Dark Matter Macroscopic Pearls,
3.55 keV X-ray line, How big 
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Abstract
We study the 3.55 keV X-ray suspected to arise from dark matter in our model of dark matter consisting of a bubble of a new phase of the vacuum, the surface tension of which keeps ordinary matter under high pressure inside the bubble. We consider two versions of the model:

• Old large pearls model: We worked for a long time on a pearl picture with pearl / bubbles of cm-size adjusted so that the impacts of them on earth could be identified with events of the mysterious type that happened in Tunguska in 1908. We fit both the very frequency, the 3.55 keV, and the overall intensity of the X-ray line coming from the center of the Milky Way and from galaxy clusters with one parameter in the model in which this radiation comes from collisions of pearls.

• New small pearl model: Our latest idea is to let the pearls be smaller than atoms but bigger than nuclei so as to manage to fit the 3.5 keV X-rays coming from the Tycho supernova remnant in which Jeltema and Profumo observed this line. Further we also crudely fit the DAMA-LIBRA observation with the small pearls, and even see a possibility for including the electron-recoil-excess seen by the Xenon1T experiment as being due to de-excitation via electron emission of our pearls. The important point of even our small size pearl model is that the cross section of our “macroscopic” pearls is so large that the pearls interact several times in the shielding but, due to their much larger mass than the typical nuclei, are not stopped by only a few interactions. Nevertheless only a minute fraction of the relatively strongly interacting pearls reach the 1400 m down to the DAMA experiment, but due to the higher cross section we can fit the data anyway.

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1 Introduction
The main purpose of the present article is to put forward the latest developments of our long speculated idea that the so far mysterious dark matter found via its gravitational forces, instead of consisting of particle of atomic masses or an Axion-like condensate, could consist of our proposed type of macroscopic objects with a mass much bigger than that of genuine atoms.

We started our speculations already years ago by supposing cm-size pearls make up the dark matter, but they will be developed in the section 8 below into the idea that these pearls could indeed be much smaller and of geometrical size even smallish compared to atoms, although the mass should still be appreciably larger than that of atoms.

We shall stress small macroscopic pearls.
Even such a dramatic change in our old model into a version with much smaller pearls would not be observed via the gravitational effects provided just that the density of mass per unit volume is kept the same. It is also this fact that really only the mass density matters for the gravitational effects, that makes it possible that these effects cannot distinguish our types of heavy or relatively lighter pearls from the more usual assumption of only atomic weight particles, such as supersymmetric partners of $Z^0$ or photon say in superstring theory.

However, assuming that indeed the X-ray radiation [1, 2] observed by satellites and suspected to come from dark matter does indeed come form dark matter requires more specific models for what the dark matter could be; e.g. it could consist of some new sort of sterile neutrino able to decay although very seldomly into a photon and e.g. an ordinary neutrino. Such a sterile neutrino should then of course have a mass equal to just two times the photon energy number 3.55 keV of the observed X-ray radiation counted in the rest frame of the supposed dark matter in the region observed.

- **Our Old Model:** We develop an alternative version of our model [3, 4, 5, 6] in which dark matter consists of cm-size pearls with masses of $10^8$ kg under the attempt to identify the X-ray radiation seen by satellites and supposed to originate from dark matter with the energy per photon 3.55 keV. We shall discuss the possibility that the dark matter pearls be much smaller but still macroscopic. This is our new model with small pearls of a size smaller than atoms but bigger than atomic nuclei.

Actually we assume that our pearls have a skin surrounding them keeping some ordinary matter inside the pearls under such an (appropriate) pressure that, in the electron system of this ordinary matter inside, there appears an energy gap between filled and empty electron states - called the homolumo gap (to be explained later) - of size close to the energy difference just 3.55 keV of the observed radiation. The idea then is that there can be excitations being (loosely) bound states of an electron in one of the lowest empty states and a hole in one of the at first filled states. These excitons should have an energy close to the observed photon energy in the line. Then one could have that the photons observed astronomically by the satellites are photons from the decay of such excitons in the highly compressed ordinary matter material in our model supposed to exist inside pearls making up the dark matter.

It is a major part of our work [3] to evaluate the rate of such X-ray radiation that will result under the assumption that the main production of the 3.5 keV radiation comes about when two of our dark-matter-pearls collide with each other. We claim it to be a great success that the magnitude of this rate of radiation can be fit together with the energy per photon, the number 3.5 keV.

We shall in the present article have in mind really two models, which are essentially inconsistent with each other. In the first model the mass of one pearl is about $1.4 \times 10^5 kg$ and in the other model the mass is about $10^4 GeV = 10^{-23} kg$. The old value of $1.4 \times 10^5 kg$ was taken as a fit to the famous Tunguska-event in 1908 taken to be due to the impact of one of our pearls. The small mass proposal of about $10^{-23} kg$ is rather inspired by an attempt to fit to the DAMA (-LIBRA) experiment (by
most people presumably believed to be due to something else other than dark matter). (A presentation of the DAMA results is given in the present Bled Workshop proceedings).

- **Observational Discussion:**

  Our small mass $10^4$ GeV $\approx 10^{-23} \text{kg}$ pearl proposal is filled with ordinary matter with an estimated density of the order of $10^{14} \text{kg/m}^3$ as we fit the size of the pearl, It is clear that the size of such a small pearl will nevertheless be so big - bigger than an atomic nucleus - that the cross section is likely to be so big that it could not possibly pass through about 1400 m into the earth without interacting. So in this sense our dark matter pearls are not WIMPS since the WI in this acronym stands for weakly interacting. It could still be dark in the sense that the interaction with e.g. light per mass unit could be small, but not small per pearl.

  With such a strong interaction one may worry whether such pearls have any chance of reaching down to give any signal in underground experiments looking for dark matter, because the pearls might be stopped in the shielding above the experimental apparatus; but here the reader should have in mind that a pearl that is heavy compared to atoms or nuclei, when it hits, will not be stopped but just deliver a smaller part of its kinetic energy to the hit particle, so that the latter obtains a speed of the same order as the speed of the incoming pearl.

  Of course, if one has a hugely heavy pearl as we estimated of cm-size and with the large mass of $1.4 \times 10^8 \text{ kg}$, then it will cause a major catastrophe, like the famous one in Tunguska, and a potential underground laboratory would be destroyed rather than making a proper observation.

  But with the small size pearl having a mass in the $10^4$ GeV range the pearl would still interact a lot with the earth in the shielding, but possibly not enough to be fully stopped before reaching say the DAMA-LIBRA laboratory proper. Actually we shall imagine that a very small fraction of the pearls come through to the laboratory, by accident so to say.

  If the pearls interact several times passing through the experimental apparatus they will be disqualified as dark matter, which is usually assumed to have so small a cross section that they only interact once in the detector. Even if a dark matter pearl interacts several times in the shielding - but is not observed to interact because a high mass is not stopped but can continue - it may well be observed essentially as a dark matter event anyway.

  Really we would like to propose a picture for the $10^4$ GeV mass pearls that a major part of the pearls end up getting stopped in the shielding - the earth above the experimental hall underground - but that the pearls with the smallest cross sections come through to the experimental apparatus and is observed there. If the pearls have a much bigger cross section than normal WIMPs they may well produce a non-negligible number of events even if the number reaching through is much lower than the number of WIMPs one would have expected.

  In other words for the $10^4$ GeV mass pearls we shall speculate that compared to the usual WIMP picture the much higher cross section of our
pearls than that of the WIMPs can compensate for the lower number of pearls than of WIMPs reaching to the experimental apparatus for two reasons:

- There are fewer pearls than WIMPs if the pearls are as suggested heavier than the WIMPs, because we have to keep the gravitational effects the same to have the same mass density in the universe.
- There are few pearls also because some of the pearls get stopped in the shielding due to the bigger cross section in spite of them being heavy and not so easy to stop.

Now we should also mention that what is truly measured in the DAMA-LIBRA experiment is not so much the full numbers of presumed dark matter particles interacting with the apparatus, but rather the seasonal variation of the number of events. If indeed what they see in DAMA-LIBRA were due to our rather strongly interacting pearls, then there would be a seasonal effect partly due to the pearls coming in one season with higher speed than in another so they would be able to penetrate deeper. If by chance the depth of the laboratory is close to the average stopping place of the pearls, such an effect of different penetration depths in the different seasons might be delicate to estimate, but could make it possible to get a bigger seasonal effect than estimated in a more simple way.

Let us immediately remark, that if indeed such seasonal variation due to relatively small changes with season of the penetration depth of interacting pearls (dark matter particles), then this could mean that the DAMA-LIBRA type of experiment measuring mainly the seasonal effect could be favoured in finding a signal over other experiments not using this technique. This would help solving the main problem or mystery in connection with the DAMA-LIBRA experiment: Why do the other underground experiments looking for dark matter not see the same amount of it as DAMA-LIBRA? Now we would answer that DAMA-LIBRA may sit close to the average penetration depth and in one season this penetration depth is a bit deeper and DAMA-LIBRA sees a lot, while in another season the average penetration depth is a bit higher up and one does not see so much. Actually our fit suggests that the average penetration depth is only a small part of the way down the 1400 m but the falling off tail of the distribution which DAMA observes varies exponentially with the variation in average penetration depth and a rather big seasonal effect is indeed expected.

We want to conclude that IMPs (= interacting heavy particles) as our pearls could be denoted rather that the usual WIMP picture is a possibility for what the underground experiment DAMA-LIBRA could have observed.

And our argument about the penetration depth could be used to explain that other experiments did not see the same dark matter.

1.1 Plan

In the following section we present a couple of figures about the dark matter as known already via its gravitational forces, and in the following section we give
a couple of figures about impacts of objects like meteors falling on earth with the purpose of comparing the energy delivered with that which dark matter could deliver, if it fell like other objects. Then in section 4 we review some of the ideas needed to understand our type of model with pearls consisting of a bubble of a new type of vacuum (this is just our speculation because so far nobody really saw any new vacuum convincingly). In the subsections of this section we present in 4.1 our postulated new law of Nature “Multiple Point Principle”, which is the main new assumption in our work in as far as, except for this multiple point principle, we only need the Standard Model as the laws of nature. We only make further speculations on the dynamics such as the existence of bound states or in general on results of the too hard to calculate, but by far not excluded possibilities in the Standard Model. In the subsection 4.2 we say a few words about the domain walls that will separate such different phases of the vacuum that we speculate exist. In subsection 4.3 we mention the effects other than gravitational ones which are probably due to the dark matter. The most important such effect for the present work is the excess X-ray radiation observed as a tiny peak above the best understanding fit to the X-ray spectrum at the photon energy 3.55 keV. Other such likely dark matter effects are an excess of positrons and the associated gamma rays; and then, what we are very keen on, one of the experiments Xenon1T meant to look for dark matter saw a little excess of electrons appearing in the apparatus, at first seemingly not dark matter; but we think it could be our dark matter pearls passing slowly through and delivering electrons with just the energy 3.55 keV.

In section 6 we mention that the type of dark matter models most popular in the literature, except for black holes making up the dark matter, need to modify the Standard Model by introducing extra particles corresponding to extra fields. Most popular is to use supersymmetry models in which there has to be included as many new physics particles as there are particles already. Compared to that one should understand that we only add a new fine-tuning principle the “Multiple Point Principle”, which is an extra assumption about the values of coupling constants that can even be checked and at least are close to work, while the usual modified Standard Model has lots of extra particles not yet found.

Next in section 7 we discuss the fitting with our large pearl model, and in section 8 we then consider the model with the “small”, meaning little less than atomic size, pearls. Really this “small” size is in fact very large compared to what is considered in more conventional models (such as supersymmetry). In the subsection 8.1 we extract the ratio of cross section to mass for the dark matter required from the observation of the 3.55 keV X-rays from the Tycho supernova remnant and compare it to the corresponding ratio for nuclei in subsection 8.2. Then in the subsection 8.3 we present the fit of the small pearl model, but the fitting is based on the discussion of the DAMA(-LIBRA) experiment that we have first put in the next subsection 8.4.

In section 9 we resume and conclude the article.
Figure 1: **Motion relative to Dark Matter** Here is drawn how the solar system moves along relative to the supposed rest system of the bulk of the dark matter. One shall imagine the earth going around the ellipse drawn which in perspective is an approximate circle representing the orbit of the earth. Note how the speed of the earth w.r.t. the dark matter average will vary with the season.

2 We know something from the gravitational studies

As is well-known the dark matter has mainly and in fact possibly only been seen by its gravitational effects - and it could still be a possibility that there is no dark matter, but instead that something is wrong with our understanding of the gravitational force - but even from only observing it via the gravitational force, one can nevertheless derive some understanding of its distribution and velocity.

In fact one can already estimate that the solar system as a whole moves relative to the local dark matter average velocity with a speed of 232 km/s according to the figure 1.

Further the distribution of the dark matter **Motion of Dark Matter, stars etc.**

**Numbers for Crude Estimates**

- **Density of Dark Matter in Solar System Neighborhood:**
  \[
  D = \frac{0.3 \text{GeV}}{\text{cm}^3} = 5.35 \times 10^{-22} \frac{\text{kg}}{\text{m}^3} \quad (1)
  \]

- **Typical Speed (also relative to each other):**
  \[
  v = 200 \text{ km/s} = 2 \times 10^5 \text{ m/s} \quad (2)
  \]
Figure 2: Velocity histogram of different components of the Milky Way, as seen in the ERIS simulation. The black histogram shows the velocity distribution of dark matter. The cyan histogram illustrates the velocity of all stars, and has a much larger central peak than the dark matter distribution. The orange histogram, however, which includes only metal-poor stars, is very similar to the dark matter velocity distribution. (Herzog-Arbeitman et al. [7])

- Rate of Impacts on crossing Area, per $m^2$:

\[
Rate = vD = 1.07 \times 10^{-16} \frac{kg}{m^2s}
\]  

(3)

These numbers may be crudely estimated by looking at the distributions in figure 2, which have been gotten from the ERIS simulation of the dark matter.

3 Compare to Rates of Impacts on Earth

For the dark matter we have thus found the rate

\[
Rate = vD = 1.07 \times 10^{-16} \frac{kg}{m^2s}
\]  

(4)

In Table 1 we use this $vD$ for dark matter in our neighborhood to derive a few estimates of impact rates for dark matter, if dark matter were indeed macroscopic particles with the masses listed in the first column of this table:

**Hitting Rates for some Masses:**

In the first column is given the mass of the dark matter pearl. The second column gives the rate of impacts such a mass would give per $m^2$ and in the third column this rate is translated into the time between the impacts on this square meter. The fourth and fifth column similarly give the rates and the time in between impacts for impacts on the Earth in total instead of just on a square meter. Notice that in the row corresponding to the mass of the dark matter
particle being $10^8 \text{kg}$ there is - in the last column - about 100 years between the impacts. Now it was approximately 100 years ago when the famous Tunguska event occurred, meaning that if the Tunguska event should be caused by a dark matter pearl, then the mass would be of the order of $10^8 \text{kg}$.

Table 1: A few rates for hypothetical dark matter pearls

| mass     | $m^2$ rate | $m^2$ time | earth rate | earth time |
|----------|------------|------------|------------|------------|
| $10^{-16} \text{kg}$ | $5 \times 10^{10} \text{GeV}$ | $1 \text{s}^{-1}$ | $1 \text{s}$ | $5 \times 10^{16} \text{s}^{-1}$ | $2 \times 10^{-15} \text{s}$ |
| $10^{-8} \text{kg} = 10 \mu \text{g}$ | | $10^{-8} \text{s}^{-1}$ | $10^9 \text{s} = 3 \text{y}$ | $5 \times 10^8 \text{s}^{-1}$ | $2 \times 10^{-9} \text{s}$ |
| $1 \text{kg}$ | | $10^{-18} \text{s}^{-1}$ | $10^{11} \text{s}$ | $5 \text{s}^{-1}$ | $0.2 \text{s}$ |
| $10^8 \text{kg} = 10^{8} \text{ton}$ | | $10^{-22} \text{s}^{-1}$ | $10^{22} \text{s}$ | $5 \times 10^{-19} \text{s}^{-1}$ | $2 \times 10^{9} \text{s}$ |

Next we now give a similar table for meteor impacts as observed, impacts a priori expected to be made from “ordinary matter” (i.e. atoms). Here it is meant that the impacts are counted for the whole Earth:

**Compare Impacts of Ordinary Matter**

$10^{-2} \text{kg} : 10^5$ per year

$1 \text{kg} : 10^4$ per year.

$10^8 \text{kg} : 10^{-3}$ per year.

You may consider the numbers in this table as extracted from the figure.

Since a year has $3.16 \times 10^7 \text{ s}$ this corresponds to a mass density $D_{\text{meteors}}$ times the velocity $v_{\text{meteors}}$ being of the order

$$v_{\text{meteors}} D_{\text{meteors}} \sim \frac{10^4 \text{kg/year/eartharea}}{3.16 \times 10^7 \text{s/year}} \quad (5)$$

$$= \frac{3 \times 10^{-3} \text{kg/eartharea/s}}{0.5 \times 10^{15} \text{m}^2/\text{eartharea}} \quad (6)$$

$$= 2 \times 10^{-18} \text{kg s}^{-1} \text{m}^{-2}; \quad (7)$$

formally a **factor 50 smaller** than the dark matter. Rather than the mass of the impact object you might use its size and then we get the graph in figure.

From this figure we can read off an approximate dependence of the size of the impacts on earth and their frequency. Approximately the inverse frequency being the “time between” goes as the square of the size of the impacting object. So a formula easy to remember is:

$$\text{“impact size” in m} = \sqrt{\text{av. “time between” in years}} \quad (8)$$

on earth.

On the figure we see the relation between energy release by the impact and again the frequency measured in impacts per year.

**Would Macroscopic Dark Matter Dominate Meteors?**
Figure 3: Size of Impact goes as square root of “time in between”

Figure 4: Relation between energy released and impacts per year
Taking very roughly the graph as having the slope -1 in the logarithmic plot we may read off that the energy of impacts per year is of the order of magnitude of $10^{13} \text{ J/y}$ to $10^{14} \text{ J/y}$.

To compare with that the kinetic energy in the column of dark matter hitting the earth per year is for non-relativistic dark matter particles of the order of

$$\text{"dark matter power on earth" } = \quad (9)$$

$$= \frac{1}{2} * (300 \text{ km/s})^3 * 0.3 \text{GeV/cm}^3 * \pi * (6.38 * 10^6 \text{ m})^2 \quad (10)$$

$$= \frac{1}{2} (3 * 10^5 \text{ m/s})^3 0.3 * 1.78 * 10^{-21} \text{ kg/m}^3 * \pi * (6.38 * 10^6 \text{ m})^2 \quad (11)$$

$$= 1.27 * 10^{16} \text{ J/y} \quad (12)$$

(using 1 year = 31556952 s)

So it looks that unless some of the kinetic energy of the dark matter hitting the earth is lost from showing up as observable impacts, there is too much energy in the dark matter to match the impacts as observed.

In our old work [6] we took it that because of the smallness of even cm-sized pearls they penetrate so deeply into the earth that it is realistic that an appreciable part possibly $19/20$ of the energy is penetrating so deep into the earth, that it does not appear as observed energy on the surface of the earth. Since we could well find it consistent that our big pearl (=cm-size) would go thousands of km into the earth, it would indeed be hard to get all the energy out so quickly as to be identified with the energy of the impact.

### 4 Requisites for Our Model(s)

Before going on to fit our type of model and discussing how well such pearl models for the dark matter matches much of our knowledge about the dark matter, as it actually will, we shall put forward a few prerequisites needed for understanding the speculations making up at least one concrete example of a macroscopic pearl model of the dark matter.

As a motivation for just our concrete picture for how the pearls could come about let us stress: **Our picture of dark matter pearls can come about in the pure Standard Model, i.e. without any new physics in the sense of new basic particles.** We shall rather only speculate about new particles which are bound states of the already known particles, and thus do not require any modification of the Standard Model. We have e.g. no supersymmetric partners, because we do not have supersymmetry at least not in the relevant region of energy for our model.

Gia Dvali showed that the existence of several vacua is inconsistent unless they are degenerate in the article “Safety of Minkowski Vacuum” [8].

#### 4.1 Multiple Point (Criticality) Principle

The point in our work, which comes closest to assuming new physics, is the principle that the coupling constants of the true model for physics - for our
purpose here the Standard Model - are by a “new Law of Nature” tuned in to
just arrange that there are a series different phases of the vacuum - different
vacua we could say - which all have the same energy density ($=\text{cosmological}$
constant) $[9, 10, 11, 12]$. We call this principle of such fine-tuning of the coupling
constants the **Multiple Point (Criticality) Principle** (MPP) $[9, 10, 11, 12]$. There has been given various arguments for it $[8, 9, 10, 11, 12]$, and we can
claim that using it we have even made correct predictions, e.g. the number
of families, prior to the LEP measurement of the number of light neutrino
species. We fitted fine structure constants in a rather complicated model called
ANTIGUT and the fitting parameter was indeed the number of families. We
predicted that to be 3. Later we obtained a mass prediction $[13]$ for the Higgs
mass $m_{\text{Higgs}} = 135 \pm 10 \text{ GeV}$ before the Higgs was found.

For our pearl-models of the dark matter it is important that Nature should
have this fine-tuning at least to an appreciable accuracy making the inside
and the outside vacua for our pearls of equal energy density. This is because
otherwise almost certainly one of the phases would spread out and it would
be very hard to get pearls that are stable. Actually even with the degenerate
vacua we have in our model the need for getting the pearls filled by ordinary
matter under high pressure to withstand the pressure coming from the tension
of the surrounding skin or domain wall. Guesses as to the order of magnitude
for what the energy density difference should be, if not tuned to be small, would
be so high that our model would become unlikely. Though, if e.g. the energy
density difference was only of the order corresponding to the observed order of
magnitude for the vacuum energy in the universe it would contribute so little
over one of our pearls that it would not disturb our calculations taking the
difference to be zero.

### 4.2 Domain walls in general

There is also a discussion of walls in another article $[14]$ in these proceedings.

We ourselves like to point out, that once we have the “Multiple Point Prin-
ciple” we have in principle the possibility that some even large regions in space
could be filled by one phase while another region could be filled by another
phase of the vacuum. Had we had a spontaneously broken discrete symmetry it
would induce a case of “Multiple point principle” in as far as two or more phases
related by the broken symmetry would of course have for symmetry reasons the
same energy density. It is however, not such a case of a spontaneously broken
discrete symmetry, which we imagine in our model. We rather speculate that
two a priori different, and not connected to each other by symmetry, vacuum
phases are to be used. Having the spontaneously broken discrete symmetry is also phenomenologically badly working, in as far it would typically lead to
random vacua coming to dominate in various regions outside the horizons of
each other. Such outside each others horizon different dominating vacua would
cause domain walls extending over longer distances than the horizon and in turn
make up huge amounts of domain walls in cosmology. Unless the wall tension
was extremely small such horizon scale walls would get to dominate under all
circumstances in the long run; and that would spoil our cosmological models.

So we must hope, and we actually do expect, that the domain walls due
to the asymmetry between their sides - i.e. due to the fact that the different
vacuum phases are not connected by symmetry - will contract a bit more towards
diminishing one vacuum than the other one. Thus at an early stage in the history of
the universe one of the vacua only survives in small bubbles compared to
the universe size. It is such small surviving bubbles that should be the dark
matter. Actually even the small bubbles only survive because at a stage they
get stopped from contracting by having collected so many nucleons inside that
they can provide a sufficient pressure to stop the contraction.

For our cm-size pearls we had an estimate that the contraction of the pearls
to the stability point where they just have the size given by their content of
nucleons, counter acting the pressure, would end about the time in cosmology,
when the big bang nuclear synthesis is about to start and temperature is of MeV
size. It is very needed for our model that the pearls have become so compact
and effectively disconnected from the rest of the plasma before the big bang
nuclear synthesis properly begins, because otherwise our model would modify
this big bang nuclear synthesis, and it would be an unconvincing refitting even
if we managed to fit the abundances of the various light isotopes resulting form
the big bang nuclear synthesis.

Nevertheless one should of course investigate astronomically if some of the
big voids observed in the matter distribution should actually be a result of do-
main walls. If one had, for some accidental or other reason, an astronomical size
region with the same vacuum as inside our pearls, formally an enormously large
dark matter pearl, then we would expect there to be the same matter density
inside this huge pearl as on the average in the universe. But now there would be
no way to have true dark matter in the region, because the whole region is al-
ready formally dark matter. Pearls inside it of the present phase vacuum would
repel rather than attract nucleons and would thus totally collapse. Therefore
in such regions one would in practice lack the dark matter and have it replaced
by a higher density of ordinary matter. The latter would, however, have elec-
trons staying relativistic longer than dark matter would have stayed relativistic.
Thus these regions would presumably develop their inhomogeneities later than
the regions where the present vacuum dominates. This could then be likely to
delay the development of stars and galaxies in such formal huge dark matter
bubbles of astronomical size. Such regions might appear as voids?

4.3 Non-gravitational Dark Matter Observations

We believe it is true to say that all non-gravitational signs from dark matter are
somewhat doubtful. Nevertheless our main aim in this article to look especially
for whether our model can get support from the observations of one of the
presumed non-gravitational observations of dark matter, the 3.55 keV X-ray
radiation in outer space, mainly seen\textsuperscript{[1, 2]} from our Milky Way Center or from
big clusters of galaxies.

4.3.1 The 3.55 keV X-rays

We have already mentioned this for us so important X-ray observation in a
line of frequency 3.55 keV, which seems not to be explained by the atomic ion
transitions expected in the plasmas from which the X-rays come. But it is only
a tiny little deviation from the main fit of the X-ray spectrum and e.g. an
unexpectedly high abundance of potassium in the plasmas could make a line in
the region of the 3.55 keV be increased so much as to replace the tiny suspected dark matter line.

Using the expectations from the gravitational knowledge about the distribution of the dark matter, fits have been made to the 3.55 keV radiation expected both under the assumption that the emission from a region depends linearly on the density $D$ of dark matter and under the assumption, that the amount of 3.55 keV line radiation is proportional to the square of the dark matter density $D^2$. It is the latter dependence that should come out of our model, because we postulate that the 3.55 keV radiation arises when our pearls collide. Both types of fits are not hopeless, and even the rather well fitting analysis by Cline and Frey [15], which we use in our work, has at least one severe discrepancy: one of the measurements in the outskirts of the Perseus Cluster delivers about 1000 times more 3.55 keV radiation experimentally than one should expect by extrapolating the fits to the other observations.

In our use of the analysis of Cline and Frey, we simply had to delete this observation to obtain a meaningful average for the overall scale of the radiation which is then what we ourselves sought to fit.

We should investigate, if we could understand this deviating measurement in the Perseus Cluster as due to our pearls getting energy for 3.55 keV radiation in a different way than from the collisions. In fact we have similar problem with the Tycho supernova remnant in which the square of the density $D^2$ over the supernova remnant region is very tiny in comparison to galaxy clusters and the Milky Way Center extensive volumes. The supernova remnant region, even taking into account the closeness of the Tycho supernova remnant, is so small that it would not be expected that Jeltema and Profumo should have seen the 3.55 X-ray line from the dark matter there. But in fact Jeltema and Profumo [21] have seen 3.55 keV radiation from the supernova remnant.

Our suggestion is that the cosmic rays or X-rays in the Tycho supernova region can excite the pearls, which then whatever the excitation energy - collision or cosmic ray excitation - will emit an appreciable part of the energy as 3.55 keV radiation.

One could of course hope - and we hope to find out - that there are some similar cosmic rays or X-rays reaching the outskirts of the Perseus Galaxy Cluster.

Of course, if the cosmic ray or X-ray activity is about the same in two neighboring regions in say the Perseus Cluster, then the ratio of the X-ray or cosmic ray feded radiation relative to the one feeded by the collisions will go in the ratio $\frac{D^2}{D^1} = D^{-1}$. This is because the rate from cosmic ray feeding goes as $D$′ “density of cosmic rays”, while the collision rate goes as $D^2$. In the outskirts of the cluster the density of dark matter $D$ presumably goes down, and thus the cosmic ray feded radiation becomes relatively more important.

4.3.2 Positrons and Other Gamma-rays

Also positrons above some 10 GeV in energy have shown an excess suggested to be due to dark matter together, as one could imagine, with gamma-rays not in a line but in a broader spectrum. In this connection there is a little problem:

Using usual types of model for dark matter identified with some type of particle simply decaying into among other things the positron to make the excess, it is very hard to avoid that associated with this positron emission one
does not also get some gamma-rays. Now, however, the fitting does not go well and it seems that experimentally there are not so many gamma-rays as is almost unavoidably needed for matching the positron excess!

This little tension with an elementary particle dark matter interpretation could provide support for our type of model, because at the collision and strong heating up of the uniting pearls a large amount of electrons will be emitted and can easily create electric fields that in a rather low acceleration way can accelerate e.g. positrons. Thus one can get positrons which are not produced at high speed almost abruptly, but which are “slowly” accelerated. The latter gives much less electromagnetic radiation and thus our model has the potential of making positrons with much fewer gamma rays connected with them. This would agree better with the too few observed gamma-rays.

4.3.3 Xenon1T Electron Recoil Excess

Yet another effect, which we shall count as a non-gravitational effect of dark matter, but which is not obviously dark matter at all: the Xenon1T electron recoil excess.

Apart from the DAMA/LIBRA and the DAMA experiment all other experiments seem to find only negative results, when looking for the dark matter in direct searches. There was, however, found one unexpected result [16] although at first not seemingly related to dark matter:

The experiment Xenon1T investigated what they call electron recoil in their Xenon experiment. In the Xenon experiment one has a big tank of liquid xenon with some gaseous xenon above it and photomultipliers looking for the scintillation of this xenon, the philosophy being that a dark matter WIMP e.g. hits a nucleus inside the xenon and the recoil of this creates a scintillation signal S1 and also an electron, which is then driven up the xenon tank by an electric field and at the end by a further electric field made to give a signal at the top S2. By the relative size of the signals S1 and S2 one may classify the events - which are taken to be almost coinciding pairs of these signals S1 and S2 - as being nucleus recoil or electron recoil. One expects to find the dark matter in the nucleus recoils, since a dark matter particle is not expected to make an electron have sufficient energy to make an observable electron recoil event.

But now by carefully estimating the expected background, the Xenon1T experimenters found an excess of electron recoil events.

Ideas proposed for explaining it include axions from the sun or neutrinos having bigger magnetic moments or perhaps less interestingly that there could be more tritium than expected in the xenon.

But here with our model of relatively stronger interacting particles able to radiate the line 3.55 keV when excited we have a possible explanation:

Going through the earth above the detector and the rest of the shielding, the pearls or particles get excited so as to emit 3.55 keV X-ray just as they would do in the Tycho supernova remnant, where they also get excited by matter or cosmic rays. But then the particles passing through the deep underground Xenon1T experiment are already excited and prepared for emitting the 3.55 keV radiation. Now they could possibly simply do that in the xenon tank or they might dispose of the energy by a sort of Auger effect by rather sending out an electron with an extra energy of 3.55 keV. Such an electron with an energy of a
few keV could be detected and taken for an electron recoil event in the Xenon1T experiment.

It is remarkable that the signal of these excess electron recoil events appears as having just an energy of the recoiling electron very close to the value 3.55 keV. Indeed the most important bins for the excess are the bins between 2 and 3 keV and the bin between 3 and 4 keV.

So we would claim that there is in our model no need for extra solar axions or a neutrino magnetic moment, nor tritium.

But we claim it to be 3.55 keV radiating dark matter one sees in the xenon experiment!

4.3.4 The Dark Ages, 21 cm line

As a possible place to look for information about dark matter - especially of the pearl type say - is the influence it could have had in the “Dark ages” before the stars lit up the universe, a time that may be investigated through the study of the H1 radio line of 21 cm wavelength. Recent studies [17, 18] were pointed out to us by Astri Kleppe.

4.3.5 Supernova Introductional Burst

As an interesting possibility for studying our dark matter pearls astronomically, we should also mention our older work, in which we claim [19] that our dark matter pearls can not only help the supernovae to explode more, which is what is called for, but also to explain a neutrino burst appearing some hours before the genuine explosion, as appears to have been observed by the neutrino experiment LSD [20].

5 Status of Searches

Before going on to describe our models for dark matter being pearls of a new phase of vacuum, let us shortly review the status of the searches for dark matter in underground experiments. The plot in figure 5 shows the excluded regions in the cross section versus mass plane for dark matter particles in the usual WIMP-theory: It is important to notice for our work below that inside the region excluded by several experiments there is a spot in which the DAMA-LIBRA experiment - in fact by 9 standard deviations - claim to have found the dark matter (or at least something with very similar properties) by their special technology of looking for seasonal variations, that should appear because the speed of the Earth relative to the average velocity of the dark matter varies with season (see figure 1 above).

6 Dark Matter with only the Standard Model (except MPP)

Contrary to everybody else, except for the people who take primordial black holes for dark matter, we want to propose a dark matter model inside the Standard Model, only with a certain assumption about the coupling constants
Figure 5: Areas of the cross section versus mass of WIMP dark matter particles above the curves are excluded. So one sees that regions favoured by DAMA and CDMS-Si are seemingly in disagreement (although not in a theory independent way). See reference [21].
in the Standard Model, that there are several vacua fine-tuned to have the same energy density. So we have very little “new physics”:

- We assume a law of nature - of a somewhat unusual kind - the “Multiple Point Principle” saying: there are several different vacuum phases, and they all have the same energy density (or we can include that they have $\sim 0$ energy density.)
- Apart then from mentioning an attempt mainly with Yasutaka Takanish to explain the baryon excess, we shall use only the Standard Model, even for dark matter!

7 Our Fit

We performed a detailed fit with the model [3] in which we first of all looked for the absolute scale of the intensity of our model of dark matter pearls or balls emitting the X-ray line with photon energies of 3.55 keV in the rest system as apparently observed by satellites etc.

7.1 The Intensity

The intensity we take in our model to be emitted by pearls, that have collided with one another - a rather infrequent event - but when they finally collide it is assumed, that the very strong skin surrounding the pearls can contract and thereby deliver energy, which can be used for the radiation in the 3.5 keV line or for other frequencies. There is in our model so to speak an active “energy production from the contraction”. But this we can in fact estimate, if we have the parameters of the model. Of course the fact that we need collisions of a pair of pearls to get the radiation in the 3.5 keV line means, that the intensity resulting in a given region of the space becomes proportional to the square $\rho_D$ of dark matter in that region. A fit to a model of this kind- which would also be applicable for a model in which the dark matter particles annihilate with each other - was performed using the astronomical - mainly satellite - data by Cline and Frey [15]. For the purpose of our model we can interpret it that they measure an intensity proportional parameter, which basically is in our language $N\sigma M^2$, where $M$ is the mass of the typical / average pearl, $\sigma$ the cross section for one such pearl hitting another one, and $N$ the number of 3.5 keV photons emitted when such a collision actually happens. From the results of Cline and Frey we find the number

$$\left(\frac{N\sigma}{M^2}\right)_{exp} = (1.0 \pm 0.2) \times 10^{23} cm^2/kg^2$$

(13)

or rather we extract this number from their table:

It should be noticed though that something is not fitting well in the case of the Perseus Cluster in as far as one measurement in the outskirts of this galaxy cluster turns out to give a factor 1000 more radiation in the 3.5 keV line than the one that would have fitted with the proportionality to the squared density estimated from gravitational considerations. In our averaging we left this observation out totally, since it would have led to a very bad fitting for
Table 2: This table is based on the table 1 in reference [15].

| Name          | $N < \sigma_{CF}v > *$ | $v$ | boost | $(\frac{N<\sigma_{CF}v>}{10^{13}cm^2})^* v$ | Remark |
|---------------|------------------------|-----|-------|---------------------------------------------|--------|
| Units         | $10^{-24}cm^2s^{-1}$   | $km/s$ |       | $(\frac{N<\sigma_{CF}v>}{10^{13}cm^2})^* km^2$ |        |
| Clusters[1]   | 480 ± 250              | 975 | 30    | 0.016 ± 0.008                              |        |
| Perseus[1]    | 1400 - 3400            | 1280| 30    | 0.037 - 0.09                               |        |
| Perseus[2]    | (1 - 2) *10^5         | 1280| 30    | 2.7 - 5.3                                  | ignored|
| Perseus[23]   | 2600 - 4100           | 1280| 30    | 0.07 - 0.11                                |        |
| CCO[1]        | 1200 - 2000           | 926 | 30    | 0.04 - 0.07                                |        |
| M31[2]        | 10 - 30(NFW)          | 116 | 10    | 0.0086 - 0.026                             |        |
|               | 30 - 50 (Burkert)     |     |       | 0.026-0.043                               |        |
| MW[22]        | 0.1 -0.7 (NFW)        | 118 | 5     | 0.00017 - 0.0012                           | ignored|
|               | 50 -550 (Burkert)     |     |       | 0.084 - 0.93                              |        |
| Average       |                        |     |       | 0.032±0.006                                |        |

the other observations. But without this badly fitting observation we get the average [13].

7.2 The Frequency

The very frequency or the photon energy 3.5 keV, we sought to fit with the "homolumo gap" in the ordinary material under high pressure - comparable to that in white dwarf stars - inside our dark matter pearls. Such a "homolumo gap" is a very general feature for materials containing a degenerate Fermi sea of fermions, say electrons, and in addition has some structure -like a glass or almost all materials - consisting in that the material in detail adjusts so as to partly lower the energy density of the Fermi-sea. It is obvious that the energy of the Fermi sea is lower the lower in energy the filled fermion states, whereas lowering the energy of the empty states does not lower the total energy. The adjustment to a ground state of the material will therefore (almost) unavoidably lead to a lowering of the filled states and thus cause a gap between the filled and the empty states. It is this gap between the filled and the empty single particle states which is called the homolumo-gap. It is namely the gap between highest occupied molecular orbit (the chemist expression for single particle fermion state), HOMO and the lowest unoccupied molecular orbit, LUMO.

We estimated in [3] the value in energy of this homolumo gap partly just by a dimensional argument and partly by using a Thomas-Fermi approximation.

The formula for our estimate of the homolumo gap, which also turns out to be the expected frequency or photon energy for the line, was

$$E_H = \sqrt{2 \left( \frac{\alpha}{c} \right)^{3/2} E_f}.$$  (14)

Here $\alpha$ is the fine structure constant considered for the purpose of our dimensional arguments as a velocity (by multiplying it by the velocity of light $c$) and $E_f$ is the Fermi energy of the electrons in the hard compressed material inside our pearls.
7.3 The fitting and theoretical speculations

In our model we imagine that there are at least two phases of the vacuum - in addition presumably to several other ones too, but in the work now being reviewed we cared for only two important ones - and that the one in which we do not live, but which is realized inside the dark matter pearls, is distinguished from the present vacuum by there being a (boson) condensate of a speculated bound state of 6 top plus 6 anti-top quarks. In the vacuum phase inside the pearls we would at first have speculated that the expectation value of the Higgs field should go to zero, but that would give us an estimate of the tension of the skin separating interior and the exterior of the pearls, which would not give an acceptable fit. Indeed assuming that the usual Higgs spontaneous breakdown of the weak gauge symmetry in the vacuum inside the pearl is absent would suggest an order of magnitude of the tension in the skin of the pearls of the order of \((100 \text{ GeV})^3\), but the fitting we made gives an appreciably smaller tension.

\[
\xi = 10 \text{ MeV} \times \frac{R}{R_{\text{crit}}}
\]

The essential parameter we used in our fit was defined as

\[
\frac{\xi \times 10 \text{ MeV}}{\Delta V} = \frac{10 \text{ MeV} \times R/R_{\text{crit}}}{\Delta V} = \text{"potential difference for nucleon in the two vacua"}, \tag{15}
\]

In order to reduce the number of parameters in our earlier paper \[6\] we assumed that the pearls just had such a size that they were on the borderline to collapse and we call the radius of such barely stable pearls \(R_{\text{crit}}\). We now denote the actual radius of the (typical) pearl by just \(R\) and define the parameter \(\xi = \frac{R}{R_{\text{crit}}}\).

The parameter \(\Delta V\) is the binding energy of a nucleon relative to when it is in the vacuum phase in the interior of the pearls. One should imagine that nucleons are attracted by the pearls by having a lower potential by the amount \(\Delta V\) inside the pearl. If the pearl gets too small and the pressure from the skin thus too high it will pay energetically for the nucleons inside the pearl to escape and the pearl thus collapses; this is what happens when the radius is smaller than the

| Name | \(\frac{\xi \times 10 \text{ MeV}}{\Delta V}\) | \(\ln \frac{\xi \times 10 \text{ MeV}}{\Delta V}\) | Uncertainty |
|------|--------------------------------|---------------------------------|-------------|
| Frequency “3.5keV” | 5.0 | 1.61 | 100% |
| Intensity \(\frac{S}{M}\) | 3.8 | 1.3 | 90% |
| \(S^{1/3}\) theory 1) | 0.28 | -1.3 | 40% |
| \(S^{1/3}\) theory 2) | 1 | 0 | 40% |
| Combined theory \(\xi, \Delta V\) | 0.18 | -1.7 | 100% |
| Ratio \(\frac{t_{\text{spread}}}{t_{\text{radiation}}} = 1\) | 2.4 | 0.88 | 80% |

Table 3: Table of four theoretical predictions of the parameter \(\frac{\xi \times 10 \text{ MeV}}{\Delta V}\) on which the quantities happen to mainly depend. The first column denotes the quantities for which we can provide a theoretical or experimental value to be expected for our fit to that quantity. The next column gives what these expected values need the parameter combination \(\frac{\xi \times 10 \text{ MeV}}{\Delta V}\) to be. The third column is the natural logarithm of that required value for the ratio \(\frac{\xi \times 10 \text{ MeV}}{\Delta V}\), i.e. \(\ln \frac{\xi \times 10 \text{ MeV}}{\Delta V}\). The fourth column contains crudely estimated uncertainties of the parameter thus fitted counted in this natural logarithm. In the last column we just marked the ratio \(\frac{t_{\text{spread}}}{t_{\text{radiation}}} = 1\) with l.b. to stress that it is only a lower bound and shall not be considered a great agreement for our theory.
Figure 6: The values of the ratio $\frac{\xi \cdot 10 \text{ MeV}}{\Delta V}$ as needed for four constraints. There are two experimental constraints from the frequency and intensity of the 3.5 keV radiation respectively and two theoretical constraints in two versions corresponding to taking theory 1 or theory 2 for the tension. We make the simplifying assumption that all energy from the surface contraction in a collision gets emitted as 3.5 keV X-rays. The sixth line “Ratio $\frac{\text{spread}}{\text{radiation}} = 1$” represents the lower bound ensuring that all the energy actually goes into 3.5 keV radiation.

critical radius $R_{cr1}$. The 10 MeV was just a conventional number, we put in to make the parameter dimensionless.

It turned out from our calculations that the combined parameter ratio $\frac{\xi \cdot 10 \text{ MeV}}{\Delta V}$ is the main one to fit, because the interesting measurable and theoretically interesting quantities mainly depend on it.

We thus used it to make fits especially to the experimentally predictable quantities, the intensity of the 3.5 keV radiation scale and the very frequency 3.5 keV. The fitted values of the combined parameter $\frac{\xi \cdot 10 \text{ MeV}}{\Delta V}$ for these quantities are presented in Table 3 together with those expected for a tension of $(100 \text{ GeV})^3$ as obtained from the Higgs field consideration above (theory 1) - even a somewhat smaller value for the tension is speculated about and called theory 2 - and for a theoretical expectation. These predictions are also plotted in Figure 6.

We see that the theoretical expectations for the tension $S$ tend to fit with too small values of our parameter combination $\frac{\xi \cdot 10 \text{ MeV}}{\Delta V}$ and so does our theoretical estimate of the $\xi$ deviation from criticality combined with the expected value for $\Delta V$ represented in the table and the figure below as “combined theory”. The last line in the table and the figure represents a parameter value below which it is expected that more and more energy is lost to higher frequency radiation than the 3.5 keV one. This is because the pearl in the collision gets heated up and then the heat spreads out so quickly that only a very little part goes into the line observed as the 3.5 keV line. The point is indeed that we expect the temperature from the contraction of the surface to be much higher than 3.5 keV, but then this heat spreads out of course gradually on a second time scale to the whole pearl. Under this spreading out there is a spreading border at
the place to which the heating has reached at any moment. Near that border
the temperature is about 3.5 keV and the 3.5 keV radiation is produced and
because the pearl material is supposed to be transparent to the 3.5 keV and
lower frequency radiation, it is radiated out to outer space. But if the heat
reaches all through the pearl the outer surface of the pearl gets appreciably
hotter than 3.5 keV; then most radiation comes with higher frequency and is
correspondingly lost for radiation in the observed 3.5 keV line. The “time ratio
\( t_{\text{peak}}/t_{\text{eq}} = 1 \)” represents the fitting to the value 2.4 of our parameter \( \xi^{+10\text{MeV}} \Delta V \) at
which the heat just reaches to the border of the pearl. That is to say for smaller
parameter values there is a significant loss in energy to higher frequencies, while
for larger values of our parameter we expect that a major part of the energy
from the contractions manages to be emitted as the line.

8 Latest Idea: Smaller Pearls giving also DAMA
observation and Tycho Supernova Remnant
Observation of 3.5 keV

After the Bled conference we have looked at the idea that we could ignore the
connection to the Tunguska event, which was at first so terribly important for
our studies and instead seek a combined fitting of not only as just presented the
3.5 keV radiation from the clusters of galaxies and the center of our Milky Way,
but also an observation, that would at first look like spoiling the hypothesis that
the 3.55 keV line comes from dark matter. In fact this observation was consid-
ered by the authors of [24] to be a clear sign that the 3.5 keV line must after
all be an effect of some ordinary ions - such as an unexpectedly high abundance
of potassium (K) - but not a signal from dark matter. This observation is the
observation by Jeltema and Profumo that the 3.5 keV line is indeed also emit-
ted from the Tycho supernova remnant! In almost all usual dark matter models
as elementary particles this appearance from the supernova remnant with very
little dark matter compared to ordinary matter is rather absurd. It can only
come about if the dark matter can somehow absorb the energy present in the
remnant region and convert it into the 3.5 keV line.

We are now working on fitting the requirement to get the sufficient 3.5 keV
radiation from the supernova remnant and it certainly points towards smaller
values for the tension than even the fit above.

In fact we have a crude fit to both the observation by Jeltema et al. and the
DAMA and DAMA LIBRA observations, but now with both the cubic root of
the tension \( S^{1/3} \) and the potential difference for a nucleon passing through the
skin of the pearl \( \Delta V \) being of the order of 1 or 2 MeV only.

In this picture the pearls are less than atomic size and thus much more like
dark matter models with WIMPs. But, especially to cope with the amount
of interaction needed for the Tycho supernova remnant observation, they have
to interact so strongly that they will interact several times on the way down
through the earth to the DAMA-LIBRA observatory. So they should not be
called weakly interacting, i.e. the W in WIMP should be left out. Because
they are, however, still very heavy, say \( 10^3 \) GeV or even heavier, compared to
usual WIMP speculations, they are difficult to stop even when they hit matter
in the shielding. So they can pass on and penetrate into the apparatus even
if they have been somewhat hitting on the way down. Assuming that they as macroscopic objects - they are still pearls although now smaller - have somewhat different cross sections, some pearls may come through. Then even if only a small part comes through the shielding they could cause a number of events, as the observations suggest anyway in experiments like DAMA-LIBRA. Actually such a survival is only expected for some exceptional ones among the dark matter particles, which could easily lead to an enhanced dependence on the season and thus be especially suitable to be detected by DAMA-LIBRA relative to other experiments, that just observe the events independent of their season variation.

8.1 \( \frac{\sigma}{M} \) from Tycho Observation

The mysterious 3.55 keV line has been seen, corrected to zero Doppler shift, not only from various galaxy clusters and the Milky Way Center, but also from the remnant of the supernova described by Tycho Brahe after its appearance in 1572. This at first seems to be in contradiction to the hypothesis that the X-rays should come from dark matter at all.

The authors Jeltema et al. [24] take it that this Tycho supernova remnant observation means that the 3.55 keV line radiation cannot come from dark matter because basically there would not be dark matter in sufficient amounts in the supernova remnant. It would then have to be an ordinary transition line in excited ions, which must have been underestimated in the theoretical calculation of the other radiation from the supernova remnant say. Actually some underestimate of the abundance of potassium K could deliver a line in the region.

But we basically take the point of view, that dark matter consists of some (type of) particles which have the possibility of being excited, and then when excited to send out especially X-rays in the 3.55 keV line. So we have the option of having the activity in the supernova remnant excite the dark matter particles there and thus make them radiate with their characteristic frequency 3.55 keV. (In the galactic clusters etc. we have a model of exciting them by collisions causing skin contraction and thus extra energy being set free. But the emission is again the characteristic line 3.55 keV.)

But of course the absolute imperative for such a model for creating the 3.55 keV line radiation in the supernova remnant is that the dark matter particles (whatever they may be) have sufficiently big cross sections to at least pick up enough energy for the emission of the observed 3.55 keV line radiation.

8.1.1 How we got the need for \( \frac{\sigma}{M} \geq 6 \times 10^{-7} \text{m}^2/\text{kg} \)

8.1.2 What observed:

Jeltema and Profumo claim [24] that they have observed an X-ray spectral peak - fitted with difficulty, but nonetheless fitted to be there - with an intensity of \( 2.2 \times 10^{-5} \) photons per \( \text{cm}^2 \) per s. Thus in each \( \text{cm}^2 \) of the sphere around Tycho passing through the earth, there passes \( 2.2 \times 10^{-5} \) photons per s per \( \text{cm}^2 \) (or is it \( 2.2 \times 10^{-6} \) as there is a discrepancy with the figure in [24], and if the figure is right).

The distance to Tycho (SN1572) is about 9000 light-years. In fact, according to Wikipedia:
“The distance to the supernova remnant has been estimated to be between 2 and 5 kpc (approx. 6,500 and 16,300 light-years), with recent studies suggesting a narrower range of 2.5 and 3 kpc (approx. 8,000 and 9,800 light-years).”

Taking 1 light-year = \(10^{16}\) m, the area of the sphere around Tycho going through the earth is

\[
sphere\,\text{area} = 4\pi \times (9000\text{ly} \times 10^{16}\text{m/ly})^2
\]

\[
= 10^{41}\text{m}^2\quad (16)
\]

So the number of 3.55 keV photons passing through this surface will be

\[
\#\,\text{of photons} = \left(2.2 \pm 0.3\right) \times 10^{-5}\text{cm}^{-2}\text{s}^{-1} \times 10^{41} \times 10^4\text{cm}^2
\]

\[
= 2 \times 10^{49}\text{s}^{-1}\quad (18)
\]

\[
\sim \text{“an energy rate” : } 3.5\text{keV} \times 2 \times 10^{49}\text{s}^{-1}
\]

\[
= 10^{32}\text{erg/s}.\quad (20)
\]

### 8.1.3 Rate of Energy Ploughing up

The total energy in the remnant region will still in first approximation be equal to the energy ejected from the supernova, if we assume that the energy escaping as light going so far away that we no more can count it as belonging to the remnant is small compared to the part remaining in the remnant region. A major part of this energy is presumably in the form of fast moving particles or even X-rays, so that order of magnitudewise we may count it as cosmic rays moving with the speed of light relative to the dark matter pearls, which of course have a much lower velocity of the order of the escape velocity from the Galaxy.

All over the remnant region we assume that the density of dark matter is very similar to that in the neighborhood of our solar system

\[
D_{\text{sun}} = \frac{0.3\text{GeV}}{\text{cm}^3},\quad (22)
\]

so that the number of pearls we have in every \(\text{cm}^3\) is \(\frac{0.3\text{GeV}}{M}\). In each second each of these pearls pick up the cosmic rays or whatever material in the remnant in a volume \(\sigma \times v \approx \sigma \times c\) where \(\sigma\) is the cross section for a pearl and \(v\) is the average relative velocity of the pearl and the remnant matter or radiation. That is to say, that during a second the fraction of the volume getting ploughed through is

\[
\text{“Fraction ploughed through”} = \frac{D_{\text{sun}} \times \sigma \times v}{M}.\quad (23)
\]

So if one observes a 3.55 keV line with an intensity \(I = 2.2 \times 10^{-5}\) photons per s per \(\text{cm}^2\) we need the total energy rate (power) at a distance \(d = 9 \times 10^{19}\text{m}\) to be

\[
W = I \times 4\pi \times d^2 \times 3.55\text{keV} \times 2.2 \times 10^{-5}\text{cm}^{-2}\text{s}^{-1} = 10^{32}\text{erg/s}.\quad (24)
\]

Then we must have

\[
W = E_{\text{remnant}} \times vD_{\text{sun}} \times \frac{\sigma}{M}.\quad (25)
\]
\[
\sigma \left| \frac{M}{M_{\text{Tycho}}} \right| = \frac{W}{E_{\text{remnant}} * D_{\text{sun}} v \sqrt{12}}
\]

or

\[
\sigma \left| \frac{M}{M_{\text{nuclear}}} \right| = \frac{\pi * 1.2^2 f m^2 * A^{2/3}}{A * 0.94 GeV}
\]

\[
= \frac{123 GeV^{-3}}{\sqrt{12}}
\]

\[
= \frac{1}{(0.265 GeV)^3}
\]

8.2 Comparing to Nuclear \(\sigma/M\) Ratio

The material inside our pearls is highly compressed and taken to be mainly carbon (with atomic number \(A = 12\)). Then using a crude formula \(1.2A^{1/3}fm\) for the radius of a nucleus and \(\pi(1.2A^{1/3})^2 fm^2\) for the cross section for some smaller particle scattering on the nucleus, we get for nucleus scattering:

\[
\sigma \left| \frac{M}{M_{\text{nuclear}}} \right| = \frac{\pi * 1.2^2 f m^2 * A^{2/3}}{A * 0.94 GeV}
\]

\[
= \frac{123 GeV^{-3}}{\sqrt{12}}
\]

\[
= \frac{1}{(0.265 GeV)^3}
\]

Combining these numbers for the ratio \(\sigma/M\) needed for the dark matter in the supernova remnant (30) with the one for a suitable nucleus (31) we see that the needed lower bound is

\[
\frac{\sigma}{M} \left| \frac{M}{M_{\text{Tycho}}} \right| = \frac{(0.26 GeV)^3}{(3.4 GeV)^3}
\]

\[
= 0.076^3 = 4.5 * 10^{-4}
\]

This means that about 1/2000 of the accessible energy would indeed become 3.5 keV photons, if the cross section for the pearls in Tycho was actually equal to the nuclear cross section. Actually such an efficiency of \(4.5 * 10^{-4}\) is not at all unlikely. So we could claim that, having in mind that the orders of magnitude could have run out to wildly different values, the rather close agreement could be taken to mean that indeed the true \(\frac{\sigma}{M}\) for the dark matter pearls being excited is indeed equal to the nuclear one (31). If indeed the pearls were so small that there was no significant shadowing by one nucleus of another of the nuclei in the pearls, then the cross section to mass ratio would just be the nuclear one. So an order of magnitude agreement with the actual cross section to mass ratio being the nuclear value should be taken almost as successful agreement.

Let us say this in other words:

If we assume that the tension \(S\) and the parameter \(\xi_f\) have such values that formally the cross section to mass ratio \(\frac{\sigma}{M}\) would be smaller than the corresponding nuclear ratio (31), the actual cross section to mass ratio would only be approximately equal to the nuclear ratio. (Here \(\xi_f\) is the radius scaling
factor for fixed tension $S$, see section 8.3.2). For so thin pearls a cosmic ray say could with high probability pass through the pearl without hitting any nuclei inside. For such parameters one would obtain for the cross section to mass ratio just the nuclear value, see Figure 2. But anyway of course there would be an appreciable loss of energy that would not go to the 3.5 keV radiation, even compared to the amount of 3.5 keV radiation having been corrected with the time ratio for the fact that the emission into 3.5 keV radiation only takes place in a short period of time $t_{\text{spread}}$. Let us say that it is only the fraction $1/l$ of the energy available in the period when the surface of the pearl is still cold that really comes out as this radiation.

Having in mind instead of the collision events the events in the Tycho supernova remnant this time ratio correction is not present, because the single cosmic ray exciting the pearl is supposed not to heat it up so much that the problem of the pearl being hot comes up. So for the Tycho supernova remnant the emission of the 3.5 keV radiation should be calculated without this time ratio correction. But it should still for “general” inefficiency be reduced by the factor $l$.

For pedagogical reasons we could imagine, that we could estimate the efficiency $1/l$ sufficiently accurately that we could say: Fantastic that we just get the radiation as observed by Jeltema et al. from the Tycho Supernova remnant equal to this $l$ divided into the rate expected if all the energy went to 3.5 keV radiation and the cross section to mass ratio was just the nuclear physics one (31). In this optimistic thinking we would have an empirically based suggestion saying that the size of the pearls are actually so small that the cross section to mass ratio becomes equal to the nuclear ratio. But for this to happen it would have to be that the formally calculated ratio should be larger than or equal to this nuclear ratio. This in turn will put an upper limit on the tension $S$ depending somewhat on our parameter $\xi_f S \Delta V$, since the cross section to mass ratio is a decreasing function of the tension $S$ and then of course also as a function of the third root of this tension $S^{1/3}$ which we mainly use in our text and figures. The upper limit following from this consideration based on claiming the nearness of the ratio actually estimated from Jeltema et al. to the nuclear ratio is shown on Figure 9 below as the line labeled “nuclear”.

8.2.1 Resume of Comparison with Nuclear Ratio $\frac{1}{l}$

But let us stress again that, if the loss of energy by the inefficiency of making 3.5 keV radiation from all the energy available could be estimated to be a factor of the order of $l = 2000$, then we could claim the very value of the Jeltema et al. observation strength as a victory for the picture.

8.3 Combined Fitting, Small Pearl Model

8.3.1 Formulas for the Critical Case, Pearls Just about to Collapse

First let us give a list of the interesting quantities in terms of the cubic root of the tension of the surface $S^{1/3}$ and the energy difference for the nucleon on passing the domain wall $\Delta V$ in the case of a critical sized pearl. By this we mean the case in which a further parameter has been avoided by adjusting it so that the tension provides a pressure on the material inside the pearl making it just on
Figure 7: This figure illustrates that for the density inside a pearl being very high a cosmic ray particle hitting the pearl will sooner or later in the interior hit a nucleus, while for a very little pearl with the same density the thickness of the pearl is insufficient for all cosmic ray particles to hit a nucleus and the cross section will be less than the geometrical one $\sigma = \pi R^2$. The ratio $\frac{\sigma}{\pi}$ is then rather equal to the nuclear value.\[31\]
the border to collapse by spitting out nucleons. In other words providing enough
pressure to just barely compensate the potential difference \( \Delta V \) per nucleon. So
now we should note the various parameters in this borderline/critical situation
(see reference \[3\] for details on the notation):

\[
\begin{align*}
\text{Pearl radius } R_{\text{crit}} &= \frac{3\pi^2 S}{2(\Delta V)^4} \quad (36) \\
\text{Fermi momentum } p_{f\text{ crit}} &= 2\Delta V \quad (37) \\
\text{Energy release by collision } E_{S\text{ crit}} &= S(\sim 4\pi)R_{\text{crit}}^2 \quad (38) \\
&= \pi^5 * 9.8^3 / (\Delta V)^8 \quad (39) \\
\text{Collision cross section } \sigma_{\text{crit}} &= \pi * (2R_{\text{crit}})^2 = 6 * \pi^3 S^2 / (\Delta V)^8 \quad (40) \\
\tau_{\text{spread crit}} &= \frac{\rho c}{4k} * R_{\text{crit}}^2 \quad (41) \\
&= \frac{0.55 R_{\text{crit}}^2 T_{\text{crit}}}{24c^3} \quad (42) \\
\tau_{\text{radiation crit}} &= \frac{E_{S\text{ crit}}}{4\pi^2 \sigma_{ST}(3.5\text{keV})^2} \quad (43) \\
&= \frac{60S}{\pi^2(3.5\text{keV})^2} \quad (44) \\
\frac{\sigma_{\text{crit}}}{M_{\text{crit}}} &= \frac{6 * \pi^4 S^2 / (\Delta V)^8}{m_N * \frac{24\pi^5 S^2}{(\Delta V)^8}} \quad (45) \\
&= \frac{\Delta V}{4\pi^2 S m_N} \quad (46) \\
\frac{E_{S\text{ crit}}}{M_{\text{crit}}} &= \frac{S(\sim 4\pi)(\frac{9\pi^2 S}{2})^2}{m_N \frac{24\pi^5 S^2}{(\Delta V)^8}} \quad (47) \\
&\sim \frac{\Delta V}{2m_N} \quad (48) \\
\frac{N_{\text{crit}}}{M_{\text{crit}}} &= \frac{E_{S\text{ crit}}}{\Delta V} \sim \frac{\Delta V}{2m_N * 3.55\text{keV}} \quad (49) \\
&= \frac{N_{\text{crit}}}{M_{\text{crit}}} \frac{\sigma_{\text{crit}}}{M_{\text{crit}}} \frac{1}{m_N} \quad (50) \\
&= \frac{(\Delta V)^2}{8\pi^2 S m_N^2 * 3.55\text{keV}} \quad (51) \\
\frac{\tau_{\text{spread}}}{\tau_{\text{radiation}}} &= \frac{N_{\text{crit}}}{M_{\text{crit}}} \frac{\sigma_{\text{crit}}}{M_{\text{crit}}} \frac{1}{m_N} \quad (52) \\
&= (\Delta V)^{-5}(3.5\text{keV})^3 \\
\text{frequency } f_H &= \frac{137^{-3/2} \sqrt{\rho_f} = 137^{-3/2} \sqrt{22\Delta V}}{(R_{f\text{ crit}})_{\text{crit}}} \quad (53) \\
&= \frac{24\pi^5 S^3}{(\Delta V)^9}. \quad (54)
\end{align*}
\]
8.3.2 With Radius Scale up Parameter $\xi_{FS}$

The critical case is not realistic except very crudely. The pearls would collapse by the tiniest deformation during the contraction in the early universe situation. We must expect that there must be an appreciable safety margin in the sense, that the number of nucleons inside the contracting pearl for the pearl not to collapse immediately must be so large, that the final radius, when the fluctuations from the contraction have died out will be say $R = \xi_{FS} \cdot R_{crit}$ with $\xi_{FS} \approx 5$.

We estimated in earlier articles this expected ratio of the average radius to the critical or borderline one to be $\sqrt{\frac{4\pi}{24}} \approx 5$.

The dependence of some of the important quantities with this $\xi_{FS}$ goes as follows. Here we also include the dependence on $\Delta V$ and on $S$:

- **Pearl radius**
  \[ R = \xi_{FS} R_{crit} = \xi_{FS} \frac{S \cdot 24\pi^2}{(2\Delta V)^4} \] (56)

- **Cubic root of tension** $S^{\frac{1}{3}}$
  \[ S^{\frac{1}{3}} = S^{\frac{1}{3}}(\text{fixed}) \] (57)

- **Fermi momentum** $p_f$
  \[ p_f^{\frac{1}{3}} = \xi_{FS}^{\frac{1}{3}} 2\Delta V \] (58)

- **Energy release by collision** $E_S$
  \[ E_S = \pi^5 \cdot 9S^3 \xi_{FS}^2/(\Delta V)^8 \] (59)

- **Collision cross section** $\sigma$
  \[ \frac{\sigma}{M} = \frac{6 \pi^3 S^2 \left( \xi_{FS}^{1/4} \Delta V \right)^8}{m_N \cdot 24\pi^5 S^3 \left( \xi_{FS}^{1/4} \Delta V \right)^9} \] (68)

- **Energy release by collision**
  \[ \frac{E_S}{M} = \frac{S(\sim \pi)R_{crit}^2}{m_N \cdot 24\pi^5 S^3 \left( \xi_{FS}^{1/4} \Delta V \right)^9} \] (70)

\[ t_{\text{spread}} = \frac{\alpha 55R^2T}{24e^3} \] (61)

\[ t_{\text{spread}} = \frac{1.10\Delta V \cdot S^2 \left( \xi_{FS}^{1/4} \Delta V \right)^8}{60S \frac{(3.55keV)^4}{\pi^2(3.55keV)^4}} \] (63)

\[ t_{\text{radiation}} = 60S \frac{(3.55keV)^4}{\pi^2(3.55keV)^4} \] (64)

\[ t_{\text{radiation}} = 6.08S \frac{(3.55keV)^4}{\pi^2(3.55keV)^4} \] (65)

\[ t_{\text{spread}} = \frac{1.10\Delta V \cdot S^2 \left( \xi_{FS}^{1/4} \Delta V \right)^8}{6.08S \frac{(3.55keV)^4}{\pi^2(3.55keV)^4}} \] (66)

\[ t_{\text{spread}} = 0.18 \cdot (3.55keV)^4 \cdot S \left( \xi_{FS}^{1/4} \Delta V \right)^8 \] (67)

\[ \frac{\sigma}{M} = \frac{6 \pi^3 S^2 \left( \xi_{FS}^{1/4} \Delta V \right)^8}{m_N \cdot 24\pi^5 S^3 \left( \xi_{FS}^{1/4} \Delta V \right)^9} \] (68)

\[ \frac{E_S}{M} = \frac{S(\sim \pi)R_{crit}^2}{m_N \cdot 24\pi^5 S^3 \left( \xi_{FS}^{1/4} \Delta V \right)^9} \] (70)
\[
\frac{N}{M} = \frac{E_S}{M \cdot 3.55\text{keV}} \sim \frac{1}{2m_N \frac{\xi^{1/4}}{\Delta V}} \text{ (71)}
\]

\[
\frac{N\sigma}{M^2} \bigg|_{\text{all} E_S \to 3.5\text{keV}} = \frac{N}{M} \frac{\sigma}{M} \text{ (72)}
\]

\[
\frac{t_{\text{spread}}}{t_{\text{radiation}}} \cdot \frac{N\sigma}{M^2} \bigg|_{\text{all} E_S \to 3.5\text{keV}} = \frac{0.18 \cdot (3.55\text{keV})^4 S \left(\frac{\xi^{1/4}}{\Delta V}\right)^8 \Delta V \star (73)}{8\pi^2 S m_N^2 \left(\frac{\xi^{1/4}}{\Delta V}\right)^2 \cdot 3.55\text{keV}} \text{ (74)}
\]

\[
\text{frequency} = E_H = 137^{-3/2} \cdot 2p_f = \frac{\xi f^{1/4}}{137^{3/2}} \Delta V \text{ (75)}
\]

8.3.3 Fitting with also inefficiency, Only 1/l goes to 3.5 keV

We have to take into account that even though there is the possibility energy-wise for producing 3.5 keV X-rays of a certain amount only say $1/l$ of the a priori expected amount is actually produced and emitted. So to get a fit for a given experimental observation, we will have to take the calculated value with the initially chosen parameters $S^{1/3}$, $\Delta V$, and $\xi f^{1/4}$ for emission of an amount of 3.5 keV radiation to be corrected to actually deliver a larger amount by a factor $l$. In order to get a larger amount of 3.5 keV line emission we shall take a smaller cubic root of tension $S^{1/3}$ and a bigger value of the combined parameter $\frac{\xi^{1/4}}{\Delta V}$. This means, that corresponding to a combination of a couple of values ($S^{1/3}$, $\frac{\xi^{1/4}}{\Delta V}$) we get a track, a half line, of possibilities by switching on the further parameter $l$ (which is larger than or equal to unity). Here we had in mind a double logarithmic plot, otherwise the half curve would not be a half line.

The final step in our small pearl fitting assumes that one can estimate the mass of the pearls by looking at how many events are observed by the DAMA-LIBRA experiment. We do this by using the fact that the flux of pearls must of course be bigger the smaller in mass the pearls, so as to agree with the density of

\[
M \frac{m_N}{m} = \frac{8}{9\pi} (R p_f)^3 \text{ (76)}
\]

\[
= 24\pi^5 \left(\frac{S^{1/3} \xi^{1/4}}{\Delta V}\right)^9 \text{ (77)}
\]
Figure 8: This figure illustrates the fitting of our two parameters $S^{1/3}$ along the ordinate, $\xi f^{\Delta V}$ along the abscissa, while our third parameter $l$ is just illustrated by shifting the two fitting restriction lines from $l = 1$, thickest line to slightly thinner lines for $l = 82^2$. The lines are marked by: I for the fitting to the intensity from galactic clusters etc, T for the Tycho observation, F for the frequency, and M for the DAMA mass restriction. It is only the restriction lines for I and T that move when $l$ is shifted to be less than unity. Even our $l = 82^2$ does not completely fit, but the reader can extrapolate by eye to see that even a bit larger $l$ somewhere around $l = 800^2$ would give a crude fit around $S^{1/3} = 1MeV$ and $\xi f^{\Delta V} = 1000 \ GeV^{-1} = 1 \ MeV^{-1}$. But this points to a surprisingly large value of $l$. 
dark matter as needed from the gravitational effects. However, since our pearls interact rather strongly on their way through the shielding, this estimate has to be severely corrected to get the mass needed at the end.

The fitting procedure is illustrated in Figure 8.

For the sake of fitting in such a way to the DAMA-LIBRA observations we take the “observed mass” $M_{\text{obs}} = 10^3$ GeV to $10^4$ GeV. But it is rather uncertain, because the pearls are strongly interacting and only reach through the shielding earth because of their very high masses ($\sim 10^3$ GeV) compared to usual WIMP expectations so that they do not get stopped even when hitting a nucleus, but rather continue slightly slower. Nevertheless we imagine the majority of the pearls to get stopped before reaching the instrument, so that only about 1 in $10^{12}$ come through and thus a $10^{12}$ times smaller mass is needed than the mass $M' = 1.56 \times 10^{14}$ GeV, which corresponds to getting the observed number of event match with number of pearls hitting the region at all. The value $10^{-12}$ of the suppression of the number of pearls coming through was estimated by comparing our expected $\sigma_M$ from the supernova remnant measurement with the observations of such a ratio in the DAMA-fitting by the experimentalists.

The Figure 9 illustrating the final fit is complicated by there being an inconsistency in the Jeltema and Profumo paper by the number in their figure for the rate of 3.55 keV radiation observed deviating by a factor 10 from the number in the text. But ignoring one of these two versions of the figure, we may give here the meaning of the lines on the figure:

The value of the frequency of the radiation, i.e. the very number 3.55 keV happens to depend only on our combined parameter and it fits it to the value $\xi_{1/4}/\Delta V = 0.5 \text{ MeV}^{-1}$. If we ignore an extra very weak dependence on the $\Delta V$ and put say $\Delta V = 20 \text{ MeV}$ then also the intensity of the 3.55 keV line radiation mainly depends on our combined variable and requires a fitted value of $\xi_{1/4}/\Delta V = 0.086 \text{ MeV}^{-1}$. So the fitting of the intensity of the various clusters of galaxies etc. requires the vertical line of our plot to the left at $0.086 \text{ MeV}^{-1}$. The lines crossing the figure and denoted “Tycho figure” and “Tycho text” are the spaces for the allowed parameter combinations for the $l$ fixed to unity to fit the intensity of radiation from the supernova remnant when the intensity is taken from the figure and text respectively of the Jeltema et al. paper. The important point here is where these two lines cross the vertical line at $0.086 \text{ MeV}^{-1}$ which is the requirement of the intensity measurement. From the crossing point on the figure is then drawn a half line representing the pairs $(\xi_{1/4}/\Delta V, S^{1/3})$ which by varying the $l$-parameter give the possible allowed values fitting both the intensity of the galactic clusters etc and the Tycho supernova remnant. These half lines go down from the upper left to the lower right. Similarly we have actually two (because of the slight inconsistency in the Jeltema article) half lines on which one, using the $l$-parameter in combination, can fit the mass required by the DAMA-LIBRA experiment and our considerations for the number of events in DAMA-LIBRA and again the intensity of the 3.55 keV radiation from the galactic clusters etc.

Now the success of the fitting can be taken to be that for a given - the right one - interpretation of the Jeltema article data (text or figure right) the two lines, one corresponding to the variation of $l$ called “l-track” and the other called “DAMAmasss”, cross each other just on the vertical line corresponding to the frequency 3.55 keV.
Figure 9: This is the same as the foregoing figure but with a line added corresponding to the $\sigma_M$ being as for nuclei, thus called “nuclear”. It represents with our assumptions an upper limit for $S^{1/3}$ as a function of the other variable. In fact the piece of the “l-track” below this line represents the factor in $l$ called $l_{\text{penetration}}$ represents the correction to the geometrical cross section to mass ratio due to the say cosmic ray just penetrating the pearl instead of interacting.

For instance the “text” three lines cross in a really very small triangle meaning the fit is very good! The middle of this very small triangle is the point with $(\frac{1}{2}, S^{1/3}) = (0.6 \, MeV^{-1}, 1.6 \, MeV)$. This is a very small value we would think for the tension $S^{1/3}$ and a surprisingly big value for our combined parameter. But translated to energy scale the two parameters are both surprisingly small
being an MeV in order of magnitude.

We note that the fitted values of the parameters at the center of the triangle lie below the very heavy line which represents the nuclear value for the ratio of cross section to mass. This is in apparent conflict with our hypothesis above claiming that the Tycho supernova observation was consistent with the coincidence of the cross section to mass ratio for the pearls being equal to the nuclear value.

8.3.4 More Coincidences

Really the accuracy of our estimates is so crude that we have e.g. the point we find for fitting \( \left( \frac{\xi^{1/4}}{\Delta V}, \frac{S^{1/3}}{3} \right) = (0.5 \text{ MeV}^{-1}, 2 \text{ MeV}) \) could be considered lying on the line marked “nuclear”, which would mean that the true cross section to mass ratio of the pearls would be equal to that of carbon nuclei.

But by a little by eye improvement, we could make this story even a bit better:

In fact if we take it that it is remarkable and in fact true that the mass of the pearls coincide with the lower limit at which the macroscopic calculation stops working and the density of electrons spreads out in a bigger cloud than the pearl as marked by just the skin, then the situation should be that the density of electrons is actually somewhat lowered compared to the calculation we used.

Crudely correcting for that would mean, that since the predicted line frequency - that should end up 3.55 keV - would fall by the density being lowered, we would have to correct it a bit back by claiming that the fitting value of the \( \xi^{1/4} \) parameter should be a bit smaller than the value 0.5 MeV\(^{-1} \) which we used without such improvement.

Because the crossing lines in the figure go skewly down from left to right, such a diminishing of the fitting value of the abscissa would mean that the fitting \( S^{1/3} \) would tend to rise. In fact this would then make it even easier to claim that we just have the nuclear sigma to mass ratio.

Indeed we would then be able to claim that we have the following coincidences:

- The \( \sigma_M \) ratio for the pearls would be just the nuclear one.
- The mass of the pearls would (as the dominant value) just be the lower bound for the macroscopic picture to work, i.e. the electron would just not expand outside significantly.
- Then of course as before it is a coincidence that one gets a fit at all, although our number of parameters was only one below the number of fitted quantities.

So we would claim a somewhat more remarkable fit!

8.4 DAMA-LIBRA Mass Extraction

The major speculation and idea behind the small pearl study, in addition to the inclusion of the Jeltema and Profumo observation of 3.55 keV X-ray radiation from the Tycho supernova remnant, is the inclusion of an attempt to fit and
explain the controversial DAMA-LIBRA experiment\cite{25}. In contrast to other underground searches for dark matter, DAMA-LIBRA did find the dark matter by the technique of seasonal variation.

According to the above crude coincidence discussed in subsections 8.2 and 8.2.1 the cross section to mass ratio $\frac{\sigma}{M}$ for our pearls needed to fit reasonably the Tycho supernova remnant observation agrees - we wanted to say as a “coincidence” (but that is only very optimistically true) - with the same ratio for e.g. carbon nuclei.

Indeed we found \cite{31}

$$\frac{\sigma}{M}_{\text{nuclear}} = \frac{1}{(0.26\text{ GeV})^3}$$

while the DAMA-LIBRA experiment presented two allowed regions for WIMP observation in the mass of the particle versus cross section plane:

$$(M, \sigma) = (18 \text{ GeV}, 2 \times 10^{-4} \text{ pb}) = (3.2 \times 10^{-26} \text{ kg}, 2 \times 10^{-44} \text{ m}^2)$$

and

$$(M, \sigma) = (180 \text{ GeV}, 10^{-4} \text{ pb}) = (3.2 \times 10^{-26} \text{ kg}, 10^{-44} \text{ m}^2),$$

giving respectively

$$\frac{\sigma}{M} = \frac{2 \times 10^{-4} \text{ pb}}{18 \text{ GeV}} = 6.24 \times 10^{-19} \text{ m}^2/\text{kg}$$

and

$$\frac{\sigma}{M} = \frac{10^{-4} \text{ pb}}{180 \text{ GeV}} = 3.1 \times 10^{-20} \text{ m}^2/\text{kg}.$$  

It means that the ratio $\frac{\sigma}{M}$ fitted to WIMPs by DAMA is about a factor $10^{12}$ (or even $10^{13}$) lower than the number which our fit using the Jeltema and Profumo 3.55 keV observation points to, namely $6 \times 10^{-7} \text{ m}^2/\text{kg}$ (if we use the “figure-value” $6 \times 10^{-8} \text{ m}^2/\text{kg}$ we could get $10^{11}$ only). If we take it that really the $\frac{\sigma}{M}$ ratio for our pearls is equal to the nuclear value, then the deviation from the observed ratio in DAMA-LIBRA is even larger, by about a factor 2000 bigger.

As we shall see in the next subsubsection 8.4.1 we estimate that the number of particles / events observed requires that the mass be at most $1.56 \times 10^{14} \text{ GeV}$, since otherwise with the known density $D_{\text{sol}} \approx 0.3 \text{ GeV/cm}^3$ there could not be enough particles so as to fit the observed ones.

The main idea now is that we assume that, due to some filtering and breaking of the particles that come in with our speculated rather high cross section and thus cannot avoid interacting with the shielding amounts of earth, removes effectively all but one particle in $10^{12}$. This number was just taking from the comparison of the assumed cross section and the seemingly measured one being $10^{12}$ as we just discussed. To cope with this suppression of the number of
particles we need an increase in the number coming in by the factor $10^{12}$ and thus to reduce the mass to fit our model relative to the $1.56 \times 10^{14} \text{GeV}$ to the mass estimate:

$$\text{“Mass estimate from DAMA” } \approx 1.56 \times 10^{14} \text{GeV} / 10^{12} \quad (89)$$

$$= 160 \text{GeV}. \quad (90)$$

Had we used the supposed more correct value by taking the factor $10^{12}$ bigger by a factor 2000, the pearl mass estimate would be reduced by a further factor 2000. But we could not tolerate that in our model because there would then not even be one nucleon in the pearls and the macroscopic estimates of e.g. the homolumo gap leading to the frequency $3.55 \text{keV}$ would not appear. Our pearls must not just be ordinary atoms surrounded by a skin, they must be many atoms surrounded by the skin. There should at least be so many $Z$ charges on protons in the pearl that a potential of the order of magnitude of $\Delta V$ can be achieved. Using the well-known formula for the ground state of the electron binding energy for a hydrogen like atom $Z\text{Ry} \approx Z \times 13 \text{eV}$, we need to get $Z \approx 10^5$ at least, just to reach even the surprisingly small $\Delta V$ coming out of our fit to the small pearls. So we cannot keep the model unless we let the mass $M$ of the pearls be at least $10^5 \text{GeV}$. This is a factor 100 or 1000 times bigger mass than the estimates used on the figure called respectively “DAMAmass figure” and “DAMAmass text”. Thus the line representing the DAMAmass on the figure should be lifted by the logarithm of the ninth root of 100 compared to “DAMAmass figure” or by the logarithm of the ninth root of 1000 compared to the line marked “DAMAmass text”. In both cases the line as needed by the requirement of making sense of our macroscopic estimates passes the vertical line for $\frac{\xi^{1/4}}{2} = 0.1 \text{MeV}^{-1}$ at $S^{1/3} = 14 \text{MeV}$. Including the possibility for varying $l$ leads to the allowed line which then passes through $(0.1 \text{MeV}^{-1}, 14 \text{MeV})$ and is parallel to the other “DAMAmass”-lines drawn. It fits actually even better than the previous fits and both the “text” and the “figure” lines concerning the Tycho supernova measurement.

### 8.4.1 How Many Particle Hit the DAMA Experiment?

In this subsubsection we shall now estimate the promised approximate absolutely lowest needed number of dark matter particles coming in and thereby the upper bound on the mass of these particles as follows:

The modulated part of the signal is found by DAMA/LIBRA to be of the order 0.01 cpd/kg/keV in the region of energy of the signal in the range 1keV to 6 keV where any modulation if found at all. Taking this as averaged over the range of 5 keV it means that one in total saw at least 0.05 cpd/kg even modulated and thus dark matter related events meaning for the whole apparatus about $250 \text{kg} \times 0.05 \text{cpd/kg} = 12.5 \text{cpd}$. Since the apparatus has an area of the order of $1/4 \text{m}^2$ - it consists of 25 essentially $10 \times 10 \times \ldots$ blocks - this means an absolutely needed flux - whatever the theory - of $50 \text{cpd/m}^2$. Here cpd means counts per day, and should be compared to what we trust about the dark matter: We have in our region a mass density $0.3 \text{GeV/cm}^3 = 3 \times 10^5 \text{GeV/m}^3$ and a velocity of the order 300 km/s meaning 300 km/s $\times 86400 \text{s/day} = 2.6 \times 10^{10} \text{km/day} = 2.6 \times 10^{15} \text{m/day}$. So $1/4 \text{m}^2$ tracks per day a volume $1/4 \times 2.6 \times 10^{10} \text{m}^3 = 6.5 \times 10^9 \text{m}^3$ containing a mass of $6.5 \times 10^9 \text{m}^3 \times 3 \times 10^5 \text{GeV/m}^3 = 19.5 \times 10^{14} \text{GeV} = 2.0 \times 10^{15} \text{GeV}$.
This $2.0 \times 10^{15} \text{ GeV}$ mass is to be shared on 12.5 counts, since there have been seen 12.5 cpd. Thus the particles must at least have masses less than or equal to $2.0 \times 10^{15} \text{ GeV}/12.5 = 1.56 \times 10^{14} \text{ GeV}$. There is the possibility that with the strongly interacting pearls in our small mass model the modulation part relative to the total number of interactions with the apparatus gets appreciably enhanced. In fact the depth into which the pearls penetrate must be strongly dependent on the impact velocity, since it takes more collisions to stop a fast pearl than a slow one (compared to Earth velocity). Since presumably the DAMA-LIBRA experiment is working with the few pearls coming especially deep down the number of them could be very strongly velocity dependent. It is in fact possible that these modulation part particles are almost the only dark matter particles, although this would usually be a bit strange if it were so. Such enhancement of the modulation could explain the long standing mystery, why DAMA-LIBRA sees the dark matter while the other experiments - not using the modulation technique - do not see anything.

Now we estimated that to just get that there were as many particles at all passing the DAMA/LIBRA detector, even if being WIMPs, as the number of observed events would require a mass of the order $M = 1.56 \times 10^{14} \text{ GeV}$. We have now to say that we need the mass $M$ to be $10^{12}$ times smaller than this number, so that we can get $10^{12}$ times more particles to begin with. That means we need a mass of the order

$$M = 10^{-12} \times 1.6 \times 10^{14} \text{ GeV}$$

$$= 1.6 \times 10^{2} \text{ GeV}. \quad (91)$$

We then even need that the particles that come through essentially almost all interact in the apparatus, but that may not be so impossible in our model with rather strongly interacting particles. You would rather have to consider how many of them may become disqualified by interacting several times.

Because of a printing mistake in the Jeltema et al. paper one can choose not to believe their published rate for the number of 3.55 keV photons they observe, but instead use the value in their figure. This then gives a factor 10 times lower observation rate, and thus with the figure used instead of the number in the article, we could claim that they find rather $\sigma = 6 \times 10^{-8} m^2/\text{kg}$. In this case the shielding caused factor would not be $10^{12}$ as above but rather only $10^{11}$ and our estimate of the mass $M$ would then go up to $1.6 \times 10^{3} \text{ GeV}$.

In the following subsection 8.5 we redo this estimate in a slightly different way using some rather simple formulas:

### 8.5 Simple Formulas on Underground Searches for Dark Matter

Usually people assume that dark matter consists of weakly interacting particles, so called WIMPs (= weakly interacting massive particles). But if the particles could be heavy, they could also be so strongly interacting that the particles would interact several times on the way down through the earth shielding the experiments looking for dark matter underground. However they do not need to be sufficiently strongly interacting that it would make them visible on the sky. Such particles would not deserve the name WIMP but rather only IMP.
Since all we know from the gravitational effect of the dark matter is the mass density $D$, the quantity that crudely measures the degree of visibility of the dark matter would be the amount of absorption or of any kind of observable effect, say some cross section $\sigma$ per unit volume in outer space. For fixed $D$ that quantity would be proportional to the ratio $\frac{\sigma}{M}$, i.e. to the amount of cross section per unit mass.

We shall in this section, taking just this ratio $\frac{\sigma}{M}$, look for what one crudely measures in experiments looking for WIMPs or IMPs impacting on earth.

Calling the mass of the average nucleus or whatever is taken to be the most important constituent of the earth hitting the dark matter particles $M_{\text{nucleon}}$, we may crudely estimate that the number of collisions it takes for a dark matter particle to be effectively stopped in passing through the shielding is

$$\text{"Number hit for stop"} \approx \frac{M}{M_{\text{nucleus}}}. \quad (93)$$

The argument for this estimate is the following:

During its passage through the shielding - the layer of earth above the detector - the dark matter particle / pearl of mass $M$ hits earth particles of mass $M_{\text{nucleus}}$, which then obtain a speed of the order of magnitude of the speed $v$ of the dark matter particle itself. Thereby the hit particles achieve a kinetic energy of the order of $M_{\text{nucleus}}v^2/2$ which is $\frac{M_{\text{nucleus}}}{M}$ times the kinetic energy of the dark matter pearl itself $Mv^2/2$. Thus to bring the kinetic energy of this pearl down to about zero it is needed of the order of the inverse of the fraction $\frac{M_{\text{nucleus}}}{M}$ such hits. But that is just what (93) says.

### 8.5.1 Estimation of Number of Hits Needed

As we shall see in a moment we shall avoid the pearl making too many hits when passing the counting sensitive region of the experiment. The reasons are:

- If one sees more than one hit in the experiment, one counts it as a background interaction and does not include it in the usual searches for WIMPs.

- Below we shall give an estimate of the number of hits to be seen in the experimental sensitive region. If there are many interactions/hits in this region there will not be so many counts of something happening as the estimation below. They will so to speak be used up on multiple hits instead.

We estimate now an effective thickness of the experimentally sensitive region in say the DAMA-LIBRA experiment to be of the order of $l_{\text{sensitive}} = \frac{1}{2} m$. Then we argue that the stopping length $l_{\text{stop}}$ divided by "Number hit for stop" $\approx \frac{M}{M_{\text{nucleus}}}$, should be larger than or of order of magnitude of $\frac{1}{2} m$. I.e.

$$\frac{l_{\text{stop}}M_{\text{nucleus}}}{M} \geq l_{\text{sensitive}} \approx \frac{1}{2} m. \quad (94)$$

### 8.5.2 Penetration in Terms of $\frac{\sigma}{M}$

If one thinks of WIMPs the very number of observed dark matter particles or pearls in an underground experiment is proportional (crudely at least) to the
ratio $\frac{\sigma}{M}$ of cross section to mass. This is because, taking the density of dark matter $D$ in the astronomical neighborhood and the typical velocity $v$ as given, the flux of dark matter particles passing by becomes inversely proportional to the mass $M$ and the interaction rate must of course always be proportional to the cross section $\sigma$ for hitting.

Therefore really the ratio $\frac{\sigma}{M}$ estimated by an underground experiment is basically an estimate of the intensity of hits in the sensitive part of the apparatus. Assuming dark matter consists of WIMPs this number is basically measured by the underground experiments, essentially just by counting events.

Now, however, if the pearls interact several times on their way down through the shielding then the effect of such full or partial stopping of the particles can of course drastically change the result of measuring the ratio $\frac{\sigma}{M}$ as if they were WIMPs.

Almost by dimensional arguments we could write down the stopping length

$$l_{\text{stop}} = \frac{M}{\sigma \rho_{\text{shield}}}.$$  \tag{95}

In fact supposing that the shielding material is mass-wise dominated by the one particle - presumably a nucleus - of mass $M_{\text{nucleus}}$ the (mass) density is given as

$$\rho_{\text{shield}} = \text{"number density"} \ast M_{\text{nucleus}}.$$  \tag{96}

and the distribution of the pearl’s first hit on this material is given as

$$\propto \exp(-l_{\text{hit}}x) \text{ (where } x \text{ is depth into shielding)}.$$  \tag{97}

where

$$l_{\text{hit}} = \frac{1}{\text{"number density"} \ast \sigma}$$  \tag{98}

$$= \frac{M_{\text{nucleus}}}{\rho_{\text{shield}} \ast \sigma}.$$  \tag{99}

we obtain

$$l_{\text{stop}} = \frac{M}{M_{\text{nucleus}}} \ast l_{\text{hit}}$$  \tag{100}

$$= \frac{M}{\sigma \rho_{\text{shield}}}.$$  \tag{101}

For simplicity we shall at first assume that the suppression of the rate of the part of the dark matter coming through the shielding is proportional to $\exp(-x/l_{\text{stop}})$ where $x$ is the depth, meaning the penetration depth into the earth, even in the case of multiple scattering. This simplification is of course not mathematically true and we shall return to it later. However proceeding with our simplifying assumption we find that the cross section to mass ratio $\sigma M |_{\text{WIMP}}$ to be effectively found as if we had WIMPs will be

$$\frac{\sigma}{M} |_{\text{as WIMP}} = \frac{\sigma}{M} \ast \exp(-x/l_{\text{stop}}).$$  \tag{102}
Using (100) we write this in the form
\[
\frac{\sigma}{M}_{\text{as WIMP}} = \frac{\sigma}{M} \star \exp\left(\frac{x\rho_{\text{shield}}\sigma}{M}\right),
\]
which we can consider as a transcendental equation from which to determine the true $\sigma_{\text{as WIMP}}$ for the dark matter pearls from the experimentally observed “as if WIMP” value $\frac{\sigma}{M}_{\text{as WIMP}}$, which can be identified with the DAMA-LIBRA fitted value. There is in this equation for a small value of the $\sigma_{\text{as WIMP}}$ WIMP-solution, but there are two solutions. The second solution is a strong coupling solution. To solve the equation in this strong coupling case we of course have to put in the value of the depth $x$ under earth of the experiment. It is given as 3400 mwe (= meters water equivalent), which means we can put $x = 3400$ m and then $\rho_{\text{shield}} = 1000$ kg/m$^3$. In principle we have to correct for the fact that the dark matter particles will typically move in a skew direction and the true value of $x$ will be somewhat larger than the minimal distance from the earth’s surface to the experiment. Since we anyway calculate very crudely and since in the strongly interacting case the shortest way down will come to give the dominant contribution, we here simply take $x = 3400$ m and $\rho_{\text{shield}} = 1000$ kg/m$^3$. Then we obtain
\[
(x\rho_{\text{shield}})_{\text{for DAMA}} = 3400 \text{ m } \times 1000 \text{ kg/m}^3 = 3.4 \times 10^6 \text{ kg/m}^2
\]

For illustration let us remark that e.g. for what we called “nuclear” cross section to mass ratio $1.25 \times 10^{-3}$ m$^2$/kg, see equation (82), the exponent would become $-3.4 \times 10^5$ kg/m$^2 \times 1.25 \times 10^{-3}$ m$^2$/kg = $-4.3 \times 10^5$.

The cross section to mass ratio for WIMPs seemingly observed in the DAMA-LIBRA controversial underground experiment may be taken from the two allowed regions in the mass of particle versus cross section plane as presented by the experimentalists:

\[
(M, \sigma) = (18 \text{ GeV}, 2 \times 10^{-4} \text{ pb}) = (3.2 \times 10^{-26} \text{ kg}, 2 \times 10^{-44} \text{ m}^2) \quad (106)
\]

and

\[
(M, \sigma) = (180 \text{ GeV}, 10^{-4} \text{ pb}) = (3.2 \times 10^{-26} \text{ kg}, 10^{-44} \text{ m}^2), \quad (107)
\]
giving respectively
\[
\frac{\sigma}{M}_{\text{as WIMP}} = \frac{2 \times 10^{-4} \text{ pb}}{18 \text{ GeV}} = \frac{2 \times 10^{-44} \text{ m}^2}{3.2 \times 10^{-26} \text{ kg}} \quad (108)
\]
\[
= 6.24 \times 10^{-19} \text{ m}^2/\text{kg} \quad (109)
\]

and
\[
\frac{\sigma}{M}_{\text{as WIMP}} = \frac{10^{-4} \text{ pb}}{180 \text{ GeV}} = \frac{10^{-44} \text{ m}^2}{3.2 \times 10^{-25} \text{ kg}} \quad (110)
\]
\[
= 3.1 \times 10^{-20} \text{ m}^2/\text{kg} \quad (111)
\]

Solving the transcendental equation (103) iteratively we first find that
\[
x\rho_{\text{shield}} \star \frac{\sigma}{M} \approx \ln\left(\frac{\sigma}{M} \star \frac{M}{\sigma}_{\text{as WIMP}}\right). \quad (112)
\]
Taken at first the logarithm to be of order unity we shall test as first iteration
\[ \sigma_M = (x \rho_{\text{shield}})^{-1} = (3.4 \times 10^6 \text{kg/m}^2)^{-1} = 2.94 \times 10^{-7} \text{m}^2/\text{kg}. \] But inserting that value into the logarithm gives the value
\[ \ln\left(\frac{2.94 \times 10^{-7} \text{m}^2/\text{kg}}{10^{-12} \text{m}^2/\text{kg}}\right) = \ln(3 \times 10^{13}) = 31. \]
So the next iteration gives
\[ \left. \frac{\sigma}{M} \right|_{\text{2nd sol.}} \approx 2.94 \times 10^{-7} \text{m}^2/\text{kg} \times 31 \] (113)
\[ = 9.1 \times 10^{-6} \text{m}^2/\text{kg}. \] (114)
Crudely we can consider this number \(9.1 \times 10^{-6} \text{m}^2/\text{kg}\) as the DAMA measured value for the cross section to mass ratio provided the second - i.e. the strong interaction solution - is taken.

This value is then to be compared to the value we need for the Jeltema and Profumo Tycho supernova observation:
\[ \left. \frac{\sigma}{M} \right|_{\text{Tycho}} = 5.6 \times 10^{-7} \text{m}^2/\text{kg} \] (for text). (115)
The “measured” value is only 15 times larger than the one required for the Tycho supernova remnant observation. Had we used the “figure” reading of the paper instead of the “text” value, we would have got the 10 times smaller value
\[ \left. \frac{\sigma}{M} \right|_{\text{Tycho}} = 5.6 \times 10^{-8} \text{m}^2/\text{kg} \] (for figure). (116)

But remember now we speculated that these numbers from the Tycho observation are only lower limits and that we suggested the \(\frac{\sigma}{M}\) ratio should be a factor \(l = 2000\) times bigger than the Tycho measurement. Such a factor as that would bring the deviation from the “measured ratio” to the opposite side. So we should really conclude that the agreement of the DAMA estimation of the ratio and that from Tycho is very good.

### 8.5.3 Number of Hits during Stopping

The number 31 which we got for the value of the logarithm in the solving of the transcendental equation above is actually equal to the depth \(x\) measured in stopping lengths \(l_{\text{stop}}\). And so we would conclude that
\[ 31 \times \rho_{\text{shield}} l_{\text{stop}} = (3400 \text{ mwe}) \times \rho_{\text{water}} = 3.4 \times 10^6 \text{kg/m}^2, \] (117)
giving
\[ \rho_{\text{shield}} l_{\text{stop}} = \frac{3.4 \times 10^6 \text{kg/m}^2}{31} = 1.1 \times 10^5 \text{kg/m}^2. \] (118)

Now in order to avoid getting more than one hit in the sensitive thickness of the apparatus taken to be 1/2 m, we have the inequality:
\[ l_{\text{hit}} \geq \frac{1}{2} \text{m}. \] (119)
So taking the density in this sensitive apparatus to be say \(\rho_{\text{apparatus}} = 3000 \text{ kg/m}^3\), we have
\[ \frac{\rho_{\text{apparatus}} l_{\text{hit}}}{\rho_{\text{water}} l_{\text{stop}}} \geq \frac{(31 \times 3000 \text{ kg/m}^3) \times \frac{1}{2}}{3400 \text{ m} \times 1000 \text{ kg/m}^3} \] (120)
\[ = 1.37 \times 10^{-2} = \frac{1}{73}, \] (121)
This means that there is at most 73 times as much weight in the pearl compared to the important nucleus weight in the shield. If say the important or average nucleus in the shield is silicon with mass 28 GeV, then the pearl’s mass is of the order of $73 \times 28 \text{ GeV} = 2000 \text{ GeV}$.

Now in order to have a proper macroscopic electron cloud in the pearl that can give the macroscopically estimated homolumo gap, we need that the pearl nuclear charge $Z$ (i.e. the number of protons) is at least large enough that an atom of this atomic number can provide $\Delta V$ order of magnitude binding energies. Taking the binding energy to be of the order of $Z$ Rydberg, it means we need $Z \geq \frac{\Delta V}{\text{Rydberg}}$, so that for say $\Delta V = 1 \text{ MeV}$ we would need $Z \geq 10^4$. This would be a problem for our model if we took the above estimate of 2000 GeV too accurately. But this limit is so close that we shall of course rather take it that now we know the bound must be very close and we shall take the mass to be $M \approx 2000$ to 10000 GeV - see Figure 10.

8.5.4 An Interesting Coincidence

Let us note, that we have got almost coincidence between the mass $10^4 \text{GeV}$ needed for our macroscopic approximation to be valid and the value obtained above. In other words we can say that the mass needed for keeping a sufficiently high electron density such that e.g. our homolumo-gap calculation is still valid and the mass estimated from DAMA-LIBRA, say 2000 GeV, are essentially the same, which is a funny coincidence!

Actually if we begin to fit with a mass a bit smaller than $10^4 \text{ GeV}$, there will be a correction to the formula for the homolumo gap size and thus for our prediction of the very frequency 3.55 keV. So the true prediction of this frequency would be a bit lower, if such corrections for the bigger extension of the electron cloud than the size of the skin is corrected for.

This actually means that the true homolumo gap has a maximum very near to the values we here use to fit with. This may be of some significance for really getting a peak in the X-ray spectrum (at 3.5 keV), since a priori pearls of a bit different size will give different frequencies for the radiation and thus smear out the peak relative to what would appear, if all the pearls have exactly the same size. It may only go with the fourth root that there is such a dependence but still it is a smearing out.

Suppose it happens that the dominant size of the pearls is just around a point where the approximation of the electron cloud keeping inside the skin of the pearls stops being valid. Then there will be a correction that for making the pearl smaller counteracts the increase in frequency that the smaller pearl should cause. The result is a maximum in the frequency spectrum of the X-ray radiation. This means an improvement in the sharpness of the line is predicted.

If we somehow argue that just such a maximum is favoured it would mean we could consider this coincidence as a success.

8.6 Xenon1T Electron Recoil Excess

An observation that may fit very well into our version of the pearl model for dark matter with the less than atomic size pearls is the Xenon1T Electron Recoil Excess [16]. This effect of electrons seemingly appearing with energy close to just 3.5 keV - note the coincidence we want to stress with the 3.5 keV X-ray
Figure 10: How we get the mass suggested by DAMA-LIBRA for our model as a “compromise” (denoted by “compr.” on the figure) to be $\sim 2000$ GeV. Formally, using the “simple formulas”, we have an upper bound of $200$ GeV and similar crude upper bounds using the number of events in DAMA-Libra. Using the “figure” or the “text” values in the Jeltema and Profumo paper give upper limits for the pearl mass of 1600 GeV or 160 GeV respectively. But if one corrects for the energy lost from going to the 3.5 keV line, as indicated by “l-impr.” in the figure, the $\sigma_M$ for the pearls is increased by a factor of the order 2000 and we get the upper limits indicated with a thick line of about 1 GeV or 0.1 GeV. So formally we have an inconsistency of our requirement but, considering that we only have order of magnitude bounds which should approximately be equalities, we have a good compromise value.
line photon energy - would independent of the details the dark matter model be very indicative, since we already have a strong suggestion that dark matter tends to emit light with the 3.5 keV frequency.

Apart from the DAMA/LIBRA and DAMA experiment the other direct search experiments seem to find only negative results when looking for the dark matter. There was, however, found one unexpected result although at first not seemingly due to dark matter:

The experiment Xenon1T investigated what they call electron recoil in their Xenon experiment. In the Xenon experiment one has a big tank of liquid Xenon with some gaseous Xenon above it and photomultipliers looking for the scintillation of this xenon. The philosophy behind the experiment that a dark matter WIMP e.g. hits a nucleus inside the xenon and the recoil of this creates a scintillation signal S1 and also an electron which is then driven up the xenon tank by an electric field and at the end by a further electric field made to give a signal at the top S2. By the relative size of the signals S1 and S2 one may classify the events - which are taken to be almost coinciding pairs of these signals S1 and S2 - as being nucleon recoil or electron recoil. One expects to find the dark matter in the nucleus recoils, since a dark matter particle is not expected to make an electron with sufficient energy to make an observable electron recoil event.

But now carefully estimating the background expected the Xenon1T experimenters found an excess of electron recoil events.

Proposed ideas for explaining it include axions from the sun or neutrinos having bigger magnetic moments or perhaps less interestingly that there could be more tritium than expected in the xenon.

But here our model of relatively stronger interacting particles able to radiate the line 3.55 keV when excited provides a possible explanation:

Going through the earth and the rest of the shielding the pearls or particles get excited so as to emit 3.55 keV X-ray just as they would do it in the Tycho supernova remnant, where they also get excited by matter or cosmic rays. But then the particles passing through the deep underground Xenon1T experiment are already excited and prepared for sending out the 3.55 keV radiation. Now they could possibly simply do that in the xenon tank or they might dispose of the energy by a sort of Auger effect by rather sending out an electron with an extra energy of 3.55 keV. Such an electron with an energy of a few keV could be detected and taken for an electron recoil event in the Xenon1T experiment.

It is remarkable that the signal of these excess electron recoil events appears to have just an energy of the recoiling electron very close to the value 3.55 keV. Indeed the most important bins for the excess are the bins between 2 and 3 keV and the bin between 3 and 4 keV.

So we would claim that there is in our model no need for extra solar axions or neutrino magnetic moment, nor tritium. But we claim it to be 3.55 keV radiating dark matter one sees in the xenon experiment!

9 Conclusion

We have put up two slightly different models for dark matter being actually pearls which have a new phase or type of vacuum inside, which by our “Multiple Point Principle” is supposed to have the same energy density as the present vacuum. The two models only differ by taking the parameters different, espe-
cially the tension of the surface separating the inside with its vacuum from the outside with the present vacuum.

The two models are thus given as roughly:

- **Big pearls**, adjusted to the Tunguska event being due to one falling down onto the earth:
  
  The cubic root $S^{1/3}$ of the tension is several GeV, the size of the pearls is cm-size.

- **Small pearls**:
  
  The cubic root of the tension $S^{1/3}$ is of the order of 1 MeV, the size of the pearls a bit bigger than atomic nuclei.

Our main result was that we could fit both very frequency 3.5 keV of the X-ray radiation suspected to come from dark matter and the intensity as fitted by Cline and Frey to a series of observations of this line from various galaxy clusters with essentially one parameter, which we wrote as $\frac{\xi + 10 \text{MeV}}{\Delta V}$. So two observed quantities by one parameter. Both observations concern the still doubtful 3.5 keV X-ray radiation.

We can essentially keep this parameter whether we take the pearls big with a big surface tension or small with a small surface tension.

Taking the model with the small pearls, on which we have far from finished everything, we hope that we can further:

- Make the DAMA-LIBRA controversial observation of dark matter by the seasonal variation technique compatible with the model.
- Fit the a priori very strange observation by Jeltema and Profumo of 3.5 keV radiation coming from the Tycho supernova remnant in the picture with the 3.5 keV radiation coming from dark matter. (Something they take themselves as the sign that this 3.5 keV line is not coming from dark matter but from some ion such as potassium).
- We have for our model a very promising coincidence of the electron excess energy from the Xenon1T experiment with the number 3.5 keV. The point is that the our pearls - in the small size model - come through the apparatus of the Xenon1T experiment and are excited with some extra electrons or simply have some excitons in them - excited during the passage through the shielding - which then deliver just the 3.5 keV energy to an electron in the Xenon1T experiment. And that is then giving an excess of such events with just an excited electron which was the ununderstood effect seen by Xenon1T.

### 9.1 The fitting of the Small Pearl Version

We basically make predictions from the small pearl version with the following parameters:

- The surface tension represented by its cubic root: $\xi^{1/3}$,

- Essentially the potential difference $\Delta V$ for a nucleon inside versus outside the pearl, represented by the combination $\frac{\xi^{1/4}}{\Delta V}$ (where $\xi_{\text{FS}}$ is the ratio of...
the radius of the pearl to the “critical” radius at which the nucleons would be just about to be spit out. Presumably even coming in under the fourth root this ratio $\xi_{FS}$ is not of much significance and probably is $\sim 5$.

- An efficiency parameter $l$ for getting 3.55 KeV radiation compared to what our estimates at first suggest. One gets really $1/l$ times the energy available in the time during which the pearl is sufficiently cold for radiating appreciably in the 3.55 keV line.

With these parameters we fit 1) the intensities of the Cline-Frey fit, 2) the Supernova remnant intensity, 3) the very frequency 3.55 keV and 4) a crude mass extracted from the observations of DAMA-LIBRA in the way it is interpreted by us, namely with somewhat strongly interacting pearls, only coming through by means of their high mass. So we fit 4 data point with 3 parameters. This is still formally a success, but now we claim that in addition and crudely consistent with the fit we have that the actual cross section to mass ratio for our small pearls coincides with the cross section to mass ratio for e.g. carbon nuclei. This corresponds to the fact that our pearls are so small that cosmic rays in the supernova remnant say passing though the pearls only interact when they hit a nucleus but otherwise can escape through without touching the pearl. The pearls are so to speak so thinly filled that the cosmic rays “see” the single nuclei in the sack making up the pearl.

Further it is a coincidence, although not obviously reasonable to understand physically, that the size of the pearls is just such that the electron cloud begins to emerge significantly outside the skin surrounding the pearl. This means that the homolumo gap providing the very frequency 3.55 keV for the radiation has a maximum at just this fitted situation. Thus the 3.55 keV line will be especially sharp compared to the possibility that this coincidence was not realized.

If we even counted this last coincidence as understandable as say a stable point more likely than a general point, then we could claim we rather fitted 4 data points with 3 parameters and 2 constraints, meaning really only with 3-2 = 1 parameter.

### 9.2 Parameters $S^{1/3}$ and $\Delta V$ Small and Outlook

The parameter values we obtained with our “Small Pearls Version” were

\[
S^{1/3} = 3 \text{ MeV} \tag{122}
\]

\[
\frac{\xi_{FS}^{1/4}}{\Delta V} = 0.5 \text{ MeV}^{-1}, \tag{123}
\]

which with

\[
\xi_{FS} \approx 2^{4/9} \sqrt[3]{\frac{\pi}{4}} \approx 5 \tag{124}
\]

gives

\[
\Delta V \approx 1.34 \text{ MeV}. \tag{125}
\]

Both these values for the parameters in the notation in which they have dimension of energy are - one would say embarrassingly - small compared to the dimensional argument expectations, if one speculated that Higgs physics
and top-quark physics were involved. That would namely instead give e.g. $S^{1/3} \sim 100 \text{ GeV}$. This means that Higgs and/or top-quark physics is not at all a promising possible explanation behind the vacuum-phases. We rather need physics of an energy order of magnitude even under or at least in the very low energy scale end of strong interaction physics, or it should be rather a kind of atomic physics involved.

We have ideas under development taking as a starting point the work by Kryjevski Kaplan and Schaefer [26], who calculated the phase diagram for nuclear matter under various high nuclear densities and considered the so called CFL phase. This stands for color flavour locking phase meaning that the $SU(3)_c$ color group is broken spontaneously in a direction locked with that of the flavour $SU(3)_f$ group. It is remarkable that these authors find a triple point as a function of the light quark masses coinciding with the experimental quark masses. This is, however, not quite what we would need to have a case of MPP degenerate vacuum-phases. Because of the high baryon density used in the study of Kryjevski Kaplan and Schaefer [26] their phases are namely not vacua.

Nevertheless we are working on arguing that their phase diagram might be extrapolated down to zero baryon density and thus tell us about vacuum phases. In that case an energy scale for the phase transition physics of the order of the strong interaction scale $\Lambda_{QCD} \approx 300 \text{ MeV}$ could be understandable. Even reaching down to a few MeV is at least closer than if one should begin with the Higgs-mass scale.

Such surprisingly low tension domain walls also bring the chances for them to really be acceptable astronomically much closer. The problem with domain walls coming to dominate energetically the whole cosmology and thus being phenomenologically unacceptable is of course weakened the lower the tension and thereby from Lorentz invariance also the energy per unit wall-area is.

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