POSSIBLE SOLUTION OF DARK MATTER, THE SOLUTION OF DARK ENERGY AND GELL-MANN AS GREAT THEORETICIAN

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This talk discusses the formation of primordial intermediate-mass black holes, in a double-inflationary theory, of sufficient abundance possibly to provide all of the cosmological dark matter. There follows my, hopefully convincing, explanation of the dark energy problem, based on the observation that the visible universe is well approximated by a black hole. Finally, I discuss that Gell-Mann is among the five greatest theoreticians of the twentieth century.

This work is dedicated to Murray Gell-Mann for his 80th birthday.

Keywords: black hole, dark matter, holographic principle, entropy

1. Outline of talk

It is an honor to talk at a festschrift for Murray Gell-Mann, who dominated research in particle phenomenology for at least twenty years.

At the beginning of my talk, I shall discuss a recent paper on the production of primordial intermediate-mass black holes of mass \( M_{BH} = M_p \) with \(-8 \leq p \leq +5\), providing a sufficient abundance, that the primordial IMBHs can possibly act as all the cosmological dark matter.

I then discuss my solution for the difficult dark energy problem which was first identified from observations of supernovae, twelve years ago. Although I knew all the correct theoretical ingredients back then, the solution hit me only on February 6, 2010. Because this was an overwhelming human experience, I self-indulgently discuss it.

Finally, I discuss why Gell-Mann, who must himself have experienced a similar personally fulfilling moment, for the \( \Omega^- \) particle, is to be correctly, regarded as among the five greatest theoreticians, of the twentieth century.
2. Possible Solution for Dark Matter

If the dark matter (DM) is made of a weakly interacting massive particle (WIMP), we may be able to observe collider, direct and indirect DM signatures; the DM particles may be produced at LHC, and the next-generation direct search experiments will probe a significant portion of parameter space predicted by various theoretical DM models. In spite of thorough DM searches using widely different techniques, the results are negative so far. If no DM signature is found in the future experiments, it may suggest that the basic assumption that the DM is made of unknown particles is simply wrong.

There actually is a DM candidate in the framework of SM, namely, a primordial black hole (PBH). In the early Universe PBHs can form when the density perturbation becomes large, and it has been known that a PBH of mass greater than $10^{15}$ g survives evaporation, and therefore contributes to the DM density.

In consideration of the entropy of the universe it was pointed out in Ref. [5] that if all DM were in the form of $10^5 M_\odot$ black holes it would contribute a thousand times more entropy than the supermassive black holes at galactic centers and hence be a statistically favored configuration. Here we consider primordial black holes (PBHs) with masses from $10^5 M_\odot$ to $10^{-8} M_\odot$ and, subject to observational constraints, any of these masses can comprise all DM although the entropy argument favors the heaviest $10^5 M_\odot$ mass.

There are several ways to realize large density fluctuations leading to PBH formation. One possibility is the production of PBHs from density fluctuations generated during inflation. Since the blue spectrum with a spectral index $n_s > 1$ is disfavored by the WMAP data, a single inflation may not be able to produce large density fluctuations at small scales unless some dynamics is introduced during inflation. On the other hand, the density fluctuations can be easily enhanced at small scales in a double inflation model.

In Ref. [4], we discuss a double inflation model that consists of a smooth-hybrid inflation and a new inflation. In this set-up PBHs with a narrow mass distribution are formed as a result of an explosive particle production between the two inflations. We show that the PBH mass can take a wide range of values from $10^{-8} M_\odot$ up to $10^5 M_\odot$. Also, the resultant PBH mass has a correlation with running of spectral index. We numerically calculated the correlation, which can be tested by future observations.

The black hole mass, and the formation epoch, are related to each other, due to the causality. In the early Universe, the mass contained in the Hubble horizon sets an upper bound on the PBH mass formed at that time. Assuming that the whole mass in the horizon is absorbed into one black hole, we obtain
\[ M_{\text{BH}} = \frac{4\pi \sqrt{3} M_P^3}{\sqrt{\rho_f}} \approx 0.05 \frac{g_*}{100} \frac{1}{2 \text{GeV}} \sqrt{T_f} - 2, \]
\[ \approx 1.4 \times 10^{13} \frac{g_*}{100} \frac{1}{6 \text{Mpc}^{-1}} - 2, \] (1)

where \( M_{\text{BH}} \) is the black hole mass, \( M_P \approx 2.4 \times 10^{18} \text{GeV} \) is the reduced Planck mass, \( M_\odot \approx 2 \times 10^{33} \text{g} \) is the solar mass, \( g_* \) counts the light degrees of freedom in thermal equilibrium, \( \rho_f, T_f \) and \( k_f \) are the energy density, the plasma temperature and the comoving wavenumber corresponding to the Hubble horizon at the formation, respectively. The radiation domination was assumed in the second equality.

As is well known, any black holes have a temperature inversely proportional to its mass and evaporates in a finite time \( \tau_{\text{BH}} \),

\[ \tau_{\text{BH}} \approx 10^{64} \frac{M_{\text{BH}}}{M_\odot} \text{3yr}. \] (2)

Thus the black holes with mass less than \( 10^{15} \text{g} \) must have evaporated by now. PBHs which remain as (a part of) DM must therefore be created at a temperature below \( 10^9 \text{GeV} \). In the following we assume that PBHs account for all DM in our Universe.

The cosmological effects of PBHs have been extensively studied so far. While PBHs with masses below \( 10^{15} \text{g} \) are significantly constrained, it is very difficult to detect PBHs heavier than \( 10^{15} \text{g} \) because of negligible amount of the radiation. The MACHO and EROS collaborations monitored millions of stars in the Magellanic Clouds to search for microlensing events caused by MAssive Compact Objects (MACHOs) passing near the line of sight. The MACHO collaboration excluded the objects in the mass range 0.3\( M_\odot \) to 30\( M_\odot \), and the latest result of the EROS-1 and EROS-2 excluded the mass range \( 0.6 \times 10^{-7} M_\odot < M < 15 M_\odot \), as the bulk component of the galactic DM. On the other hand, if we assume that the PBH formation occurs before the big bang nucleosynthesis (BBN) epoch, the PBH mass should be lighter than \( 10^5 M_\odot \). Therefore we consider PBHs with masses (i) \( M_{\text{BH}} < 10^{-7} M_\odot \) and (ii) \( 30 M_\odot < M_{\text{BH}} < 10^5 M_\odot \).

The above observational constraints provide us with information on the PBH formation. If PBHs are produced at different times, the mass function tends to be broad, thereby making it difficult to be consistent with observations. In order to realize the PBH mass function with a sharp peak, most of the PBHs should be produced at the same time. Thus the production mechanism must involve such a dynamics that only the density fluctuation of a certain wavelength rapidly grows.

What kind of dynamics can create PBHs? First of all, density perturbation must become large for PBHs to be formed. There are several ways to realize large density
fluctuations leading to the PBH formation. One possibility is the production of PBHs from density fluctuations generated during inflation. In the standard picture of inflation, the inflation driven by a slow-rolling scalar field lasts for more than about 60 e-foldings to solve theoretical problems of the big bang cosmology. Then no dynamics for producing a sharp peak in the density perturbation is expected. However, there is no a priori reason to believe that our Universe experienced only one inflationary expansion. Indeed, the cosmological gravitino or modulus problem can be relaxed if the energy scale of the last inflation is rather low, and it is then quite likely that there was another inflation before the last one. If the multiple inflation is a common phenomenon, we expect that explosive particle production between the successive inflation periods may produce a sharp peak in the density perturbation at the desired scales, which leads to the PBH formation at a later time. In the next section, we show that this is actually feasible using a concrete double inflation model.

We provide a double inflation model, producing PBHs with a sharp mass function, as an existence proof. The first inflation is realized by smooth hybrid inflation. The smooth hybrid inflation model is built in framework of supergravity and the superpotential and Kähler potential are given by

\[ W_H = S \left( \mu^2 + \frac{(\bar{\Psi}\Psi)^m}{M^{2(m-1)}} \right) \]  \( m = 2, 3, \ldots \), \hspace{1cm} (3)

\[ K_H = |S|^2 + |\Psi|^2 + |\bar{\Psi}|^2, \] \hspace{1cm} (4)

where \( S \) is the inflaton superfield, \( \Psi \) and \( \bar{\Psi} \) are waterfall superfields, \( \mu \) is the inflation scale and \( M \) is the cut-off scale which controls the nonrenormalizable term. From the above superpotential and Kähler potential together with phase redefinition and the D-flat condition, we obtain the scalar potential as

\[ V_H(\sigma, \psi) \simeq \left( 1 + \frac{\sigma^4}{8} + \frac{\psi^2}{2} \right) \left( -\mu^2 + \frac{\psi^4}{4M^2} \right)^2 + \frac{\sigma^2\psi^6}{16M^4}, \] \hspace{1cm} (5)

where \( \sigma \equiv \sqrt{2}ReS \) and \( \psi \equiv 2Re\Psi = 2Re\bar{\Psi} \). Here and in what follows we use the Planck unit \( M_P = 1 \) and take \( m = 2 \) for simplicity. Although the scalar potential (5) is derived in the framework of supergravity, one may start with (5) without assuming supersymmetry. The potential (5) has a true vacuum at \( \sigma = 0 \) and \( \psi = 2\sqrt{\mu M} \). For \( \sigma \gtrsim \sqrt{\mu M}/2 \), however, the potential for \( \psi \) has a \( \sigma \)-dependent minimum at

\[ \psi_{\text{min}} \simeq \frac{2}{\sqrt{3}} \frac{\mu M}{\sigma}. \] \hspace{1cm} (6)

Note that \( \psi \) quickly settles down at the minimum during inflation since its mass is larger than the Hubble parameter. Then we can integrated out \( \psi \) and obtain the effective potential for \( \sigma \) as
\[ V(\sigma) = \mu^4 \left( 1 + \frac{\sigma^4}{8} - \frac{2}{27} \frac{\mu^2 M^2}{\sigma^4} \right) = \mu^4 + \frac{\mu^4}{8} \left( \sigma^4 - \sigma_d^4 \left( \frac{\sigma_d}{\sigma} \right)^4 \right), \] 

(7)

where \( \sigma_d \equiv \sqrt{2}/3^{1/8}(\mu M)^{1/4} \). If the scalar potential is dominated by the first term, the inflaton \( \sigma \) slow rolls and therefore inflation occurs.

According to the WMAP 5yr data, the curvature perturbation \( R \), the spectral index \( n_s \) and its running \( \frac{dn_s}{d\ln k} \) at the pivot scale \( k_\ast = 0.002\text{Mpc}^{-1} \) are

\[ R = 4.9 \times 10^{-5}, \quad n_s = 1.031 \pm 0.055, \quad \frac{dn_s}{d\ln k} = -0.037 \pm 0.028. \] 

(8) (9) (10)

From the effective potential, we obtain

\[ R = \frac{V^{3/2}}{\sqrt{3\pi} V'} = \frac{\mu^2}{\sqrt{3\pi}} \left[ \sigma_s^2 + \sigma_d^2 \left( \frac{\sigma_d}{\sigma_s} \right)^5 \right]^{-1}, \quad (11) \]

\[ n_s - 1 \simeq 2 \frac{V''}{V} = \left[ 3\sigma_s^2 - 5\sigma_d^2 \left( \frac{\sigma_d}{\sigma_s} \right)^6 \right], \quad (12) \]

\[ \frac{dn_s}{d\ln k} \simeq -2 \frac{V'''}{V^2} = -3 \left[ \sigma_s^3 + \sigma_d^3 \left( \frac{\sigma_d}{\sigma_s} \right)^5 \right] \left[ \sigma_s + 5\sigma_d \left( \frac{\sigma_d}{\sigma_s} \right)^7 \right], \quad (13) \]

where \( \sigma_s \) is the field value of the inflaton when the fluctuation corresponding to the pivot scale exits the Hubble horizon.

The fluctuation corresponding to the pivot scale \( k_\ast \) exits the horizon at \( t = t_\ast \) when \( k_\ast/a(t_\ast) = H_H = \mu^2/\sqrt{3} \) (\( H_H \): hubble during the smooth hybrid inflation). Thus the scale factor \( a_\ast = a(t_\ast) \) is given by

\[ \ln a_\ast = -2 \ln \mu - 136. \quad (14) \]

The e-folding number between the horizon exit of the pivot scale and the end of the smooth hybrid inflation is estimated as

\[ N_\ast(\sigma) = \int_{\sigma_s}^{\sigma_\ast} d\sigma \frac{V}{V'} \]

\[ \simeq \frac{4}{3\sigma_d^2} - \frac{1}{\sigma_s^2} \quad (\sigma_s > \sigma_d) \]

\[ \simeq \frac{\sigma_s^6}{3\sigma_d^8} \quad (\sigma_s < \sigma_d) \quad (15) \]

where \( \sigma_s(\ll \sigma_d) \) denotes the field value when the smooth hybrid inflation ends.
After the smooth hybrid inflation, $\sigma$ and $\psi$ oscillate about their minima and decay into the $\sigma$ and $\psi$ quanta via self-couplings and mutual coupling of the two fields. Since their effective masses depend on the field amplitudes and therefore time-dependent, specific modes of the $\sigma$ and $\psi$ quanta are strongly amplified by parametric resonance. To see this, let us write down the evolution equation for the Fourier modes of fluctuations $\sigma_k$ from (5) as

$$
\sigma_k'' + 3H\sigma_k' + \left[ \frac{k^2}{a^2} + m_\sigma^2 + 3m_\sigma^2 \frac{\dot{\psi}}{\sqrt{\mu M}} \cos(m_\sigma t) \right] \sigma_k \simeq 0, 
$$

where $m_\sigma = \sqrt{8\mu^3/M}$ and $\dot{\psi}$ is the amplitude of the $\psi$ oscillations. ($\dot{\psi} \sim \sqrt{\mu M}$ at the beginning of the oscillations.) Neglecting the cosmic expansion, Eq. (16) has a form similar to the Mathieu equation which is known to have an exponentially growing solution. The detailed numerical simulation showed that the wave number for the fastest growing mode is given by

$$
\frac{k_p}{a_{osc}} \simeq 0.3 m_\sigma.
$$

The fluctuations amplified by the parametric resonance eventually produce PBHs when they reenter the horizon after inflation. The mass of the PBH is approximately given by the horizon mass when the fluctuations reenter the horizon. Thus the PBH mass is estimated as

$$
M_{BH} \simeq 1.4 \times 10^{13} M_\odot \left( \frac{k_p}{\text{Mpc}} \right)^{-2}.
$$

From Eqs. (17) and (18) the scale factor at the beginning of the oscillation phase is estimated as

$$
\ln a_{osc} = -114 - \ln m_\sigma - 0.5 \ln(M_{BH}/M_\odot).
$$

Because the e-folding number $N_*$ is equal to $\ln a_{osc} - \ln a_*$, we obtain

$$
N_* = 21 + 0.5 \ln(\mu M) - 0.5 \ln(M_{BH}/M_\odot).
$$

For a fixed black hole mass $M_{BH}$, there are two parameters in the model, i.e., $\mu$ and $M$, one of which can be removed by using the WMAP normalization. Therefore observable quantities can be expressed in terms of one free parameter, leading to a non-trivial relation between $n_s$ and $dn_s/d\ln k$. In practice, we adopt $\mu M$ as the free parameter, and solve Eqs. (13) and (20) for $\sigma_*$ in terms of $\mu M$. Then $\mu$ and $M$ are determined with use of Eqs. (11) and (8) for a fixed $\mu M$. Thus, varying $\mu M$, we obtain sets of model parameters which are consistent with the observed curvature perturbations.
After $\sigma$ and $\psi$ decay, the second inflation (= new inflation) starts. As mentioned before, the role of the new inflation is to stretch the fluctuations produced during the smooth hybrid inflation and subsequent preheating phase to appropriate cosmological scales. The effective potential for the new inflation is given by

$$V_{\text{new}} = v^4 \left( 1 - \frac{c}{2} \phi^2 \right) - \frac{g}{2} v^2 \phi^4 + \frac{g^2}{16} \phi^8,$$

where $\phi$ is the inflaton of the new inflation, $v$ is the scale of the new inflation and $g$ and $c$ are constants. The scale factor $a_f$ at the end of the new inflation is estimated as

$$\ln a_f = -68 + \frac{1}{3} \ln \left( \frac{T_R}{10^9 \text{GeV}} \right) - \frac{4}{3} \left( \frac{v}{10^{15} \text{GeV}} \right),$$

where $T_R$ is the reheating temperature after the new inflation. Therefore, the new inflation should provide the total e-fold number $\simeq (\ln a_f - \ln a_{\text{osc}})$.

What makes the PBH particularly attractive as a DM candidate is that it is naturally long-lived due to the gravitationally suppressed evaporation rate. No discrete symmetries need to be introduced in an ad hoc manner. Also the PBH DM may be motivated from the arguments based on entropy of the Universe.

3. The Solution for Dark Energy

At the beginning of the twenty-first century, there existed a problem in mathematics which was considered so difficult that it was expected that the century might end without solution. The problem was the Poincaré Conjecture in topology.

In fundamental theoretical physics, there was, at the beginning of the twenty-first century, an equally impossible seeming problem which likewise might not be solved for a hundred years. The problem was the Dark Energy in cosmology.

The creativity of *homo sapiens* had been underestimated. The Poincaré Conjecture was proved by Perelman, in less than three years. The Dark Energy problem was solved, by myself, in less than ten years.

In my Festschrift from 2003, there is a photograph of a four-year-old boy with three special properties - a talent for mathematics, infinite chutzpah and he said he is cleverer than Newton. The talent meant that if the young boy were given a three-digit number, say, 506, he could, within seconds, answer $22 \times 23$; at most, one percent of four-year-olds could do, similarly. At that time, in 1948, Newton was better known, even than any of the monarchs, except possibly the then monarch, King George VI. Surely, Newton was among the top one percent of human intelligence, so to be cleverer would require further reality checks. One would be forthcoming in 1965.
On the road from 1948 to 2010, I will make mercifully brief rest stops at 1957, 1965 and 2006. The first of these, 1957, is when I learned, at King Charles I School, about the universal law of gravitation. This was a key stage, because I clearly recall looking up at the Moon and feeling my own weight, and being so impressed by the idea that I decided, then and there, that I would, one day, have a grander idea, than Newton’s. At about the same time, in 1957, my French teacher recommended, to my parents, a career, as a university professor, in linguistics. I might have done that, were it not for the call of Newton. Finally, in 1957, it was a memorable year because I met, for twelve seconds in Kidderminster Town Hall, the monarch, Queen Elizabeth II. Having bowed, I was ready to answer absolutely any question but all she said was that it was very nice to meet me. I should have worn a sign, soliciting a royal question.

In 1965, it was my turn for the opportunity of the Oxford Final Honors Schools (OFHS) with its six three-hour examinations, two each on Wednesday, Thursday and Friday June 6 - 8, 1965. The three morning exams were conventional while the afternoon OFHS exams were open-ended essay questions, with no instruction, even on how many questions to answer.

For the four months February - May, 1965 I did nothing, except study and make extensive notes, and memory cards. I was sequestered, in Frewin Hall, and talked to nobody, except college servants who could bring me food, or physics books from Blackwell’s. What is pertinent to the sequel, in 2007 and 2010, is that of the hundred physics books I accumulated in Frewin Hall, my personal favorite was always Tolman’s *Relativity, Thermodynamics and Cosmology*, a clear and endearingly modest discussion, of the role of entropy in cyclic cosmology. I do recall spending hours then intrigued by the apparent contradiction, between the attractive idea of cyclic cosmology, and the second law of thermodynamics; the contents of Tolman’s book, however, did not appear on my examinations.

For the OFHS paper on Thursday afternoon (June 7, 1965) my strategy was to answer only one essay question. I had retained extensive material on a dozen topics, with a good probability at least one of them would appear on the question paper. There it was: X-ray diffraction. In three hours, I produced a meticulously-detailed 100-page monograph on X-ray diffraction, later described by an experienced examiner, as the most detailed answer, he had ever seen. This required some of Gell-Mann’s attributes: clear thinking, profound understanding and extensive retention. Incidentally, it also needed fast handwriting. My OFHS grades on my six papers were α, α, α, α⁺, α, α. This is called straight alphas. Two alphas were necessary for First Class Honours. The unprecedented α⁺ led to some discussion, in the Brasenose College (BNC) senior common room, and the BNC Fellows decided to allow me dining rights, on High Table, for as long as I would remain at BNC, as a doctoral student. The α⁺ did support my being in the top one percent of
human intelligence, just like Newton. At High Table dinners, I befriended a philologist, who had collected numerous honorary doctorates, and could understand a hundred languages. He once mentioned that he had met, dining in BNC, just the previous evening, Gell-Mann who had explained his ideas, about the origin, of the Basque language. Therefore, I could have first met Gell-Mann in 1965, in BNC, had I attended that dinner. Instead I first met Gell-Mann the following year, 1966, as discussed in the next section.

More than forty years after my OFHS experience, and after the accelerated cosmic expansion had been discovered, in 1998, I took on a new PhD student at UNC-Chapel Hill, Lauris Baum, in 2006 and suggested that he study, assiduously, existing papers on cyclic cosmology. This he did, and we discussed, at length, the issue of the Tolman conundrum, which had first piqued my intellectual curiosity, in 1965. The result was the first, and still only, solution to the 75-year-old conundrum. In 2010, at Tokyo, on Thursday, February 4, Hirosi Ooguri who is a distinguished professor at the California Institute of Technology and, like me, a professor at the University of Tokyo (I am also a distinguished professor in Chapel Hill) wrote, to inform me that, on Saturday, a Todai visitor, Professor Dam Son, would give three lectures on the holographic principle at Hongo campus, starting at 1:30 PM. Son’s lectures exceeded expectations. During the lectures (February 6, 2010), I realized, writing in my notebook, that the visible universe is approximated by a black hole, and that this leads to a resolution of the dark energy problem.

Consider the Schwarzschild radius \( r_s \), and the physical radius \( R \), of the Sun \((\odot)\). They are \( r_s(\odot) = 3\text{km} \) and \( R(\odot) = 800,000\text{km} \). Their ratio is \( \rho(\odot) = (R/r_s)(\odot) = 2.7 \times 10^9 \). One can readily check that, for the Earth or for the Milky Way, that the ratio \( \rho = (R/r_s) \) is likewise much larger than one: \( \rho >> 1 \). Such objects are nowhere close to being black hole. Now consider the visible universe \((VU)\), with mass \( M_{VU} = 10^{23}M_\odot \). It has \( r_s(VU) = 30\text{Gly} \), and \( R(VU) = 48\text{Gly} \), hence \( \rho(VU) = 1.6 \). The visible universe, within which we all live, is close to being a black hole. The solution to the dark energy problem follows, providing I so approximate the visible universe. At the horizon, there is a PBH temperature, \( T_\beta \), which I can estimate as

\[
T_\beta = \frac{\hbar}{k_B} \frac{H}{2\pi} \sim 3 \times 10^{-30} \text{K}.
\]  

This temperature of the horizon information screen leads to a concomitant FDU acceleration, \( a_{\text{Horizon}} \), outward, of the horizon given by the relationship

\[^{a}\text{A useful communication, from Ooguri san, at IPMU, is acknowledged.}\]
\[ a_{\text{Horizon}} = \left( \frac{2\pi \epsilon c k T_B}{\hbar} \right) = cH \sim 10^{-9} \text{ m/s}^2. \] (24)

When \( T_B \) is used in Eq. (24), I arrive at a cosmic acceleration which is essentially in agreement with the observations.\(^{15,16}\)

It would be wonderful to have lunch, maybe at L’Atelier de Joël Robuchon in Roppongi Hills, with Murray Gell-Mann, Isaac Newton, and Grigori Perelman to compare notes on personal fulfillment. What does Grigori Perelman mean, when he tells journalist, in turning down a million dollars, I have all I want. I’m not interested in money or fame? This seems to baffle some americans, whose idea of happiness, as an inalienable right, is a three-comma net worth. Yet, a two-comma net worth suffices, for all practical purposes. Fame can hardly exceed that of the singer and entertainer, Elvis Presley (1935-1977), whose name, from my non-scientific studies in public transportation, is still recognizable by one billion people. He died, when he was only forty-two, so his fame was not very useful.

After Son’s lectures on February 6, 2010, I went to the nearby Yushima Shrine around 6:00 PM and, impossibly, hoped that one of the many Japanese strolling around the shrine was Nambu sensei, to tell him. One ramification was that most of the work on quantum gravity, since the discovery of quantum mechanics, was called into question. There was an indescribable feeling of personal fulfillment, that the 66 years and 98 days, so far, of my life, had a significance. This was/is a totally individual experience which, unlike money or fame, involves no other person, and is therefore different. Because the visible universe is much bigger than the Solar System\(^b\), I had vindicated my claim, as a four-year-old, to be cleverer than Newton. Because, in my opinion, time travel into the past will forever be impossible, I cannot return to Isaac Newton in 1686 and forewarn him that a cleverer person will be born on October 31, 1943; nor can I return to 1948 and tell the four-year-old on a tricycle that he is right to say he is cleverer than Newton. The first reaction is to want to achieve the personal fulfillment again, and again. I am certain that Perelman is presently pursuing the six other Clay problems, in alphabetical order: Birch and Swinnerton-Dyer Conjecture, Hodge Conjecture, Navier-Stokes Equations, P vs NP, Riemann Hypothesis and Yang-Mills Theory. More likely, Perelman is considering a more profound direction, in mathematics.

Newton finished Book I of *Principia*, entitled *De Motu Corporum I*, in 1686; then Book II (*De Motu Corporum II*) and Book III (*De Systemata Mundi*) in 1687. Book III adds more empiricism. I now explain why PHF would write, even then in 1685,

\(^b\)A useful discussion, with Gerard ’t Hooft, at the Gell-Mann Festschrift, is acknowledged.
a better *Principia* than Newton. PHF would start, in 1685, with Book II (Newton’s grade, B-), knowing that Book I (Newton’s grade, A+) was easier.

In order to explain why his sound speed formula
\[ v_s = \sqrt{\frac{p}{\rho}} \]
gives
\[ v_s = 290 \text{ m/s} \]
whereas the experimental value for \( v_s \) at one atmospheric pressure and \( T = 20^\circ C \) is \( v_s = 343 \text{ m/s} \), Newton needed a large correction. About a half of this correction arises, according to *Principia* Book II, from Newton’s crassitude, where the sound propagates instantaneously through particles in the air. The remaining discrepancy leads to, surely, the most confused passage, in all of the *Principia*. Although I know that Gell-Mann reads Latin as well as I do, other non-British-educated theoreticians may not, so I quote, instead of Latin, an English translation of a Scholium:

*Moreover, the vapors floating in the air, being of another spring, and a different tone, will hardly, if at all, partake of the motion of the true air in which the sounds are propagated. Now if these vapors remain unmoved, that motion will be propagated the swifter through the true air alone, and that in the subduplicate ratio of the defect of the matter. So if the atmosphere consists of ten parts of true air and one part of vapors, the motion of sounds will be swifter in the subduplicate ratio of 11 to 10, or very nearly in the entire ratio of 21 to 20, than if it were propagated through eleven parts of true air: and therefore the motion of sounds above discovered must be increased in that ratio.*

Newton was not only clever in mathematics, he was also a brilliant experimentalist. He himself measured the speed of sound in Nevile’s Court at Trinity College in Cambridge by hitting the paving stone with a hammer at such a frequency that the echo coincided with the next hit. Other experimentalists, such as Sauveur, cited by Newton, had determined \( v_s \), so there was no doubt the theory was wrong.

The cleverer PHF would have thought more deeply, than Newton, about the ratio
\[ r = \frac{(v_s)_{\text{expt}}}{(v_s)_{\text{theory}}} \].

It is not too difficult to see, that this requires the isothermal Boyle’s equation of state for an ideal gas, \( PV = \text{constant} \) to become the adiabatic \( PV r^2 = \text{constant} \). From theory and experiment, one knows \( r^2 = 7/5 \) and then, via diatomic molecules and statistical mechanics, I arrive smoothly at the entropy defined by Clausius, whose birthname was Gottlieb, in 1865. What emerges is Boltzmann’s equation \( S = k \ln W \) as more profound than the equations of Newton, like \( F = Gm_1m_2/R^2 \), or those of the, still future, Einstein, like \( E = mc^2 \). Here the emphasis is not on exactitude, but on profundity.

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\[ ^a \] A useful discussion, with Murray Gell-Mann, at the Gell-Mann Festschrift, is acknowledged.

\[ ^d \] A useful discussion, with Bernard Carr, at IPMU, is acknowledged.

\[ ^e \] A useful discussion, with Finn Ravndal, at the Gell-Mann Festschrift, is acknowledged.

\[ ^f \] A useful discussion, with Murayama san, at IPMU, is acknowledged.
The aforementioned solution, of the dark energy problem, not only solves a cosmological problem, it casts a completely new light, on the nature of the gravitational force. Since the expansion of the universe, including the acceleration thereof, can only be a gravitational phenomenon, I arrive at the viewpoint, that gravity is a classical result, of the second law of thermodynamics. This means that gravity cannot be regarded as, on a footing with, the electroweak and strong interactions. Although this can be the most radical change, in gravity theory, for over three centuries, it is worth emphasizing, that general relativity remains unscathed.

My result calls into question, almost all of the work done on quantum gravity, since the discovery of quantum mechanics. For gravity, there is no longer necessity for a graviton. In the case of string theory, the principal motivation for the profound, and historical, suggestion, by Scherk and Schwarz, that string theory be reinterpreted, not as a theory of the strong interaction, but instead as a theory of the gravitational interaction, came from the natural appearance, of a massless graviton, in the closed string sector. I am not saying that string theory is dead. What I am saying is, that string theory cannot be a theory of the fundamental gravitational interaction, since there is no fundamental gravitational interaction.

The way this new insight emerged, and the solution of the dark energy problem itself, was as a natural line of thought, following the discovery of a cyclic model in and the subsequent investigations of the entropy of the universe, including a possible candidate for dark matter.

Another ramification, of my solution of the dark energy, problem is the status, fundamental versus emergent, of the three spatial dimensions, that we all observe every day. Because the solution assumes the holographic principle at least one spatial dimension appears as emergent. Regarding the visible universe as a sphere, with radius of about 48 Gly, the emergent space dimension is then, in spherical polar coordinates, the radial coordinate, while the other two coordinates, the polar and azimuthal angles, remain fundamental. Physical intuition, related to the isotropy of space, may suggest that, if one space dimension is emergent, then so must be all three. This merits further investigation, and may require a generalization of the holographic principle in. On the other hand, a fundamental time coordinate is useful in dynamics. This present discussion is merely one step towards the goal of a cyclic model, in which time never begins or ends.

4. Gell-Mann in Twentieth Century Physics

Whereas I have published research in particle phenomenology for forty years, and whereas I will not include my own name in the list, these are sufficient credentials

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\(^6\)A useful discussion, with John Schwarz, at the Gell-Mann Festschrift, is acknowledged.

\(^7\)A useful discussion, with Sugimoto san, at IPMU, is acknowledged.
to assess the greatest theoreticians of the twentieth century. I shall arrive at a
top-ten list, which includes: four very distinguished Europeans, four truly brilliant
Americans all born, by coincidence, in the great state of New York and two living-
legend Asians, of whom, only Yang has been significantly influenced, in adult life,
by the Confucian analects.

In alphabetical order, the top five, with two chosen accomplishments:

- Paul Dirac (**antimatter and \( g = 2 \))
- Albert Einstein (**relativity and photoelectric effect**)
- Murray Gell-Mann (**\( \Omega^- \) and quarks**)
- Gerard ’t Hooft (**holographic principle and renormalizability**)
- Yang Zhenning (**gauge theories and parity violation**)

The next five are, again in alphabetical order: Richard Feynman, Sheldon Glashow,
Werner Heisenberg, Nambu sensei and Julian Schwinger. Below these, the ordering
becomes more subjective, but my top ten choices, I believe, are close to the general
opinion.

It should be noted that, in 1948, Nambu sensei, independently of the late Julian
Schwinger, derived the one-loop quantum electrodynamics correction to \( (g-2) \). That
would give Nambu sensei (**symmetry breaking and \( (g-2) \)**) which is very strong,
and could displace one of the top five. However, Nambu sensei did not publish,
possibly because he did not want to overshadow Tomonaga sensei, fourteen years
senior, chronological age being all-important in Japanese society.

I first met Murray (if I may) in 1966 when I was starting research in particle phe-
nomenology and my Oxford doctoral adviser, J.C. Taylor, considered it worth driv-
ing ten miles to the Rutherford Laboratory. It was indeed worthwhile. Murray spoke
with infinite self-confidence, and, in answering questions, provided information, like
a computer download, reflecting encyclopaedic knowledge. In those times, Murray’s
prescient paper **Symmetries of Baryons and Mesons** was a standard reference for
Oxford students.

Murray has many first-rate accomplishments. Equally impressive, is the sheer num-
ber of new results, sometimes several in the same year of which I can mention, in
the time available, just a hint of Murray’s gigantic contributions, with the renor-
malization group, the sigma model and the invention of the theory of strong
interactions. As one speaker at this Festschrift put it, everything in particle phe-
nomenology was either by Murray, or named by Murray, who enriched the field.

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1. A useful discussion, with Yang Zhenning, at the Gell-Mann Festschrift, is acknowledged.
2. A useful discussion, with Nambu sensei, at Osaka University, is acknowledged.
3. A useful discussion, with Kenneth Wilson, at the Gell-Mann Festschrift, is acknowledged.
with erudite names, like strangeness, and quark. In his monumental quark paper, perhaps the best two pages ever printed in Physics Letters B, Murray’s infinite self confidence wobbled, when he discussed non-existence of real quarks.

Murray, I wish you many more years of creativity. You are, forever, a giant in particle phenomenology.

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