Observational Consequences of Dark Energy Decay

Ue-Li Pen\textsuperscript{1} and Pengjie Zhang\textsuperscript{2}

(Dated: February 2, 2012)

We consider the generic scenario of dark energy which arises through the latent heat of a hidden sector first order cosmological phase transition. This field could account for the extra radiation degree of freedom suggested by the CMB. We present the bubble nucleation solution for the viscous limit. The decay rate of the field is constrained by published KSZ data, and may be an explanation of current excess ISW correlations. Cross correlation of current and future surveys can further constrain or test the parameter space. The decay model is plausibly in the observable range, and avoids anthropic problems. This class of models is not well constrained by the popular dark energy figure of merit.

PACS numbers: 98.80.Es,98.80.Cq

Introduction. – Dark Energy is one of the most mysterious puzzles in modern physics. In this paper we consider the possibility that dark energy is a mundane first order phase transition in a hidden sector thermal field. Such phase transitions have been proposed at these low temperatures\textsuperscript{2,3}, and the energy scales might arise naturally in a seesaw mechanism\textsuperscript{4}. Standard cosmological phase transitions are described in textbooks\textsuperscript{5}. In order for a false vacuum to sustain an accelerating epoch dominated by dark energy, the phase transition must be strongly first order. The nucleation to the true vacuum can occur through quantum and thermal tunnelling processes. The rates depend exponentially on the details of the potential. In order for the universe to appear accelerating over a substantial history, the rates cannot be much higher than the inverse age of the universe. Thus, the phase transition must occur through the nucleation of discrete bubbles. If the false vacuum life time is shorter than 19 Gyr\textsuperscript{1}, the phase transition will eventually complete through the collision of bubbles, which have sizes and separations comparable to the visible universe today. Otherwise, the expansion rate of the universe wins over the nucleation rate, and the vacuum dominates regions dominate in volume. This has been interpreted to lead to problems with Boltzman brains (ibid). So it is interesting to observationally test if the nucleation rate might indeed be high enough to eliminate this potential problem.

It has been debated how generic a very strongly first order phase transition is\textsuperscript{6}, and some amount of tuning is required to be “just right” for it to explain the supernova data. We feel that this amount of tuning is modest compared to that required for a slow roll scenario\textsuperscript{7}, which is the most fashionable dark energy model today\textsuperscript{8}.

We compute the physical properties of nucleating bubbles, and observational consequences if we live inside one. The bubble boundary expands at close to the speed of light, and the line of sight will generally not intersect a bubble boundary unless we live inside it. We find that most of the dark energy decays into a fluid concentrated in the outer 0.01% of the bubble radius. KSZ constrains our region to have nucleated not more than about 3 Gyr ago. We propose future observational tests for these bubbles, which include KSZ cross correlations, and high precision dipole anisotropy searches in the local matter distribution.

Scenario. – The simplest scenario is a hidden sector radiation fluid which currently only interacts with baryonic matter through gravity, much like dark matter. Current CMB data suggests that an extra radiative degree of freedom may be present\textsuperscript{8}, at a temperature comparable to that of neutrinos. The number of radiation degrees of freedom is usually quoted as the effective number of neutrino species, $N_{\text{eff}} = 4.34^{+0.86}_{-0.88}$. There are 3 known neutrino species, leaving room for an extra light field or radiation fluid at $z \sim 1000$. As the universe expands and cools, this fluid could undergo a first order phase transition. For a phase transition temperature of $\sim 20\text{K}$, at $z \sim 10$, the resulting false vacuum energy could explain today’s apparent cosmological constant. As the universe expands, the false vacuum state can tunnel to the true vacuum, either thermally or quantum mechanically. If the tunnelling rate is comparable to today’s universe age, the universe could exit the trapped dark energy state through bubble nucleation. During the factor of ten cosmic expansion since the false vacuum trapping, the fluid has cooled to a tenth of the potential energy difference. The decaying vacuum will expand into this fluid. If viscosity is negligible, the vacuum energy decay will all end up in the kinetic energy of the bubble wall, which would then move at ultra relativistic speeds. In the presence of viscosity, the wall sweeps up the ambient radiation fluid, and the vacuum decay generates entropy in the fluid, which moves outward. The details of the bubble wall not important, all the energetics is dominated by the swept up fluid and the entropy generated by the decayed vacuum. We shall solve the dynamics in the next section.

Dynamics. – The hydrodynamic solution of decay of vacuum energy was solved in\textsuperscript{9}. In the cosmological context, we are in the limit of a relativistic perfect ambient fluid and a positive potential energy, with about 10,000 times the density of the fluid. In a bubble nucleation,
FIG. 1: bubble nucleation schematic. $t_0$ labels a present day observer centered at a bubble nucleation event which occurred $\delta t = r_0/c$ in the past. The last triangle denotes the true vacuum region. The dotted line denotes the trajectory of a dark matter shell in a $\Lambda$CDM cosmology. The solid tangent to this line denotes the actual post nucleation trajectory. The deviation of these two lines is observed on the past light cone indicated by the dashed line. The parameters correspond to a bubble nucleation event half a Hubble time in the past. On the left is a schematic second (unobservable) bubble nucleation event which occurs outside our past light cone. The shaded region is the collision region of the bubbles, inside of which our analysis is not applicable.

FIG. 2: bubble density profile. Plotted is the dark matter frame 00 component of the radiation fluid stress energy tensor $\rho \gamma^2$, which is the conserved matter quantity. The inset shows the shock front on a linear scale.

this potential energy is released and results in raising the entropy of the ambient fluid, and accelerating the fluid outward, at a Lorenz factor $\gamma \sim 100$. The numerical solution is shown in figure 2. We note that actual phase transitions can be more complex depending on the properties of the viscosity. Because most of the energy always piles up near the bubble wall, the infinite viscosity limit and zero viscosity limits result in similar net observables.

Most of the converted energy piles up within about $1/\gamma^2$ of the bubble wall, with a local overdensity of $\sim \gamma^2$. As we will see below, a bubble might be as big as $\sim$ Gpc, which would have a thickness of a few kpc. A bubble edge passing through our galaxy or solar system would have minimal impact, except on the most weakly bound structures. The Oort cloud could experience non-negligible perturbations, perhaps resulting in enhanced cometary impacts on earth. The dynamical time at the Oort cloud is $\sim 10^7$ yr. At this radius, the dark energy contributes a $\sim 10^{-3}$ fractional force of gravity. A bubble passage changes this force abruptly (shock impulse), potentially repopulating the loss cone that enters the inner solar sys-

tem. While small compared to galactic tides, it is also far out of the adiabatic limit, with a correspondingly larger effect. It would be tempting to associate a bubble passage with the dinosaur extinction event 65 Myr ago.

The dynamics of dark matter and baryons inside a bubble is straightforward on subhorizon scales. Each expanding matter shell suddenly stops its dark energy acceleration when the shell passes, and continues moving on a roughly straight trajectory. For an observer near the center of the nucleation event the universe still appears isotropic, but not homogeneous.

We first compute the test particle evolution centered on the nucleation event. We make the simplifying assumptions that we nucleate from a vacuum dominated phase, and neglect the finite contribution of dark matter. These assumptions are good to 20% today, and are progressively worse in the past. We denote the present time by $t_0$. We work in the limit where the Hubble constant is the cosmological constant $\Lambda = H_0^2$. The bubble nucleates at a lookback time $\delta t = r_0/c \ll 1/H_0$. Each shell labelled by $m = cz/H_0$ deviates from its accelerated expansion rate by a (inward) peculiar velocity

$$v_p = \frac{H_0^2 m(r_0 - 2m)}{c}$$

(1)

The peak blueshift is reached halfway at $m = r_0/4$. The peak peculiar velocity relative to the unperturbed (CMB) frame is $v_{\text{max}} = (H_0 r_0)^2/8c$.

Statistics. – We can currently be living in the false vacuum, in which case we would be unlikely to see any
FIG. 3: Bubble size and position allowed by CMB data.

other bubbles on our past lightcone, since any such bubble would expand at close to the speed of light. The chance of perfect timing coincidence that we could see both walls of a bubble are \( \sim 10^{-4} \). We can also live inside either one bubble, or in the past history of more than one.

If we live inside a true vacuum bubble, we could either live near the center, half way to the edge, or near the edge. We will go through each of these possibilities. Figure 3 plots the parameter space that is allowed by observations.

The CMB is an important constraint on isotropy and homogeneity. Locating us half way out to the bubble edge maximizes the local velocity relative to the CMB rest frame. If this is larger than the observed CMB dipole, the parameter space is ruled out. Our observed dipole is 700 km/sec. The local peculiar velocity can cancel out some of the bulk flow. We use a bulk flow of 2000 km/sec for purposes of setting an upper bound.

The change of background cosmology inside the bubble leads to large scale bulk flows. One of the most sensitive probes is the kinetic Sunyaev-Zeldovich (kSZ) effect. An observer at the center of the bubble sees matter within the true vacuum bubble at a systematic blueshift relative to the CMB: a matter overdensity results in a higher CMB temperature, and thus a positive correlation between matter and the CMB.

The kinetic Sunyaev Zel’dovich effect. The diffuse kSZ effect has not been detected yet. However, the upper limit of the kSZ power spectrum is tightened significantly by ongoing experiments such as ACT and SPT. The latest upper limit of the kSZ power spectrum \( \Delta T^2 \) at \( \ell = 3000 \) is 2.8-6.5\( \mu \)K\(^2\) for SPT and 8\( \mu \)K\(^2\) for ACT. Following the same procedure as in \( \cite{13} \), we calculate the bubble generated kSZ effect, as seen by an observer at the center (Fig. 4). The kSZ power spectrum increases steeply with increasing \( r_0 \) (\( \Delta T^2 \propto r_0^{-5.5} \)), making the kSZ effect a sensitive test of dark energy decay. The kSZ test puts a constraint \( r_0 < 1 \) Gpc (Fig. 4). This constraint assumes no other kSZ contributions. In reality, the kSZ contributions from free electrons after reionization(e.g. \( \cite{17} \)) and from patchy reionization can both reach a few \( \mu \)K\(^2\) (e.g \( \cite{18} \)). In this sense, the kSZ constraint \( r_0 < 1 \) Gpc is rather conservative.

Matter Anisotropy. For an observer not centered at the nucleation event, the mean cosmic density will appear larger in the direction of the nucleation center. The observer’s peculiar velocity vector relative to the CMB points towards this center as well. The Hubble constant exhibits anisotropies. These effects all scale as \( (H_0 \delta t)^2 \).

We have seen above that the KSZ constraints are less than 1%. A direct dipole search would need to make precise measurements of a local dipole.

Cross Correlation. More sensitive tests arise in a cross correlation of the distribution of matter with the CMB. The bubble induced kSZ has the same sign as the ISW effect, which positively correlates matter fluctuations with CMB temperature. Since we have already constrained the bubble flow peak to occur at \( z \lesssim 0.05 \), a shallow all sky survey is most sensitive. There are indications of such positive detections in an SDSS-WMAP
cross correlation, which appear larger than expected for pure ISW. Similarly, it produces a 2MASS-WMAP cross correlation at sub-degree scales, which can be compared to the current weak reported correlations\footnote{S. Dutta, S. D. H. Hsu, D. Reeb, and R. J. Scherrer, Phys. Rev. D 79, 103504 (2009), 0902.4699.}. A cross correlation of with Planck could confirm this detection. The peak velocity \( v_{\text{max}} \approx 2 \times 10^3(r_0/\text{Gpc})^2 \text{ km/s} \) at redshift \( z_{\text{max}} \approx 0.07(r_0/\text{Gpc})^2 \). Since there are no published 2MASS-Planck measurements, we will not perform numerical calculation of the cross correlation signal here. We use a simple scaling. The dark flow generated kSZ cross correlation (Fig. 4\footnote{E. Komatsu, K. M. Smith, J. Dunkley, C. L. Bennett, B. Gold, G. Hinshaw, N. Jarosik, D. Larson, M. R. Nolta, L. Page, et al., ApJS 192, 18 (2011), 1001.4538.}) predicts a \( \sim 10\sigma \) detection of a bubble with \( r_0 = 1 \text{ Gpc} \) through 2MASS-Planck cross correlation.

Conclusion. We have studied the physical properties and observational consequences of recent bubble nucleation events. These events are generic consequences if our dark energy is a false vacuum due to a strongly first order hidden sector phase transition, and depends only weakly on the microscopic properties of the field. They may account for the current enhanced SDSS-WMAP correlations. Further studies with Planck and 2MASS have the sensitivity to confirm the presence of these bubbles. Previous predictions of decay rates shorter than \( \sim 20 \text{ Gyr} \) likely result in observable consequences.

We thank Eric Switzer and Eugene Lim and for helpful discussions. ULP thanks NSERC and SHAO for financial support. PJZ Thanks the support by the NSFC grants and the Beyond the Horizons program.

[1] D. N. Page, Phys. Rev. D 78, 063535 (2008), arXiv:hep-th/0610079.
[2] H. Goldberg, Physics Letters B 492, 153 (2000), ISSN 0370-2693, URL http://www.sciencedirect.com/science/article/pii/S0370269300010455.
[3] S. Dutta, S. D. H. Hsu, D. Reeb, and R. J. Scherrer, Phys. Rev. D 79, 103504 (2009), 0902.4699.
[4] Z. Chacko, L. J. Hall, and Y. Nomura, J. Cosmology Astropart. Phys. 10, 11 (2004), arXiv:astro-ph/0405596.
[5] E. W. Kolb and M. S. Turner, The early universe. (1990).
[6] A. Mégevand and A. D. Sánchez, Phys. Rev. D 77, 063519 (2008), URL http://link.aps.org/doi/10.1103/PhysRevD.77.063519.
[7] A. Albrecht, G. Bernstein, R. Cahn, W. L. Freedman, J. Hewitt, W. Hu, J. Huth, M. Kamionkowski, E. W. Kolb, L. Knox, et al., ArXiv Astrophysics e-prints (2006), arXiv:astro-ph/0609591.
[8] E. Komatsu, K. M. Smith, J. Dunkley, C. L. Bennett, B. Gold, G. Hinshaw, N. Jarosik, D. Larson, M. R. Nolta, L. Page, et al., ApJS 192, 18 (2011), 1001.4538.
[9] U.-L. Pen, A. Loeb, and N. Turok, Astrophys. J. 509, 537 (1998), arXiv:astro-ph/9712178.
[10] J. R. Espinosa, T. Konstandin, J. M. No, and G. Servant, J. Cosmology Astropart. Phys. 6, 28 (2010), 1004.4187.
[11] P. P. Avelino, A. Canavese, J. P. M. de Carvalho, and C. J. A. P. Martins, Astroparticle Physics 17, 367 (2002), arXiv:astro-ph/0106245.
[12] R. Maartens, G. F. R. Ellis, and W. R. Stoeger, Phys. Rev. D 51, 1525 (1995), arXiv:astro-ph/9501016.
[13] P. Zhang and A. Stebbins, Physical Review Letters 107, 041301 (2011), 1009.3967.
[14] E. Shirokoff, C. L. Reichardt, L. Shaw, M. Millea, P. A. R. Ade, K. A. Aird, B. A. Benson, L. E. Bleem, J. E. Carlstrom, C. L. Chang, et al., Astrophys. J. 736, 61 (2011), 1012.4788.
[15] C. L. Reichardt, L. Shaw, O. Zahn, K. A. Aird, B. A. Benson, L. E. Bleem, J. E. Carlstrom, C. L. Chang, H. M. Cho, T. M. Crawford, et al., ArXiv e-prints (2011), 1111.0932.
[16] J. Dunkley, R. Hlozek, J. Sievers, V. Acquaviva, P. A. R. Ade, P. Aguirre, M. Amiri, J. W. Appel, L. F. Barrientos, E. S. Battistelli, et al., Astrophysics J. 739, 52 (2011), 1009.0866.
[17] P. Zhang, U.-L. Pen, and H. Trac, MNRAS 347, 1224 (2004), arXiv:astro-ph/0304534.
[18] O. Zahn, C. L. Reichardt, L. Shaw, A. Lidz, K. A. Aird, B. A. Benson, L. E. Bleem, J. E. Carlstrom, C. L. Chang, H. M. Cho, et al., ArXiv e-prints (2011), 1111.6386.
[19] A. Cabrè, E. Gaztañaga, M. Manera, P. Fosalba, and F. Castander, MNRAS 372, L23 (2006), arXiv:astro-ph/0603690.
[20] K. Aird, B. A. Benson, L. E. Bleem, J. E. Carlstrom, C. L. Chang, H. M. Cho, et al., ArXiv e-prints (2011), 1111.0932.
[21] H. M. Cho, T. M. Crawford, et al., ArXiv e-prints (2011), 1111.6386.
[22] P. Zhang, MNRAS 407, L36 (2010), 1004.0990.
[23] S. Ho, C. Hirata, N. Padmanabhan, U. Seljak, and N. Bahcall, Phys. Rev. D 78, 043519 (2008), 0801.0642.