Dark Energy from Cosmological Phase Transitions

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Overview

- Dark Energy Scenarios
- Boltzman brains
- Cosmological Phase Transitions
- Observable Consequences
- Conclusions

Dark Energy Scenarios

- Cosmological Constant (Einstein 1916)
- Inflation: Slowly varying constant (vast majority of alternatives). Substantially fine tuned.
- $w - w'$ basis for DoE/NSF Dark Energy Task Force
- Discontinuous transitions: generic consequence of first order phase transition (e.g. water-steam)

Boltzman Brains: One World – One Dream?

- Boltzman (1897), Eddington (1931)
- future of ΛCDM:
- thermal fluctuations
- reoccurence of planets, people
- statistically far outweighed by brains dreaming of worlds!
- controversial in some scientific circles

Instant BBrain Experiment

- How to tell if you are a Boltzmann brain?
- If we are a random fluctuation, all order is a coincidence, no arrow of time.
- Close your eyes for two seconds. Open again. If you are a Boltzman brain, the universe will be random, and this room will disappear. If the universe is ordered, the talk will make sense.

Evading BBs

- ΛCDM has finite temperature and infinite future time
- Page 2008: decay rate $\Gamma < 19$ Gyr
- latent energy (dark energy) converts into (hidden) thermal radiation
- universe could still collape ($\Omega > 1$ or $\Lambda < 0$)

Cosmological Phase Transitions

- Strongly first order transition
- e.g.: water-stream
- GUT, Electro-weak, QCD. Latter two probably not 1st order.
- NOT: recombination
- generically occurs out of equilibrium, through bubble nucleation

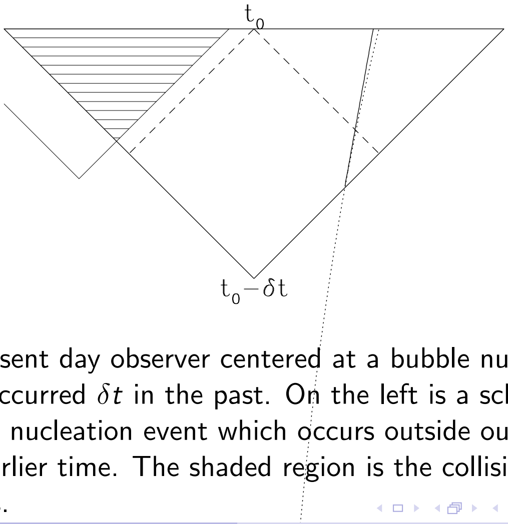
Simplest Scenario

- Hidden sector field. E.g., see-saw neutrinos (Acceleressence, Chacko et al 2004)
- $T \sim 2$K: WMAP CMB $N_\nu = 4.34 \pm 0.87$.
- initial false vacuum phase starts at $z = 10$, $T \sim 20$K
- dominates at $z \sim 1$
- exits at $z \sim 0$ through bubble nucleation
- requires 10x supercooling: substantial barrier to nucleation.

Bubbles

- phase transition converts vacuum energy into (hidden) radiation
- Energy and momentum conservation determines bubble evolution
- presence of thermal fluid limits speed (Pen et al 1998)
- possible alternative outcomes (Konstantin et al 2010).
- EoM: $T^{\mu\nu}_{;\mu} = 0$

Space-Time Schematic



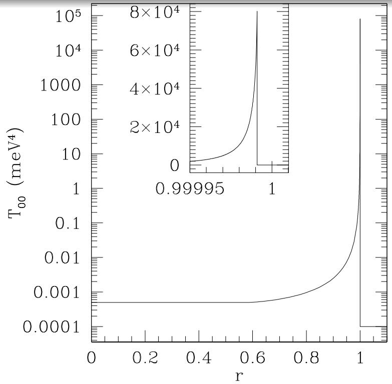
t_0 labels a present day observer centered at a bubble nucleation event which occurred δt in the past. On the left is a schematic second bubble nucleation event which occurs outside our past light cone, at an earlier time. The shaded region is the collision region of the bubbles.

EoM

Vacuum decaying into an ambient perfect radiation fluid:

$$\begin{aligned} \frac{\partial}{\partial t}\frac{\rho + p\beta^2}{1-\beta^2} + \frac{1}{r^2}\frac{\partial}{\partial r}\frac{r^2(\rho+p)\beta}{1-\beta^2} &= 0, \\ \frac{\partial}{\partial t}\frac{(\rho+p)\beta}{1-\beta^2} + \frac{1}{r^2}\frac{\partial}{\partial r}\frac{r^2(\rho+p)\beta^2}{1-\beta^2} + \frac{\partial p}{\partial r} &= 0, \end{aligned} \quad (1)$$

Bubble dynamics

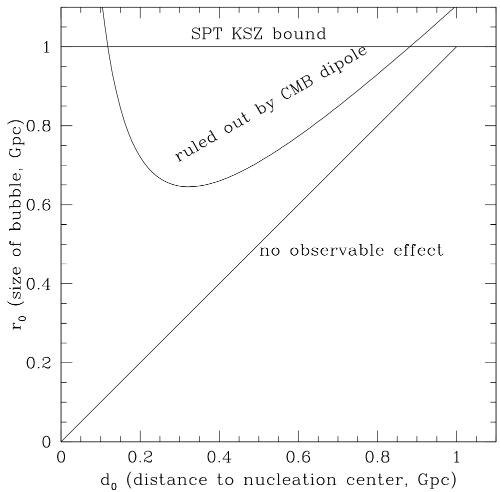


bubble density profile. Plotted is the dark matter frame 00 component of the radiation fluid stress energy tensor $\rho\gamma^2$, which is the conserved matter quantity. The inset shows the shock front on a linear scale.

Observable Effects

- for observer at bubble center: isotropic, inhomogeneous universe
- half way out to edge: dipole density distortion, bulk flow
- near edge: small conical distortion.
- use 95% estimates. Constraints relatively weak.

Observational Constraints



Conclusions

- Dark Energy dynamics could be discontinuous: generic property of phase transitions.
- short nucleation time scale eliminates Boltzmann Brains
- aesthetic advantages, possibly ekpyrotic? $\Lambda < 0$?
- Observable consequences in current and future data.
- statistically favoured by small number of papers (e.g. lottery, Press 1998).