Dark Enery from ultra-low energy phase transition and concordant Dark Matter

BY U A YAJNIK

Indian Institute of Technology Bombay

Indo-UK workshop,

Confronting particle-cosmology with Planck and LHC

IUCAA 10-8-2011

Outline

- Overview of the dilemmas
- Phenomenology of Domain wall Dark Energy
- Itinerant ferromagnetism as a model
  - Concordant Dark Matter?

The dilemmas in a nutshell

A problem of scales :

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{1}{M_{\rm Pl}^2}\rho$$

$\rightarrow$ Time scale of development of a is $M_{\rm Pl}/\sqrt{\rho}$

$\rightarrow$ $M_{\rm Pl} \sim (10^{-44}{\rm sec}\ )^{-1}$ —> Impossible to get a Universe $t_0 \sim 10^{17}$sec unless we fine tune ρ at the Planck scale.

- $\rightarrow$ If a cosmological constant $\Lambda \sim [L^{-2}]$ is to be inserted, which scale is the natural one for it? Primordial $M_{\rm Pl}$ or phenomenologically visible t_0?
- $\rightarrow$ Large t_0 can be obtained by stipulating a *transient* $\Lambda \lesssim M_{\rm Pl}^2$
- $\rightarrow$ But at epoch t_0 we also see a $\Lambda_{\rm DE} \approx \sqrt{\rho_0}/M_{\rm Pl}$

Cosmic concordance?

- → Matter became dominant only at the large scales t_0
  - – Most of the matter is non-baryonic – Dark
- → $\Lambda_{\rm DE}$ was also meant to become dominant on the scale t_0
- → Is there an interconnection between DE, and DM and the scale t_0?

Anthropic principle?

→ The *creation* has conspired to ensure that *we* (human beings) come around to witness it and record its glory

→ This allows the tiny cosmological constant but not the Inflation related one.

Are humans at the centre stage of scheme of being?

Isn't the descent to the scale where the Higgs could acquire a VEV and transform the phase of the Weak force an interesting occurance?

Isn't the formation of galaxies interesting?

Isn't the formation of AGN 10^6- 10^9 solar mass black holes interesting?

Wouldn't the occurance of planetary systems be interesting even if they did not support life?

A Copernican alternative

The principle of manifestation of maximum avataras

The Universe evolves in such a way as to permit all the possible manifestations of all the forms of matter/energy present at the Big Bang scale.

Let us see if the DM, DE phenomenon can be explained along with a new phase transition waiting to happen at scale t_0.

Phenomenology of Domain Wall Dark Energy

Cons and pros of DW DE:

- Wrong equation of state; Generically $p_{\rm DW} = -\frac{2}{3}\rho_{\rm DW}$

  Observations support $w = -1$
- Inhomogeneous imprints on CMB
- Tying up the low scale with particle physics

Responses/Pros :

- CMB result is best fit in a large parameter space;

  SN Ia data may permit deviations from $w = -1$

  Sahni, Shafieloo, Starobinsky (2009); Jassal, Bagla and Padmanabhan (2004), (2010).

  The possibility of being a component of the DE still exists.

- Most phenomenological models involve a scalar field with bizarre properties

- Sterile neutrinos may be and indication of a hidden sector with low mass scales.

The “pros” who have made such proposals :

Battye, Bucher, Spergel

Friedland, Murayama, Perelstein

Conversi, Melchiorri, Mersini, Silk

Kibble-Zurek theory

A cosmological symmetry breaking phase transition can give rise to defects. The size of the domains can be estimated from critical exponent theory.

$$\xi = \frac{\xi_0}{|\varepsilon|^{\nu}}; \qquad \tau = \frac{\tau_0}{|\varepsilon|^{\nu z}}; \qquad \varepsilon = \frac{T_c - T}{T_c}$$

Correlation length and relaxation time diverge as T_c is approached.

If there is an external tuning of the temperature, it characterises a quenching time scale τ_Q and we can estimate the limiting size of the domains as

$$\hat{\xi} = \xi_0 \left(\frac{\tau_Q}{\tau_0} \right)^{\nu/(1+\nu z)}$$

In practice domain sizes can be $\sim 10\hat{\xi}$.

Cosmological density of domain walls

$\tau_Q = H^{-1}$ and for a phase transition at temperature T_2

$$\hat{\xi} H_2 \approx \left(\frac{T_2}{M_{\rm Pl}} \right)^{(1+\nu z - \nu)/(1+\nu z)} \approx 10^{-20} \left(\frac{T_2}{10^{-2} {\rm eV}} \right)^{2/3}$$

and we estimate, with intrinsic energy trapped per unit area in the walls to be σ^3,

$$\rho_{\rm wall\,gas} \sim \sigma^3 \hat{\xi}$$

Ferromagnetism of fermion gas

Pauli paramagnetism of a gas of free spin$1/2$ fermions

$$\chi_P = \mu_M^2 D(E_F) = \mu_M^2 \frac{3}{2} \frac{n_M}{E_F}$$

Here $D(E_F)$ is the density of states at the fermi surface.

Ferromagnetism occurs in a strongly coupled system, where magnetism persists in the absence of external field. Heisenber ansatz for loclaised electrons has been popular for a long time, however, of late Stoner theory which is applicable to itinerant electrons has been found to be applicable in 2-d systems.

The Stoner ansatz (1934)

A shift in single particle energies, proportional to the difference between the spin up ($N_\uparrow$) and the spin down ($N_\downarrow$) populations.

$$E_{\uparrow,\downarrow}(\boldsymbol{k}) = E(\boldsymbol{k}) - I\frac{N_{\uparrow,\downarrow}}{N}$$

I assumed independent of $\boldsymbol{k}$ is the Stoner Parameter.

I is a single particle quantity of dimension of energy.

The ferromagnetic susceptibility is

$$\chi = \frac{\chi_P}{1 - I\frac{D(E_F)}{2n_M}} = \frac{\chi_P}{1 - I\frac{3}{4E_F}}$$

The condition for spontaneous magnetization is negative χ, which is ensured provided the second term in the denominator dominates. A sufficient condition for the occurrence of ferromagnetism is the Stoner criterion,

$$I > \frac{4}{3}E_F$$

Magnino hypothesis

Dirac fermions light enough and dilute enough that their magnetic interaction dominates over their Coulomb interaction.

$$\frac{\mu_{_M}^2}{r^3} > \frac{e_{_M}^2}{r}; \qquad \frac{\alpha_{_M}}{m_{_M}^2} n_{_M}^{2/3} \gg \alpha_{_M}$$

For such itinerant fermions, the mass $m_{_M}$ and the cosmological parameter $n_{_M}$ are sufficient to charactarise the ferromagnetic state.

Proposal for Stoner parameter

Dipolar replusion energy [UAY PASCOS 2005 proceedings; ArXiv 2011]

$$I = \mu_{_M}^2 |\Delta n_{_M}| \kappa_{_{\rm JM}}$$

$\Delta n_{_M}$ is local number density deficit due to Pauli principle, and $\kappa_{_{\rm JM}}$ is a geometric factor computed by Jha and Mohanti [JPhys 2006, PRE 2009] Fregoso and Fradkin [PRL 2009]

Contributions to energy density

$$\rho_{\text{gas}} + \rho_{\text{magnetic}} < \rho_{\text{gas}}$$

At the site of the defects (walls) ρ_{magnetic} is absent. Thus $|\rho_{\text{magnetic}}|$ is the contribution of the defects to the vacuum energy.

We propose $\rho_{\text{DE}} \approx \rho_{\text{wall gas}}$, i.e., the above contrinution averaged over normal regions traversed by walls.

Finally, we shall take

$$\sigma^3 = I n_{_M} \approx \left(\mu_{_M}^2 n_{_M}^2\right)^{3/4}$$

Conjecturing the magnino sector

Let us parameterise the abundance $n_{_M} = \Upsilon n_\gamma$.

Standard value $n_\gamma \approx 3.2 \times 10^{-12} (\mathrm{eV})^3$. I get the constraint

$$\frac{m_{_M}}{\Upsilon} \left(\frac{R_{_0}}{R_{_2}} \right)^{1/2} \lesssim 10^{-8} \mathrm{eV}$$

The partner dark component

For neutrality, we have the oppositely charged particle, X. We assume this to be heavy, with short thermal wavelength and not condensing.

How light can DM be? (C. Boehme's talk) $m_{\rm DM} \gtrsim 2$keV.

Boyarsky, Lesgourgues, Ruchayskiy and

Boyarsky, Ruchayskiy, Iakubovski

With $\Upsilon \approx 10^{-3}$, the X particles can be the ultra-light Dark Matter without overclosing the Universe.

Conclusion

- Dark Energy presents a deep challenge to theory
- A common origin for Dark Energy and Dark Matter would be desirable (at least keeps the two unknowns together)
- A particular model with hidden unbroken $U(1)$ with corresponding fermions has been given
- Condensed matter calculations permit purely dipolar mechanism for itinerant ferromagnetism viable.
- Need to verify Stoner mechanism for relativistic fermions.
- In search of observables ...