Title: Magnetic domain walls of relic fermions as Dark Energy

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Abstract:

Relic fermion ferromagnetism as Dark Energy

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Abdus Salam ICTP, June 7, 2006

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The new (tentative) Standard Model of Cosmology

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Homogeneous features

Age 13.7 ± 0.2 G. yr,

$H = 0.71^{+004}_{-0.03} \times 100$km/s/Mpc

Independently from Hubble Key project :

$H_0 = 72 \pm 3(\text{stat}) \pm 7$(systematic) km/s/Mpc.

$T_{CMB} = 2.725 \times 10^6 \mu$K

Concordance of CMB and SN Ia data require presence of large vacuum energy.

$\Omega = 1.02 \pm 0.02$

$\Omega_{matter} = 0.27 \pm 0.04$

$\Omega_{baryon} = 0.044 \pm 0.004,$

Equation of State for Dark Energy

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$w\ (\equiv p/\rho) < -0.9$

Tension exists at present between SN Ia data which want $w < -1$, and WMAP by itself which is consistent with $w \sim -0.95$

Two broad pardigms :

1. Λ-CDM ie, Cosmological constant + Cold Dark Matter
2. Quintessence ie, Ascribe various dynamics to the Dark Energy

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Relic fermion Ferromagnetism

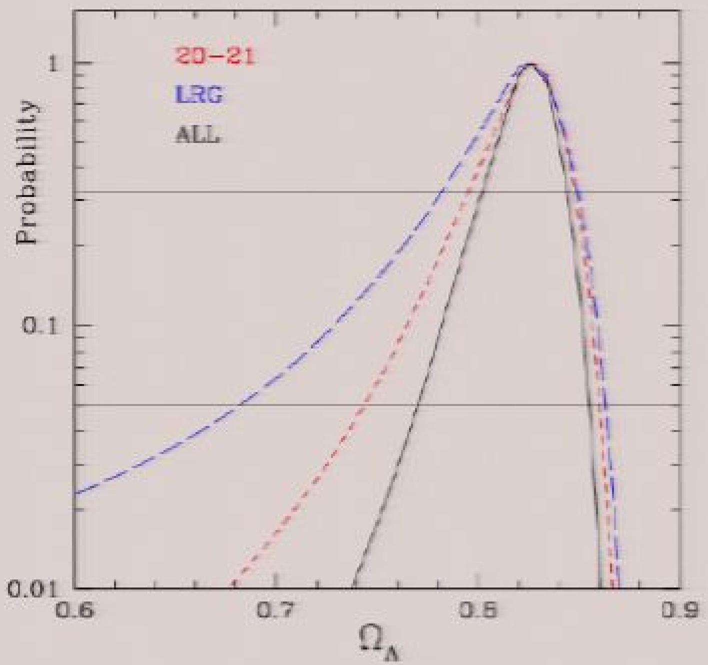
- A reassessment of the current model
- Ferromagnetism of relic fermions
  - "Domain Wall" matter as Dark Energy
  - Stoner condition for ferromagnetism
  - Candidates
- Conclusion

Reassessing the tentative Standard Model

Analysis of Dark Energy equation of state

A.Cabre, E.Gaztanaga, M.Manera, P.Fosalba and F.Castander
Arxiv:astro-ph/0603690

Cross-correlation of the third-year WMAP data with galaxy samples extracted from the SDSS DR4 (SDSS4)



Probability distribution: $1 - P_\chi[> \Delta\chi^2, \nu = 1]$ for Ω_Λ in the $r = 20 - 21$ sample (short-dashed line), the LRG sample (long-dashed line) and the combined analysis (continuous middle curve). The range of 68% and 95% confidence regions in Ω_Λ are defined by the intersection with the corresponding horizontal lines.

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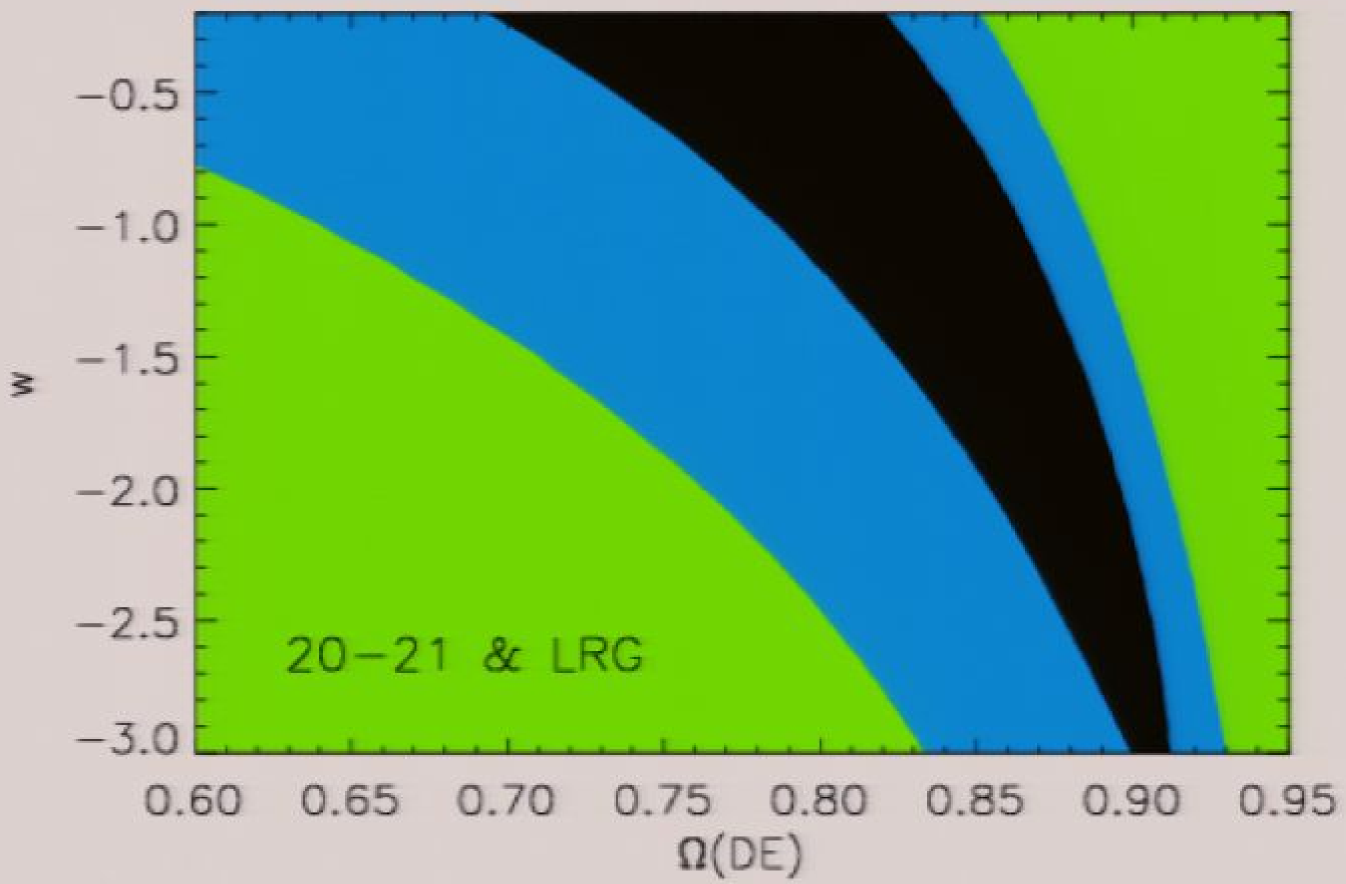


Jassal, Bagla and Padmanabhan *MNRAS* (2004)

For their model for variation of w as

$$w(z) = w_0 + w_1 \frac{z}{(1+z)}$$

with the priors

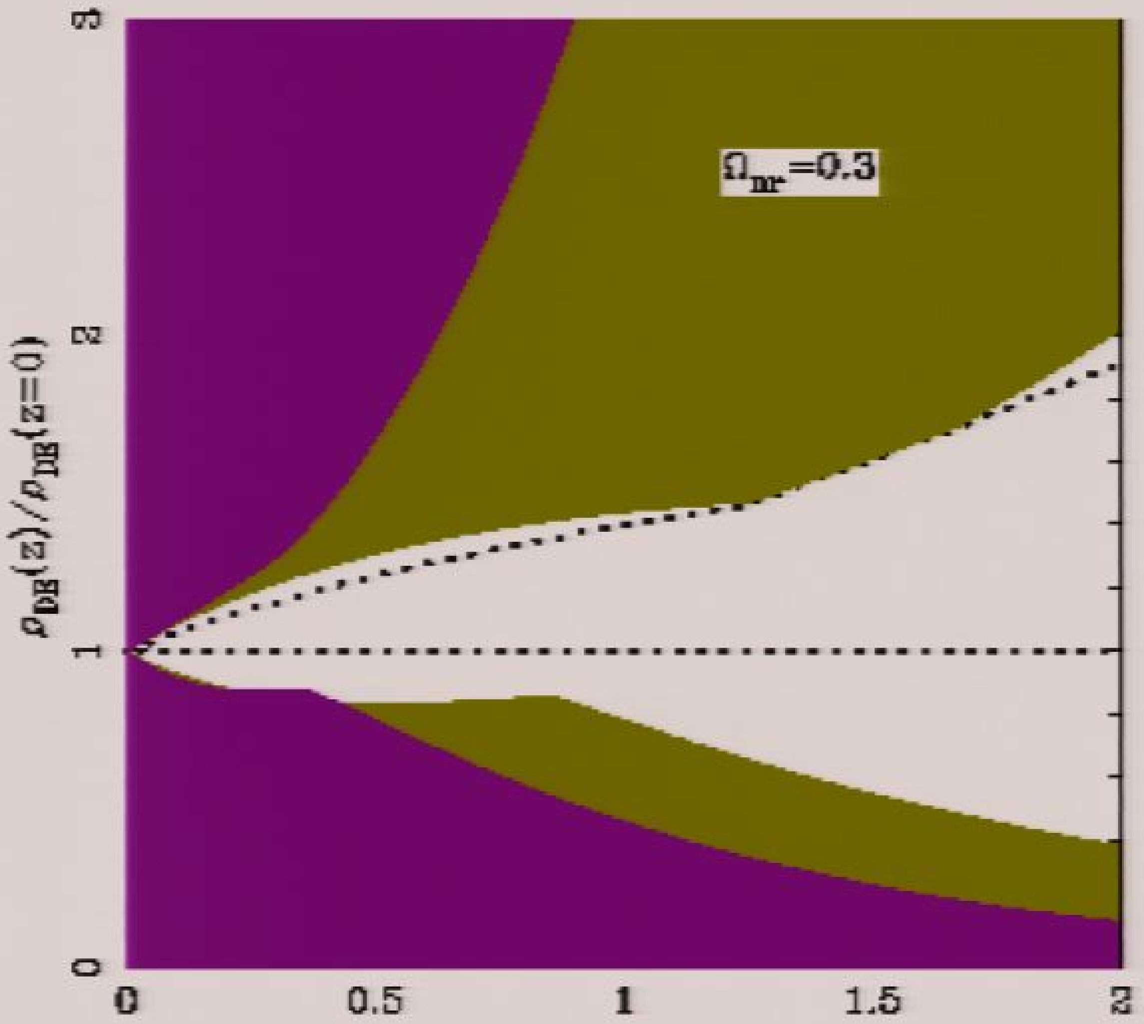
$$H_0 = 70kms^{-1}Mpc^{-1}, \qquad 0.2 < \Omega_M < 0.4 \qquad , \Omega_B = 0.05$$

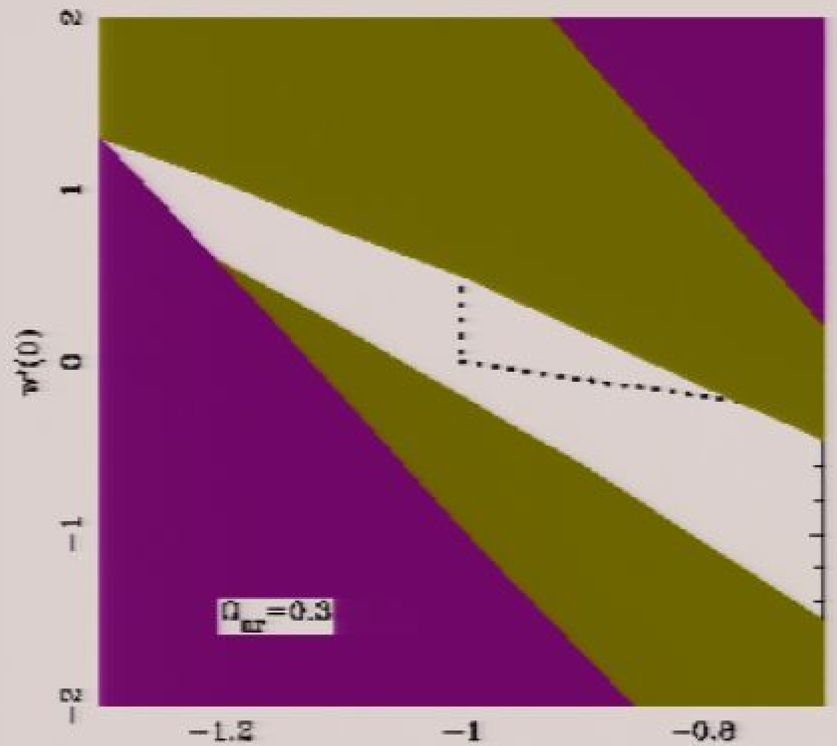
$$n_s = 1, \qquad n_t = 0,$$

and

$$-1.5 < w_0 < -0.7, \qquad -2 < w_1 < 2$$

they obtain


Ω_{m}=0.3
$\rho_{DE}(z)/\rho_{DE}(z=0)$
0
1
2
3
0
0.5
1
1.5
2

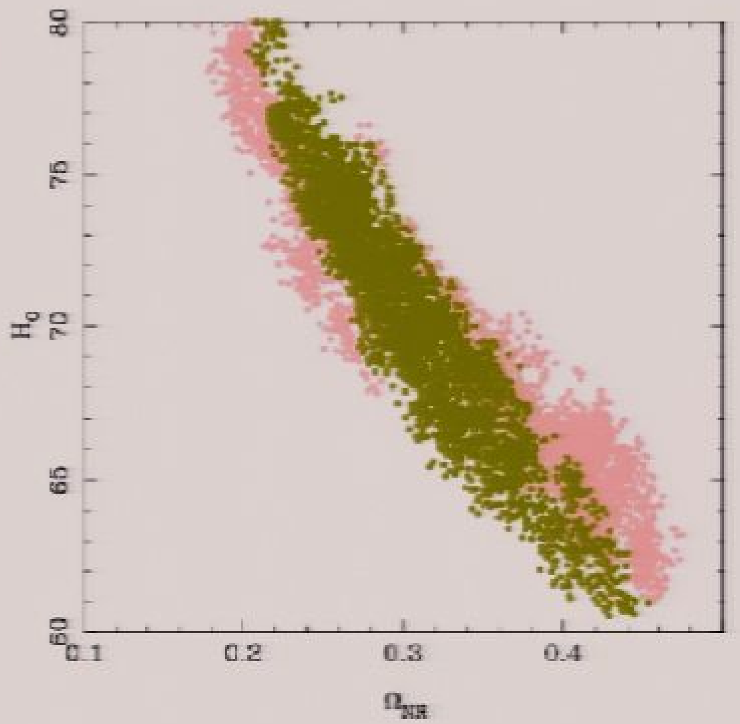


w'(0)
2
1
0
−1
−2
−1.2
−1
−0.8
Ω_m=0.3

Their analysis strongly suggests

- WMAP data considerably more reliable than SNIa
- Central value of w close of -0.8
- No significant variation in w over the timescales spanned by WMAP data

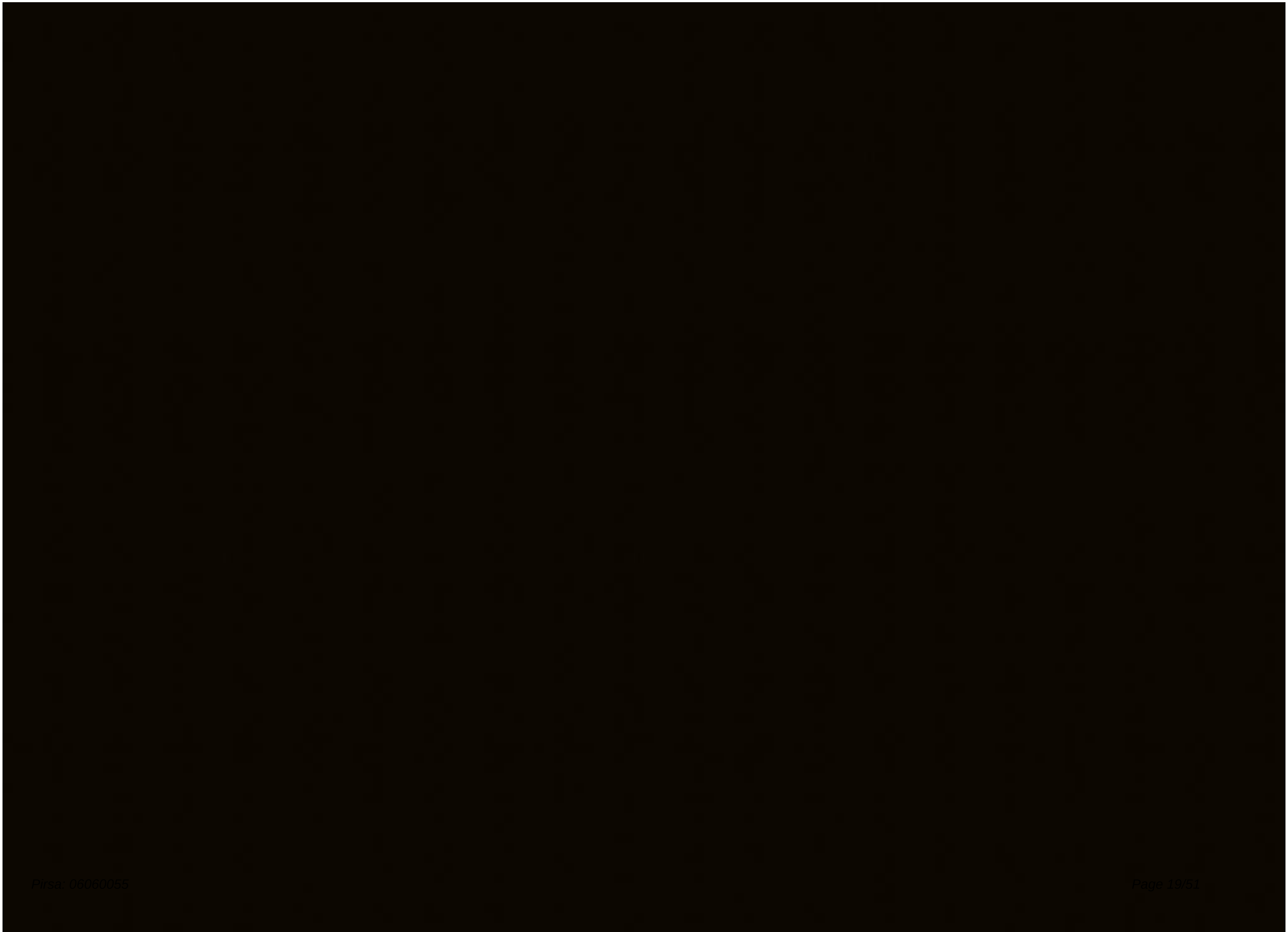
Also, in Jassal, Bagla, Padmanabhan PRD (2005) we find Markov Chain allowed parameters for for Λ-CDM show a degeneracy


80
75
70
65
60
H_0
0.1
0.2
0.3
0.4
Ω_{NR}

A heterodox possibility

- Battye, Bucher and Spergel Astro-ph 1999, PRD 2000
  Suggest "Solid Dark Matter" derived from topological defects
- Friedland, Murayama and Perelstein PRD 2001
  Possible domain walls with $\mu \sim 100keV$
- Conversi, Melchiorri, Mersini and Silk APPhy 21 (2004)
  "Are domain walls ruled out?"

  Claim : better fit for WMAP data with lower value of Hubble parameter $h < 0.65$ and with higher value of $\Omega_m > 0.53$ consistent with recent XMM-Newton satellite data on temperature- luminosity relation for distant clusters.



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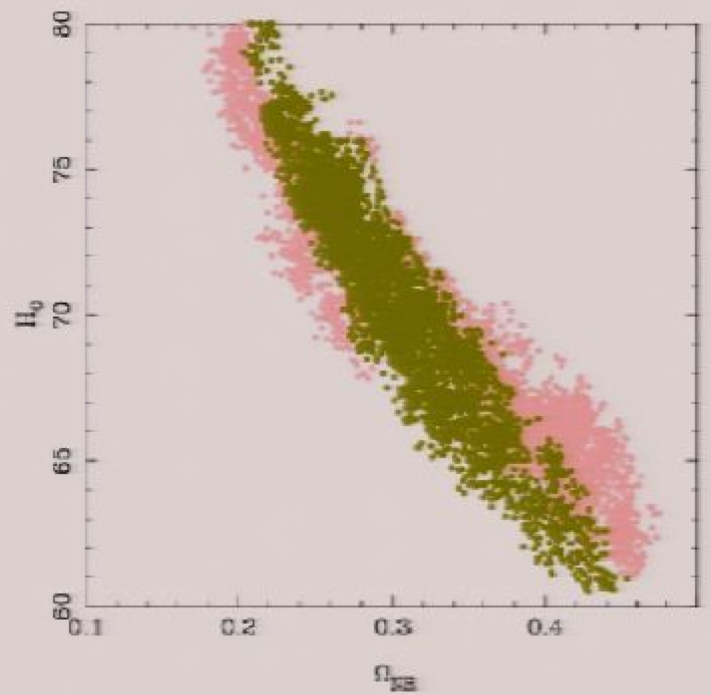

17/42

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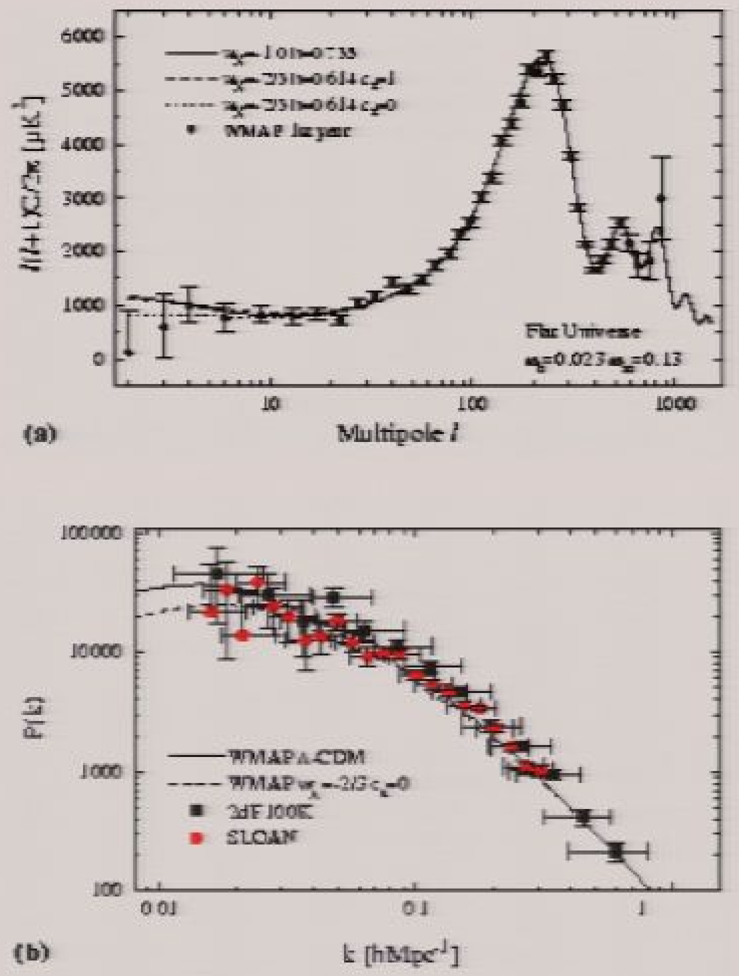

Fig. 1. (a) Comparison of the Λ-CDM and domain walls best fit models with first year WMAP CMB data. (b) Comparison of the Λ-CDM and domain walls best fit models with SLOAN and 2dF galaxy surveys data.

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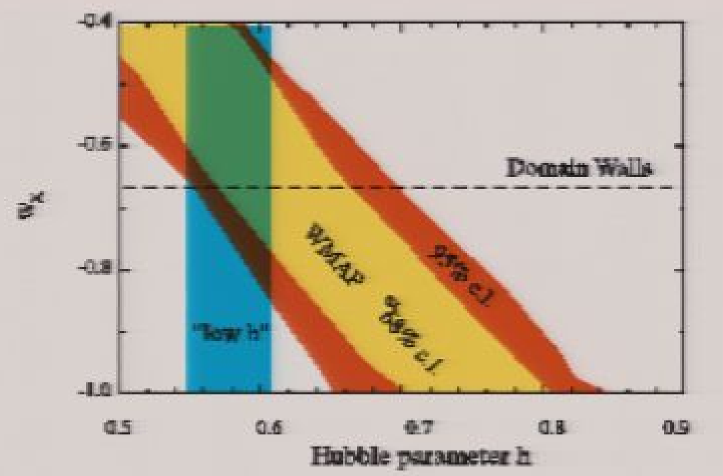

Fig. 2. One- and two-σ likelihood contours in the w–h plane from the first year WMAP plus ACBAR + CBI data. As we can see, values of the Hubble parameter $h \sim 0.6$ (shaded region) are in good agreement with the data and prefers $w \sim -2/3$.

Main idea :

- The limit $w < -0.9$ is too stringent and subject to certain priors.
- Were the value closer to $-2/3$, Domain Wall matter could qualify as Dark Energy
- How to get acceptable Domain Walls?
  - A relic fermion species should possess magnetic moment
  - It must enter a collective ferromagnetic state
  - This ferromagnetic state develops a Domain structure

What we need to assume :

- Very small mass scale as suggested by neutrino data
- An intrinsic magnetic moment for the relic species
- Possibly a large abundance for this species – accounting for all of Dark Energy

Theoretical ingredient

- Band ferromagnetism – Stoner theory of Magnetism of Itinerant Fermions

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Ferromagnetism of fermion gas

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

$$\chi_P = \mu_0 \mu_F^2 D(E_F) = \mu_0 \mu_F^2 \frac{3}{2} \frac{n_F}{E_F}$$

Here μ_0 is the free space permeability, and $D(E_F)$ is the density of states at the fermi surface.

The Stoner ansatz :

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

$$E_{\uparrow,\downarrow}(\mathbf{k}) = E(\mathbf{k}) - I \frac{N_{\uparrow,\downarrow}}{N} \qquad (1)$$

I assumed independent of $\mathbf{k}$ is the Stoner Parameter. I is a single particle quantity of dimension of energy.

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The ferromagnetic susceptibility is

$$\chi = \frac{\chi_P}{1 - I\frac{D(E_F)}{2n_F}} = \frac{\chi_P}{1 - I\frac{3}{4E_F}} = \frac{\chi_P}{1 - I\frac{2\chi_P}{\mu_0\mu_F^2 n_F}} \quad (2)$$

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,

$$I > \frac{4E_F}{3} \quad (3)$$

26/42

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Ferromagnetism of fermion gas

25/42

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Cosmological setting

The cosmological epoch we focus on is the one when the energy density in Dark Energy became comparable to that in the form of non-relativistic matter. This gives

$$(S_1/S_0)^2 = 3/7$$

Photon temperature at this epoch is $T_1 = 4.18K = 5.0 \times 10^{-4} eV$

We take the number density of the fermions comparable to entropy density of photons at time t_1 to be

$$n_F(t_1) \approx 3.2 \times 10^{-12} \Upsilon (eV)^3$$

Anomalous magnetic moment

We assume that individual particles have an anomalous magnetic moment,

$$\mu_F = g_F \frac{|e|\,\hbar}{2m_F} \equiv g_F \left(\frac{m_e}{m_F}\right) \mu_B \qquad (5)$$

where μ_B is the usual Bohr magneton.

The requirement is that the "exchange interaction", induce a split in the single particle energy of similar spin electrons of the same order as the value of the Fermi energy. In a simple model of a free gas, the local density deficit of fermions of the same spin is

$$\Delta n_\nu \;=\; -0.86 n_\nu$$

This deficit density contributes to the single-particle energy only if there is a long range interaction between the particles.

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The factor Υ constrained :

At the present epoch t_0, the density fraction Ω_F of a potential *hot* dark matter member must remain less than 0.003; $\rho_{crit} = 3.6 \times 10^{-6}(eV)^4$

$$\Omega_F \;=\; \frac{m_F n_F(t_1)}{\rho_{crit}} \;=\; 2.25 \times 10^{-7} \times \Upsilon \left(\frac{m_F}{eV}\right) < 0.003$$

Or,

$$\Upsilon(m_F/eV) \sim 10^4$$

For the chemical potential we use

$$E_F = (p_F^2 + m_F^2)^{1/2} - m_F \qquad (4)$$

with $p_F = (3\pi^2 n_F)^{1/3}$

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Dipole interaction

Let us denote this coupling γ^2,

$$\gamma^2 = \mu_0 \mu_\nu^2 |\Delta n_\nu|$$

Here we attempt a simple possibility for this coupling namely the magnetic one, which is repulsive between same spins and therefore the density deficit leads to increase in single particle energy.

Can such coupling indeed bring about the Stoner phenomenon?

S. Mahanti and S. S. Jha Jour. Phy. A (2006)

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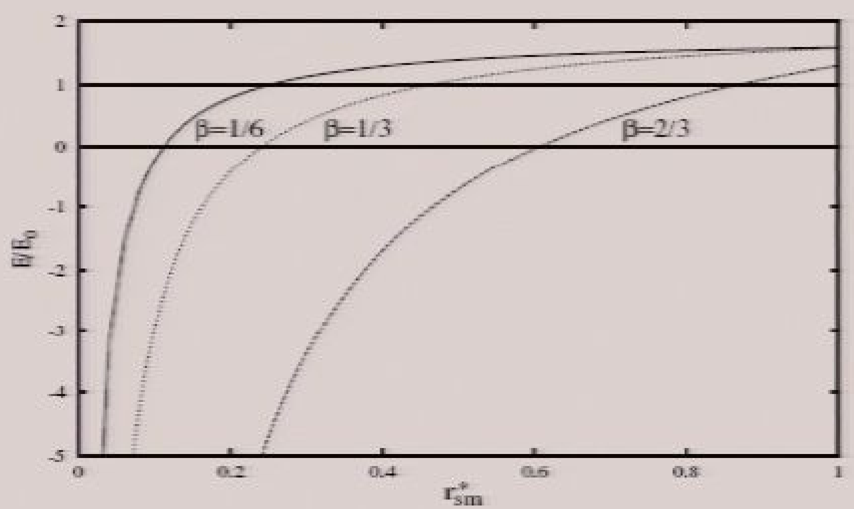

Figure 1. Comparison of the ground state energy E of the variational polarized ferromagnetic state having a deformed Fermi surface with the ground state energy E_0 of the non-interacting paramagnetic state. The ratio is plotted as a function of density parameter $r^*_{sm} = r_0/r^*_m \approx (3/4\pi n)^{1/3}/[(2m\mu^2/\hbar^2) \times 191]$ for different values of the deformation parameter β in the allowed range of 0 to $2/3$.

32/42

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The resulting reduction in single particle energy is

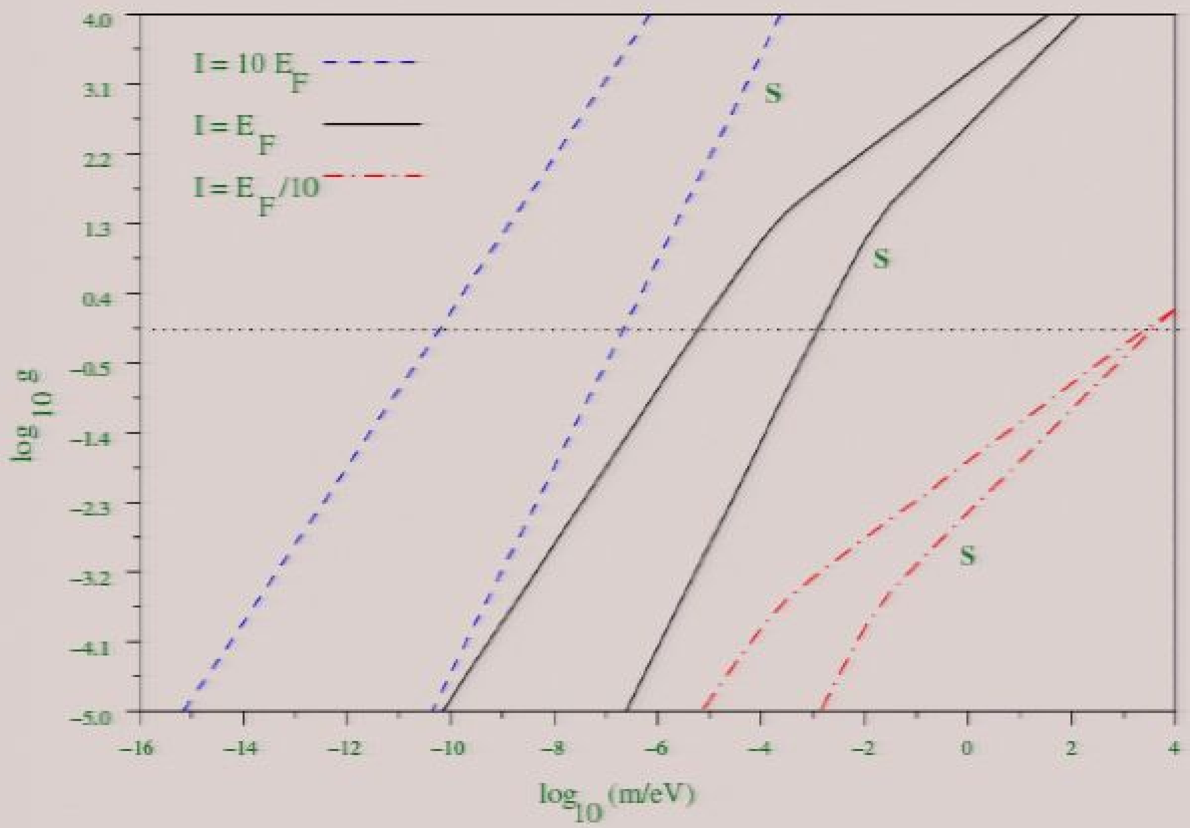
$$I = \gamma^2 \left| \frac{\Delta n_\nu}{n_\nu} \right|$$

$$n_F \left(\frac{g_F}{m_F} \right)^2 > 1.2 \times 10^4 \left\{ \left((3\pi^2 n_F)^{2/3} + m_F^2 \right)^{1/2} - m_F \right\}$$

The three unknown quantities involved in this relation are the particle properties g_F, m_F and the possible excess abundance factor Υ in n_F.

Analysis

35/42



Assessment

Neutrinos!!!

No :-(

The current upper bounds (PDG; Raffelt 90) on the neutrino magnetic moments are 10^{-10} for ν_e and ν_μ and 4×10^{-7} for ν_τ. In the conventions used here, these can be stated as

$$\log g_{\nu_{e,\mu}} - \log m_{\nu_{e,\mu}} < -15.7; \qquad \log g_{\nu_\tau} - \log m_{\nu_\tau} < -12.2$$

The resulting lines would be far lower in the graph and the permitted regions will be to the *right* of the lines. We must conclude that neutrinos cannot participate in such a mechanism. We also note that the excess abundance factor for neutrinos has been recently well constrained to be small, as deduced from neutrino oscillations (DHPPRS)(AbaBeaBell).

Dark Energy

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Making Dark Energy ??

- If this has to really work as dark energy, the domain walls must account for half the energy content at the epoch chosen.
- Estimate energy per unit volume traped within the walls

$$\frac{E}{Aw} = I|\Delta n_F| \geq \frac{1}{2}\rho_{crit}\left(\frac{T_1}{T_0}\right)^4$$

- For domains of size L, need

$$L/w \gtrsim 10$$

This gives following bounds on g_F and m_F

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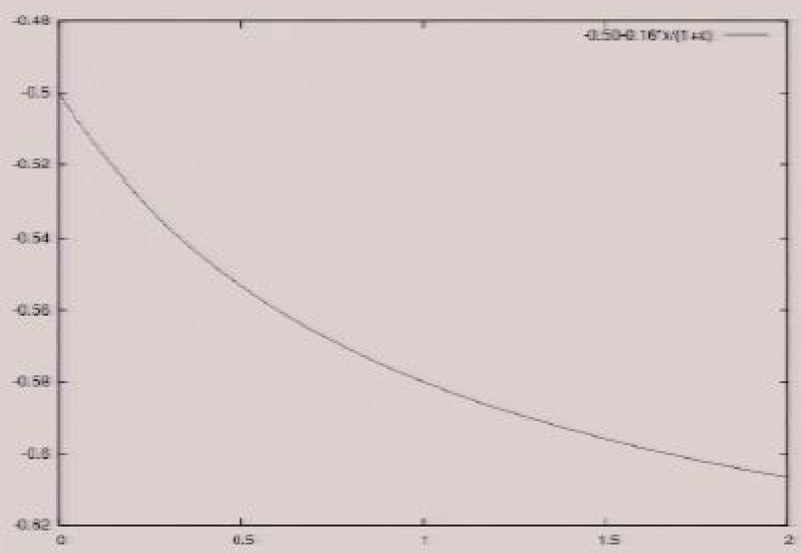
Possible confirmations?

40/42

- Crumbling of Domain Walls should reuslt in effective w which is closer to zero today and decreasing towards $-2/3$ with increasing z



- An intriguing possiblity is the mixing of the new $U(1)$

with electromagnetism.

$$\mathcal{L}_{\rm mix} = \delta \quad F_{\mu\nu} F^{(1)\mu\nu}$$

Existing constraint on the mixing is $\delta < 10^{-3}$. A numerical estimate suggests that the residual rms value of magnetic fields over sizes of galactic clusters ($1 Mpc$) could, after mixing with standard electromagnetism produce required seeds for generating extra-galactic magnetic fields.

41/42

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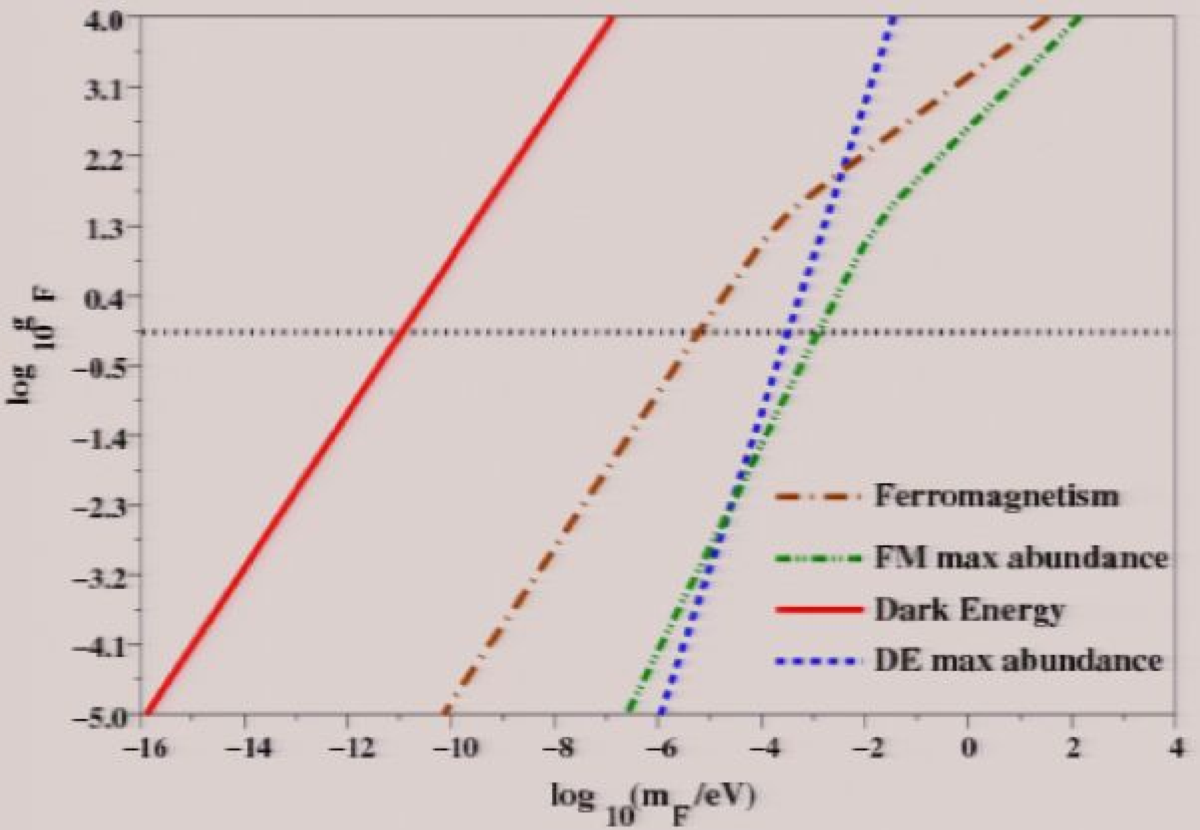

39/42

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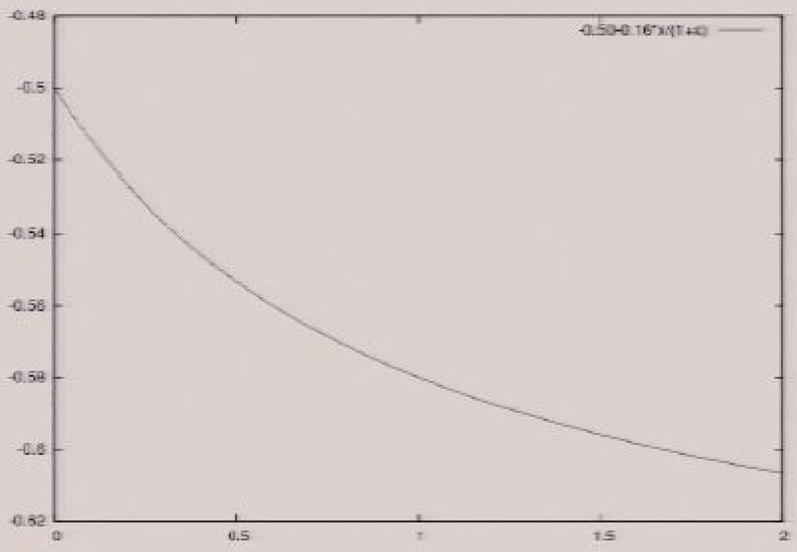

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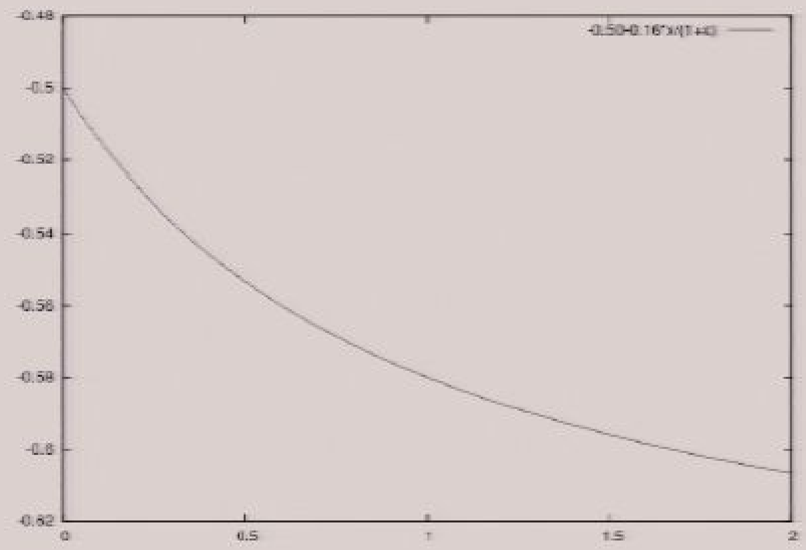

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Conclusion

- Attempt to fit theory of itinerant ferromagnetism to possible relic fermionic species; neutral but with anomalous magnetic moment
- Neutrinos do not work – magnetic moment required large
- Requires new species to be very light $\lesssim 10^{-10} eV$
  - *A whole new ultra-light sector ...??*
- Electromagnetism or hidden sector $U(1)_H$??

...work in progress ...

For details, PASCOS 2005 Proceedngs, AIP Proc. vol 805 (2006); Arxiv:astro-ph/0501348

Prepared with Linux, LaTeX 2e and pdfslide.