PAAI in the sky

Towards a particulate explanation of Dark Energy

by U A Yajnik

Hiroshima University-IIT Bombay meeting

25 October 2021

1 Outline

Based on "Cosmic Ferromagnetism of Magninos" ArXiv:1901:00995

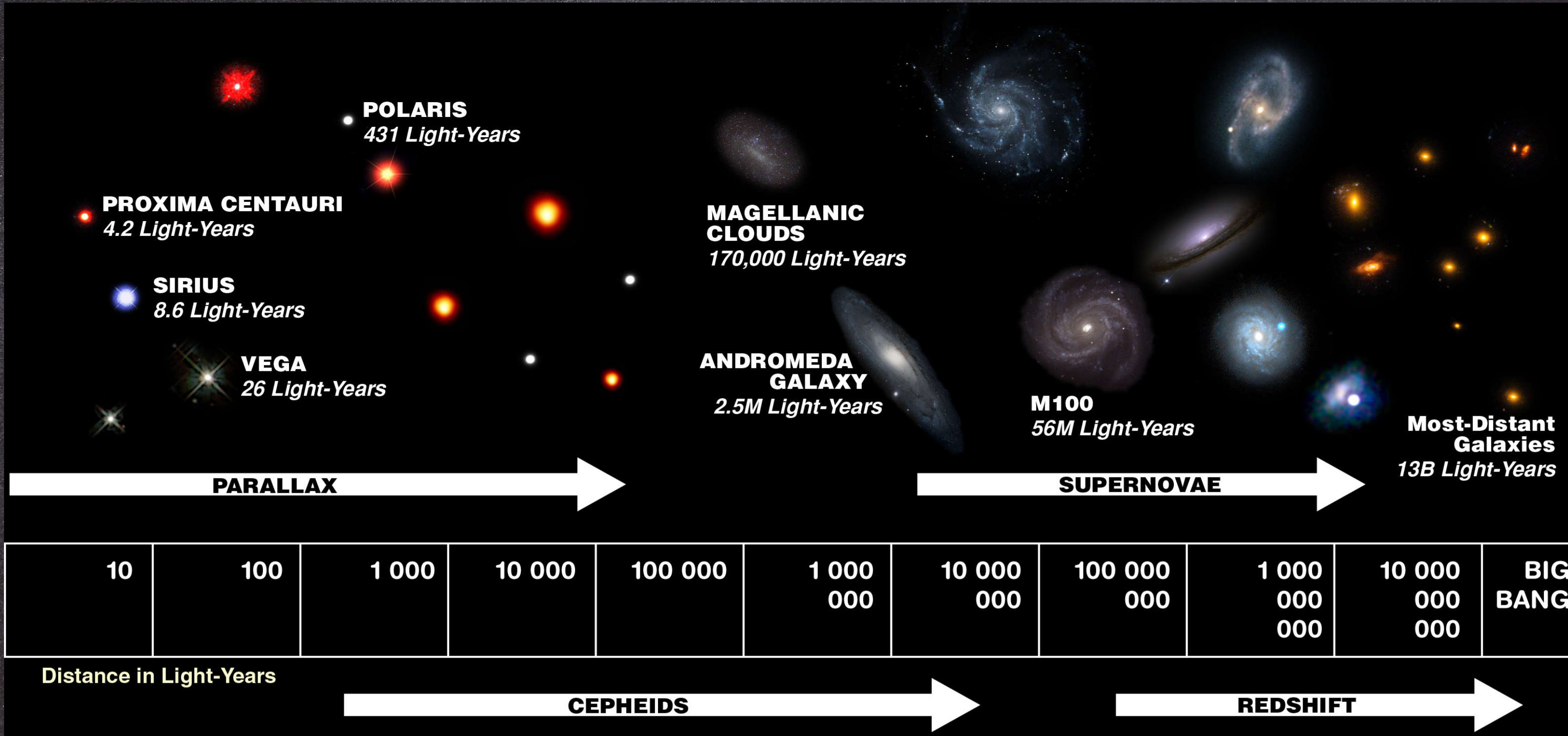
with Richard MacKenzie and Manu Paranjape, U. de Montréal

- Overview of the dilemmas
- Phenomenology of Domain wall Dark Energy
- Itinerant ferromagnetism as a model
  - Concordant Dark Matter
  - Origin of cosmic magnetic fields

2 Dark Energy

- Determination of Hubble rate crucially dependent upon *standard candles*
- Hubble Space Telescope helped to locate Type Ia supernovae whose time of flare up (a few weeks) is directly related to their absolute luminosity.
    - Type Ia -> White dwarfs which begin accreting material from another star
    - Upper limit on White dwarf mass is 1.4 solar mass (Chandrasekhar, Nobel 1983)
    - Universal spectral features, absence of H lines, prsence of Si lines

- The Type Ia supernovae caught in real time (7 b. years after they actually flared up!) are the new far reaching standard candles
  - The shape of the light curve over the full event gives away the Type, (see the sudden change in slope in the movie)
  - The total time baseline gives the absolute magnitude
- Upto now almost 550 such ancient Type Ia supernovae recorded



SCALING THE UNIVERSE

Astronomers use several techniques to measure the distances to stars and galaxies. These techniques overlap, providing greater confidence that each one is accurate.

PARALLAX
The most accurate method of measuring distance. Astronomers look at a star when Earth is on opposite sides of its orbit. The star shifts position with respect to more-distant stars. The size of the shift reveals the star's distance.

CEPHEIDS
These big, bright stars pulse in and out like a beating heart. The length of the pulse reveals the star's brightness. Comparing *true* brightness to the star's *apparent* brightess reveals its distance. Used to measure nearby galaxies.

SUPERNOVAE
Certain types of exploding stars brighten and fade in a way that reveals their true brightness, which astronomers then use to calculate their distances. Effective out to several billion light-years.

REDSHIFT
Distant galaxies move away from us because the universe is expanding. Astronomers can measure this motion, which varies with distance: faster galaxies are farther away. Least-accurate method because it depends on models of how the universe is expanding.

TIM JONES/DAMOND BENNINGFIELD

3 The dilemmas in a nutshell

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} - \Lambda = \frac{8\pi}{M_{Pl}^2}\rho$$

- → But at epoch t_0 we also see a $\Lambda_{DE} \approx \sqrt{\rho_0}/M_{Pl}$
- → Dark Energy parameterised by $p = w(z)\rho$
  - Cosmological constant : $w = -1$
  - More generally

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

3.1 Pantheon update

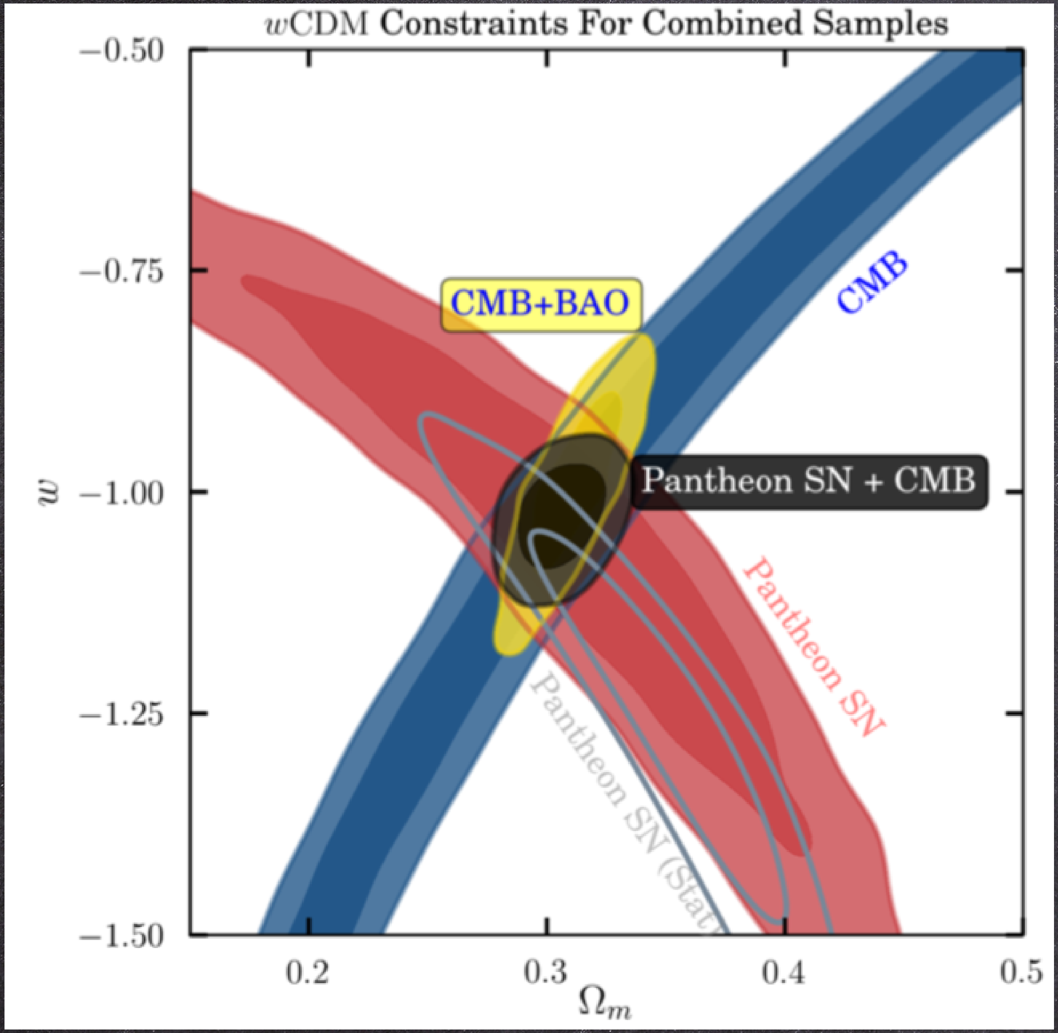
Multi-source data on SN Ia combined

Cosmological models:

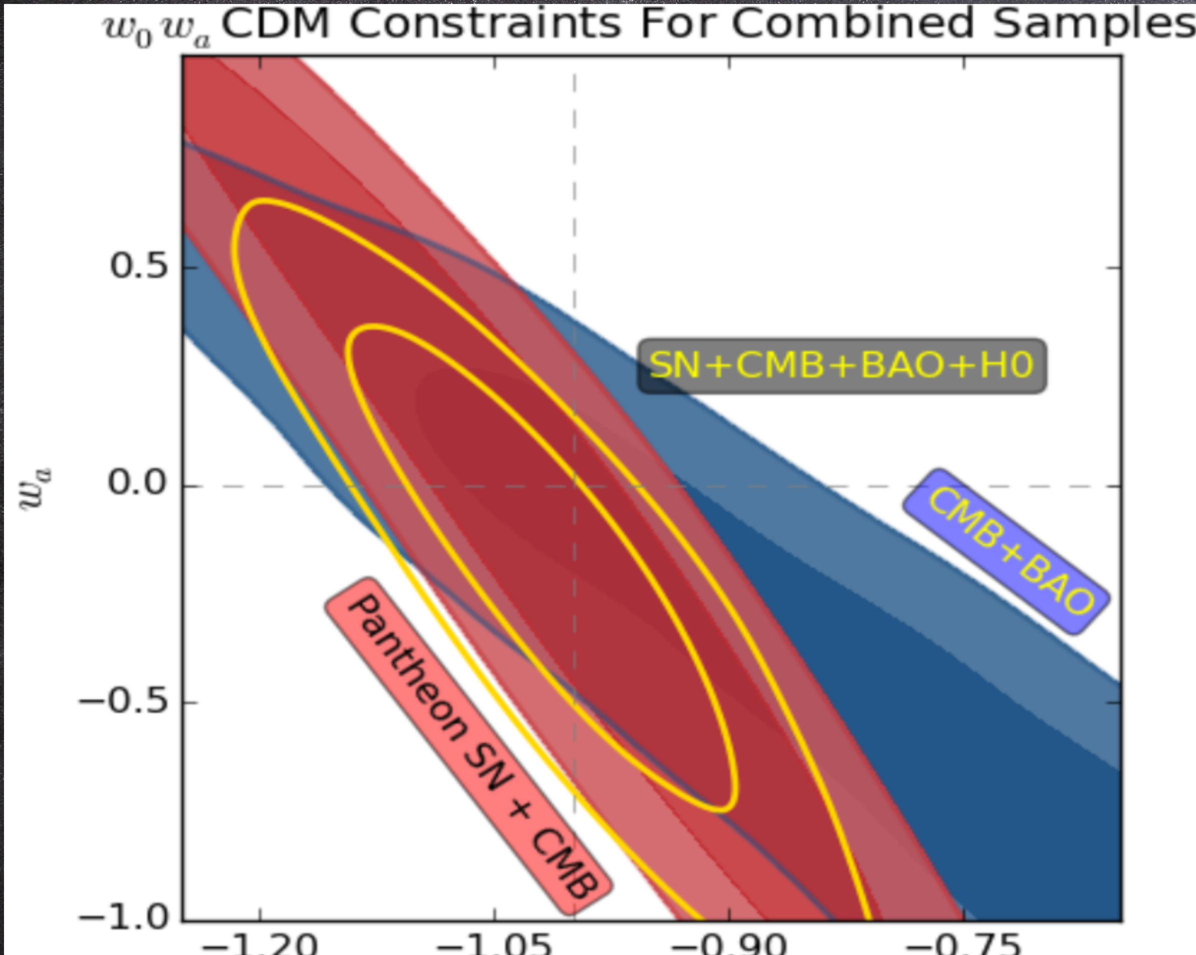
A flat ΛCDM model ($w = -1$, $k = 0$),

A flat wCDM model (w_0 varies, $w_a = 0$)

A flat w_0w_aCDM model (w_0, w_a both vary, $k = 0$).



Confidence contours at 68% and 95% for the Ωm and w cosmological parameters for the wCDM model. Constraints from CMB (blue), SN - with systematic uncertainties (red), SN - with only statistical uncertainties (gray-line), and SN+CMB (black) are shown.



Confidence contours at 68% and 95% for the w and wa cosmological parameters for the w0waCDM model. Constraints from BAO+CMB (blue), SN+CMB (red), SN+CMB+BAO (yellow) and SN+CMB+BAO+HST (yellow) are shown.

3.2 Cosmic concordance ?

→ Matter became dominant only at the large scales t_0

- Most of the matter is non-baryonic -- Dark

→ Λ_{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?

4 Phenomenology of Domain Wall Dark Energy

4.1 Cons and pros of DW DE:

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

  Observations support $\omega = -1$

- Inhomogeneous imprints on CMB

Responses :

→ $-2/3$ applies to scaling DW. Fixed DW evolve to fill space

- Very light extended structure made after recombination

4.2 Others who have made such proposals :

Battye, Bucher, Spergel 2001

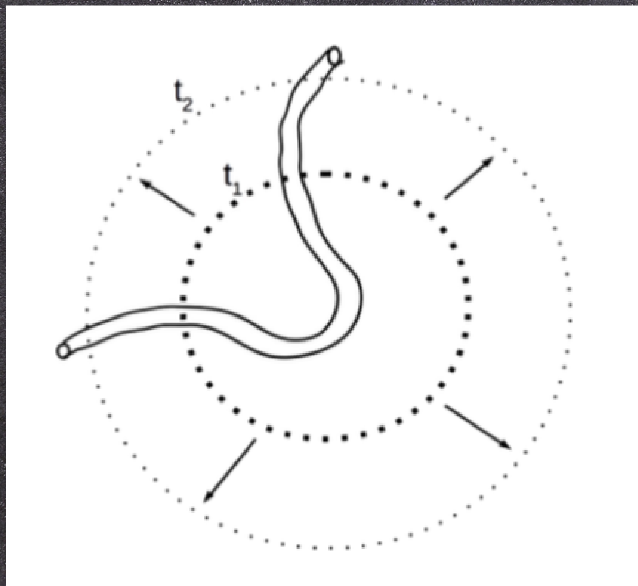
Friedland, Murayama, Perelstein 2001 - 2013

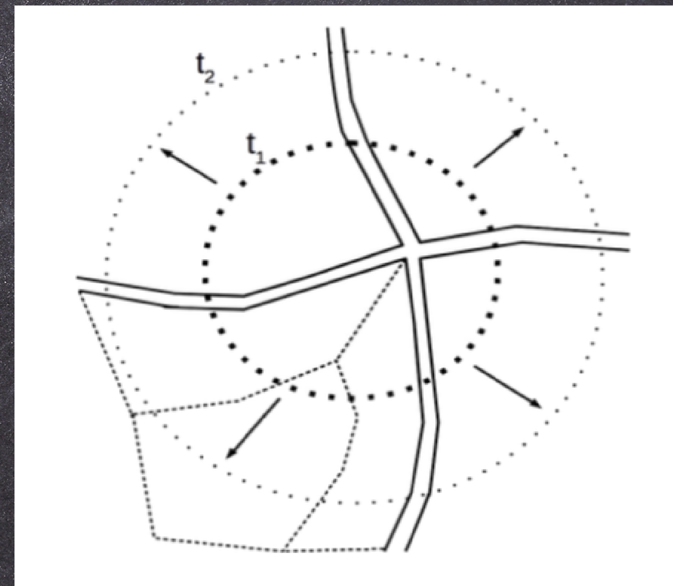
Conversi, Melchiorri, Mersini, Silk 2001

Kapusta 2005

Utpal Sarkar 2018

4.3 Some useful cartoons



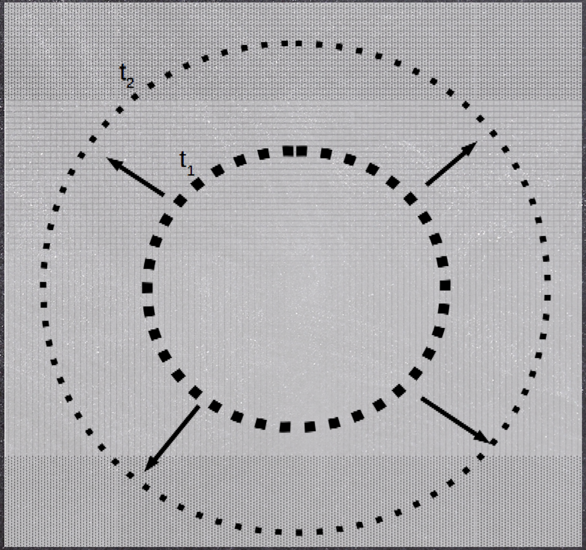


→ Expansion of comoving sphere from t_1 to t_2

→ Additional energy engulfed $\propto a$ for vortices, $\propto a^2$ for DW

→ $\rho_{\text{vortex}} \sim a^{-2}$; $\rho_{\text{DW}} \sim a^{-1}$

... cartoons contd.



- For space filling homogeneous "substance" additional energy engulfed $\propto a^3$

- In this case, $\rho = \text{constant}$

- *It is not necessary to have any exceptional substance to achieve Dark Energy.*

→ There must be stuff that is

a confined by internal stresses

b space filling

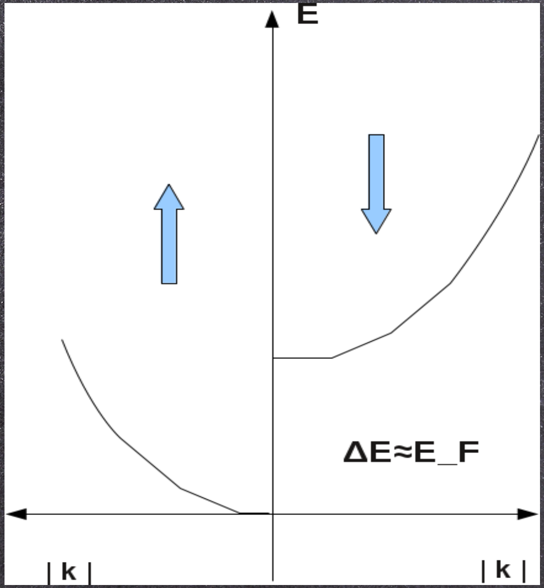
c homogeneous over cosmic scales.

5 Ferromagnetism of fermion gas

- Band ferromagnetism or "Itinerant electron" fer-romganetism
  - first considered by Bloch 1929
  - an ansatz given by Stoner 1936; unproven till date but applicable
  - Further developments for Density Functional Theory mid 1970's to mid 1980's by Baym, Chin, Rajagopal, MacDonald ...

5.1 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.



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

Why do same spins align? Aligned state pushes them apart due to Pauli exclusion, thus reducing repulsion energy.

6 Magnino hypothesis – version I

- Dirac fermions
  - whose magntic property must dominate their Coulomb interaction
  - … even at cosmic dilution of number density

$$\vec{B}\cdot\vec{\mu} \sim \frac{\mu_M^2}{r^3} > \frac{e_M^2}{r} \quad \text{using } \mu = \frac{e}{2m}; \quad n \sim \frac{1}{r^3}$$

$$\frac{a_M}{m_M^2} n_M^{2/3} \gg a_M \quad \text{NB: } a \text{ is } e^2/4\pi$$

$$m_M^3 \ll \sim 10^{-12} (\mathrm{eV})^3$$

Determined by the mass m_M; cosmological density n_M

6.1 Proposal for Stoner parameter

Dipolar replusion energy

[UAY PASCOS 2005 proceedings; ArXiv:1102.2562;

EPJ Web Conf. 70 (2014) 00046]

$$I = \mu_M^2 |\Delta n_M| \kappa$$

Δn_M is local number density deficit due to Pauli principle, and κ is a geometric factor

- κ_{JM} computed by Jha and Mohanti [Pramana; JPhys 2006; PRE 2009] who showed that the domains need to be oblate

- verified for large parameter space by Fregoso and Fradkin [PRL 2009]
- .... however, Stoner phenomenon seems to be impossible to derive for a pure ionic plasma (Rajagopal 1984). Lattice effects perhaps needed.
- Functional dependence of I on n needs to be assumed ad hoc

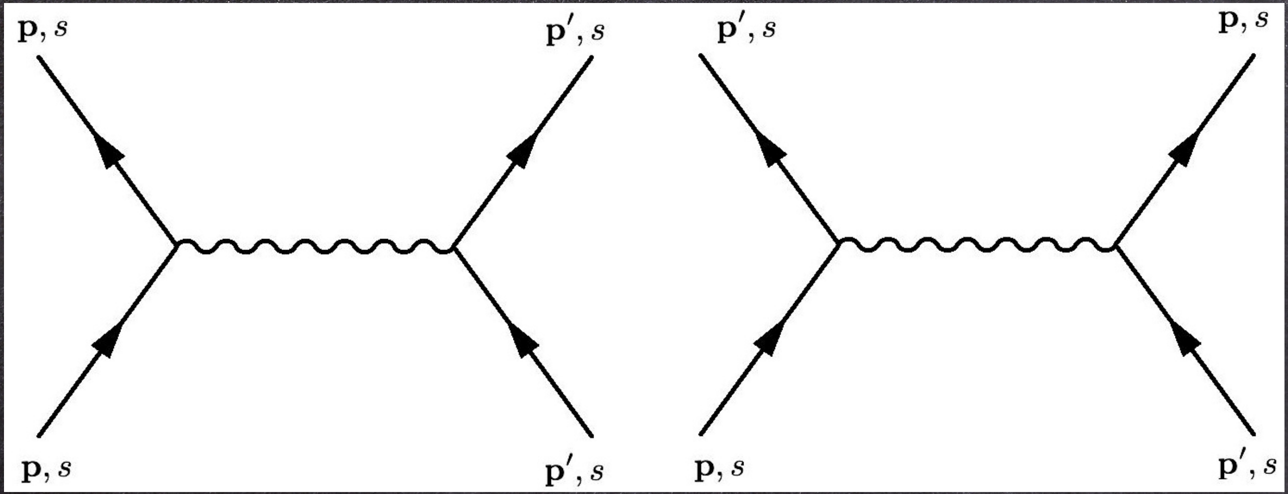
7 Magnino hypothesis - PAAI version

- Seek a microscopic derivation of spontaneous magnetisation
  - → valid for the relativistic case
- The key many body effect is the "Exchange energy"
  - → introduced as a part of the "Landau liquid" programme as an additional correction from forward scattering at finite density
  - → systematised by Baym and Chin as a two-loop contribution to the effective potential
- Needed : a calculation at finite number density and finite spin imbalance

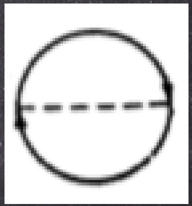
7.1 E_{ex} according to XRR

Xu, Rajagopal and Ramana 1984

based on a series papers on *relativistic* DFT by A K Rajagopal over the previous decade



=



The density and spin dependent Feynman propagator

$$S_F = \sum_{\pm \mathbf{s}} \frac{(\not{p}_+ + m)(1+\gamma^5 \not{\mathcal{S}}_+)}{4E_p}\left(\frac{n_{F\mathbf{s}}(\mathbf{p})}{p^0 - E_p - i\eta} + \frac{1 - n_{F\mathbf{s}}(\mathbf{p})}{p^0 - E_p + i\eta}\right)$$
$$- \sum_{\pm \mathbf{s}} \frac{(\not{p}_- + m)(1+\gamma^5 \not{\mathcal{S}}_-)}{4E_p}\left(\frac{1 - \bar{n}_{F\mathbf{s}}(\mathbf{p})}{p^0 + E_p - i\eta} + \frac{\bar{n}_{F\mathbf{s}}(\mathbf{p})}{p^0 + E_p + i\eta}\right)T$$

where we need spin 4-vector expressed in particle momentum basis

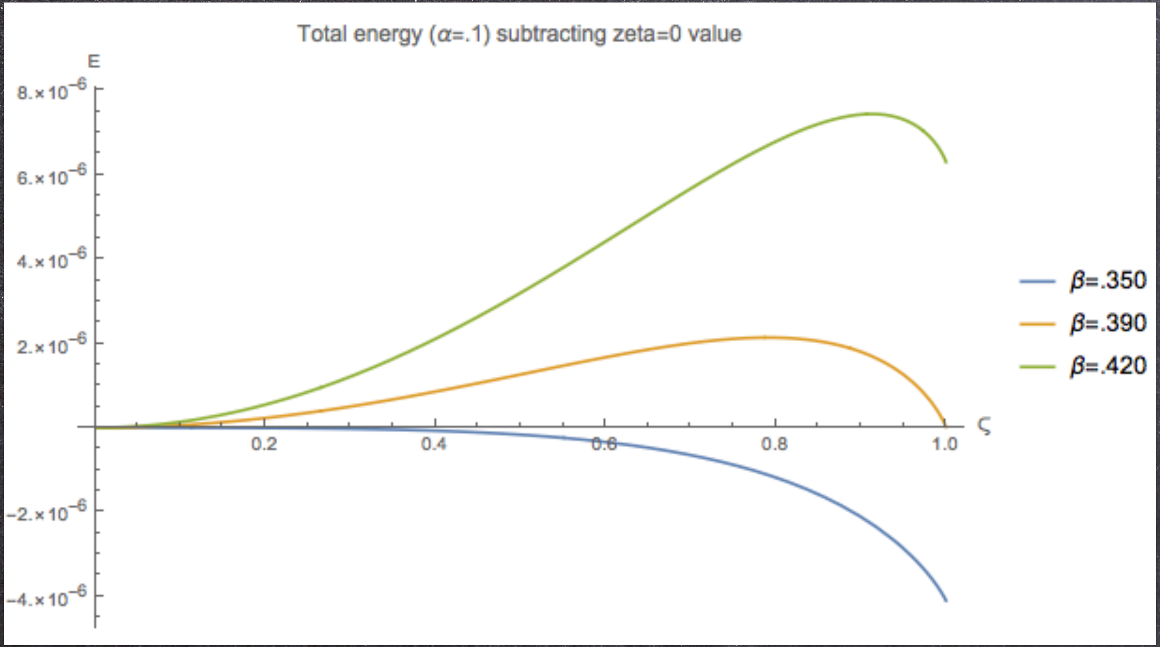
$$\mathcal{S}^0 = \frac{\mathbf{p}\cdot\mathbf{s}}{m}, \qquad \vec{\mathcal{S}} = \mathbf{s} + \frac{\mathbf{p}(\mathbf{p}\cdot\mathbf{s})}{m(E_p+m)}$$

Introduce the spin imbalance parameter ζ

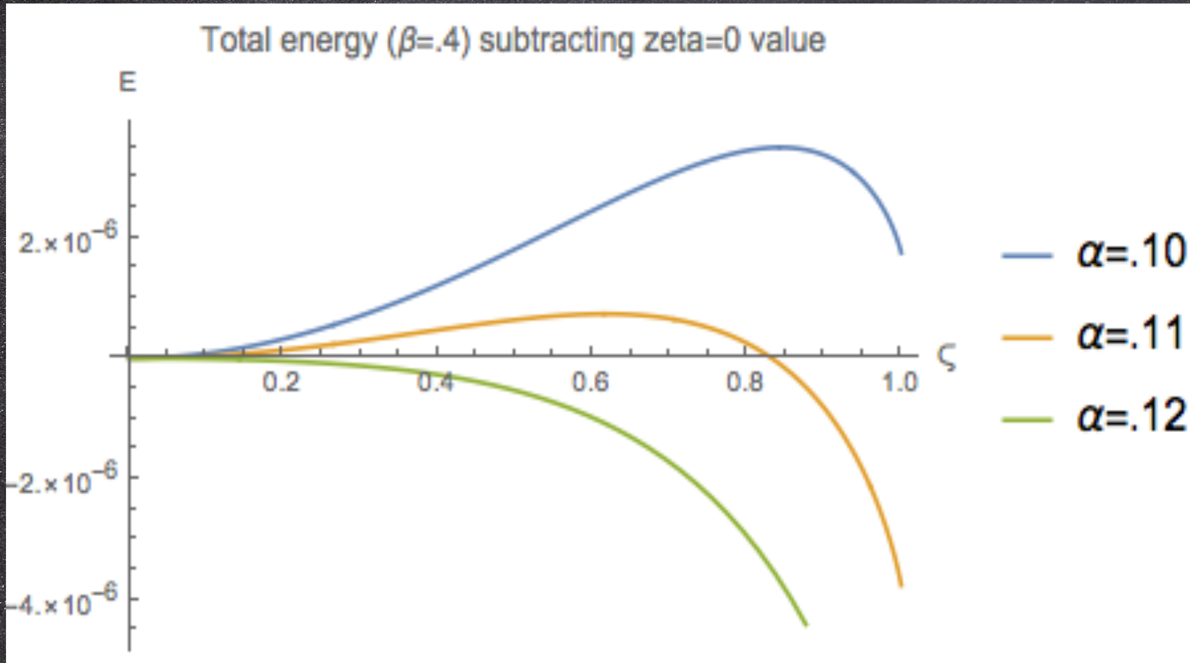
$$n_\uparrow = n(1+\zeta) \quad \text{and} \quad n_\downarrow = n(1-\zeta)$$

7.2 Phase diagram and EoS

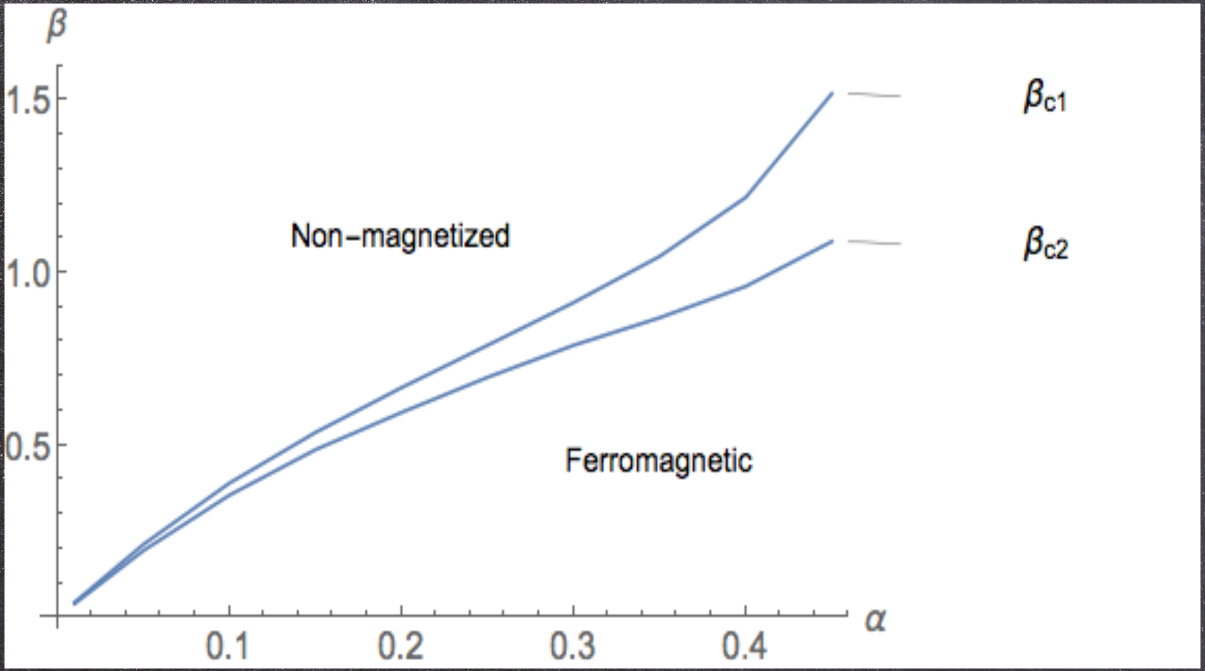
... after a lengthy calculation,



$$E = E_{kin} + E_{ex} \sim m^4(\beta^5 \ldots - a\beta^4); \qquad \beta = \frac{p_F}{m}; \qquad p_F^3 = 3\pi^2 n$$


Total energy (β=.4) subtracting zeta=0 value
E
2.×10^-6
-2.×10^-6
-4.×10^-6
0.2
0.4
0.6
0.8
1.0
ς
α=.10
α=.11
α=.12

The phase diagram



We refer to this medium as *PAAI*

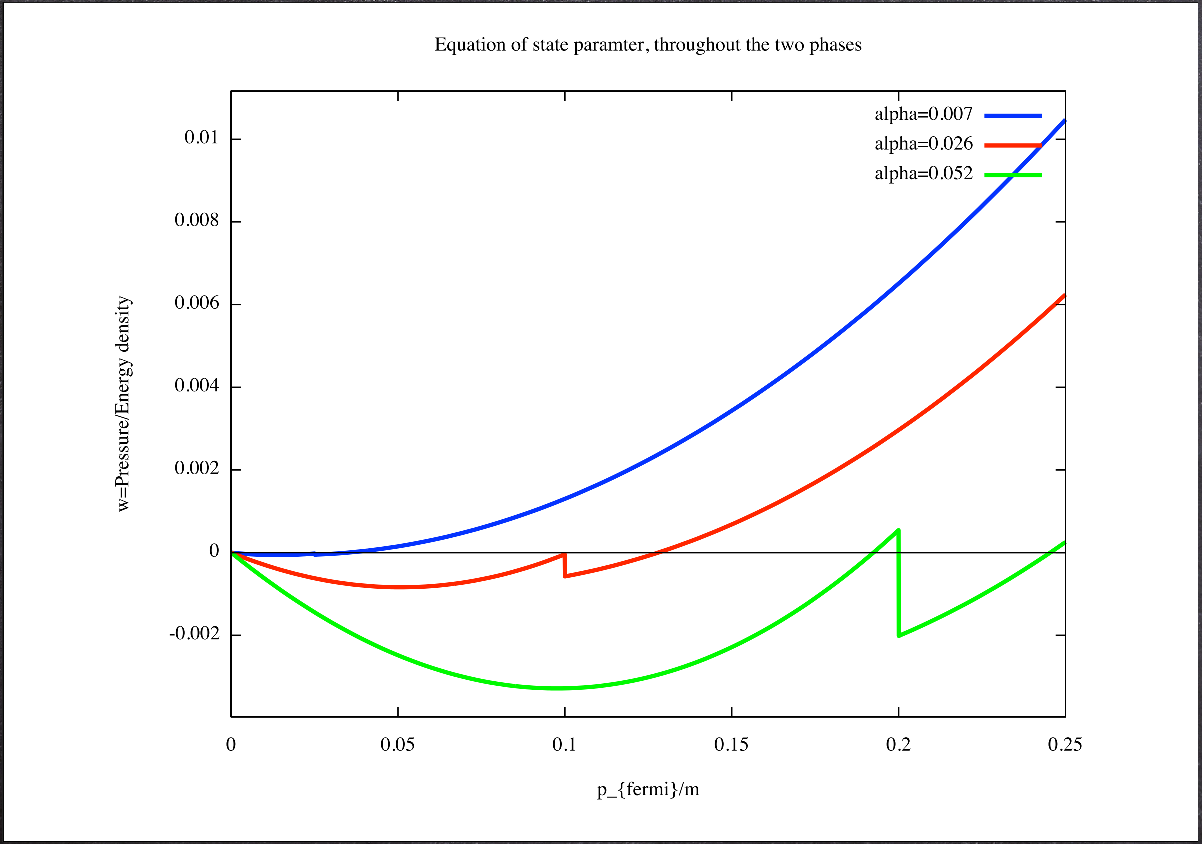
plasma which is asymmtric abelian and idealised

It is neutral due to heavy ionic background.

Screened Coulomb < the magnetic dipole repulsion.

The equation of state : $p = \rho \frac{\partial \rho}{\partial n} - \rho$;

$\omega = p/\rho$ as a function of $p_F \sim n^{(1/3)}$



Jumps inserted at B_{c1}

a = 0.007, 0.026 and 0.052

Representative numbers

Fine structure constant α_X	p_F/m	Energy density $E(\zeta = 1)$ in m^4 units	ΔE =E(0)-E(1) in m^4 units	Rest mass energy density in m^4 units
0.01	0.01	-1.618×10^{-9}	5.4×10^{-11}	2.162×10^{-6}
0.05	0.02	-9.70×10^{-10}	1.90×10^{-10}	2.702×10^{-7}
0.10	0.10	-1.12×10^{-6}	2.1×10^{-7}	3.38×10^{-5}
0.10	0.30	-5.84×10^{-5}	5.3×10^{-6}	9.12×10^{-4}

8 PAAI in the sky

We now demand the existence of a hidden sector much like ours...

- Magnino M mass m_M
- Oppositely charged partner Y with $m_Y \gg m_M$
- A hidden $B-L$ number keeps them from annihilating
- $U(1)_X$ photons at a temperature $T > \alpha_X^2 m_X$ over $10^3 \gtrsim z \gtrsim 0.5$

8.1 Dark energy

Domains of M as bags containing Y

From neutrality $\langle n^M \rangle = \langle n^Y \rangle$

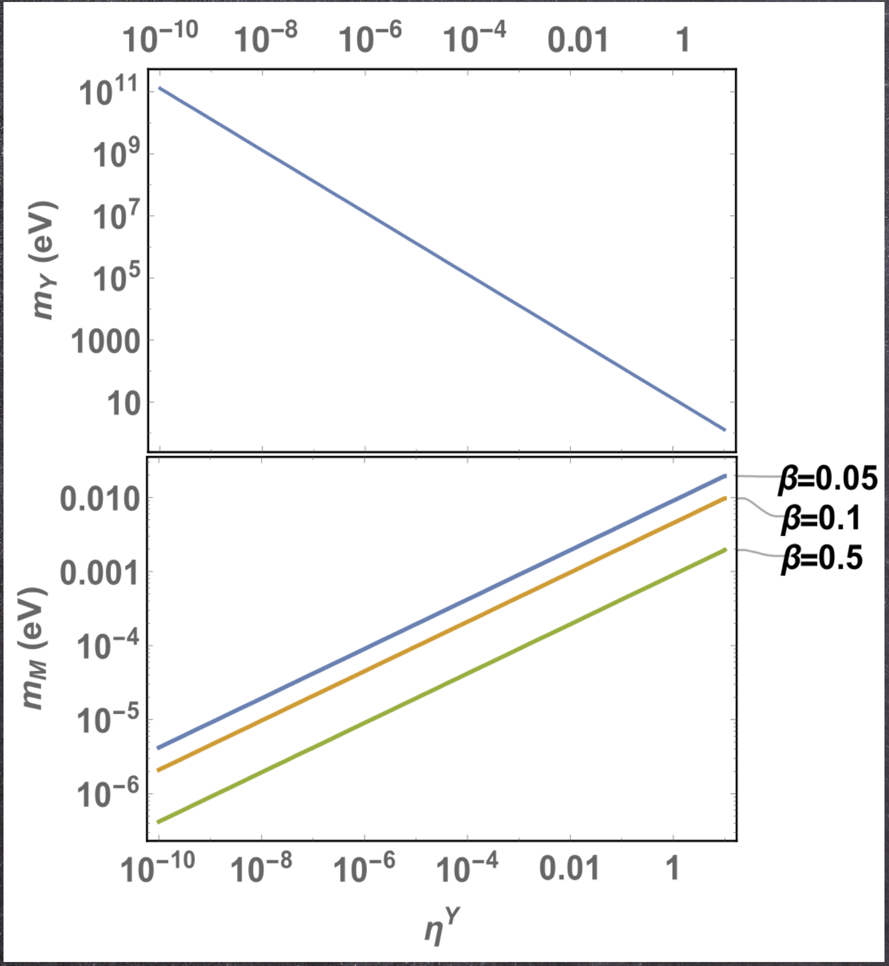
And we demand that the $\rho^M + \rho^Y \approx \rho^Y$ determines ρ_{DE}

$$m^Y n^Y \approx 2.81 \times 10^{-11} (\mathrm{eV})^4$$

Let $$n^Y = \eta^Y n_\gamma = \eta^Y \times 3.12 \times 10^{-12} (\mathrm{eV})^3$$

Next, M and Y share the same p_F. And the phase diagram dictates upper limit on B for the ferromagnetism to occur. Thus we get

$$m_M \overset{?}{\sim} (\eta^Y)^{1/3} \left(\frac{0.1}{B} \right) 4.52 \times 10^{-3}$$



10^{-10} 10^{-8} 10^{-6} 10^{-4} 0.01 1
m_Y (eV)
10^{11}
10^{9}
10^{7}
10^{5}
1000
10
m_M (eV)
0.010
0.001
10^{-4}
10^{-5}
10^{-6}
β=0.05
β=0.1
β=0.5
η^Y

8.2 Concordance puzzle - a flavoured model

DM requires energy scaling like matter. This cannot be accounted for the M and Y which must simulate DE.

Assume several M type and Y type species M_1, M_2 ... and Y_1, Y_2 ...

The heavier flavour(s) can account for Dark Matter, presumably also forming Dark Atoms as the ambient X-temperature is much smaller.

Reuire :

$$(m_{M_2} + m_{Y_2}) n_{Y_2} = \rho_{DM} = 1.04 \times 10^{-11} (eV)^4$$

But also, m_{M_2}, m_{Y_2} must be at least keV to serve as DM.

This gives an upper bound on the abundance of higher flavours.

$$\eta^{Y_2} \lesssim 10^{-3}\left(\frac{\mathrm{keV}}{m_{M_2}+m_{Y_2}}\right)$$

8.3 The origin of cosmic magnetic fields

Let the sizes of the domains be set by a scale L.

From the many body thoery we can also deduce

$$B_{\text{domain}} \approx \left(\frac{m_M}{\text{eV}}\right)^2 \left(\frac{e'}{e}\right) \left(\frac{B}{0.1}\right)^3 \times 2.2 \times 10^{-8}\ T$$

- Net magnetic field on global scale vanishes
- the rms field left over N domains would go as $1/\sqrt{N}$.

- Thus over galactic scales,

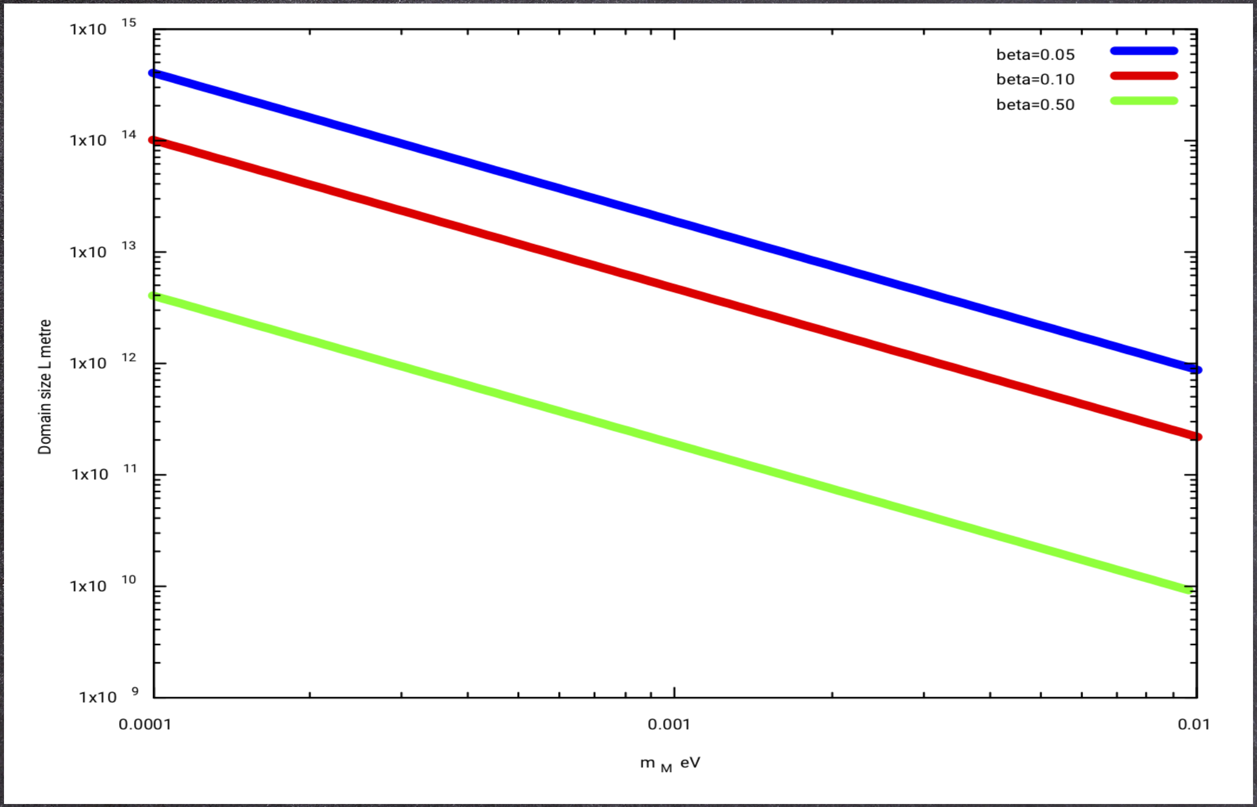
$$\overline{\Delta B} \equiv B_{domain} (L / L_{gal})^{3/2}$$

- Assume kinetic mixing $\xi F^{\mu\nu} F^{X}_{\mu\nu}$ with standard electromagnetism

- Example : a seed of 10^{-30}T needed with a coherence length of 0.1 kpc$\sim 3 \times 10^{18}$ metre obtained with $\xi = 10^{-8}$.

$$\overline{\Delta B}_{seed} = 10^{-30}\, T$$

$$\sim \left(\frac{\xi}{10^{-8}}\right)\left(\frac{m_M}{eV}\right)^2\left(\frac{e'}{e}\right) B^3 \left(\frac{L}{metre}\right)^{3/2} \times 10^{-48}\, T$$



We have set $e'/e = 1$ for simplicity.

It can be seen that the representative values for L for $\beta = 0.1$ are in the range 10^{11}–10^{13} metre which is solar system size.

9 Future work

9.1 Needs completion

- The nature of the phase transition
- FLustuations and stability
- The nature of degradation
- Connetion to SM in a reasonable intermediate scale model

9.2 In search of observables ...

- Small kinetic mixing with standard Maxwell - light shining through the wall "ALP"

- Minicharged particles in DM - upto 1% possible as per analysis of EDGES (Munoz and Loeb)
- A late phase transition should dump entropy during the reionisation era

10 Conclusion

- A common origin for Dark Energy and Dark Matter would be desirable
- Above is a particular model with hidden unbroken $U(1)$ with oppositely charged but asymmetrically massive fermions.
- Effective potential of a PAAI admits ferromagnetism for a substantial range of values.
- Dark Matter abundance constrained in flavoured model
- Seed for intergalactic magnetic fields available
- In search of observables ...

Thank you !!

Typeset using $\mathrm{T_EX_{MACS}}$