Emergent Dark Energy

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1 Outline

- Overview of the dilemmas
- Observational : Pantheon, Xenon1T, ... CMB
- Some classes of models
- Hidden $U(1)_X$ ferromagnetism as a model
  - Concordant Dark Matter
  - Origin of cosmic magnetic fields

2 The dilemmas in a nutshell

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

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi}{M_{Pl}^2}(\rho_{known} + \rho_{DE})$$

→ Dark Matter contributes $\rho_{DM} \approx 0.26\rho_0$

→ But at epoch t_0 we also see $\rho_{DE} \approx 0.7\rho_0 \sim 10^{-10}(eV)^4$

- Smallness compared to any HEP scale

→ Cosmic coincidence in the Dark Sector at t_0?

- $\rho_{DM} \approx \rho_{DE}$ *in the late universe*

3 Some key data I - Pantheon 2018

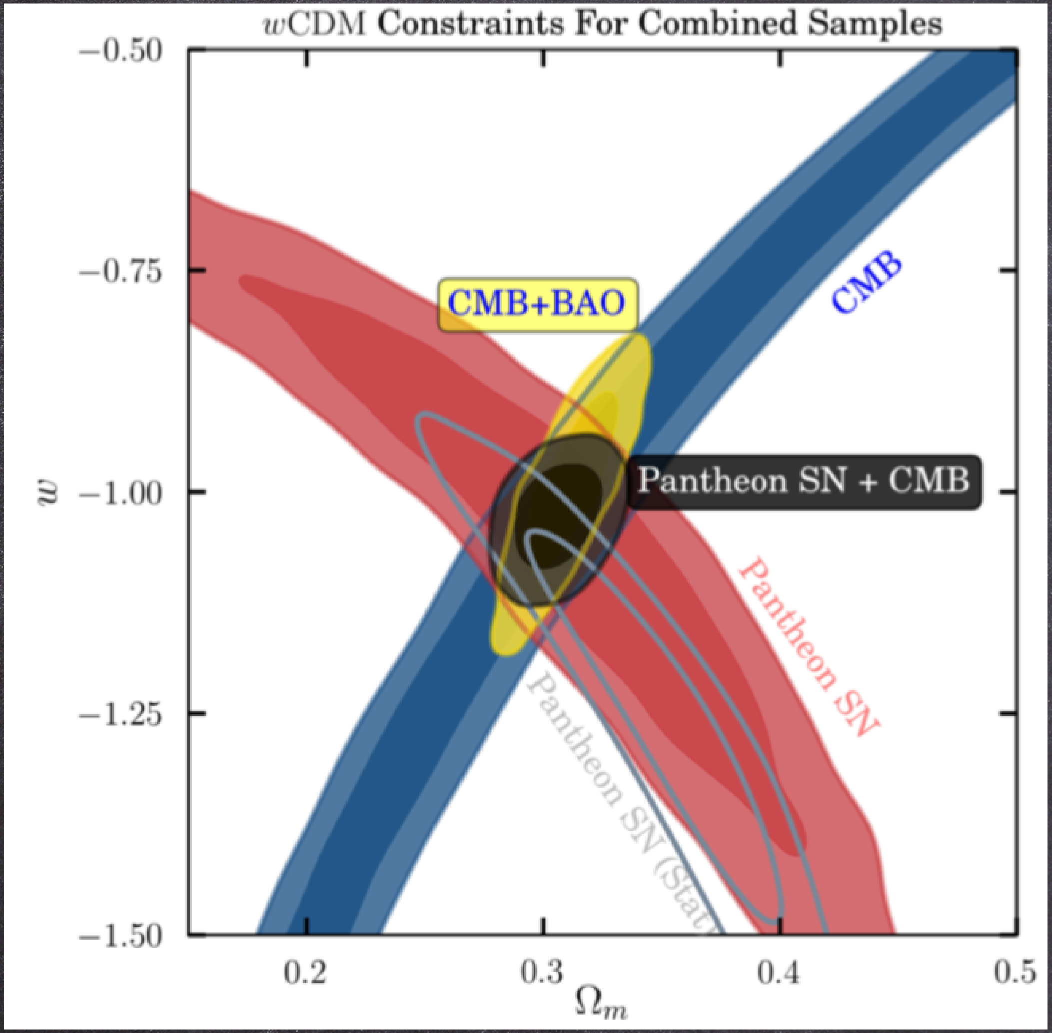
Multi-source data on SN Ia combined

Cosmological models:

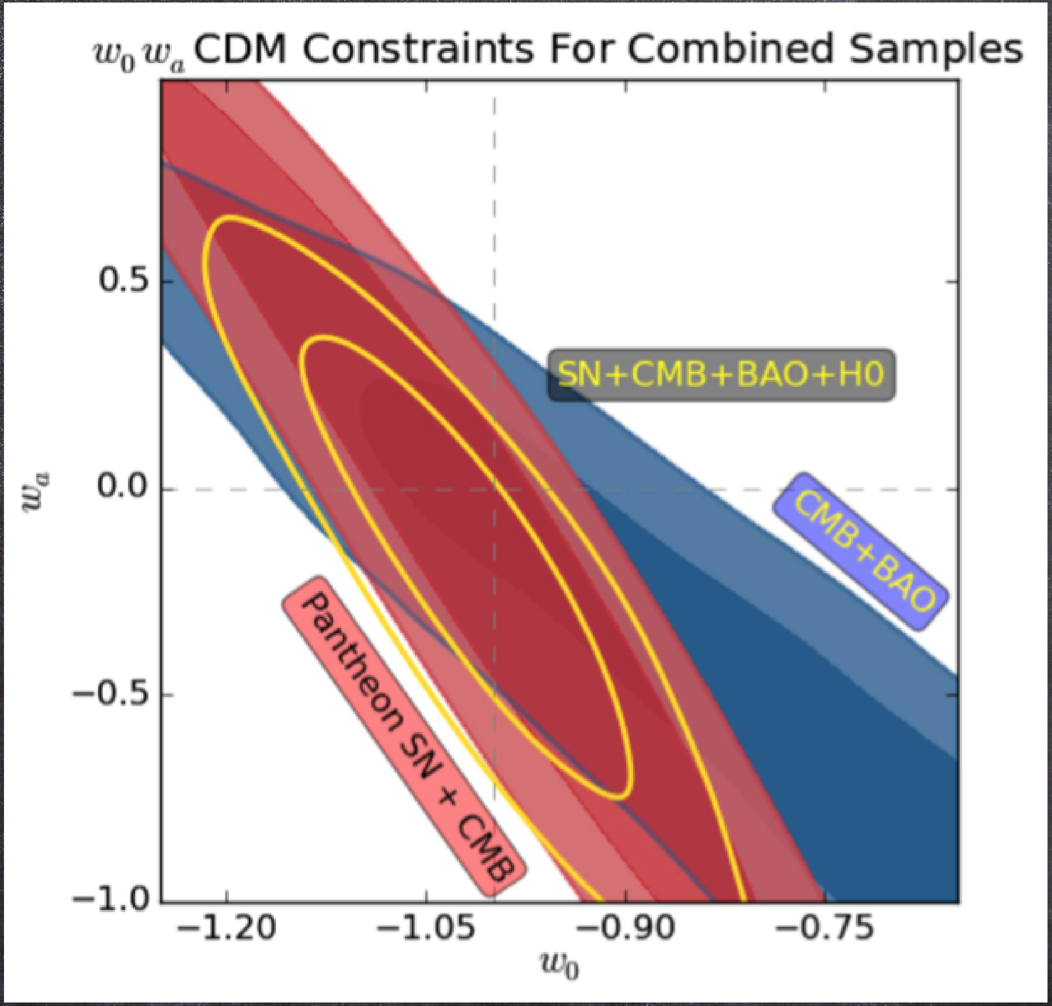
A flat ΛCDM model ($w = -1$, $k = 0$),

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

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



wCDM Constraints For Combined Samples
CMB+BAO
CMB
Pantheon SN + CMB
Pantheon SN
Pantheon SN (Stat
w
−0.50
−0.75
−1.00
−1.25
−1.50
0.2
0.3
0.4
0.5
Ω_m

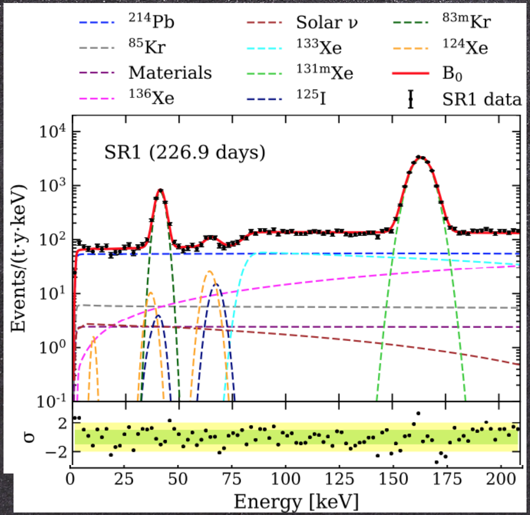

$w_0\, w_a$ CDM Constraints For Combined Samples
SN+CMB+BAO+H0
CMB+BAO
Pantheon SN + CMB
0.5
0.0
−0.5
−1.0
w_a
−1.20
−1.05
−0.90
−0.75
w_0

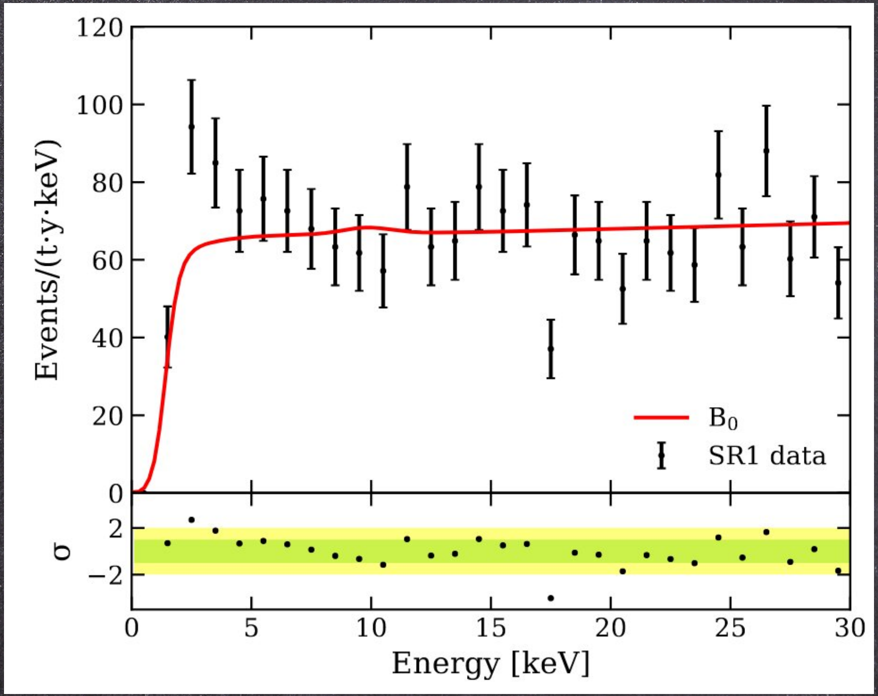
4 Dark World - usual suspects

The fabulous Five 2102.12143

Portal	Coupling
Dark Photon, A'	$-\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Axion-like particles, a	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Dark Higgs, S	$(\mu S + \lambda_{\mathrm{HS}} S^2) H^\dagger H$
Heavy Neutral Lepton, N	$y_N L H N$
milicharged particle, χ	$\epsilon A^\mu \bar{\chi}\gamma_\mu\chi$

5 Some key data II - Xenon1T anomaly





Left : Full range of data

Right : Zoomed plot of electron excess

5.1 XenonT1 - possible explanations

a) Non-DM : Solar axions

b) Neutrino magnetic moment

c) DM : Relic bosons / axionlike particles ALP

5.2 Also Dark Energy?

Vagnozzi, Visinelli, Brax, A-C Davis, Sakstein PRD104, 2021

- Chameleon field which introduces screening in dense objects but production of DE quanta from solar "tachocline" (trubulent shear layer at the base of convection zone).
- Chameleon quanta to explain X1T.

6 Mirror-like Dark sector

Dark $U(1)_X$

Dark electron(s) and

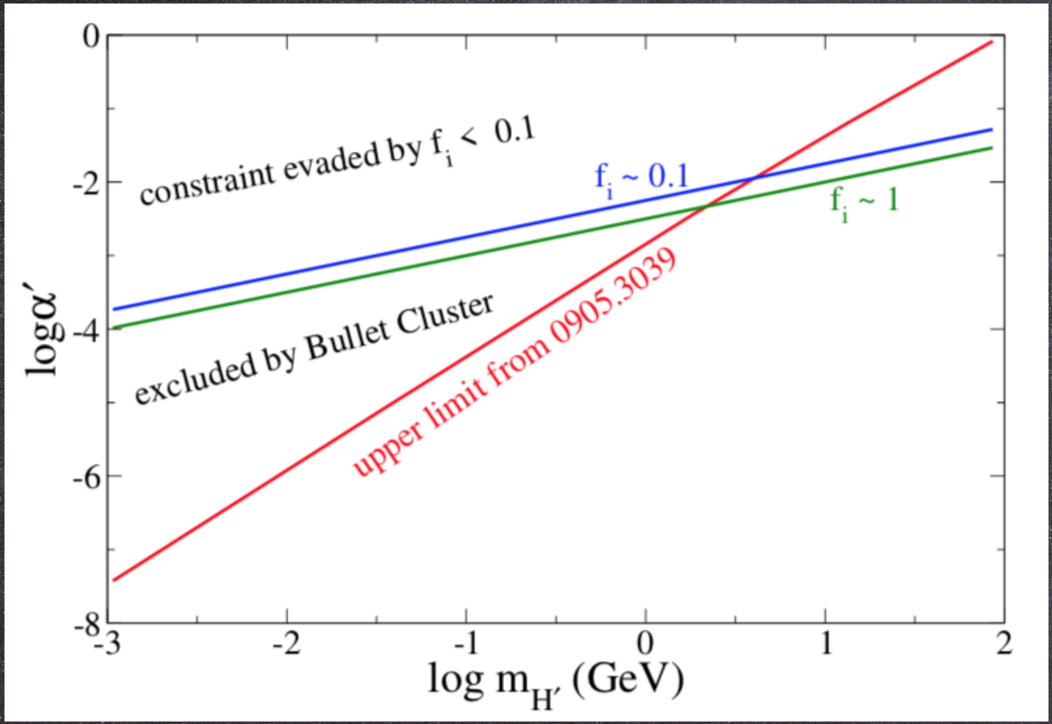
$SU(N_X)_c$ Quarks and resulting baryons

Working assumption : $R \equiv m'_e / m'_p = 1$

- Van der Waals interaction of dark atoms => solves cusp core, missing satellites and too big to fail problems if

$$\frac{\sigma}{m} \sim 0.9 \frac{\text{barn}}{\text{GeV}} \quad \text{(Rocha et al 2013)}$$

- Bullet cluster places a bound on $a_X (= e_X^2 / 4\pi)$ for given ionisation fraction f_i at hidden sector recombination



from J Cline Les Houches 2021

0905.3039

Feng, Kaplighat, Tu and Yu

- ξ=Hidden sector temperature T'/T visible

Then from Planck 2018 $\Delta N_{eff} = \frac{4}{7}\left(\frac{11}{4}\right)^{4/3} g'_* \xi^4 < 0.45 \Rightarrow$

$$\xi = \frac{T'}{T} < 0.57$$

7 Extended objects as Dark Energy

Battye, Bucher, Spergel 2001

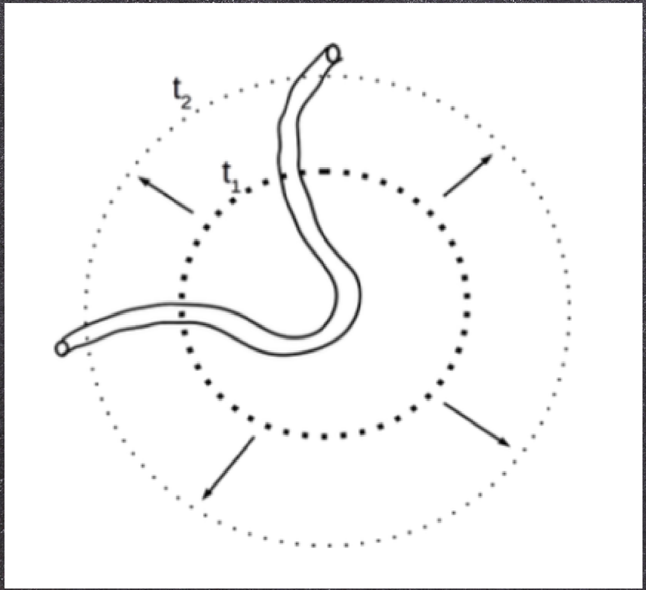
Friedland, Murayama, Perelstein 2001 - 2013

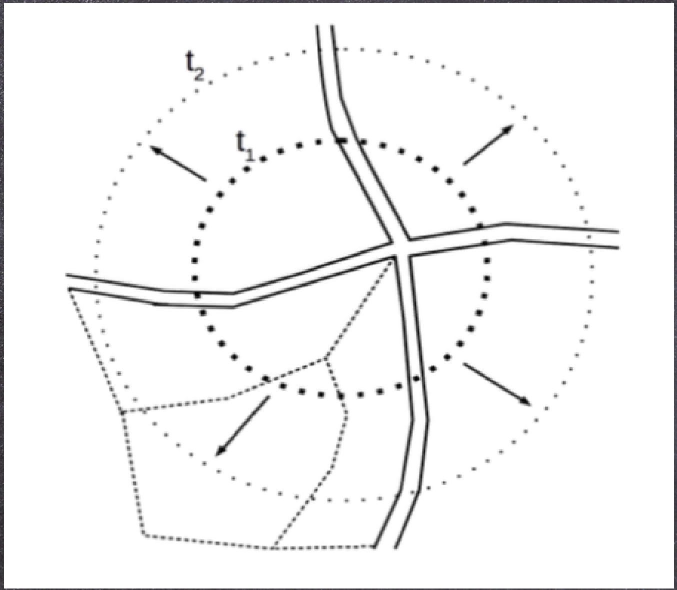
Conversi, Melchiorri, Mersini, Silk 2001

Kapusta 2005

Utpal Sarkar 2018

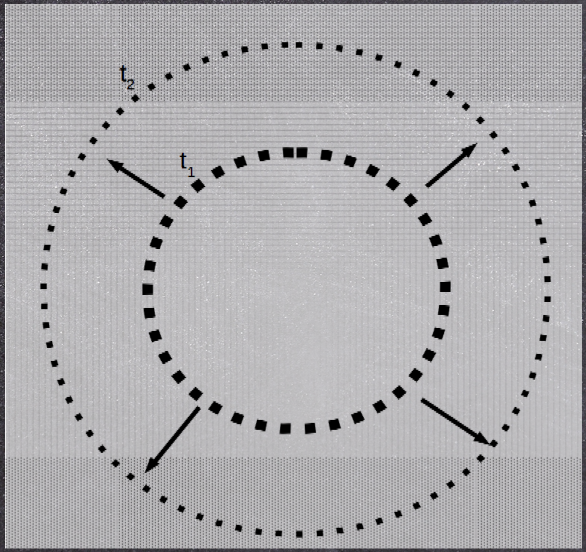
7.1 Some useful cartoons





- → Expansion of comoving sphere from t_1 to t_2
- → Additional energy engulfed $\propto a$ for vortices, $\propto a^2$ for DW
- → $\rho_{vortex} \sim a^{-2}$; $\rho_{DW} \sim a^{-1}$

… 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.

8 Ferromagnetism of fermion gas

- Band ferromagnetism or "Itinerant electron" ferromganetism
  - 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 ...

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

9 Magnino hypothesis - PAAI version

"Cosmic Ferromagnetism of Magninos" ArXiv:1901:00995

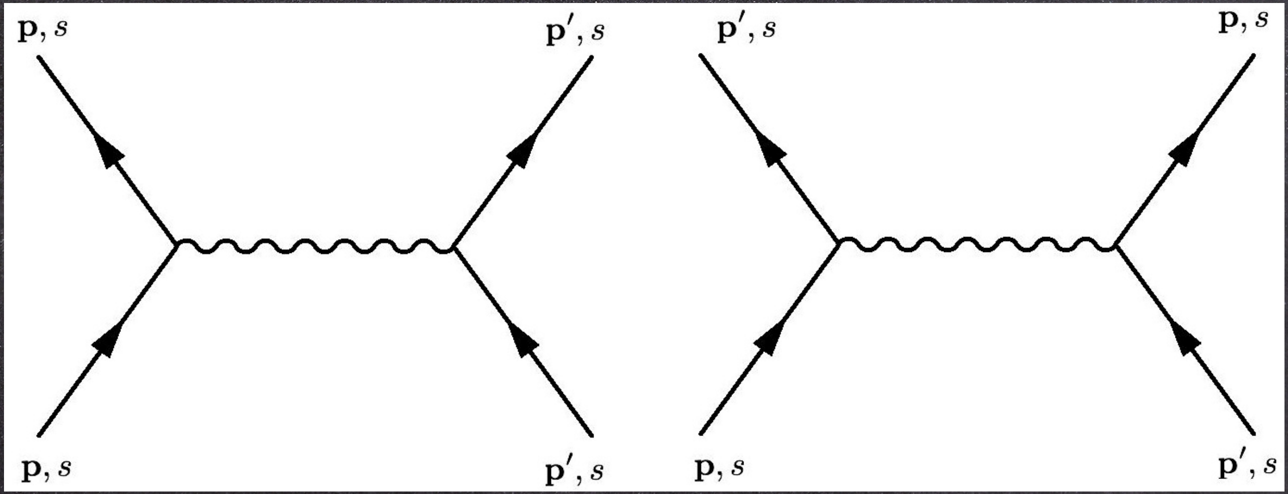
MacKenzie, Paranjape and UAY

- 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

9.1 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



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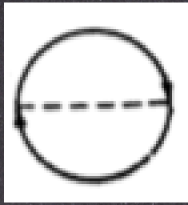


The density and spin dependent Feynman propagator

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

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

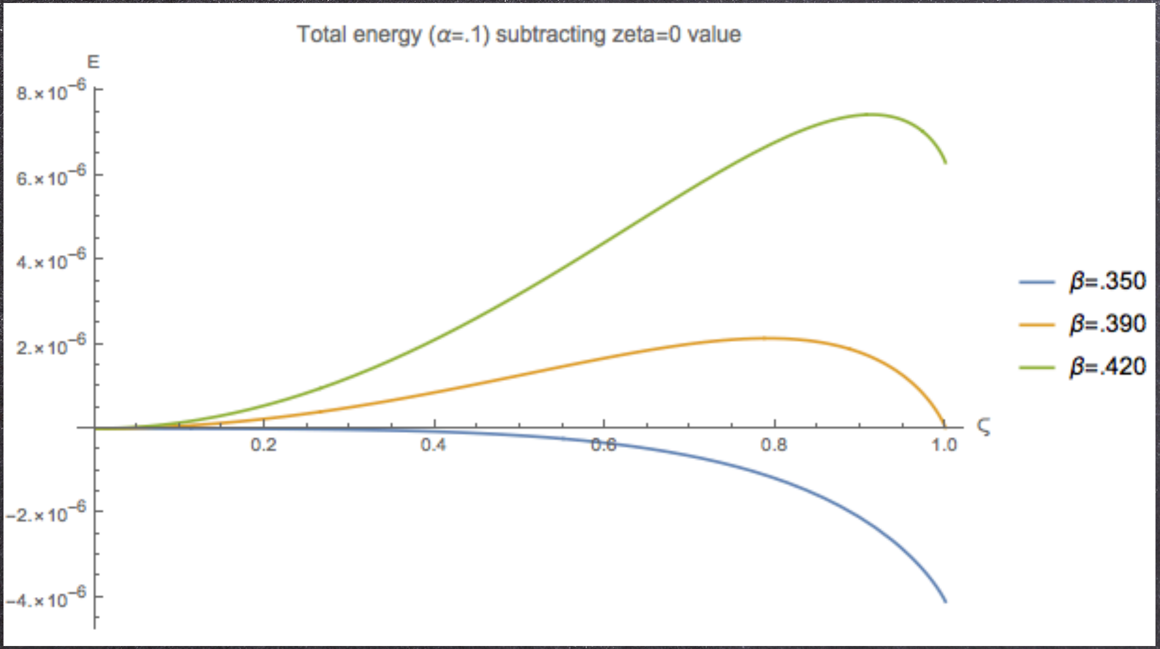
$$\mathcal{S}^0 = \frac{\mathbf{p} \cdot \mathbf{s}}{m}, \qquad \vec{\mathcal{S}} = \mathbf{s} + \frac{\mathbf{p}(\mathbf{p} \cdot \mathbf{s})}{m(E_p + m)}$$

Introduce the spin imbalance parameter ζ

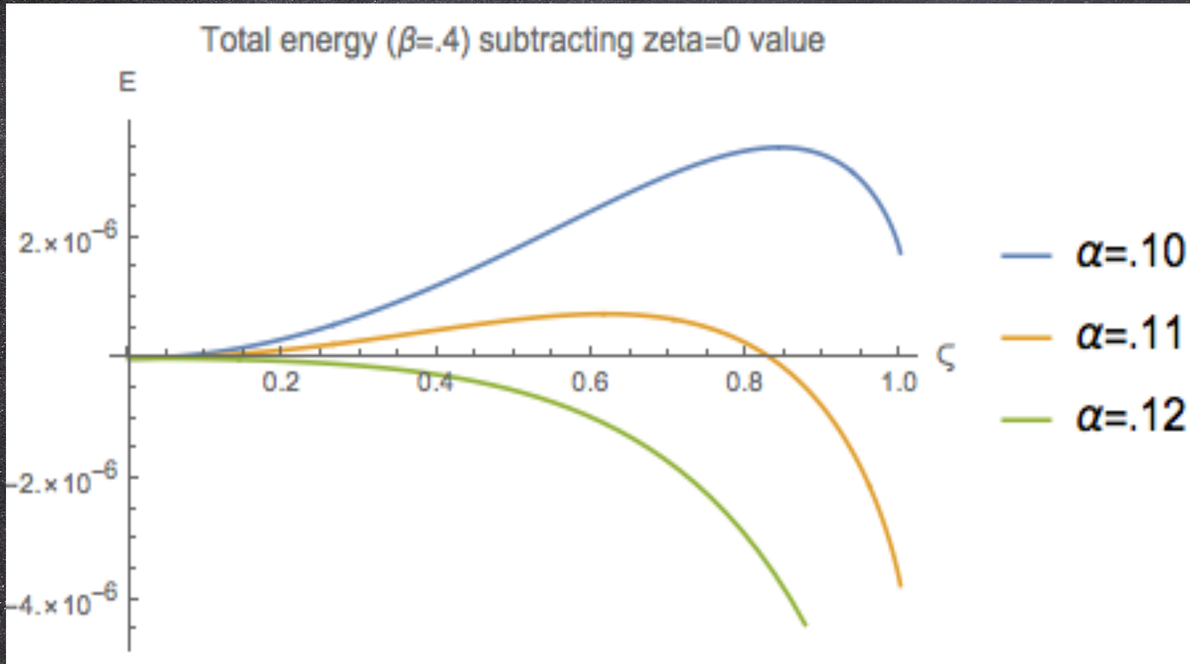
$$n_\uparrow = n(1+\zeta) \quad \text{and} \quad n_\downarrow = n(1-\zeta)$$

9.2 Phase diagram and EoS

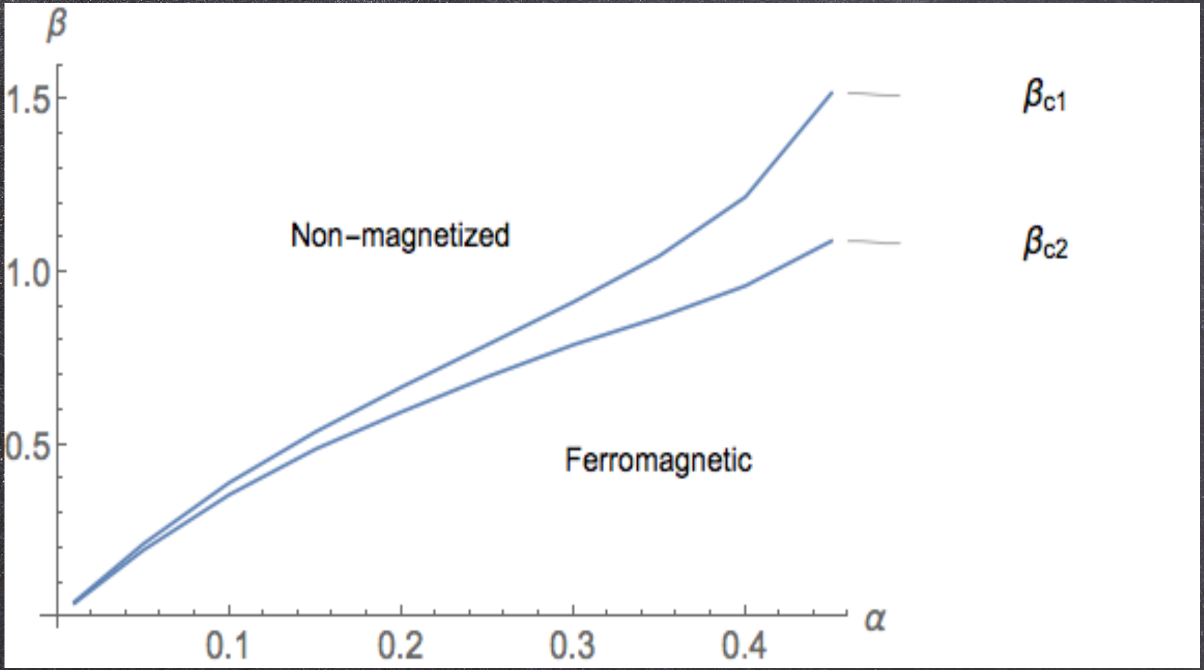
... after a lengthy calculation,



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


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

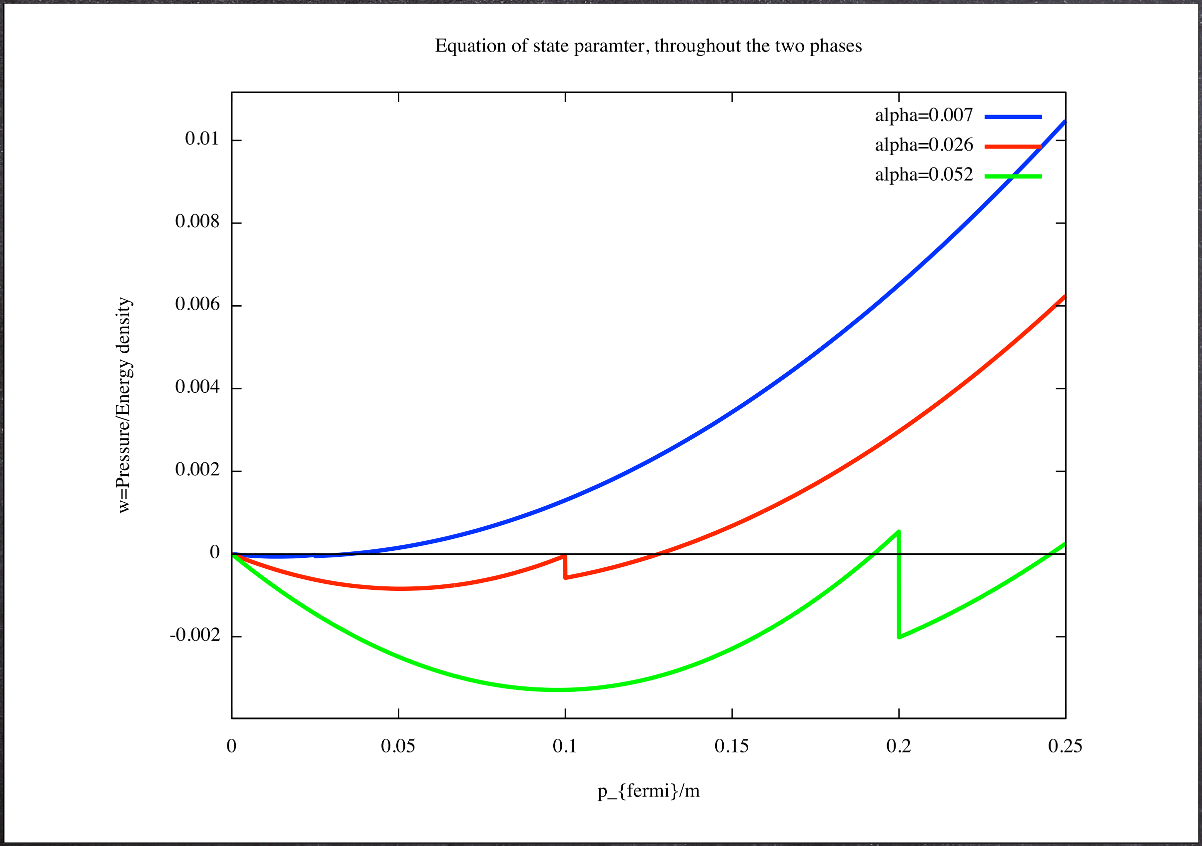
plasma which is asymmtric abelian and idealised

It is neutral due to heavy ionic background.

Screened Coulomb < the magnetic dipole repulsion.

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

$w = p/\rho$ 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}

10 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 $10^3 \gtrsim z \gtrsim 0.5$

10.1 Dark energy

Domains of $\mathcal{M}$ as bags containing $\mathcal{Y}$

From neutrality $\langle n^{\mathcal{M}} \rangle = \langle n^{\mathcal{Y}} \rangle$

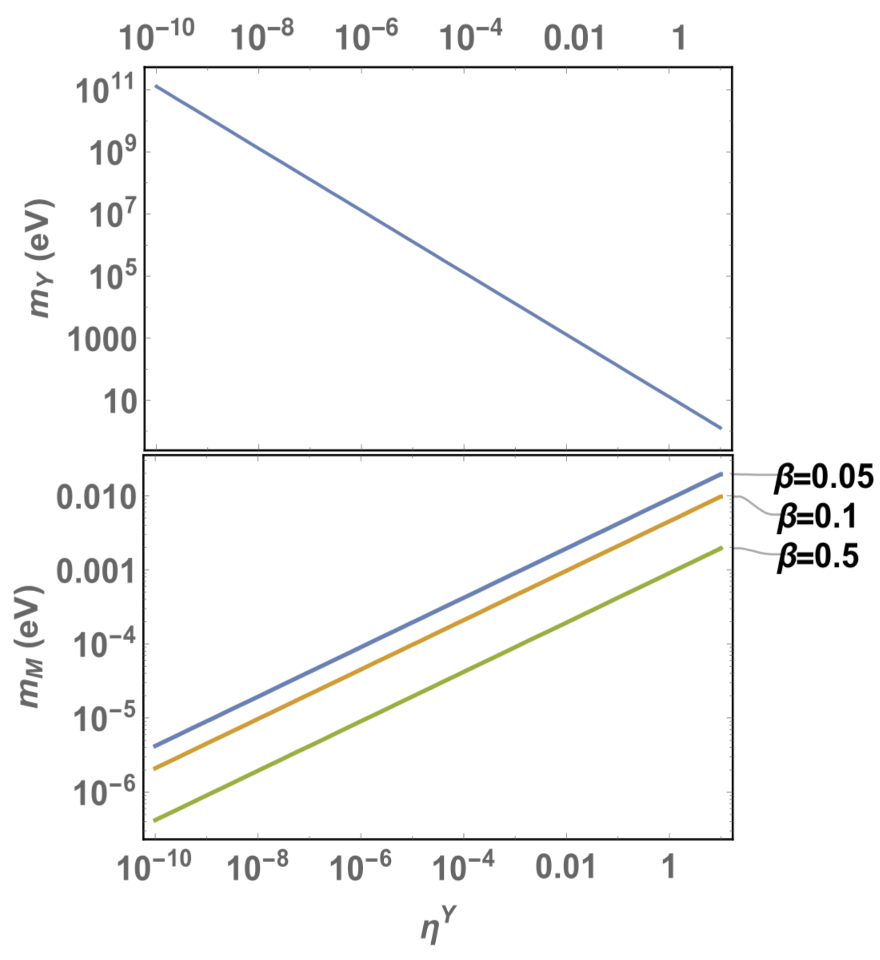
And we demand that the $\rho^{\mathcal{M}} + \rho^{\mathcal{Y}} \approx \rho^{\mathcal{Y}}$ determines ρ_{DE}

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

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

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

$$m_{\mathcal{M}} \gtrsim (\eta^{\mathcal{Y}})^{1/3} \left(\frac{0.1}{B} \right) 4.52 \times 10^{-3}$$



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

10.2 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.

$$\eta^{1/2} \lesssim 10^{-3} \left(\frac{\text{keV}}{m_{M_2} + m_{Y_2}} \right)$$

10.3 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

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

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

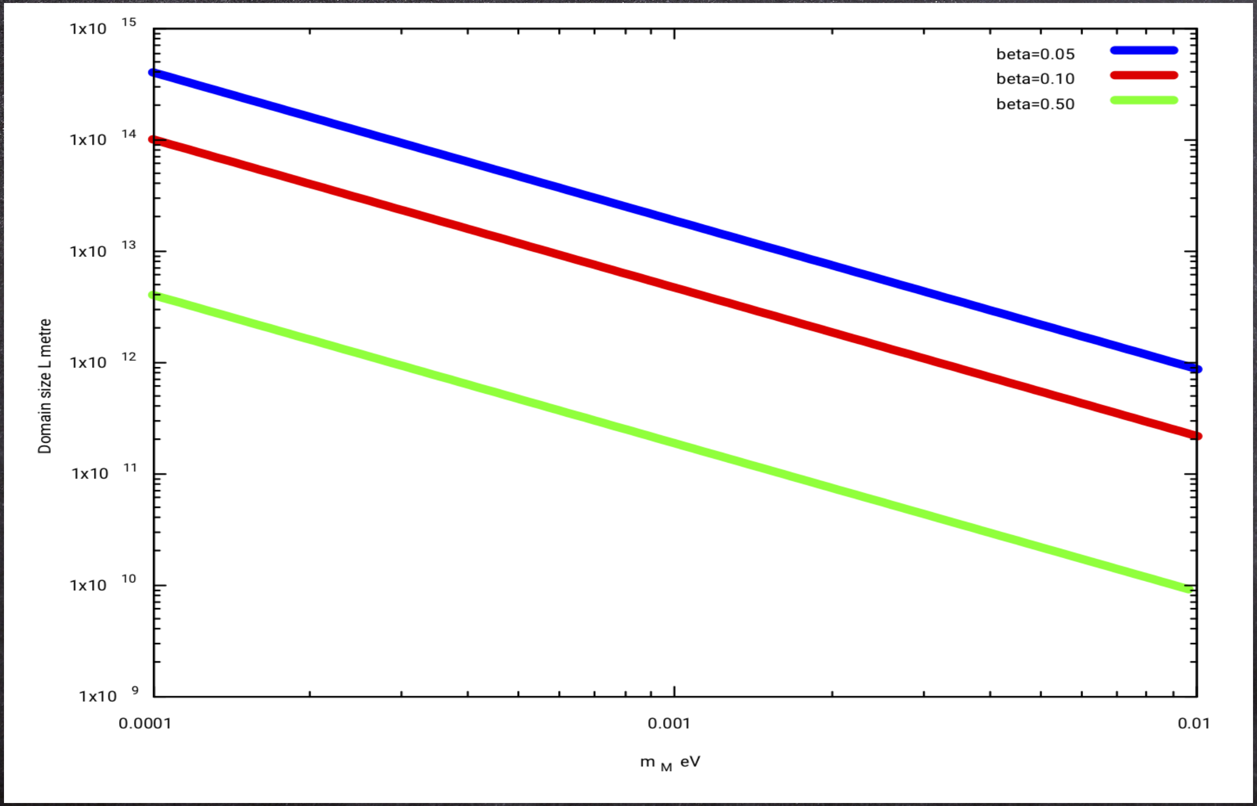
$$\overline{\Delta B} \equiv B_{domain} (L/L_{gal})^{3/2}$$

- Assume kinetic mixing $\xi F^{\mu\nu} F^{X}_{\mu\nu}$ with standard electro-magnetism
- Example : a seed of 10^{-30}T needed with a coherence

length of 0.1 kpc $\sim 3\times 10^{18}$ metre obtained with $\xi = 10^{-8}$.

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

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



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

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

11 Future work

11.1 Needs completion

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

11.2 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

12 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 !!

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