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Exorcising w<-1

Overview

- Dark energy: Discords of Concordance Cosmology
- What is w? Could we imagine $w<-1$?
- Exorcisms
- Summary

Concordance Cosmology

- A Golden Age of cosmology: ever better data from CMB, LSS and SNe yield new insights into our Universe.

- Our Universe is **WEIRD:** about 70% dark energy, about 30% dark matter, spatially flat (with 1% precision), with a 'whiff' of baryons, and with a nearly flat spectrum of initial inhomogeneities.

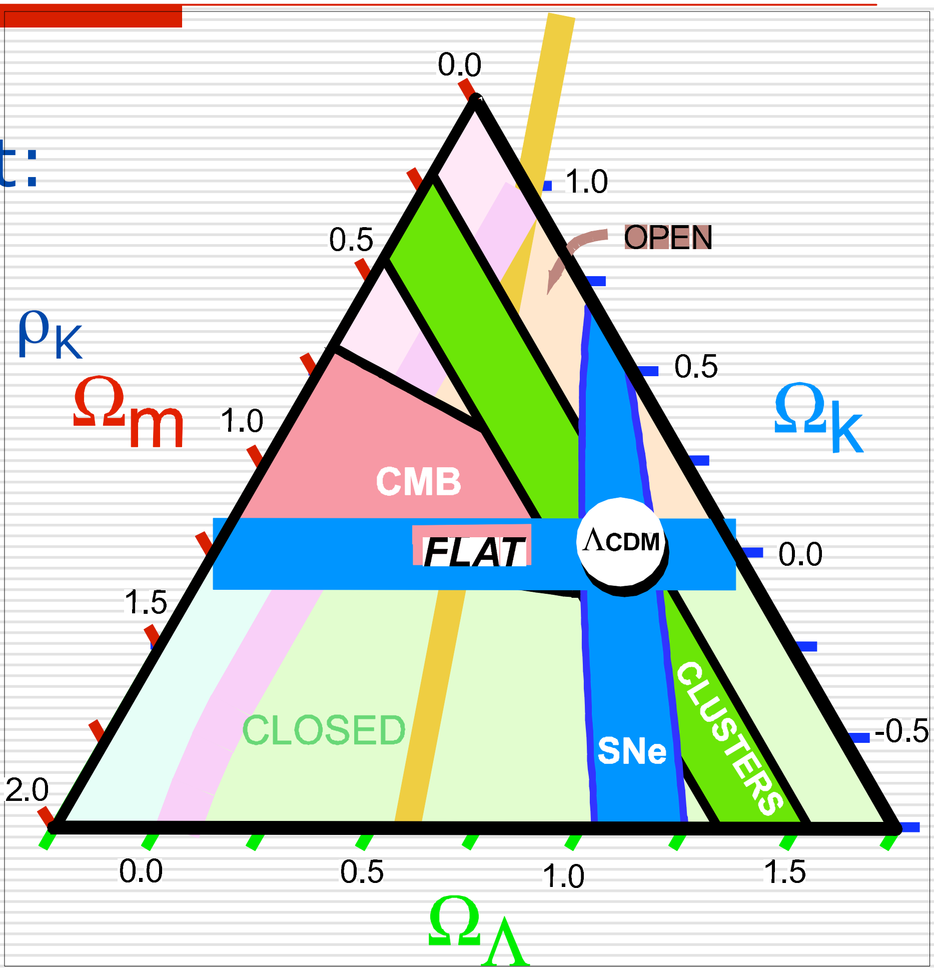
- Emerging paradigm: **'CONCORDANCE COSMOLOGY':** DE+DM. But: this means Universe is controlled by *cosmic coincidences*: nearly equal amounts of various ingredients today evolved very differently in the past. *This Universe gave up on Occam 14 billion years ago…*

COSMIC TRIANGLE

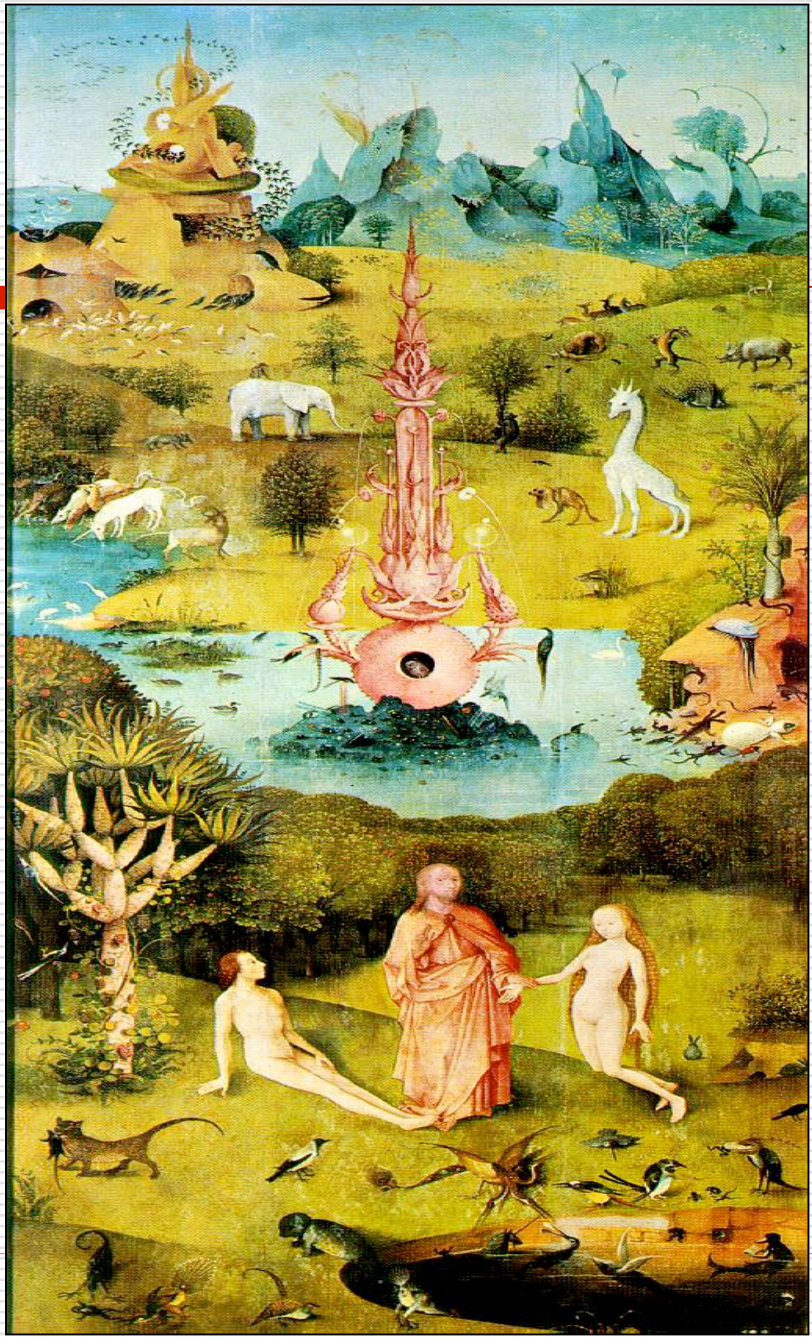
Cosmological Dalitz plot:

$$3\,M_4^2\,H^2 = \rho_{DE} + \rho_{DM} + \rho_K$$

$$\Omega_j = \rho_j \,/\, 3\,M_4^2\,H^2$$



Bahcall, Ostriker, Perlmutter
& Steinhardt, Science 284 (1999) 1481.



Discords in The Garden of Cosmic Delights?

- We have ideas on explaining the coincidences of some relic abundances, ie photons, baryons, neutrinos and dark matter: **Inflation** → **thermal equilibrium** in the Early Universe.
- However we do not understand the worst problem: **DARK ENERGY** - a smooth, non-clumping component contributing almost 70% of the critical energy density today, with negative equation of state $w = p/\rho < 0$.
- Usual suspects:

1) Cosmological constant: $w = -1$, $\rho = (10^{-3}\ \mathrm{eV})^4$

2) Quintessence: ultra-light scalar, $\rho=(\phi')^2/2 + V(\phi)$, $w>-1$

- But: to model dark energy in this way we have to live with **HEAVY FINE-TUNING**!

See, e.g. S. Weinberg, '89.

MORE DISCORDS

- It is important to explore the nature of dark energy: we may gain insights into new physics from the IR! How does string theory explain the accelerating universe?

- We *might* learn to "tolerate" dark energy (?): a *miracle* sorts out the cosmological constant problem and sets the stage for cosmic structures (still: *fine tunings extremely severe: 10^{-60}-10^{-120} in the value of the vacuum energy, and for quintessence, 10^{-30} in the value of its mass, as well as sub-gravitational couplings*!). But then this stage stays put…

- But how well do we know the nature of dark energy? Is it even there? Observationally the most interesting property is w. What is it? Could it even be that $w<-1$? The data, at least, does not preclude this possibility…

WHAT COULD w BE?

- At present there is a lot of degeneracy in the data. We need priors to extract the information. SNe alone however are consistent with w in the range, roughly

Hannestad et al

$$-1.5 \leq w_{eff} \leq -0.7$$

Melchiorri et al

Carroll et al

- One can try to model w<-1 with scalar fields like quintessence. But that requires **GHOSTS**: fields with negative kinetic energy, and so with a Hamiltonian not bounded from below:

$$3\, M_4^2\, H^2 = -\, (\phi')^2/2 + V(\phi)$$

`Phantom field' , Caldwell, 2002

`Pole inflation', Pollock, 1985.

- Ghost **INSTABILITIES**: no stable ground state, unstable perturbations! The instabilities are fast, and the Universe is OLD: $\tau \sim 14$ billion years. We should have seen the 'damage'...

SHOULD WE CARE ABOUT w<-1?

- Theoretical prejudice against w<-1 is strong!
- The case for w<-1 from the data is **NOT** very strong!

Caldwell, 2002; Alam et al, 2003;Huterer et al, 2004

- Maybe different (better?) averaging procedures erode the support for w<-1 further…

Wang et al, 2002

- Maybe w changes in time, such that while w always >-1, <w> looks <-1… Maor et al, 2002

Csaki, NK, Terning, 2005 (see astro-ph tomorrow!)

- So maybe support for w<-1 will go away altogether…
- BUT WHAT IF IT DOES NOT??? Would we have to live with Phantoms and their ills: instabilities, negative energies…, giving up **Effective Field Theory**?

MAYBE NOT!

- *Conspiracies are more convincing if they **DO NOT** rely on supernatural elements!*

- Ghostless explanations:

  1) Change gravity in the IR, eg. scalar-tensor theory (`failed attempt', Carroll et al) or DGP braneworlds (Sahni et al; Lue et al;)

  In these approaches modifying gravity affect **EVERYTHING** in the same way (SNe, CMB, LSS), so the effects are limited to at most w ~ -1.1. Yet SNe might be the only indicator of w<-1.

  2) Another option: EXTRA DIMMING of SNe only.

  Λ + (photon → axion conversion) has the **SAME EFFECT** on SNe like w<-1 dark energy! In general, it can significantly affect determination of w, even if w>-1!

Csaki, NK & Terning, 2001; 2004.

STRATAGEM

- Photon-axion mixing does not remove the requirement for dark energy – one can infer it from CMB+LSS alone.

- However photon-axion mechanism affects luminosity distance determination, and in turn w. Because SNe are the most sensitive to w, its determination is influenced if SNe are affected by the photon-axion mechanism even if we use other sources of data as well.

- Photon-axion mixing can even make w appear more negative than -1, without any instabilities.

- If the photon-axion mechanism is ruled out, one may be able to get strongest bounds on ultra-light axions to date.

PHOTON-AXION CONVERSION

- Consider a pseudo-scalar axion a which couples to **E** · **B**:

$$\mathcal{L}_{int} = \frac{a}{4M}\epsilon^{\mu\nu\lambda\sigma}F_{\mu\nu}F_{\lambda\sigma} = \frac{a}{M}\vec{E}\cdot\vec{B}$$

- In the extra-galactic space, **B** ~ few x 10^{-9} Gauss with coherence length *l* ~ MPc. So photon with **E** ll **B** mixes with the axion:

$$\{\frac{d^2}{dy^2} + \mathcal{E}^2 - \begin{pmatrix} 0 & i\mathcal{E}\frac{B}{M} \\ -i\mathcal{E}\frac{B}{M} & m^2 \end{pmatrix}\}\begin{pmatrix} |\gamma\rangle \\ |a\rangle \end{pmatrix} = 0$$

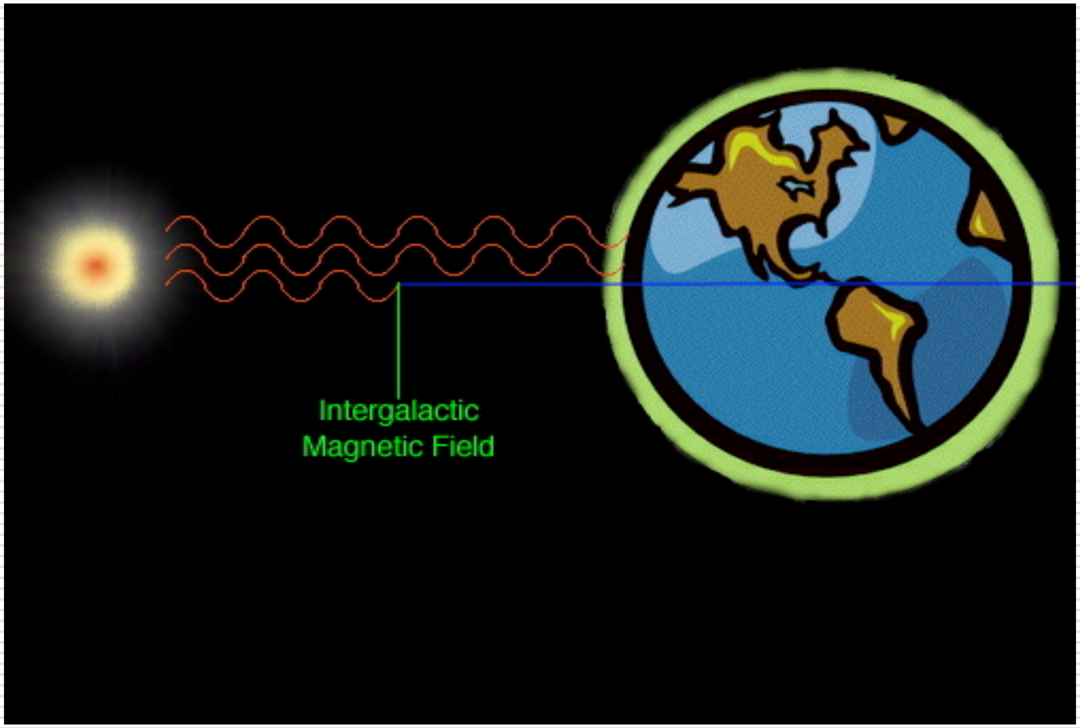
- Completely analogous to ν oscillations.

UNIVERSE AS A MAGNET IN A DISORDERED PHASE

Typical distance between us and SNe: ~ 10^3 MPc.

Magnetic field coherence length: ~ MPc.

THERE IS ABOUT ~ $O(10^3)$ magnetic domains between us and a supernova at $z \geq 0.5$, where ***B*** field has random orientation.



LUMINOSITY

Luminosity:

$$\mathcal{L} = \frac{\text{Luminosity}}{\text{distance}^2} \, \mathrm{P}_{\gamma \to \gamma}$$

SNe may appear farther away since we may reinterpret additional dimming as distance:

$$d_{\mathbf{eff}} = d \,/\, P^{\,\mathbf{1/2}}(\text{ photon survival })$$

PHANTOMS EXORCISED!

- Note: the effective Lagrangian is

$$\mathcal{L}_{int} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}(\partial a)^2 - V(a) + \frac{a}{4M}\epsilon^{\mu\nu\lambda\sigma}F_{\mu\nu}F_{\lambda\sigma}$$

where $V(a) \approx m^2 a^2 + \ldots$ is the potential generated by instanton effects; protected from radiative corrections by the shift symmetry $a \to a + const$ valid in perturbation theory.

- Hence: since the coupling is a scalar x Chern-Simons form,

$$H \geq 0$$

and so there are no Phantoms, negative energies, negative norm states, instabilities…

USUAL EFFECTIVE FIELD THEORY STILL WORKS !

PHOTON SURVIVAL PROBABILITY INSIDE A HOMOGENEOUS DOMAIN

Definition:

$$P_{\gamma\to\gamma} = |\langle\gamma(y_0)|\gamma(y)\rangle|^2$$

where inside a homogeneous domain Δ y « *Lo* , with the oscillation length, in the limit *E » m, μ = B/M*,

$$L_O = \frac{4\pi\mathcal{E}}{\sqrt{m^4+4\mu^2\mathcal{E}^2}}$$

the probability is computed from Schrodinger eq,

$$P_{\gamma\to\gamma} = 1 - \frac{4\mu^2\mathcal{E}^2}{m^4+4\mu^2\mathcal{E}^2}\sin^2\left[\pi\frac{\Delta y}{L_0}\right]$$

the mixing angle is $$\sin\theta = \frac{\mu\mathcal{E}}{\sqrt{m^4+4\mu^2\mathcal{E}^2}}$$

LIMITS

- When $E \gg m^2/\mu$: maximal mixing, with $L_0 \sim 2p/m$.

  In this limit photon-axion conversion is achromatic, which is crucial to match SNe observations.

- When $E \ll m^2/\mu$: tiny mixing.

  Energy-dependent but unobservable, since the mixing angle and probability are very small. Hence, can avoid affecting CMB.

Those limits are a bit quick…

- Even when $E \sim m^2/\mu$ **,** frequency dependence can be miniscule!

Trick: the conversion probability of photon into axion is

$$\boldsymbol{P = A(\omega) \sin^2 \delta(\omega)}$$

where the phase is $\delta(\omega) \sim L_{dom}/L_0$*. For higher frequencies and smaller domains* $\delta(\omega) \ll 1$ *and so* $\sin^2 \delta(\omega) \sim \delta^2(\omega)$*; frequency dependence in* $P = A(\omega)\, \delta^2(\omega)$ *cancels exactly between the two terms to the leading order! With the parameters we choose, the transition frequency is in the infrared – so optical frequencies are safe! This is the regime where the photon-axion mixing reigns…*

DYNAMICS OF CONVERSION I

- Inside each magnetic domain only about 1 in 10000 photons converts into an axion.
- But there is about few 1000s of magnetic domains with randomly oriented magnetic fields along each line of sight.
- Hence we find flavor equilibration between three active degrees of freedom (two photon polarizations and the axion).
- Because the initial axion flux was tiny, about 1/3 of photons will turn into axions after traveling a huge distance.

DYNAMICS OF CONVERSION II

- For a given set of scales we compute the transition probability inside a typical domain and solve numerically for the evolution through an array of domains with random magnetic field orientation.
- For small domains the survival probability is well approximated by

$$P_{\gamma\to\gamma} = \frac{2}{3} + \frac{1}{3} e^{-\Delta y / L_{\rm dec}}$$

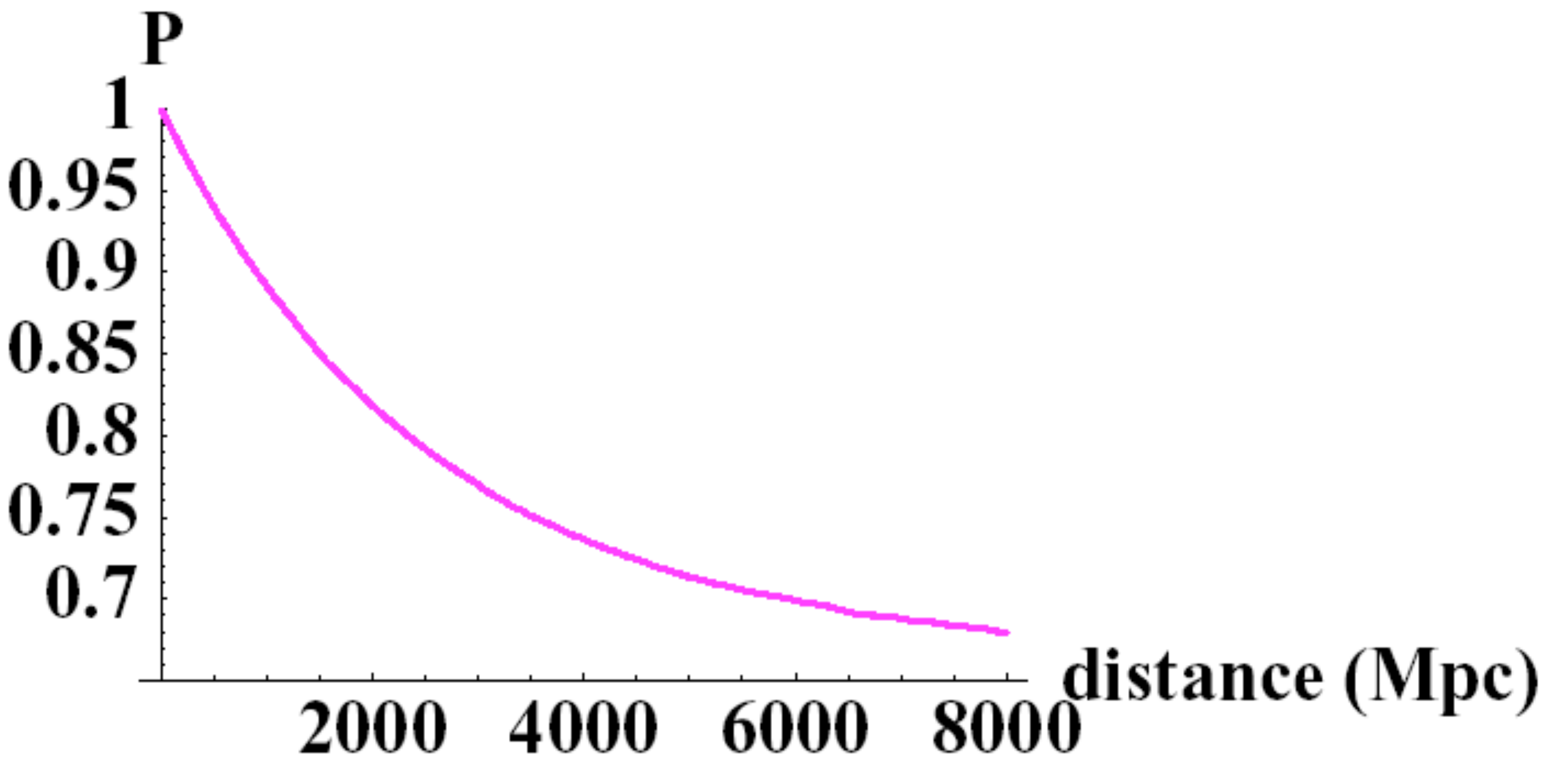
where the decay length is approximately:

$$L_{\rm dec} = \frac{8}{3\mu^2 L_{\rm dom}}$$

and Δy is the distance traversed:

$$\Delta y = \frac{1}{H_0} \int_0^z \frac{dz}{\left((1+z)^2(1+\Omega_m z) - z(1+z)\Omega_{DE}\right)^{1/2}}$$

SURVIVAL PROBABILITY



SCALES:

- Need large mixing for optical photons to dim SNe by say 20% or so.
- Need small mixing for microwave photons to leave primordial CMB anisotropy intact.

  Assume at early times $\boldsymbol{B} \rightarrow 0$ (large z)
- Pick the scales:

$$m \sim few \times 10^{-16}\ \text{eV}, \qquad M \sim 4 \cdot 10^{11}\ \text{GeV}$$

- Within existing observational limits! For ultralight axions with $m < 10^{-9}$ eV, the bounds are weak:

LAB: $M \geq 1.6 \cdot 10^{9}$ GeV (PDG)

Solar Helioscope: $M \geq 10^{10}$ GeV (CAST)

SN1987A: $M \geq 10^{11}$ GeV (Raffelt et al)

CLOSE BUT STILL ALIVE!

ORIGIN OF AXION SCALES

- This is not the QCD axion. It is another, much lighter, particle but otherwise very similar. It may come from string theory, which provides many avenues for such fields to arise.
- E.g. in a world with two axions, one linear combination couples to QCD becoming heavy (mass ~ meV), another remains light (*arion*, A. Anselm, `84). It may acquire a small mass from another symmetry breaking, similar to chiral symmetry breaking, with scales $f_a \sim 10^{11}$ GeV, $\Lambda \sim 100$ eV. Then,

$$V(a) \approx \Lambda^4 (1 + \cos(a/f_a)) \approx m^2 a^2/2 + \ldots$$

- Similar mechanisms were employed for developing the only radiatively stable quintessence models (Frieman et al, Nomura et al, Kim et al).
- Cosmologically safe!

IGM PLASMA

- So far we have ignored that the Universe is reionized at $z \leq 10$ (roughly) : energy released during structure formation disassociates the neutral H and He in the IGM.
- Photons propagating through an electron plasma in the IGM acquire an effective mass from Debye screening.
- Ignoring clumping: $m_\gamma \sim \omega_{\boldsymbol{P}} \sim 10^{-14}$ eV. The photon mass plays a role similar to the axion mass, suppressing mixing and leading to chromaticity of the conversions.

A POSSIBLE SOURCE OF BOUNDS!

Deffayet et al; Csaki, NK & Terning

- However: at low $z \leq 1\text{-}2$, baryons clump into small over-dense regions and most of the space where SNe reside is safely under-dense.

OSCILLATIONS IN PLASMA

In the presence of IGM plasma, the Schrodinger equation is

$$\{\frac{d^2}{dy^2} + \mathcal{E}^2 - \begin{pmatrix} \omega_P^2 & i\mathcal{E}\frac{B}{M} \\ -i\mathcal{E}\frac{B}{M} & m^2 \end{pmatrix}\} \begin{pmatrix} |\gamma\rangle \\ |a\rangle \end{pmatrix} = 0$$

the photon plasma mass is

$$\omega_P^2 = 4\pi\alpha\frac{n_e}{m_e}$$

the survival probability

$$P_{\gamma\to\gamma} = 1 - \frac{4\mu^2\mathcal{E}^2}{(m^2-\omega_P^2)^2+4\mu^2\mathcal{E}^2}\sin^2\left[\pi\frac{\Delta y}{L_0}\right]$$

the oscillation length and mixing angle are

$$L_O = \frac{4\pi\mathcal{E}}{\sqrt{(m^2-\omega_P^2)^2+4\mu^2\mathcal{E}^2}}$$

$$\sin\theta = \frac{\mu\mathcal{E}}{\sqrt{(m^2-\omega_P^2)^2+4\mu^2\mathcal{E}^2}}$$

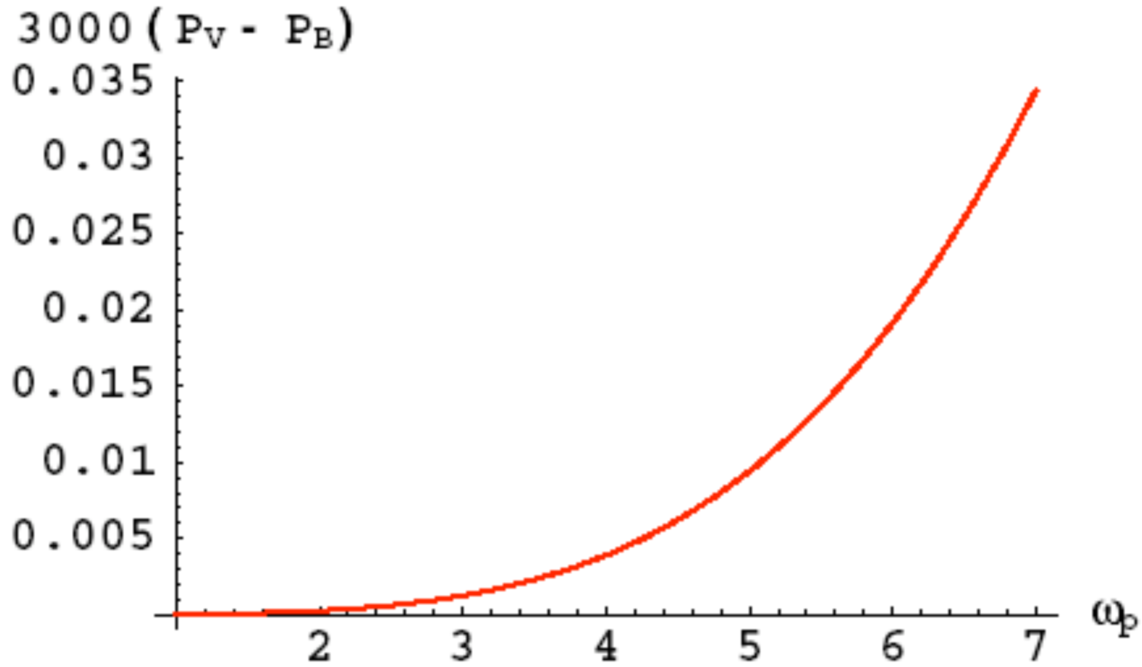
WHERE ARE THE BARYONS?

- Lucky: baryon budget problem (Fukugita, Hogan & Peebles, '97).
- Outcome: at $z \leq 1$, 2/3 very clumped up, 1/3 in Lyα clouds (Dave et al, '98).
- Simulations (Valageas, Schaeffer, Silk, `99): 97% of space is under-dense by at least a factor of 10 compared to the uniform background density set by the ρ_{cr}.
- Bottomline:

$$n_e \leq 6 \cdot 10^{-9}\ \text{cm}^{-3}, \quad \omega_P \leq 3 \cdot 10^{-15}\ \text{eV}$$

in most of the $z \leq 1$ space. Numerical solution: if $\omega_P \leq 5 \cdot 10^{-15}$ eV, then the color variation of the photon to axion conversion rate is less than 0.1 mag – within current observational limits. (this will improve, and may be a signature of the axion to look for!)

PLASMA-INDUCED FREQUENCY DEPENDENCE



BOTTOMLINE SCALES FOR THE SIMULATION OF THE DIMMING

- The scales are:

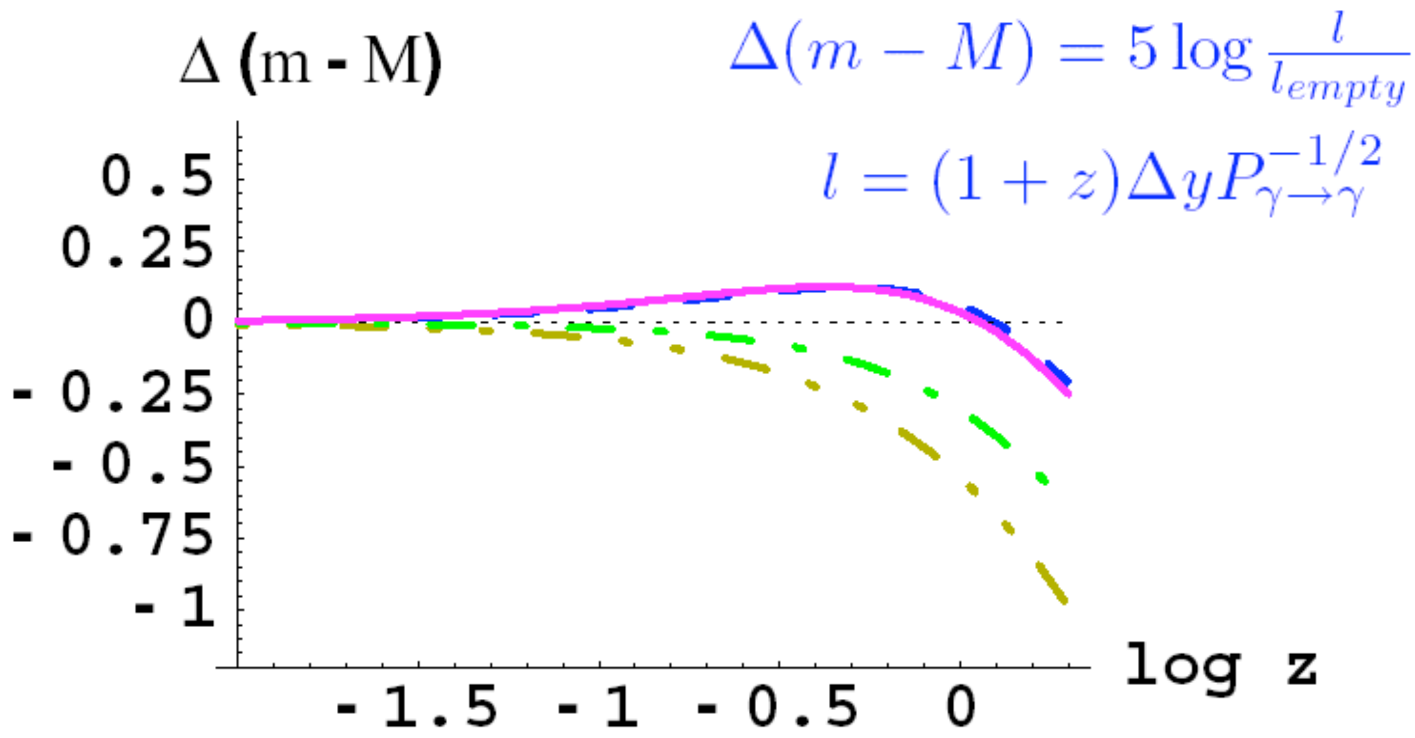
$\boldsymbol{B} \sim 5\cdot 10^{-9}$ Gauss
$L_{dom} \leq$ MPc
$M \sim 4\cdot 10^{11}$ Gev
$m \sim 10^{-15}$ eV *
$\omega_P \leq 3\cdot 10^{-15}$ eV

- This yields a weak color (i.e. frequency) dependence of the dimming. For SNe this is unobservable. For distant quasars which emit in the IR it could be observable. However: 1) as long as frequency dependence is less than about 0.06 to 0.15 mag, this is OK; 2) these bounds depend on the origin and evolution of extragalactic magnetic fields, and currently we know little about them. (Goobar & Mortsell; Mortsell & Ostman)

*Recently revisited by Raffelt et al; limits from deviations of CMB from the thermal spectrum improve the earlier bound on *m* by a factor of 2, to the value given, but **DO NOT** exclude the mechanism.

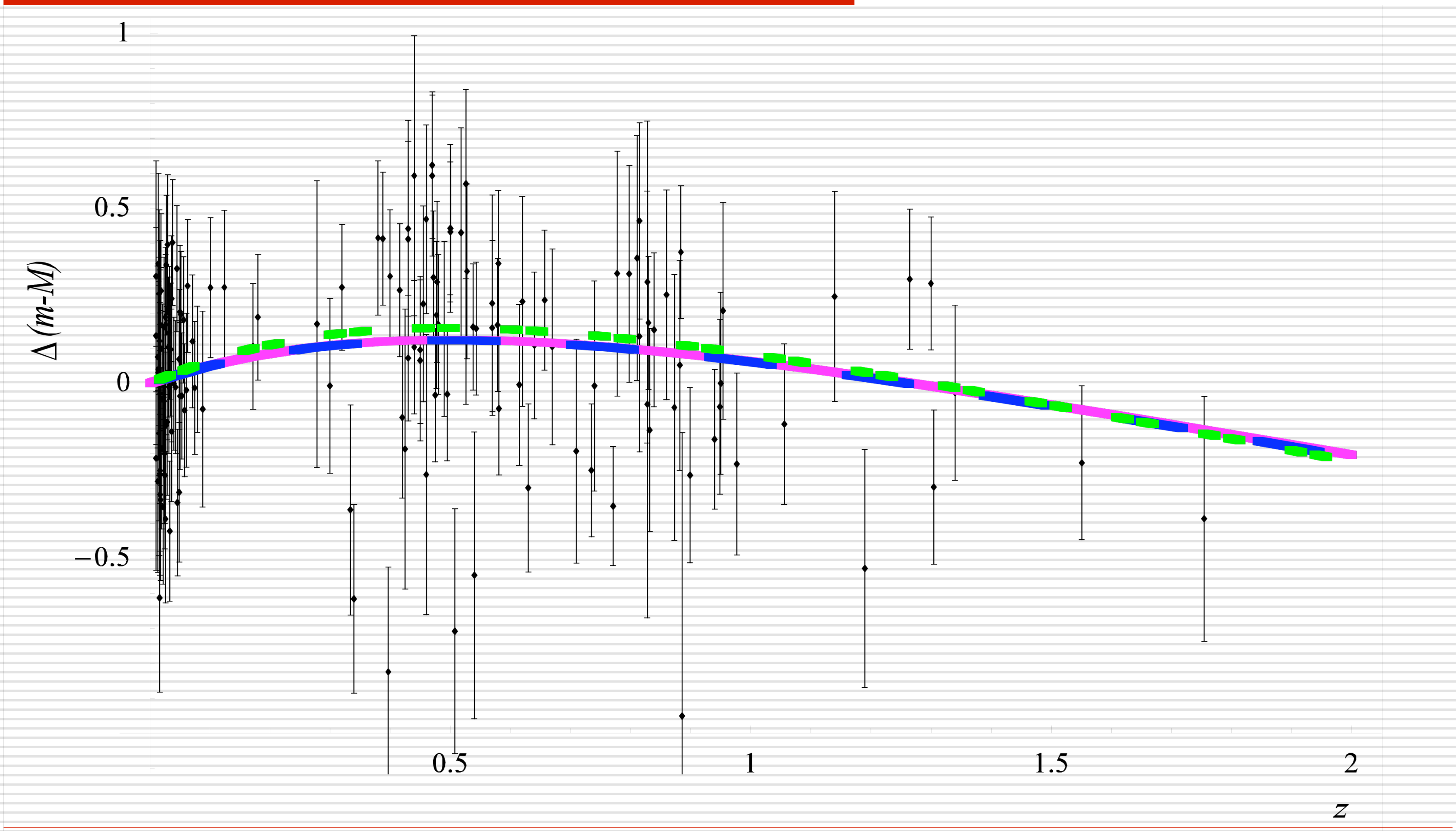
Hubble Diagrams

Gold: $\Omega_M = 1$; Green: $\Omega_{DE} = 0.7$, w = -1/3;
Blue: Concordance model, ΛCDM;
Purple: Ω_M=0.7, w=-1/3 + axions.



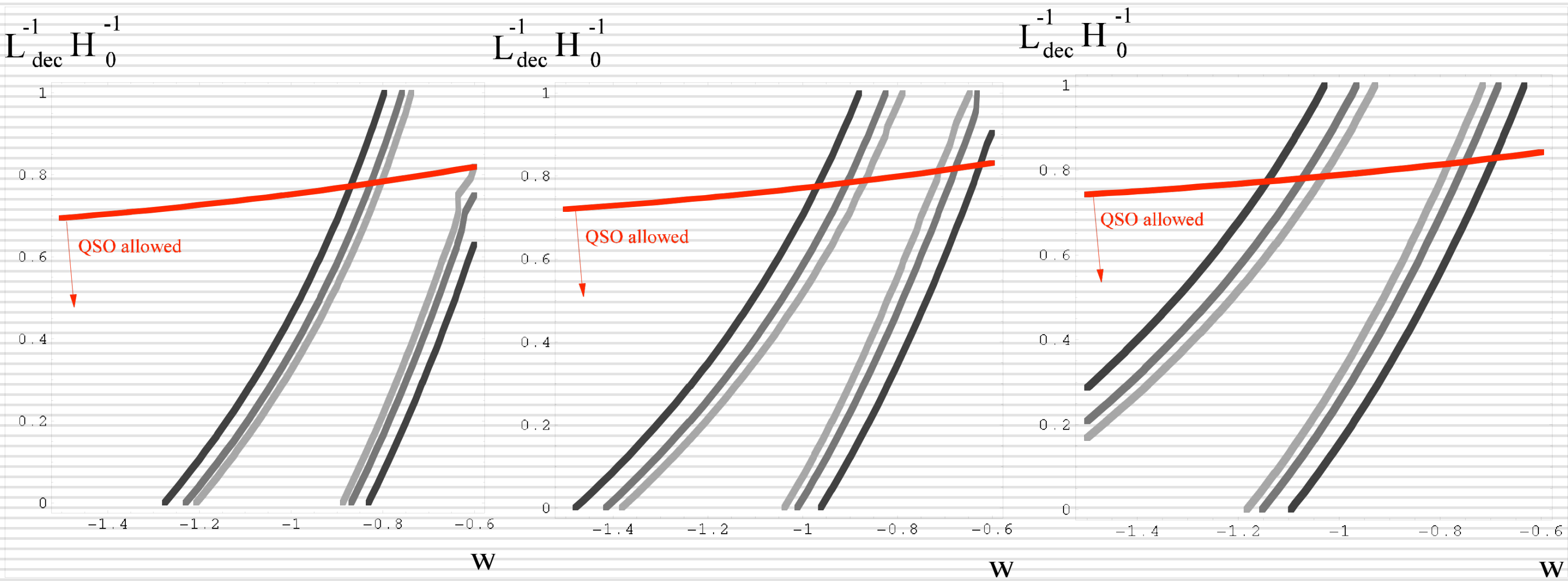
FITTING SNe

Green: Ω_{DE} = 0.65, w = -1.25;
Blue: Concordance model, ΛCDM;
Purple: Ω_{Λ}=0.65+ axions, mimicking w<-1.



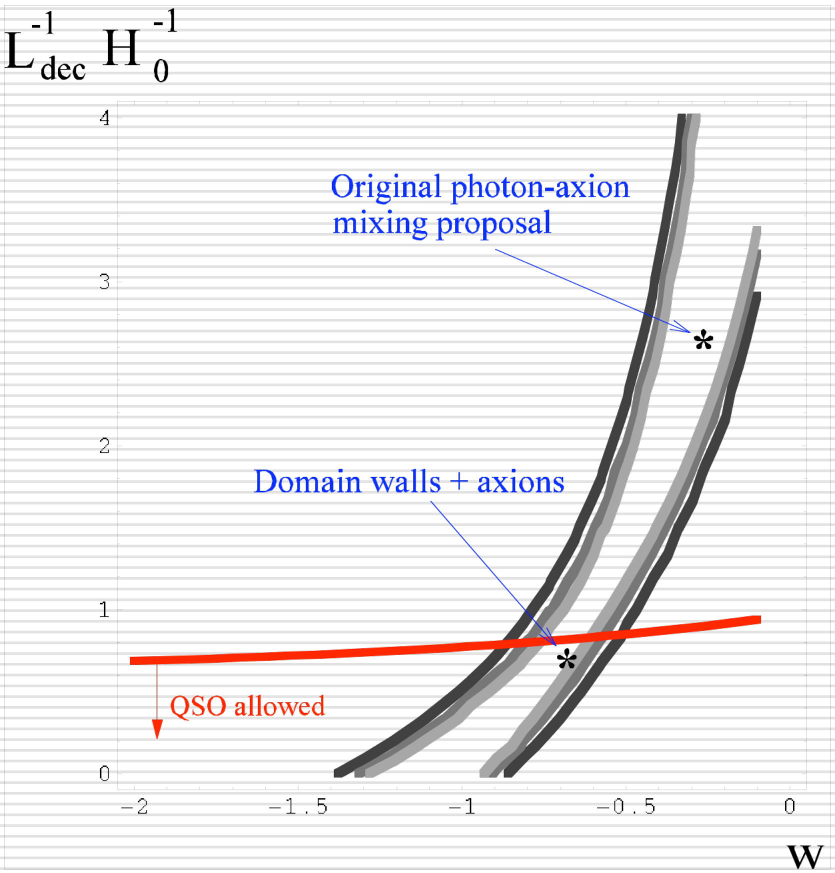
data: “gold sample” of 157 SNe, Riess et al.

ALLOWED REGIONS FOR PHOTON-AXION MIXING



The red line is the QSO bound of Goobar & Mortsell and Mortsell & Ostman (who have found an error in GM analysis, relaxing the bounds). Also consistent with bounds claimed by Basset and Kunz from FRIIb radio galaxies, although those are MUCH MORE suspect!

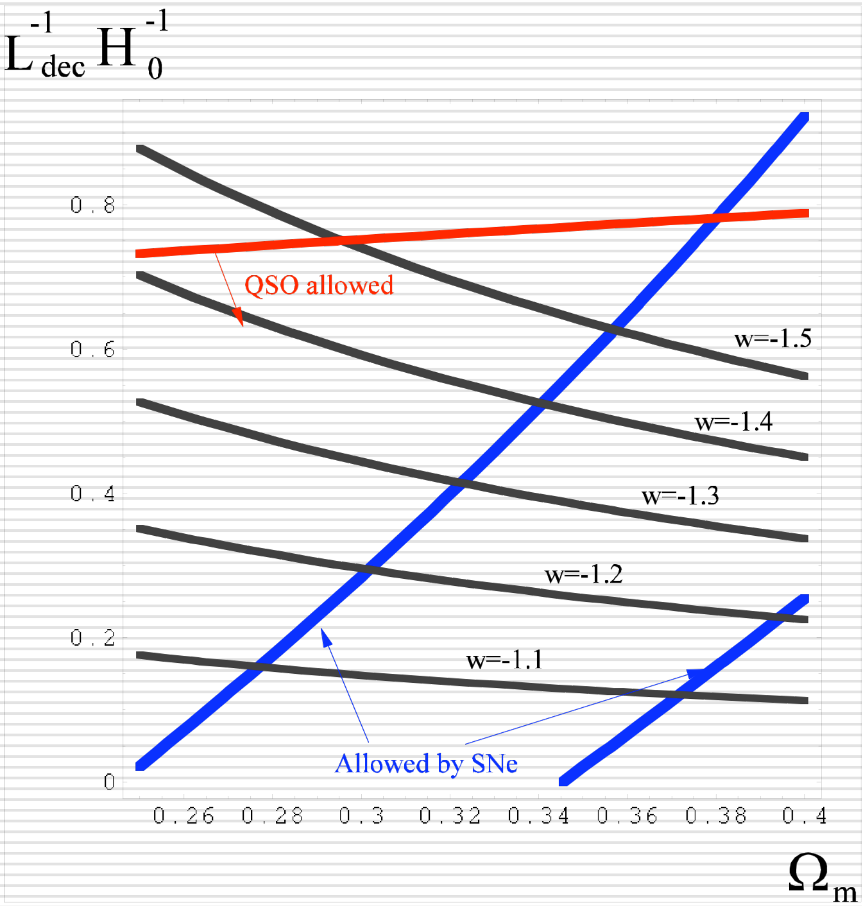
WHAT ABOUT COASTING?



Having relaxed their earlier bounds, Mortsell and Ostman even allow that the data from both SNe and QSO might not exclude w=-1/3 for *atypical* parameters (*B* and n_e). But: QSO bounds are model-dependent.

Note, that even if we take QSO bounds at face value, with these axions it is still possible to have w= -2/3, implying domain walls as dark energy; without axions they are ***excluded***.

IMPERSONATING w<-1



GEOMETRY VERSUS DISTANCE

- Photon→axion conversion will only affect distances obtained by measuring luminosities.
- It will NOT affect geometric relations such as angular diameter distances. In GR, d_A and d_L are related by a known function of z:

$$d_L \sim (1+z)^2\, d_A$$

(see, e.g. S. Weinberg, "Gravitation…"). A violation of this relation could point to the axion!
- Basset and Kunz claim no violation, using FRIIb radio galaxies; but data not so good – at most, this implies a bound equivalent to QSO limits of Mortsell et al.
- Uzan, Aghanim and Mellier suggest that there IS a DISCREPANCY between d_A and d_L using SZ and X-ray observations of clusters (but again, data not so good).
- Data will eventually improve…

SUMMARY I

- Λ+photon→axion conversion is

  1) consistent with the data!
  2) consistent with EFT!
  3) impersonates w<-1!

  goes almost as negative as w~-1.5!

- This explanation affects only luminosity distances: info from for example LSS surveys would be consistent with w ≥ -1, while SNe would indicate w<-1. So one would need BOTH JDEM and LSST!
- VERY PREDICTIVE: a number of other signatures: frequency dependence, line of sight variations, super-GZK photons; the scale M is very close to the current limits (SN1987A), another SN may probe it.

SUMMARY II

In the very least:

- photon→axion conversion mechanism is a meaningful `straw man' to use in evaluating SNe as a probe of the equation of state of dark energy - without giving up any of the usual rules of Effective Field Theory!
- if it is ruled out, one may get the best bounds on the ultra-light axions, better than those from any other terrestrial or astrophysical experiments.

We need more such exciting opportunities to look for new physics!