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'HOW I LEARNED TO LIKE $w<-1$ DARK ENERGY...'

OVERVIEW

- Dark Energy: discords of Cosmic Concordance
- What is w? Could it be w<-1?
- Exorcisms
- Summary…

CONCERT OF COSMOS…

- A Golden Age of cosmology: ever better data from CMB, LSS, SNe, … yield new insights into our Universe…
- From this a picture emerges…
- The Universe is really ***WEIRD*** **:** too old, too big, too smooth, and filled with too much strange stuff!

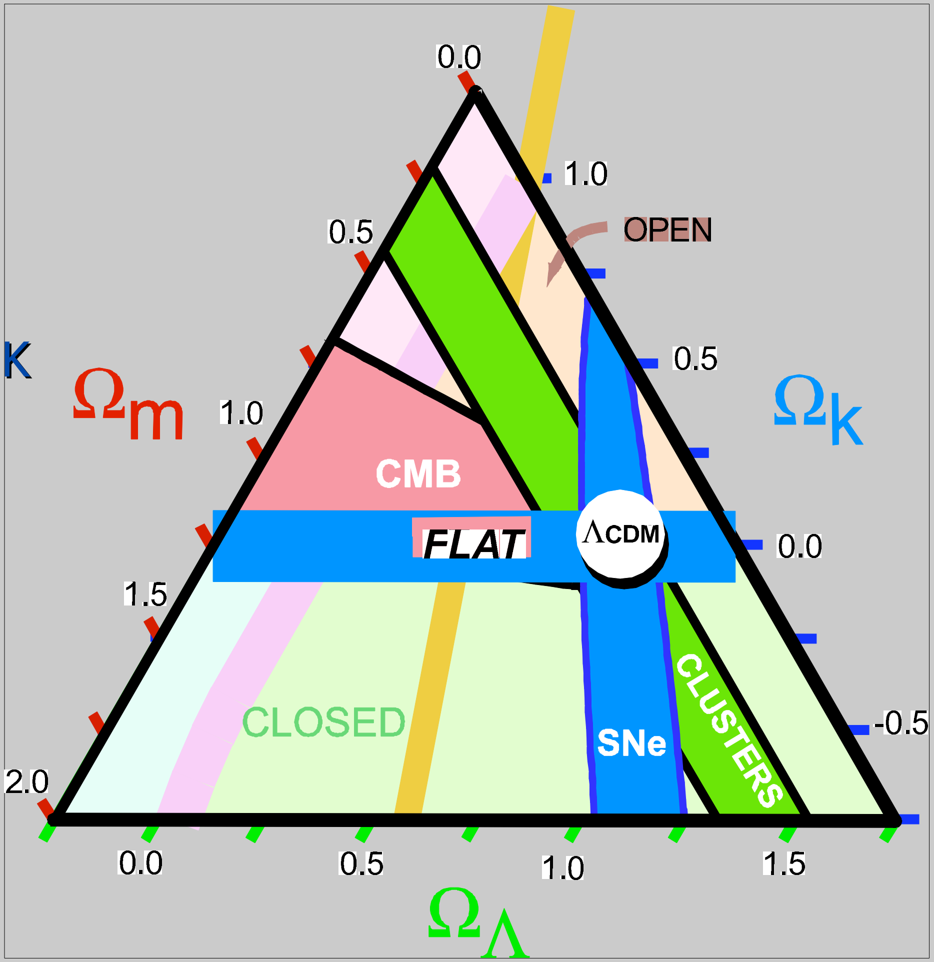
COSMIC TRIANGLE

Cosmological Dalitz plot:

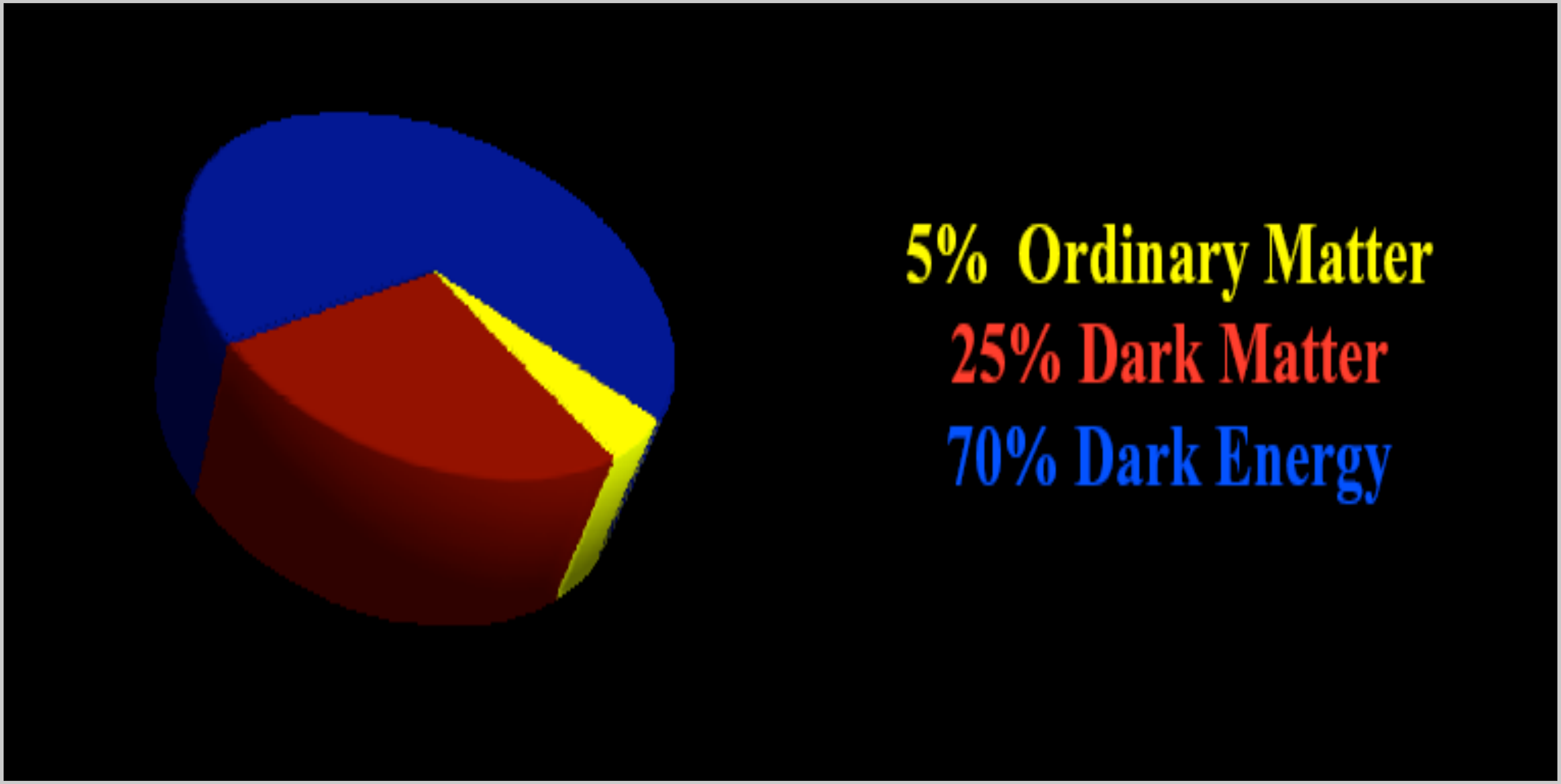
$$3\, M_4^2\, H^2 = \rho_{DE} + \rho_{DM} + \rho_K$$

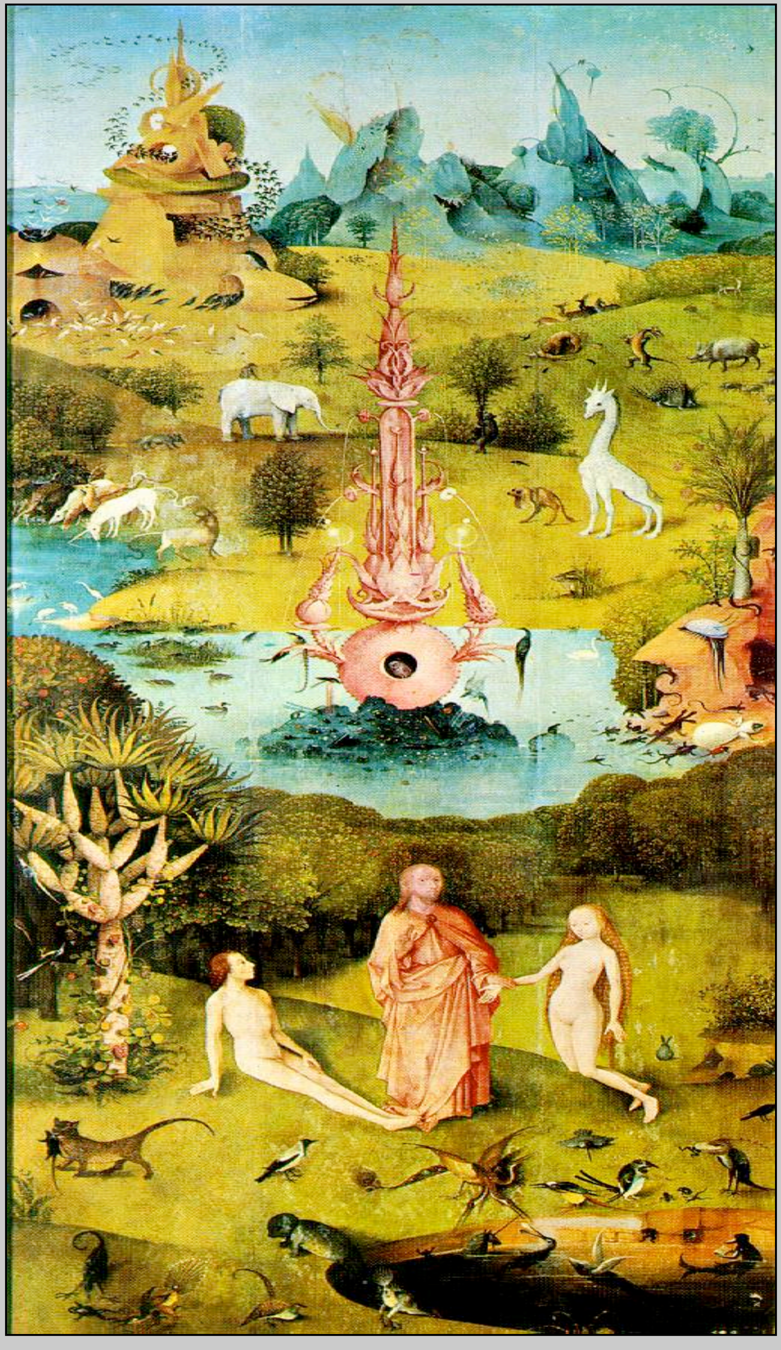
$$\Omega_n = \rho_n / 3\, M_4^2\, H^2$$

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



Emerging paradigm: **CONCORDANCE COSMOLOGY**, of a Universe defined by *cosmic coincidences*: today there are nearly equal amounts of various ingredients (some of) which must have evolved dramatically differently at early times!





DISCORDS IN THE CONCORDATE?

- We have ideas for explaining the near identities of some of the cosmic relic abundances, such as *dark matter, baryon, photon and neutrino*: inflation + reheating, with Universe in thermal equilibrium.
- However there's much we do not understand; the worst problem:

DARK ENERGY

WHAT WE KNOW ABOUT DARK ENERGY

- *Not a whole lot!*
- *Imagine it as a gravitating fluid, with energy density ρ and pressure p, obeying $p= w \rho$*
- *Conservation of energy: $\rho' = - 3H(\rho+p)$, $H = a'/a$*

$$\rho = \rho_0 (a_0/a)^{3(1+w)}$$

- *Smooth, non-clumping, ~ 70% of the critical energy density; hence it must be:*

  1) $w = p/\rho < 0$ $(-1.5 \leq w_{eff} \leq -0.7)$

  2) $\rho_0 \approx 0.7 \rho_{cr} \approx (10^{-3}\ eV)^4$

USUAL SUSPECTS

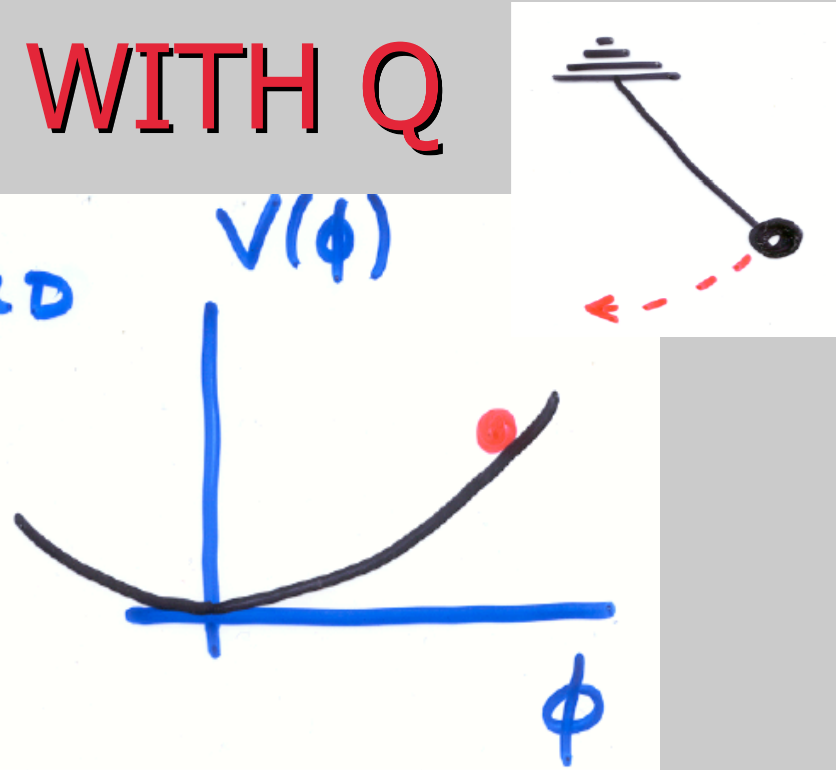
- ***Λ***, or cosmological constant; introduced and subsequently discarded by Einstein, only to be resurrected by deSitter; long thought that it should be zero…
- ***Q***, or quintessence: many incarnations, all involve an ultra-light scalar, amounting to making ***Λ*** slowly changing in time…

COSMOLOGICAL CONSTANT FAILURE

- What's the problem? A (very!) heuristic argument:
  - Legendre transforms**:** adding $\int$ ***dx*** Φ***(x) J(x)*** to ***S*** trades an independent variable Φ***(x)*** for an independent variable ***J(x)***.
  - Cosmological constant term $\int$ ***dx*** $\sqrt{}$***det(g)*** Λ ***is*** a Legendre transform.
  - In GR, general covariance $\rightarrow$ ***det(g)*** does not propagate!
  - So the Legendre transform $\int$ ***dx*** $\sqrt{}$***det(g)*** Λ 'loses' information about **only ONE** IR parameter - Λ.

Thus Λ is not calculable, but is an input!

TROUBLE WITH Q



φ : INFLATON FIELD

$$H = \frac{\dot{a}}{a}$$

$$3H^2 = 8\pi G_N \left(\frac{\dot{\phi}^2}{2} + V(\phi) \right); \quad \ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} = 0$$

- In addition to tuning *V* to $(10^{-3}\ eV)^4$ one also needs a very flat potential, with $\partial^2 V \sim (10^{-33}\ eV)^2$ and very weak couplings of Φ to matter.

CURSE OF DARK ENERGY ☹

- Why should Λ be so much smaller than its natural cutoff, $\Lambda \sim 10^{-120} M_{Pl}^4$?
- Why should it not be zero? What is it made of? How are ultra-low scales governing dark energy sector generated?
- Why should its energy density be close to DM (25%), or baryons (5%) now?

remember: $w_{DE} < 0$, $w_{DM} = 0$, so they must have been tremendously disparate in the early universe by $\rho = \rho_0 (a_0/a)^{3(1+w)}$

BLESSING OF DARK ENERGY ☺

- Many interesting ideas:
  - **SUSY**: *helps half-way, but still fails by 60 orders of magnitude*
  - **Self-tuning and X-dim-s**: *but singularities unresolved*
  - **Misaligned symmetries** : *but what is their EFT guise*
  - **Modified gravity**: *but a consistent theory is still awaited*
  - **Landscape arguments**: *but how do we compute probabilities*
  - …
- Weinberg's no-go Thm: impossible to dynamically adjust Λ in 4D Poincare invariant theory with finitely many fields: very powerful! Do we need new physics?
- Age of discovery: dichotomy between observations and theoretical thought forces a crisis upon us!

SO WHAT COULD w BE?

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

Hannestad et al

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

Melchiorri et al

Carroll et al

- Modelling w<-1 with scalars requires ***GHOSTS*** : fields with negative kinetic energy, and so with a Hamiltonian not bounded from below:

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

\`Phantom field' , Caldwell, 2002

\`Pole inflation', Pollock, 1985.

- Such theories suffer from ***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'…

WHO CARES?

- 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 it is always >-1, <w> looks <-1…

Maor et al, 2002

- So maybe support for w<-1 will go away altogether…

BUT WHAT IF IT DOES NOT???

- Would w<-1 force Phantoms on us (and their ills: instabilities, negative energies…), giving up Effective Field Theory and conventional symmetries?

- A maximally constraining approach: take the data seriously but require the theory to be minimalistic and frugal in order to maximize predictivity!

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

EXORCISMS

1) Change gravity in the IR, eg. scalar-tensor theory (Carroll et al) or DGP braneworlds (Sahni&Shtanov; Lue&Starkman)

Harder since it requires changing theory only at largest scales

2) Extra dimming of SNe only!

Λ + **(photon → axion conversion)** has the **SAME EFFECT** on SNe like w<-1 dark energy! Csaki, NK & Terning, 2001; 2004.

3) Accelerate the universe more at late times!

'Conventional' quintessence with $m \sim H_0$ so it rolls up a potential slope! Very minimalistic… Csaki, NK & Terning, 2005.

PHOTON-AXION CONVERSION

- Let a pseudo-scalar axion a couple 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** ~ nano Gauss in domains of size *l* ~ MPc. So photon with **E** ll **B** mixes with the axion!

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

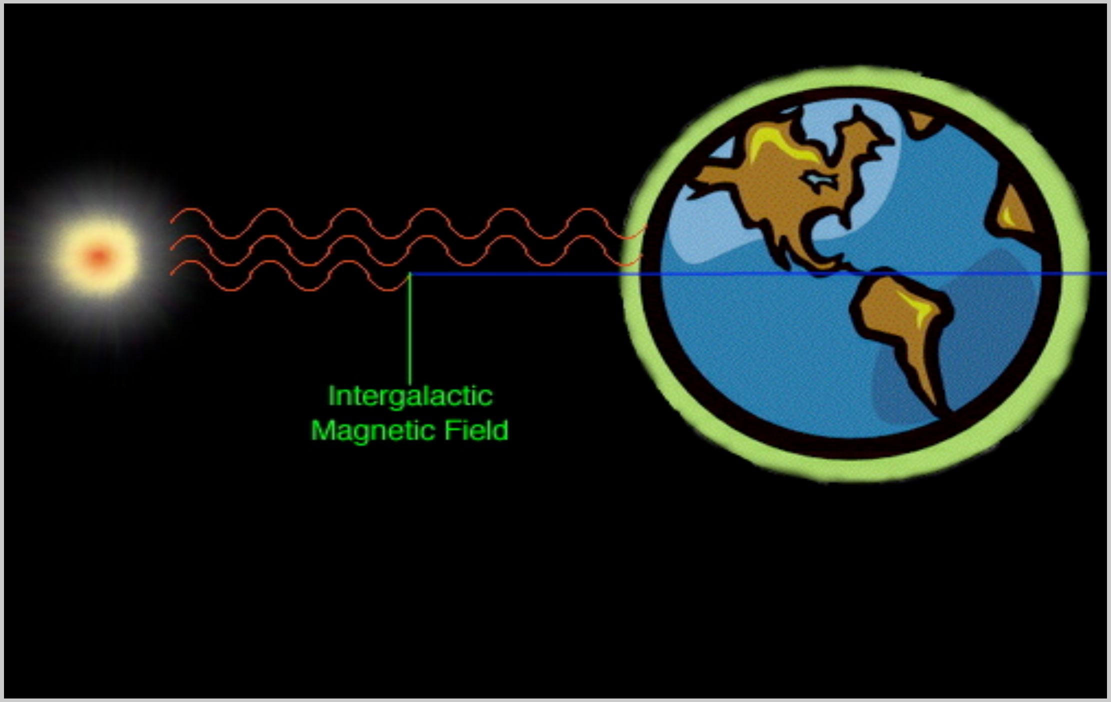
- Completely analogous to ν oscillations!

UNIVERSE AS A MAGNET IN A DISORDERED PHASE

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

Magnetic field coherence length: ~ MPc

There's about ~ $O(10^3)$ cosmic magnetic (Weiss) comains between us and a supernova at $z \geq 0.5$



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:

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

LIMITS AND COLORS

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

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

Trick: the conversion probability of photon into axion is

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

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!

With the parameters we choose, the transition frequency is in the IR – so optical frequencies are safe!

…This is the regime where the photon-axion mixing reigns…

DYNAMICS OF CONVERSION

- *Inside each magnetic domain only about 1 in 10000 photons converts into an axion.*
- *But there is about few 1000 domains along each line of sight.*
- *Flavors equi-partake: three active degrees of freedom (two photons and the axion).*
- *Because the initial axion flux was tiny, about 1/3 of photons will turn into axions after traveling a huge distance.*

IGM PLASMA

- But: the Universe is reionized at $z \leq 10$ (roughly): energy released during structure formation disassociates the neutral H and He.
- Photons propagating through an electron plasma in the IGM acquire an effective mass from Debye screening.
- Ignoring clumping: $m_\gamma \sim \omega_P \sim 10^{-14}$ eV. It is similar to the axion mass, suppressing mixing and yielding chromatic conversions.

A POSSIBLE SOURCE OF BOUNDS!

Deffayet et al; Csaki, NK & Terning; Raffelt et al;

- 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. (97% underdense by at least a 10; Valageas, Schaeffer, Silk, `99)

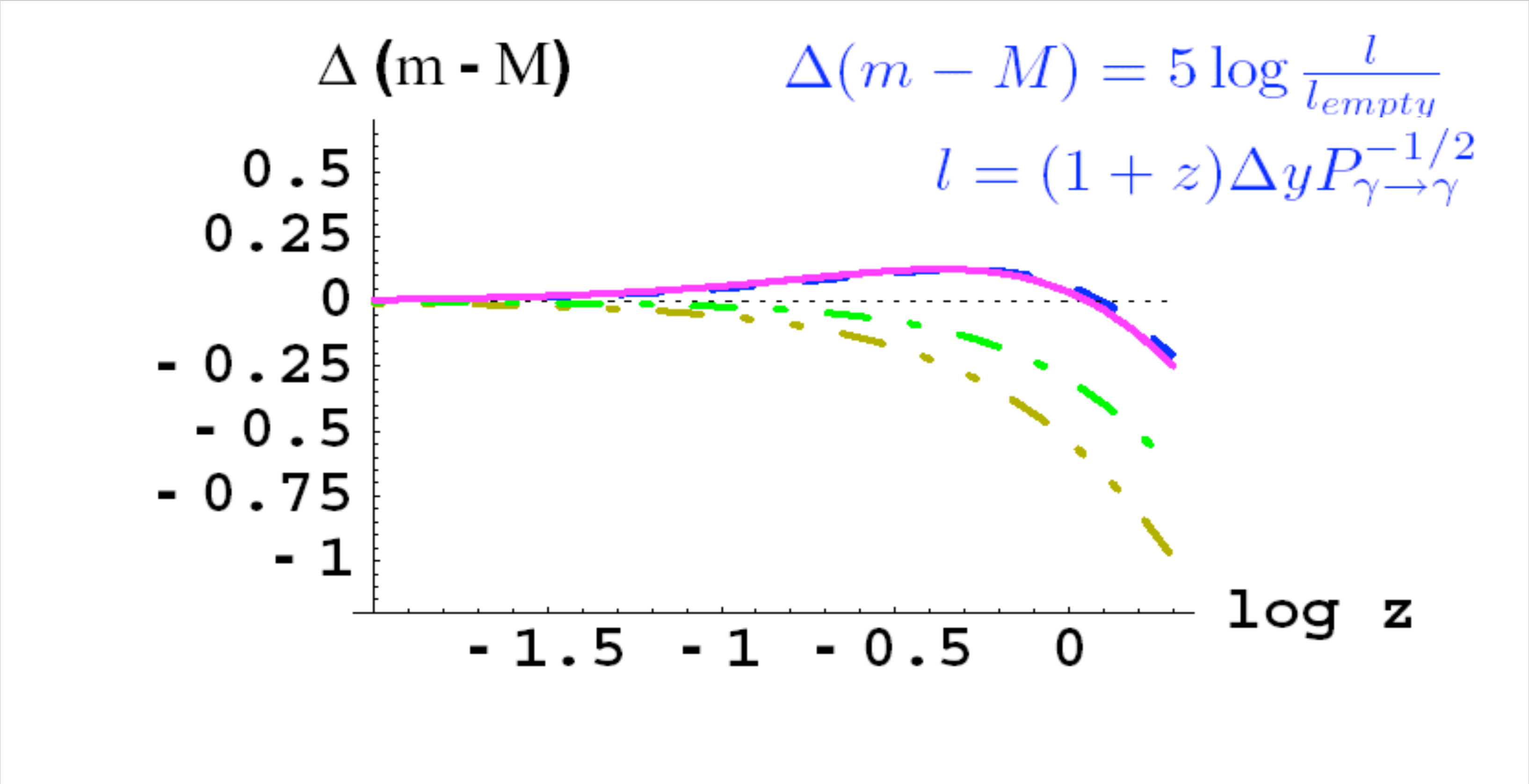
BOTTOMLINE SCALES FOR THE SIMULATION OF THE DIMMING

- 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 dependence of the dimming. For SNe this is unobservable, yielding > 20% of photon conversion ☺.
- The primordial CMB spectrum is not disturbed at an observable level (recently revisited by Raffelt et al) ☺.
- Emission of distant quasars, in the microwave range, may be sensitive. ☹ ☺ ?? However:
  - 1) as long as frequency dependence is less than about 0.06 to 0.15 mag, this is allowed; ☺
  - 2) the ensuing bounds depend on the origin, evolution and distribution of extragalactic magnetic fields, of which little is known at present. (Goobar & Mortsell; Mortsell & Ostman) 😐

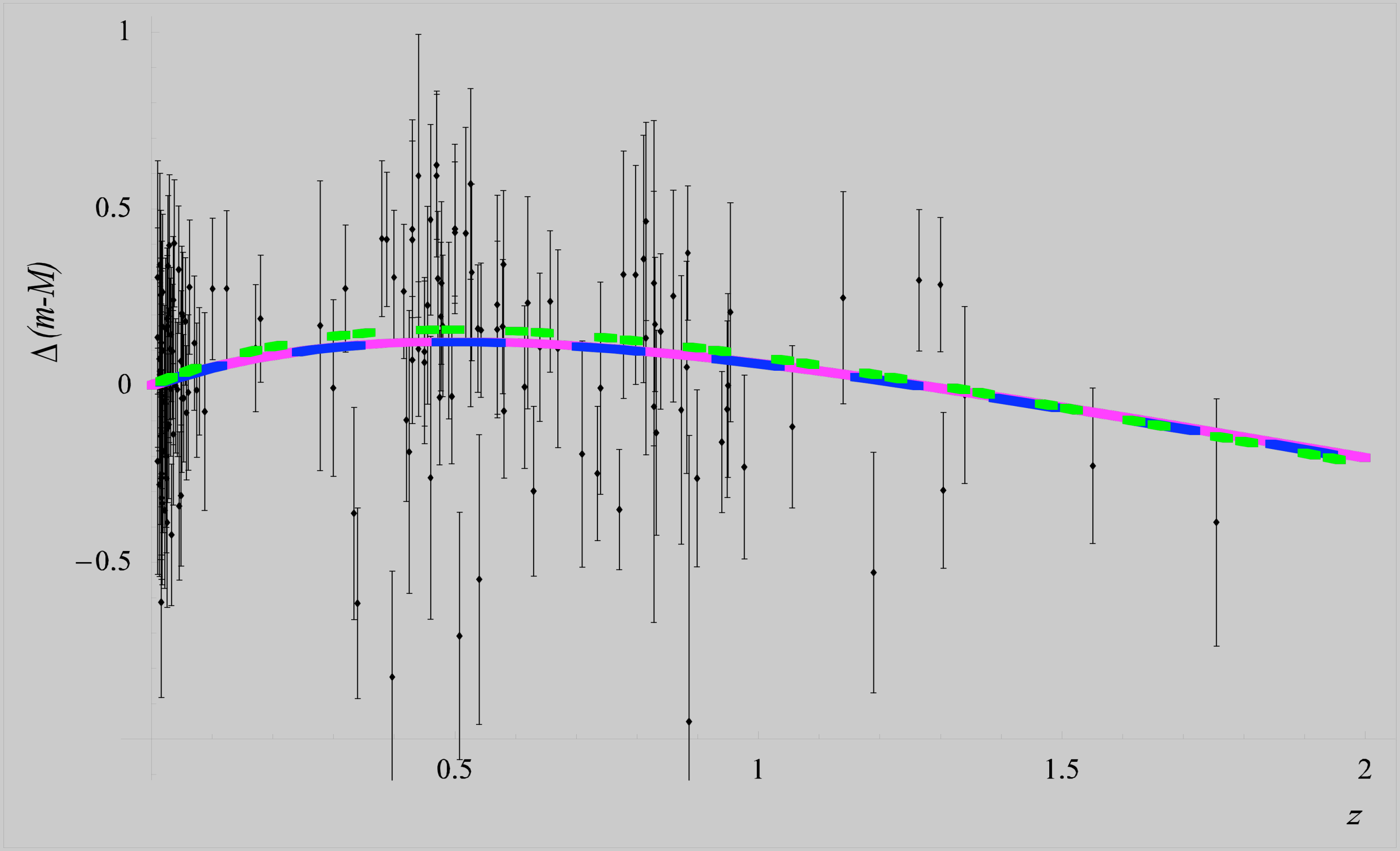
HUBBLE DIAGRAMS

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.



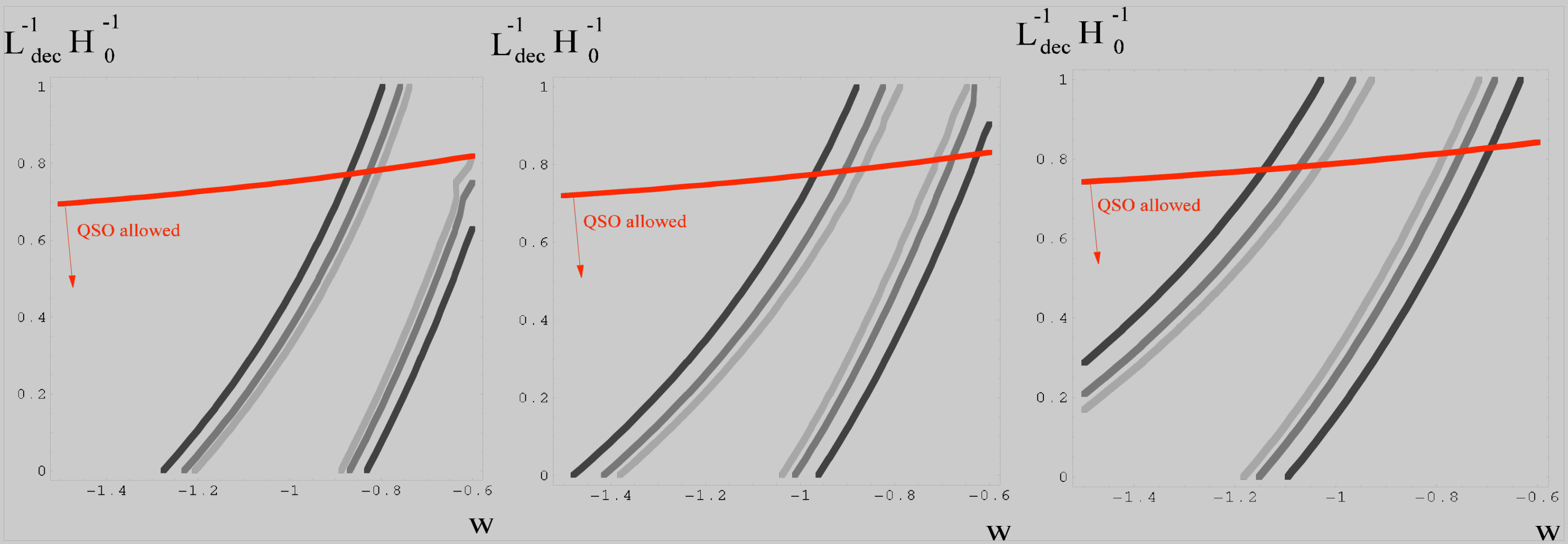
FITTING SNe

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



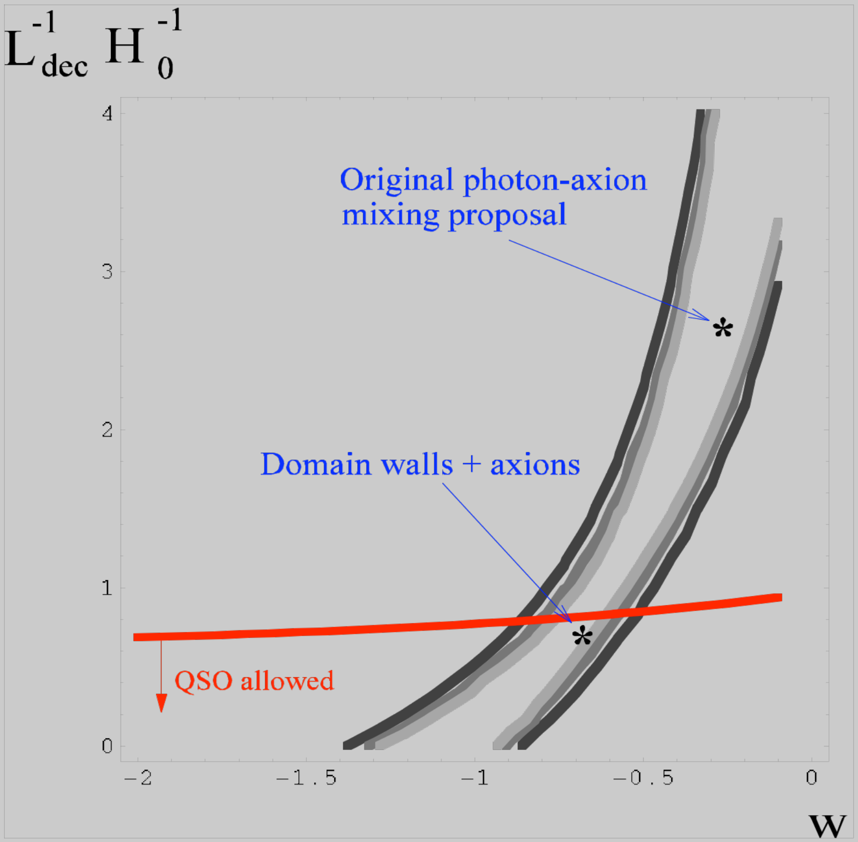
data: “gold sample” of 157 SNe, Riess et al.

ALLOWED REGIONS FOR PHOTON-AXION MIXING



The red line is the revised QSO bound of Goobar & Mortsell and Mortsell & Ostman. Also consistent with bounds claimed by Basset and Kunz from FRIIb radio galaxies, although those are MUCH MORE suspect!

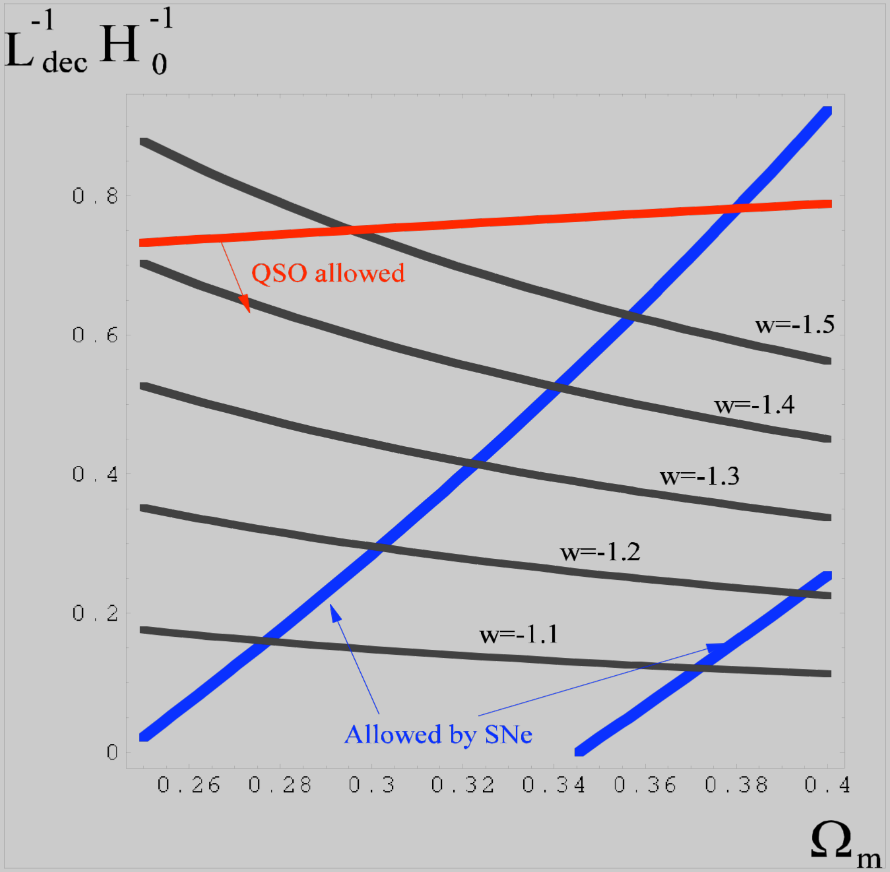
WHAT ABOUT COASTING?



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 *MAY BE* 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… ☺

THE ACCELERATED ACCELERATION

- But there may be even simpler ways for faking $w<-1$…
- Ask not:
  - *"Where the Phantom cometh from?"*

but instead

  - *"What is it that could make w look more negative than -1?"*

HOW DO WE DETERMINE w FROM SNe?

- We infer the distance from measured luminosity, and from the inferred distance we determine the contents of the universe as a function of redshift!

$$D_L(z) = (1+z)H_0 \int_0^z \frac{1}{H(z')}dz'$$
$$m(z) = 5\log_{10} D_L(z).$$

where

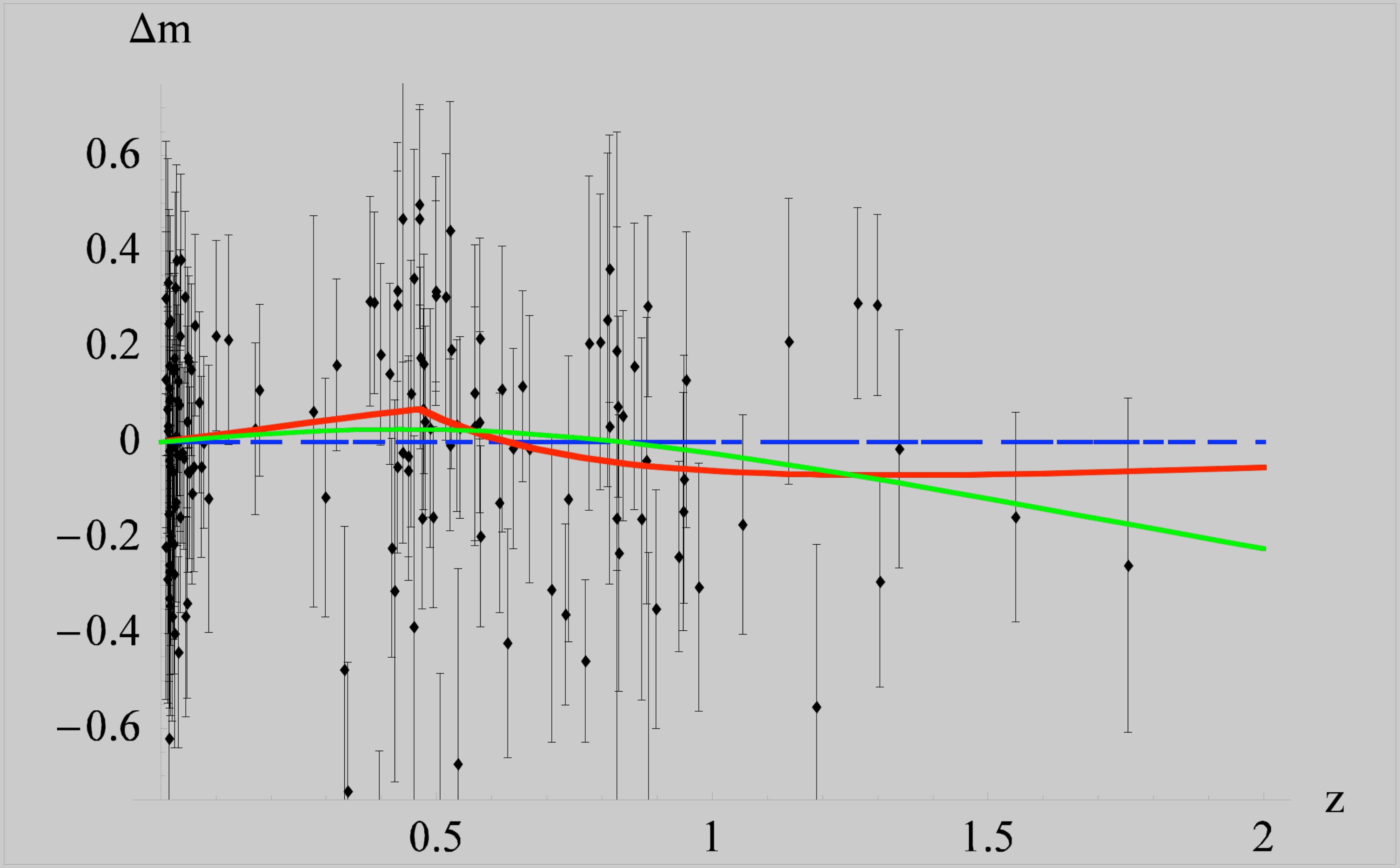
$$3H^2 = \frac{\rho}{M_{Pl}^2}$$

$$\rho = \rho_{cr}\frac{\Omega_M}{a^3} + \rho_{DE}$$

- If at greater redshifts (ie earlier times) *H* were bigger, D_L and *m would have been smaller; hence a universe which expands faster at late times will have greater m.*

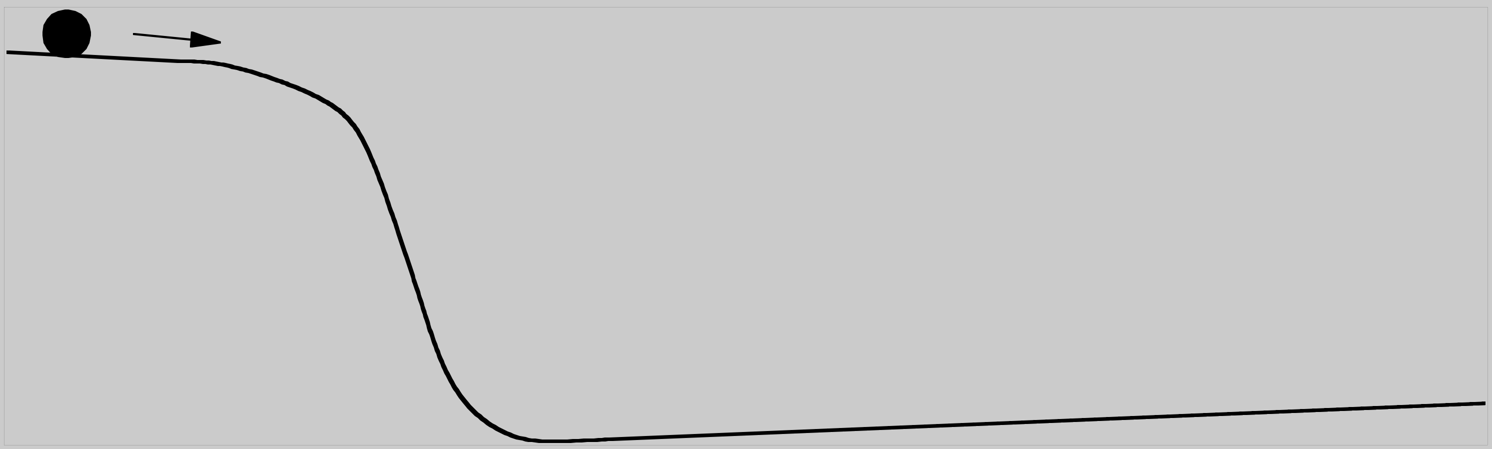
DATA FITS, ONCE MORE

Blue: Concordance model, ΛCDM;
Red: step in w at z=0.47: -0.73 to -1;
Green: field running ***UP*** a linear potential.



MODULAR POTENTIAL

- Why would a field ever move ***UP*** a $V(\phi)$?



- Once the field slides down the precipice it will continue slowly climbing the linear slope and the universe will begin to increase its rate of acceleration!

MODULAR POTENTIAL

- Consider a radius of some extra dimension after stabilization

$$V(\phi) = \lambda\, M_{Pl}^4\, f\left(\frac{\phi}{M_{Pl}}\right)$$

- Let *V* have a Taylor expansion with *O(1)* coefficients; approximate the potential to the left of the minimum by

$$V(\phi) = \mu^3 \phi$$

BOUNDARY CONDITIONS

- This will work as long as the potential dominates kinetic energy; moreover potential energy cannot exceed critical energy:

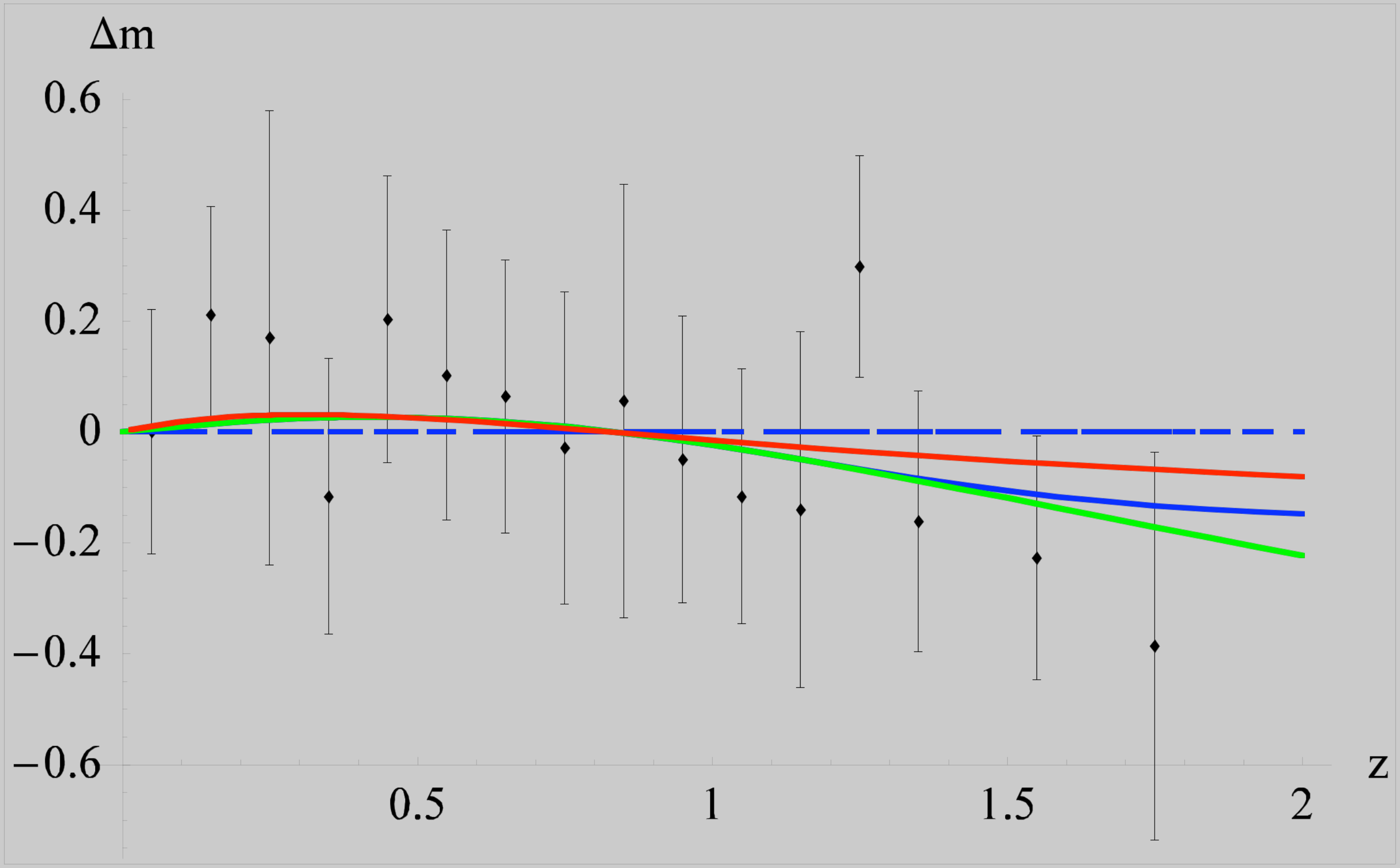
$$\frac{1}{2}\dot{\phi}_*^2 \lesssim M_{Pl}^2 H_0^2$$
$$\mu^3 \phi_* \lesssim M_{Pl}^2 H_0^2$$

- The total time of variation must be comparable to the age of the universe, $\phi'/H_0 \sim \phi$ so

$$\begin{aligned} \mu^3 &\lesssim M_{Pl} H_0^2 \,, \\ \phi_* &\gtrsim M_{Pl} \,, \end{aligned}$$

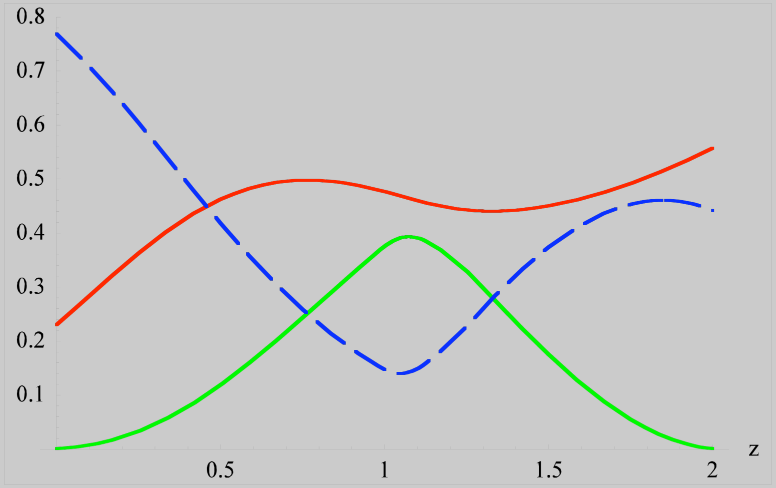
VARIABLE w FITS

Red: phantom $w = -1.4 + \Omega_{DM} = 0.6;$
Green: linear potential $+ \Omega_{DM} = 0.77;$
Blue: linear potential $+ \Omega_{DM} = 0.77$, followed by quadratic potential which arrests ϕ.

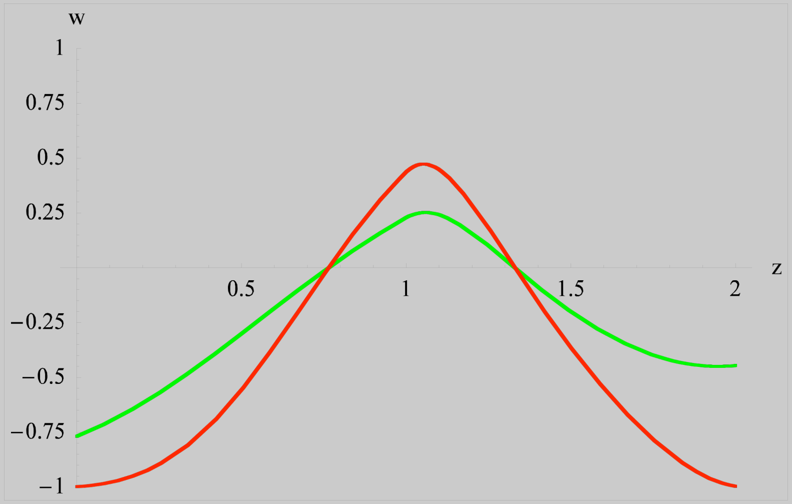


EVOLUTION

- Ω_M matter density
- Ω_{KE} kinetic energy
- Ω_{DE} dark energy



- w_{DE} w dark energy
- w_{DE+M} total w



IN LIEU OF A SUMMARY

- *Our job: classify the weirdness of the universe using the DATA as the ULTIMATE ARBITER and theoretical prejudice as a guideline.*
- As far as we can tell: this Universe is **NOT** so simple!

It may have given up on Occam's razor 14 billion years ago…

- Thus we ought to be careful about dismissing possibilities, but remain guarded about ideas.
- w < -1 is one such interesting bit of weirdness. The data may yet force it upon us, and it is NOT in conflict with earthly physics – no phantoms are ever needed.
- Be careful when using SNe as a tool of precision cosmology. The SNe observations may be infected by other effects such as photon→ axion conversion. We may need BOTH JDEM and LSST!

…AND A BIT OF PROPAGANDA…

- *Cosmology is really coming of age as a predictive science*
- *Let the good times roll…*