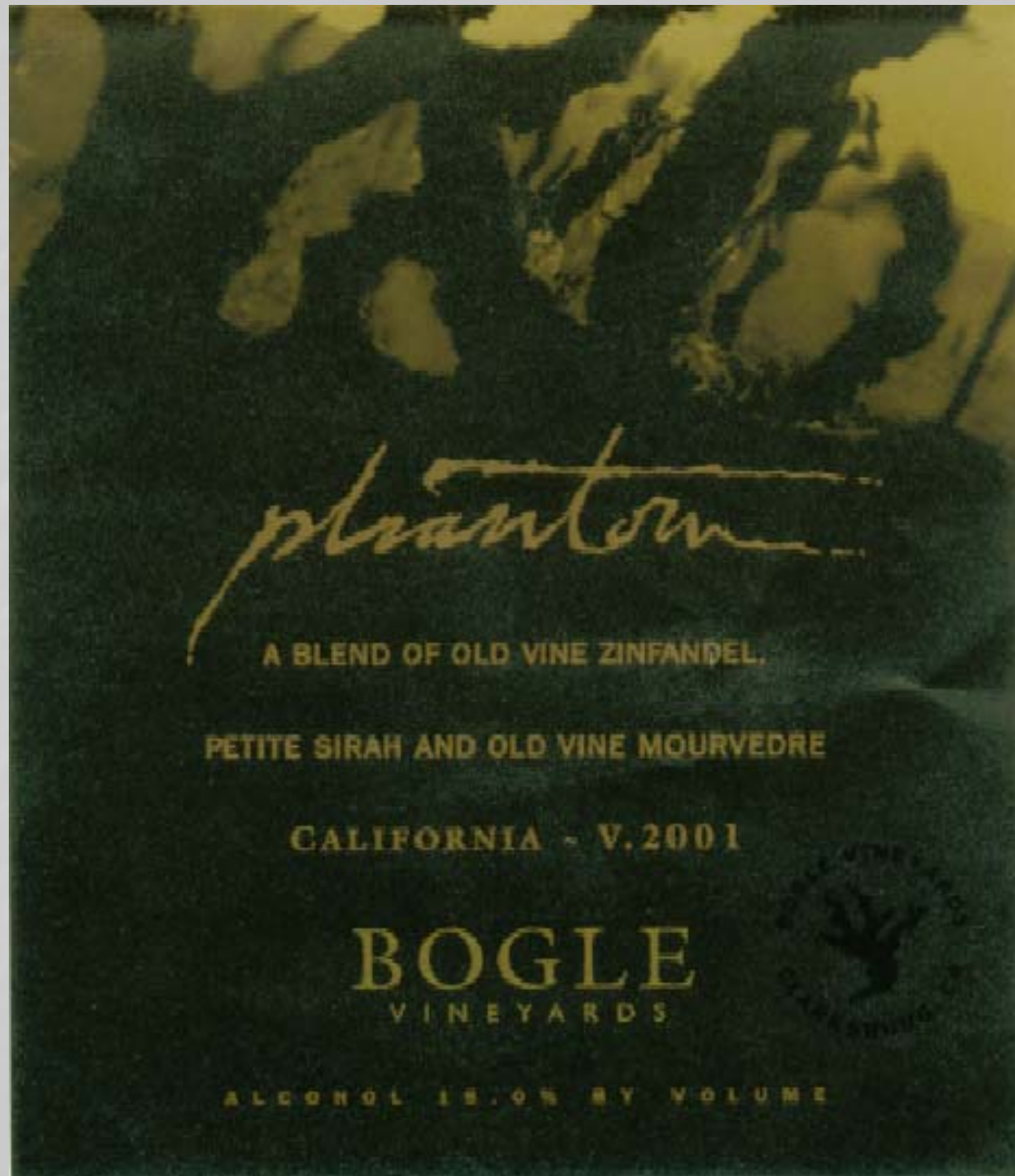


Nemanja Kaloper, UC Davis

*How I Learned to Like $w < -1$
Dark Energy...*

This is not a talk about “phantoms”, since in general I do not like them...

...WITH SOME EXCEPTIONS...



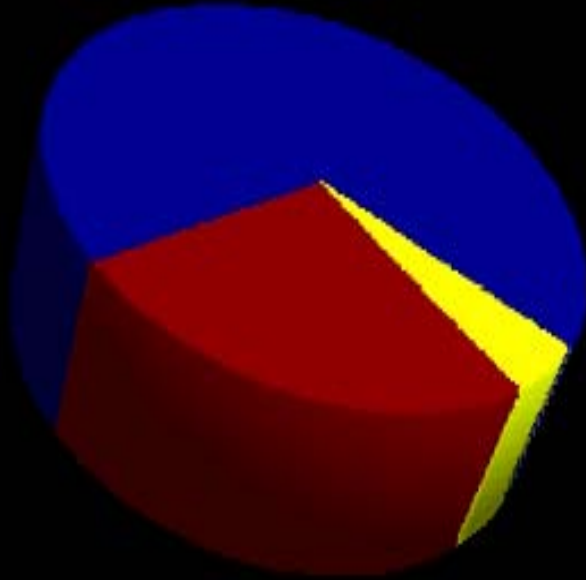
INSTEAD - I WILL TALK ON:

- Dark Energy: *discords of Cosmic Concordance*
- What is $w (= p/\rho)$? Could it be $w < -1$? Should you care about it?
- Exorcisms: explaining $w < -1$ without phantoms and other occult beasts...
- 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!

SPLITTING THE COSMIC PIE

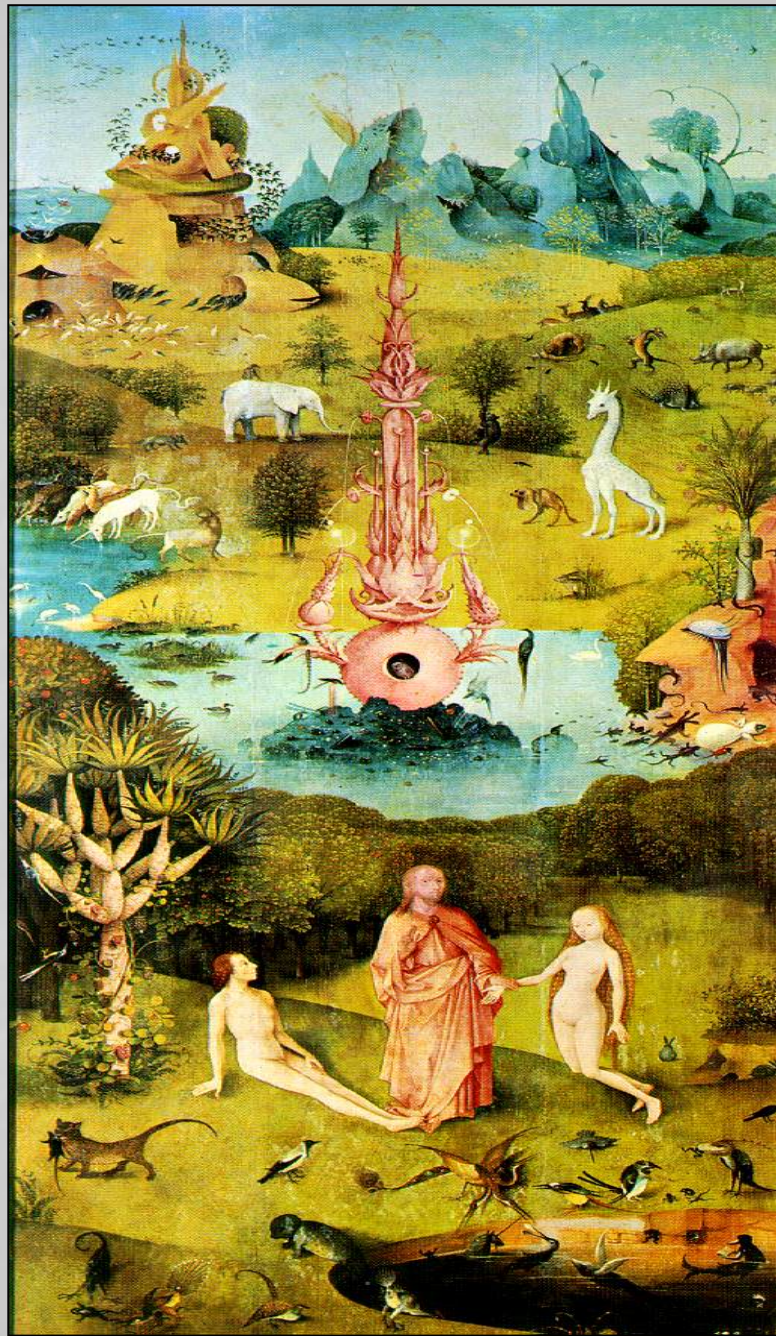


5% Ordinary Matter

25% Dark Matter

70% Dark Energy

Emerging paradigm: **CONCORDANCE COSMOLOGY**, of a Universe defined by *cosmic coincidences*: today there are nearly equal amounts of various ingredients which must have evolved dramatically differently.



DISCORDS IN THE CONCORDATE?

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

DARK ENERGY

BLESSINGS OF THE DARK ENERGY CURSE 😊

- How do we get small Λ ? Is it anthropic? Is it even Λ ? Or do we need some *really weird* new physics?
- **Age of discovery: the dichotomy between observations and theoretical thought forces a crisis upon us!**
- **A possible strategy is to determine all that needs explaining, and be careful about dismissals based on current theoretical prejudice (learning to be humble from the story of Λ ...)**



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

$$-2.7 \leq w_{\text{eff}} \leq -0.7$$

Hannestad et al

Melchiorri et al

Carroll et al

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

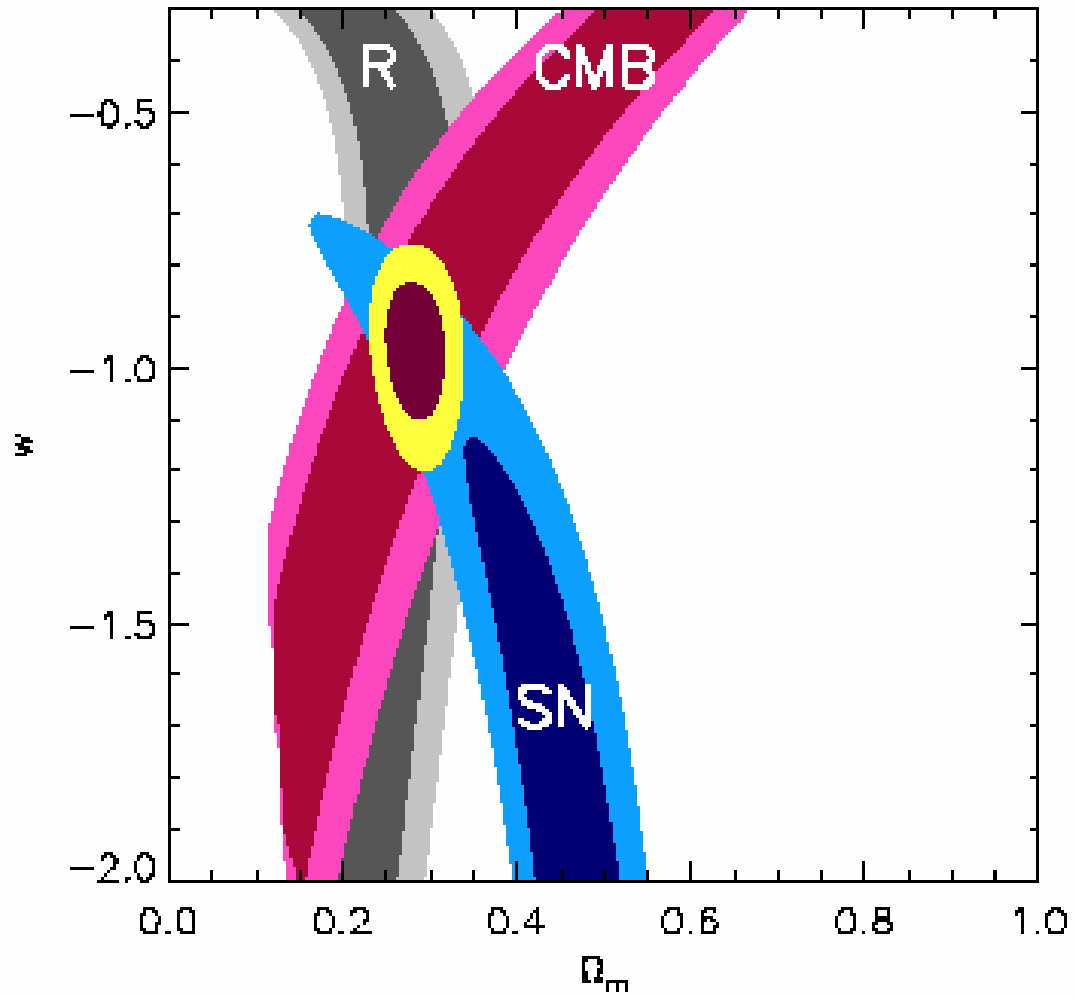
$$3 M_p^2 H^2 = -(\dot{\phi})^2/2 + V(\phi)$$

`Phantom field', Caldwell, 2002

`Pole inflation', Pollock, 1985.

- Such theories tend to be plagued with fast **INSTABILITIES**: no stable ground state, unstable perturbations! The Universe is OLD: $\tau \sim 14$ billion years. We should have seen the 'damage'... (maybe making gravity composite at a mm and breaking Lorentz symmetry might slow the instabilities down... but is this *cure* better than the *disease*?)

W. Hu & Y-S. Song, astro-ph/0508002



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 , $\langle w \rangle$ 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**?
- Seek 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 ?"

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

EXORCISMS





1) **Accelerate the universe more at late times!**

'Conventional' quintessence with $m \sim H_0$ so it rolls *up* a potential slope! Very minimalistic...

C. Csaki, NK & J. Terning, 2005.

2) **Extra dimming of SNe only!**

Λ + (photon \rightarrow axion conversion) has the **SAME EFFECT** on SNe like $w < -1$ dark energy!

C. Csaki, NK & J. Terning, 2004.

...? Changing gravity ?...

THE ACCELERATED ACCELERATION

- A very simple way for faking $w < -1$...
- Pay a closer look to the question:
"What is it that could make w look more negative than -1 ?"
- What is it in the data that makes us think about $w < -1$ in the first place?

HOW DO WE DETERMINE w FROM SNe?

- We infer the distance from measured luminosity, and from it 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 .*

MODULAR POTENTIAL

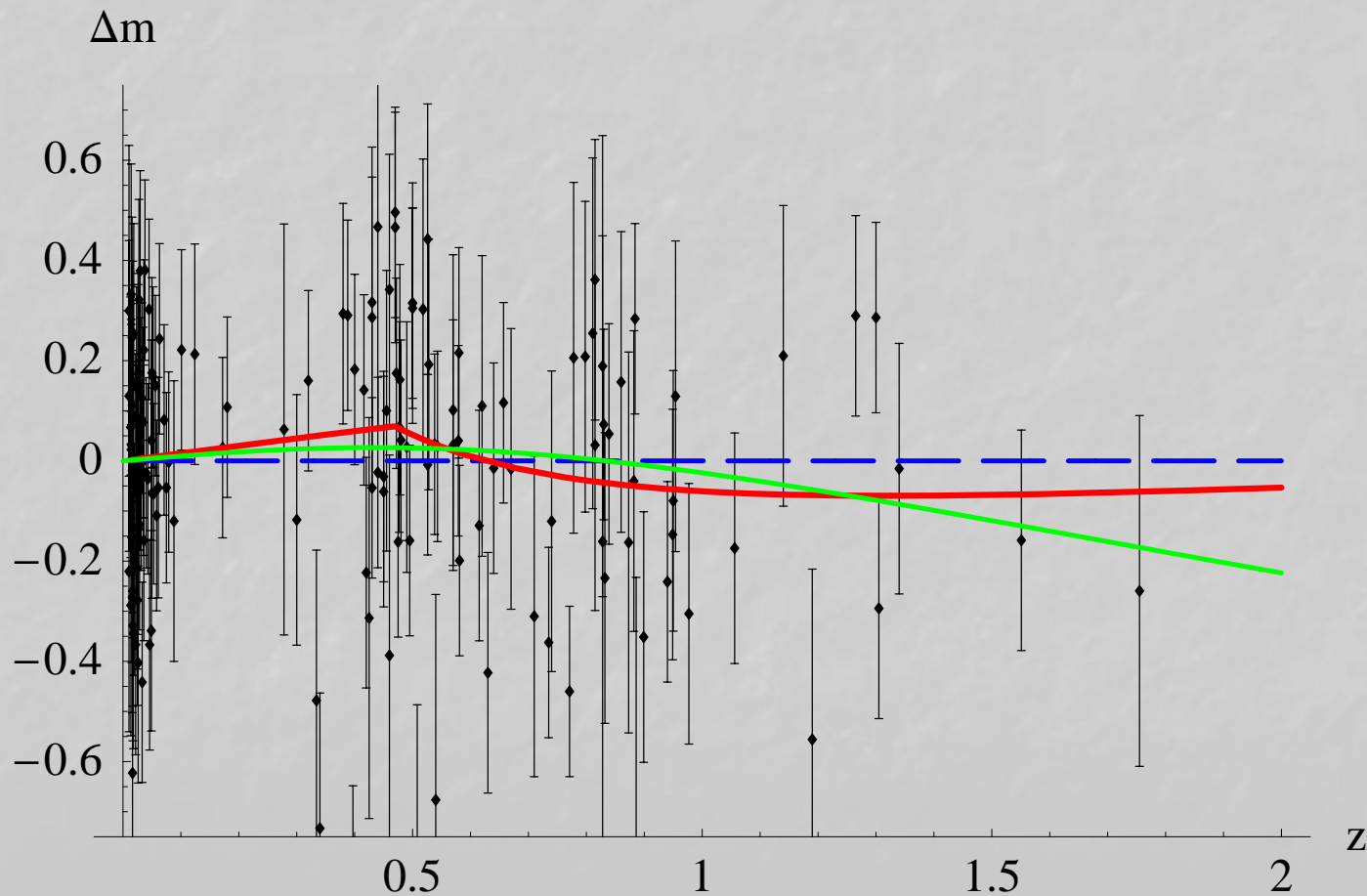
- If acceleration picks up at low z it could yield extra dimming; a field moving up the potential could do it.
- But why would a field ever move **UP** a $V(\phi)$?



- 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!

DATA FITS

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



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 it to the right 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:

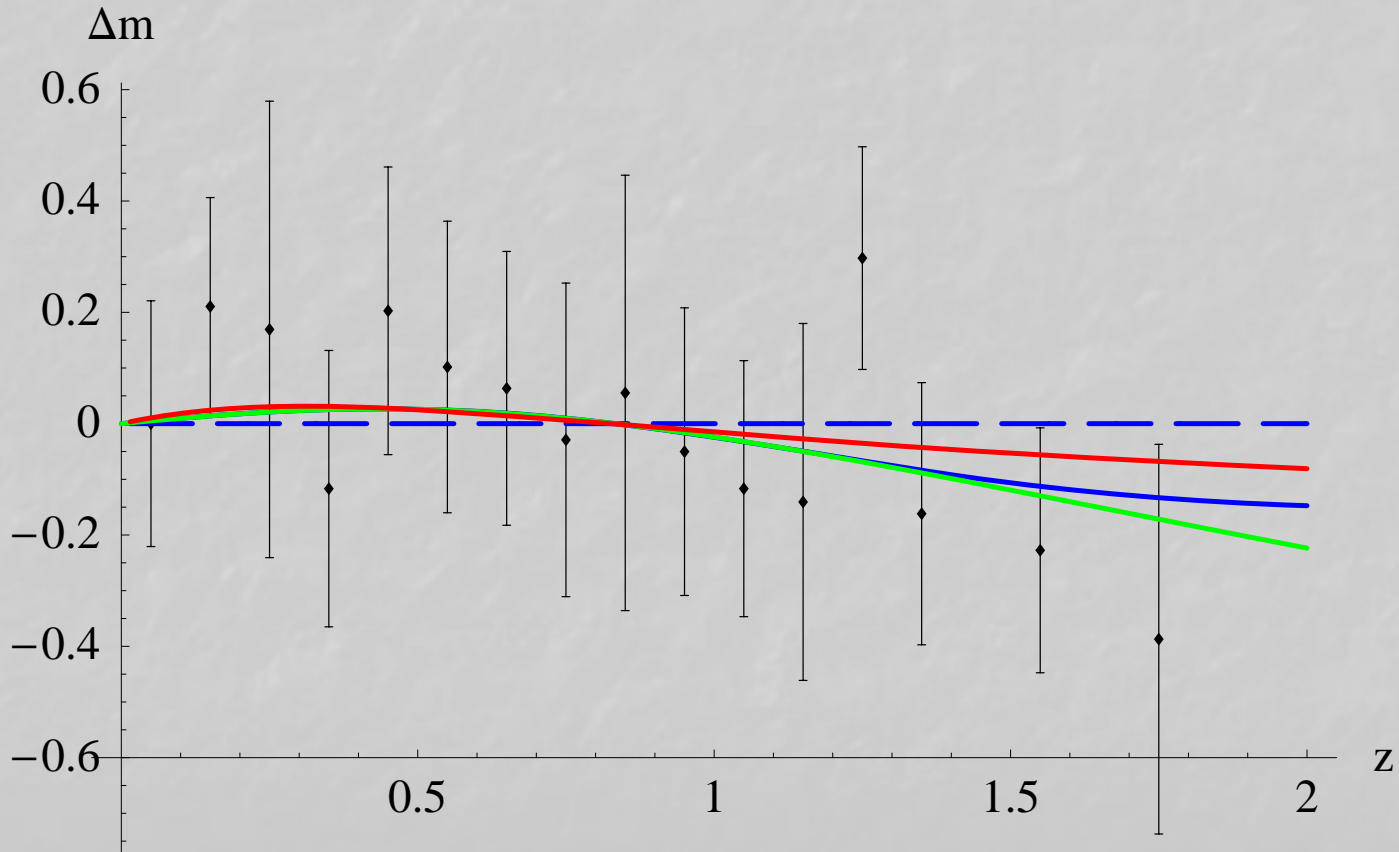
$$\begin{aligned}\frac{1}{2}\dot{\phi}_*^2 &\lesssim M_{Pl}^2 H_0^2 \\ \mu^3 \phi_* &\lesssim M_{Pl}^2 H_0^2\end{aligned}$$

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

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

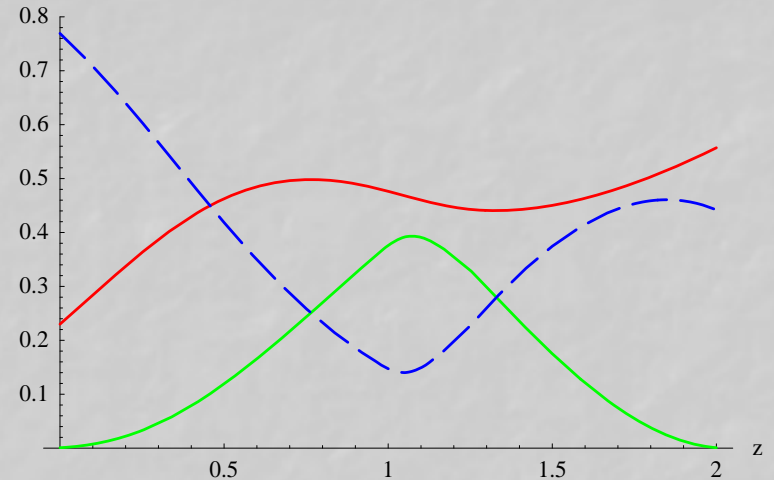
VARIABLE w FITS

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

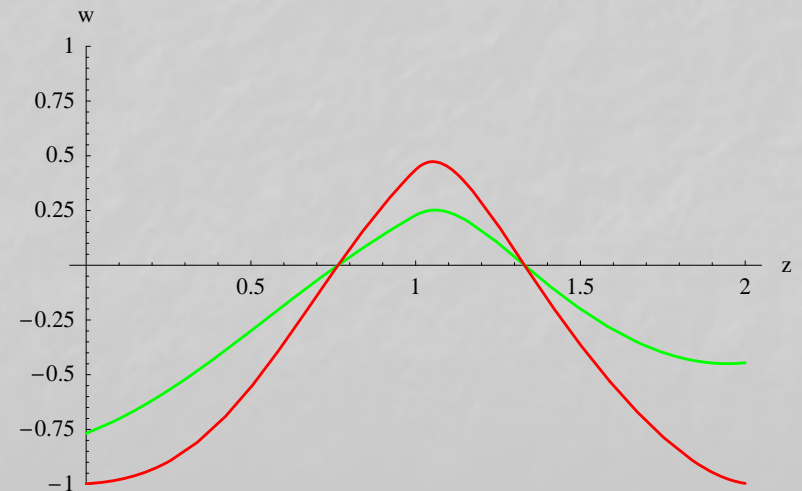


EVOLUTION

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



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



γ - a STRATAGEM

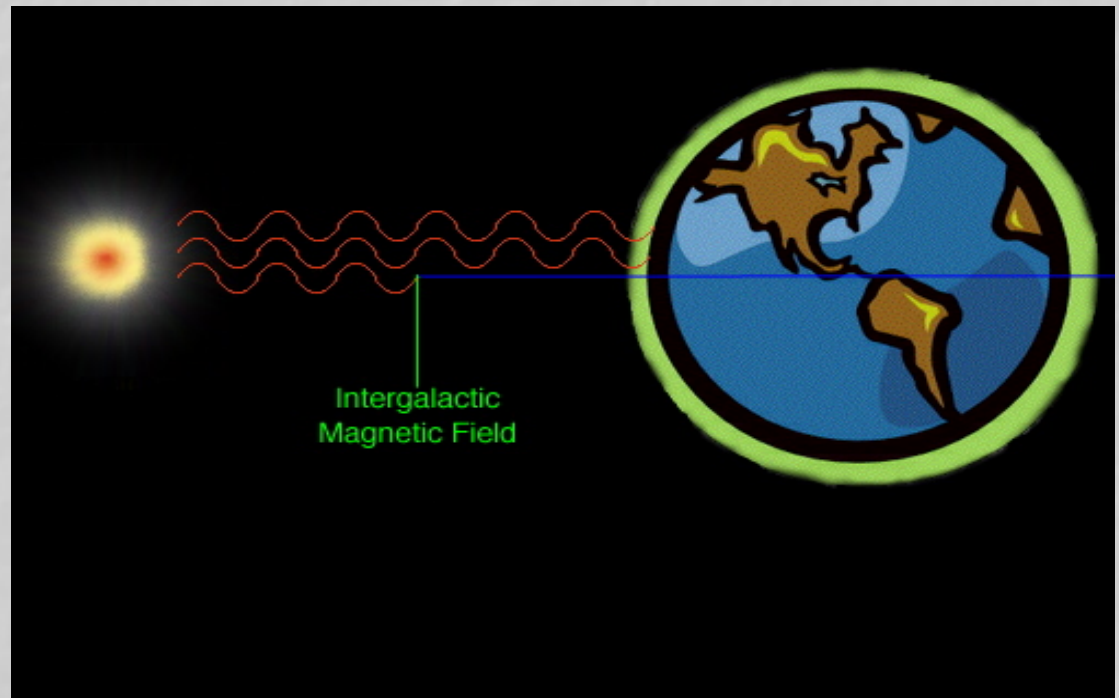
- Photons convert into axions *en route* to us, with the transition catalyzed by extragalactic magnetic fields.
- This mixing does not remove the requirement for dark energy – one can infer it from CMB+LSS alone.
- However photon-axion mechanism affects luminosity distance determination, and in turn w , **because SNe are the most sensitive probe of w .**
- Photon-axion mixing can make w appear more negative than -1, without any instabilities.

PHOTON-AXION CONVERSION IN A MAGNETIZED UNIVERSE

Typical distance
between us and
SNe: $\sim 10^3$ Mpc

Magnetic field
coherence length:
 \sim Mpc

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



LUMINOSITY

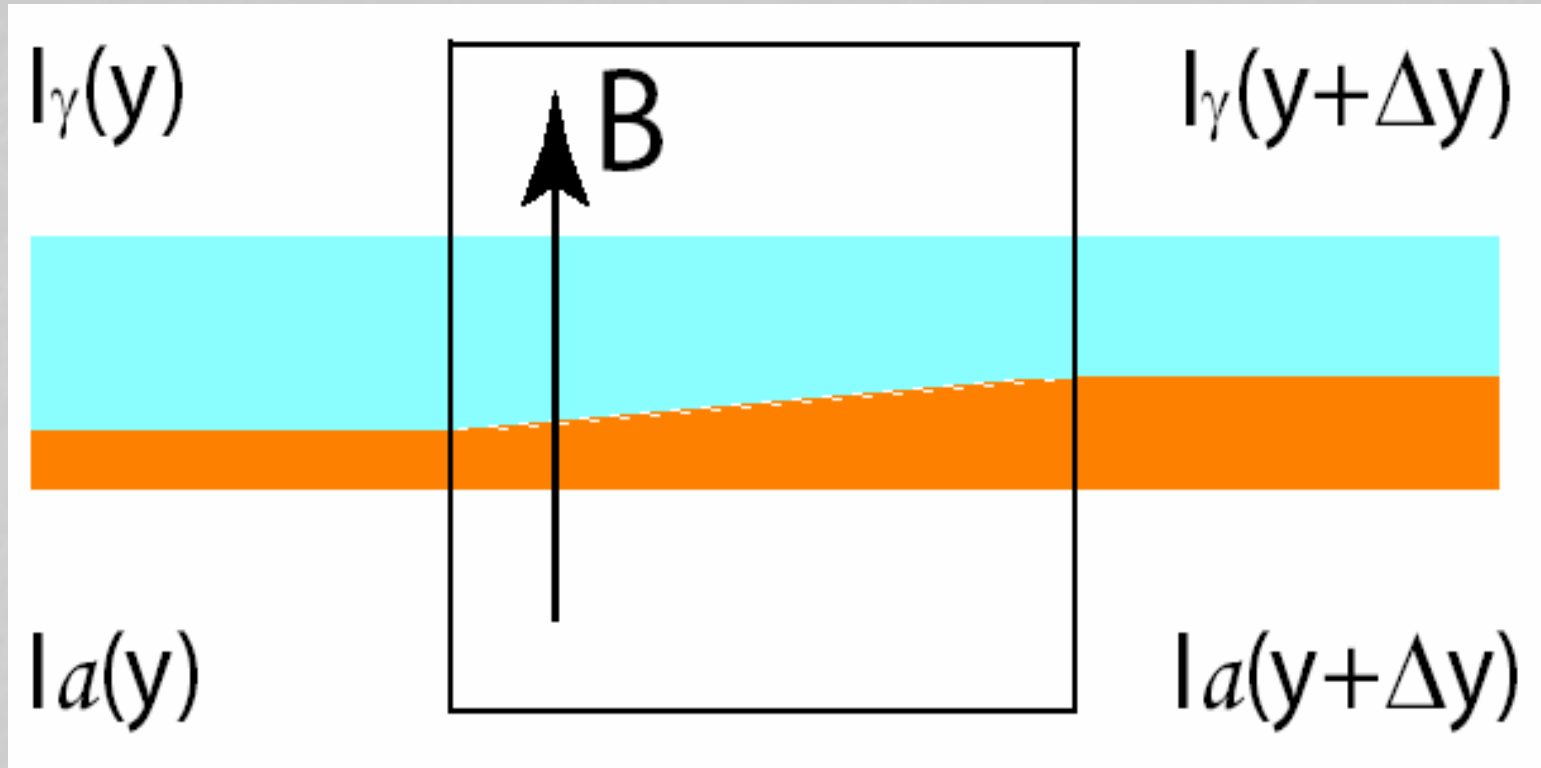
Luminosity:

$$\mathcal{L} = \frac{\text{Luminosity}}{\text{distance}^2} P_{\gamma \rightarrow \gamma}$$

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

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

EVOLUTION IN RANDOM FIELDS



$$I_\gamma(y+\Delta y) = I_\gamma(y) - p I_\gamma(y)/2 + p I_a(y)$$

$$I_a(y+\Delta y) = I_a(y) - p I_\gamma(y) + p I_\gamma(y)/2$$

DYNAMICS OF CONVERSION

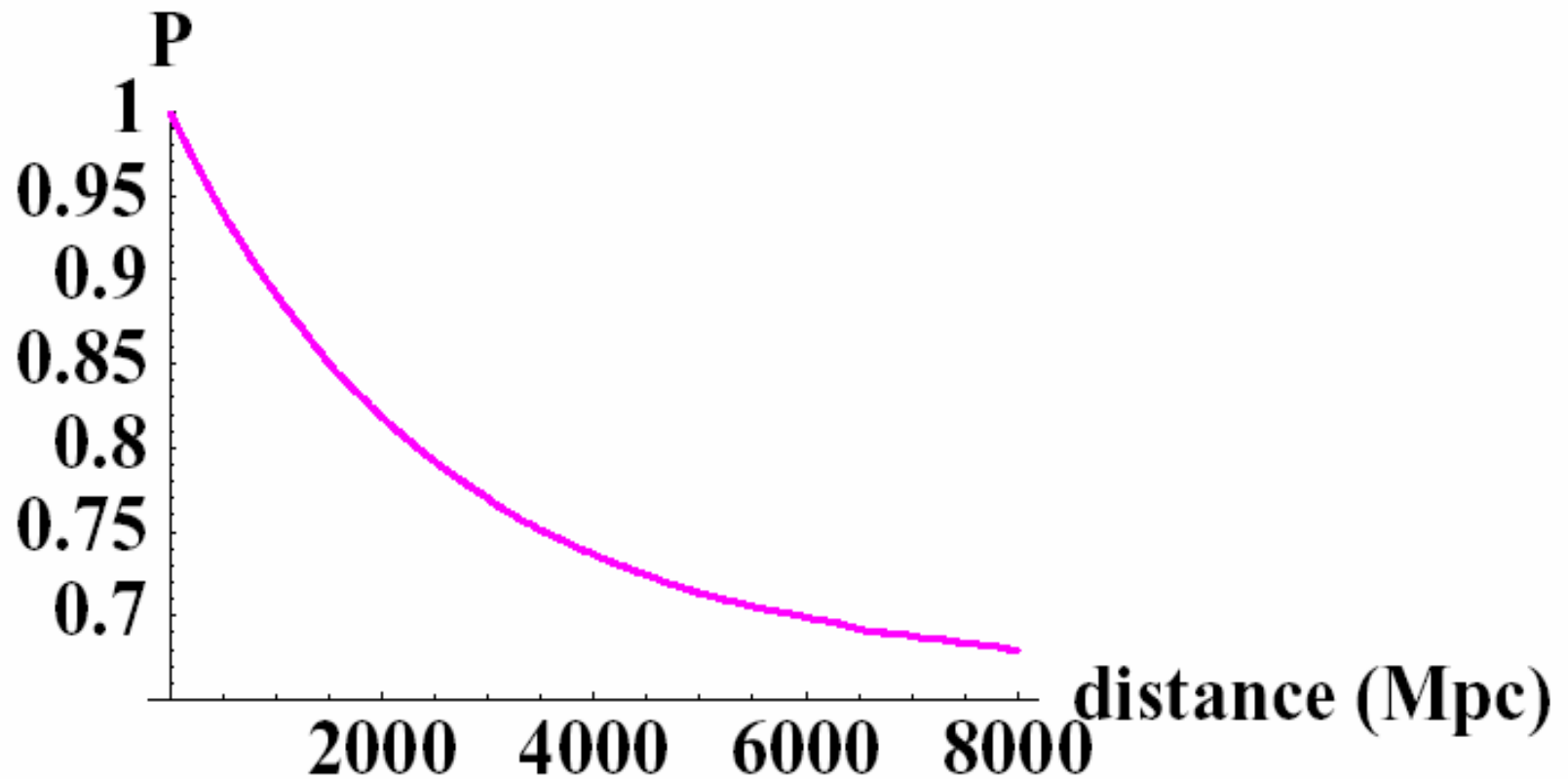
- *Take the continuum limit, $\Delta y \rightarrow dy$, expand, solve the system of 2 ODE; initial condition is that $I_a(0) \ll I_\gamma(0)$, because axions are weakly coupled.*

$$I_\gamma(y) = (2 + e^{-3py/2L}) I_\gamma(0)/3$$

$$I_a(y) = (1 - e^{-3py/2L}) I_\gamma(0)/3$$

- *Survival probability: $P = I_\gamma(y)/I_\gamma(0)$*
- *$p \ll 1$, so only one in 10000 photons converts, 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 is tiny, about 1/3 of photons will turn into axions after a long trip.*

SURVIVAL PROBABILITY



CALCULATING p IN A DOMAIN

- Let a pseudo-scalar axion a couple to $\mathbf{E} \cdot \mathbf{B}$:

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

- In the extra-galactic space, $\mathbf{B} \sim$ nano Gauss in domains of size $l \sim$ Mpc. So photon with $\mathbf{E} \parallel \mathbf{B}$ **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!

PHOTON SURVIVAL PROBABILITY INSIDE A HOMOGENEOUS DOMAIN

Definition:

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

where inside a homogeneous domain $\Delta y \ll L_0$, with the oscillation length, in the limit $E \gg m$, $\mu = B/M$,

$$L_0 = \frac{4\pi\mathcal{E}}{\sqrt{m^4 + 4\mu^2\mathcal{E}^2}}$$

the probability is computed from Schrodinger eq,

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

the mixing angle is

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

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. Effect: $m^2 \rightarrow m_{eff}^2 = |m^2 - \omega_p^2|$ (by unitarity).

A POSSIBLE SOURCE OF BOUNDS!

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

- However: at low $z \leq 1-2$, 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). At this moment .1 mag of color dependence is allowed, but this will improve and may be a signature of the axion to look for or to rule it out by!

LIMITS AND COLORS

When $E \gg m^2_{\text{eff}}/\mu$: maximal mixing, with $L_0 \sim 2\pi/\mu$. But...

Even when $E \sim m^2_{\text{eff}}/\mu$, 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...

BOTTOMLINE SCALES FOR THE SIMULATION OF THE DIMMING

- The scales are:

$$\mathbf{B} \sim 5 \cdot 10^{-9} \text{ Gauss}$$

$$L_{dom} \leq \text{Mpc}$$

$$M \sim 4 \cdot 10^{11} \text{ Gev}$$

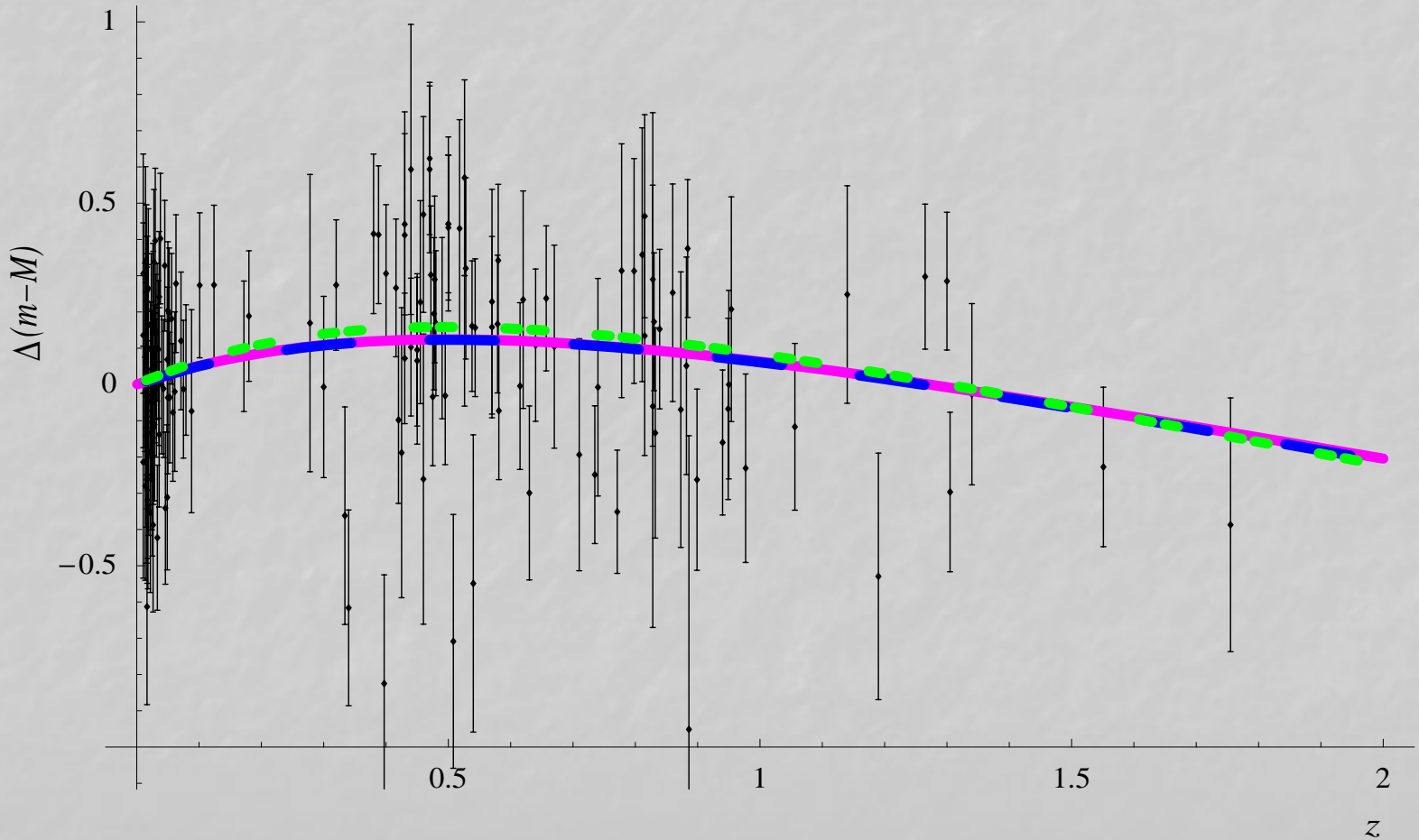
$$m \sim 10^{-15} \text{ eV}$$

$$\omega_p \leq 3 \cdot 10^{-15} \text{ eV}$$

- 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 improved a little 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) 😊

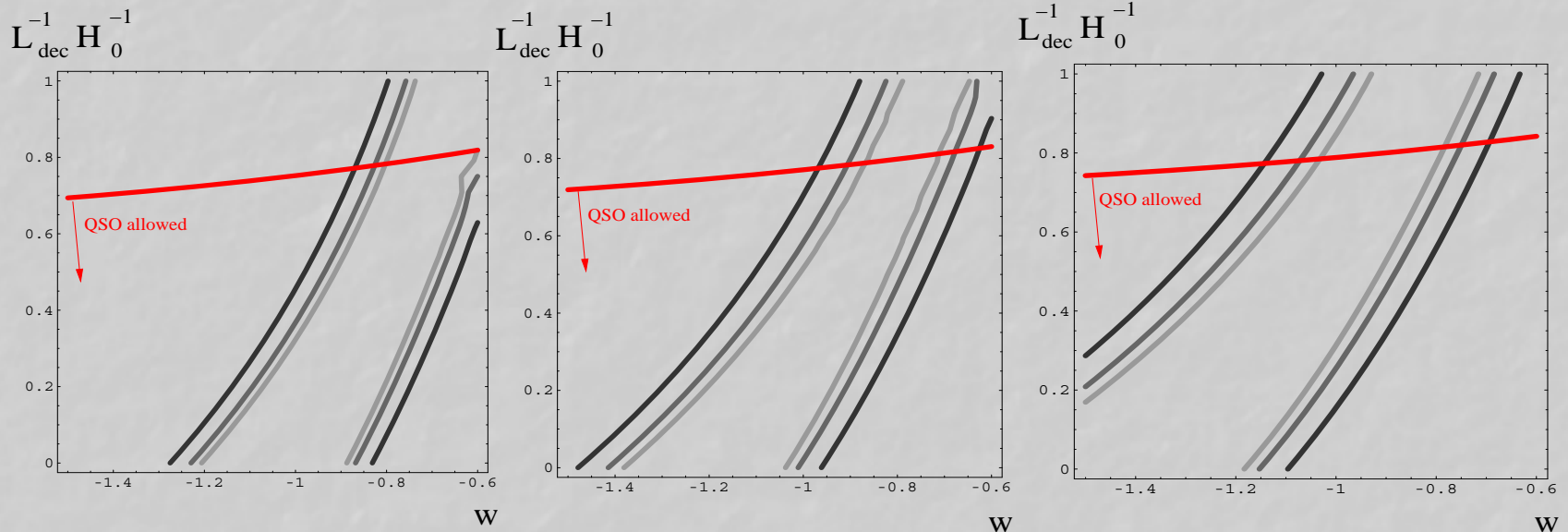
FITTING SNe

Green: $\Omega_{\text{DE}} = 0.65, w = -1.25$;
Blue: Concordance model, ΛCDM ;
Purple: $\Omega_{\Lambda} = 0.65 + \text{axions, mimicking } w < -1$.



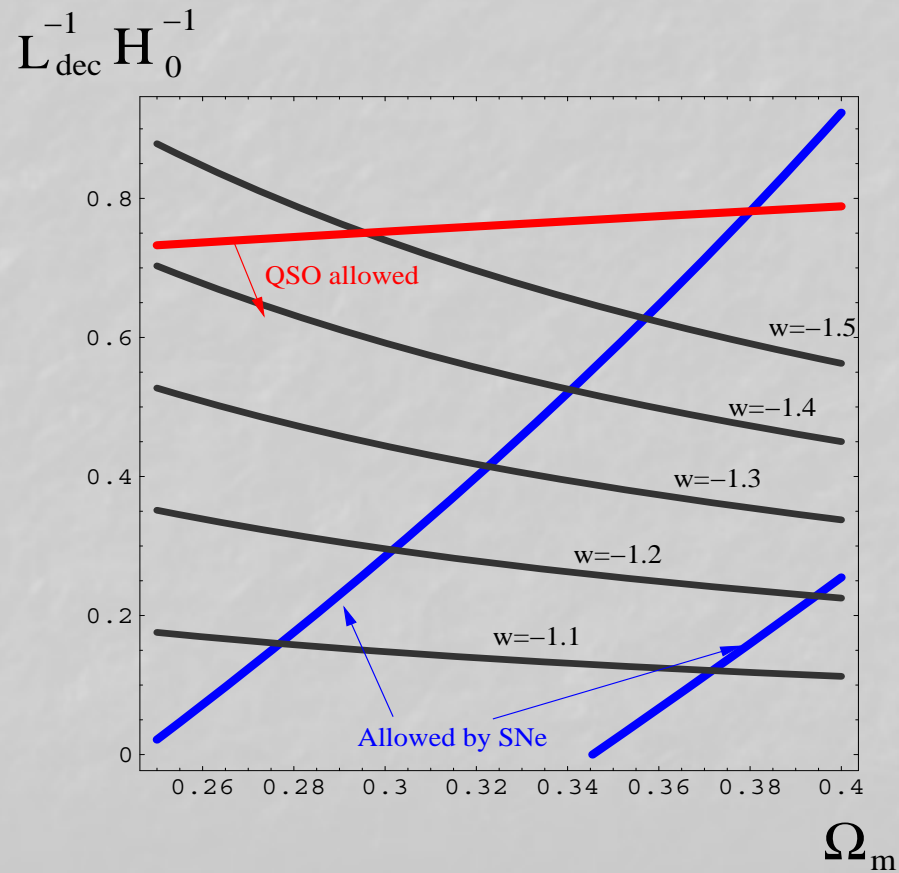
data: "gold sample" of 157 SNe, Riess et al.

ALLOWED REGIONS FOR PHOTON-AXION MIXING

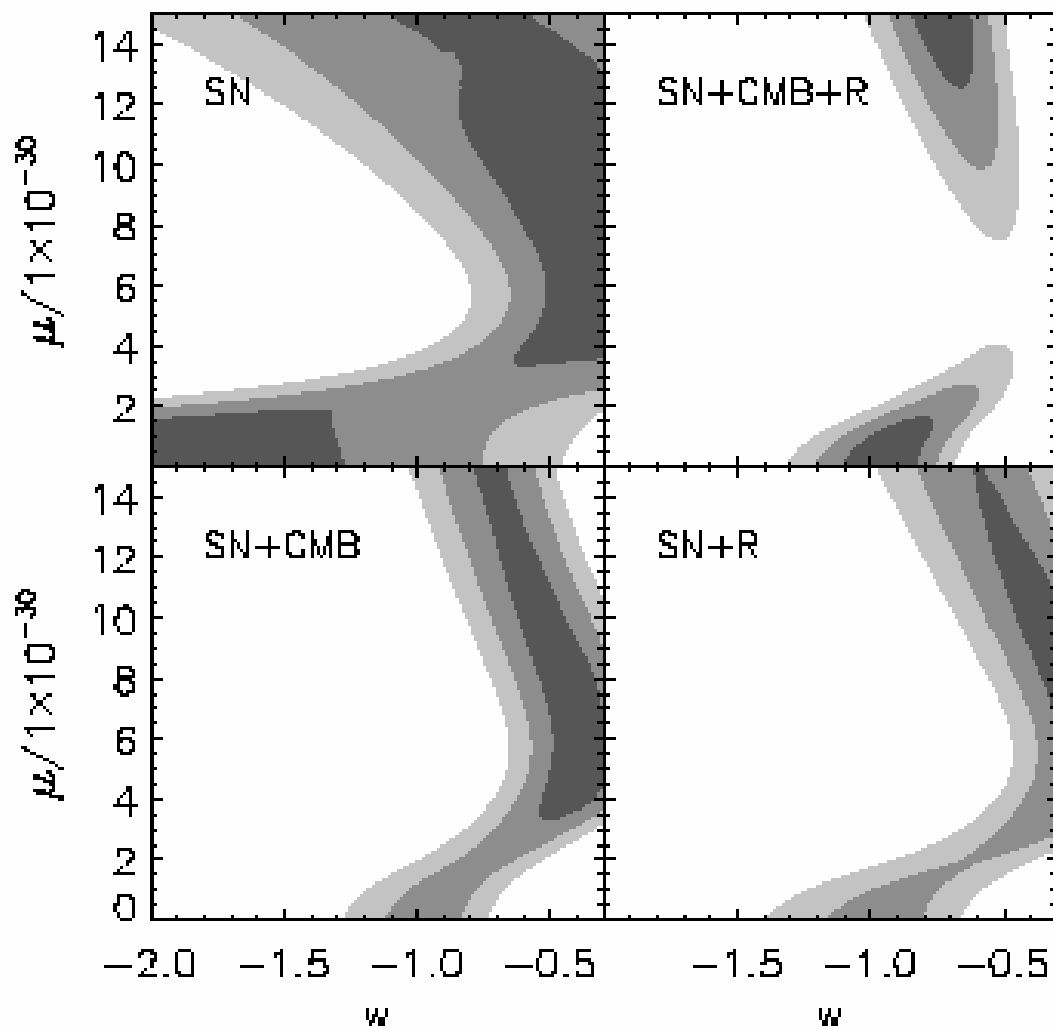


The red line is the revised QSO bound of Goobar & Mortsell and Mortsell & Ostman. Note that this is model-dependent and sensitive to the Quasar systematics! How good 'standard candles' are they?

IMPERSONATING $w < -1$



$$\mu = B/M$$



W. Hu & Y-S. Song, astro-ph/0508002

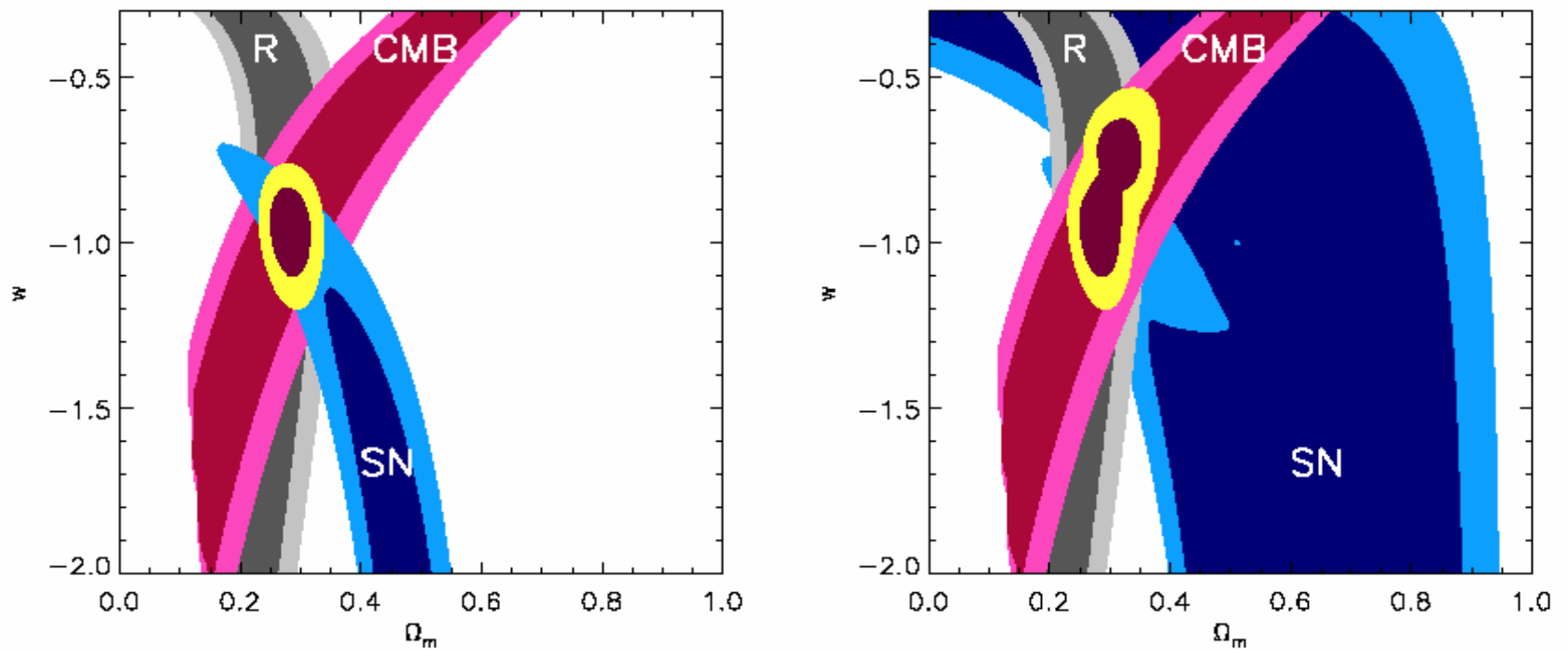


FIG. 2: $\Omega_m - w$ constraints at the 68% and 95% CL. Cosmologies without p-p dimming are shown in the left panel and those with dimming in the right. Separate contours denote supernovae constraints (SN), baryon oscillations (R), and CMB acoustic peak constraints (CMB) as labeled. The ellipses at the intersection denote the combination of all constraints.

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..."). *Its violation would suggest that universe is not transparent, as if axion were there!*

- 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 a 20% **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... Presumably SDSS data may also be useful to check cosmic transparency. 😊

SUMMARY

- As far as we can tell: this Universe is **NOT** so simple!

... It may have given up on Ockham's razor 14 billion years ago ...

- $w < -1$ would be an intriguing bit of weirdness, if the data force it upon us; but this need not conflict the **Earthly Physics** as no phantoms are needed.
- Be careful when using SNe as a tool of precision cosmology. The SNe observations may be infected by other effects. We may need **BOTH JDEM** and **LSST!**
- These mechanisms are testable in forthcoming experiments. In the very least, they are useful '*straw men*' to knock down...