Models of Dark Energy

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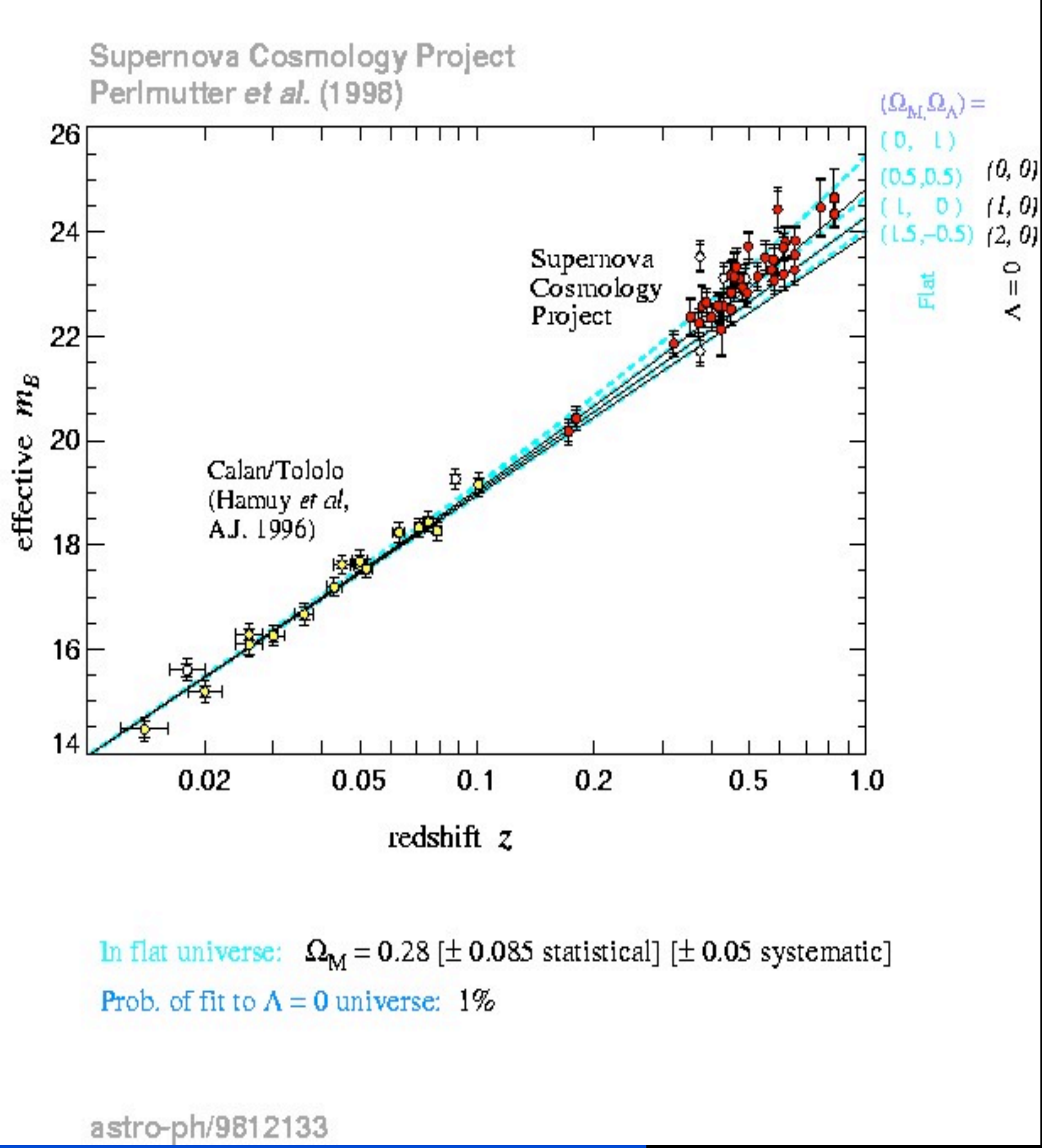
1. Evidence for Dark Energy
2. Models of Lambda -- and problems
3. Scalar field models -- and problems
4. Modified gravity -- and problems

Madrid -- XVI IFT UAM/CSIC Xmas Workshop -- Dec 16th 2010

1. The Big Bang – (1sec → today)

The cosmological principle -- isotropy and homogeneity on large scales



Test 1

- **The expansion of the Universe $v=H_0 d$**

H_0=74.2±3.6 km s^{-1} Mpc^{-1}

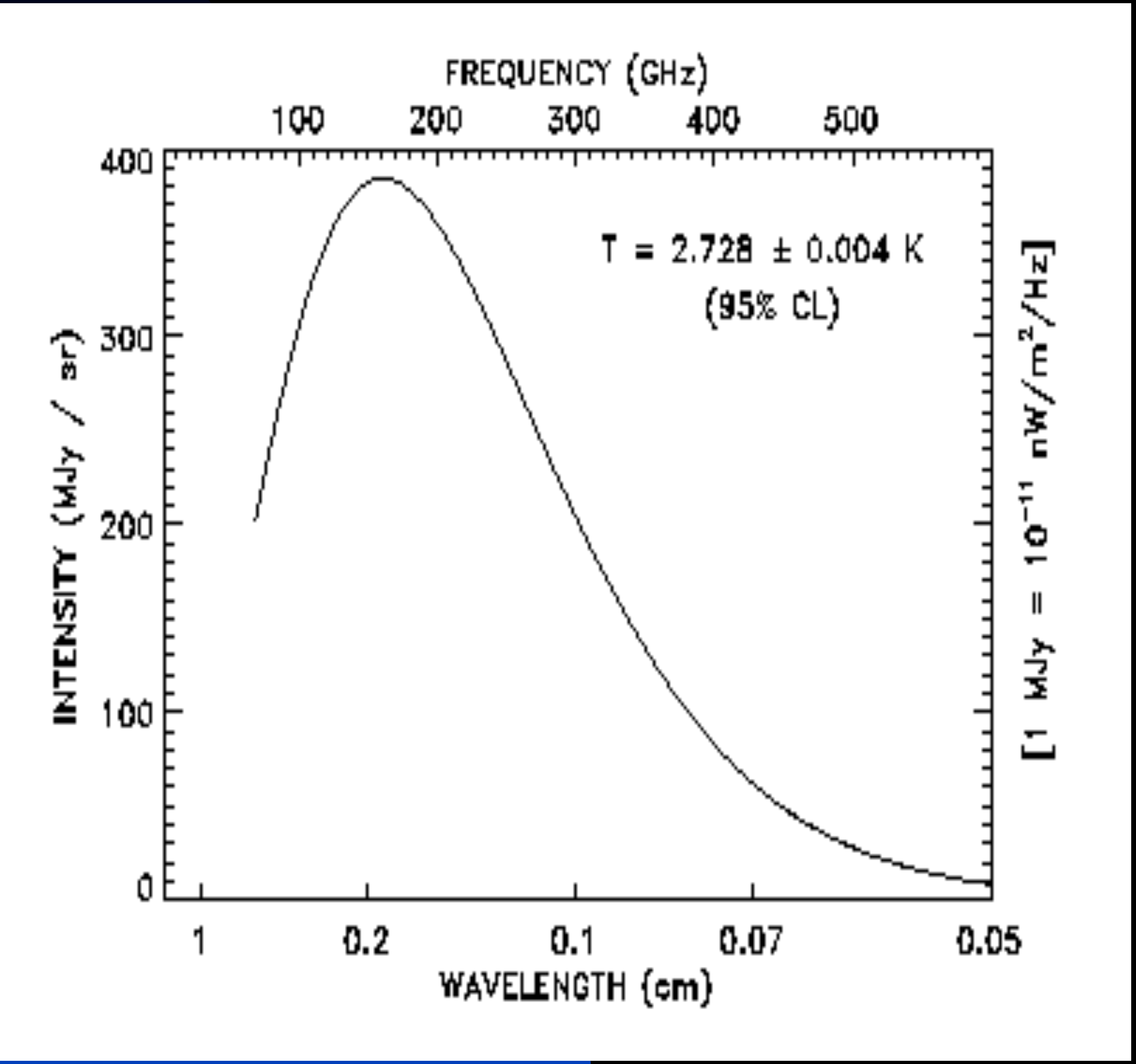
(Riess et al, 2009)

Distant galaxies receding with vel proportional to distance away.

Relative distance at different times measured by scale factor a(t) with

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

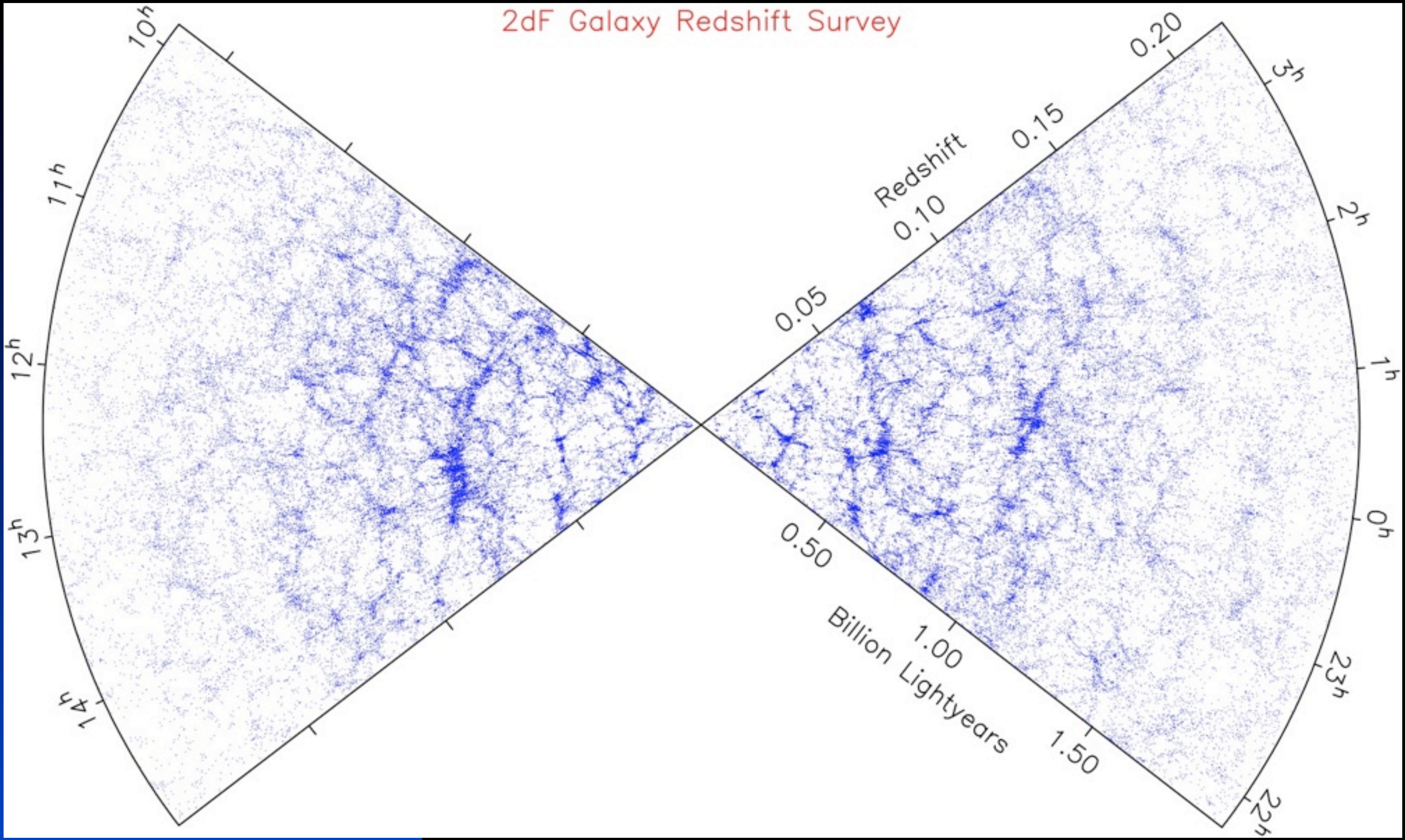
The Big Bang – (1sec → today)



Test 2

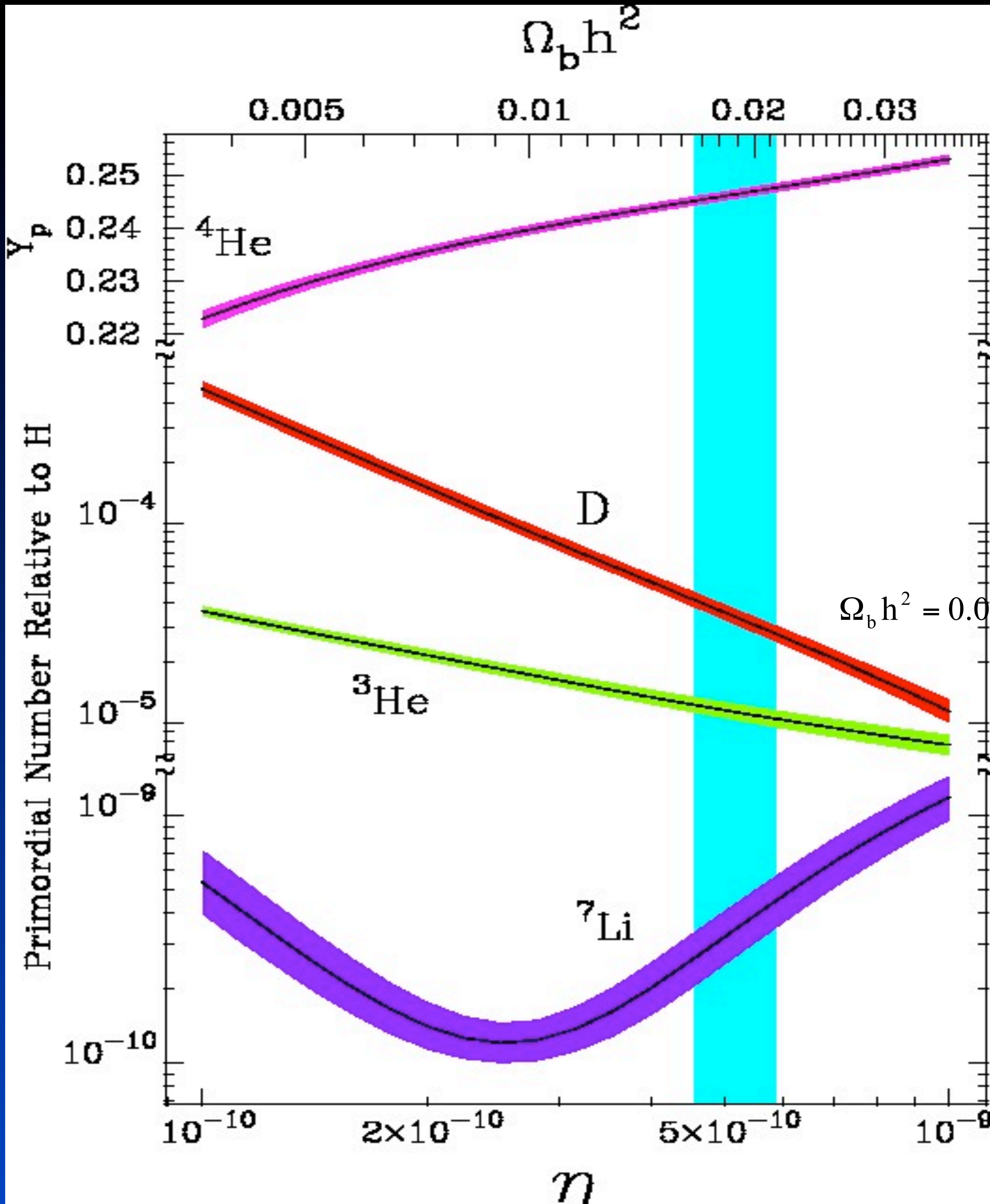
- **The existence and spectrum of the CMBR**
- **T_0=2.728 ± 0.004 K**
- Evidence of isotropy -- detected by COBE to such incredible precision in 1992
- Nobel prize for John Mather 2006

2dF Galaxy Redshift Survey



Homogeneous on large scales?

The Big Bang – (1sec → today)



Test 3

- **The abundance of light elements in the Universe.**
- **Most of the visible matter just hydrogen and helium.**

$\Omega_b h^2 = 0.02$

WMAP7 - detected effect of primordial He on temperature power spectrum, giving new test of primordial nucleosynthesis.

$$Y_P = 0.326 \pm 0.075$$

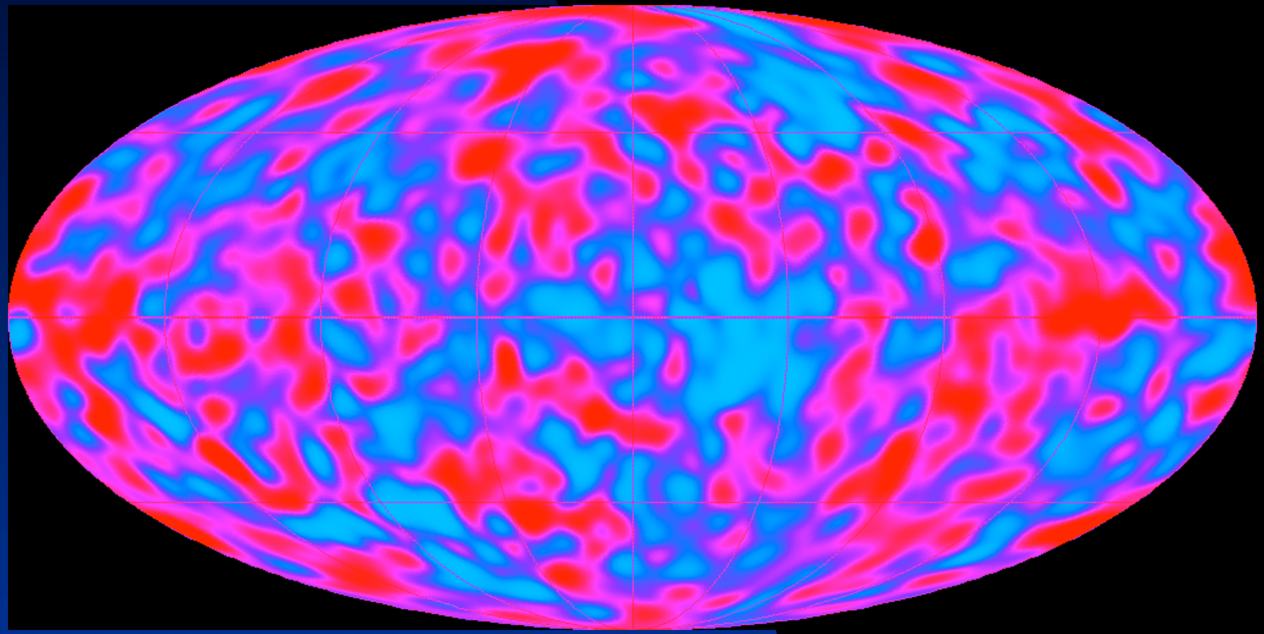
(Komatsu et al, 2010)

$$\Omega_b h^2 = 0.0225 \pm 0.0005 \ (68\% \ CL)$$

The Big Bang – (1sec → today)

Test 4

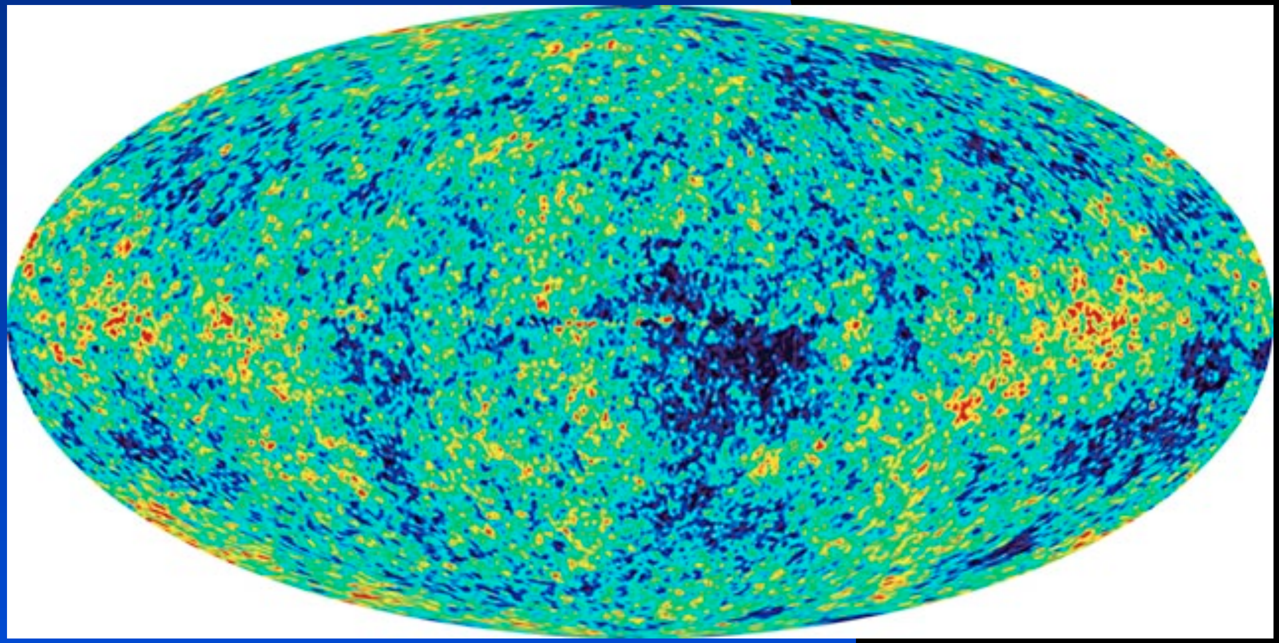
- Given the irregularities seen in the CMBR, the development of structure can be explained through gravitational collapse.



COBE - 1992, 2006

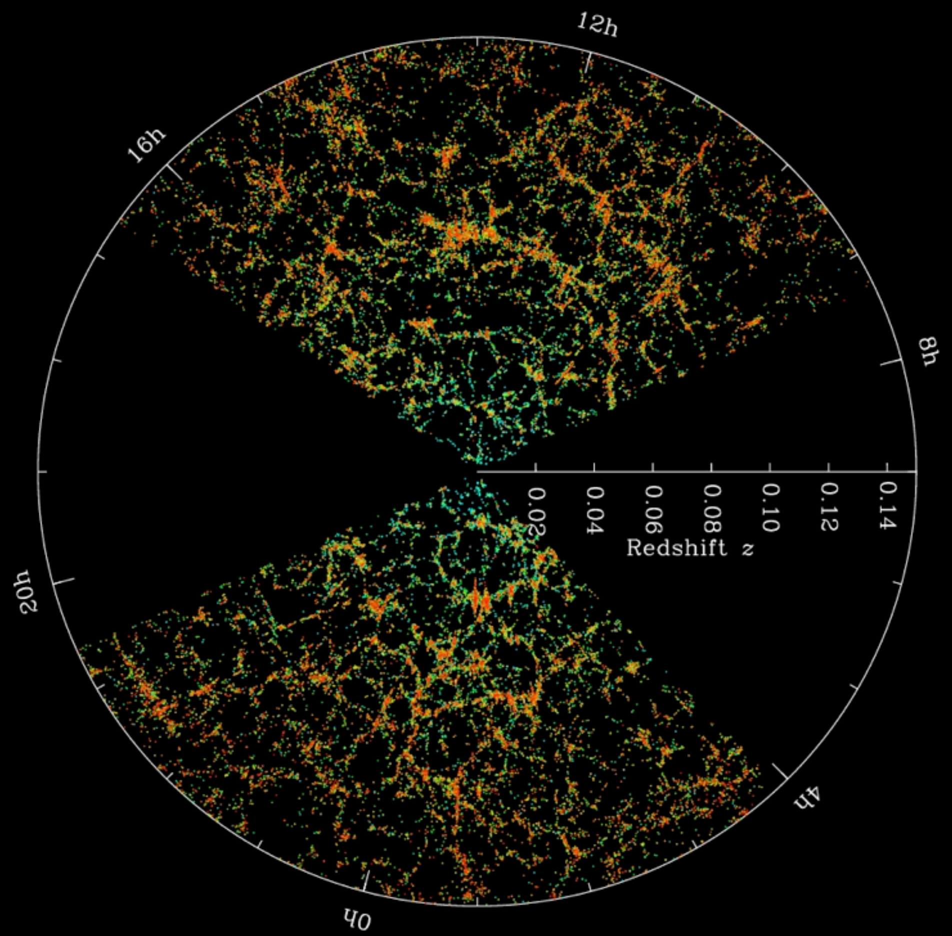
Nobel prize for

George Smoot



WMAP-2010

SDSS



Some basic equations

Friedmann:

$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{8\pi}{3} G\rho - \frac{k}{a^2} + \frac{\Lambda}{3}$$

a(t) depends on matter.

Energy density $\rho(t)$: Pressure $p(t)$

Related through : $p = w\rho$

w=1/3 – Rad dom: w=0 – Mat dom: w=-1– Vac dom

Eqns (Λ=0):

Friedmann + Fluid conservation

$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{8\pi}{3} G\rho - \frac{k}{a^2}$$

$$\dot{\rho} + 3(\rho + p)\frac{\dot{a}}{a} = 0$$

Combine

$$\frac{\ddot{a}}{a} = -\frac{8\pi}{3} G\left(\rho + 3p\right) --- Accn$$

$$If \ \ \rho + 3p < 0 \Rightarrow \ddot{a} > 0$$

$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{8\pi}{3} G\rho - \frac{k}{a^2}$$

$$\dot{\rho} + 3(\rho + p)\frac{\dot{a}}{a} = 0$$

$$\rho(t) = \rho_0 \left(\frac{a}{a_0}\right)^{-3(1+w)} \quad ; a(t) = a_0 \left(\frac{t}{t_0}\right)^{\frac{2}{3(1+w)}}$$

$$\mathrm{RD} \quad : \quad w = \frac{1}{3} : \rho(t) = \rho_0 \left(\frac{a}{a_0}\right)^{-4} \ ; \ a(t) = a_0 \left(\frac{t}{t_0}\right)^{\frac{1}{2}}$$

$$\mathrm{MD} \quad : \quad w = 0 : \rho(t) = \rho_0 \left(\frac{a}{a_0}\right)^{-3} \ ; \ a(t) = a_0 \left(\frac{t}{t_0}\right)^{\frac{2}{3}}$$

$$\mathrm{VD} \quad : \quad w = -1 : \rho(t) = \rho_0 \ ; \ a(t) \propto e^{Ht}$$

A neat equation

$$\rho_c(t) \equiv \frac{3H^2}{8\pi G} \quad ; \quad \Omega(t) \equiv \frac{\rho}{\rho_c}$$

Friedmann eqn

$$\Omega_m + \Omega_\Lambda + \Omega_k = 1$$

Ω_m - baryons, dark matter, neutrinos, electrons, radiation ...

Ω_Λ - dark energy ; Ω_k - spatial curvature

$$\rho_c(t_0) \equiv 1.88 h^2 * 10^{-29} \, g cm^{-3}$$

Critical density

Current bounds on H(z) -- Komatsu et al 2010 - (WMAP7+BAO+SN)

$$\mathbf{H^2(z) = H_0^2 \left(\Omega_r (1+z)^4 + \Omega_m (1+z)^3 + \Omega_k (1+z)^2 + \Omega_{de} \exp\left(3 \int_0^z \frac{1+w(z')}{1+z'} dz' \right) \right)}$$

(Expansion rate) -- H_0=70.4 ± 1.3 km/s/Mpc

(radiation) -- $\Omega_r = (8.5 \pm 0.3) \times 10^{-5}$

(baryons) -- $\Omega_b = 0.0456 \pm 0.0016$

(dark matter) -- $\Omega_m = 0.227 \pm 0.014$

(curvature) -- $\Omega_k < 0.008$ (95%CL)

(dark energy) -- $\Omega_{de} = 0.728 \pm 0.015$

(de eqn of state) -- $1+w = 0.001 \pm 0.057$ -- looks like a cosm const.

If allow variation of form : $w(z) = w_0 + w' z/(1+z)$ then
$w_0 = -0.93 \pm 0.12$ and $w' = -0.38 \pm 0.65$ (68% CL)

Weighing the Universe

$$\Omega_m + \Omega_\Lambda + \Omega_k = 1$$

$1.\ \Omega_m$

a. Cluster baryon abundance using X-ray measurements of intracluster gas, or SZ measurements.

b. Weak grav lensing and large scale peculiar velocities.

c. Large scale structure distribution.

d. Numerical simulations of cluster formation.

$$\Omega_m h^2 = 0.1369 \pm 0.0037$$

$$\Omega_m << 1$$

(Komatsu et al, 2008) (WMAP5)

$H_0 = 70.4 \pm 1.3$ km s^{-1} Mpc^{-1}

2. Ω_b

BBN → $\Omega_b h^2 = 0.0225 \pm 0.0005 \ (68\% \ CL)$

↓

Majority of baryonic matter dark.

$\Omega_b << \Omega_m$

↓

Require Dark matter !!

CDM	HDM – strongly constrained
Axions	Neutrinos
Neutralinos	WDM
PBH's	Sterile neutrinos
Supermassive relics …	

Supersymmetry and dark matter

Neutrinos not likely unless almost degenerate in mass, require 5-40eV.

WIMPS such as neutralinos, axions, axinos, gravitinos…

Interactions with matter vary enormously in strength: neutralinos (10^{-2}) – gravitinos (10^{-33}).

Neutralino- well motivated, LSP (assumption), gives closure for range of SUSY masses below a few TeV.

Ex: Gaugino like neutralino has allowed mass in range 30-150 GeV.

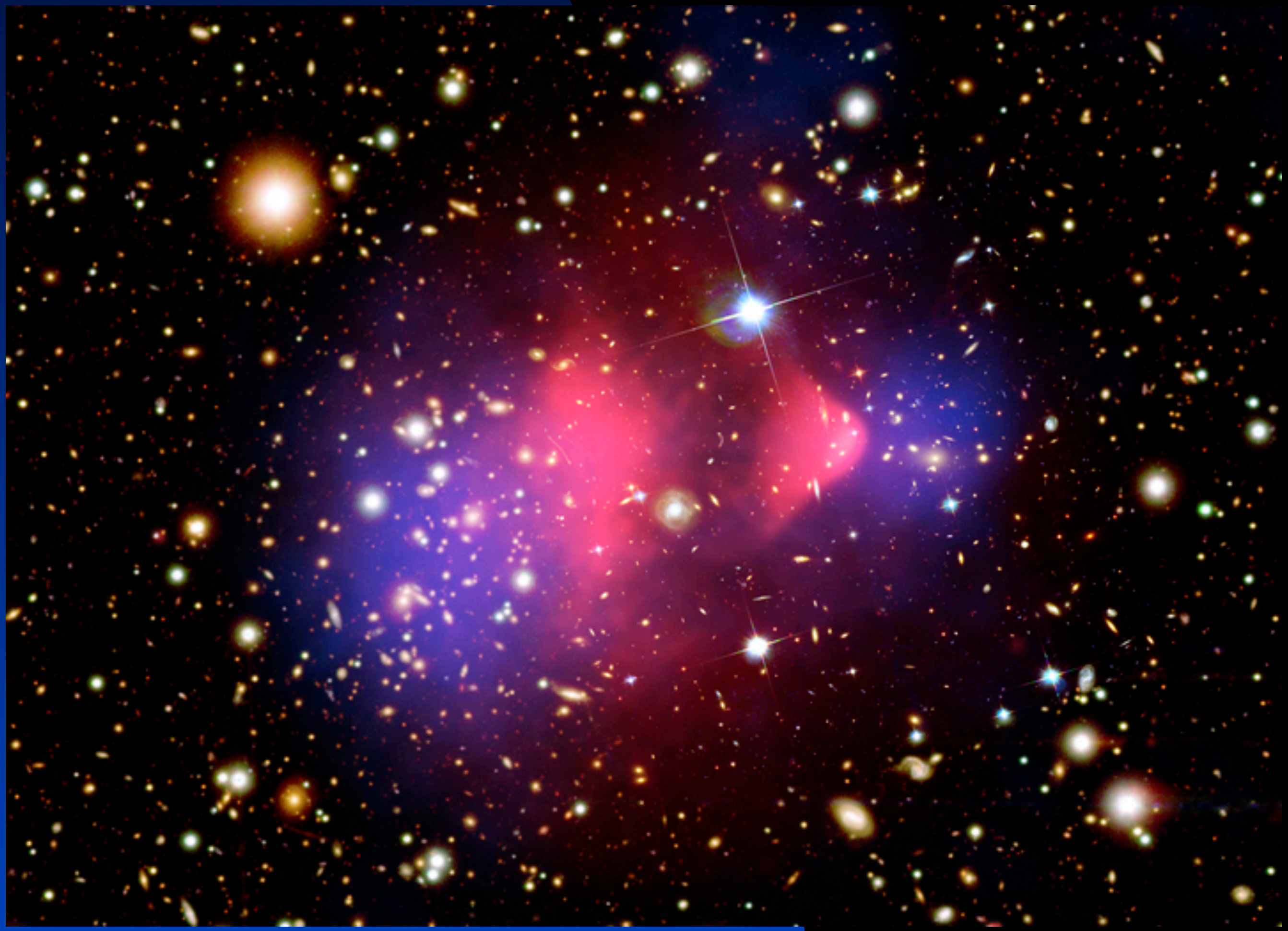
Fingers crossed for LHC

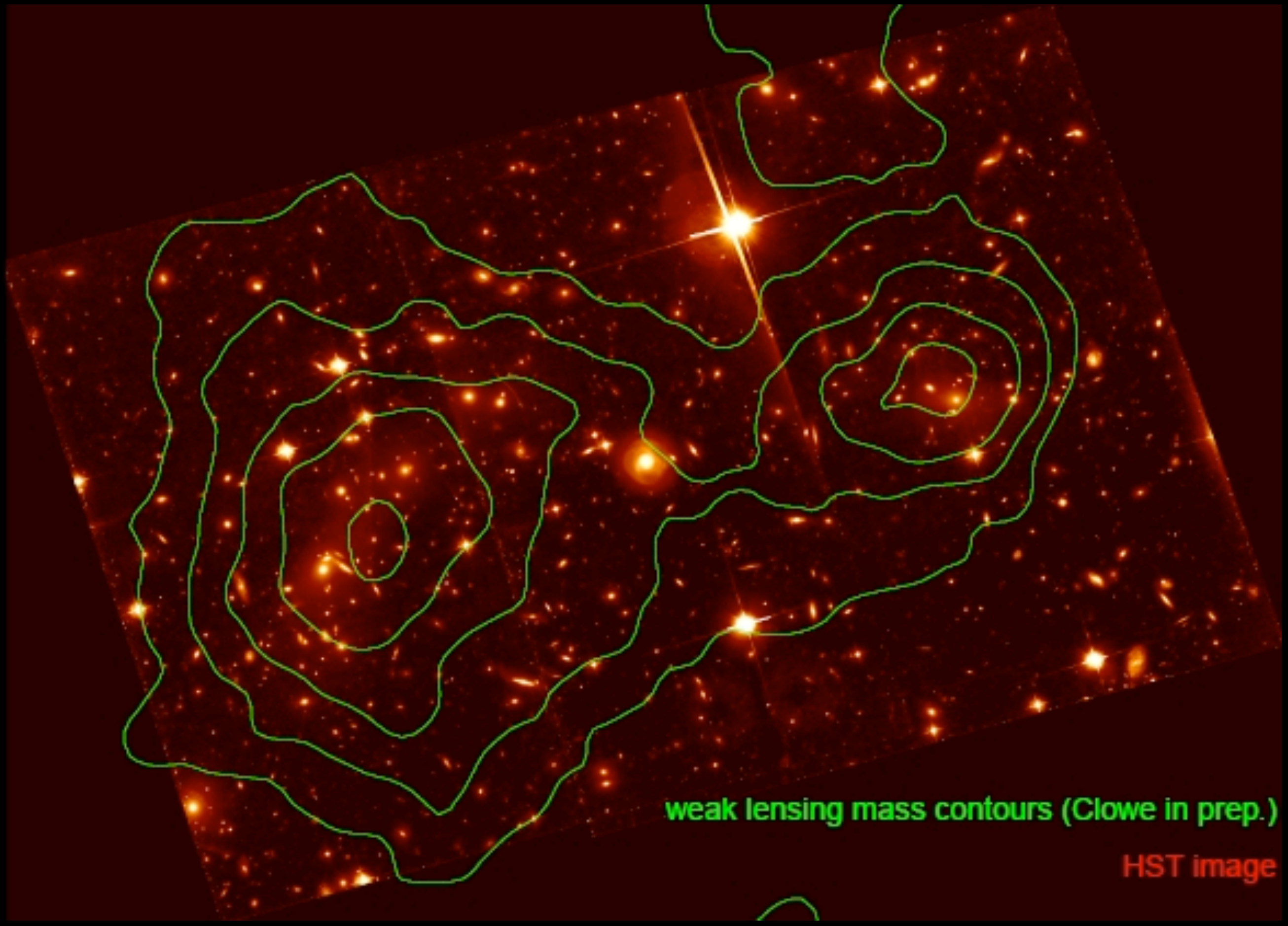
Indirect evidence for Dark Matter -- Bullet Cluster

Two clusters of galaxies colliding.

Dark matter in each passes straight through and doesn't interact -- seen through weak lensing in right image.

Ordinary matter in each interacts in collision and heats up -- seen through infra red image on left.





Clowe et al 2006

Evidence for Dark Energy?

Enter CMBR:

$$3.\ \Omega_0 = \Omega_m + \Omega_\Lambda$$

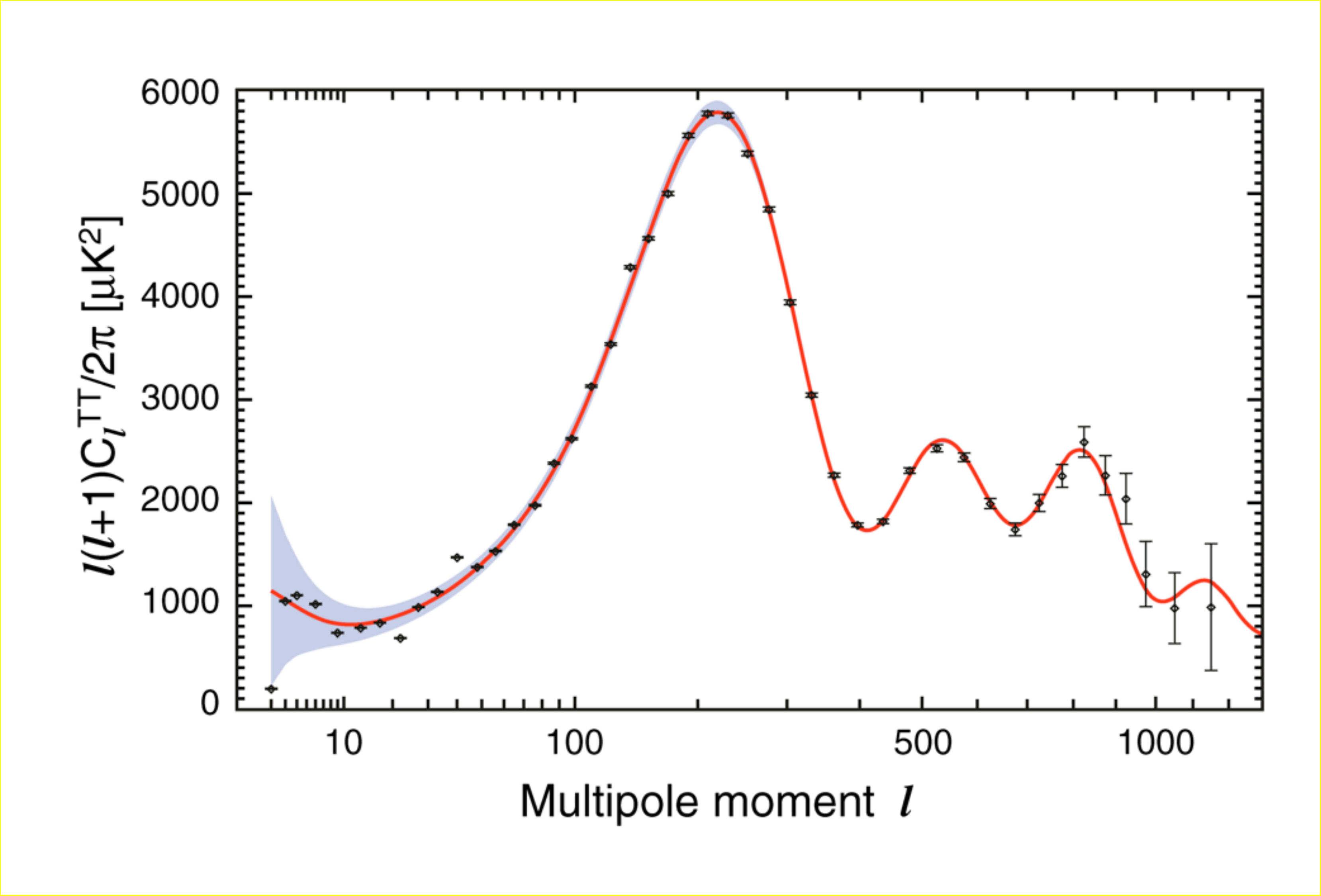
Provides clue. 1st angular peak in power spectrum.

$$l_{peak} \approx \frac{220}{\sqrt{\Omega_0}}$$

$$|1 - \Omega_0| = 0.03^{+0.026}_{-0.025}$$

WMAP3-Depends on assumed priors

Spergel et al 2006



$$-0.0175 < \Omega_k < 0.0085$$

Dunkley et al 2008 (WMAP5)

WMAP7 and dark energy

(Komatsu et al, 2010)

Assume flat univ +
+BAO+ SNLS:

$$w = -0.980 \pm 0.053$$

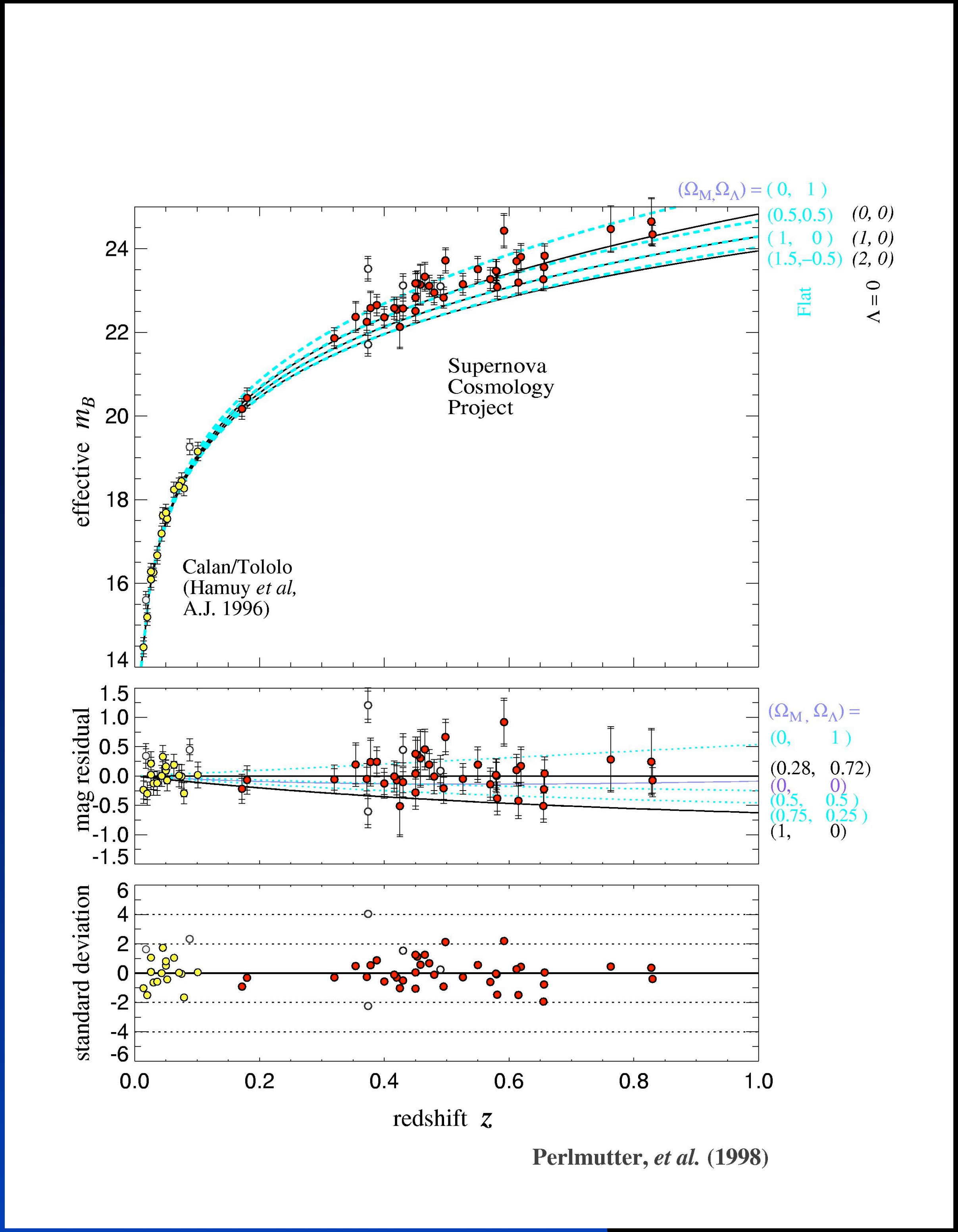
Drop prior of flat univ:
WMAP + BAO +
SNLS:

$$w = -0.999^{+0.057}_{-0.056} \quad \Omega_k = -0.0057^{+0.0067}_{-0.0068}$$

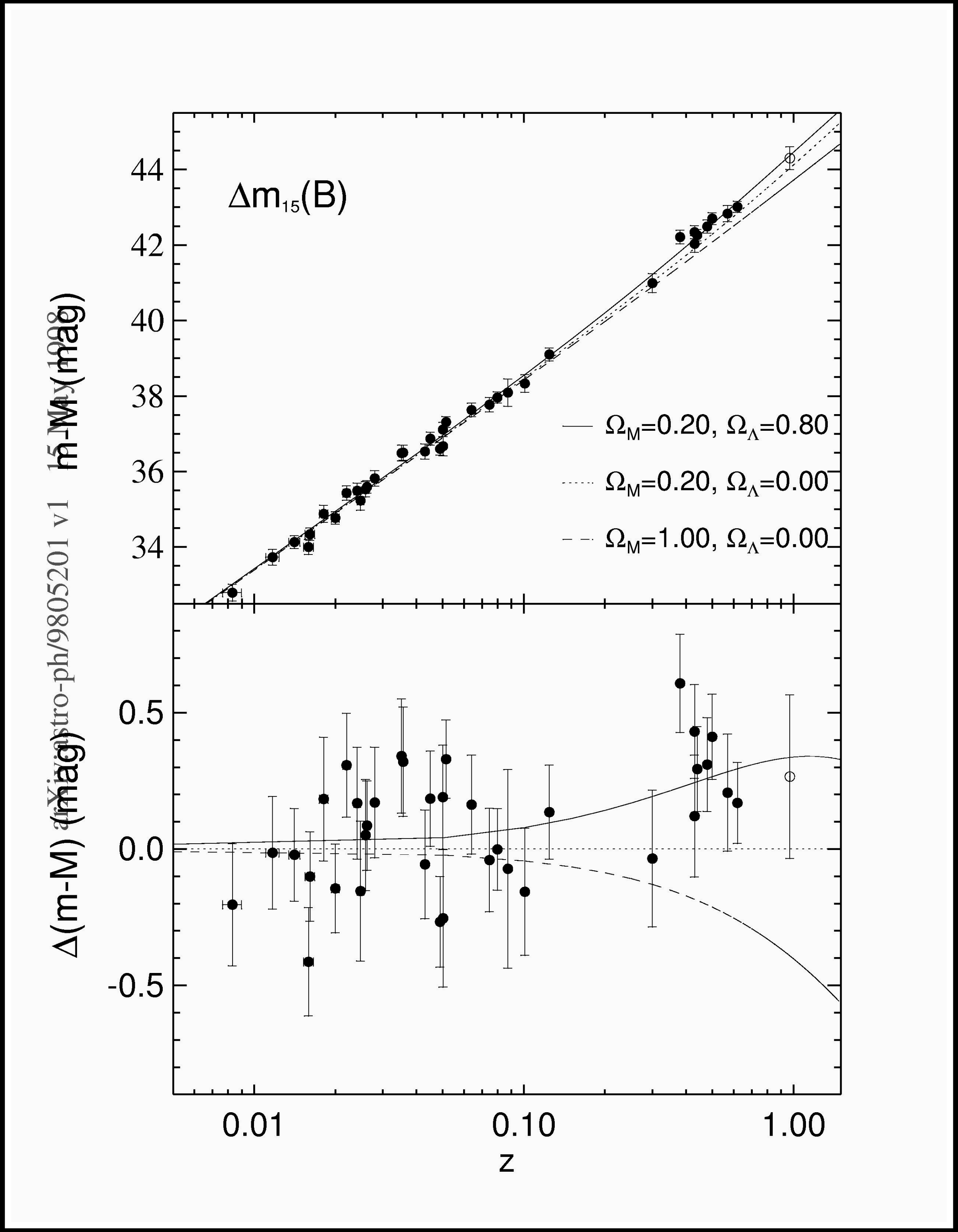
Drop assumption of
const w but keep flat
univ: WMAP + BAO
+ SNLS:

$$\begin{aligned} w_0 &= -0.93 \pm 0.12 \\ w_a &= -0.38^{+0.66}_{-0.65} \end{aligned}$$

The Supernova breakthrough 1998

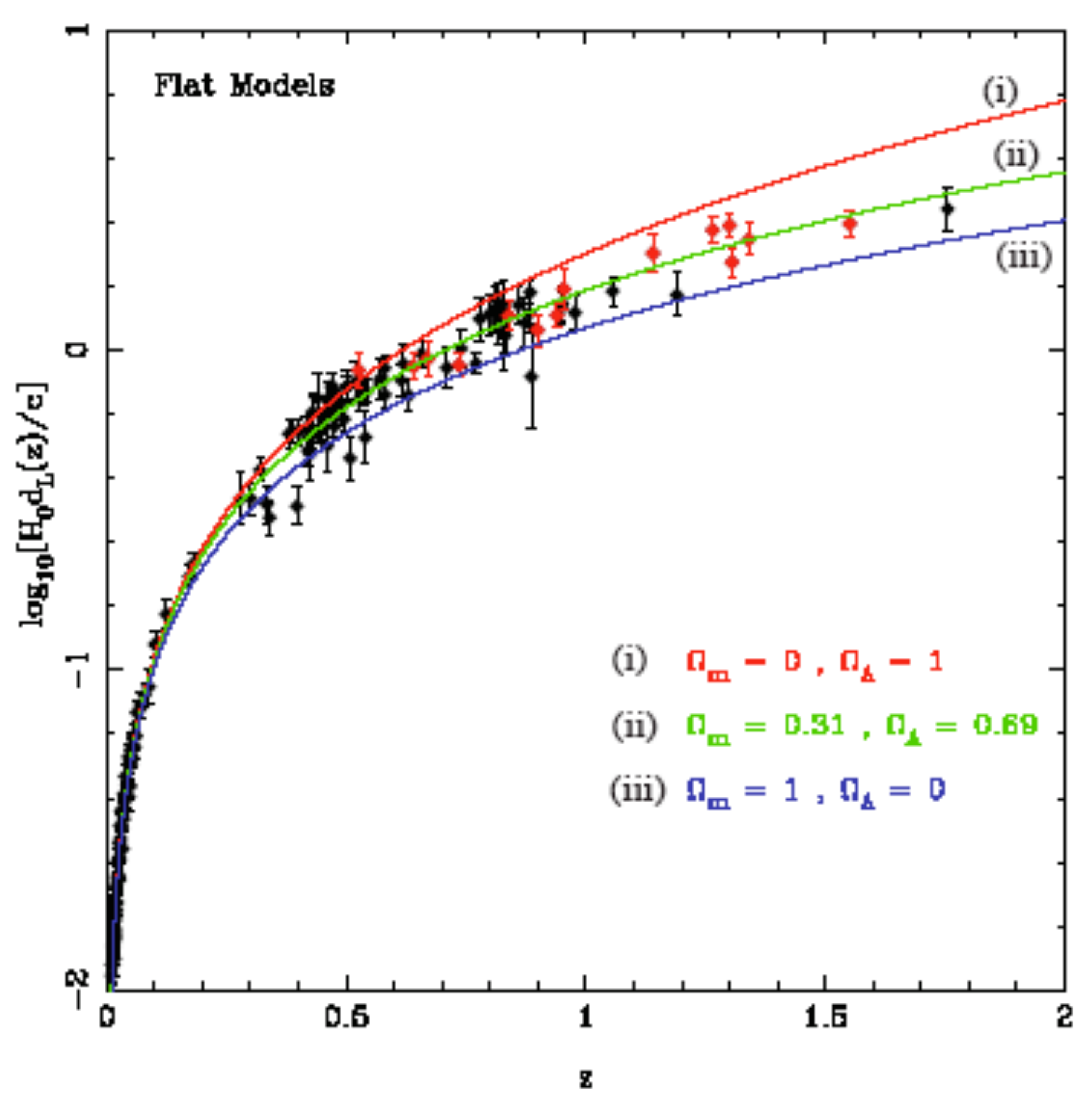


Perlmutter et al 1999



Riess et al 1998

Type Ia Luminosity distance v z [Reiss et al 2004]



Flat model
Black dots -- Gold data set
Red dots -- HST

$$(i)\Omega_m = 0,\ \Omega_\Lambda = 1 \quad (ii)\Omega_m = 0.31,\ \Omega_\Lambda = 0.69 \quad (iii)\Omega_m = 1,\ \Omega_\Lambda = 0$$

Coincidence problem – why now?

Recall: $\frac{\ddot{a}}{a} \geq 0 <-> = (\rho + 3p) \leq 0$

If: $\rho_x = \rho_x^0 \, a^{-3(1+w_x)}$

Universe dom by Quintessence at: $z_x = \left(\frac{\Omega_x}{\Omega_m}\right)^{\frac{1}{3w_x}} - 1$

$$\left(\frac{\Omega_x}{\Omega_m}\right) = \frac{7}{3} \rightarrow z_x = 0.5,\ 0.3 \text{ for } w_x = -\frac{2}{3},\ -1$$

Univ accelerates at: $z_a = \left(-(1+3w_x)\frac{\Omega_x}{\Omega_m}\right)^{\frac{-1}{3w_x}} - 1$

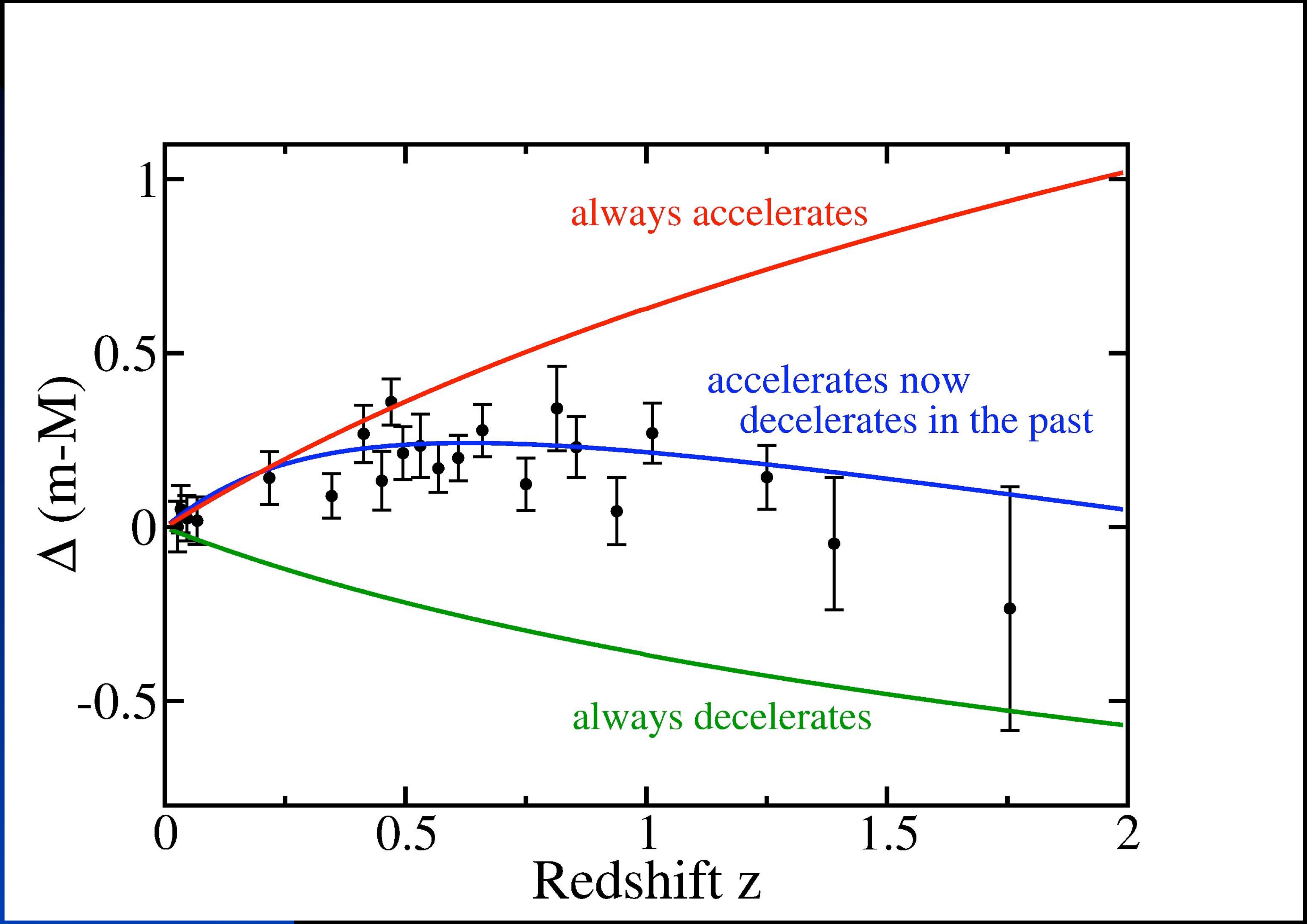
$$z_a = 0.7,\ 0.5 \text{ for } w_x = -\frac{2}{3},\ -1$$

Constraint:

$$-0.11 < 1 + w < 0.14$$

Komatsu et al 2008 (WMAP5)

The acceleration has not been forever -- pinning down the turnover will provide a very useful piece of information.



Different approaches to Dark Energy include amongst many:

- A true cosmological constant -- but why this value?
- Time dependent solutions arising out of evolving scalar fields -- Quintessence/K-essence.
- Modifications of Einstein gravity leading to acceleration today.
- Anthropic arguments.
- Perhaps GR but Universe is inhomogeneous.

Over 2500 papers on archives since 1998 with dark energy in title.

Early evidence for a cosmological constant type term.

1987: Weinberg argued that anthropically ρ_{vac} could not be too large and positive otherwise galaxies and stars would not form. It should be not be very different from the mean of the values suitable for life which is positive, and he obtained $\Omega_{vac} \sim 0.6$

1990: Observations of LSS begin to kick in showing the standard $\Omega_{CDM} = 1$ struggling to fit clustering data on large scales, first through IRAS survey then through APM (Efstathiou et al)

1990: Efstathiou, Sutherland and Maddox - Nature (238) -- explicitly suggest a cosmology dominated today by a cosmological constant with $\Omega_{vac} < 0.8$!

1998: Type Ia SN show striking evidence of cosm const and the field takes off.

The problem with the cosmological constant

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} - \lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Einstein (1917) -- static universe with dust

Not easy to get rid of it, once universe found to be expanding.

Anything that contributes to energy density of vacuum acts like a cosmological constant

$$< T_{\mu\nu} > = < \rho > g_{\mu\nu}$$

Lorentz inv

$$\lambda_{eff} = \lambda + 8\pi G < \rho >$$

or

$$\rho_V = \lambda_{eff} / 8\pi G$$

Effective cosm const

Effective vac energy

$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{8\pi G}{3}\rho + \lambda - \frac{k}{a^2}$$

$$H_0 \simeq 10^{-10} yr^{-1} : \frac{|k|}{a_0^2} \leq H_0^2 : |\rho - < \rho > | \leq \frac{3H_0^2}{8\pi G}$$

Age

Flat

Non-vac matter

$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{8\pi G}{3}\rho + \lambda - \frac{k}{a^2}$$

$$H_0 \simeq 10^{-10} yr^{-1} : \frac{|k|}{a_0^2} \leq H_0^2 : |\rho - <\rho>| \leq \frac{3H_0^2}{8\pi G}$$

Hence: $$\lambda_{eff} \leq H_0^2 \; or |\rho_V| \leq 10^{-29} gcm^{-3} \simeq 10^{-47} GeV^4$$

Problem: expect <ρ> of empty space to be much larger. Consider summing zero-point energies (ħω/2) of all normal modes of some field of mass m up to wave number cut off Λ>>m:

$$<\rho> = \int_0^\Lambda \frac{4\pi k^2 dk}{2(2\pi)^3}\sqrt{k^2+m^2} \simeq \frac{\Lambda^4}{16\pi^2}$$

For many fields (i.e. leptons, quarks, gauge fields etc...):

$$<\rho> = \frac{1}{2}\sum_{\text{fields}} g_i \int_0^{\Lambda_i} \sqrt{k^2+m^2}\frac{d^3k}{(2\pi)^3} \simeq \sum_{\text{fields}} \frac{g_i \Lambda_i^4}{16\pi^2}$$

where g_i are the dof of the field (+ for bosons, - for fermions).

Imagine just one field contributed an energy density $\rho_{cr} \sim (10^{-3}\ eV)^4$. Implies the cut-off scale Λ<0.01 eV -- well below scales we understand the physics of.

Planck scale: $\Lambda \simeq (8\pi G)^{-1/2} \rightarrow <\rho> \simeq 2\times 10^{71} GeV^4$

But: $|\rho_V| = |<\rho> + \lambda/8\pi G| \leq 2\times 10^{-47} GeV^4$

Must cancel to better than 118 decimal places.

Even at QCD scale require 41 decimal places!

Very unlikely a classical contribution to the vacuum energy density will cancel this quantum contribution to such high precision

Not all is lost -- what if there is a symmetry present to reduce it? Supersymmetry does that. Every boson has an equal mass SUSY fermion partner and vice-versa, so their contributions to $<\rho>$ cancel.

However, SUSY seems broken today - no SUSY partners have been observed, so they must be much heavier than their standard model partners. If SUSY broken at scale M, expect $<\rho>\sim M^4$ because of breakdown of cancellations. Current bounds suggest M~1TeV which leads to a discrepancy of 60 orders of magnitude as opposed to 118 !

Still a problem of course -- is there some unknown mechanism perhaps from quantum gravity that will make the vacuum energy vanish ?

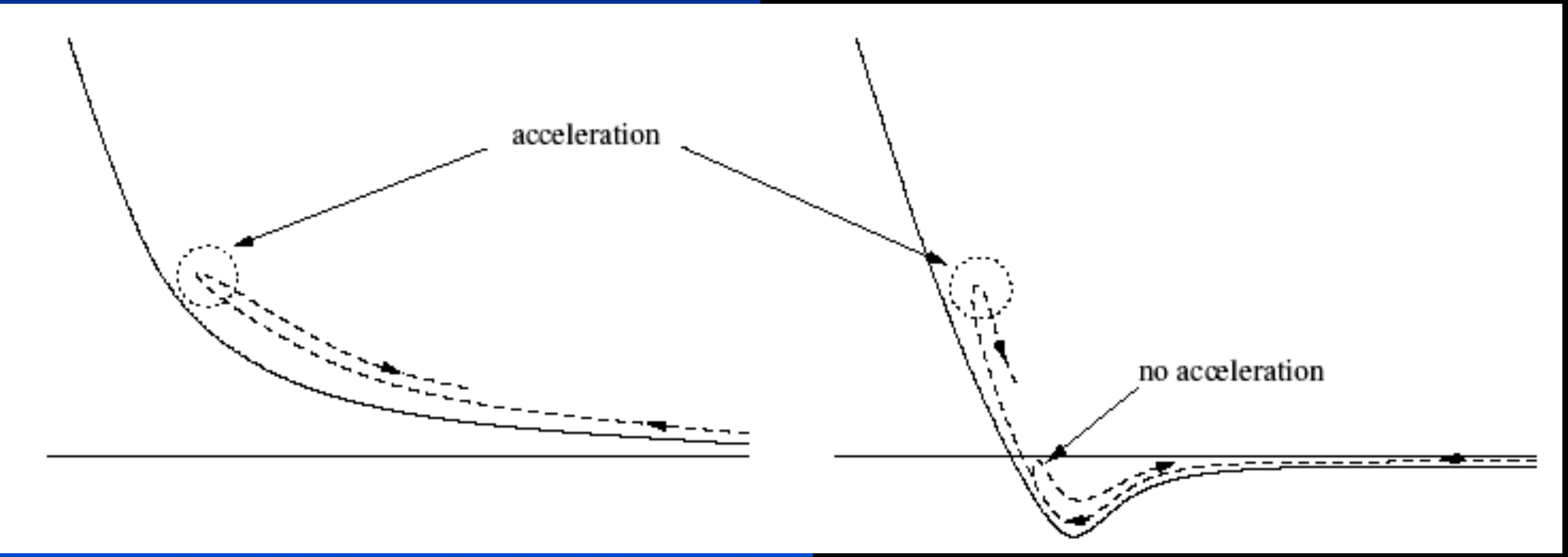
Quintessence and M-theory -- where are the realistic models?

`No go' theorem: forbids cosmic acceleration in cosmological solutions arising from compactification of pure SUGR models where internal space is time-independent, non-singular compact manifold without boundary --[Gibbons]

Recent extension: forbids four dimensional cosmic acceleration in cosmological solutions arising from warped dimensional reduction --[Wesley 08]

Avoid no-go theorem by relaxing conditions of the theorem.

1. Allow internal space to be time-dependent, analogue of time-dependent scalar fields (radion)



Current realistic potentials are too steep

Models kinetic, not matter domination before entering accelerated phase.

Four form Flux and the cosm const: [Bousso and Polchinski]

Effective 4D theory from $M^4 x S^7$ compactification

$$S = \int d^4x \sqrt{-g}\left(\frac{1}{2\kappa^2}R + \Lambda_b - \frac{1}{2\cdot 4!}F_4^2\right)$$

Negative bare cosm const: $-\Lambda_b$

EOM: $\nabla_\mu\left(\sqrt{-g}F^{\mu\nu\rho\sigma}\right) = 0$ $\longrightarrow F^{\mu\nu\rho\sigma} = c\epsilon^{\mu\nu\rho\sigma}$

Eff cosm const: $\Lambda = -\Lambda_b - \frac{1}{48}F_4^2 = -\Lambda_b + \frac{c^2}{2}$

Quantising c and considering J fluxes $\Lambda = -\Lambda_b + \frac{1}{2}\sum_{i=1}^{J} n_i^2 q_i^2$

Observed cosm const with J~100

Still needed to stabilise moduli but opened up way of obtaining many de Sitter vacua using fluxes -- String Landscape in which all the vacua would be explored because of eternal inflation.

1.The String Landscape approach

Type IIB String theory compactified from 10 dimensions to 4.

Internal dimensions stabilised by fluxes.

Many many vacua ~ 10^{500} !

Typical separation ~ $10^{-500}\ \Lambda_{pl}$

Assume randomly distributed, tunnelling allowed between vacua --> separate universes .

Anthropic : Galaxies require vacua < $10^{-118}\ \Lambda_{pl}$ [Weinberg] Most likely to find values not equal to zero!

[Witten 2008]

Landscape gives a realisation of the multiverse picture.

There isn't one true vacuum but many so that makes it almost impossible to find our vacuum in such a Universe which is really a multiverse.

So how can we hope to understand or predict why we have our particular particle content and couplings when there are so many choices in different parts of the universe, none of them special ?

This sounds like bad news, we will rely on anthropic arguments to explain it through introducing the correct measures and establishing peaks in probability distributions.

Or perhaps, it isn't a cosmological constant, but a new field such as Quintessence which will eventually drive us to a unique vacuum with zero vacuum energy -- that too has problems, such as fifth force constraints, as we will see.

2. Λ from a self-tuning universe [Feng et al 2001].

Λ relaxes through nucleation of branes coupled to gauge potential, the particular branes depending on the compactification assumed.

3. Relaxation of Λ [Kachru et al 2000, Arkani Hamad et al 2000, Burgess et al].

Relies on presence of extra dimension to remove the gravitational effect of the vacuum energy.

3 brane solns in 5D eff theories leads to standard model vacuum energy warping the higher dimensional spacetime while preserving 4D flatness with no cosm constant.

4. Λ from the Cyclic Perspective [Steinhardt and Turok 2002, 2006].

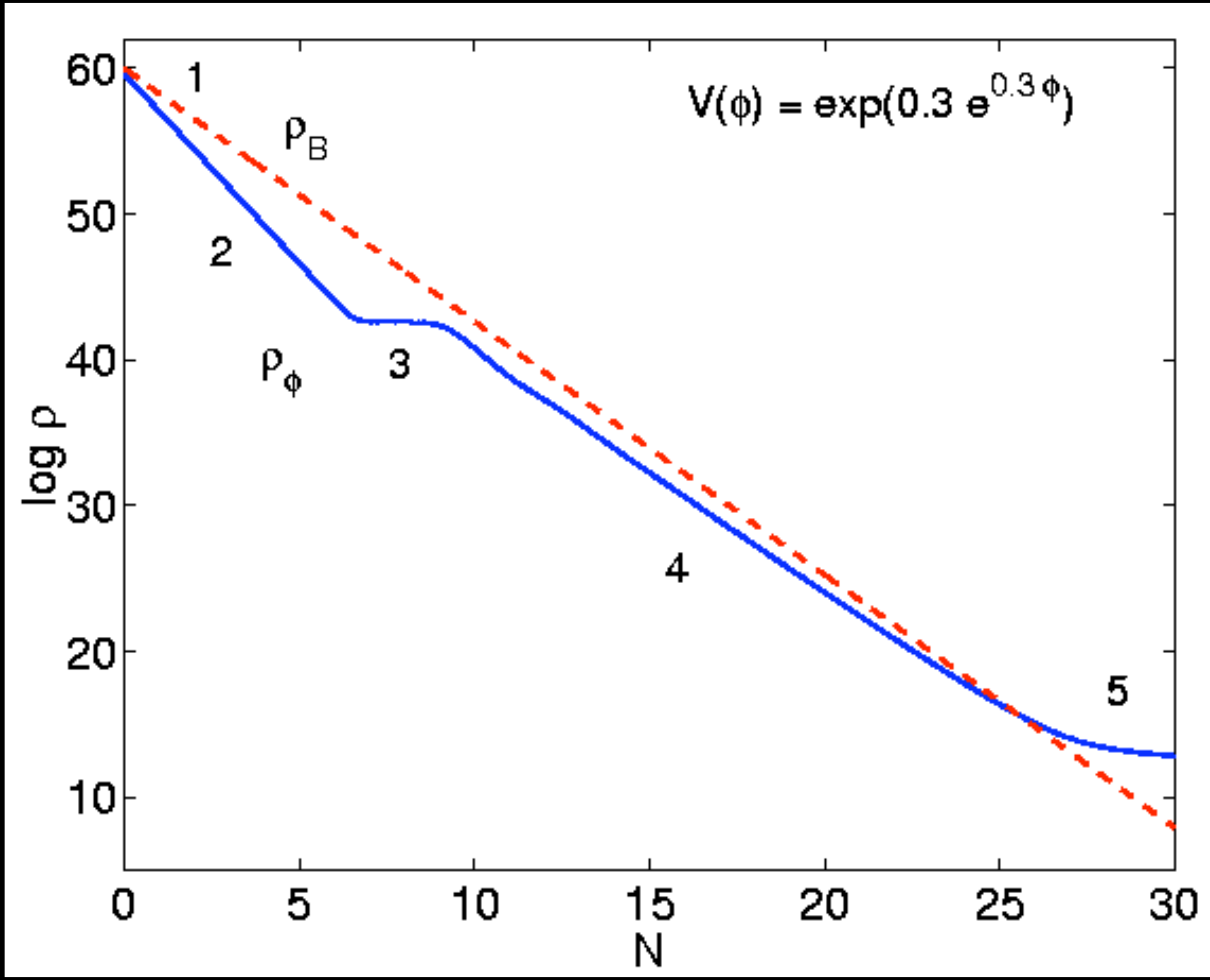
Key feature, because many cycles and each cycle lasts a trillion years, universe today is much older than today's Hubble time, so Λ has had long time to reduce to the observed value today.

Slowly rolling scalar fields -- Quintessence

Peebles and Ratra;

Zlatev, Wang and Steinhardt

1. PE → KE
2. KE dom scalar field energy den.
3. Const field.
4. Attractor solution: almost const ratio KE/PE.
5. PE dom.

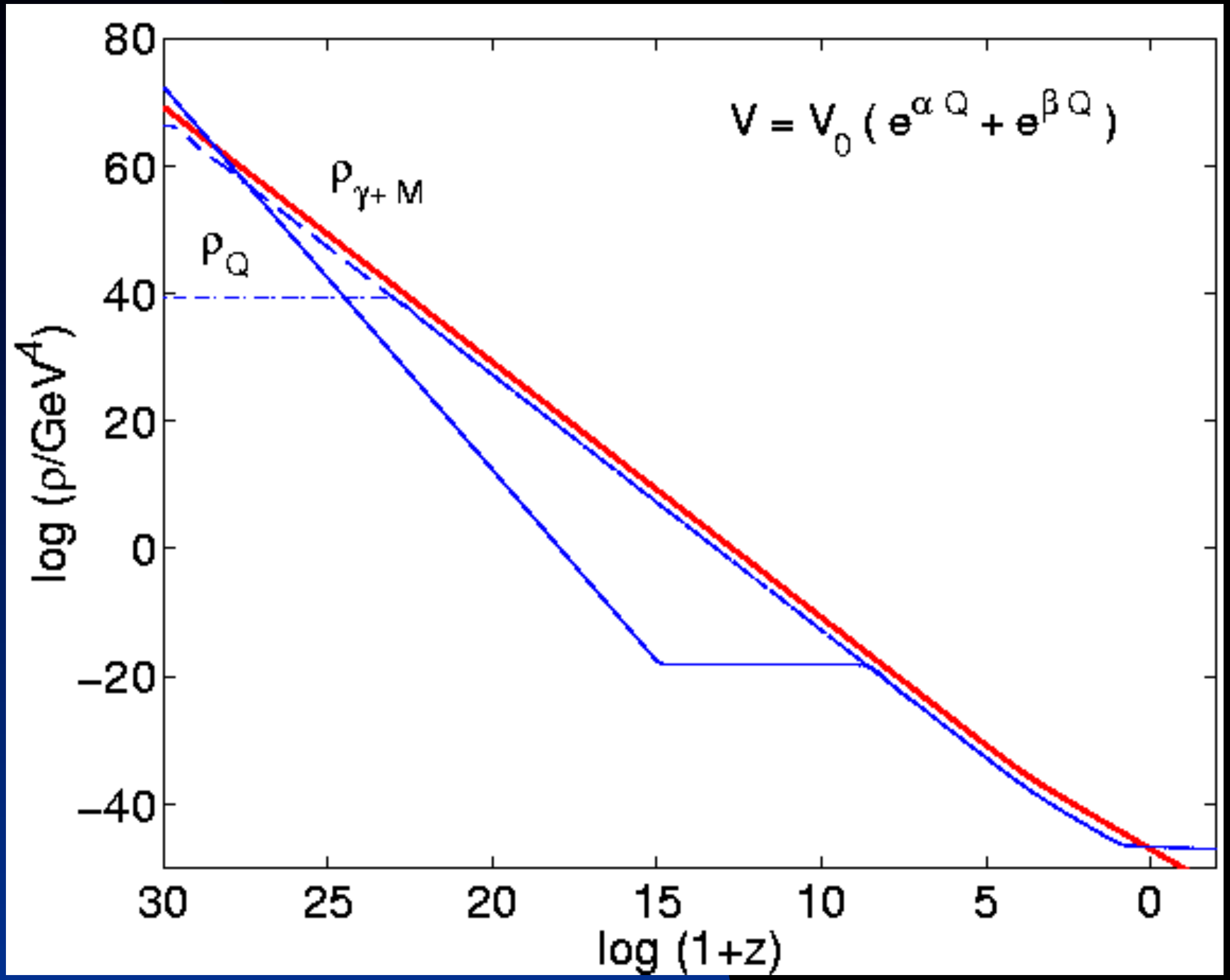


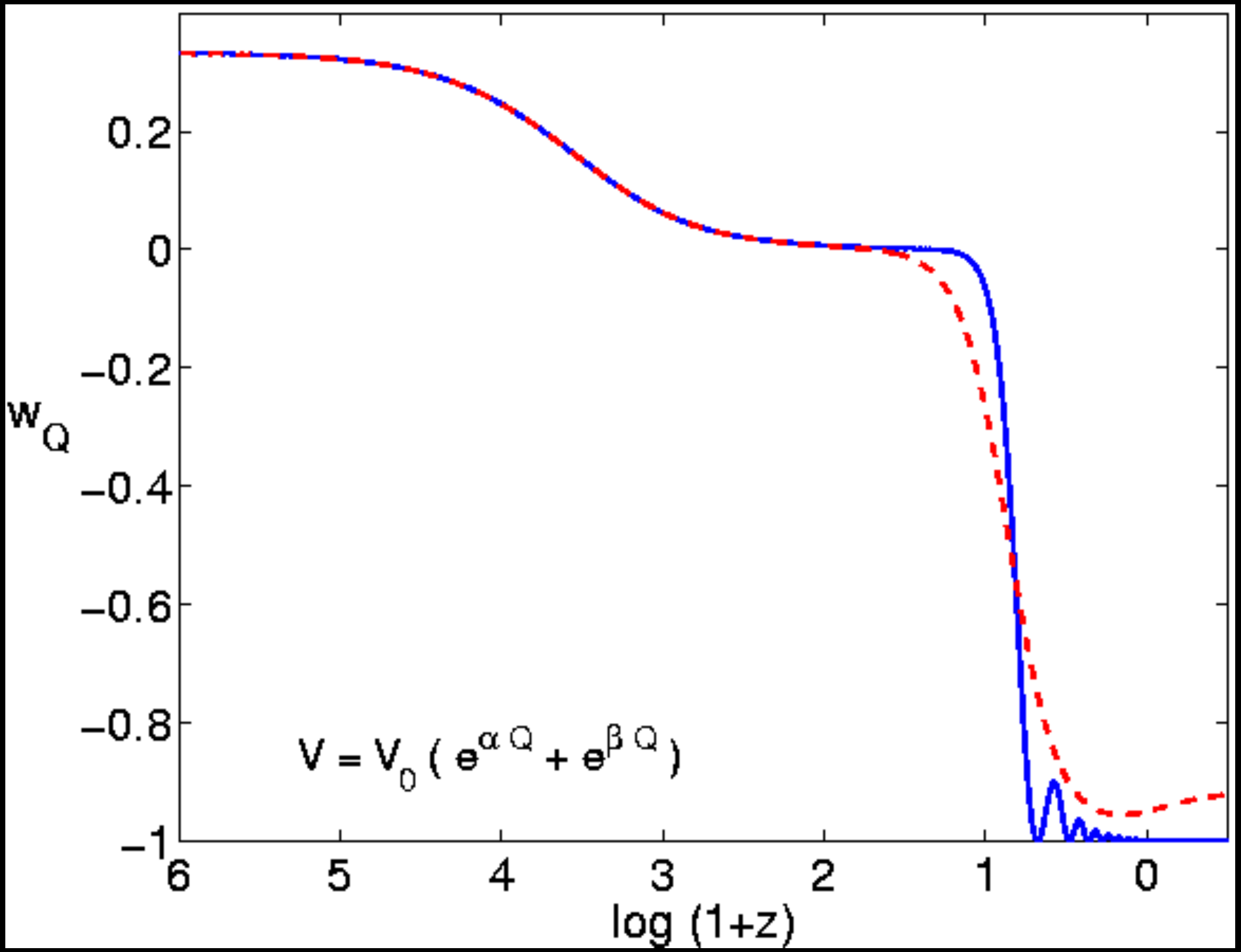
Nunes

Attractors make initial conditions less important

$$V(\phi) = V_1 + V_2 = V_{01} e^{-\kappa\lambda_1\phi} + V_{02} e^{-\kappa\lambda_2\phi}$$

EC and Nunes





$\alpha = 20; \beta = 0.5$ Scaling for wide range of i.c.

Fine tuning: $V_0 \approx \rho_\phi \approx 10^{-47}\ \mathrm{GeV}^4 \approx (10^{-3}\ \mathrm{eV})^4$

Mass: $m \approx \sqrt{\frac{V_0}{M_{pl}^2}} \approx 10^{-33}\ \mathrm{eV}$

Fifth force !

4. Quintessential Inflation – Peebles and Vilenkin

Same field provides both initial inflaton and todays Quintessence – not tracker.

$$V(\phi) = \lambda(\phi^4 + M^4) \quad \text{for } \phi < 0$$
$$= \frac{\lambda M^4}{1 + (\phi/M)^\alpha} \quad \text{for } \phi \geq 0$$

Reheating at end of inflation from grav particle production

Avoids need for minima in inflaton potential

Ford

$$\lambda = 10^{-14} : \Omega_{\phi_0} = 0.7 \Rightarrow \alpha = 4 ; M = 10^5 \text{ GeV},$$

Need to be careful do not overproduce grav waves.

Recent interesting proposal to link inflation, dark matter and dark energy through single mechanism

Liddle et al

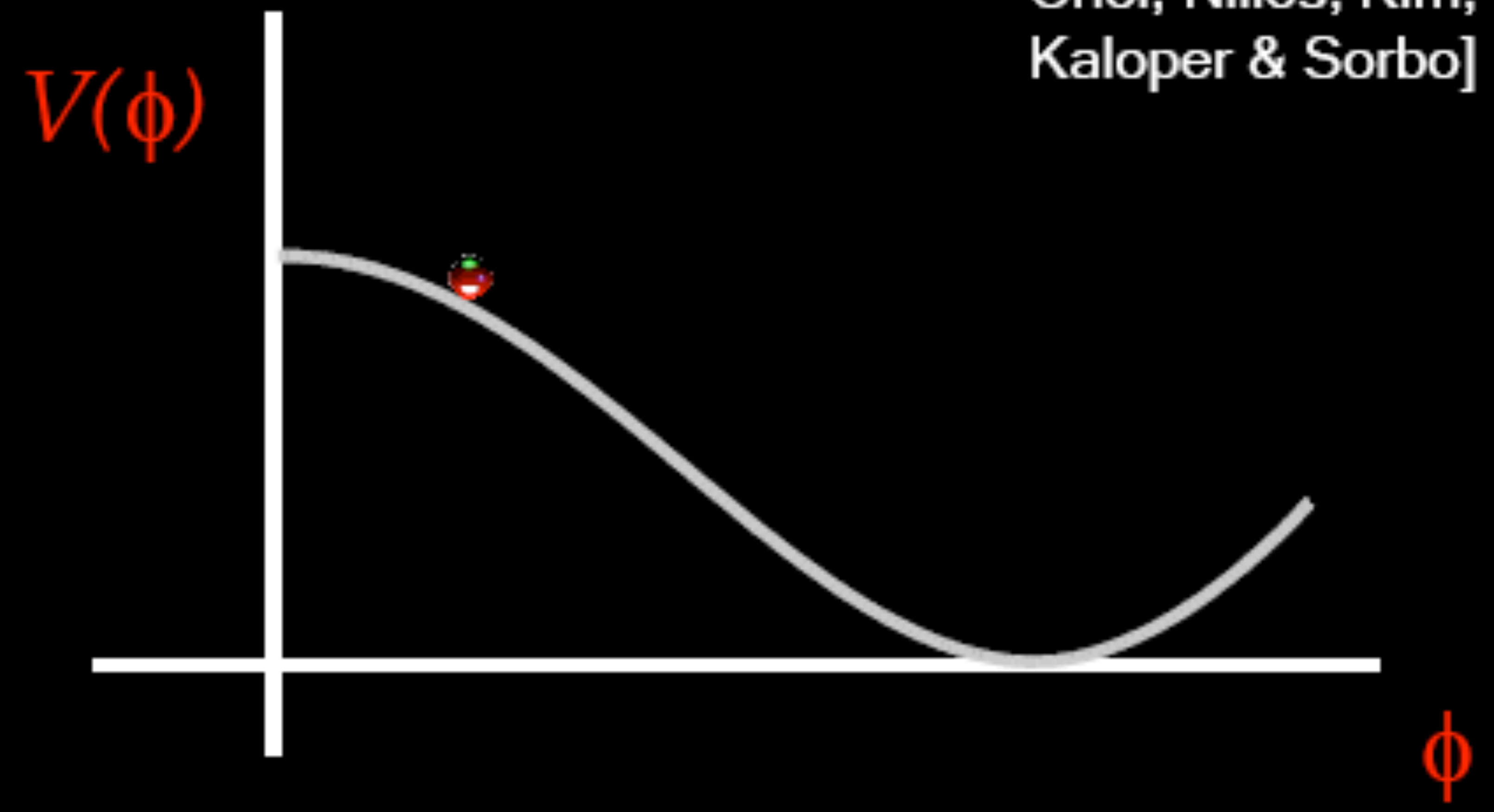
Particle physics inspired models?

Pseudo-Goldstone Bosons -- approx sym ϕ --> ϕ + const.

Leads to naturally small masses, naturally small couplings

[Hill, Freiman, et al; Choi; Nilles; Kim; Kaloper & Sorbo]

Barbieri et al



$$V(\phi) = \lambda^4 (1 + \cos(\phi / F_a))$$

Axions could be useful for strong CP problem, dark matter and dark energy.

1. Chameleon fields [Khoury and Weltman (2003) …]

Key idea: in order to avoid fifth force type constraints on Quintessence models, have a situation where the mass of the field depends on the local matter density, so it is massive in high density regions and light (m~H) in low density regions (cosmological scales).

2. Phantom fields [Caldwell (2002) …]

The data does not rule out w<-1. Can not accommodate in standard quintessence models but can by allowing negative kinetic energy for scalar field (amongst other approaches).

3. K-essence [Armendariz-Picon et al …]

Scalar fields with non-canonical kinetic terms. Advantage over Quintessence through solving the coincidence model?

Long period of perfect tracking, followed by domination of dark energy triggered by transition to matter domination -- an epoch during which structures can form. Similar fine tuning to Quintessence.

4. Interacting Dark Energy [Kodama & Sasaki (1985), Wetterich (1995), Amendola (2000) + others…]

Idea: why not directly couple dark energy and dark matter?

$$\begin{aligned} \text{Ein eqn} \quad &: \quad G_{\mu\nu} = 8\pi G T_{\mu\nu} \\ \text{General covariance} \quad &: \quad \nabla_\mu G^\mu_\nu = 0 \rightarrow \nabla_\mu T^\mu_\nu = 0 \end{aligned}$$

$$T_{\mu\nu} = \sum_i T^{(i)}_{\mu\nu} \rightarrow \nabla_\mu T^{\mu\,(i)}_\nu = -\nabla_\mu T^{\mu\,(j)}_\nu \quad \text{is ok}$$

Couple dark energy and dark matter fluid in form:

$$\begin{aligned} \nabla_\mu T^{\mu\,(\phi)}_\nu &= \sqrt{\frac{2}{3}}\kappa\beta(\phi) T^{\alpha\,(m)}_\alpha \nabla_\nu \phi \\ \nabla_\mu T^{\mu\,(m)}_\nu &= -\sqrt{\frac{2}{3}}\kappa\beta(\phi) T^{\alpha\,(m)}_\alpha \nabla_\nu \phi \end{aligned}$$

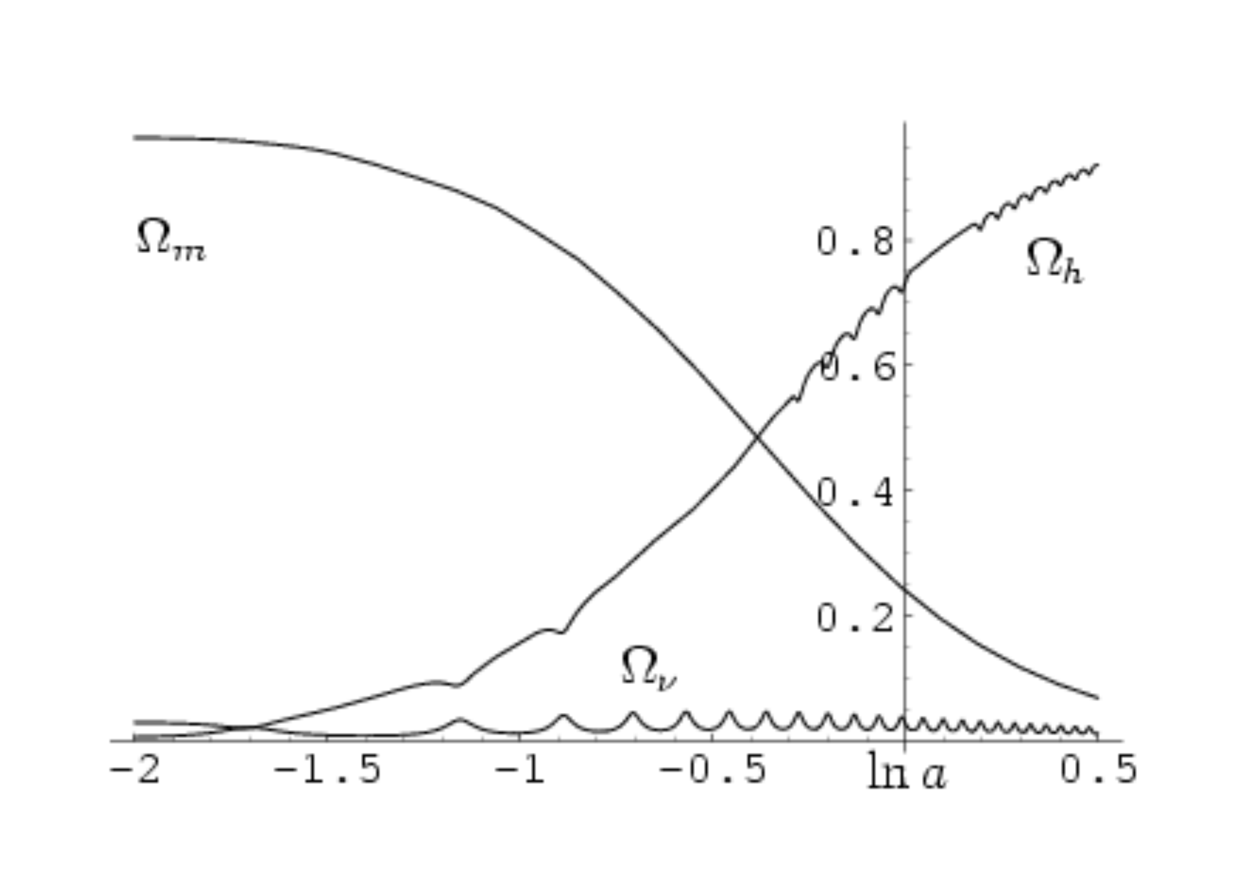
Including neutrinos -- 2 distinct DM families -- resolve coincidence problem [Amendola et al (2007)]

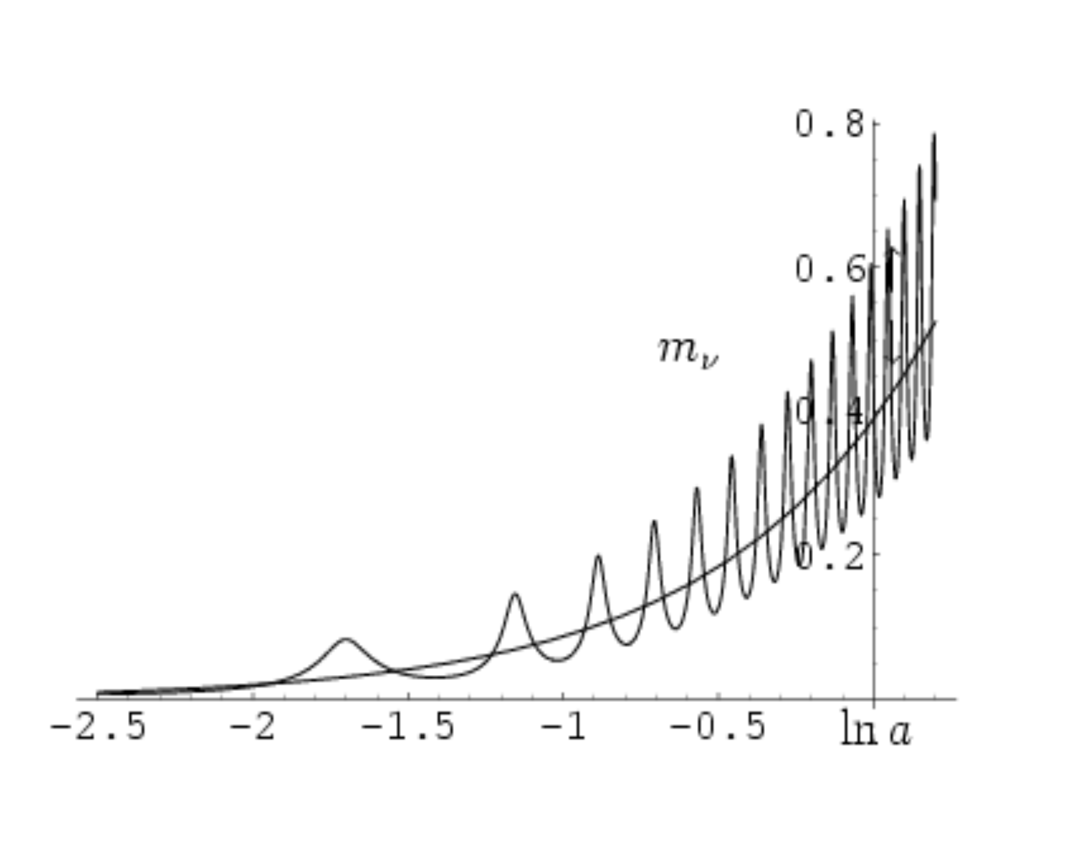
Depending on the coupling, find that the neutrino mass grows at late times and this triggers a transition to almost static dark energy.

Trigger scale set by when neutrinos become non-rel

$$[\rho_h(t_0)]^{\frac{1}{4}} = 1.07 \left(\frac{\gamma m_\nu(t_0)}{eV}\right)^{\frac{1}{4}} 10^{-3} eV$$

$$w_0 \approx -1 + \frac{m_\nu(t_0)}{12\mathrm{eV}}$$





m_ν

Perturbations in Interacting Dark Energy Models [Baldi et al (2008)]

Perturb everything linearly : Matter fluid example

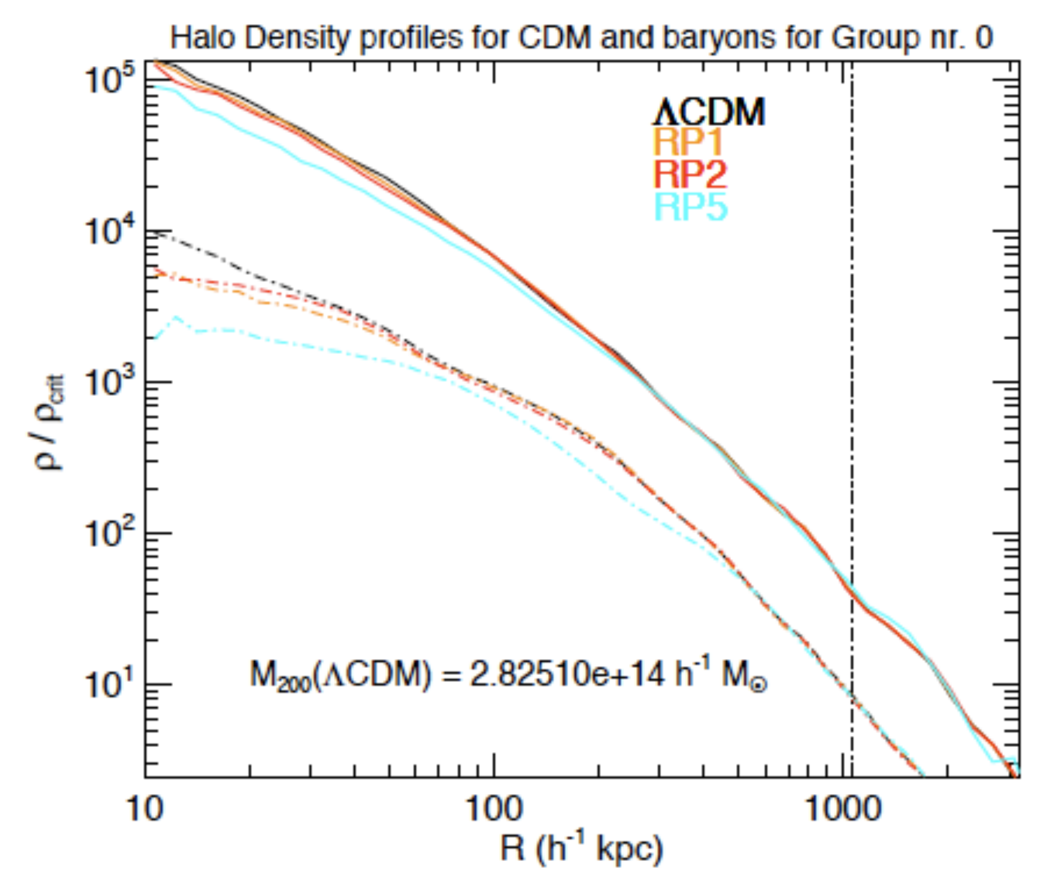
$$\ddot{\delta}_c + \left(2H - 2\beta\frac{\dot{\phi}}{M}\right)\dot{\delta}_c - \frac{3}{2}H^2[(1+2\beta^2)\Omega_c\delta_c + \Omega_b\delta_b] = 0$$

extra friction

modified grav interaction

vary DM particle mass

Include in simulations of structure formation : GADGET [Springel (2005)]



Density decreases as coupling β increases

Halo mass function modified.

Halos remain well fit by NFW profile.

Density decreases compared to ΛCDM as coupling β increases.

Scale dep bias develops from fifth force acting between CDM particles. enhanced as go from linear to smaller non-linear scales.

Still early days -- but this is where there should be a great deal of development.

Do we need Dark Energy?

Buchert (2000), Kolb et al (2006), Wiltshire (2007), Hunt and Sarkar (2007), Garcia-Bellido and Haugbolle (2008) + many others...

Attempts to describe universe without recourse to the fine tuned cosmological constant we appear to need.

Allow for possibility we live in an inhomogeneous universe -- voids arising from inhomogeneous flucns in early universe. Evidence is there for possible voids of scale ~ Gpc in local universe (i.e. cold spot in CMB)

We could be living close to the centre of a large void where Hubble flow is 30% faster than global rate. Void size ~ 2.5 Gpc in otherwise E-deS universe on large scales.

Apparent acceleration arises from curved photon paths in `open' patch of universe.

There is fine tuning required of course, must be within 100Mpc of centre of void to avoid induced dipole in CMB. Such LTB models not favoured from Bayesian Evidence compared to ΛCDM.

Garcia-Bellido and Haugbolle (2008)

Determining the best way to test for dark energy and parameterise the dark energy equation of state is a difficult task, not least given the number of approaches that exist to modeling it .

A thorough review competed by Rocky Kolb and his colleagues making up the Dark Energy Task Force.

Albrecht et al : astro-ph/0609591

Then their findings on the search for the best figure of merit:

Albrecht et al: arXiv:0901.0721

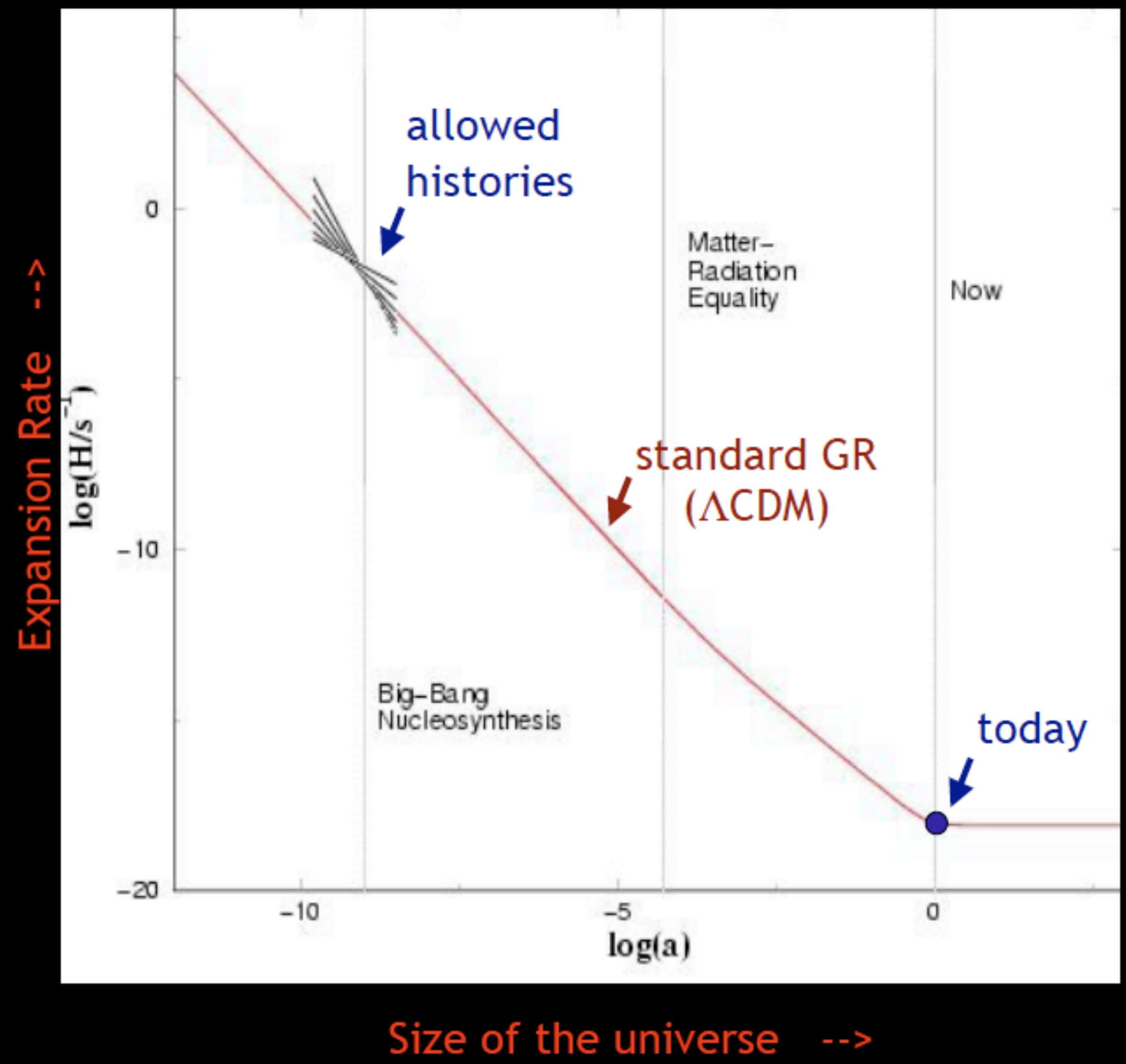
One of the key goals of DES - is the dark energy a cosmological constant, does it evolve or maybe its the gravity side we need to worry about.

Perhaps we are wrong -- maybe the question should be not whether dark energy exists, rather should we be modifying gravity?

Has become a big industry but it turns out to be hard to do too much to General Relativity without falling foul of data.

BBN occurred when the universe was about one minute old, about one billionth its current size. It fits well with GR and provides a test for it in the early universe.

Any alternative had better deliver the same successes not deviate too much at early times, but turn on at late times .



[Carroll & Kaplinghat 2001]

Any theory deviating from GR must do so at late times yet remain consistent with Solar System tests. Potential examples include:

- f(R) gravity -- coupled to higher curv terms, changes the dynamical equations for the spacetime metric.

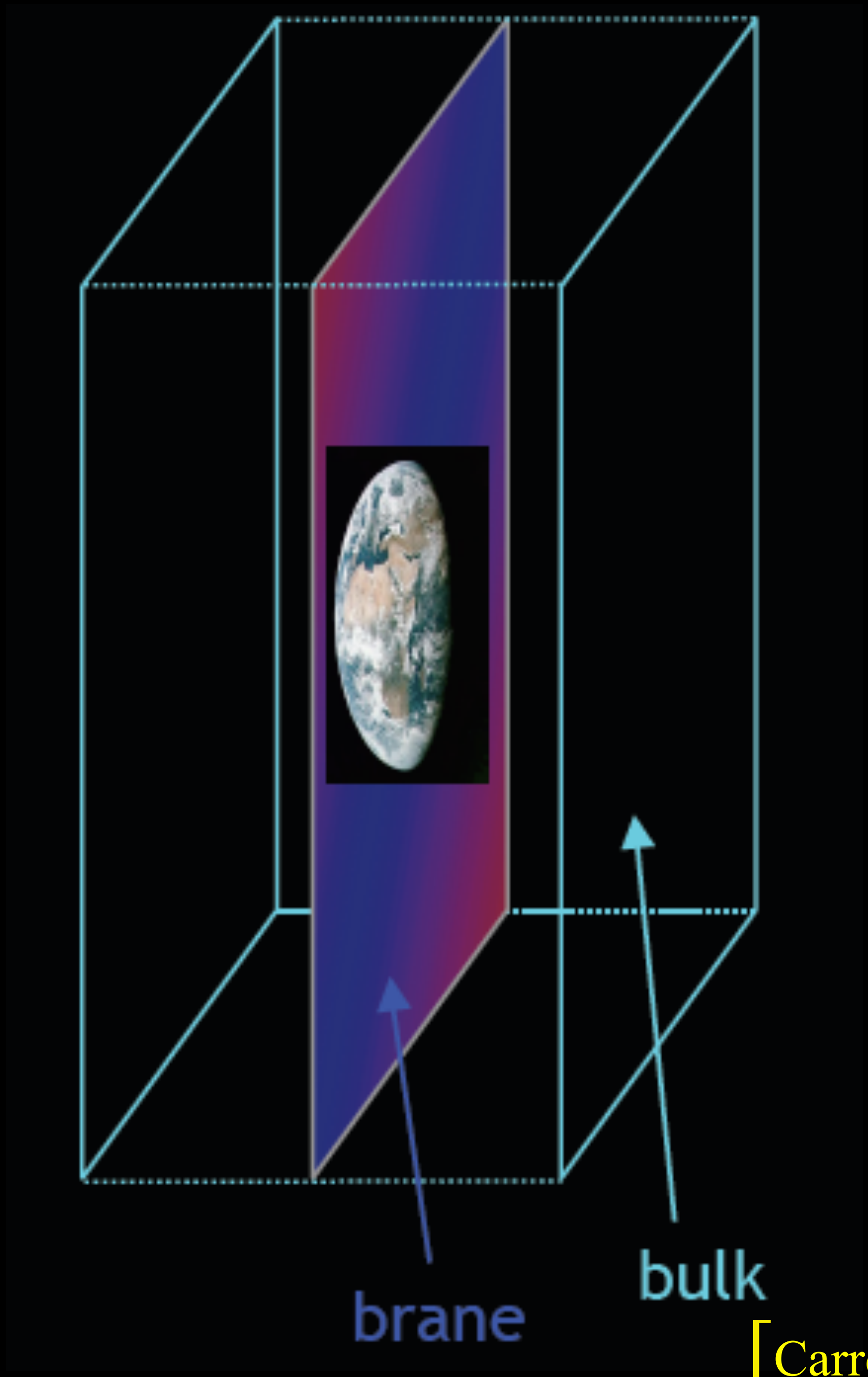
[Starobinski 1980, Carroll et al 2003, ...]

- Modified source gravity -- gravity depends on nonlinear function of the energy.

- Gravity based on the existence of extra dimensions -- DGP gravity

We live on a brane in an infinite extra dimension. Gravity is stronger in the bulk, and therefore wants to stick close to the brane -- looks locally four-dimensional.

Tightly constrained -- both from theory [ghosts] and observations



[Carroll]

Designer f (R) or f(G) models [Hu and Sawicki (2007), ...]

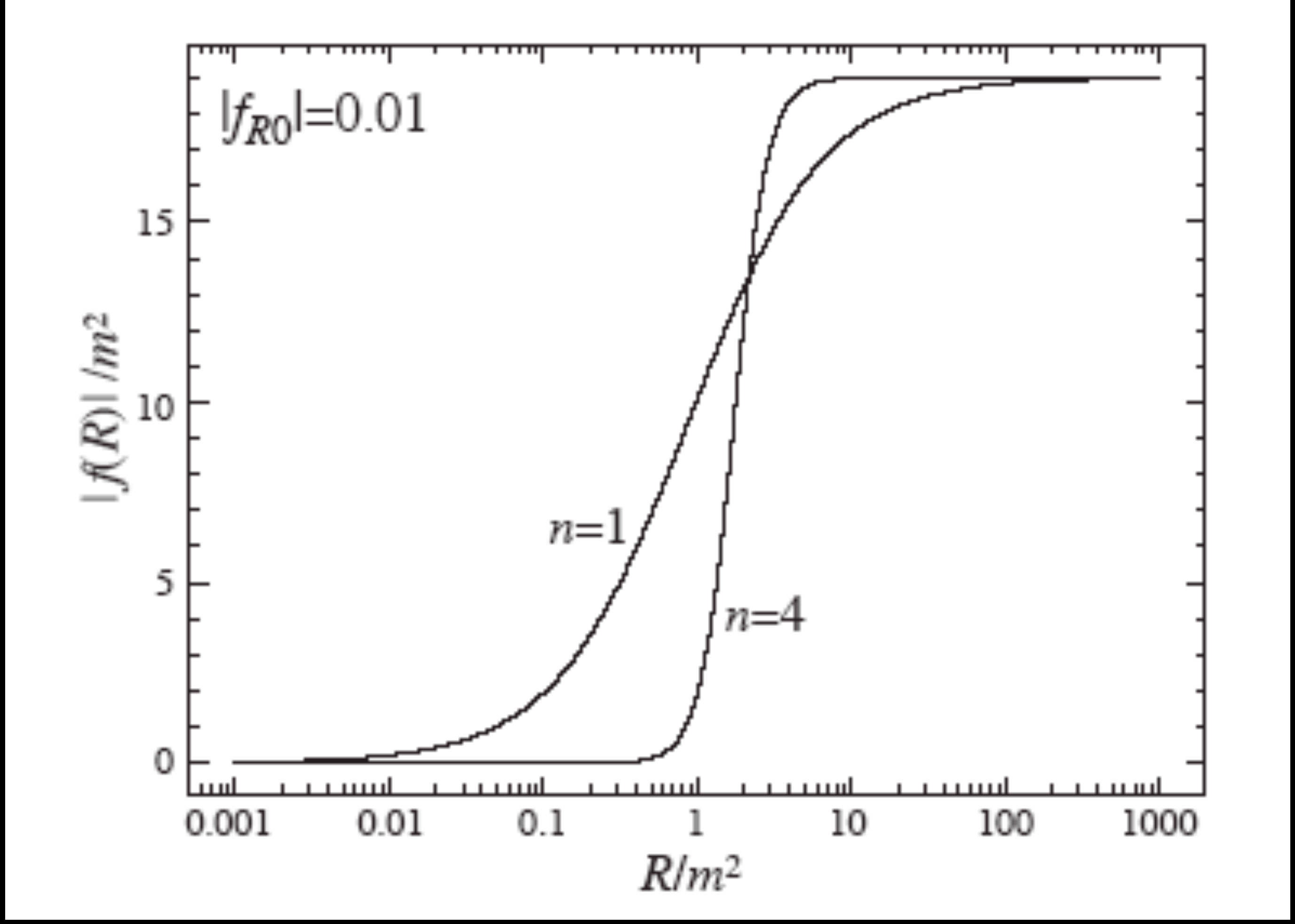
Construct a model to satisfy observational requirements:

1. Mimic LCDM at high z as suggested by CMB
2. Accelerate univ at low z
3. Include enough dof to allow for variety of low z phenomena
4. Include phenom of LCDM as limiting case.

$$\lim_{R\to\infty} f(R) = \text{const.}\,,$$
$$\lim_{R\to 0} f(R) = 0\,,$$

$$f(R) = -m^2 \frac{c_1 (R/m^2)^n}{c_2 (R/m^2)^n + 1}\,,$$

$$f_{RR} \equiv \frac{\mathrm{d}^2 f(R)}{\mathrm{d}R^2} > 0$$



More general f (R) models [Gurovich & Starobinsky (79); Tkachev (92); Carloni et al (04,07,09); Amendola & Tsujikawa 08; Bean et al 07; Wu & Sawicki 07; Appleby & Battye (07) and (08); Starobinsky (07); Evans et al (07); Frolov (08)…]

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{R+f(R)}{2\kappa^2} + \mathcal{L}_{\mathrm{m}}\right]$$

No Λ

Usually f (R) struggles to satisfy both solar system bounds on deviations from GR and late time acceleration. It brings in extra light degree of freedom --> fifth force constraints.

Ans: Make scalar dof massive in high density solar vicinity and hidden from solar system tests by chameleon mechanism.

Requires form for f (R) where mass of scalar is large and positive at high curvature.

Issue over high freq oscillations in R and singularity in finite past.

Has to look like a standard cosmological constant [Song et al, Amendola et al]

Testing General Relativity on Cosmological Scales

$$G_{ab} = 8\pi G T_{ab}^{(\mathrm{known})} + U_{ab}.$$

[Skordis (2009)]

U_{ab} -- encapsulates unknown fields/modifications.

Assume no more than second order field equations places constraints on number of derivatives of the extra fields in U_{ab}.

Bianchi Identity: $\nabla_a U^a{}_b = 0$

Obtains most general diffeomorphism invariant modification to Einstein's eqns for which bgd cosmology is ΛCDM, no extra fields present and no higher deriv than 2 in field equations. Does this by adding gauge invariant terms to Einstein eqns.

One solution parameterizes deviations from GR through a single parameter β which appears only in the perturbed eqns and not the bgd.

[Skordis (2009)]

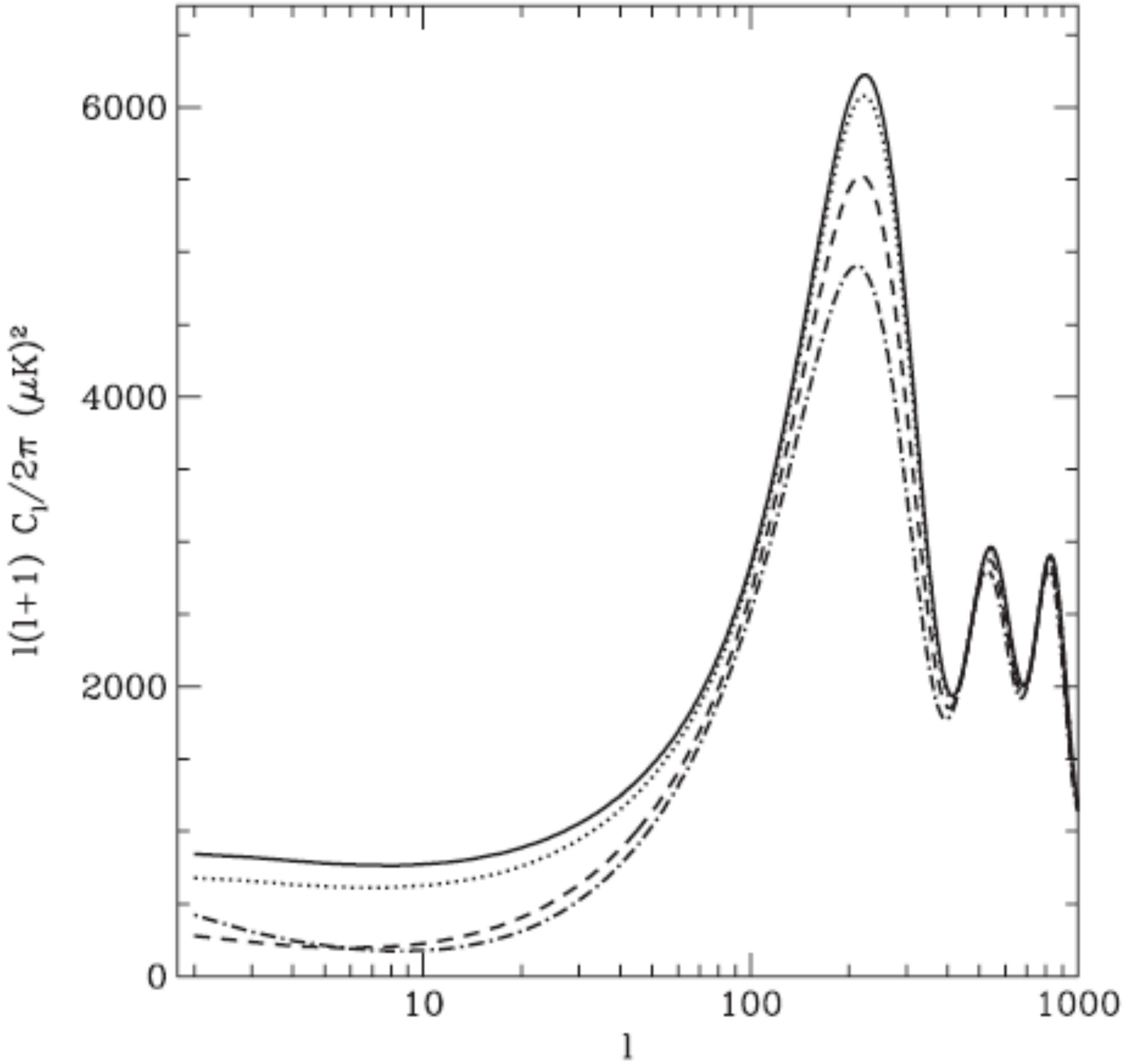


FIG. 1. The CMB spectrum for the simple modified gravity model in the text. The solid curve is the plain ΛCMD model ($\beta = 0$), while the dotted, dashed, and dotted-dashed curves are with $\beta = \{0.1, 0.5, 1\}$, respectively.

As β increases power decreases

[Skordis (2009)]

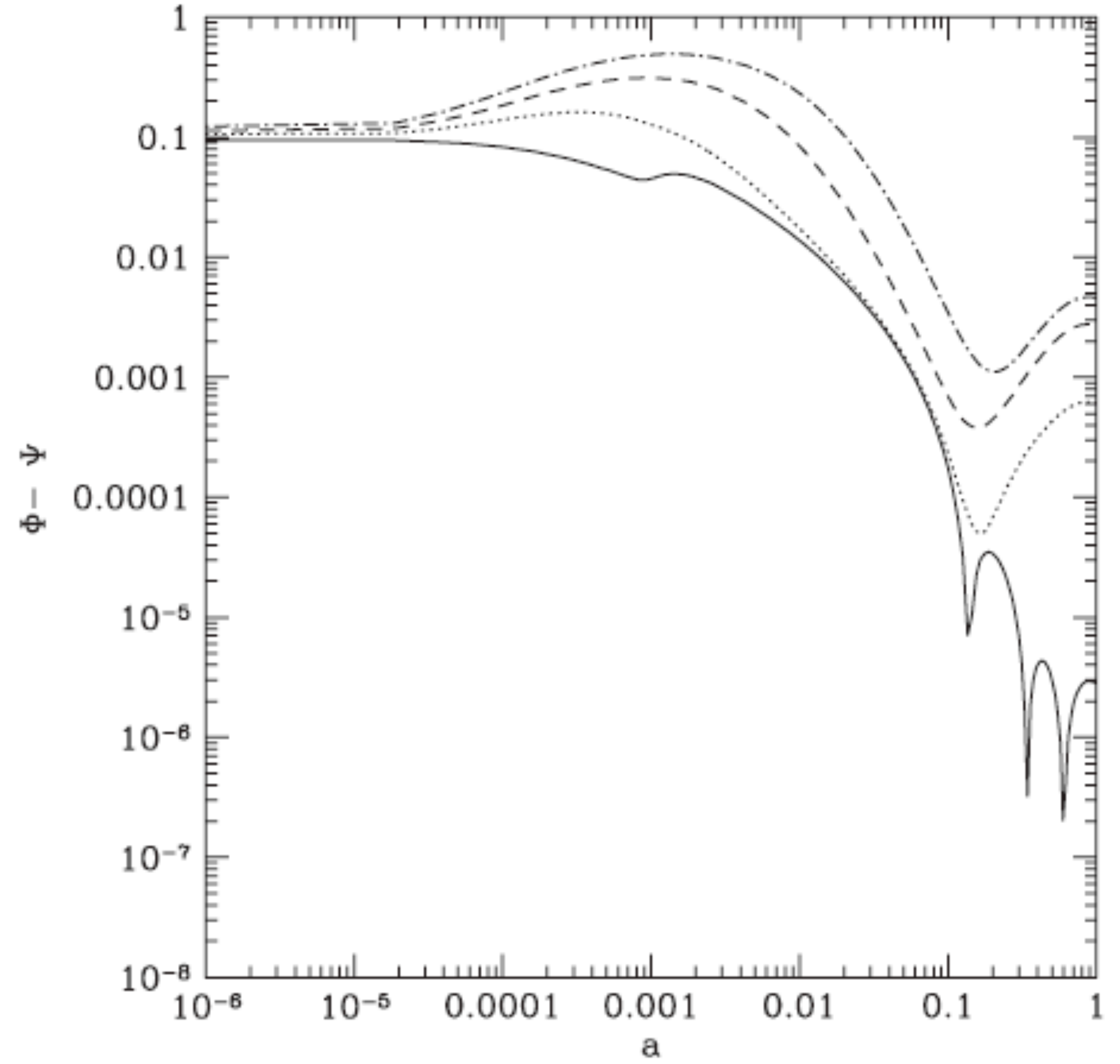


FIG. 2. The time evolution of $\hat{\Phi} - \hat{\Psi}$ at $k = 10^{-3}$ Mpc^{-1} for $\beta = 0$ (solid), $\beta = 0.1$ (dotted), $\beta = 0.5$ (dashed), and $\beta = 1$ (dotted-dashed).

As β increases Φ-ψ increases

The Future

- Particle physicists engaged since the beginning.
- Implications for fundamental physics are profound.

- Europe

CMBR: Planck

- USA

Summary

- Data currently consistent with a pure cosmological constant -- but why that value?
- Why is the universe inflating today?
- Is w = - 1, the cosmological constant ? If not, then what value has it?
- Is w(z) -- dynamical. How should this be parameterized?
- New Gravitational Physics -- perhaps modifying Einstein equations on large scales? Key differences arising in perturbations.
- Perhaps we will only be able to determine it from anthropic arguments and not from fundamental theory.
- or -- could we be wrong and we can avoid the need for a lambda term?

Still plenty to do.