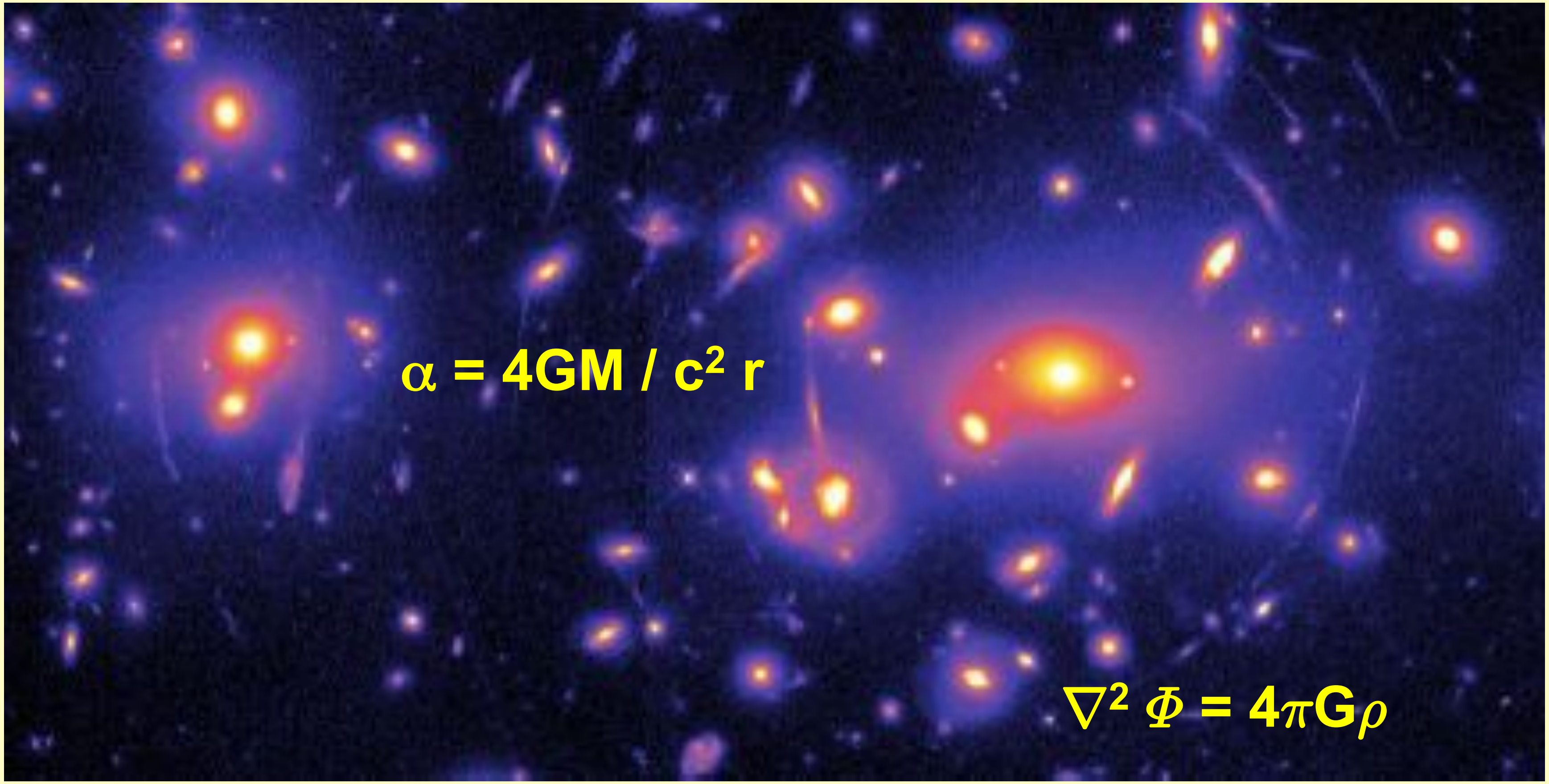
Laws of physics in the cosmos



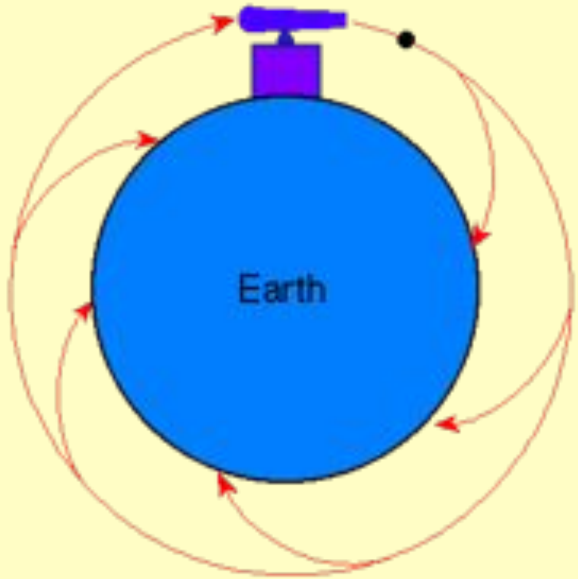
John Peacock **CosmoCaixa Barcelona** **2 April 2009**

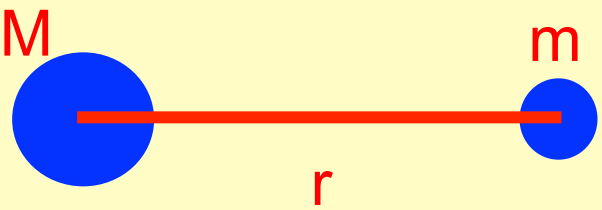
Overview

- Motivation for new physics in the cosmos
- Cases where new physics is not required
- Unsolved cosmological puzzles
- Anthropic approach and new physics

What is a law of Physics?

Isaac Newton (1643-1727)





$$F = \frac{GMm}{r^2}$$

A mathematical description of Nature. Newton: “no hypotheses” about what gravity is

Physics and symmetry

- Most fundamental physical laws are in the form of conserved quantities related to symmetry:
  - Energy: Physics independent of time
  - Momentum: Physics independent of position
  - Charge: Physics independent of phase of matter wave function
- Also limited by requirement of relativistic covariance: Physical Laws must apply to all viewpoints

$$\partial_\mu J^\mu = \partial\rho/\partial t + \nabla\cdot\mathbf{j} = 0$$

- Cosmology assumes this local physics is all we need

How could this not apply to the cosmos?

- Dependence on spacetime curvature (which depends on position)
  - Ricci Scalar R is a measure of curvature (small on Earth)
  - Einstein gravity: curvature proportional to matter content. Could be more complex

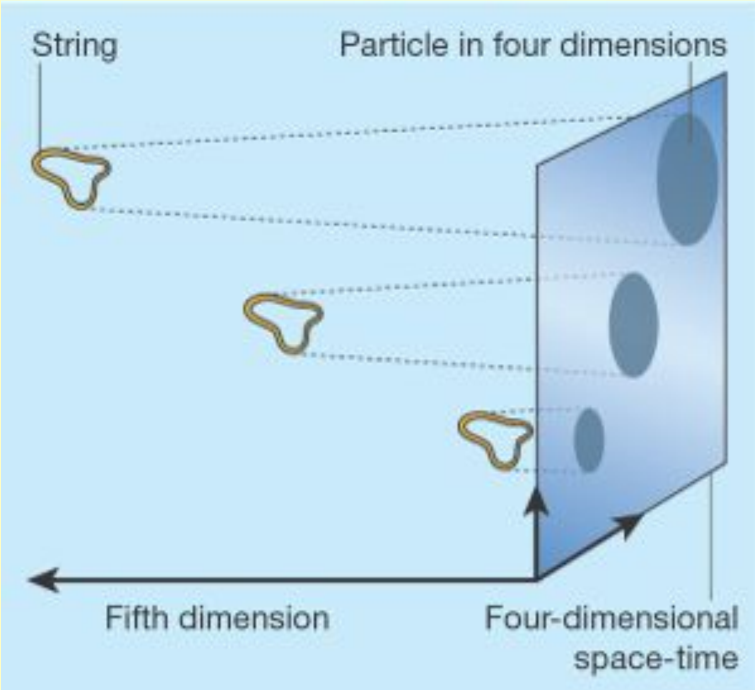
$$G^{\mu\nu} = -8\pi T^{\mu\nu} \qquad G^{\mu\nu} \to (1+R)G^{\mu\nu}?$$

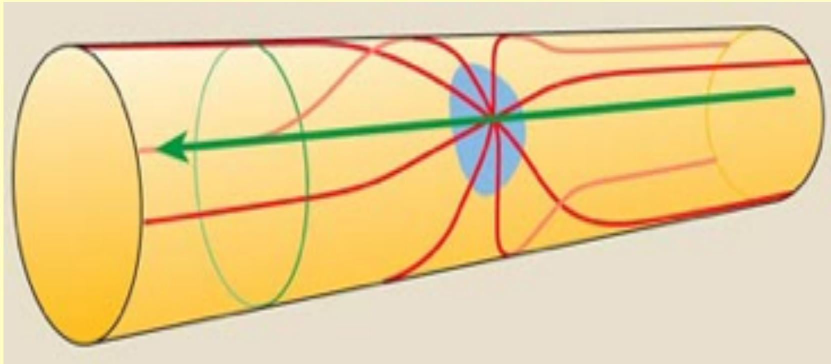
  - Test near black holes, or on scale of visible universe

- Time dependence from universal expansion
  - Dark energy can have slow epoch dependence
  - Can couple to constants of nature

Where to look for new physics?

- Local unfinished business
  - Gravity as effective theory (GR unrenormalisable)
  - Unification – strings and/or extra dimensions (braneworld)?



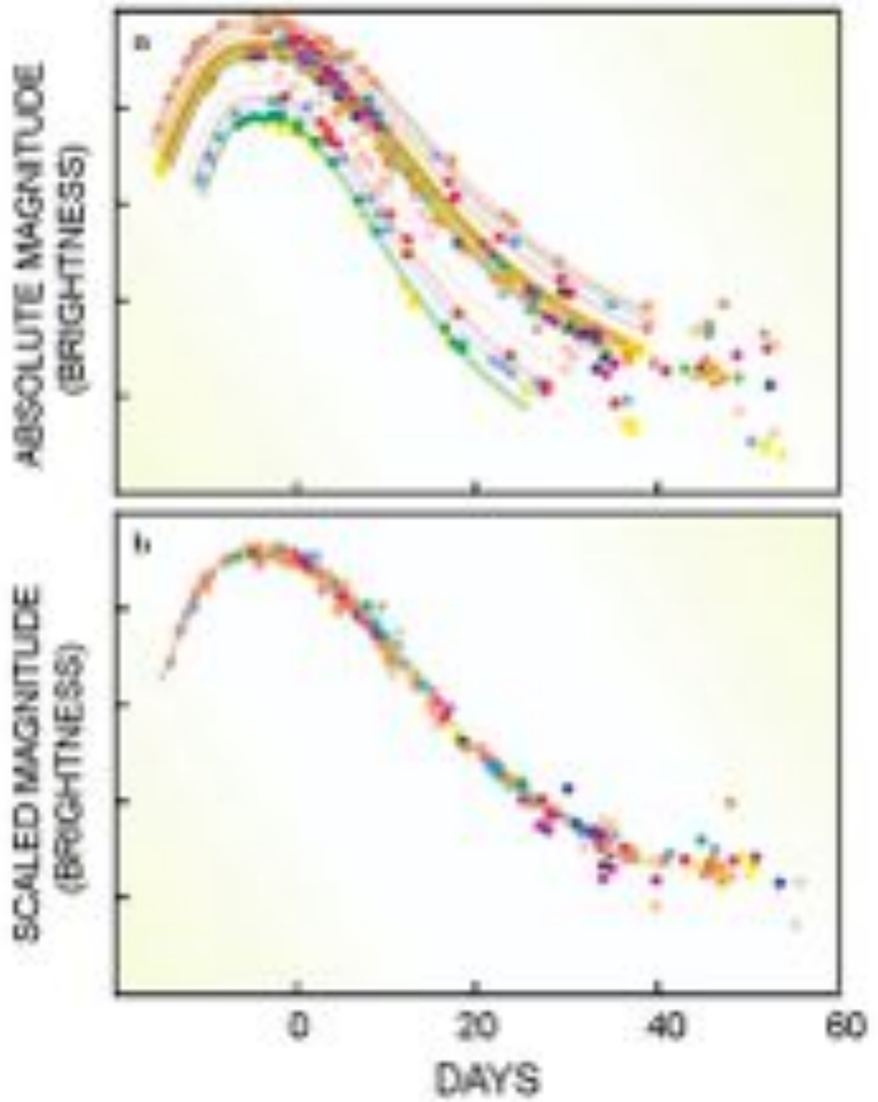


'Leakage' of gravity into 5th dimension changes strength with scale

- Empirical problems in cosmology

Meaning of redshift: tired light?

- Redshift: $cz = v = H_0 D$ Just a loss of energy with distance?
- If redshift is really a doppler shift, it should be accompanied by time dilation
- Seen to high accuracy in SNe Ia



Dirac's Large Number Hypothesis

- Dirac (1937) noted rough coincidence between ratio of gravitational to electrostatic force in Hydrogen atom, and ratio of classical radius of electron to size of Universe

$$\frac{r_e}{ct} \simeq \frac{4\pi\epsilon_0 G m_e m_p}{e^2} \simeq 10^{-40}$$

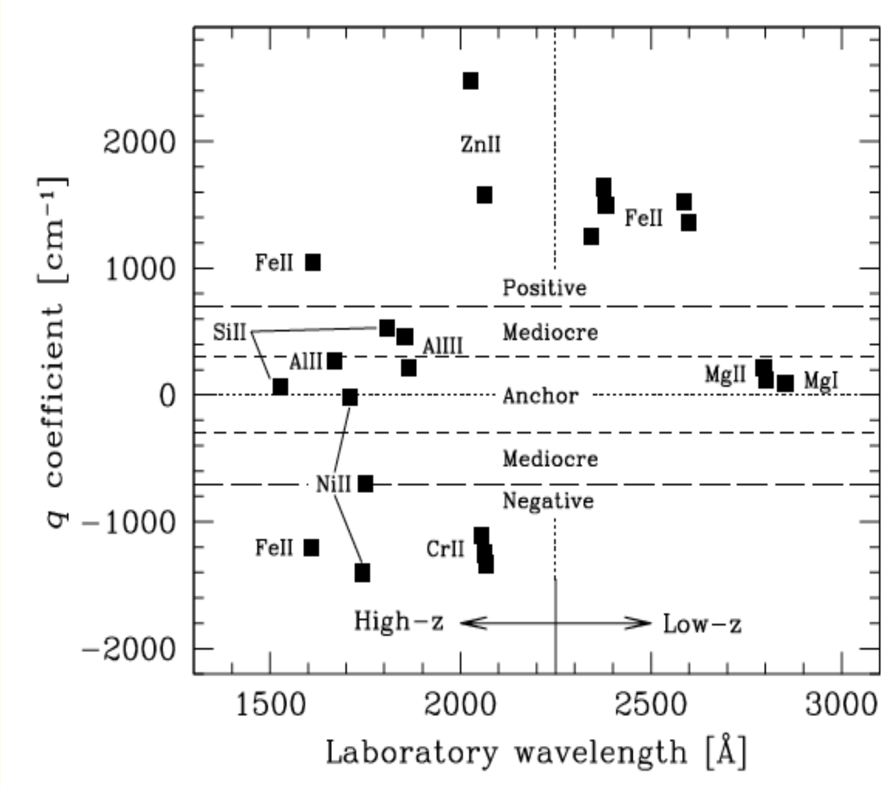
- Suggested always true: $G(t) \propto 1/t$
  - But disfavoured (hotter sun in past)
  - Resolved if age of universe is typical stellar age (weak anthropic argument)

Variable speed of light?

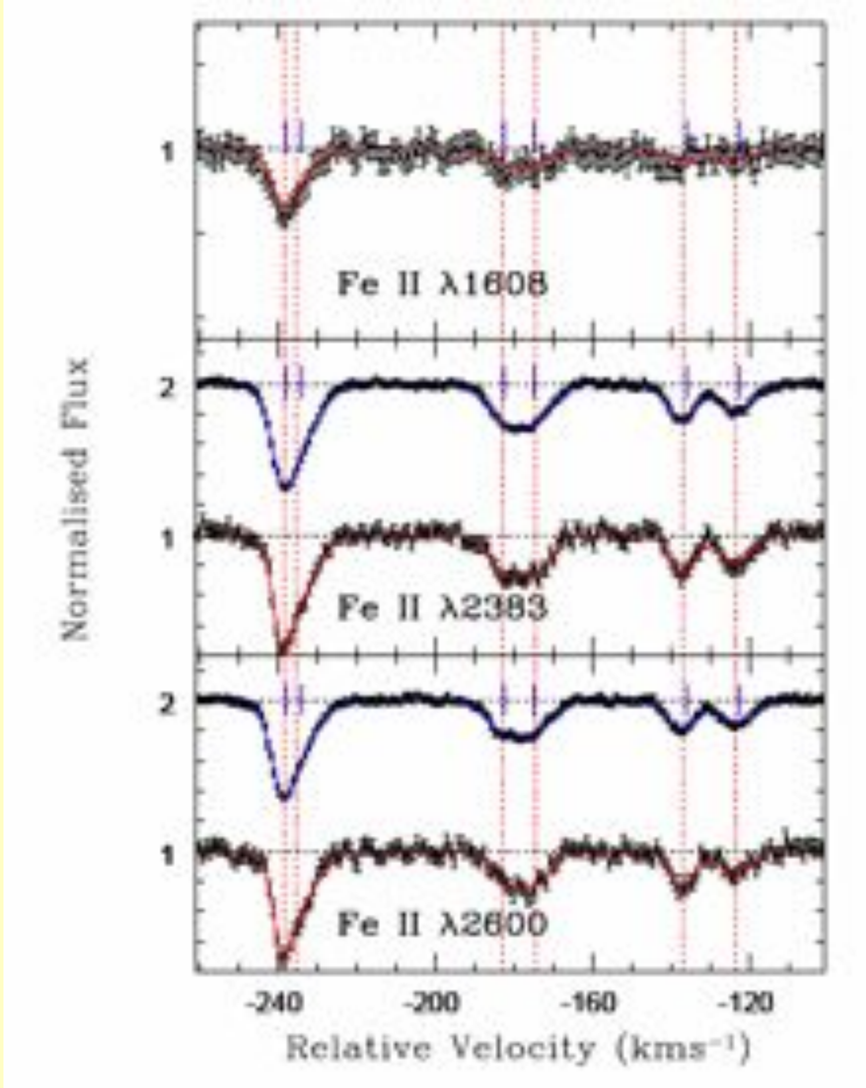
- Horizon problem: earliest time we can imagine is scale of quantum gravity, or Planck scale. This is a time of 10^{-43} s, so ct was $10^{-34.5}$ m.
- But present universe was 0.001 mm then. How can it be so much larger than ct and yet (almost) uniform?
  - Perhaps speed of light was larger in past?
  - But this is meaningless: what do we use for clocks?
- Must use dimensionless ratios such as fine-structure constant (measurable because it affects relativistic corrections to atomic frequencies)

$$\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c} \simeq 1/137$$

Evolution of the fine-structure constant

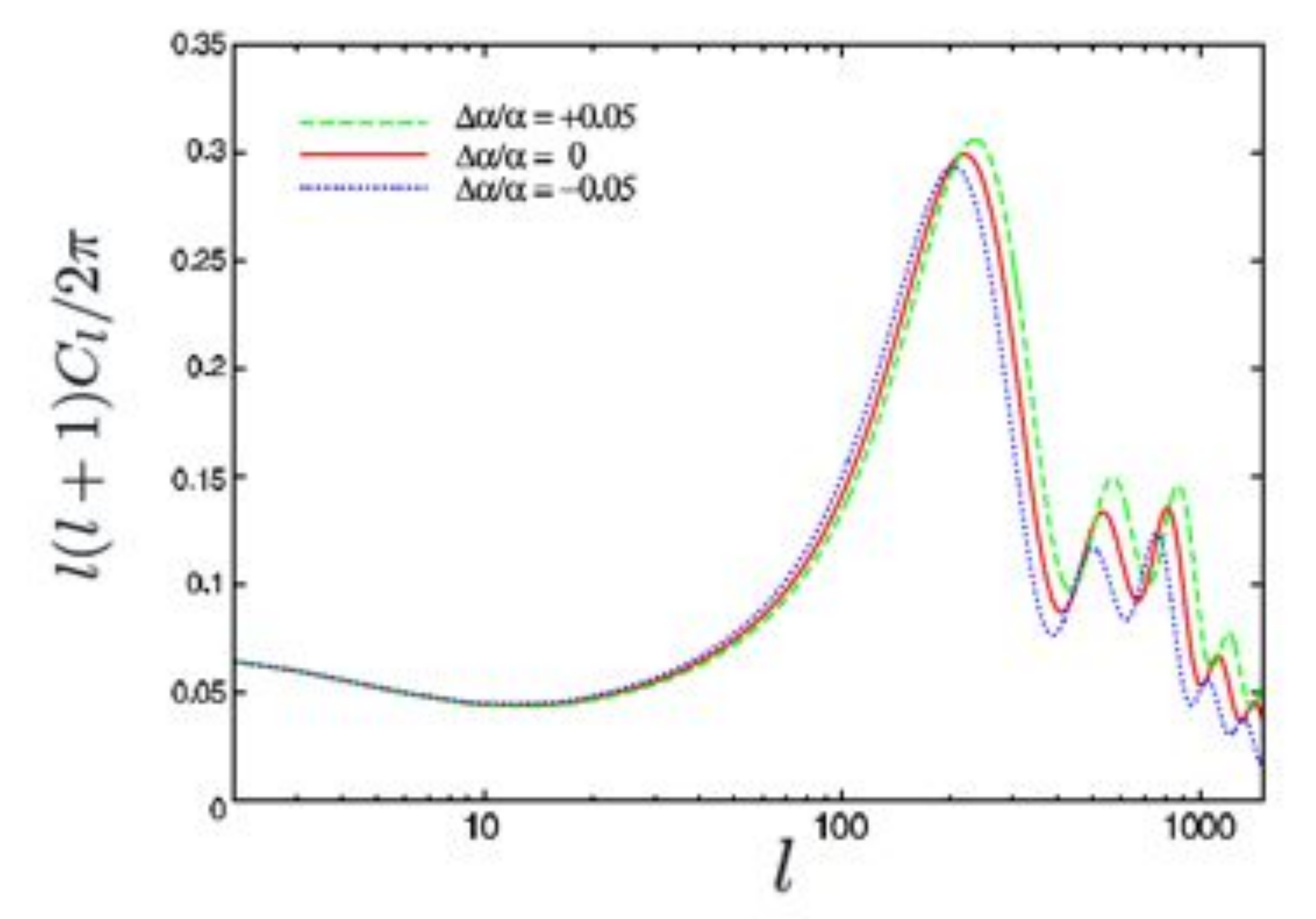


Murphy et al. 0306483: different lines have different α sensitivities



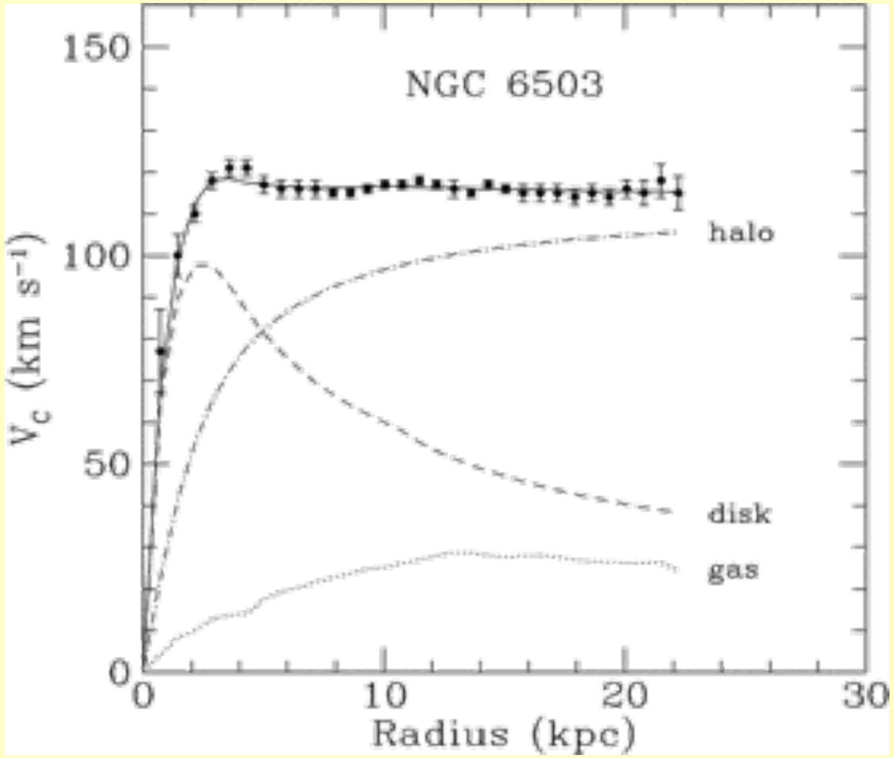
Chand et al. 0601194: $\Delta\alpha/\alpha < 5 \times 10^{-6}$ at z = 1.15

Evolution of the fine-structure constant



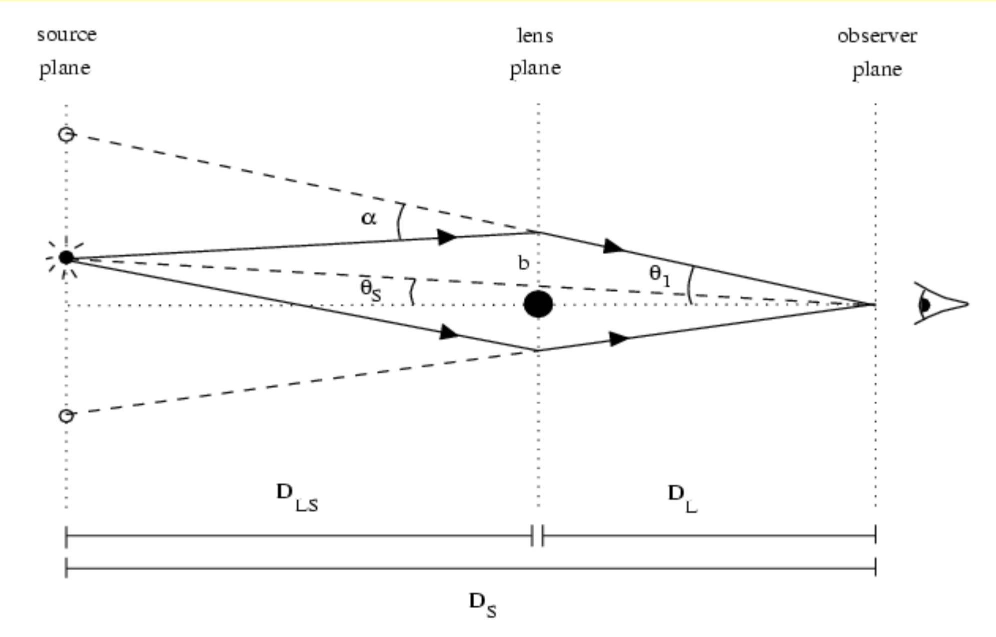
Ichikawa et al. 0602577: $\Delta\alpha/\alpha$ < 0.04 at z = 1100

Dark matter: MOND?



Flat rotation curves: dark matter or departure from F = ma at low accelerations? (Modified Newtonian Dynamics)

Gravitational Lensing: consistent masses



Relativistic factor 2 in deflection angle

$$\alpha = \frac{2}{c^2} \int a_\perp \, d\ell.$$

Lensing masses require factor 2 to agree with other mass estimates (galaxy dynamics, hydrostatic equilibrium of IGM)

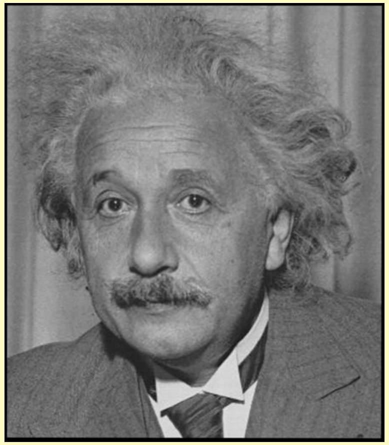
The bullet cluster: collisionless DM

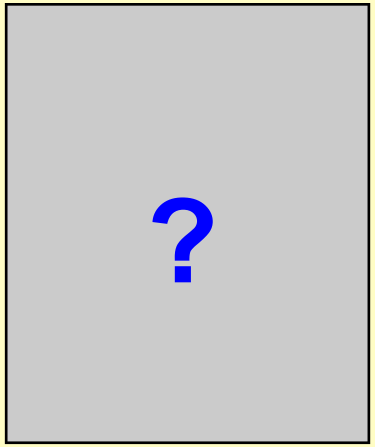
Is Dark Energy a failure of gravity?

All current measurements relate to expansion rate, assuming H(z) comes from General Relativity equation

$$H^2(z) = H^2_0 \; [\, (1-\Omega)\,(1+z)^{2} + \Omega_M\,(1+z)^{3} + \Omega_R\,(1+z)^{4} + \Omega_{DE}\,(1+z)^{3\,(1+w)} \,]$$

Curvature · **matter** · **radiation** · **extra term from non-GR?**





How can we tell?

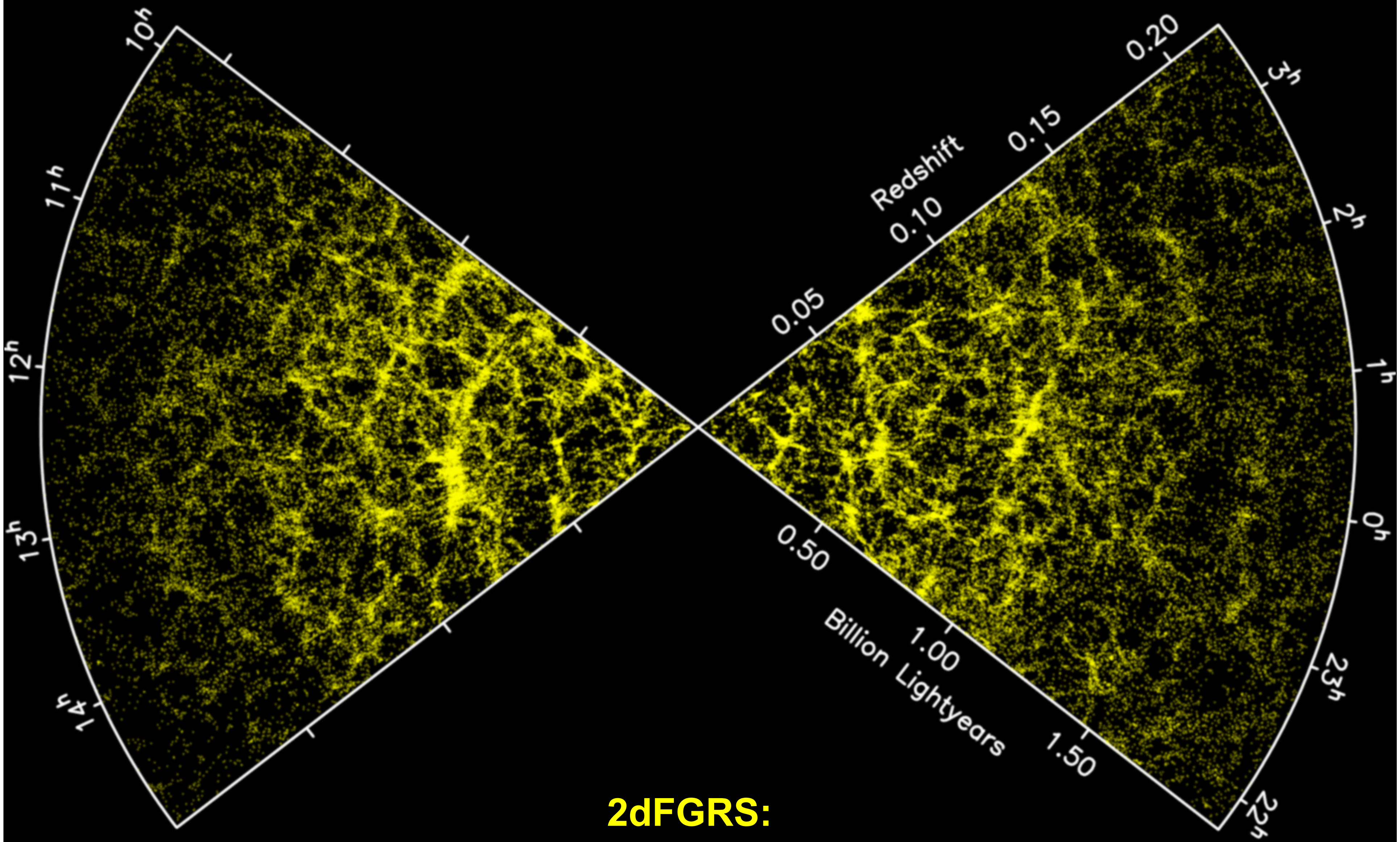
(1) Dark Energy equation of state

- Ratio of pressure to energy density $w = P / \rho c^2$
- $w = -1$ for cosmological constant

(2) Evolution of density fluctuations

- $\delta\rho/\rho$ measures small-scale gravity
- Growth at a different rate to DE prediction indicates need for modified gravity

Large-scale structure probes DE & gravity

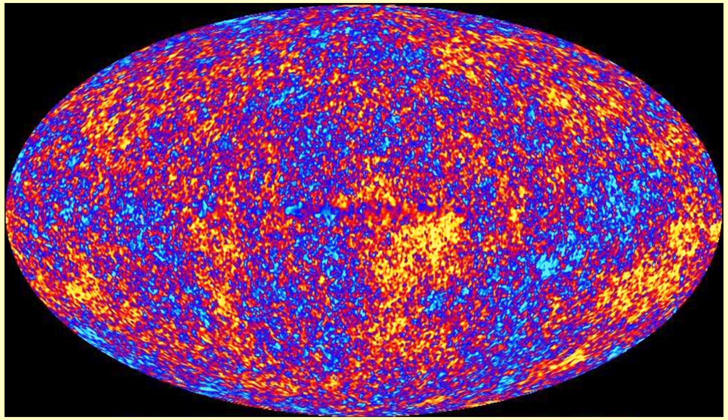


2dFGRS:

220,000 z's 1997-2003

Geometrical tools: the BAO signature

Growth of structure defines natural measuring rods:



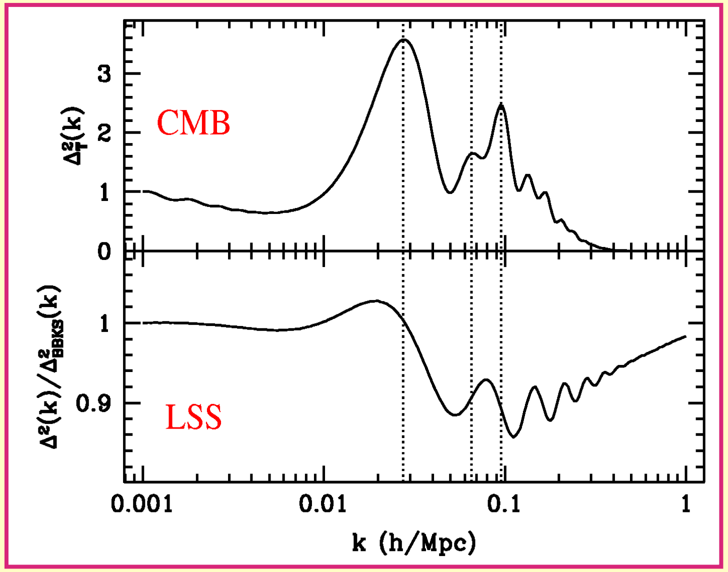
(1) Matter-radiation horizon:

123 (Ω_m h^2 / 0.13)$^{-1}$ Mpc

(2) Acoustic horizon at last scattering :

147 (Ω_m h^2 / 0.13)$^{-0.25}$ (Ω_b h^2 / 0.024)$^{-0.08}$ Mpc

– BAO (Baryon Acoustic Oscillations)

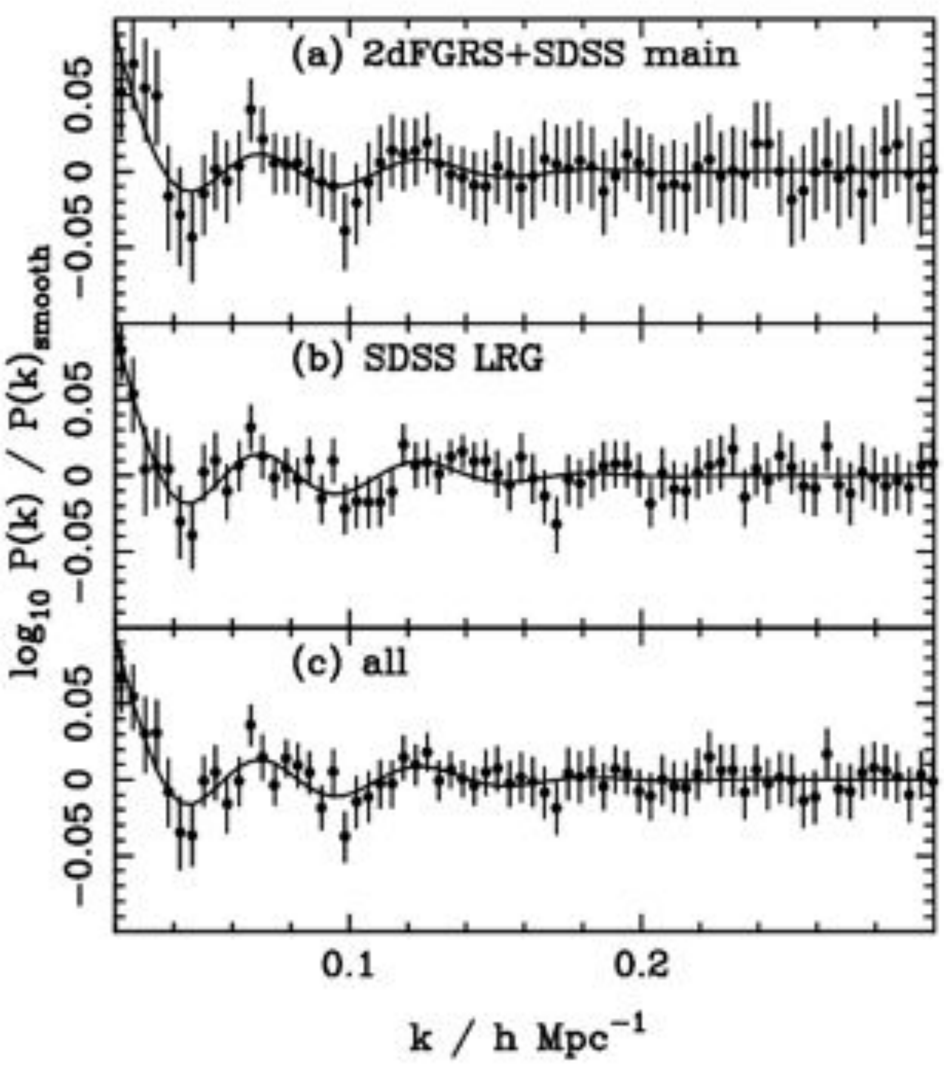


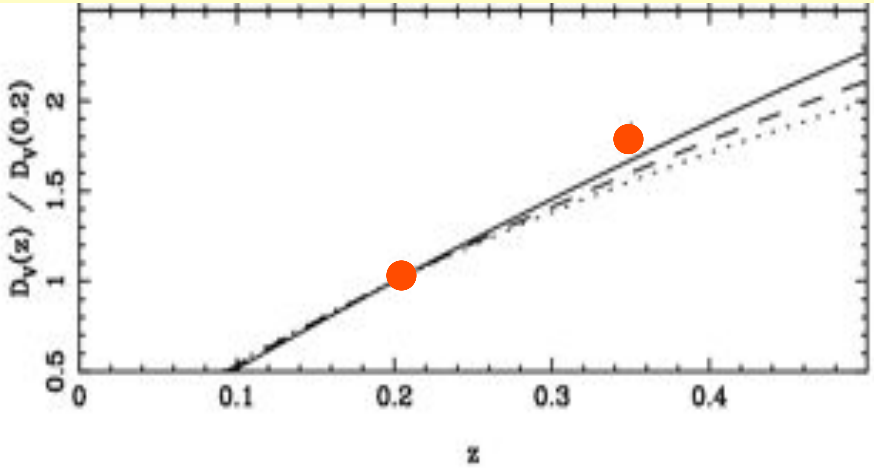
Observe radially in LSS via H(z)

Observe angle in LSS/CMB via D(z):

$$D(z) = \frac{c}{H_0} \int_0^z \frac{dz}{[\Omega_v(1+z)^{3+3w} + \Omega_m(1+z)^3 + \Omega_k(1+z)^2]^{1/2}}$$

BAO: rulers in the sky





Angle subtended by Baryon Acoustic Oscillations (residue of sound waves in early universe) measures distance as a function of redshift, which depends on DE properties

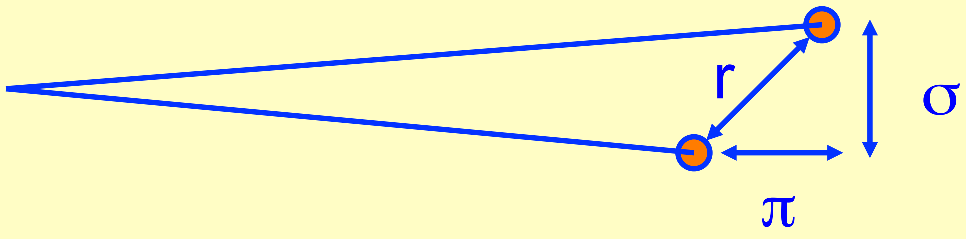
Current limit: **w = –1 ± 6%**

Close to cosmological constant

Probing modified gravity

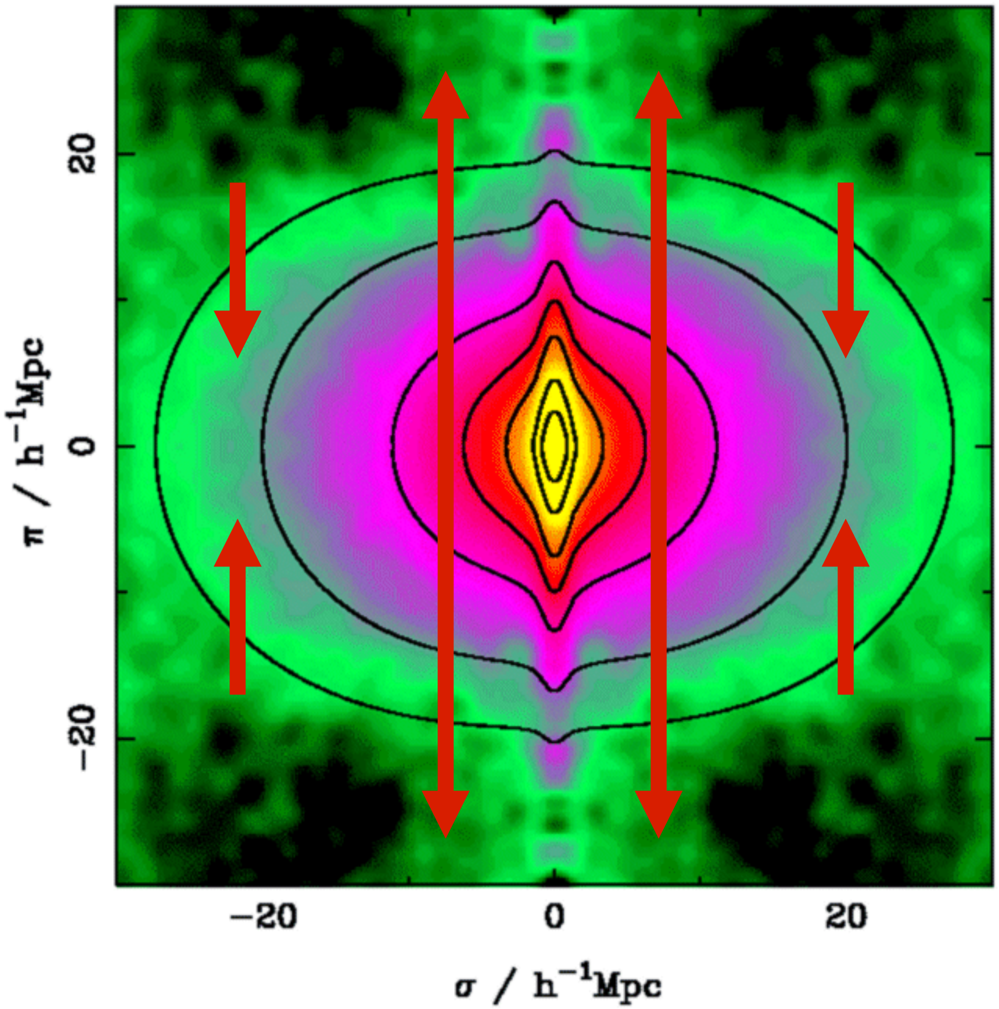
- Growth of structure induces velocities proportional to density growth rate $f_g = d \ln \delta / d \ln a$
- These cause characteristic Redshift-Space Distortions
- Modified gravity equal in importance to w(a) $\Rightarrow$ use RSD to measure f_g while using BAO to study DE

Redshift-Space Distortions



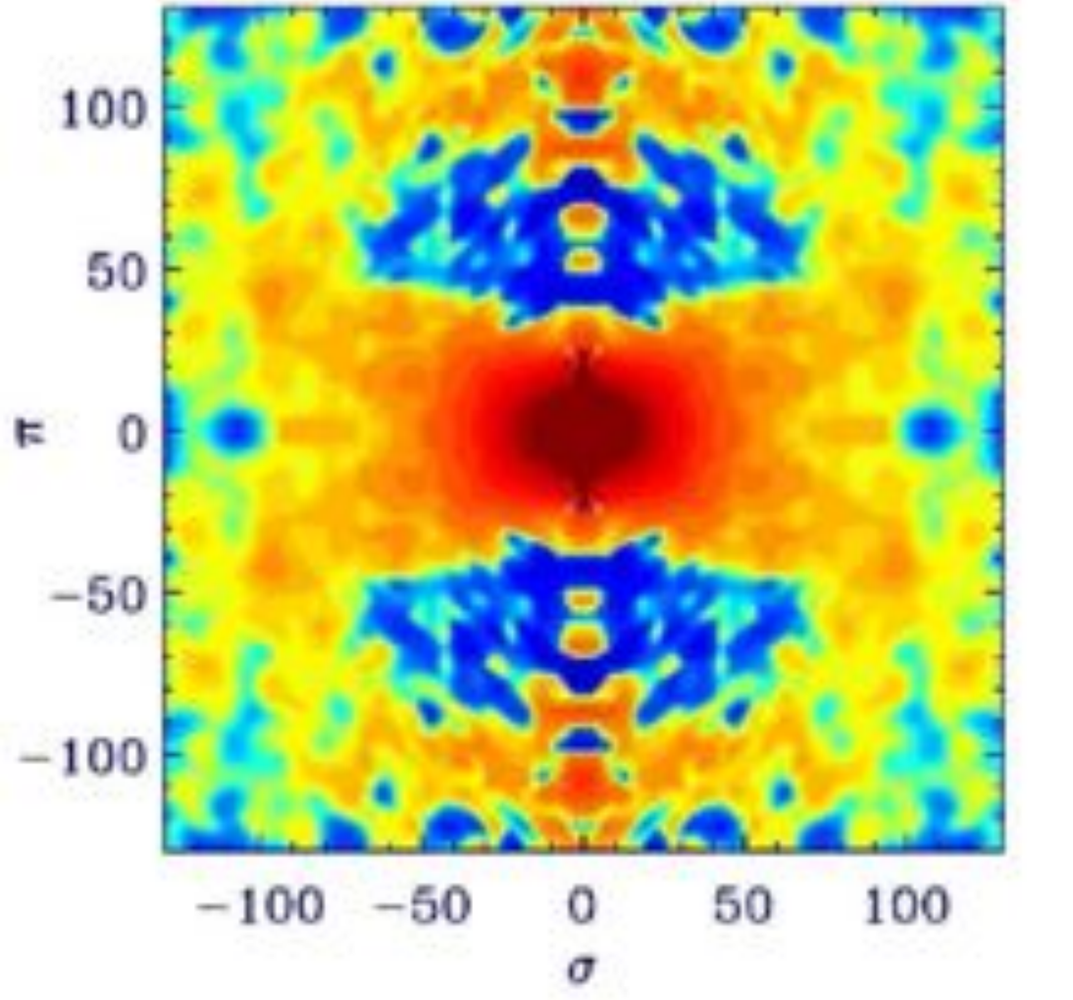
- RSD due to peculiar velocities are quantified by correlation fn $\xi(\sigma,\pi)$: enhanced density of galaxy neighbours
- Two effects visible:
  - Small separations on sky: ‘Finger-of-God’;
  - Large separations on sky: flattening along line of sight, sensitive to f_g

2dFGRS: Peacock et al. 2001



BAO and RSD: complementary information from a single survey

SDSS LRG Redshift-space 2D $\xi(\sigma,\pi)$ Gaztanaga et al. 0807.3551
Note RSD flattening has little effect on BAO ring

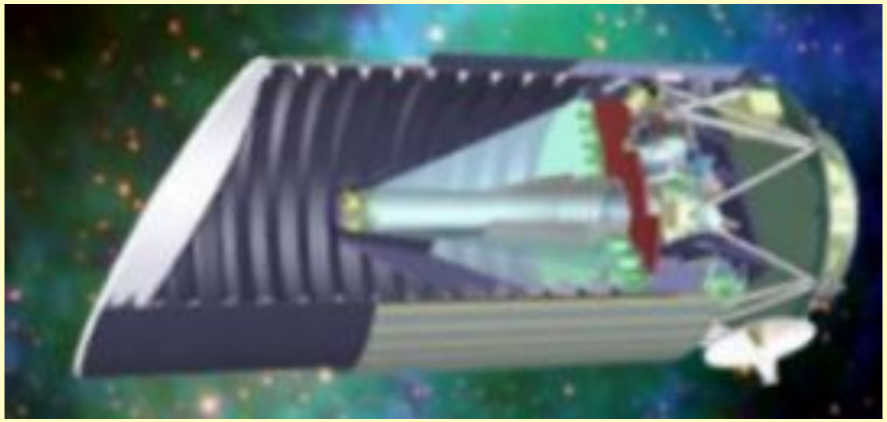


Single large redshift survey can provide a simultaneous probe of dark energy and modified gravity

Prospects for BAO & RSD

- **2010 – 2020: BOSS (2.5m) & WFMOS (8m) 10^7 redshifts**
- **W and f_g to 2%**

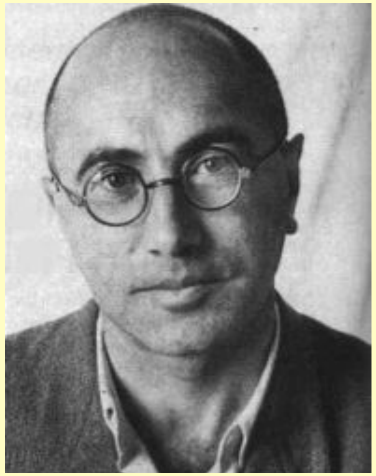
- **2020+: IDECS (1.5m) 10^8 redshifts from space**



What if it's Λ + GR?

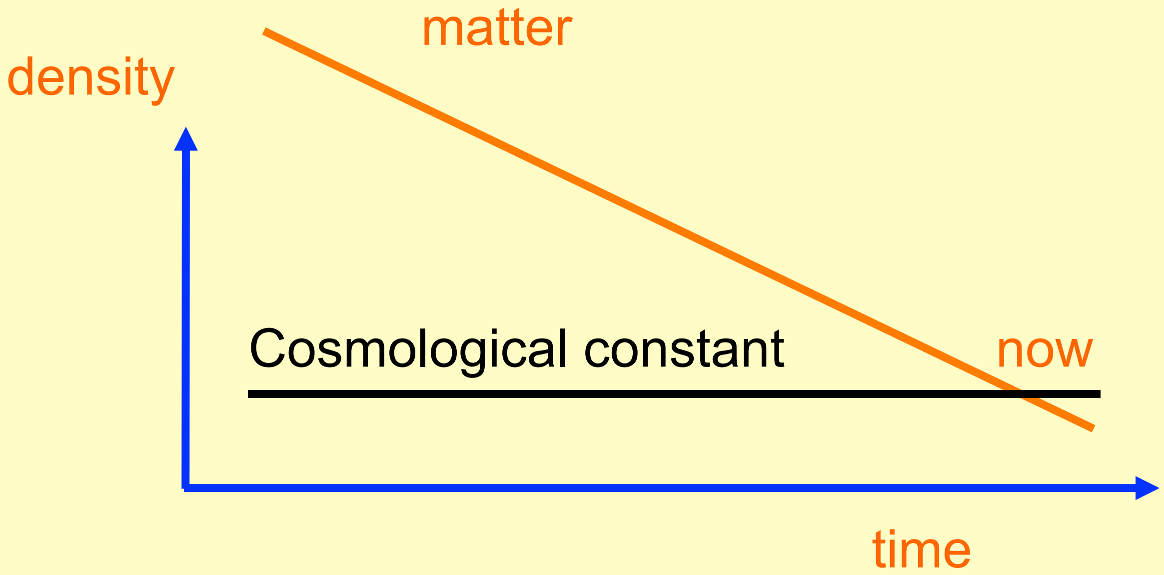
The dark-energy puzzles

$$\rho_{\rm vac} = \sum_{0}^{E_{\rm max}} \hbar\omega/2 \sim E_{\rm max}^4$$



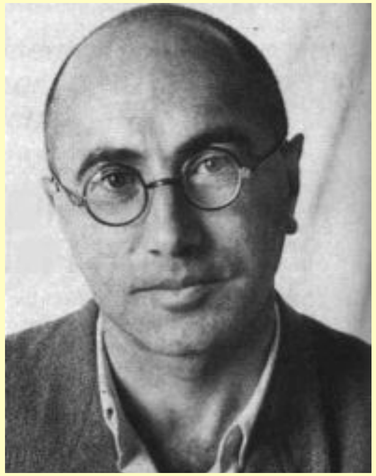
Zeldovich (1967): a cosmological constant
vacuum density from zero-point energy.
But E_{max} is apparently 2.4 meV

The ‘why now’
problem:



The dark-energy puzzles

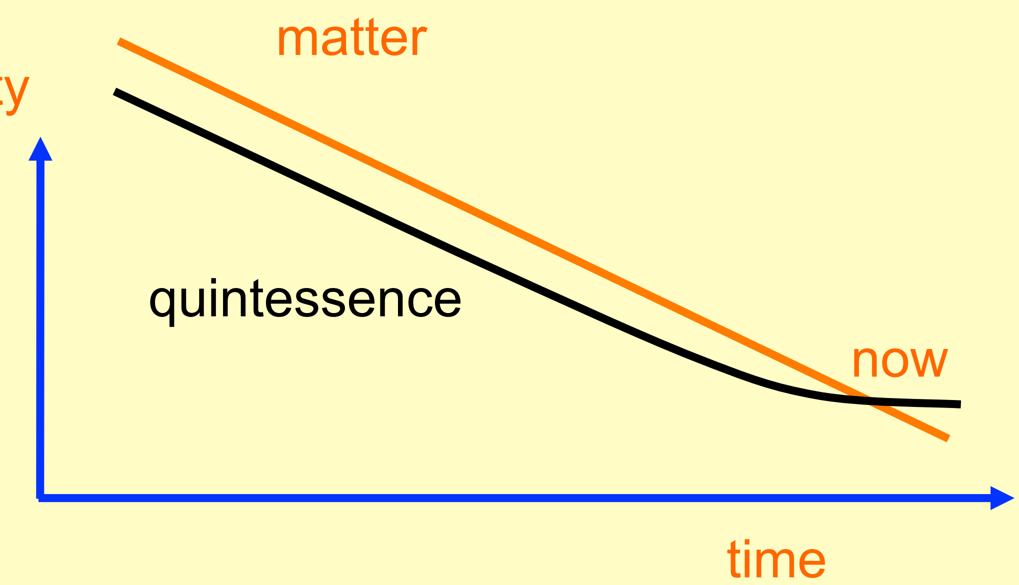
$$\rho_{\mathrm{vac}} = \sum_{0}^{E_{\mathrm{max}}} \hbar\omega/2 \sim E_{\mathrm{max}}^4$$



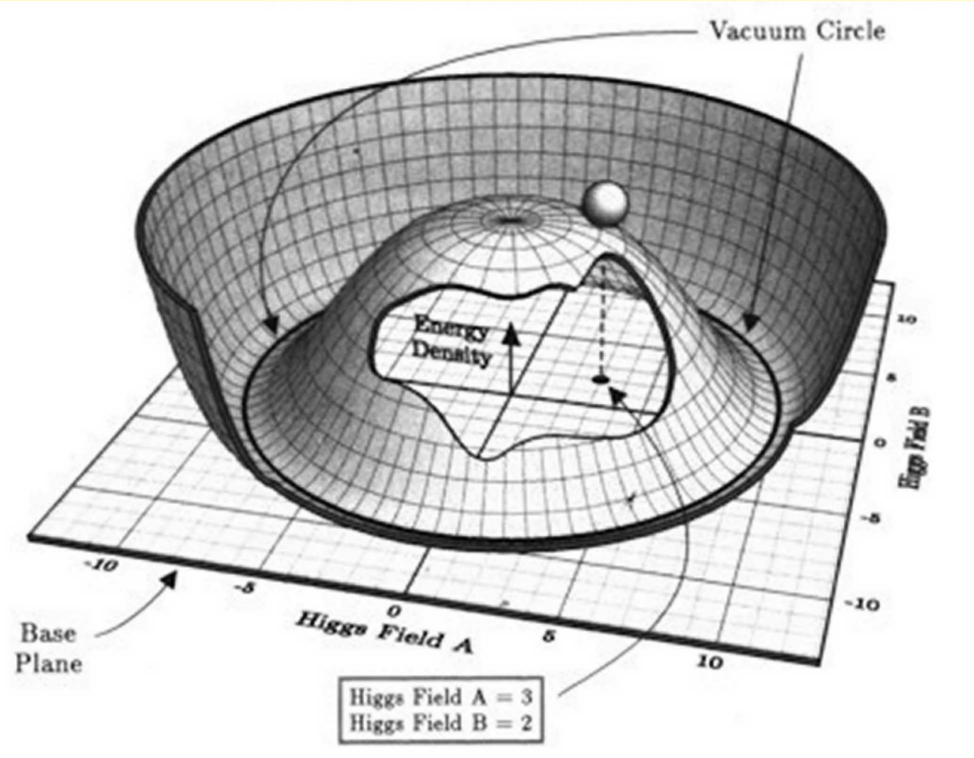
Zeldovich (1967): a cosmological constant vacuum density from zero-point energy.
But E_{max} is apparently 2.4 meV

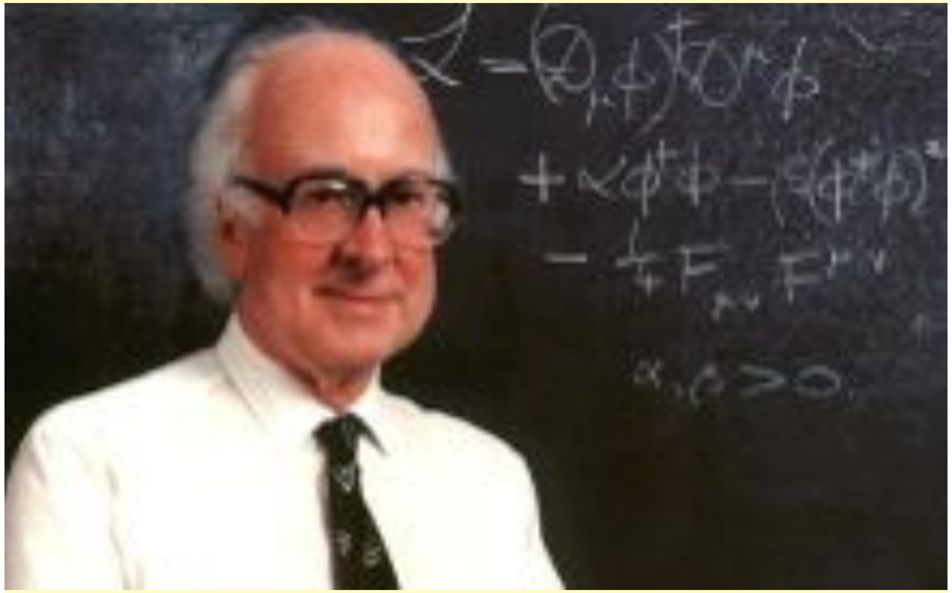
The 'why now' problem:

Perhaps DE evolves (Ratra & Peebles 1988) – 'quintessence'



Quintessence: variable vacuum density with scalar fields





Scalar field ϕ: like electric field but no direction. Has potential energy density V(ϕ) – e.g. 'Higgs field' in particle physics

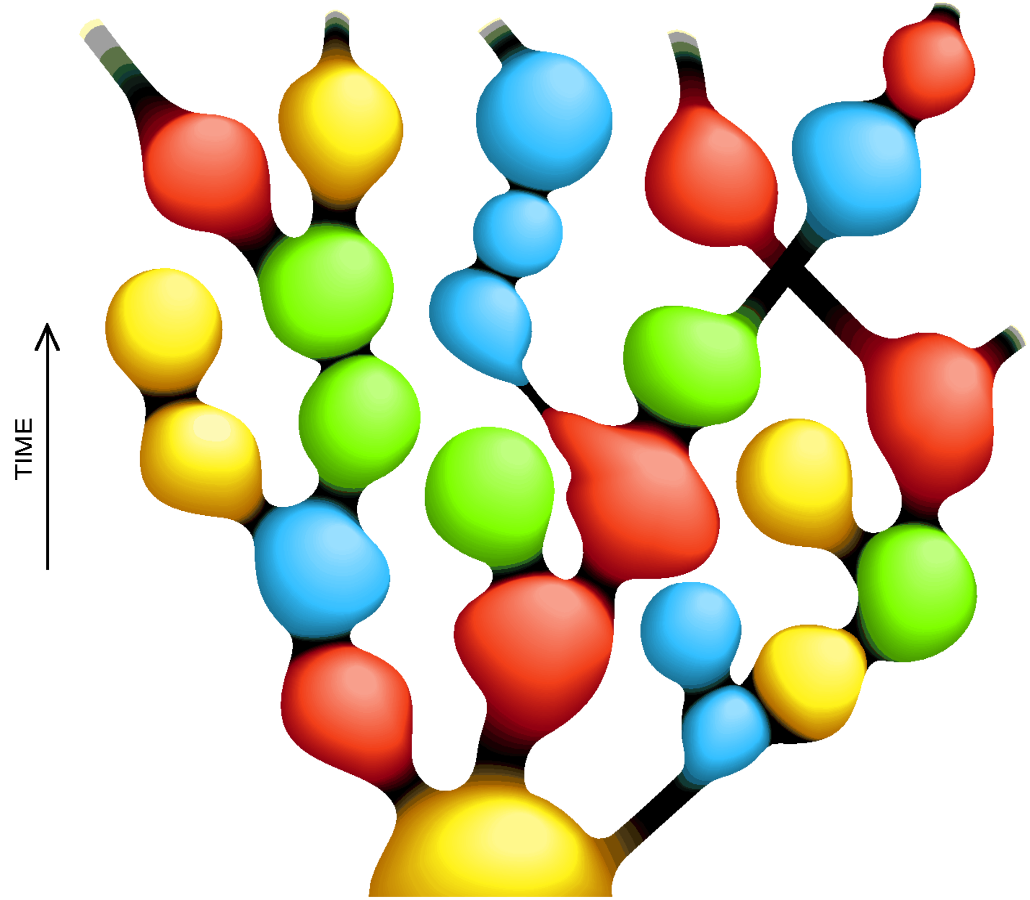
Field dynamics are dictated by potential: density evolves

But this doesn't solve the 'classical Λ problem': can always add constant to V(ϕ)

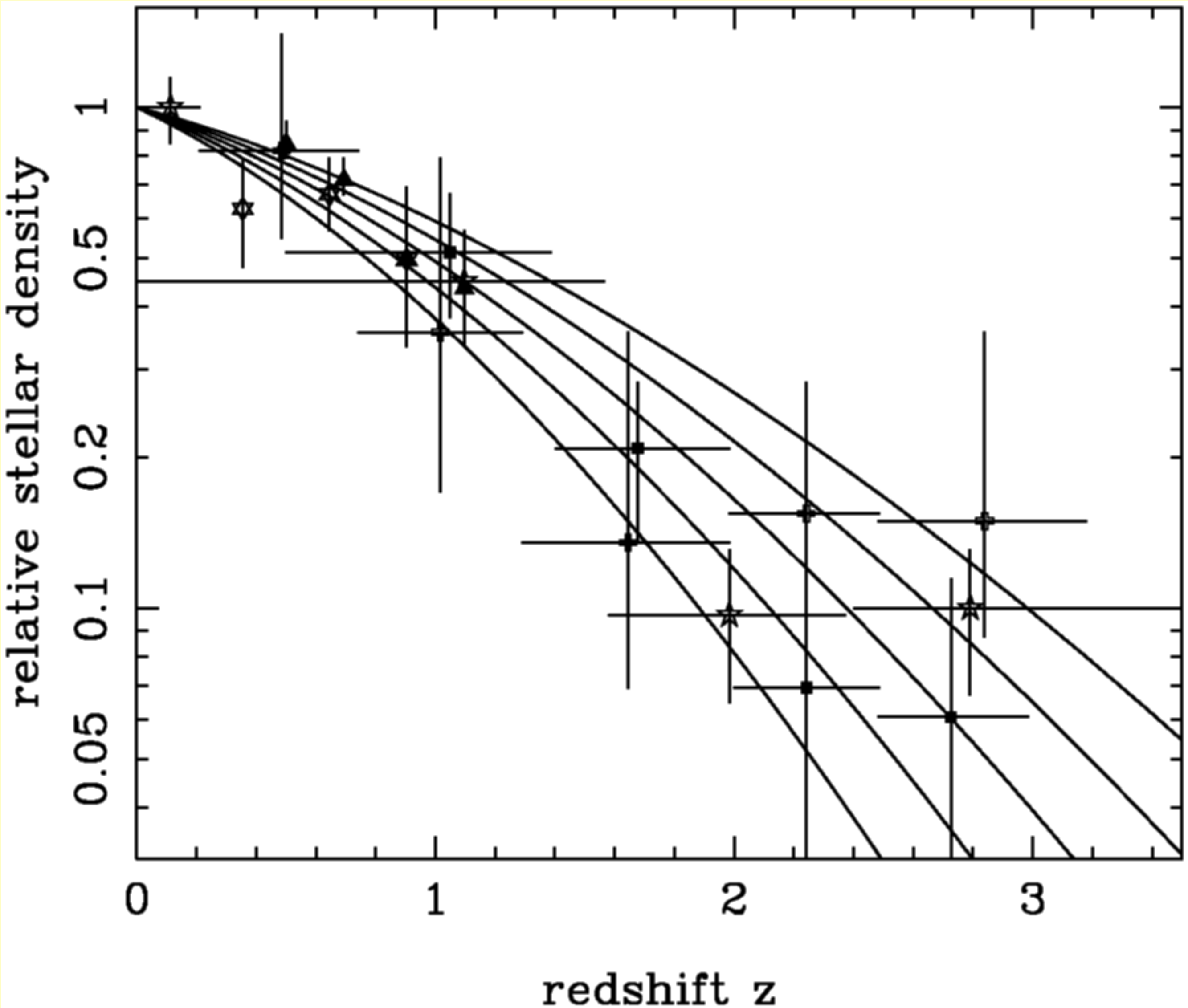
The answer to ‘why now’ must be anthropic

- One-universe anthropic
  - Life (structure) only after matter-radiation equality
  - Not controversial
  - Quintessence might change its dynamics then
  - But need to solve classical Λ=0 problem

- Many-universe anthropic
  - Requires new physics for variable Λ
  - Sound logic (exoplanets)
  - What is this multiverse?
  - Is it testable?

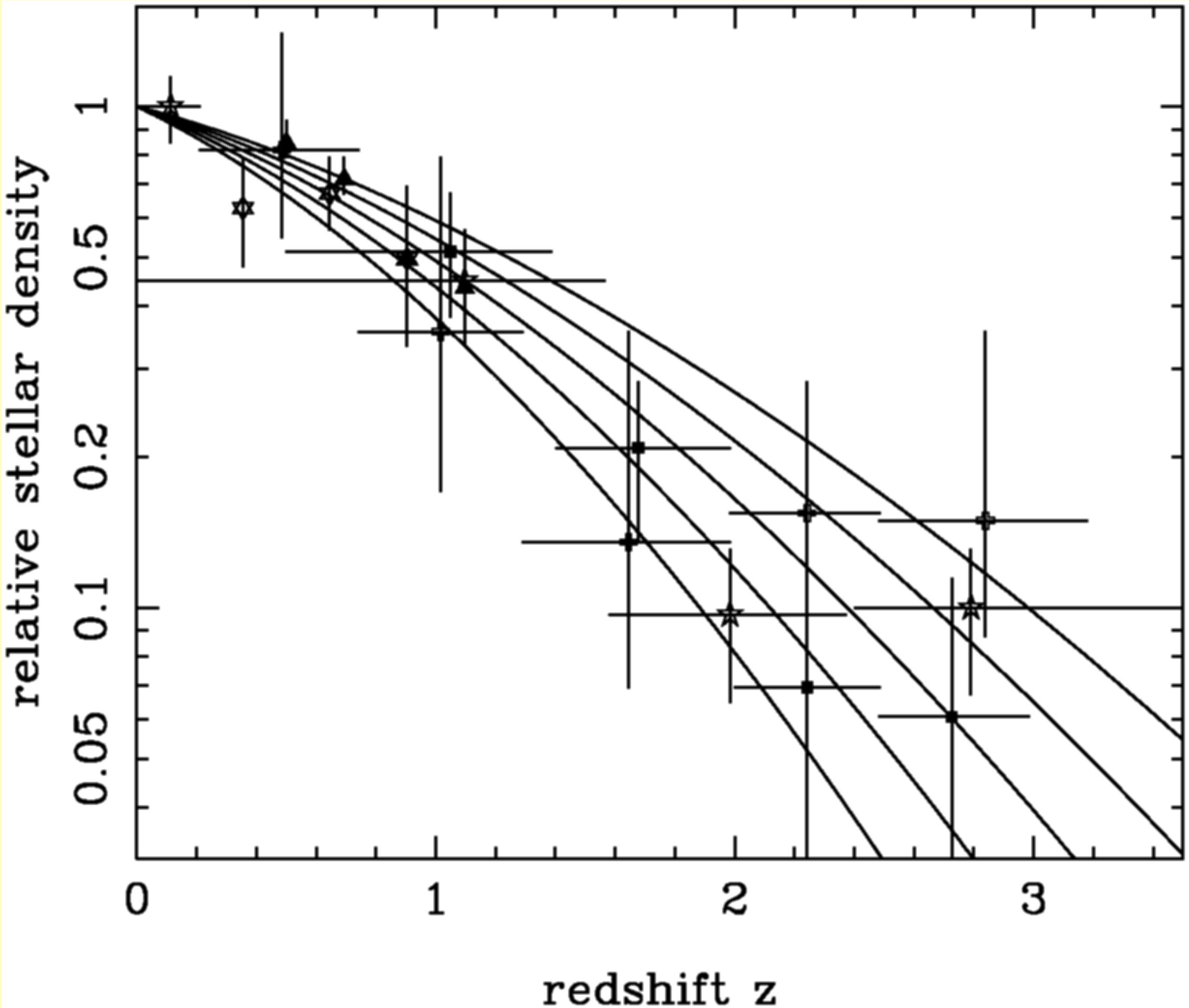


Build-up of total mass of stars in galaxies

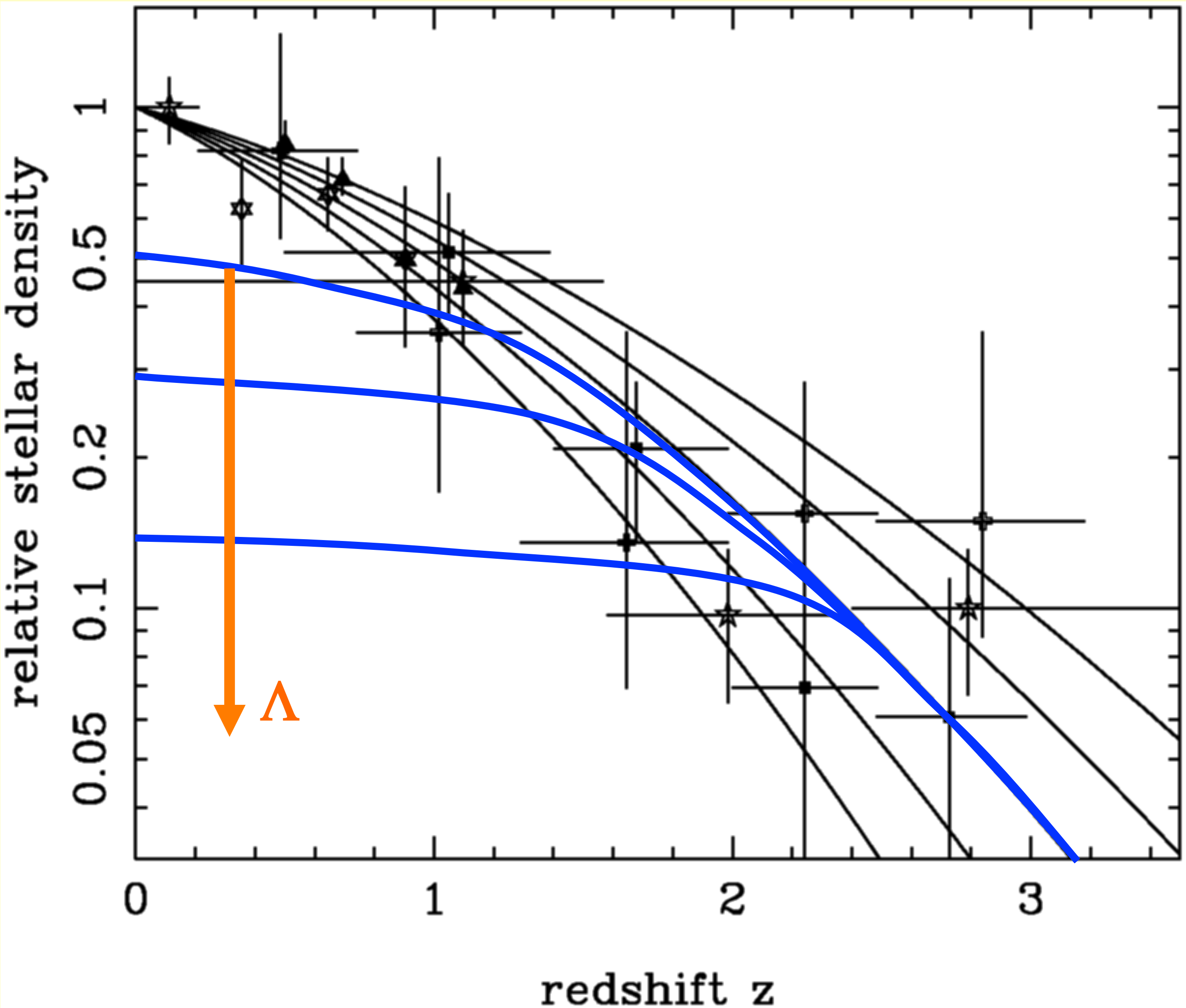


Well modelled by collapse fraction into haloes of mass $2 \times 10^{12}\ M_{\odot}$

What if Λ were bigger?



What if Λ were bigger?



Growth of structure freezes out at vacuum domination

The probability of Λ

Assume you are a randomly-selected member of all observers ever generated in the multiverse

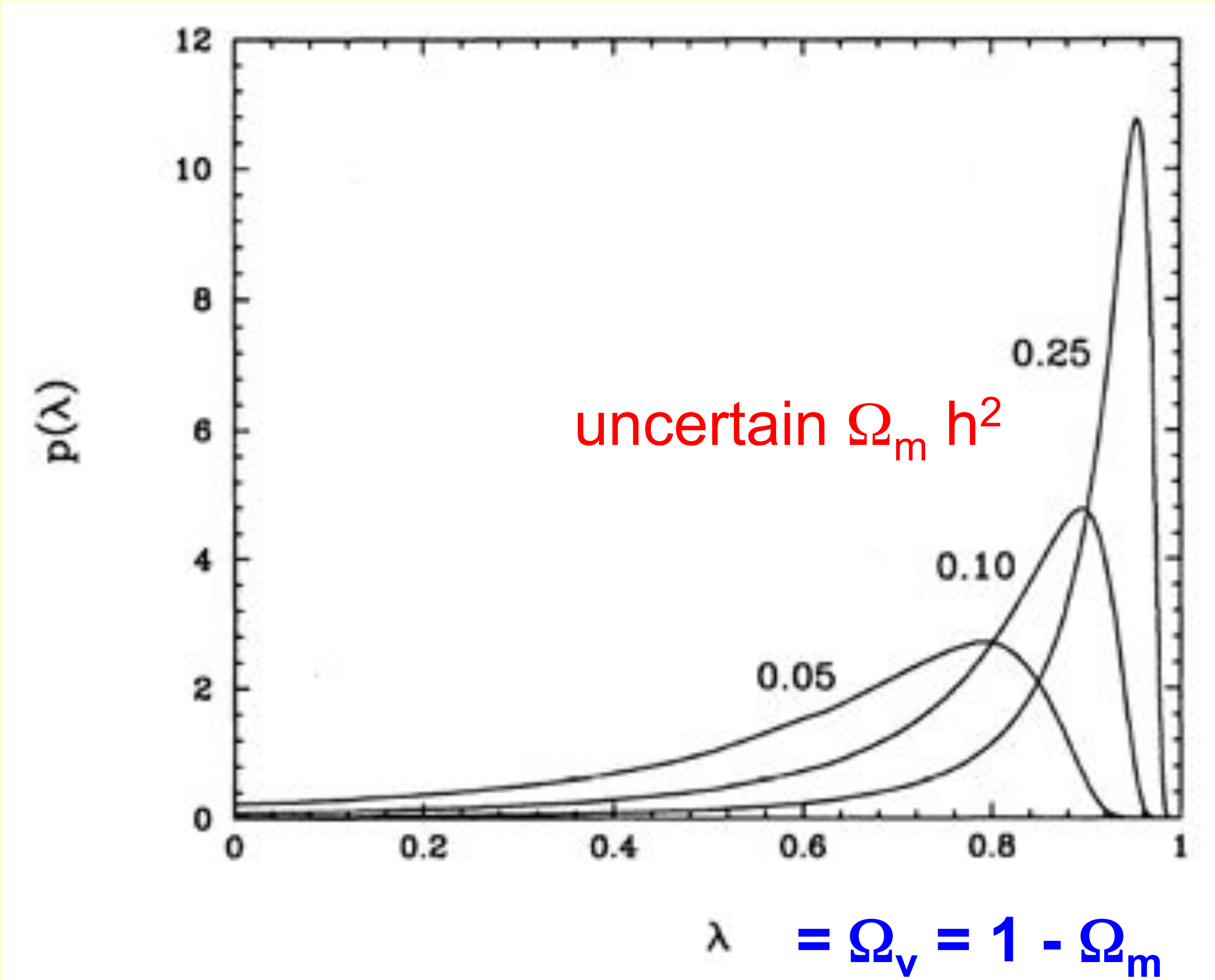
Bayes: $P(\Lambda \mid \text{observer}) \propto P_{prior}(\Lambda)\, N_{gal}(\Lambda)$

Take prior on vacuum energy constant over small range around zero (not a special value)

Number of galaxies depends on fraction of universe collapsed into characteristic mass

$$M_G \sim \alpha^5 \left(\frac{\hbar c}{G m_p^2}\right)^2 \left(\frac{m_p}{m_e}\right)^{1/2} m_p$$

Efstathiou 1995



Consistent with observed $\Omega_v = 0.75$ in our universe

Weinberg's 1989 prediction

The cosmological constant problem*

Steven Weinberg

Theory Group, Department of Physics, University of Texas, Austin, Texas 78712

Astronomical observations indicate that the cosmological constant is many orders of magnitude smaller than estimated in modern theories of elementary particles. After a brief review of the history of this problem, five different approaches to its solution are described.

Reviews of Modern Physics, Vol. 61, No. 1, January 1989

A large cosmological constant would interfere with the appearance of life in different ways, depending on the sign of λ_{eff}. For a large *positive* λ_{eff}, the universe very early enters an exponentially expanding de Sitter phase, which then lasts forever. The exponential expansion interferes with the formation of gravitational condensations, but once a clump of matter becomes gravitationally bound, its subsequent evolution is unaffected by the cosmological constant. Now, we do not know what weird forms life may take, but it is hard to imagine that it could develop at all without gravitational condensations out of an initially smooth universe. Therefore the anthropic principle makes a rather crisp prediction: λ_{eff} must be small enough to allow the formation of sufficiently large gravitational condensations (Weinberg, 1987).

This result suggests strongly that if it is the anthropic principle that accounts for the smallness of the cosmological constant, then we would expect a vacuum energy density $\rho_V \sim (10-100)\rho_{M_0}$, because there is no anthropic reason for it to be any smaller.

Is such a large vacuum energy density observationally allowed? There are a number of different types of astronomical data that indicate differing answers to this question.

Ground rules

What do we keep constant?

Baryon fraction: $f_B = \rho_B / \rho_M$

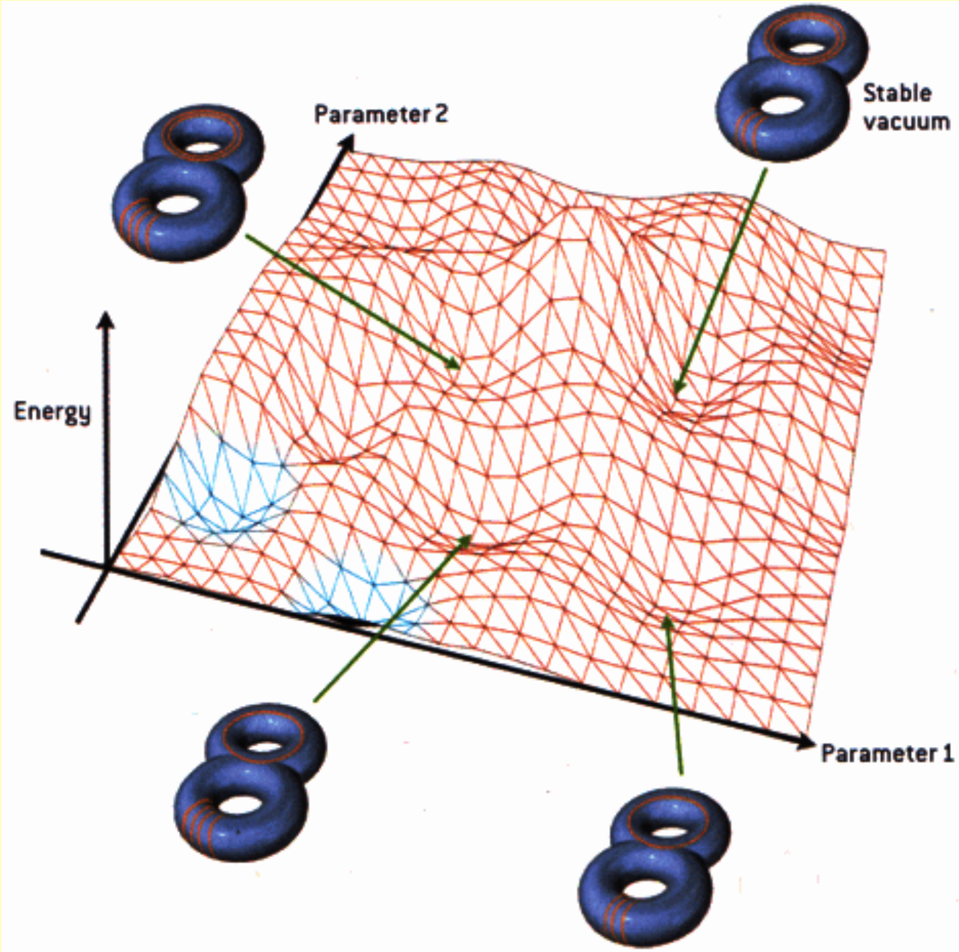
Entropy per DM particle: $S = (T/2.73)^3 / \Omega_M h^2$

Horizon-scale inhomogeneity: $\delta_H = 10^{-5}$

Variation in Λ only – easy to arrange with e.g. frozen scalar field.

Take an experimental approach to what can vary.

The landscape of string theory



10^{500} different vacuum states. Just what's needed for the anthropic ensemble?

Conclusions

- Much of standard physics has been verified on the scale of the cosmos

- But new galaxy surveys might rule out Λ or require a new theory of gravity on >100 Mpc scales

- Either way, we need a solution to the classical Λ problem, or must accept an ensemble picture, where we include the role of observers in cosmological explanation