Dark Energy Theory and Observations

Bruce Bassett

Outline of the Lecture

- Some 'unusual' evidence for acceleration
- Dangers, caveats and lessons learned
- Some interesting theoretical models
- Challenges for the future: a case study

FLRW Background Basics

$$\left(\frac{\dot{a}}{a}\right)^2 = 8\pi G\rho - \frac{K}{a^2}$$

Positive Energy

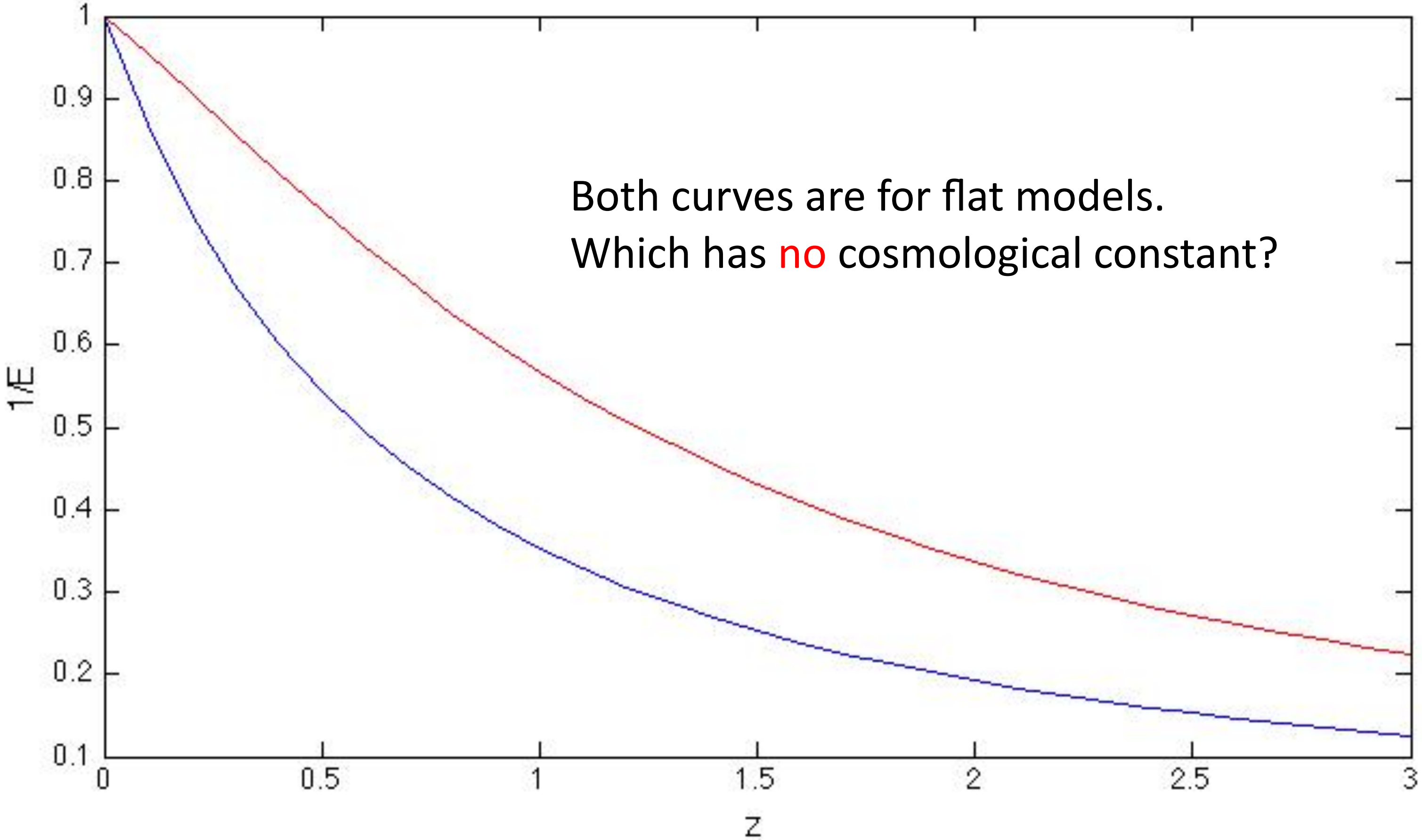
$$\frac{\ddot{a}}{a} = -4\pi G(\rho + 3p)$$

Weak Energy Condition

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

Strong Energy Condition

1/E for Flat ΛCDM



$$E \equiv \frac{H(z)}{H_0} = \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$$

Distances

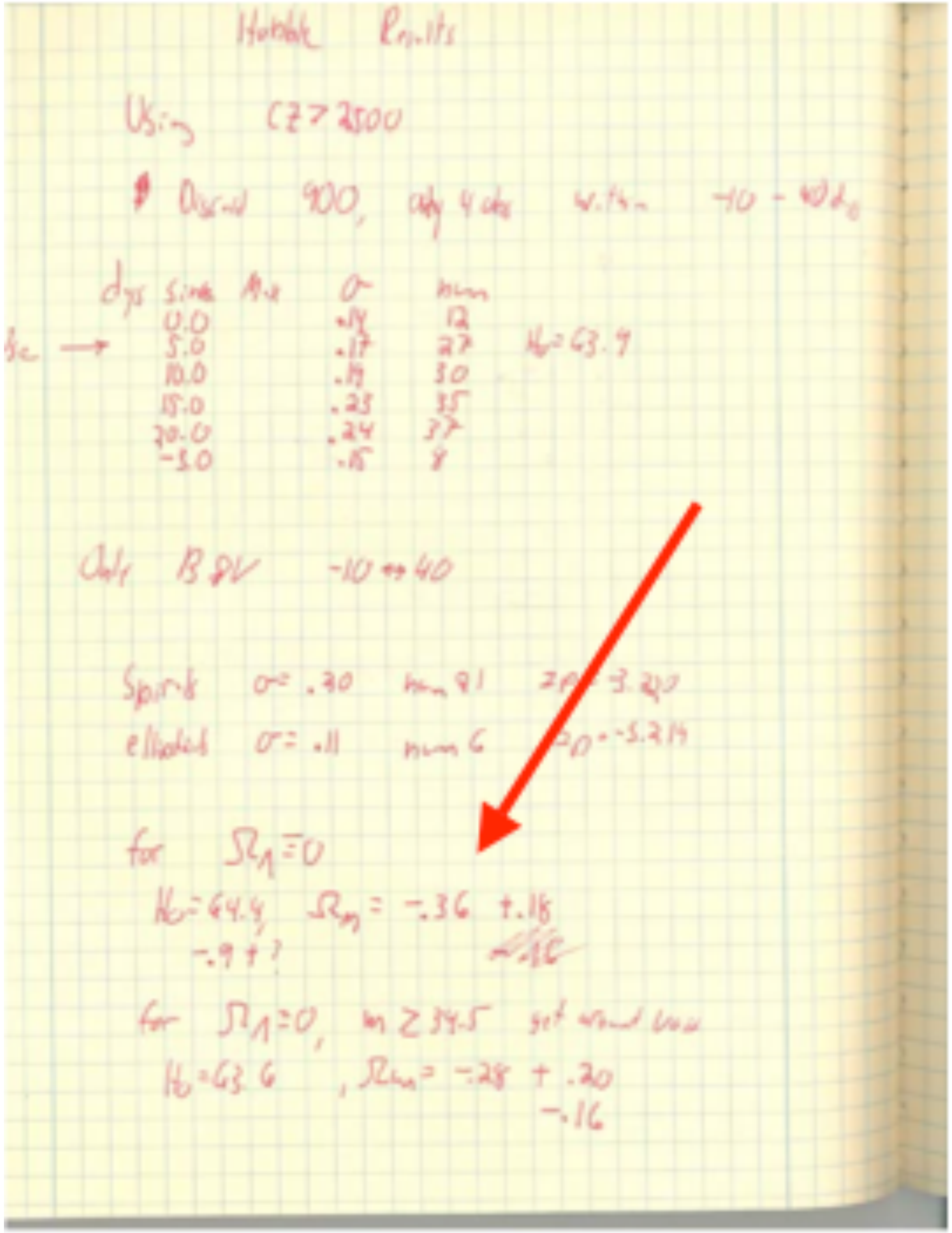
$$d_L(z) = \frac{c(1+z)}{H_0\sqrt{-\Omega_k}} \sin\left(\sqrt{-\Omega_k}\int_0^z \frac{dz'}{E(z')}\right)$$

Distance Duality

$$d_L(z) = (1+z)^2 d_A(z)$$

astro-ph/0312443

- 1997


Hubble Results
Using cz > 2500
H0=63.9
for ΩΛ=0
H0=64.4 Ωm = -.36 +.18
H0=63.6 , Ωm= -.28 +.20
-.16

A. Riess

Exercise Race

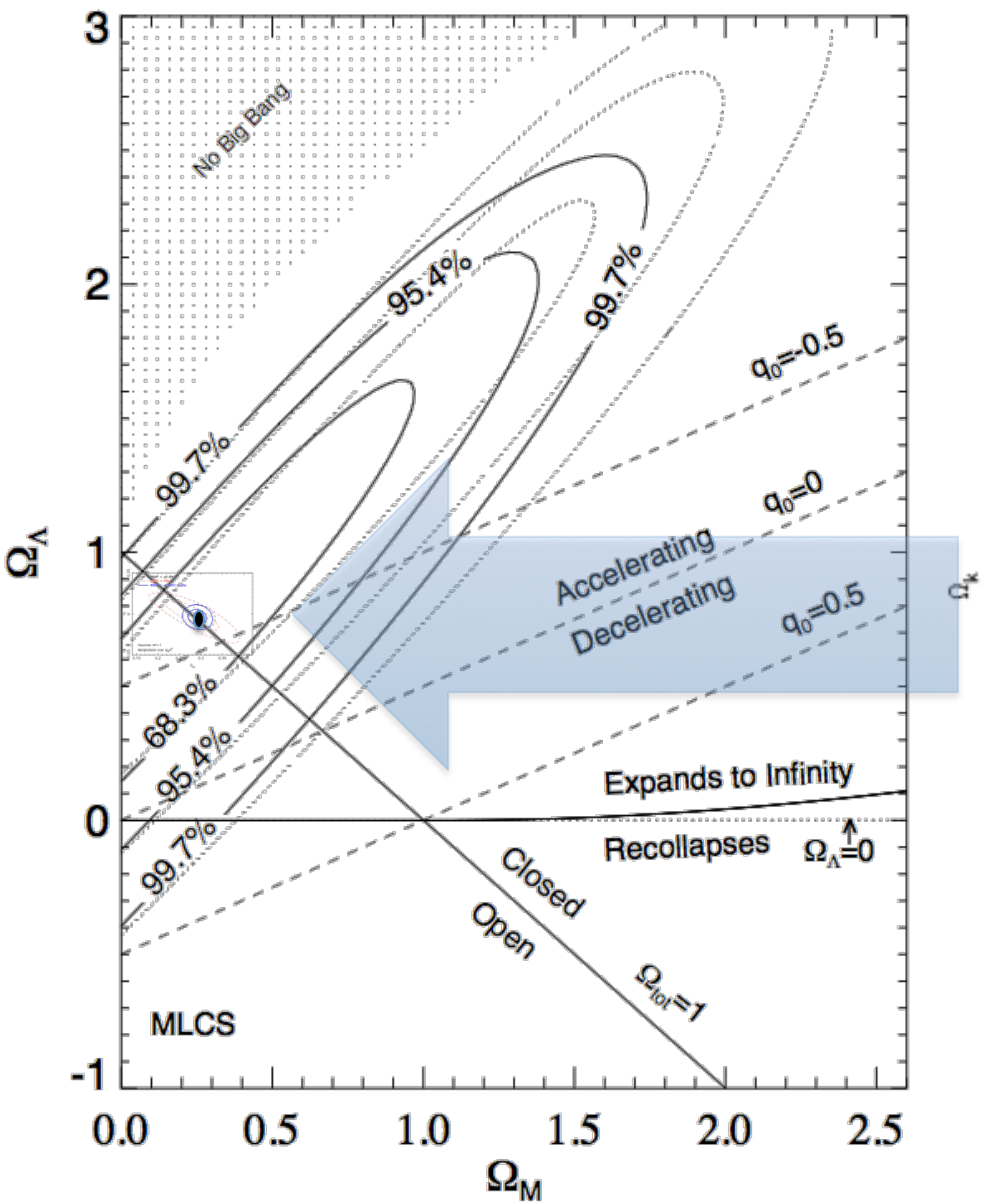
- You measure a SNIa at z=1 with $\mu = 43.8$. At what confidence level is the flat CDM model (Λ=0) ruled out if $\sigma = 0.1$ mag?

$$d_L(z) = c(1+z)\int \frac{dz'}{H(z')}$$

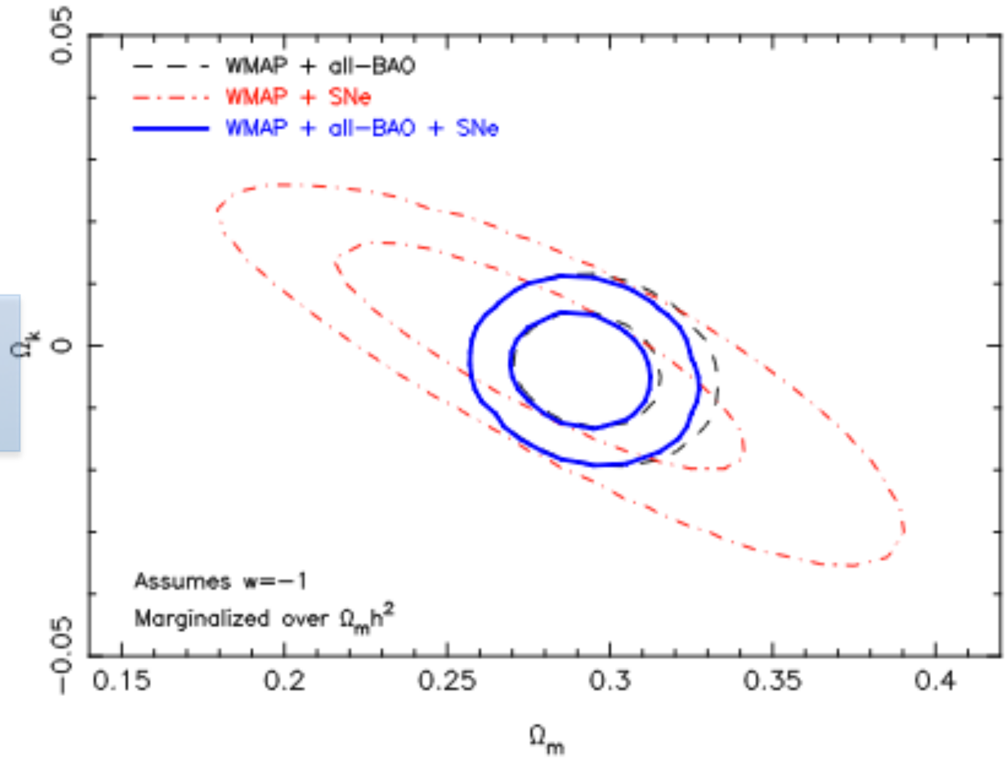
$$\mu(z) = 5\log_{10}\left(\frac{d_L(z)}{Mpc}\right) + 25$$

$$\chi^2 = \sum_i \left(\frac{t_i - d_i}{\sigma_i}\right)^2$$

How far have we come since 1998?

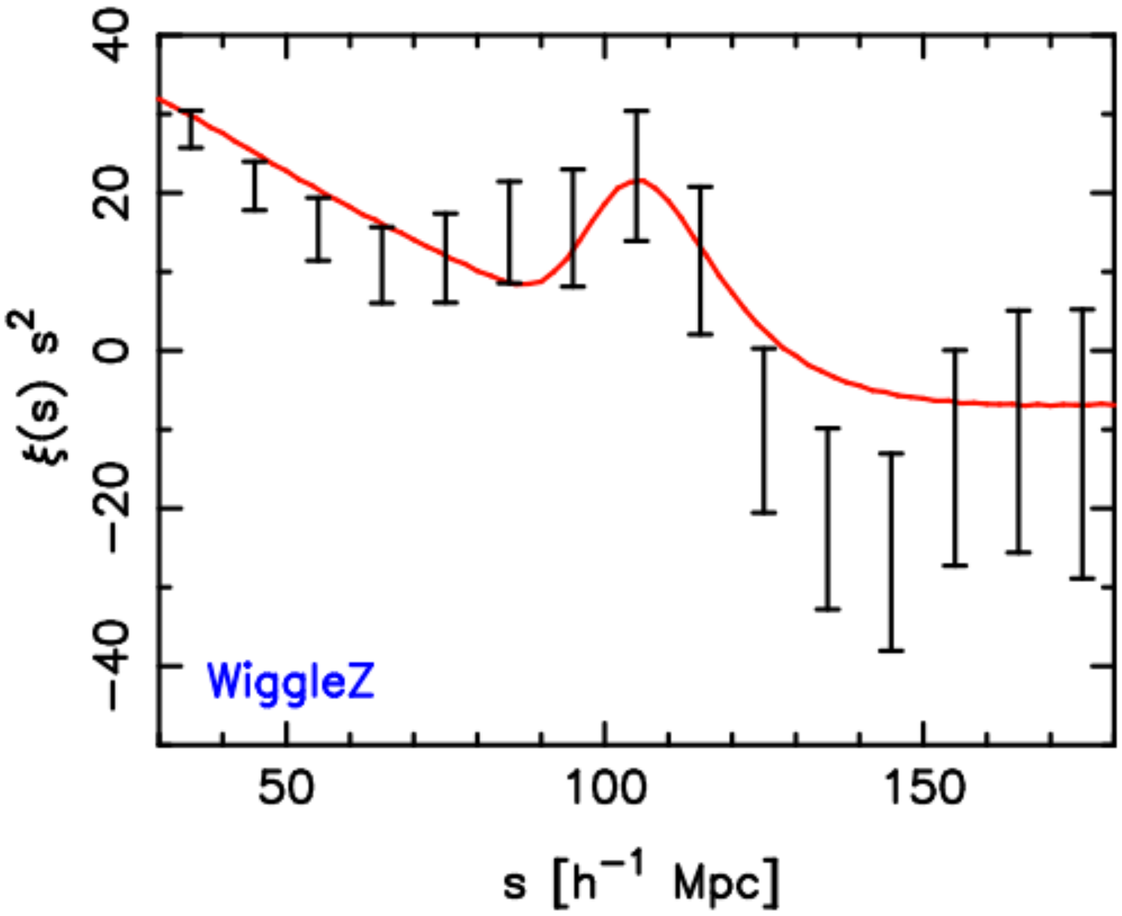


Riess *et al,* 1998

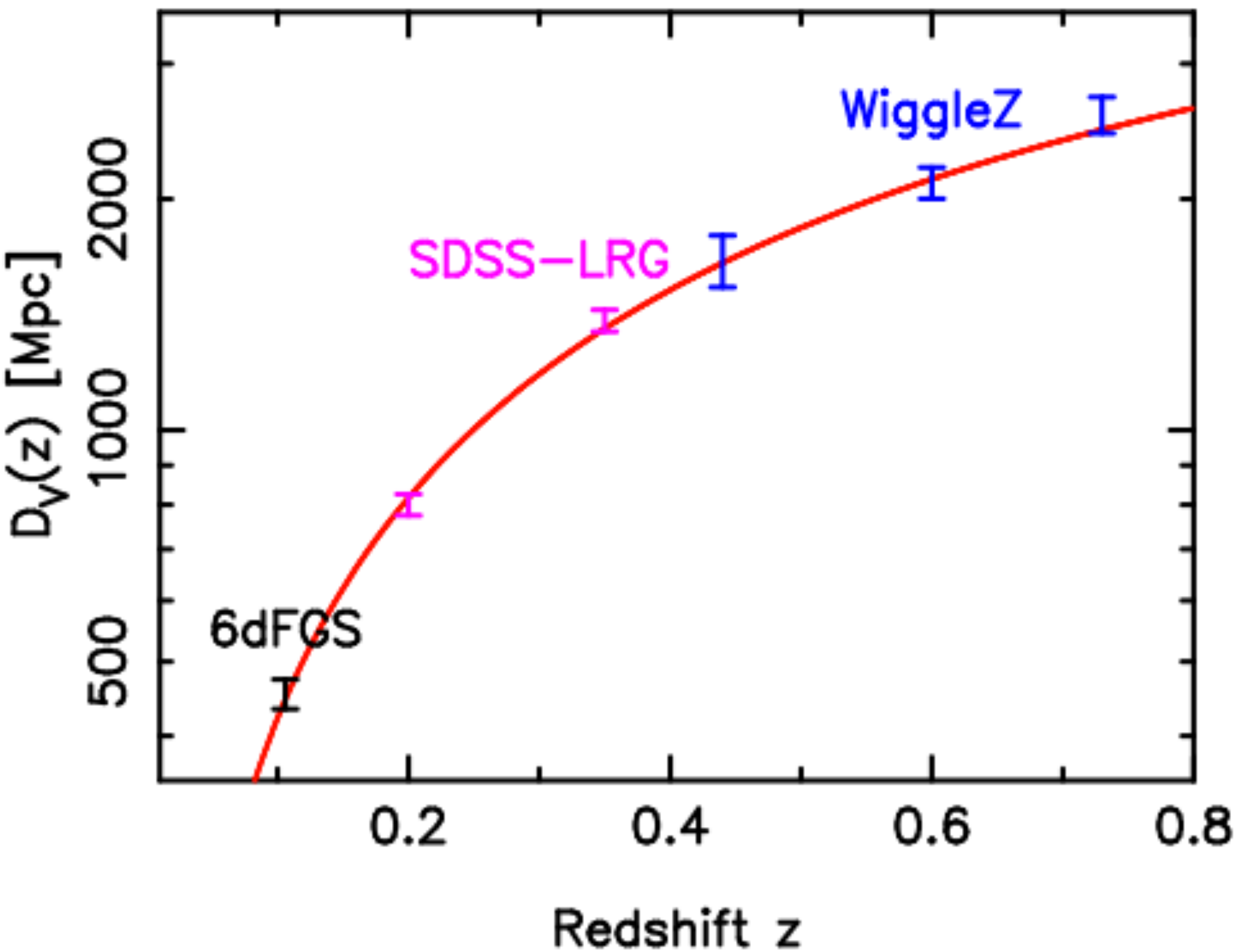


Blake *et al,* 2011

Angular Diameter Distances - BAO



Blake *et al,* 2011



Blake *et al,* 2011

Age of the Universe

- Various objects suggest the universe is very old (> 12 Gyr)

$$t_0 = \int_0^{t_0} dt = -\int_\infty^0 \frac{dz}{(1+z)H} = H_0^{-1} \int_0^\infty \frac{dz}{E(z)(1+z)}$$

- This implies at least one of:
  - low H_0
  - low Ω_{tot}
  - something that suppresses E(z) at low redshift.
  - Inhomogeneous universe (bang-time is a free function)

- Lead to claims around 1995 that either the Universe has a large cosmological constant or H_0 is small…

THE COSMOLOGICAL CONSTANT IS BACK

Lawrence M. Krauss[1] and Michael S. Turner[2,3]

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Enrico Fermi Institute, The University of Chicago, Chicago, IL 60637-1433

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Fermi National Accelerator Laboratory, Batavia, IL 60510-0500

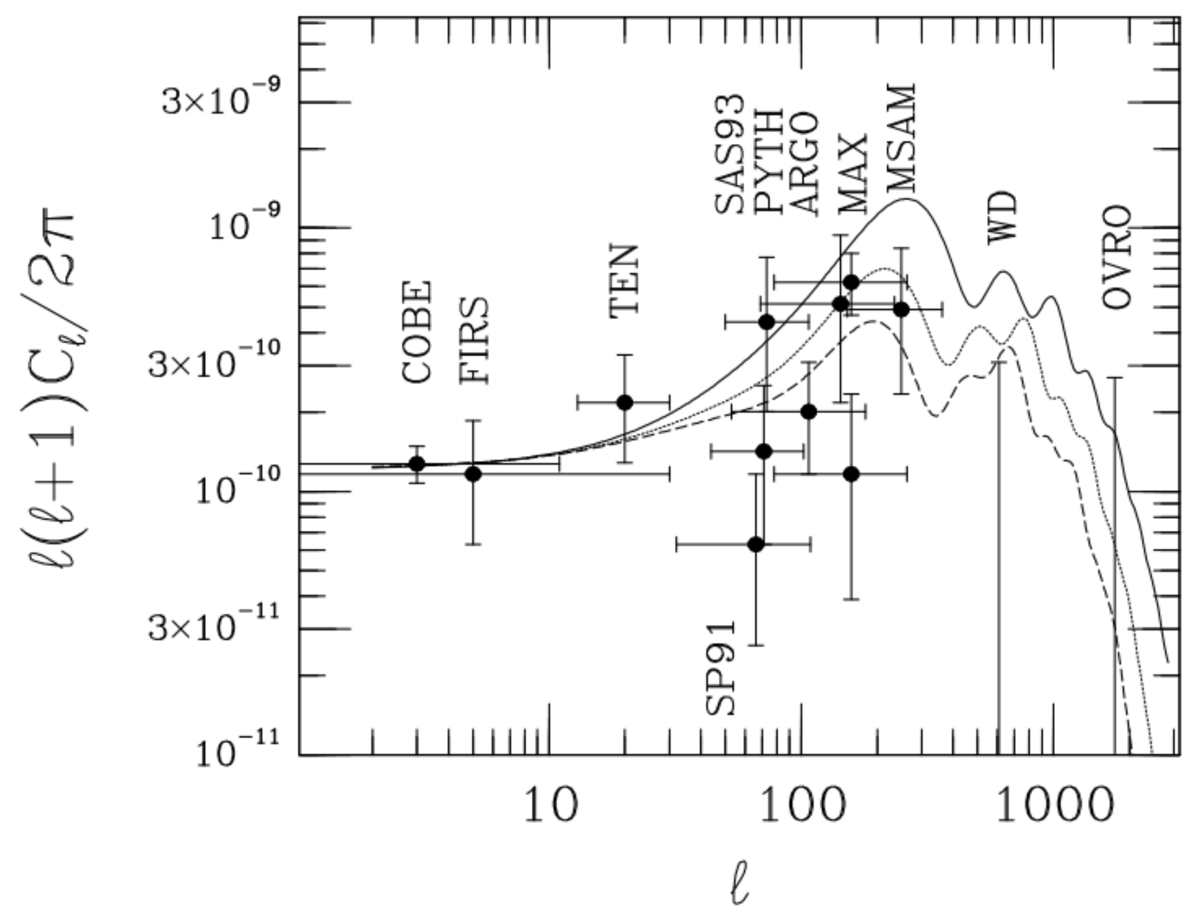
(submitted to *Gravity Research Foundation Essay Competition*)

SUMMARY

A diverse set of observations now compellingly suggest that Universe possesses a nonzero cosmological constant. In the context of quantum-field theory a cosmological constant corresponds to the energy density of the vacuum, and the wanted value for the cosmological constant corresponds to a very tiny vacuum energy density. We discuss future observational tests for a cosmological constant as well as the fundamental theoretical challenges—and opportunities—that this poses for particle physics and for extending our understanding of the evolution of the Universe back to the earliest moments.

FERMILAB–Pub–94/173-A
astro-ph/yymmnnn
submitted to *Nature*

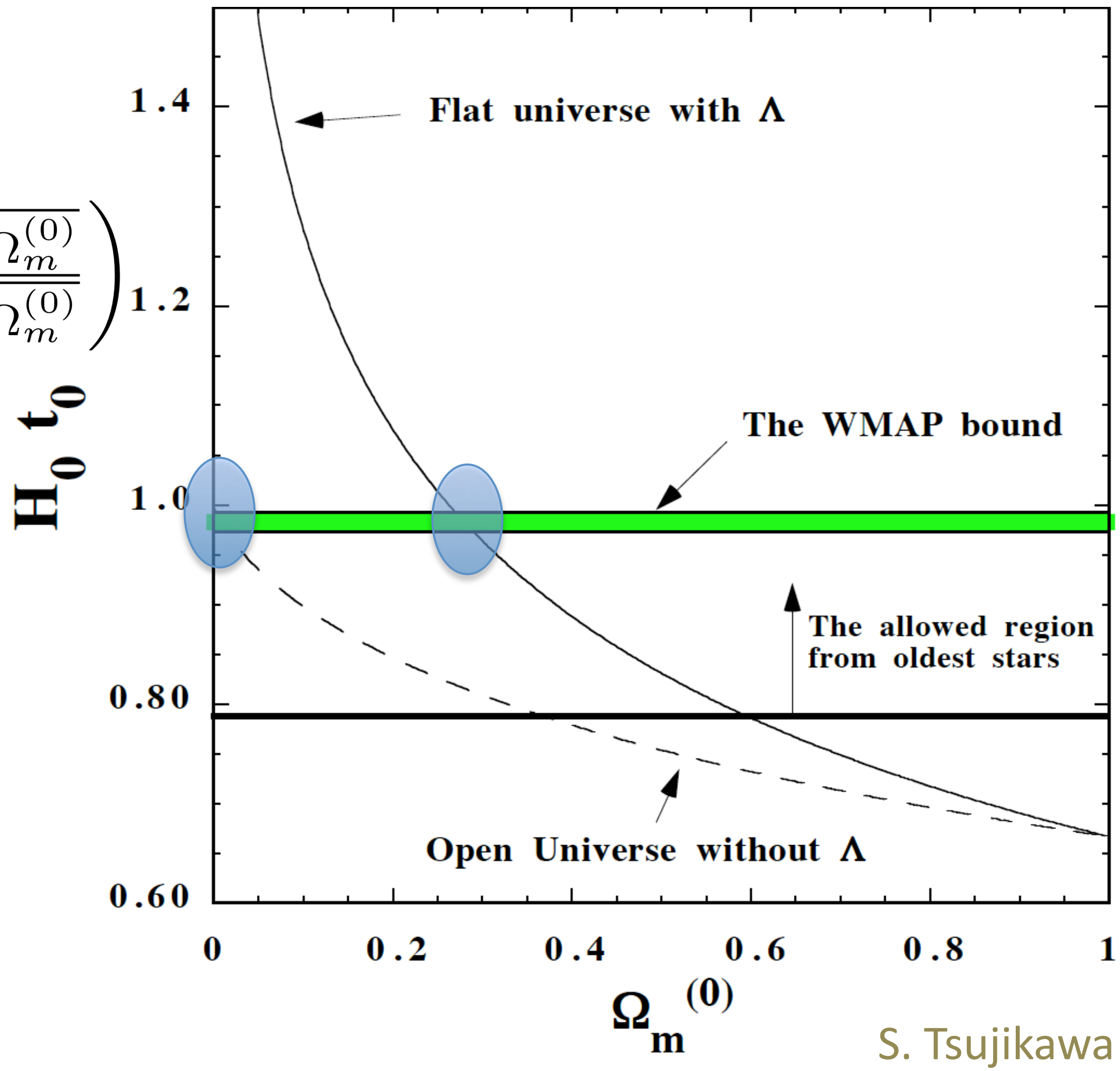
THE CASE FOR A HUBBLE CONSTANT OF $30\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$



- For a flat LCDM model:

$$t_0 = \frac{H_0^{-1}}{3\sqrt{1-\Omega_m^{(0)}}} \ln \left(\frac{1+\sqrt{1-\Omega_m^{(0)}}}{1-\sqrt{1-\Omega_m^{(0)}}} \right)$$

(Home exercise)



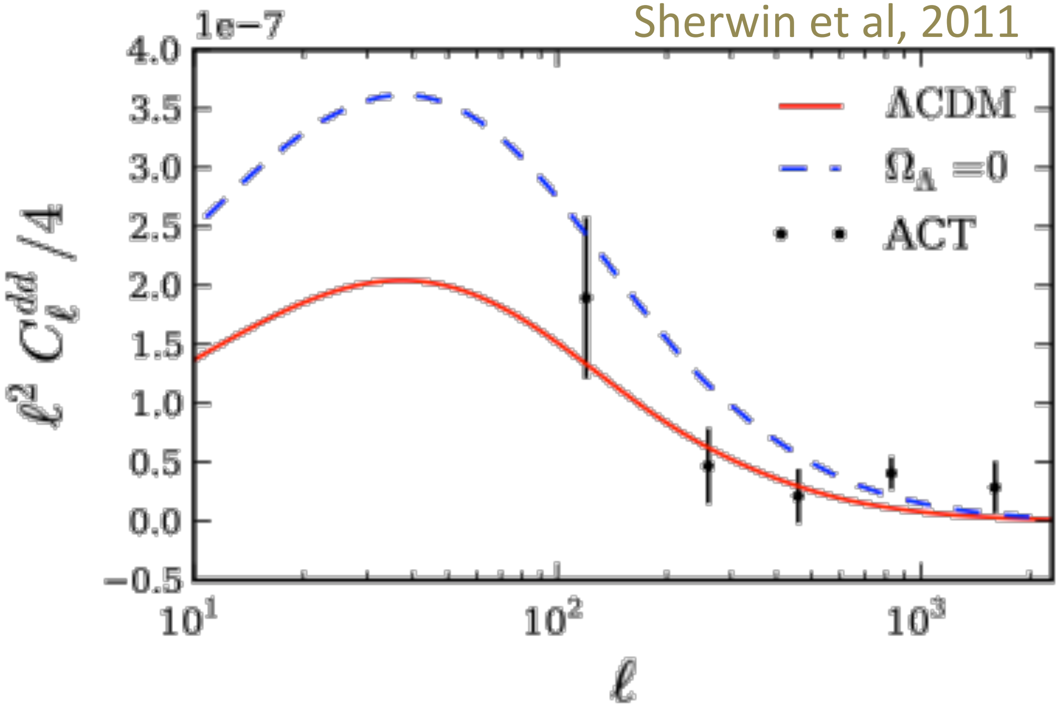
S. Tsujikawa

CMB lensing

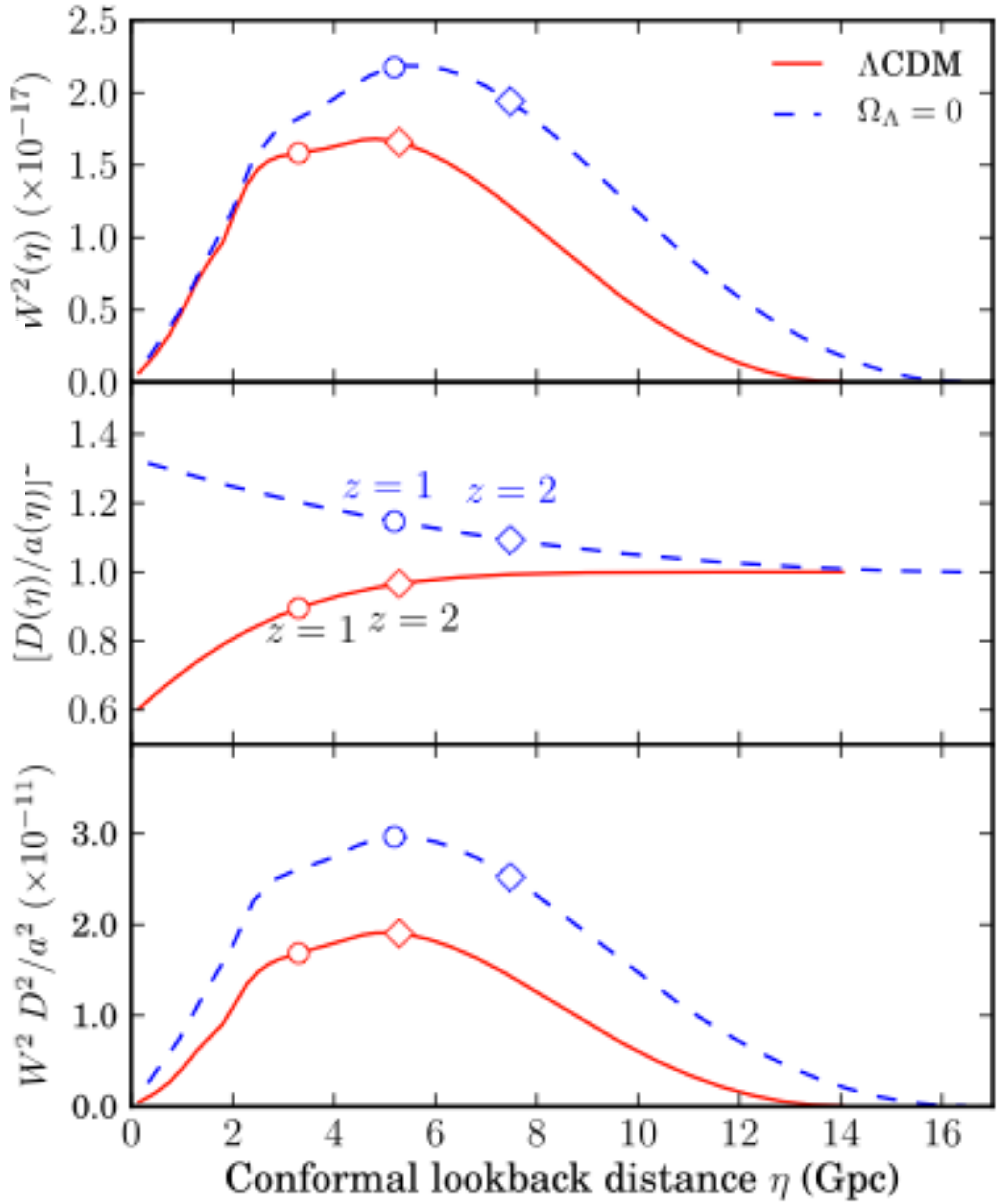
- Smaller 4-point lensing function in the CMB than expected from a flat, decelerating universe

- Hence either:
  - acceleration
  - Other suppression of growth

Sherwin et al, 2011



$$\frac{\ell^2}{4} C_\ell^{dd} = \int_0^{\eta_*} d\eta \, \underbrace{W^2(\eta)}_{\text{geometry}} \, \underbrace{\left[D(\eta)/a(\eta)\right]^2}_{\text{growth}}$$

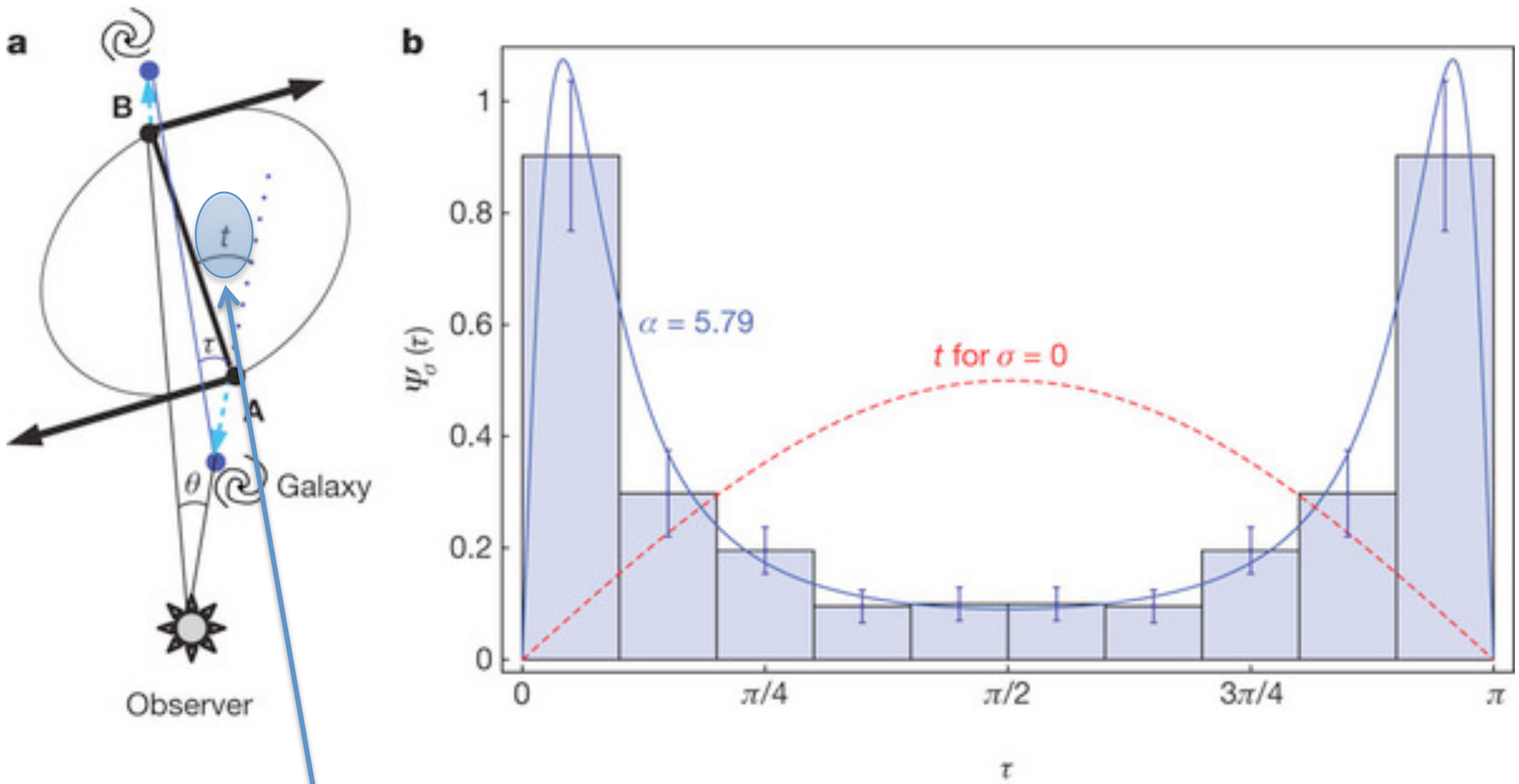


Sherwin et al, 2011

A New Alcock-Paczynski Test

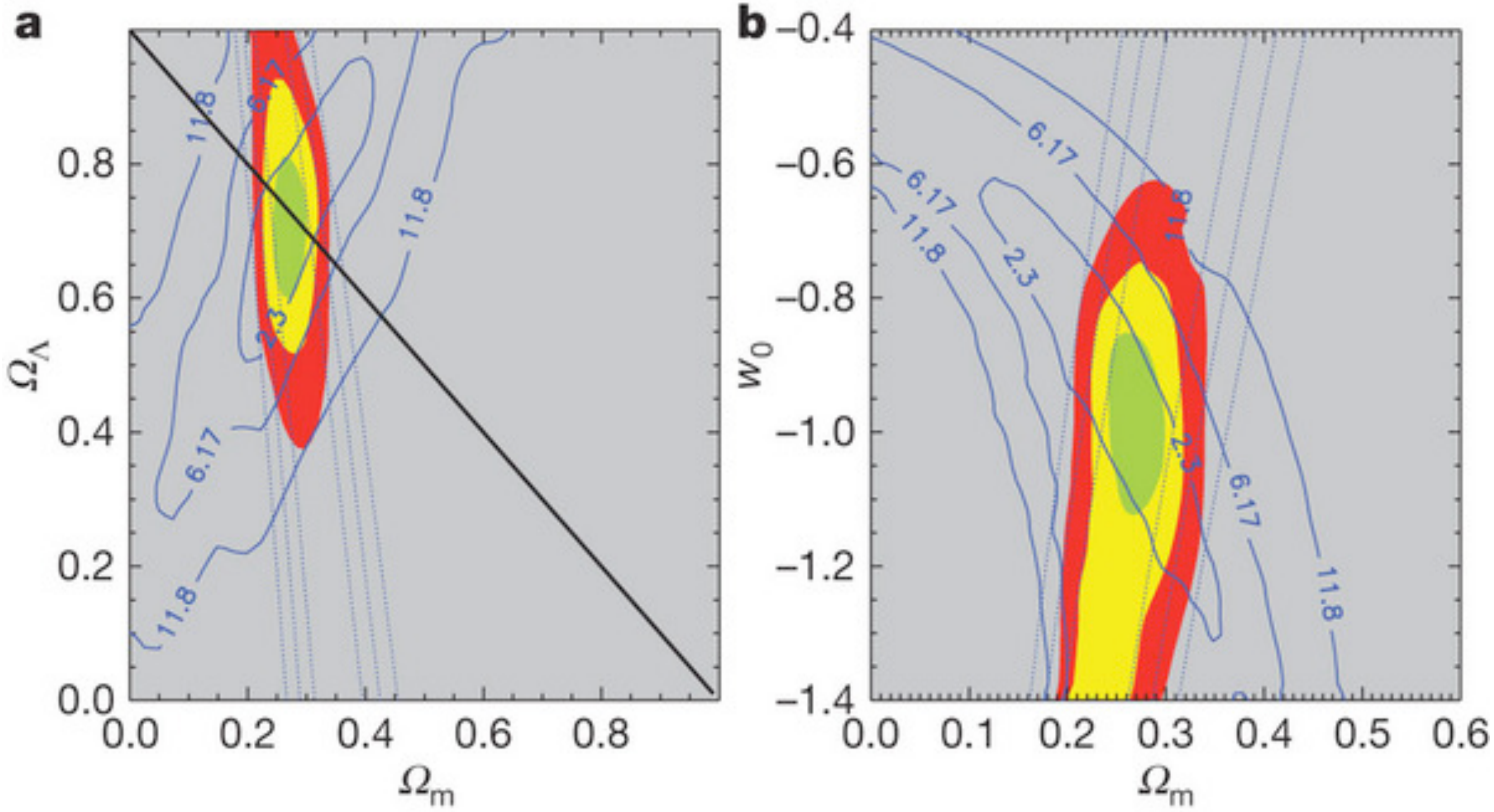
- Use the Copernican Principle:

  The angles between us and pairs of other galaxies should be uniformly distributed in real space…



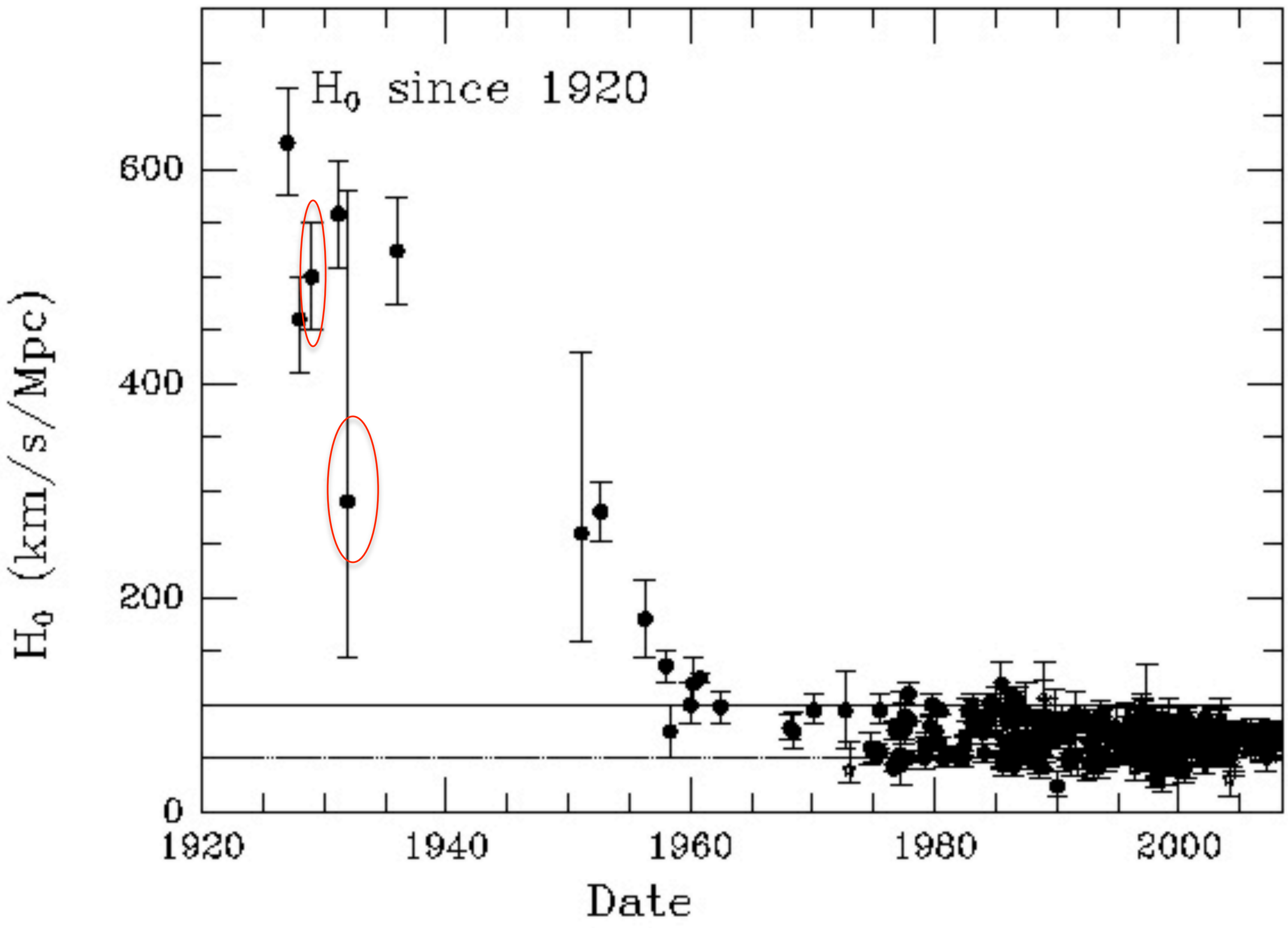
$$\sin^2 t = \left\{ 1 + \left[C_k(\chi_A)\cot\theta - \frac{S_k(\chi_A)C_k(\chi_B)}{S_k(\chi_B)\sin\theta} \right]^2 \right\}^{-1}$$

Marinoni and Buzzi, 2010



- Very early days: See the discussion and extension in arXiv: 1108.0932

Dangers, Caveats and Lessons



H_0 since 1920
600
400
200
0
H_0 (km/s/Mpc)
1920
1940
1960
1980
2000
Date

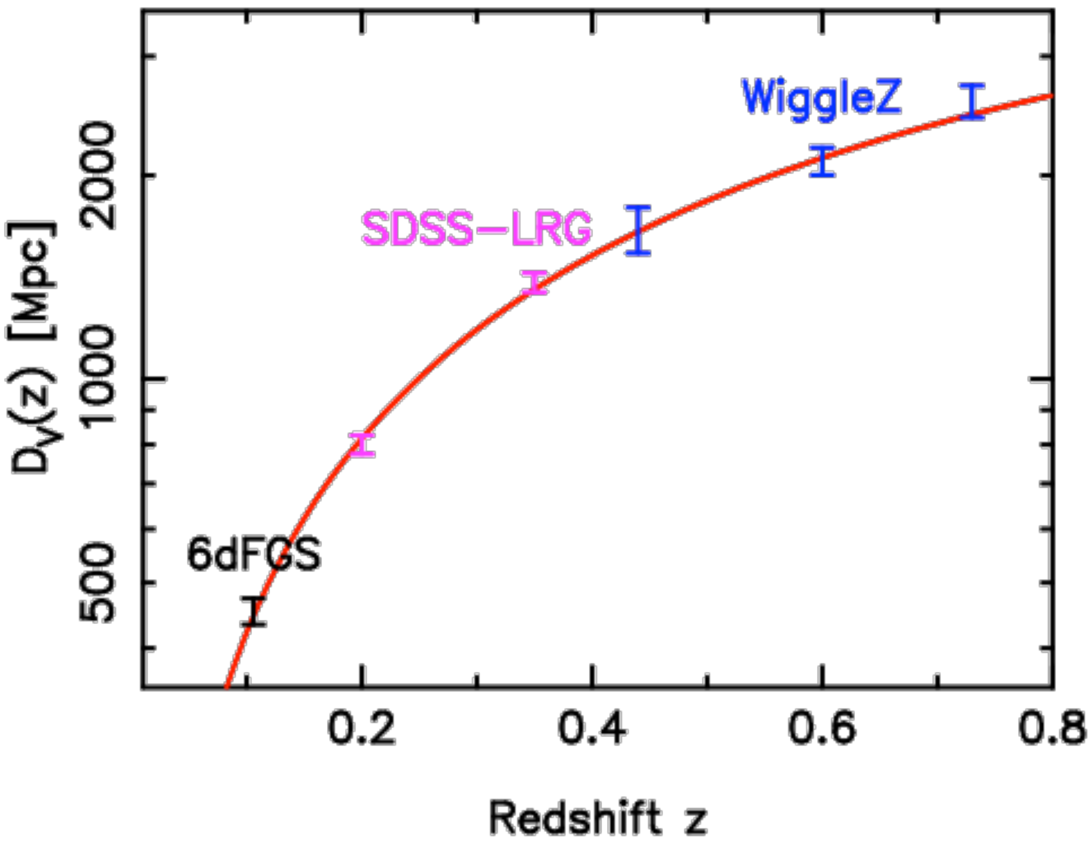
J. Huchra

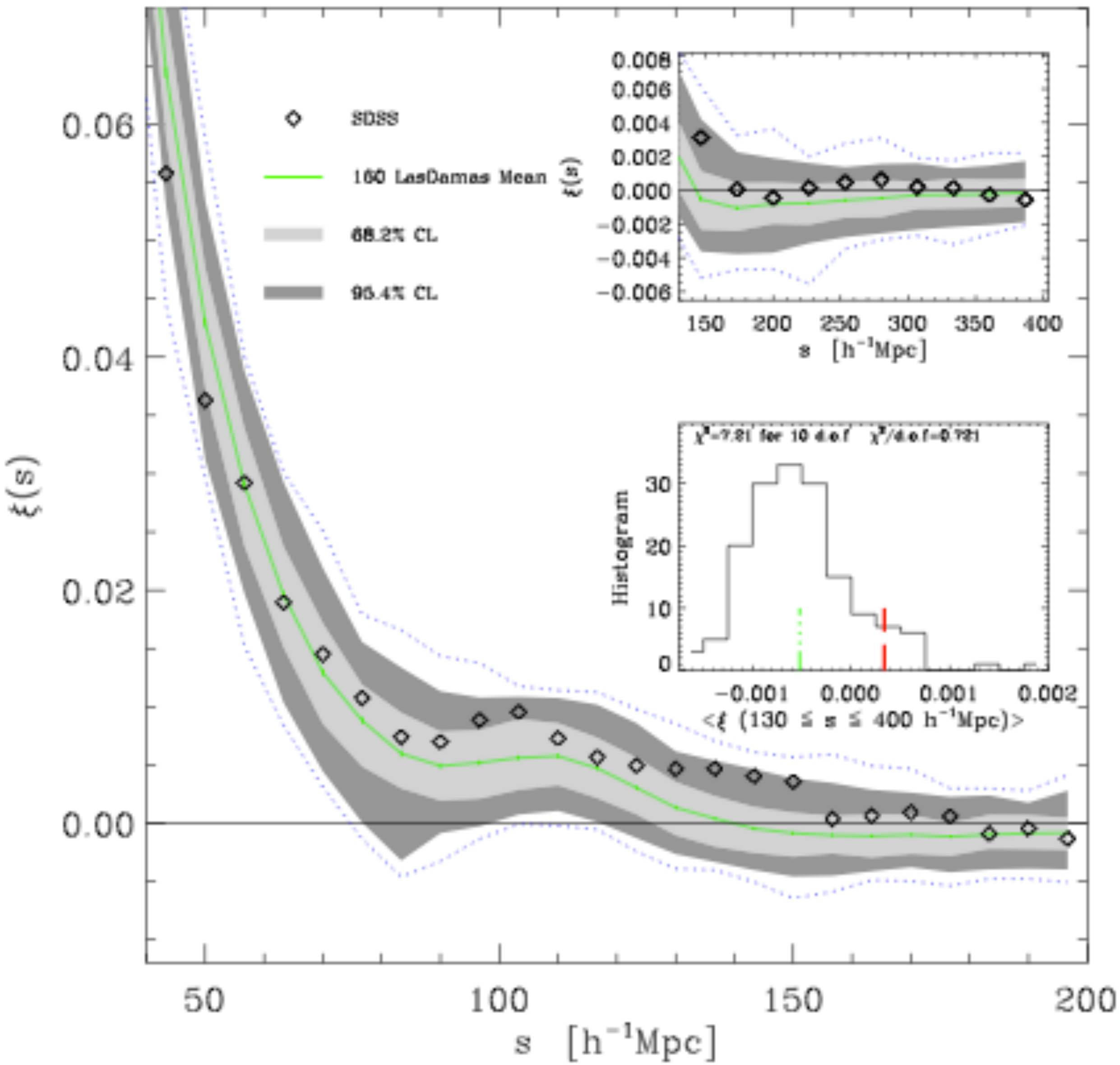
Sting in the Posterior

- How should you use BAO results in your cosmological analysis?

- If we only detect something at nσ, you cant draw any new conclusions at more then nσ.

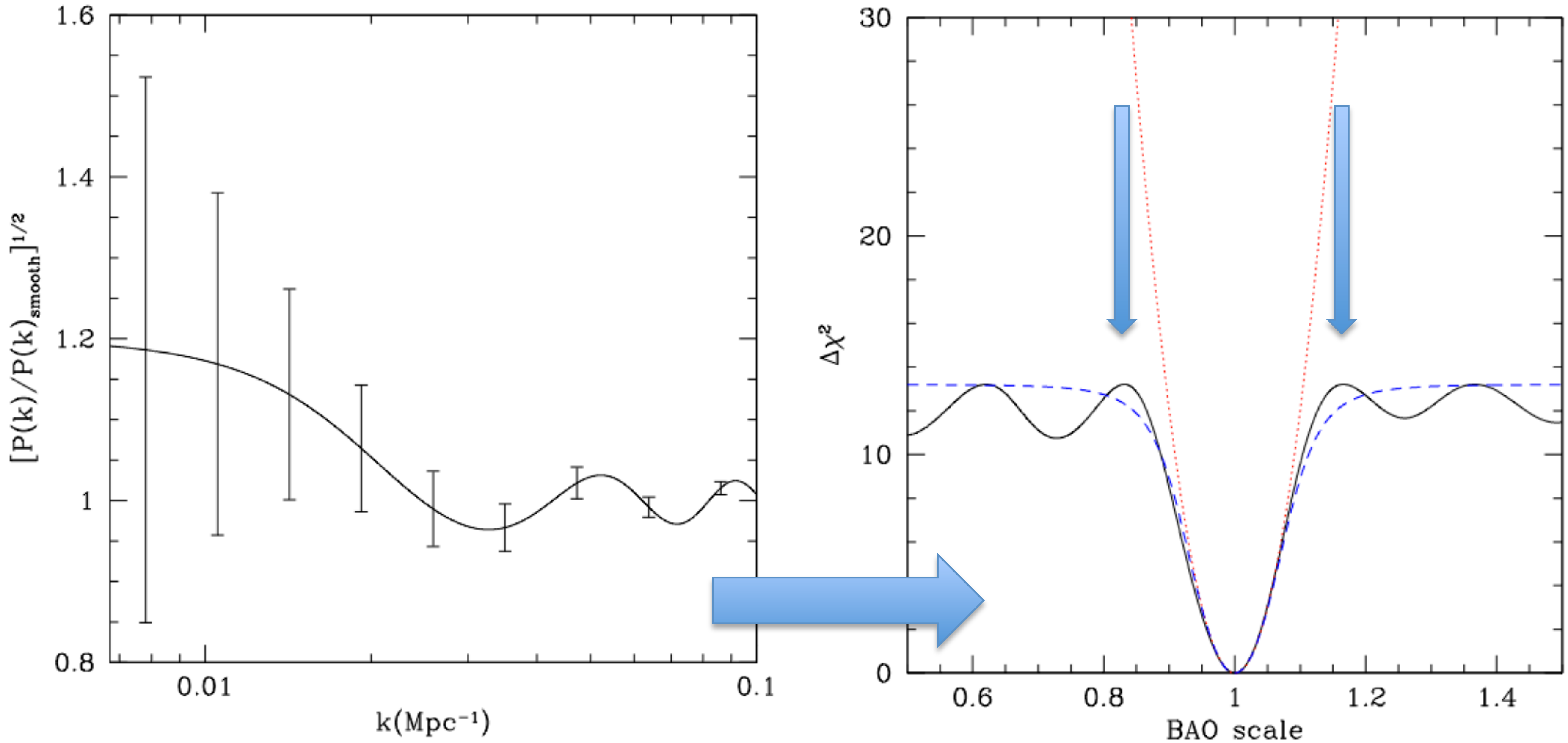
Arxiv: 1005.1664



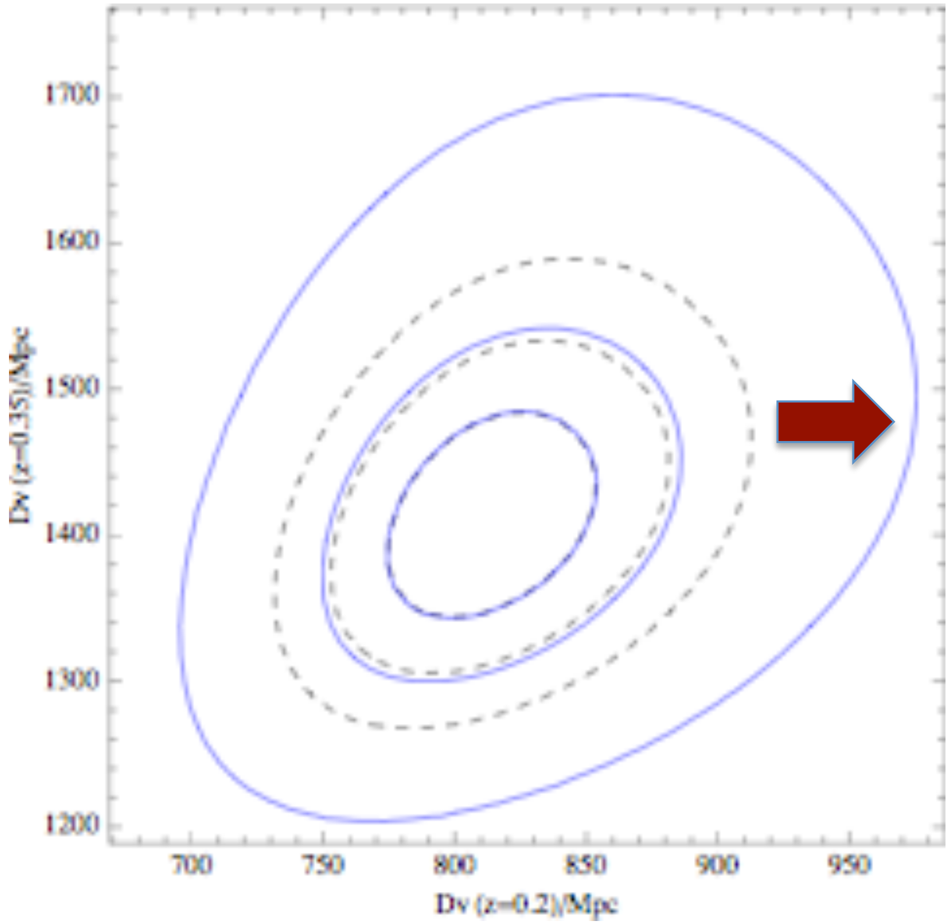


Kazin et al, 2009

Arxiv: 1005.1664



What happens to SDSS-like BAO Contours?



- Big effect on the >99% confidence intervals. Must be included in any analysis.

$$G_{\mu\nu} = T_{\mu\nu}$$

- The Einstein equations couple geometry only to the **total** stress tensor, $T_{\mu\nu}$
- In 1916 that was no problem: photons, electrons & something else…

But what does this mean for our knowledge of dark matter and dark energy today?

We actually know '**nothing**' about Ω_M

- But doesn't $\Omega_M = 0.281 \pm 0.026$ from Constitution + BAO, and didn't Alessandro argue that we have a 23σ detection of dark matter from the CMB?
- Yes, but as he pointed out, it assumes a model prior: **ΛCDM**
- **What happens if we drop the Λ assumption?**

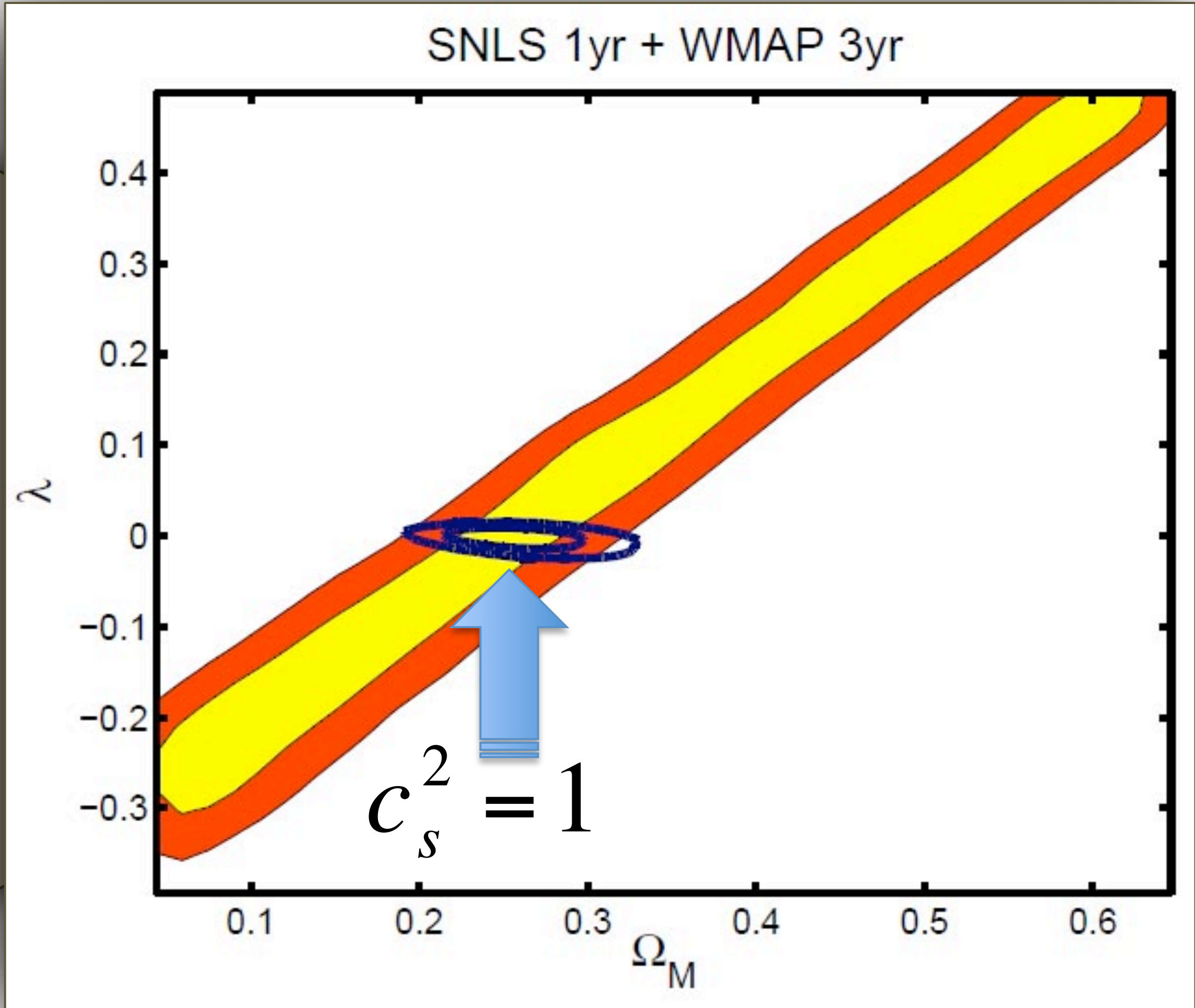
A Toy Example

Assume Dark Energy has

$$w(z) = \frac{1}{\lambda(1+z)^3 - 1}$$

Now use available data to measure both λ and Ω_M

M. Kunz 07

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Degeneracy

- Even with perfect **distance** measurements there is a perfect degeneracy between **the curvature** (Ω_k) and **w(z)** (Weinberg, '73)

$$d_L(z) = \frac{(1+z)}{H_0\sqrt{-\Omega_k}} \sin\left(H_0\sqrt{-\Omega_k} \int \frac{dz'}{H(z')} \right)$$

$$\underbrace{\{d_L(z_i)\}}_{N} \rightarrow \underbrace{\{w(z_i), \Omega_k\}}_{N+1}$$

- *You must* ***assume*** *you know one of the two…(Ned Wright)*

$$\Lambda$$

Data Set	Ω_K
WMAP + $h = 0.72 \pm 0.0$[illegible]	$-0.003^{+0.013}_{-0.017}$

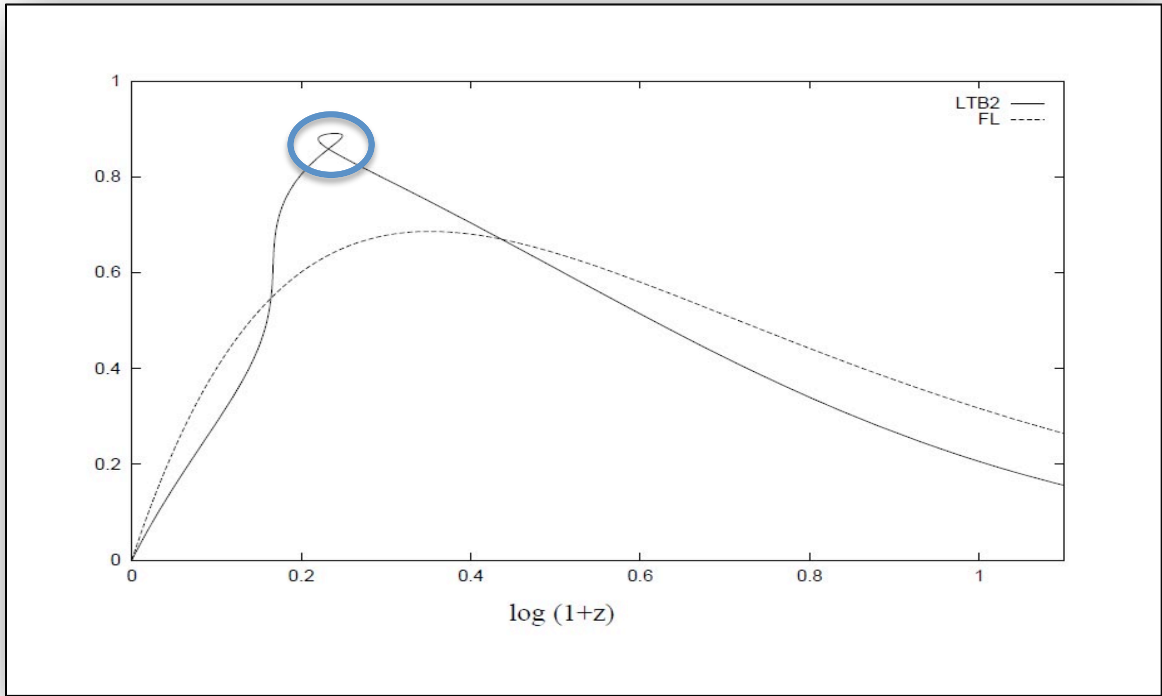
Spergel *et al*, WMAP3

Or you need H(z) independently of distances:

$$\Omega_k = \frac{[H(z)D'(z)]^2 - 1}{[H_0 D(z)]^2}$$

Testing the Copernican Principle

- Spherically symmetric LTB models can fit **any** redshift-distance relation trivially.



Mustapha et al, 97

CP-II

- Any conformally-FLRW metric will have an exactly isotropic CMB for **all** observers

- If observers are moving non-*geodesically*, **all** observers can see an isotropic CMB (Hence the SZ effect is no use as a test)

Barrett and Clarkson, 2000

CP-III

- Fortunately there is a general test of FLRW geometry independent of General Relativity:

$$\Omega_k = \frac{[H(z)D'(z)]^2 - 1}{[H_0 D(z)]^2}$$

Independent of z
In FLRW

Clarkson, BB, Lui 09

An interesting model you may not have heard of…

Dark Goo – Imperfect Fluid

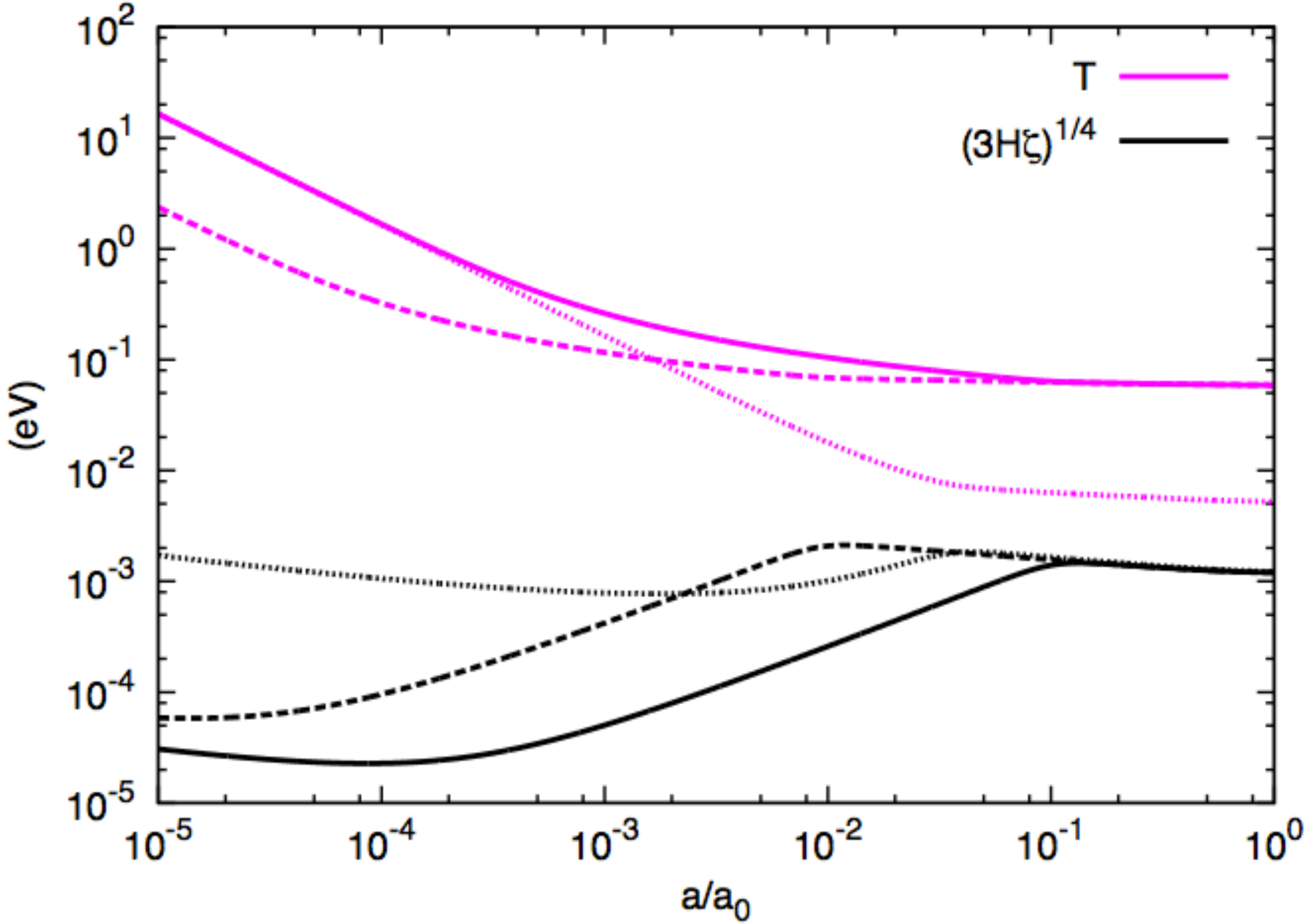
- arXiv:1107.1503

Controls mean free time between collisions

$$T^{\mu\nu}_{\text{viscous}} = T^{\mu\nu}_{\text{perfect}} - \zeta (g^{\mu\nu} + U^{\mu}U^{\nu}) D_{\gamma}U^{\gamma}$$

$$p_{\text{eff}} = p - 3\zeta \dot{a}/a$$

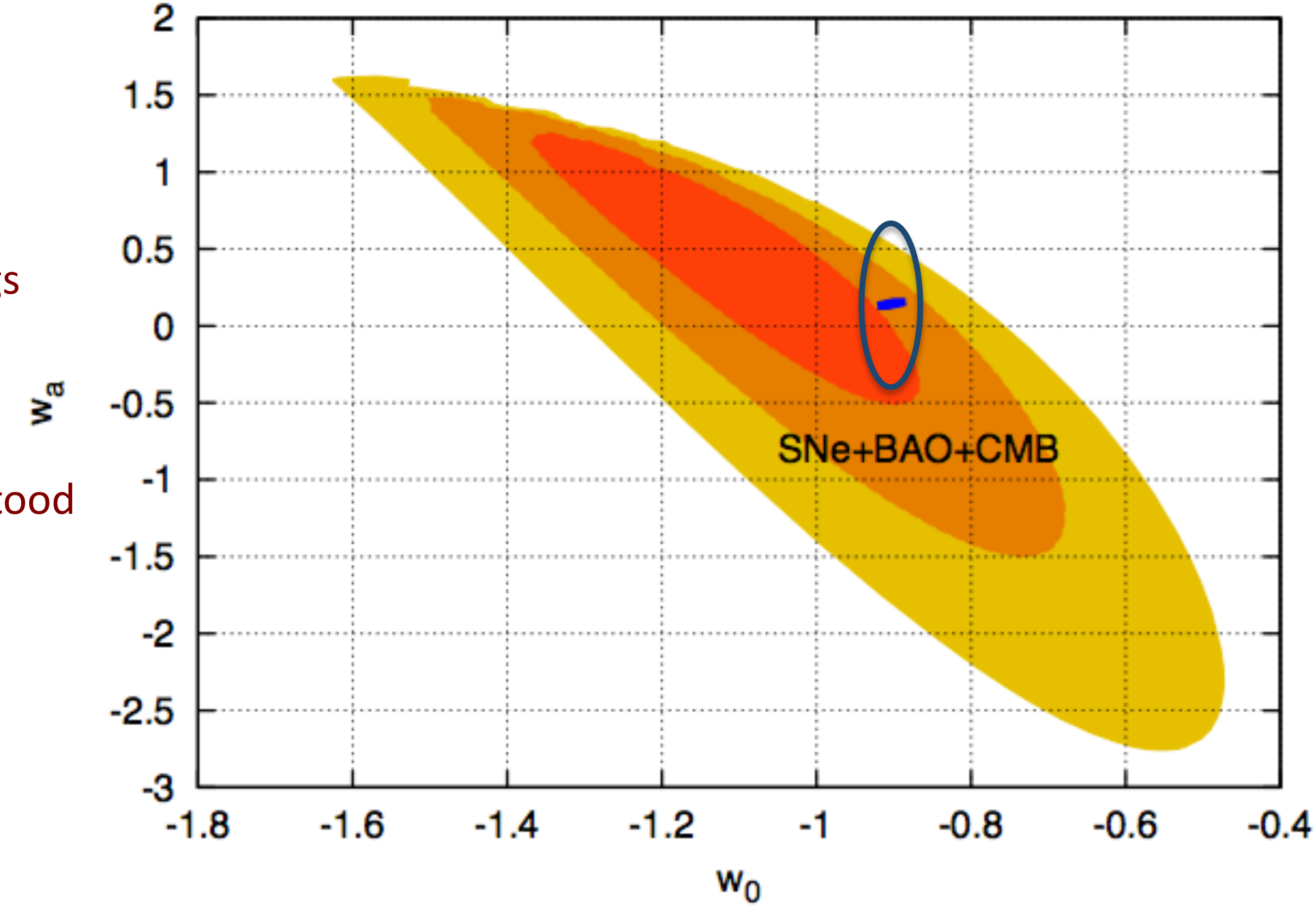
$$V(\phi) = \frac{m^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4 \quad \Rightarrow \quad \zeta \propto \frac{m^2}{\lambda^4} e^{\kappa/T}$$



T
(3Hζ)^1/4
(eV)
a/a_0
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-5
10^-4
10^-3
10^-2
10^-1
10^0

No apparent fine-tunings Required.

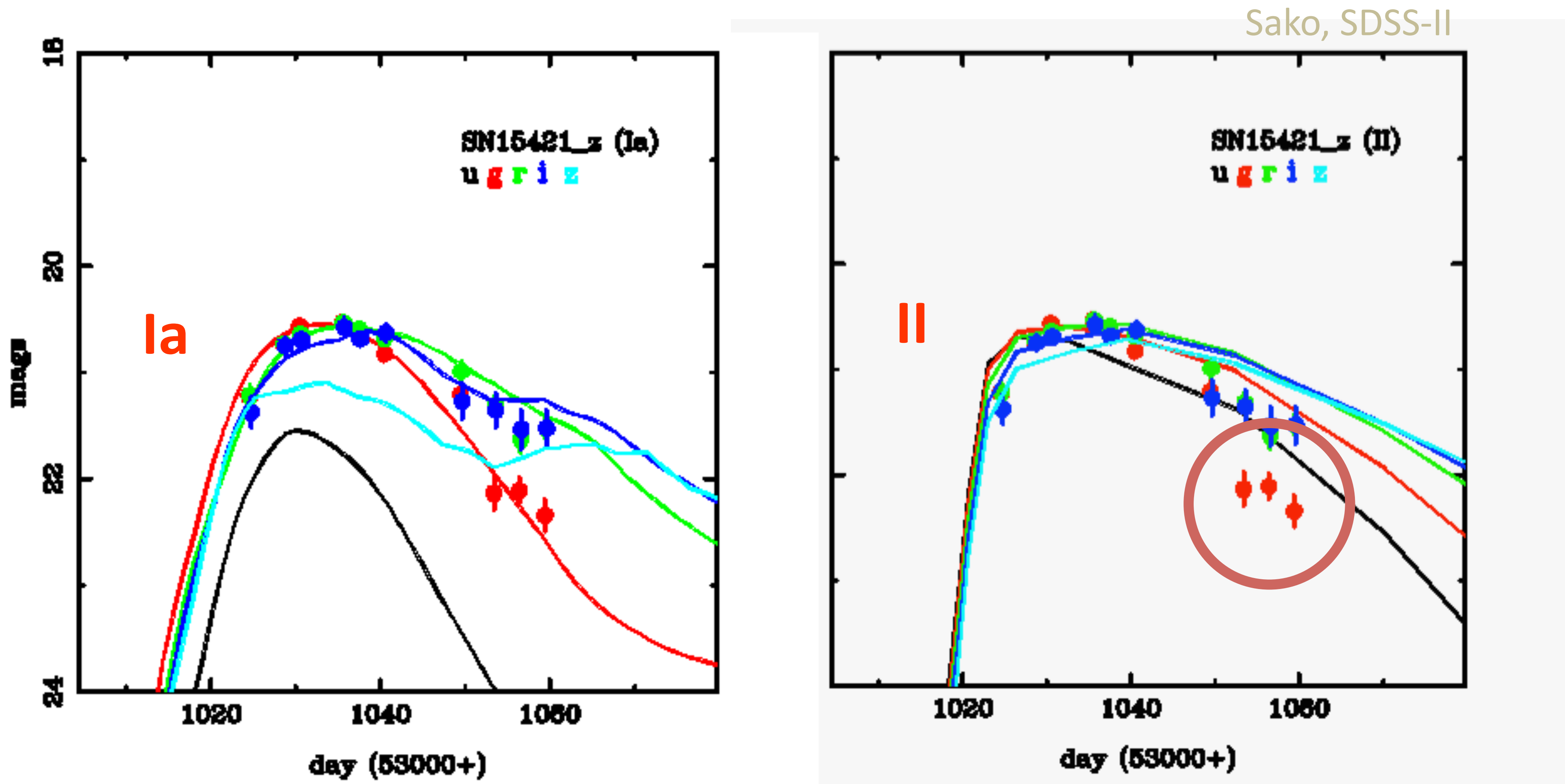
How can this be understood intuitively?



Challenges for the future: A Case Study

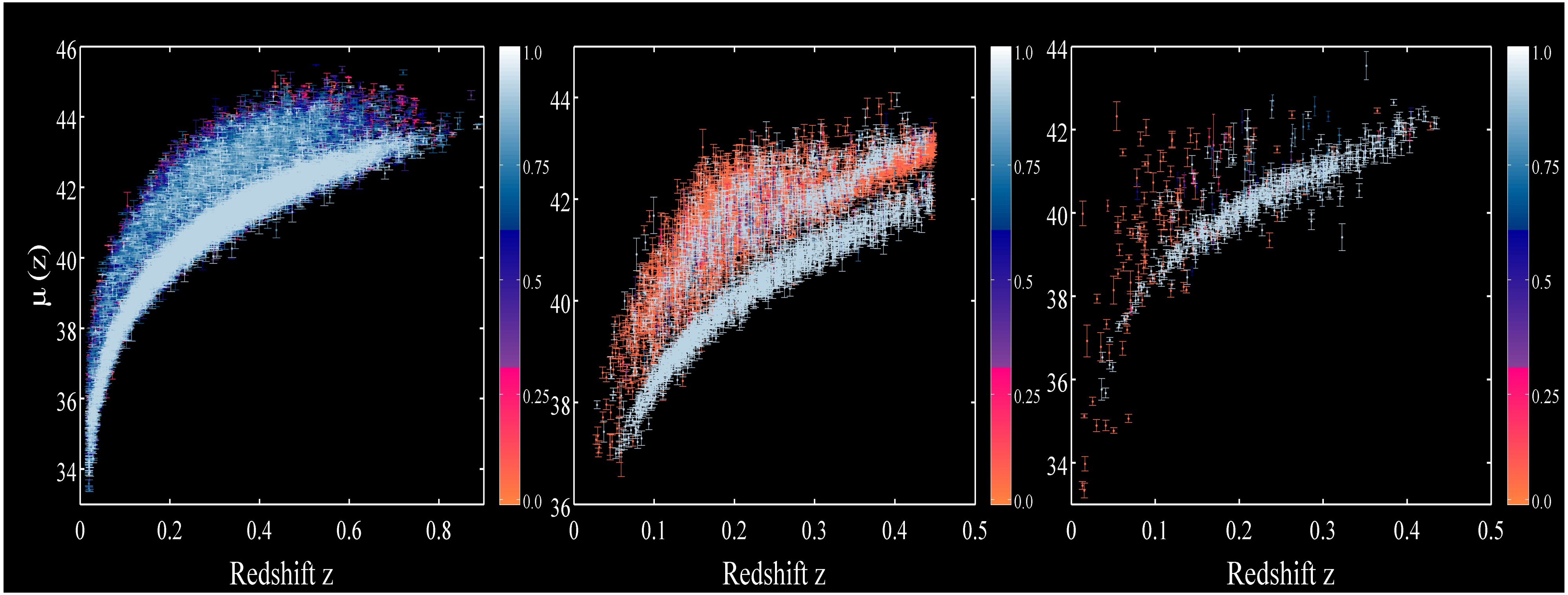
- LSST will find about 10^5 SNIa every year
- How can we deal with contamination from Type Ibc and II supernovae?
- **No** analysis until now has purely used photometric supernova data (see also Heather's talk today)

SNIa Probabilities from light curves



Gives **P**

Simulations and real data



optimistic:
37.5k SNe (25k type Ia)
satisfies BEAMS
assumptions

realistic:
5.4k SNe (1.3k type Ia)
simulated lightcurves
run through analysis
pipeline

real data (SDSS-II):
792 SNe (? type Ia)
based on 3 seasons
all redshifts known

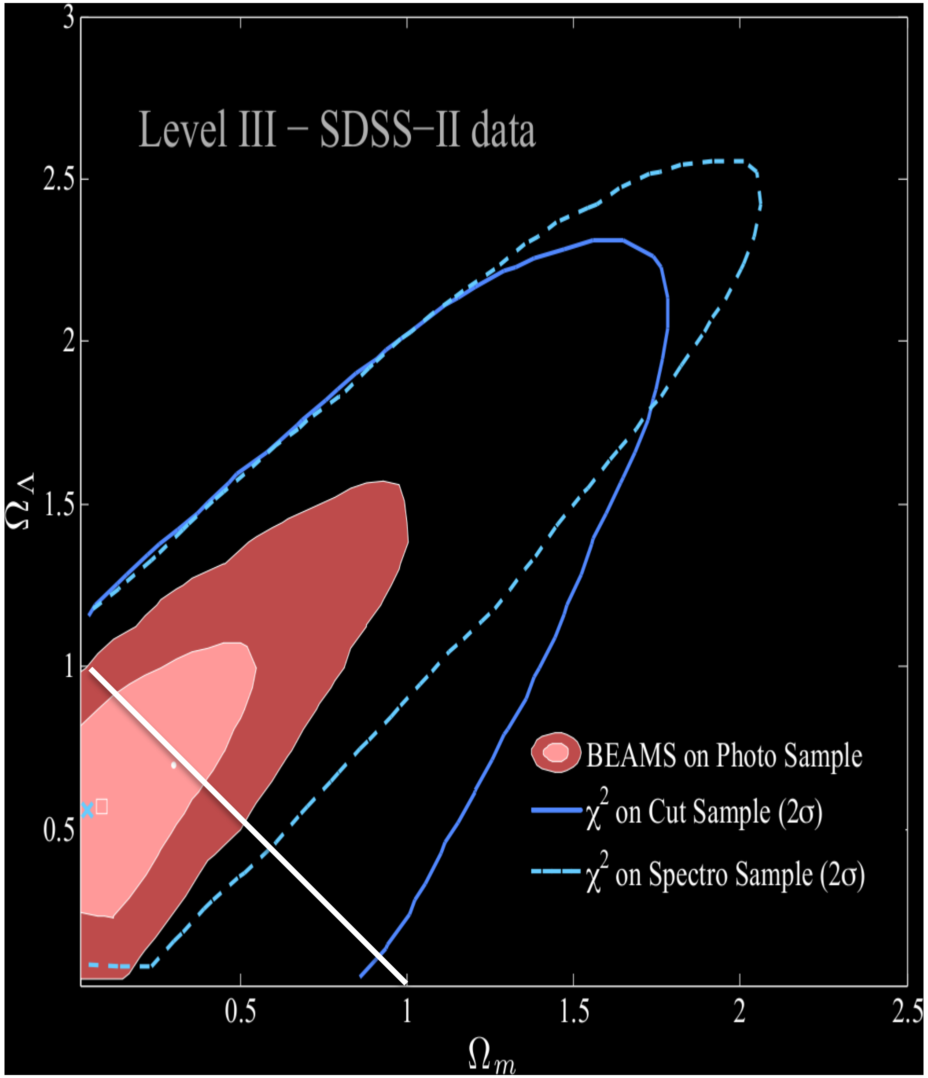
Hlozek et al., SDSS-II, 2011

SDSS-II 3-year data

$$P(\theta|D) = \Pi_i \, [P^i_{Ia} \, P(\theta|D, Ia) + (1 - P^i_{Ia}) \, P(\theta|D, non\text{-}Ia)]$$

3-year SDSS-II supernova data:

792 SNe of which 297 spectroscopically confirmed Ia.



Hlozek et al, SDSS-II, 2011

ORGANISED BY **AIMS**, **ICTP** & **PI**

The Cape Town International Cosmology School will be held at the Stellenbosch Institute for Advanced Studies in Stellenbosch from the 15-28 January 2012. The school will consist of lectures, tutorials and project work.

TOPICS

Cosmic Microwave Background
Inflation
Supernovae, Baryon Acoustic Oscillations
Cosmic Acceleration
Large Scale Structure
Dark Matter and its Detection
Bayesian Statistics
Multi-Wavelength Cosmology
Future Surveys
Testing Homogeneity
Modified Gravity
Advanced Topics in Cosmology

INVITED SPEAKERS

Niayesh Afshordi (PI)
Bruce Bassett (AIMS/SAAO/UCT)
Chris Clarkson (UCT)
Sergio Colafrancesco (INAF/Rome/Wits)
Paolo Creminelli (ICTP)
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