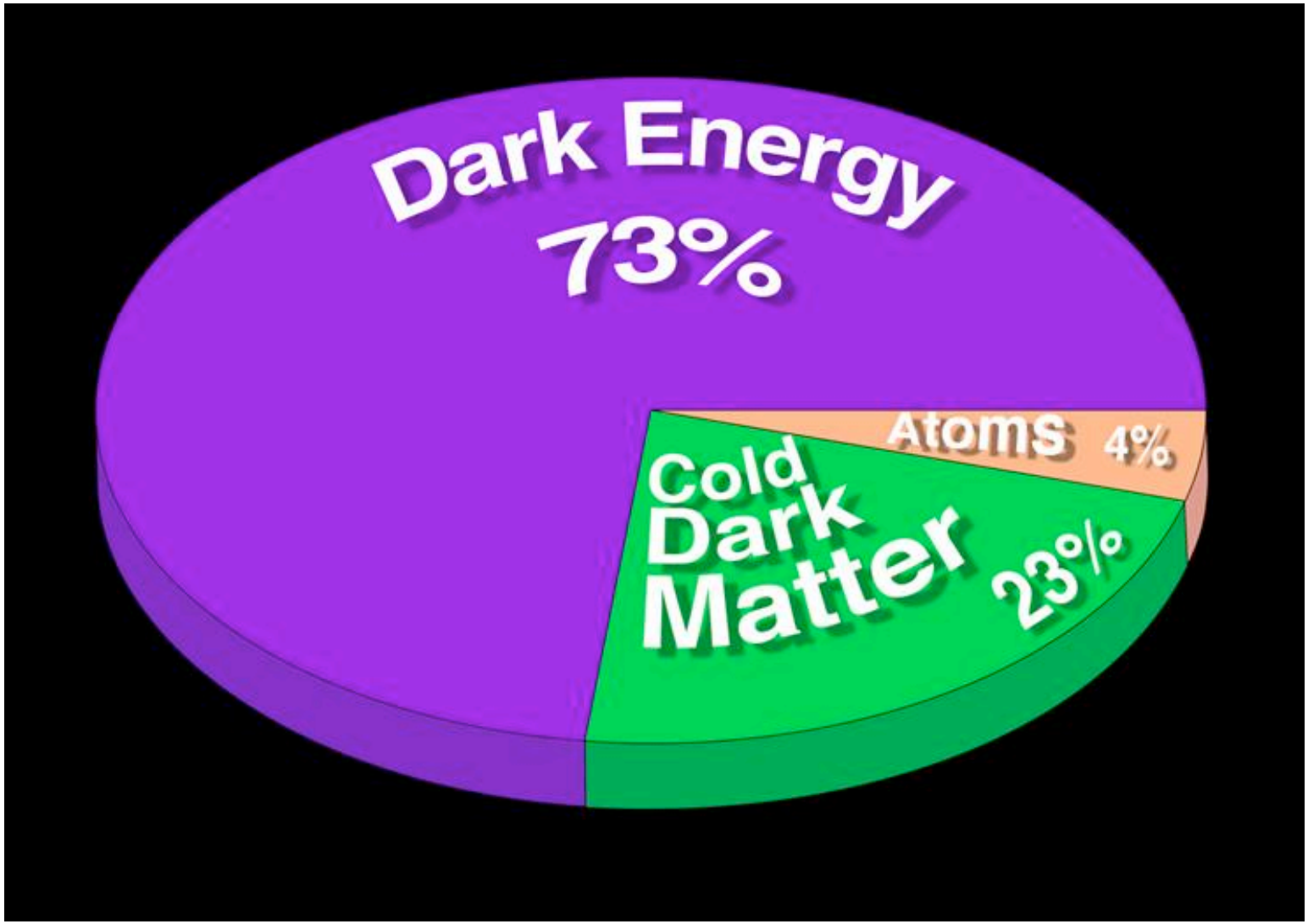
The Dark Energy Hypothesis.

Pedro G. Ferreira
University of Oxford

The Cosmic Cocktail



The Problem

New Force

$$\Phi(r) = -\frac{GM}{r} + \Lambda r^2$$

$$8\pi G\Lambda = 10^{-123}$$

New Energy

$$\rho_\Lambda = 10^{-47} GeV^4$$

$$\frac{\rho_\Lambda}{\rho_{Pl}} = 10^{-123}$$

$$G_{\mu\nu} = 8\pi G T_{\mu\nu} + \Lambda g_{\mu\nu}$$

Homogeneity
And
Isotropy

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3}$$

Science with Mathematica…

$$\left(\frac{\dot{a}}{a}\right)^2 = H_0^2 E^2 a \equiv H_0^2 \left(\frac{\Omega_M}{a^3} + \frac{\Omega_K}{a^2} + \Omega_\Lambda\right)$$

Age of the Universe

$$t_0 = \frac{D_c}{c} \int_0^1 \frac{da}{aE(a)}$$

$$D_M = \frac{D_c}{c} \int_0^1 \frac{da}{a^2 E(a)}$$

$$D_{\rm M} = \begin{cases} D_{\rm H} \frac{1}{\sqrt{\Omega_k}} \sinh\left[\sqrt{\Omega_k}\, D_{\rm C}/D_{\rm H}\right] & \text{for } \Omega_k > 0 \\ D_{\rm C} & \text{for } \Omega_k = 0 \\ D_{\rm H} \frac{1}{\sqrt{|\Omega_k|}} \sin\left[\sqrt{|\Omega_k|}\, D_{\rm C}/D_{\rm H}\right] & \text{for } \Omega_k < 0 \end{cases}$$

$$D_{\rm A} = \frac{D_{\rm M}}{1+z}$$

Angular Diameter Distance

$$D_L = (1+z)^2 D_A$$

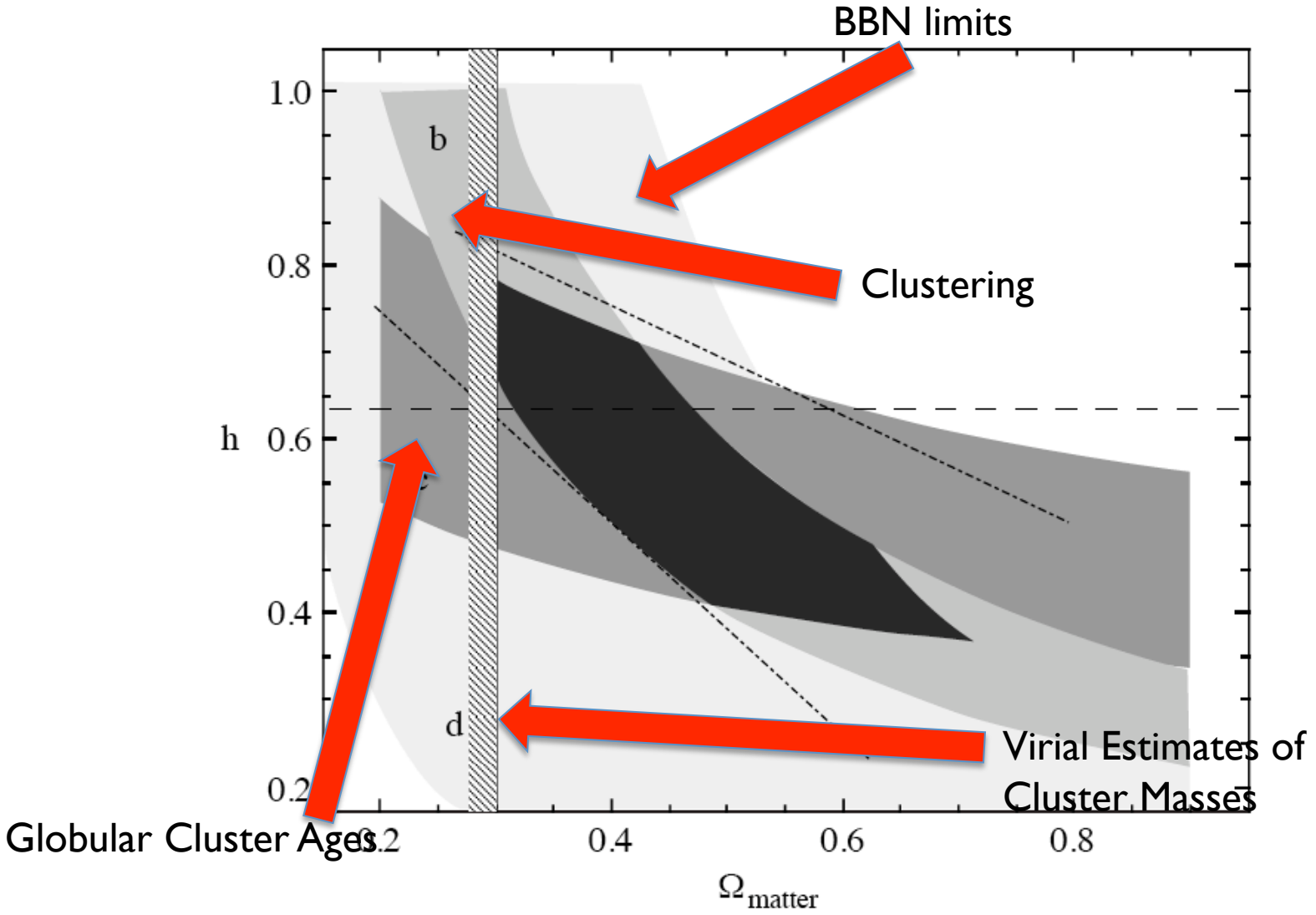
Luminosity Distance

$$D_{\rm H} \equiv \frac{c}{H_0} = 3000\, h^{-1}\ {\rm Mpc} = 9.26 \times 10^{25}\, h^{-1}\ {\rm m}$$

1984

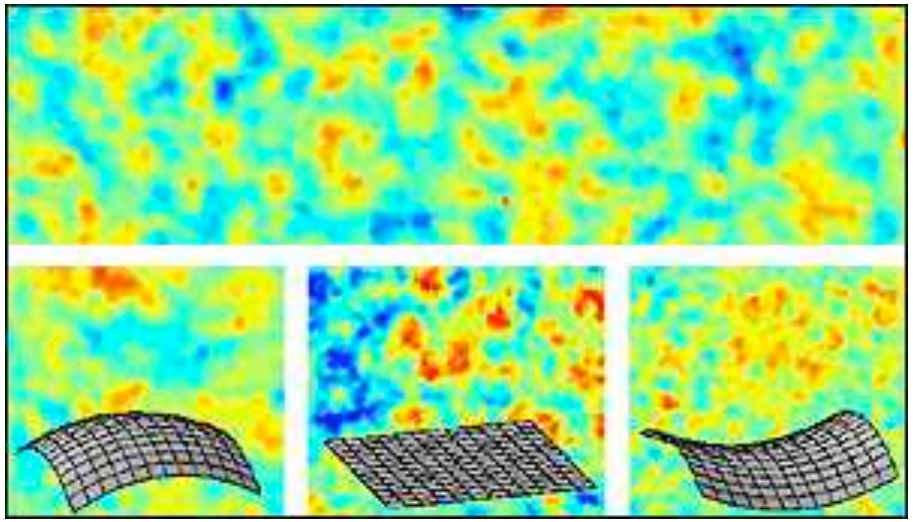
1995

Universe must be Flat: $\Omega_K = 0$



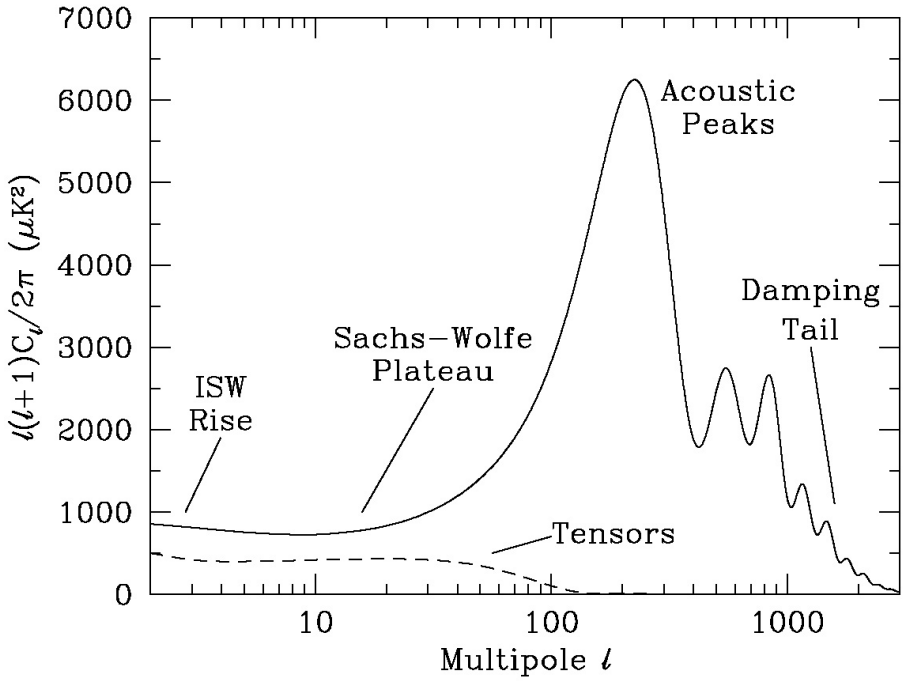
Krauss and Turner 1994

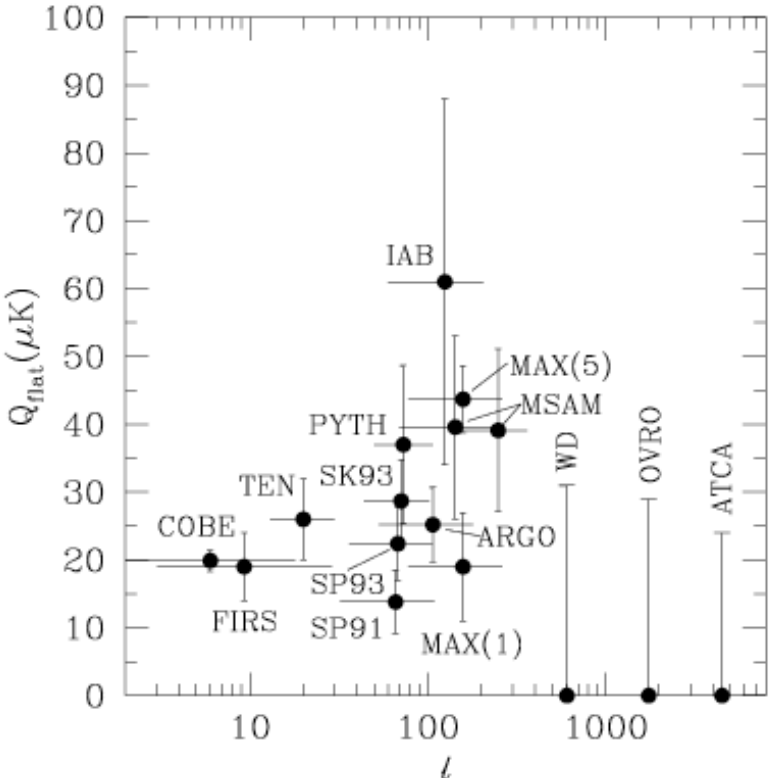
Is the Universe Flat?



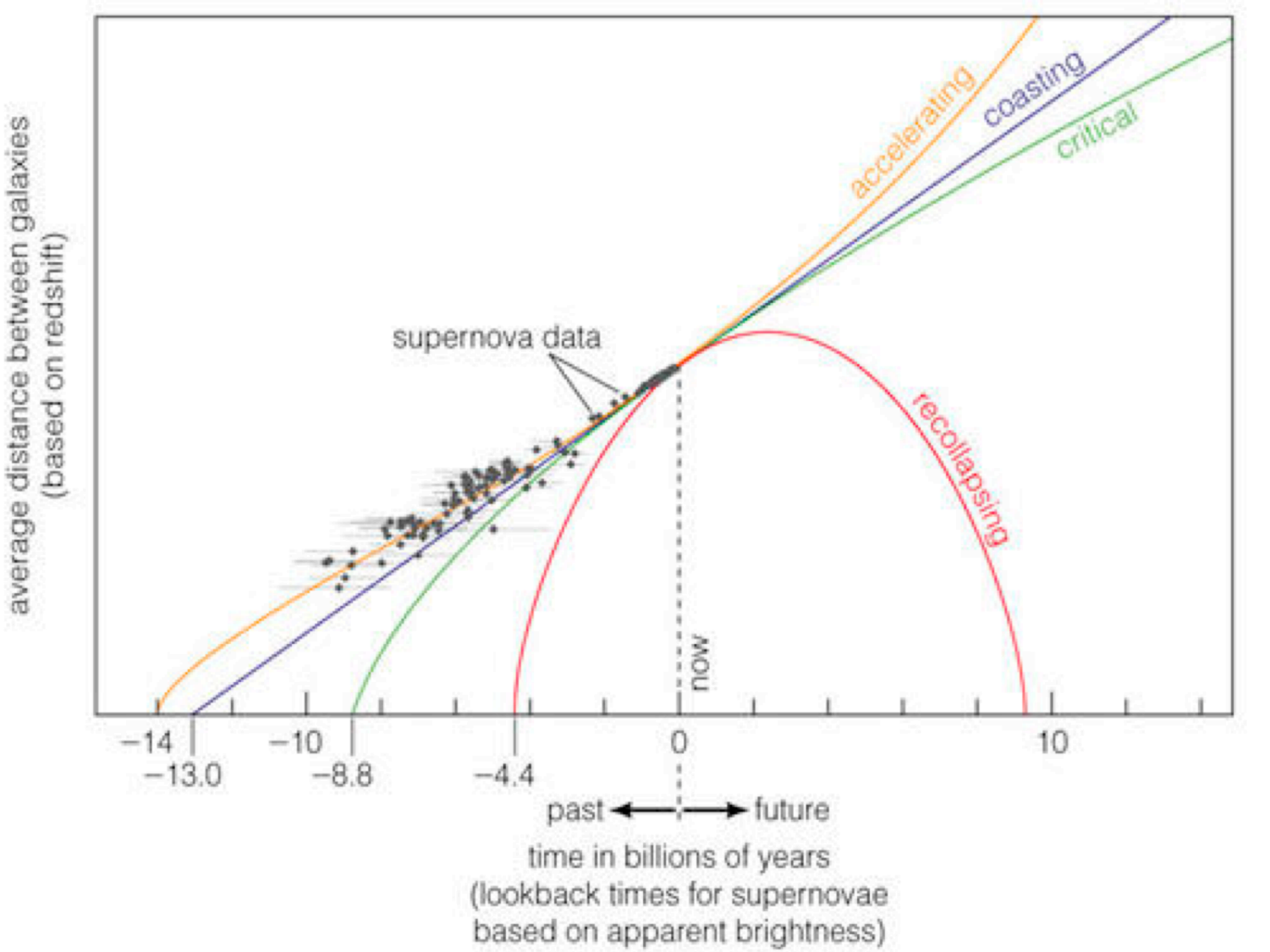
Angular Diameter Distance from CMB

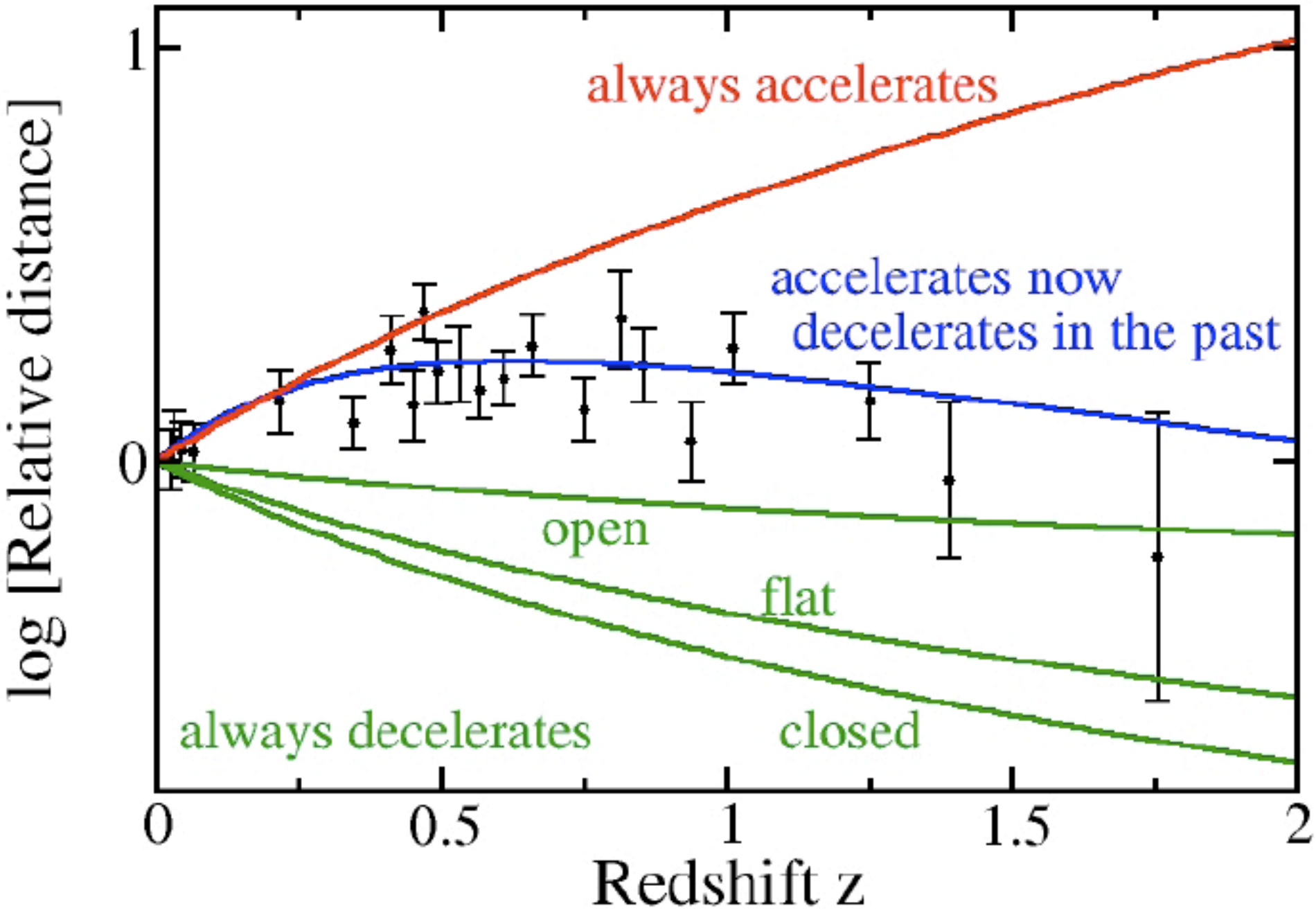
Scott 1995



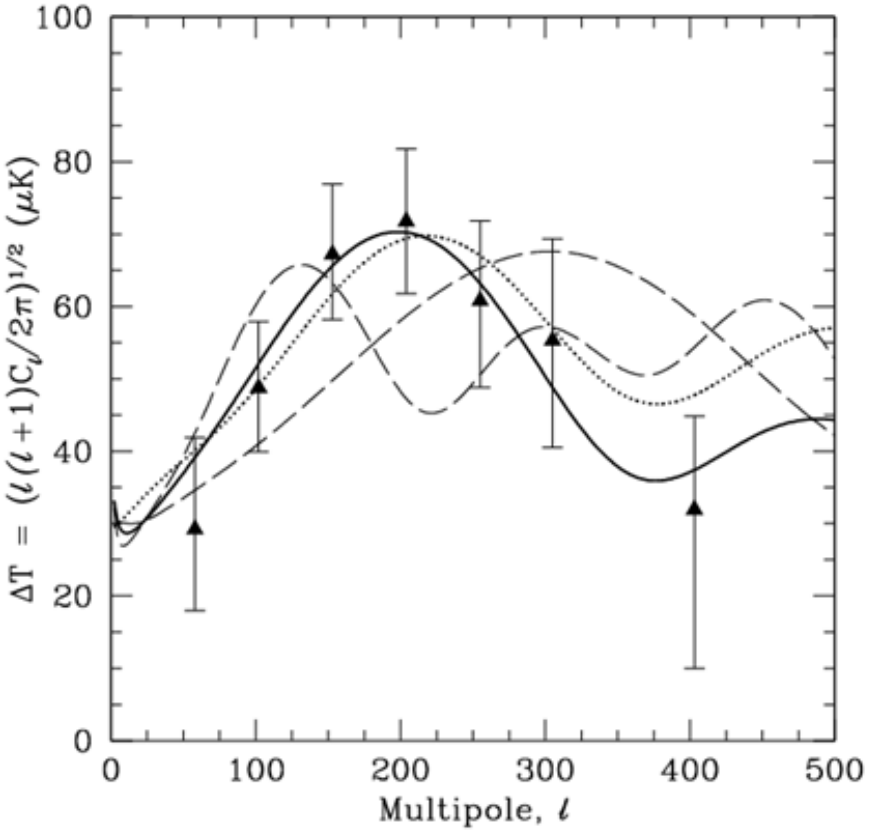


1998: Supernovae



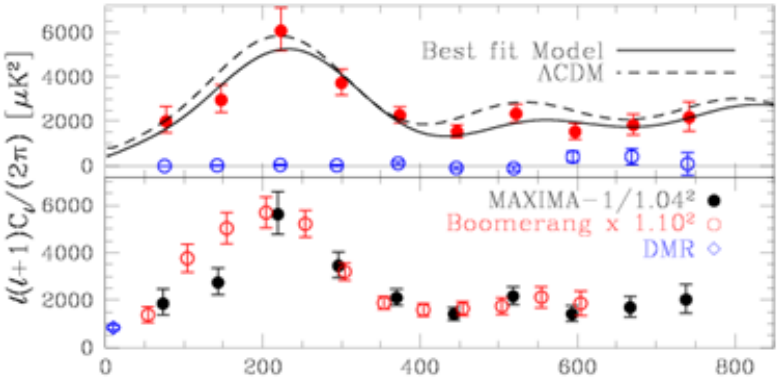

always accelerates
accelerates now
decelerates in the past
open
flat
closed
always decelerates
log [Relative distance]
Redshift z
1
0
0
0.5
1
1.5
2

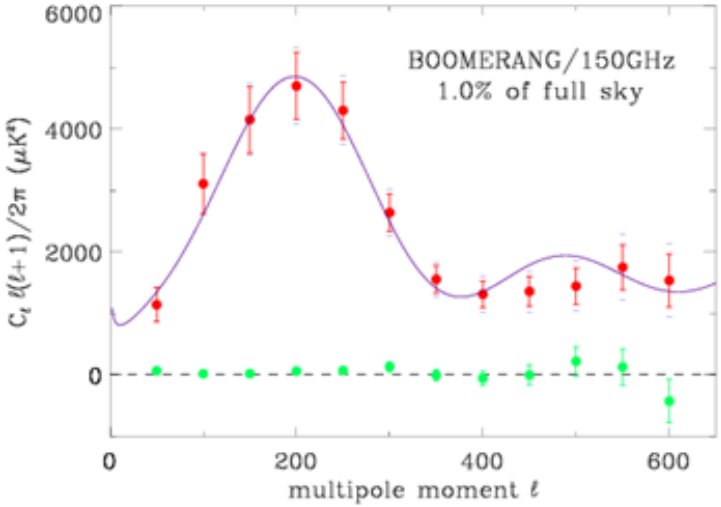
2000: The first peak



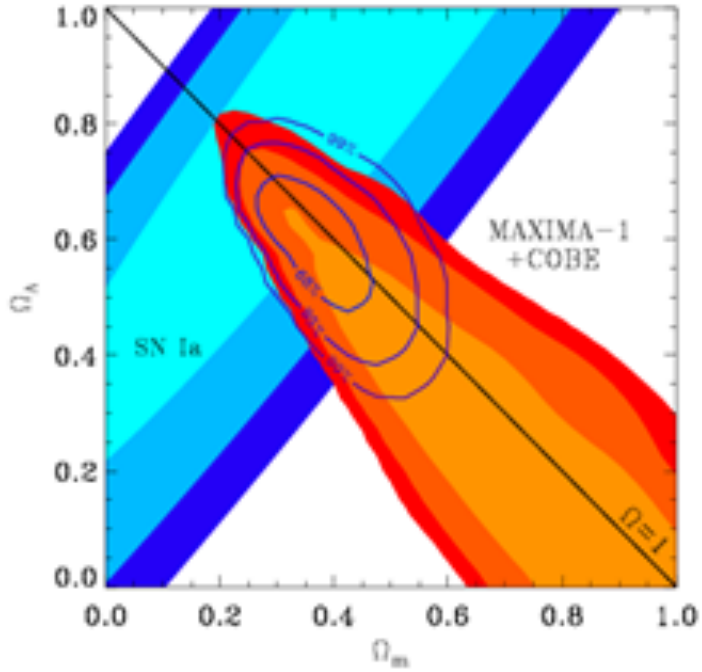
BOOMERanG North America Flight

MAXIMA-1



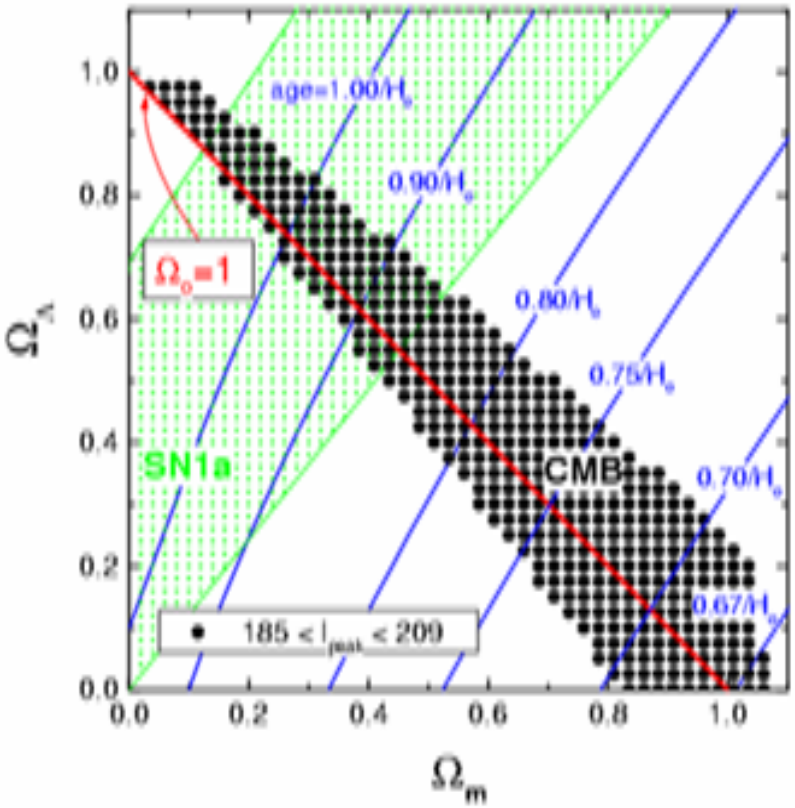


BOOMERanG Antartica Flight



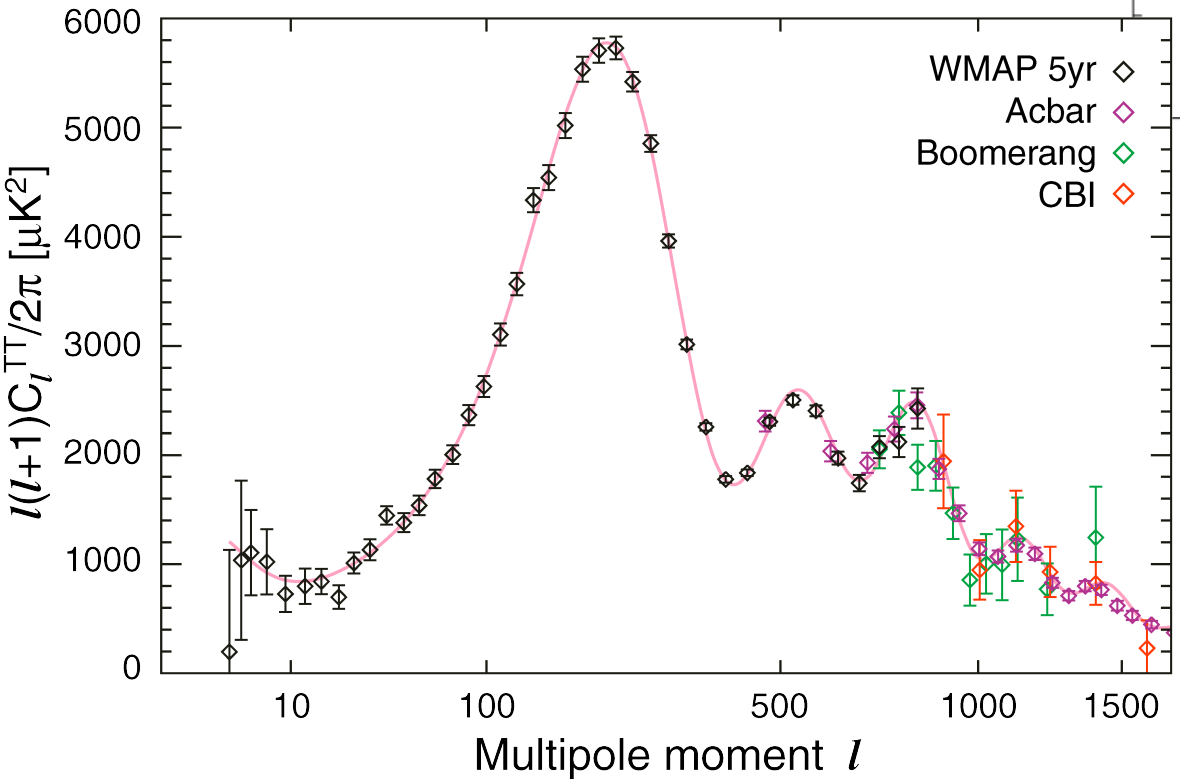
MAXIMA-1

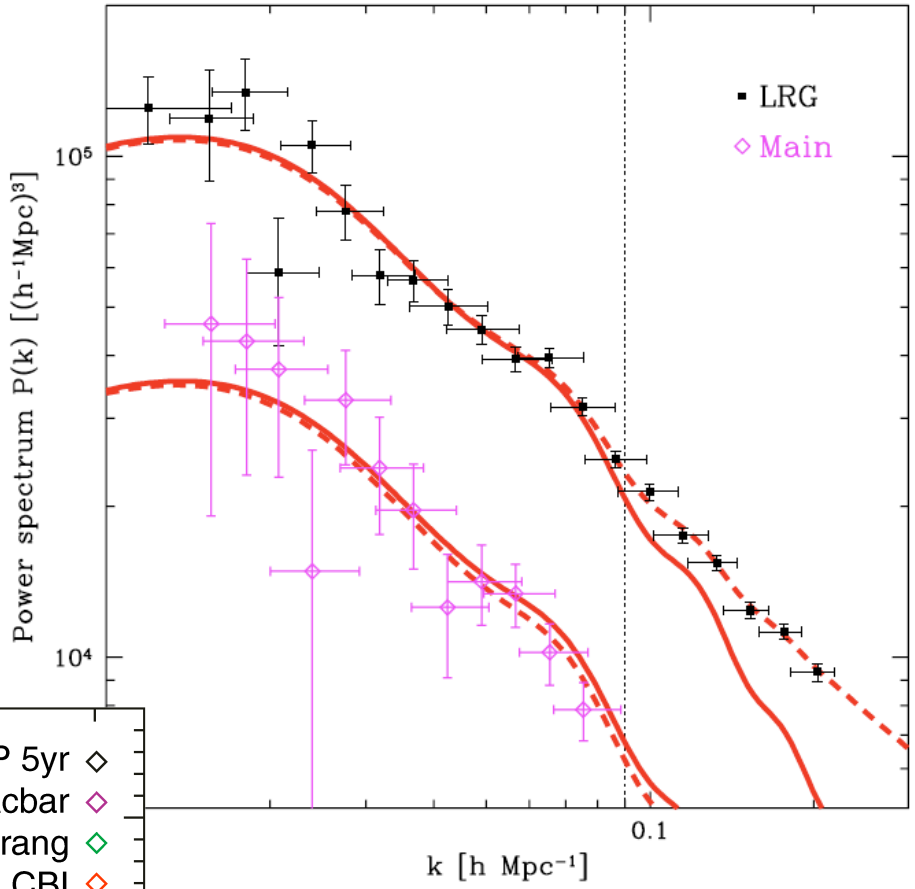
BOOMERanG Antartica Flight



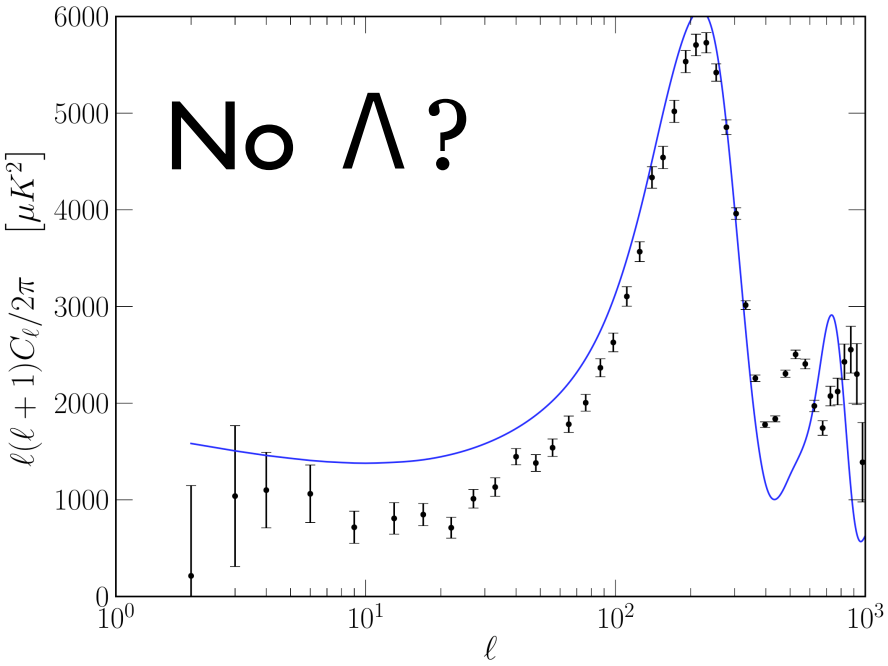
Now: Λ CDM

WMAP 5

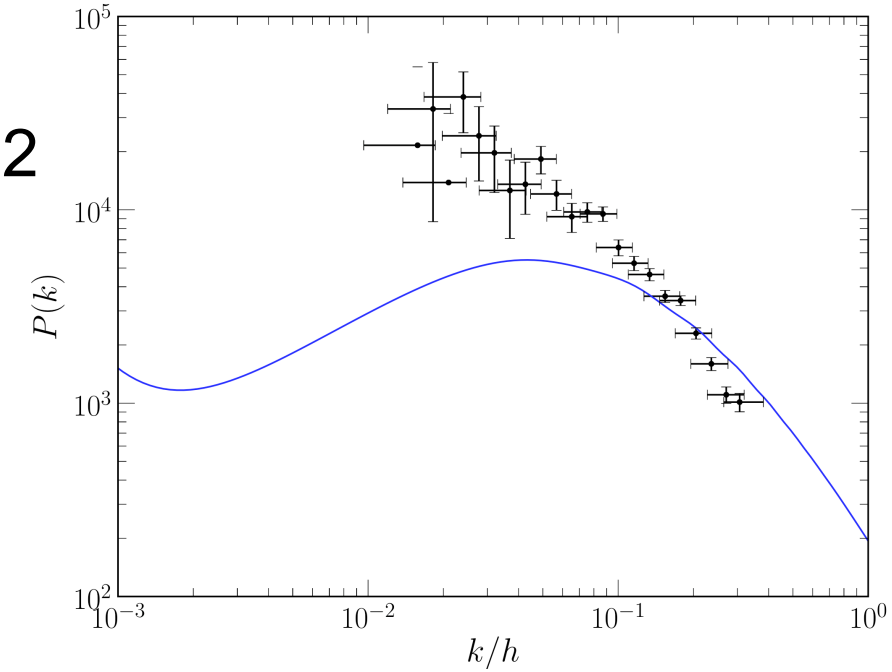


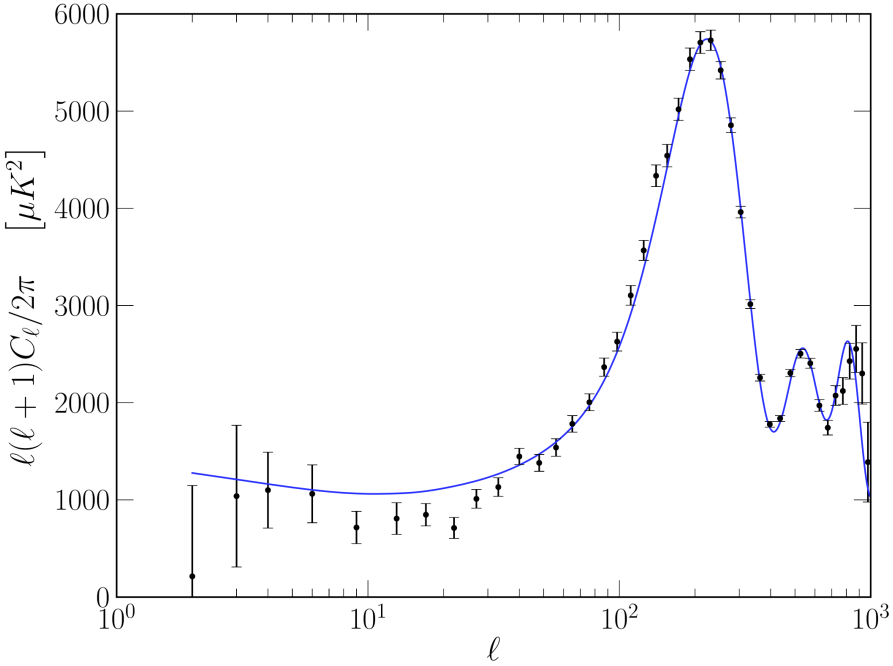


SDSS

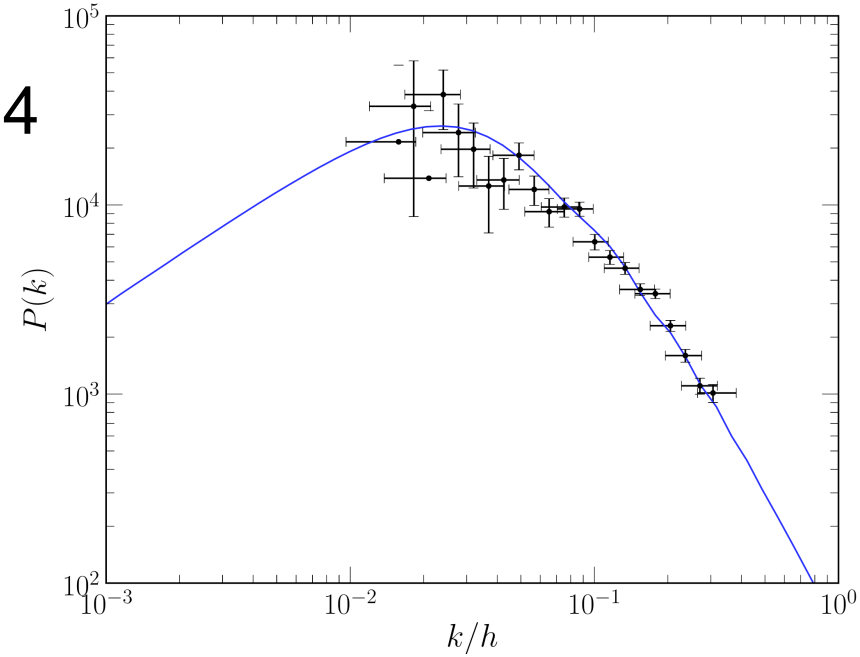

No Λ?
$\ell(\ell+1)C_\ell/2\pi \quad [\mu K^2]$
ℓ

H_0= 72


$P(k)$
k/h


$\ell(\ell+1)C_\ell/2\pi \quad [\mu K^2]$
ℓ

H_0= 44


$P(k)$
k/h

Dark Energy

$$P = w\rho \qquad \rho = a^{-3(1+w)}$$

Equation of state

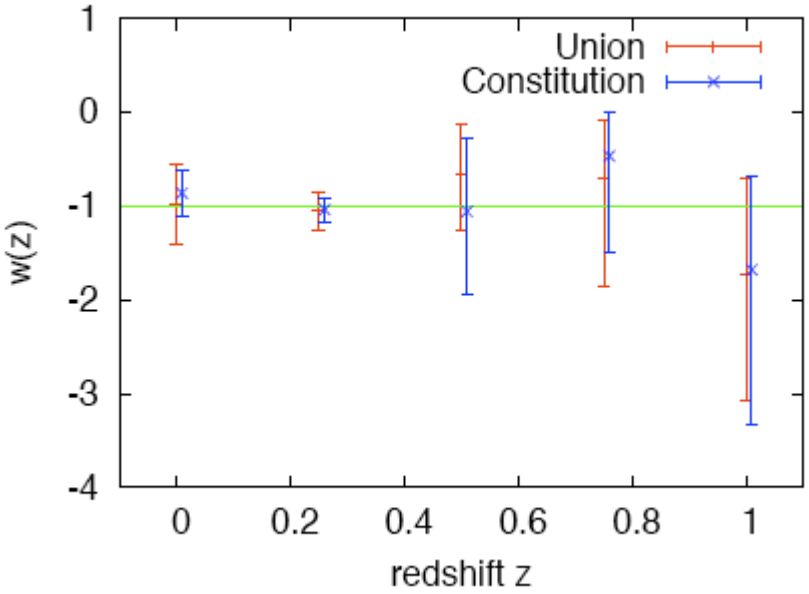
$$\Lambda \longrightarrow \left| \begin{array}{l} P_\Lambda = -\rho_\Lambda \\ w = -1 \end{array} \right.$$

General and time varying, e.g. $w = w_0 + w_1 z$

What is Dark Energy?

Quintessence, K-essence, scaling field, phantom field, aether, solid dark energy, domain walls, tangled cosmic strings, cardassian, saltatory dark energy, brane world, Jordan-Brans-Dicke field, time varying massive neutrinos, four forms, tachyonic, dilatonic, chaplygin gas, varying alpha, DGP, transplankian, …

Measure w(z) to distinguish between the different models.



Serra et al, 2009

An Arsenal of Cosmological Probes

- Supernovae Ia
- Baryon Acoustic Oscillations
- Redshift Space Distortions
- Weak Lensing
- Integrated Sachs Wolfe

Cosmology with SNe Ia

SNe Ia are not standard candles:

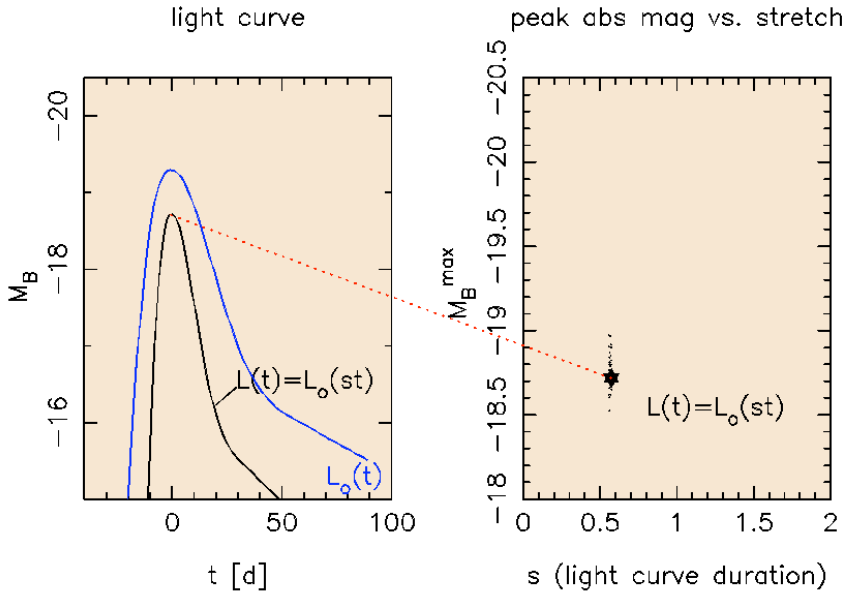
$$\mu_B = m_B - M_B + \alpha(s-1) - \beta c$$

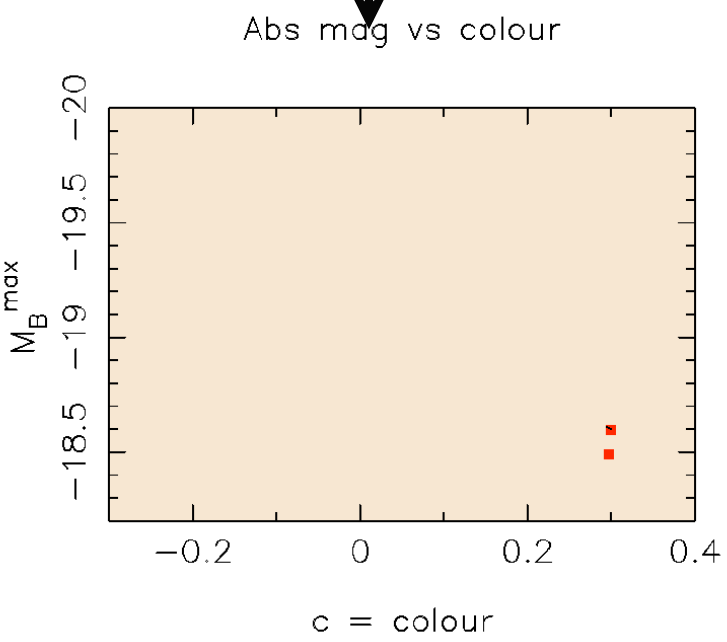
"Measured" maximum light magnitude

Standard absolute B-band magnitude

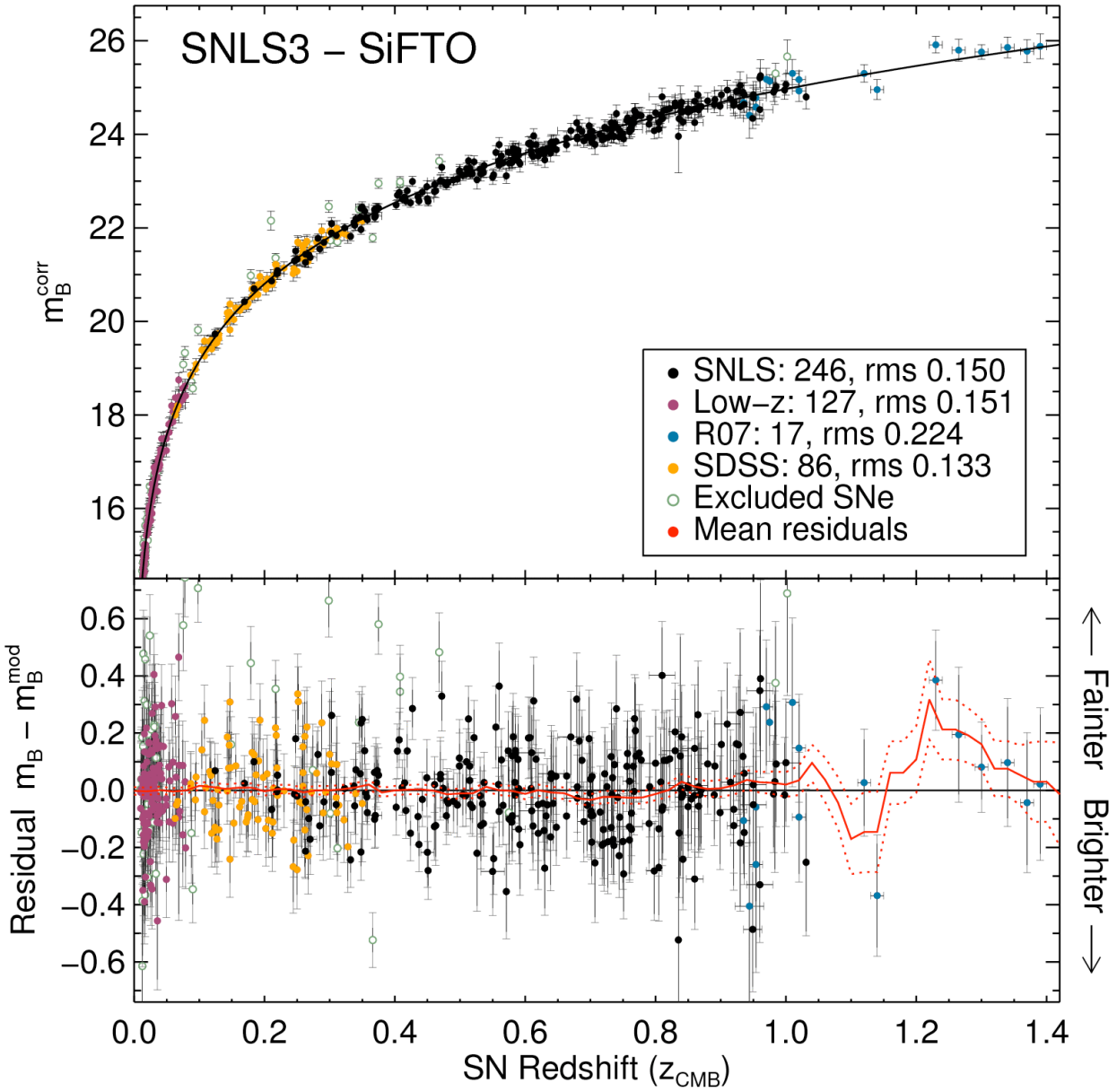
s – "stretch" corrects for light-curve shape via α

c – B-V "colour" corrects for extinction and/or intrinsic variation via β





SNLS3 Hubble Diagram (**preliminary**)

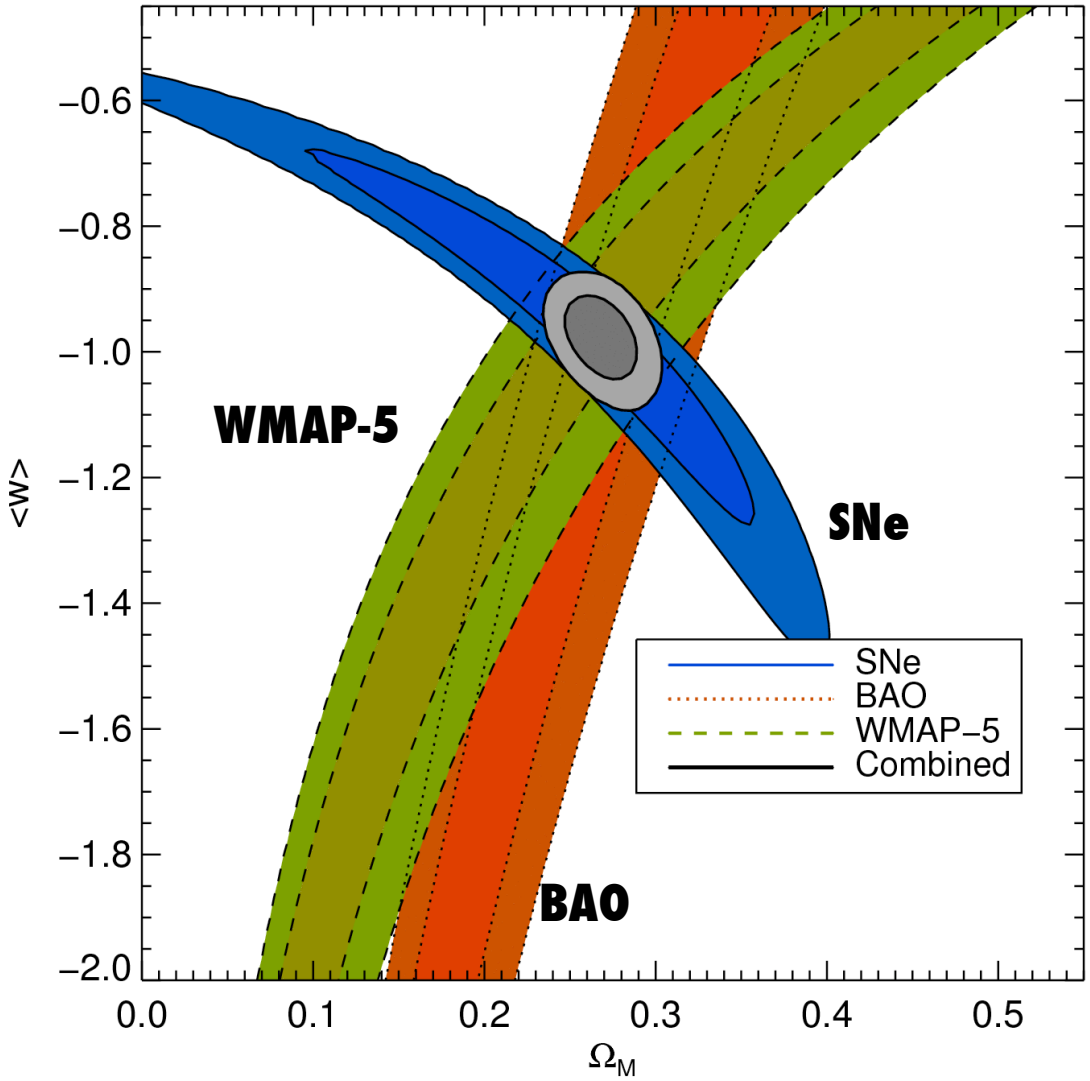


~250 distant SNLS SNe Ia
127 local SNe Ia
86 SDSS-SN Ia
17 from HST
476 SNe total

SNLS+flatness+w=-1:

$\Omega_M \approx 0.27$ 6% error

SNLS3 Cosmological Constraints (**Preliminary**)



$$\langle w \rangle \approx -0.97$$

4.5% statistical measure of <w>

SNLS3 + BAO + WMAP5 "shifts" + **Flat**

SNe Ia: Systematics

- **"Experimental Systematics"**
  - *Calibration; photometric system; Malmquist effects*
- **Non-SN systematics**
  - *Peculiar velocities; Weak lensing*
- **SN model and K-corrections**
  - *SED uncertainties; colour relations; light curve fitters*
- **Extinction/Colour**
  - *Effective R_V; colour vs dust*
- **Redshift evolution in the mix of SNe**
  - *"Population drift" – environment?*
- **Evolution in SN properties**
  - *Light-curves/Colours/Luminosities*

Tractable, can be modelled

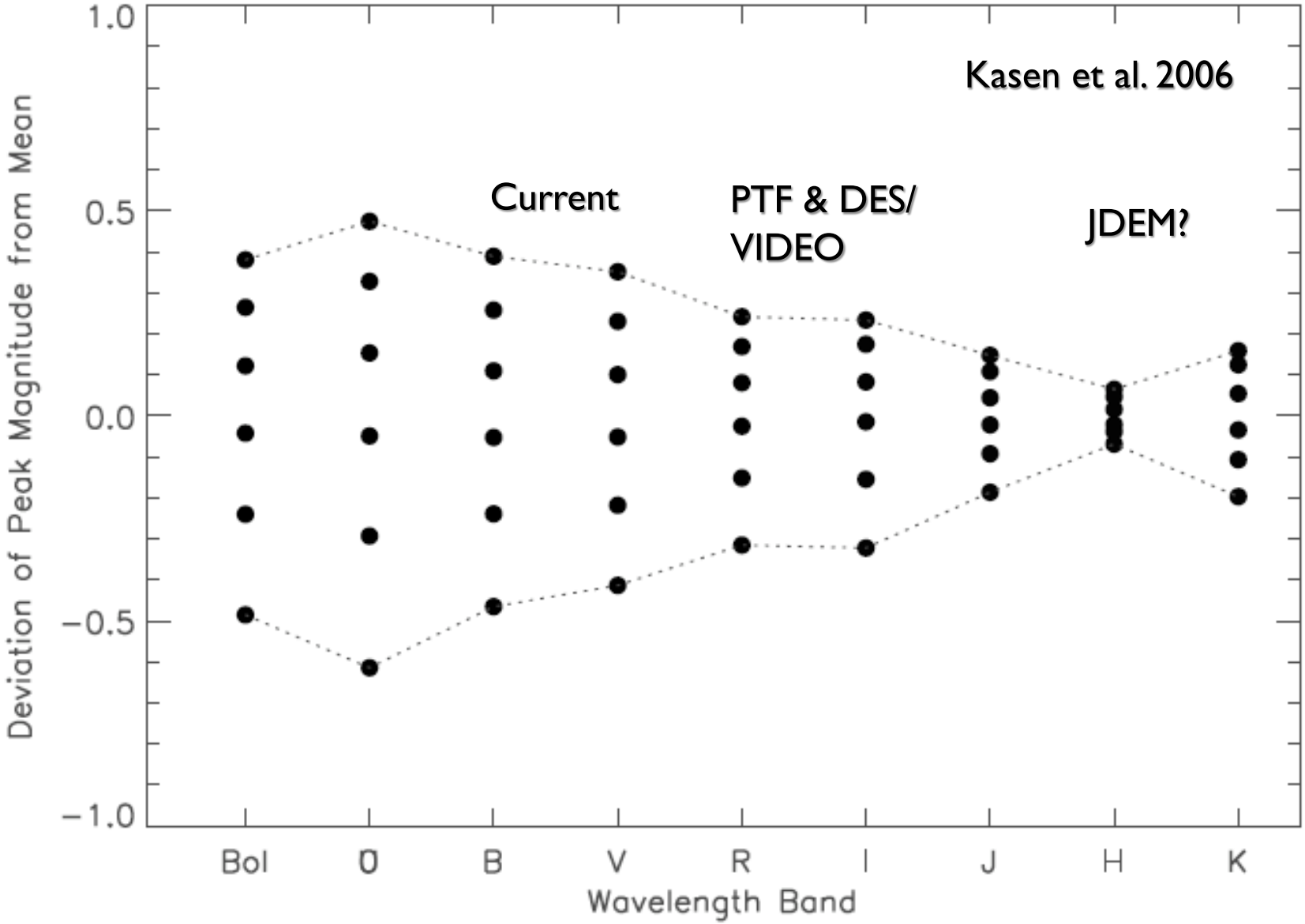
"Extinction"

Increasing knowledge of SN physics

"Population Evolution"

Are SNe Ia *really* standard candles?

Near-IR: Models predict smaller dispersion



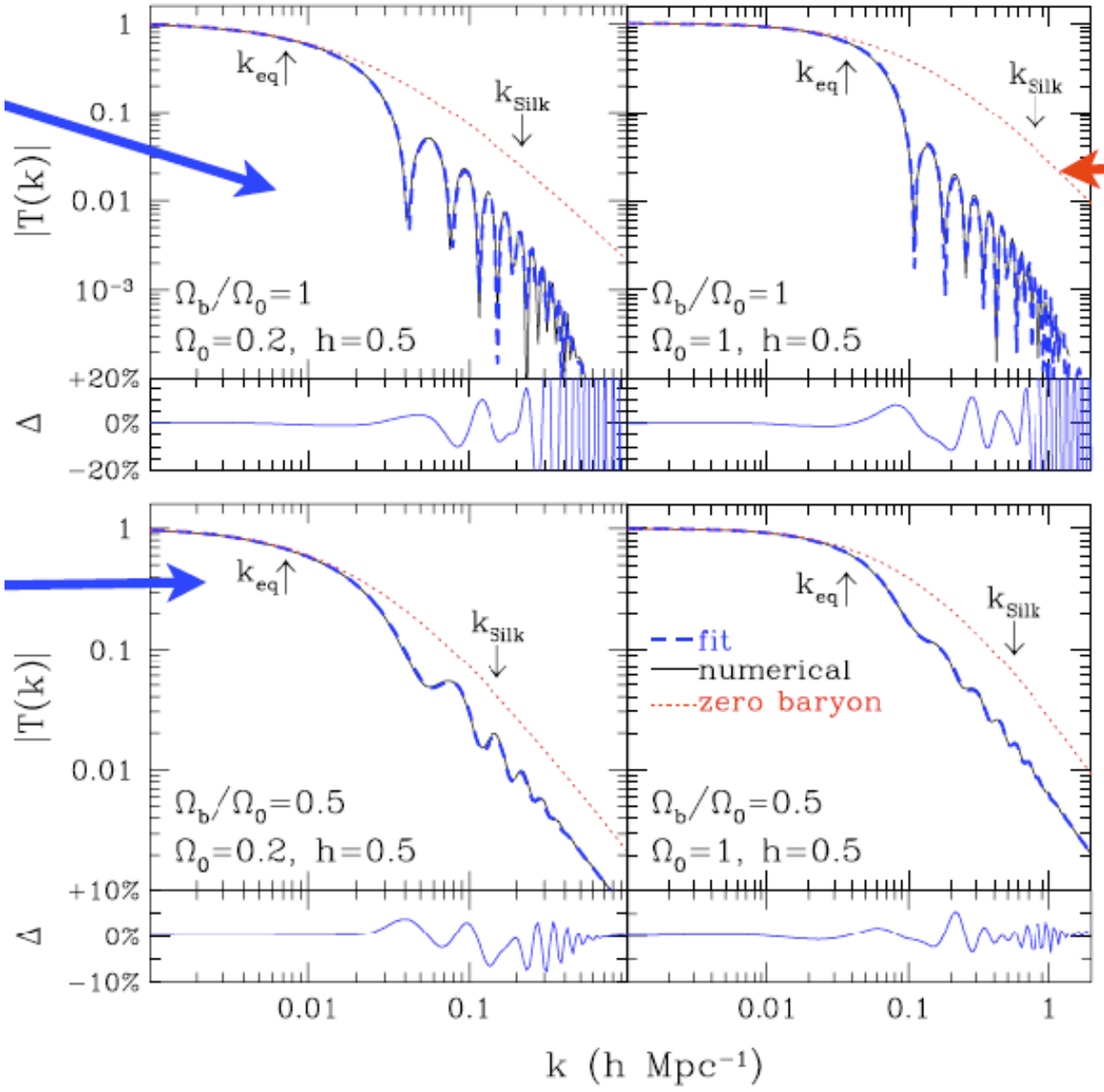
BAO: Baryonic Acoustic Oscillations

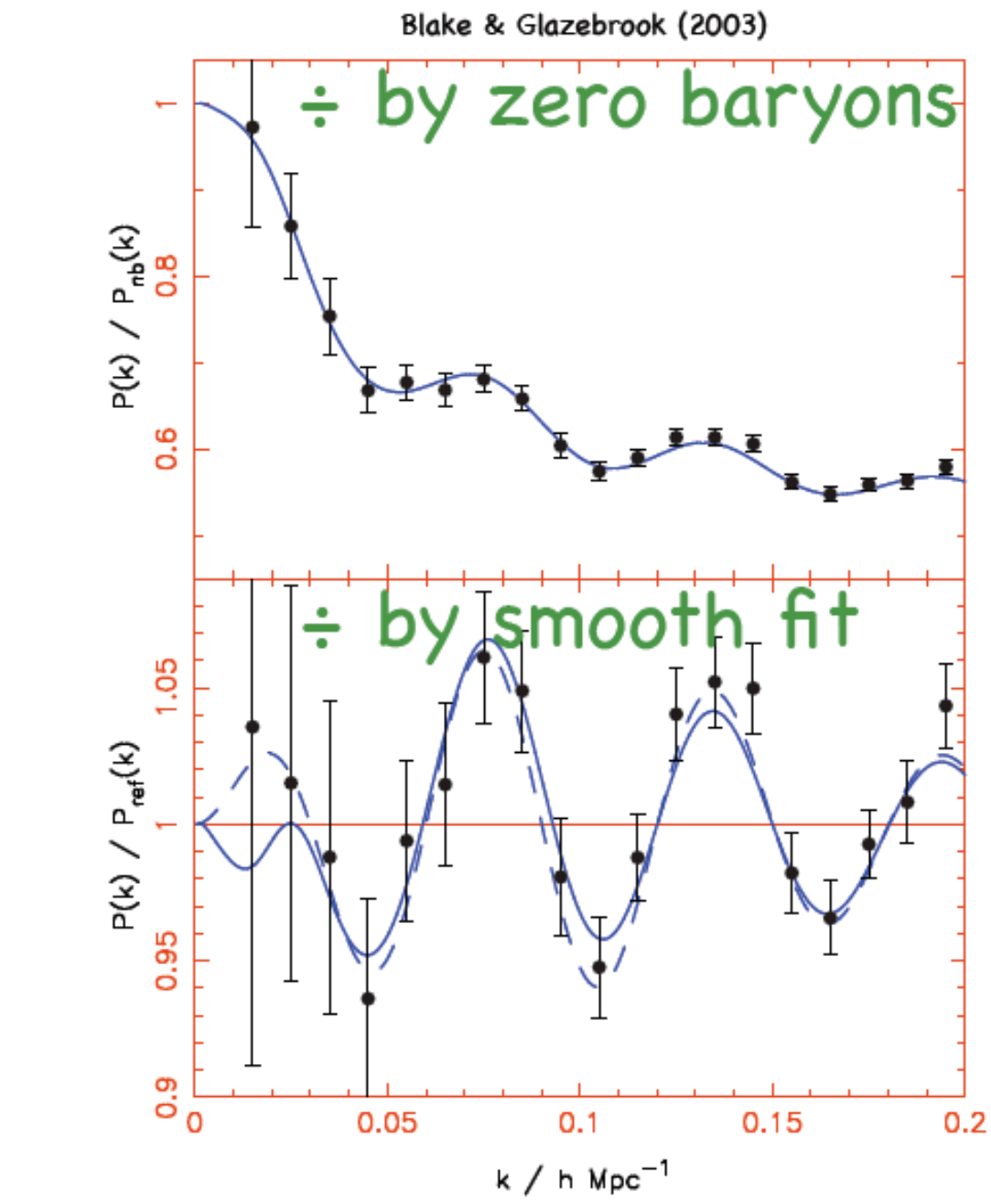
Only baryons, Open Universe

Only baryons, Flat Universe

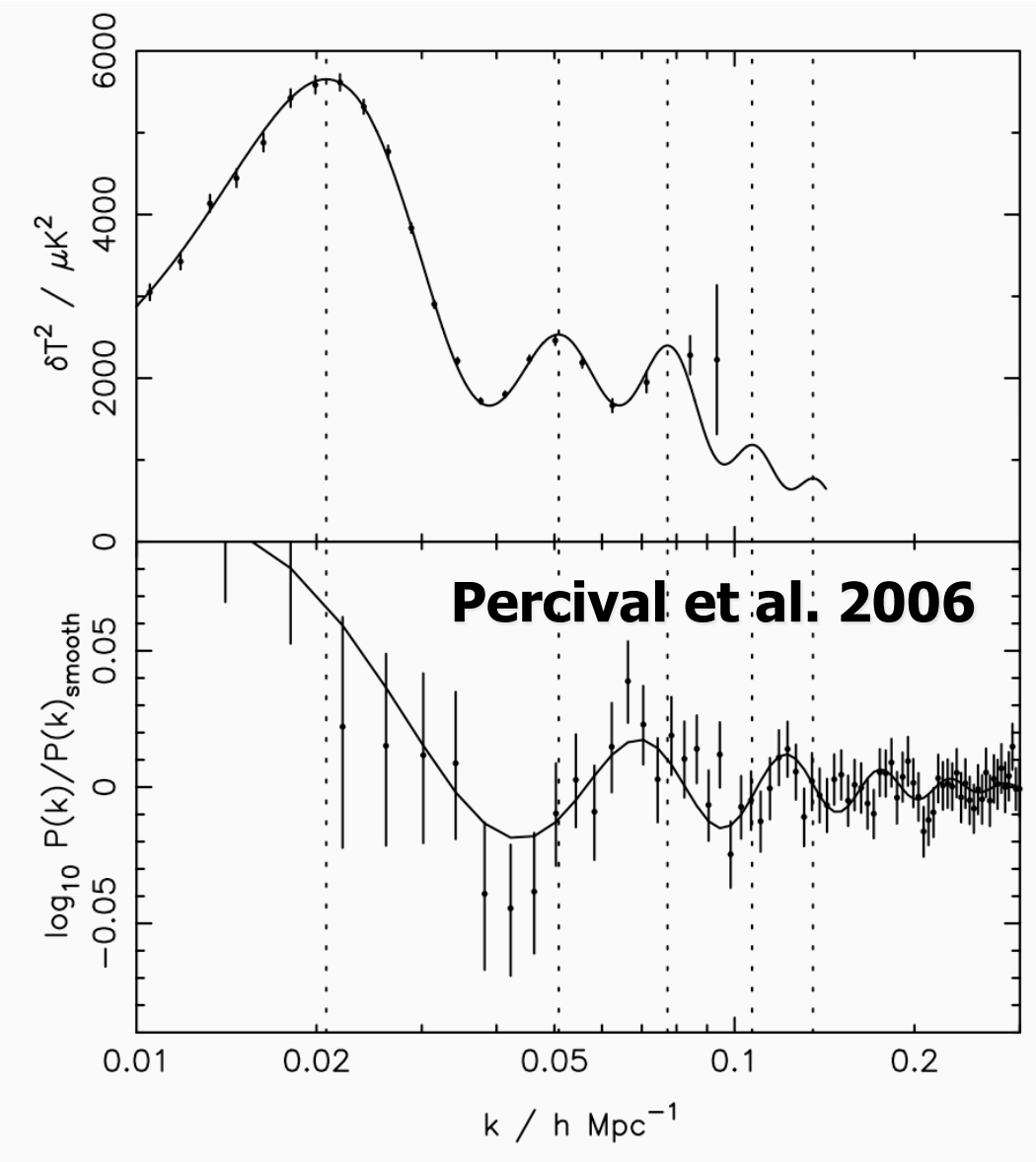
Baryons+CDM Open Universe

Baryons+CDM Flat Universe



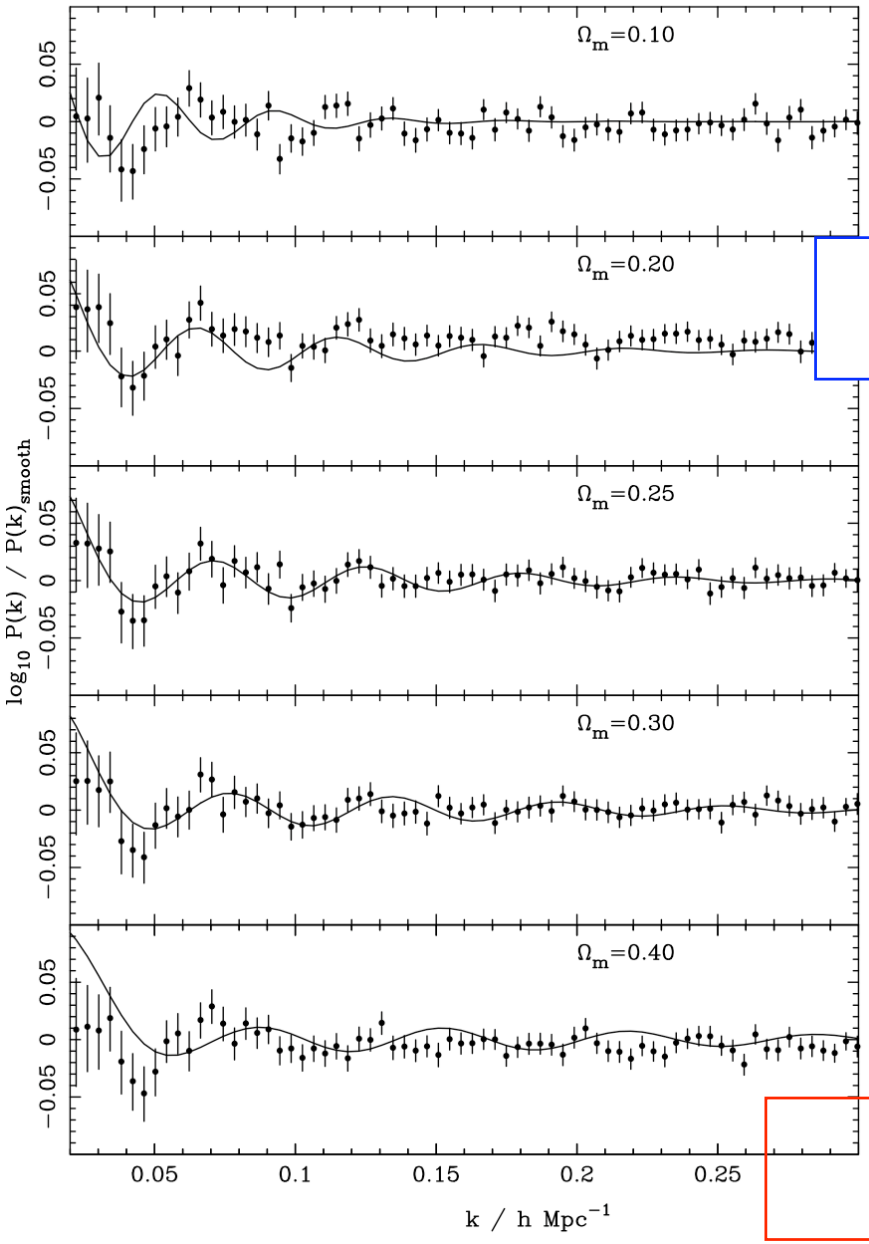

Blake & Glazebrook (2003)
÷ by zero baryons
÷ by smooth fit
P(k) / P_nb(k)
P(k) / P_ref(k)
1
0.8
0.6
1.05
1
0.95
0.9
0
0.05
0.1
0.15
0.2
k / h Mpc^-1

Detection from 2DFGRS and SDSS



Miller et al. 2001,
Percival et al. 2001,
Tegmark et al. 2001,
Cole et al. 2005,
Eisenstein et al. 2005,
Hutsei 2006,
Blake et al. 2006, Padmanabhan et al. 2006

Standard ruler (flat,h=0.73,Ω_b=0.17)



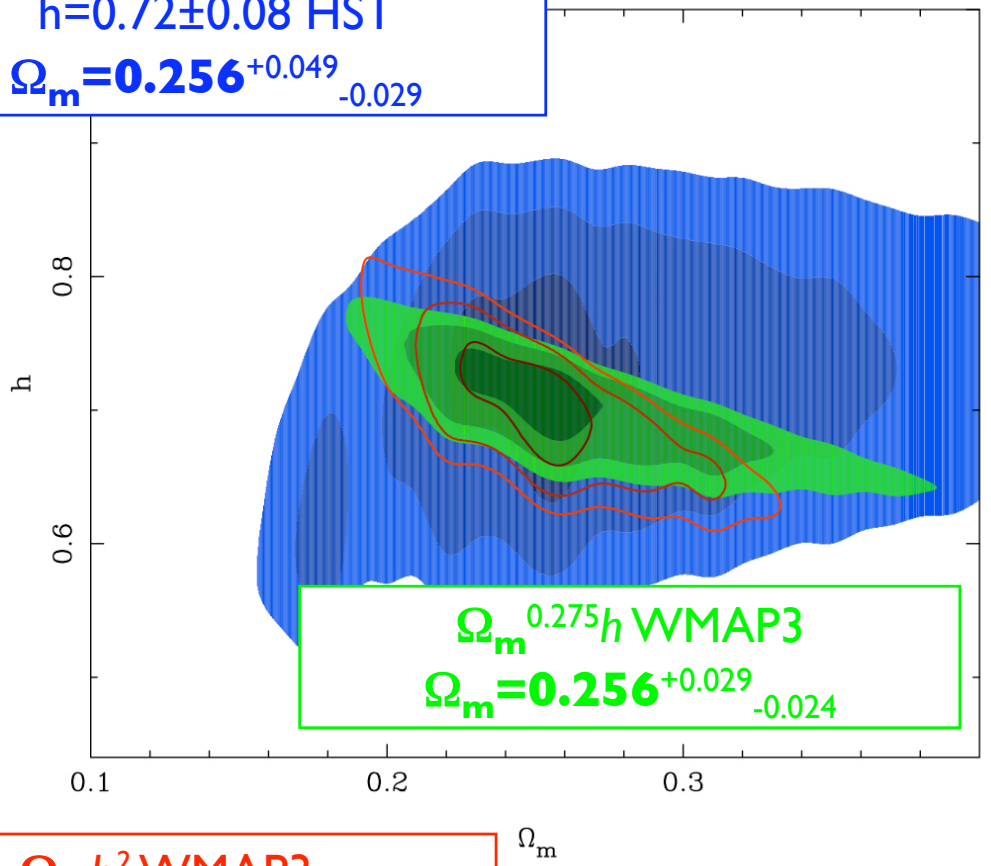
99.74% detection

Best fit Ω_m=0.26

Percival et al. (2006)

h=0.72±0.08 HST

Ω_m=**0.256**$^{+0.049}_{-0.029}$

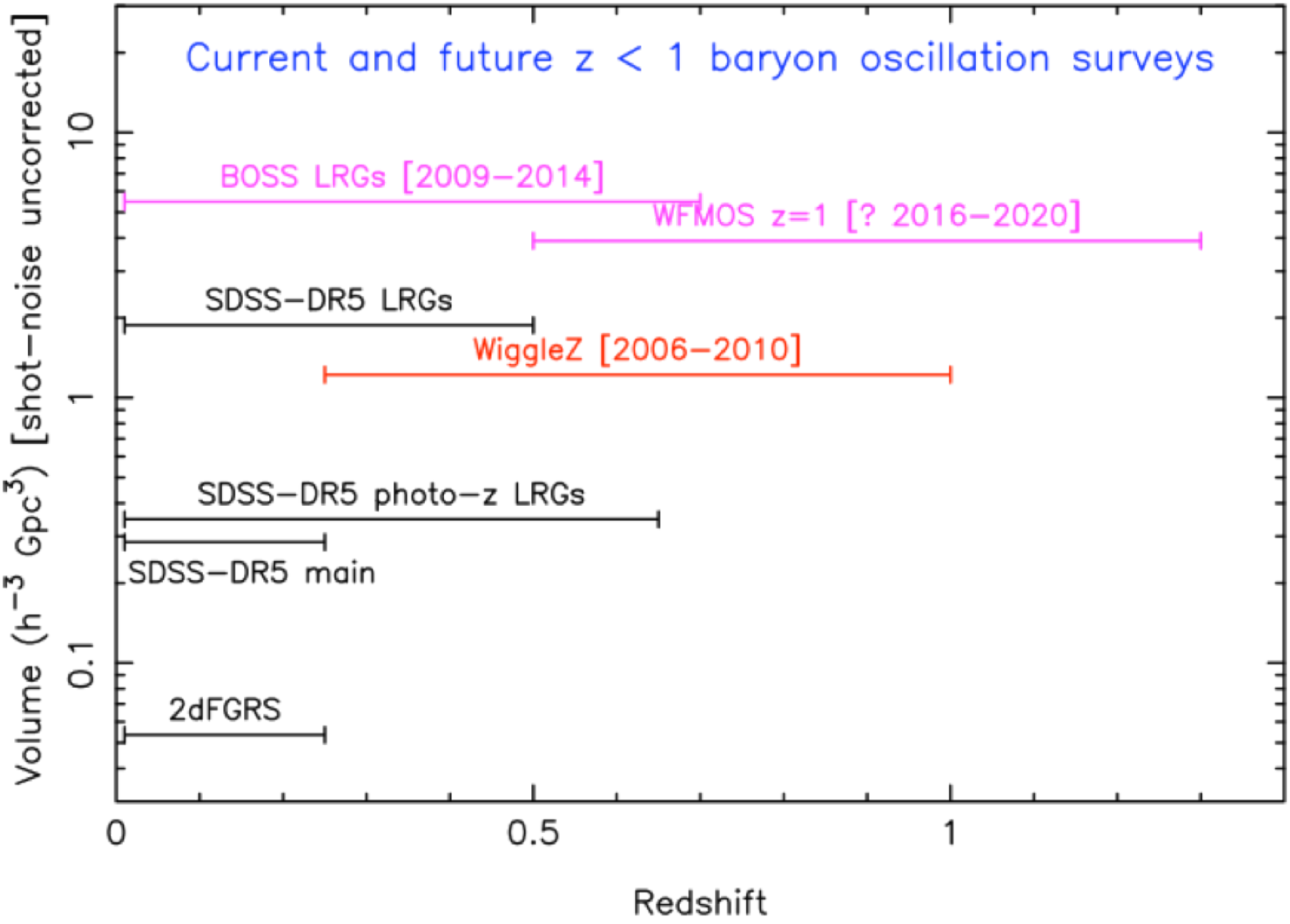


$\Omega_m^{0.275}h$ WMAP3

Ω_m=**0.256**$^{+0.029}_{-0.024}$

$\Omega_m h^2$ WMAP3

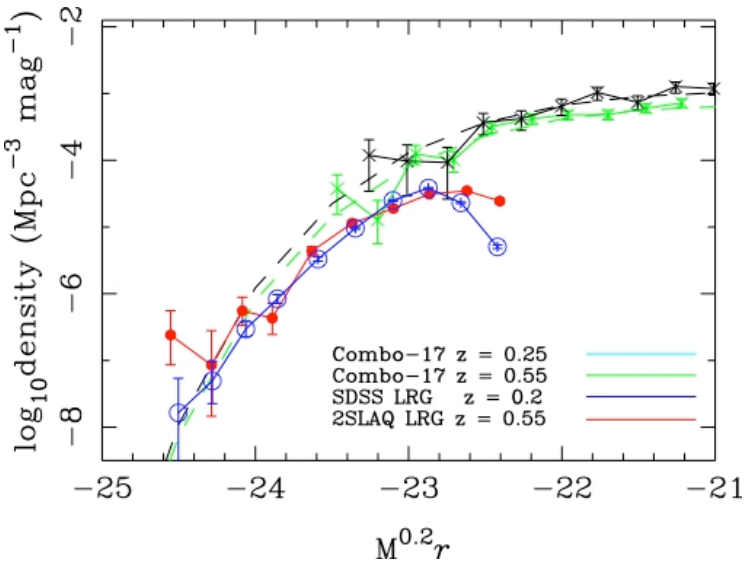
Ω_m=**0.256**$^{+0.019}_{-0.023}$

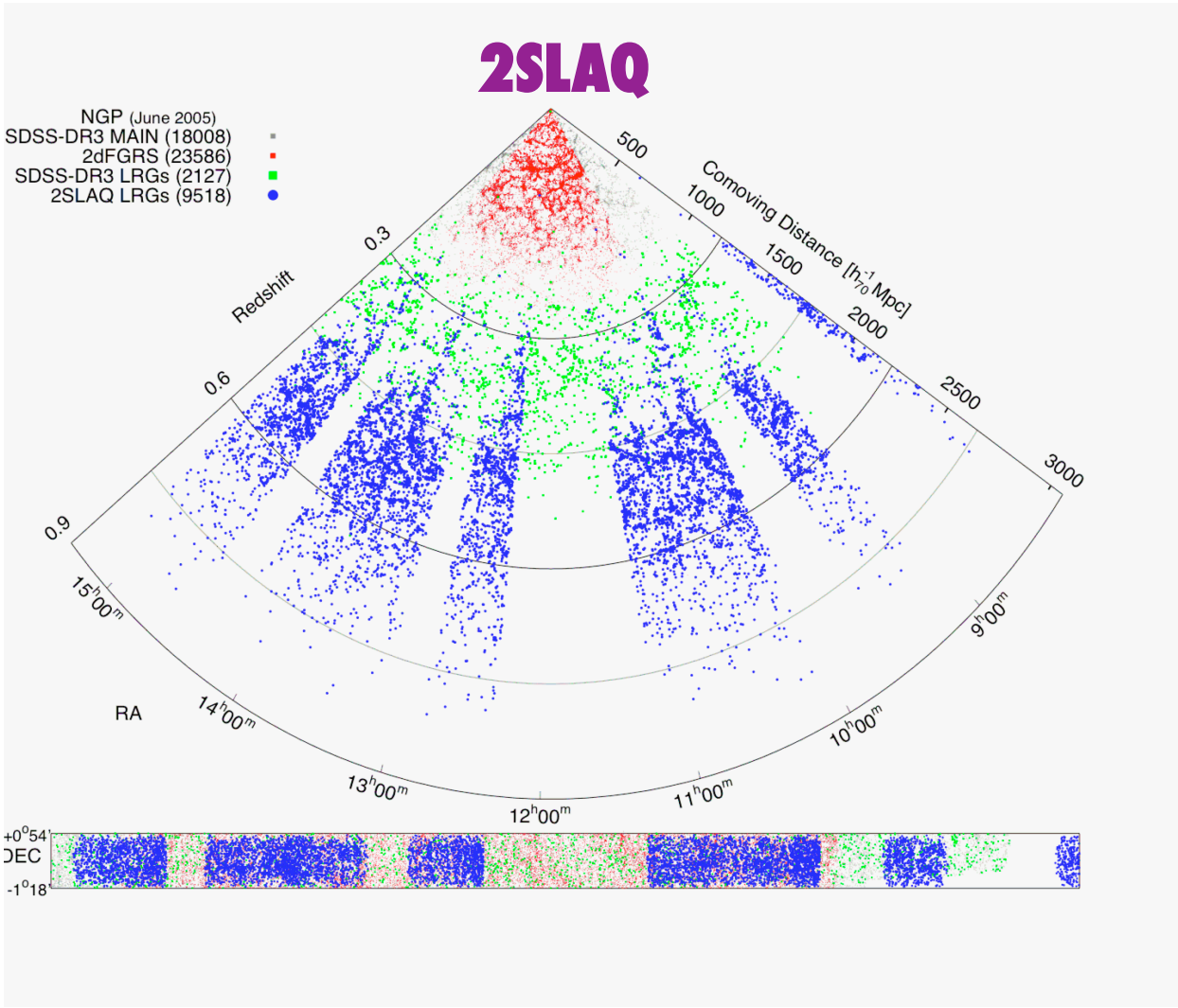

Current and future z < 1 baryon oscillation surveys
BOSS LRGs [2009–2014]
WFMOS z=1 [? 2016–2020]
SDSS–DR5 LRGs
WiggleZ [2006–2010]
SDSS–DR5 photo–z LRGs
SDSS–DR5 main
2dFGRS
Volume (h^-3 Gpc^3) [shot–noise uncorrected]
10
1
0.1
0
0.5
1
Redshift

SDSS again...

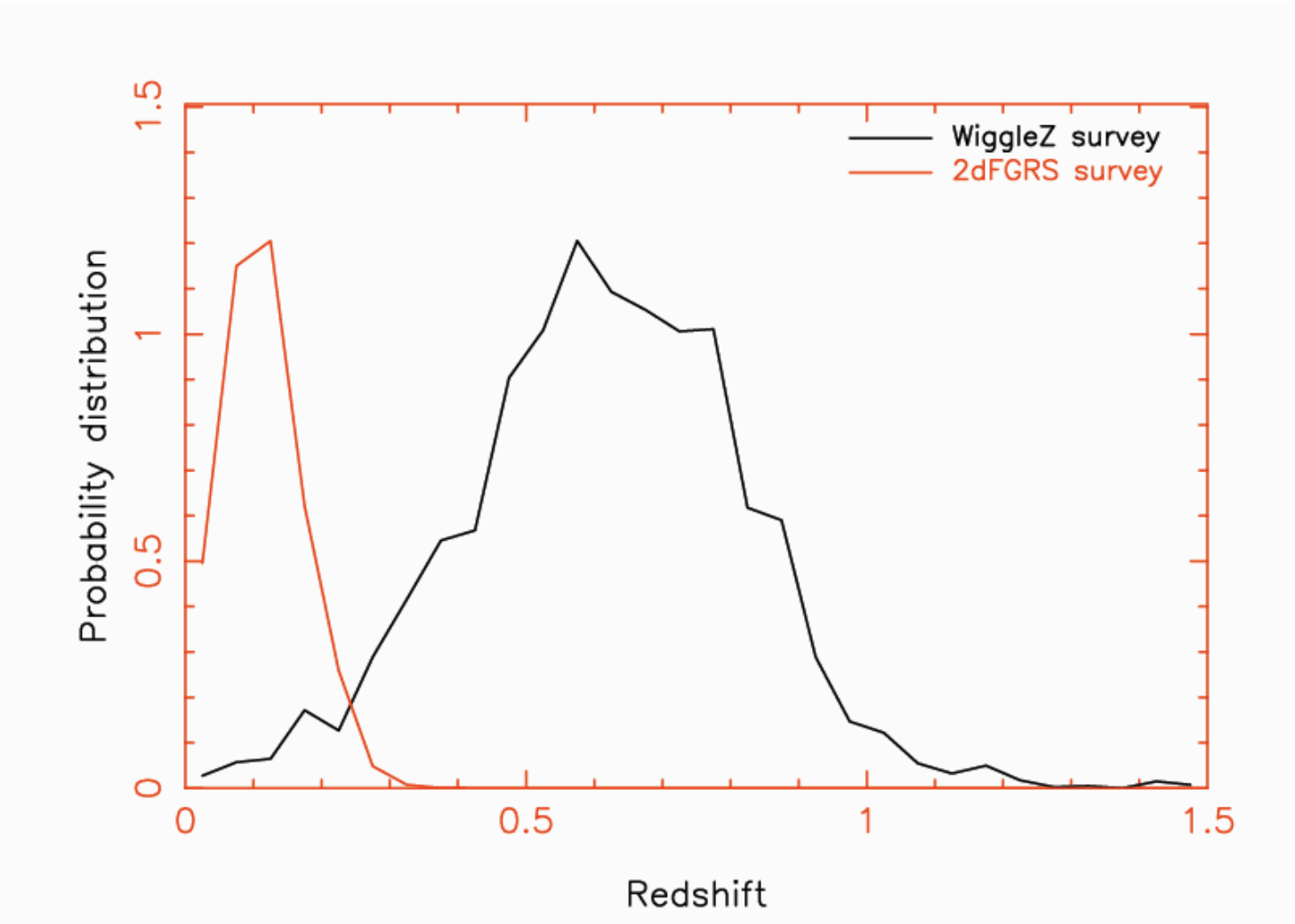
Baryon Oscillation Spectroscopic Survey (BOSS)

- Measure distance to 1% at z=0.35 and z=0.6
- 10000 deg^2 with 1.5m LRGs to z=0.8 (median z= 0.5)
- 100k quasars as well
- Starting 2009
- 7 times more volume





WiggleZ


WiggleZ survey
2dFGRS survey
Probability distribution
Redshift
0
0.5
1
1.5
0
0.5
1
1.5

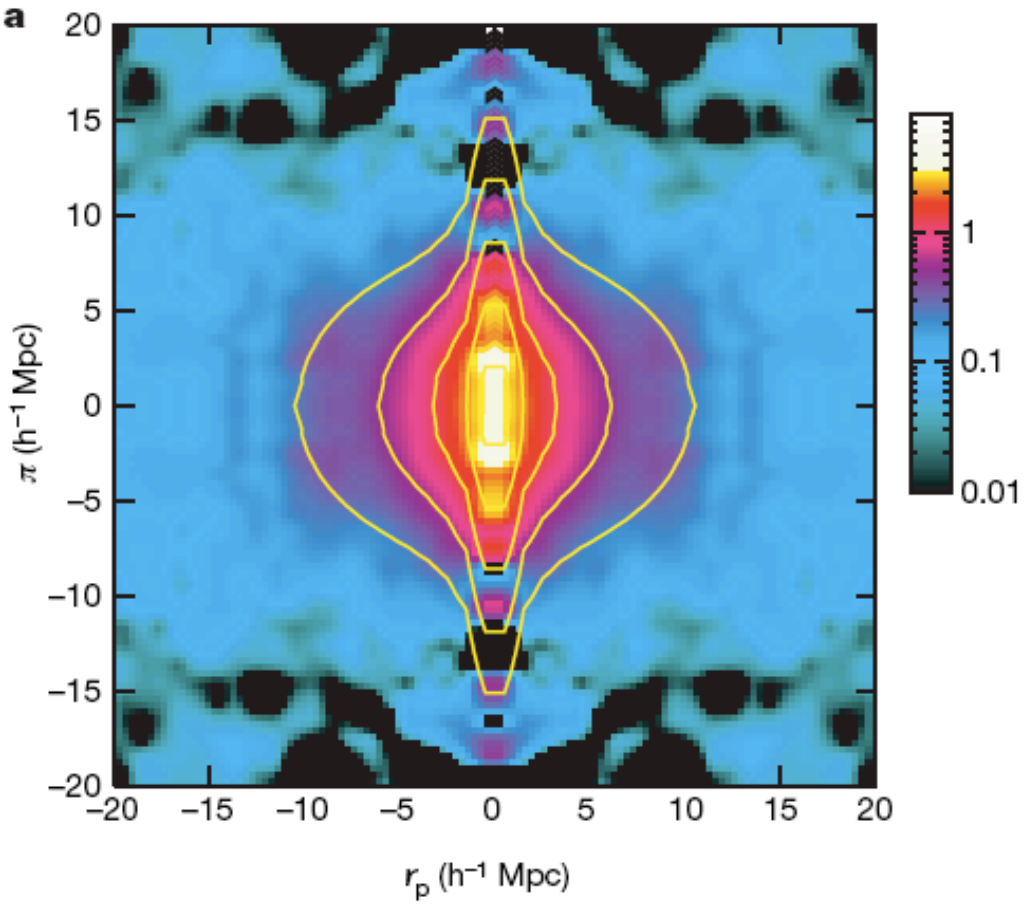
Redshift Space Distortions

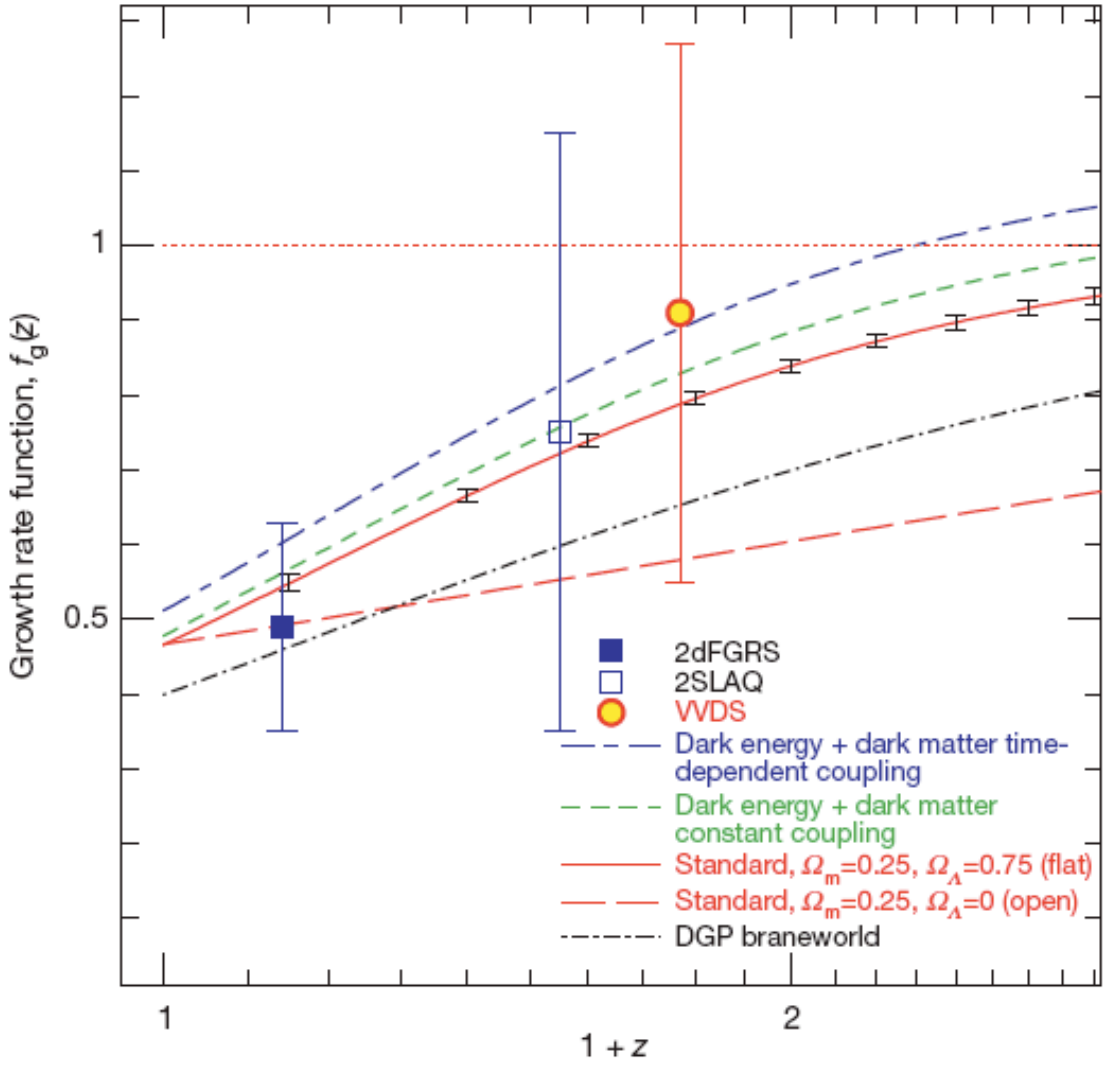
$$\xi(s) = \xi(r)\left(1 + \frac{2}{3}\beta + \frac{1}{5}\beta^2\right)$$

Redshift space correlation function

Real space correlation function

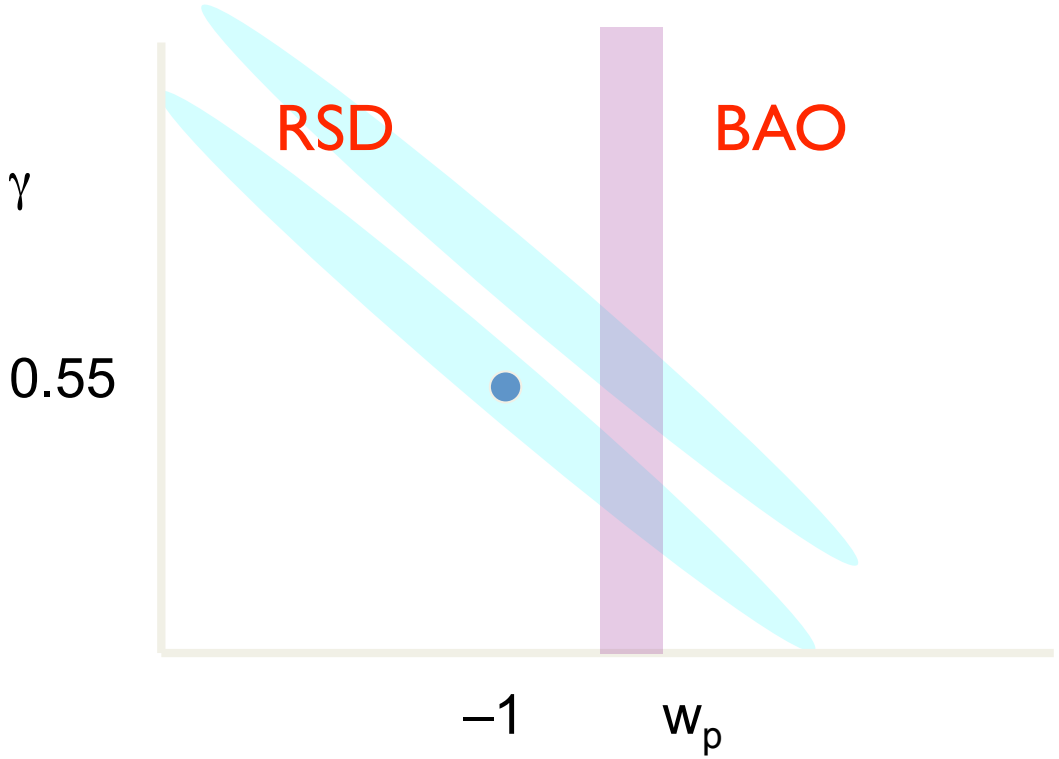
$$\beta \cong \frac{\Omega_M^{0.6}(z)}{b}$$





Guzzo et al, 2008

DE-gravity degeneracy

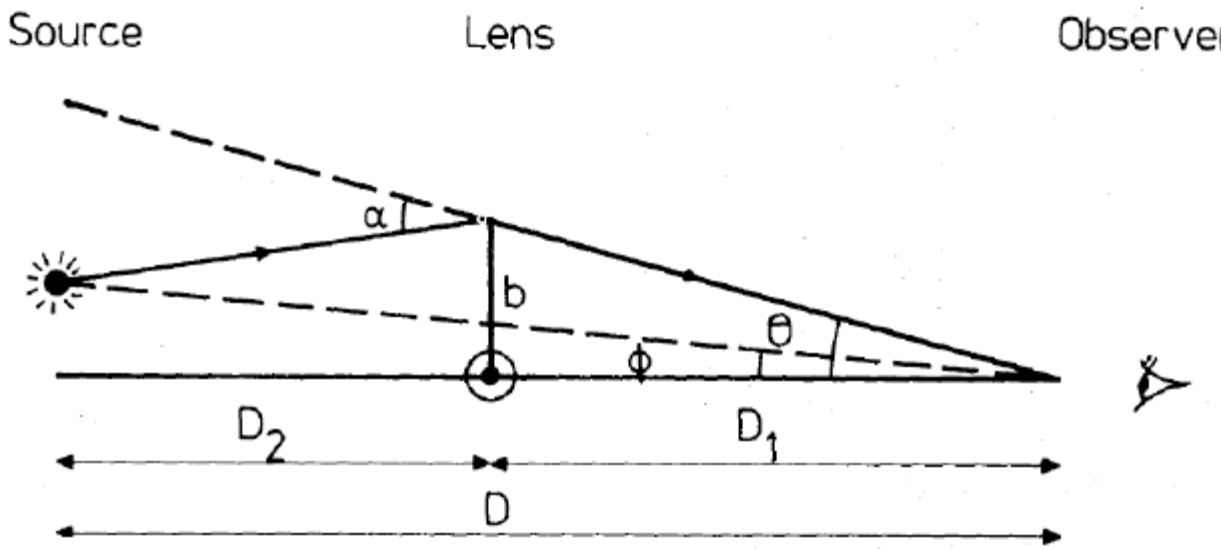


Good to have both errors comparable.

Good case for FoM based on joint area of confidence ellipsoid in this plane

Peacock and Simpson, 2009

3D Cosmic Shear Lensing and Tomography



$$\theta D = \phi D + \alpha D_2$$

$$\alpha(b) \equiv \alpha(D_1\theta) = \frac{D}{D_2}(\theta - \phi)$$

Peacock 1982

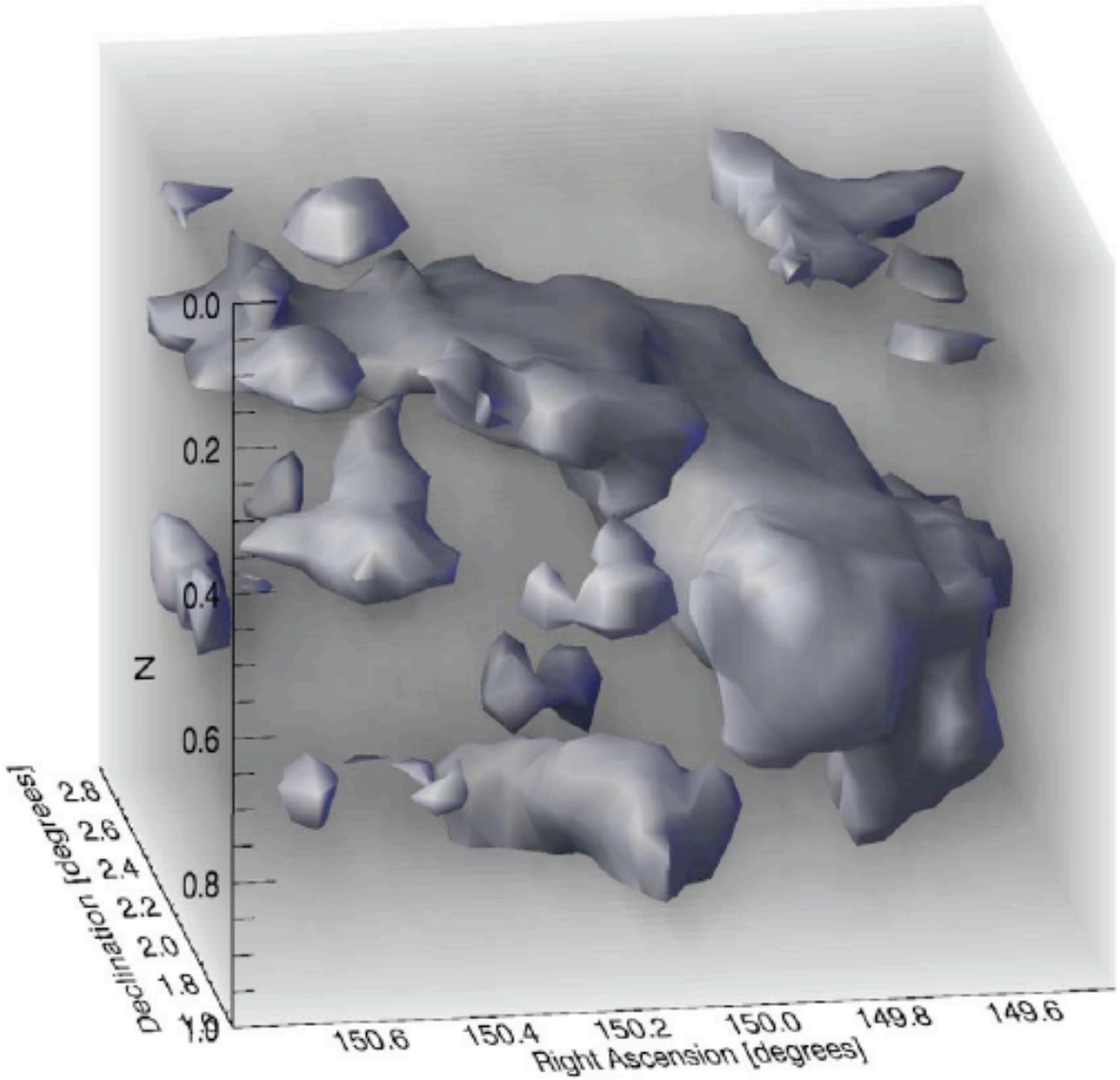
Sample D (from z or photometric z) to infer D_1

What gravitational lensing looks like

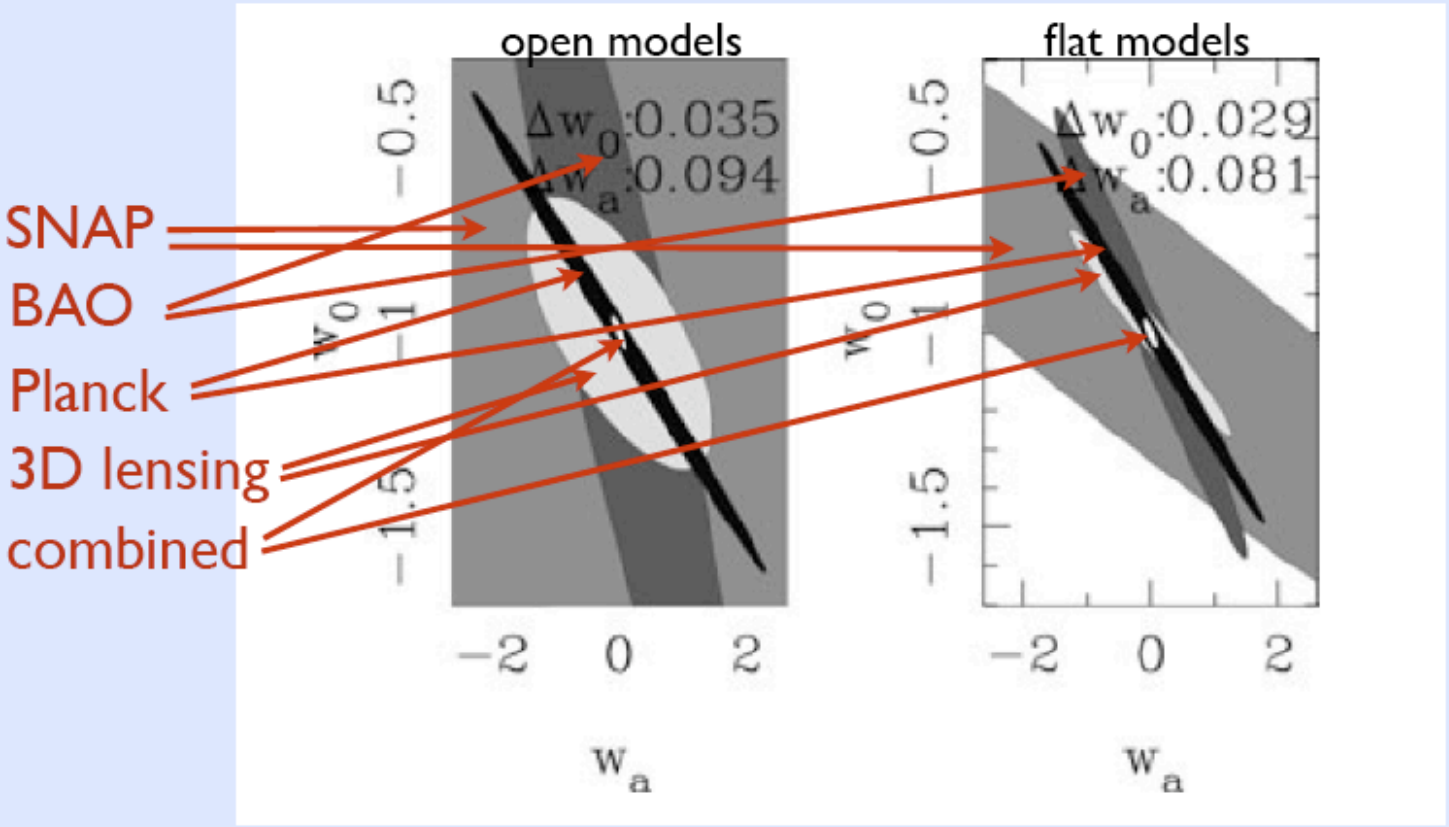
Ingredients

- True image
- Lensed image
- Distance to lens
- Amount of glass/mass
- Physics of light deflection

Map the dark matter in the Universe:



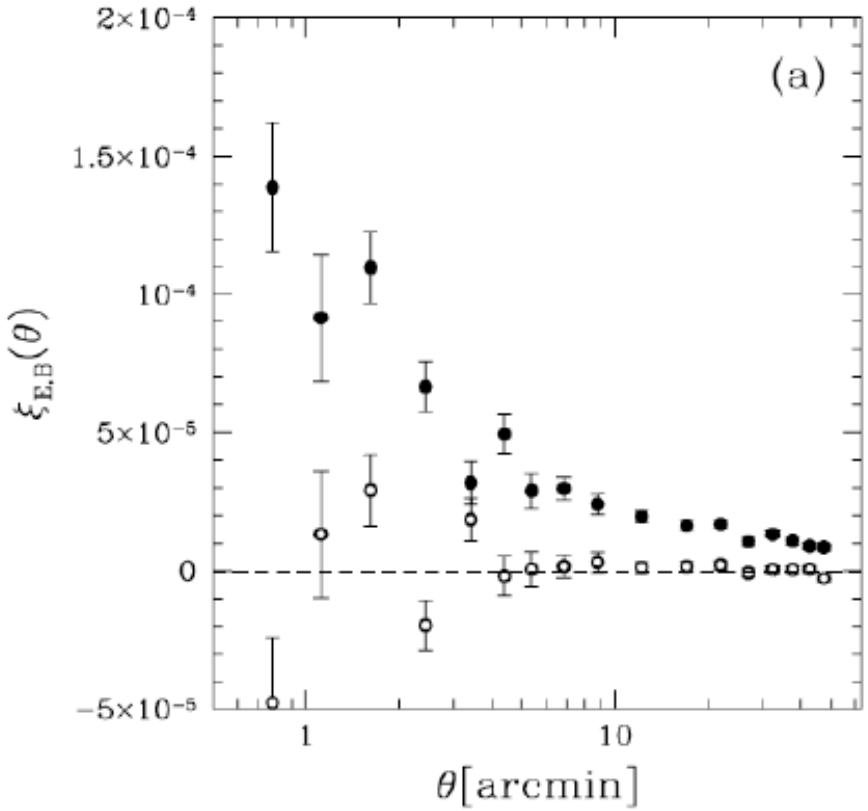
Massey et al, 2007

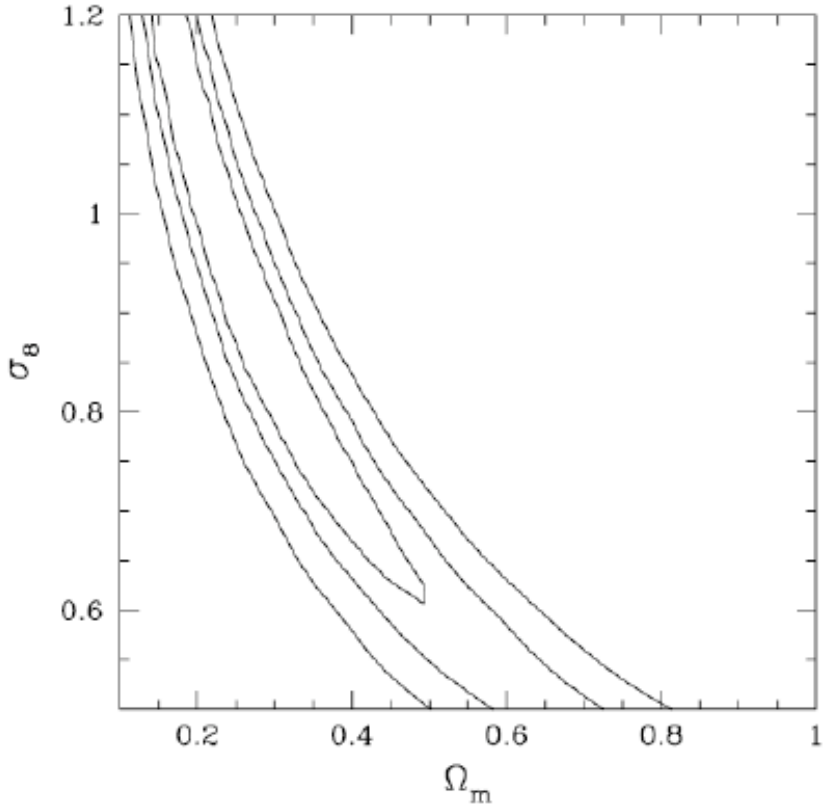


$w(z) = w_0 + w_a(1-a)$

Heavens, Kitching & Taylor 2006

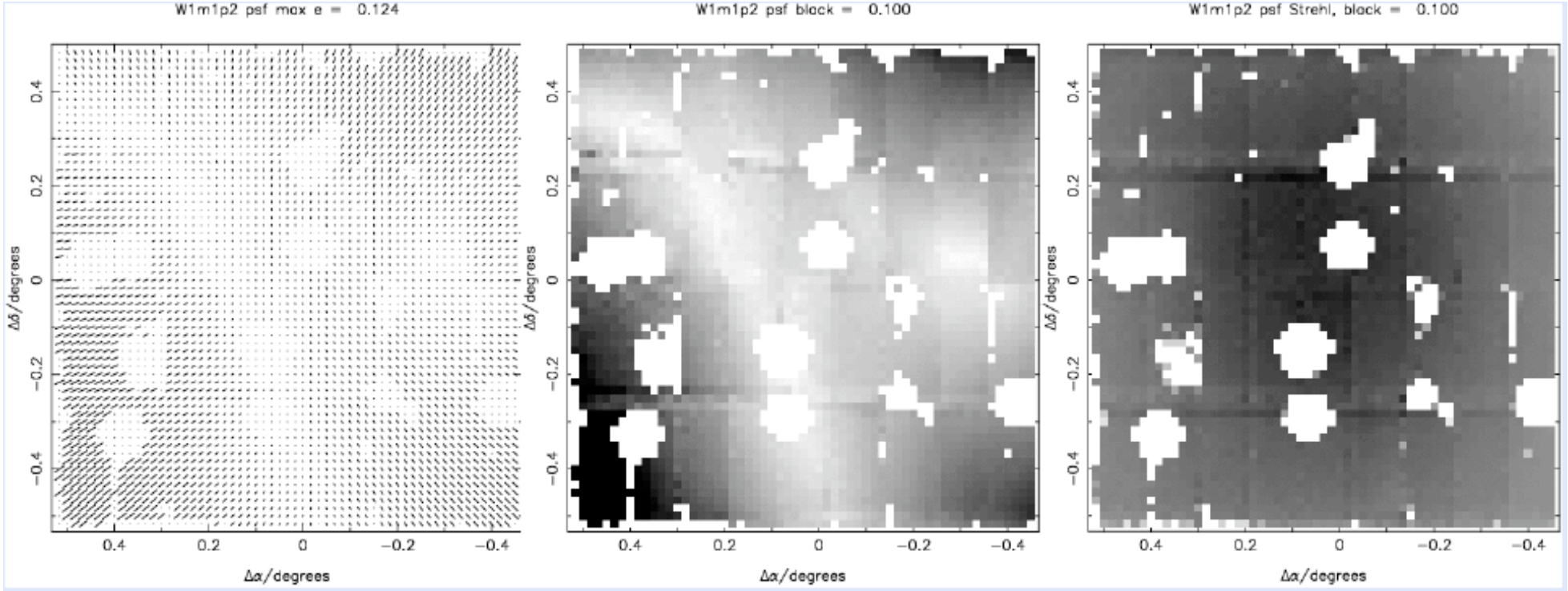
CFHT Legacy Survey (wide)





Hoekstra et al (2006) 2D shear analysis in i-band

The Point Spread Function ("PSF") will distort the images



Ellipticity vector

Ellipticity amplitude

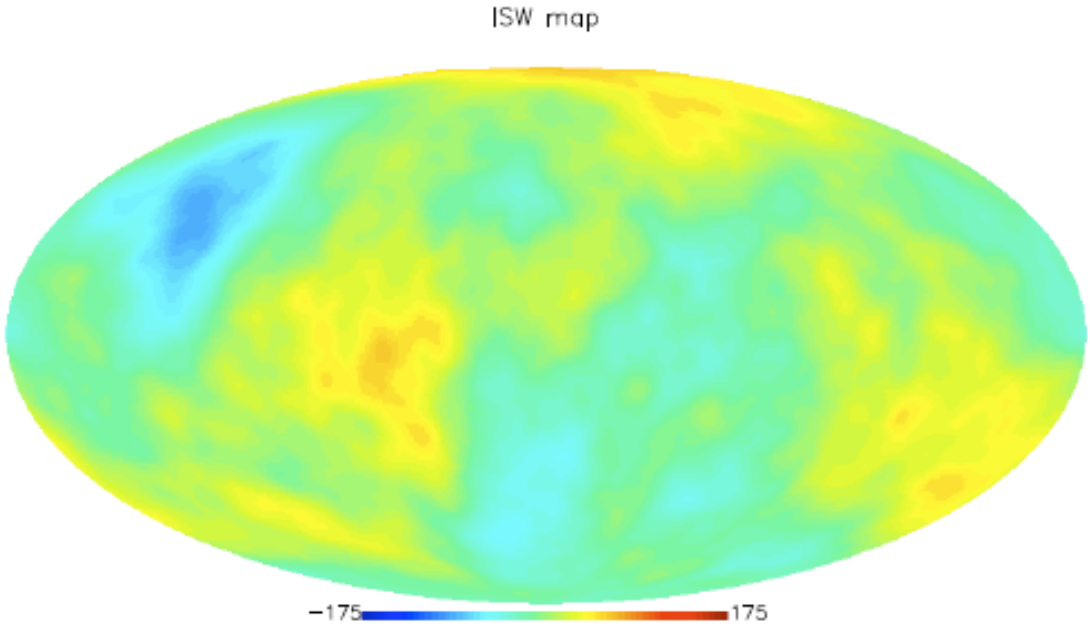
Ellipticity peakiness

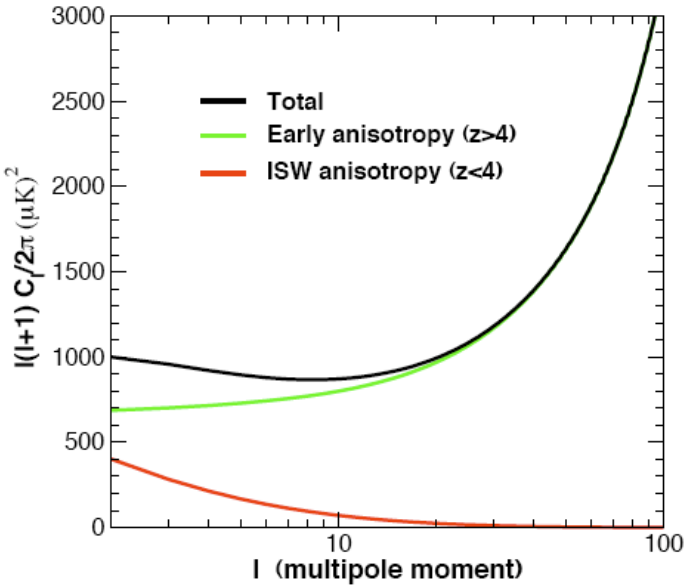
Caused by: atmospheric seeing, differential refraction, field tracking rotation, optics, focal plane layout, …

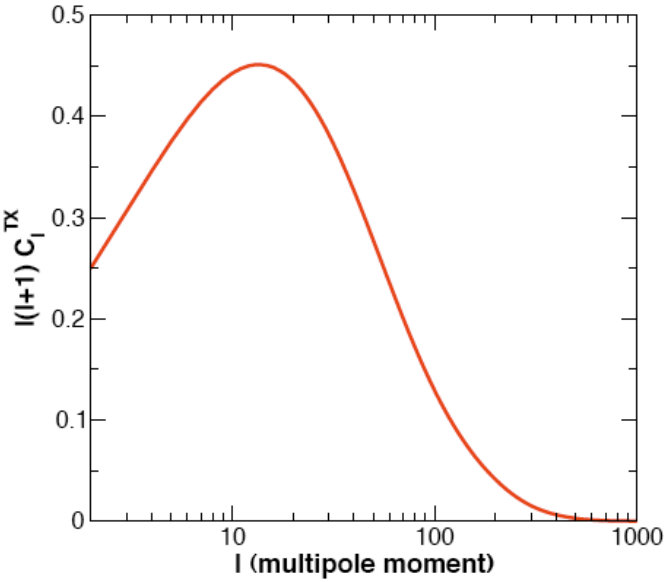
Integrated Sachs-Wolfe Effect.

$$\frac{\Delta T}{T} = -2 \int d\tau \, \dot{\Phi}$$

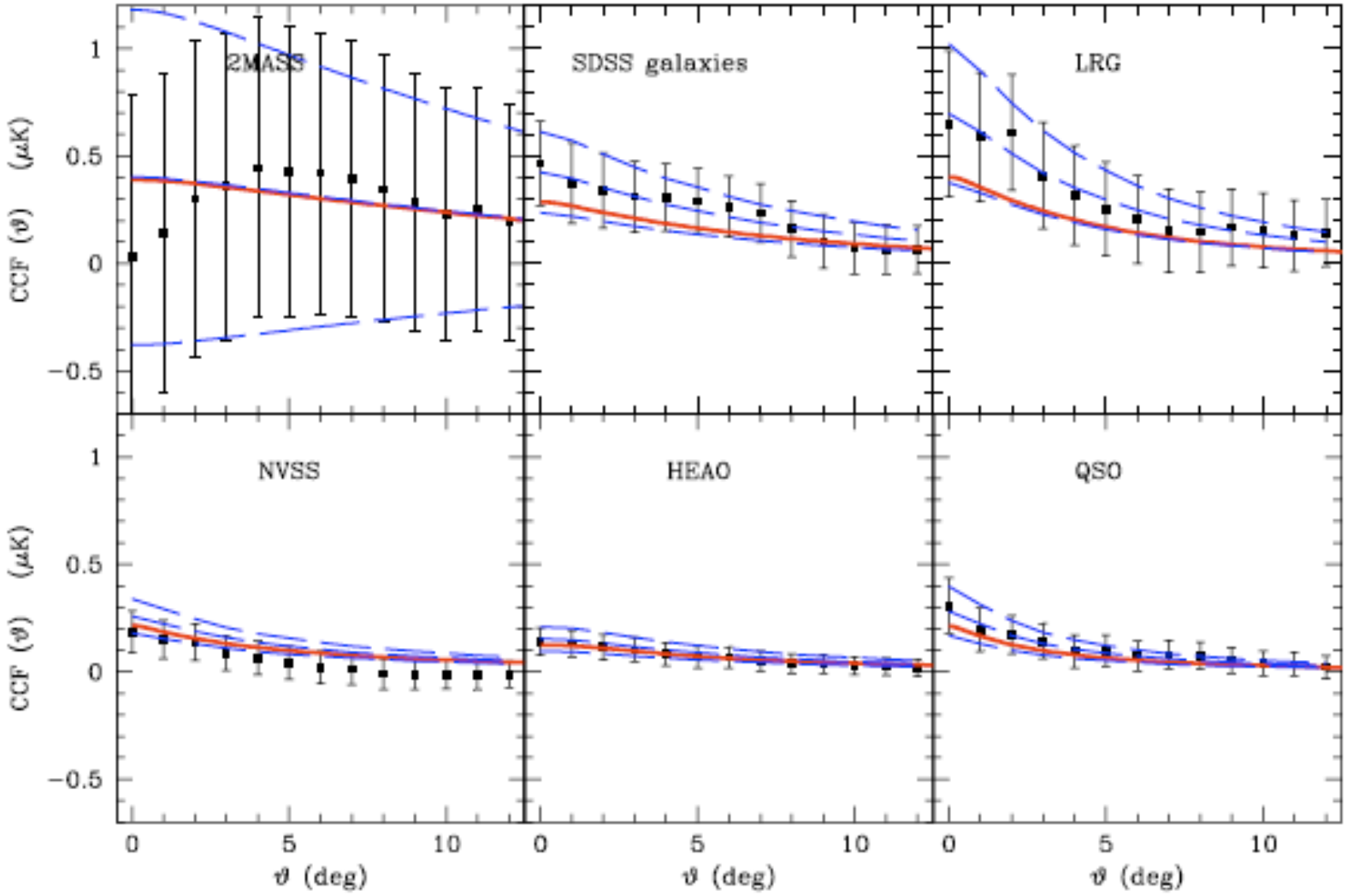
$$\Phi = -\frac{4\pi G a^2}{k^2} \bar{\rho}_m \delta_m$$



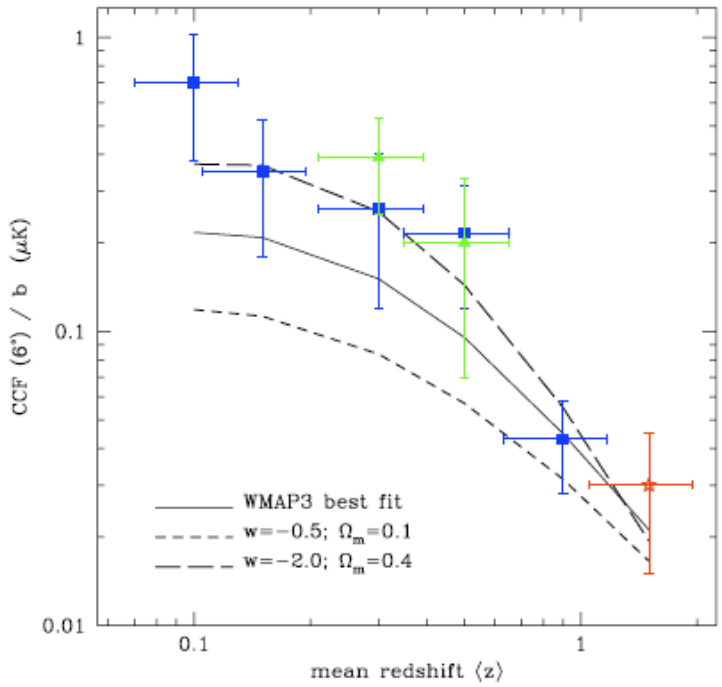


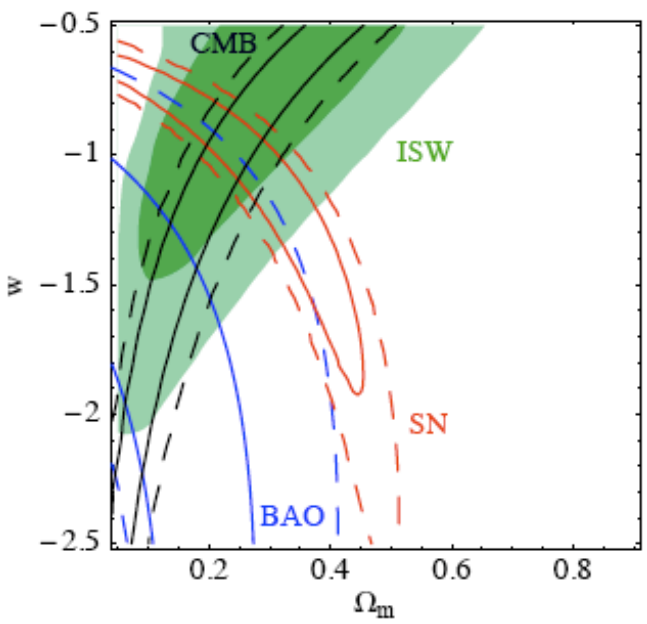


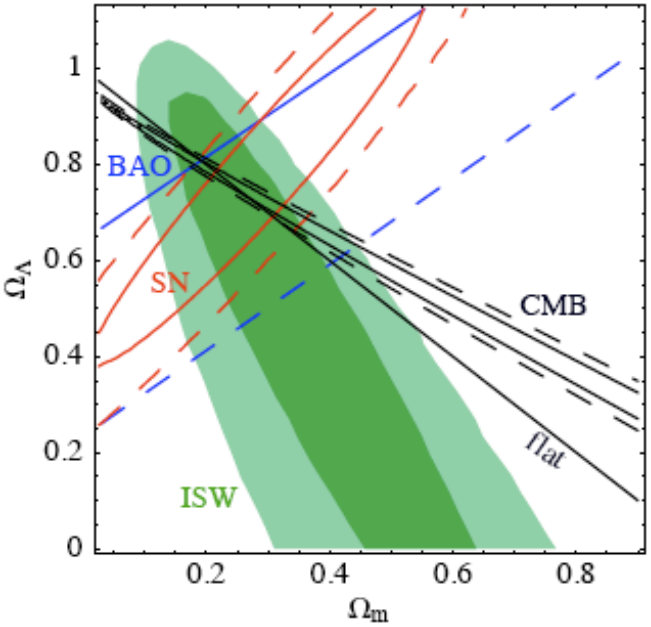
Current Results



Crittenden, Giannantonio et al


CCF (6°) / b (μK)
mean redshift ⟨z⟩
WMAP3 best fit
w=−0.5; Ωm=0.1
w=−2.0; Ωm=0.4


CMB
ISW
SN
BAO
w
Ωm


BAO
SN
CMB
flat
ISW
ΩΛ
Ωm

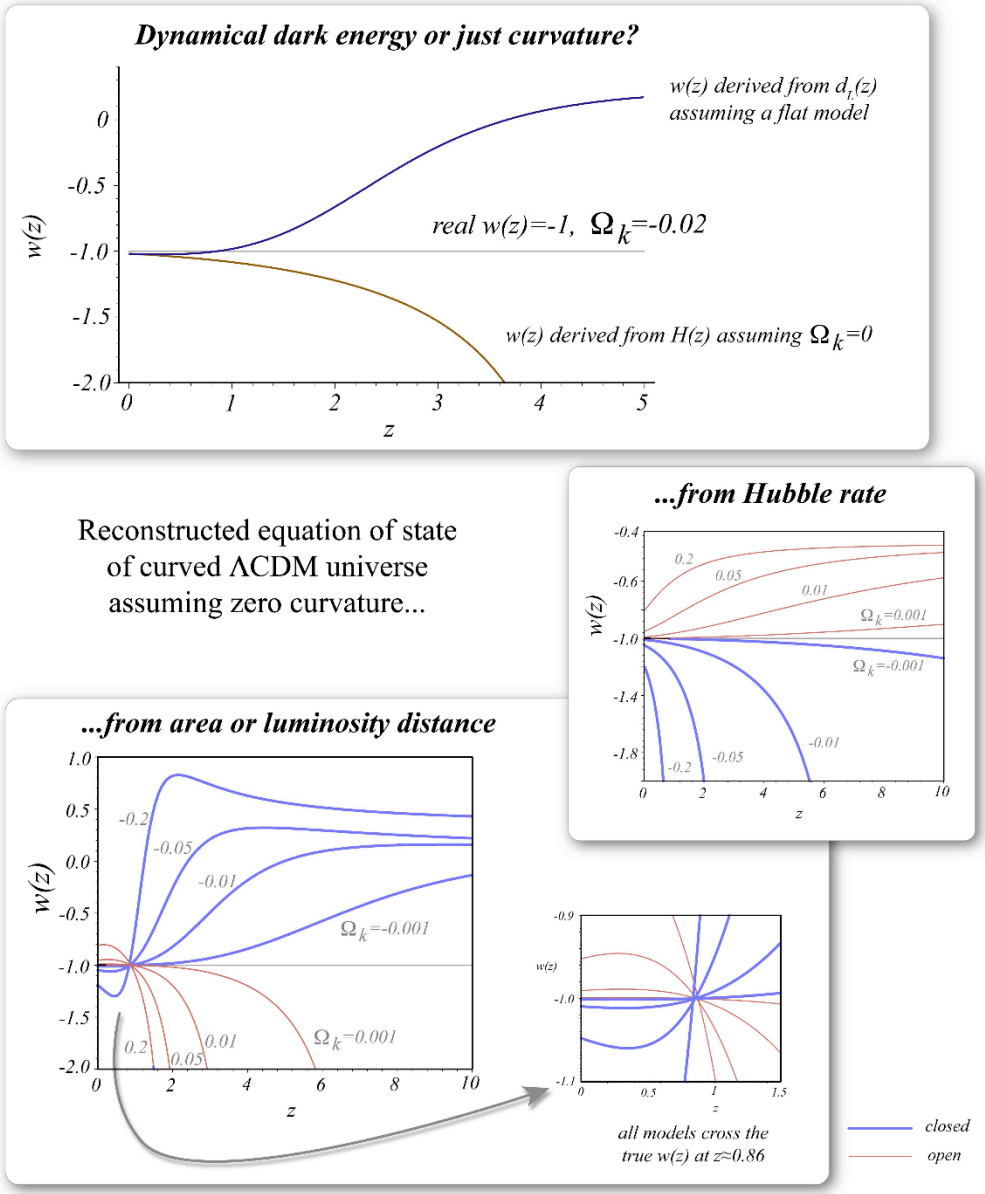
How robust is the evidence for Dark Energy?

- How important is flatness?
- Do we have the correct theory of gravity?
- Is the Universe locally homogeneous?
- Is the Universe smooth or discrete?

Now, I am willing to believe, indeed I firmly believe, that other solutions to this problem might have been found, and indeed may still be found, no less sound, but much more elegant, than the one I shall now describe, if I can.

Samuel Beckett

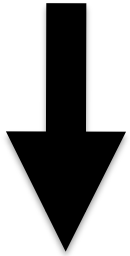
Curvature mimics Dark Energy and vice versa



Clarkson et al

Modifying Gravity

$$\frac{1}{16\pi G}\int d^4x\sqrt{-g}R(g)$$



$$\frac{1}{16\pi G}\int d^4x\sqrt{-g}\mathcal{F}(R, R_{\alpha\beta}, R_{\alpha\beta\mu\nu}, ...)$$

Notes: extra degrees of freedom, ghosts, instabilities,…

On “small scales” we have the PPN parametrization of deviations from General Relativity

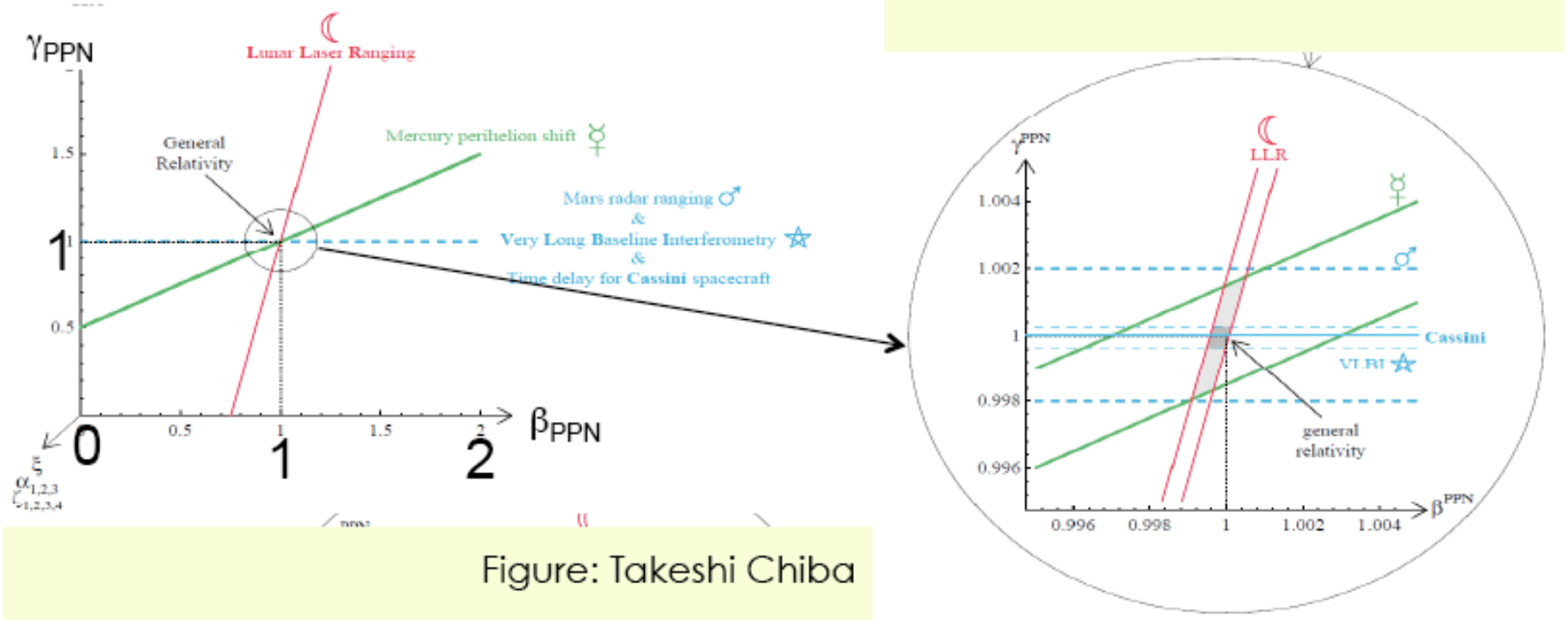


Figure: Takeshi Chiba

Cosmological Modifications of General Relativity

$$ds^2 = -(1+2\Psi)dt^2 + a^2(t)(1-2\Phi)dx^2$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

$$\nabla^2\Phi = 4\pi G\delta\rho$$

$$g_i = \nabla_i\Psi$$

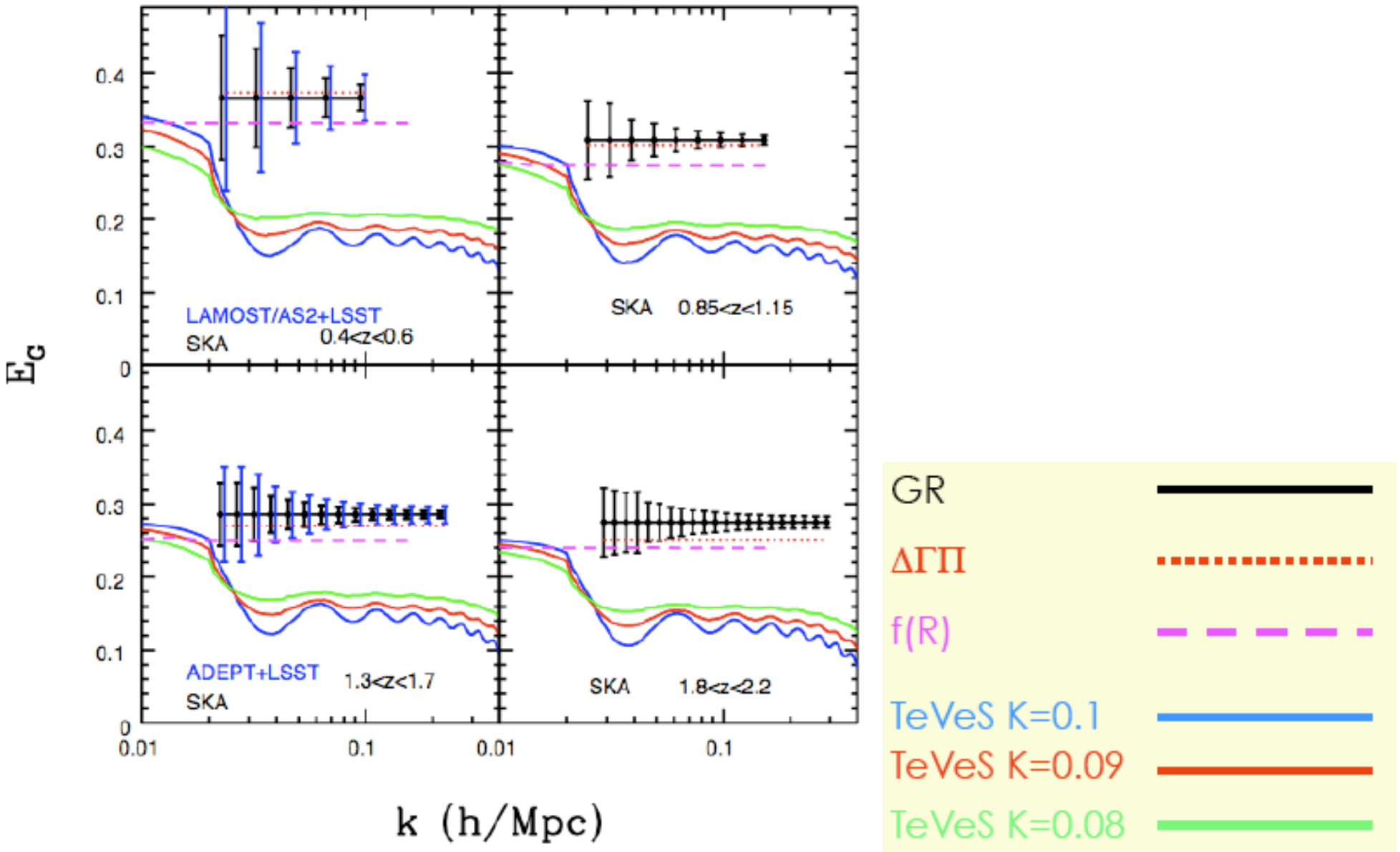
$$\Psi = \Phi$$

$$\mathcal{F}[a, \dot{a}, \ddot{a}, \cdots] = \frac{8\pi G_{eff}}{3}\rho$$

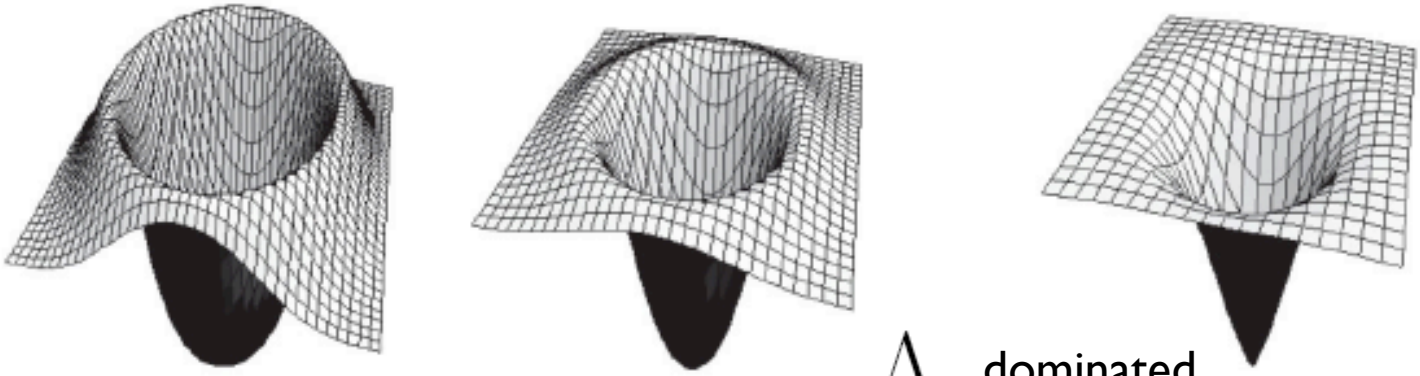
$$\nabla^2\Phi = 4\pi G_{eff}\delta\rho$$

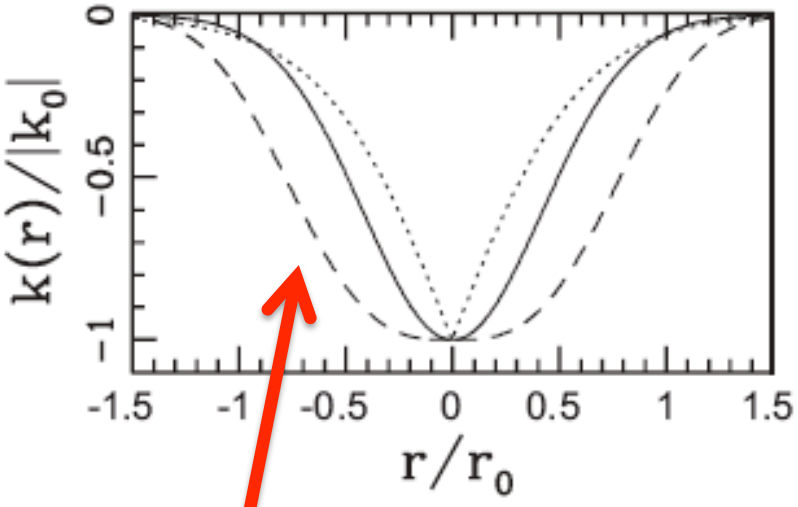
$$g_i = \nabla_i\Psi$$

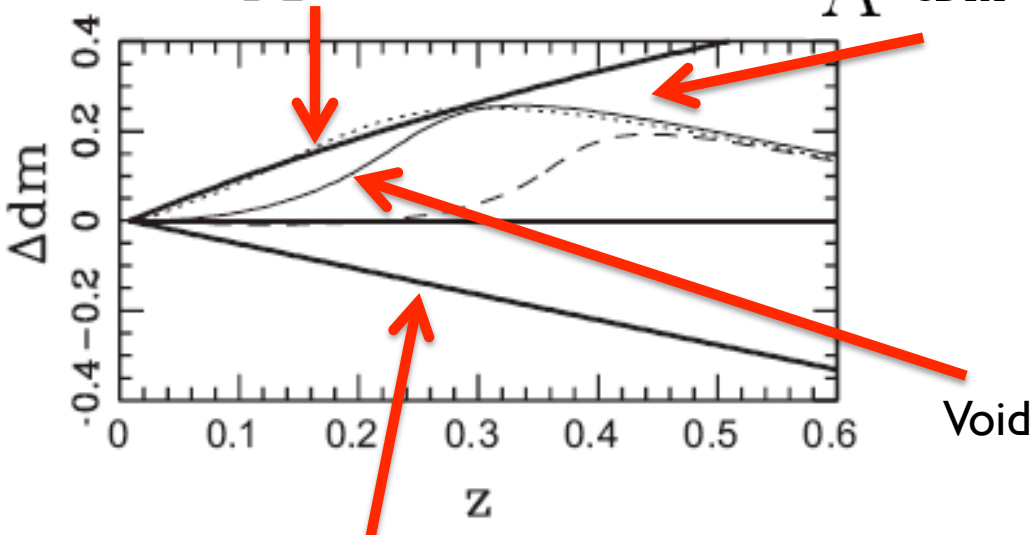
$$\Psi = (1+\gamma)\Phi$$


E_G
LAMOST/AS2+LSST
SKA 0.4<z<0.6
SKA 0.85<z<1.15
ADEPT+LSST
SKA 1.3<z<1.7
SKA 1.8<z<2.2
0.4
0.3
0.2
0.1
0
0.01
0.1
k (h/Mpc)
GR
ΔΓΠ
f(R)
TeVeS K=0.1
TeVeS K=0.09
TeVeS K=0.08

Isotropic but Inhomogeneous: living in a void



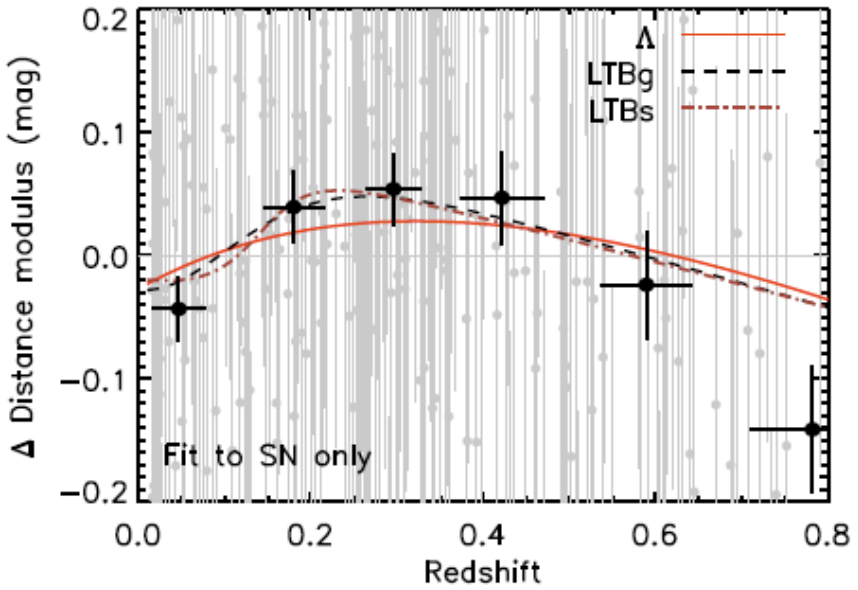




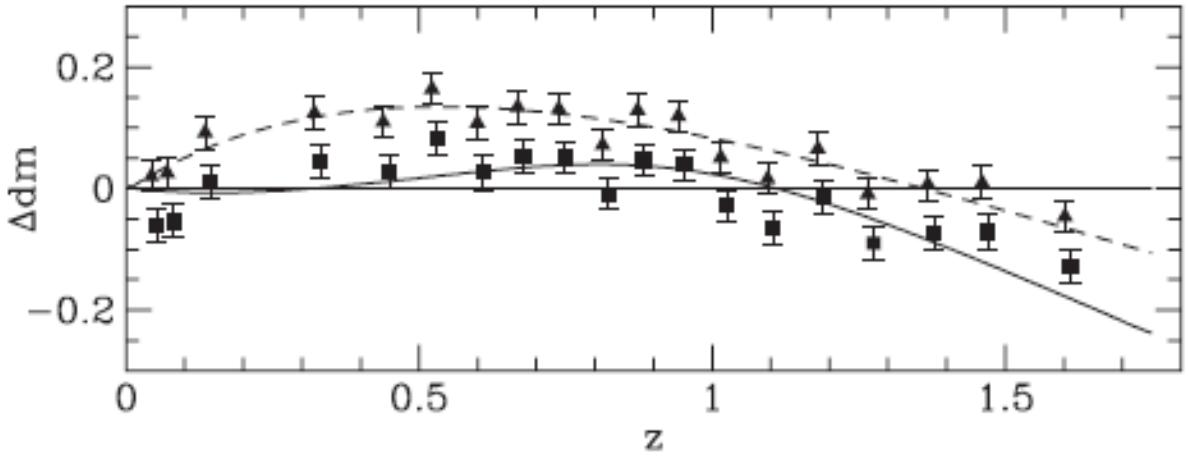
Curvature profile

Matter dominated

Current constraints



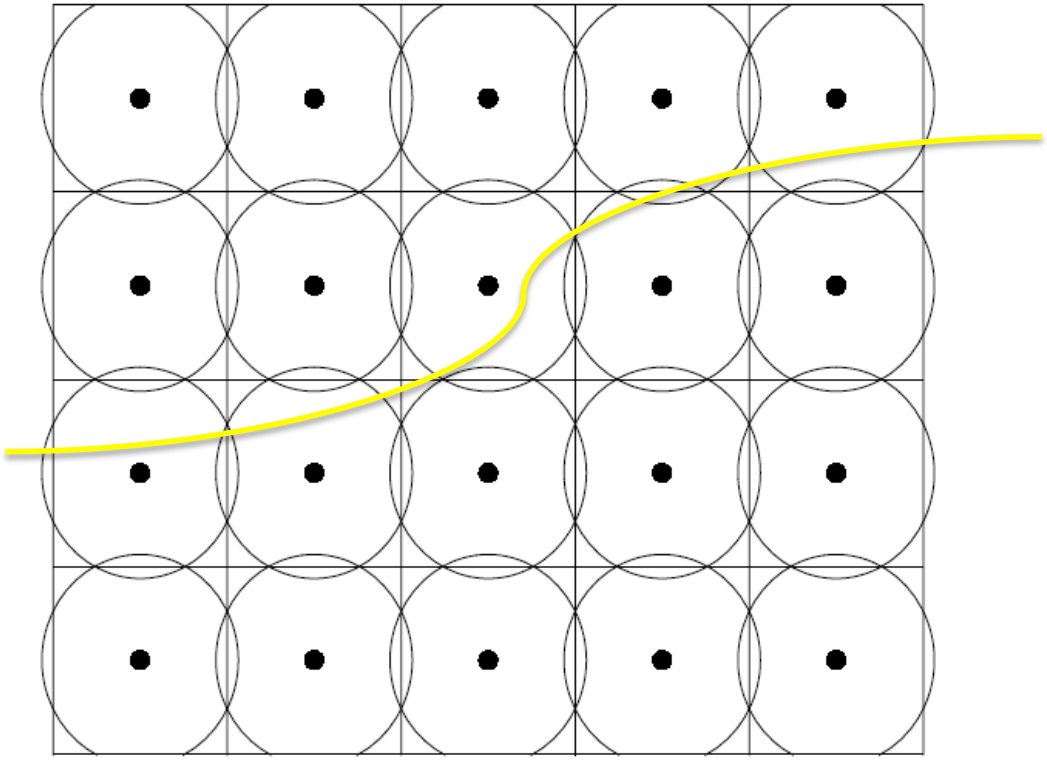
Sollerman et al, 2009 (SDSSII)



The future?

A discretized Universe.

Fundamental building blocks of the Universe at late times are Galaxies, not a smooth fluid.

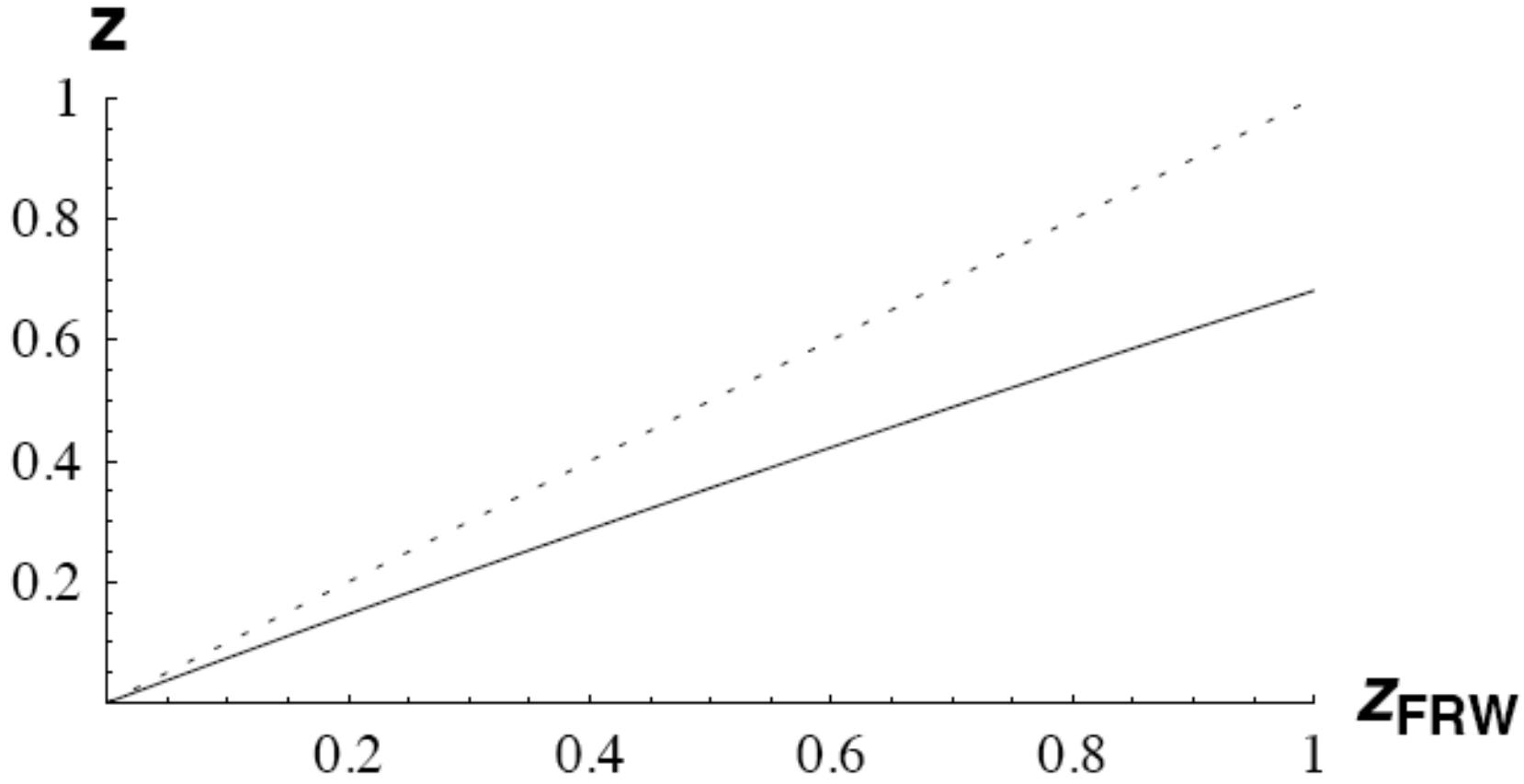


Light ray

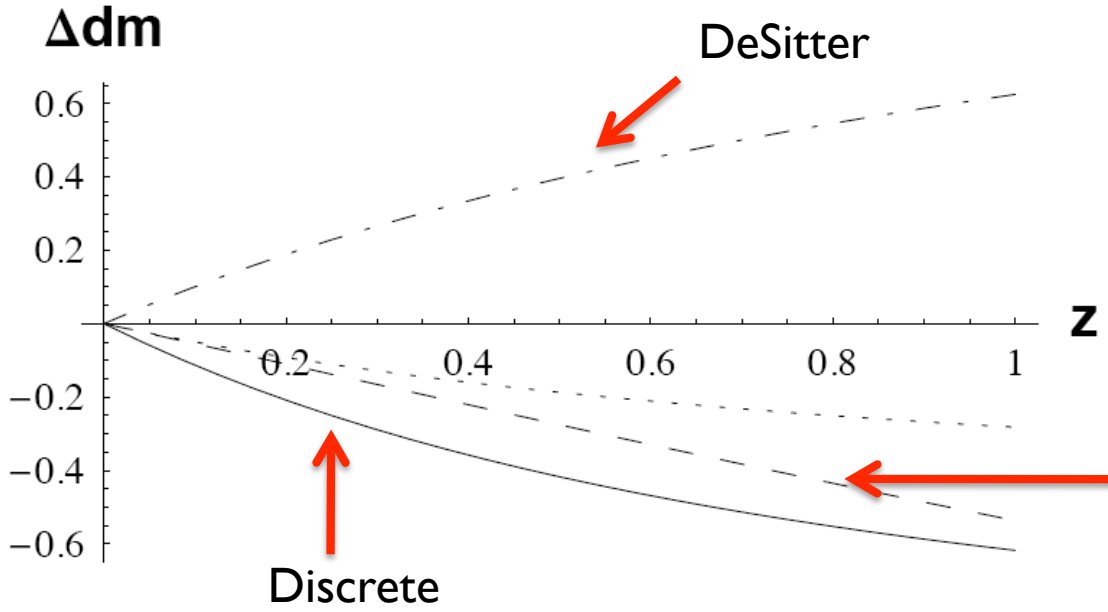
Construct a lattice of Schwarzschild cells

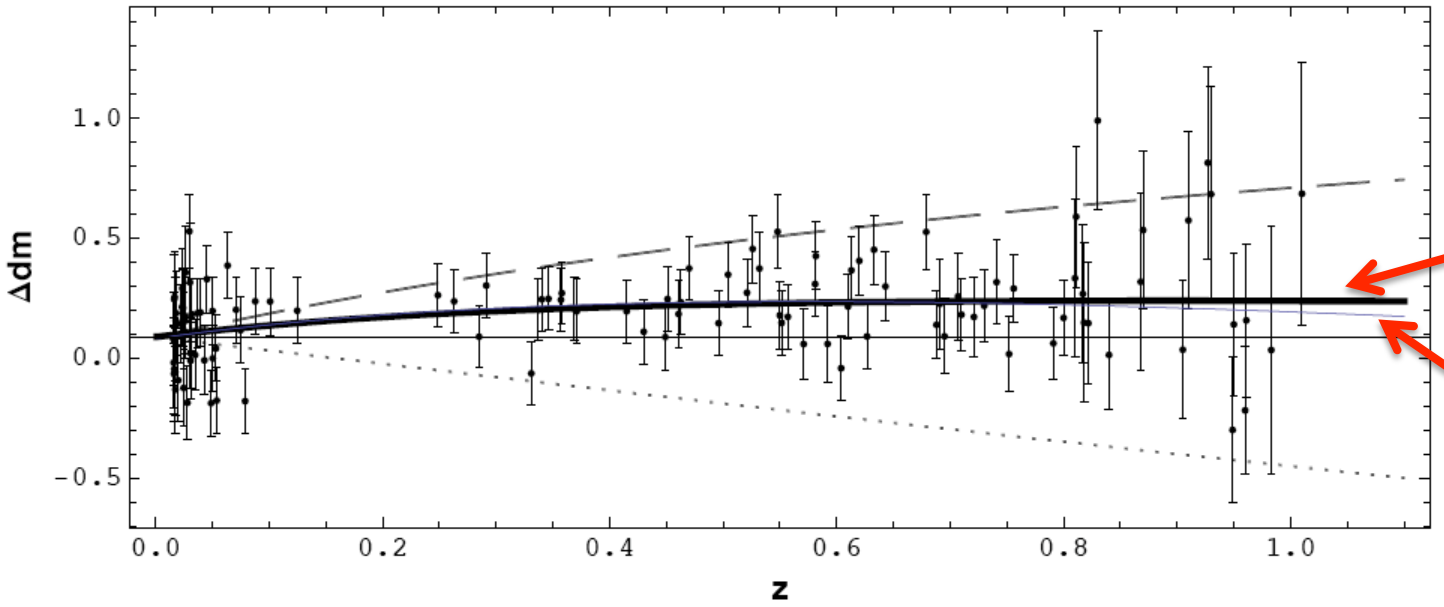
Lindquist-Wheeler, 1957

Expansion is locally anisotropic.



Clifton and Ferreira, 2009





Discretized

$\Lambda = 0.66$

Smooth

$\Lambda = 0.74$

"The only thing we know about dark energy is that we don't know anything about it…",

Rocky Kolb, Cosmologist

"No, you're not thinking, your just being logical."

Neils Bohr