Cosmology Probes

N. Regnault

(LPNHE, Paris)

Cosmology Probes

- Type Ia supernovae
- Type II supernovae
- Baryon acoustic oscillations
- Cosmic shear
- Lensing amplification
- Galaxy-galaxy lensing
- Redshift space distorsions
- Alcock-Paczynsky effect
- GRBs as standard candles
- CMB
- Integrated Sachs-Wolfe effect
- Weak-lensing of CMB
- Abundance of galaxy clusters
- Cluster gas mass fraction
- GW from spiraling neutron stars
- Strong lensing of distant QSOs
- Abundances of lensed arcs

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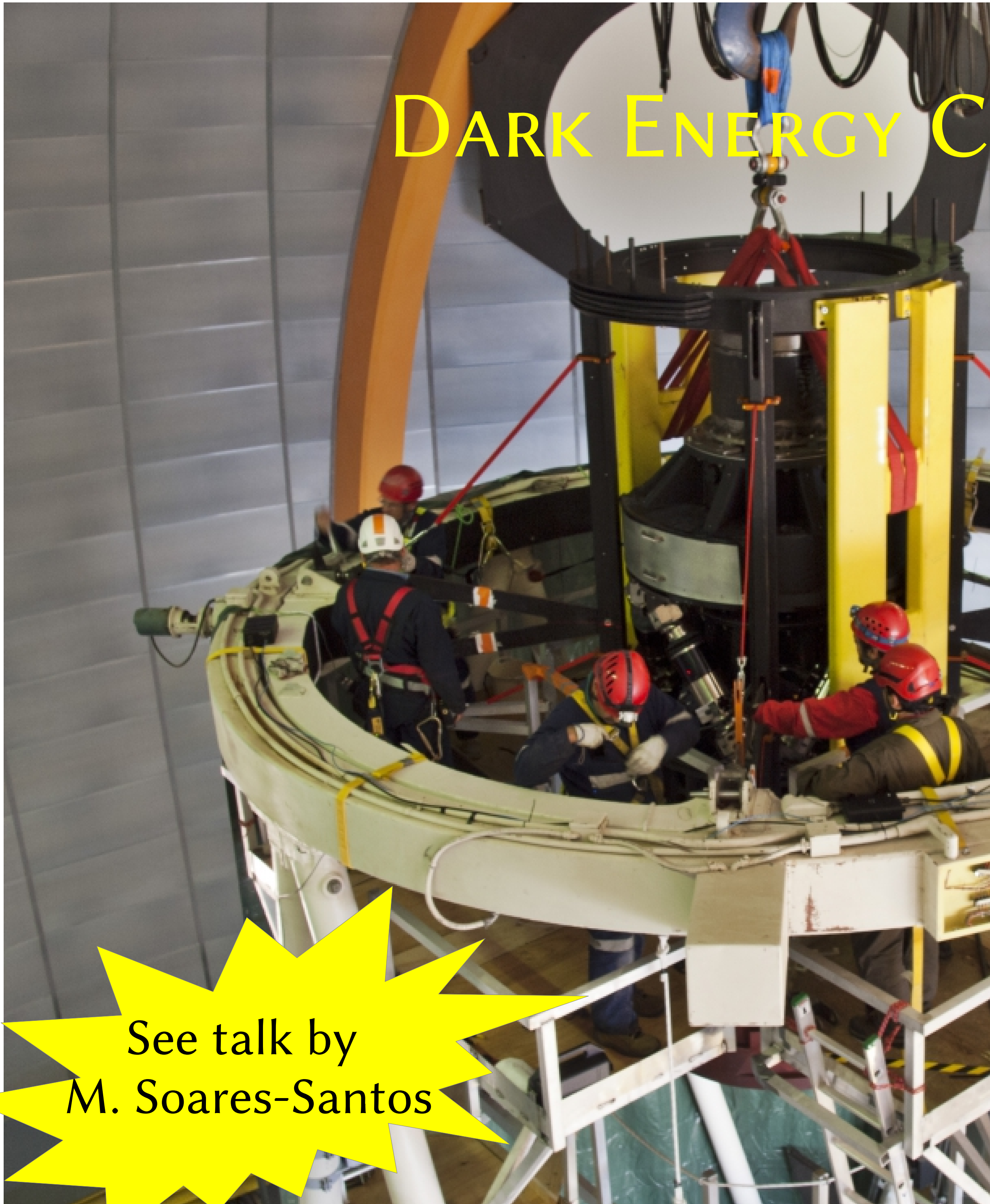
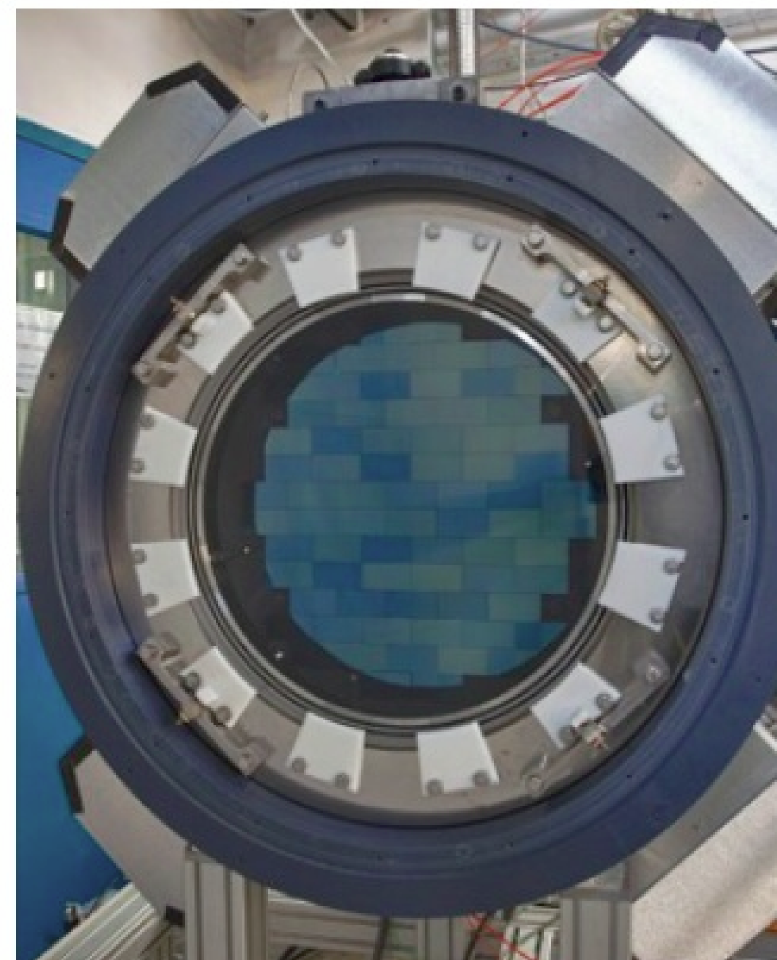
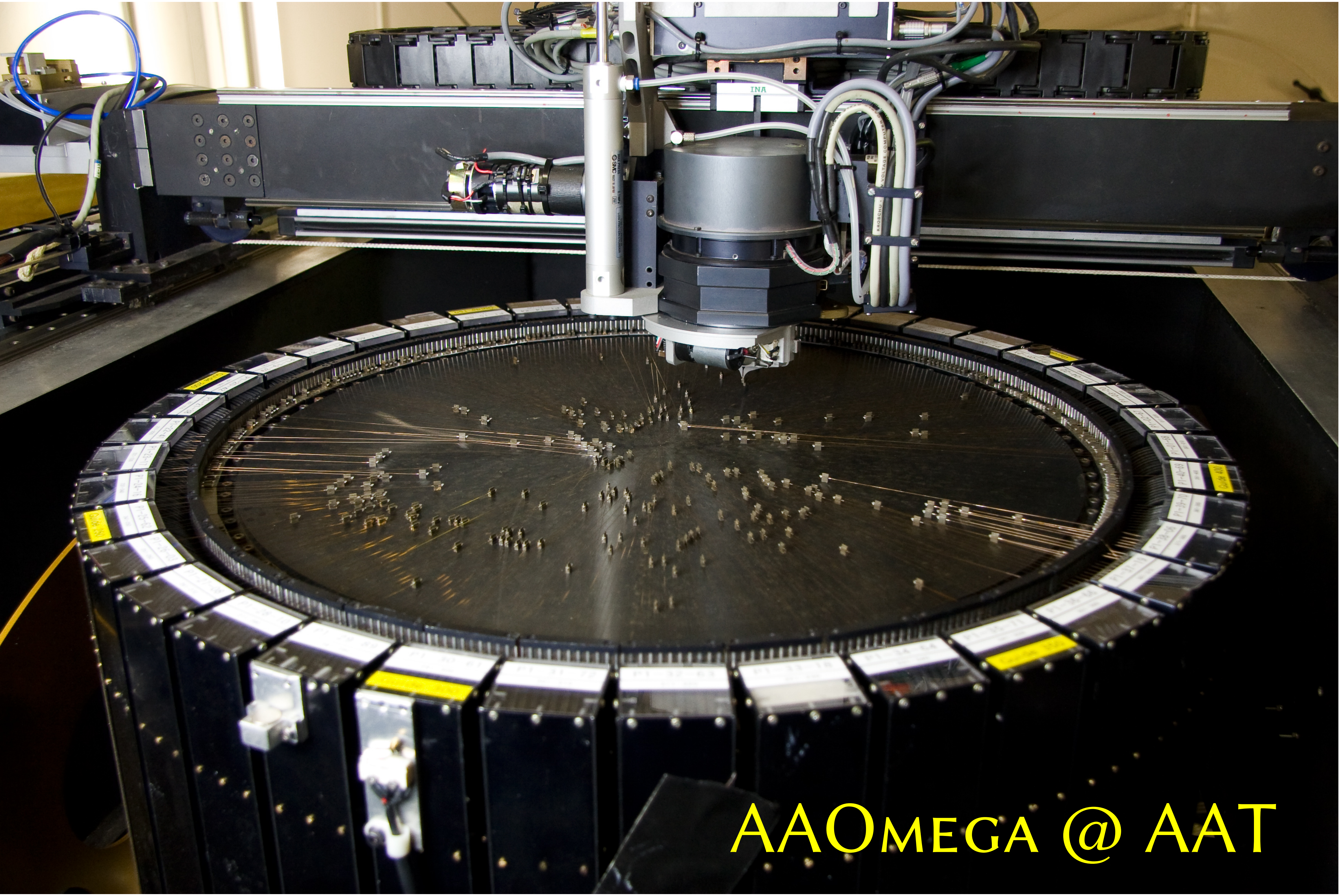
Dark Energy Camera

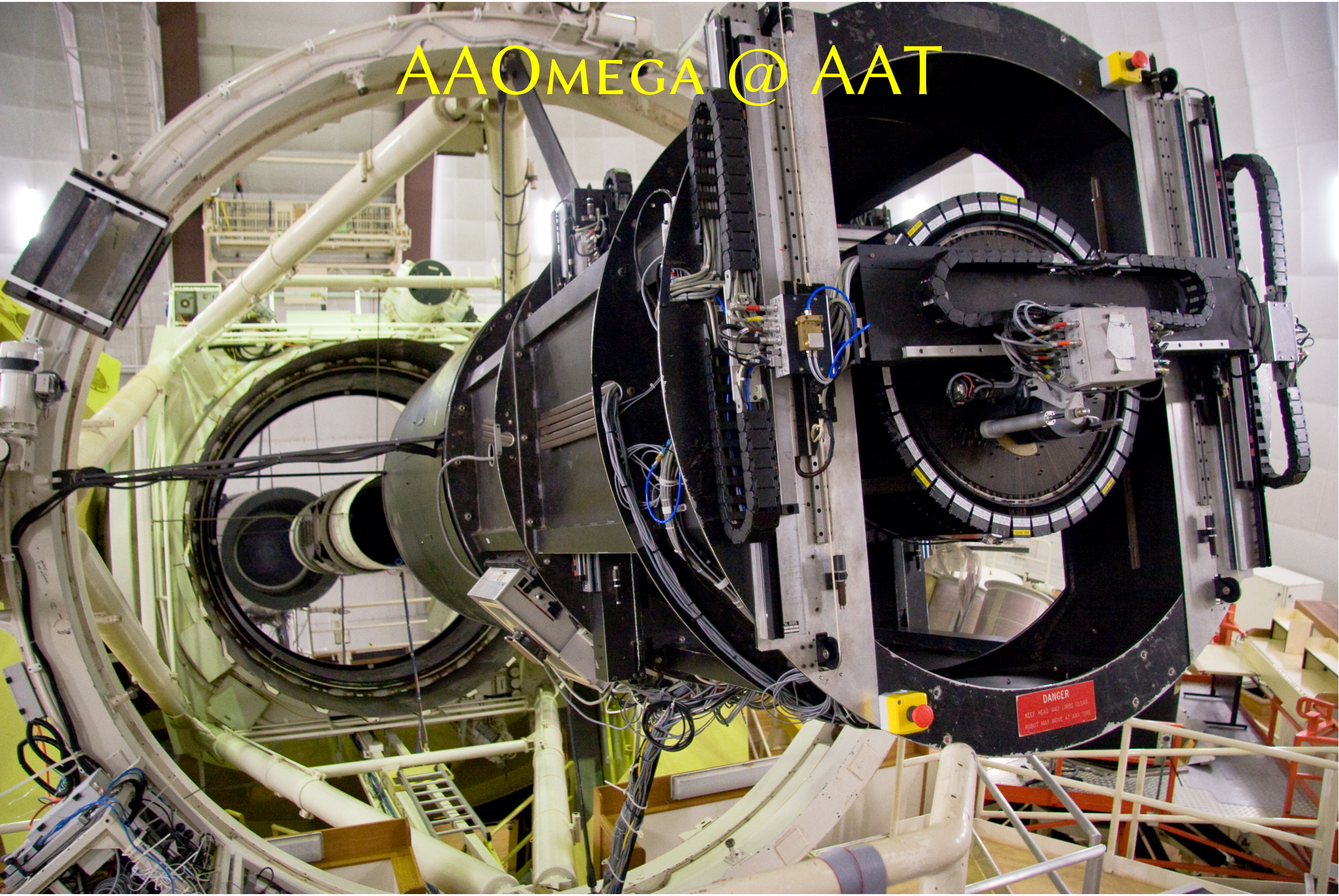


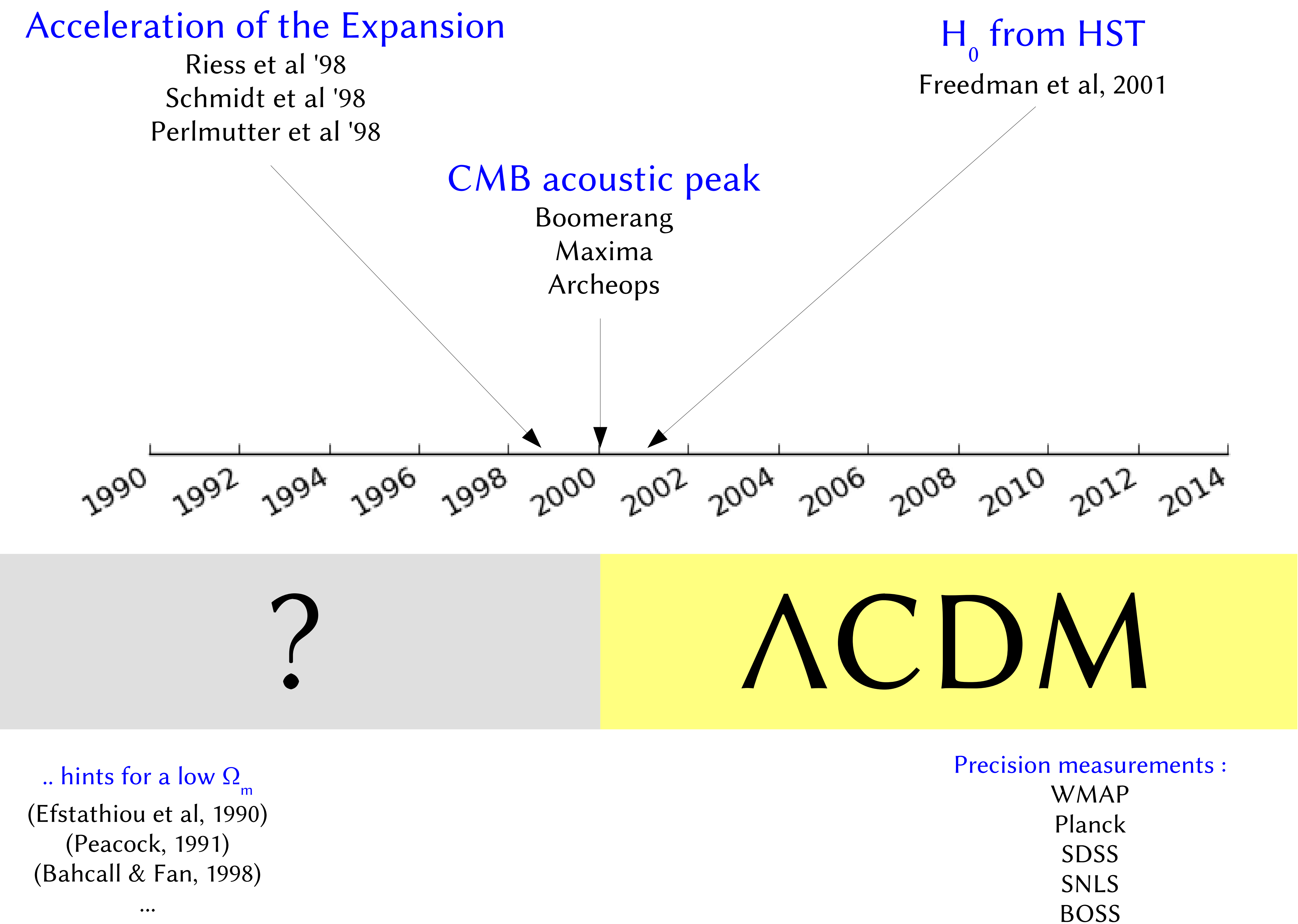


See talk by
M. Soares-Santos


AAOmega @ AAT

AAOmega @ AAT




Acceleration of the Expansion
Riess et al '98
Schmidt et al '98
Perlmutter et al '98
CMB acoustic peak
Boomerang
Maxima
Archeops
H0 from HST
Freedman et al, 2001
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
?
ΛCDM
.. hints for a low Ωm
(Efstathiou et al, 1990)
(Peacock, 1991)
(Bahcall & Fan, 1998)
...
Precision measurements :
WMAP
Planck
SDSS
SNLS
BOSS

6 PARAMETERS ONLY …

$\Omega_b h^2$

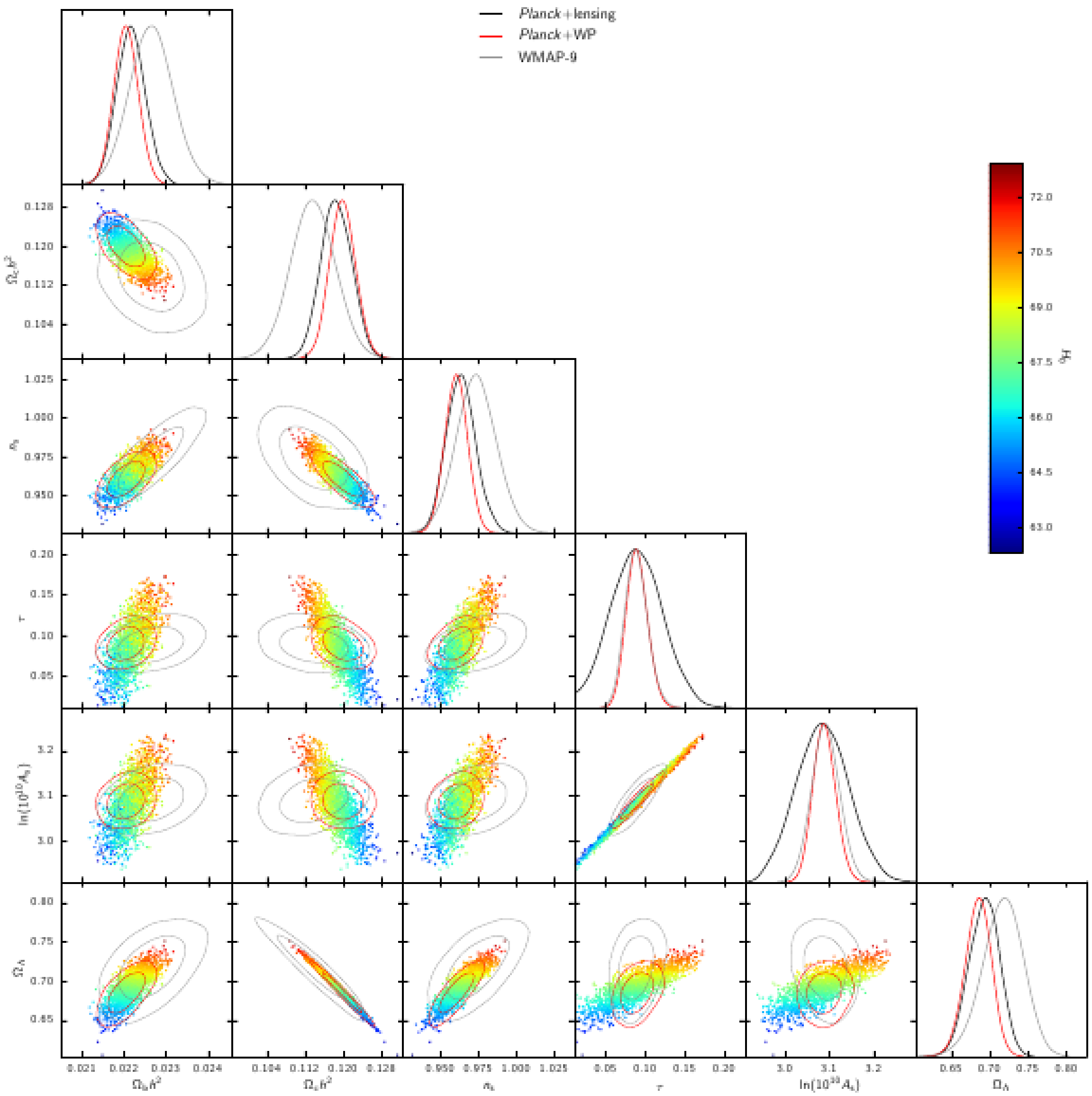
$\Omega_c h^2$

n_s

τ

$\ln\left(10^{10} A_s\right)$

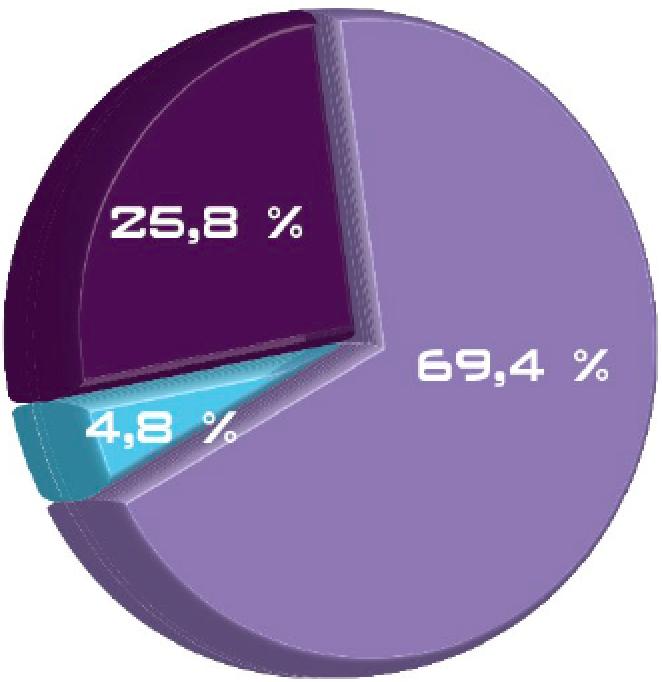
Ω_Λ



(Planck collaboration XVI)

+ extensions (w, Ω_K, …)

… BUT A RATHER STRANGE BREW …



Dark Energy	**69.4%**
Dark Matter	**25.8%**
Baryons	**4.8%**

- Nature of Dark Energy ?
  - Equation of state

$$p = w(z) \times \rho$$

OR

  - Growth rate of structure

$$f = \Omega_m^{\gamma}(z)$$

0.55 (GR)

Probes

- The smooth Universe
  - Type Ia Supernovae
  - Baryon acoustic oscillations

"0th order cosmology"
Kinematic probes

- Inhomogeneities
  - Clusters
  - Lensing by Large scale structures
  - Redshift space distorsions

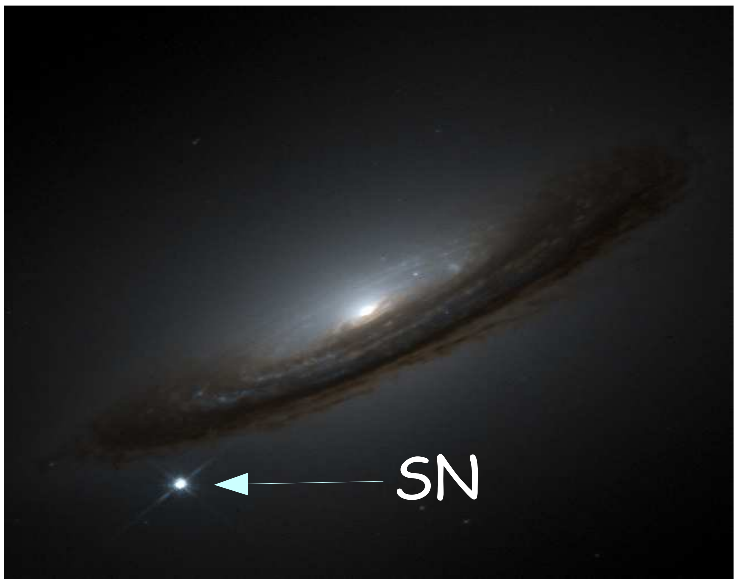
"1st order cosmology"
Dynamical probes

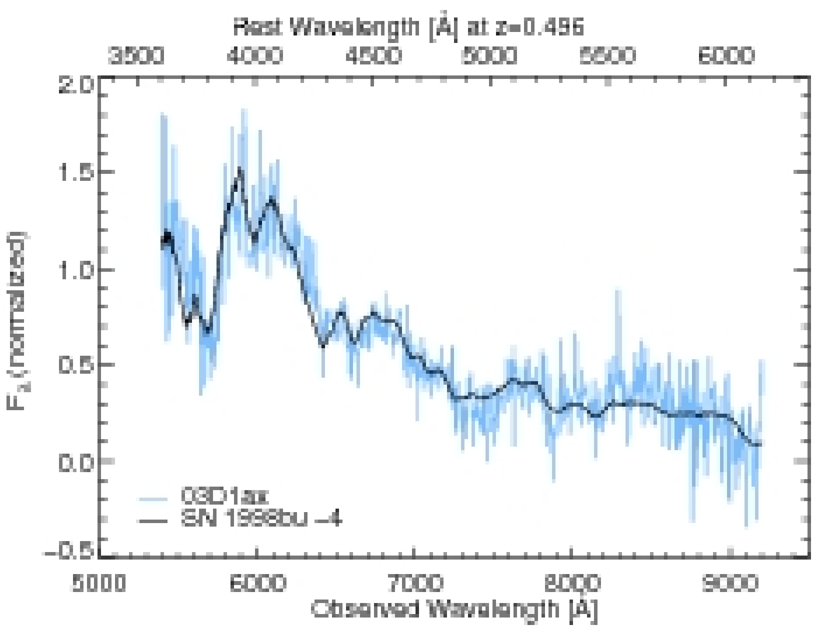
Type Ia Supernovae

See talk by
P. El-Hage

(Image by D. Dixon)

Type Ia Supernovae



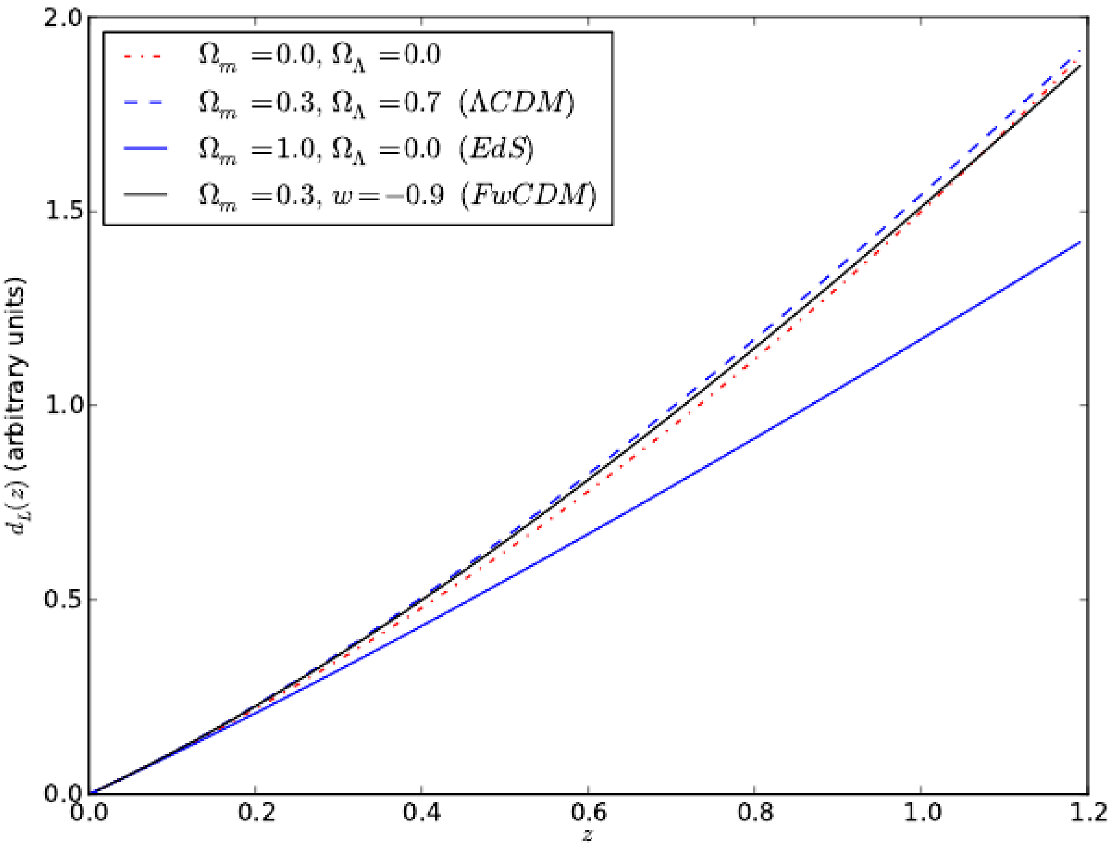


- Thermonuclear explosion of WD
  - Rare events (~1 / Gal / 1000 yr)
  - Very bright (~10^{10} solar luminosities)
  - Transients (~ 1 month)
  - $\sigma(L_{MAX})$ ~ 40%

Standardizable ⟶ σ(Lmax) ~ 15%

- Spectroscopy
  - ➔ Identification (broad features)
  - ➔ Chemical composition & velocities

Standard Candles in Cosmology



→ 1 constraint

- Observables:
  - Redshift $z = \delta\lambda/\lambda$
  - Apparent flux
- Standard candles

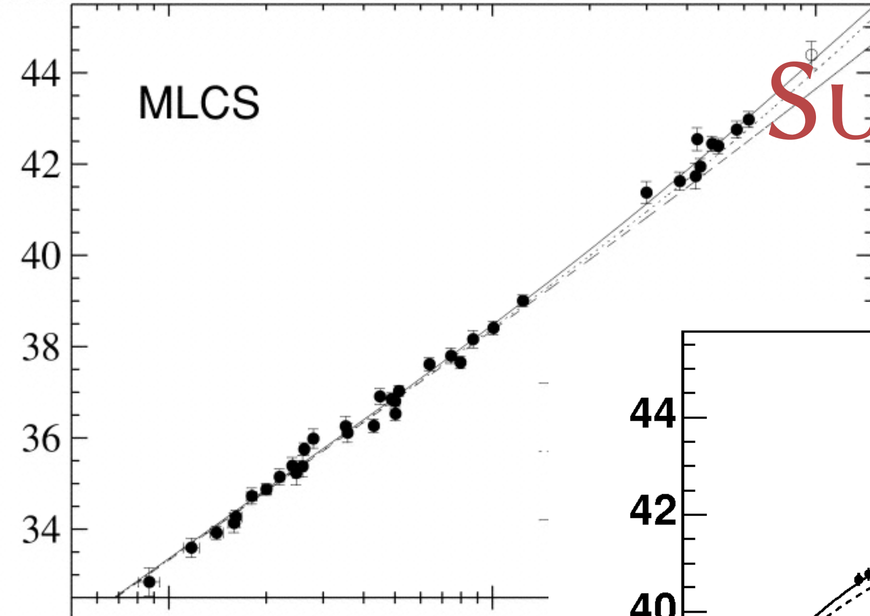
  $f = L / 4\pi\, d_L^2(z)$

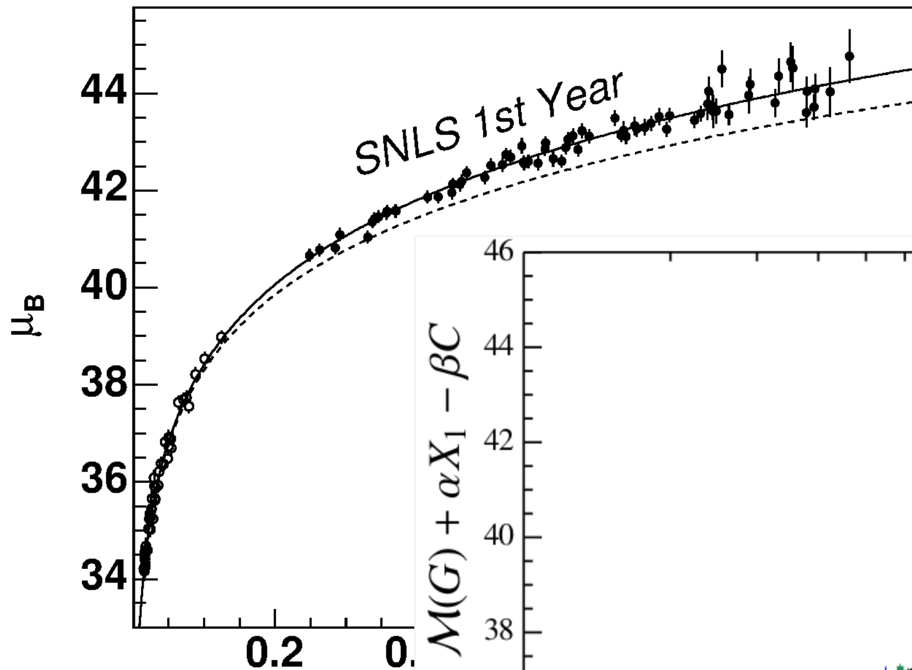
- $d_L(z)$ ⟶ integrated history of the expansion

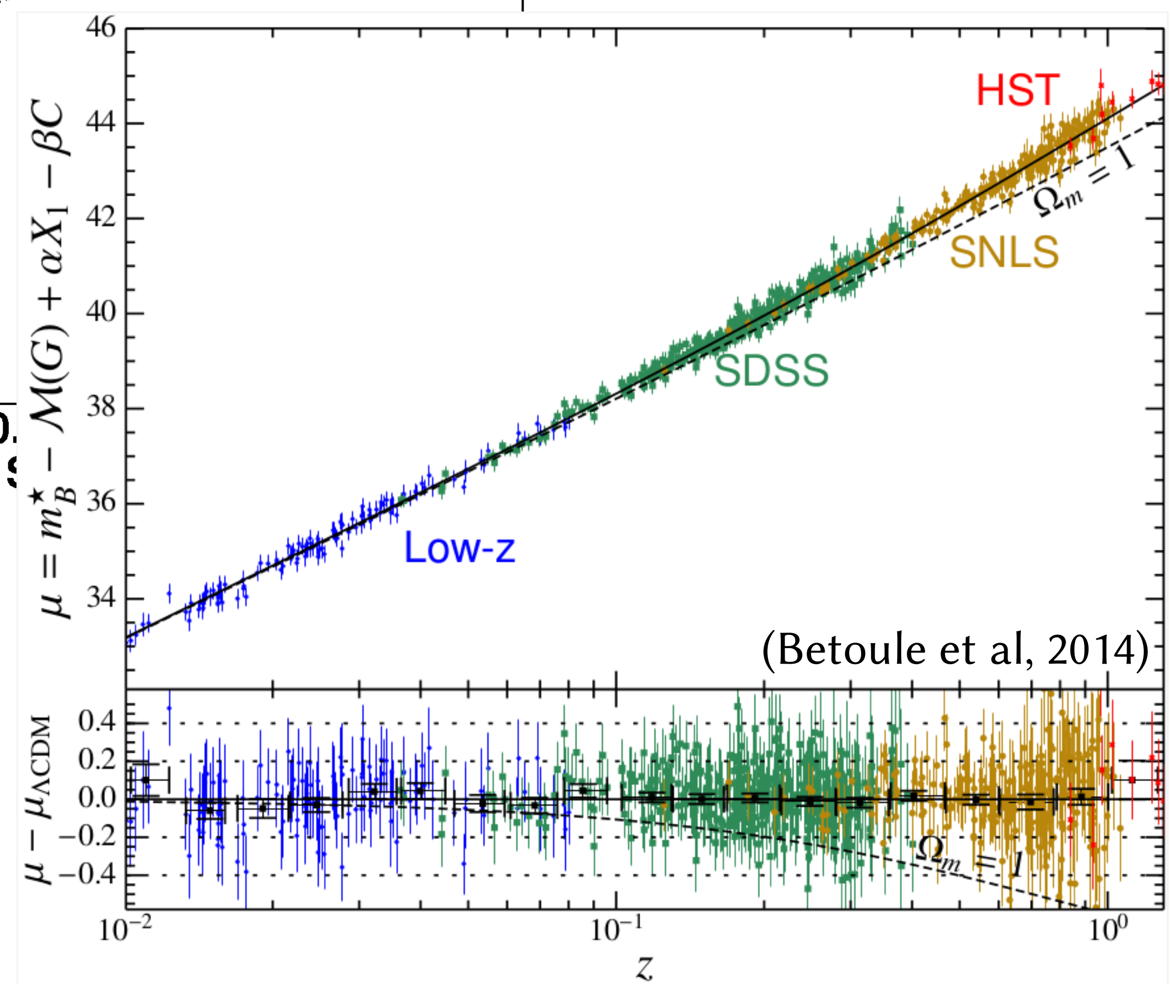
$$\propto \int \frac{dz}{H(z)}$$

$$d_L(z) = (1+z)\frac{c}{H_0}\int dz' \left(\Omega_m(1+z)^2 + \Omega_k(1+z)^2 + \Omega_X \exp\left(\int_0^z 3\frac{1+w(z')}{1+z'}dz'\right)\right)^{-1/2}$$

Supernovae

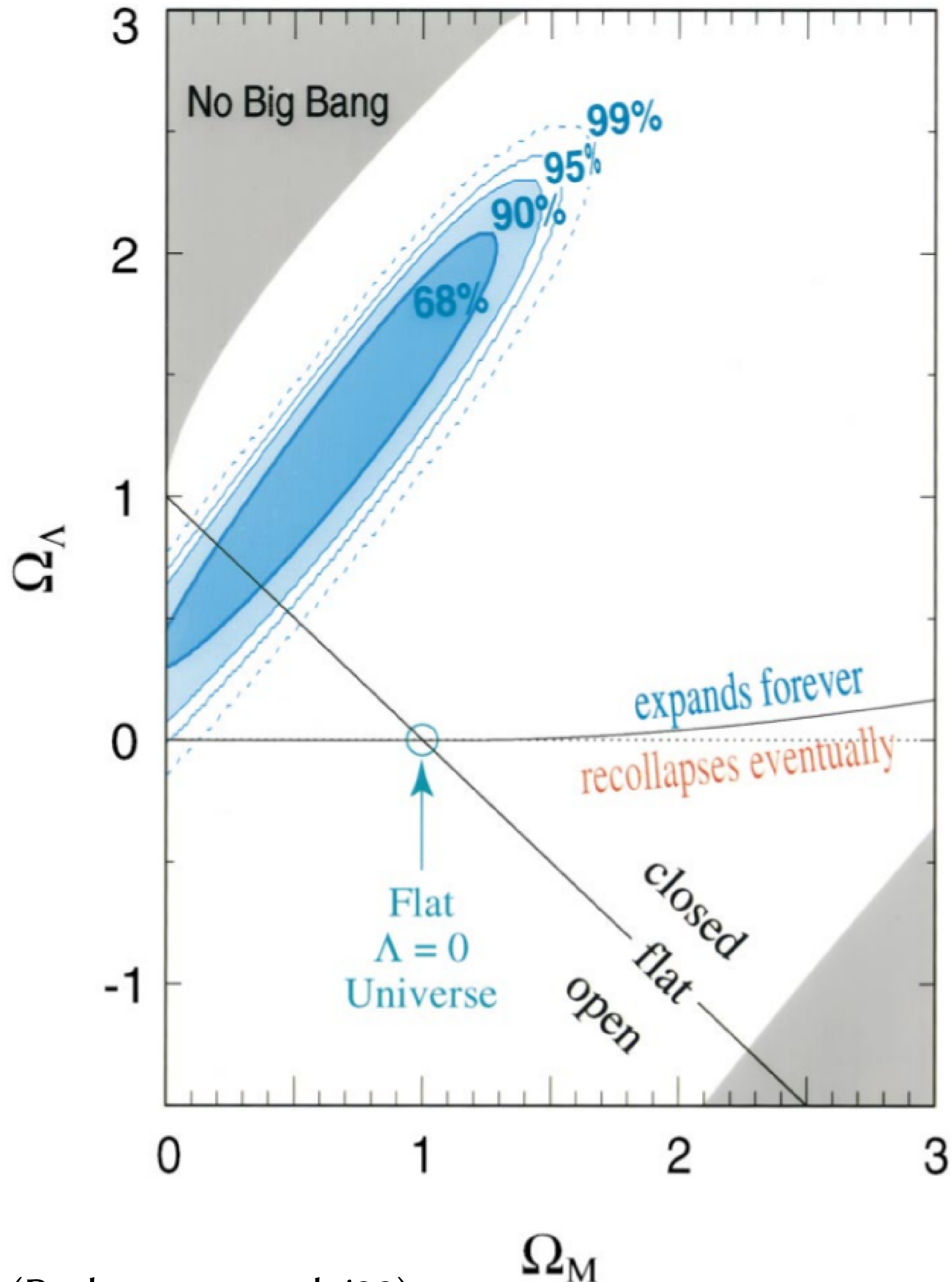




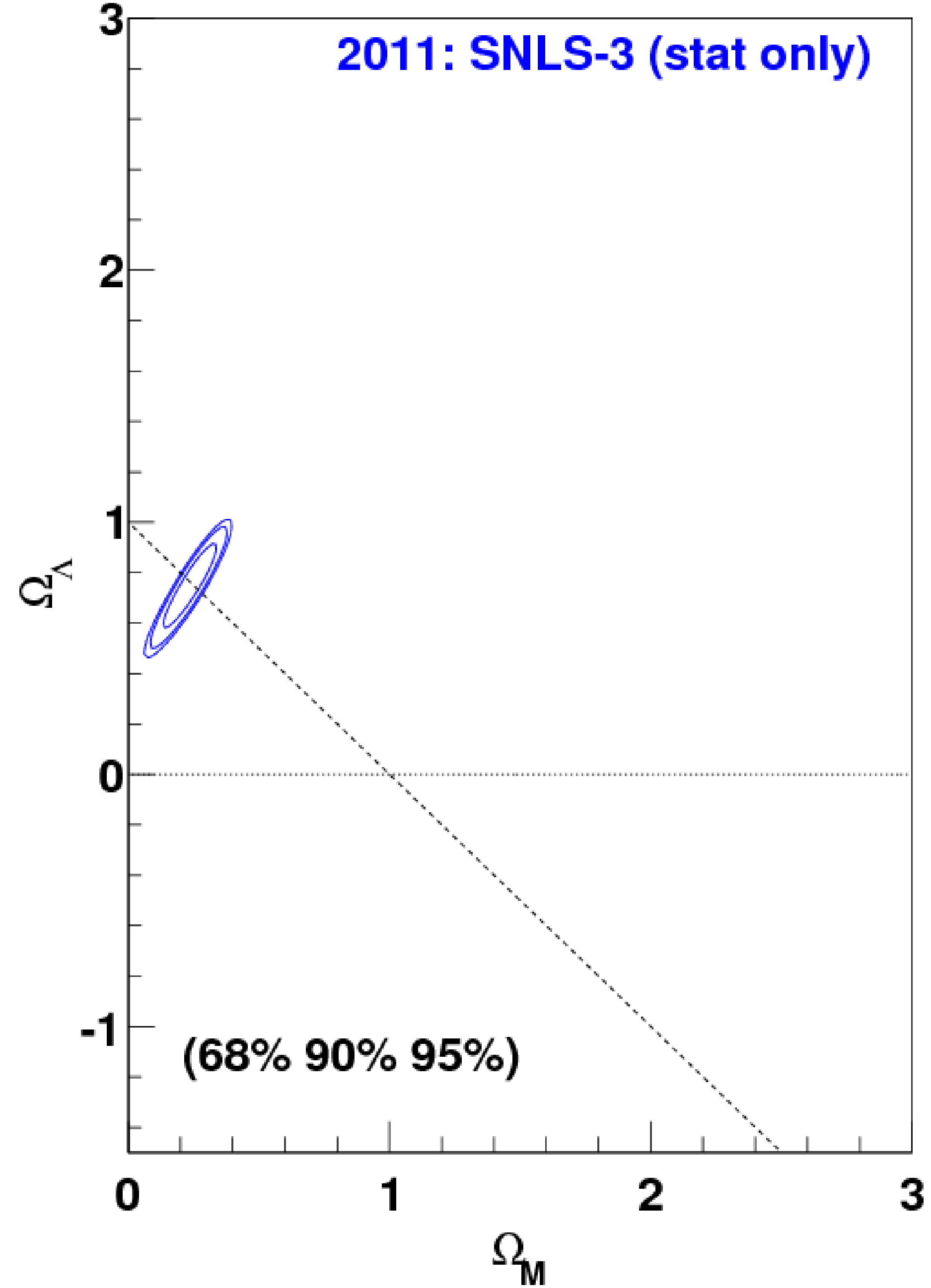


- 1998 : O(50) SNe
- 2005 : O(100) SNe
- 2014 : O(1000) Sne

(x 20 in statistics)

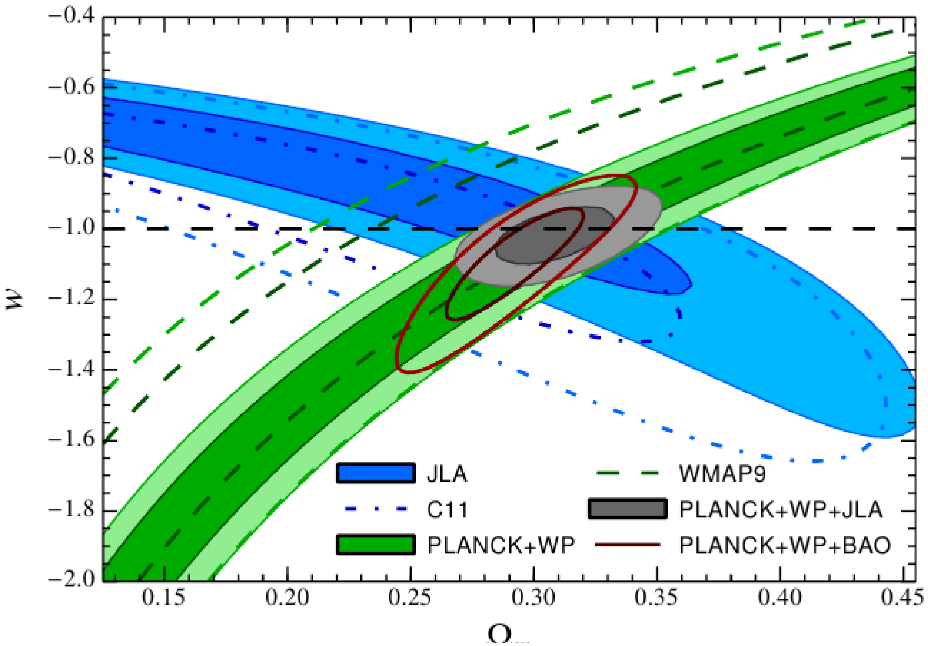


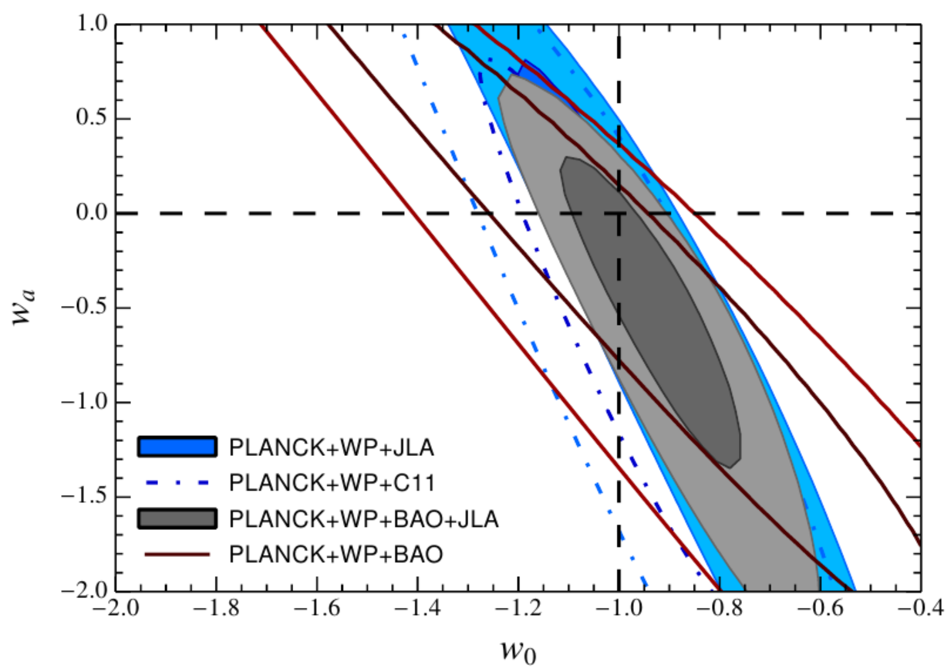
(Perlmutter et al, '99)



(Conley et al, '11, Sullivan et al, '11, Guy et al '10)

CURRENT CONSTRAINTS ON W





- Planck + SNe Ia

$$w = -1.018 \pm 0.057$$

- FoM ~ 30 (SNe + Planck + BOSS)

- Note : Planck + BAO

$$w = -1.01 \pm 0.08$$

(see also Suzuki et al '12,
Rest et al '13, Scolnic et al '13...)

Systematics

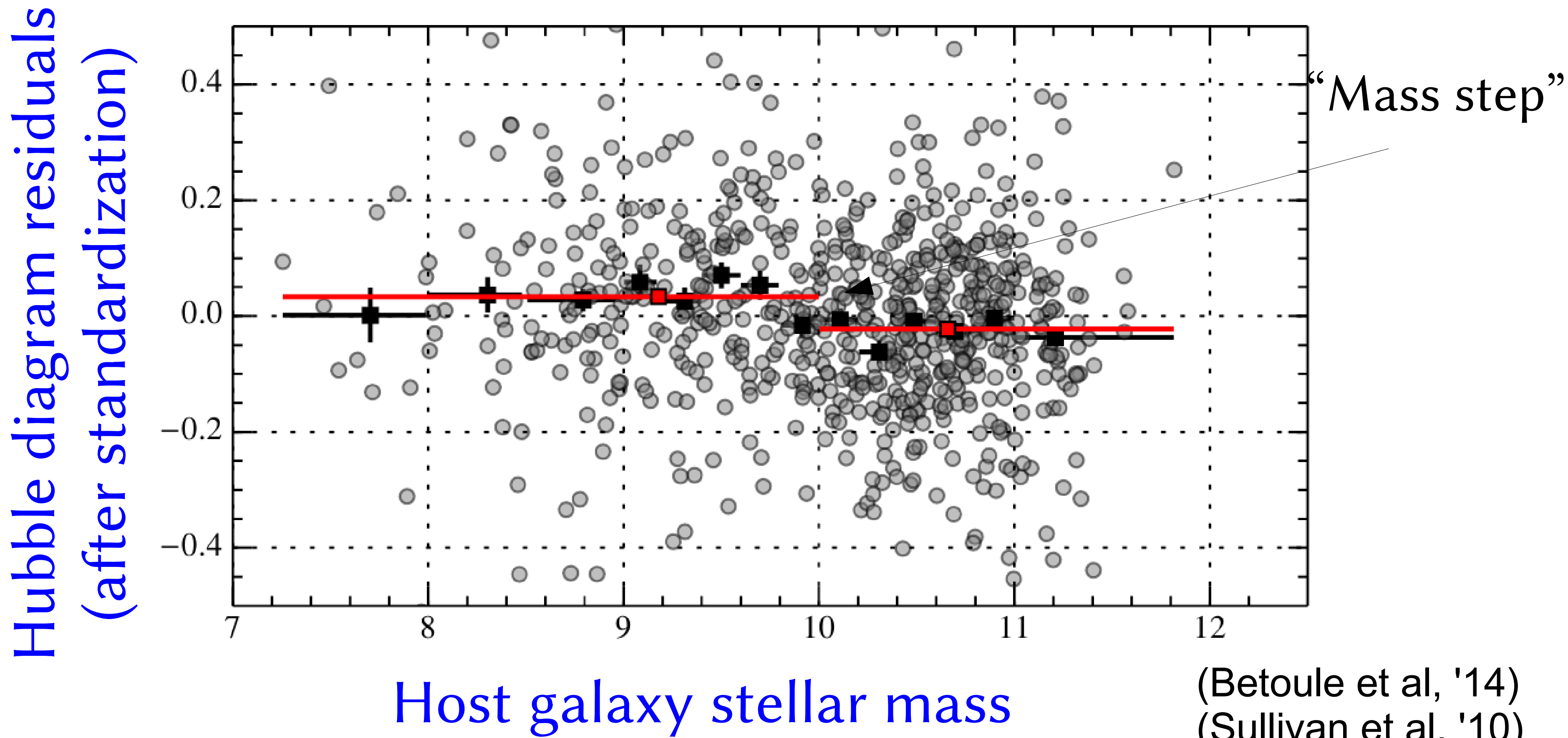
Uncertainty sources	$\sigma_x(\Omega_m)$	% of $\sigma^2(\Omega_m)$
Calibration	0.0203	36.7
Milky Way extinction	0.0072	4.6
Light-curve model	0.0069	4.3
Bias corrections	0.0040	1.4
Host relation[a]	0.0038	1.3
Contamination	0.0008	0.1
Peculiar velocity	0.0007	0.0
Stat	0.0241	51.6

(Betoule et al, 2014)

Photometric calibration (still) dominates

the systematic uncertainty budget.

Astrophysical systematics

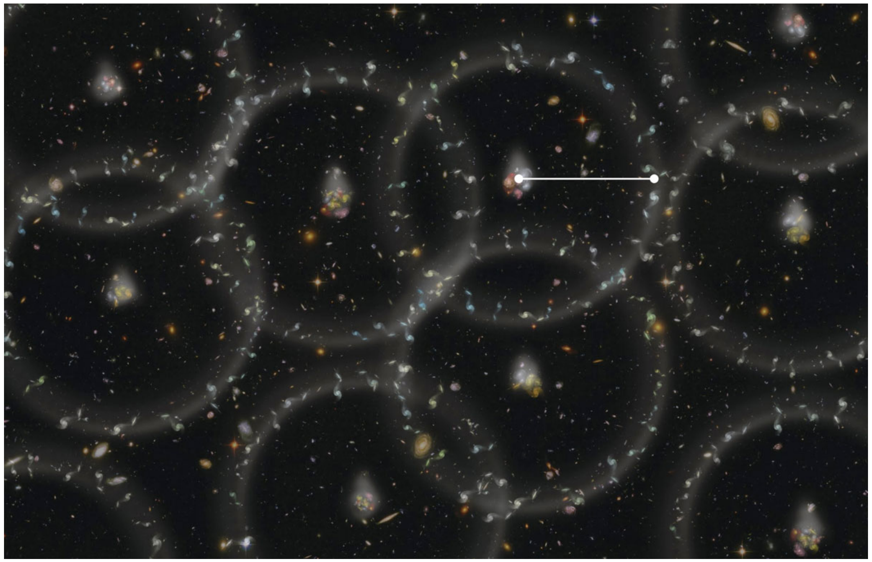


(Betoule et al, '14)
(Sullivan et al, '10)

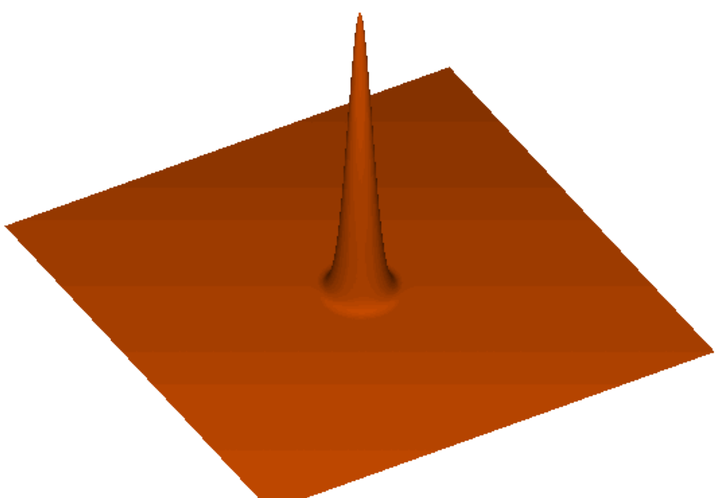
- Astrophysical systematics
  - 2 populations + evolving demographics ?
  - Absorbed into 1 additional parameter

Baryon acoustic oscillations

= 147.5

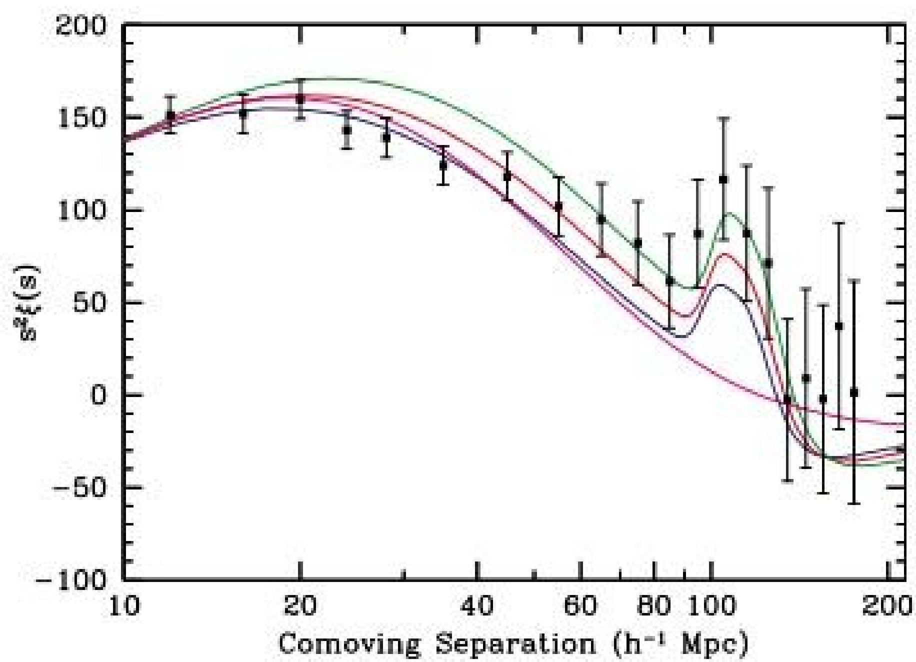


Credit: Zosia Rostomian, LBNL



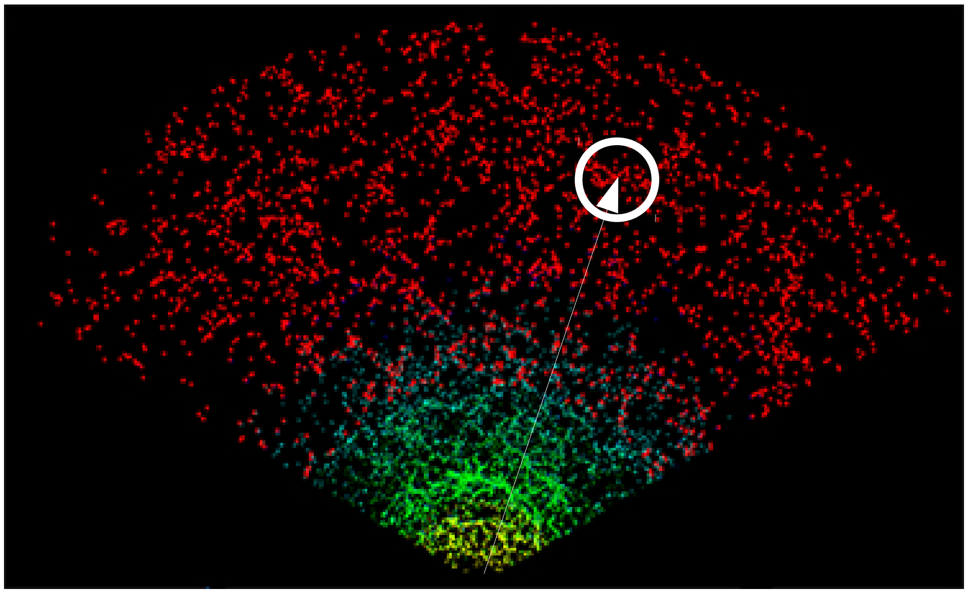
- Oscillations in primordial plasma
  - $r_s = \int_0^{t_\star} \frac{c_s(t)}{a(t)} dt$ = 147.5 ± 0.6 Mpc

(Planck Coll XVI)



(Eisenstein et al, '05 Cole et al '05)

Baryon acoustic oscillations

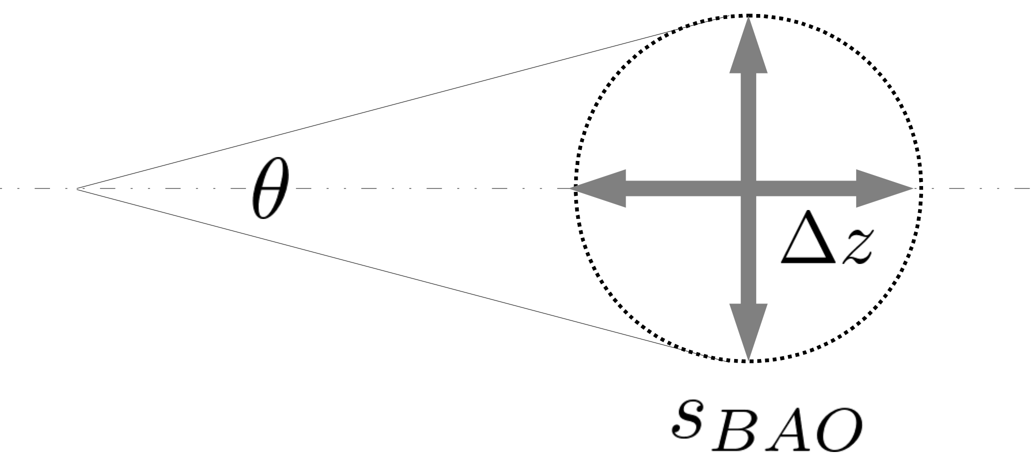


- Transverse direction

$$s_{BAO\perp} = (1+z)D_A(z)\Delta\theta$$

- Parallel direction

$$s_{BAO\parallel} = \frac{c}{H(z)}\Delta z$$



- "Angle averaged" ruler

$$D_V = s_{BAO} \times \left(D_A^2 \frac{cz}{H}\right)^{1/3}$$

- with more statistics

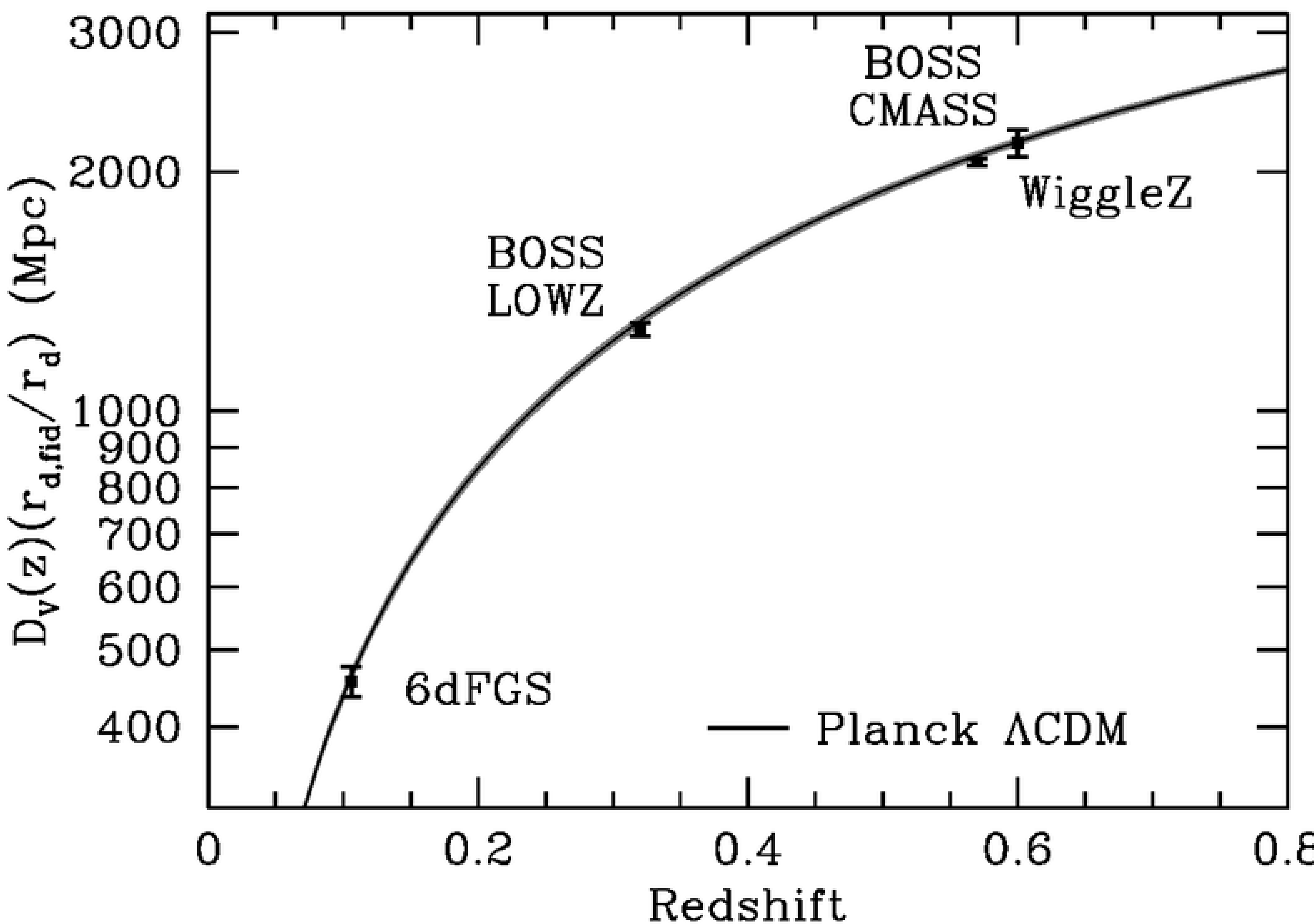
  → separate D_A(z) & H(z)

Baryon acoustic oscillations

- Geometric measurement
- *Absolute* angular distances (r_s is known)
- Sensitivity to H(z)
- Measurable wherever there are baryons
  - (Galaxies, Ly-α forest, quasars…)

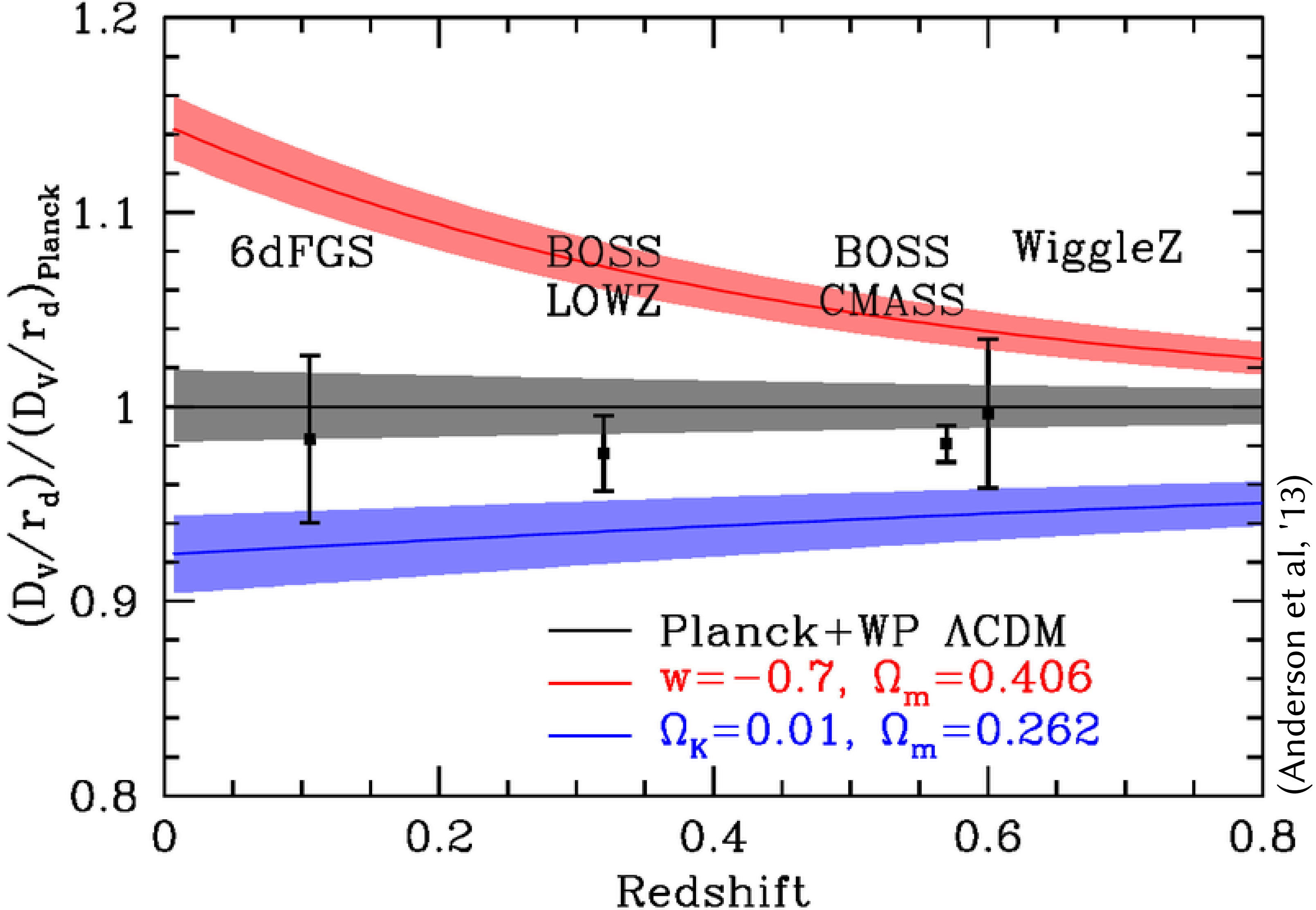
- Expensive probe : millions of redshifts needed
- Cosmic variance at low redshift

BAO Hubble diagram



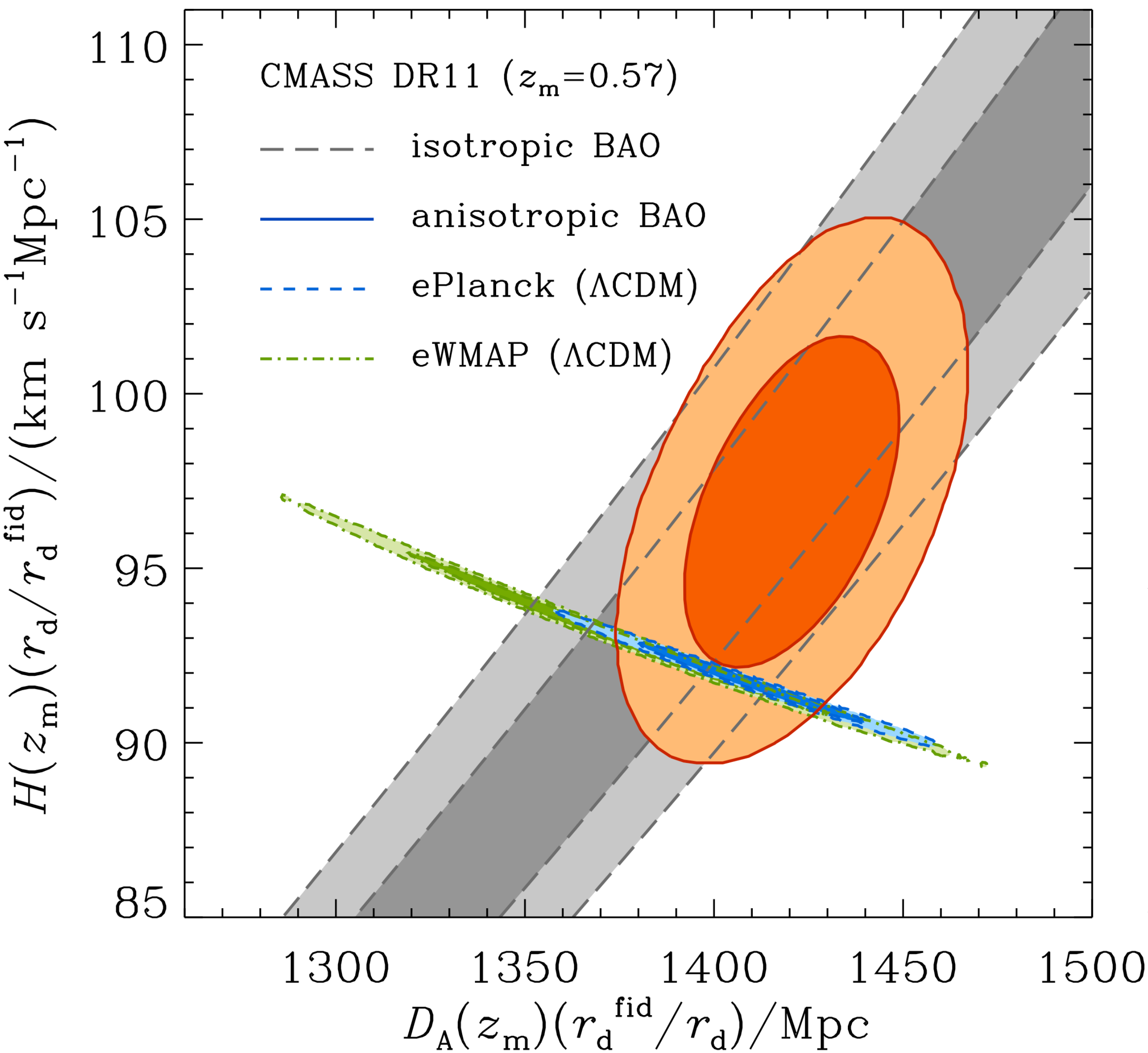
(Anderson et al, '13)

Sensitivity to cosmology



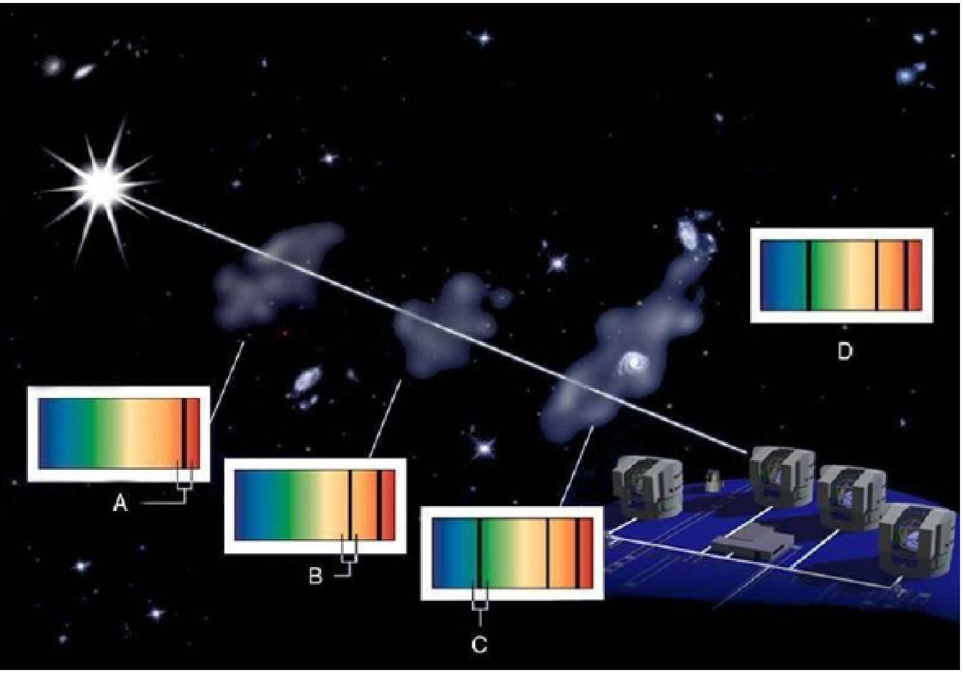
- Constrains extensions of ΛCDM. Sensitive to w and curvature.

Disentangling H(z) & $D_A(z)$



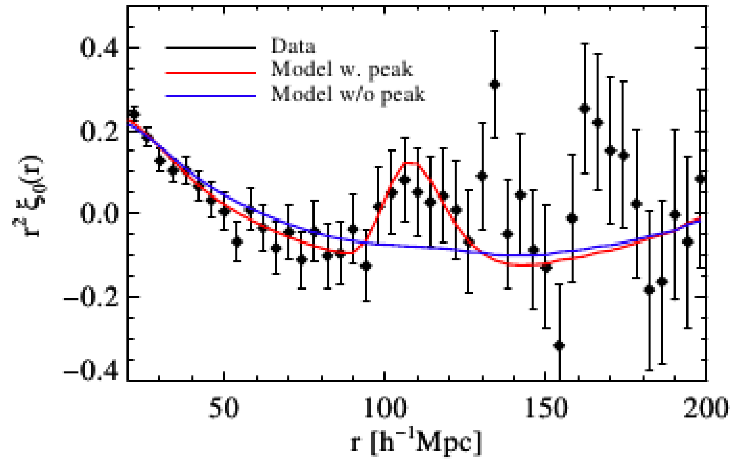
(Anderson et al, '13)

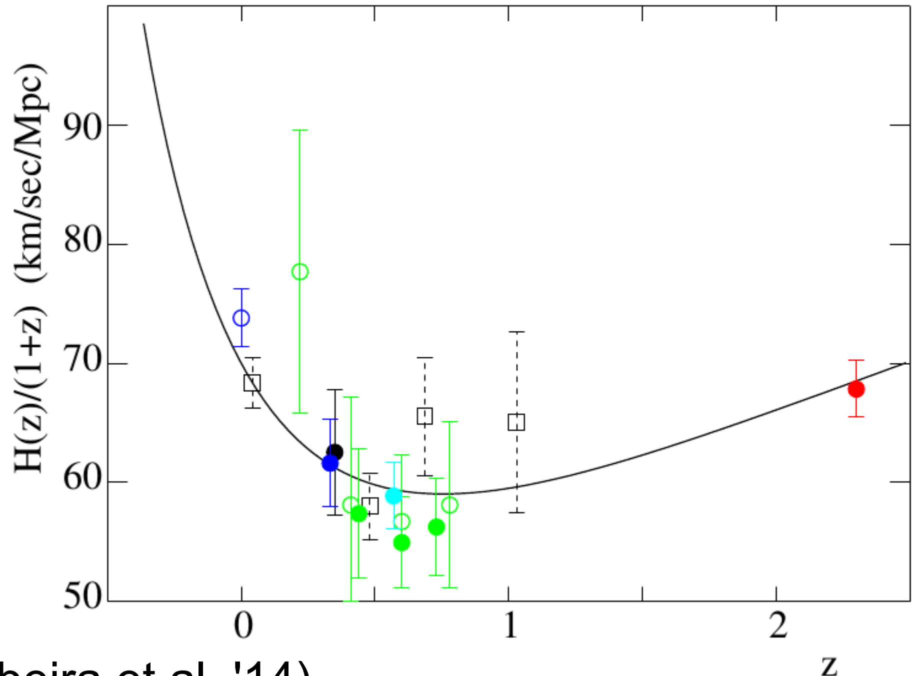
BAO in the Ly-α Forest



- Background quasars
- Light travels through the intergalactic medium (ionized H)
- Ly-α, absorption line

$\lambda = 1215\text{Å}$





(See e.g. Busca et al, '12, Slosar et al, '13, Font Ribeira et al, '14)

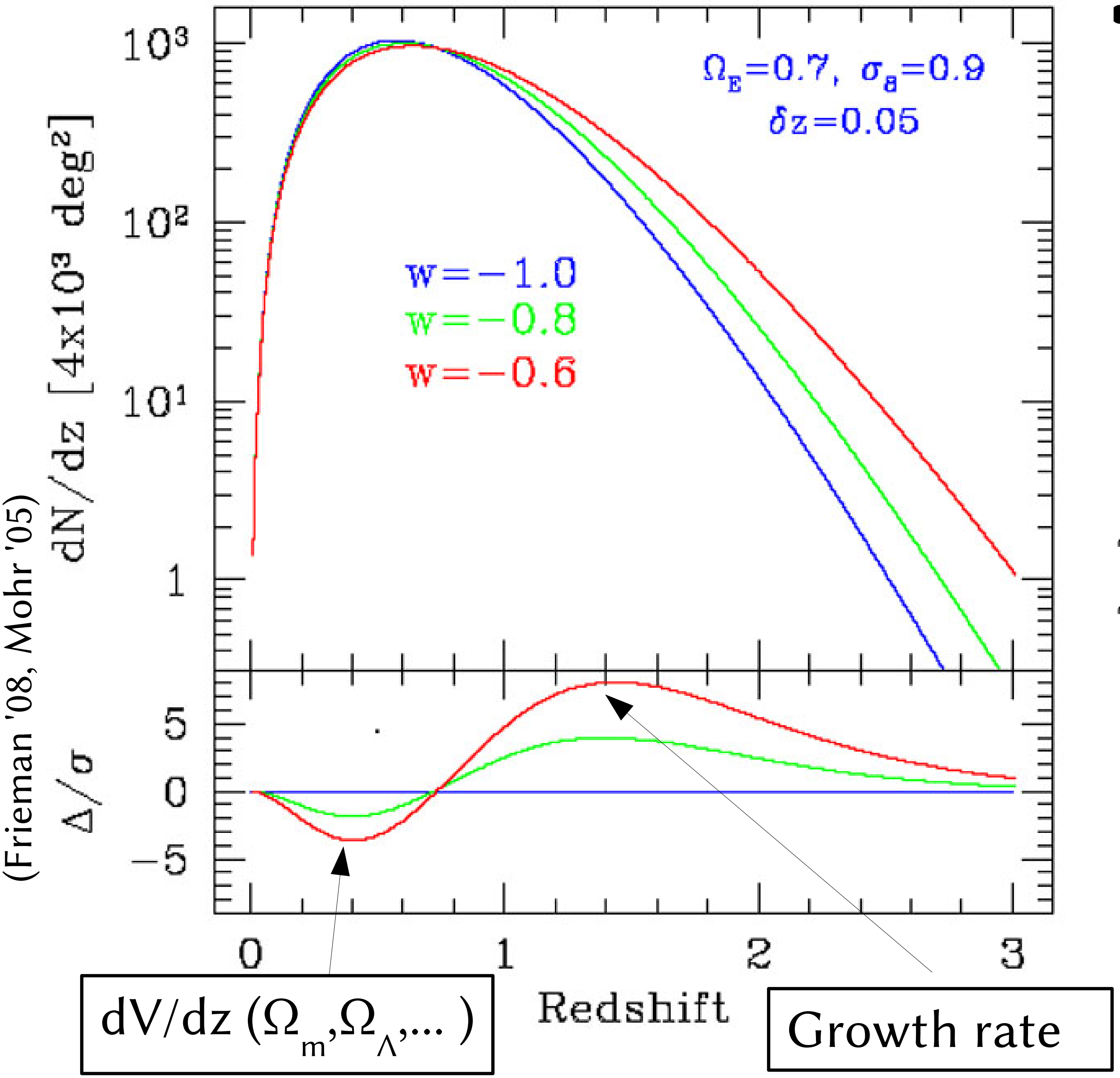
Galaxy clusters

X   Optical   SZ

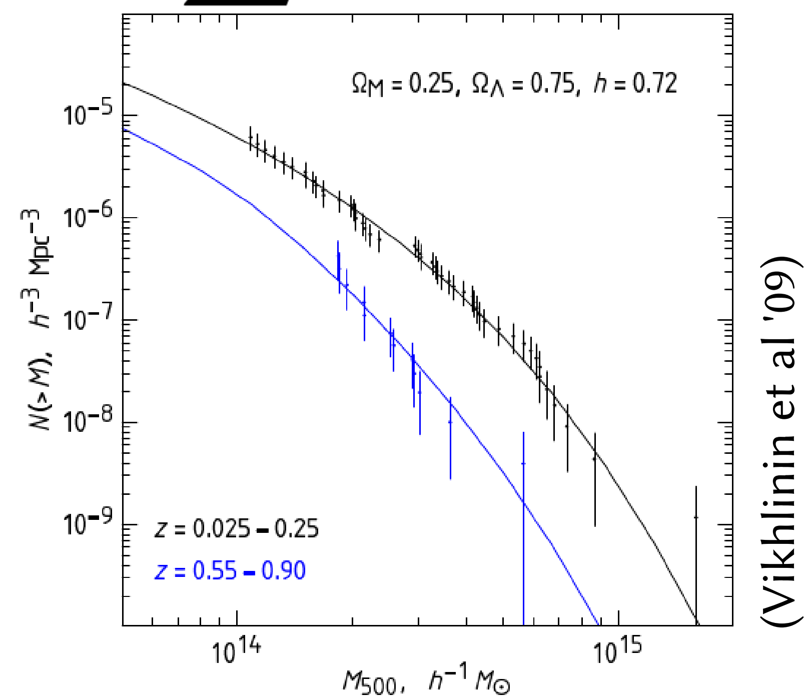
(Abell 1835, z = 0.25)

(Allen, Evrard, Mantz, '11)

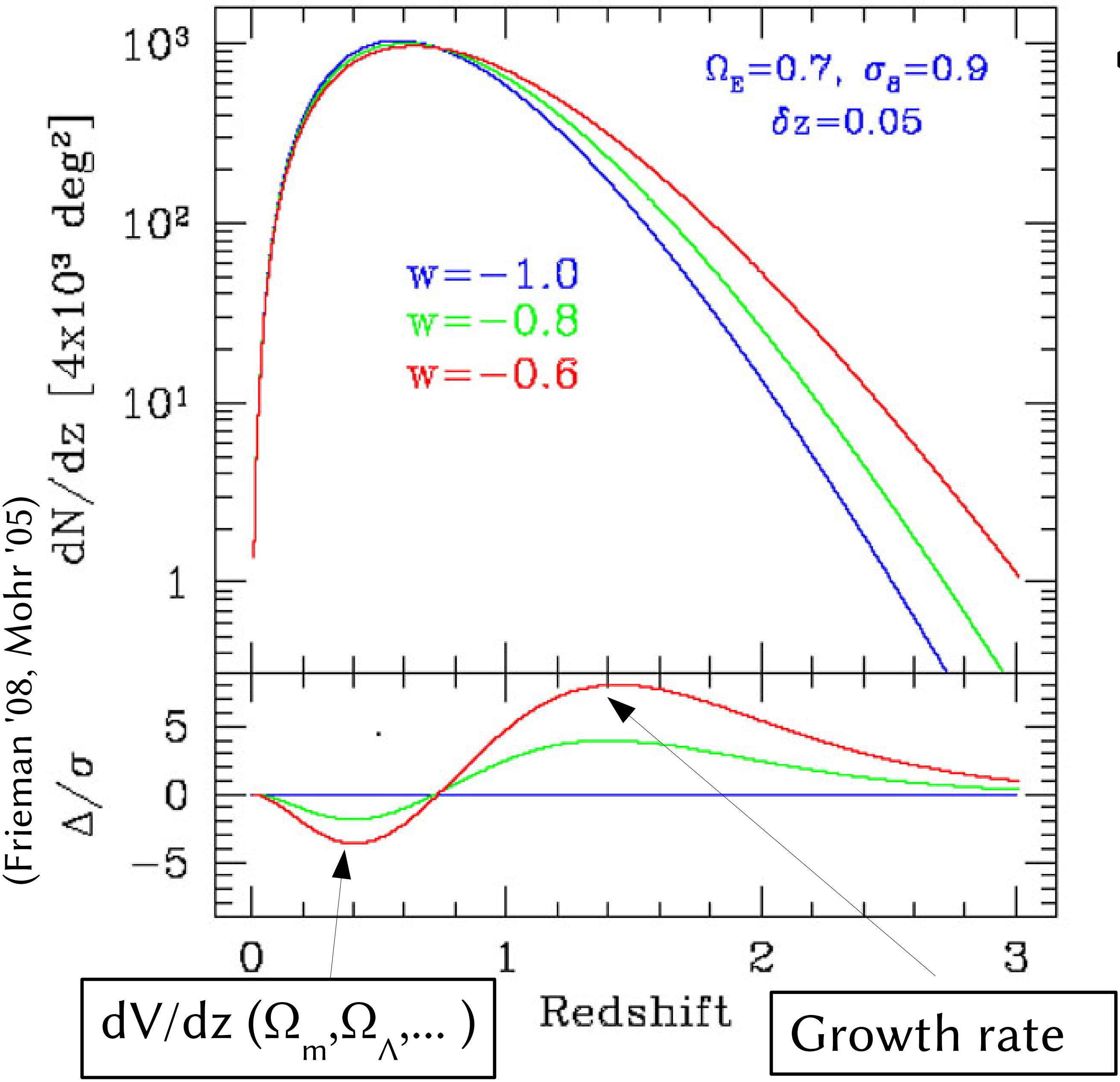
CLUSTERS



- Sensitive to
  - $\sigma_8 \times \Omega_m^\alpha \quad \Omega_\Lambda$
  - Growth of structure
  - $\sum m_\nu$



Clusters



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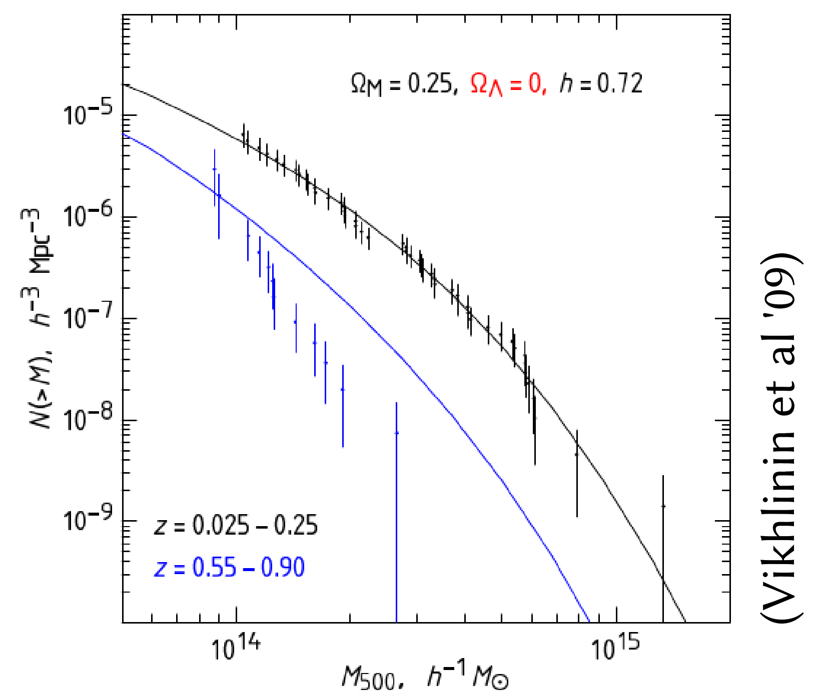
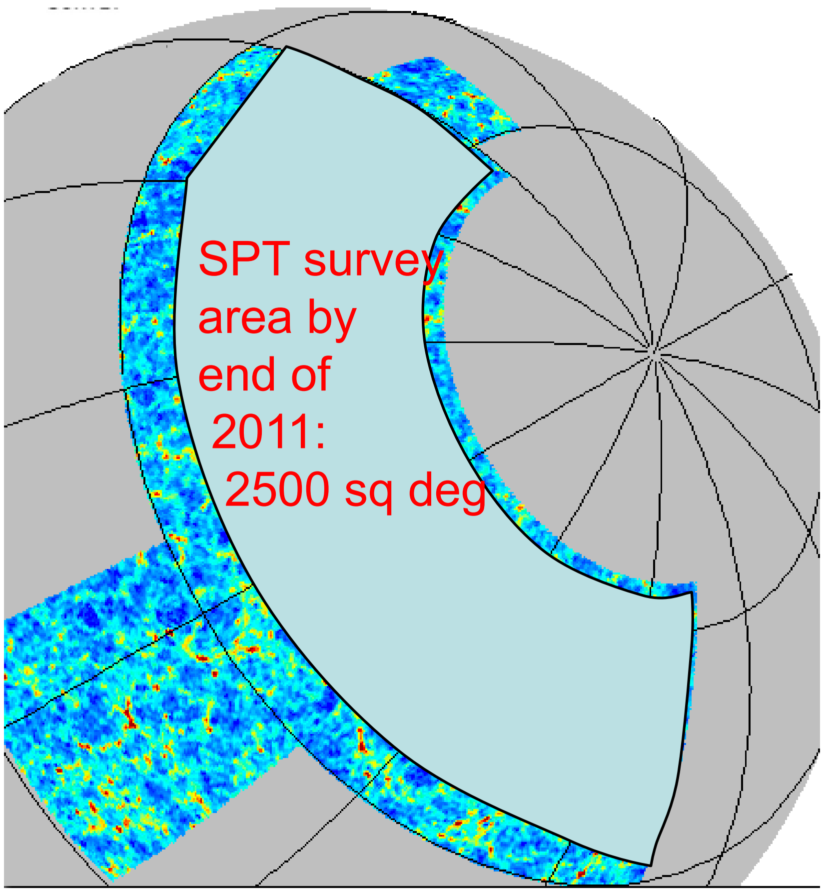


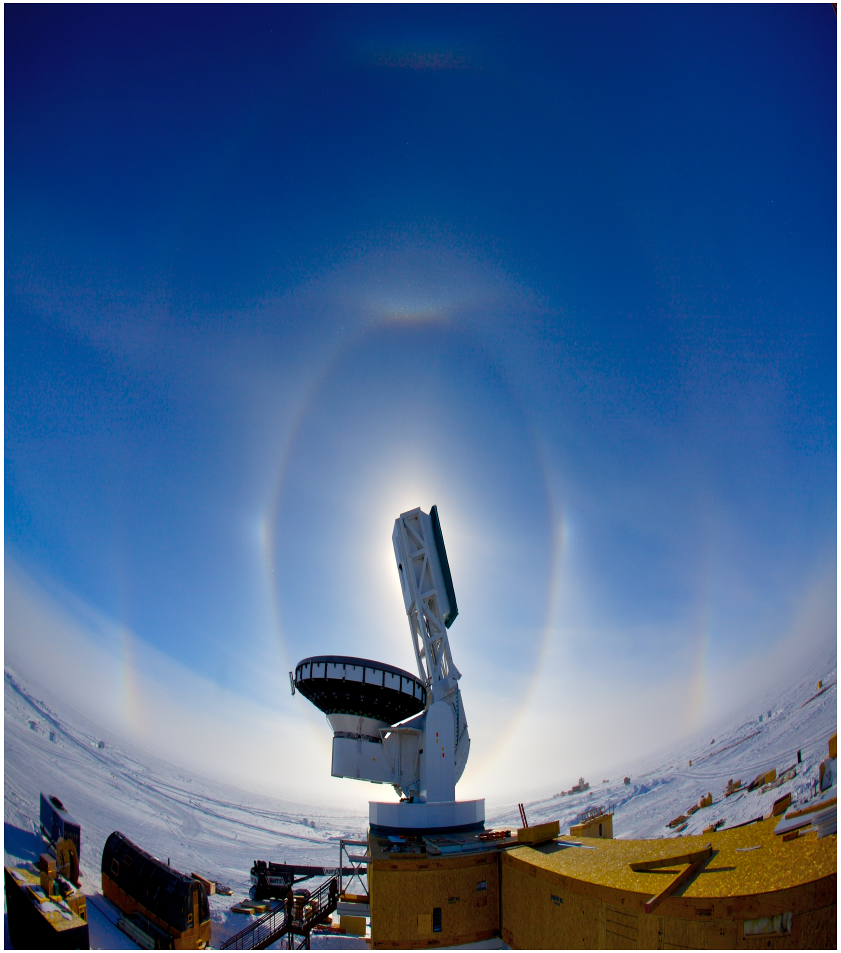
Detecting clusters



Optics → low masses

DES survey : ~ 5000 deg^2

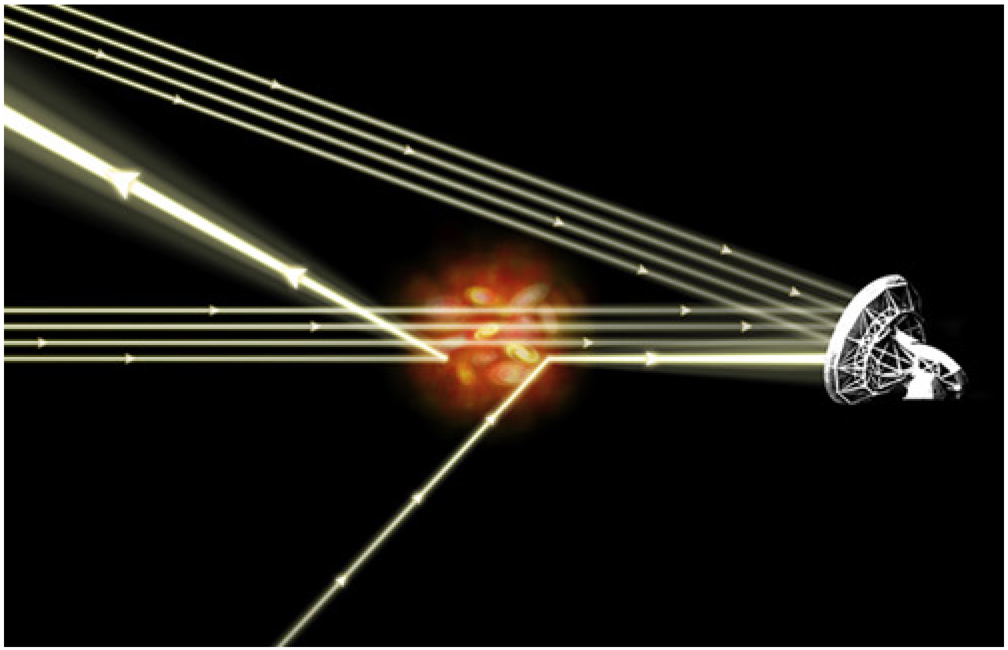
South Pole Telescope

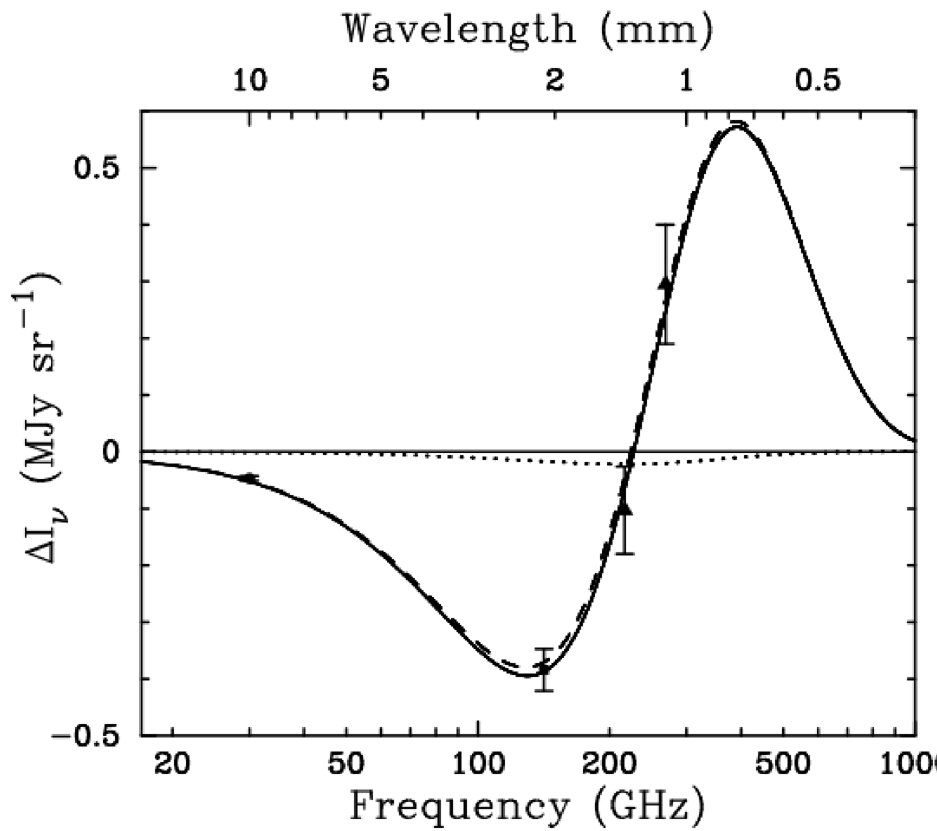


Microwave : SZ effect

SPT survey : ~ 2500 deg^2

SZ EFFECT





Inverse compton scattering on CMB
hot intracluster gas

→ cold spots in CMB @ orig freq

→ hot spots at higher freqs

Clusters counts

$$\frac{dN}{dz} = \Delta\Omega \frac{dV}{dz\,d\Omega} \int_{M_{\rm lim}}^{\infty} \frac{dN}{dV\,dM} dM$$

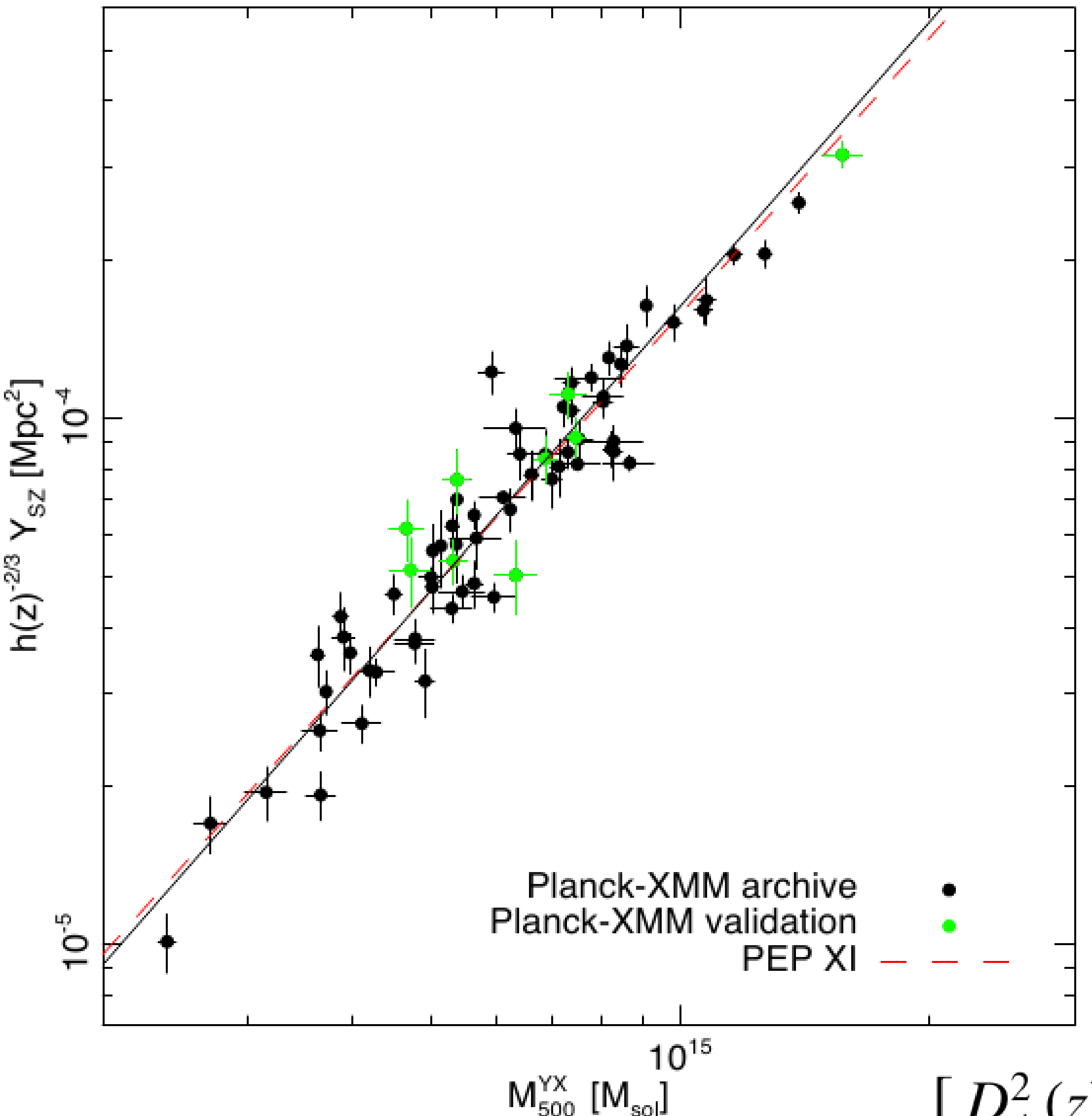
Survey Area

Cosmological Volume Element

Lots of astrophysics Hidden here

Cluster mass function

CLUSTER MASSES



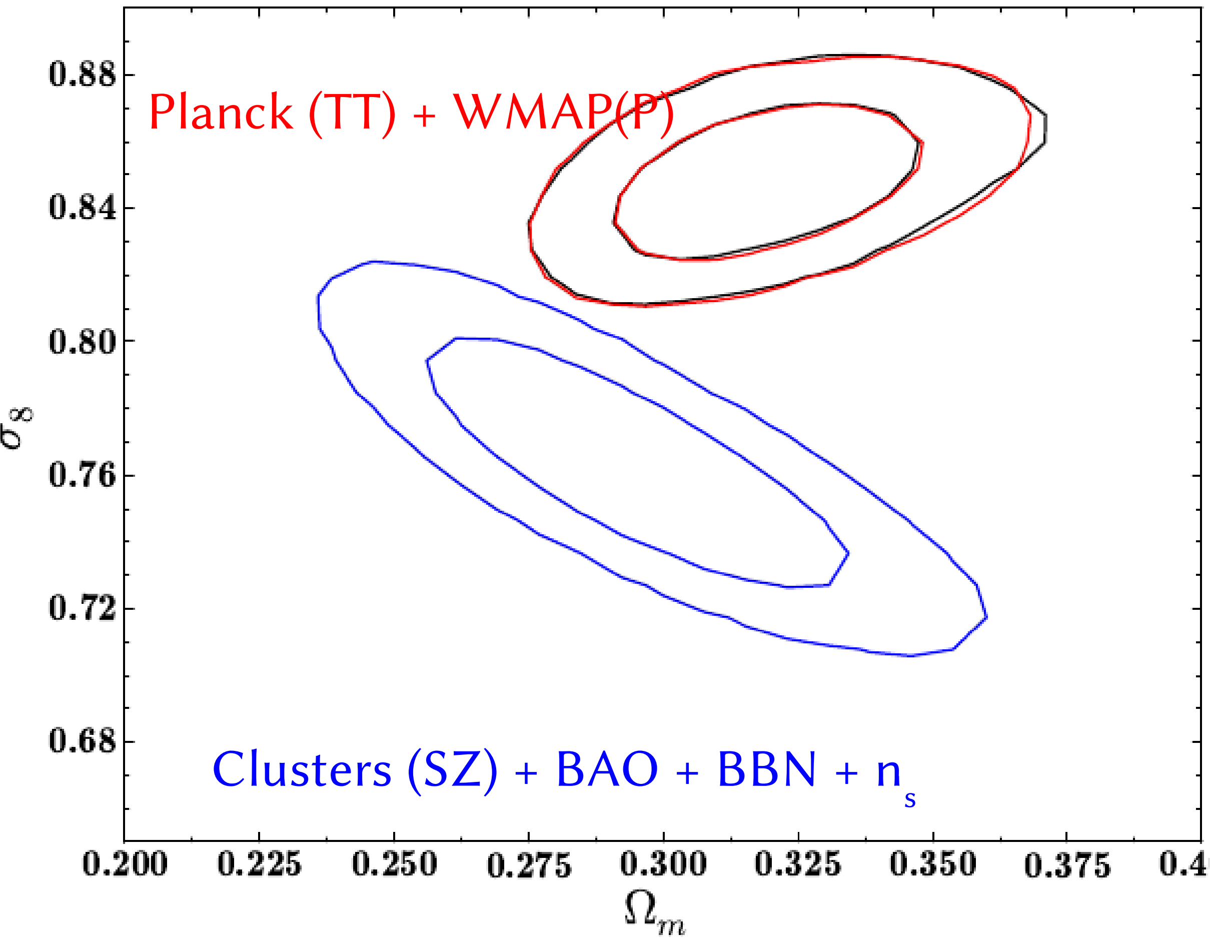
(Planck results 2013 XX)

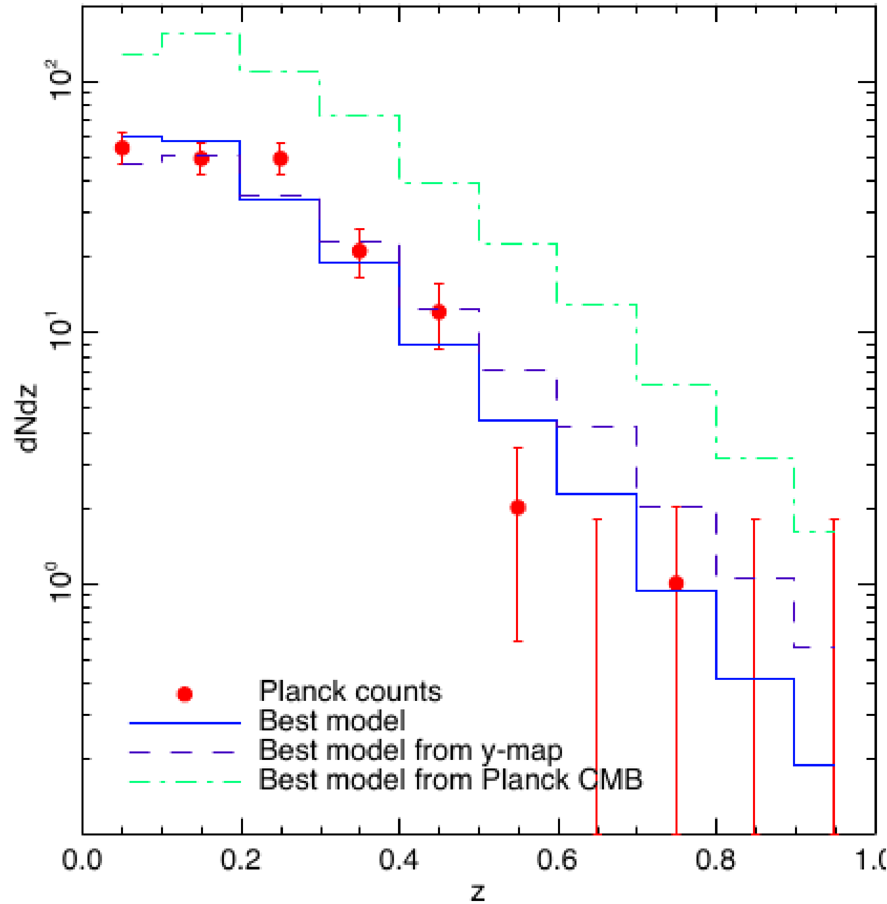
- Relate the mass of the clusters to an observable
  - SZ flux (Y)
  - X-ray ($Y_X = M_{gas} \times T_X$)
  - Lensing

Bias factor
true mass ↔ mass estimate

$$E^{-\beta}(z)\left[\frac{D_A^2(z)\,\bar{Y}_{500}}{10^{-4}\,\mathrm{Mpc}^2}\right] = Y_*\left[\frac{h}{0.7}\right]^{-2+\alpha}\left[\frac{(1-b)\,M_{500}}{6\times10^{14}\,\mathrm{M_{sol}}}\right]^{\alpha}$$

Recent constraints from Planck





189 SZ clusters
(with high SNR)

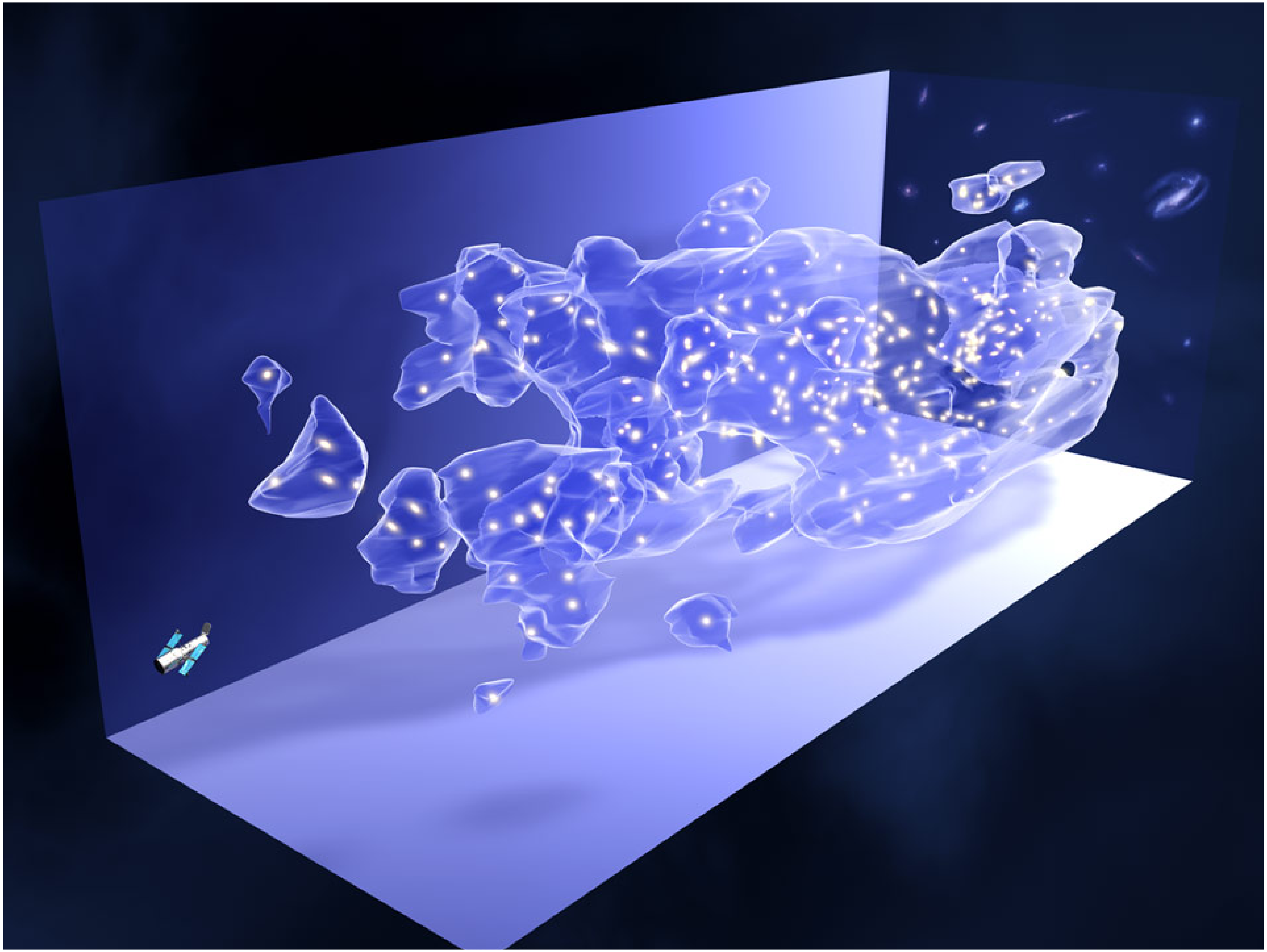
Tension with CMB on σ_8

→ Mass bias ?

→ Massive ν's

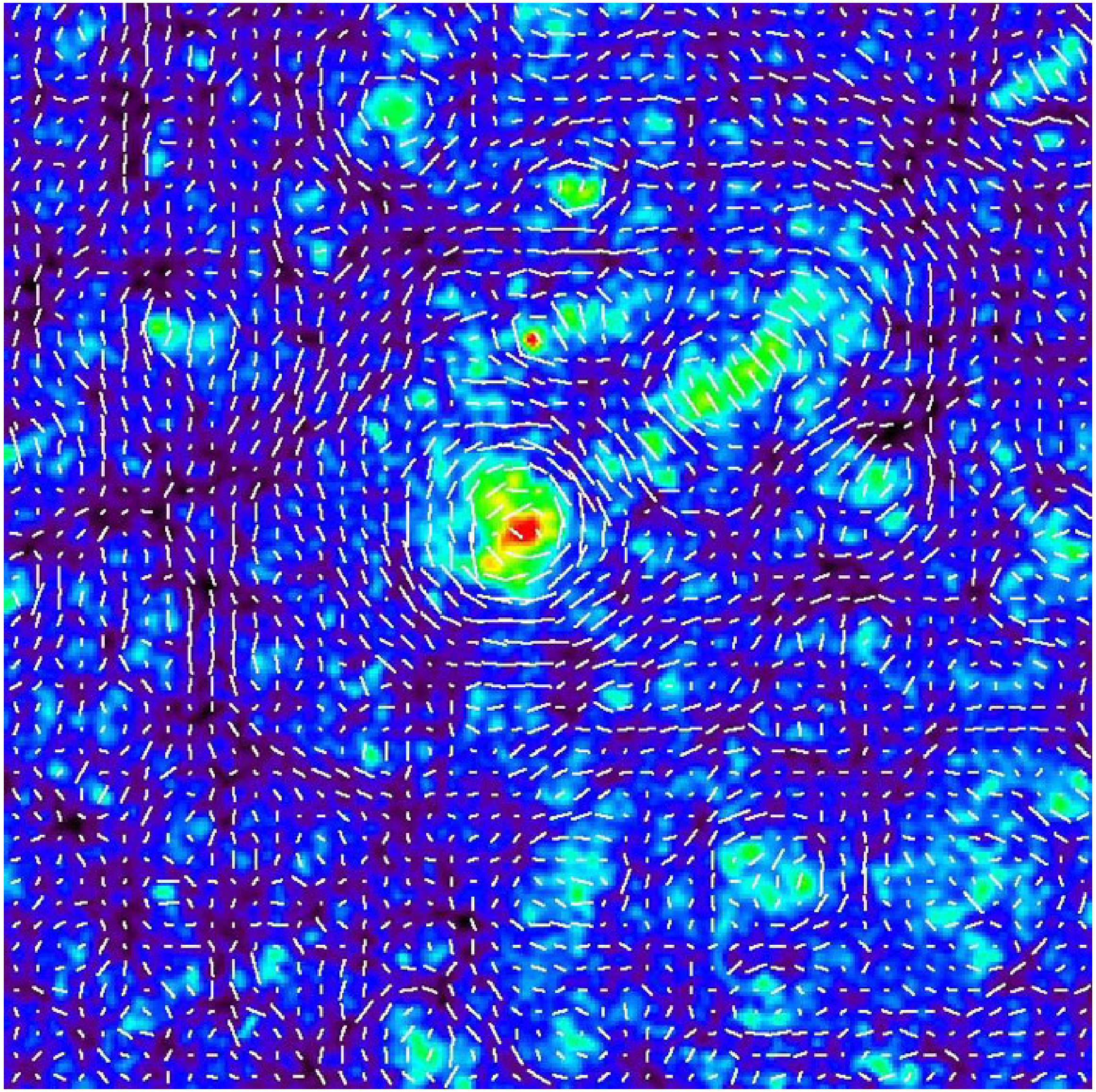
(Planck results 2013 XX)

Cosmic shear



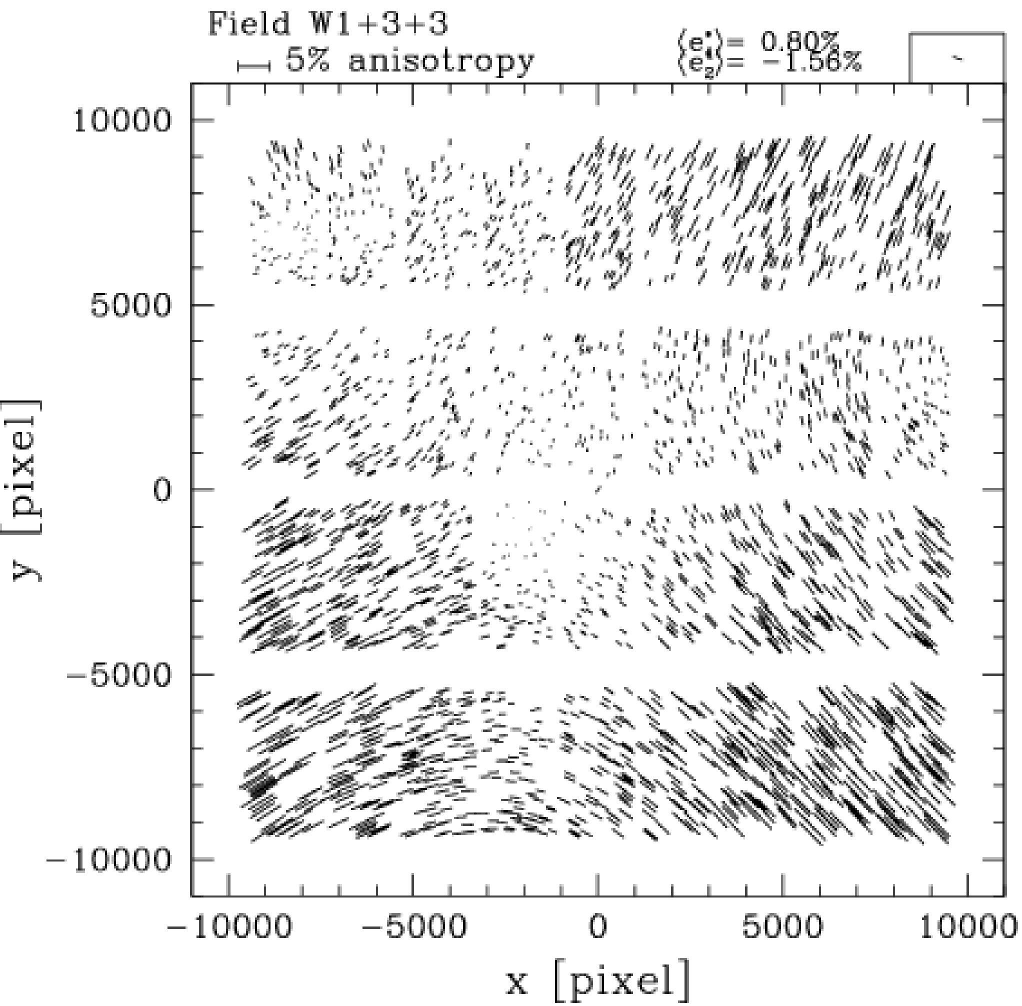
Credit: R. Massey
http://www.astro.caltech.edu

Cosmic shear



T, Hamana, via ned.ipac.caltech.edu

Weak shear measurements



Measured ellipticity of stars
(CFHT/Megacam) Hoekstra et al 2005

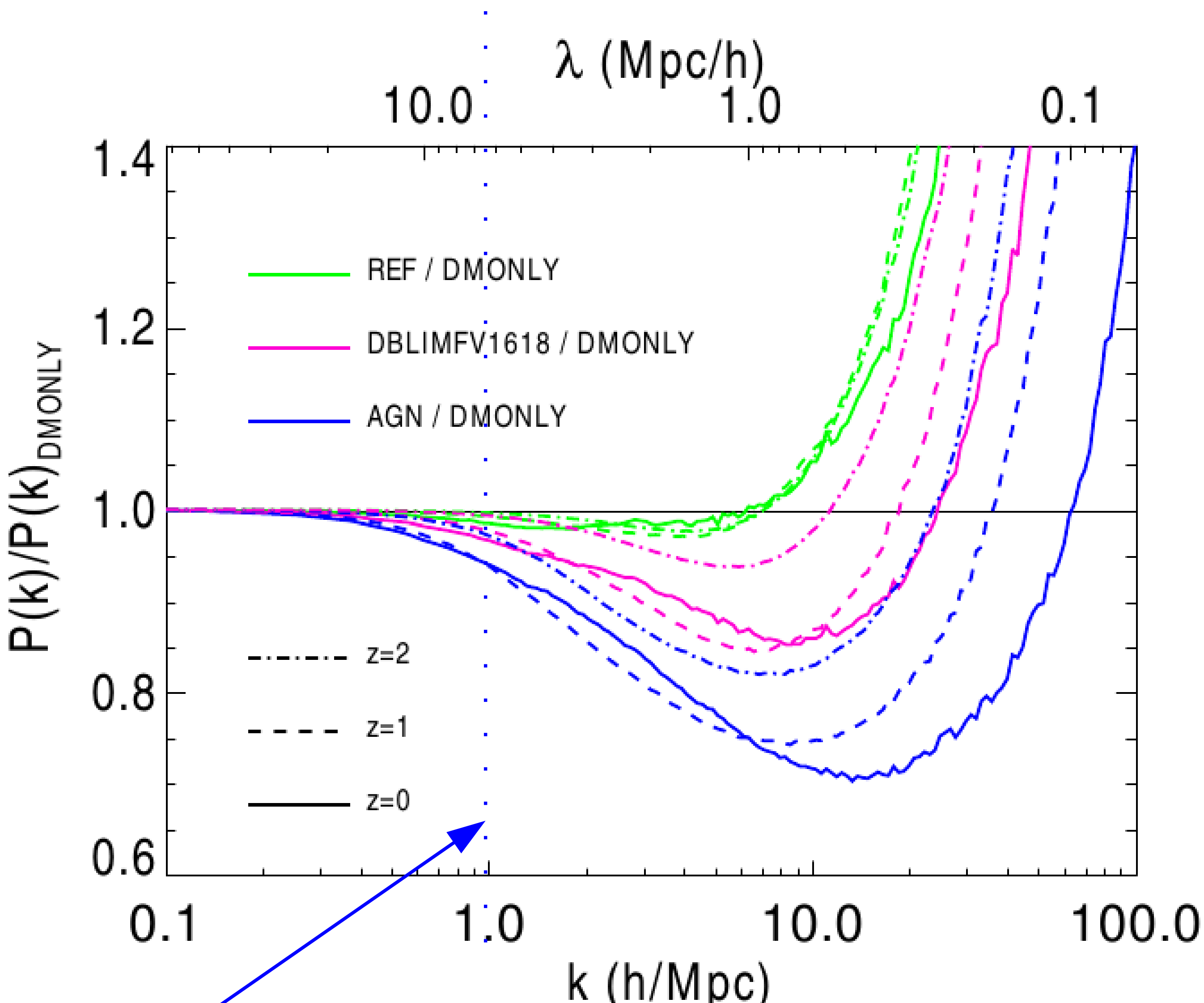
- Weak shear signal
  - correlations of ellipticities of distant galaxies (as a function of angular separation)

- Sources of ellipticity:
  - natural galaxy ellipticity : ~ 30%

    ⇒average over many galaxies
  - Imaging system : 0 – 10 %

    ⇒ measure ellipticity of stars
  - cosmological signal : ~ 1%

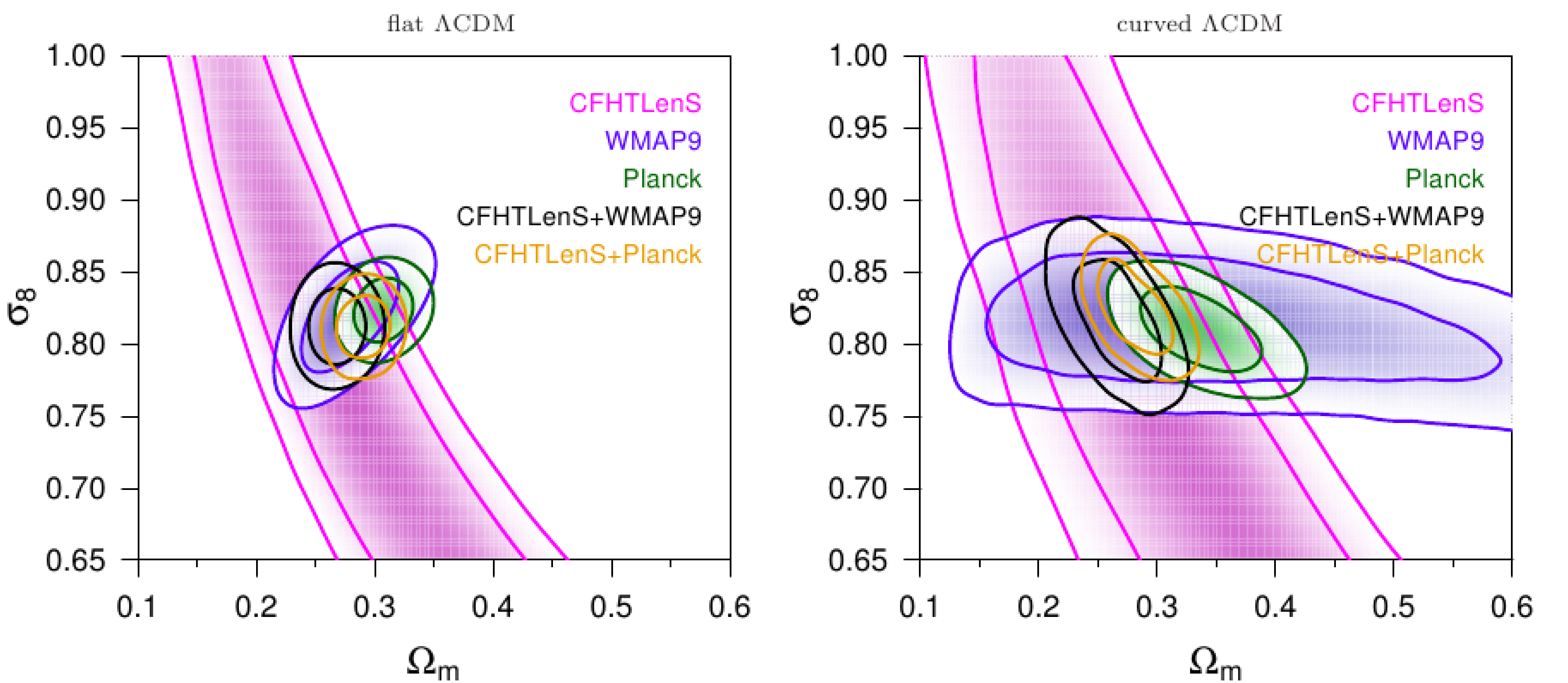
Baryons



3 x stat uncertainties

(Semboloni et al, 2012)

Constraints from shear measurements



(Fu et al, '14)

See also Heymans et al, '13

Redshift space distorsions

- Density contrast

$$\delta = \frac{\rho_m - \overline{\rho}}{\overline{\rho}}$$

- Growth rate of structure

$$f(z) = \frac{d \ln \delta(k)}{d \ln a}$$

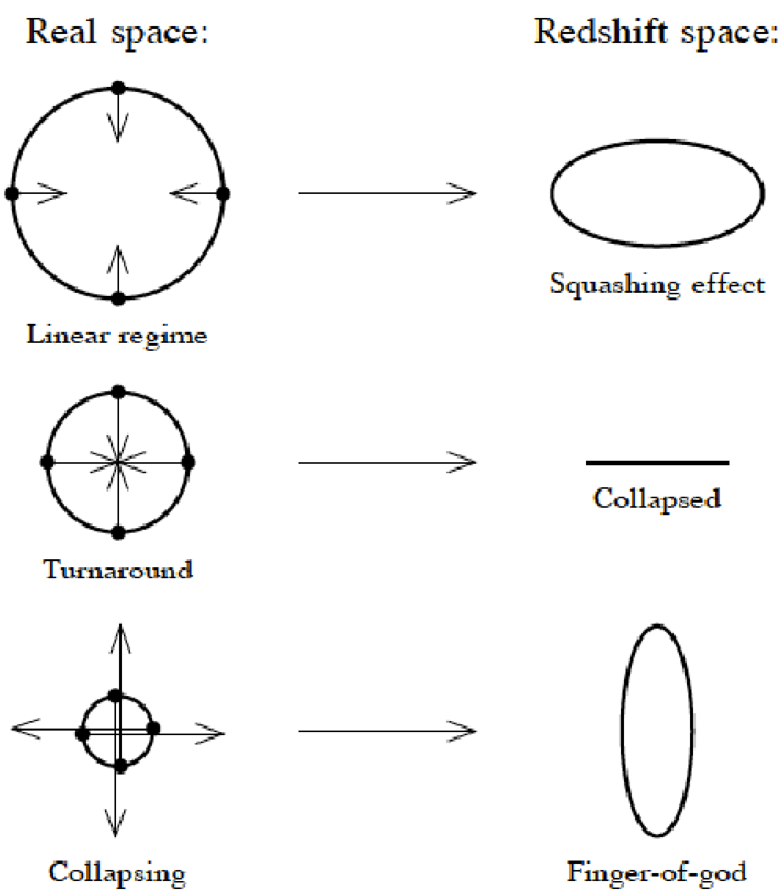
- Parametrized as

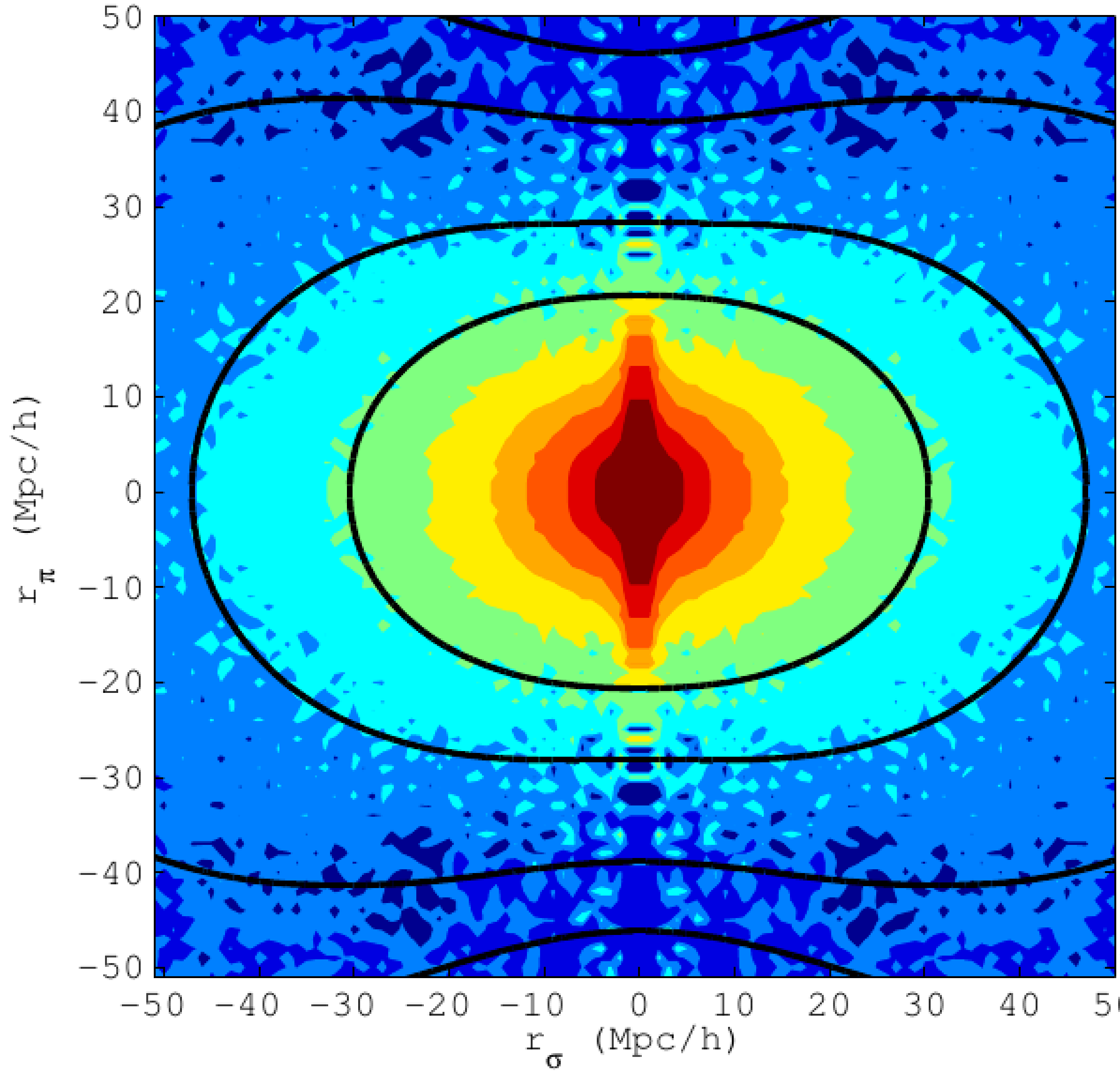
$$f(z) = \Omega_m^{\gamma}(z)$$

  - ΛCDM/GR predict $\gamma \sim 0.55$

  → measurement of f(z) → tests of gravity

Redshift space distorsions

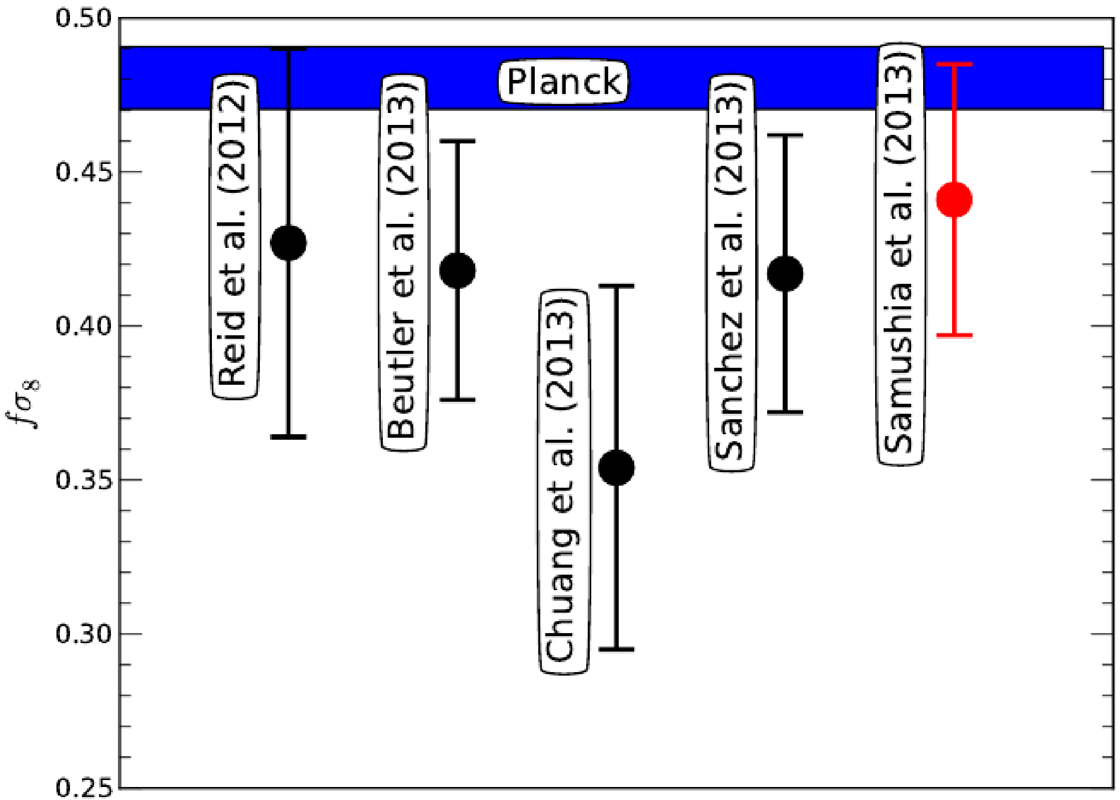




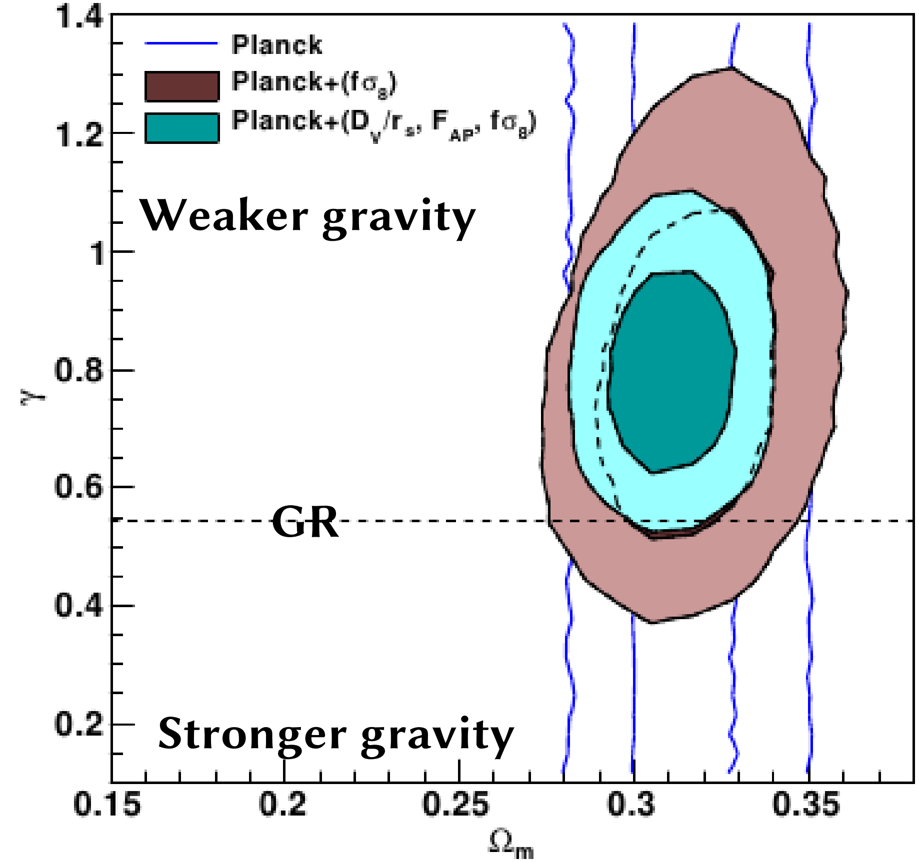
(Reid et al, '12)

- RSD ⟶ f (in fact $f\sigma_8$)
- Alcock-Paczynski test ⟶ $F(z) = (1+z)\, D_A(z)\, H(z)$ (quadrupoles)

Redshift space distorsions



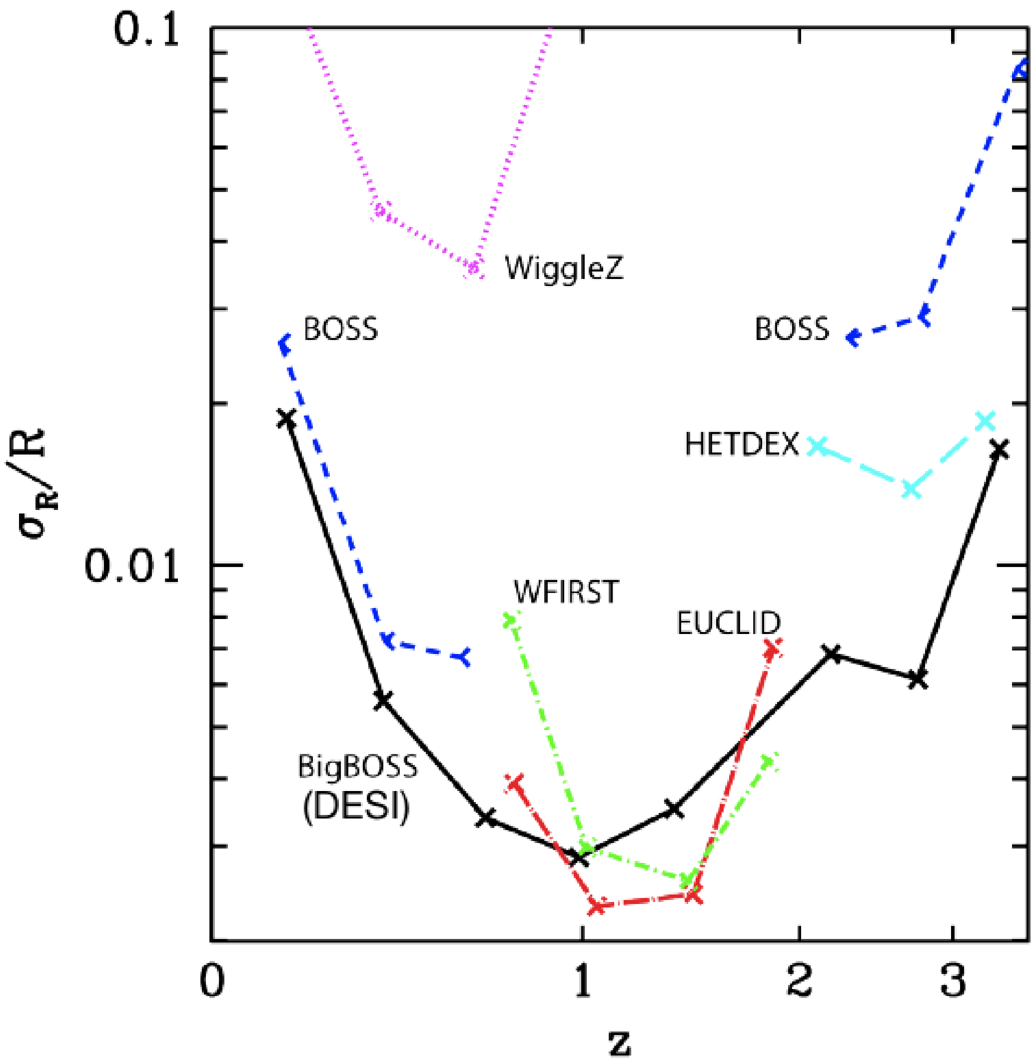
(Samushia et al, '14, BOSS Coll)

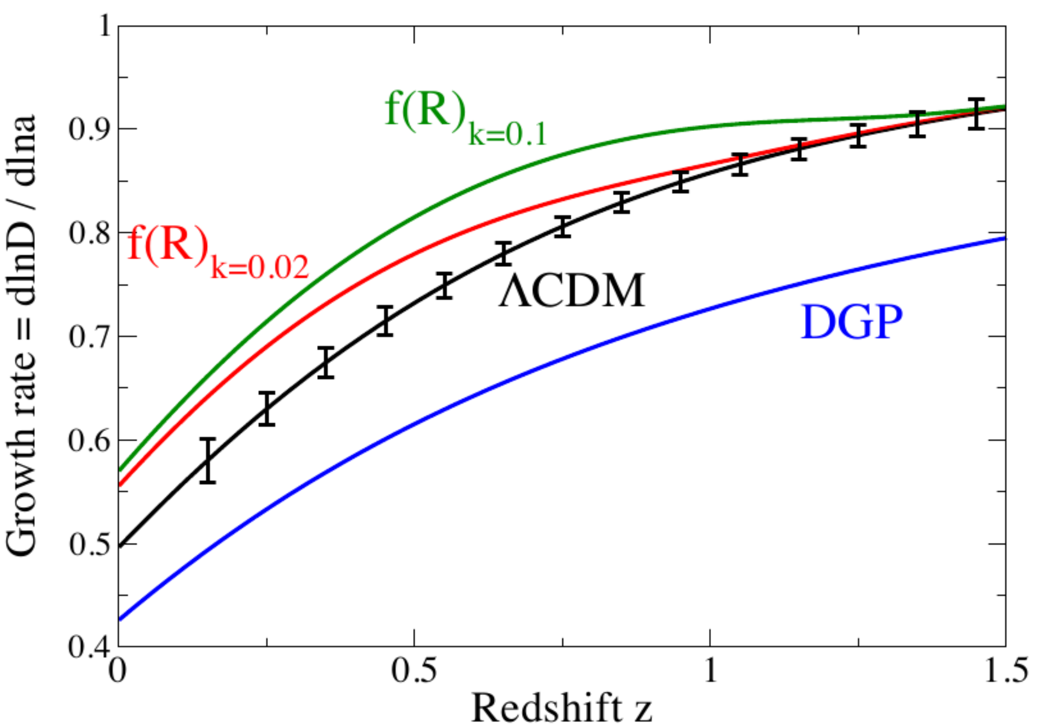


(Beutler et al '13, BOSS Coll.)

(Reid et al, '14)
(de la Torre et al, '13)

The future


0.1
0.01
σ_R/R
WiggleZ
BOSS
BOSS
HETDEX
WFIRST
EUCLID
BigBOSS
(DESI)
0
1
2
3
z


Growth rate = dlnD / dlna
Redshift z
$f(R)_{k=0.1}$
$f(R)_{k=0.02}$
ΛCDM
DGP
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.5
1
1.5