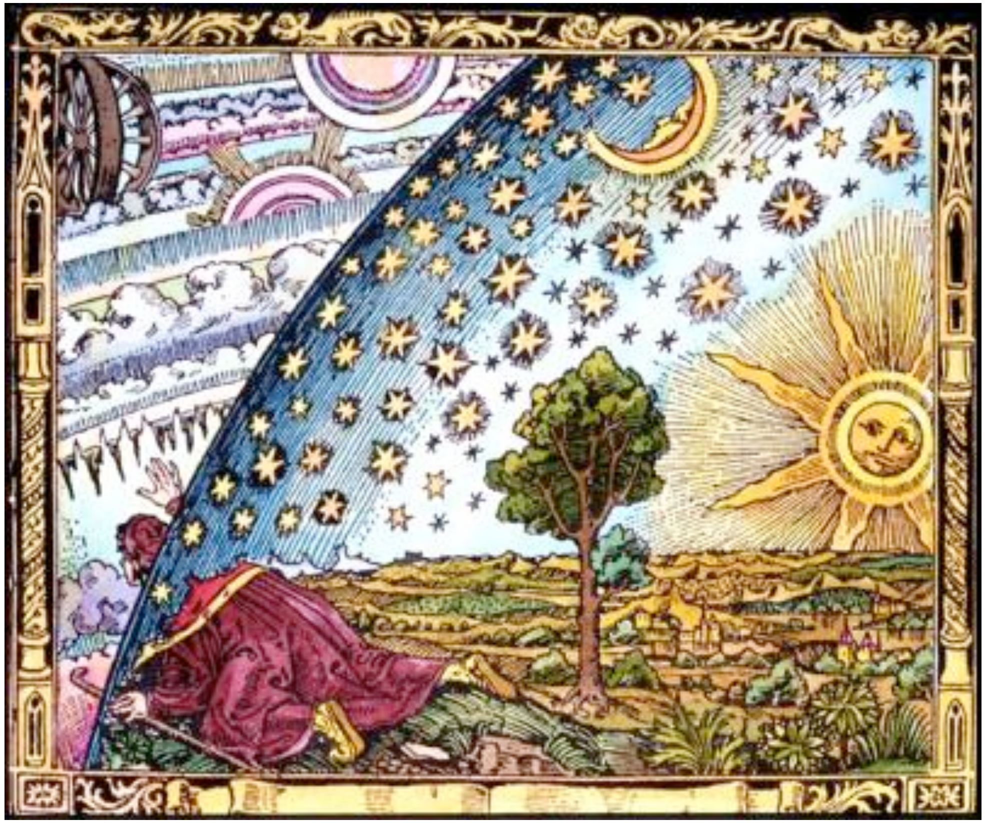
Observational Cosmology

- a laboratory for fundamental physics



MPI-K, Heidelberg 24.11.2011

Marek Kowalski

universitätbonn

Outline

- Introduction
- Cosmological probes
- Cosmological constraints

Our Cosmological Framework derives from…

Observation:	The Universe is Expanding
Principles:	Homogeneous, isotropic
Theory:	General Relativity

$\Rightarrow$ Friedman Equation, which governs expansion

$$H^2 \equiv \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3}\rho_M + \frac{\Lambda}{3} - \frac{k}{R^2} \quad \Big| \quad \frac{1}{H^2}$$

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

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Matter Density

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Matter Density

Cosmological Constant/ Dark Energy

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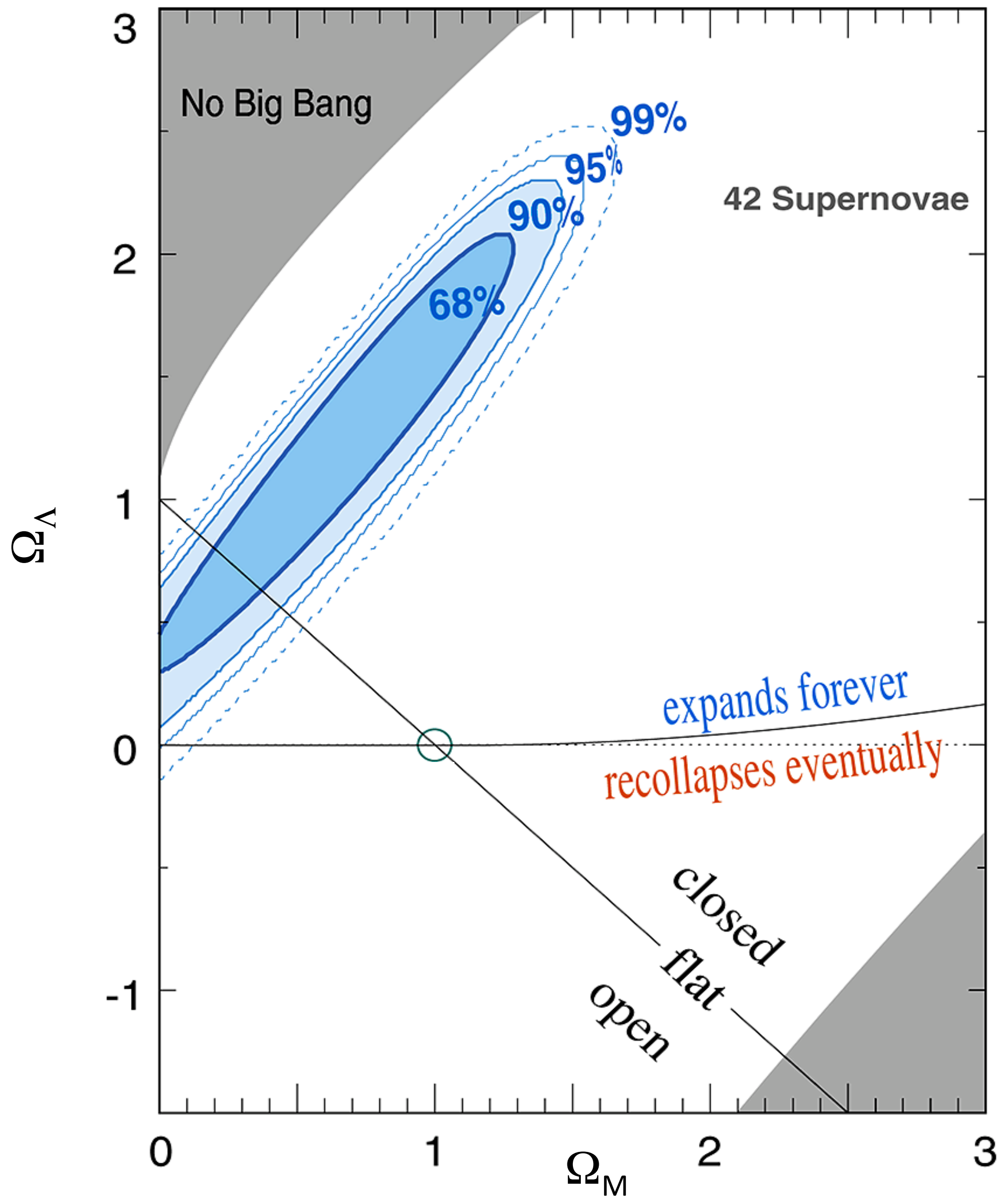
Matter Density

Cosmological Constant/ Dark Energy

Curvature

1998: Discovery of Dark Energy



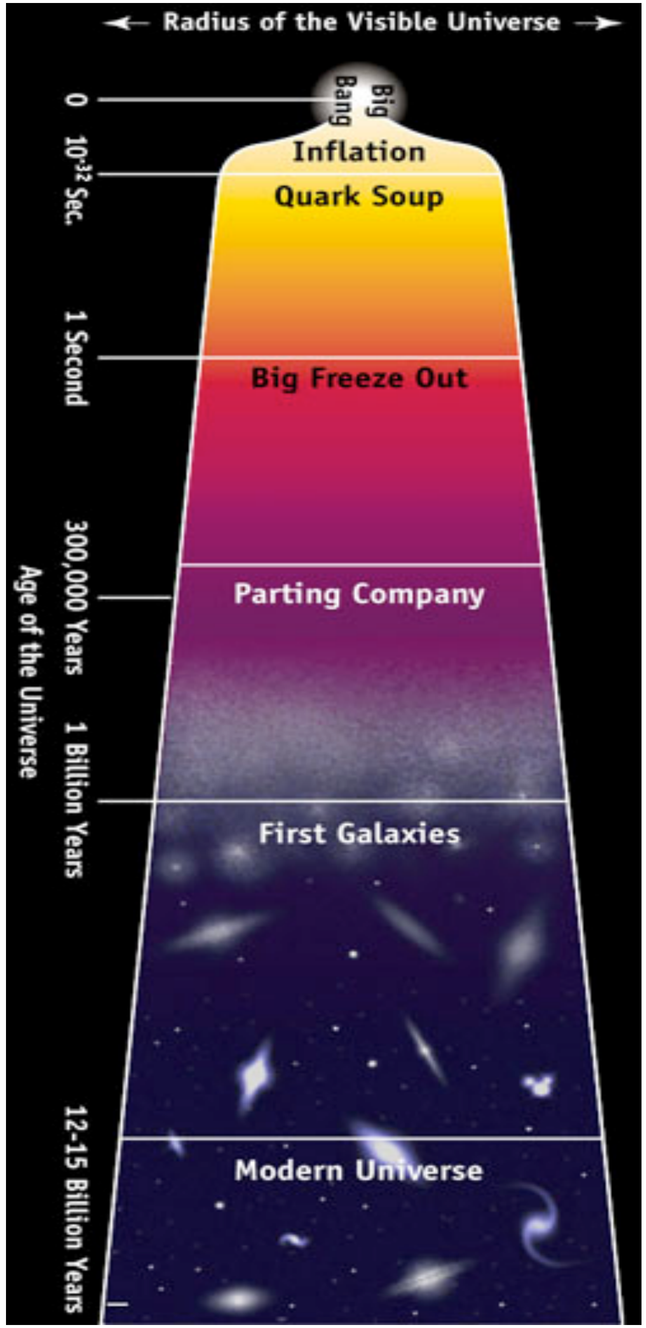
Nobel prize for physics 2011

Nobel prize for physics 2011

The standard model of cosmology: ΛCDM

Ingredients of ΛCDM:

- Cosmological constant
- Cold Dark Matter
- Baryons
- 3 light neutrino flavors
- Ampl. of primord. fluctuations
- Index of power spectrum

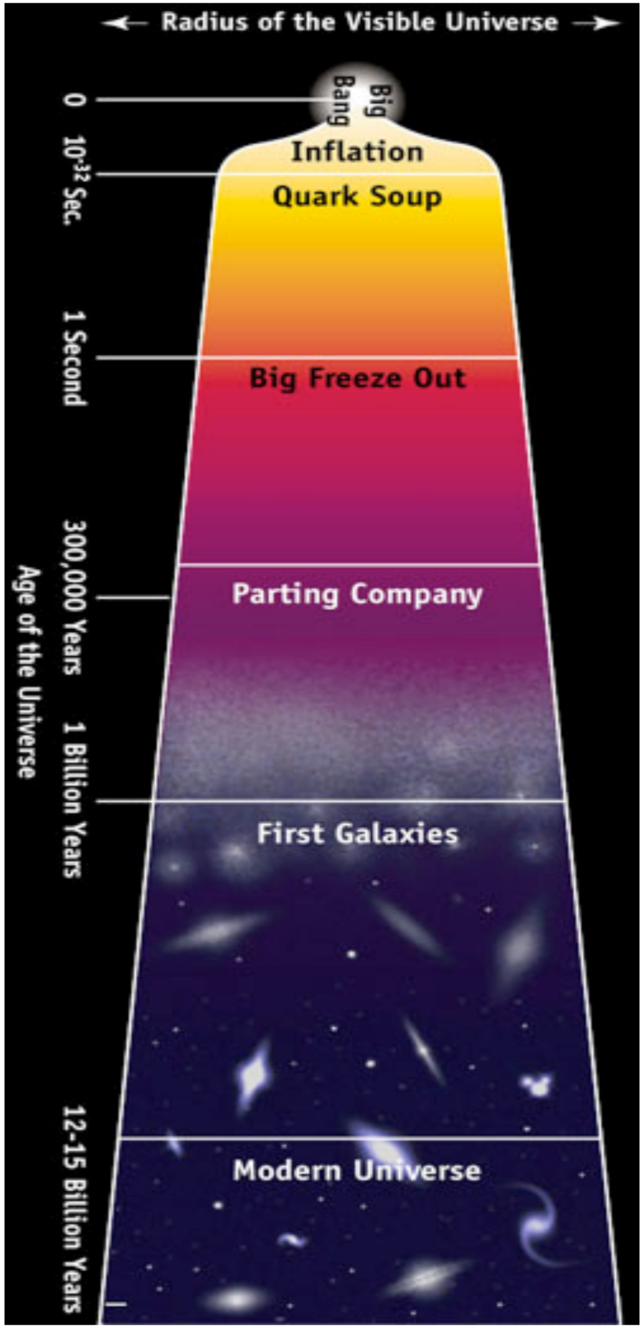


The standard model of cosmology: ΛCDM

Beyond the standard model:

- **Non-Λ dark energy**
- Hot dark matter, e.g. **massive neutrinos**
- Additional relativistic species, e.g **extra neutrino species**
- Tensor perturbations & running spectral index

⇒ **physics of Inflation**

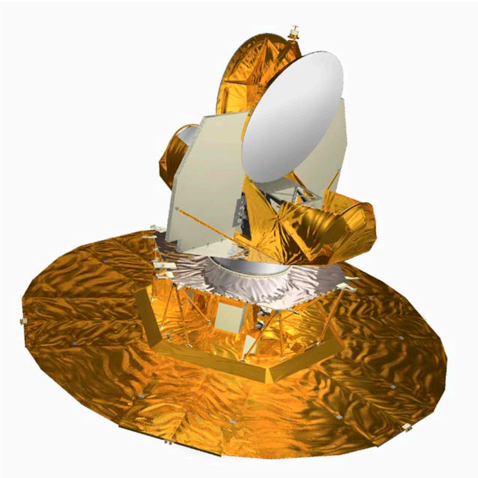


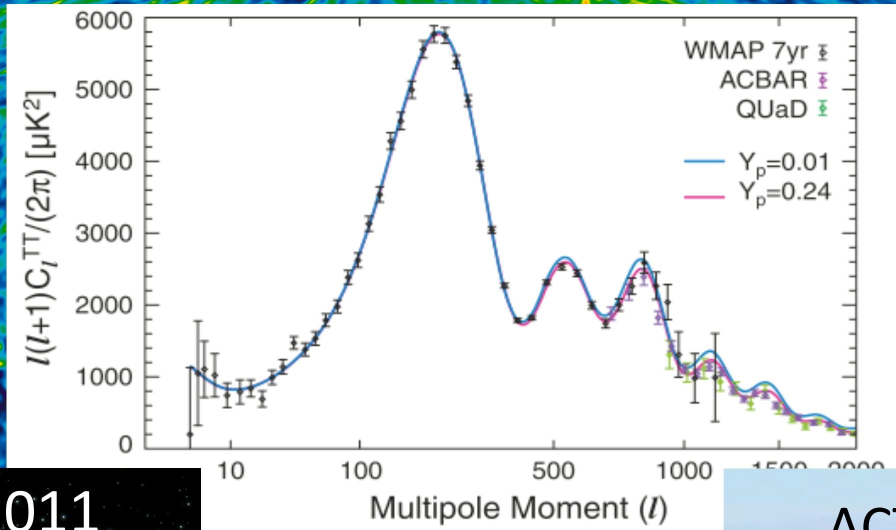
Cosmological Probes:
Selected new results

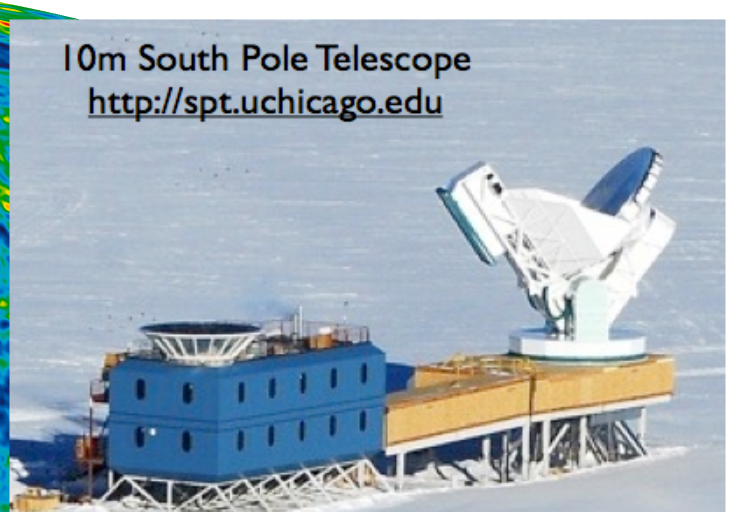
Cosmic Microwave Background

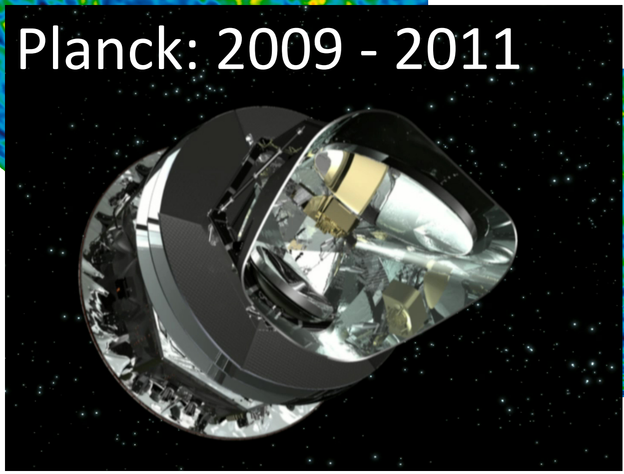
WMAP

New ground based data from:
South Pole Telescope (SPT) &
Atacama Cosmology Telescope (ACT)

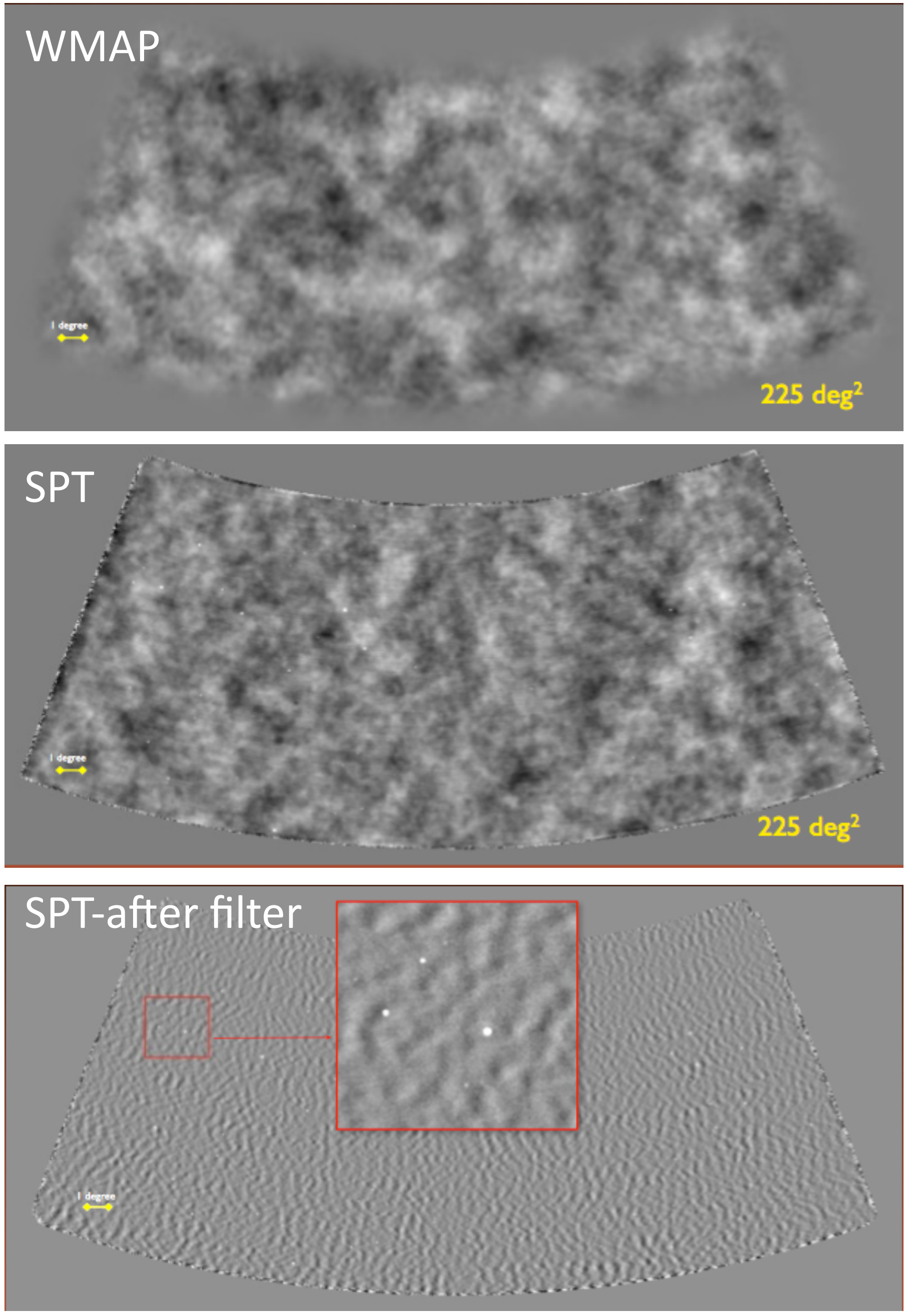








Cosmic Microwave Background



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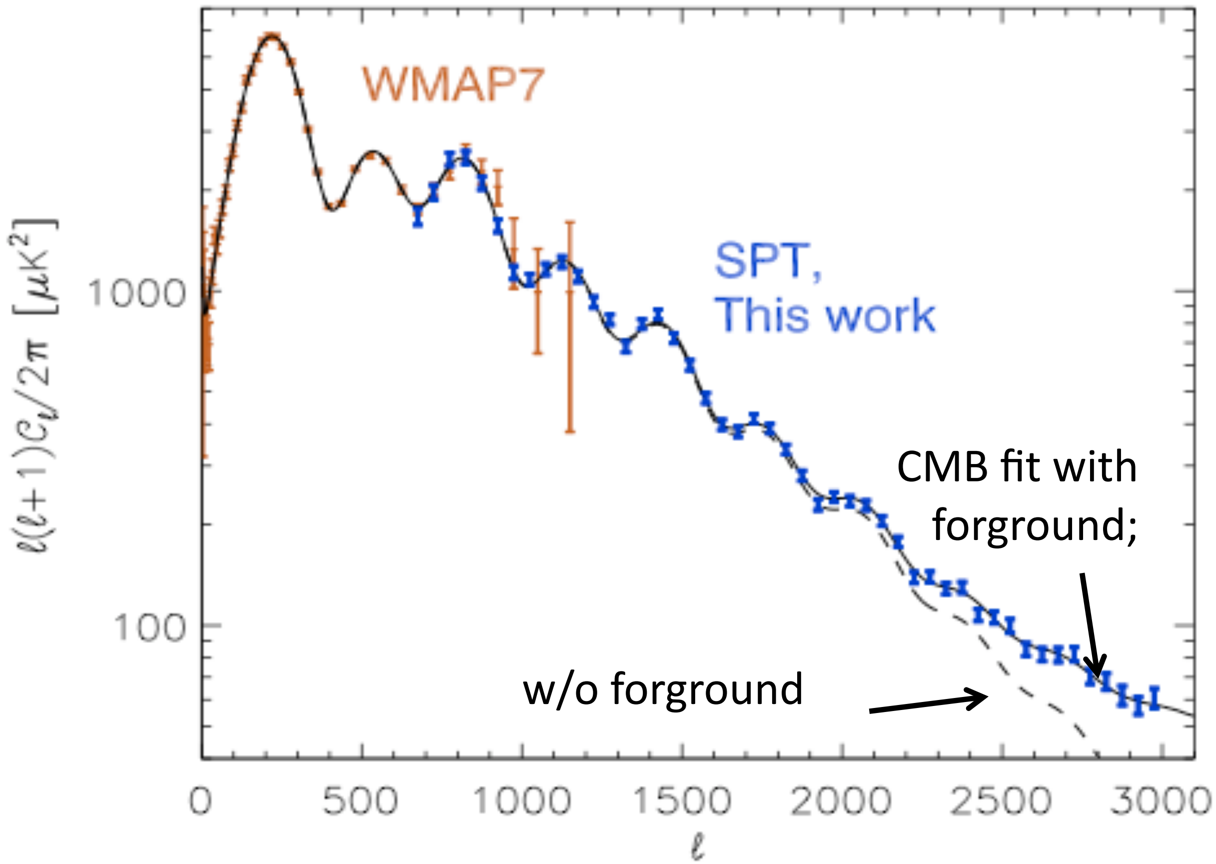
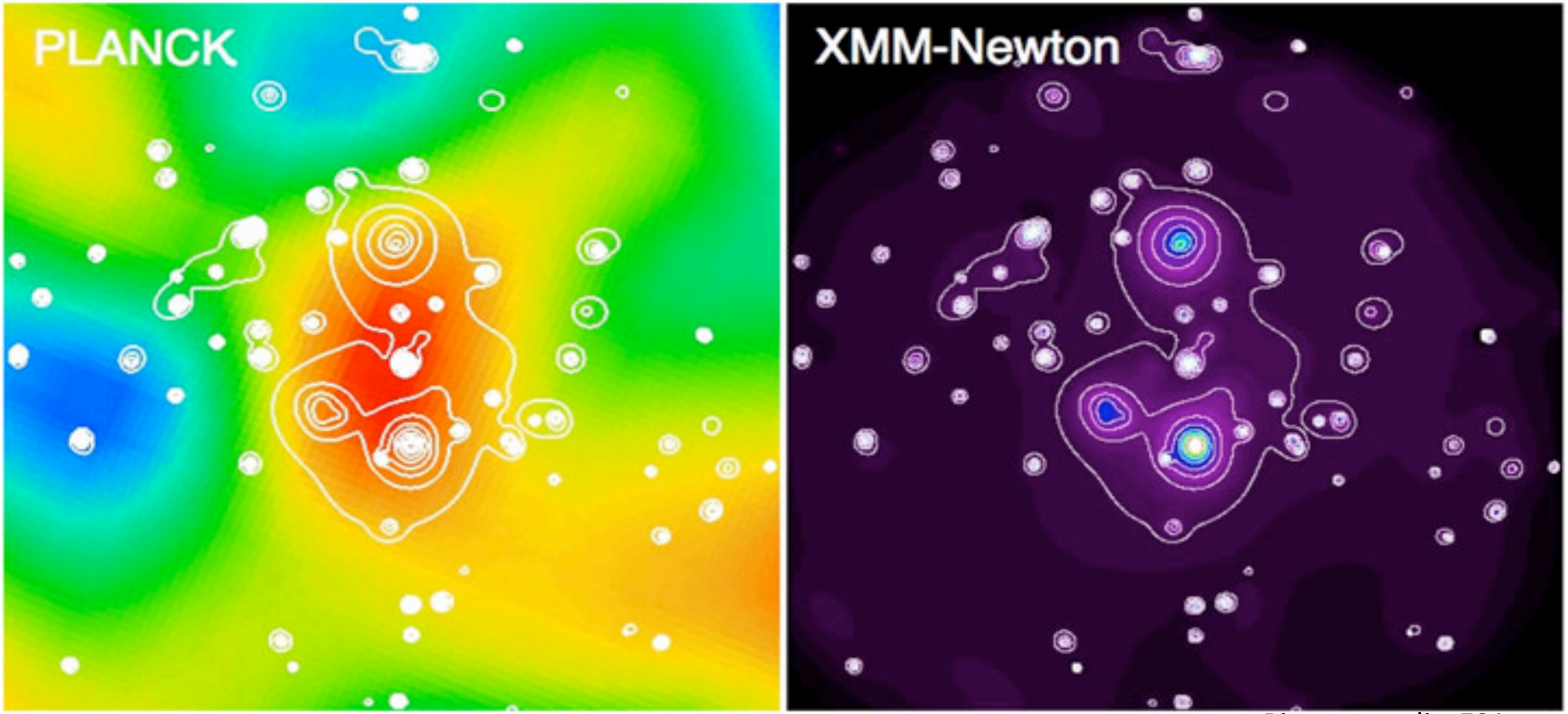


4σ detections of CMB weak lensing

Galaxy Clusters

CMB footprint

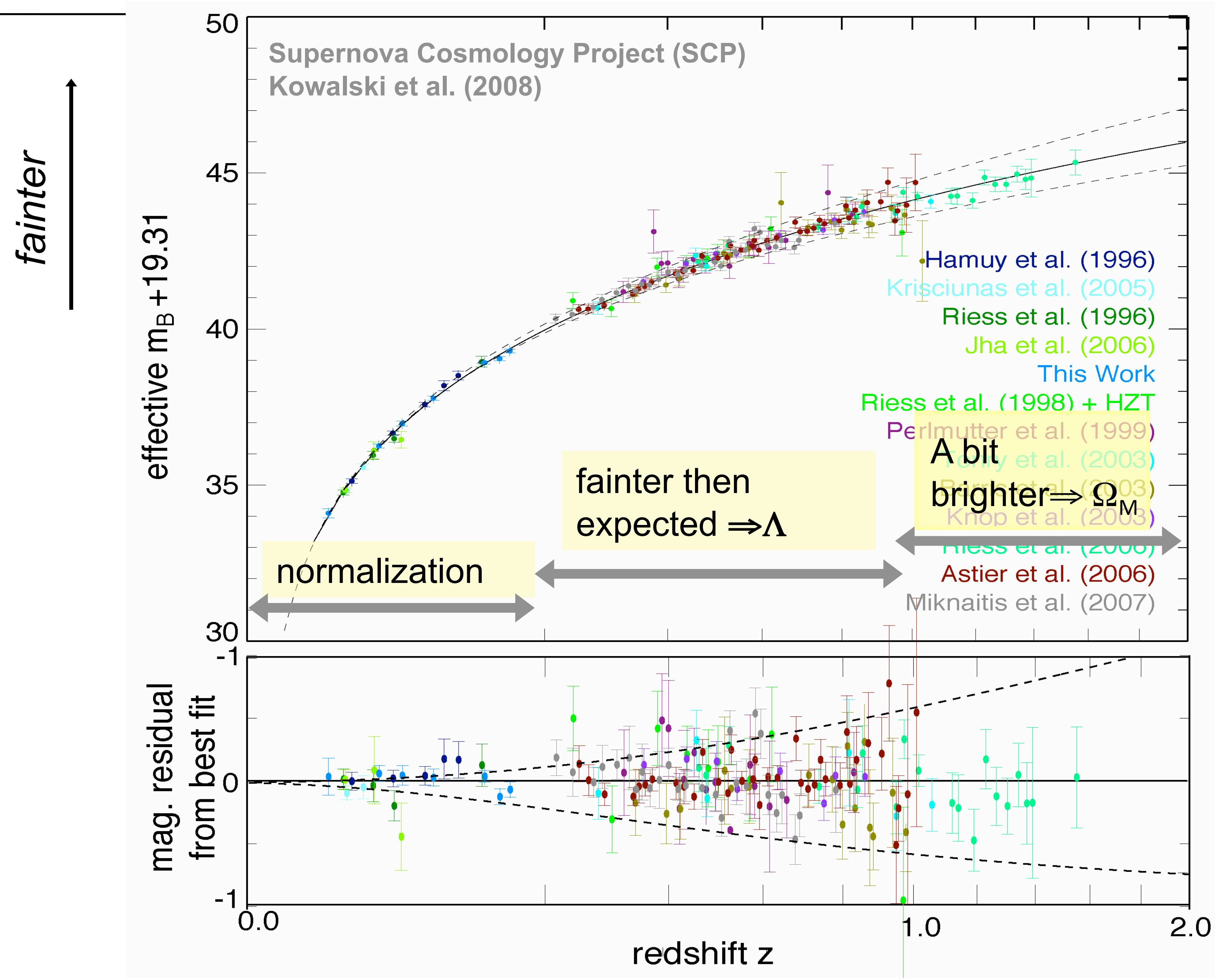
X-ray footprint



Picture credit: ESA

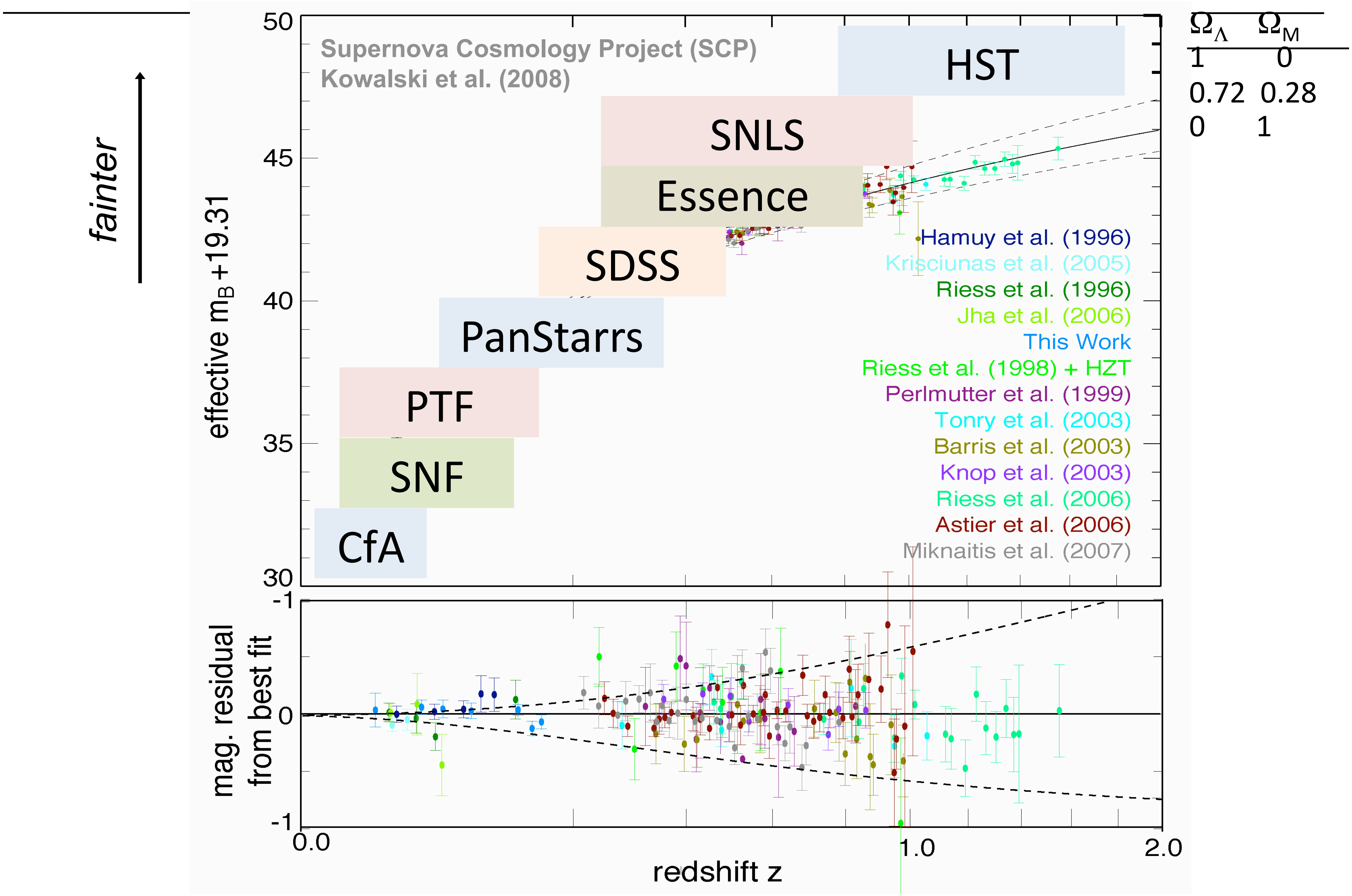
First science results of Planck (A&A, 2011)

SNe Ia Hubble Diagram



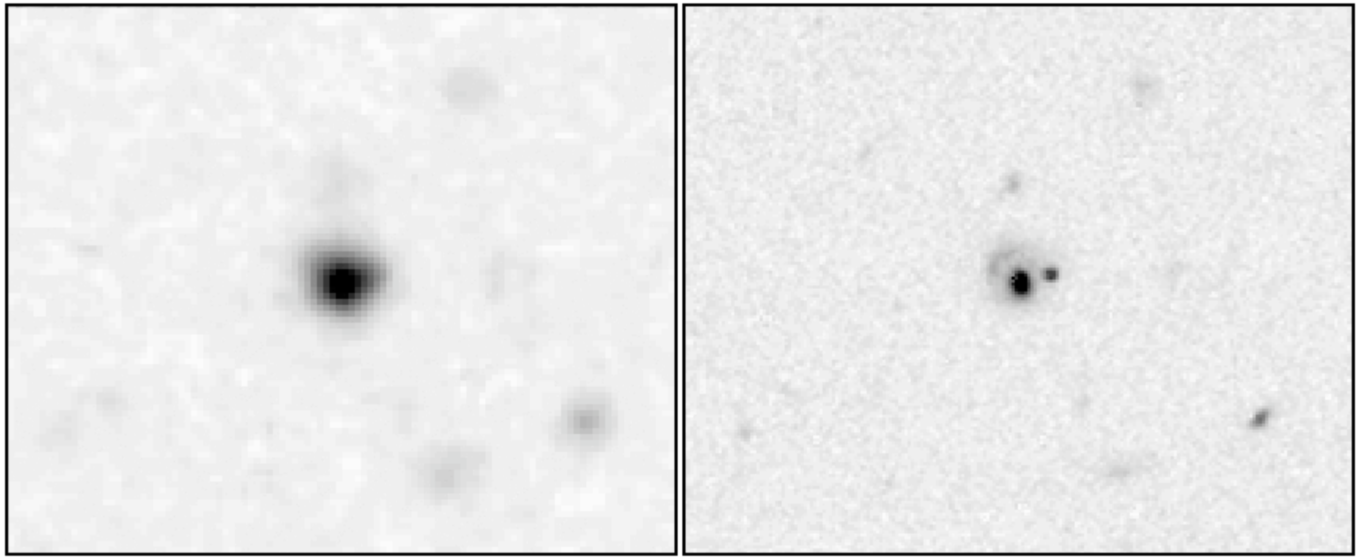
Ω_Λ	Ω_M
1	0
0.72	0.28
0	1

SNe Ia Hubble Diagram



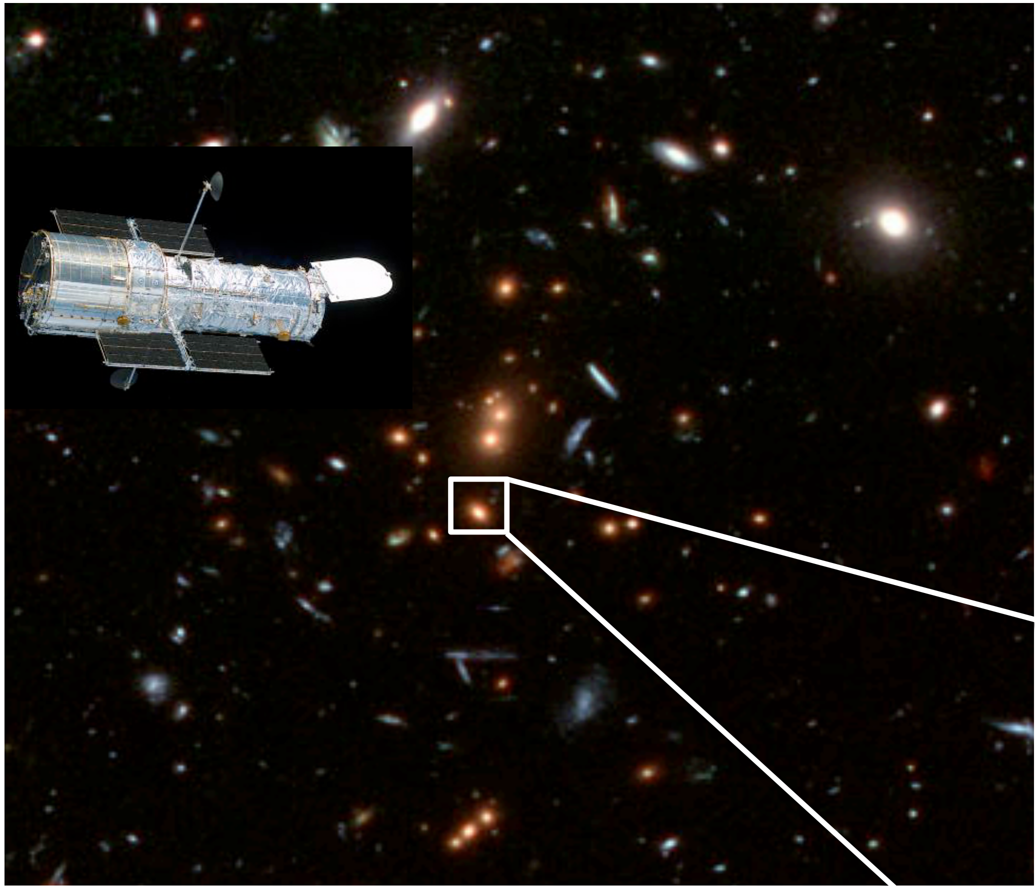
SNe at large Redshifts (z>1)

SN 1997cj



Twin Keck telescopes on Mauna Kea.

HST Survey of Clusters with $z \geq 1$



Survey of z>0.9 galaxy clusters

⇒ SNe from cluster & field

⇒ about 2 x more efficient

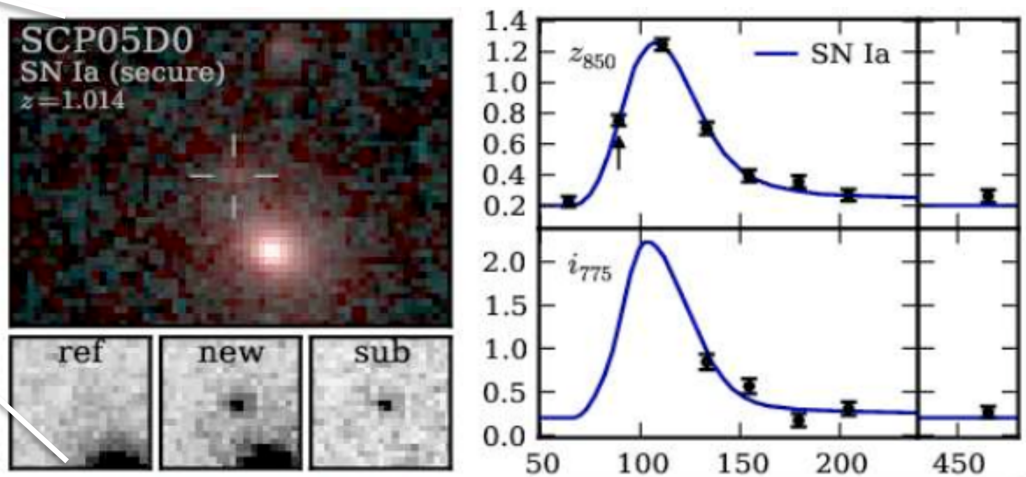
⇒ enhencement of early hosts

⇒ 20 new HST SNe

⇒ 10 high quality z>1 SNe!

Cycle 14, 219 orbits (PI S. Perlmutter)

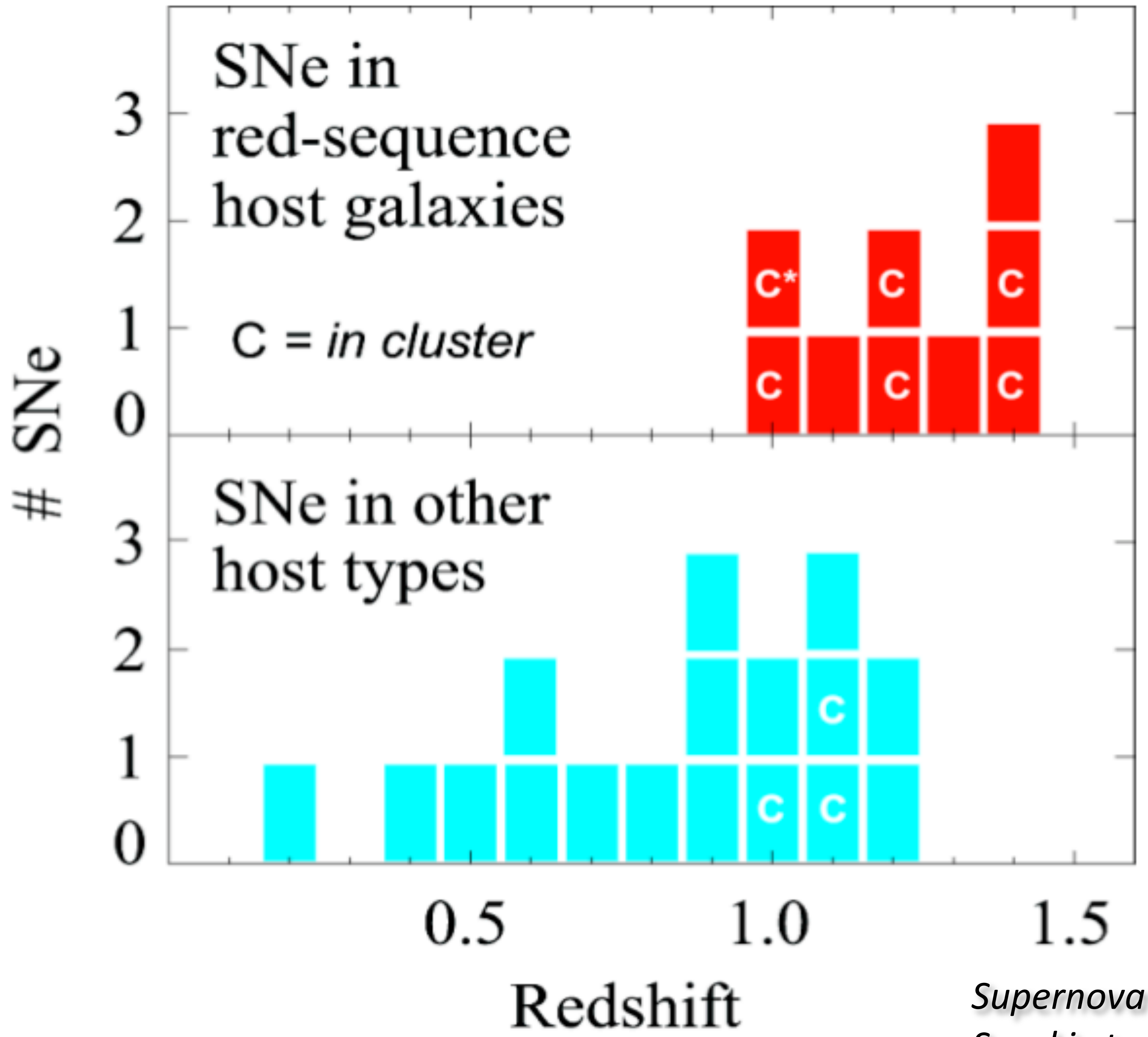
24 clusters from RCS, RDCS,IRAC, XMM



Supernova Cosmology Project

Suzuki et al., 2011

HST Survey of Clusters with z ≥ 1



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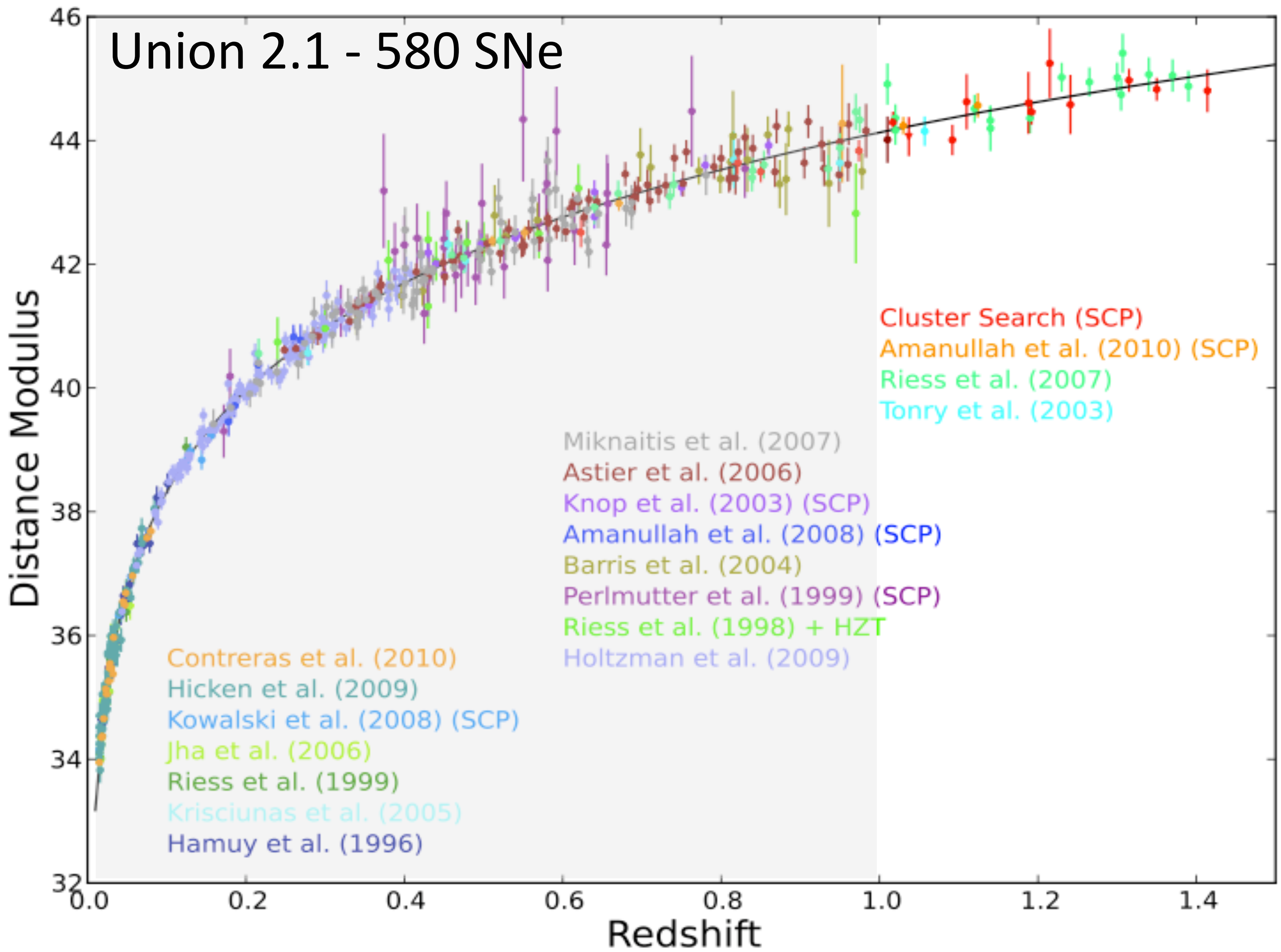
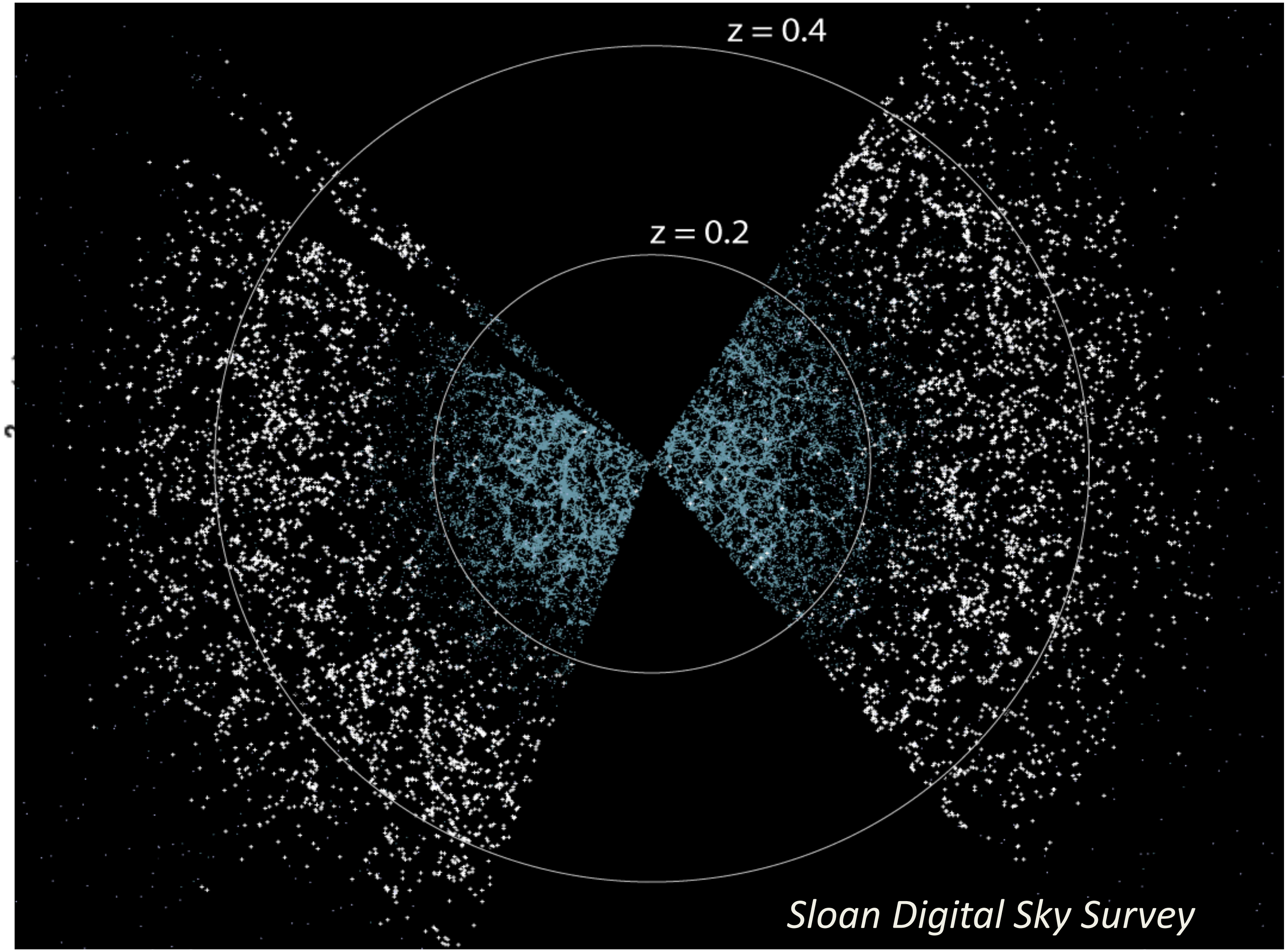


Baryon Acoustic Oscillation

Acoustic „oscillation“ lengh scale from CMB visible in the distribution of galaxies ⇒ Standard ruler of cosmology.



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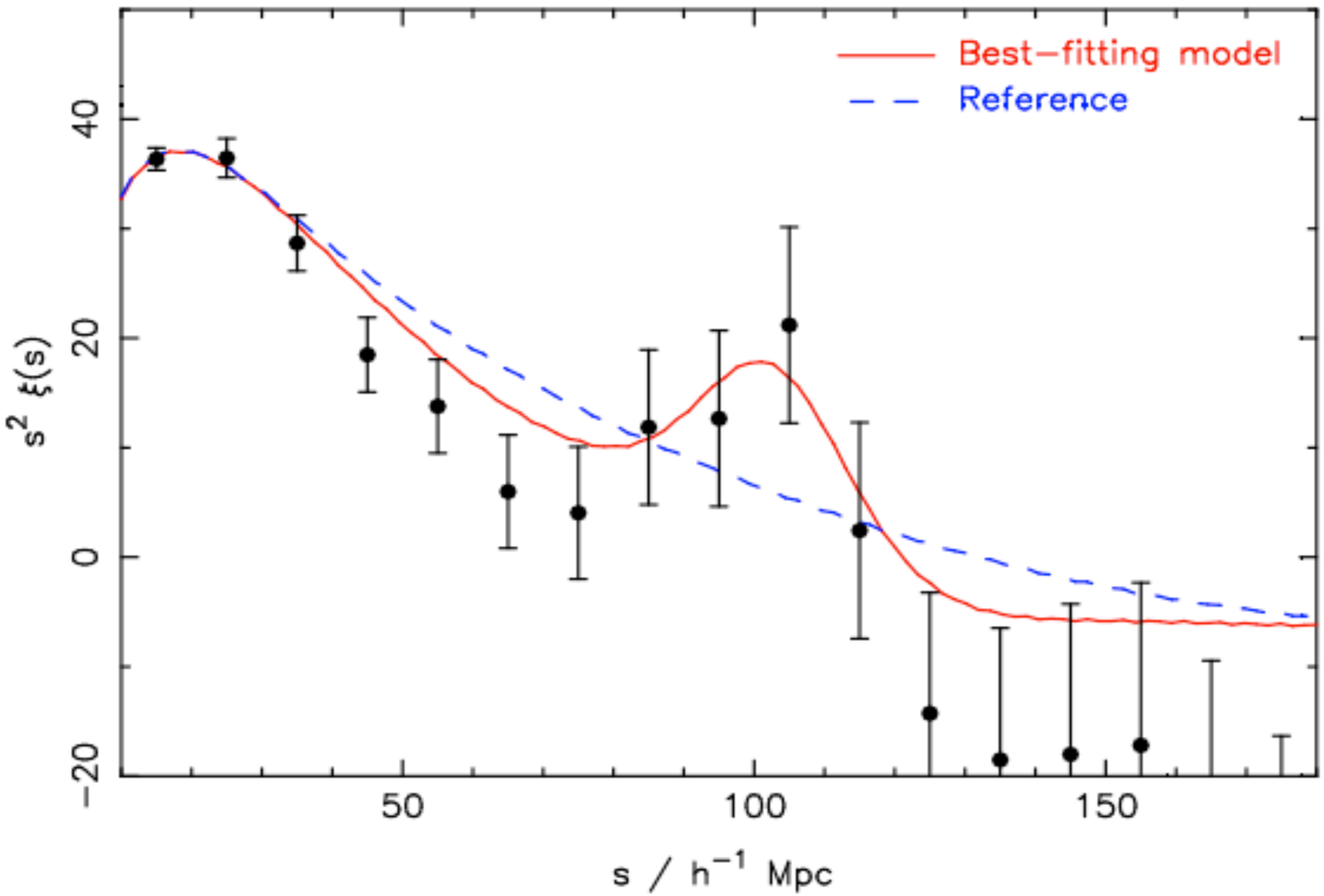

WiggleZ survey – Blake et al, 2011

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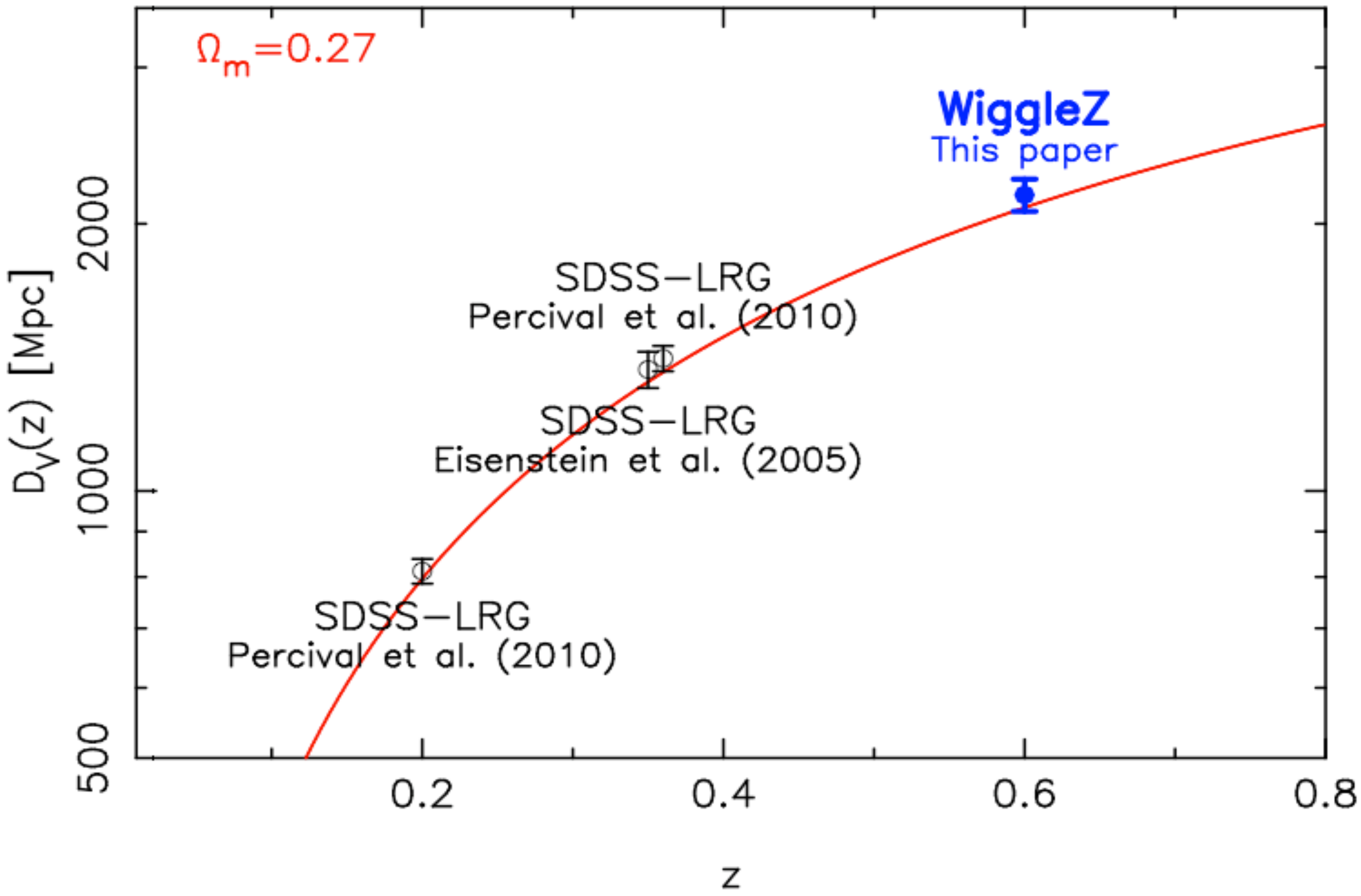
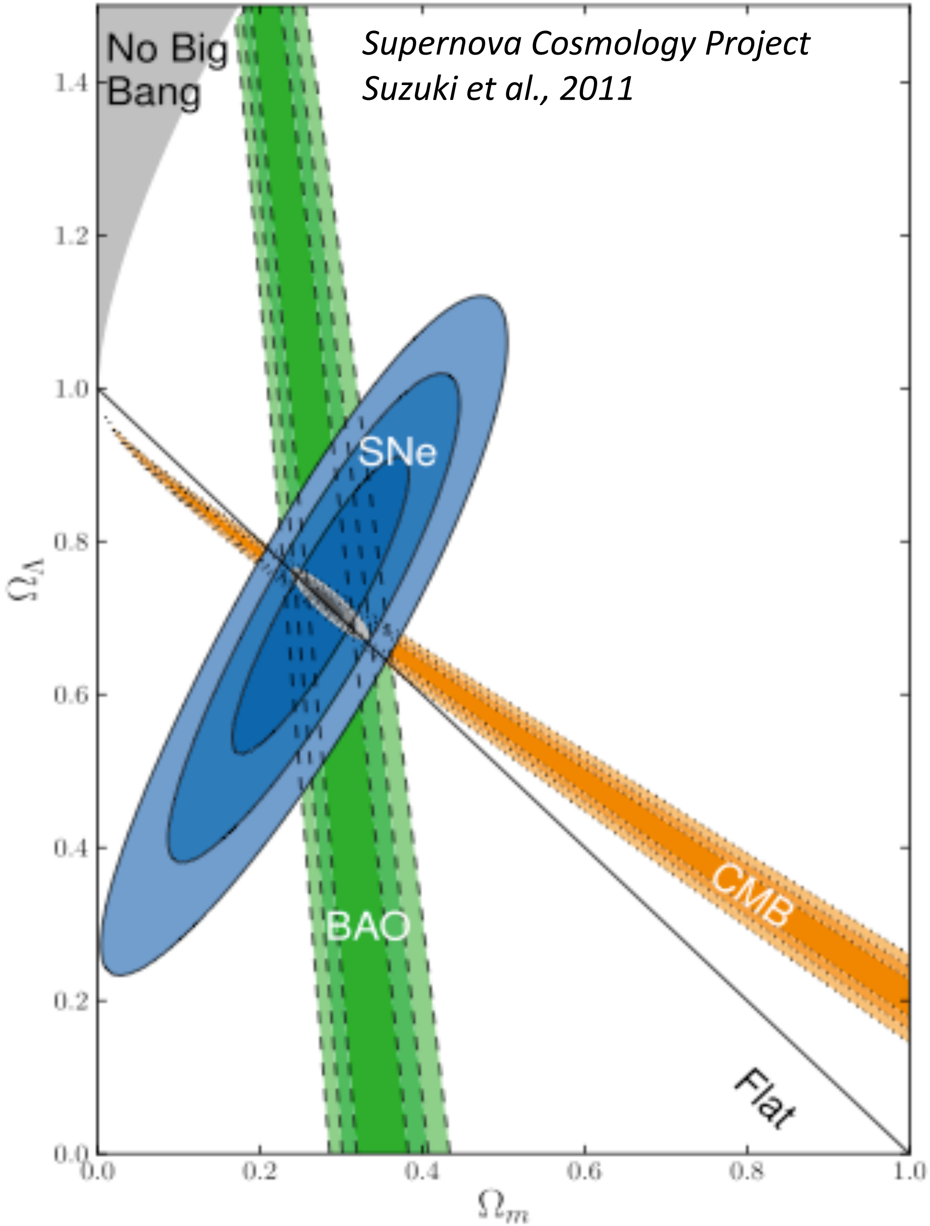


Promising technique & much activity: BOSS, HETDEX,...

Cosmological Constraints: Selected new results

ΛCDM



SNe (Union 2.1, Suzuki et. al, 2011)
BAO (Percival et. al, 2010)
CMB (WMAP-7 year data, 2010)

$$\Omega_\Lambda = 0.729 \pm 0.014$$

and allowing for curvature:

$$\Omega_k = 0.002 \pm 0.005$$

Fundamental Problems of Vacuum Energy/Cosmological Constant:

Why so small?

Expectation: $\rho_\Lambda \sim (M_{\text{planck}})^4$

$\Rightarrow$120 orders of magnitudes larger then the observed value!

Why now?

Matter: $\rho \propto R^{-3}$

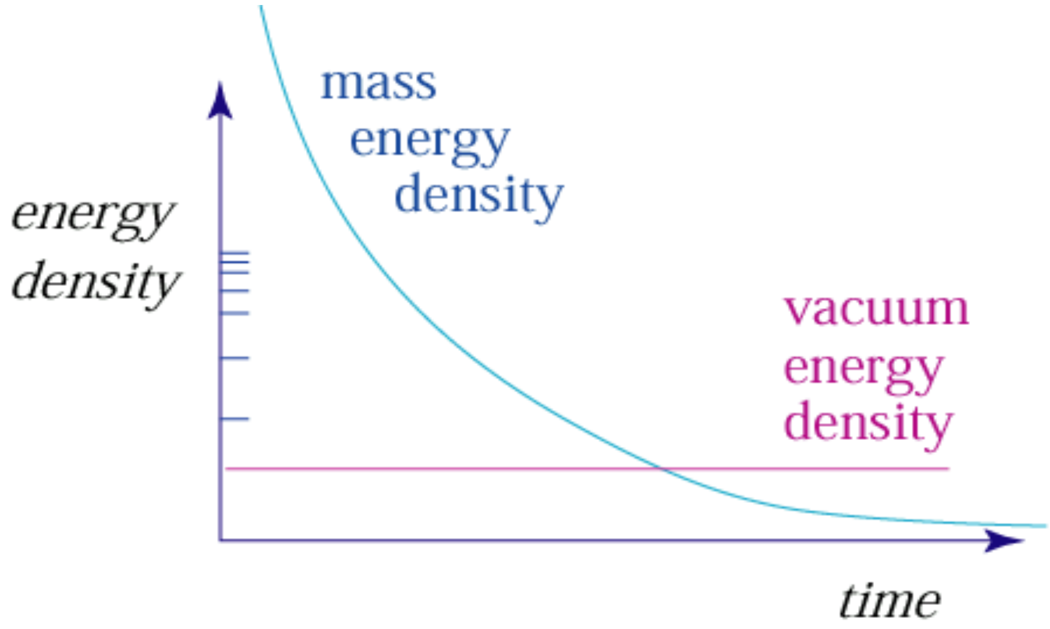
Vakuum Energy: $\rho = constant$

Dark Energy with equation-of-state:

$p = w\rho$

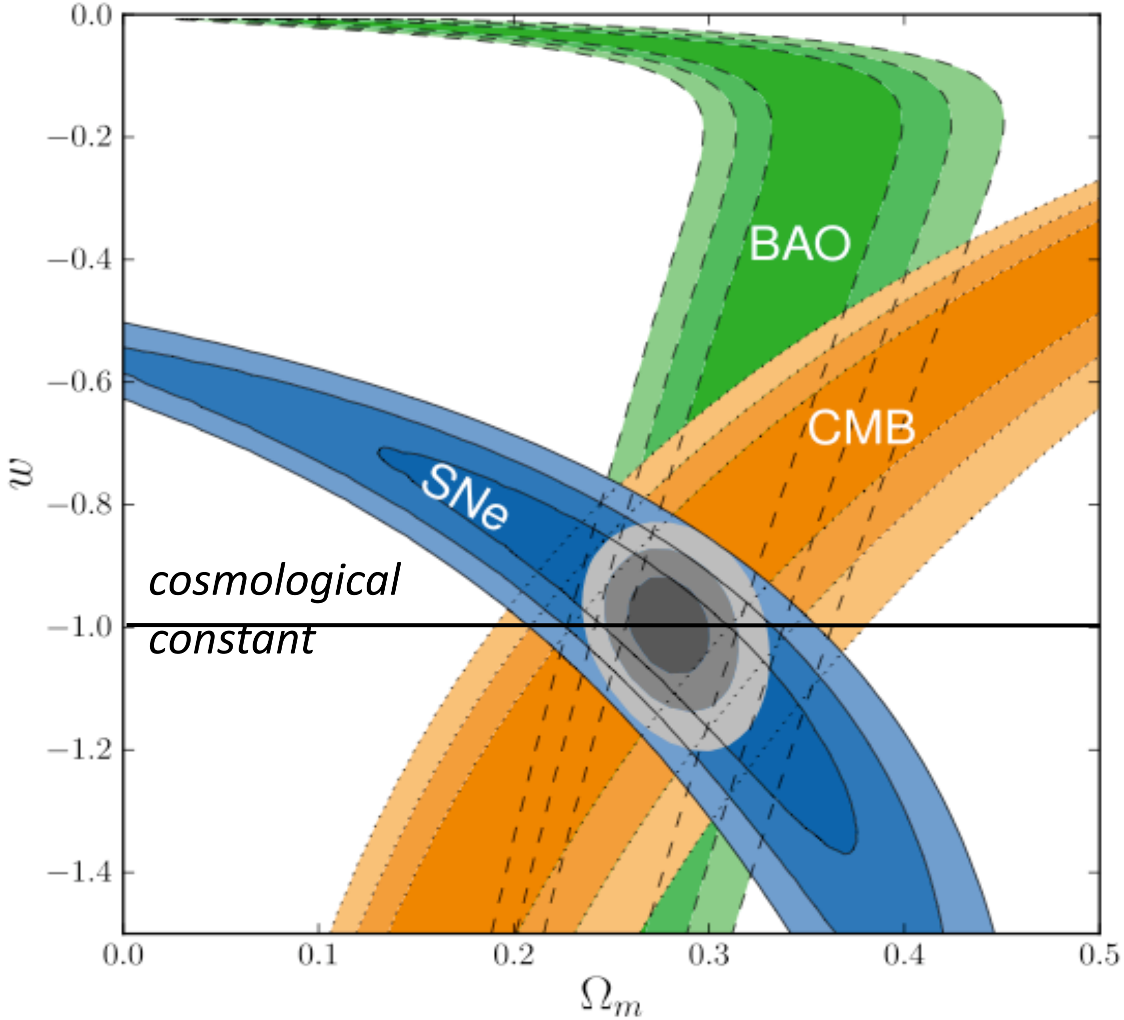
(p = pressure; ρ = density)

$\Rightarrow \rho \propto R^{-3(1+w)}$



Dark Energy

Supernova Cosmology Project
Suzuki et al., 2011

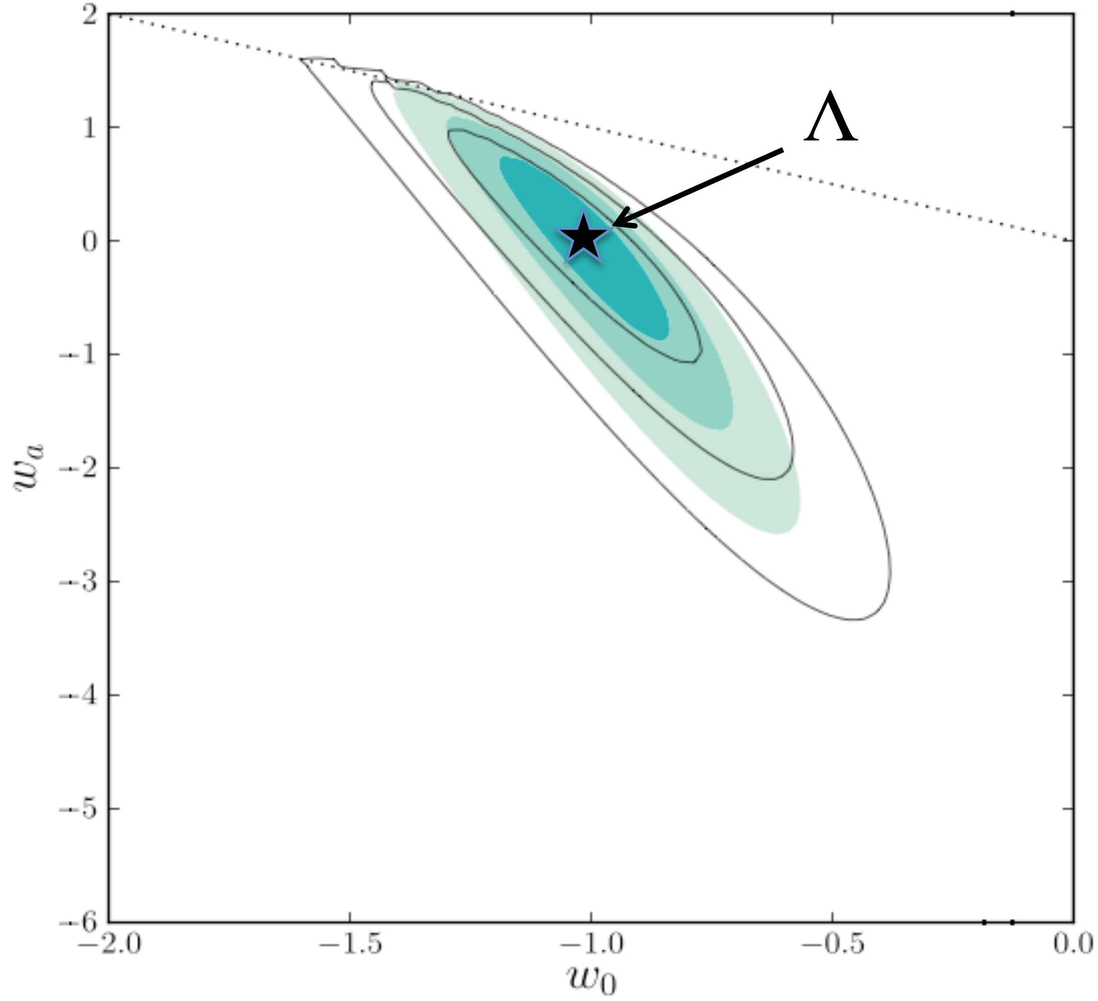


Equation of state: *p=wρ*

Constant w:
w=-0.995±0.078

Dark Energy

Supernova Cosmology Project
Suzuki et al., 2011



Equation of state: $p = w\rho$

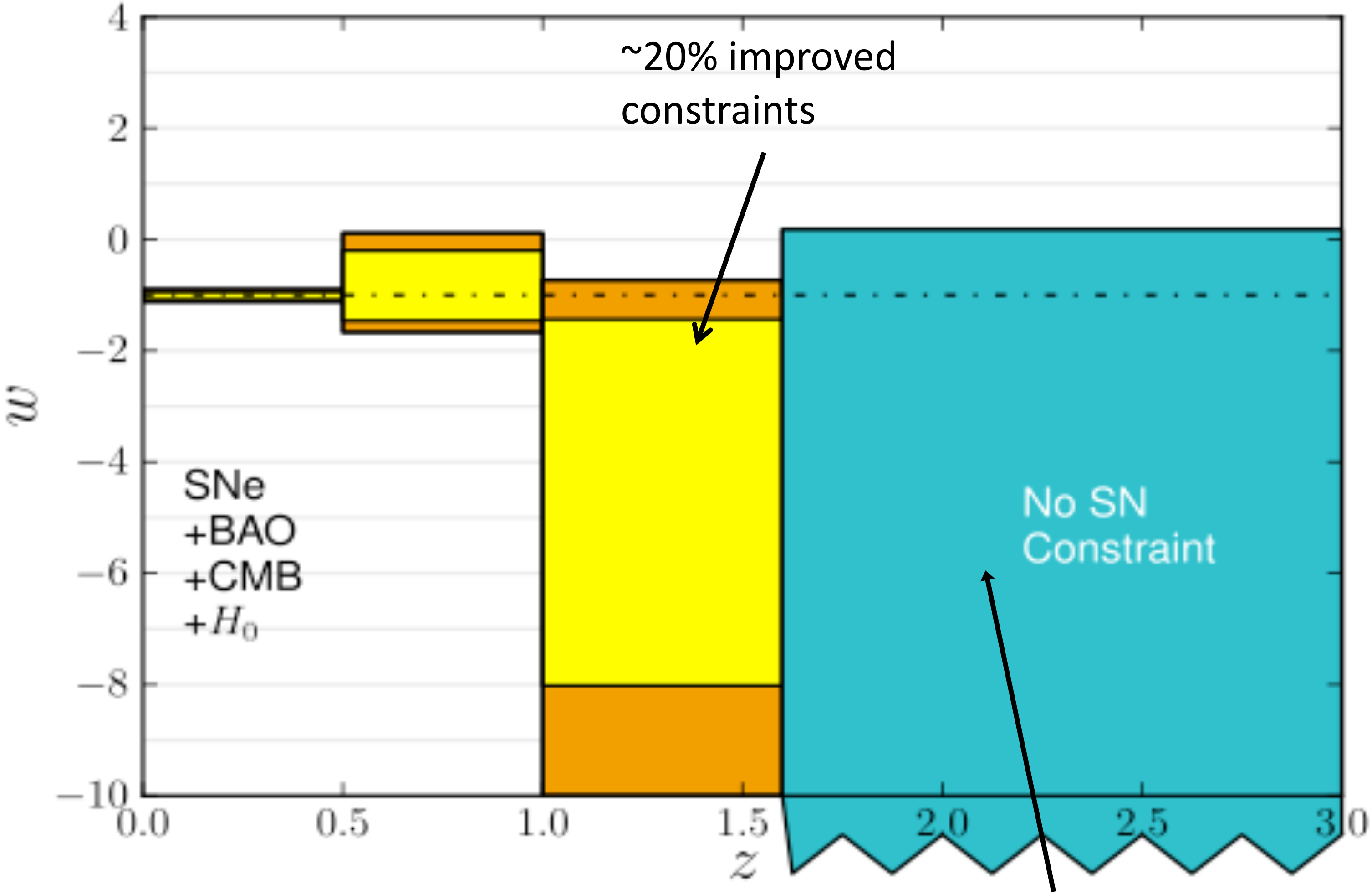
Constant w:
$w = -0.951 \pm 0.078$

Redshift dependent w:
$w(a) = w_0 + (1-a) \times w_a$
$W_a = 0.14 \pm 0.68$

No deviation from $w = -1$ (i.e. Λ)

Redshift dependent EOS

Assuming step-wise constant *w*:

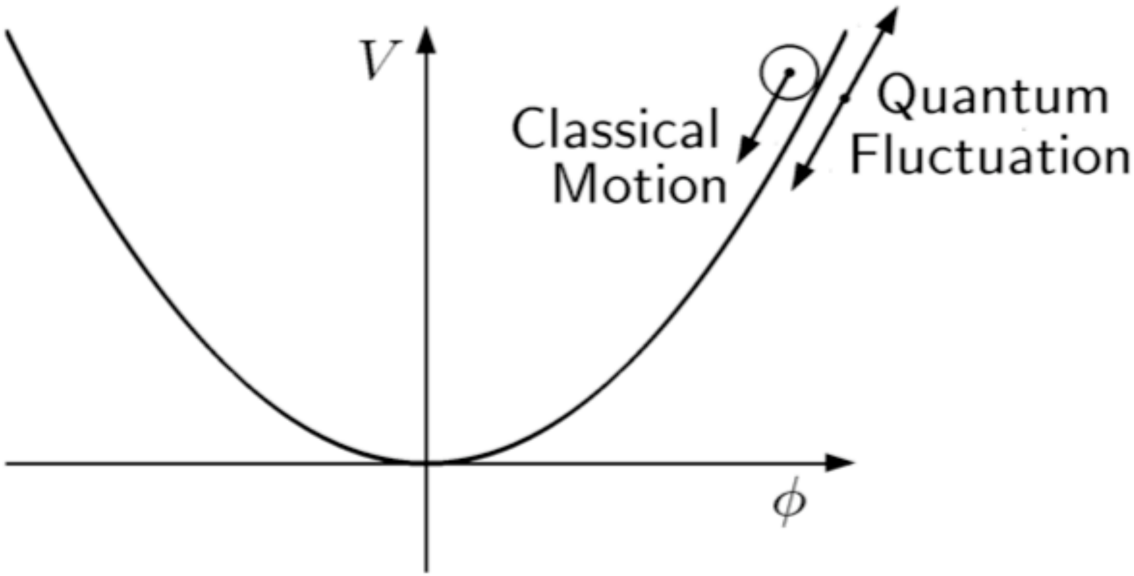


A floating non-SNe bin to decouple low from high-redshift constraints

Constraints on Inflation parameters

e.g. Chaotic Inflation (Linde, 1983)

$$V(\phi) = \lambda \phi^p$$



Power spectrum of curvature perturbations

$$\Delta_R^2(k) \propto \left(\frac{k}{k_0}\right)^{n_s - 1}$$

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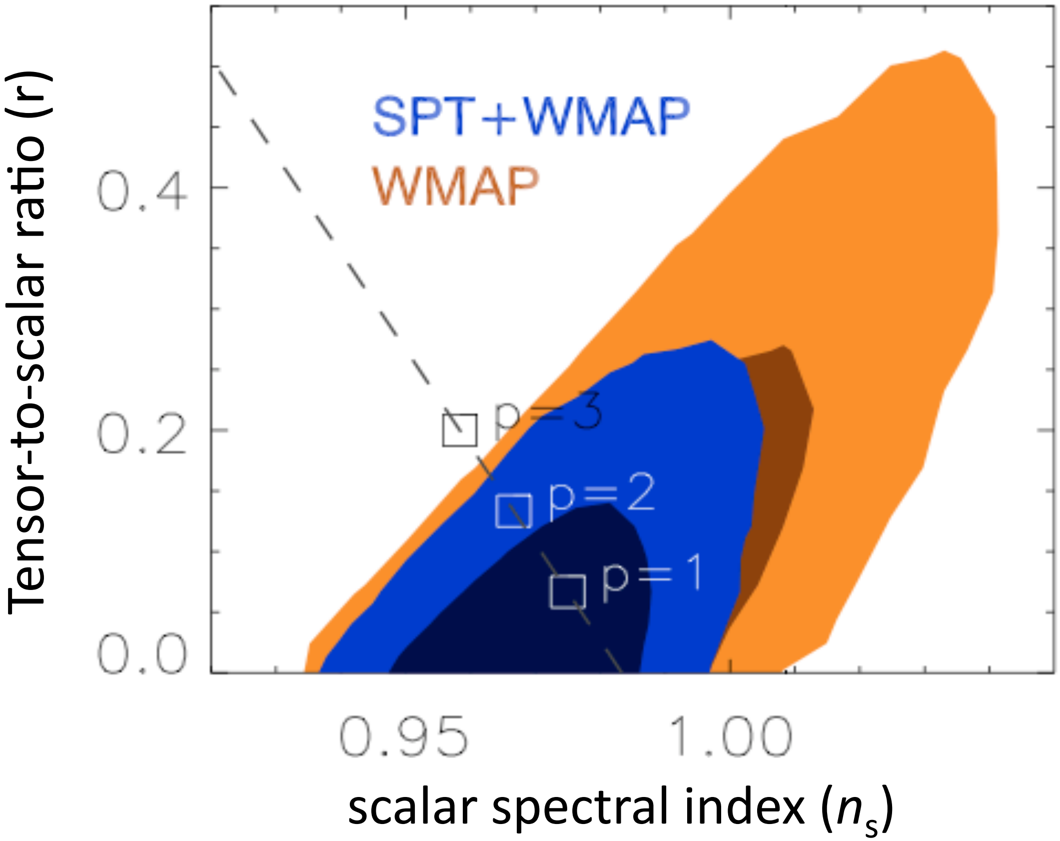


Power spectrum of curvature perturbations

$$\Delta_R^2(k) \propto \left(\frac{k}{k_0}\right)^{n_s - 1}$$

Scalar spectral index

n_s =0.966±0.011

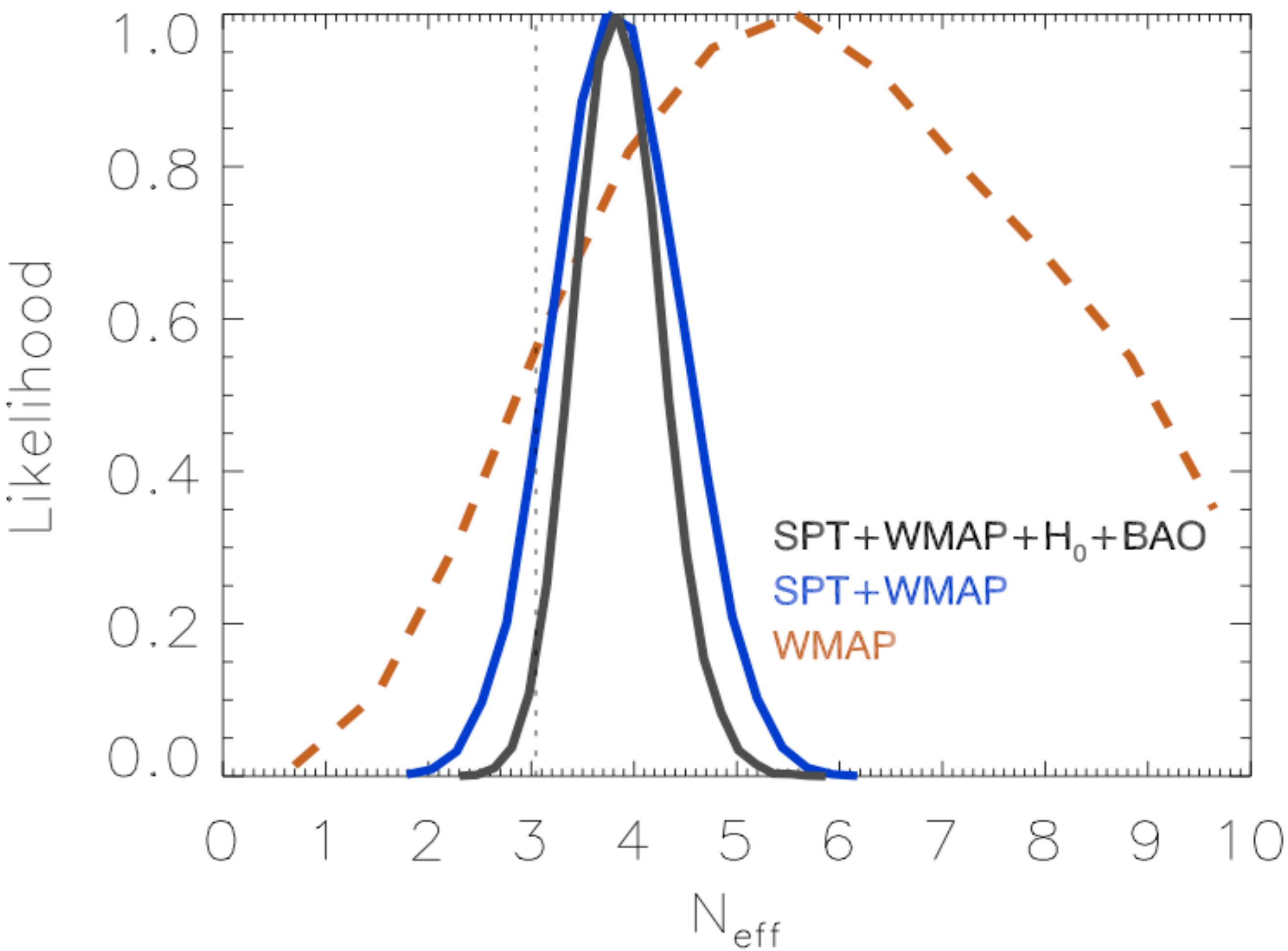
Tensor-to-scalar ratio

r<0.21

SPT+ WMAP7 (Keisler et al. 2011)

Number of relativistic species (neutrinos!)

CMB (& Baryon Nucleosynthesis) sensitive to number of neutrino species N_{eff}

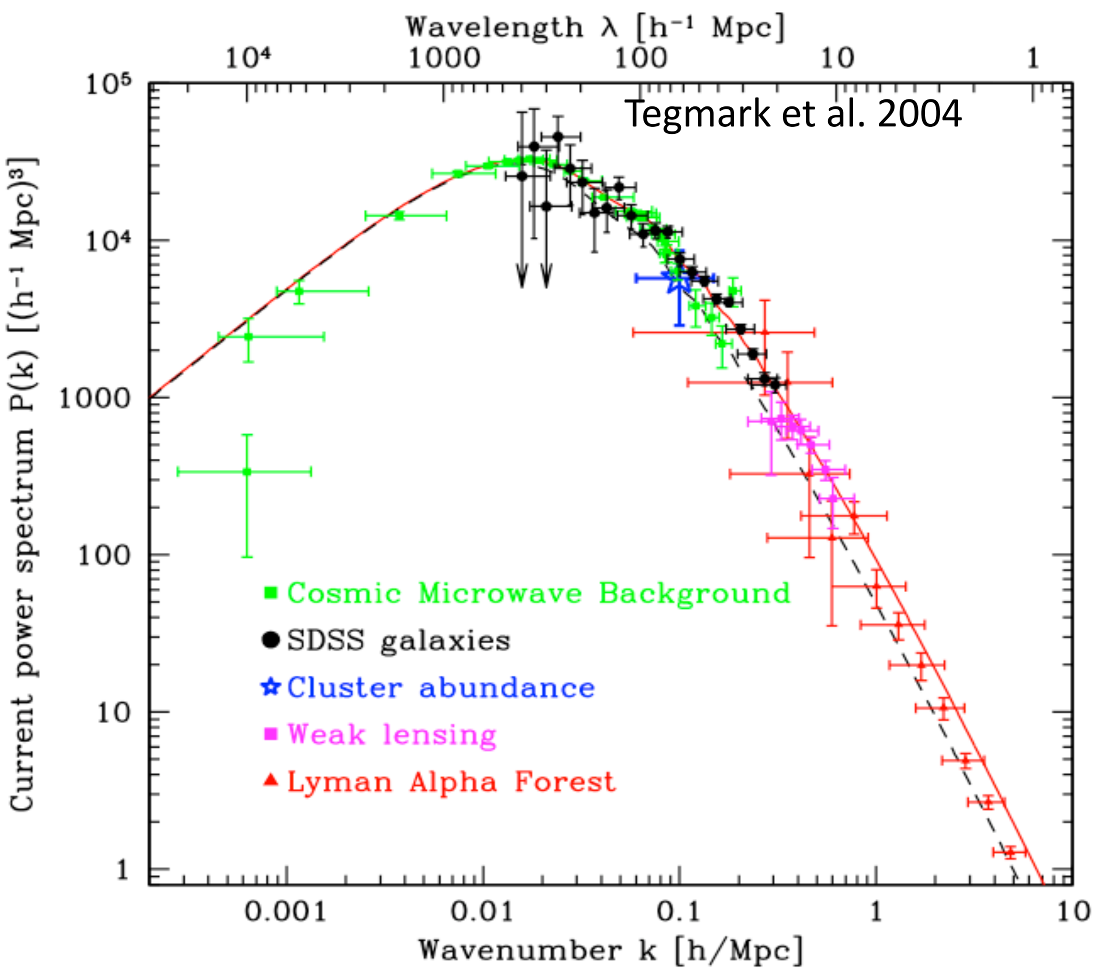


SPT+WMAP7: N_{eff} = 3.85±0.62 (68% CL)

Neutrino mass from CMB & large scale structure

Damping of correlation power due to free streaming at epoch of radiation-matter equality:

$$\left(\frac{\Delta P}{P}\right) \approx -0.8\left(\frac{\sum m_\nu}{1\ \mathrm{eV}}\right)\left(\frac{0.1}{\Omega_m h^2}\right)$$



Combination of CMB+BAO+H_0:

$$\sum m_\nu < 0.5\ \mathrm{eV}\ (95\%\mathrm{CL})$$

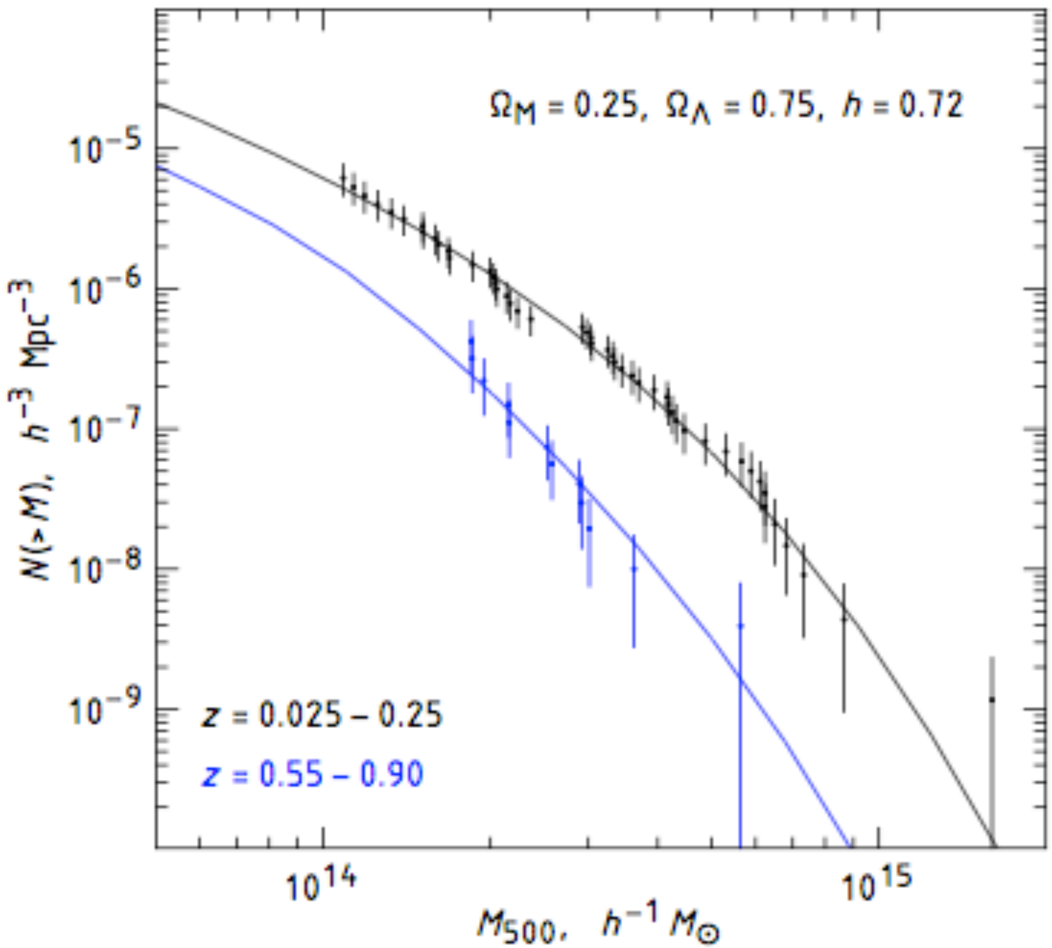
e.g. Komatsu et al (2010)

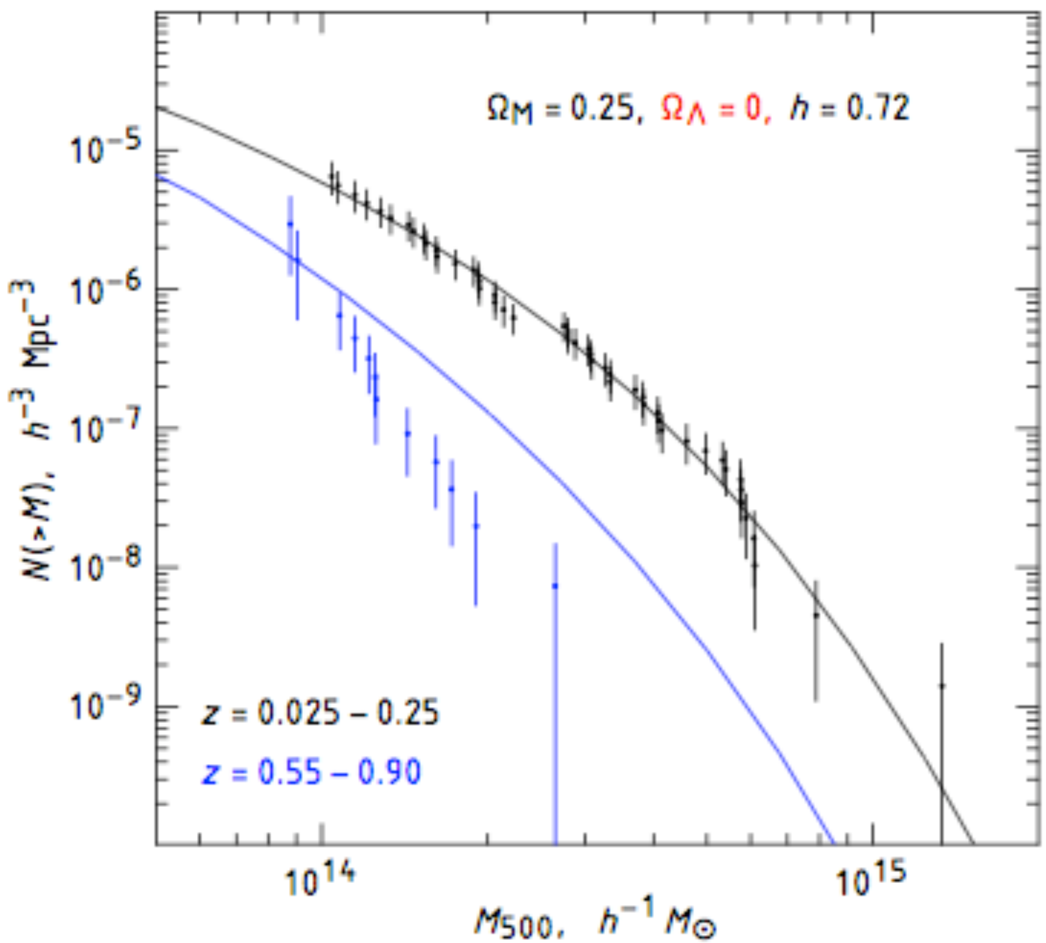
Similar mass bounds also for LSND-like sterile neutrinos

Hamann et al (2010)

Summary

- Cosmology today is about precision
- Multiple probes for highest sensitivity
- ΛCDM looks strong so far – despite interpretational problems with dark energy
- Many new surveys committed, hence significant progress expected!

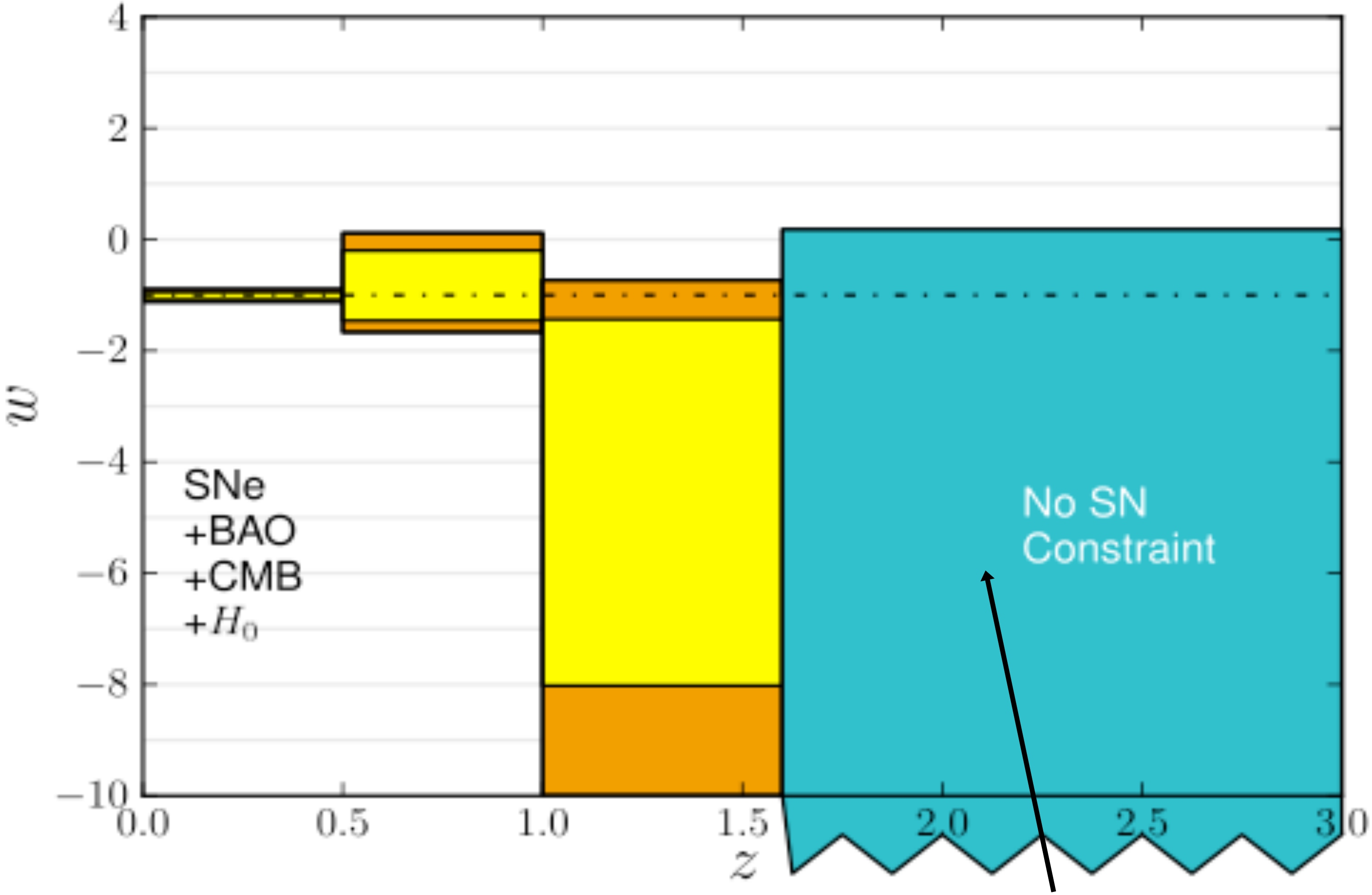




Vikhlini et al. ApJ, 2009

Upcoming surveys: eROSITA, DES, ...

Assuming step-wise constant *w*:



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