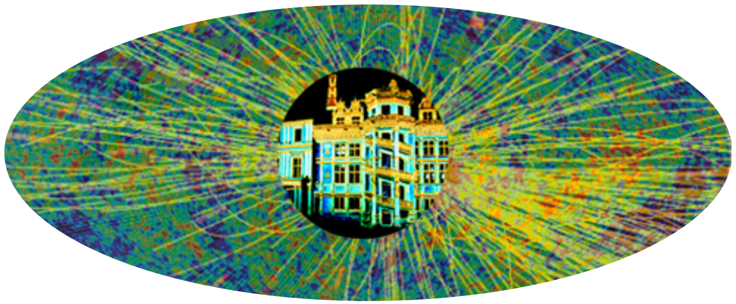
Observational Cosmology
- a unique laboratory for fundamental physics



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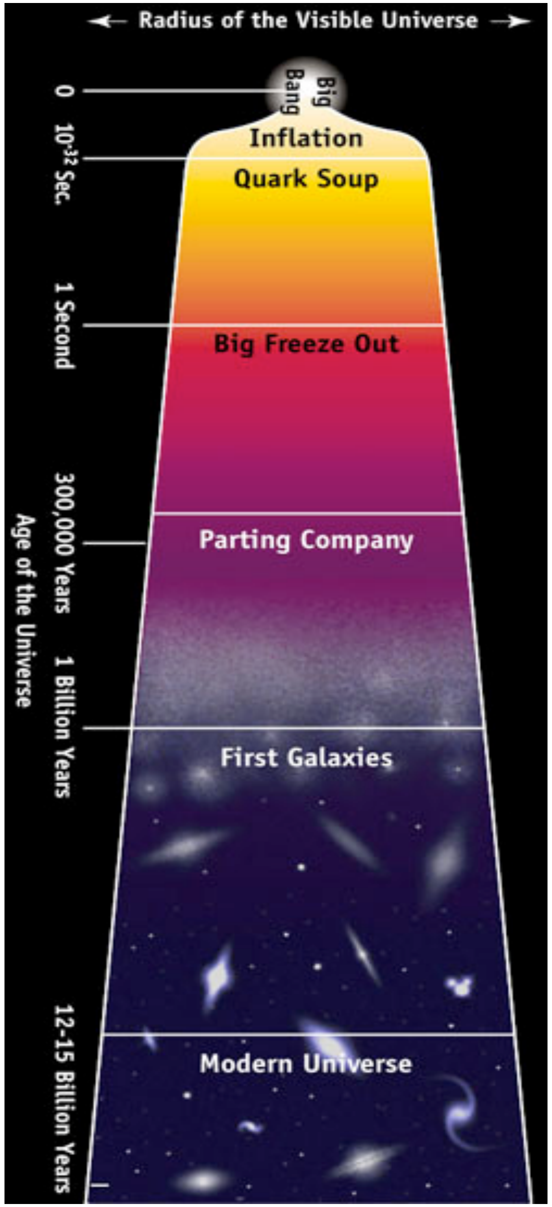
Outline

- Introduction
- Cosmological probes
- Cosmological constraints

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:

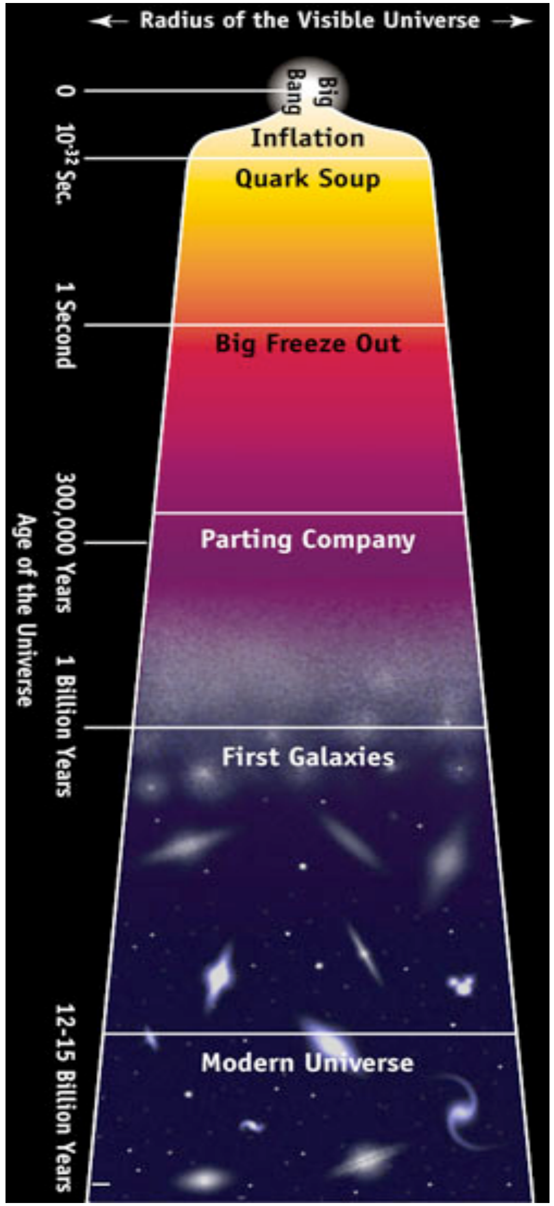
- **Non-Λ dark energy**
- Hot dark matter,

  e.g. **massive neutrinos**
- Additional relativistic species,

  e.g **extra neutrino species**
- Tensor perturbations

  & running spectral index

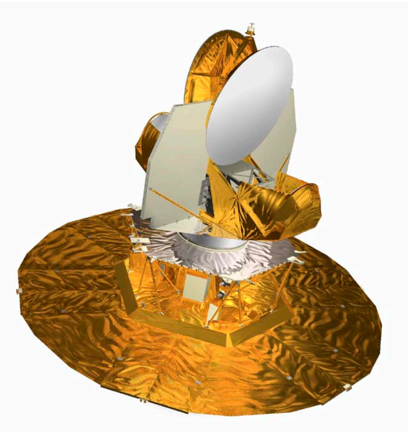
  ⇒ **physics of Inflation**



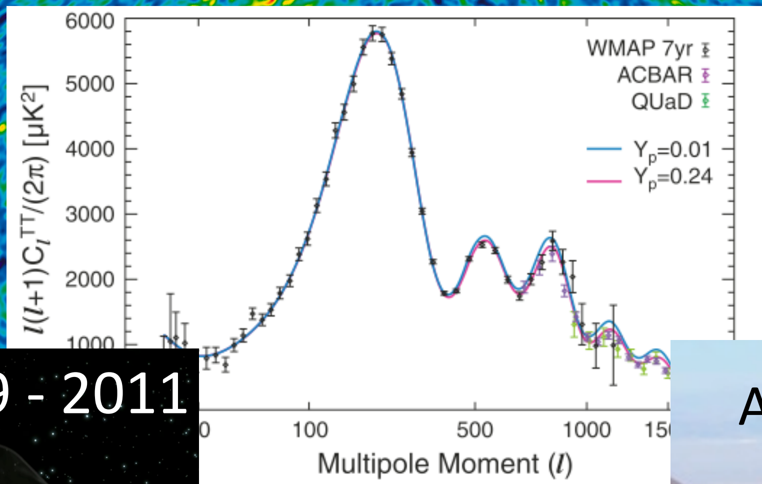
Cosmological Probes: Selected new results

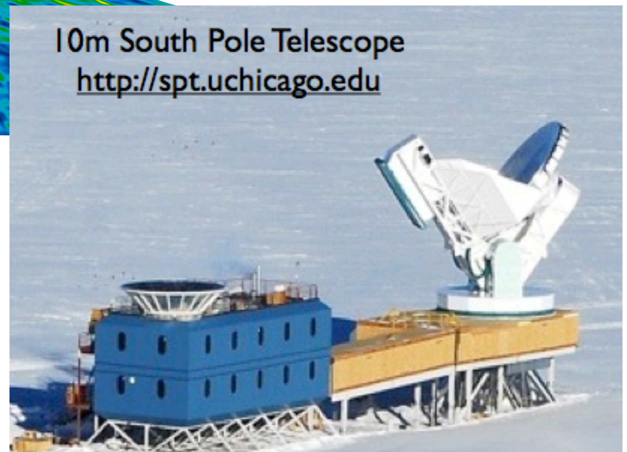
Cosmic Microwave Background

WMAP



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





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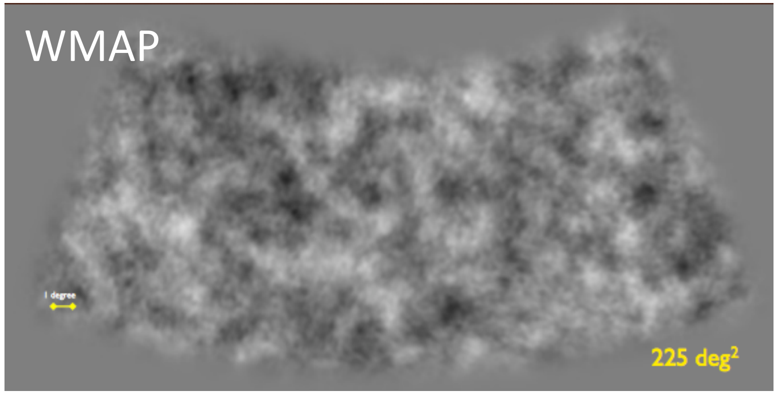

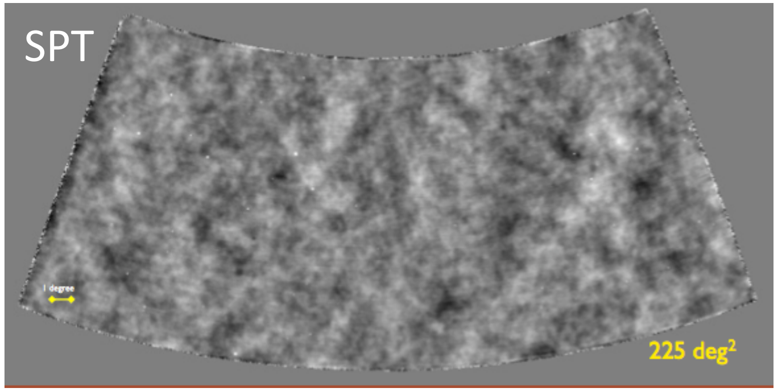

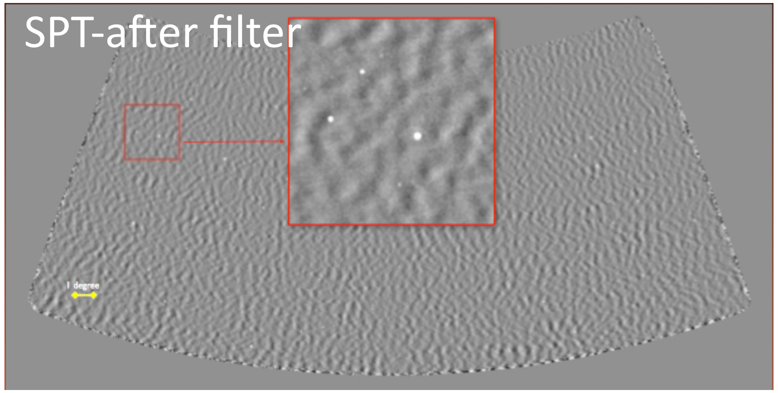

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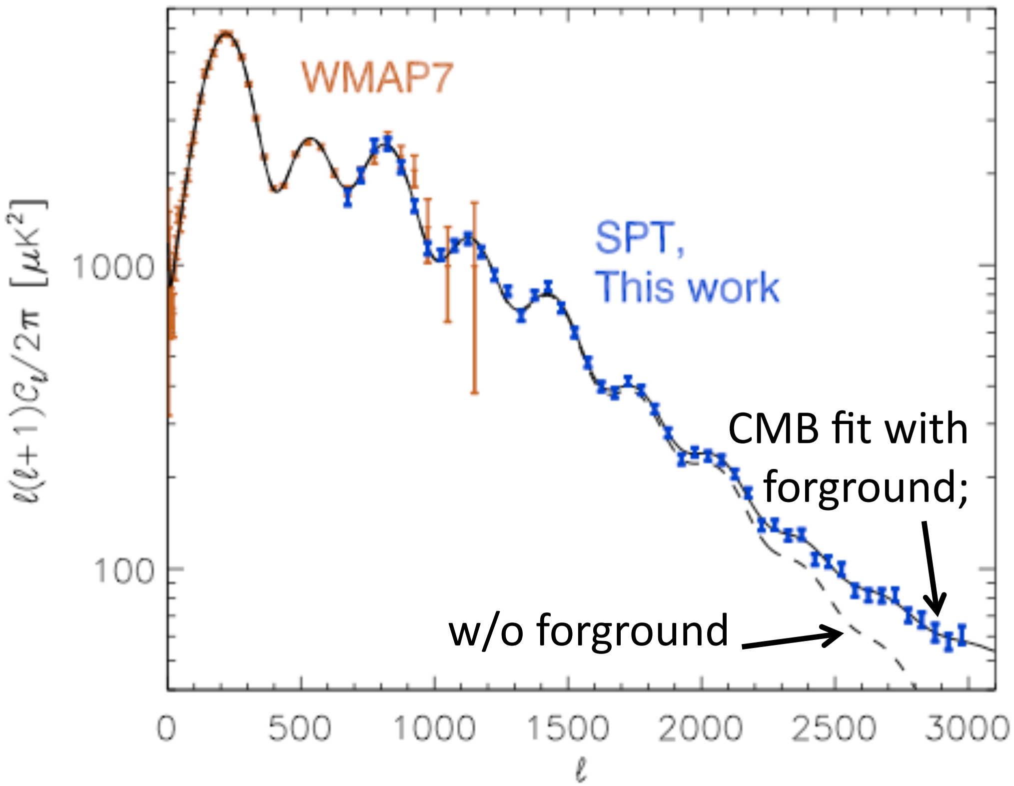
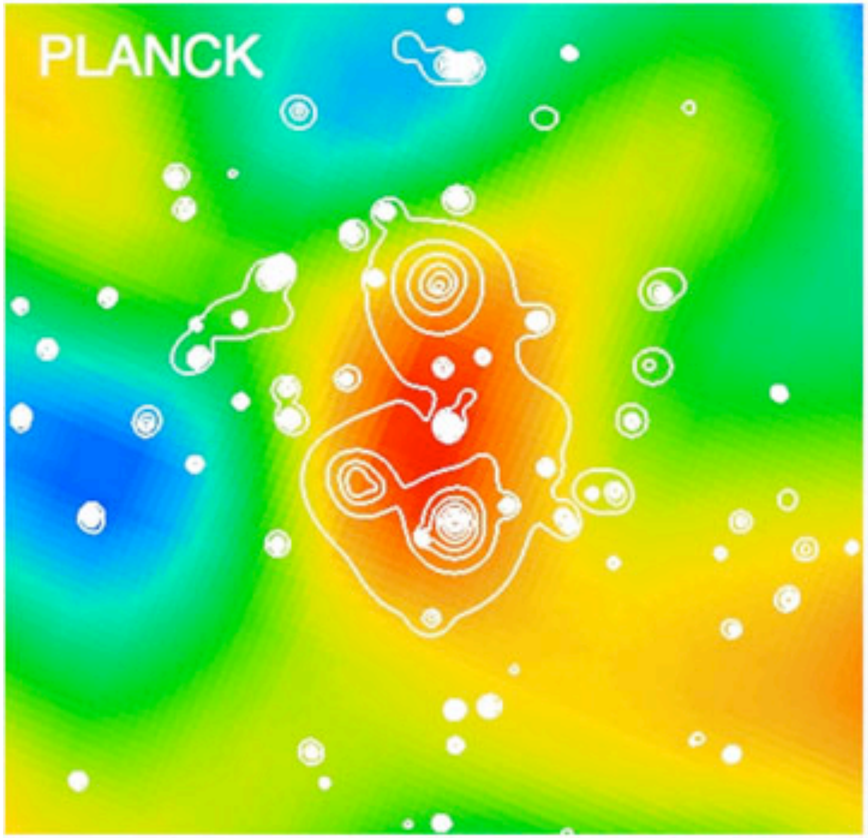


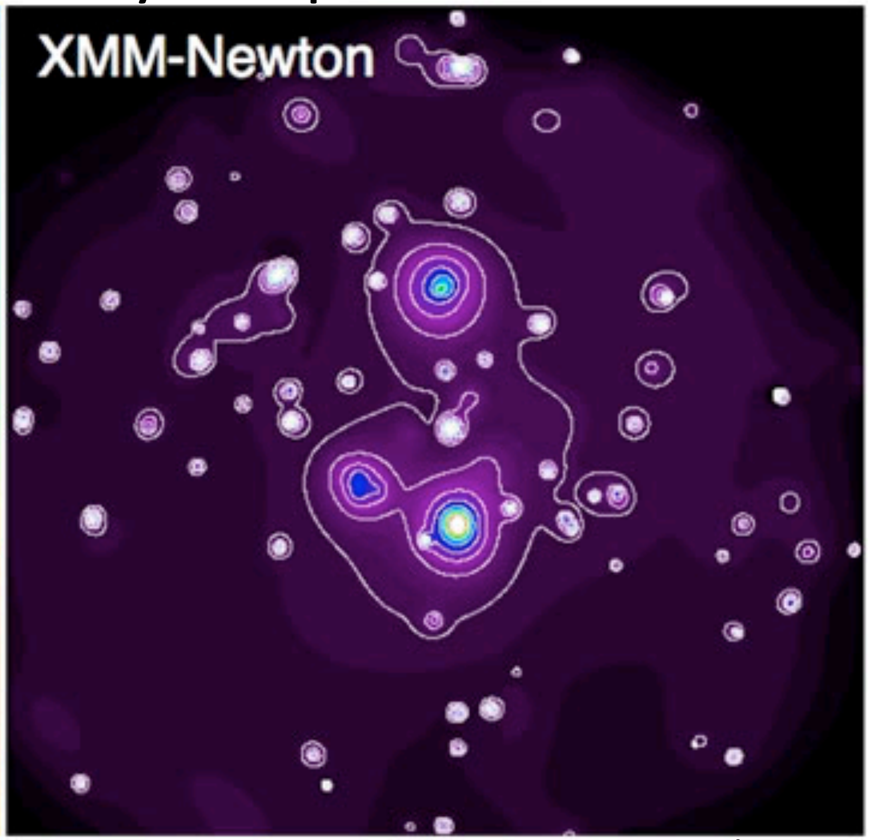
4σ detections of CMB weak lensing!

Galaxy Clusters

CMB footprint

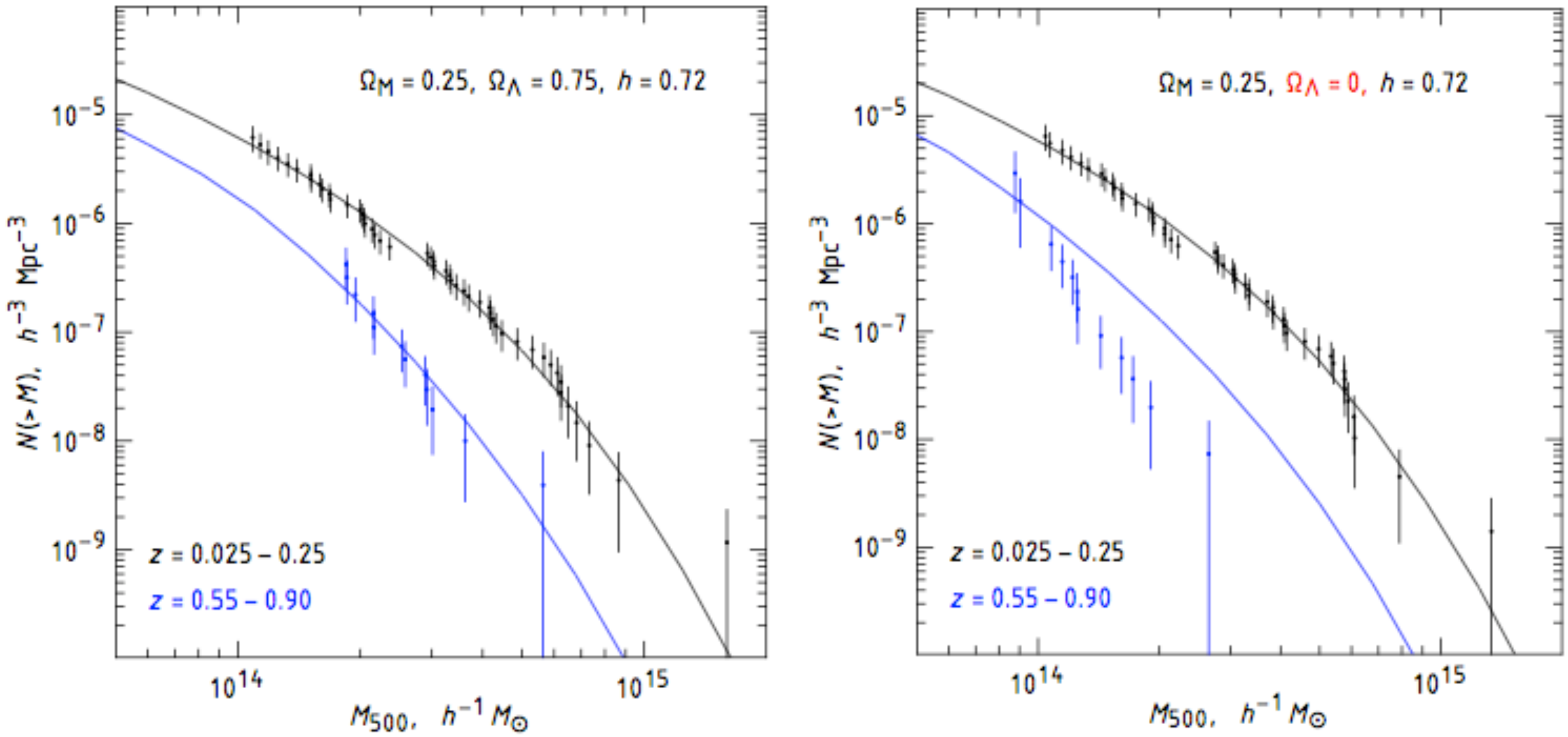


X-ray footprint



Picture credit: ESA

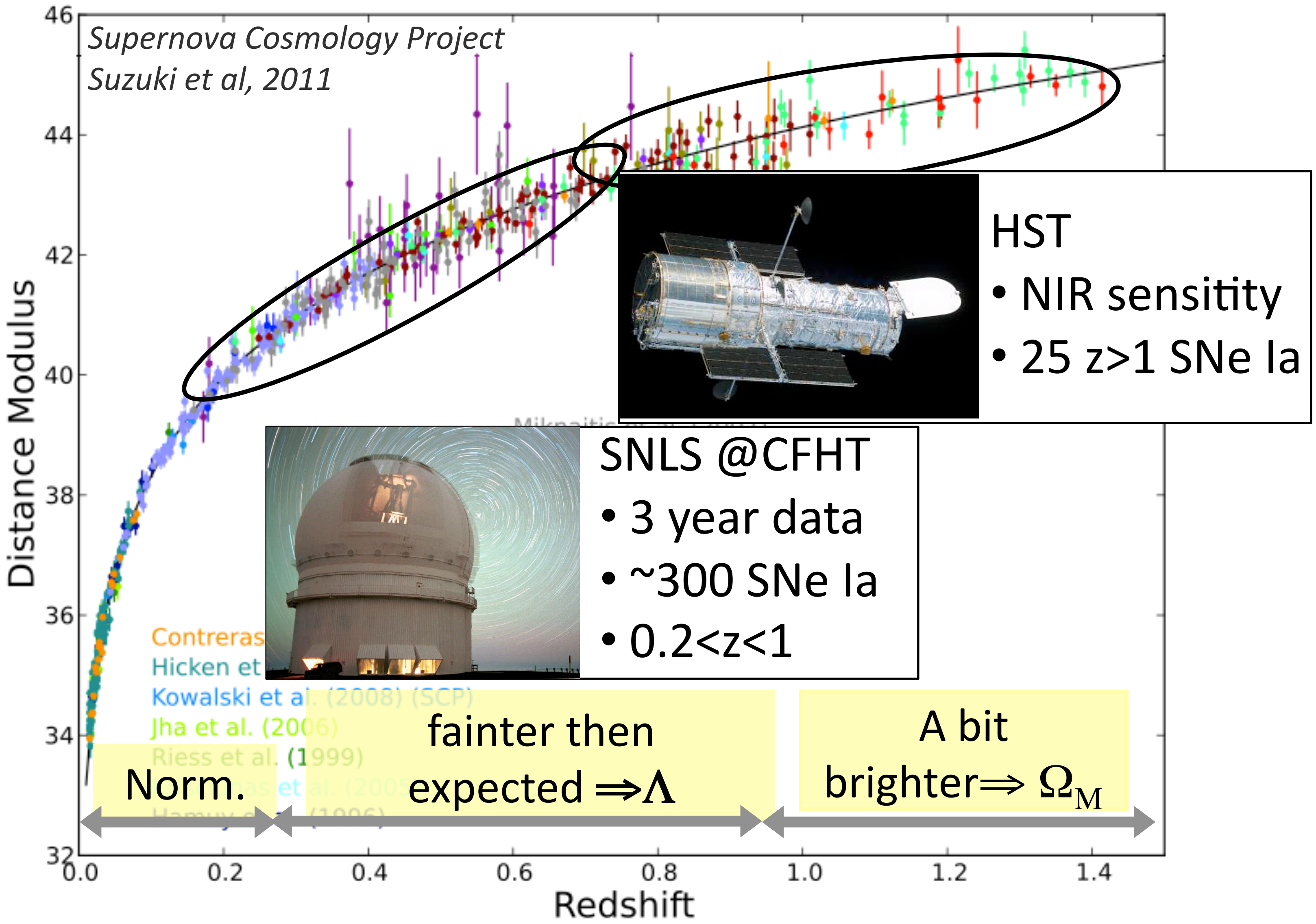
Counting Galaxy Clusters



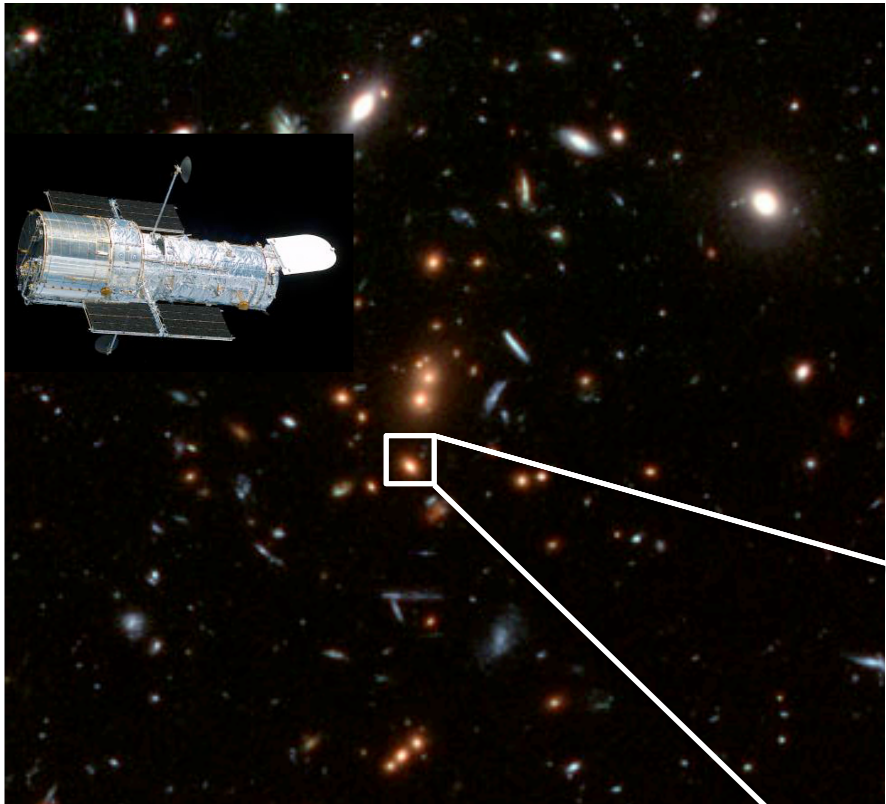
Vikhlini et al. ApJ, 2009

Upcoming surveys: eROSITA, DES, ...

Supernova Hubble Diagram



Efficient HST survey for z>1 SNe



Survey of z>0.9 galaxy clusters

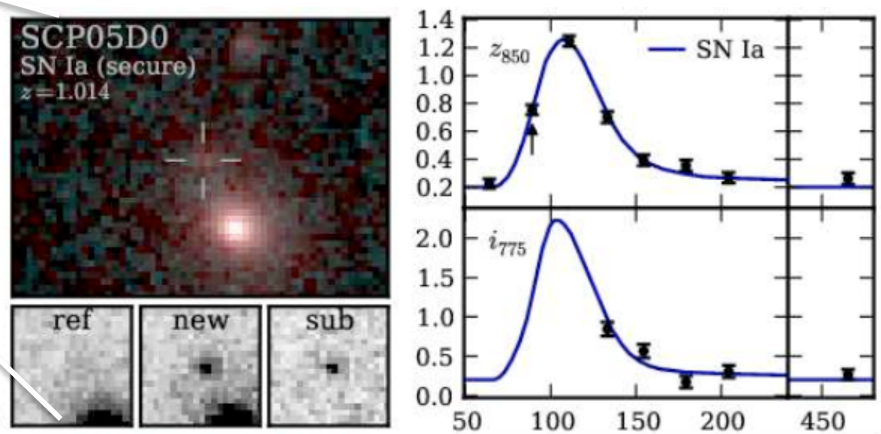
⇒ SNe from cluster & field

⇒ about 2 x more efficient

⇒ enhencement of early hosts

⇒ 20 new HST SNe

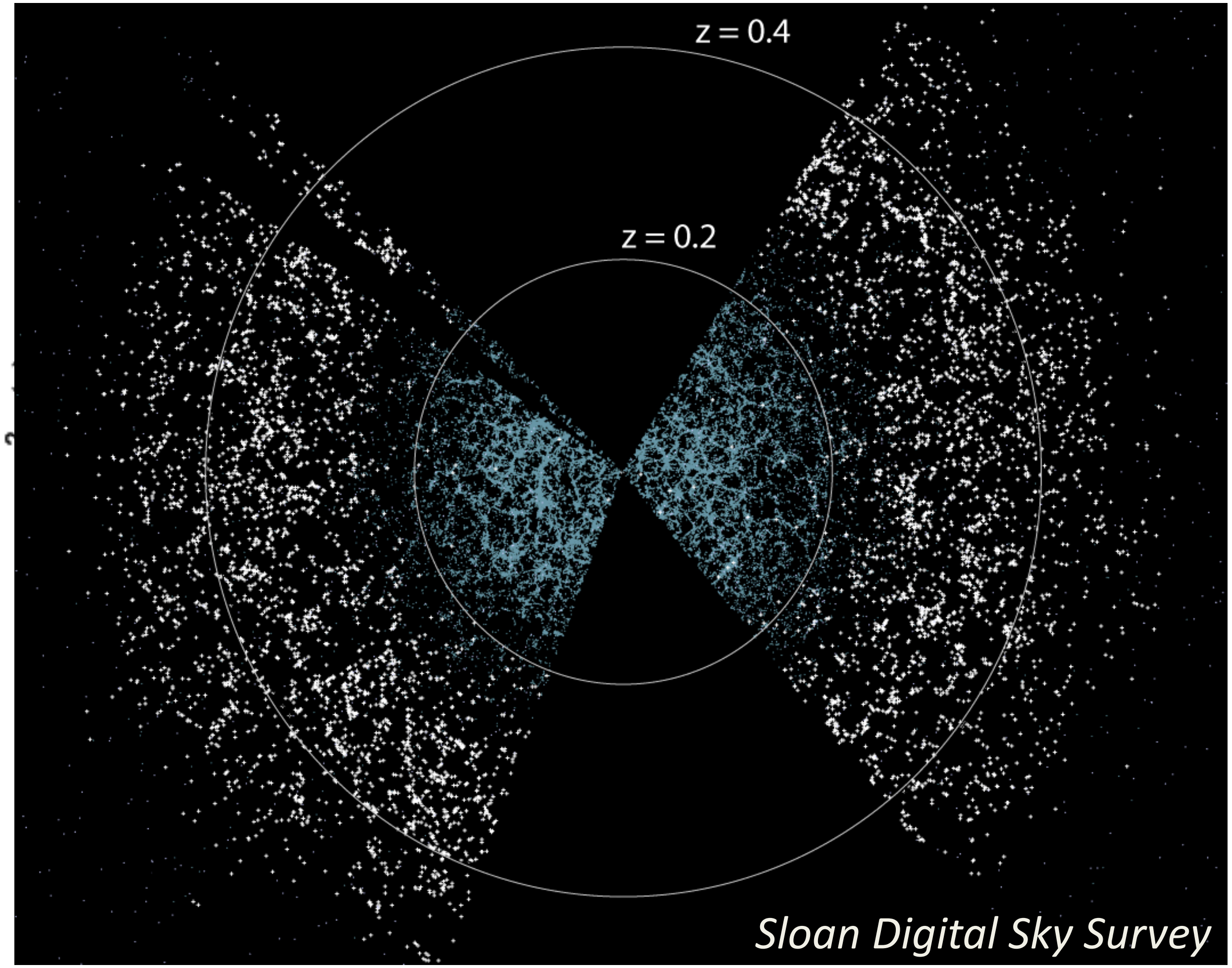
⇒ 10 high quality z>1 SNe!



Supernova Cosmology Project
Suzuki et al., 2011

Baryon Acoustic Oscillation

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



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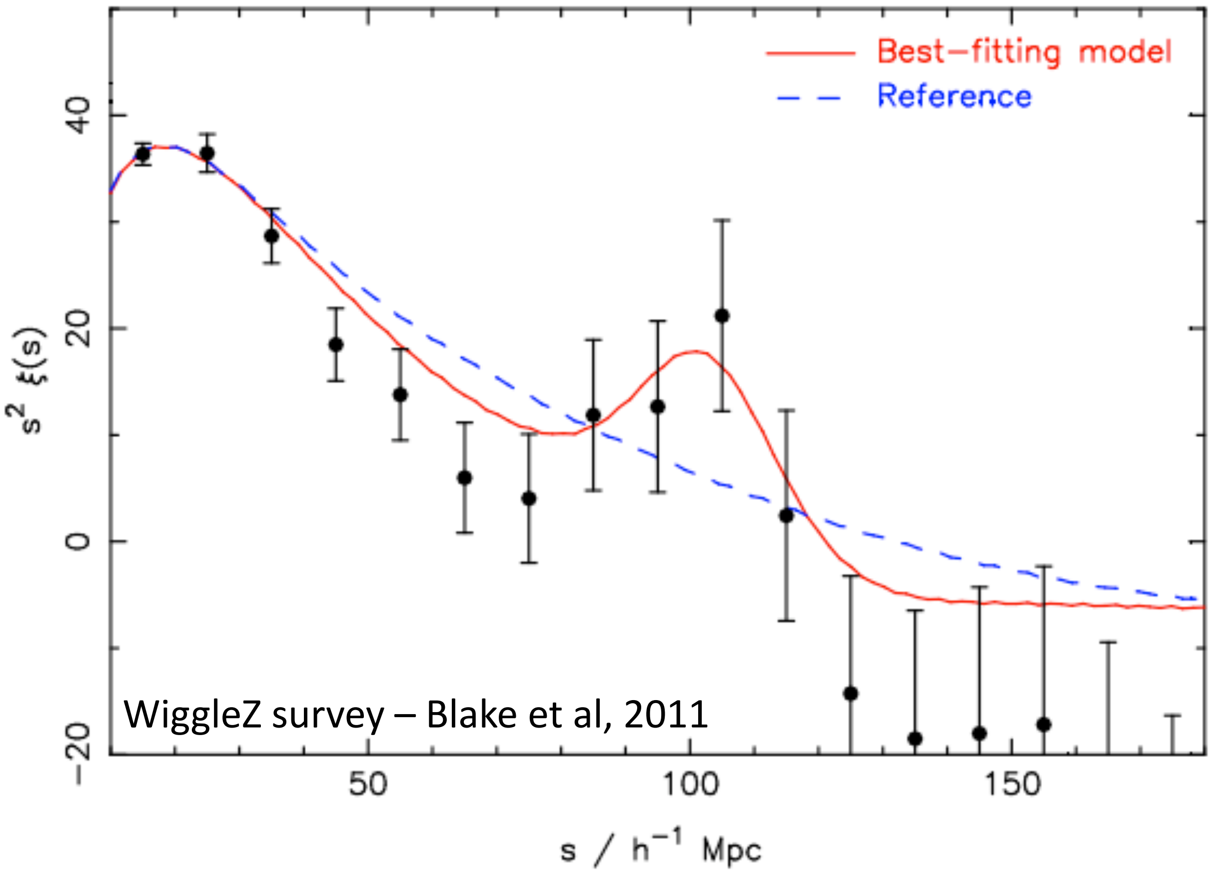

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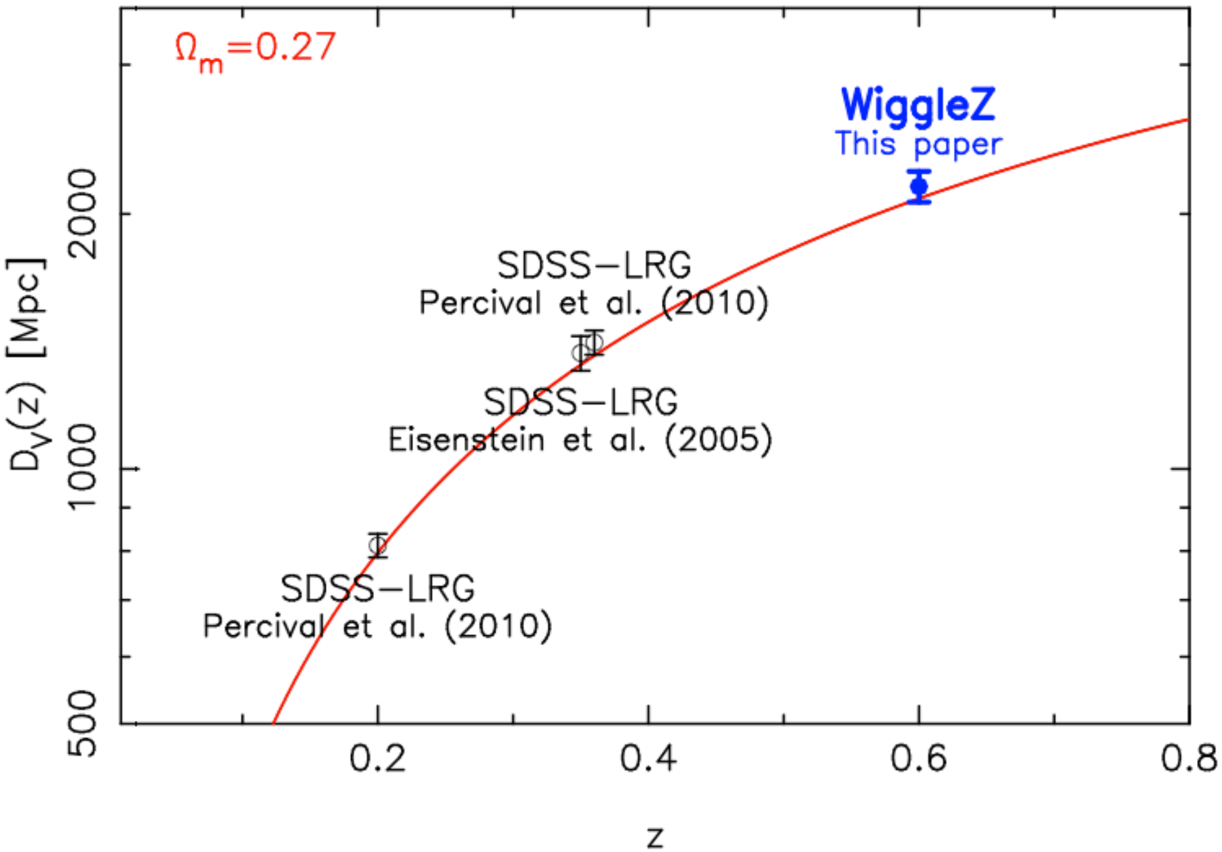
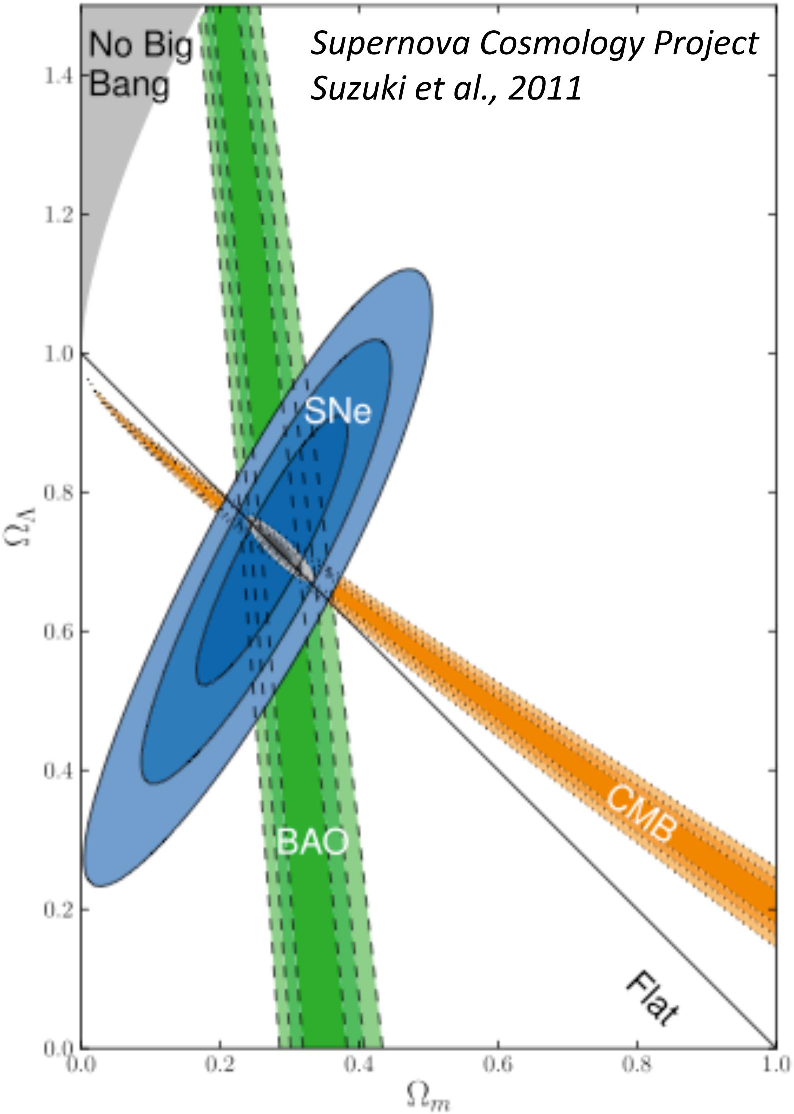


Promising technique & much activity: BOSS, HETDEX,...

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)

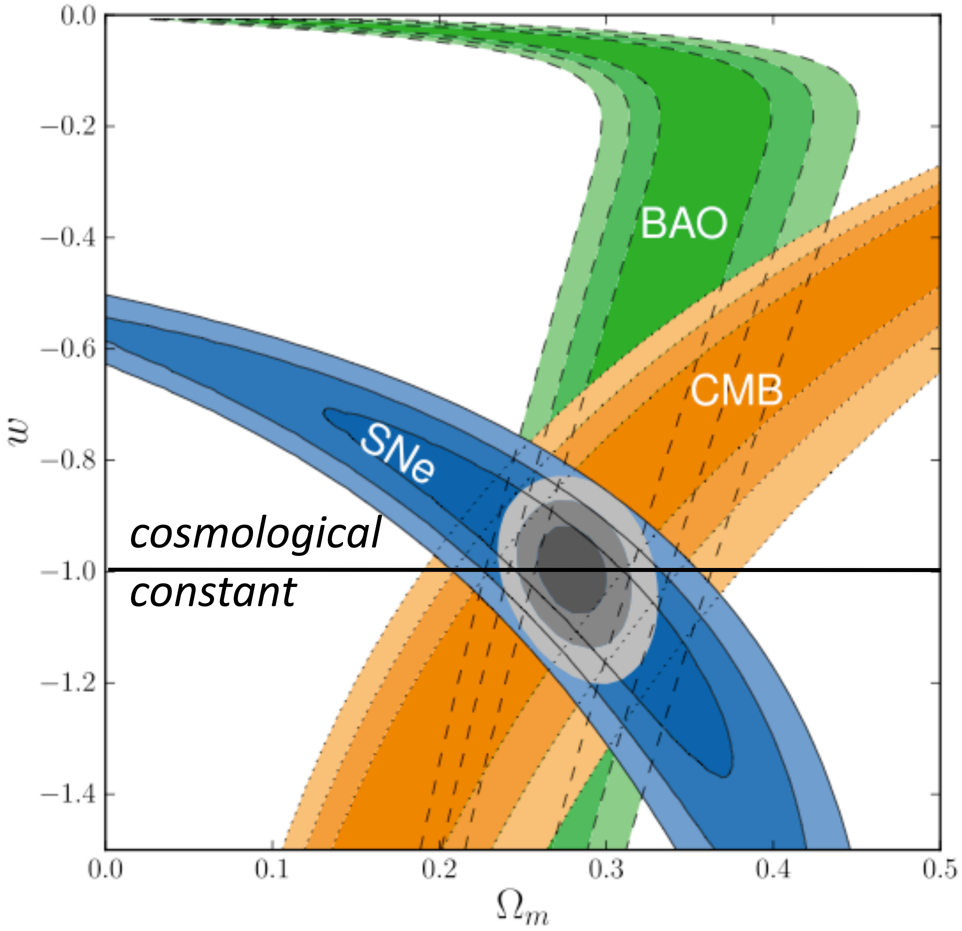
$$\Omega_m = 0.729 \pm 0.014$$

and allowing for curvature:

$$\Omega_k = 0.002 \pm 0.005$$

Dark Energy

Supernova Cosmology Project
Suzuki et al., 2011



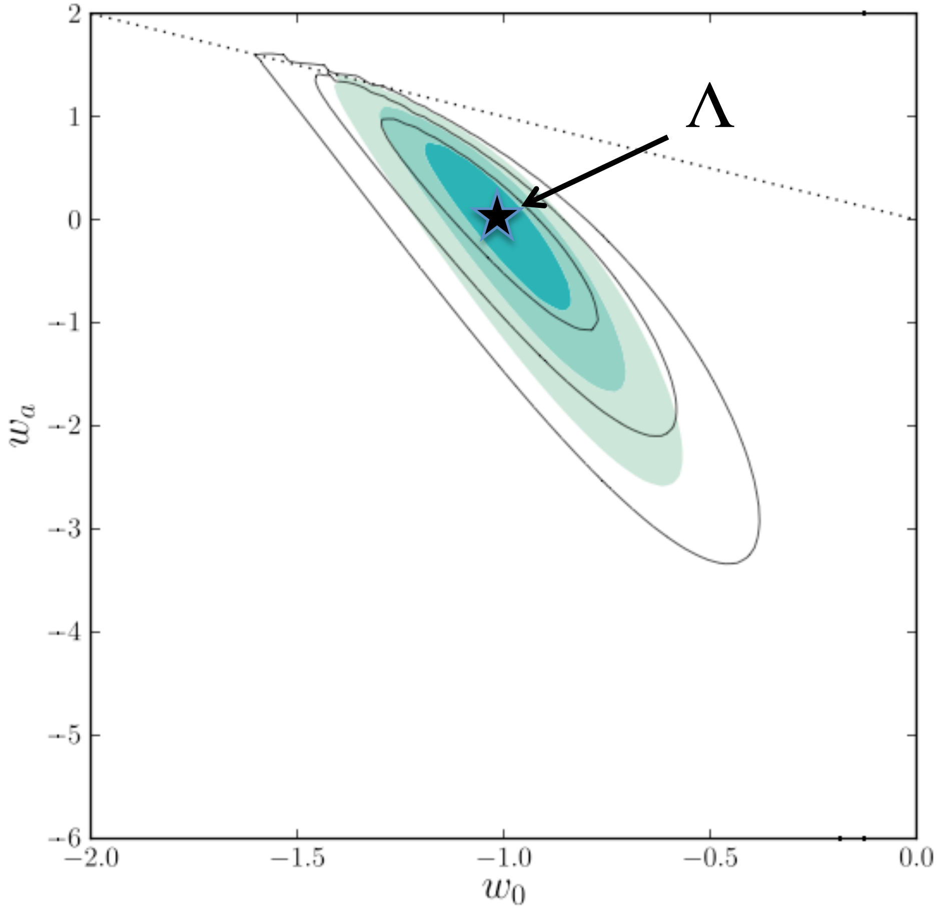
Equation of state: *p=wρ*

Constant w:

w=-0.995±0.078

Dark Energy

Supernova Cosmology Project
Suzuki et al., 2011



Equation of state: *p=wρ*

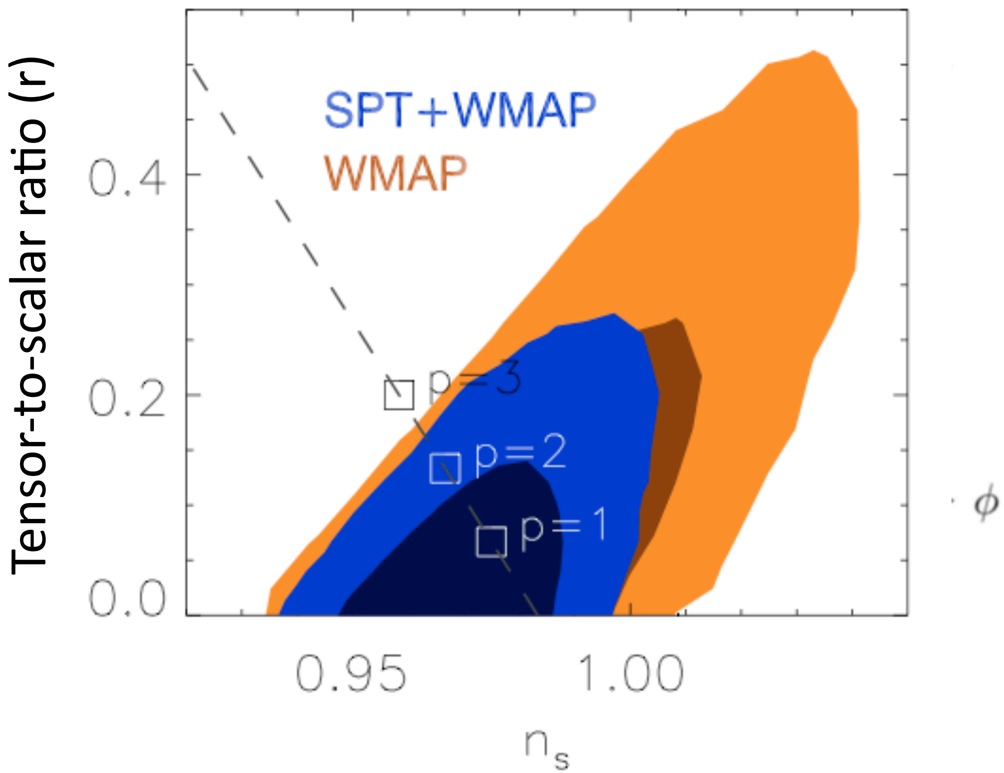
Constant w:
w=-0.995±0.078

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

No deviation from
***w*=-1 (i.e. Λ)**

Constraints on Inflation parameters

e.g. Chaotic Inflation (Linde, 1983) $V(\phi) = \lambda\phi^p$



Power spectrum of curvature perturbations

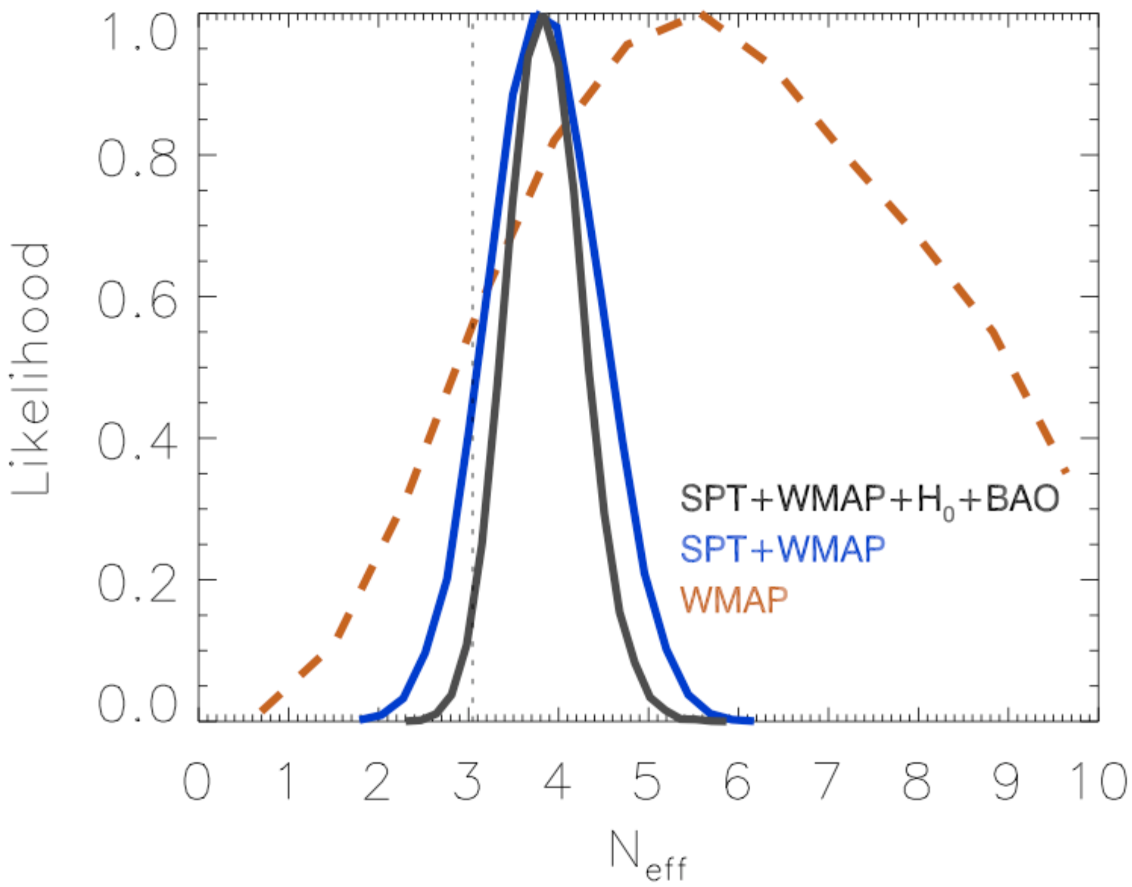
$$\Delta_R^2(k) \propto \left(\frac{k}{k_0}\right)^{n_s - 1}$$

Scalar spectral index*	Tensor-to-scalar ratio*	Spectral tilt*
$n_s = 0.966 \pm 0.011$	$r < 0.21$	$dn_s/d\ln k = -0.024 \pm 0.013$

*SPT+ WMAP7 (Keisler et al. 2011), constraints are model dependent

Number of relativistic species (neutrinos!)

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

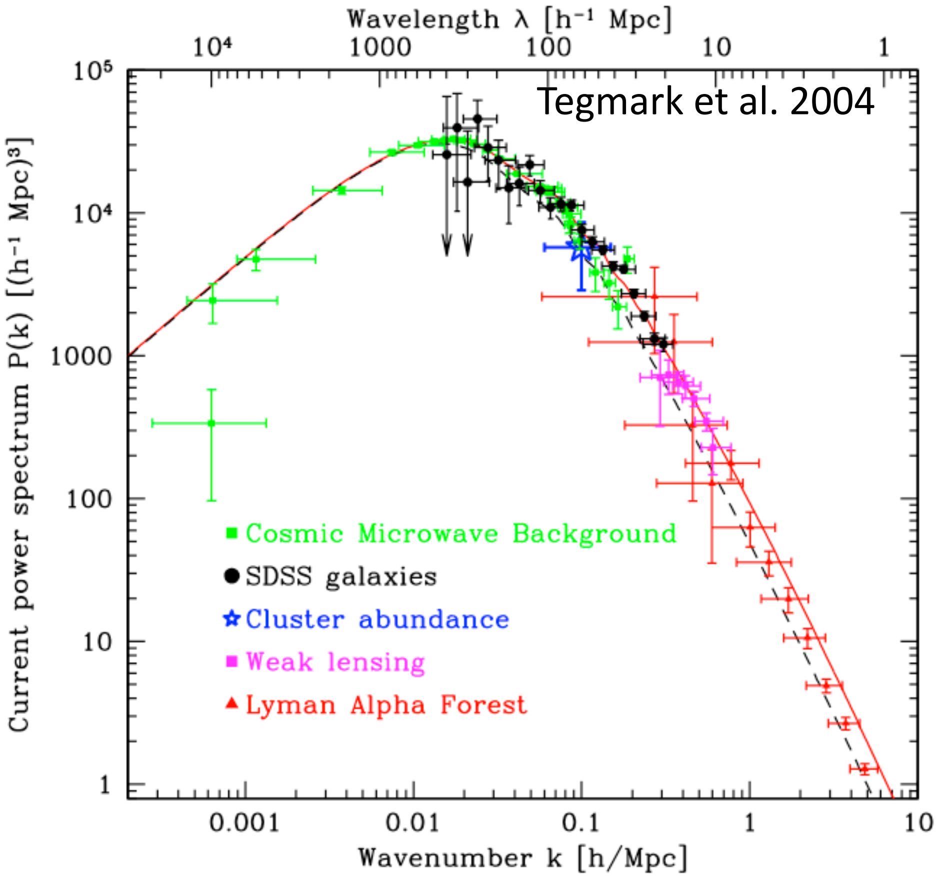


SPT+WMAP7: N_{eff} = 3.85±0.62

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

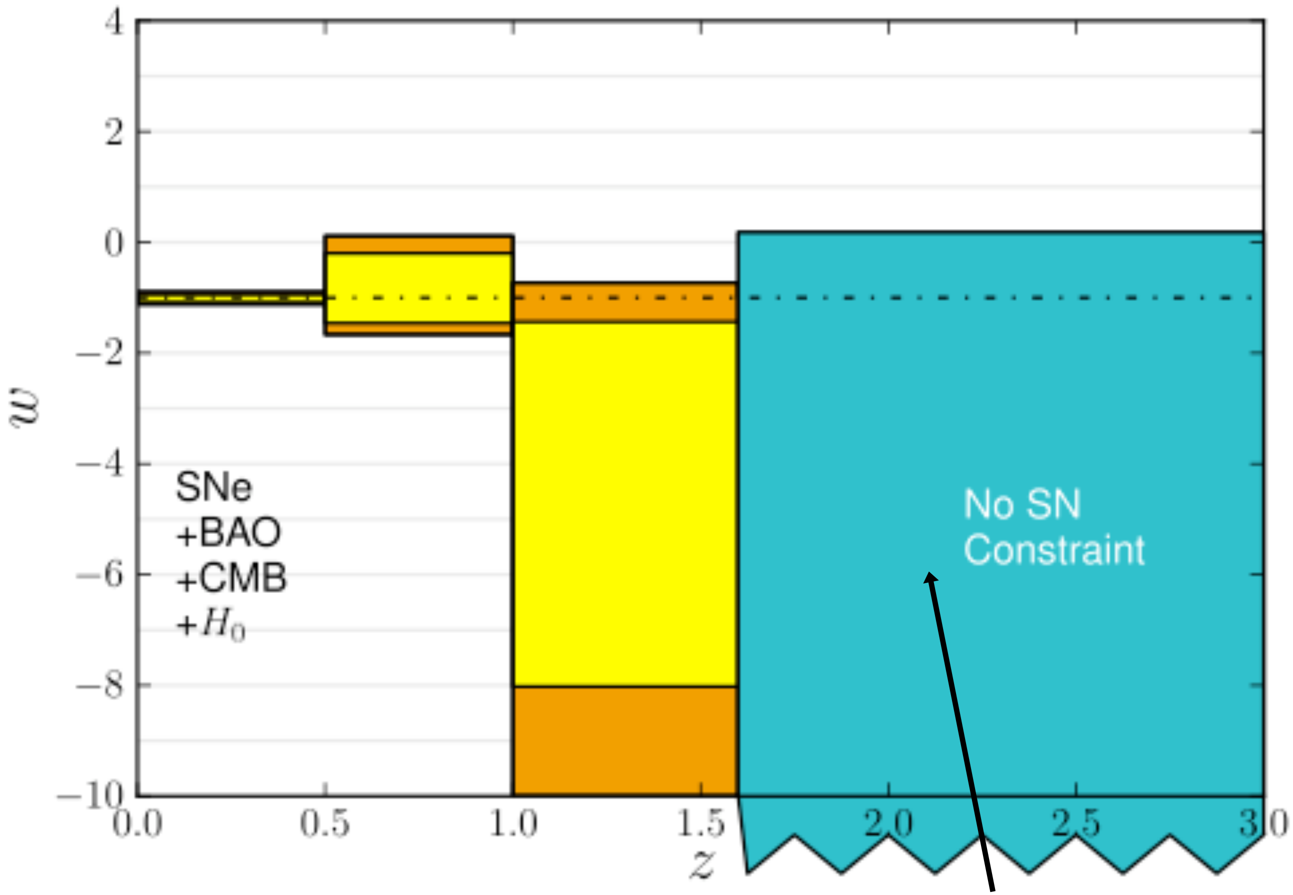
Hamann et al (2010)

Summary

- Cosmology today is about precision
- Multiple probes for highest sensitivity
- ΛCDM looks strong, however, physics beyond the standard model might just be around the corner
- Many new surveys commited, hence tremendous progress expected!

Redshift dependent EOS

Assuming step-wise constant *w*:



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