CMB evidence for non-baryonic matter

Erminia Calabrese
Oxford University

Alternative Gravity and Alternative Matter Workshop – May 20th 2015

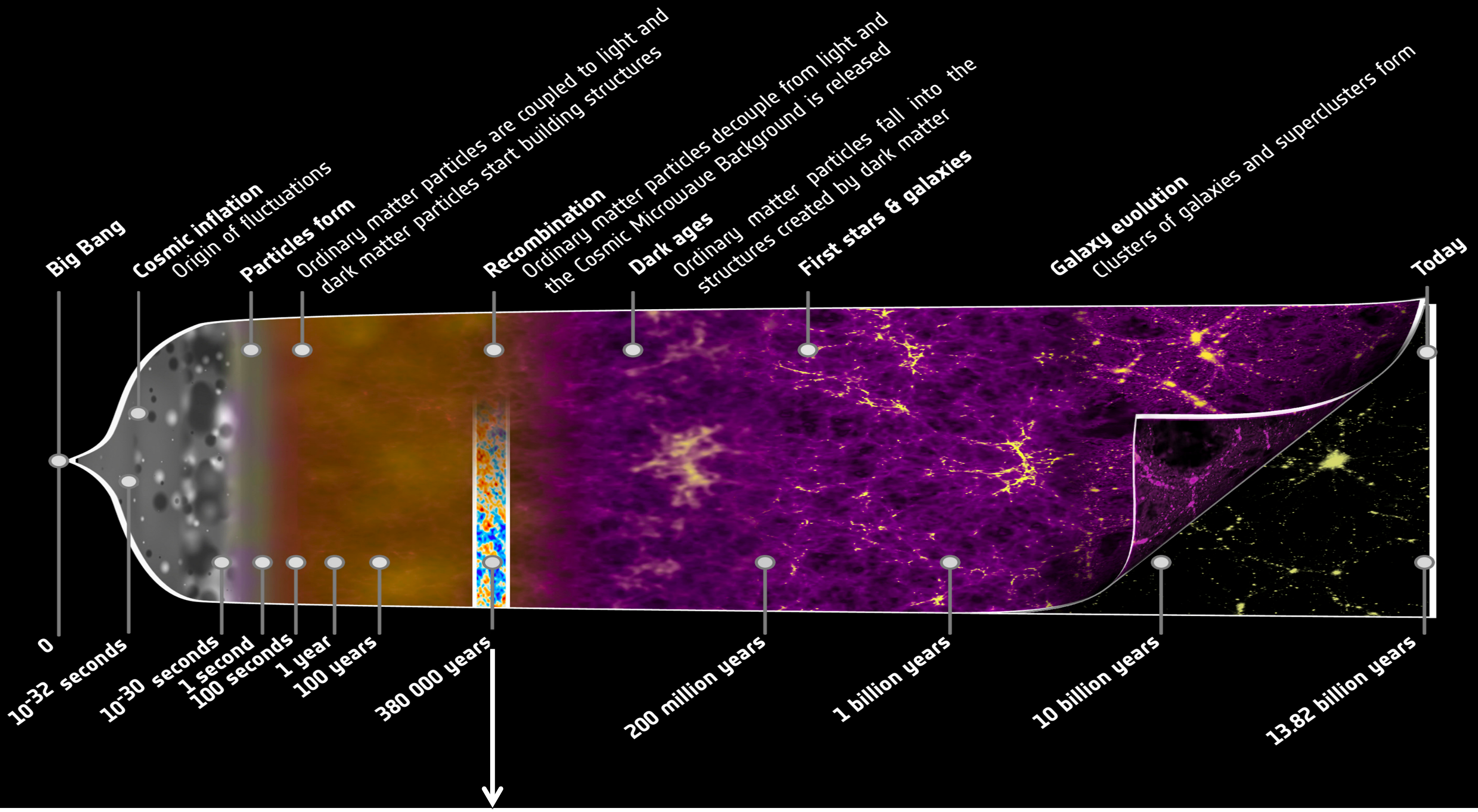
Outline

- The Cosmic Microwave Background
  - Physics/Data/Analysis
  - Theory predictions: how to distinguish parameters
  - Current standard model measurements
  - CMB lensing: how to break degeneracies

- Dark Energy
- Dark Matter
- Neutrinos

- Coming next
  - CMB polarization
  - Cross-correlations with galaxy surveys

The Cosmic Microwave Background



Big Bang

Cosmic inflation
Origin of fluctuations

Particles form

Ordinary matter particles are coupled to light and dark matter particles start building structures

Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released

Dark ages
Ordinary matter particles fall into the structures created by dark matter

First stars & galaxies

Galaxy evolution
Clusters of galaxies and superclusters form

Today

0

10^{-32} seconds

10^{-30} seconds

1 second

100 seconds

1 year

100 years

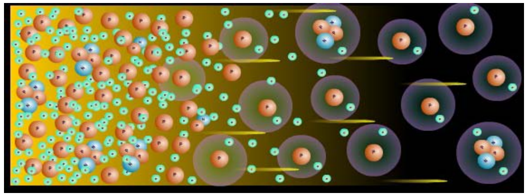
380 000 years

200 million years

1 billion years

10 billion years

13.82 billion years



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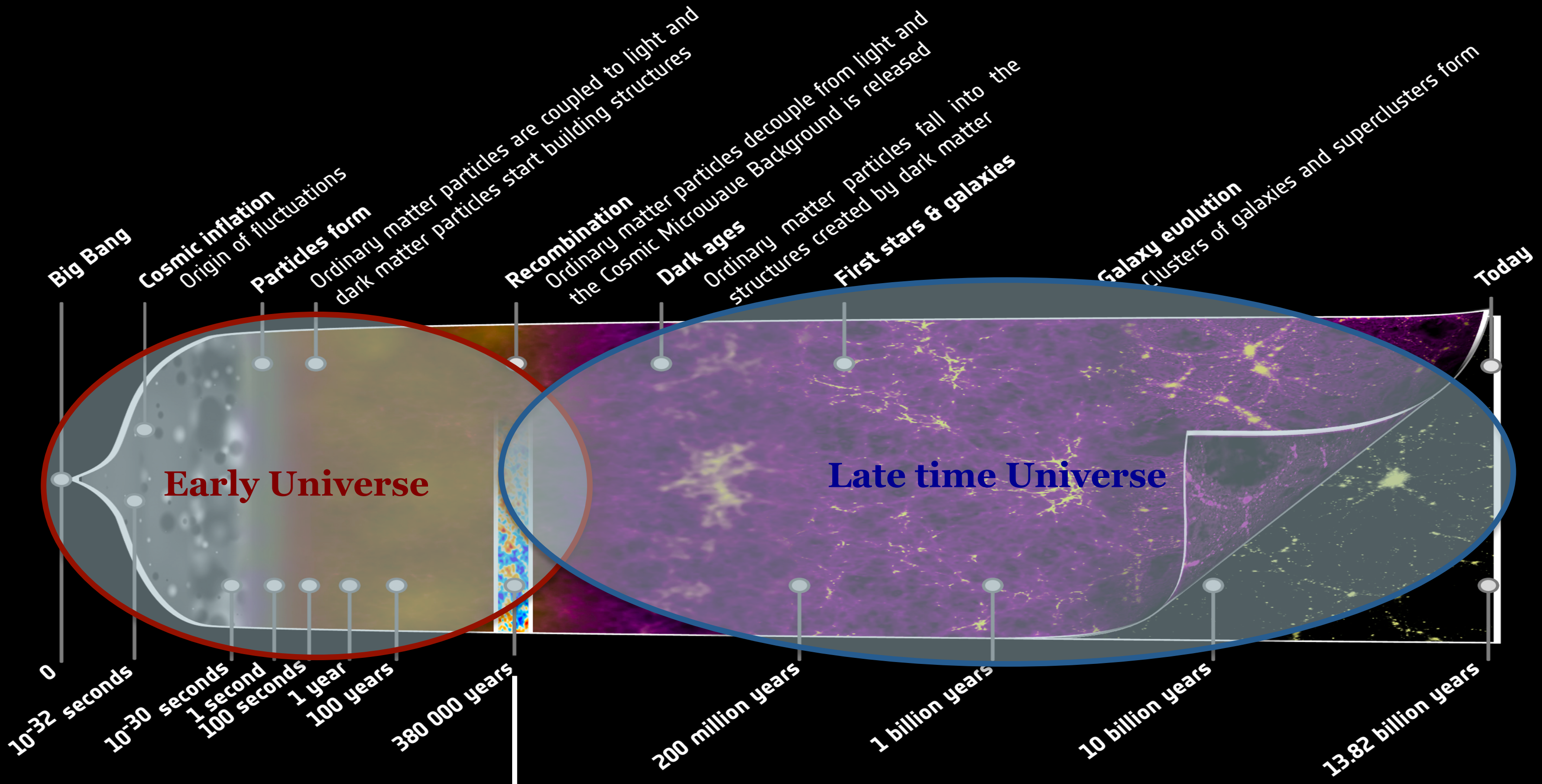

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Early Universe

Late time Universe

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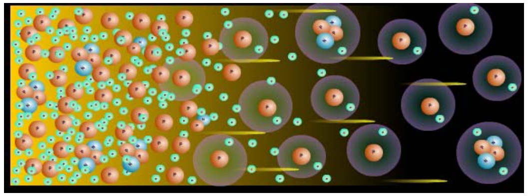

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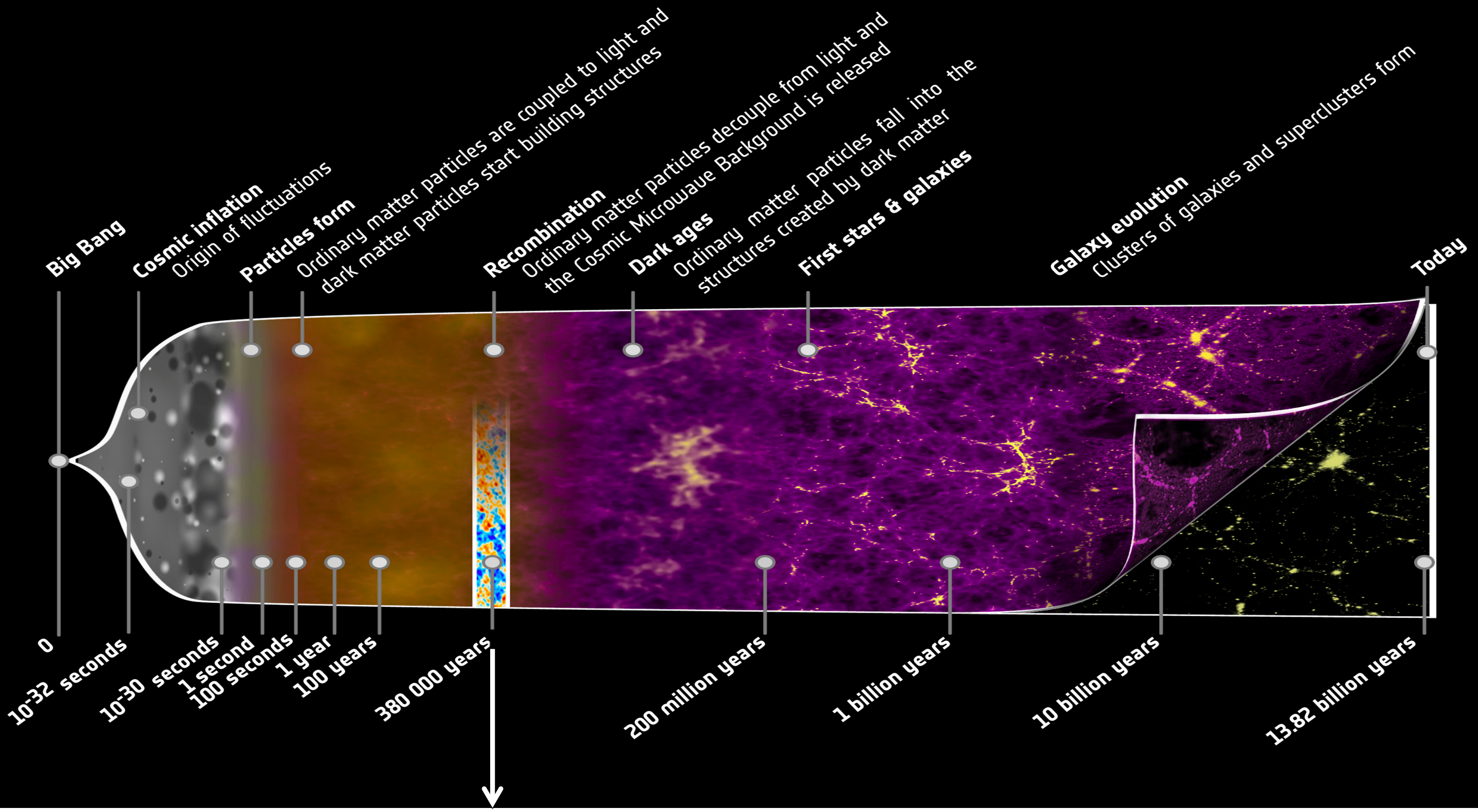
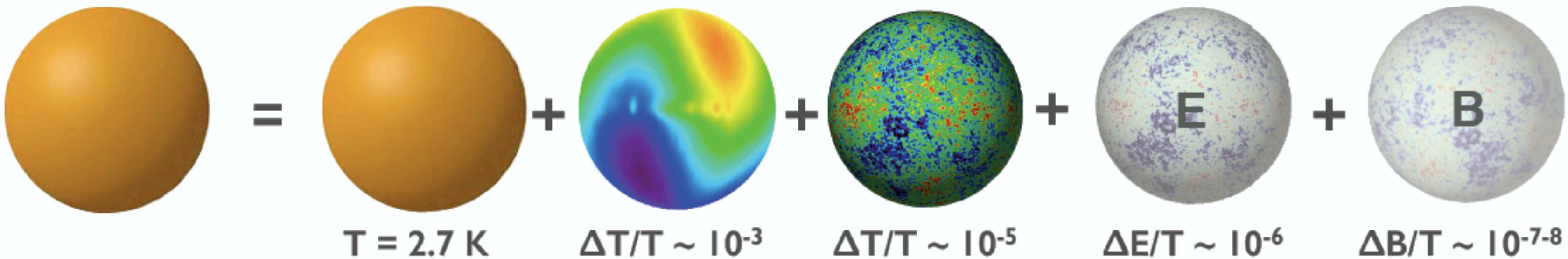
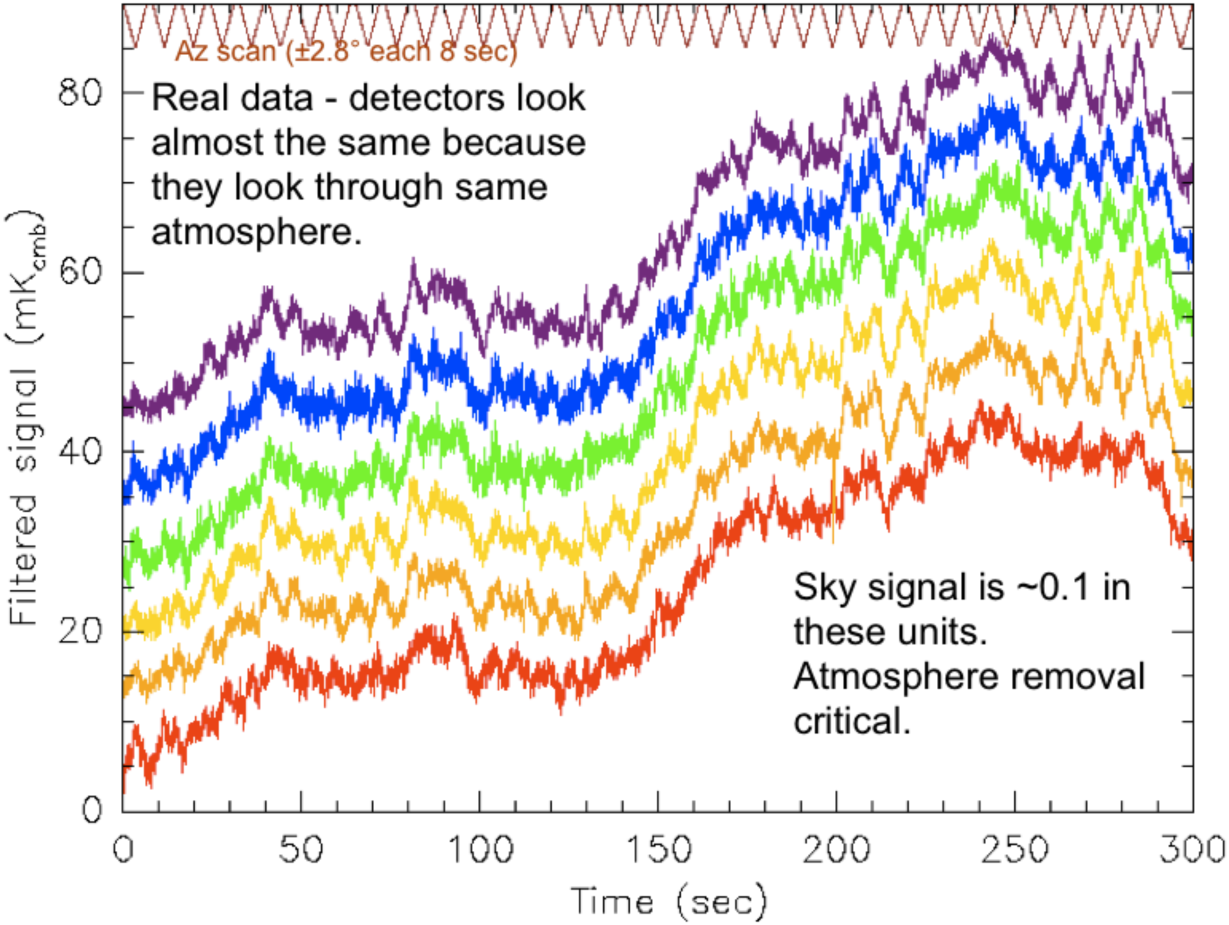




credits: Josquin Errard (josquin.errard@gmail.com)

CMB analysis

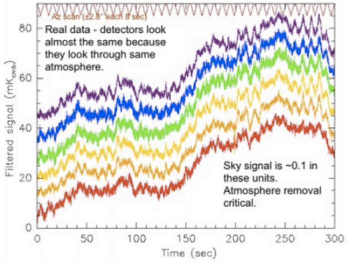
CMB analysis



Real data - detectors look almost the same because they look through same atmosphere.

Sky signal is ~0.1 in these units. Atmosphere removal critical.

CMB analysis



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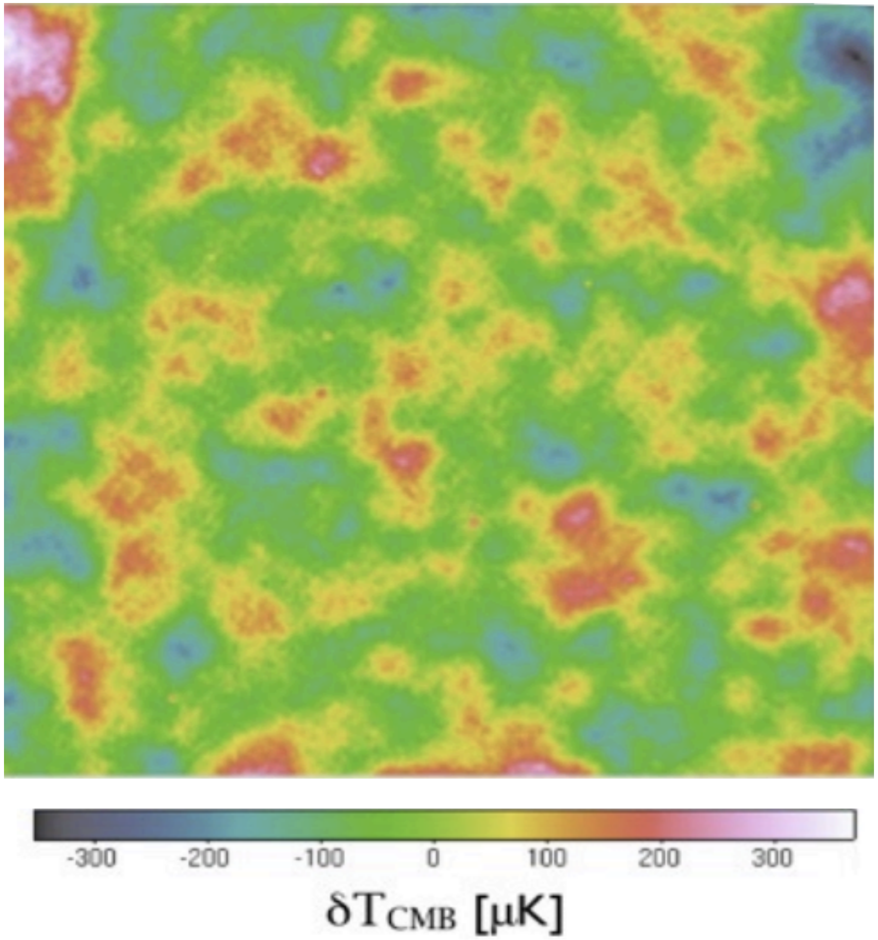
$$d = Pm + n \rightarrow P^T N^{-1} P\, m = P^T N^{-1} d$$



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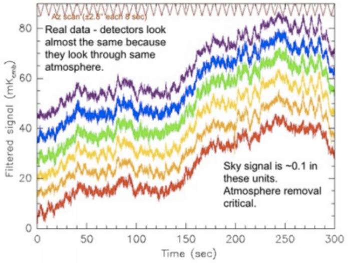
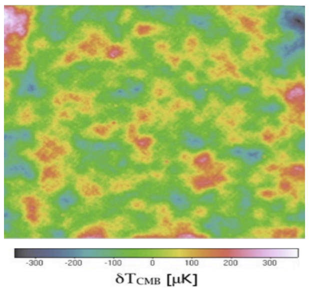
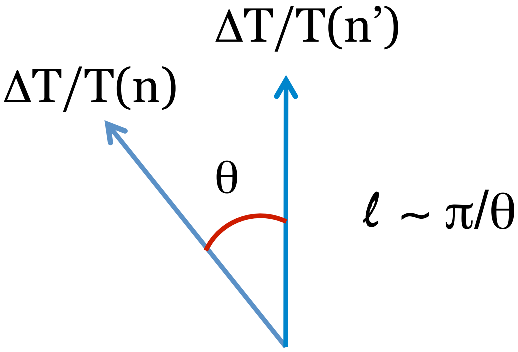




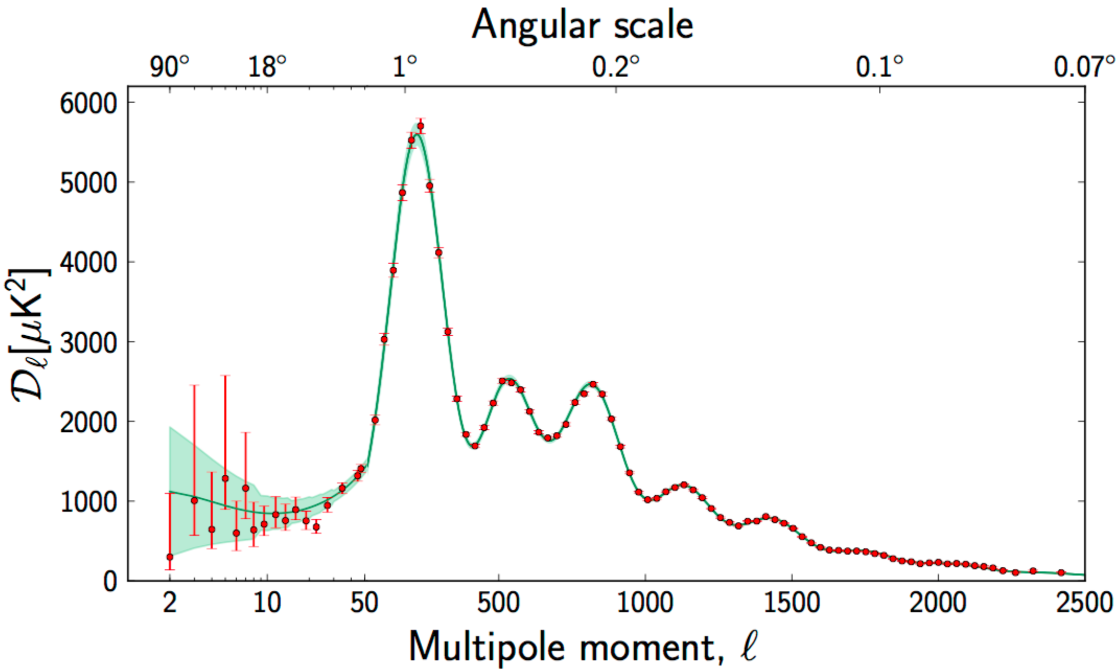


$\Delta T/T(n')$

$\Delta T/T(n)$

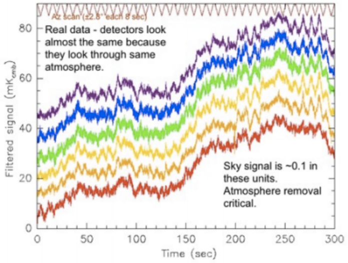
θ

$\ell \sim \pi/\theta$



Planck Collaboration 2013

CMB analysis



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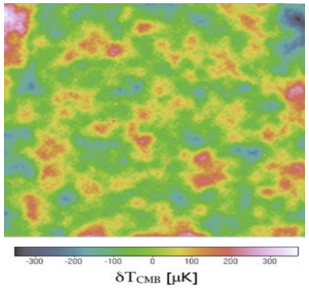

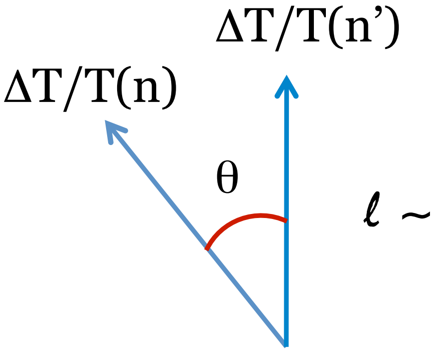

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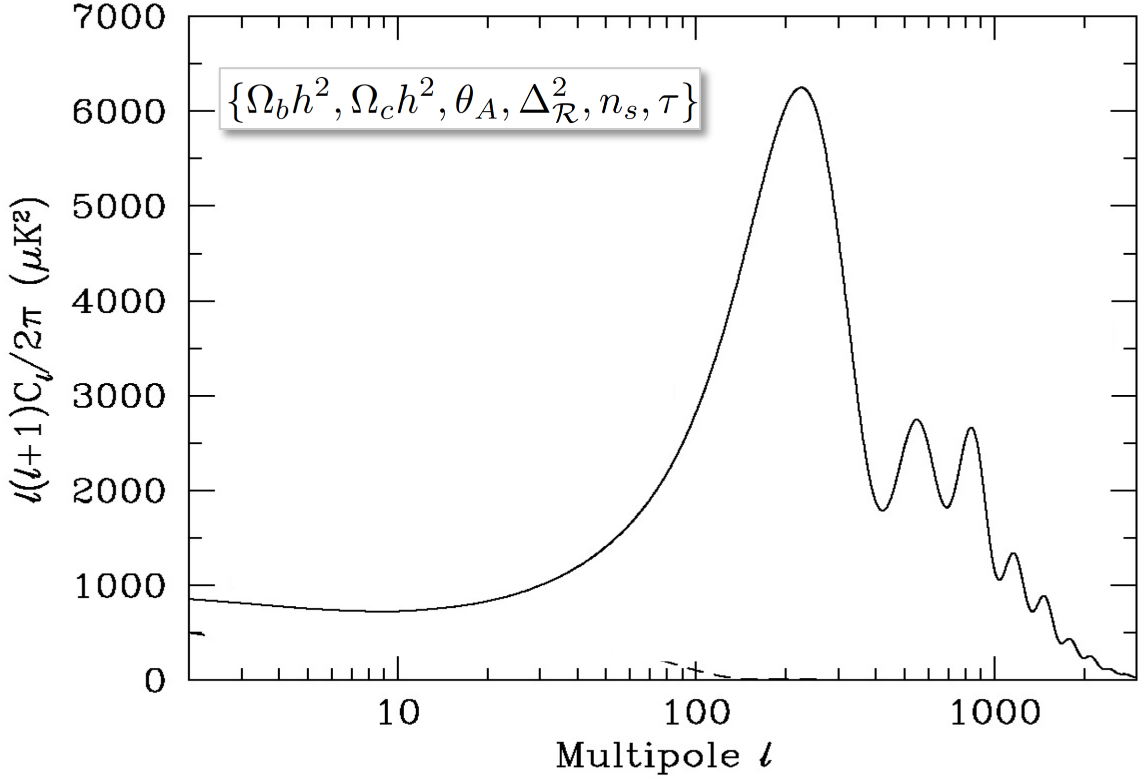

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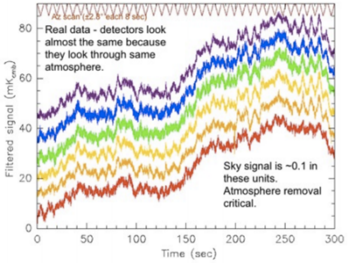

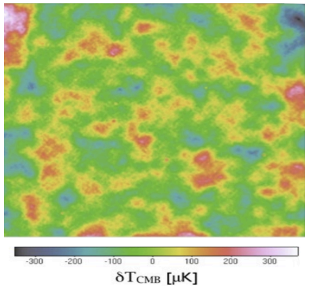

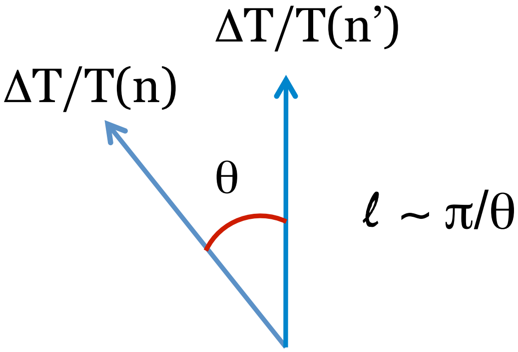

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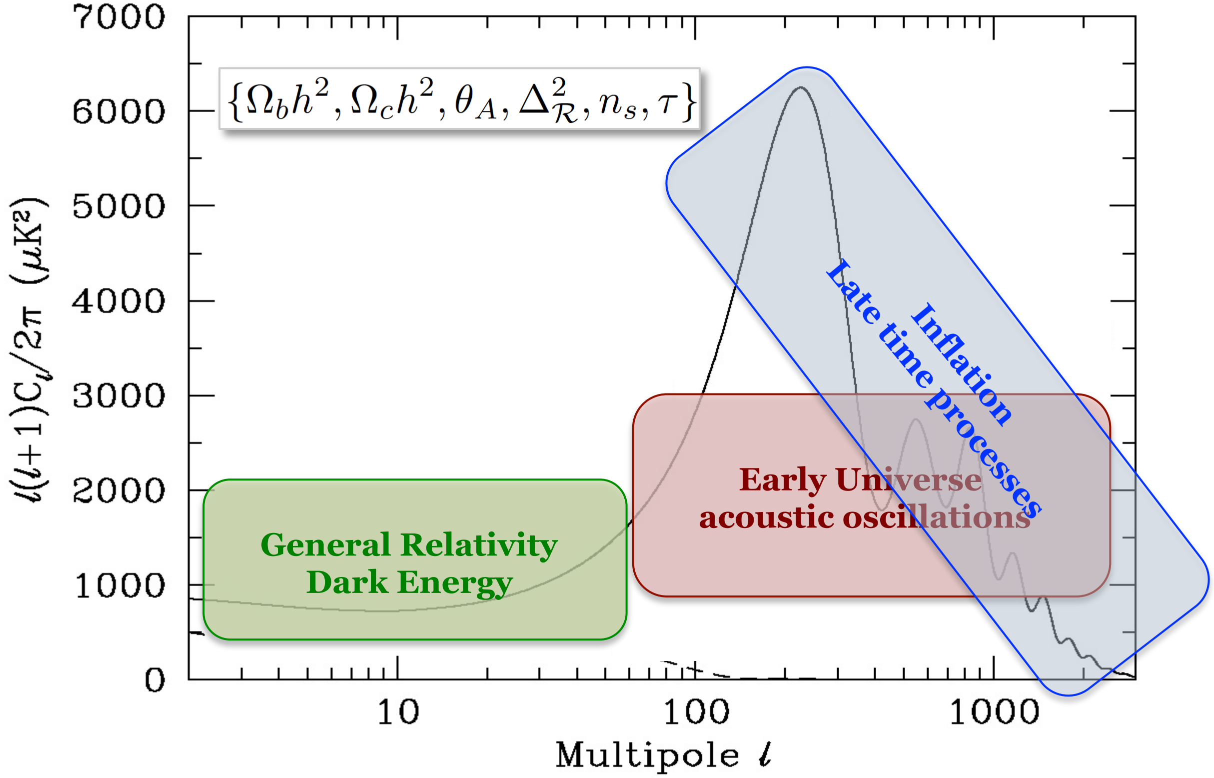


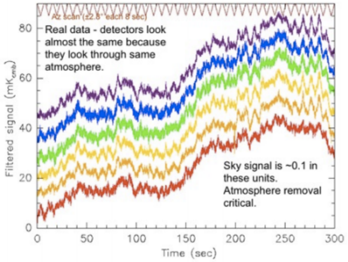
$\{\Omega_b h^2, \Omega_c h^2, \theta_A, \Delta^2_{\mathcal{R}}, n_s, \tau\}$

General Relativity
Dark Energy

Early Universe acoustic oscillations

Inflation
Late time processes

CMB analysis



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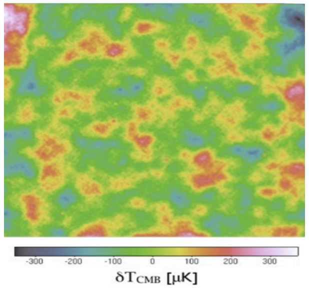
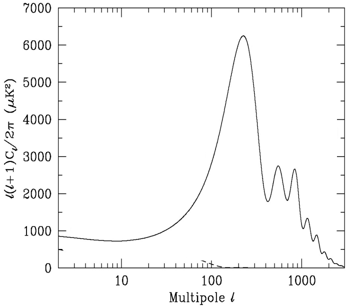
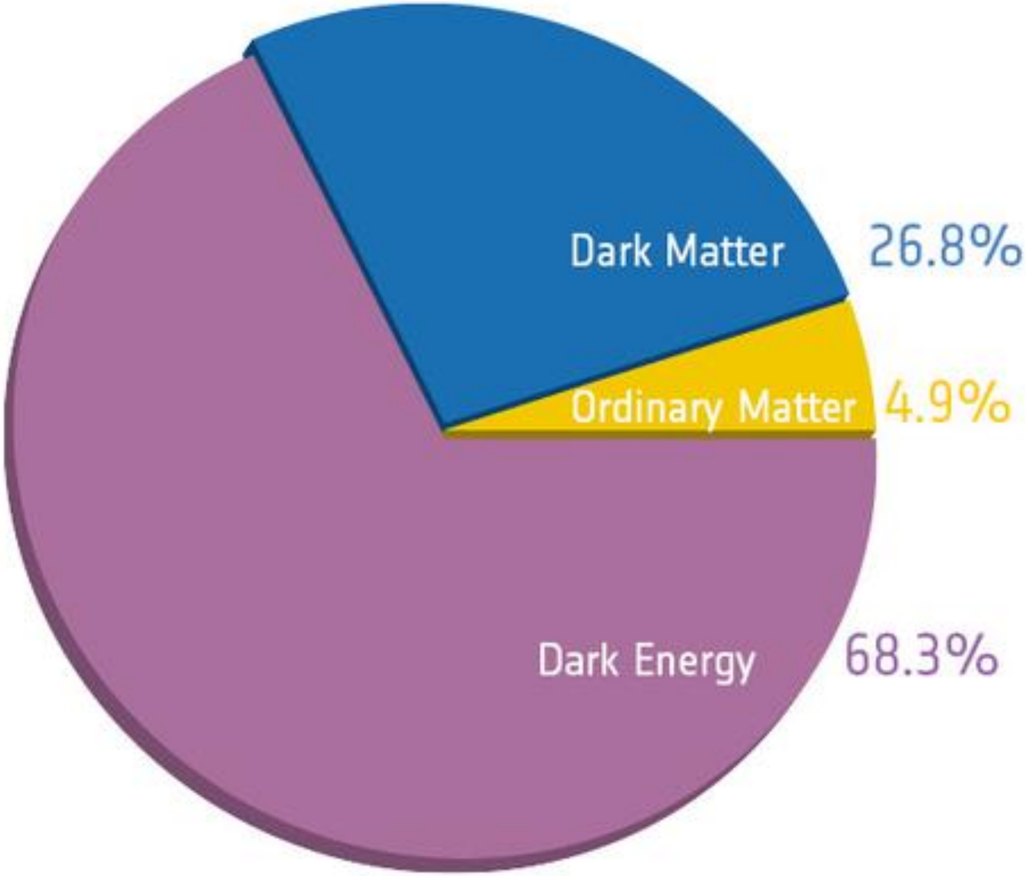
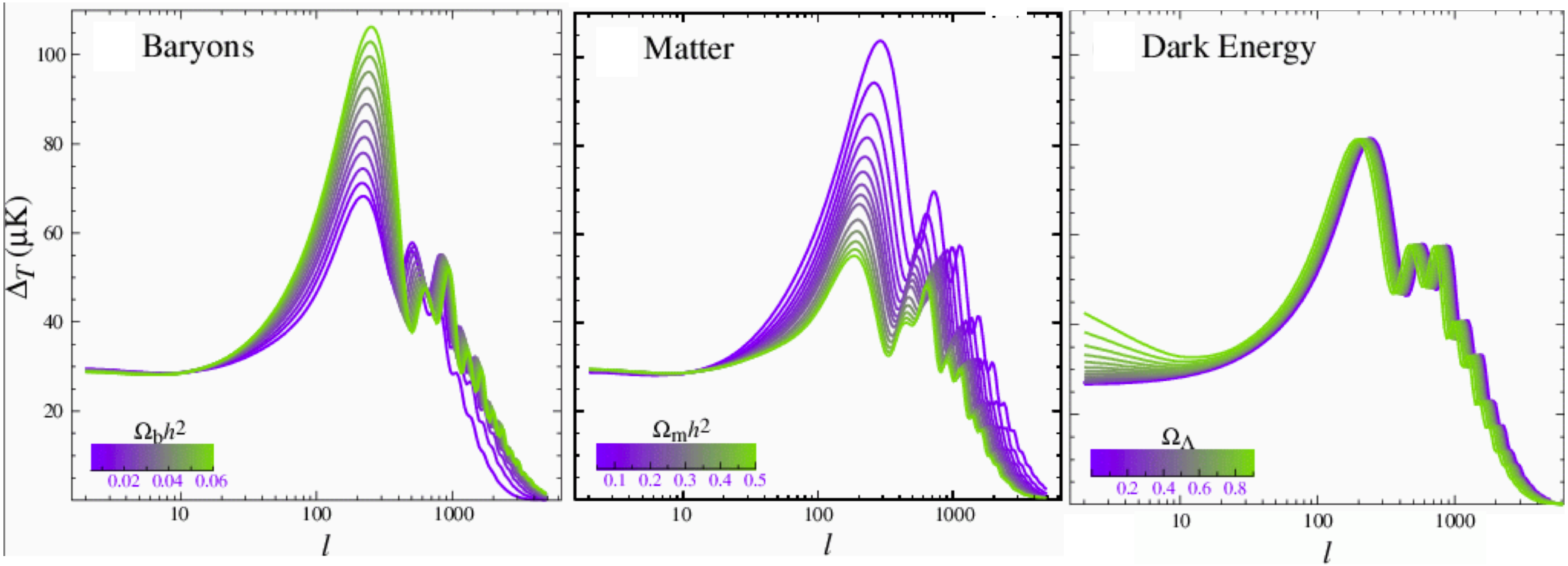






Universe content and CMB power spectrum



Hu & Dodelson 2002

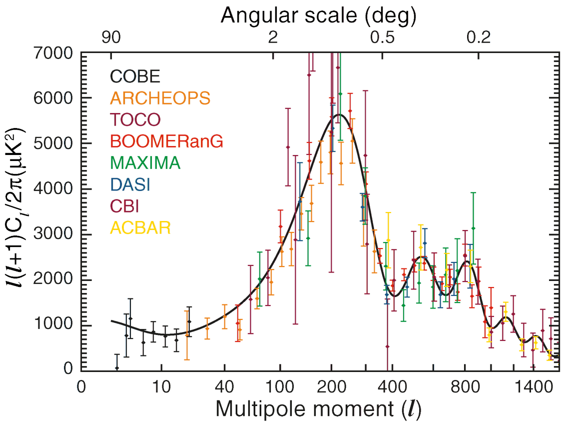
- odd peaks enhanced in amplitude over the even ones
- second peak is suppressed compared with the first and third
- frequency of the oscillations decreases pushing the position of the peaks to slightly higher l

  sound waves damp the power spectrum at high multipoles

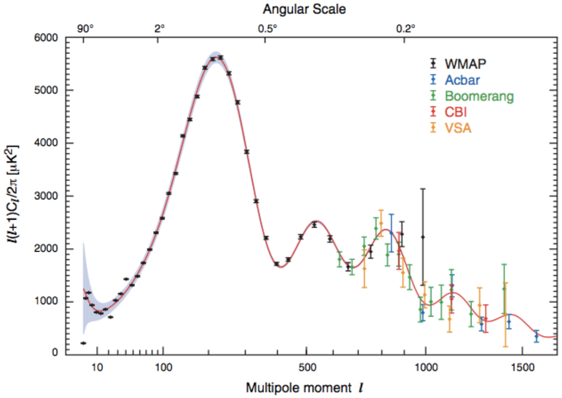
- overall amplitude of the peaks decreases
- high third peak is an indication of dark matter dominating over radiation
- with three peaks, its effects are distinct from the baryons and curvature

- DE cannot be isolated in the PS alone – a small amount of curvature or different Ho can mimic its effects
- higher ISW effect – but in CV dominated region

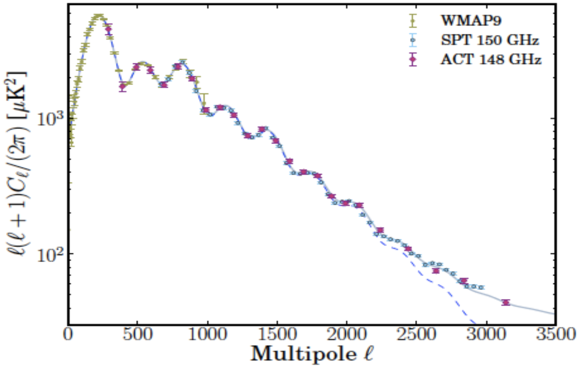
Status-of-the-art of CMB observations



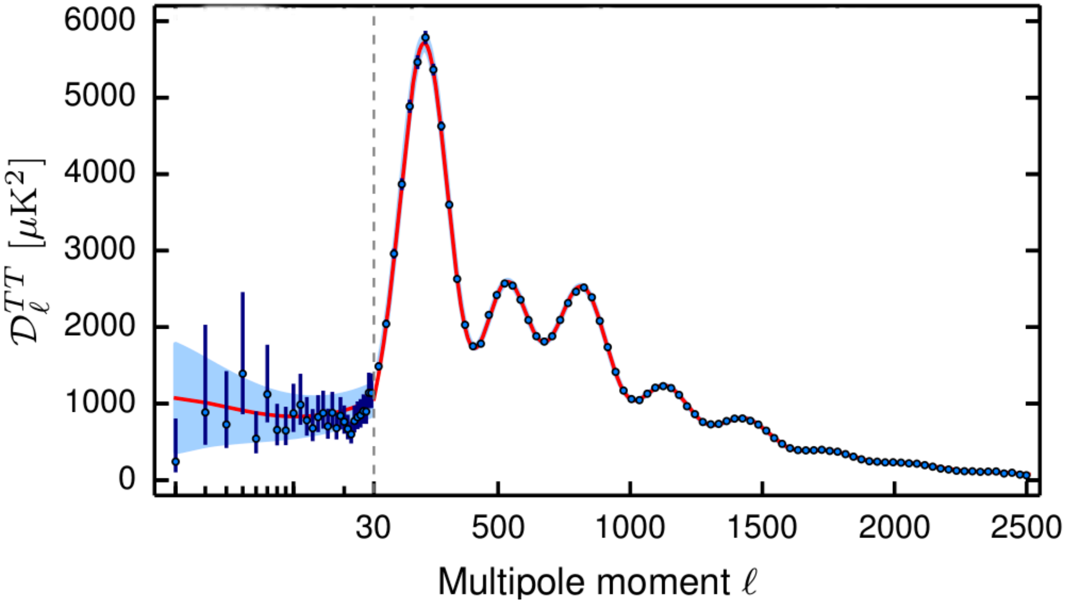
Hinshaw et al. 2003



Hinshaw et al. 2006



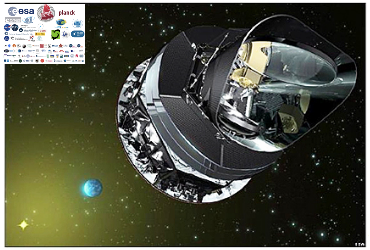
Das et al. 2013



Planck Collaboration 2015

The Planck Mission

ACT/SPT



Launch

Data

Full-sky temperature and polarization at 9 frequencies

1st data release

~15 months of T data, cosmological parameters with percent precision

2nd data release

Full mission T data and some P

3rd data release

Full mission polarization data

2008

2009

2010

2011

2012

2013

2014

2015

2016

2020

ACT/SPT

Temperature observations at high resolution over 600/2500 deg^2

ACTPol/SPTPol

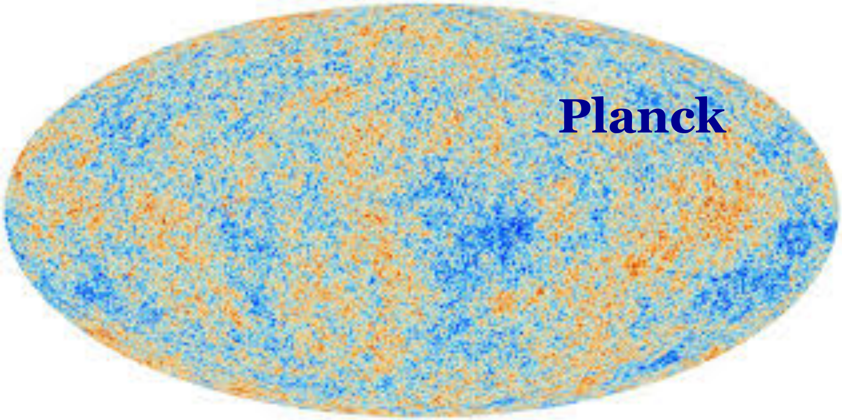
Polarization at 150 GHz, 1’ resolution, over 270/100 deg^2

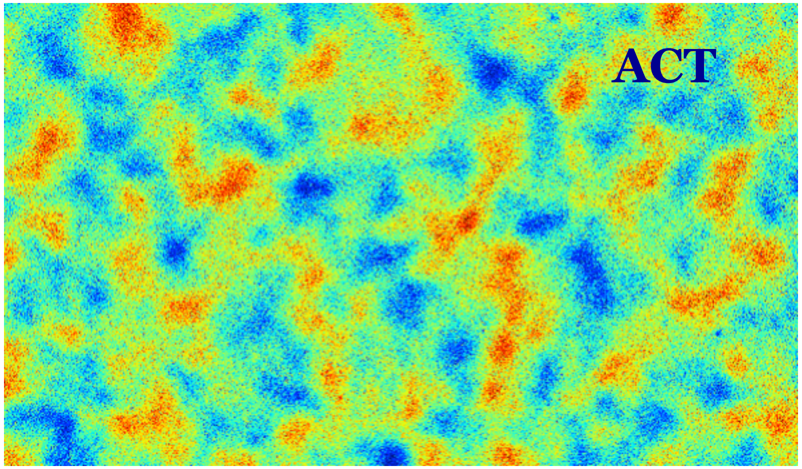
2 more seasons with extra 90GHz on patches ideally chosen to do cross-correlation studies with other surveys

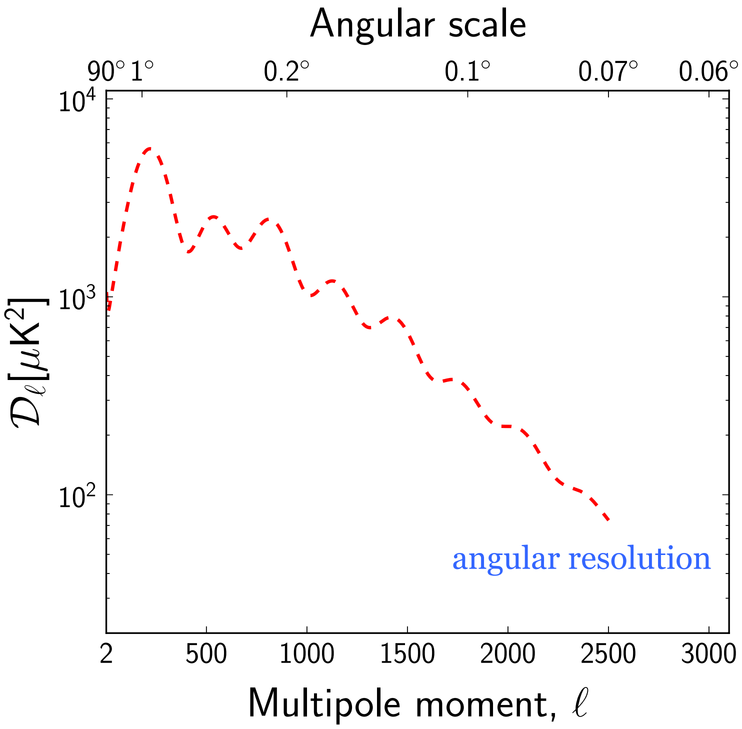
Advanced ACTPol/SPT-3G

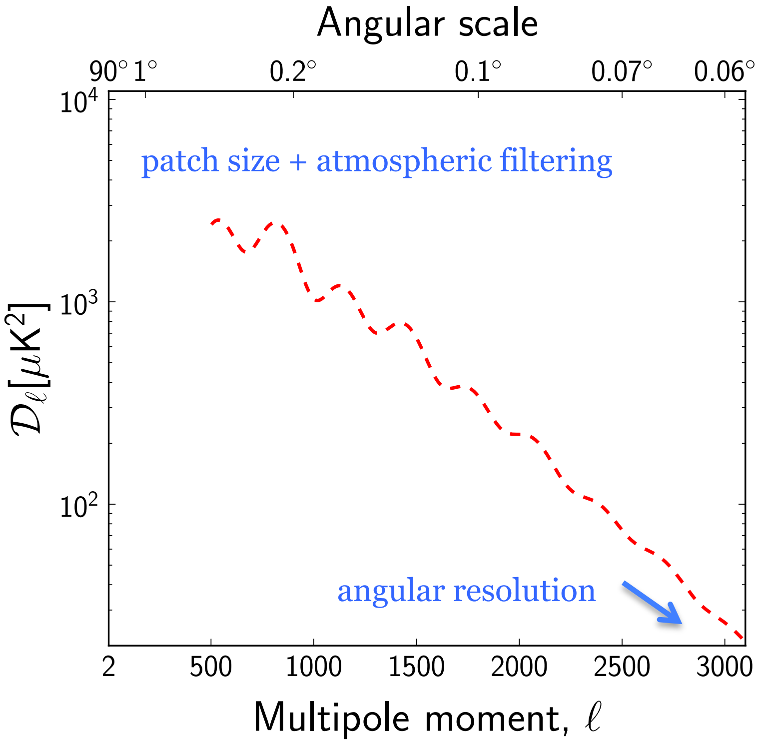
CV limited polarization with 1’ resolution at many frequencies over ~ half sky

Combining probes to robustly extract cosmology

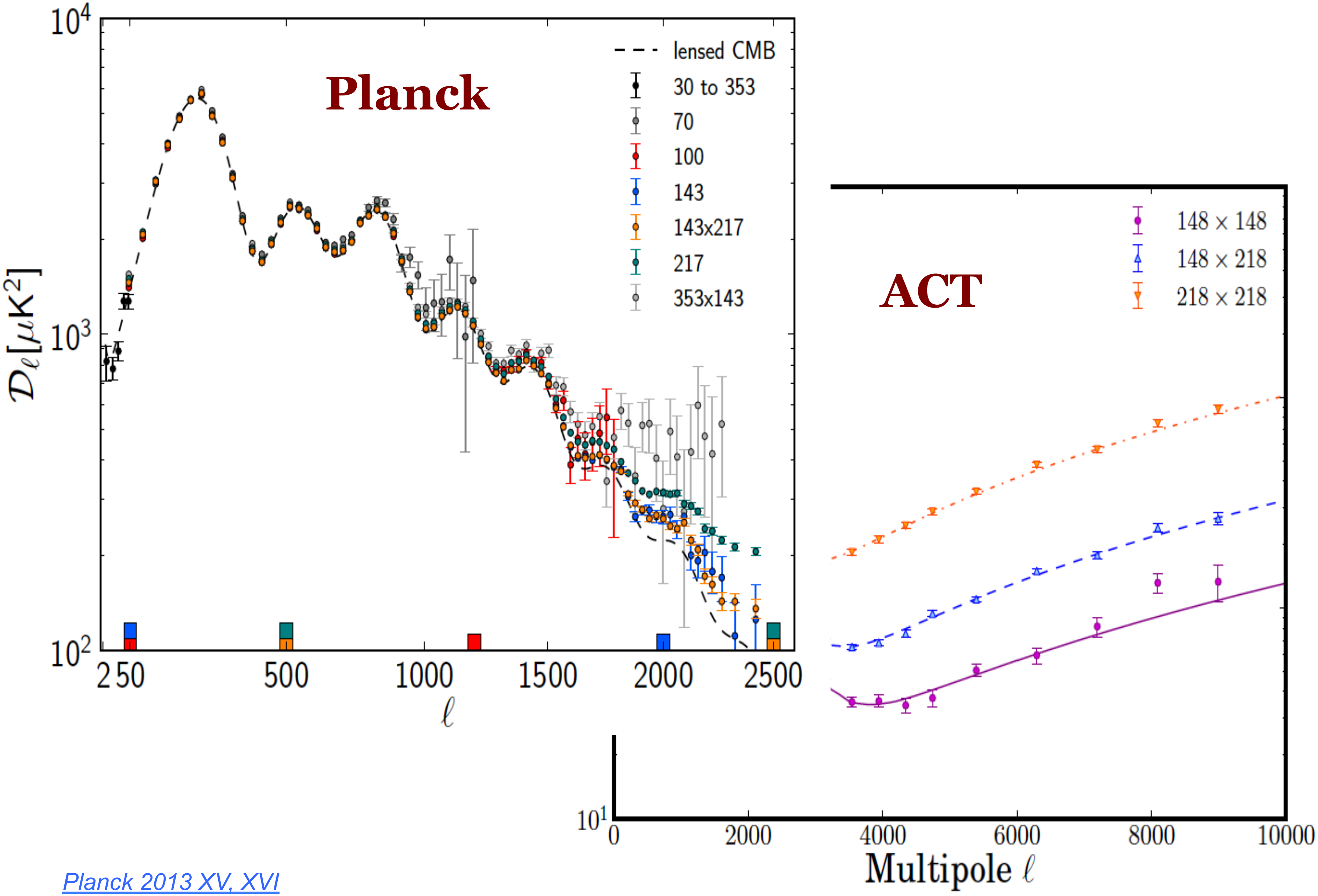








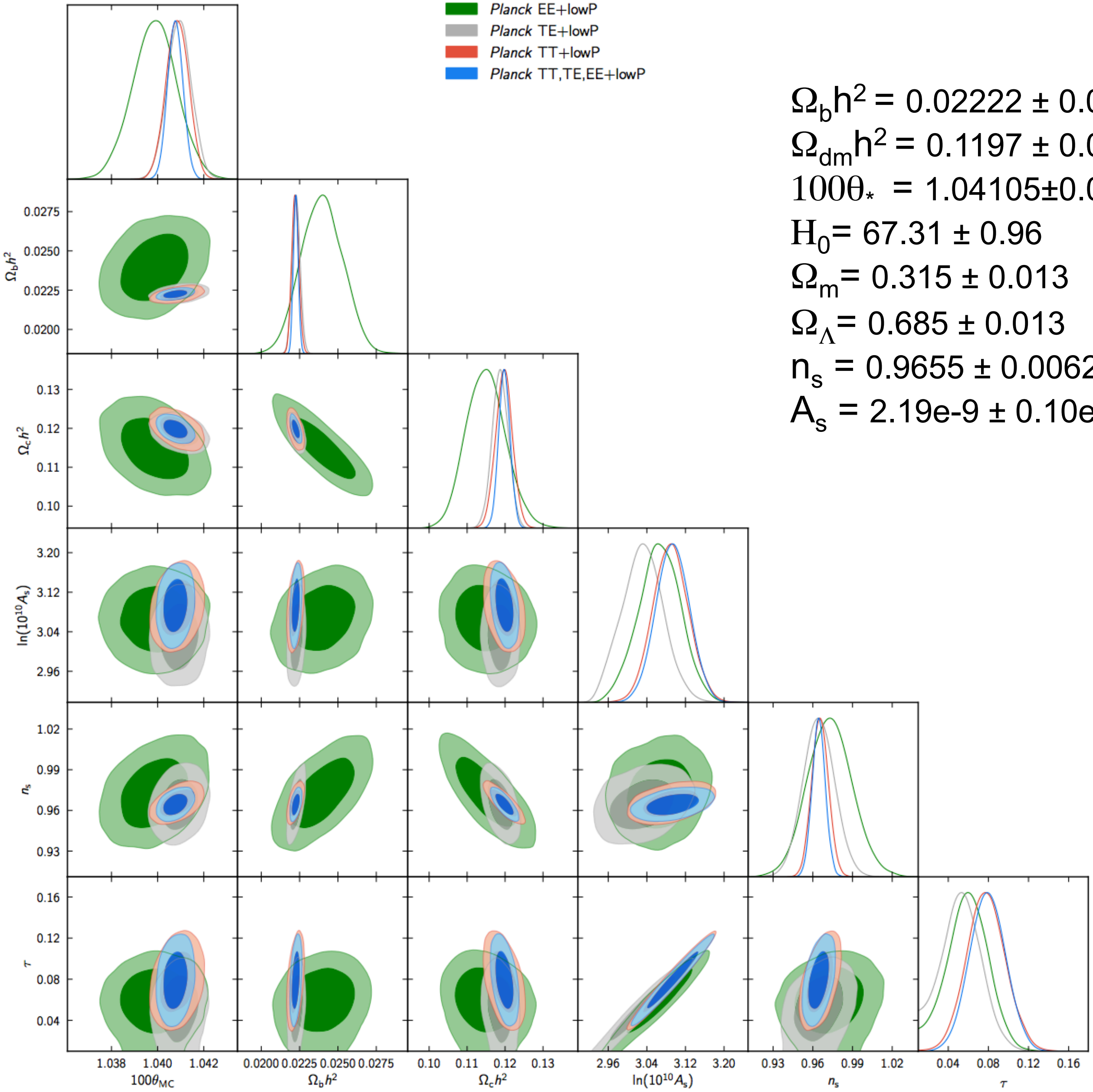
Combining probes to robustly extract cosmology



[Planck 2013 XV, XVI](#)

[Dunkley, Calabrese et al. 2013](#)

Where we are: the Universe at percent precision



$\Omega_b h^2$ = 0.02222 ± 0.00023 1%

$\Omega_{dm} h^2$ = 0.1197 ± 0.0022 2%

$100\theta_*$ = 1.04105±0.00046 0.04%

H_0= 67.31 ± 0.96 1%

Ω_m= 0.315 ± 0.013 4%

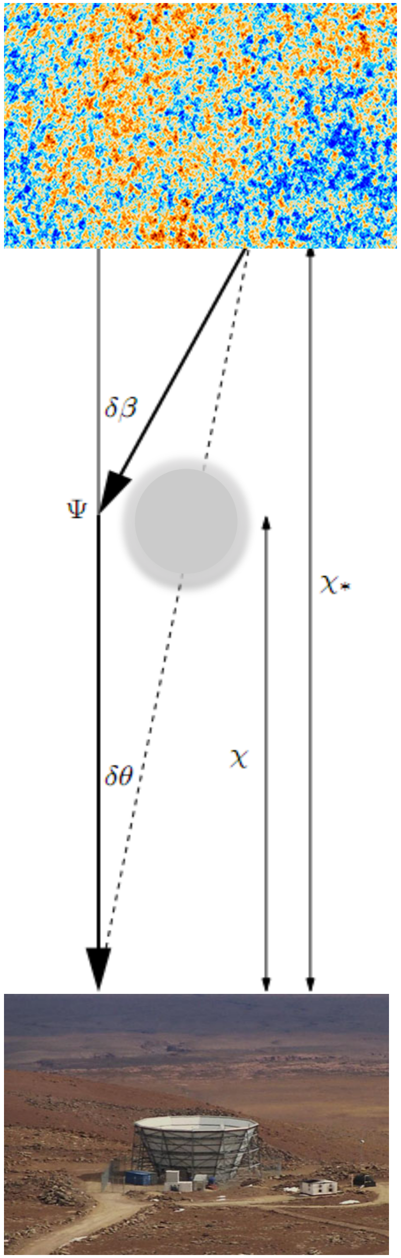
Ω_Λ= 0.685 ± 0.013 2%

n_s = 0.9655 ± 0.0062 0.6%

A_s = 2.19e-9 ± 0.10e-9 4%

Planck 2015 results. XIII

CMB gravitational lensing



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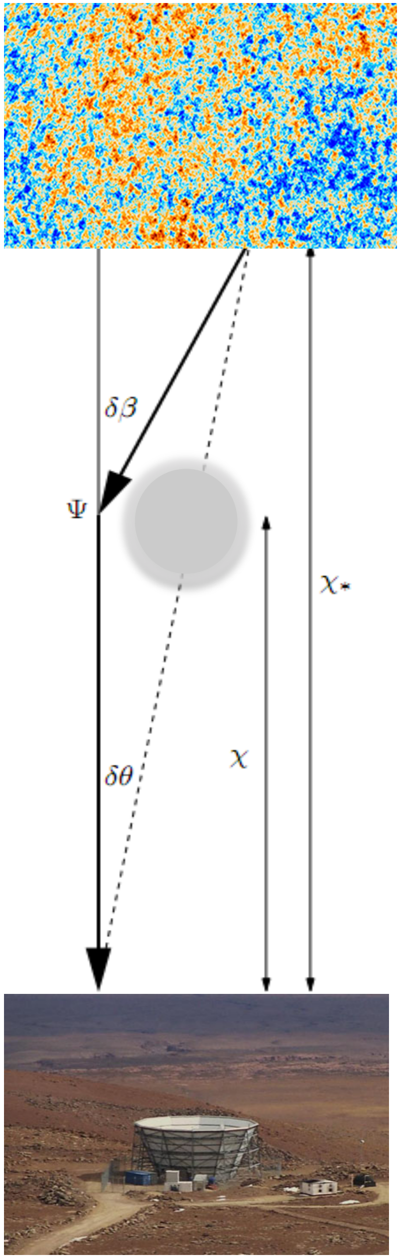


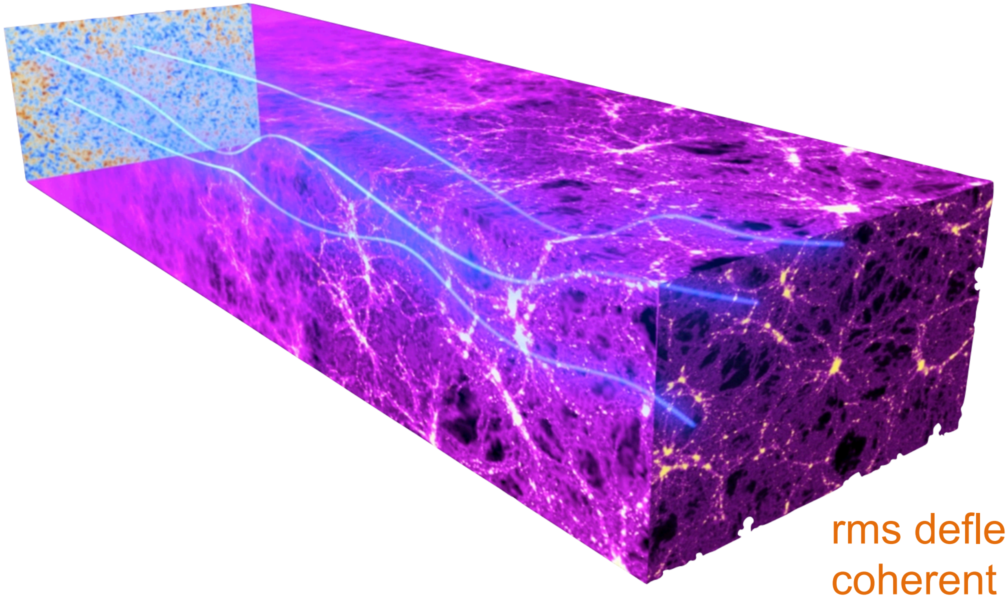
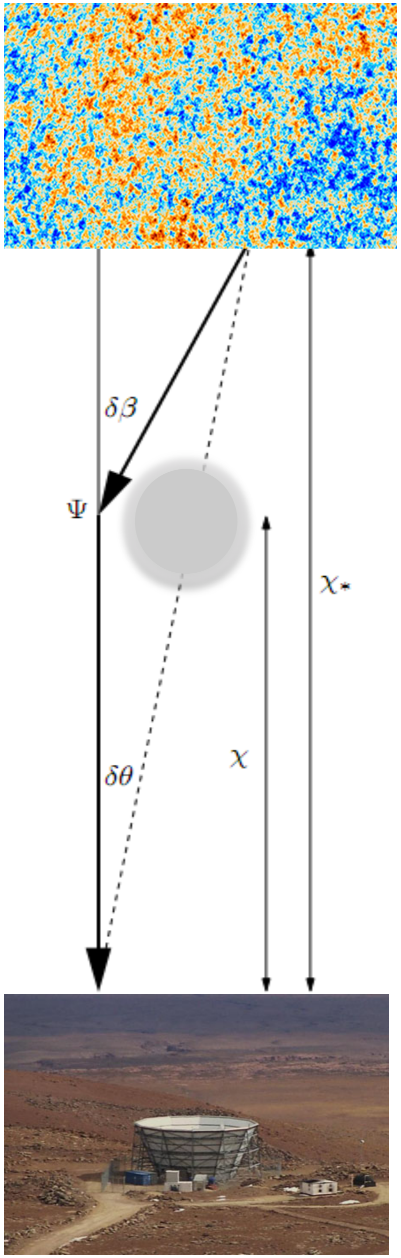


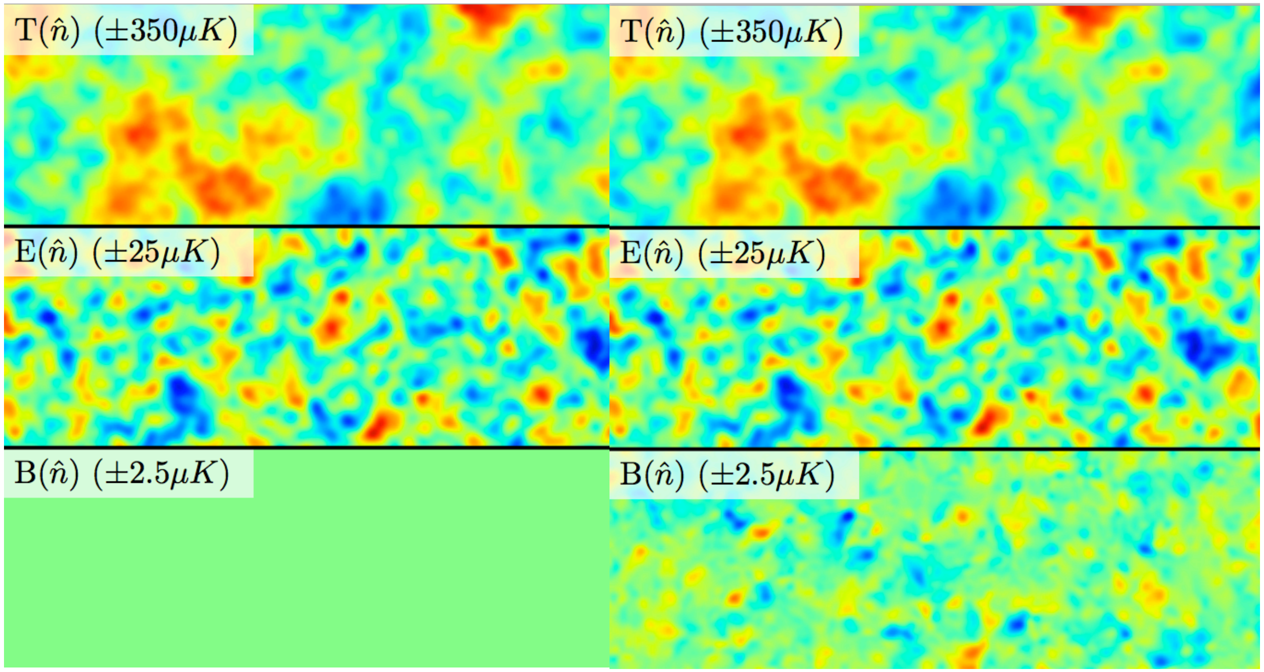
Image credit: ESA and Planck Collaboration

rms deflection of 2’ coherent over 2^{o}

CMB gravitational lensing

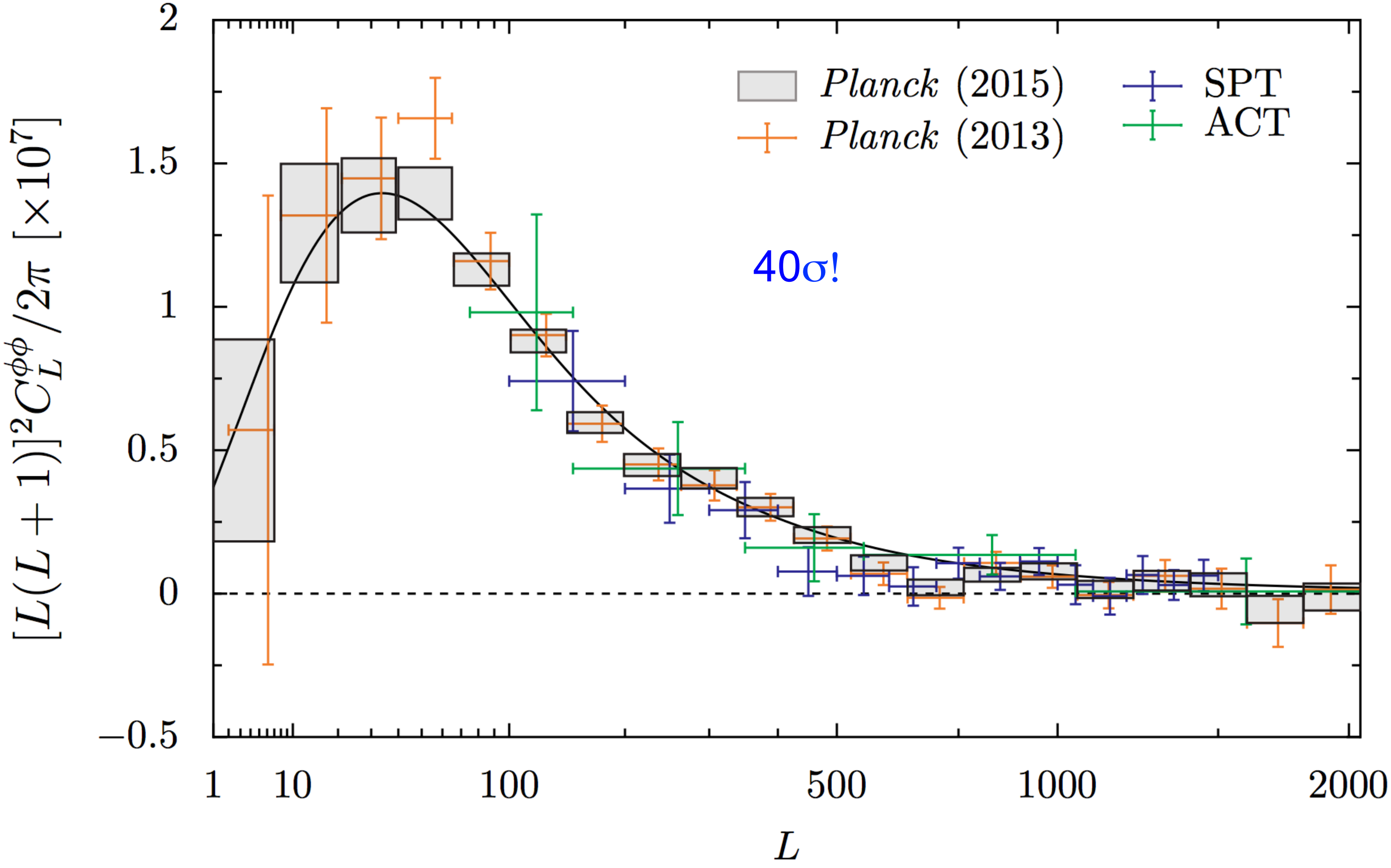


$$\tilde{\Theta}(\mathbf{x}) = \Theta(\mathbf{x}') = \Theta(\mathbf{x} + \boldsymbol{\nabla}\psi)$$



$$\frac{\ell^2}{4} C_\ell^{dd} = \int_0^{\eta_*} \mathrm{d}\eta \, \underbrace{W^2(\eta)}_{\text{geometry}} \; \underbrace{P\left(k = \frac{\ell + 1/2}{d_A(\eta)}, \eta\right)}_{\text{matter}}$$

CMB gravitational lensing



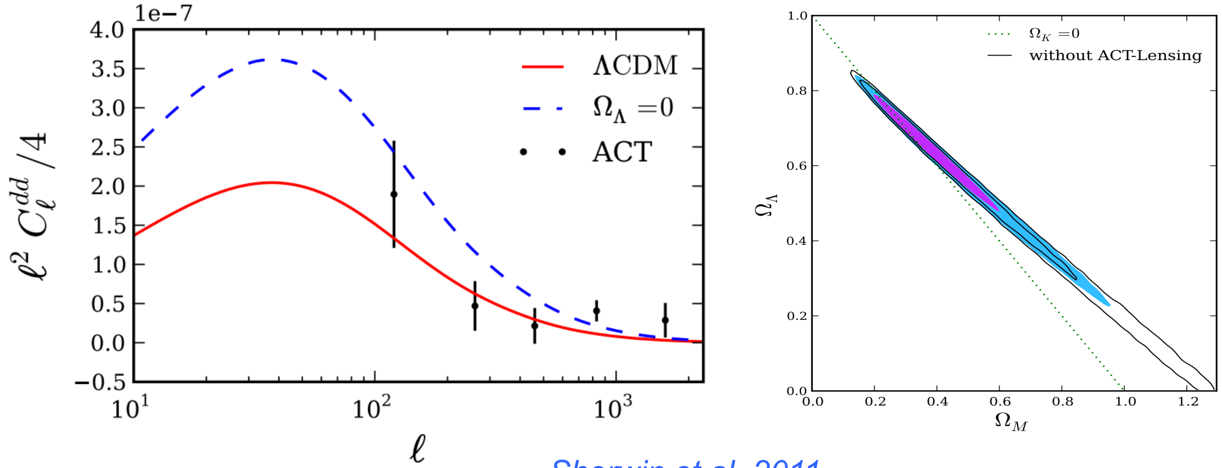
40σ!

Planck 2015 results. XV

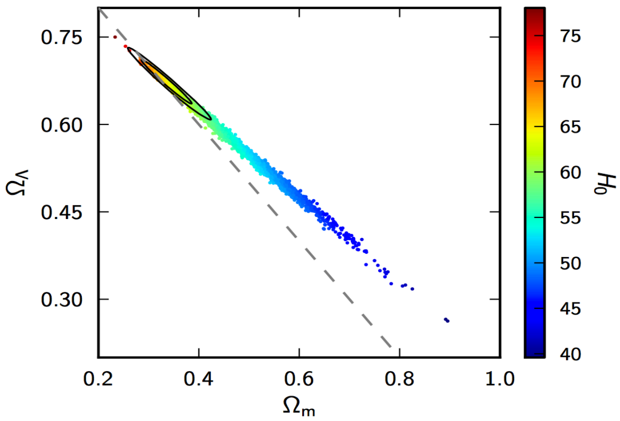
Dark Energy

Evidence for Λ from CMB alone

lensing breaks the angular diameter distance degeneracy

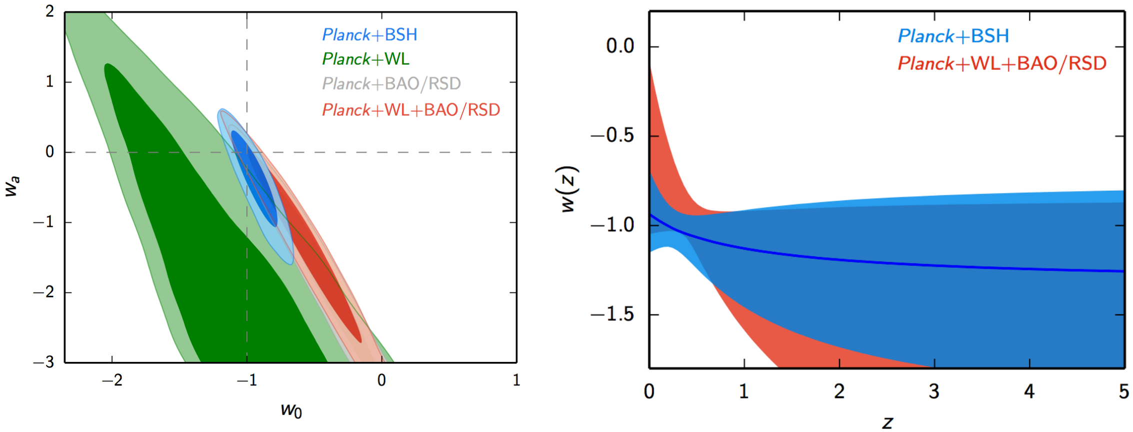


Sherwin et al. 2011



Planck 2013 XVII

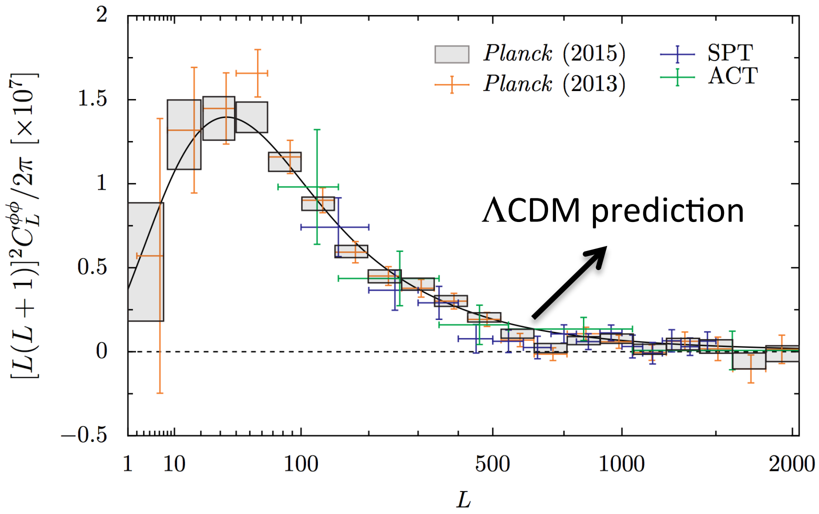
Constraints on DE equation of state



Planck 2015 results. XIII

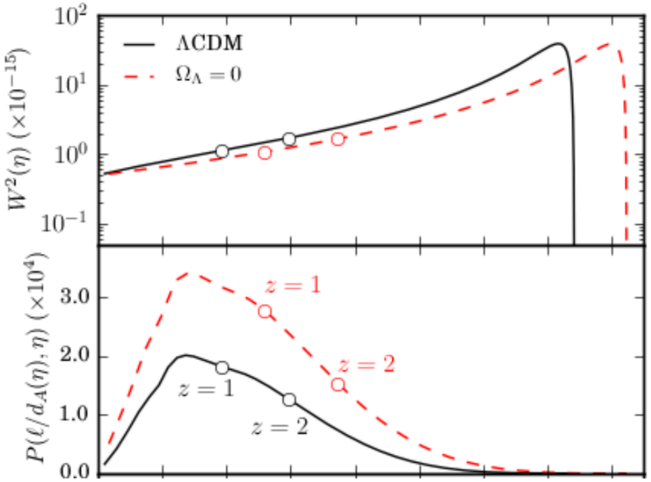
Dark Matter

CMB lensing is a probe of DM out to z=1100
2% constraint on amplitude of matter fluctuations at z~2



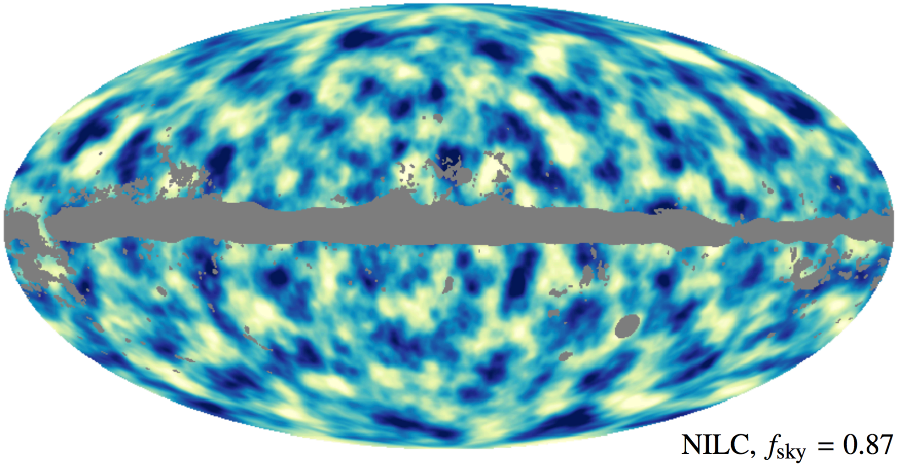
ΛCDM prediction

Planck 2015 results. XV



Sherwin et al. 2011

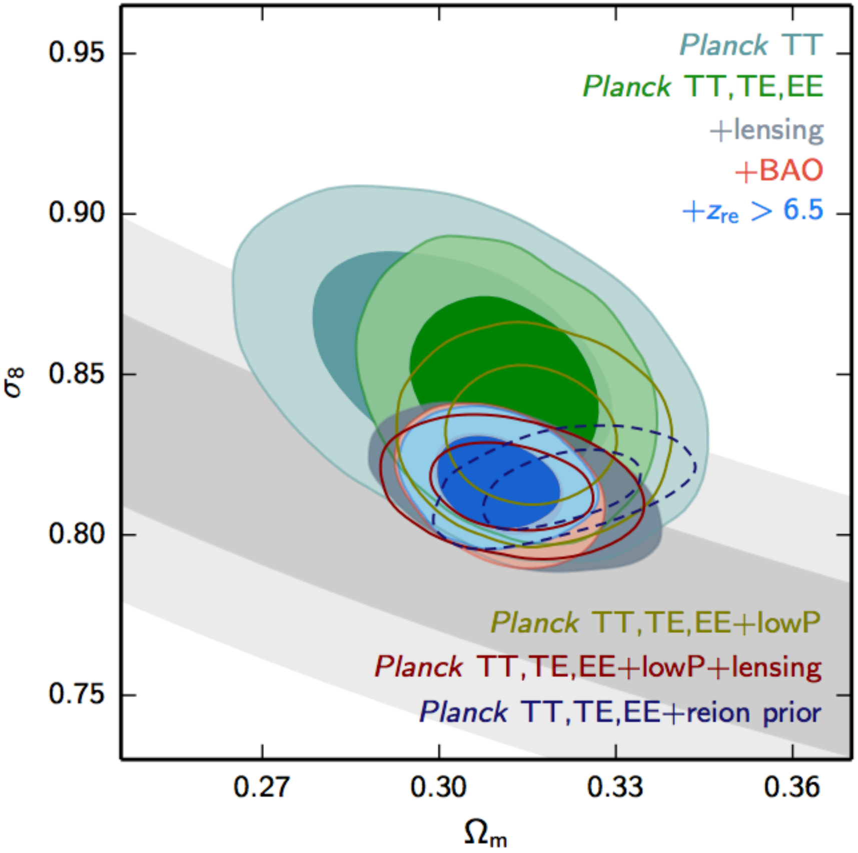
Gravitational Potential/Dark Matter mapping

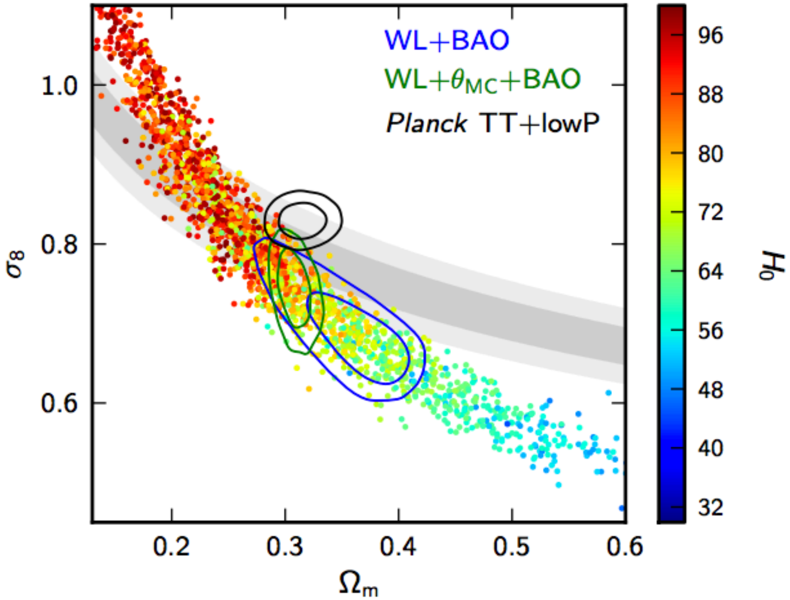


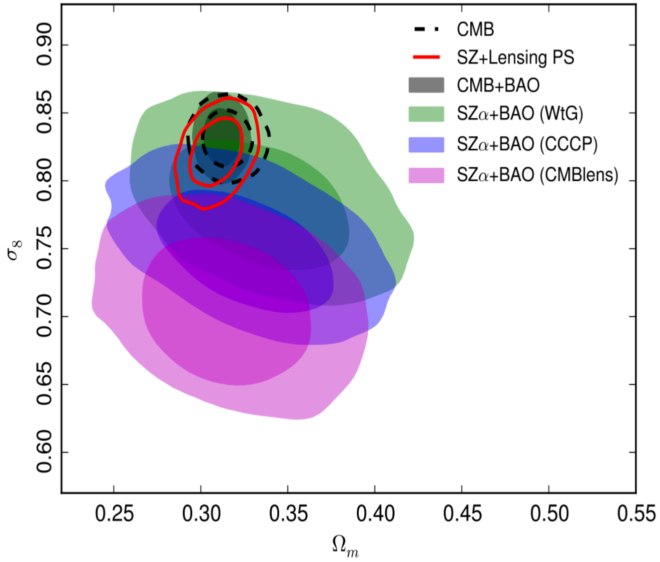
Planck 2015 results. XV

High-z/low-z matter density

$\Omega_m = 0.315 \pm 0.013$
$\sigma_8 = 0.829 \pm 0.014$





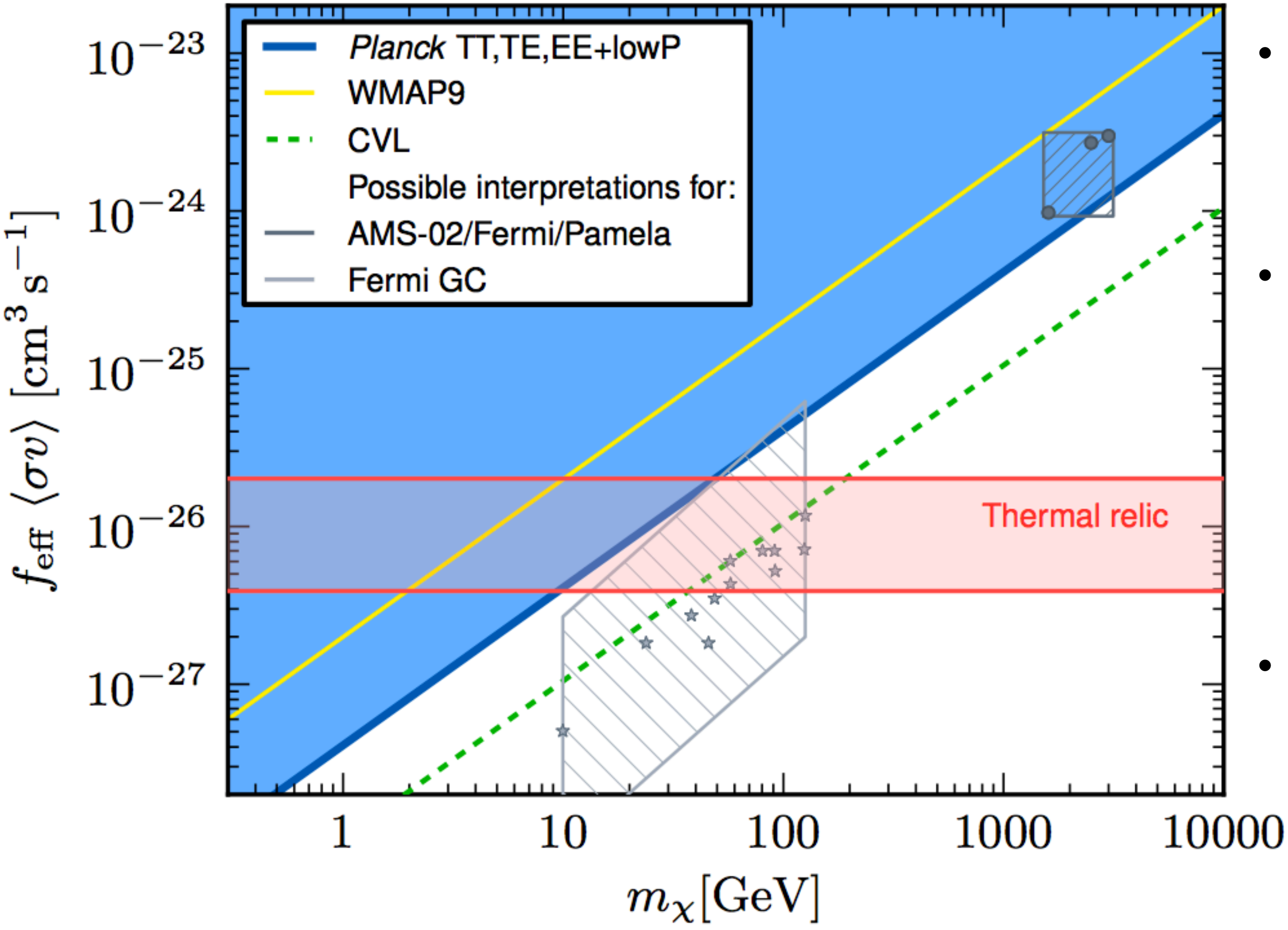


Planck 2015 results. XIV
Planck 2015 results. XIII

Dark Matter

$$\frac{dE}{dt} = \rho_c^2 c^2 \Omega_{DM}^2 (1+z)^6 f_{eff} \frac{\langle \sigma v \rangle}{m_\chi}$$

Energy injection by DM annahilation



- Fermi/Pamela/AMS-02 excess ruled out at 95% if $<\sigma v>(z=100)=<\sigma v>(z=0)$
- Thermal Relic cross sections at z=1000 ruled out for:

  m~<40GeV (e^-e^+)
  m~<20GeV $(\mu^+\mu^-)$
  m~<10 GeV $(\tau^+\tau^-)$.

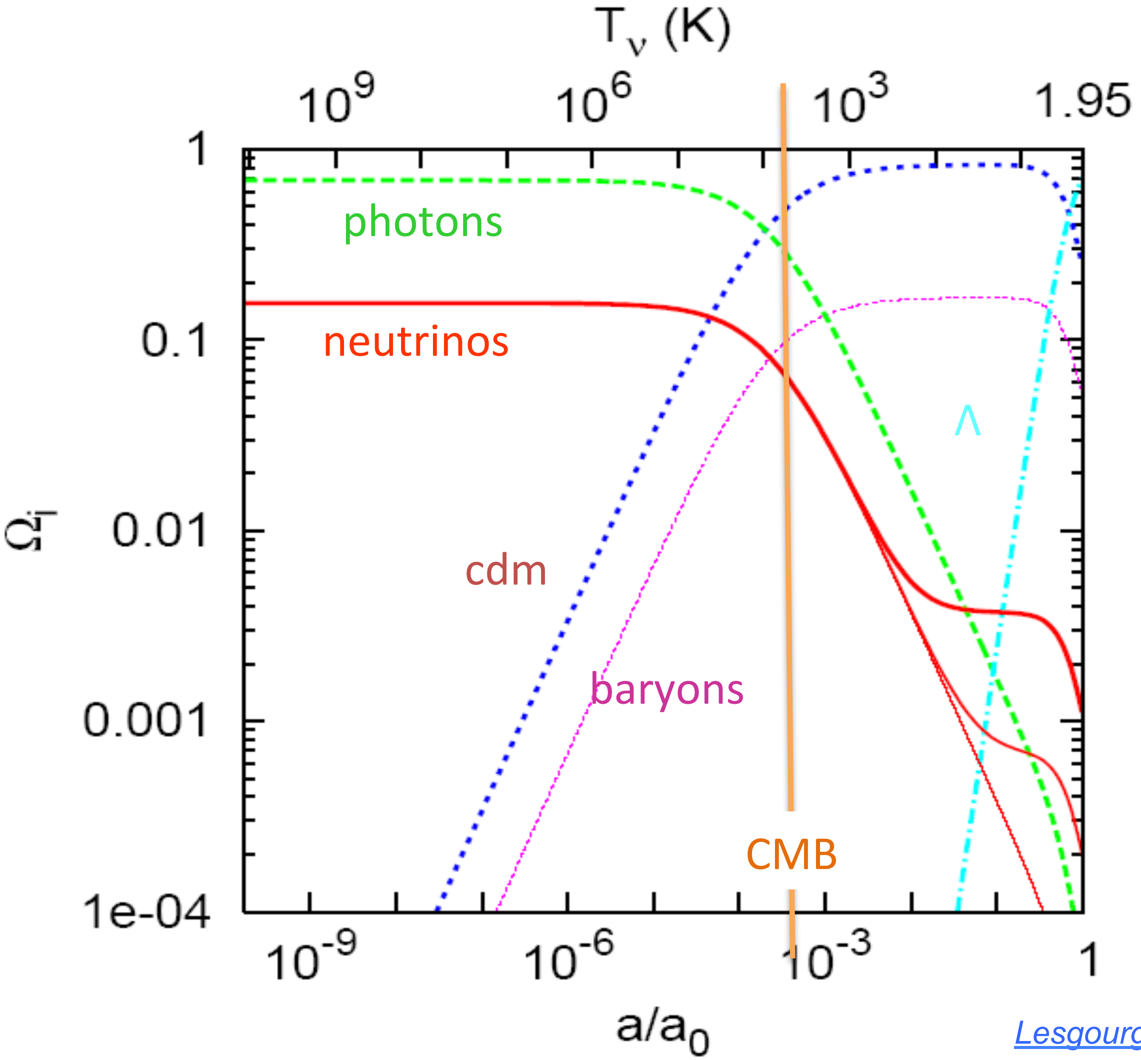
- Small part of Fermi GC excluded

Planck 2015 results. XIII

Neutrinos 0.1-2%

Relativistic – Radiation like $$\rho_\nu(m_\nu \ll T_\nu) = \frac{7\pi^2}{120}\left(\frac{4}{11}\right)^{4/3} T_\gamma^4 \,,$$

Non-relativistic – Matter like $$\rho_\nu(m_\nu \gg T_\nu) = m_\nu n_\nu \,.$$



Lesgourgues & Pastor 2006

Neutrinos

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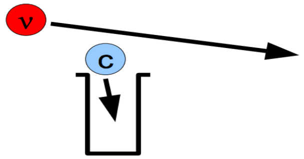
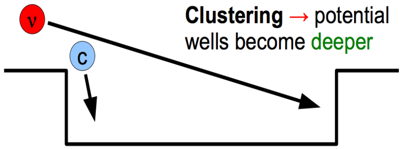
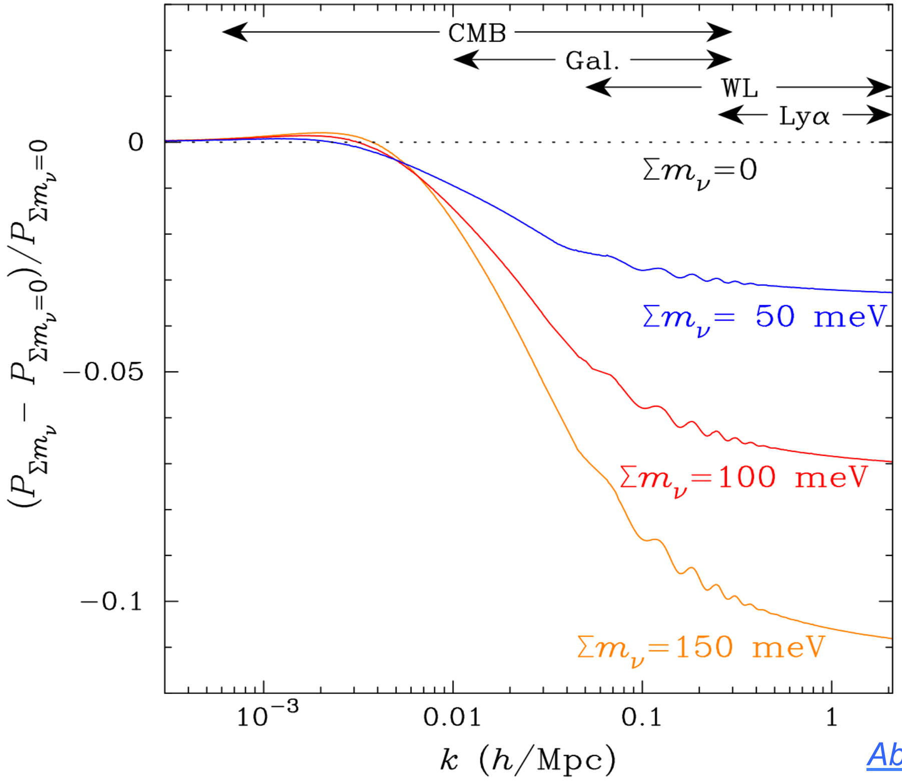
$$\lambda_{\mathrm{FS}} \equiv \sqrt{\frac{8\pi^2 c_\nu^2}{3\Omega_m H^2}} \simeq 4.2\sqrt{\frac{1+z}{\Omega_{m,0}}}\left(\frac{\mathrm{eV}}{m_\nu}\right) \; h^{-1}\ \mathrm{Mpc}$$

$$k_{\mathrm{FS}} \equiv \frac{2\pi}{\lambda_{\mathrm{FS}}}$$



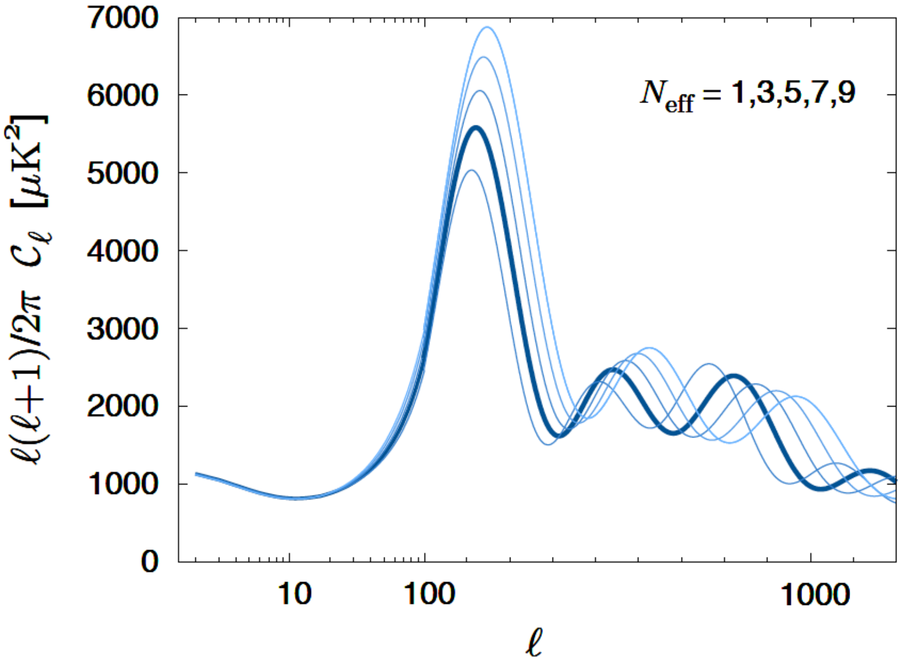


Clustering → potential wells become deeper

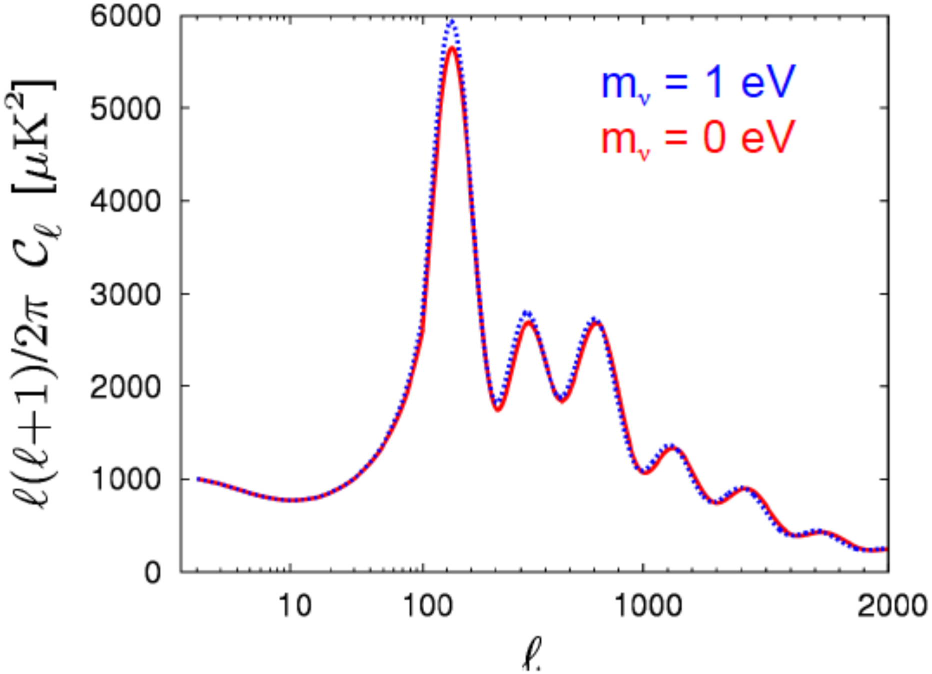


Abazajian et al. arXiv:1309.5383

Neutrinos

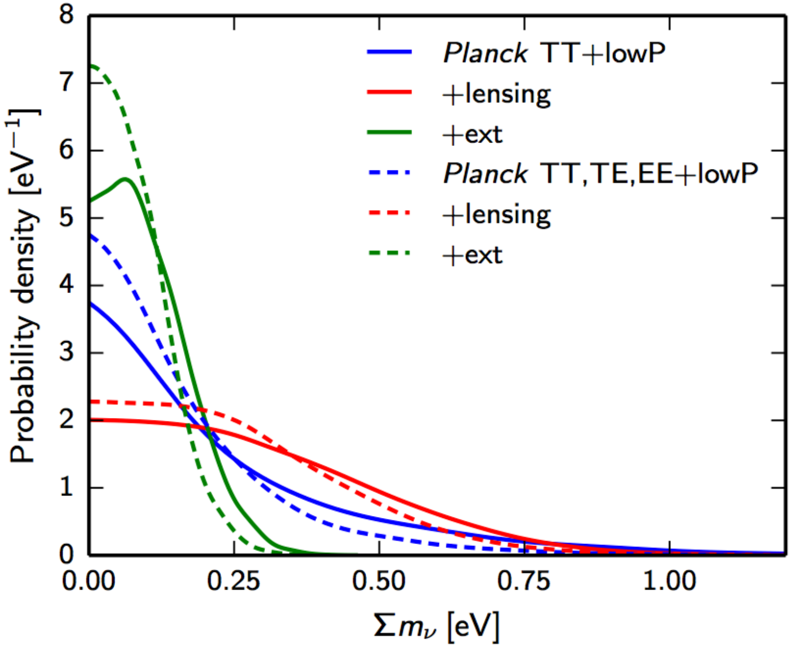


- matter-radiation equality, higher first peak
- larger sound horizon, peaks shift to higher l
- anisotropic stresses dampens fluctuations during radiation domination, suppression of power at multipoles > 200
- anisotropies on scales smaller than the photon diffusion length are damped , for fixed peak positions, increasing N_{eff} enhances damping



- matter-radiation equality, higher first peak, completely degenerate with number and matter density
- lower sound horizon, peaks shift to lower multipoles

Neutrinos



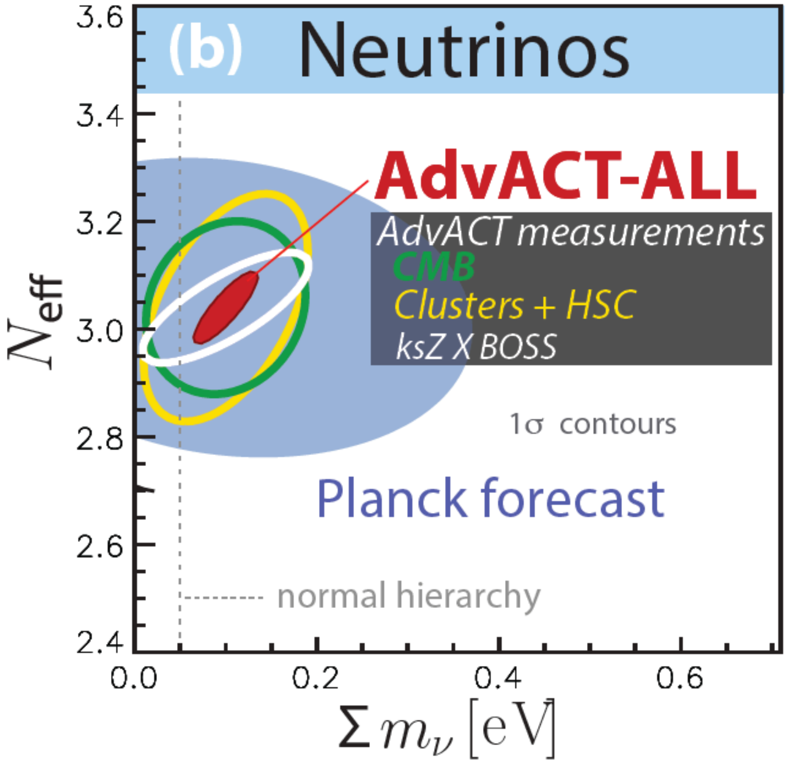
$$\sum m_\nu < 0.72 \text{ eV} \quad \textit{Planck} \text{ TT+lowP};$$

$$\sum m_\nu < 0.21 \text{ eV} \quad \textit{Planck} \text{ TT+lowP+BAO};$$

$$\sum m_\nu < 0.49 \text{ eV} \quad \textit{Planck} \text{ TT, TE, EE+lowP};$$

$$\sum m_\nu < 0.17 \text{ eV} \quad \textit{Planck} \text{ TT, TE, EE+lowP+BAO}.$$

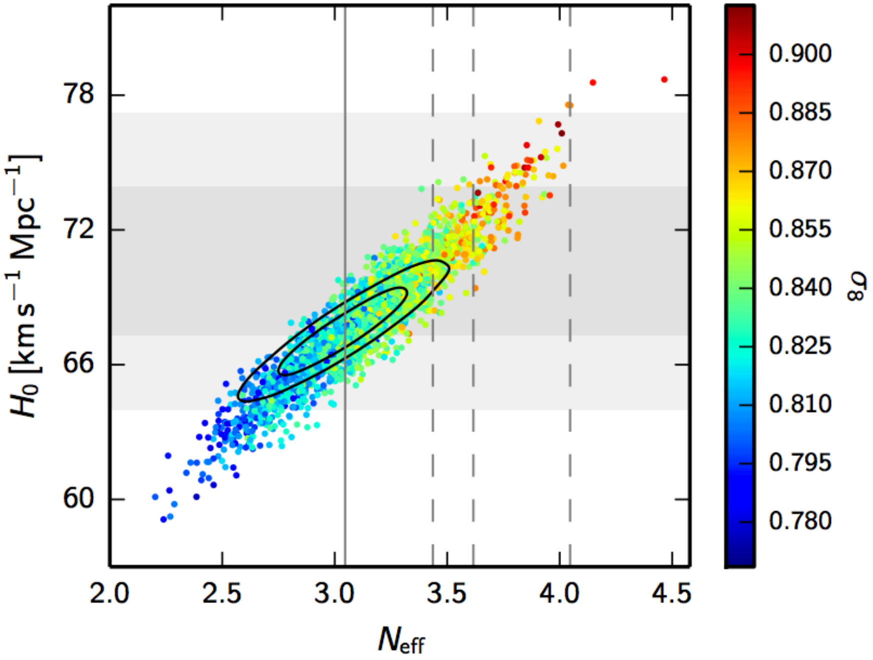
Planck 2015 results. XIII

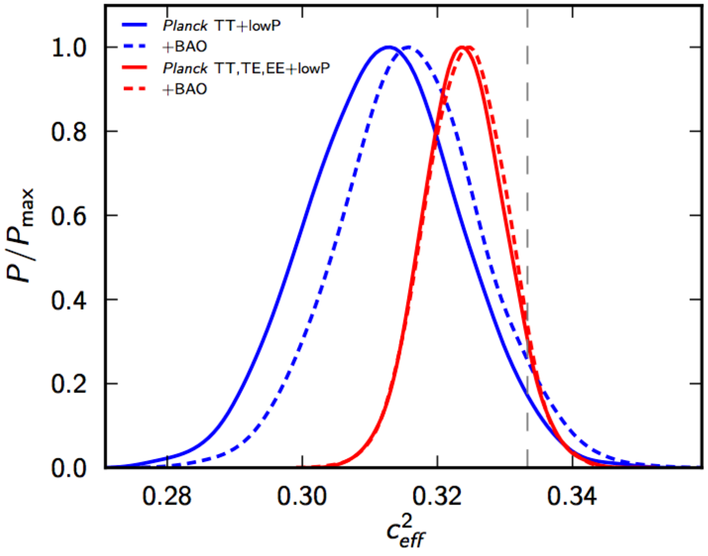


We expect definitive detection in next 5 years with improved lensing measurements – targeting 0.05 eV

Calabrese et al. 2014

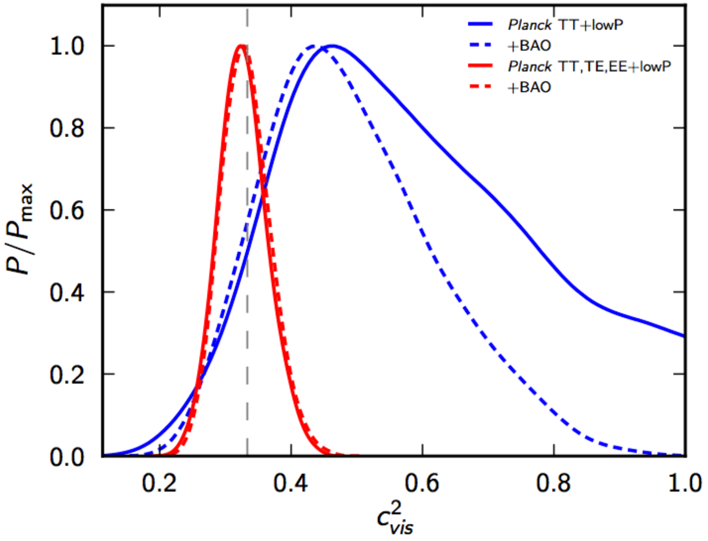
Neutrinos





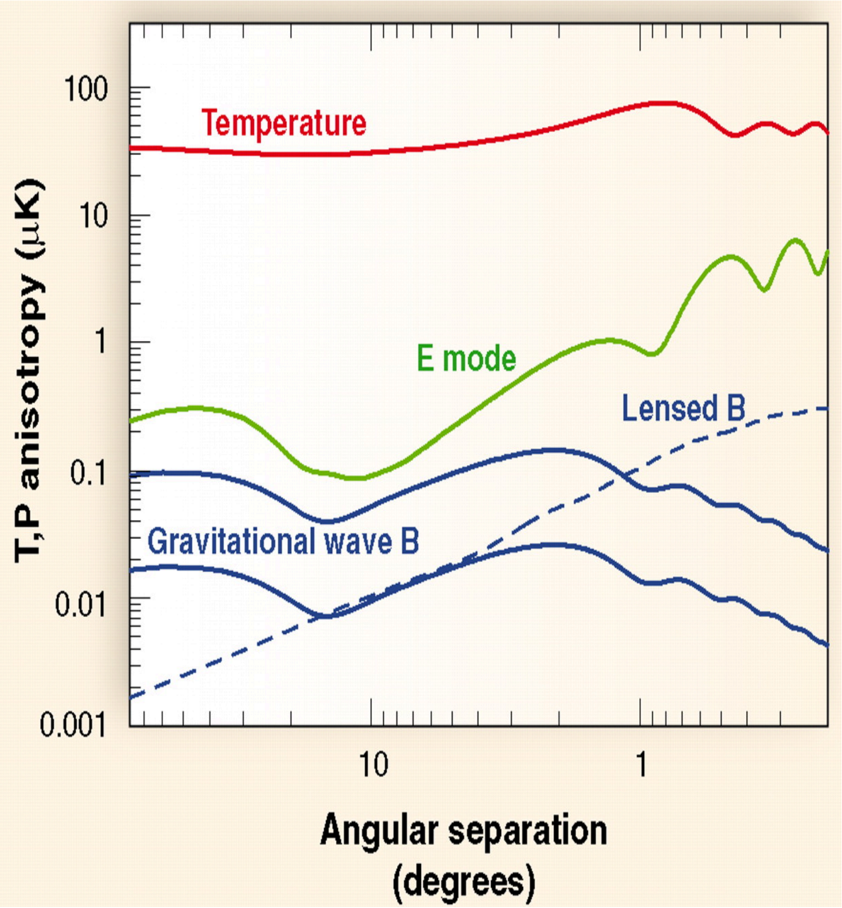
$$N_{\rm eff} = 3.13 \pm 0.32 \quad \textit{Planck}\ \text{TT+lowP}\,;$$
$$N_{\rm eff} = 3.15 \pm 0.23 \quad \textit{Planck}\ \text{TT+lowP+BAO}\,;$$
$$N_{\rm eff} = 2.99 \pm 0.20 \quad \textit{Planck}\ \text{TT, TE, EE+lowP}\,;$$
$$N_{\rm eff} = 3.04 \pm 0.18 \quad \textit{Planck}\ \text{TT, TE, EE+lowP+BAO}\,.$$

Planck 2015 results. XIII



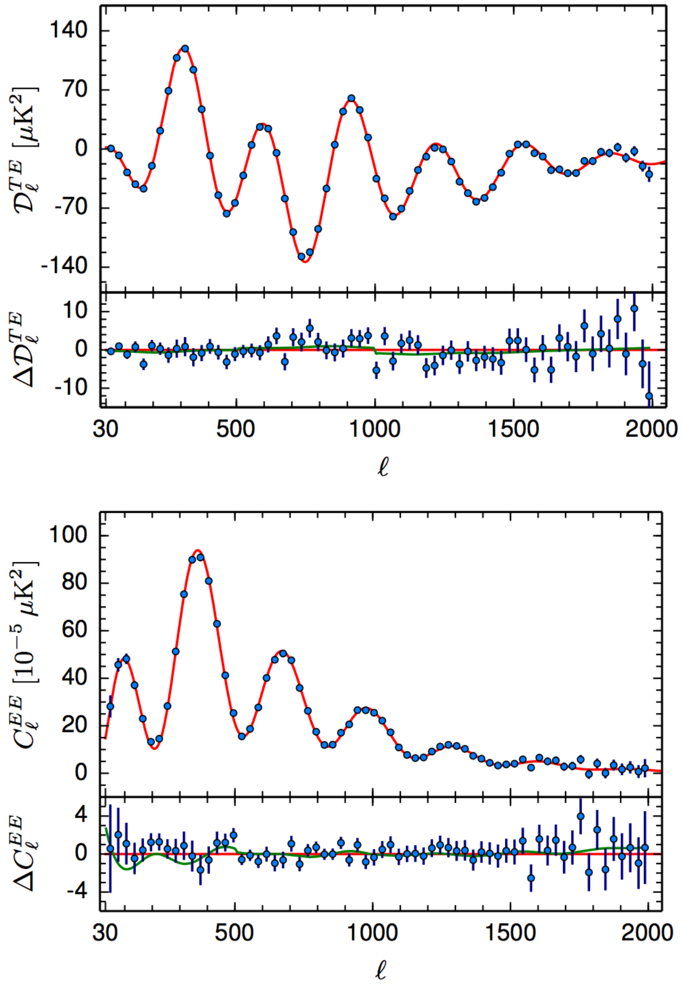
Parameter	TT	TT,TE,EE	TT,TE,EE+BAO
$c^2_{\rm vis}$	0.57 ± 0.16	0.336 ± 0.039	0.338 ± 0.040
$c^2_{\rm eff}$	0.314 ± 0.012	0.3256 ± 0.0063	0.3257 ± 0.0059

Next 5 years: CMB Polarization

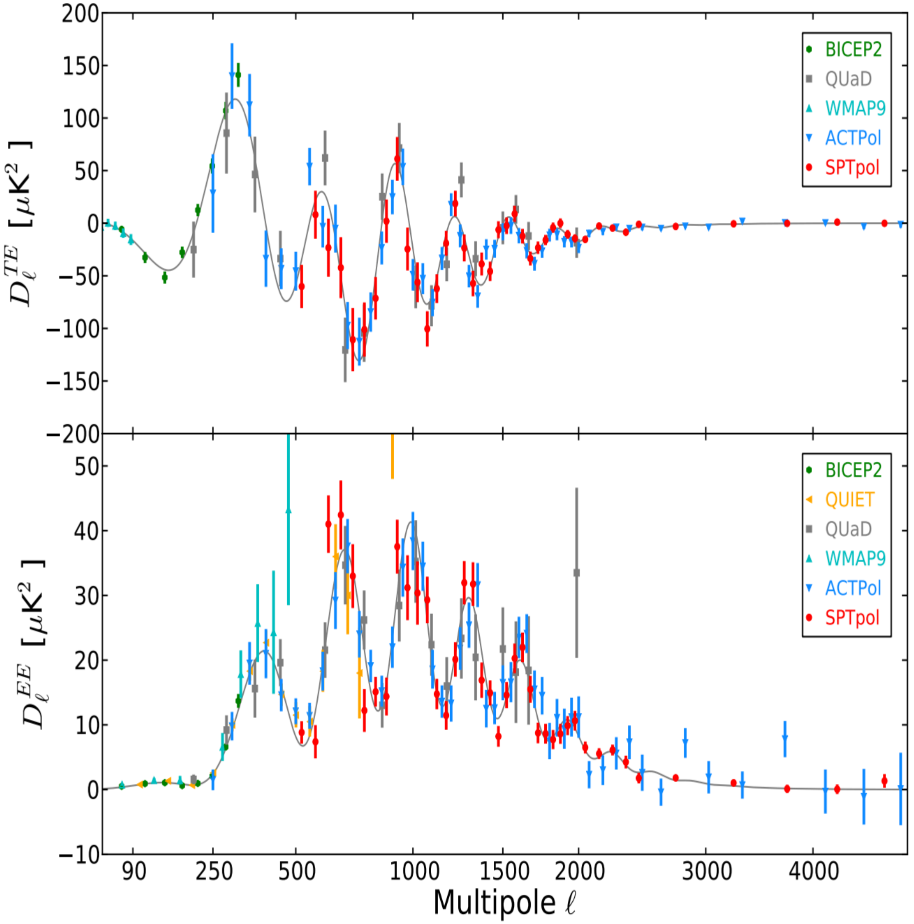


- Extremely sensitive to the matter distribution and the particle content
- Much smaller than temperature
- A robust measurement requires multi-wavelength and large area observations
- Consistency test for temperature
- Probing single cosmic epochs – complementary to temperature
- Probing high-energy scales not testable on the Earth
- Less contaminated by extra-galactic foregrounds

Next 5 years: CMB Polarization



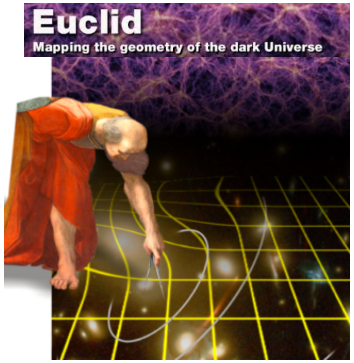
Planck 2015 results. XIII

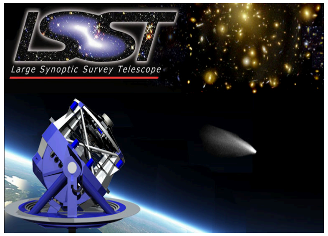


Crites et al. 2015

From 2020s: cross-correlations with galaxy surveys

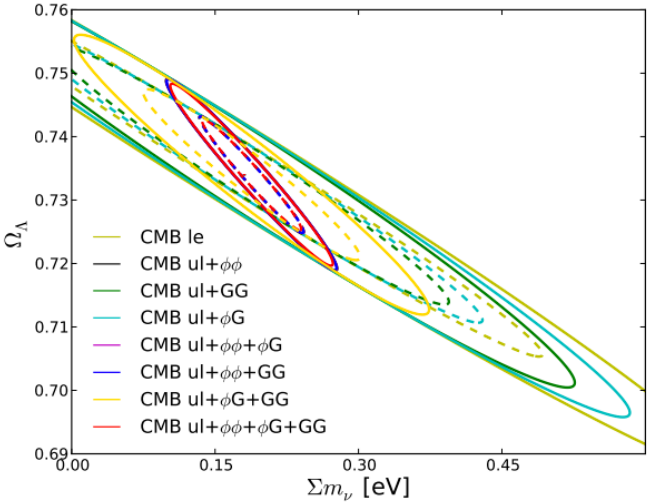
Probe of the geometry and the matter distribution with galaxy statistics





Probe	Observable	Science
Weak Lensing	Distortion of galaxy shapes	Geometry and growth of structure
Baryon Acoustic Oscillation	Power Spectrum of galaxy distribution	Distance-redshift relation
Galaxy Clusters	Cluster counts	Geometry and growth of structure
Type Ia Supernovae	Luminosity of standard candles	Distance-redshift relation
Strong Lensing	Time delays of multiply lensed sources	Geometry and DM distribution

Early-late time Universe combined studies



Pearson & Zahn 2014

Conclusions

The Universe:

- is described by the ΛCDM model
- is made of 5% baryonic ordinary matter
- is dominated by dark energy and dark matter
- has a cosmic neutrino background with a very small mass
- underwent a super-luminal expansion in the first fraction of a second after the big bang – cosmic inflation
- preliminary CMB polarization data are consistent with temperature information

But…:

- what is the dark energy and dark matter nature?
- what is the exact neutrino mass?
- are the laws of gravity valid on cosmic scales?
- did inflation really happen and what drove it?

Coming soon:

- accurate CMB polarization data enabling cross-correlation with LSS and redshift surveys to reduce systematics and provide robust cosmological estimates