IMPRS Student Symposium
Garching, March 2016

An overview of cosmology

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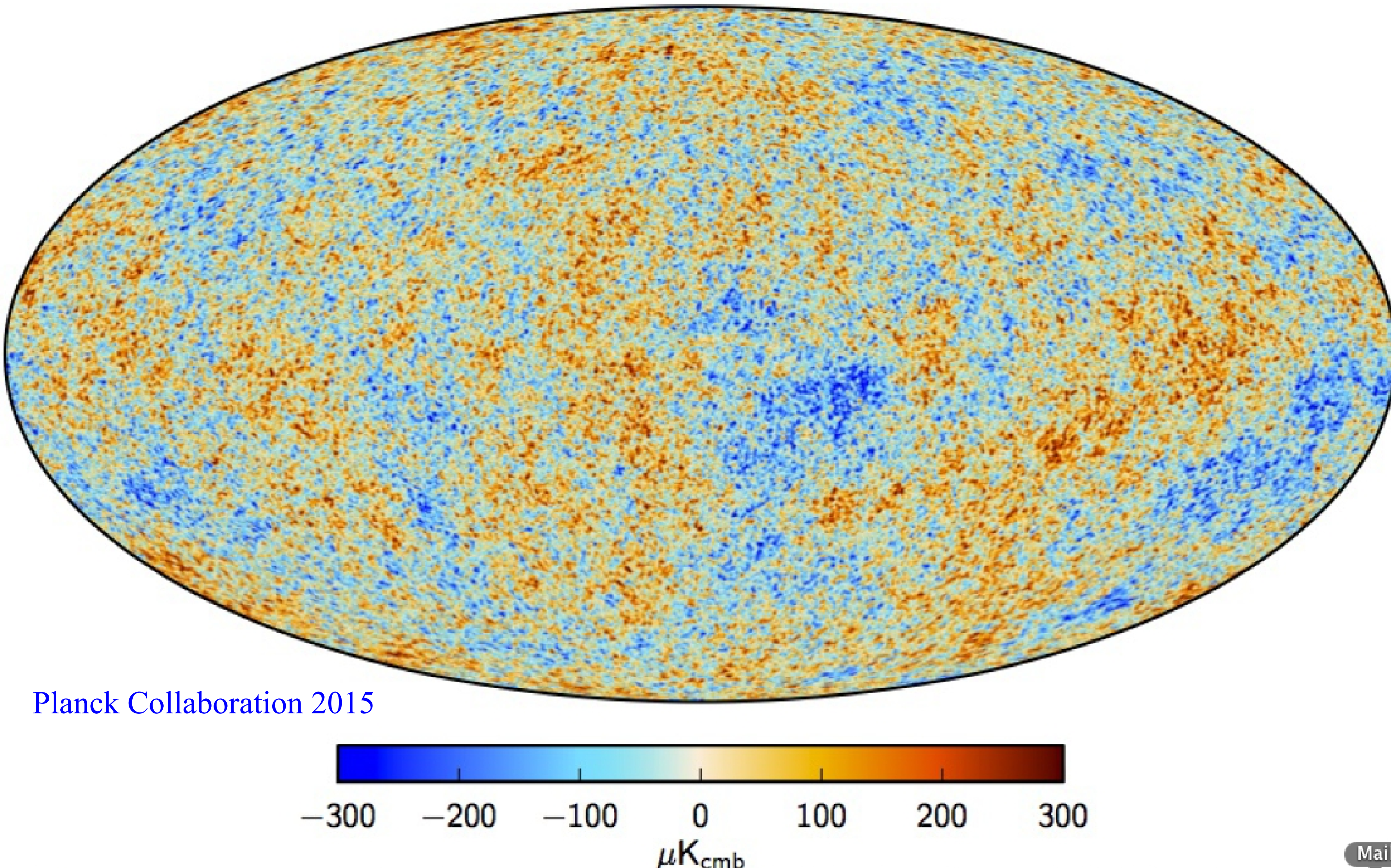
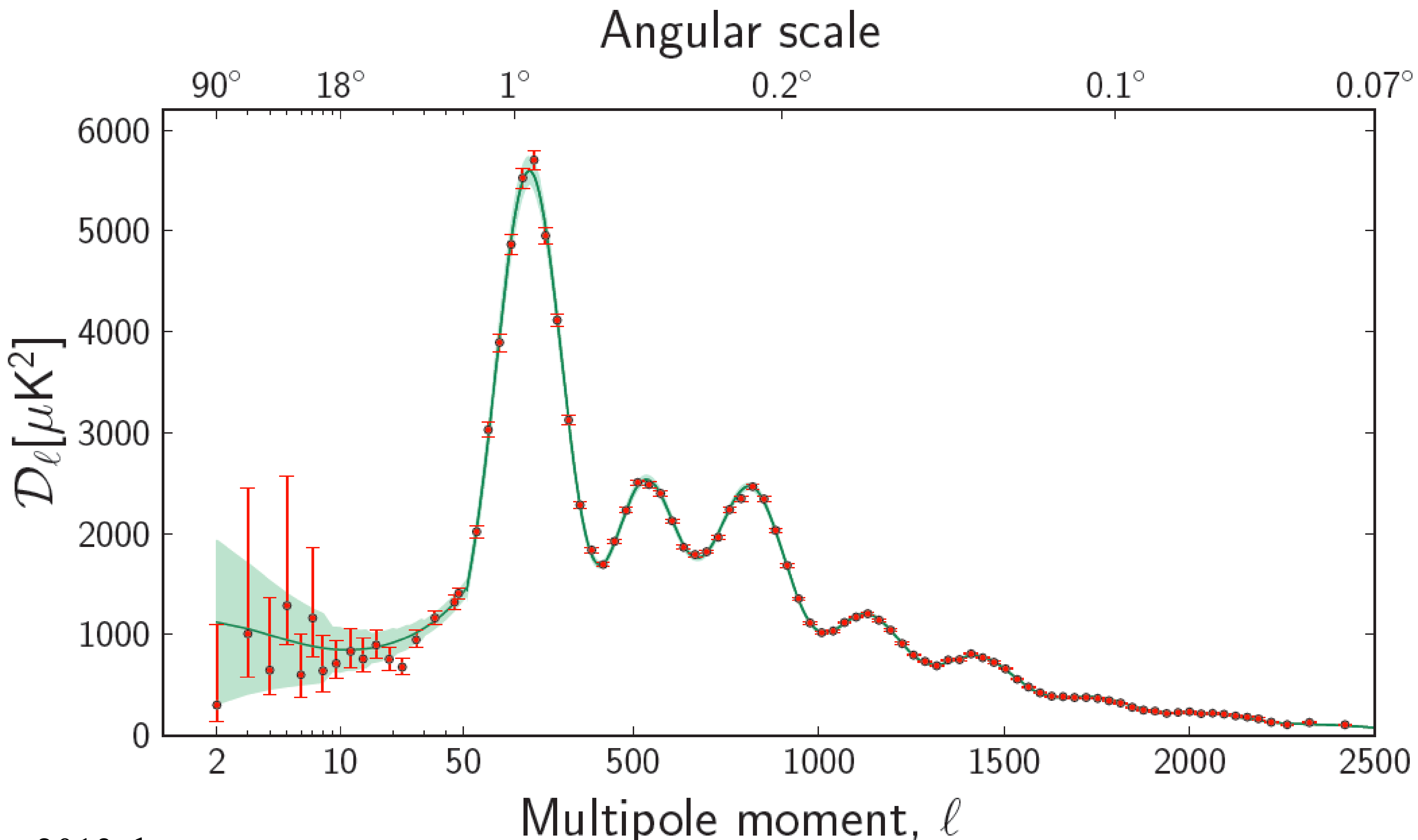
and the Planck Collaboration

The boundary of the visible Universe



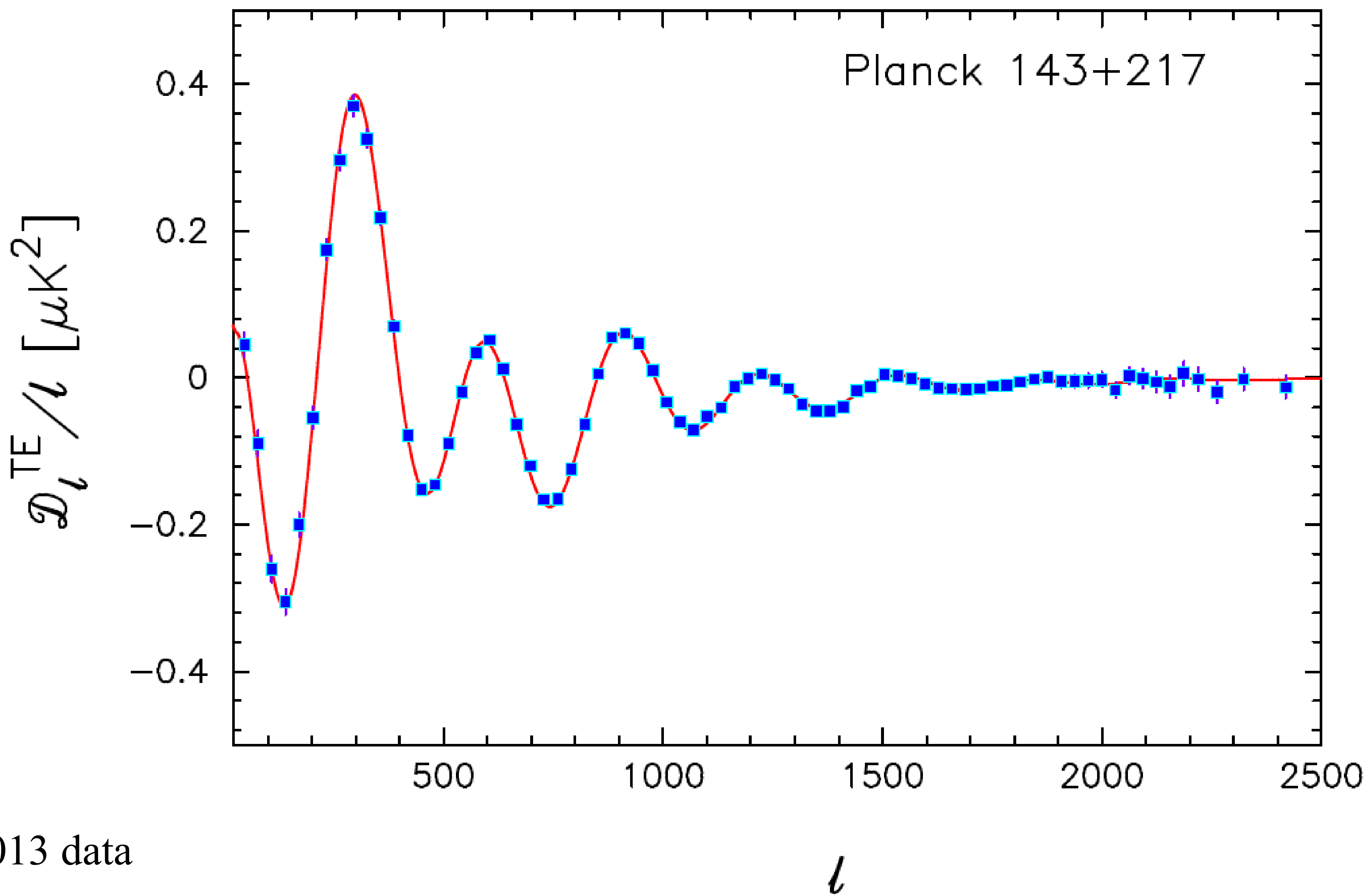
Planck Collaboration 2015

Planck CMB power spectrum from 2.5 surveys



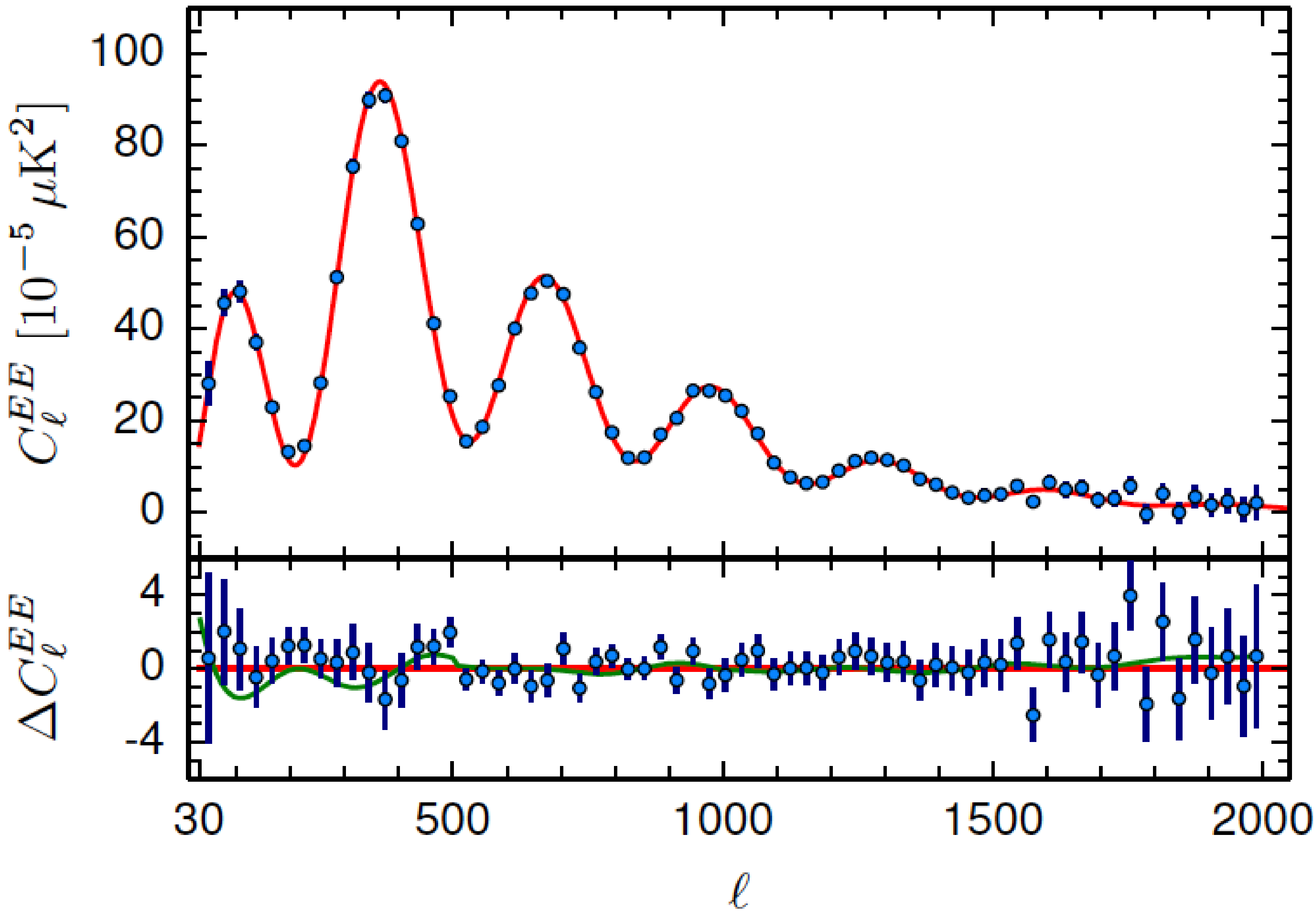
2013 data

Planck TE power spectrum from 2.5 surveys



2013 data

Planck EE power spectrum from the full mission



The temperature/polarisation pattern on the CMB surface depends on

- The geometry and topology of the Universe – flat? periodic?
- The content of the Universe at $z \sim 1000$ – baryons, DM, ν's
- The high-redshift process which created all structure – inflation?
- Gravitational lensing by foreground matter

Simplest model for inflation at early times implies

- Gaussian statistics
- nearly scale-invariant power spectrum (*n* slightly below unity)
- flat geometry
- a B-mode polarisation signal from primordial gravitational waves

The six parameters of the base ΛCDM model

Planck Collab'n 2015

Parameter	TT+lowP 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02225 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1198 ± 0.0015	0.1188 ± 0.0010
$100\theta_{MC}$	1.04085 ± 0.00047	1.04077 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.079 ± 0.017	0.066 ± 0.012
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.094 ± 0.034	3.064 ± 0.023
n_s	0.9655 ± 0.0062	0.9645 ± 0.0049	0.9667 ± 0.0040

The six parameters of the base ΛCDM model

Derived parameters

Parameter	TT+lowP 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
H_0	67.31 ± 0.96	67.27 ± 0.66	67.74 ± 0.46
Ω_Λ	0.685 ± 0.013	0.6844 ± 0.0091	0.6911 ± 0.0062
Ω_m	0.315 ± 0.013	0.3156 ± 0.0091	0.3089 ± 0.0062
σ_8	0.829 ± 0.014	0.831 ± 0.013	0.8159 ± 0.0086
z_{re}	$9.9^{+1.8}_{-1.6}$	$10.0^{+1.7}_{-1.5}$	$8.8^{+1.2}_{-1.1}$
Age/Gyr	13.813 ± 0.038	13.813 ± 0.026	13.799 ± 0.021

One parameter extensions of the base ΛCDM model

Planck Collab'n 2015

Parameter	TT, TE, EE	TT, TE, EE+lensing+ext
Ω_K	$-0.040^{+0.038}_{-0.041}$	$0.0008^{+0.0040}_{-0.0039}$
Σm_ν [eV]	< 0.492	< 0.194
$N_{\rm eff}$	$2.99^{+0.41}_{-0.39}$	$3.04^{+0.33}_{-0.33}$
$Y_{\rm P}$	$0.250^{+0.026}_{-0.027}$	$0.249^{+0.025}_{-0.026}$
$dn_s/d\ln k$	$-0.006^{+0.014}_{-0.014}$	$-0.002^{+0.013}_{-0.013}$
$r_{0.002}$	< 0.0987	< 0.113
w	$-1.55^{+0.58}_{-0.48}$	$-1.019^{+0.075}_{-0.080}$

Planck results bearing on models of inflation

Parameter values

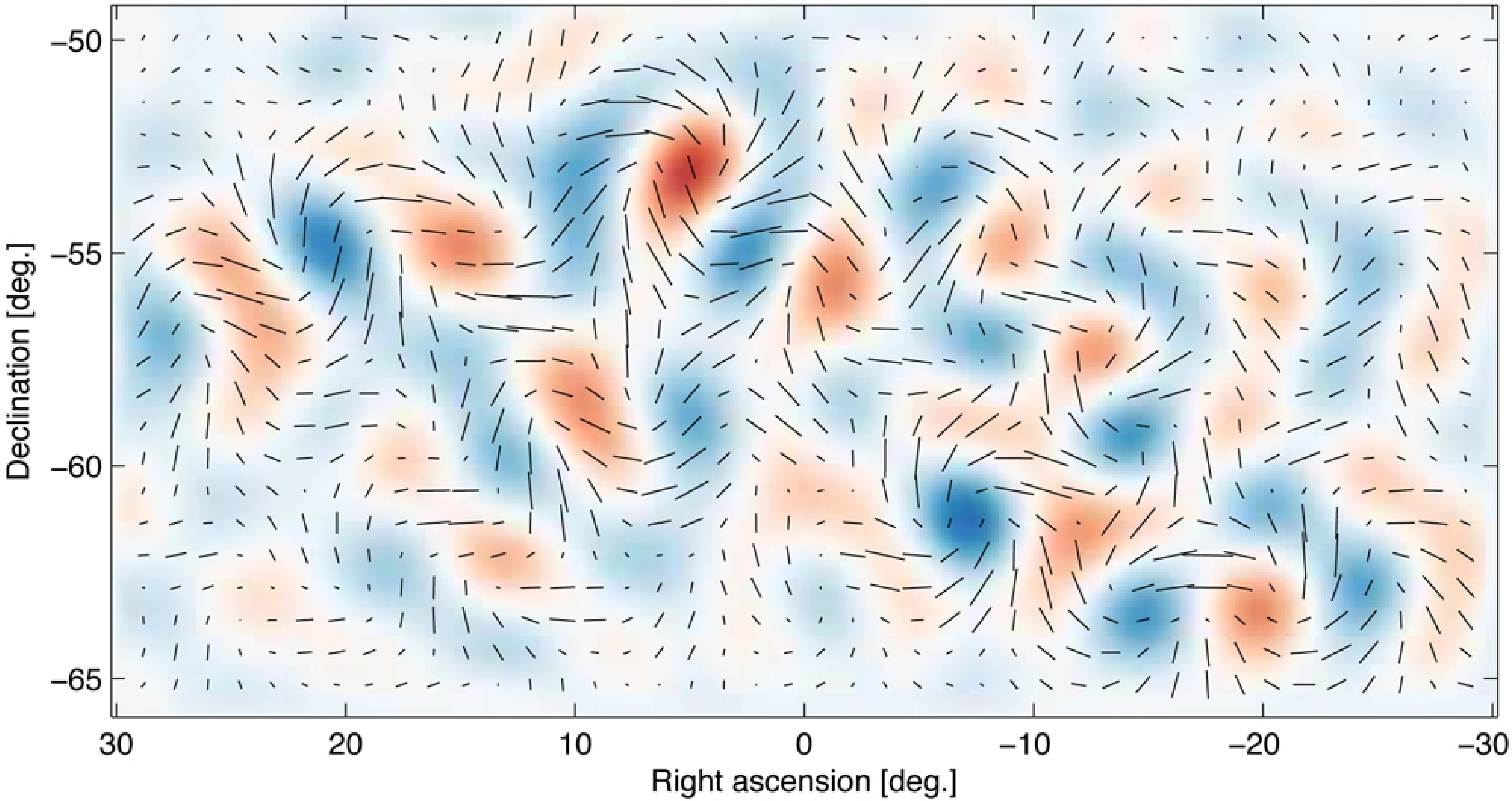
Parameter	TT, TE, EE+lensing+ext
Ω_K	$0.0008^{+0.0040}_{-0.0039}$
n_s	0.9667 ± 0.0040 ← ~ 8σ !
$dn_s/d\ln k$	$-0.002^{+0.013}_{-0.013}$
$r_{0.002}$	< 0.113

Non-Gaussianity constraints

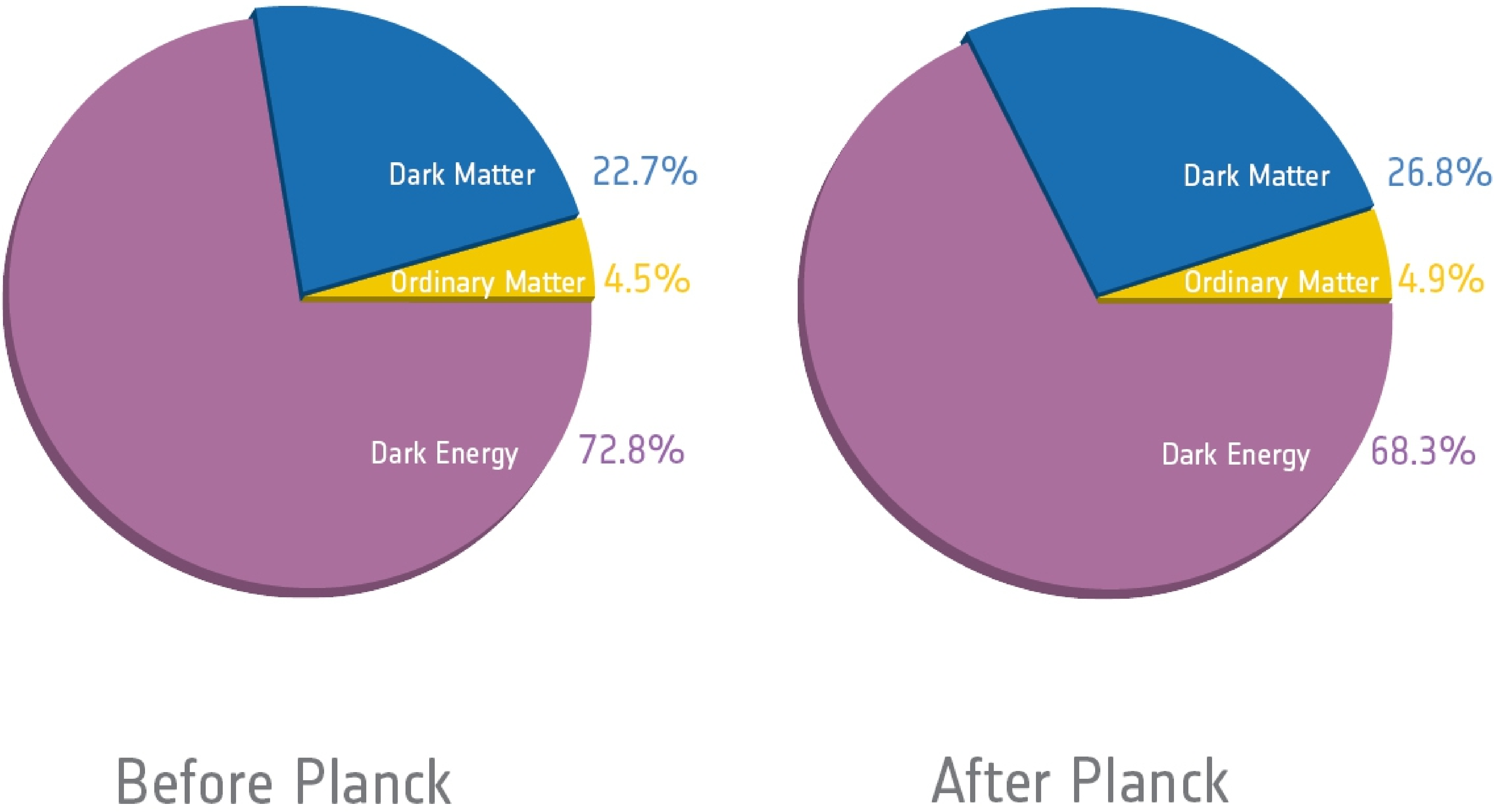
f_{NL}

	Independent KSW	ISW-lensing subtracted KSW
SMICA (T+E)		
Local	6.5 ± 5.0	**0.8 ± 5.0**
Equilateral	3 ± 43	**-4 ± 43**
Orthogonal	-36 ± 21	**-26 ± 21**

BICEP2 results on B-mode polarisation



Such "B-modes" are produced by gravitational lensing of "E-modes" and by initial tensor (i.e. gravitational wave) fluctuations. Simple models for inflationary generation of structure produce these with comparable amplitude to scalar (i.e. density) fluctuations. *Planck* multi-frequency data showed, however, that the signal is probably due to Galactic dust.



The Universe is also expanding 7% slower than before and is 80,000,000 years older!

Outstanding questions for post-CMB study i.e. observation!

– What is Dark Energy? a new mass/energy field? a failure of GR?

  – expansion history; $D_L(z)$ [SNe], $D_A(z)$, H(z) [BAO]
  – linear growth history; f(z) = d ln G / d ln a [RSD]
  – interaction with DM? neutrinos? baryons?

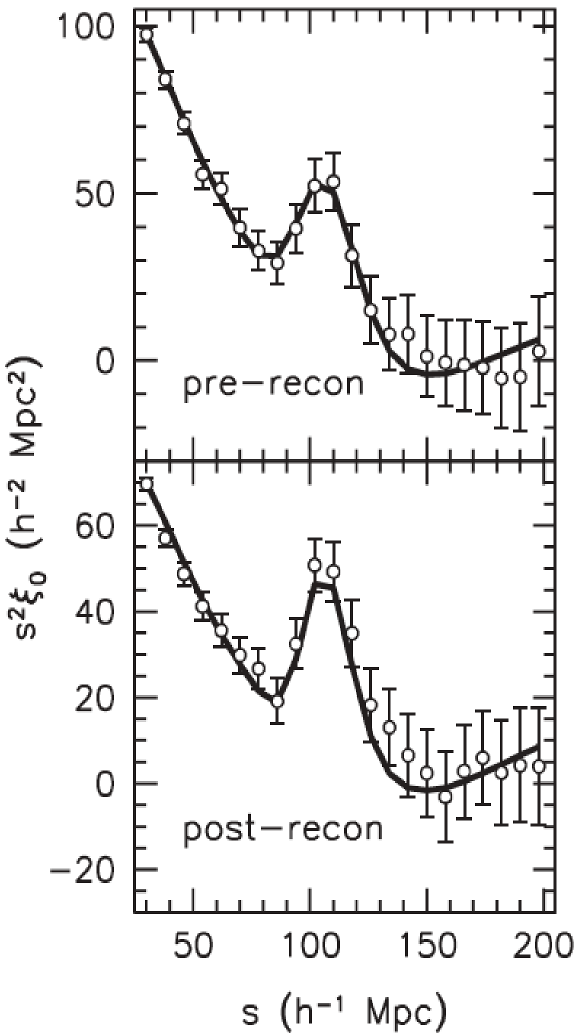
– What is Dark Matter? a new elementary particle? a failure of GR?

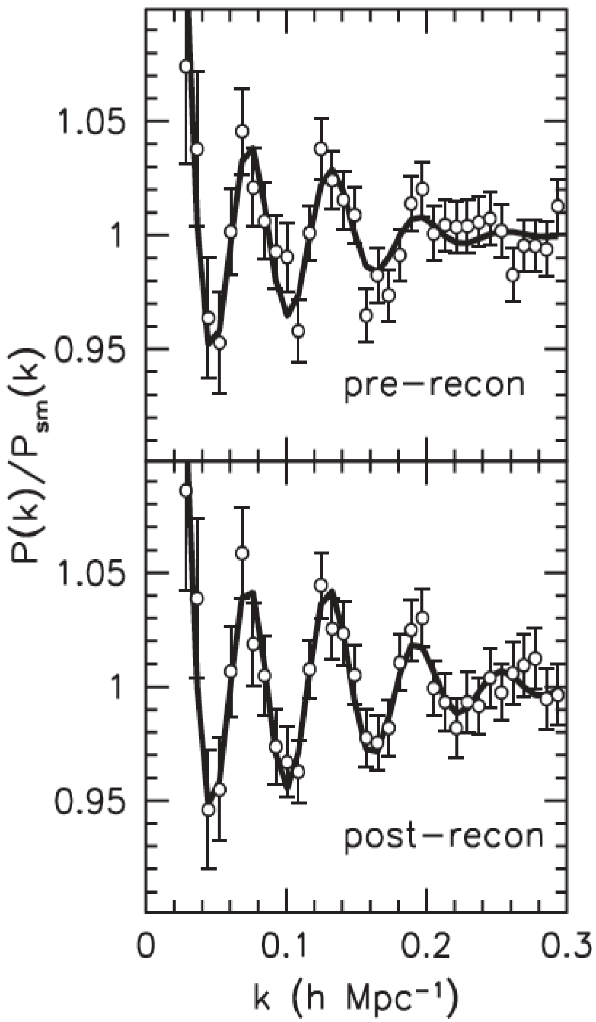
  – direct detection in the laboratory – axions? WIMPs?
  – indirect detection through annihilation radiation – γ-rays?
  – small-scale structures – Ly α forest, dwarf cores, lensing
  – effects of neutrino DM

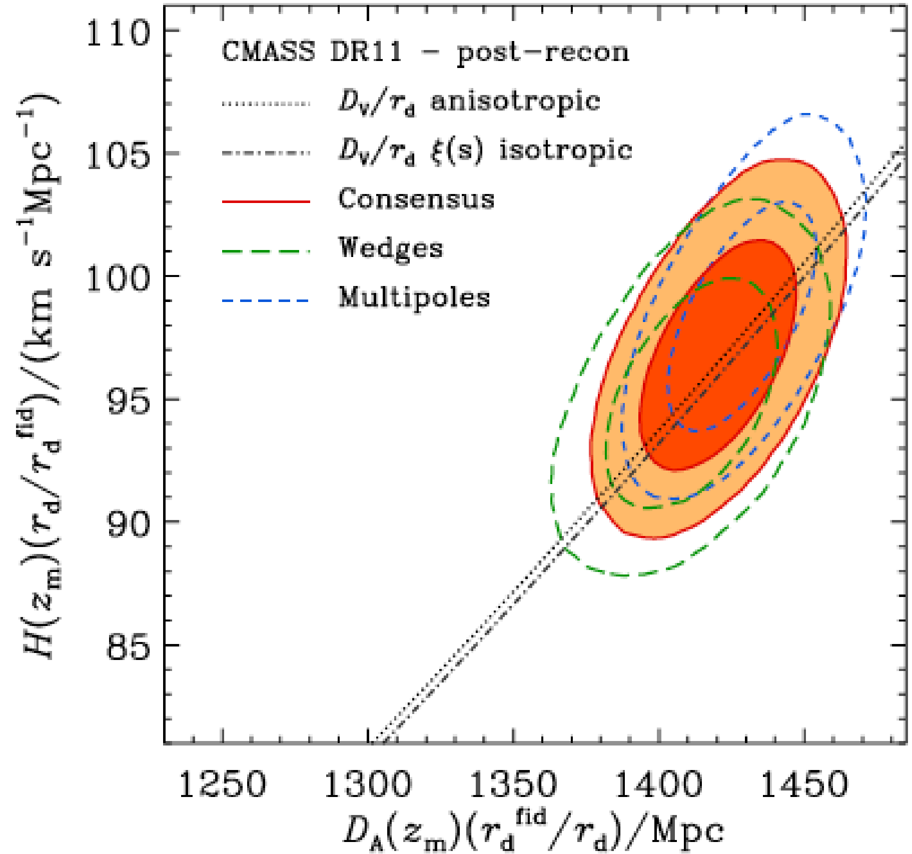
– Deviations from (primordial linear) gaussian statistics

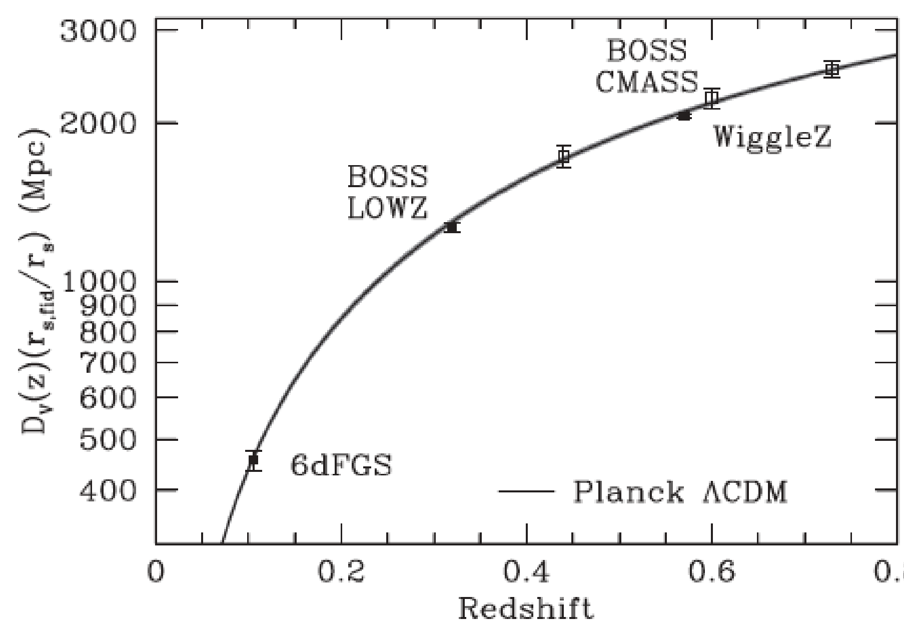
  – confusion with nonlinear effects, given *Planck* constraints

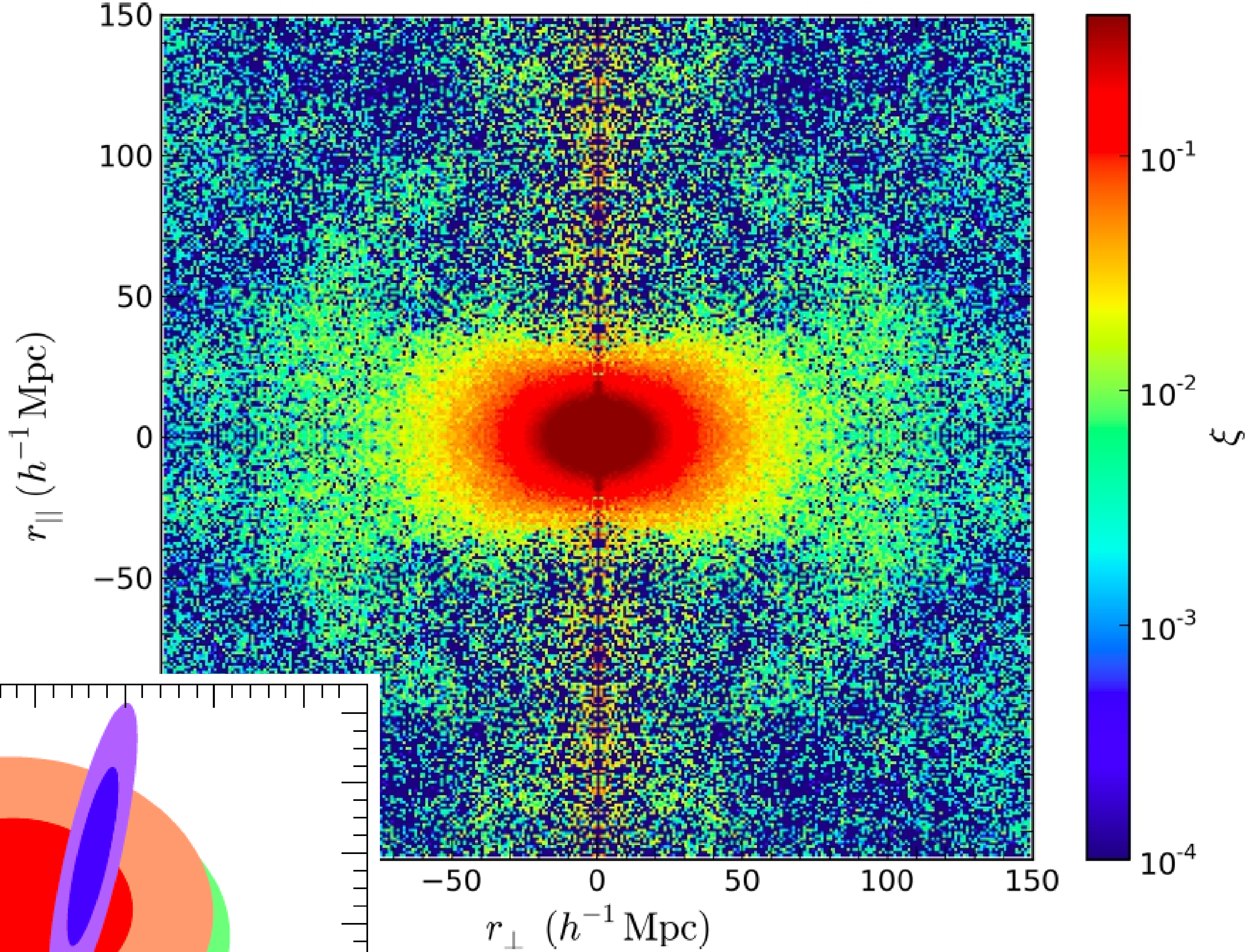
Baryon Acoustic Oscillations in SDSS-III/DR11

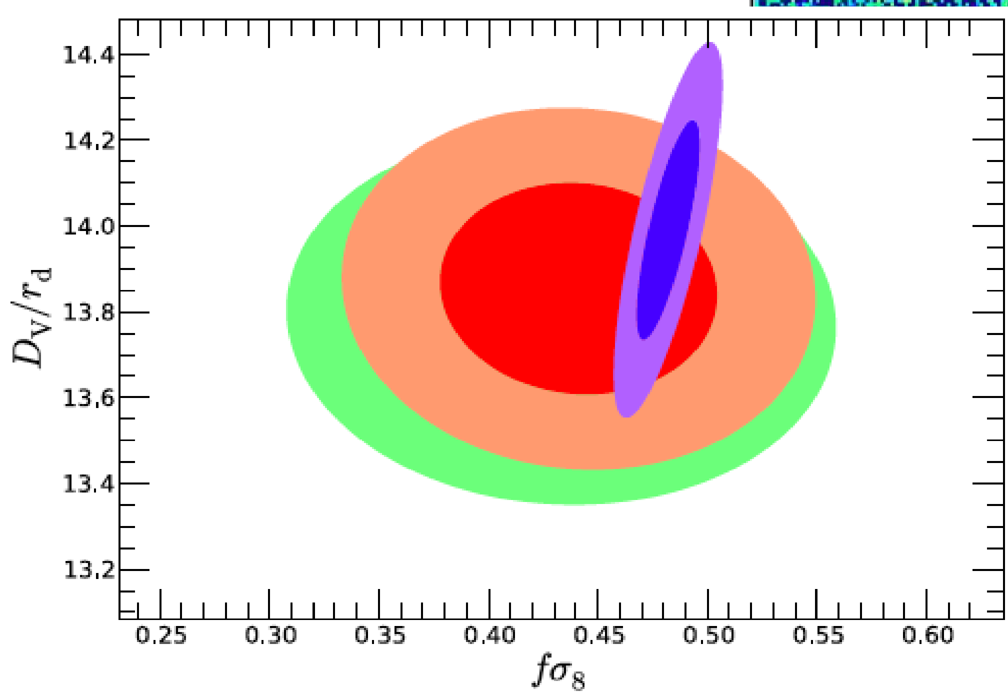






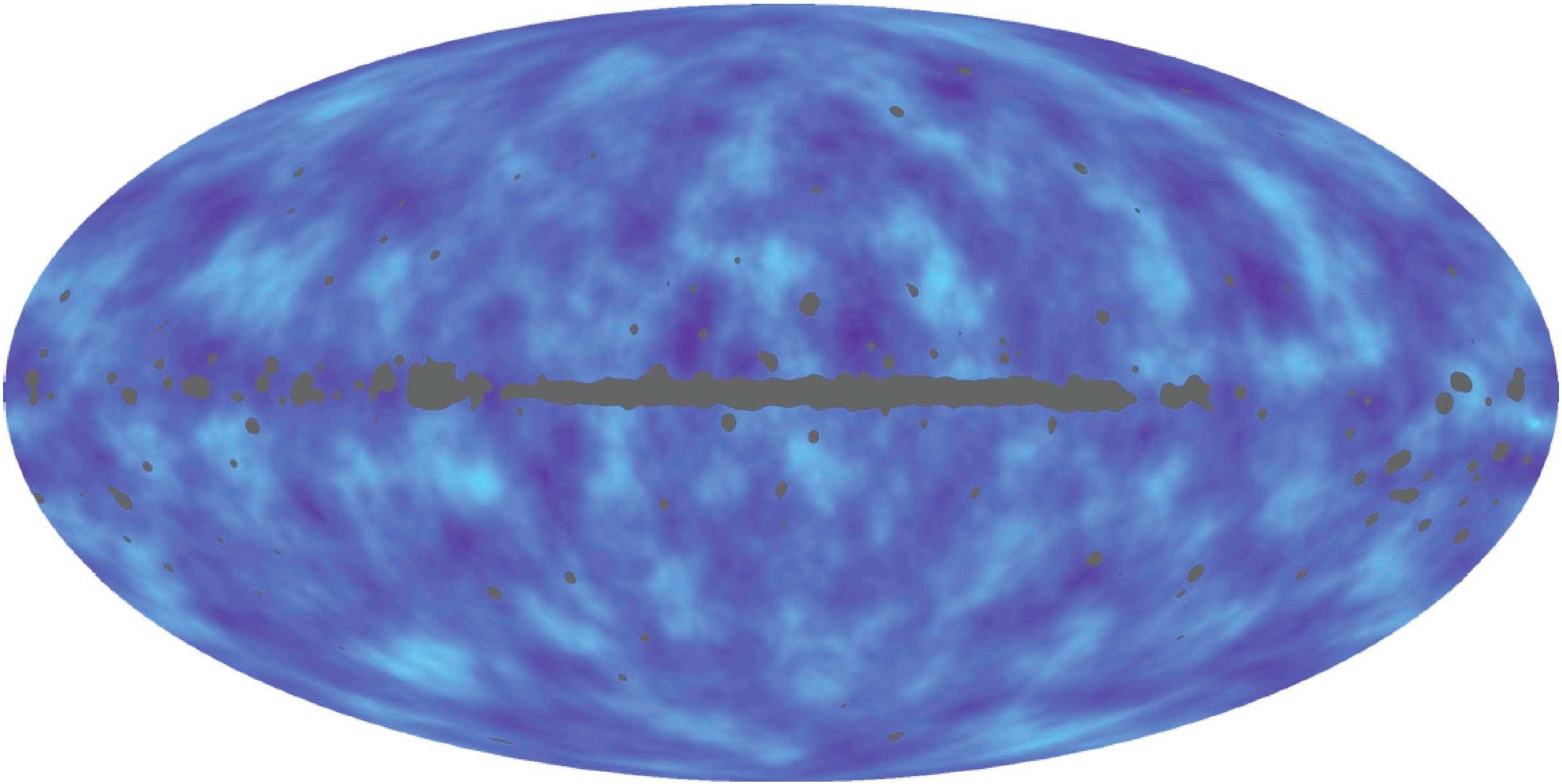






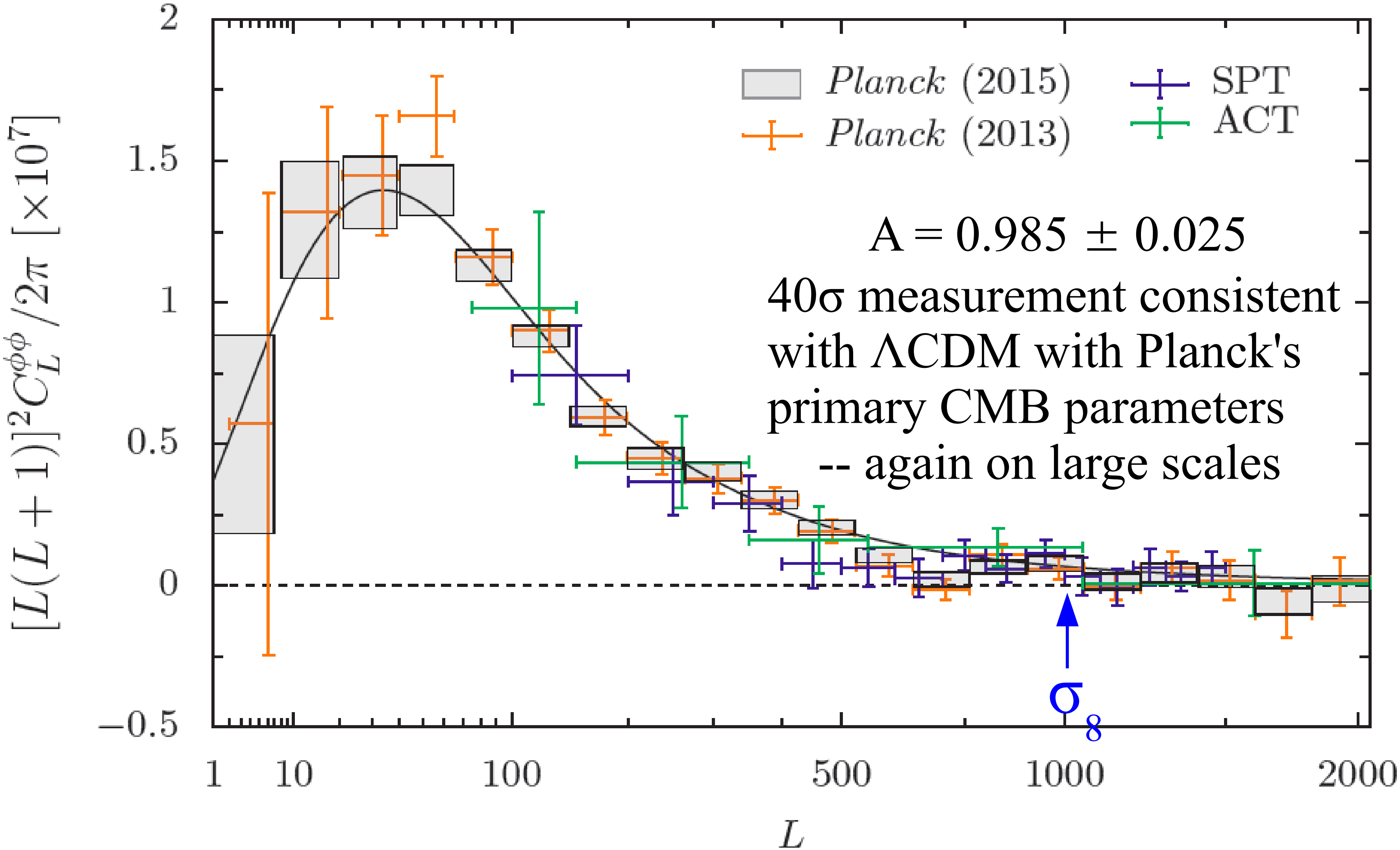
Redshift Space Distortions in SDSS-III/DR11

Planck results on DM in the visible Universe



Projected mass map reconstructed from non-gaussianities in the CMB temperature fluctuation pattern induced by gravitational lensing

Late-time mass fluctuations from CMB lensing



Provides statistics of the *total* mass distribution in front of the CMB

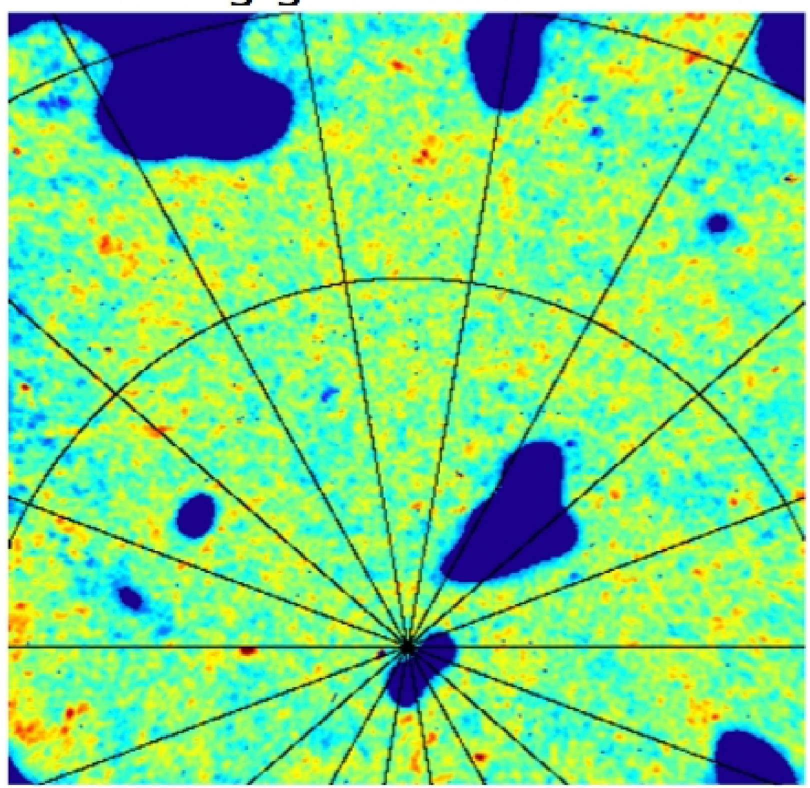
Dominated by material at redshifts $0.5 < z < 3.0$

Planck results on DM in the visible Universe

Planck image of part of the sky with little Milky Way dust emission. What there is has been removed using Galactic hydrogen maps made by other telescopes.

This map primarily shows the **Cosmic Infrared Background**, emission from warm dust in distant star-forming galaxies at redshifts between 1 and 3

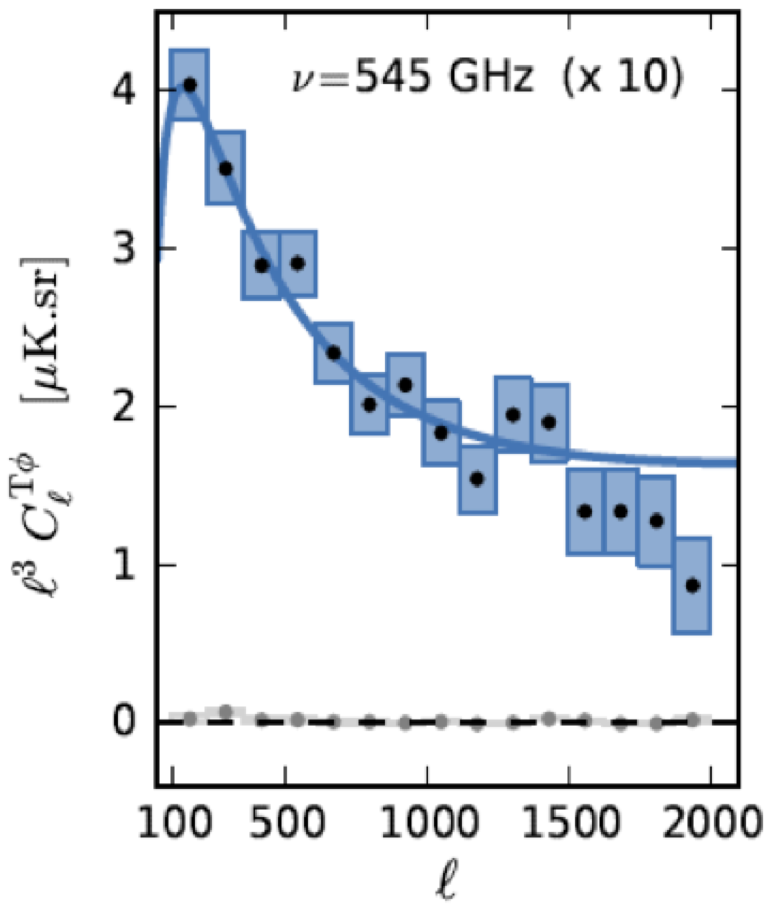
545 GHz



2013 data

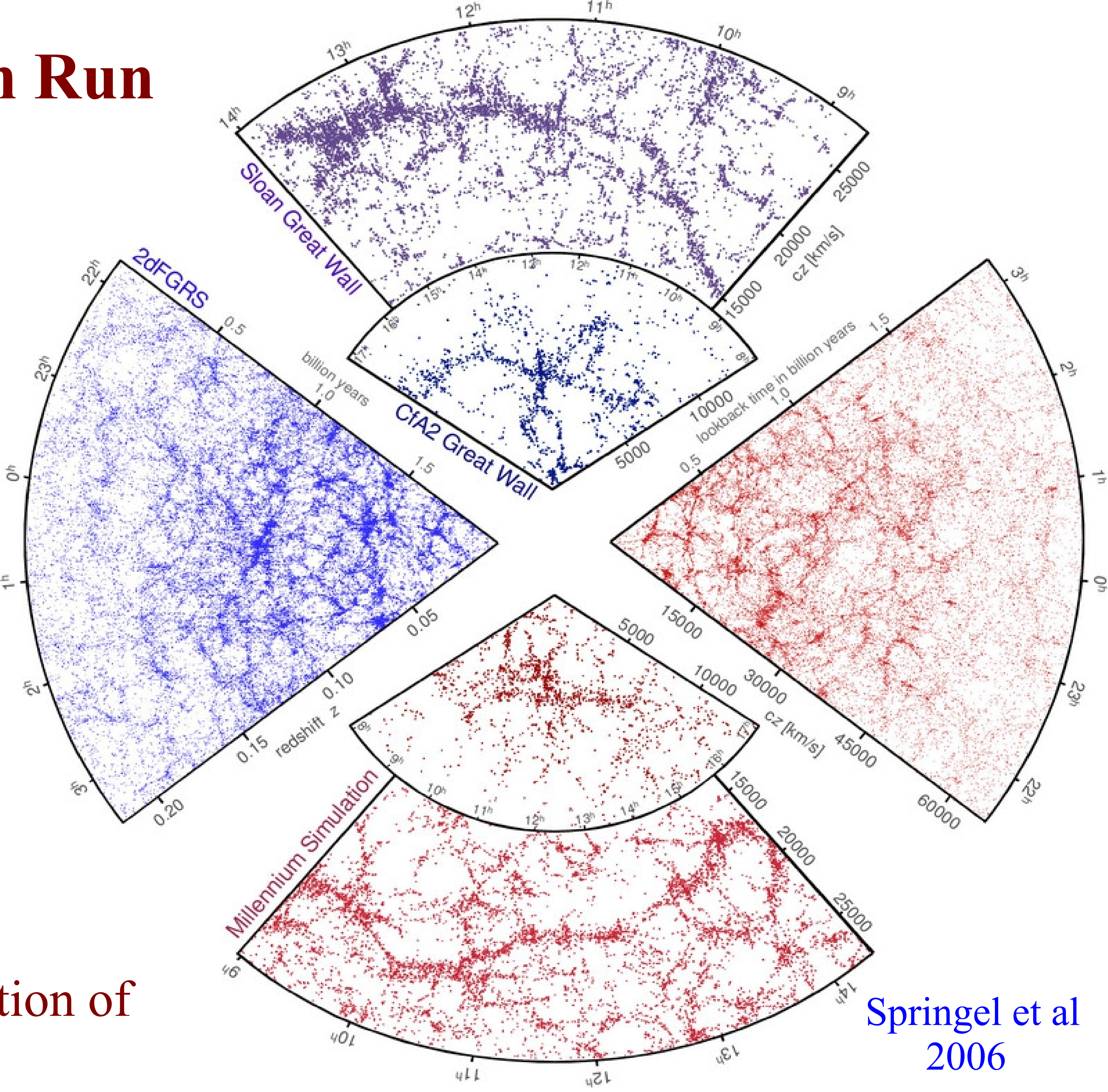
Planck results on DM in the visible Universe

The Planck mass map correlates very strongly with the CIB maps. This is a direct detection of the total mass associated with galaxies at the time they were making most of their stars. During this epoch, the Universe went from 20% to 50% of its present age.



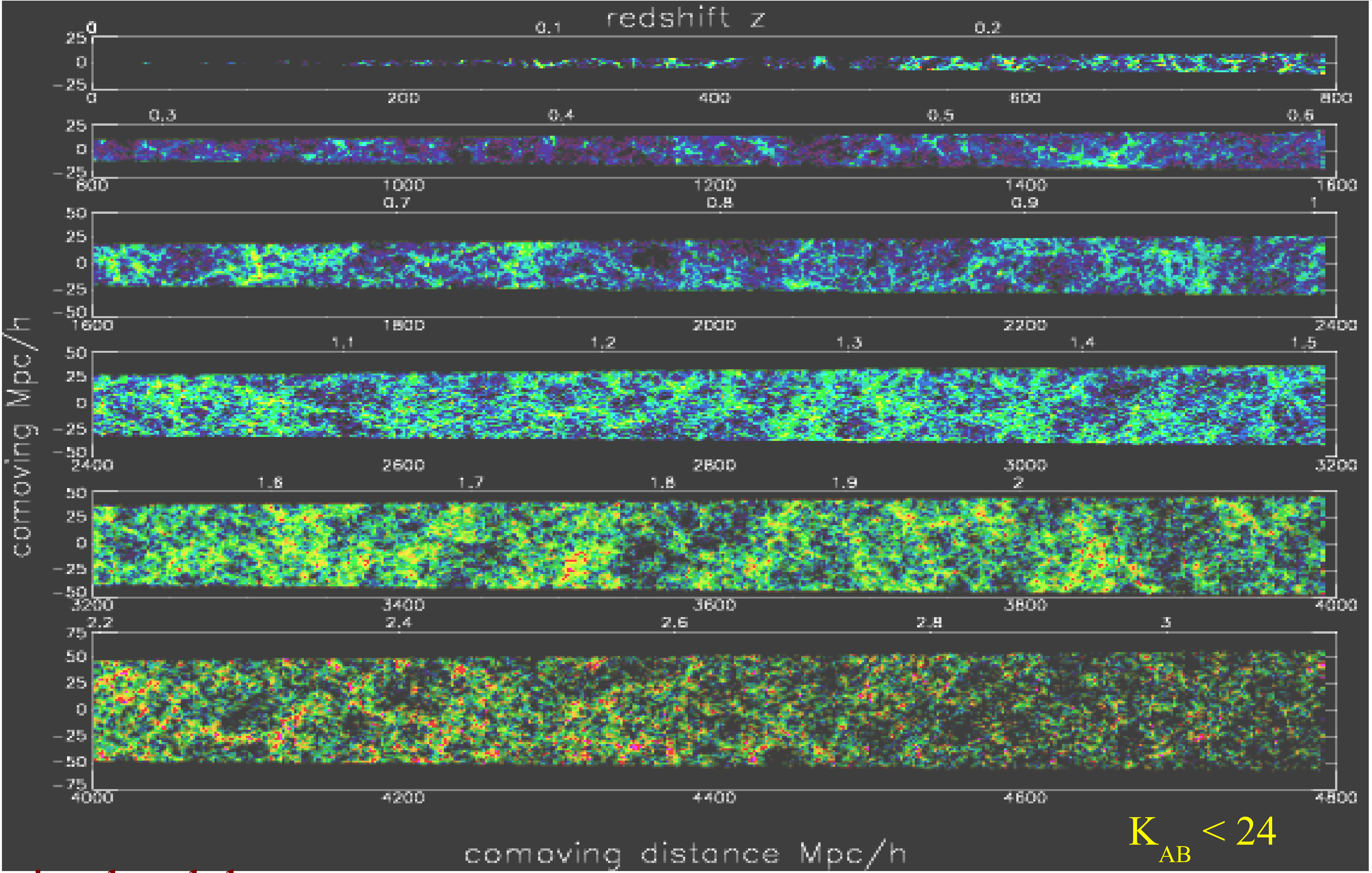
2013 data

Millennium Run 2004



simulated the formation/evolution of $2x10^7$ galaxies

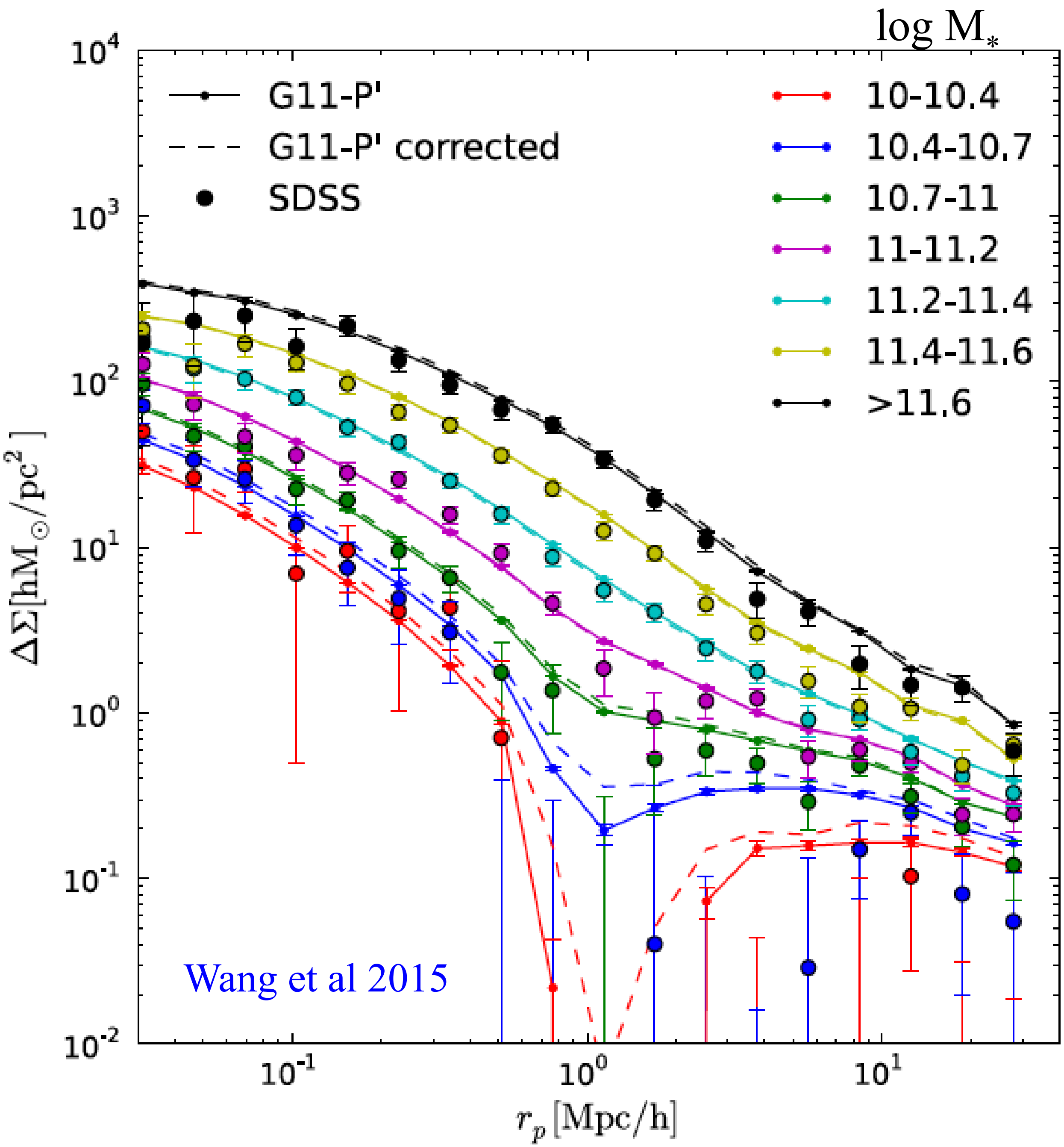
Springel et al 2006



simulated the formation/evolution of $2x10^7$ galaxies from z = 10 to z = 0

Kitzbichler & White
2007

Mean mass profiles around low-redshift galaxies

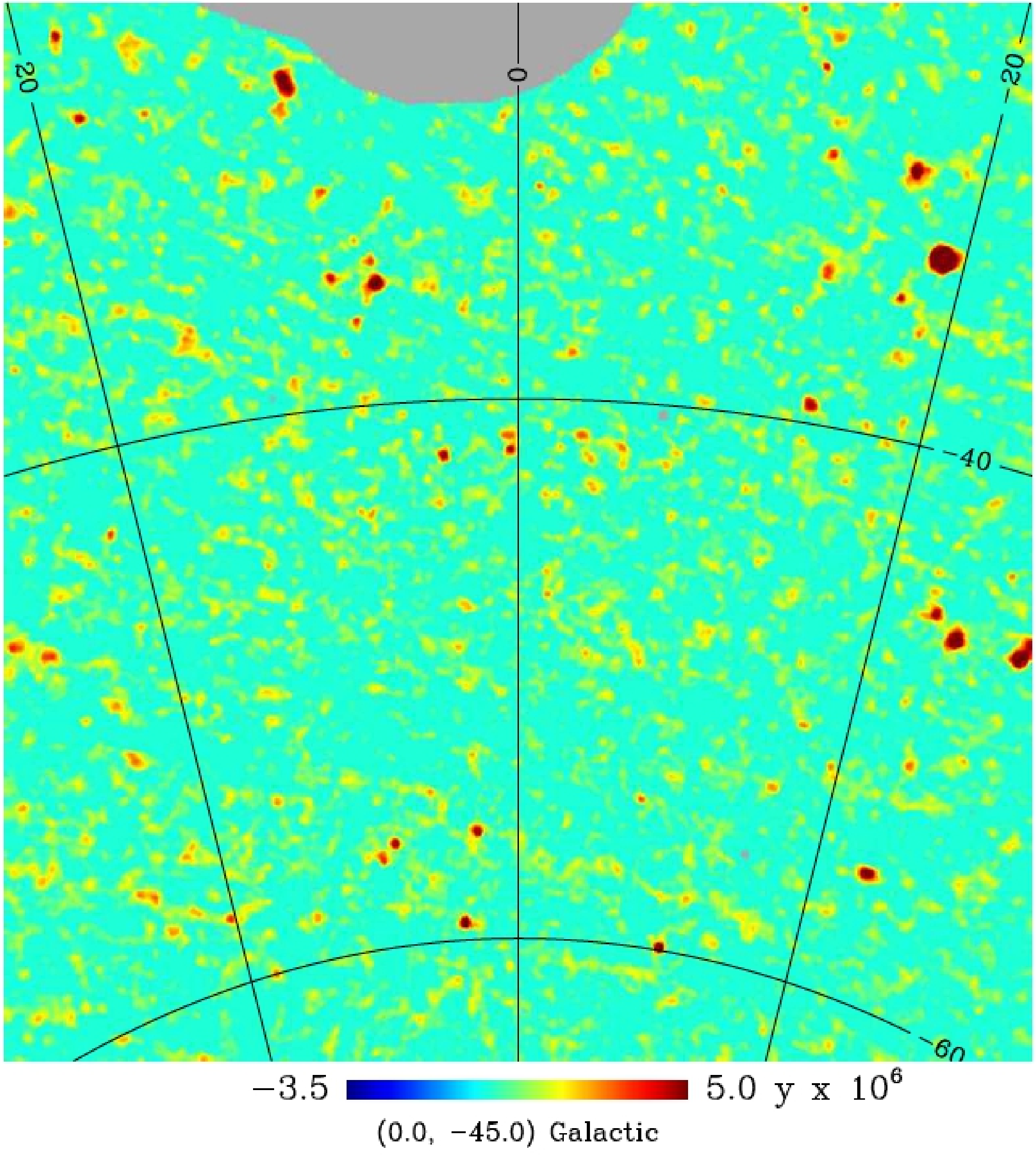


Points are mean weak lensing profiles around SDSS “central” galaxies as a function of their stellar mass.

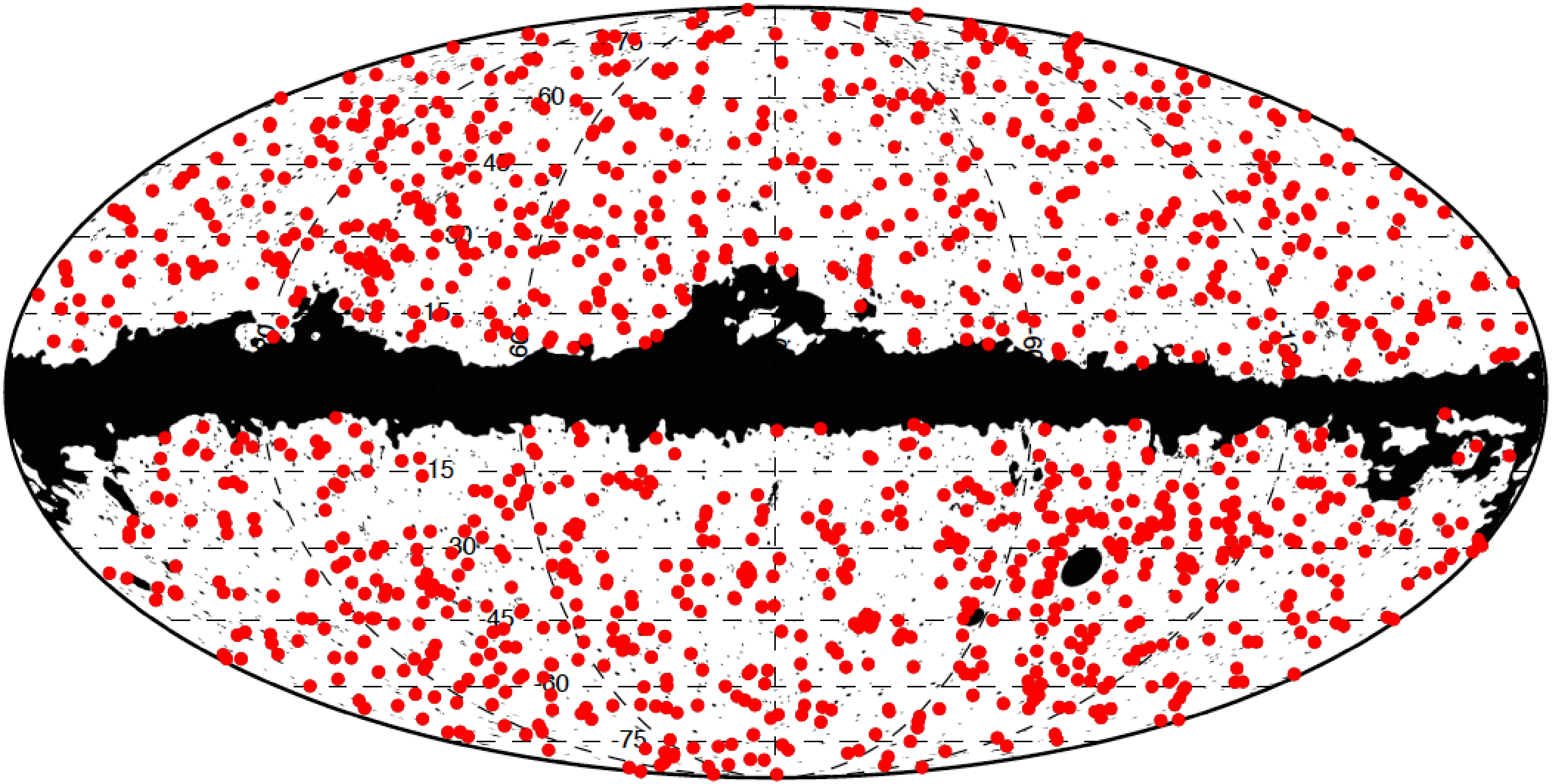
Lines are from a <u>simulation</u> of the formation of the galaxy population within ΛCDM, assuming Planck parameters.

No simulation parameters were adjusted in this comparison, but the agreement <u>does</u> depend on the astrophysical modelling.

SZ map from the first 2.5 surveys

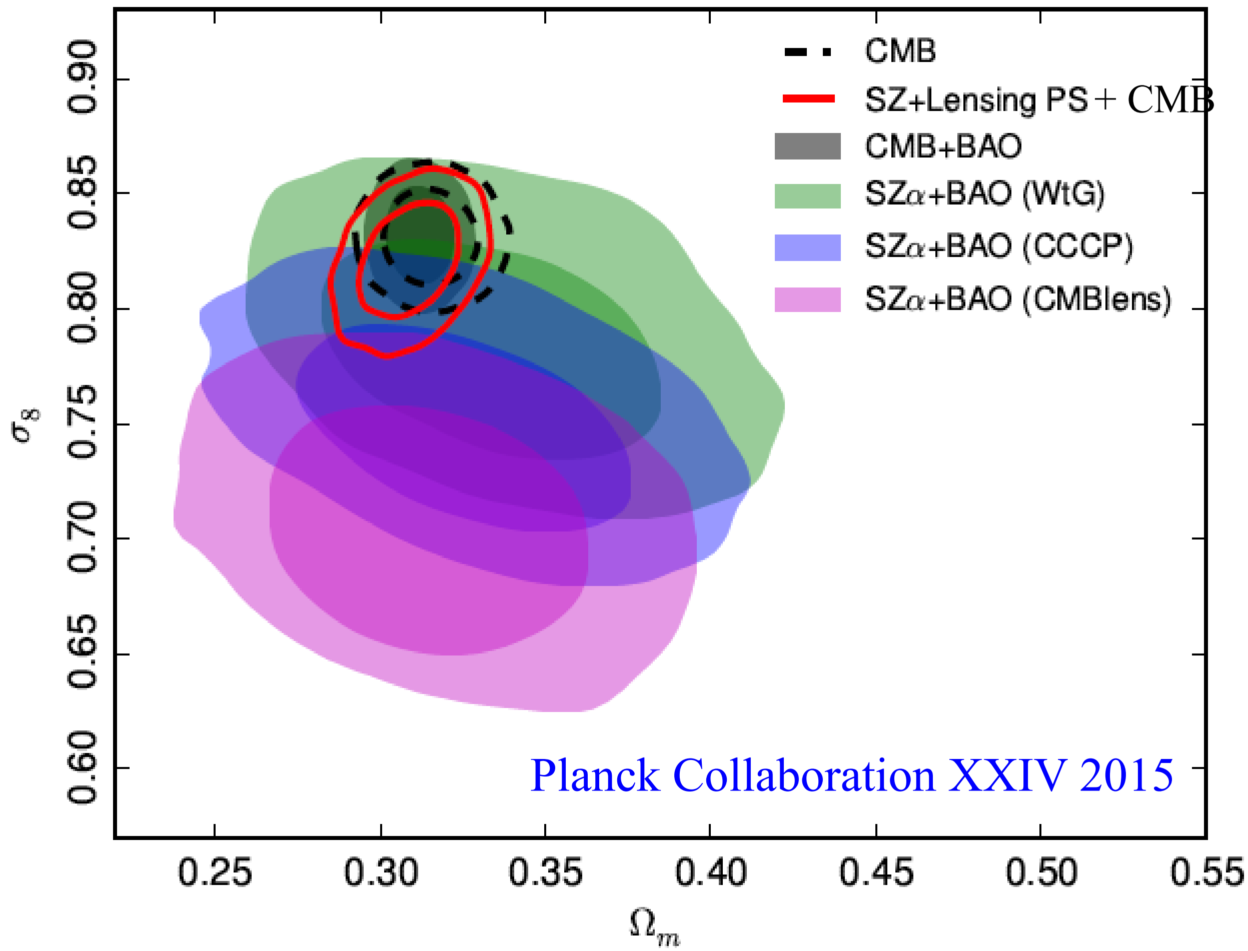


Planck's 2013 catalogue of SZ-detected sources



1227 SZ sources with S/N>4.5 over 83.7% of the sky.   861 confirmed clusters

Problems with cluster abundances?

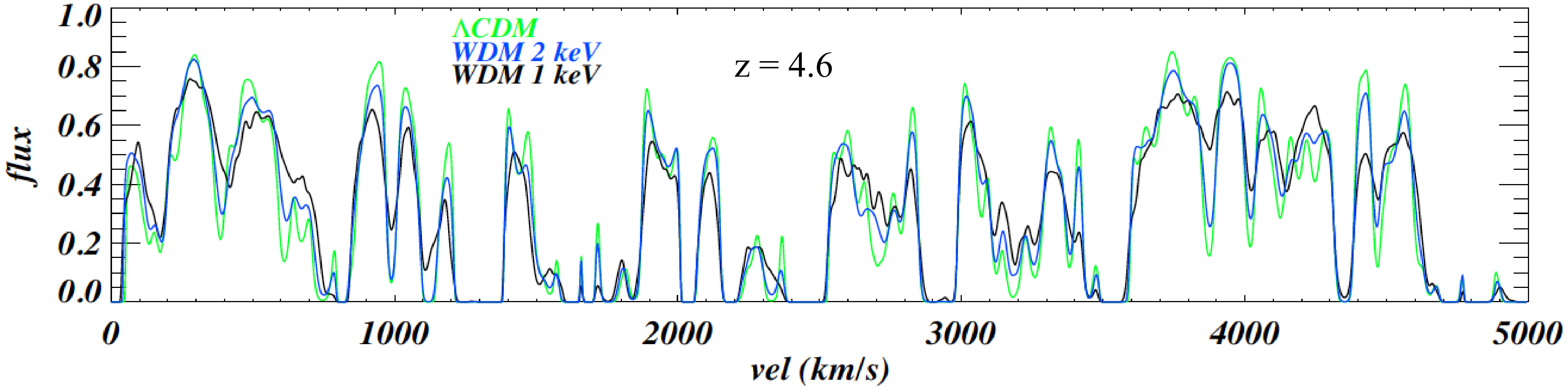


- Cluster counts as a function of SZ flux (or X-ray mass proxy) and z imply a lower σ_8 than *Planck* infers from primary CMB fluctuations

- This depends critically on the $M_h – Y$ or $M_h – Y_x$ calibration
  - are calibrations obtained for the "right" clusters? – massive ν's?

Ly α forest spectra and small-scale initial structure

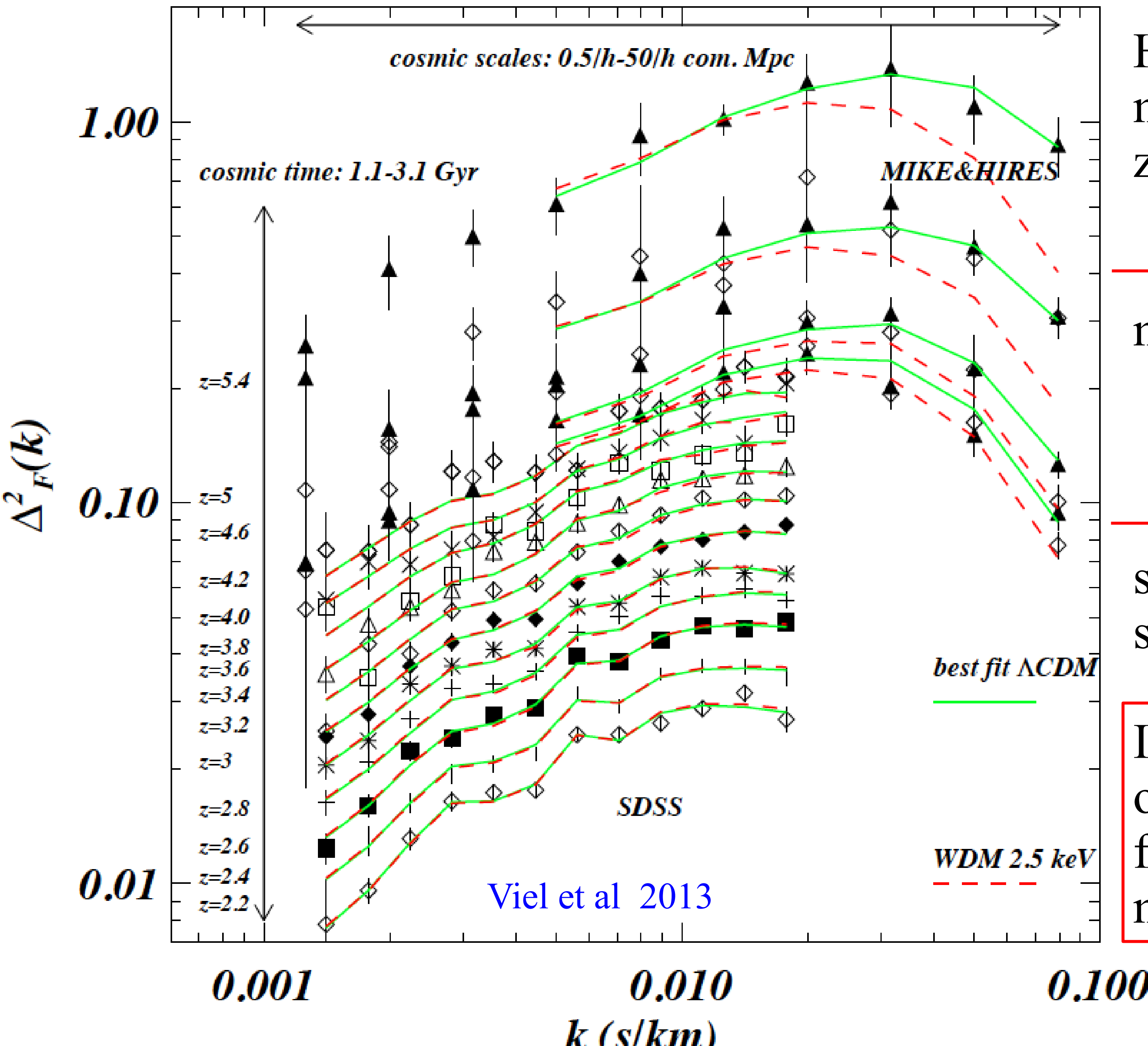
Viel, Becker, Bolton & Haehnelt 2013



Transmitted quasar flux in hydrodynamic simulations of the intergalactic medium in ΛCDM and WDM models.

High-frequency power is missing in the WDM case

Lyman α forest spectra for WDM relative to CDM



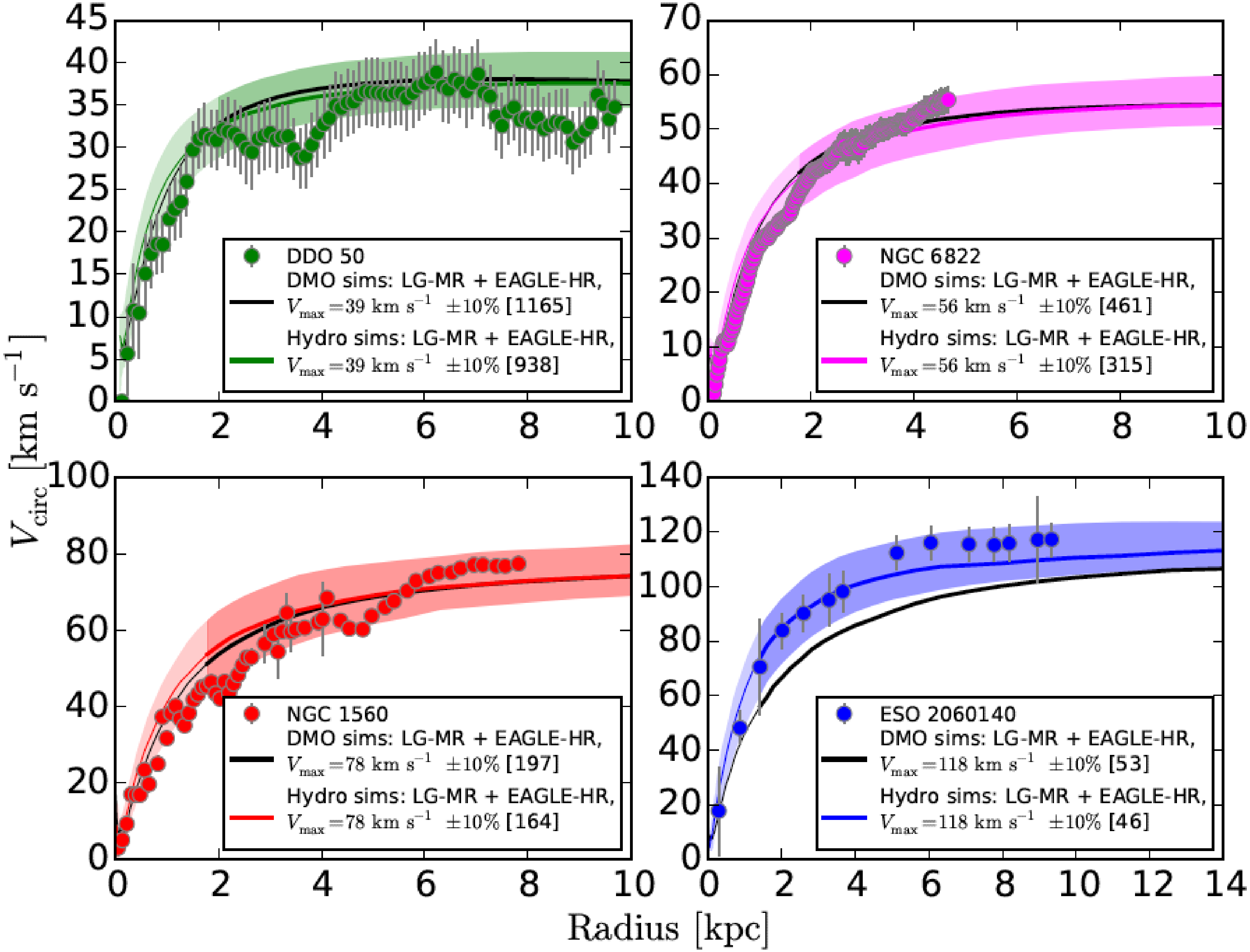
High-resolution spectra match ΛCDM up to z = 5.4

2σ lower limit on the mass of a thermal relic $m_{WDM} > 3.3$ keV

WDM can affect the structure only of the smallest galaxies

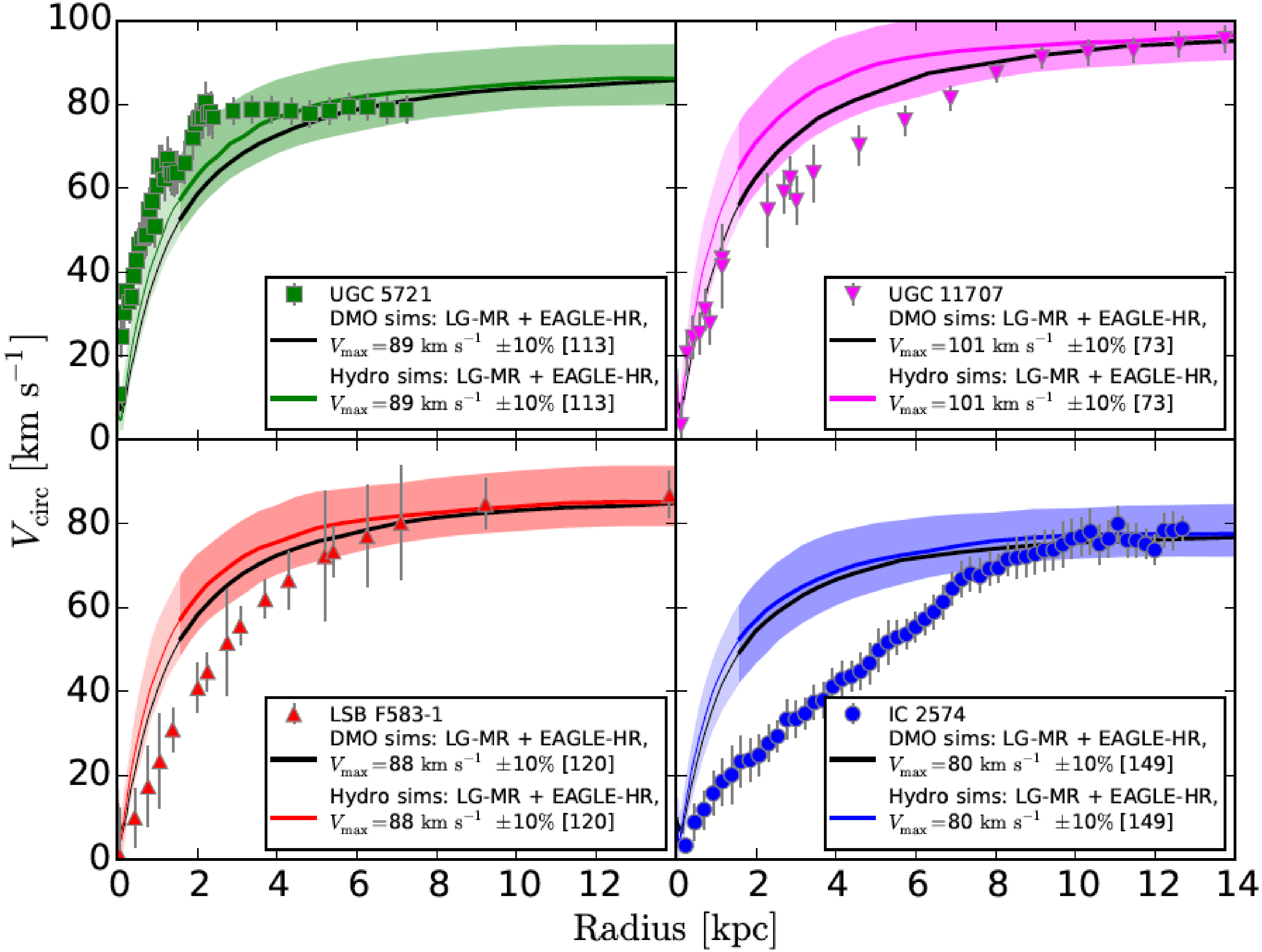
IC's are well measured on all scales relevant for the formation of the main galaxy population

Dwarf galaxy rotation curves: cusps vs cores



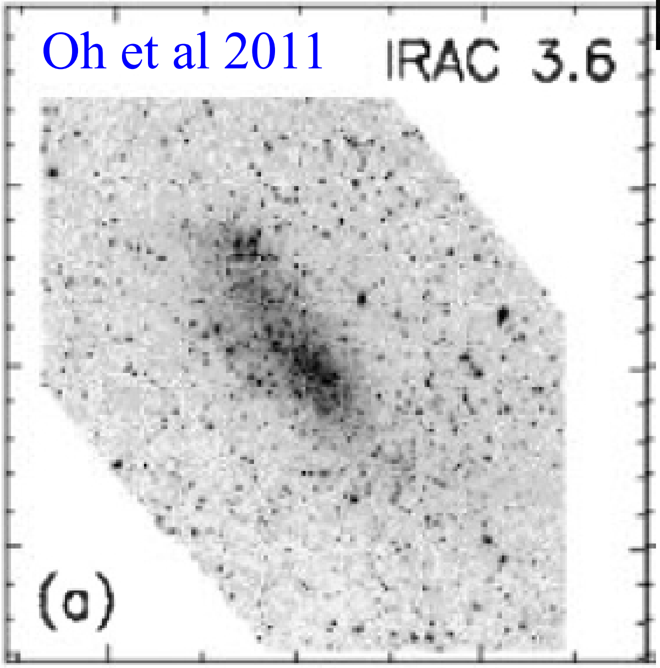
Many dwarf galaxies have rotation curves that fit ΛCDM predictions well

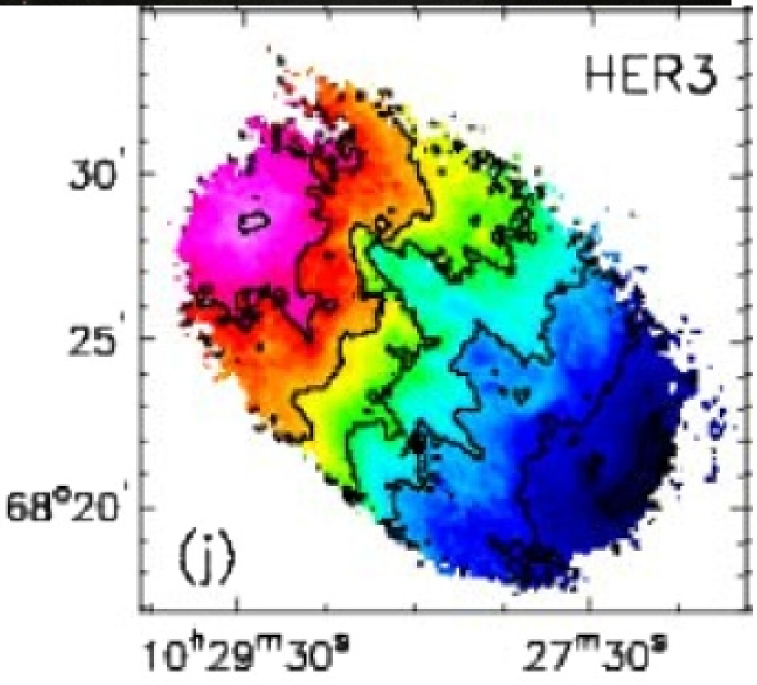
Dwarf galaxy rotation curves: cusps vs cores



Many others fail dramatically to fit ΛCDM predictions.
"Cores" from: (i) DM properties? (ii) Baryon effects? (iii) Incorrect modelling?

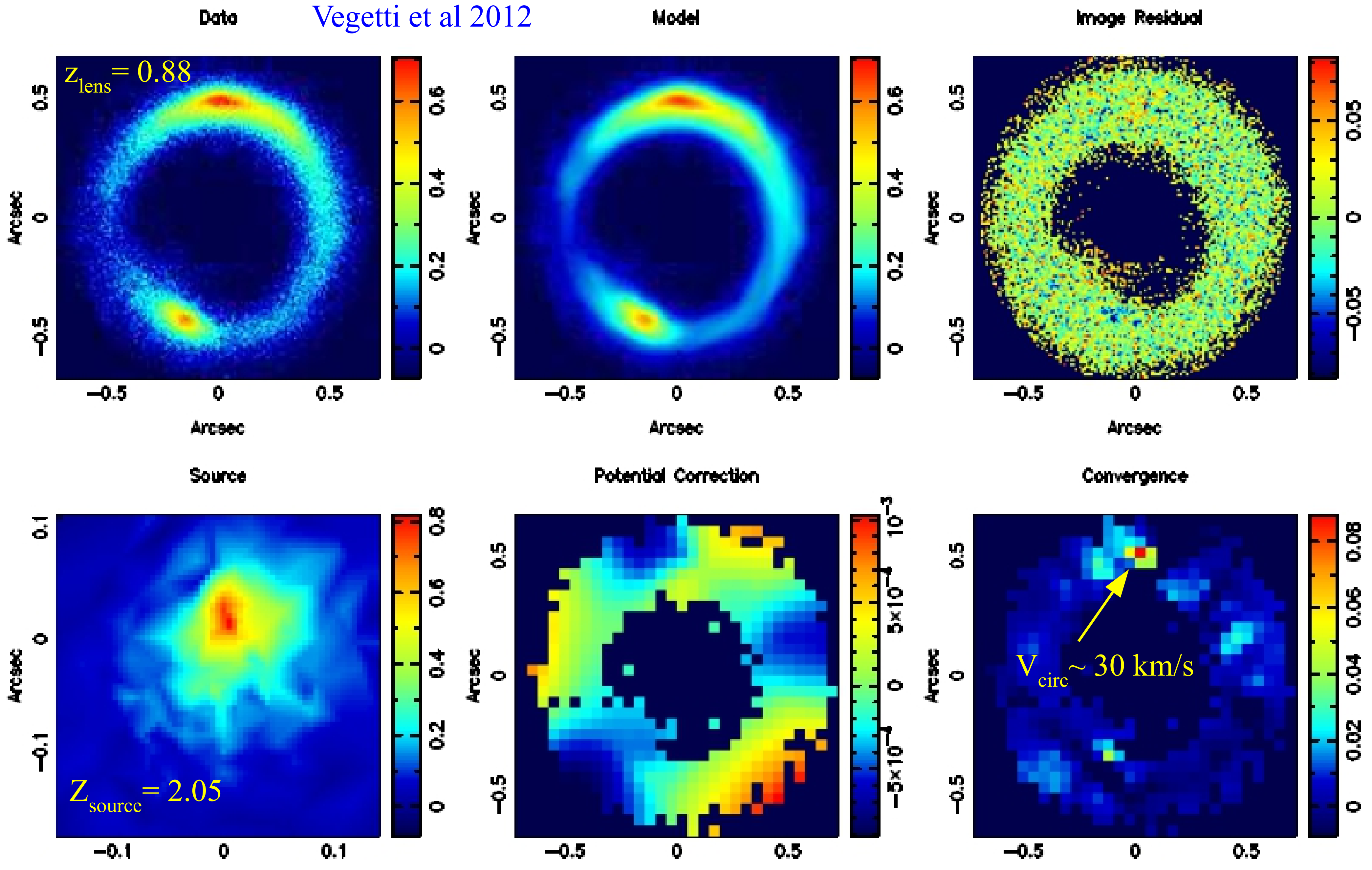

IC 2574


Oh et al 2011
IRAC 3.6
(a)


HER3
30'
25'
68°20'
(j)
10h29m30s
27m30s

Detecting substructures with no stars...

Vegetti et al 2012



“Precision cosmology” projects is now limited by poorly understood *astrophysical* systematics (SN properties, galaxy formation biases)

Currently no convincing indications for deviations from ΛCDM

Planned DE surveys could tighten limits by up to an order order of magnitude only if relevant astrophysics is sufficiently understood

Simple inflation is now supported by all measurements. B-mode detection in CMB is last “easily” reachable test.

Small-scale structure of dwarfs may indicate deviations from CDM
– perturbation to strongly lensed images should provide a definitive test between CDM and WDM/SIDM