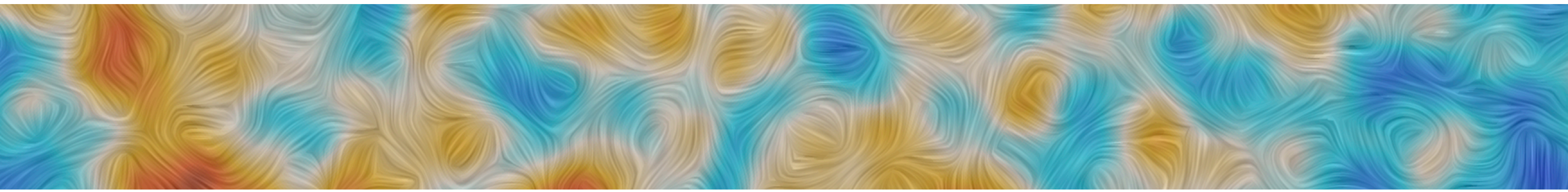
Cosmology after *Planck*



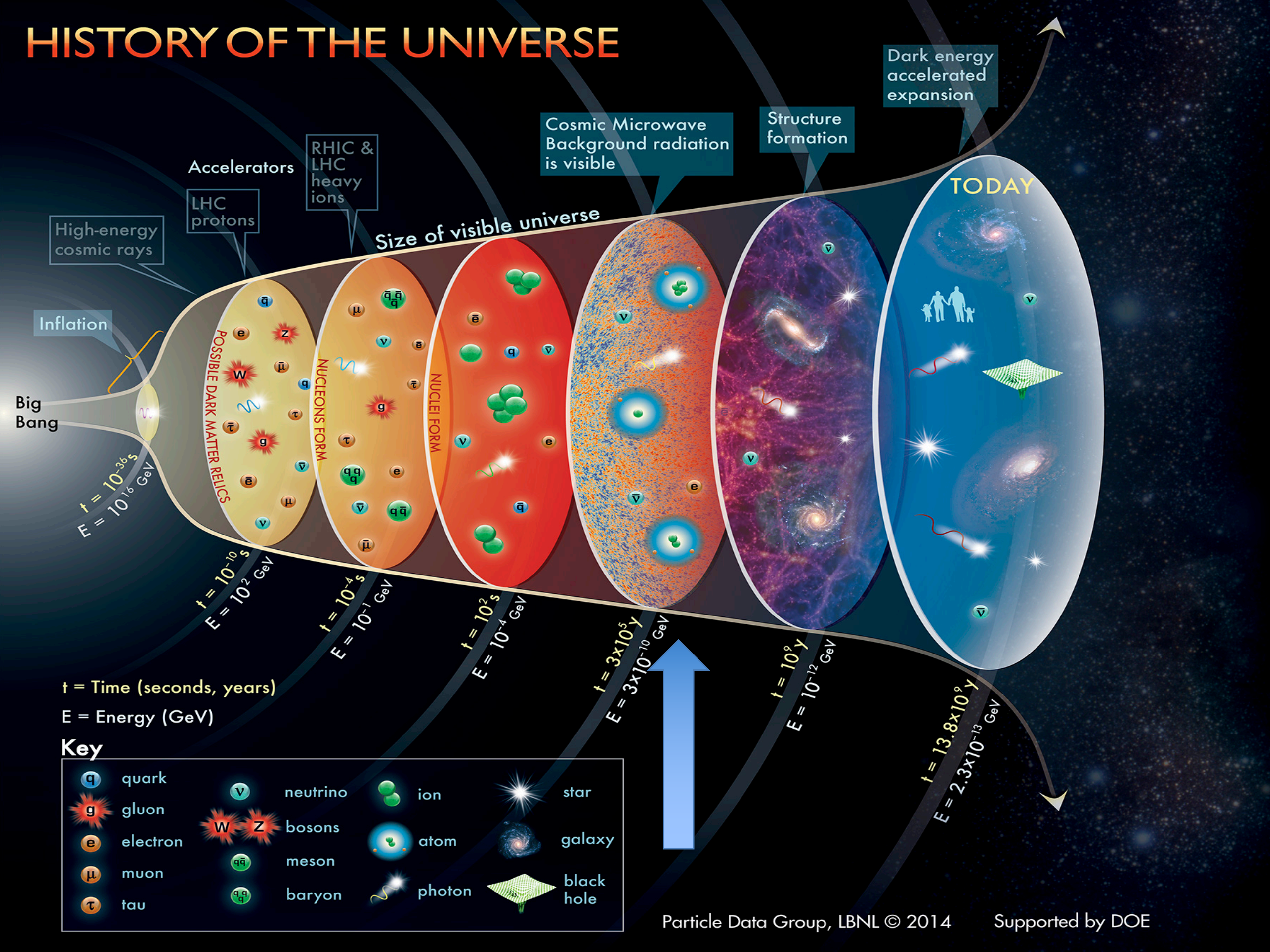
Jan Hamann

(The University of New South Wales)

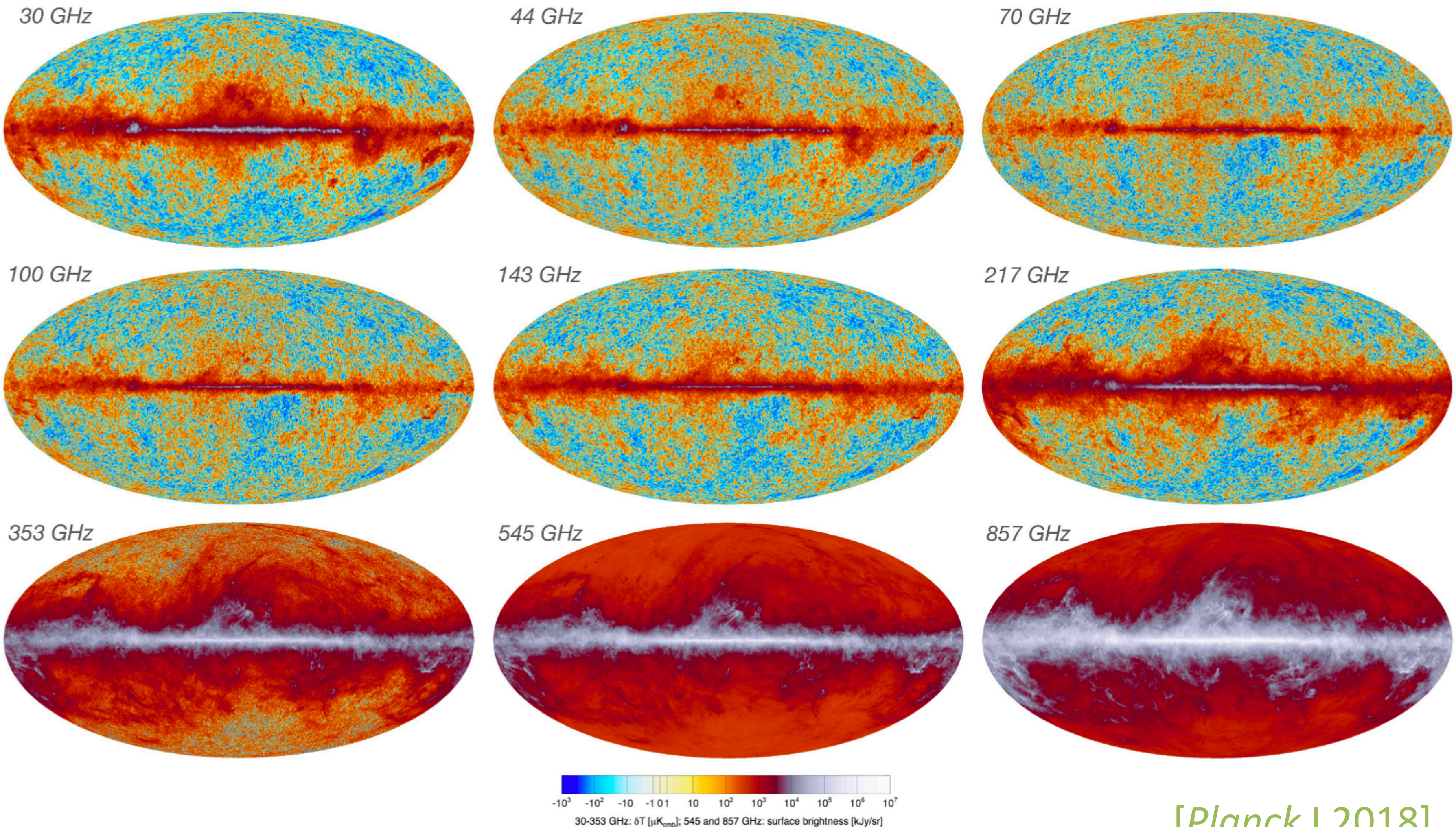
TeV Particle Astrophysics conference (TeVPA) 2019

2nd-6th December 2019, Sydney

Planck (2009-2013)


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
$t = 10^{-36}$ s
$E = 10^{16}$ GeV
$t = 10^{-10}$ s
$E = 10^{2}$ GeV
$t = 10^{-4}$ s
$E = 10^{-1}$ GeV
$t = 10^{2}$ s
$E = 10^{-4}$ GeV
$t = 3x10^{5}$ y
$E = 3x10^{-10}$ GeV
$t = 10^{9}$ y
$E = 10^{-12}$ GeV
$t = 13.8x10^{9}$ y
$E = 2.3x10^{-13}$ GeV
t = Time (seconds, years)
E = Energy (GeV)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL © 2014
Supported by DOE

The sky seen through *Planck*'s eyes



[*Planck* I 2018]

The sky seen through *Planck*'s eyes

Primary CMB perturbations

+

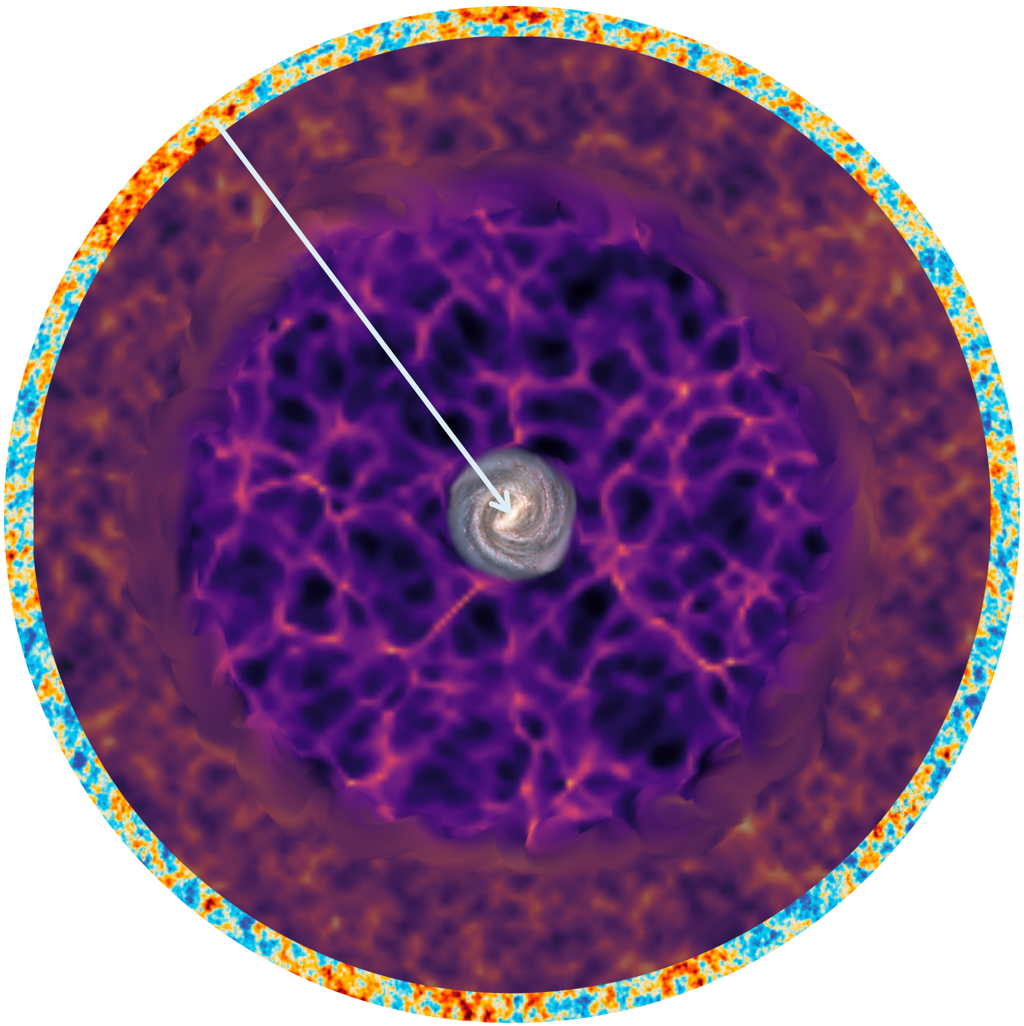
Secondary CMB perturbations

- integrated Sachs-Wolfe effect
- weak gravitational lensing
- kinetic/thermal Sunyaev-Zel'dovich effect

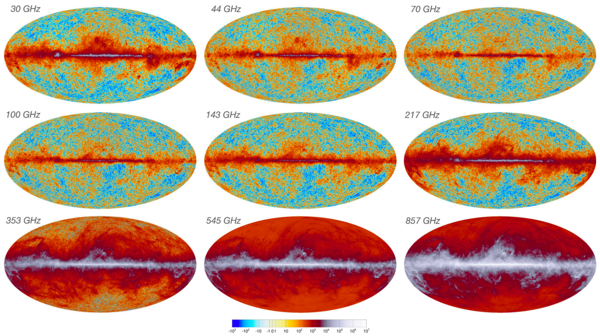
+

Galactic foregrounds

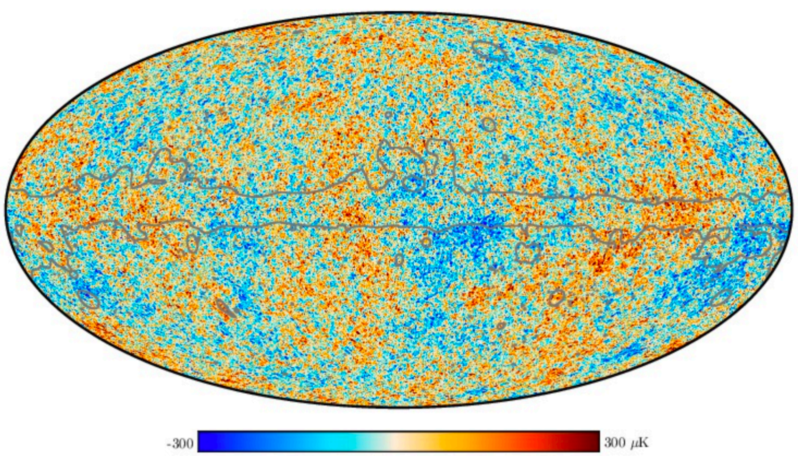
- dust emission
- bremsstrahlung
- synchrotron emission
- …

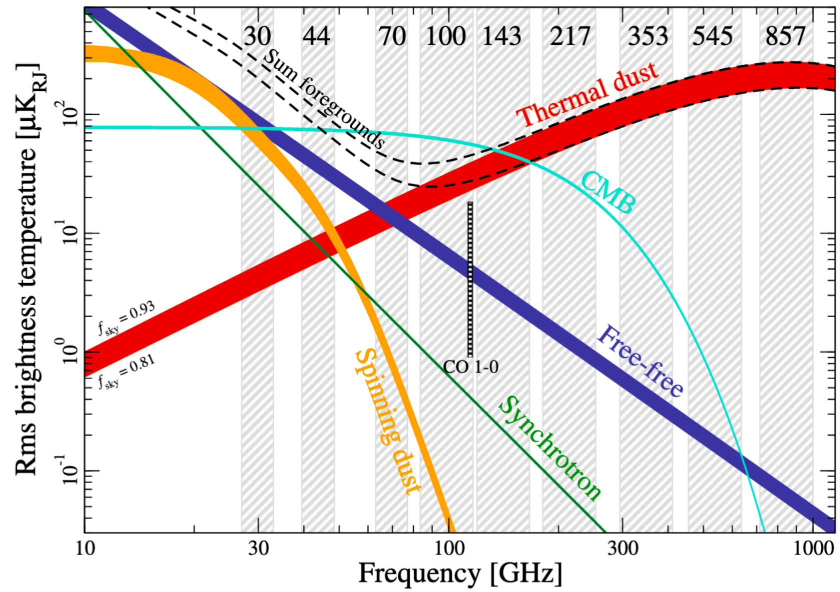


Disentangling the mess: foreground separation

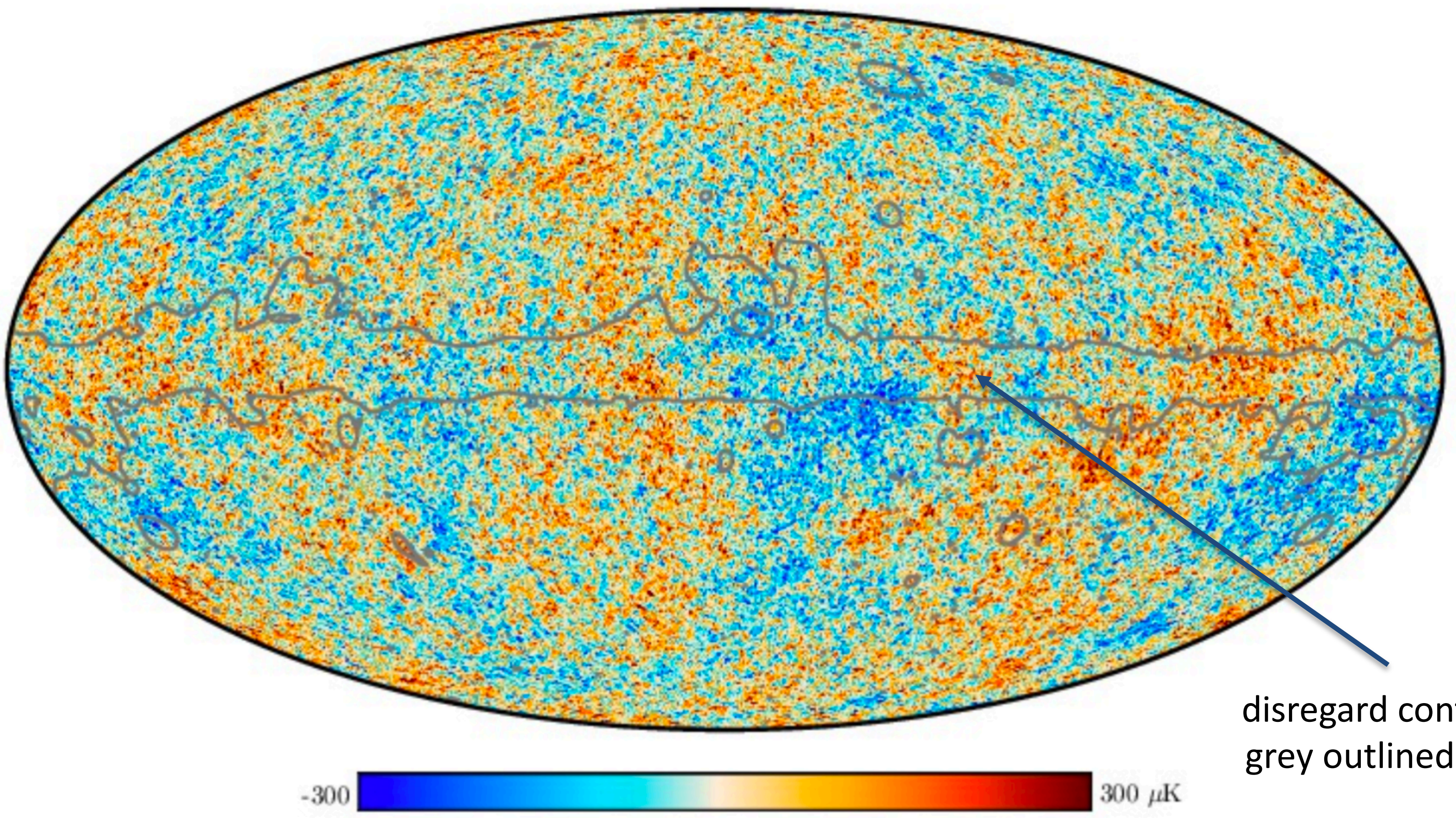


exploit different frequency dependence of foregrounds





Disentangling the mess: masking

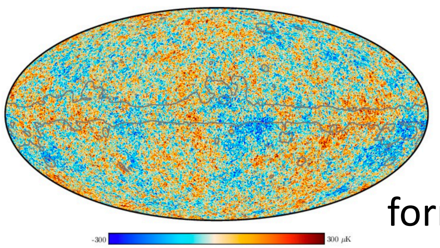


disregard content of grey outlined areas

remaining uncertainties: parametrise and marginalise

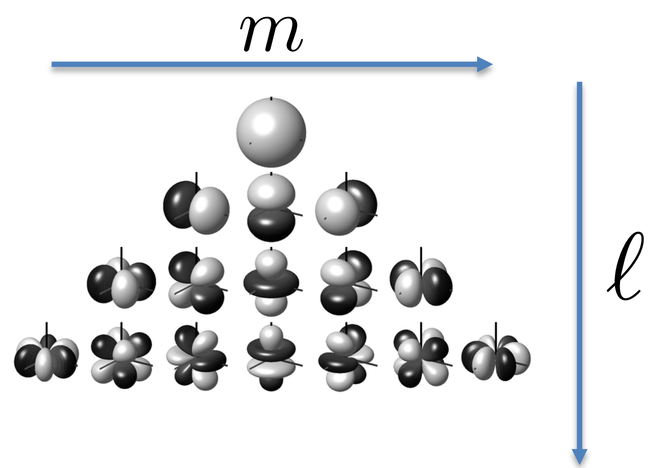
[*Planck* I 2018]

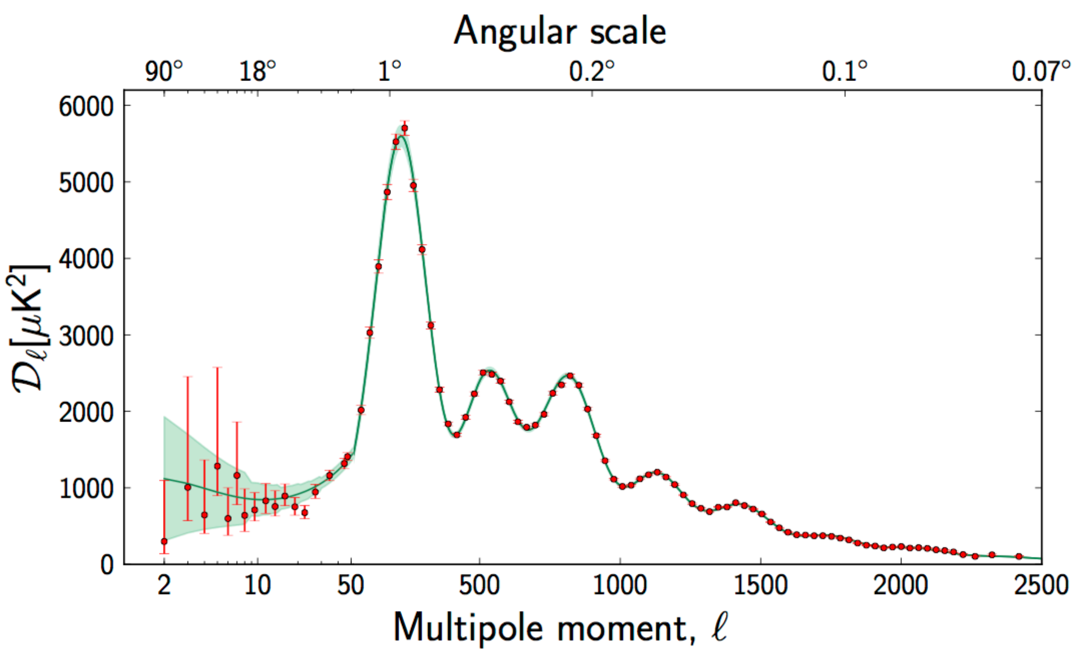
From map to angular power spectrum



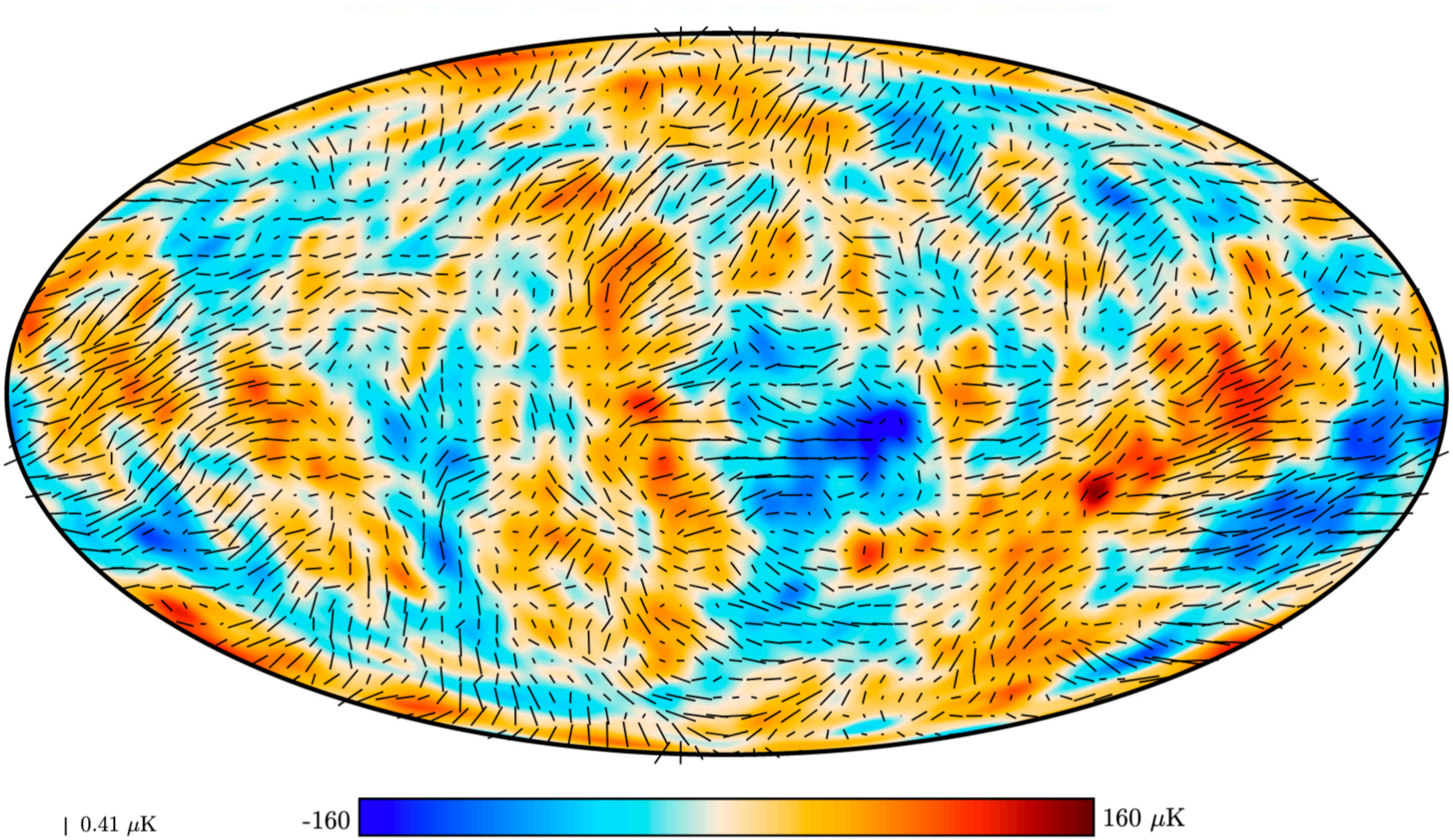
expand in spherical harmonics

form autocorrelation
of components





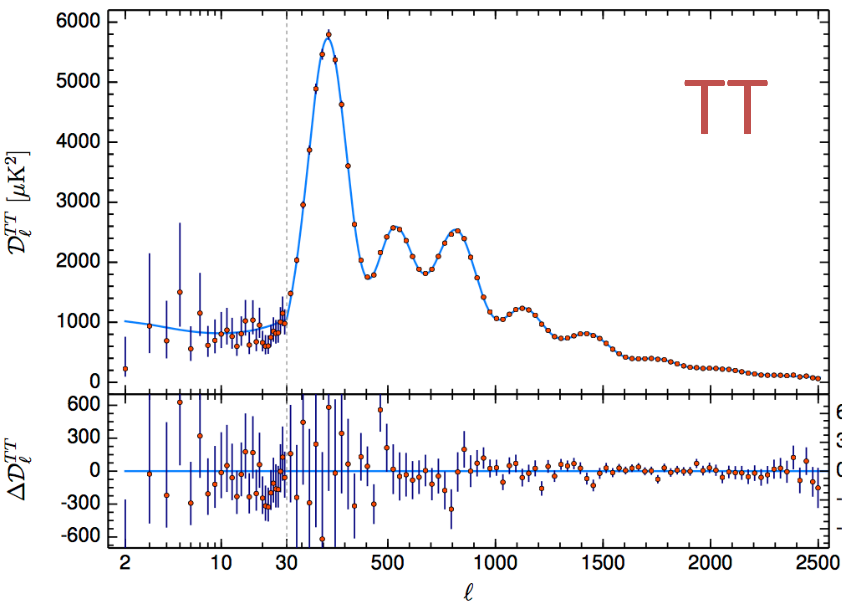
CMB polarisation

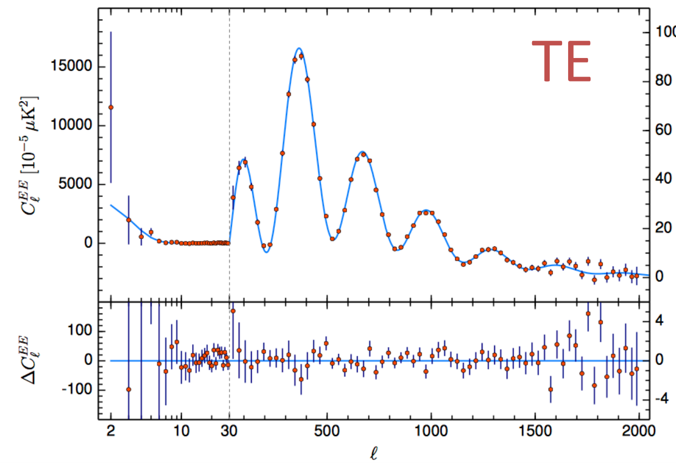


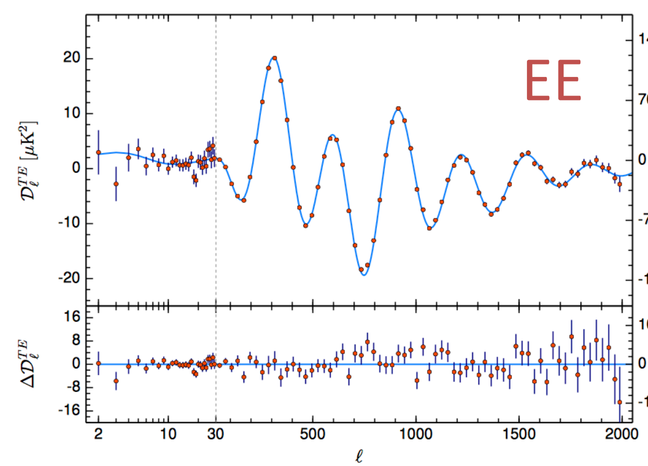
2 d.o.f. → decompose into E-/B-mode

[*Planck* I 2018]

Temperature and E-polarization spectra



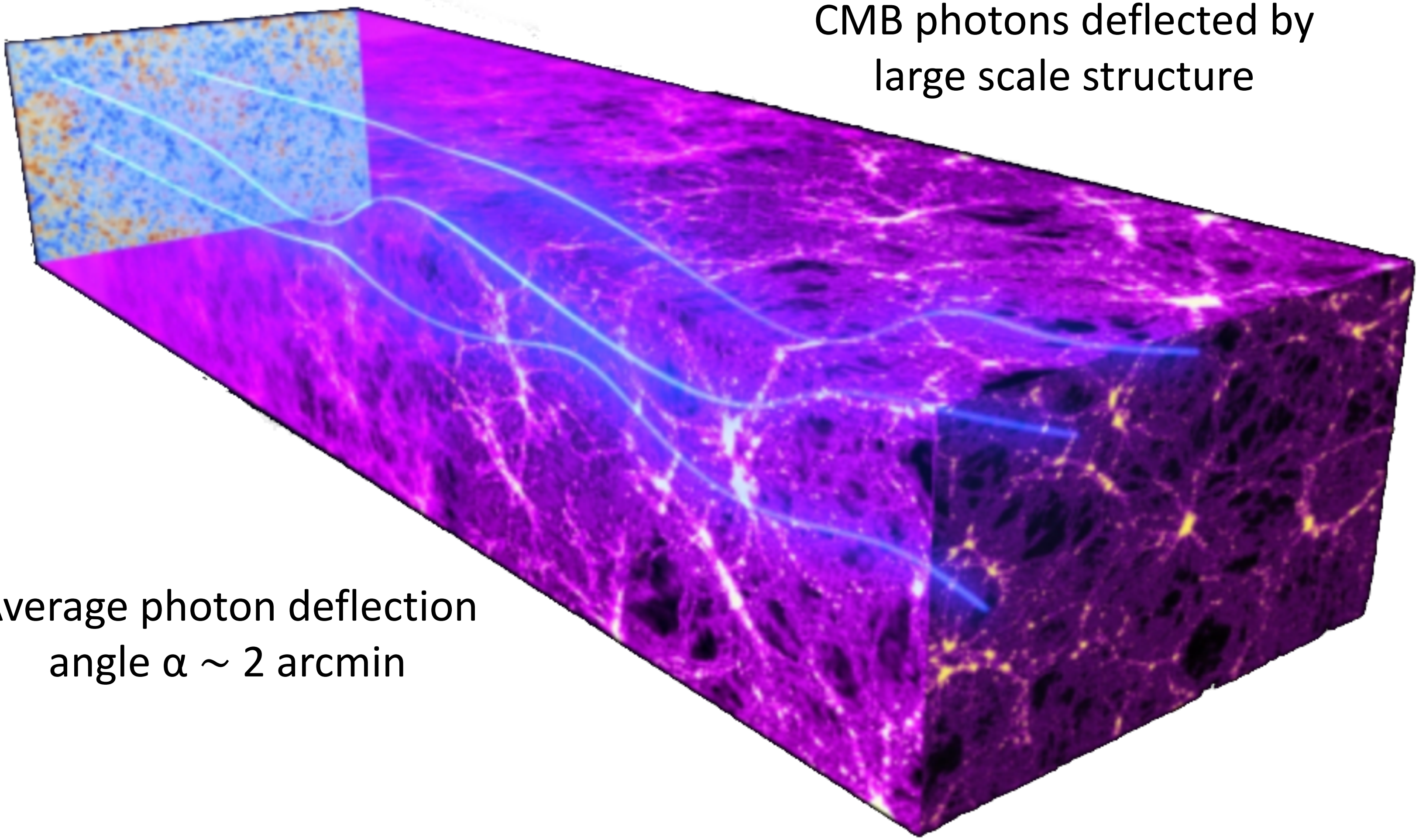




[*Planck* I 2018]

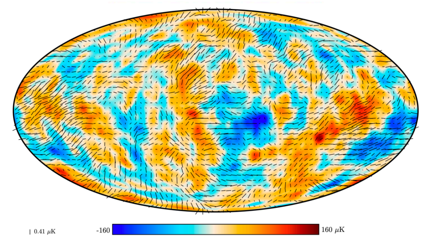
CMB lensing

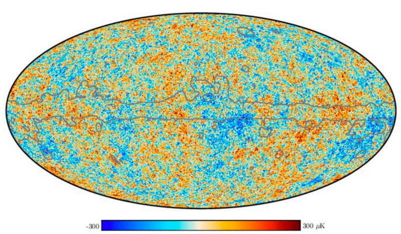
CMB photons deflected by large scale structure



Average photon deflection angle $\alpha \sim 2$ arcmin

CMB lensing potential



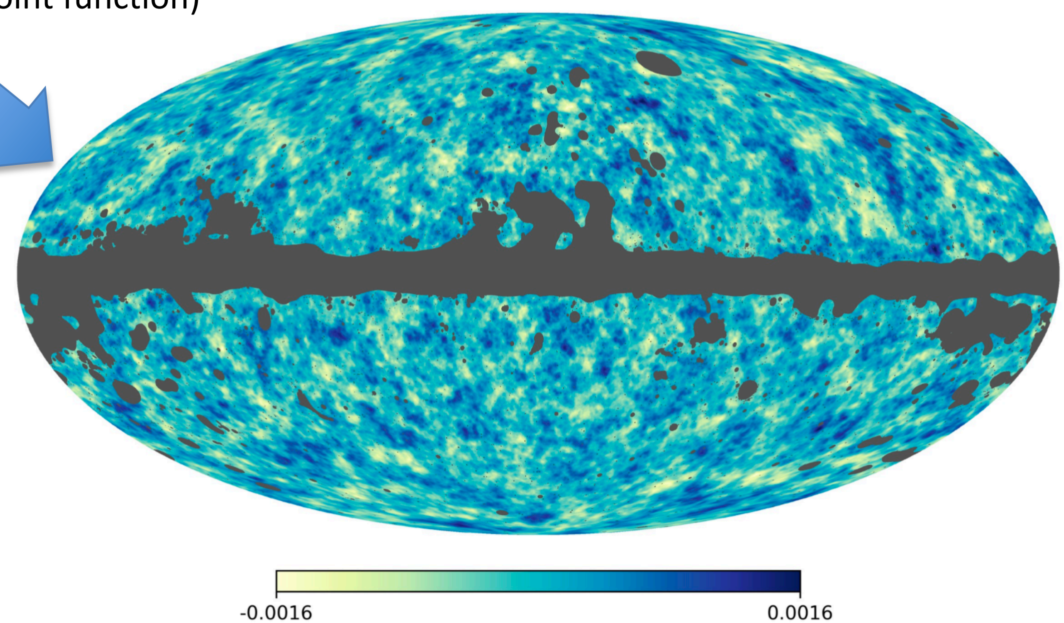


quadratic estimator
(information about
4-point function)

[Hu & Okamoto 2012]

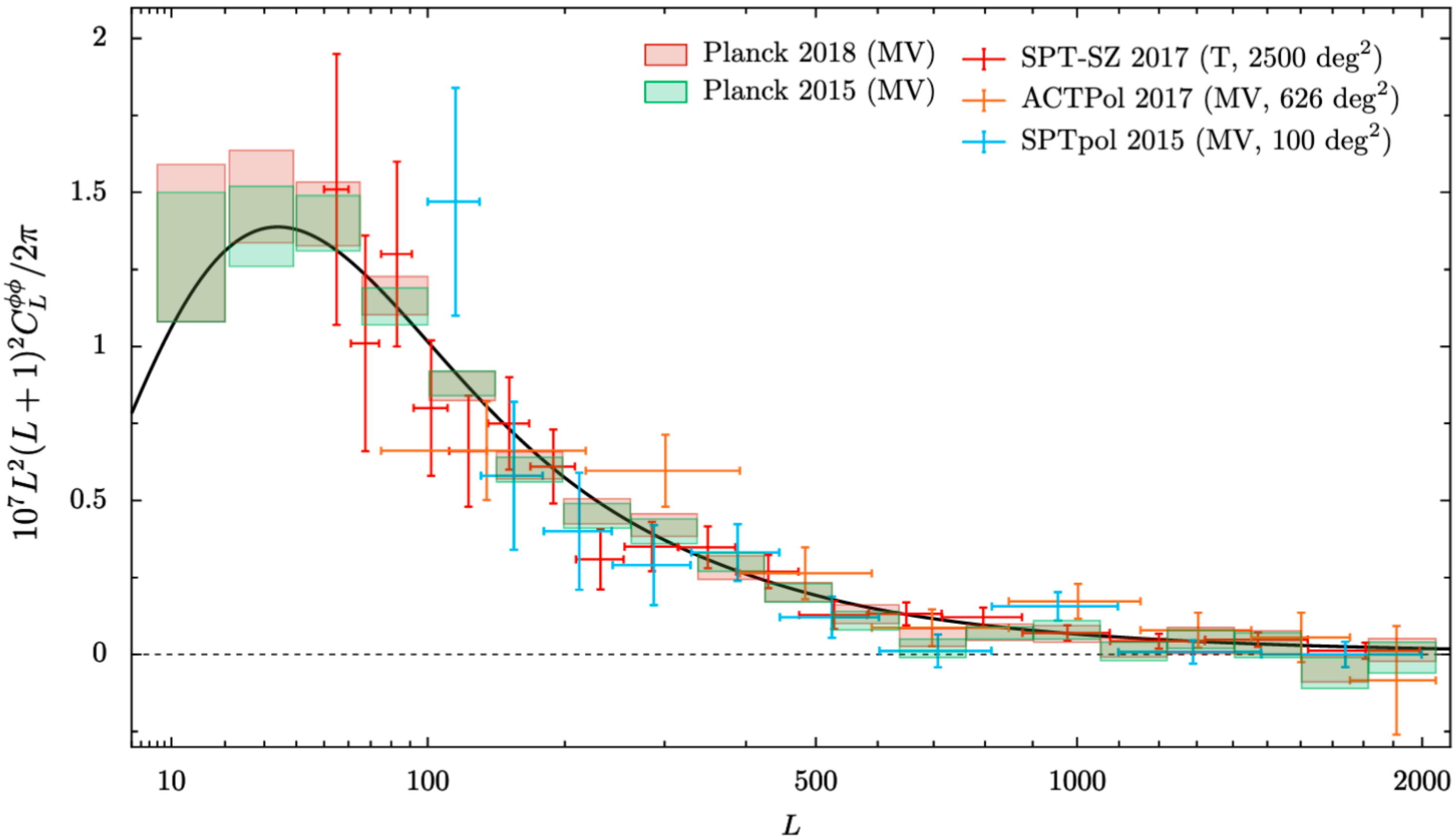
lensing potential

$$\vec{\alpha} \equiv \vec{\nabla}\Phi$$



[*Planck* VIII 2018]

CMB lensing spectrum

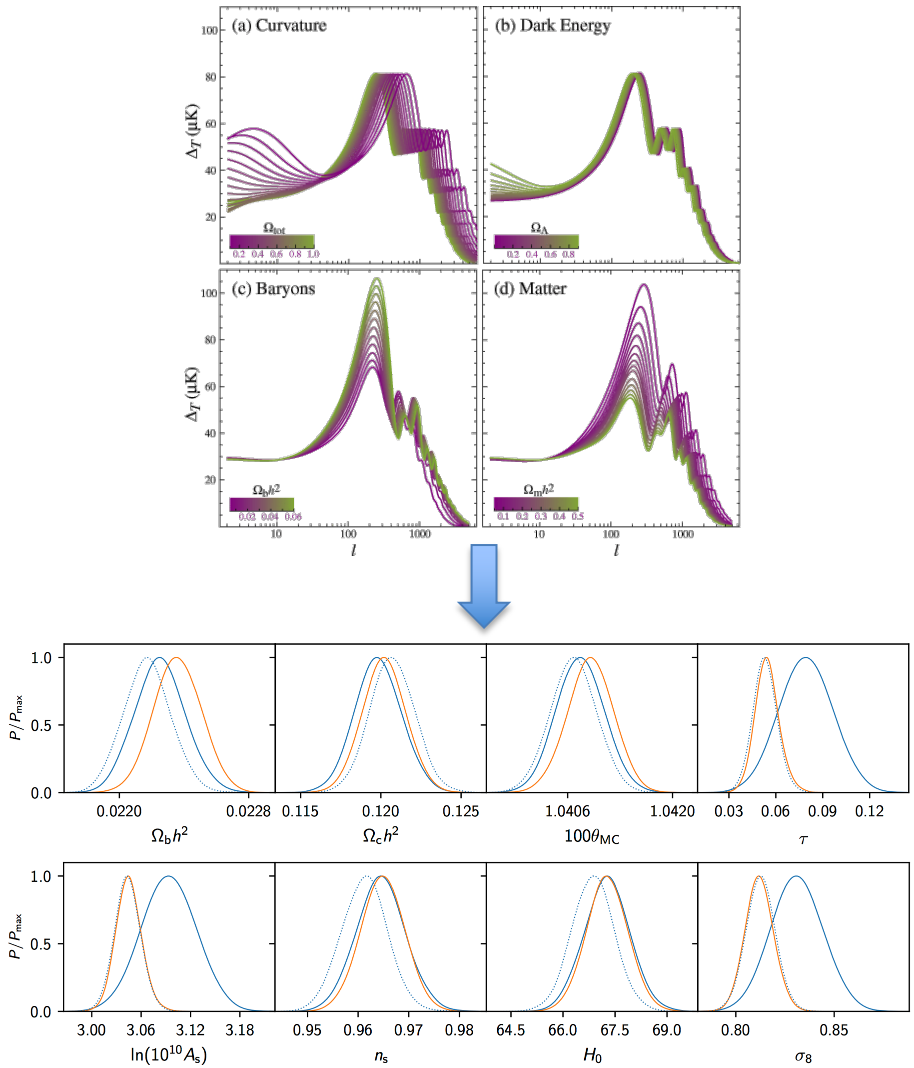


Planck detection at > 40σ

see also Yuqi Kang's talk on Thursday

[*Planck* VIII 2018]

Parameter inference



- *Assume a physical model*
- Calculate theoretical expectation of observables
- Plug into likelihood function
- Explore parameter space (e.g., MCMC)
- Construct posterior probability distributions of parameters

[figure by Wayne Hu]

The standard model of cosmology: ΛCDM

Ingredients of ΛCDM

General Relativity

$$R_{\mu\nu} - \frac{1}{2}R\, g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

Geometry

Content

Ingredients of ΛCDM

General Relativity

$$R_{\mu\nu} - \frac{1}{2} R \, g_{\mu\nu} = 8\pi G \, T_{\mu\nu}$$

Geometry   Content

- Cosmological principle
  (homogeneity and isotropy)
- spatially flat

Ingredients of ΛCDM

General Relativity

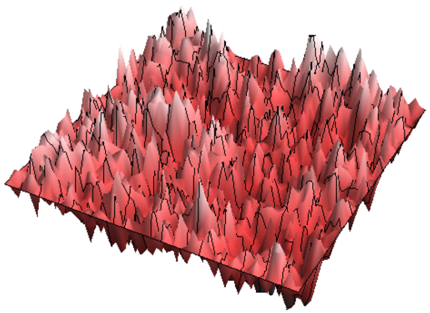
$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

Geometry

Content

- Cosmological principle
  (homogeneous and isotropic)
- spatially flat

+ initial perturbations



Ingredients of ΛCDM

General Relativity

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

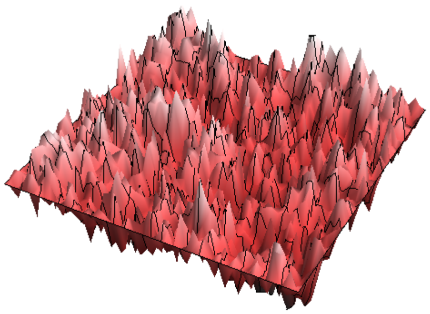
Geometry

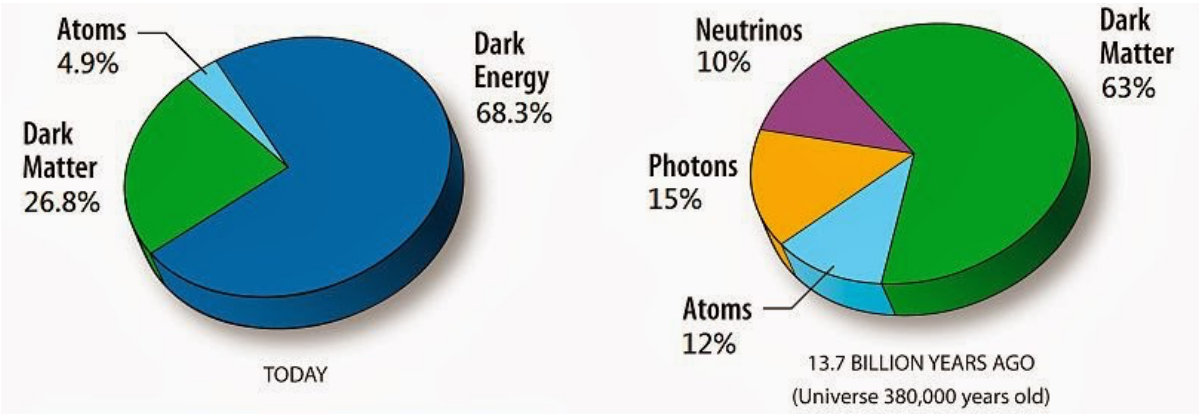
- Cosmological principle (homogeneous and isotropic)
- spatially flat

Content

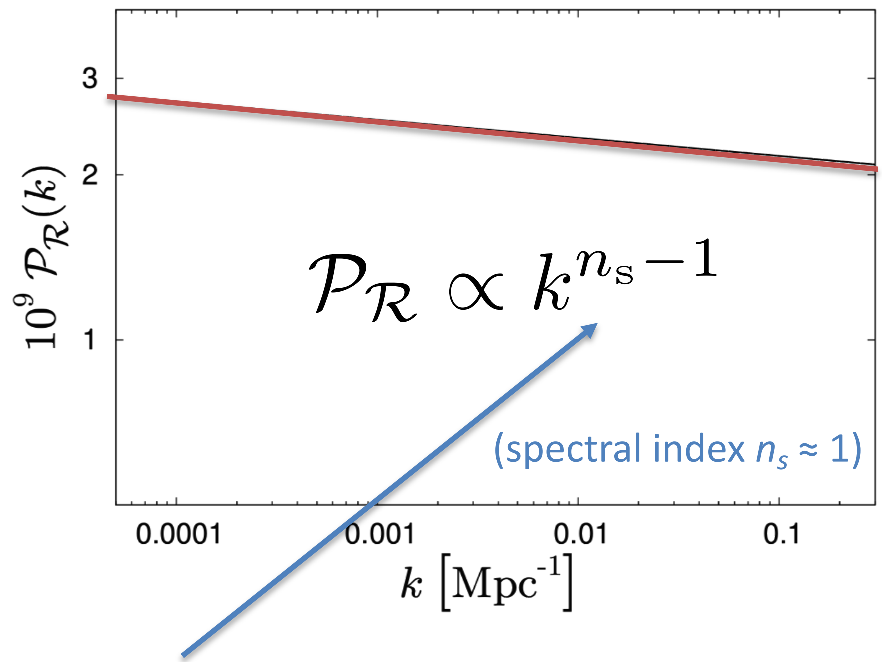
- Standard model particles + interactions
- Cold dark matter
- Cosmological constant

+ initial perturbations





ΛCDM: initial perturbations

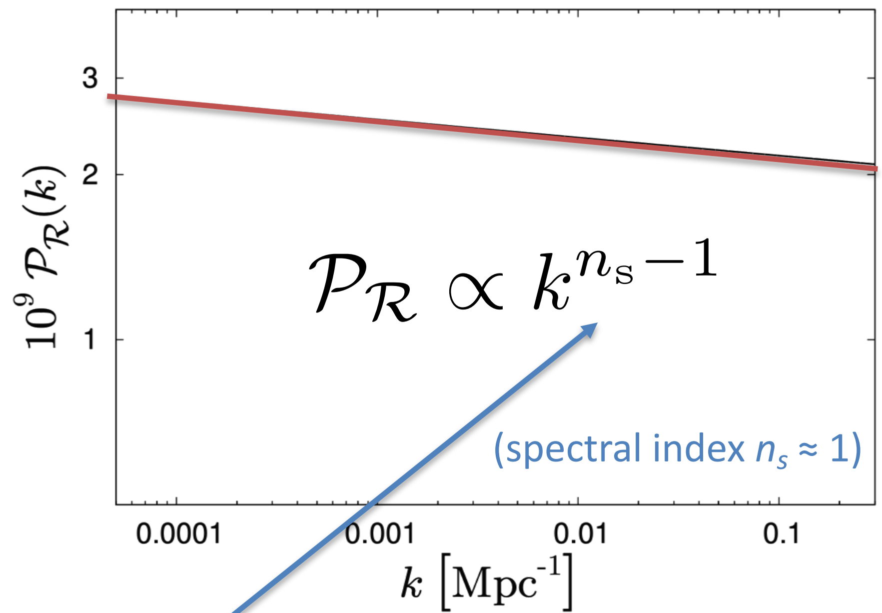


Almost scale-invariant power-law spectrum of

- adiabatic (no entropy perturbations)
- Gaussian (no non-trivial higher order correlations)
- statistically isotropic and homogeneous
- scalar (no vector or tensor perturbations)

perturbations

ΛCDM: initial perturbations



Inflation

slow-roll
single-field
quasi-linear
low-scale

Almost scale-invariant power-law spectrum of

- adiabatic (no entropy perturbations)
- Gaussian (no non-trivial higher order correlations)
- statistically isotropic and homogeneous
- scalar (no vector or tensor perturbations)

perturbations

Challenging ΛCDM?

General Relativity — modified gravity?

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

Geometry

inhomogeneous background?

- Cosmological principle (homogeneous and isotropic)
- spatially flat — spatial curvature?

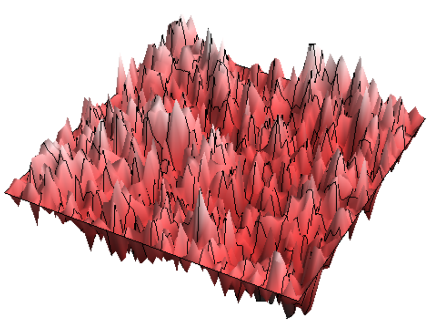
Content

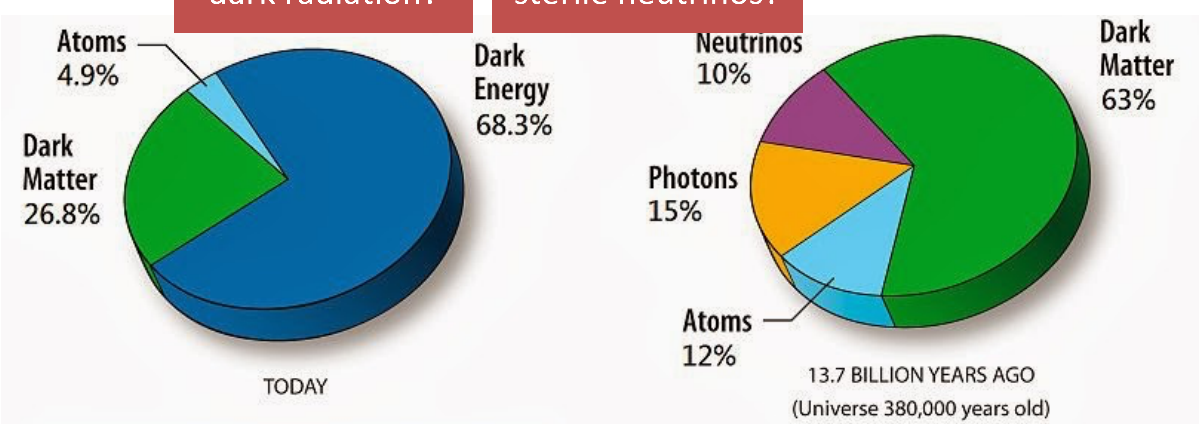
massive neutrinos

- Standard model particles + interactions
- Cold dark matter — warm? — new interactions?
- Cosmological constant — dynamical dark energy?

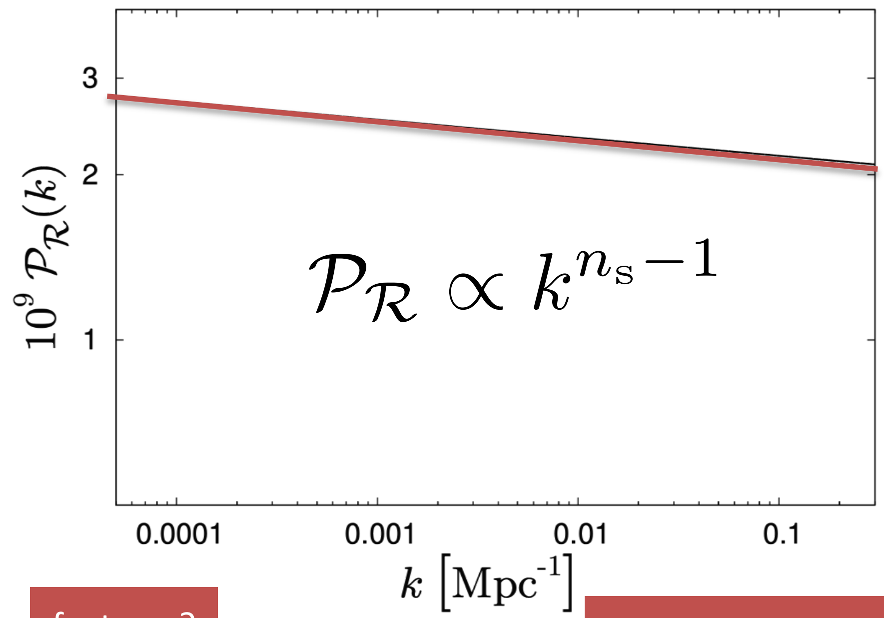
dark radiation? — sterile neutrinos?

+ initial perturbations





Challenging ΛCDM: initial perturbations



features?

scale-dependent tilt?

Almost scale-invariant power-law spectrum of

- adiabatic — isocurvature?
- Gaussian — non-Gaussianity?
- statistically isotropic and homogeneous — statistical anisotropy?
- scalar — primordial gravitational waves?

perturbations

Consistency of *Planck* data

Internal consistency

``Official'' likelihood

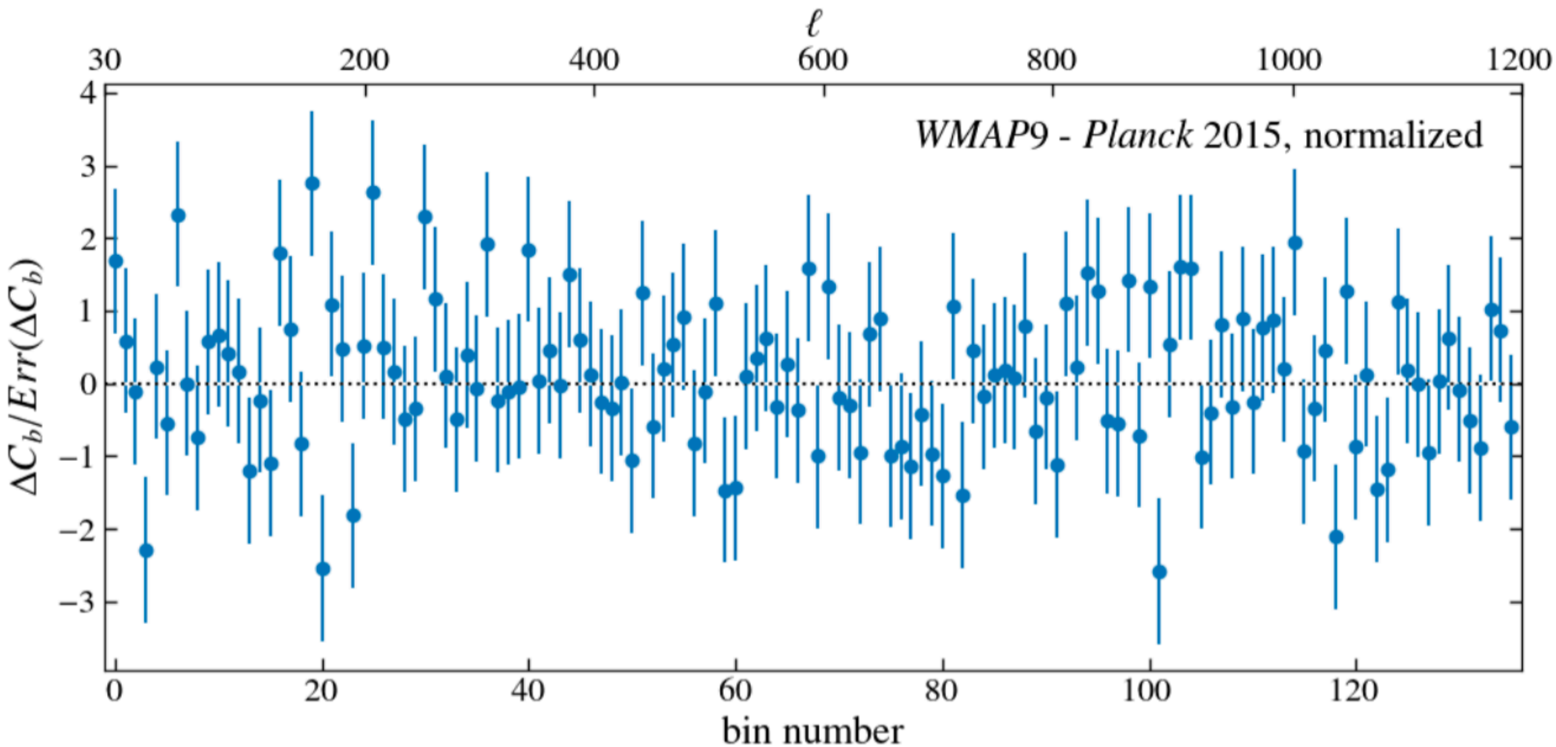
``Alternative'' likelihood

Parameter	Plik best fit	Plik [1]	CamSpec [2]	$([2]-[1])/\sigma_1$	Combined
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015	0.02229 ± 0.00015	−0.5	0.02233 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012	0.1197 ± 0.0012	−0.3	0.1198 ± 0.0012
$100\theta_{MC}$	1.040909	1.04092 ± 0.00031	1.04087 ± 0.00031	−0.2	1.04089 ± 0.00031
τ	0.0543	0.0544 ± 0.0073	$0.0536^{+0.0069}_{-0.0077}$	−0.1	0.0540 ± 0.0074
$\ln(10^{10} A_s)$	3.0448	3.044 ± 0.014	3.041 ± 0.015	−0.3	3.043 ± 0.014
n_s	0.96605	0.9649 ± 0.0042	0.9656 ± 0.0042	+0.2	0.9652 ± 0.0042
$\Omega_m h^2$	0.14314	0.1430 ± 0.0011	0.1426 ± 0.0011	−0.3	0.1428 ± 0.0011
H_0 [km s^{-1}Mpc^{-1}] . . .	67.32	67.36 ± 0.54	67.39 ± 0.54	+0.1	67.37 ± 0.54
Ω_m	0.3158	0.3153 ± 0.0073	0.3142 ± 0.0074	−0.2	0.3147 ± 0.0074
Age [Gyr]	13.7971	13.797 ± 0.023	13.805 ± 0.023	+0.4	13.801 ± 0.024
σ_8	0.8120	0.8111 ± 0.0060	0.8091 ± 0.0060	−0.3	0.8101 ± 0.0061
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$ . .	0.8331	0.832 ± 0.013	0.828 ± 0.013	−0.3	0.830 ± 0.013
z_{re}	7.68	7.67 ± 0.73	7.61 ± 0.75	−0.1	7.64 ± 0.74
$100\theta_*$	1.041085	1.04110 ± 0.00031	1.04106 ± 0.00031	−0.1	1.04108 ± 0.00031
r_{drag} [Mpc]	147.049	147.09 ± 0.26	147.26 ± 0.28	+0.6	147.18 ± 0.29

Residual systematics hard to quantify,
probably in the 0.1 – 0.5σ range

Consistency with WMAP at larger scales

Normalised difference between WMAP and *Planck* angular power spectrum



[*Planck* LI 2016, Huang+ 2018]

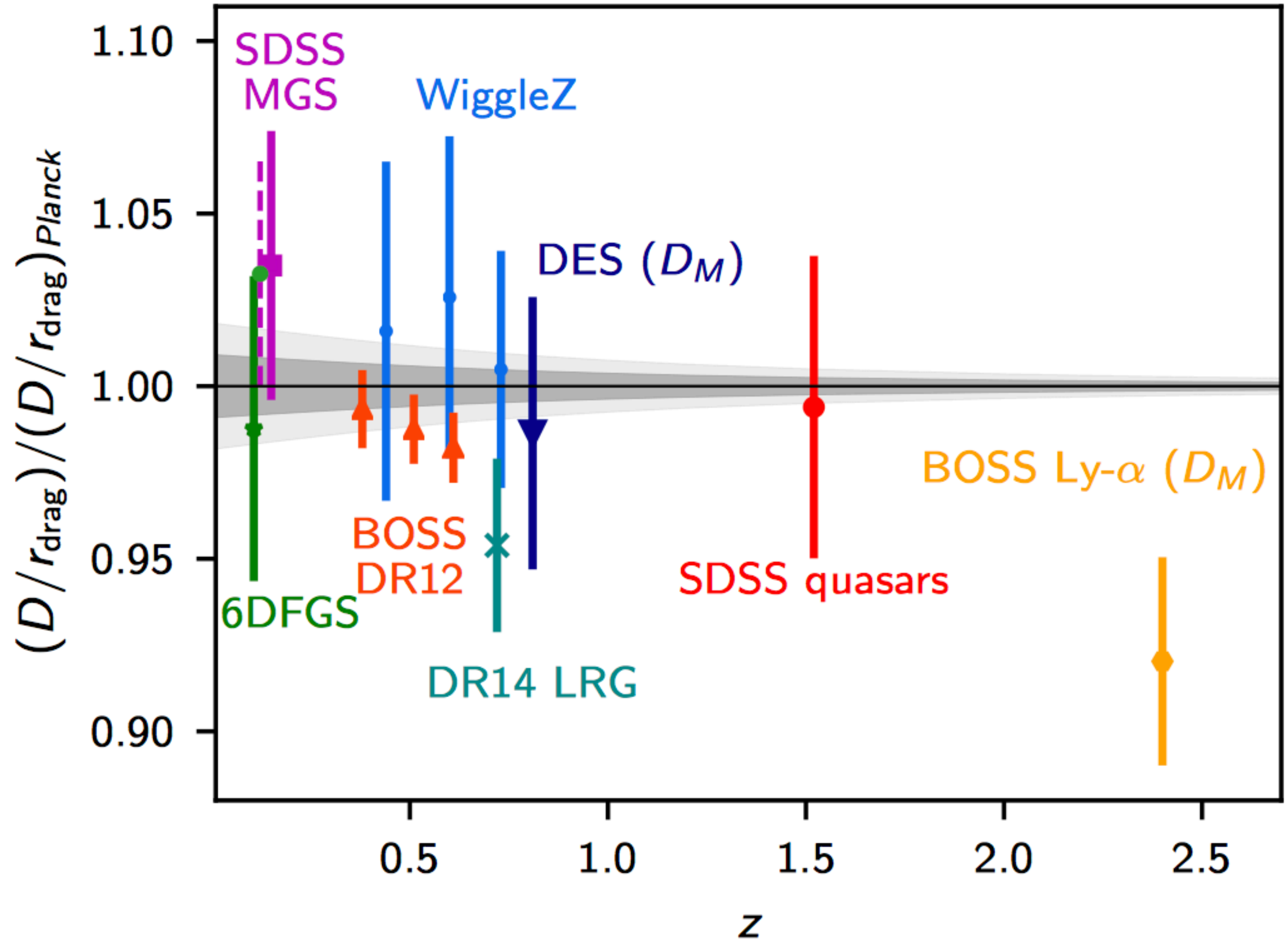
Also consistent with SPT results at smaller scales
(within the patch measured by SPT)

[Aylor+ 2017]

Consistency with non-CMB data (assuming ΛCDM)

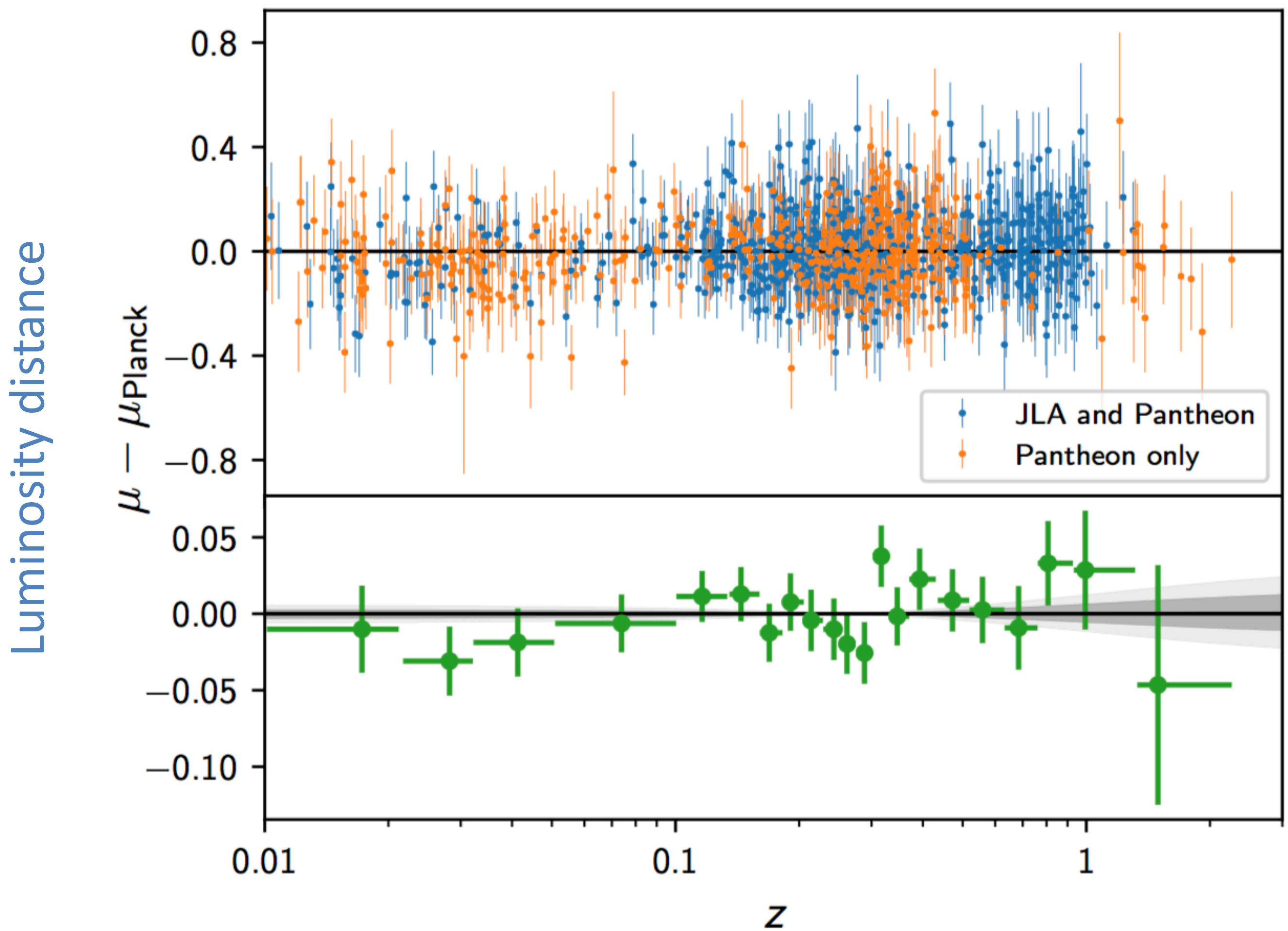
Consistency with BAO scale measurements

Baryon acoustic oscillation scale



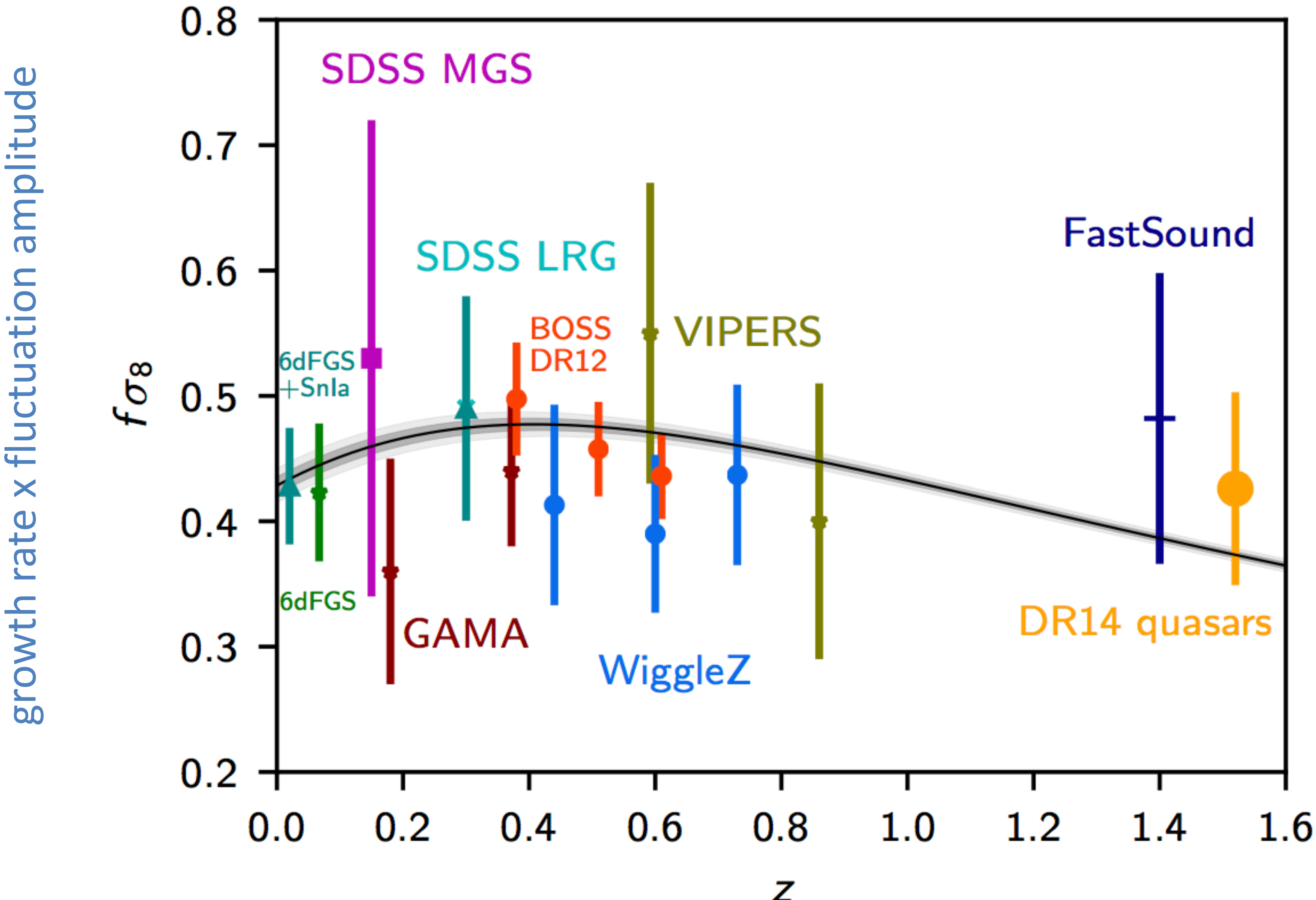
[*Planck* VI 2018]

Consistency with type Ia supernovae



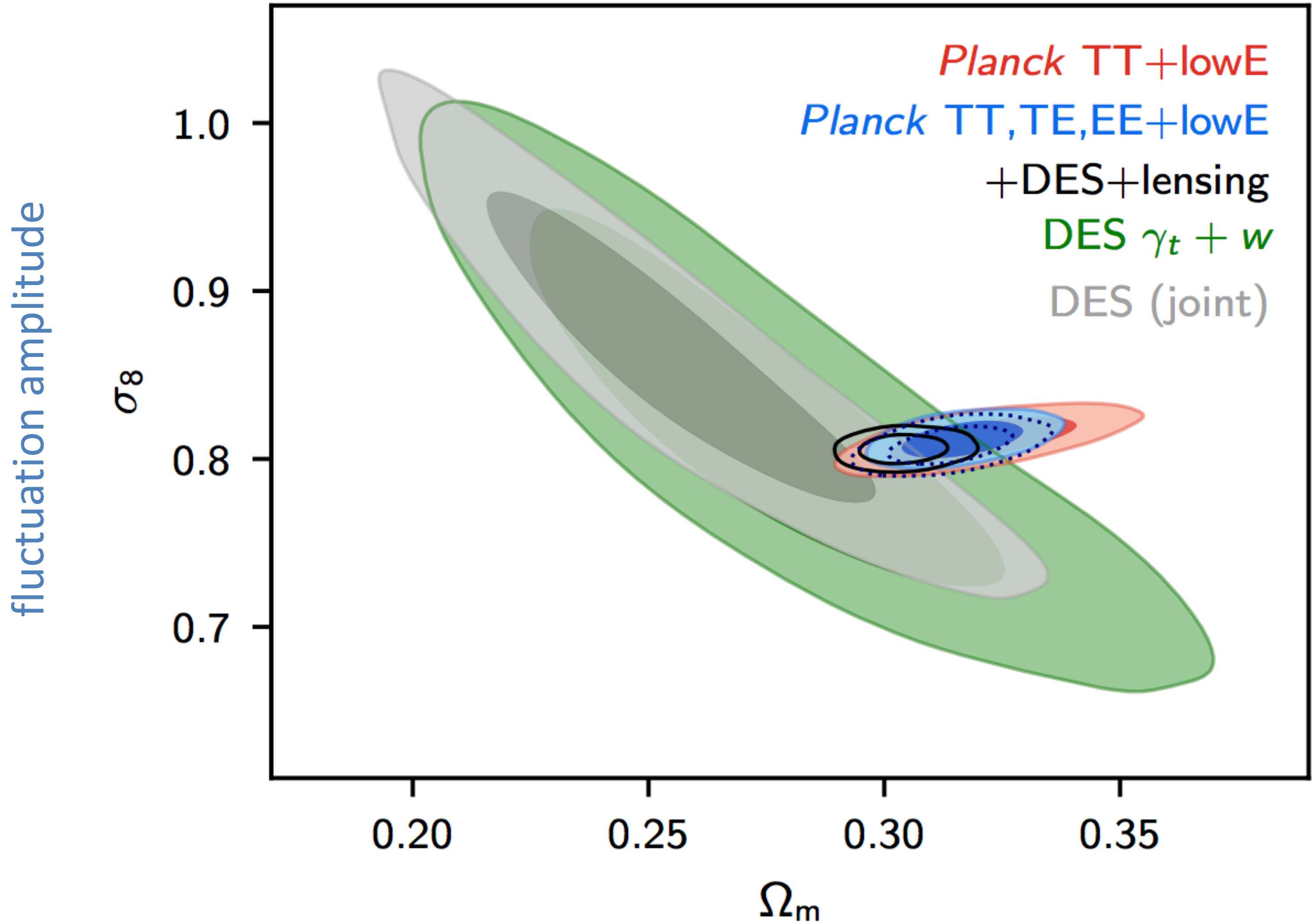
[*Planck* VI 2018]

Consistency with redshift-space distortion



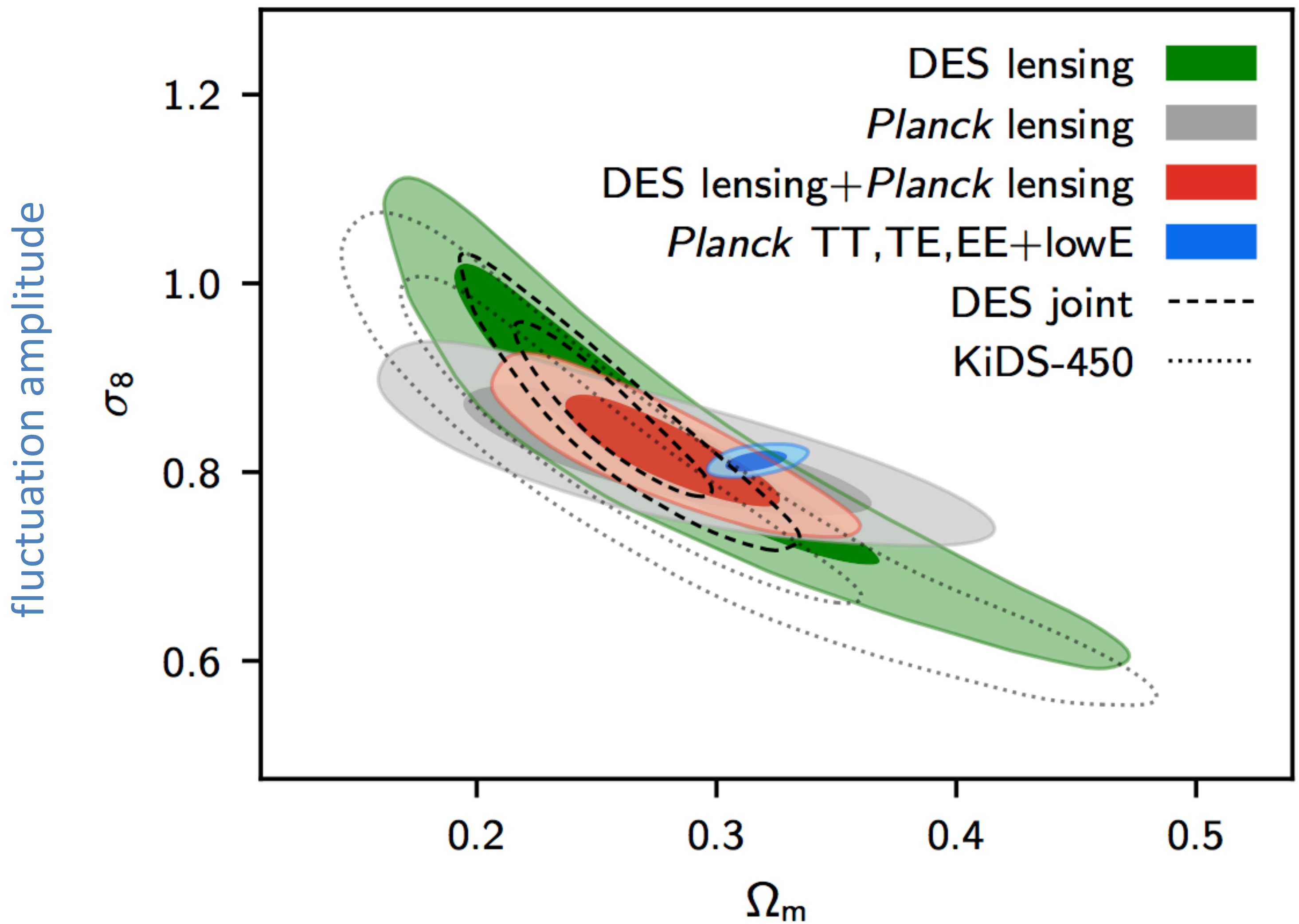
[*Planck* VI 2018]

Consistency with galaxy clustering



[*Planck* VI 2018]

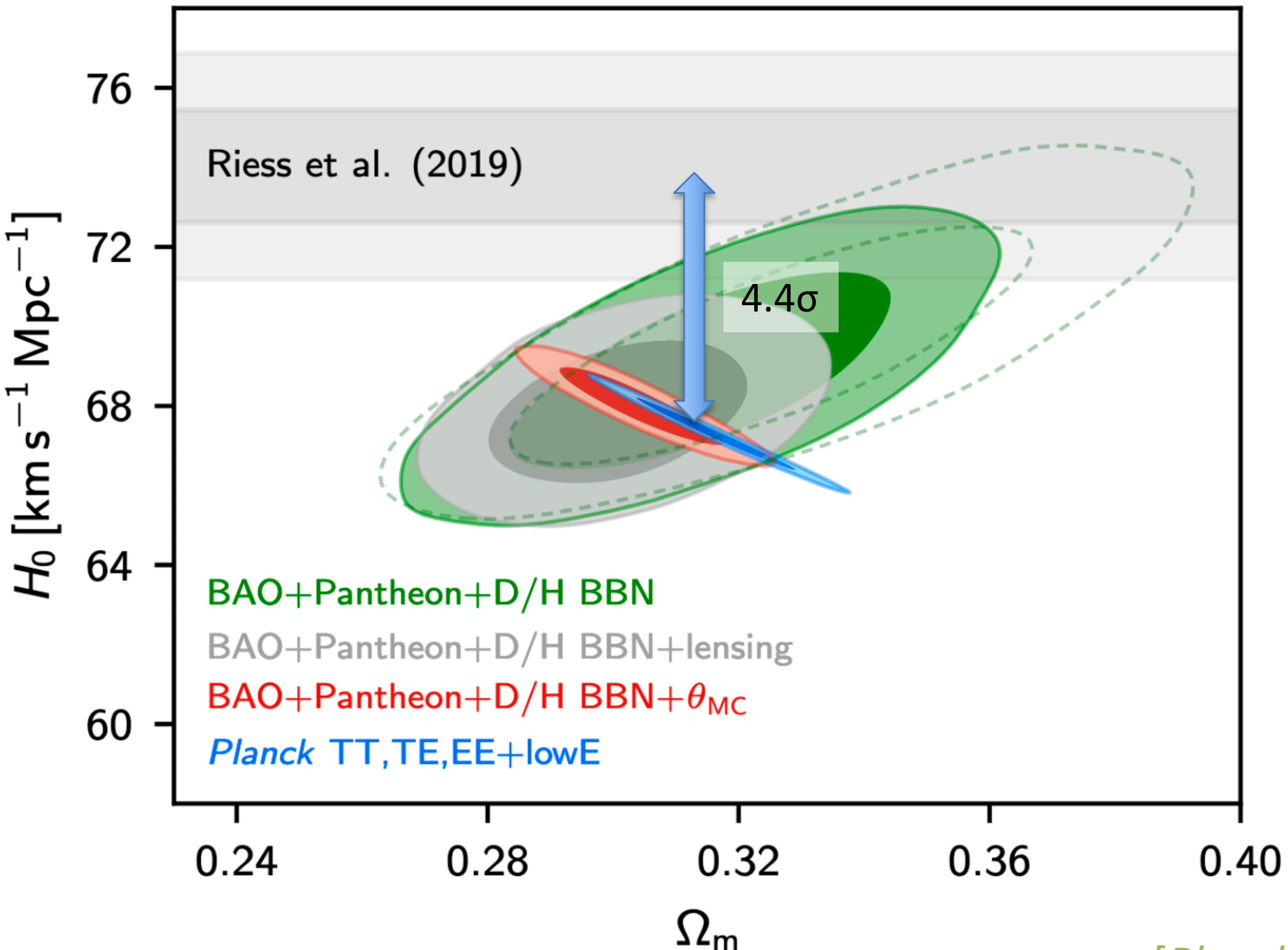
Consistency with galaxy weak lensing



[*Planck* VI 2018]

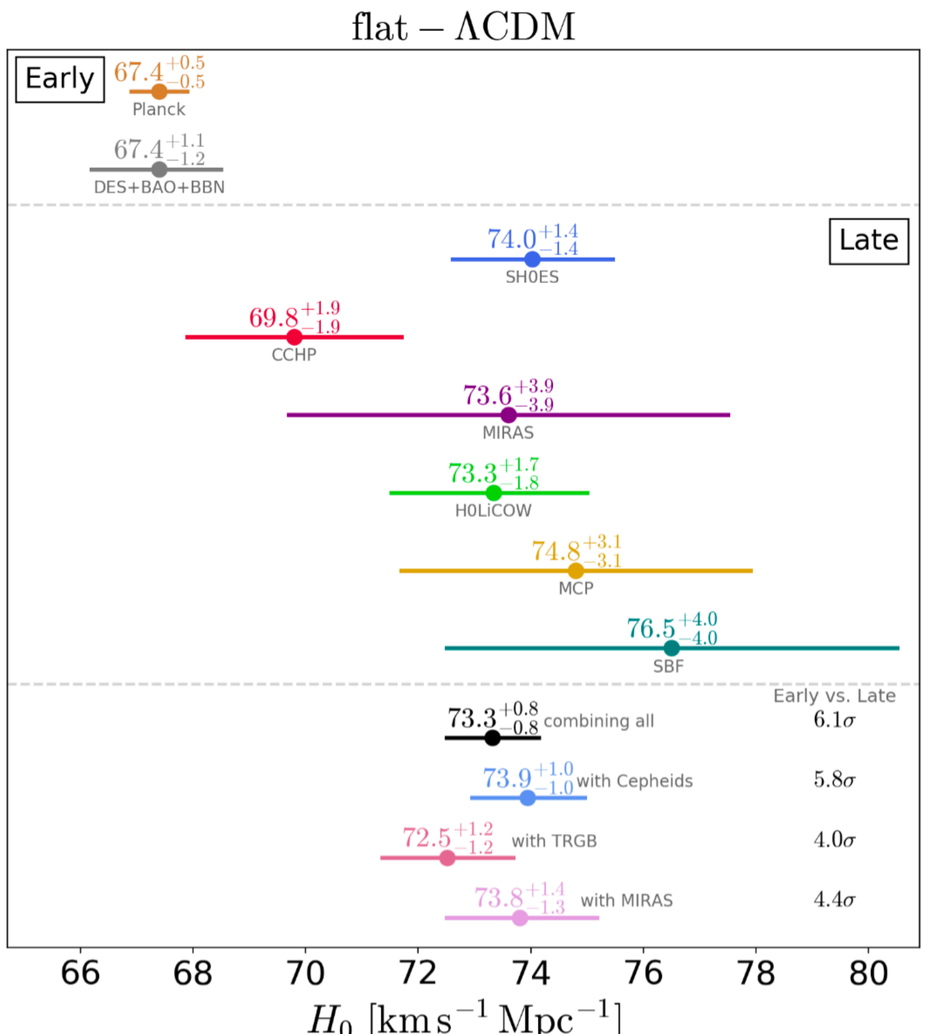
The Hubble parameter discrepancy

The Hubble problem



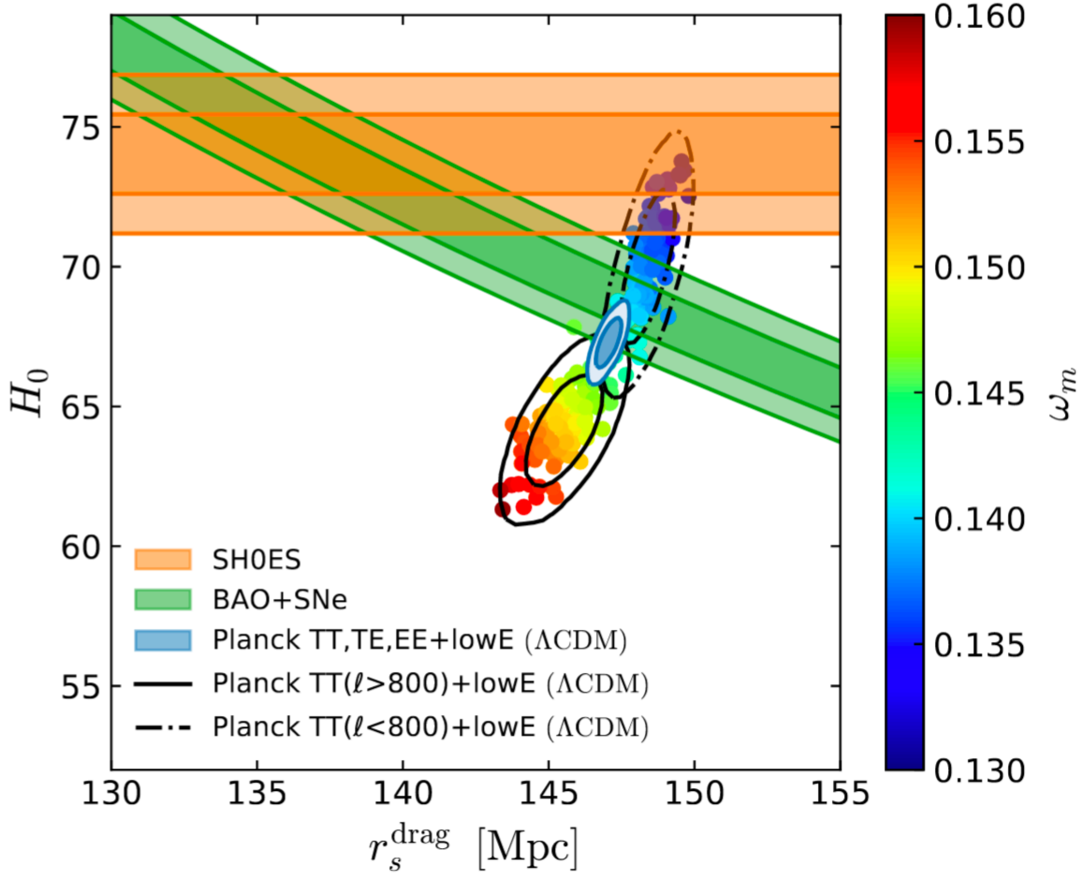
[*Planck* VI 2018]

H_0 discrepancy – early vs late?



[Verde, Treu & Riess 2019]

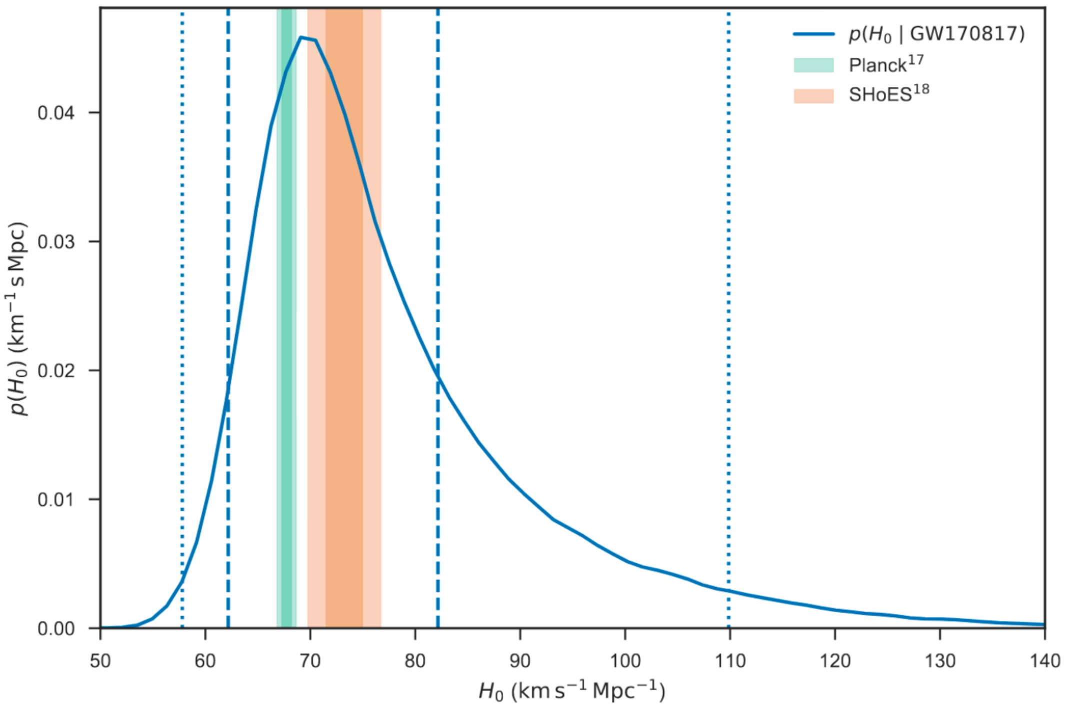
Fixing the H_0 discrepancy – beyond ΛCDM?



Very hard to reconcile H0, BAO+SNe and *Planck* data convincingly using modifications of the ΛCDM model

[Knox & Millea 2019]

Standard sirens to the rescue?



Gravitational wave standard sirens
(merger events involving a neutron star)
will give clean and independent measurement
of local expansion rate

[Abbott+ 2017]

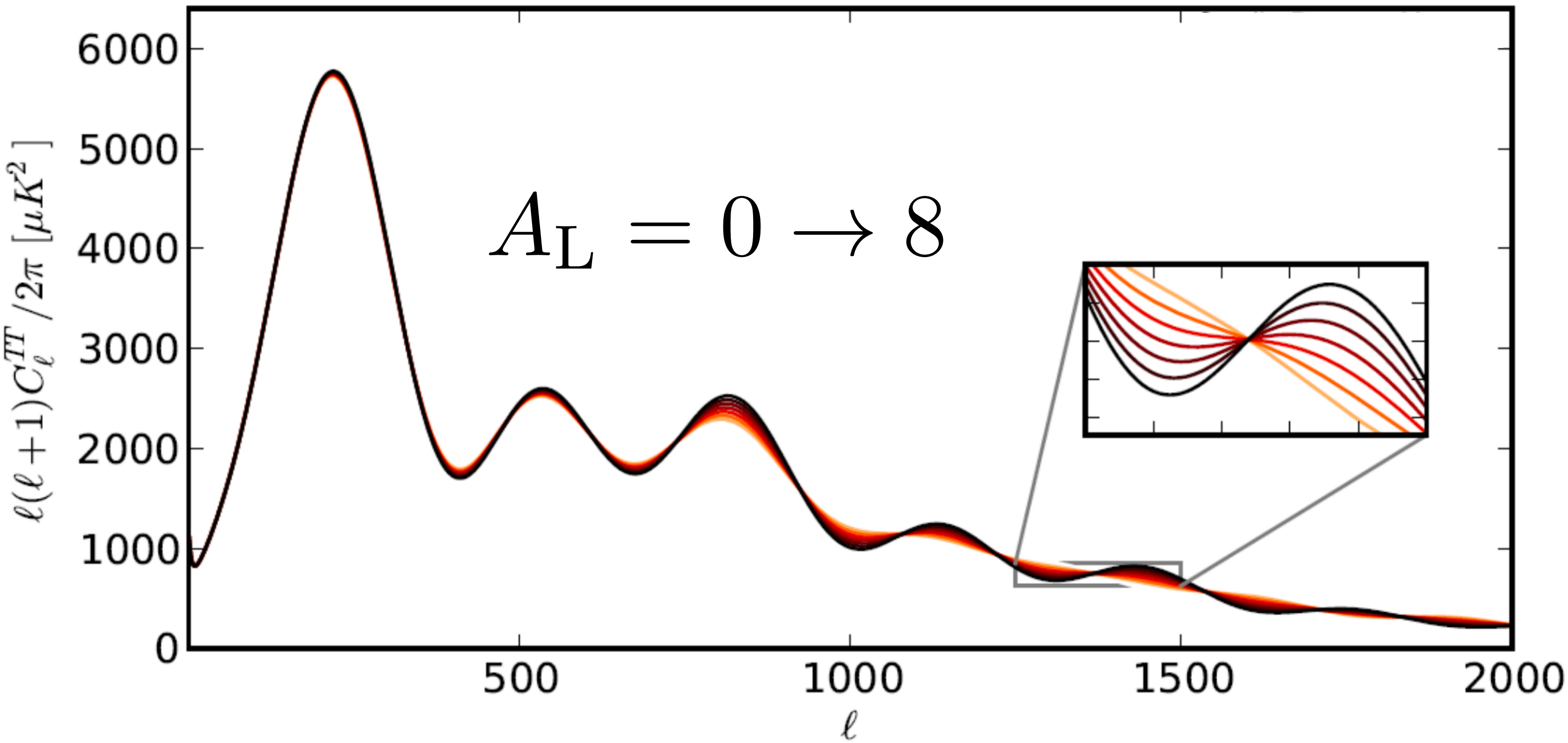
The lensing parameter discrepancy

The lensing amplitude parameter

A_L scales the amount of lensing taking place

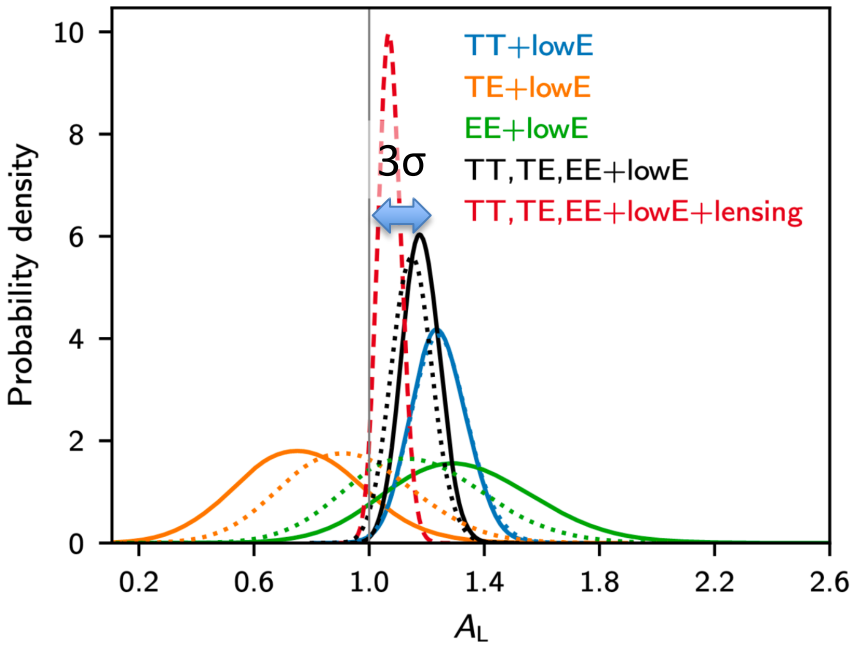
$A_{\rm L} = 0$ no lensing

$A_{\rm L} = 1$ standard lensing

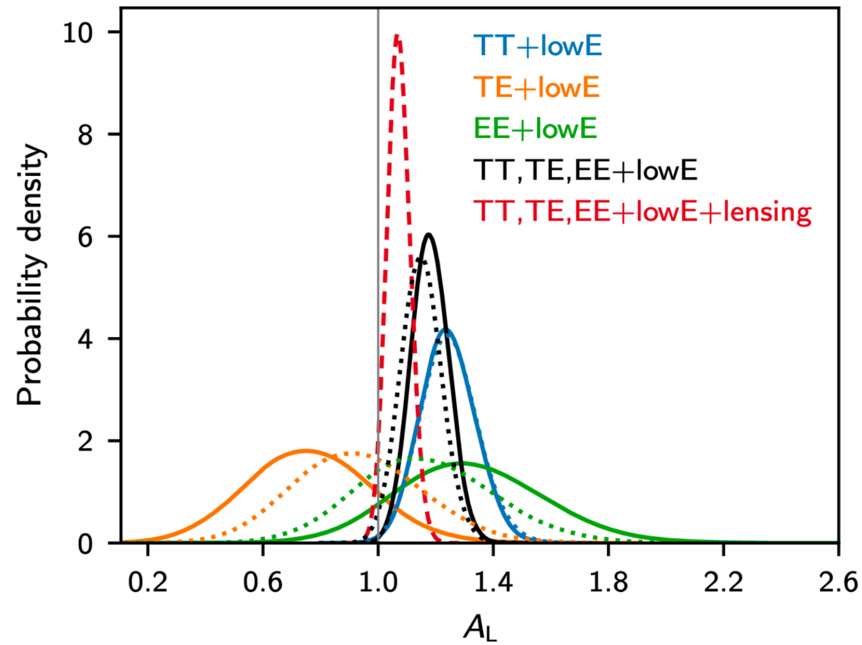


[figure by Duncan Hanson]

The lensing amplitude parameter – a problem with lensing?



inferred from power spectrum



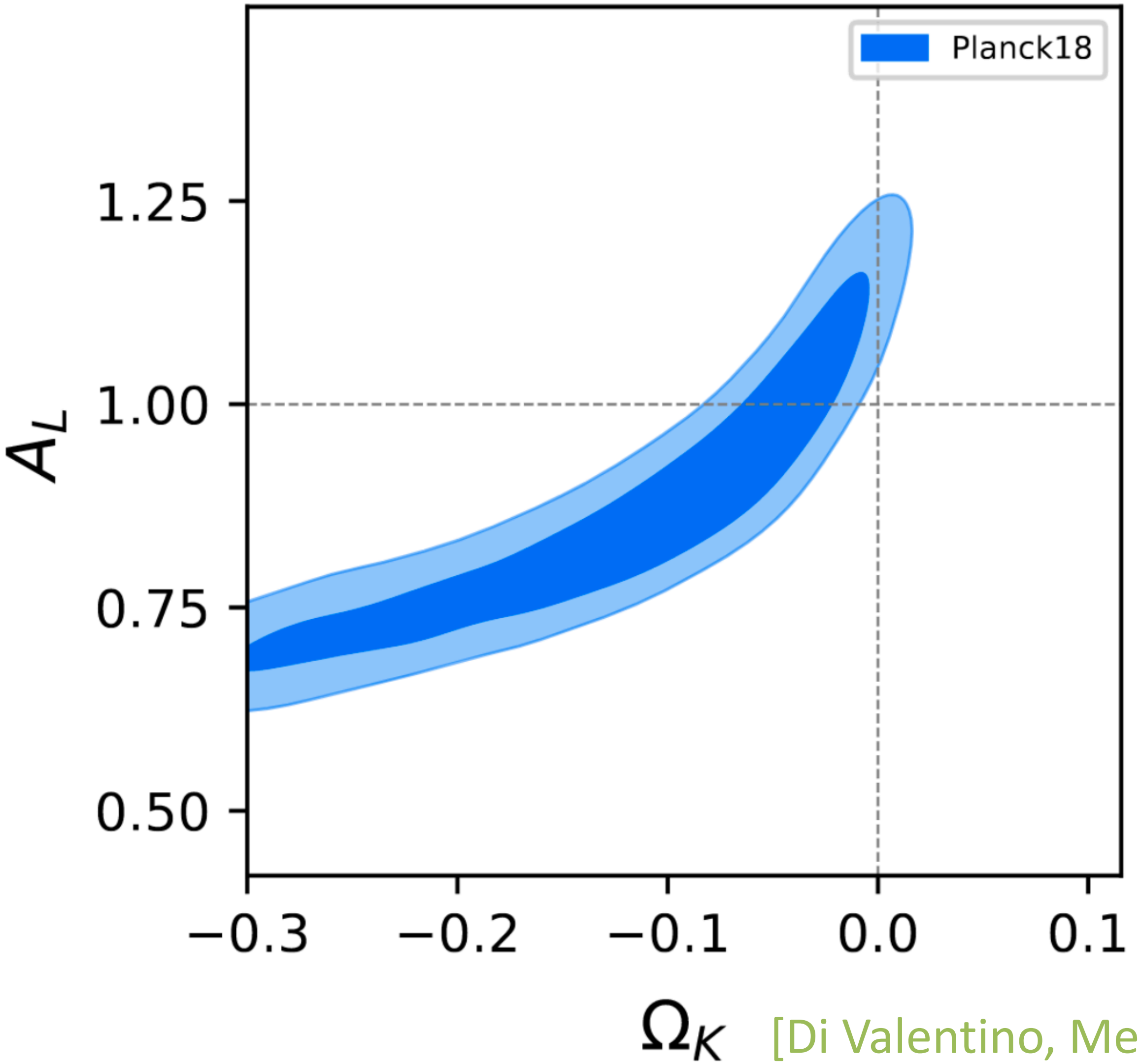
actual lensing measurement

Very unlikely.

A_L isn't even a proper physical parameter anyway!

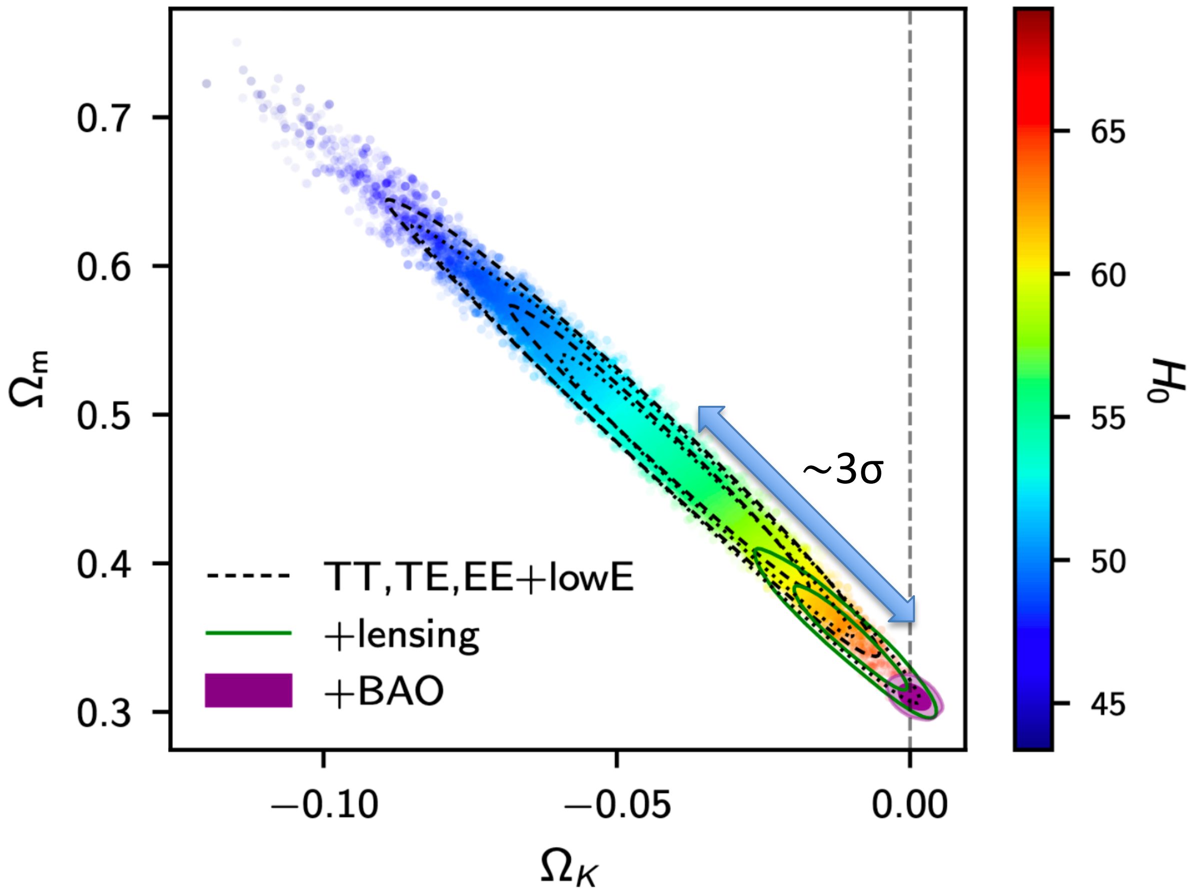
[*Planck* VI 2018]

Lensing amplitude parameter or curvature?



[Di Valentino, Melchiorri & Silk 2019]

Curvature?



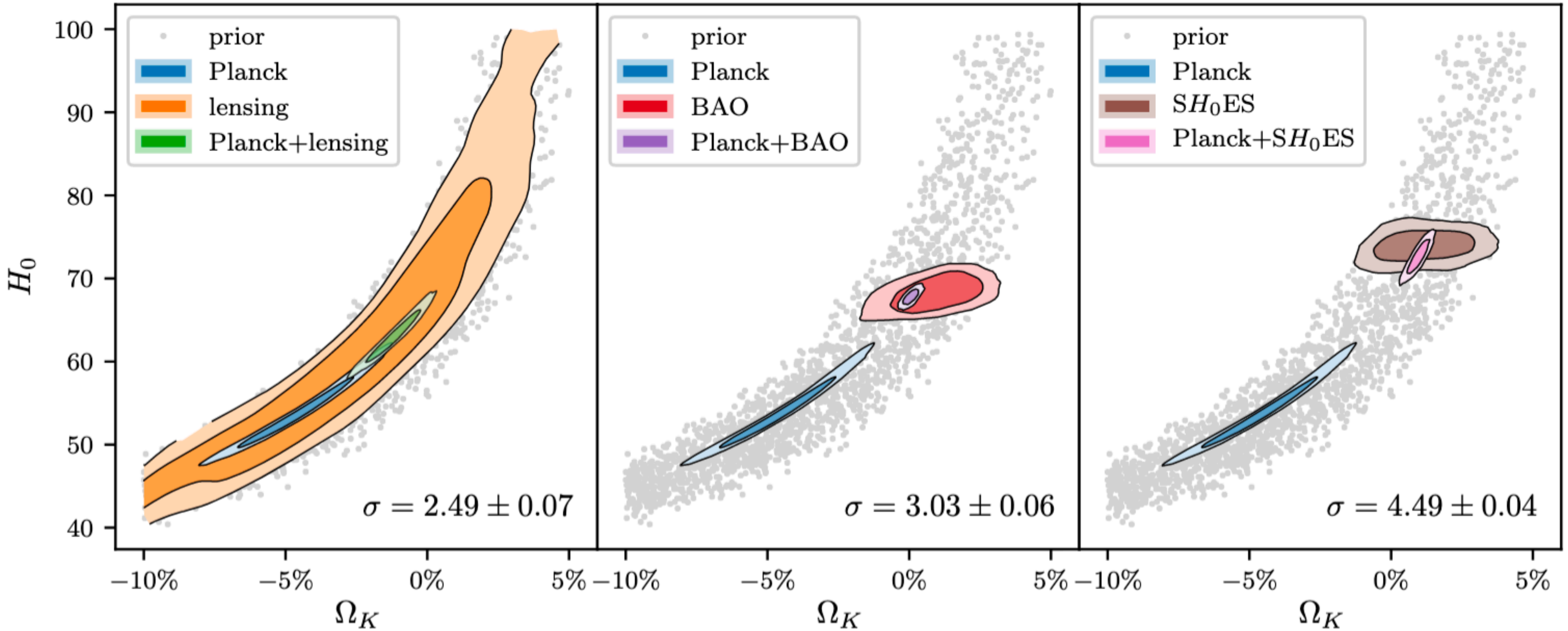
If real, bad news for inflation? – sort of, but not catastrophic

Would imply h ~ 55 km s^{-1} Mpc^{-1} though…

[*Planck* VI 2018]

Curvature?

ΛCDM+curvature would introduce uncomfortable tension with lensing and BAO data as well



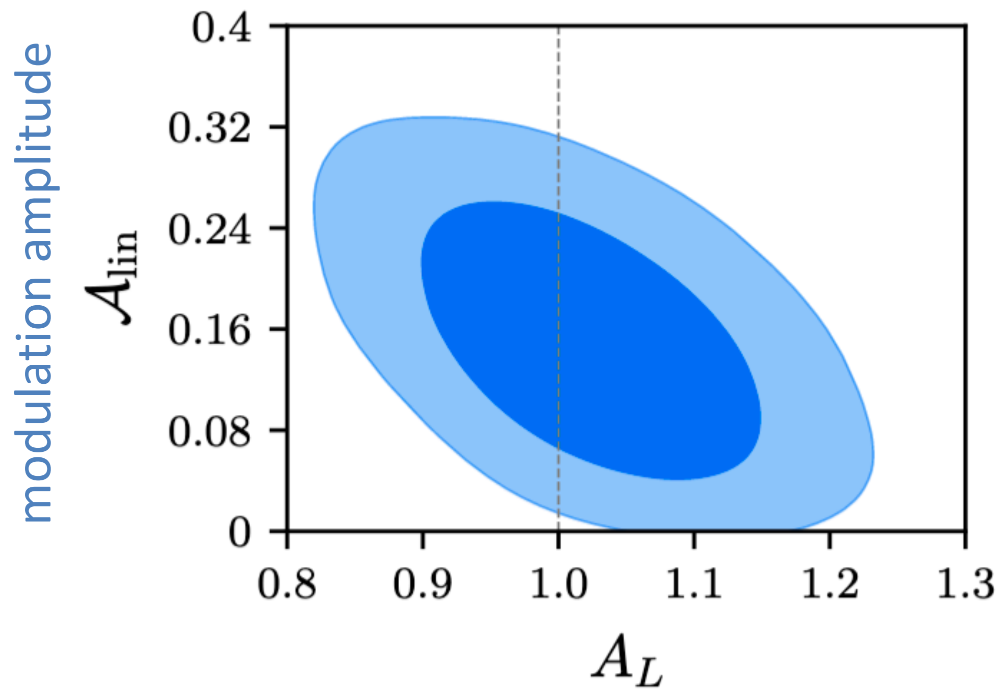
Possibly *Planck* systematics? Tension is somewhat less pronounced in alternative likelihood (`CamSpec`)

[Handley 2019]

Features in the primordial spectrum?

How about a (*horribly fine-tuned*) modulation of the initial power spectrum to fit the residuals?

$$\mathcal{P}_{\mathcal{R}}(k) \;=\; \mathcal{P}^0_{\mathcal{R}}(k)\left[1 + \mathcal{A}_{\rm lin}\,\exp(-(k-\mu_{\rm env})^2/2\sigma^2_{\rm env})\,\cos\left(\omega_{\rm lin}k/k_* + \varphi_{\rm lin}\right)\right]$$

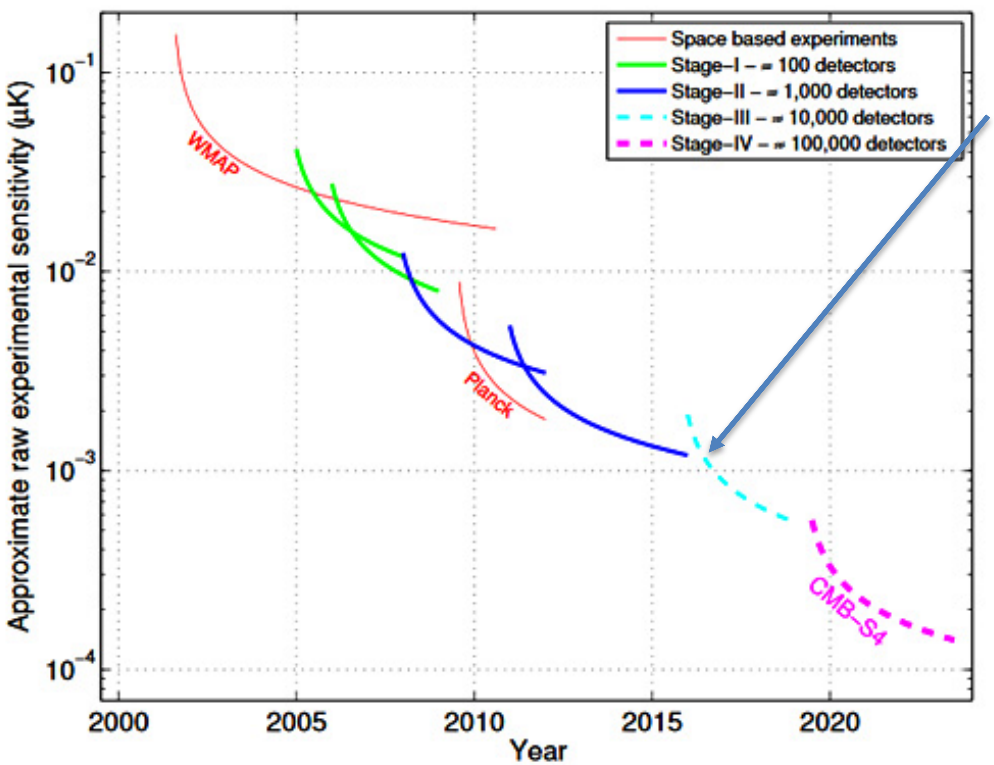


Could be distinguished by future polarization data…

[*Planck* X 2018]

Where to next?

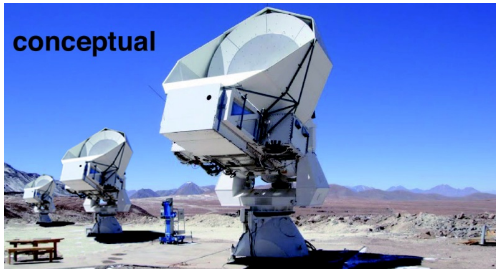
- CMB Temperature: exhausted by Planck
- Next frontier: CMB polarisation and CMB lensing



Stage II-III

POLARBEAR, BICEP 3/Keck array, SPTpol, ACTpol

Stage III



Simons array, Simons observatory

see Yuji Chinone's talk this afternoon

Conclusions

- All *Planck* maps, likelihoods, data products all available for download from the Planck Legacy Archive

  `https://pla.esac.esa.int`

- ΛCDM has been very resilient for 20 years, but is it finally starting to show cracks?
  - Hubble parameter discrepancy
  - Residuals associated with lensing parameter/curvature?
- Plenty of exciting things left to learn from CMB polarization/lensing!