Cosmological probes of gravity

Lecture 3

Observing the sky

The Hubble constant (H_0)

Big Bang Nucleosynthesis (BBN)

Type-Ia supernovae (SNIa)

Baryon acoustic oscillations (BAO)

Lecture 4

Summary of first lecture

Cosmic microwave background (CMB)

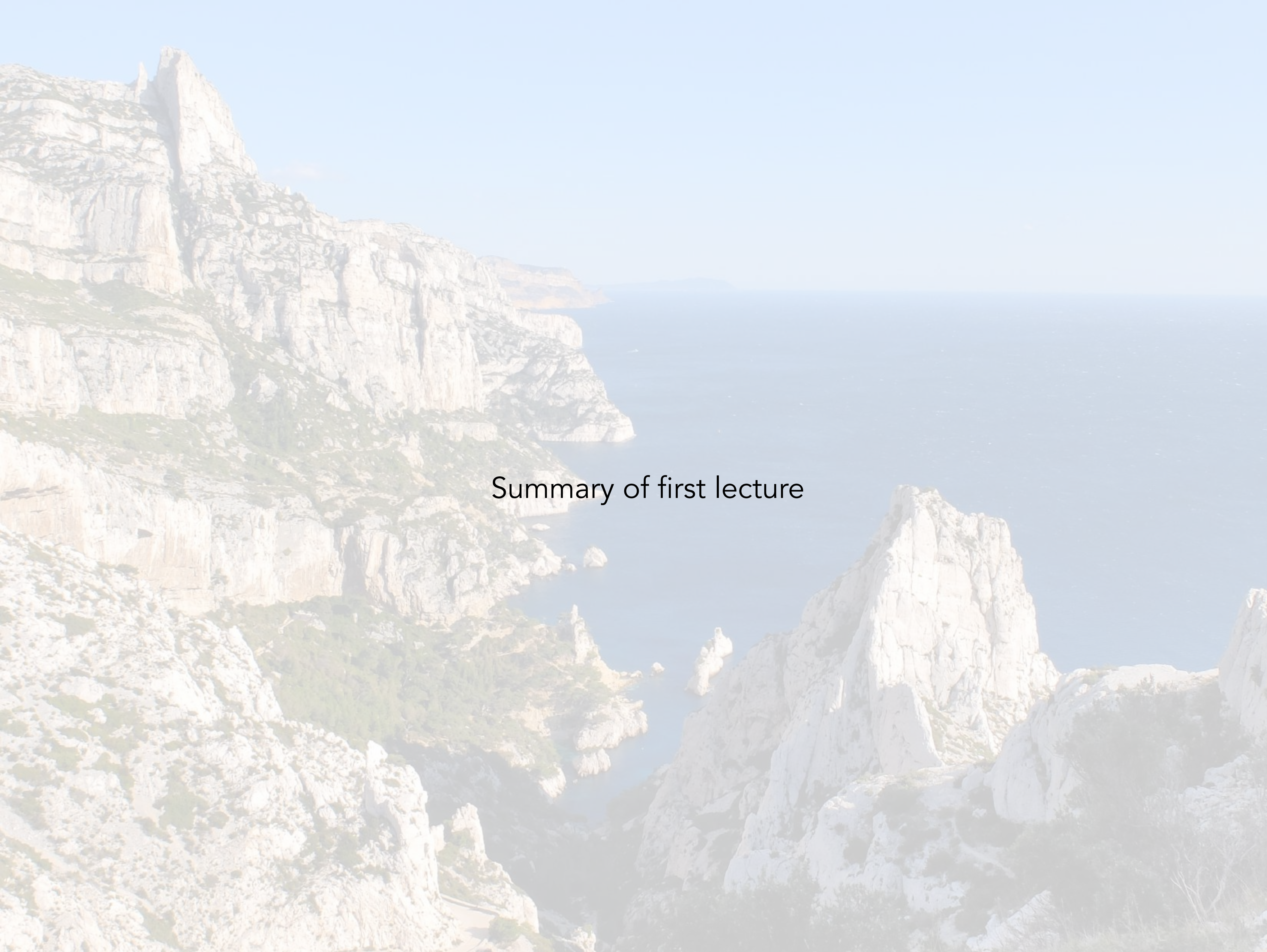
Redshift-space distortions (RSD)

Weak gravitational lensing (WL)

The future

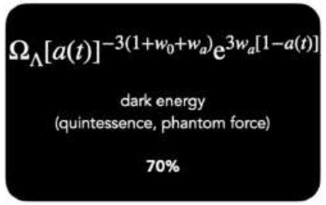
Based on "*Modern Cosmology*" by Dodelson & Schmidt 2019

"*Observational probes of cosmic acceleration*" by Weinberg et al. 2013



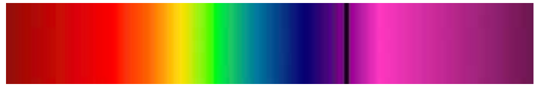
Summary of first lecture

The expansion is accelerating and we do not know why



or

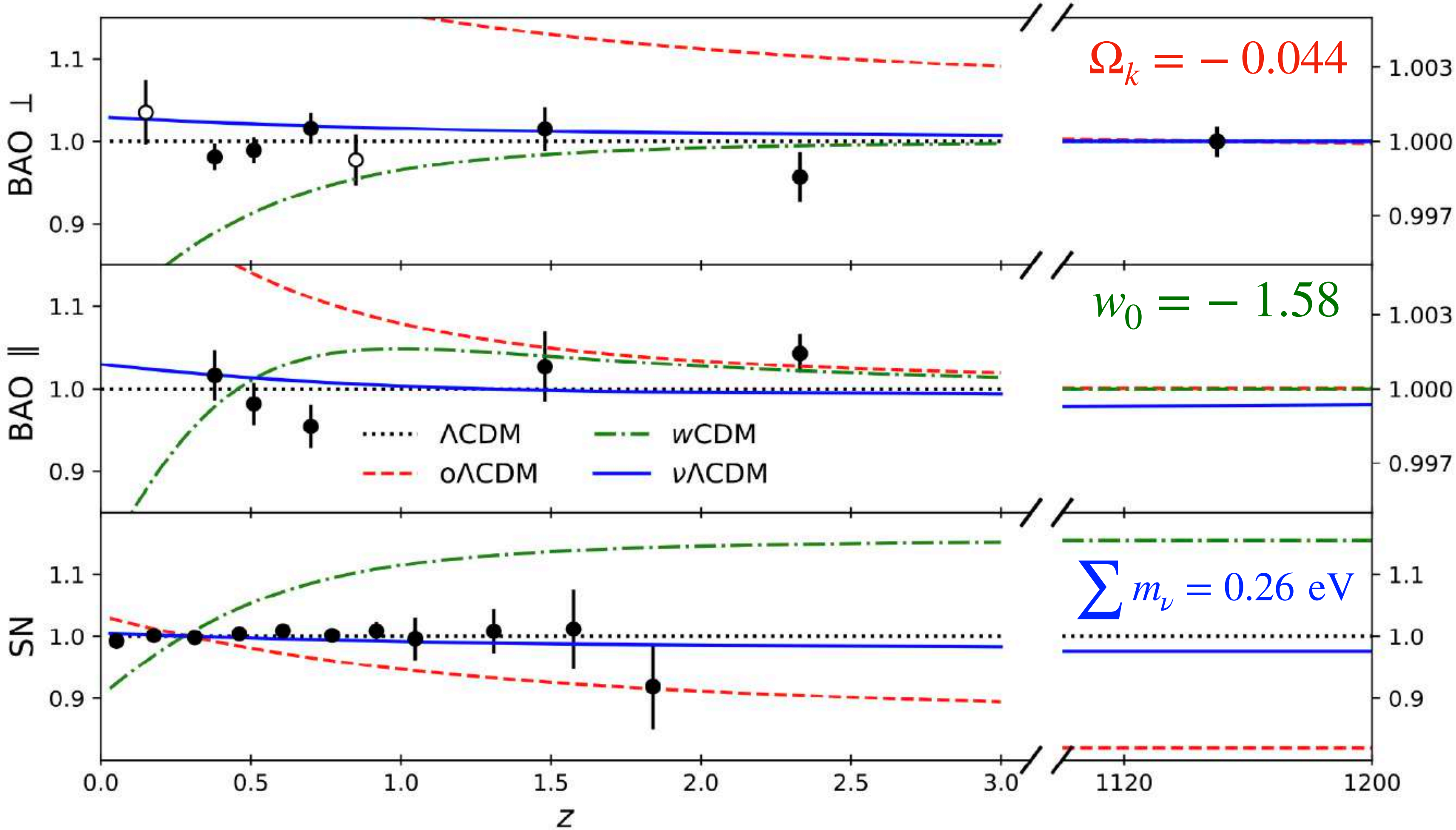
Most of the information we receive is in electromagnetic form
but we have a new way of "observing gravity" !



$$\frac{D_M(z)/r_d}{[D_M(z)/r_d]_{\text{Planck}}}$$

$$\frac{D_H(z)/r_d}{[D_H(z)/r_d]_{\text{Planck}}}$$

$$\frac{D_L(z)}{[D_L(z)]_{\text{Planck}}}$$



+ a bunch of different measurements of H_0

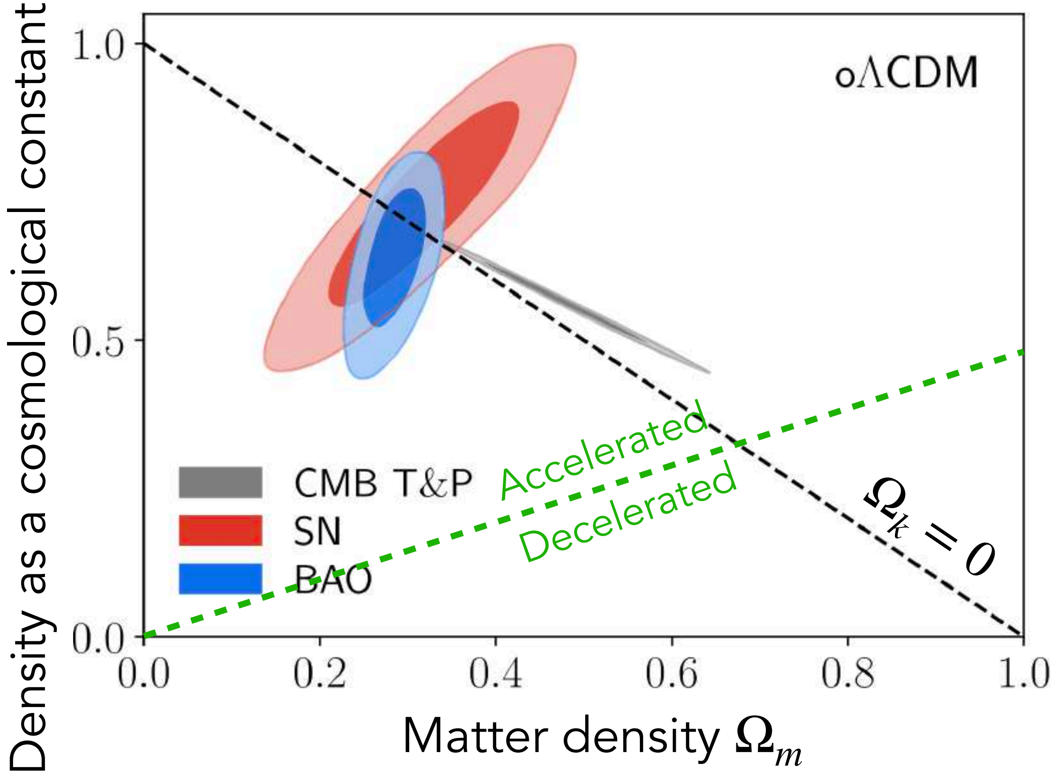
eBOSS Collab 2021

Baryon Acoustic Oscillations (BAO)

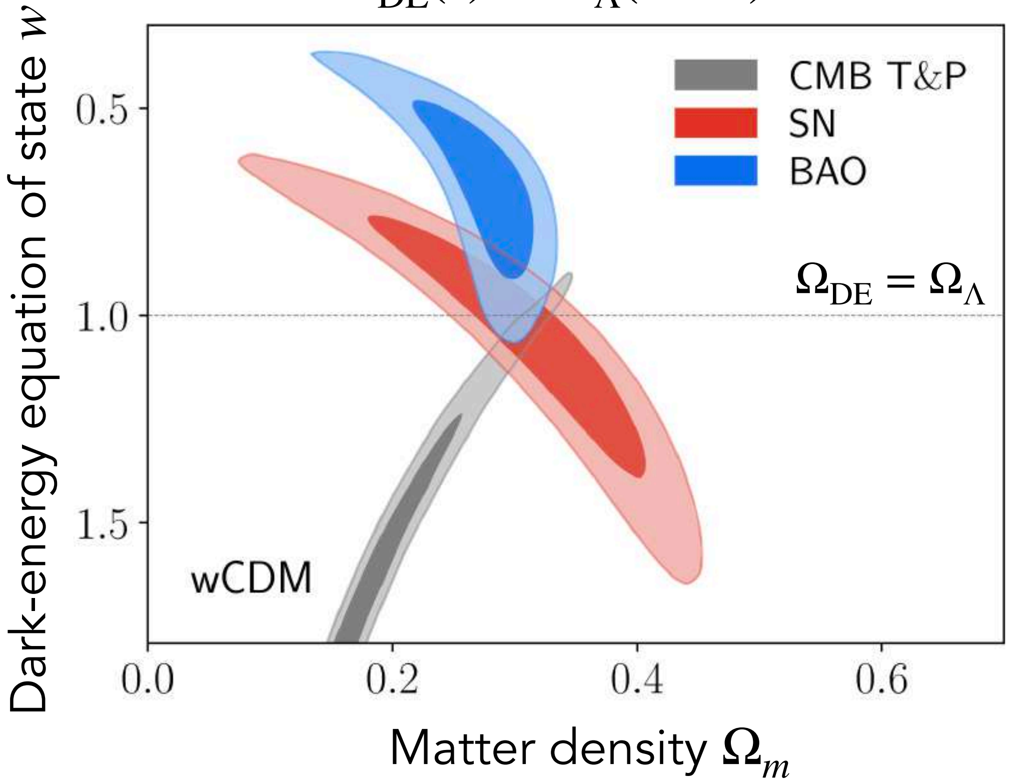
Constraints on dark-energy from the distance-redshift relation

$$H^2(z) \approx H_0^2 \left[\Omega_m(1+z)^3 + \Omega_{\rm DE}(z) + \Omega_k(1+z)^2\right] \qquad \text{(at z < 100)}$$

If $\Omega_{\rm DE}(z) = \Omega_\Lambda$



If $\Omega_{\rm DE}(z) = \Omega_\Lambda(1+z)^{3(1+w)}$



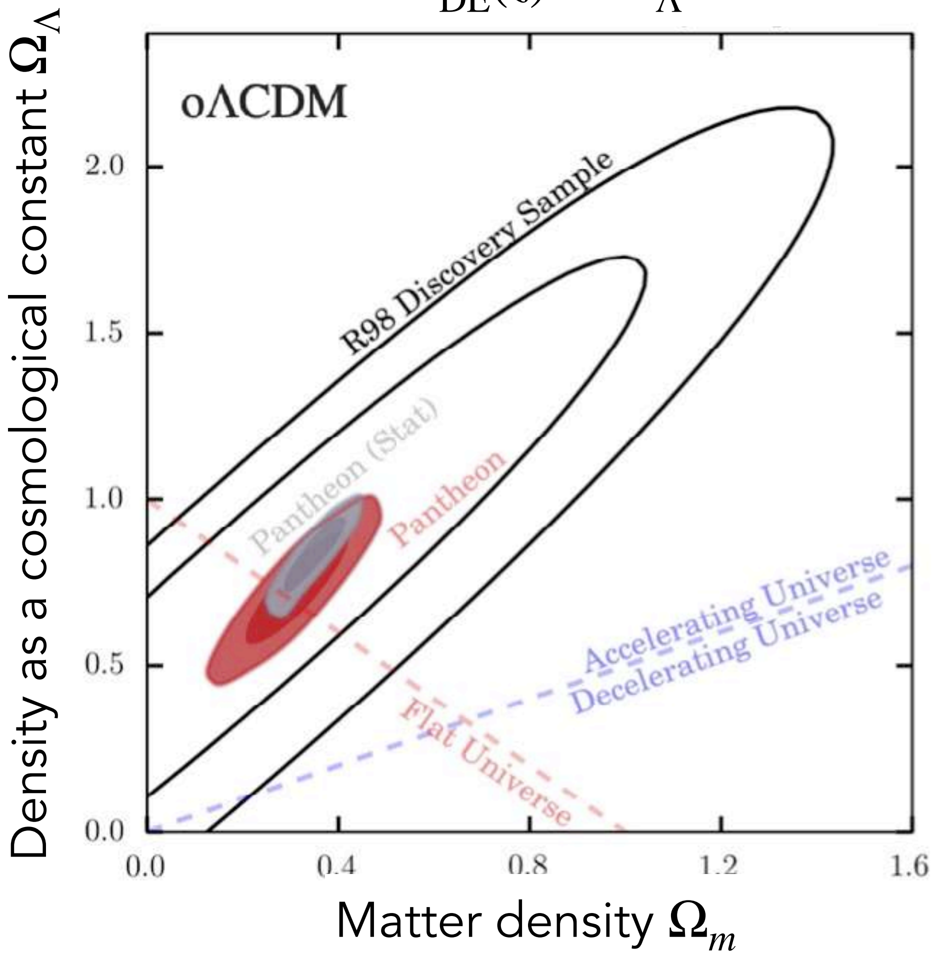
BAO as powerful as SNIa, and independently showing acceleration !

Cosmology with Type Ia Supernovae (SNIa)

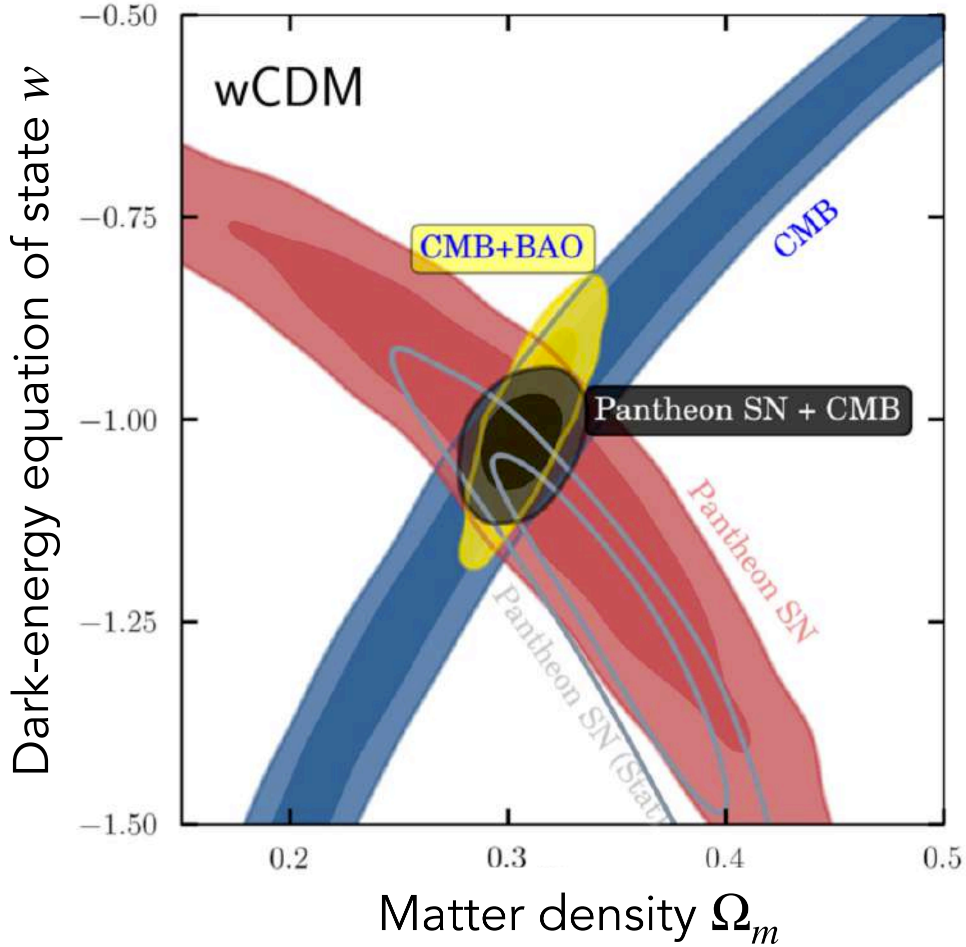
Constraints on dark-energy from the distance-redshift relation

$$H^2(z) \approx H_0^2 \left[\Omega_m(1+z)^3 + \Omega_{\mathrm{DE}}(z) + \Omega_k(1+z)^2\right] \quad \text{(at z < 100)}$$

If $\Omega_{\mathrm{DE}}(z) = \Omega_\Lambda$



If $\Omega_{\mathrm{DE}}(z) = \Omega_\Lambda(1+z)^{3(1+w)}$



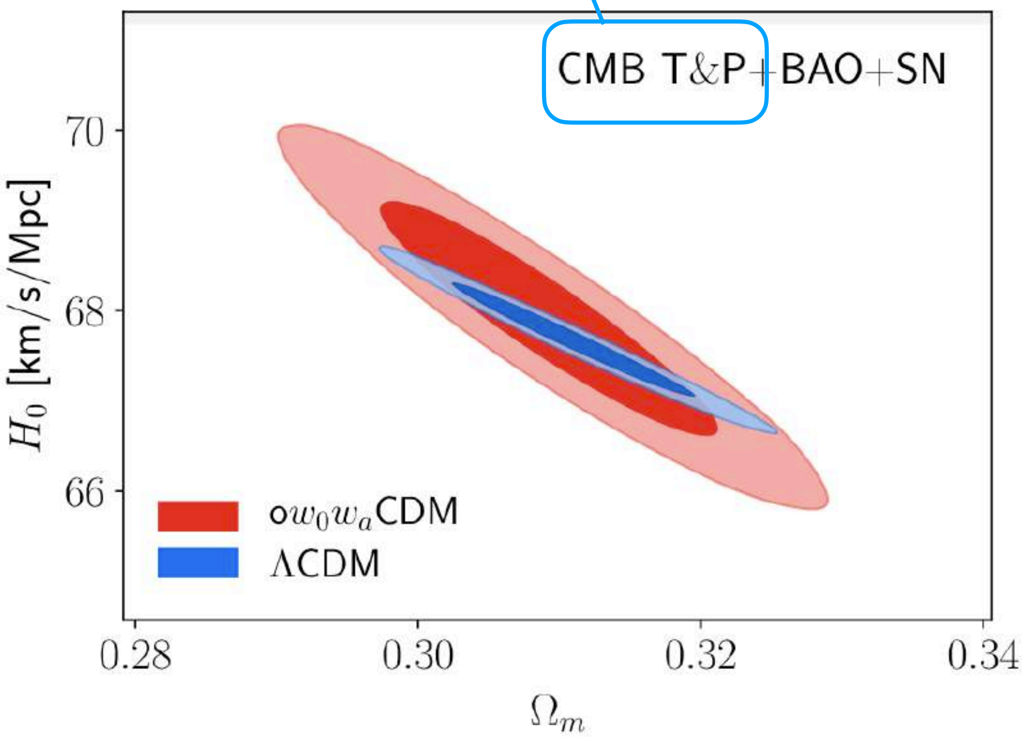
Scolnic et al. 2018

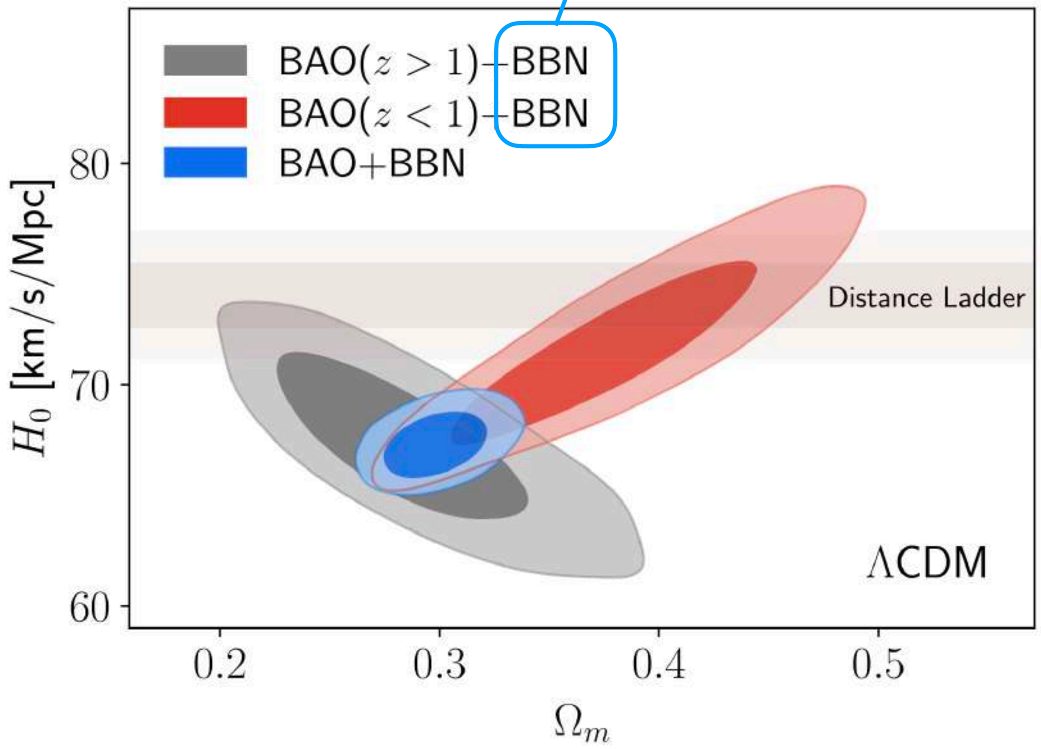
$r_{\text{ruler}} \leftarrow \Omega_b h^2$

The Hubble Constant H_0

Inverse distance ladder

$\Omega_b h^2 \rightarrow r_{\text{ruler}}$



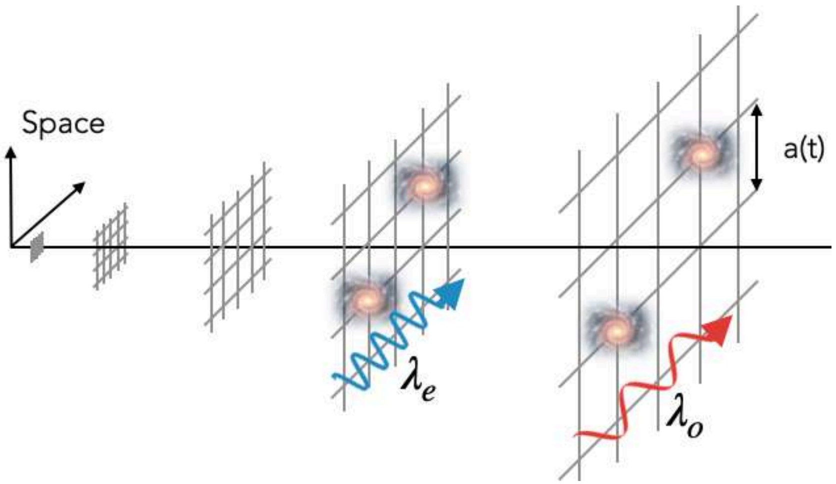


Dataset	Cosmological model	H_0 (km s^{-1} Mpc^{-1})
CMB T & P + BAO + SN	ow_0w_aCDM	67.91 ± 0.87
BBN + BAO	ΛCDM	67.33 ± 0.98
CMB T&P	ΛCDM	67.28 ± 0.61
CMB T&P	oΛCDM	$54.5^{+3.3}_{-3.9}$
Lensing time delays	ΛCDM	73.3 ± 1.8
Distance ladder	...	74.0 ± 1.4
GW sirens	...	70 ± 10
TRGB	...	69.6 ± 1.9
TFR	...	76.2 ± 4.3
Maser galaxies	...	73.9 ± 3.0

eBOSS Collab 2021

What is dark energy ?

The acceleration problem

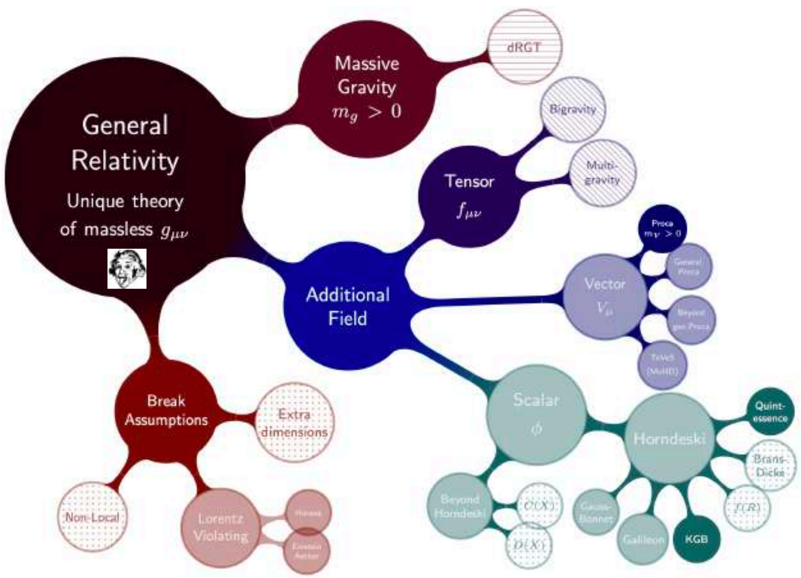


$$\Omega_\Lambda[a(t)]^{-3(1+w_0+w_a)}e^{3w_a[1-a(t)]}$$

dark energy
(quintessence, phantom force)

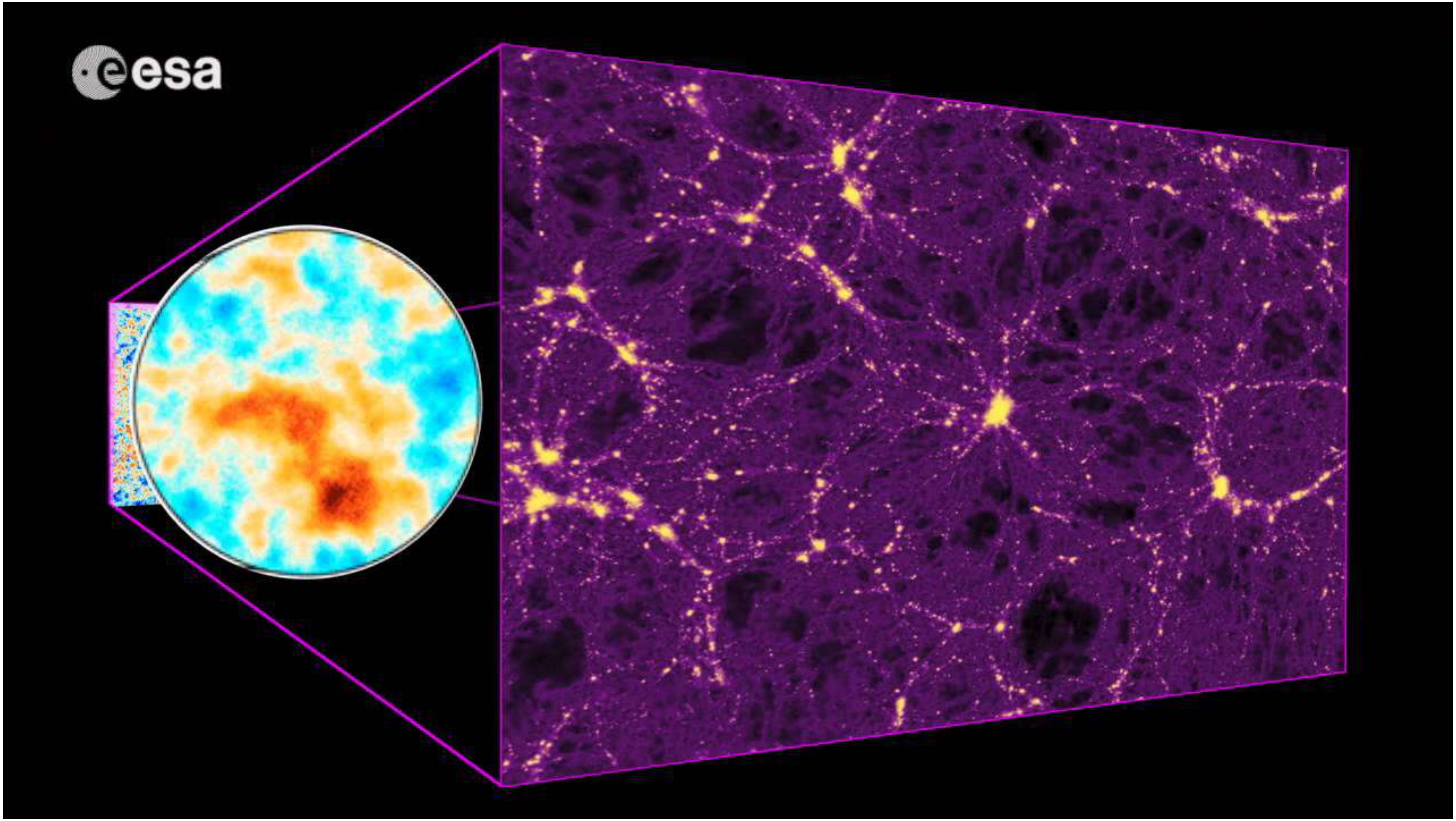
70%

or



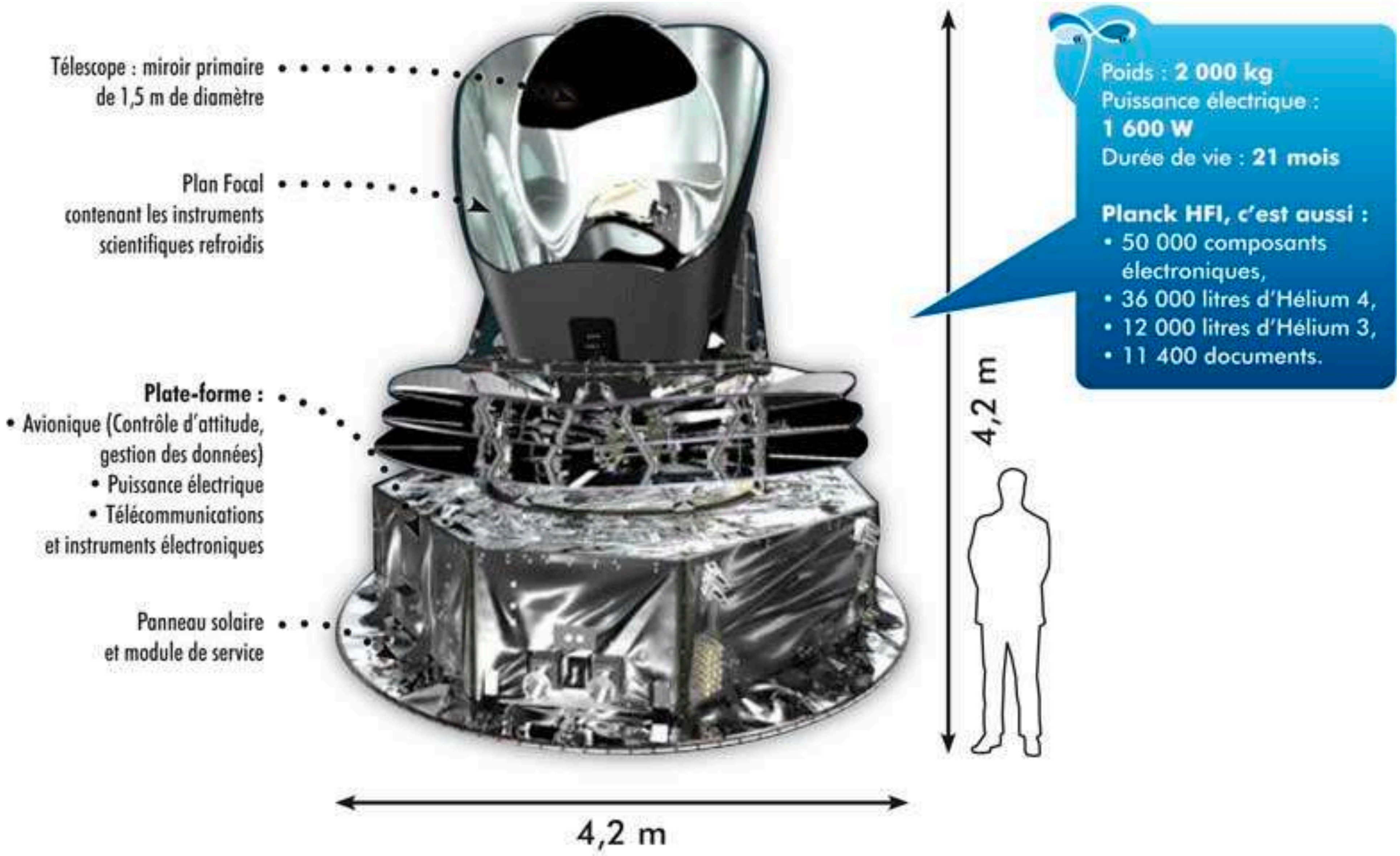
Cosmic Microwave Background (CMB)

Cosmic Microwave Background (CMB)



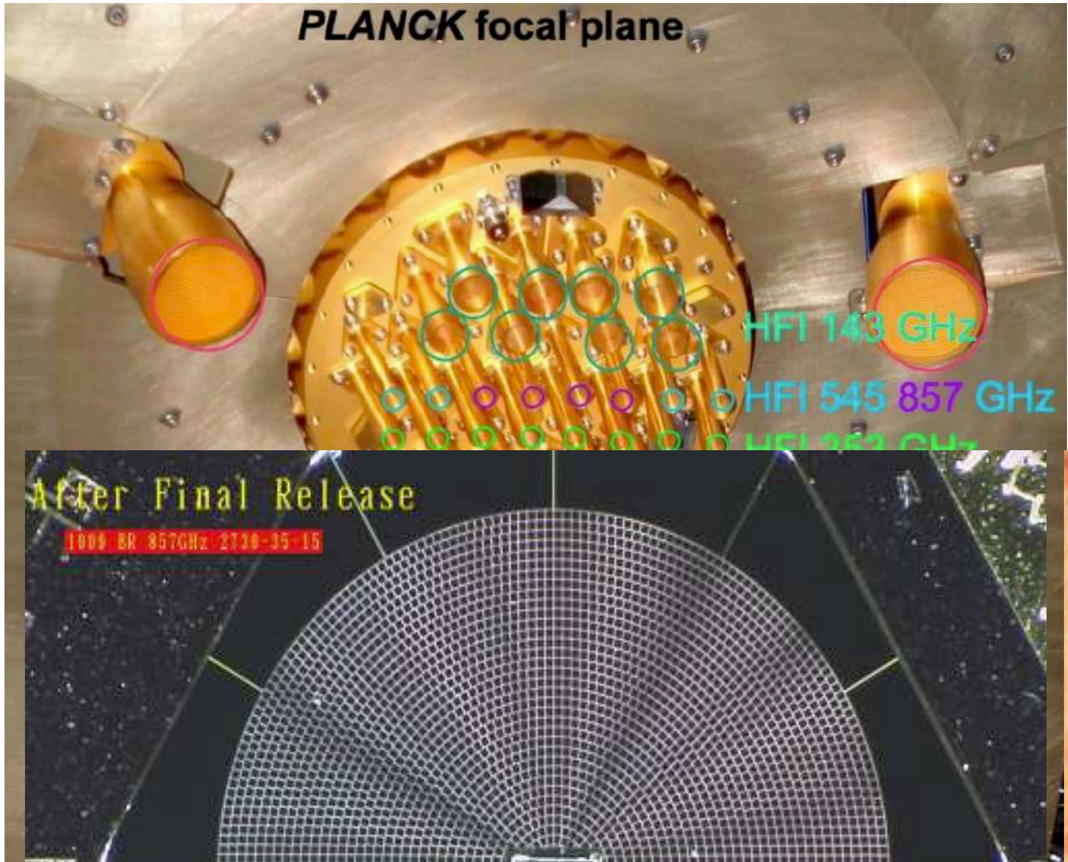
How do we observe it ?

Planck satellite



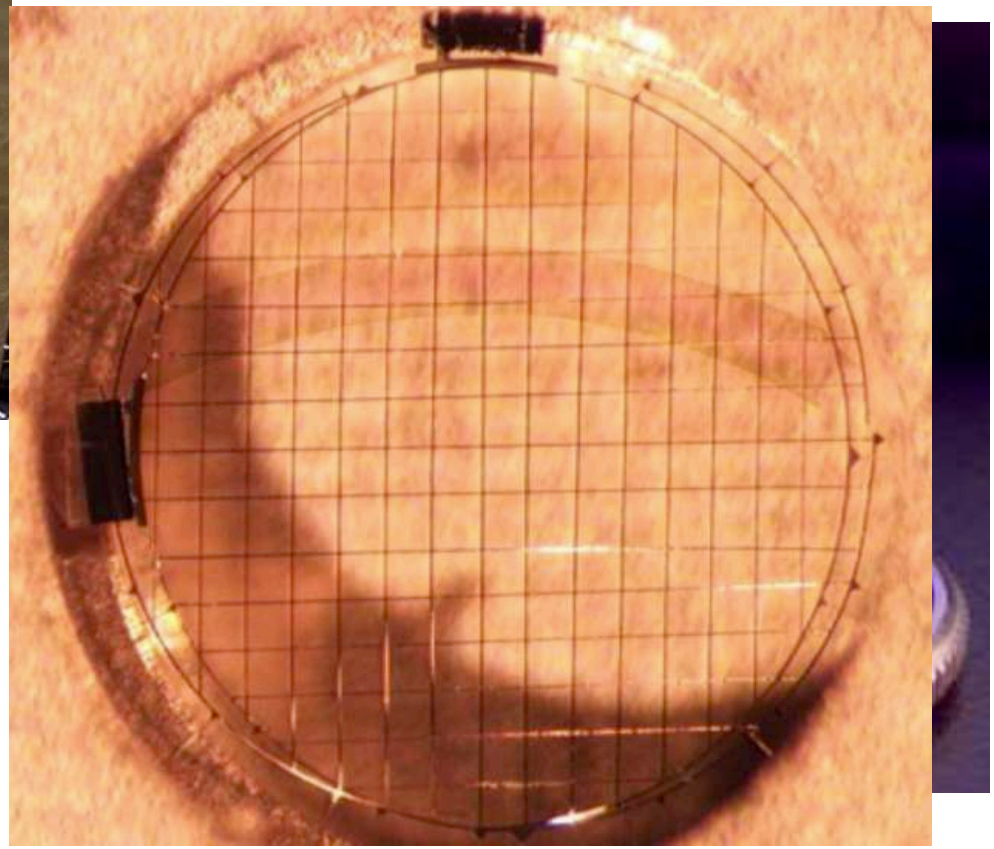
How do we observe ?

Bolometers



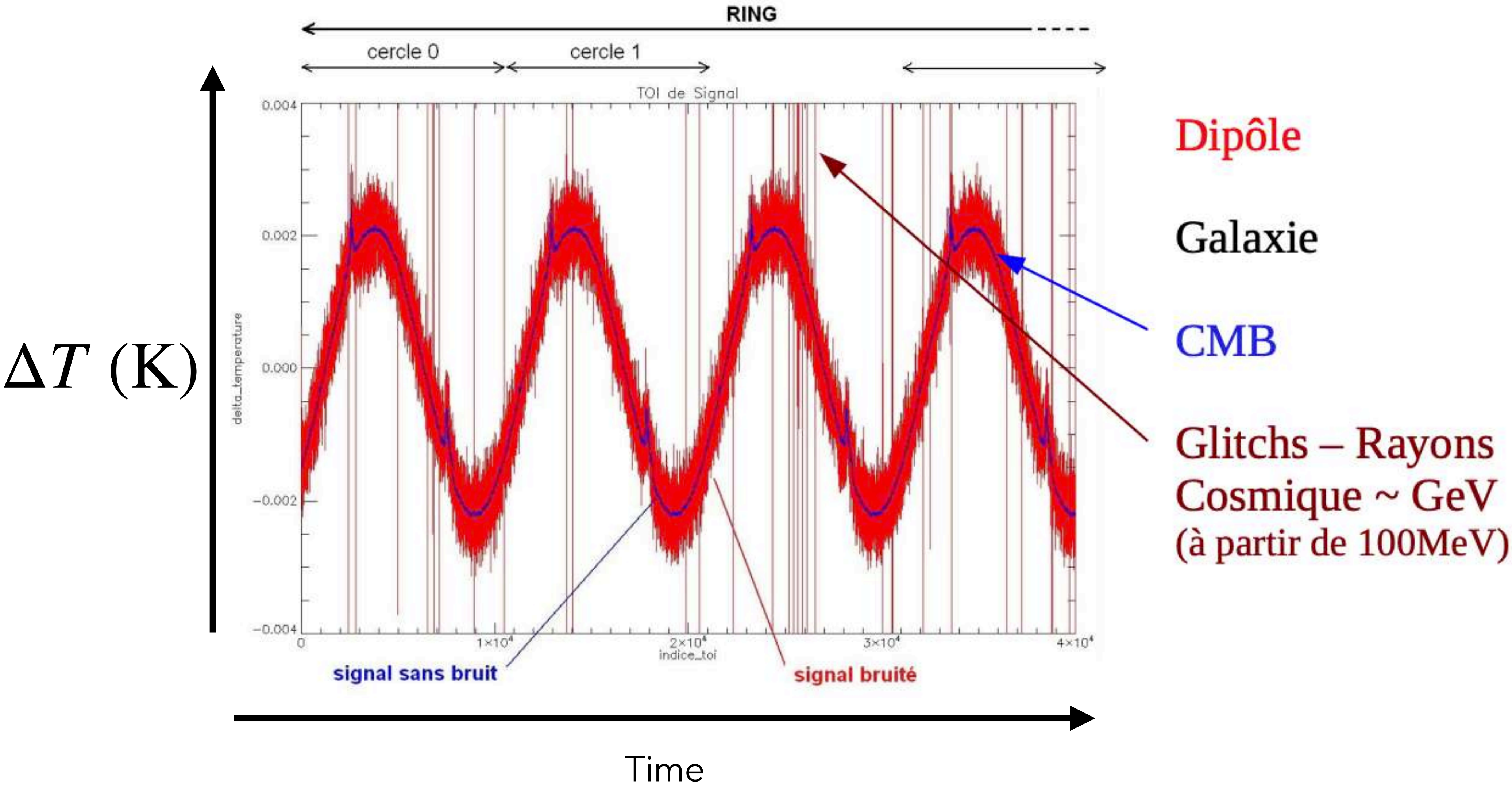
Observes polarisation as well

Kept at 0.1 Kelvin !

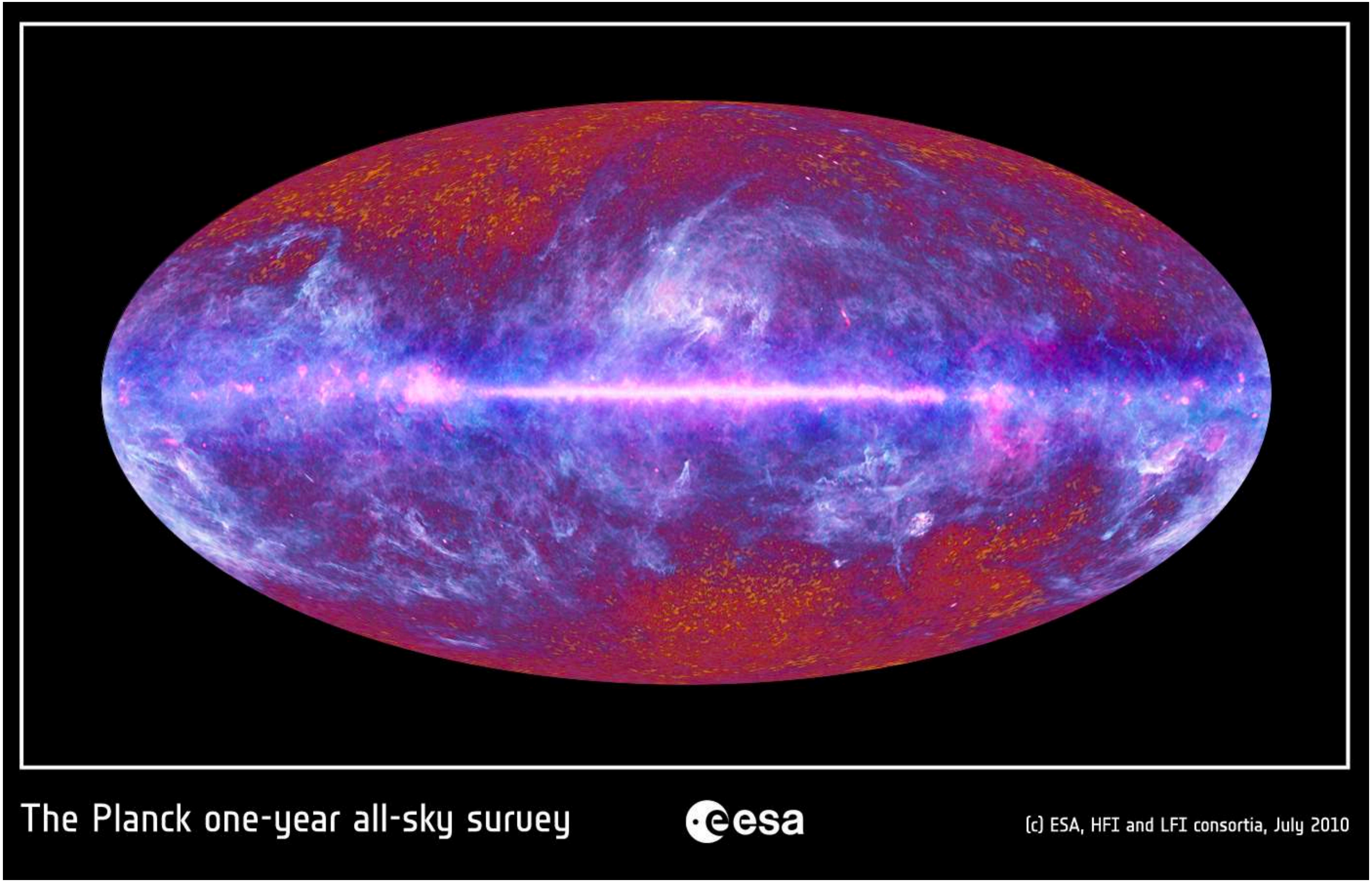


What do we observe ?

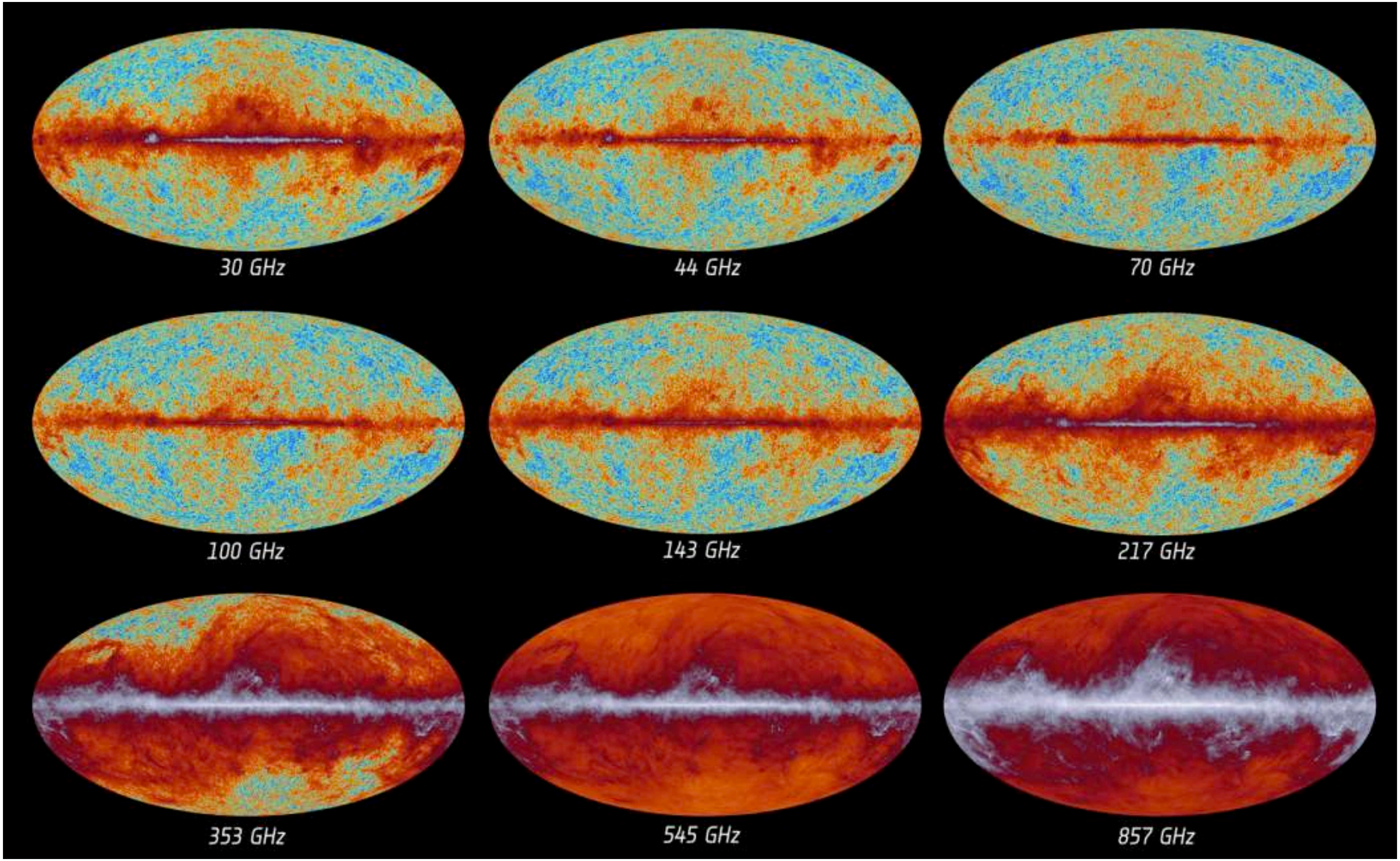
Low energy photons



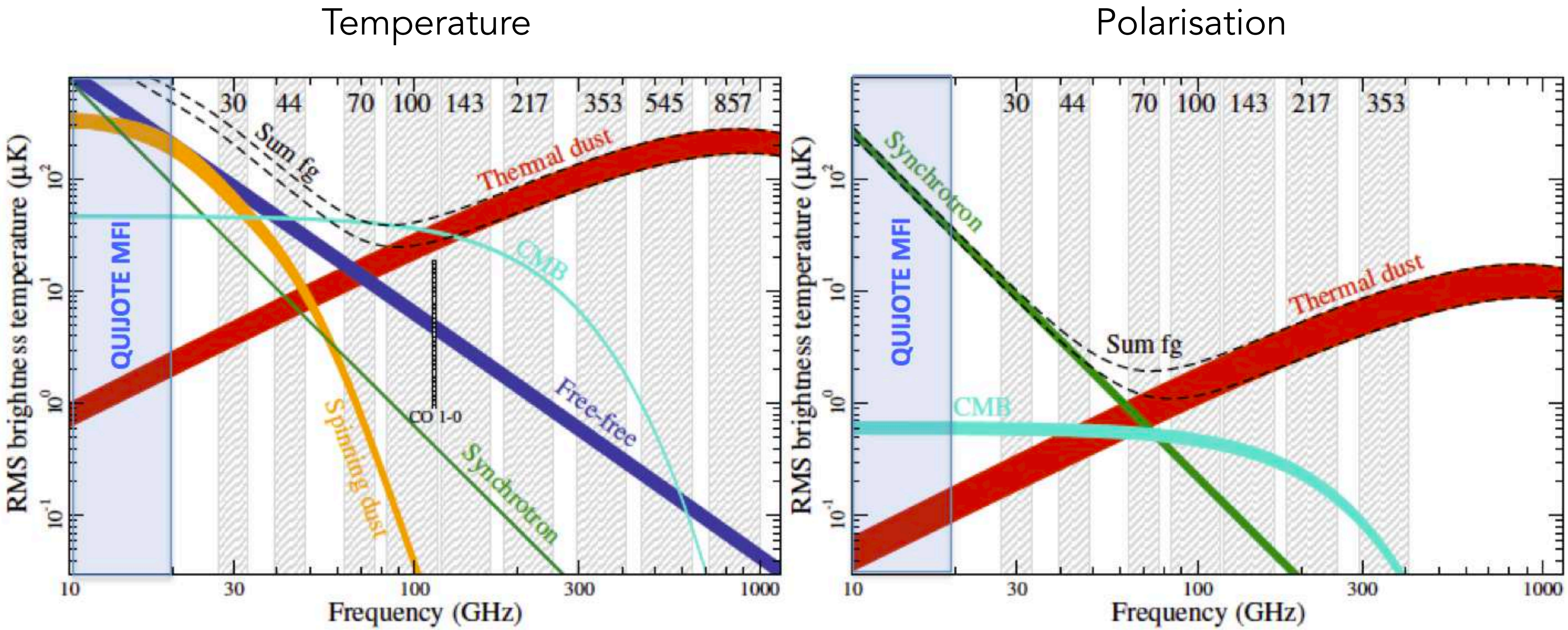
The microwave emission of the sky



The microwave emission of the sky

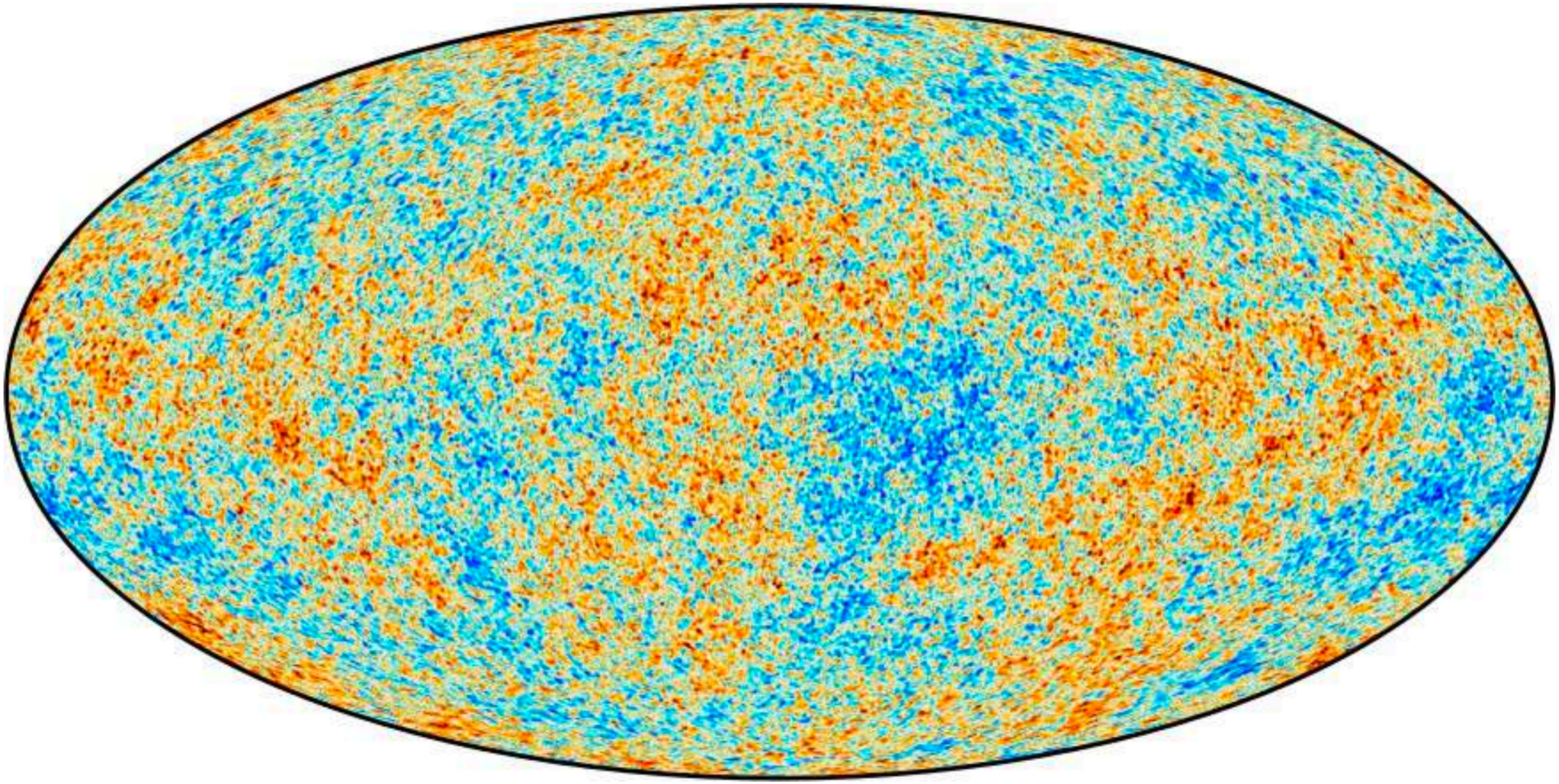


Removing foreground emission



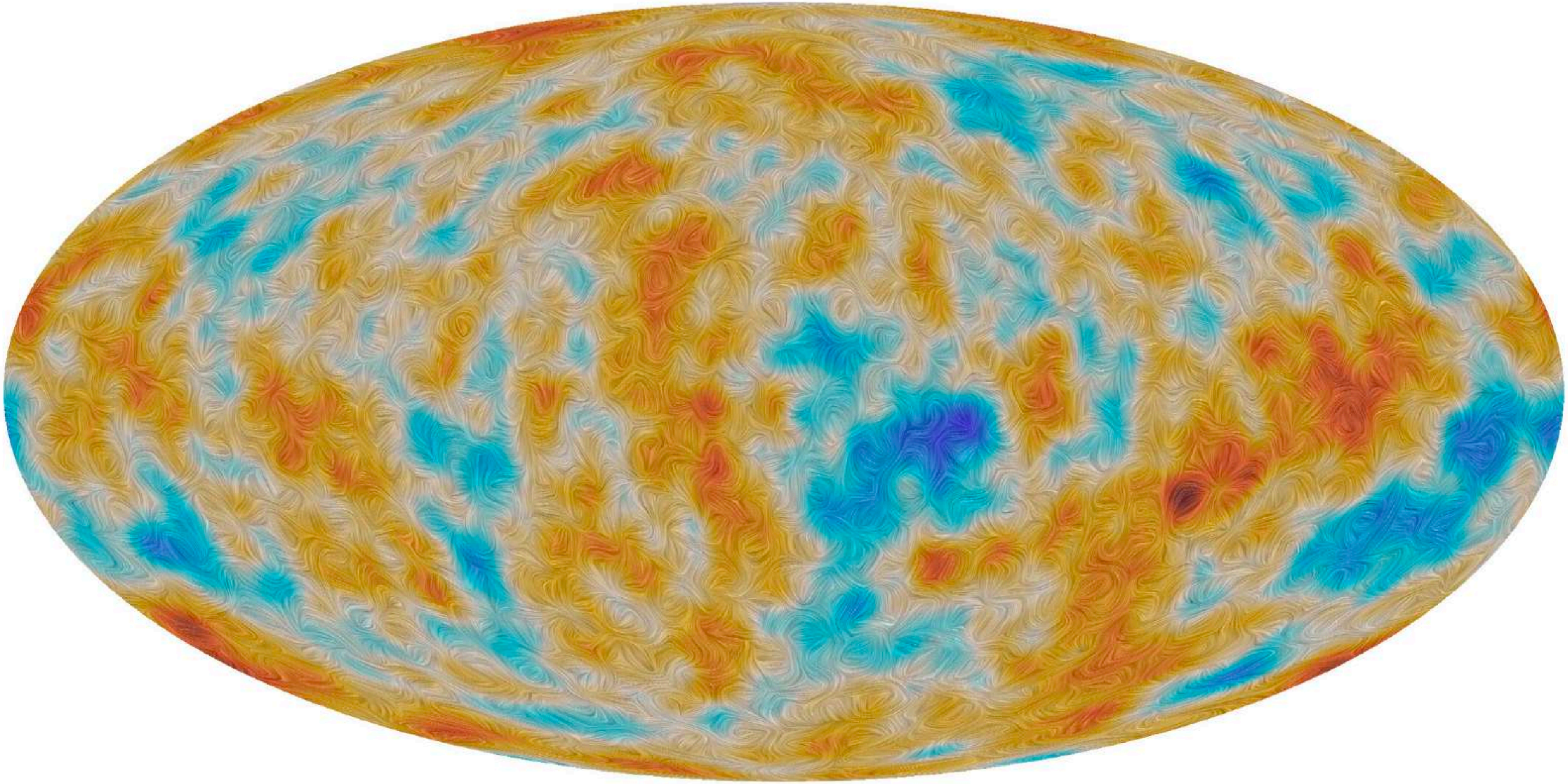
The cleaned CMB

Temperature



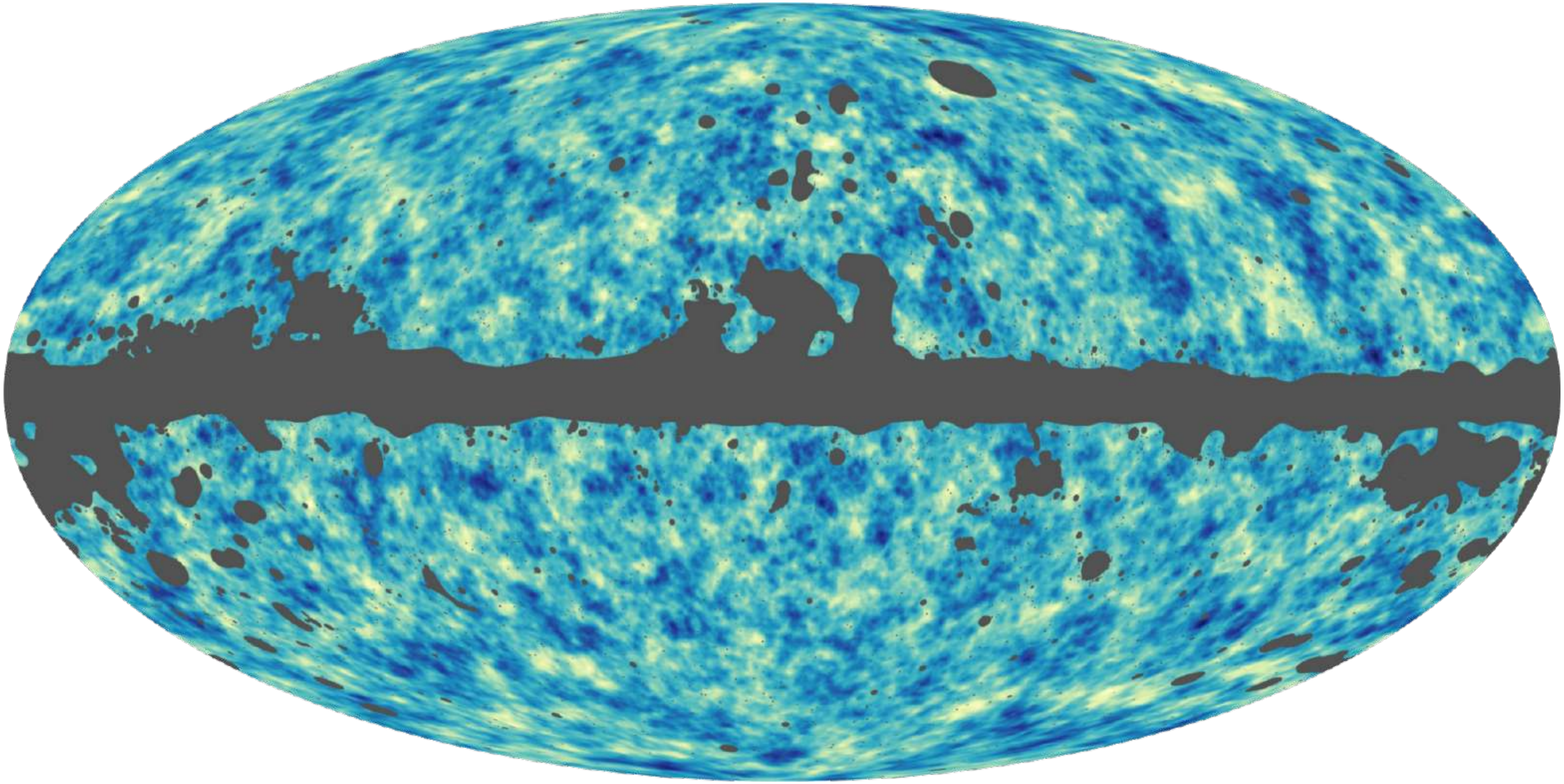
The cleaned CMB

Polarisation

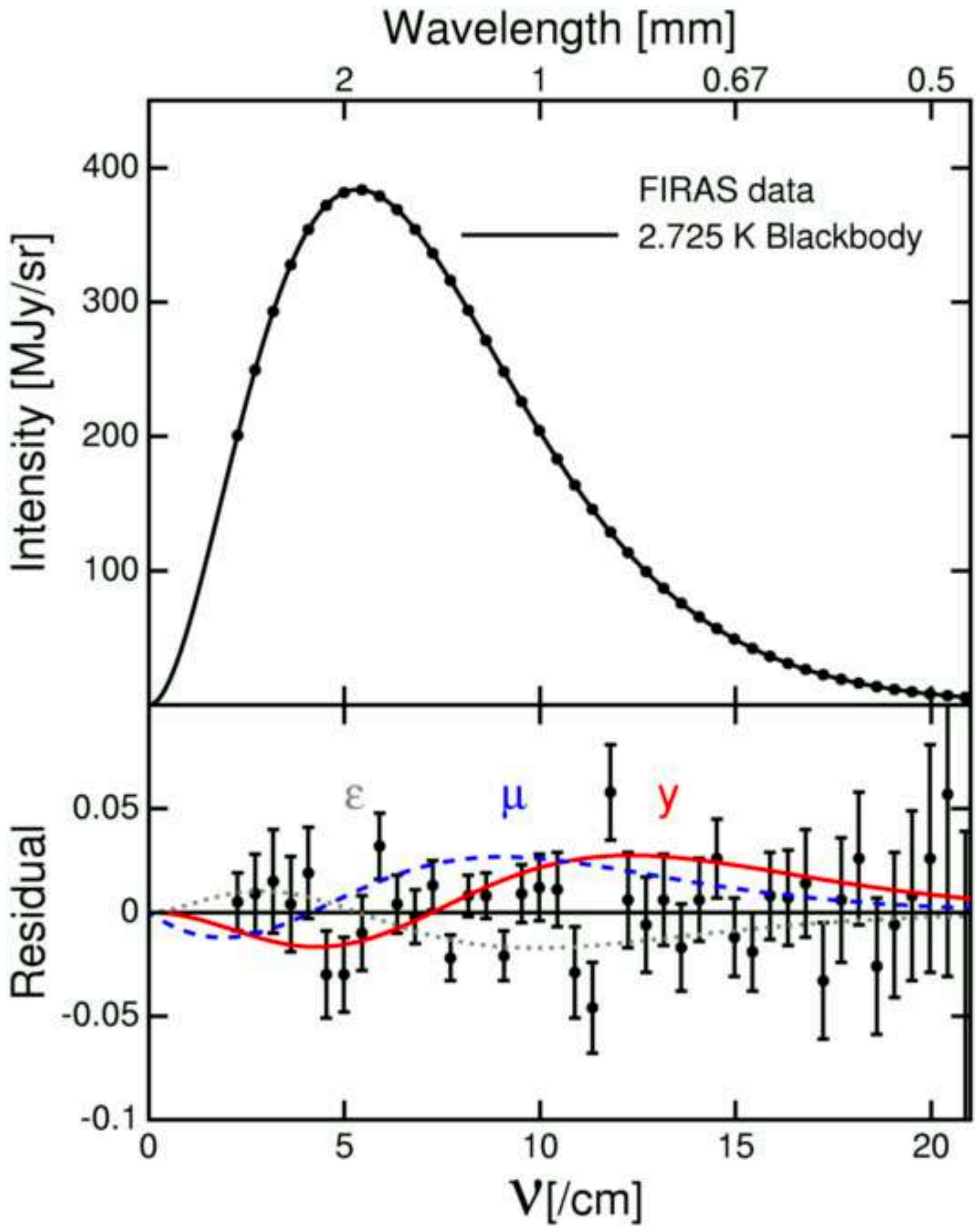


The cleaned CMB

Lensing potential



The absolute temperature of the CMB



Last measurement from COBE satellite

T = 2.7255 +/- 0.0006 K

Fixsen 2009

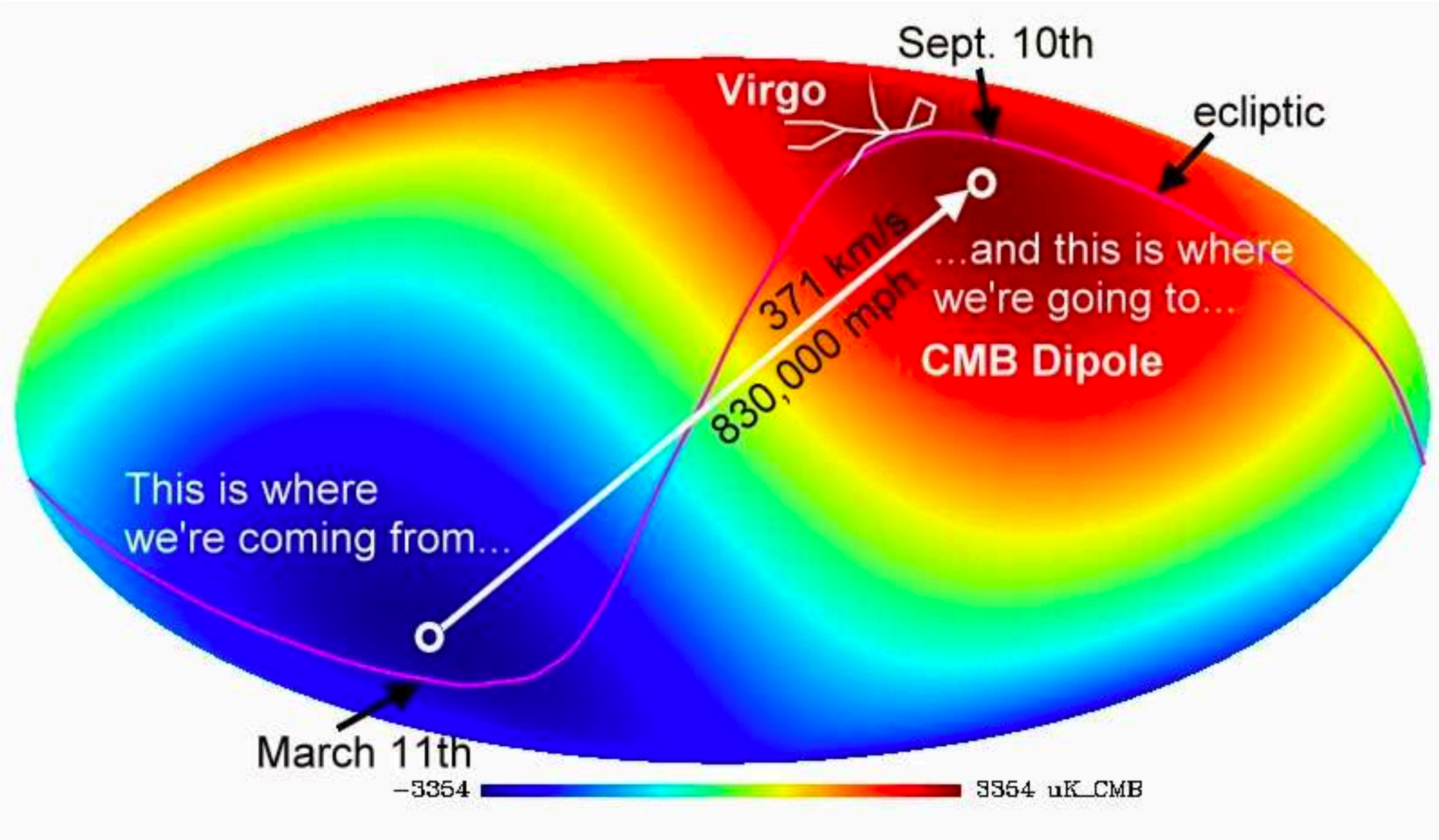
$$\rho_\gamma = \left(\frac{\pi^2 k_B^4}{15 c^3 \hbar^3}\right) T^4$$

$$+$$

$$\rho_\nu = N_{\rm eff}\, \frac{7}{8} \left(\frac{4}{11}\right)^{4/3} \rho_\gamma$$

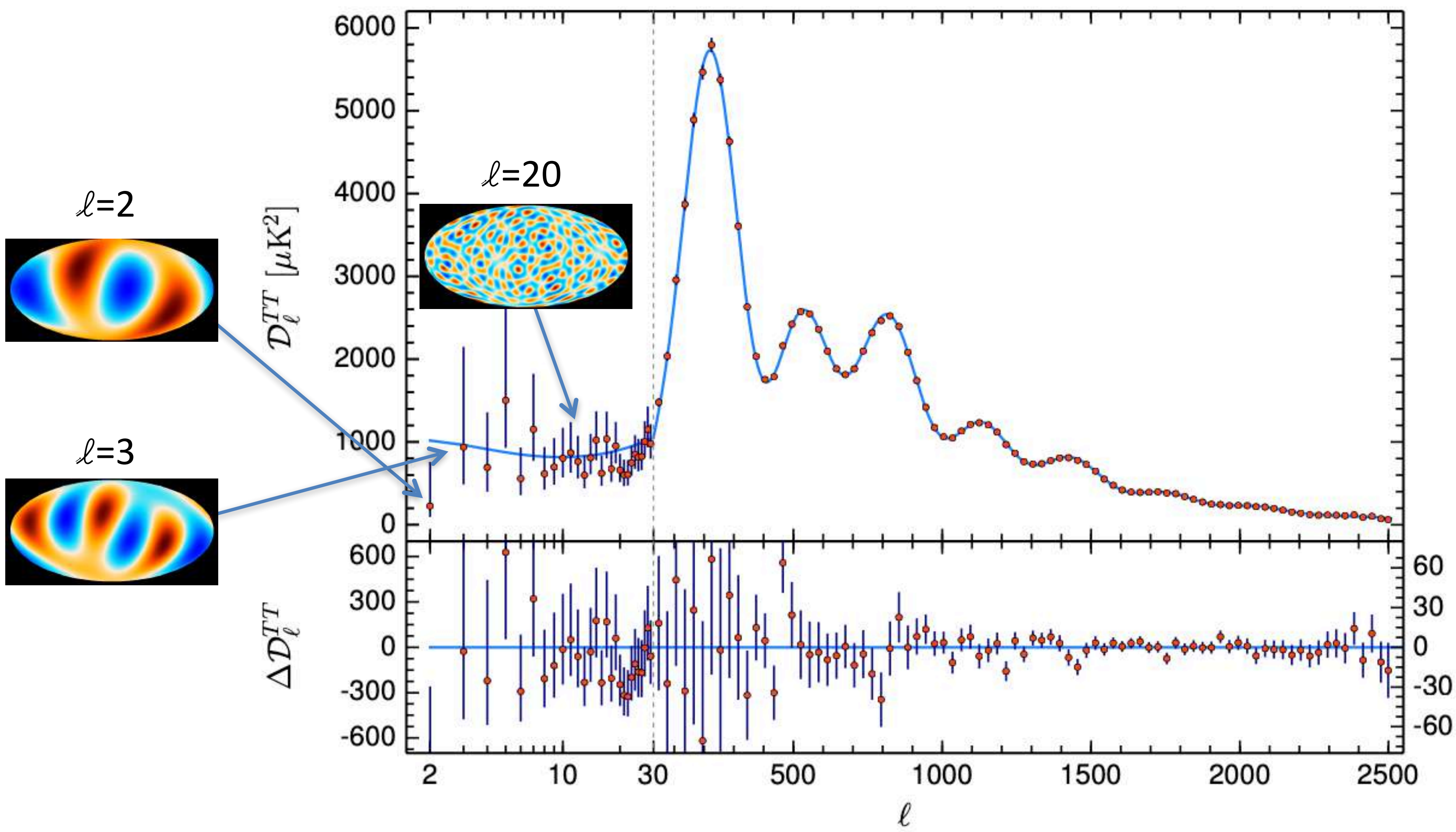
$$\rho_r = \rho_\gamma + \rho_\nu$$

The dipole of the CMB

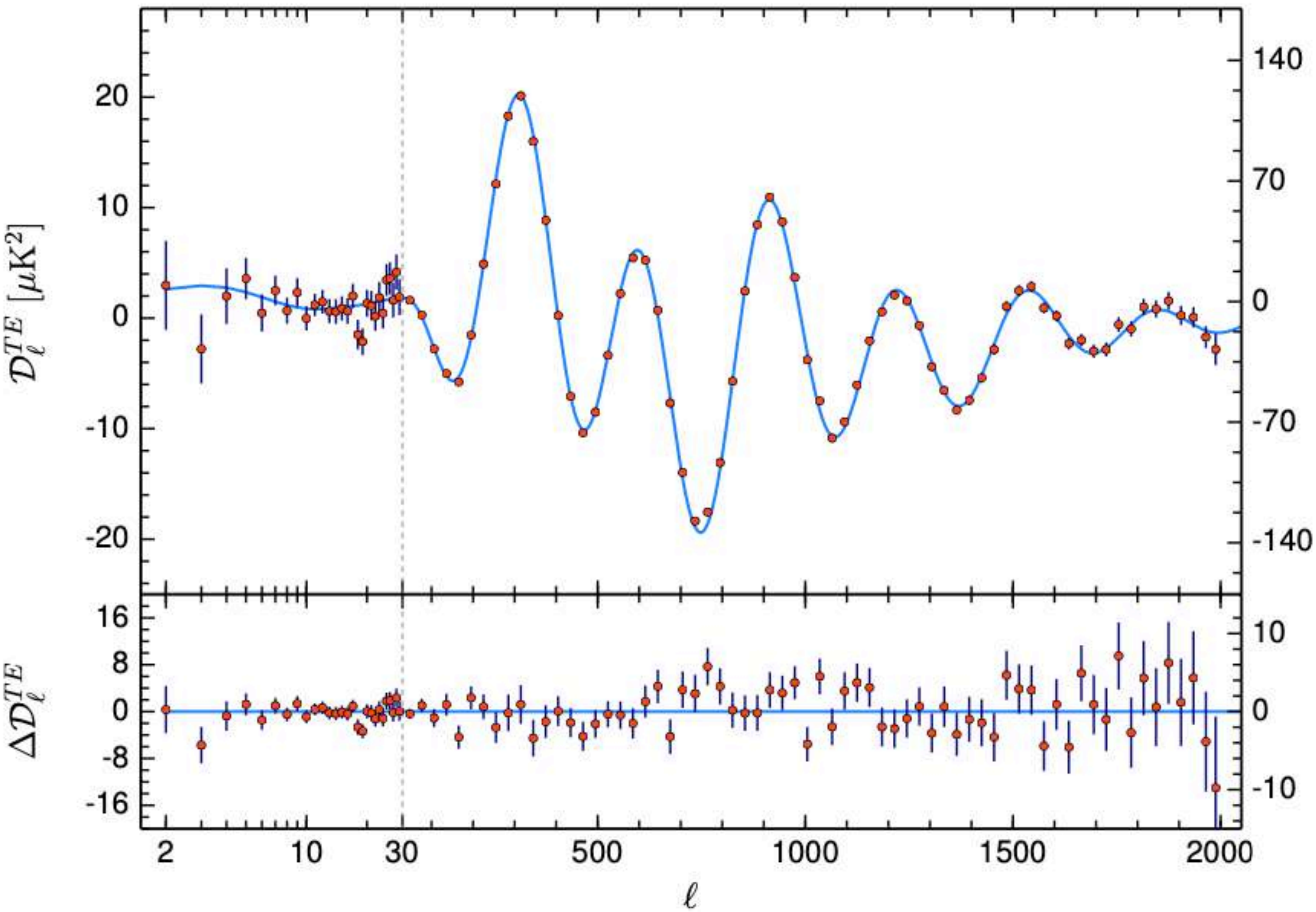


mili Kelvin fluctuations

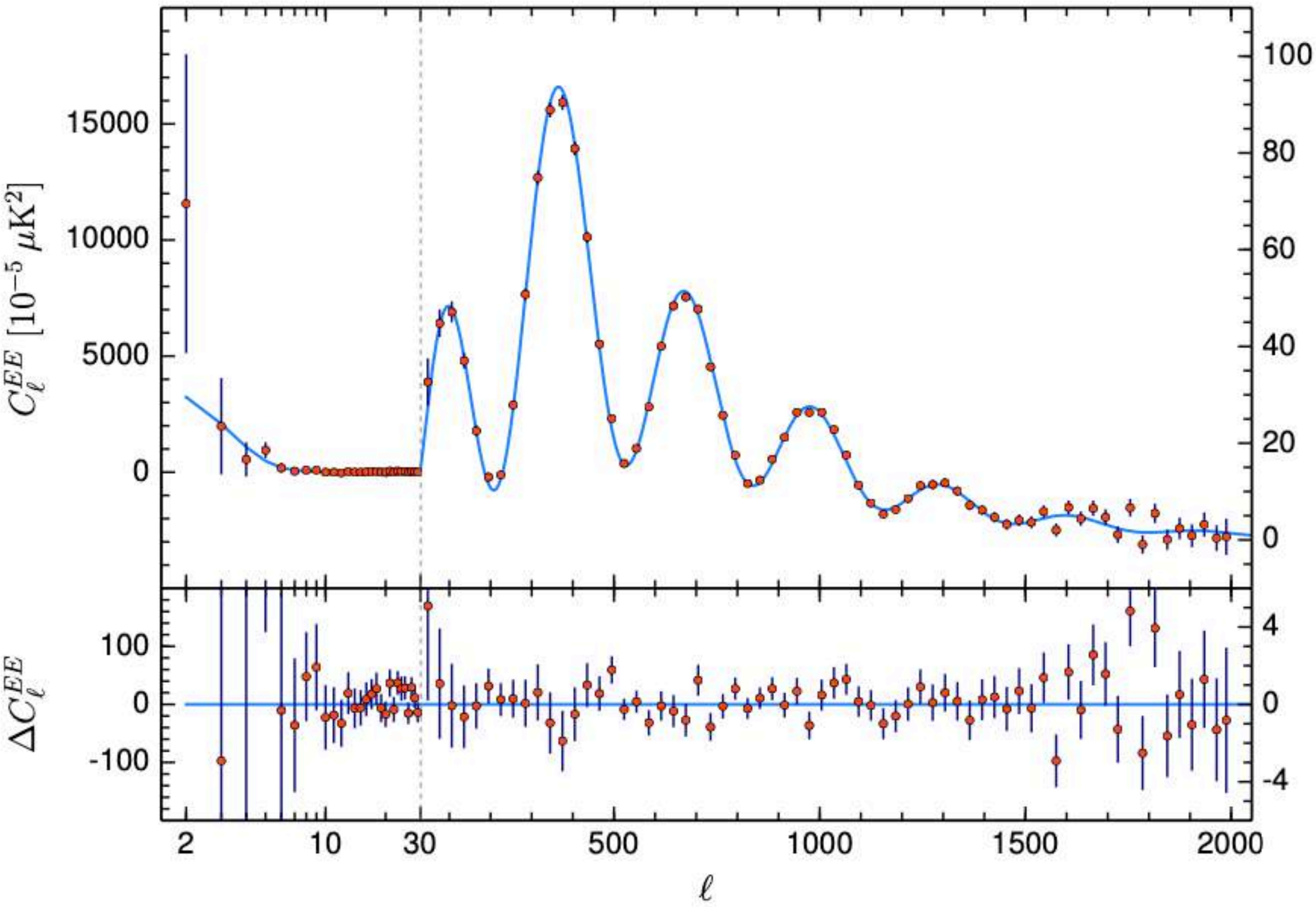
Temperature angular power spectrum



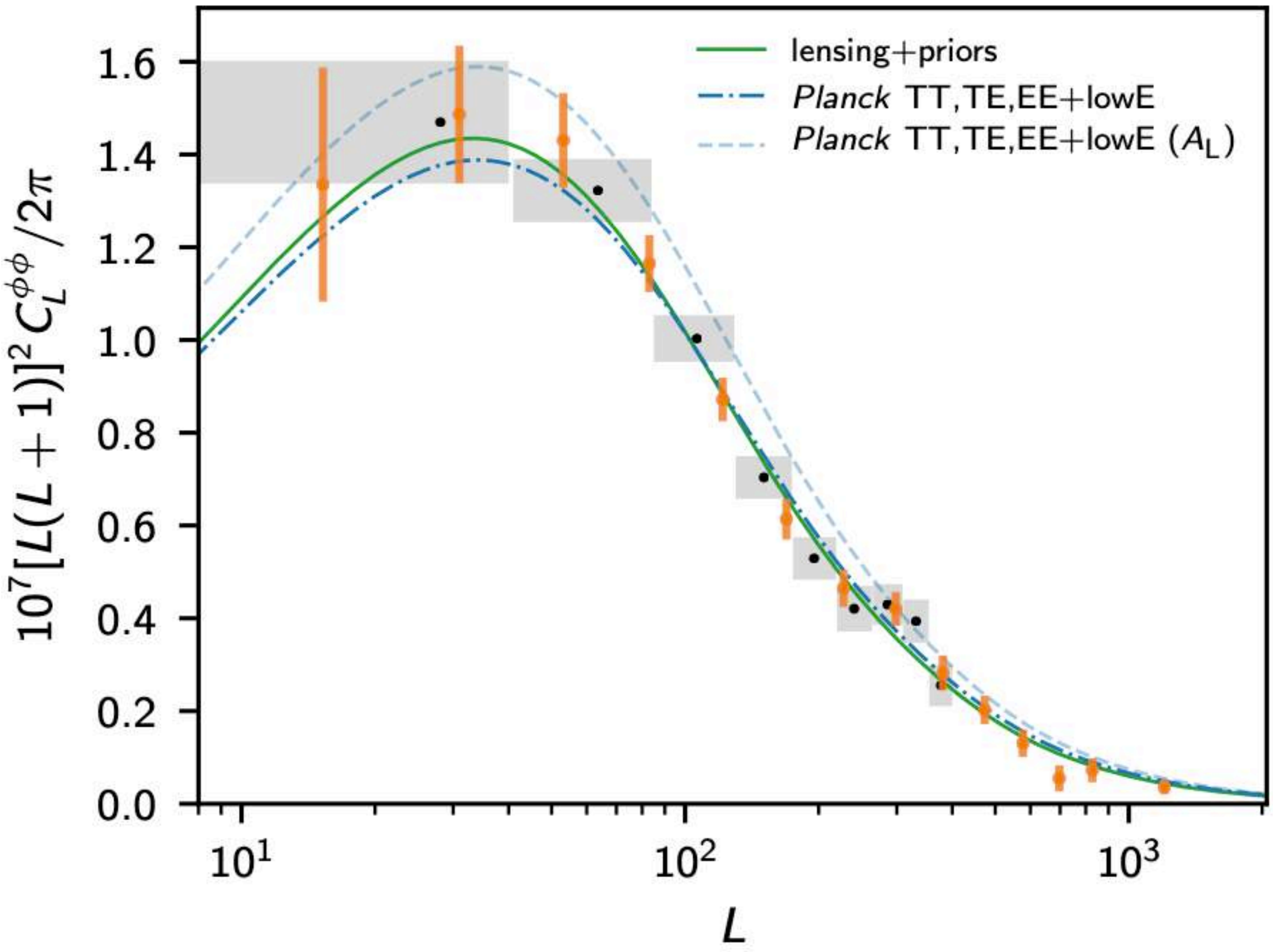
Temperature-E polarisation angular cross power spectrum



E mode polarisation angular power spectrum



Lensing potential angular power spectrum



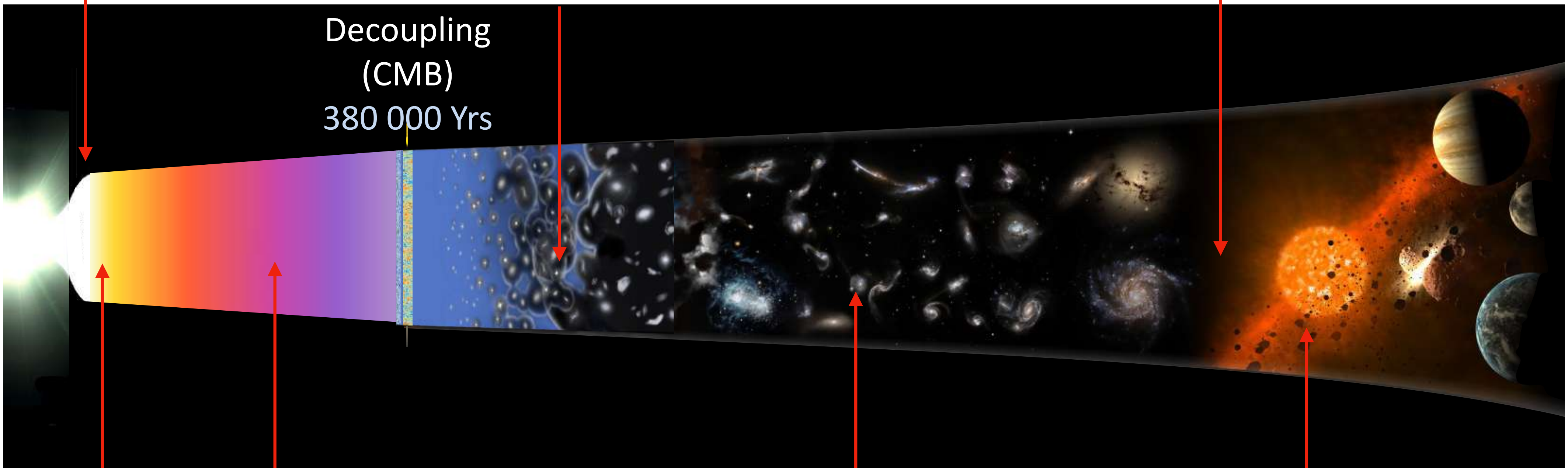
Need a model : perturbation theory !

Initial power-spectrum of Gaussian perturbations after inflation

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

Reionisation: free-electrons make CMB photons scatter away

Dark-energy and curvature change the physical distance to the last scattering surface



BBN

BAO: sound waves propagating in the baryon+photon plasma
Dark matter fluctuations keep growing

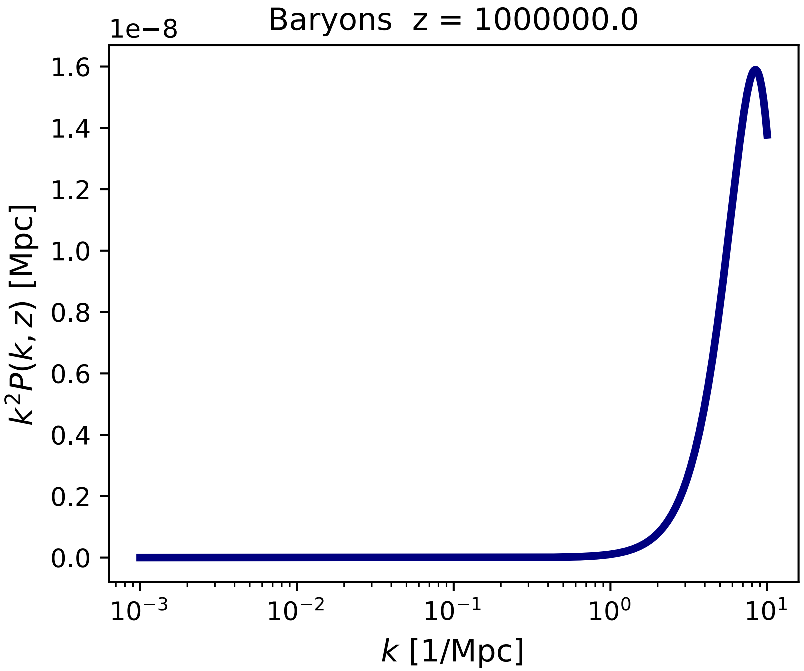
Large-scale structures bend light from CMB

Hot gas in clusters boost CMB photons (tSZ)

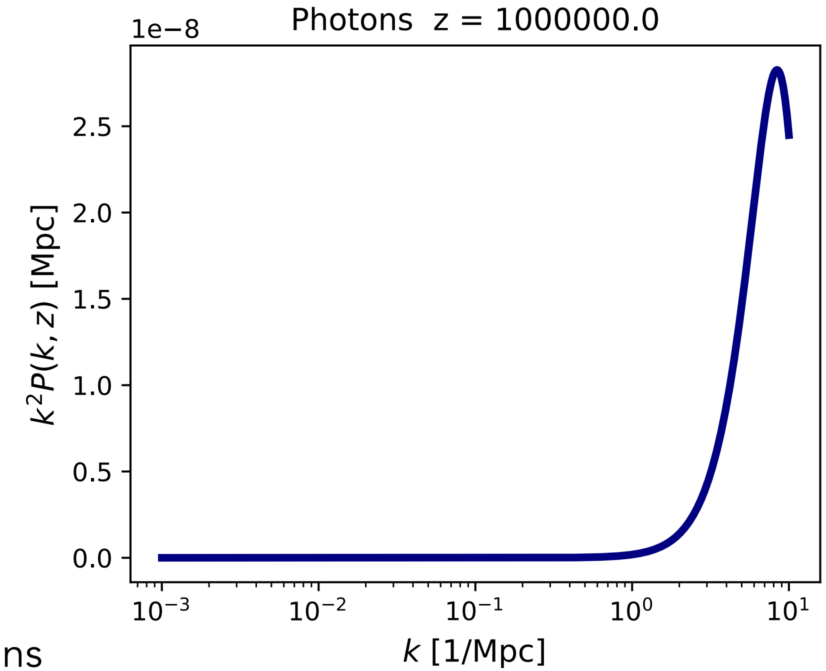
Integrated Sachs-Wolf effect

Perturbation theory

Baryons

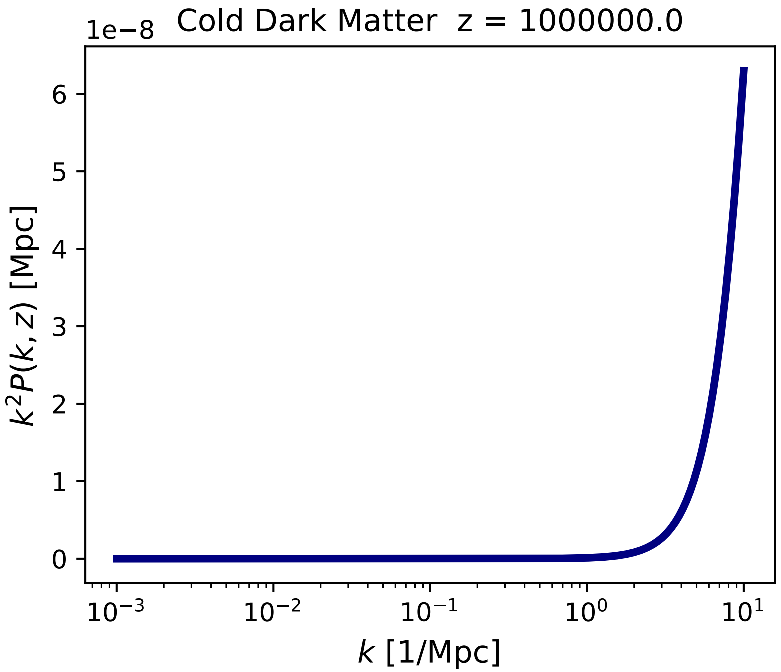


Photons

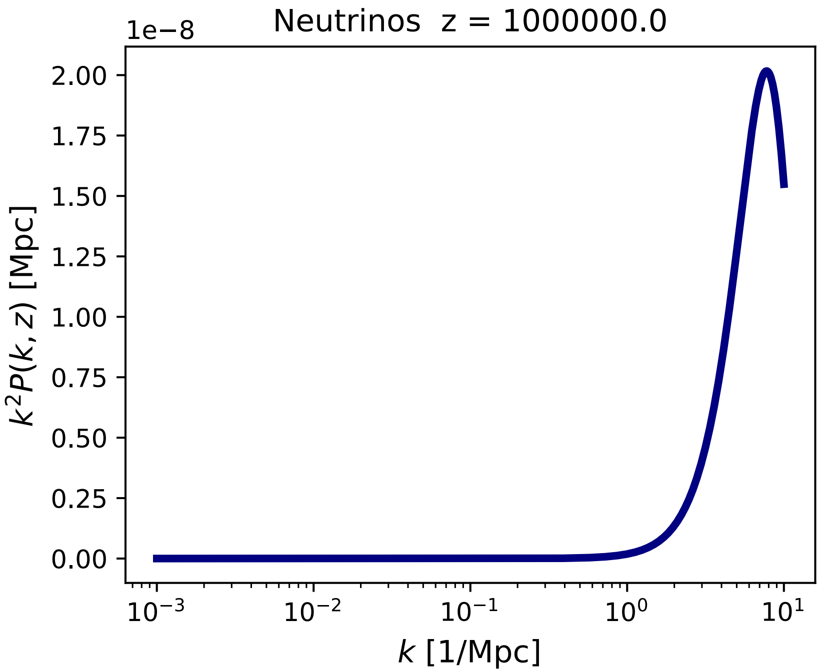


All perturbations look the same

Dark Matter

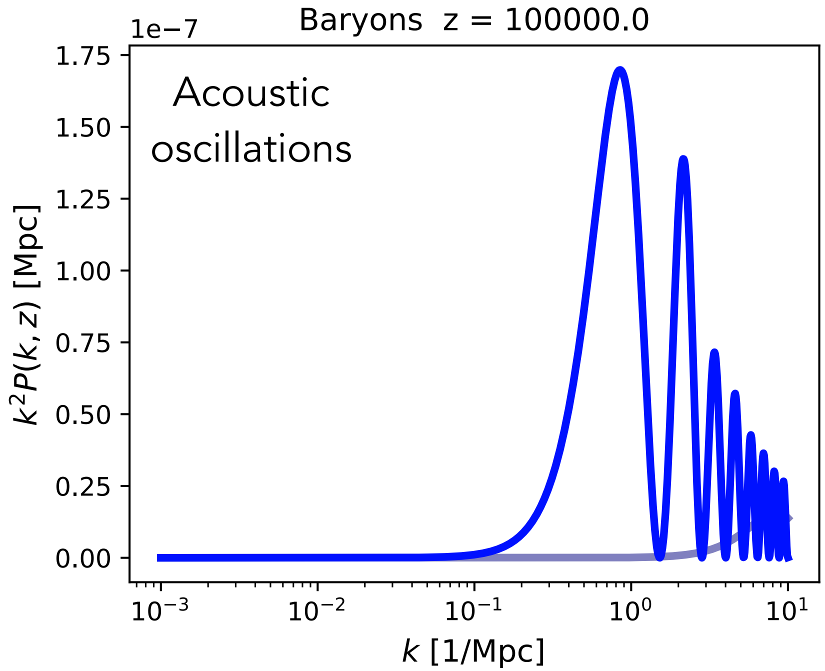


Neutrinos

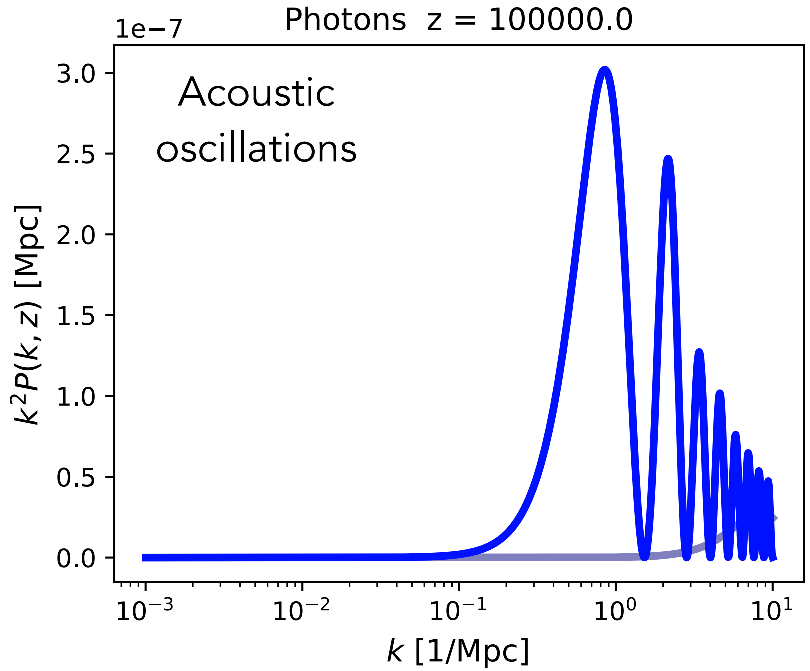


Perturbation theory

Baryons

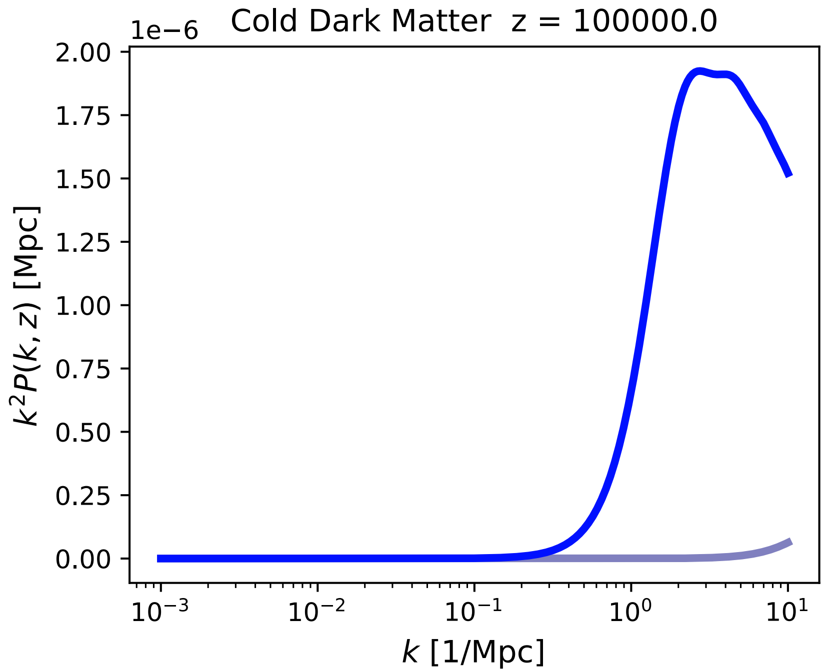


Photons

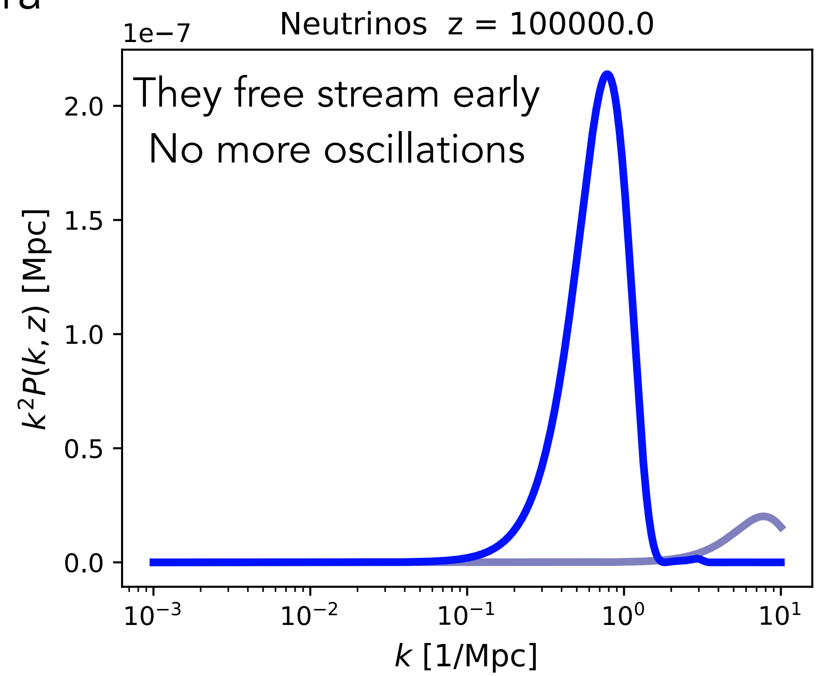


Radiation dominated era

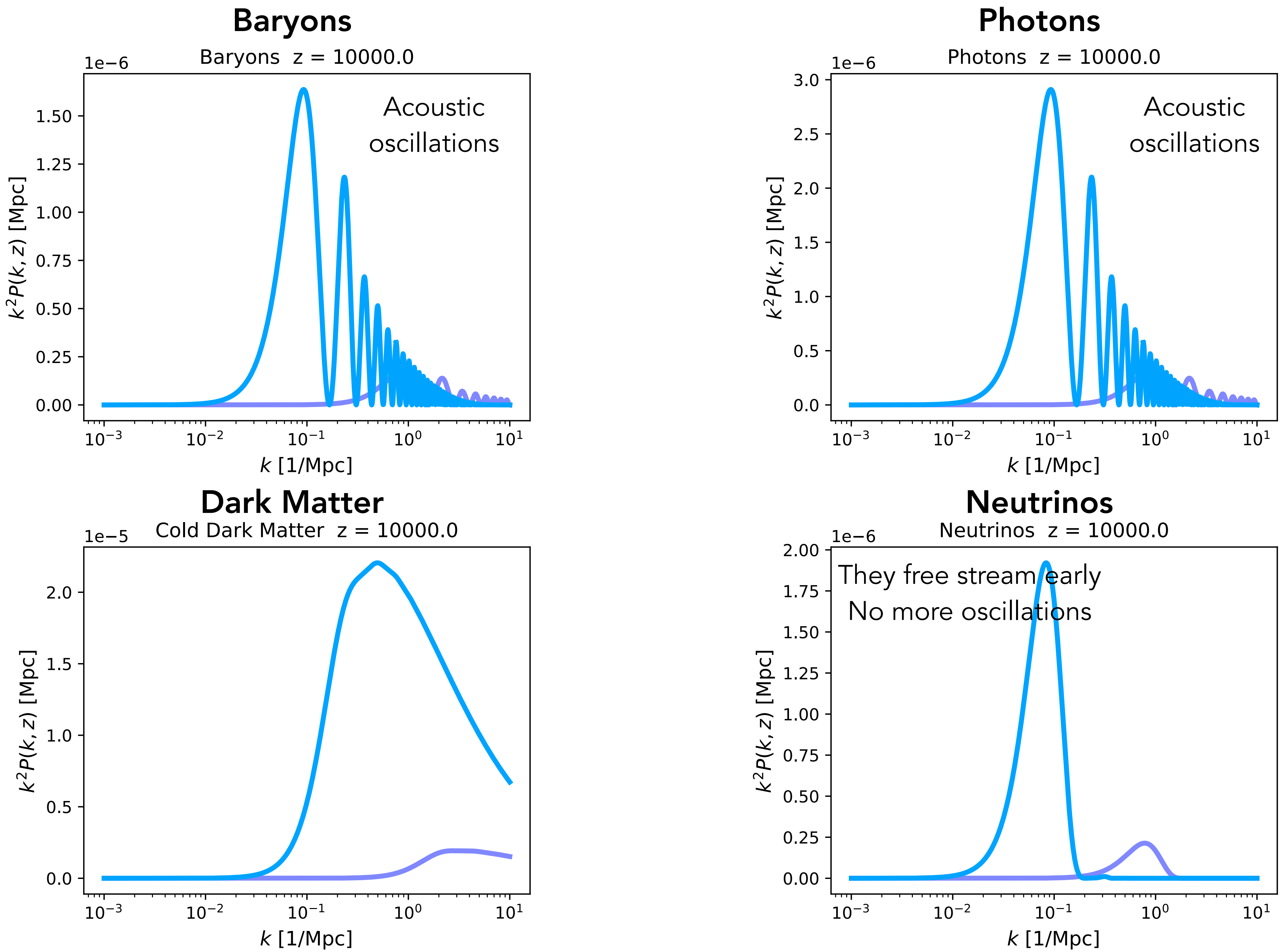
Dark Matter



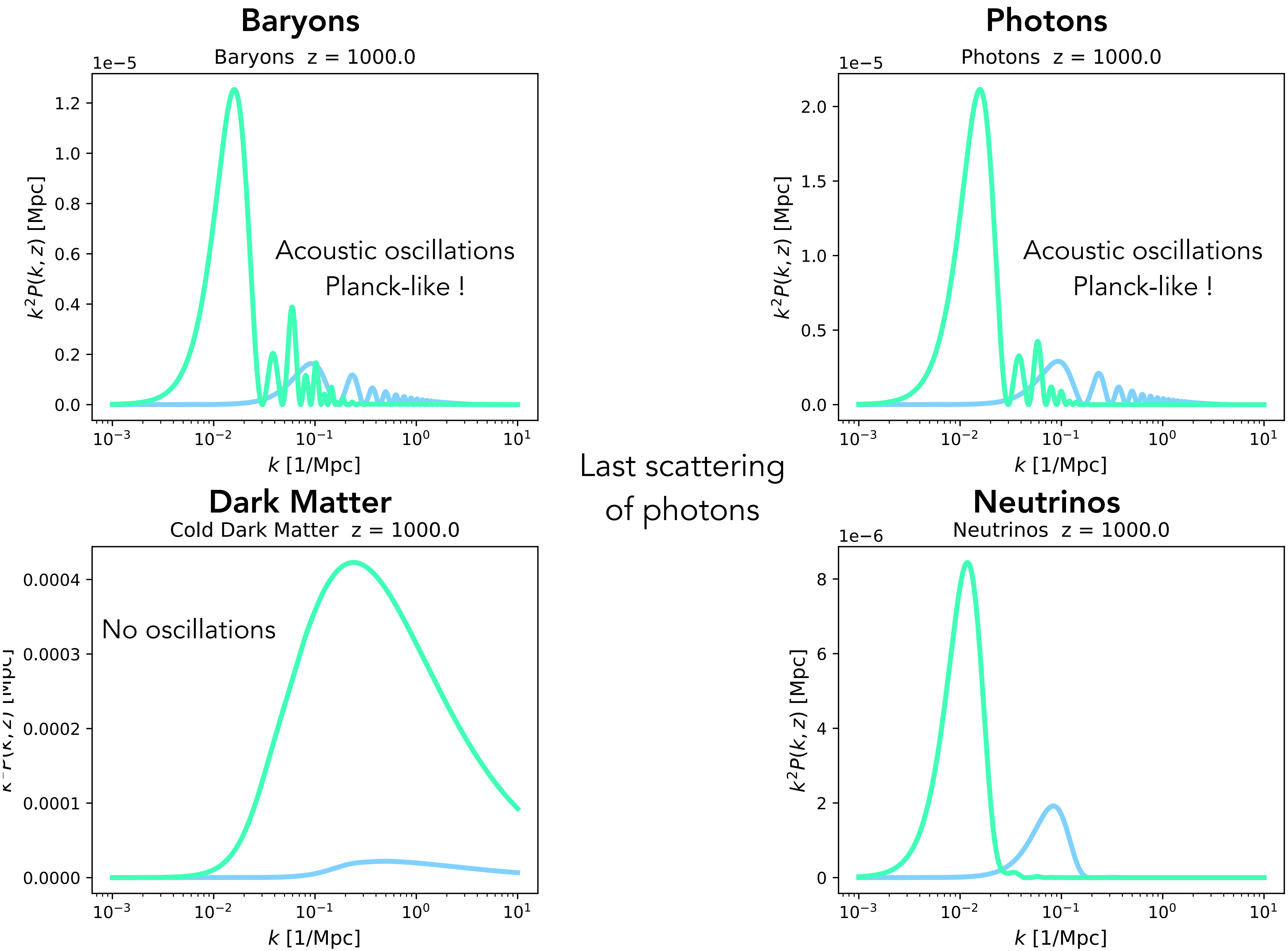
Neutrinos



Perturbation theory

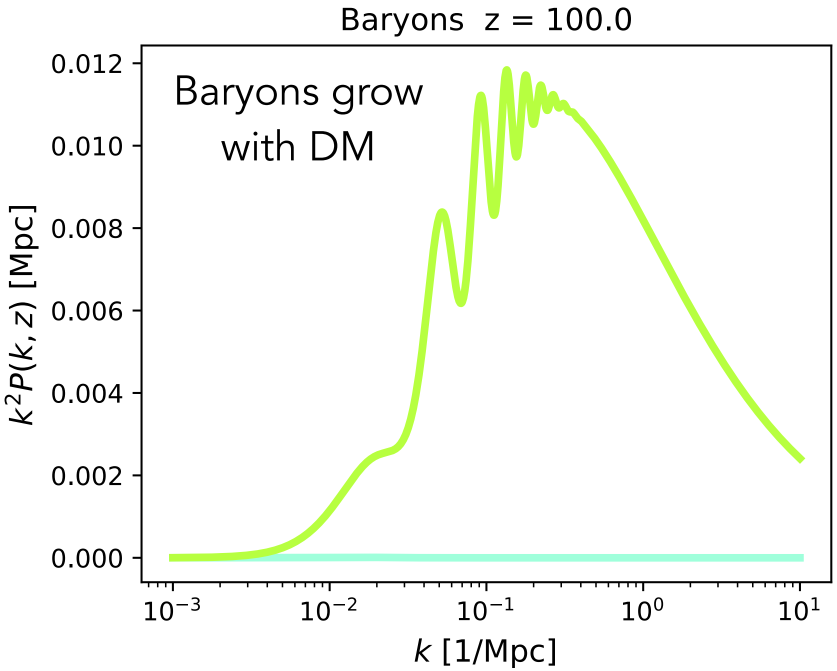


Perturbation theory

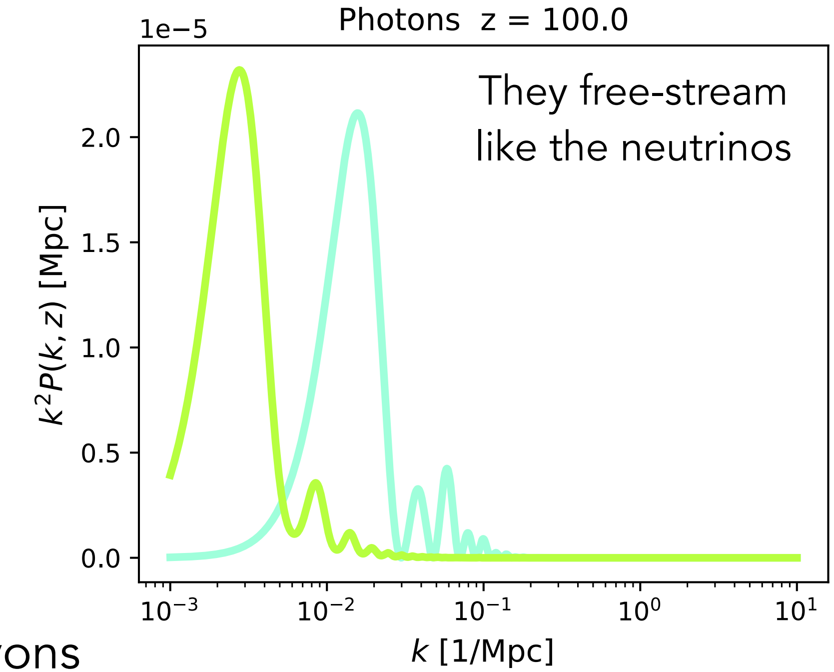


Perturbation theory

Baryons

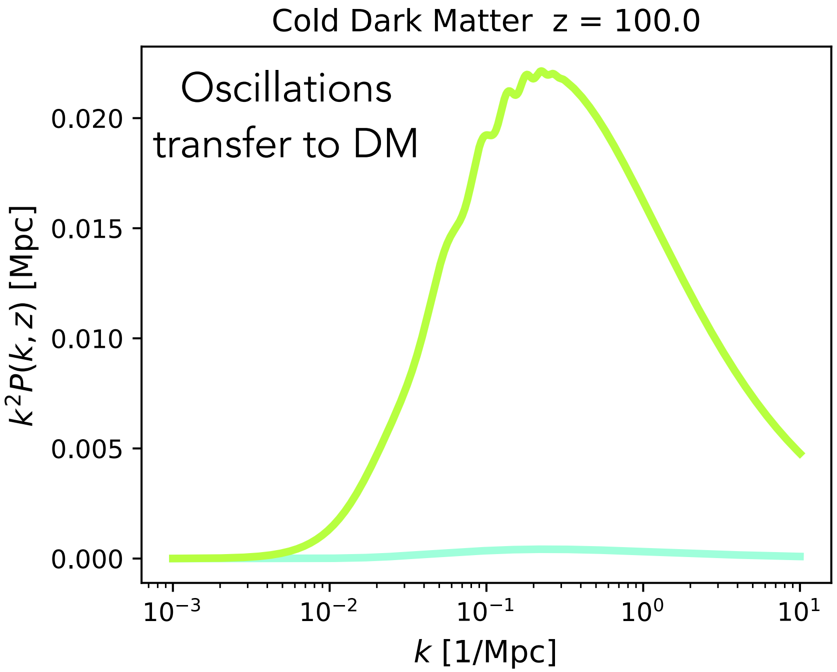


Photons

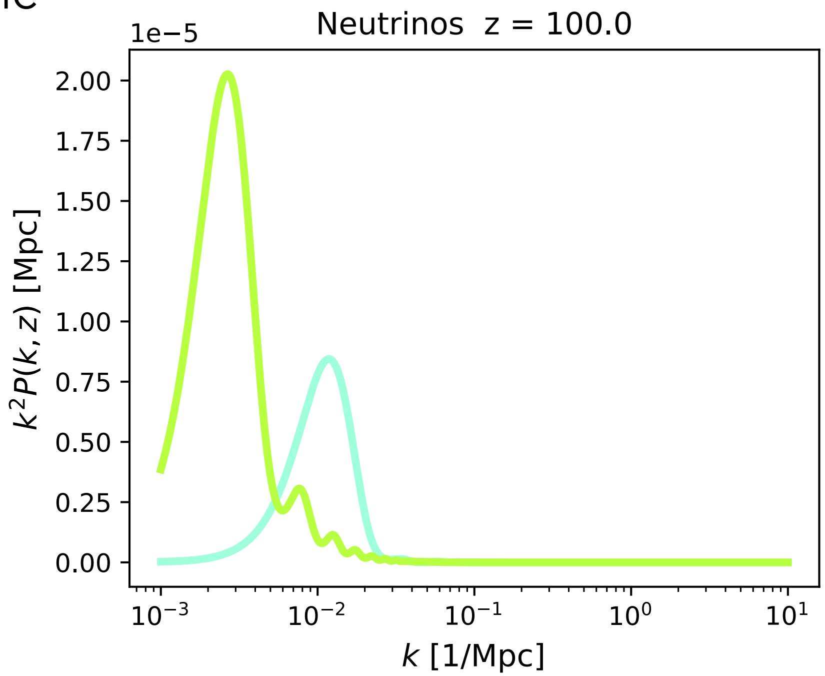


DM and baryons evolve as one

Dark Matter

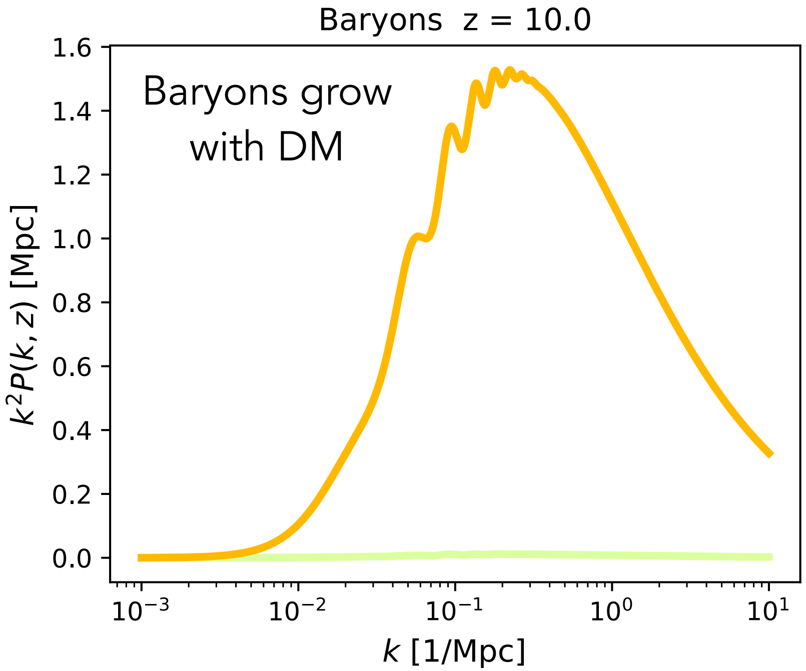


Neutrinos

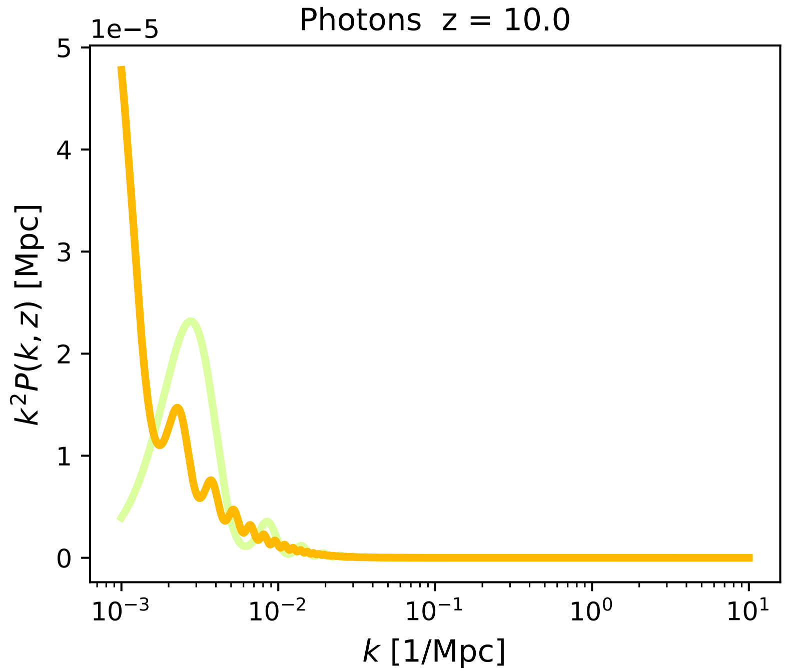


Perturbation theory

Baryons

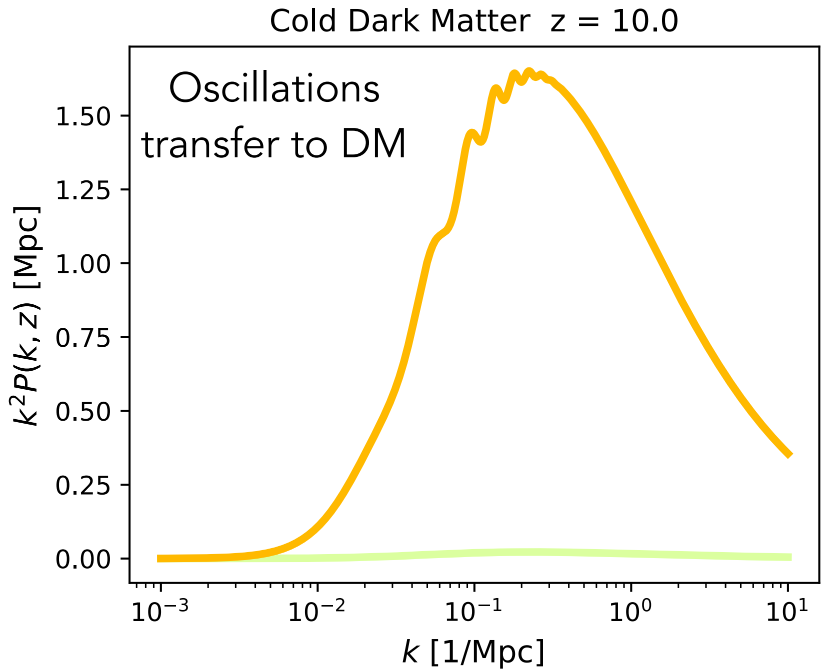


Photons

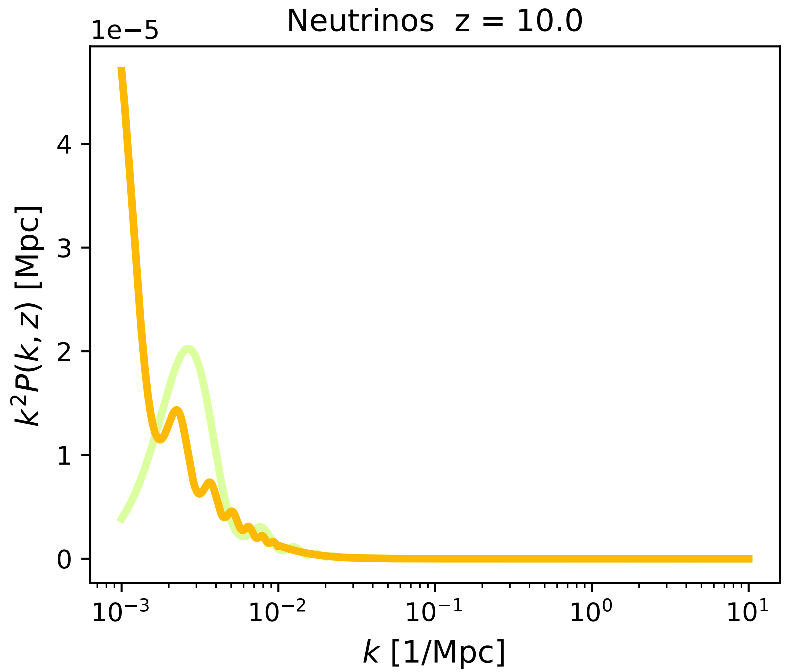


Formation of galaxies

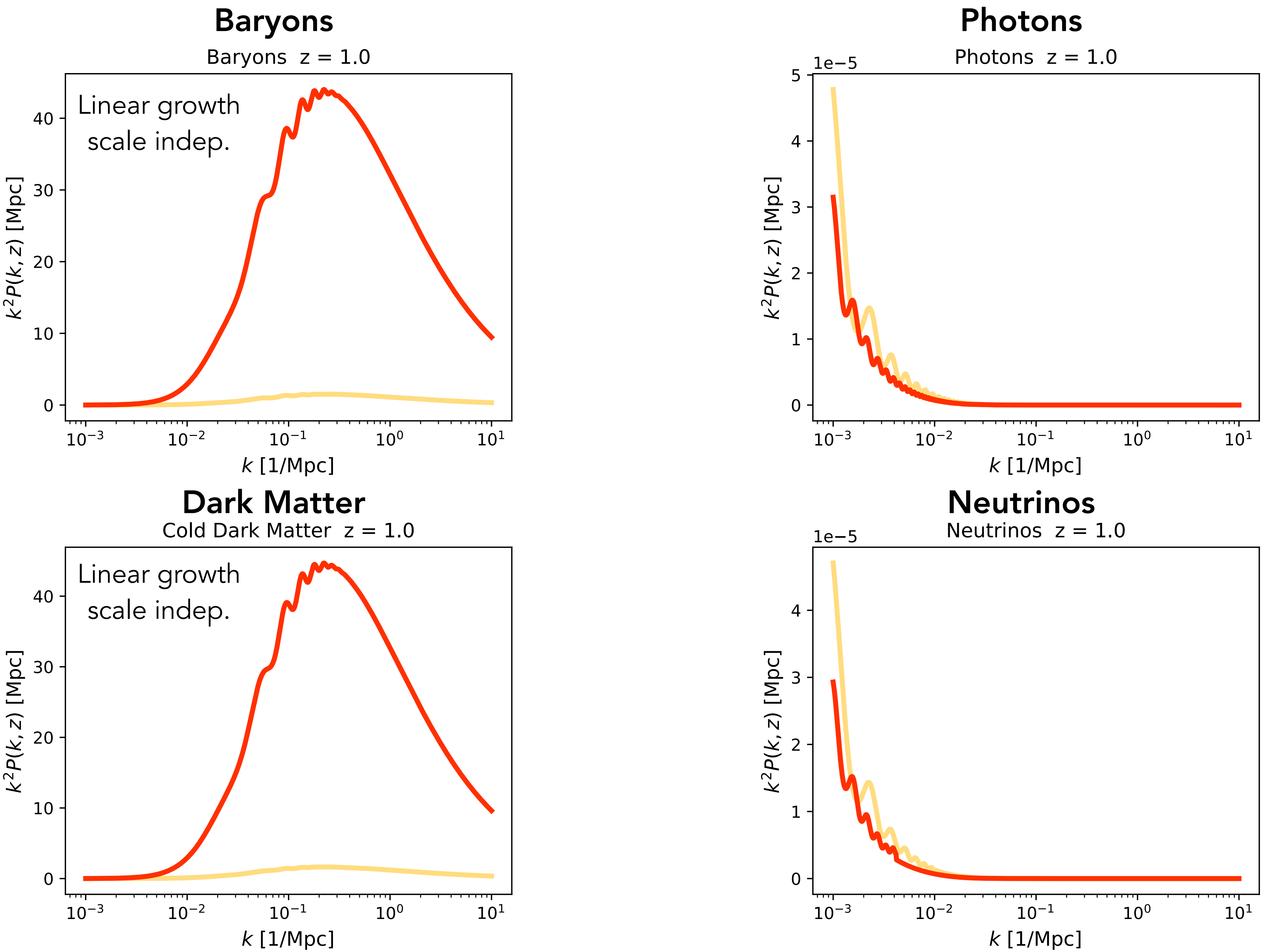
Dark Matter



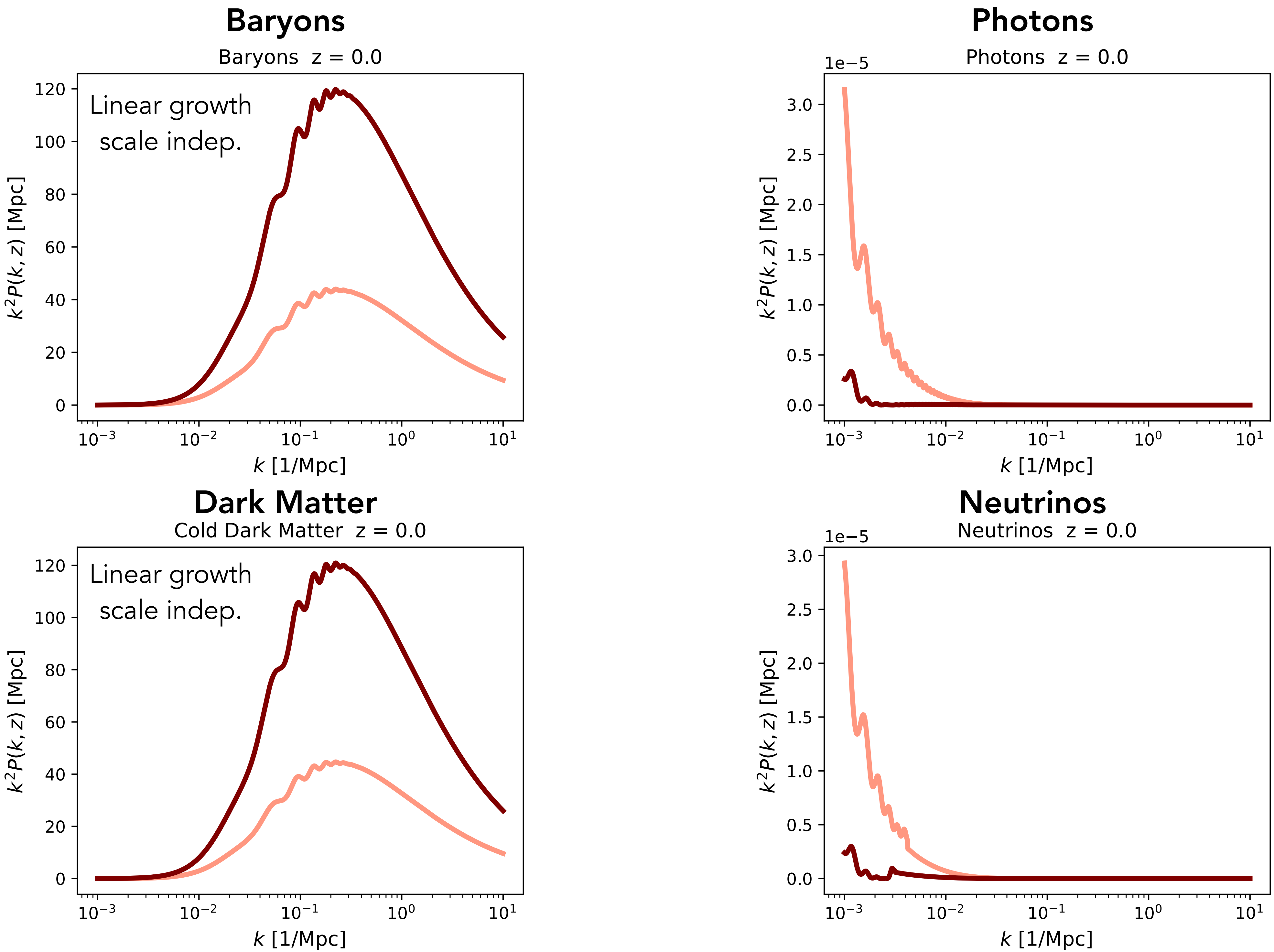
Neutrinos



Perturbation theory



Perturbation theory



Model for the CMB

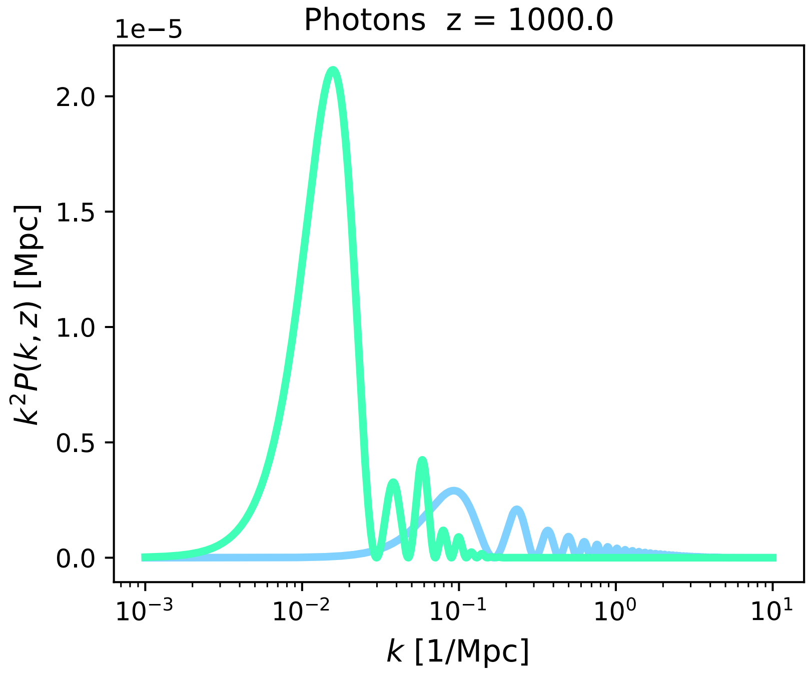
Propagate photons

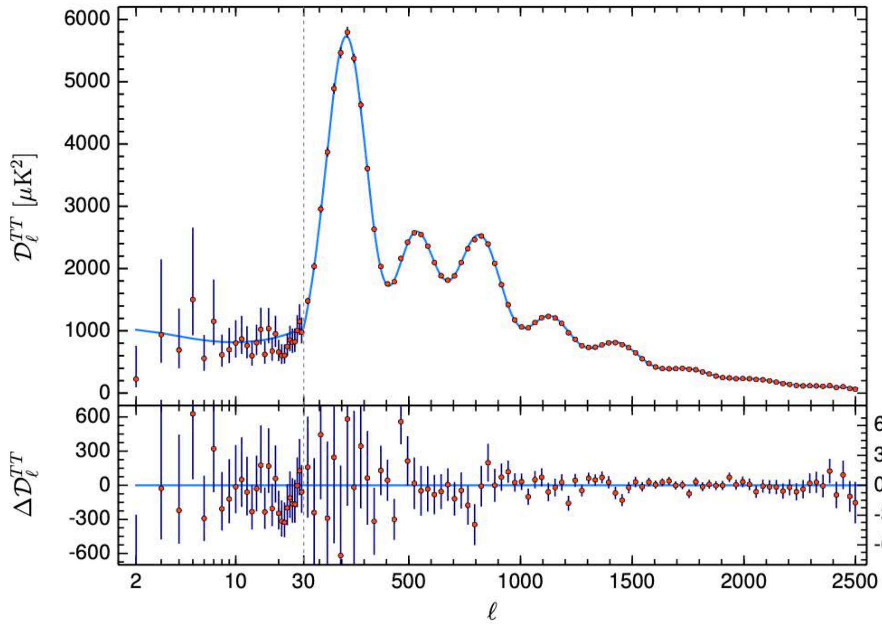
Apply lensing

Absorb a fraction $e^{-\tau}$

Add ISW

Convert to angular power spectrum





Angular sound horizon

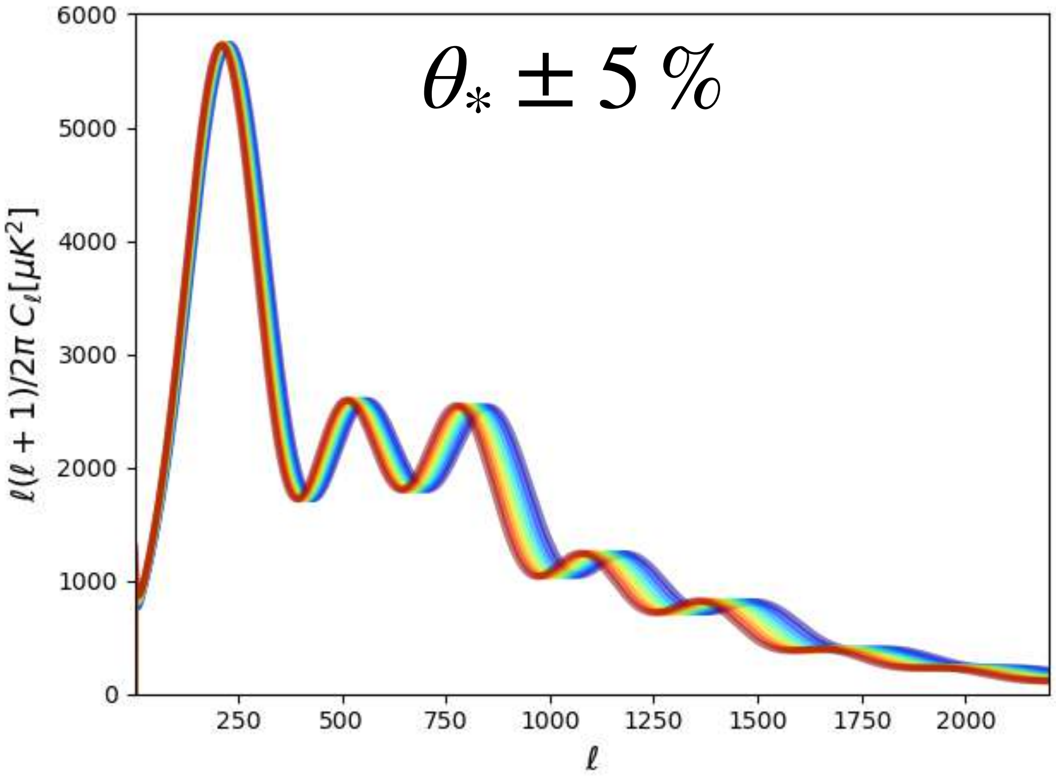
$$\theta_* \equiv r_* / D_\mathrm{M}$$

$$100\theta_* = 1.04109 \pm 0.00030$$

(3 parts in 10,000 !)

$$r_s(z) = \int_0^{\eta(z)} \frac{\mathrm{d}\eta'}{\left[3\left(1+\frac{3\rho_b(z)}{4\rho_\gamma(z)}\right)\right]^{1/2}} \Rightarrow \Omega_b h^2, \Omega_\gamma h^2$$

$$D_M(z) = D_C(z)\mathrm{sinc}\left(\sqrt{-\Omega_k}\frac{D_C(z)}{D_H(z=0)}\right) \Rightarrow H_0, \Omega_m, \Omega_\mathrm{DE}, \Omega_k$$



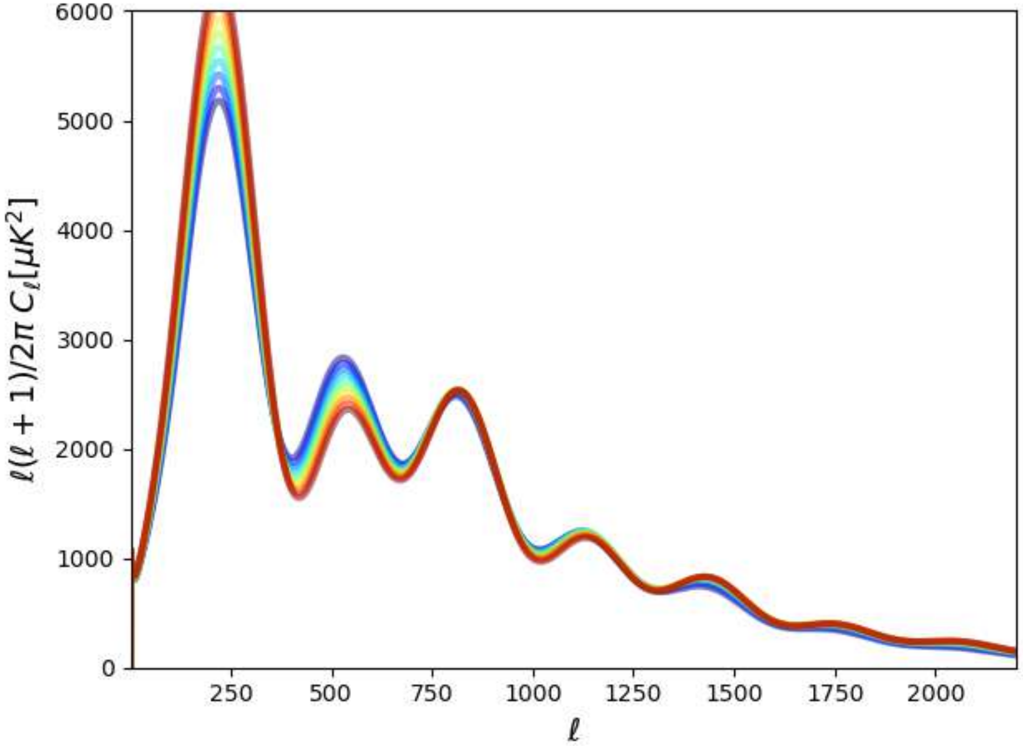
Geometrical degeneracy!

Main constraints assume a flat ΛCDM model !

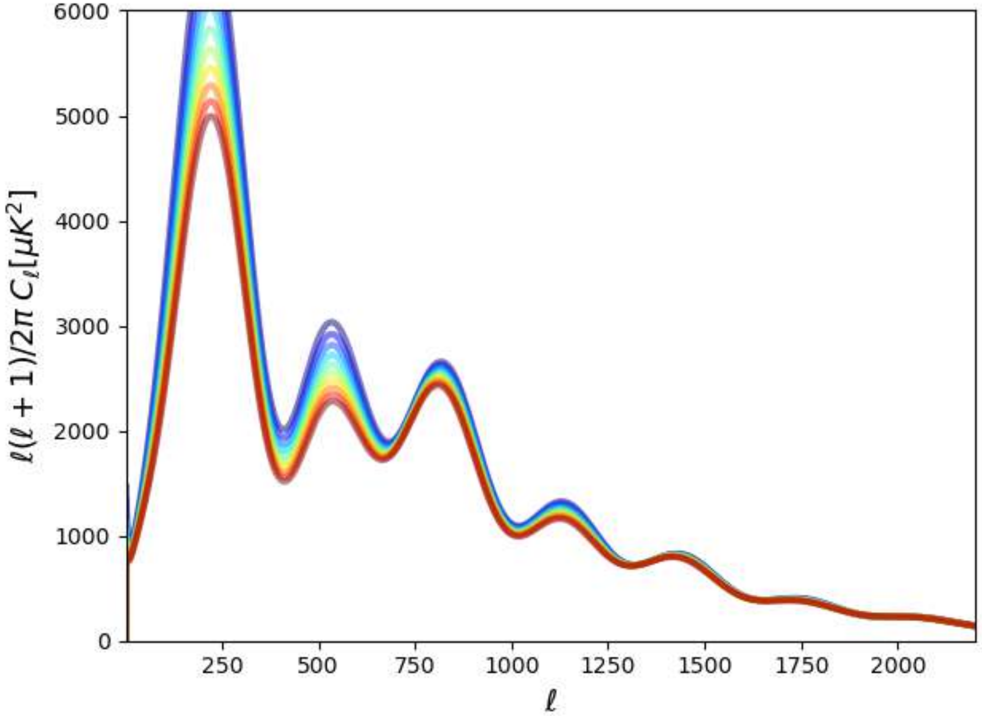
Baryon and cold dark-matter densities

Information from relative heights of the acoustic peaks

$$\omega_b = \Omega_b h^2 \pm 10\,\%$$



$$\omega_c = \Omega_c h^2 \pm 10\,\%$$



$\Omega_b h^2 = 0.02237 \pm 0.00015$ (68%, *Planck* TT,TE,EE+lowE+lensing).

$\Omega_c h^2 = 0.1200 \pm 0.0012$ (68%, *Planck* TT,TE,EE+lowE+lensing).

Some information from total matter from CMB lensing

1% precision !

Optical depth and primordial amplitude

Degeneracy : $A_s e^{-2\tau}$

$$\mathcal{P}_{\mathcal{R}}(k) = A_{\rm s}\left(\frac{k}{k_0}\right)^{n_{\rm s}-1}$$

Solutions :

Reionization free-electrons scatter CMB photons and damp scales smaller than the horizon

Relative amplitudes of large-scale temperature and polarization CMB anisotropies

$$A_{\rm s} = (2.101^{+0.031}_{-0.034}) \times 10^{-9} \quad \text{(68\%, TT,TE,EE+lowE).}$$

$$\tau = 0.0544^{+0.0070}_{-0.0081} \quad \text{(68\%, TT,TE,EE+lowE).}$$

$z_{reion} = 7.68 \pm 0.79$

$$n_{\rm s} = 0.9649 \pm 0.0042 \quad \text{(68\%, \textit{Planck} TT,TE,EE+lowE+lensing),}$$

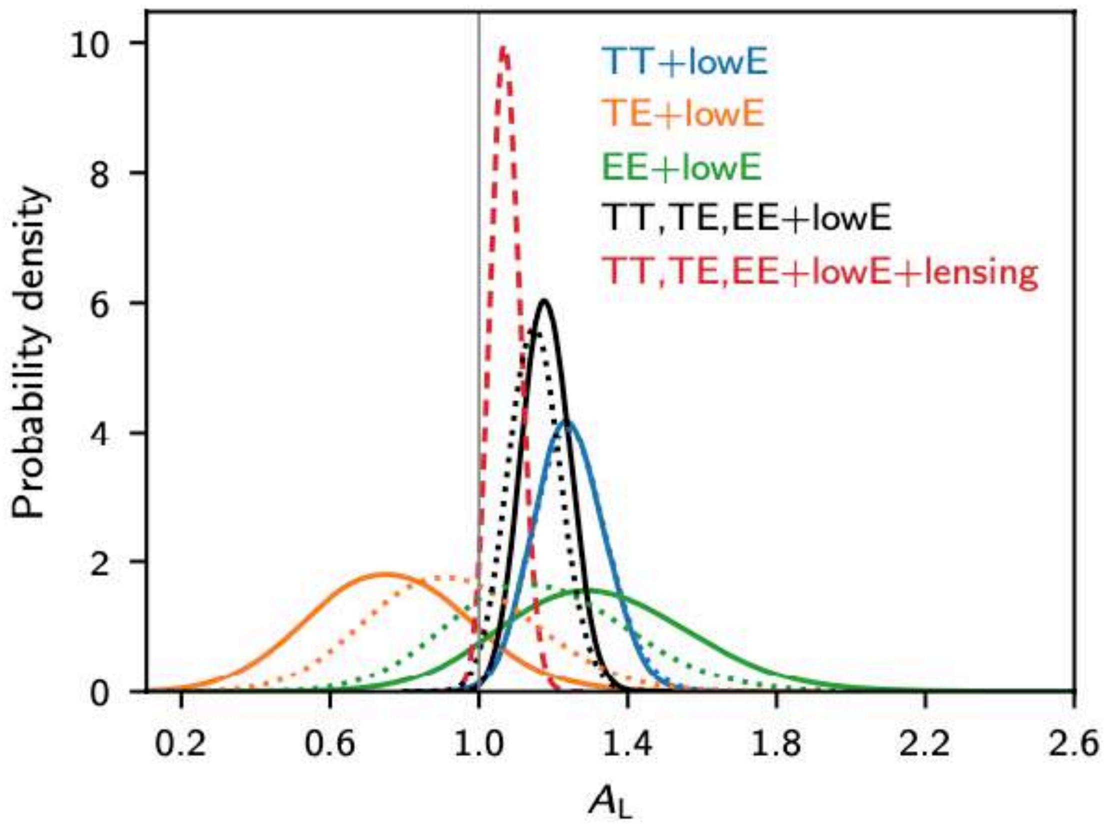
8-sigma from scale-invariant

Lensing of the CMB

Two effects :

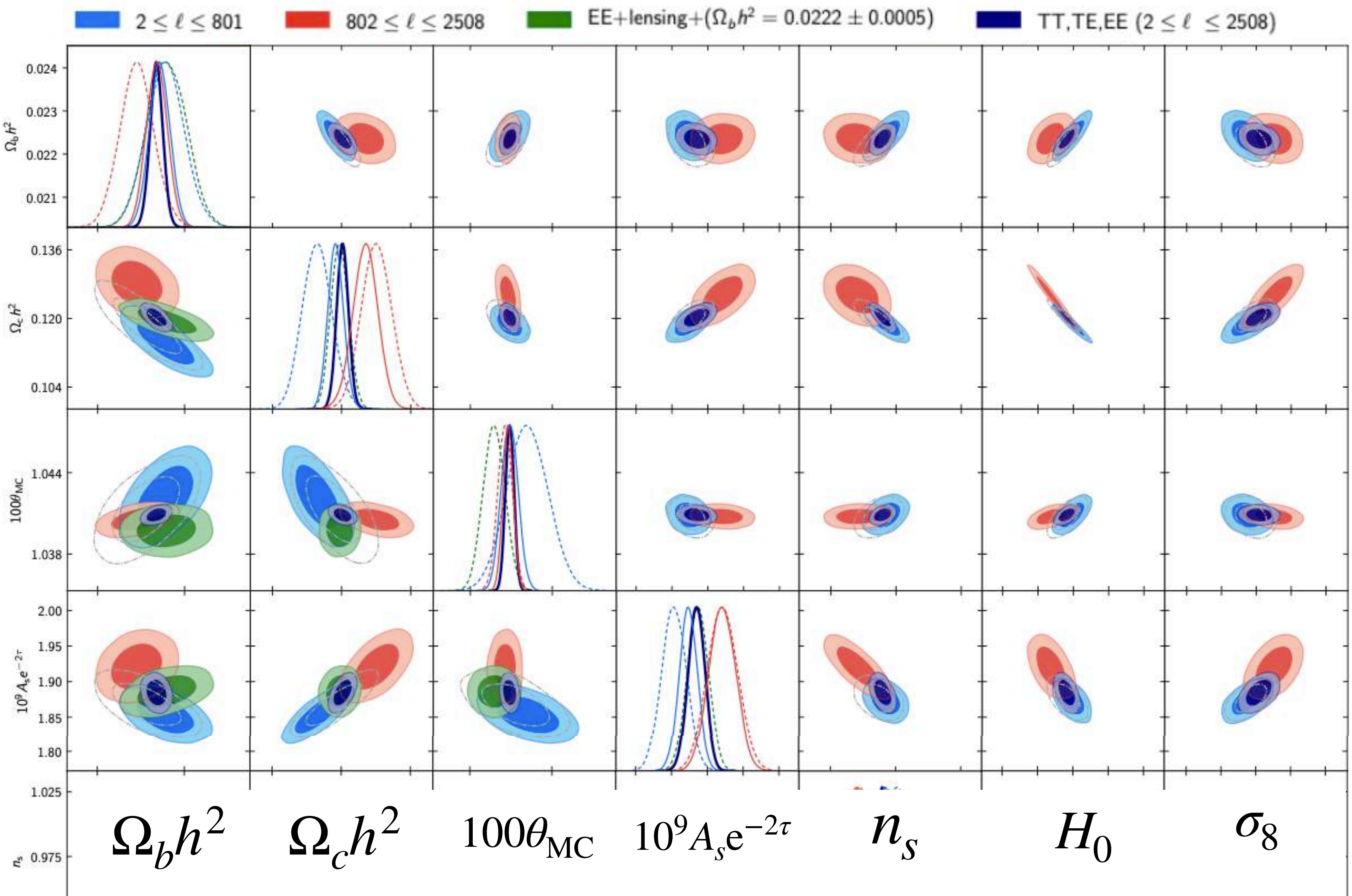
Smooths the acoustic peaks
Transfer of power to small-scales

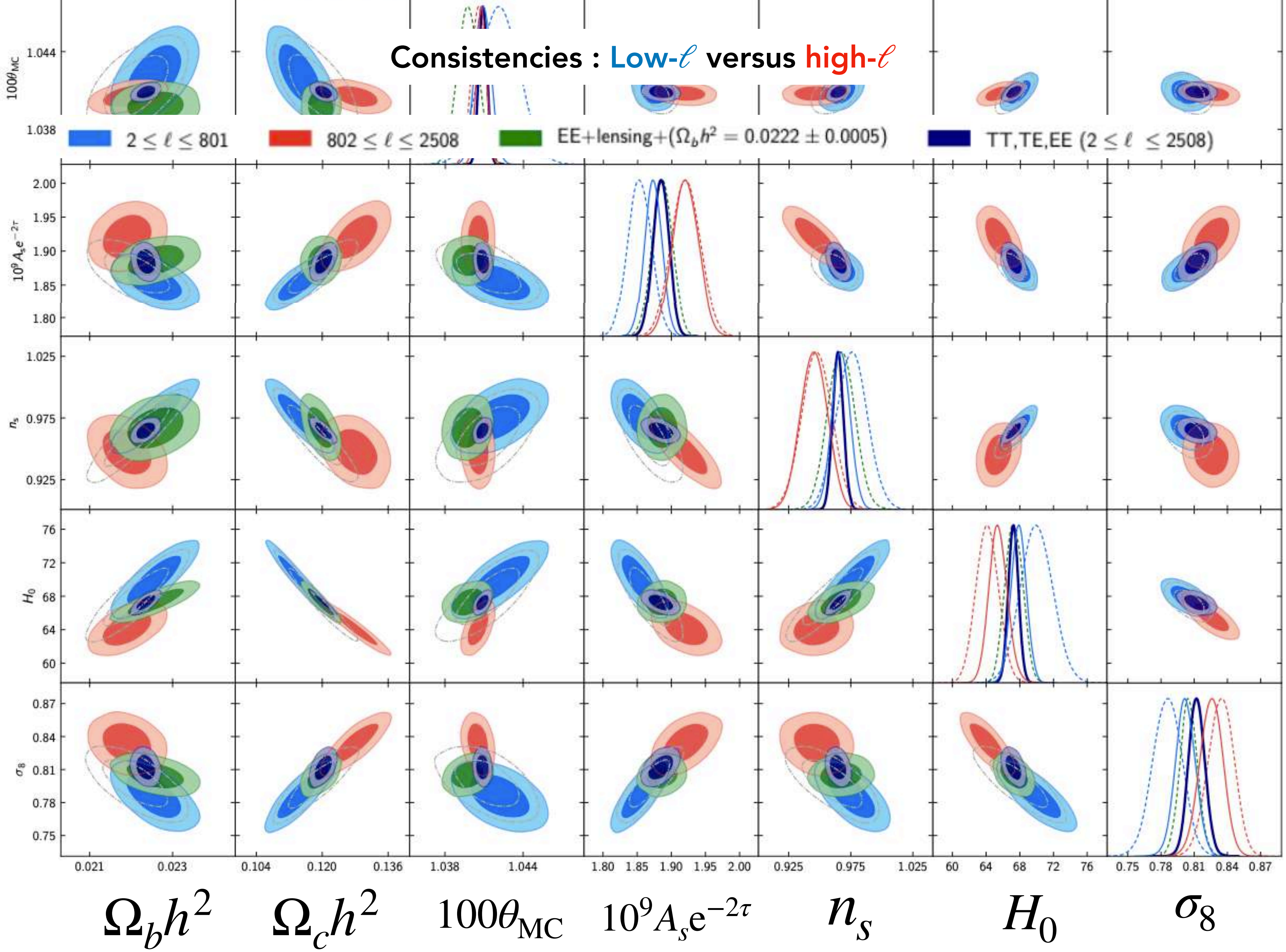
Potential can be reconstructed from 4-point function
or
Lensing template is fitted with amplitude A_L



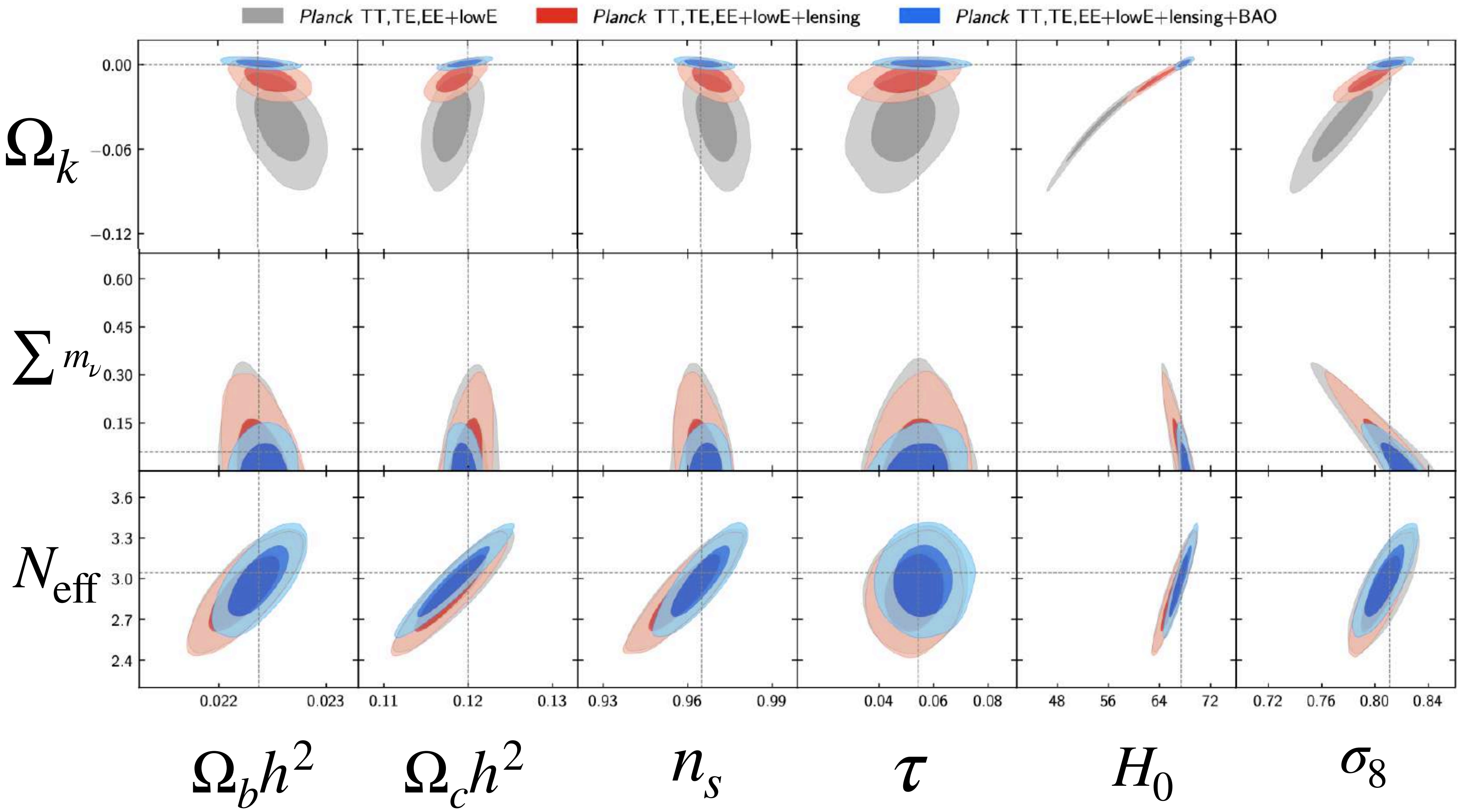
Late-time structures bring information and break some geometrical degeneracy

Consistencies : Low-ℓ versus high-ℓ



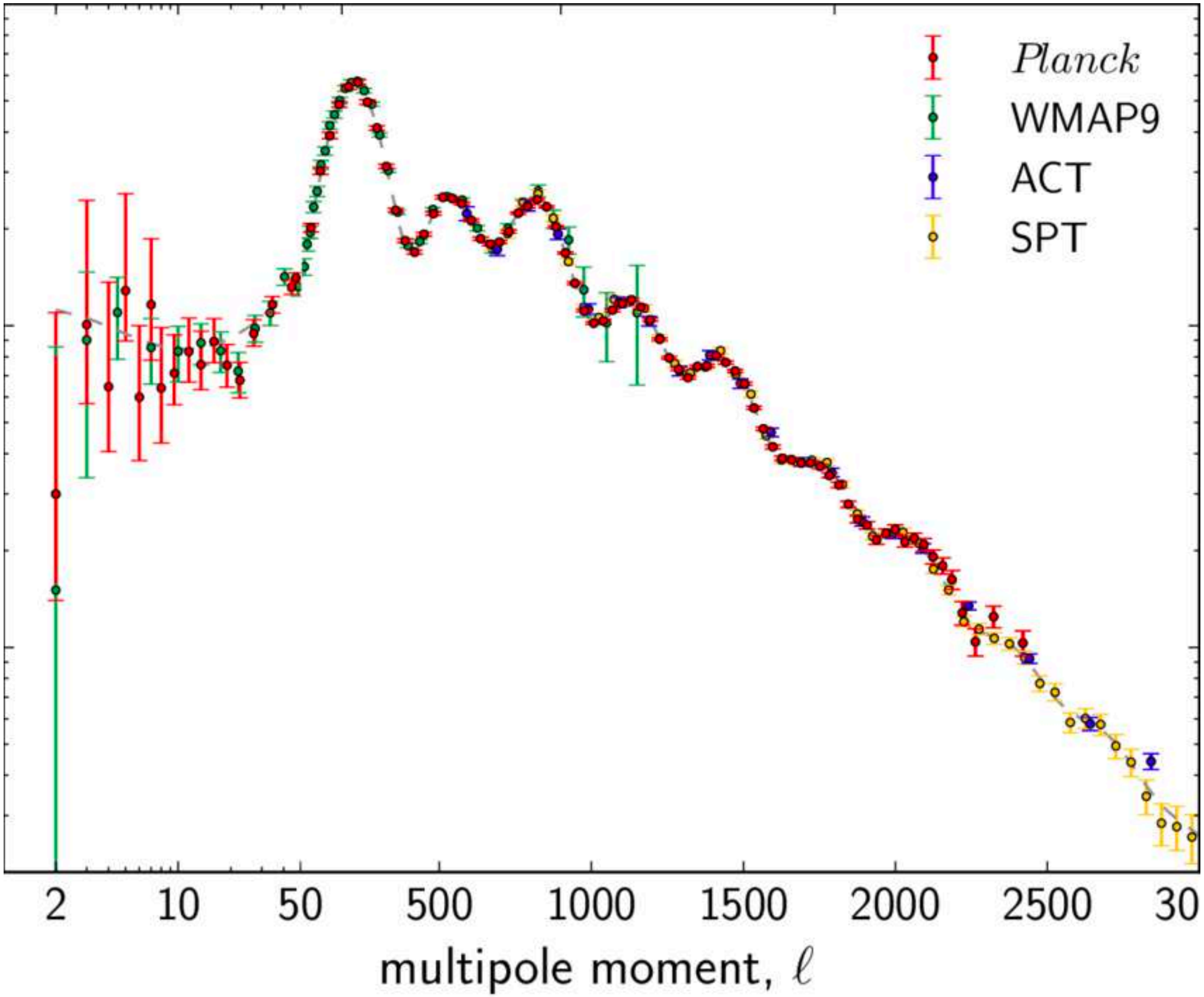

Consistencies : Low-ℓ versus high-ℓ
$2 \leq \ell \leq 801$
$802 \leq \ell \leq 2508$
EE+lensing+($\Omega_b h^2 = 0.0222 \pm 0.0005$)
TT,TE,EE ($2 \leq \ell \leq 2508$)
$\Omega_b h^2$
$\Omega_c h^2$
$100\theta_{\rm MC}$
$10^9 A_s e^{-2\tau}$
n_s
H_0
σ_8

Some one-parameter extensions



Ground based CMB experiments: ACT and SPT

Better resolution, smaller sky -> higher ell

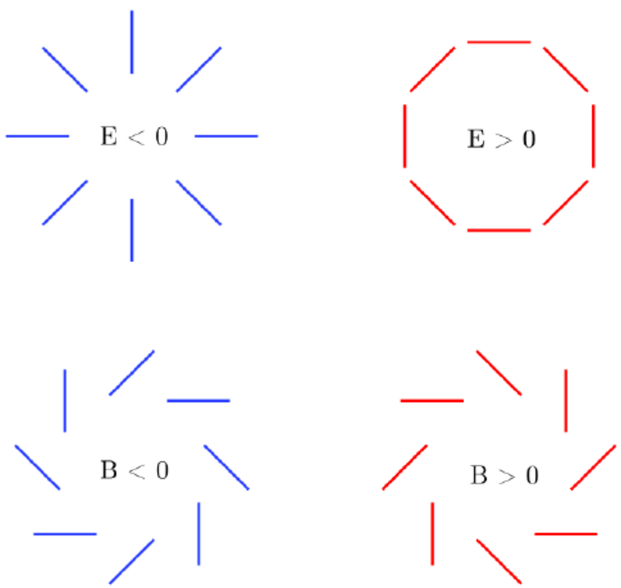


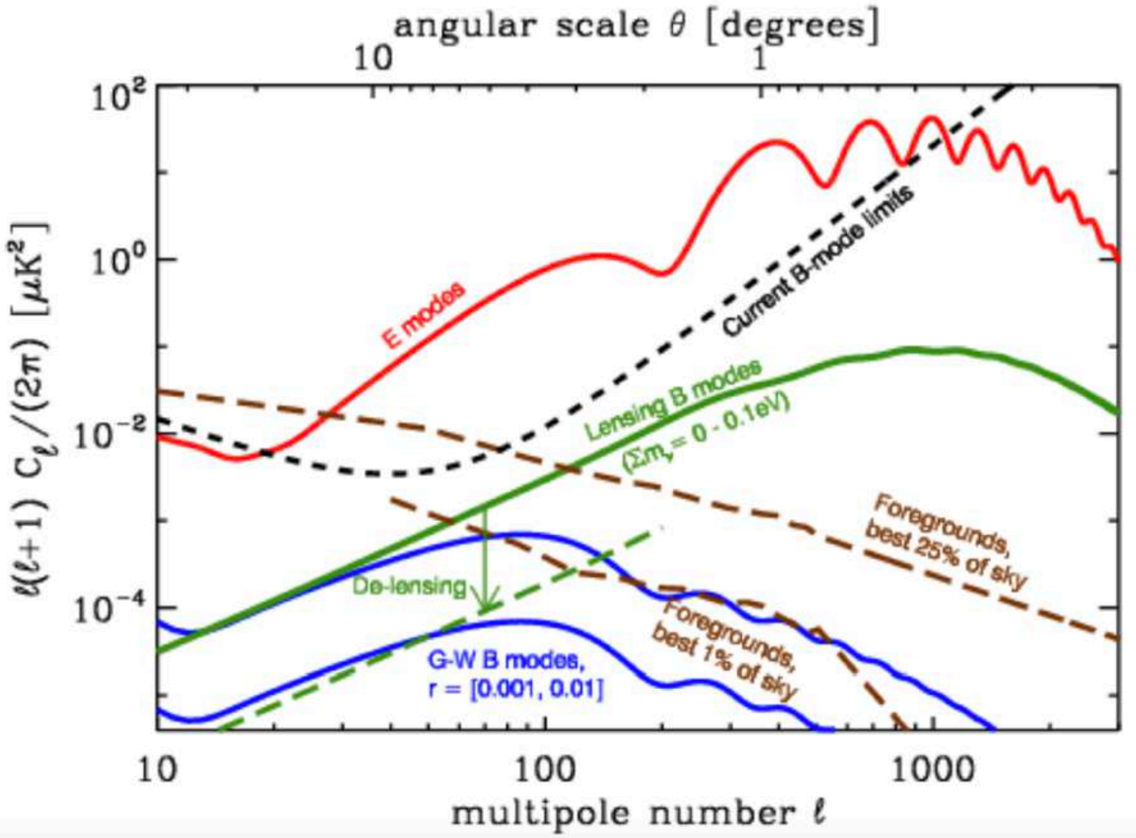
Primordial gravitational waves

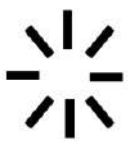
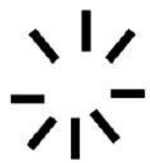
Scalar perturbations $$\mathcal{P}_{\mathcal{R}}(k) = A_{\rm s}\left(\frac{k}{k_0}\right)^{n_{\rm s}-1}$$

Tensor perturbations $$\mathcal{P}_{\rm t}(k) = A_{\rm t}\left(\frac{k}{k_0}\right)^{n_{\rm t}}$$

Tensor-to-scalar ratio : $$r_{0.05} \equiv A_{\rm t}/A_{\rm s}$$





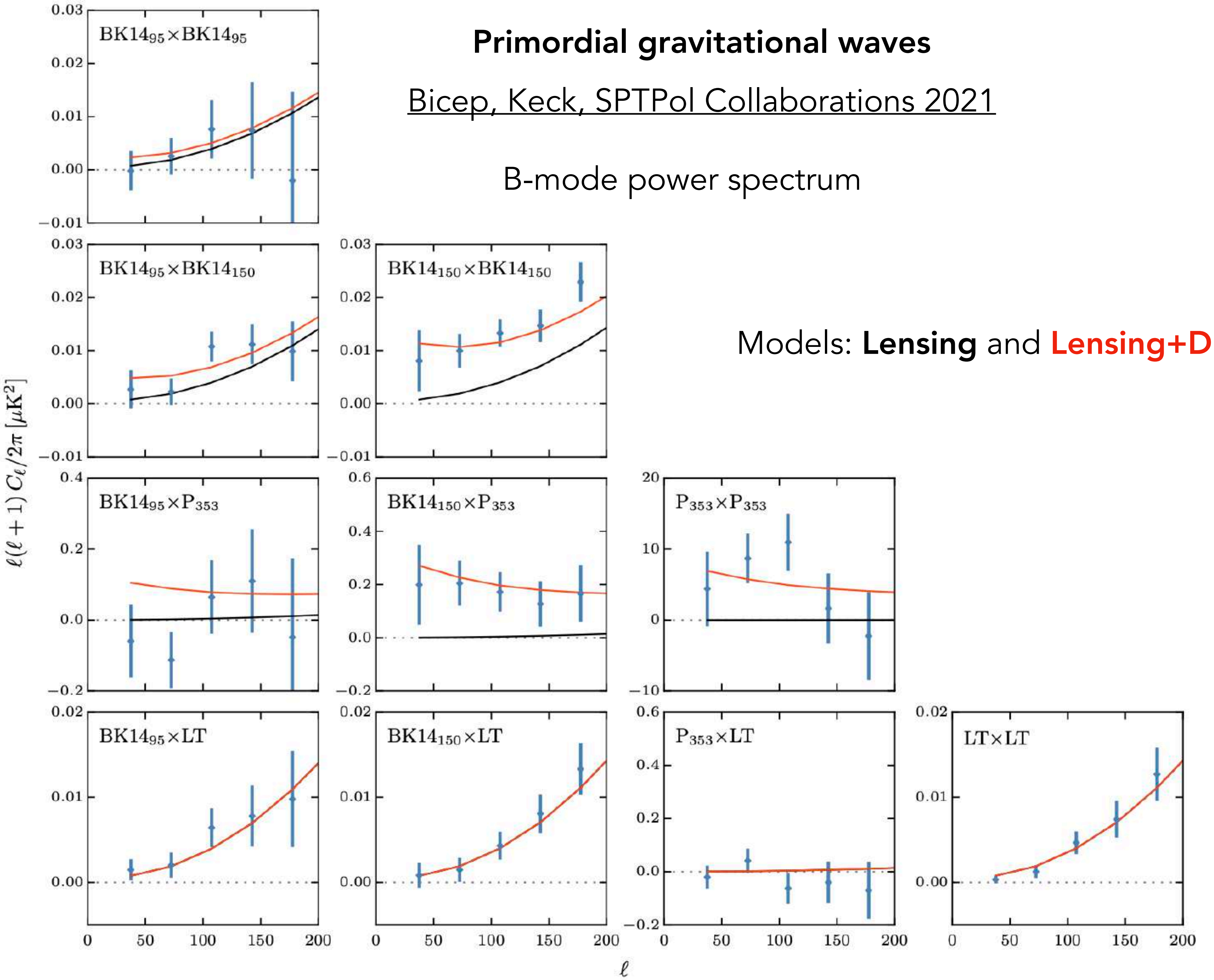
Effect of lensing :  "Turning" E mode into B mode 

Primordial gravitational waves

Bicep, Keck, SPTPol Collaborations 2021

B-mode power spectrum

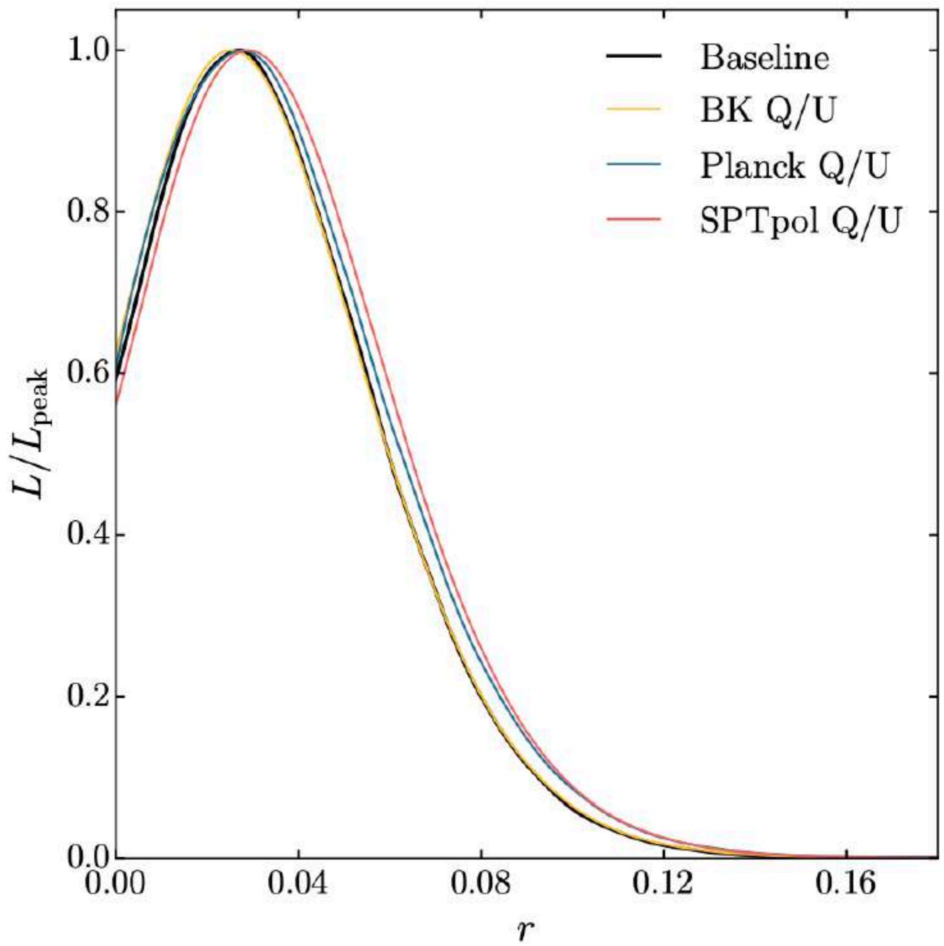
Models: **Lensing** and **Lensing+Dust**



Primordial gravitational waves

Bicep, Keck, SPTPol Collaborations 2021

B-mode power spectrum



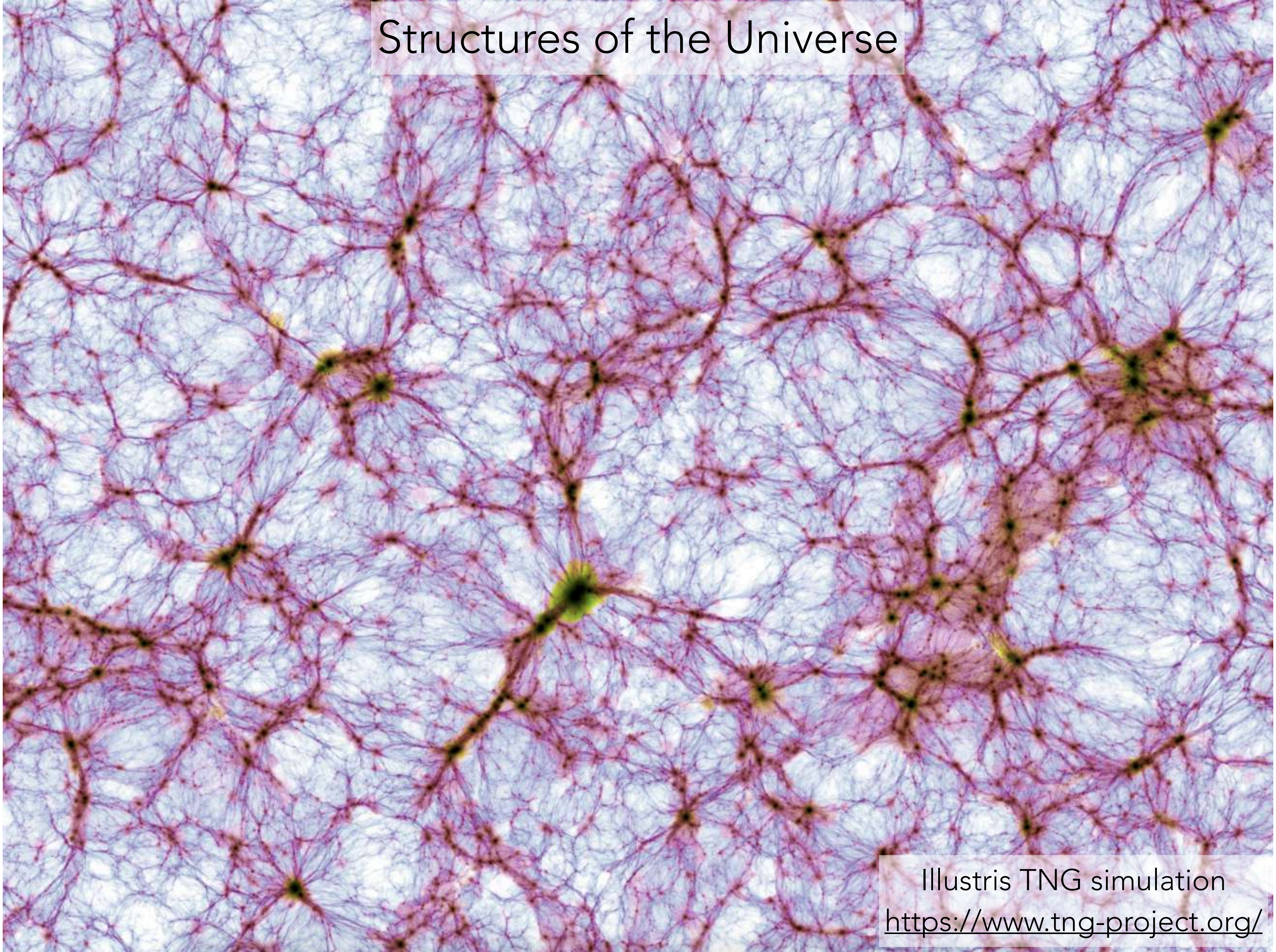
Posterior on tensor-to-scalar ratio

Still no detection

$r < 0.082$ (95% C.L.)

Redshift-Space Distortions (RSD)

Structures of the Universe



Illustris TNG simulation
https://www.tng-project.org/

Model for the structures

smooth Universe

$\rho(t)$

density perturbations: $\delta(\mathbf{x},t) = \dfrac{\rho(\mathbf{x},t) - \bar{\rho}(t)}{\bar{\rho}(t)}$

velocities: $\mathbf{v}(\mathbf{x},t)$

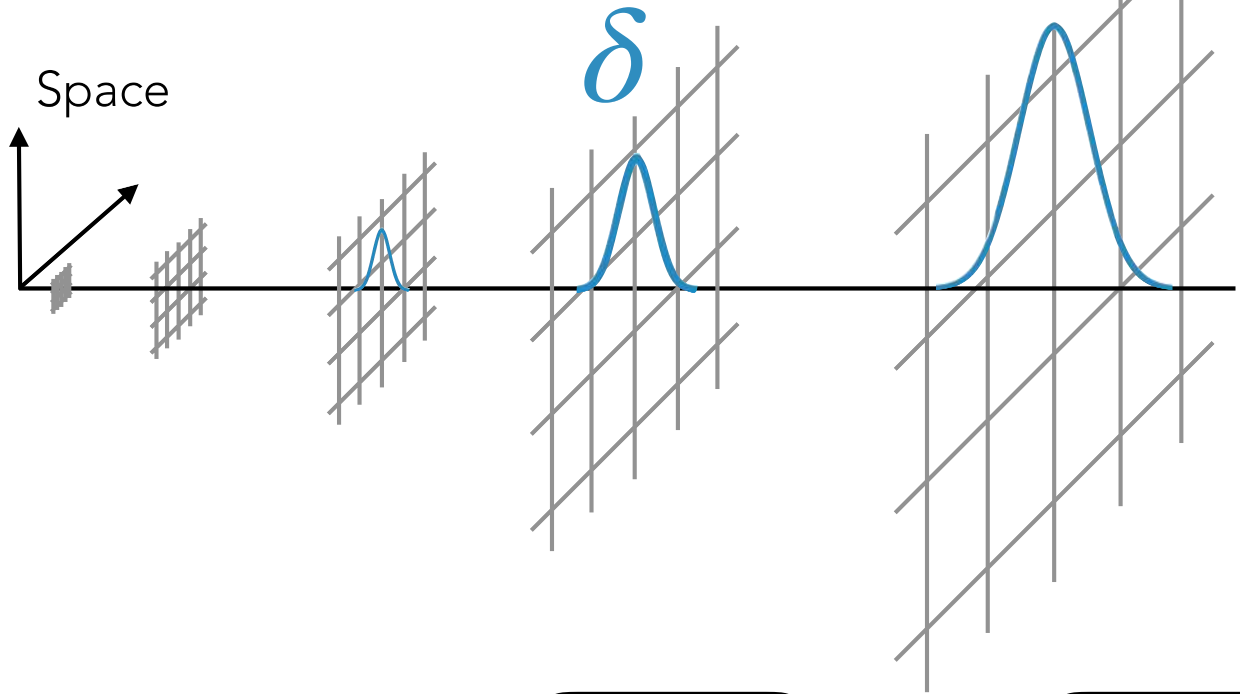
Space-time properties

=

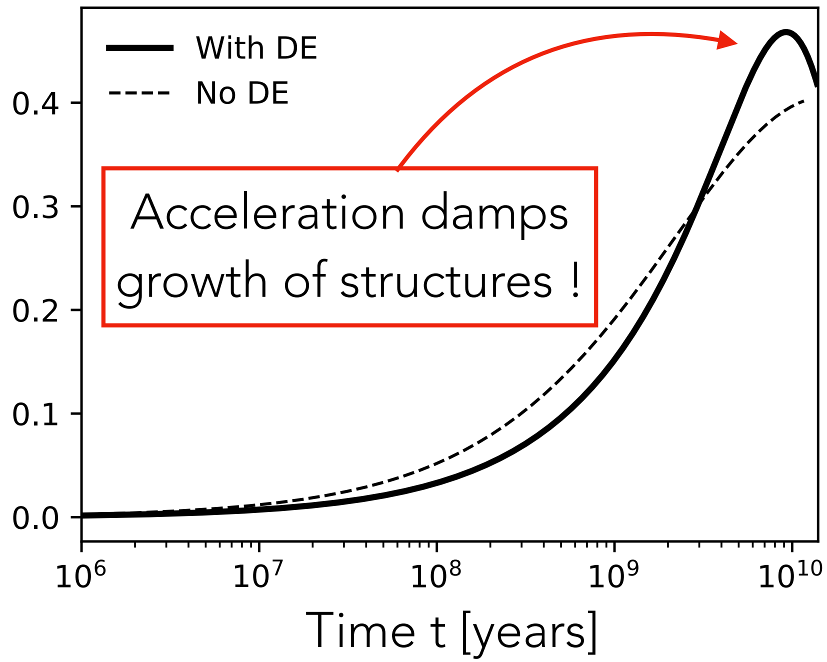
Energy content of the Universe

$$\ddot{\delta} + \boxed{\text{expansion, pressure}}\,\dot{\delta} - \boxed{\text{gravity}}\,\delta = 0$$

Model for the structures



$$\frac{\mathrm{d}\delta}{\mathrm{d}t}(t)$$ ~ Growth-rate

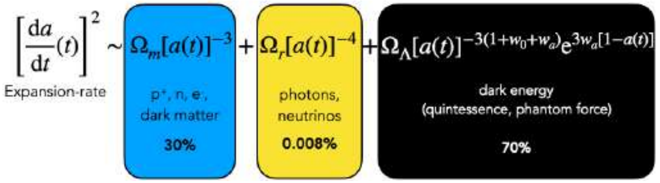


$$\ddot{\delta} + \boxed{\text{expansion, pressure}}\,\dot{\delta} - \boxed{\text{gravity}}\,\delta = 0$$

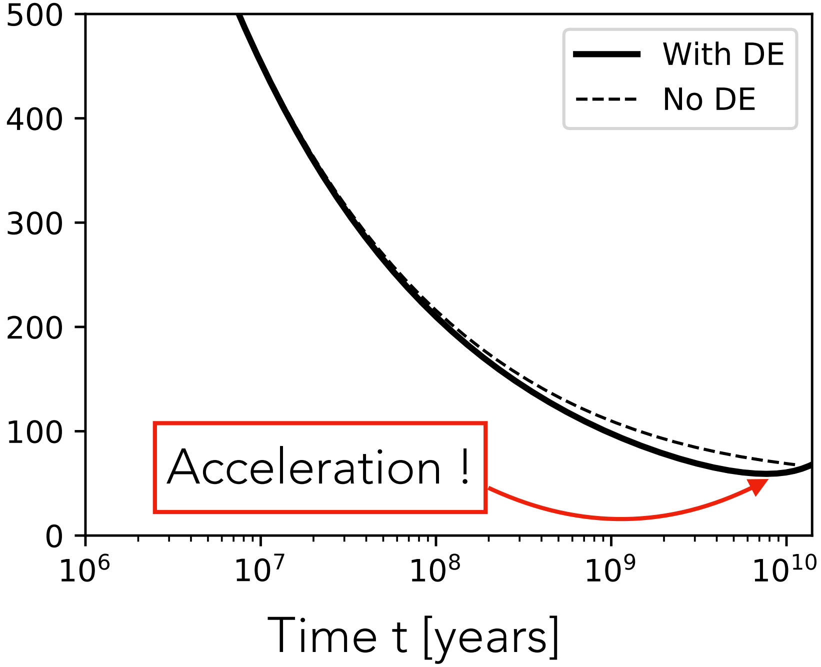
$$\ddot{\delta}(\vec{x},t) + 2H(z)\dot{\delta}(\vec{x},t) - \frac{3}{2}\Omega_m H_0^2 (1+z)^3 \delta(\vec{x},t) = 0$$ (GR + linear)

Smooth Universe

$$\left[\frac{\mathrm{d}a}{\mathrm{d}t}(t)\right]^2 \sim \Omega_m[a(t)]^{-3} + \Omega_r[a(t)]^{-4} + \Omega_\Lambda[a(t)]^{-3(1+w_0+w_a)}e^{3w_a[1-a(t)]}$$



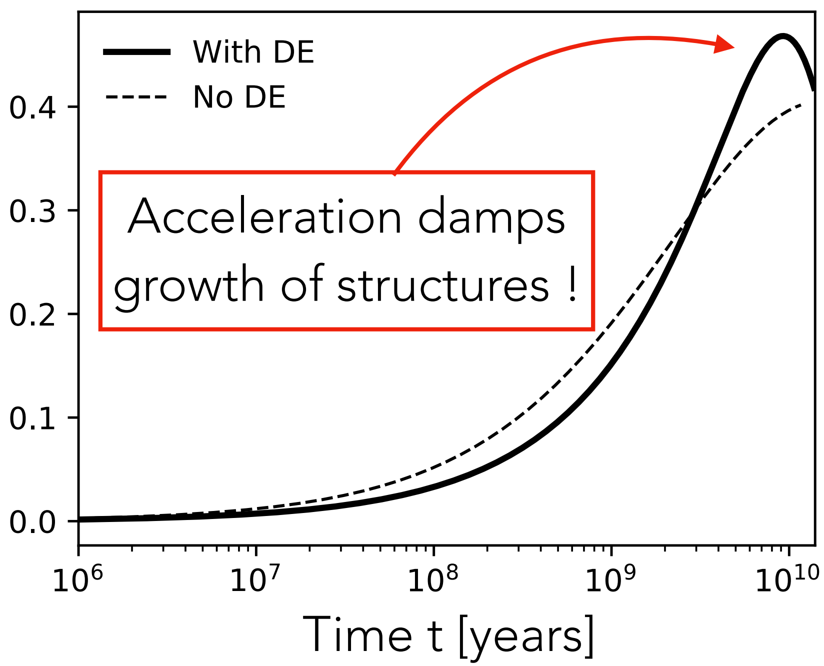
$$\frac{\mathrm{d}a}{\mathrm{d}t}(t) = \text{Expansion-rate}$$



Structures

$$\ddot{\delta} + \boxed{\text{expansion, pressure}}\,\dot{\delta} - \boxed{\text{gravity}}\,\delta = 0$$

$$\frac{\mathrm{d}\delta}{\mathrm{d}t}(t) \sim \text{Growth-rate}$$

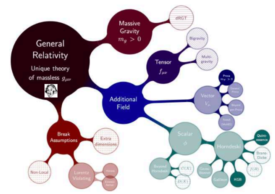


$$\Omega_\Lambda[a(t)]^{-3(1+w_0+w_a)}e^{3w_a[1-a(t)]}$$

dark energy (quintessence, phantom force)

70%

Expansion-rate and growth-rate can **break degeneracies** between Λ and alternatives to general relativity



Statistics of the structures

One Universe,
one realisation: $\delta(\mathbf{x})$ not so useful by itself,
so we look at statistical properties !

Average: $\langle\delta(\mathbf{x})\rangle = 0$ by definition... not very useful

Variance: $\langle\delta^2(\mathbf{x})\rangle$ useful! but there is more...

Correlation function: $\langle\delta(\mathbf{x})\delta(\mathbf{y})\rangle$

Fourier Transform

Power-spectrum: $\langle\tilde{\delta}(\mathbf{k})\tilde{\delta}(\mathbf{k}')\rangle$

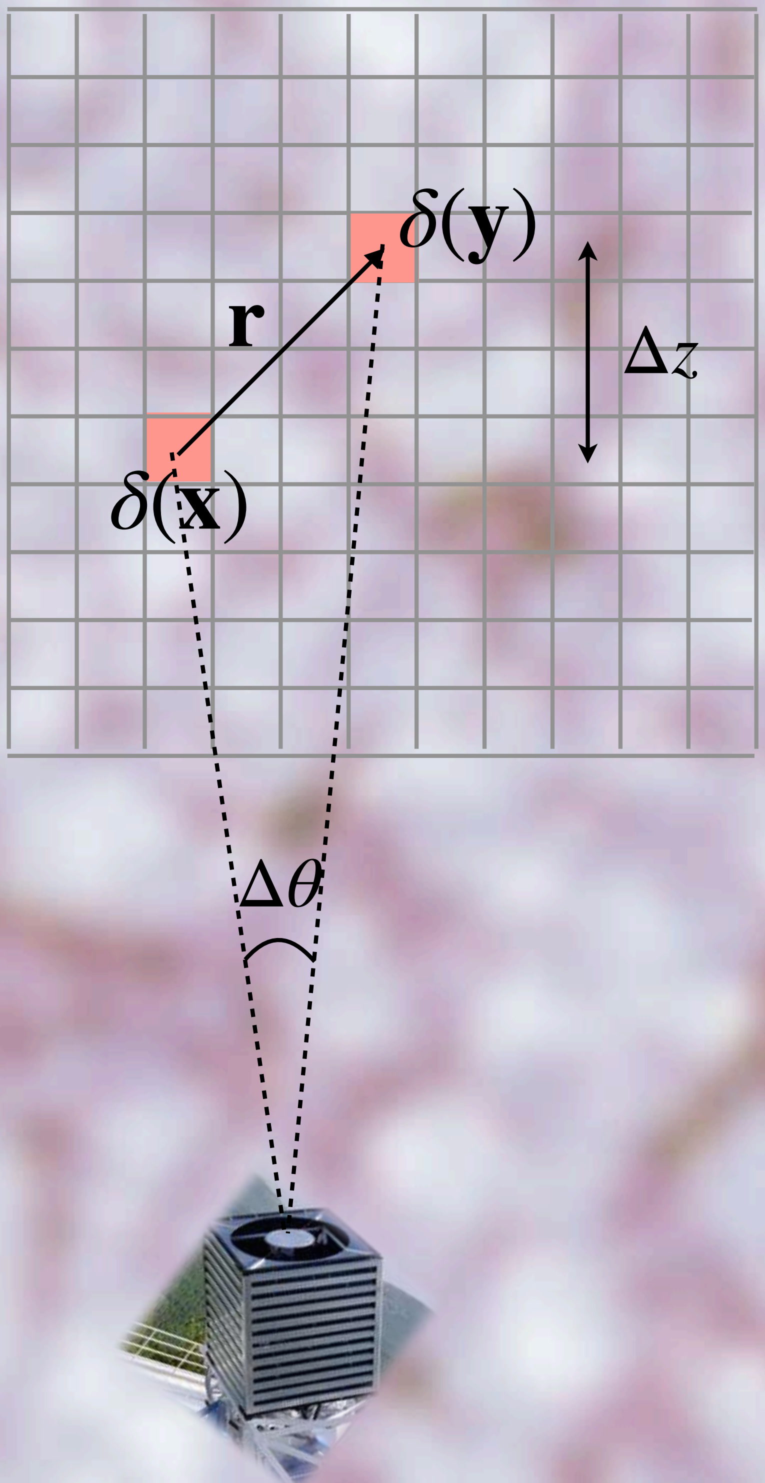
contain most information
(most used)

Higher-order: $\langle\delta(\mathbf{x_1})\delta(\mathbf{x_2})\ldots\delta(\mathbf{x_n})\rangle$ also very interesting

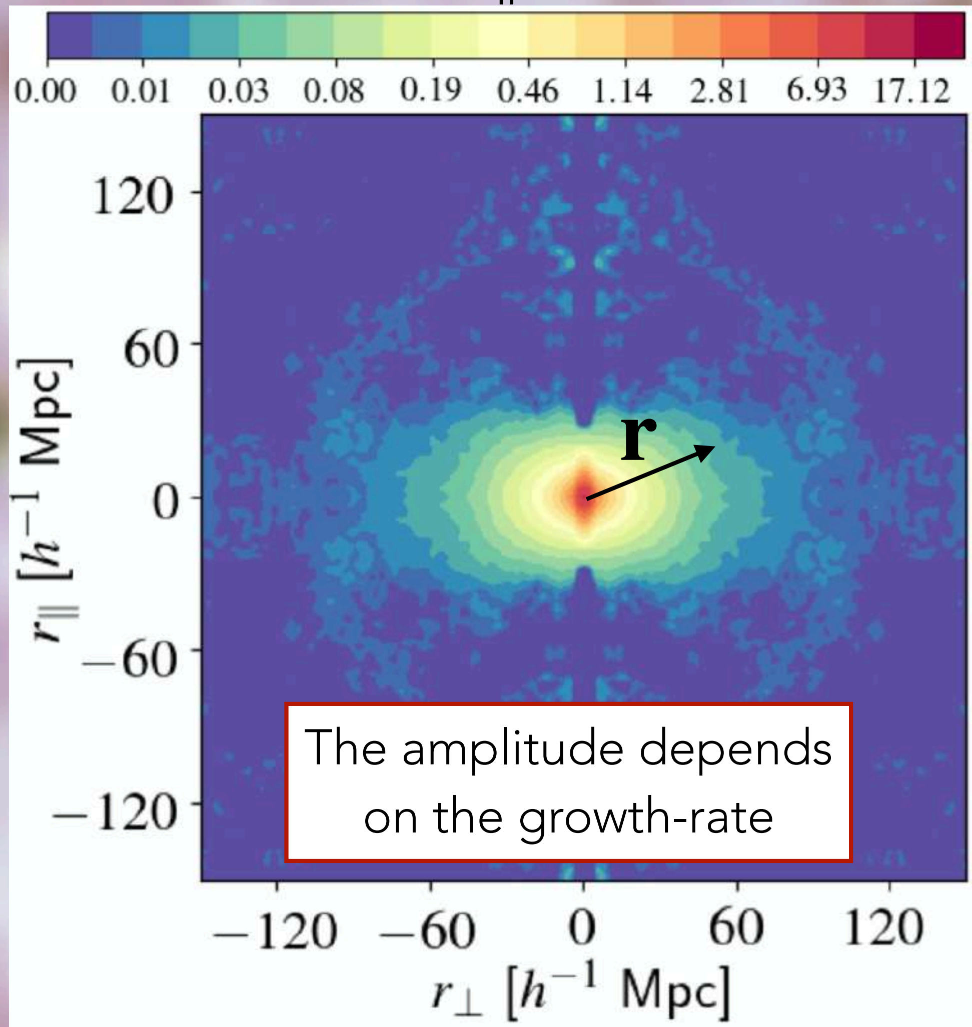
Correlation function: $\langle \delta(\mathbf{x})\delta(\mathbf{y}) \rangle$

$\langle \, . \, \rangle =$ average over all pairs in the volume

$$\langle \delta(\mathbf{x})\delta(\mathbf{x}+\mathbf{r}) \rangle = \xi(\mathbf{r}) = \xi(r_{\parallel}, r_{\perp})$$

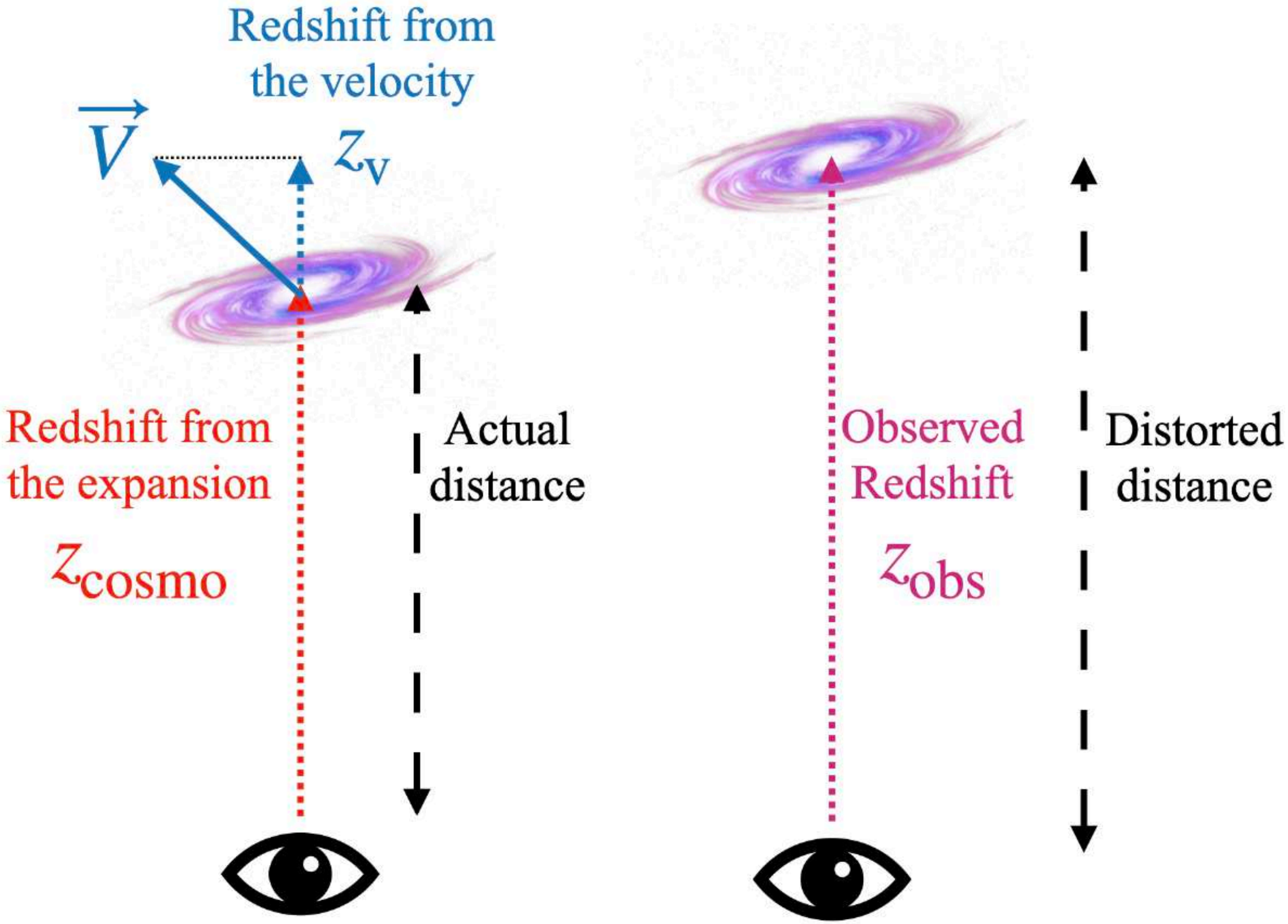


$\xi(r_{\parallel}, r_{\perp})$



Redshift-space distortions (RSD)

We measure redshifts : peculiar velocities affect our distance inferences



Redshift-space distortions (RSD)

BAO - Baryon Acoustic Oscillations

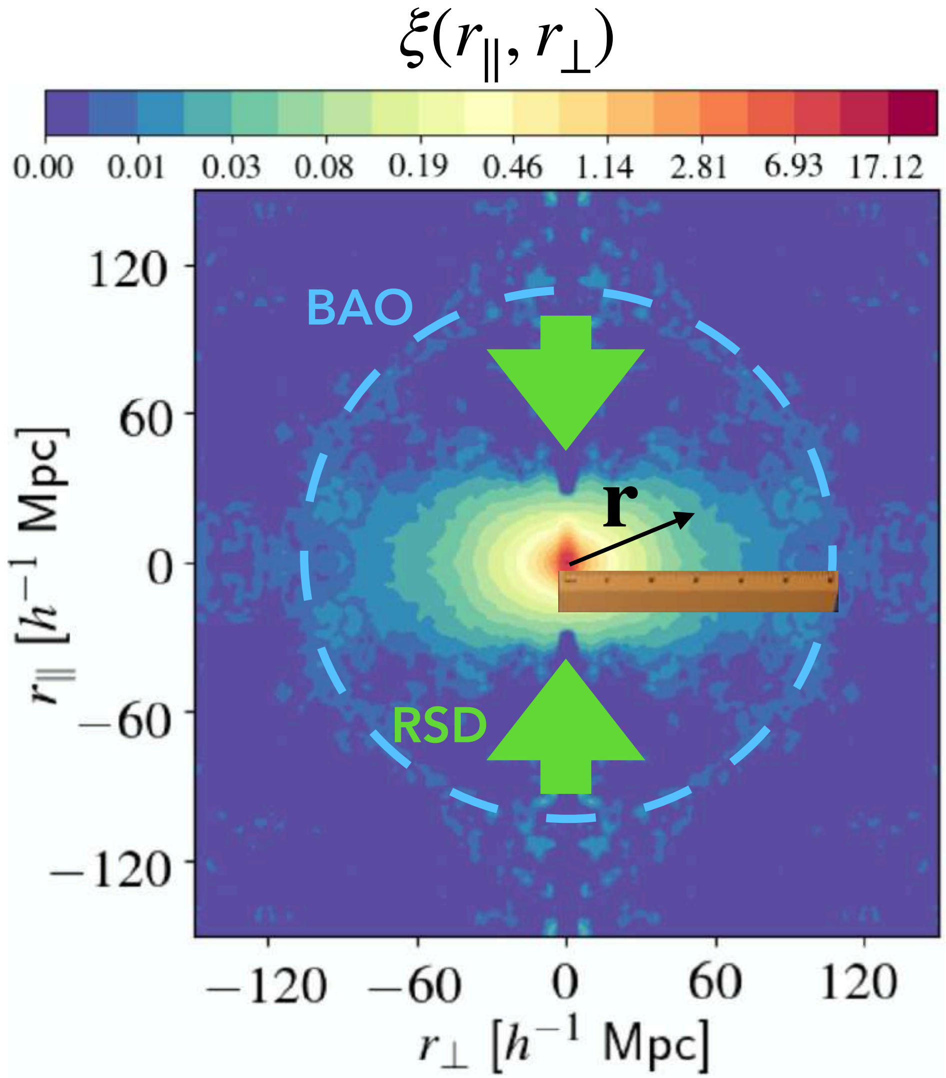
Expansion rate H(z)

General Relativity
+
Λ, w_0, w_a: dark energy

RSD - Redshift-space distortions

Growth rate of structures f(z)

Modifications or
alternatives to
General Relativity



Bautista et al. 2020

Redshift-space distortions (RSD)

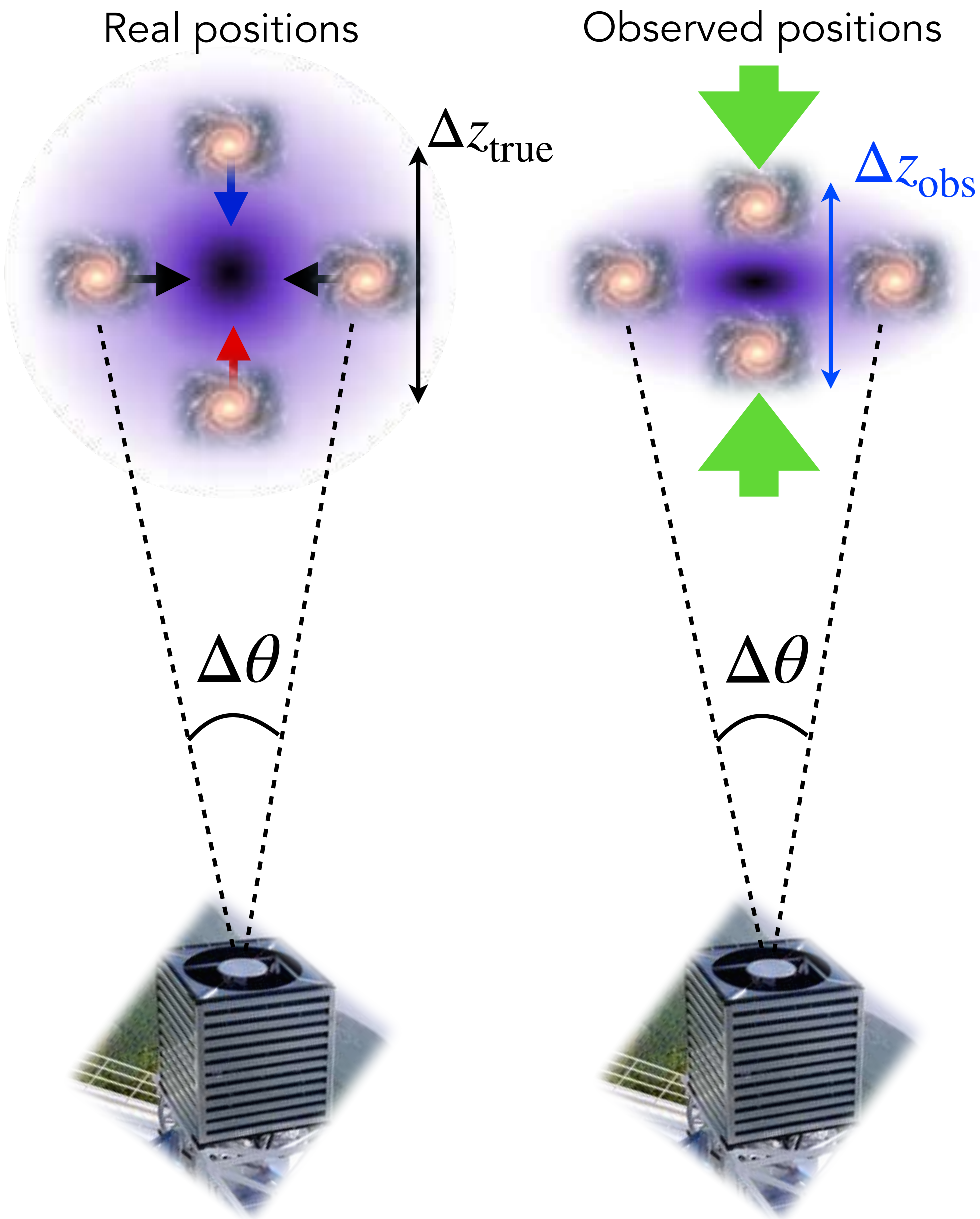
Velocities "flatten"
the structures radially

Growth rate of structures
in general relativity

$$\boxed{f(z)} \sim \left[\Omega_m(z)\right]^{\gamma=0.55}$$

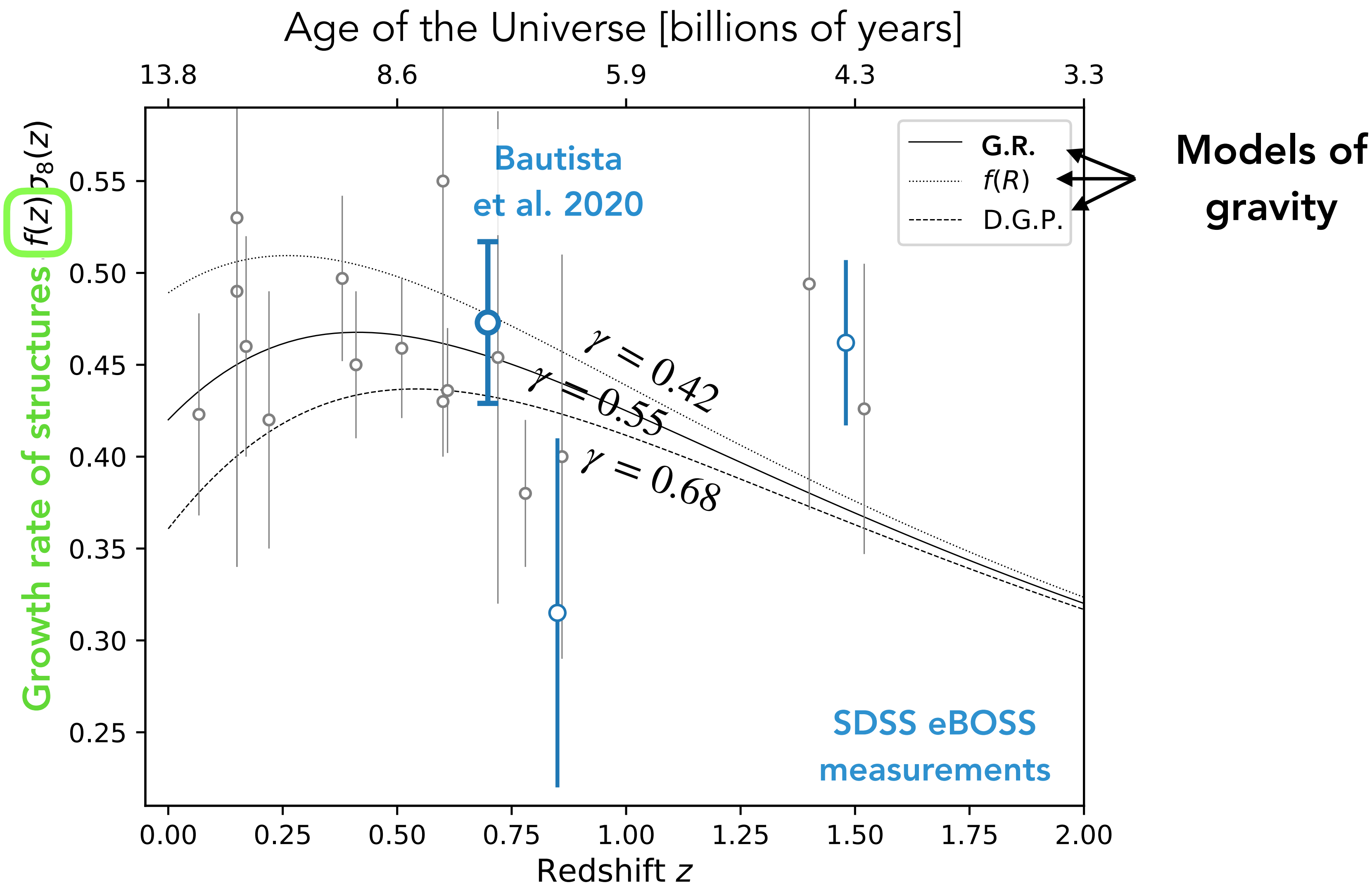
Else: $\gamma \neq 0.55$

Modifications or
alternatives to
General Relativity



Redshift-space distortions (RSD)

State-of-the-art measurements from galaxy surveys

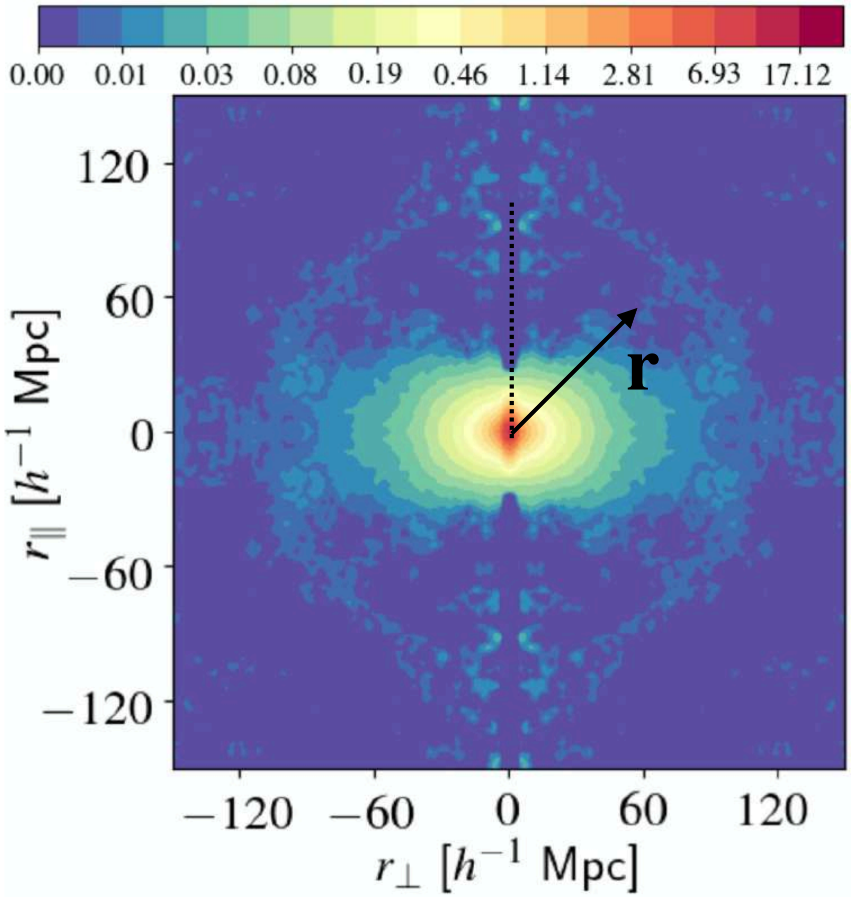


Uncertainties are still large to see deviations from GR

RSD analysis

eBOSS LRG sample

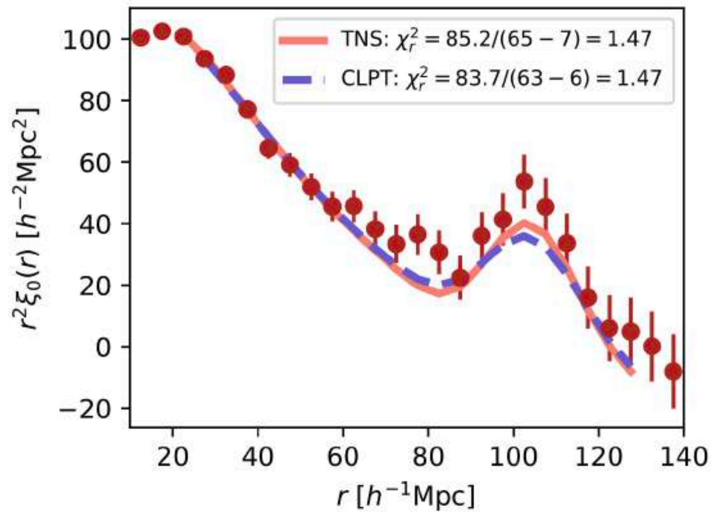
$\xi(r_\parallel, r_\perp)$



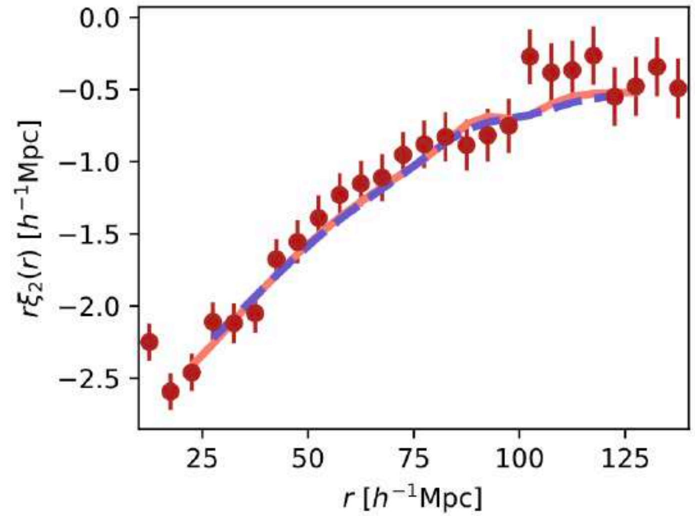
$$\xi(r, \mu) = \sum_{\ell=0}^{\ell_{\max}} L_\ell(\mu)\xi_\ell(r)$$

where $\mu = r_\parallel / r$

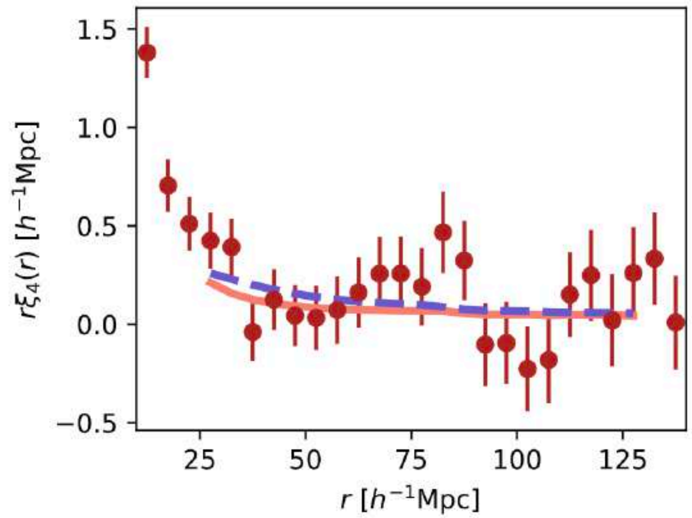
Monopole



Quadrupole



Hexadecapole



RSD analysis

How to model the galaxy clustering ?

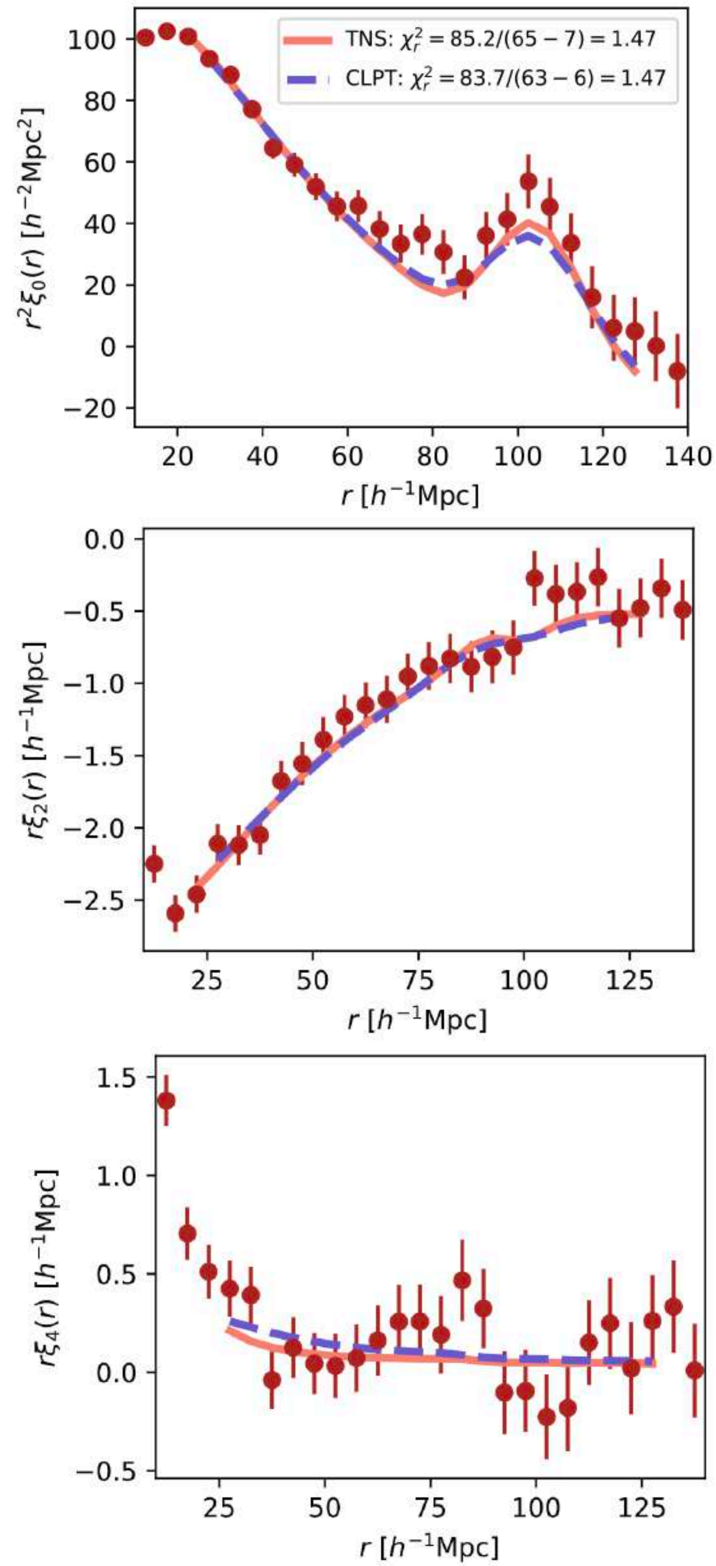
Non-linear matter power spectrum

Halos, bias and clustering

How galaxies are distributed among halos

Redshift-space

Selection effects



RSD analysis

How to model the galaxy clustering ?

Non-linear matter power spectrum

Halos, bias and clustering

How galaxies are distributed among halos

Redshift-space

Selection effects

This is a large field of theoretical research

Realism

Approaches:

- n-body simulations
- hybrid : emulators, machine learning
- theoretical formulations

Speed

Large-scale structure of the Universe and cosmological perturbation theory
Bernardeau, Colombi, Gaztanaga, Scoccimarro 2002

Large-scale galaxy bias
Desjacques, Jeong & Schmidt 2018

RSD analysis

Growth rate of structures

Estimate D_M/r_d, D_H/r_d and $\boxed{f\sigma_8}$ from the full-shape of the correlation function or power spectrum

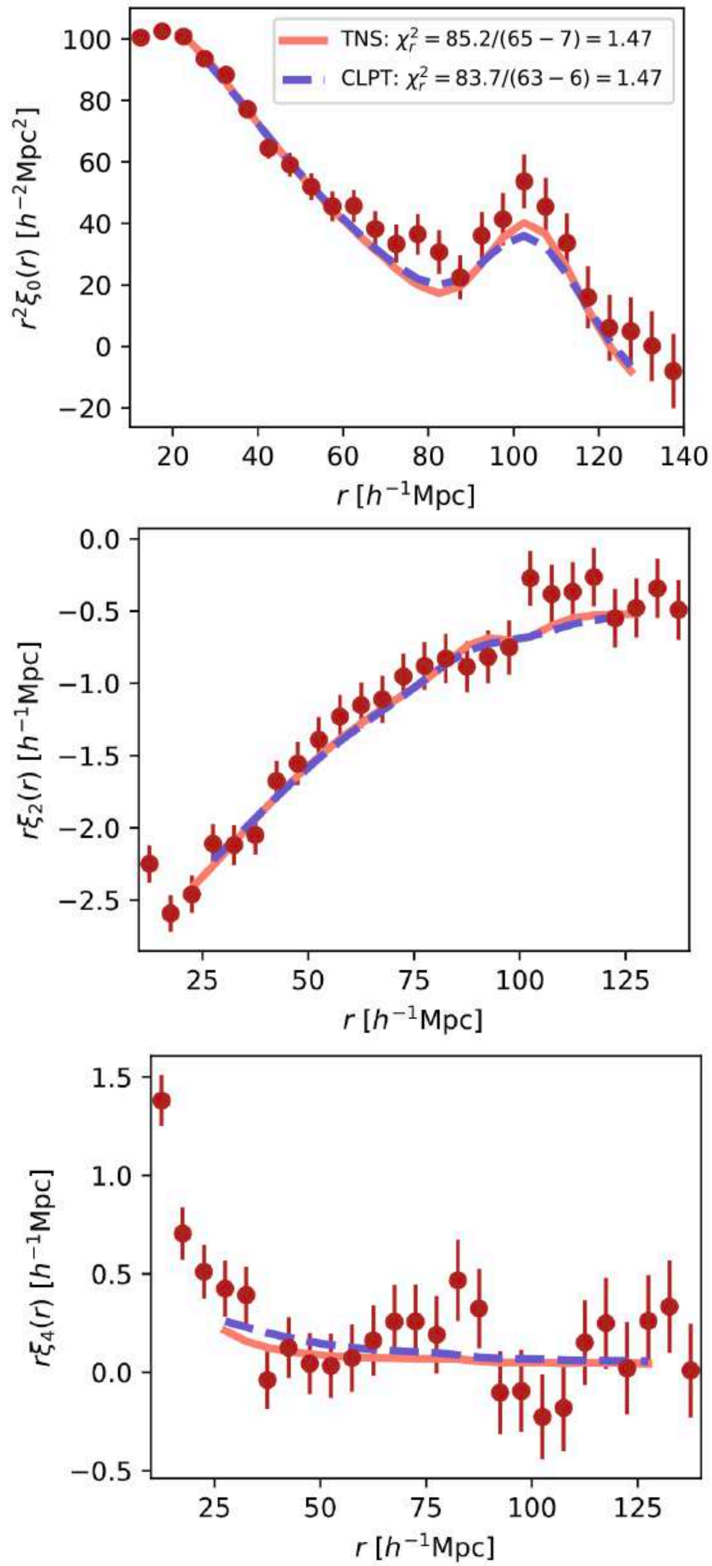
Two examples models:

TNS (Taruya, Nishimishi & Saito 2010)
+ non-linear bias

Comoving Lagrangian Perturbation Theory (Carlson et al. 2013)
+ Gaussian streaming (Reid & White 2011)

$$P_g^s(k,\mu) = D(k\mu\sigma_v)\left[P_{gg}(k) + 2\mu^2 f P_{g\theta} + \mu^4 f^2 P_{\theta\theta}(k) + C_A(k,\mu,f,b_1) + C_B(k,\mu,f,b_1)\right],$$

$$1+\xi_X(r_\perp, r_\parallel) = \int \frac{1}{\sqrt{2\pi\left[\sigma_{12}^2(r)+\sigma_{FoG}^2\right]}}[1+\xi_X(r)] \times \exp\left\{-\frac{[r_\parallel - y - \mu v_{12}(r)]^2}{2\left[\sigma_{12}^2(r)+\sigma_{FoG}^2\right]}\right\} dy,$$



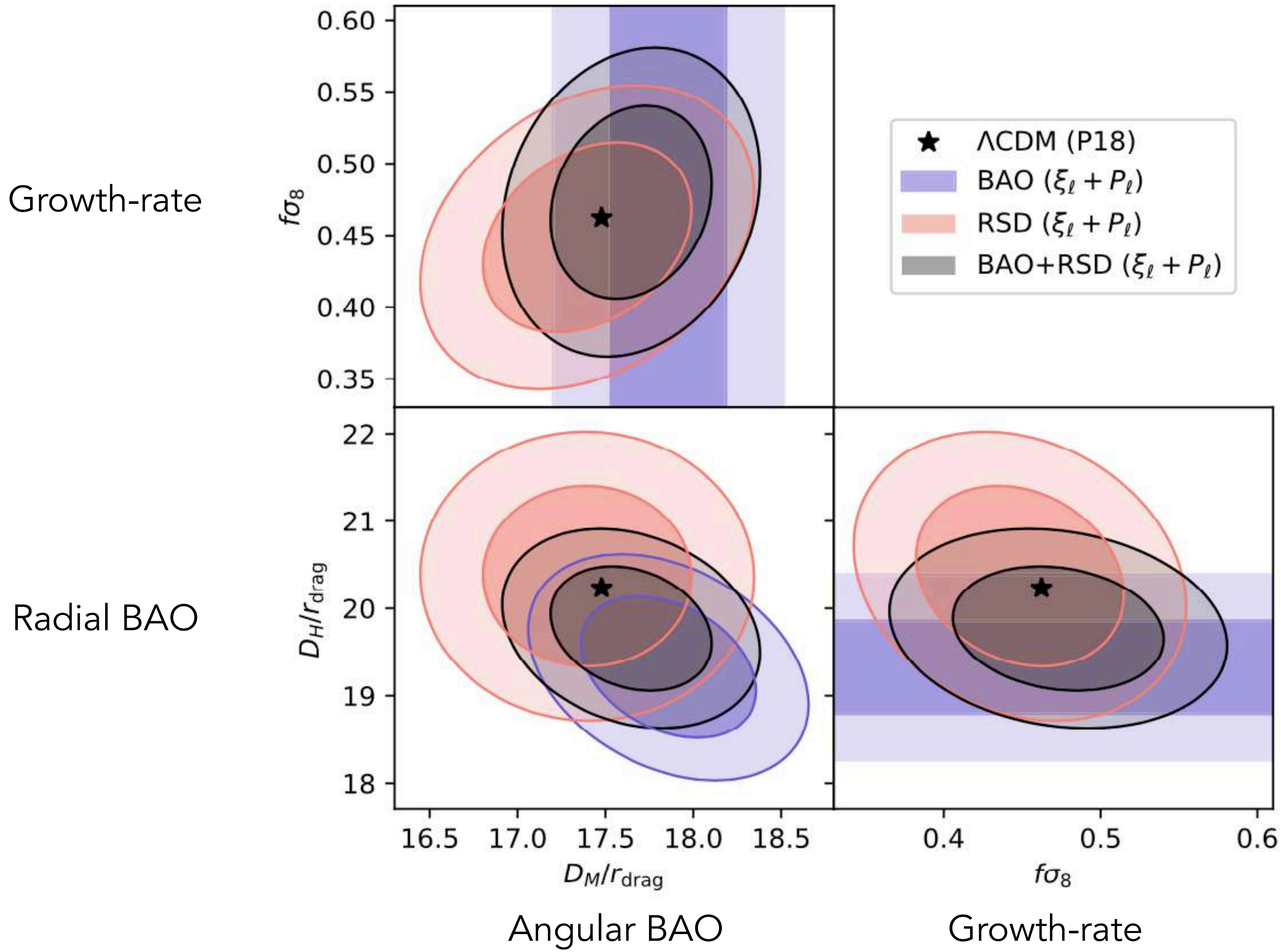
RSD analysis

Systematic errors

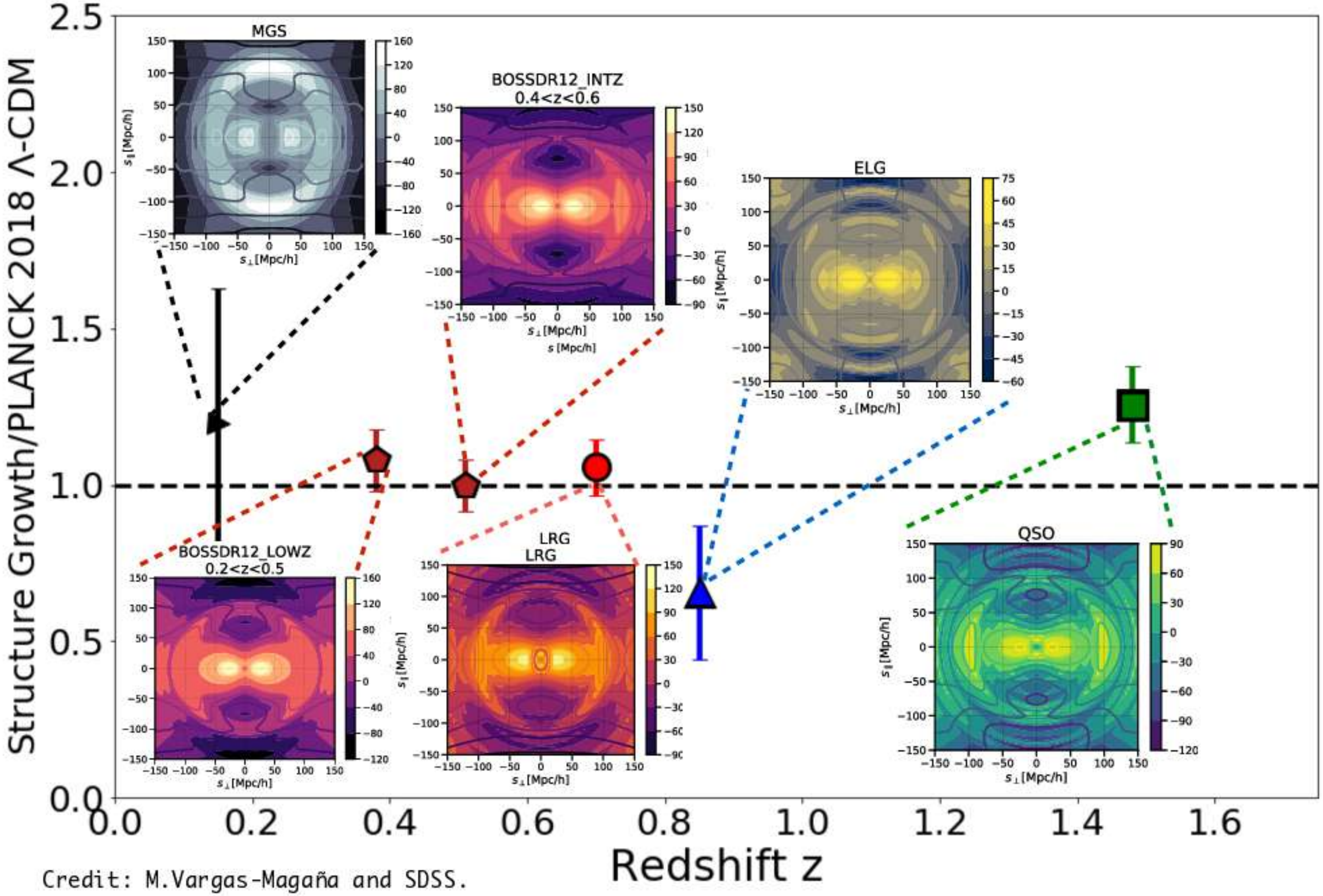
Type	Model	$\sigma_{\alpha_\perp}$	$\sigma_{\alpha_\parallel}$	$\sigma_{f\sigma_8}$
Modelling	CLPT-GS	0.004	0.009	0.010
	TNS	0.004	0.006	0.009
Fid. cosmology	CLPT-GS	0.009	0.010	0.014
	TNS	0.005	0.008	0.012
Obs. effects	CLPT-GS	0.009	0.012	0.017
	TNS	0.010	0.014	0.018
σ_{syst}	CLPT-GS	0.013	0.018	0.024
	TNS	0.012	0.017	0.023
	P_ℓ	0.012	0.013	0.024
σ_{stat}	CLPT-GS	0.020	0.028	0.045
	TNS	0.018	0.031	0.040
	P_ℓ	0.027	0.036	0.042
$\sigma_{\mathrm{syst}}/\sigma_{\mathrm{stat}}$	CLPT-GS	0.66	0.63	0.54
	TNS	0.65	0.55	0.58
	P_ℓ	0.43	0.37	0.58
$\sigma_{\mathrm{tot}} = \sqrt{\sigma_{\mathrm{syst}}^2 + \sigma_{\mathrm{stat}}^2}$	CLPT-GS	0.024	0.033	0.051
	TNS	0.021	0.035	0.046
	P_ℓ	0.029	0.038	0.048

Statistical and systematic errors are comparable

RSD analysis

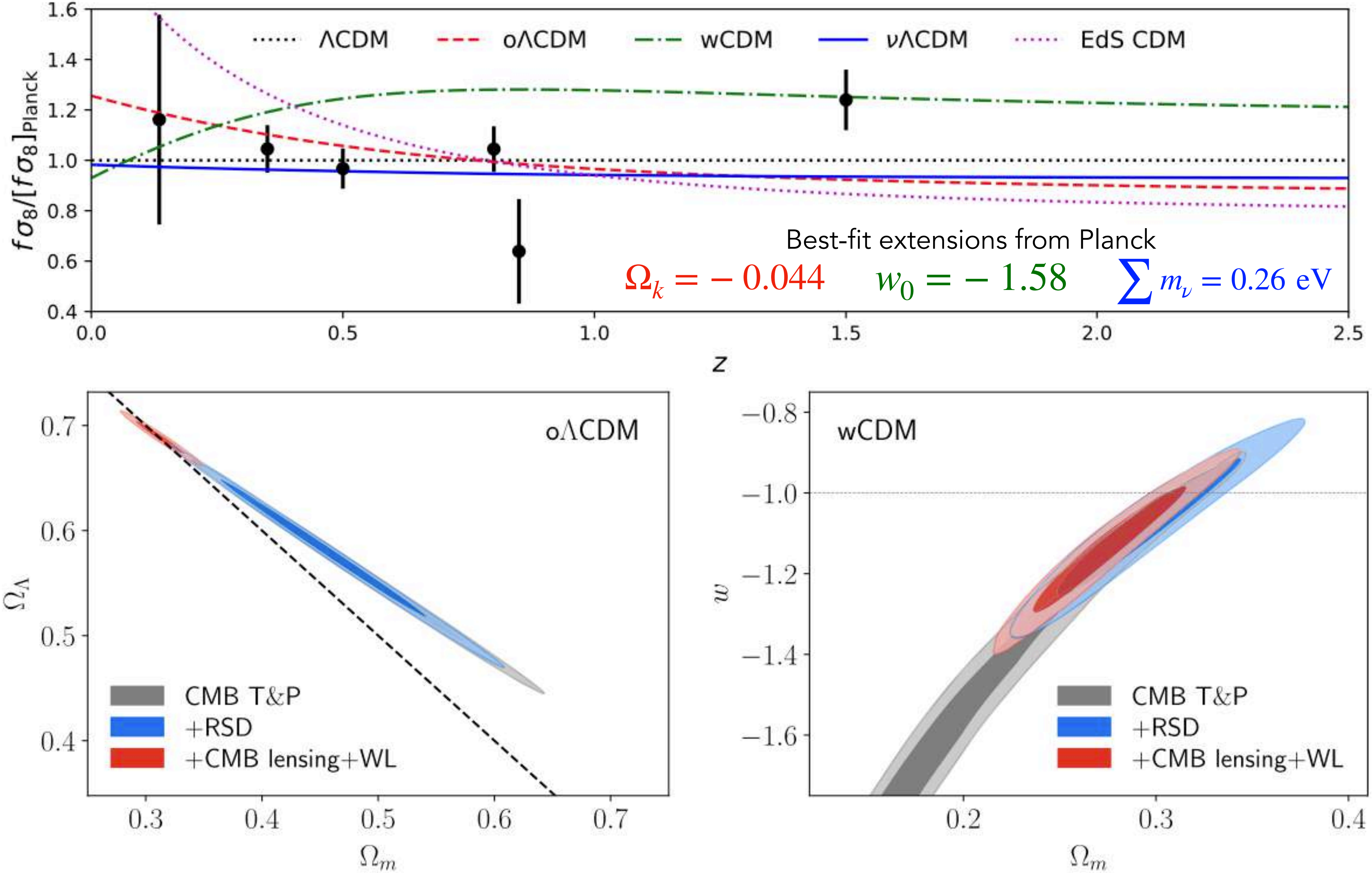


Redshift-space distortions



Also using cosmic-voids: Aubert, Cousinou, Escoffier, et al. 2020

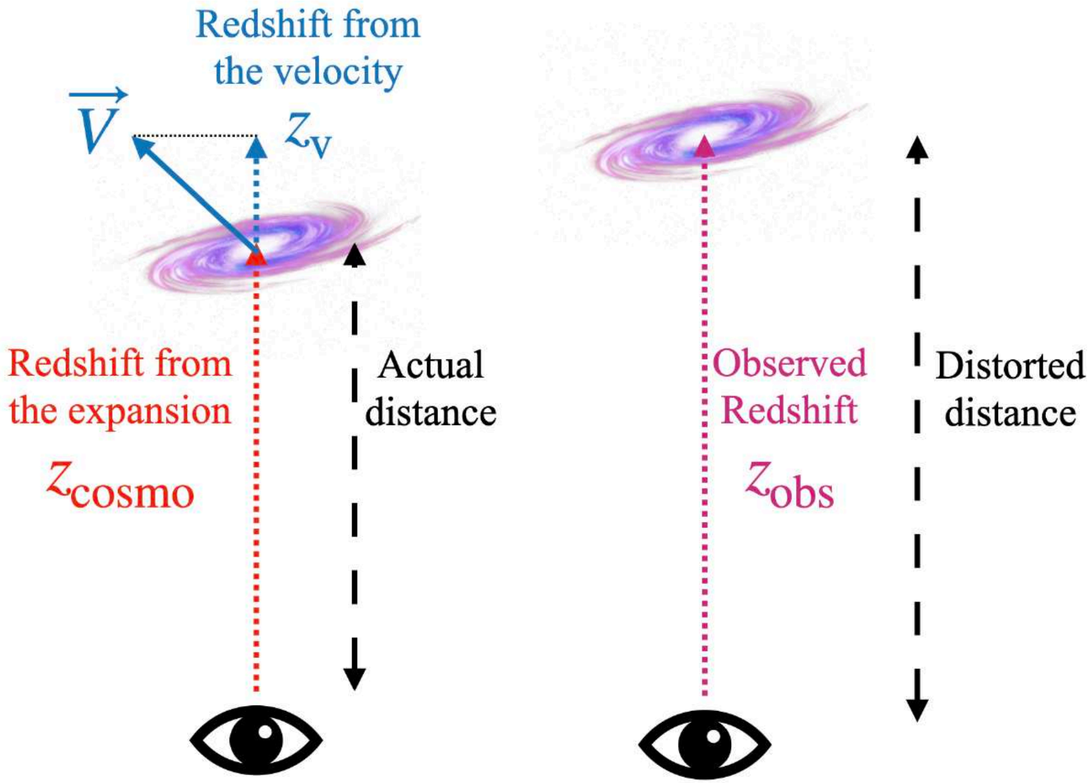
Redshift-space distortions



Constraints are not yet that competitive with other probes **within these models**

Peculiar velocities

Distance indicator + redshift = peculiar velocity



Density

Radial velocity

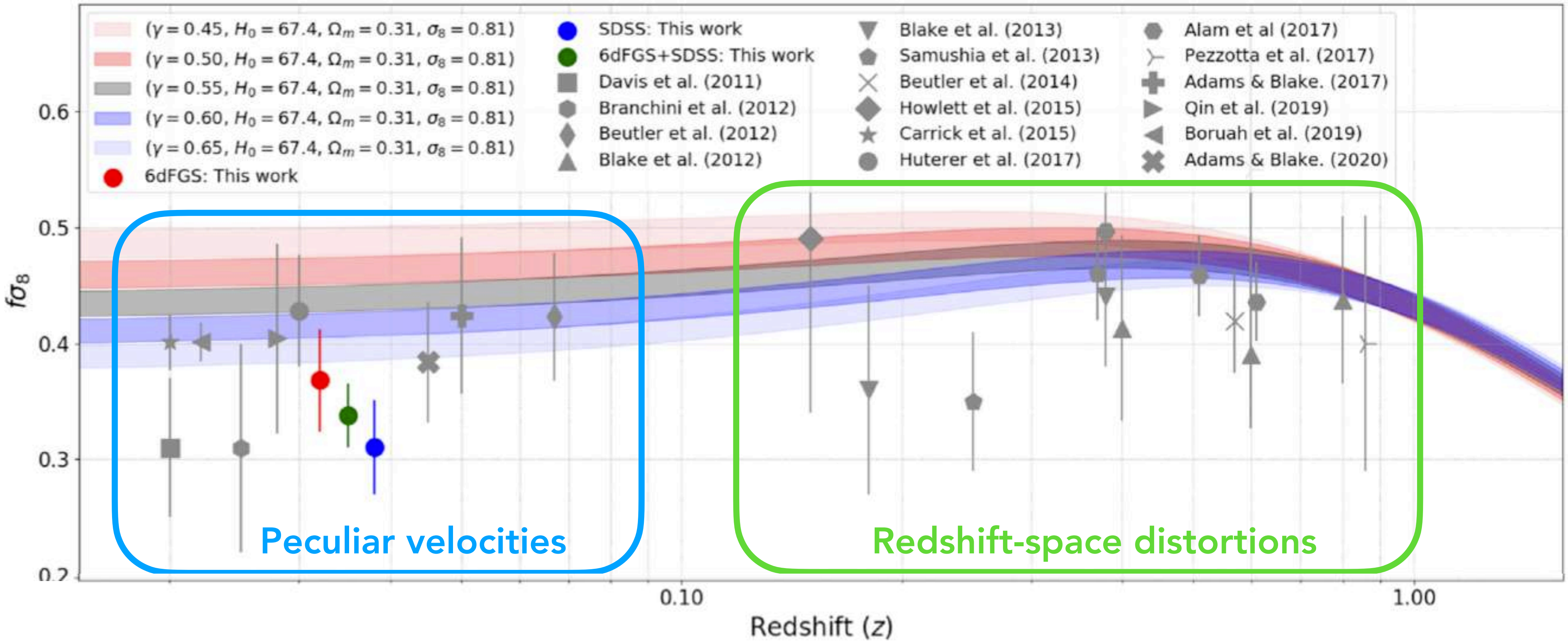
$$\vec{a} = [\delta, v_r](\vec{x})$$

Joint analysis:

$$\langle a(\vec{x})a(\vec{y})\rangle = \begin{pmatrix} P_{\delta\delta} & P_{\delta v} \\ P_{\delta v} & P_{vv} \end{pmatrix}$$

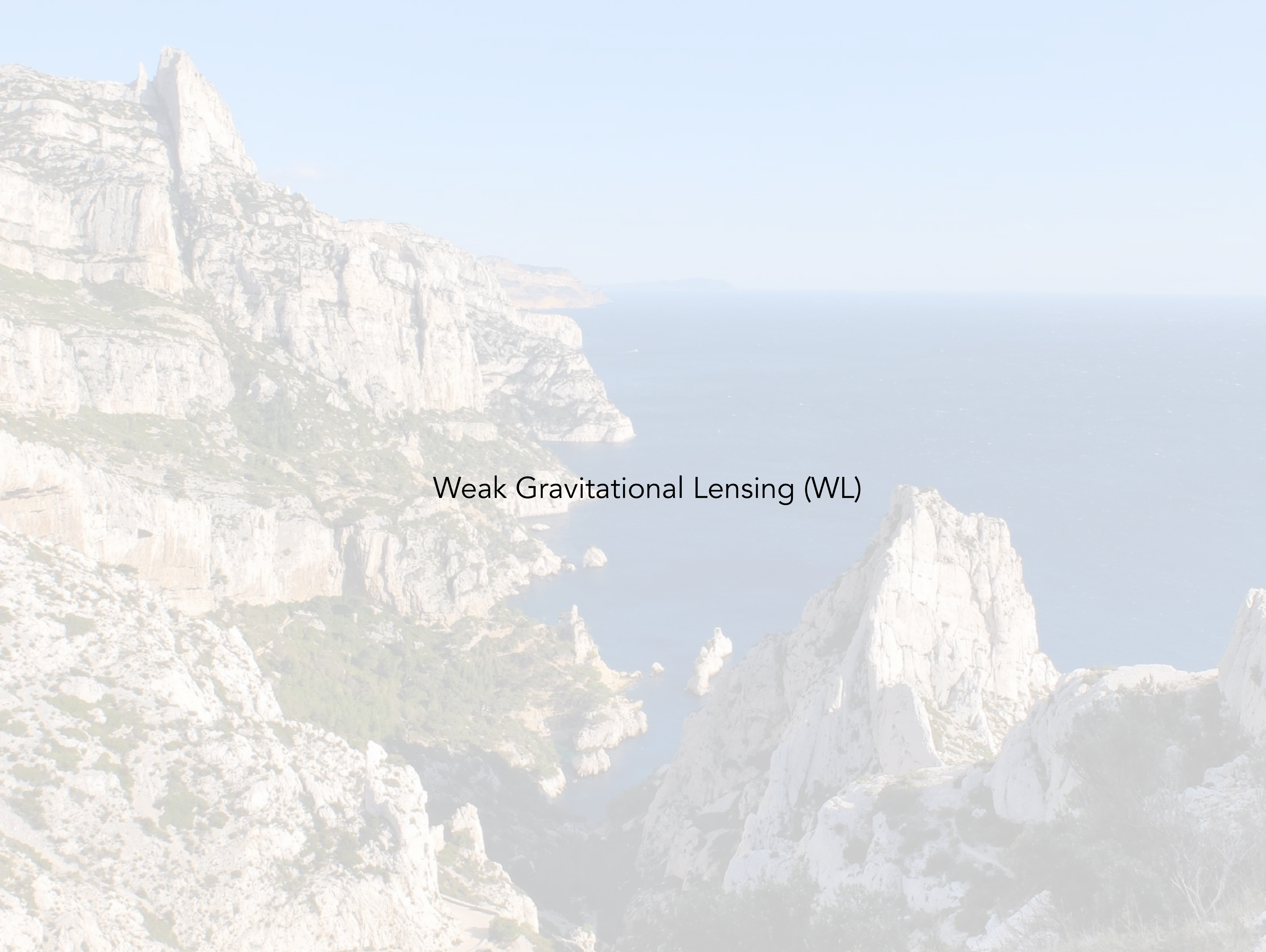
Methods to determine distances: Tully Fisher, Fundamental Plane, Type-Ia supernovae

Peculiar velocities



Said et al. 2020

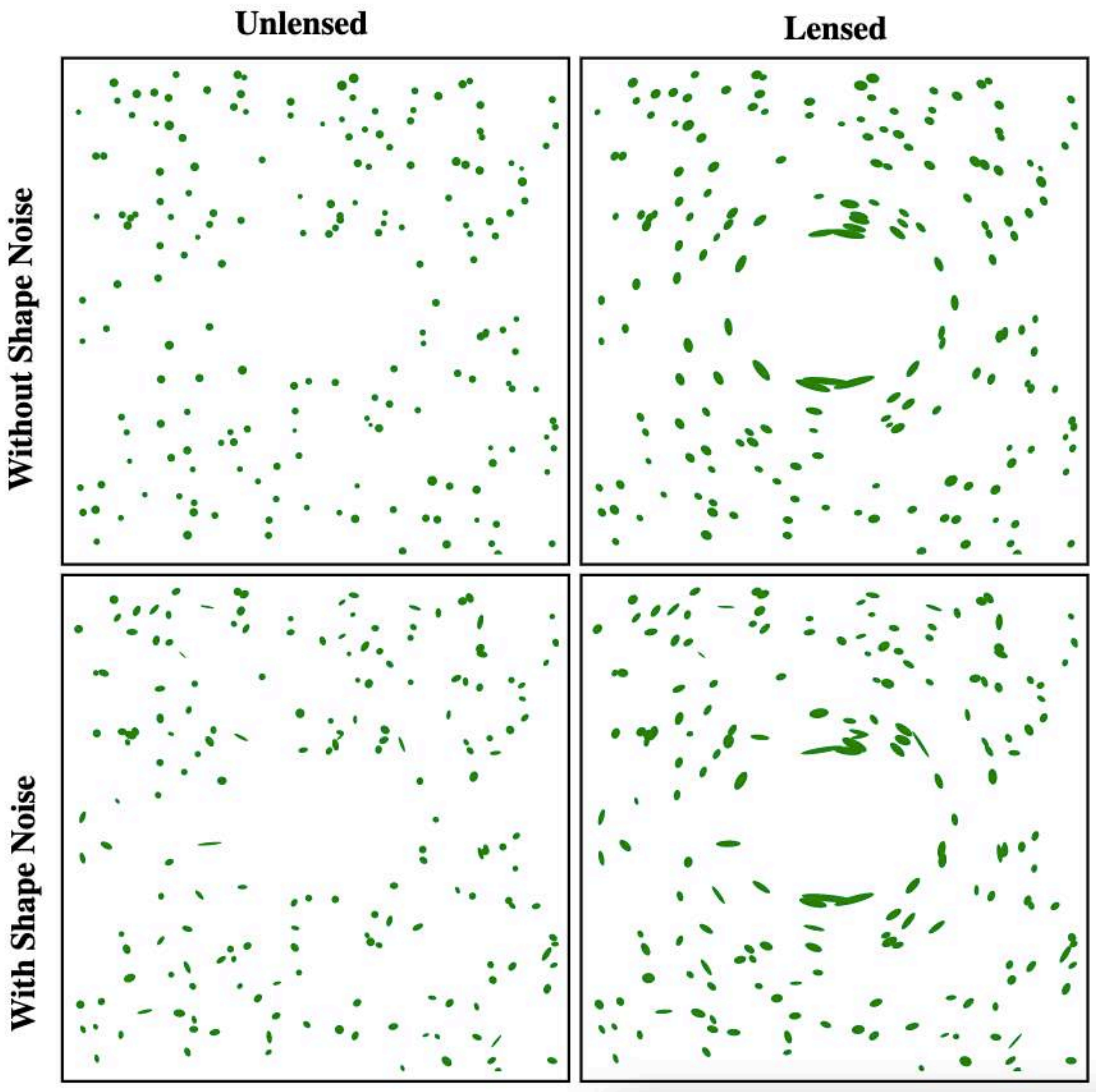
Promising information to test gravity at low redshifts



Weak Gravitational Lensing (WL)

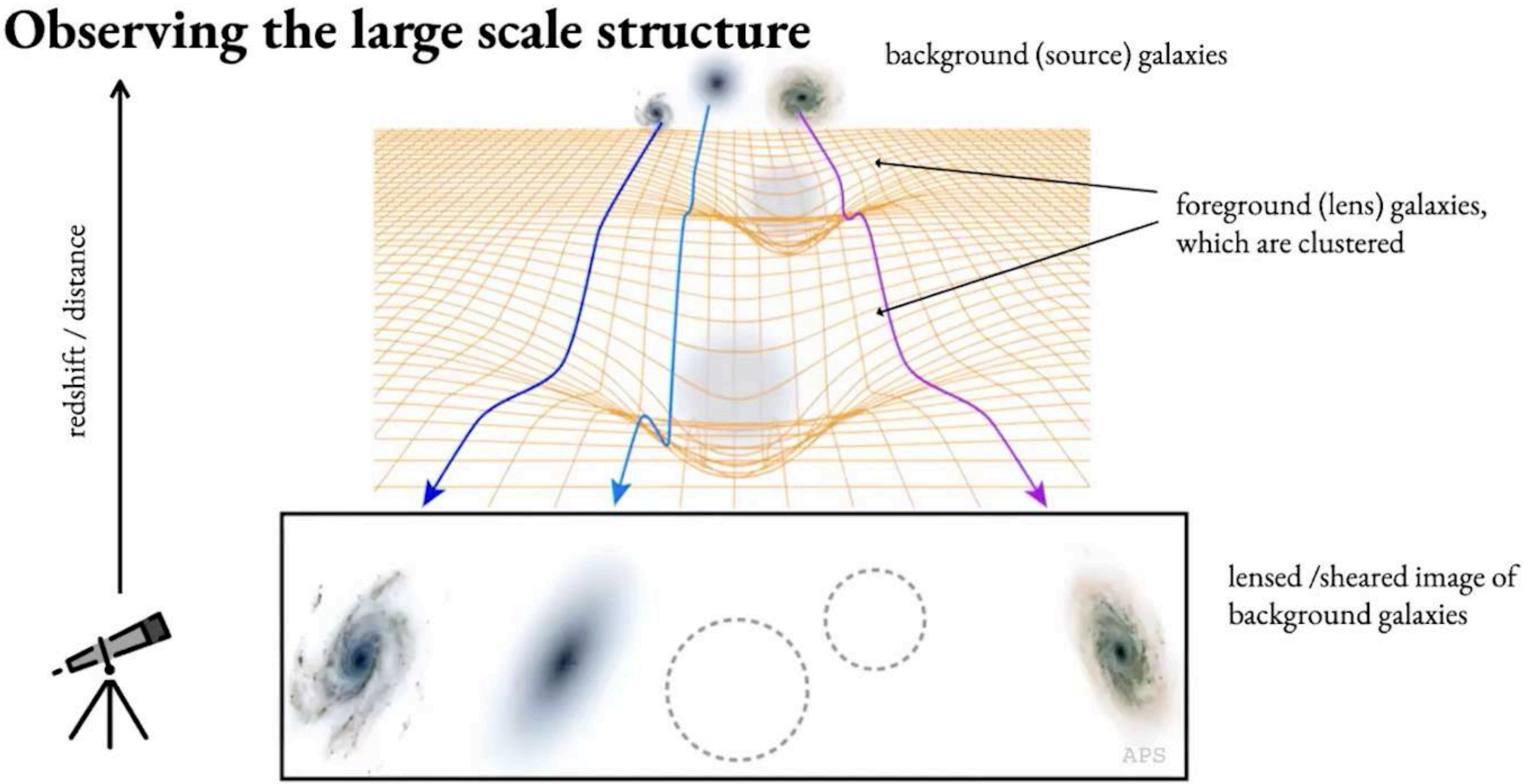
Weak Gravitational Lensing (WL)

What do we measure?
Shapes of galaxies in images



Weak Gravitational Lensing (WL)

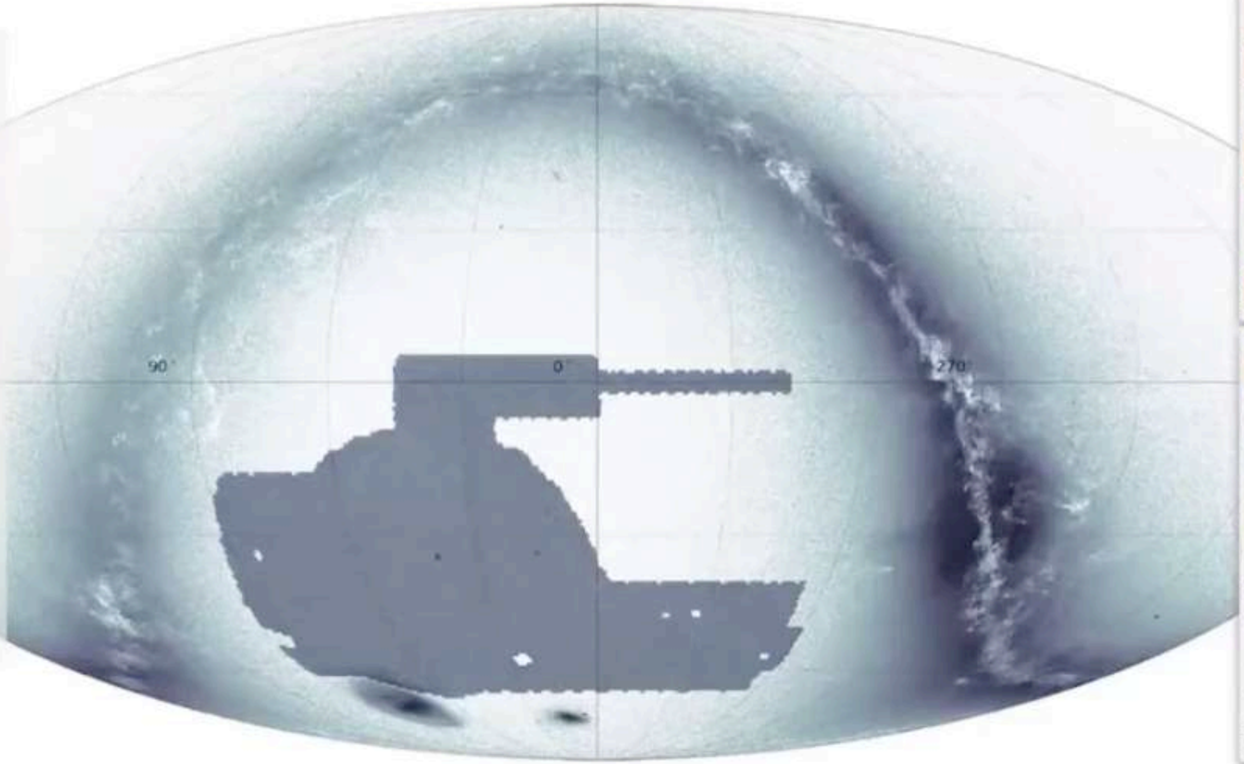
What do we measure?
Shapes of galaxies in images



https://www.youtube.com/watch?v=8aHbLMUOwLc

The Dark Energy Survey (DES)

- 570 Megapixel camera for the Blanco 4m telescope in Chile.
- Full survey 2013-2019 (Y3 2013-16).
- **Wide field:** 5000 sq. deg. in 5 bands. ~23 magnitude.
- DES Y3: Positions and shapes of > 100M galaxies.



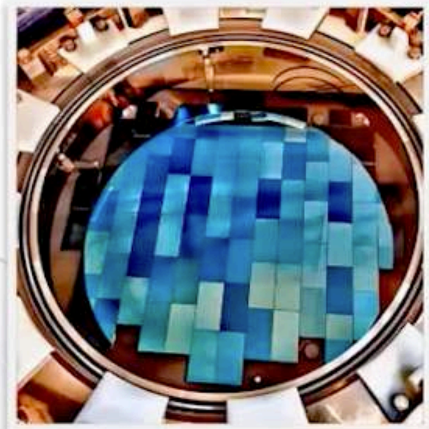
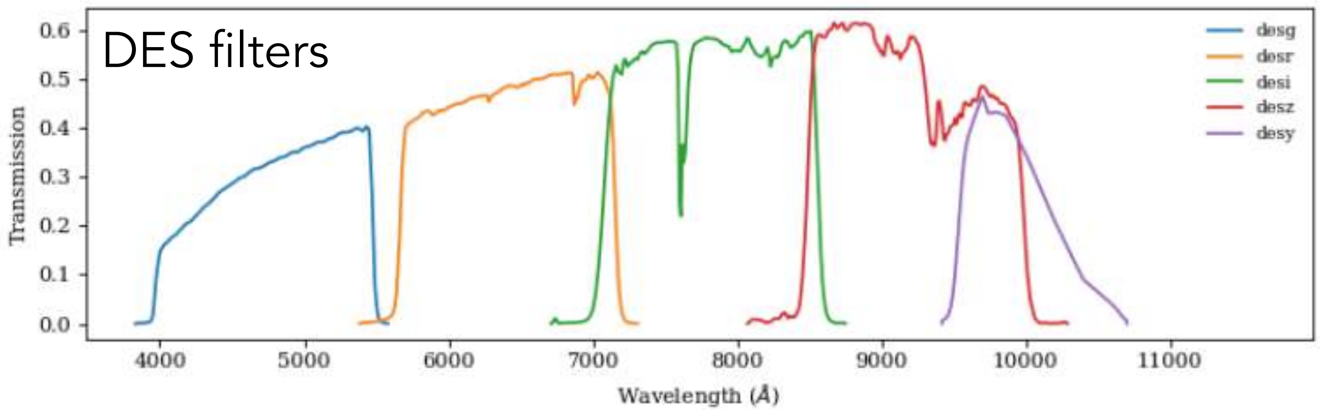
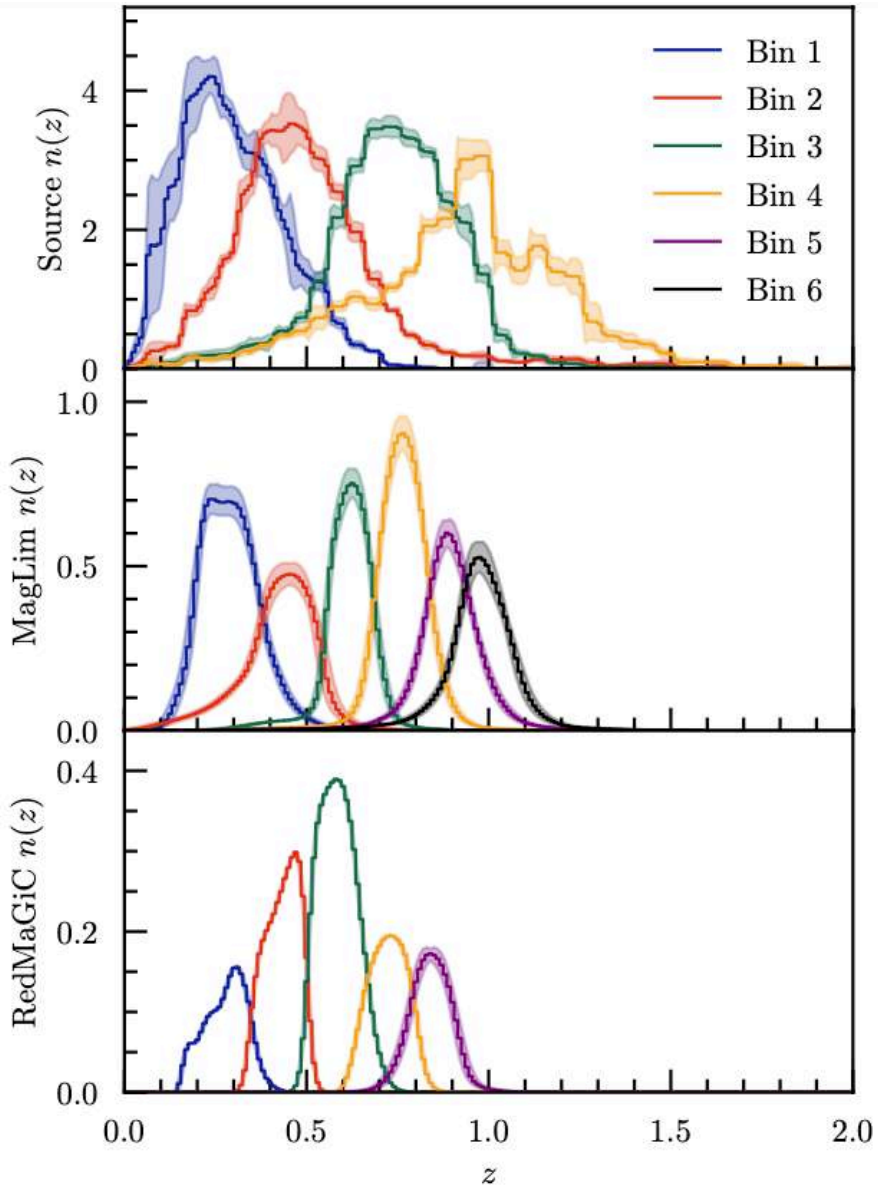


Image Credit: CosmoHub, Port d'Informació Científica (PIC)



Weak Gravitational Lensing (WL)

Photometric **redshifts** using 5 fluxes

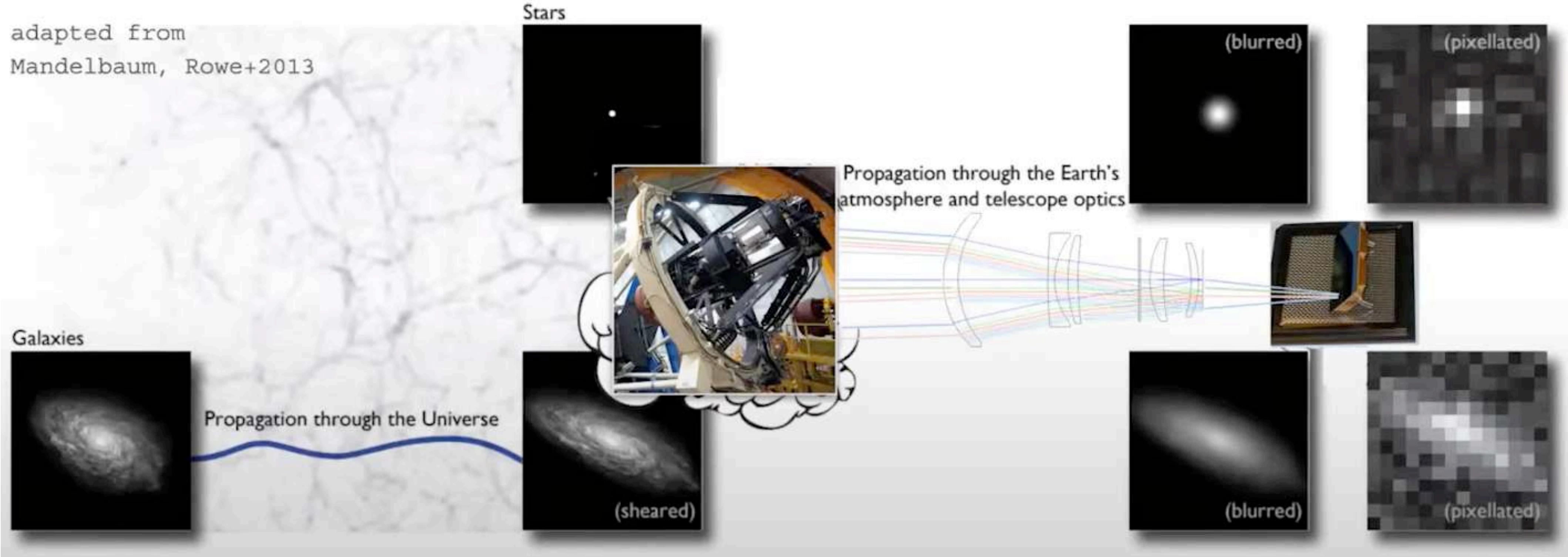


Cross-correlation with spectroscopic surveys to improve accuracy

Weak Gravitational Lensing (WL)

Measuring galaxy **shapes** for the shear

Jarvis+2021 https://github.com/rmjarvis/Piff



$$\underbrace{\bar{\epsilon}^{\mathrm{obs}}}_{\textit{observed ellipticity}} = (1 + \underbrace{m}_{\textit{multiplicative error}})\ \overbrace{\bar{\gamma}}^{\textit{lensing shear}} + \underbrace{c}_{\textit{additive error}}$$

DES measured the shape of 100 million galaxies

Weak Gravitational Lensing (WL)

We have galaxy positions and their shear, in a few redshift bins

3 x 2 point functions:

- galaxy positions x galaxy positions
- galaxy positions x galaxy lensing
- galaxy lensing x galaxy lensing

$$\hat{\mathbf{D}} \equiv \{\hat{w}^i(\theta), \hat{\gamma}_{\mathrm{t}}^{ij}(\theta), \hat{\xi}_{\pm}^{ij}(\theta)\}$$

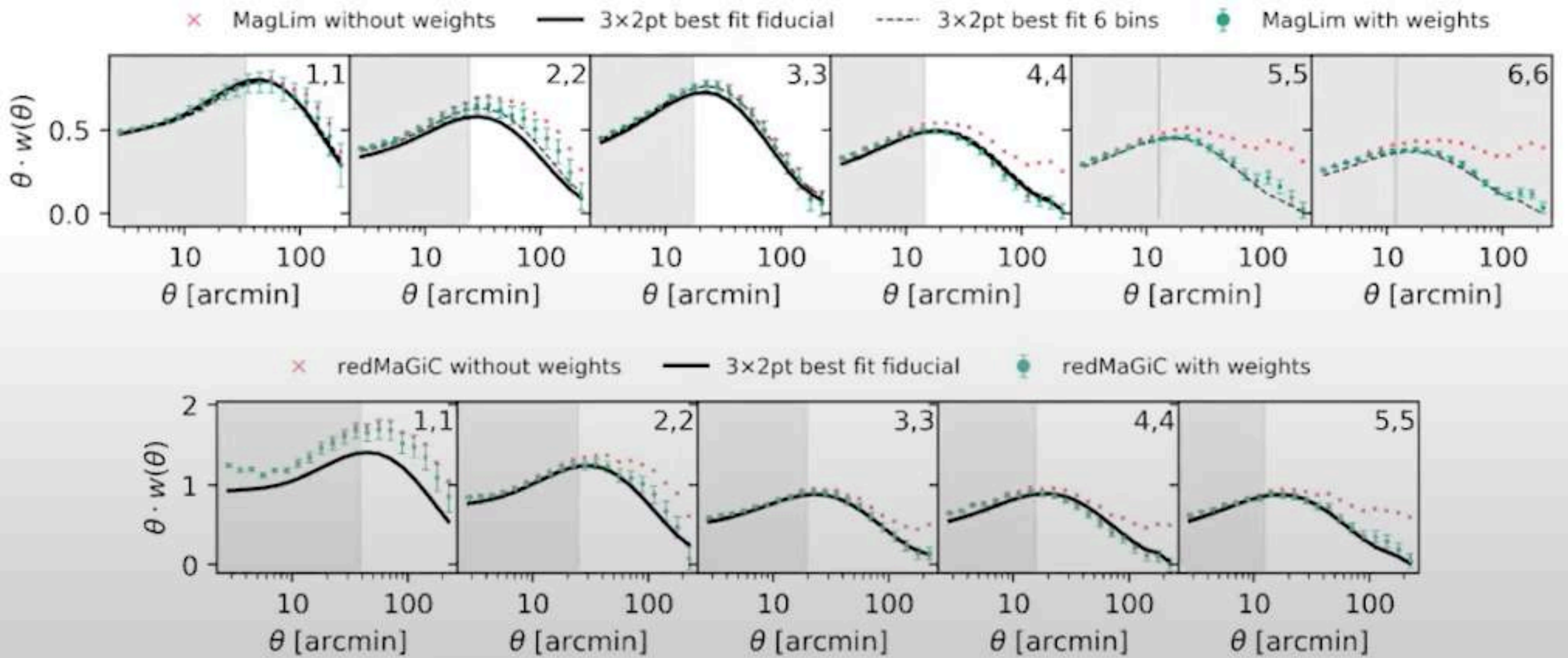
Weak Gravitational Lensing (WL)

We have galaxy positions and their shear, in a few redshift bins

3 x 2 point functions:

- **galaxy positions x galaxy positions**
- galaxy positions x galaxy lensing
- galaxy lensing x galaxy lensing

$$\hat{\mathbf{D}} \equiv \{\boxed{\hat{w}^i(\theta)}, \hat{\gamma}_t^{ij}(\theta), \hat{\xi}_{\pm}^{ij}(\theta)\}$$



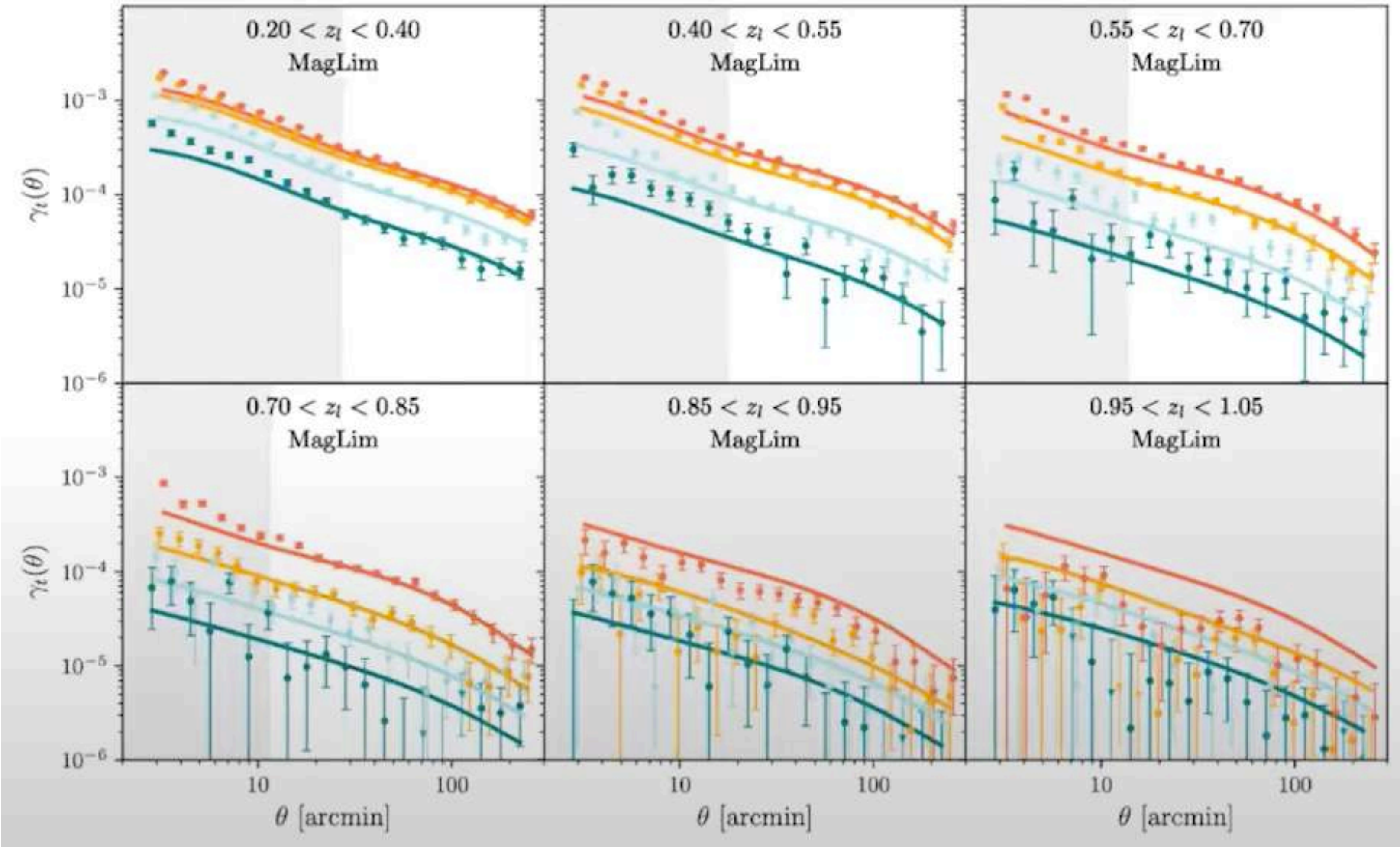
Weak Gravitational Lensing (WL)

We have galaxy positions and their shear, in a few redshift bins

3 x 2 point functions:

- galaxy positions x galaxy positions
- **galaxy positions x galaxy lensing**
- galaxy lensing x galaxy lensing

$$\hat{\mathbf{D}} \equiv \{\hat{w}^i(\theta), \boxed{\hat{\gamma}_{\rm t}^{ij}(\theta)}, \hat{\xi}_{\pm}^{ij}(\theta)\}$$

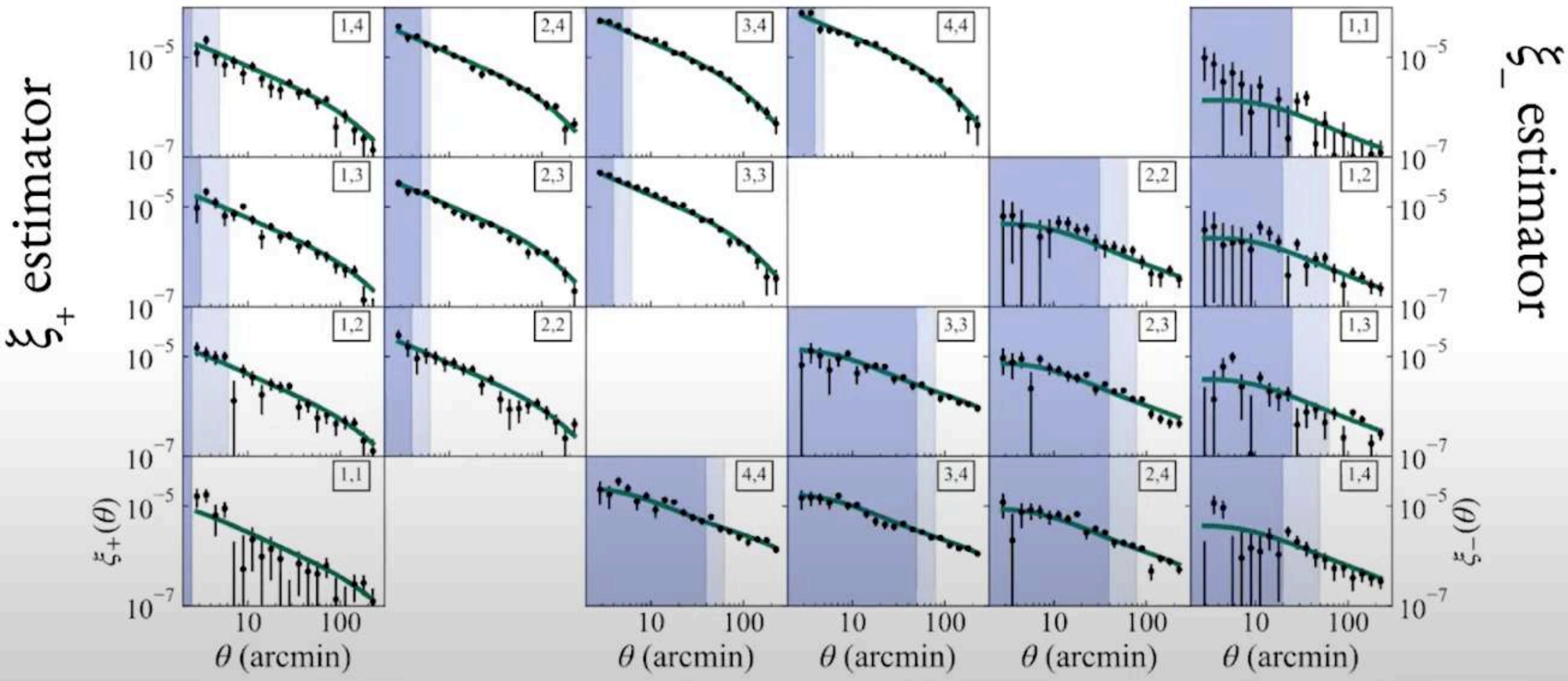


Weak Gravitational Lensing (WL)

We have galaxy positions and their shear, in a few redshift bins

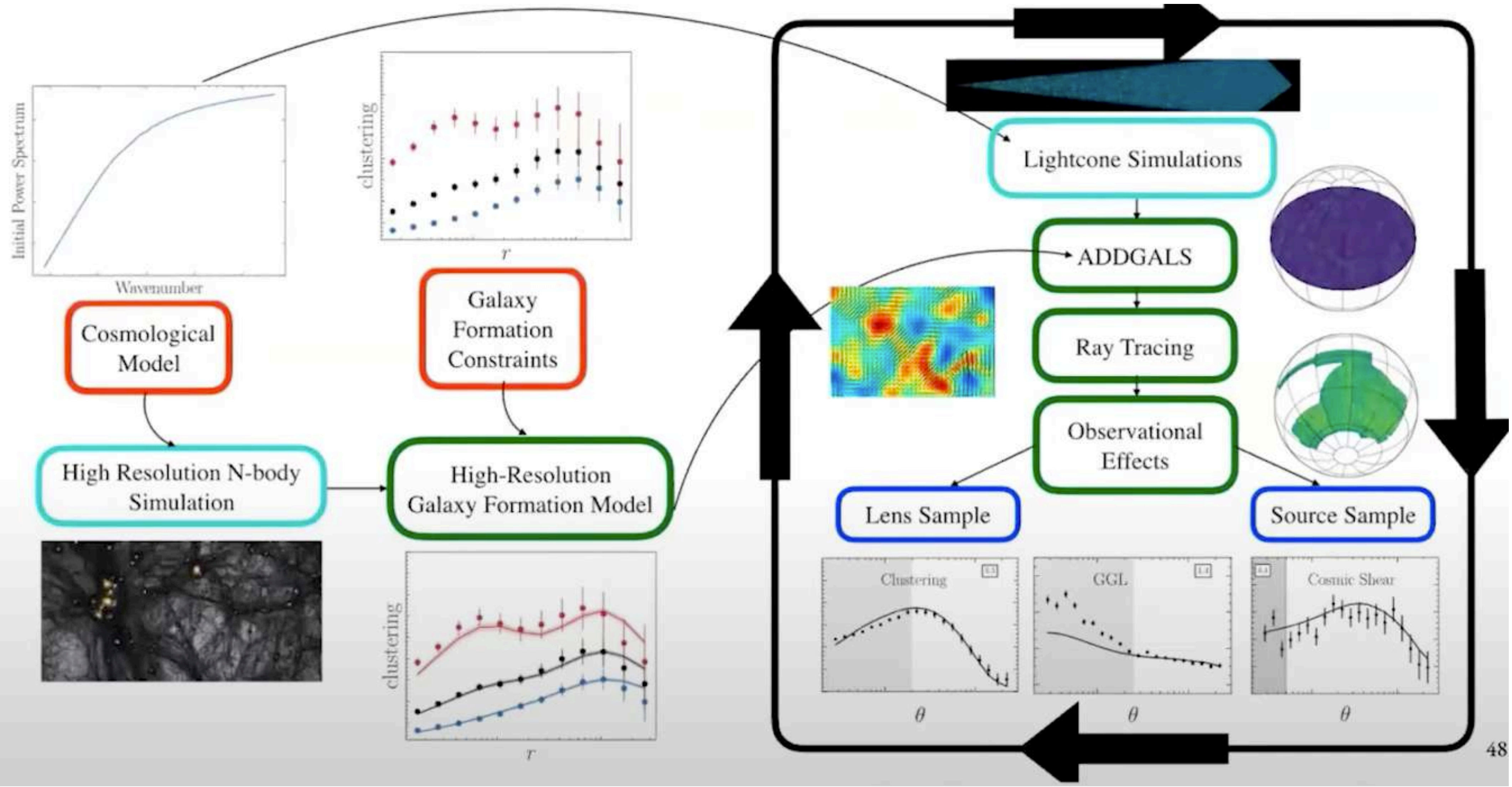
3 x 2 point functions:
- galaxy positions x galaxy positions
- galaxy positions x galaxy lensing
- **galaxy lensing x galaxy lensing**

$$\hat{\mathbf{D}} \equiv \{\hat{w}^i(\theta), \hat{\gamma}_t^{ij}(\theta), \boxed{\hat{\xi}_\pm^{ij}(\theta)}\}$$



Weak Gravitational Lensing (WL)

Simulations to test the analysis and model



Weak Gravitational Lensing (WL)

The model

Observed **density** of galaxies in a redshift bin: $\delta^i_{\rm obs}(\hat{\mathbf{n}}) = \delta^i_{\rm g}(\hat{\mathbf{n}}) + \delta^i_{\mu}(\hat{\mathbf{n}})$

Observed **shear** signal (gravity+intrinsic alignments): $\gamma^j_{\alpha}(\hat{\mathbf{n}}) = \gamma^j_{{\rm G},\alpha}(\hat{\mathbf{n}}) + \epsilon^j_{{\rm I},\alpha}(\hat{\mathbf{n}})$

In Fourier: $\gamma^j_{\rm E}(\ell) = \kappa^j(\ell) + \epsilon^j_{\rm I,E}(\ell)\,,\qquad \gamma^j_{\rm B}(\ell) = \epsilon^j_{\rm I,B}(\ell)$

Convergence field: $\kappa^j(\hat{\mathbf{n}}) = \int d\chi\, W^j_{\kappa}(\chi)\underbrace{\delta_{\rm m}}_{\text{baryons + dark matter}}(\hat{\mathbf{n}}\chi, \chi)$

Lensing kernel: $W^j_{\kappa}(\chi) = \frac{3\Omega_{\rm m}H_0^2}{2}\int_{\chi}^{\chi_H} d\chi' \underbrace{n^j_{\rm s}}_{\text{number density of galaxies}}(\chi')\frac{\chi}{a(\chi)}\frac{\chi'-\chi}{\chi'}$

Angular cross power spectra: $C^{ij}_{AB}(\ell) = \int d\chi \frac{W^i_A(\chi)W^j_B(\chi)}{\chi^2}P_{AB}\left(k=\frac{\ell+\frac{1}{2}}{\chi}, z(\chi)\right)$

Weak Gravitational Lensing (WL)

The model

Lensing kernel: $$W^j_\kappa(\chi) = \frac{3\Omega_\mathrm{m} H_0^2}{2} \int_\chi^{\chi_H} d\chi' n^j_\mathrm{s}(\chi') \frac{\chi}{a(\chi)} \frac{\chi' - \chi}{\chi'}$$

number density of galaxies

Angular cross power spectra: $$C^{ij}_{AB}(\ell) = \int d\chi \frac{W^i_A(\chi) W^j_B(\chi)}{\chi^2} P_{AB}\left(k = \frac{\ell + \frac{1}{2}}{\chi}, z(\chi)\right)$$

3D power spectrum (matter or convergence)

Convert back to configuration space:

$$w^i(\theta) = \sum_\ell \mathcal{G}_0\left(\ell, \theta_\mathrm{min}, \theta_\mathrm{max}\right) C^{ii}_{\delta_\mathrm{obs}\delta_\mathrm{obs}}(\ell)$$

$$\gamma^{ij}_\mathrm{t}(\theta) = \sum_\ell \mathcal{G}_2\left(\ell, \theta_\mathrm{min}, \theta_\mathrm{max}\right) C^{ij}_{\delta_\mathrm{obs}\mathrm{E}}(\ell)$$

$$\xi^{ij}_\pm(\theta) = \sum_\ell \mathcal{G}_{4,\pm}\left(\ell, \theta_\mathrm{min}, \theta_\mathrm{max}\right) \left[C^{ij}_\mathrm{EE}(\ell) \pm C^{ij}_\mathrm{BB}(\ell)\right]$$

Done! Compare to data! $$\hat{\mathbf{D}} \equiv \{\hat{w}^i(\theta), \hat{\gamma}^{ij}_\mathrm{t}(\theta), \hat{\xi}^{ij}_\pm(\theta)\}$$

Weak Gravitational Lensing (WL)

The model

Lensing kernel: $$W_\kappa^j(\chi) = \frac{3\Omega_\mathrm{m} H_0^2}{2} \int_\chi^{\chi_H} d\chi' n_\mathrm{s}^j(\chi') \frac{\chi}{a(\chi)} \frac{\chi' - \chi}{\chi'}$$

number density of galaxies

Angular cross power spectra: $$C_{AB}^{ij}(\ell) = \int d\chi \frac{W_A^i(\chi) W_B^j(\chi)}{\chi^2} P_{AB}\left(k = \frac{\ell + \frac{1}{2}}{\chi}, z(\chi)\right)$$

3D power spectrum (matter or convergence)

The amplitude of the signal mainly depends on:

$$S_8 = \sigma_8 \sqrt{\Omega_m / 0.3}$$

Weak Gravitational Lensing (WL)

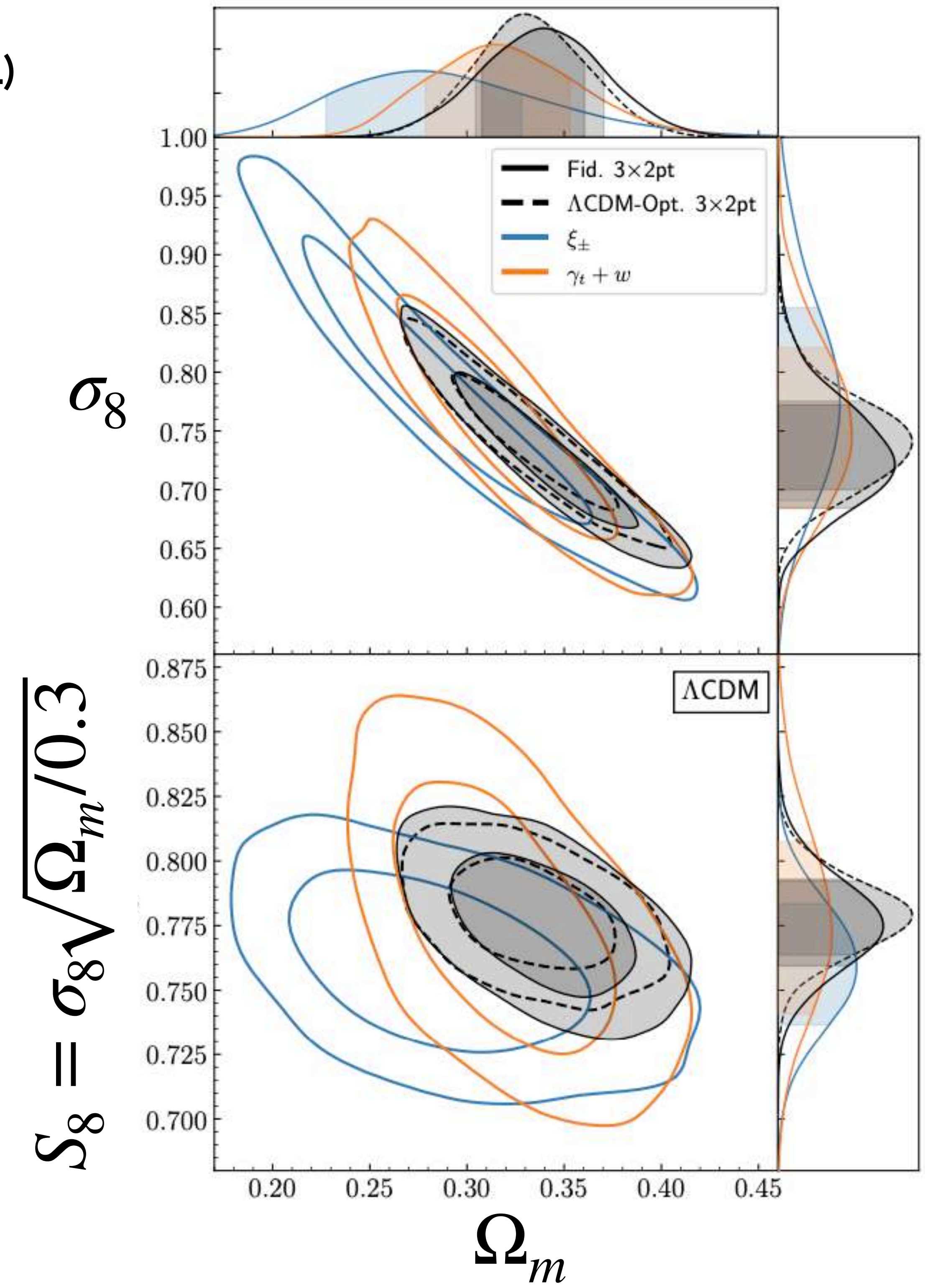
Cosmological constraints
from DES 3 years

$$S_8 = 0.776^{+0.017}_{-0.017} \quad (0.776)$$

$$\Omega_\mathrm{m} = 0.339^{+0.032}_{-0.031} \quad (0.372)$$

$$\sigma_8 = 0.733^{+0.039}_{-0.049} \quad (0.696)$$

DES Collaboration 2021

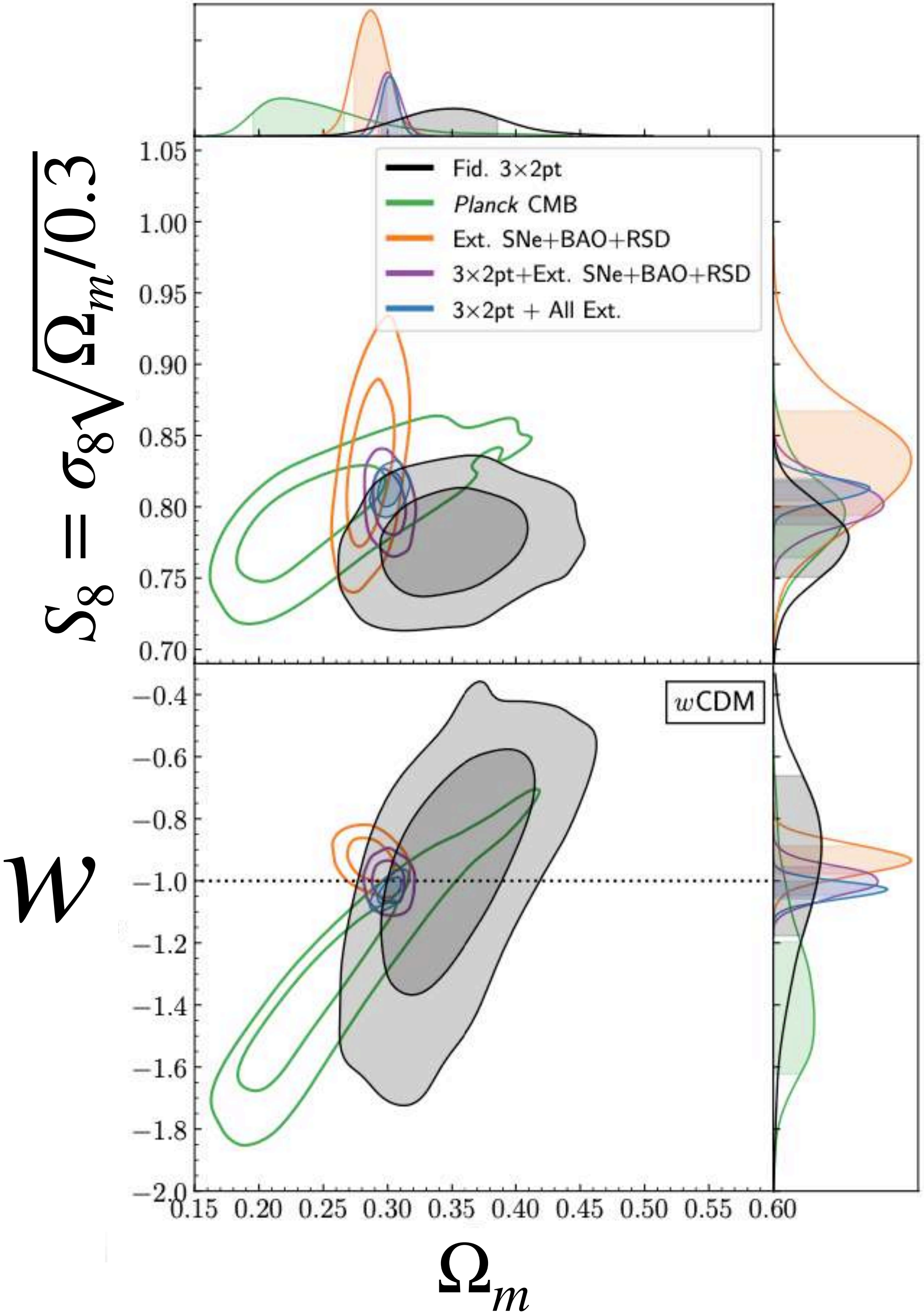


Weak Gravitational Lensing (WL)

Cosmological constraints
from DES 3 years

$$\Omega_\mathrm{m} = 0.352^{+0.035}_{-0.041} \quad (0.339),$$
$$w = -0.98^{+0.32}_{-0.20} \quad (-1.03).$$

DES Collaboration 2021



Testing modified gravity
Redshift-space distortions (RSD) + Weak gravitational lensing (WL)

Scalar metric perturbations in the conformal Newtonian gauge : $ds^2 = a^2(\tau)[(1+2\Psi)d\tau^2 - (1-2\Phi)\delta_{ij}dx_i dx_j]$

$$k^2\Psi = -4\pi G a^2(1+\mu(a))\rho\delta,$$

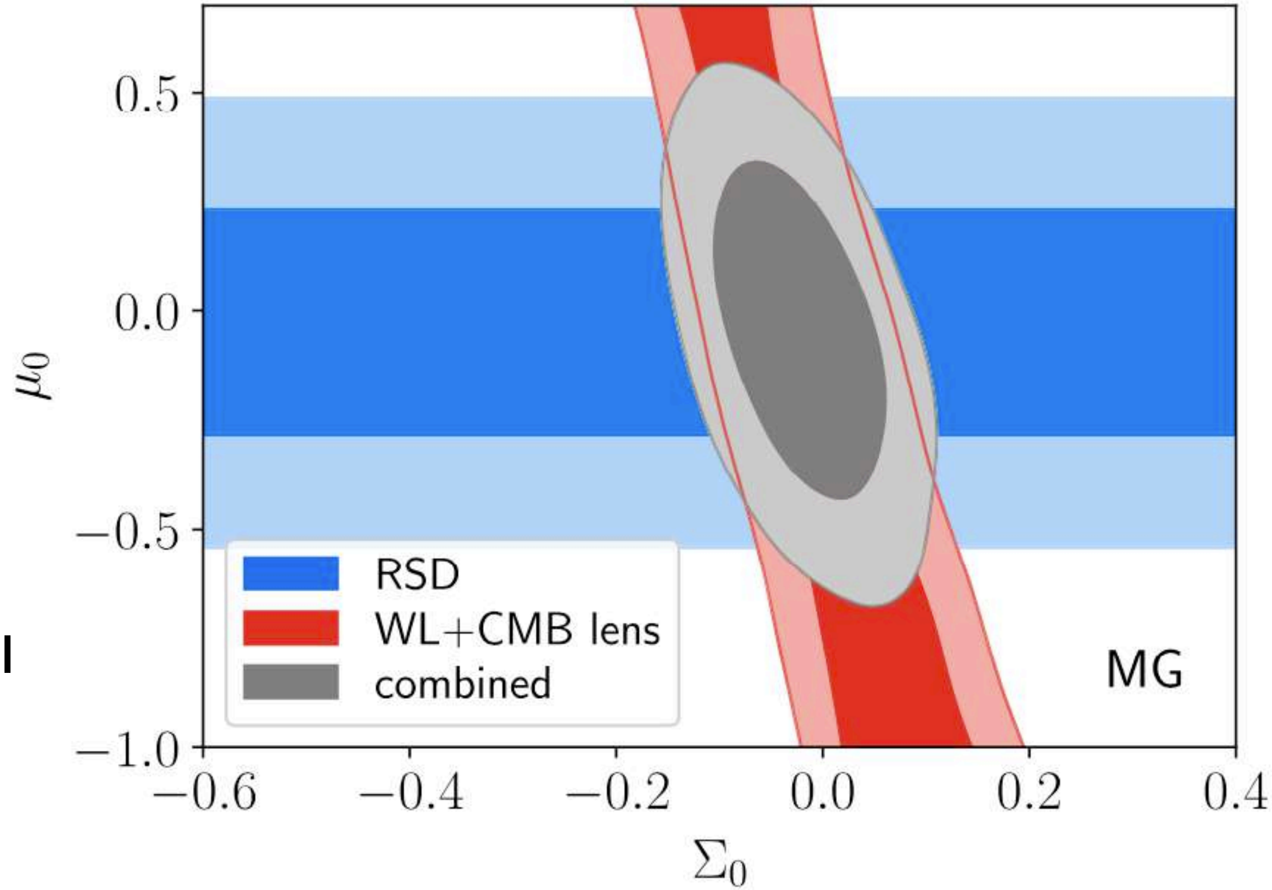
$$k^2(\Psi+\Phi) = -8\pi G a^2(1+\Sigma(a))\rho\delta,$$

where $\mu(a) = \Sigma(a) = 0$ in GR

Choosing :

$$\mu(z) = \mu_0 \frac{\Omega_\Lambda(z)}{\Omega_\Lambda},$$

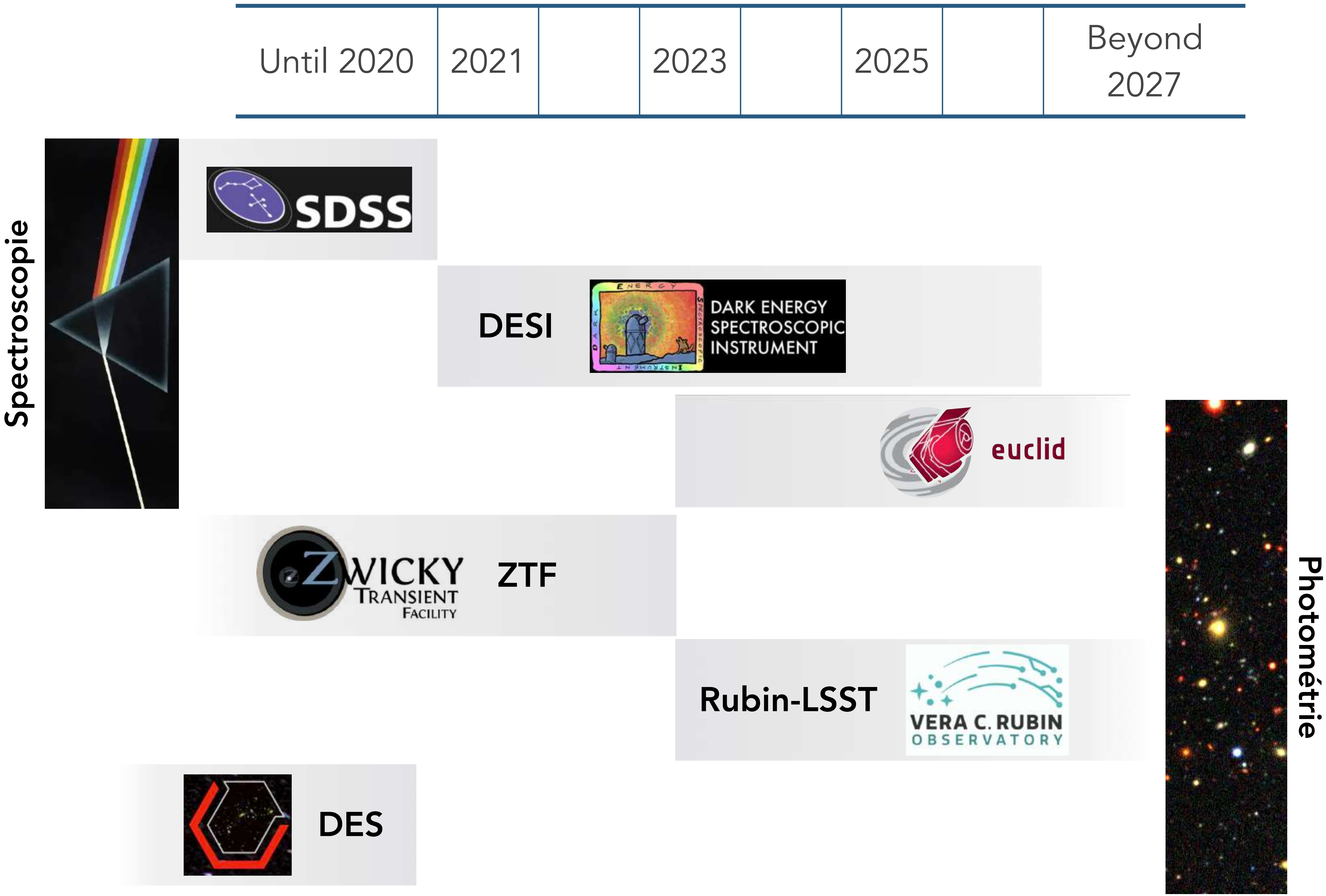
$$\Sigma(z) = \Sigma_0 \frac{\Omega_\Lambda(z)}{\Omega_\Lambda}$$



RSD and WL are both essential for testing GR !

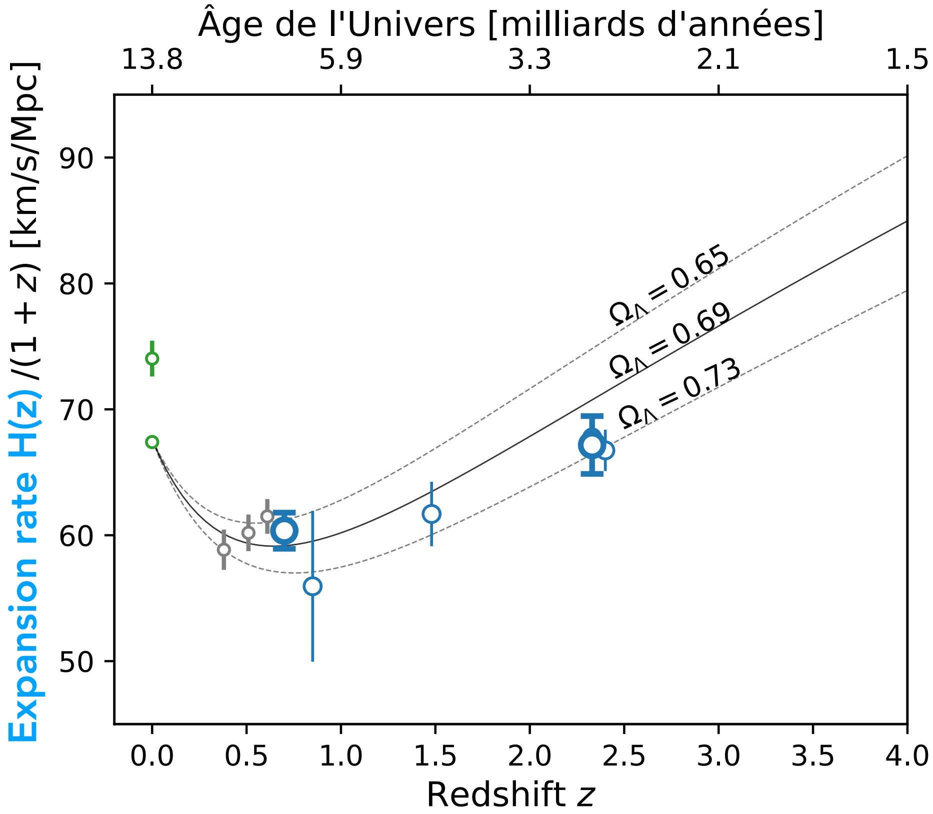
Future

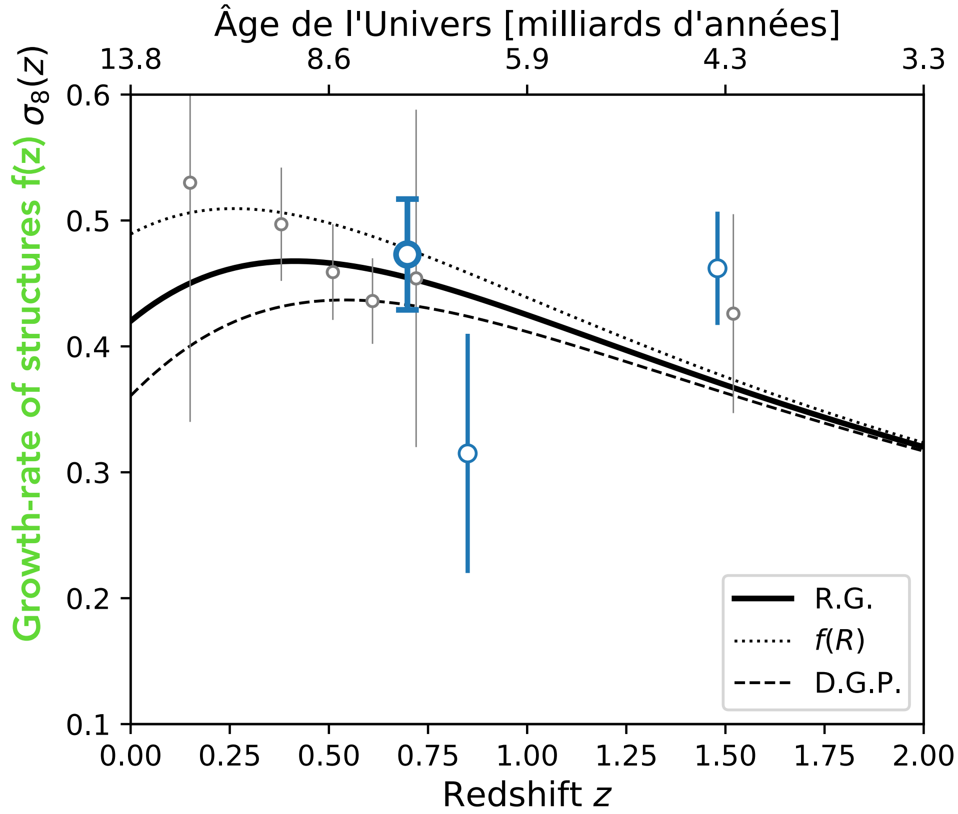
Future of optical cosmology



Expansion rate with BAO

Growth-rate of structures with RSD and peculiar velocities

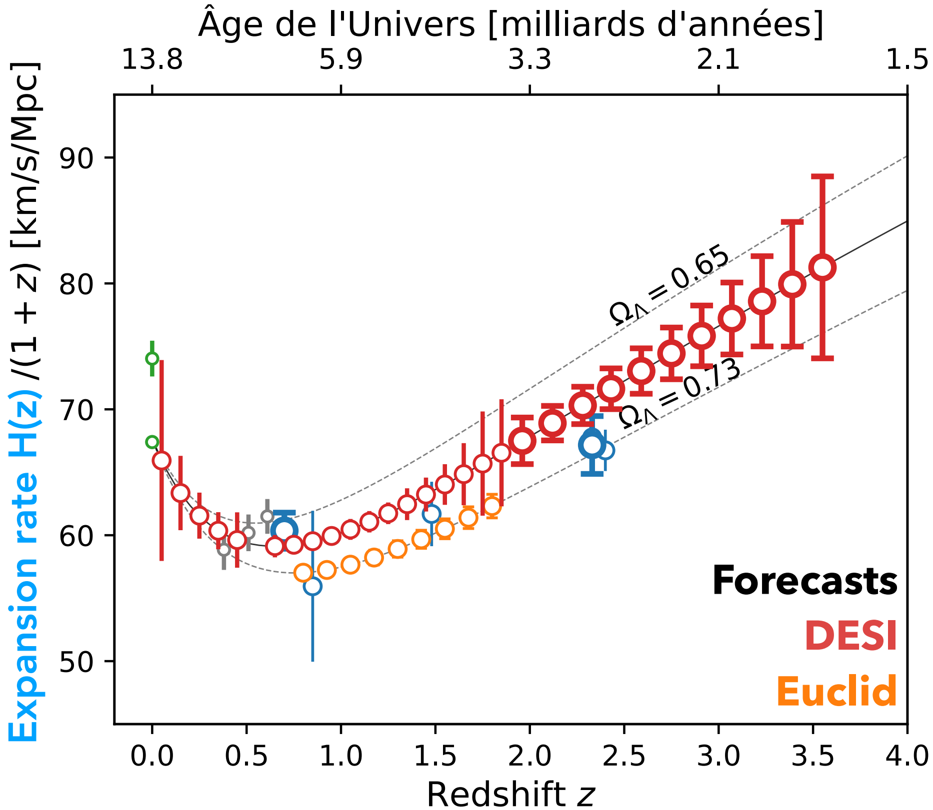


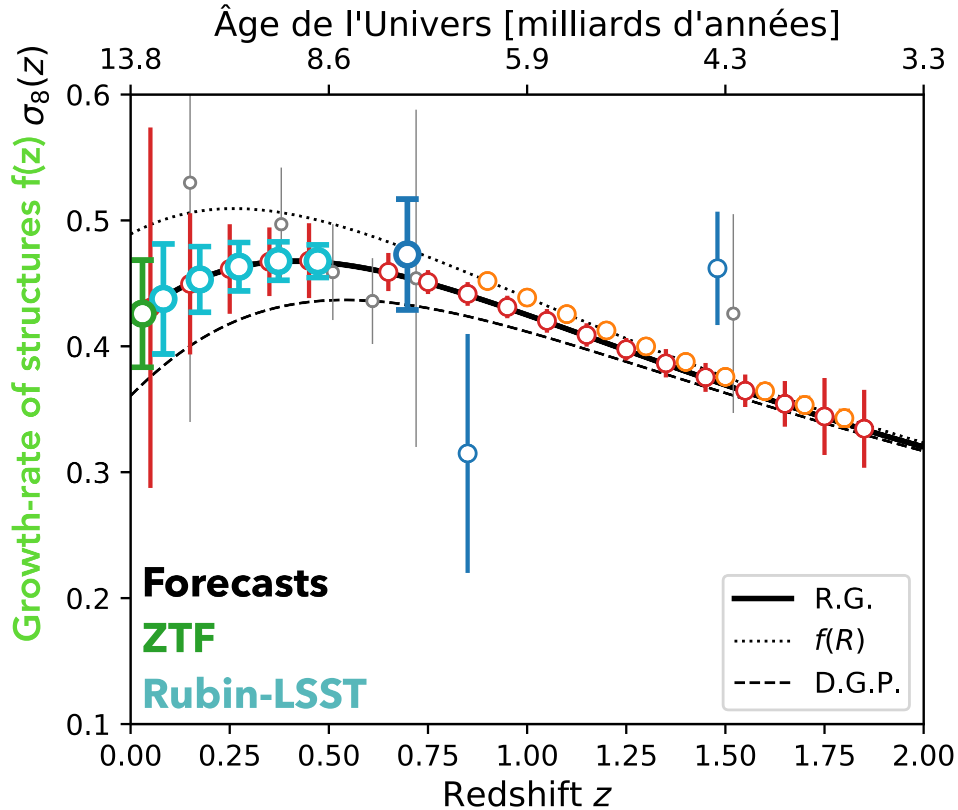


Future cosmological constraints

Expansion rate with BAO

Growth-rate of structures with RSD and peculiar velocities





We hope we can learn more about dark energy !

Future

Other optical future projects : Roman Space Telescope, Mauna Kea Spectroscopic Explorer (MSE)

Radio and CMB: Square Kilometre Array (SKA), LiteBird, Simons Observatory, CMB-S4

Gravitational waves: LISA

and many more...

Cosmological probes of gravity

Lecture 3

Observing the sky

The Hubble constant (H_0)

Big Bang Nucleosynthesis (BBN)

Type-Ia supernovae (SNIa)

Baryon acoustic oscillations (BAO)

Lecture 4

Cosmic microwave background (CMB)

Redshift-space distortions (RSD)

Weak gravitational lensing (WL)

The future

Based on "*Modern Cosmology*" by Dodelson & Schmidt 2019
"*Observational probes of cosmic acceleration*" by Weinberg et al. 2013