Cosmology and Neutrinos

Masahiro Takada (Kavli IPMU)

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

wpi

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Cosmology goals of neutrino physics in the next decade

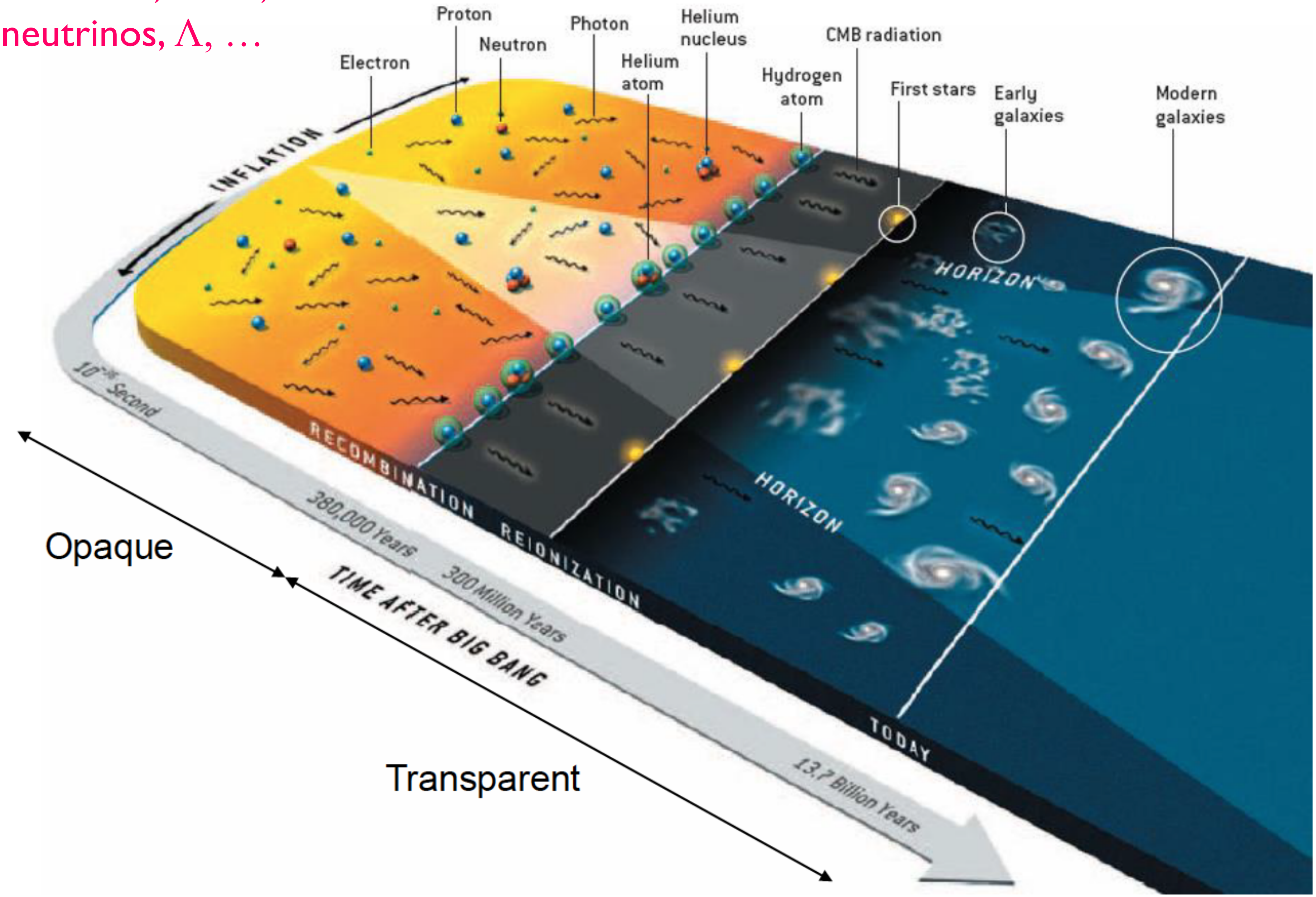
- With upcoming cosmology datasets (CMB, galaxy surveys), we aim at achieving
  - Constrain the relativistic degrees of freedom (e.g., sterile neutrinos or axion): $\sigma(N_{\rm eff}) \simeq 0.027$
  - Determine neutrino mass (the sum of three-species neutrino masses): $\sigma(m_{\nu,{\rm tot}}) \simeq 0.02~{\rm eV}$

complementary to double-beta decay exp.

- These are clear targets (no new physics needed)
- Challenges: systematic errors (e.g., galaxy bias, other astrophysics effects)

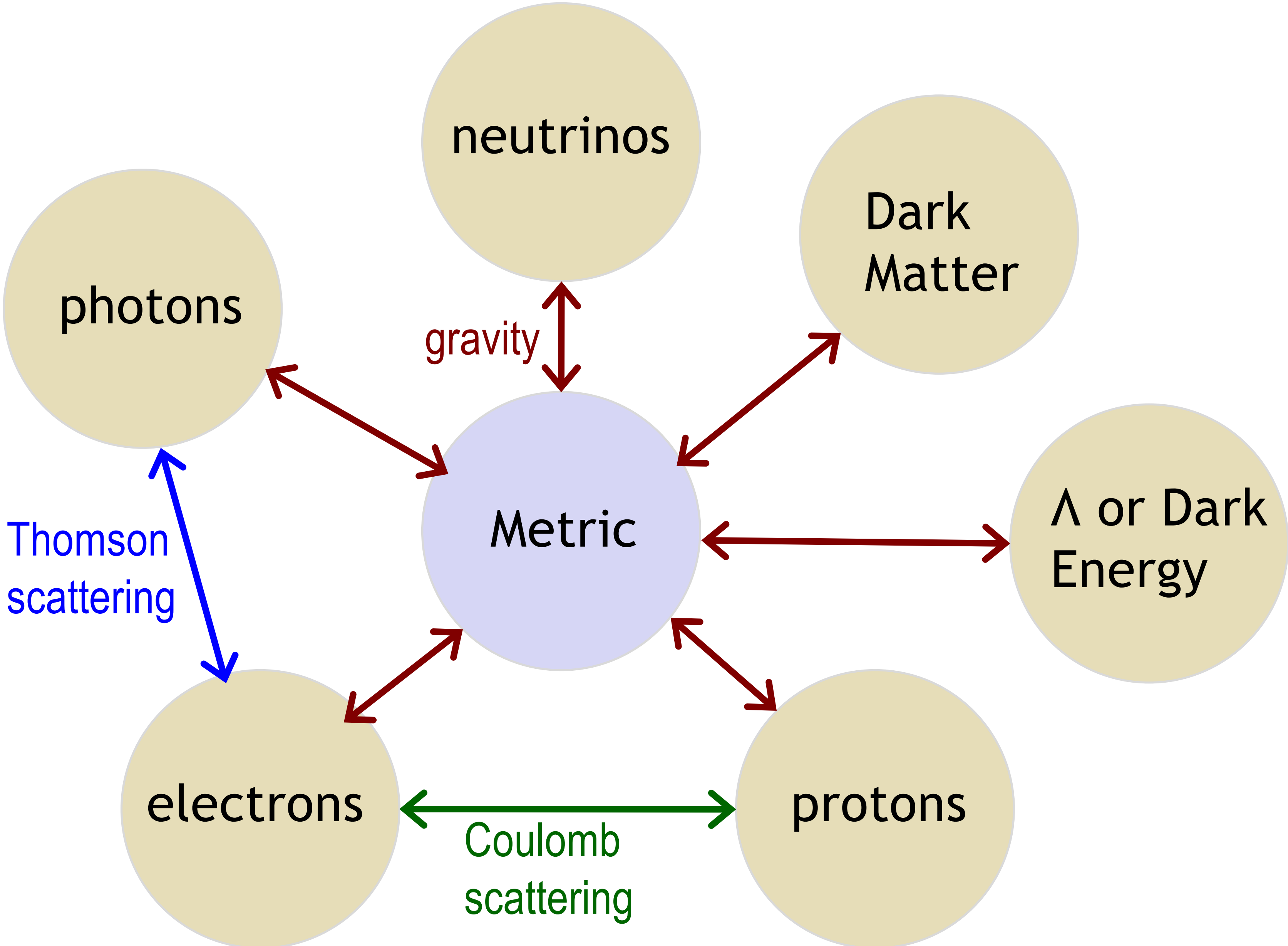
photons, baryon, electrons, CDM, neutrinos, Λ, …

Evolution of the universe



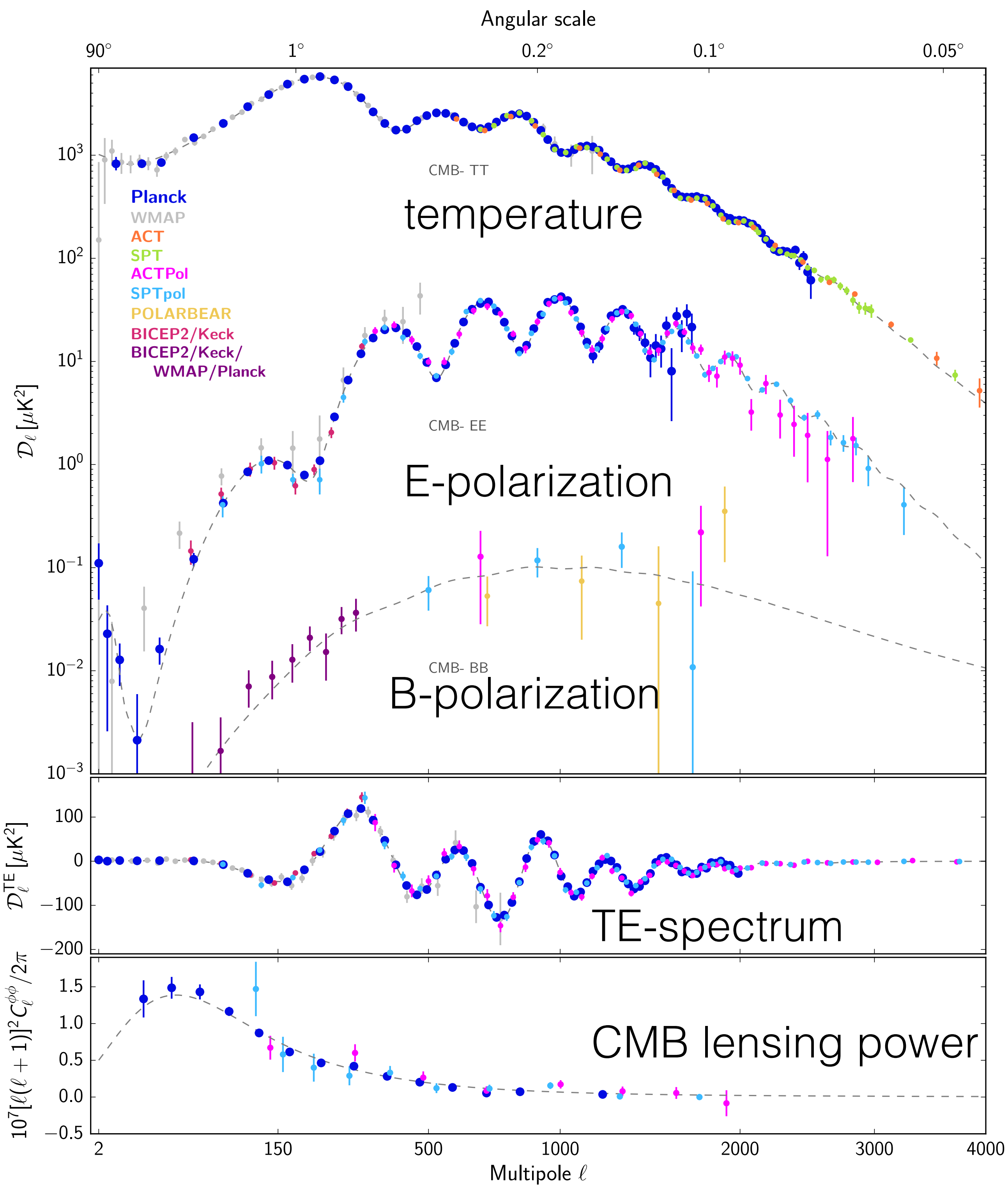
Hu & White, Sci. Am., 290 44 (2004)

Physics of large-scale structure formation



Need to solve the multi-component system before the recombination (z~1100)

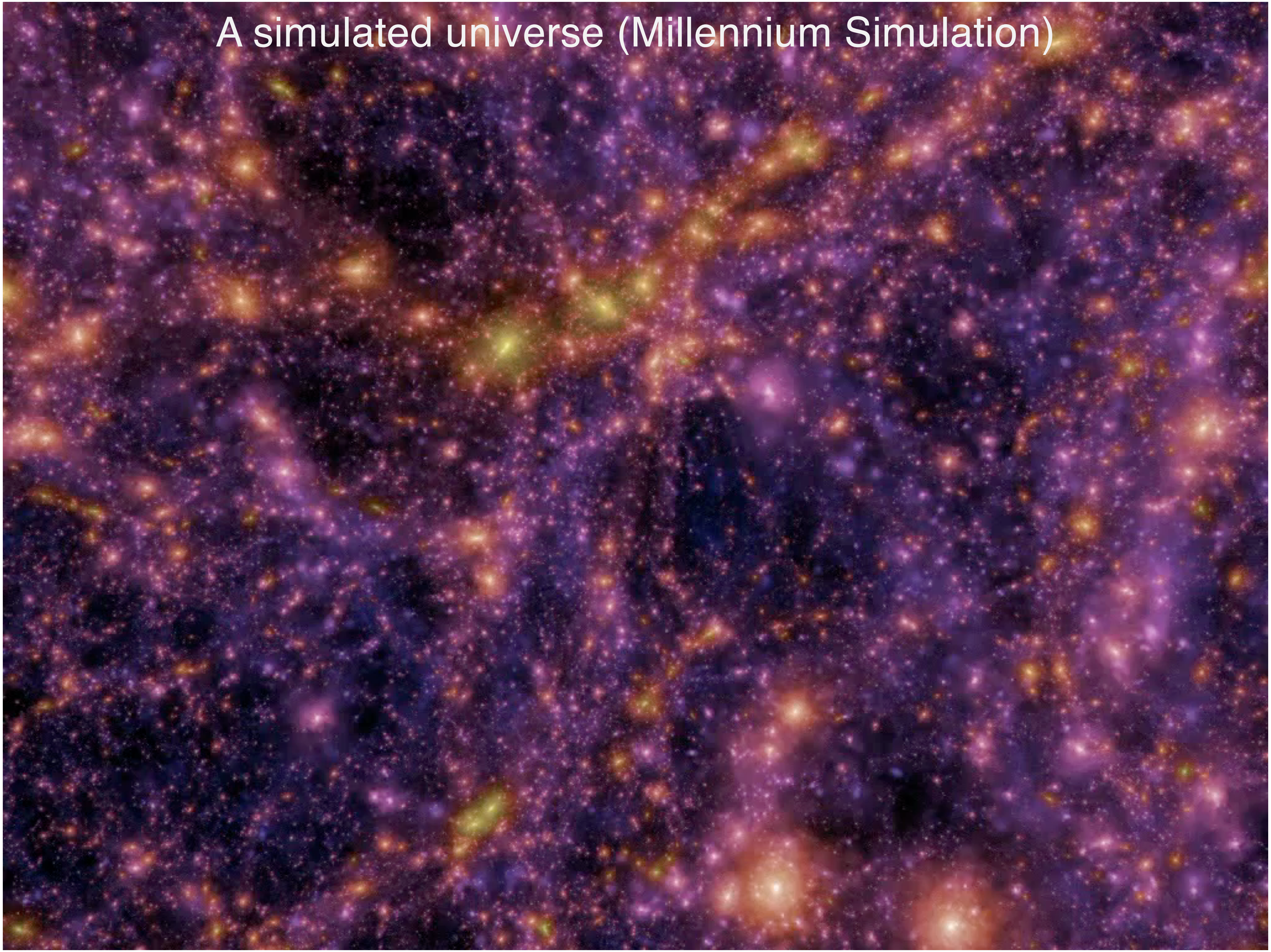
Precision Cosmology



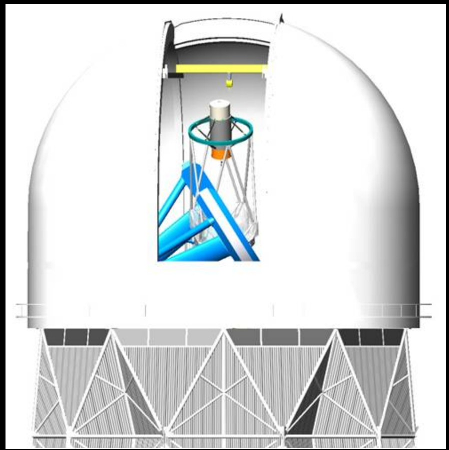
Planck 2018 (note; the paper has yet to be accepted)

Imaging + Spectroscopy (1.5M gals for 2.5m SDSS)

Subaru HSC+PFS can probe the 3D Universe at z~1!

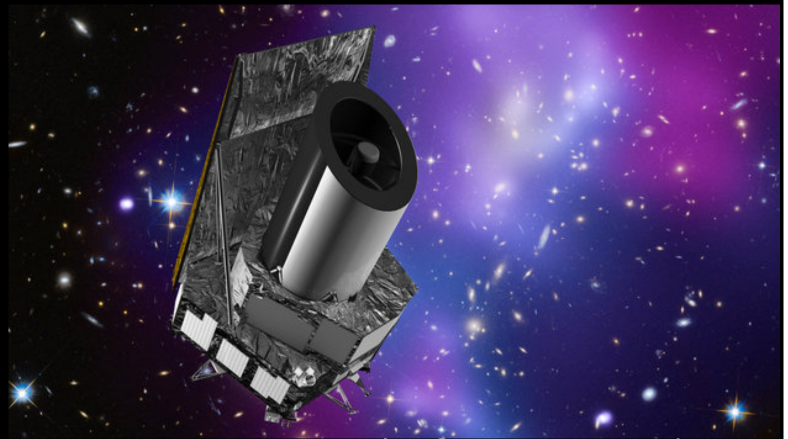

A simulated universe (Millennium Simulation)

Wide-area galaxy surveys (now – 2030)

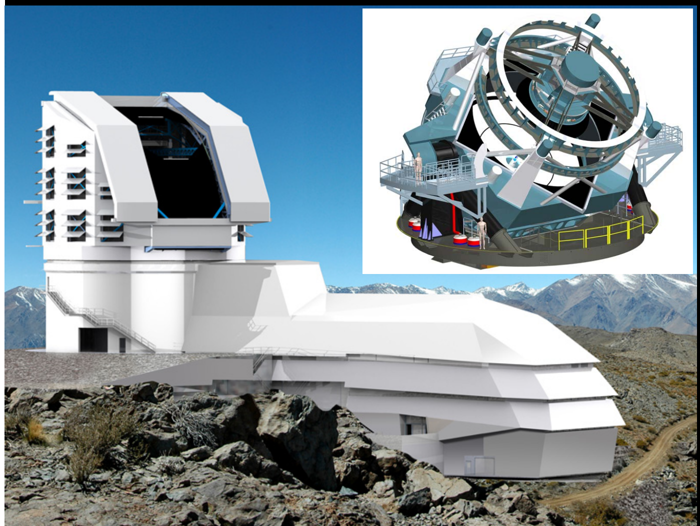


DESI (4m, LBL, 2019-)

SuMIRe (2015-25)

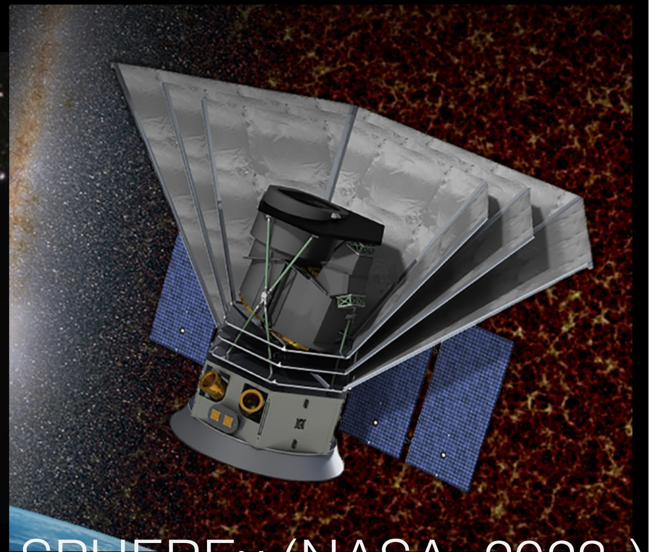


Euclid (ESA, 2022-)



LSST (6.5m, SLAC, 2022-)

WFIRST (NASA, 2025-)



SPHEREx (NASA, 2023-)

Interdisciplinary fields between particle physics and cosmology

$$N_{\mathrm{eff}}$$

N_{eff} effect on cosmological observables (CMB and galaxy BAO)

$$H^2 \propto \rho_{\rm cdm} + \rho_b + \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

- Changes the matter-radiation equality epoch
- Changes the sound horizon of photon-baryon plasma

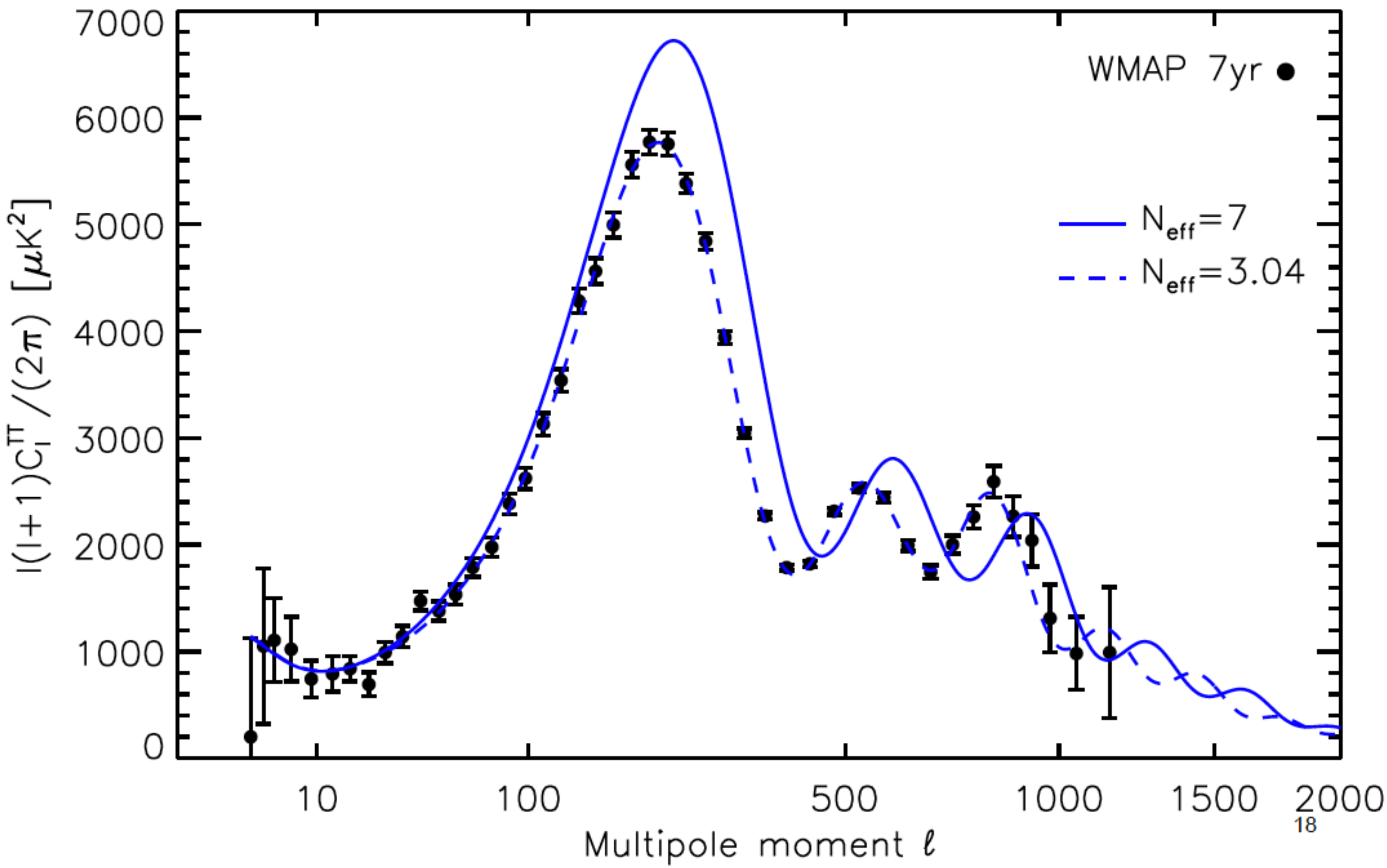
$$r_s(z_*) = \int_{z_*}^{\infty} \frac{c_s \mathrm{d}z}{H(z)} \qquad c_s^2 \equiv \frac{1}{3}\frac{1}{1 + \frac{3\rho_{\rm b}}{4\rho_\gamma}}$$

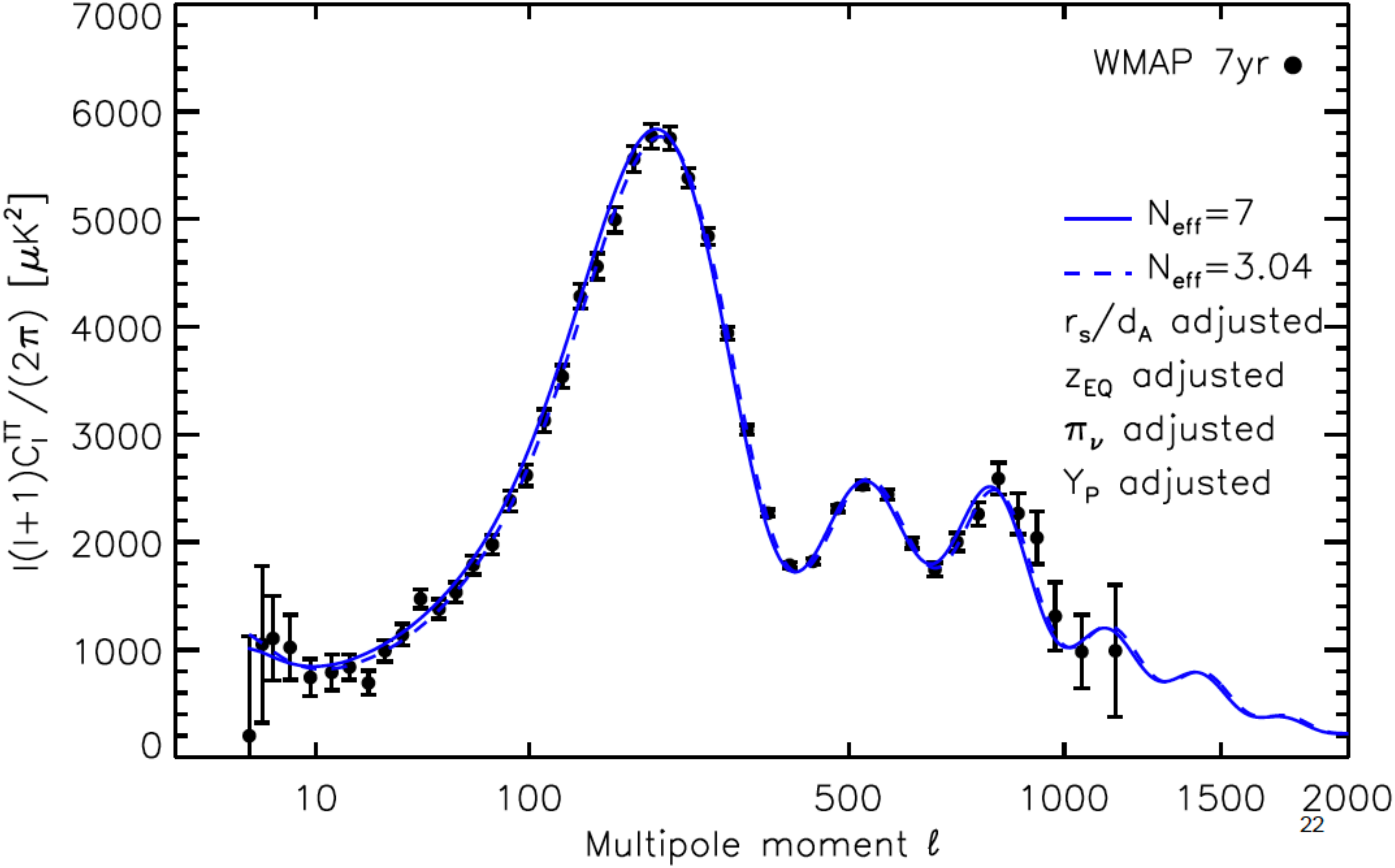
– Note: the high-ell CMB features also depend on the Silk damping scale (diffusion scale at the recombination epoch)

$$\dot{\tau} \equiv n_e \sigma_T a \simeq 2.3 \times 10^{-5}\mathrm{Mpc}^{-1}(1 - Y_{\rm p})\Omega_b h^2 (1+z)^2 x_e$$

$$k_D^{-2} \simeq \frac{1}{6}\int \mathrm{d}\eta \frac{1}{\dot{\tau}} \frac{R^2 + 16(1+R)/15}{(1+R)^2}$$

From Komatsu san's website (WMAP-7yr: Komatsu et al.11)



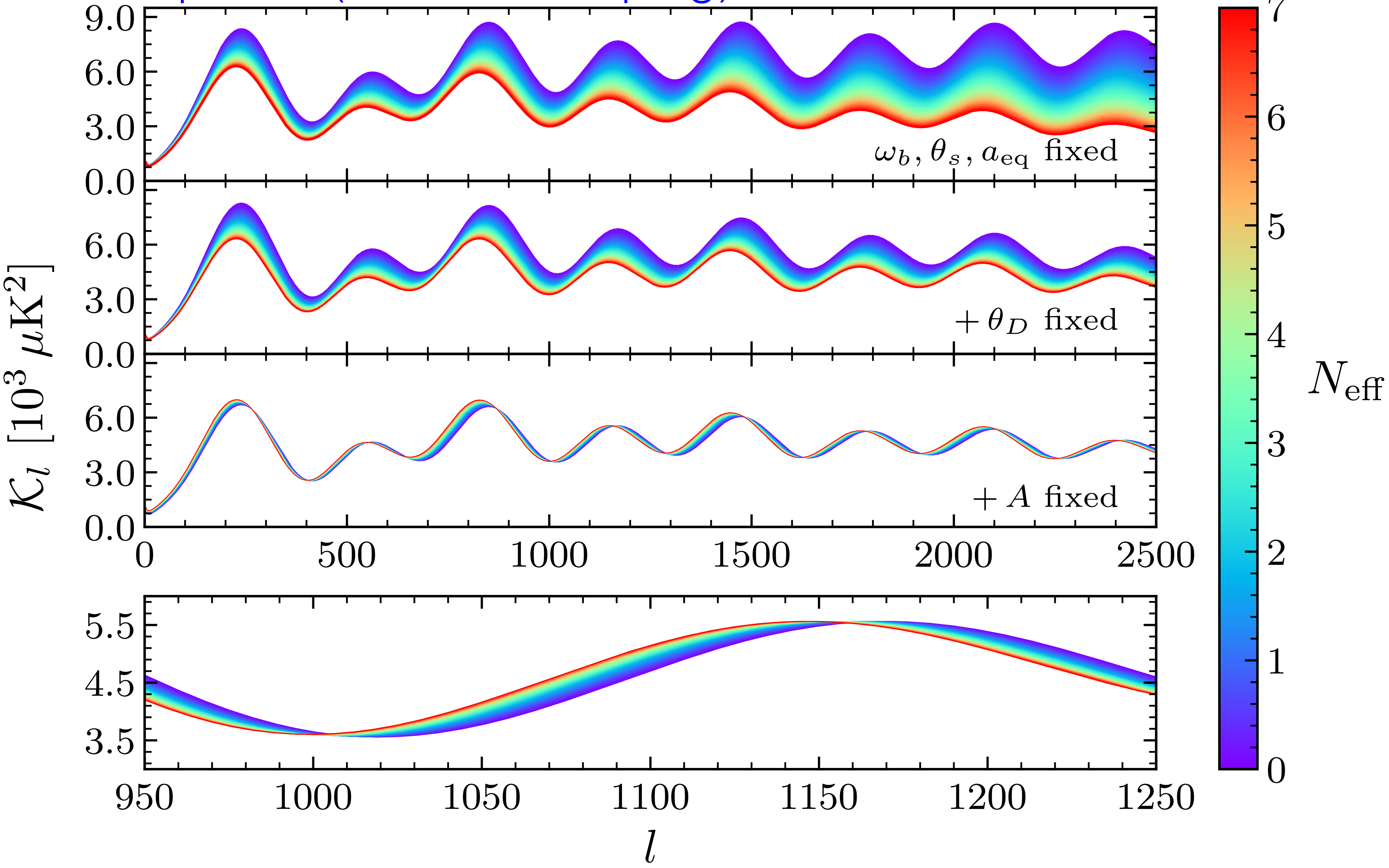


7000
6000
5000
4000
3000
2000
1000
0
l(l+1)C$_l^{TT}$/(2π) [μK^2]
WMAP 7yr
N$_{eff}$=7
N$_{eff}$=3.04
r$_s$/d$_A$ adjusted
z$_{EQ}$ adjusted
π$_ν$ adjusted
Y$_P$ adjusted
10
100
500
1000
1500
2000
Multipole moment ℓ

Phase shift in BAOs

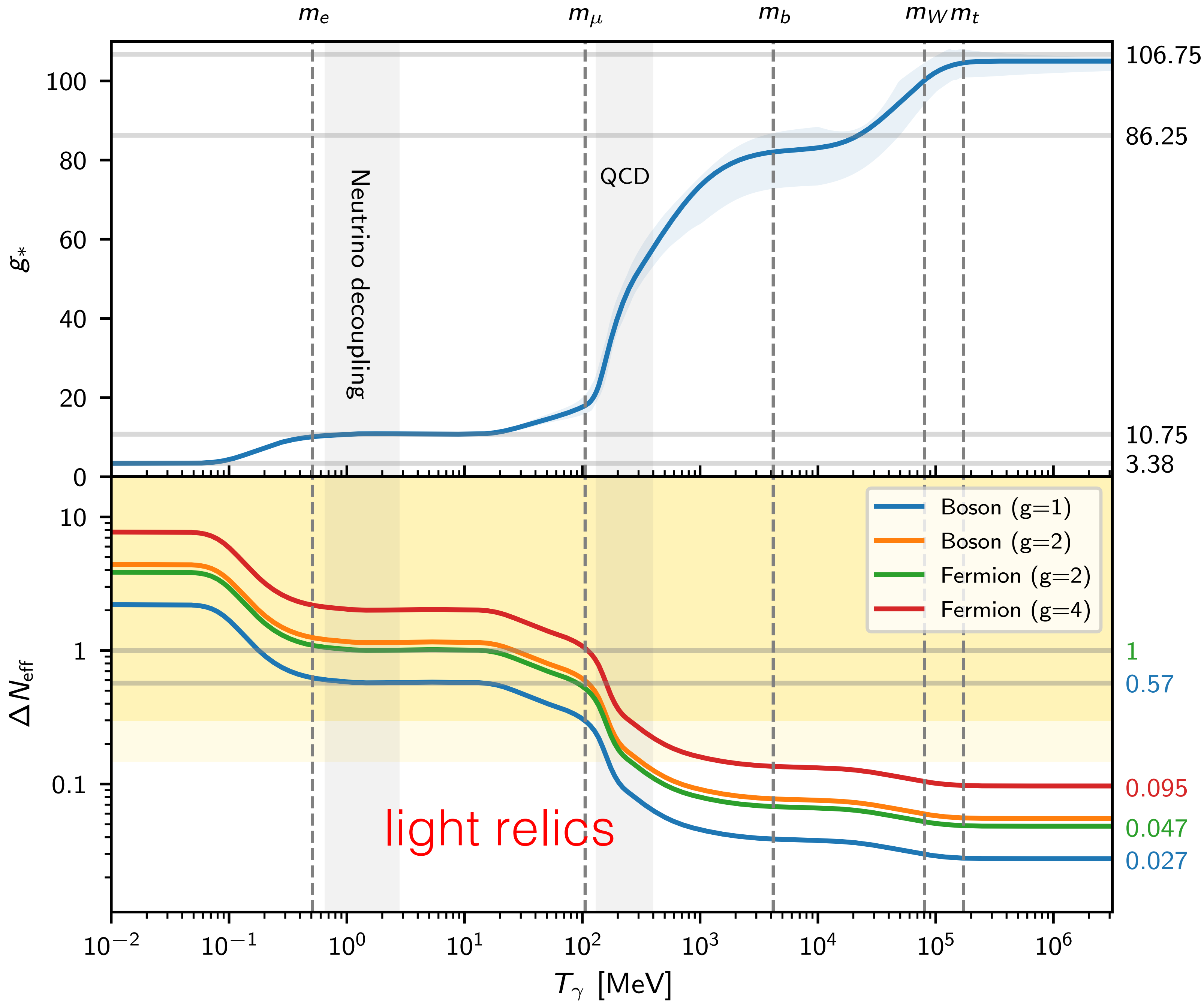
in CMB spectra (w/o Silk damping)

Baumann et al. 18



Planck 2018

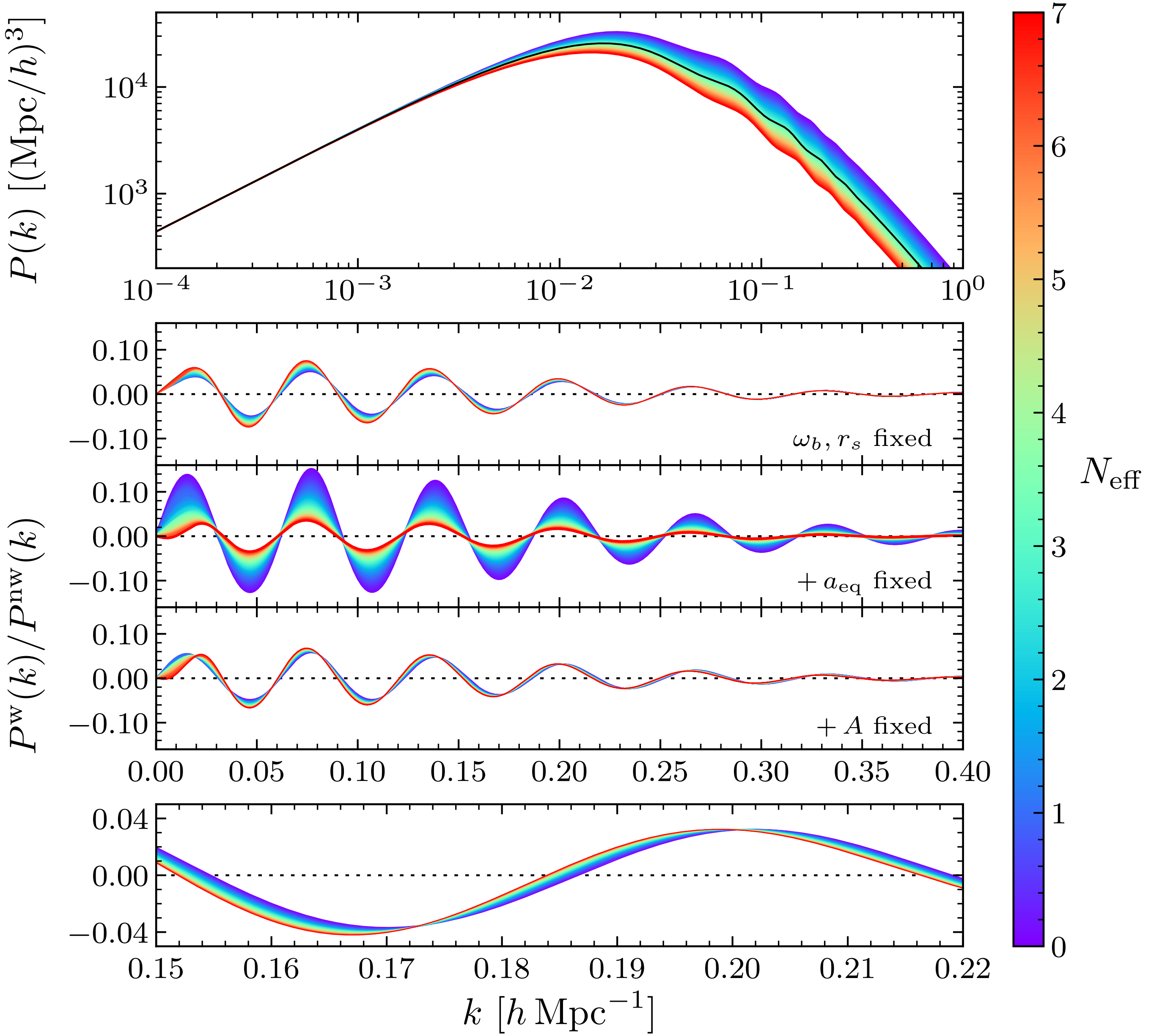
$$N_{\rm eff} = 2.99^{+0.34}_{-0.33} \quad \text{(95\% C.L., TT, TE, EE+lowE+lensing+BAO)}$$



Phase shift in BAOs (cont'd)

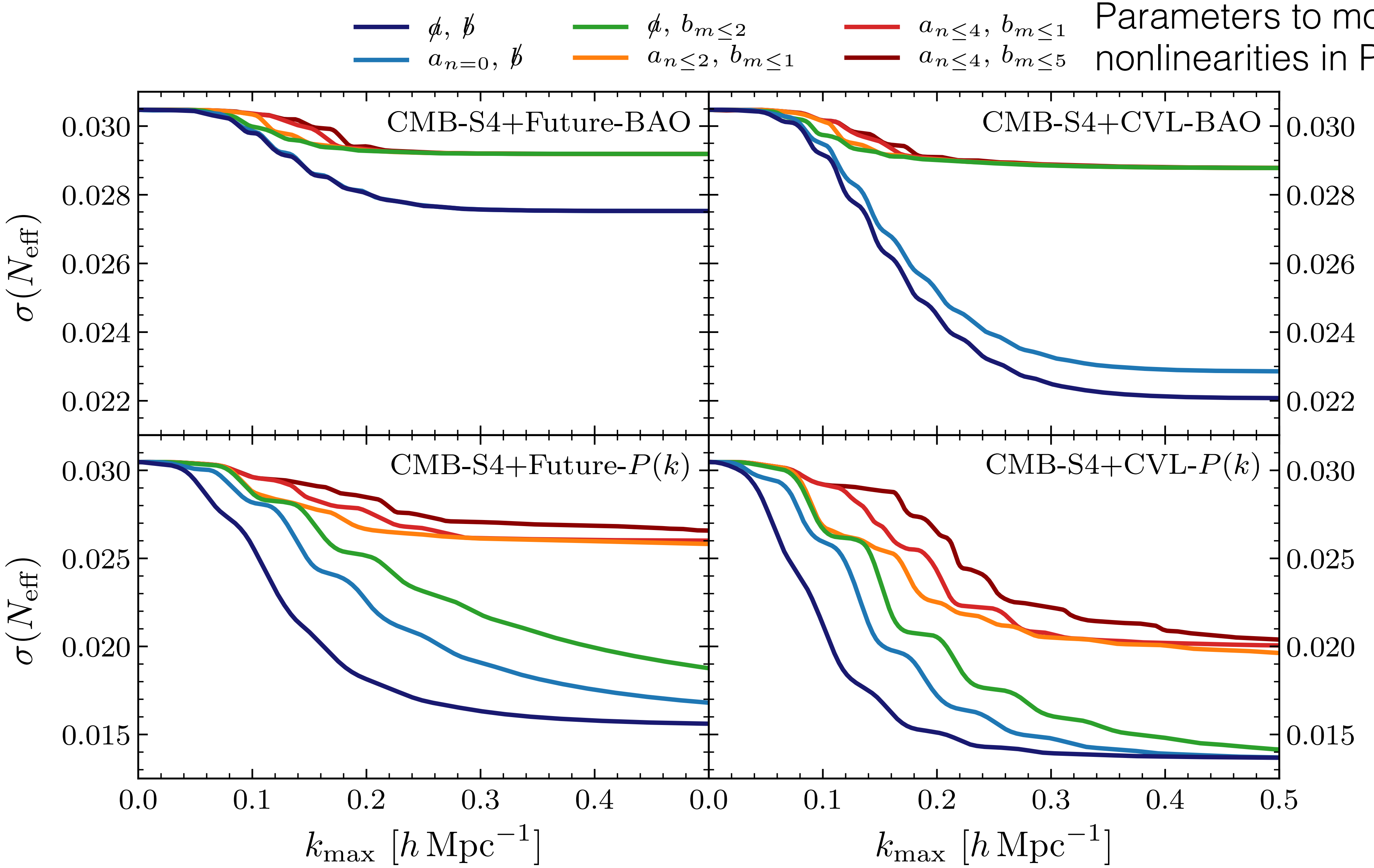
in matter (~galaxy) power spectrum

Baumann et al. 18



Prospects with future surveys

Parameters to model nonlinearities in P(k)

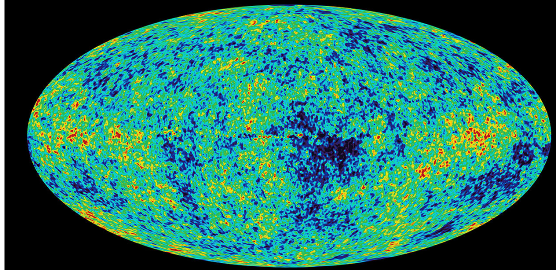


$$m_{\nu,\mathrm{tot}}$$

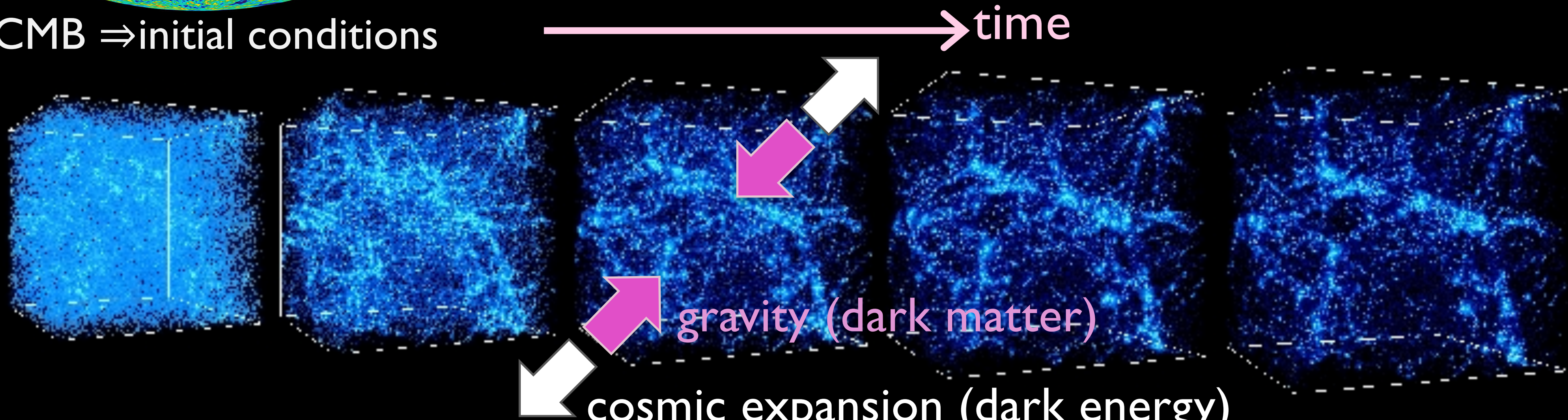
Large-scale structure formation: ΛCDM model

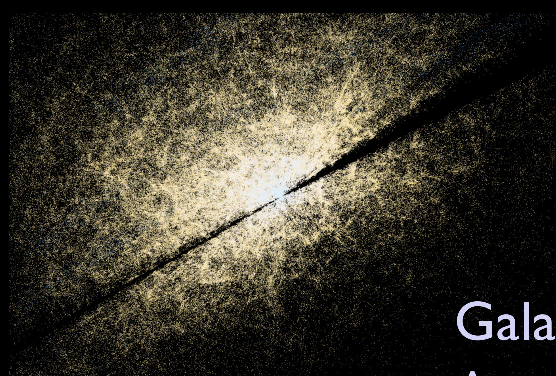
Structure formation = Time evolution of matter inhomogeneities of different scales (wavelengths)

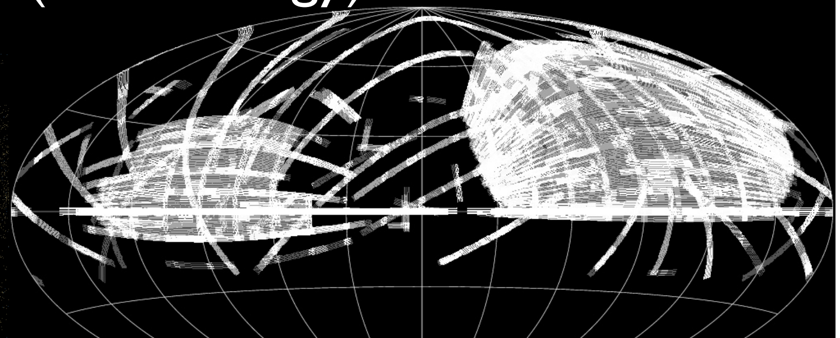
$$\ddot{\delta}_m + 2H\dot{\delta}_m - 4\pi G\bar{\rho}_m\delta_m = 0$$



CMB ⇒initial conditions

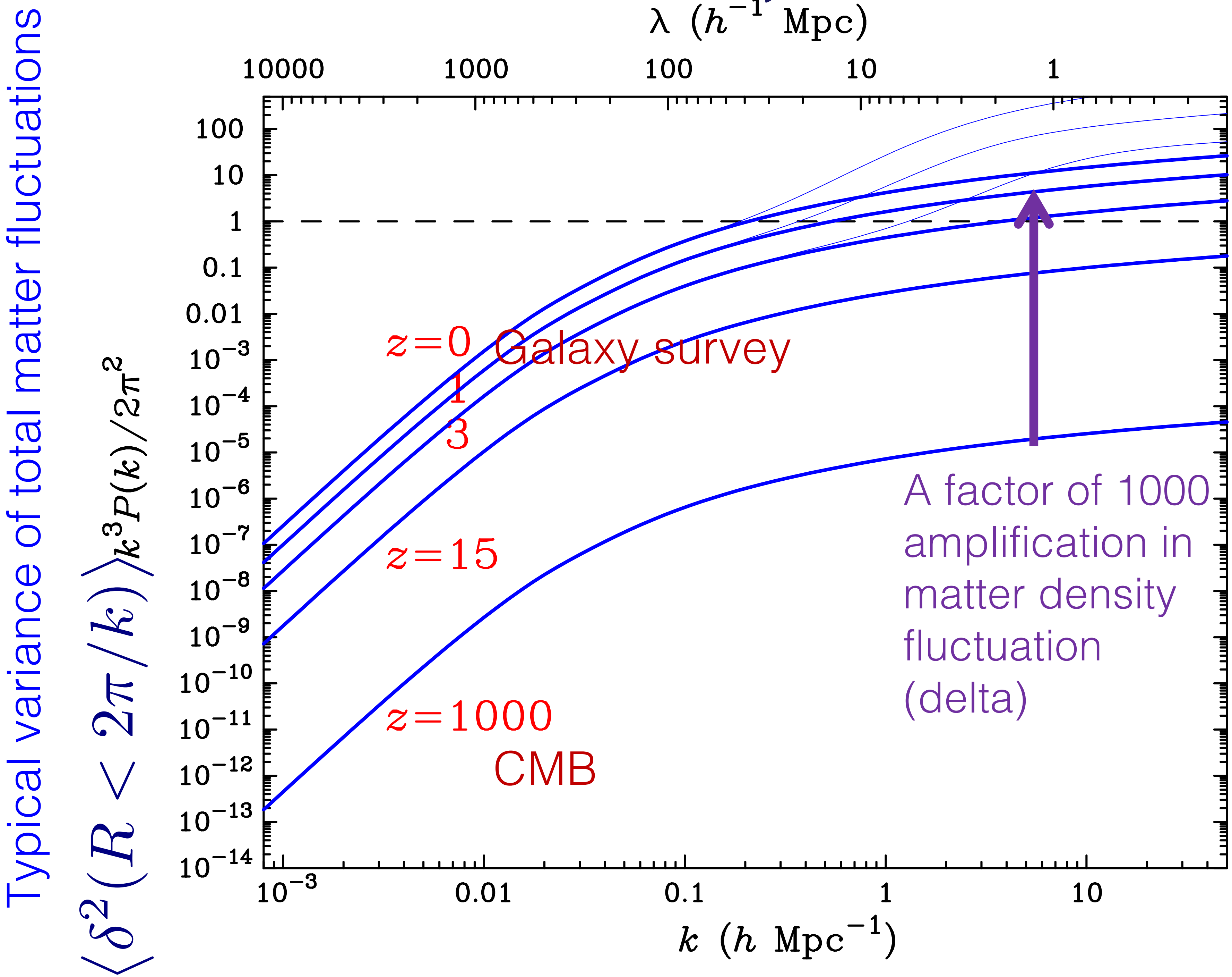






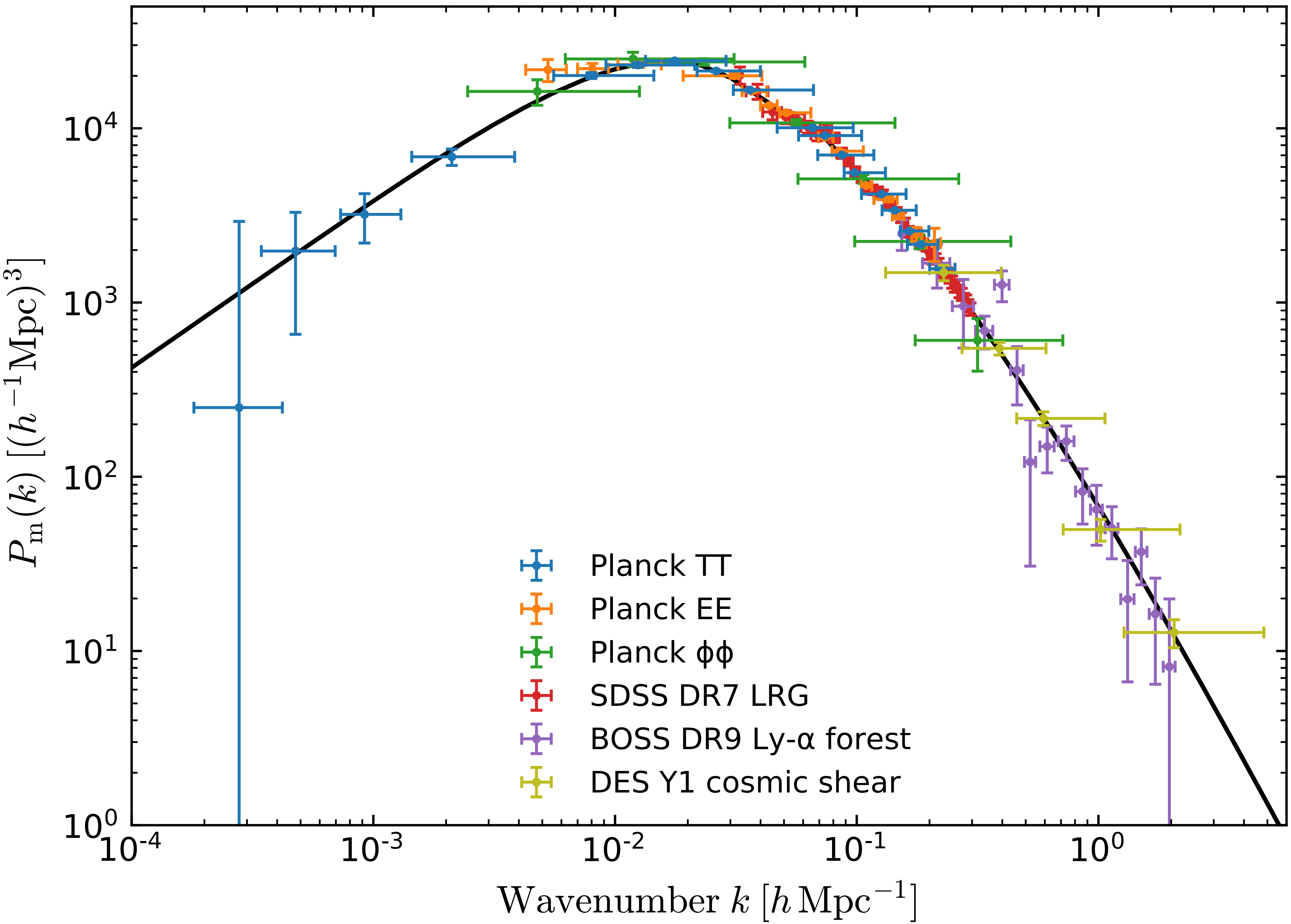
Galaxy survey ⇒ large-scale structure
A result of gravitational instability

Gravitational instability



Now various datasets available

From Planck2018



ν+ΛCDM model

- Neutrinos are very light compared to CDM/baryon
- The phase-space distribution of neutrinos, even after decoupling, obeys the relativistic Ferimi-Dirac dist. (specified by m_ν)
- The thermal velocity at redshift z relevant for LSS is larger than the gravity induced peculiar velocity

$$\sigma_\nu(z) = \sqrt{\left\langle \frac{p^2}{2m_\nu} \right\rangle} \approx 1800\mathrm{km/s}\left(\frac{m_\nu}{0.1\mathrm{eV}}\right)^{-1}(1+z)$$

  - Even a massive cluster can't much trap neutrinos

- *The free-streaming scale*, the distance neutrino can travel with the thermal vel. during cosmic expansion

$$\lambda_{\mathrm{fs}}(z) \approx \sigma_\nu H^{-1} a^{-1} \Rightarrow k_{\mathrm{fs}}(z) \approx \frac{0.037}{(1+z)^{1/2}}\left(\frac{m_\nu}{0.1\mathrm{eV}}\right)\left(\frac{\Omega_m}{0.3}\right)^{1/2} h\ \mathrm{Mpc}^{-1}$$

λ_fs is a 100Mpc scale, similar to BAO scales

Small-scale suppression in growth of LSS

- A mixed DM model: Structure formation after CMB epoch is induced by the density fluctuations of total matter

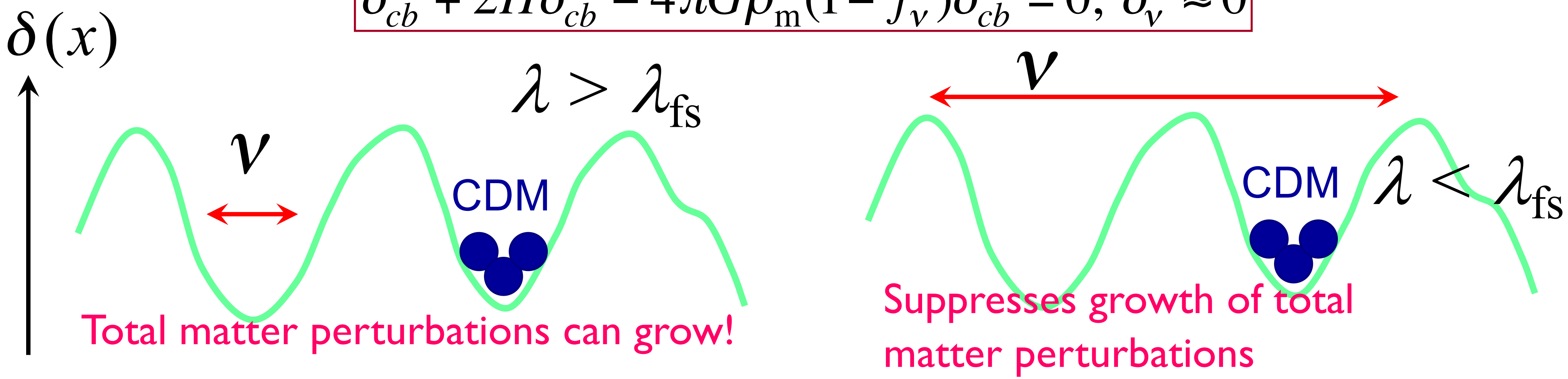
$$\delta_m = \frac{\bar{\rho}_c\delta_c + \bar{\rho}_b\delta_b + \bar{\rho}_\nu\delta_\nu}{\bar{\rho}_c + \bar{\rho}_b + \bar{\rho}_\nu} \equiv f_c\delta_c + f_b\delta_b + f_\nu\delta_\nu$$

- The neutrinos slow down LSS on small scales
  - On large scales $\lambda > \lambda_{fs}$, the neutrinos can grow together with CDM

$$\delta_c = \delta_b = \delta_\nu$$

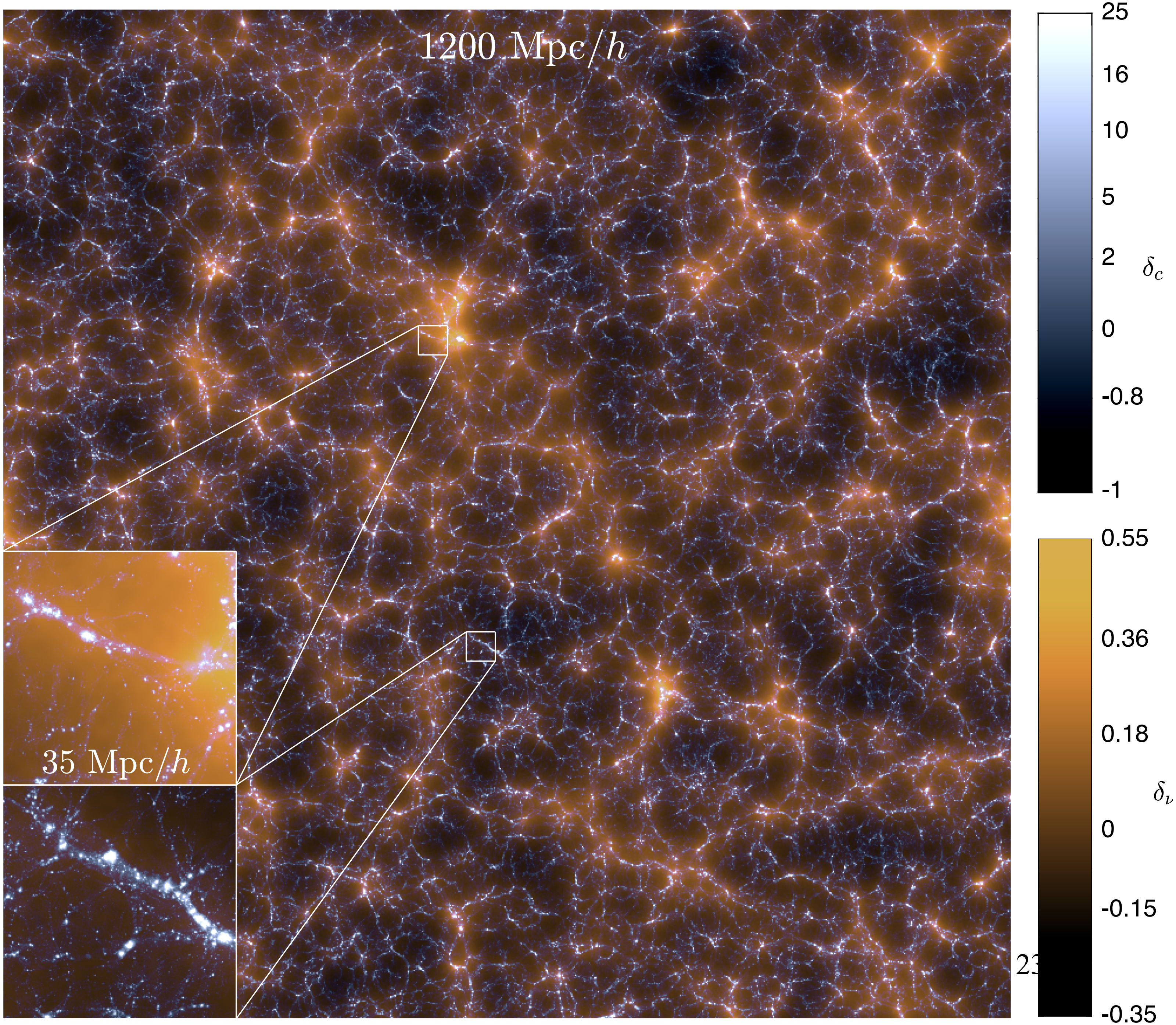
  - On small scales $\lambda < \lambda_{fs}$, the neutrinos are smooth, $\delta_\nu = 0$, therefore weaker gravitational force compared to a pure CDM case

$$\ddot{\delta}_{cb} + 2H\dot{\delta}_{cb} - 4\pi G\bar{\rho}_{\rm m}(1 - f_\nu)\delta_{cb} = 0,\ \delta_\nu \approx 0$$



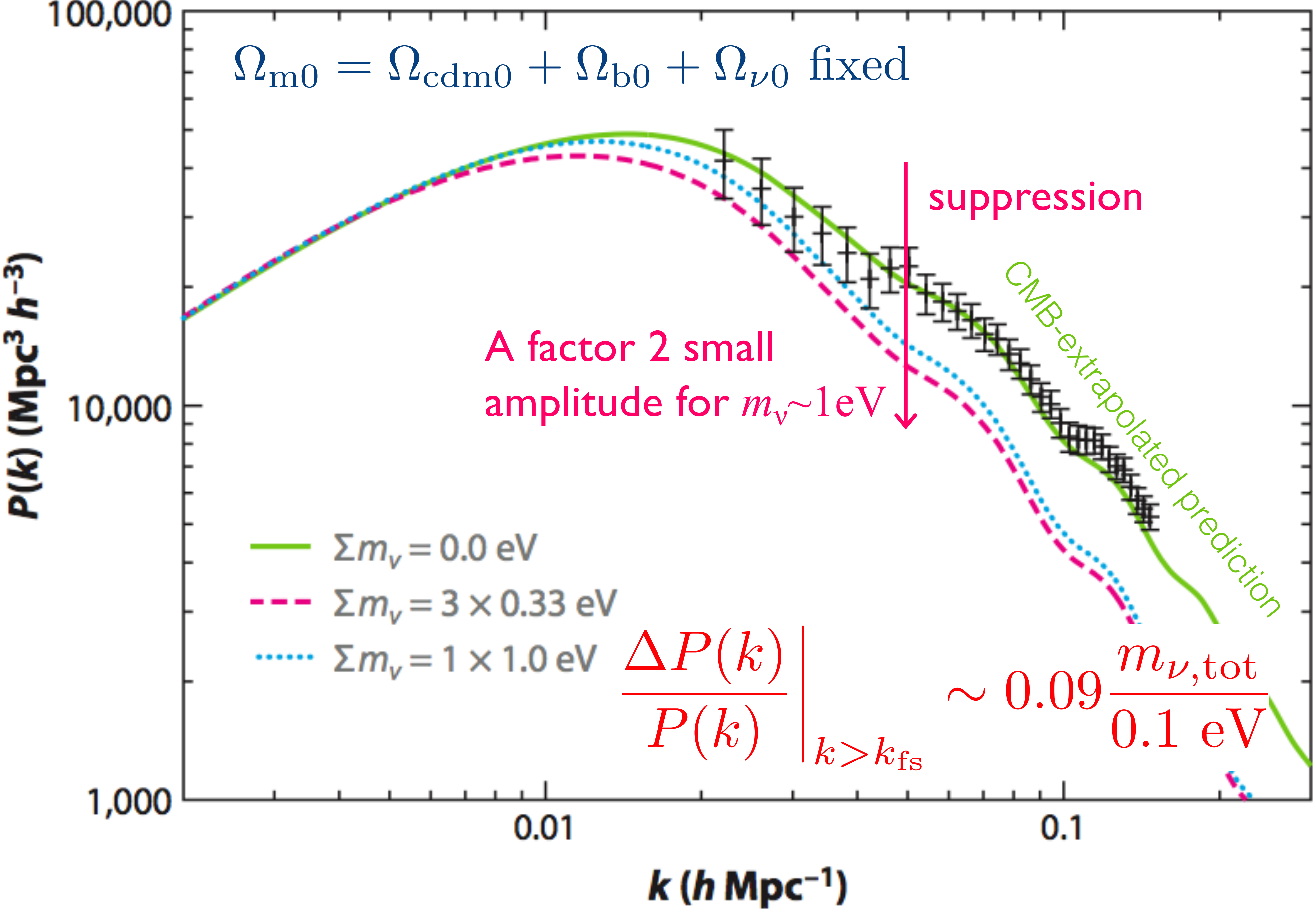
Massive Neutrinos

m_ν=0.05eV
6912^3 CDM parts
13824^3 ν parts



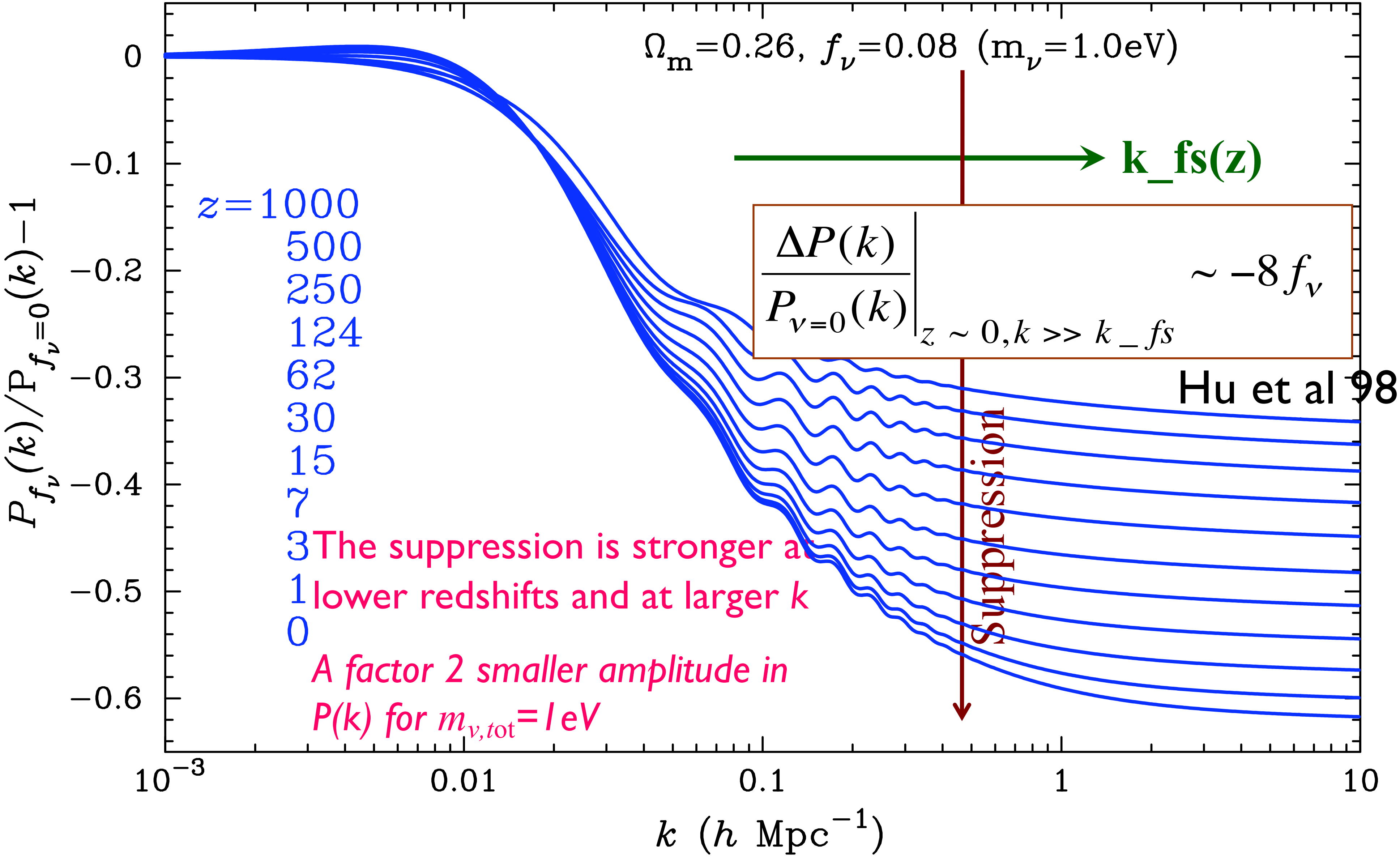
arXiv:1609.0896

Galaxy power spectrum at z=0



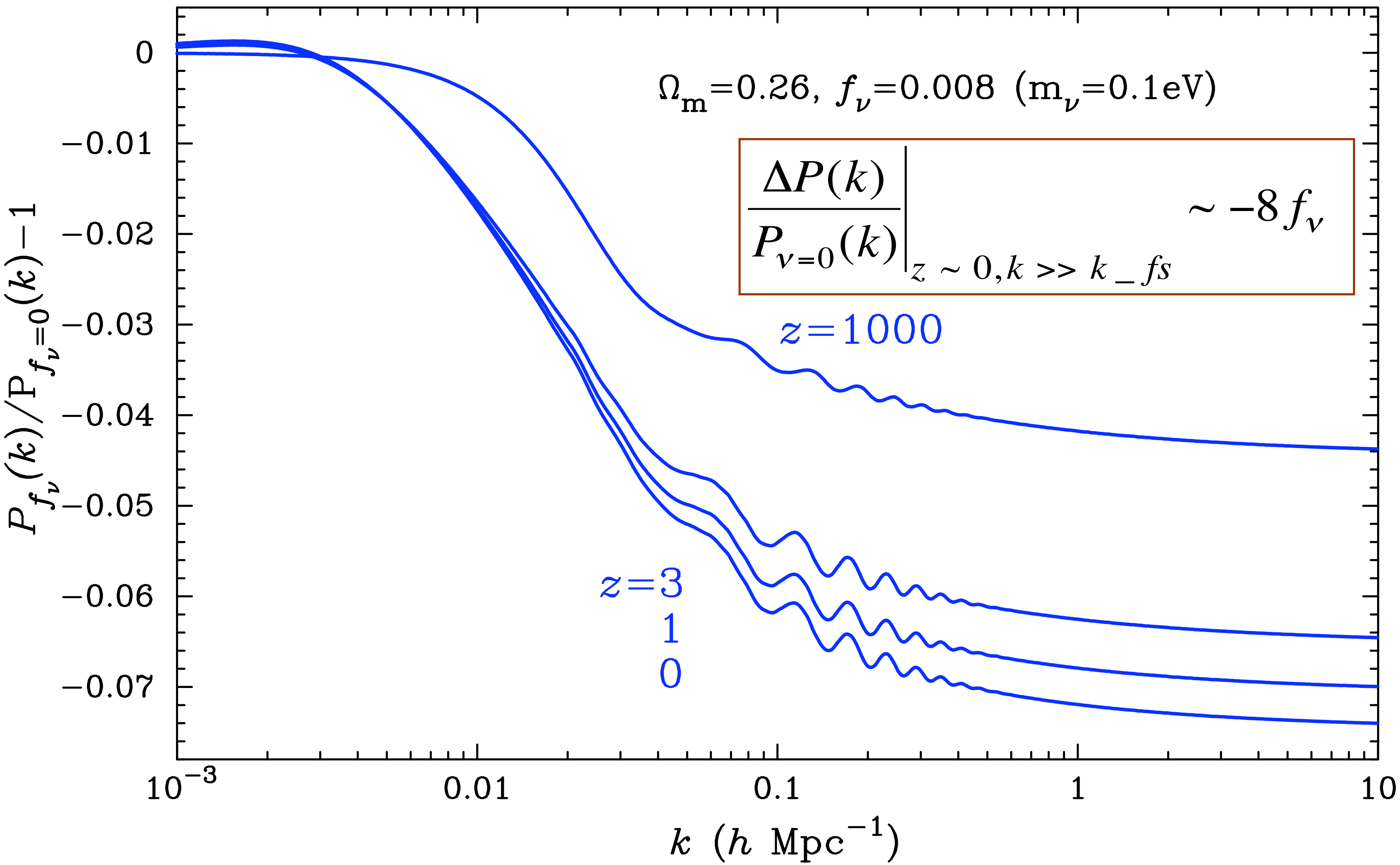
Suppression of linear P(k)

$$k_{fs}(z) \approx 0.35(1+z)^{-1/2}\left(\frac{m_\nu}{1\text{eV}}\right)\left(\frac{\Omega_m}{0.26}\right)^{1/2} h\text{Mpc}^{-1}$$

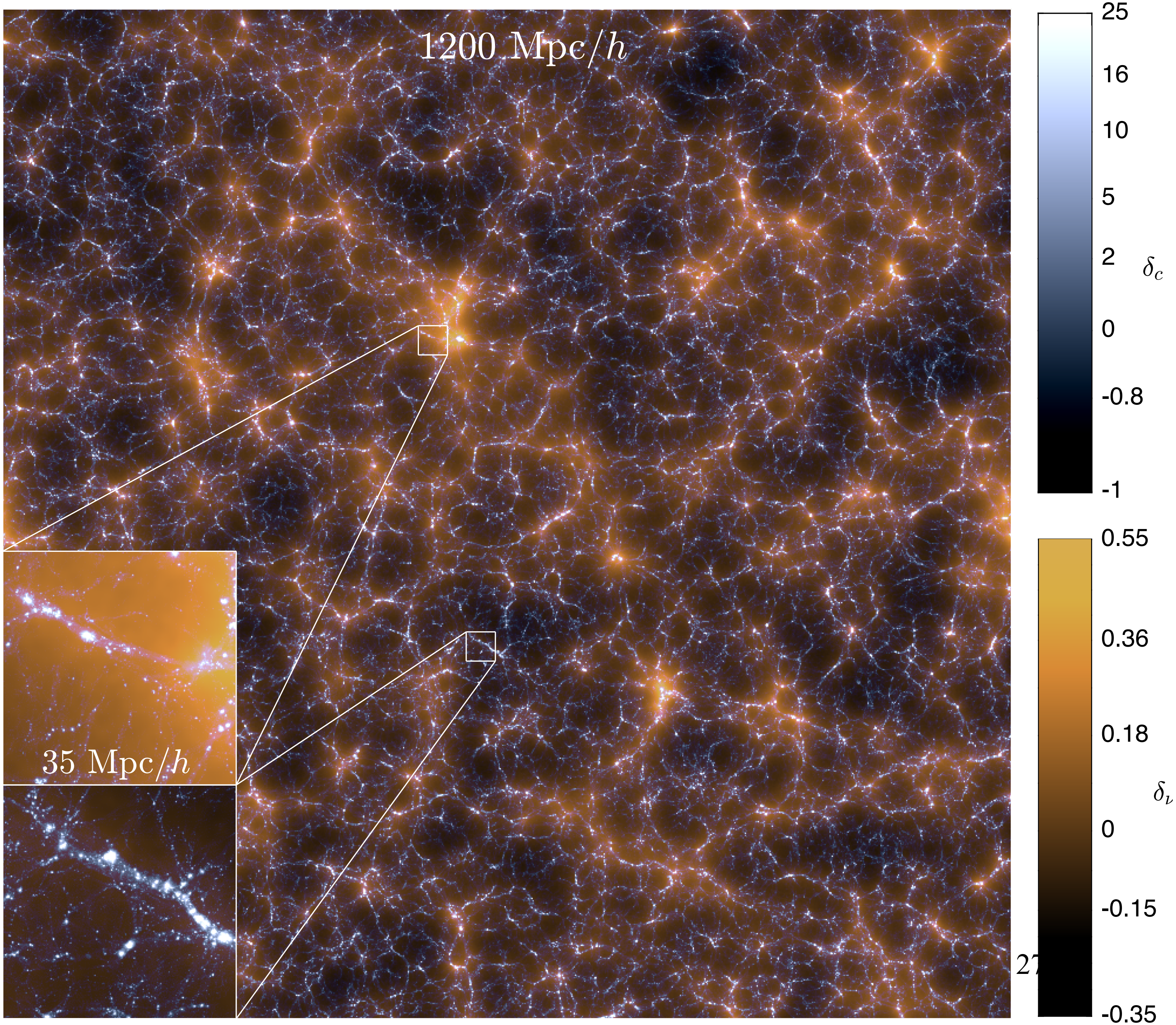


Suppression of linear P(k) (contd.)

- A more realistic f_nu~0.01 (m_nu~0.1eV): the neutrinos became non-relativistic after z~10^3
- The power spectrum amplitude is suppressed by ~8%



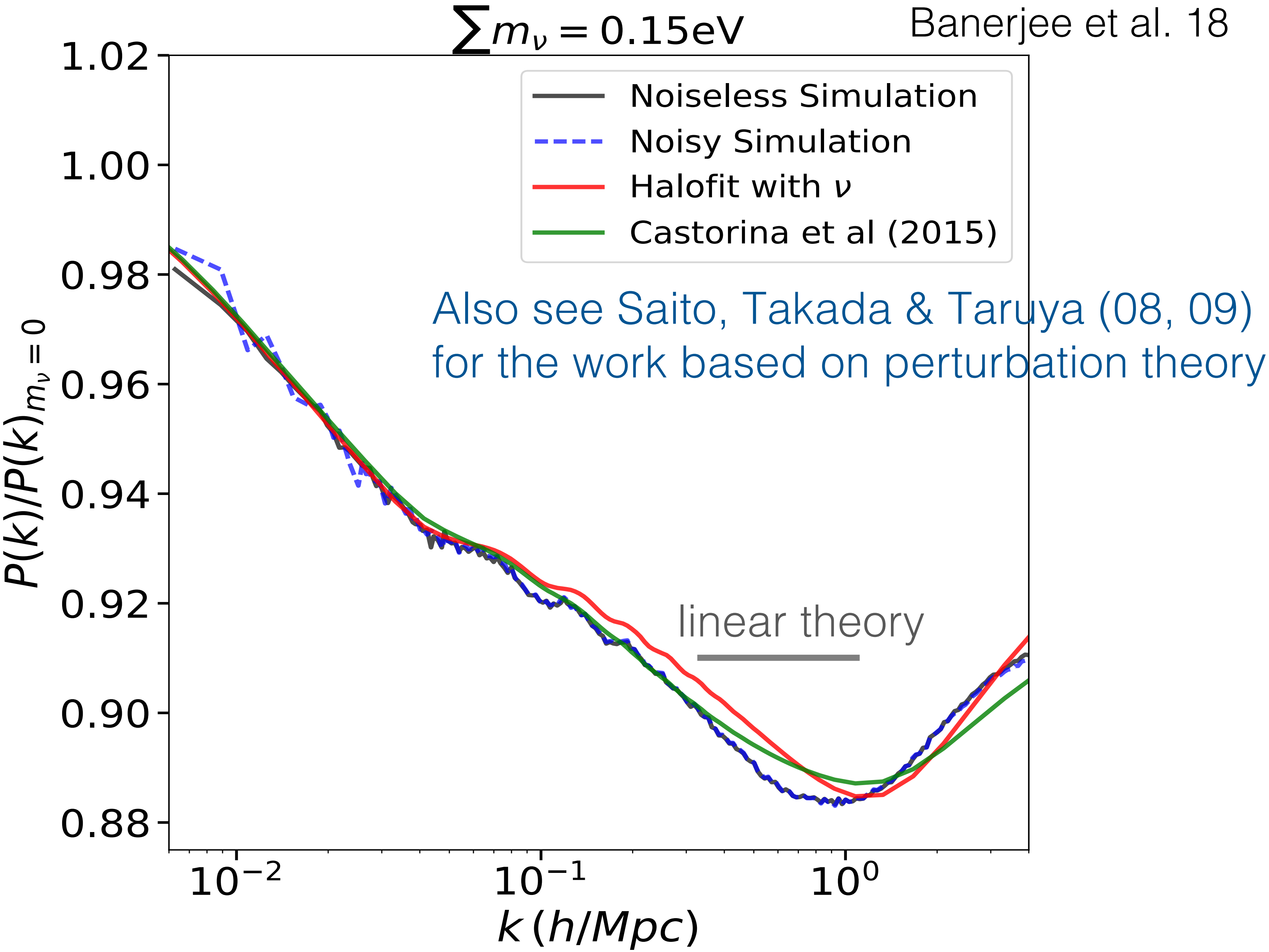
Massive Neutrinos (now sims. developed)



m_ν=0.05eV
6912^3 CDM parts
13824^3 ν parts

arXiv:1609.0896

Nonlinear boost in neutrino effect



Recap: neutrino mass determination

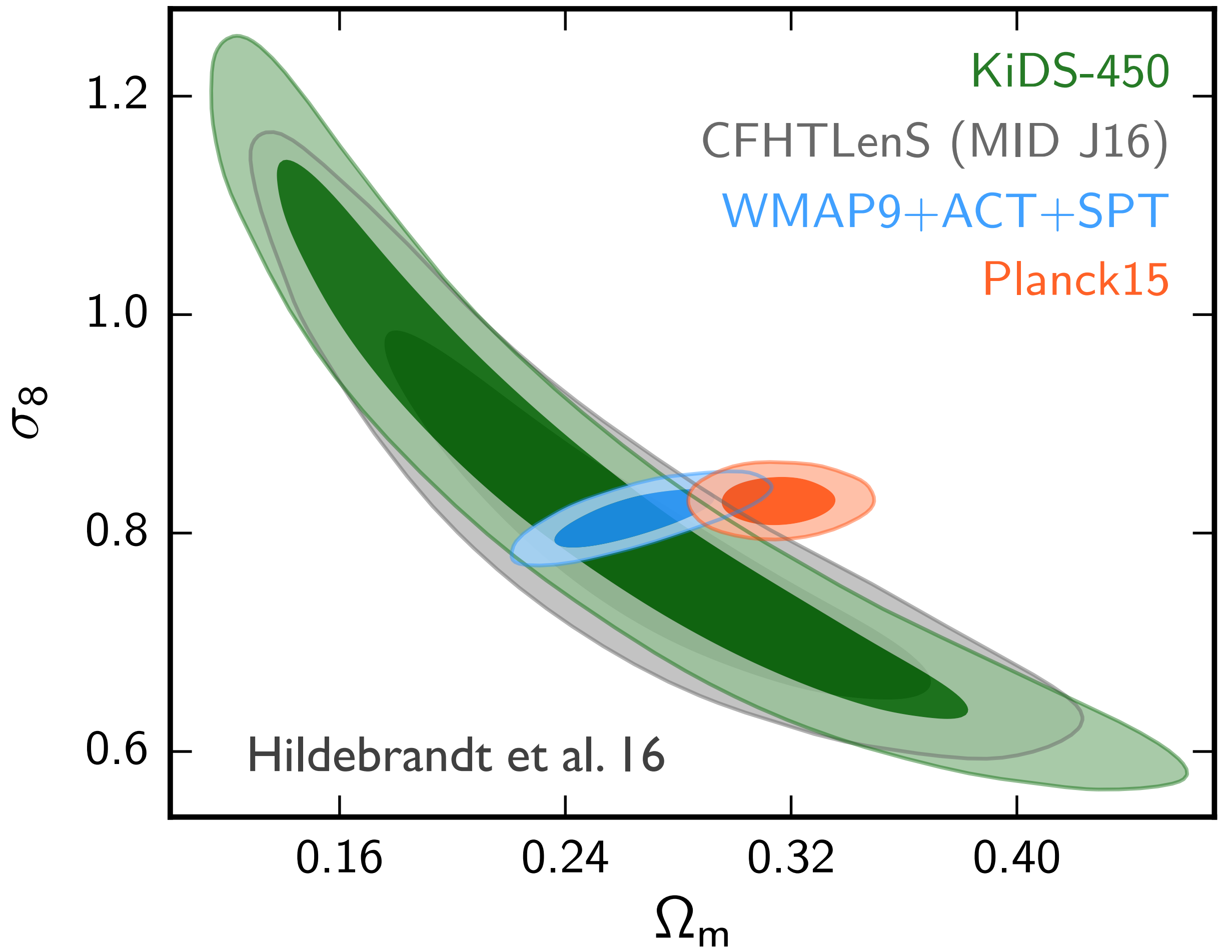
- Massive neutrinos slows down the growth of large-scale structure (LSS) formation
- If we can measure clustering amplitudes of matter inhomogeneities at low redshifts to a high precision, we then compare it with the CMB-inferred amplitude to infer the neutrino mass
- The combination of CMB and LSS can constrain neutrino mass

$$\frac{P_{\rm LSS}^{\rm obs}(k, z_{\rm low})}{P_{\rm CMB-inferred}(k, z_{\rm low}; \Omega_{\rm m}, m_\nu = 0)} - 1 \sim -8 f_\nu$$

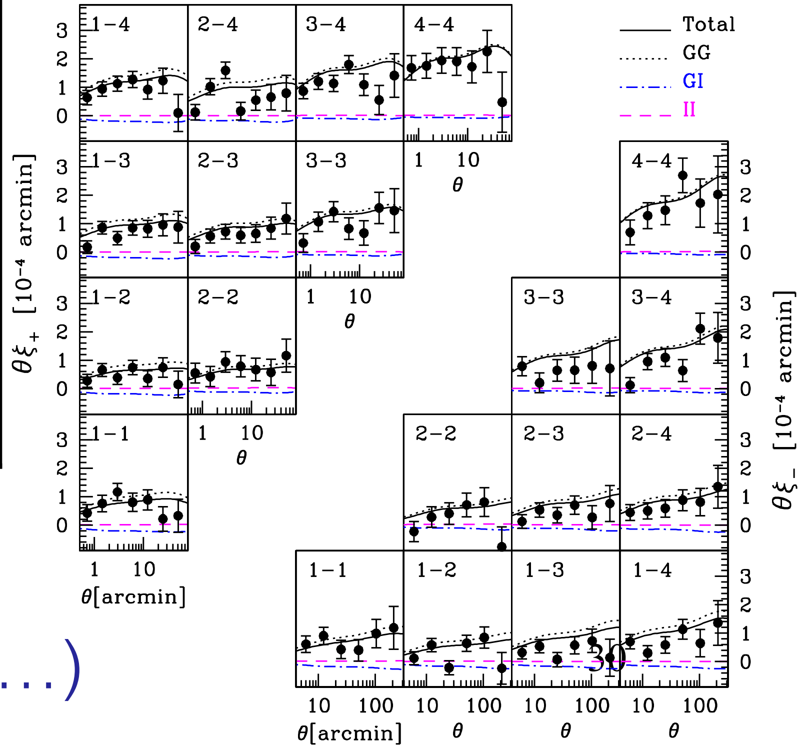
$$\simeq -8 \frac{m_{\nu,{\rm tot}}}{(94.1\ {\rm eV})\Omega_{\rm m} h^2}$$

σ_8 tension? New physics?

σ_8: the present-day rms of mass density fluctuations of 8 Mpc/h scale
Planck σ_8 value: extrapolated of fluctuations from z~1100 assuming ΛCDM

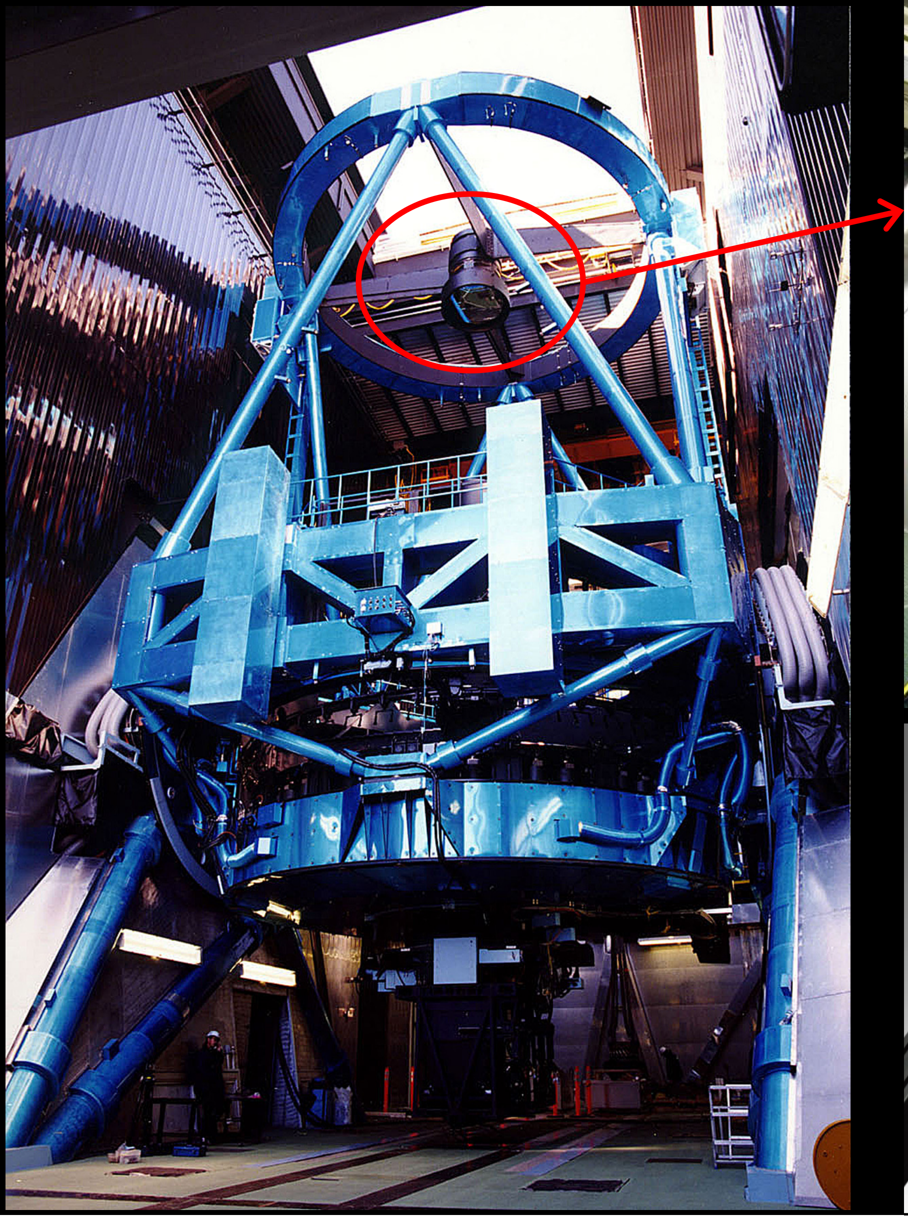


- *Planck value is not consistent* with the results of LSS probes (e.g. weak lensing)

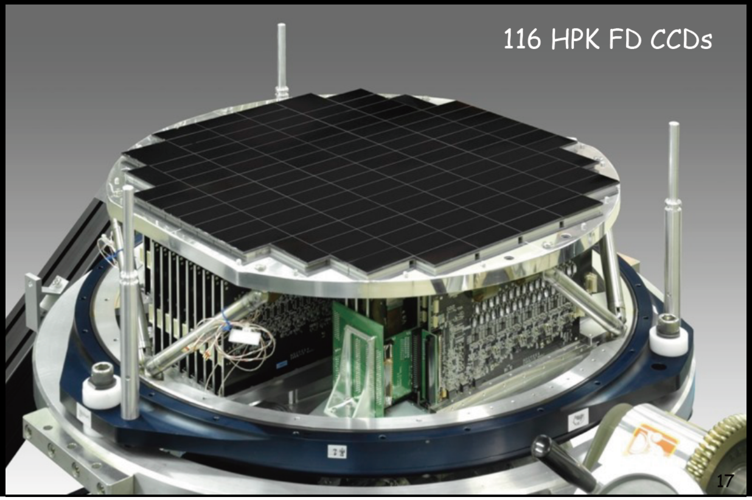


KiDS: the Kilo-Degree Survey (Leiden, …)

Hyper Suprime-Cam (HSC)

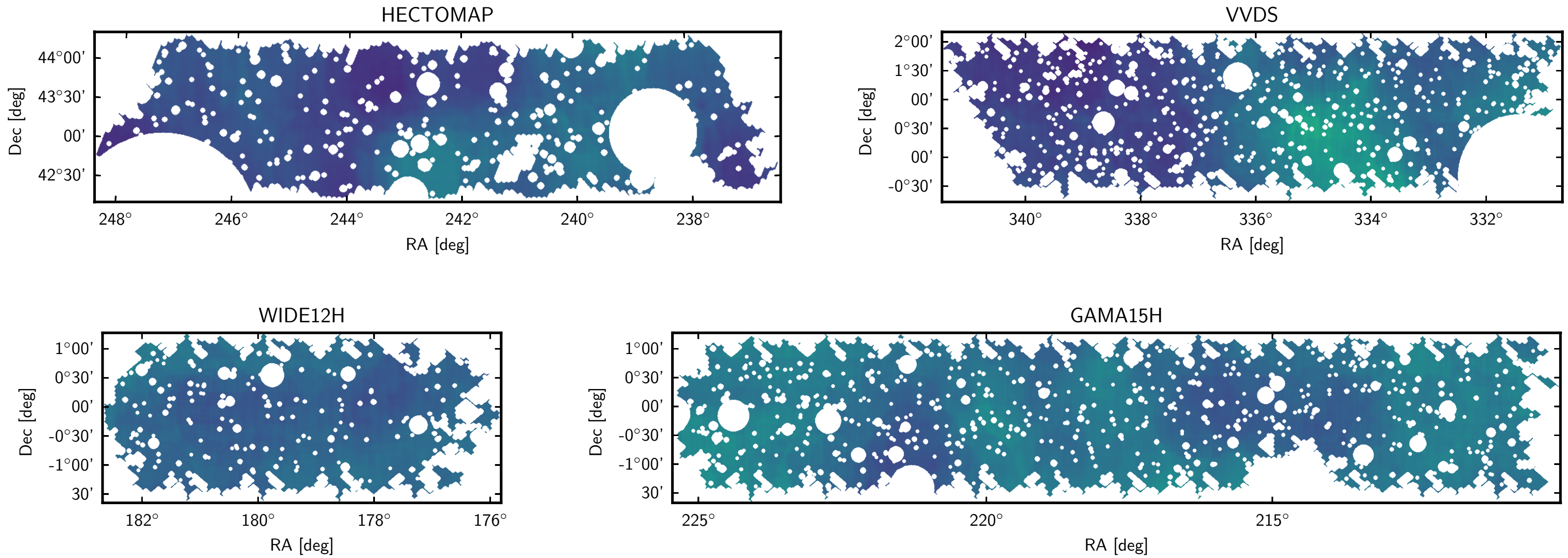


- largest camera
- 3m high
- weigh 3 ton
- 104 CCDs (~0.9B pixels)
- Japan, Taiwan and Princeton



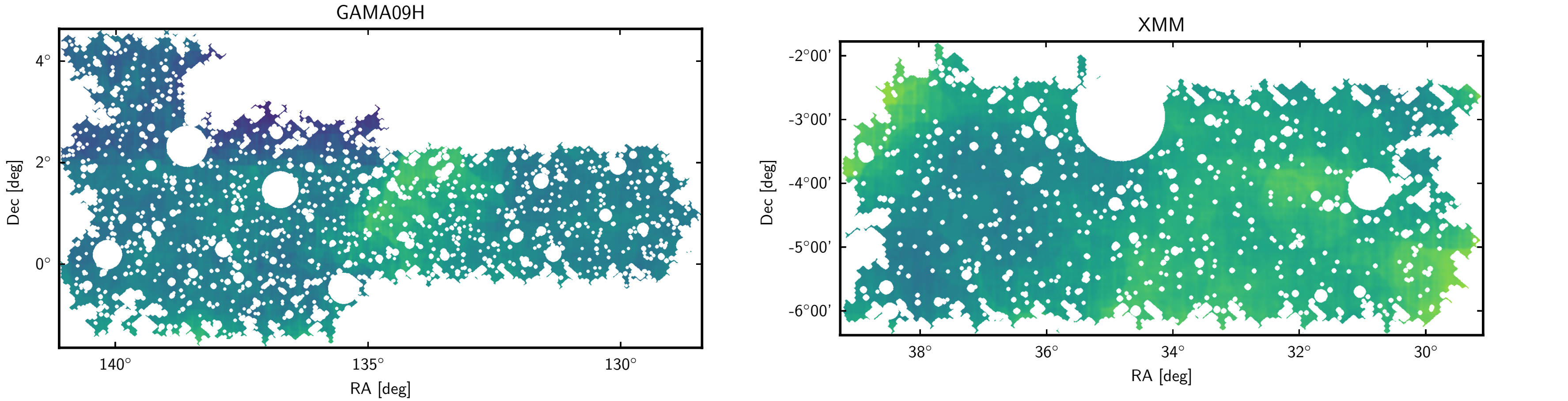
Subaru HSC = superb image quality

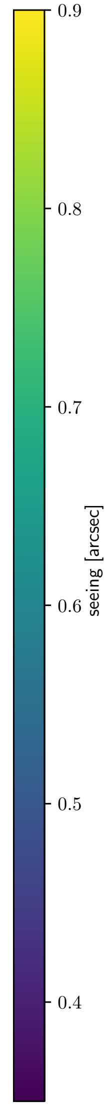
6 fields (~140 sq. deg. in total)



Subaru HSC typically **0.6” seeing** FWHM (spatial resolution)

⇔ DES: ~0.9”





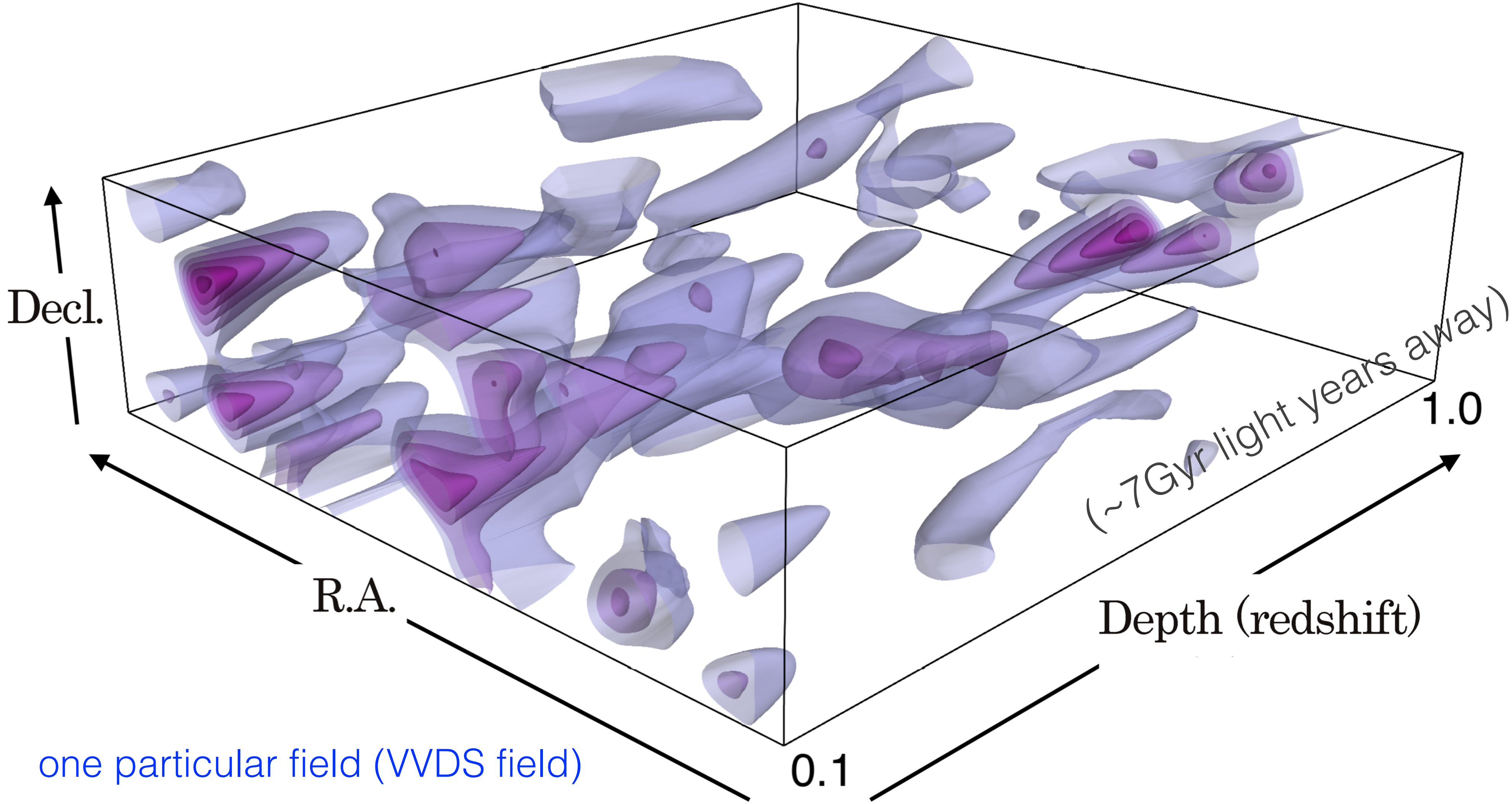
Weak gravitational lensing (shear)

Credit: NHK

Unprecedented wide and deep 3D DM map

Oguri et al. 18

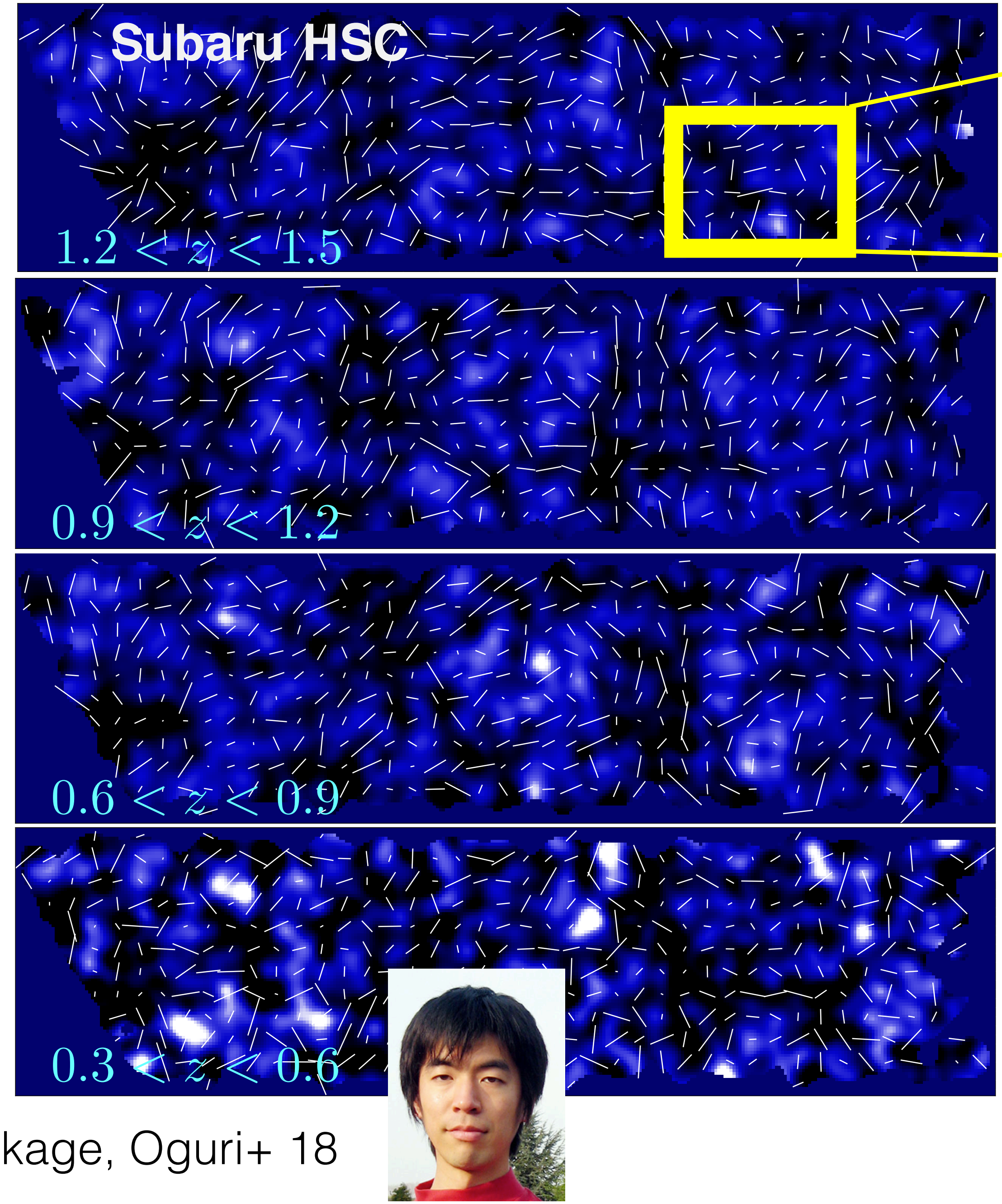
Largest 3D dark matter map



one particular field (VVDS field)

Weak lensing tomography

shape + photo-z



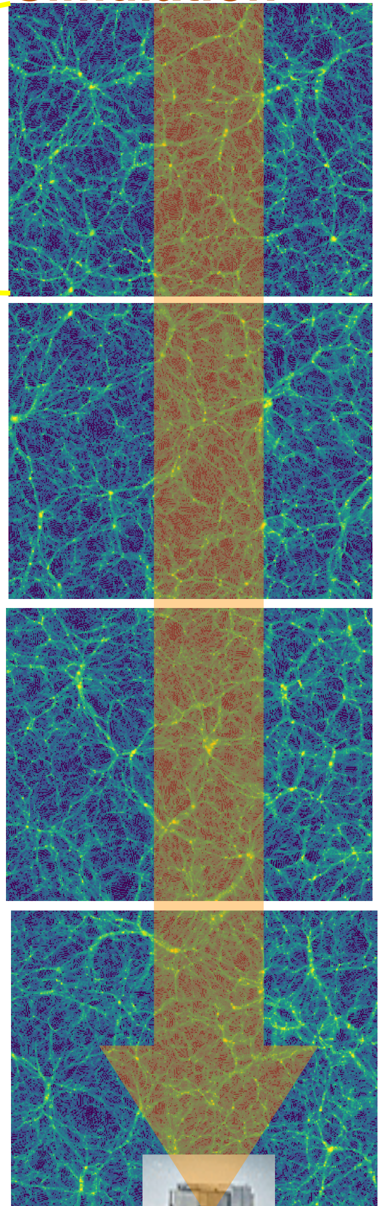
Simulation

~6G yrs ago

~5G yrs ago

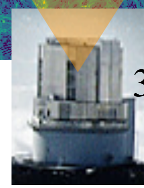
~4G yrs ago

~3G yrs ago

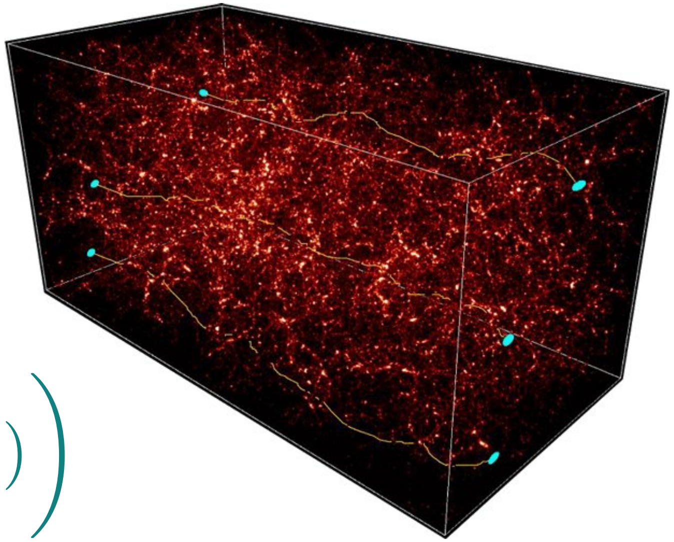


Hikage, Oguri+ 18

Subaru telescope



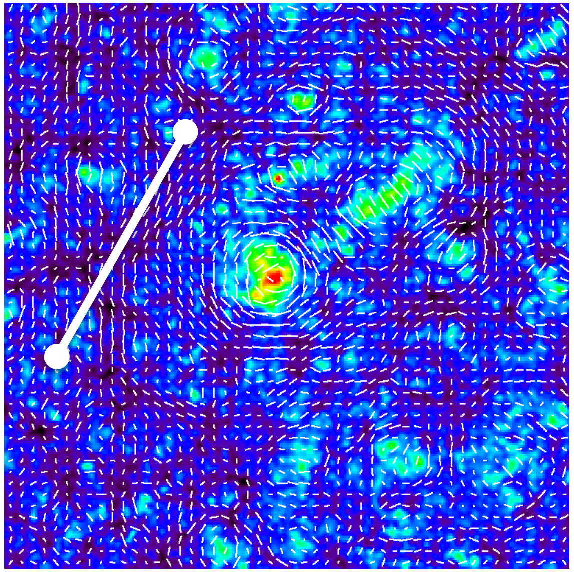
HSC-Y1 cosmic shear cosmology



- Pros
  - Can measure “total” matter power clustering

$$C_\ell = \int d\chi\, W_{\rm GL}(\chi)^2 \chi^{-2} P_{\rm m}^{\rm NL}\left(k = \frac{\ell}{\chi}; z(\chi)\right)$$

- Cons
  - All the systematic errors additively contribute the measurements (⇔ g-g lensing)
  - Challenges: Photo-z errors and baryonic physics
  - HSC data are very deep compared to DES: precursor of LSST

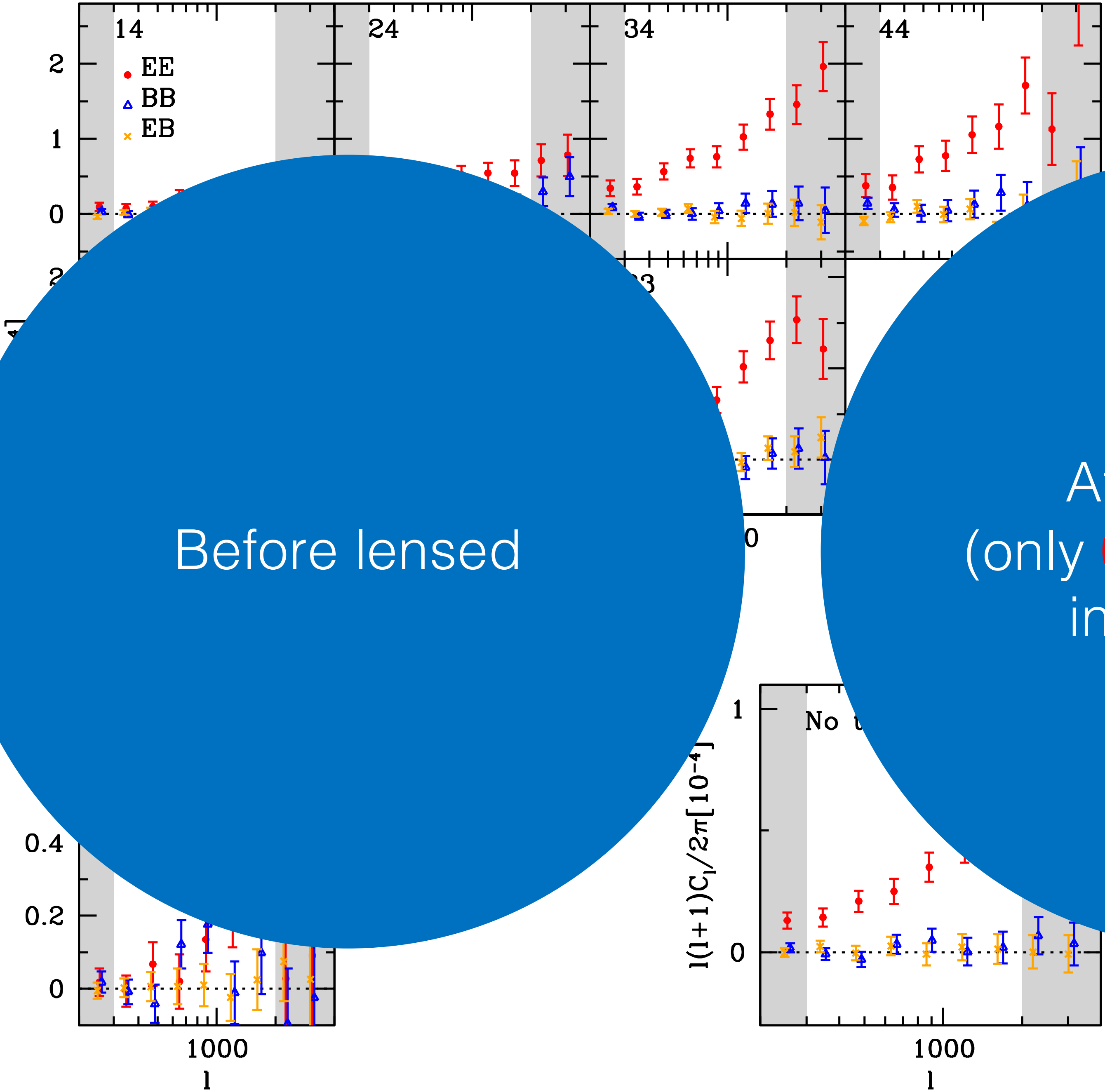


Pseudo-power spectrum estimator
(Hikage, MT, Hamana, Spergel 11)

$$\tilde{E}_{\ell m} \pm i\tilde{B}_{\ell m} = \int d^2\mathbf{n}\ w(\mathbf{n})\left[\gamma_1(\mathbf{n}) \pm i\gamma_2(\mathbf{n})\right] Y_{\ell m}(\mathbf{n})$$

$$\hat{C}_l^{EE} = \mathbf{M}_{ll'}^{-1}\left[C_{l'}^{EE} - N_{l'}\right]$$

137 sq. deg.

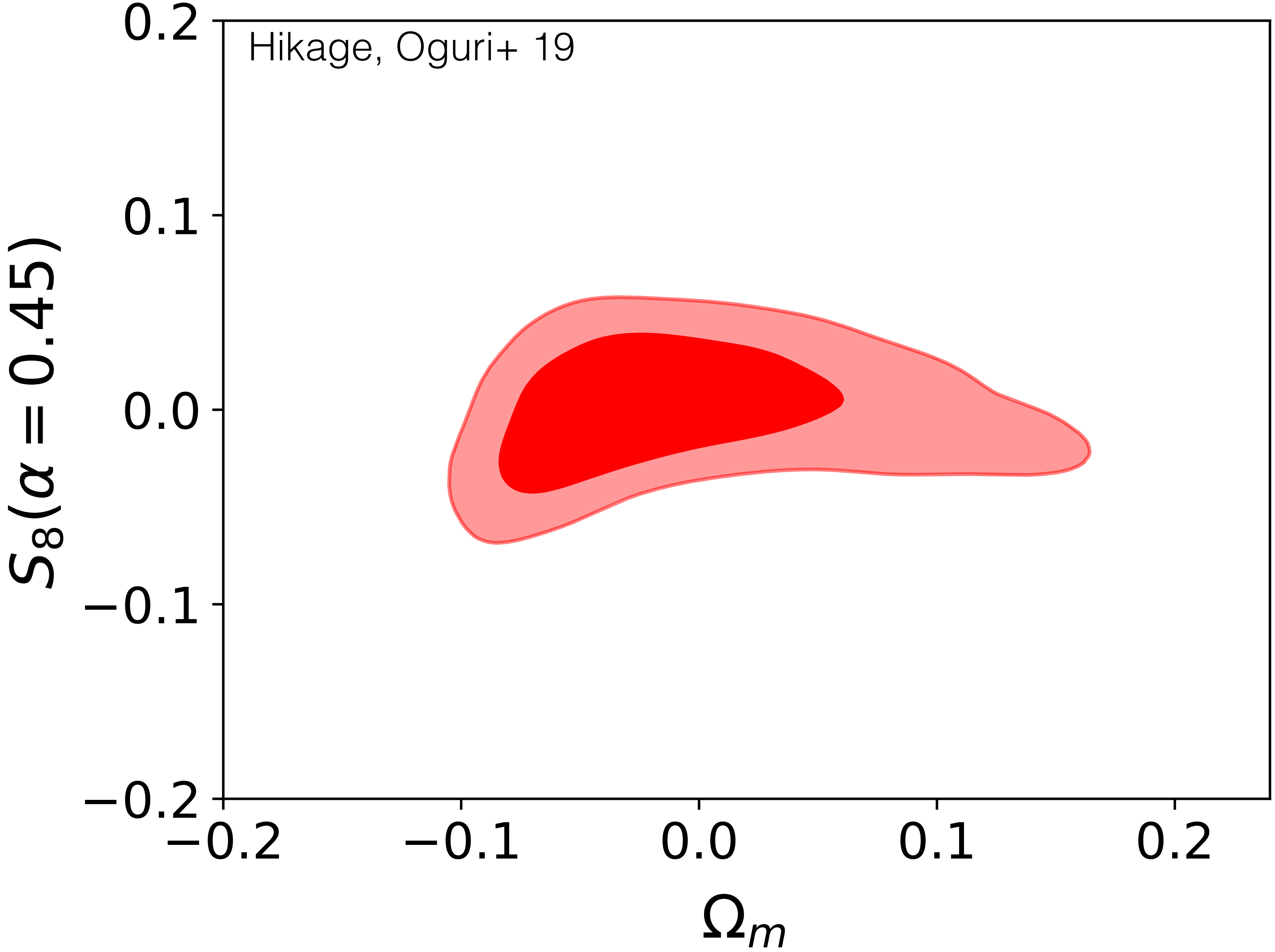


Before lensed

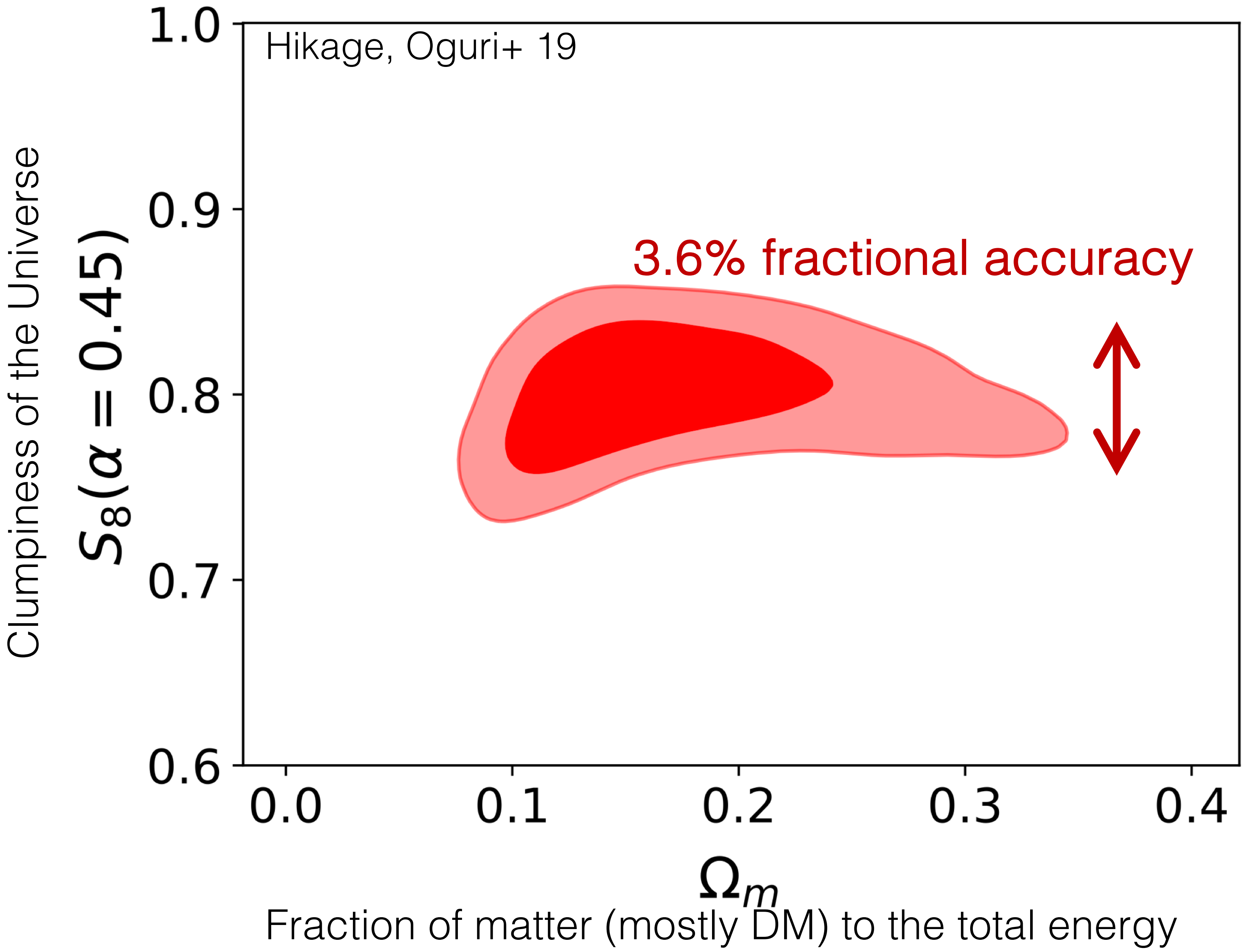
After lensed
(only 0.3% axis ratio
in ellipticity)

Hikage, Oguri+ 19

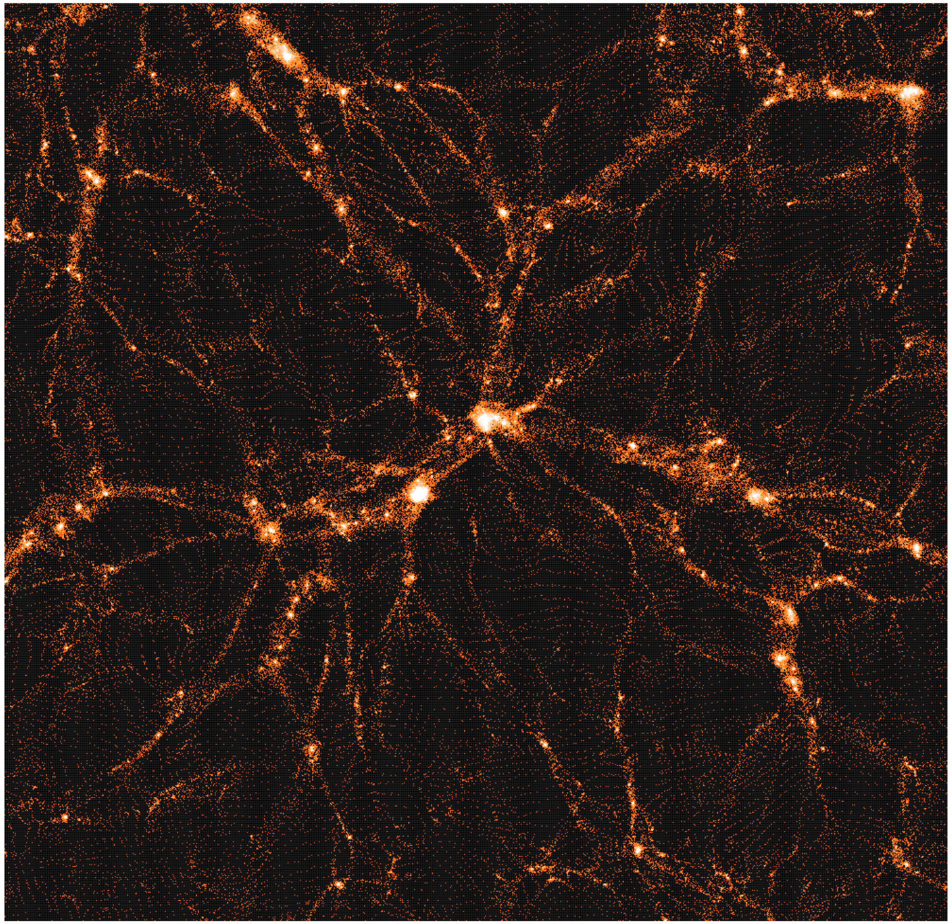
Before unblinding on 26 June, 2018



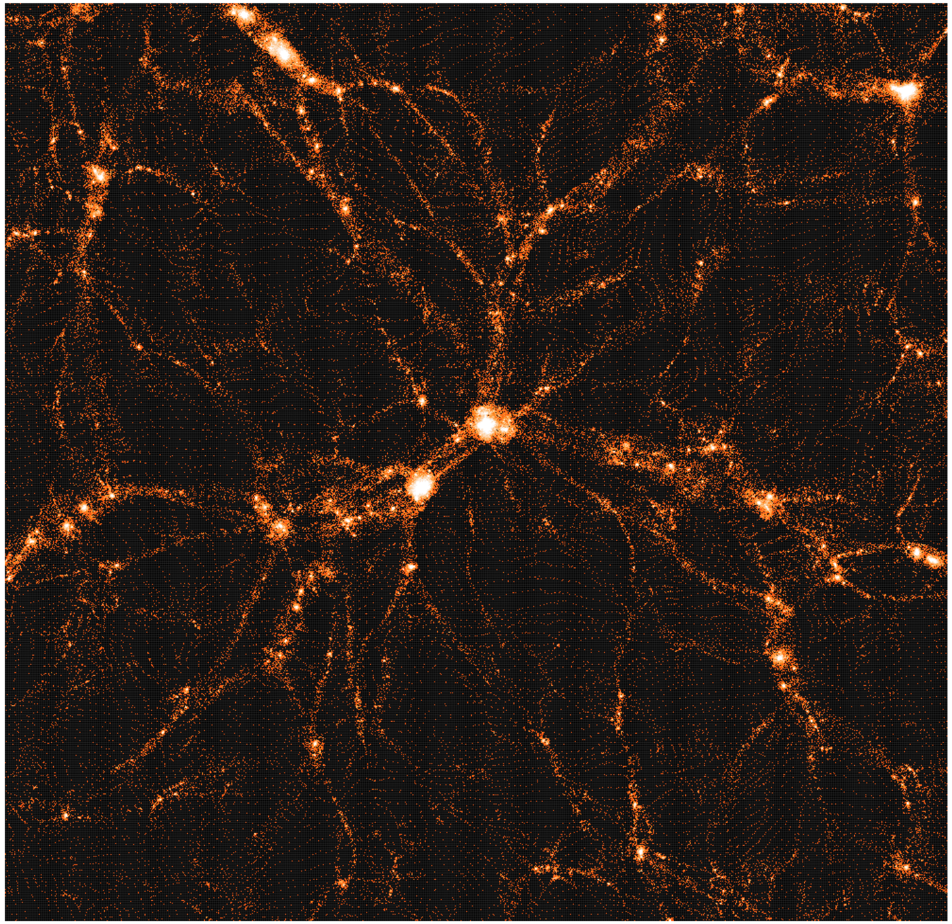
After unblinding on 26 June



HSC preferred universe

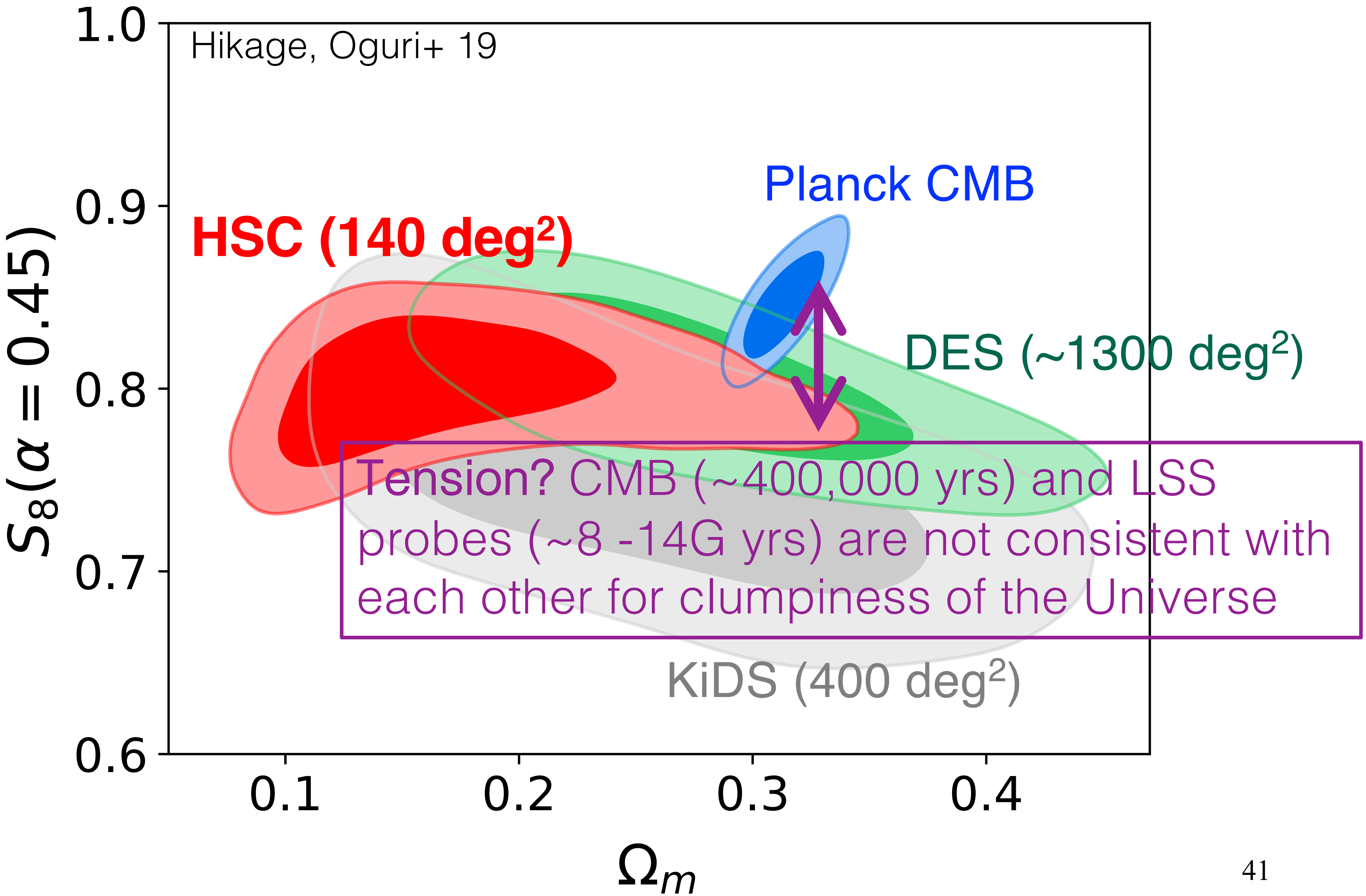


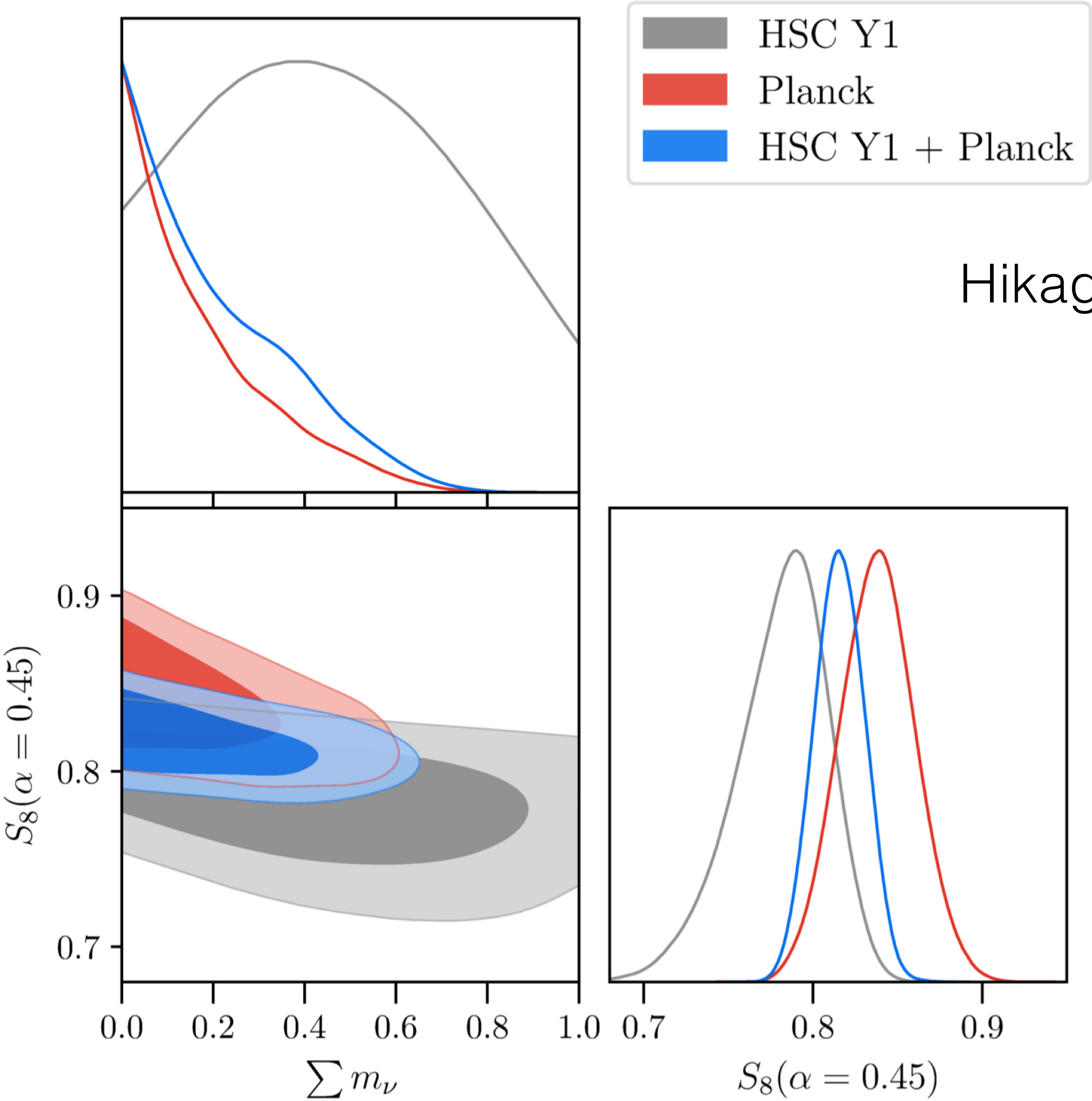
Planck preferred universe



simulated dark matter distribution in the Universe today

After unblinding on 26 June



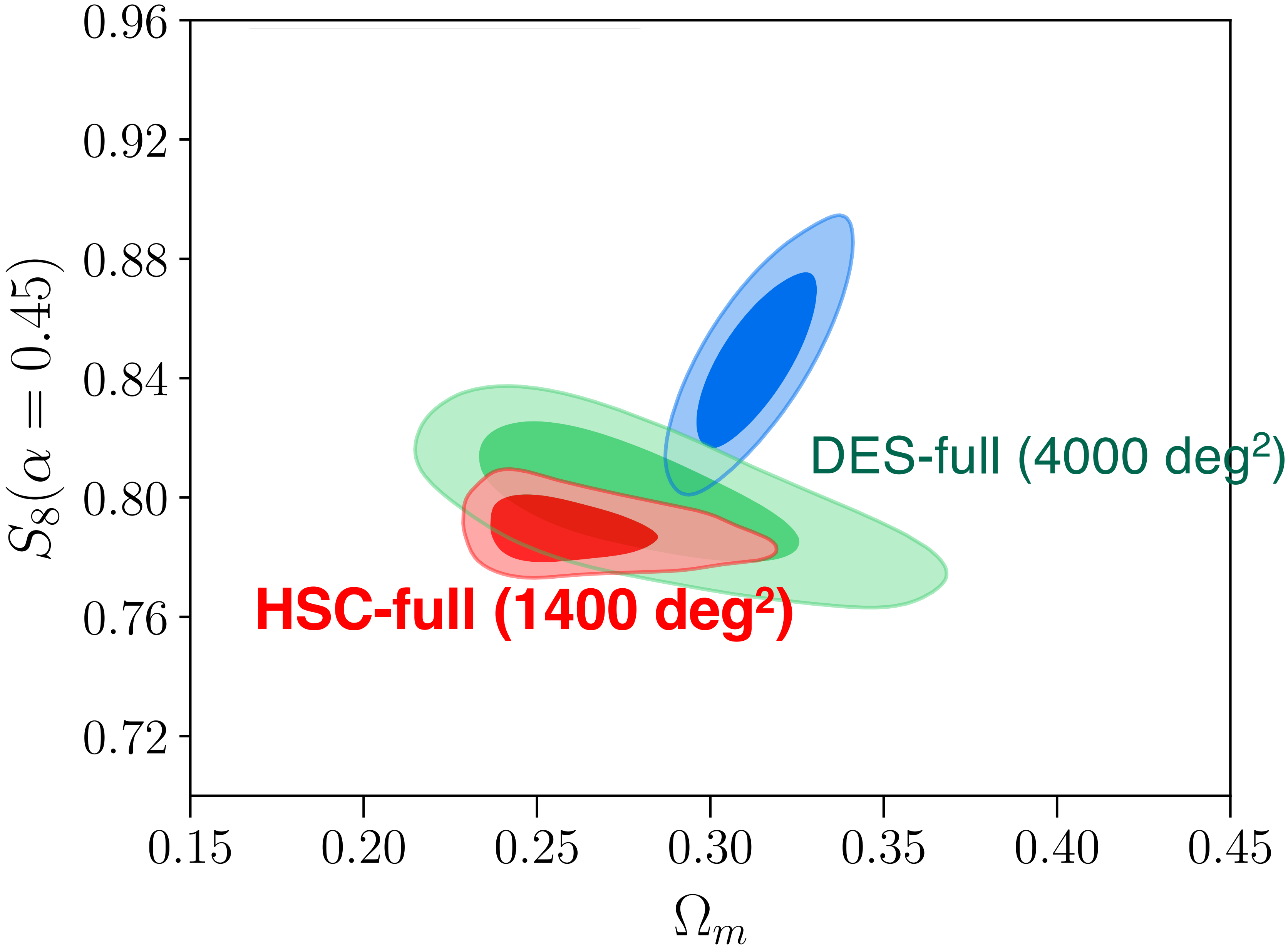


Hikage et al. 19

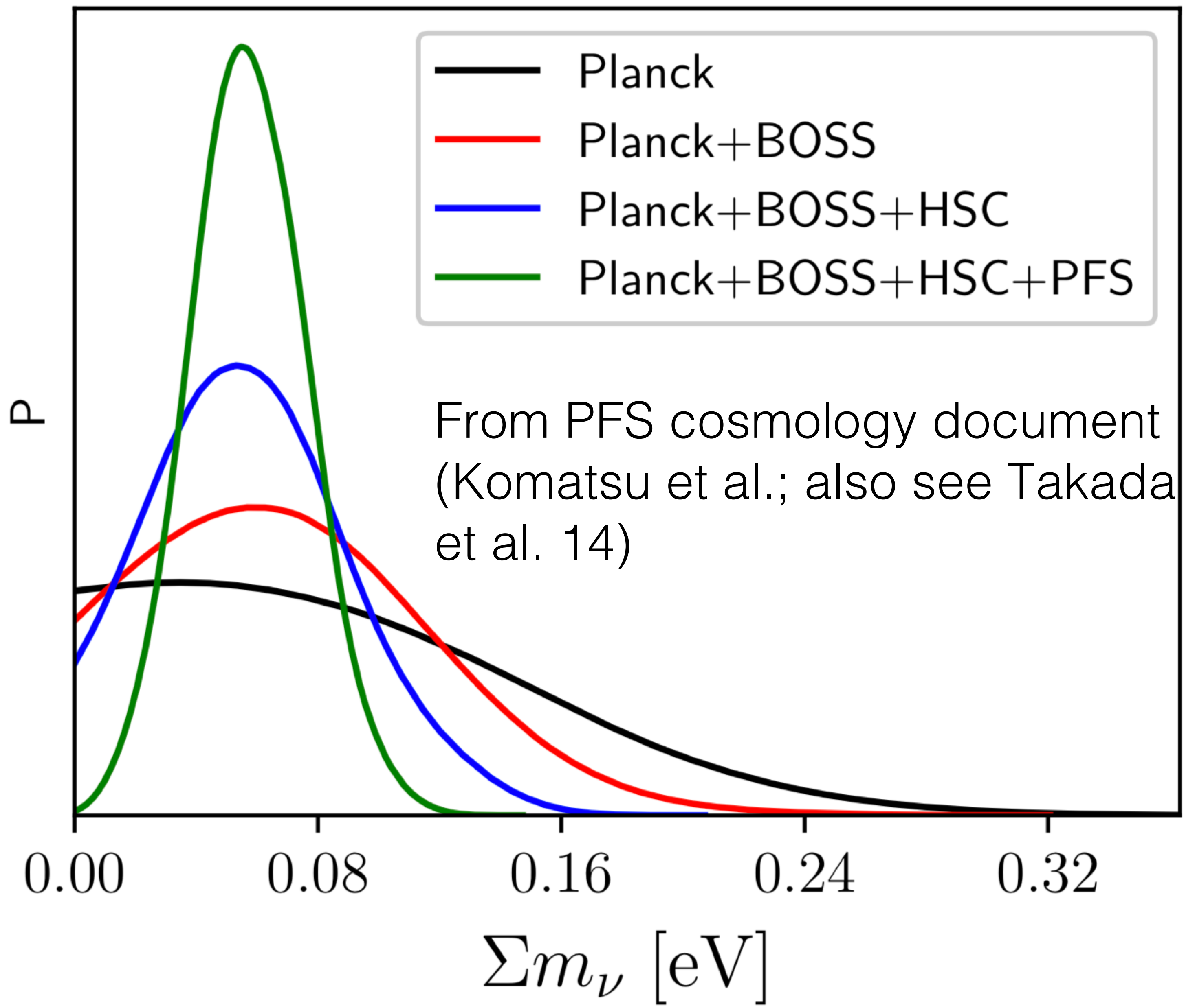
Weak neutrino mass constraint due to the preferred low-Ω_m in HSC data

Planck lensing: *M*_nu<0.2eV (95%)

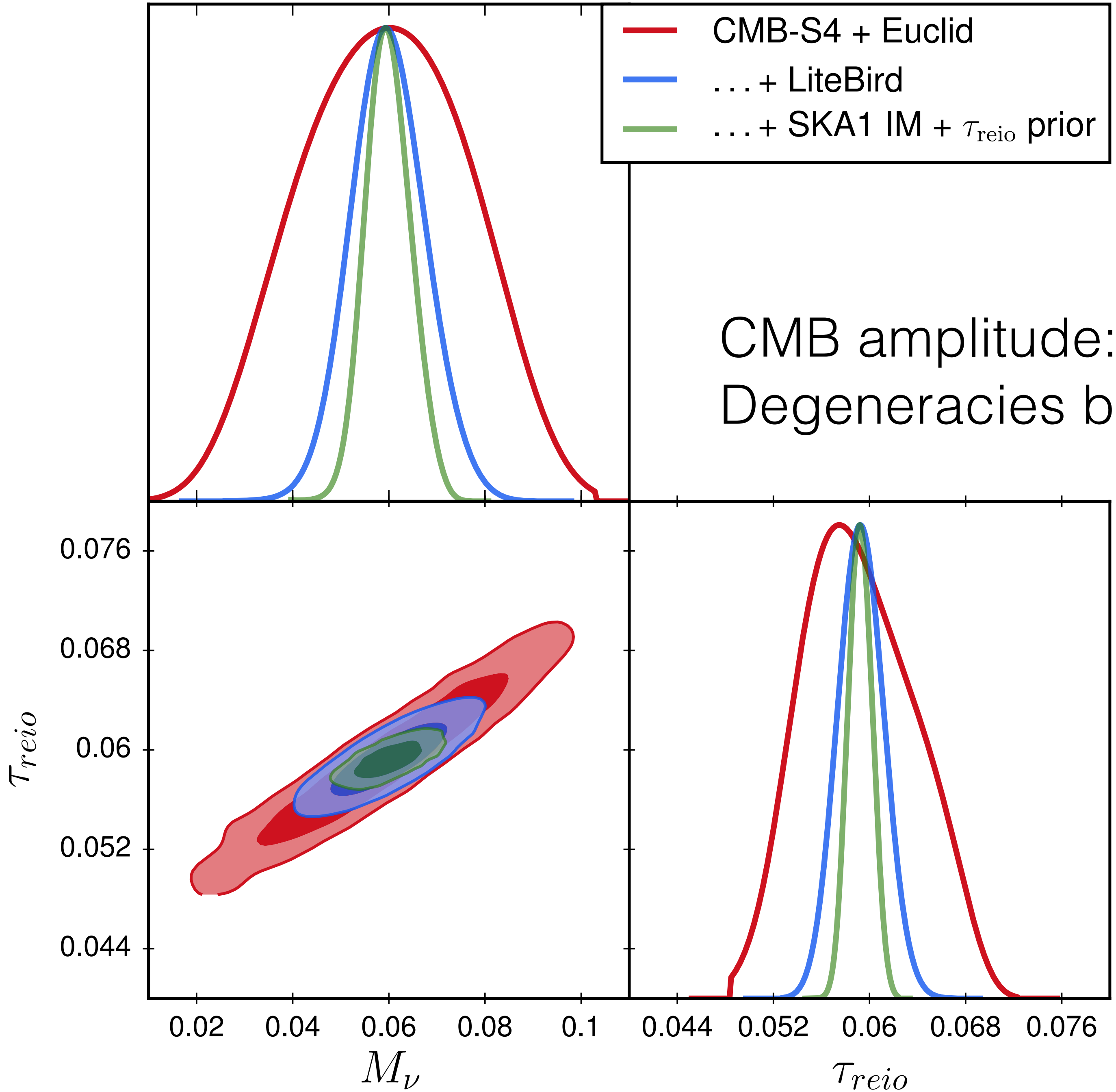
Prospects of HSC survey



Prospect for Subaru HSC+PFS



LiteBIRD important for neutrino mass!



CMB amplitude: $C_\ell^{\rm obs} \propto A_s e^{-2\tau_{\rm reio}}$

Degeneracies btw As and tau

Cosmology goals of neutrino physics in the next decade

- With upcoming cosmology datasets (CMB, galaxy surveys), we aim at achieving
  - Constrain the relativistic degrees of freedom (e.g., sterile neutrinos or axion): $\sigma(N_{\rm eff}) \simeq 0.027$
  - Determine neutrino mass (the sum of three-species neutrino masses): $\sigma(m_{\nu,{\rm tot}}) \simeq 0.02~{\rm eV}$

complementary to double-beta decay exp.

- These are clear targets (no new physics needed)
- Challenges: systematic errors (e.g., galaxy bias, other astrophysics effects)