2-5 June 2025

East Asian Meeting on Large Galaxy Surveys for Cosmology and Galaxy Formation

Center for Gravitational Physics and Quantum Information

YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

Introduction to cosmology

Atsushi Taruya
(Yukawa Institute for Theoretical Physics)

Contents

Overview of cosmology with large-scale structure observations

- Introduction
- Standard cosmological model (ΛCDM model)
- Unresolved issues & tensions
- Future prospects beyond ΛCDM model
- Summary

Cosmology

is a branch of physics dealing with the nature of the universe

=Physical cosmology

Top-down approach

builds up a theoretically consistent model and/or scenario of the origin and early universe based on fundamental theory of physics

Bottom-up approach

Constructs a theory that describes the evolution of the universe based on observations, and test the hypotheses and principles underlying the theory

wikipedia

Death Valley

Cosmological observations

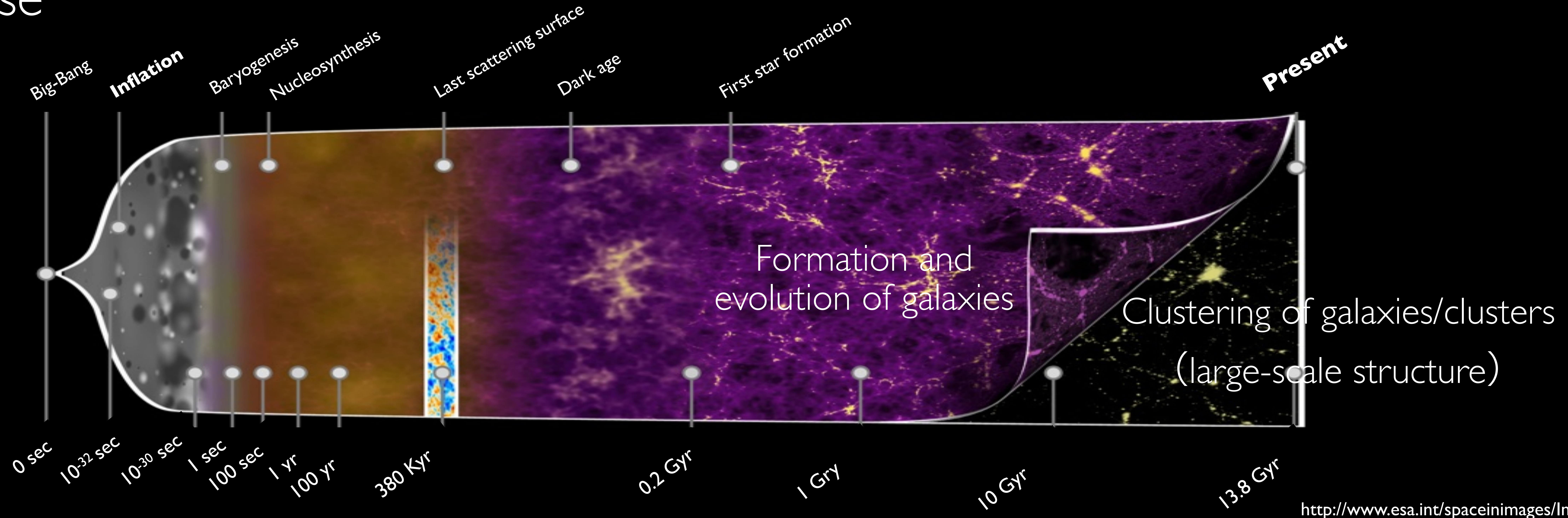
Targets are astronomical objects (or phenomena) that can carry <u>cosmological information</u>

Cosmic expansion & structure formation

ΛCDM — Standard cosmological model

established in the 2,000s through accumulated observational evidence

- Describes the formation and evolution of the universe
- Explains the cosmic expansion & the resulting matter distribution across the universe



http://www.esa.int/spaceinimages/Images/

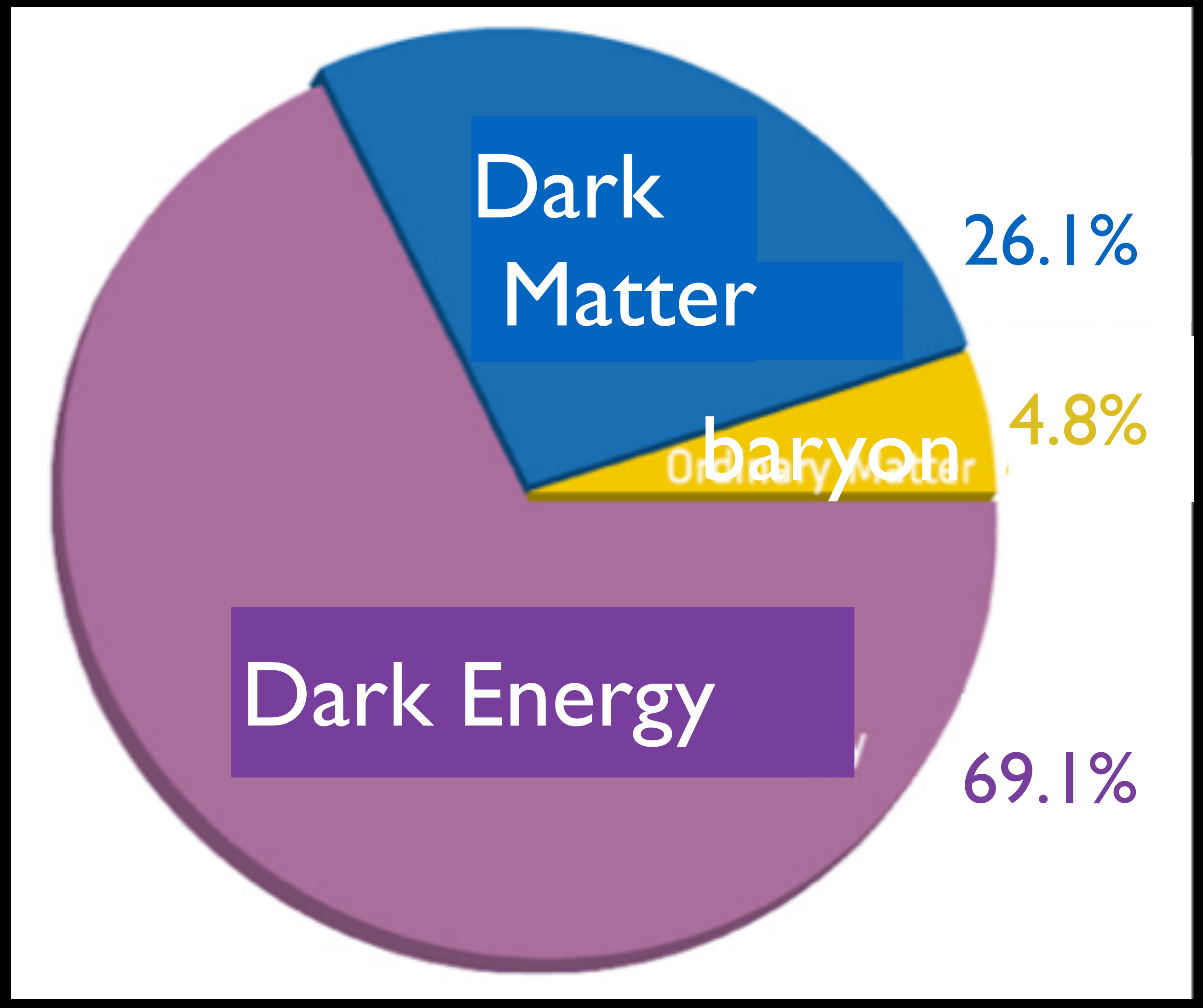
ΛCDM — Standard cosmological model

A minimal model based on **general relativity**

only with six parameters

- A spatially flat universe with a cosmological constant (Λ)
- Homogeneous & isotropic background + perturbations
- Structure formation driven by the gravitational instability of cold dark matter

⇒ Providing a self-consistent explanation that agrees with current observations



$\Omega_b h^2$: baryon density

$\Omega_c h^2$: CDM density

θ_{MC} : distance ratio to last scattering surface

} Cosmic expansion

n_s : scalar spectral index

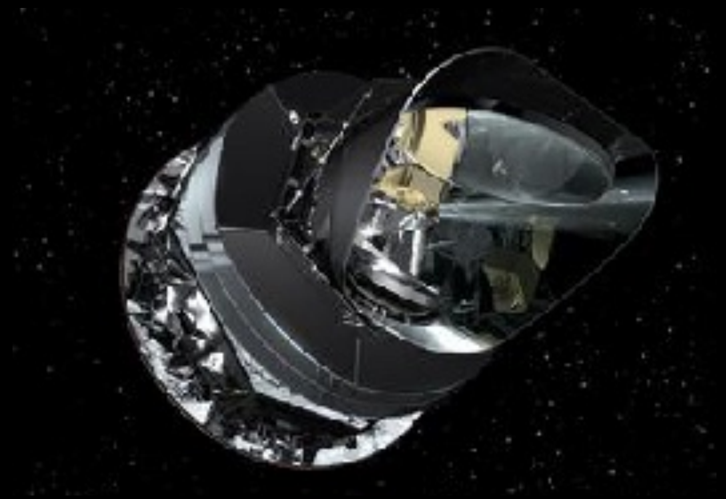
A_s : amplitude of curvature fluctuation

} Primordial density fluctuations

τ : reionization optical depth — Formation of the first cosmic structures

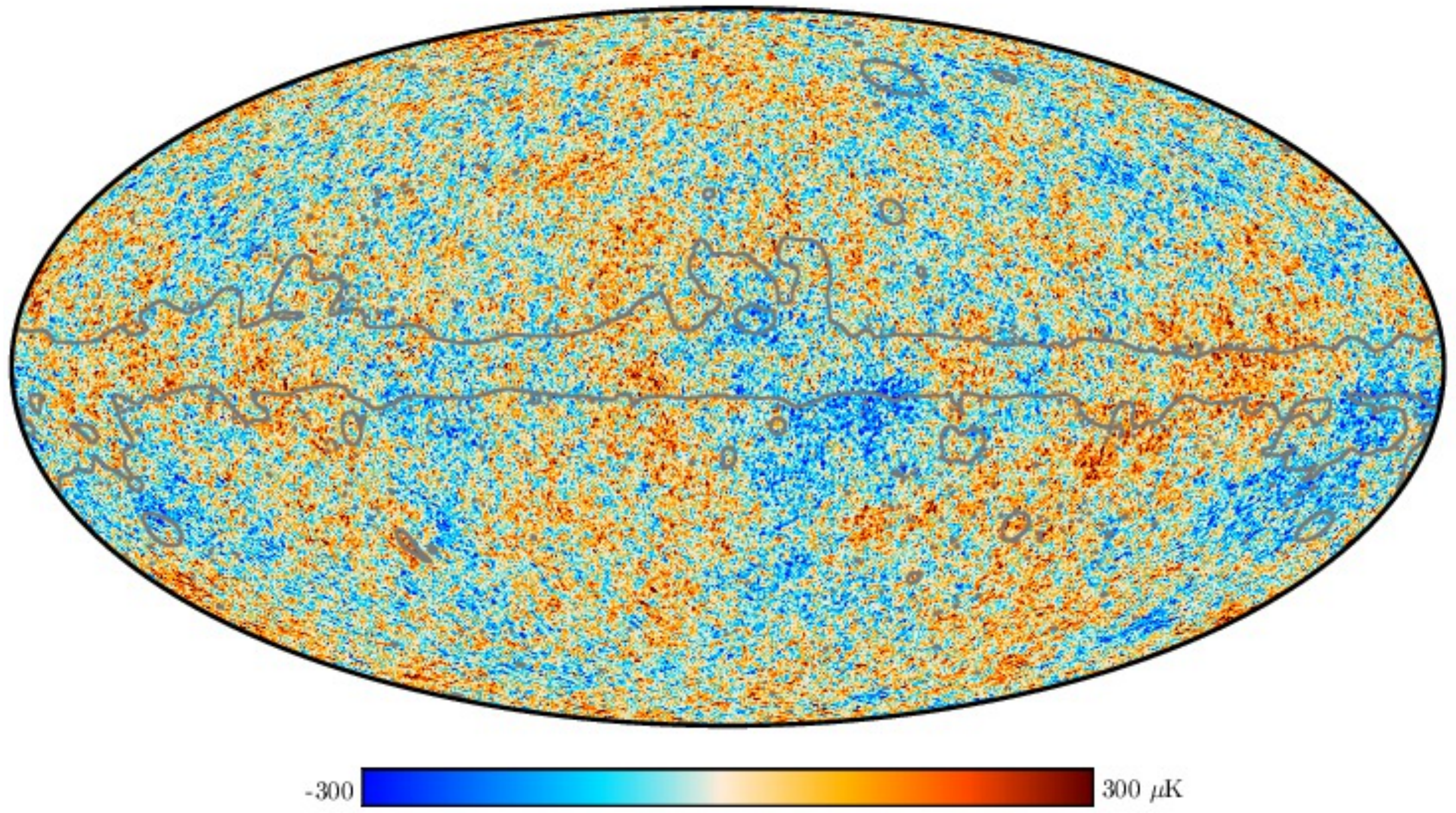
Parameters derived from CMB observations

Planck 2018

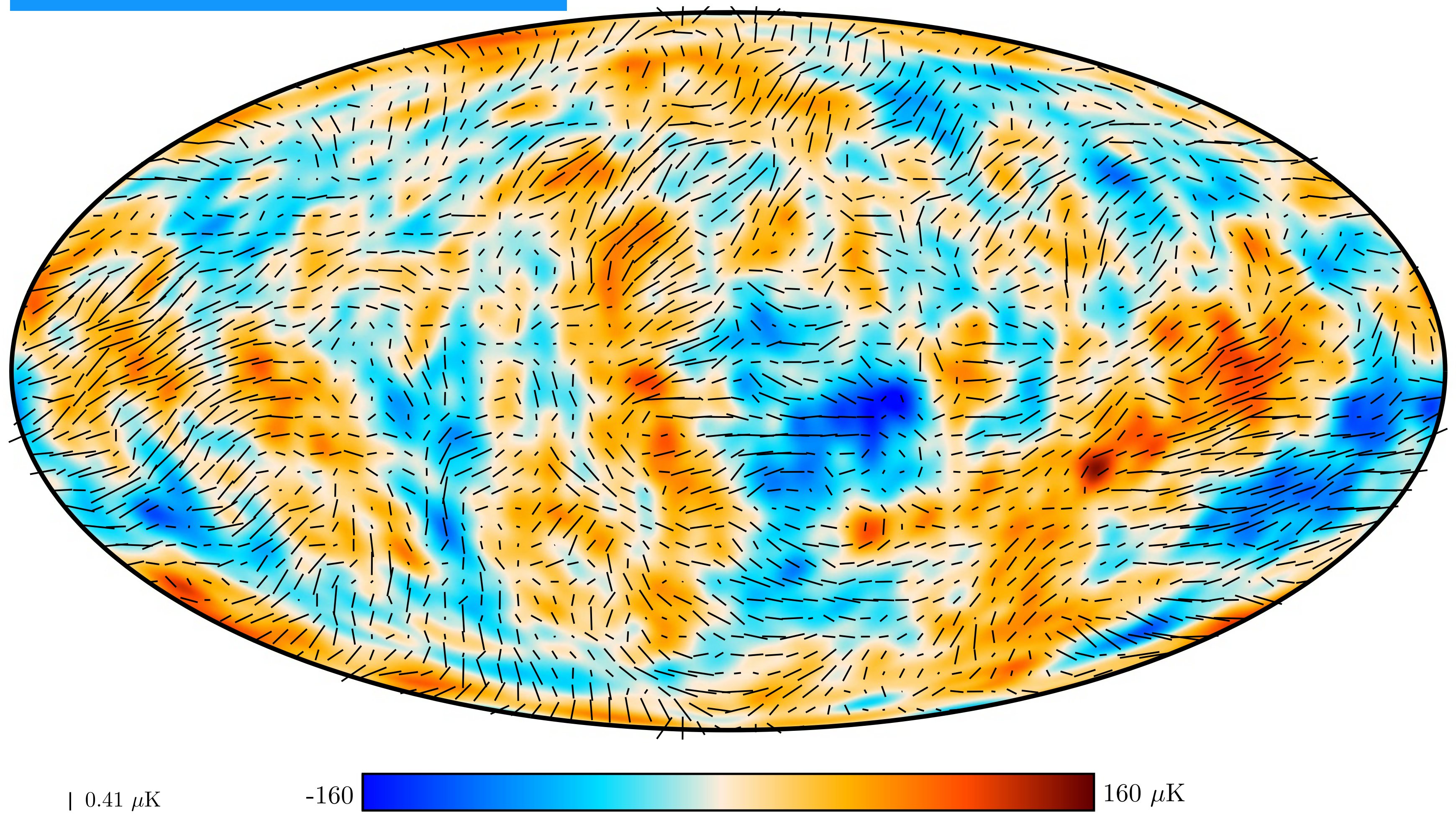


Cosmic microwave background experiment led by ESA

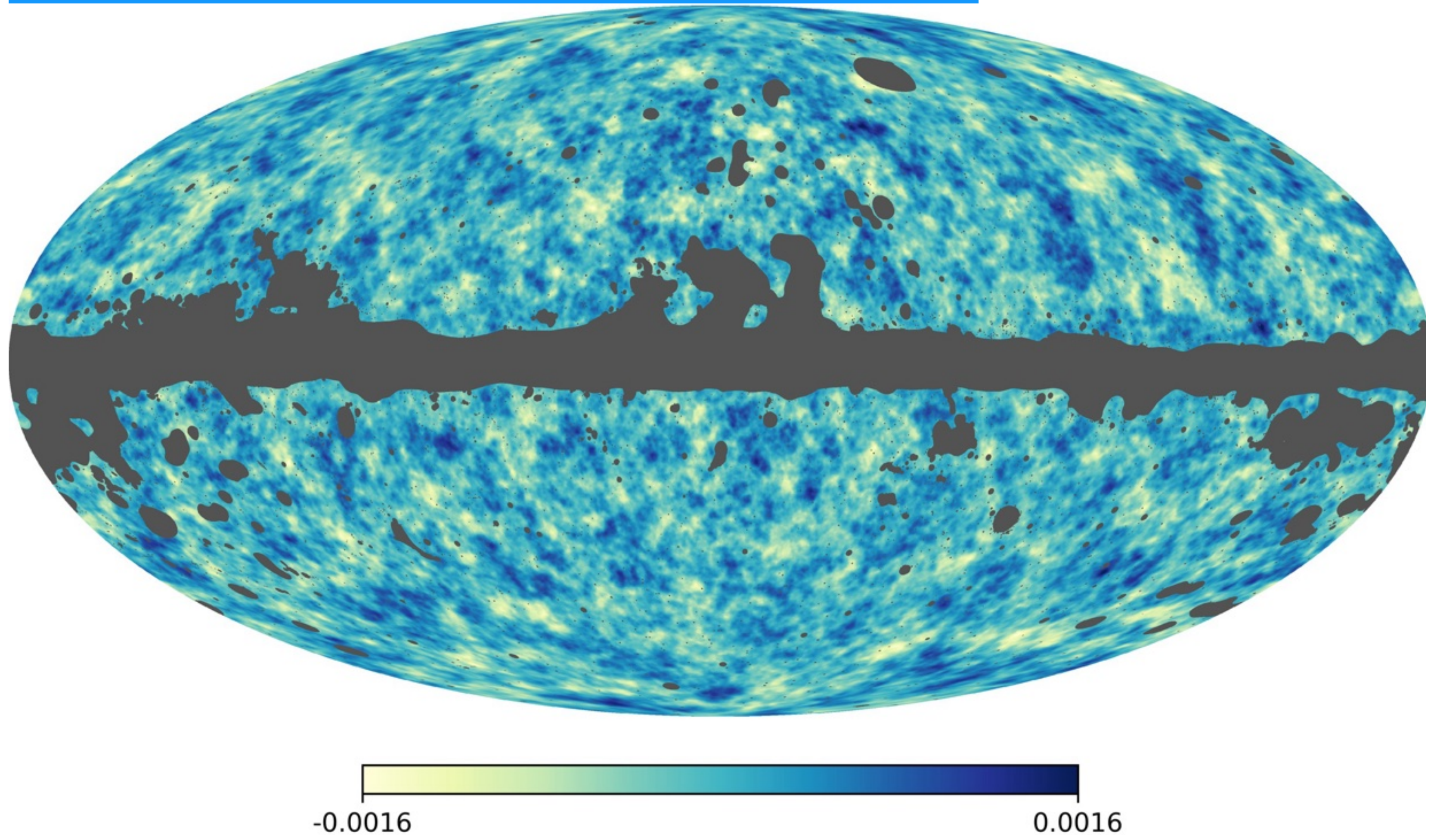
Temperature



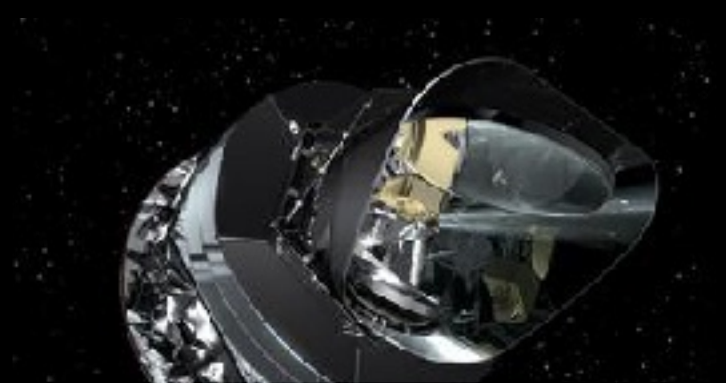
Polarization



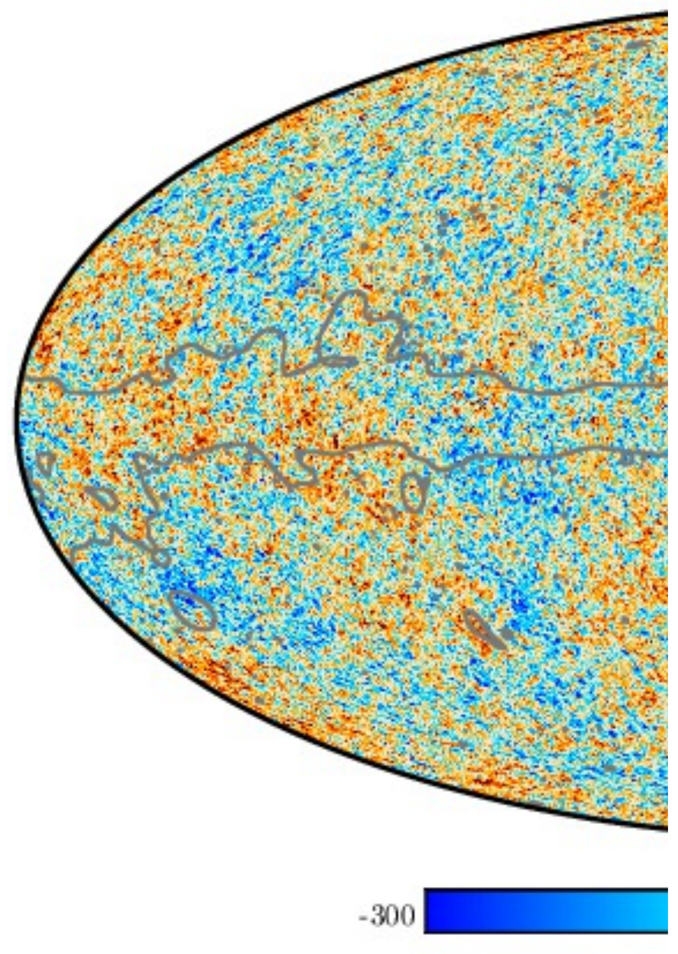
Gravitational lensing

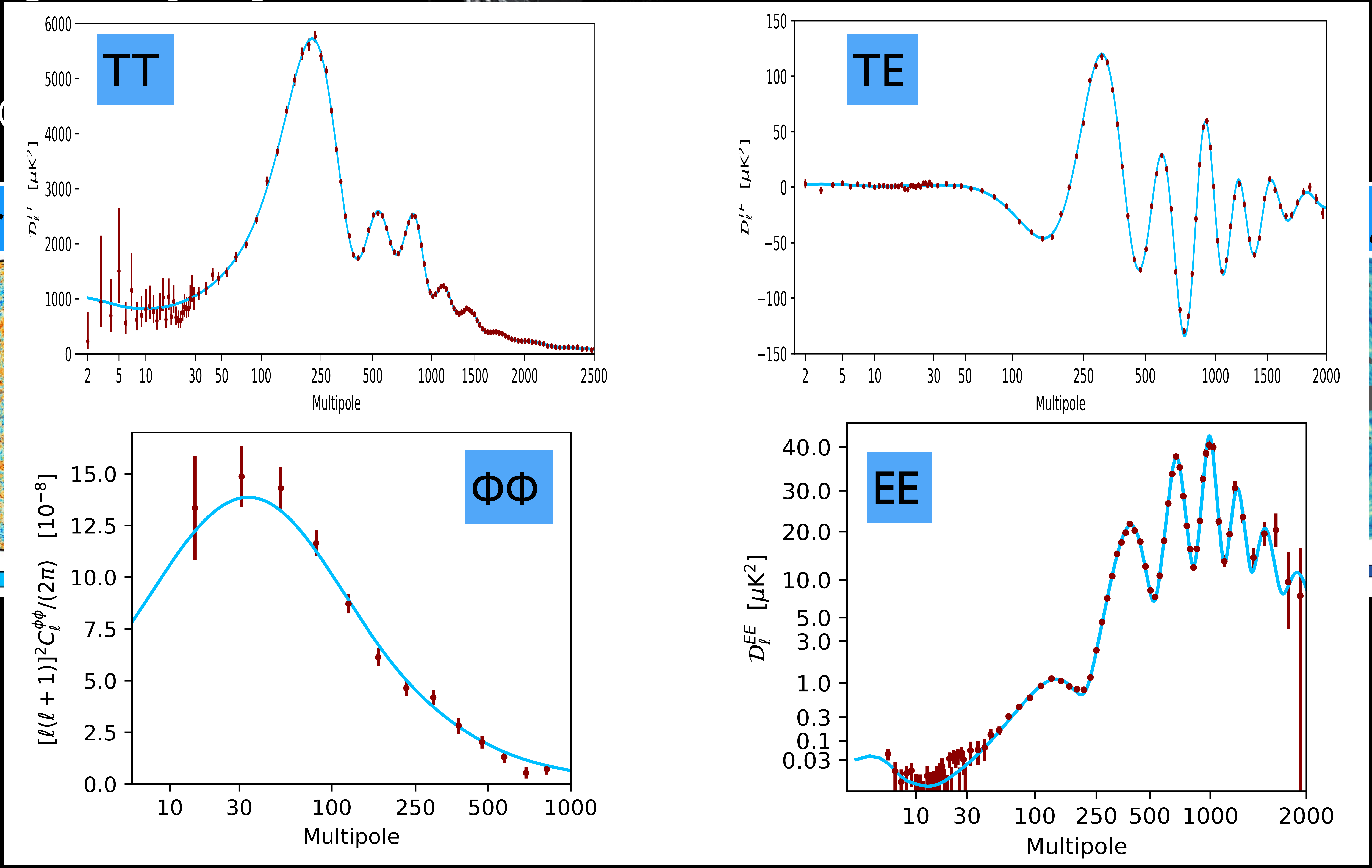


Planck 2018



Temperatur





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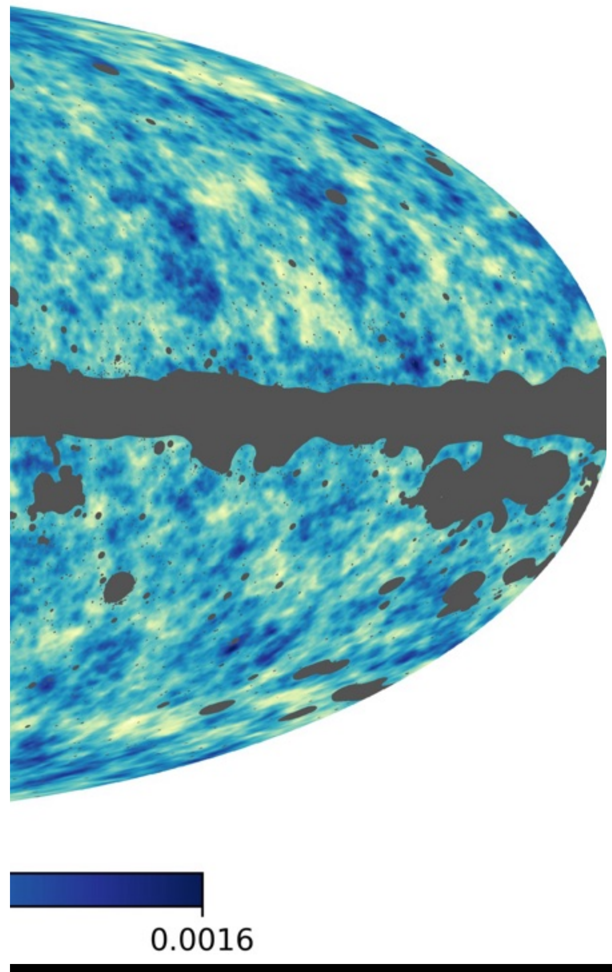
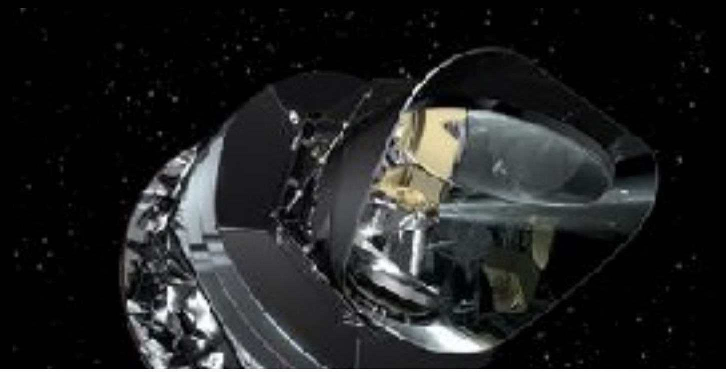
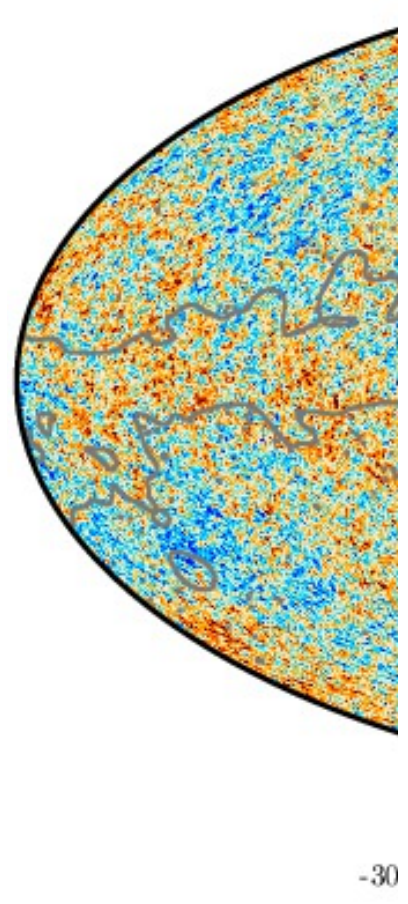


Planck 2018



Tempe

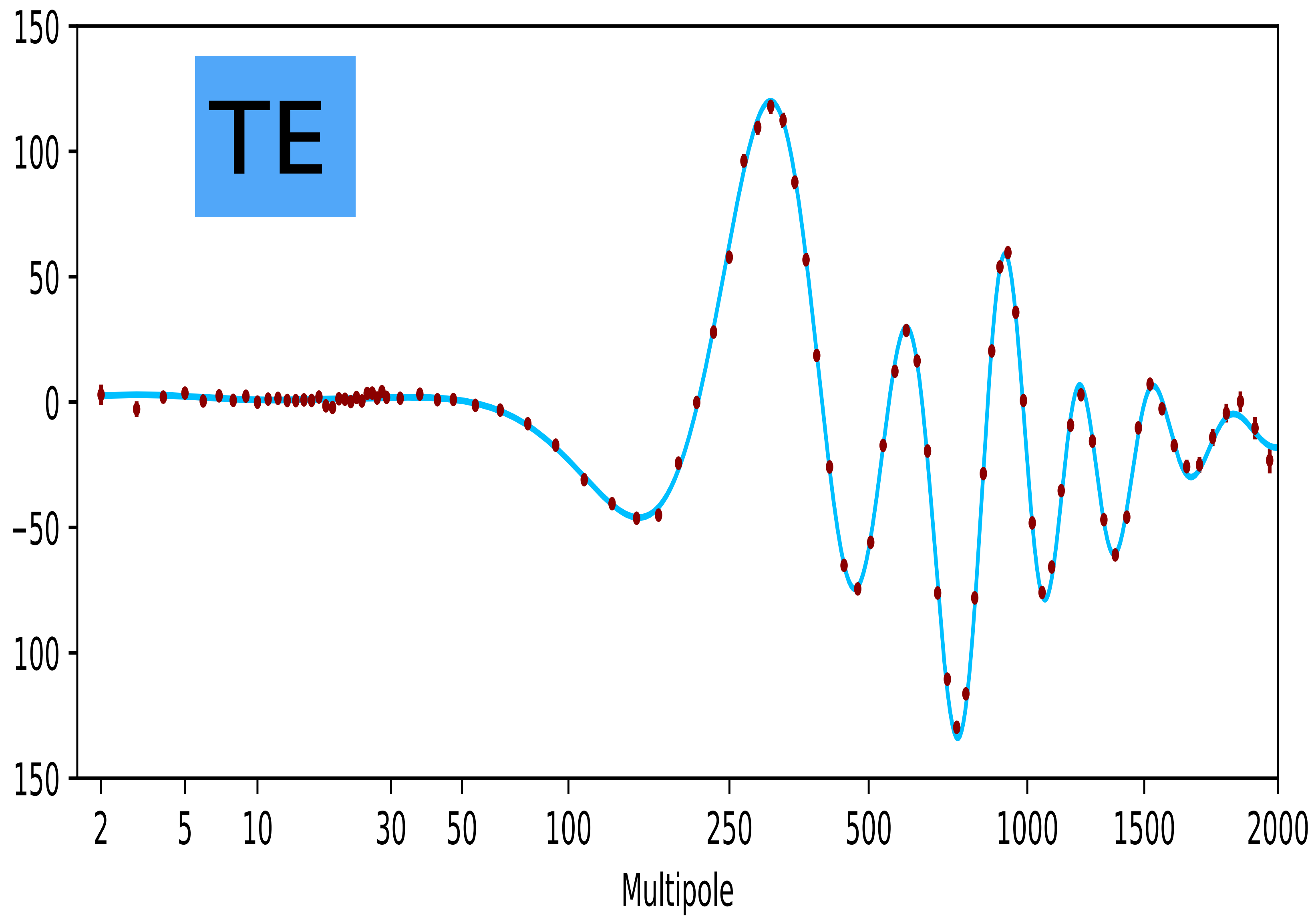


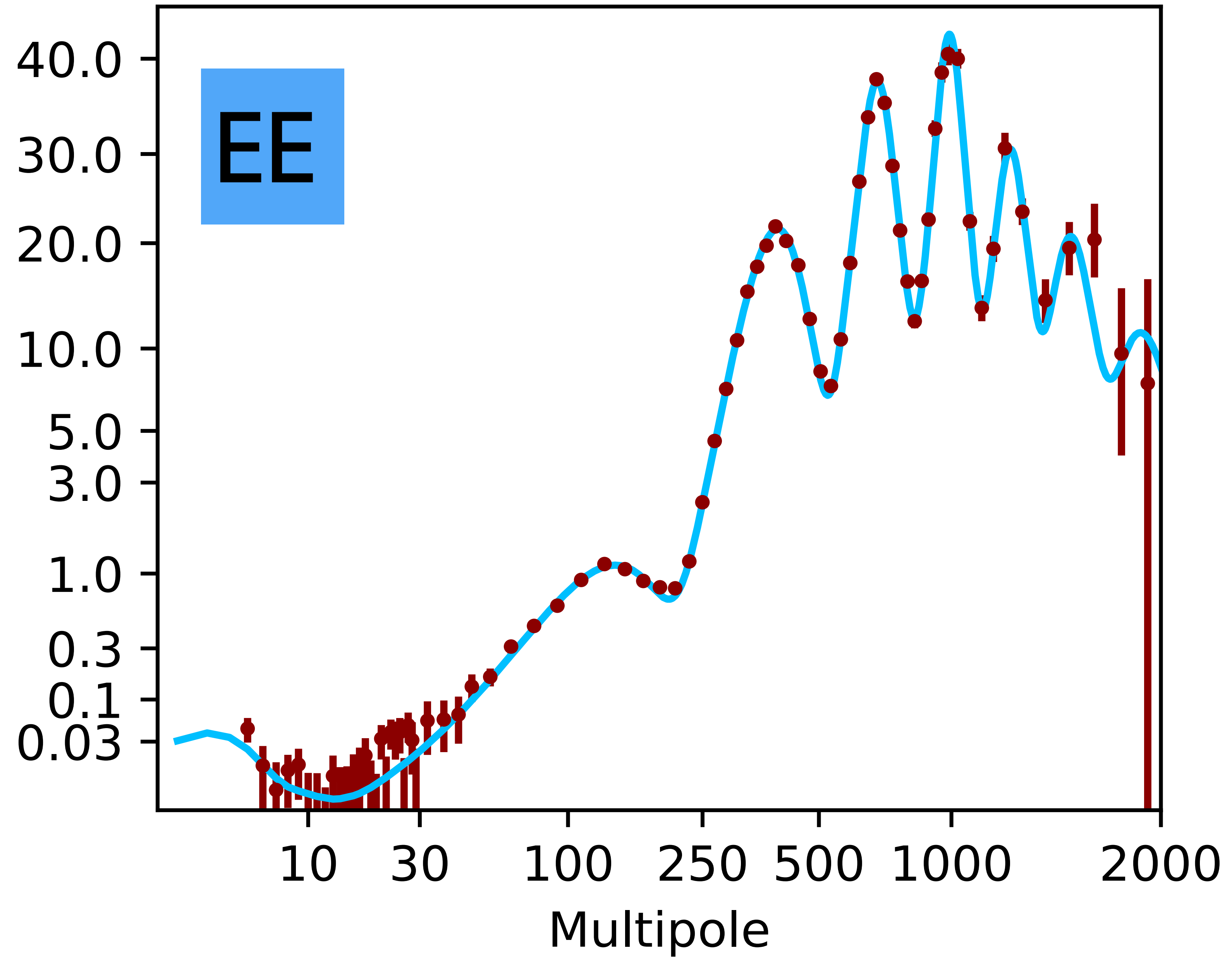
Parameter	*Planck* alone
$\Omega_b h^2$	0.02237 ± 0.00015
$\Omega_c h^2$	0.1200 ± 0.0012
$100\theta_{MC}$	1.04092 ± 0.00031
τ	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.044 ± 0.014
n_s	0.9649 ± 0.0042
H_0	67.36 ± 0.54
Ω_Λ	0.6847 ± 0.0073
Ω_m	0.3153 ± 0.0073
$\Omega_m h^2$	0.1430 ± 0.0011
$\Omega_m h^3$	0.09633 ± 0.00030
σ_8	0.8111 ± 0.0060
$\sigma_8(\Omega_m/0.3)^{0.5}$ . . .	0.832 ± 0.013
z_{re}	7.67 ± 0.73
Age[Gyr]	13.797 ± 0.023
r_*[Mpc]	144.43 ± 0.26
$100\theta_*$	1.04110 ± 0.00031
r_{drag}[Mpc]	147.09 ± 0.26
z_{eq}	3402 ± 26
$k_{eq}[\mathrm{Mpc}^{-1}]$	0.010384 ± 0.000081

Base ΛCDM parameters

- temperature
- polarization
- lensing

derived parameters





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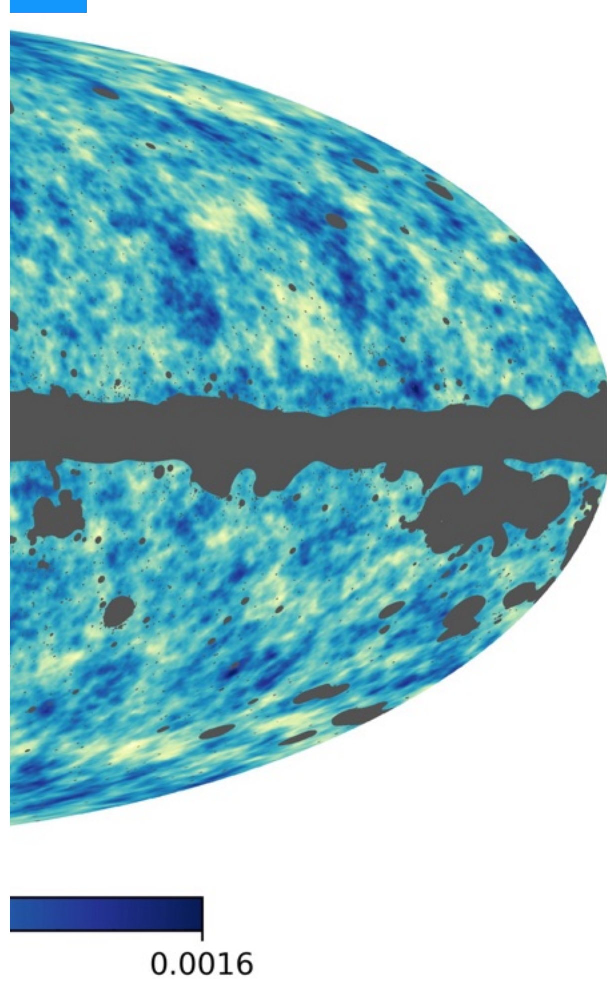
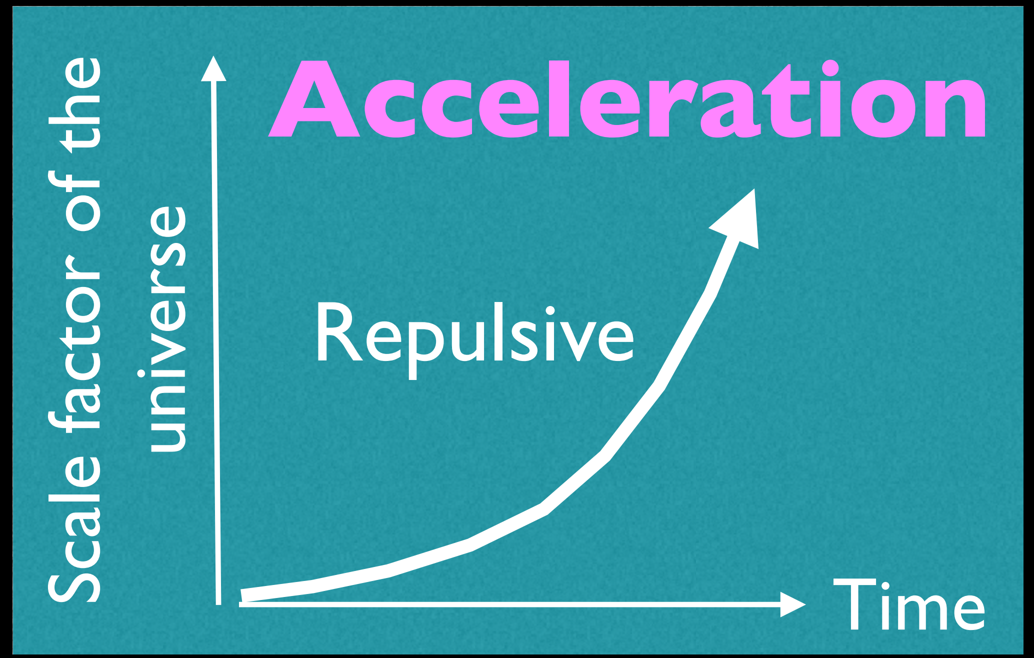


Mysteries/unresolved issues

Nature of dark energy: driver of the current accelerated cosmic expansion

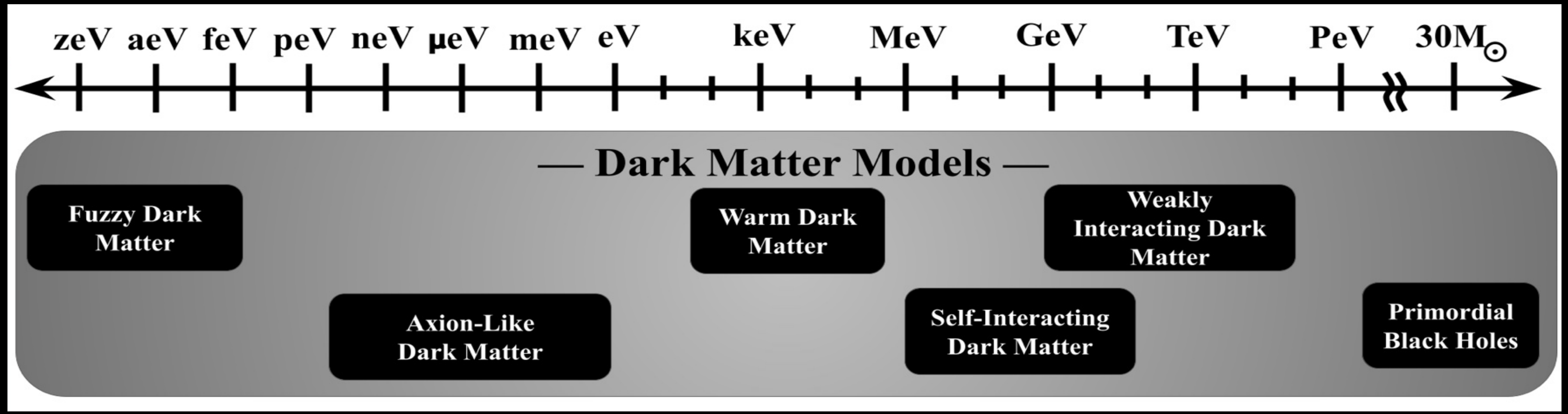
- Is it Einstein's cosmological constant ?
- Or does it signal a breakdown of general relativity ?



Nature of dark matter : backbone of structure formation in the universe.

Even its mass is unknown

→ A vast discovery space



Furthermore,

key assumptions remain untested, such as:

Inflation — a phase of rapid expansion in the early universe

Hypotheses: cosmological principle, Gaussianity of primordial fluctuations, …

Tensions across multiple observations

Cosmological parameters derived from Planck CMB observations do not agree with those obtained from local (low-z) measurements

— possibly hinting at flaws in ΛCDM model

- H_0 tension :

  A discrepancy in the Hubble parameter today, between values inferred from distance ladder observations and those derived from CMB

$$H_0 = 74.0 \pm 1.4\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

(Riess et al. '19)

↔

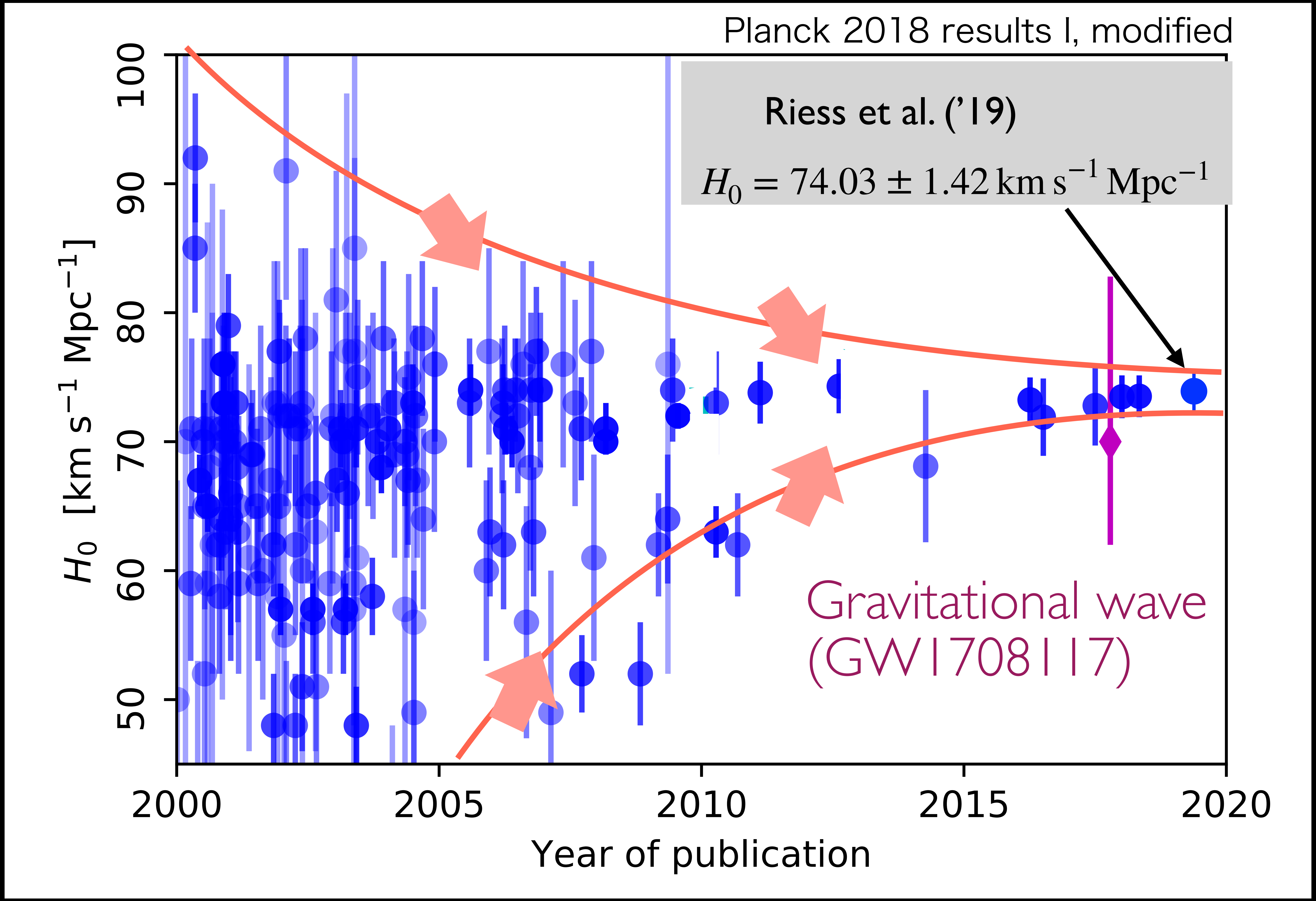
$$H_0 = 67.4 \pm 0.5\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

(Planck 2018 results IV)

Model-independent observations using Cepheids & Type Ia SNe as standard candles

"Predictions" of ΛCDM model derived from Planck CMB observations

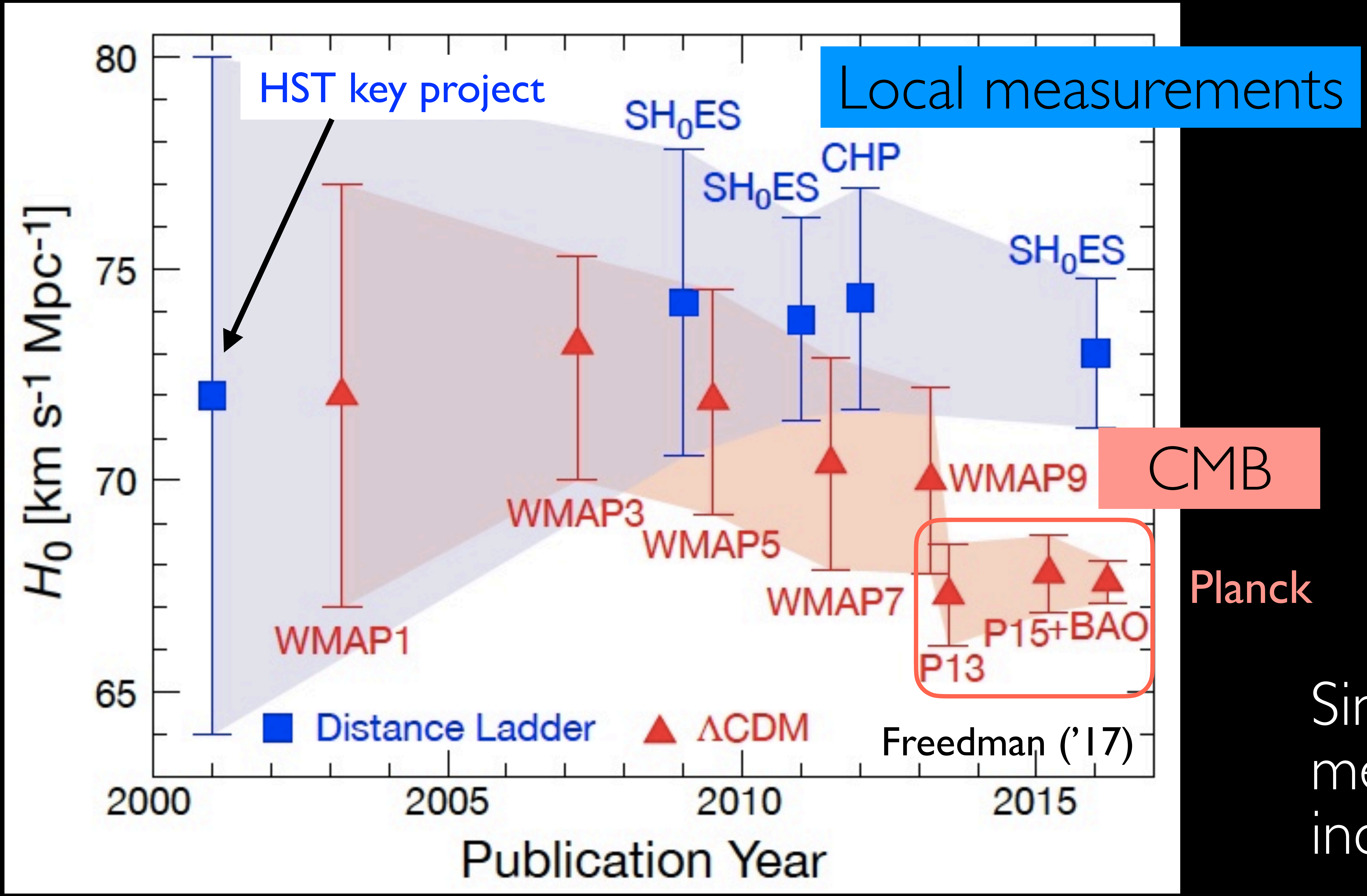
Timeline of H0 measurements



CMB results are excluded

Improving precision across methods, values are converging

Timeline of H0 measurements



Since 2010, local vs. CMB measurements has shown increasing tensions

Direct vs. Indirect Methods

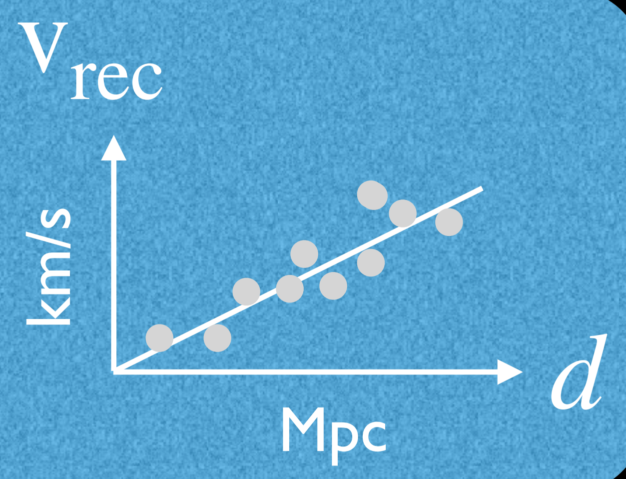
Direct (distance ladder):

Using empirical relations and observations to directly determine the distance–redshift relation.

Lemaître-Hubble law

Redshift   Distance

$$v_{\rm rec}(=c\,z)=H_0\,d$$



Indirect (inverse distance ladder):

Assuming a cosmological model to infer parameters from observables (CMB, BAO, …)

Which measurement is reliable ? or none of them are correct ?

arXiv:2203.06142v1

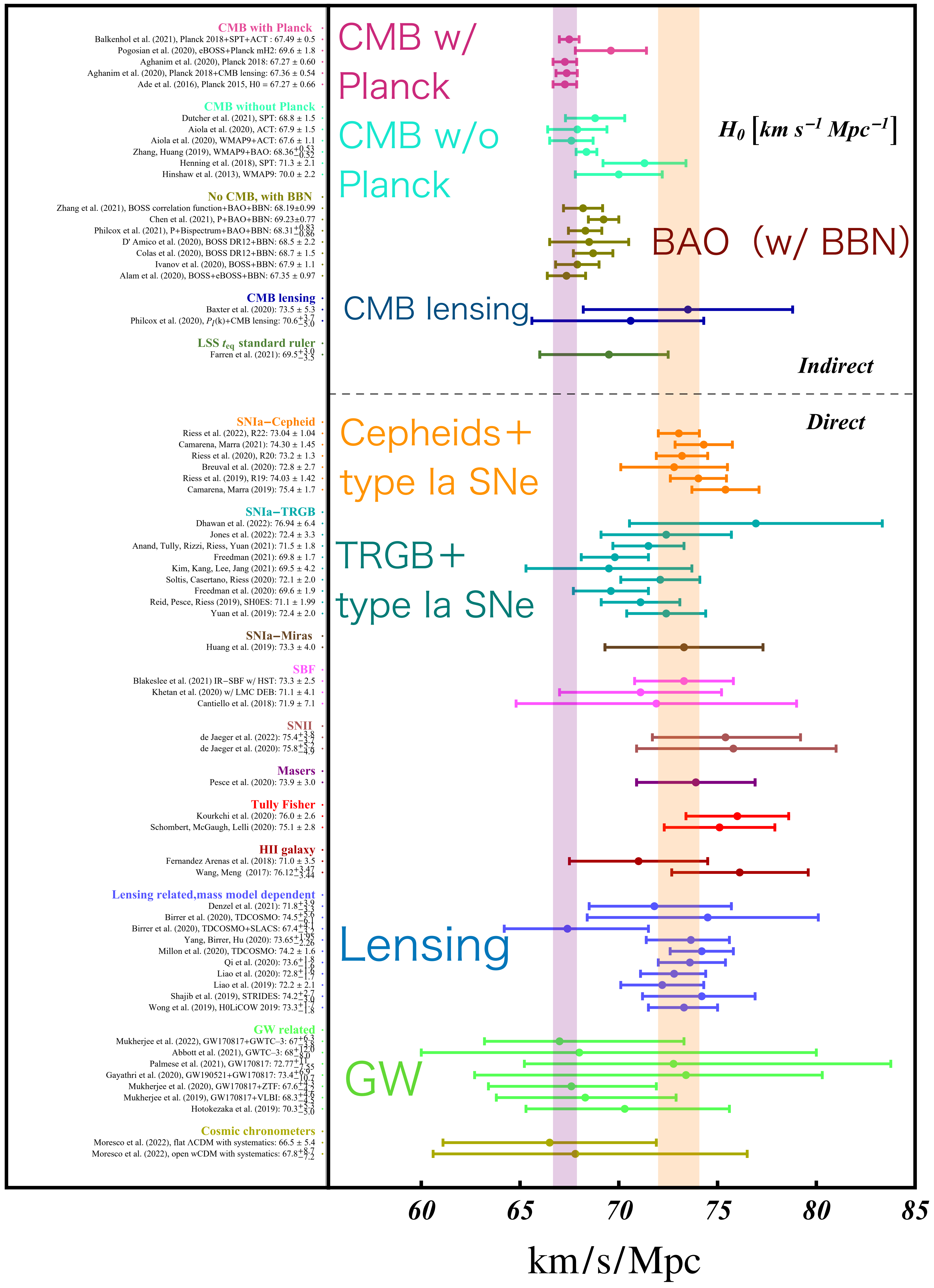
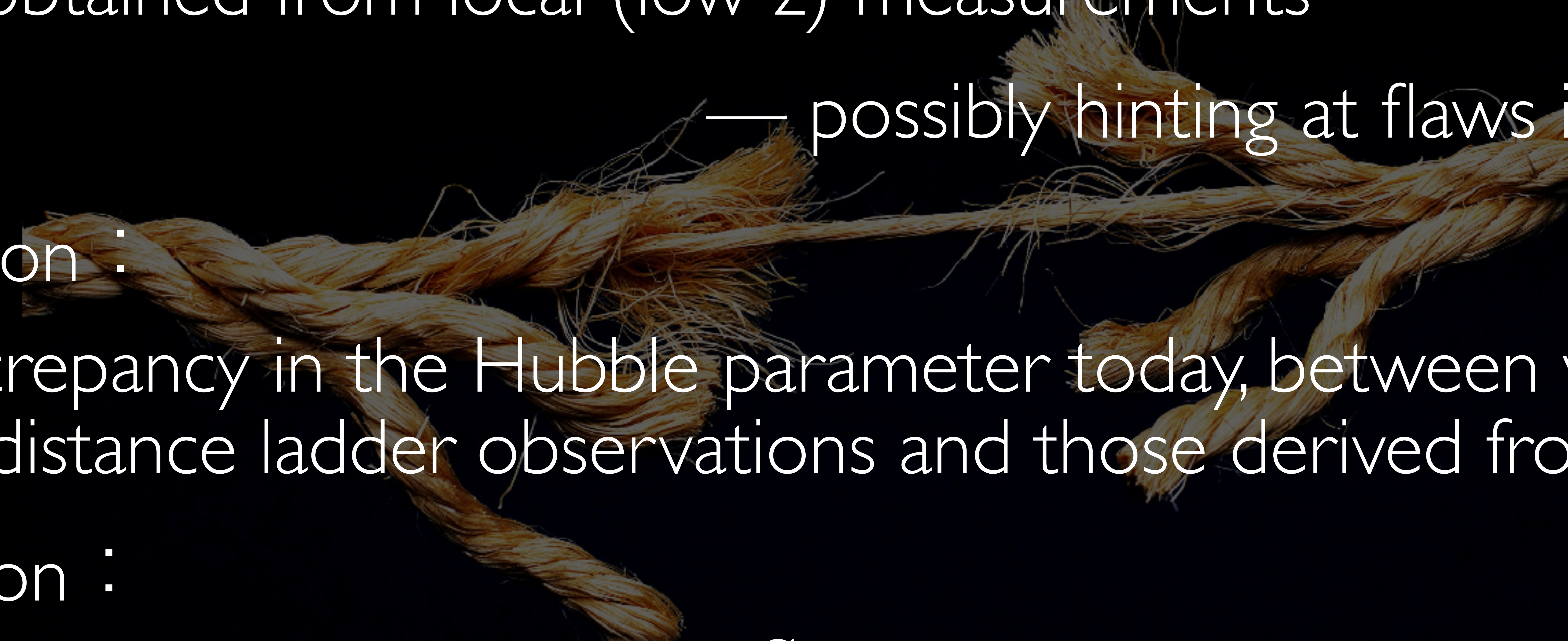


FIG. 2. 68% CL constraint on H_0 from different cosmological probes (based on Refs. [48, 49]).

Tensions across multiple observations

Cosmological parameters derived from Planck CMB observations do not agree with those obtained from local (low-z) measurements

— possibly hinting at flaws in ΛCDM model



- H_0 tension :

  A discrepancy in the Hubble parameter today, between values inferred from distance ladder observations and those derived from CMB

- S_8 tension :

  A mismatch in the parameter S_8, which characterizes the growth of cosmic structure, between weak lensing and CMB observations

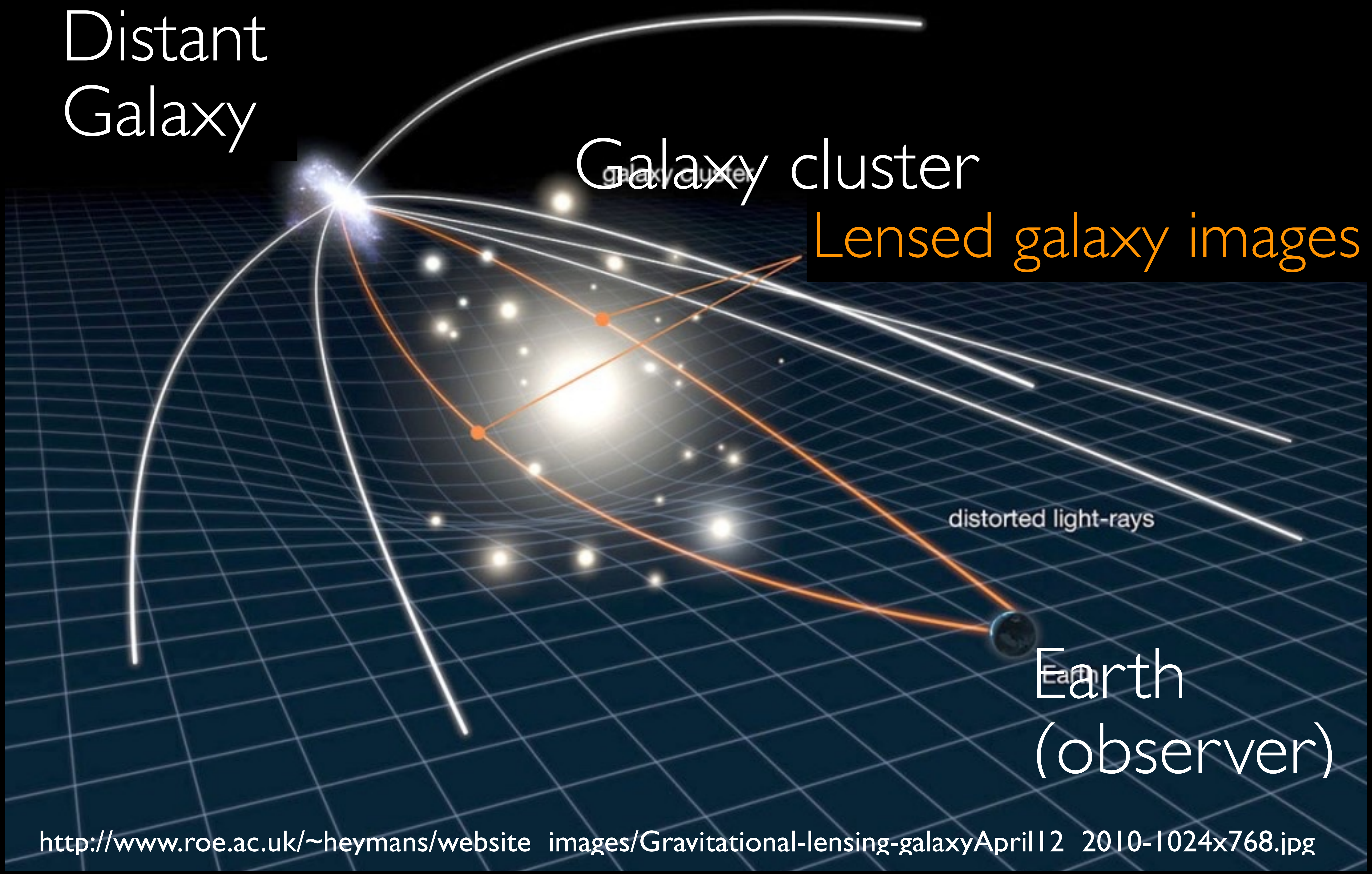
$$S_8 \equiv \sigma_8 \, (\Omega_\mathrm{m}/0.3)^{0.5}$$

Ω_m : matter density parameter

σ_8 : RMS amplitude of matter fluctuations at 8 $h^{-1}\,\mathrm{Mpc}$

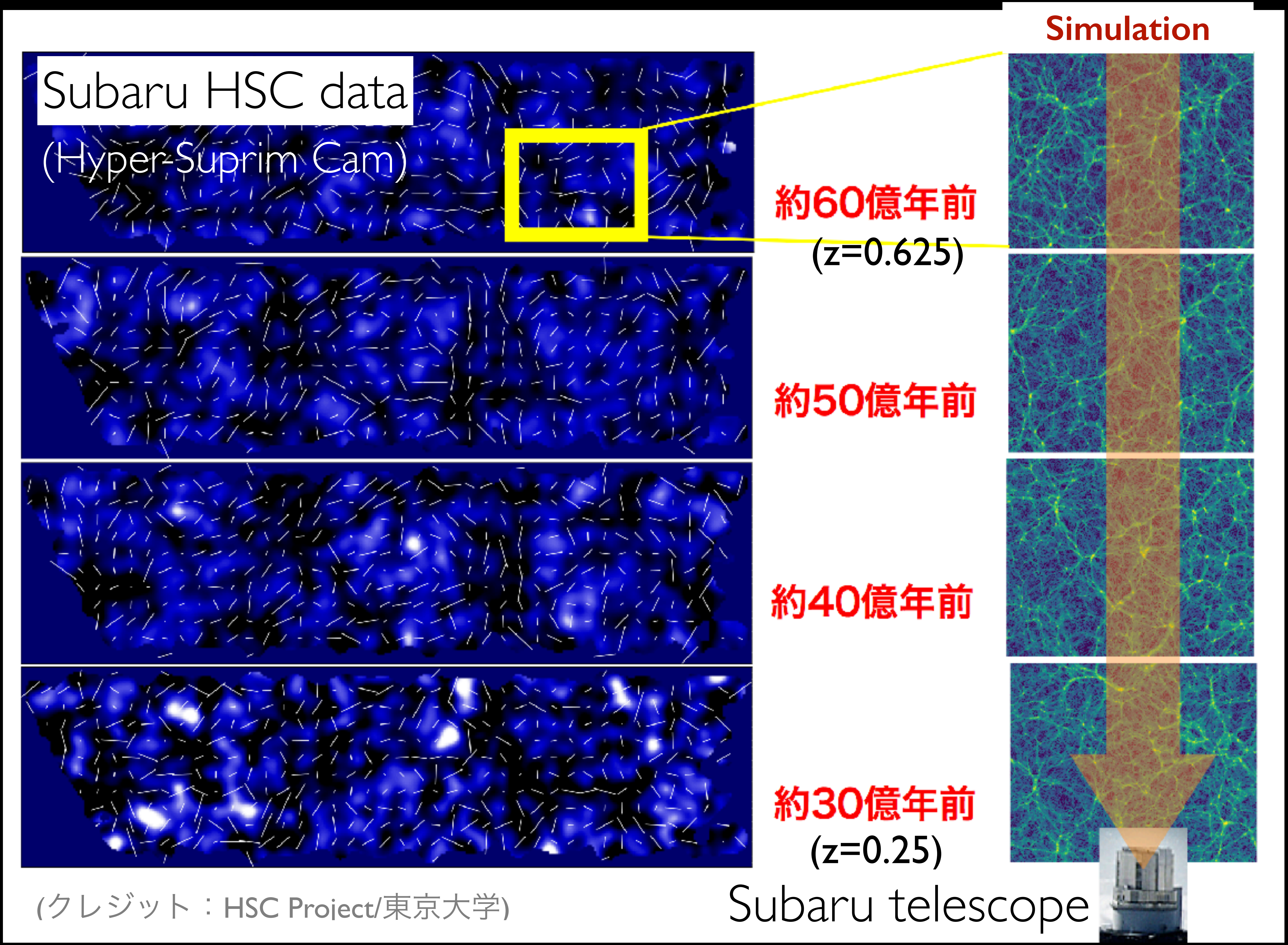
Gravitational lensing effect

Light bending by massive objects, as predicted by general relativity



Galaxy images appear distorted (weak lensing) or multiply imaged (strong lensing)

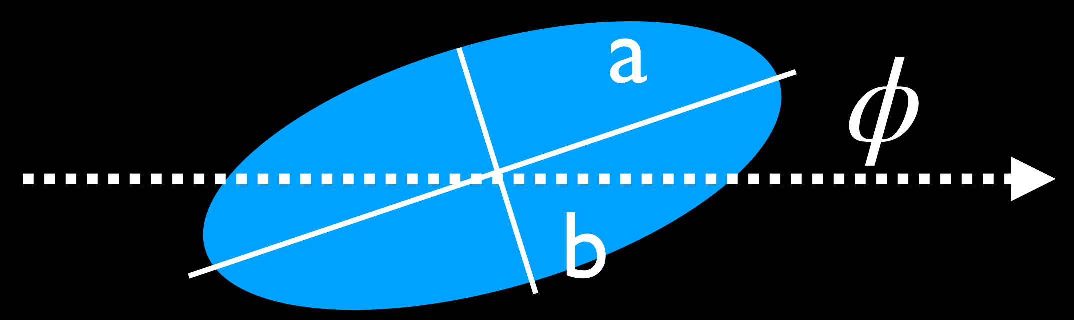
Weak lensing observations



Ellipticity field data at different redshifts

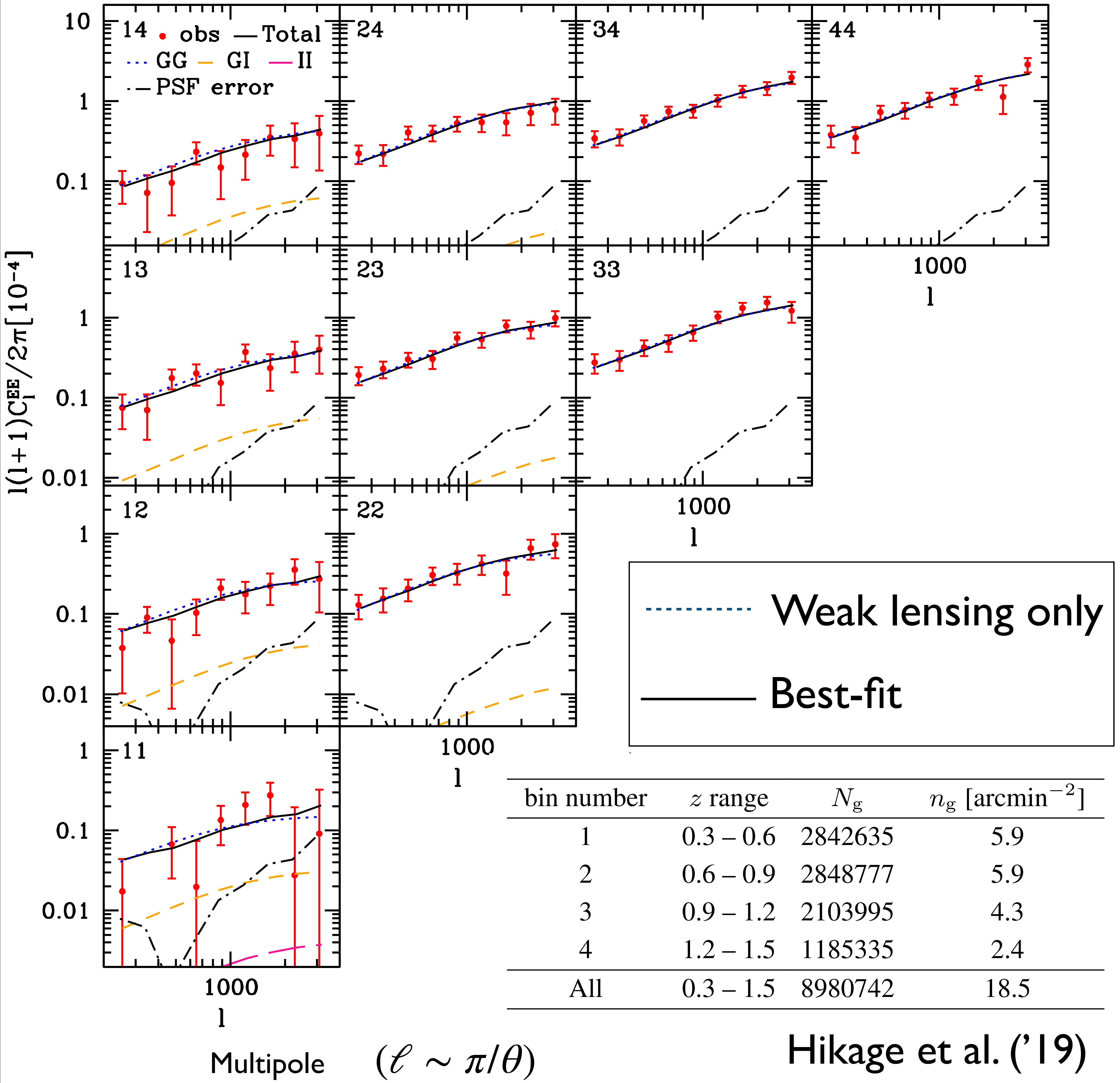
Ellipticity of distant galaxy image:

$$\boldsymbol{e} = (e_1, e_2) = \frac{1-(b/a)^2}{1+(b/a)^2}(\cos 2\phi, \sin 2\phi)$$



The effect of weak lensing is included in this ellipticity

Weak lensing (angular) power spectrum

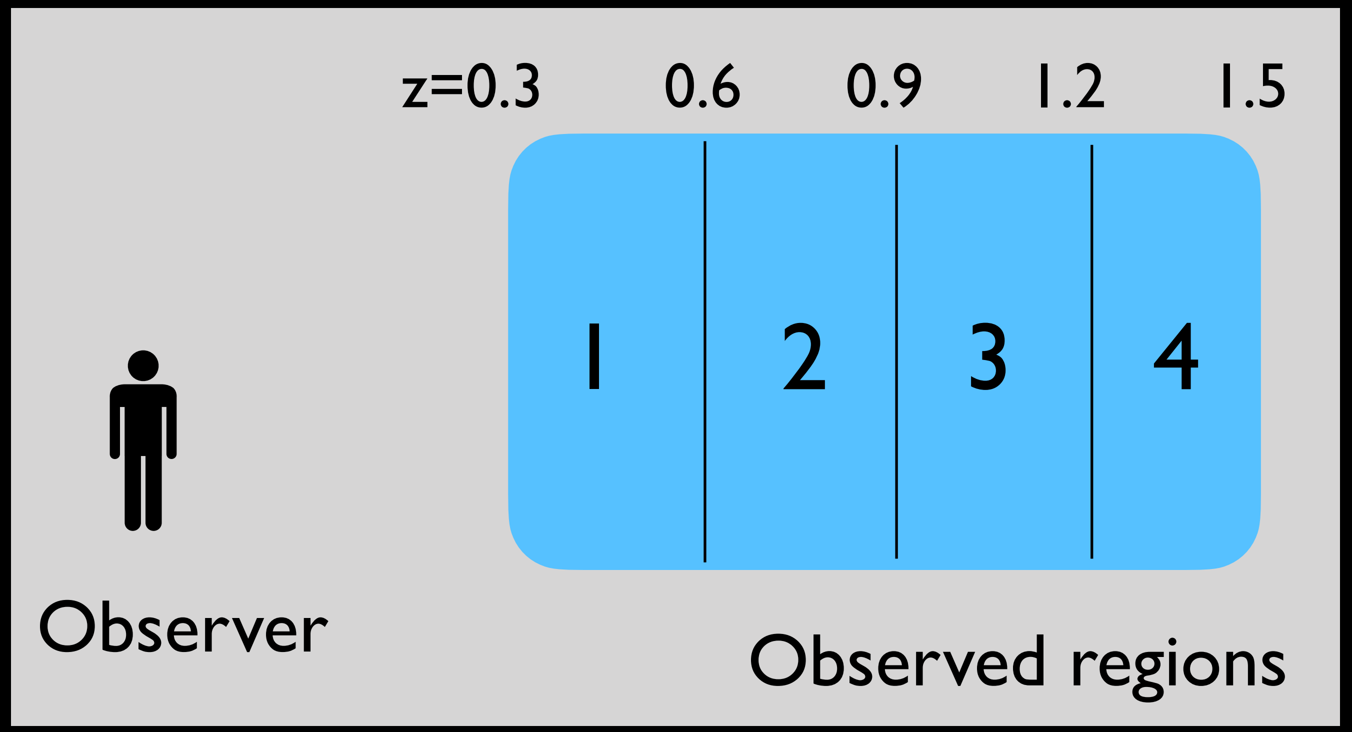


bin number	z range	N_g	n_g [arcmin^{-2}]
1	0.3 – 0.6	2842635	5.9
2	0.6 – 0.9	2848777	5.9
3	0.9 – 1.2	2103995	4.3
4	1.2 – 1.5	1185335	2.4
All	0.3 – 1.5	8980742	18.5

Hikage et al. ('19)

$$C_\ell = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} |e_{\ell m}|^2 \qquad \left(e(\vec{\theta}) = \sum_{\ell,m} e_{\ell m} Y_{\ell m}(\vec{\theta}) \right)$$

Subaru HSC 1yr result (137 deg^2)



Lensing tomography:

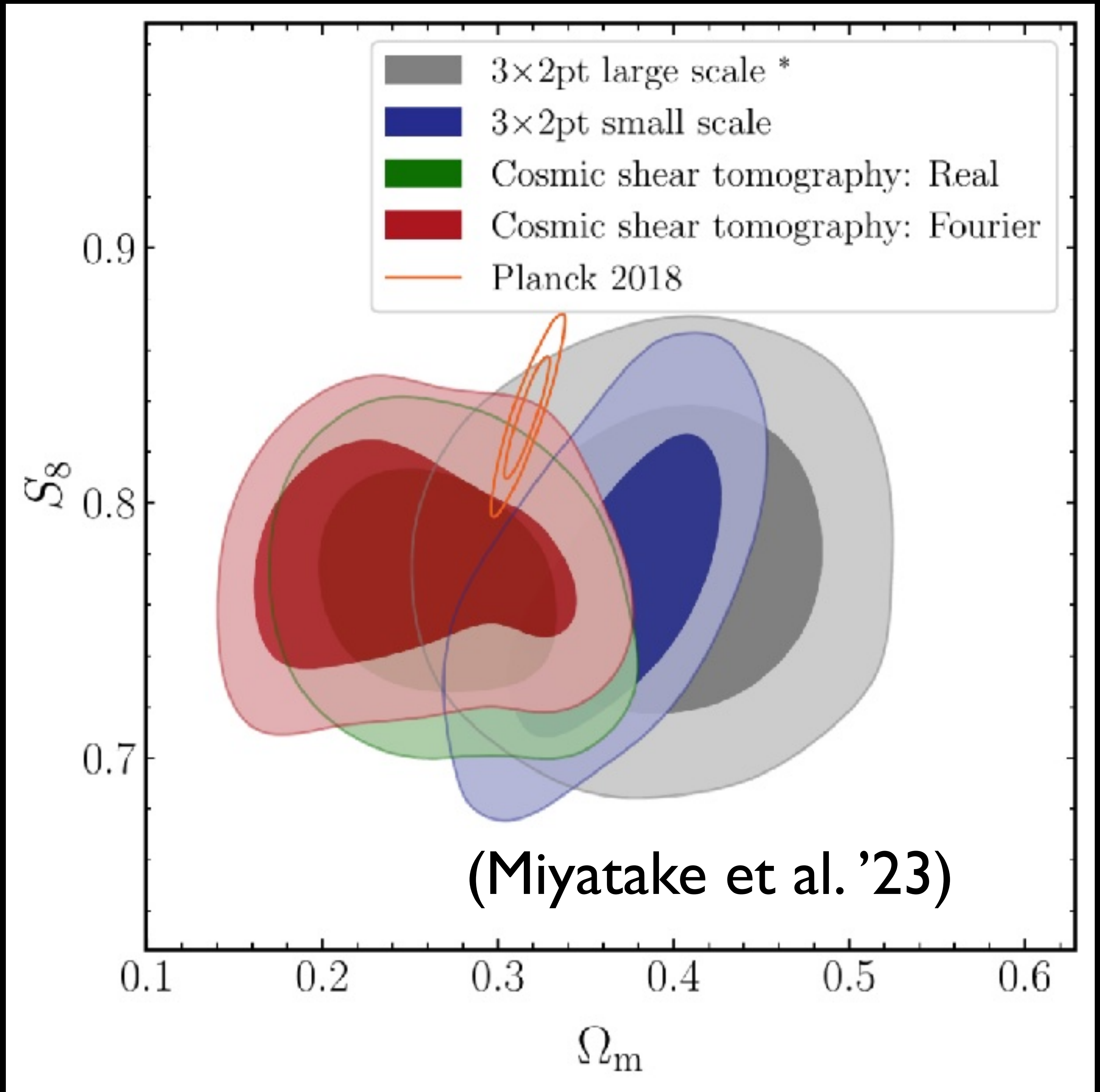
correlating galaxy ellipticity between different redshift bins

Weak lensing measurement of S_8

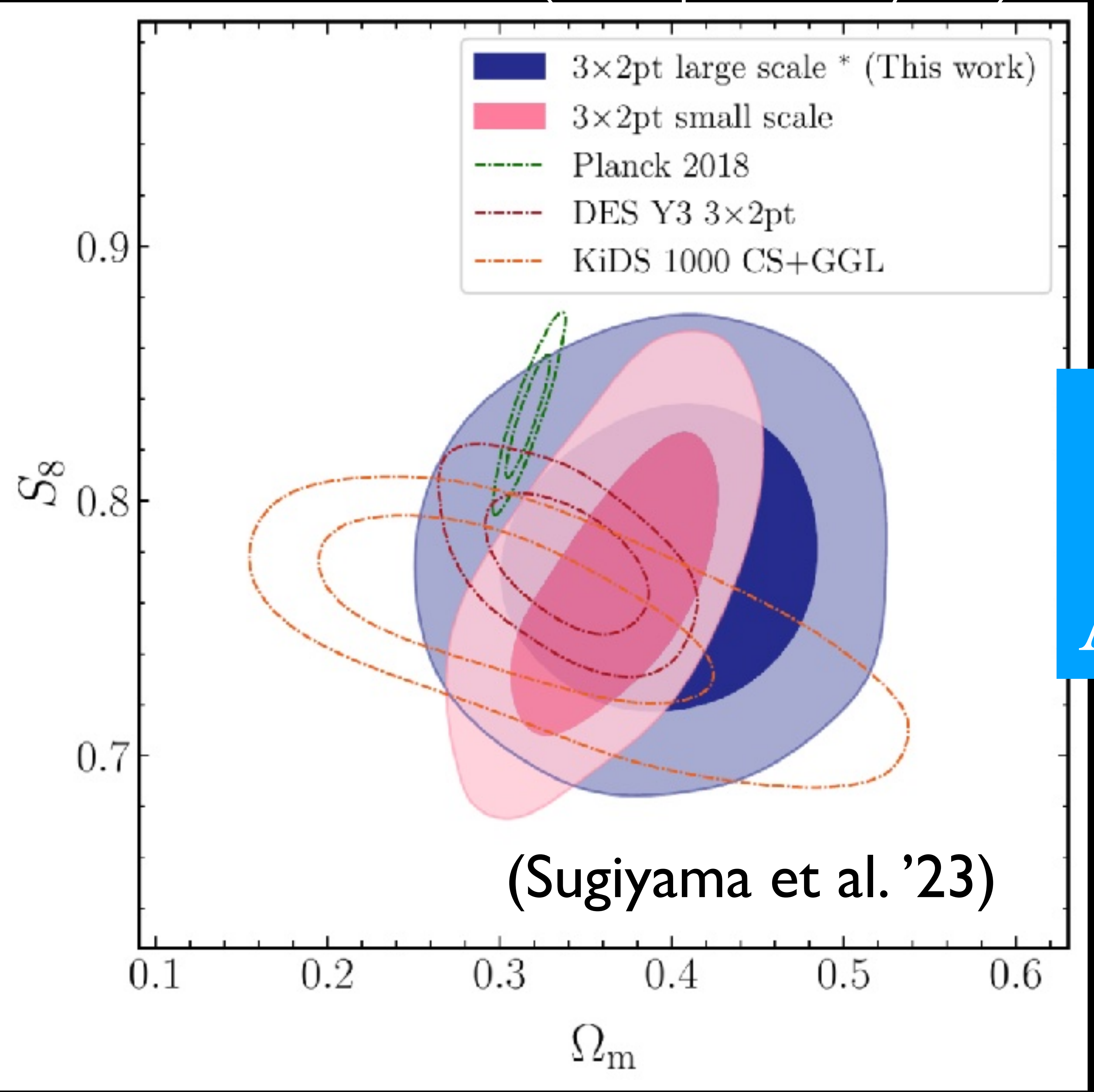
Subaru HSC 3 year result (416 deg^2)

arXiv:2304.00704
arXiv:2304.00705

Comparison between different probes



Comparison with other observations (3x2pt analysis)

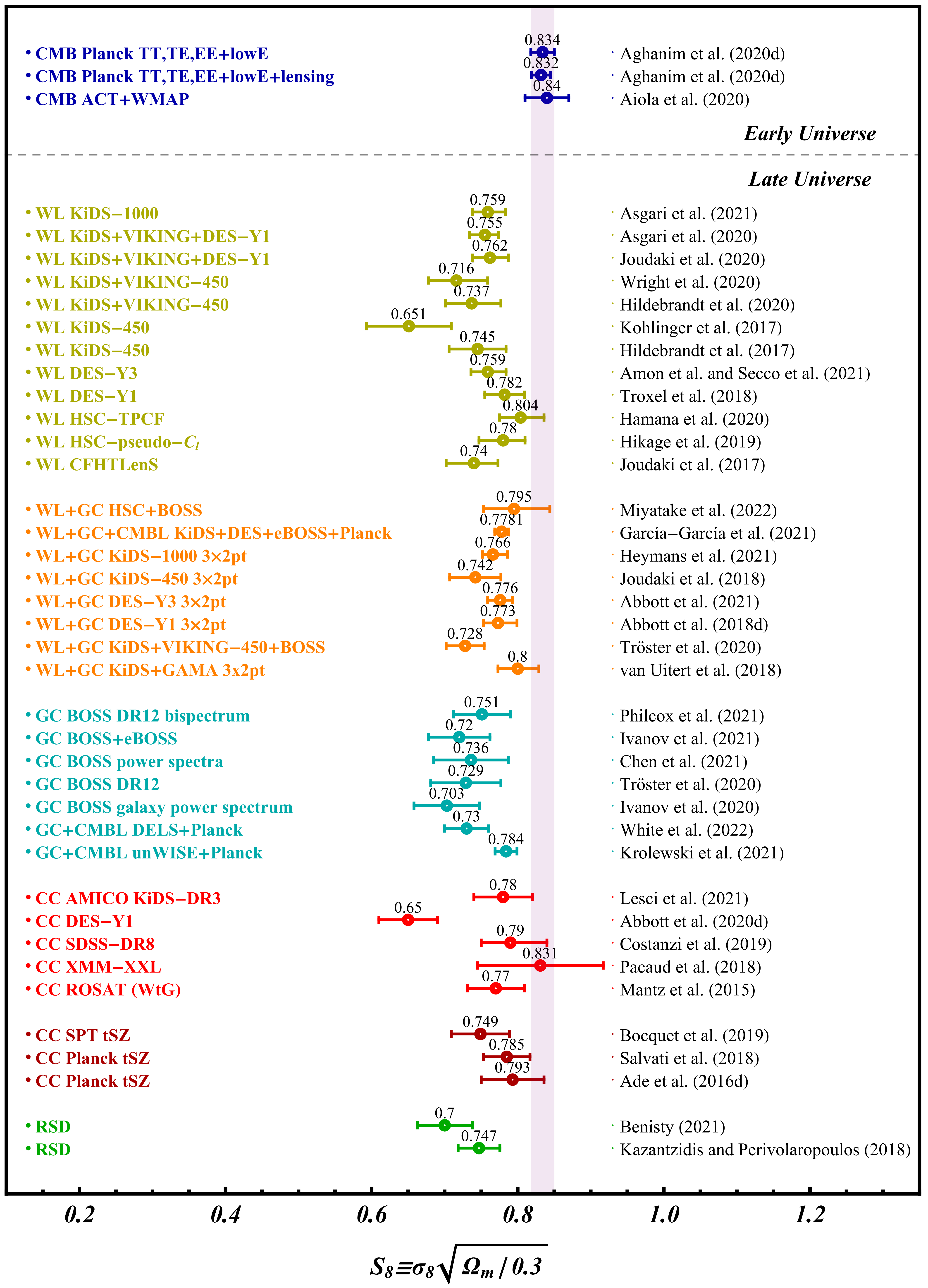


Overall, $2 \sim 3\sigma$ tension with Planck ΛCDM (as of 2023)

Is S_8 tension real ?

Compilation of various measurements

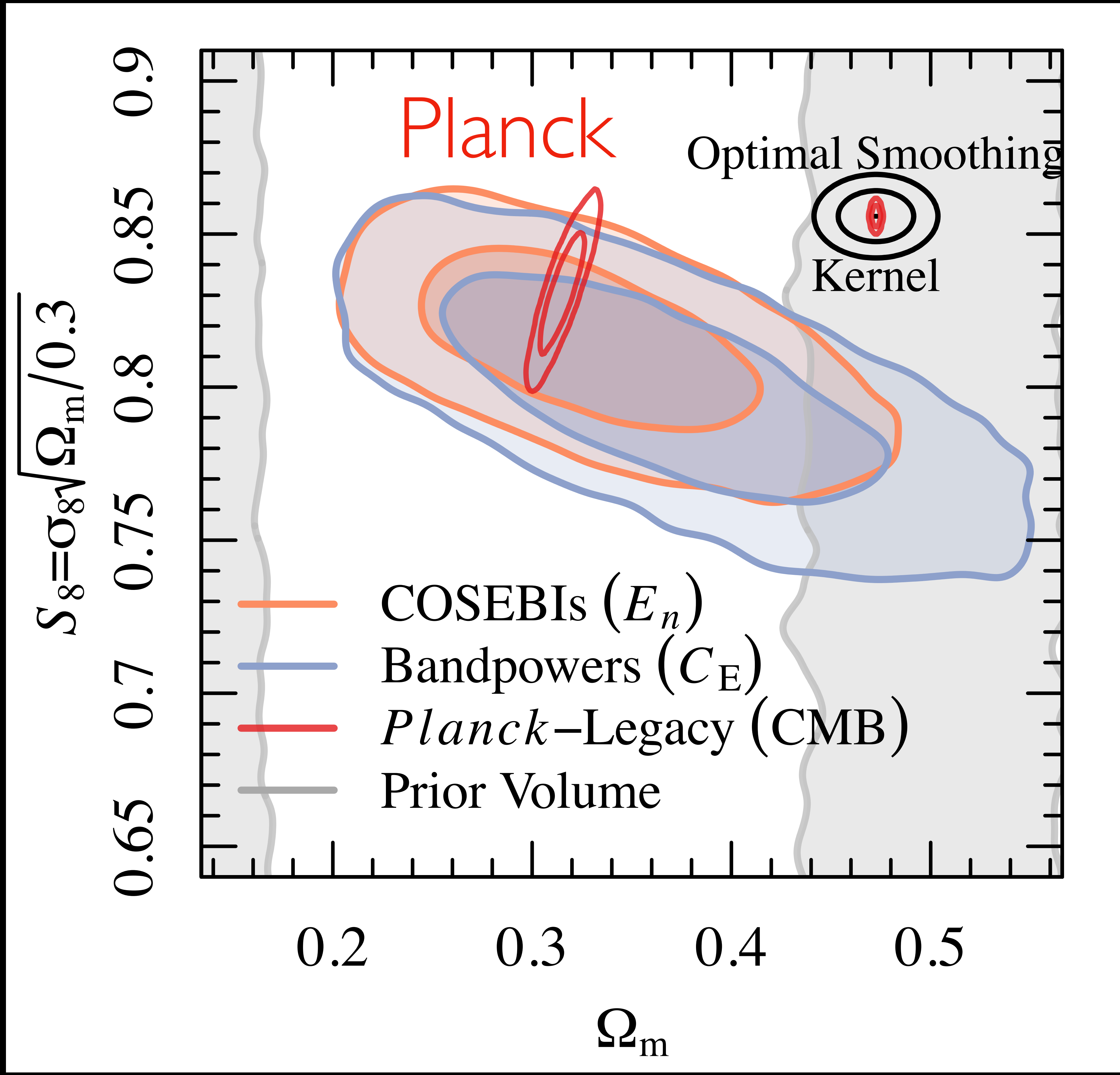
(Weak lensing, galaxy clustering, cluster counts, redshift-space distortions)



arXiv:2203.06142v1

Tension has gone ?

Latest weak lensing analysis from KiDS-Legacy (1347 deg^2)



- A larger area coverage
- Improved redshift distribution estimation out to higher-z (z~2)

Now, consistent with Planck ΛCDM

… still premature to say tension has gone

arXiv:2503.19441

What do the tensions imply ?

Systematic errors in local (low-z) measurements

Unaccounted systematics may bias local parameters, causing inconsistency with Planck results.

Breakdown of ΛCDM model

New physics beyond ΛCDM could cause *apparent* discrepancies between Planck and local measurements

To clarify the cause, more detailed observations are necessary:

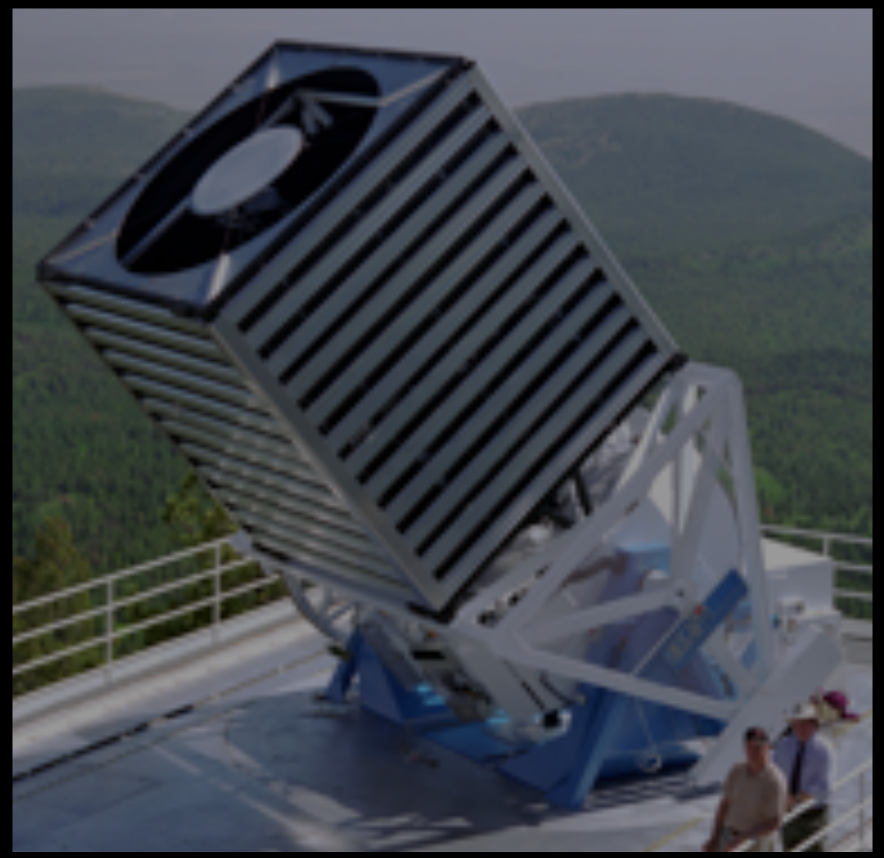
- Investigate systematic errors & cross-check with independent probes
- Test ΛCDM with observations beyond H_0 & S_8 tensions (new physics search)

Beyond ΛCDM model

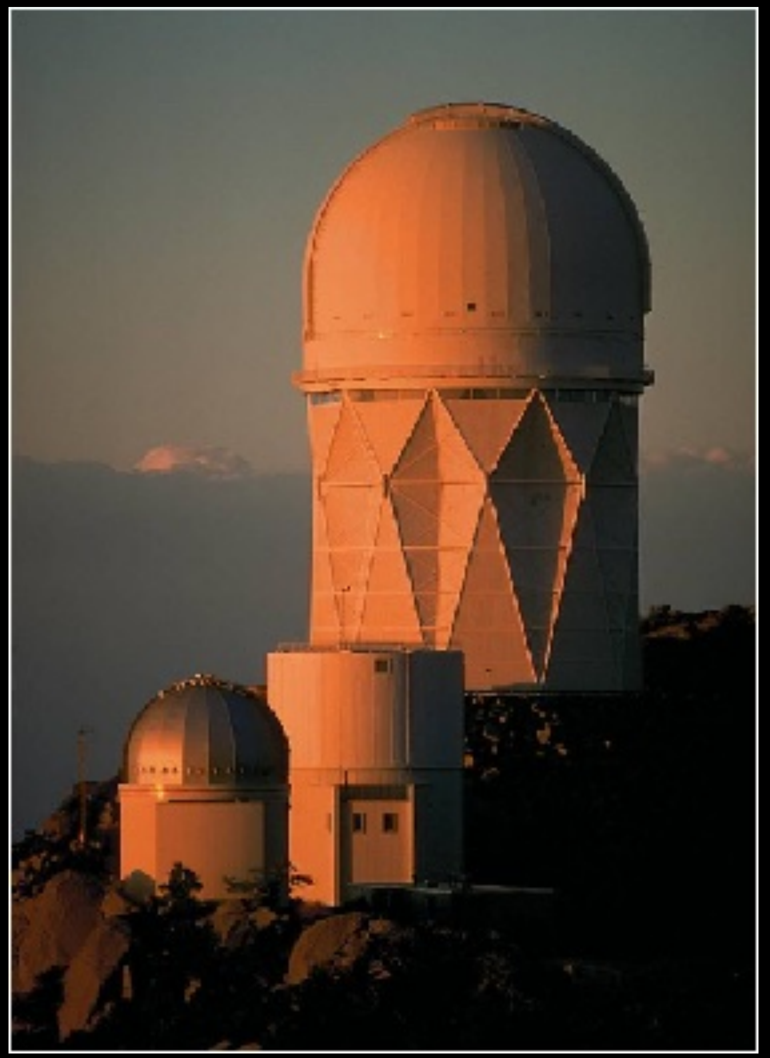
Galaxy surveys

DES (2013~2019)

HETDEX (2018~)

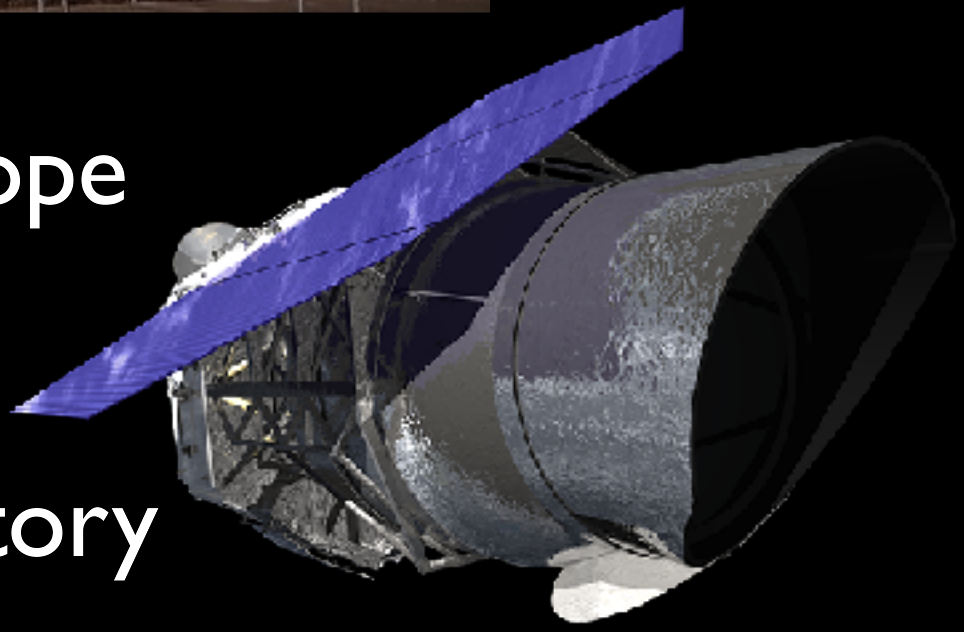


eBOSS (2014~2019)



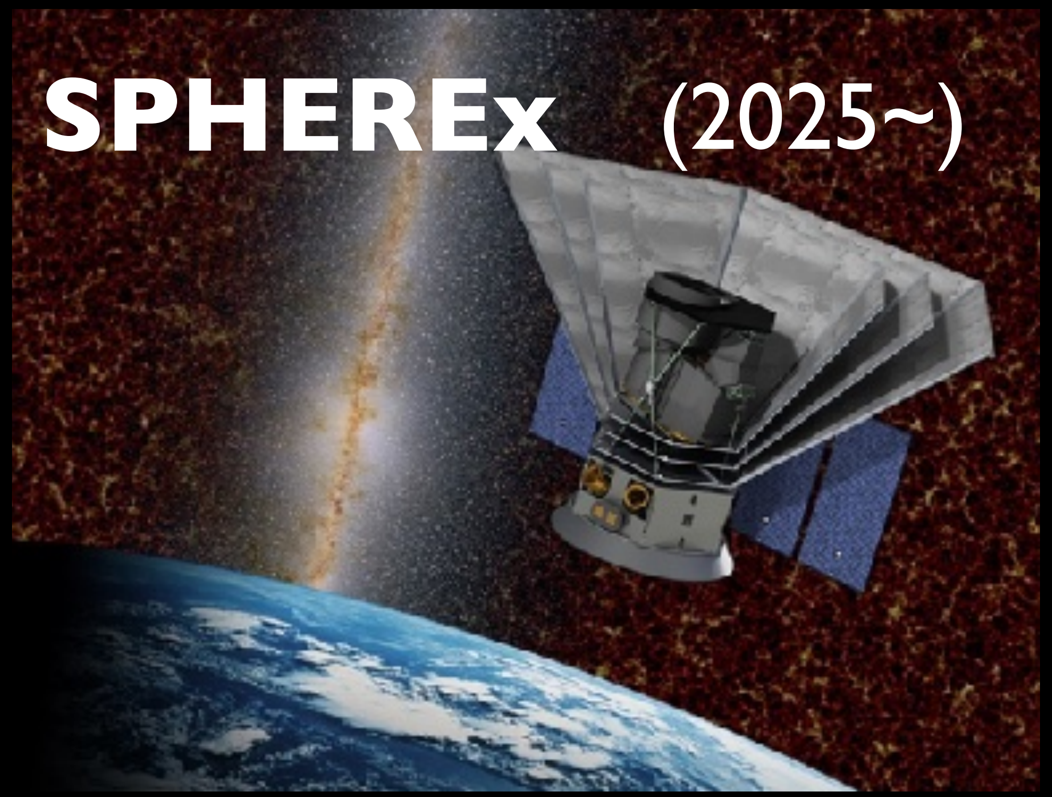
DESI (2020~)

Roman Space Telecope
(**WFIRST**)



Vera C Rubin Observatory
(**LSST**)

SPHEREx (2025~)



Euclid (2023~)

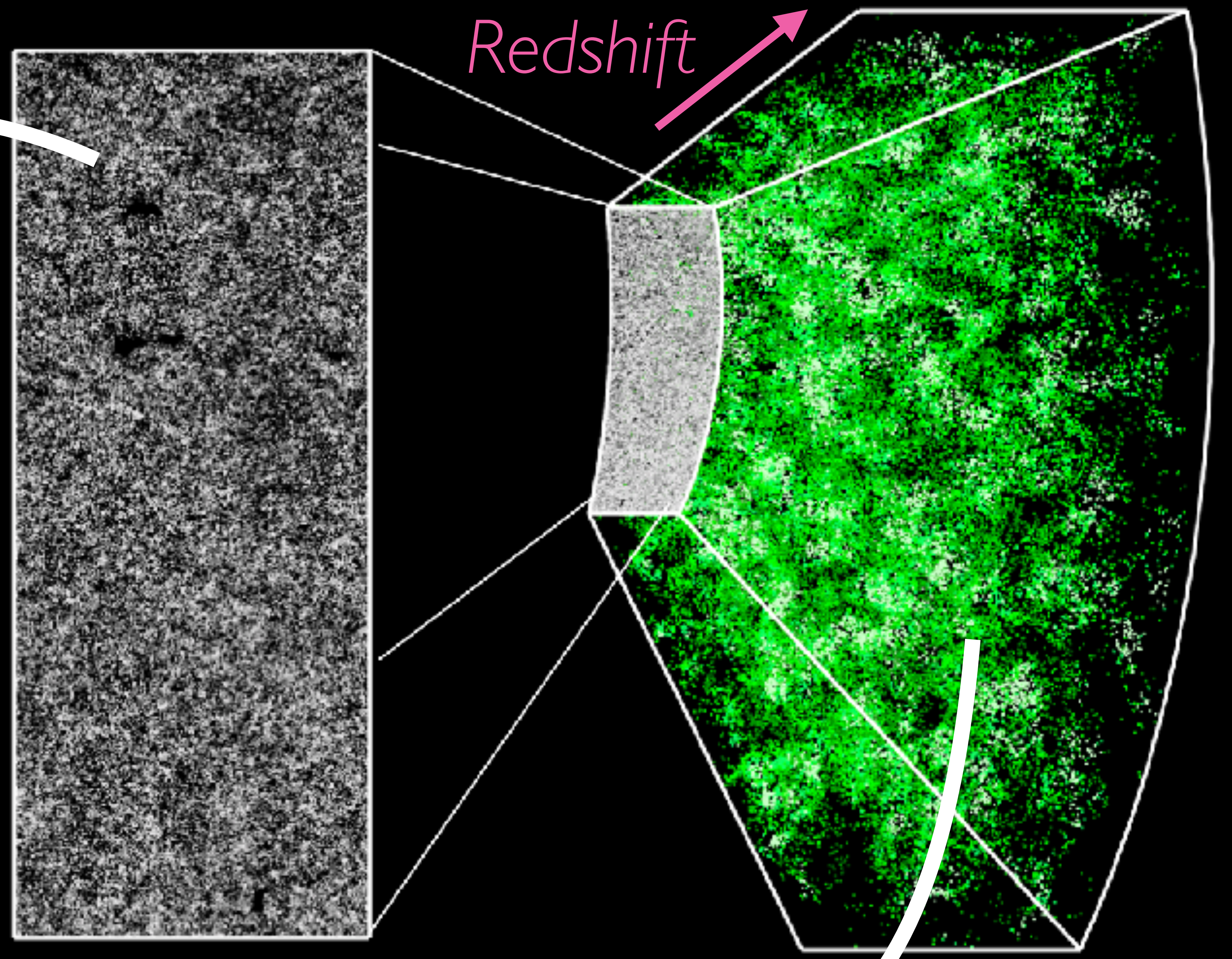
Subaru telescope

Hyper-Suprim Cam (**HSC**)

Prime Focus Spectrograph
(**PFS**)

(2014~ & 2025~)

Observational information in galaxy surveys



Imaging : galaxy shapes & angular positions on the celestial sphere

- Weak lensing
- Angular galaxy clustering (2D)

} Combining both 3x2 pt analysis

Spectroscopy : 3D positions of galaxies (angular position + redshift)

3D galaxy clustering —Decoding→

- Baryon acoustic oscillations
- Redshift-space distortions

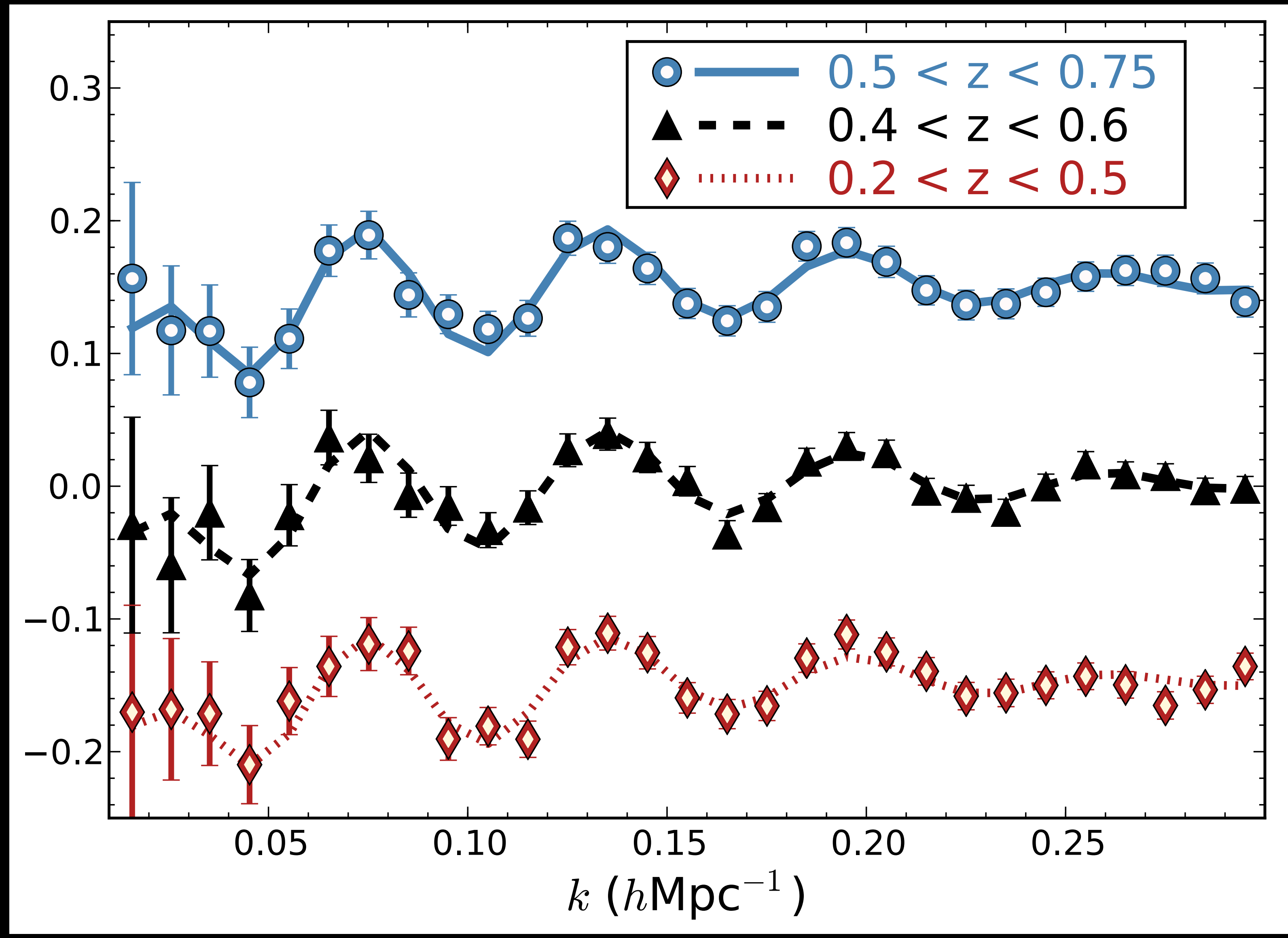
※ Combining imaging & spectroscopic data yields even more information (how and what can be extracted is nontrivial)

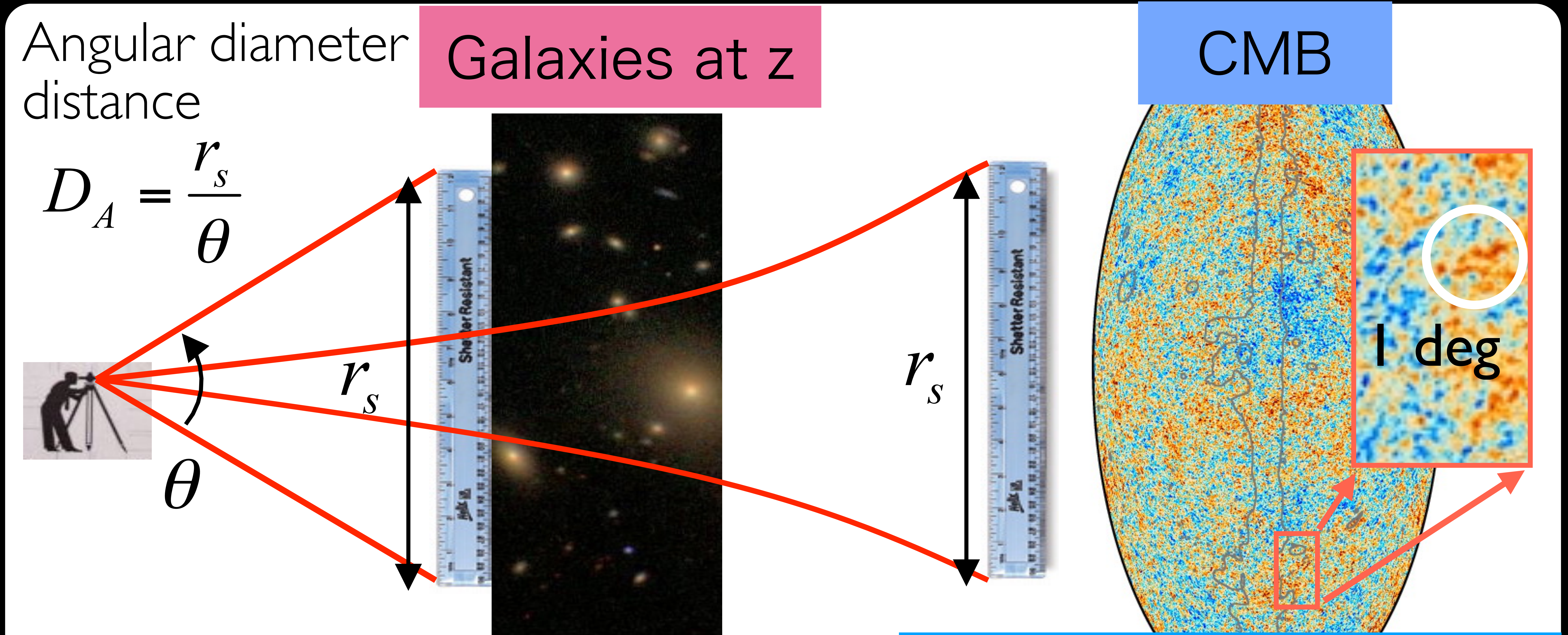
Baryon acoustic oscillations (BAO)

J. Peebles

- Characteristic scale imprinted on galaxy distribution (~100 Mpc/h)
- Acoustic sound horizon of primeval baryon-photon fluid → Cosmic standard ruler

Galaxy power spectrum
(relative to smooth component)





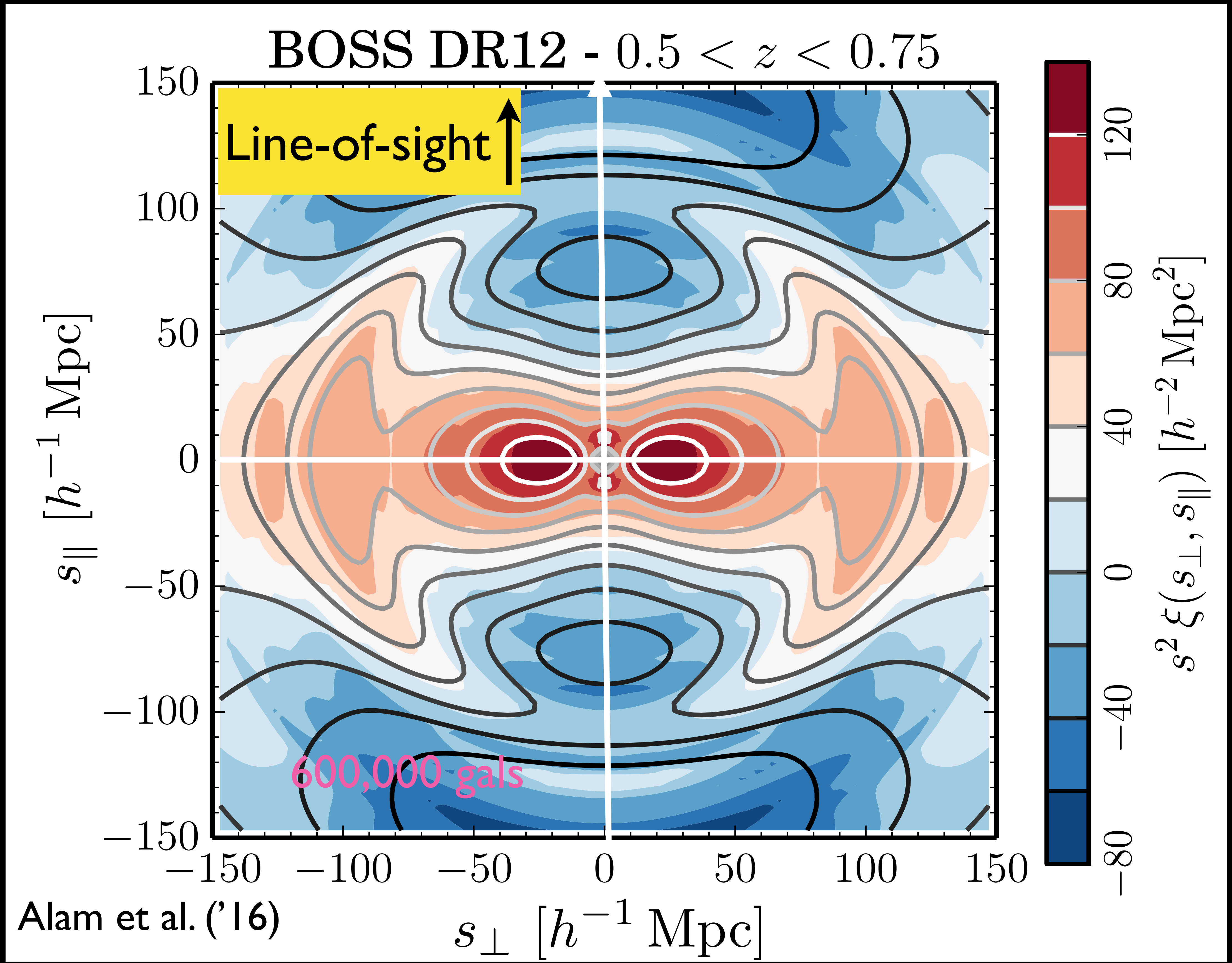
→ Teppei Okumura's talk

Using the Alcock-Paczyński effect, the Hubble parameter at z can also be measured

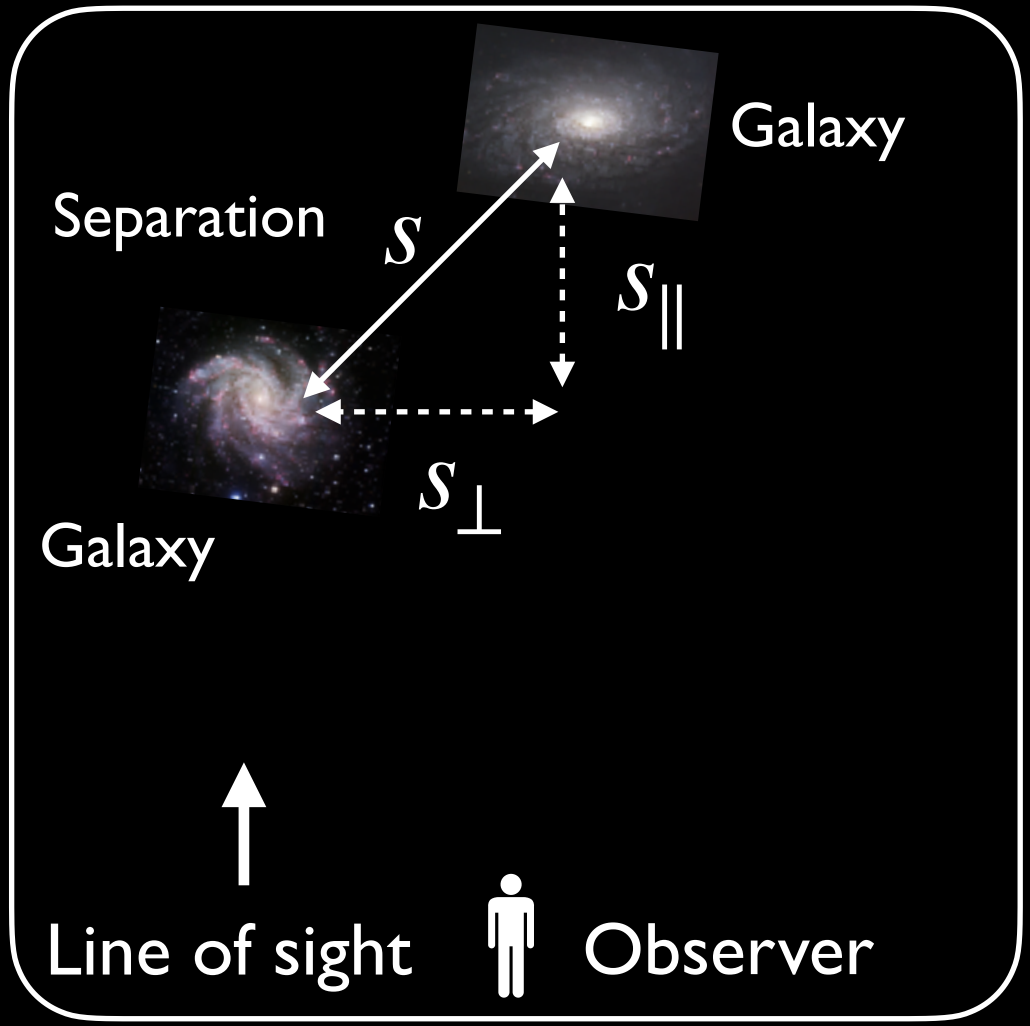
Redshift-space distortions

Peculiar velocities cause anisotropy in spectroscopically measured galaxy distributions

⟶ The strength of the anisotropy $\propto \; f\sigma_8(z) \simeq \Omega_m(z)^{0.6}\sigma_8(z)$ (Kaiser '87)



Galaxy two-point correlation function



Test of gravity on cosmological scale

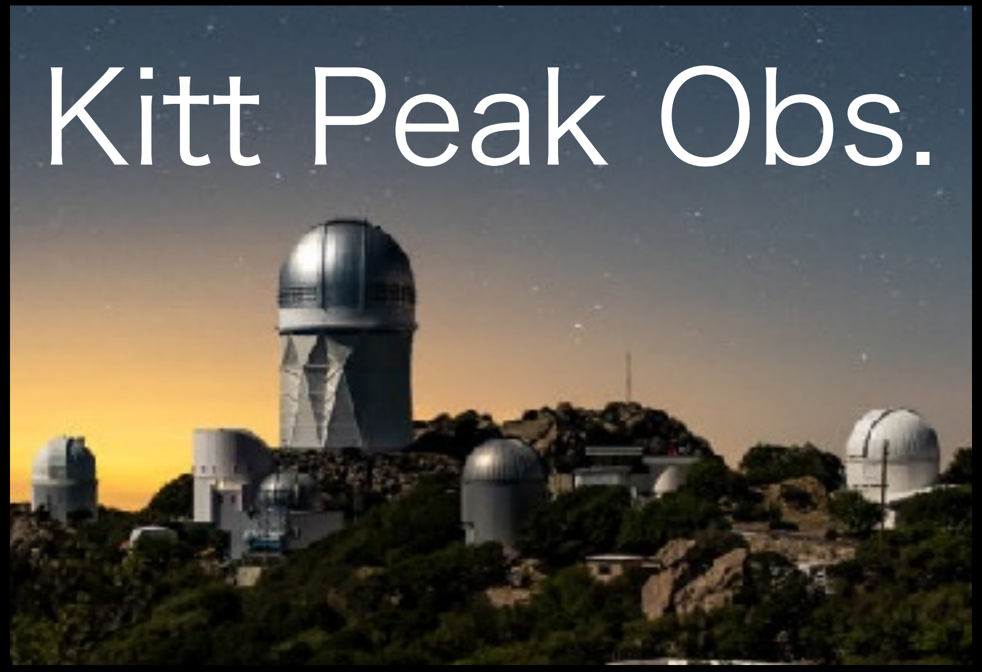
(General relativity)

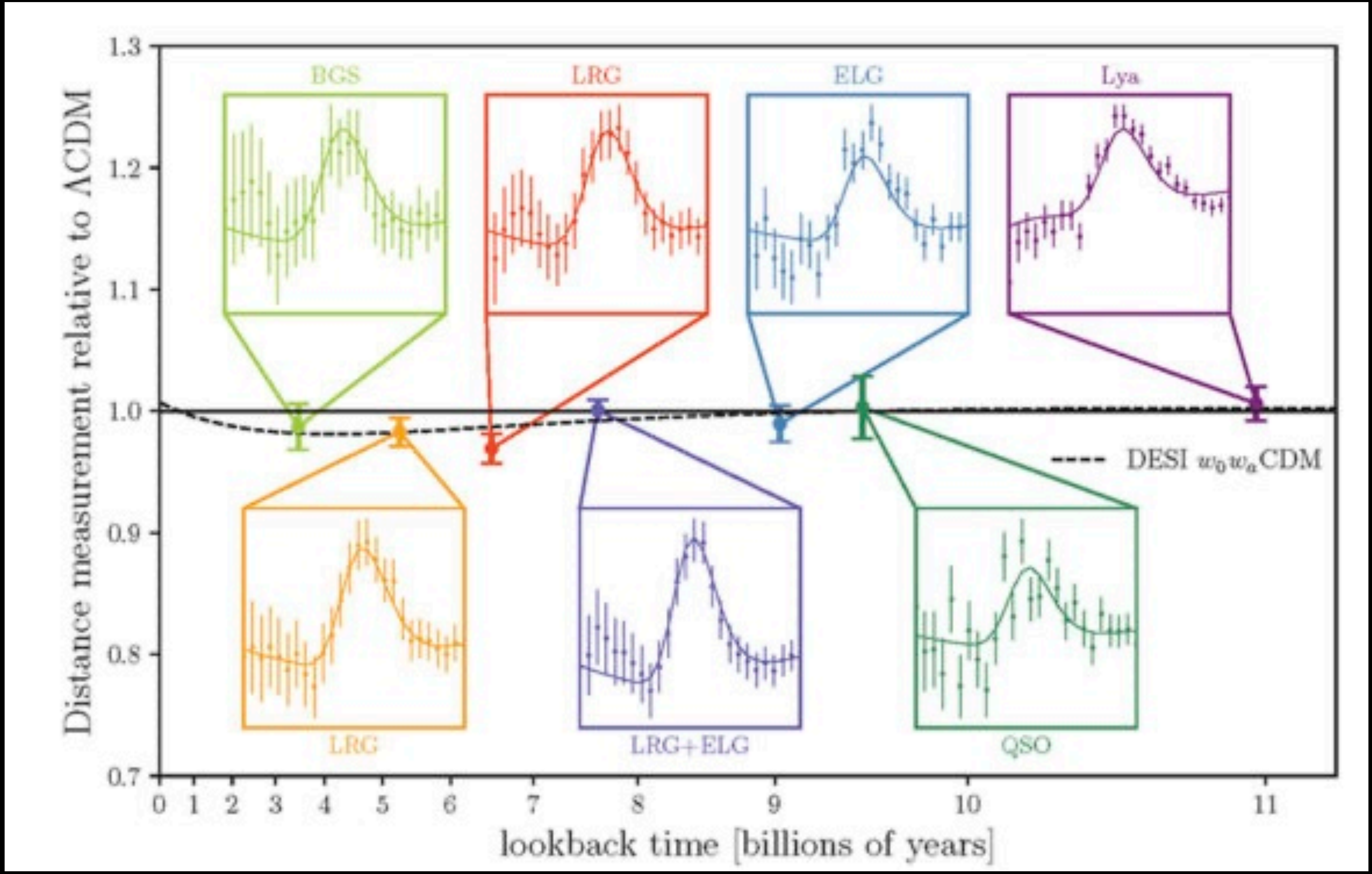
→ Teppei Okumura's talk

Dynamical dark energy？ by DESI

BAO measurements from DESI

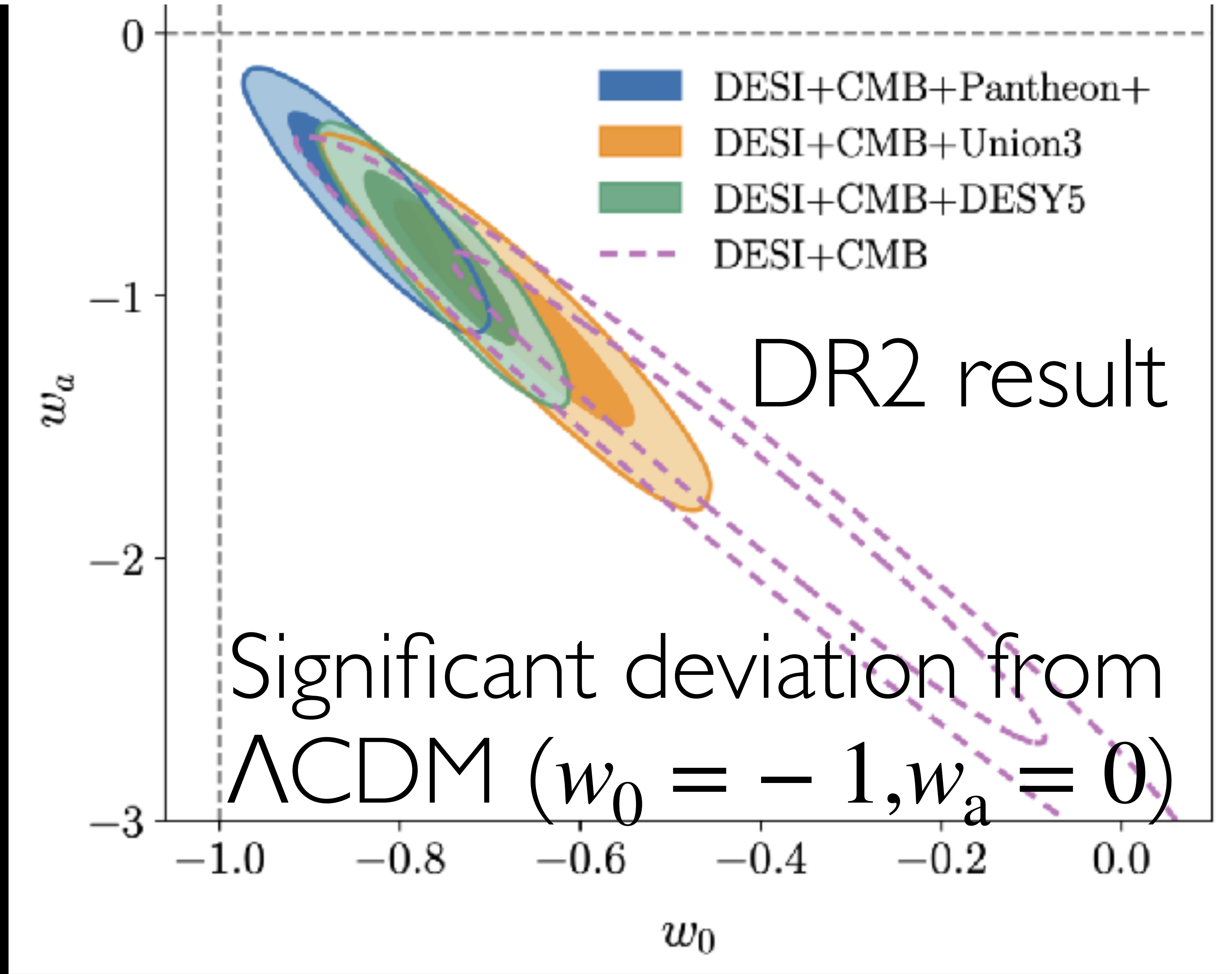
→ Francisco Prada's talk





Dark energy EOS parameter

$$w(a) = w_0 + (1 - a)w_a$$



Cosmological observations & structure formation

Cosmological information from the CMB and galaxy surveys is connected through ***structure formation*** → combining multiple observations is thus beneficial
(evolution of density fluctuations)

Cosmic inflation
(Still to be confirmed)
→
Generation of
Primordial fluctuations
With adiabatic initial condition
→

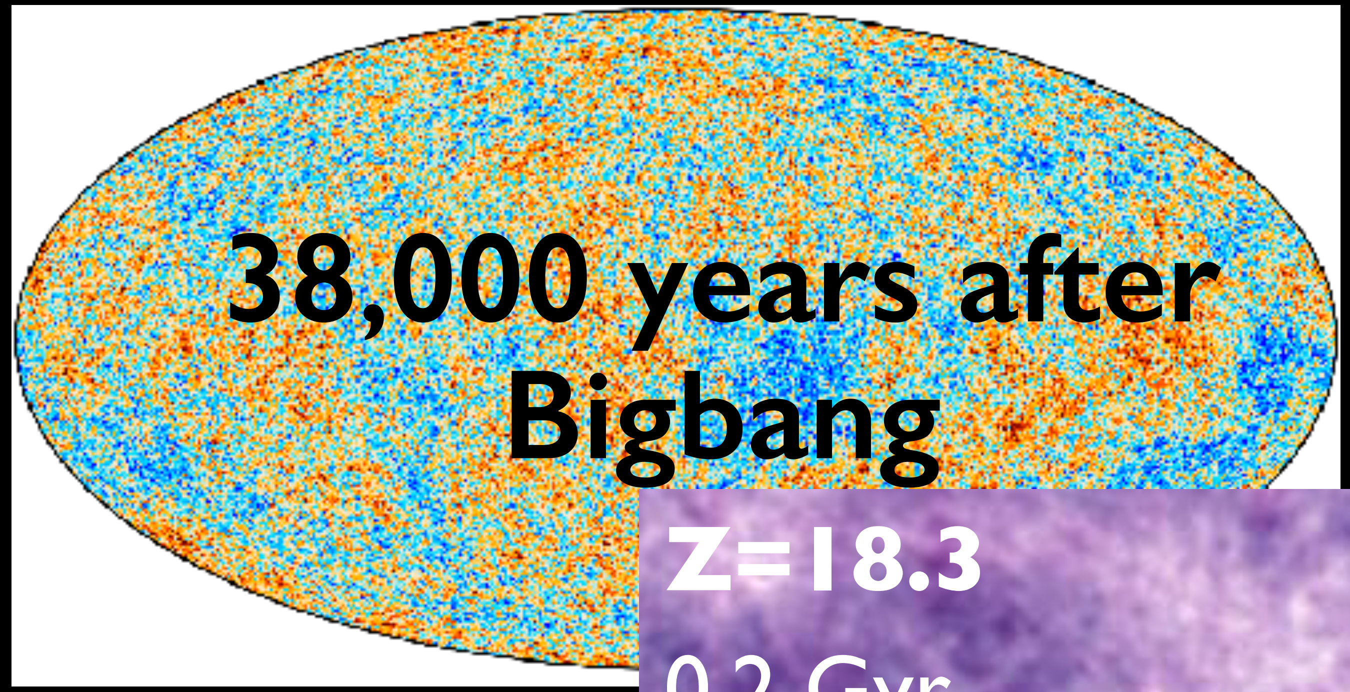
- Matter fluctuations
  (dark matter, baryon & neutrinos)
- Photon fluctuations
  (CMB anisotropies)

Theory of cosmic structure formation

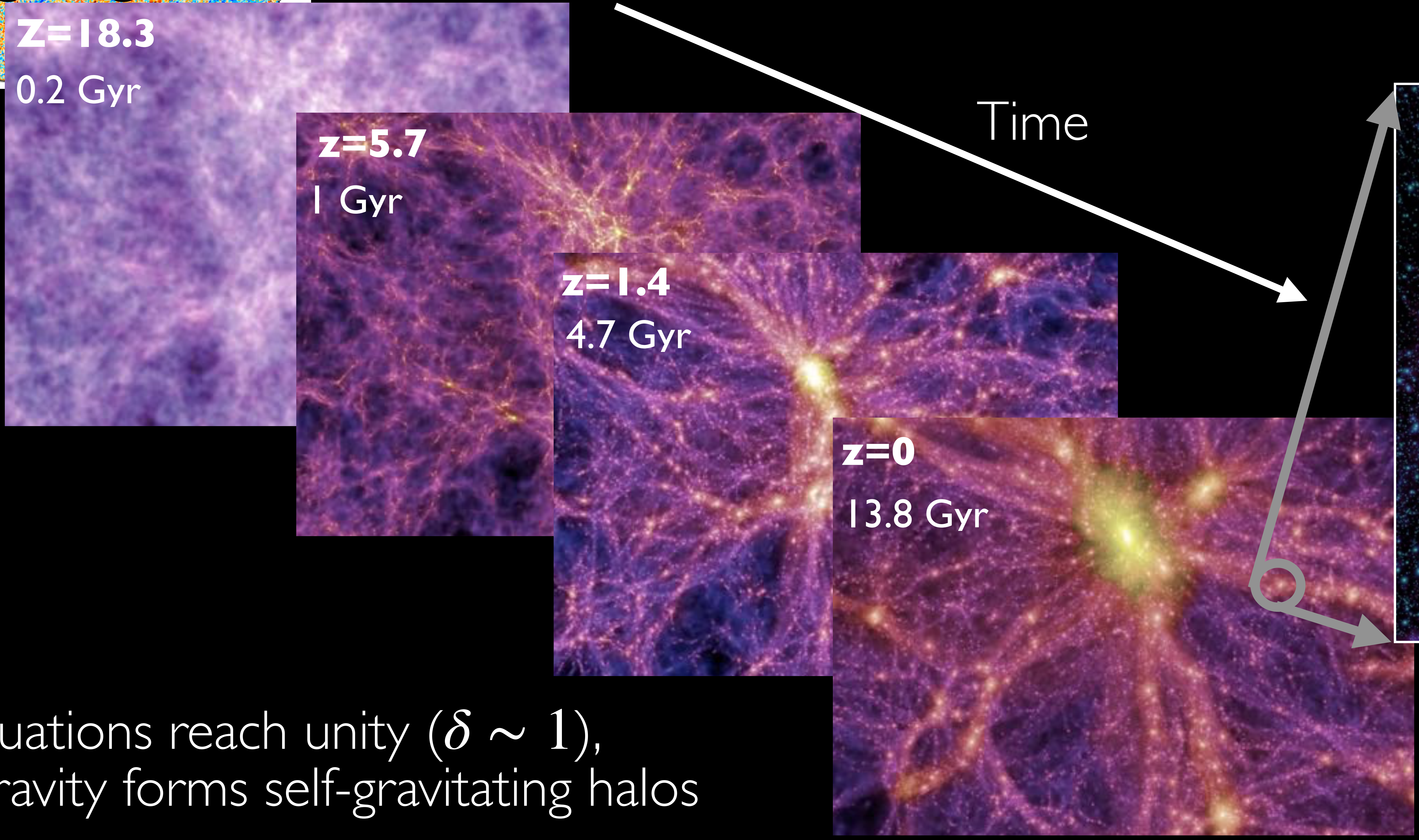
provides tools for quantifying observables & interpreting them

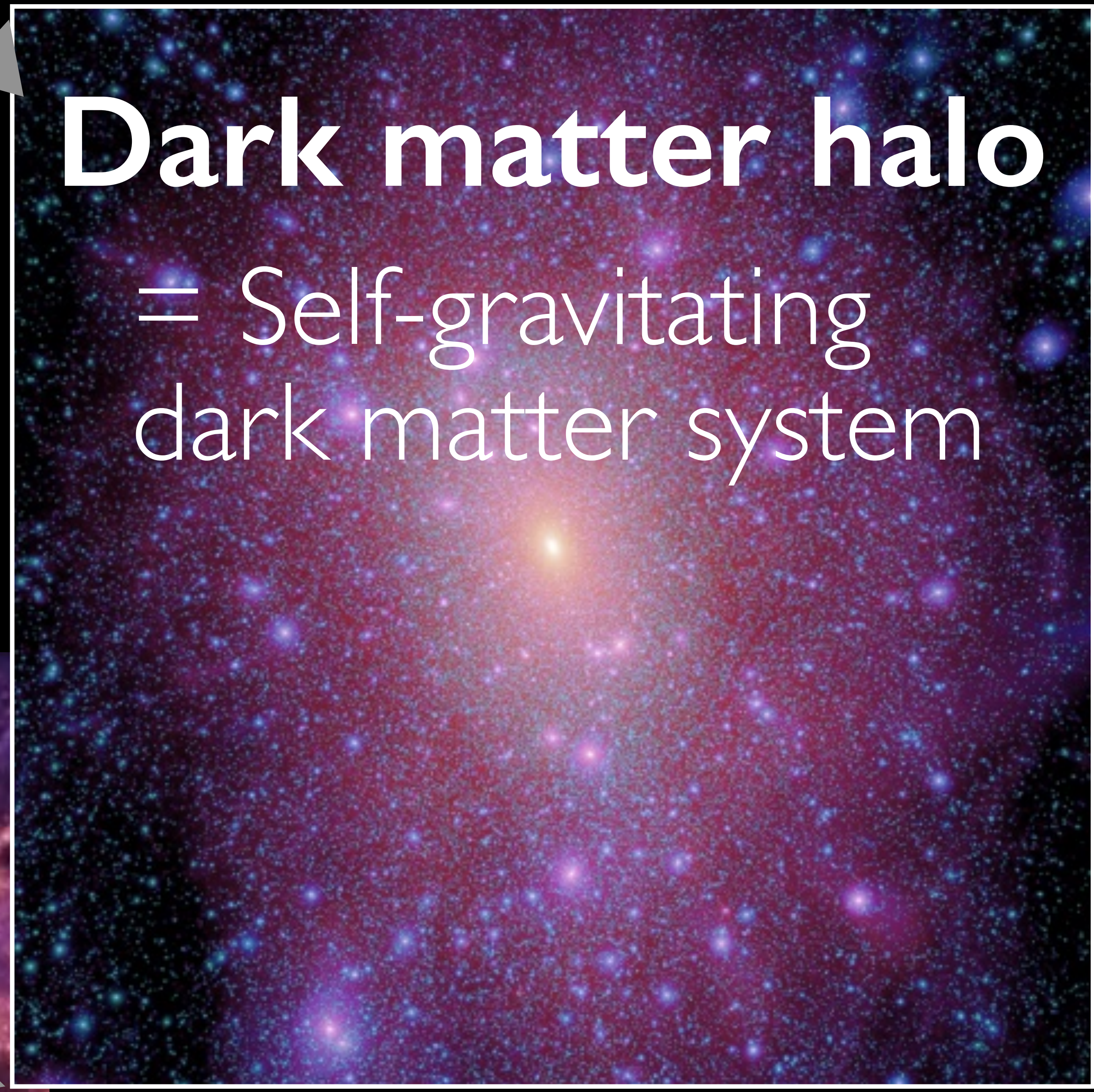
(what physics can be extracted from, how to model & interpret it quantitatively)

Cosmic structure formation: overview



After radiation domination, dark matter perturbations quickly begin growing via gravitational instability, while baryons start to grow after decoupling ($z \sim 1{,}100$), soon catching up with those of dark matter.

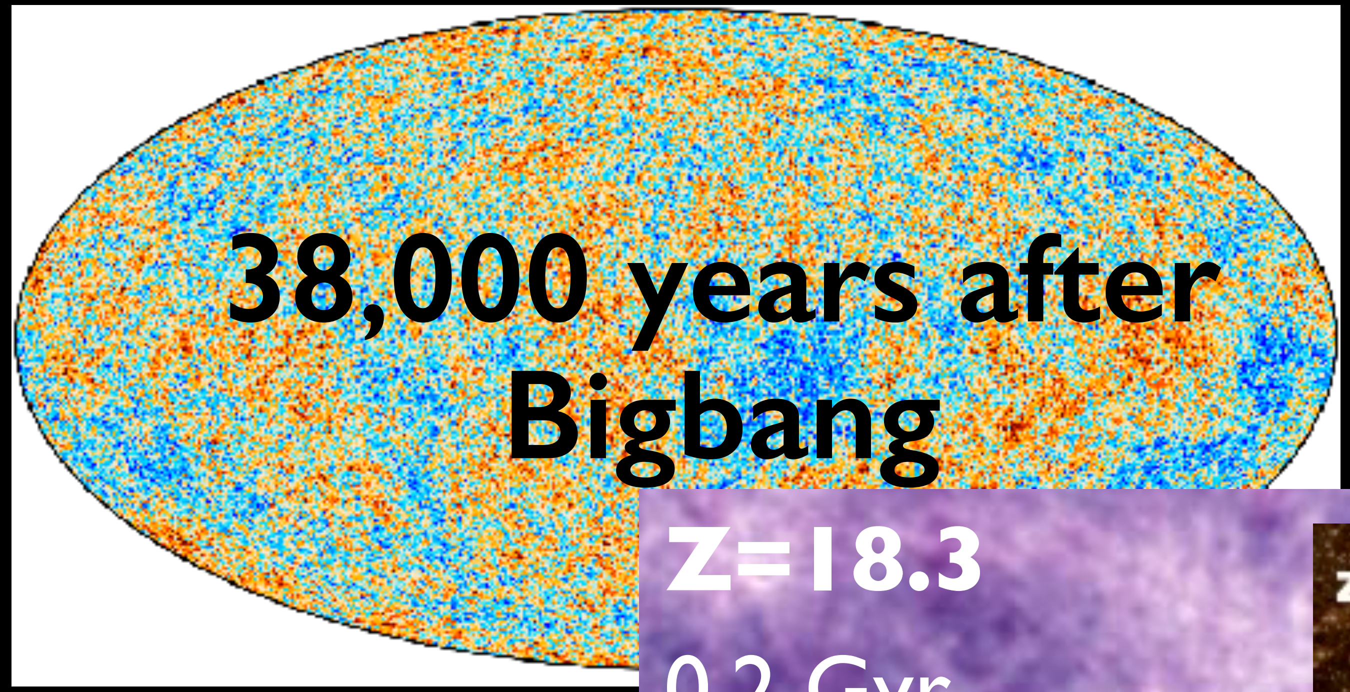




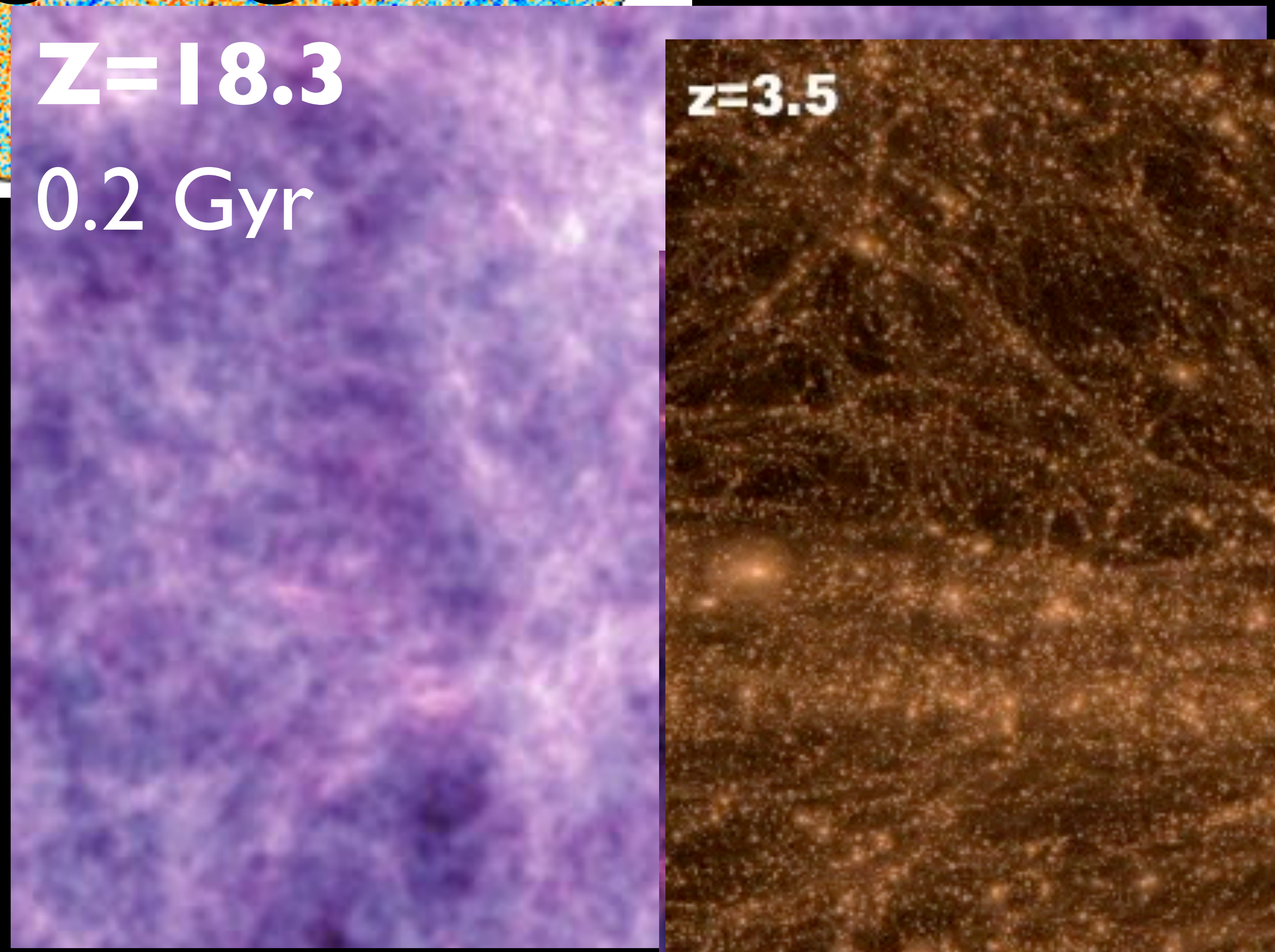
→ Unique sites of galaxy/star formation

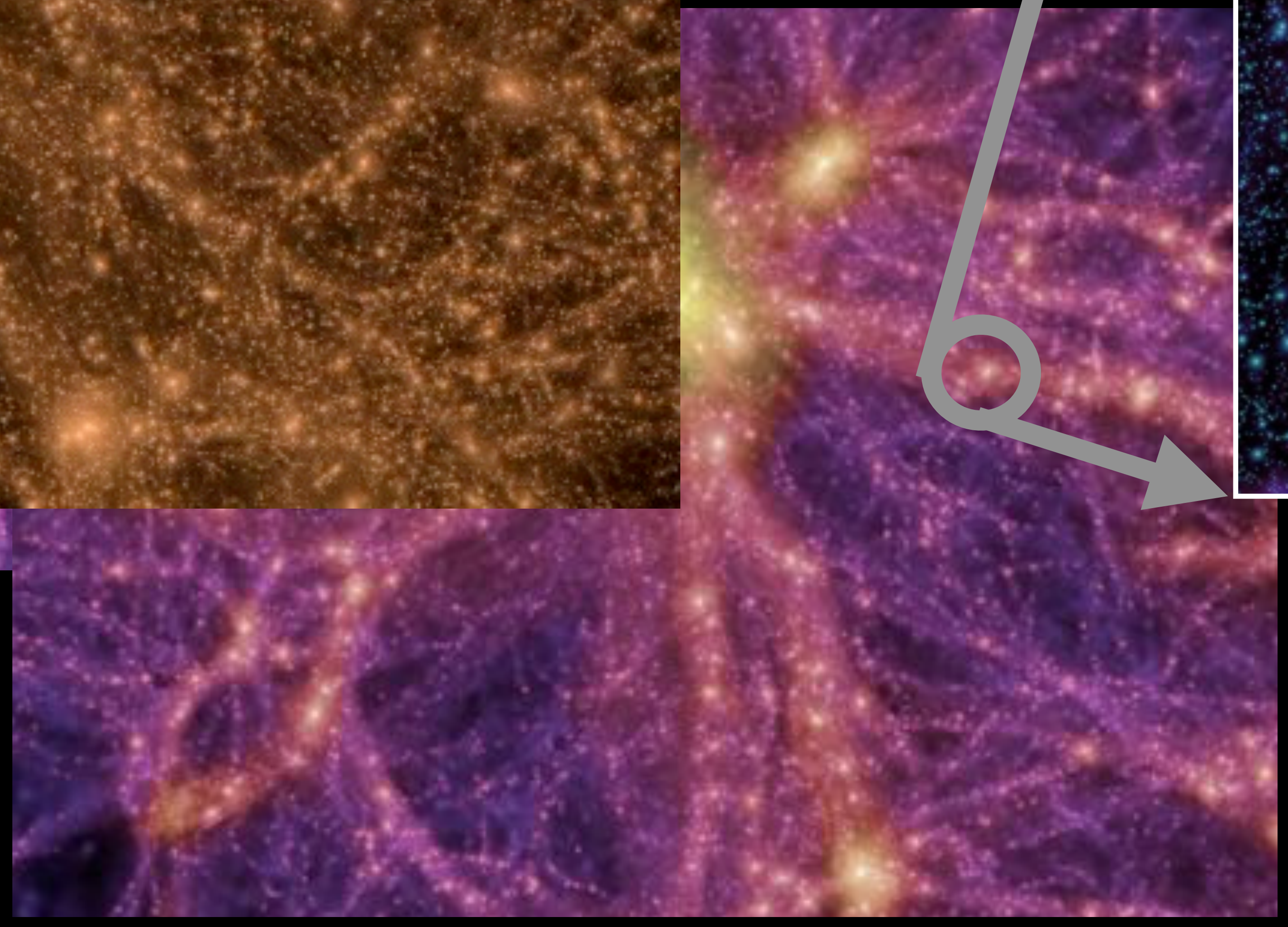
When fluctuations reach unity ($\delta \sim 1$), nonlinear gravity forms self-gravitating halos

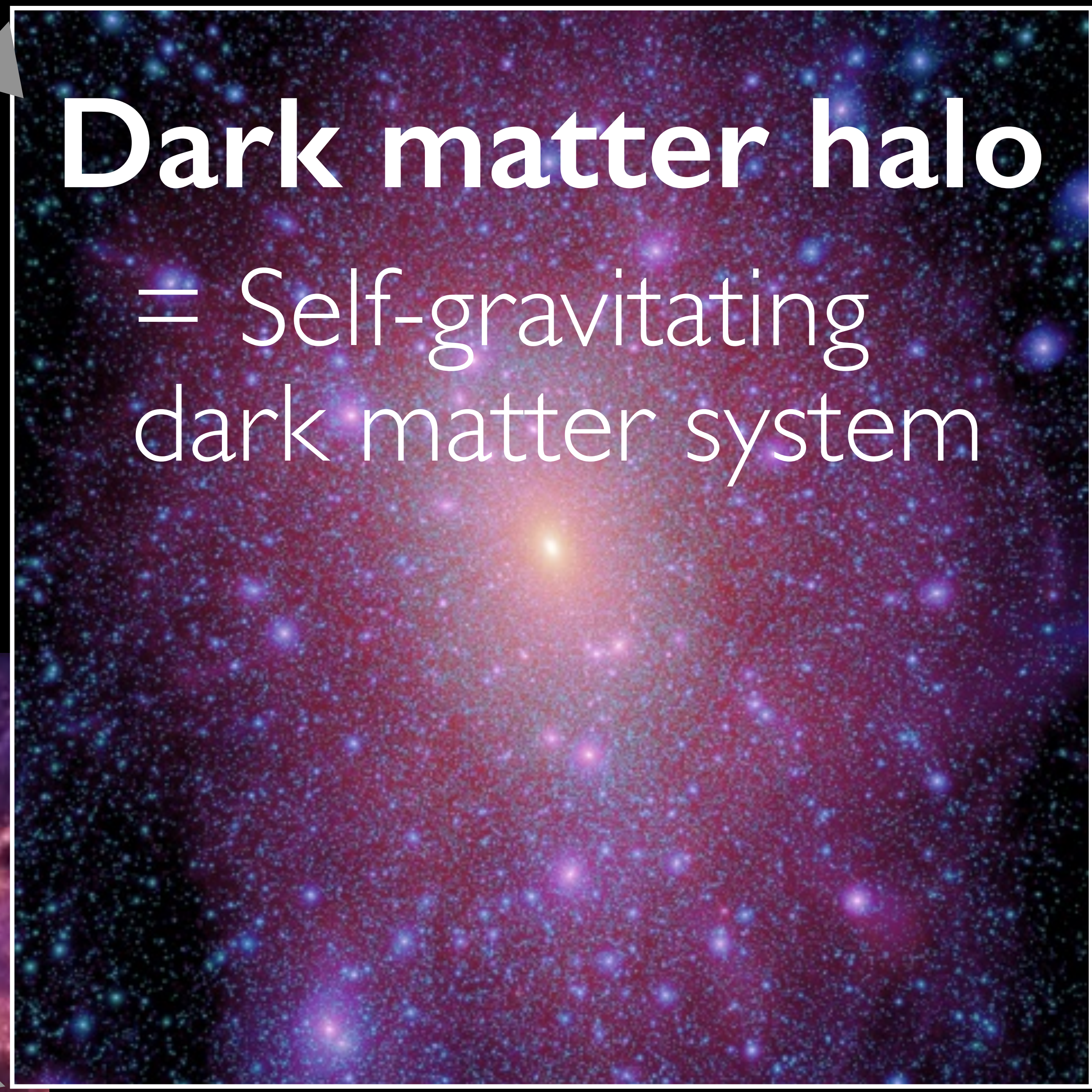
Cosmic structure formation: overview



After radiation domination, dark matter perturbations quickly begin growing via gravitational instability, while baryons start to grow after decoupling ($z \sim 1{,}100$), soon catching up with those of dark matter.





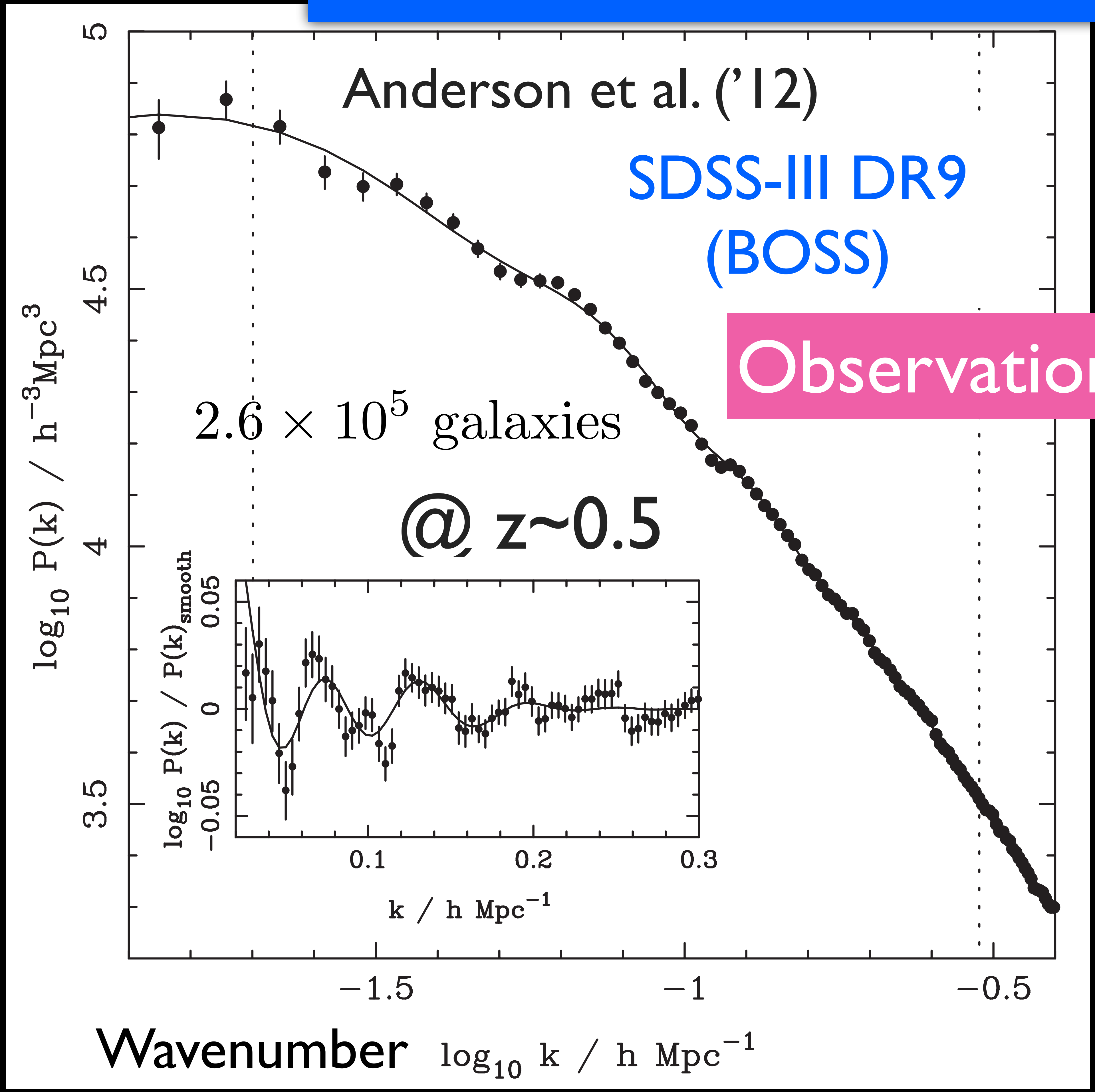


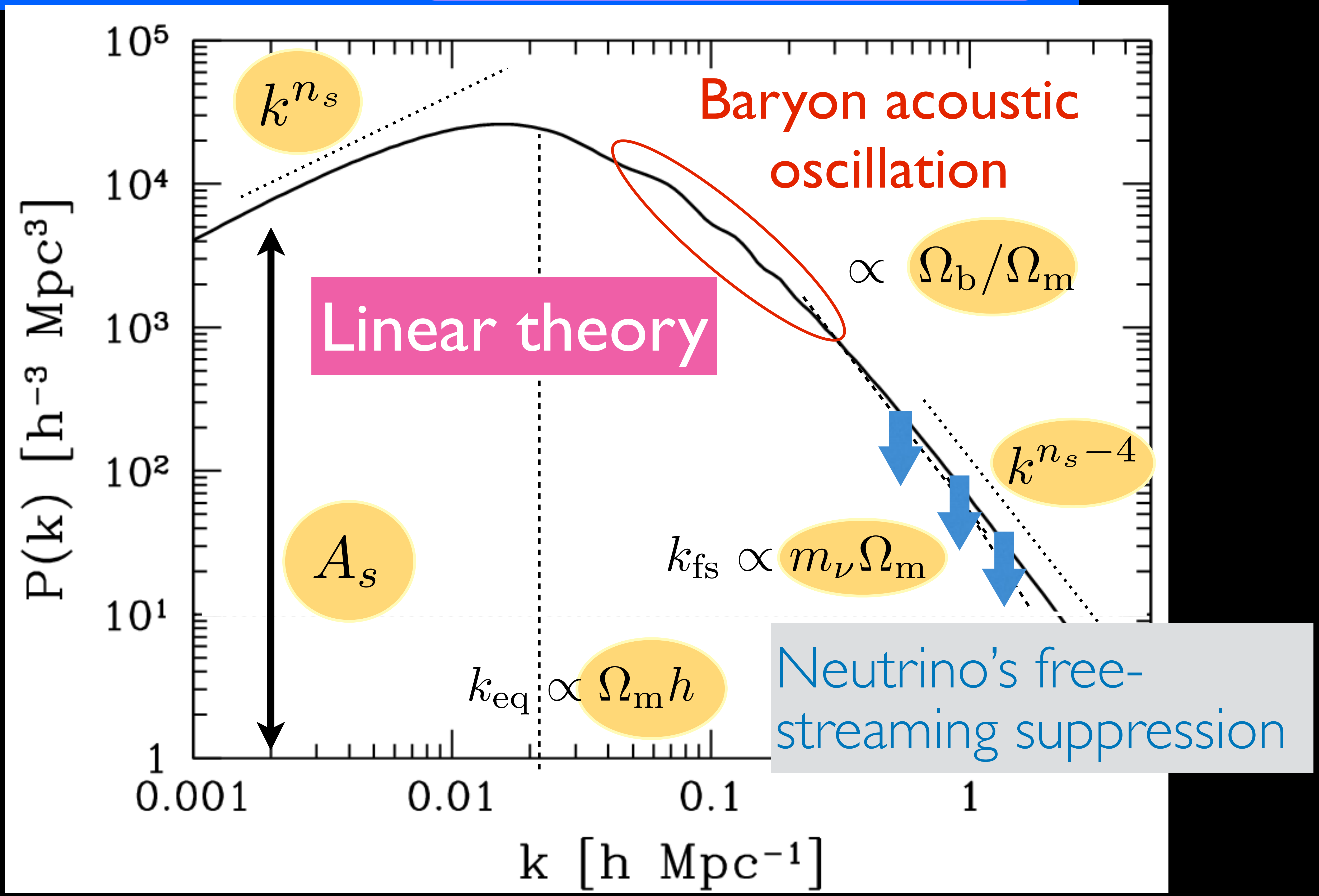
→ Unique sites of galaxy/star formation

When fluctuations reach unity ($\delta \sim 1$), nonlinear gravity forms self-gravitating halos

Matter power spectrum

$$\delta(\vec{x}) \equiv \frac{\delta\rho_{\rm m}(\vec{x})}{\bar{\rho}_{\rm m}} = \frac{1}{\sqrt{V}}\sum_{\vec{k}}\delta(\vec{k})\,e^{i\vec{k}\cdot\vec{x}} \;\Rightarrow\; P(k) = \frac{1}{N_k}\sum_{|\vec{k}|=k}|\delta(\vec{k})|^2$$





→ help constraining cosmological parameters

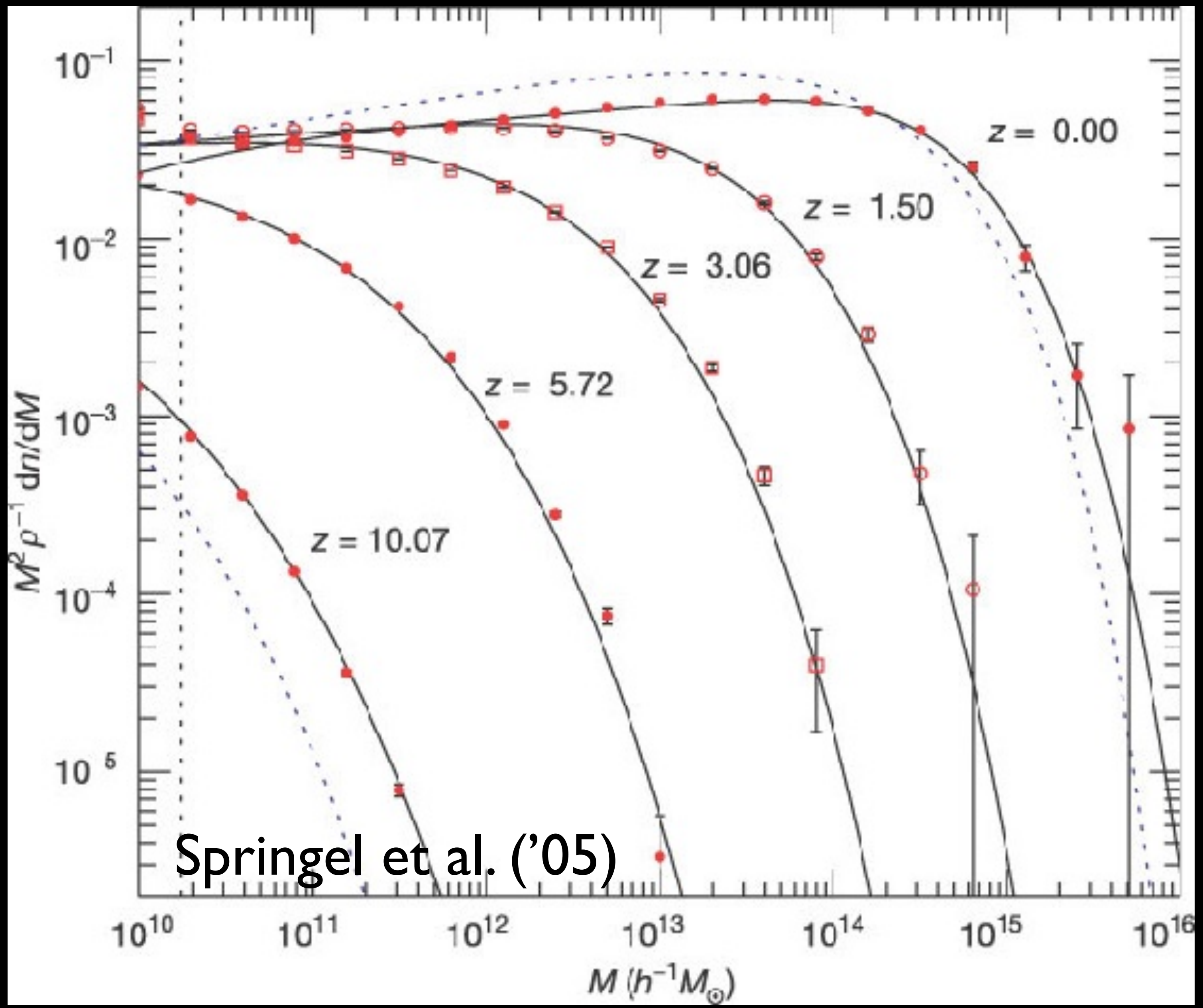
Dark matter halo: small-scale structure formation

Its structural properties & abundance

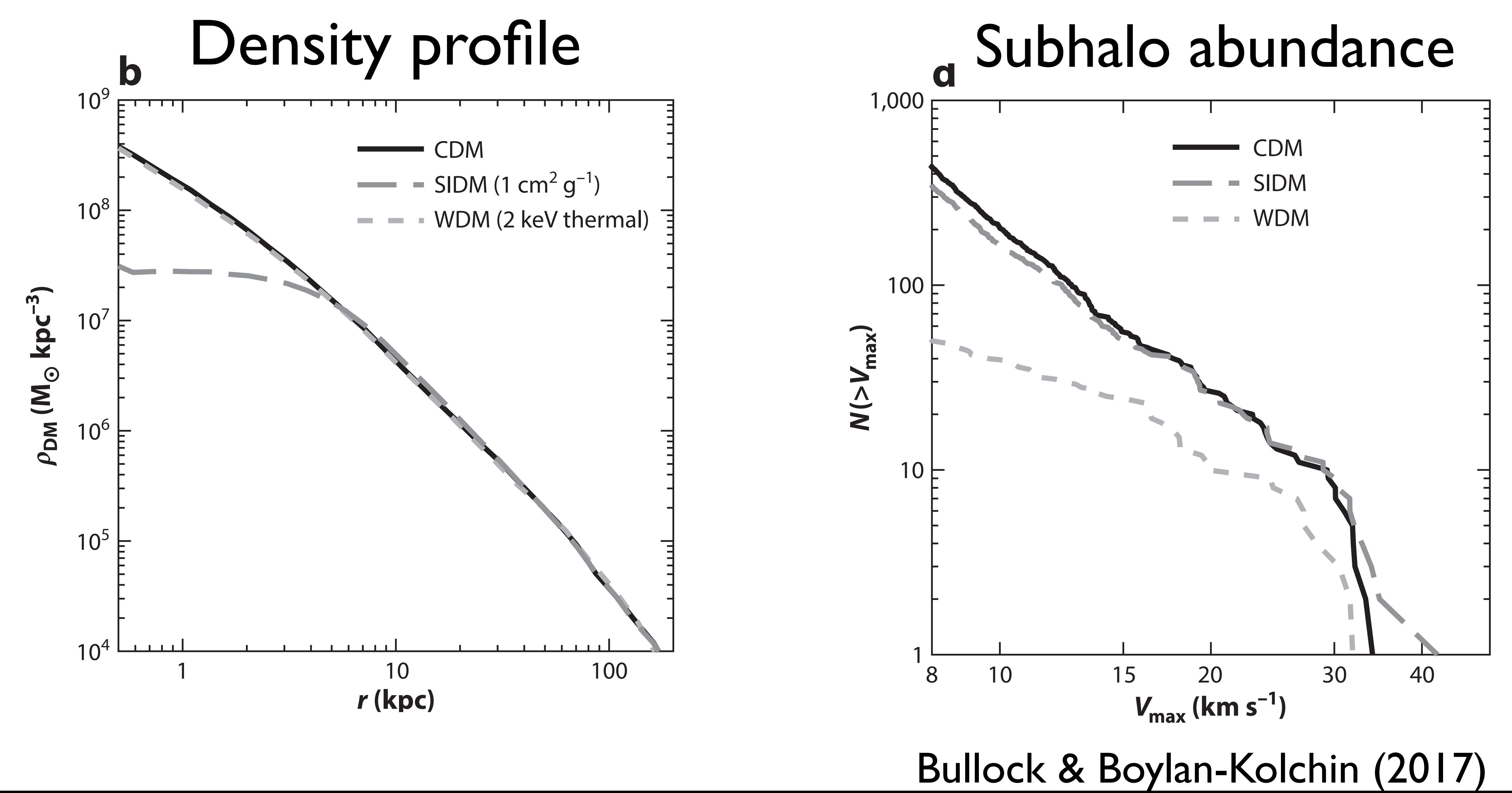
offers insights into both cosmological parameters and nature of dark matter

→ Anatoly Klypin's talk

$m_{\rm DM} \sim 100\,\mathrm{GeV}$ $m_{\rm DM} \sim \mathcal{O}(10)\,\mathrm{KeV}$ $m_{\rm DM} \sim \mathcal{O}(10^{-22})\,\mathrm{eV}$



Halo abundance (mass function)



Linking theory with observations

Linear theory of structure formation

(CMB Boltzmann code)

More theory needs to be involved to confront with precision observations

Matter fluctuations

+

Nonlinear gravity

For survey specific talks

Francisco Prada

Xin Wang

Hydrodynamics and/or baryon physics

Qiao Wang

Ken Osato

Ray-tracing (for lensing)

Redshift-space distortions

Sunyaev-Zel'dovich/X-ray clusters

Galaxy bias + α

Weak lensing (cosmic shear)

Peter Behroozi

Galaxy clustering → Statistical characterization

→Teppei Okumura

→Takahiro Nishimichi

Summary

Cosmology is a subect of physics tightly connected to observations
(from stars, galaxies to CMB)

ΛCDM model, the standard cosmological model, needs to be scrutinized by new observational data — beyond ΛCDM & new physics search

- Nature of dark energy & dark matter, and untested hypothesis
- Tensions across multiple observations (H_0, S_8)

(Stage IV class) galaxy surveys play a crucial role
(cosmological parameters, testing ΛCDM & gravity)

Theory of cosmic structure formation provides a basis to interpret observational data as well as a clue to clarify/address