Current Cosmological Constraints: A Tale of Two Tensions

Jonathan Blazek

Laboratory of Astrophysics, EPFL

DES Collaboration

EPFL

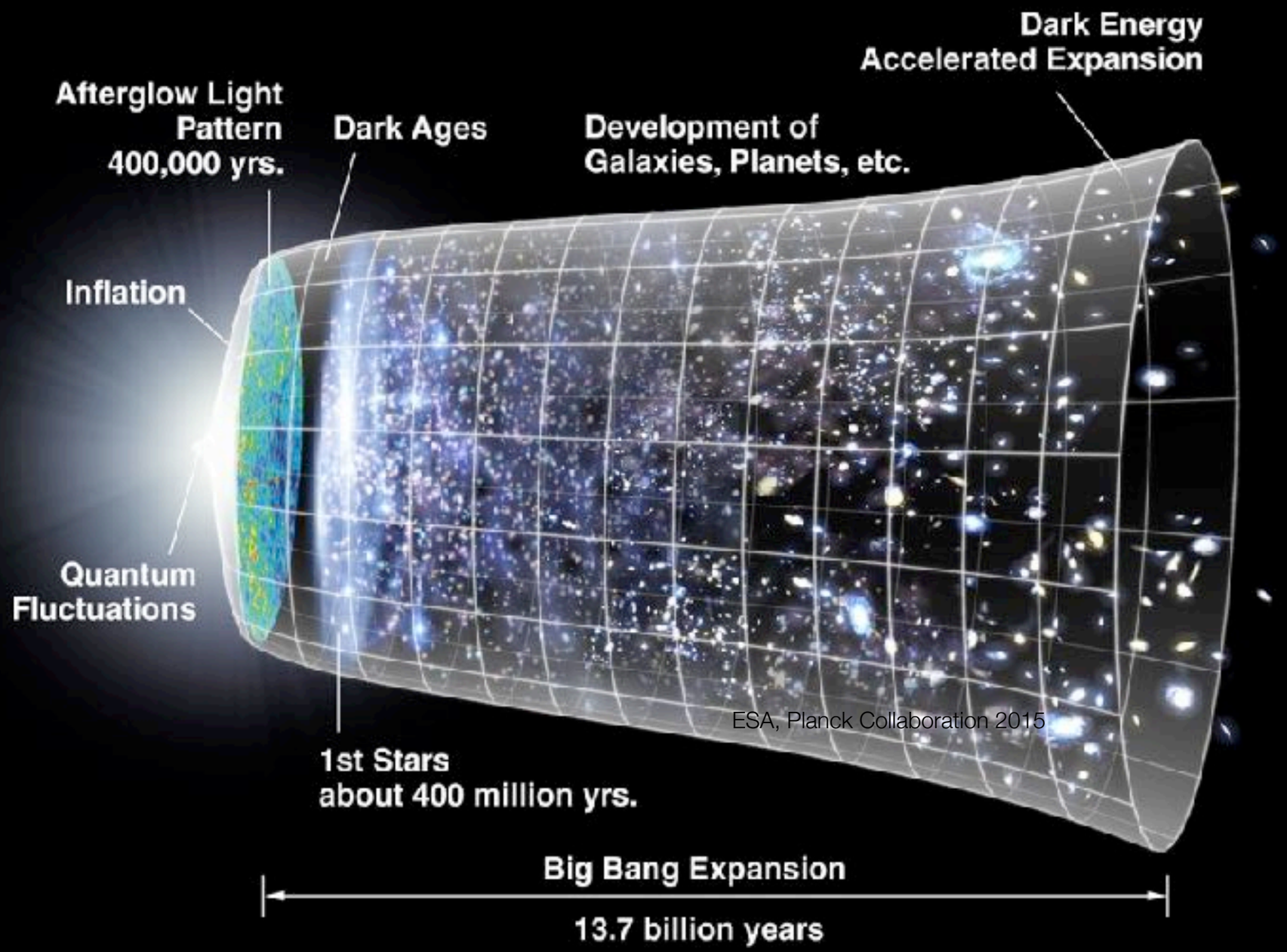
2019 DPF Northeastern

Combining and comparing probes

Different measurements of the expansion rate, or age, of the Universe do not agree

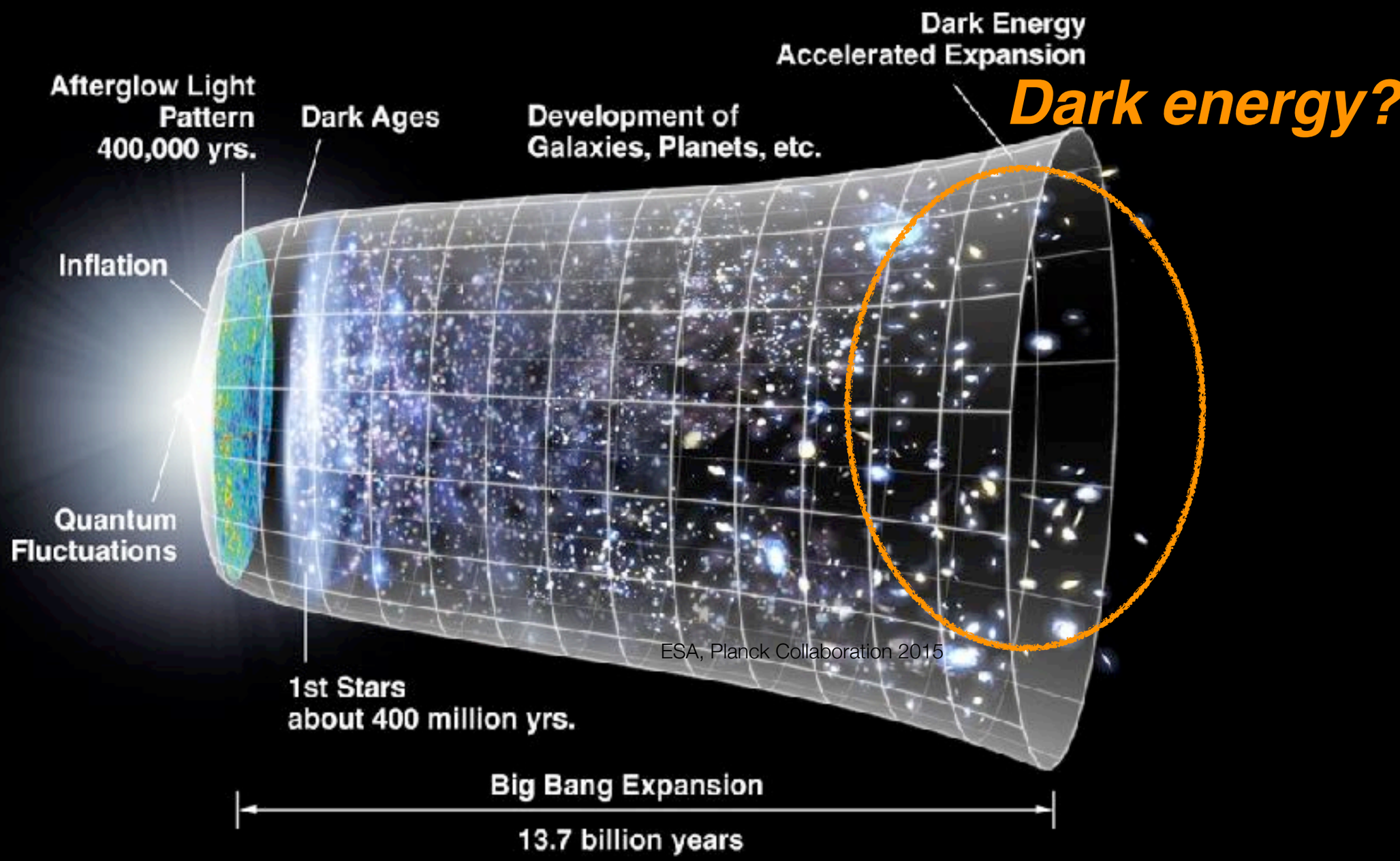
Different measurements of matter fluctuations *may* not agree

ΛCDM: Concordance Cosmology



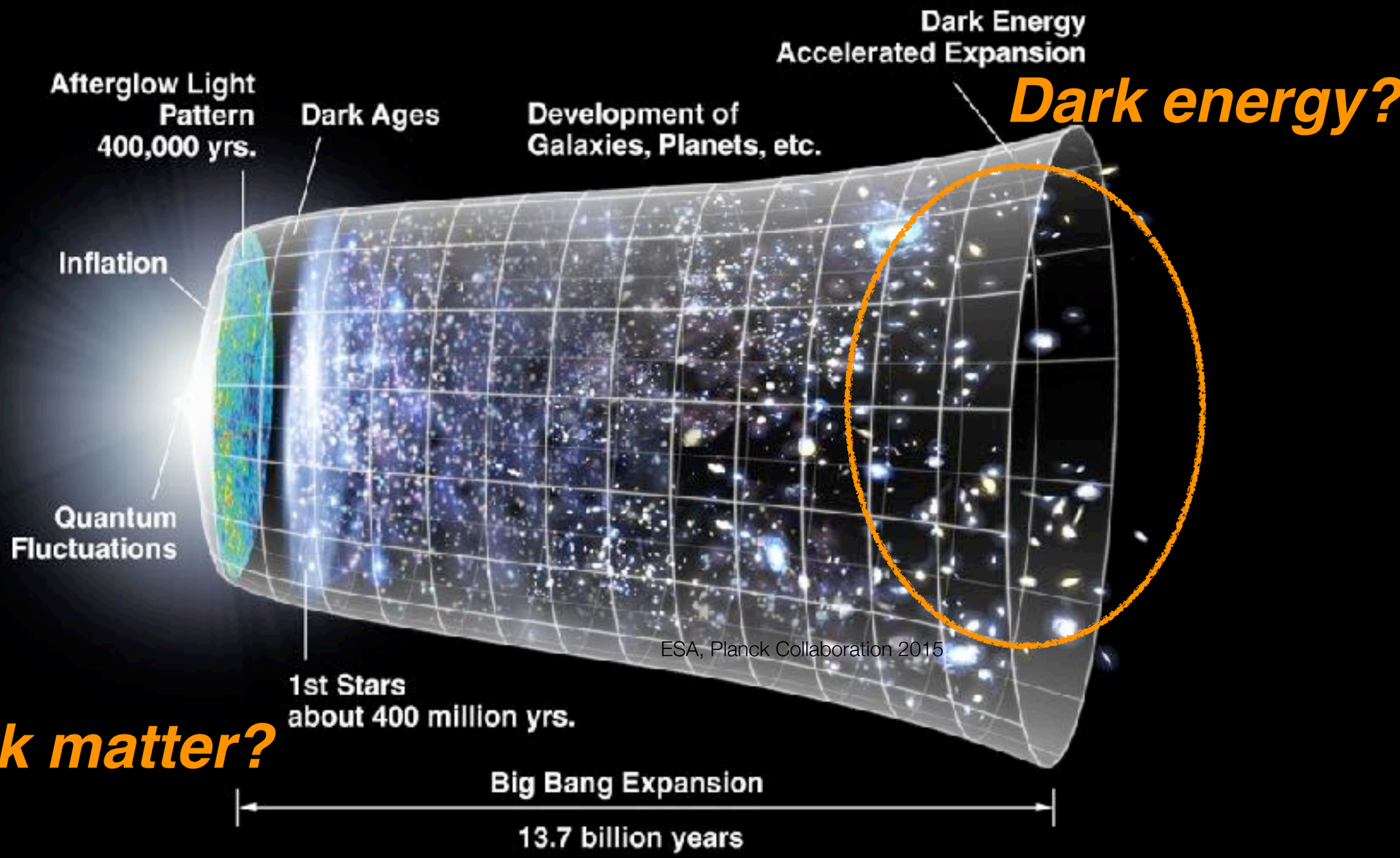
ESA, Planck Collaboration 2015

ΛCDM: Concordance Cosmology



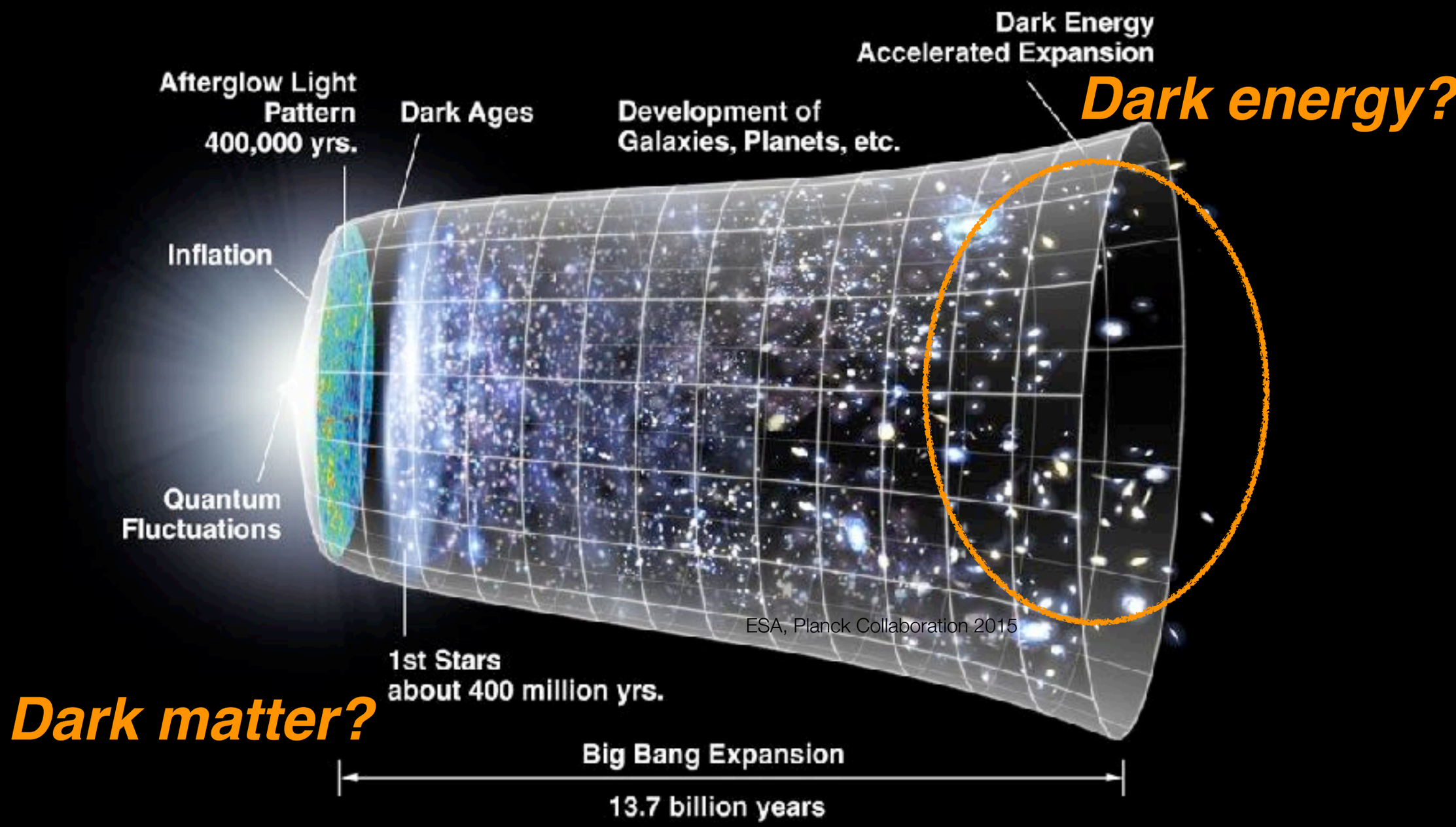
ESA, Planck Collaboration 2015

ΛCDM: Concordance Cosmology



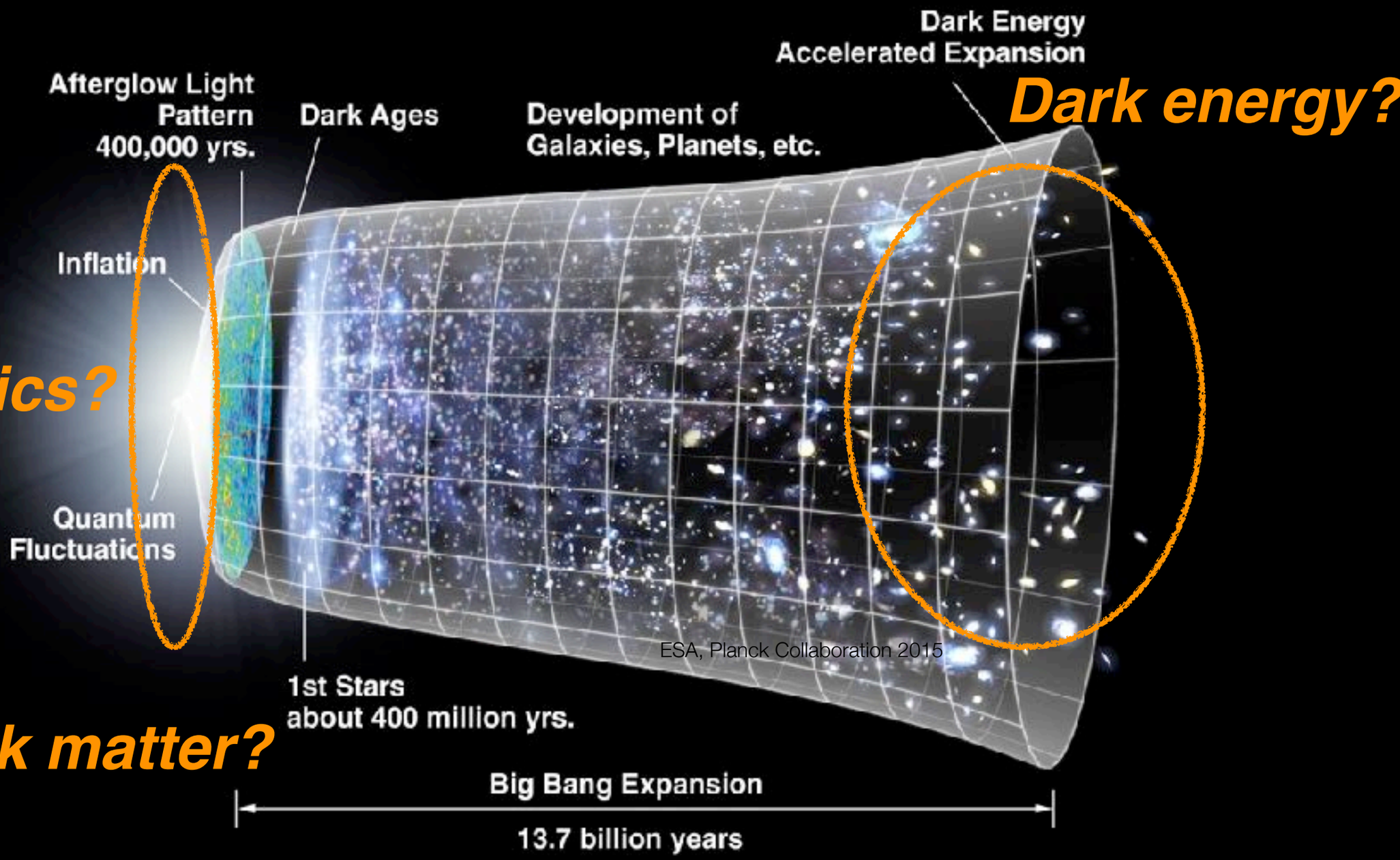
ESA, Planck Collaboration 2015

ΛCDM: Concordance Cosmology



ESA, Planck Collaboration 2015

ΛCDM: Concordance Cosmology



Dark energy?

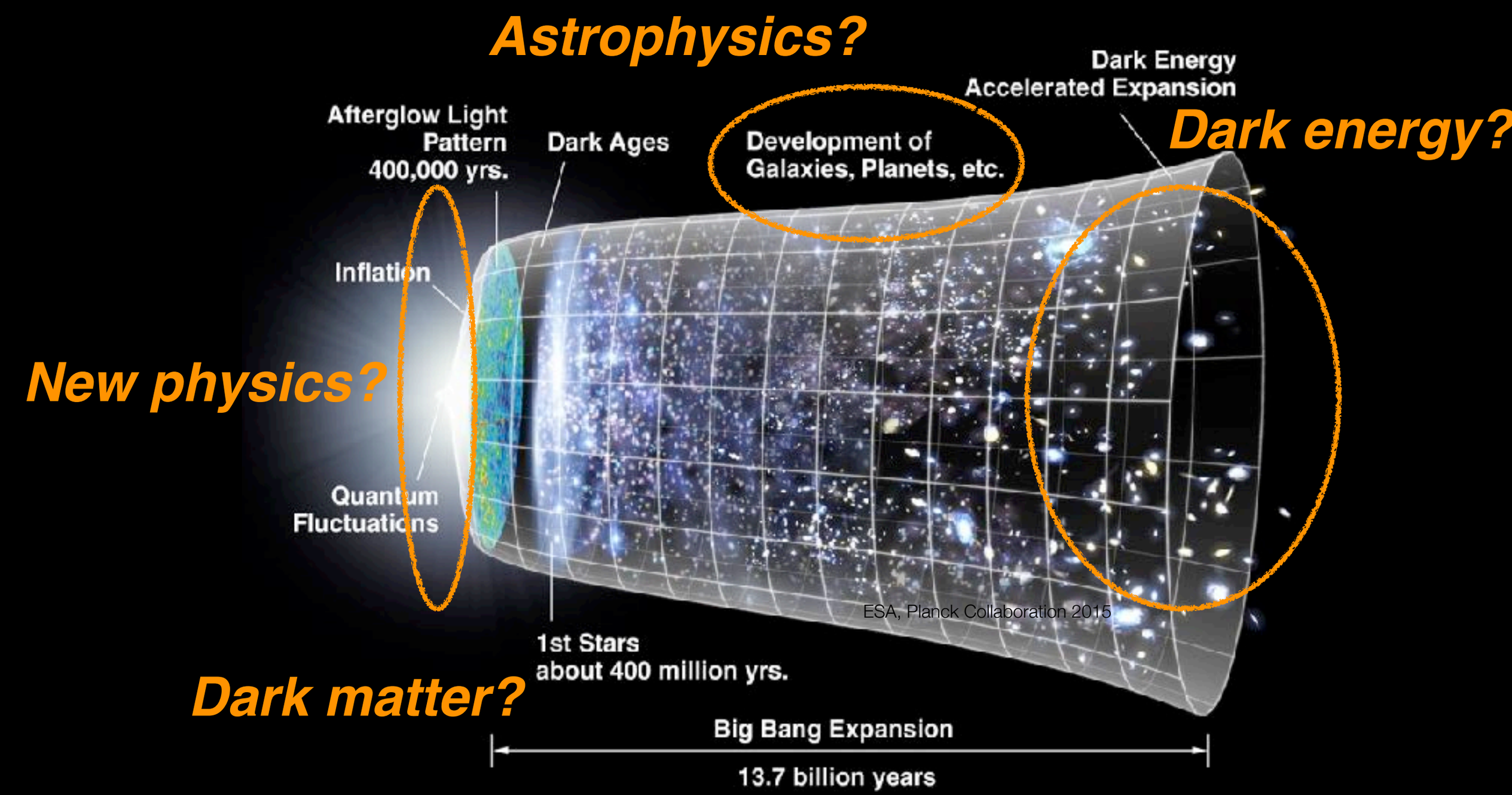
New physics?

Dark matter?

Neutrino mass?

NASA/WMAP Science Team

ΛCDM: Concordance Cosmology



$a = 0.02$

$l = 0.1$ Gyr

Basic observables

Geometry

matter radiation curvature dark energy

$$H(z) = H_0\sqrt{\Omega_{\rm m}(1+z)^3 + \Omega_{\rm r}(1+z)^4 + \Omega_{\rm k}(1+z)^2 + \Omega_\Lambda}$$

expansion rate

$$d(z) \sim \int_0^z \frac{c dz'}{H(z')}$$

distances

Growth of structure

density fluctuations on 8 Mpc → $\sigma_8(z)$

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

Tensions?

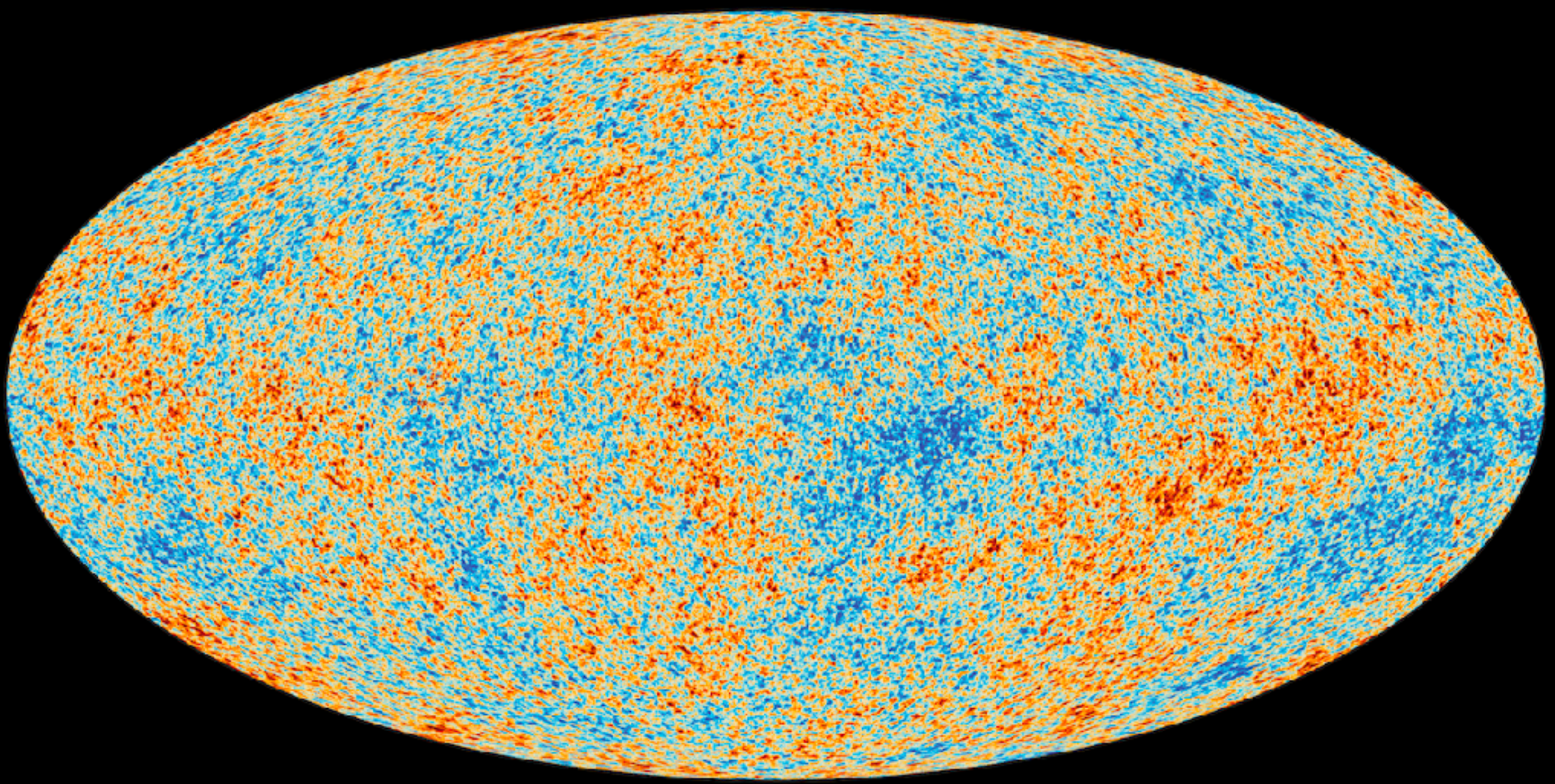
Geometry

Different measurements of expansion rate H_0, equivalently the age of the Universe, do not agree

Growth of structure

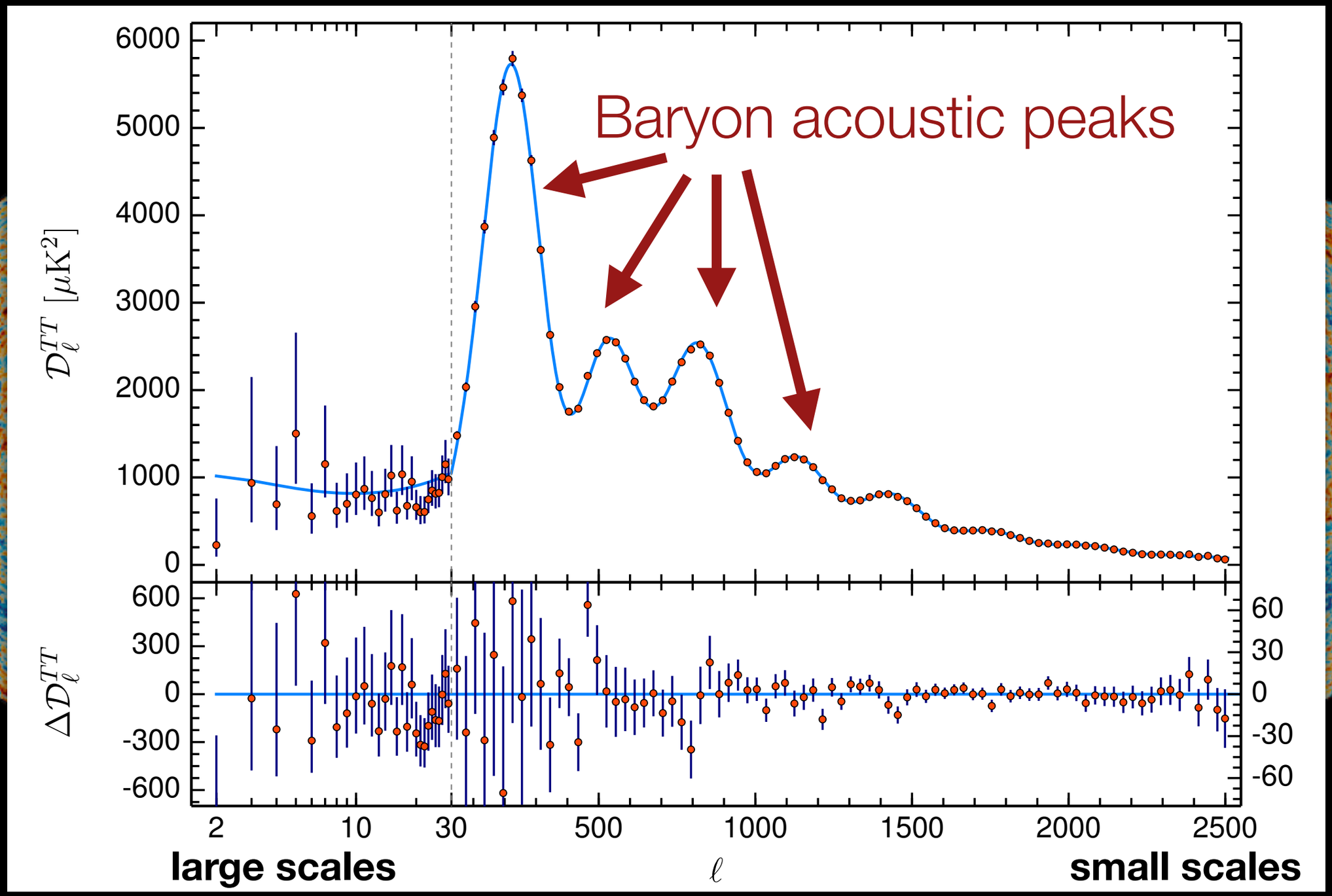
Different measurements of matter fluctuations S_8 *may* not agree

Cosmic Microwave Background



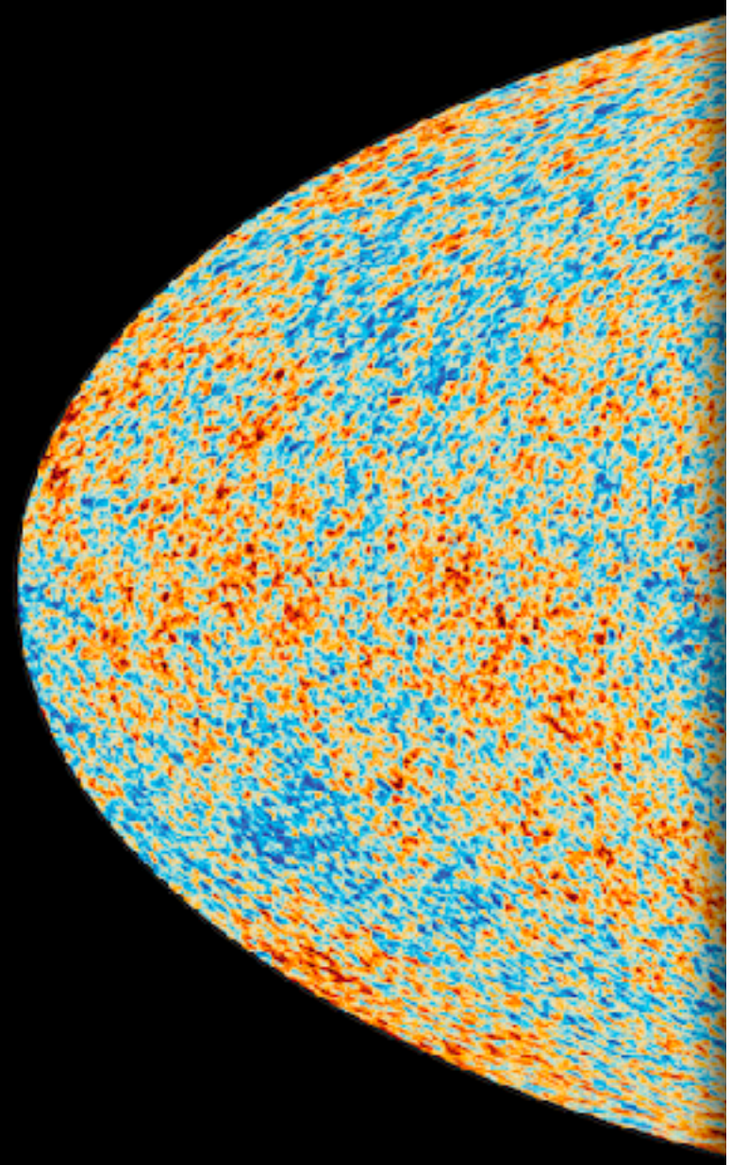
ESA/Planck Collaboration, 2018

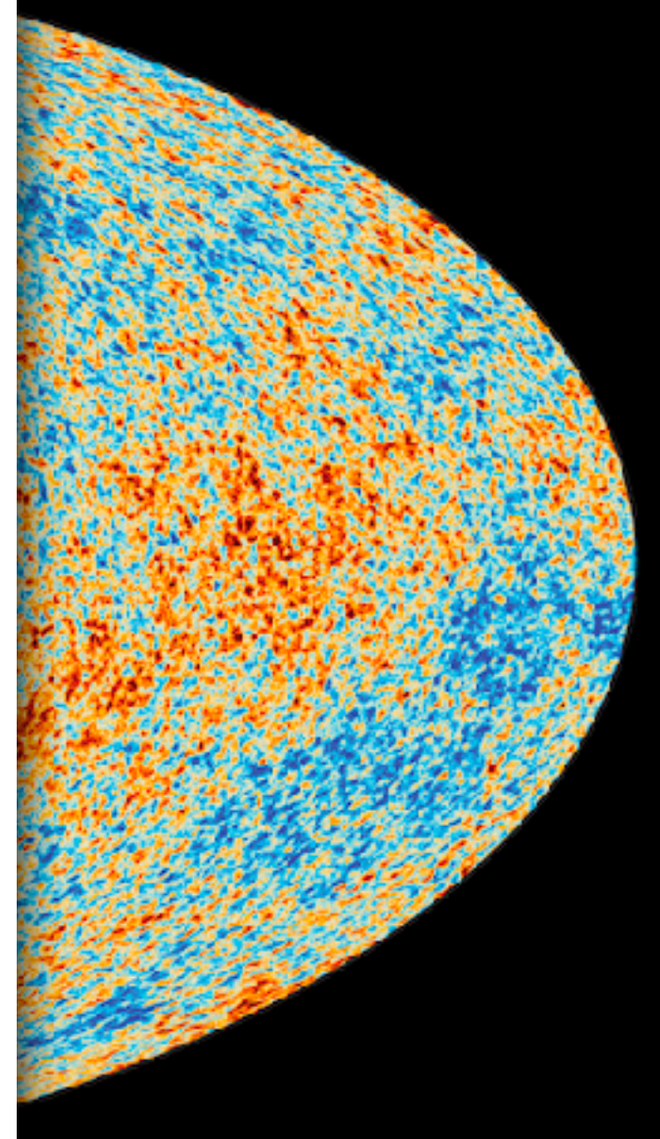
Cosmic Microwave Background



Planck Collaboration, 2018

Cosmic Microwave Background





Parameter	Plik
$\Omega_b h^2$	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
$\Omega_m h^2$	0.1430 ± 0.0011
H_0 [km s^{-1}Mpc^{-1}]	67.36 ± 0.54
Ω_m	0.3153 ± 0.0073
Age [Gyr]	13.797 ± 0.023
σ_8	0.8111 ± 0.0060
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$	0.832 ± 0.013
z_{re}	7.67 ± 0.73
$100\theta_*$	1.04110 ± 0.00031
r_{drag} [Mpc]	147.09 ± 0.26

Planck Collaboration, 2018

Mapping the full volume

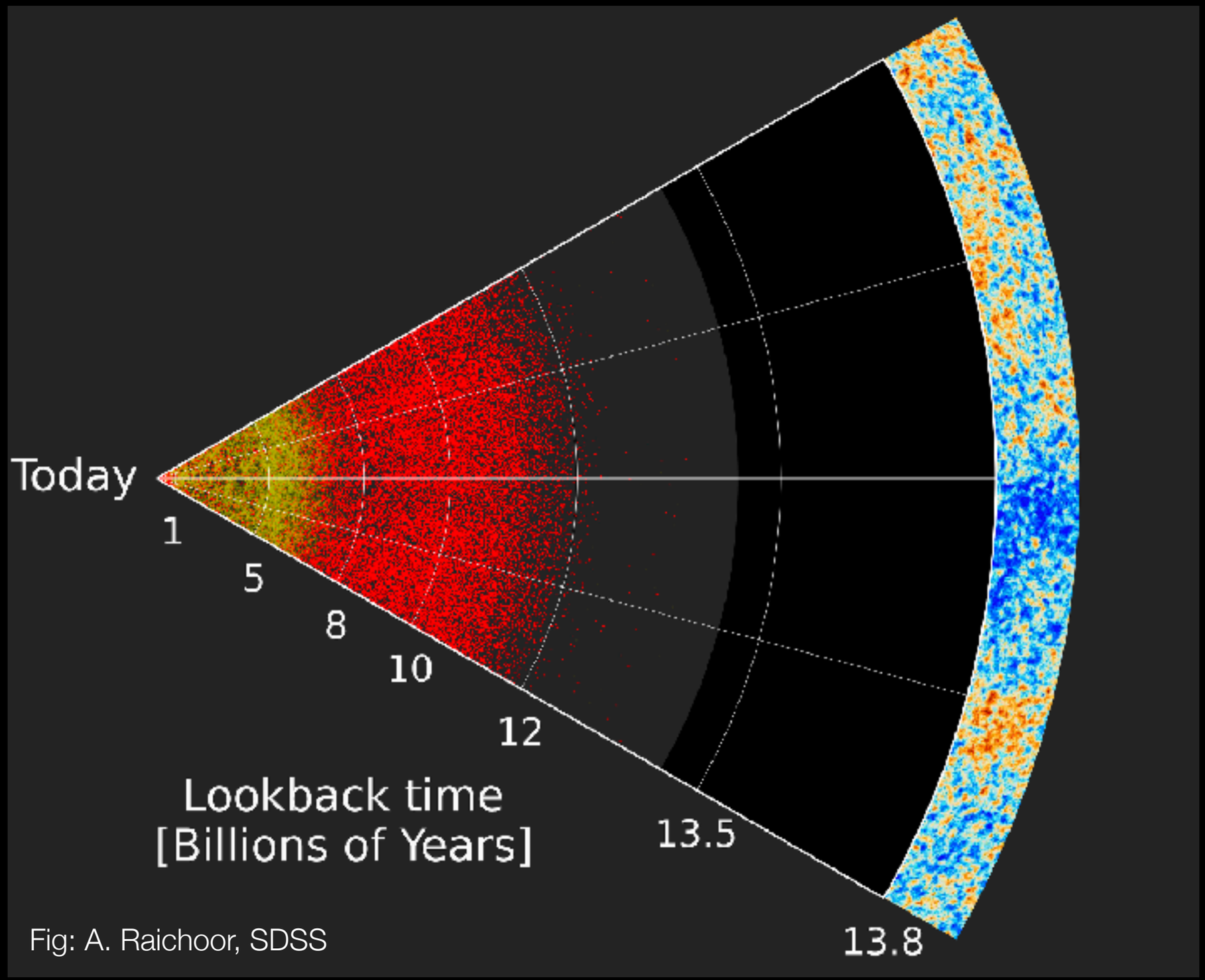
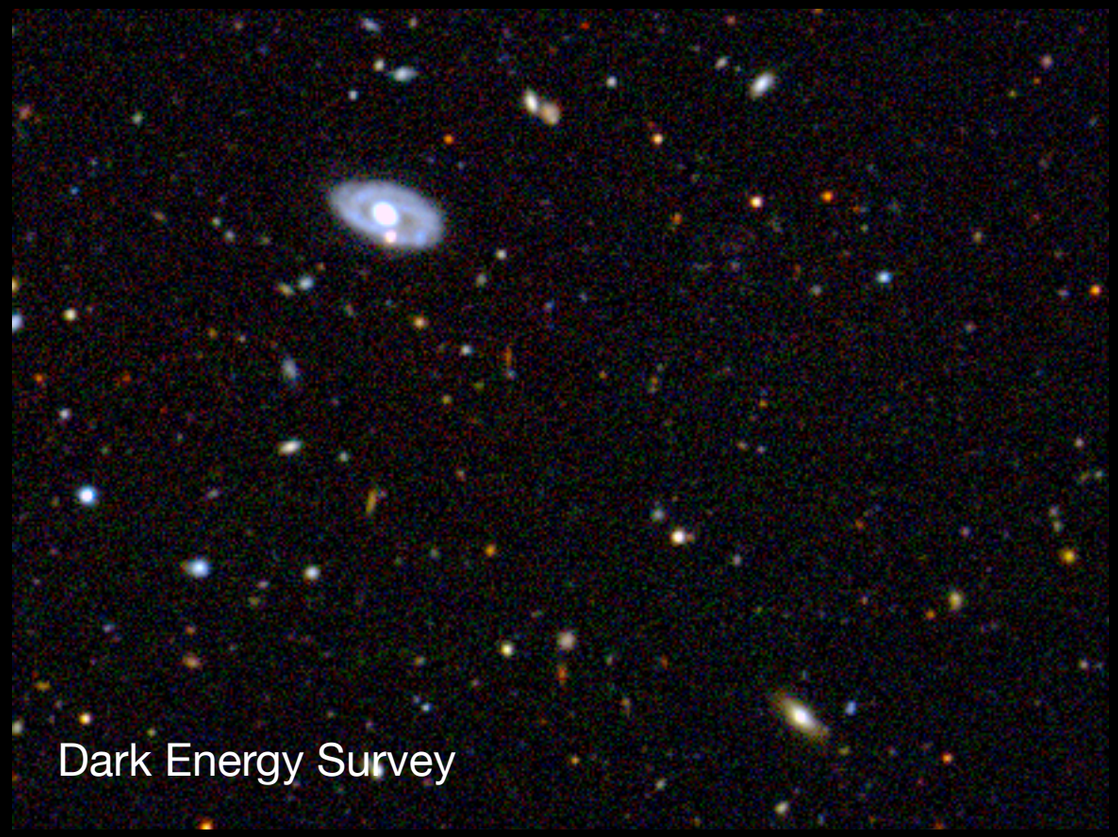
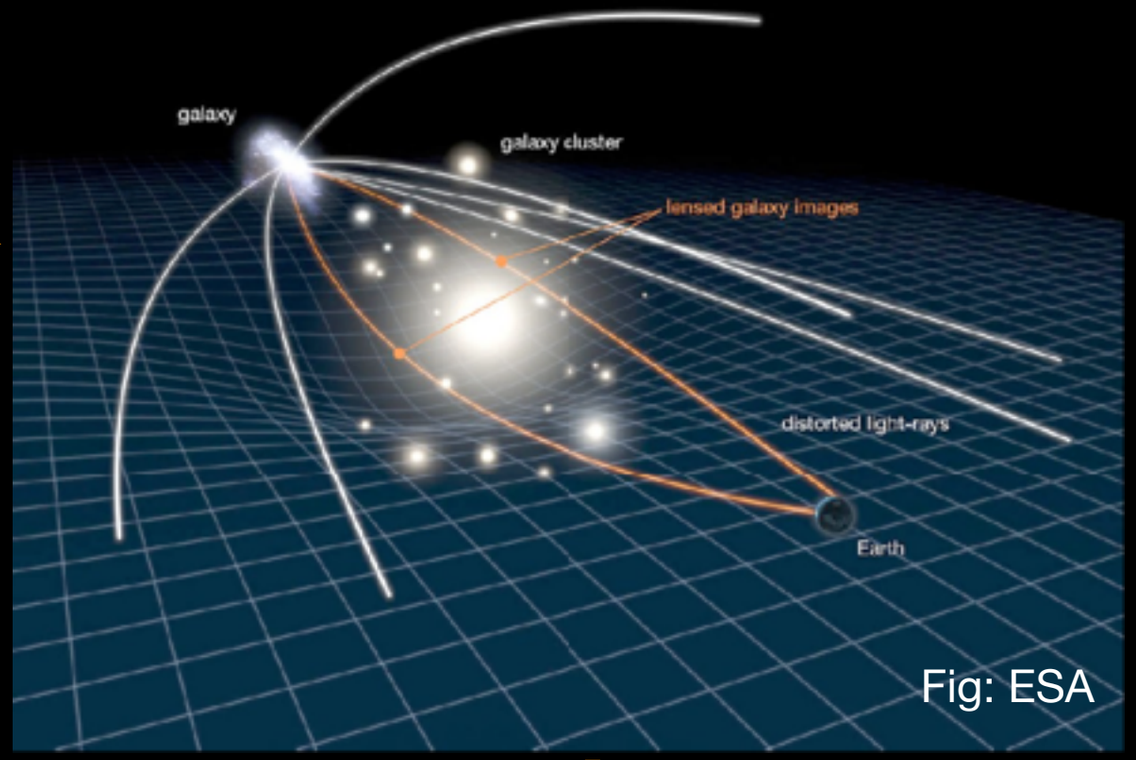


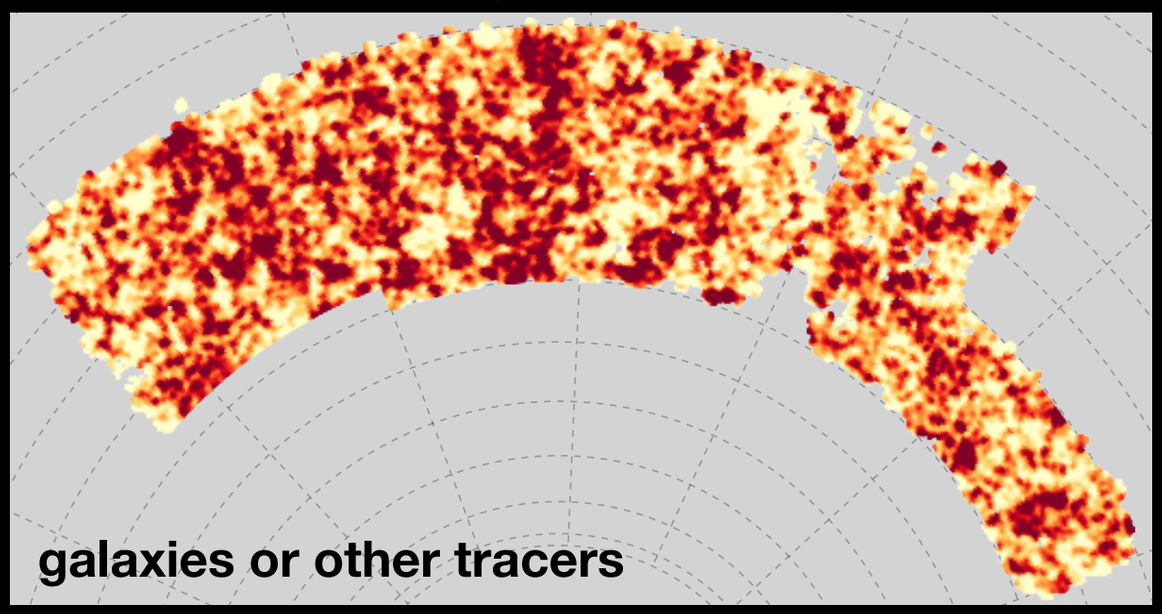
Fig: A. Raichoor, SDSS

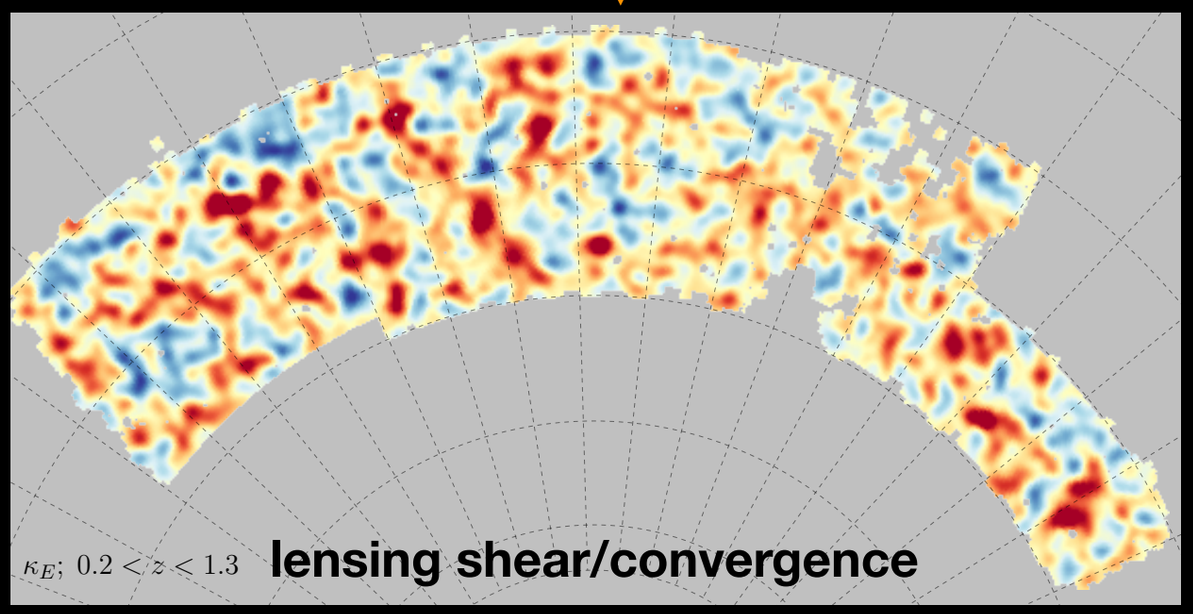
Galaxy surveys



(Weak) Gravitational Lensing

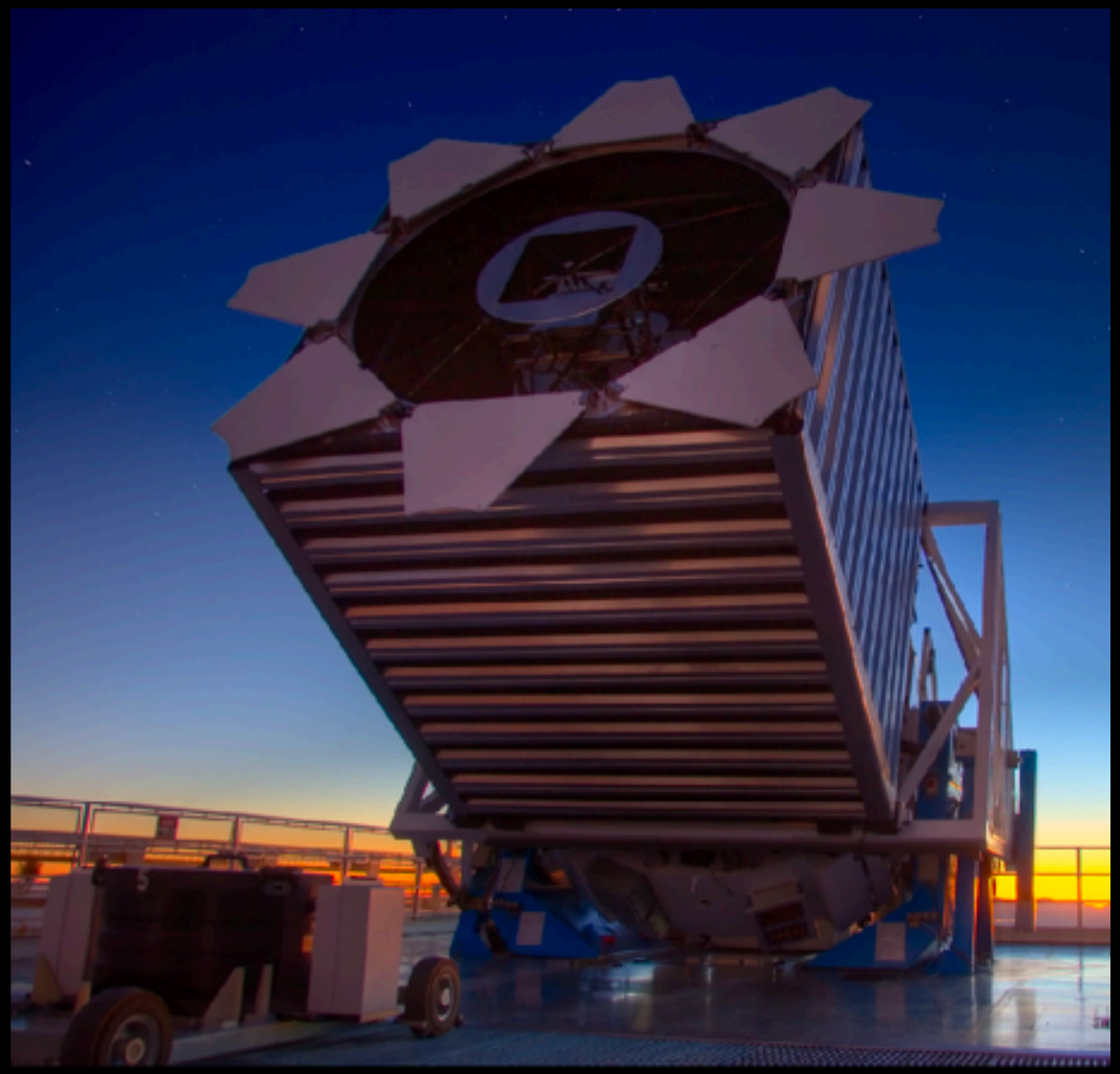






DES Year 1: Elvin-Poole+ 2018; Chang+ 2018

Sloan Digital Sky Survey



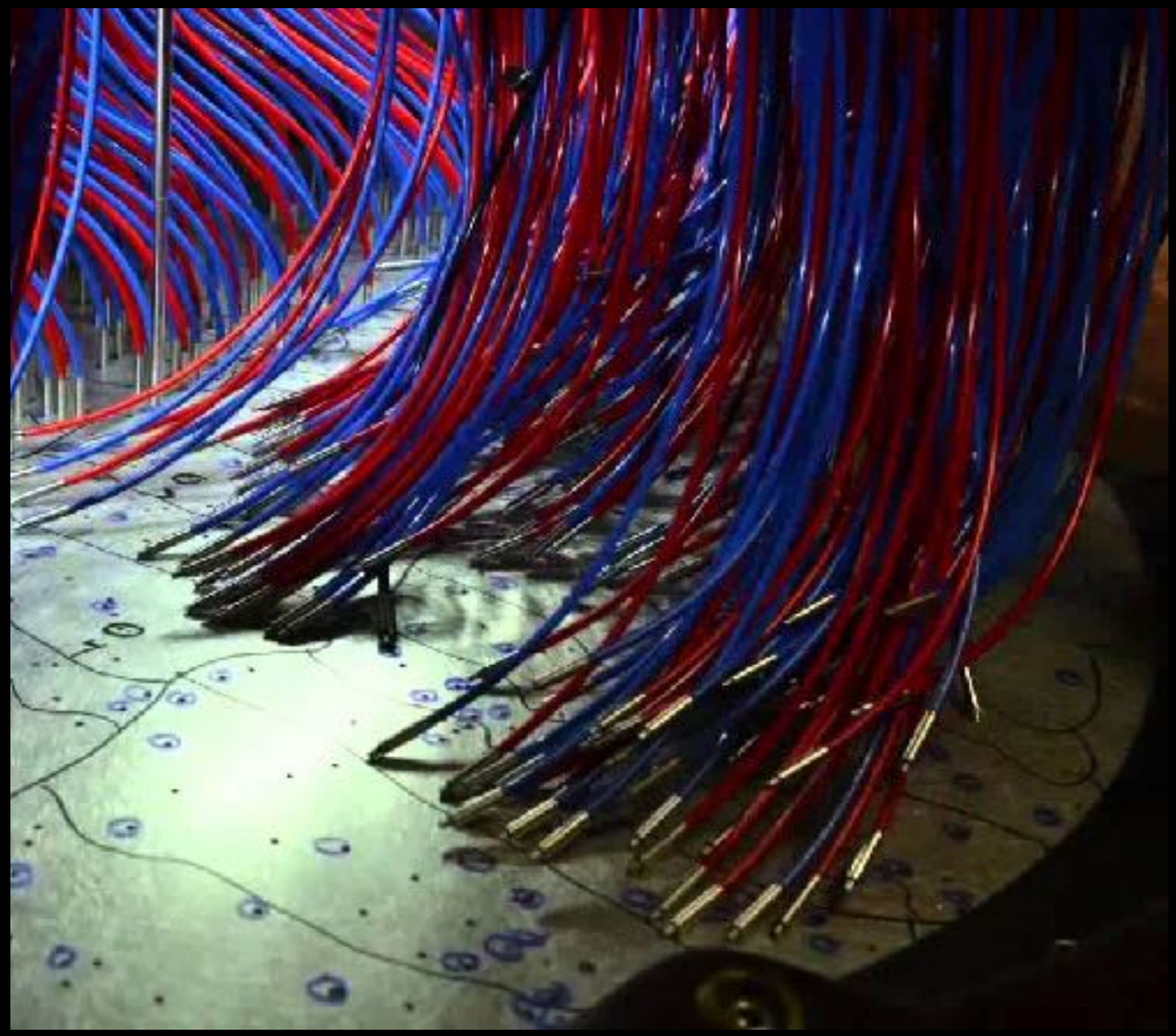
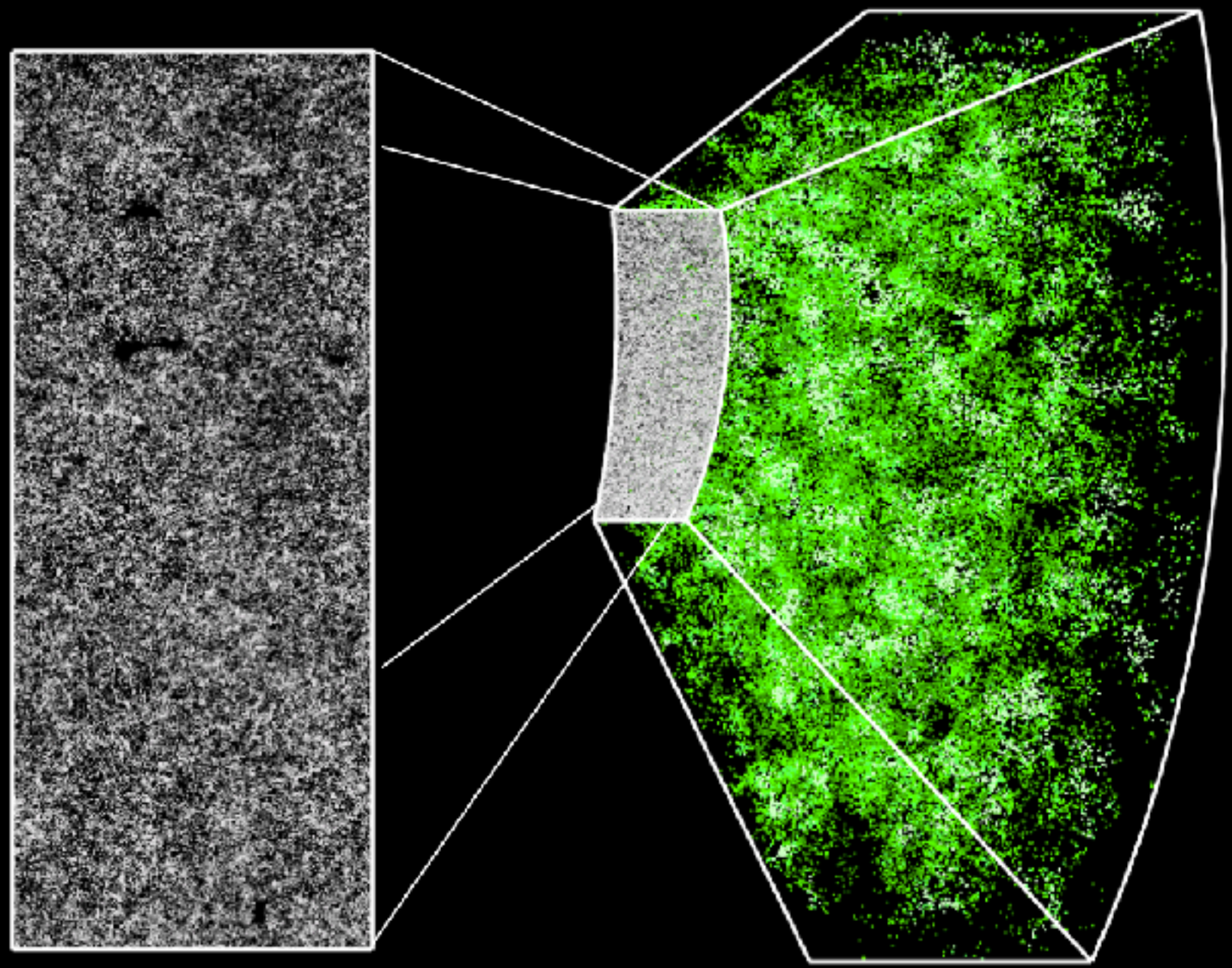


Fig: SDSS

2.5m Apache Point telescope, New Mexico

Sloan Digital Sky Survey



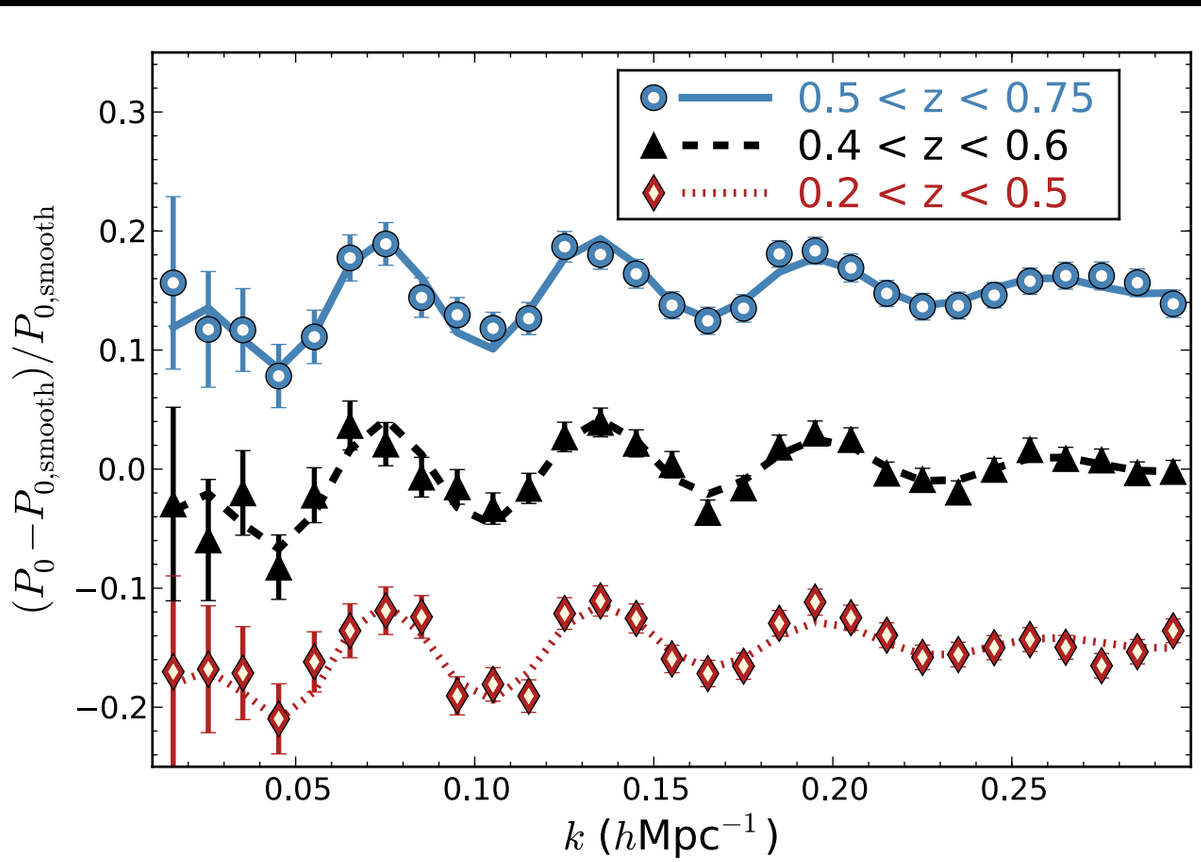
$\delta_{\rm gal}(\mathbf{x})$

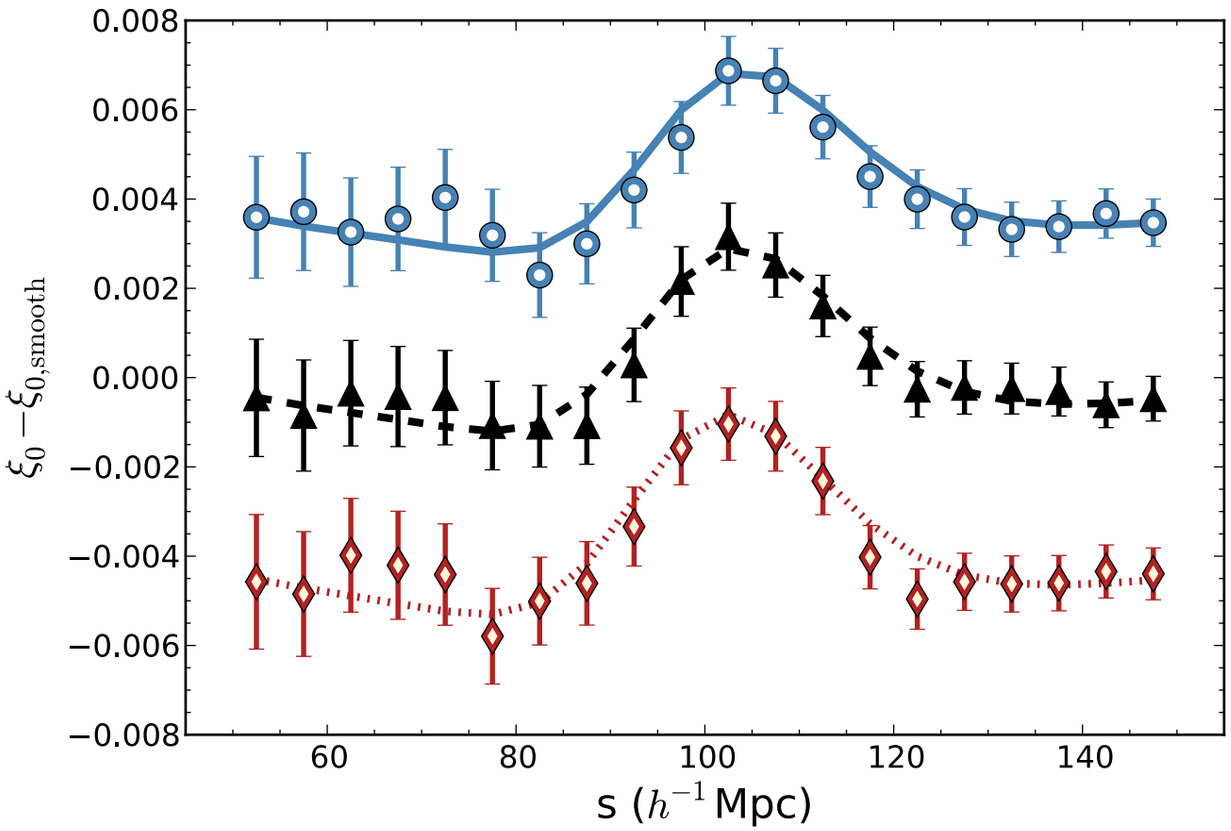
Fig: SDSS

$$\langle \delta_{\rm gal}(\mathbf{x}) \delta_{\rm gal}(\mathbf{x}+\mathbf{r}) \rangle = \xi_{\rm gal}(\mathbf{r}) \longleftrightarrow P_{\rm gal}(k) = \langle \tilde{\delta}^2_{\rm gal}(\mathbf{k}) \rangle$$

The BAO standard ruler

Baryon **O**scillation **S**pectroscopic **S**urvey

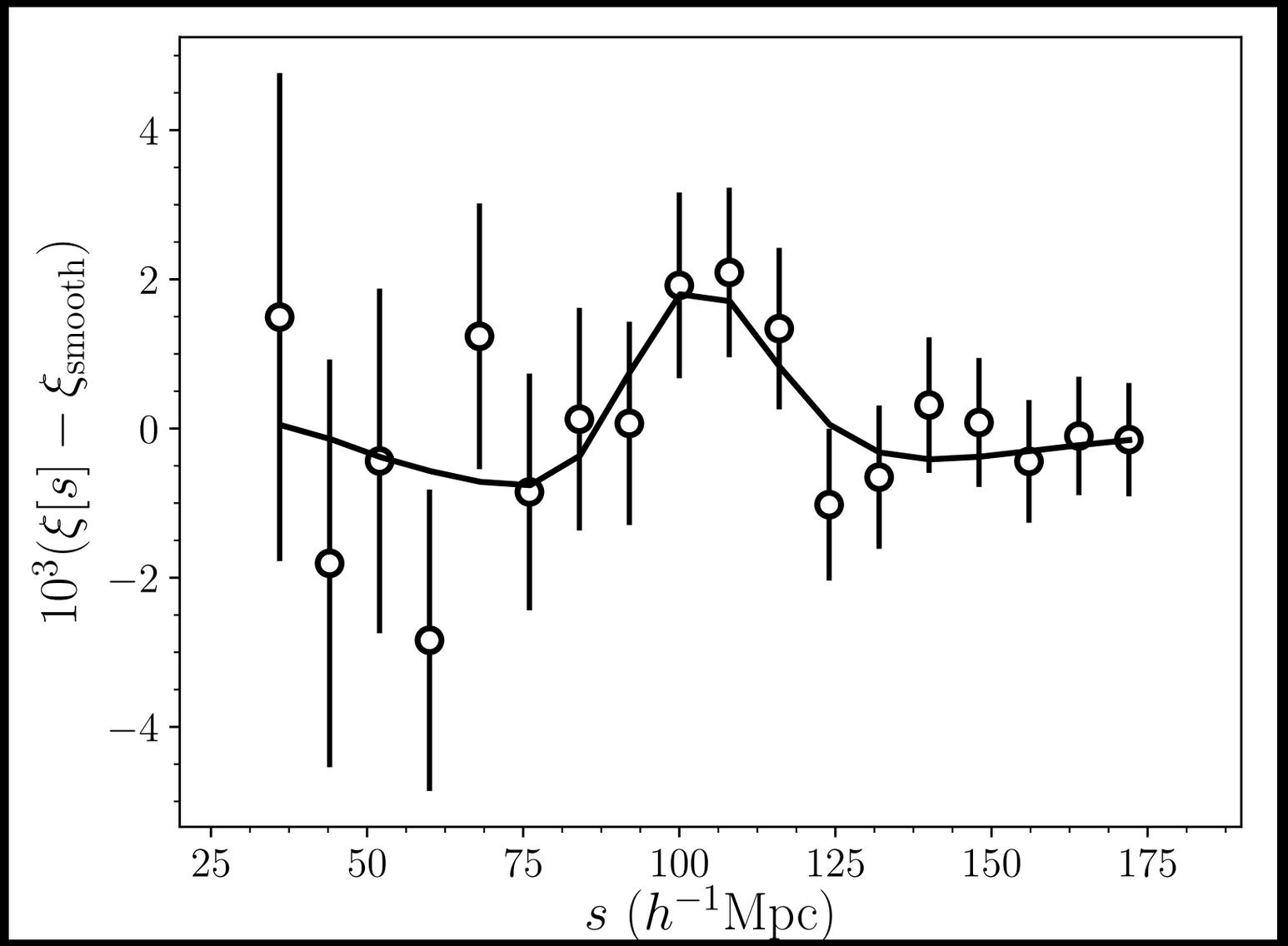




BOSS galaxies: Alam+ 2017

The BAO standard ruler

extended **B**aryon **O**scillation **S**pectroscopic **S**urvey



eBOSS quasars: Ata+ 2018

The BAO standard ruler

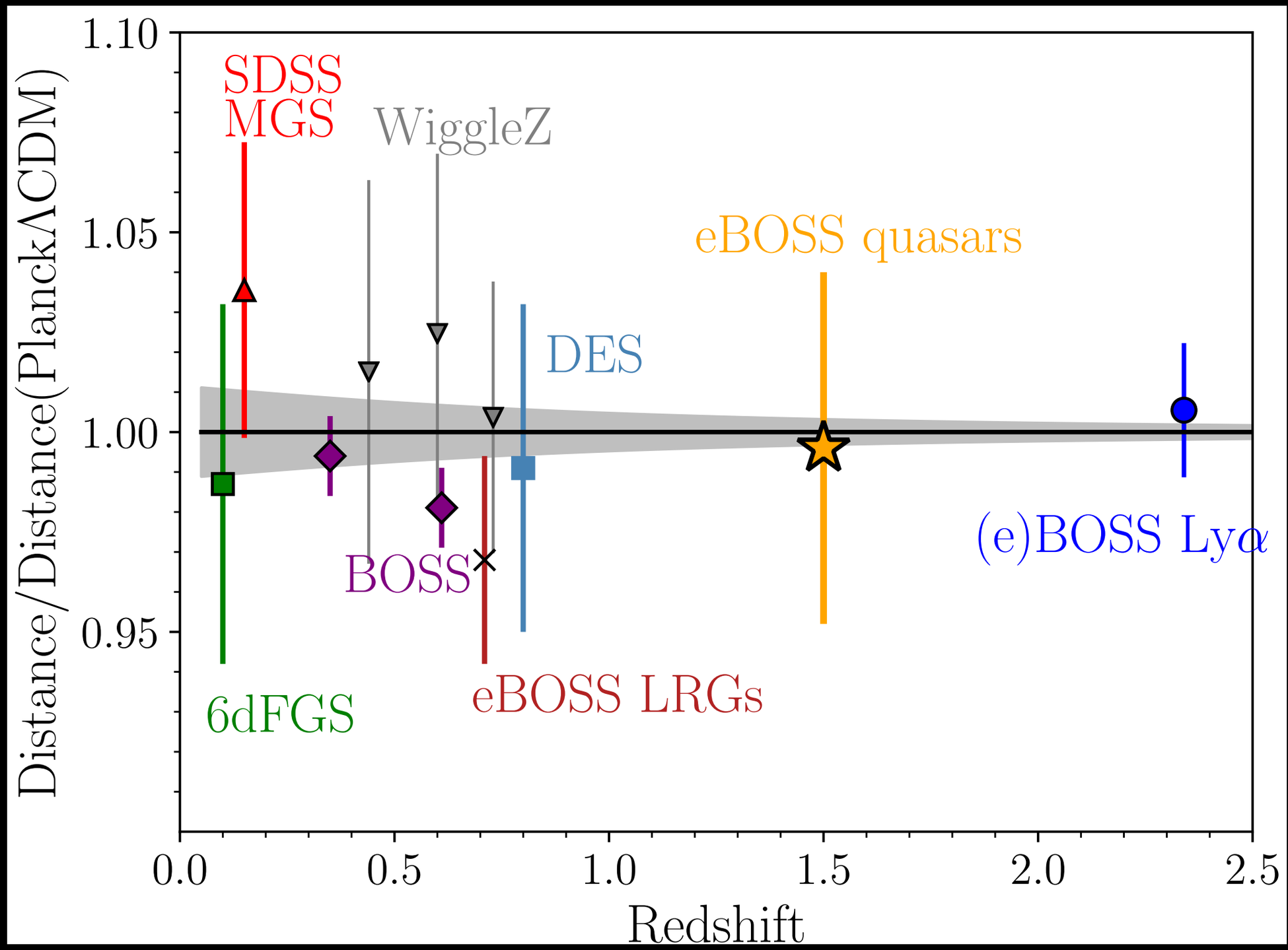
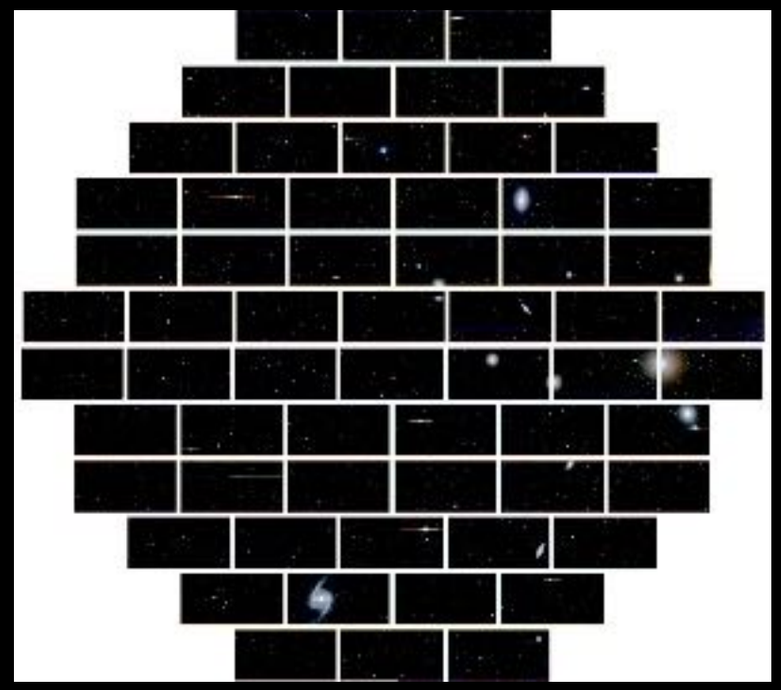


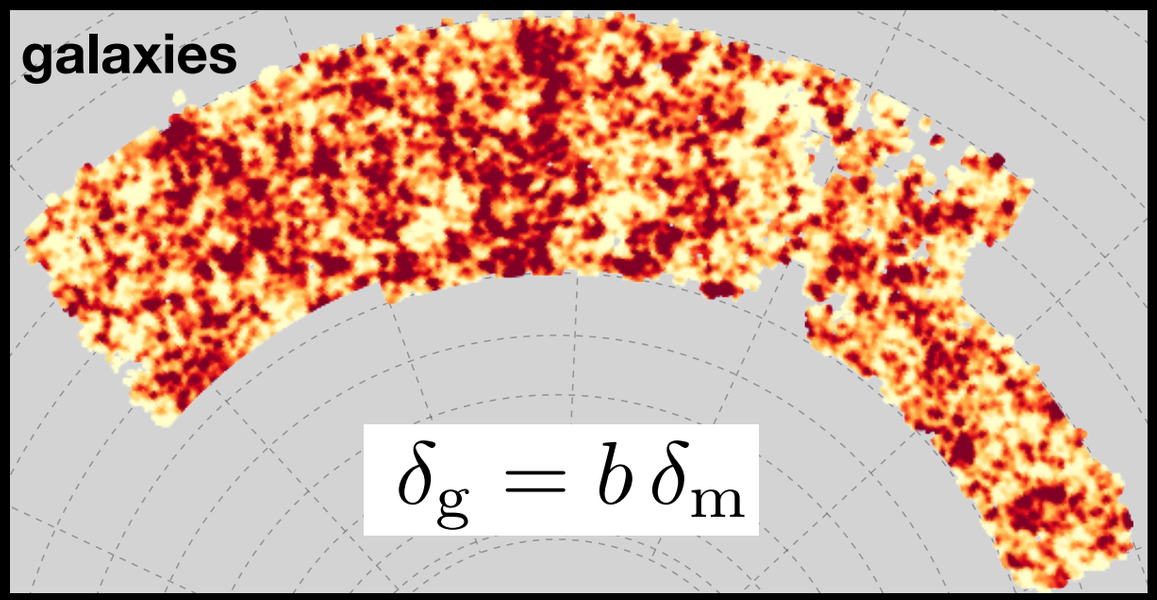
Fig: SDSS, A. Ross

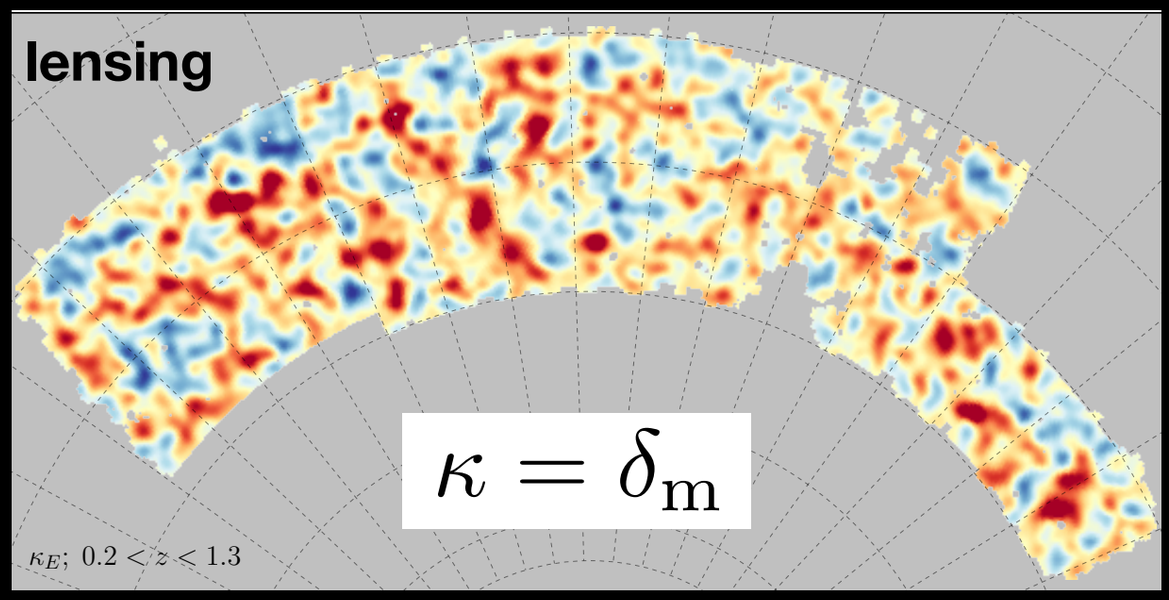
Dark Energy Survey

- DECam (520 Mpix) on 4m Blanco Telescope, Cerro Tololo, Chile
- 1/8 of sky (5000 deg^2 - Year 1 = 1300 deg^2)
- 6 year mission, 525 nights, completed Jan 2019
- *grizY* filters (photometric redshifts)
- 300 million galaxies ($0 < z < 2$)
  >100 million with WL shapes

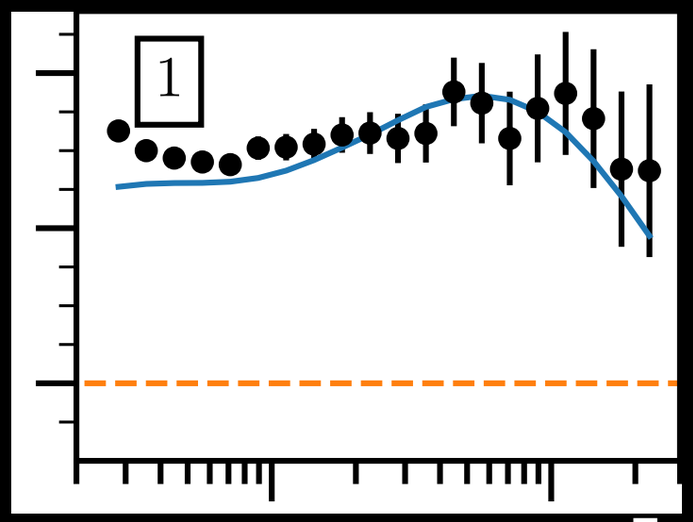


Combining probes



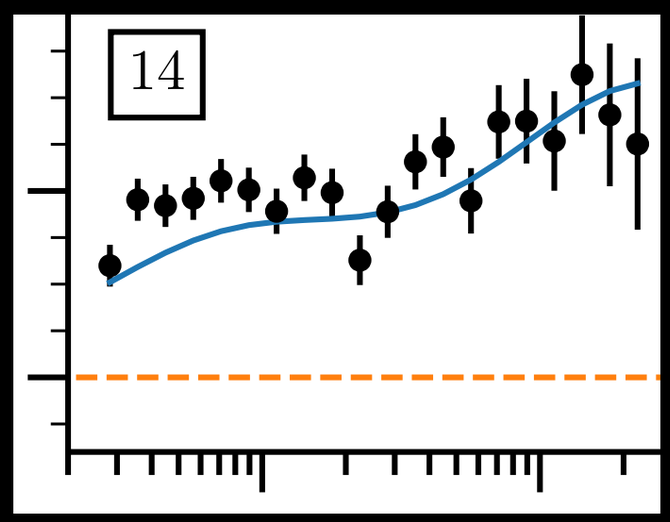


$\langle \delta_g | \delta_g \rangle = \xi_{\rm gg} \sim b^2 \sigma_8^2$



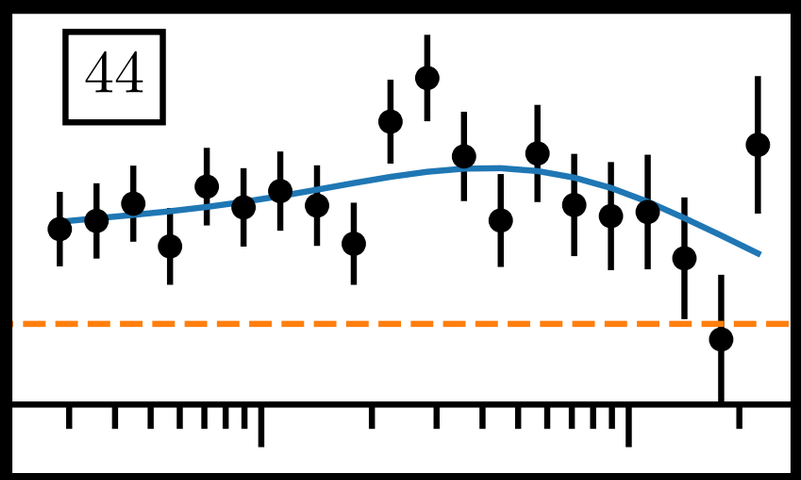
Elvin-Poole+ 2018

$\langle \delta_g | \kappa \rangle = \xi_{\rm gm} \sim b \sigma_8^2$



Prat, Sanchez+ 2018

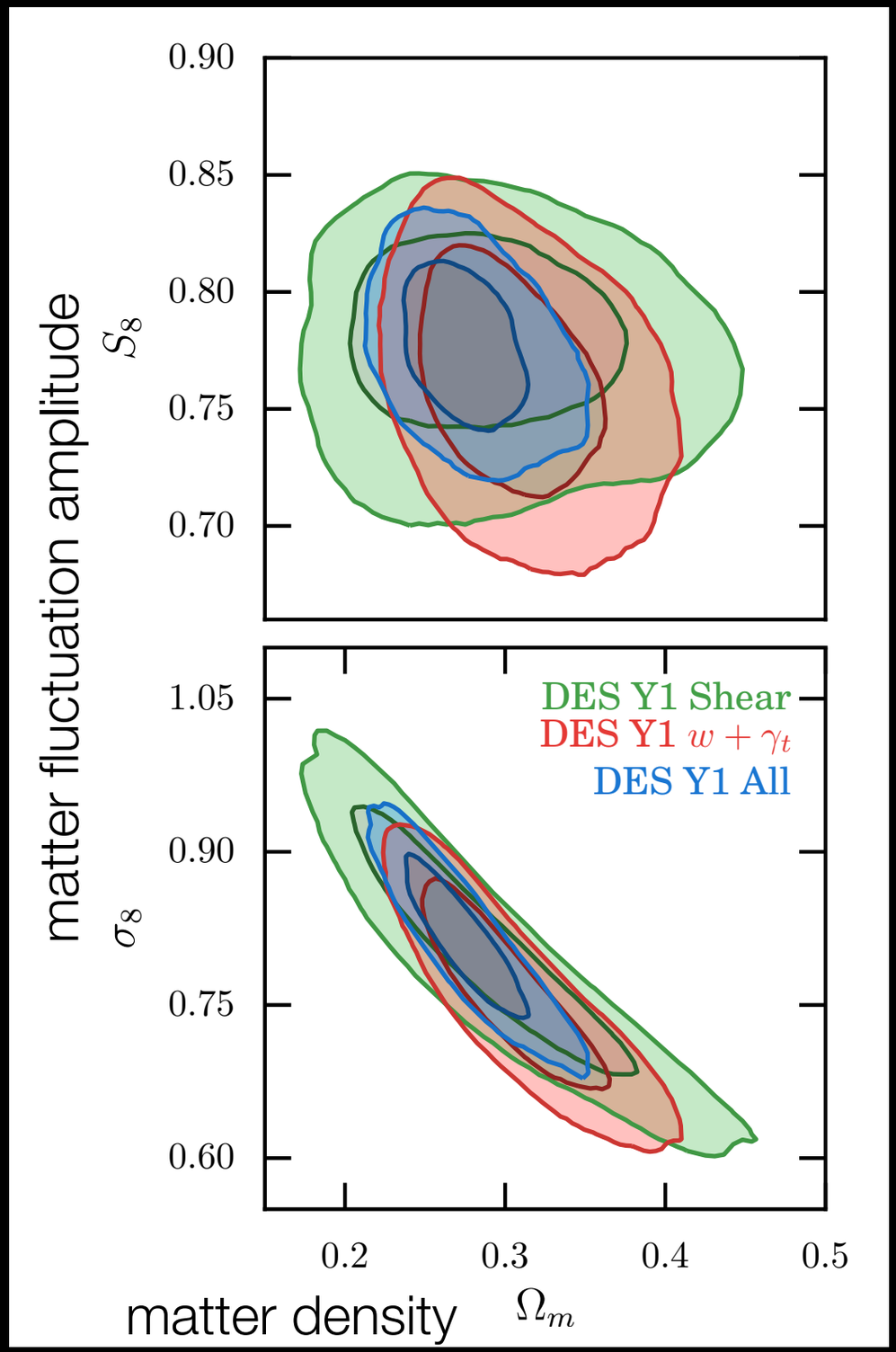
$\langle \kappa | \kappa \rangle = \xi_{\rm mm} \sim \sigma_8^2$



Troxel+ 2018

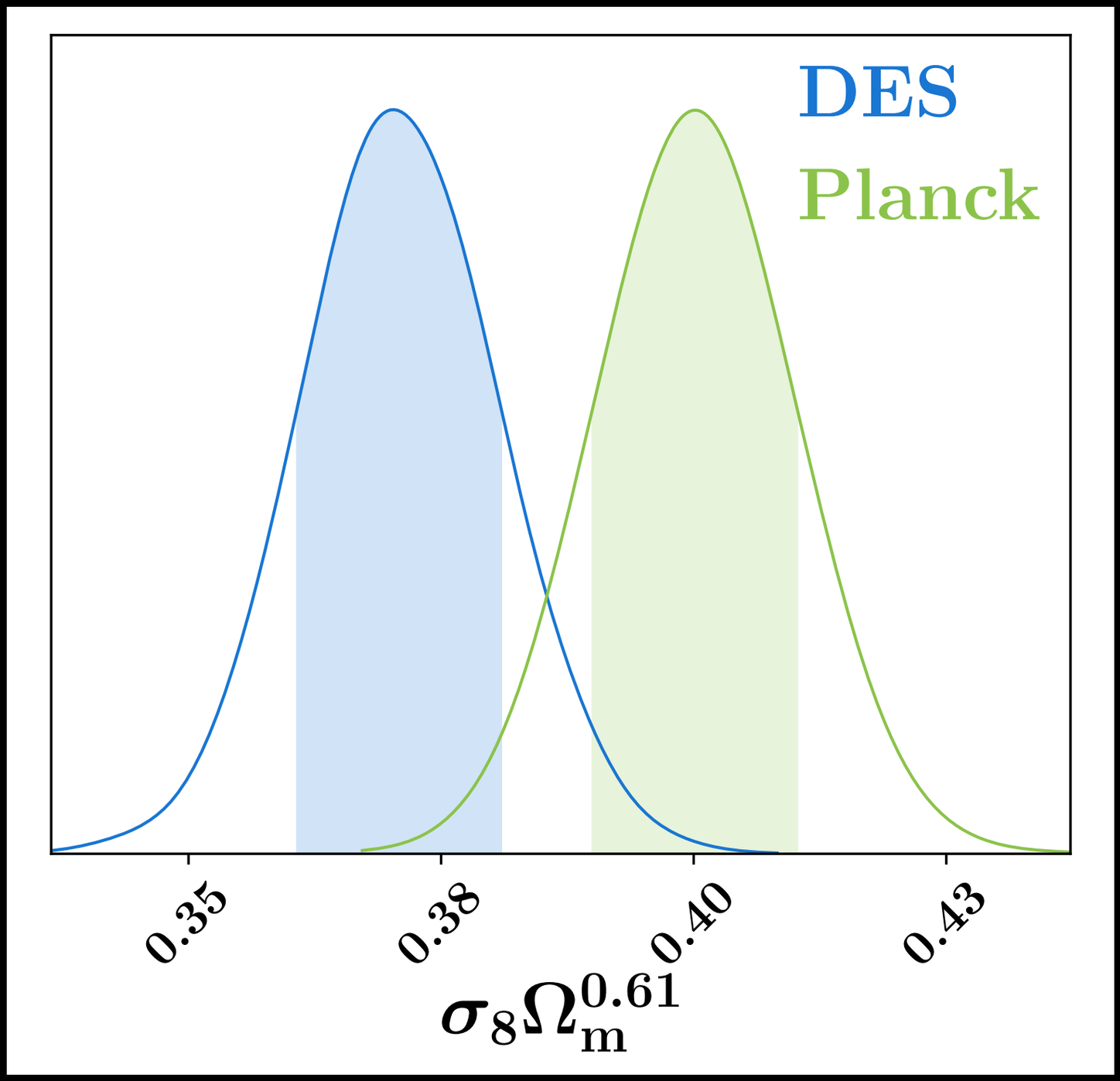
"3x2 analysis"

Matter fluctuations



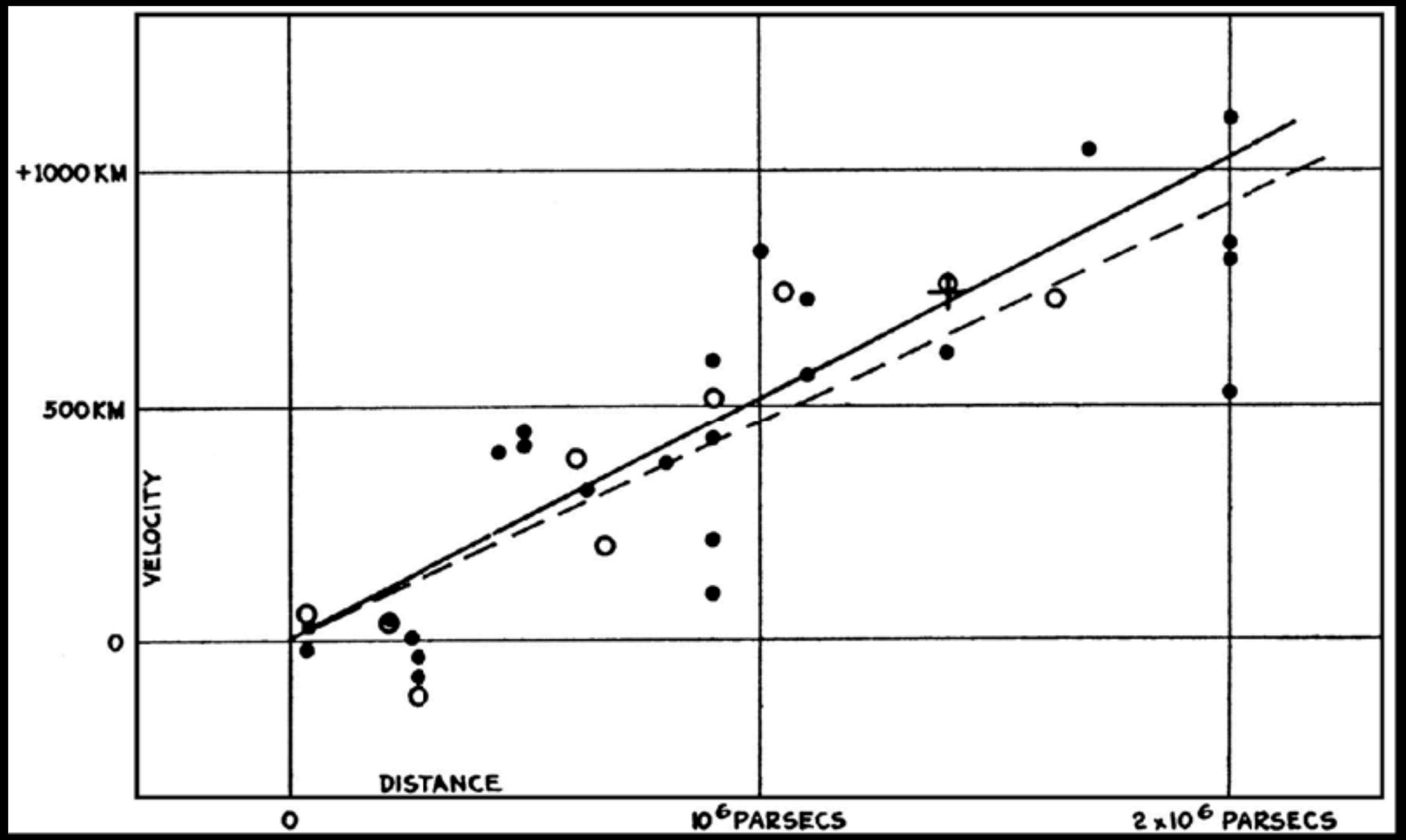
DES Collaboration 2018

Consistency?



Park & Rozo 2019

Hubble Constant

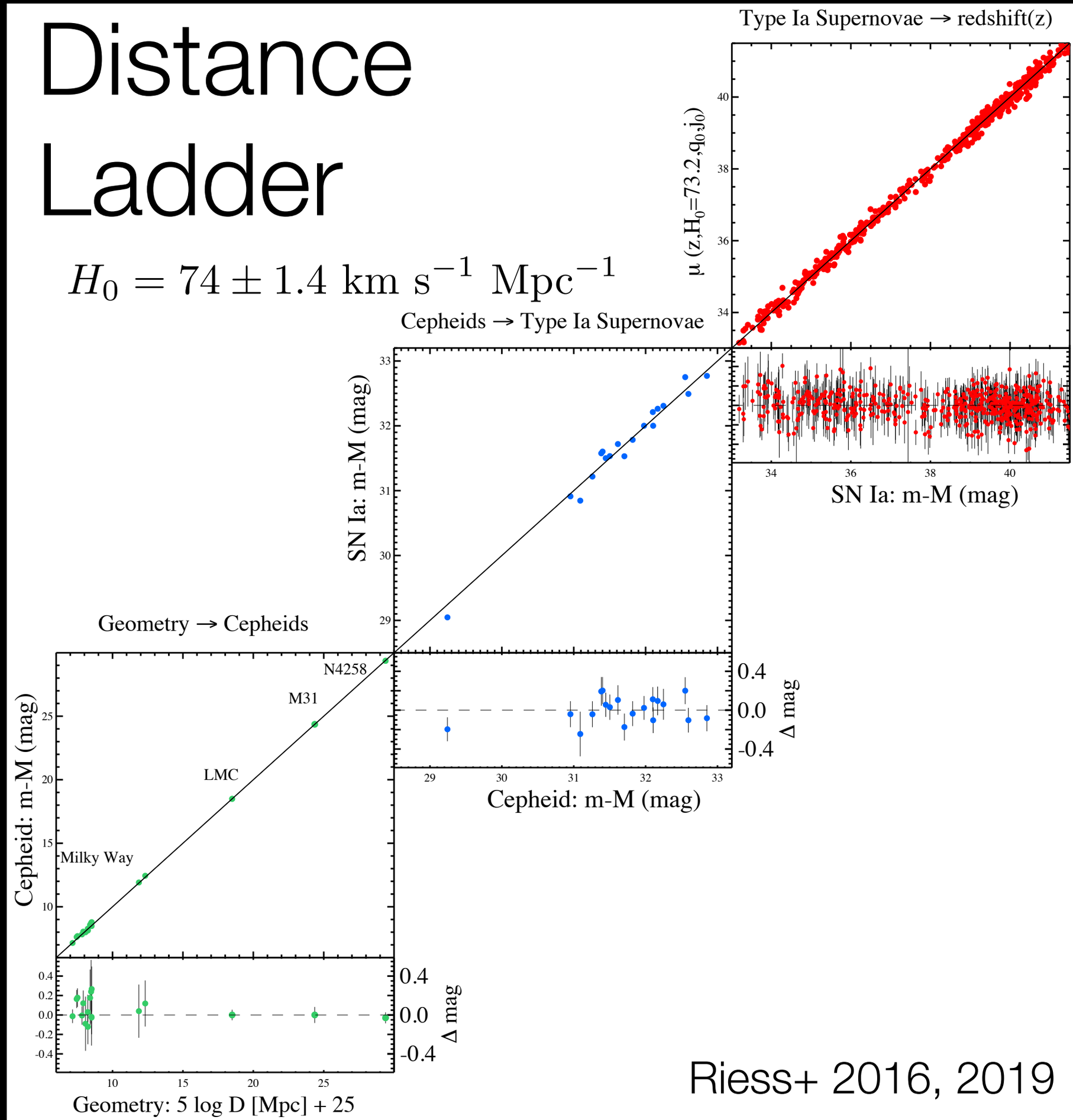


Hubble 1929

$$t_H = 1/H_0$$

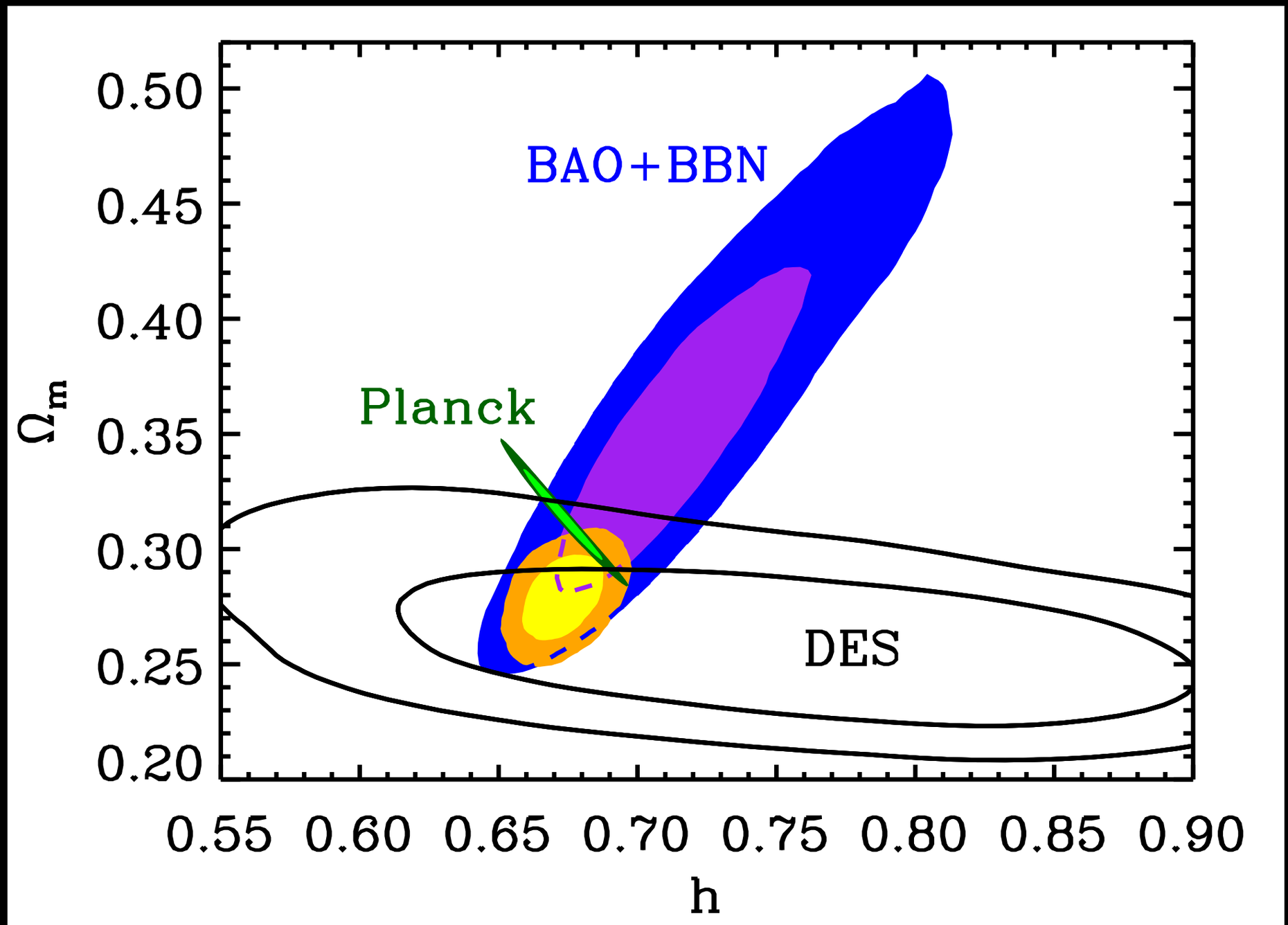
Distance Ladder

$$H_0 = 74 \pm 1.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$$



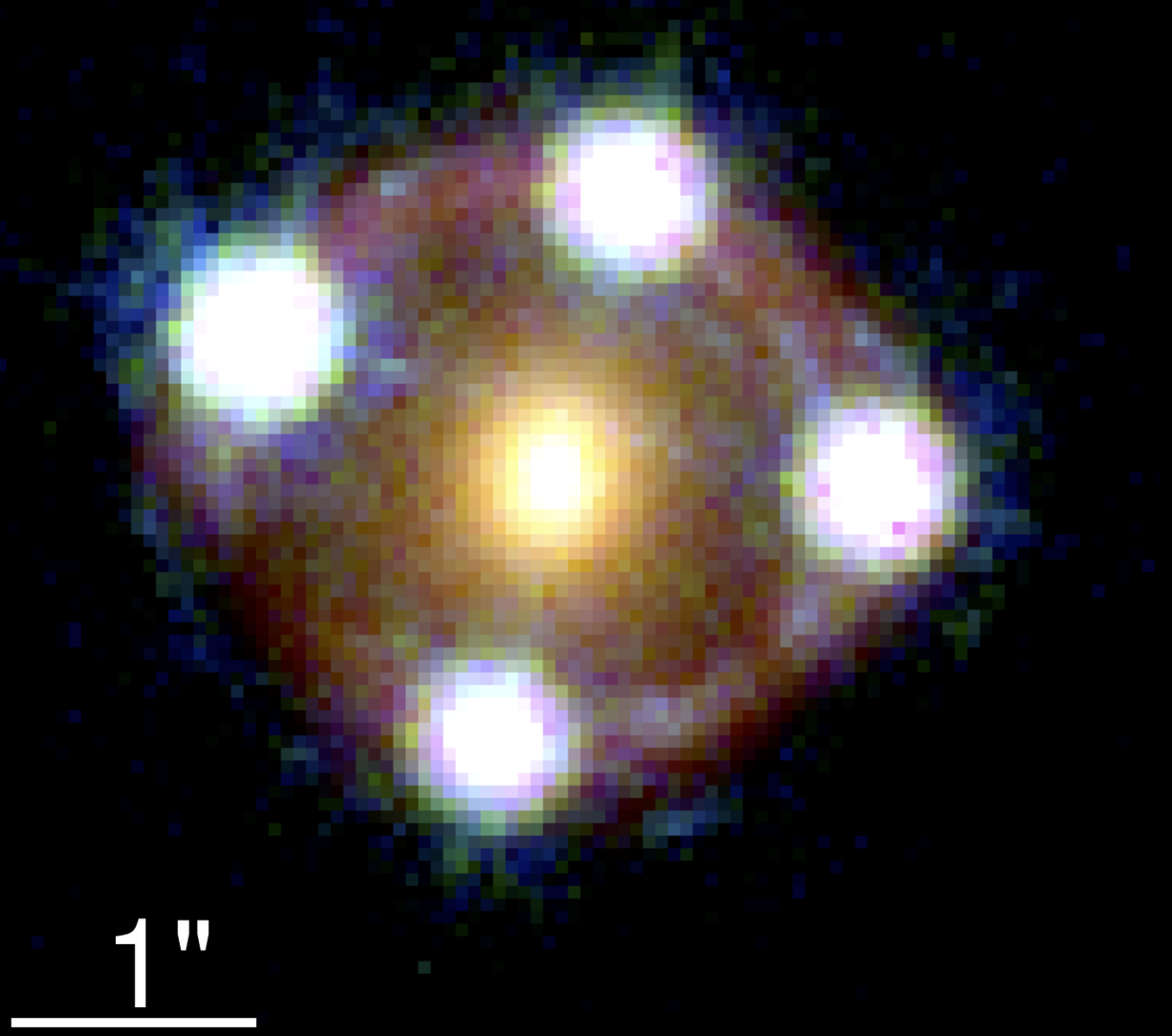
Riess+ 2016, 2019

Sound Horizon



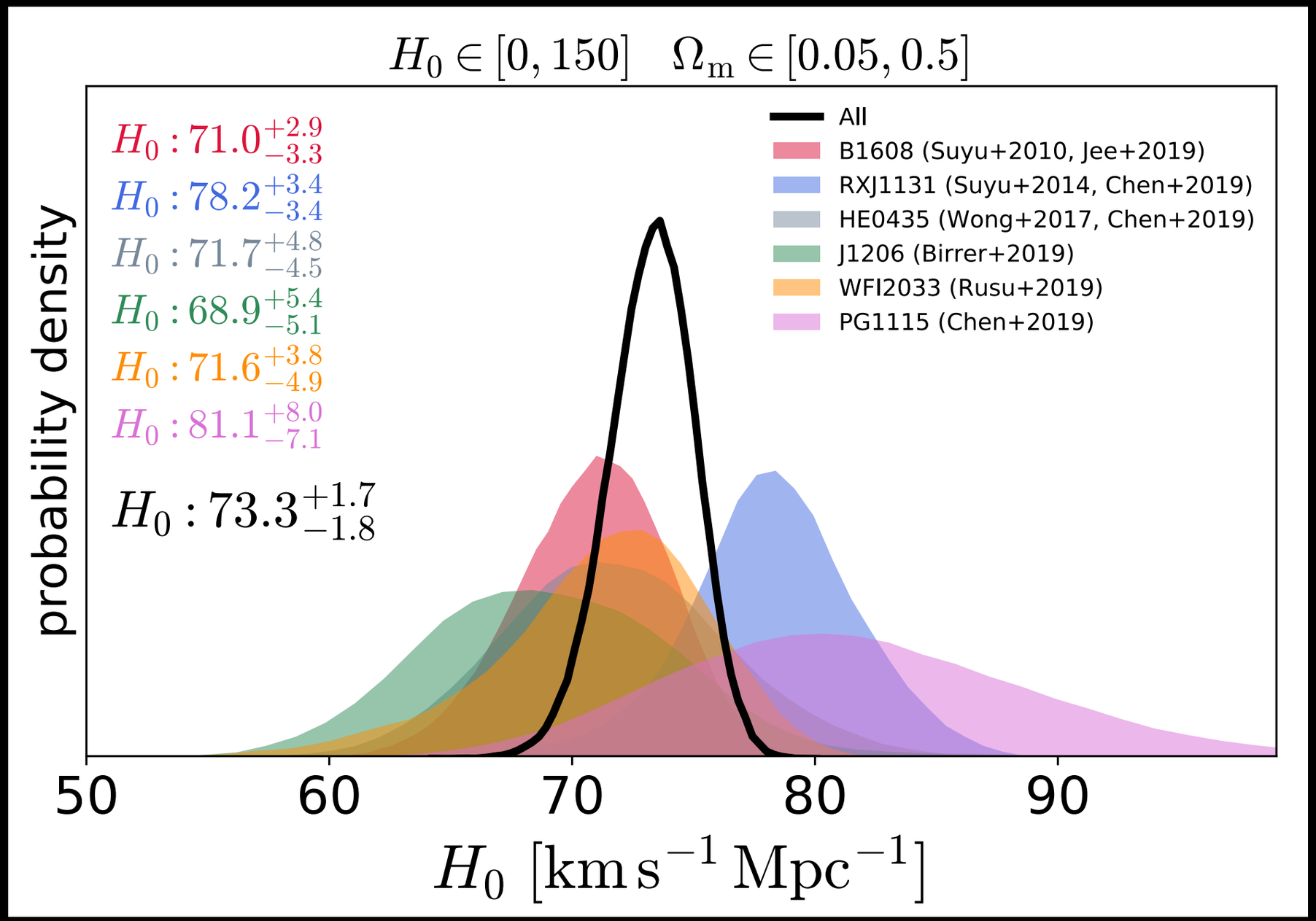
DES Collaboration 2018

Lensing time delays



Wong+ 2019 (H0LiCOW)

Lensing time delays



Wong+ 2019 (H0LiCOW)

“Tensions between the Early and the Late Universe”

Verde+ 2019

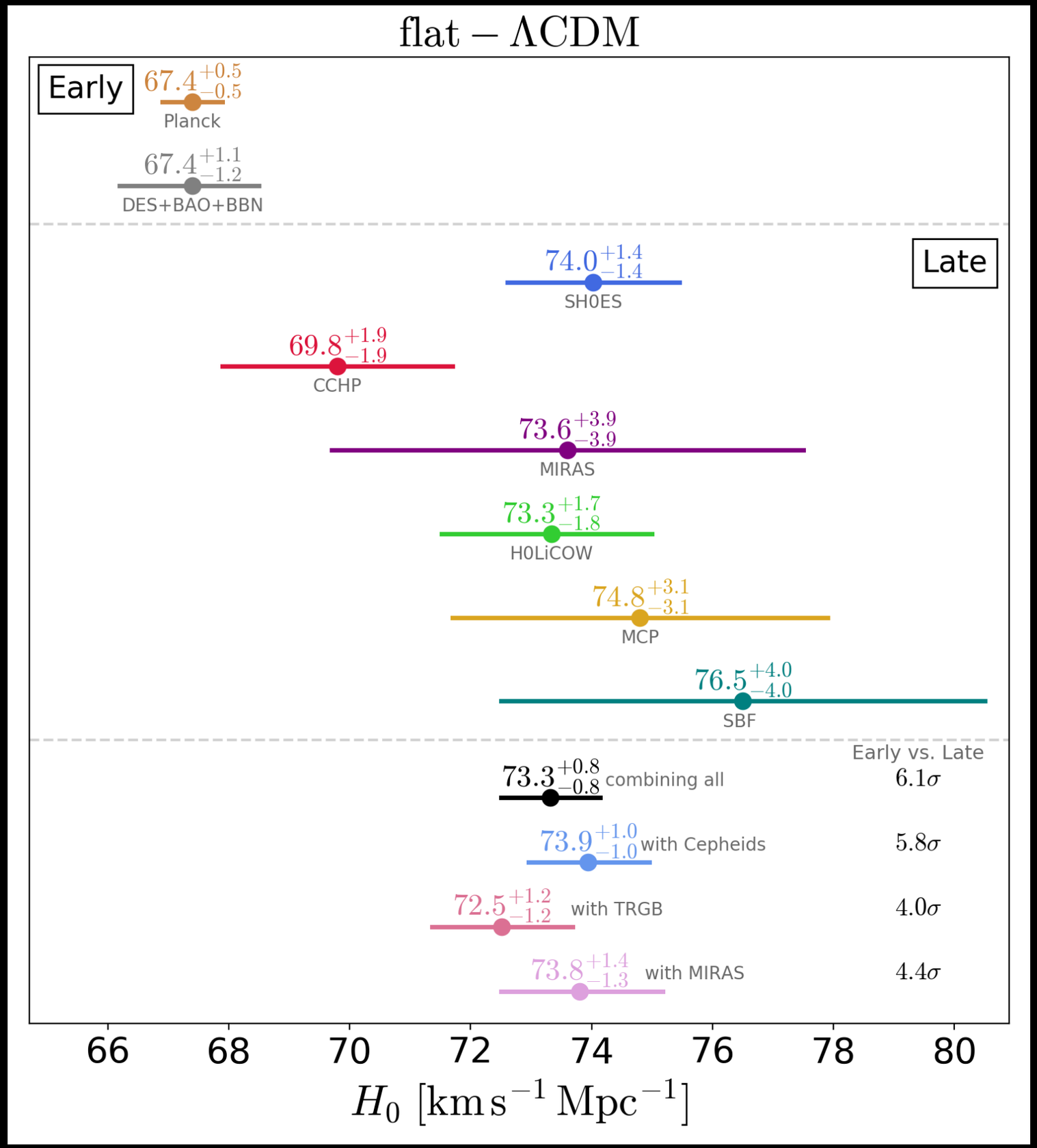


Fig: V. Bonvin

“Tensions between the Early and the Late Universe”

Verde+ 2019

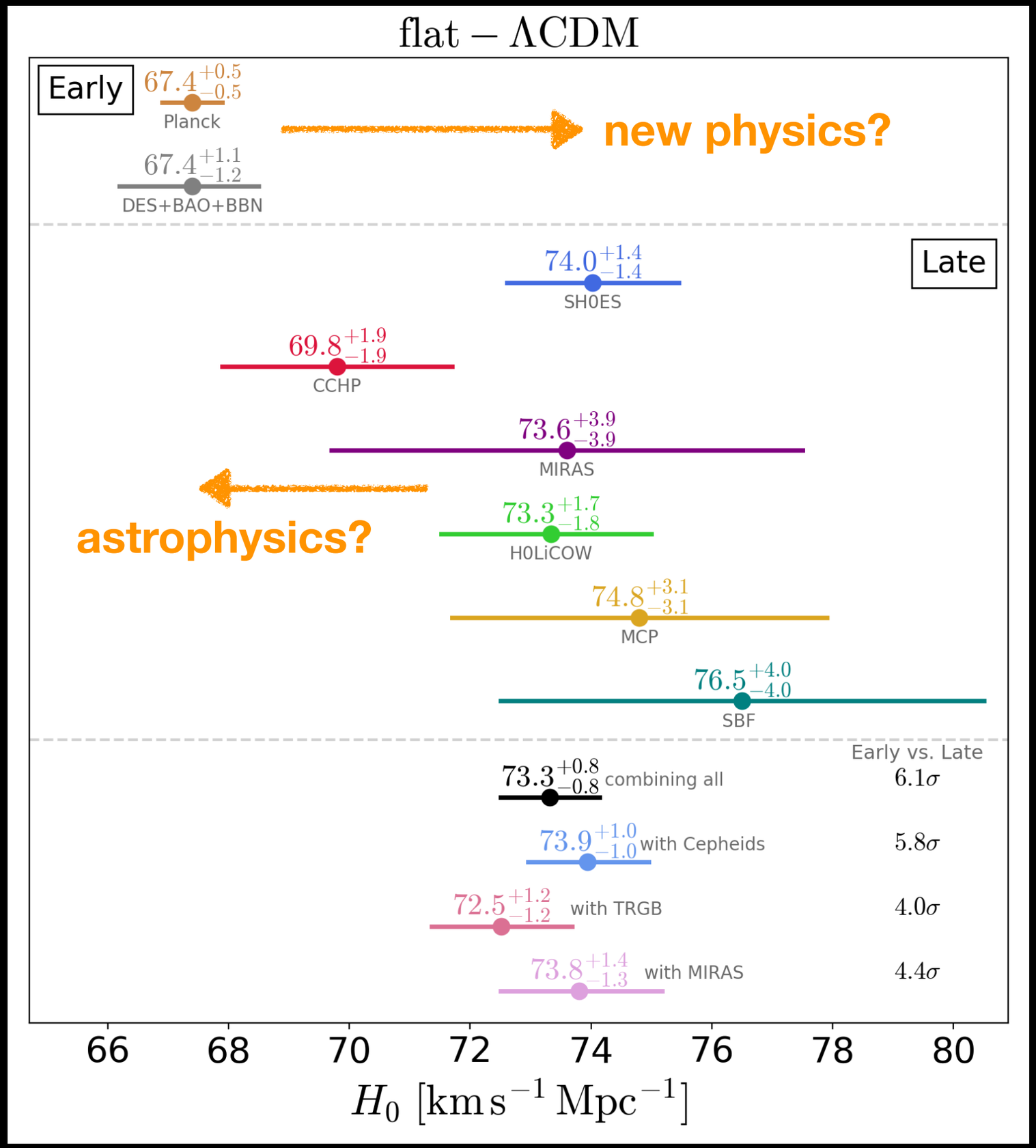
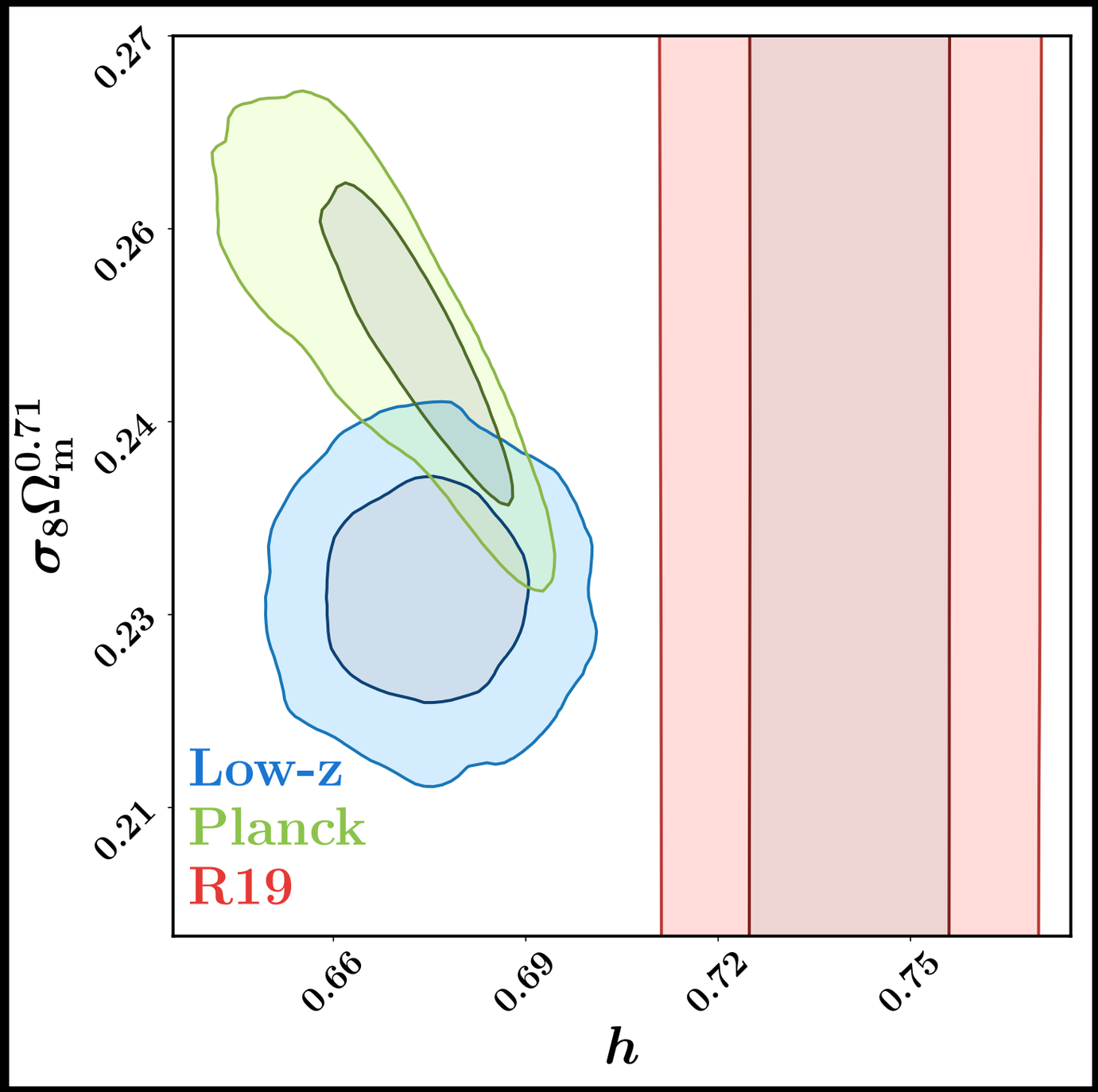


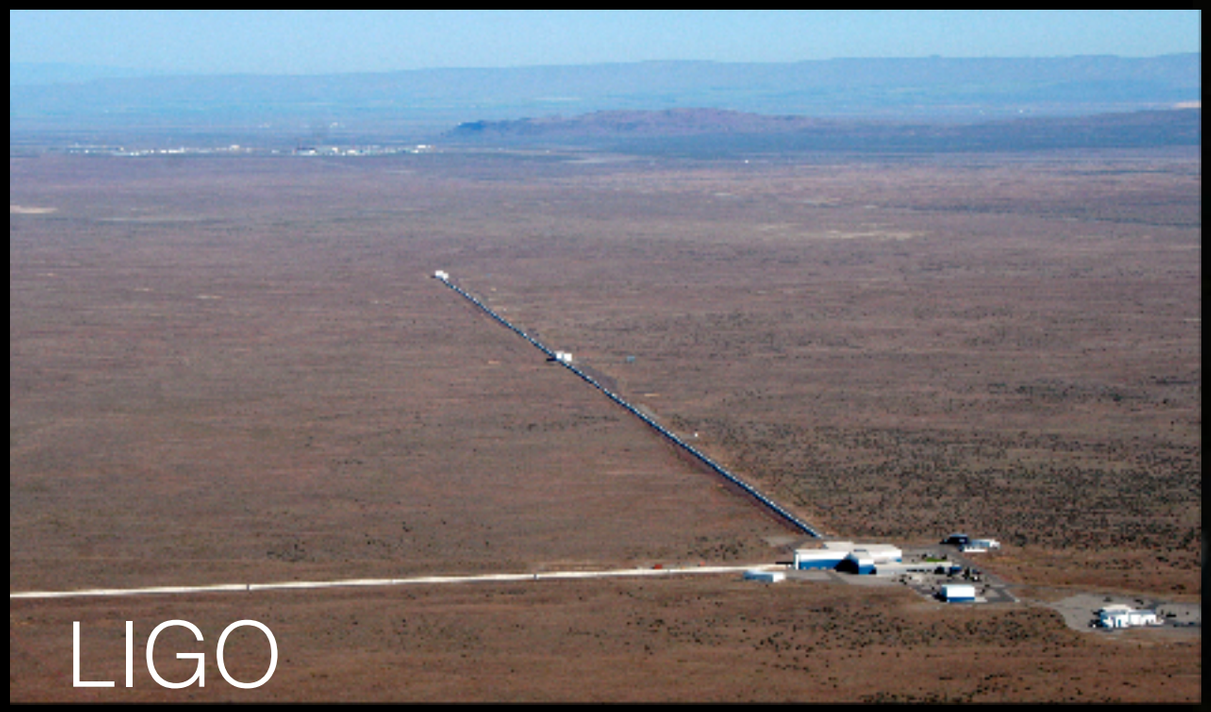
Fig: V. Bonvin

Concordance Cosmology?

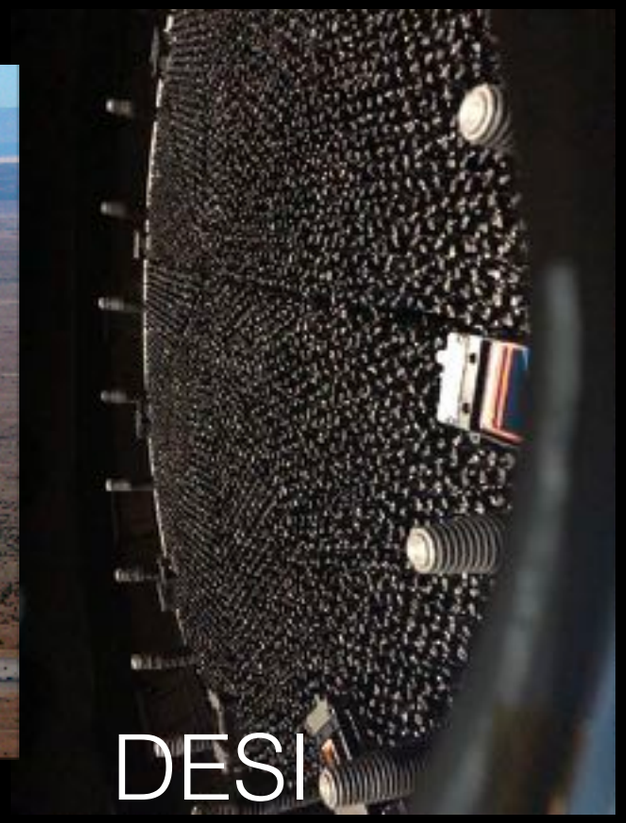


Park & Rozo 2019

What's next?

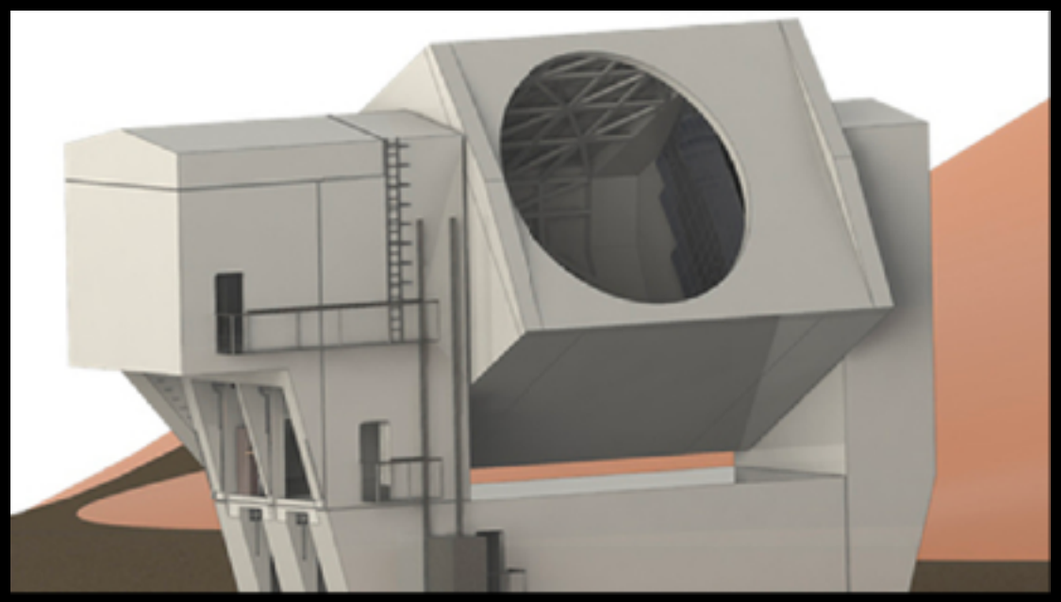


LIGO



DESI

Euclid, WFIRST



Simons Obs, CMB-S4

LSST (VRST?)

Summary

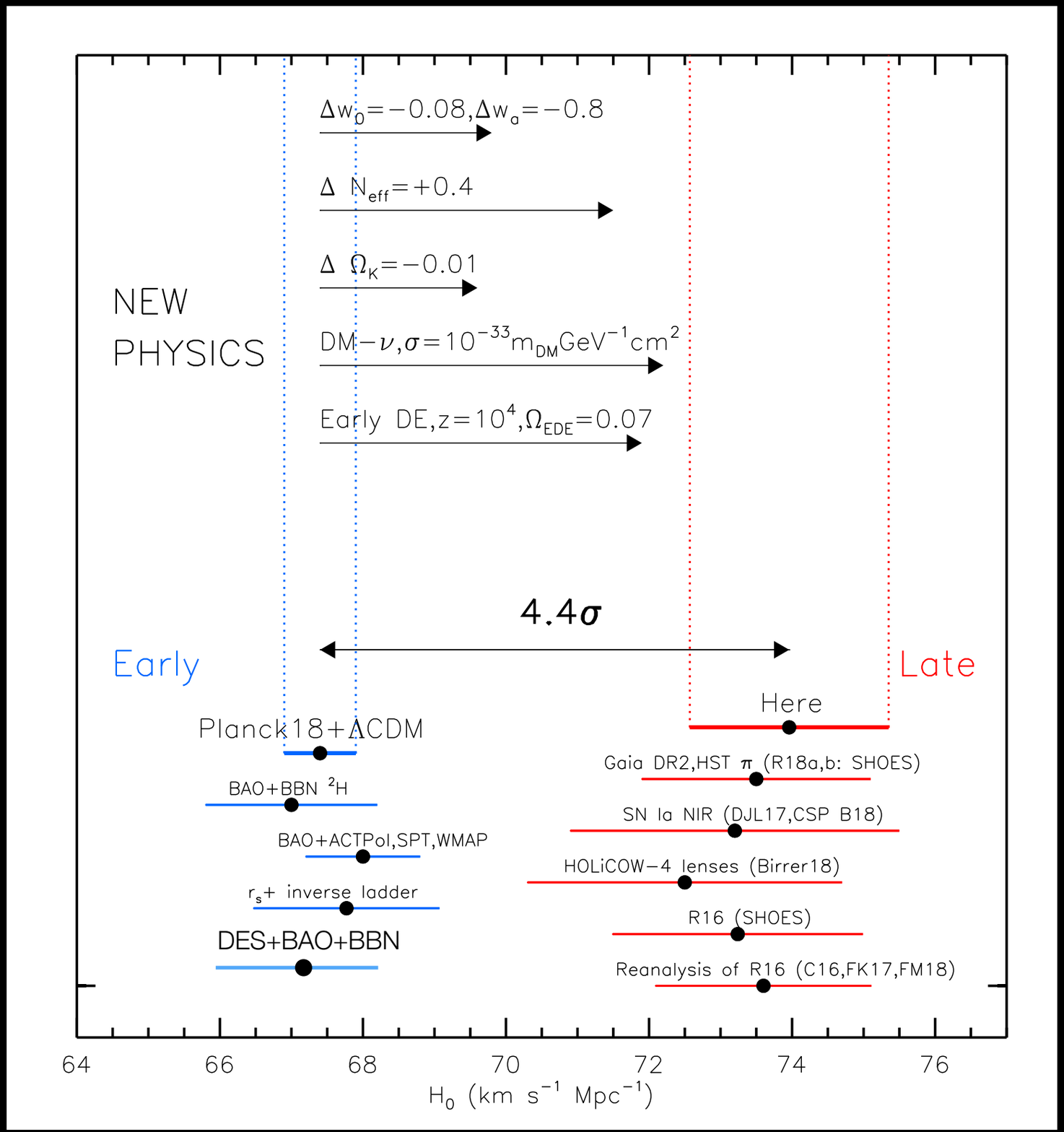
Combining and comparing multiple probes provides the most powerful tests of the cosmological model

Tensions in the expansion rate (H_0) and matter fluctuations (S_8) hint at potential new physics

The future is bright…

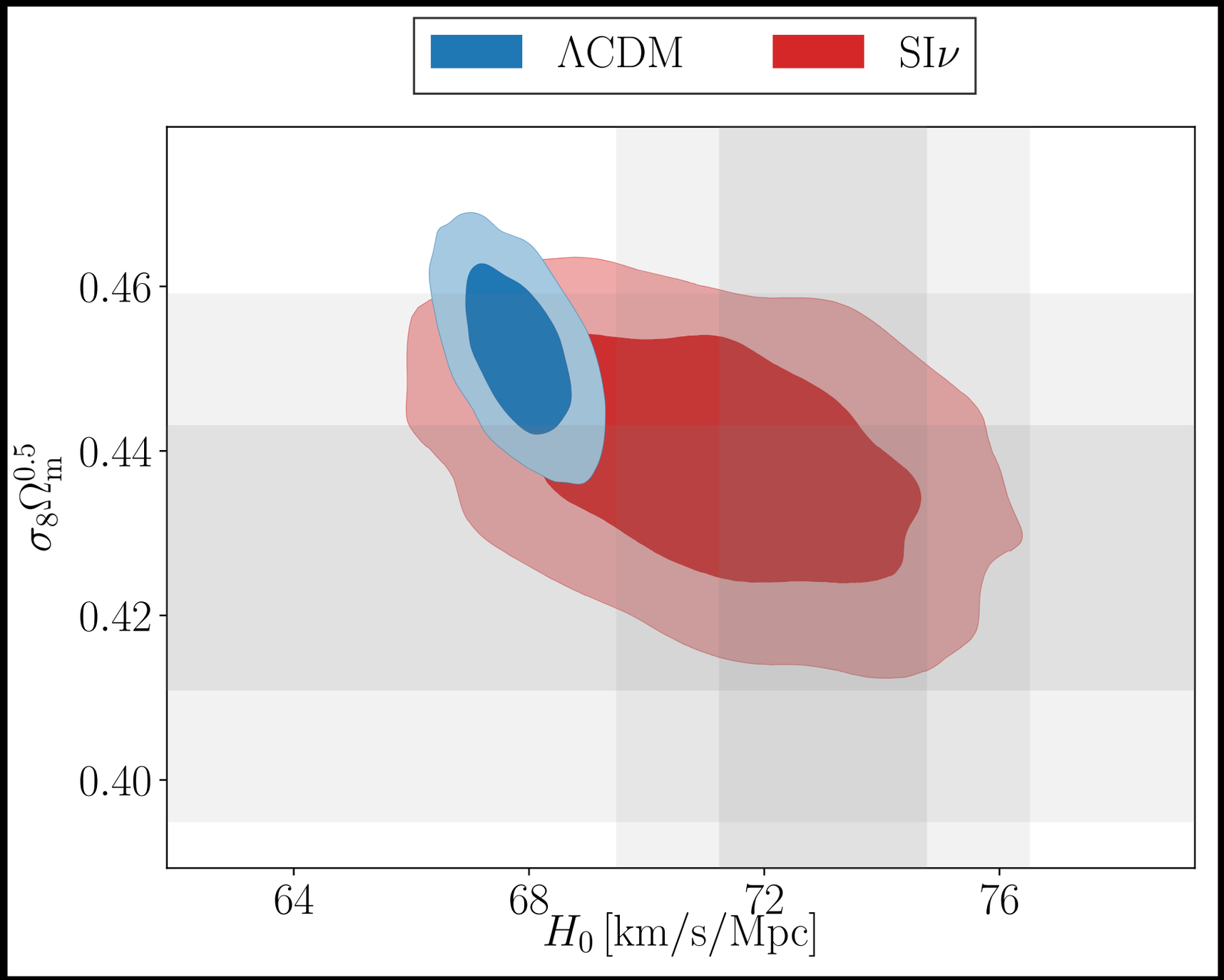
Extra slides

H_0 tension: new physics?



Riess+ 2019

Self-interacting neutrinos?



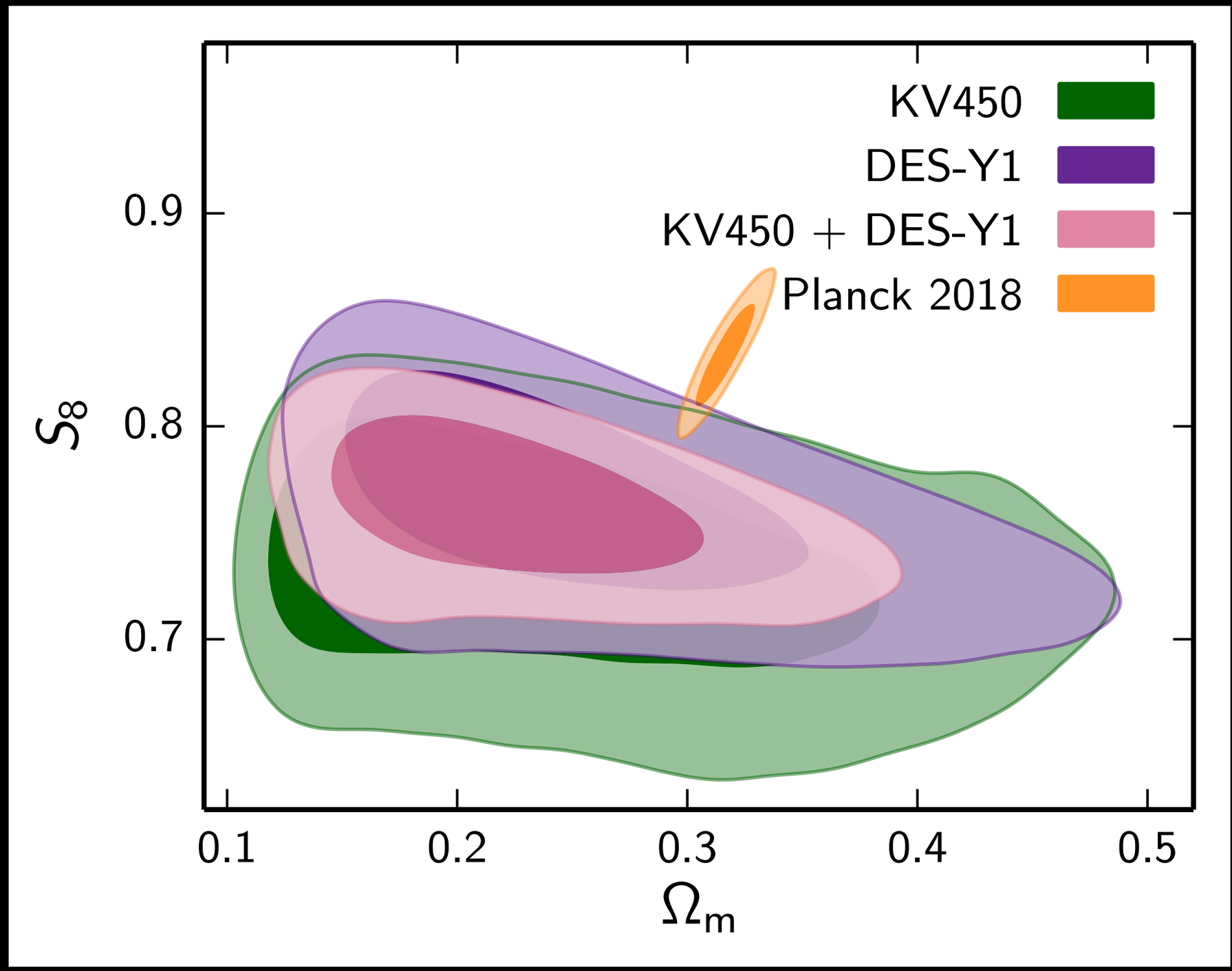
Kreisch+ 2019

Modeling and inference

$$L\left(\mathbf{D}|\mathbf{p}\right) \propto \exp\left(-\frac{1}{2}\left[\left(\mathbf{D}-\mathbf{M}(\mathbf{p})\right)^{T}\mathbf{C}^{-1}\left(\mathbf{D}-\mathbf{M}(\mathbf{p})\right)\right]\right)$$

- Cosmological signal, including nonlinearities
- Observational effects: shear measurement, atmosphere
- Astrophysics: “baryonic” effects, galaxy bias and alignments
- Full covariance (~450 data points)
- Blind analysis
- Modeling and methods: Krause+ 2017, MacCrann+ 2018, Blazek+ 2017, …

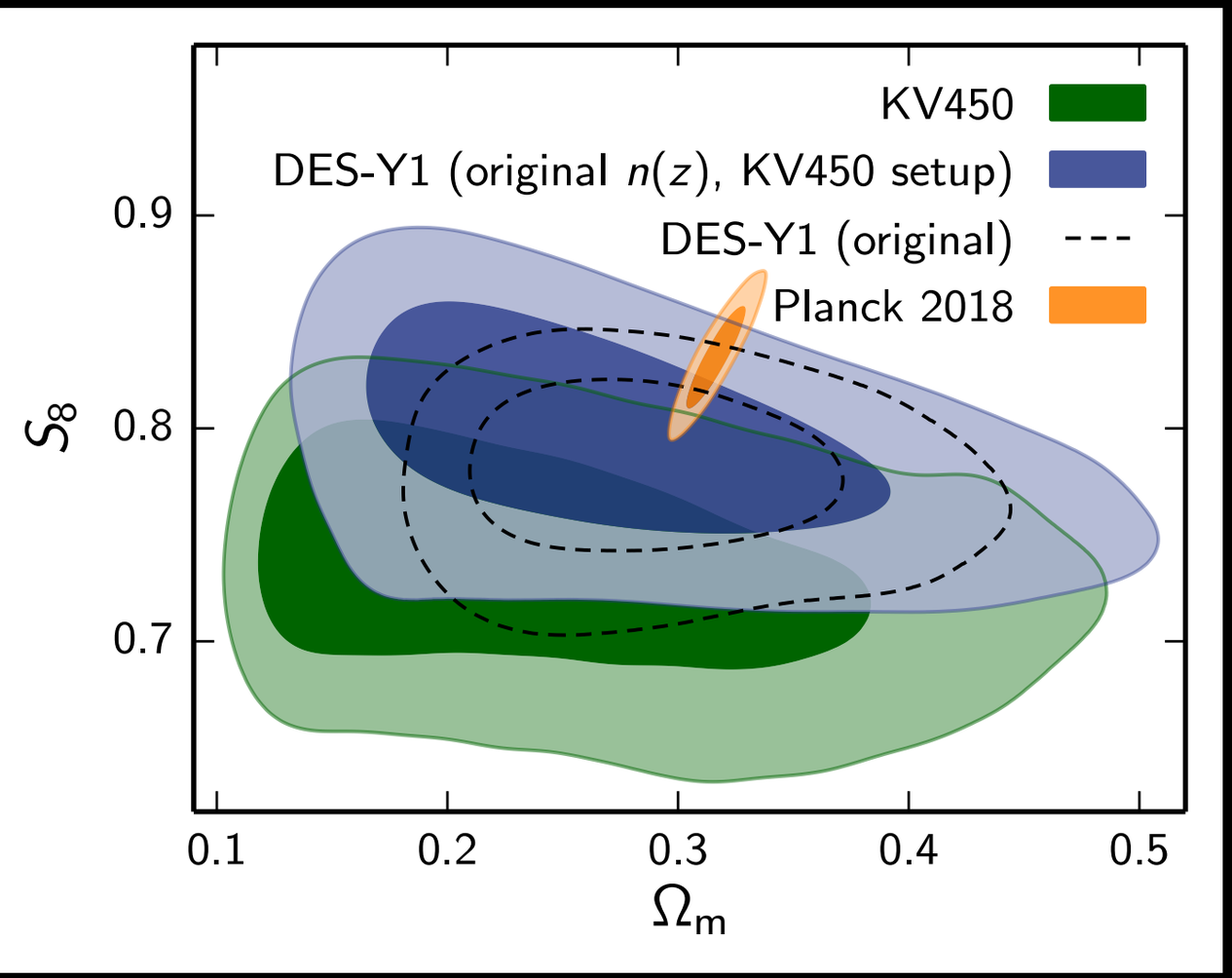
KiDS + DES weak lensing

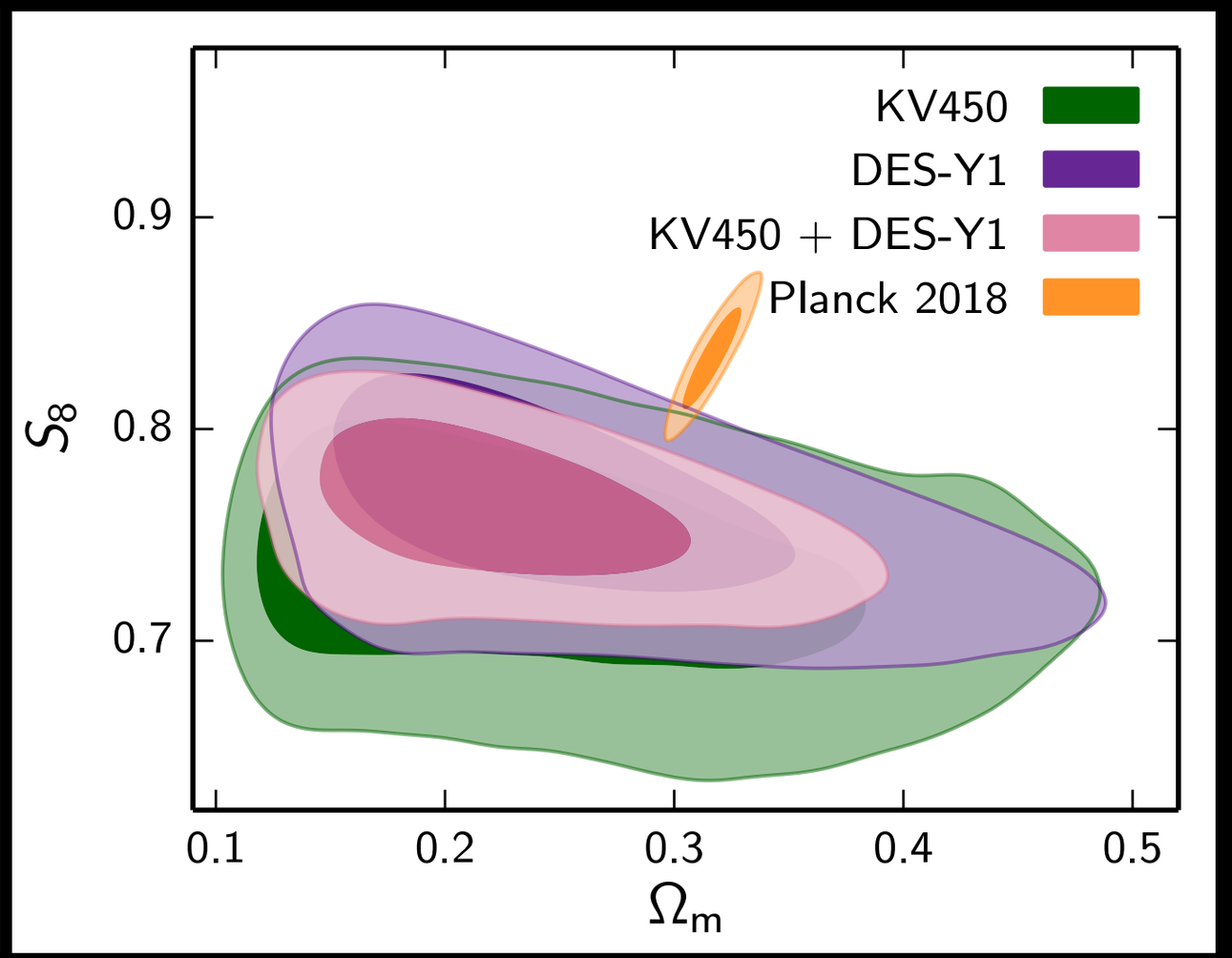


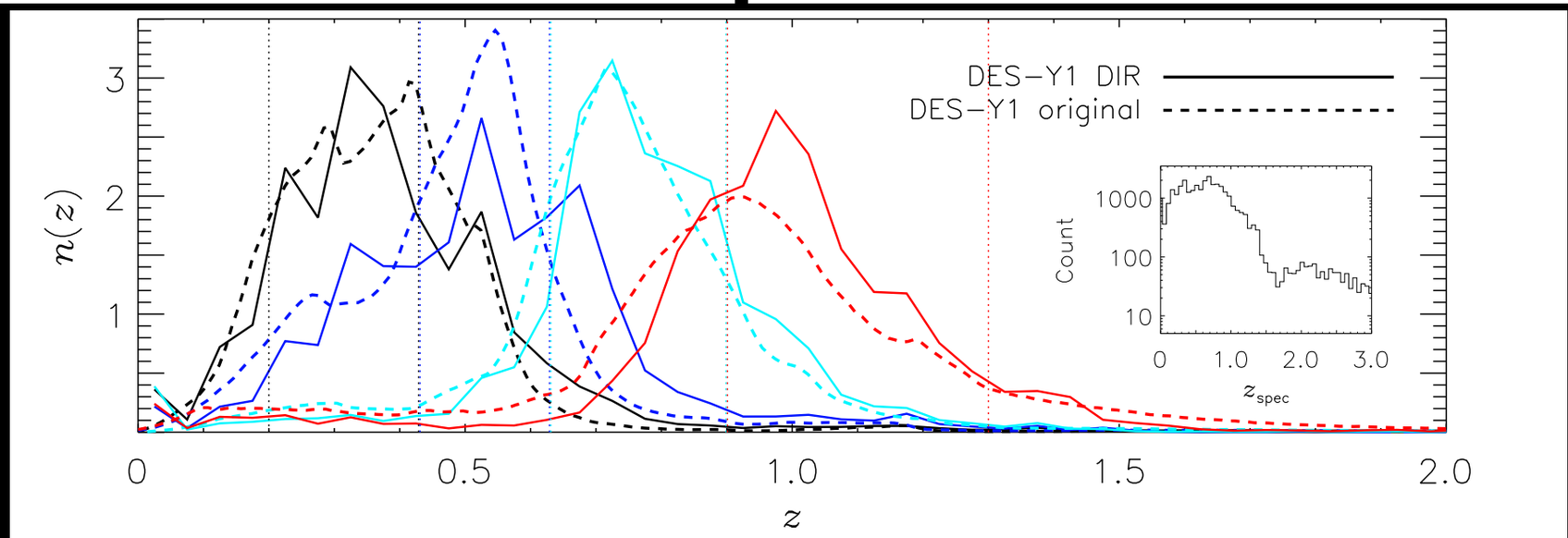
Joudaki+ 2019

KiDS +DES re-analysis

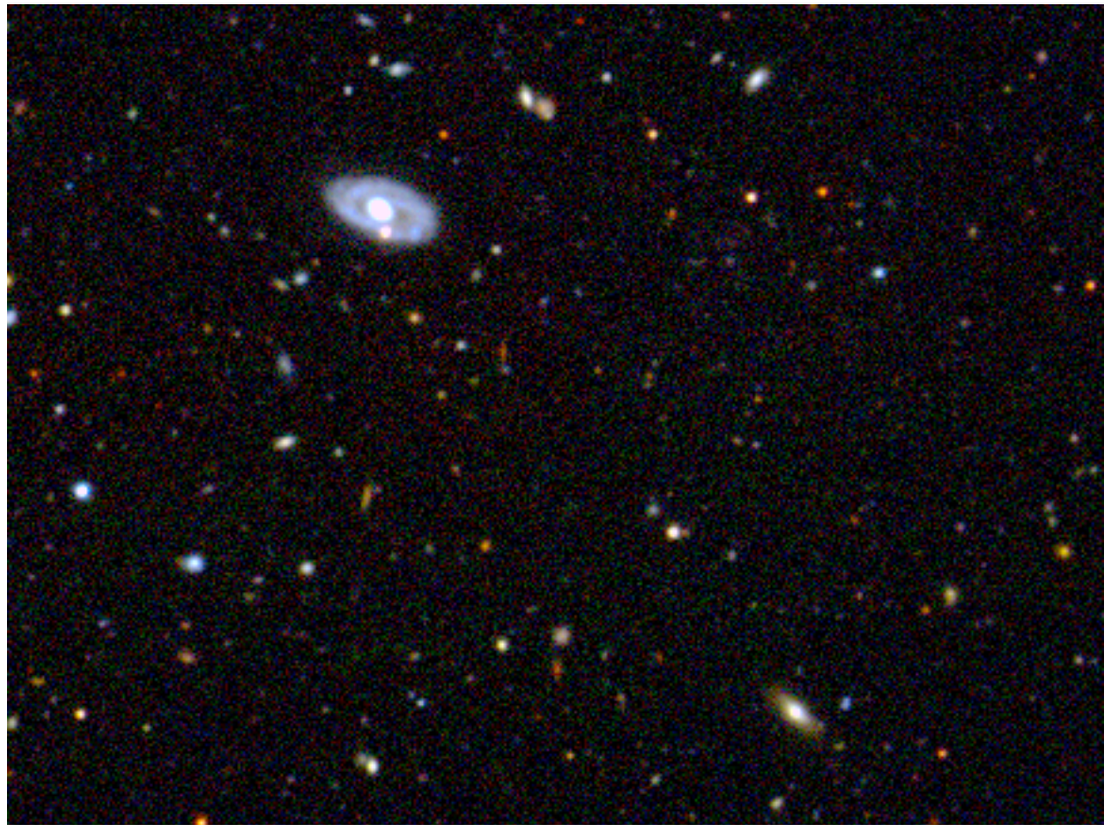
Joudaki+ 2019

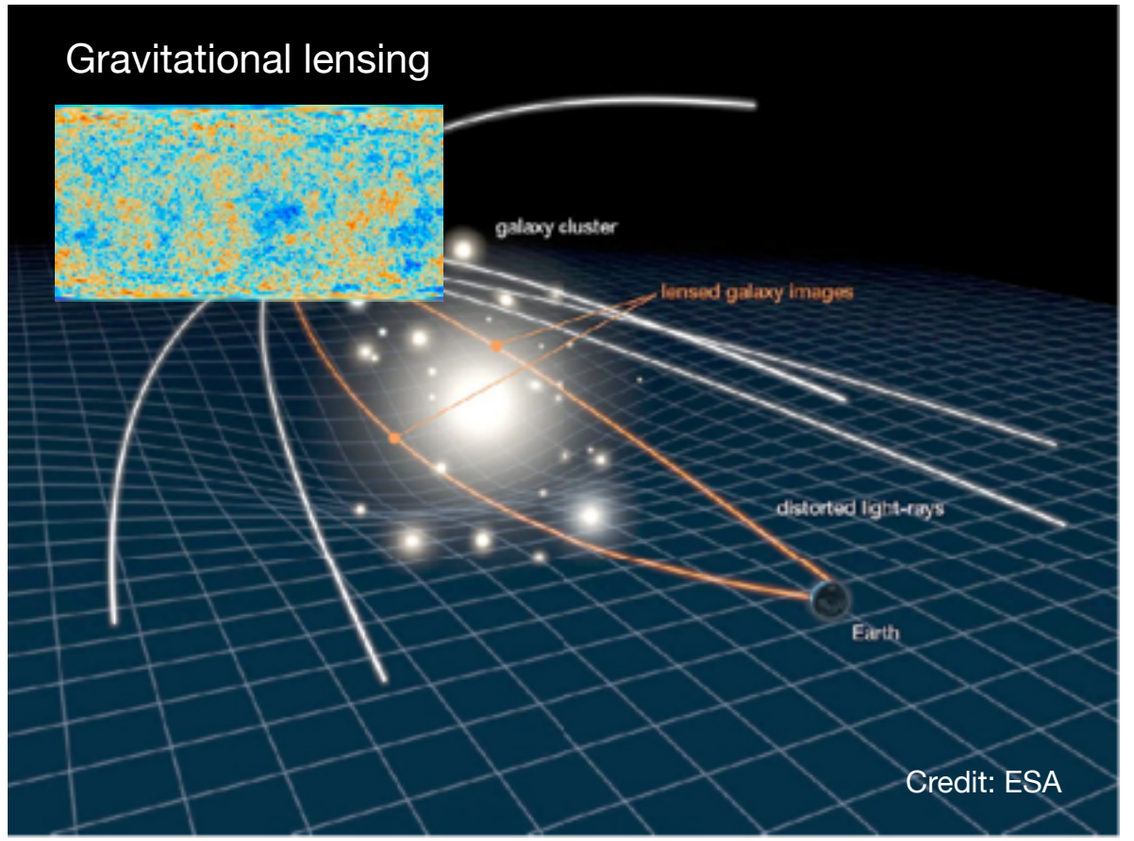


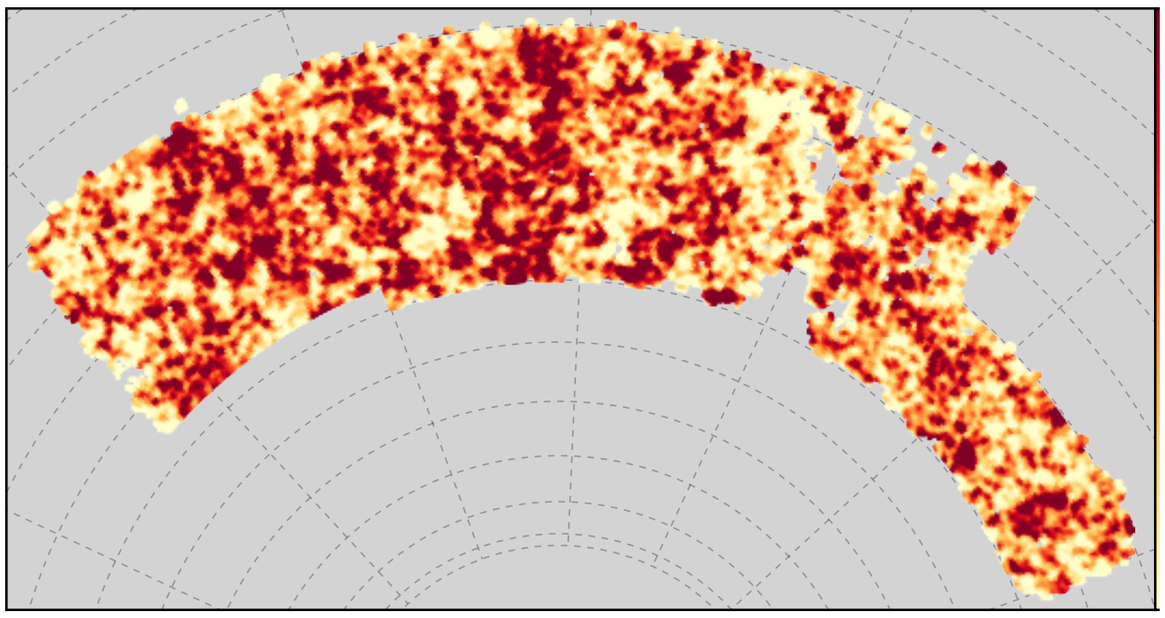


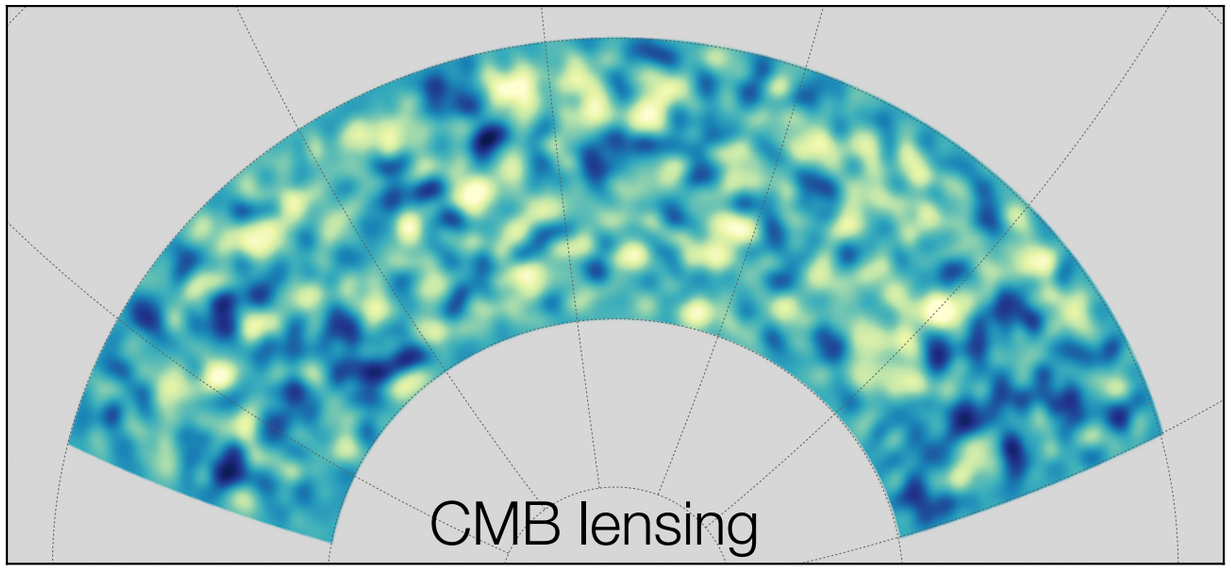


LSS/lensing observables



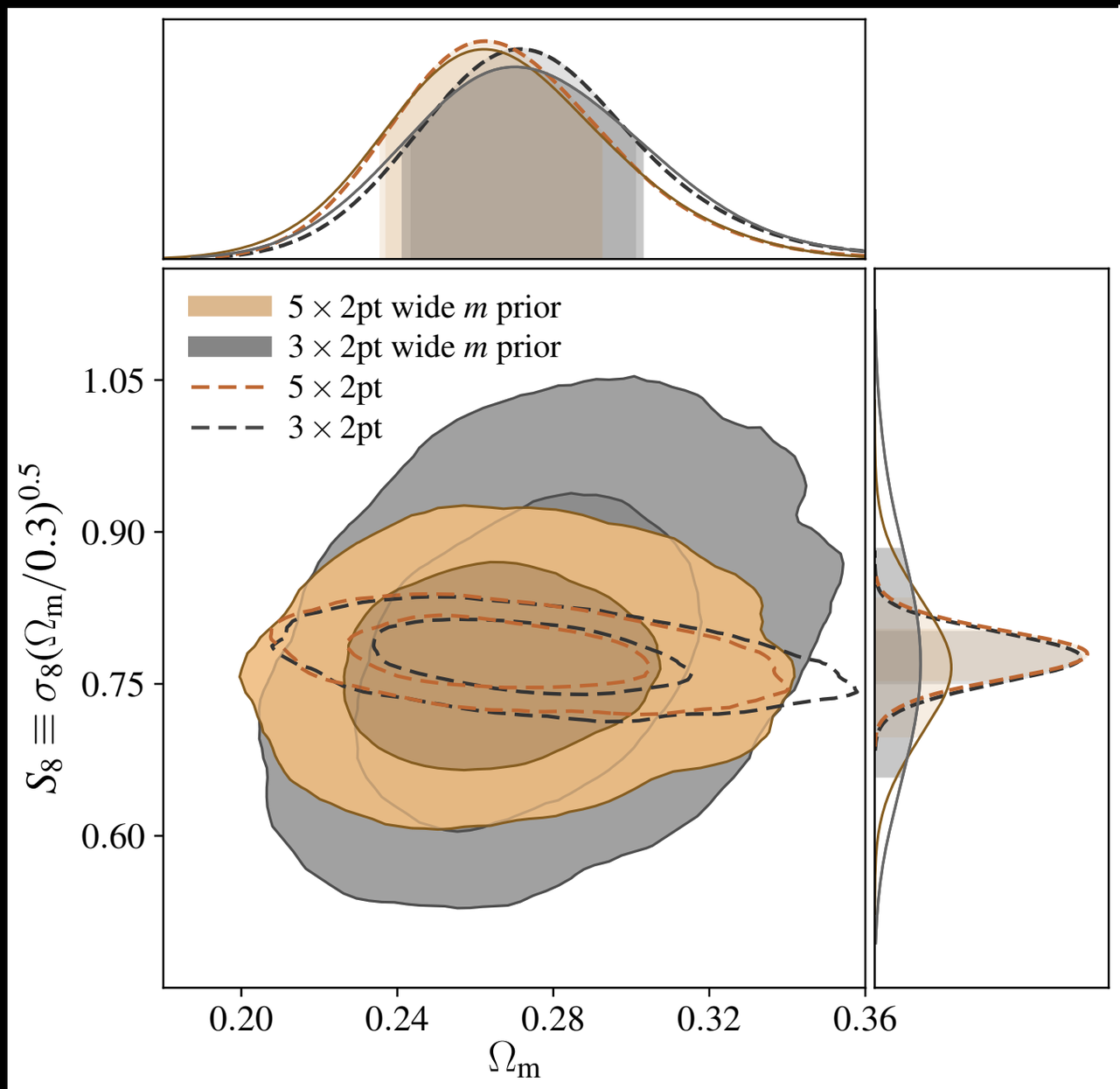


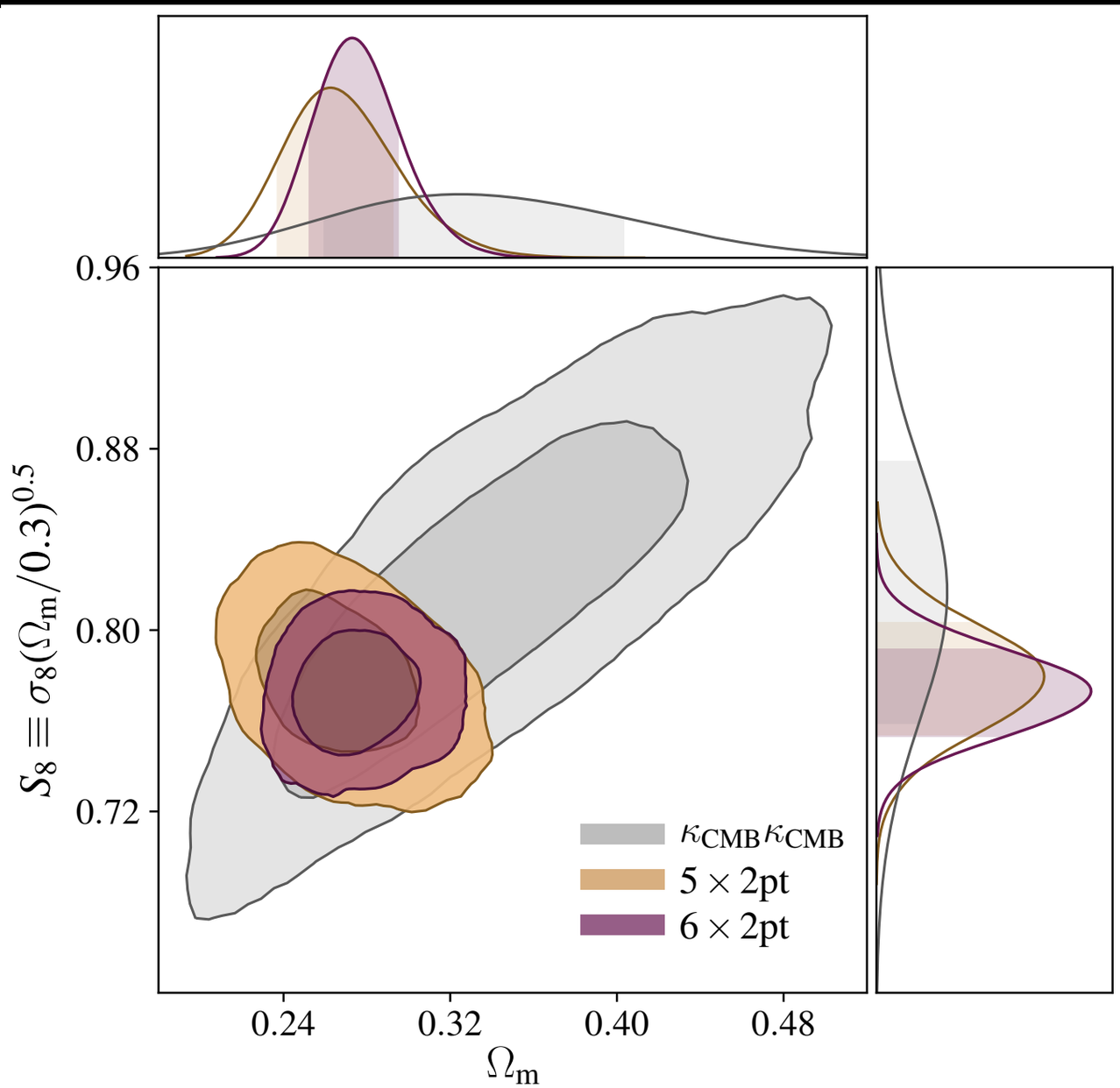




Omori+ 2018; DES+SPT 2018

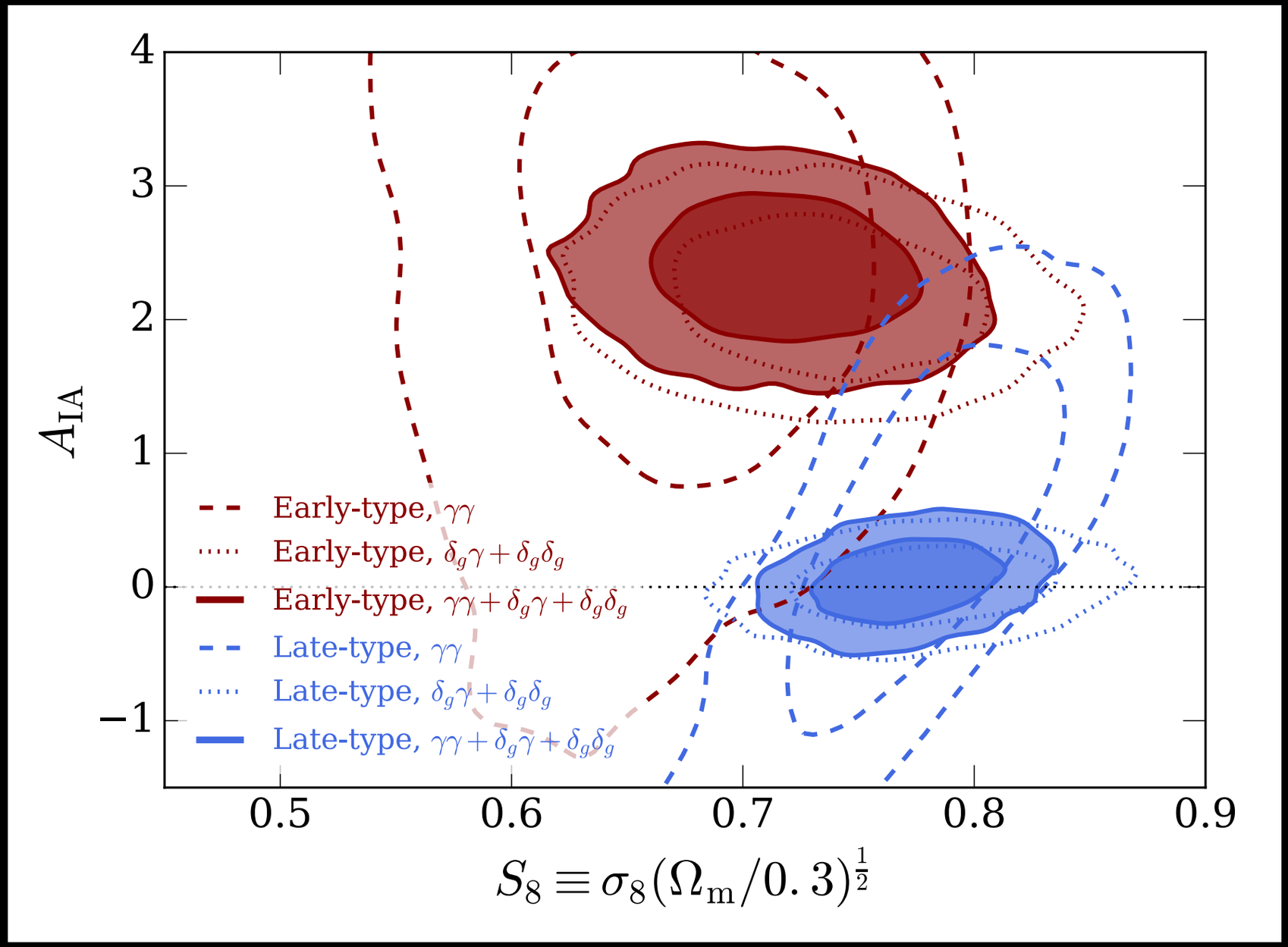
DES + SPT lensing





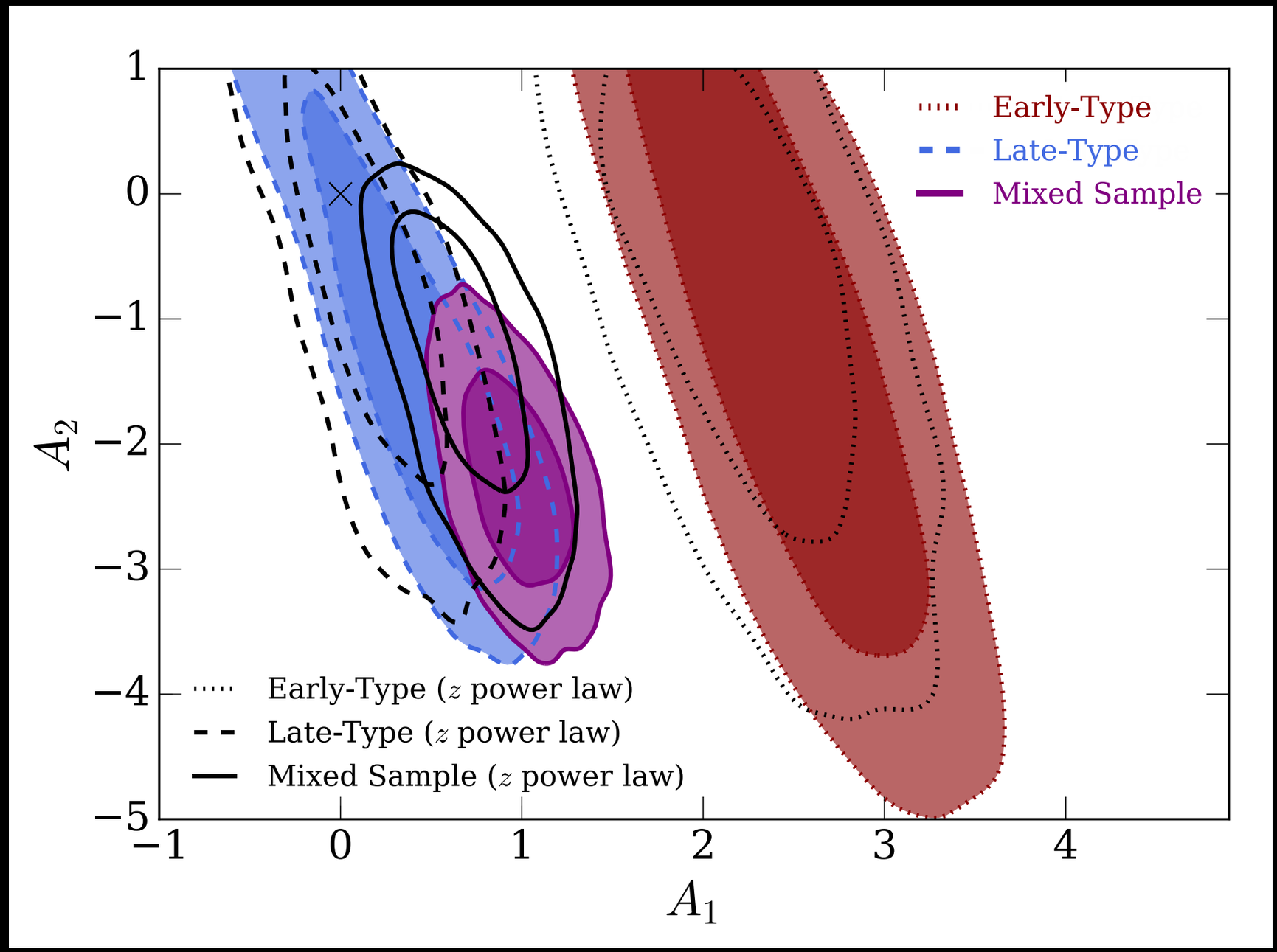
DES + SPT Collaborations 2018

Galaxy alignments



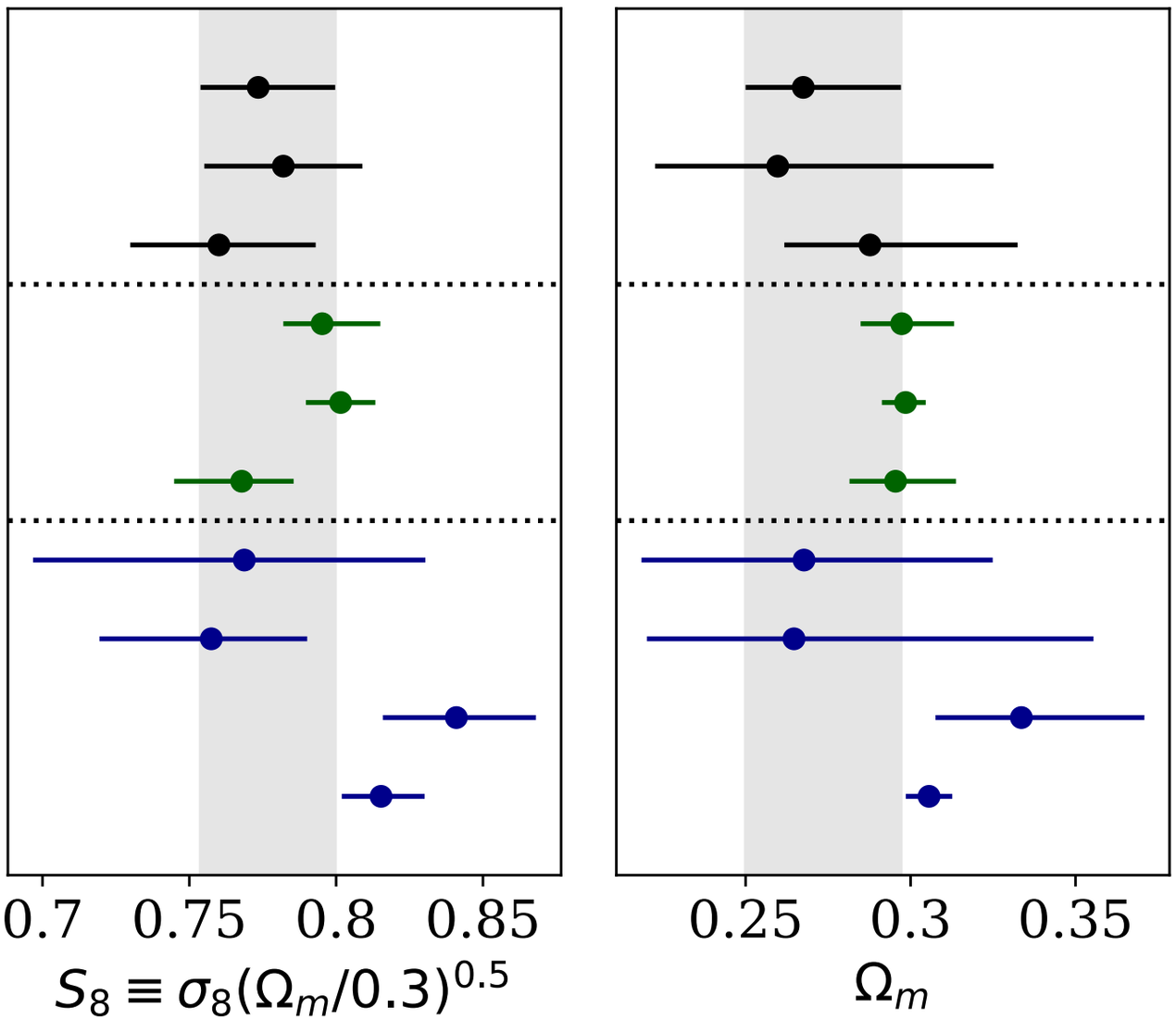
Blazek+ 2017; Samuroff, Blazek+ 2018 (DES Collaboration)

Galaxy alignments



Blazek+ 2017; Samuroff, Blazek+ 2018 (DES Collaboration)

Consistency?



DES Y1 All

DES Y1 Shear

DES Y1 $w + \gamma_t$

DES Y1 All + Planck (No Lensing)

DES Y1 All + Planck + BAO + JLA

DES Y1 All + BAO + JLA

DES SV

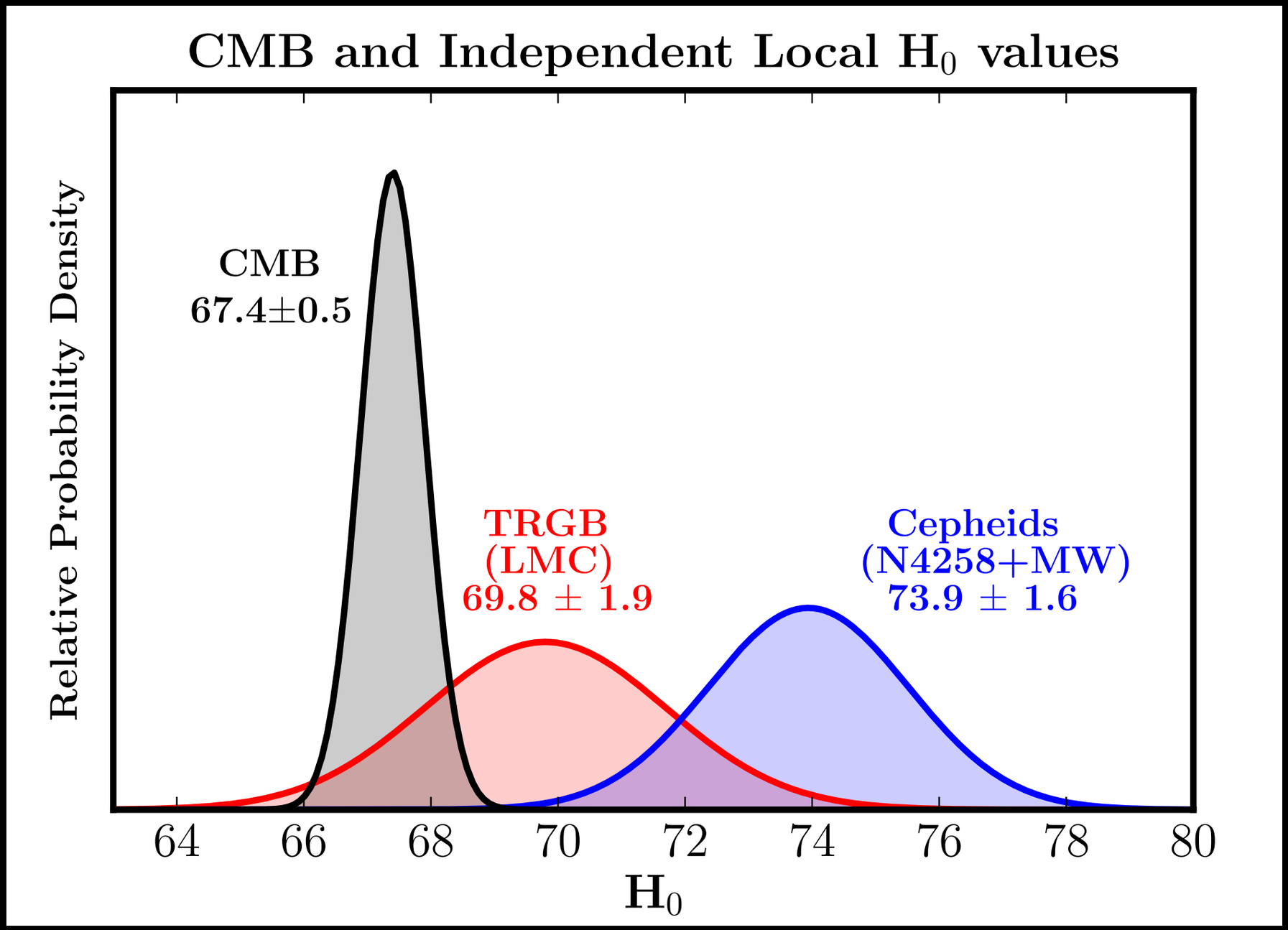
KiDS-450

Planck (No Lensing)

Planck + BAO + JLA

DES Collaboration 2018

H_0 tension



Freedman+ 2019

What's next?

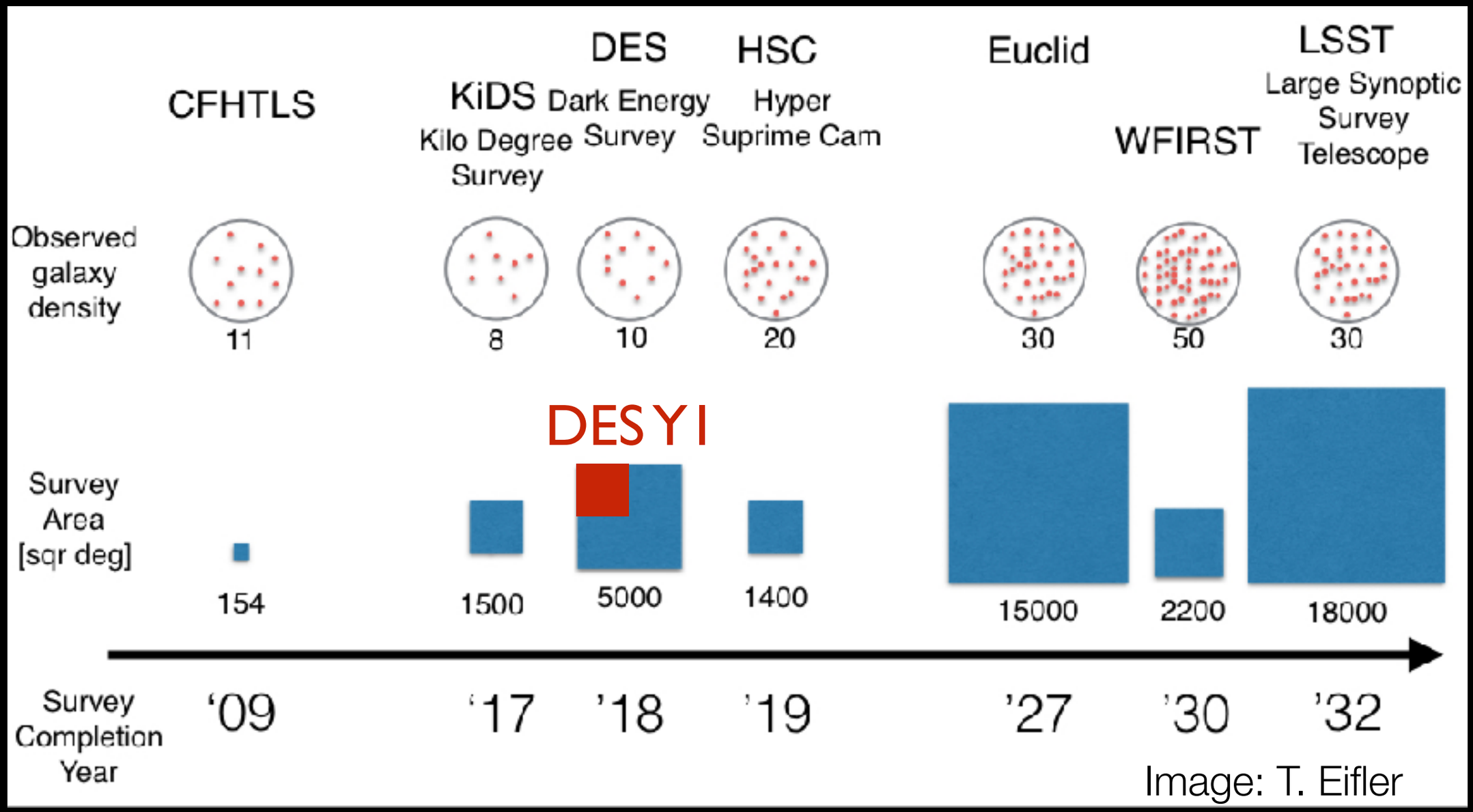
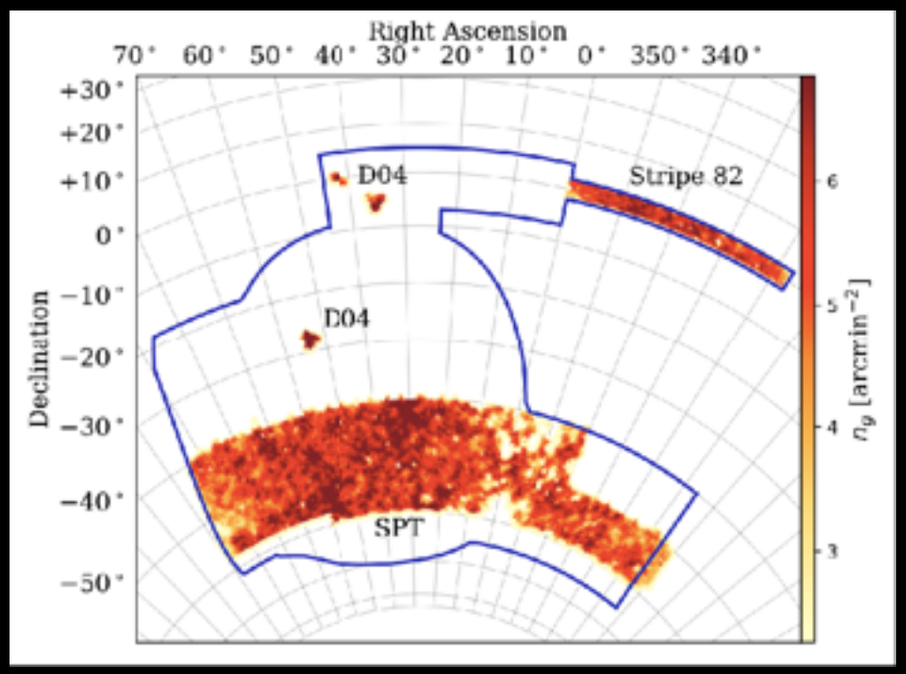


Image: T. Eifler

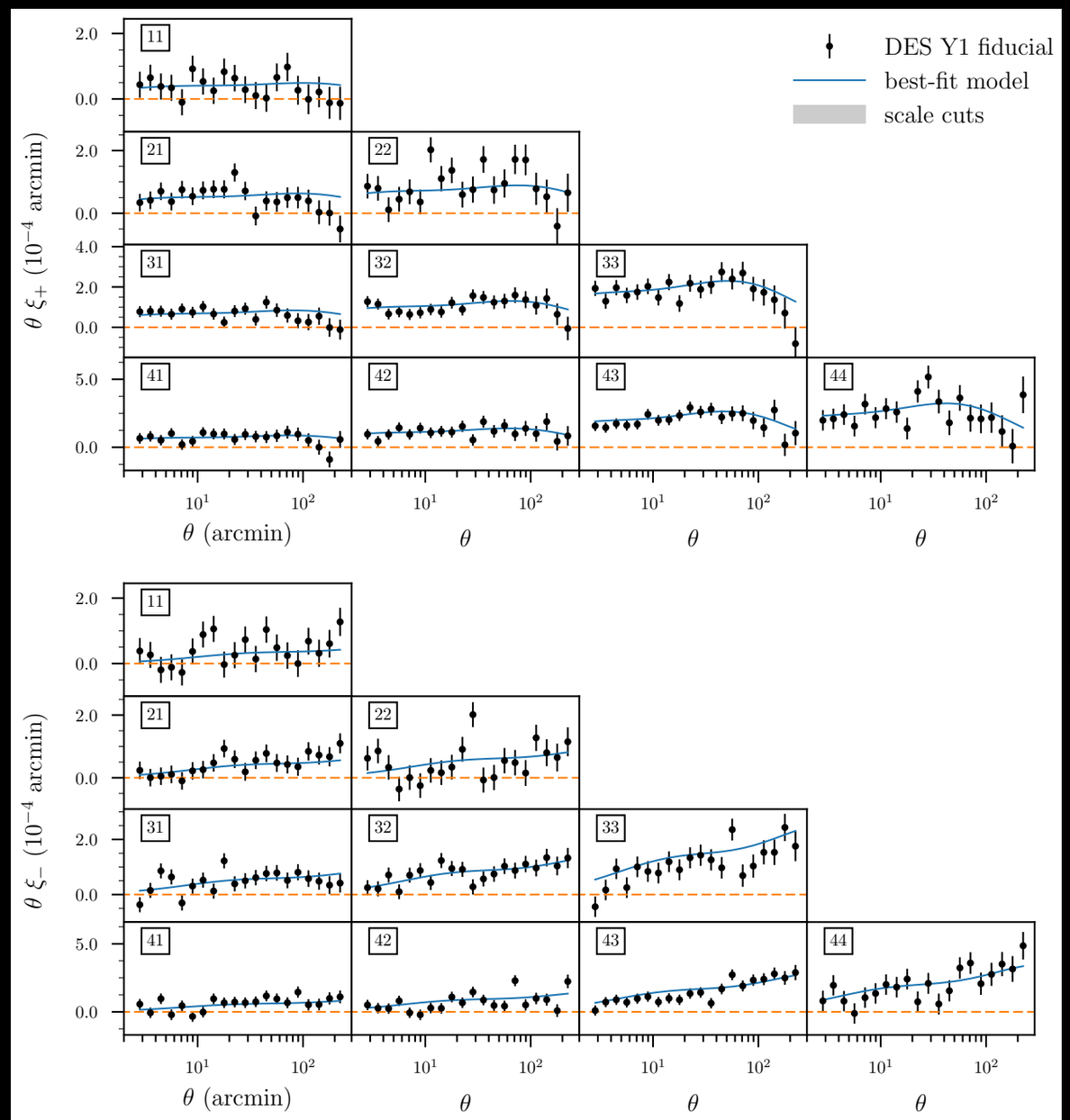
DES Year 1

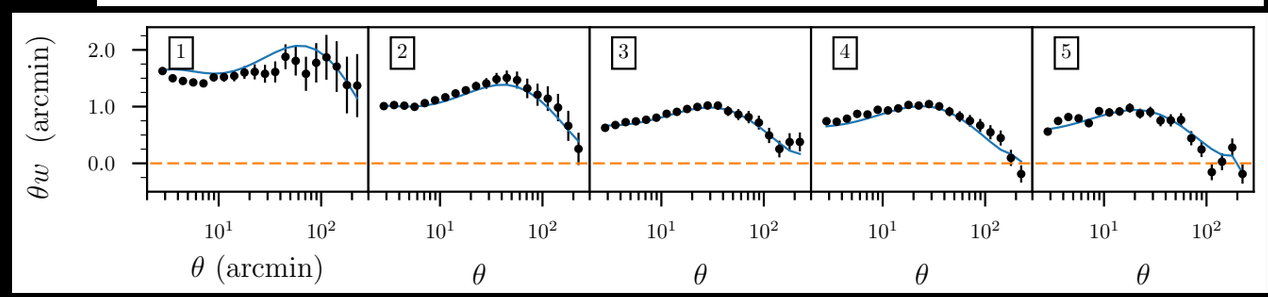


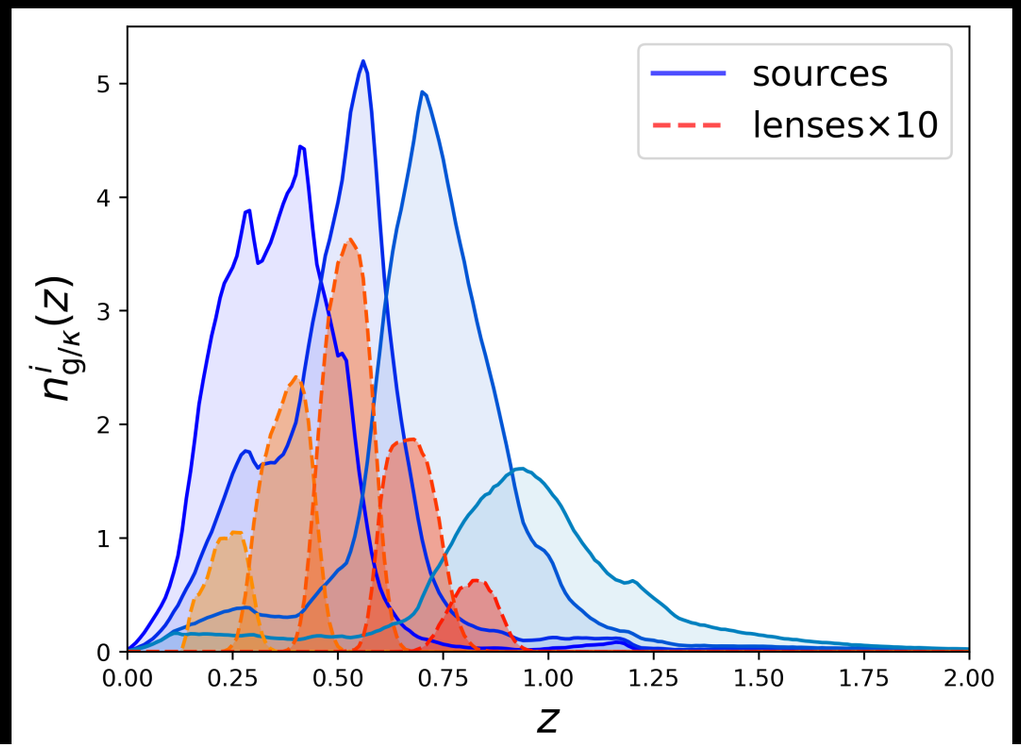
- Year 1 = 1321 deg^2 after cuts
- Calibrated shapes for weak lensing (2 pipelines). 26 million source galaxies used
- Photometric redshifts for tomography
- 660k redMaGiC galaxies as lenses
- galaxy clusters, SNe, BAO

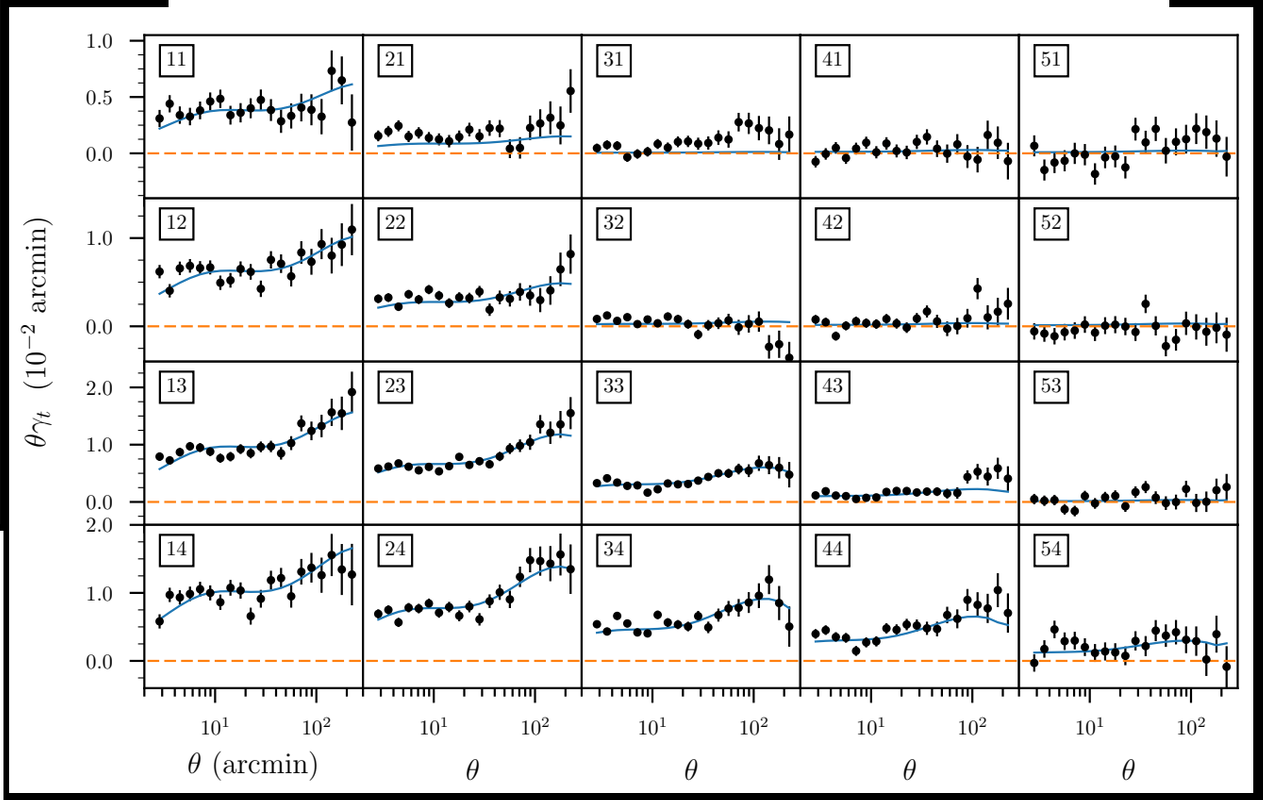
DES Y1 (~1300 deg^2)

DES Collaboration 2018, Elvin-Poole+ 2018, Troxel+ 2018, Prat, Sanchez+ 2018





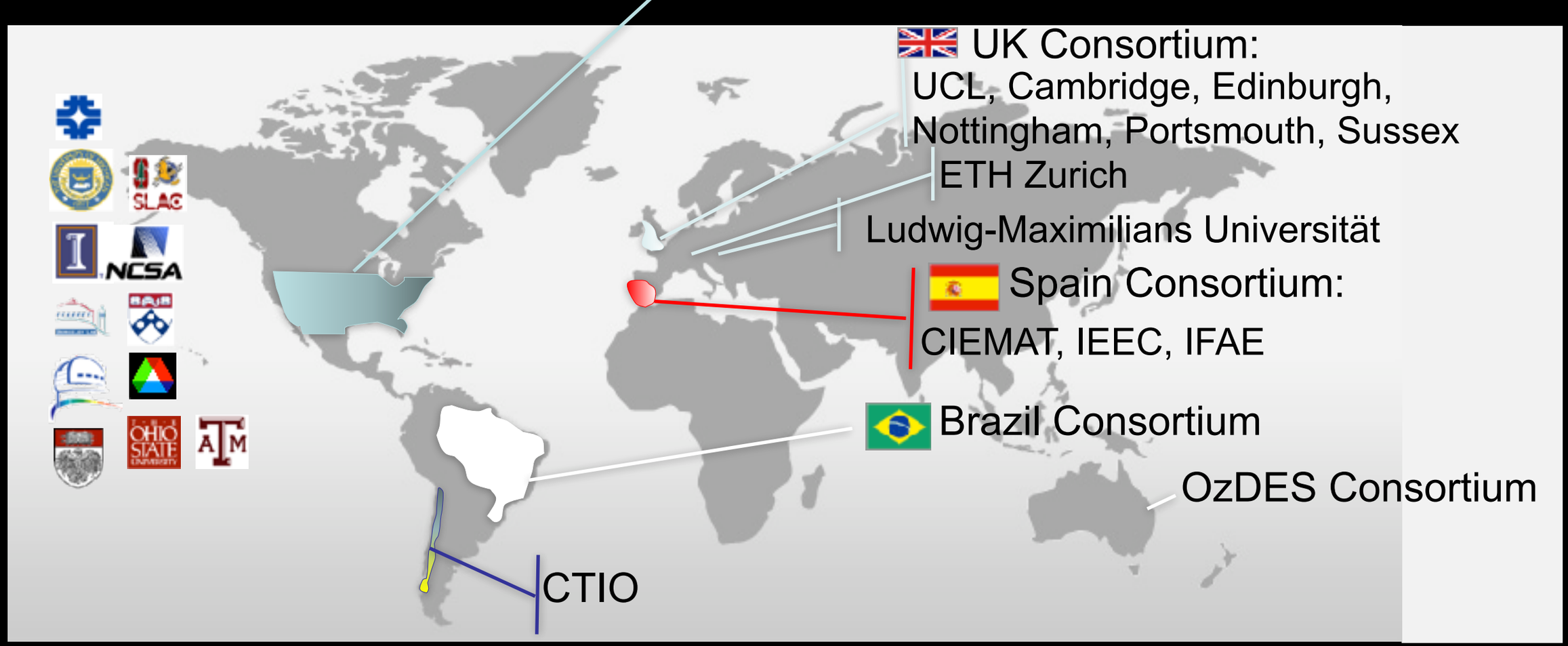




The DES Collaboration

~400 scientists;
US support from
DOE & NSF

Fermilab, UIUC/NCSA, University of Chicago, LBNL, NOAO, University of Michigan, University of Pennsylvania, Argonne National Lab, Ohio State University, Santa-Cruz/SLAC/ Stanford, Texas A&M



Cosmological Probes