Dark Energy and Weak Lensing

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Heisenberg-Programm
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$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$\downarrow$$

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

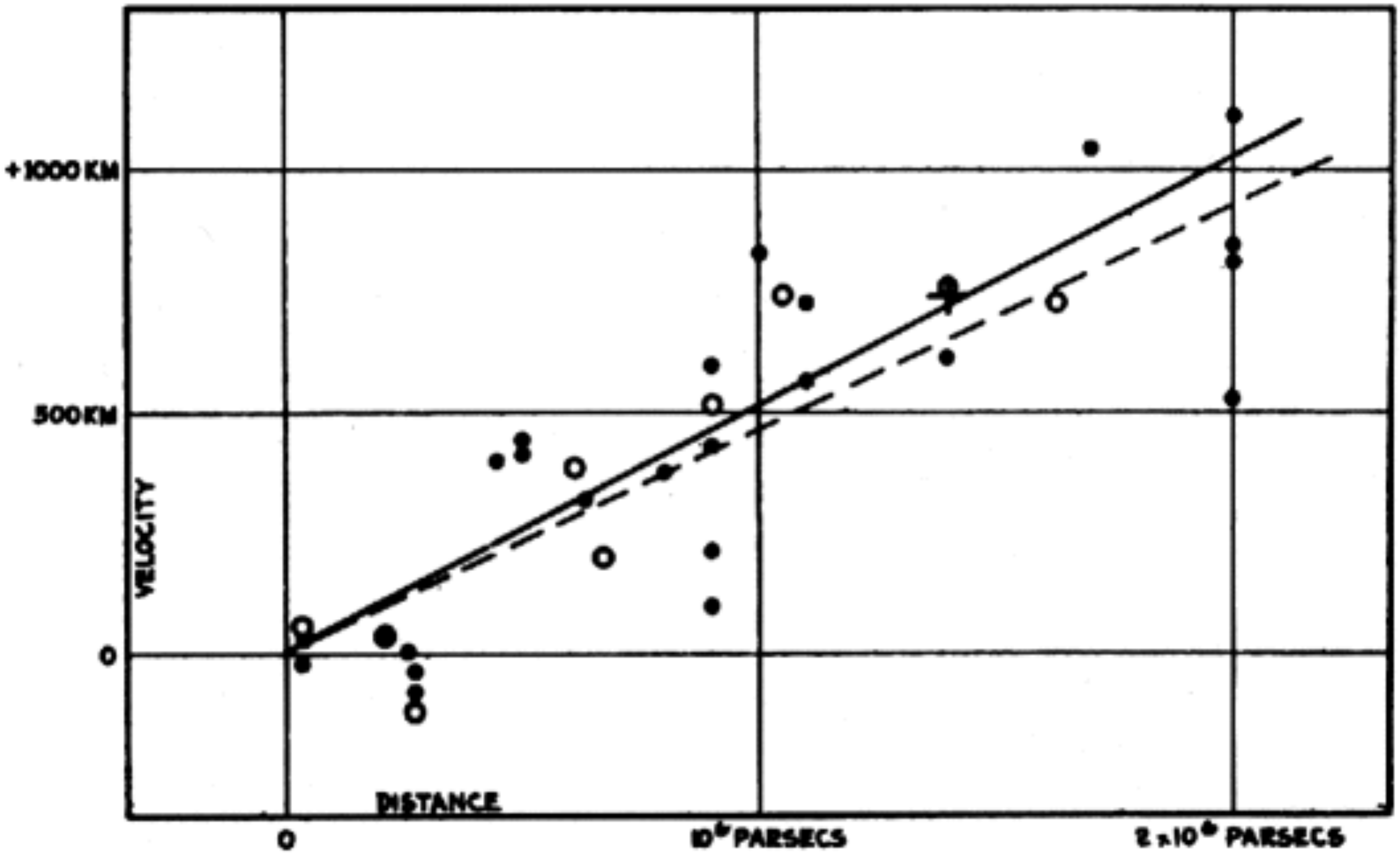
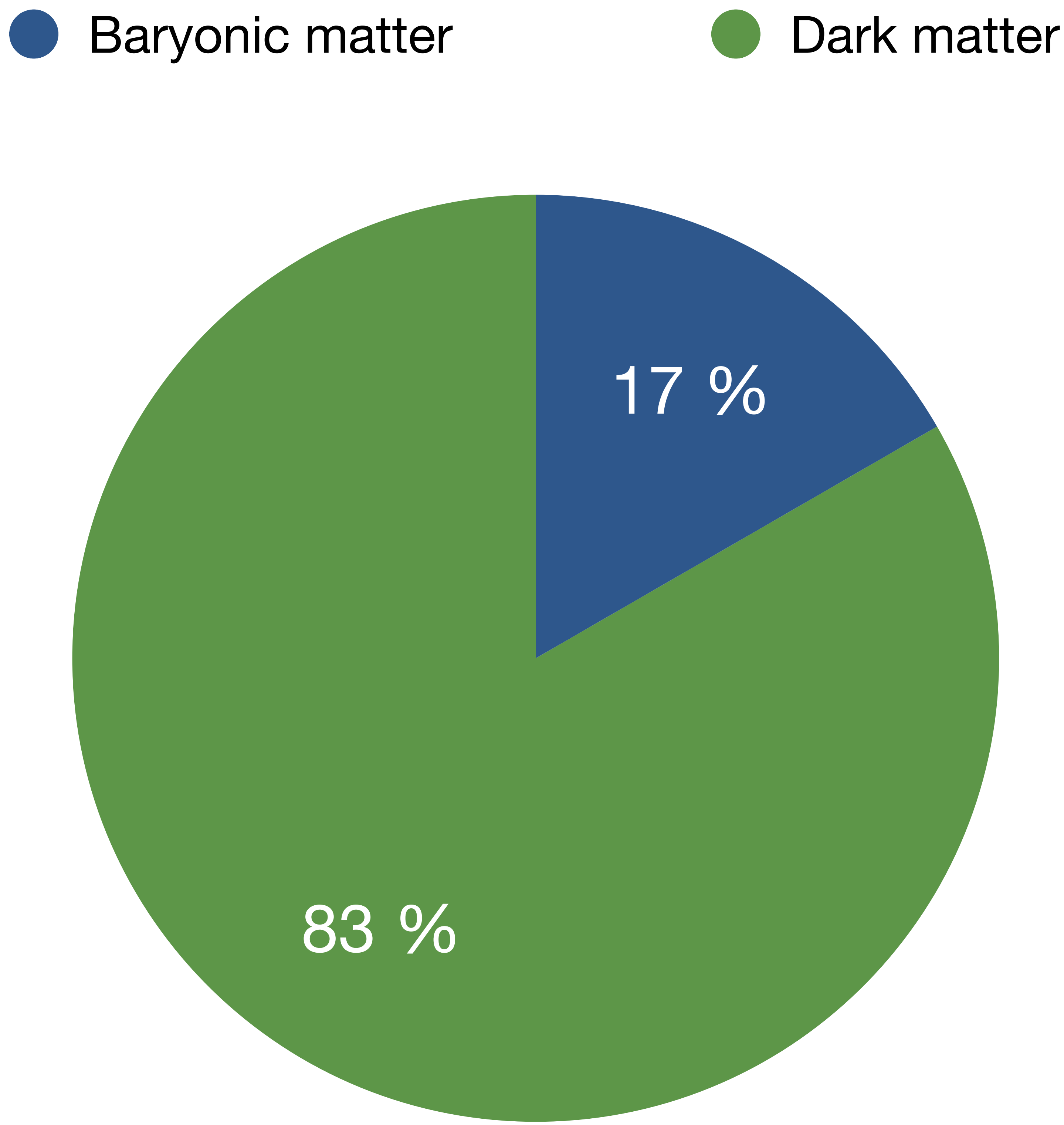


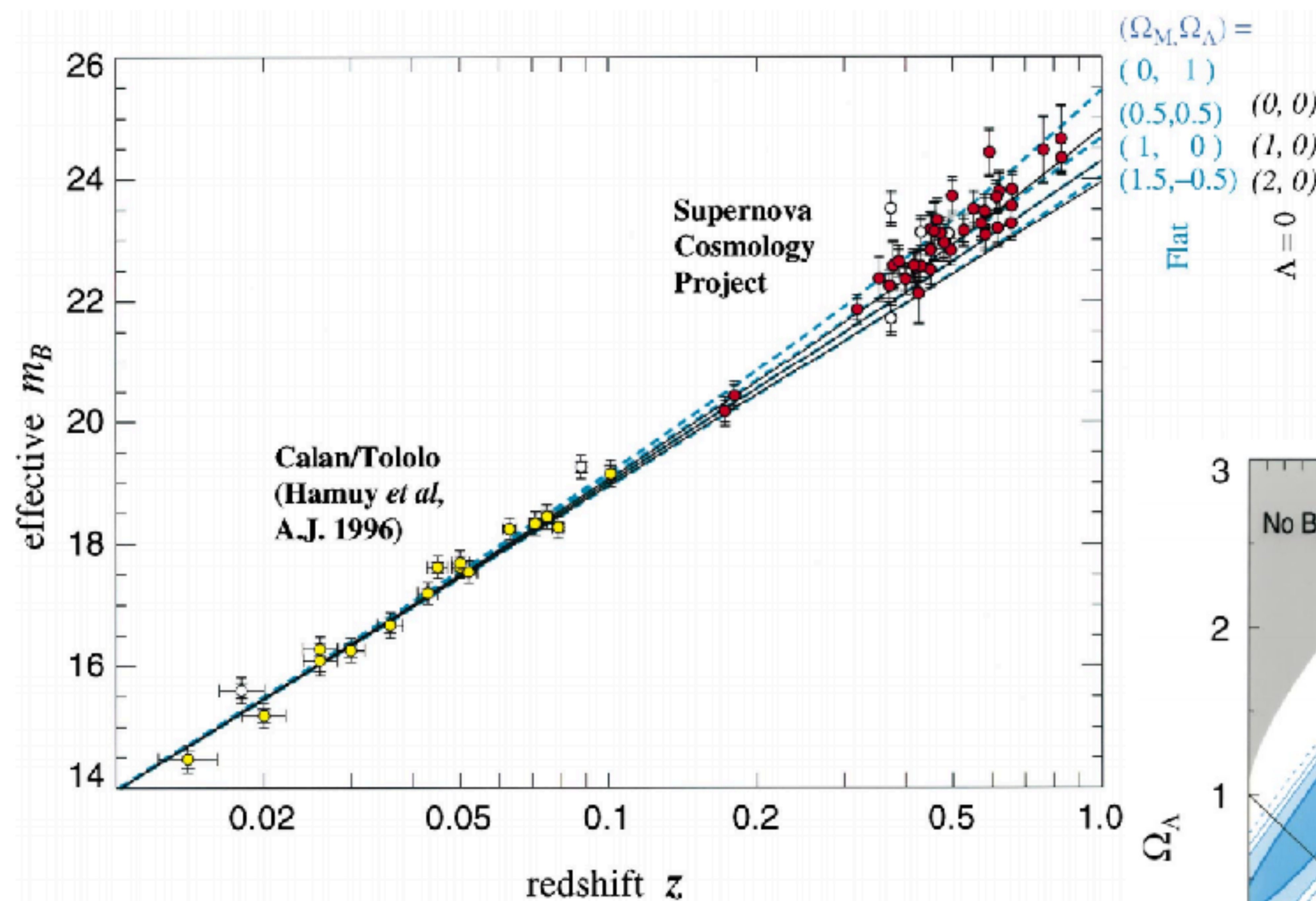
FIGURE 1

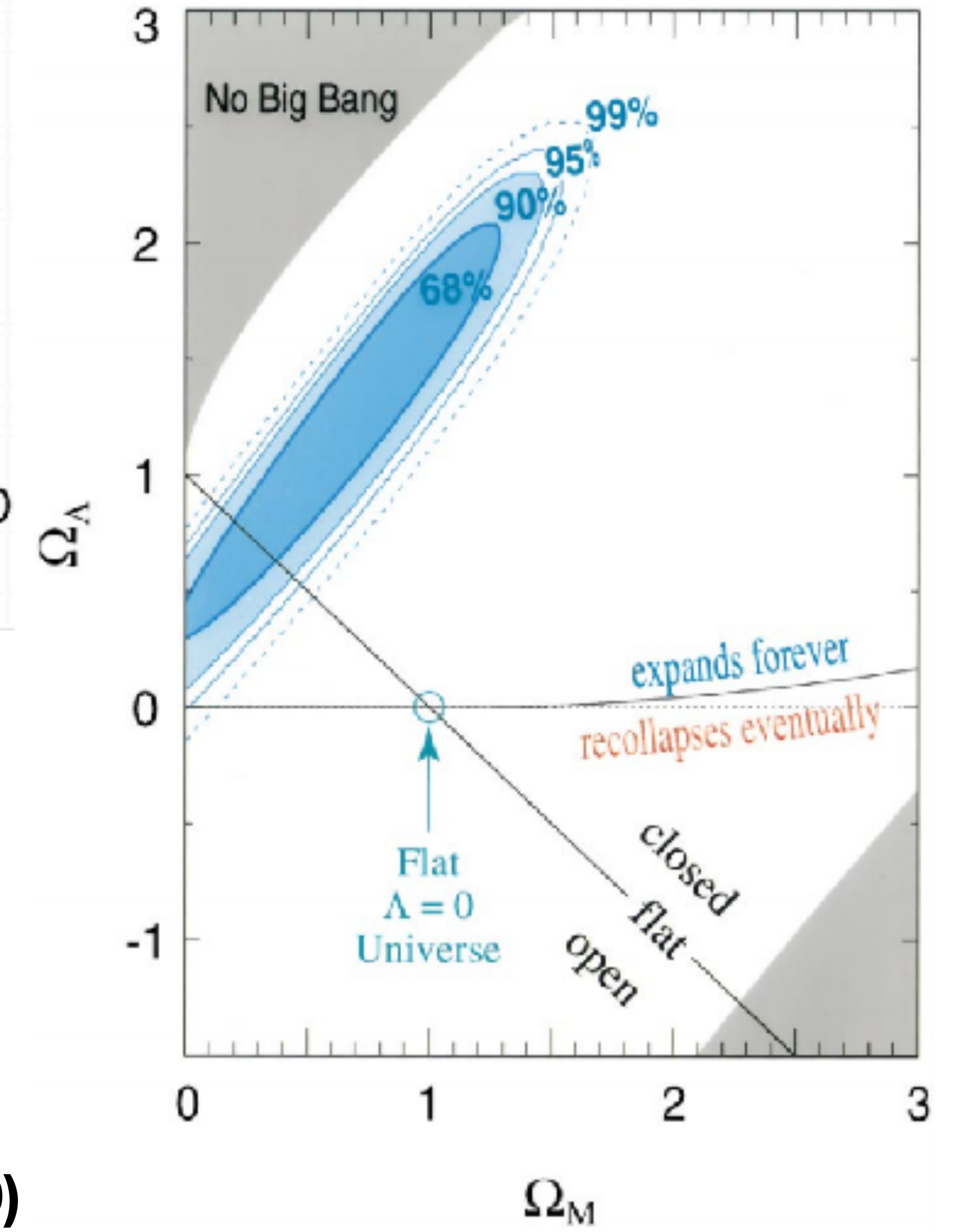
Velocity-Distance Relation among Extra-Galactic Nebulae.

Hubble (1929)



=> Decelerating expansion





Perlmutter et al. (1999)

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

or

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} - \Lambda g_{\mu\nu}$$

Left-hand side

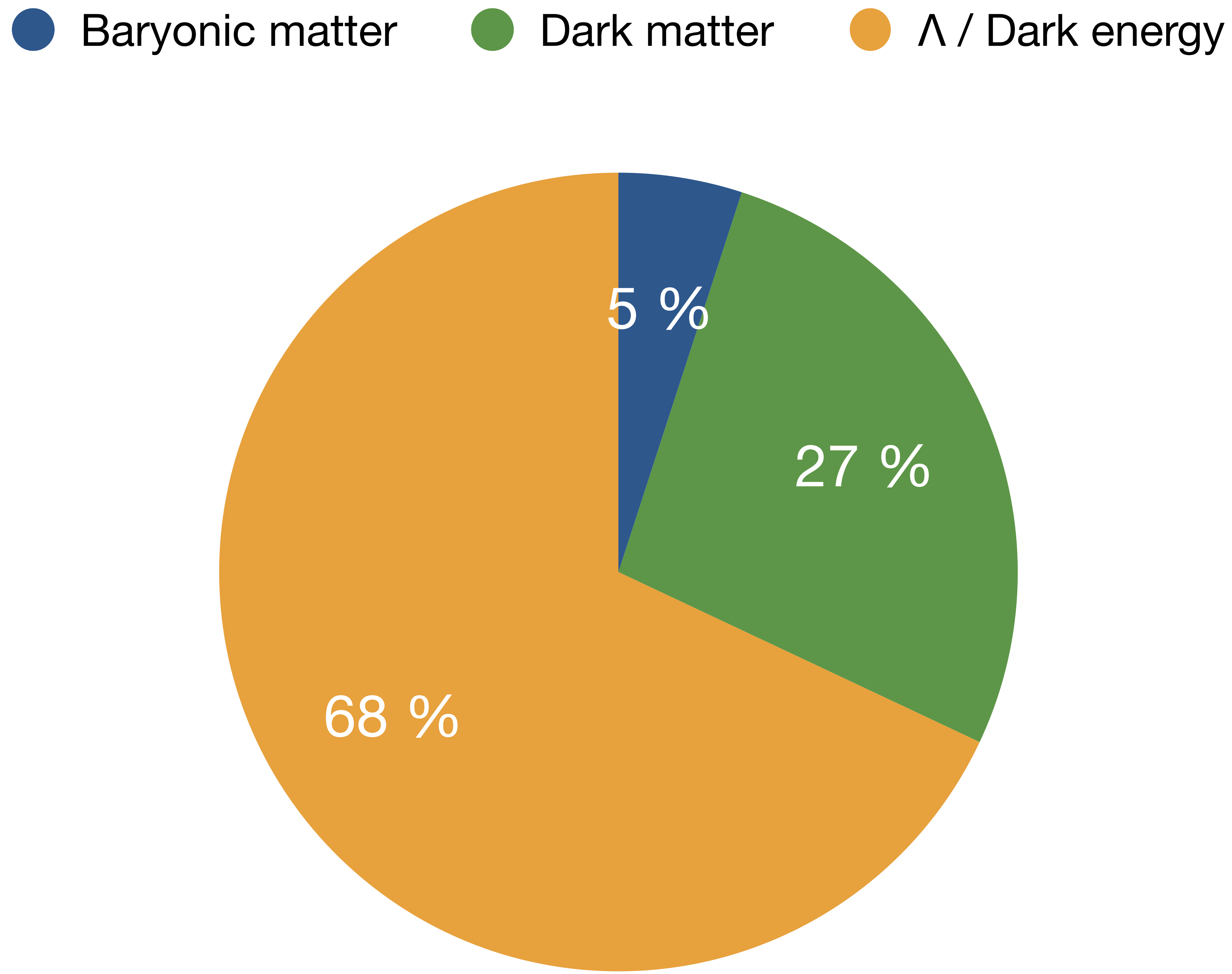
$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- Modification of gravity.
- New constant of nature.
- Can be falsified by measuring a time evolution.

Right-hand side

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} - \Lambda g_{\mu\nu}$$

- Behaves like vacuum energy.
- Quantum field theory struggles with the small value of Λ.
- $\Omega_m \sim \Omega_\Lambda$ seems like a coincidence.
- Many alternatives. **AND**



=> Late-time acceleration

$$P_{\mathrm{DE}} = w\rho_{\mathrm{DE}}c^2$$

$$w < -1/3$$ **Accelerating expansion**

$$w = -1$$ **Cosmological constant**

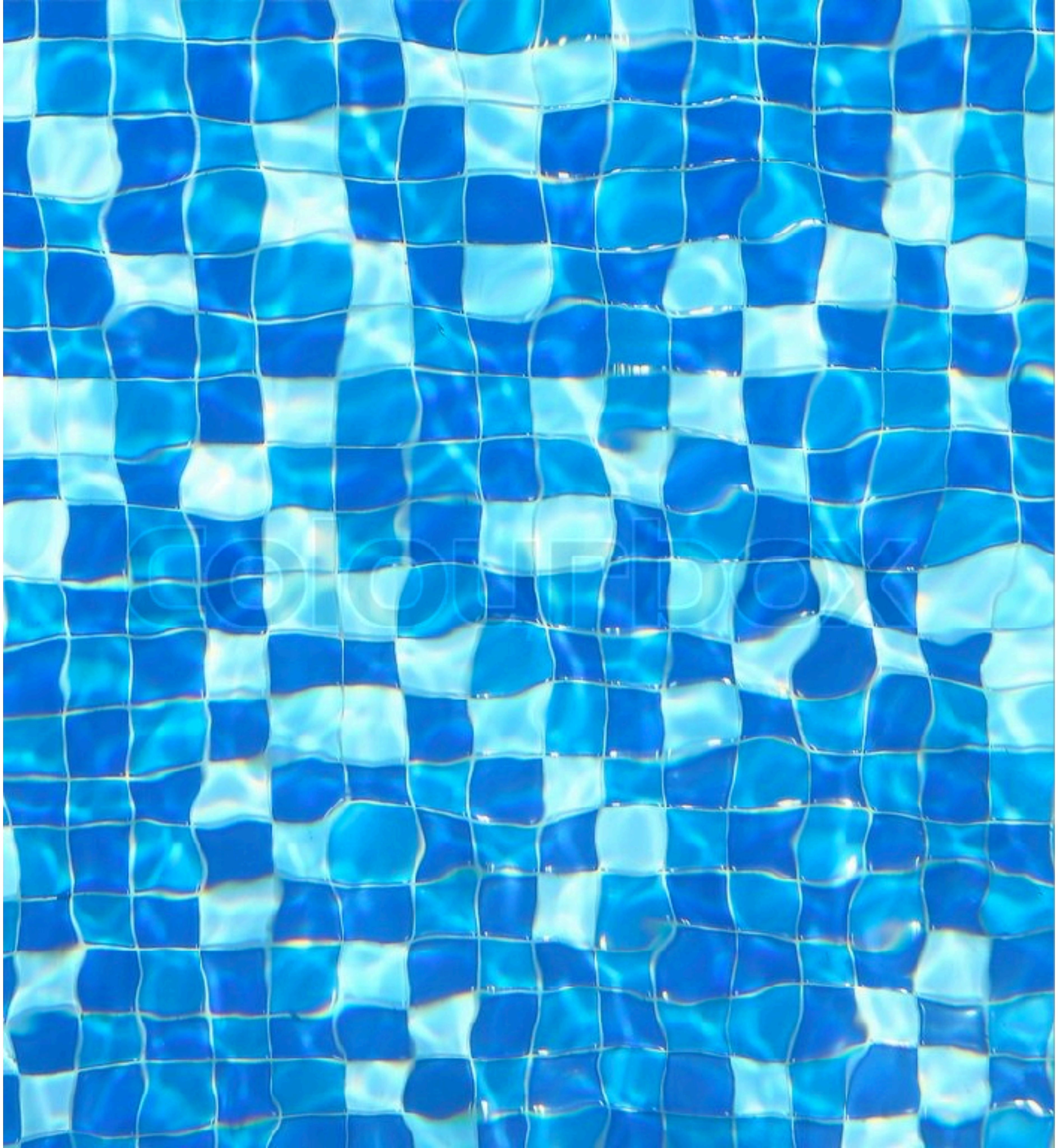
$$\rho_{\mathrm{DE}}(a) = \rho_{\mathrm{DE},0}\, a^{-3(1+w)}$$

$$a = 1/(1+z)$$

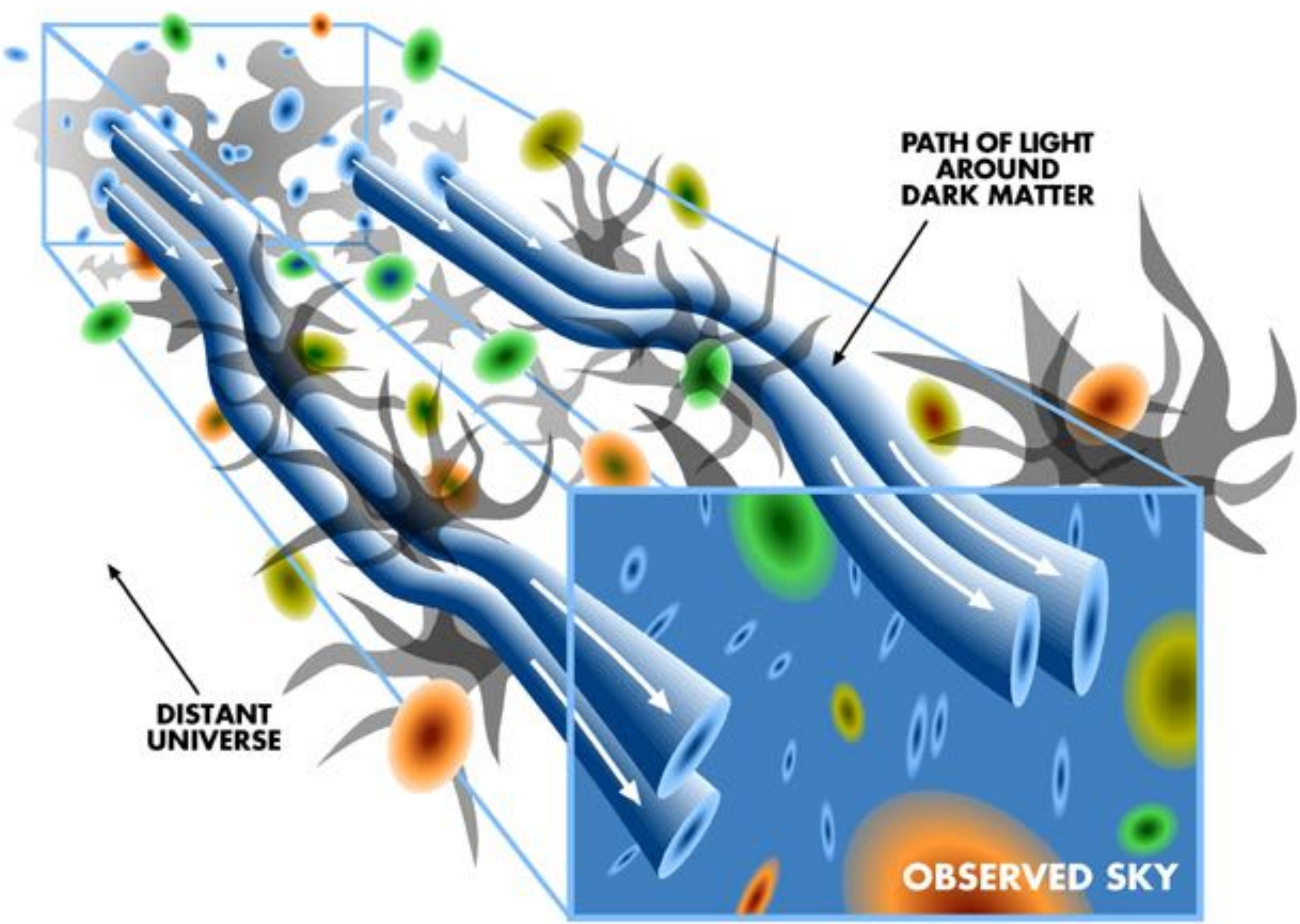
$$w(a) = w_0 + w_a(1-a)$$

Observing dark energy

- Distance-redshift relation:
  1. Supernovae type Ia
  2. Baryon acoustic oscillations
- + Growth of structures:
  3. Galaxy cluster mass function
  4. **Weak gravitational lensing of LSS (cosmic shear)**


colourbox

Cosmic shear



Wittman et al. (2000)

Sensitive to:

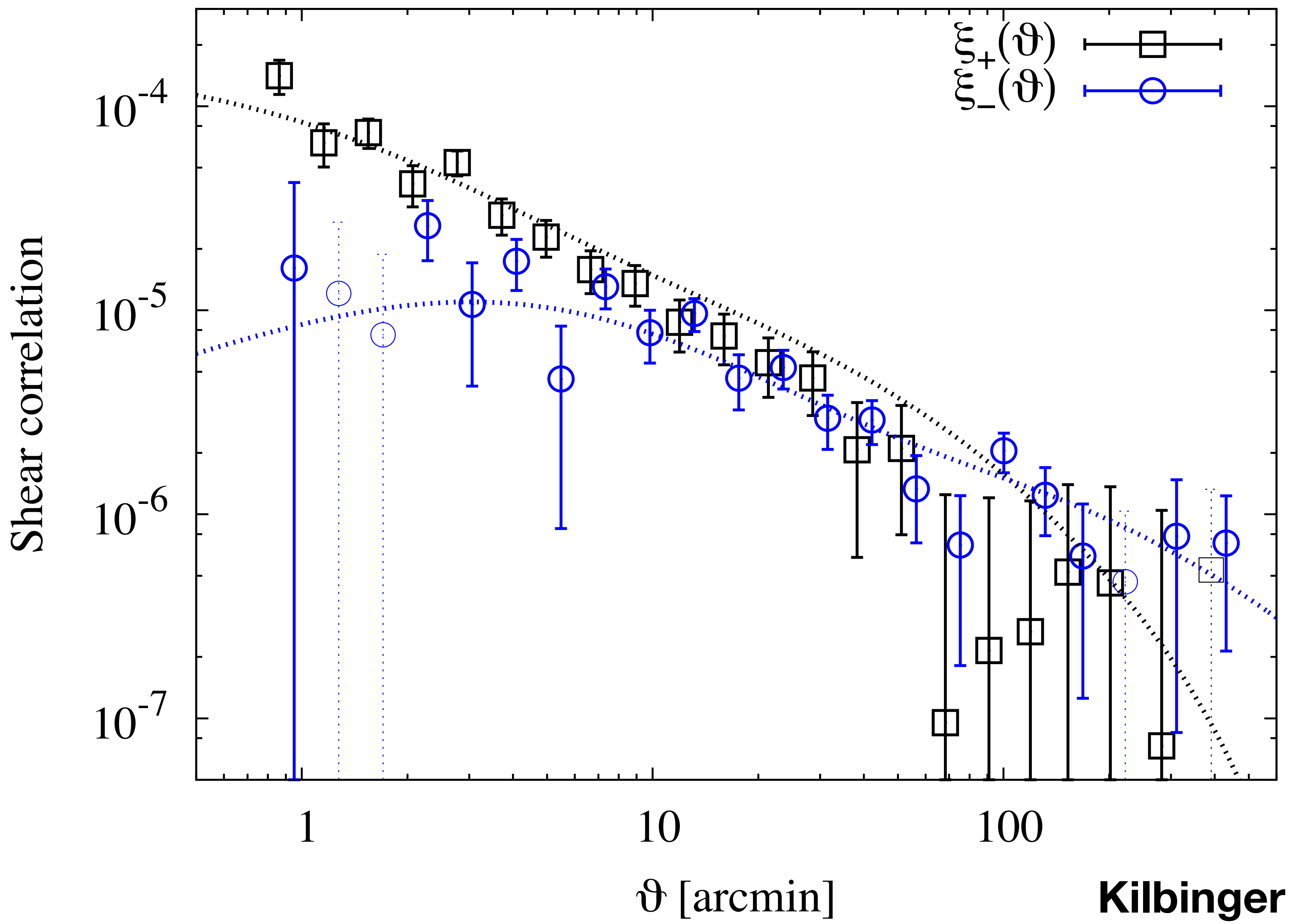
- Matter distribution
- Geometry

Observables:

- Ellipticities
- Photo-*z*

Statistical measurement of many galaxies

2pt shear correlation functions



Kilbinger et al. (2013)

Very directly related to the matter power spectrum P_δ.

Observation -> theory

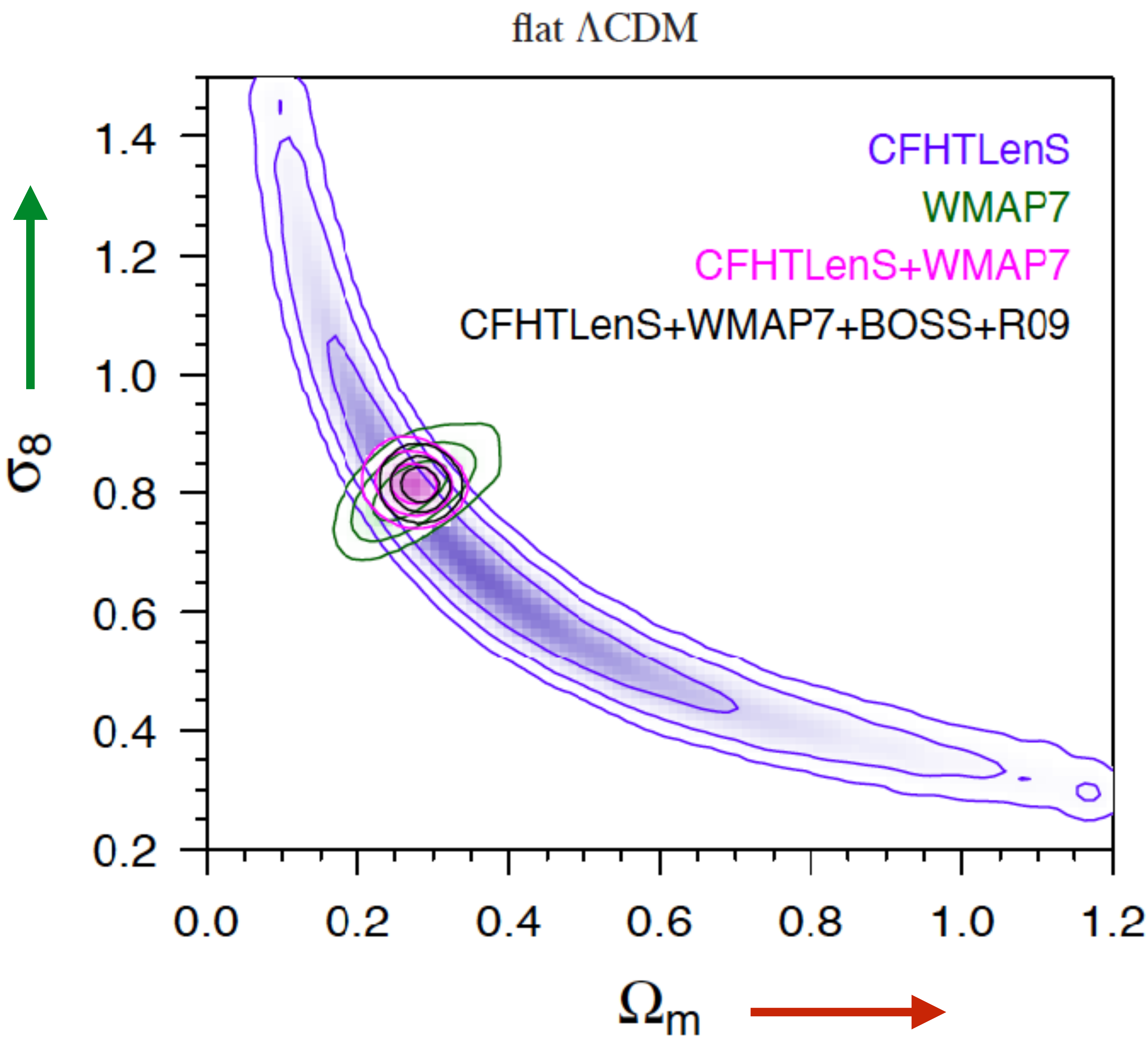
$$\xi_\pm(\theta) = \langle \gamma_\mathrm{t}\gamma_\mathrm{t} \rangle (\theta) \pm \langle \gamma_\times\gamma_\times \rangle (\theta)$$

$$\xi_+(\theta) = \int_0^\infty \frac{\mathrm{d}\ell\,\ell}{2\pi}\,\mathrm{J}_0(\ell\theta)\,P_\kappa(\ell)\ ; \quad \xi_-(\theta) = \int_0^\infty \frac{\mathrm{d}\ell\,\ell}{2\pi}\,\mathrm{J}_4(\ell\theta)\,P_\kappa(\ell)$$

$$P_\kappa(\ell) = \frac{9H_0^4\Omega_\mathrm{m}^2}{4c^4}\int_0^{\chi_\mathrm{h}} \mathrm{d}\chi\,\frac{g^2(\chi)}{a^2(\chi)}\,P_\delta\left(\frac{\ell}{f_K(\chi)}, \chi\right)$$

$$g(\chi) = \int_\chi^{\chi_\mathrm{h}} \mathrm{d}\chi'\,p_\chi(\chi')\,\frac{f_K(\chi'-\chi)}{f_K(\chi')}$$

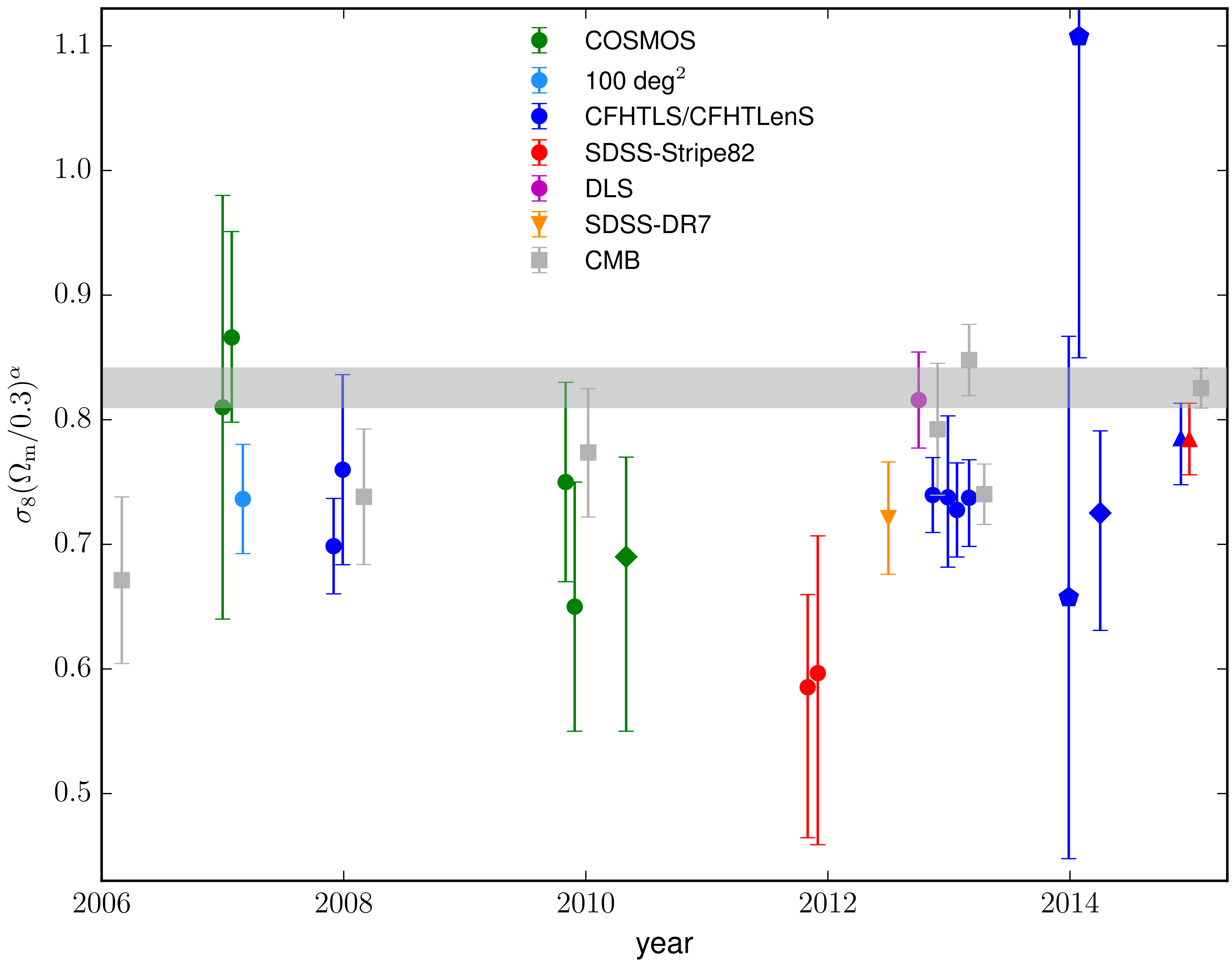
Cosmological constraints



Kilbinger et al. (2013)

- Measure **amount** of **clustered** matter
- $S_8 = \sigma_8\,(\Omega_m/0.3)^{0.5}$

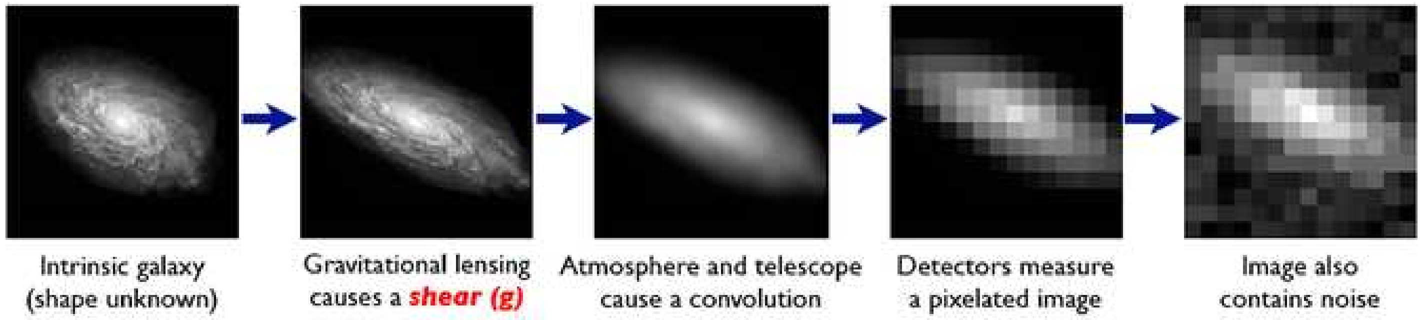
S_8 results over the years



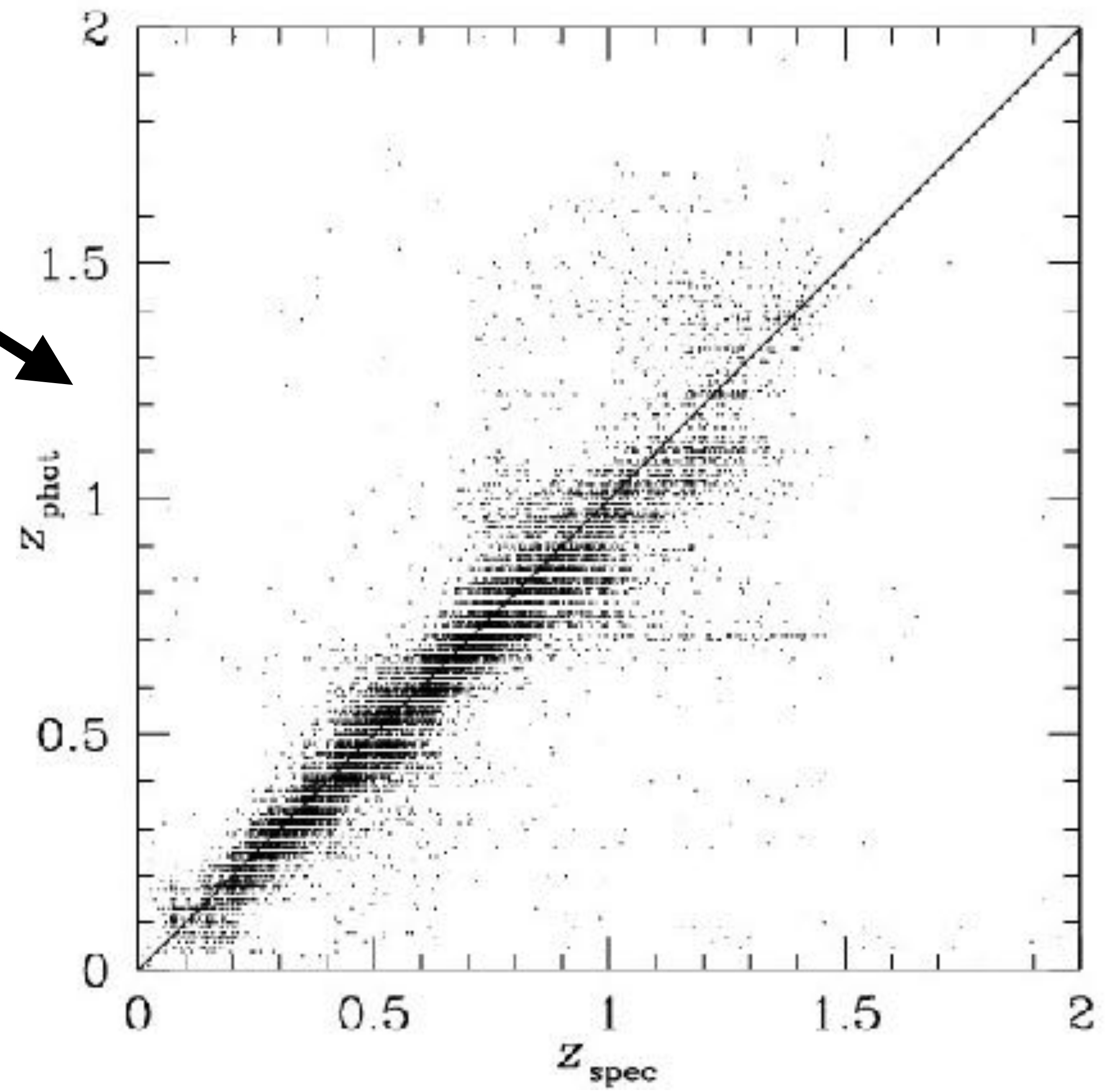
Kilbinger (2015)

Systematic errors

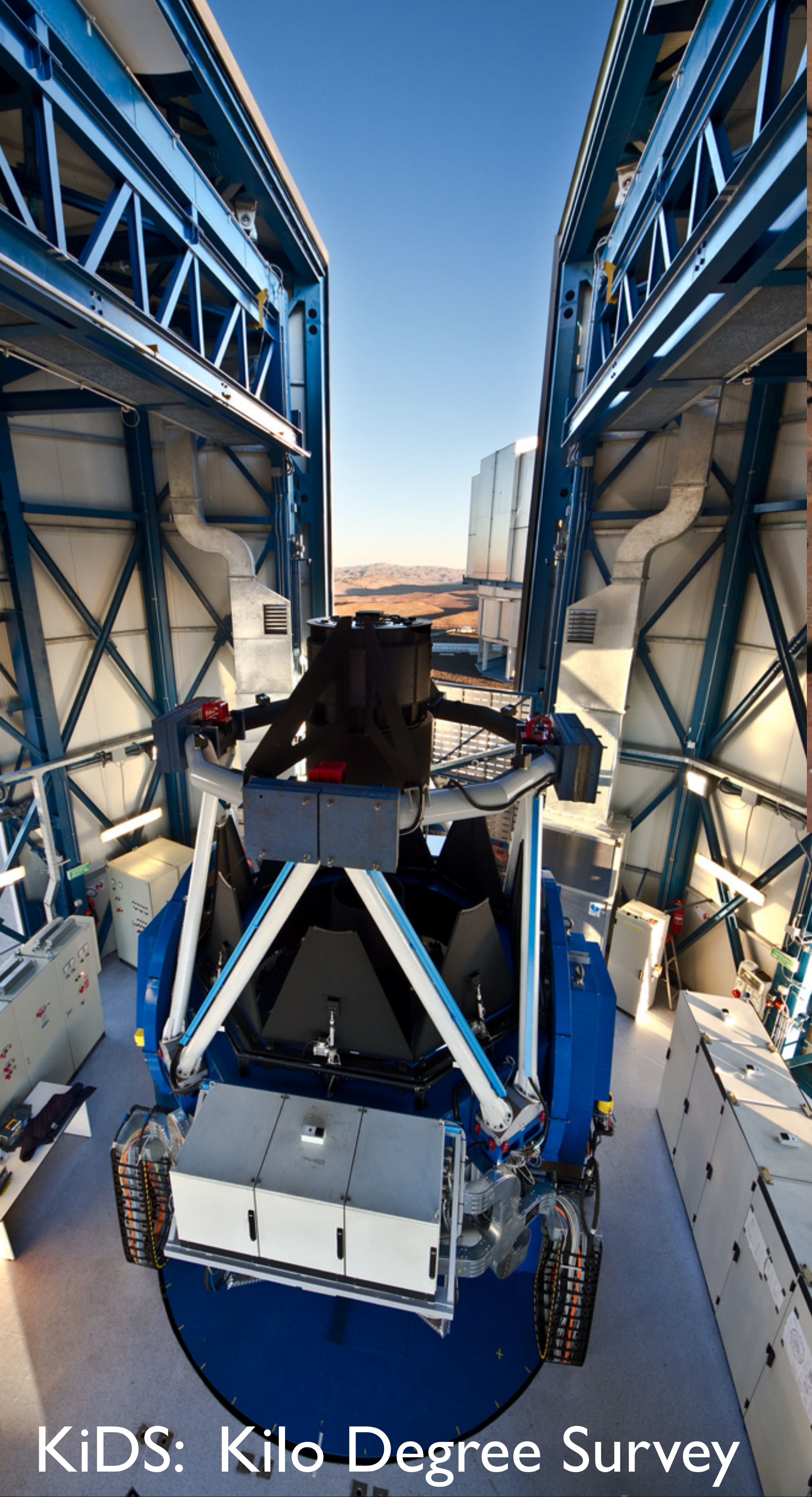
- **Shapes measurement systematics:**
  - PSF residuals
  - B modes
  - Multiplicative and additive biases



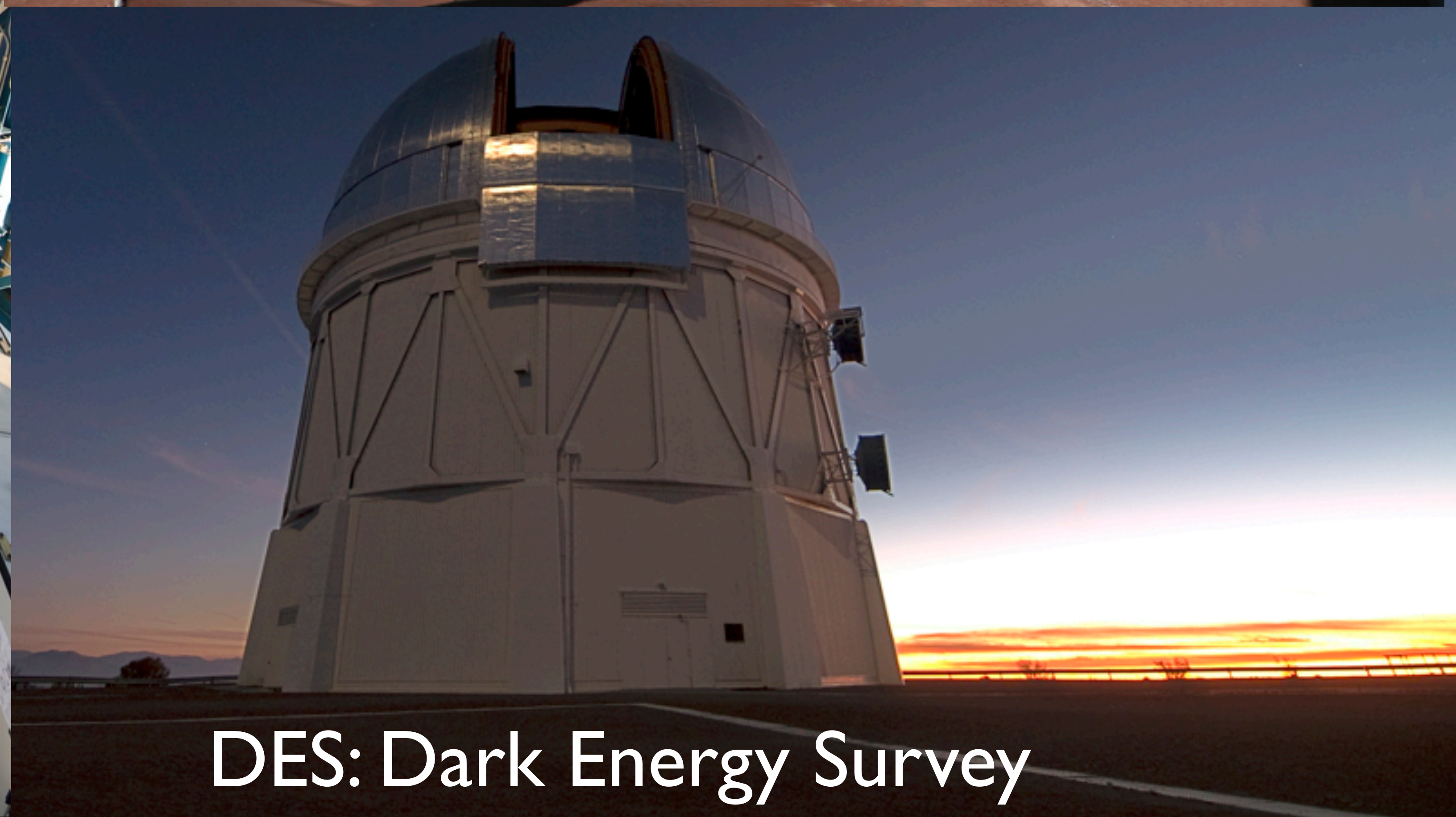
- **Photo-z systematics:**
  - Calibration sample and technique
  - Inhomogeneous multi-band data



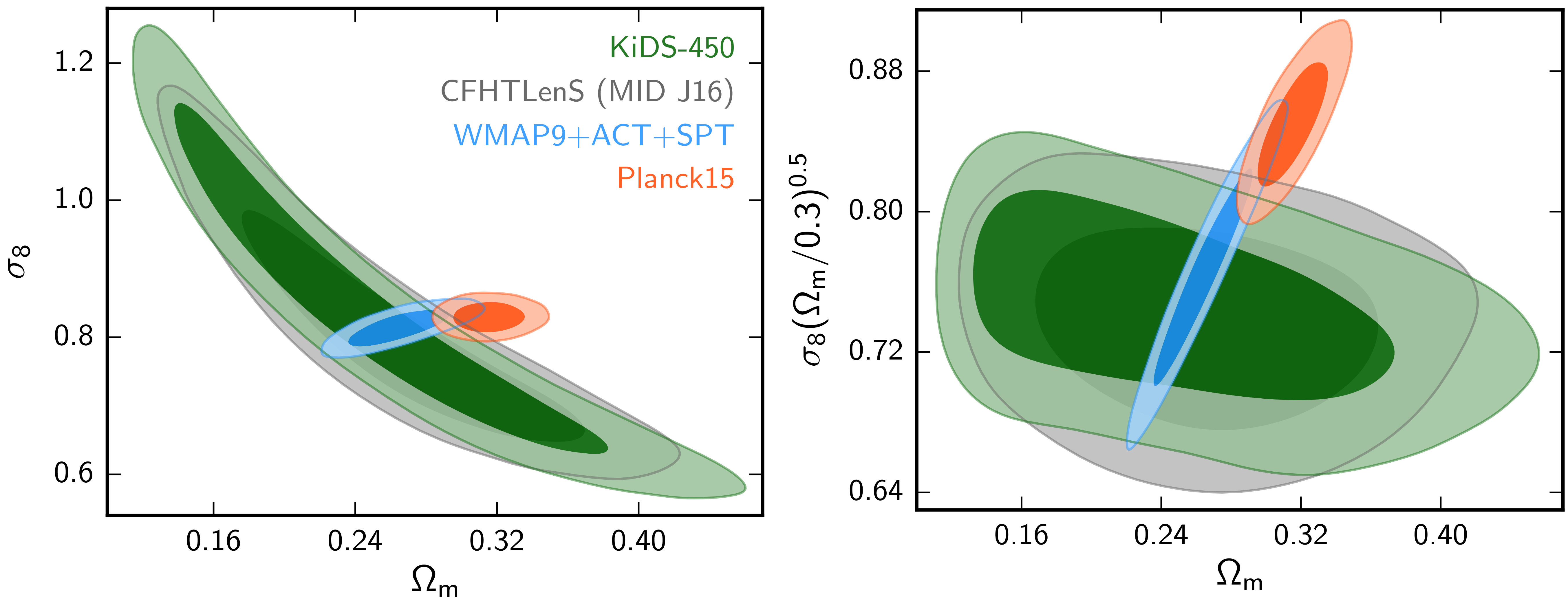
- Theoretical “systematics”:
  - Intrinsic alignments
  - Baryon feedback
  - Neutrinos
  - WDM
- Psychological systematics:
  - Blinding


KiDS: Kilo Degree Survey


HSC: Hyper-Suprime Cam Survey

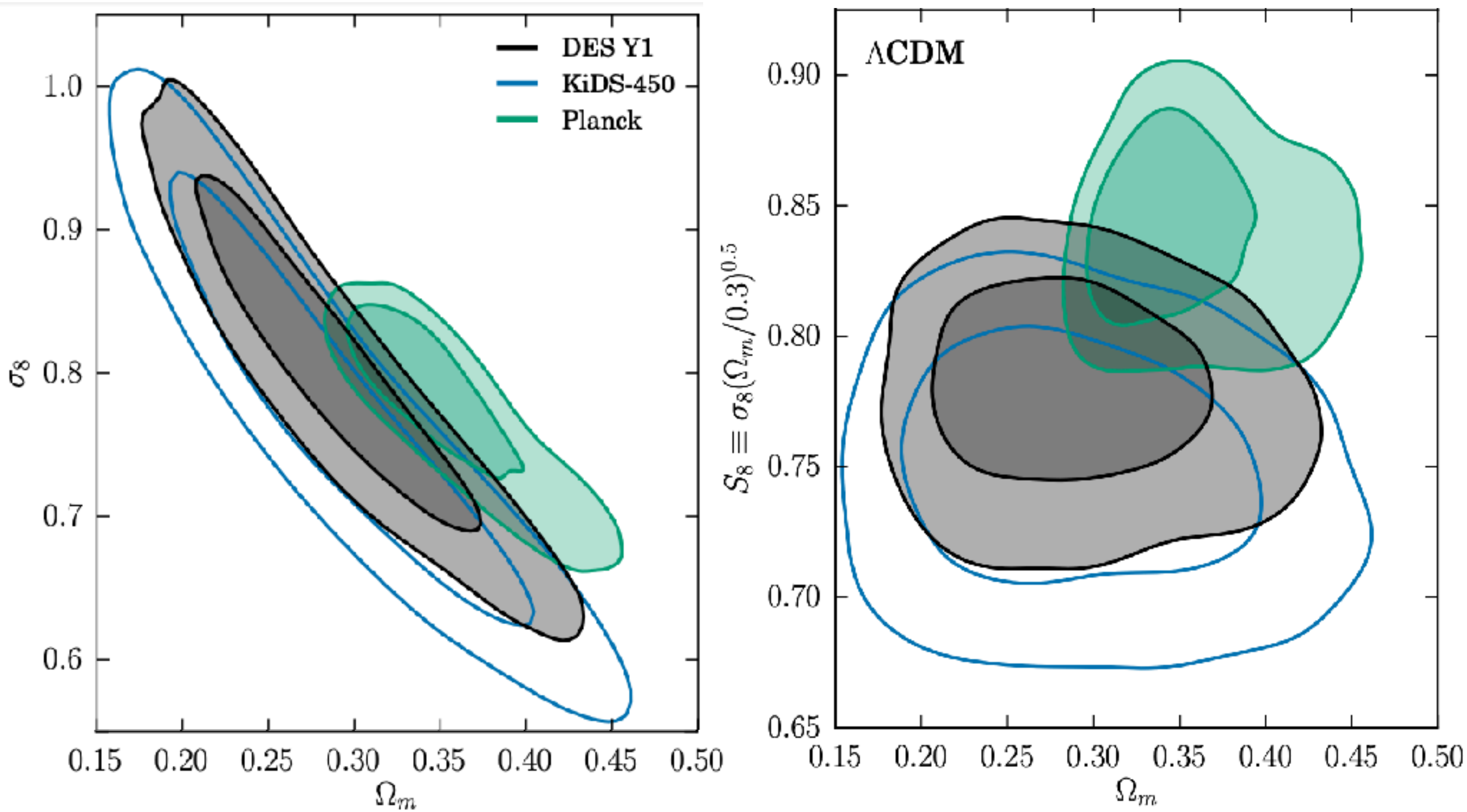

DES: Dark Energy Survey

KiDS-450



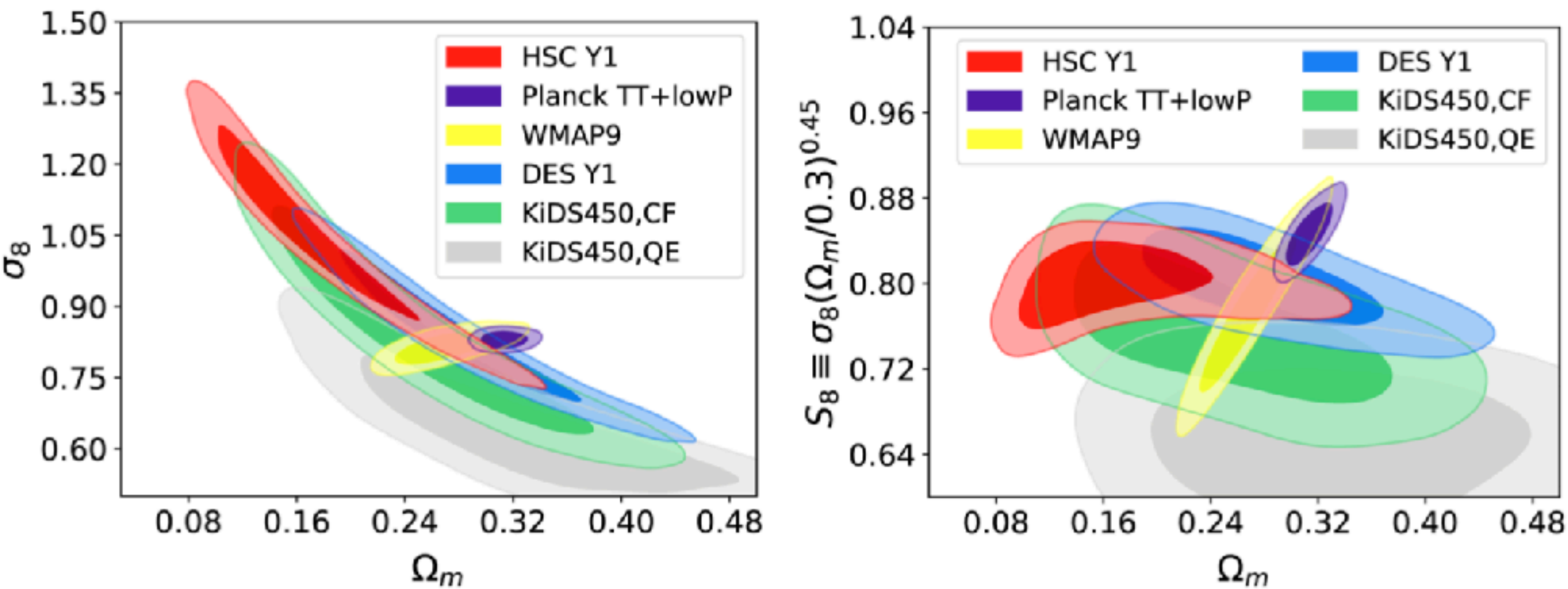
Hildebrandt et al. (2017)

DES-Y1



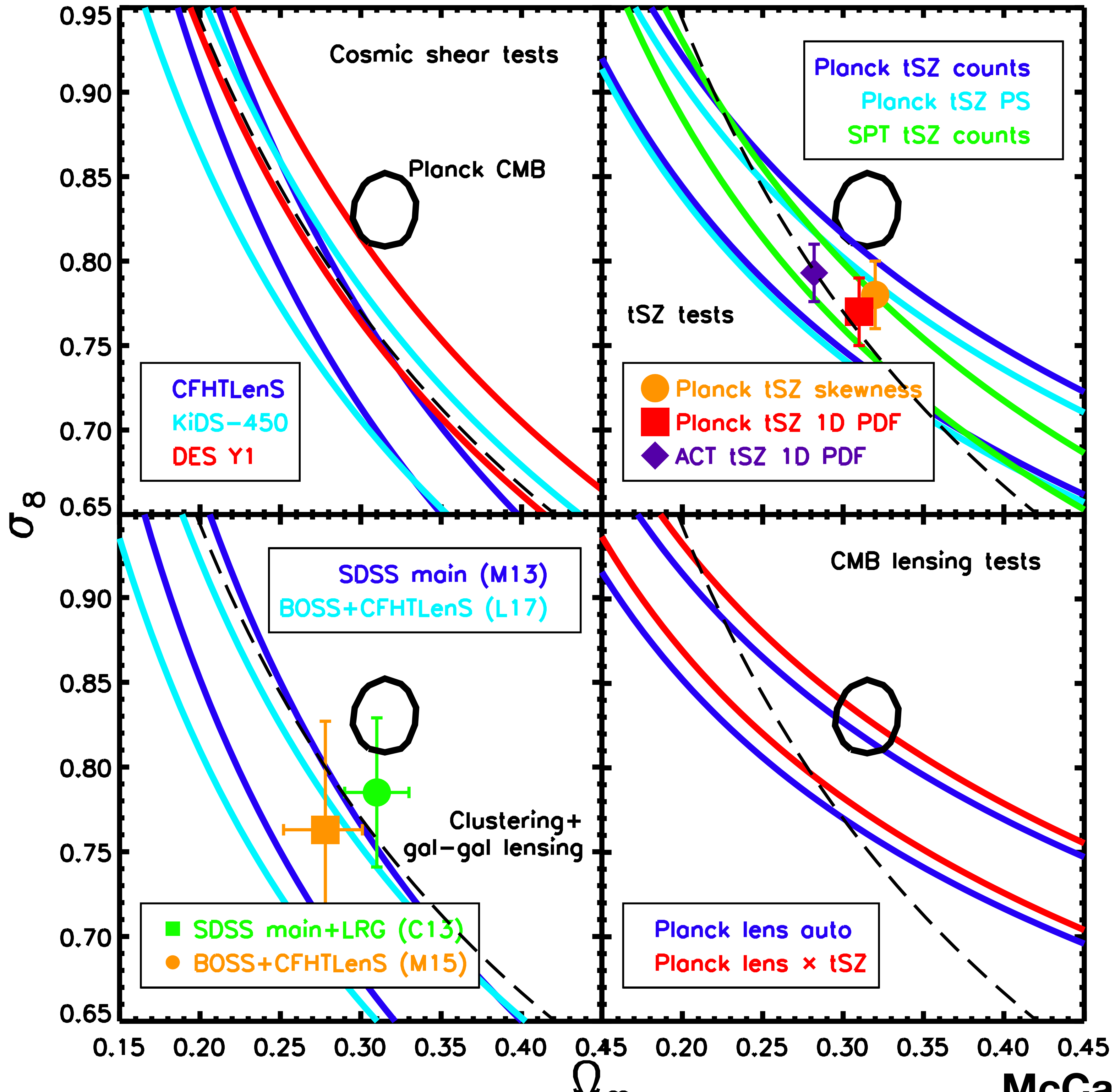
Troxel et al. (2018)

HSC-DR1



Hikage et al. (2019)

Other probes



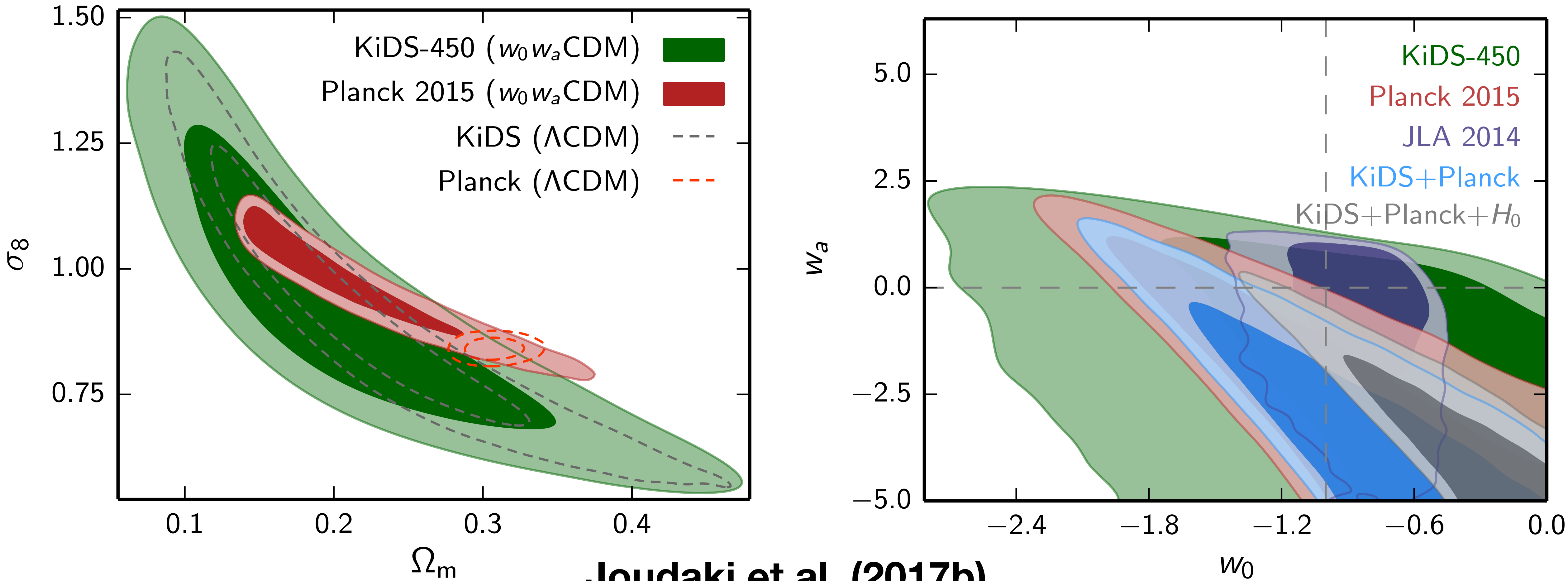
McCarthy et al. (2017)

Extended cosmologies

- Massive neutrinos
- Non-zero curvature
- Modified gravity
- Running spectral index
- DE with constant EoS
- Evolving dark energy EoS

Joudaki et al. (2017b)

Evolving dark energy

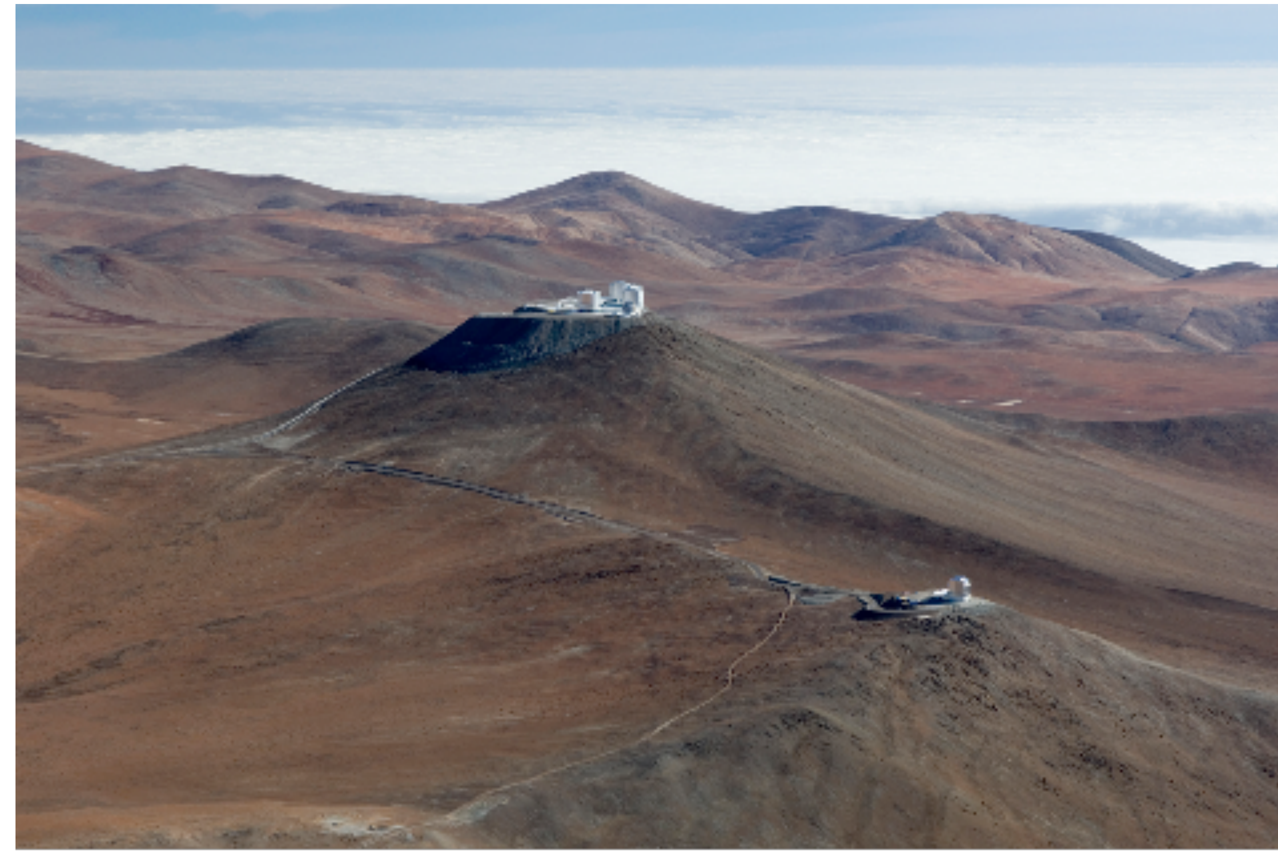


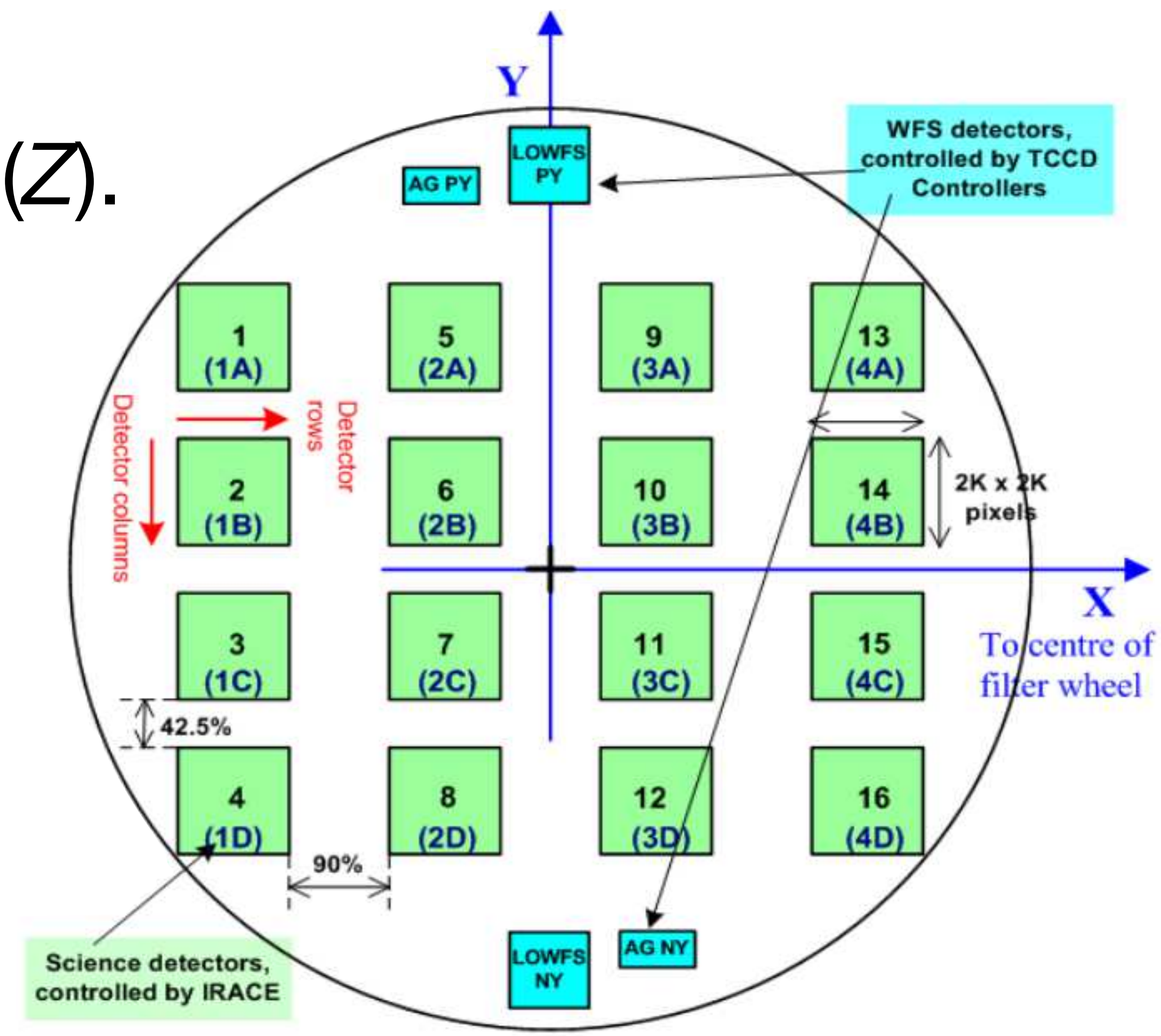
Joudaki et al. (2017b)

- Resolves tension between KiDS and Planck.
- Only extension that is moderately favoured by the data.
- Resolves tension between Riess et al. (2016) and Planck.

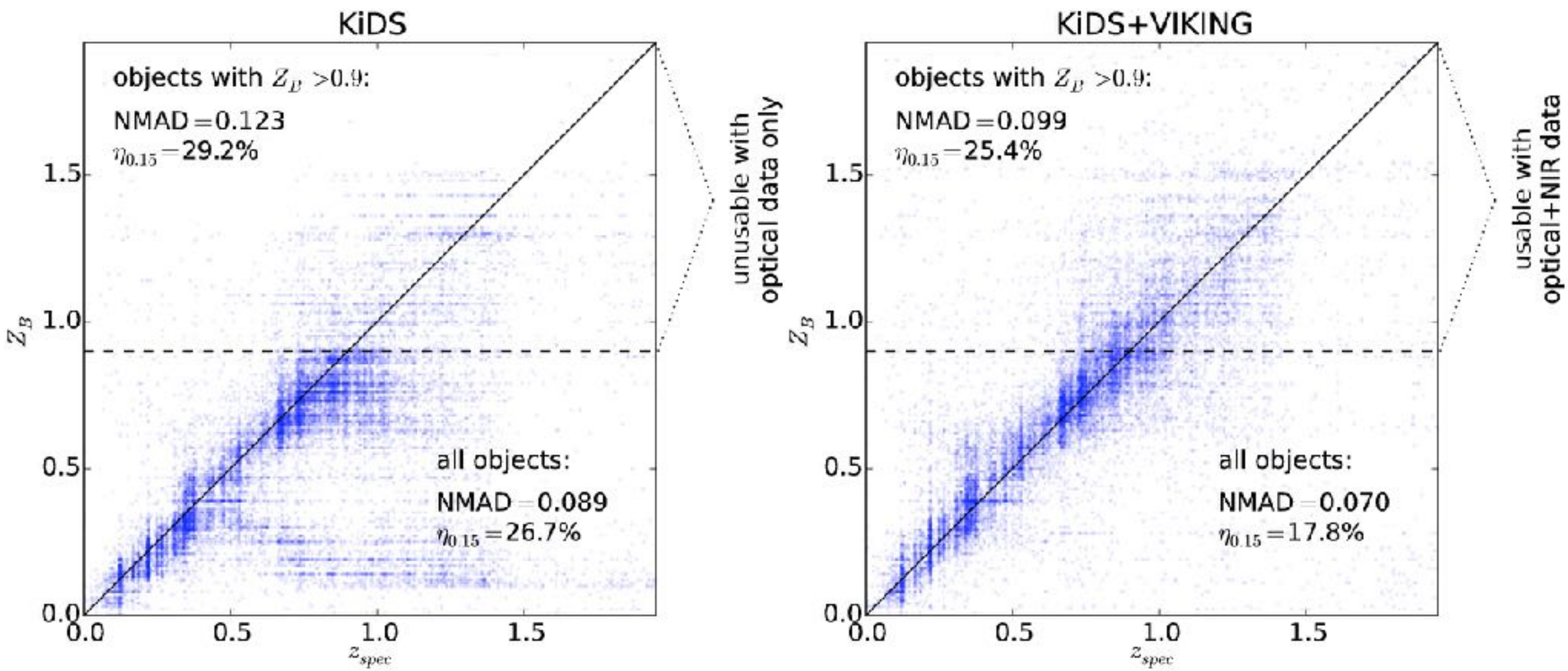
VIKING@VISTA

- Same footprint as KiDS.
- Already finished (1350deg^2).
- $ZYJHK_s$ images.
- 5σ depths of 21.2 (K_s) to 23.1 (Z).





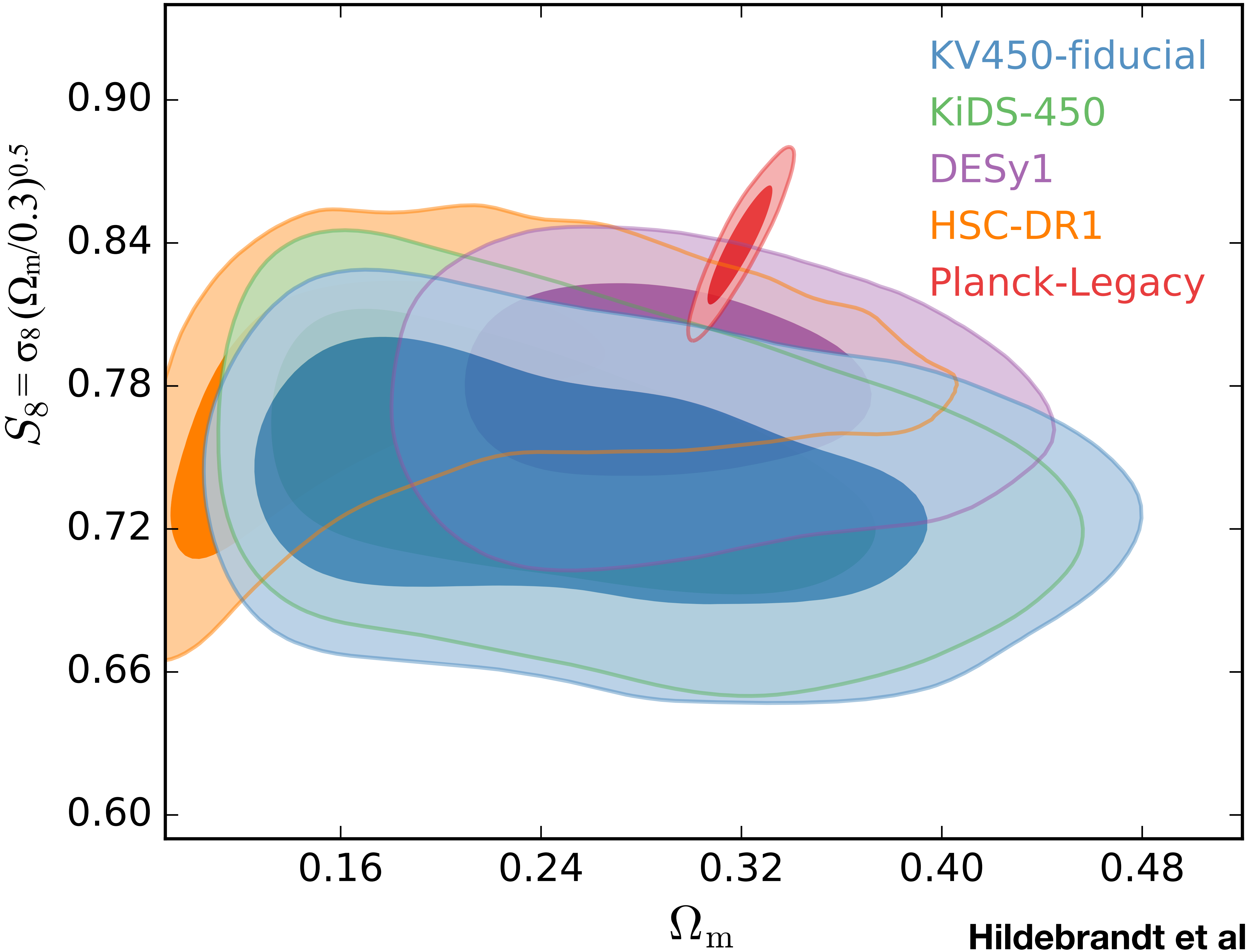
Benefits of NIR



- **20% smaller errors due to high-z galaxies alone.**
- **More robust redshifts -> better calibration.**

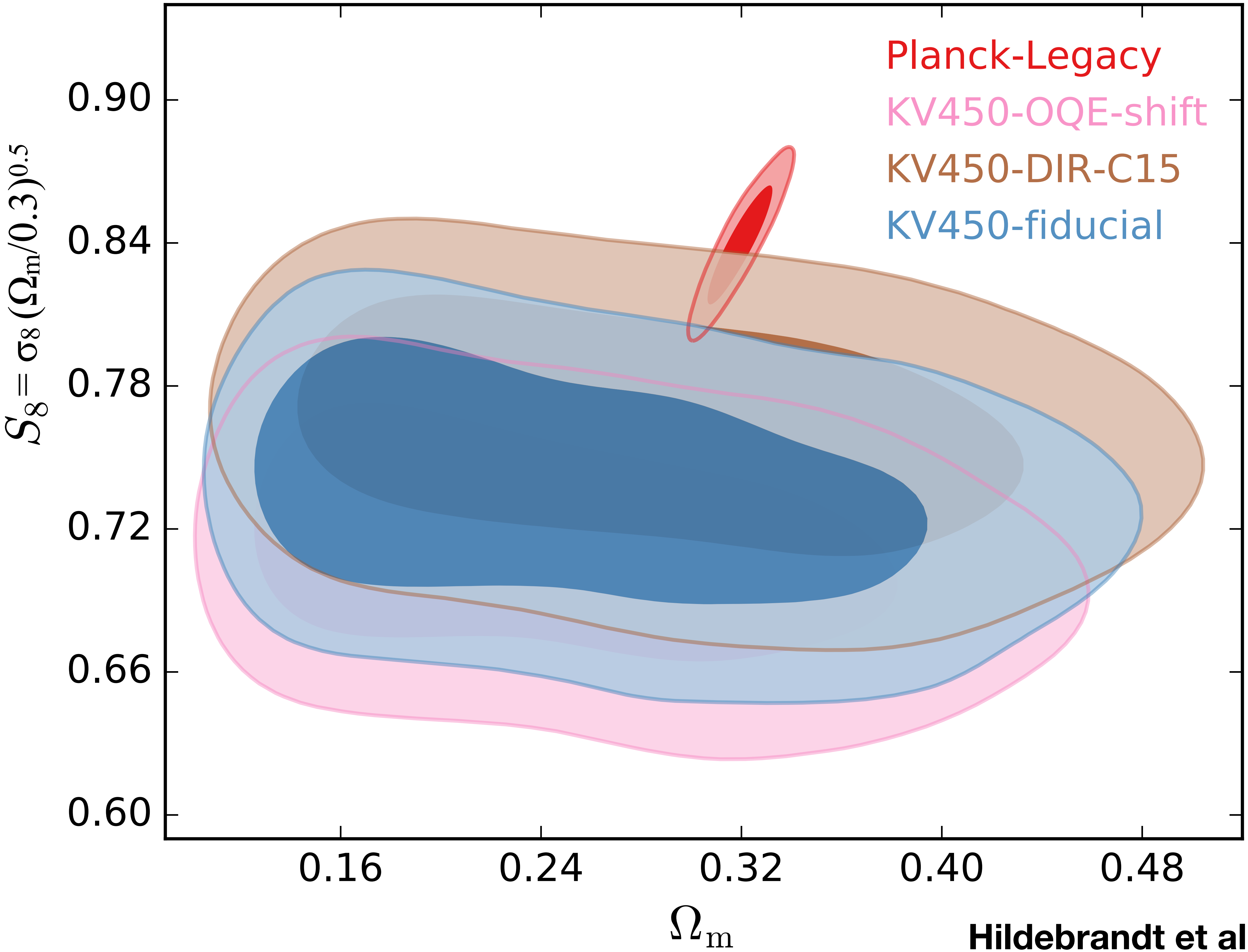
Wright et al. (2018)

Cosmological constraints

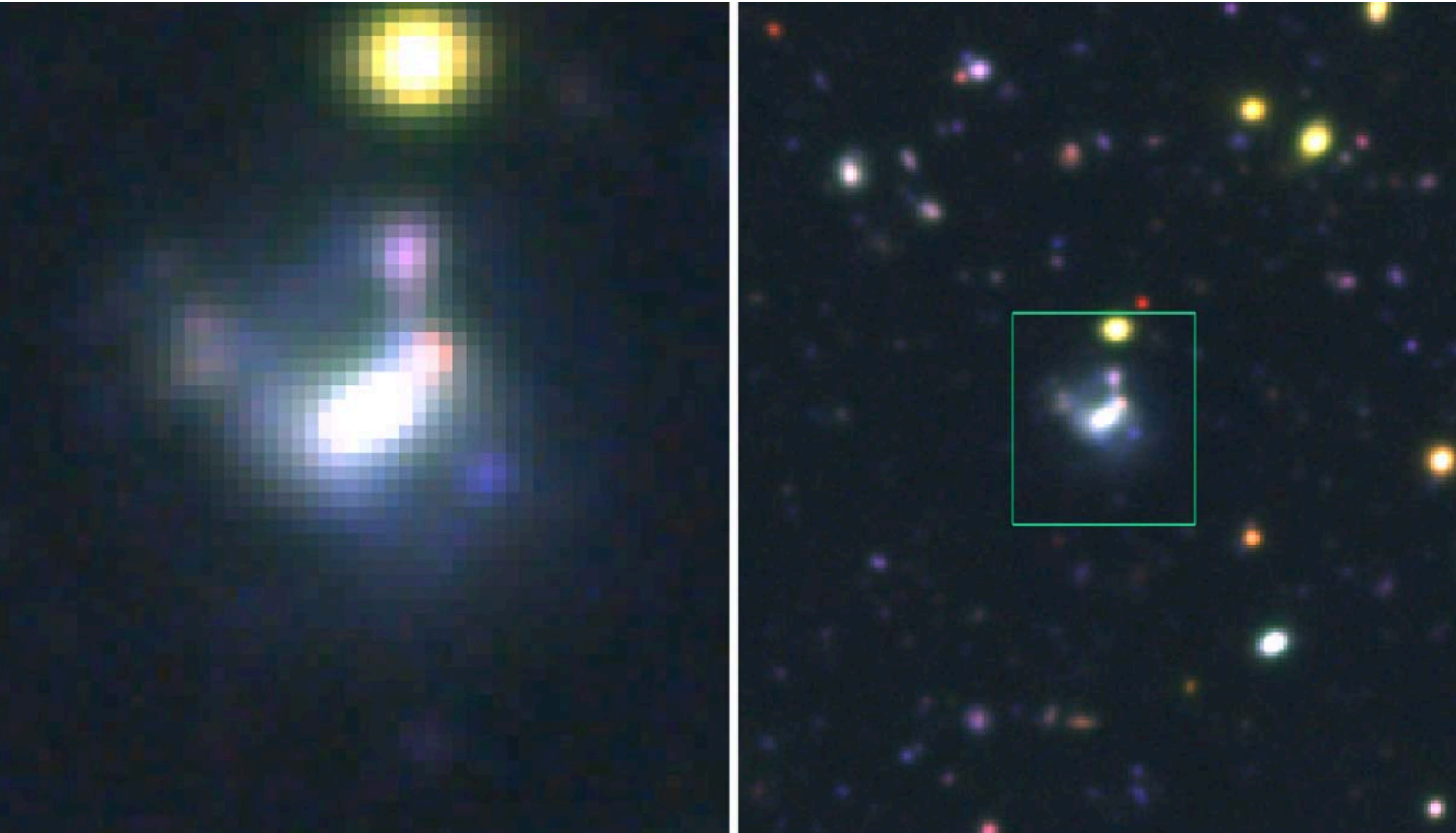


Hildebrandt et al. (2018)

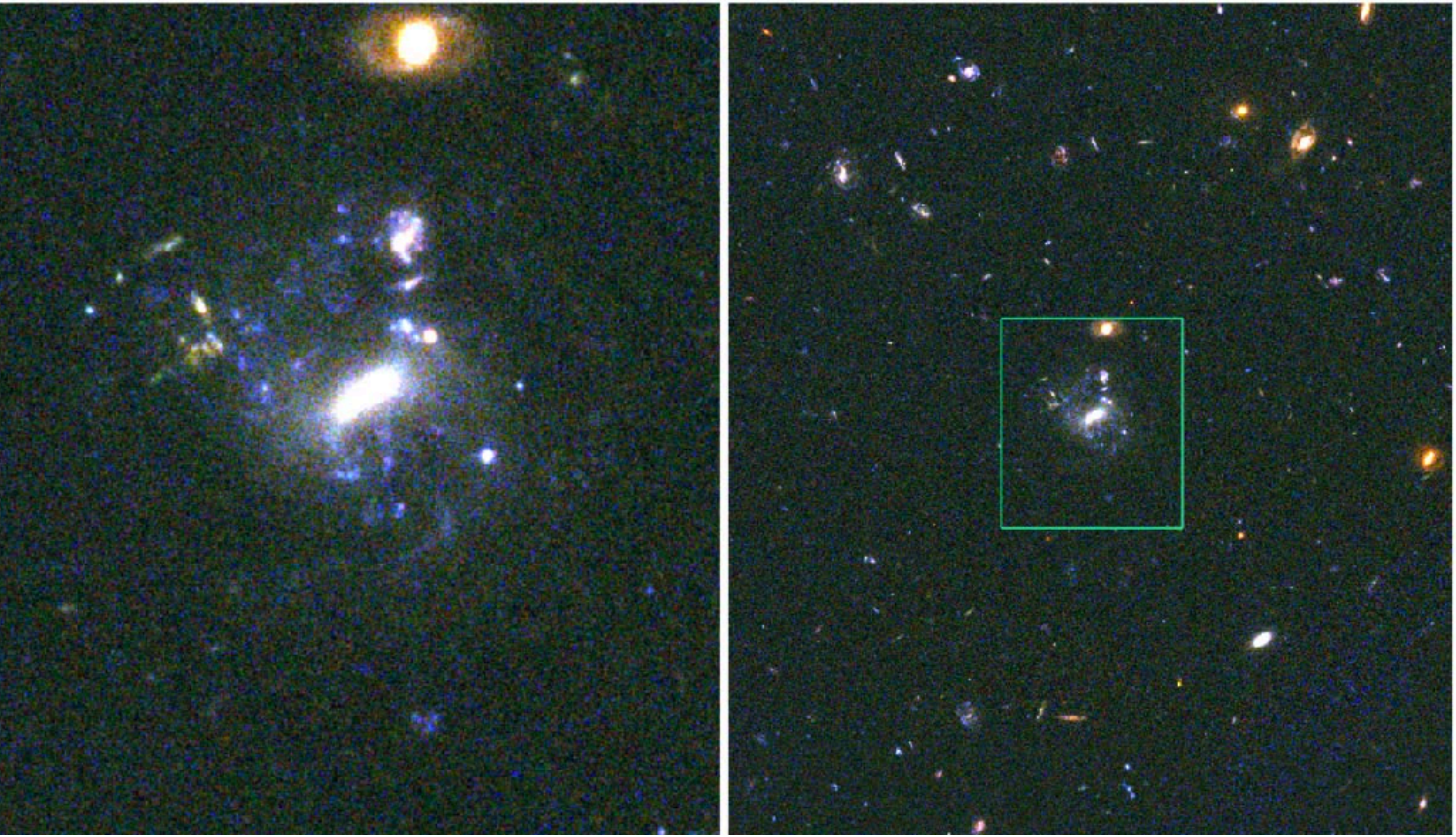
Cosmological constraints



Hildebrandt et al. (2018)

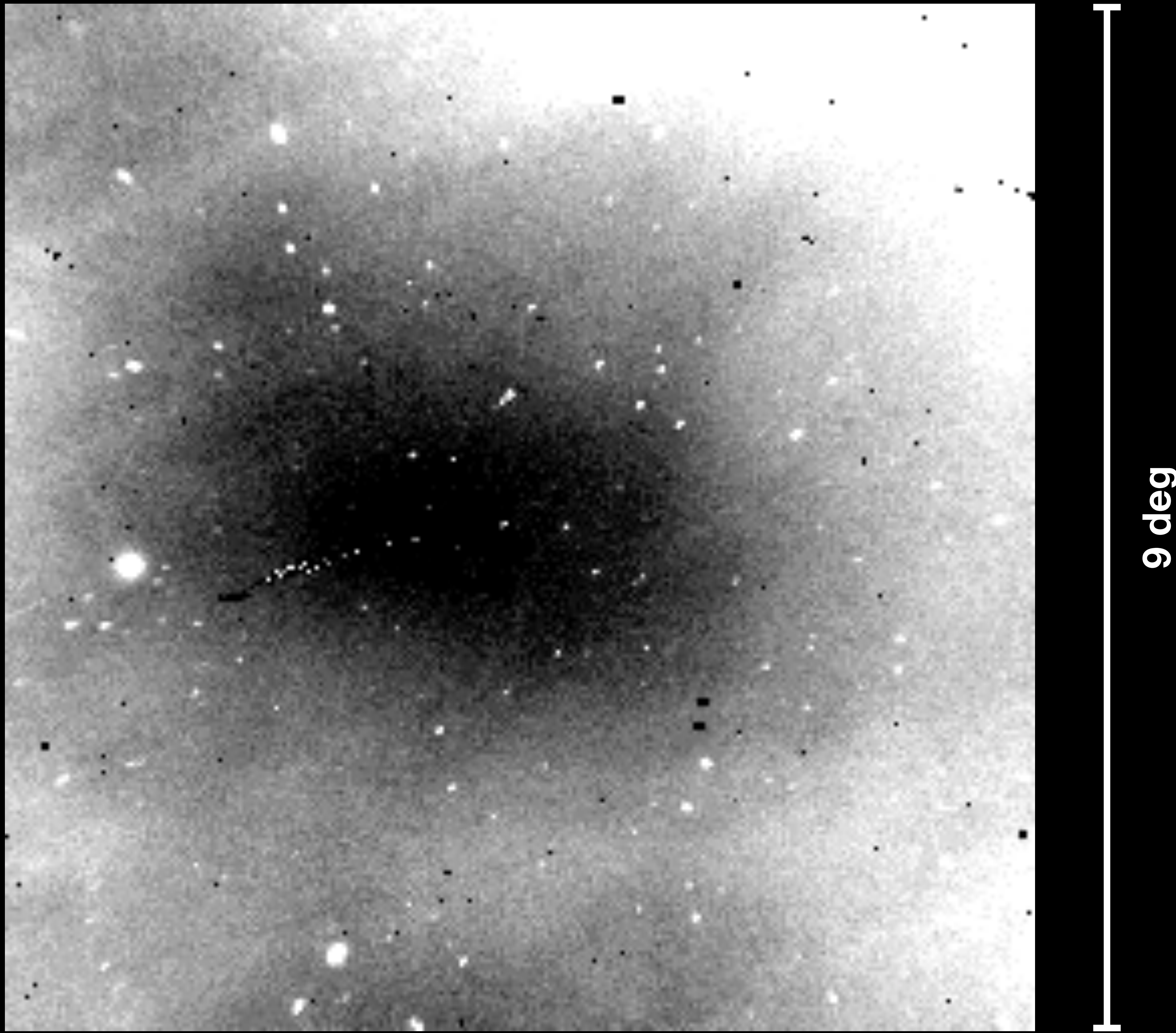


Credit: NASA, Mauro Giavalisco, Lexi Moustakas, Peter Capak, Len Cowie and the GOODS Team.



Credit: NASA, Mauro Giavalisco, Lexi Moustakas, Peter Capak, Len Cowie and the GOODS Team.

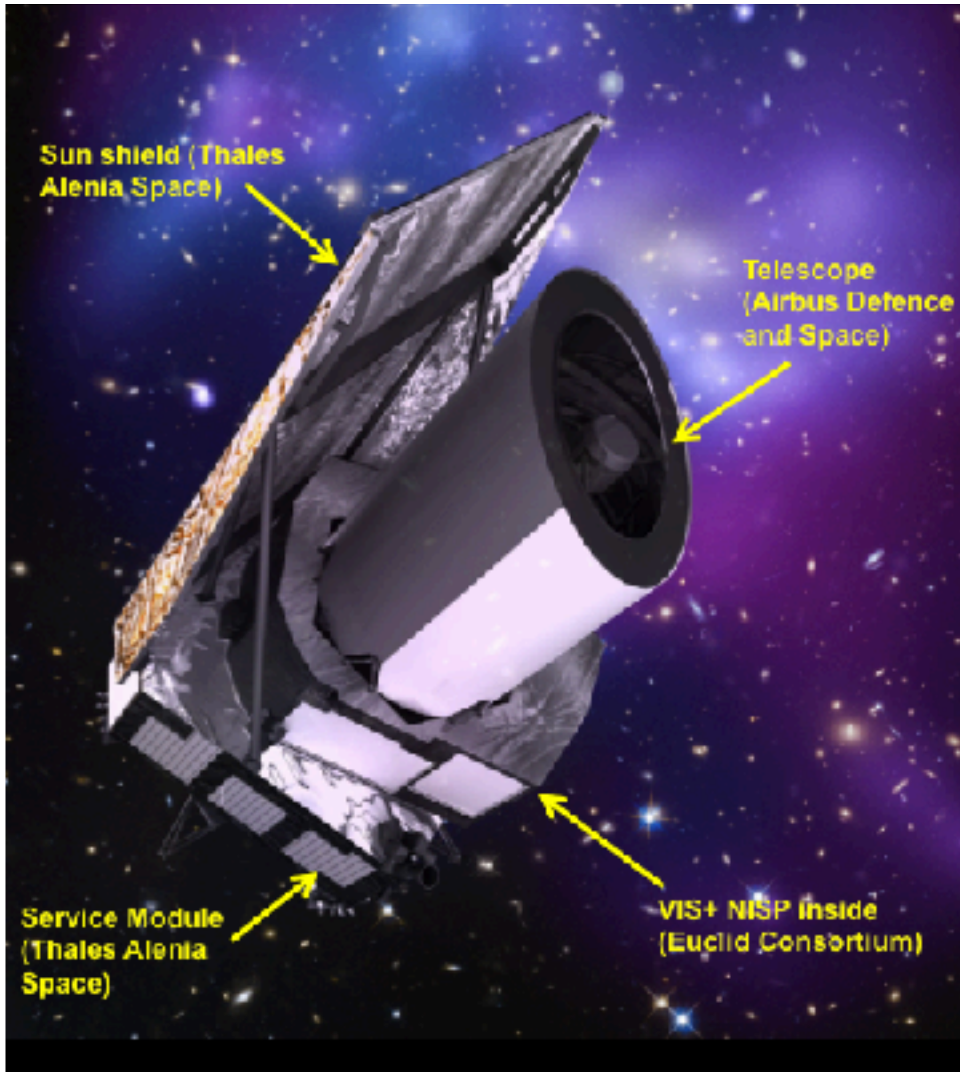
Infrared background



Credit: 2MASS

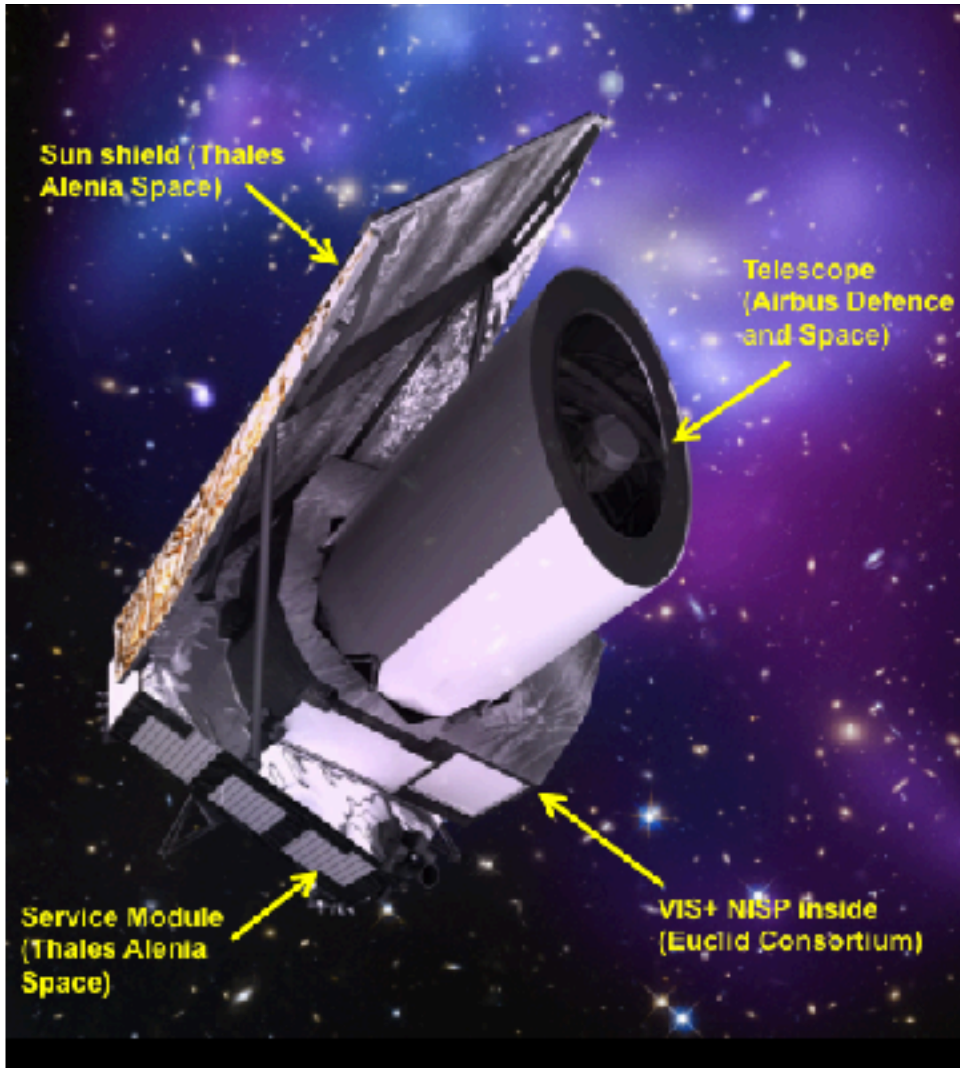
Euclid - Overview

- **Only observe those things from space that you can't do well from the ground!**
- ESA/NASA 1.2m Space Telescope
- optical + NIR imaging (cosmic shear)
- NIR spectroscopy (BAO)
- Launch in ~2022 to L2 like e.g. Planck
- survey 15 000 sq. deg. in 7 years
- 1 billion lensing sources with $0<z<2$



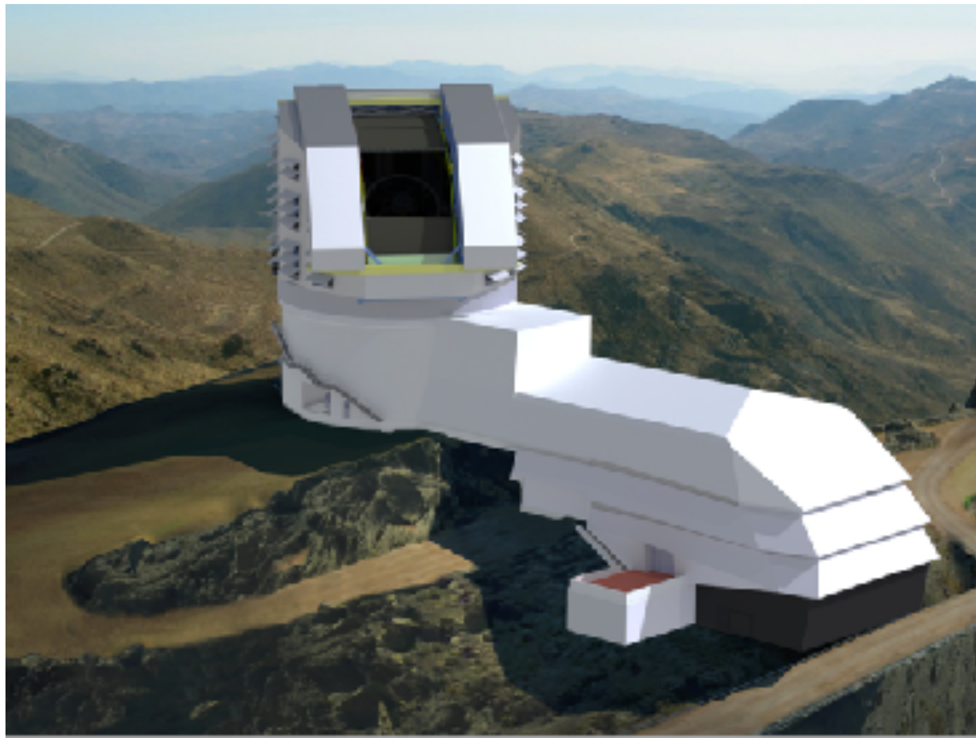
Euclid - Science Goals

- Measure w_0 to <2% and w_a to <10%
- Measure γ (growth factor ~0.5) to <0.02
- Constrain Σm_ν to <0.03eV
- PS slope ~3x better than Planck
- Lots of legacy science (NIR, deep fields, “all-sky” cross-correlations)
- **Open huge parameter space**



Large Synoptic Survey Telescope

- 8.4m optical wide-field imaging telescope
- Huge camera, rapid survey speed, 18,000deg^2 total
- Deep multi-band photometry (also time domain)
- Crucial complement to Euclid
- Very challenging big data application
- US-led with international partners



Summary

- Dynamic dark energy or cosmological constant?
- 4 observational techniques to answer this question.
- Current data show intriguing discrepancies between:
  - CMB (physics at z~1100, 400k year after BB).
  - Low-z growth of structure & H_0.
- Very exciting times: several stage-III surveys finishing now.
- Perfect dress-rehearsal for Euclid+LSST.