Galaxies far, far away…

Exploring the Universe with Weak Gravitational Lensing and Galaxy Clustering

Jonathan Blazek
Northeastern University
Dark Energy Survey, Dark Energy Science Collaboration
La Thuile, March 2024

Photometric (imaging) surveys

Dark Energy Survey

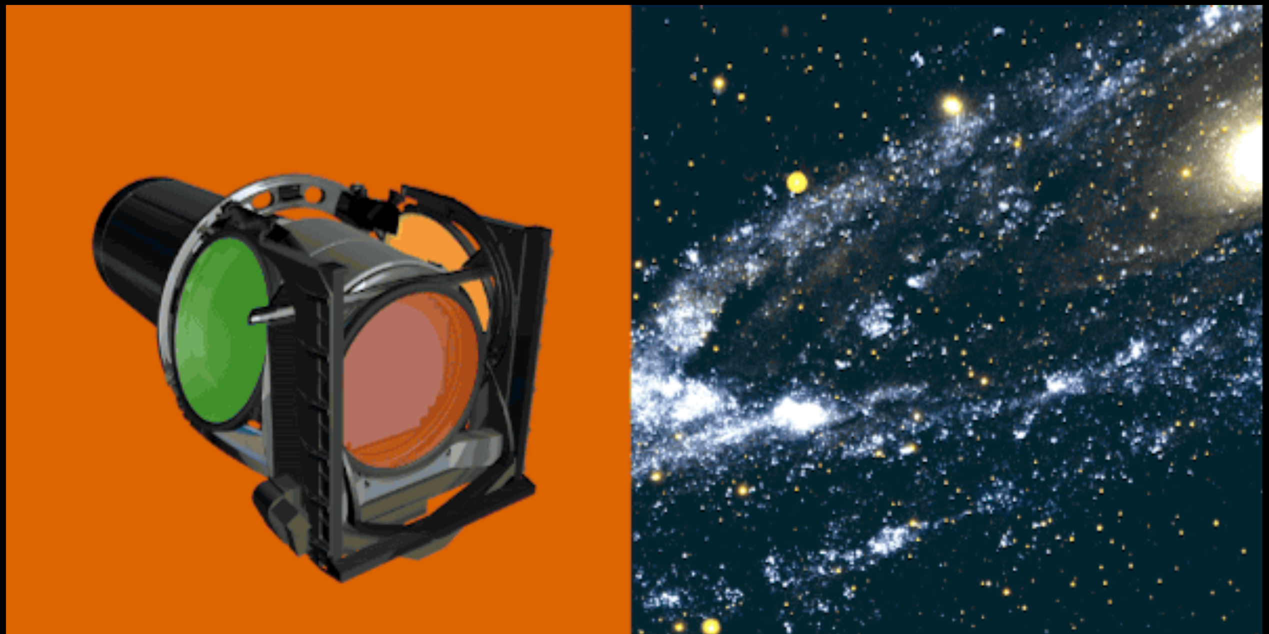


Fig: Rubin/LSST

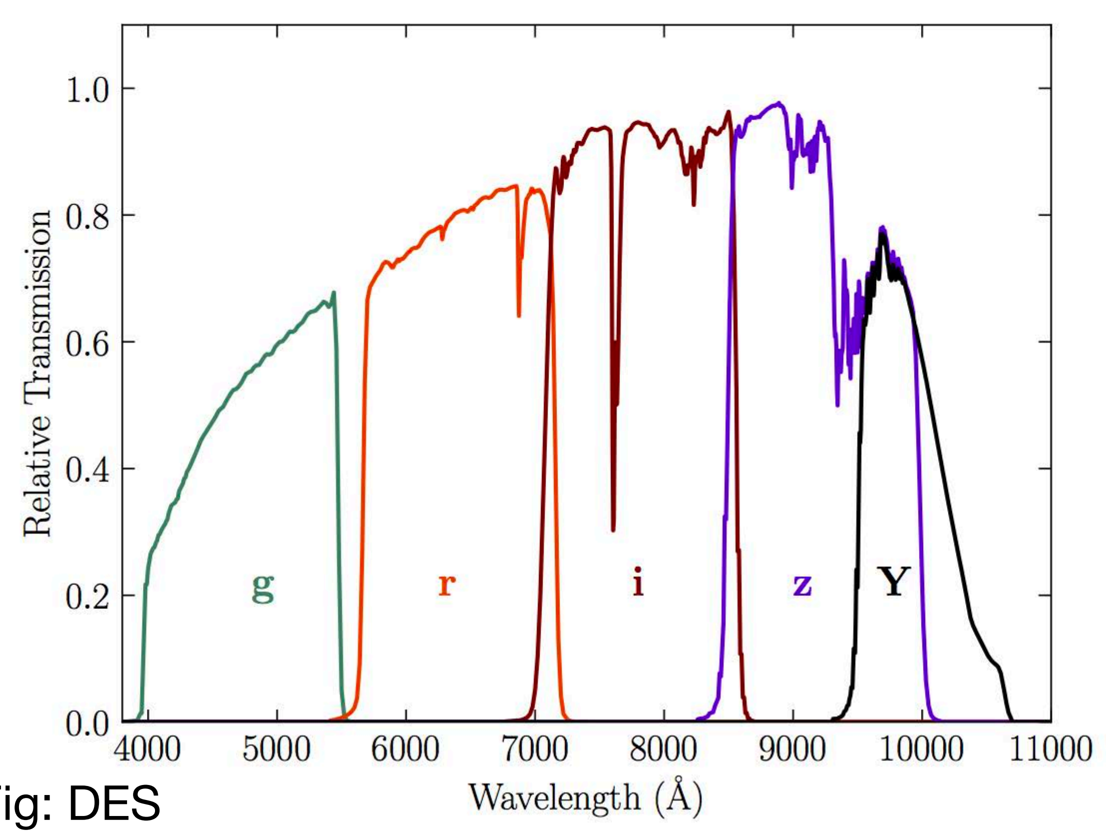
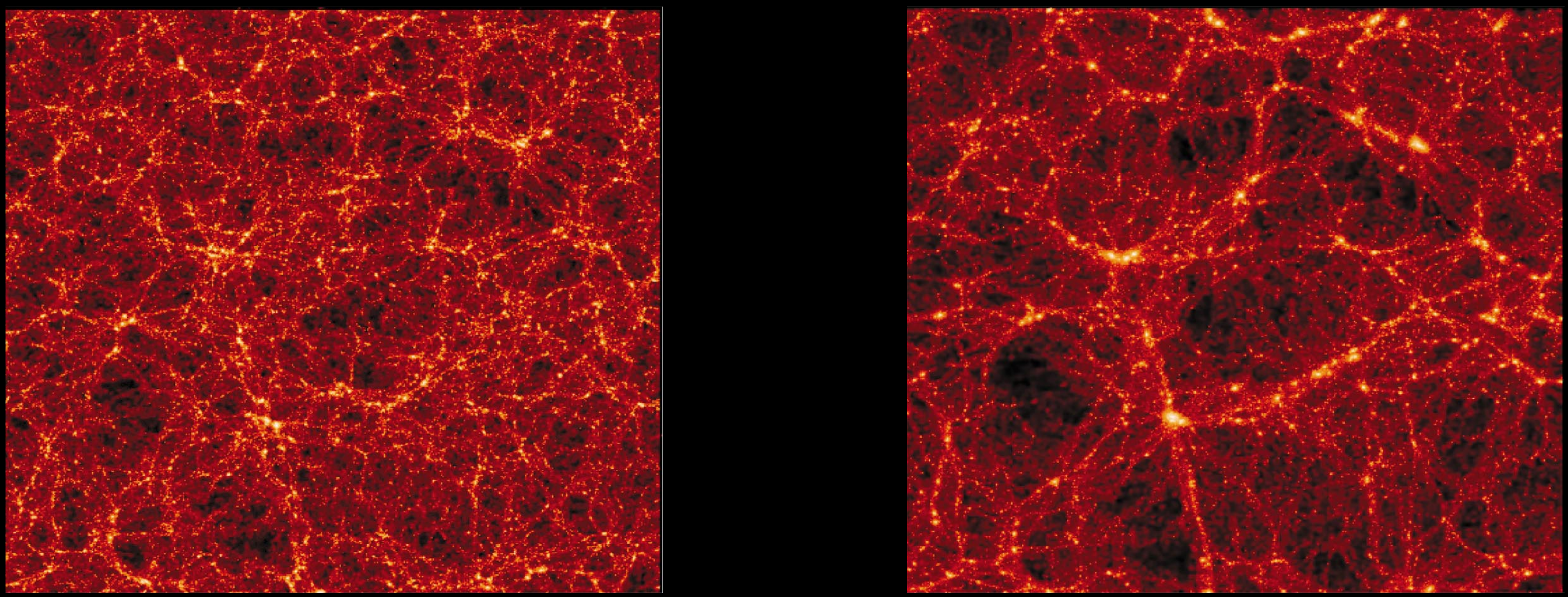


Fig: DES

Geometry and Growth

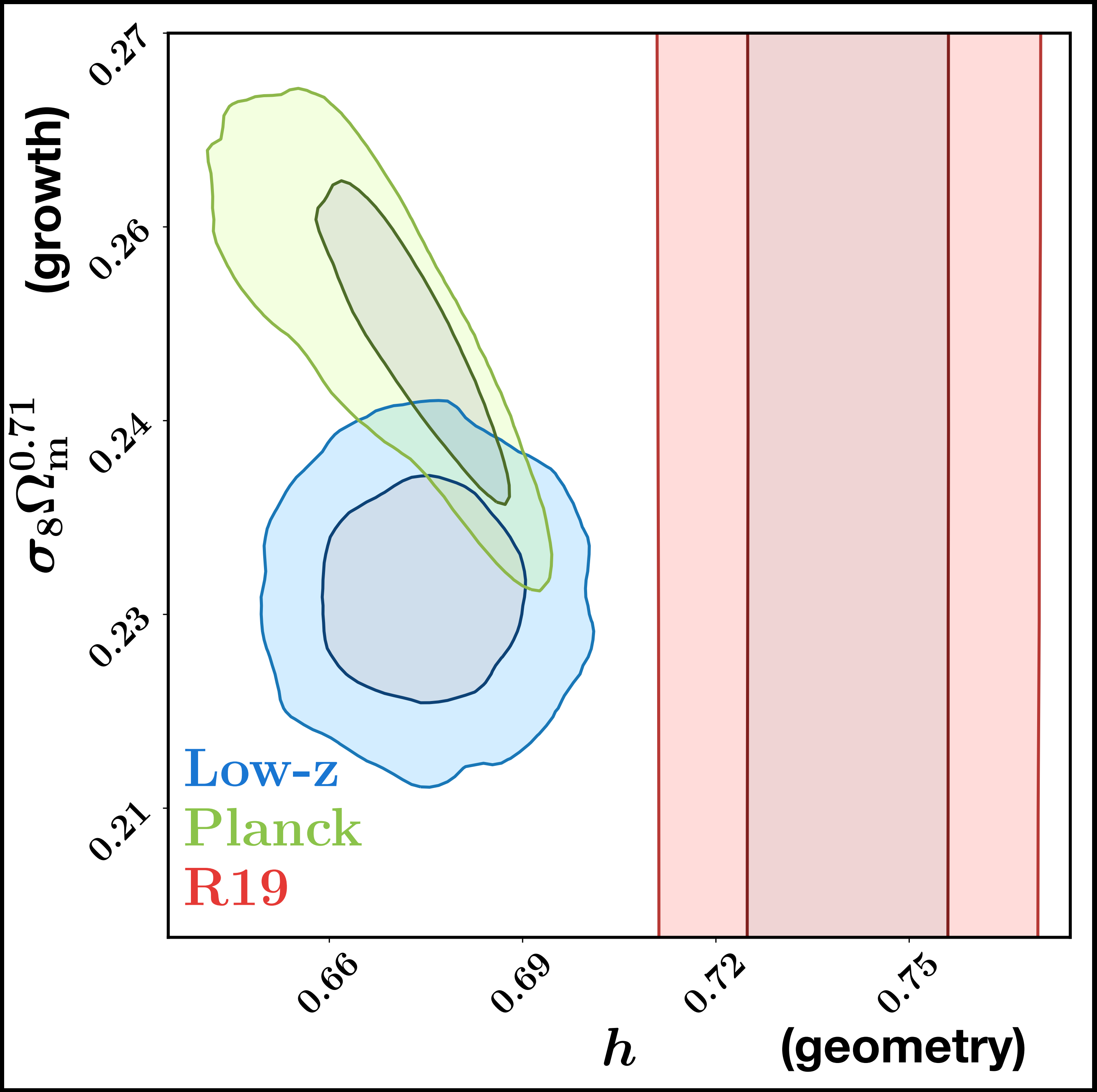


(Virgo simulations: Jenkins+ 1998)

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

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

Concordance Cosmology?

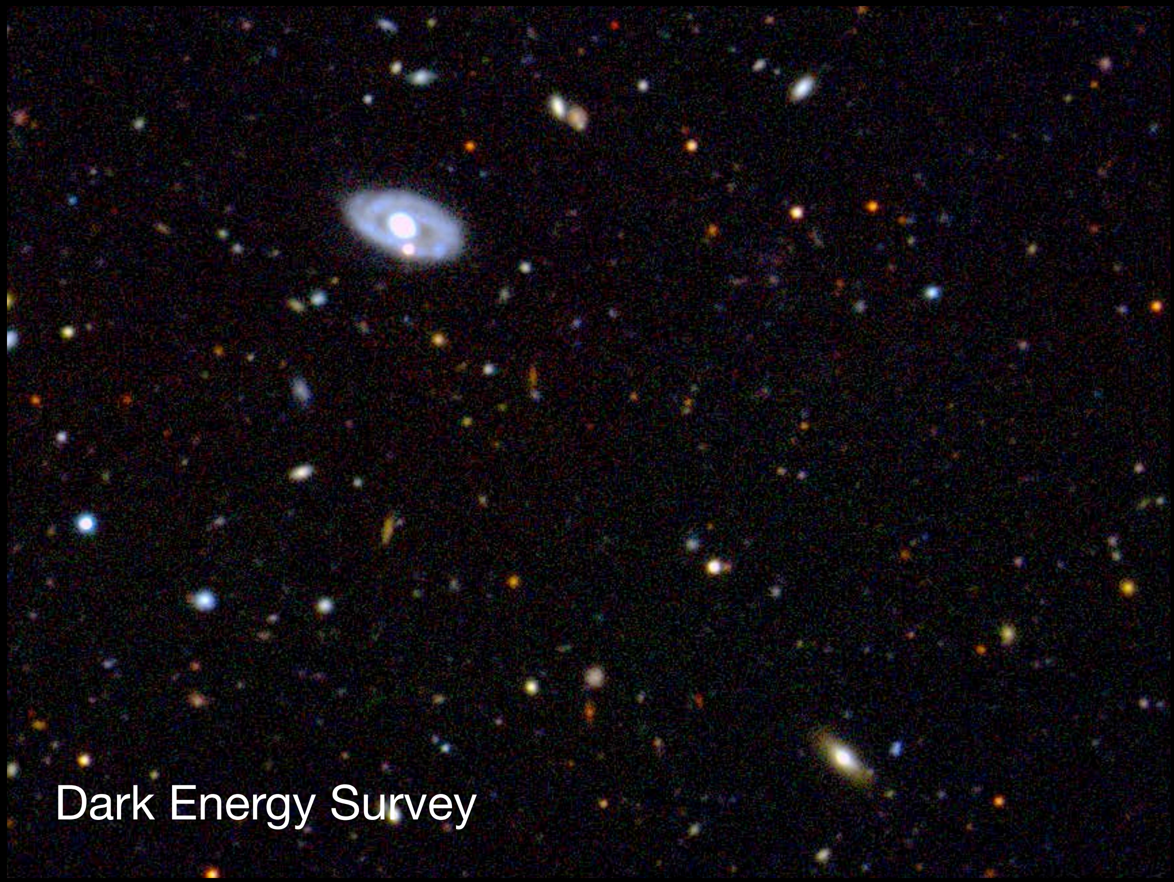


Park & Rozo 2019

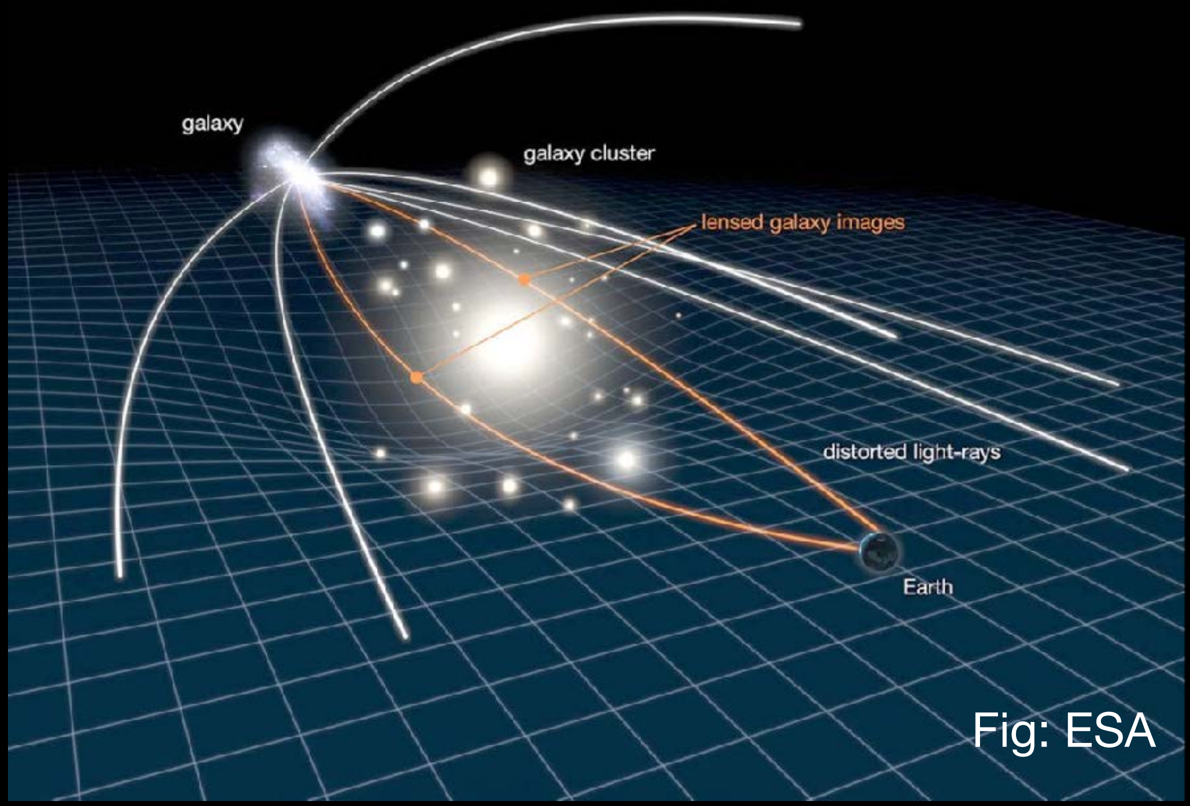
Outline

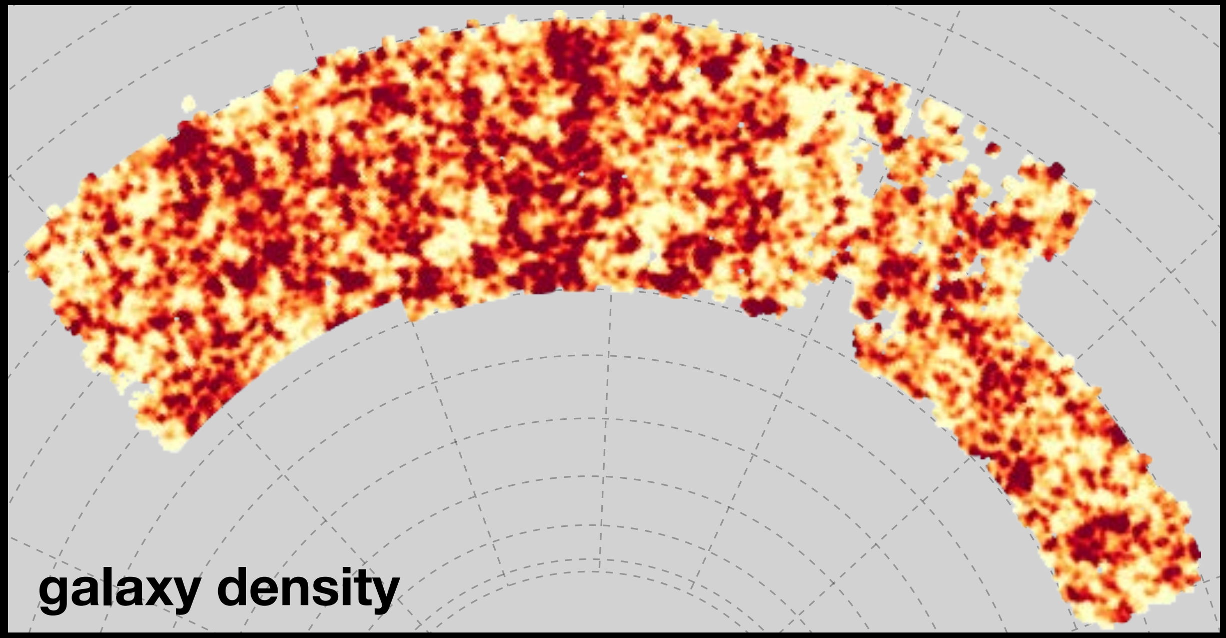
- Cosmology with galaxy surveys: combining weak lensing and galaxy clustering
- Dark Energy Survey (DES, Year 3) and joint analysis with the Kilo Degree Survey (KiDS)
- Modeling galaxy observables
- The future of galaxy surveys

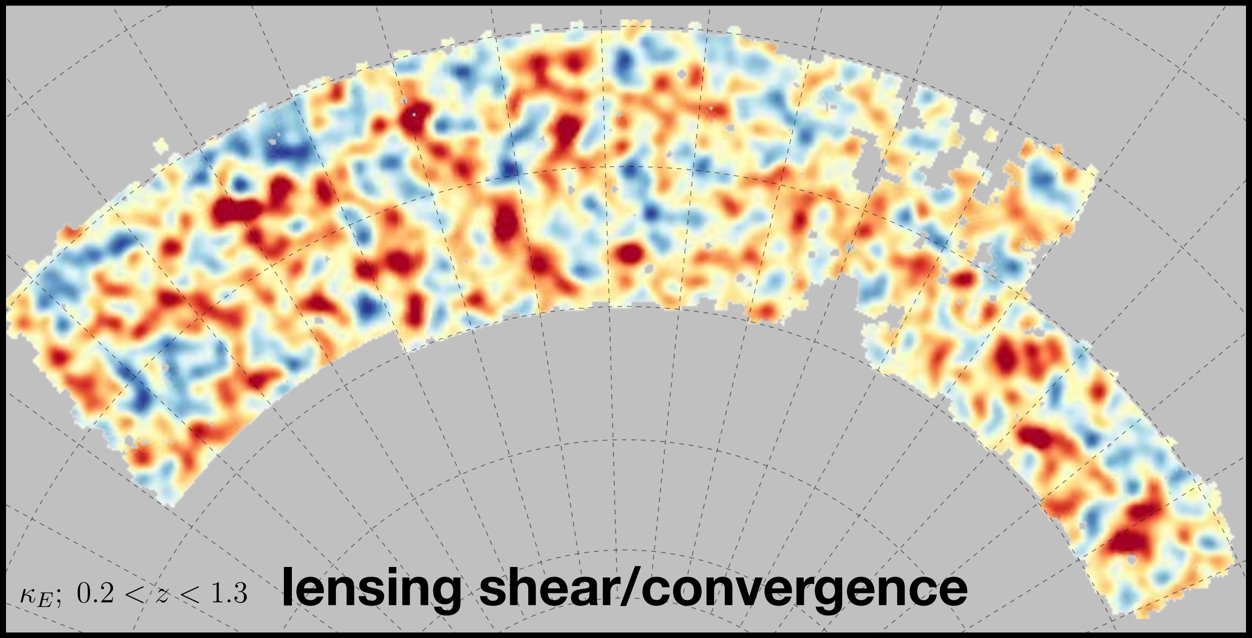
Lensing and large-scale structure



(Weak) Gravitational Lensing

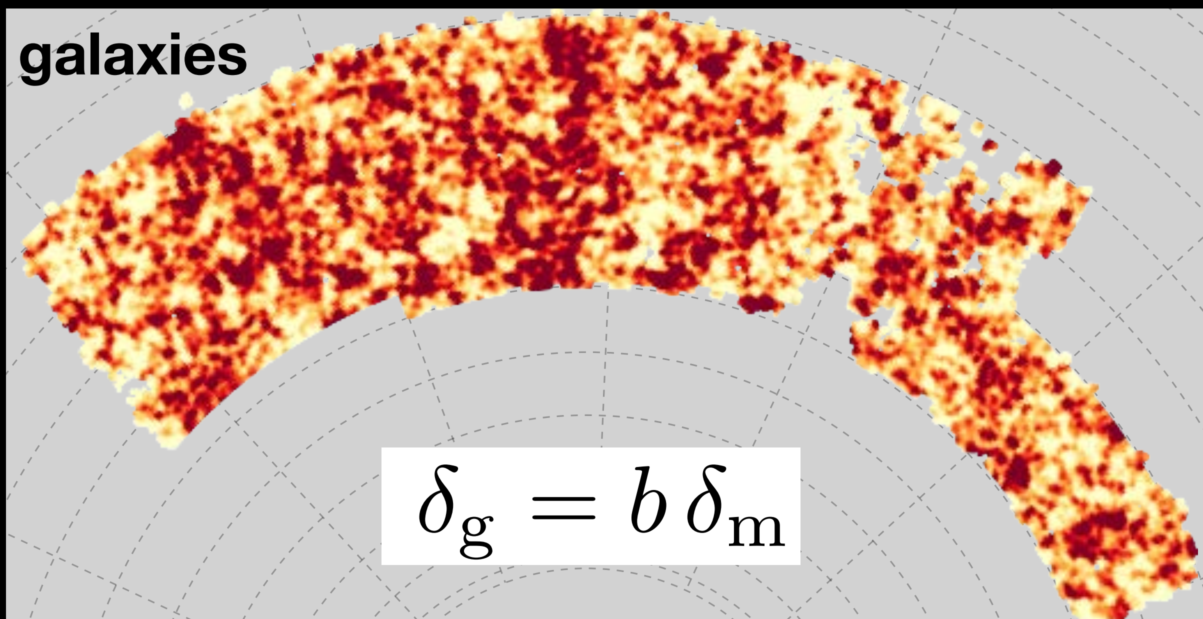


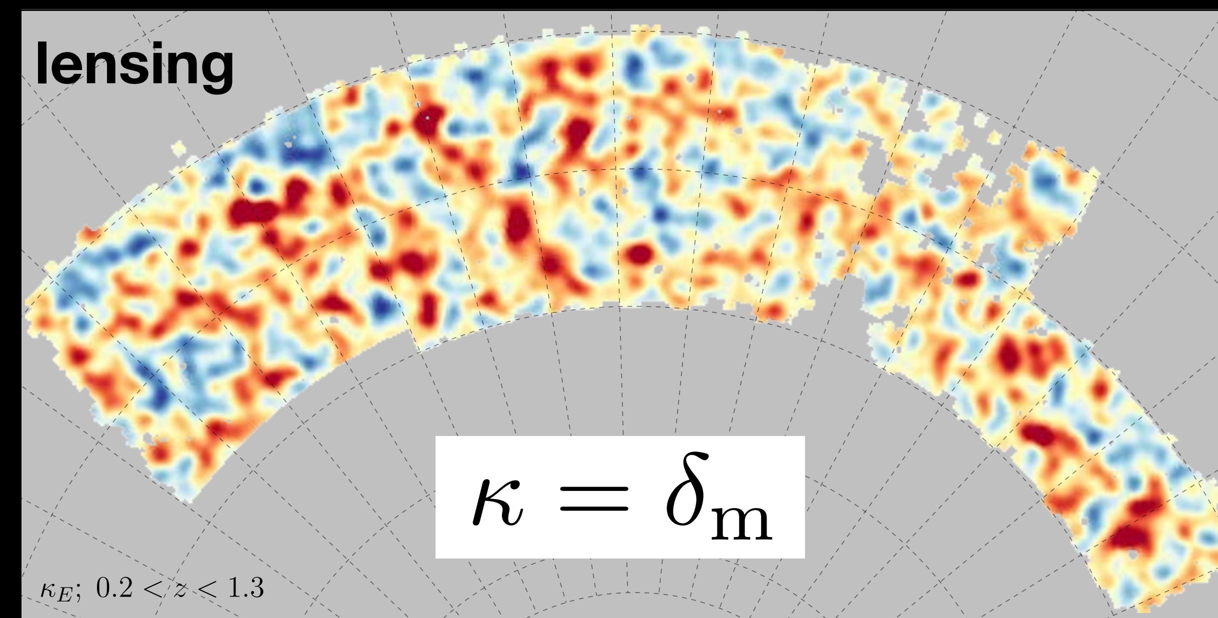




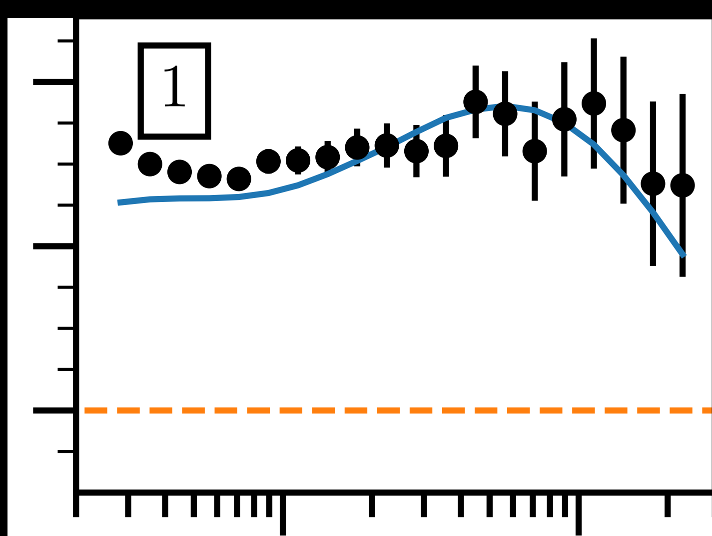
DES Year 1: Elvin-Poole+ 2018; Chang+ 2018

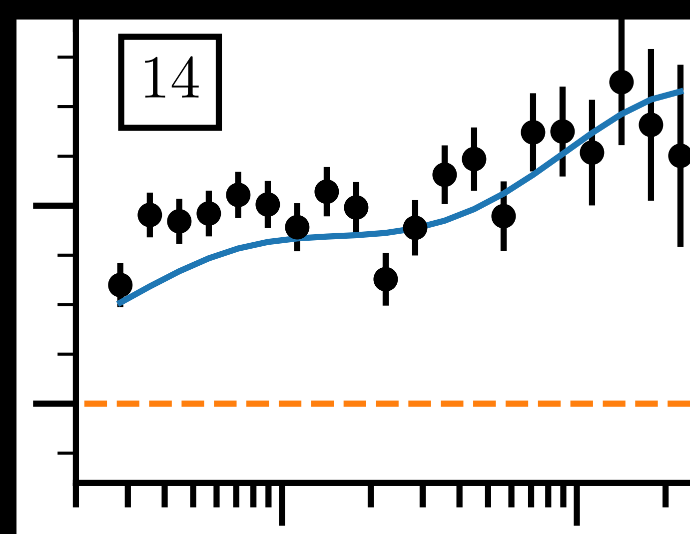
Combining probes

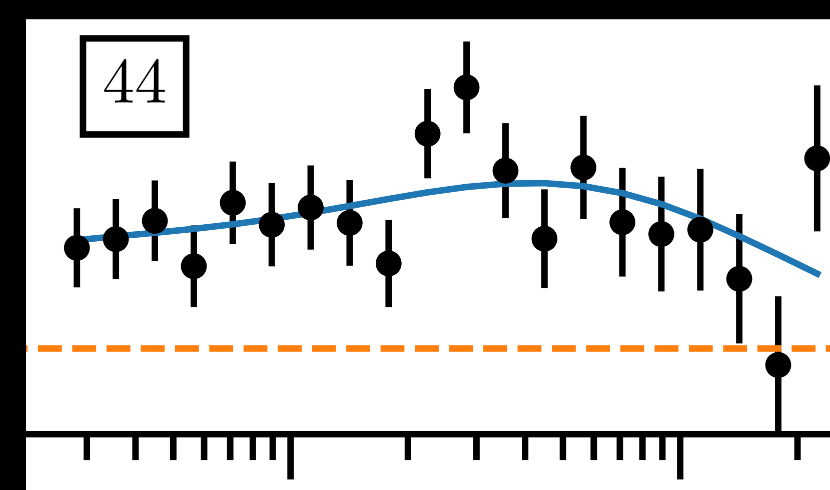




$\langle \delta_g | \delta_g \rangle = \xi_{\rm gg} \sim b^2 \sigma_8^2$ $\langle \delta_g | \kappa \rangle = \xi_{\rm gm} \sim b \sigma_8^2$ $\langle \kappa | \kappa \rangle = \xi_{\rm mm} \sim \sigma_8^2$



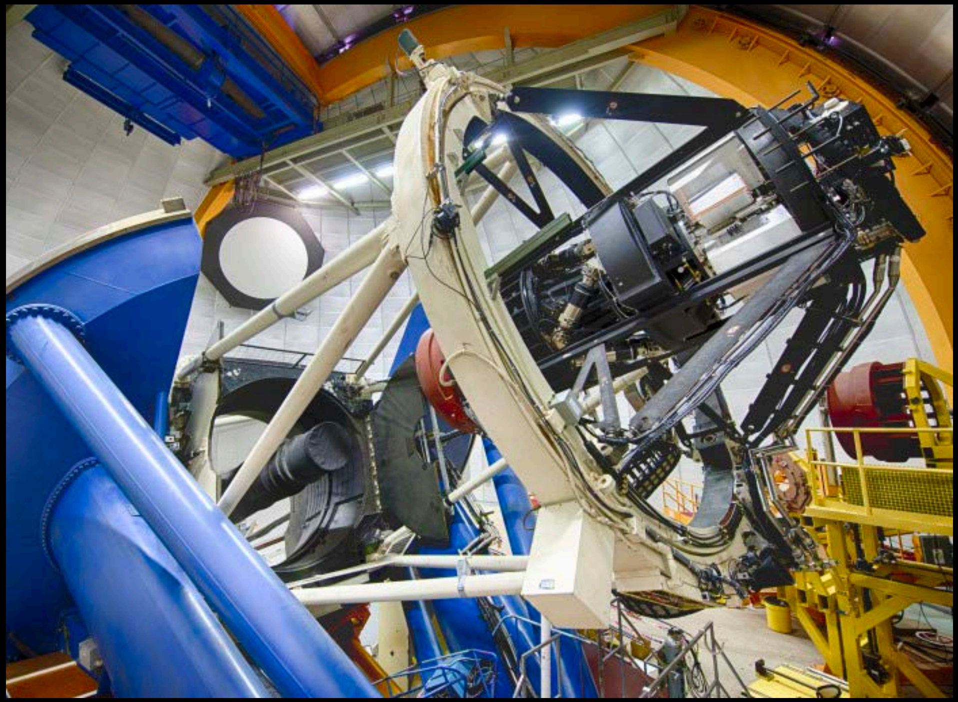




“3x2 analysis”

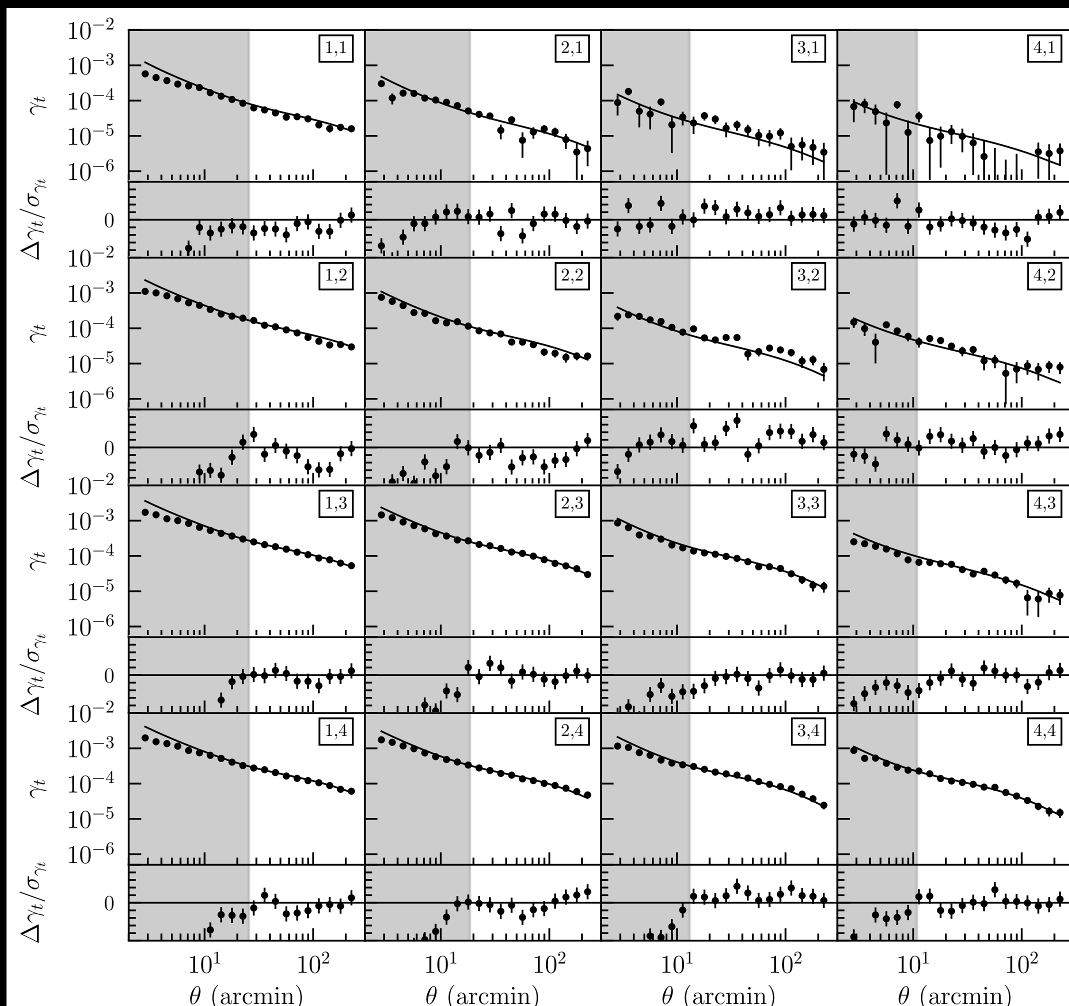
Dark Energy Survey

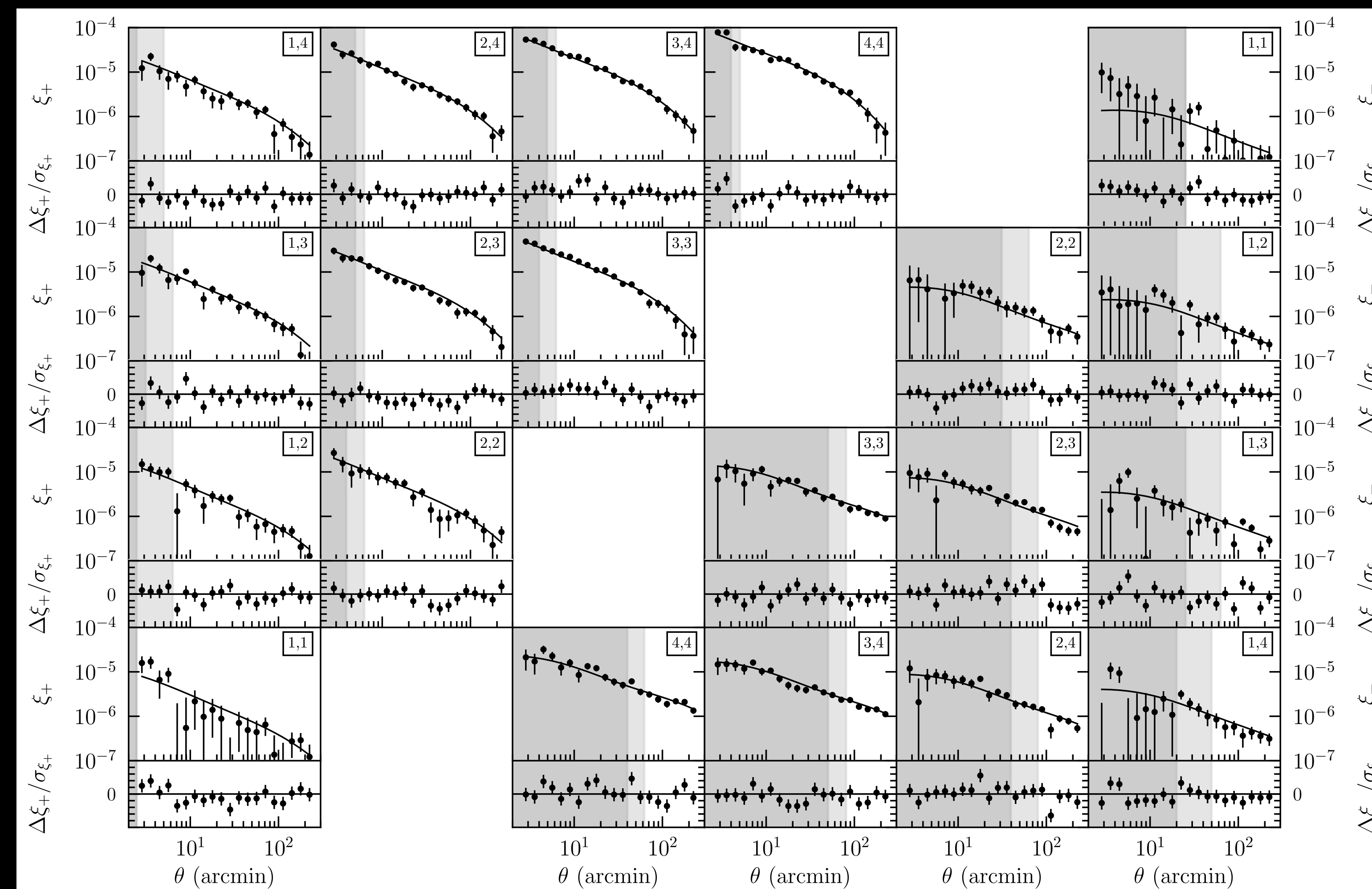
- DECam (520 Mpix) on 4m Blanco Telescope, Cerro Tololo, Chile
- 1/8 of sky (5000 deg^2)
- 6 year mission, 525 nights, completed Jan 2019. Y3 is full area. *Y6 analysis in progress*
- *grizY* filters (photometric redshifts)
- ~300 million galaxies ($0 < z < 2$)
  Y3: 100 million with WL shapes
  Y6: deeper and has a second shear measurement method

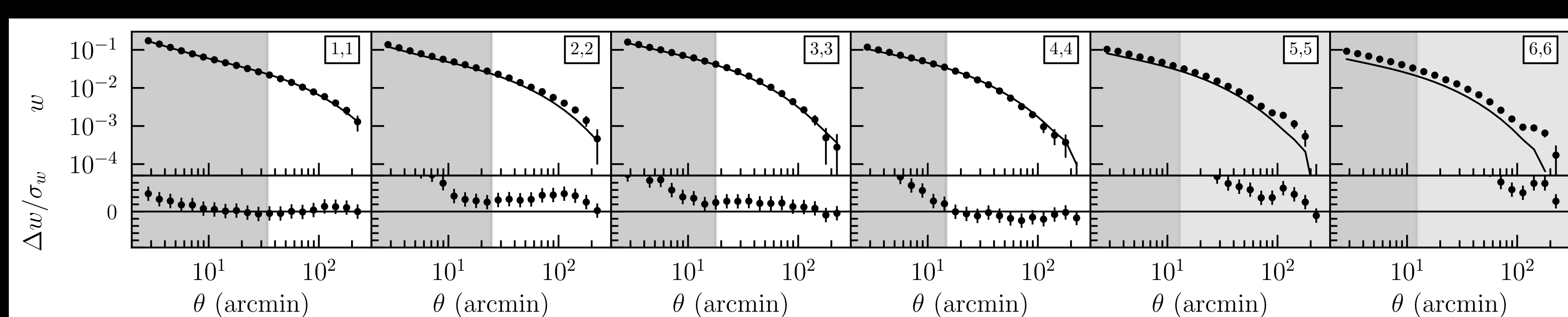


DES Y3 correlation functions

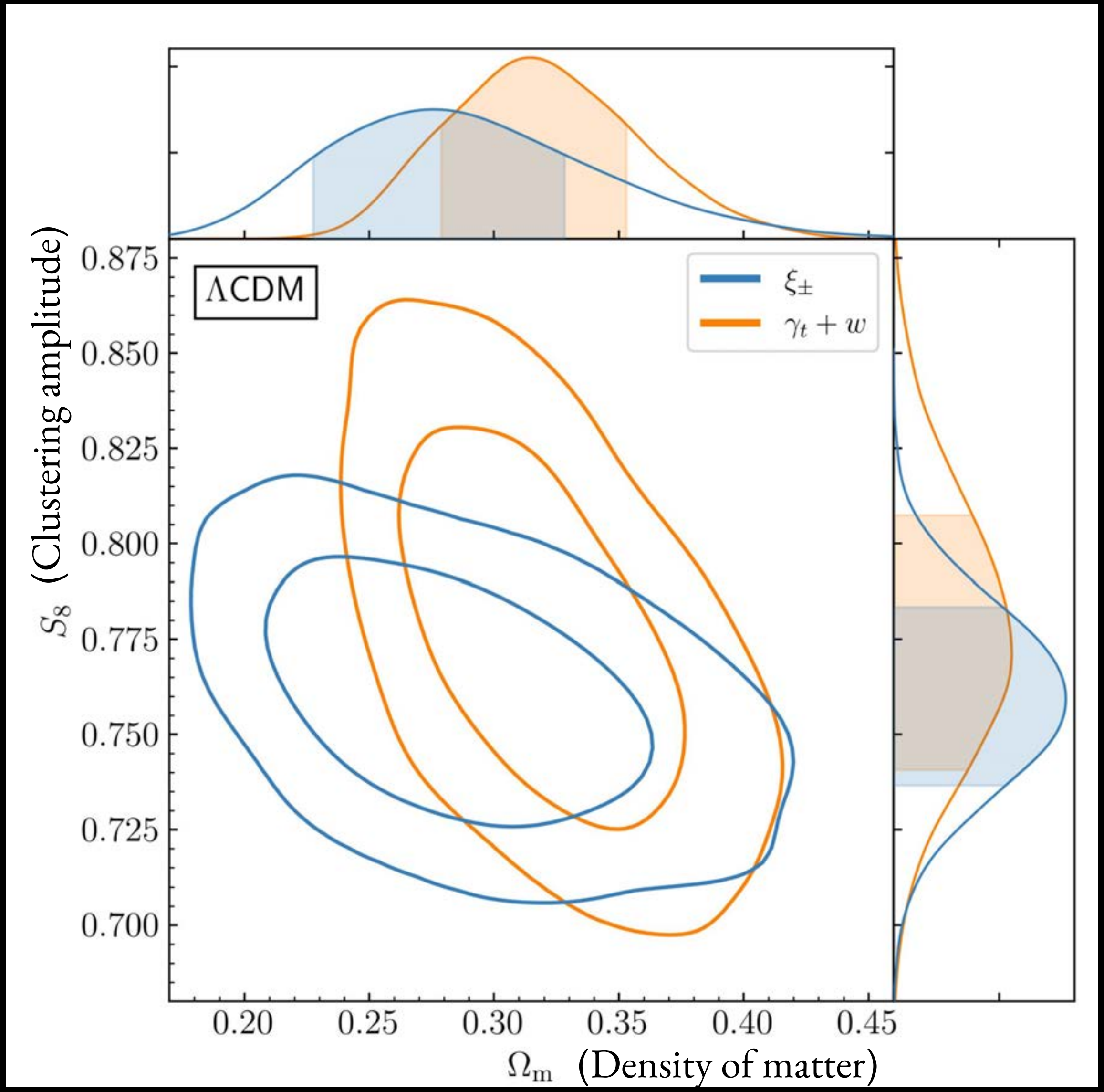
DES Collaboration Key Paper 2022 (arXiv:2105.13549)

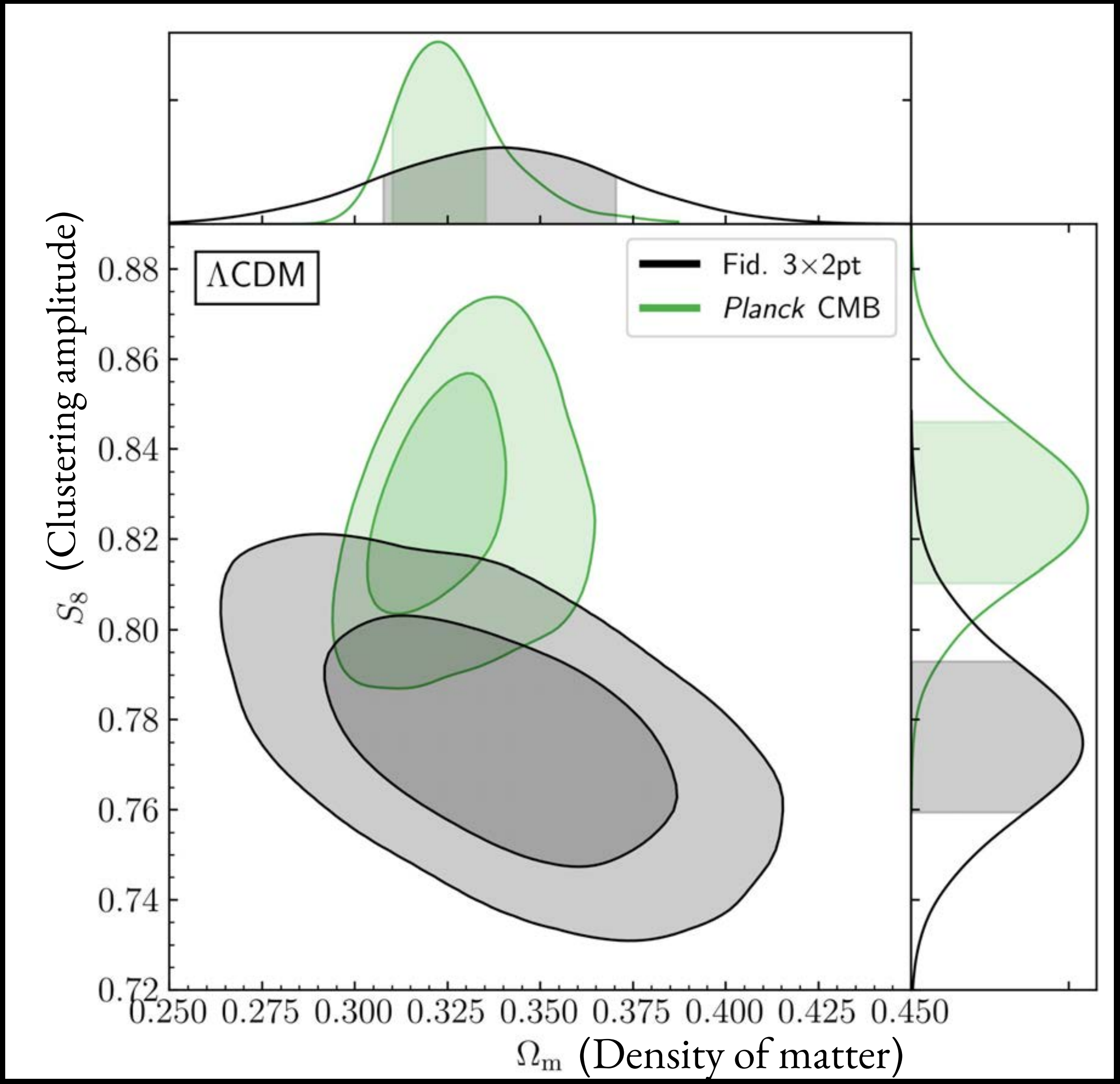






Y3 results: Consistency (?) with Planck (in ΛCDM)

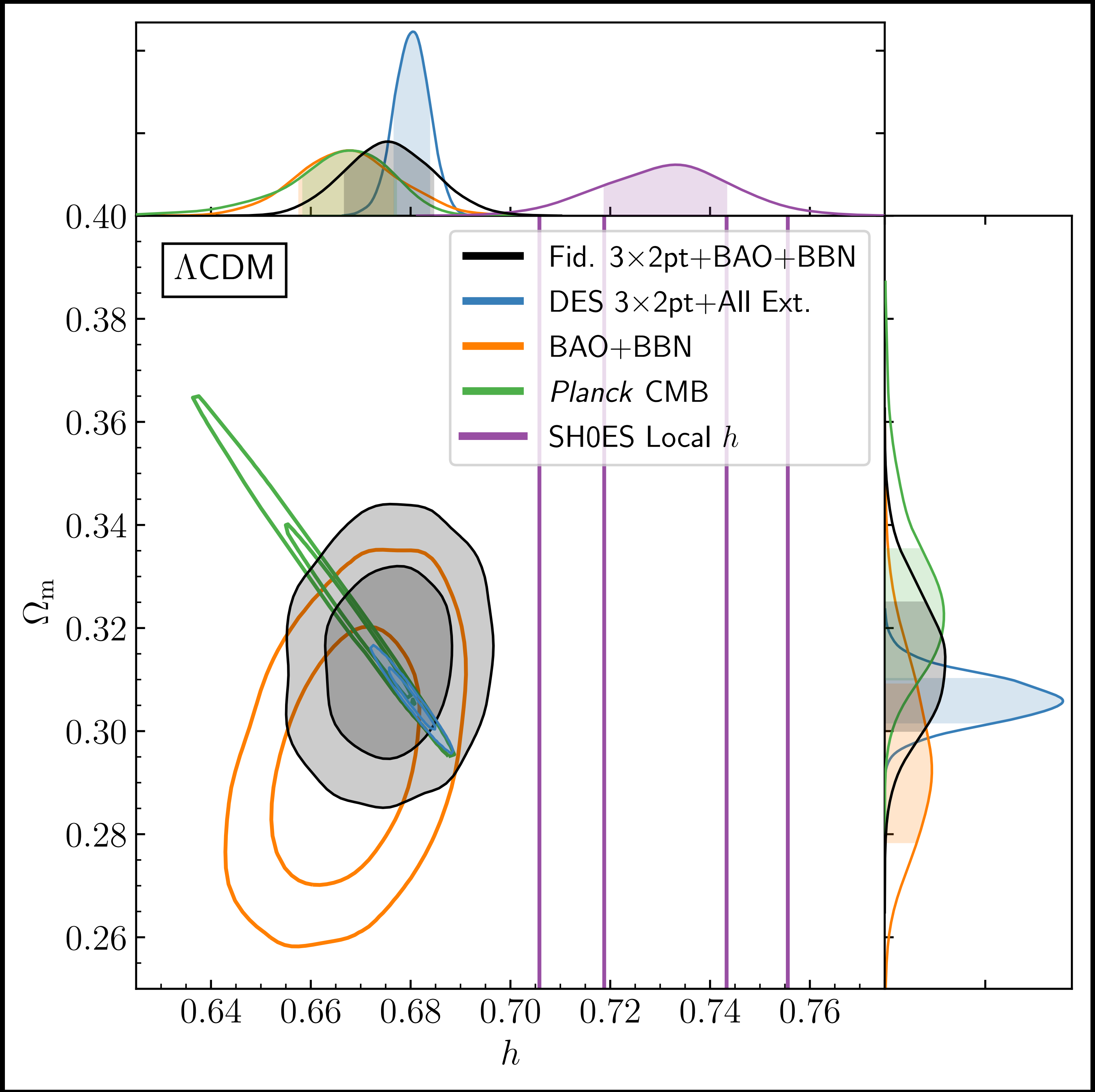




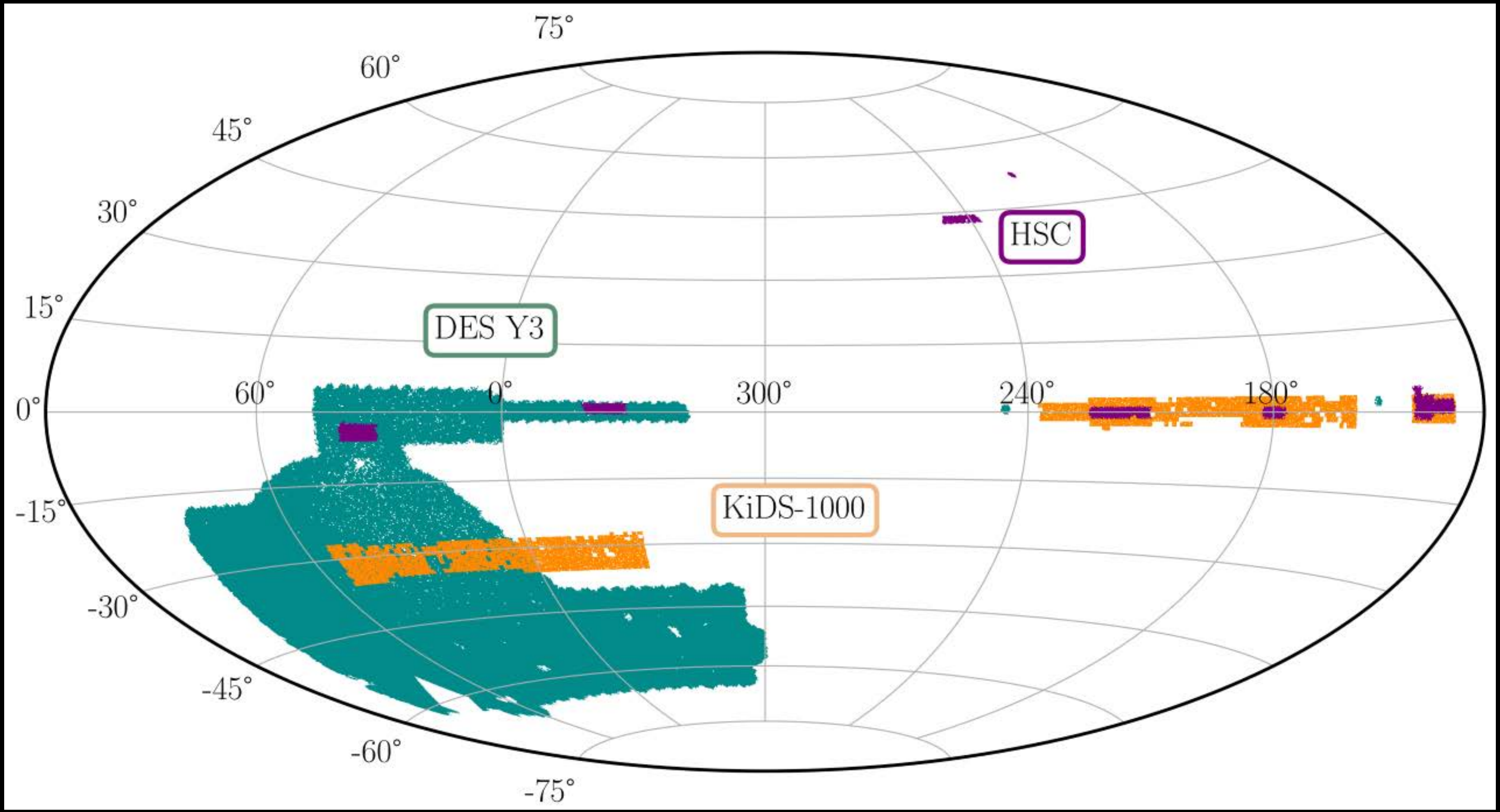
1.5**σ** parameter tension vs. 2.2**σ** in Y1

Y3 results: Hubble tension

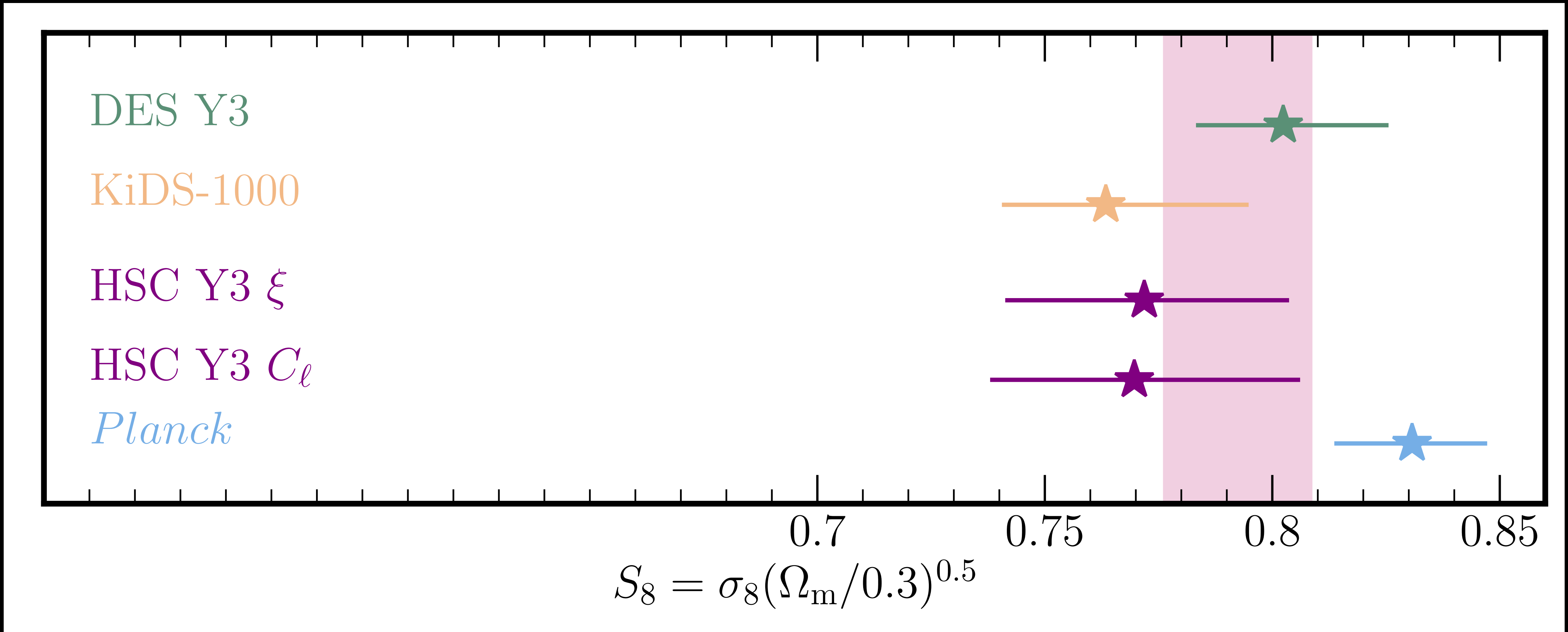
~4$\boldsymbol{\sigma}$ tension with SH0ES



Comparison to other surveys



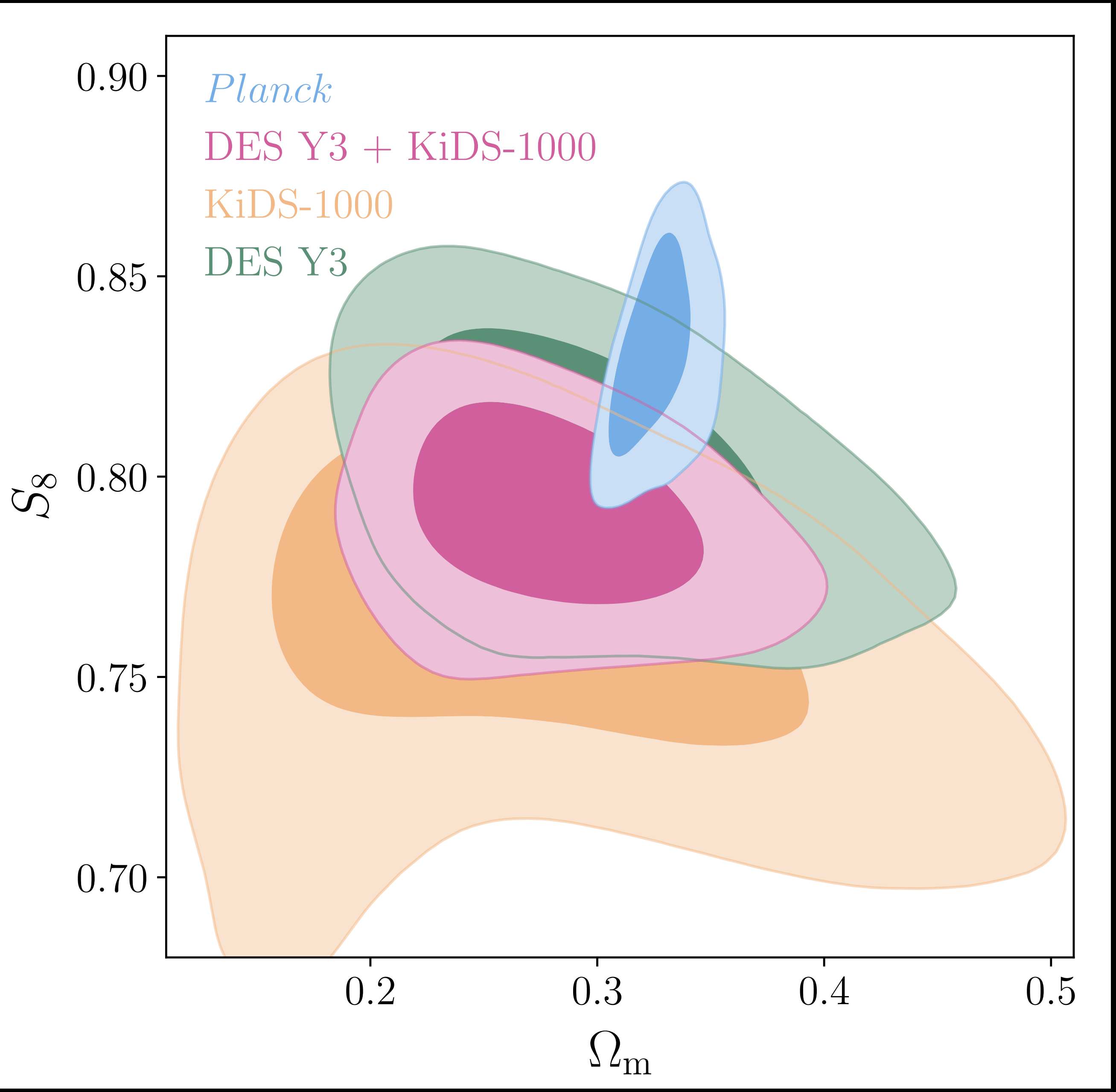
Comparison to other surveys



Cosmic shear only

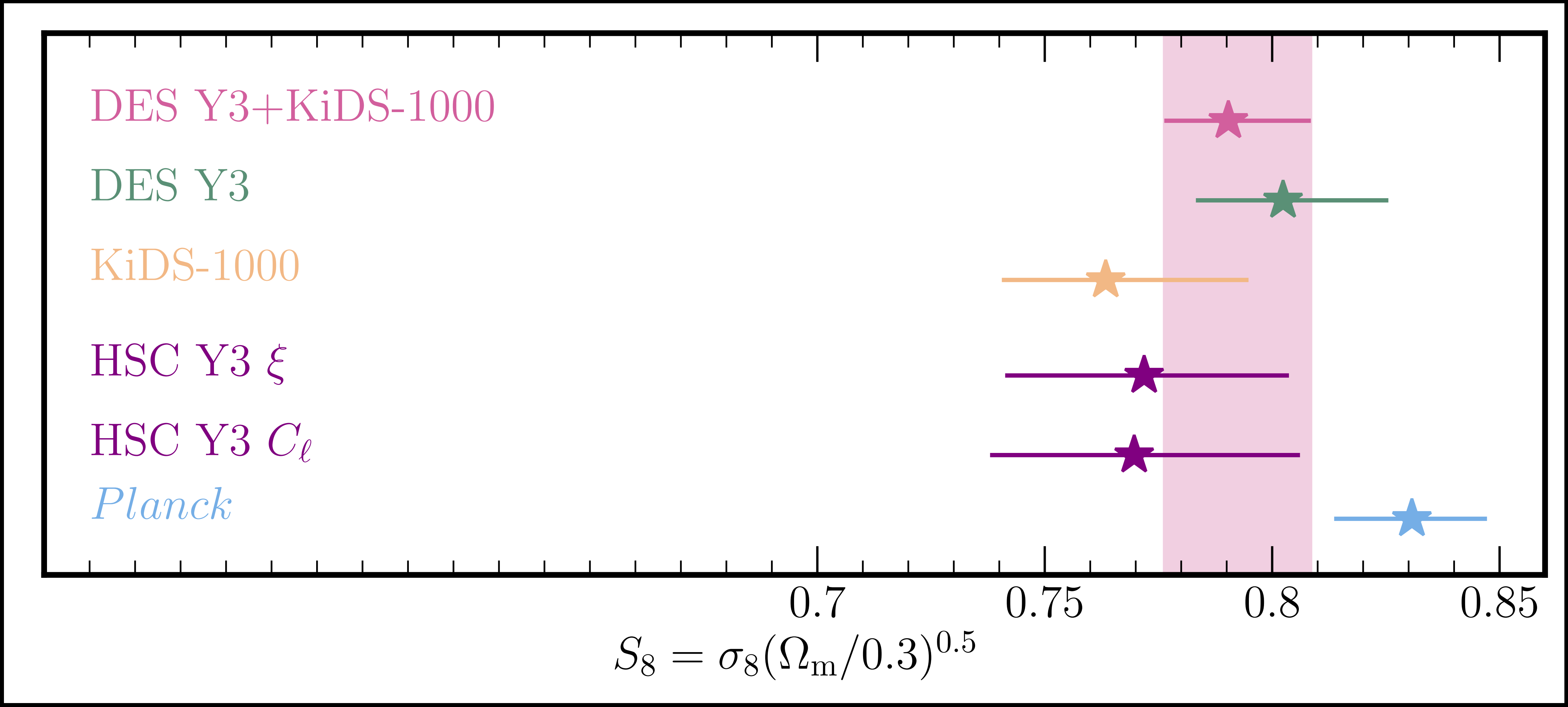
DES + KiDS 2023 (arXiv:2305.17173)

Combining surveys: DES + KiDS



Cosmic shear - Hybrid analysis pipeline
DES + KiDS 2023 (arXiv:2305.17173)

Combining surveys: DES + KiDS



Cosmic shear - Hybrid analysis pipeline
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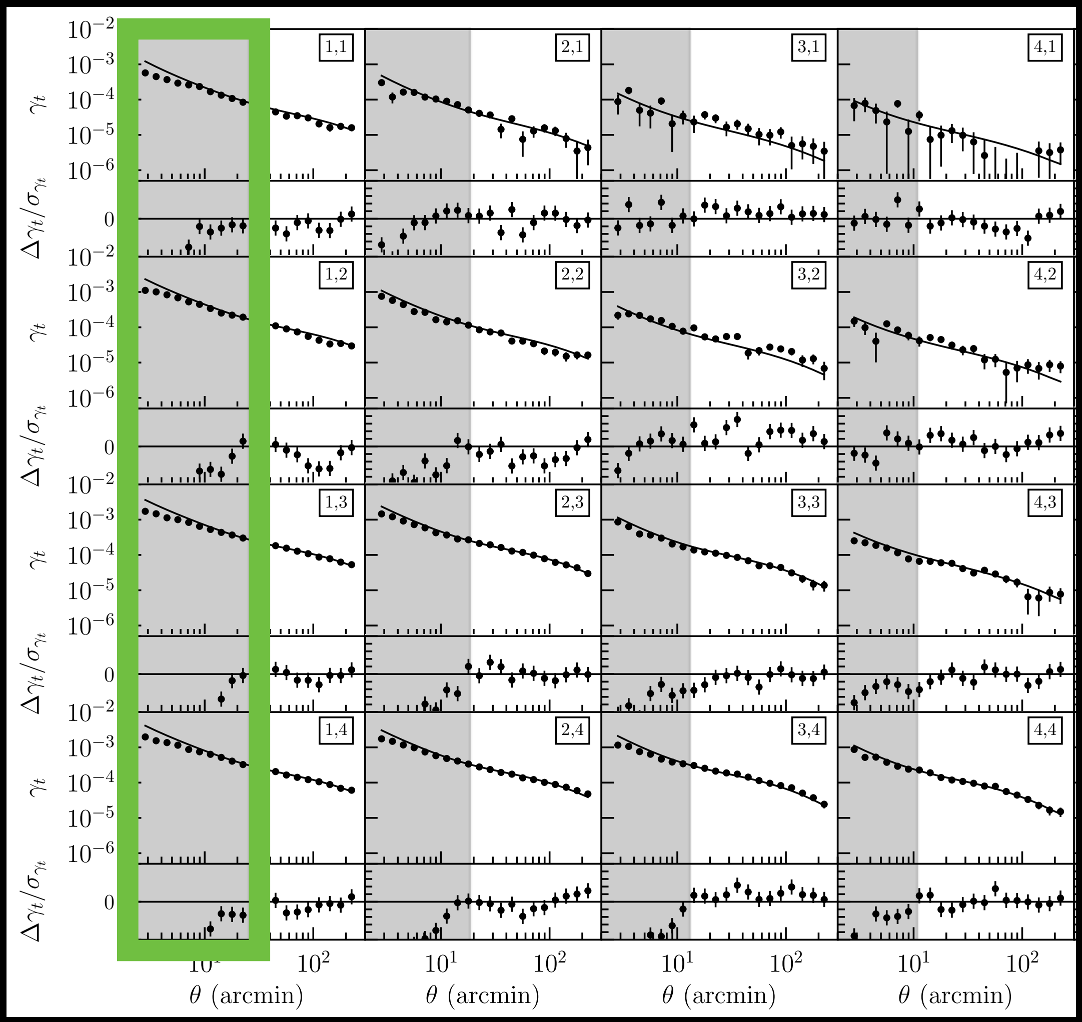
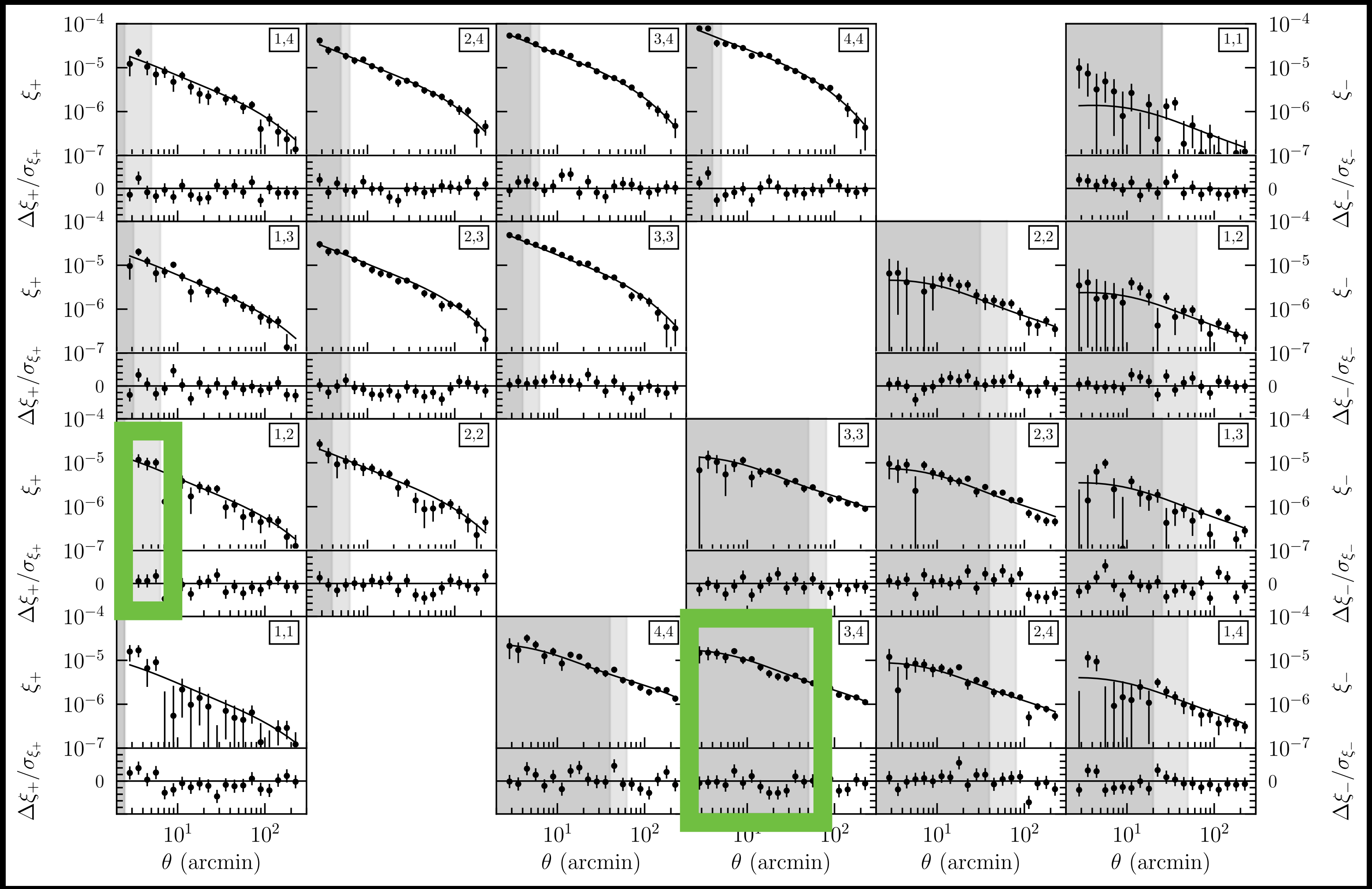
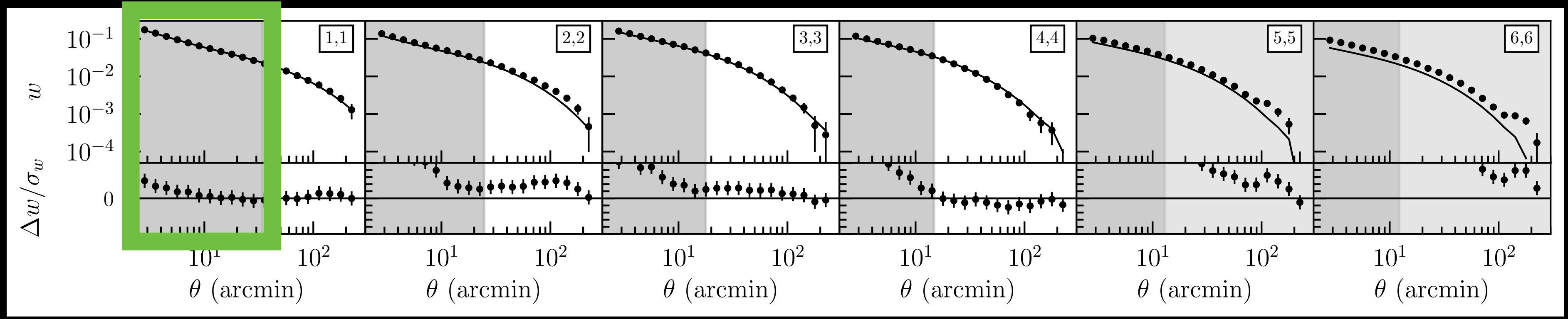
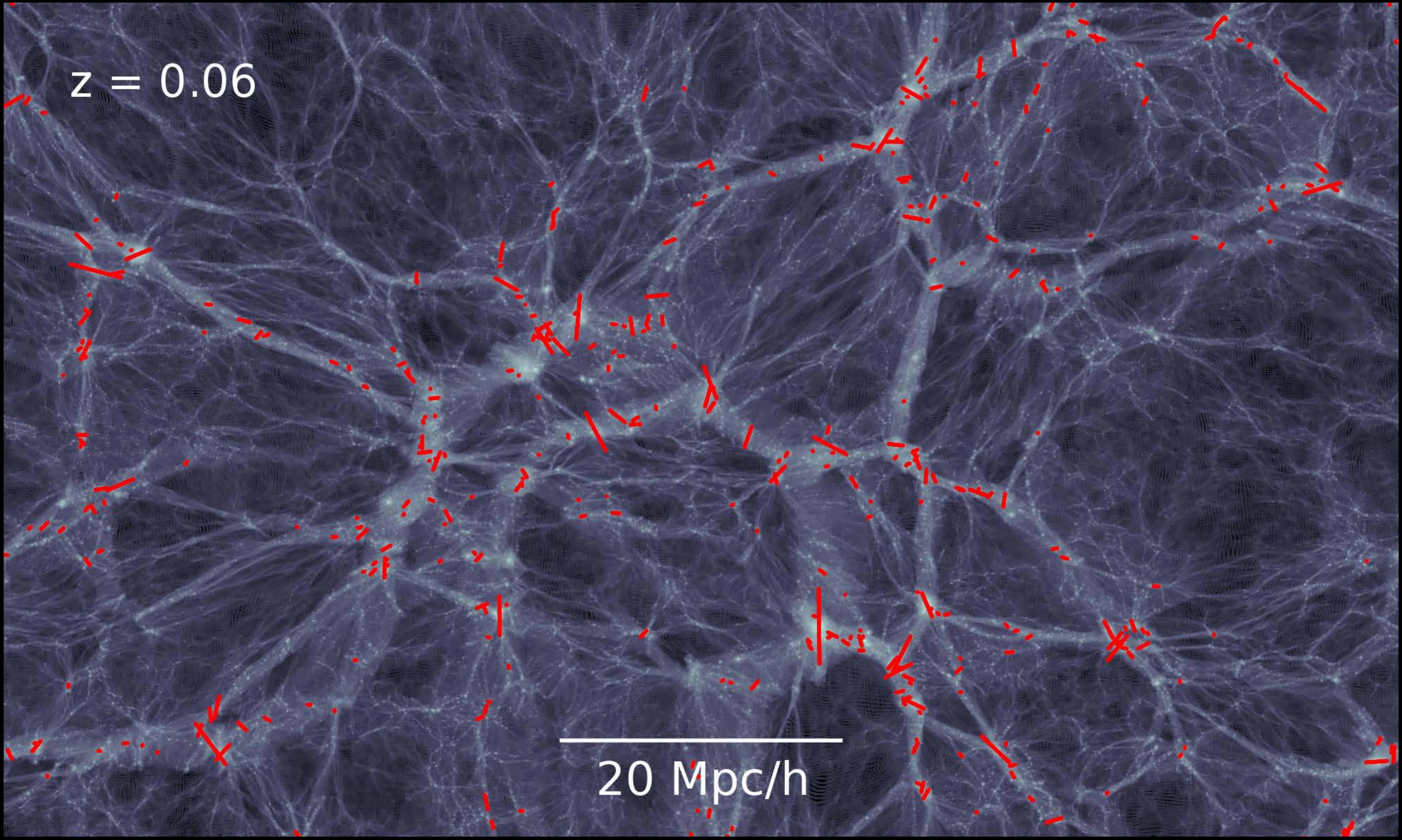
DES Y3 correlation functions





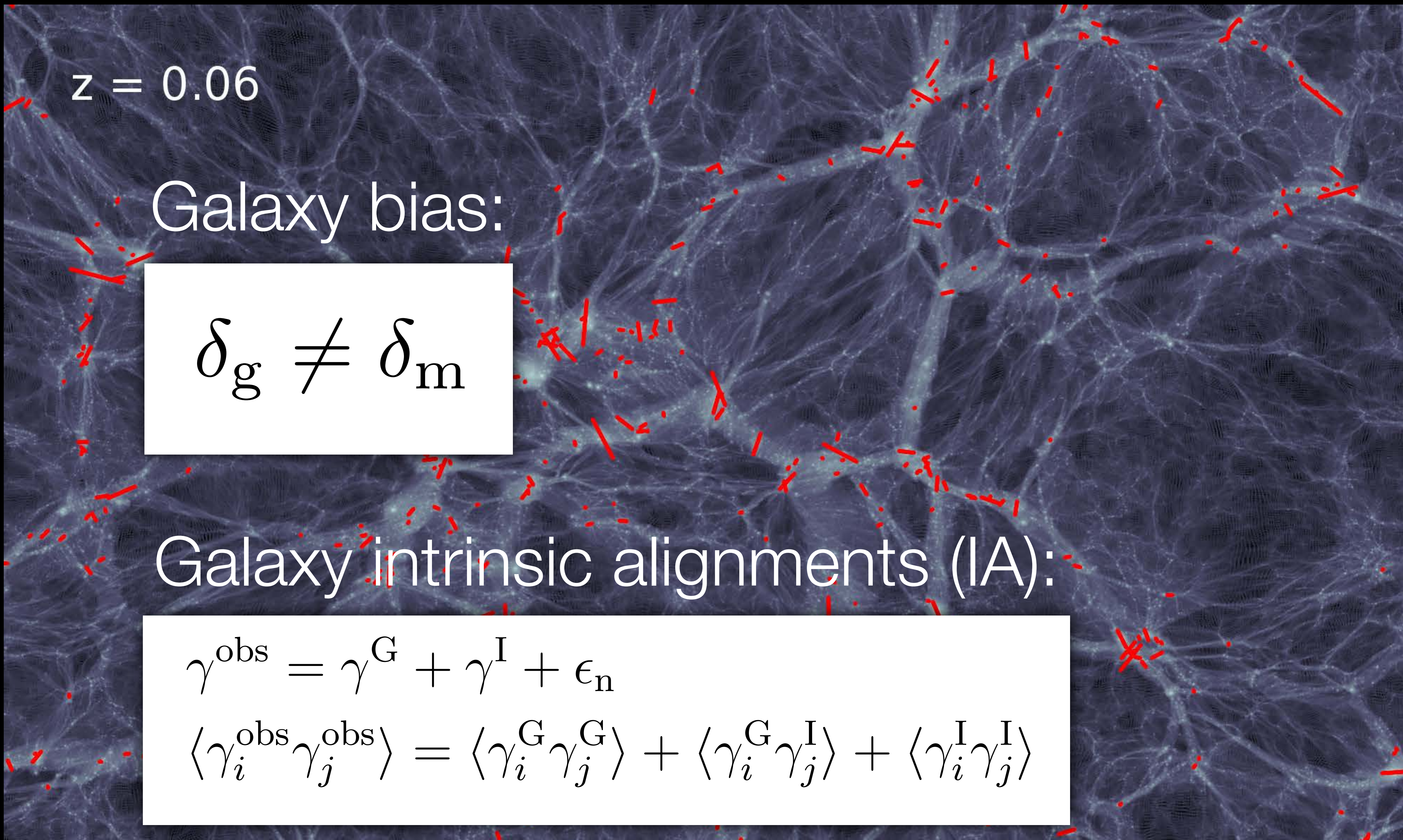


Modeling galaxy observables



(MassiveBlack II: Khandai+ 2014; Tenneti+ 2014a,b)

Modeling galaxy observables



Galaxy bias:

$$\delta_{\rm g} \neq \delta_{\rm m}$$

Galaxy intrinsic alignments (IA):

$$\gamma^{\rm obs} = \gamma^{\rm G} + \gamma^{\rm I} + \epsilon_{\rm n}$$
$$\langle \gamma_i^{\rm obs} \gamma_j^{\rm obs} \rangle = \langle \gamma_i^{\rm G} \gamma_j^{\rm G} \rangle + \langle \gamma_i^{\rm G} \gamma_j^{\rm I} \rangle + \langle \gamma_i^{\rm I} \gamma_j^{\rm I} \rangle$$

(MassiveBlack II: Khandai+ 2014; Tenneti+ 2014a,b)

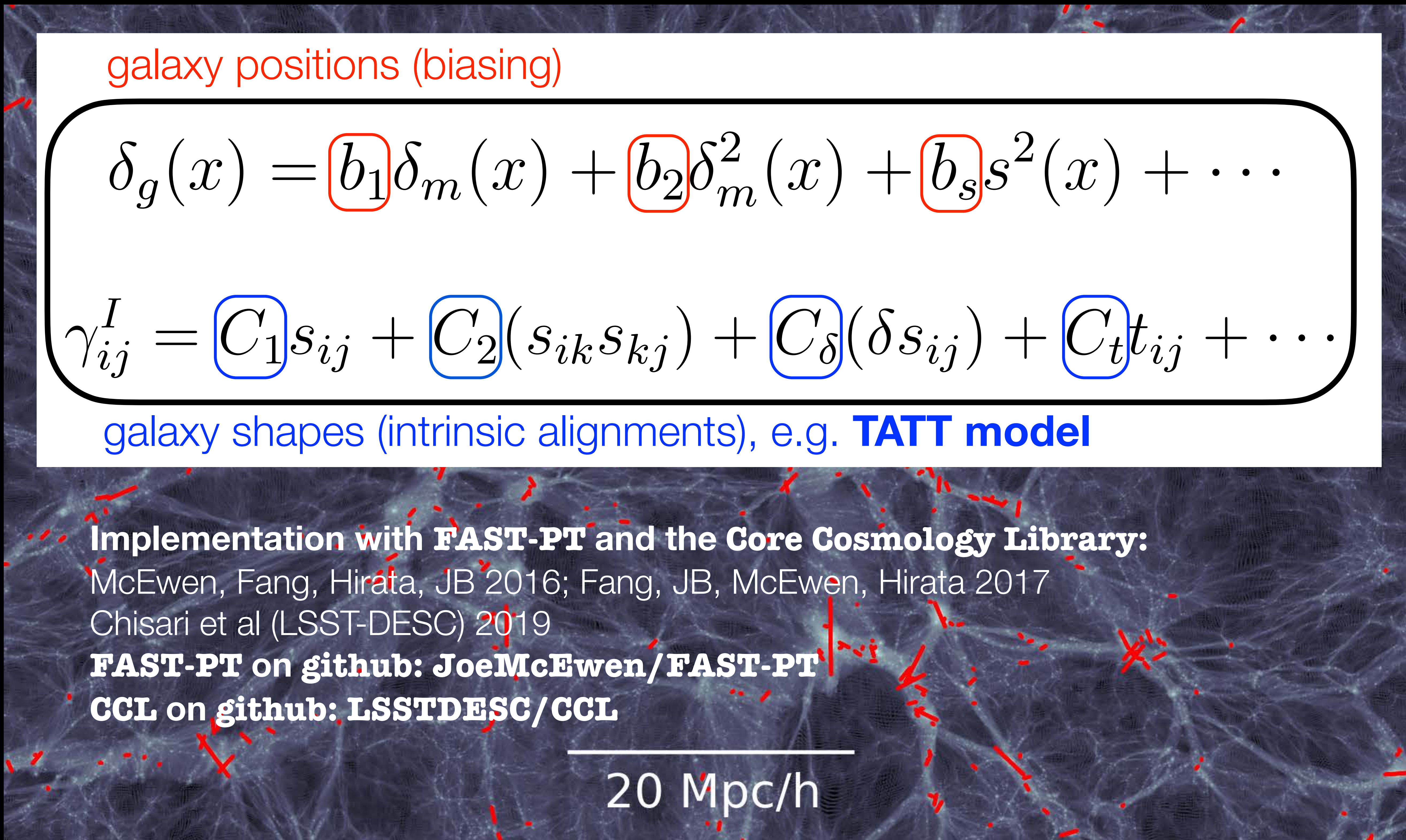
Effective perturbative expansions

galaxy positions (biasing)

$$\delta_g(x) = \boxed{b_1}\delta_m(x) + \boxed{b_2}\delta_m^2(x) + \boxed{b_s}s^2(x) + \cdots$$

$$\gamma_{ij}^I = \boxed{C_1}s_{ij} + \boxed{C_2}(s_{ik}s_{kj}) + \boxed{C_\delta}(\delta s_{ij}) + \boxed{C_t}t_{ij} + \cdots$$

galaxy shapes (intrinsic alignments), e.g. **TATT model**



Implementation with FAST-PT and the Core Cosmology Library:
McEwen, Fang, Hirata, JB 2016; Fang, JB, McEwen, Hirata 2017
Chisari et al (LSST-DESC) 2019
FAST-PT on github: JoeMcEwen/FAST-PT
CCL on github: LSSTDESC/CCL

e.g. McDonald & Roy 2009; JB+ 2015; 2019; Schmitz, Hirata, JB+ 2019; Vlah+ 2020

Simulating galaxy bias and IA with semi-analytic methods

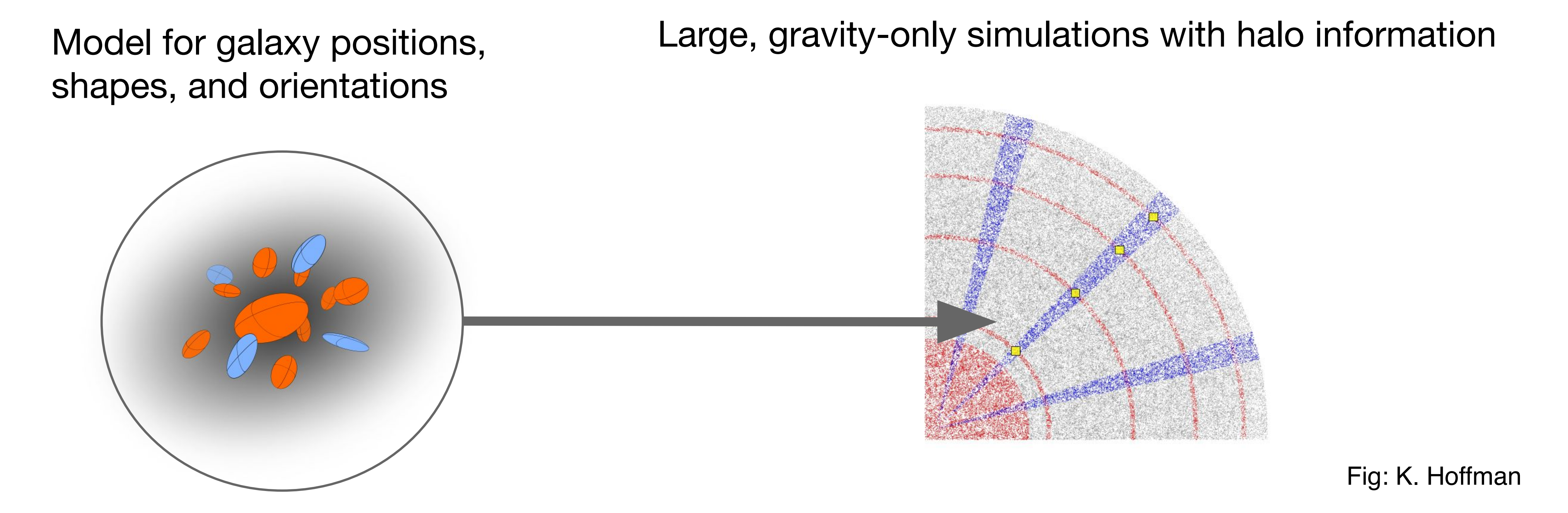
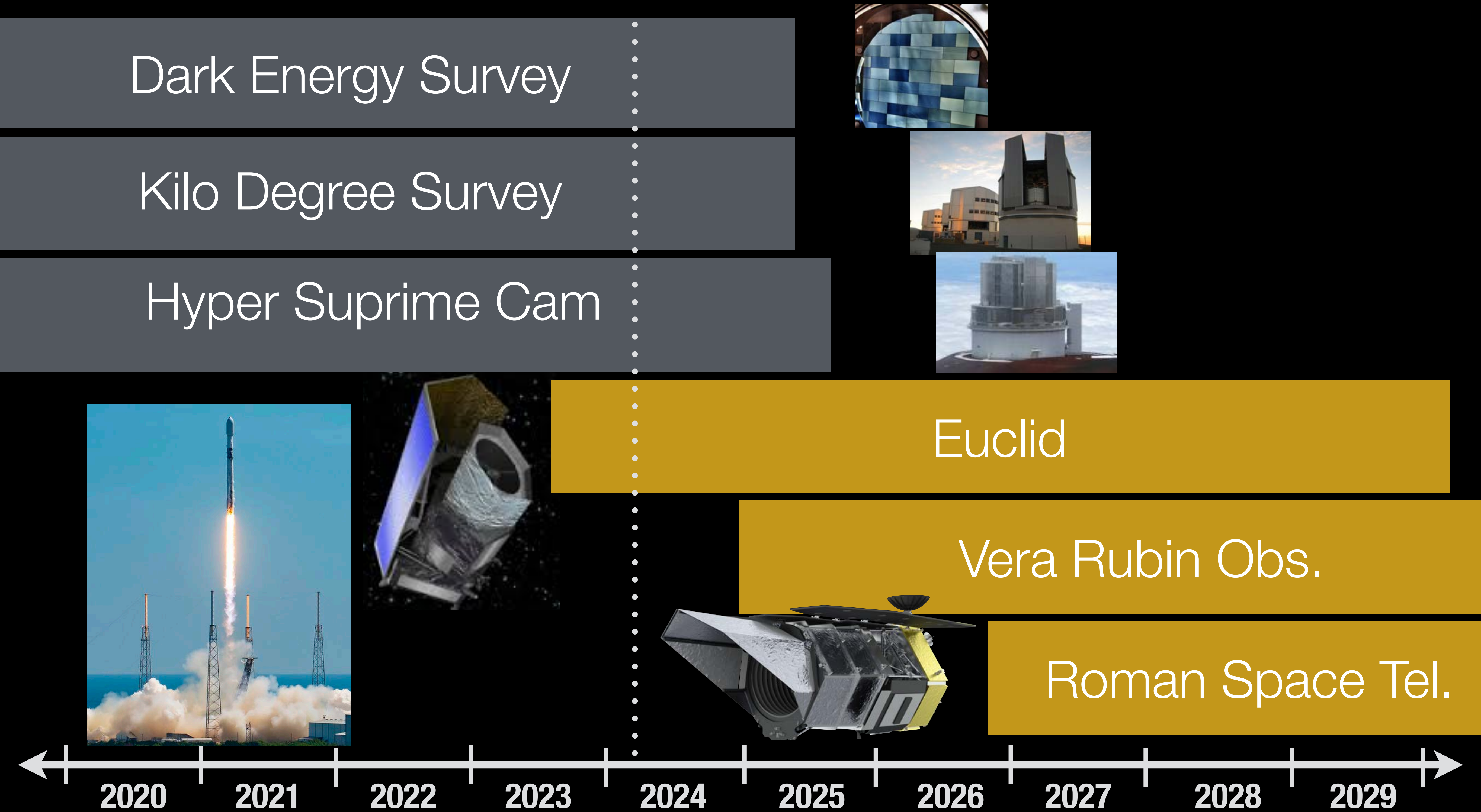


Fig: K. Hoffman

Halotools-IA
Halotools on github: astropy/halotools
Van Alfen, Campbell, JB, Lanusse, Leonard, Hearin+ 2023

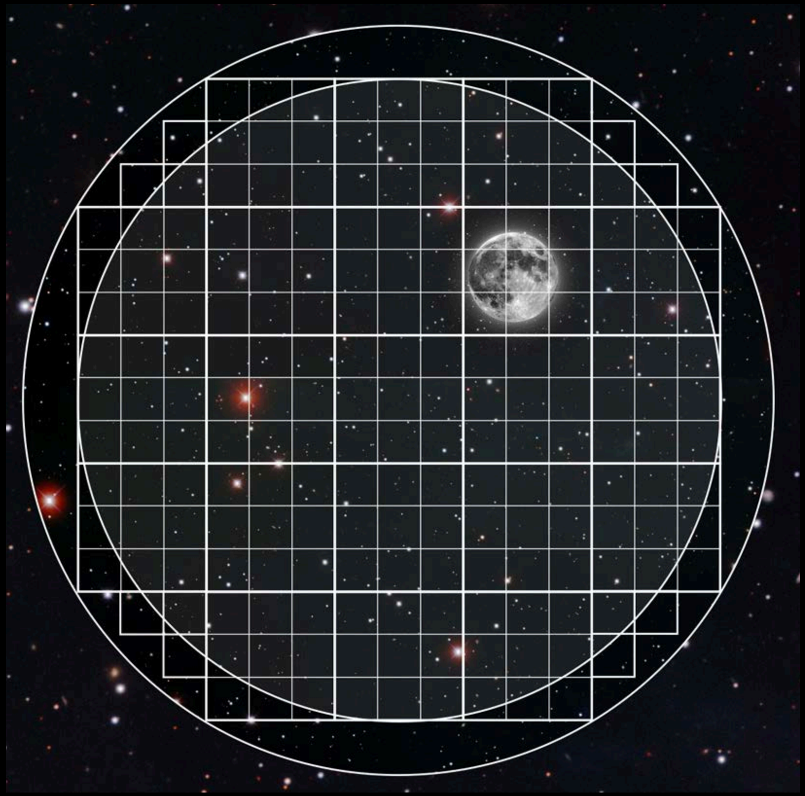
In progress: Building a neural net-based emulator for simulation-based modeling

The ~~future~~ present is exciting!



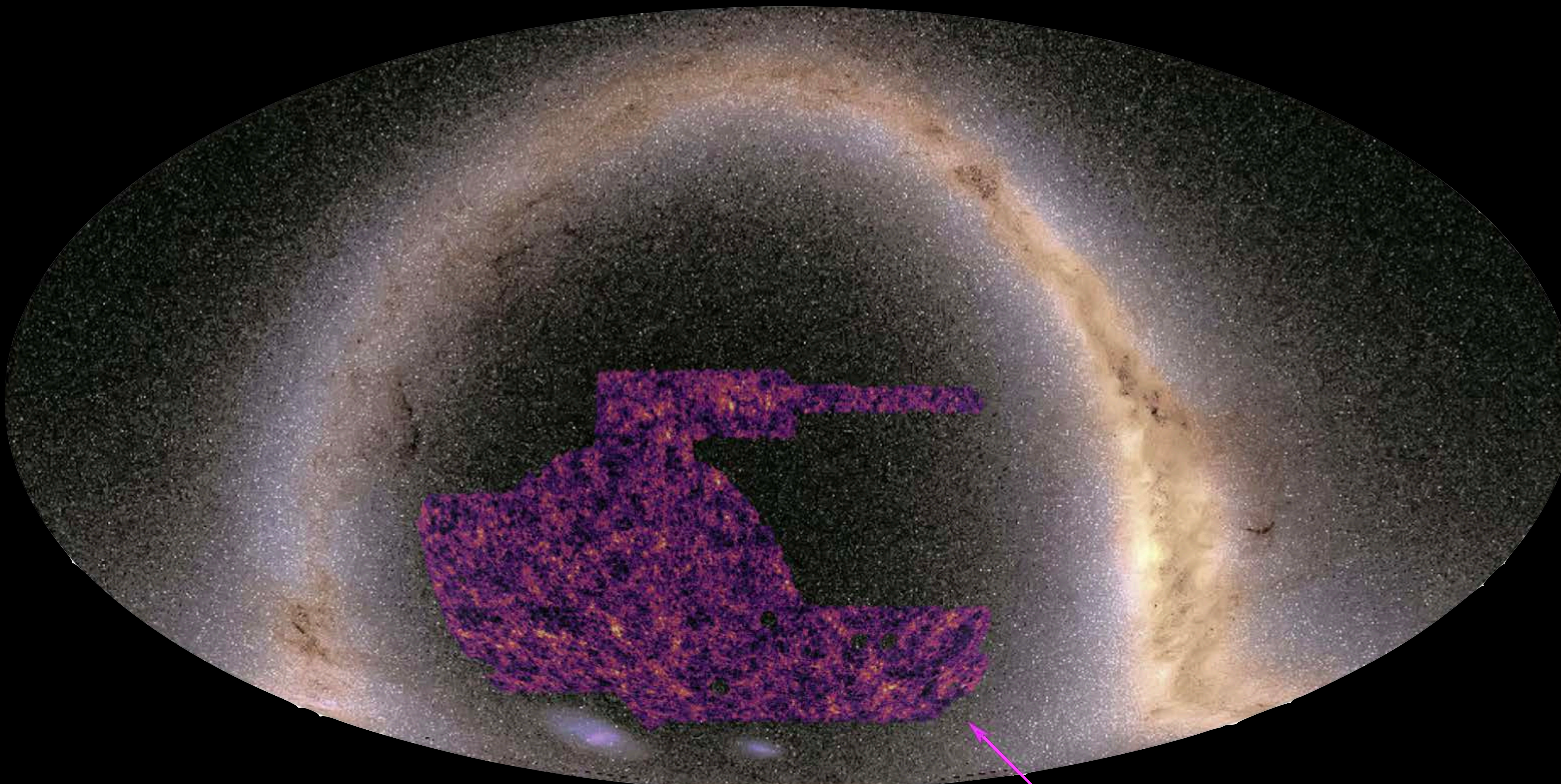
Vera C. Rubin Observatory

- Legacy Survey of Space and Time (LSST)
- LSSTCam (3.2 Gpix) on 8.4m telescope, Cerro Pachón, Chile
- ~1/2 of sky (18-25k deg^2)
- 10 year dedicated survey, *starting next year*
- ~20 billion galaxies
- 8 science collaborations: "Dark Energy" (DESC), also includes dark matter, gravity, inflation, neutrinos, etc.



~10 deg^2 field-of-view

Beyond two-point statistics

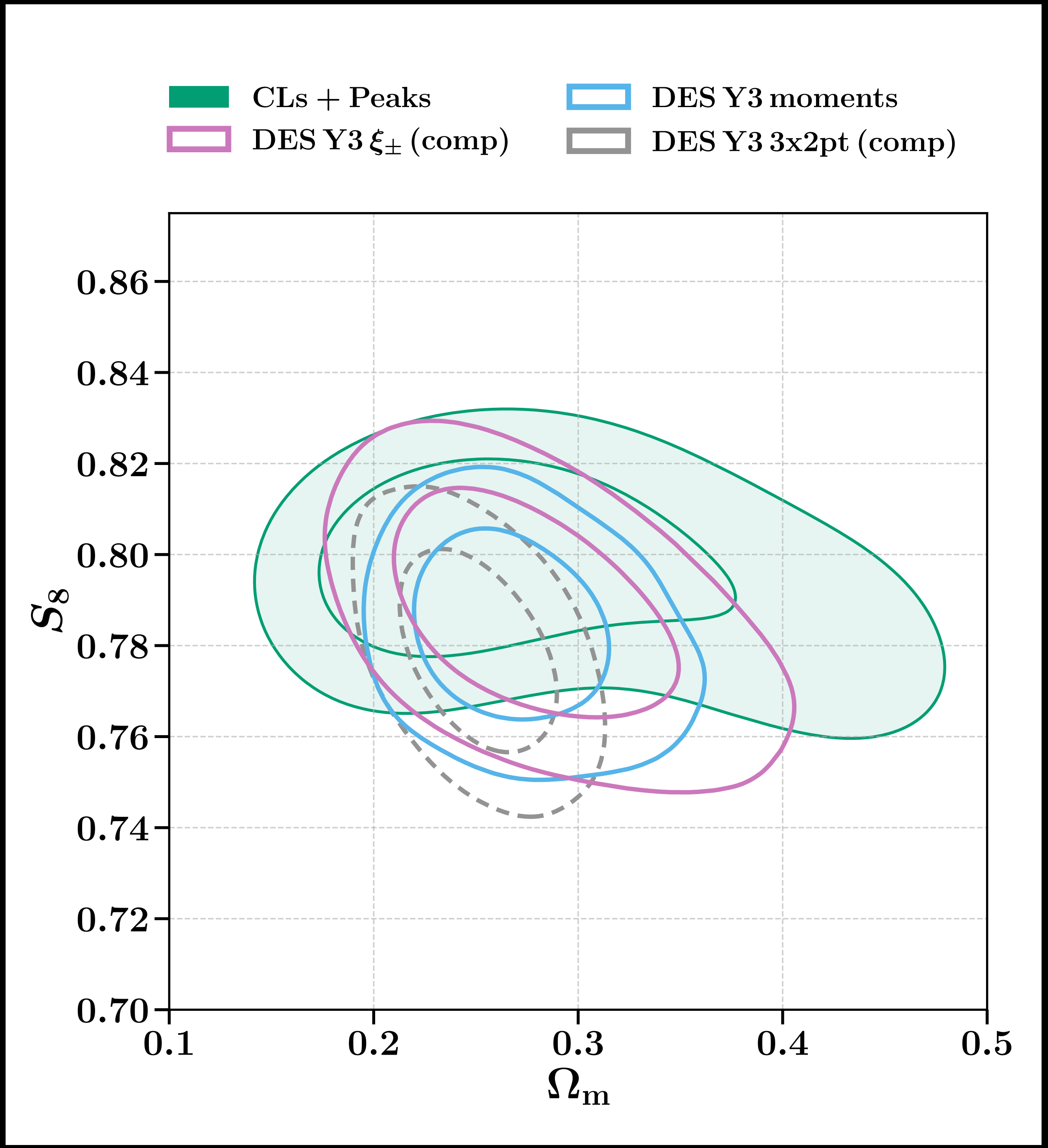


N. Jeffrey, Dark Energy Survey

Beyond two-point statistics

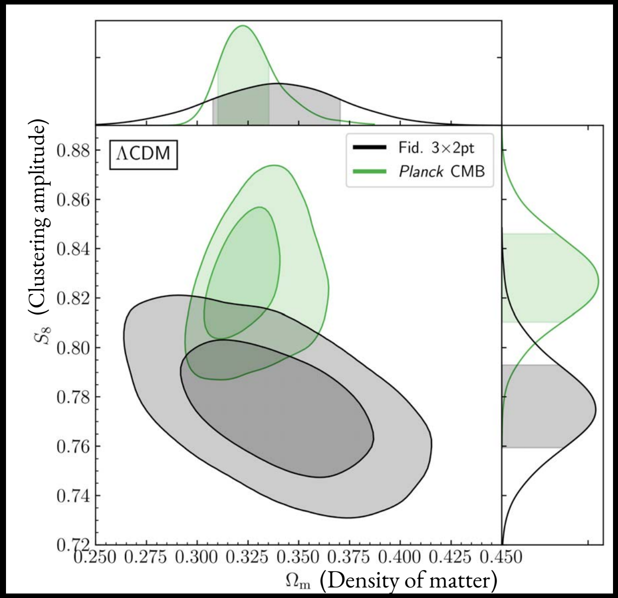
Extracting more information:

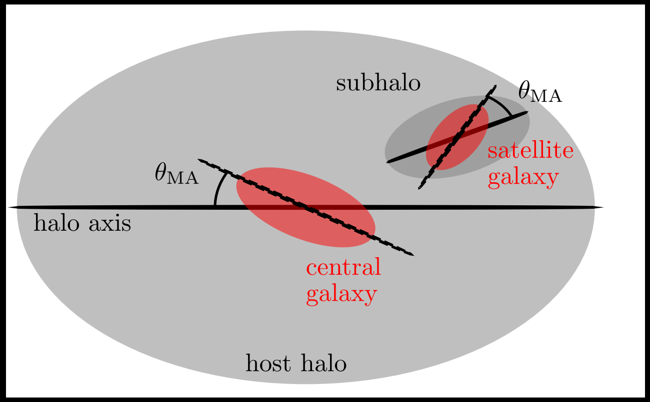
- Peaks in the mass map
  (e.g. Zürcher et al 2022)
- The distribution of convergence, including moments
  (e.g. Gatti et al 2022)
- Three-point statistics
  (e.g. Secco et al 2022)
- Field-level inference
  (e.g. Bayer, Seljak, Modi 2023)
- Other novel statistics
  (e.g. Gatti et al 2023)



Conclusions

- Studies of weak lensing and galaxy clustering are a powerful cosmological probe for current and future projects.
- Astrophysical modeling will be critical for future analyses, e.g. galaxy IA and biasing.
- New experiments starting now, combined with new statistical and modeling approaches, make the coming decade a very exciting time for observational cosmology!



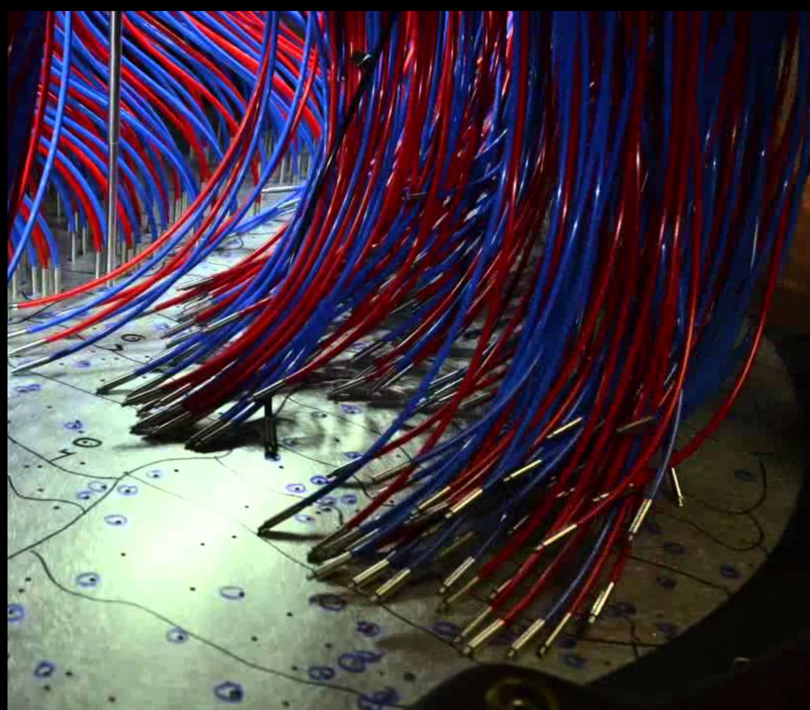


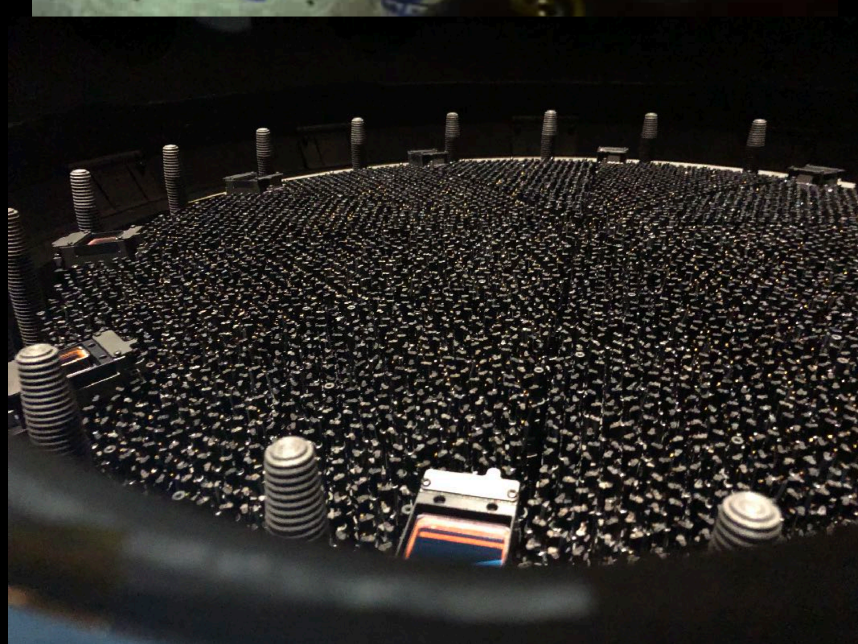

Thank you!

Extra Slides

“Spectroscopic” surveys

Sloan Digital Sky Survey





Dark Energy Spectroscopic Instrument
Robot positioners assembled here!

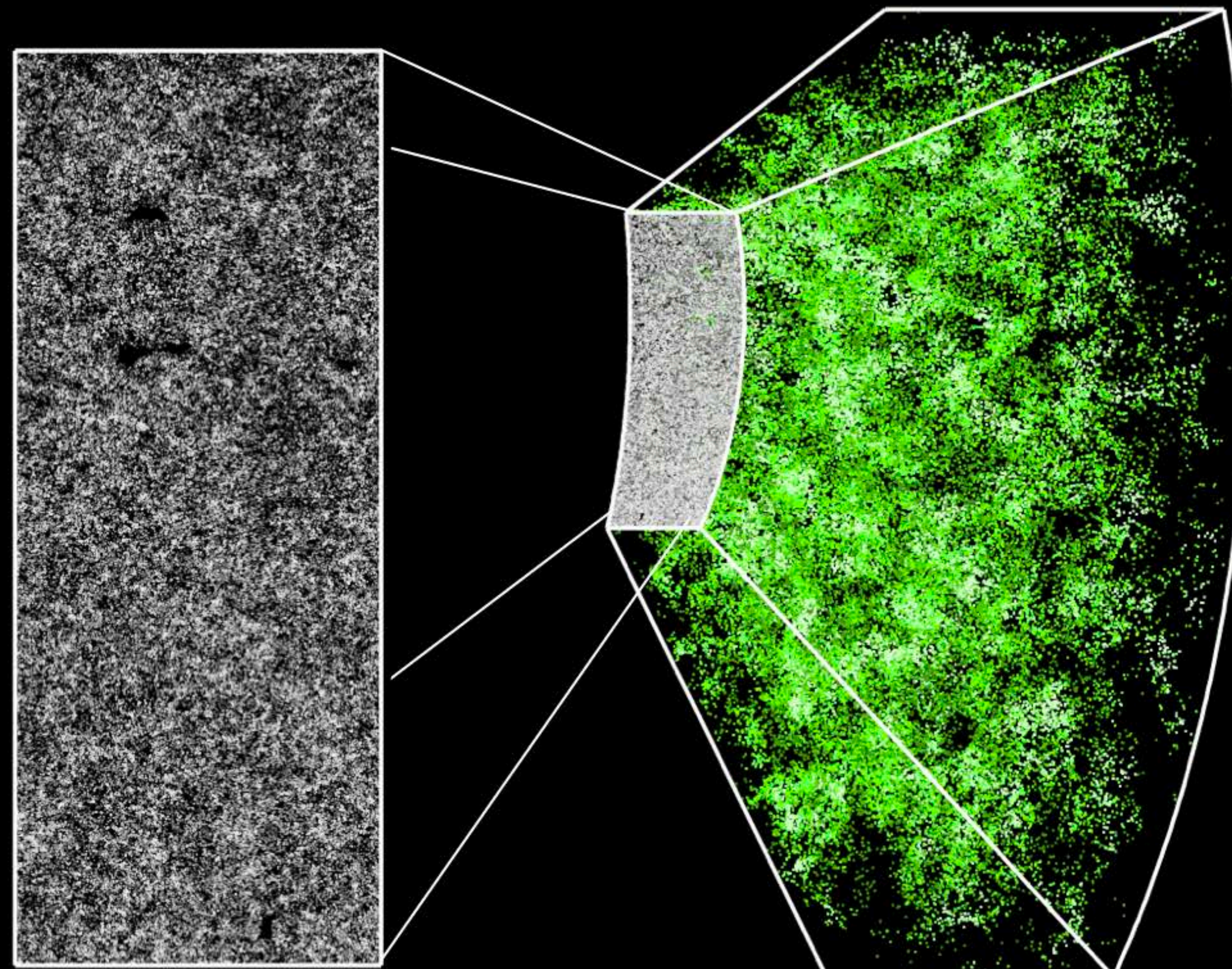
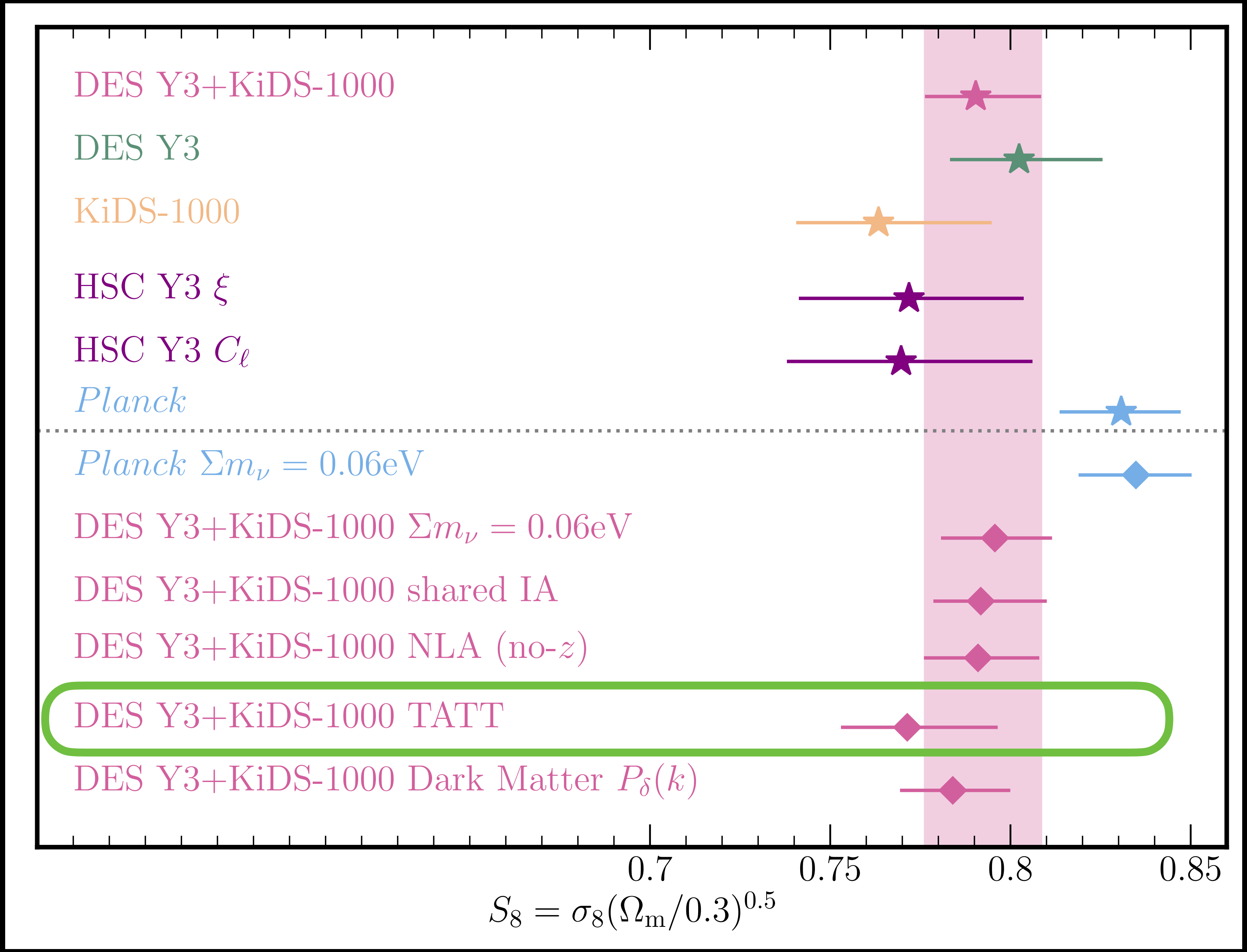


fig: SDSS

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

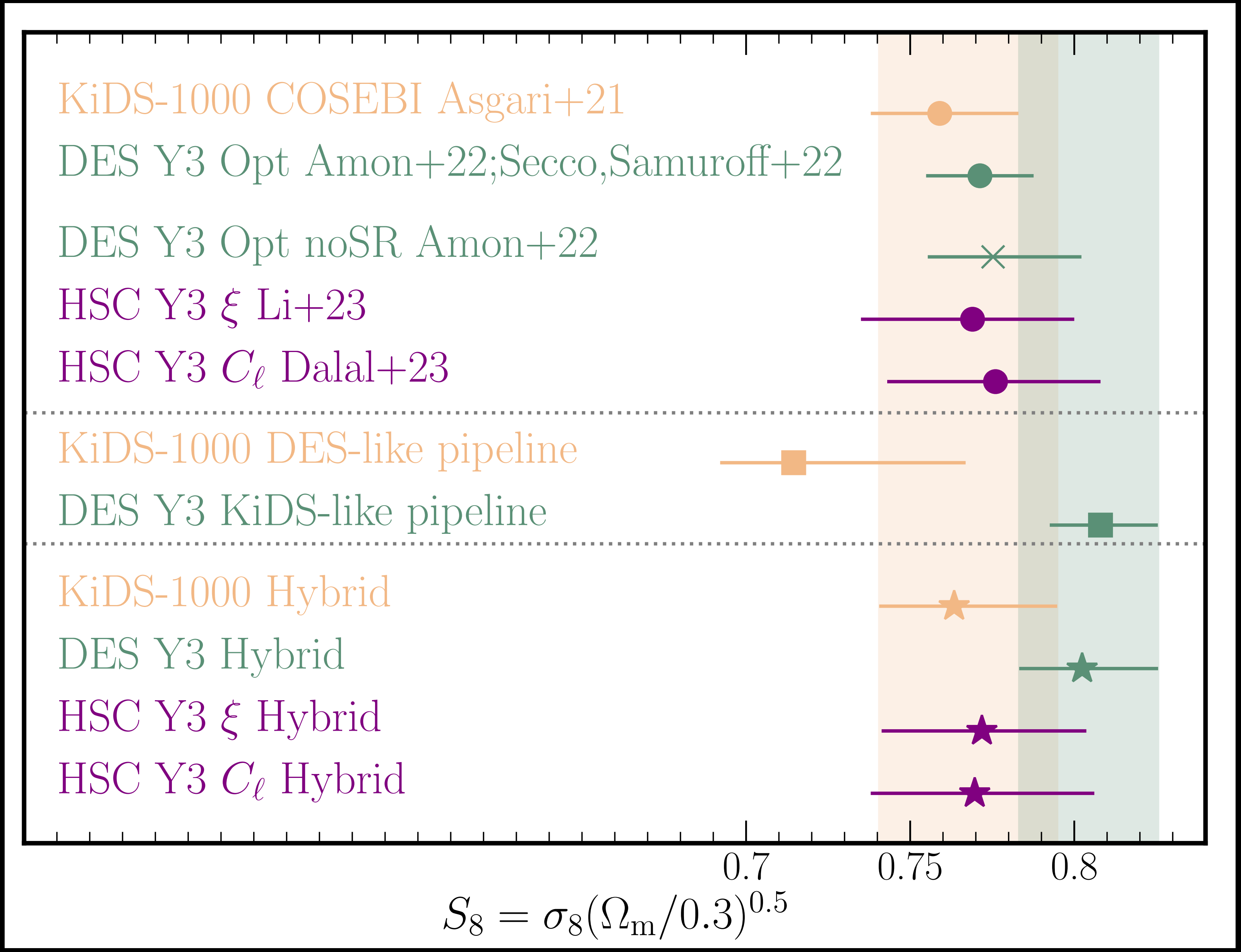
galaxy (over)density field

Combining surveys: DES + KiDS



"In both our mock and data studies, the most significant changes arise from the choice of intrinsic alignment (IA) model."

Combining surveys: DES + KiDS



Cosmic shear - Hybrid analysis pipeline
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Implementation with FAST-PT

McEwen, Fang, Hirata, JB 2016; Fang, JB, McEwen, Hirata 2017

FAST-PT on github: JoeMcEwen/FAST-PT

$$I(k) = \int \frac{d^3\boldsymbol{q}_1}{(2\pi)^3} K(\hat{\boldsymbol{q}}_1 \cdot \hat{\boldsymbol{q}}_2, \hat{\boldsymbol{q}}_1 \cdot \hat{\boldsymbol{k}}, \hat{\boldsymbol{q}}_2 \cdot \hat{\boldsymbol{k}}, q_1, q_2) P(q_1) P(q_2)$$

$$\downarrow$$

$$f(k) = \int \frac{d^3\boldsymbol{q}_1}{(2\pi)^3} \mathcal{P}_\ell(\hat{\boldsymbol{q}}_1 \cdot \hat{\boldsymbol{q}}_2) \mathcal{P}_{\ell_1}(\hat{\boldsymbol{k}} \cdot \hat{\boldsymbol{q}}_2) \mathcal{P}_{\ell_2}(\hat{\boldsymbol{k}} \cdot \hat{\boldsymbol{q}}_1) q_1^\alpha q_2^\beta P(q_1) P(q_2)$$

$$\downarrow$$

$$J^{\alpha\beta}_{J_1 J_2}(r) \equiv \left[\int_0^\infty dq_1 \; q_1^{2+\alpha} P(q_1) j_{J_1}(q_1 r)\right] \left[\int_0^\infty dq_2 \; q_2^{2+\beta} P(q_2) j_{J_2}(q_2 r)\right]$$

- Python; easy to use and integrate into other code.
- In DES and LSST analysis software.
- Euclid, Roman in progress.
- DESI? IR Res for BAO and improved RSD in progress.

The Core Cosmology Library

Chisari, …, JB+ 2019 (DESC Collaboration)

CCL on github: LSSTDESC/CCL

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Files Running Commands Cell Tools Tabs

PT_demo.ipynb

Code

Preliminaries

Let's just begin by setting up a cosmology and some biases

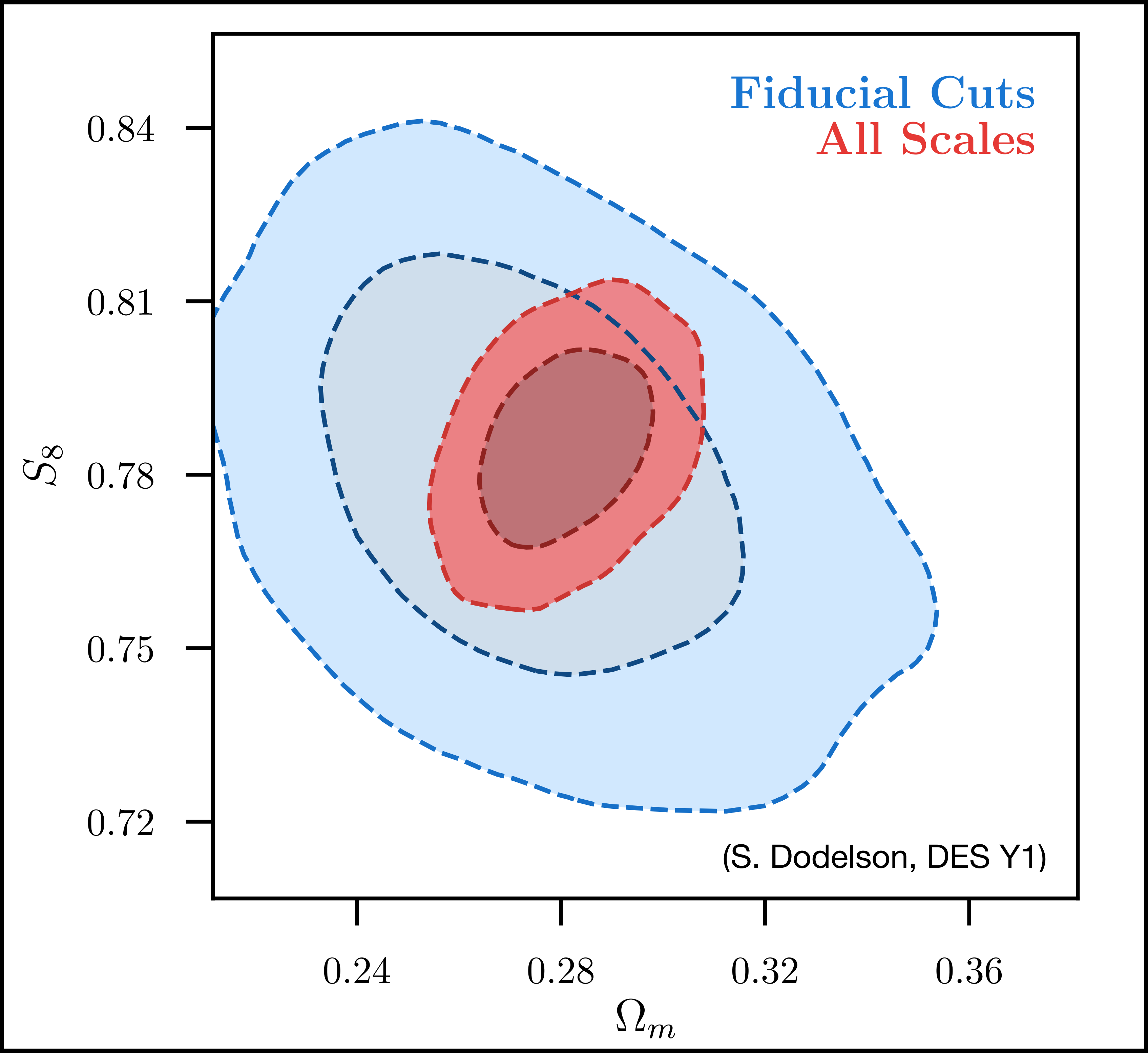
In [2]:
```
# Cosmology
cosmo = ccl.Cosmology(Omega_c=0.27, Omega_b=0.045, h=0.67, A_s=2.1e-9, n_s=0.96)

# Biases for number counts
b_1 = 2.0 # constant values for now
b_2 = 1.0
b_s = 1.0

# Biases for IAs
c_1 = 1.
c_2 = 0.5
c_d = 0.5
```

PT tracers and calculations

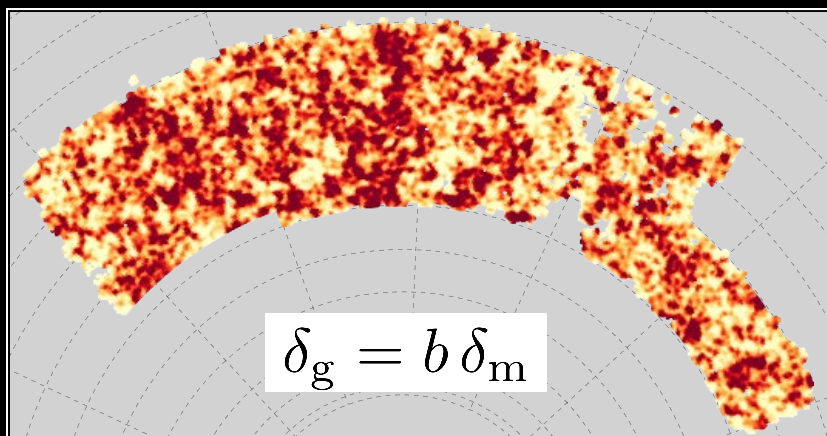
In [3]:
```
# Number counts
ptt_g = pt.PTNumberCountsTracer(b1=b_1, b2=b_2, bs=b_s)
# Intrinsic alignments
ptt_i = pt.PTIntrinsicAlignmentTracer(c1=c_1, c2=c_2, cdelta=c_d)
# Matter
ptt_m = pt.PTMatterTracer()

#initialze PT calculator
ptc = pt.PTCalculator(with_NC=True, with_IA=True,
                      log10k_min=-4, log10k_max=2, nk_per_decade=20)
# Galaxies x galaxies.
pk_gg = pt.get_pt_pk2d(cosmo, ptt_g, ptc=ptc)
# Galaxies x matter
pk_gm = pt.get_pt_pk2d(cosmo, ptt_g, tracer2=ptt_m, ptc=ptc)
# Galaxies x IAs
pk_gi = pt.get_pt_pk2d(cosmo, ptt_g, tracer2=ptt_i, ptc=ptc)
# IAs x IAs
pk_ii = pt.get_pt_pk2d(cosmo, ptt_i, tracer2=ptt_i, ptc=ptc)
# IAs x matter
pk_im = pt.get_pt_pk2d(cosmo, ptt_i, tracer2=ptt_m, ptc=ptc)
```

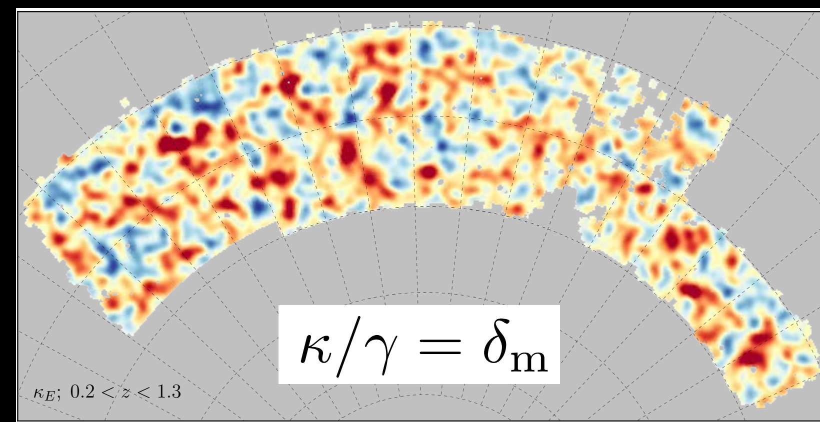
- Core theory calculations for LSST (and other) analyses
- Incorporates **FAST-PT** for nonlinear calculations.

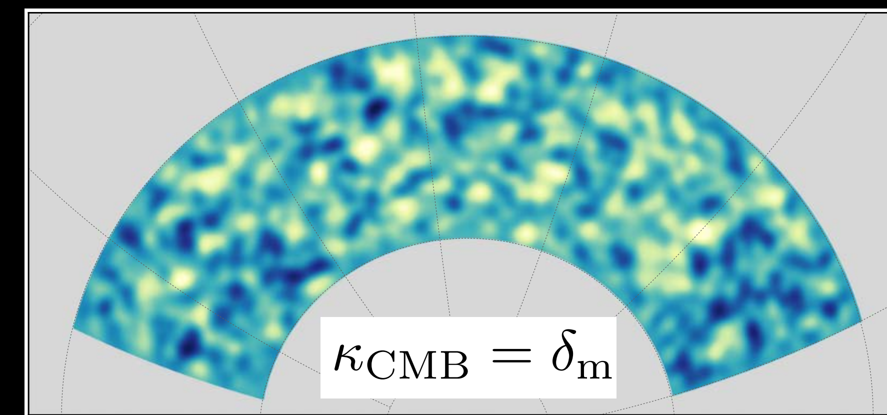
Why go beyond linear theory?



Combining probes







SPT+Planck; Omori+ 2017

galaxy bias

photo-z

observing weights

shear bias, PSF

intrinsic alignments

baryons

photo-z

CMB systematics

broad projection

independent

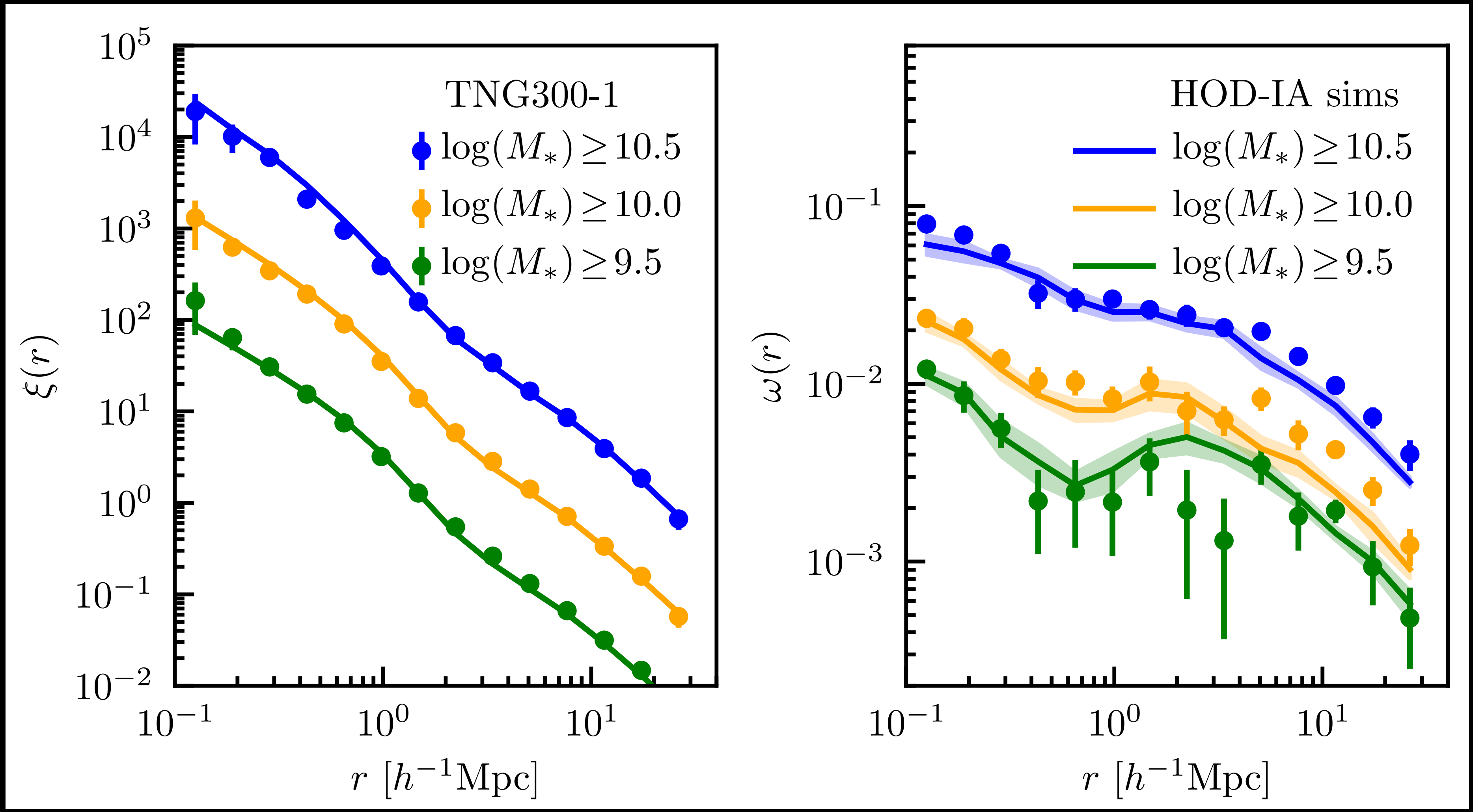
“3x2”

“6x2”

self-calibration and improved statistics

e.g. DES Y3 2023; Krolewski+ 2021 (unWISE + Planck)

Semi-analytic sims consistent with hydro sims



Van Alfen, Campbell, JB, Lanusse, Leonard, Hearin+ 2023