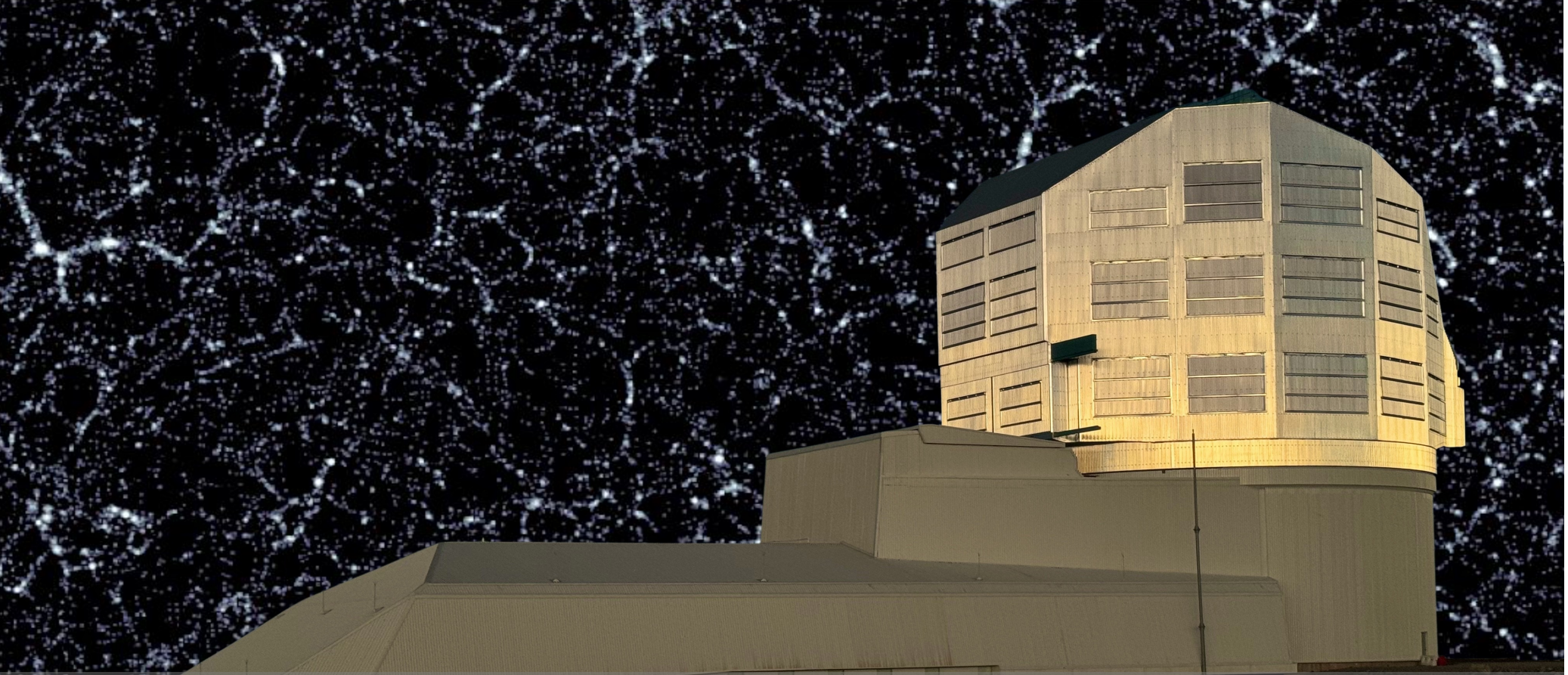


A Cosmic Challenge: The role of higher-order statistics in the Rubin era

Joaquin Armijo, Kavli IPMU (The University of Tokyo)

In collaboration with Jia Liu, Joachim Harnois-Déraps, Gabriela Marques, Daniela Grandón.

VERA C. RUBIN OBSERVATORY

LSST DESC Dark Energy Science Collaboration

KAVLI IPMU

CD3

Outline:

- The cosmological model: Lambda-CDM Universe.
- Probing the large-scale structure of the Universe.
- Gravitational lensing: The weak lensing regime.
- Higher-order statistics for weak lensing fields.
- Forecast, systematics: The example of HSC-Y1 data.
- Simulations for stage-IV surveys: HACC-Y1.

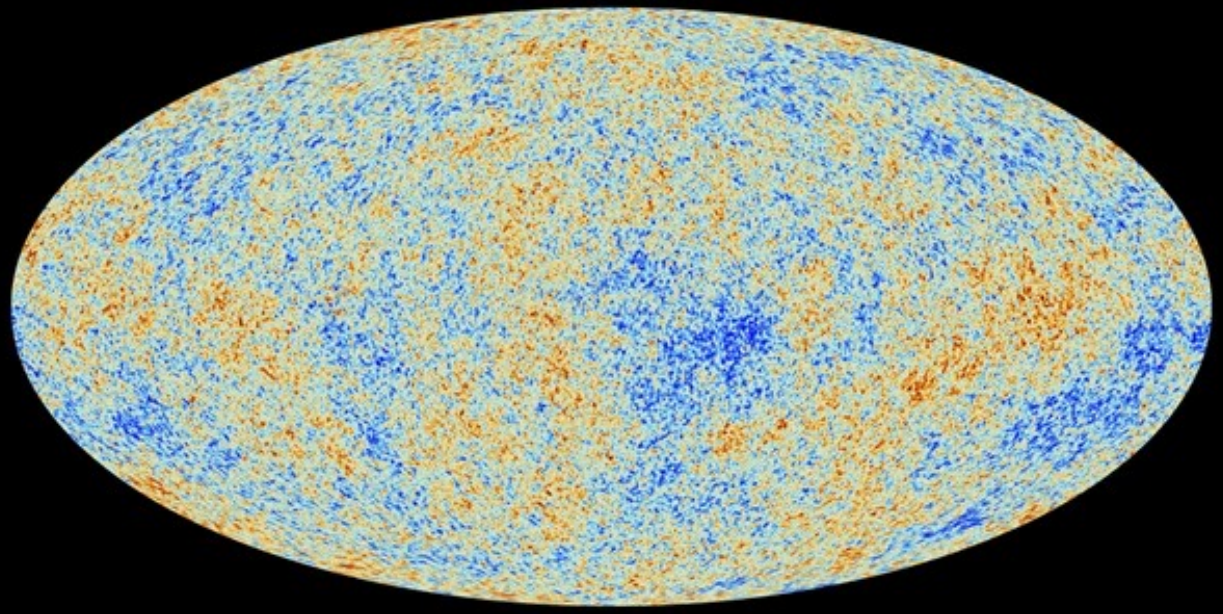
Cosmological model: The ΛCDM Universe.

Cosmology: How is our Universe shaped?

- Stage-IV surveys are already providing exciting data to study!
- The Dark Energy Spectroscopic Instrument (DESI) has published results of the first year collected data.
- These results, plus the ones provided by upcoming surveys, such as LSST will drive the scientific discussion for the next 2 decades.

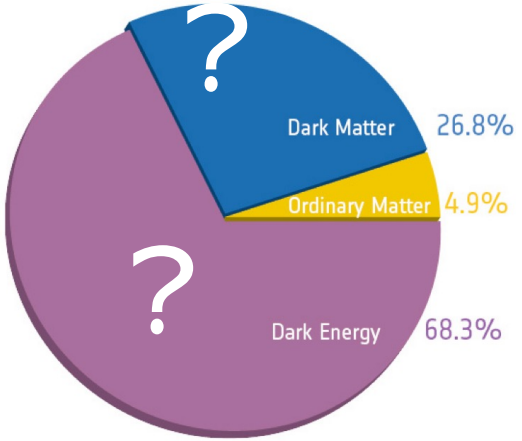
DESI experiment artistic celebration year 1. (DESI collaboration)

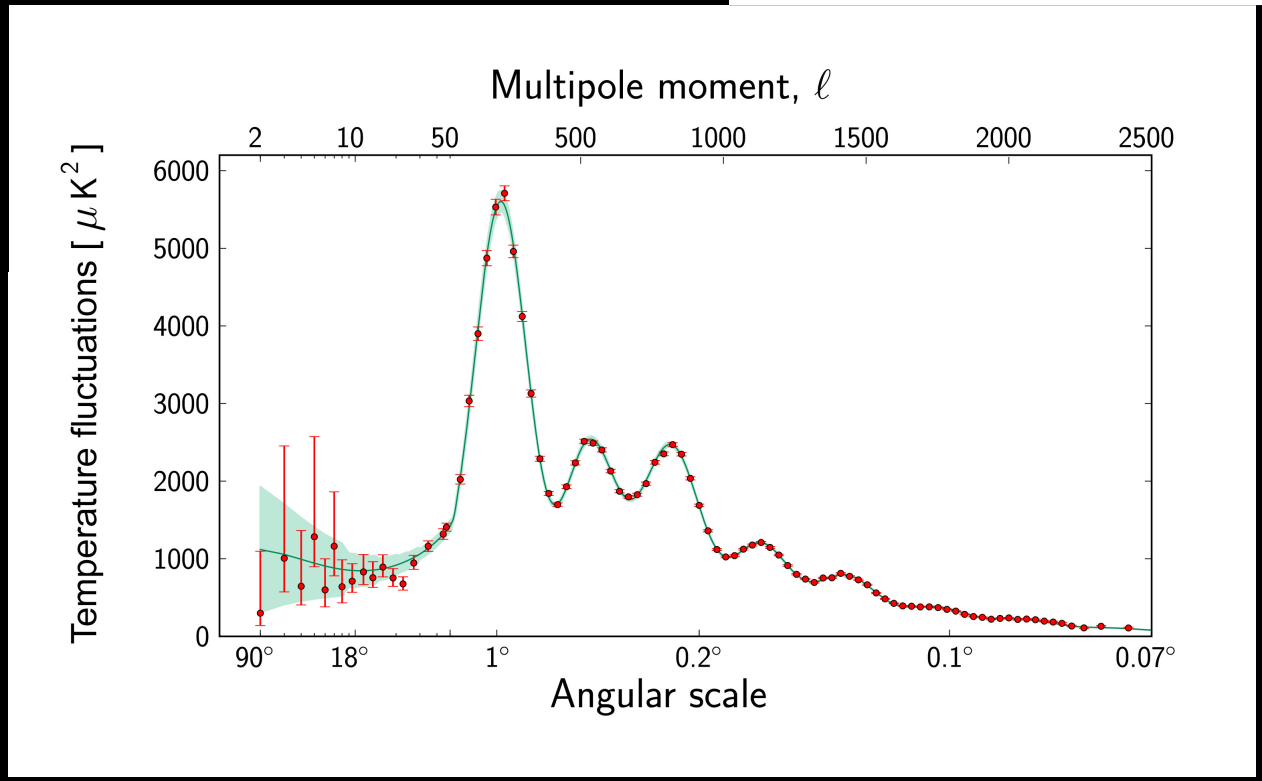
Precision cosmology: Calculating parameters



Angular power spectrum

$$C_\ell = \frac{1}{2\ell+1}\sum_m a_{l,m}a^*_{l,m}$$

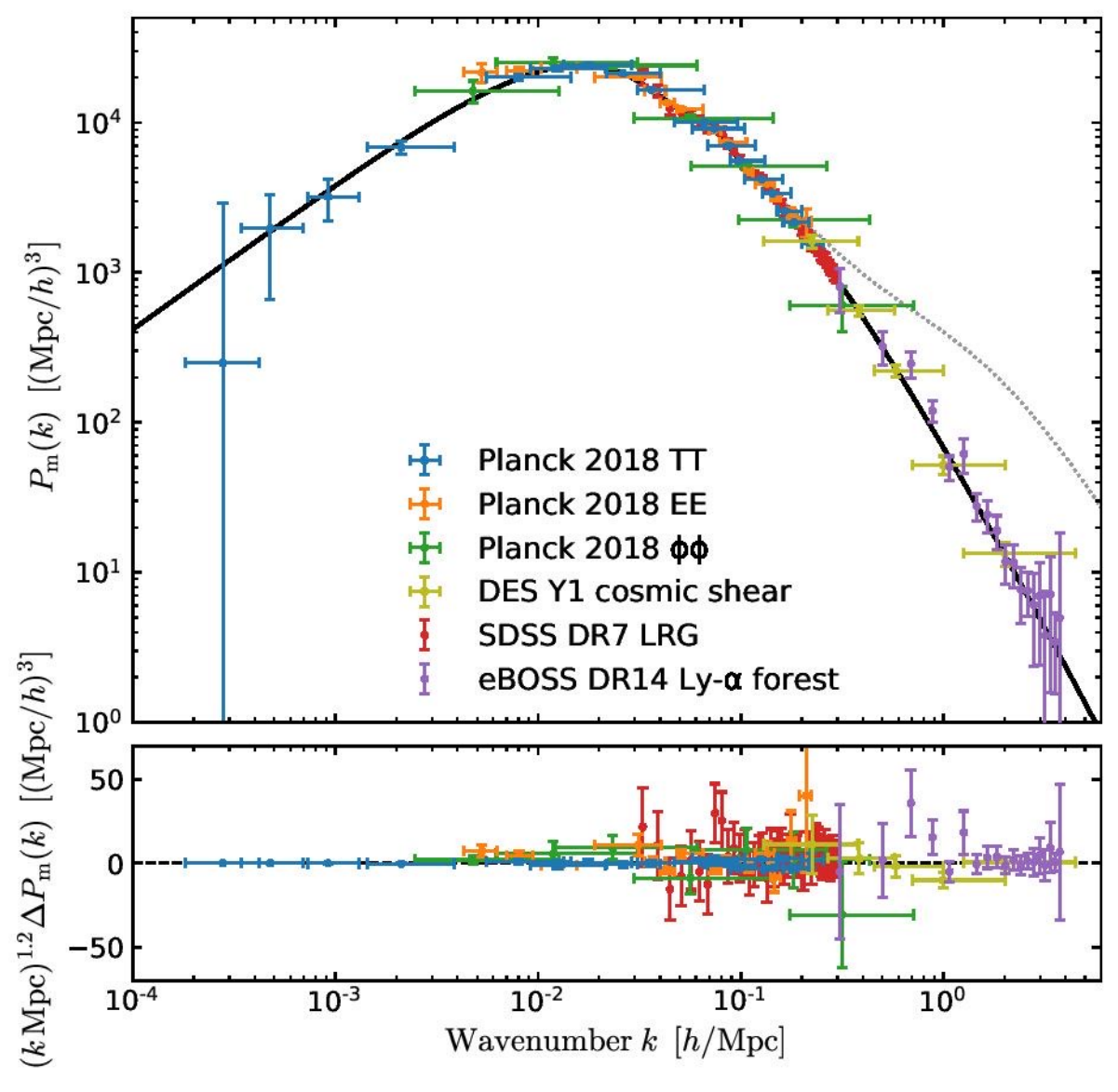




- The Universe is in accelerated expansion driven by the cosmological constant Λ.
- Composed by dark energy ~68%, dark matter 27% and baryons 5%.
- Not much is known about the dark components. Modified gravity can be a viable alternative.

Credit: ESA and the Planck collaboration

The matter power spectrum



- Power spectrum characterize the fluctuations of the matter field at the 2-point level, explaining how matter is distributed.
- The curve represents the model that better represents the data (including errorbars) from Planck (2018) and different galaxy surveys.
- CMB combined with different measurements (polarization, lensing, galaxy distance measurements) provides constraints in the model parameters ~1%.

From Chabanier et al. (2019)

Cosmological tensions: A search for 2 numbers

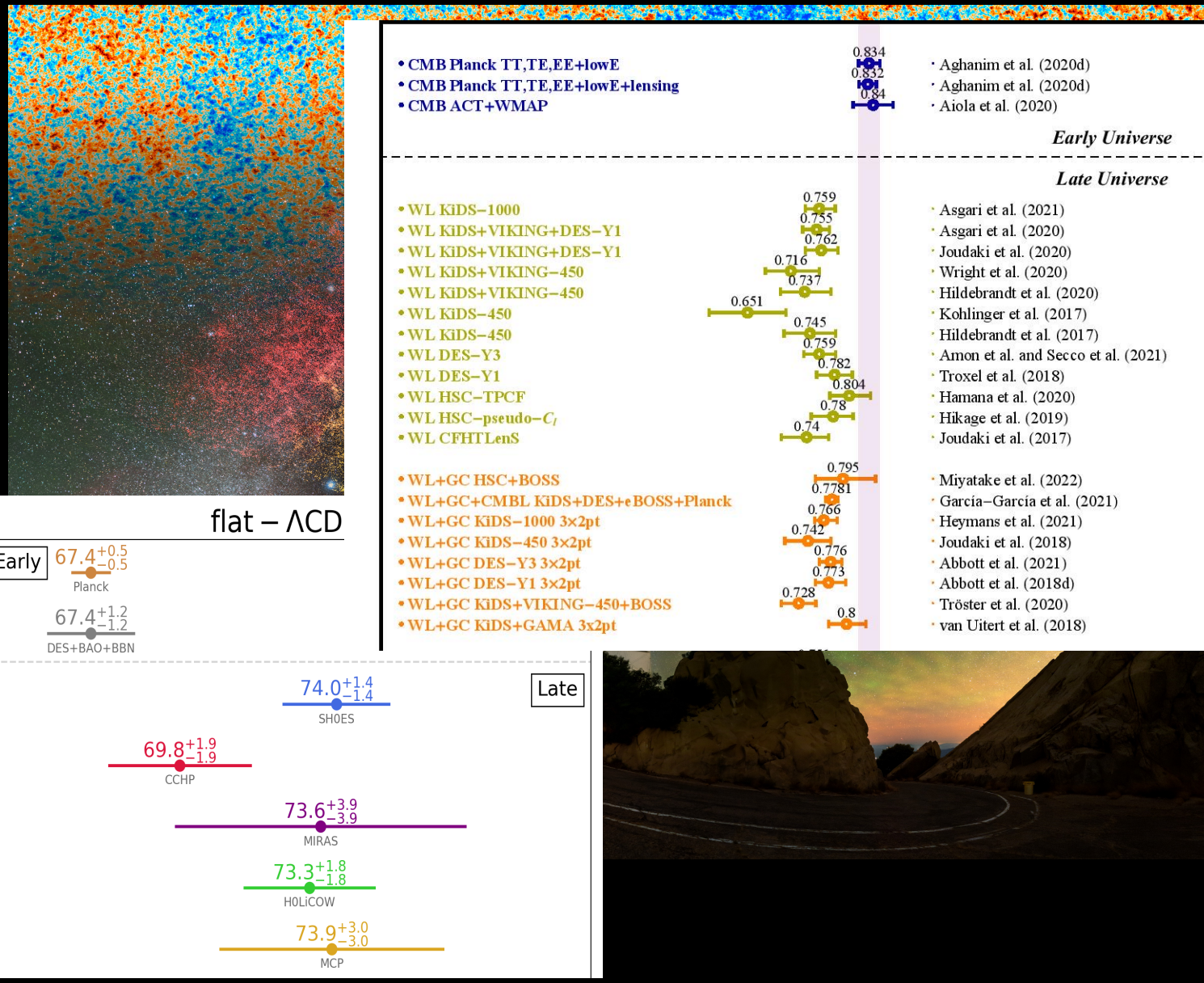
When repeating the exercise for a different dataset (lensing, galaxies, supernovae), some discrepancies appear:

$H_0 = 67.4 \pm 0.5$ (Planck, early); 74 ± 1 (SHoES, late)

$S_8 = 0.84 \pm 0.01$ (Planck, early); 0.75 ± 0.04(KiDS, late)

$$S_8 = \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{1/2}$$

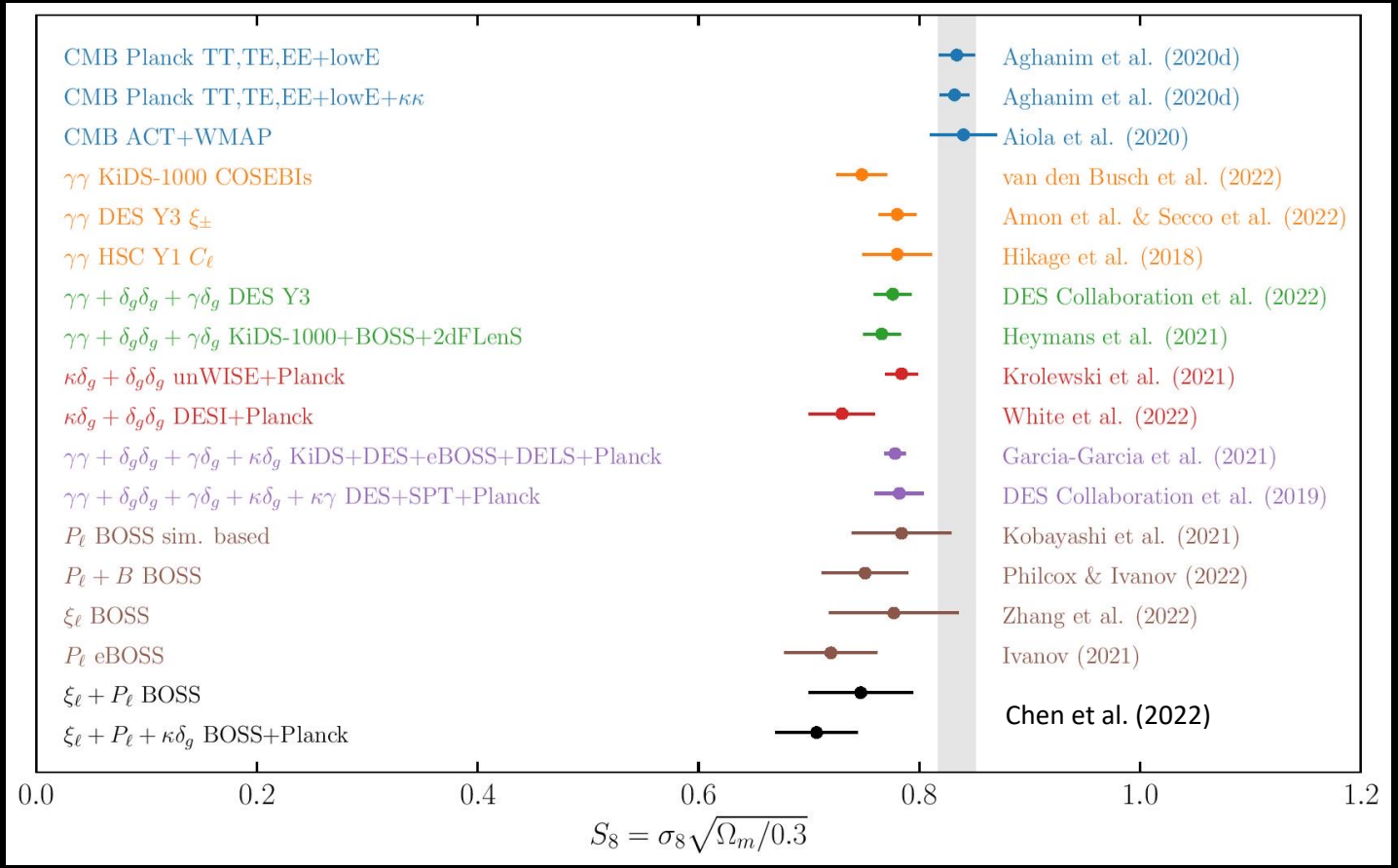
- Disagreement between early and late Universe?
- Tension when measuring small scales?
- The impact of gravity in the evolution of the Universe.
- Gravity beyond general relativity?



What does σ_8 measures?

$$\sigma^2(R,z) = \int \frac{d^3k}{(2\pi)^3} |W(kR)|^2 P_{\rm lin}(k,z)$$

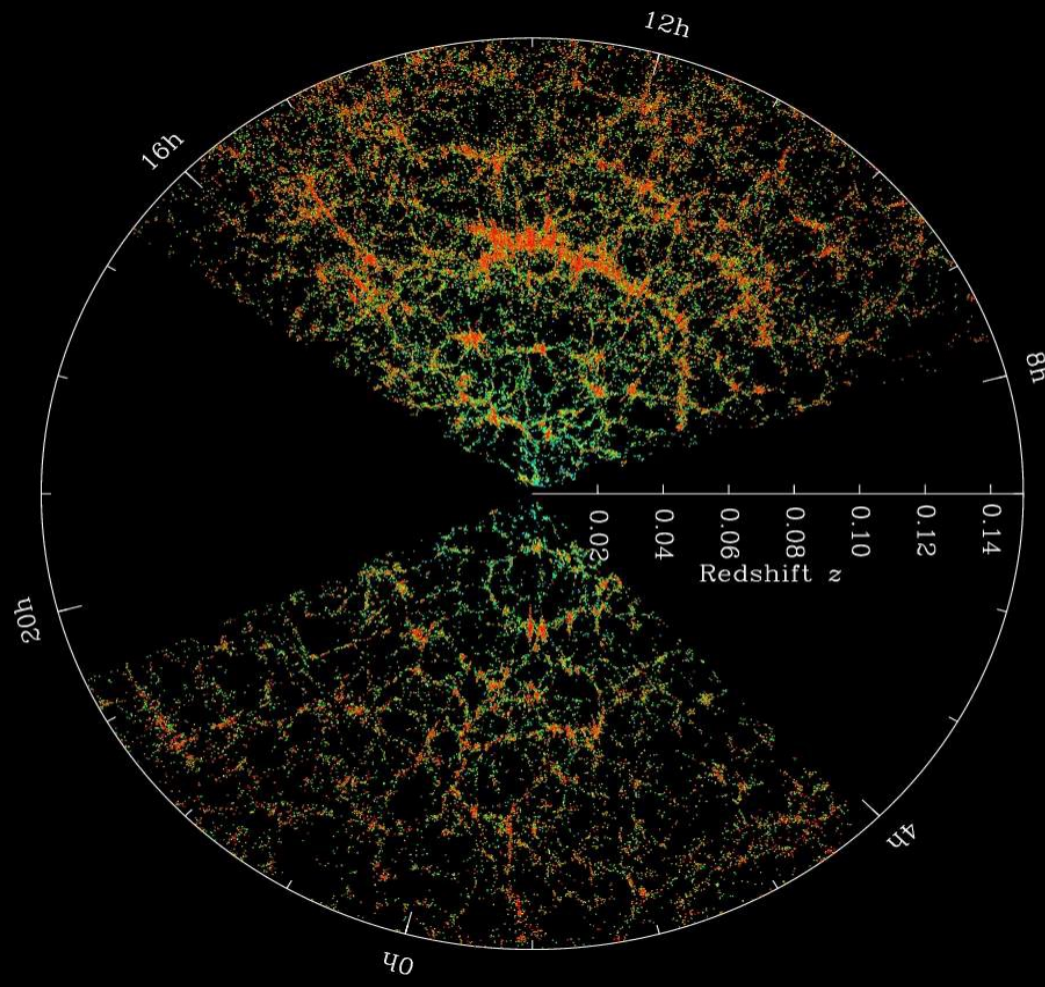
$$\sigma_8 \equiv \sqrt{\sigma^2(R = 8h^{-1}{\rm Mpc}, z = 0)}$$



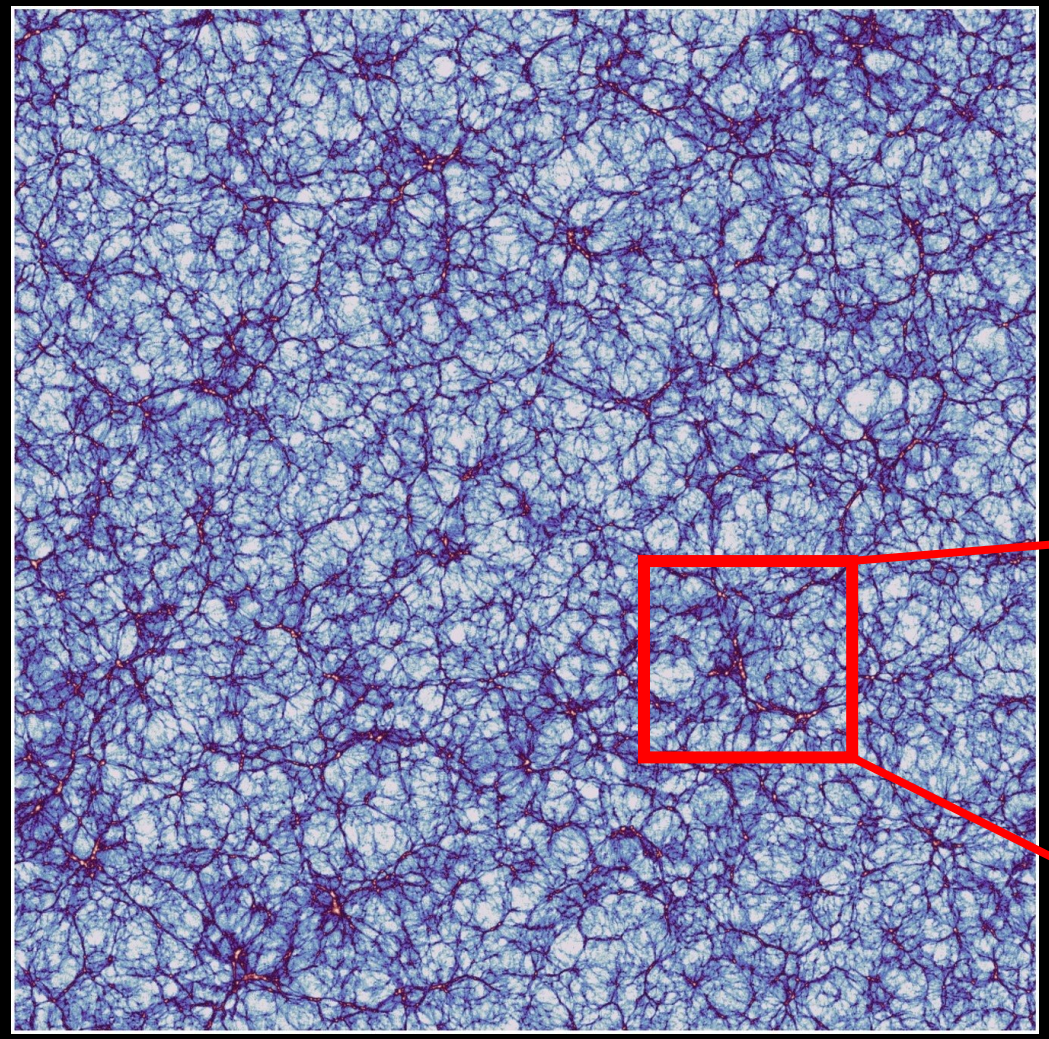
- Measurements of galaxy clustering + lensing + RSD contrast compared with CMB.
- CMB lensing, which measures matter at $z\sim2$ is in fully agreement with Planck.
- The S8 tension may not be entirely caused by an early vs late universe measurements rather something else.

Chen et al. (2022). Credits to Nick Krokon for the inspiration

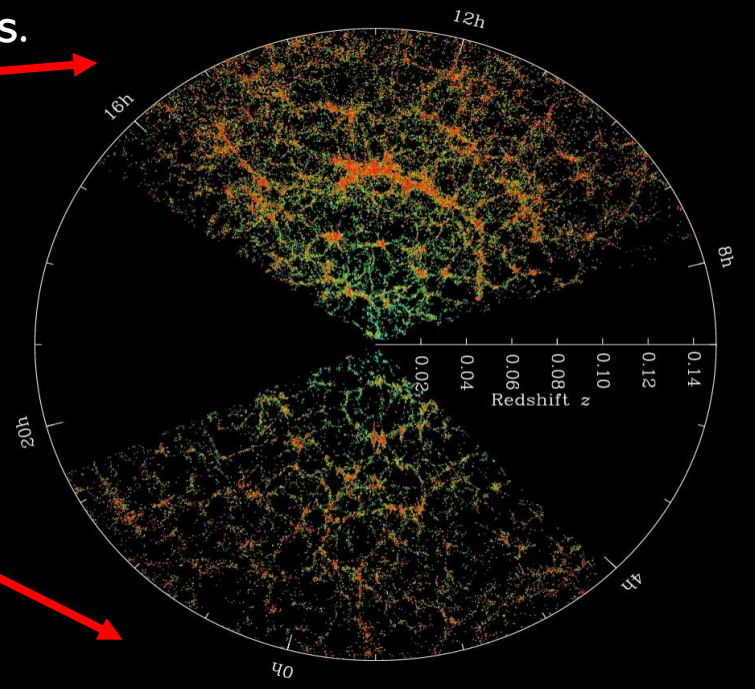
Probing the large-scale structure of the Universe.



Probing the large-scale structure of the Universe



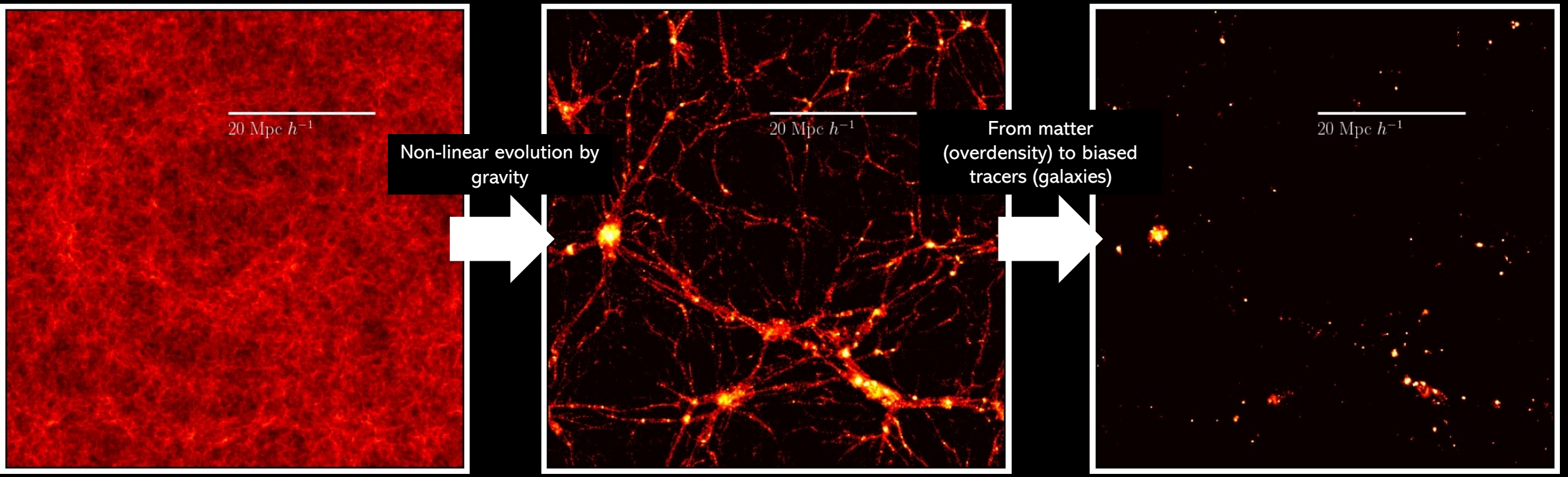
- At the early Universe matter fluctuations come from a ~**Gaussian** (random) distribution.
- Evolution of the matter field is shaped by both gravity and the effect of dark energy at late times z~0. It becomes highly **non-linear**.
- Only biased tracers (galaxies) of the field can be observed. Assumes a **connection** between overdensities and galaxies.



Credits: SDSS

Reconstruction of the cosmic web using theory and simulations

The aim is to evolve the initial **distribution** of matter to the late-time LSS

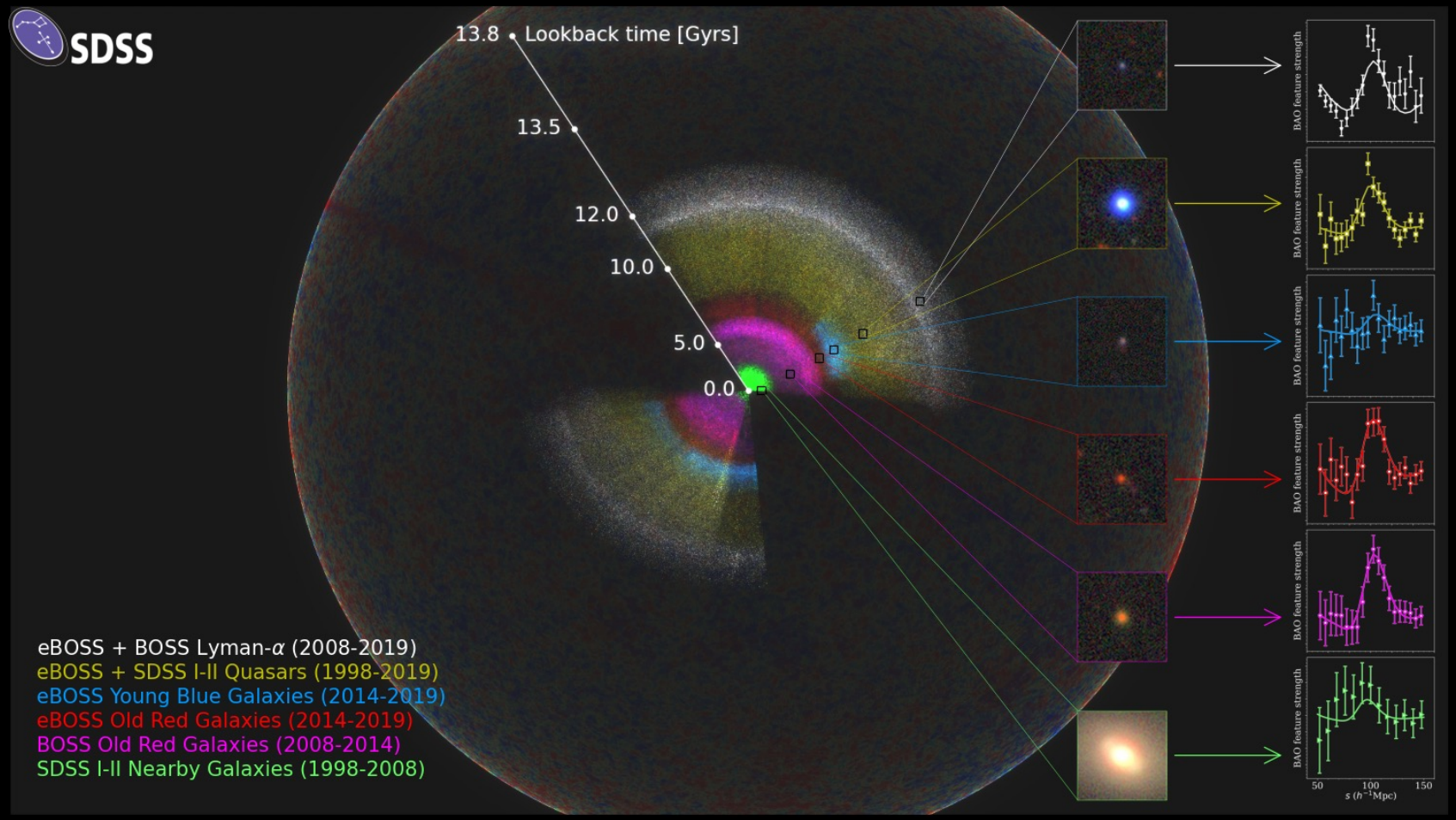


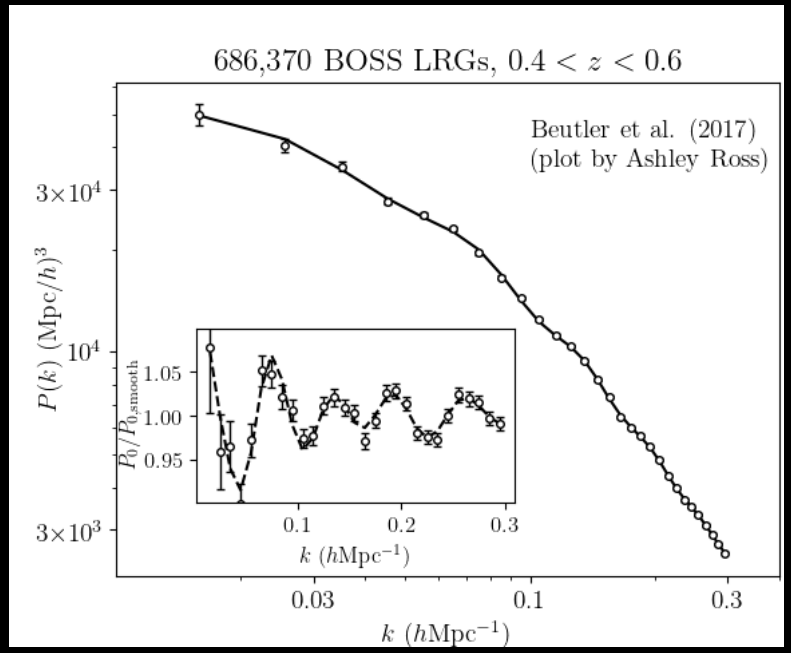
Expensive method! (~10^4 CPU-hours)

Other options:

- Perturbation theory: fastest, useful to $k{\sim}0.1\ h\ \mathrm{Mpc}^{-1}$ (linear regime).
- Hybrid methods: Needs simulations to calibrate, useful to $k{\sim}0.5\ h\ \mathrm{Mpc}^{-1}$.

Galaxy redshift surveys

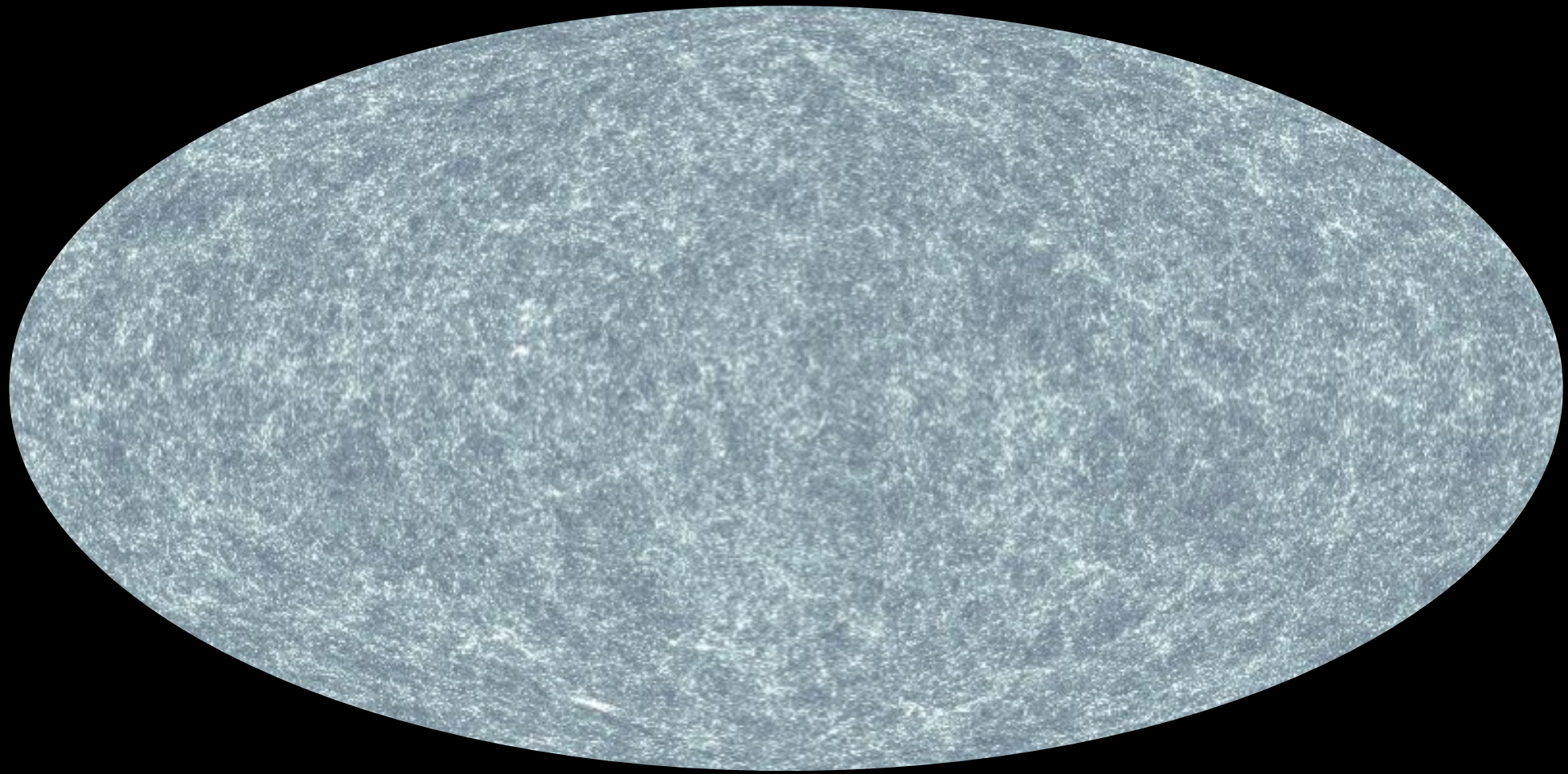




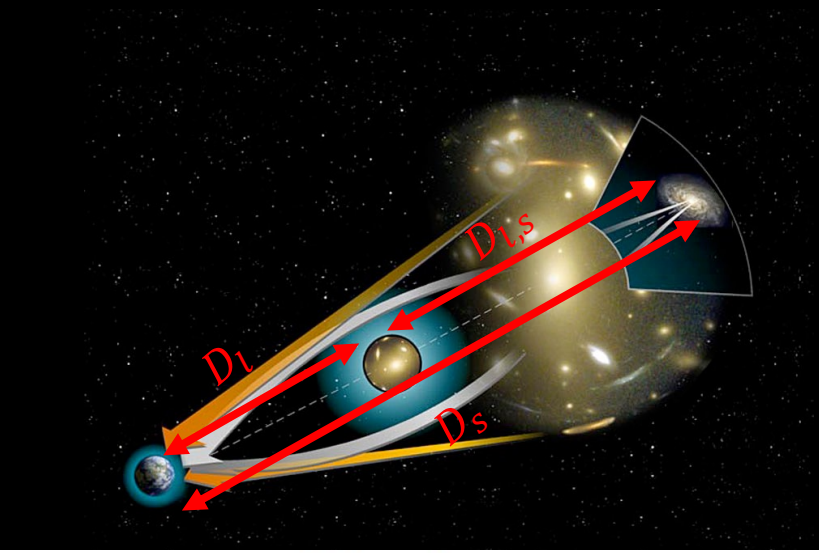
- Spectroscopic surveys provide a 3D reconstruction of the Universe.
- The goal is to measure BAO, which probes the sound horizon.
- Providing values for Ω_m gives and independent value of H_0 which agrees with Planck.

Credits SDSS-eBOSS: https://www.sdss4.org/science/final-bao-and-rsd-measurements/

Gravitational lensing: The weak lensing regime.



Weak lensing fields

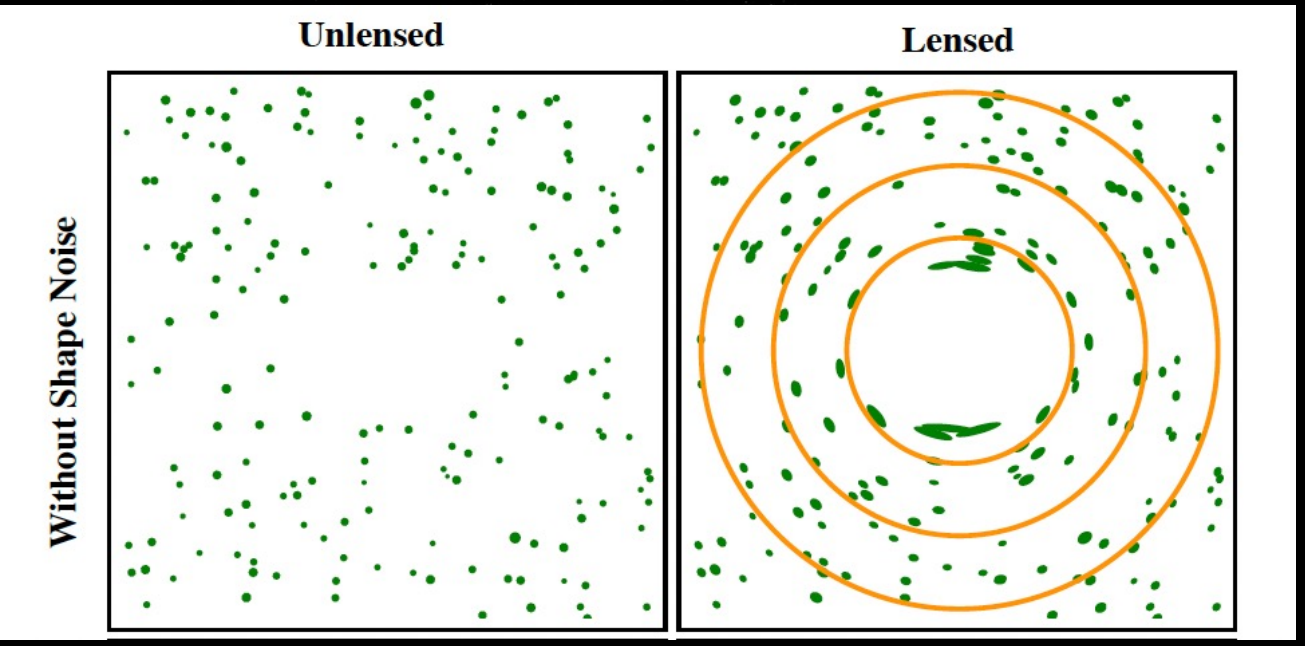


$$\kappa(\boldsymbol{\theta}) = \frac{\Sigma(\boldsymbol{\theta})}{\Sigma_{\text{crit}}}$$

$$\Sigma_{\text{crit}} \propto \frac{D_s}{D_l D_{l,S}}$$

$$\kappa(\boldsymbol{\theta}) = \int_0^{r_{\text{hor}}} dr\, w(r)\delta(x(r)\boldsymbol{\theta}, r)$$

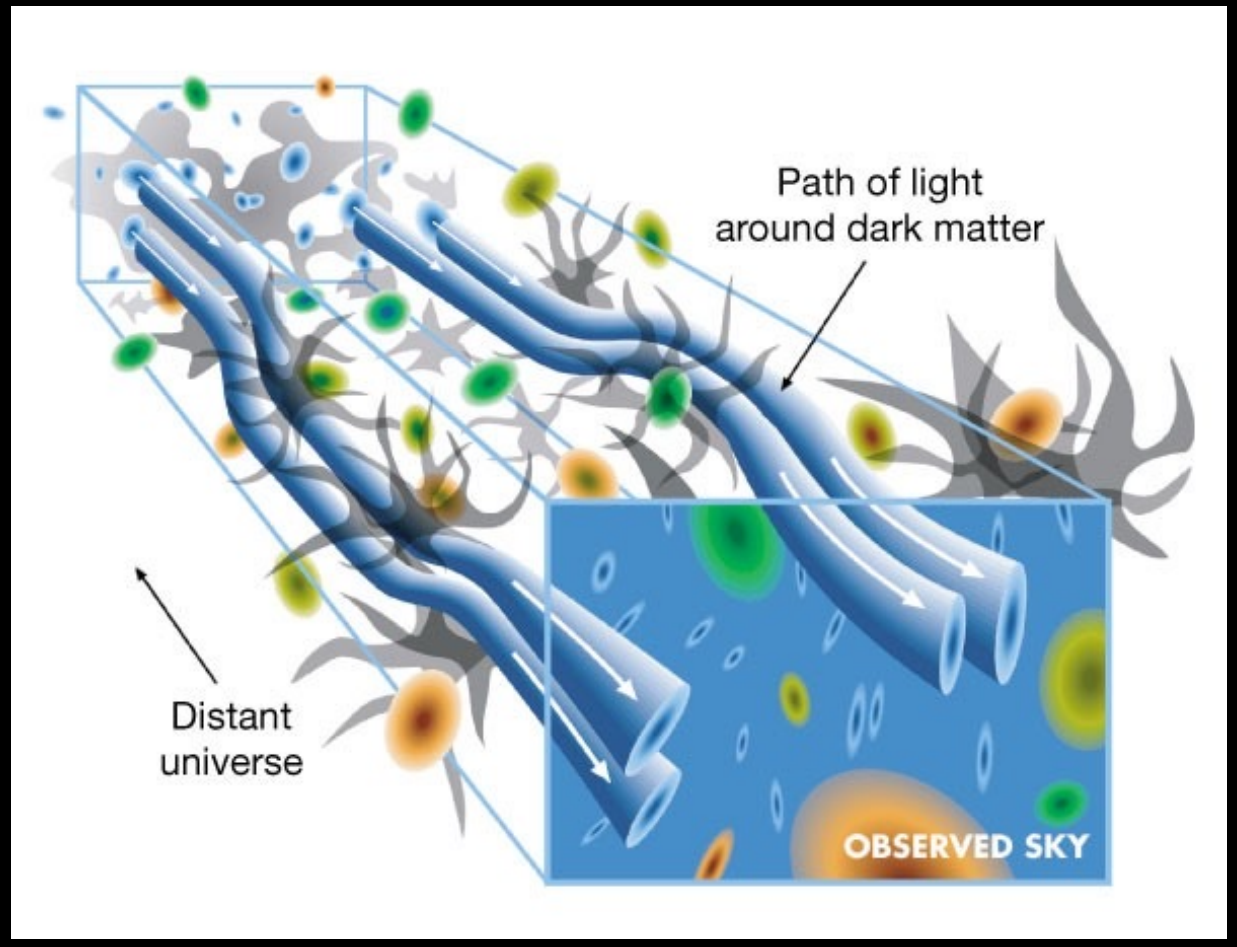
κ is a weighted measurement of the density field.

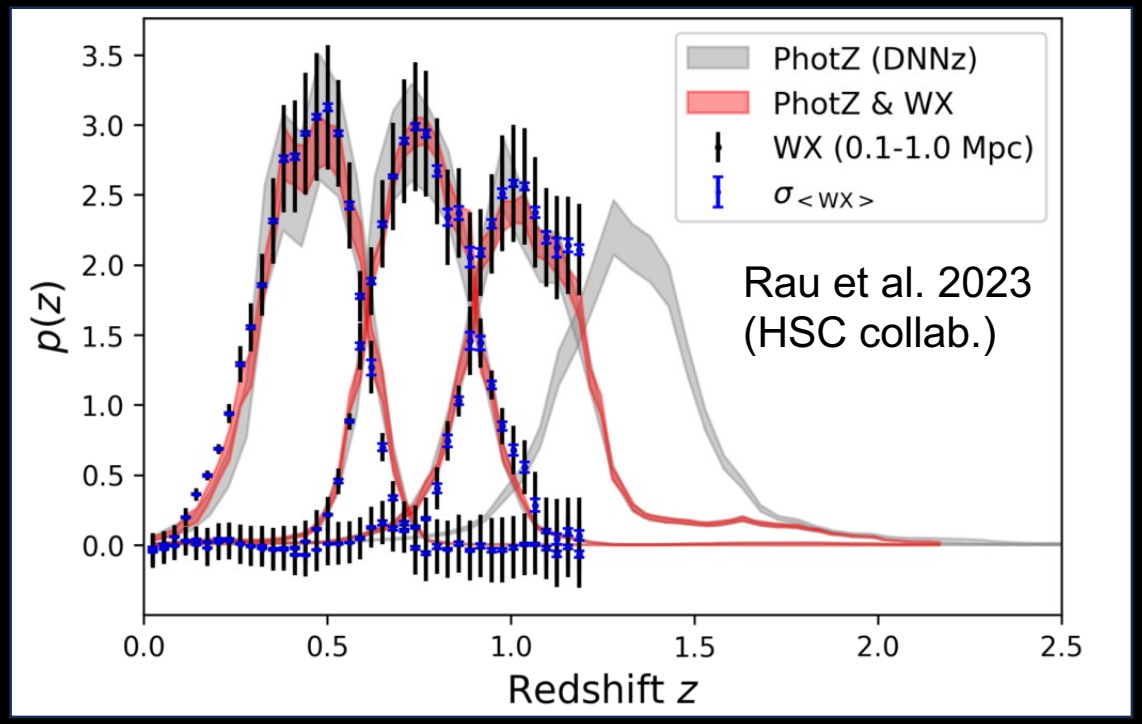


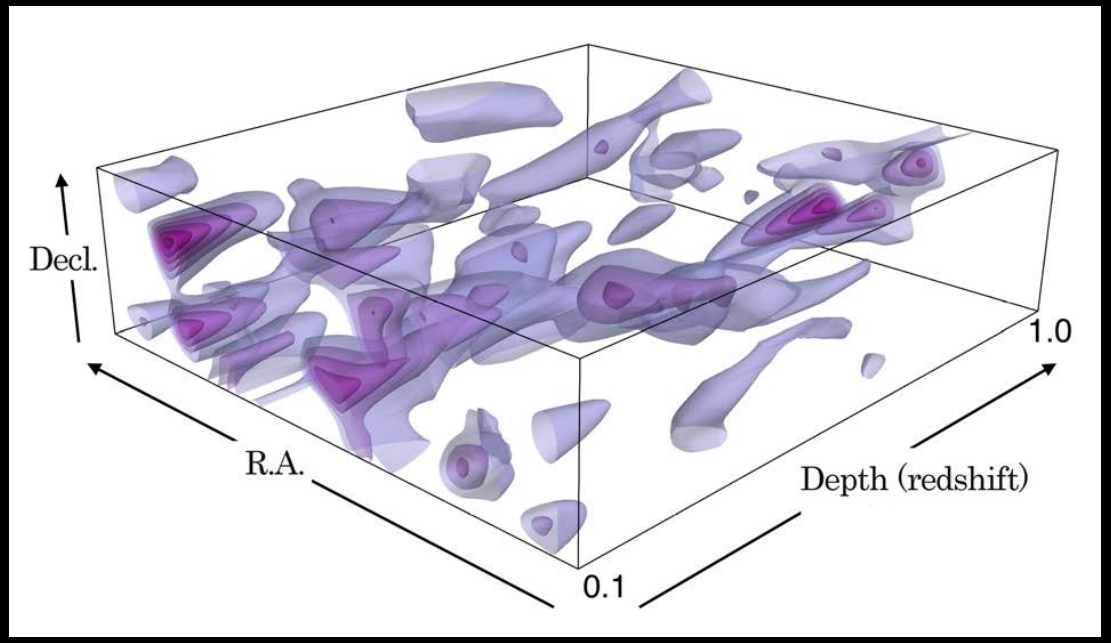
- The presence of any mass bends the light passing, including the galaxies we observe in the field.
- Weak lensing is an intrisecally **statistical measurement**. It gives information about the matter field.
- Convergence (magnifies size) and shear (tangentially stretches).

Weak lensing tomographic analysis

$$\kappa(\boldsymbol{\theta}) = \int_0^{r_{\rm hor}} dr\, w(r)\delta(x(r)\boldsymbol{\theta}, r)$$





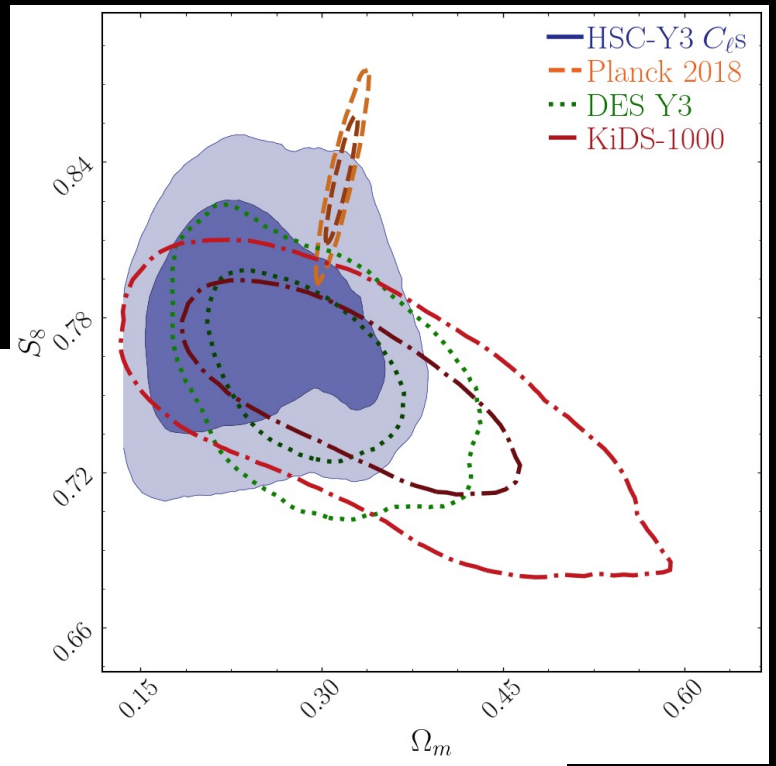


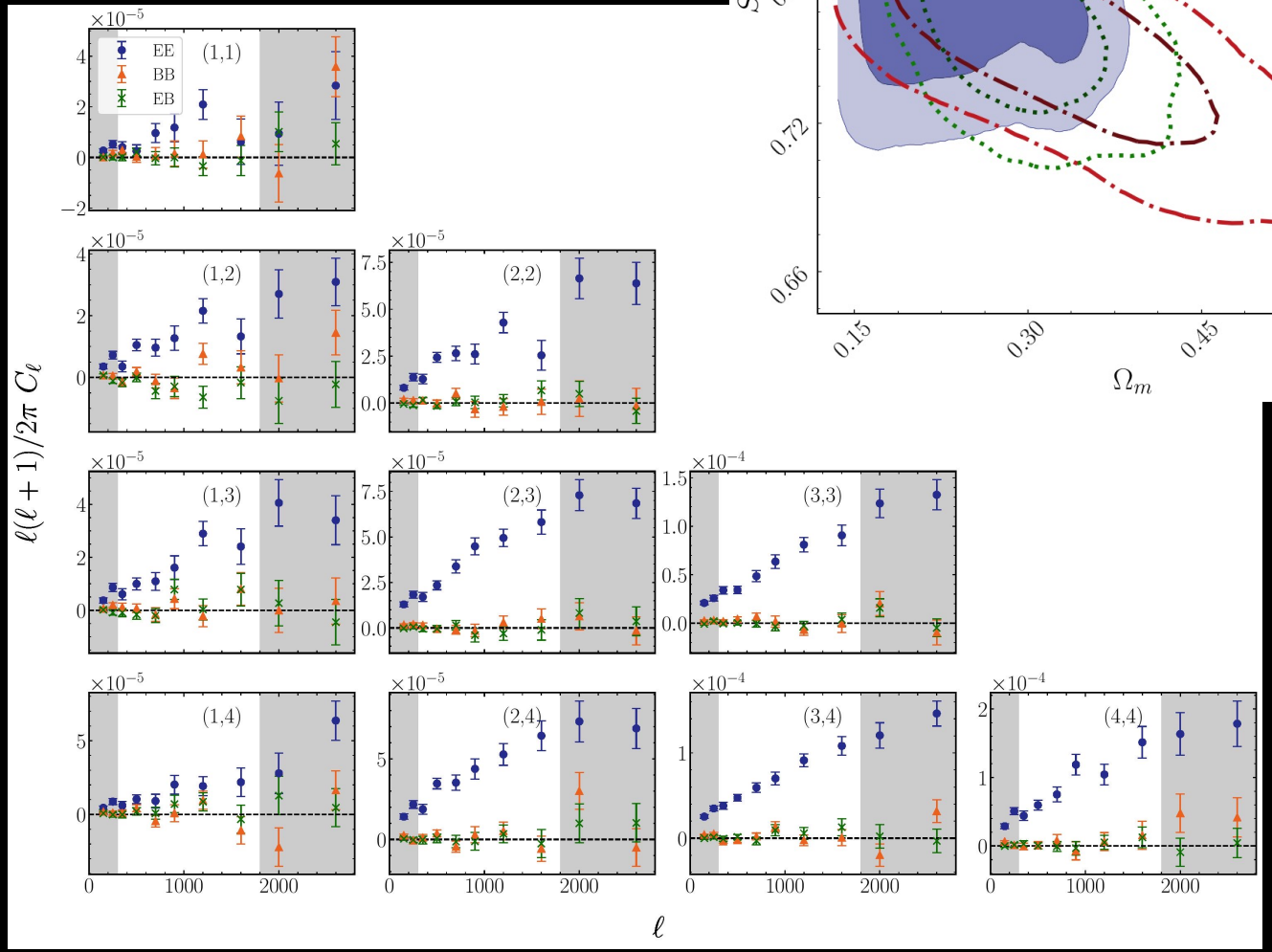
Stage-III results

Dalal et al. 2023 (HSC collab.)

Li et al. 2023

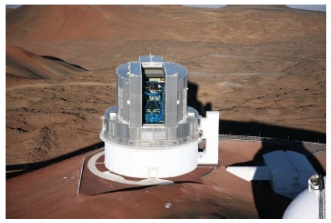
Sugiyama et al. 2023

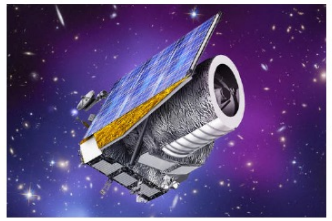


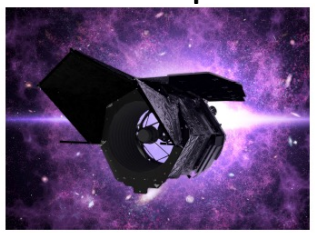


- HSC-Y3 results were released on April 2023.
- Analysis using shear power spectrum (also 2-point CF) is consistent with same type experiments (KiDS, DES), but still shows $\sim 2\sigma$ discrepancy with Planck data.
- Analysis is done for $300 < \ell < 1800$ angular scale. This is a linear regime, mostly affected by systematics (including baryons and intrinsic aligments).
- CMB lensings results gathered by ACT-DR6 were released at the same time, and they are consistent with Planck (Qu et al. 2023).

Towards stage-IV surveys







	KiDS	DES	Subaru HSC	Euclid	Rubin	Roman space telescope
Primary Mirror [m]	2.6	4.0	8.2	1.2	8.4	2.4
Galaxy Number Density [arcmin^{-2}]	11	10	25	30	30	50
Survey Area [sq. deg]	1,500	5,000	1,400	15,000	18,000	2,200

All sky ~41,253 [sq. deg]

2010 2020 2030

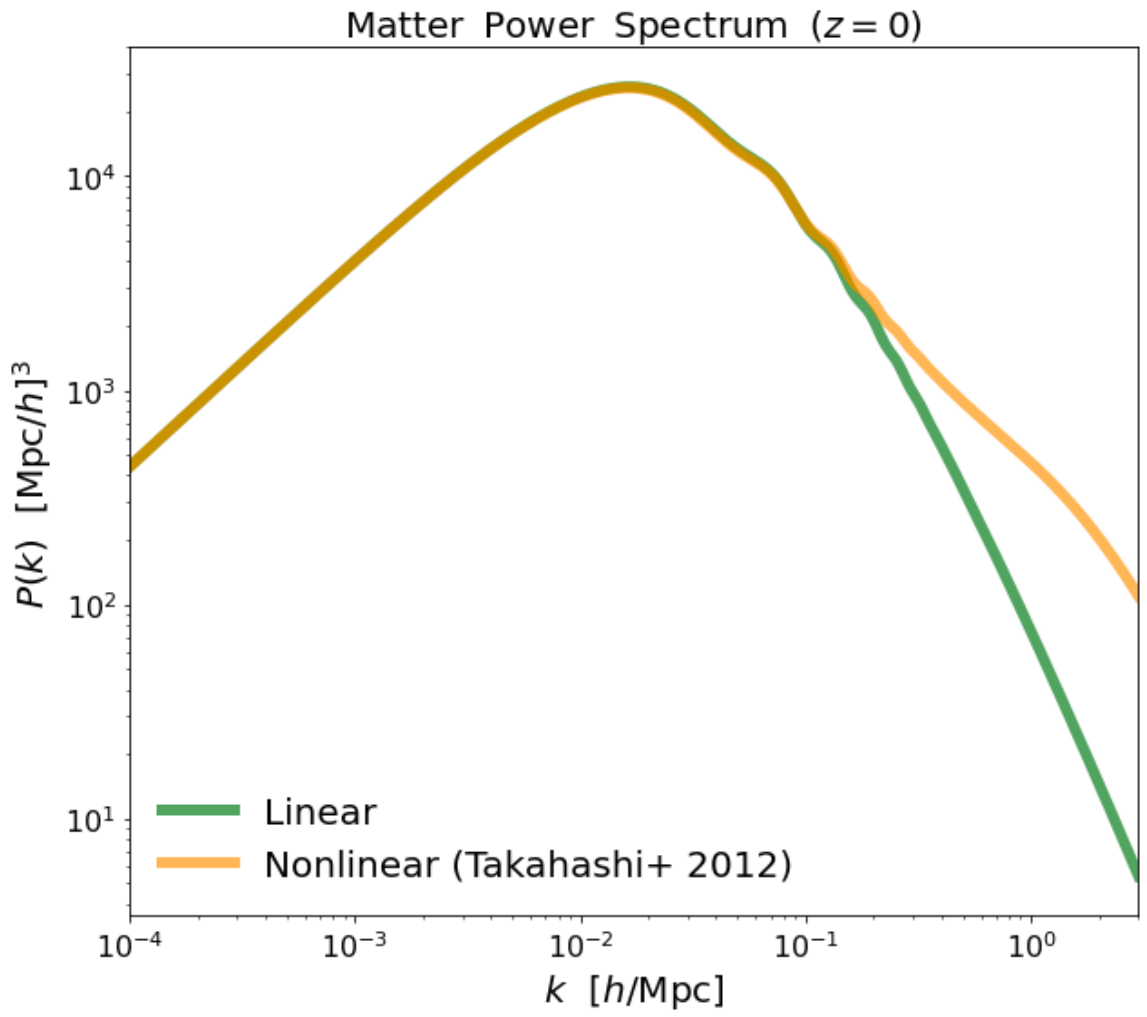
Inspired by E. Krause

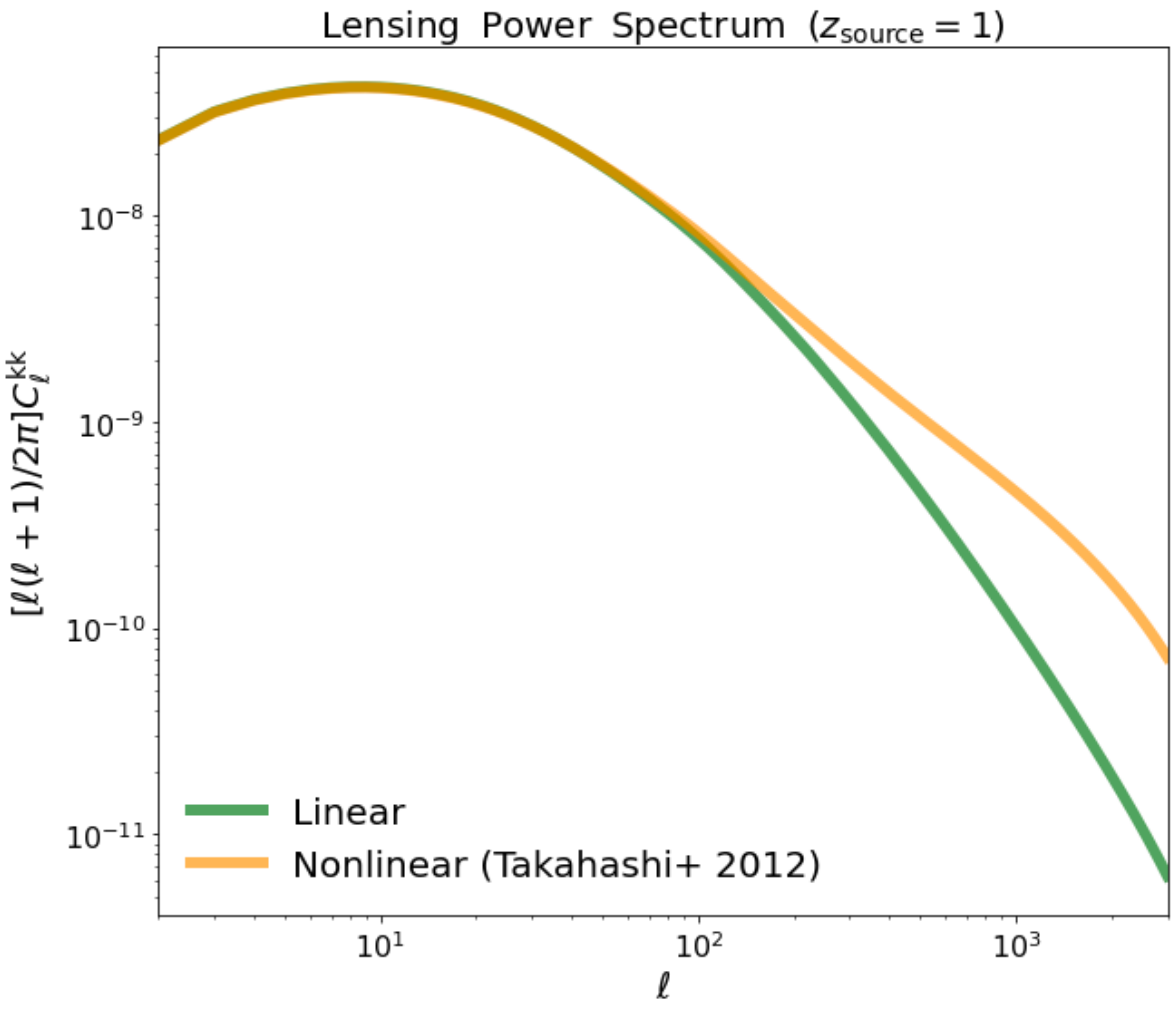
Credit: ESO, Fermilab/Reidar Hahn, NAOJ, ESA/C. Carreau, Rubin Obs/NSF/AURA, NASA

Higher-order statistics for weak lensing fields.

Non-linear effects in two-point statistics

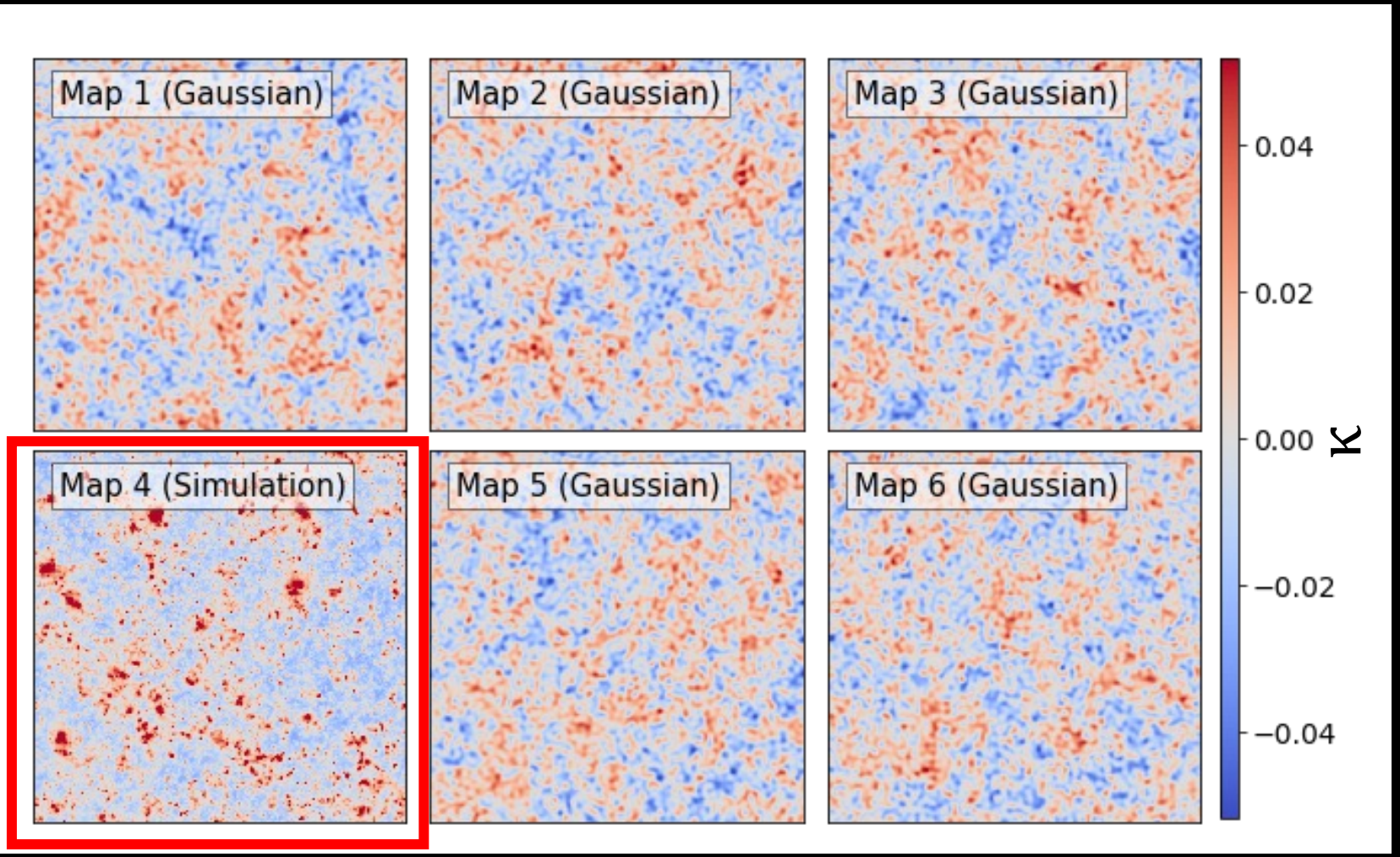
Linear power spectrum is no longer valid for small scales ($k \gtrsim 0.1, \ell \gtrsim 1500$).

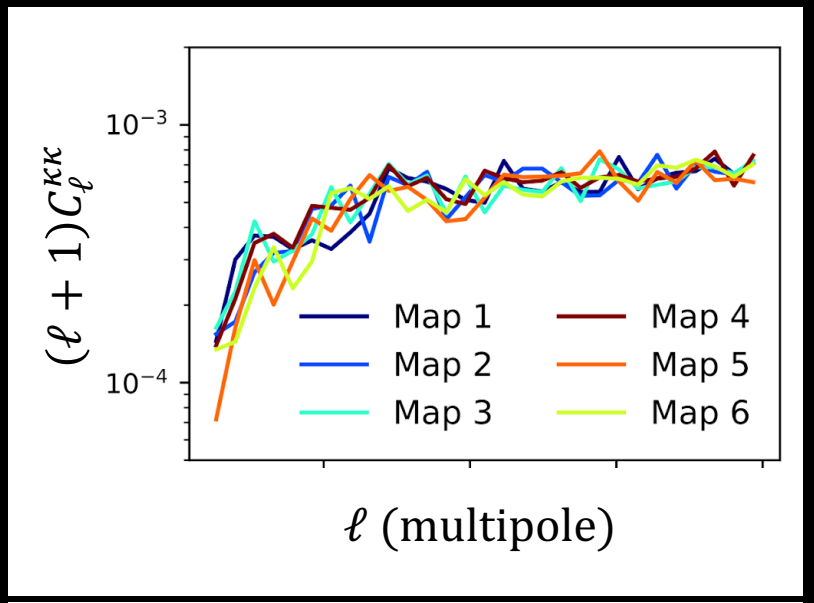


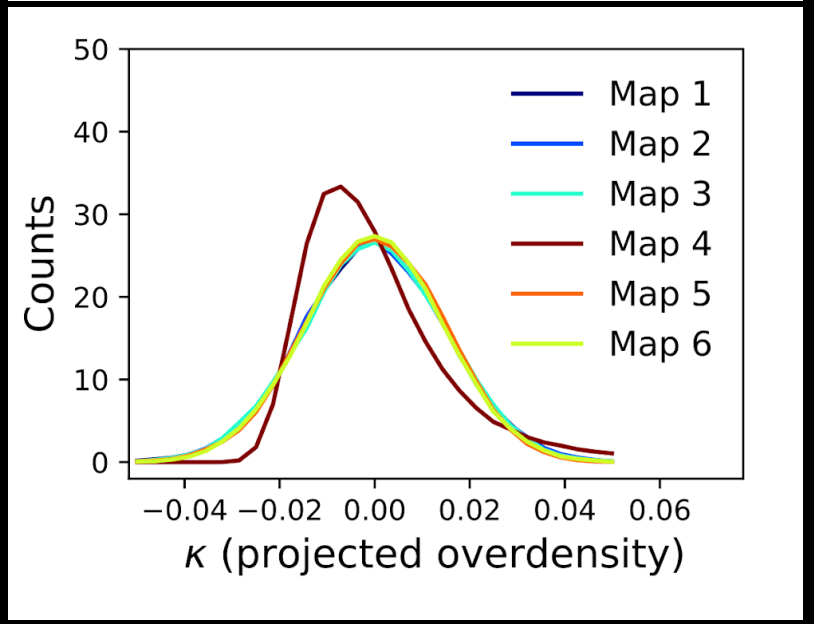


Missing information in two-point statistics

indistinguishable at power spectrum level ⇒ new statistics (peak counts) to capture all information.



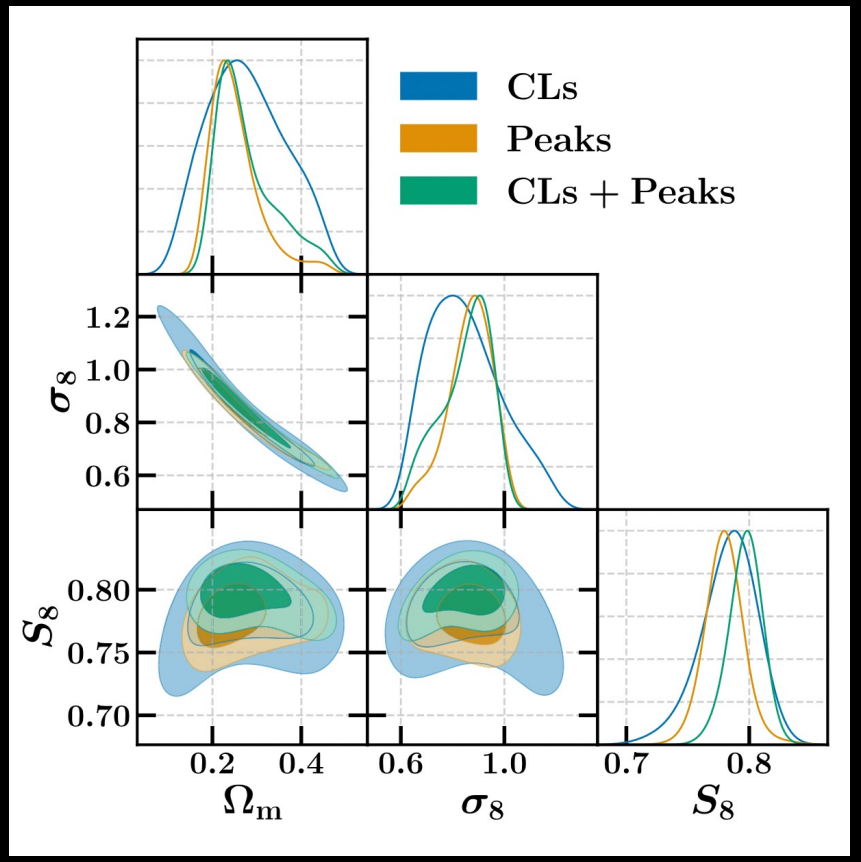


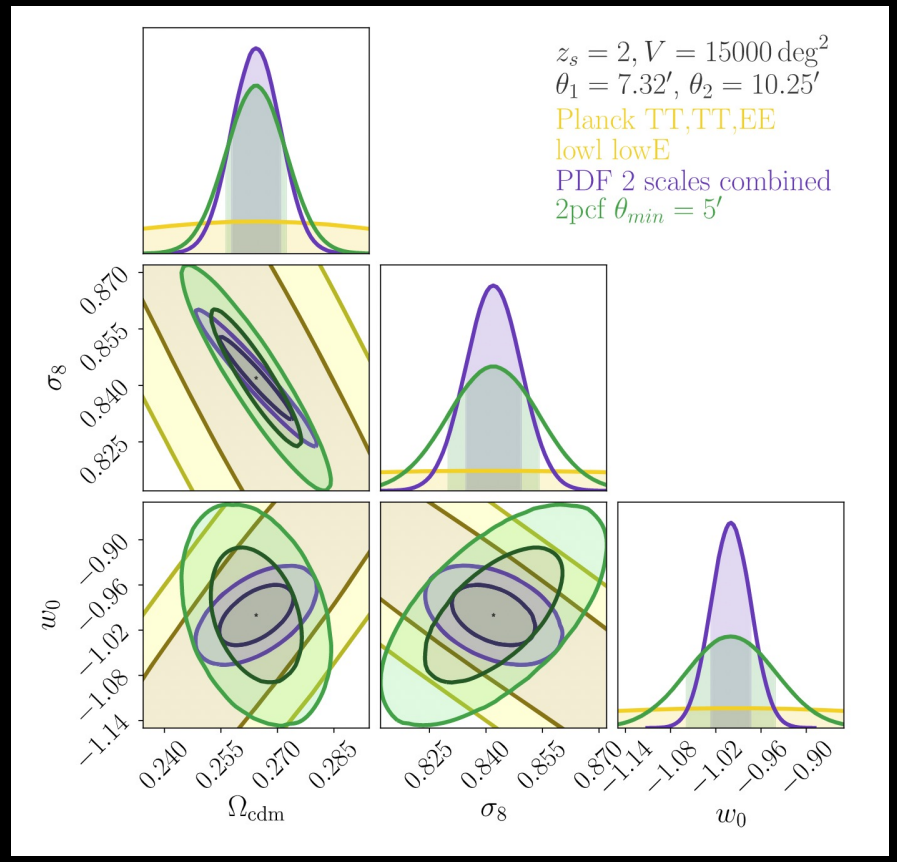


Non-Gaussian statistics results for stage-III surveys

Generally see 10-30% improvement upon 2pt

Up to a factor ~2 upon 2pt for stage-IV (forecast)





- Precision is not enough!
- We need to check accuracy (see how sensitive they are to systematics).
- Several scales can be combined.

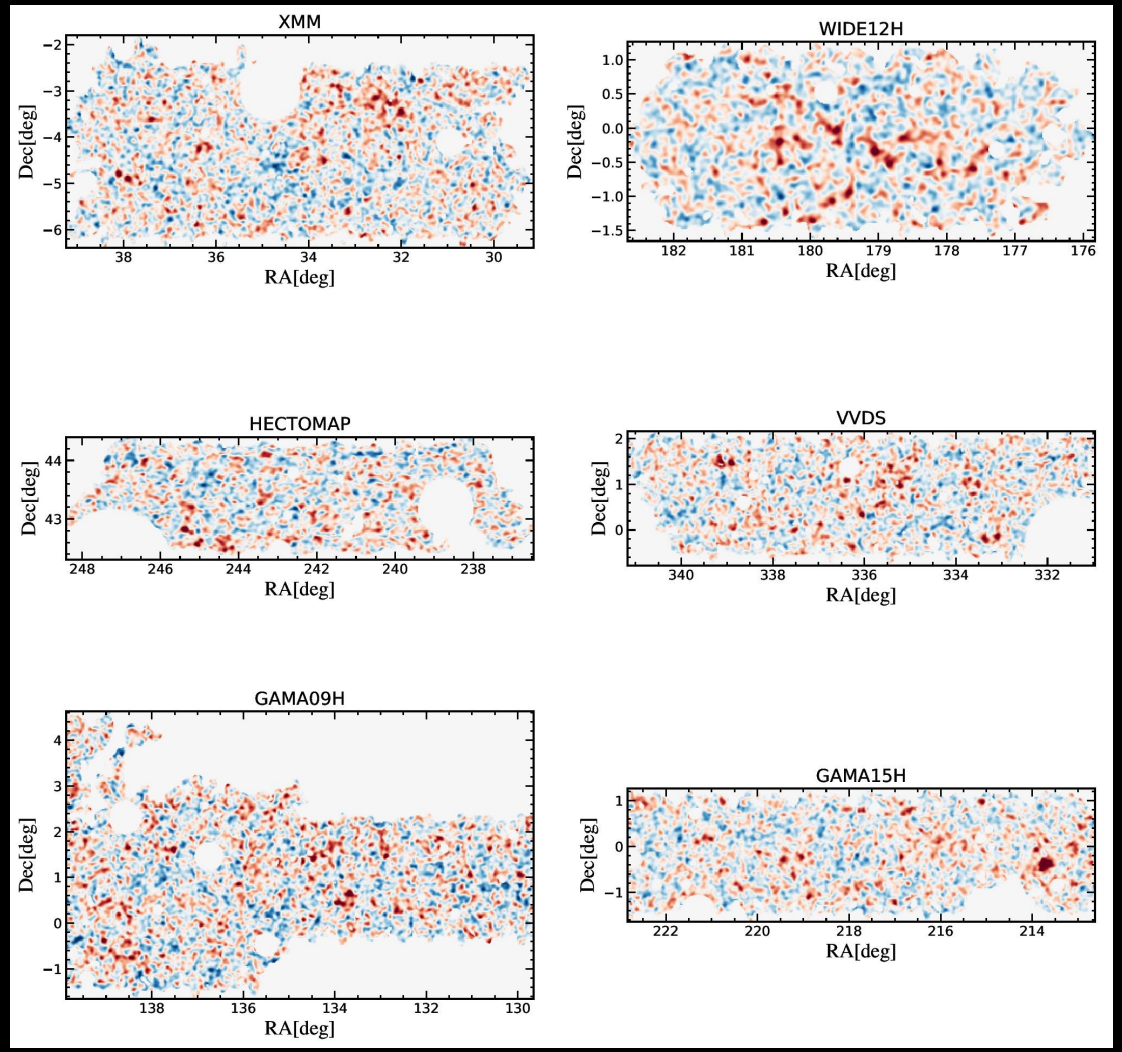
Zürcher et al. 2022
DES-Y3

Boyle et al. 2021
Euclid lensing

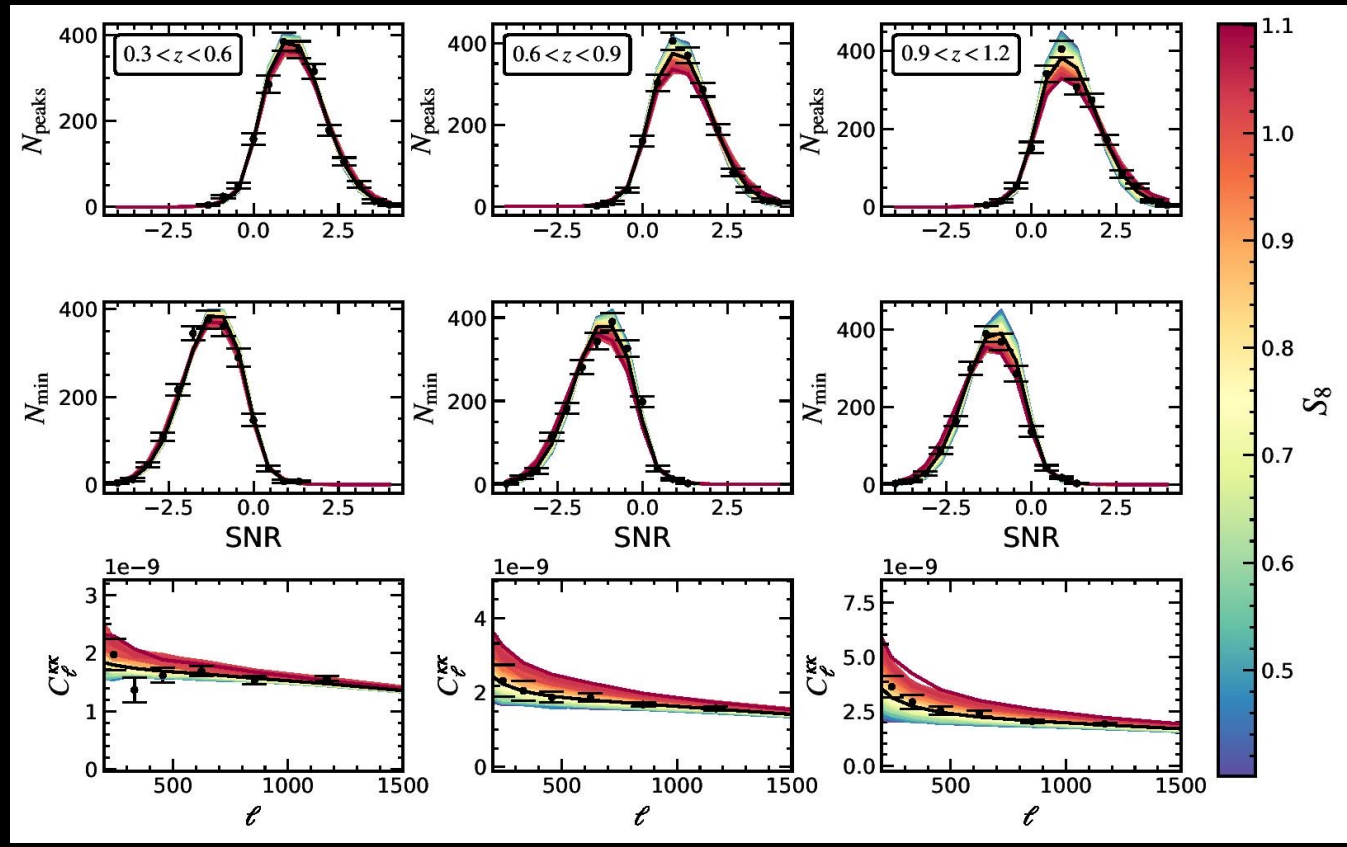
Stage-IV forecast: HSC-Y1 results.

HSC-Y1 higher-order statistics results

Using data during year-1 (modelled with simulations)

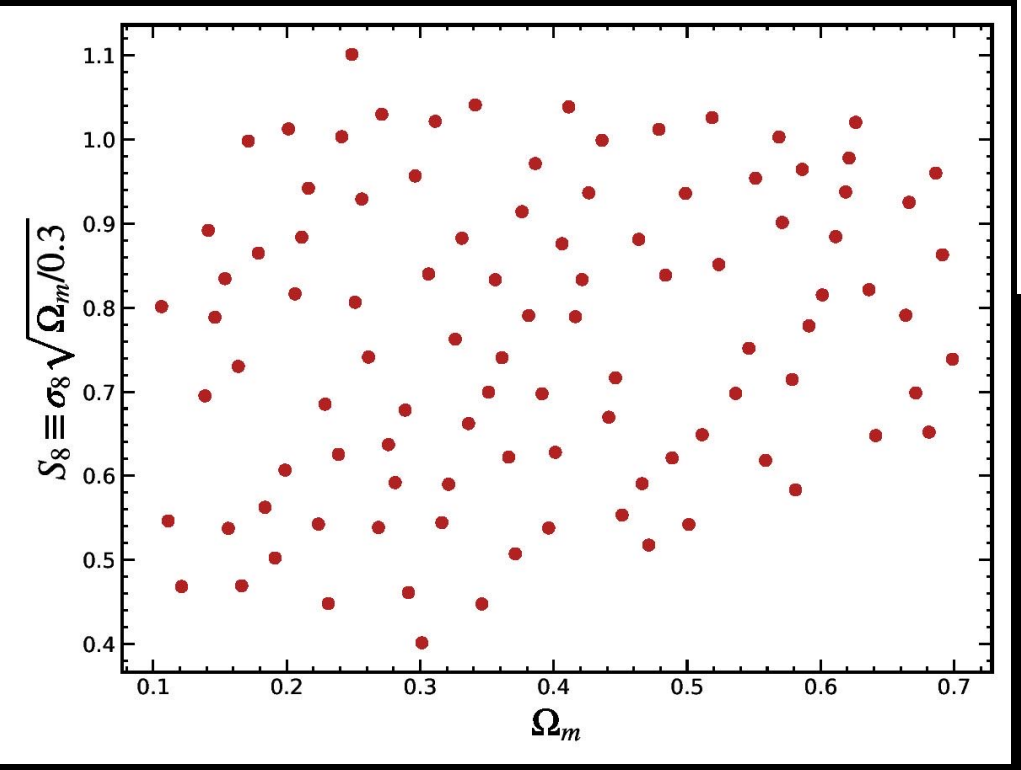


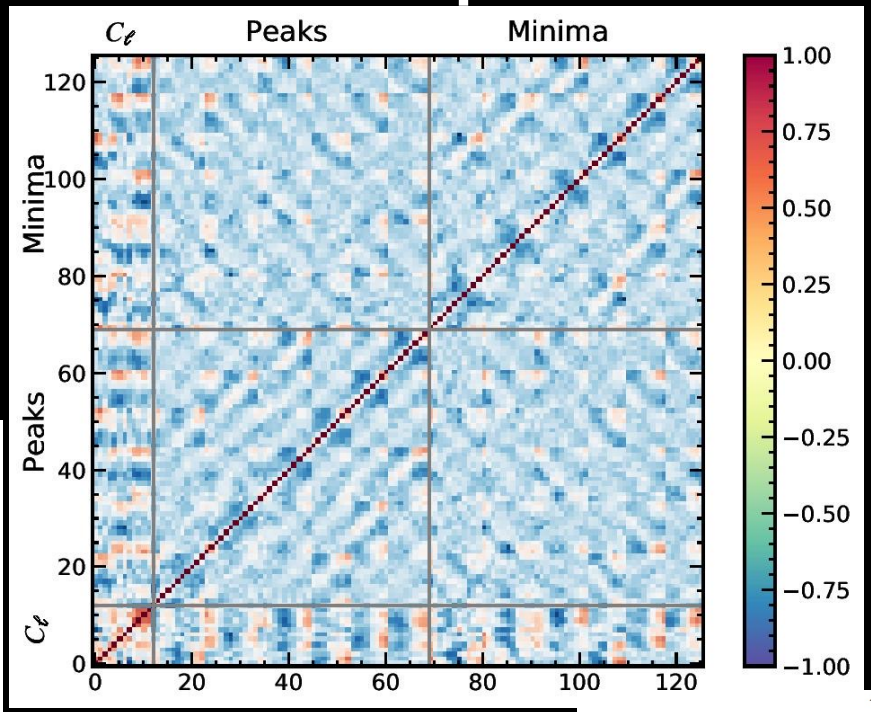
- We have simulations for several cosmologies and systematics.
- Combining statistics with power spectrum: PDF (Thiele+2023), peaks & minima (Marques+2023), Scattering transform (Cheng+2023).
- Inference done with emulator approach + linear compression.



Parameter inference with compressed data vectors

1. Use simulations to emulate data vector.
2. Use covariance from fiducial model.
3. Compress data vector (2x2 Cov. matrix).
4. Apply Gaussian likelihood.





$$D^{\mathrm{compr}} = \frac{\partial D^{\mathrm{T}}}{\partial p_m} C^{-1} D\,,$$

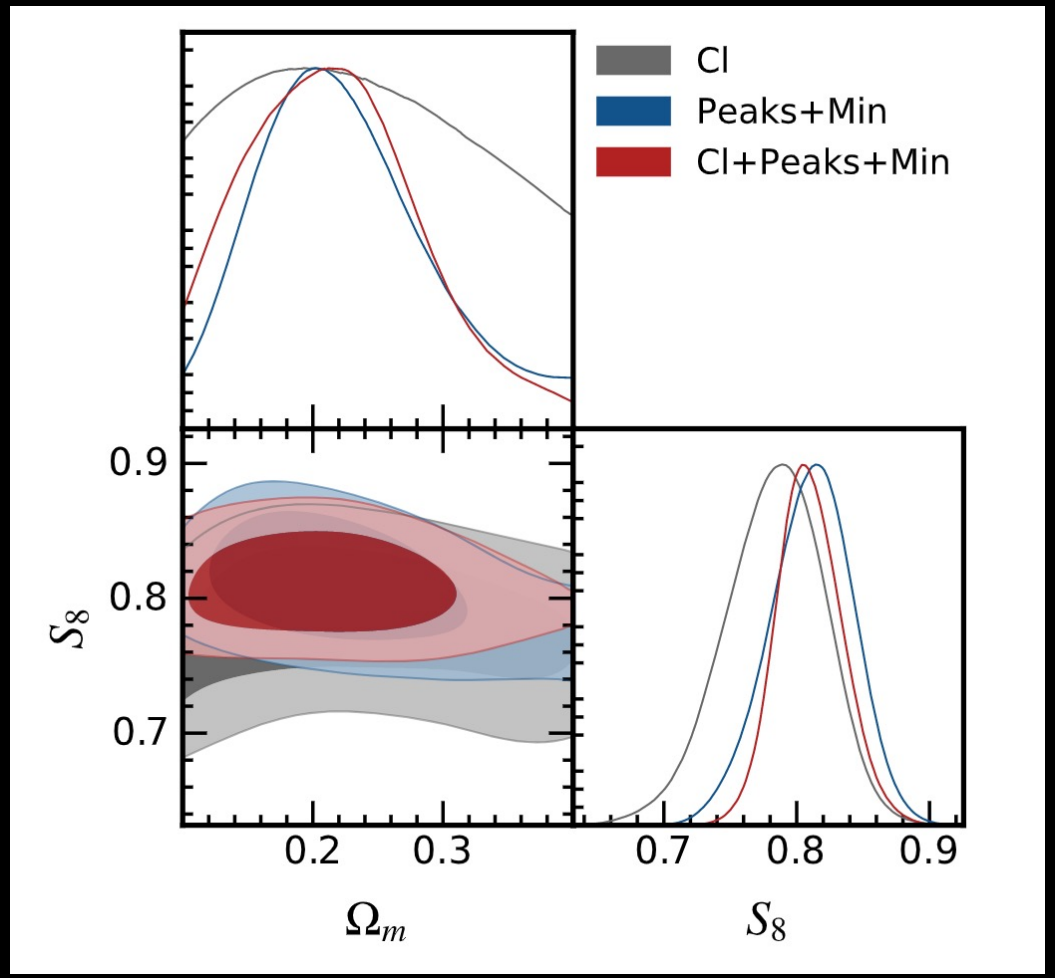
$$\ln \mathcal{L}(\mathbf{D}|\boldsymbol{\theta}) = -\frac{1}{2}[\mathbf{D} - x(\boldsymbol{\theta})]^{\mathrm{T}} \mathrm{C}^{-1} [\mathbf{D} - x(\boldsymbol{\theta})] + \mathrm{const.}$$

Moped compression conserves information (Heavens et al. 2000; Gatti et al. 2020; Zürcher et al. 2022).

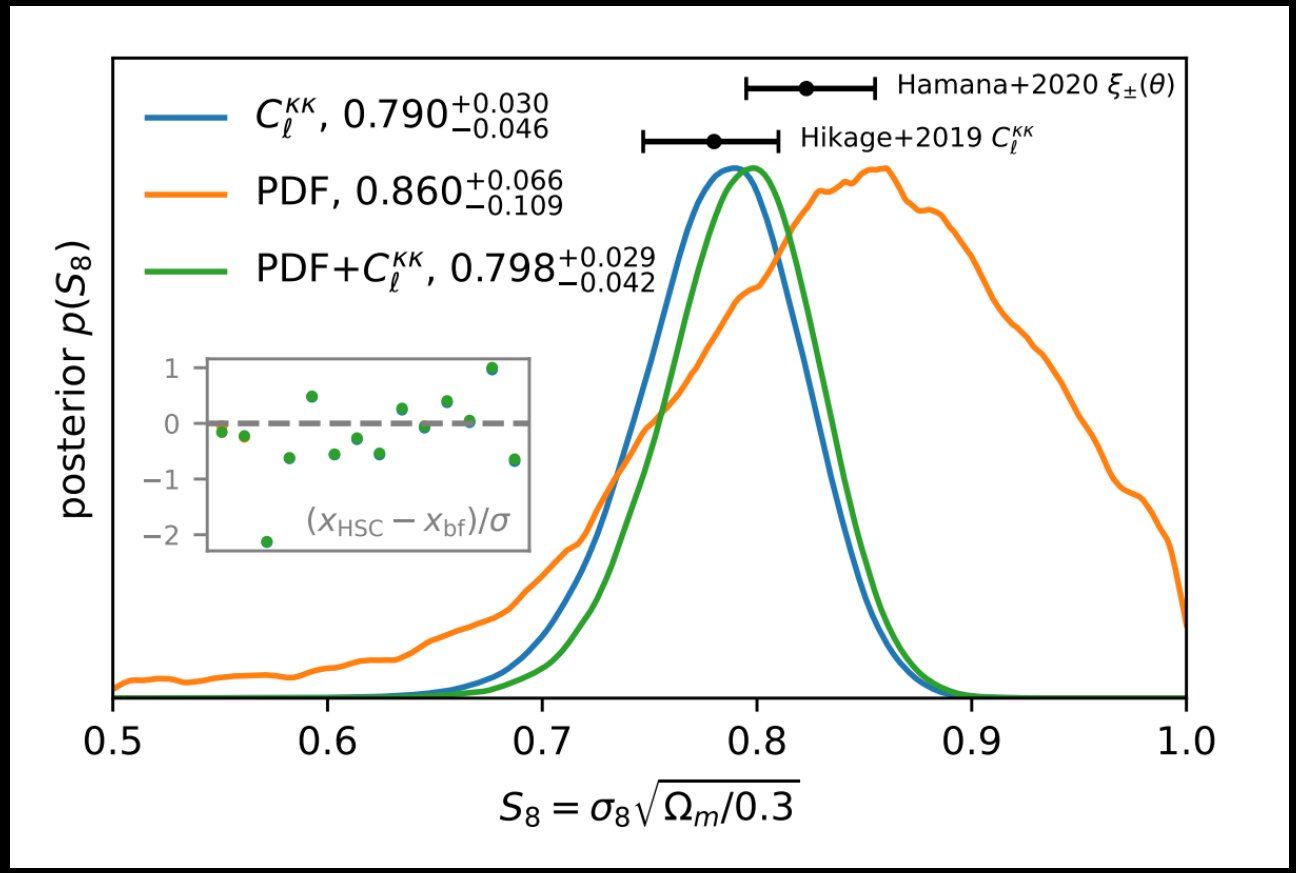
Several data vectors (redshift bins, smoothing scales) can be combined.

HSC-Y1 higher-order statistics results

PDF improves constraints 10%, Peaks+minima has 35% tighter constraints.



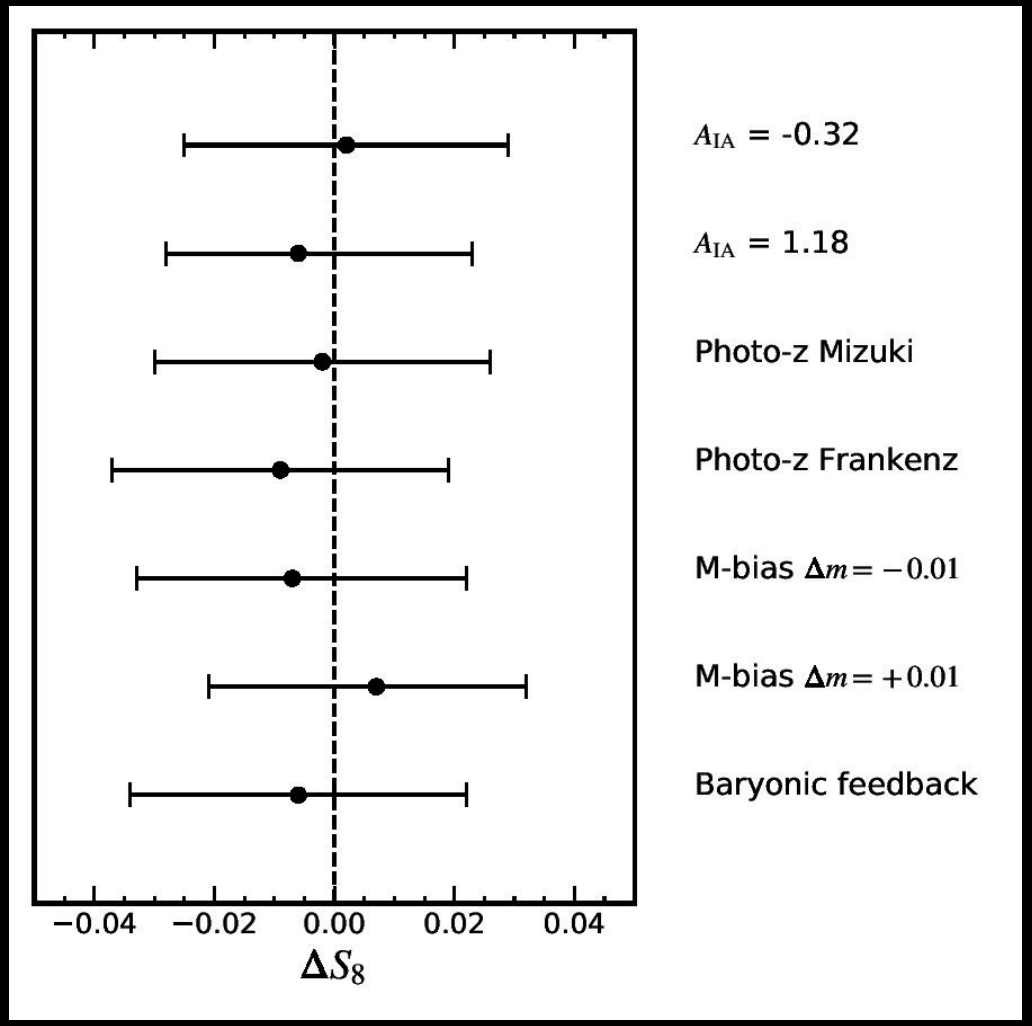
Marques et al. 2023

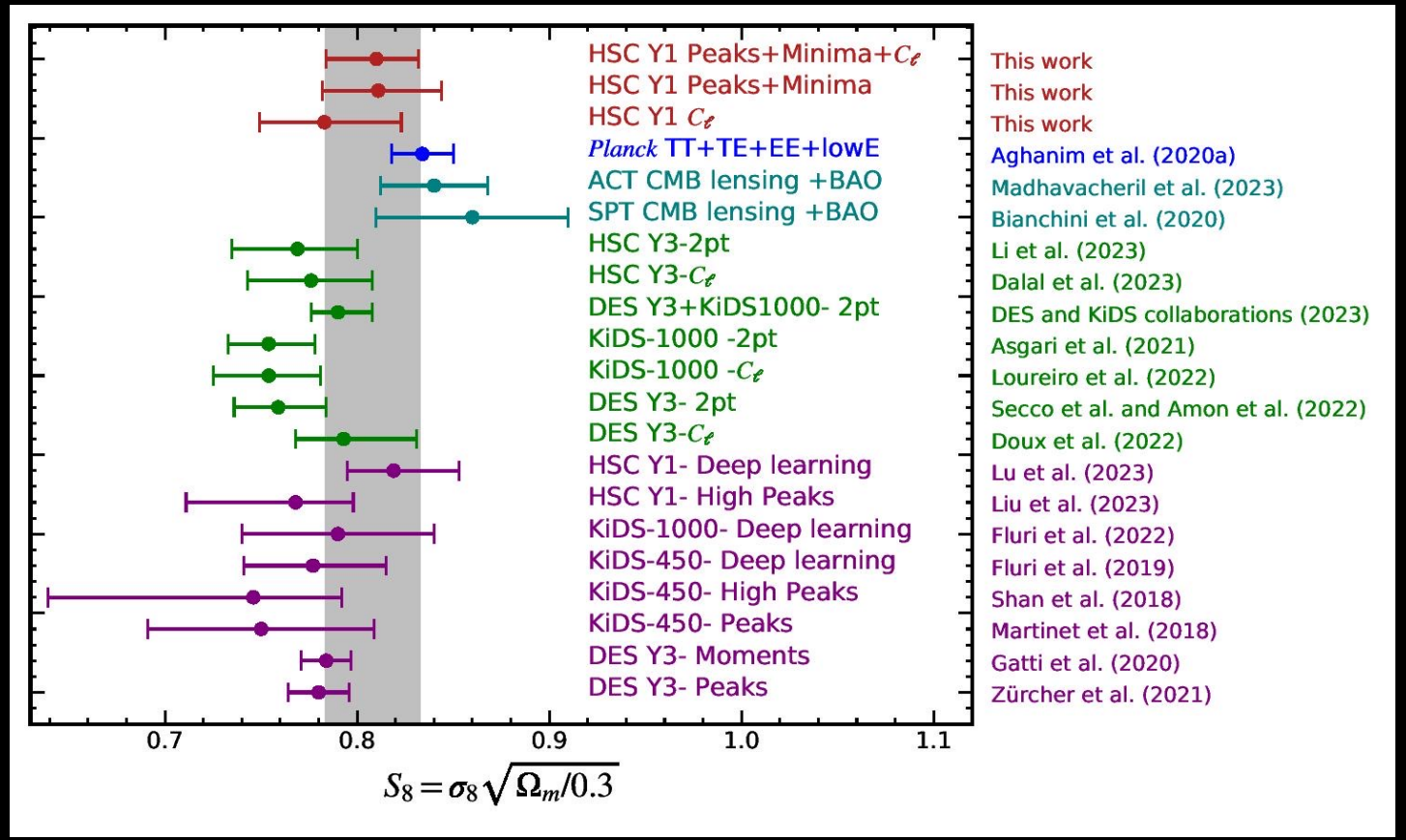


Thiele et al. 2023

HSC-Y1 higher-order statistics results

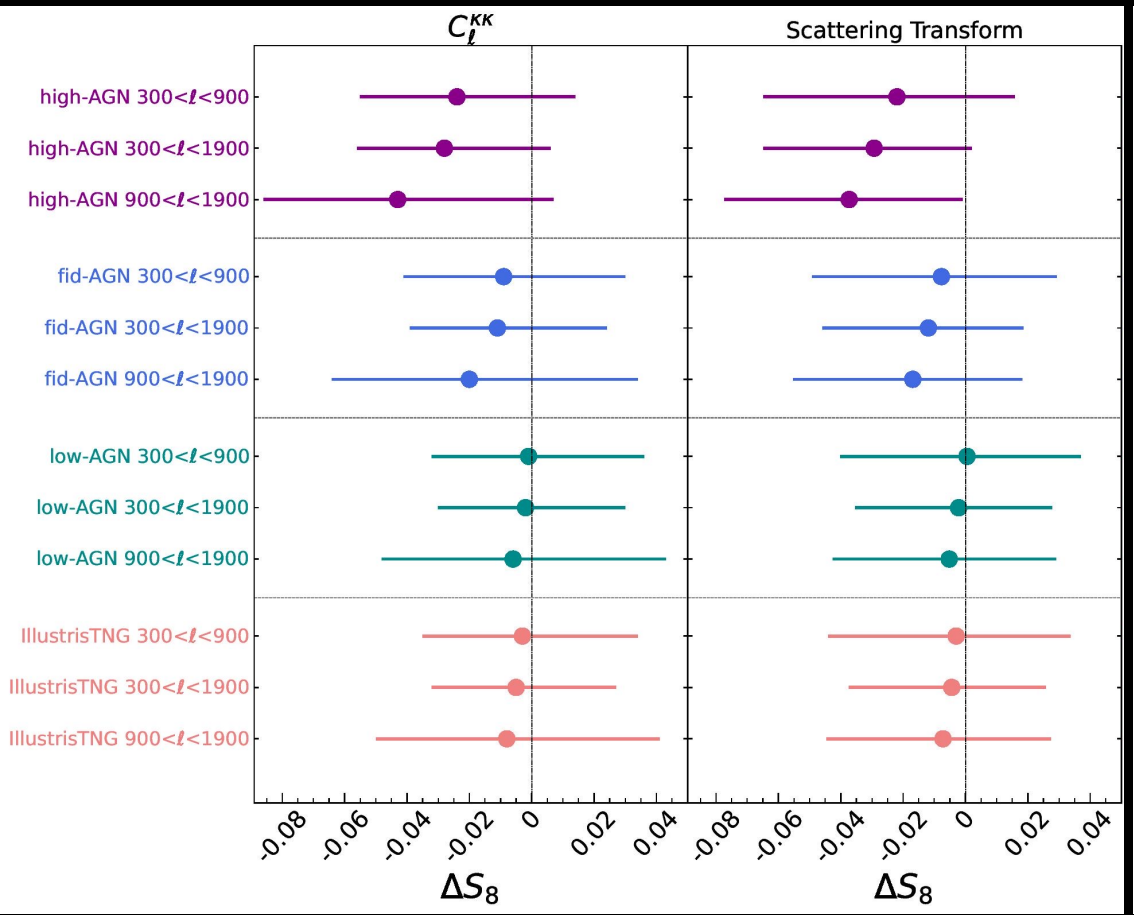
We can mitigate over various systematics! No tension is found for C_ℓ + HOS for HSC-Y1.

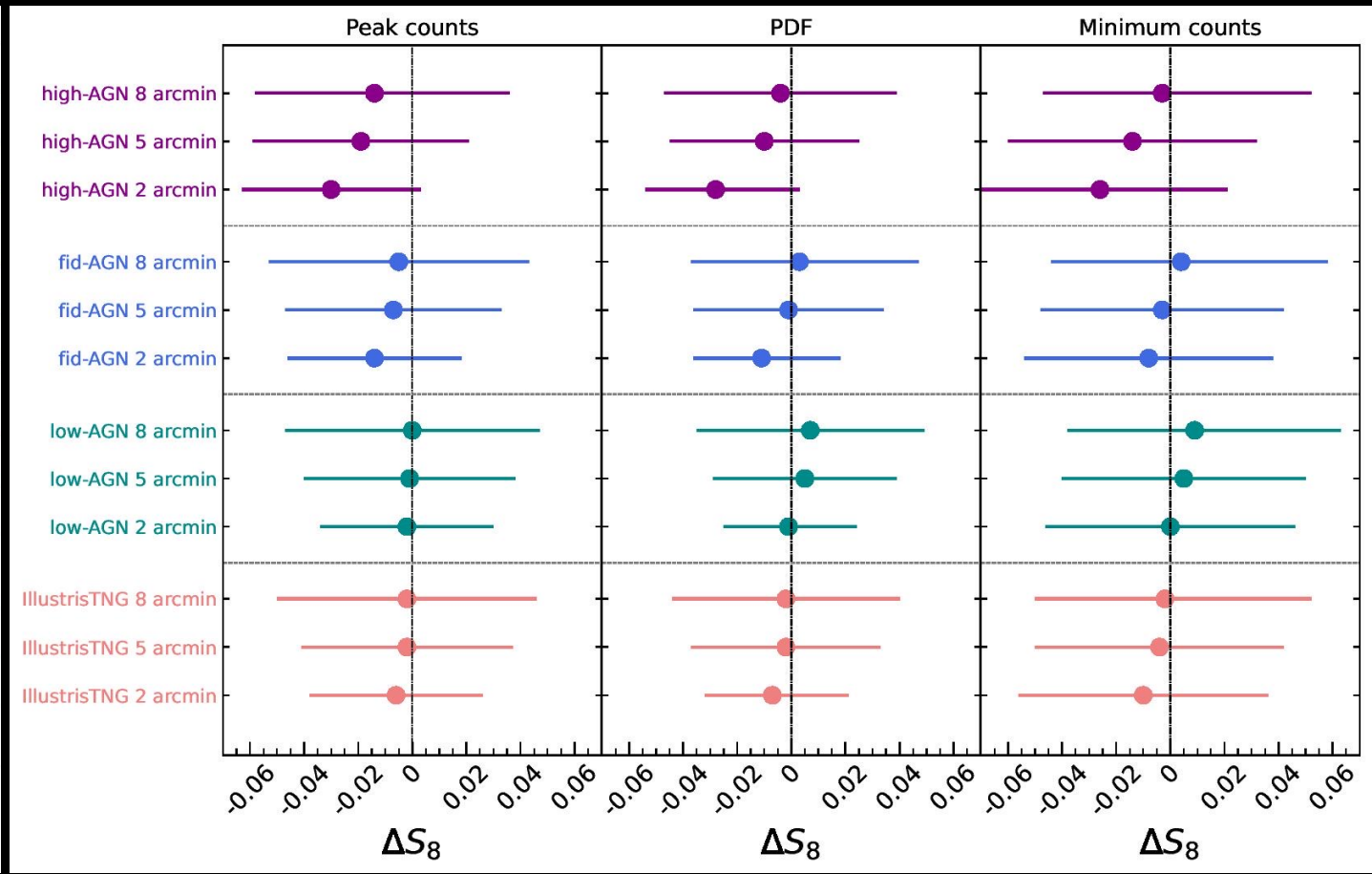




Impact of Baryon in higher order statistics

The effect of baryons for several higher-order statistics. Baryons are known for suppressing the power spectrum, but have milder effect ($< 0.5\sigma$) for HOS.

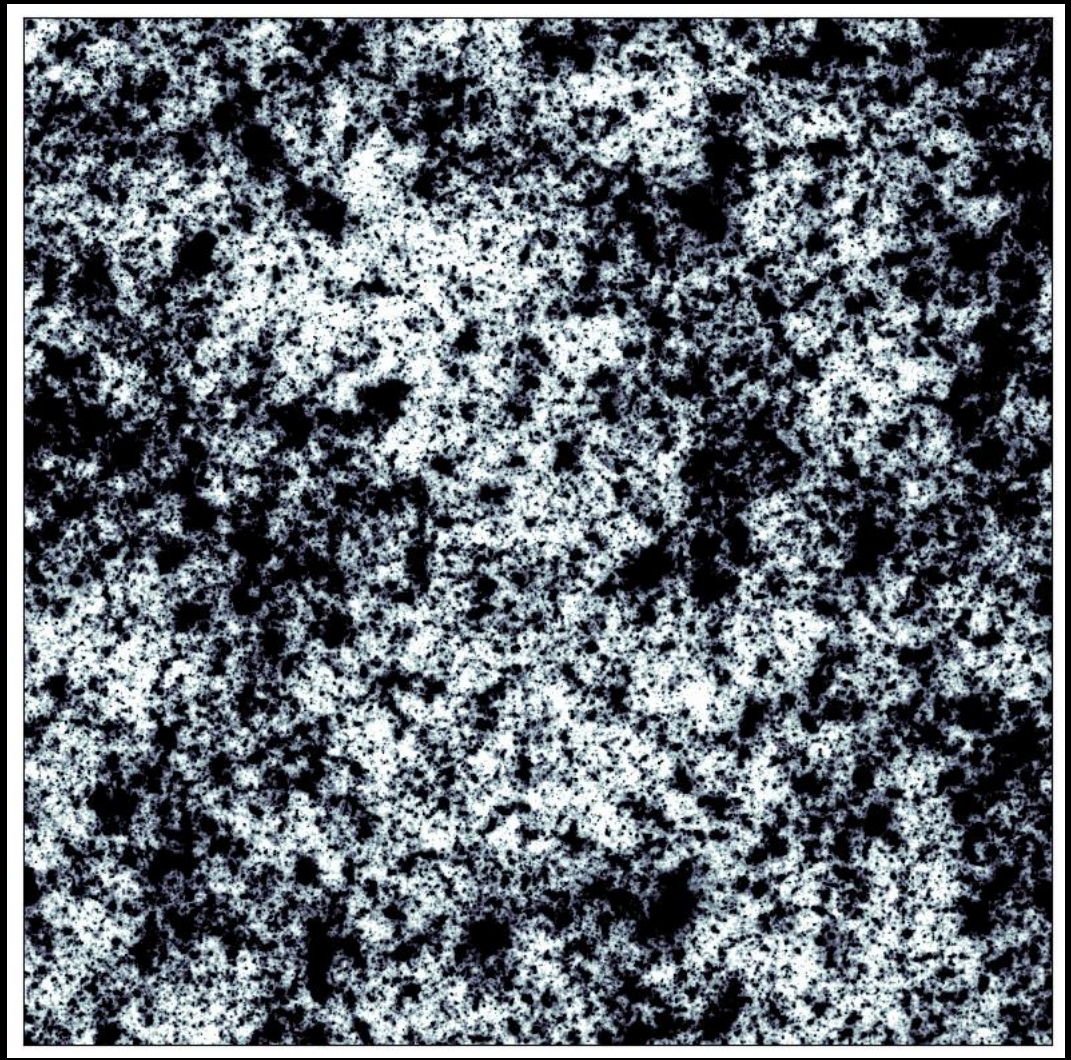


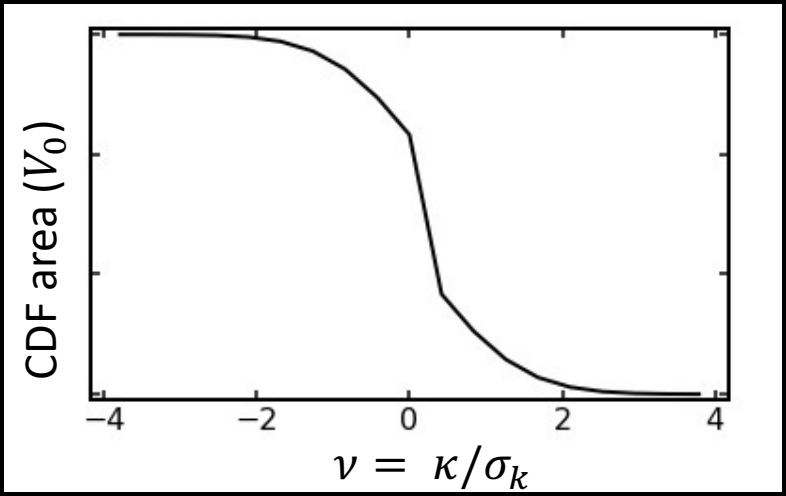


Grandón et al. (2024)

HSC-Y1 higher-order statistics

Minkowski functionals: Topological description of the field (still statistical).





$N_d + 1$ properties (Area, perimeter, genus). These are cosmology dependent.

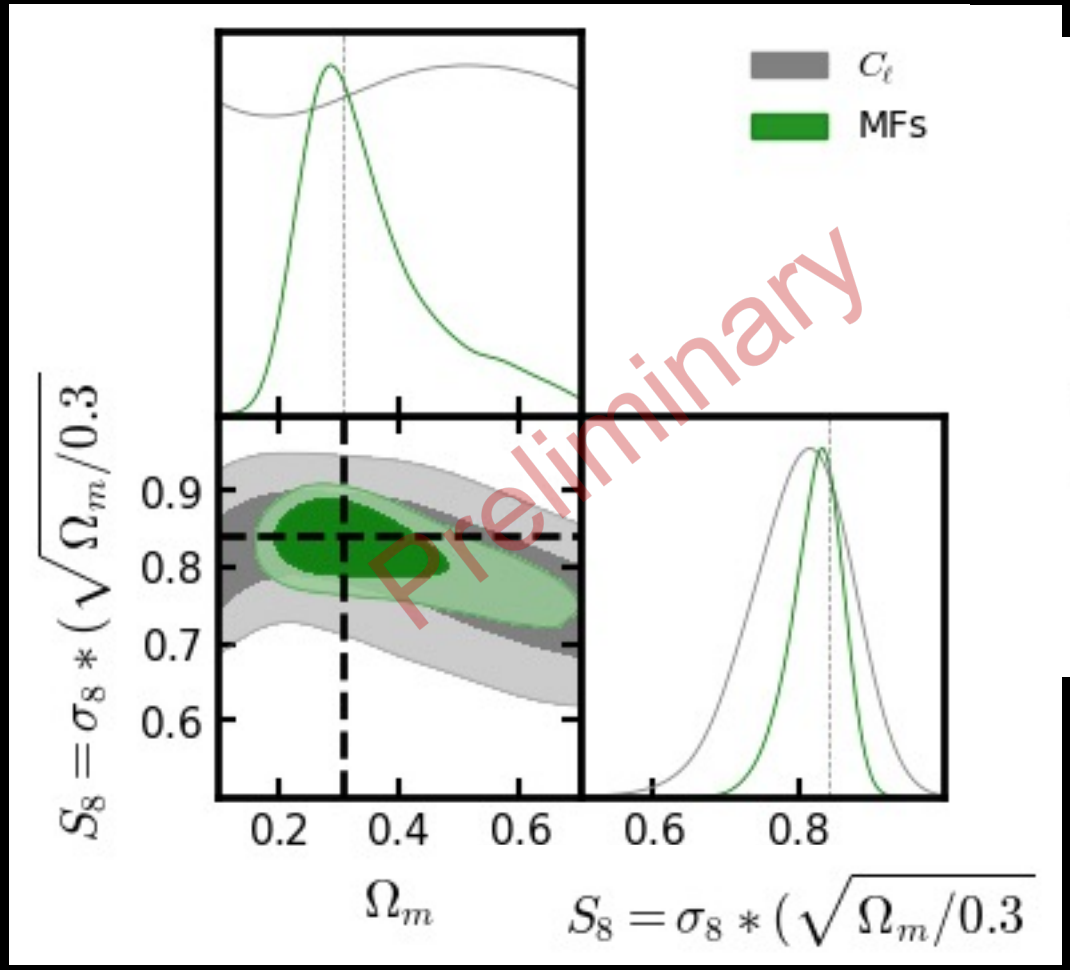
V_0 (Area): Cumulative area of patterns (pixels).

V_1 (Perimeter): Proportional to the PDF of κ.

V_2 (Euler characteristic): Sum of comps. minus the number of holes.

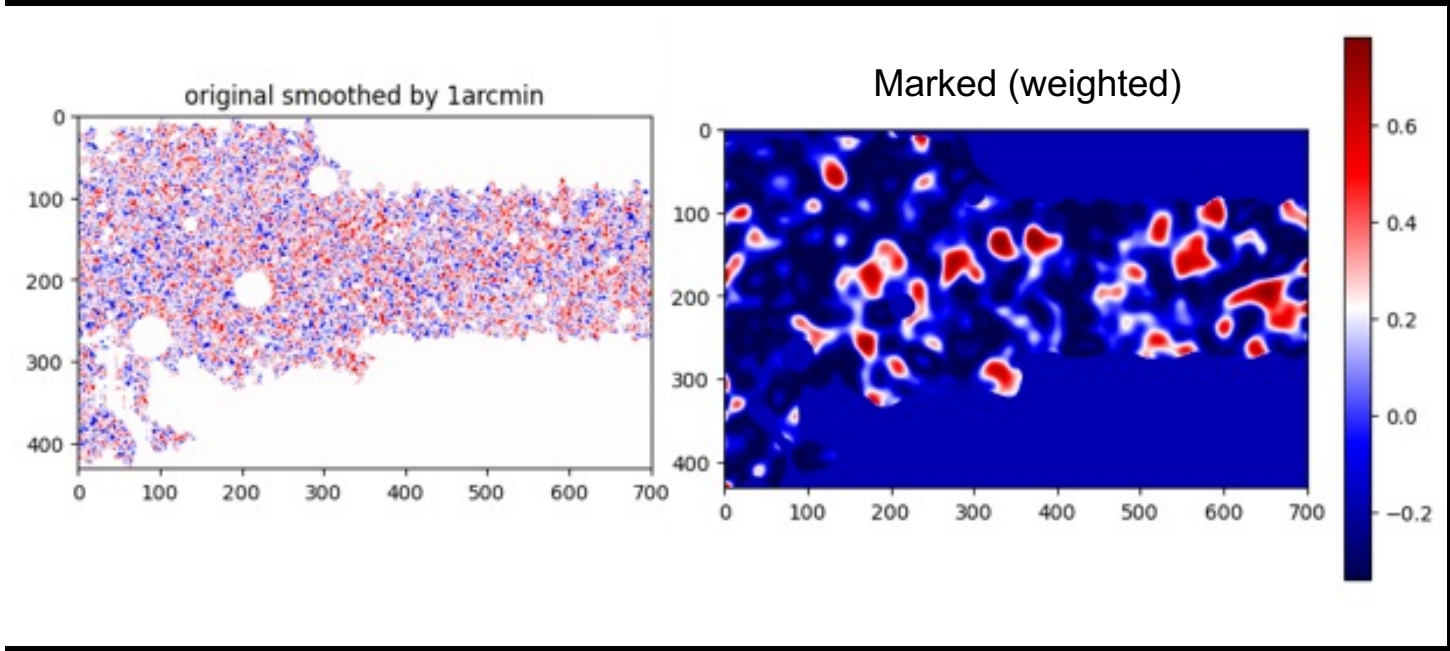
More statistics…

MFs analysis for HSC-Y1 (Armijo+ in prep.)



Marked power spectrum analysis
(Cowell+ in prep.)

$$m(x, R, p, \delta_s) = m(\delta_R) = \left[1 + \frac{\kappa_R}{1 + \delta_s}\right]^{-p}$$



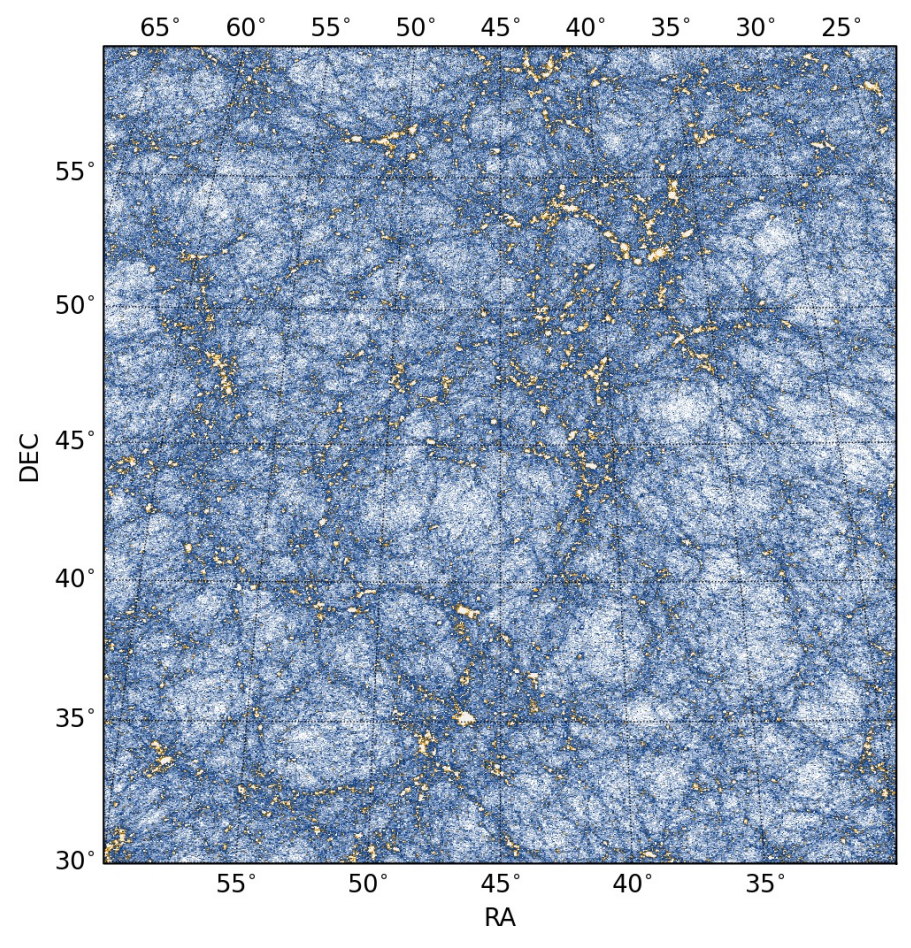
We expect ~40% better constrains (preliminary)!

We combine Powers spectrum + MFs in the same data vector, including several smoothing scales (2,4,5 arcmins).

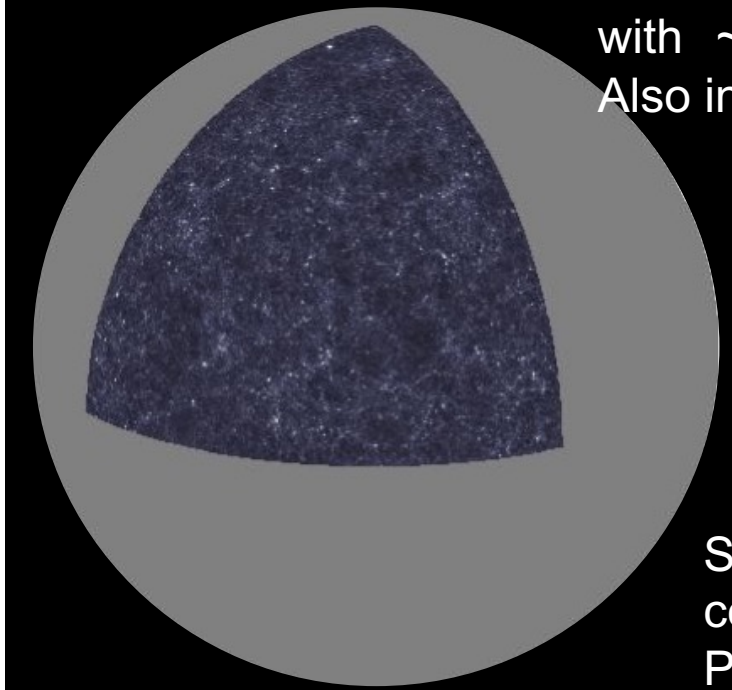
Simulations for stage-IV surveys.

HACC-Y1 simulations

We prepare simulations for weak lensing observations for LSST year-1 (~5000 sq. degrees) using HACC simulations. These are used to test several requirements for HOS studies and covariance of 3x2pt analysis.



~1/8 of the sky with galaxy tomography

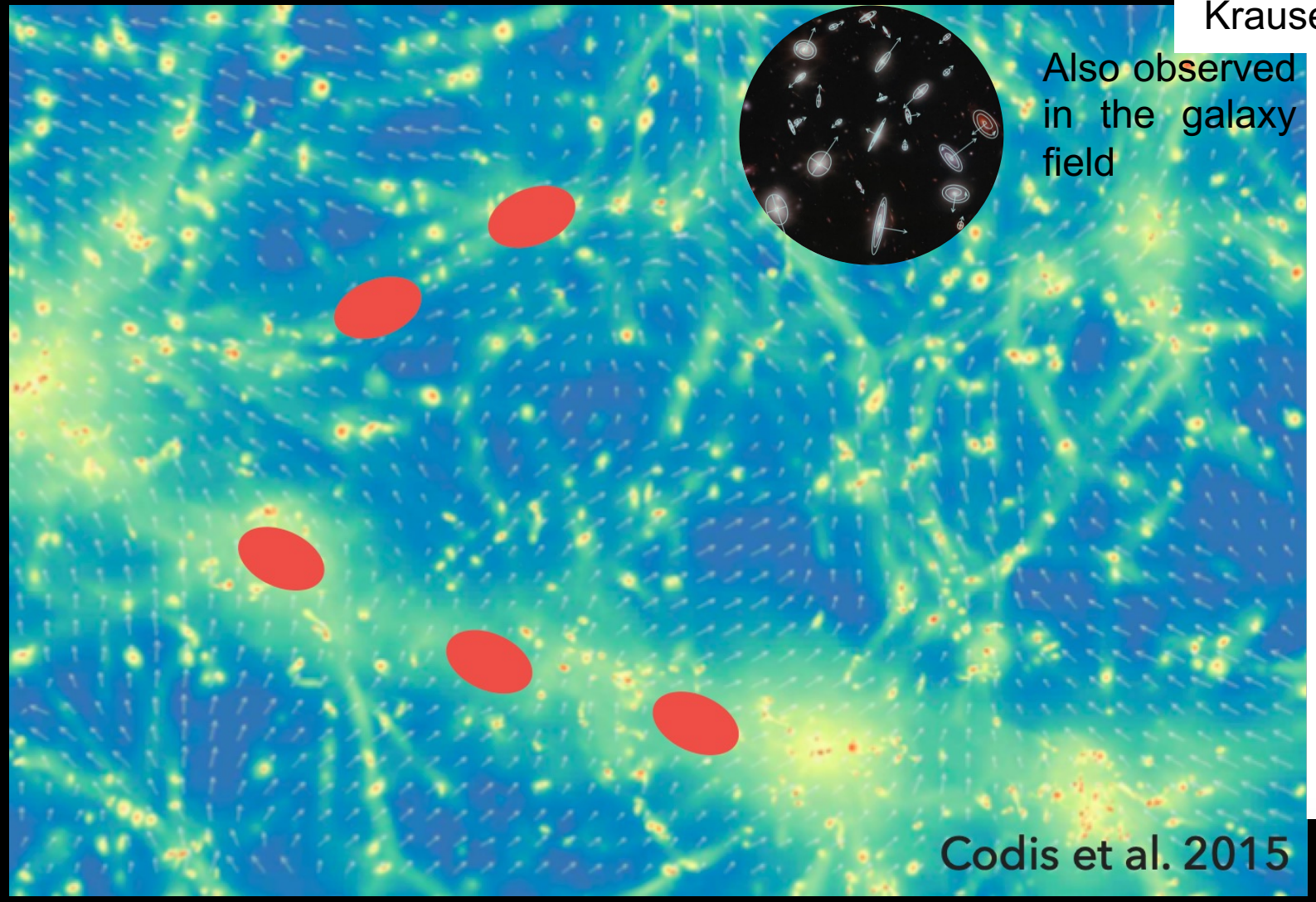


Simulations will include 100 cosmologies with ~10000 simulations for covariance. Also including systematics:

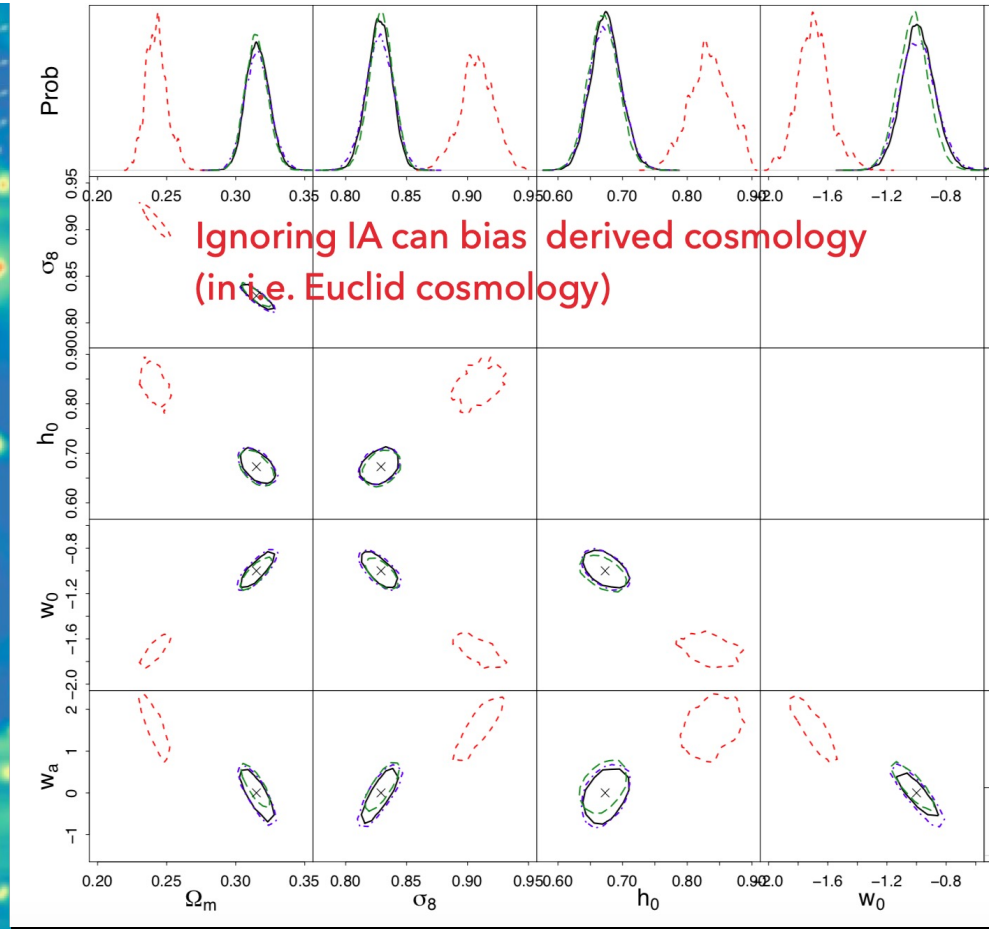
- Baryons: Using baryonification.
- Intrinsic alignments.
- Photo-z.

Still on validation for several HOS codes, but ready soon:
PDF, peaks&minima, 3point functions, MFs, density split statistics, and more incoming.

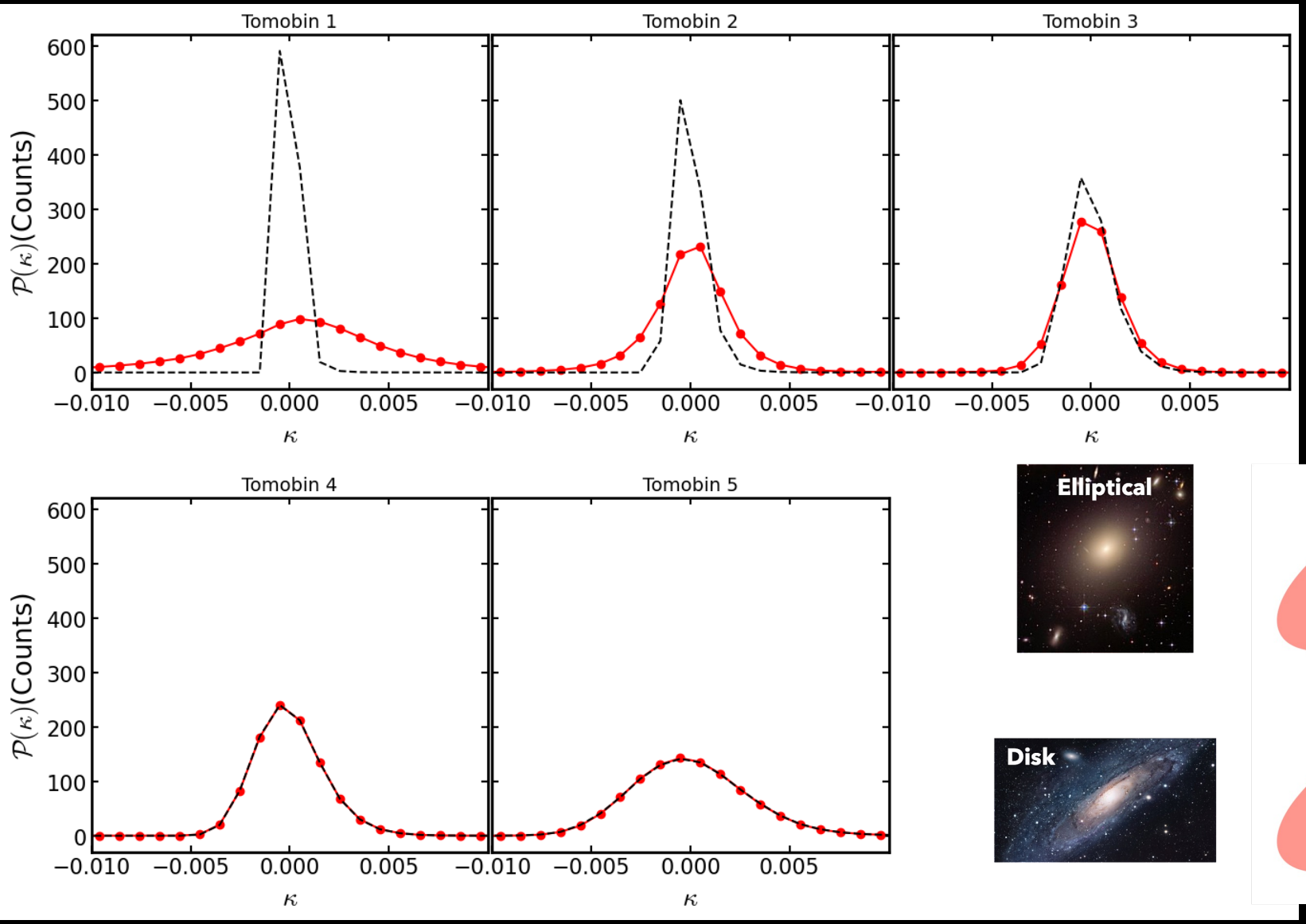
Intrinsic alignment infusion



Krause et al. 2015



Intrinsic alignment infusion

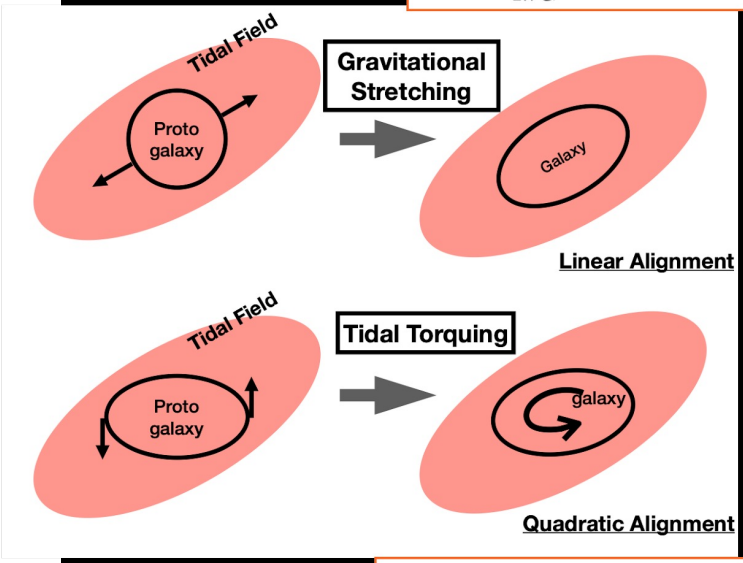


Being able to constraint parameters of some of the IA models (NLA, TT, TATT).

Tidal alignment & tidal torque (TATT) Blazek+2019

$$\gamma_{ij}^I = \underbrace{C_1 s_{ij}}_{\text{Tidal Alignment}} + \underbrace{C_{1\delta}(\delta \times s_{ij})}_{\text{Density Weighting}} + \underbrace{C_2 \left[\sum_{k=0}^{2} s_{ik}s_{kj} - \frac{1}{3}\delta_{ij}s^2\right]}_{\text{Tidal Torquing}} + \ldots,$$

$$\gamma^I = -\frac{C_1}{4\pi G}(\nabla_x^2 - \nabla_y^2, 2\nabla_x\nabla_y)\mathcal{S}[\Psi_P]$$



$$\gamma_{(+,\times)}^I = C_2(T_{1i}^2 - T_{2i}^2, 2T_{1i}T_{2i})$$

Summary and conclusions.

Summary and conclusions.

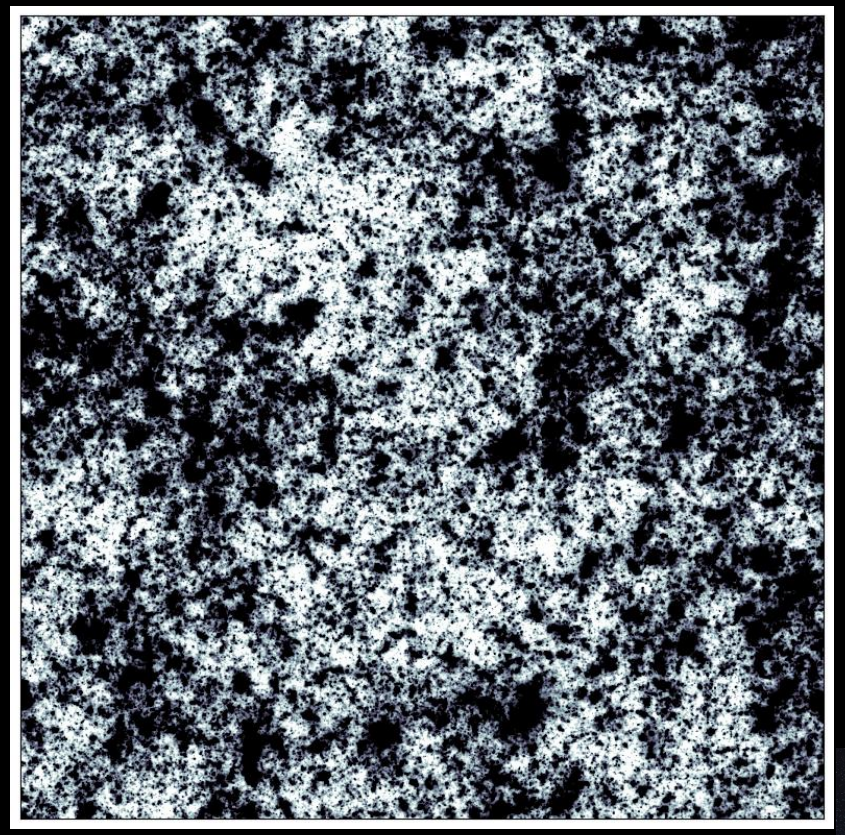
- This is exciting time for cosmology! Stage-IV era is providing constraints with unprecedent precision. **Some of these parameters are in tension**, between early and late universe data.

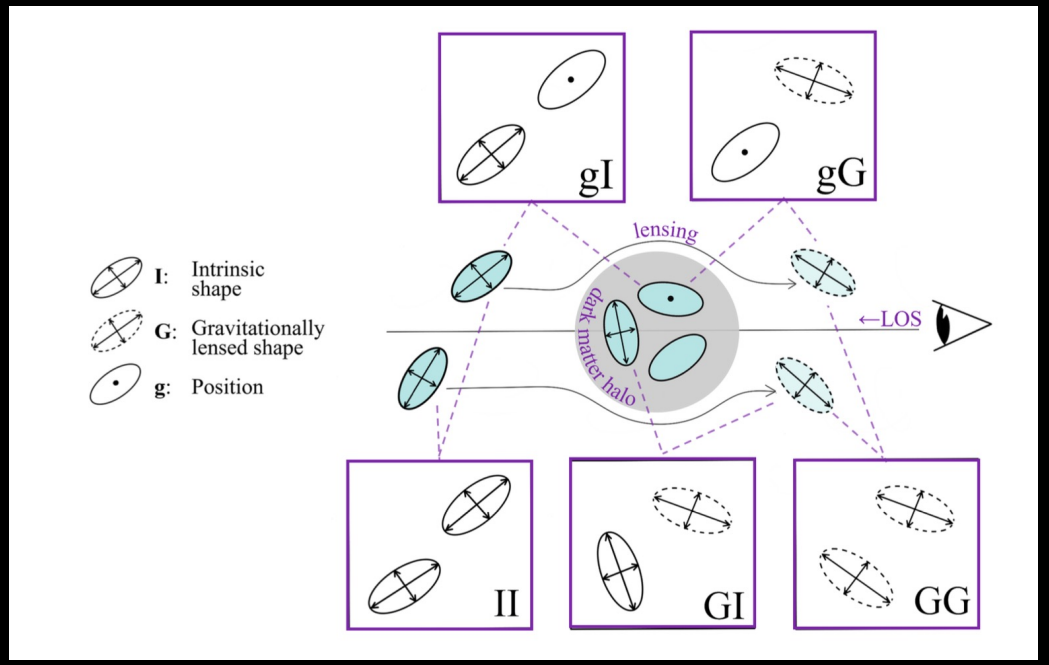
- We propose probes beyond two-point statistics, which test the non-linear regime. To access this information, non-Gaussian statistics must be applied. **Such scales might be key to solve the S8 tension.**

- Higher-order statistics **improves the constraints of power spectrum only ~30-50%.** Also, it is more sensitive to systematics. Also no tension is found we considering HOS as a complementary measurement.

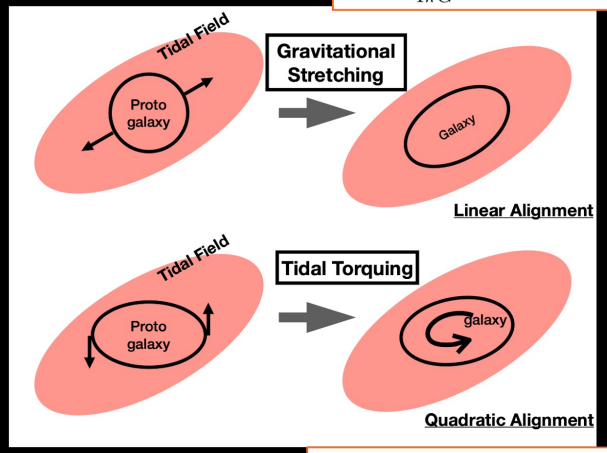
- Simulations for Rubin-LSST will allow us to **understand the effect of different systematics** that become statistically more significant for stage-IV.

Thank you for the attention!





$$\gamma^I = -\frac{C_1}{4\pi G}(\nabla_x^2 - \nabla_y^2, 2\nabla_x\nabla_y)\mathcal{S}[\Psi_P]$$



$$\gamma^I_{(+,\times)} = C_2(T^2_{1i} - T^2_{2i}, 2T_{1i}T_{2i})$$