Testing cosmological models with galaxy surveys

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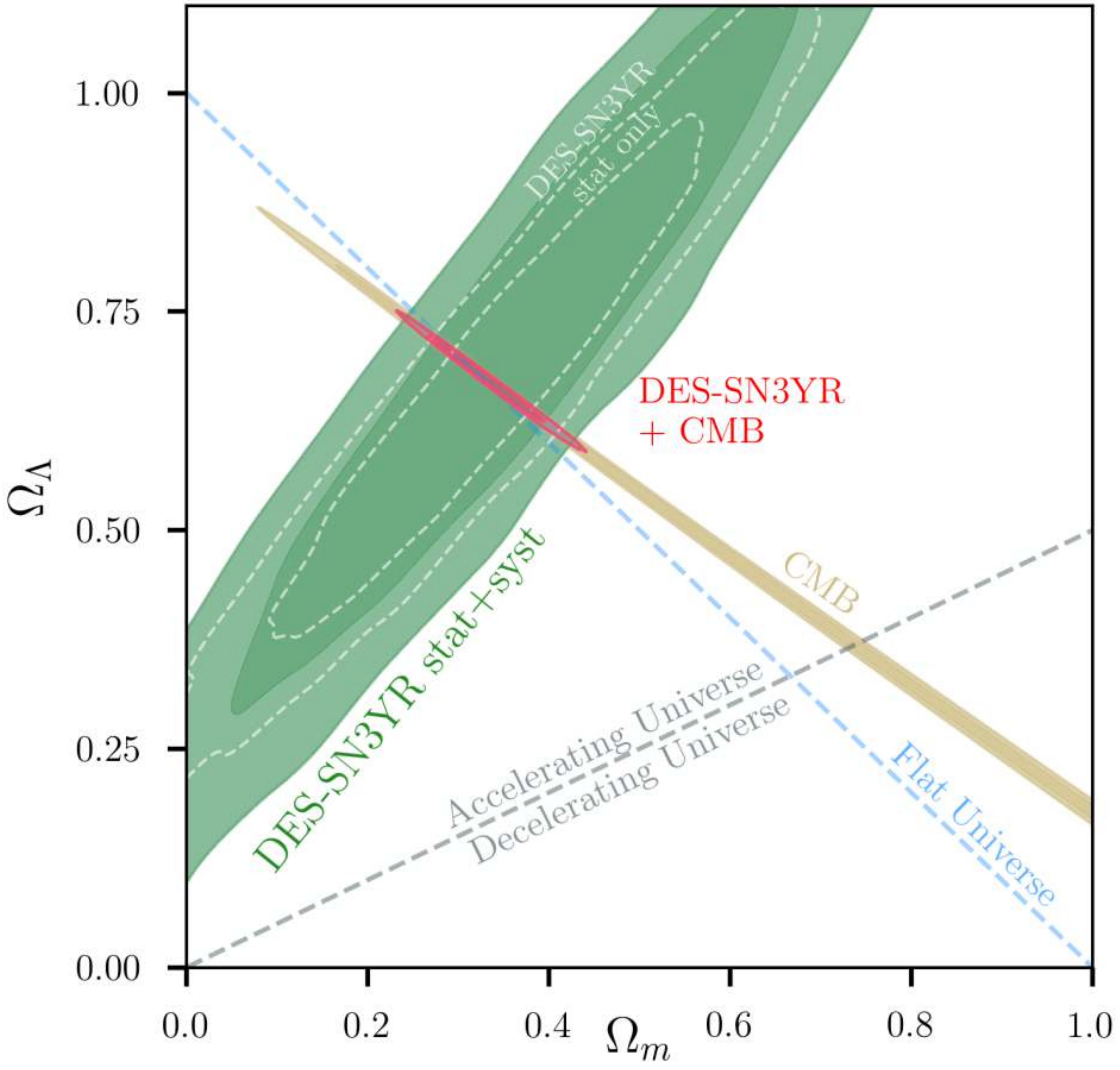
Oxford Seminar June 2023

A flat and accelerating Universe

- We have known for some time that the Universe is pretty flat mostly from CMB measurements.

- Supernovae measurements discovered the acceleration of the expansion Universe a couple of decades ago —> There is a dark energy component.

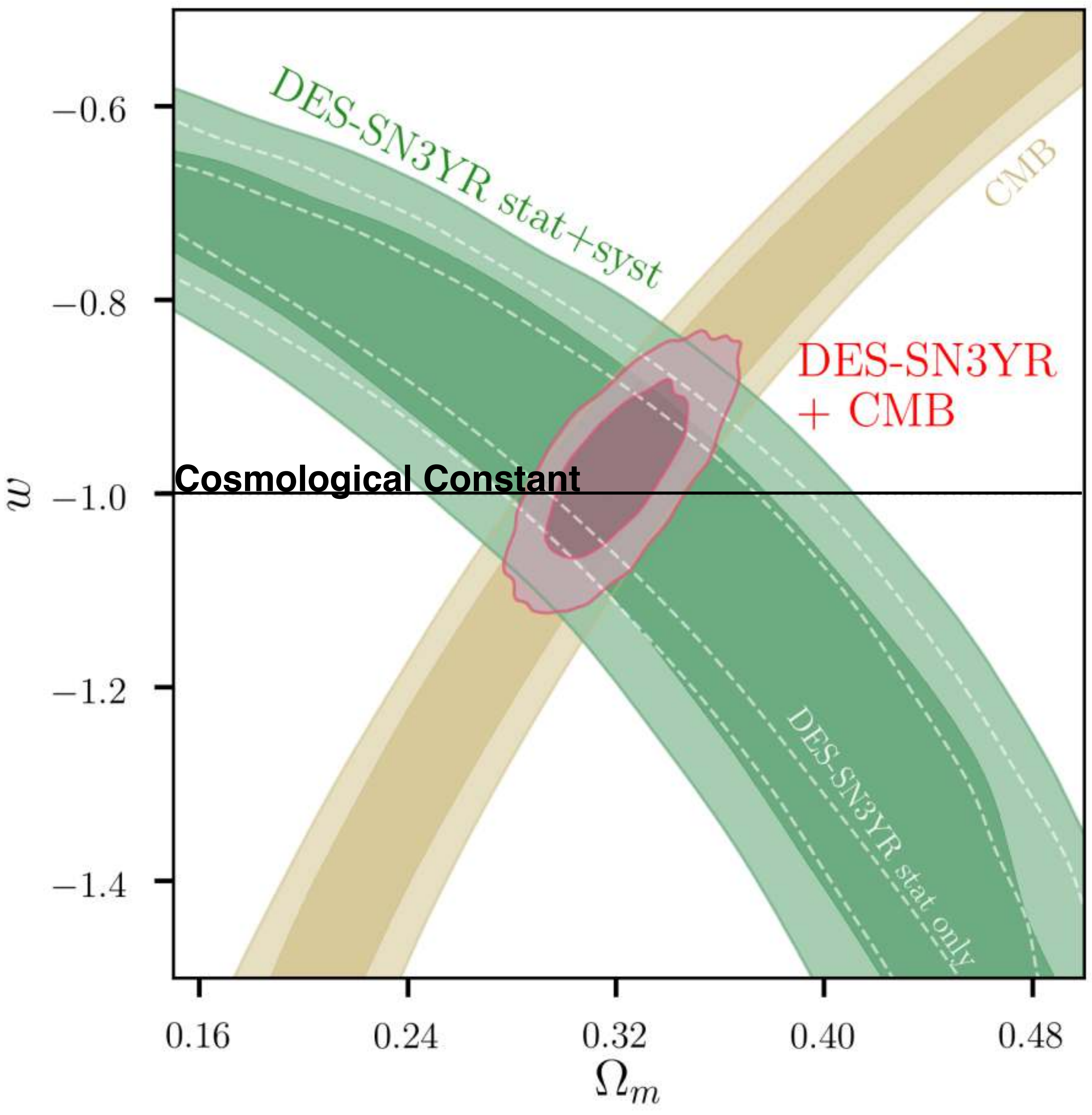
arXiv: 1811.02374 (2019)



Is Dark Energy a cosmological constant?

- Dark Energy seems to be compatible with a **cosmological constant** —> w, the parameter describing the evolution of dark energy with time is compatible with -1 given the current uncertainties.

arXiv: 1811.02374 (2019)



This leads us to the Standard Cosmological model: ΛCDM

Flat Universe with Dark Energy in the form of a cosmological constant Λ + Cold Dark Matter.

It assumes General Relativity.

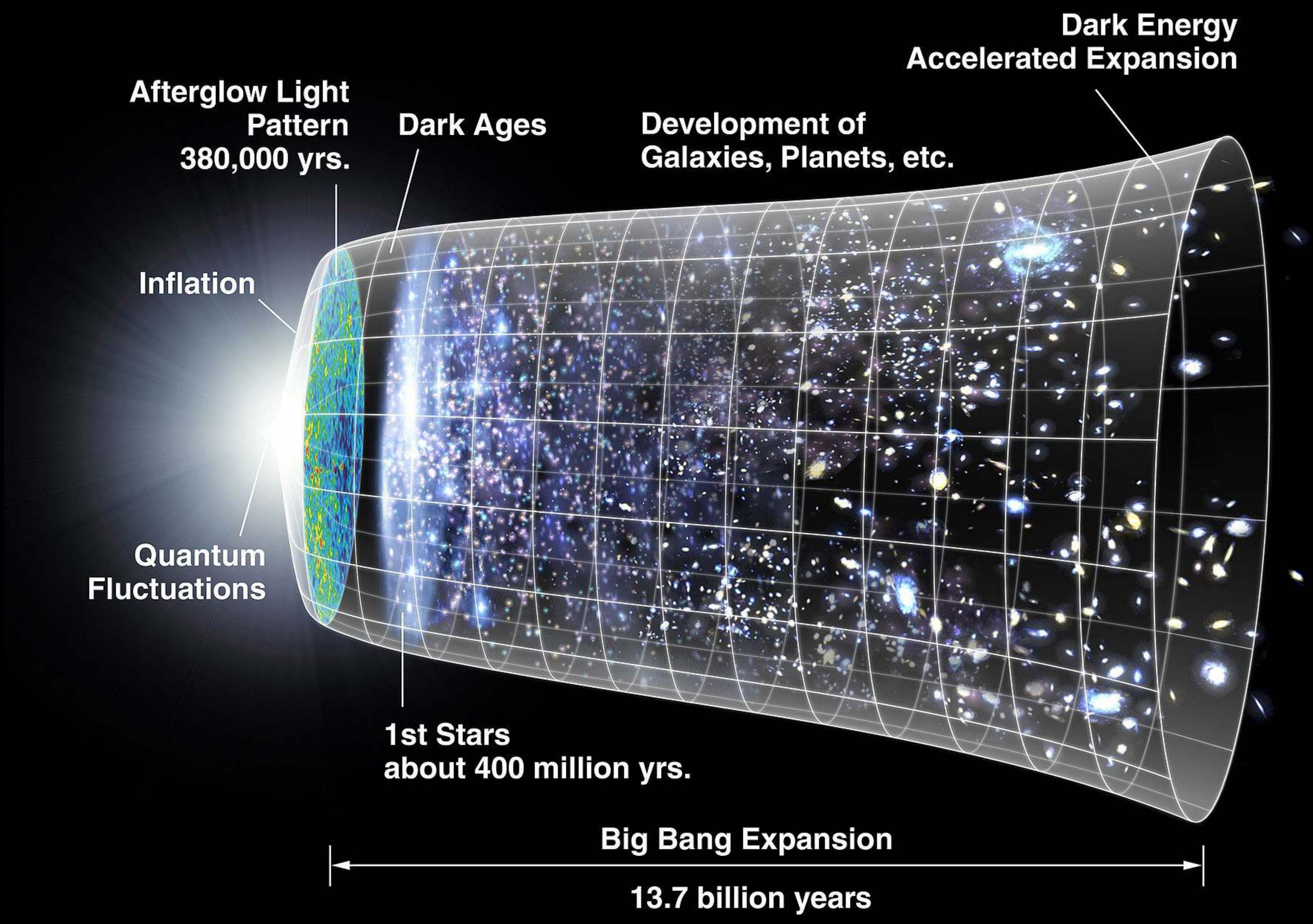


Image Credit: NASA / LAMBDA Archive / WMAP Science Team

Are we done then?

Not really… There are a few open questions

ΛCDM model under discussion

ΛCDM adds **2 new components** to the Standard Model of physics, neither of which have been observed in a laboratory.

The cosmological constant interpreted as the vacuum energy is ~**120 orders of magnitude lower** than the naive prediction coming from particle physics.

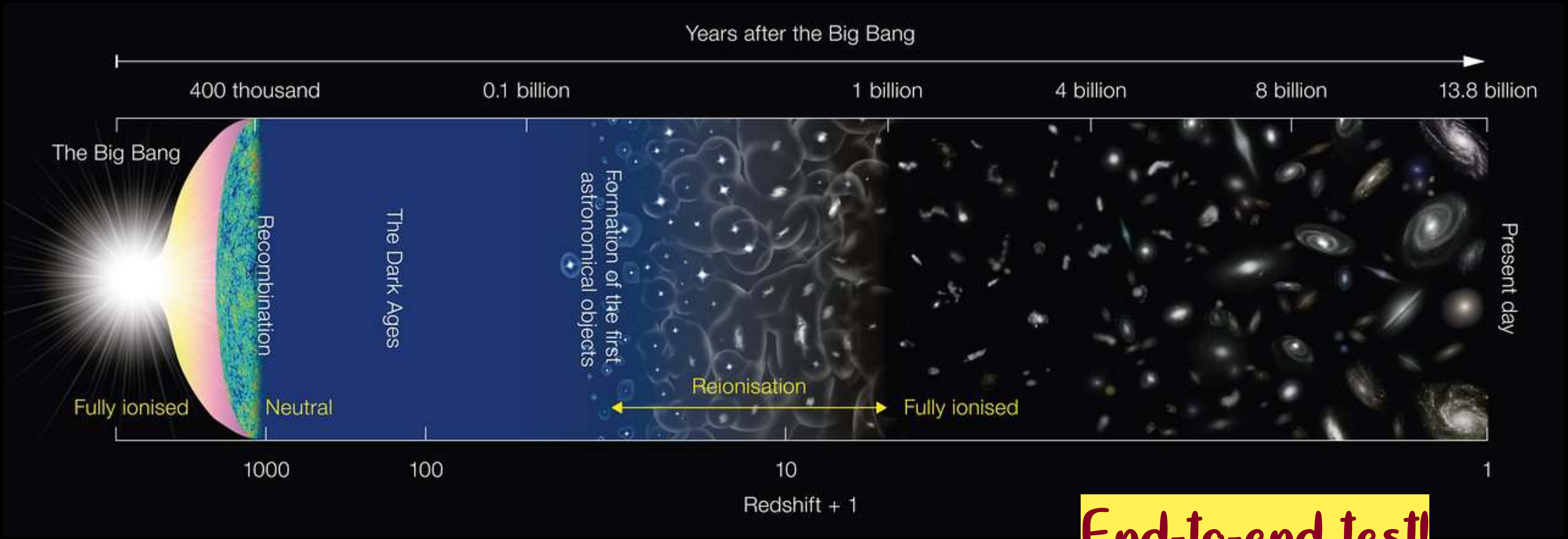
Some **tensions** are arising between cosmological probes. Are they real, systematics, or statistical fluctuations?

Is **dark energy** really not **evolving with time**? We only know that to the current statistical precision.

General Relativity may not be valid at the largest scales. This could make us think that the expansion of the Universe is accelerating when it is actually not.

Testing ΛCDM

Is the late time Universe compatible with the ΛCDM prediction assuming initial conditions from the CMB?



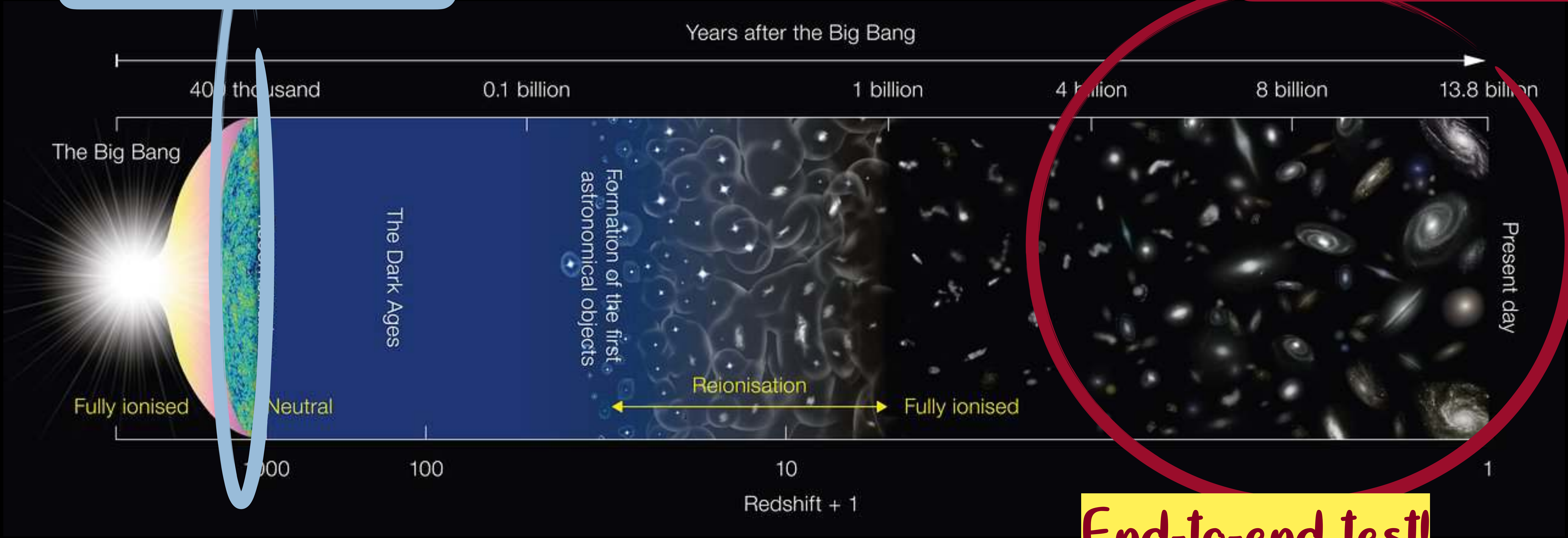
End-to-end test!

Testing ΛCDM

Is the late time Universe compatible with the ΛCDM prediction assuming initial conditions from the CMB?

CMB experiments observe the early Universe

Galaxy surveys observe the late Universe



End-to-end test!

Image credit: NAOJ

How can we measure these cosmological parameters?

How can we measure cosmological parameters?

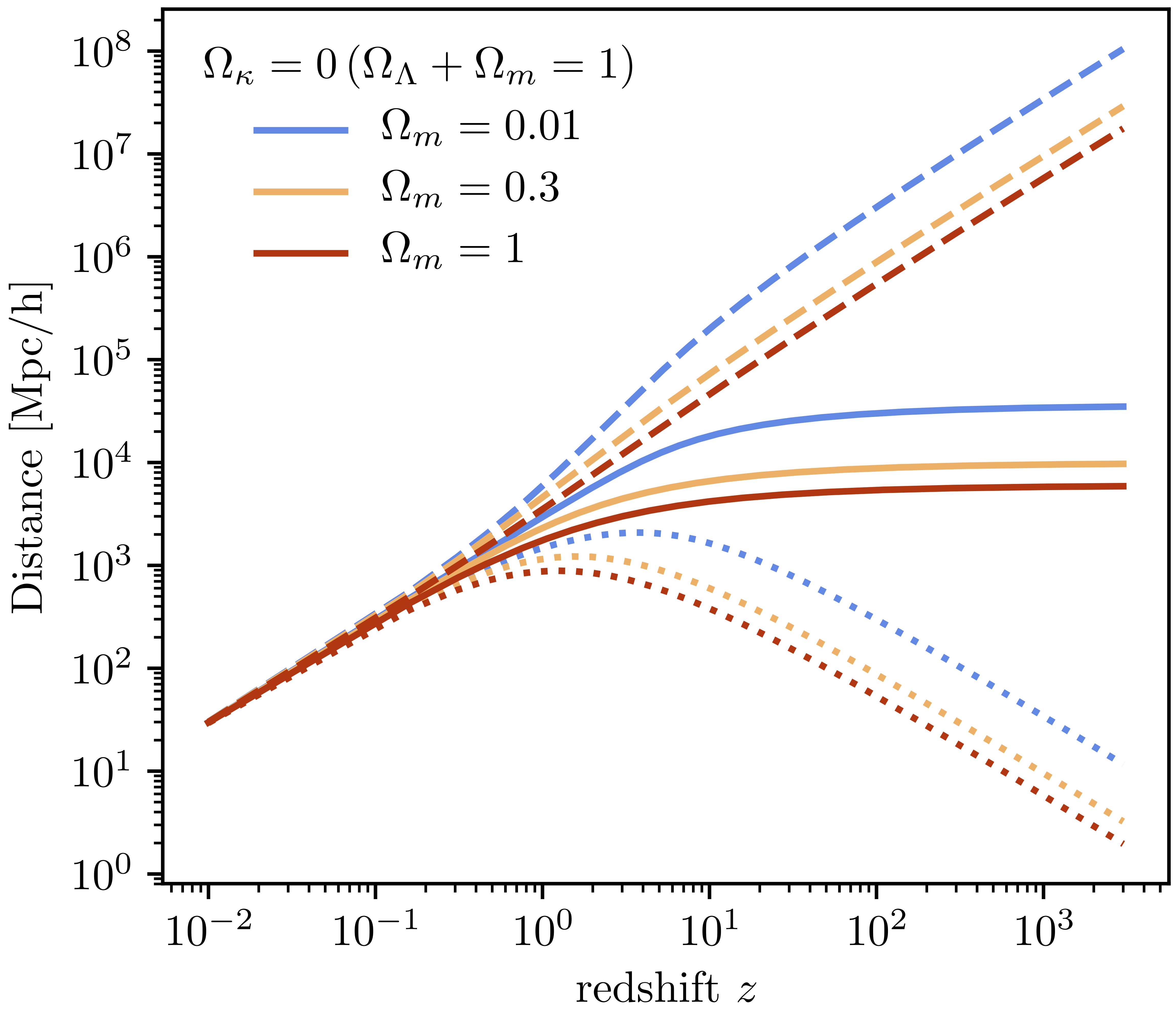
We can probe a cosmological model by studying:

(i) The history of **expansion** of the Universe (kinematics probe).

$$\chi(z) = c\int_0^{z_e} \frac{dz}{H(z)}$$

The first Friedmann equation:

$$H^2(z) = H_0^2\left[\Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_k(1+z)^2 + \Omega_{de}(1+z)^{3(1+w)}\right]$$

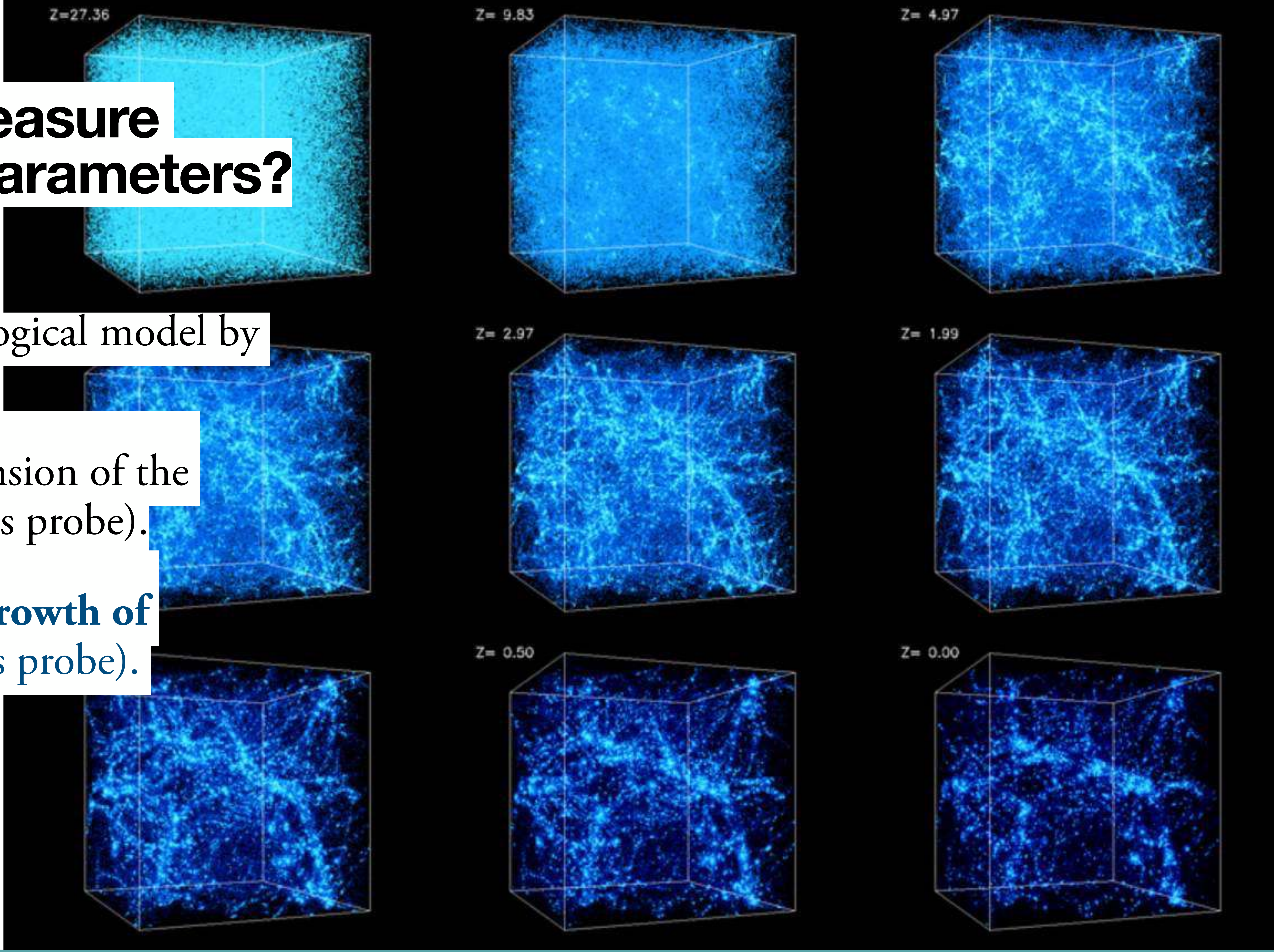


How can we measure cosmological parameters?

We can probe a cosmological model by studying:

(i) The history of expansion of the Universe (kinematics probe).

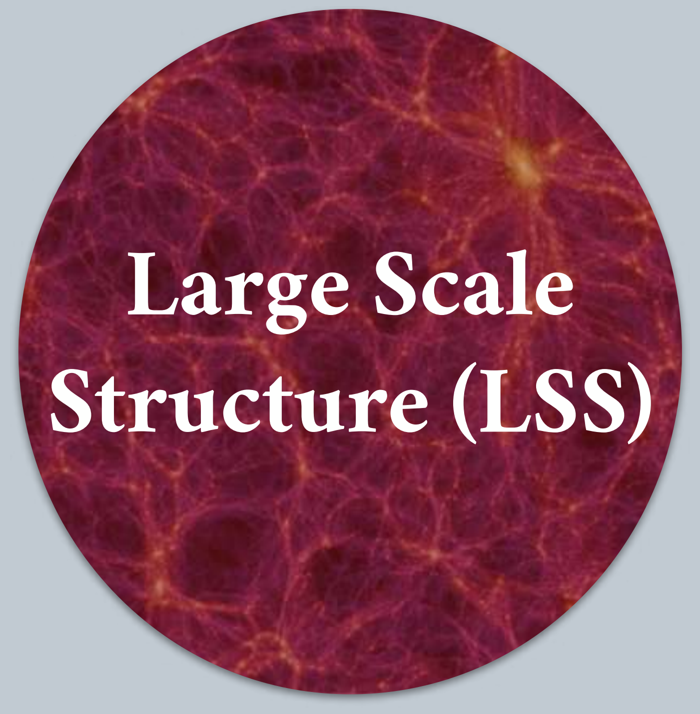
(ii) The history of the **growth of structure** (dynamics probe).



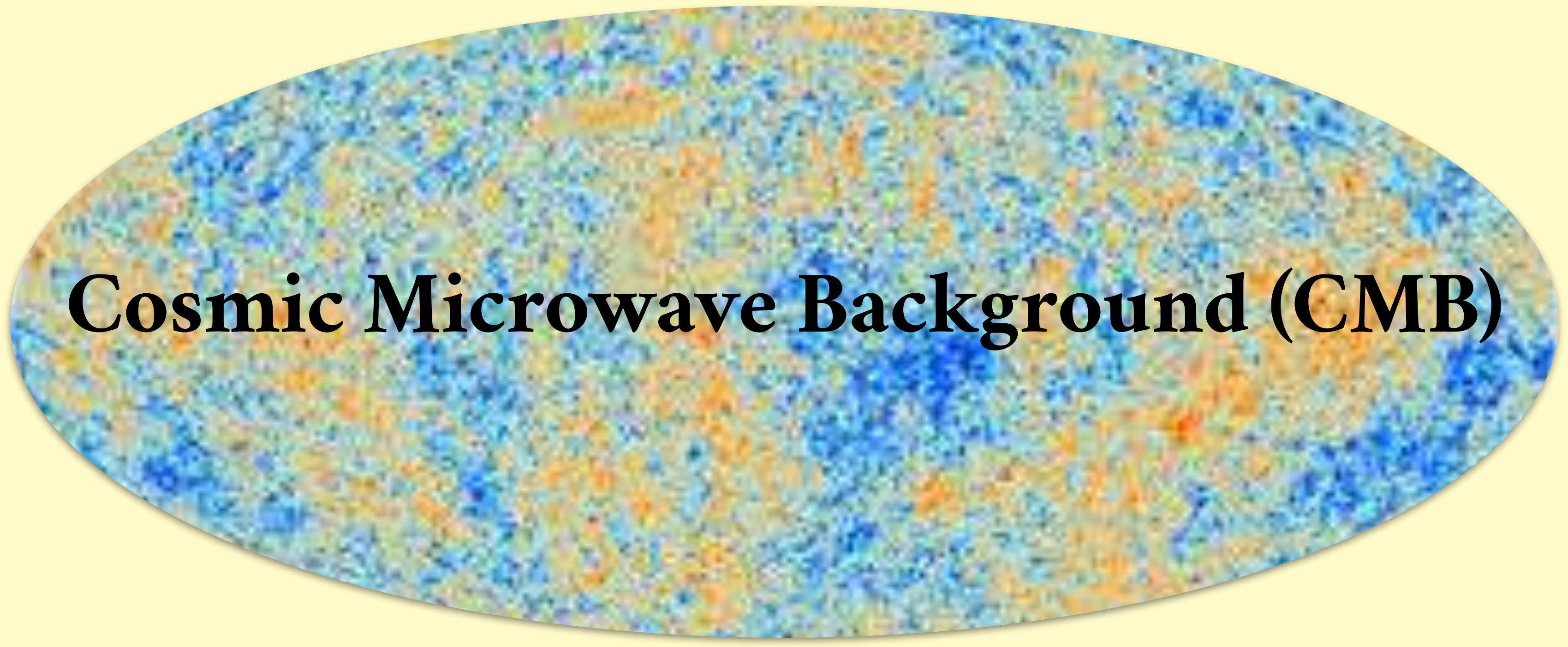
Probes to measure cosmological parameters

History of Expansion

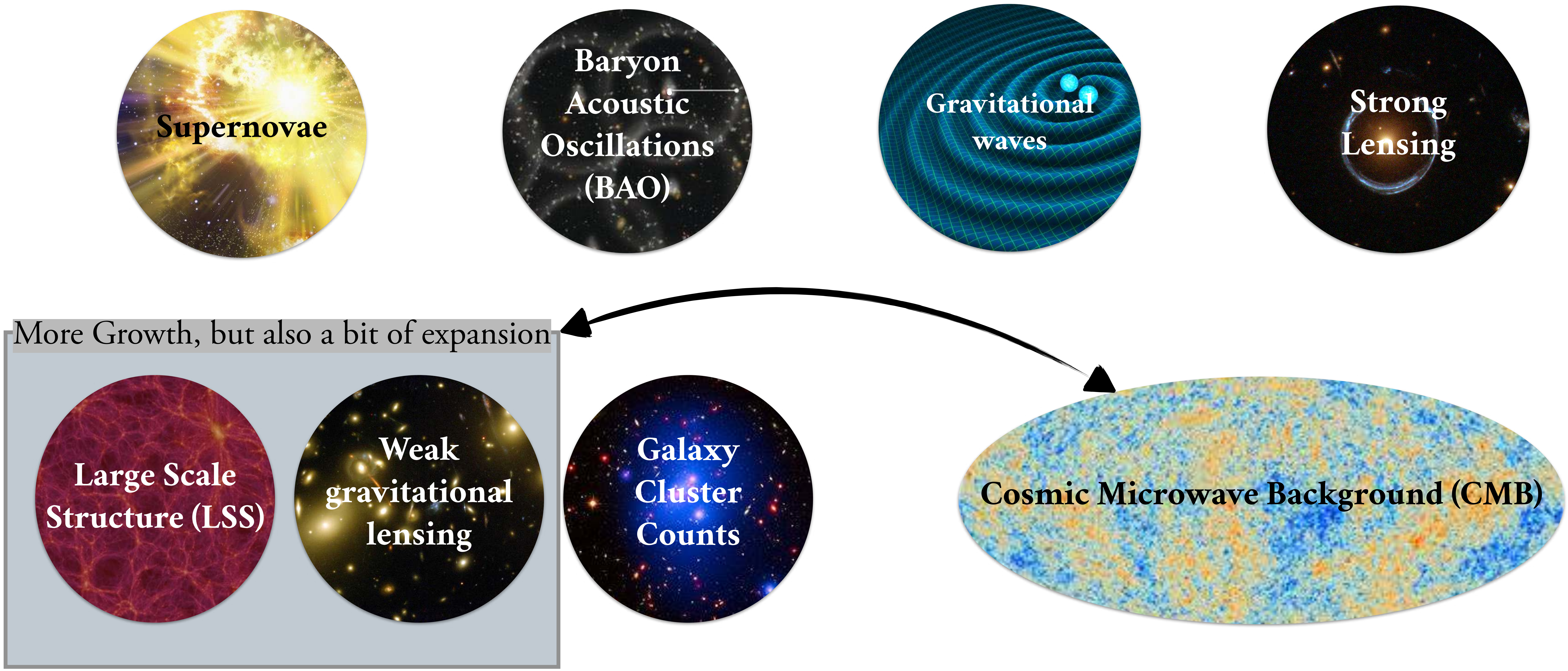
More Growth, but also a bit of expansion



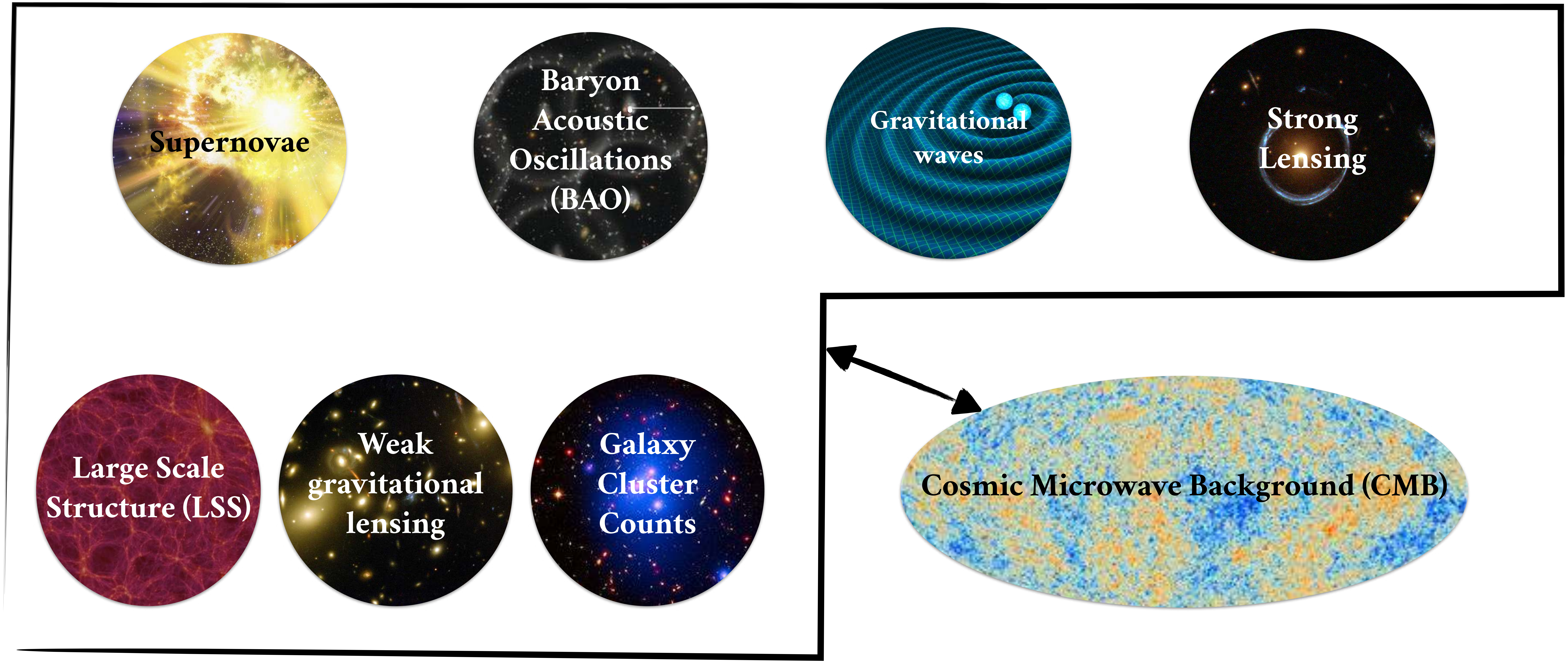
Growth and Expansion



In this talk, first…

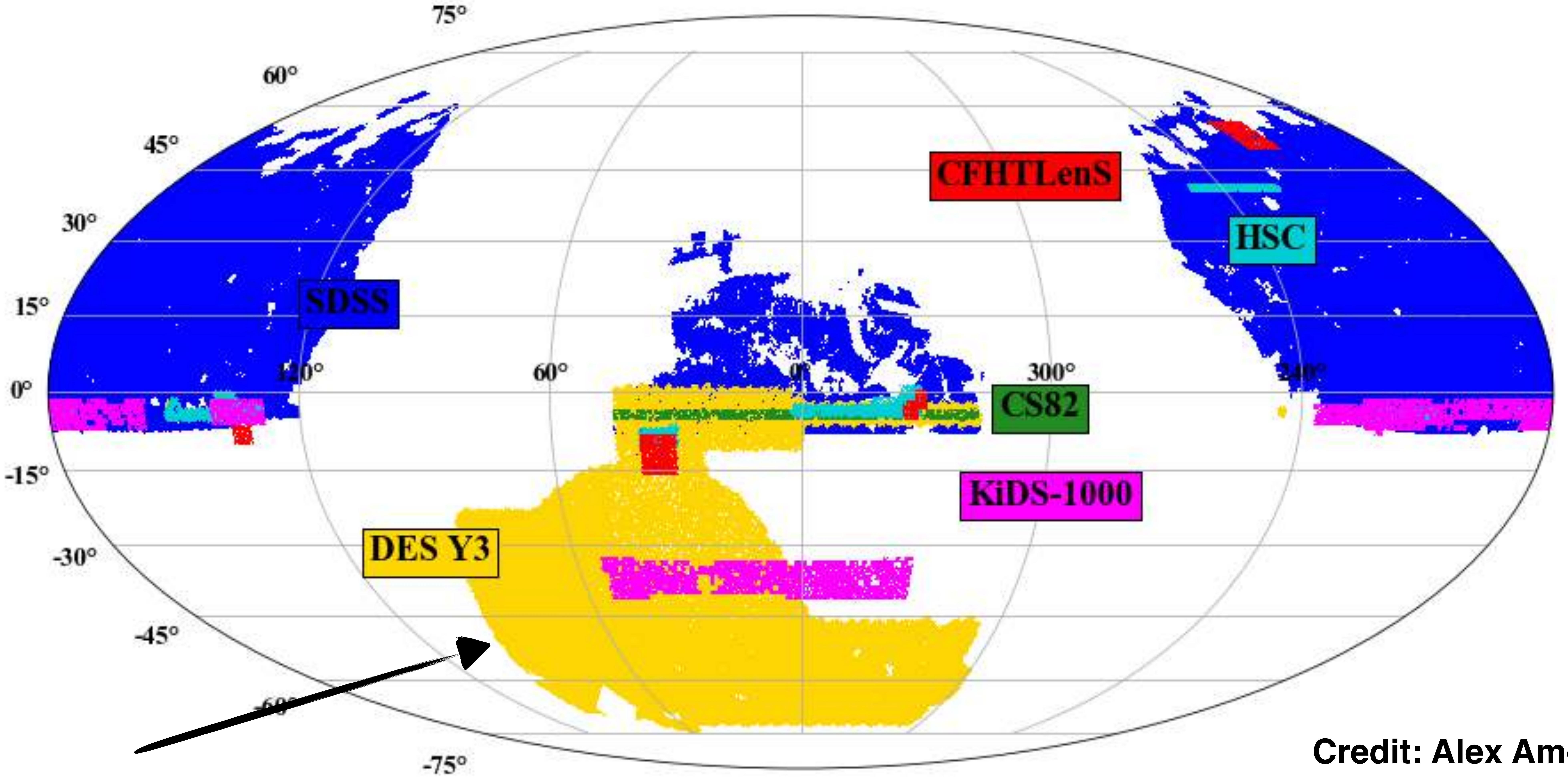


Then I will discuss synergies between late-time Universe probes



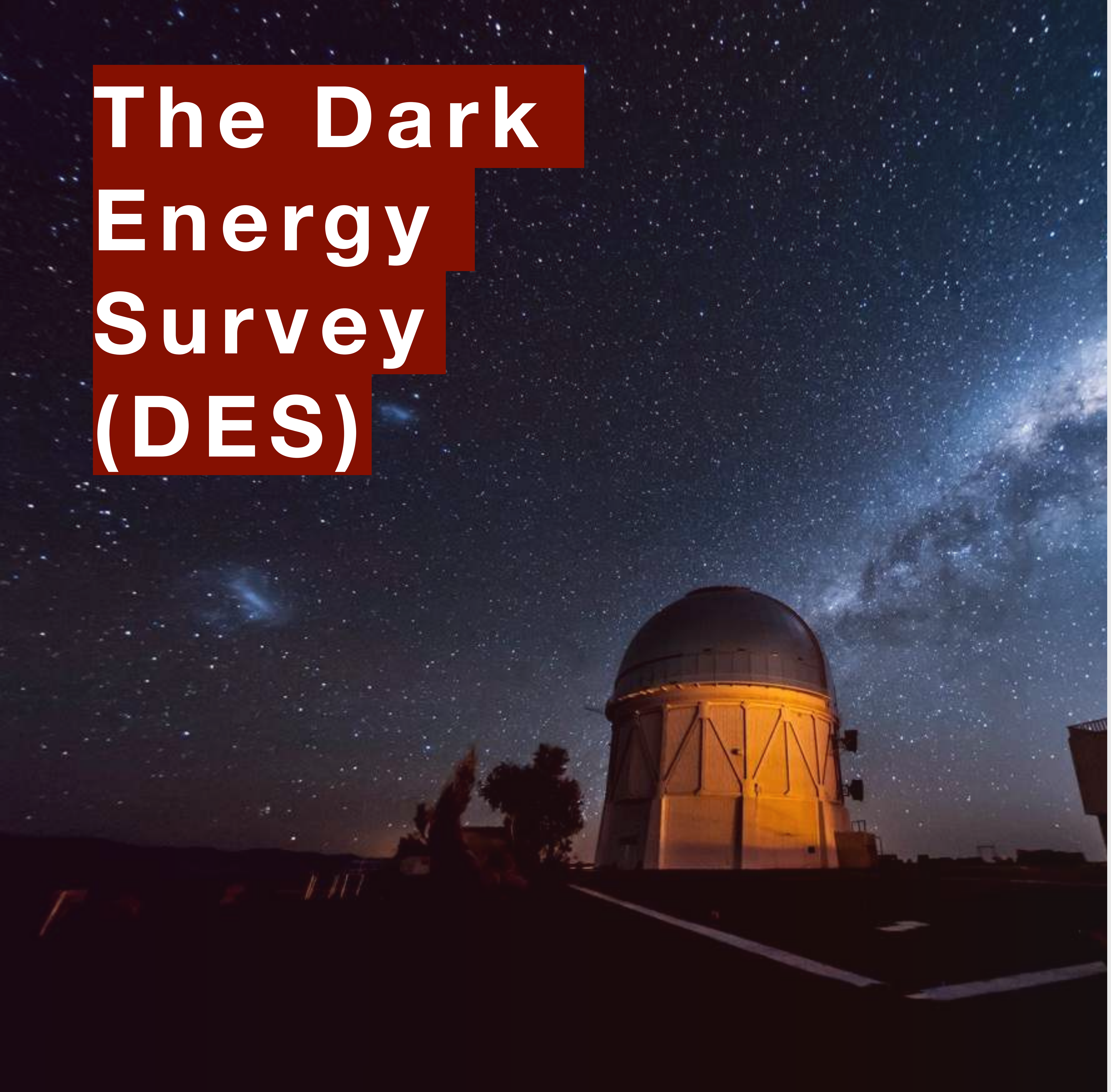
Galaxy surveys: Photometric surveys for WL

Mapping the Universe



Credit: Alex Amon

The Dark Energy Survey (DES)

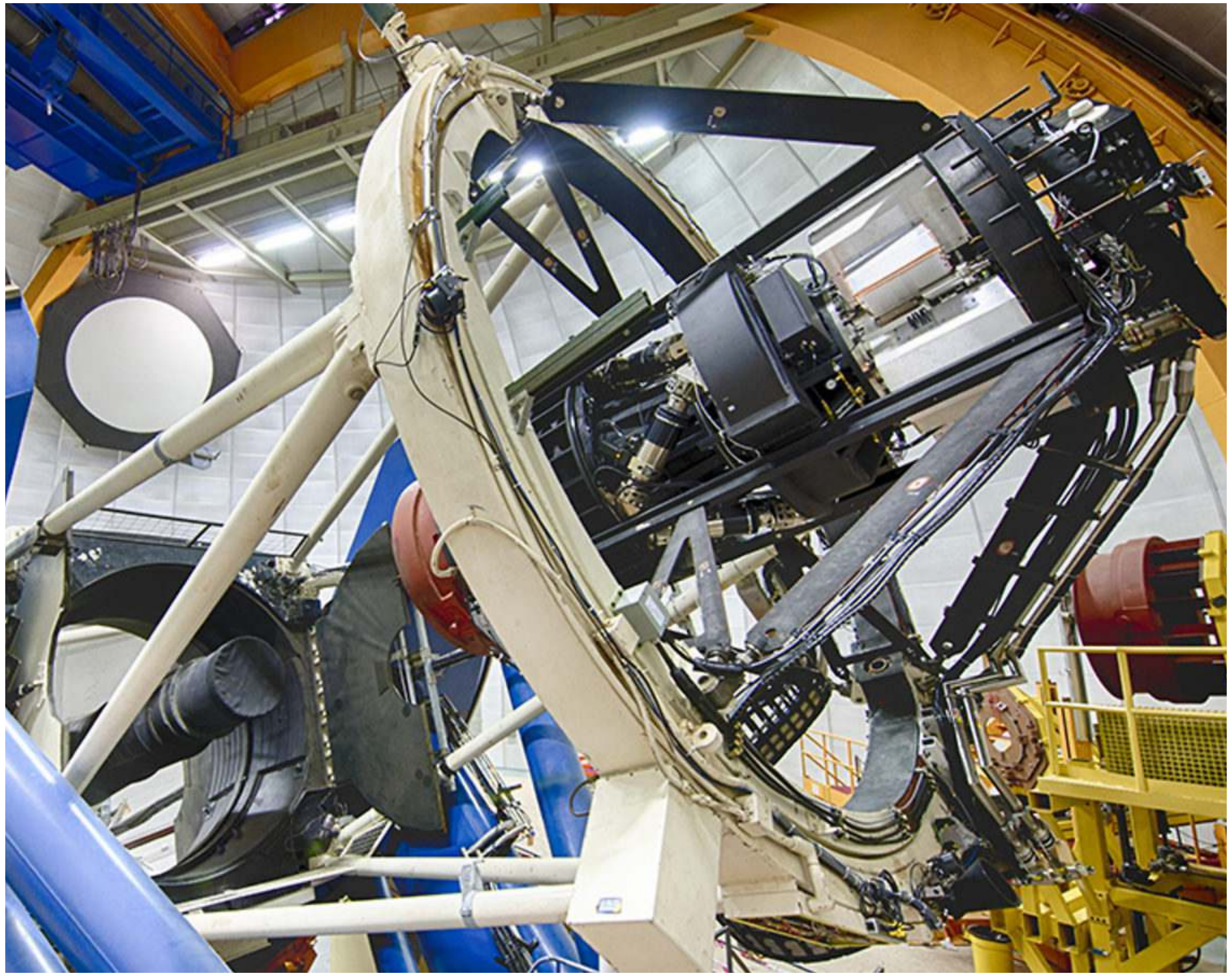


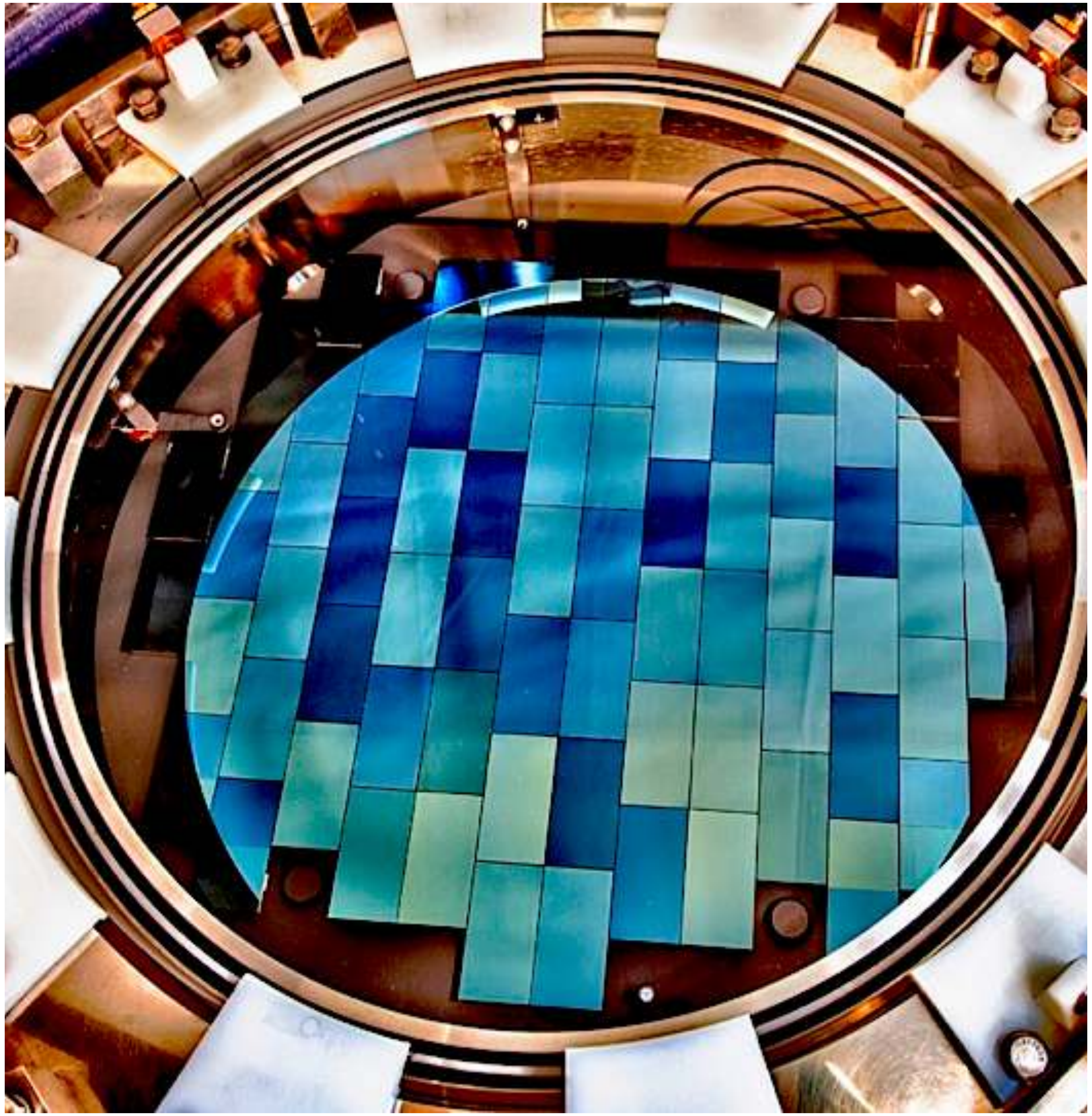
- Imaging galaxy survey.
- 5000 sq. deg. after 6 years (2013-2019)
- 570-Megapixel digital camera, DECam, mounted on the Blanco 4-meter telescope at Cerro Tololo Inter-American Observatory (Chile).
- Five filters are used (grizY) with a nominal limiting magnitude $i_{AB} \simeq 24$ and with a typical exposure time of 90 sec for griz and 45 sec for Y.


The Dark Energy Telescope

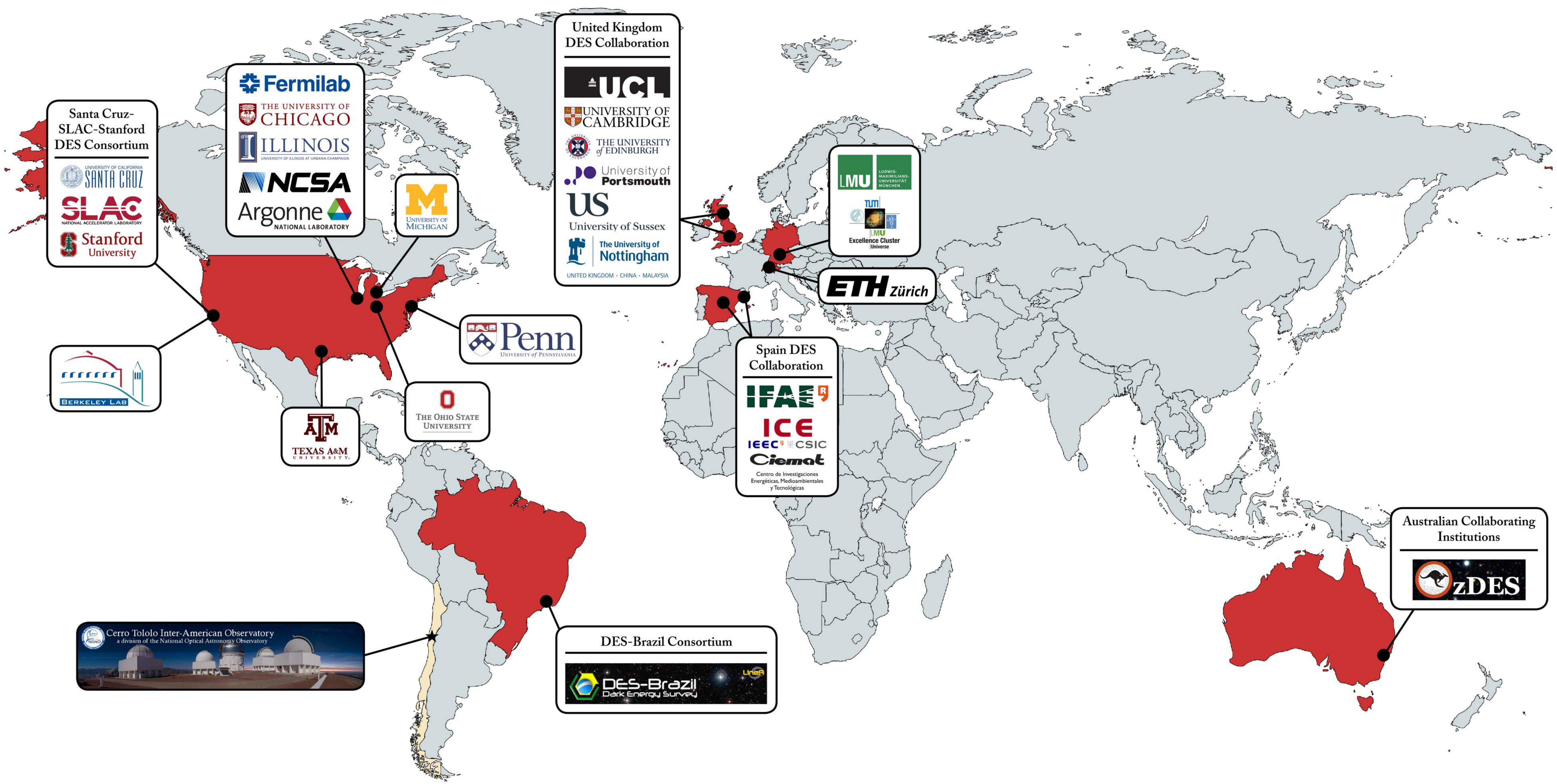
Blanco & DECam

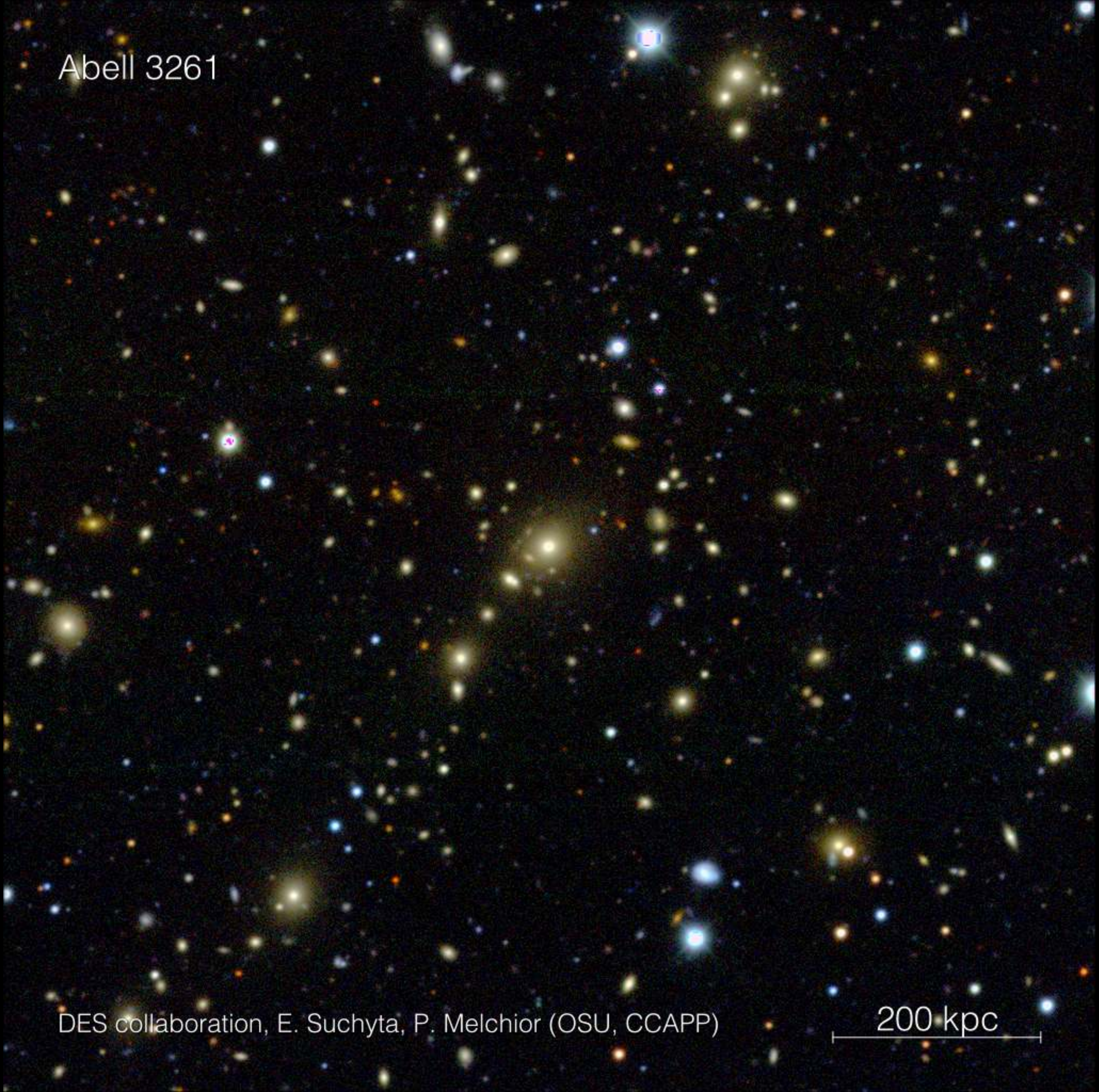
Telescope & Camera



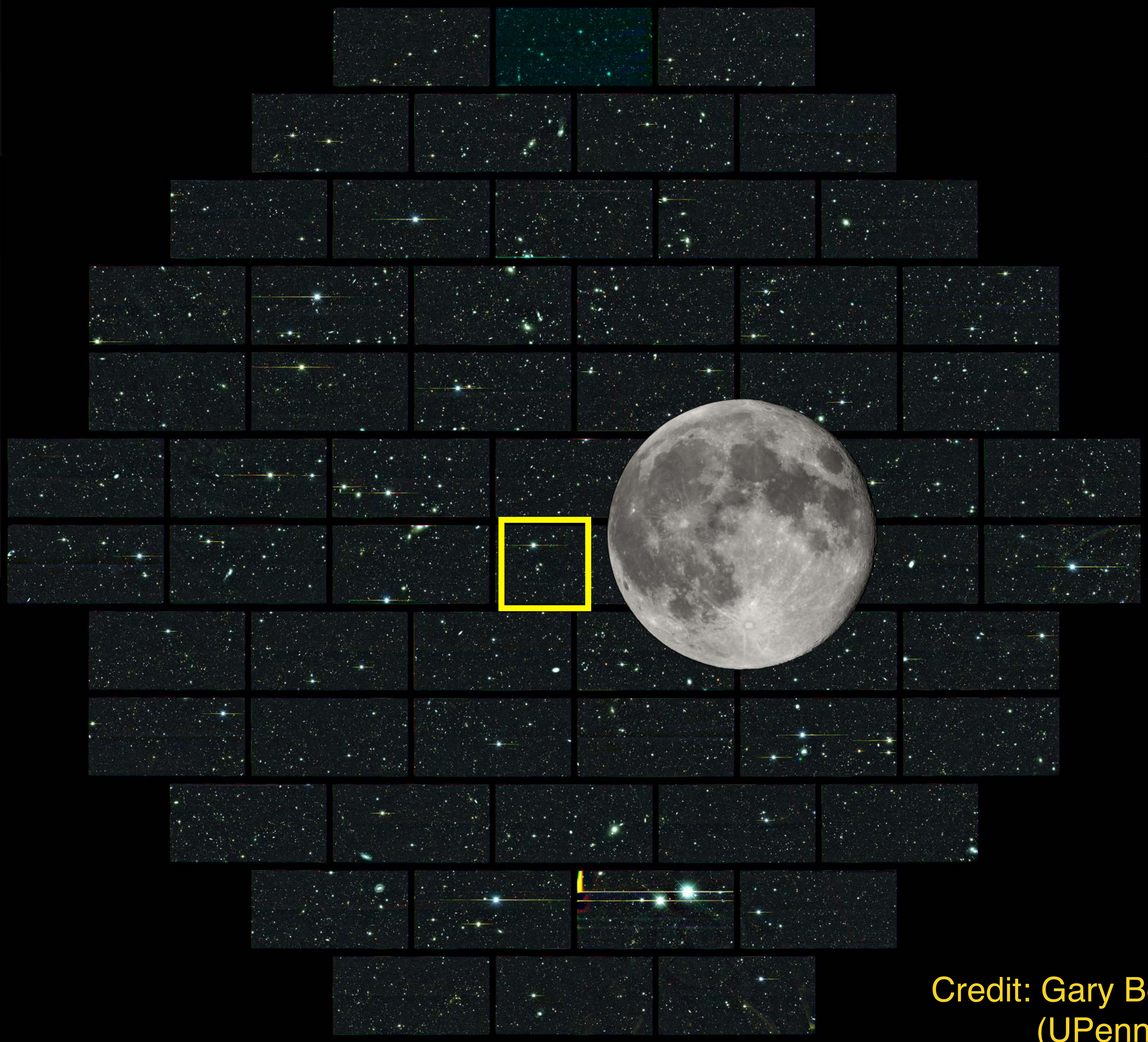


Dark Energy Survey Collaboration




Abell 3261
DES collaboration, E. Suchyta, P. Melchior (OSU, CCAPP)
200 kpc


Credit: Gary Bernstein
(UPenn)



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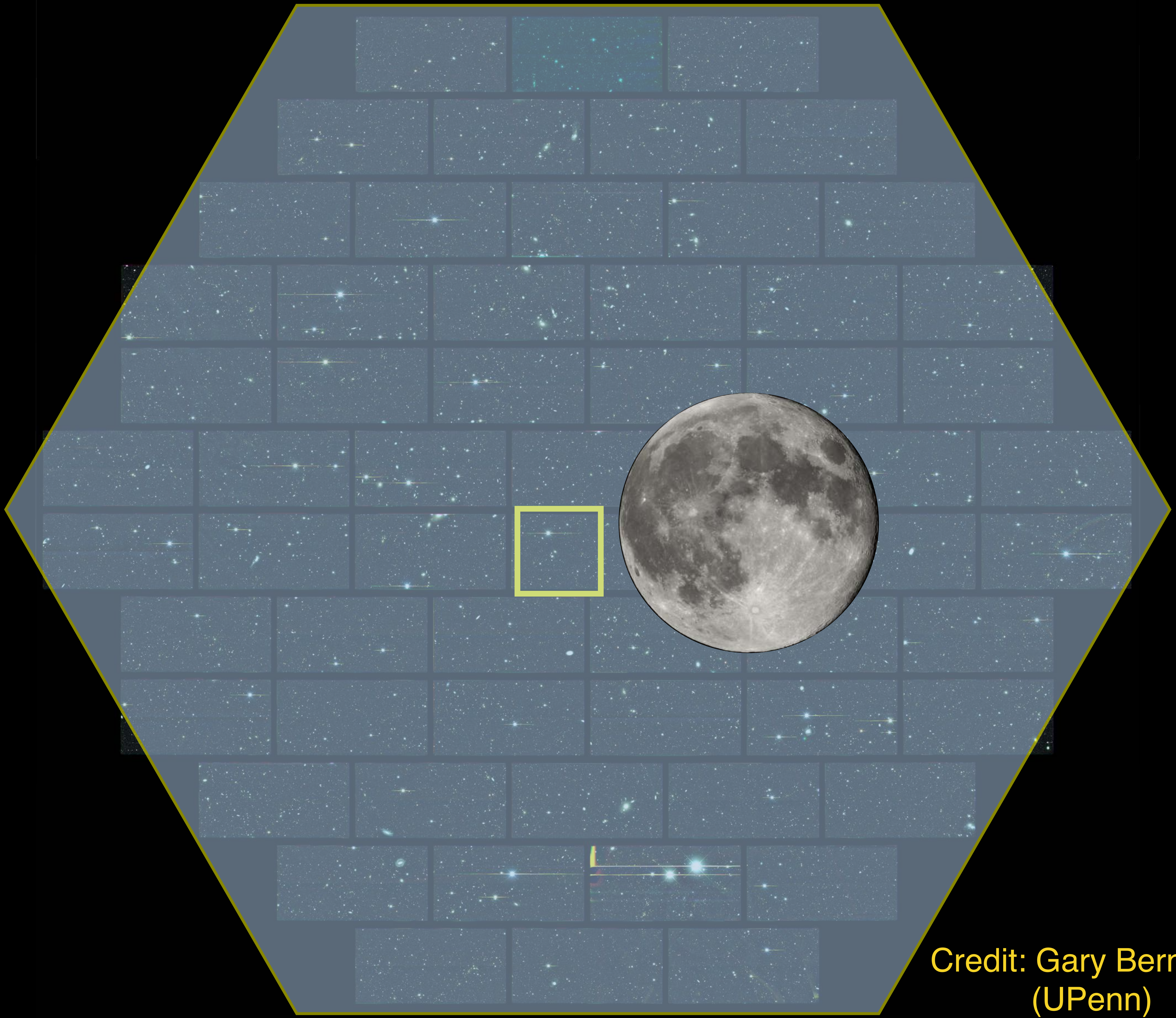

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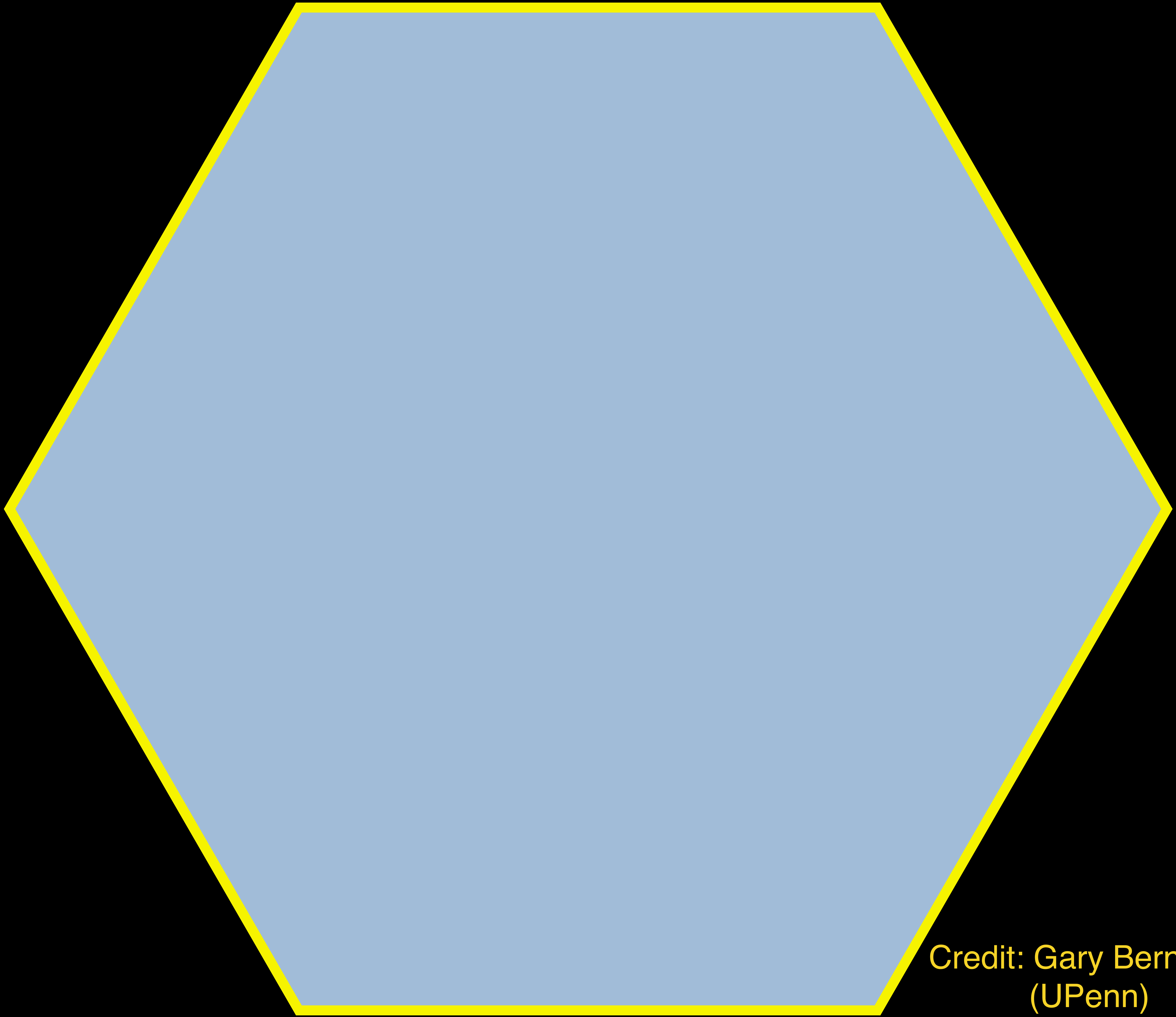

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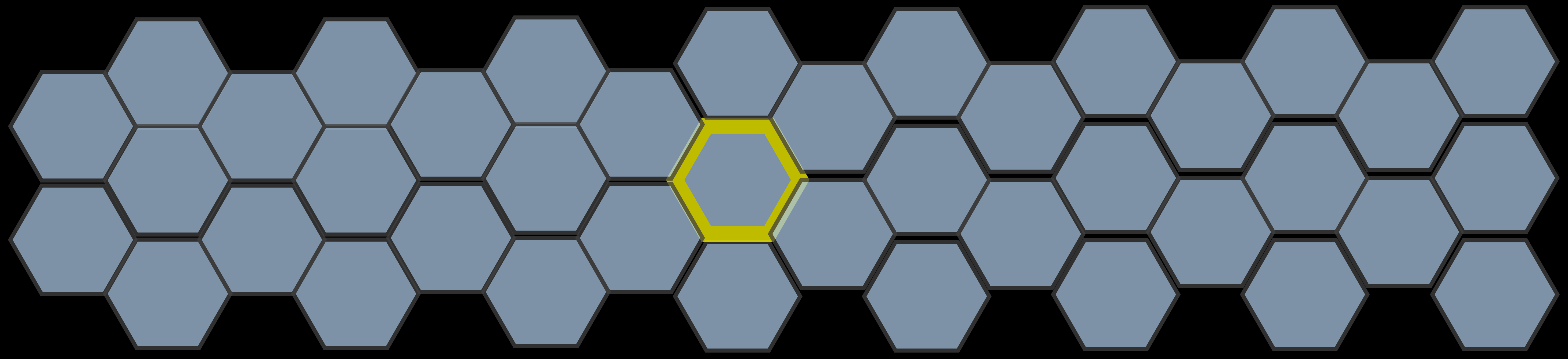

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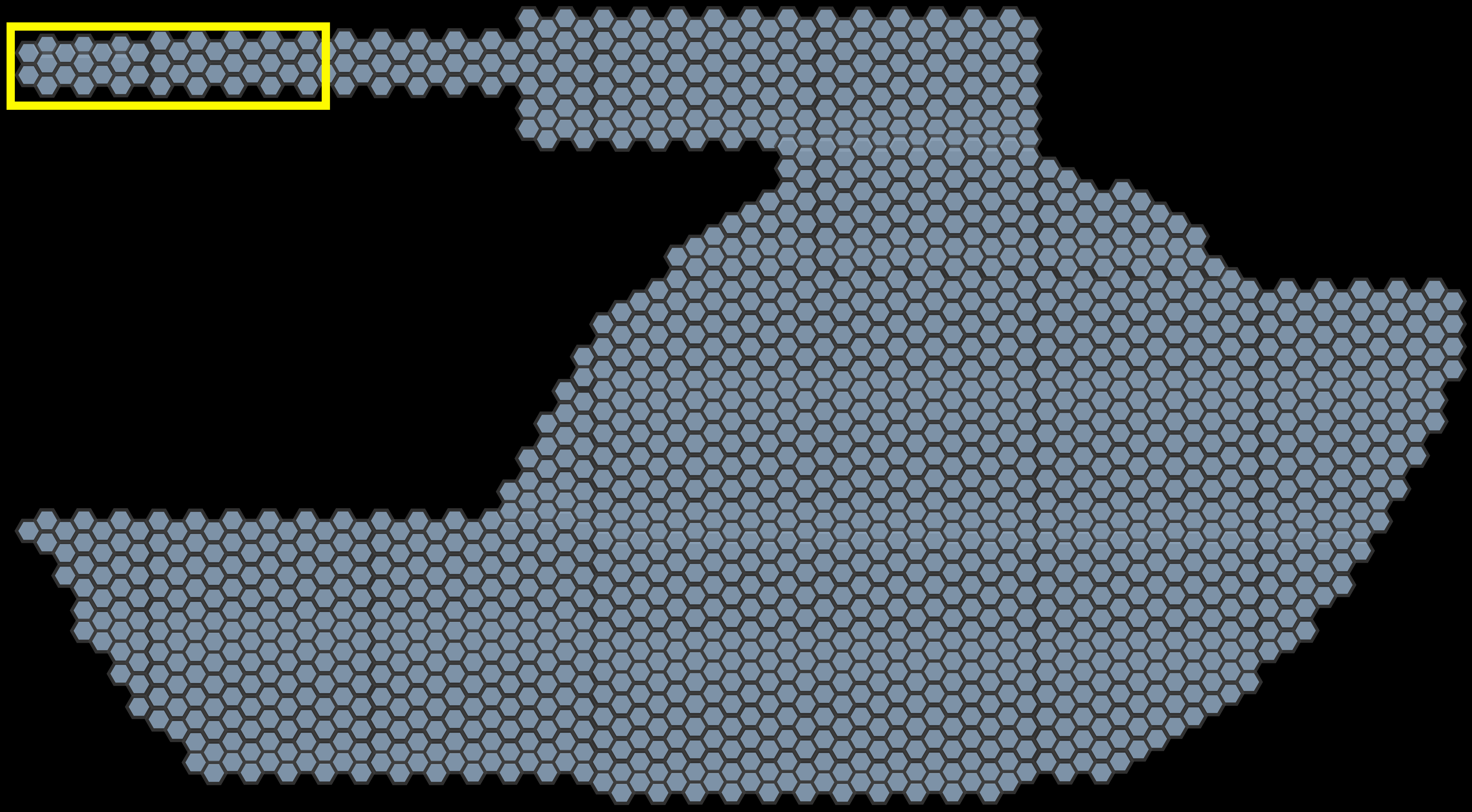

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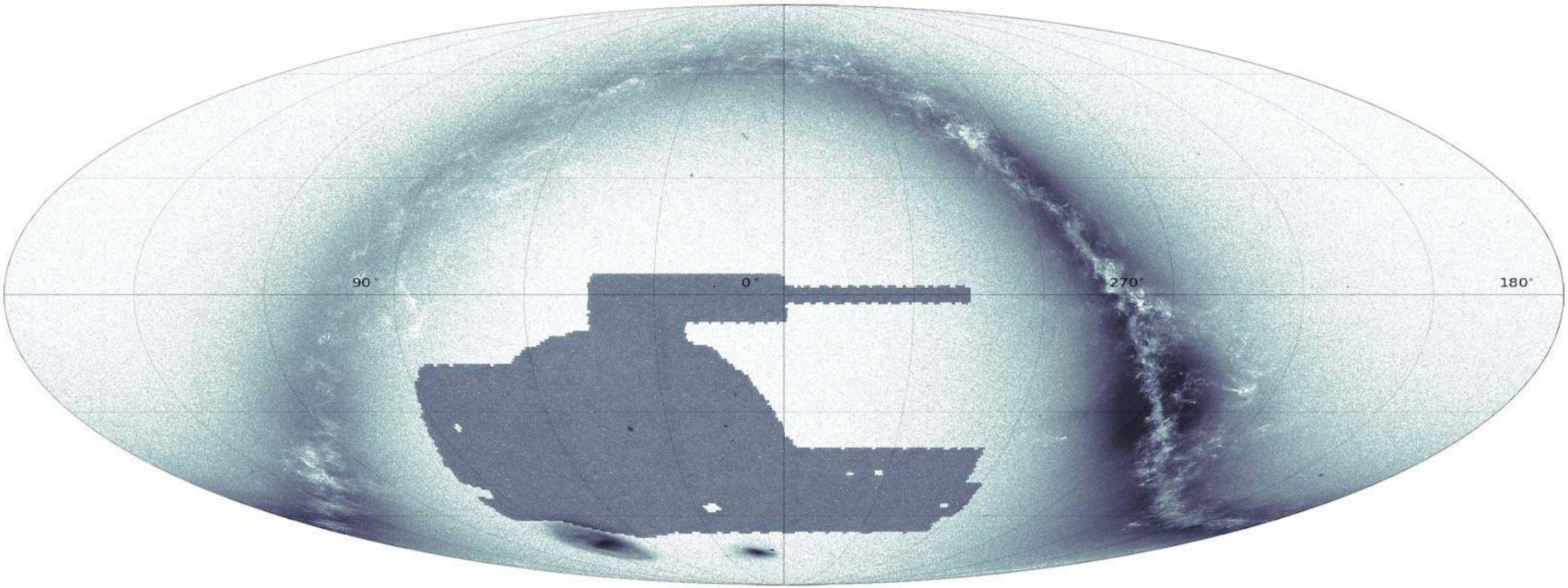
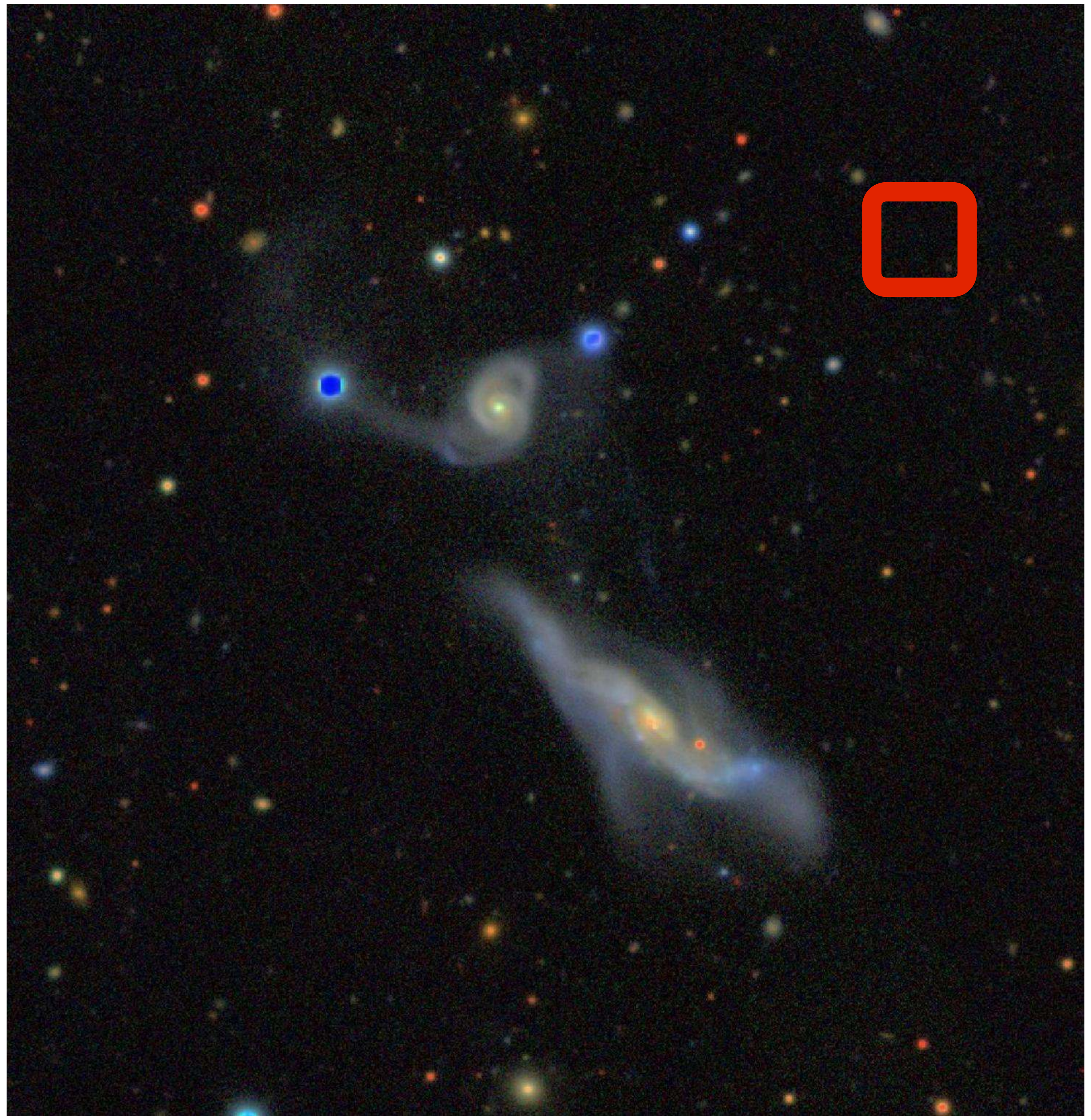
The Dark Energy Survey (DES)



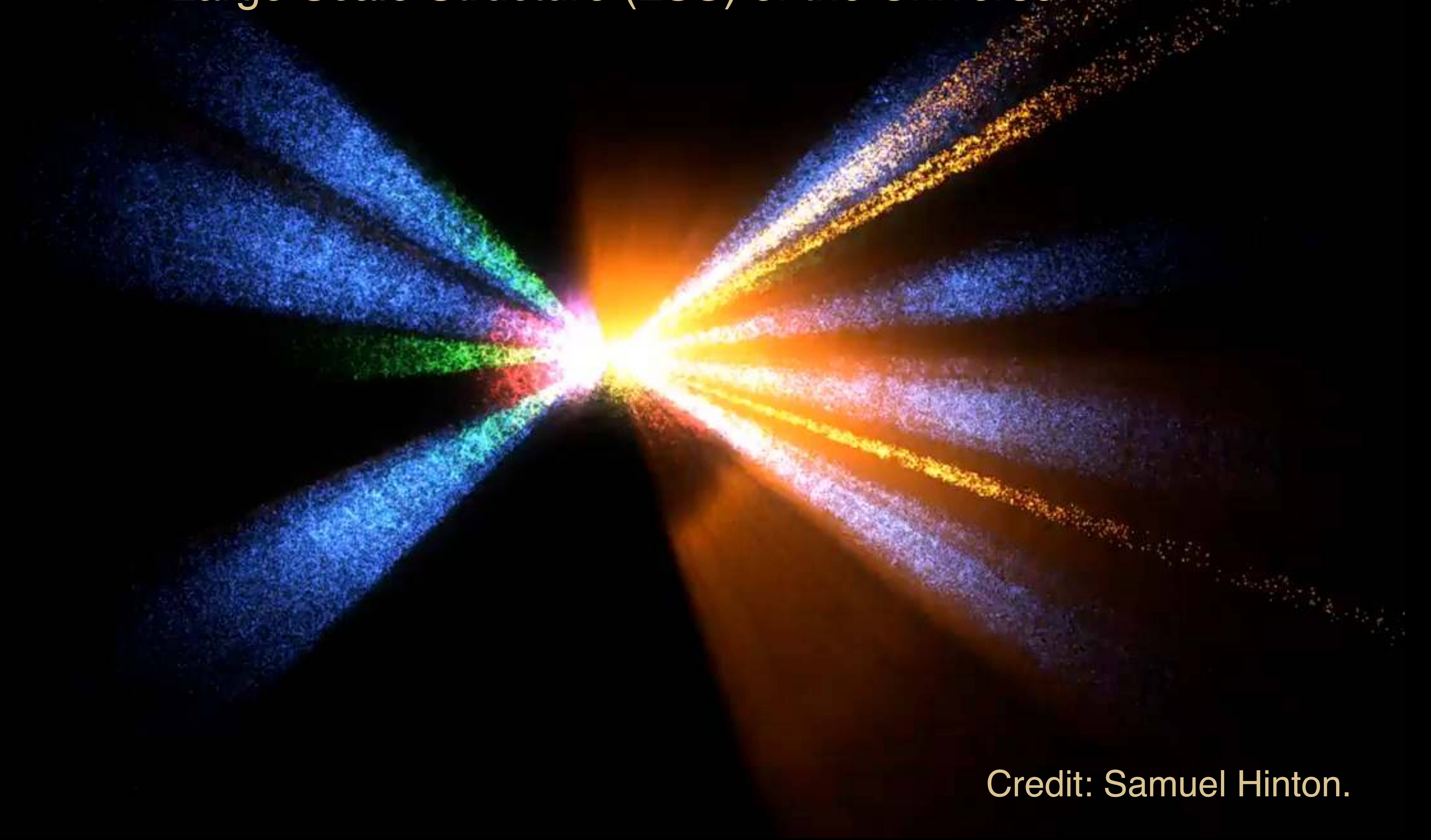
Detecting galaxies



Detecting galaxies

Large Scale Structure (LSS)

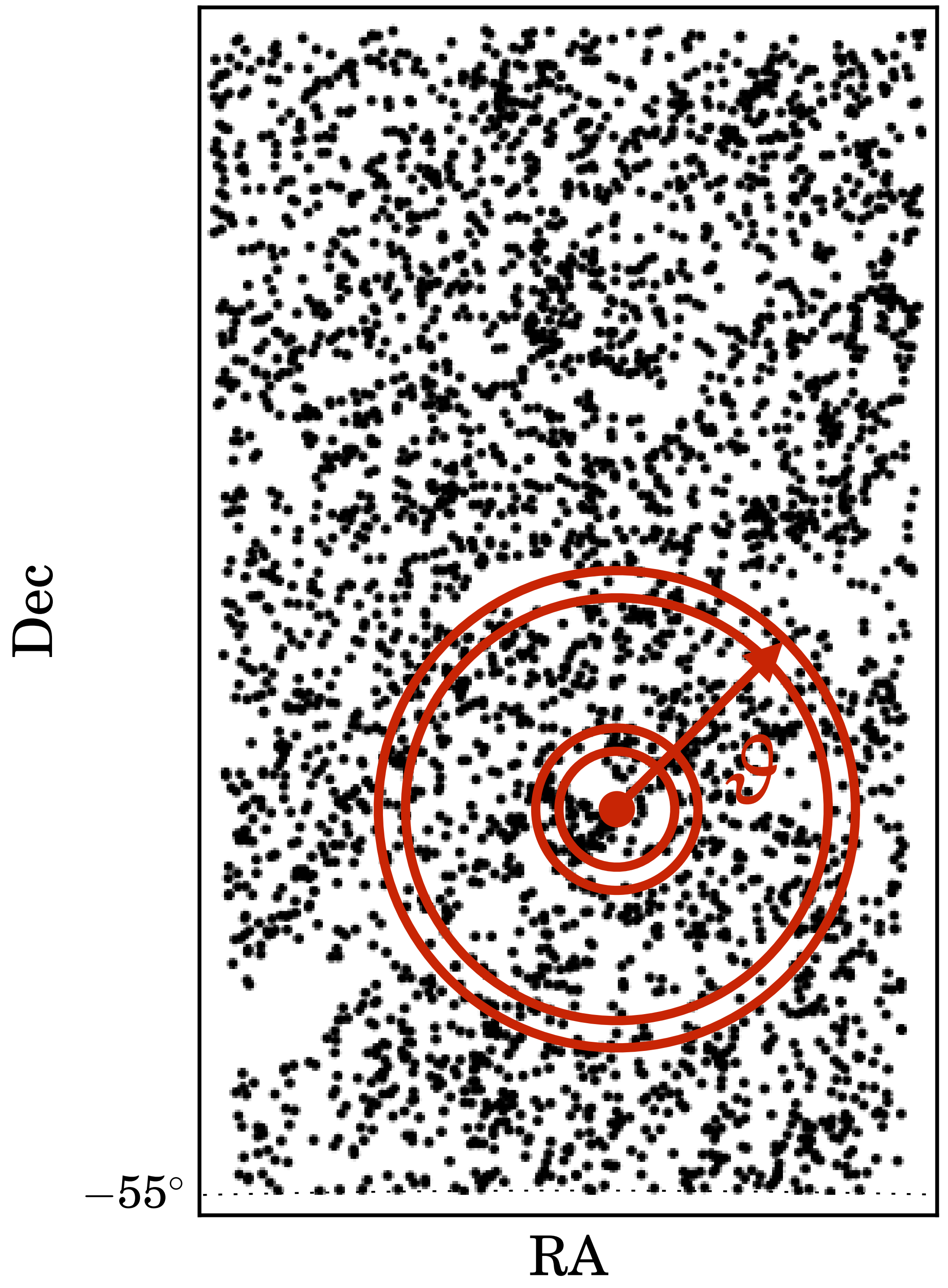
By the effect of gravity, matter (mostly dark) forms a complicated filamentary network, known as the Large Scale Structure (LSS) of the Universe.

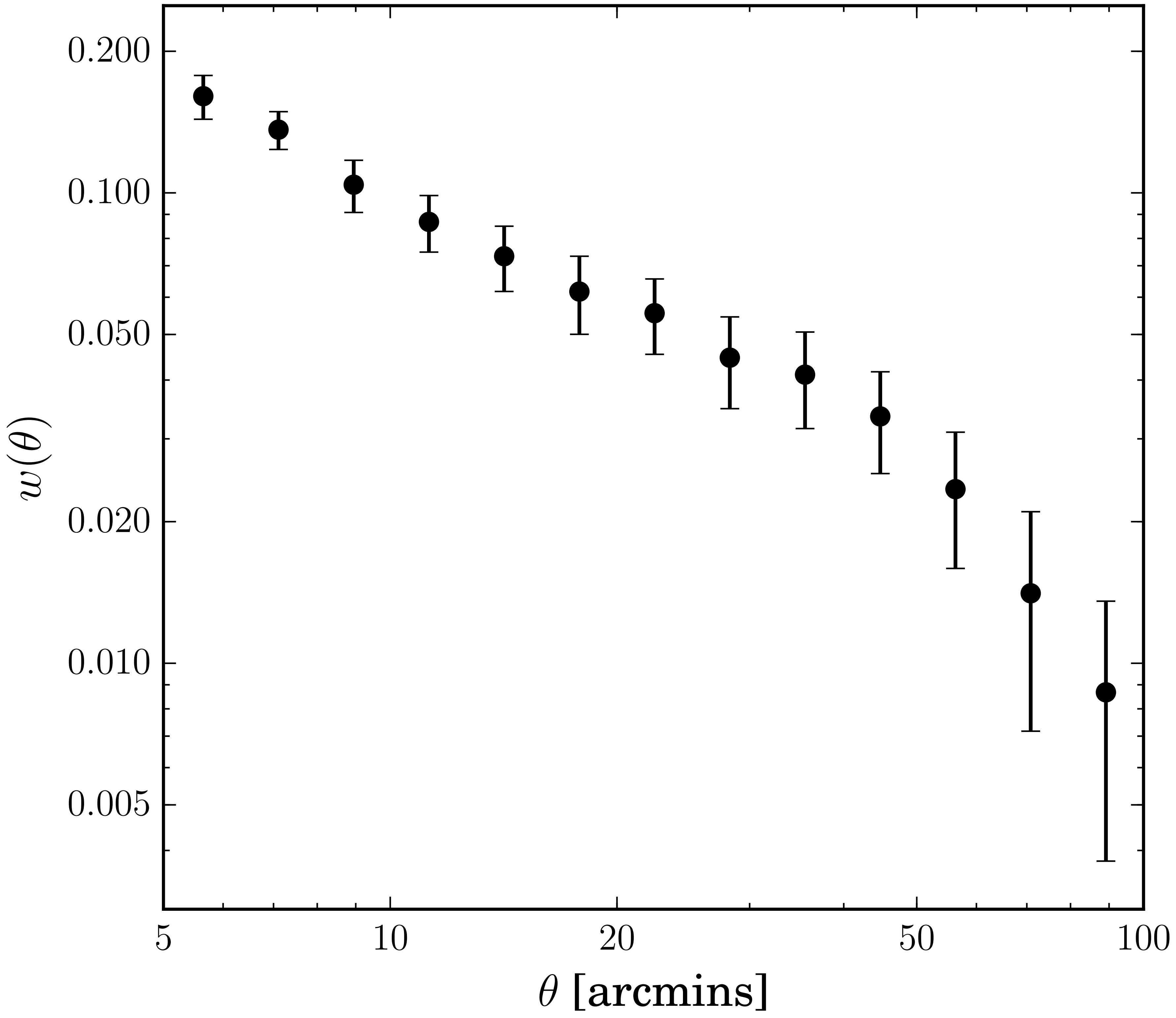


Credit: Samuel Hinton.

Galaxy clustering: two-point correlation function (2PCF)

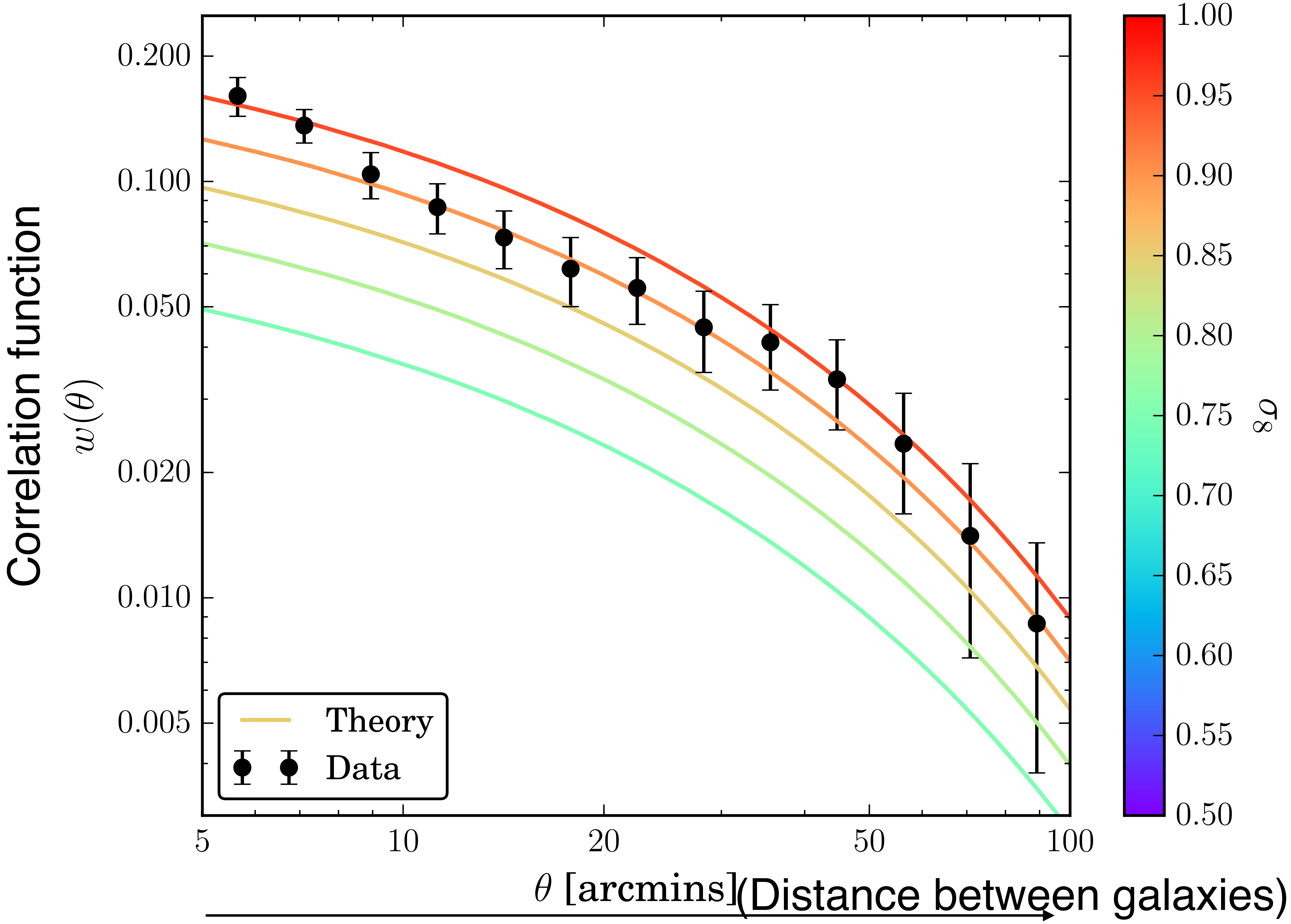
- Given a random galaxy in a location, the correlation function describes the probability that another galaxy will be found within a given distance.
- It can be thought of as a lumpiness factor - the higher the value for some distance scale, the more lumpy the Universe is at that distance scale.





Modeling two-point correlation functions…

Figure Credit: Carles Sánchez



$$w^i(\theta) = \int \frac{d\ell\,\ell}{2\pi} J_0(\ell\theta) \int d\chi \, \frac{q^i_{\delta_g}\left(\frac{\ell+1/2}{\chi}, \chi\right) q^j_{\delta_g}\left(\frac{\ell+1/2}{\chi}, \chi\right)}{\chi^2} \times P_{\rm NL}\left(\frac{\ell+1/2}{\chi}, z(\chi)\right)$$

LSS kernel

$$q^i_{\delta_g}(k,\chi) = b^i\left(k, z(\chi)\right) \frac{n^i_g(z(\chi))}{\bar{n}^i_g} \frac{dz}{d\chi}$$

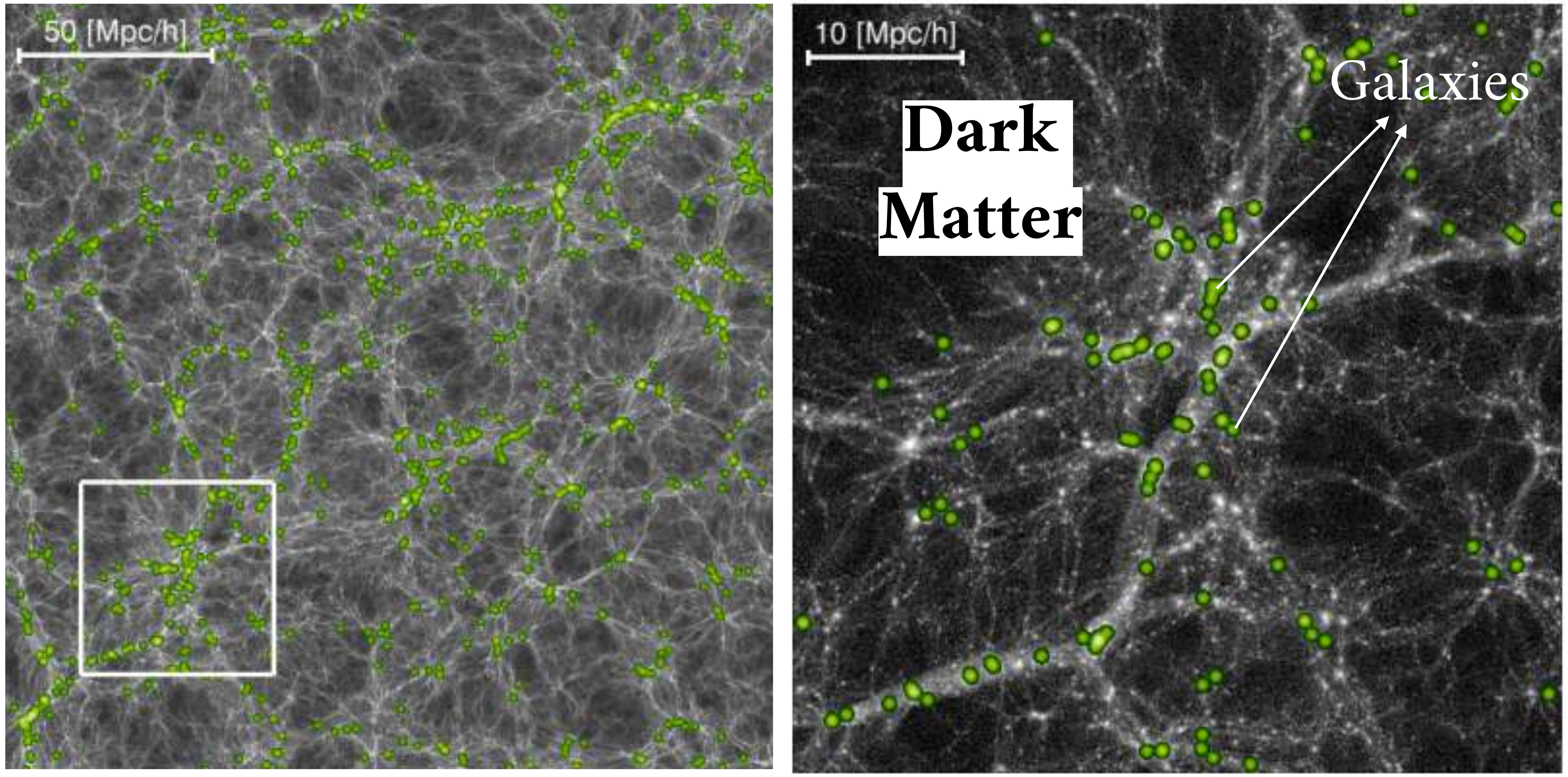
It is sensitive to the matter power spectrum (through the galaxy bias)

Galaxy bias

- Matter correlation function cannot be observed directly because most matter is in the form of dark matter. Galaxies populate dark matter haloes and thus trace dark matter, but not perfectly.

- **Galaxy bias:** The statistical difference between the clustering of galaxies and that of dark matter.

$$\xi_{gg}(r) = b^2(r)\,\xi_{\delta\delta}(r) \qquad P_{gg}(r) = b^2(r)\,P_{\delta\delta}(r)$$

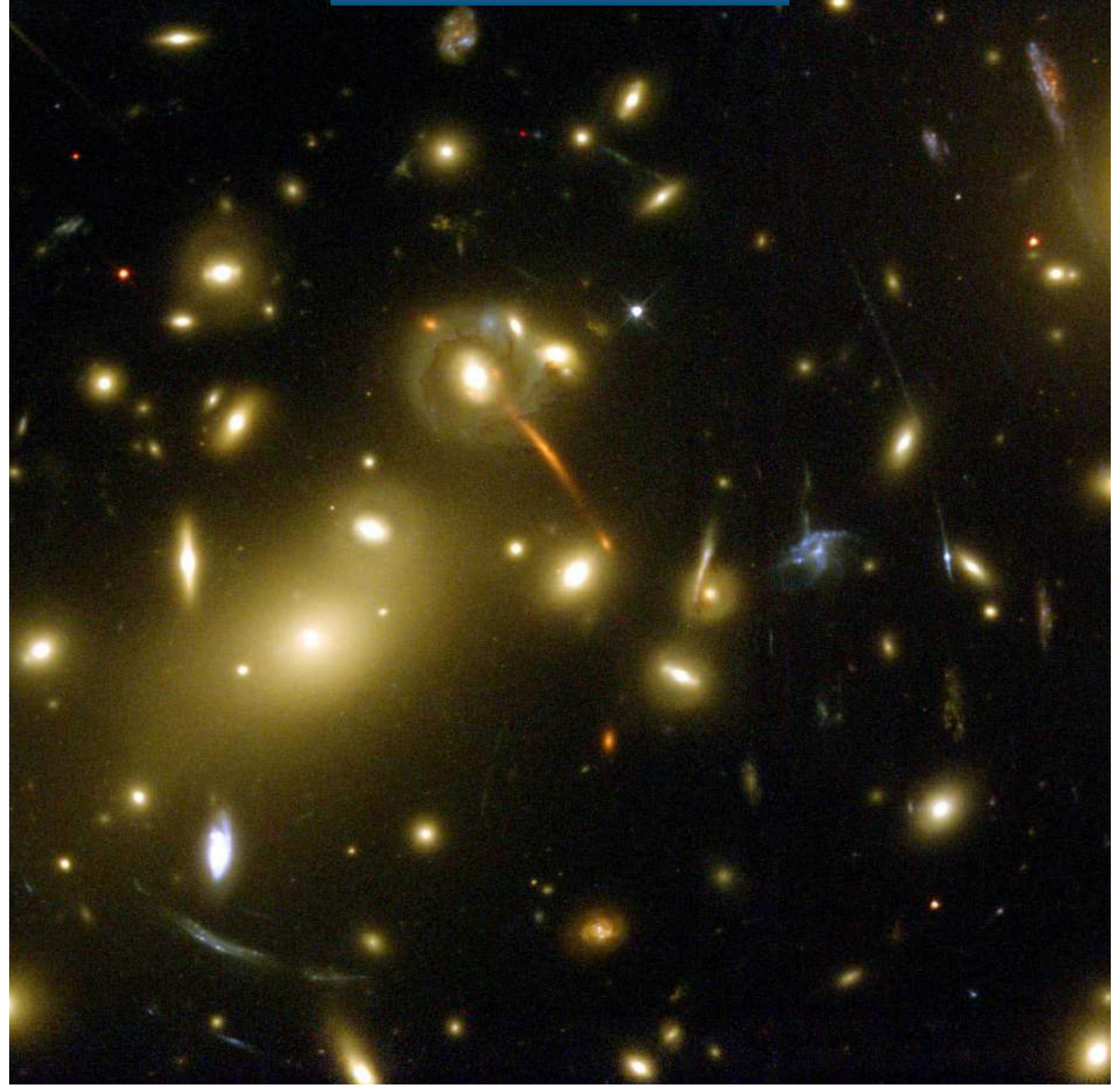


From Orsi et al. (2009)

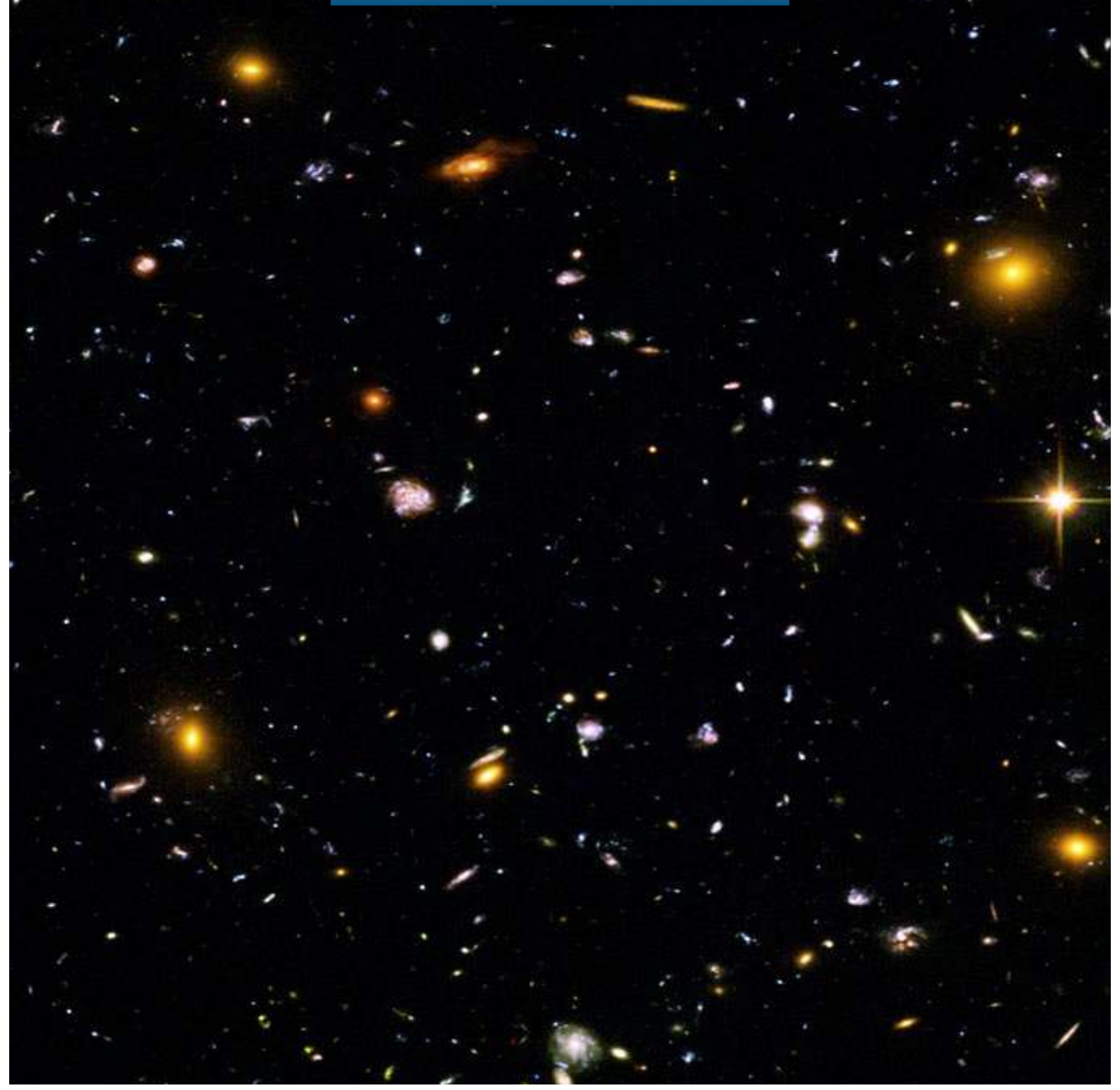
Gravitational lensing

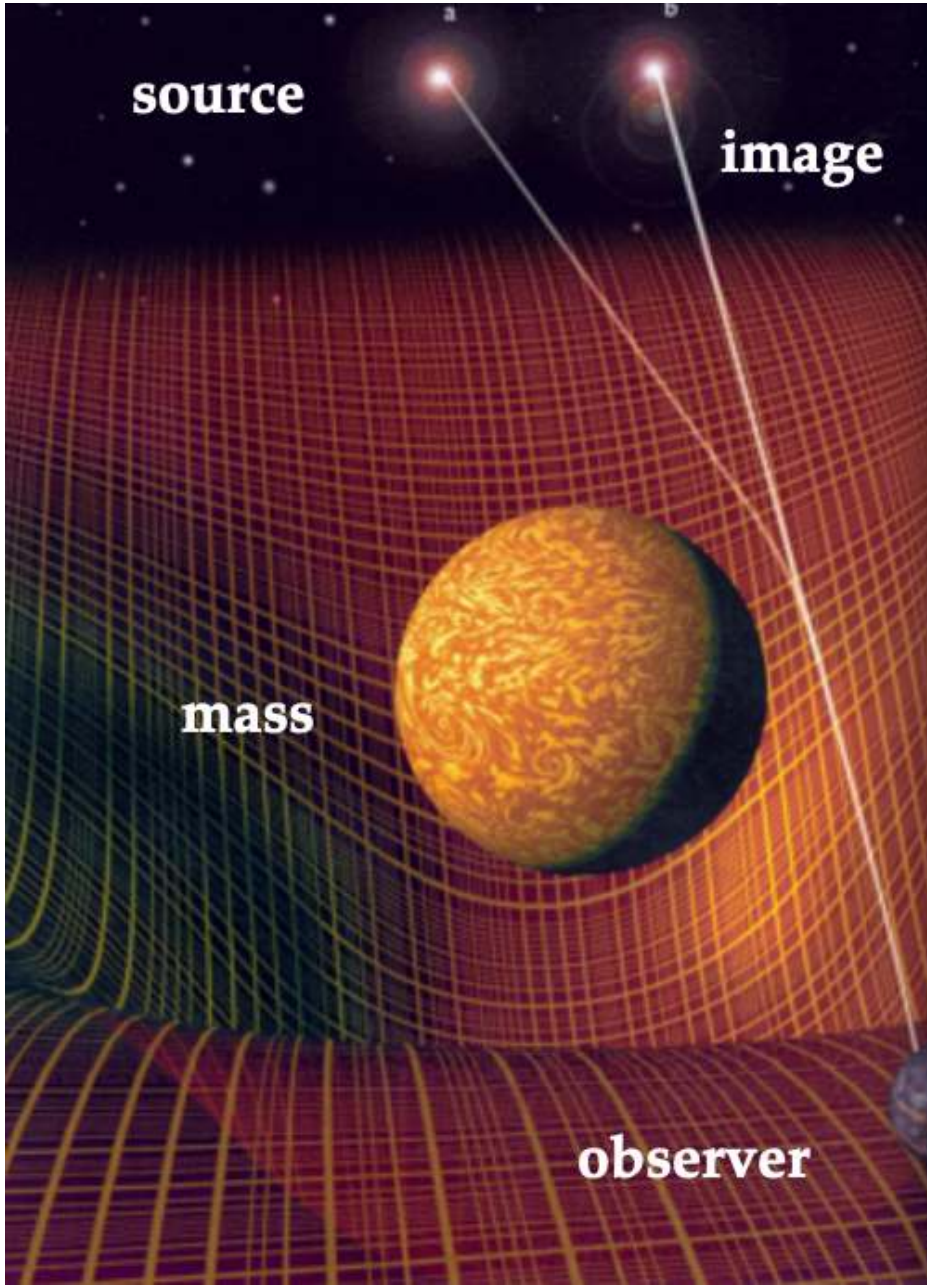
- **Strong gravitational lensing:** If the bending produces multiple images of the galaxy and/or arcs.
- **Weak gravitational lensing:** If the bending is small, the image of galaxies are distorted, stretched and magnified in small amounts. The distortion can be quantified with **shear** (shape) and **convergence** (size).

Strong lensing

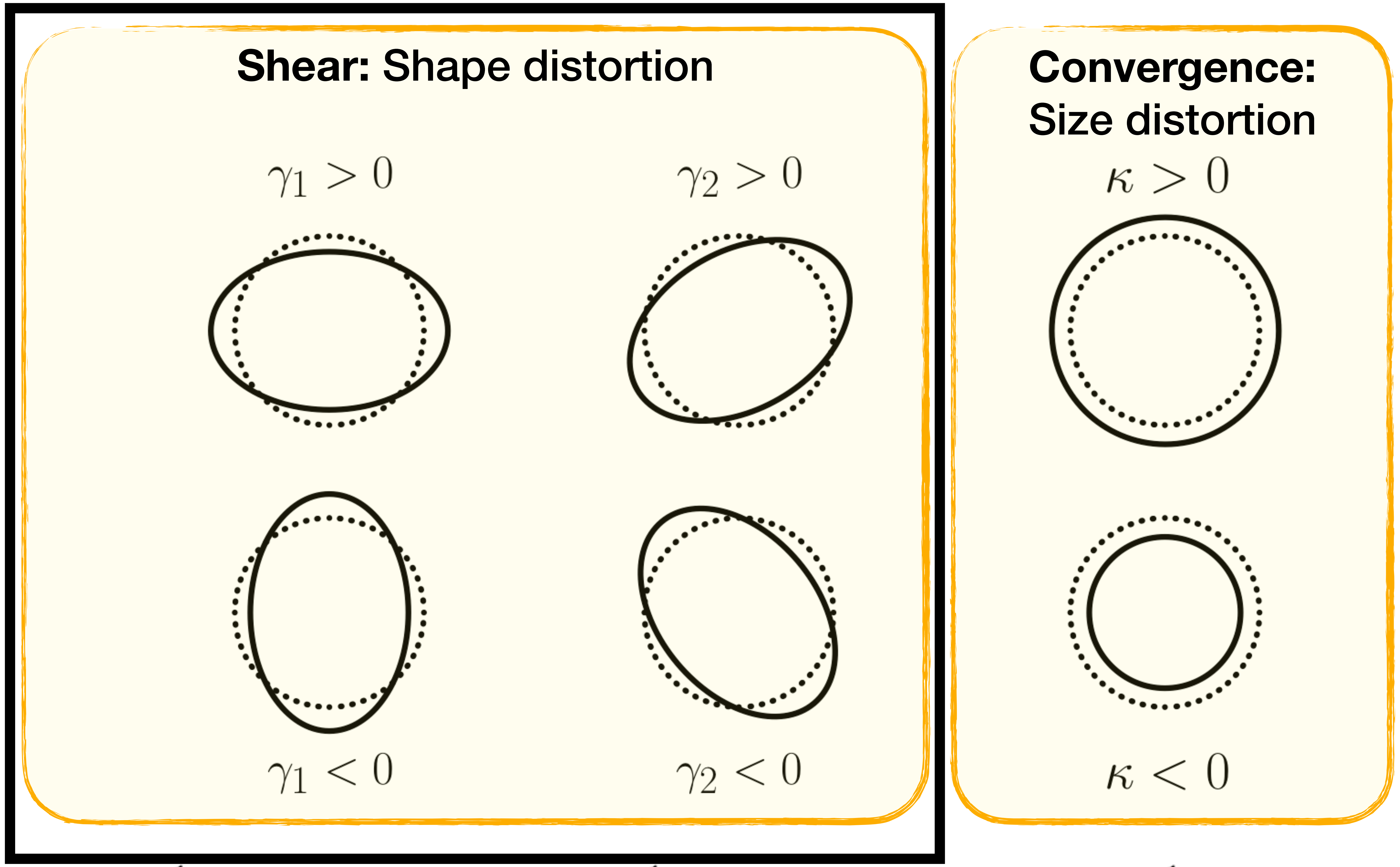


Weak lensing





Weak gravitational lensing



Lensing potential

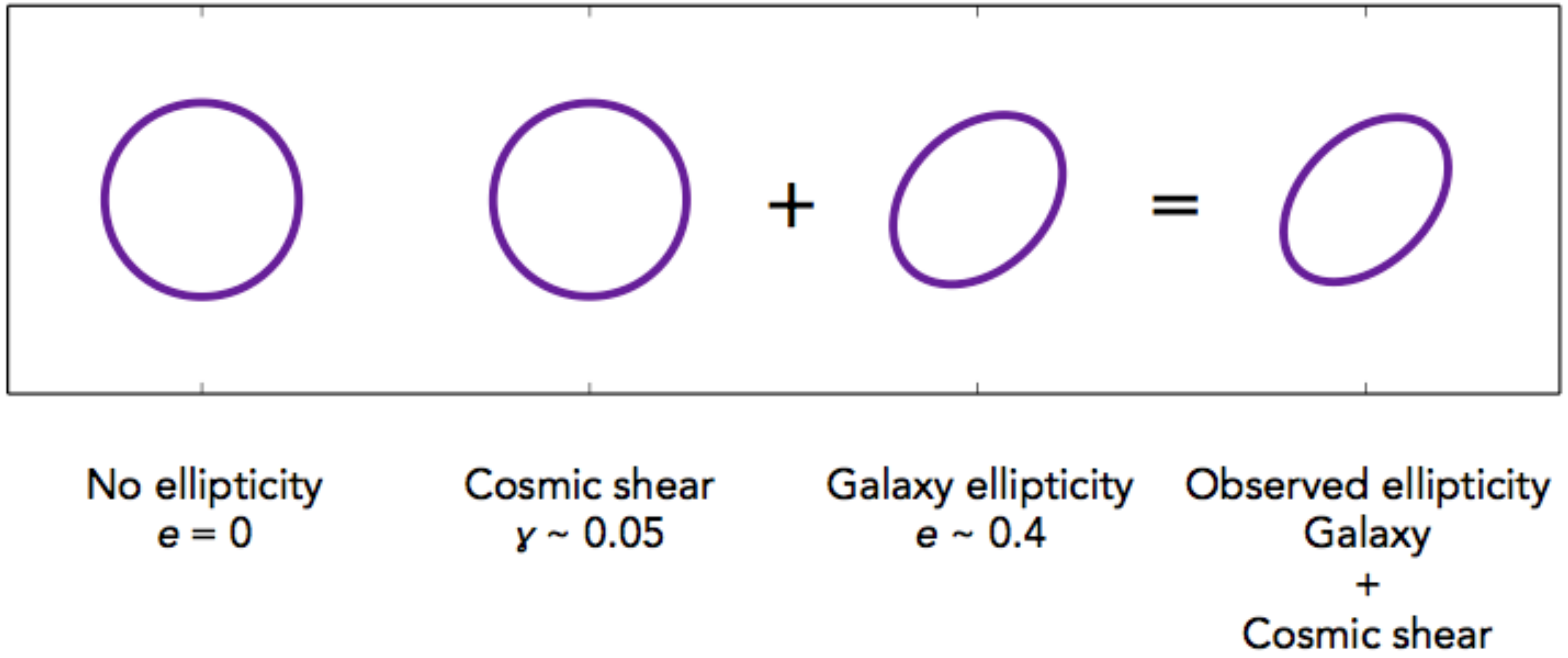
$$\psi(\vec{\theta}) = \frac{2}{c^2}\frac{D_{ls}}{D_l D_s}\int \Phi(D_l\vec{\theta}, z)\, dz$$

$$\kappa = \frac{1}{2}(\partial_1\partial_1 + \partial_2\partial_2)\psi = \frac{1}{2}\nabla^2\psi \quad ; \quad \gamma_1 = \frac{1}{2}(\partial_1\partial_1 - \partial_2\partial_2)\psi \quad ; \quad \gamma_2 = \partial_1\partial_2\psi$$

Measuring the shear

- We can't measure the shear directly because the galaxies have some intrinsic ellipticity. We need to average over hundreds of thousands of galaxies to average out the tangential component of the intrinsic ellipticity:

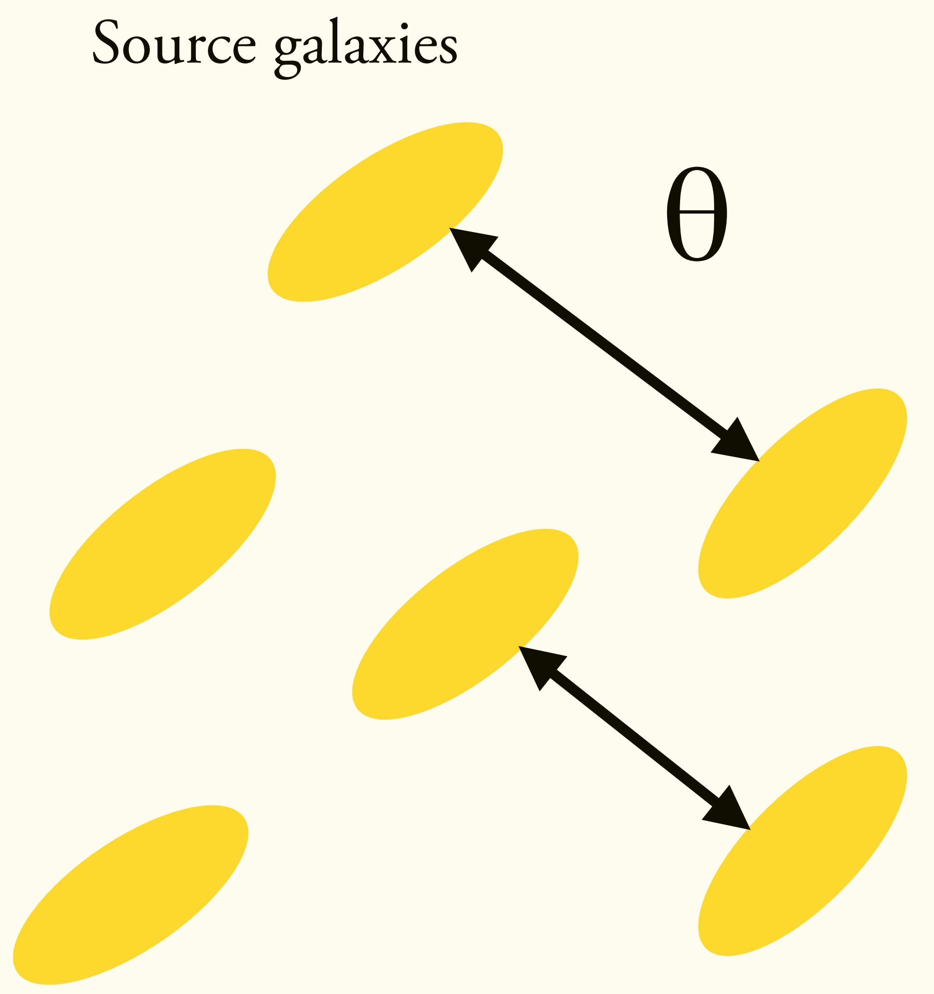
$$\epsilon \approx \epsilon^s + \gamma \qquad \langle \epsilon \rangle \approx \gamma$$



Weak gravitational lensing two-point correlation functions

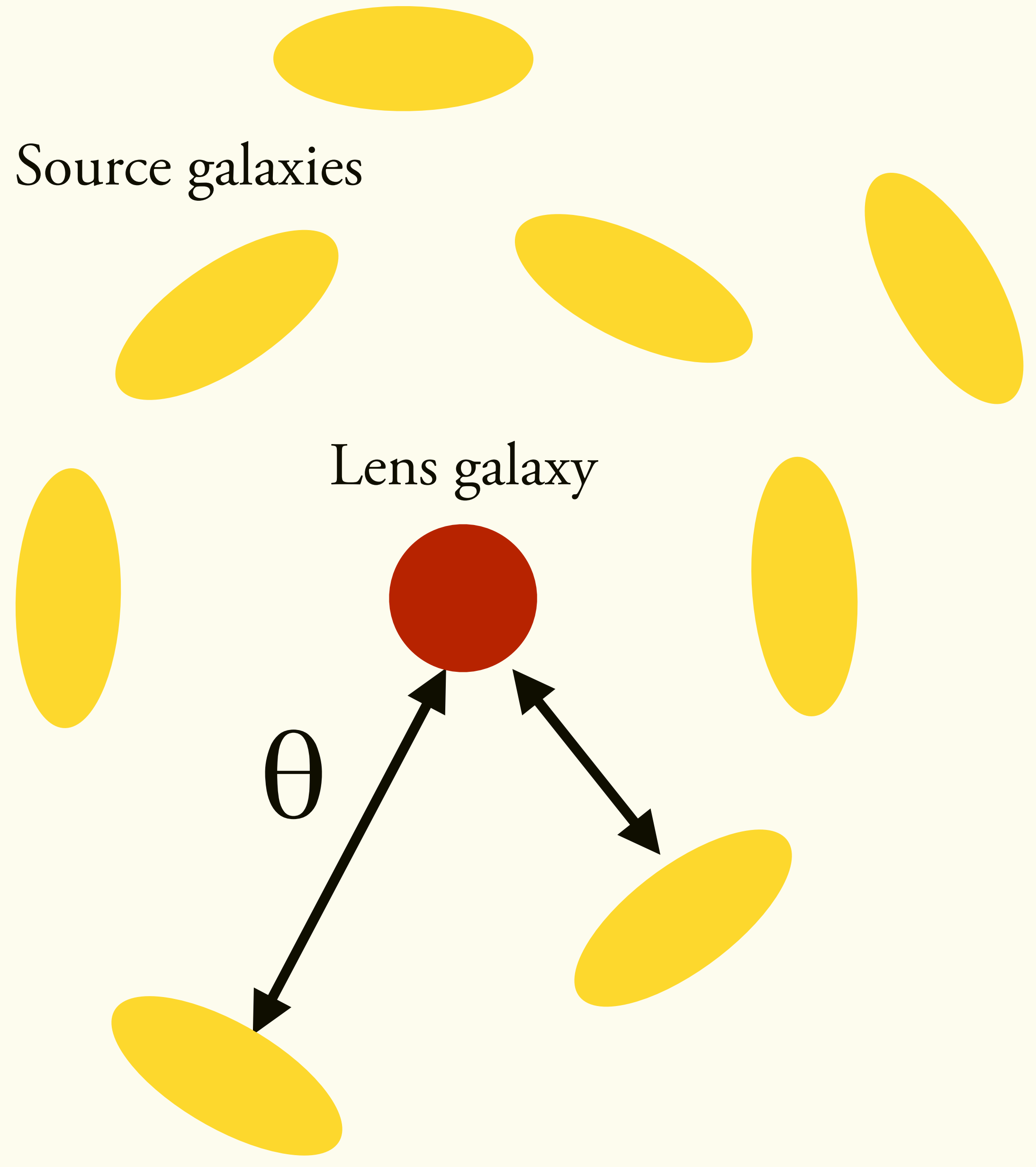
Cosmic shear: source-source correlation

Coherent distortion of galaxy shapes from large-scale structure.

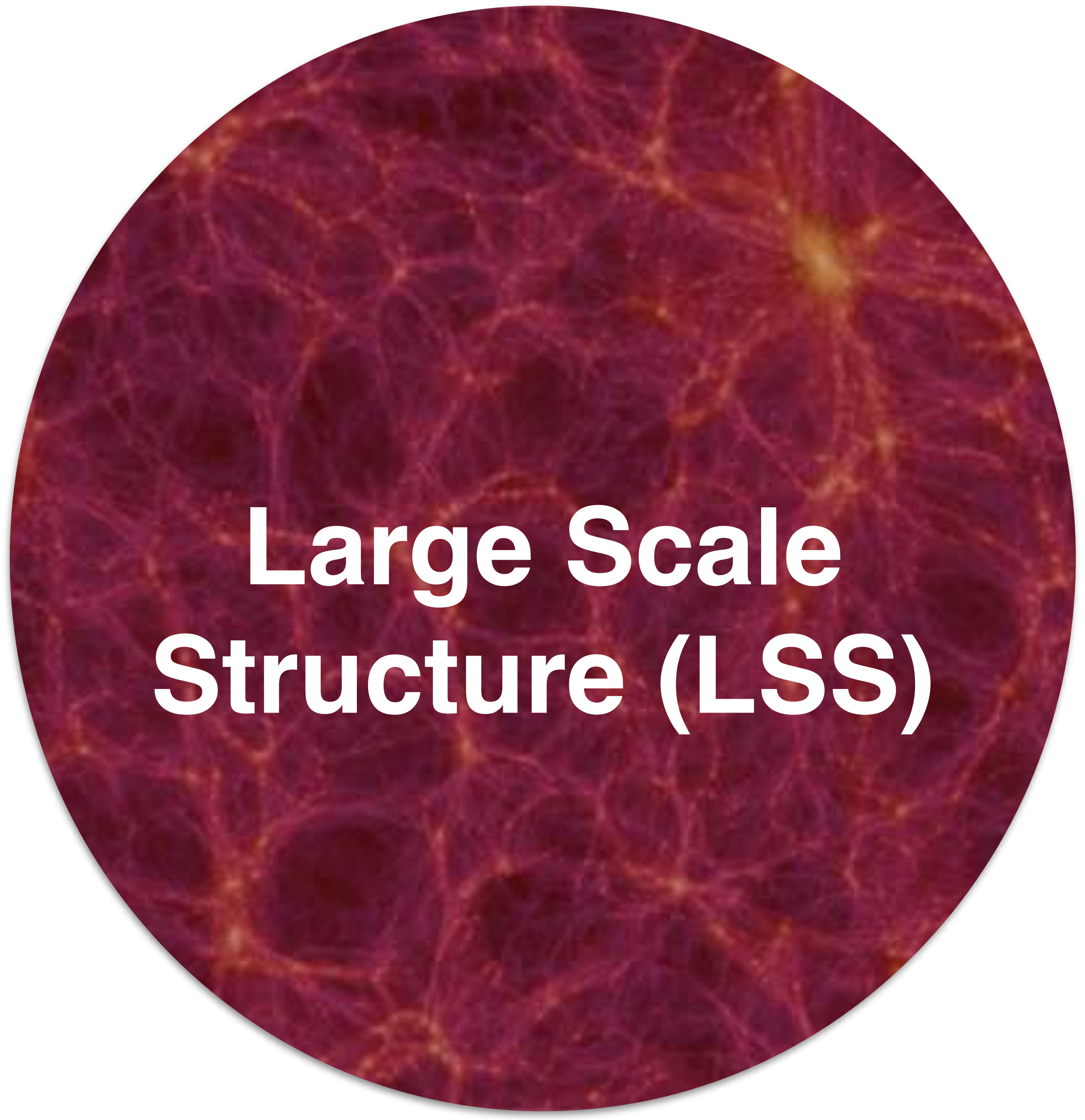


Galaxy-galaxy lensing: lens-source correlation

Tangential distortion of galaxy shapes around individual galaxies in the foreground.



LSS + WL: 3x2pt analysis



+

LSS + WL

3x2pt analysis

Large Scale

DES lens galaxies tracing the Large Scale Structure

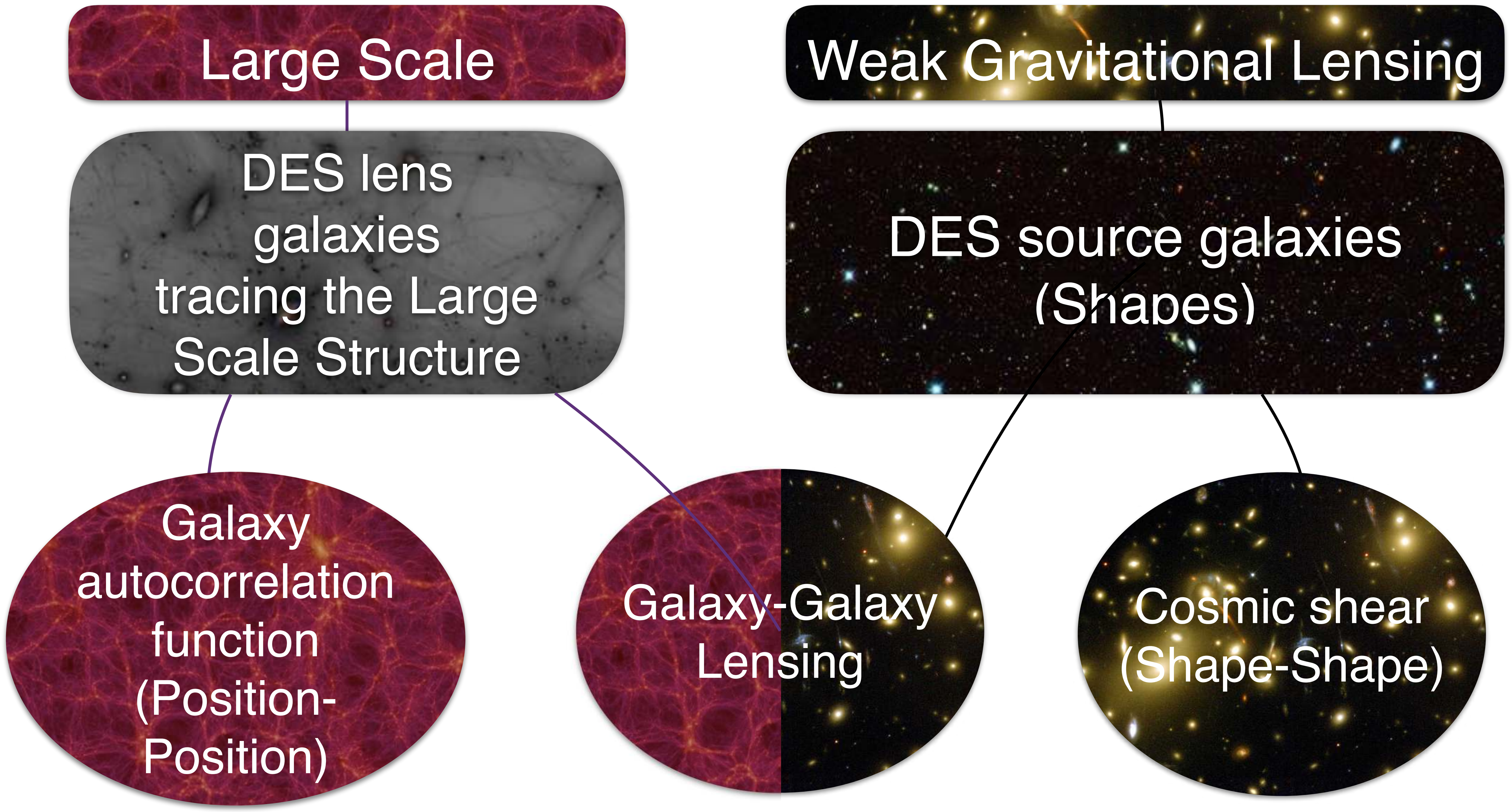
Weak Gravitational Lensing

DES source galaxies (Shapes)

LSS + WL

3x2pt analysis

- Using two galaxy samples we can construct three 2-point correlation functions.
- The combination helps break degeneracies and self-calibrate nuisance parameters.
- This kind of analysis has been performed using DES, KiDS and HSC data.



$$\xi_{gg} = \langle \delta_g \, \delta_g \rangle \propto b^2 \langle \delta_m \, \delta_m \rangle$$

$$\xi_{gm} = \langle \delta_g \, \delta_m \rangle \propto b \langle \delta_m \delta_m \rangle$$

$$\xi_{mm} = \langle \delta_m \, \delta_m \rangle$$

LSS + WL

3x2pt analysis

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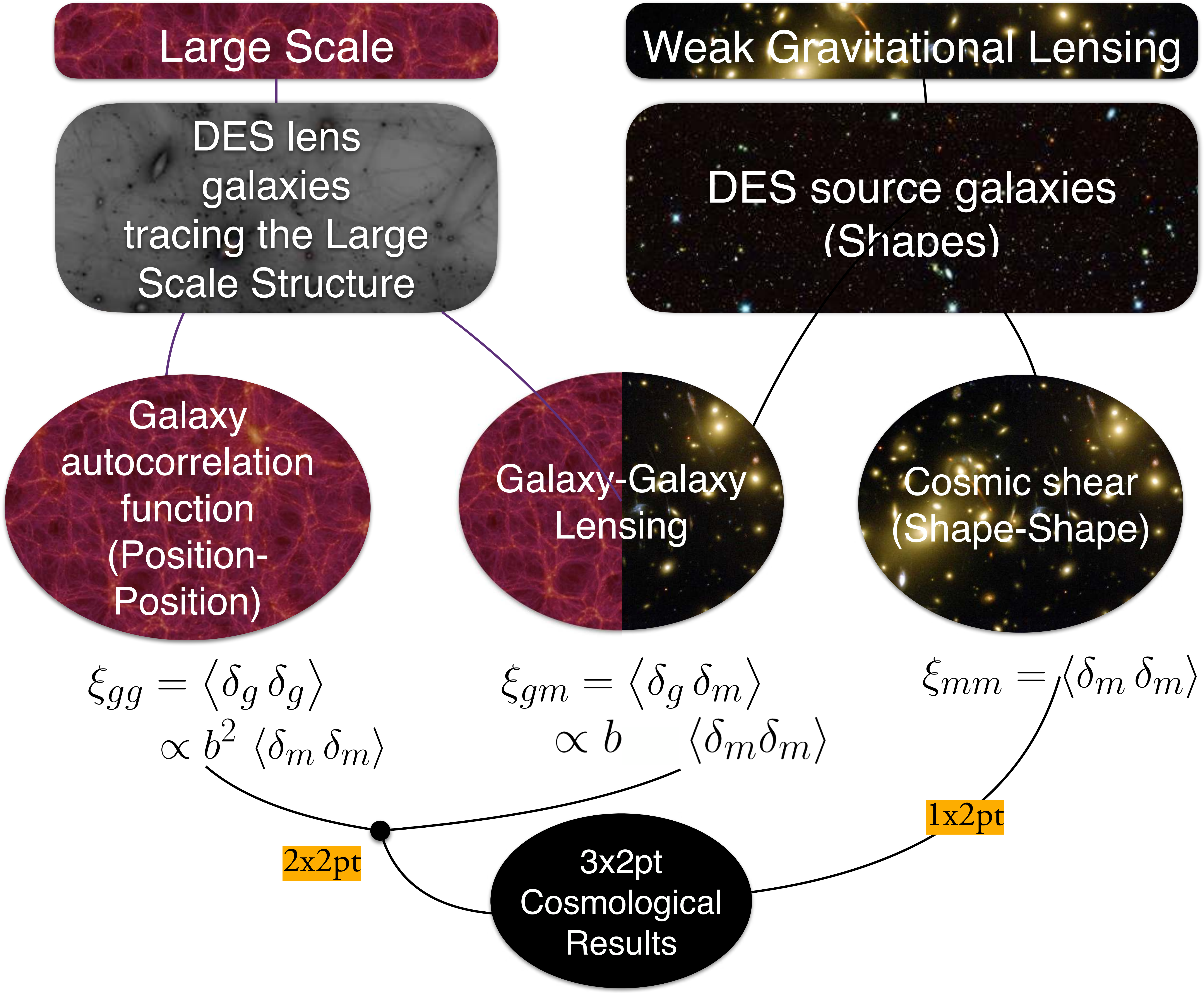
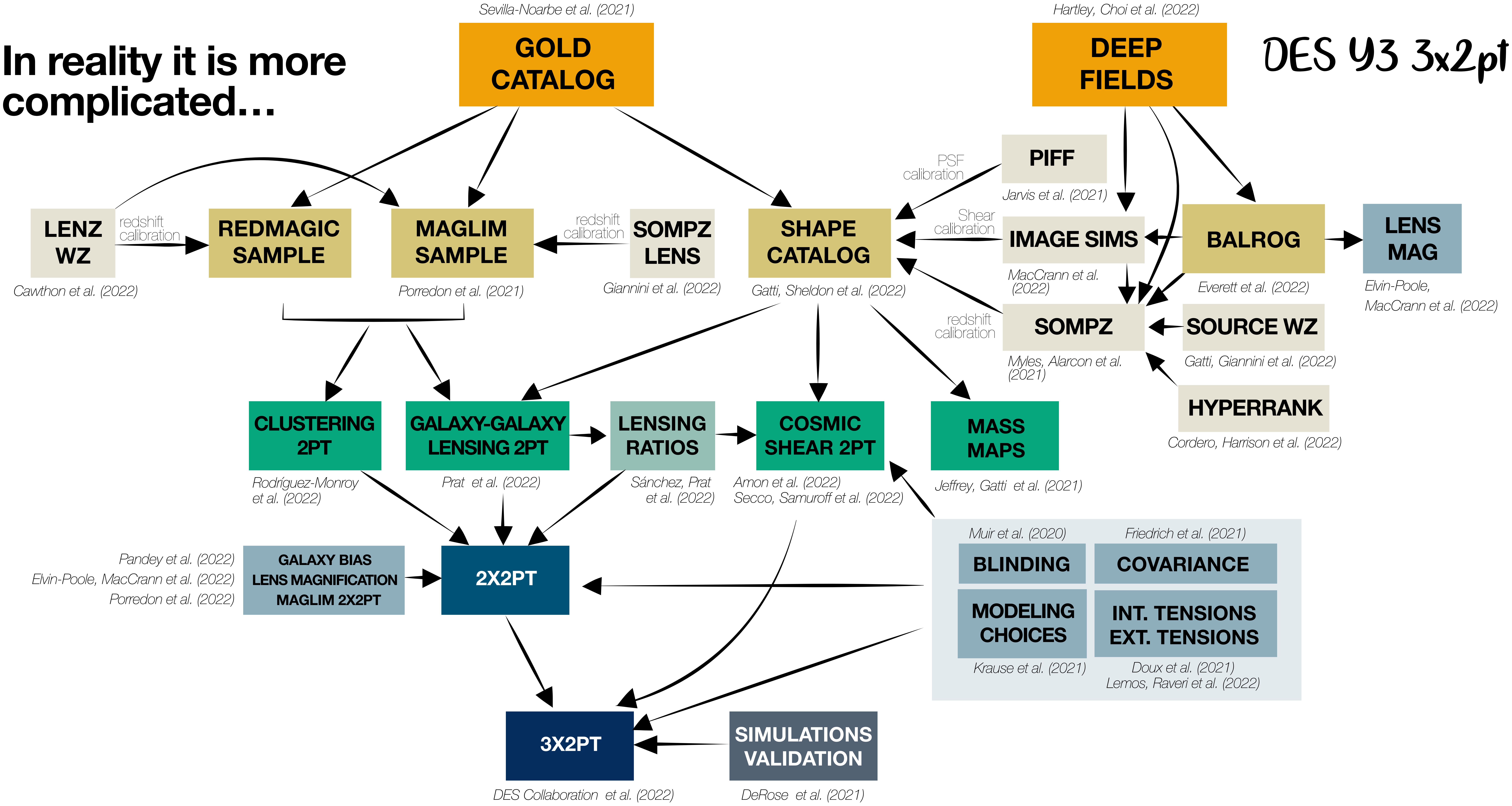


The WL + LSS analysis in DES Y3

The DES Collaboration

In reality it is more complicated…

DES Y3 3x2pt



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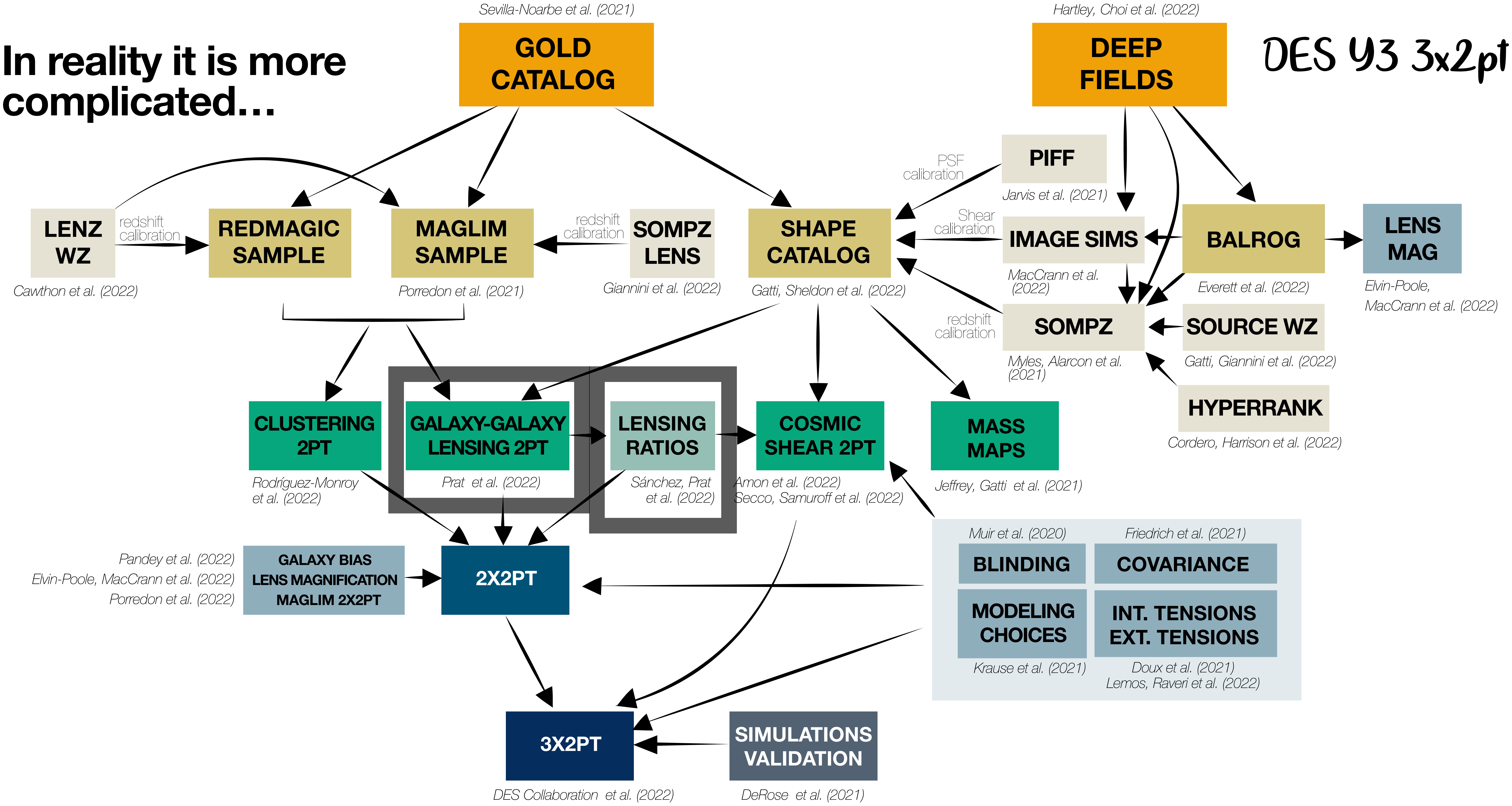
DES Y3 3x2pt



DES Y3 3x2pt

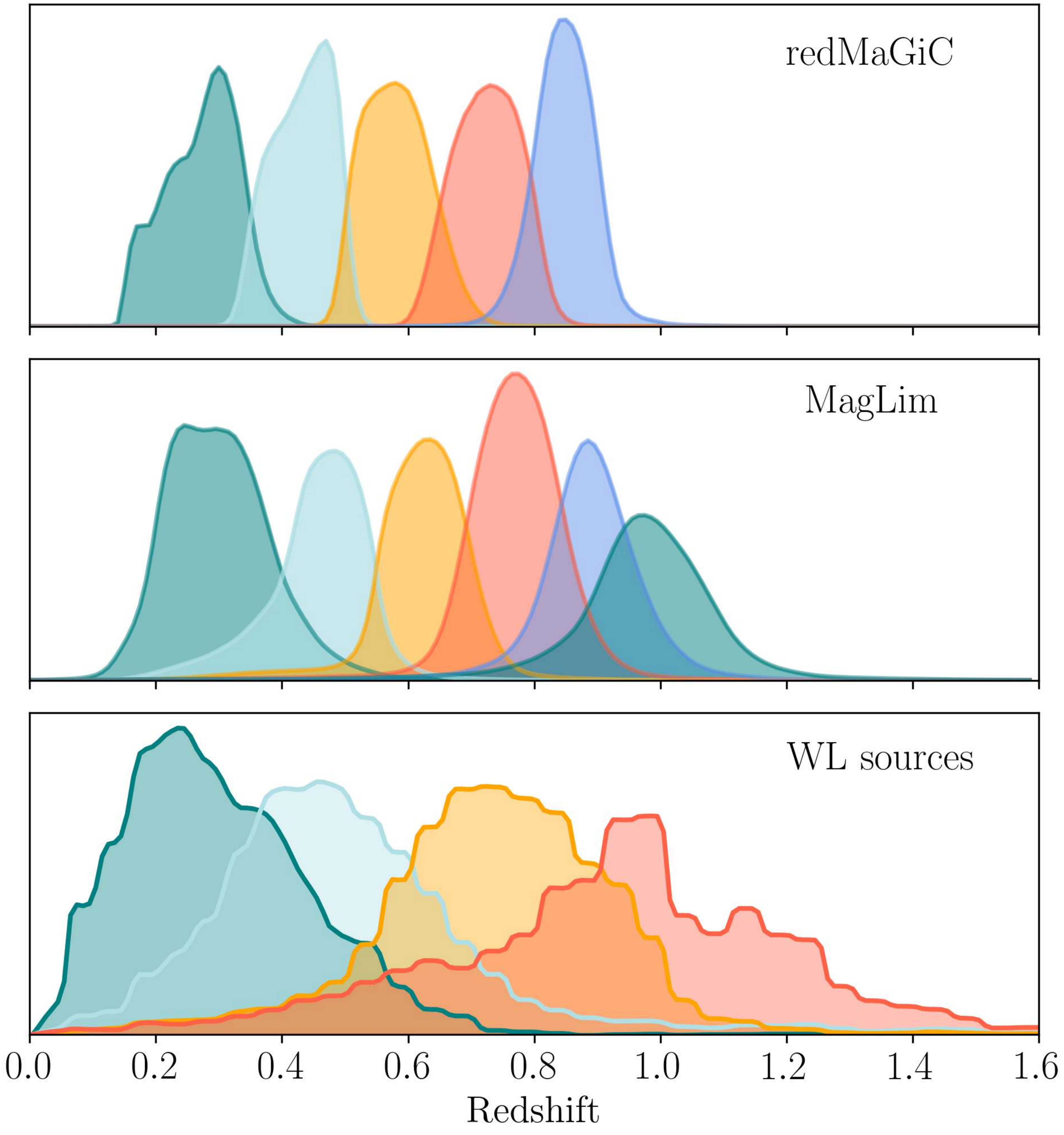
Galaxy samples

- Two lens samples, divided into 5 or 6 redshift bins.

    1. **redMaGiC:** 2.6 M galaxies. Selects Luminous Red Galaxies (LRGs) according to the magnitude-color-redshift relation of red sequence galaxies, optimized have excellent photometric redshifts.

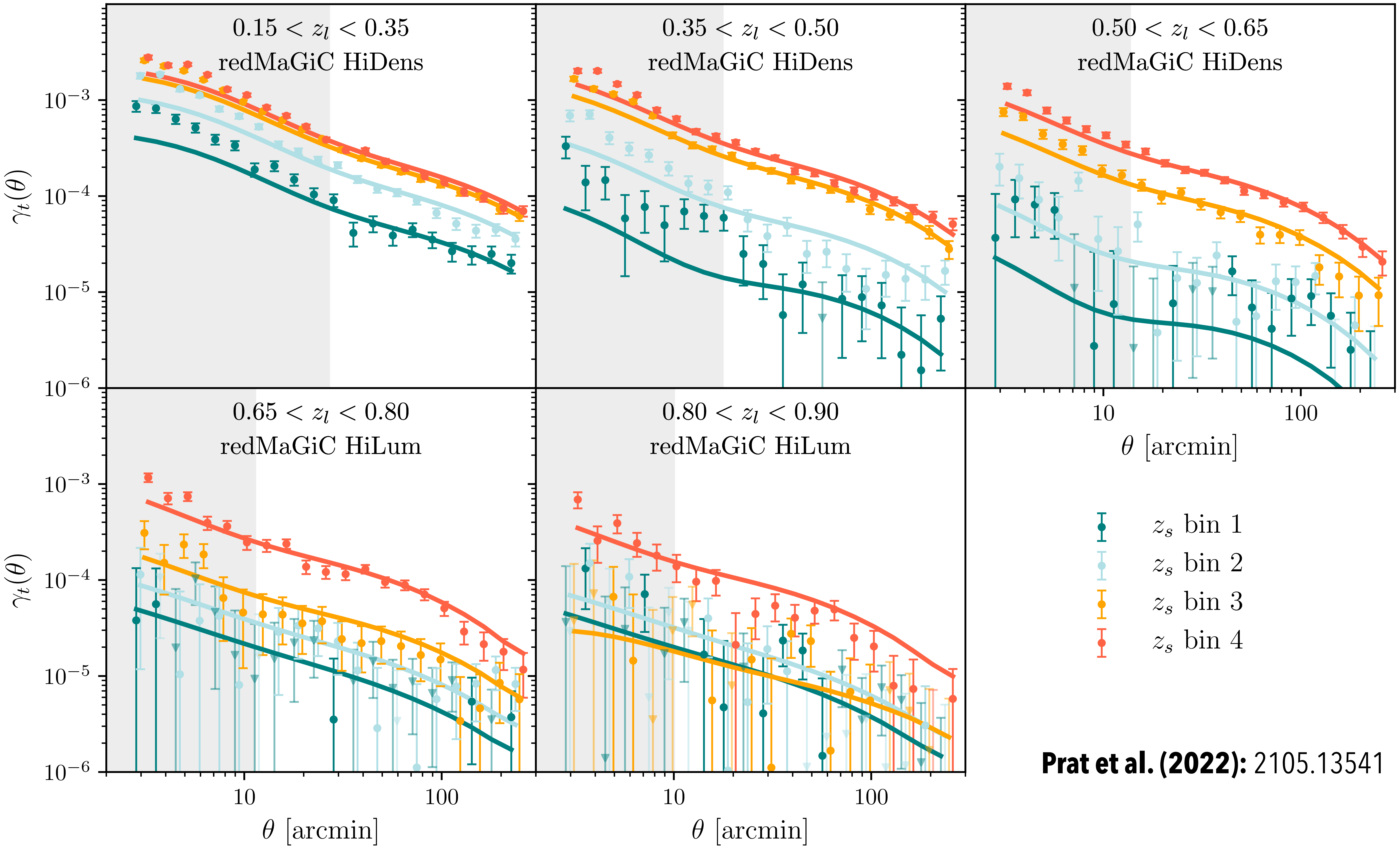
    2. **MagLim:** 10M galaxies. Denser magnitude limited sample $i < 4z_{phot} + 18$

- One source sample, using **METACALIBRATION** to obtain the shears: 100 M galaxies *(Gatti, Sheldon et al. (2020), arXiV: 2011.03408)*



Galaxy-galaxy lensing DES Y3 measurements and model

- REDMAGIC S/N:
  i. **Total:**120.
  ii. **After scale cuts** (>6Mpc/h): 55
- MAGLIM S/N:
  i. **Total:**148.
  ii. **After scale cuts** (>6Mpc/h): 67



Prat et al. (2022): 2105.13541

3x2pt combination:
Free parameters and priors

Parameter	Prior	
Cosmology		
$\Omega_{\rm m}$	Flat	$(0.1, 0.9)$
$10^9 A_{\rm s}$	Flat	$(0.5, 5.0)$
$n_{\rm s}$	Flat	$(0.87, 1.07)$
$\Omega_{\rm b}$	Flat	$(0.03, 0.07)$
h	Flat	$(0.55, 0.91)$
$10^3 \Omega_\nu h^2$	Flat	$(0.60, 6.44)$
w	Flat	$(-2.0, -0.33)$
Lens Galaxy Bias		
$b_i (i \in [1, 4])$	Flat	$(0.8, 3.0)$
Lens magnification		
$C_{\rm l}^1$	Fixed	1.21
$C_{\rm l}^2$	Fixed	1.15
$C_{\rm l}^3$	Fixed	1.88
$C_{\rm l}^4$	Fixed	1.97
Lens photo-z		
$\Delta z_{\rm l}^1 \times 10^2$	Gaussian	$(-0.9, 0.7)$
$\Delta z_{\rm l}^2 \times 10^2$	Gaussian	$(-3.5, 1.1)$
$\Delta z_{\rm l}^3 \times 10^2$	Gaussian	$(-0.5, 0.6)$
$\Delta z_{\rm l}^4 \times 10^2$	Gaussian	$(-0.7, 0.6)$
$\sigma_{z,{\rm l}}^1$	Gaussian	$(0.98, 0.06)$
$\sigma_{z,{\rm l}}^2$	Gaussian	$(1.31, 0.09)$
$\sigma_{z,{\rm l}}^3$	Gaussian	$(0.87, 0.05)$
$\sigma_{z,{\rm l}}^4$	Gaussian	$(0.92, 0.05)$
Intrinsic Alignment		
$a_i \ (i \in [1, 2])$	Flat	$(-5, 5)$
$\eta_i \ (i \in [1, 2])$	Flat	$(-5, 5)$
$b_{\rm TA}$	Flat	$(0, 2)$
z_0	Fixed	0.62
Source photo-z		
$\Delta z_{\rm s}^1 \times 10^2$	Gaussian	$(0.0, 1.8)$
$\Delta z_{\rm s}^2 \times 10^2$	Gaussian	$(0.0, 1.5)$
$\Delta z_{\rm s}^3 \times 10^2$	Gaussian	$(0.0, 1.1)$
$\Delta z_{\rm s}^4 \times 10^2$	Gaussian	$(0.0, 1.7)$
Shear calibration		
$m^1 \times 10^2$	Gaussian	$(-0.6, 0.9)$
$m^2 \times 10^2$	Gaussian	$(-2.0, 0.8)$
$m^3 \times 10^2$	Gaussian	$(-2.4, 0.8)$
$m^4 \times 10^2$	Gaussian	$(-3.7, 0.8)$

What changed from DES Y1 to Y3?

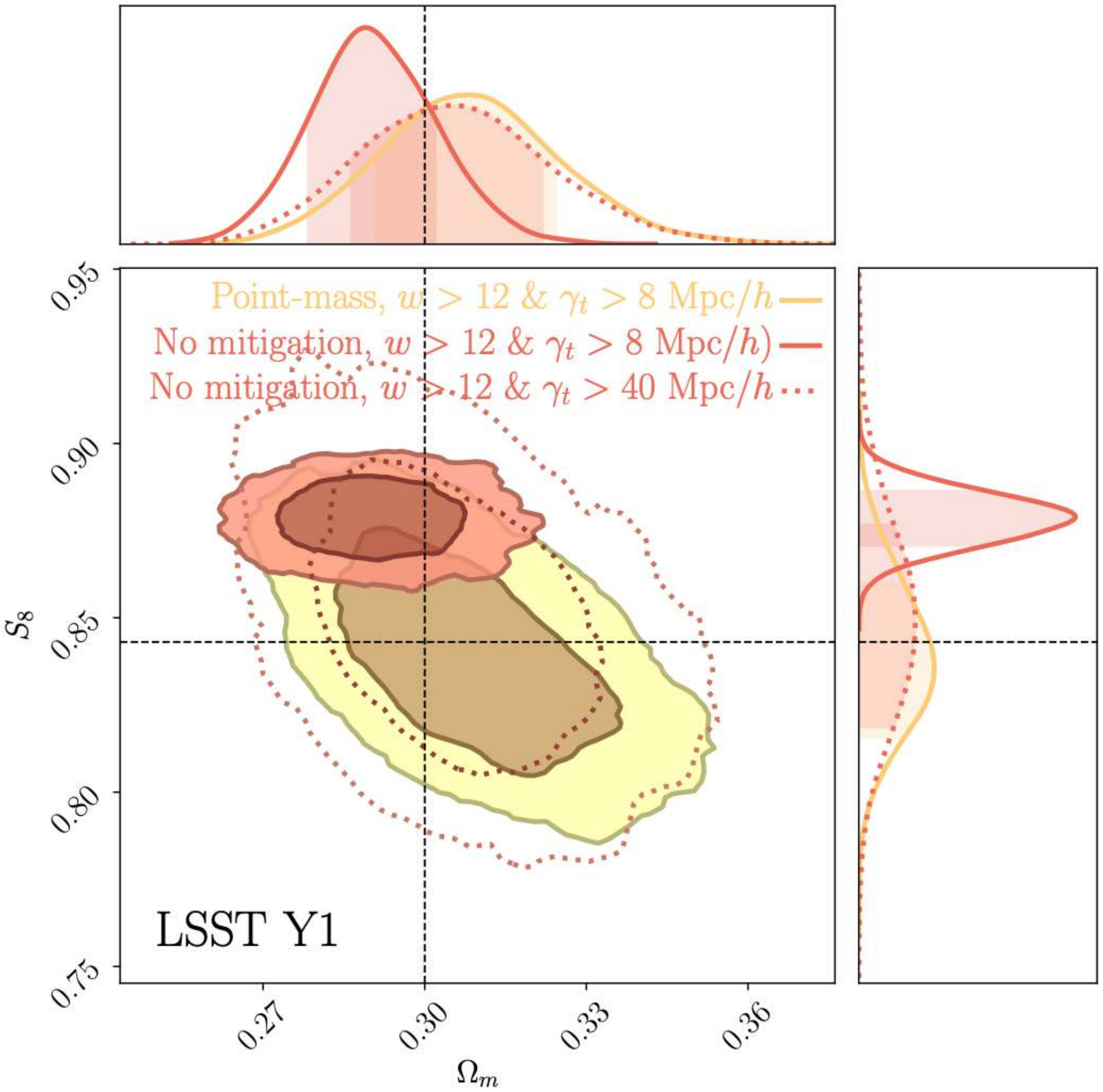
And more!
This is not complete

	DES Y1 3x2pt	DES Y3 3x2pt
Lens samples	redMaGiC	Maglim, redMaGiC
Source samples	METACALIBRATION, Im3shape.	METACALIBRATION
Intrinsic Alignment (IA) model	NLA (2 pars)	TATT (5 pars)
Lens magnification	No	Yes, fixed.
Galaxy bias	Linear	Linear, non-linear (3pars).
Point-mass marginalization for GGL	No (R >12 Mpc/h)	Yes (R >6 Mpc/h)
Lens redshifts	Mean.	Mean, width.
Source redshifts	Mean	Mean, shape with HYPERRANK.
Small scales shear-ratio	As validation for source redshifts.	Included as likelihood.
PSF model	`PSFEx`	`PIFF`
RSD and non-Limber	No	Yes, in clustering model.
Sampling	MULTINEST	POLYCHORD

Prat, Zacharegkas et al. (2023): 2212.03734

Is applying point-mass better than using larger-scale cuts?

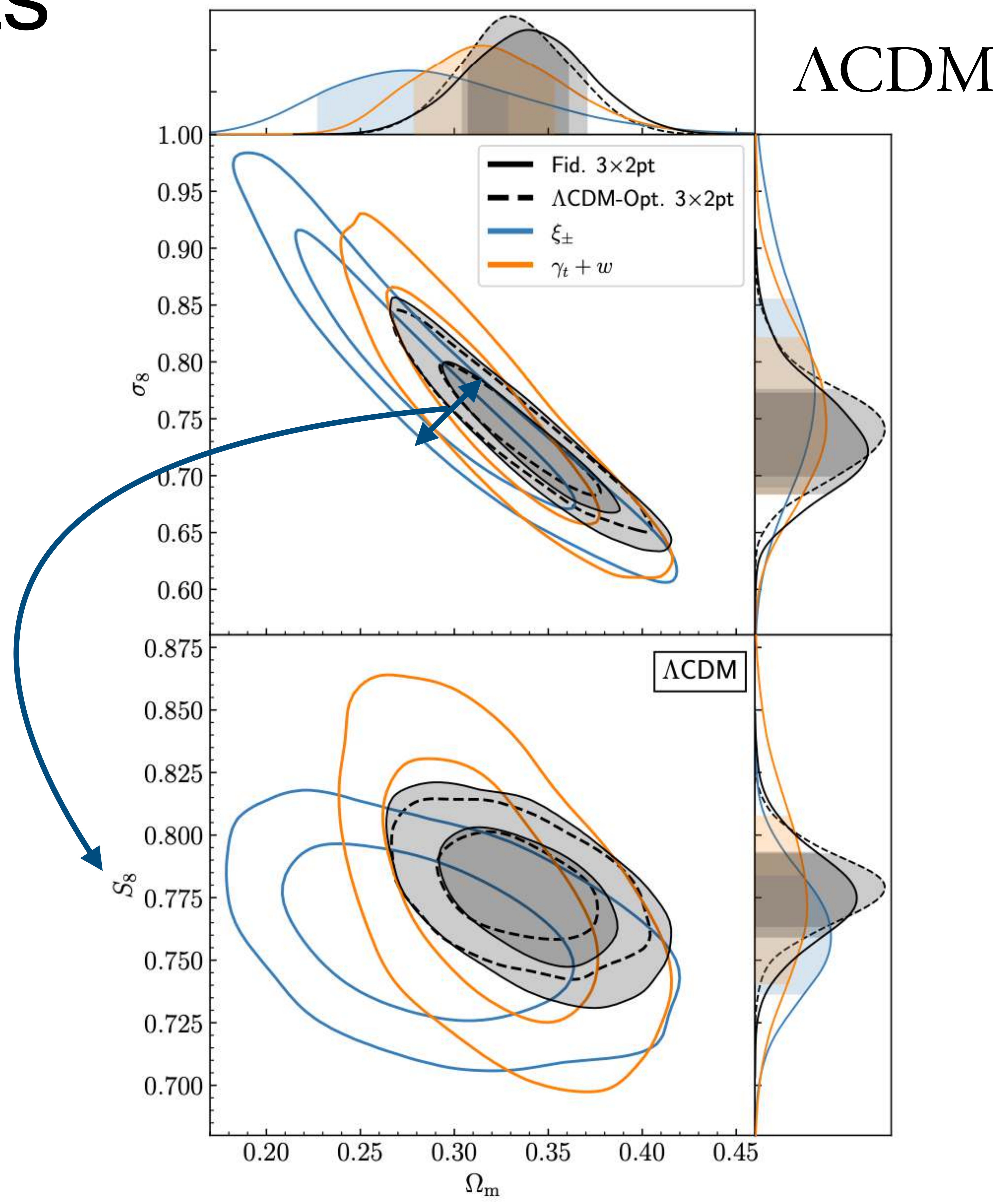
- In a recent analysis we conclude that using a marginalization scheme yields ~1.3 more constraining power on the S_8 parameter assuming a LSST Y1 simulated scenario than just applying larger scale cuts.



3x2pt combination: DES Y3 results

- We find consistency between cosmic shear and 2x2pt.
  - Cosmic shear most sensitive to clustering amplitude.
  - Galaxy clustering and galaxy-galaxy lensing more sensitive to total matter density.

DES Collaboration (2022)
2105.13549

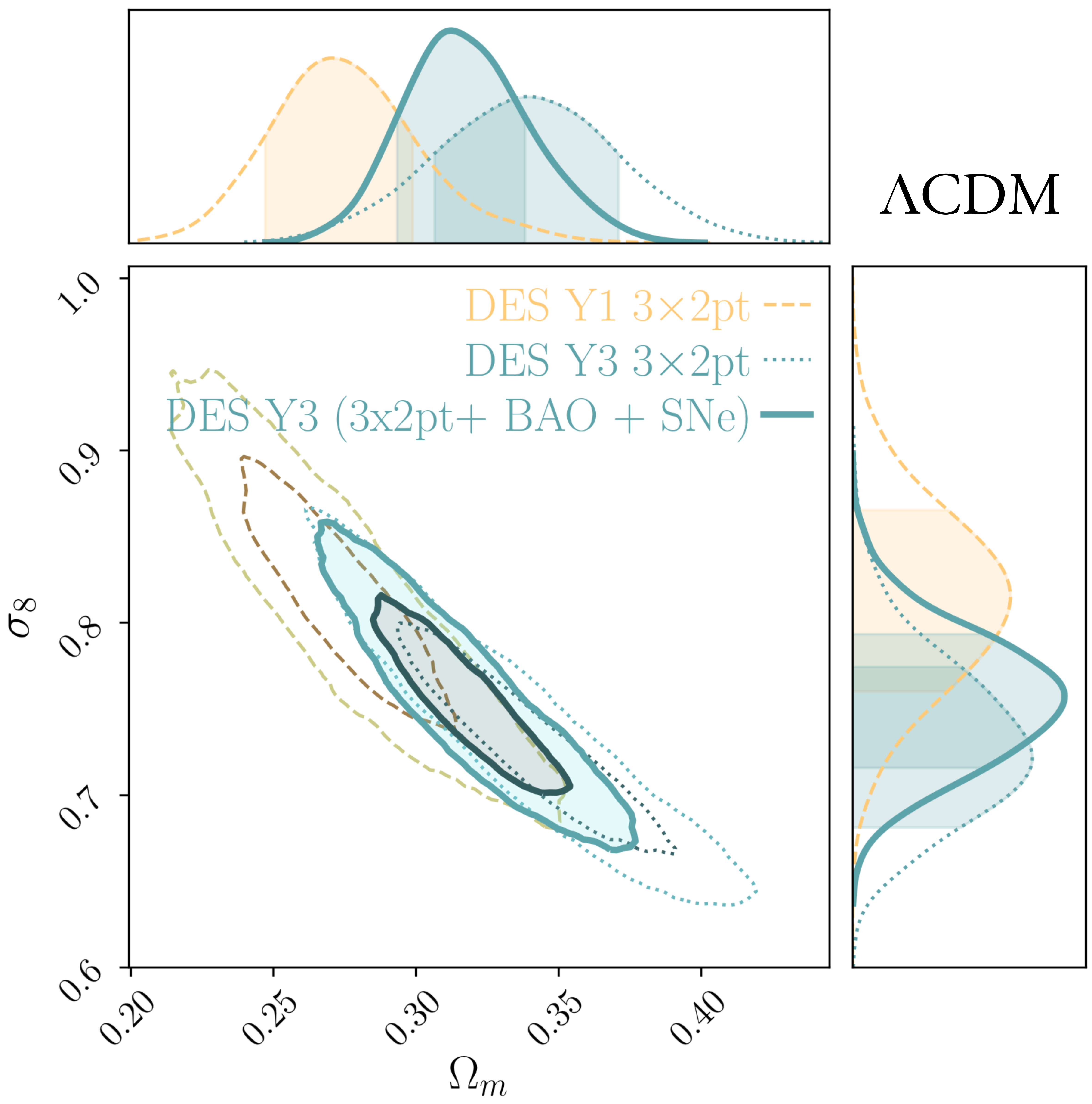


DES Y3 results: *comparison with DES Y1 and combination with other DES Probes*

- A factor of 2.1 improvement in signal-to-noise from DES Year 1, about 20% more than expected from the increase in observing area alone

- Including DES Y3 SNe IA and DES Y3 BAO tightens the constraints.

DES Collaboration (2022)
2105.13549

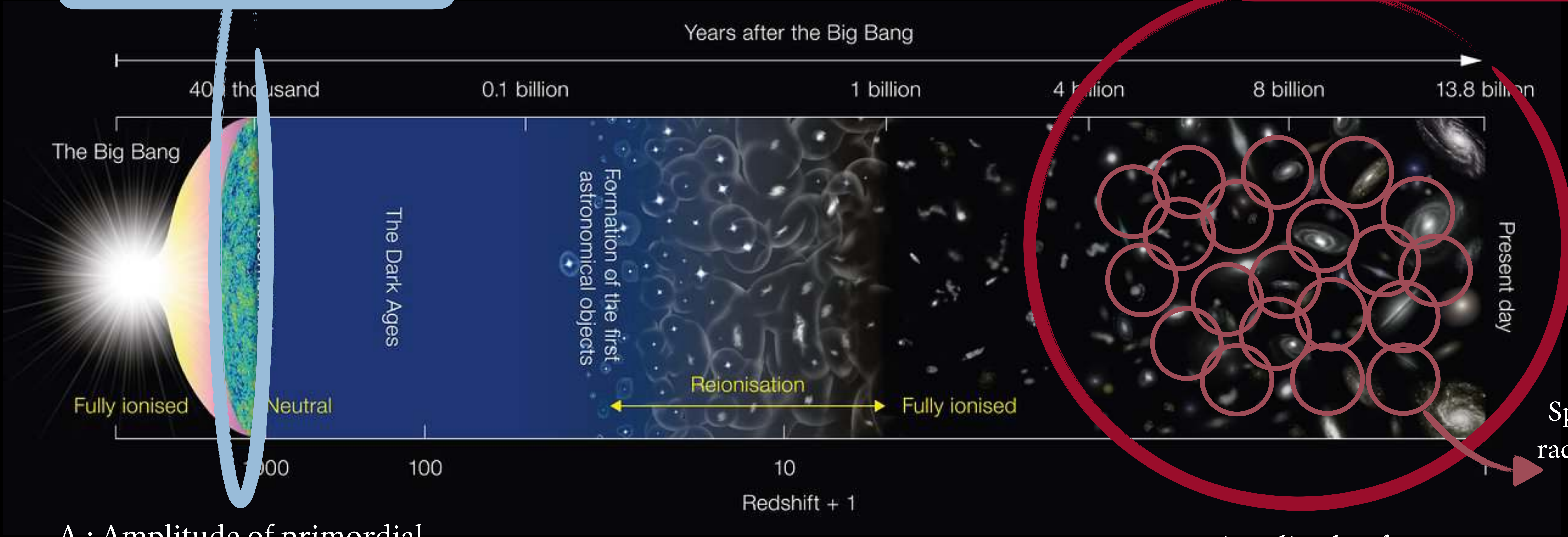


Testing ΛCDM

Is the late time clustering compatible with the ΛCDM prediction assuming initial conditions from the CMB?

CMB experiments observe the early Universe

Galaxy surveys observe the late Universe



Spheres with radius 8Mpc/h

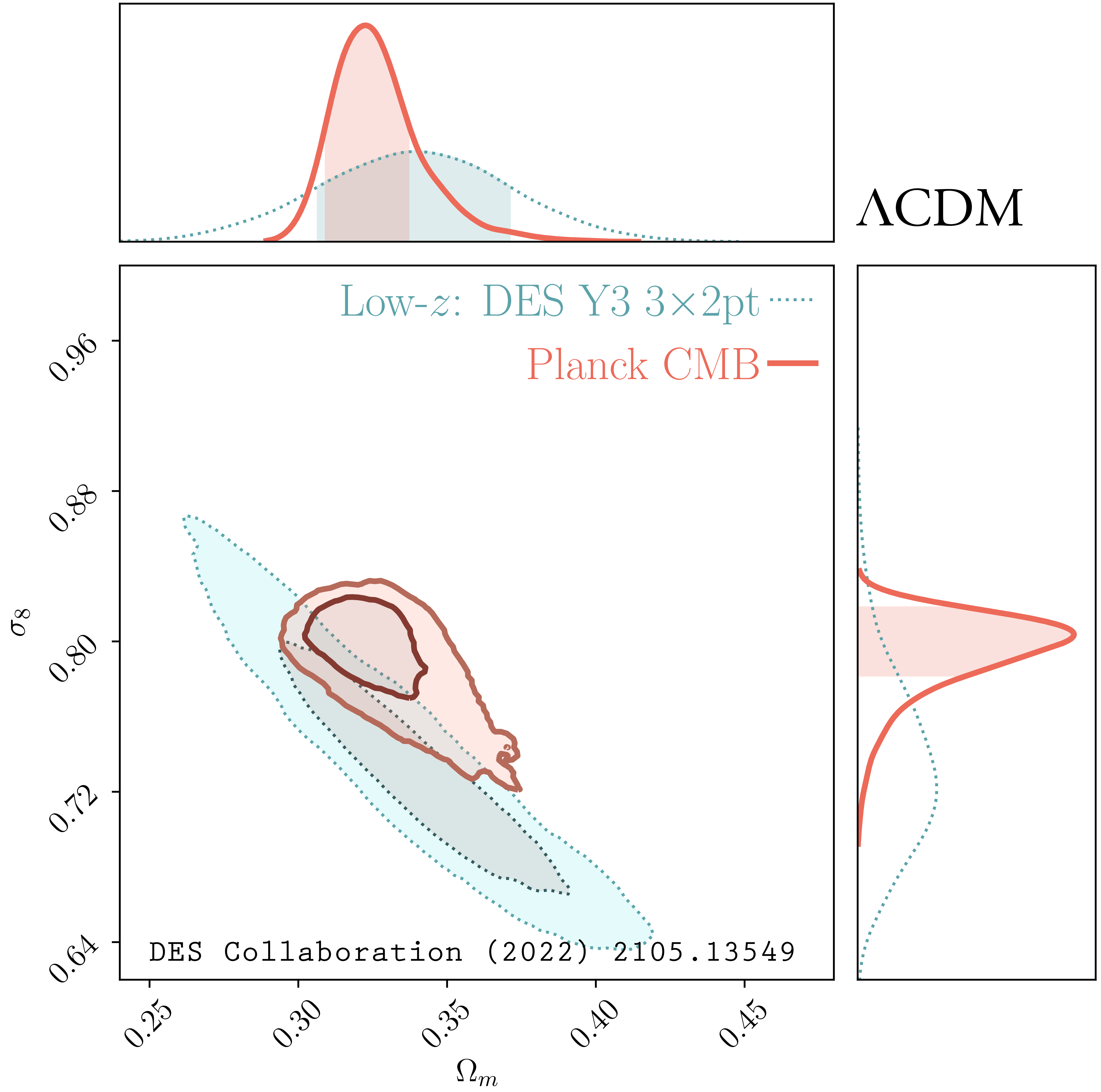
A_s: Amplitude of primordial scalar density fluctuations.

Image credit: NAOJ

σ_8: Amplitude of mass fluctuations today.

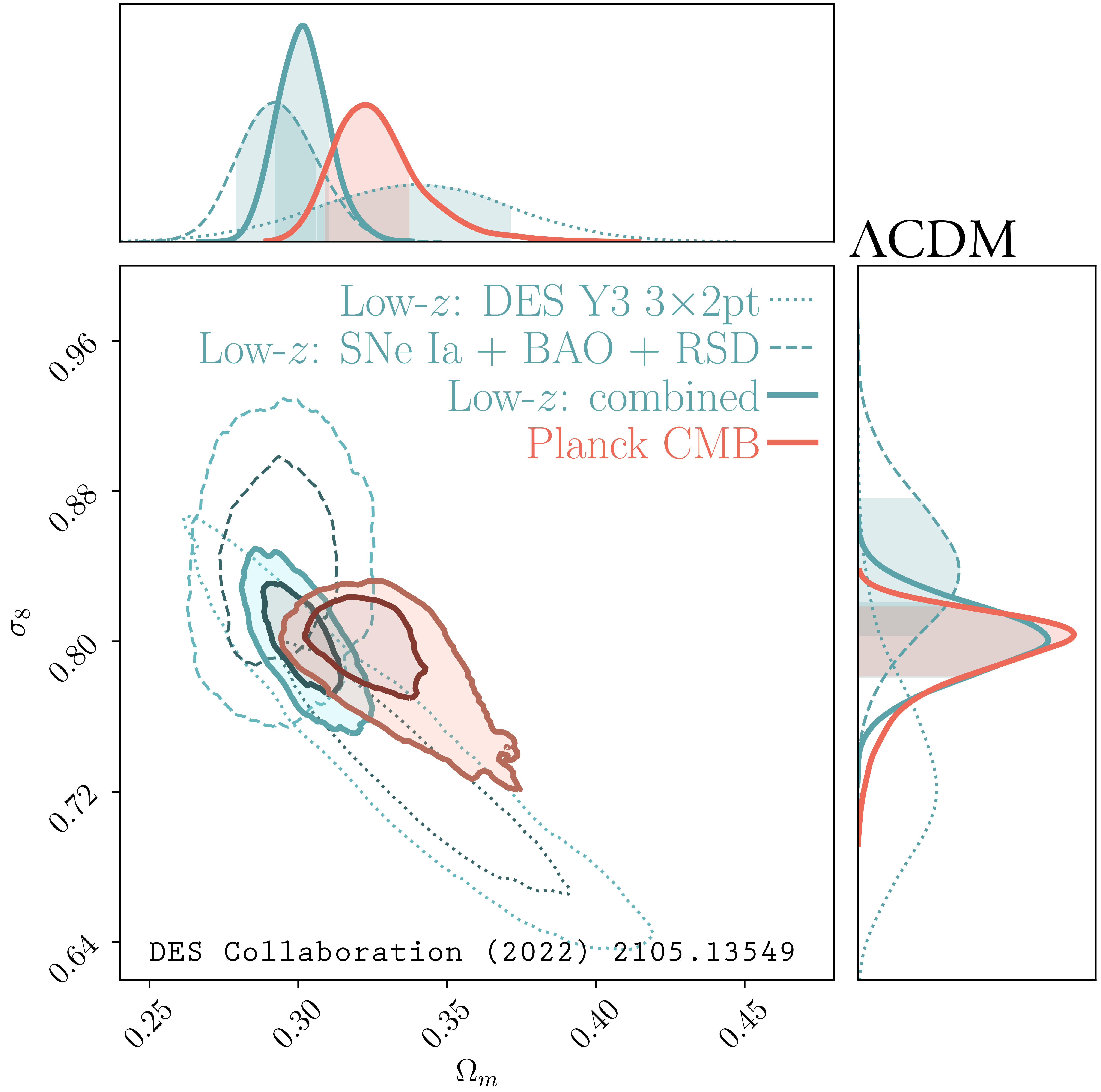
Stress testing ΛCDM:
early vs late Universe

- Planck and DES Y3 are consistent assuming the ΛCDM model (1.5σ), although the clustering amplitude is lower for DES Y3 than Planck.



Stress testing ΛCDM:
early vs late Universe

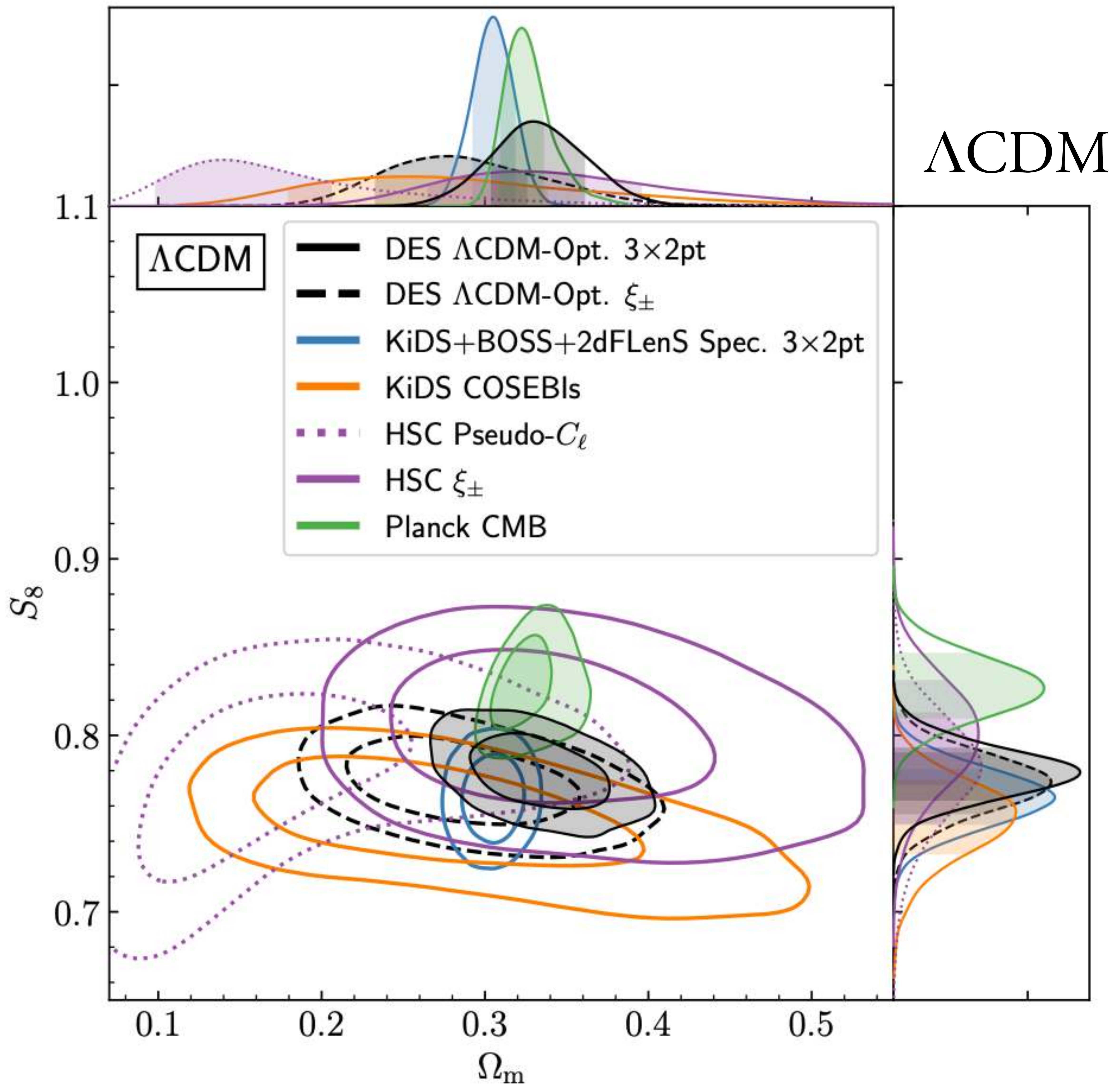
- When combined with other external redshift probes (*Pantheon SNe IA, BOSS BAO, BOSS RSD*), they are also consistent (0.9σ), with smaller uncertainties.



The real power comes when combining different probes!!

Where is the S₈ tension then?

- Cosmic shear measurements in DES Y3 are 2.3σ away from Planck.
- All the other cosmic shear and 3x2pt measurements are also below Planck.

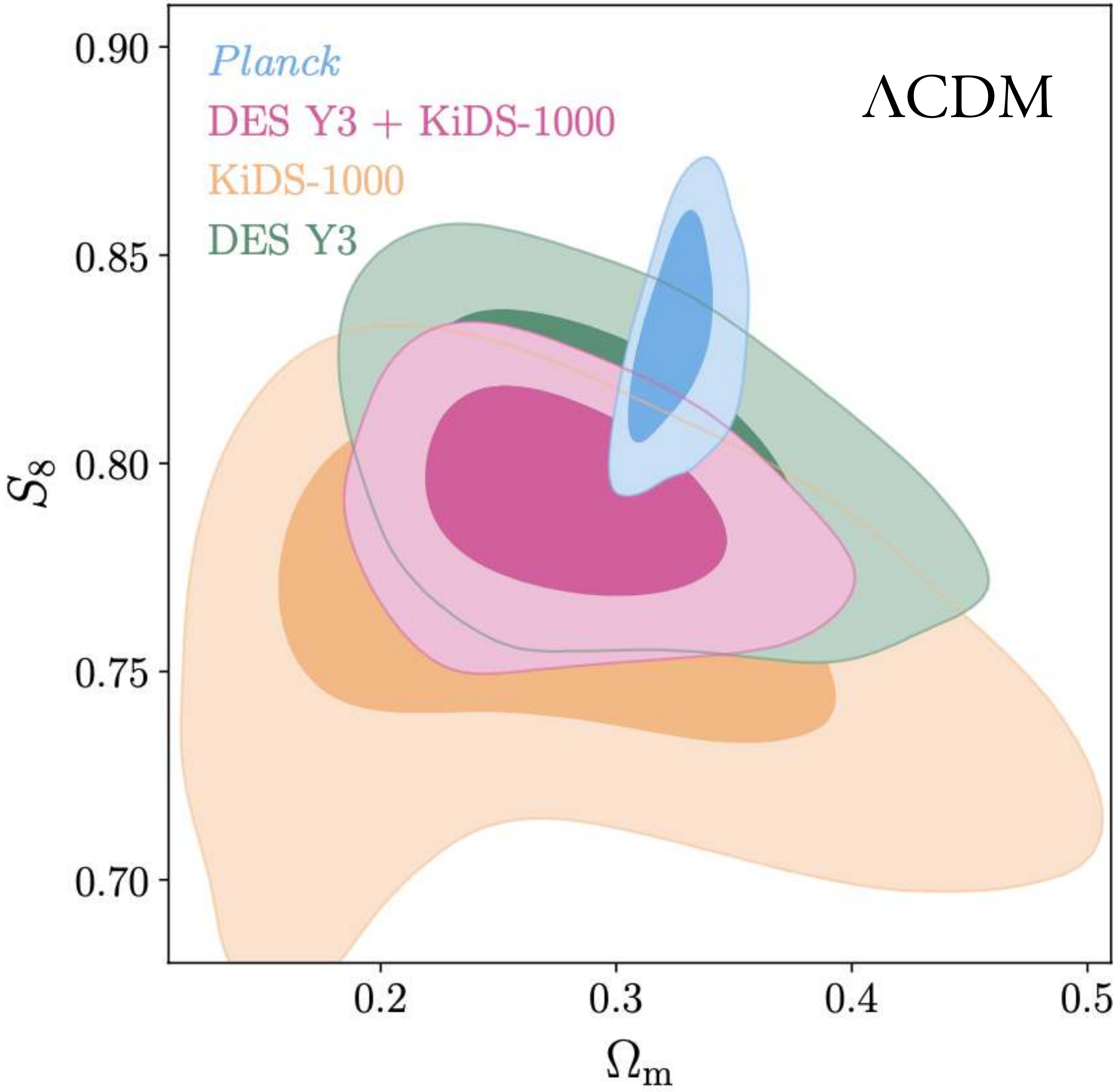


DES Collaboration (2022) 2105.13549

Where is the S_8 tension then?

- Cosmic shear results of a combined recent DES + KiDS analysis yields agreement at the 1.7σ level with Planck (but also in the same direction).

Cosmic shear only



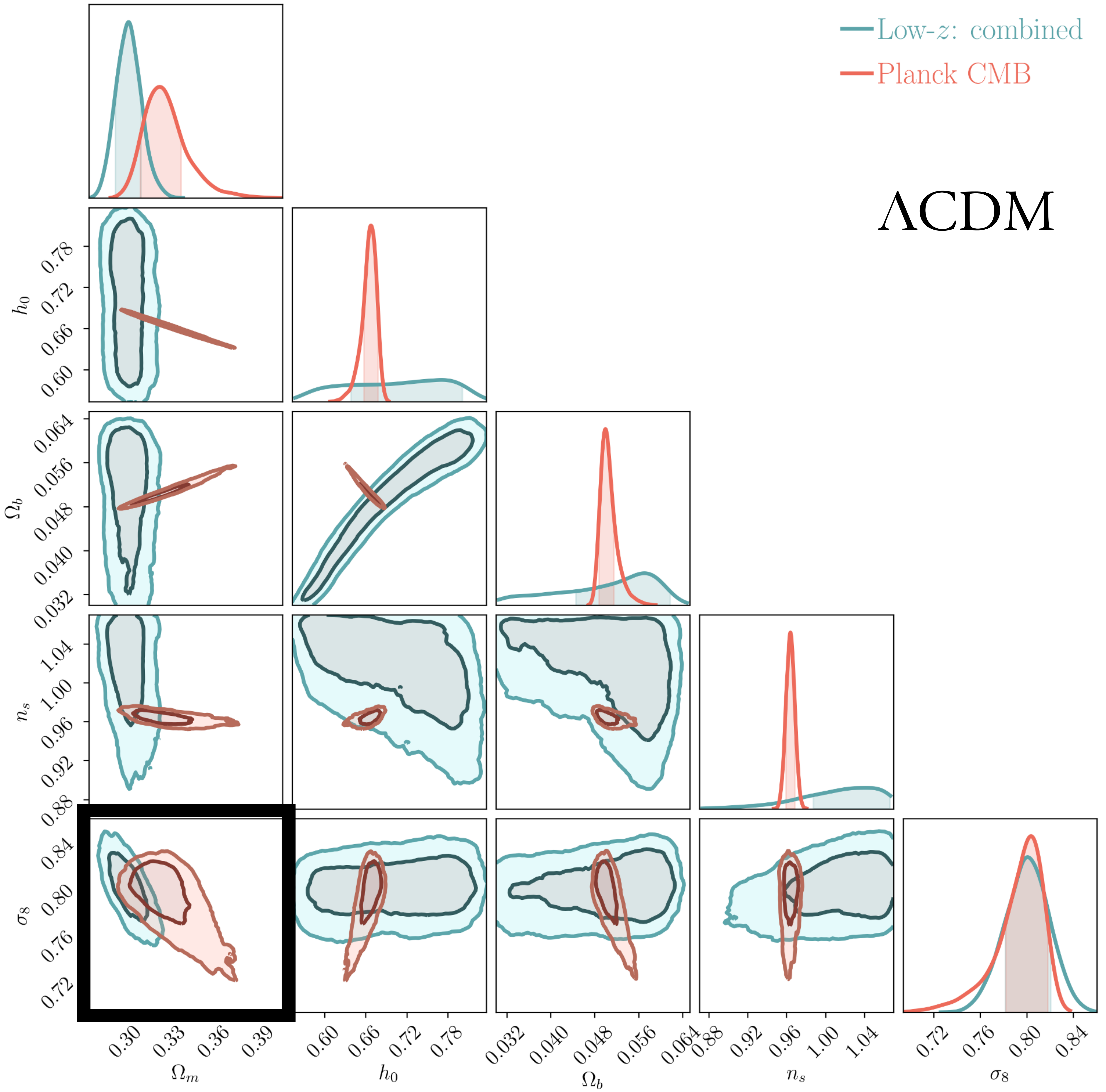
DES + KiDS Collaborations (2023) 2305.17173

Stress testing ΛCDM:

Looking at the full parameter space

- When we look at the full parameter space we can see that only two parameters are constrained to a similar precision as Planck. —>We still have a long way to go to reach the same precision in the late time Universe.
- We have work to do to be able to do an even more compelling test.

DES Collaboration (2022) 2105.13549



3 ways to move forward:

How can we get more precise constraints from the late-time Universe?

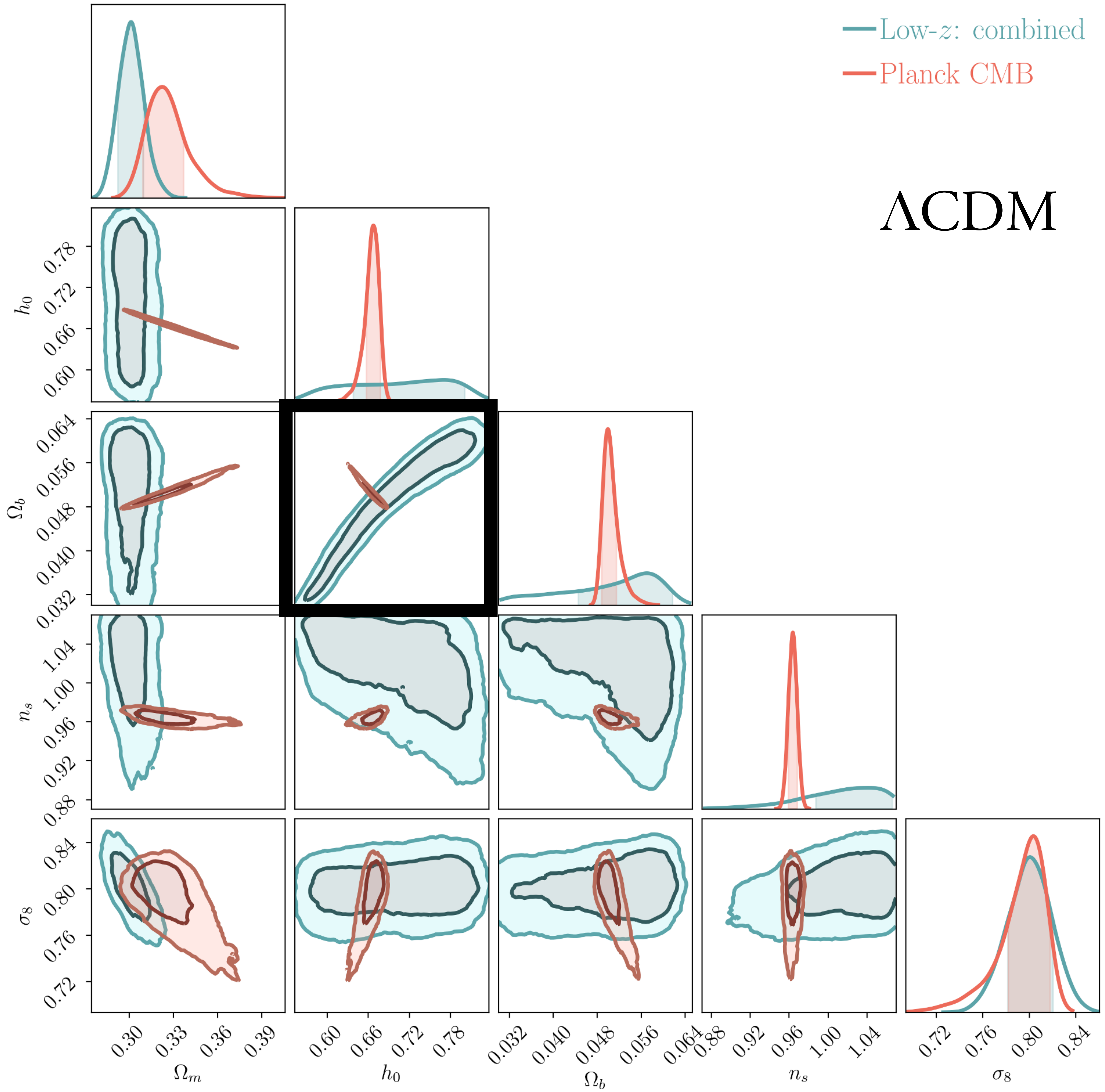
- Combining more probes from the late-time Universe.
- Extracting more information from large-scale structure
  - Capture non-gaussian information from the late-time Universe with higher-order statistics
  - Using a larger range of scales in the analysis (with better models for small scales).
- With larger, deeper upcoming galaxy surveys

Stress testing ΛCDM:

Looking at the full parameter space

- One thing we can do is to break the degeneracy between Ω_b and h.

DES Collaboration (2022) 2105.13549



Stress testing ΛCDM:

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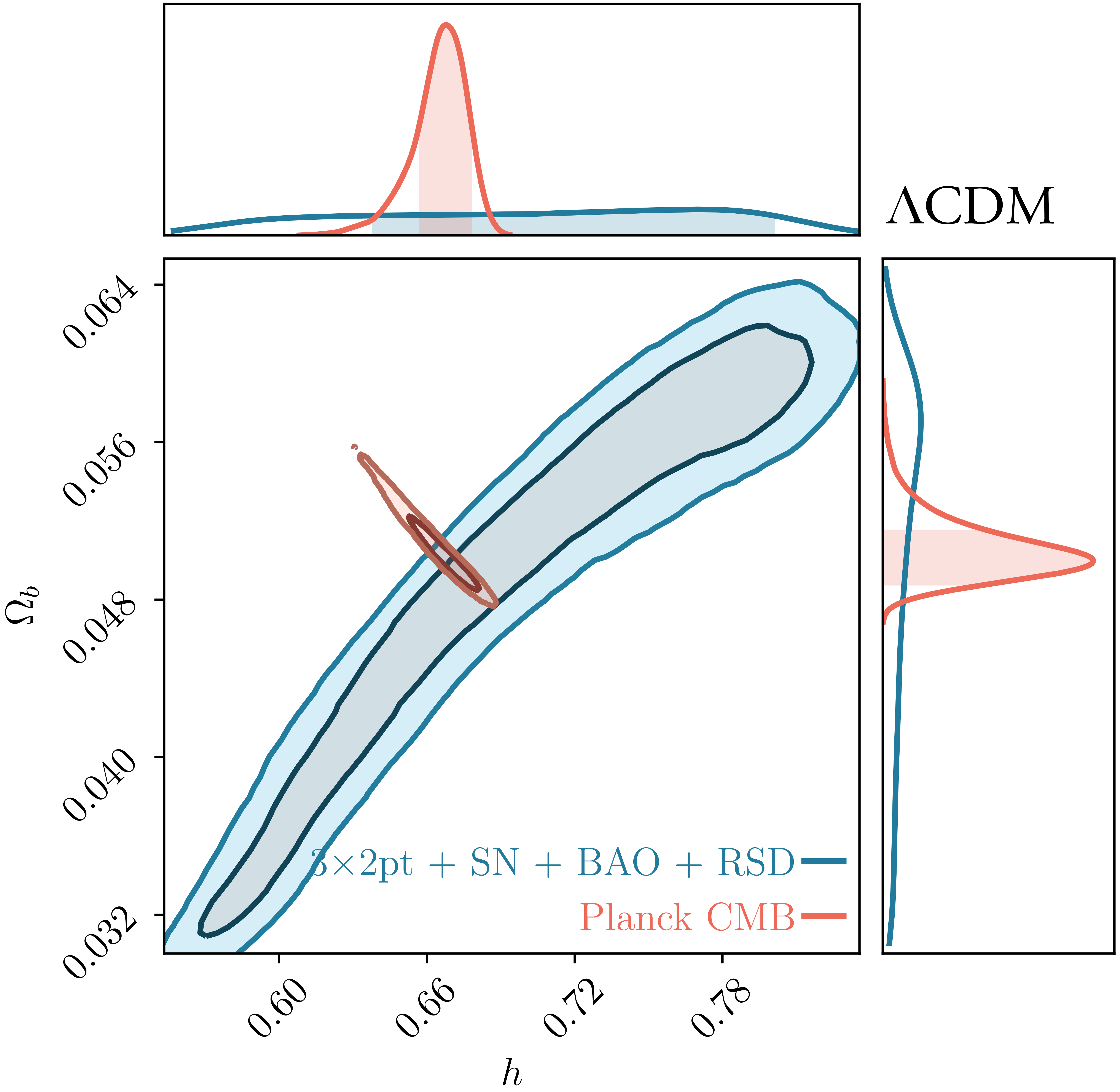
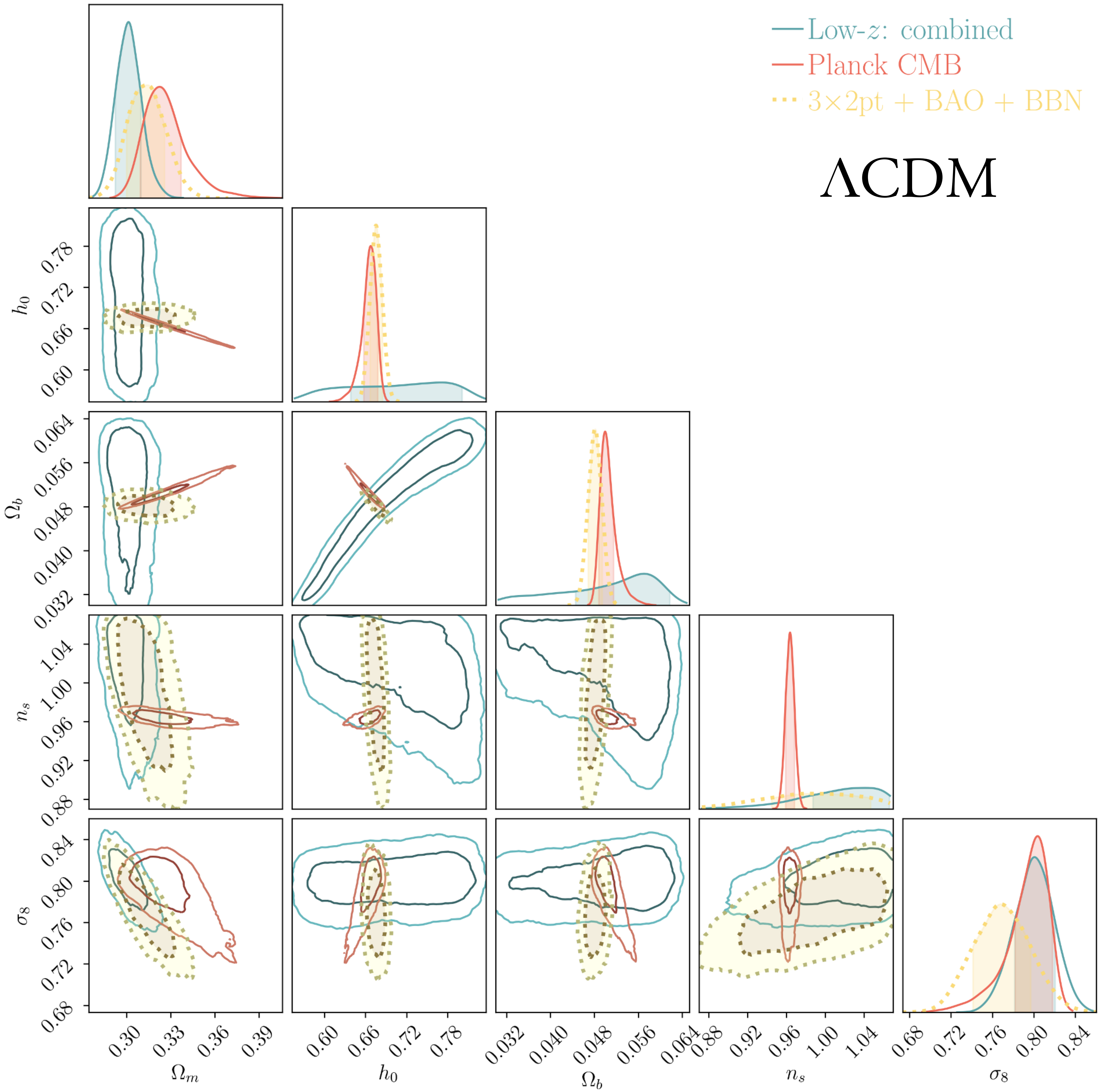


Stress testing ΛCDM:

Adding more probes

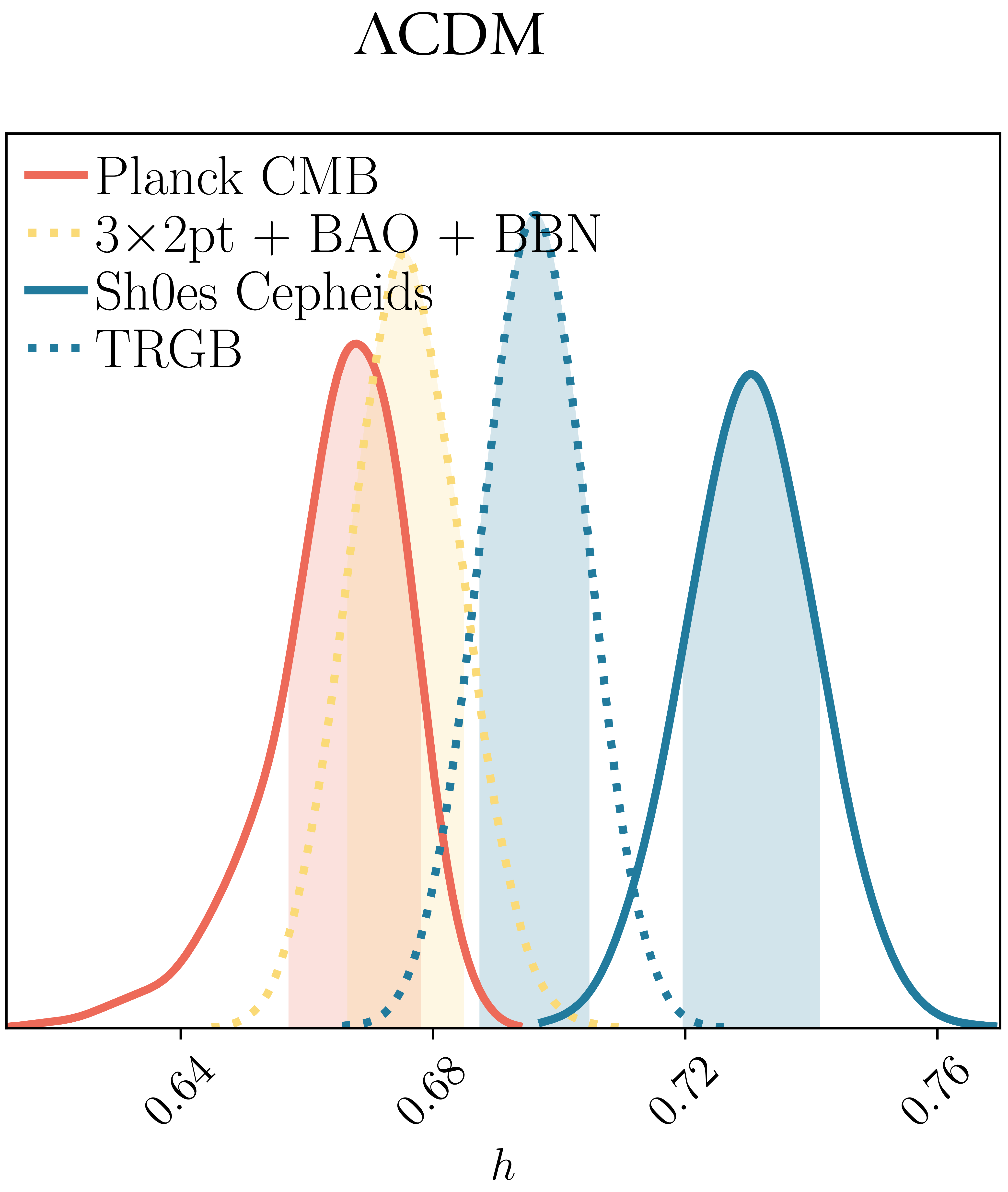
DES Collaboration (2022) 2105.13549



- This has been done placing a constraint on Ω_b from Big Bang nucleosynthesis (BBN). The primordial deuterium-to-hydrogen ratios can be translated to constraints on $\Omega_b h^2$ via Big Bang nucleosynthesis calculations.
- However, BBN is not exactly a late-time Universe probe.

Stress testing ΛCDM:
Adding more probes

- We can also constrain H_0 instead and then Ω_b will be constrained.
- However there is disagreement in low-z H_0 measurements from the distance ladder from the late-time Universe (TRB or Cepheids give different answers).
- In the near future we could combine it with other probes that will be able to measure H_0 from **strong lensing** and **gravitational waves** constraints from the late time Universe.



3 ways to move forward:

How can we get more precise constraints from the late-time Universe?

Combining more probes from the late-time Universe.

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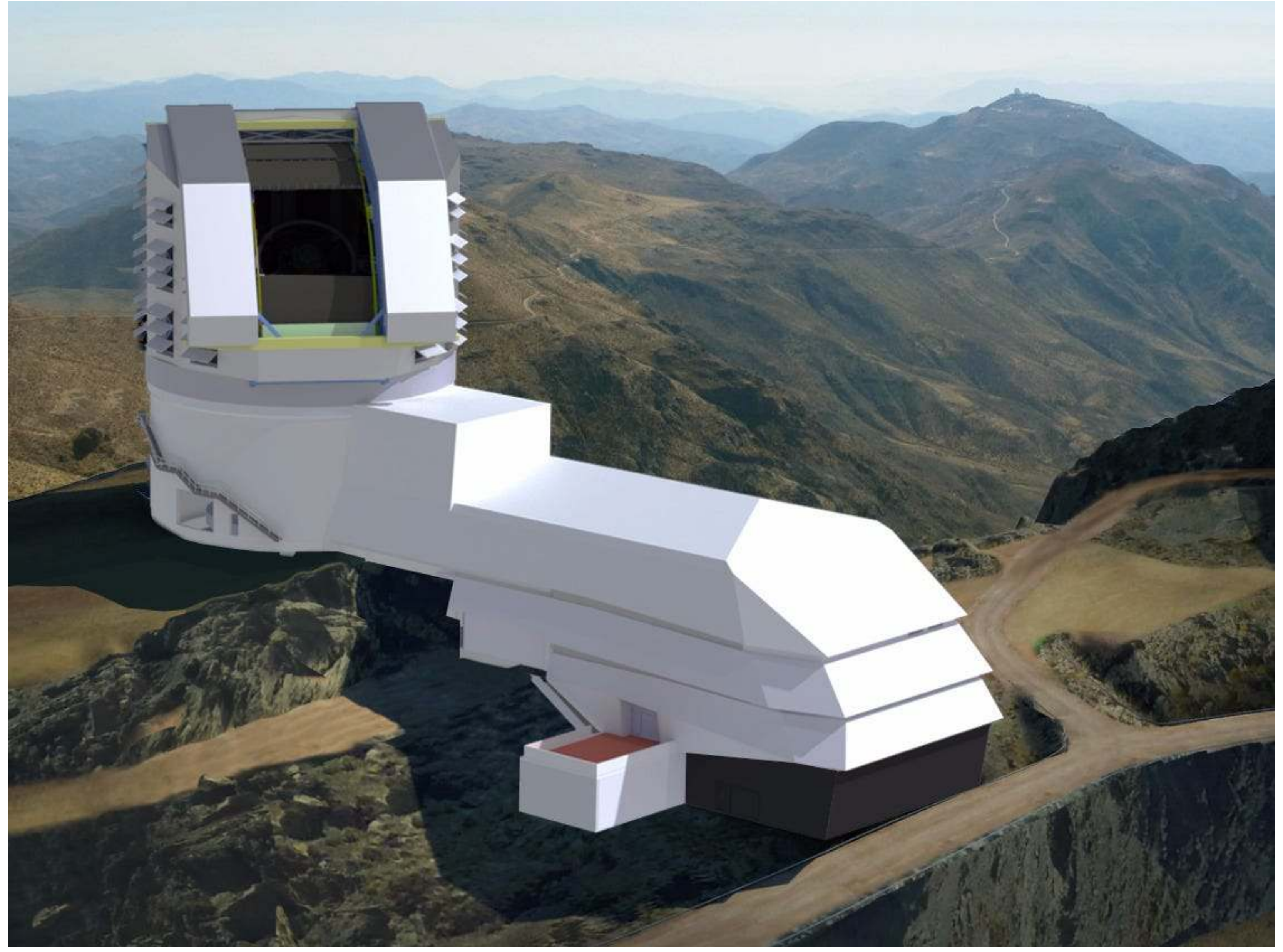
Capture non-gaussian information from the late-time Universe with higher-order statistics

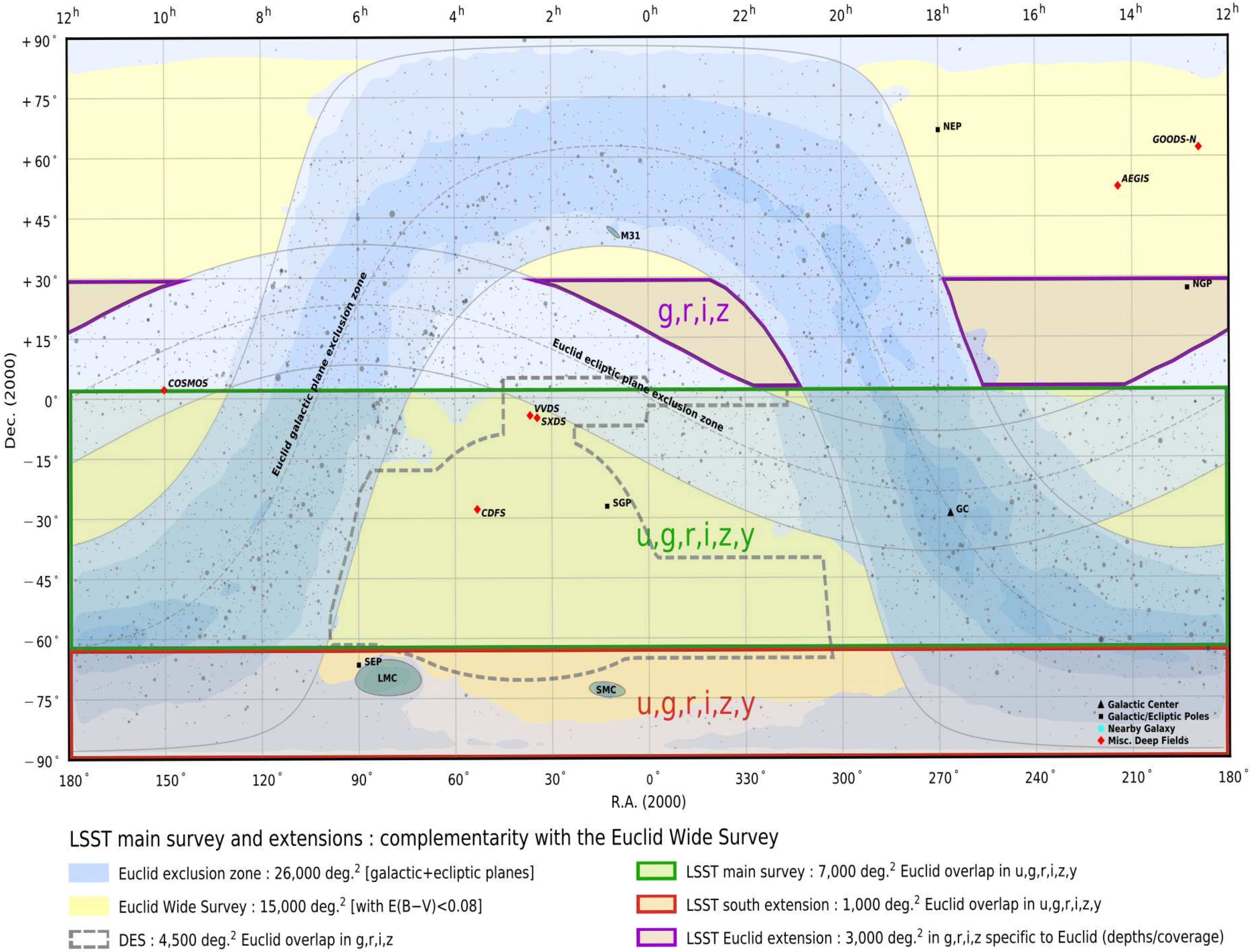
Using a larger range of scales in the analysis (with better models for small scales).

With larger, deeper upcoming galaxy surveys

Upcoming galaxy surveys

- Legacy Survey of Space and Time (LSST).
- Euclid mission.
- DESI.
- Roman.
- Spherex
- …



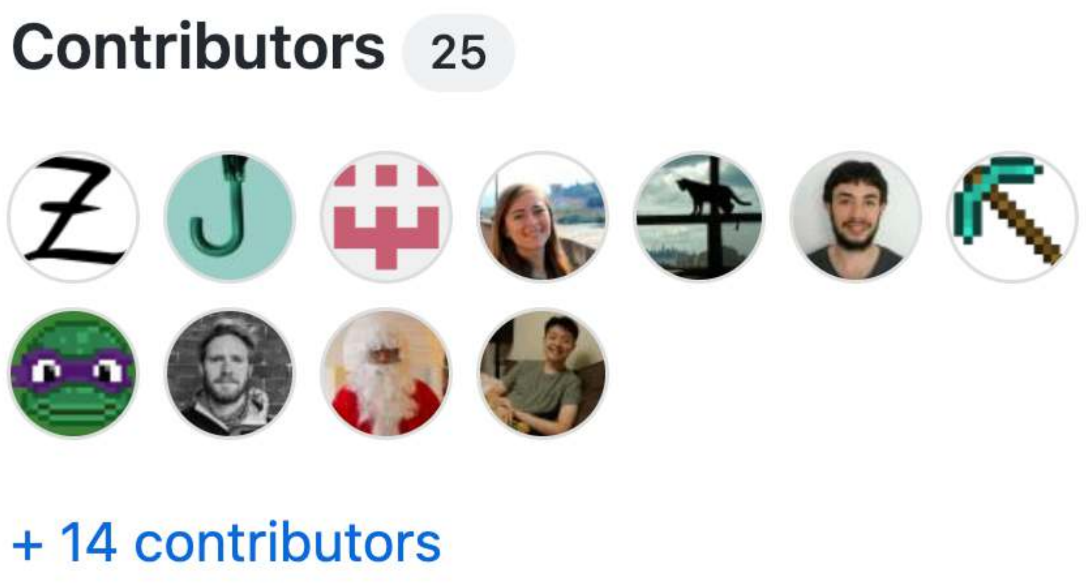


Developing and validating the framework for LSST-DESC WL+LSS cosmology

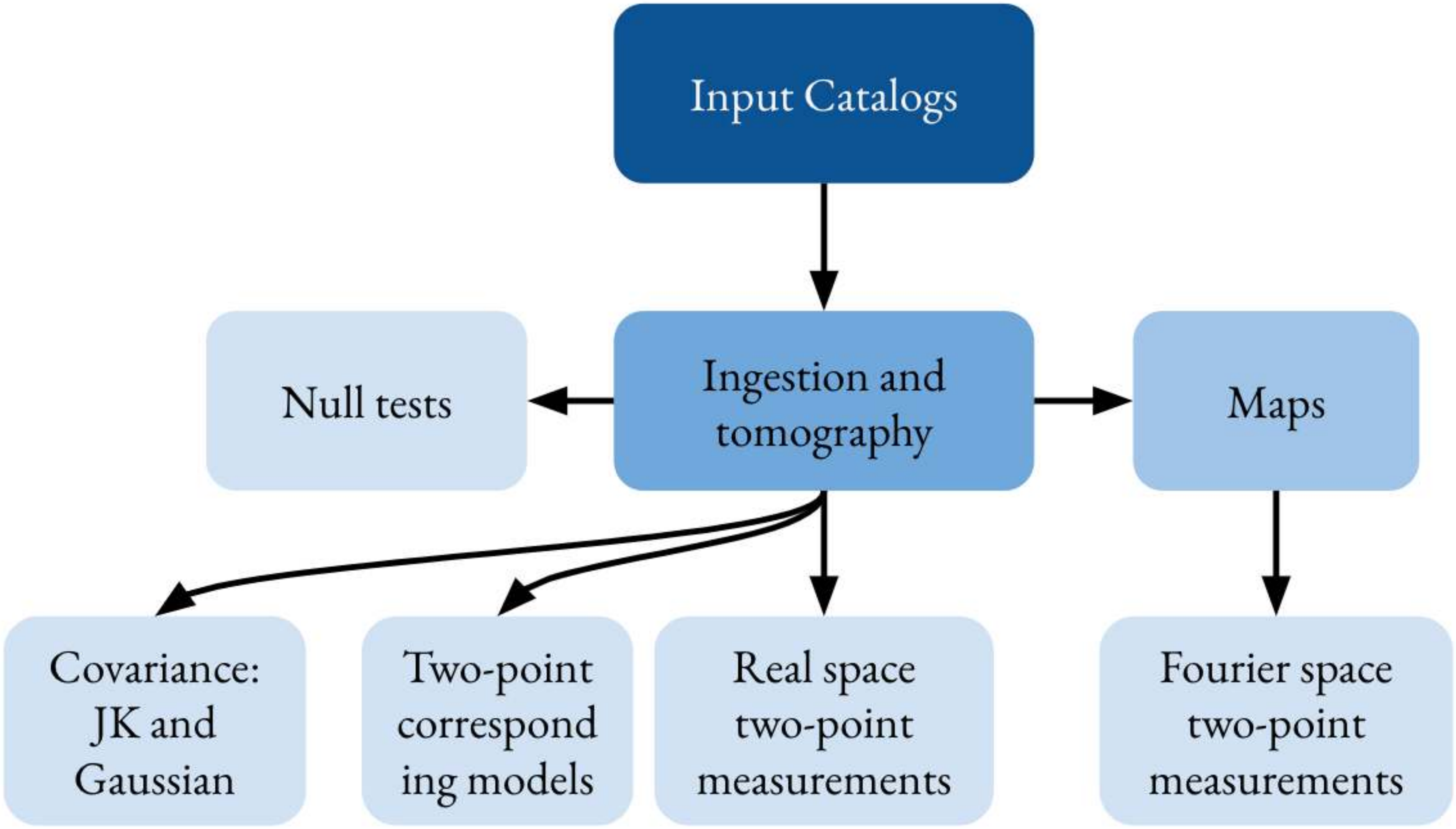
With Joe Zuntz, Yuuki Omori, Chihway Chang, Emily Phillips Longley, Eske Pedersen, Carlos Garcia-Garcia, Javier Sánchez, Tilman Troester, David Alonso, and others in DESC

Prat, Zuntz et al. (2023): 2212.09345

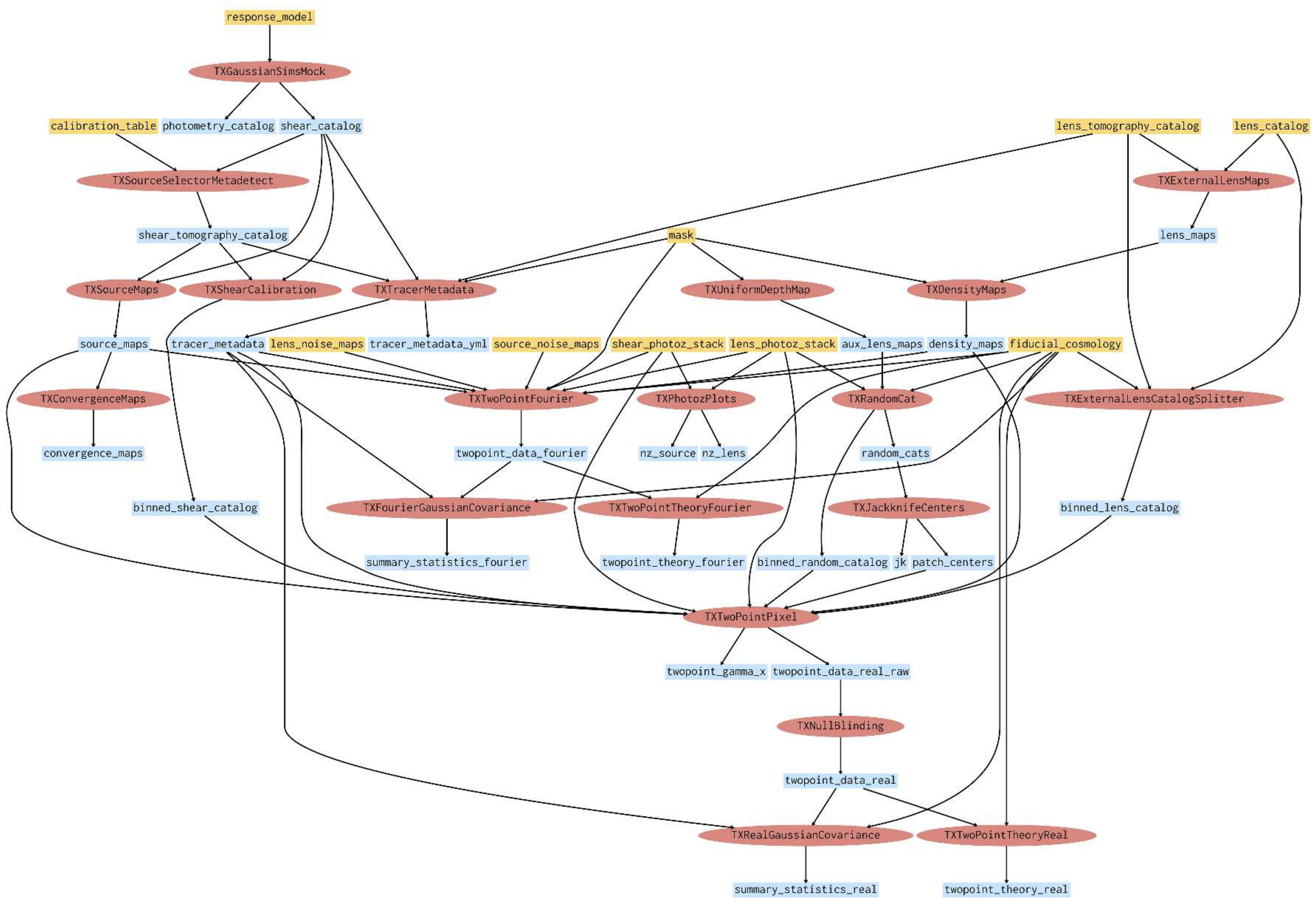
The DESC pipeline from catalogs to summary statistics: *TXPipe*



- An automatic and reproducible pipeline for the measurements within DESC in preparation for LSST data.
- Connects external codes, wraps each of these tools as a Python class, specifying input and output files required for each, and launching them using the **`Ceci`** library.
- Optimized to deal with large quantities of data, minimize memory usage and run in parallel
- Can be extended as desired to include more features.



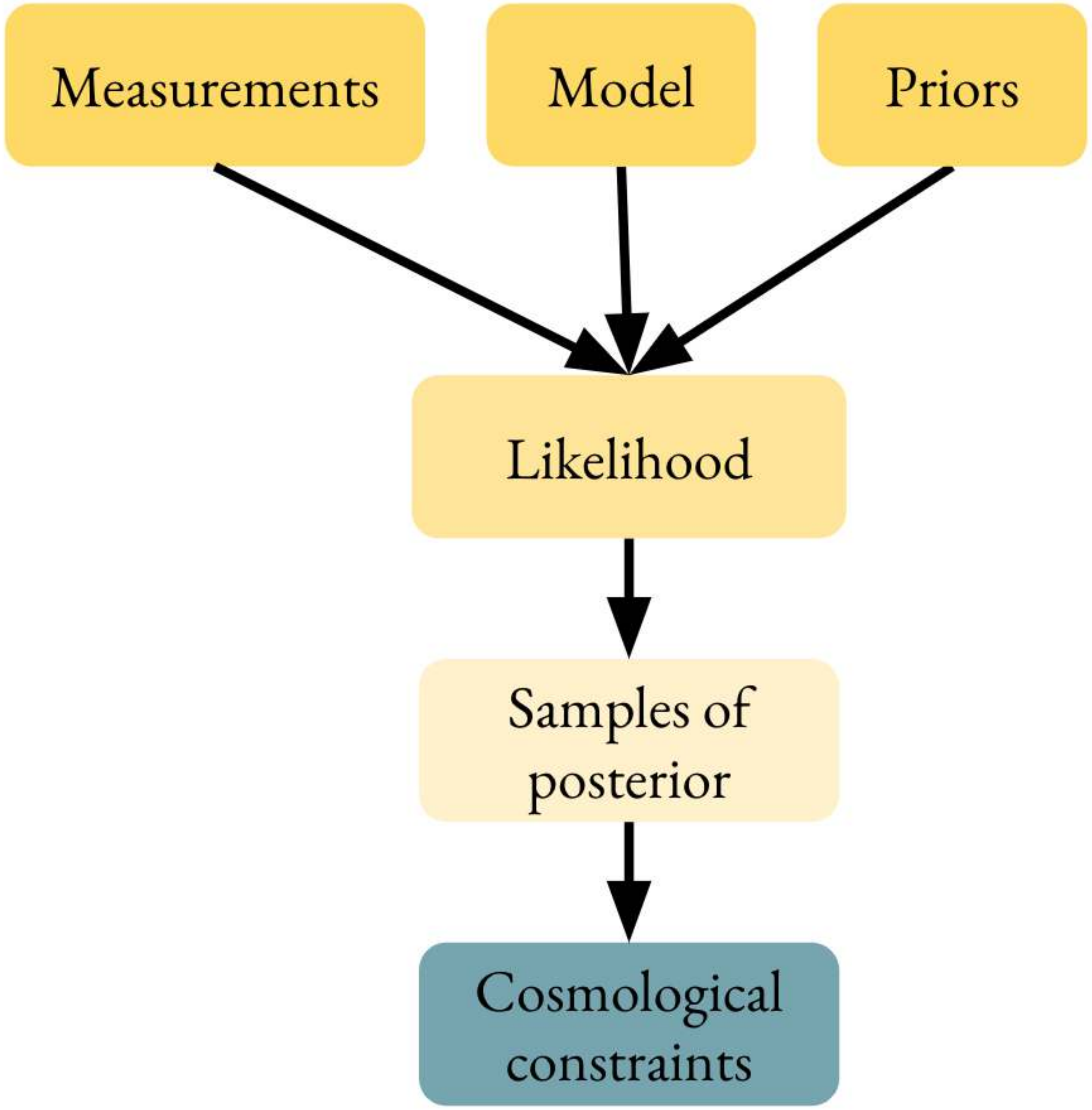
The DESC pipeline from catalogs to summary statistics: *TXPipe*



TXPIPE Stage	Time	N_{n}	N_{p}	N_{t}
TXConvergenceMaps	38 min	1	1	32
TXDensityMaps	1 min	1	1	1
TXFourierGaussianCovariance	2 min	1	1	64
TXGaussianSimsMock	49 min	1	1	20
TXJackknifeCenters	8 min	1	1	1
TXExternalLensMaps	132 min	2	10	1
TXRealGaussianCovariance	19 min	1	1	64
TXShearCalibration	7 min	1	7	1
TXSourceMaps	51 min	4	4	10
TXSourceSelectorMetadetect	11 min	2	64	1
TXTwoPointFourier	32 min	4	4	20
TXTwoPointPixel	780 min	6	6	32
TXTwoPointTheoryFourier	1 min	1	1	1
TXTwoPointTheoryReal	0.2 min	1	1	1
TXUniformDepthMap	0.1 min	1	1	1

The DESC pipeline for summary-statistics-to-cosmology: *FireCrown*

- Summary-statistics-to-cosmology pipeline within DESC in preparation for LSST data.
- It allows to choose a sampling method to sample the likelihood.

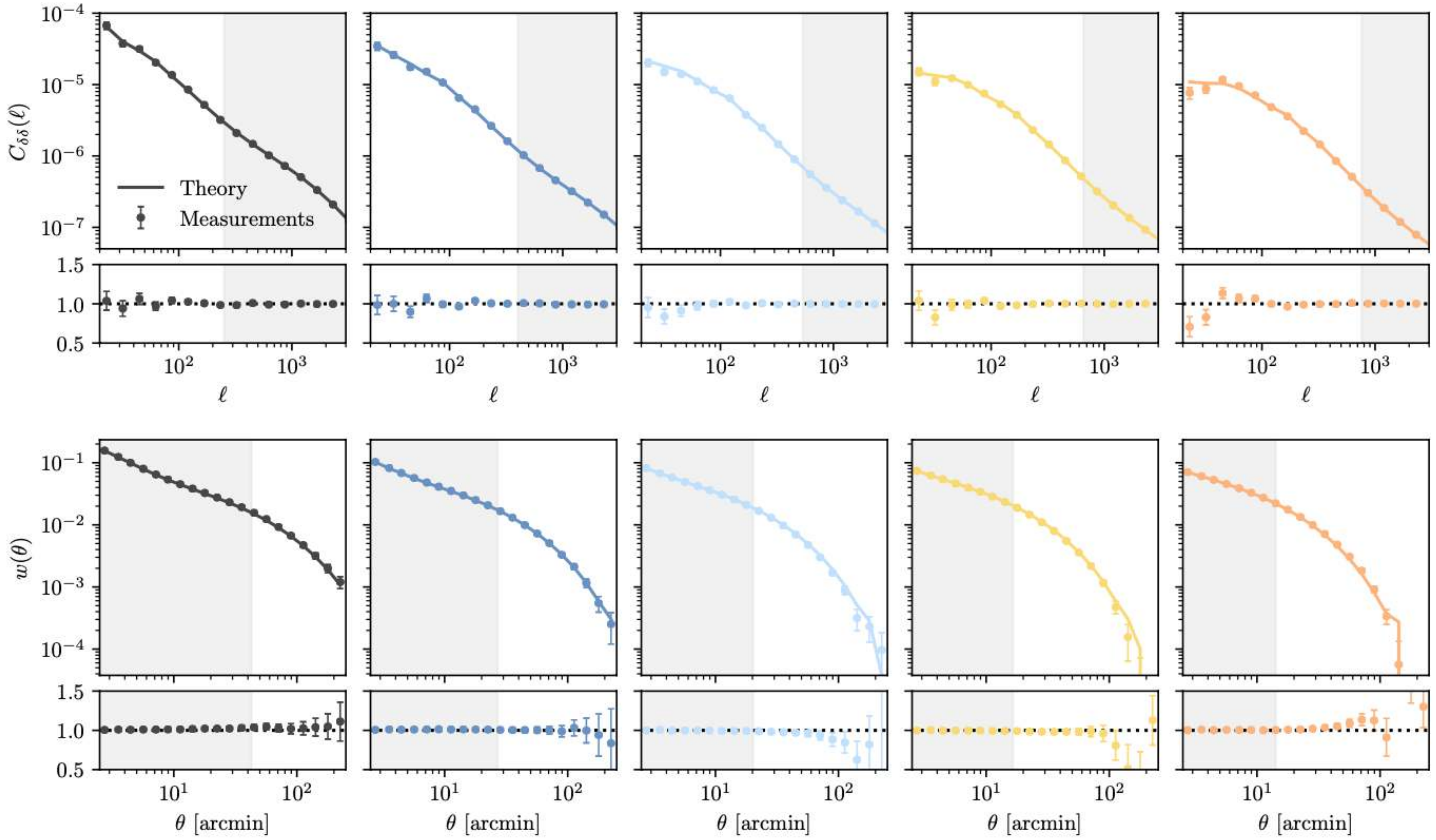


Validation with simulations: *datavector level*

- We have validated TXPipe and FireCrown end-to-end with Gaussian Simulations with a LSST Y1 setup and with a smaller N-body simulation.

	Probe	χ^2/ν (r1)	PTE (r1)	χ^2/ν (r2)	PTE (r2)
Real space	ξ_+	$259.9/300 = 0.87$	0.95	$260.8/300 = 0.87$	0.95
	ξ_-	$283.7/300 = 0.95$	0.74	$284.7/300 = 0.95$	0.73
	γ_t	$91.5/67 = 1.37$	0.02	$60.8/67 = 0.91$	0.69
	w	$57.8/53 = 1.09$	0.30	$71.3/53 = 1.35$	0.05
	3×2pt	$722.6/720 = 1.00$	0.47	$680.3/720 = 0.94$	0.85
Harmonic space	$C_{\gamma\gamma}$	$232.8/225 = 1.03$	0.35	$223.9/225 = 1.00$	0.51
	$C_{\delta_g\gamma}$	$75.3/63 = 1.20$	0.14	$56.3/63 = 0.89$	0.71
	$C_{\delta_g\delta_g}$	$55.5/49 = 1.13$	0.24	$40.2/49 = 0.82$	0.81
	3×2pt	$383.2/337 = 1.14$	0.04	$339.7/337 = 1.01$	0.45

Galaxy clustering measurements in real and harmonic space



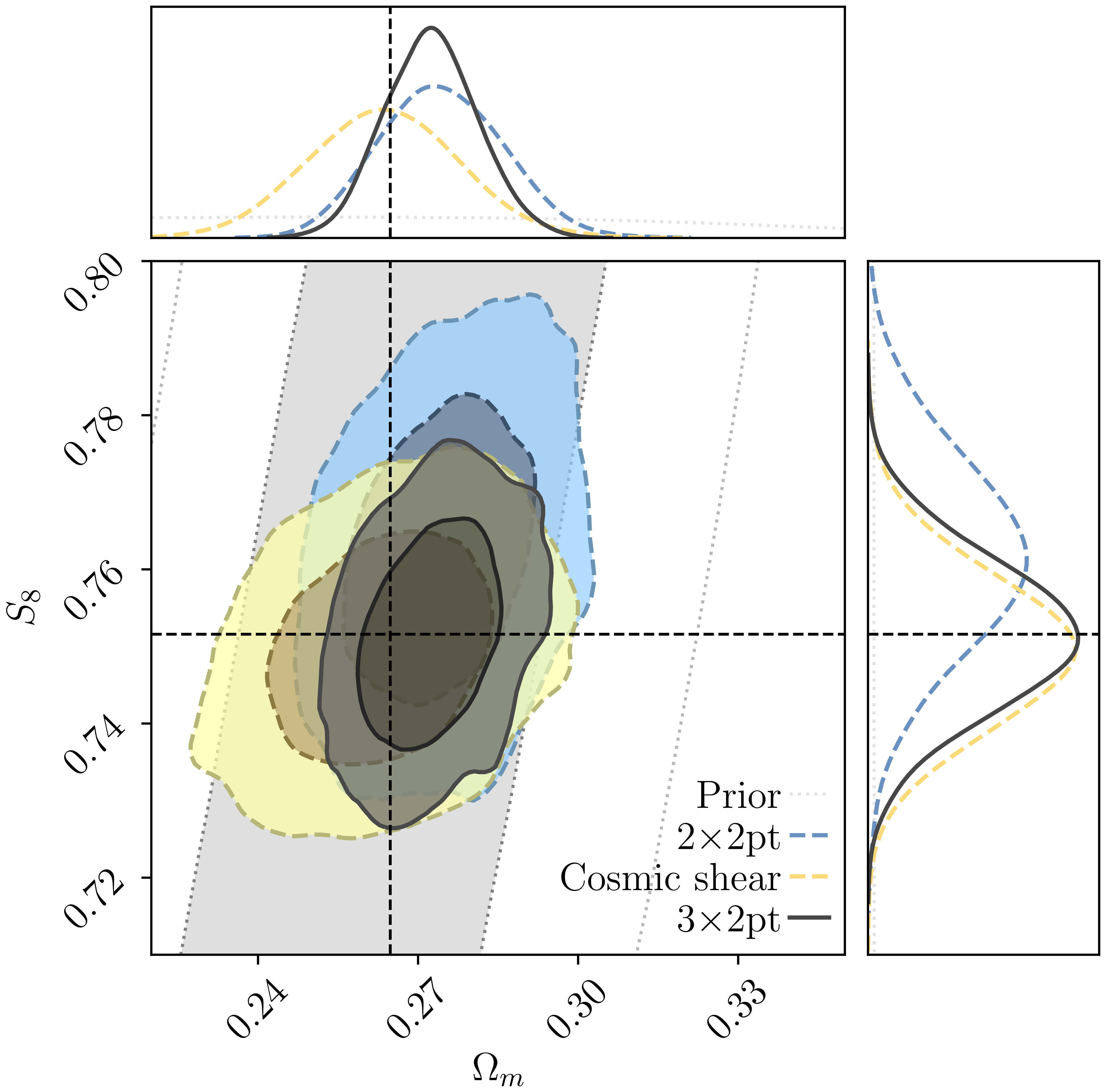
Prat, Zuntz et al. (2023): 2212.09345

Validation with simulations: *cosmology level*

- We have validated TXPipe and FireCrown end-to-end with Gaussian Simulations with a LSST Y1 setup and with a smaller N-body simulation.

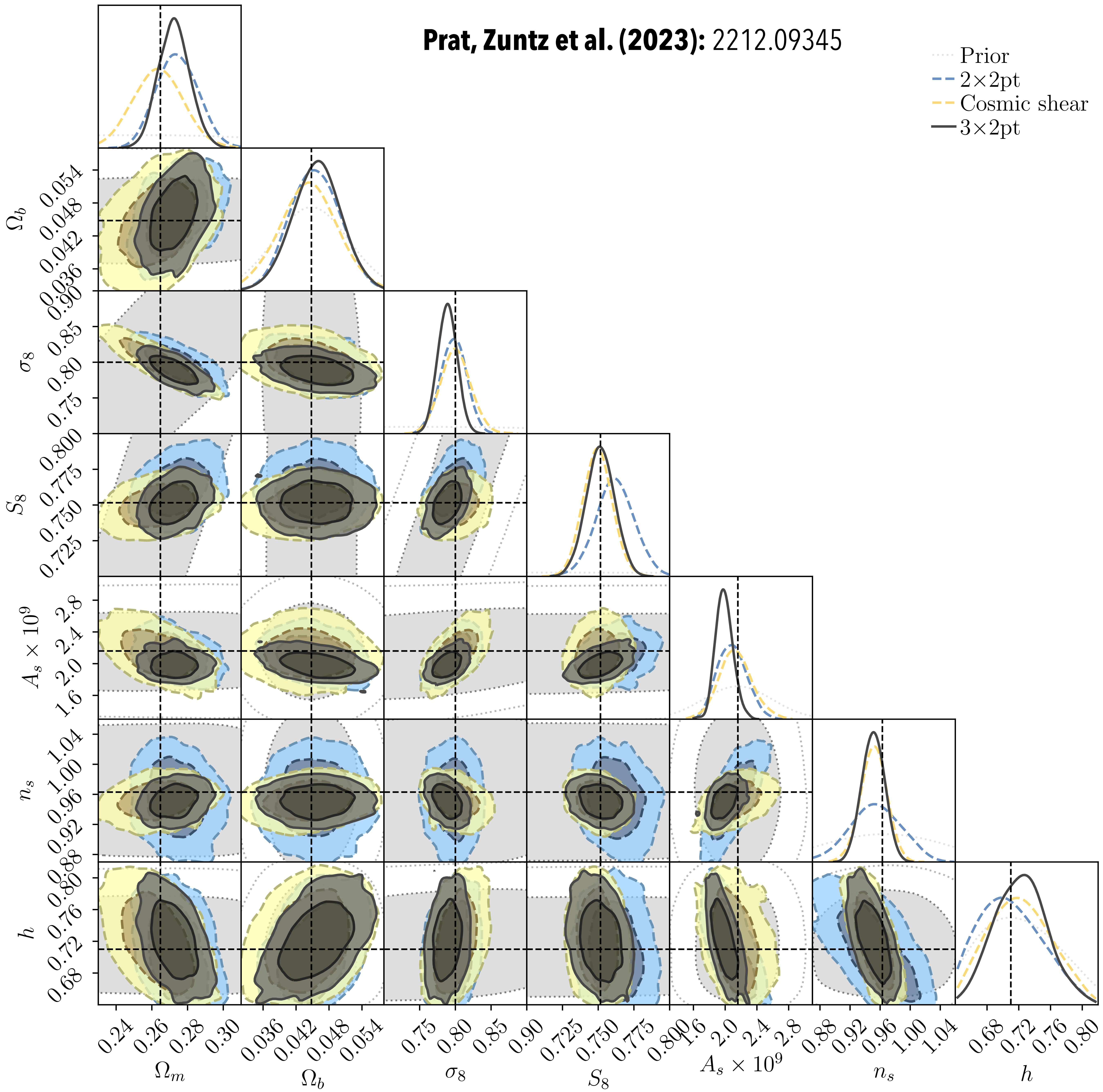
- We recover the input cosmological parameters of the simulation.

Prat, Zuntz et al. (2023): 2212.09345



Validation with simulations

- We find that all the parameters are constrained with respect to the prior, not only the usual Ω_m and σ_8 parameters.



Other things I have done that I didn't cover much today:

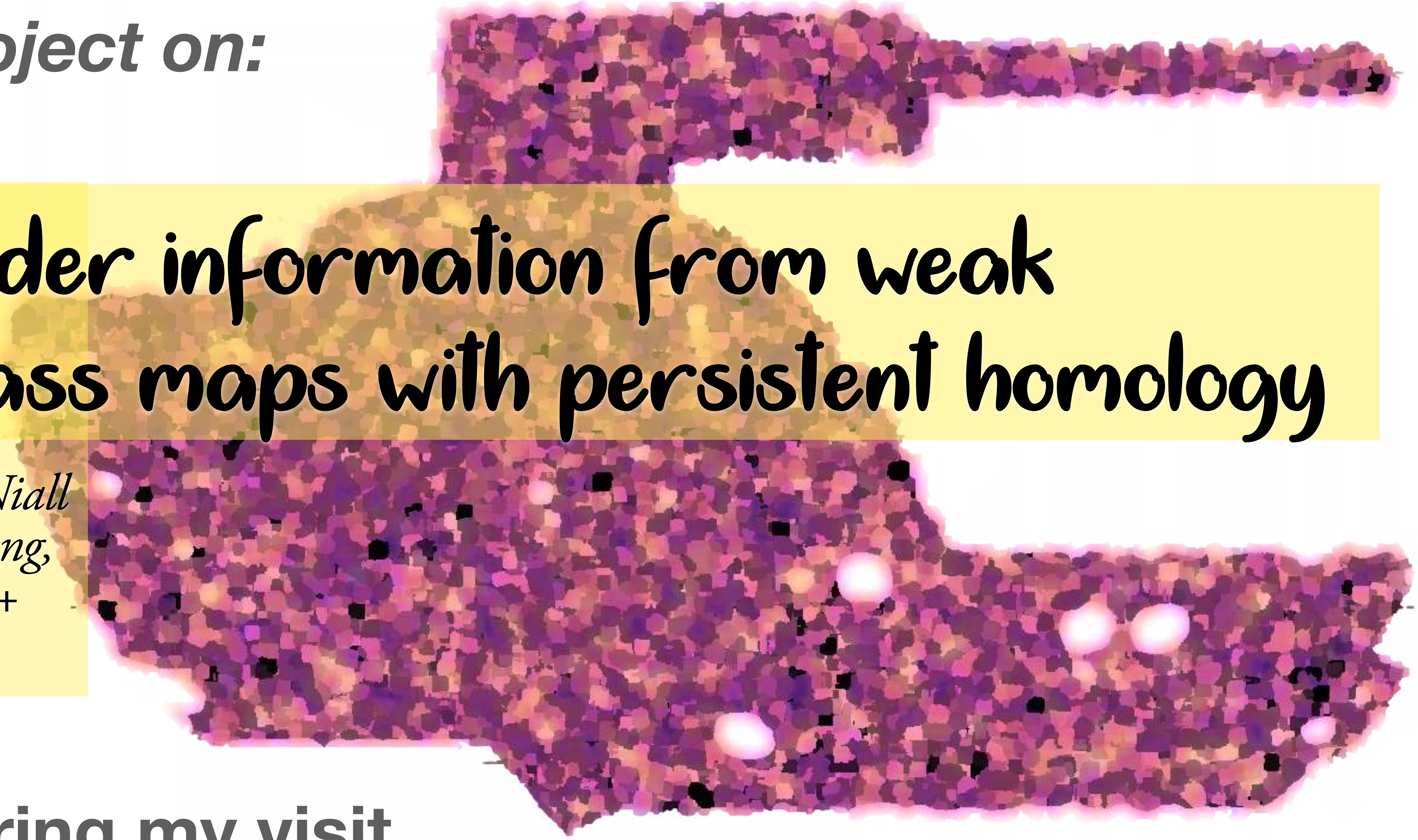
come ask me during my visit if you're interested in any of these!

- **Non-local contribution from small scales in galaxy-galaxy lensing: comparison of mitigation schemes:** *Prat, Zacharegkas et al. (2023)* — `arXiv:2212.03734`
- **Characterizing of galaxy-galaxy lensing measurements and modeling:** *Prat, et al. (2022)* — `arXiv:2105.13541`.
- **Development of lensing ratios technique:** Geometrical probe to include small scale information that otherwise would be discarded in cosmological analyses. (*Prat, Sánchez et al. 2018* — arXiv:1708.01537 , *Sánchez, Prat et al. 2022,* `arXiv:2105.13542`, *Prat, Baxter et al. 2019* — arXiv:1810.02212)
- **Galaxy-galaxy lensing around low-surface brightness galaxies** (with Nathalie Chicoine, undergraduate student at UChicago): *Chicoine, Prat et al. (in prep).*
- **Galaxy-halo connection from galaxy-galaxy lensing** (led by Georgios Zacharegkas, graduate student at UChicago), *Zacharegkas, Chang, Prat, et al. (2022)* — `arXiv:2106.08438`
- **Vacuum Energy Density Measured from Cosmological Data:** *Prat, Hogan et al. (2022)* — `arXiv:2111.08151`.

Starting project on:

Higher order information from weak lensing mass maps with persistent homology

With Marco Gatti, Niall Jeffrey, Chihway Chang, Pratyush Pranav, +++



Ask me during my visit

Conclusions and outlook

- The late-time DES Y3 3x2pt cosmology results are in agreement with early-Universe predictions assuming the ΛCDM model at the 1.5σ level. This is a very important end-to-end test of ΛCDM.
- When combined with the other most constraining low-z probes (BAO and RSD from BOSS DR16, and Type Ia Supernova from Pantheon) the agreement is at the 0.9 sigma level, with smaller uncertainties.
- However there are tensions on the Hubble parameter and a trend of low S_8 measurements from the late-time Universe vs. the early Universe.
- More stringent testing is needed to determine whether ΛCDM holds or not.
- A new generation of galaxy surveys, using more scales and higher order information and emerging probes (such as GW) and maturing of existing ones (such as strong lensing) will (hopefully) provide the answers.

Thanks!

Judit Prat
University of Chicago
Oxford seminar 2023

MacCrann et al. (2019): 1903.07101

Tangential shear modeling: Point-mass marginalization

The tangential shear is non-local, i.e. at each angular scale, the tangential shear has information down to all scales below it.

Surface mass density

$$\gamma_t(\theta) = \frac{\Delta\Sigma(\theta)}{\Sigma_{\rm crit}}$$

Non-local Lens property:

$$\Delta\Sigma(\theta) = \bar{\Sigma}(<\theta) - \Sigma(\theta)$$

Geometrical factor:

$$\Sigma^{-1}_{\rm crit}(z_l, z_s) = \frac{4\pi G}{c^2}\frac{D_{ls}\,D_l}{D_s}$$

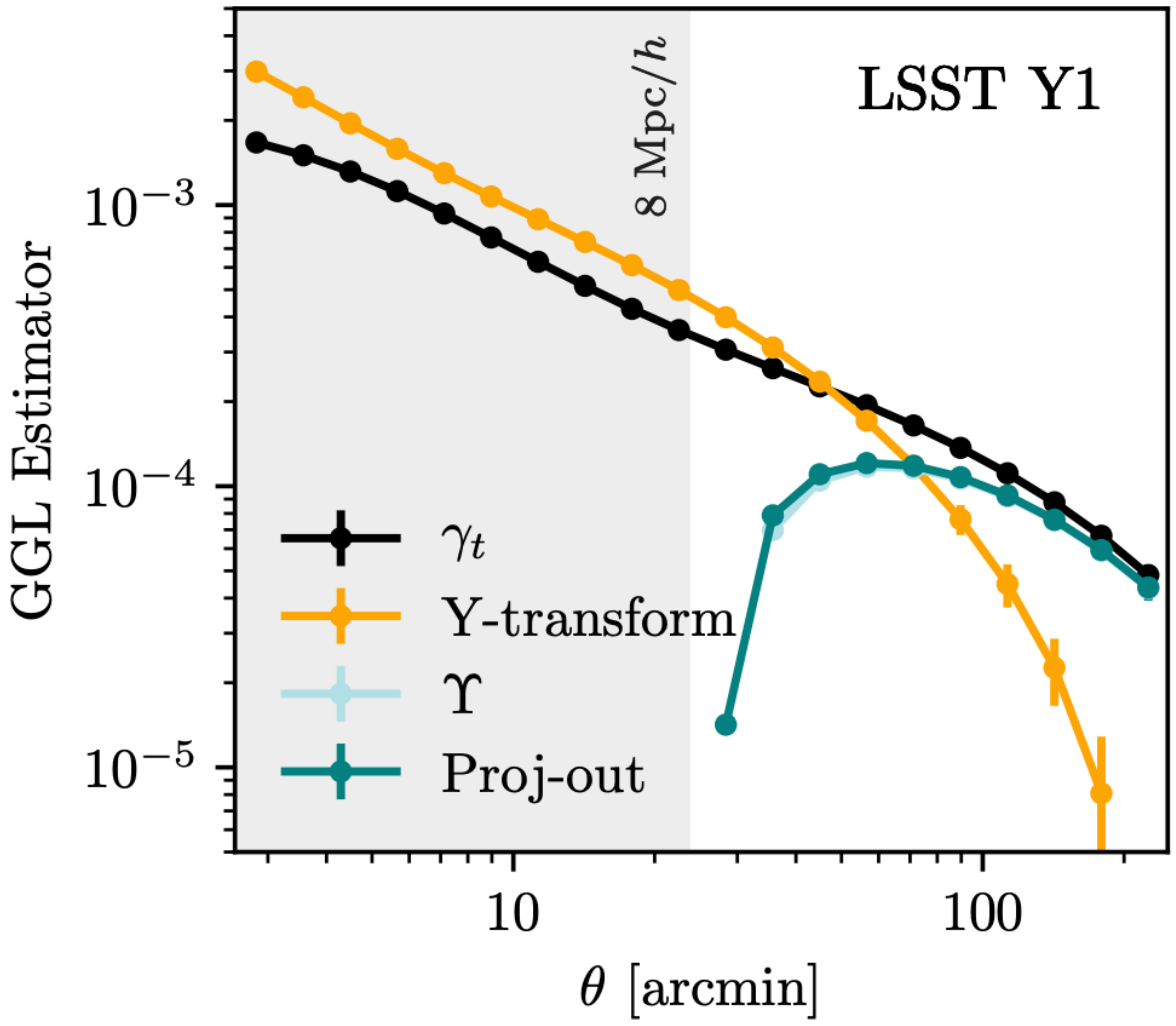
Then, we marginalize over a point mass to remove the small scale information which we can't model:

$$\gamma_t^{ij}(\theta) = \gamma^{ij}_{t,\rm model}(\theta) + \frac{A^{ij}}{\theta^2}$$

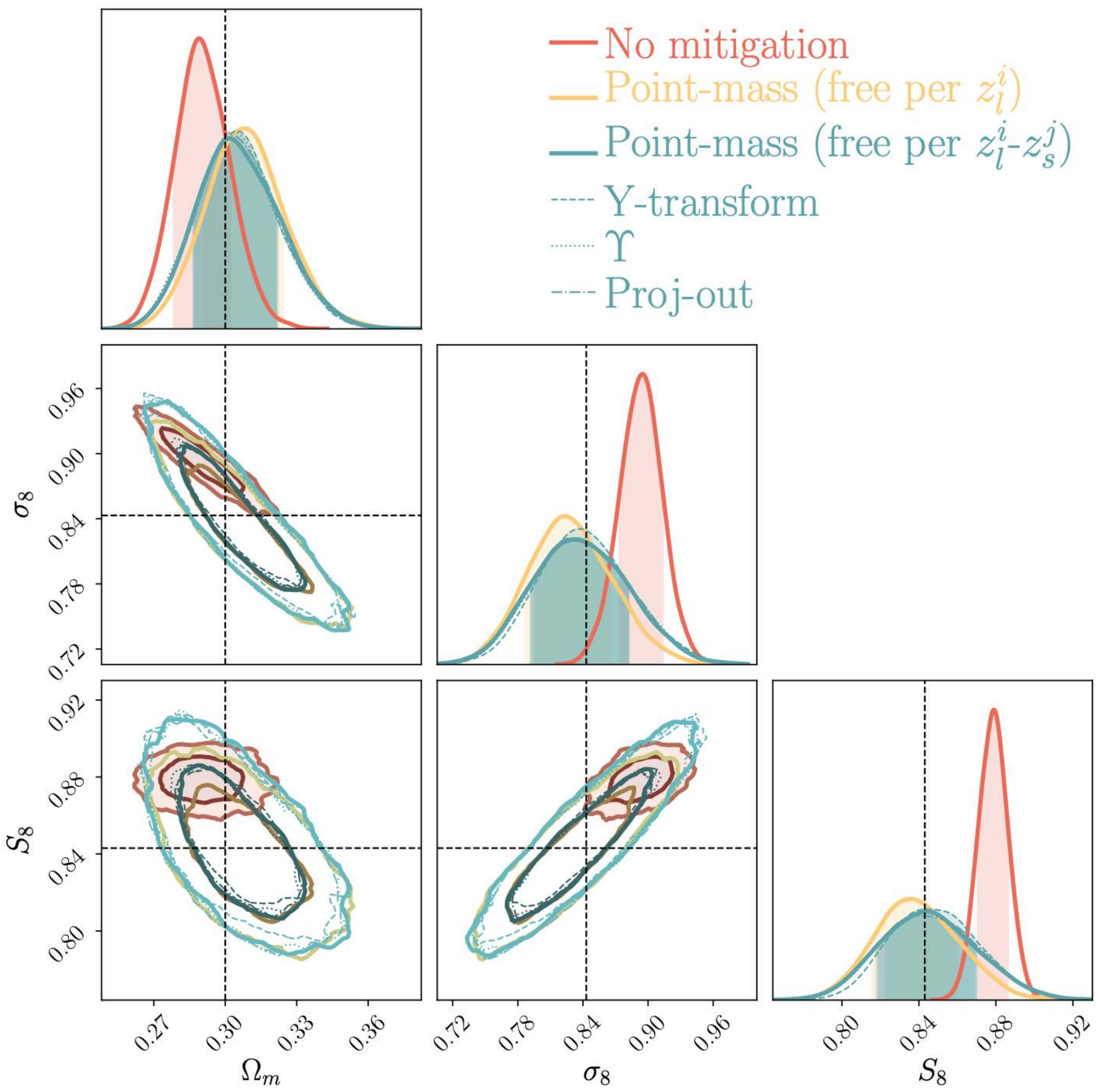
How did we define scale cuts?

- We contaminate our fiducial model with effects that are not included:
  - Non-linear galaxy bias using perturbation theory (*Pandey et. al 2020, 2008.05991).*
  - Baryonic effects (from OWLS hydrodynamical simulation) to the power spectrum.
- **Criteria:** No more than 0.3 sigma effect in the S_8-Ω_m plane.
- **Result:** Scales > 6 Mpc/h for galaxy-galaxy lensing and >8 Mpc/h for galaxy clustering.

Galaxy-galaxy lensing non-local marginalization methods



Galaxy-galaxy lensing non-local marginalization methods



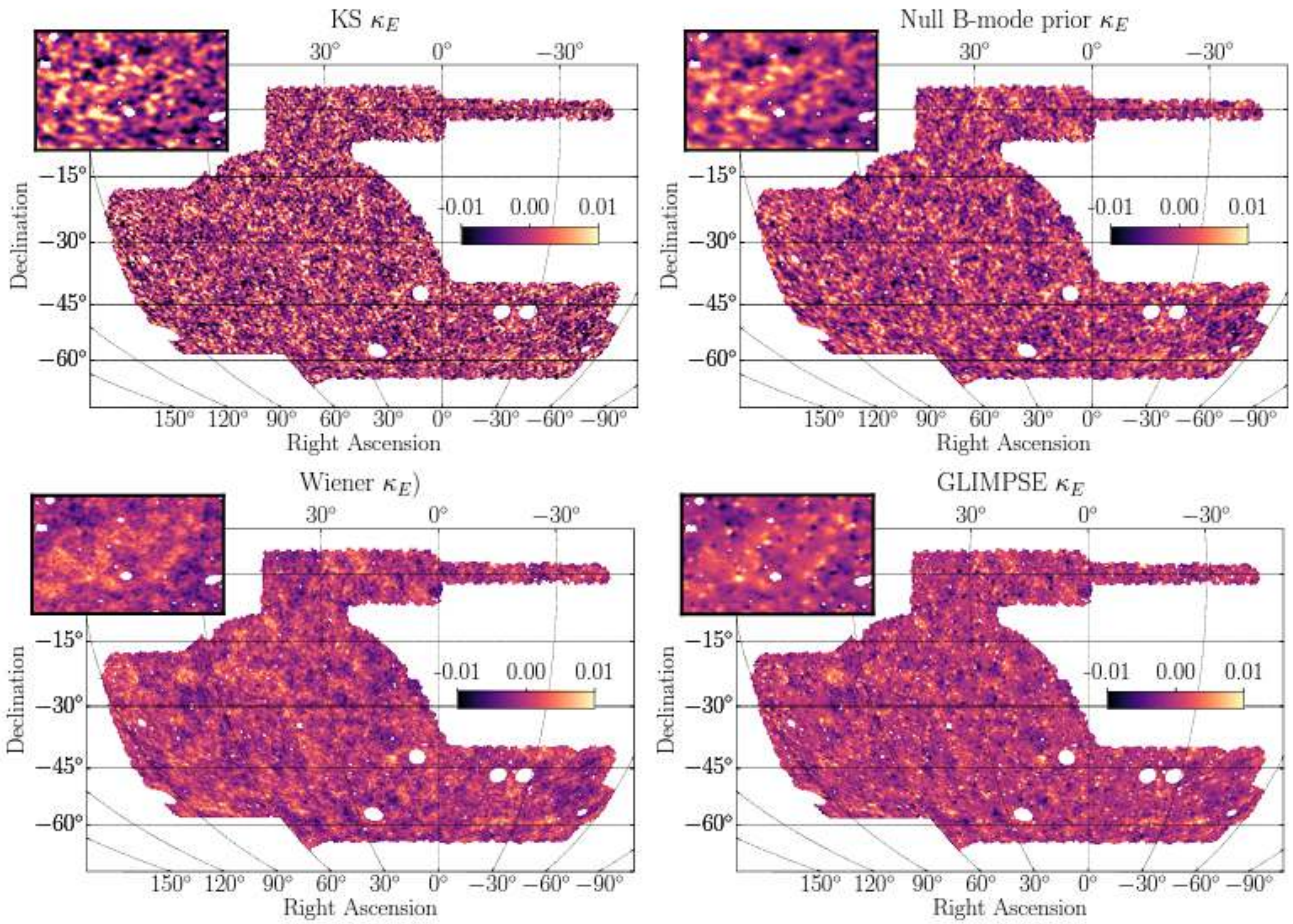
Jeffrey, Gatti, et al. (2021)

Curved sky mass maps from DES Y3

- Y3 is too big to assume flat sky.
- Go to Fourier space to do the convergence reconstruction from the shear.

$$\hat{\gamma}_{\ell m} = \int d\Omega \, \gamma(\theta, \varphi) \, {}_2Y^*_{\ell m}(\theta, \varphi)$$

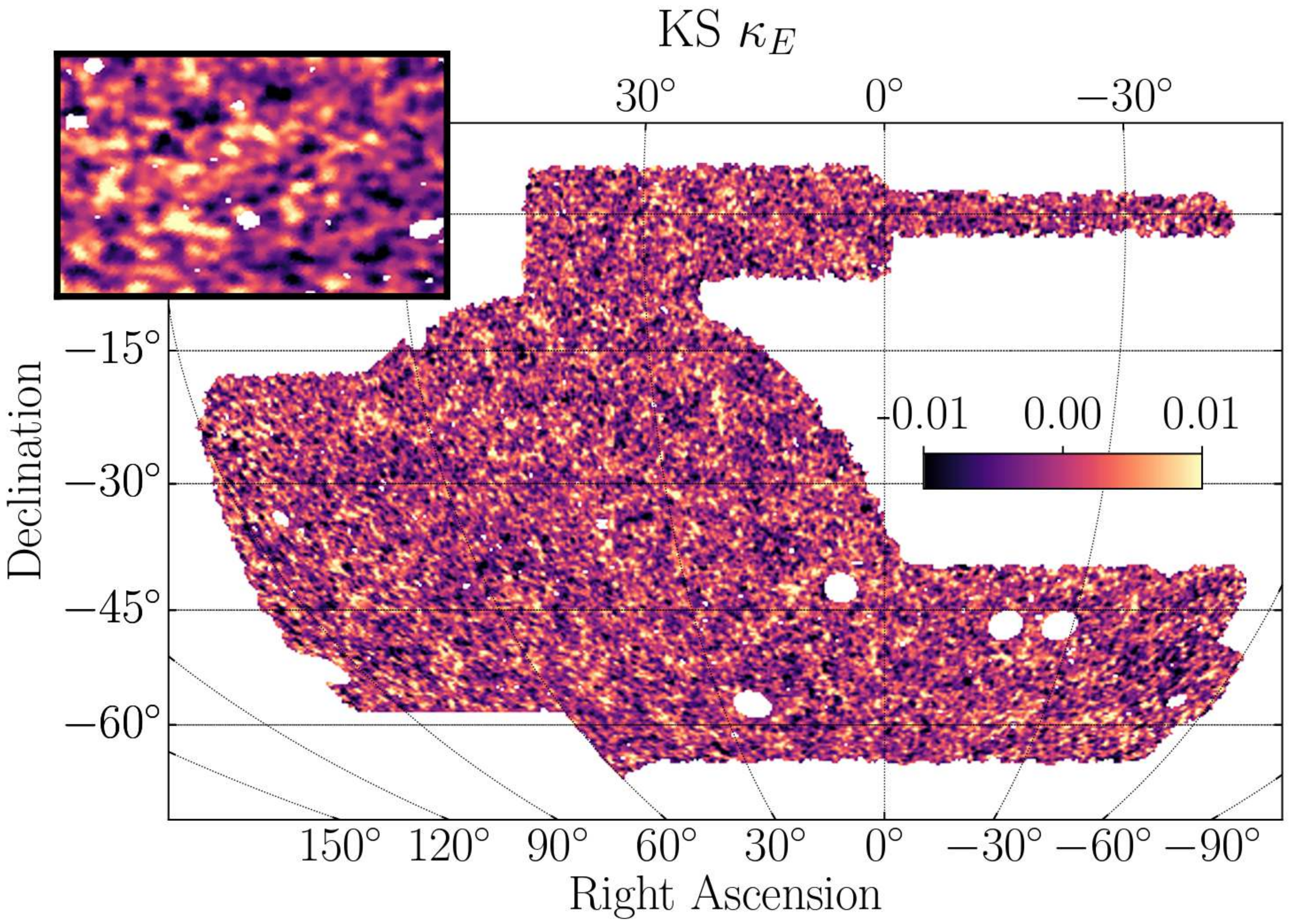
$$\hat{\gamma}_{lm} = -\sqrt{\frac{(\ell-1)(\ell+2)}{\ell(\ell+1)}} \hat{\kappa}_{\ell m}$$



Extracting information from mass maps

Options

1. Full field inference, simulation based.
2. Measure a summary statistic and perform simulation based inference.
3. Measure a summary statistic we know how to model and perform a typical likelihood analysis.



Extracting information from mass maps

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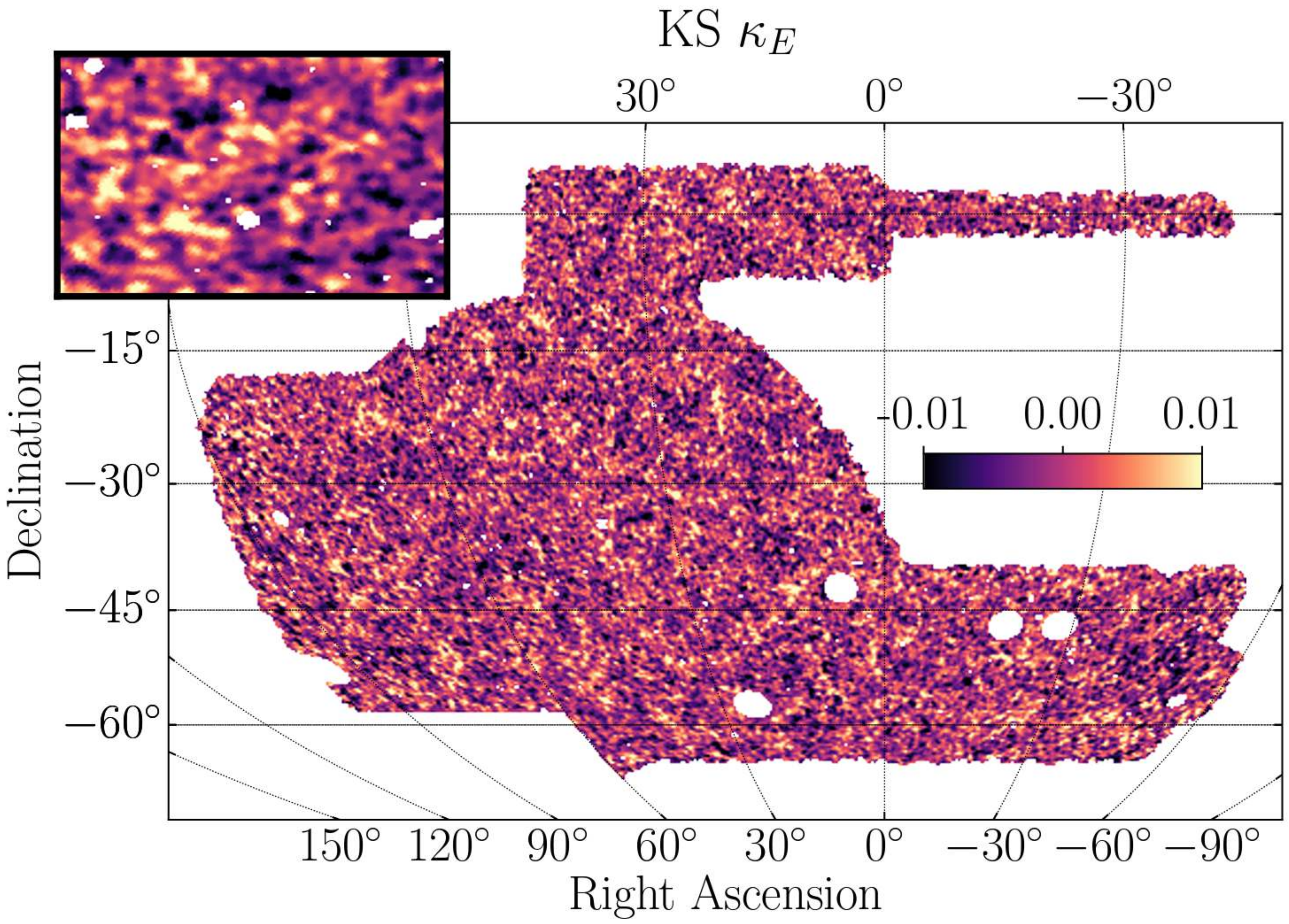


Likelihood free inference

Or simulation based inference

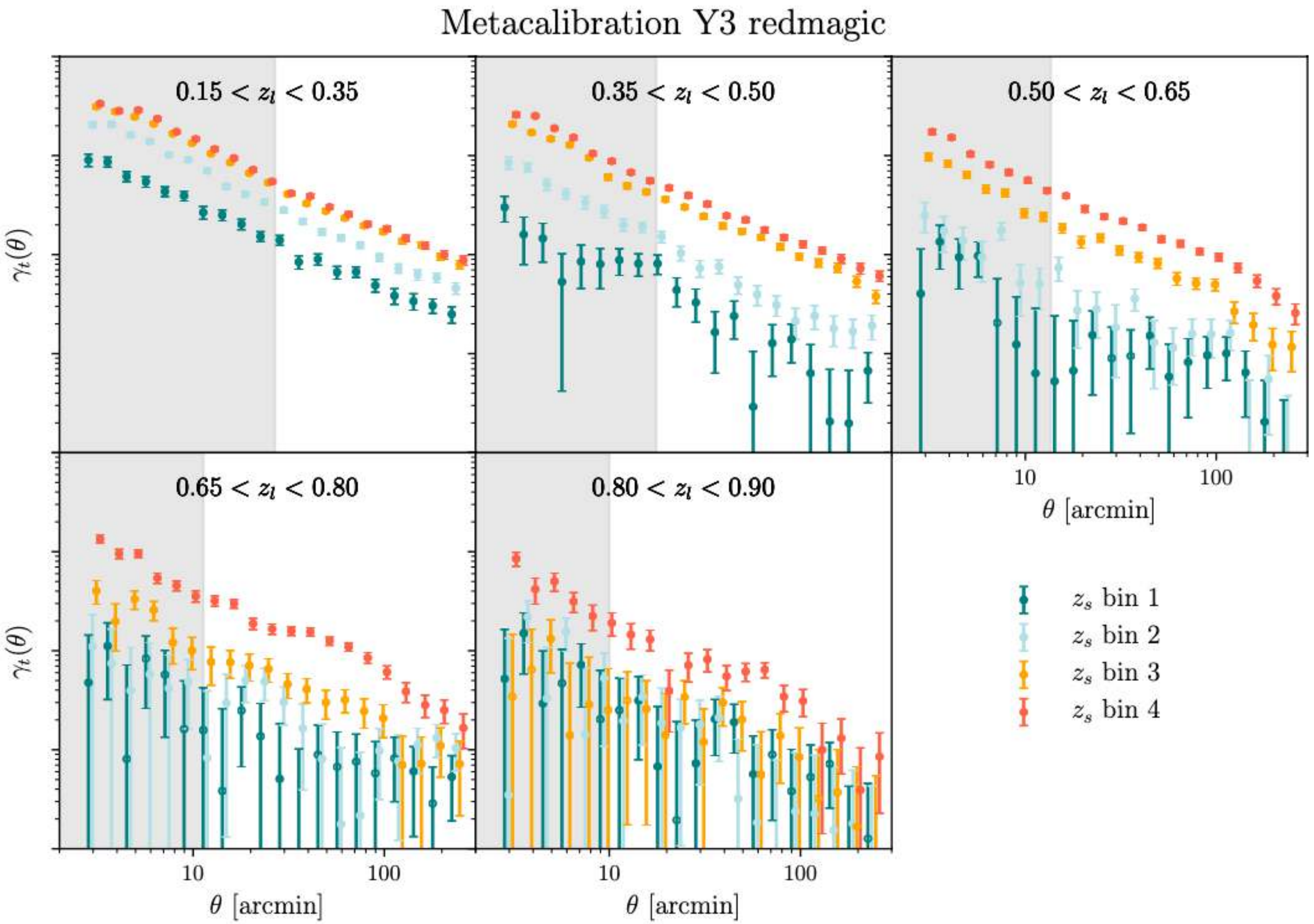
When doing simulation based inference (SBI) the likelihood is not used in closed-form, but is reconstructed from simulated mock data as part of the inference pipeline.

$$\overbrace{p(\boldsymbol{\theta}|\mathbf{d}_o,\mathcal{M})}^{\text{Posterior}} = \frac{\overbrace{p(\mathbf{d}_o|\boldsymbol{\theta},\mathcal{M})}^{\text{Likelihood}}\;\overbrace{p(\boldsymbol{\theta}|\mathcal{M})}^{\text{Prior}}}{\underbrace{p(\mathbf{d}_o|\mathcal{M})}_{\text{Evidence}}}$$

Visualization of scale cuts for galaxy-galaxy lensing

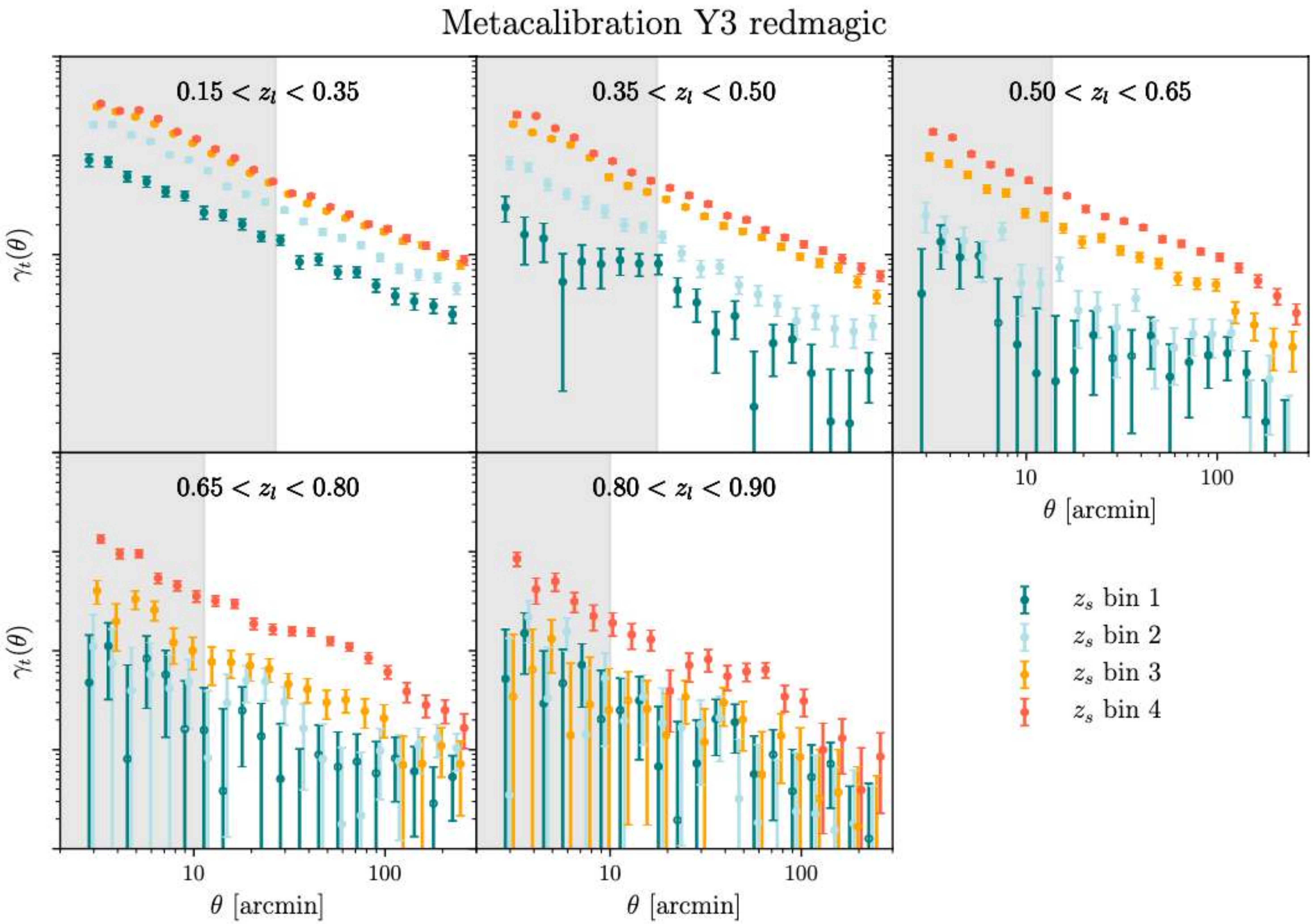
- REDMAGIC S/N:
  i. **Total:**120.
  ii. **After scale cuts** (>6Mpc/h): 55

- MAGLIM S/N:
  i. **Total:**148.
  ii. **After scale cuts** (>6Mpc/h): 67



Visualization of scale cuts for galaxy-galaxy lensing

- REDMAGIC S/N:
  i. **Total:**120.
  ii. **After scale cuts** (>6Mpc/h): 55
  iii. **With PM marg:** 28
- MAGLIM S/N:
  i. **Total:**148.
  ii. **After scale cuts** (>6Mpc/h): 67
  iii. **With PM marg:** 32



Lensing ratios idea

The tangential shear can be separated into:

We don't know how to model this part at small scales.

$$\gamma_t(\theta) = \frac{\Delta\Sigma(\theta)}{\Sigma_{\rm crit}}$$

Non-local lens property: $\Delta\Sigma(\theta) = \bar{\Sigma}(<\theta) - \Sigma(\theta)$

Geometrical factor: $\Sigma^{-1}_{\rm crit}(z_l, z_s) = \frac{4\pi G}{c^2}\frac{D_{ls}\, D_l}{D_s} \quad \text{if} z_s > z_l$

But we know how to model the geometrical factor at any scale!

Let's take ratios of the tangential shear sharing the same lens sample with different source redshift bins!

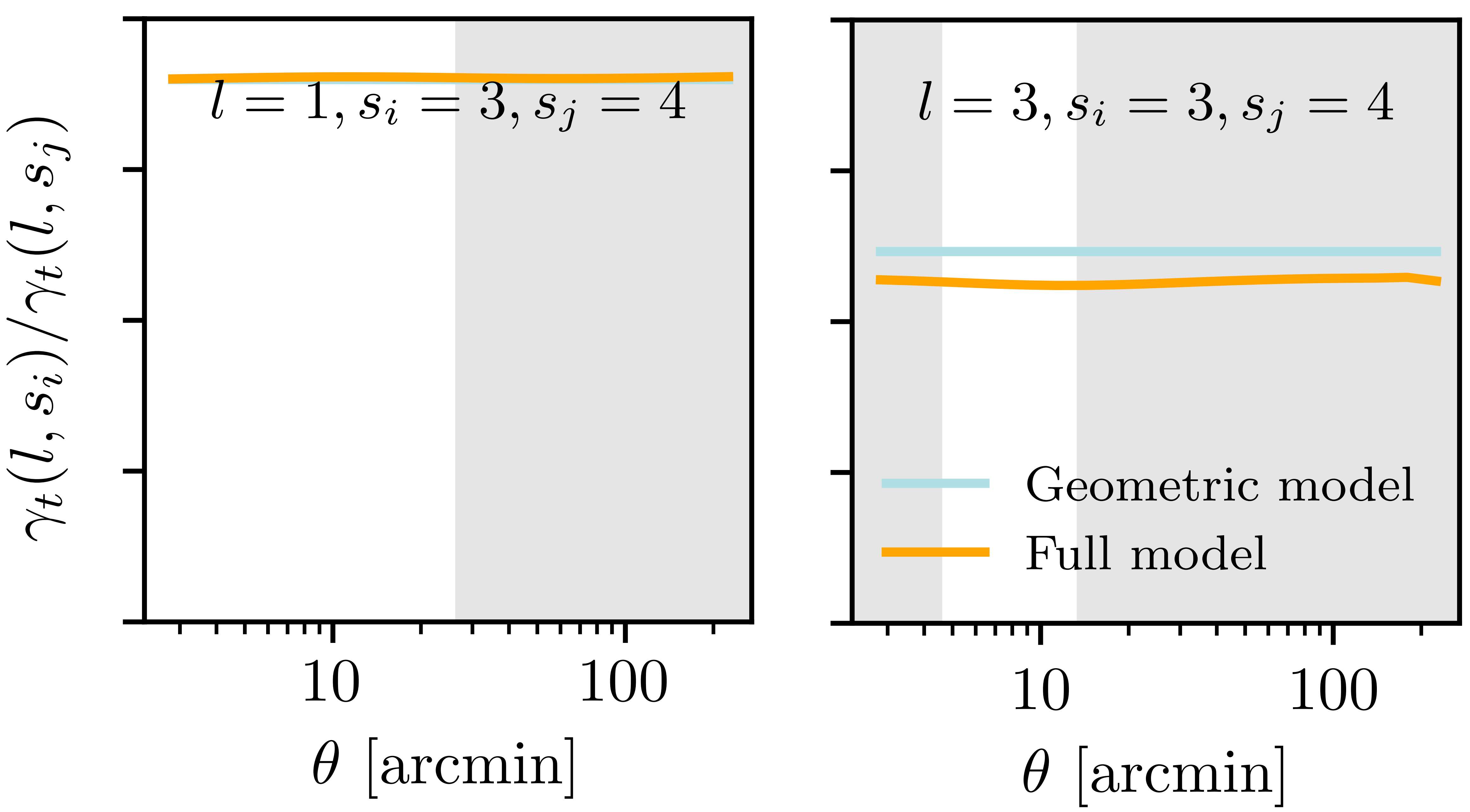
$$\frac{\gamma_t^{l,s_i}}{\gamma_t^{l,s_j}} = \frac{\Sigma^{-1}_{\rm crit}(z_l, z_{s_i})}{\Sigma^{-1}_{\rm crit}(z_l, z_{s_j})}$$

DES Y3 Lensing Ratios: *Effectively extending the GGL vector to smaller scales*

- The geometrical model is a very good approximation when the lens and source bins are well separated in redshift, otherwise taking the ratios of the full model is needed (IA and lens magnification are important).
- We can model these ratios down to smaller scales, effectively extending the tangential shear data vector.
- We can include this as an additional likelihood, since these scales are independent from the rest of the data-vector.
- It helps to self-calibrate **redshifts** and **IA parameters**.

$$\log \mathcal{L}^{\mathrm{Total}} = \log \mathcal{L}^{\mathrm{SR}} + \log \mathcal{L}^{\mathrm{2pt}}$$

Sánchez, Prat et al. (2022)



DES Y3 Lensing Ratios

Scale cuts

S/N for redMaGiC = 60
S/N for MagLim = 75

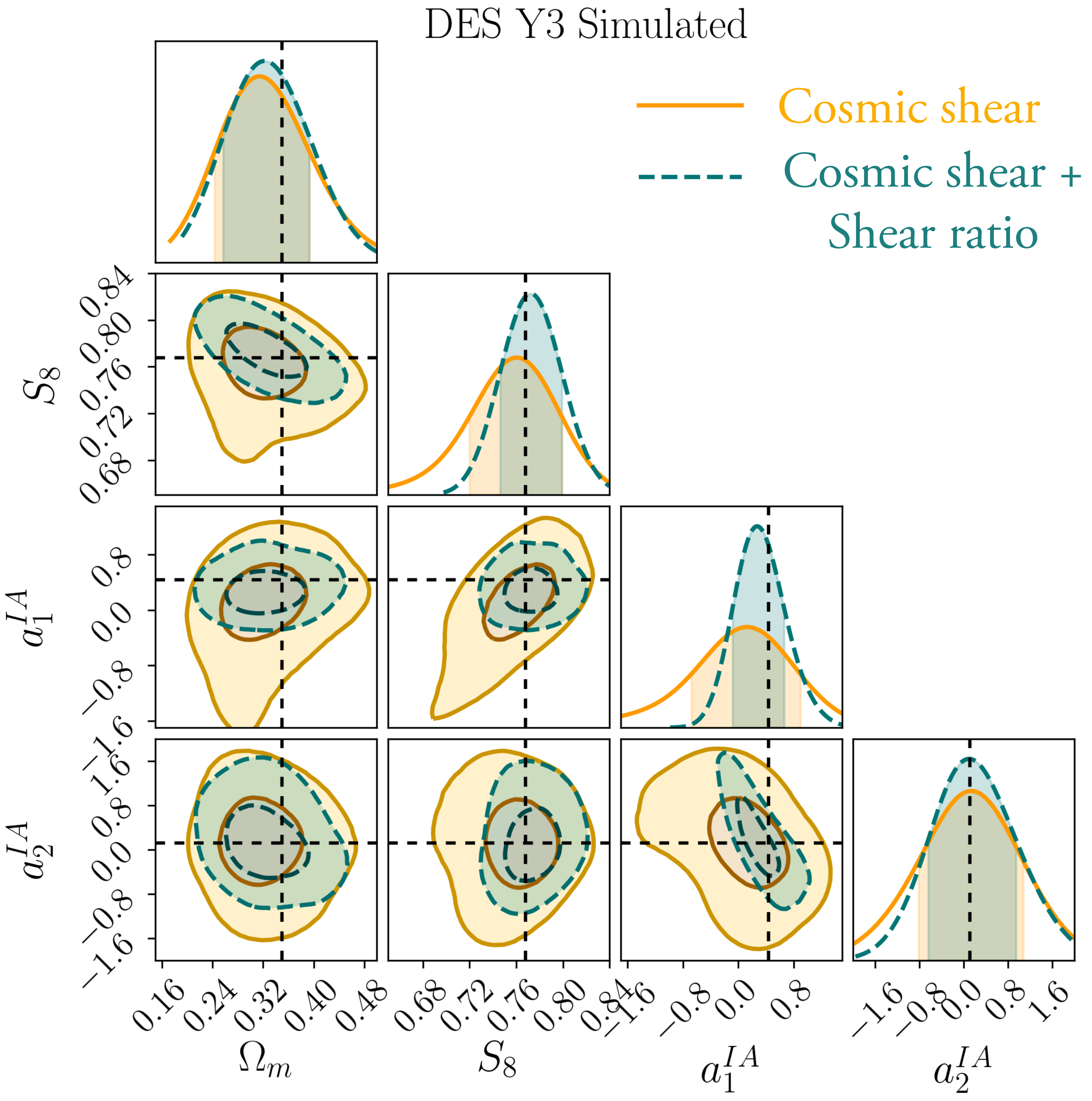
$(\boldsymbol{l_i, s_j, s_k})$	**Scales**	N_{dp} RM	N_{dp} ML
(l_1, s_1, s_4)	$2-6\ h^{-1}$Mpc	4	5
(l_1, s_2, s_4)	$2-6\ h^{-1}$Mpc	4	5
“Geometric” ratio → (l_1, s_3, s_4)	2.5 arcmin $-\ 6\ h^{-1}$Mpc	10	10
(l_2, s_1, s_4)	$2-6\ h^{-1}$Mpc	4	5
(l_2, s_2, s_4)	$2-6\ h^{-1}$Mpc	4	5
“Geometric” ratio → (l_2, s_3, s_4)	2.5 arcmin $-\ 6\ h^{-1}$Mpc	8	9
(l_3, s_1, s_4)	$2-6\ h^{-1}$Mpc	4	5
(l_3, s_2, s_4)	$2-6\ h^{-1}$Mpc	4	5
(l_3, s_3, s_4)	$2-6\ h^{-1}$Mpc	4	5

DES Y3 Lensing Ratios

Combination with other probes

$$\log \mathcal{L}^{\mathrm{Total}} = \log \mathcal{L}^{\mathrm{SR}} + \log \mathcal{L}^{\mathrm{2pt}}$$

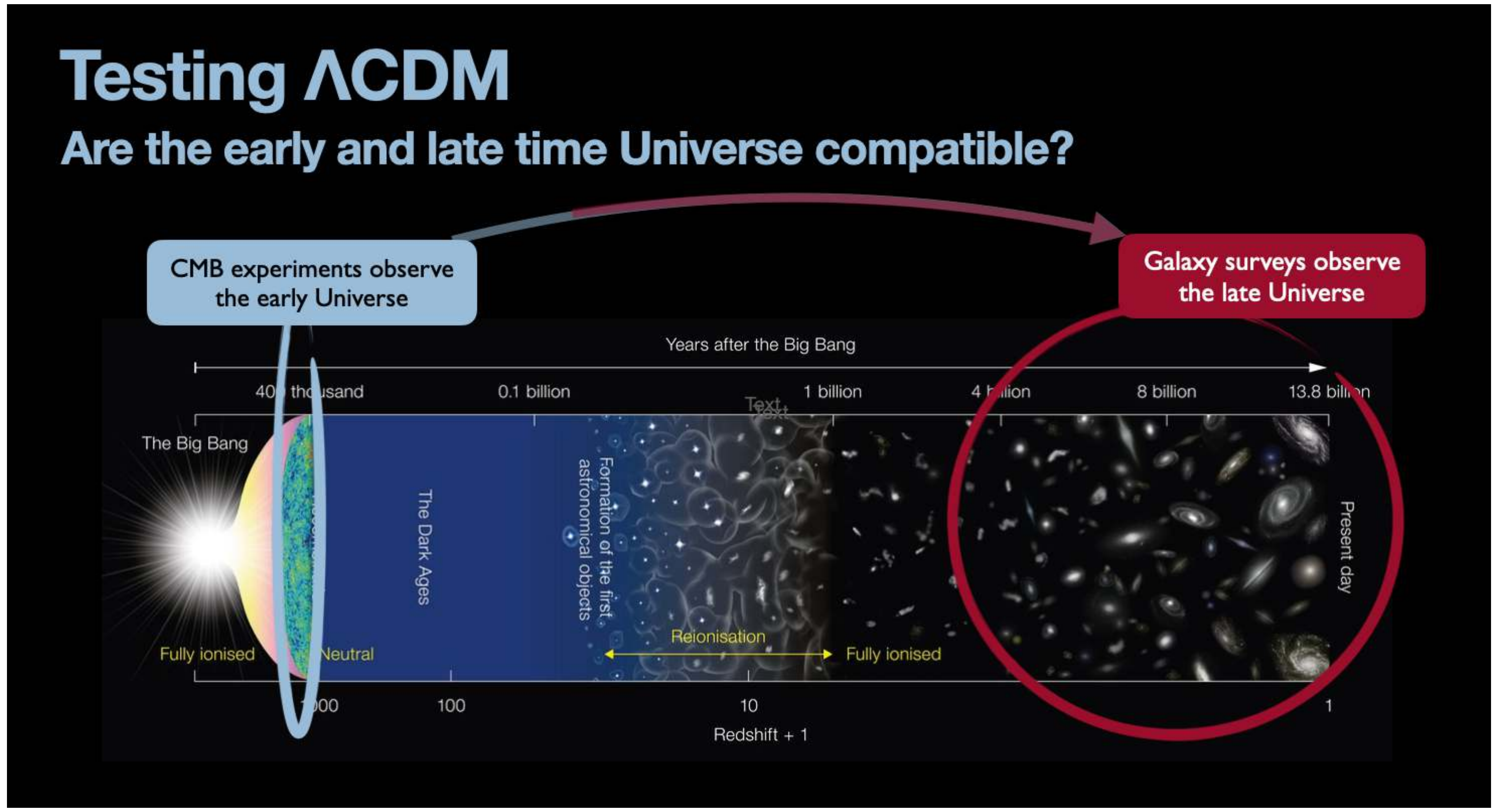
- Constraints from Cosmic Shear improve significantly with lensing ratios information (31%), mostly because it helps with IA calibration in the TATT model.
- For for 3x2pt they improve 10%.



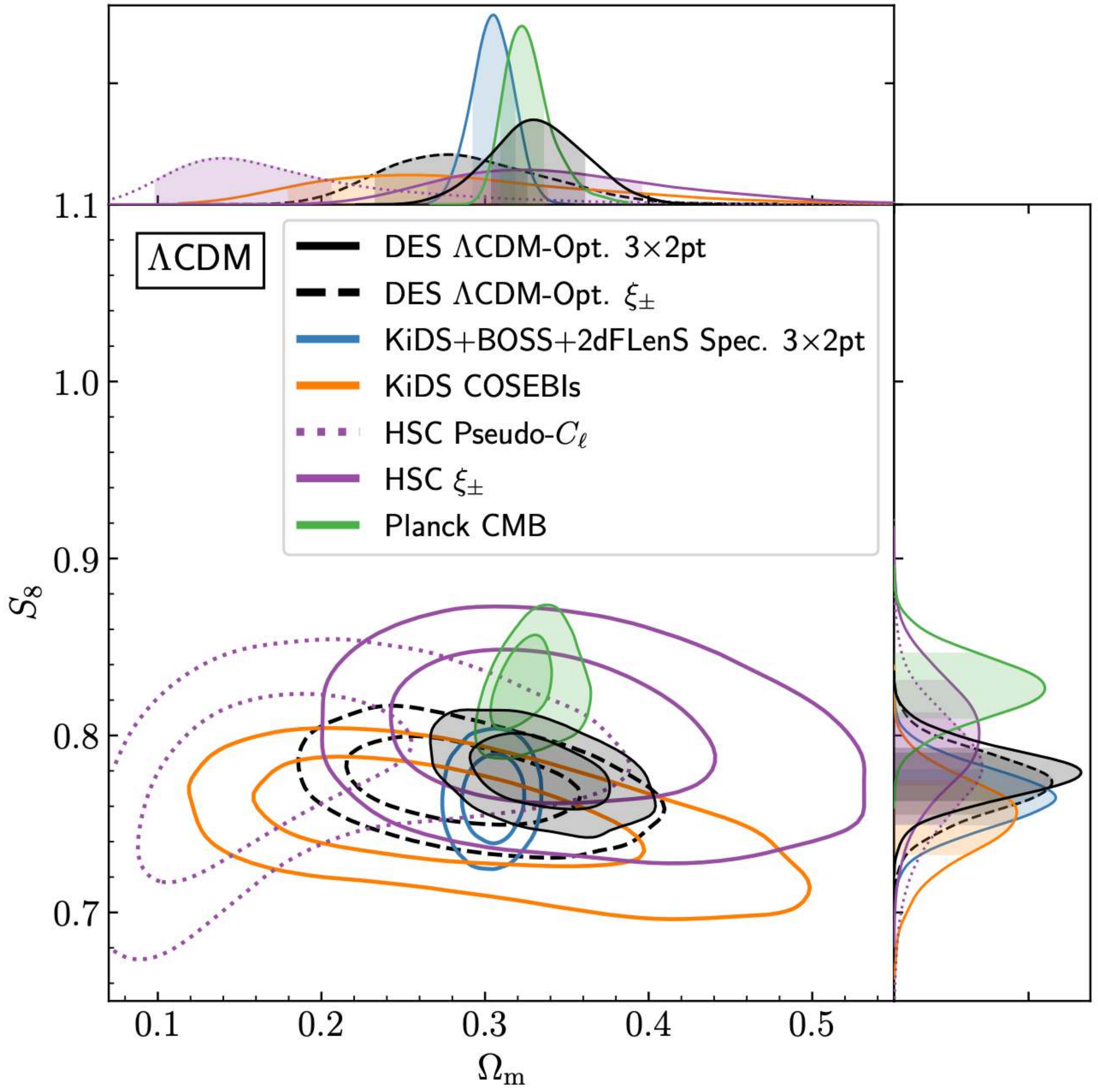
DES Y3 results: latest results on the growth of structure

- However, low redshift probes sensitive to the growth of structure have historically preferred lower values of Ω_m and σ_8.

- Is this an indication of new physics or some unaccounted systematics?



DES Collaboration (2021), arXiV: 2105.13549



MacCrann et al. (2019): 1903.07101

Tangential shear modeling: Point-mass marginalization

The tangential shear is non-local, i.e. at each angular scale, the tangential shear has information down to all scales below it.

Surface mass density

$$\gamma_t(\theta) = \frac{\Delta\Sigma(\theta)}{\Sigma_{\rm crit}}$$

Non-local Lens property:

$$\Delta\Sigma(\theta) = \bar{\Sigma}(<\theta) - \Sigma(\theta)$$

Geometrical factor:

$$\Sigma^{-1}_{\rm crit}(z_{\rm l}, z_{\rm s}) = \frac{4\pi G}{c^2}\frac{D_{ls}\,D_l}{D_s}$$

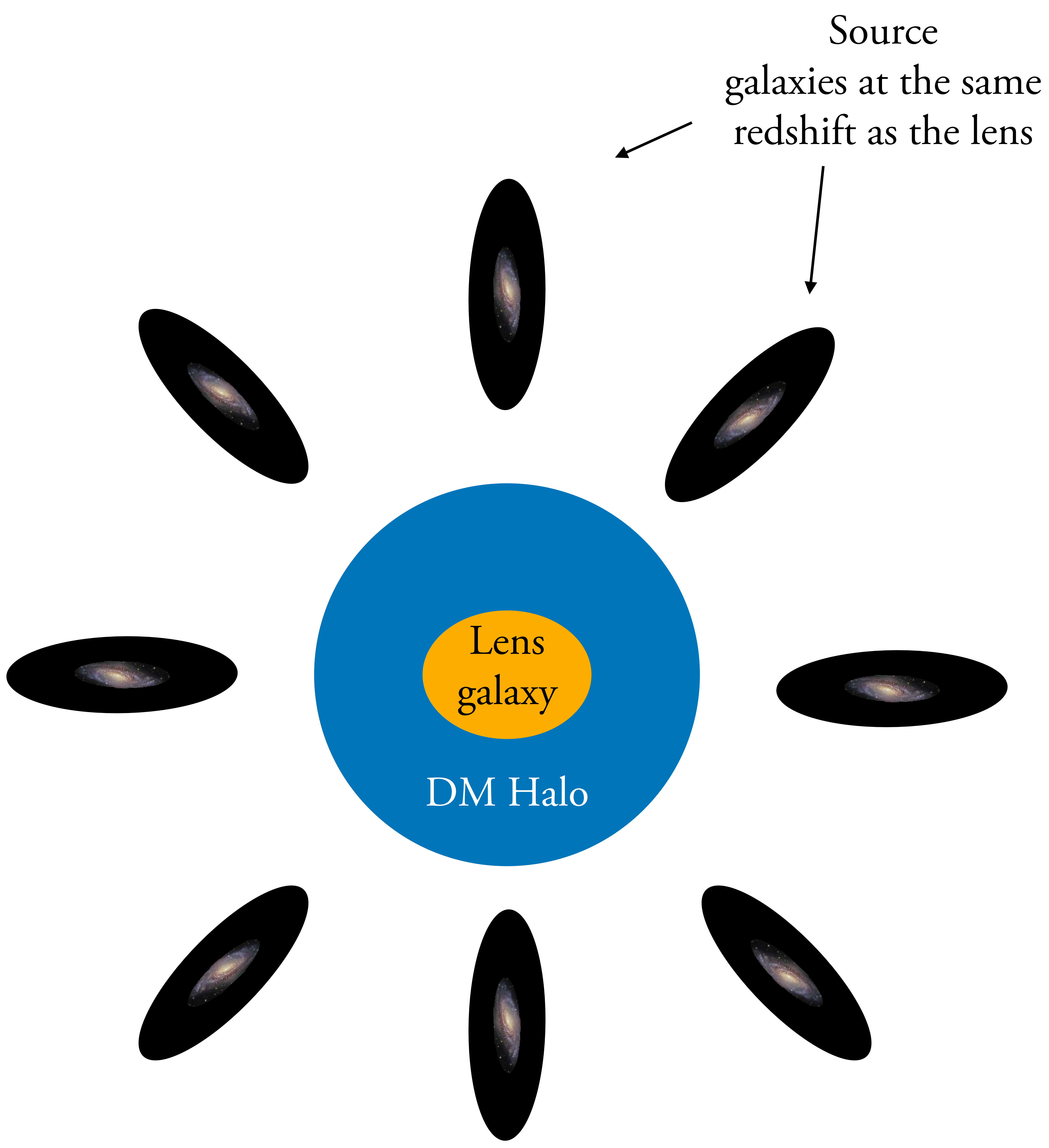
Then, we marginalize over a point mass to remove the small scale information which we can't model:

$$\gamma_t^{ij}(\theta) = \gamma^{ij}_{t,\rm model}(\theta) + \frac{A^{ij}}{\theta^2}$$

Intrinsic Alignments

For galaxy-galaxy lensing

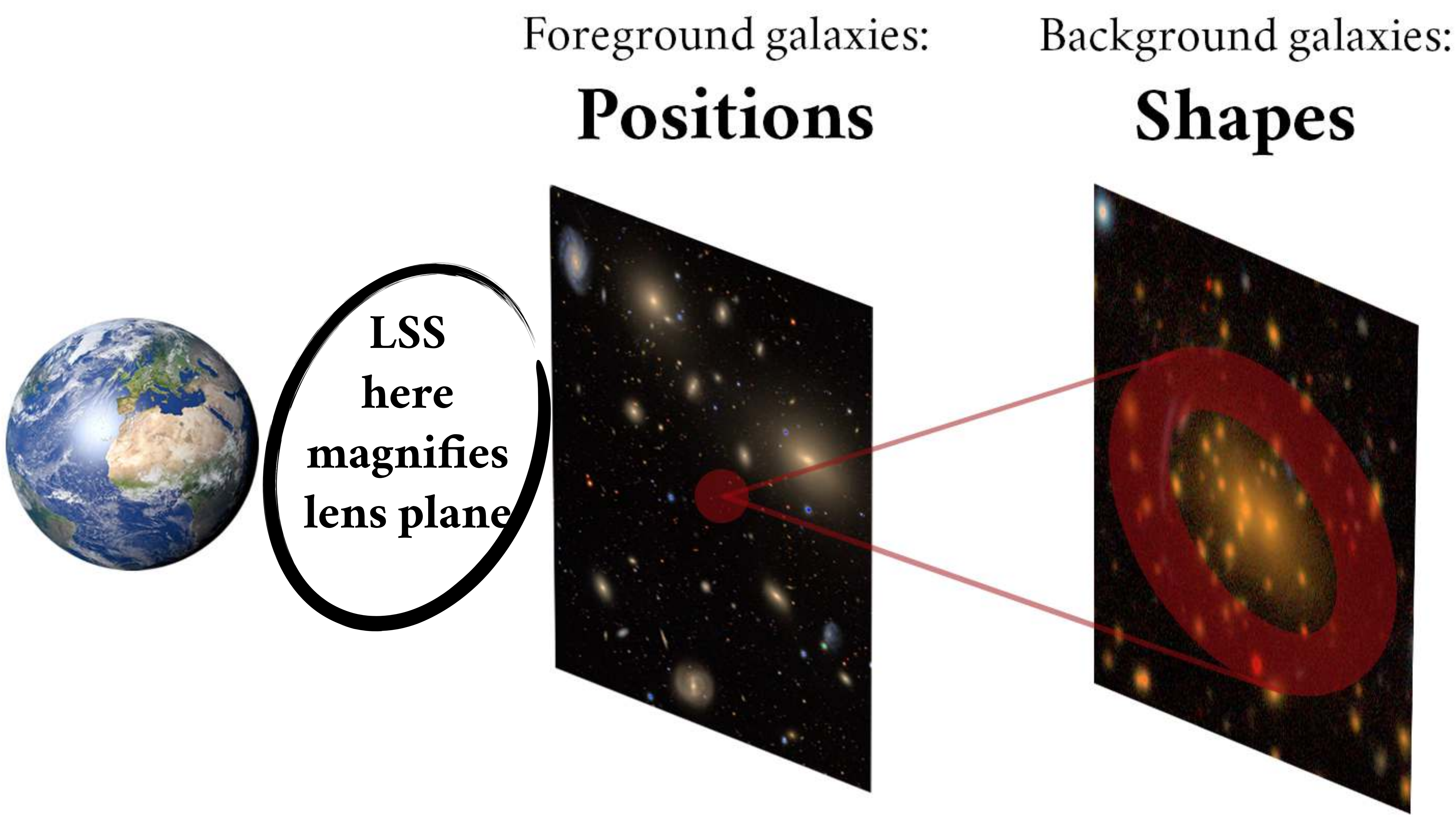
- The intrinsic galaxy shapes are not randomly oriented.
- They are correlated with the position of the lens when lenses and sources are at the same redshift.
- This effect can bias the cosmological results if not modeled properly.
- We use a 5 parameter model, Tidal Alignment and Tidal Torque (TATT) model.



Lens magnification

For galaxy-galaxy lensing

- Number density of lens galaxies changes due to the LSS in front of them.
- This change is correlated with the shear at higher redshift and can bias our signal if not taken into account properly.
- We calibrate this effect from the data itself and using image simulations (*Elvin-Poole et al. (in prep)*).



DES Y3 results: comparison between lens samples

- Cosmic shear and galaxy clustering+tangential shear (2x2pt) for redMaGiC are also formally consistent and combine to give the 3x2pt result.

- 2x2pt prefers lower S_8 and higher galaxy bias. Combination with cosmic shear brings S_8 up and bias down to agree with DES Y1.

- Evidence for potential systematics in the redMaGiC clustering data vector at all redshifts and above the fiducial lens redshift range for MagLim.

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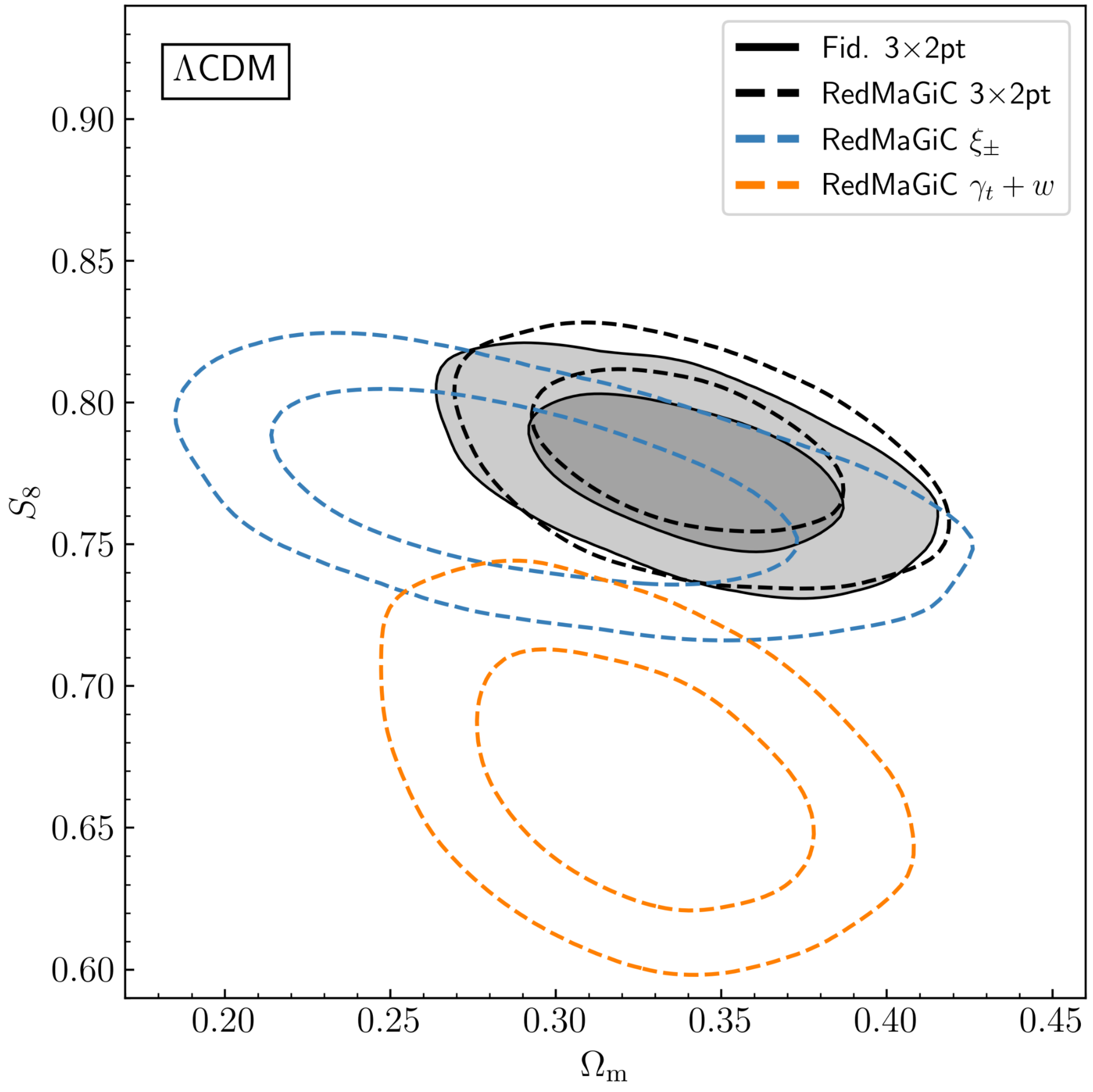

DES Y3 results: comparison between lens samples

- We introduce a parameter $X_{\rm lens}$ to model this, which decorrelates the clustering and lensing amplitudes:

$$w^{ii}(\theta) = b_i^2 \xi^{ii}_{\rm mm}(\theta)$$
$$\gamma_t^{ij}(\theta) = X_{\rm lens} b_i \xi^{ij}_{\rm mm}(\theta)$$

- We measure $X_{\rm lens} = 0.877^{+0.026}_{-0.019}$ for redMaGiC with 3x2pt in ΛCDM ($X_{\rm lens}$ should be consistent with 1; it is in fiducial redshift range for MagLim). Two highest-redshift bins removed in MagLim.

- $X_{\rm lens}$ does not strongly impact ΛCDM results, but is highly correlated with *w* in redMaGiC wCDM.

DES Collaboration (2022)