Testing cosmological models

with galaxy surveys

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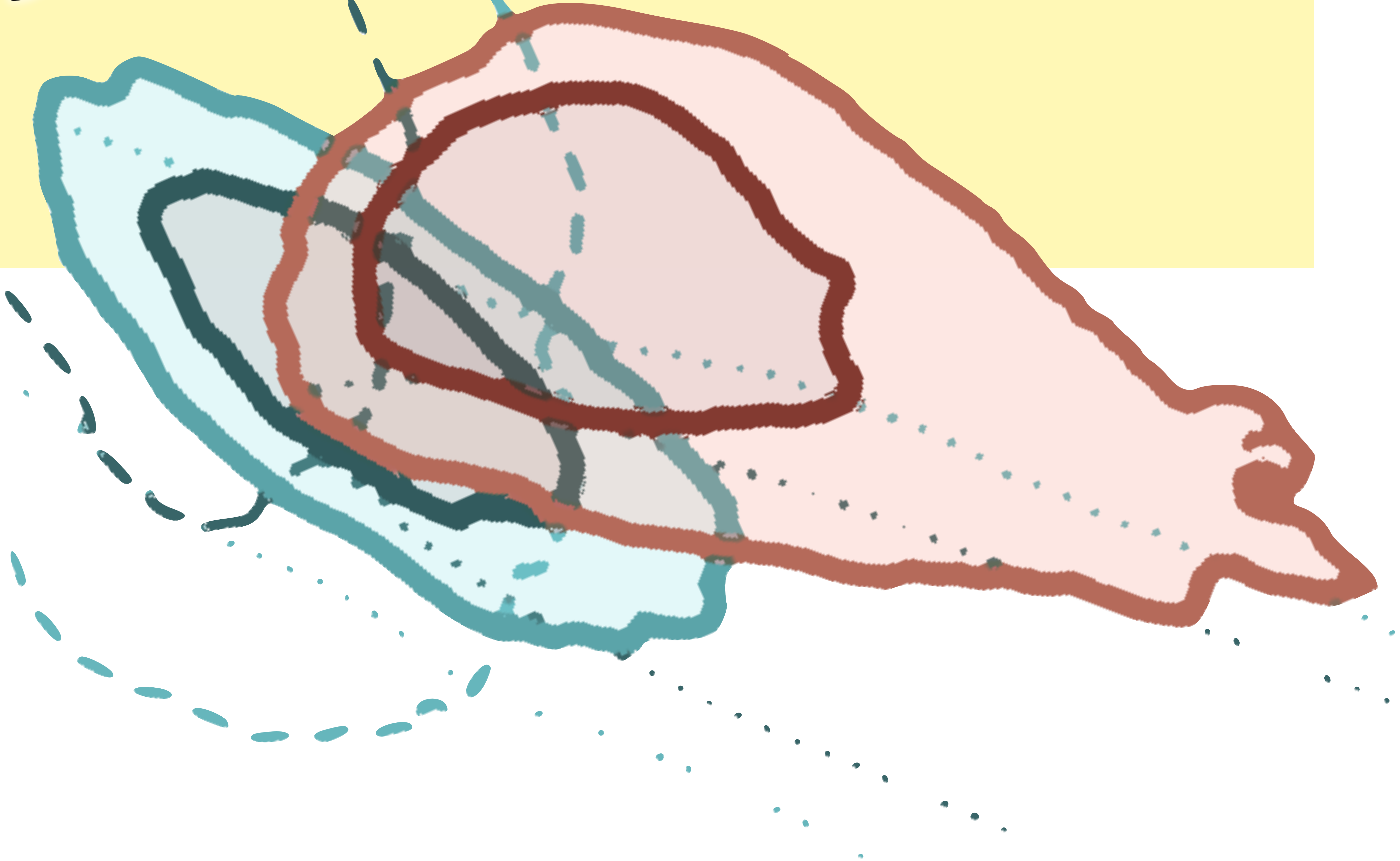
Cosmic Web Feb 2023



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.

It accurately describes a broad range of cosmological observations.

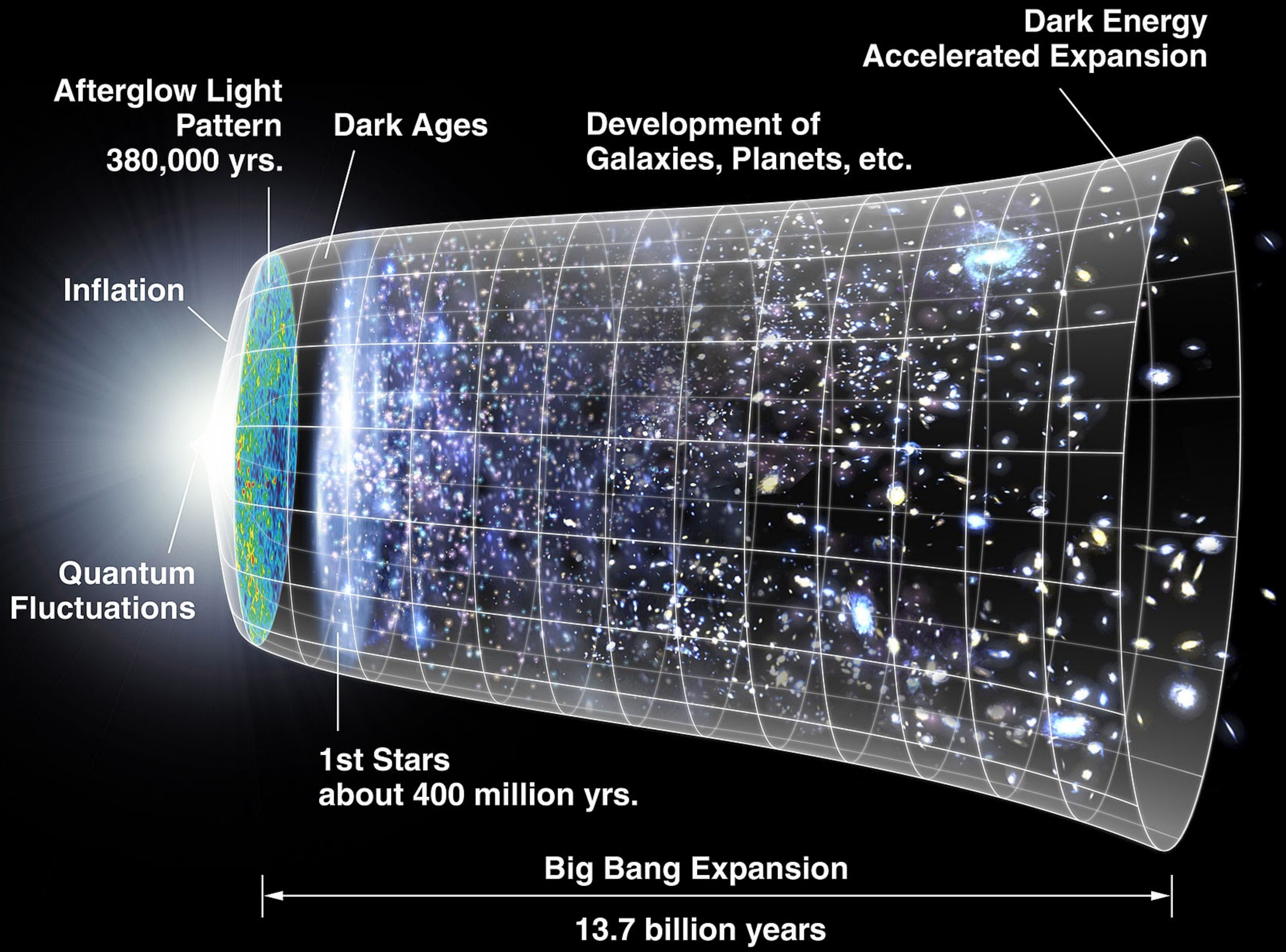


Image Credit: NASA / LAMBDA Archive / WMAP Science Team

Very successful model but there are important 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.

It requires initial conditions created by **inflation**.

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

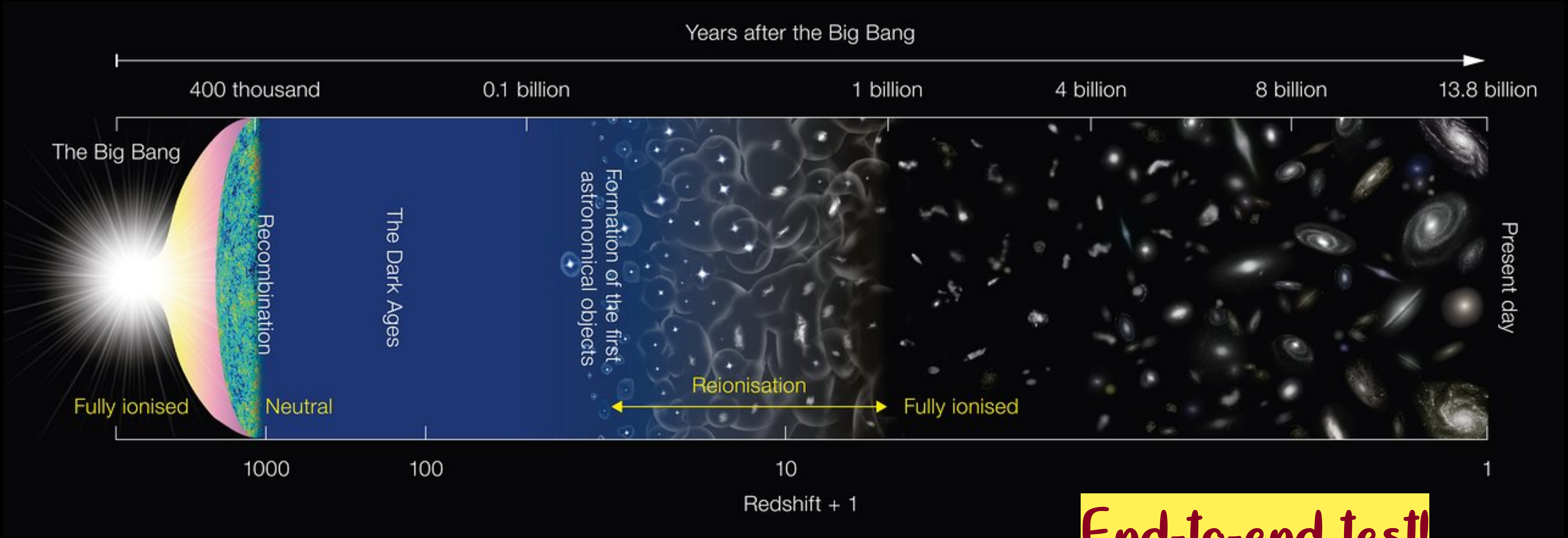
Some **tensions** are arising between cosmological probes. Are they real, systematics, or statistical fluctuations?

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?



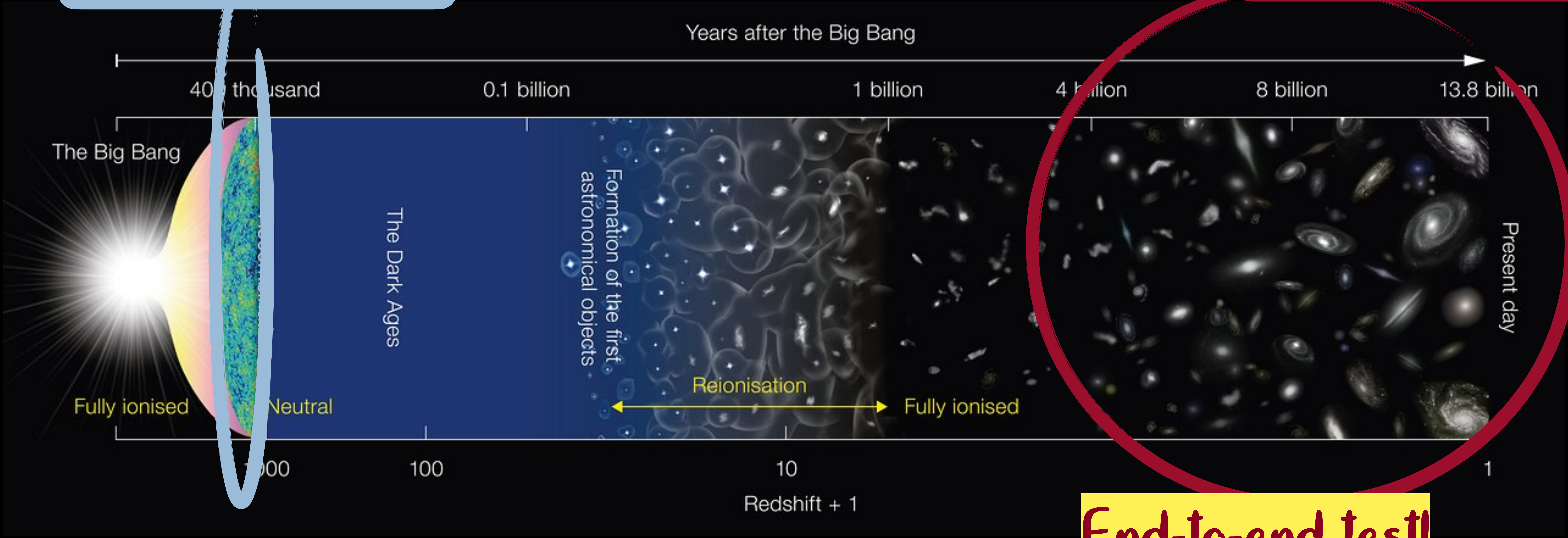
End-to-end test!

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

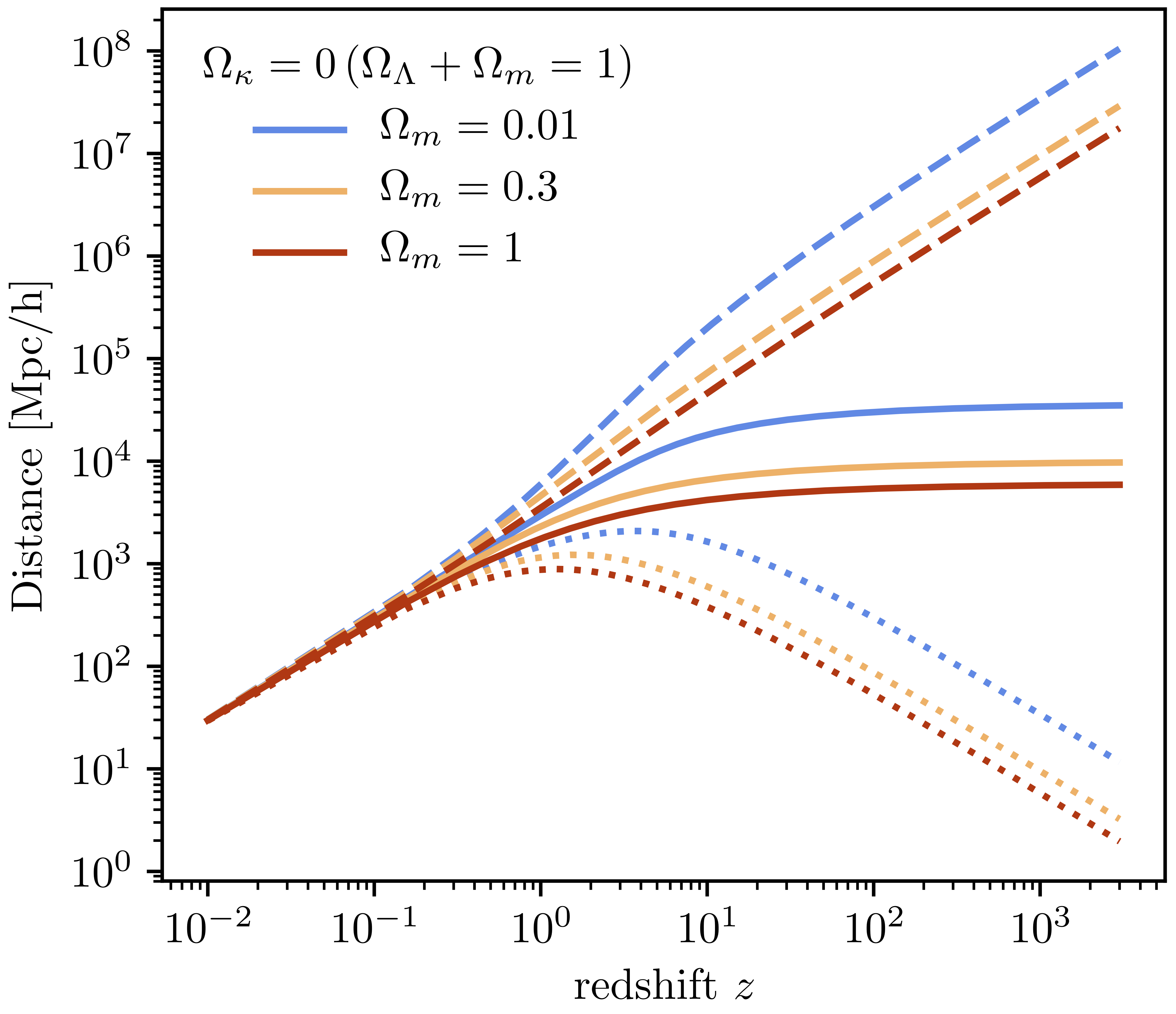
How can we measure these cosmological parameters?

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:

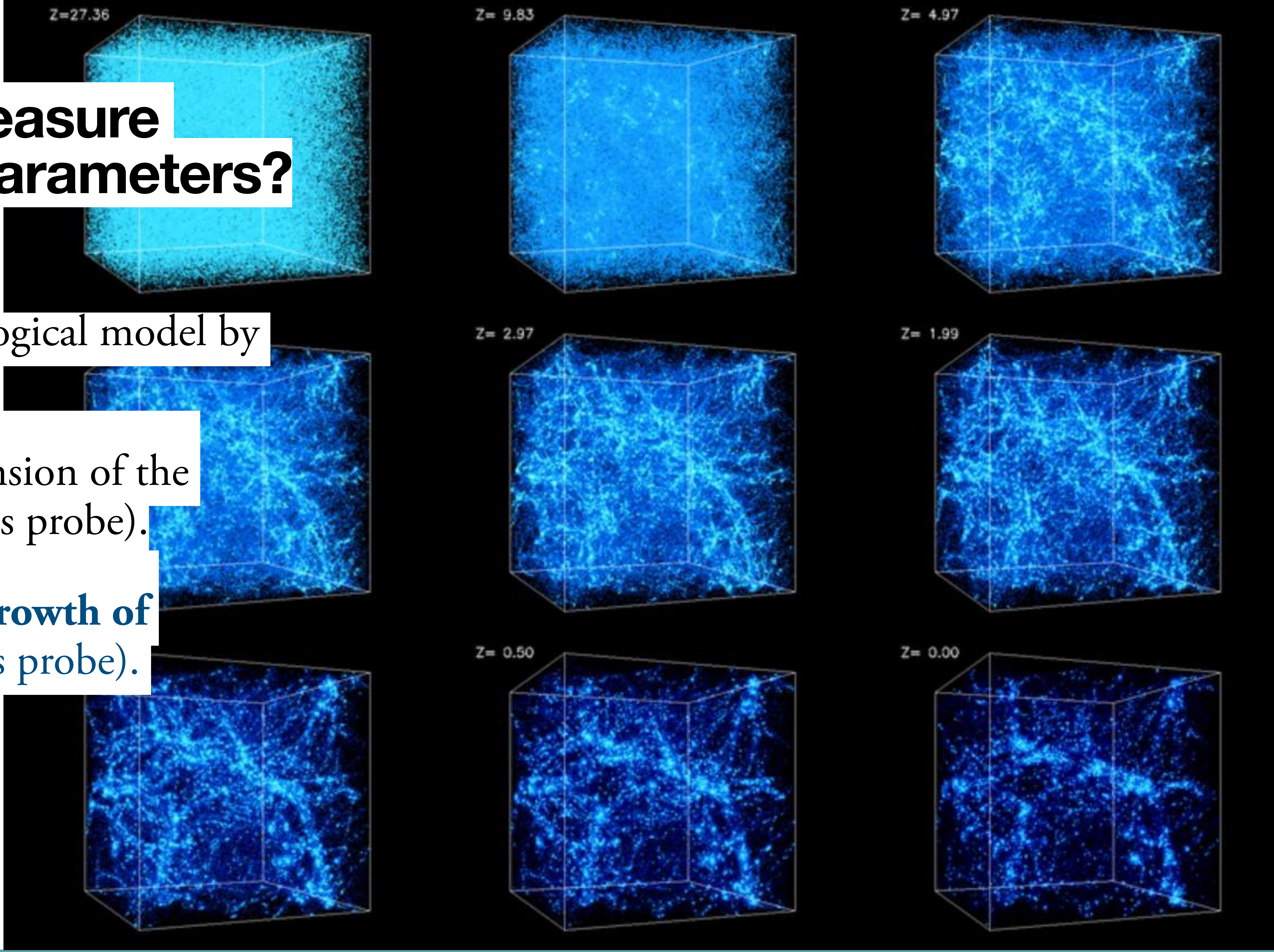
$$H^2(z) = H_0^2\left[\Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_k(1+z)^2 + \Omega_{de}(1+z)^{3(1+w)}\right]$$

How can we measure cosmological parameters?

We can probe a cosmological model by studying:

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

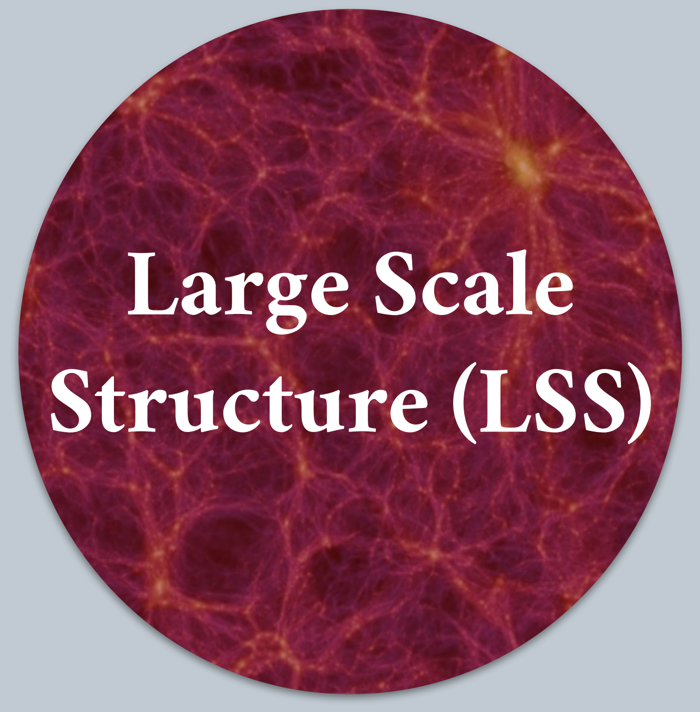
(ii) The history of the **growth of structure** (dynamics probe).



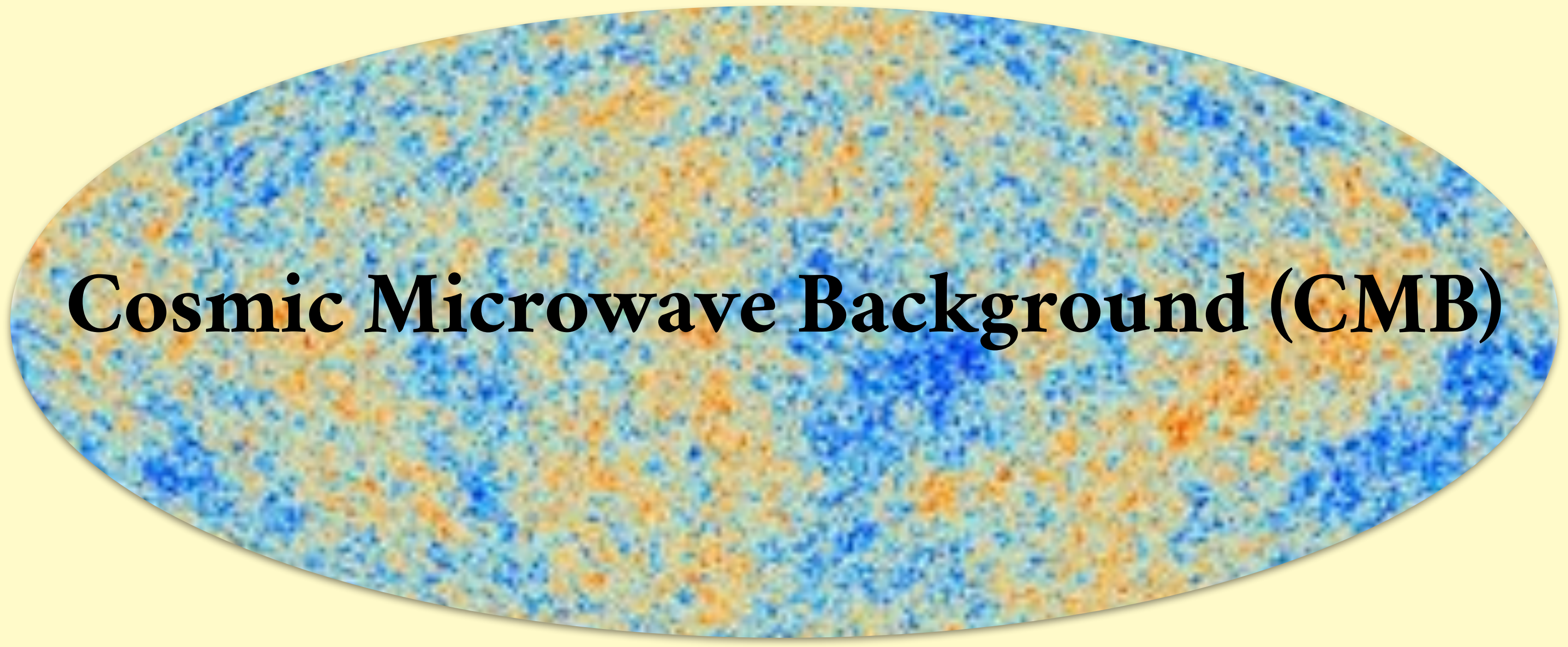
Some probes to measure cosmological parameters

History of Expansion

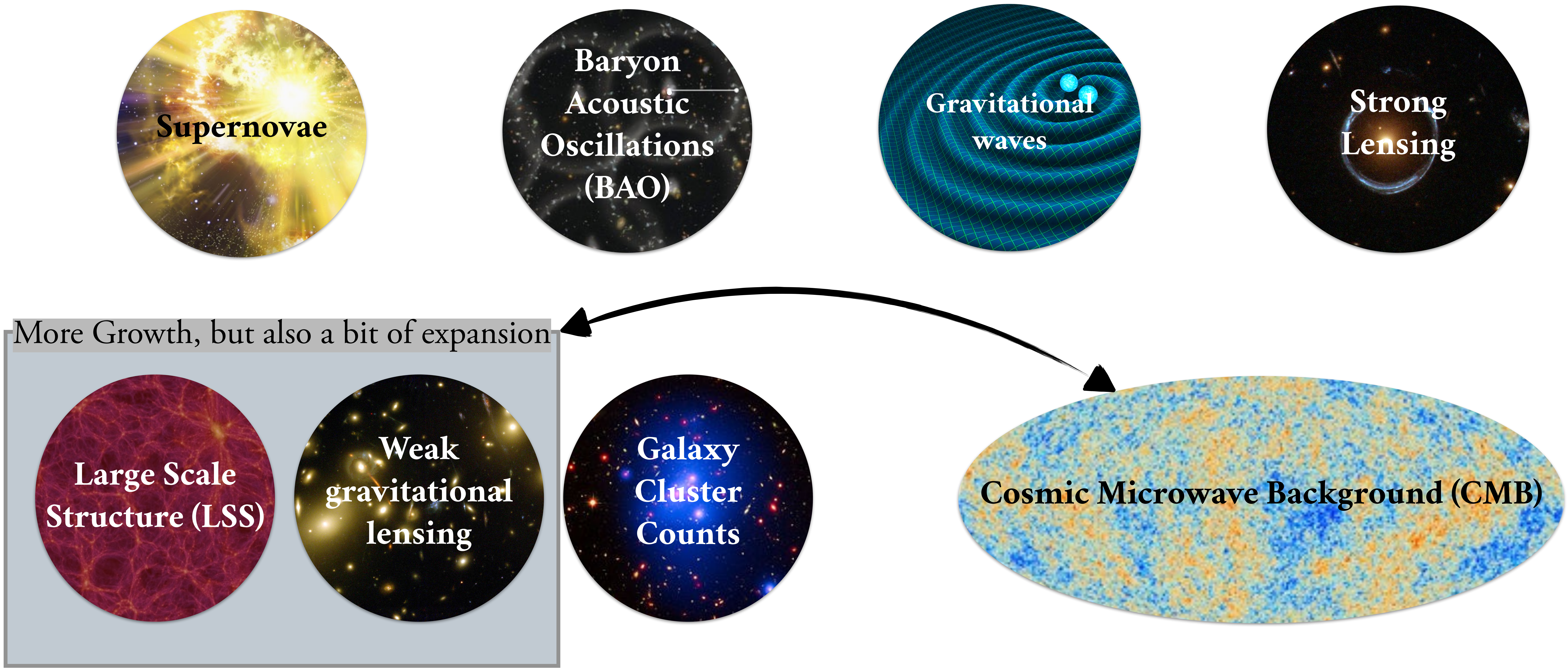
More Growth, but also a bit of expansion



Growth and Expansion

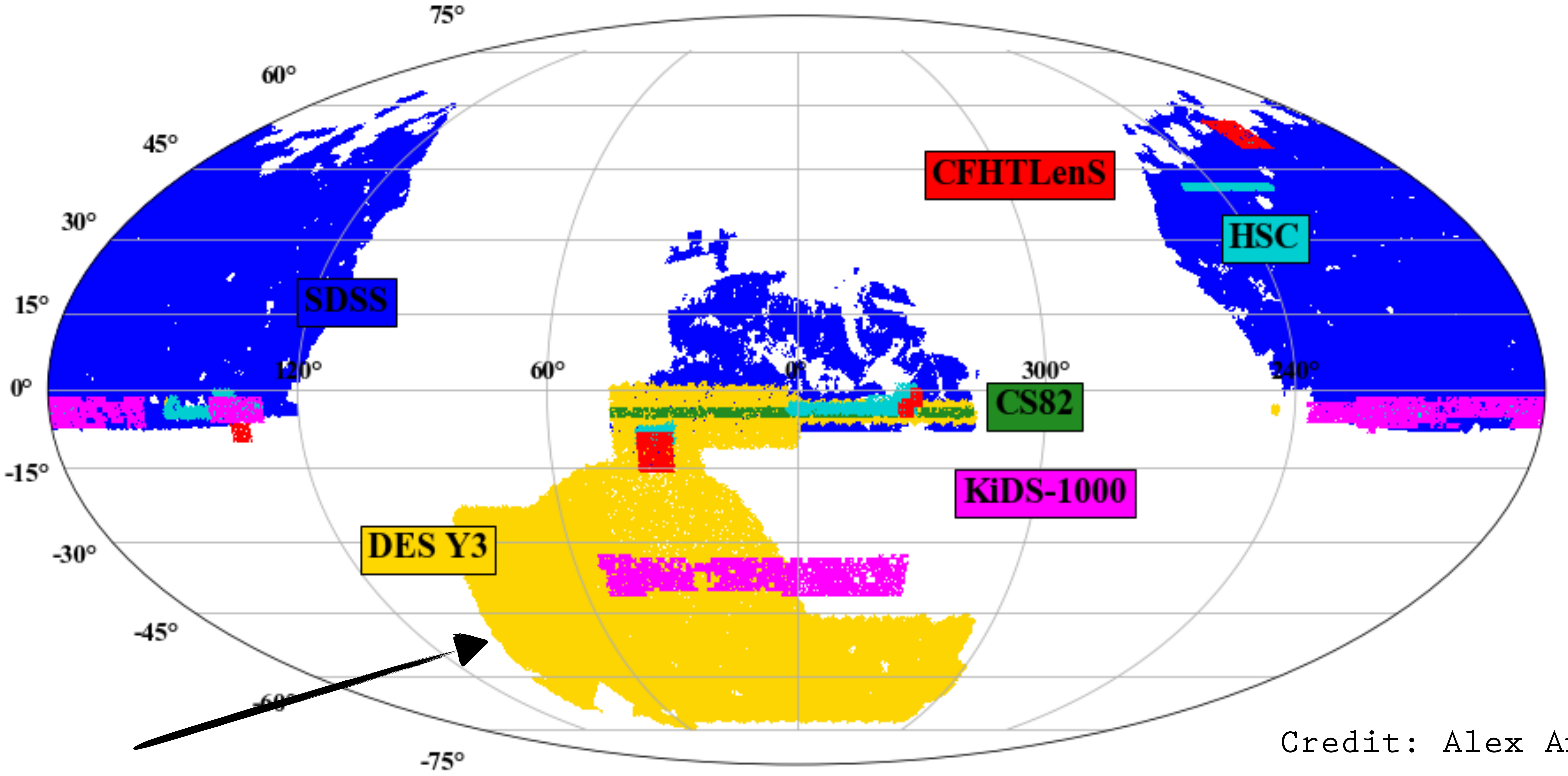


In this talk…


Supernovae
Baryon Acoustic Oscillations (BAO)
Gravitational waves
Strong Lensing
More Growth, but also a bit of expansion
Large Scale Structure (LSS)
Weak gravitational lensing
Galaxy Cluster Counts
Cosmic Microwave Background (CMB)

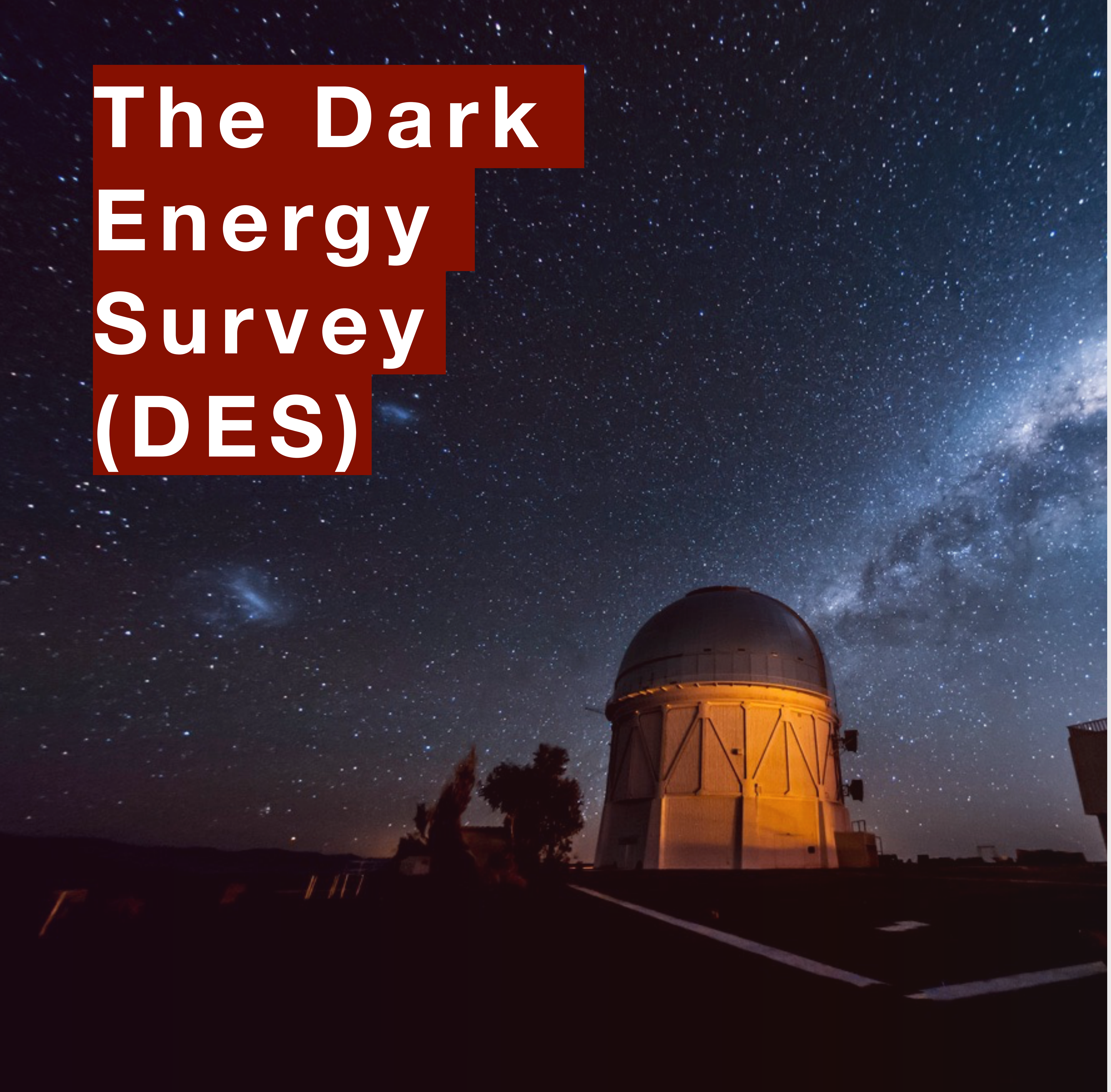
Galaxy surveys: Photometric surveys for WL

Mapping the Universe



Credit: Alex Amon

The Dark Energy Survey (DES)

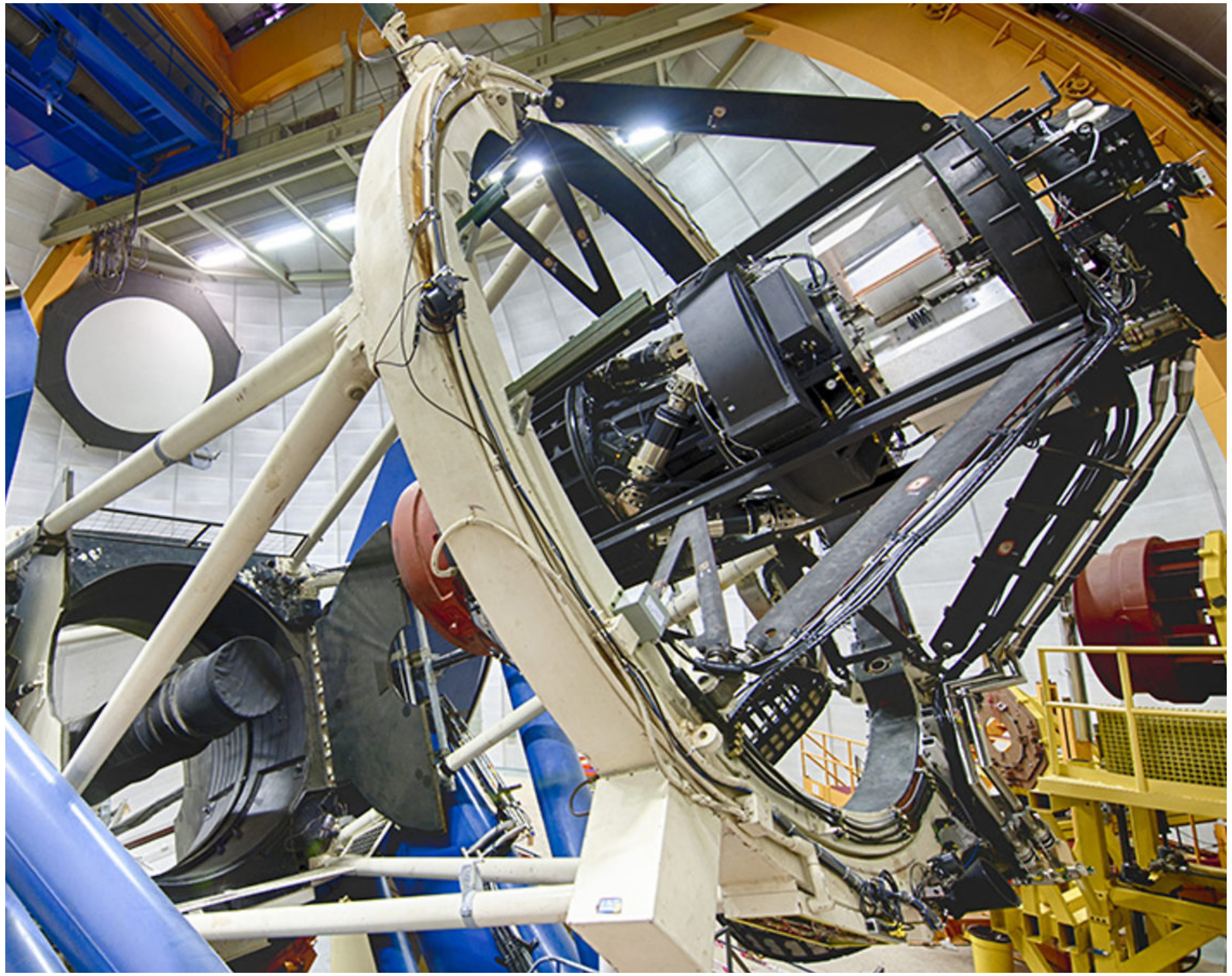


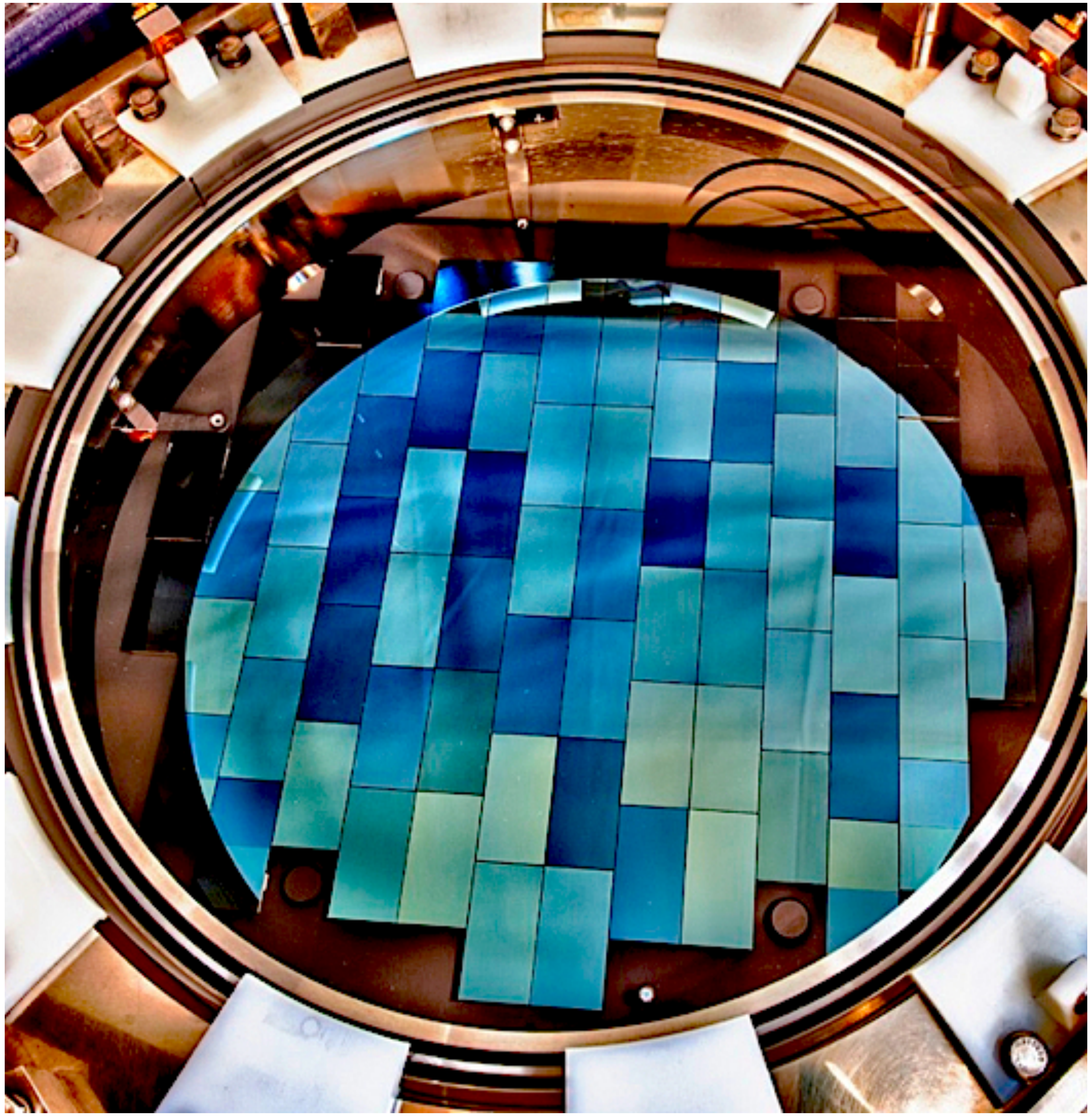
- Imaging galaxy survey.
- 5000 sq. deg. after 6 years (2013-2019)
- 570-Megapixel digital camera, DECam, mounted on the Blanco 4-meter telescope at Cerro Tololo Inter-American Observatory (Chile).
- Five filters are used (grizY) with a nominal limiting magnitude $i_{AB} \simeq 24$ and with a typical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

The Dark Energy Telescope

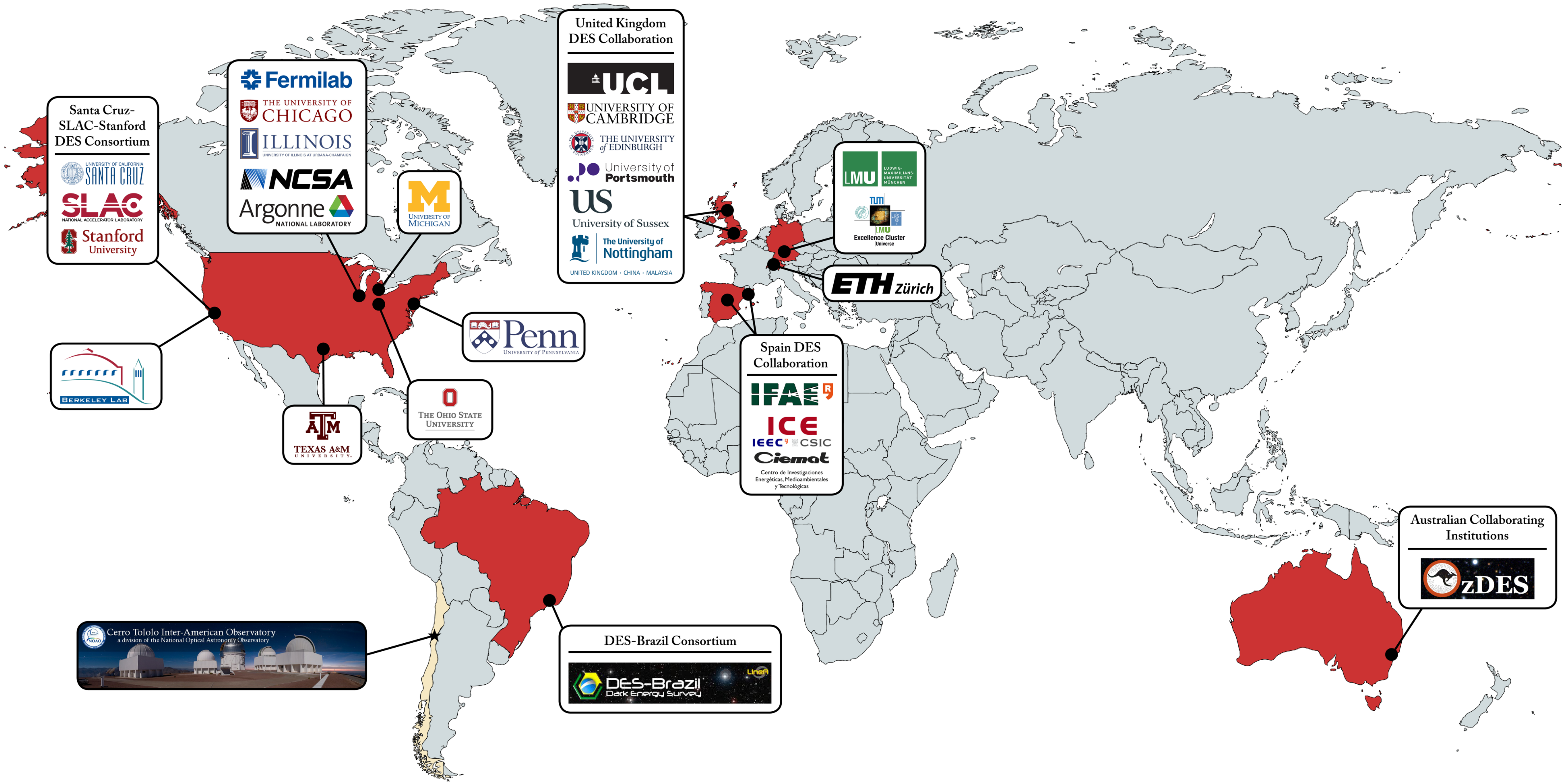
Blanco & DECam

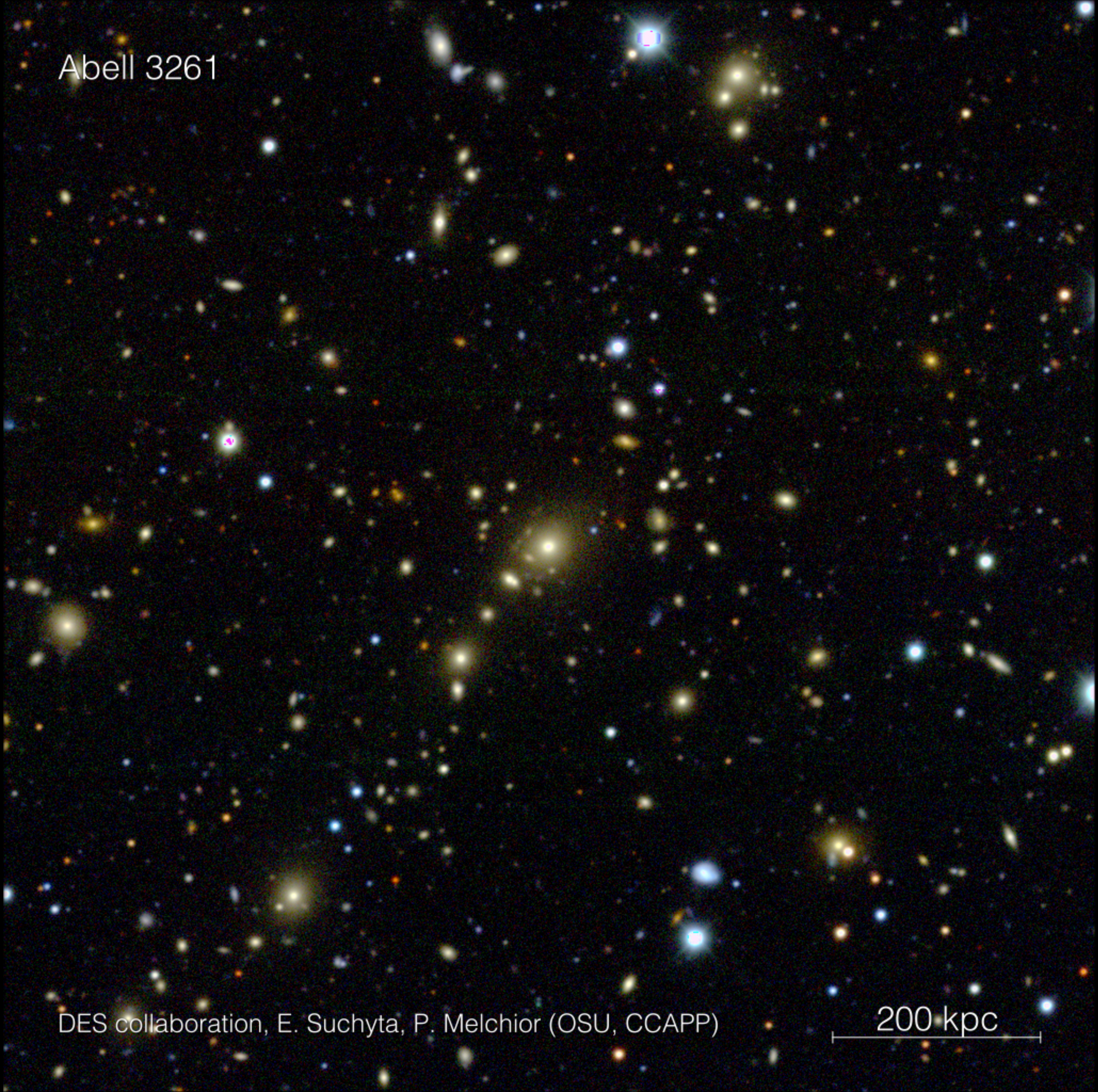
Telescope & Camera



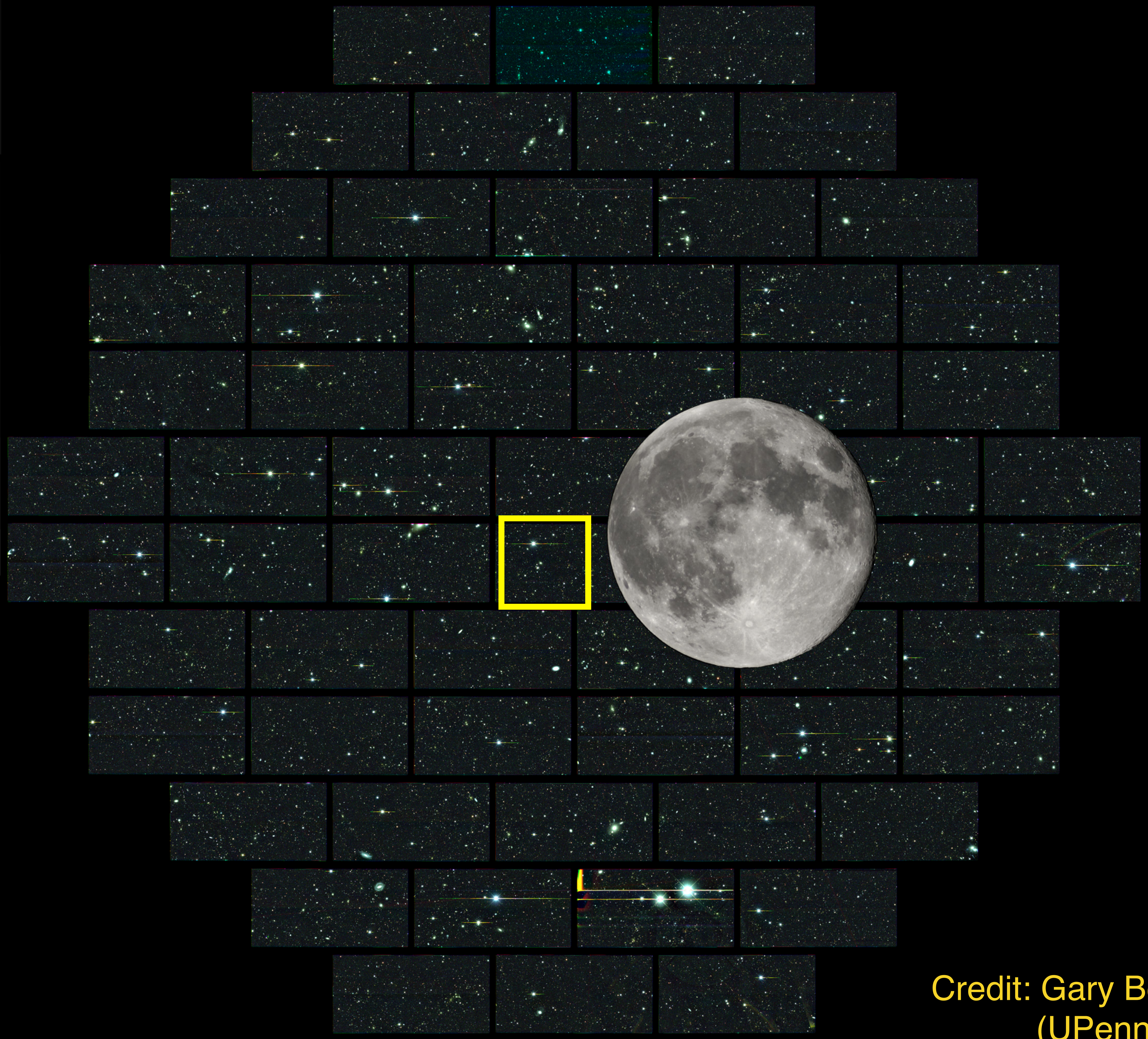


Dark Energy Survey Collaboration

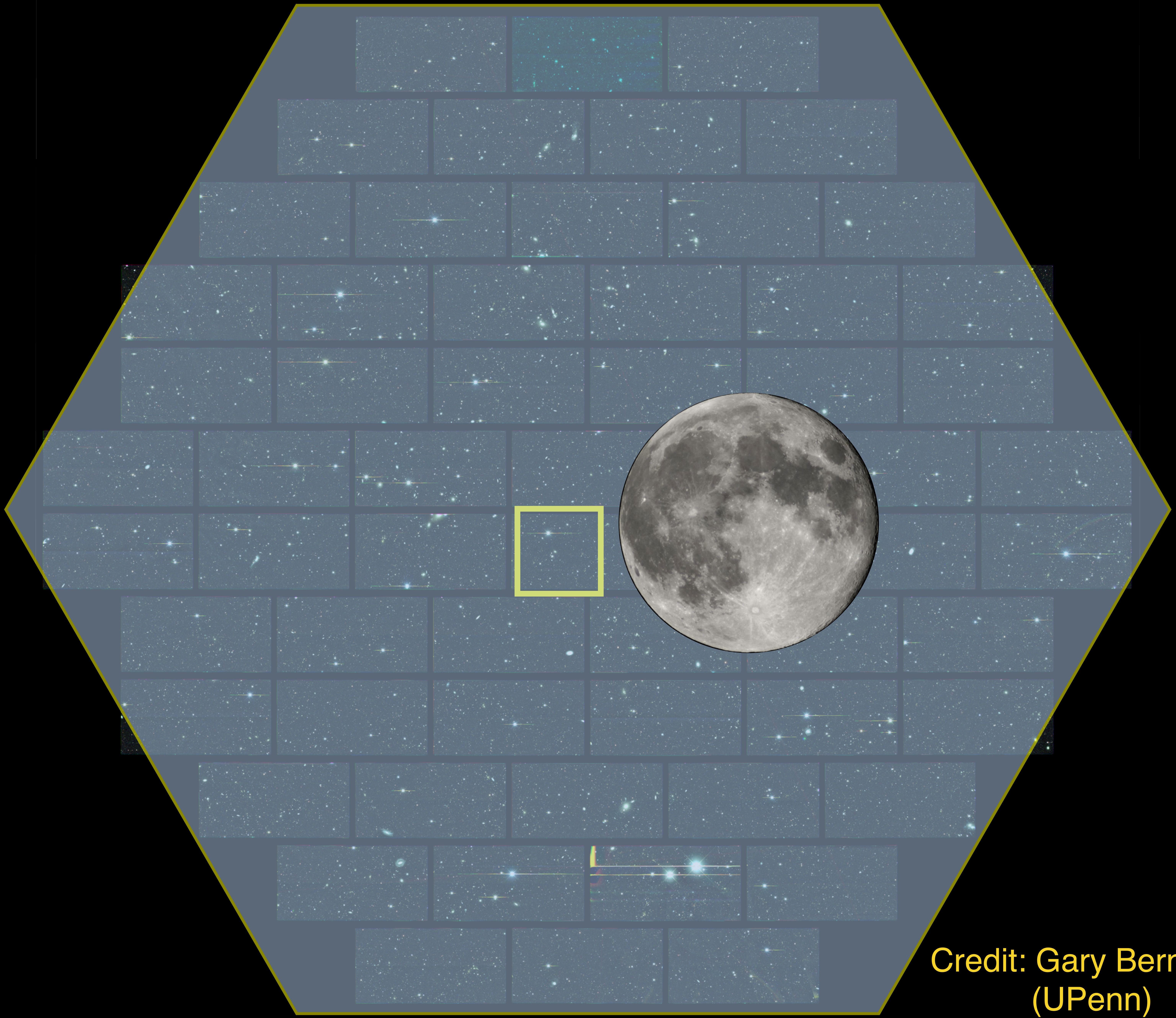



Abell 3261
DES collaboration, E. Suchyta, P. Melchior (OSU, CCAPP)
200 kpc


Credit: Gary Bernstein
(UPenn)



Credit: Gary Bernstein (UPenn)



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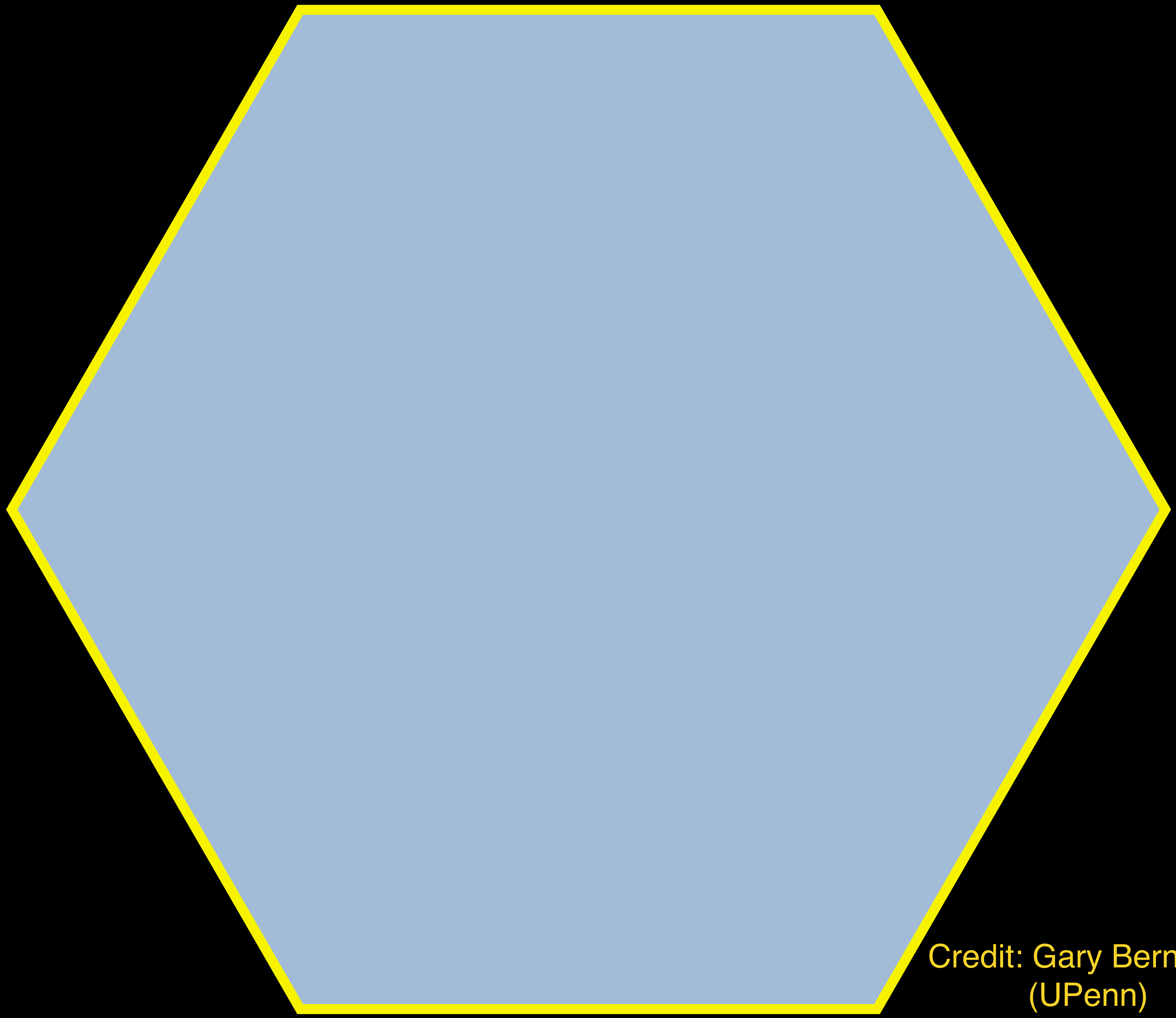

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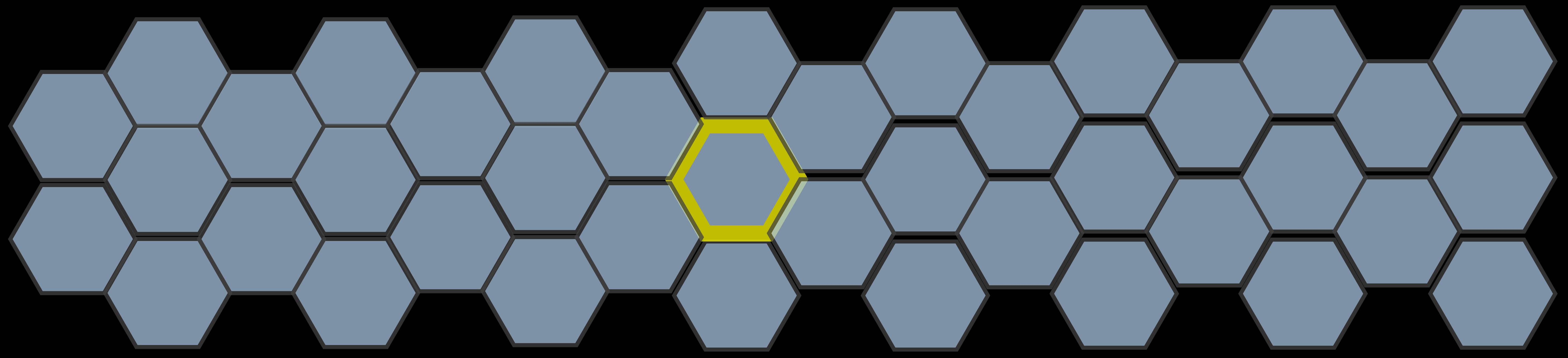

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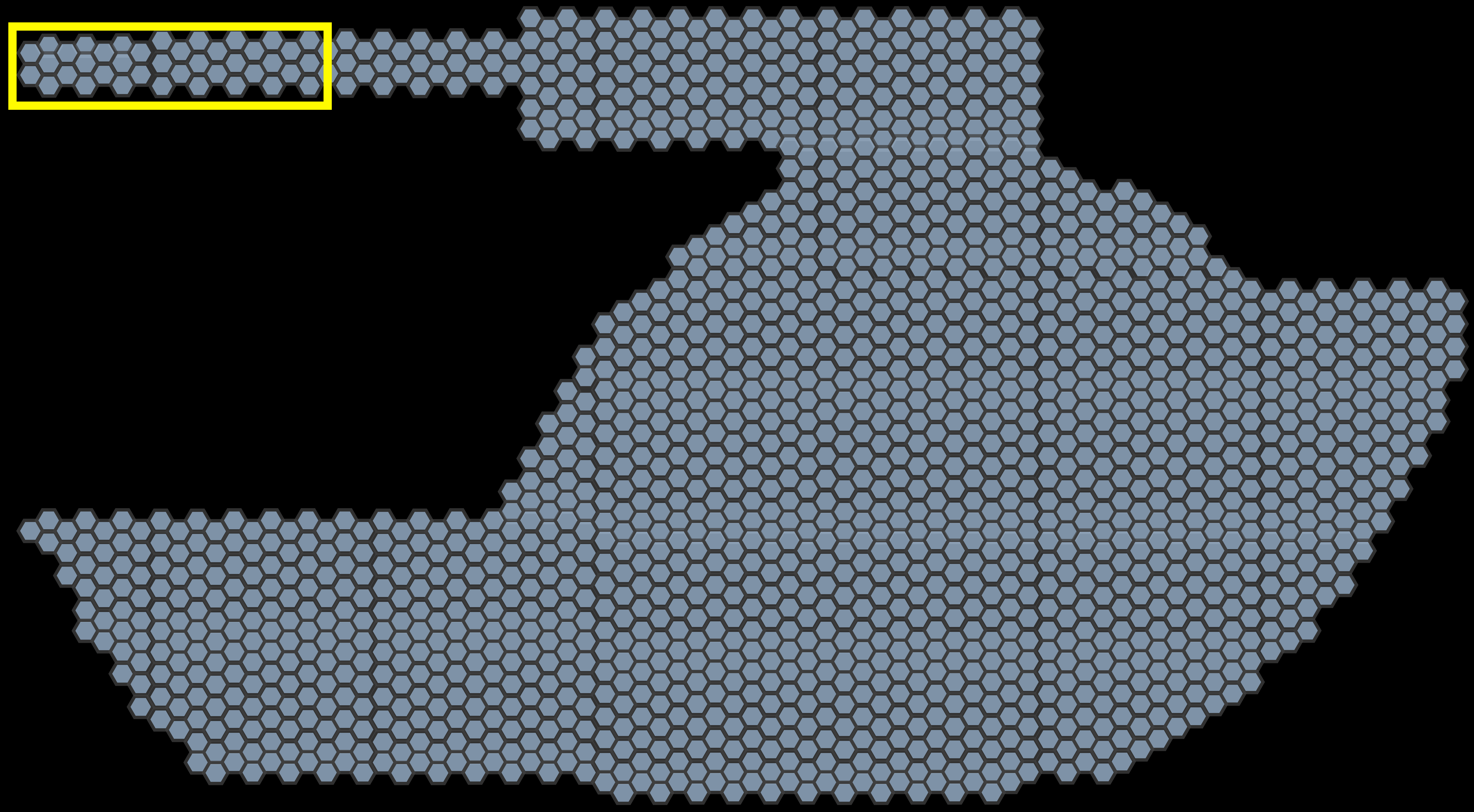

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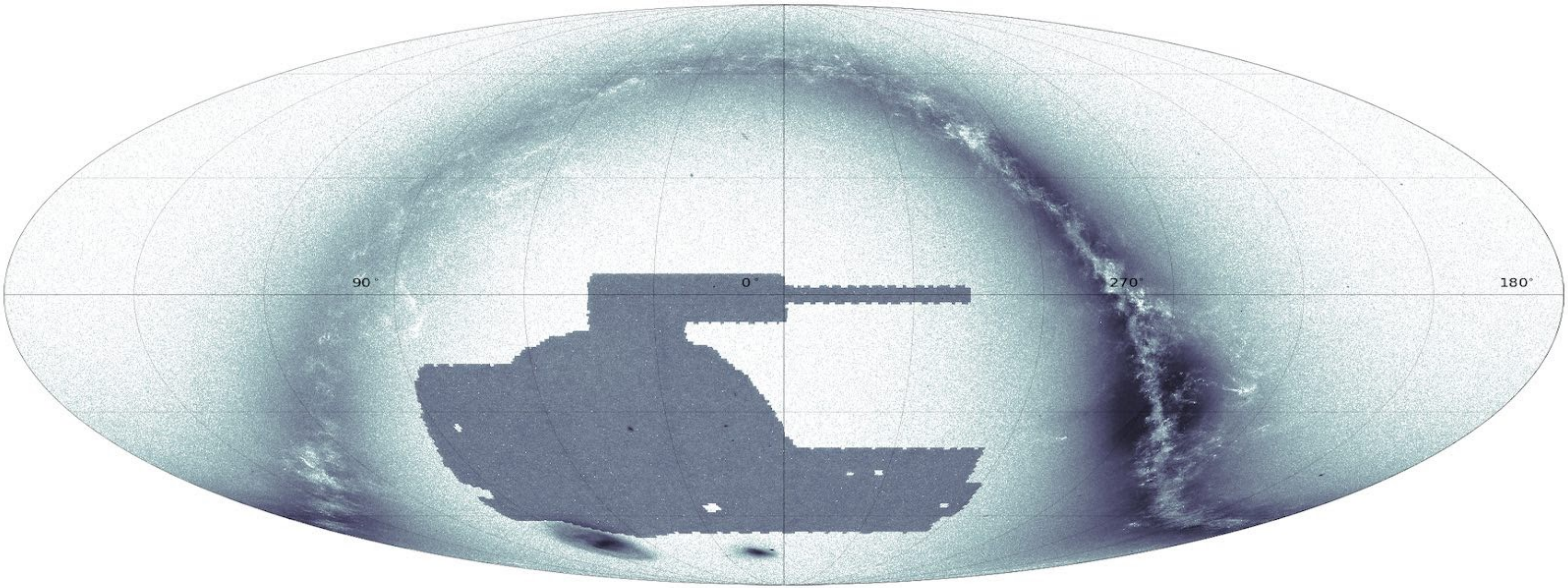
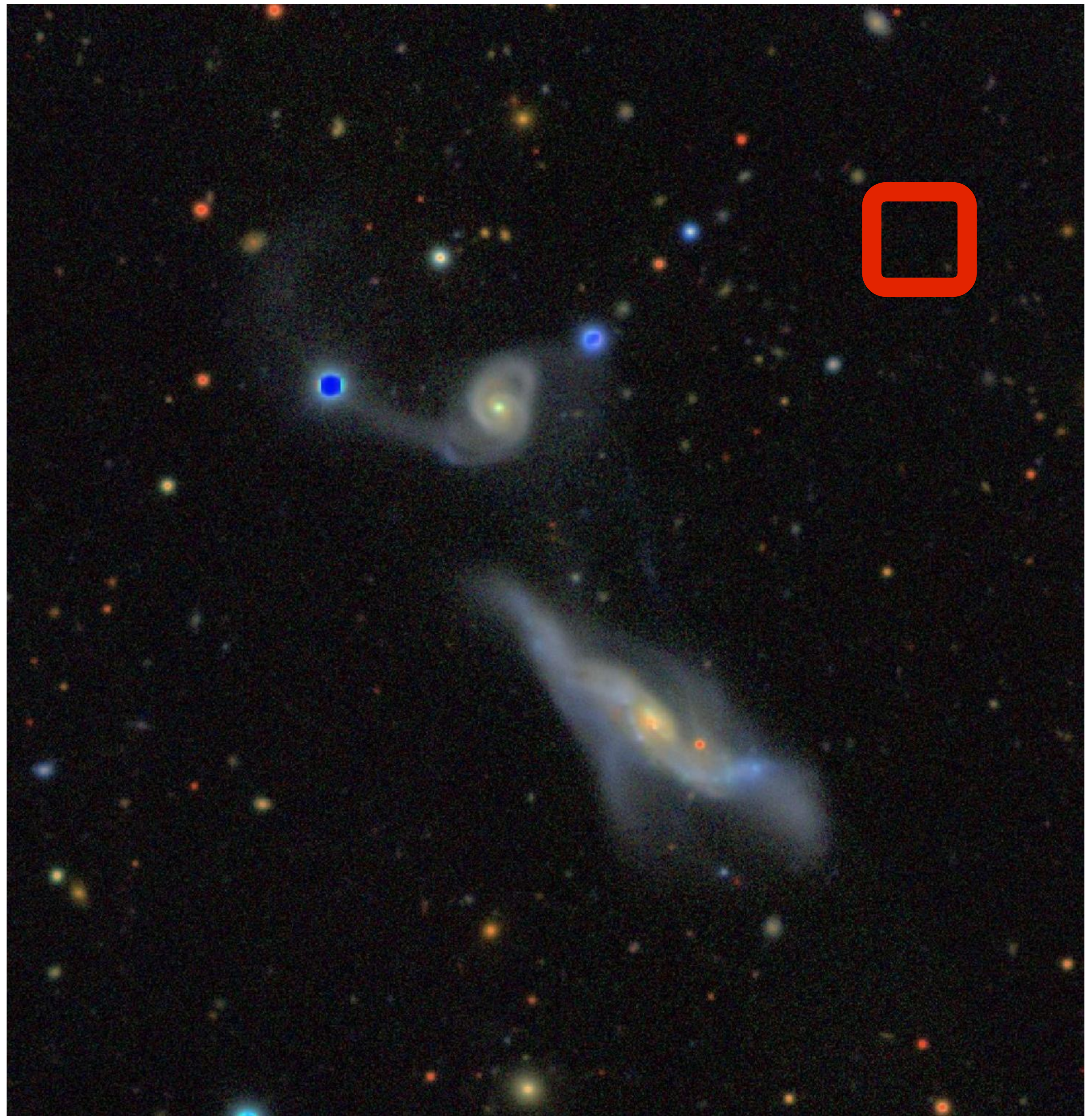
The Dark Energy Survey (DES)



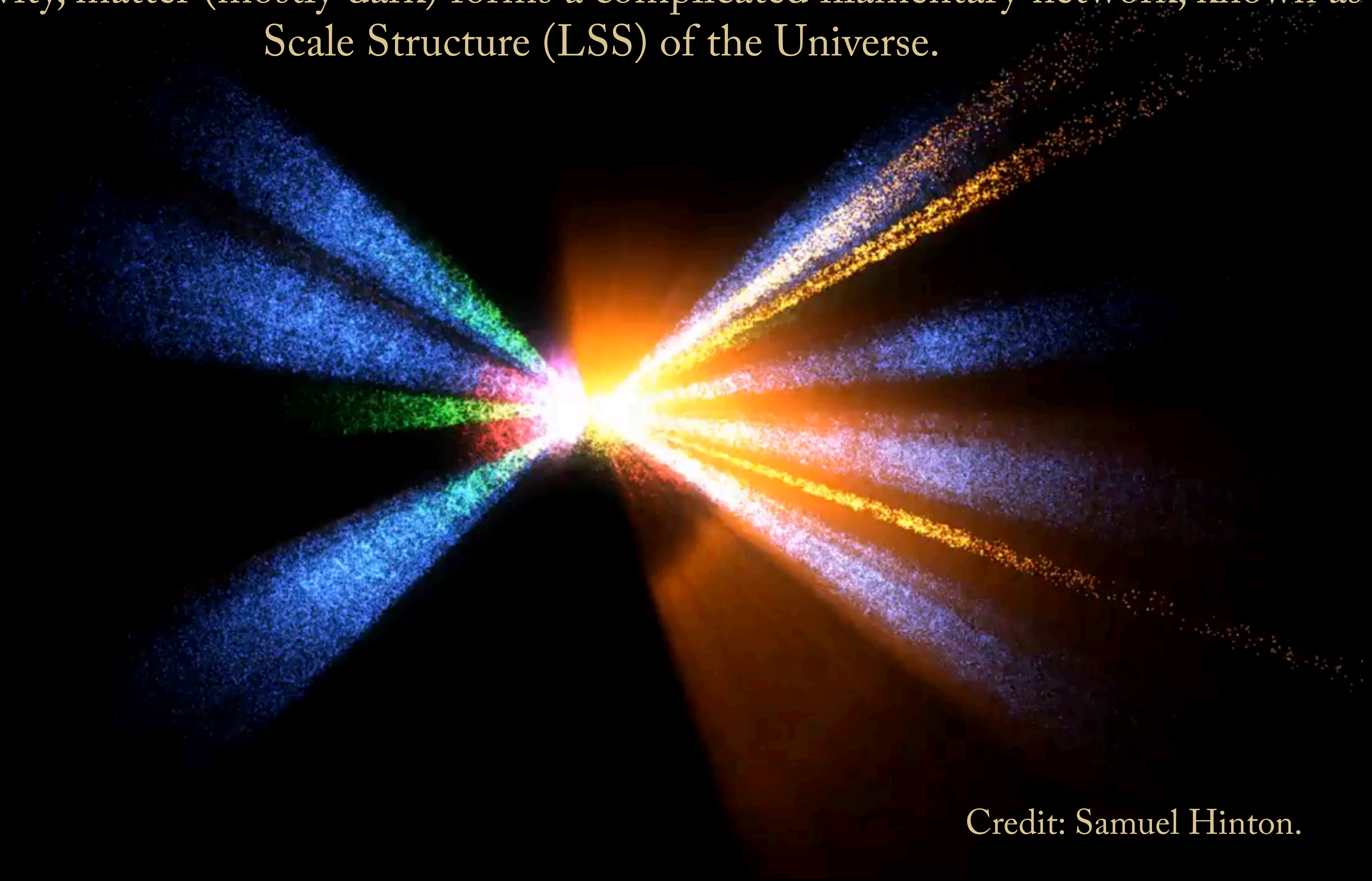
Detecting galaxies



Detecting galaxies

Large Scale Structure (LSS)

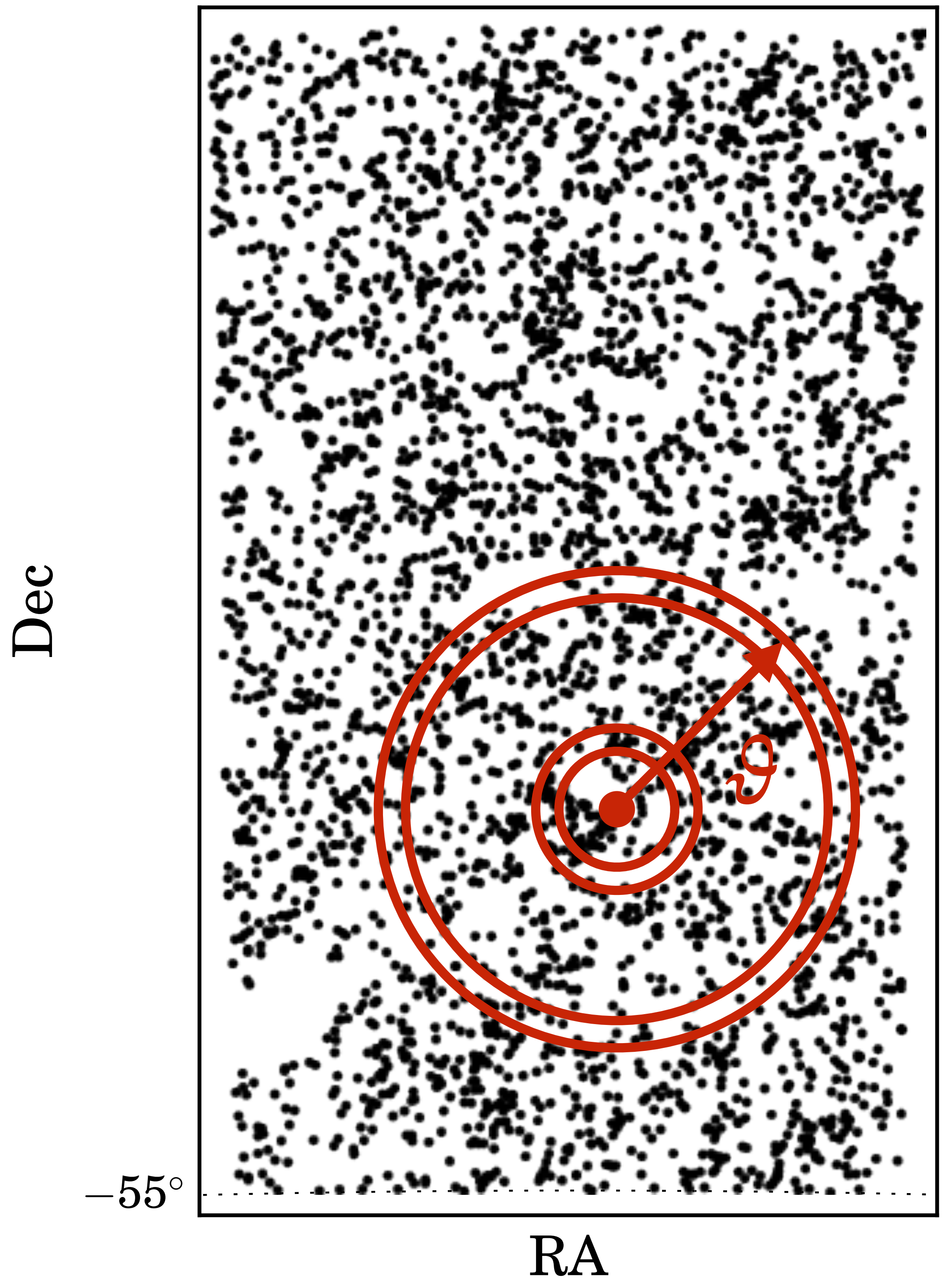
By the effect of gravity, matter (mostly dark) forms a complicated filamentary network, known as the Large Scale Structure (LSS) of the Universe.

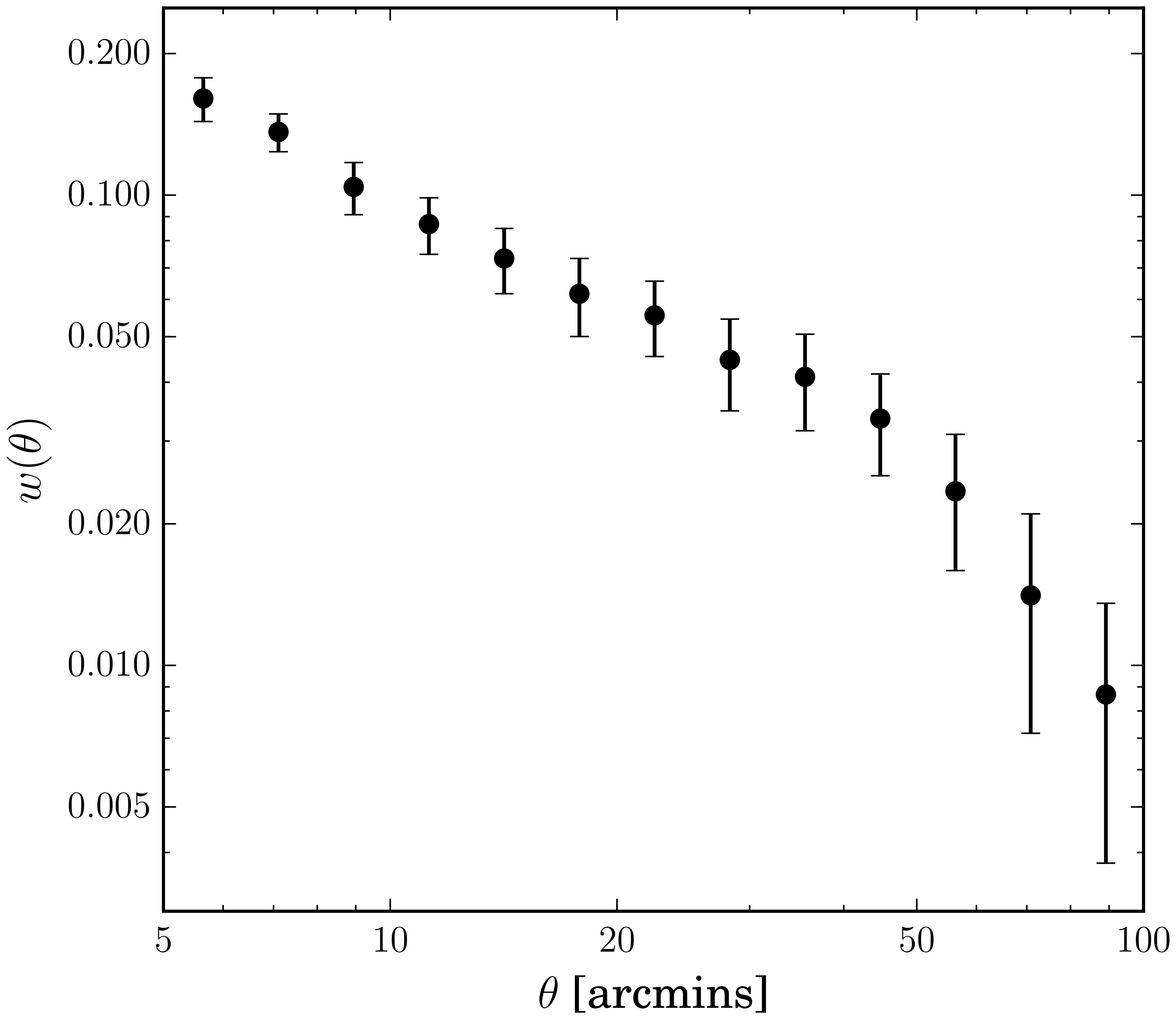


Credit: Samuel Hinton.

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

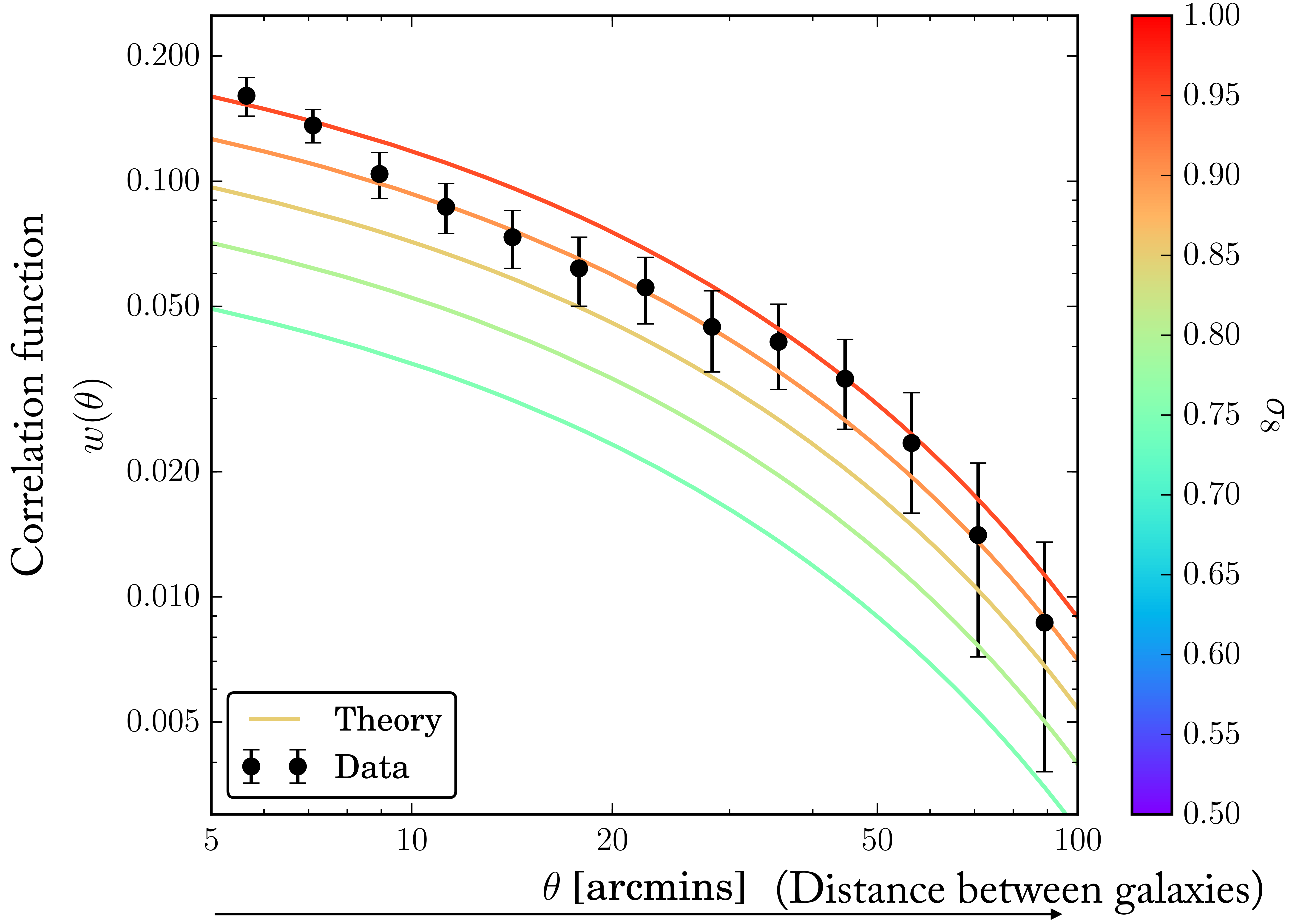
- Given a random galaxy in a location, the correlation function describes the probability that another galaxy will be found within a given distance.
- It can be thought of as a lumpiness factor - the higher the value for some distance scale, the more lumpy the Universe is at that distance scale.





Modeling two-point correlation functions…

Figure Credit: Carles Sánchez



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

LSS kernel

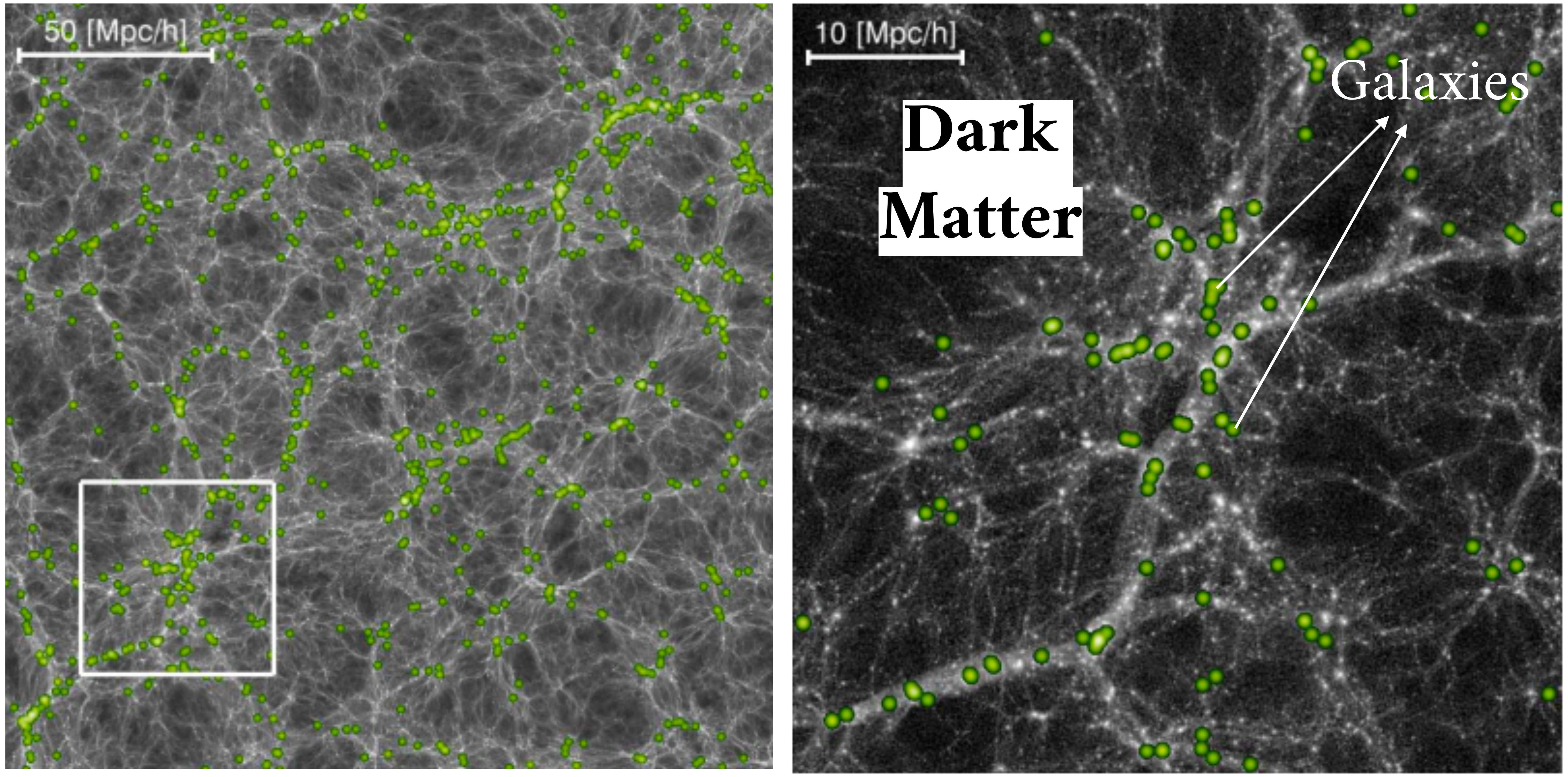
$$q^i_{\delta_g}(k, \chi) = b^i\left(k, z(\chi)\right) \frac{n^i_g(z(\chi))}{\bar{n}^i_g} \frac{dz}{d\chi}$$

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.

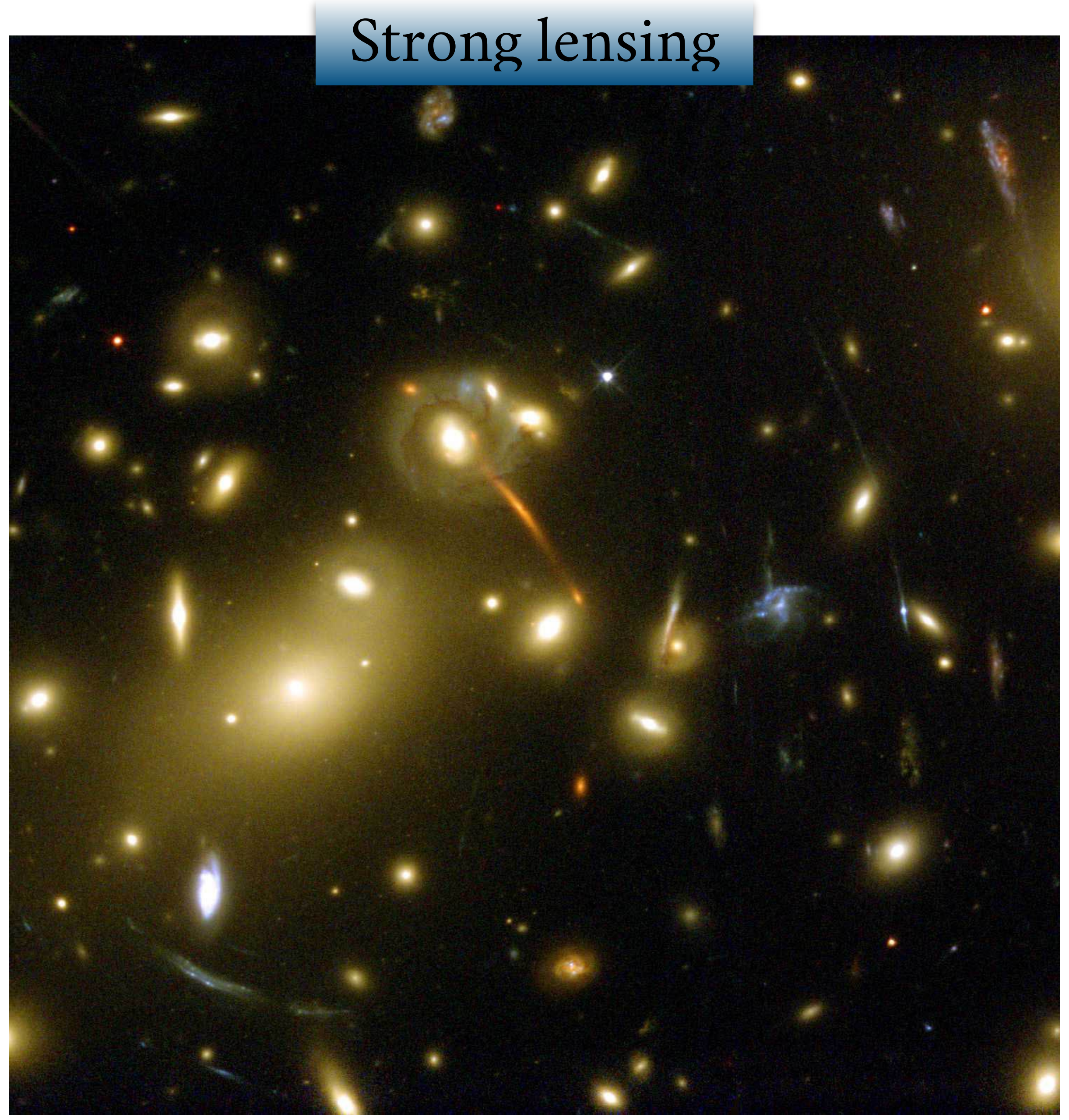
$$\xi_{gg}(r) = b^2(r)\,\xi_{\delta\delta}(r) \qquad P_{gg}(r) = b^2(r)\,P_{\delta\delta}(r)$$

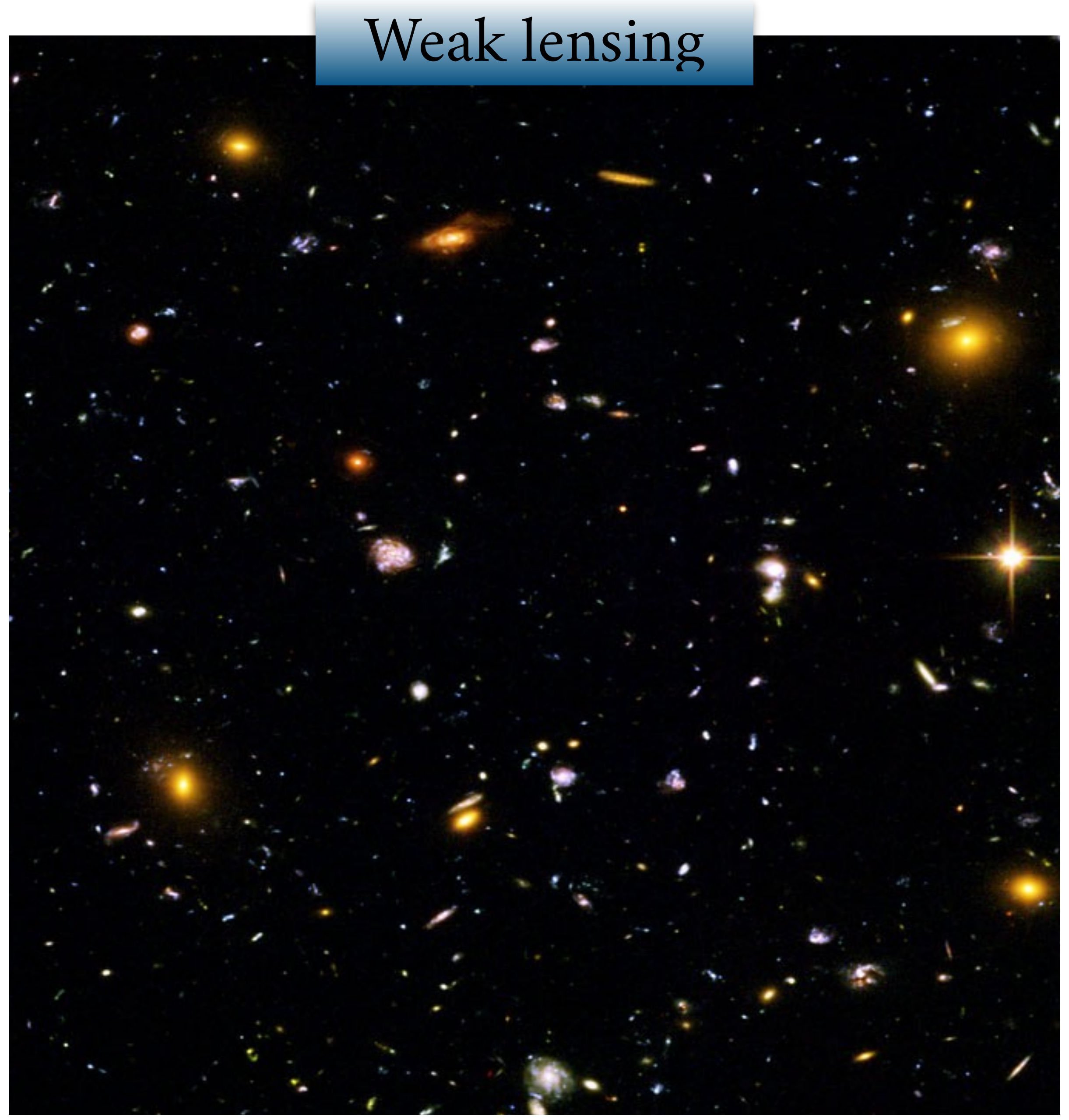


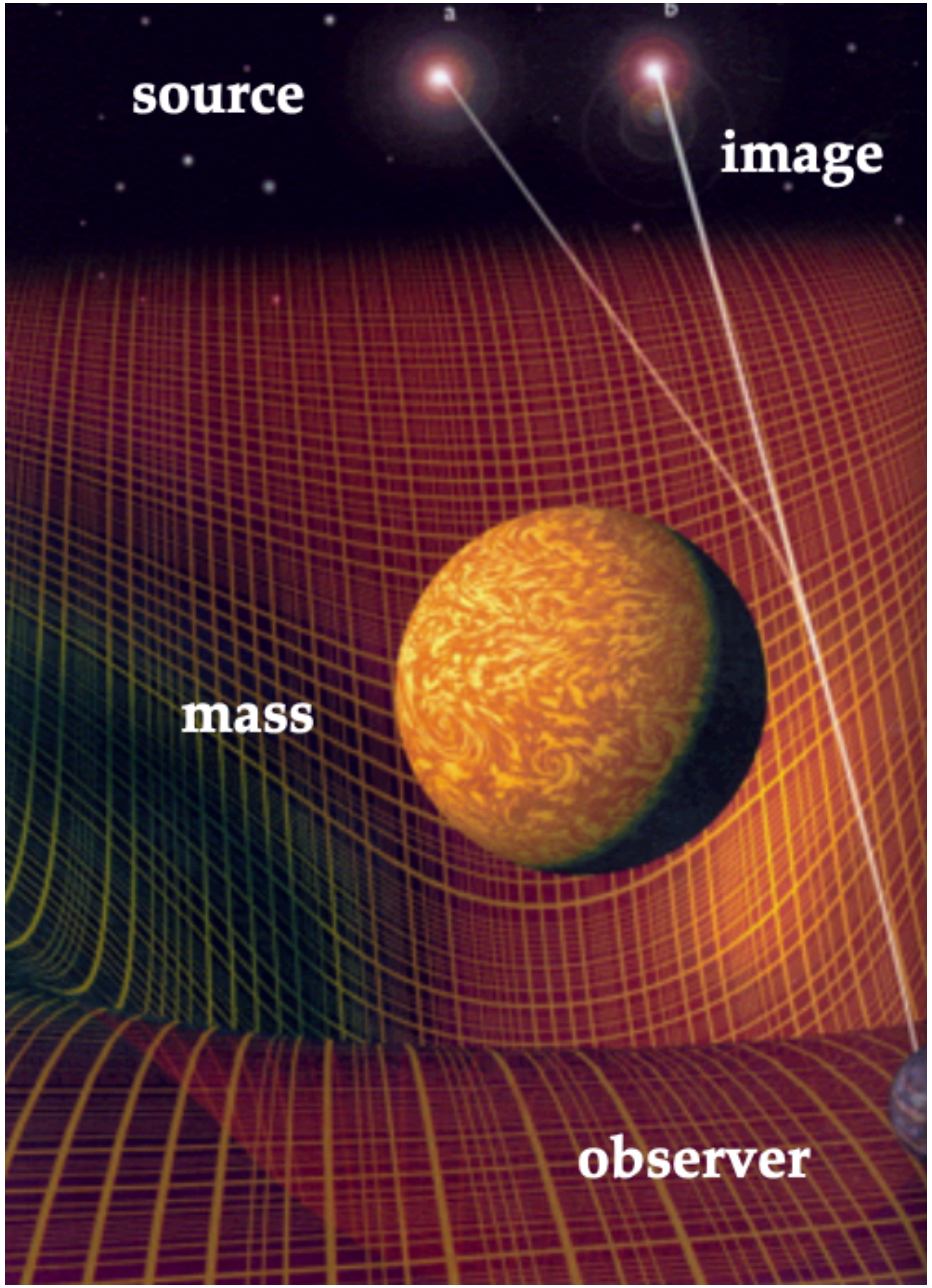
From Orsi et al. (2009)

Gravitational lensing

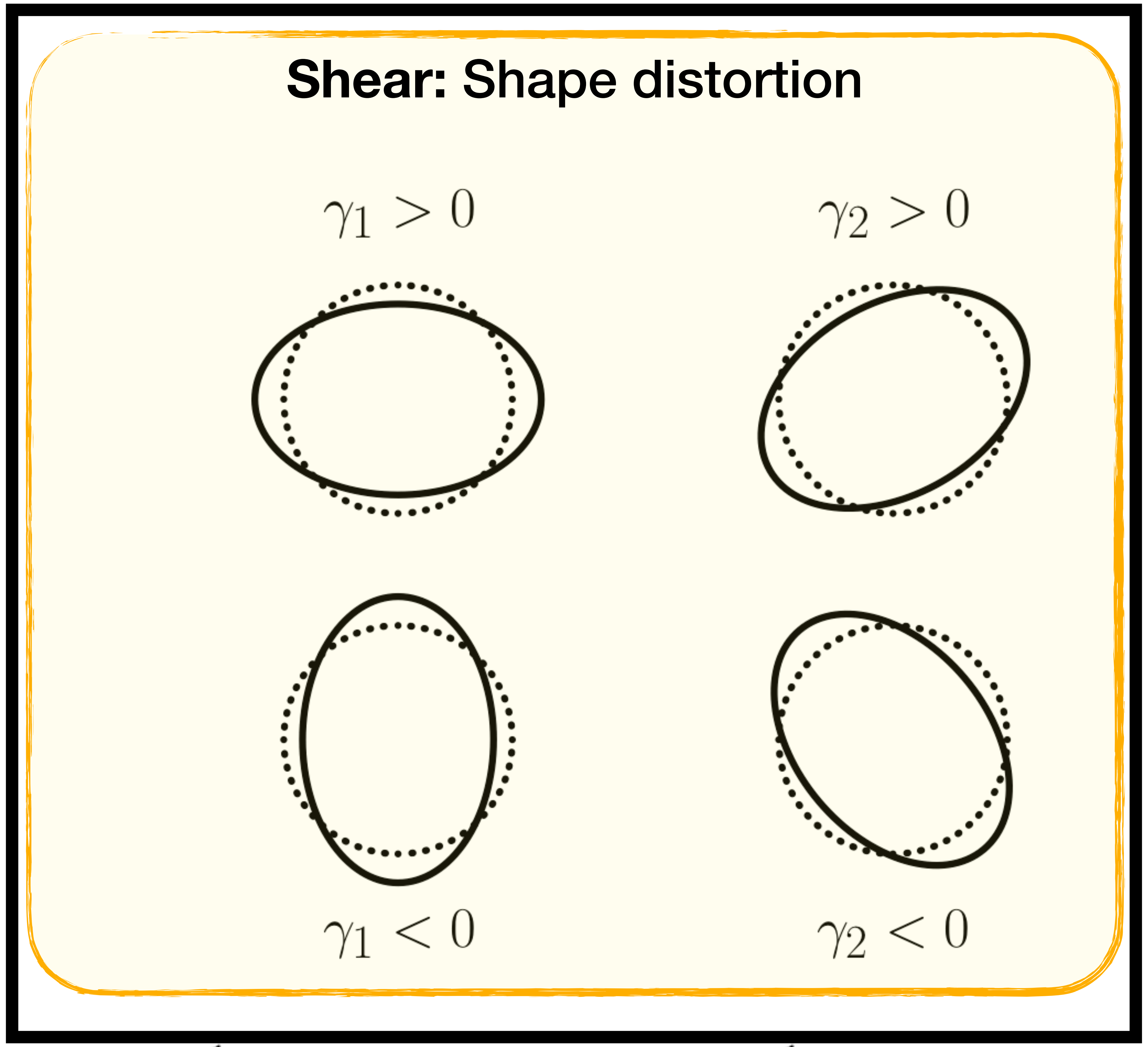
- **Strong gravitational lensing:** If the bending produces multiple images of the galaxy and/or arcs.
- **Weak gravitational lensing:** If the bending is small, the image of galaxies are distorted, stretched and magnified in small amounts. The distortion can be quantified with **shear** (shape) and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

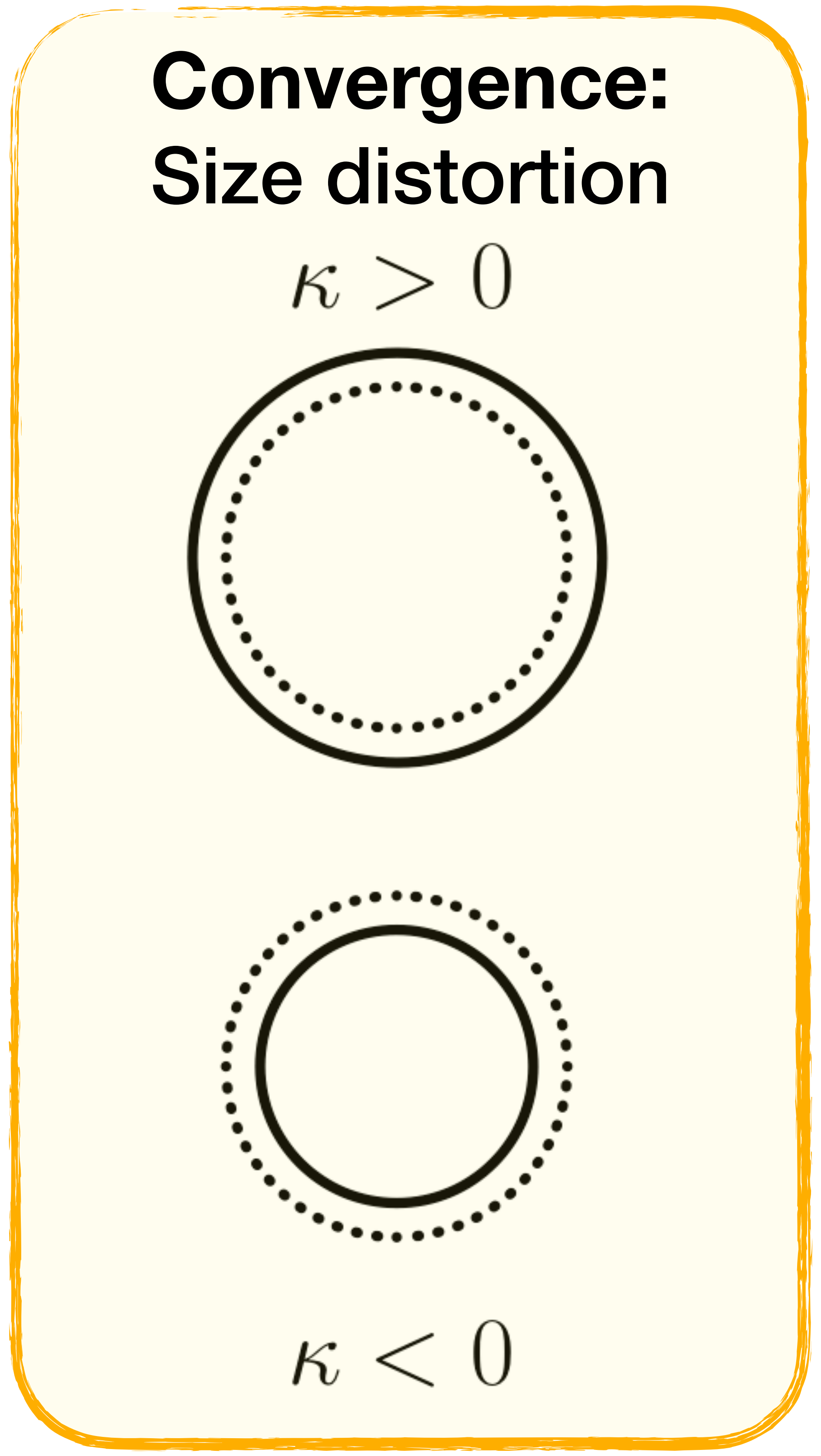






Weak gravitational lensing





Lensing potential

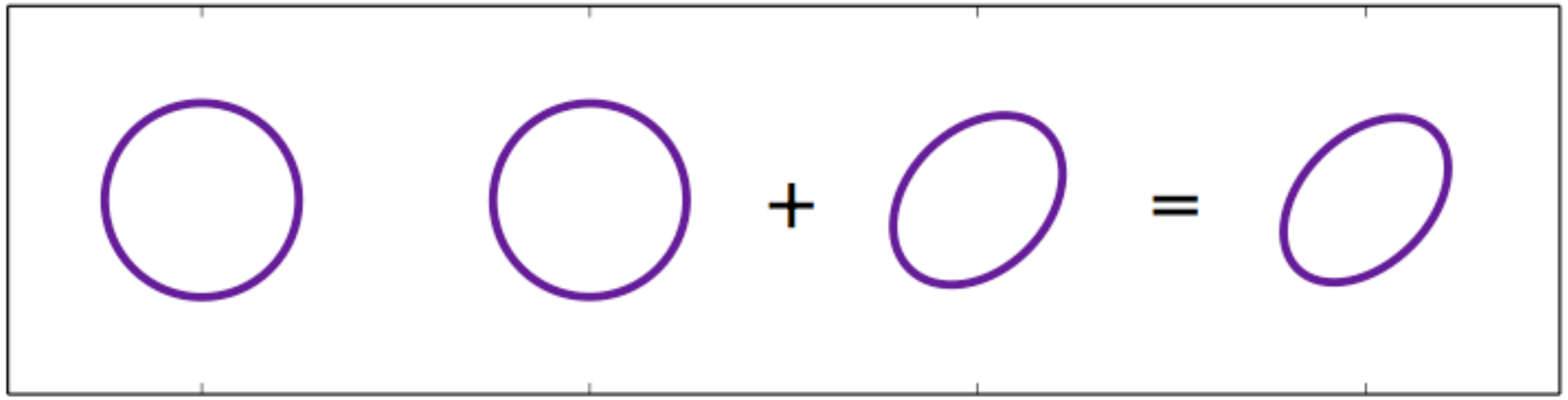
$$\psi(\vec{\theta}) = \frac{2}{c^2}\frac{D_{ls}}{D_l D_s}\int \Phi(D_l\vec{\theta}, z)\, dz$$

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

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:

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



No ellipticity
$e = 0$

Cosmic shear
$\gamma \sim 0.05$

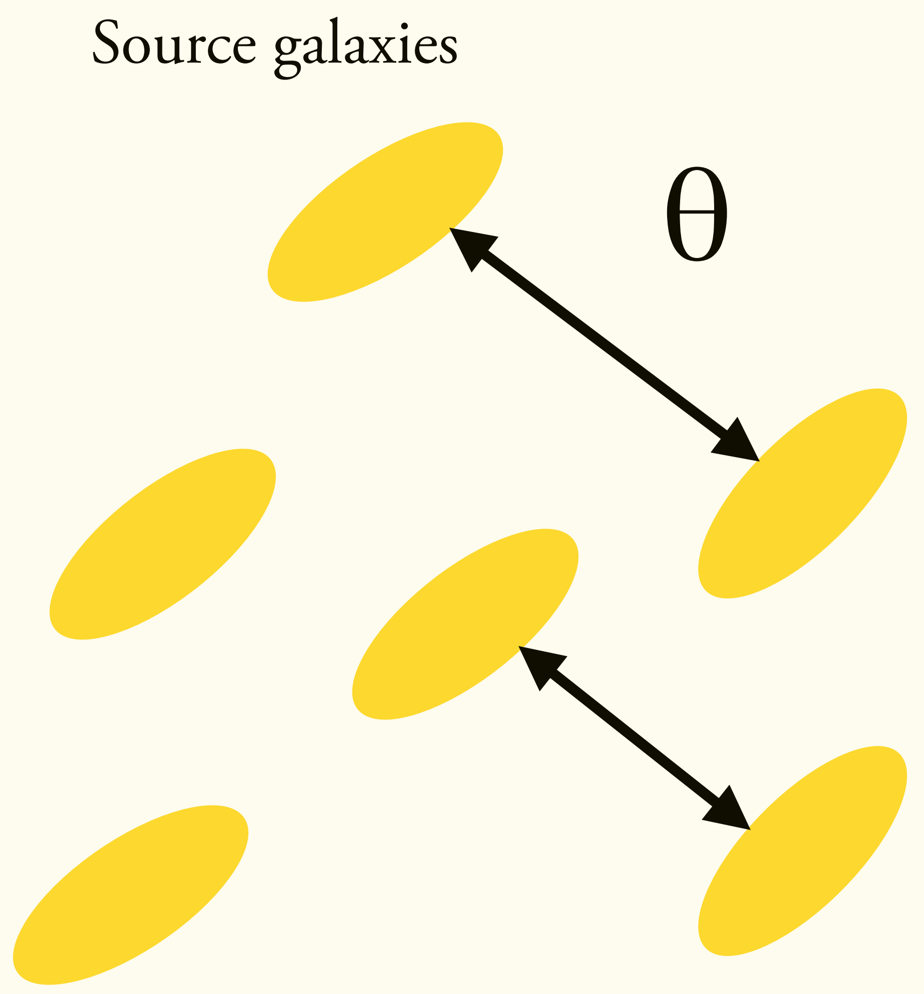
Galaxy ellipticity
$e \sim 0.4$

Observed ellipticity
Galaxy
+
Cosmic shear

Weak gravitational lensing two-point correlation functions

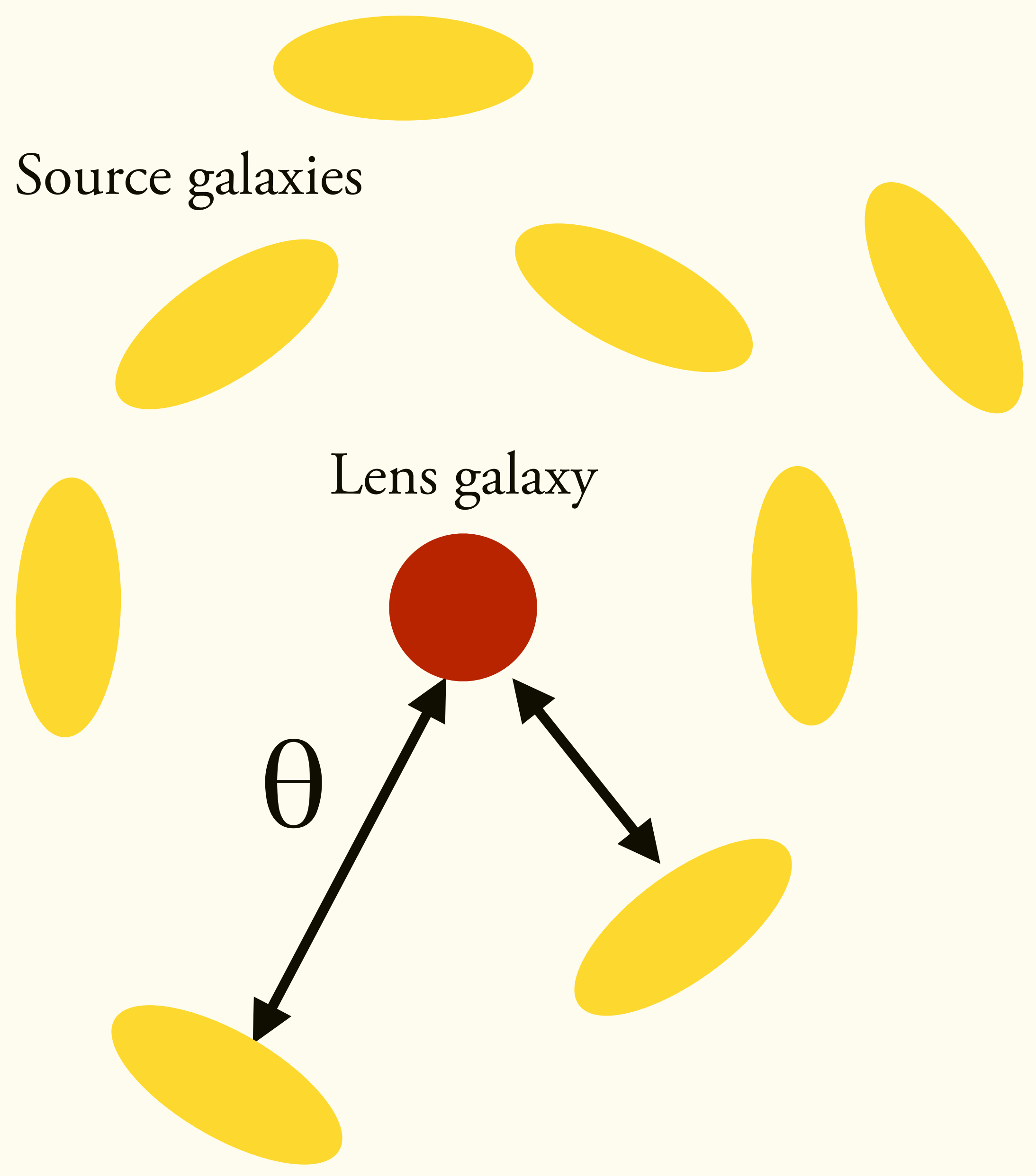
Cosmic shear: source-source correlation

Coherent distortion of galaxy shapes from large-scale structure.

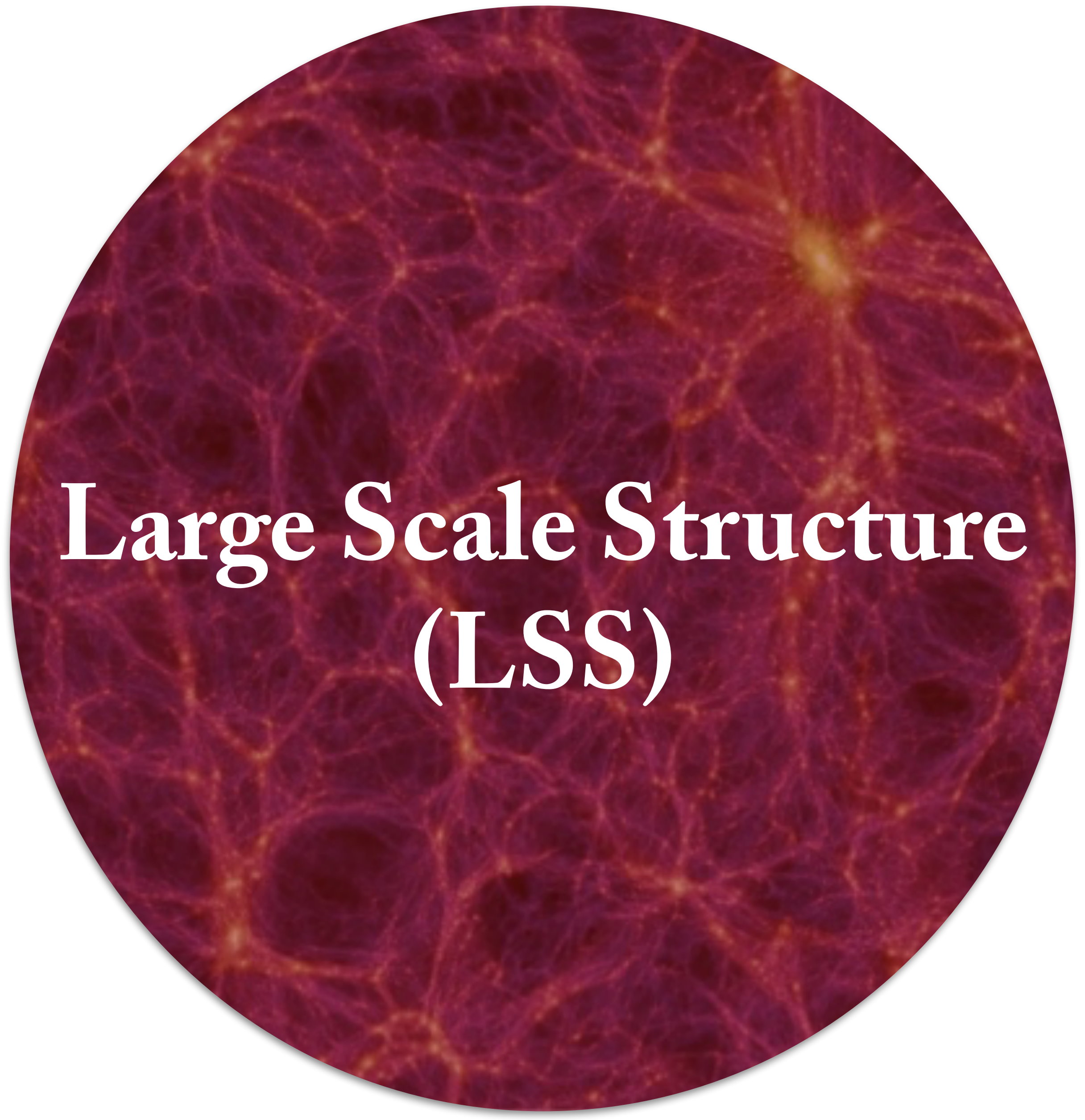


Galaxy-galaxy lensing: lens-source correlation

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



LSS + WL: 3x2pt analysis



+

LSS + WL

3x2pt analysis

Large Scale Structure

DES lens galaxies tracing the Large Scale Structure (Positions)

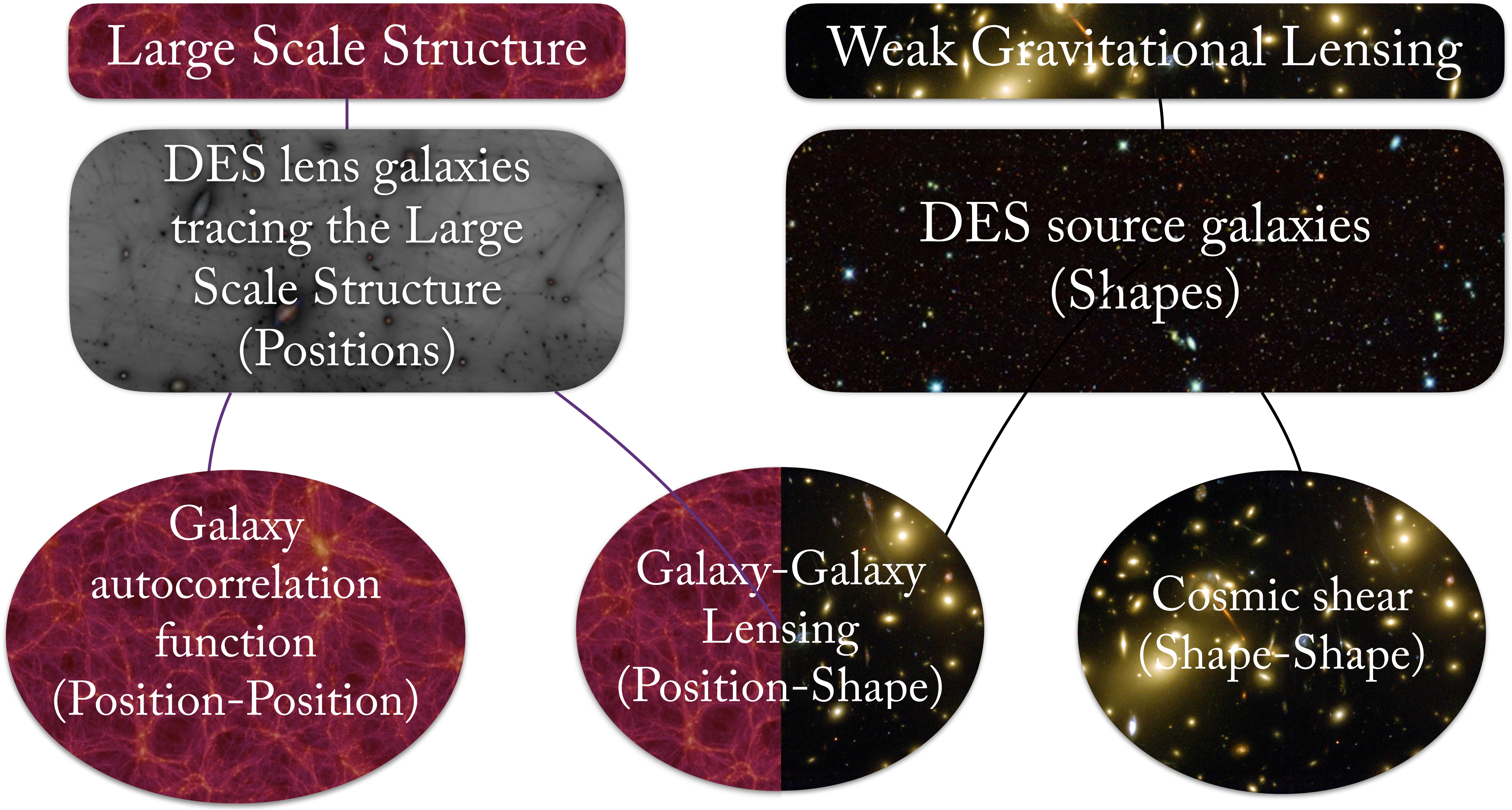
Weak Gravitational Lensing

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 and KiDS data.



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

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

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

LSS + WL

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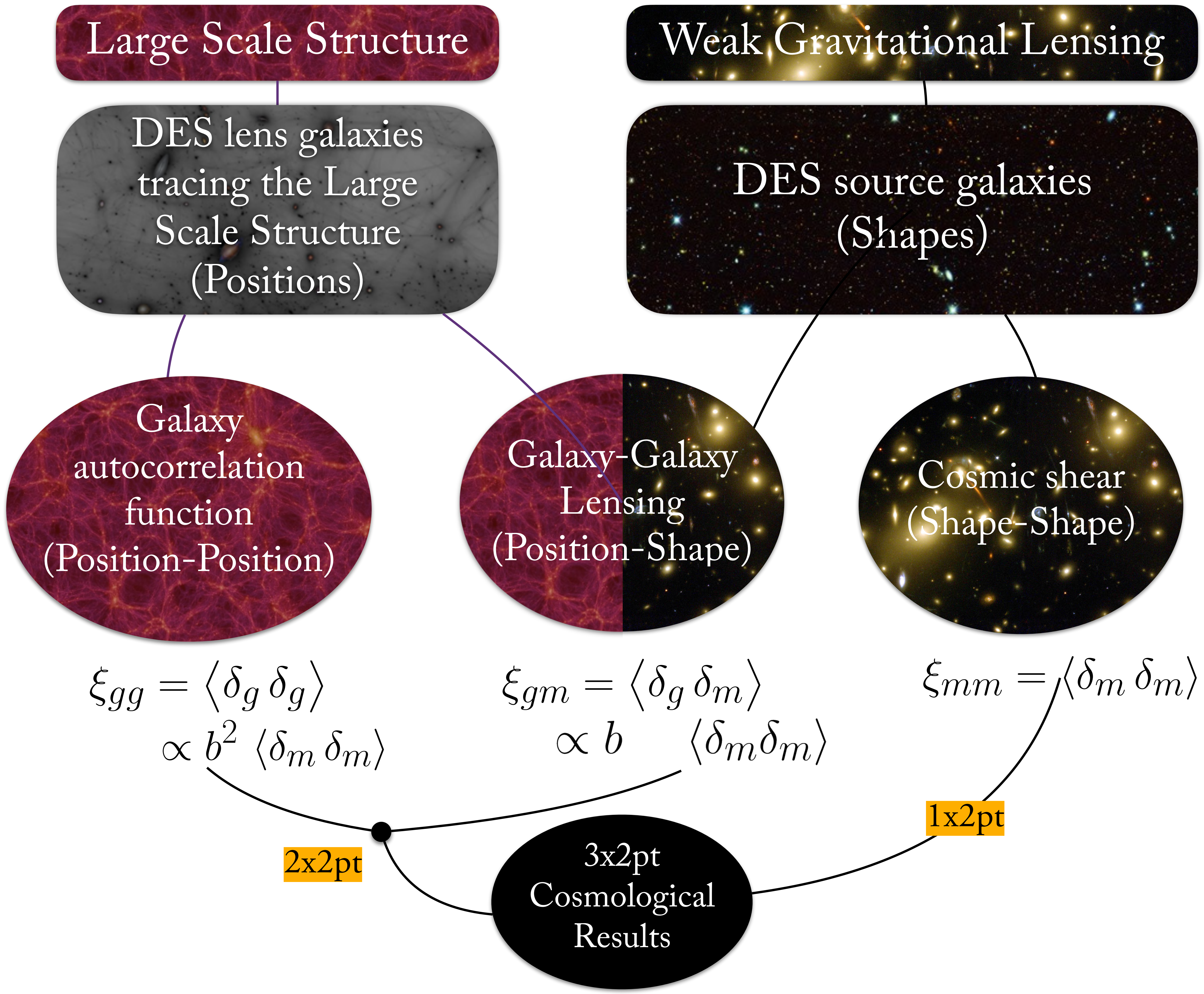
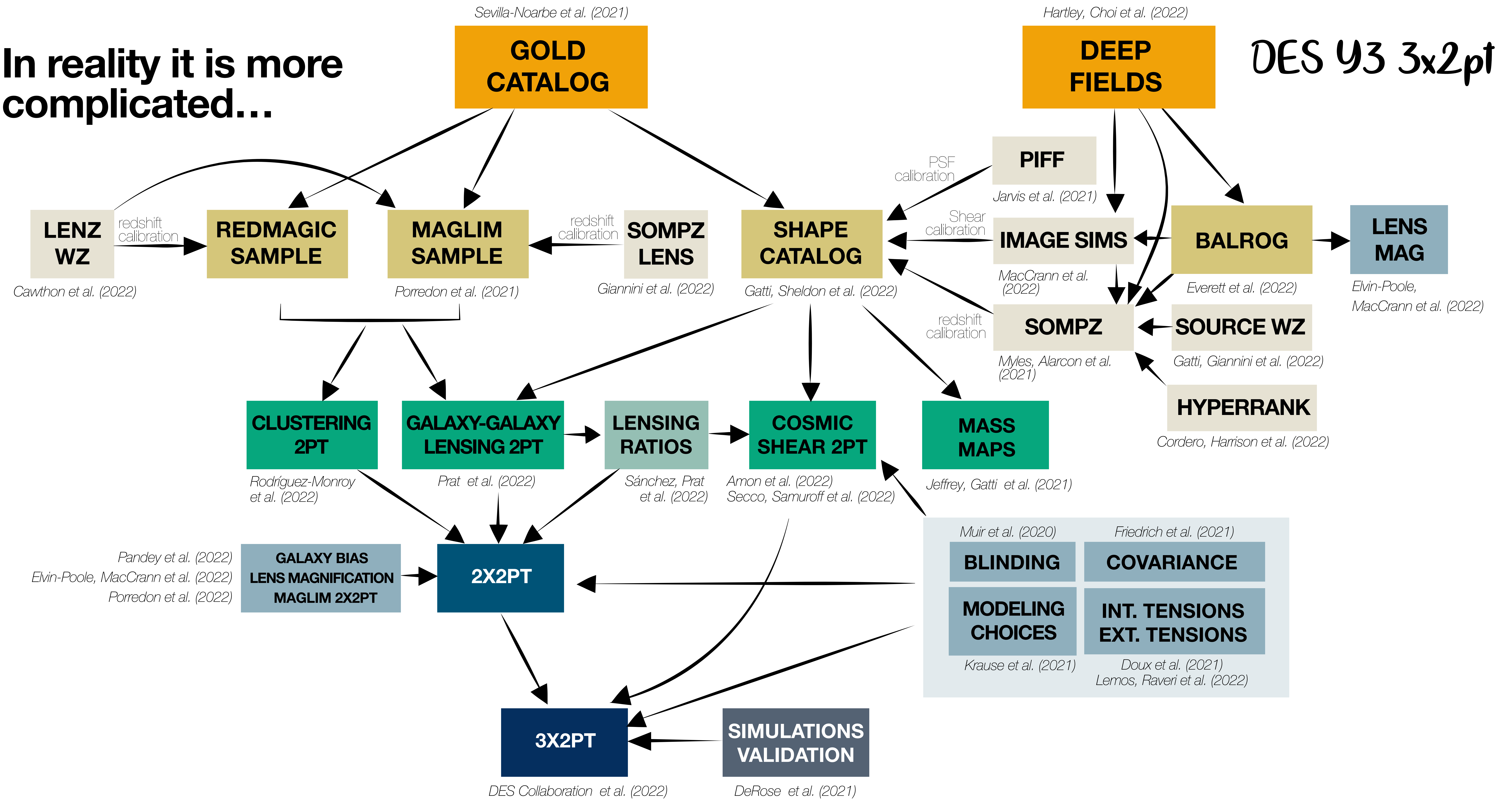


The WL + LSS analysis in DES Y3

The DES Collaboration

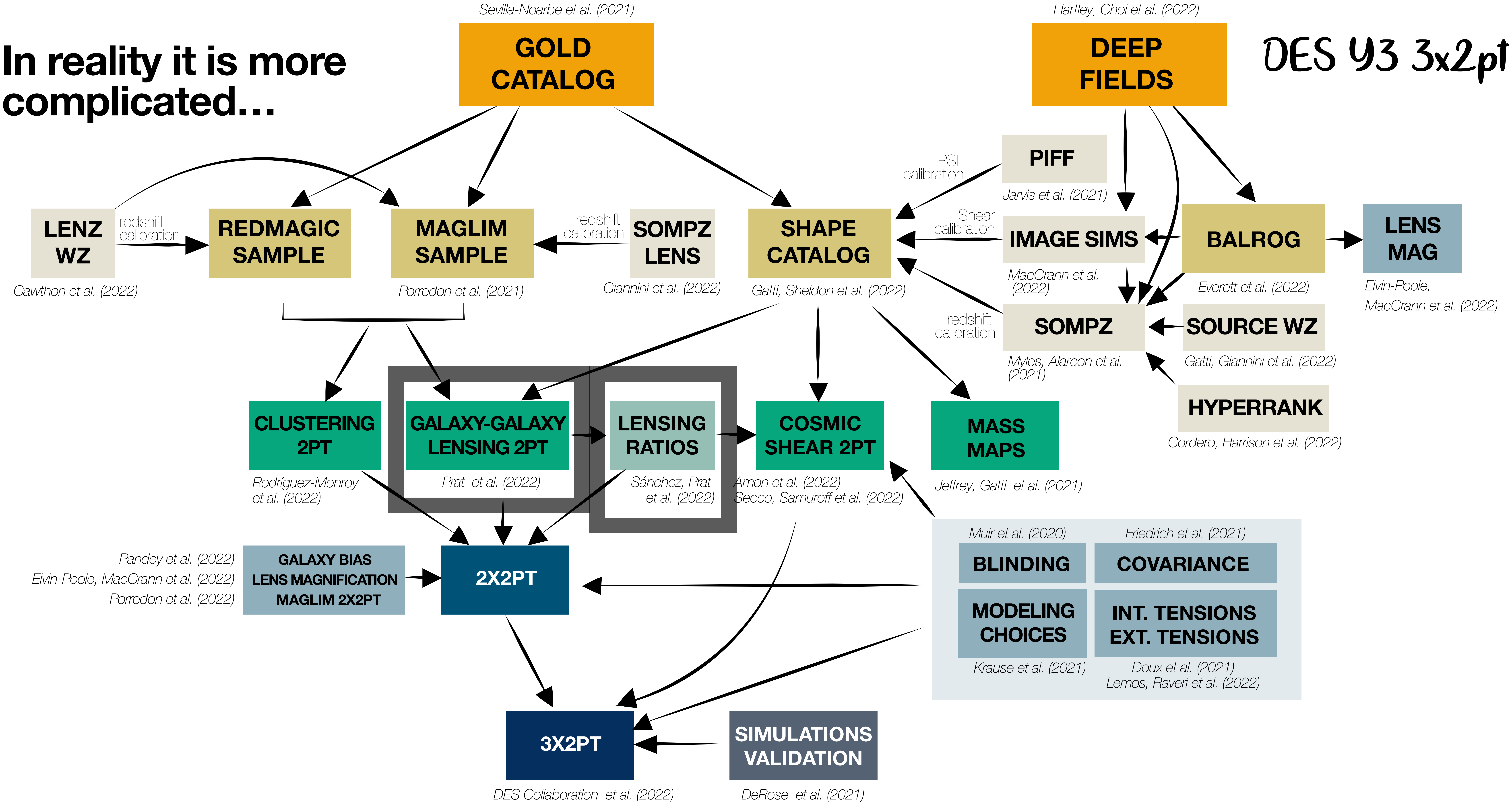
In reality it is more complicated…

DES Y3 3x2pt



In reality it is more complicated…

DES Y3 3x2pt



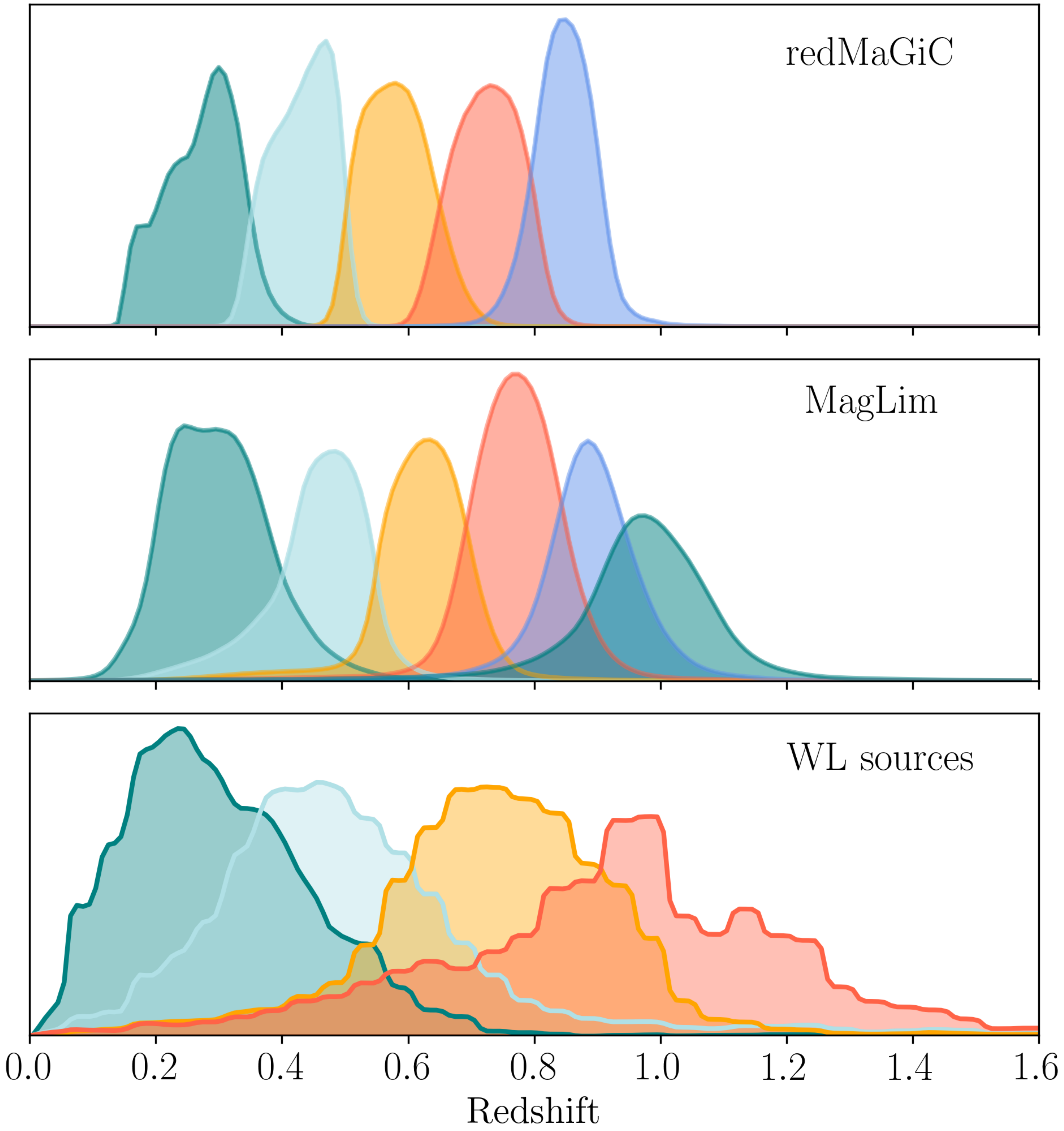
DES Y3 3x2pt
Galaxy samples

- 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.

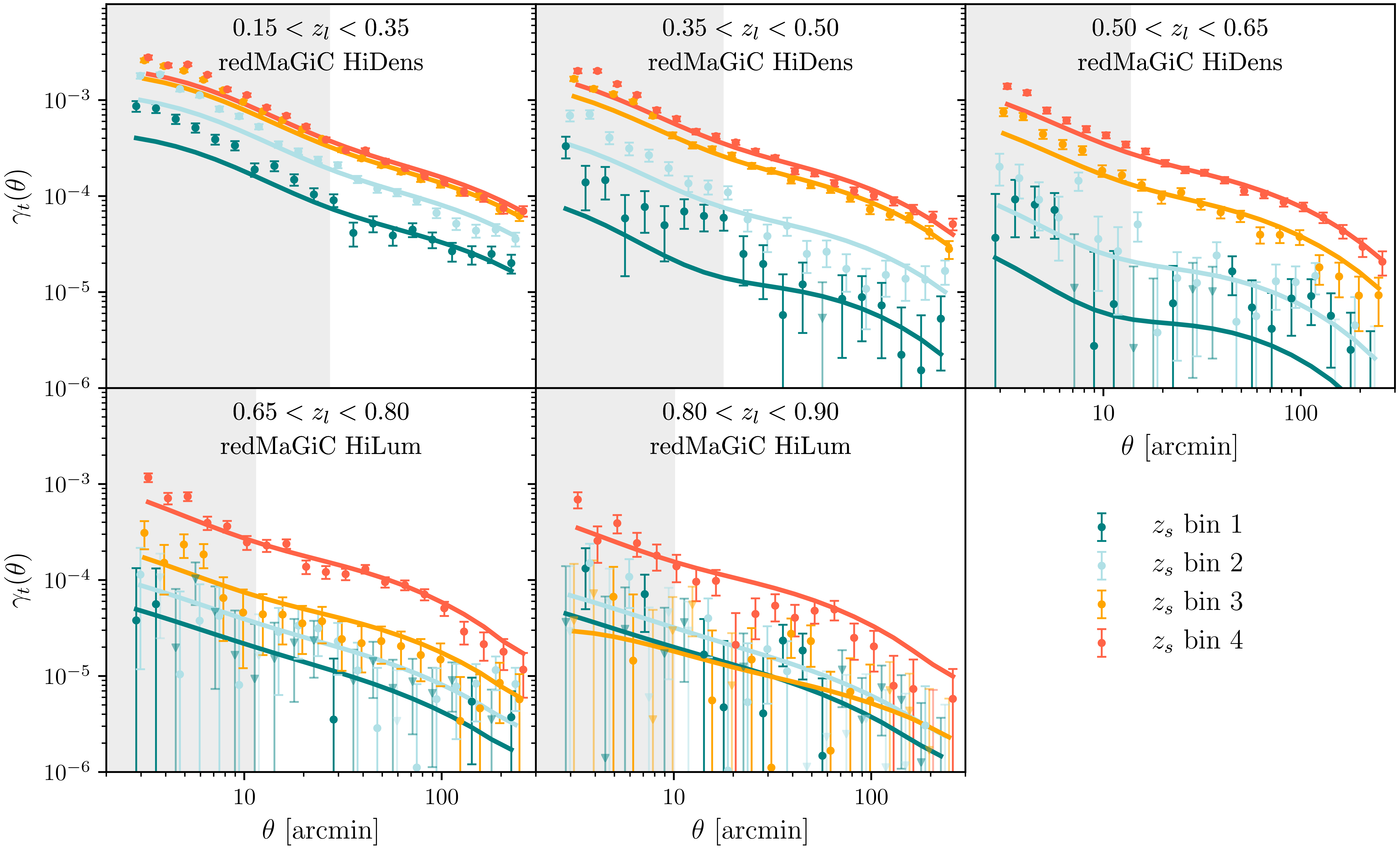
    2. **MagLim:** 10M galaxies. Denser magnitude limited sample $i < 4z_{phot} + 18$

- 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



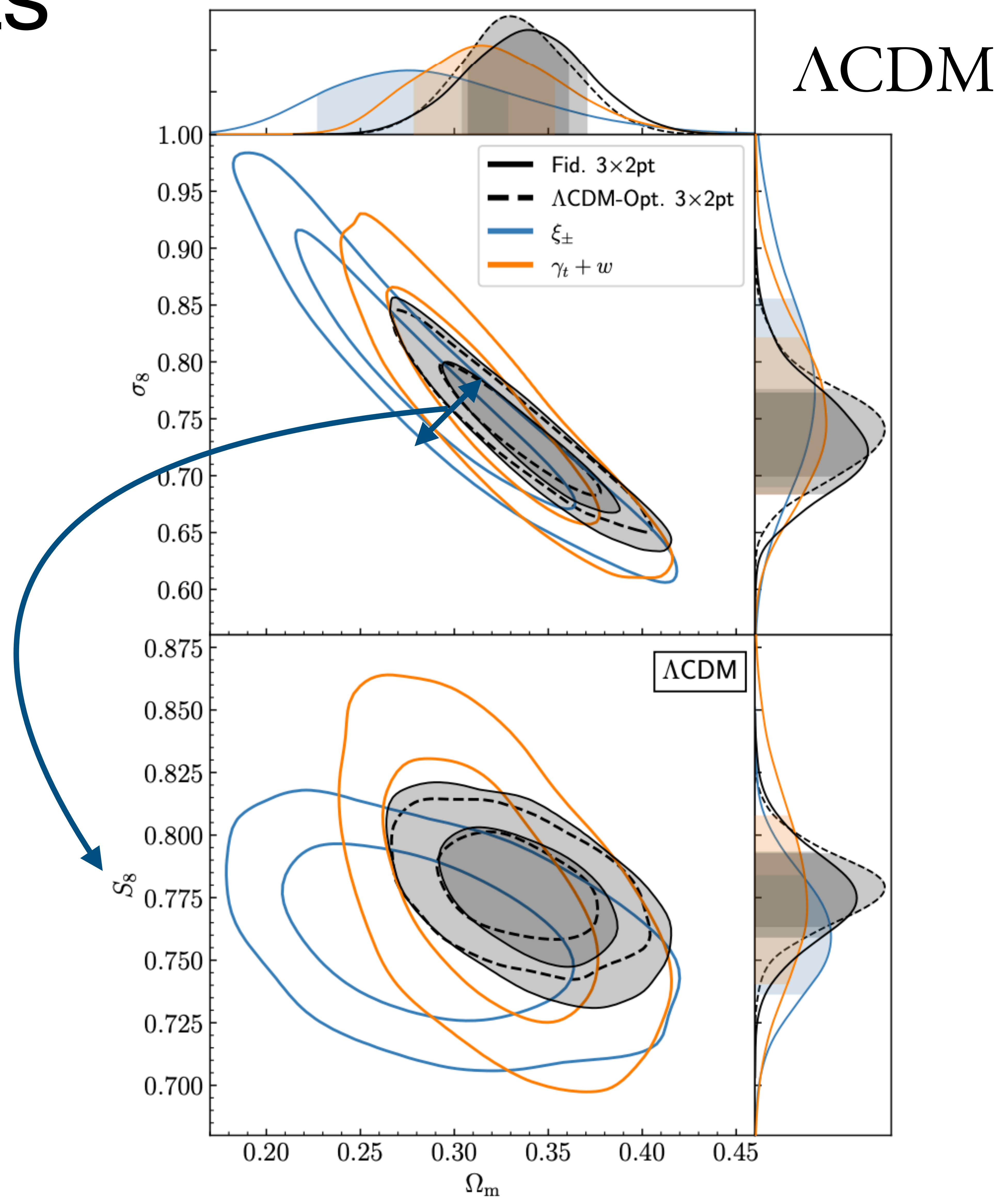
3x2pt combination: Free parameters and priors

Parameter	Prior	
Cosmology		
Ω_{m}	Flat	$(0.1, 0.9)$
$10^9 A_{\mathrm{s}}$	Flat	$(0.5, 5.0)$
n_{s}	Flat	$(0.87, 1.07)$
Ω_{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_{l}^1	Fixed	1.21
C_{l}^2	Fixed	1.15
C_{l}^3	Fixed	1.88
C_{l}^4	Fixed	1.97
Lens photo-z		
$\Delta z_{\mathrm{l}}^1 \times 10^2$	Gaussian	$(-0.9, 0.7)$
$\Delta z_{\mathrm{l}}^2 \times 10^2$	Gaussian	$(-3.5, 1.1)$
$\Delta z_{\mathrm{l}}^3 \times 10^2$	Gaussian	$(-0.5, 0.6)$
$\Delta z_{\mathrm{l}}^4 \times 10^2$	Gaussian	$(-0.7, 0.6)$
$\sigma_{z,\mathrm{l}}^1$	Gaussian	$(0.98, 0.06)$
$\sigma_{z,\mathrm{l}}^2$	Gaussian	$(1.31, 0.09)$
$\sigma_{z,\mathrm{l}}^3$	Gaussian	$(0.87, 0.05)$
$\sigma_{z,\mathrm{l}}^4$	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_{TA}	Flat	$(0, 2)$
z_0	Fixed	0.62
Source photo-z		
$\Delta z_{\mathrm{s}}^1 \times 10^2$	Gaussian	$(0.0, 1.8)$
$\Delta z_{\mathrm{s}}^2 \times 10^2$	Gaussian	$(0.0, 1.5)$
$\Delta z_{\mathrm{s}}^3 \times 10^2$	Gaussian	$(0.0, 1.1)$
$\Delta z_{\mathrm{s}}^4 \times 10^2$	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	$(-3.7, 0.8)$

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.

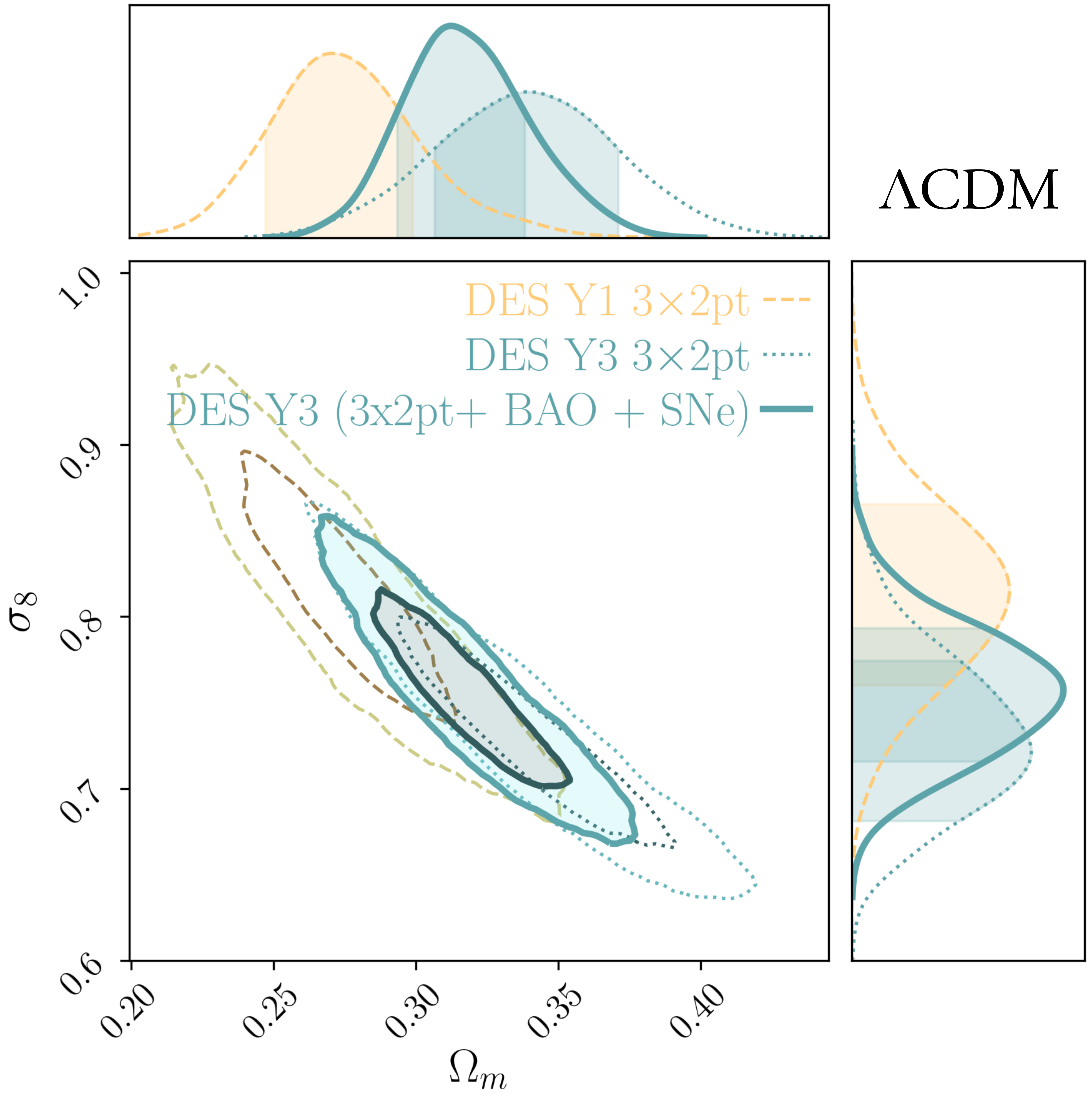
DES Collaboration (2022)
2105.13549



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

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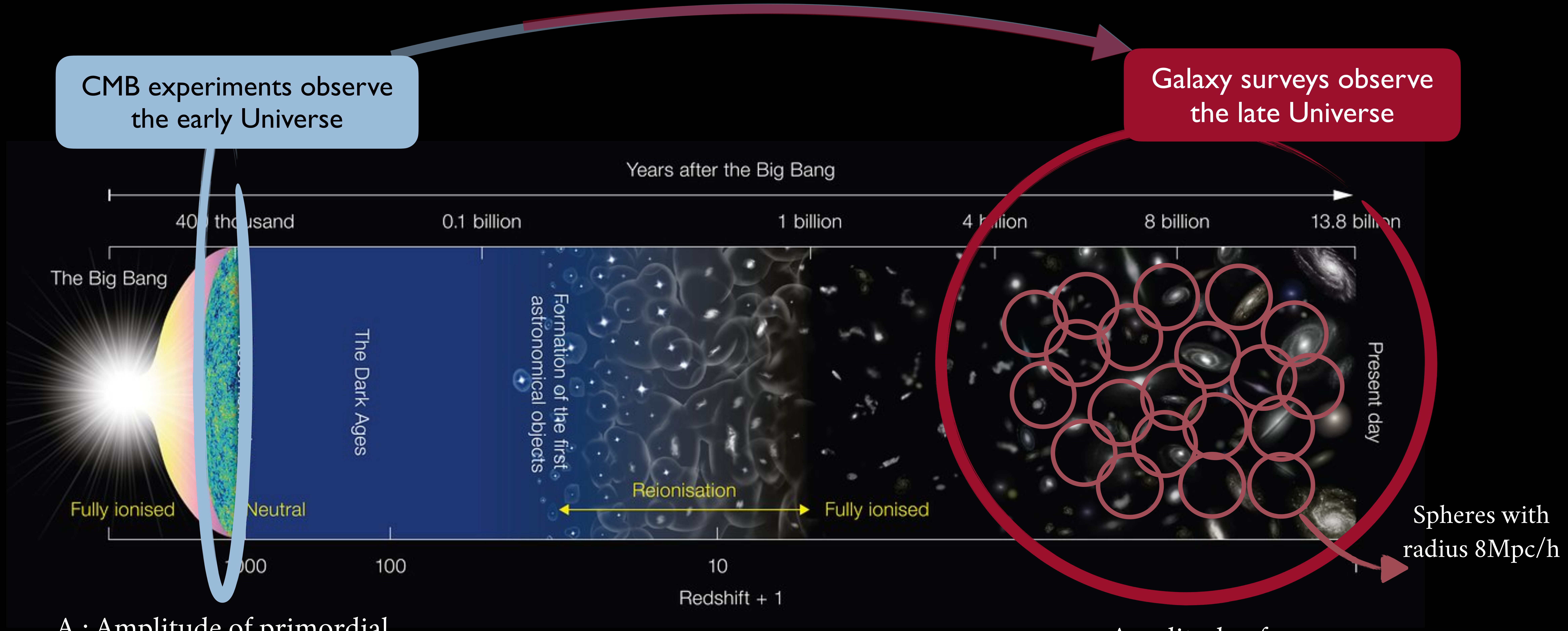


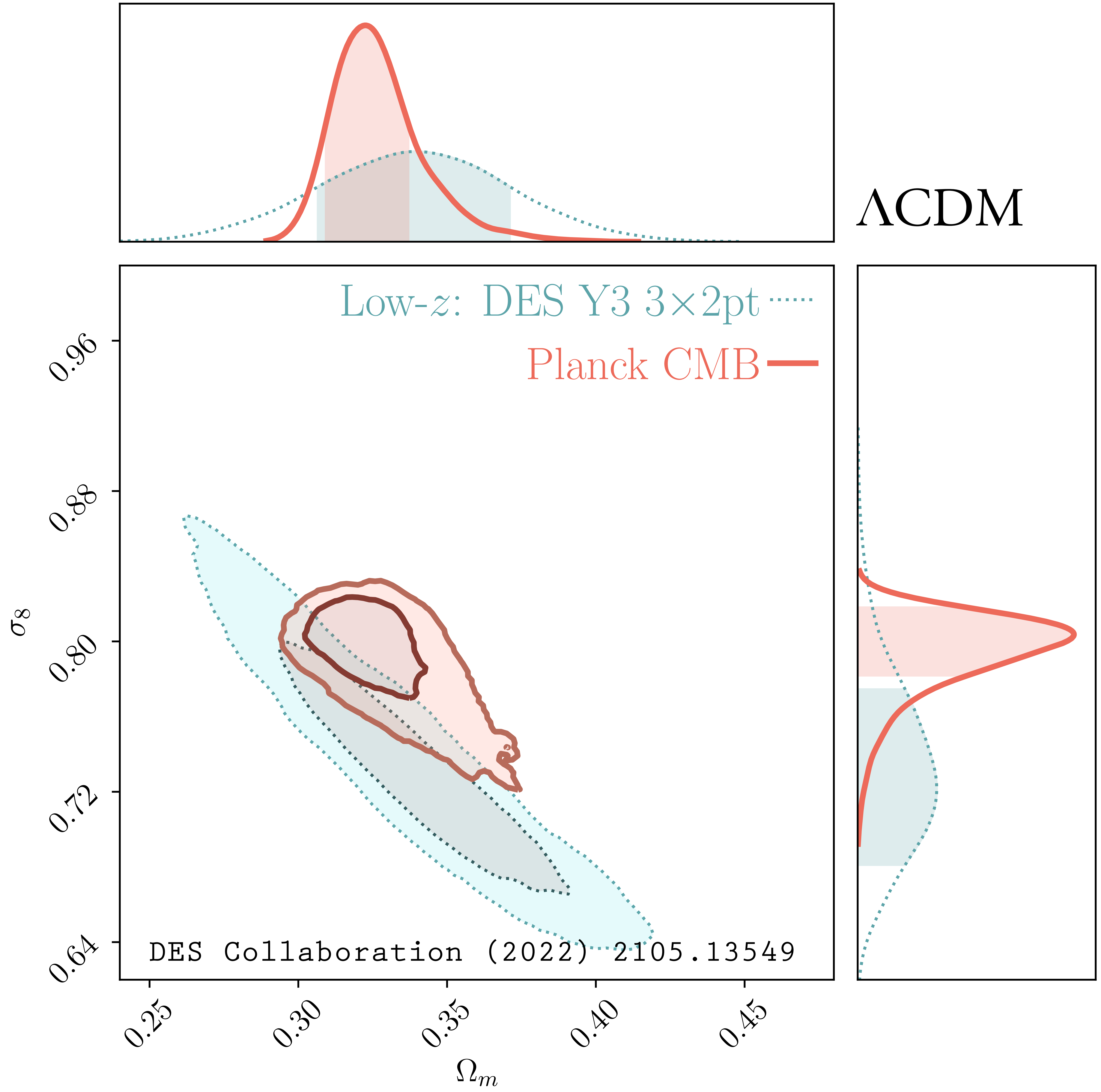
A_s: Amplitude of primordial scalar density fluctuations.

Image credit: NAOJ

σ_8: Amplitude of mass fluctuations today.

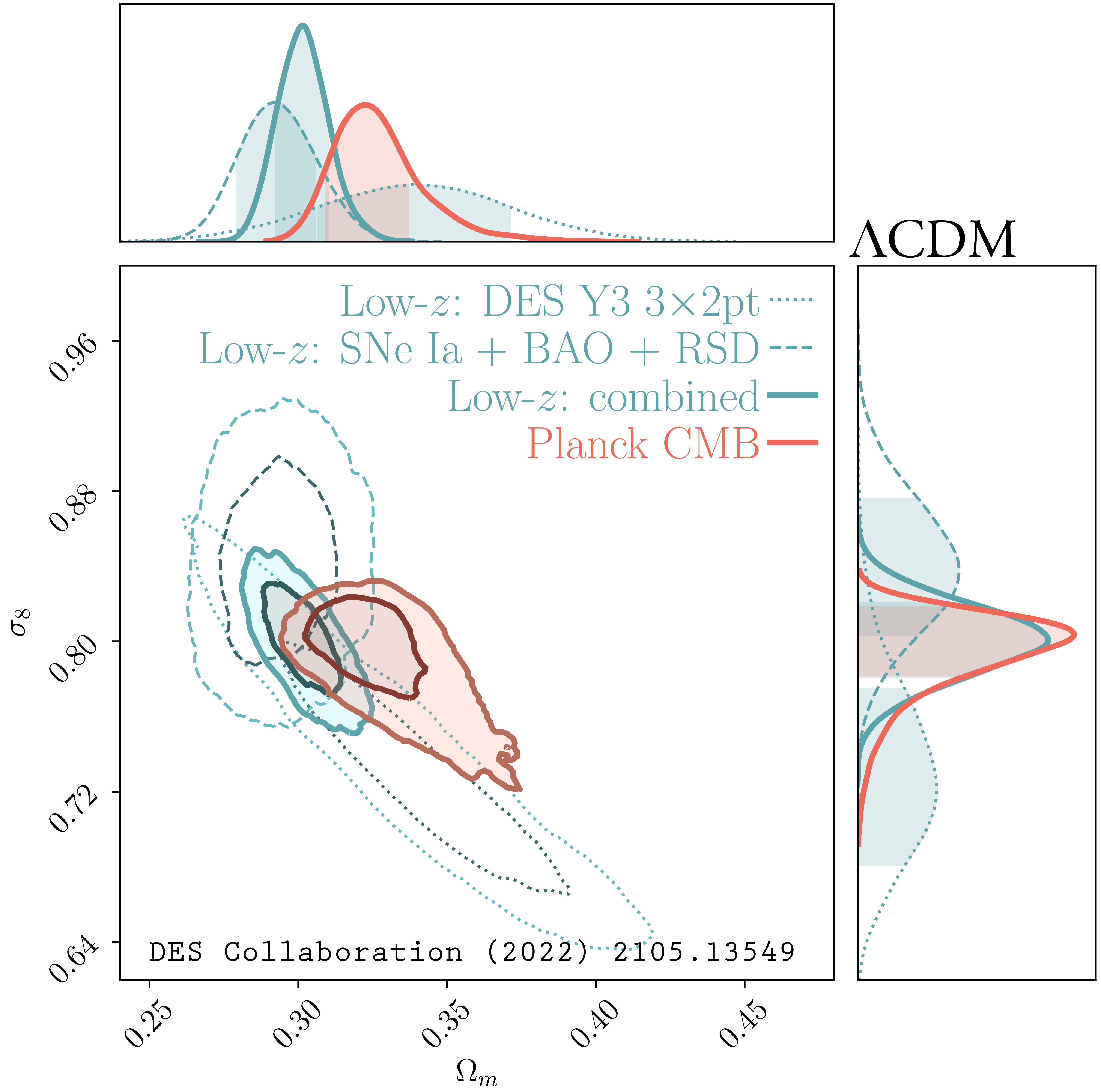
Stress testing ΛCDM:
early vs late Universe

- 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

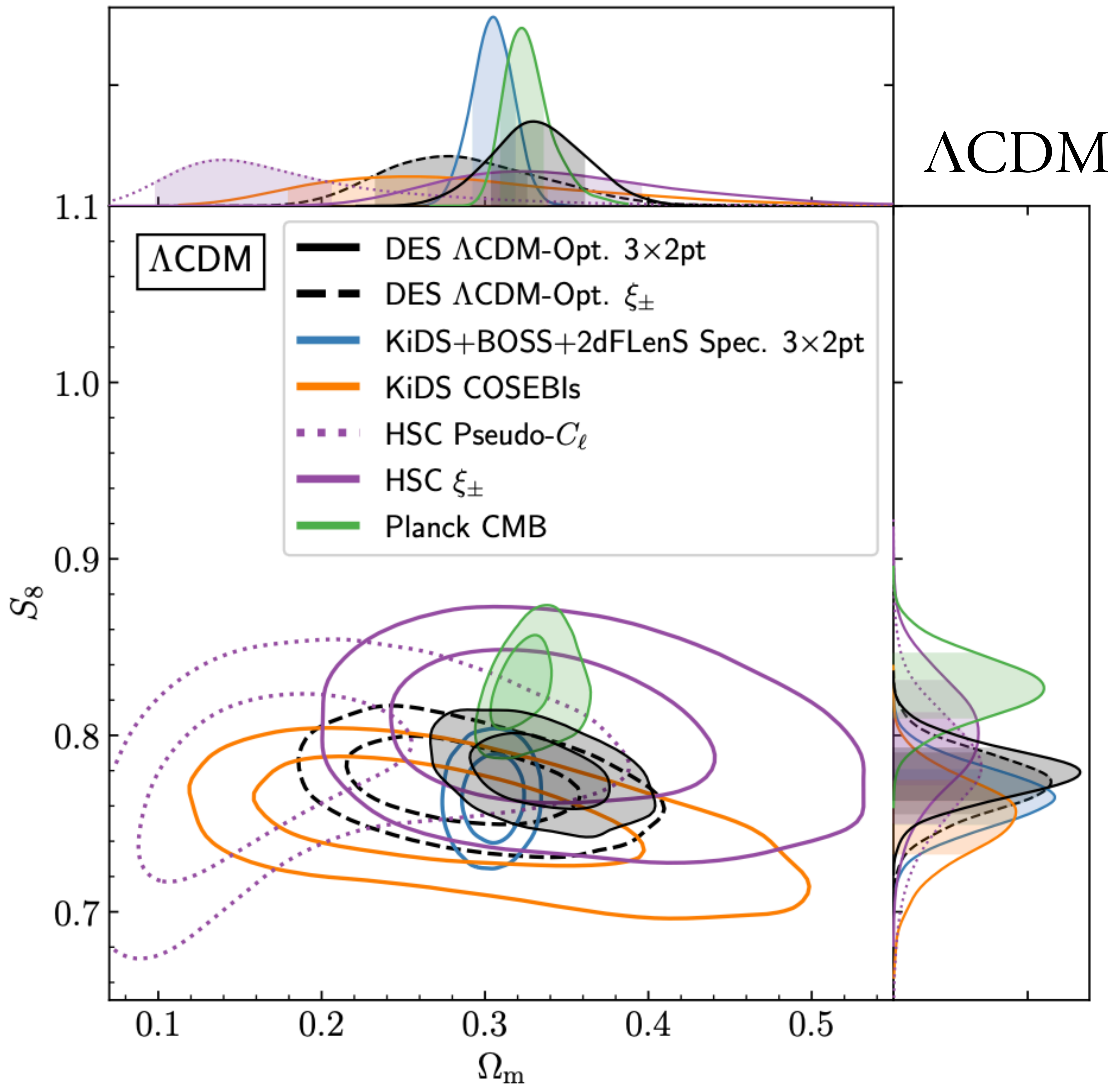
- When combined with other external redshift probes (*Pantheon SNe IA, BOSS BAO, BOSS RSD*), they are also consistent (0.9σ), with smaller uncertainties.



The real power comes when combining different probes!!

Where is the S_8 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

Limitations of current 3x2pt analyses

Moving forward

- Only using **large scales,** due to not having good enough small scale models due to:
  - Non-linear galaxy bias.
  - Baryonic effects.
- Only using **Gaussian information**.
- Marginalizing over many nuisance parameters that include uncertainties from observational systematics:
  - Intrinsic alignments.
  - Redshift uncertainties.
  - Magnification
  - Shear biases.
  - Blending.
- Speed limitations. MCMC's with so many nuisance parameters take a long time.

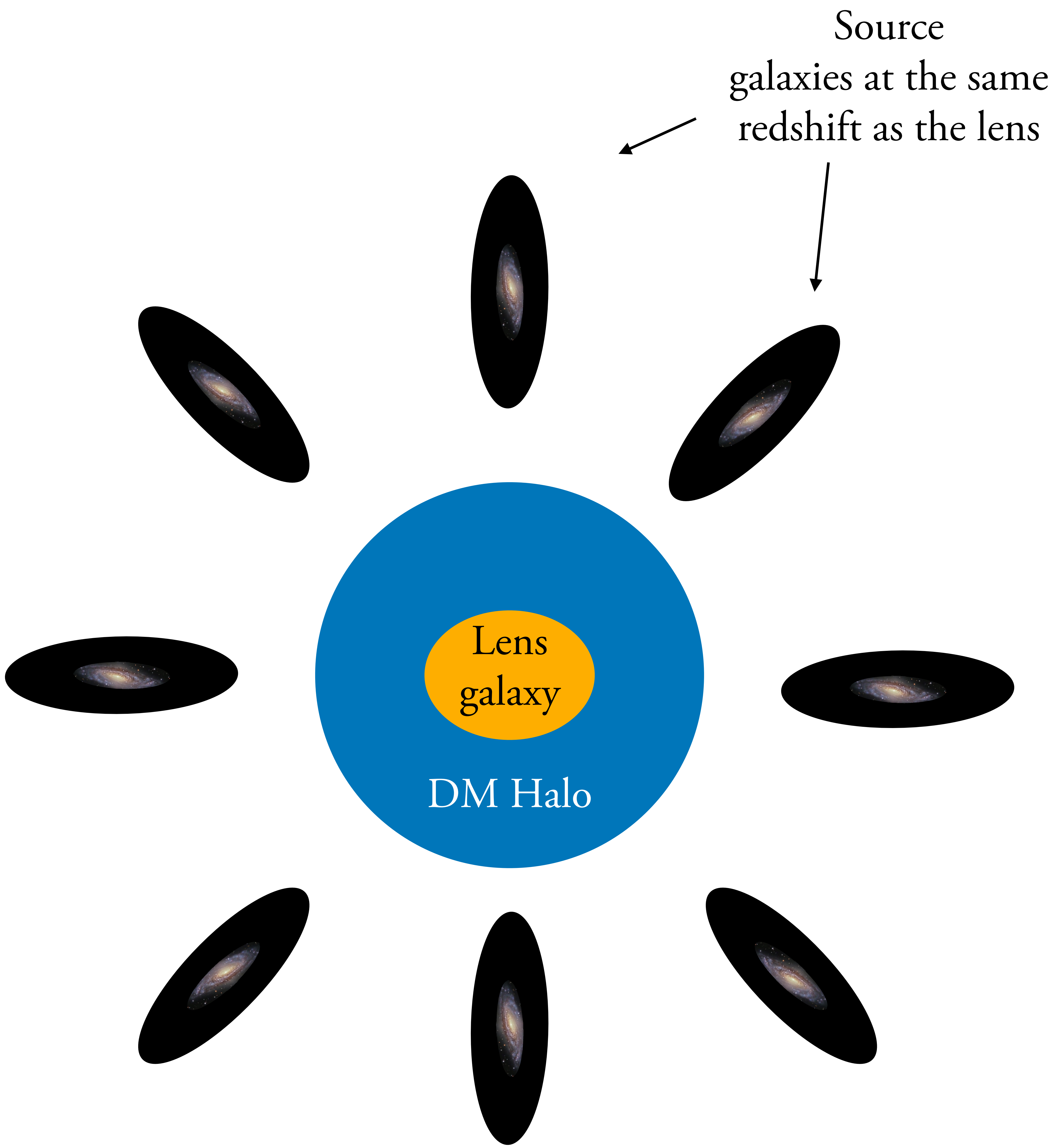
How did we define scale cuts?

- 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.

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.



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

come ask me during the workshop if you're interested in any of these!

- **The Catalog-to-Cosmology framework for weak lensing and galaxy clustering for LSST:** *Prat, Zuntz et al. (2022)* — `arXiv:2212.09345`.
- **Non-local contribution from small scales in galaxy-galaxy lensing: Comparison of mitigation schemes:** *Prat, Zacharegkas et al. (2022)* — `arXiv:2212.03734`.
- **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`.

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 —> Let's get more information from galaxy surveys and other probes!

Thanks!

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