Cosmology from weak lensing and galaxy clustering in the Dark Energy Survey:

Lessons learned and looking ahead

NORDITA
The Nordic Institute for Theoretical Physics

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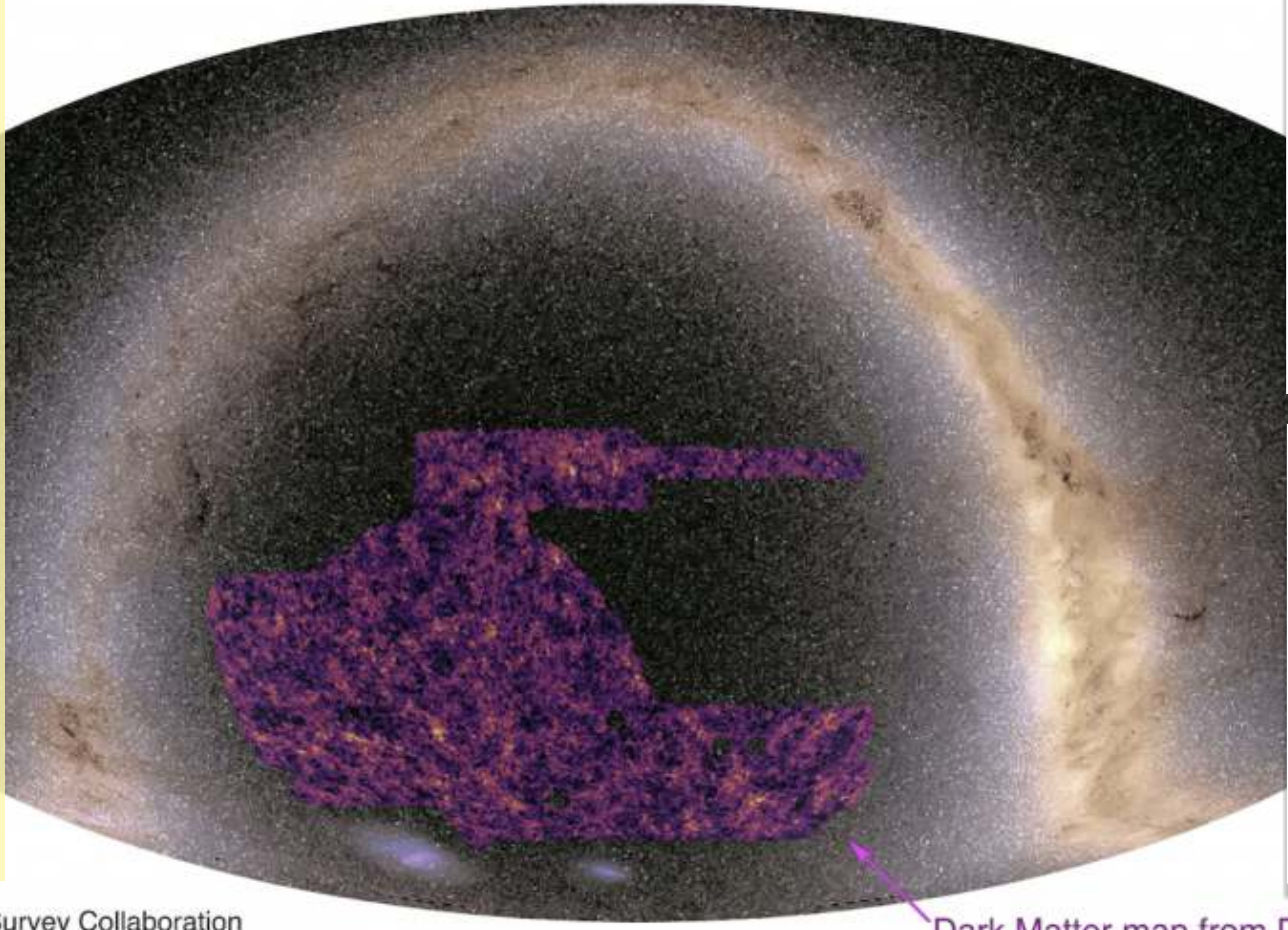
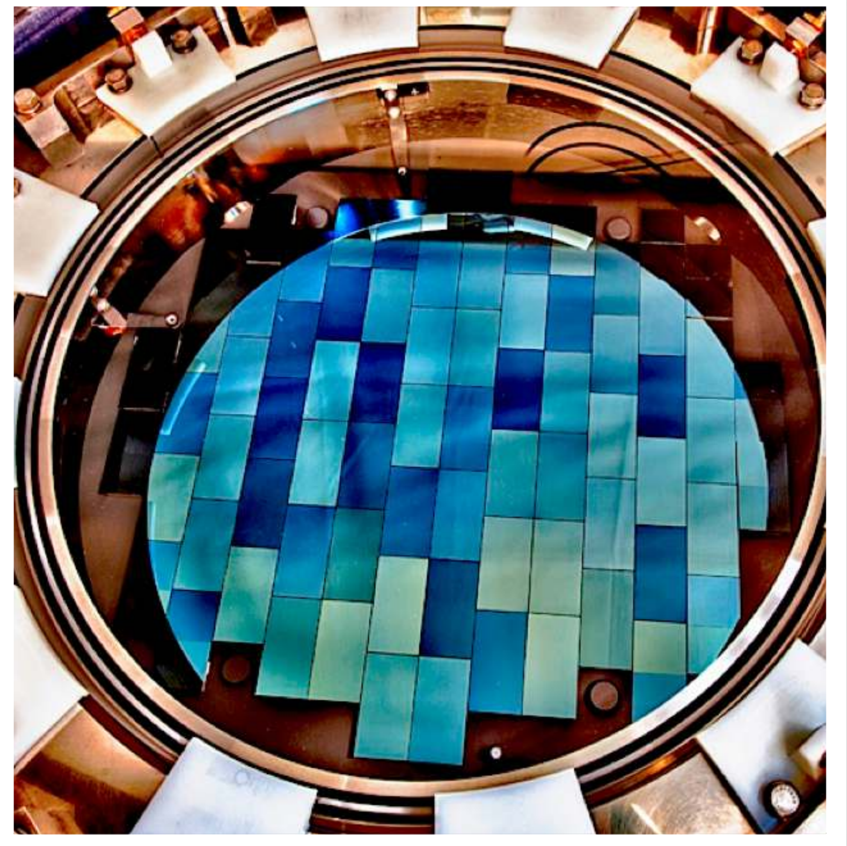
Nordita fellow at Stockholm University and KTH. October 2024.
X Fundamental Cosmology Sevilla.

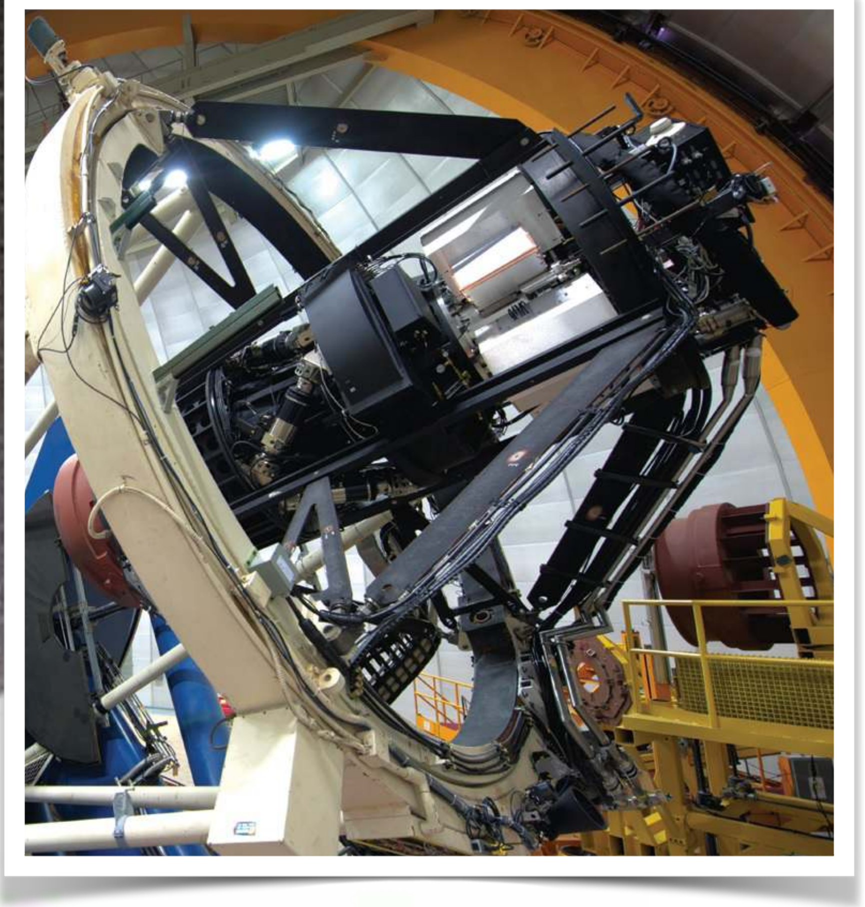
The Dark Energy Survey: *a photometric lensing survey*

- 570 Megapixel camera for the Blanco 4m telescope in Chile.
- 6 years of observations, 1/8th of the sky.
- Full data set (DES Y6): Positions and shapes of > 150M galaxies.
- DES Y3: Positions and shapes of > 100M galaxies.

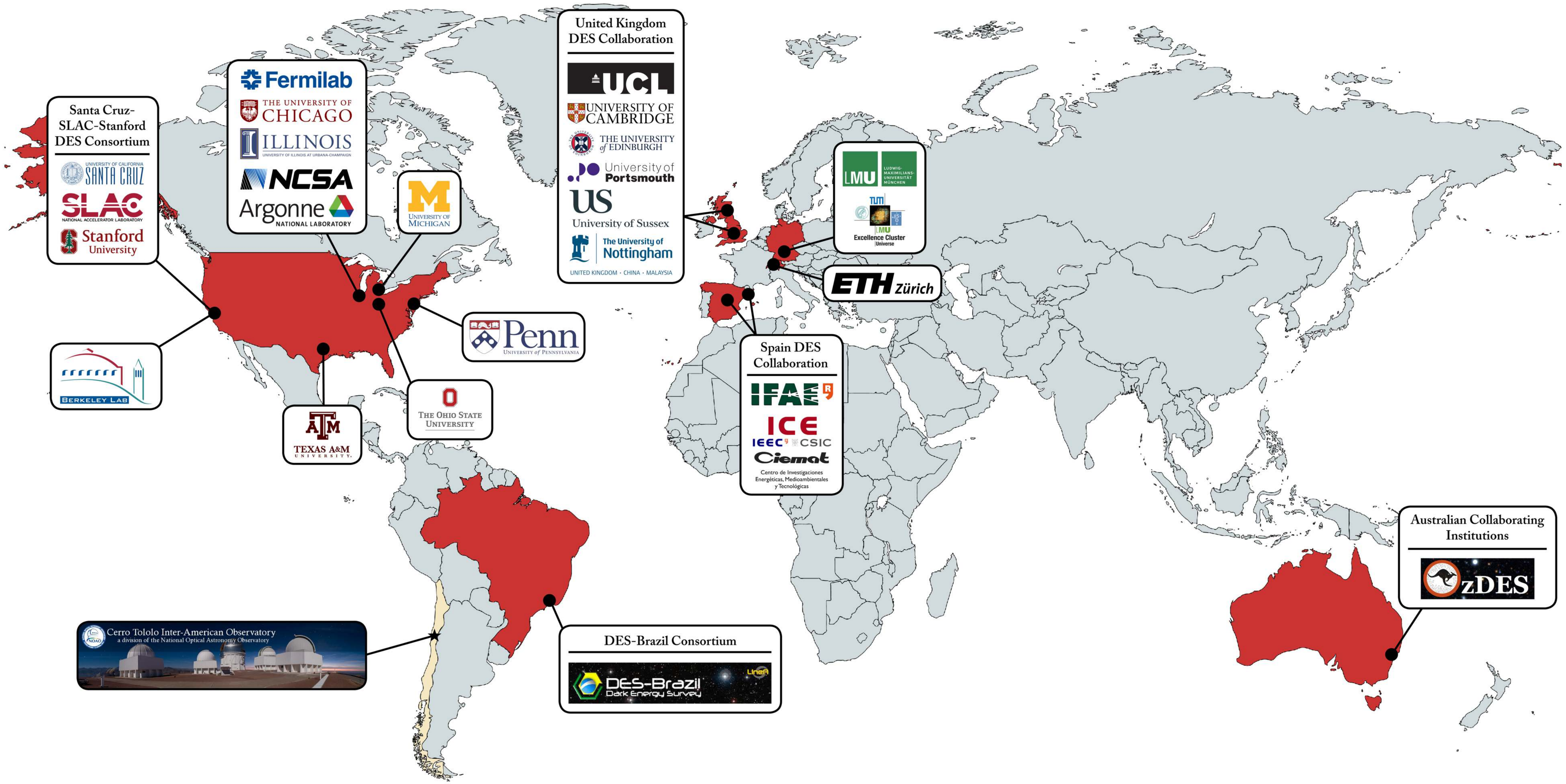


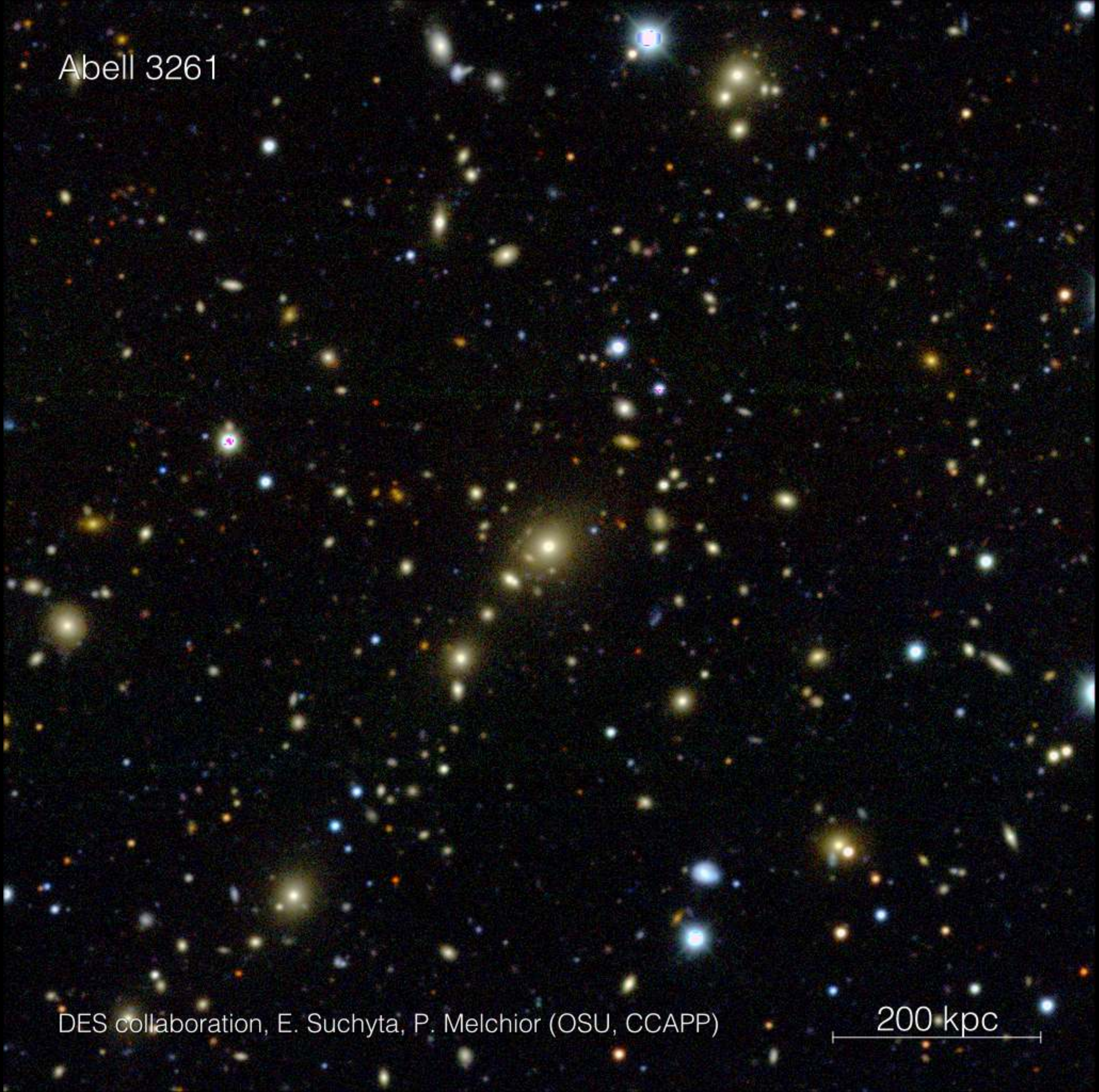
N. Jeffrey; Dark Energy Survey Collaboration



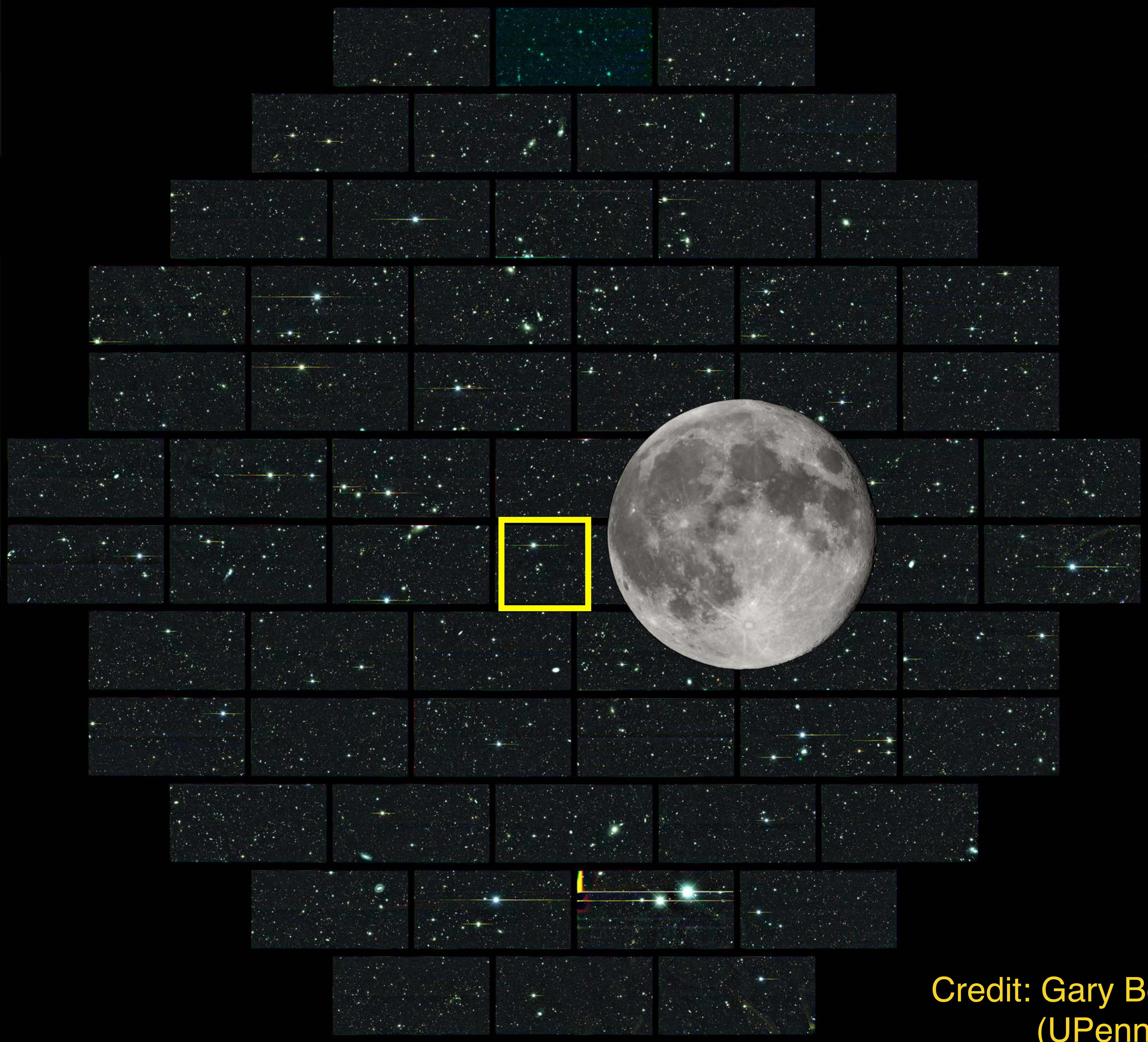


Dark Energy Survey Collaboration




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

Credit: Gary Bernstein
(UPenn)



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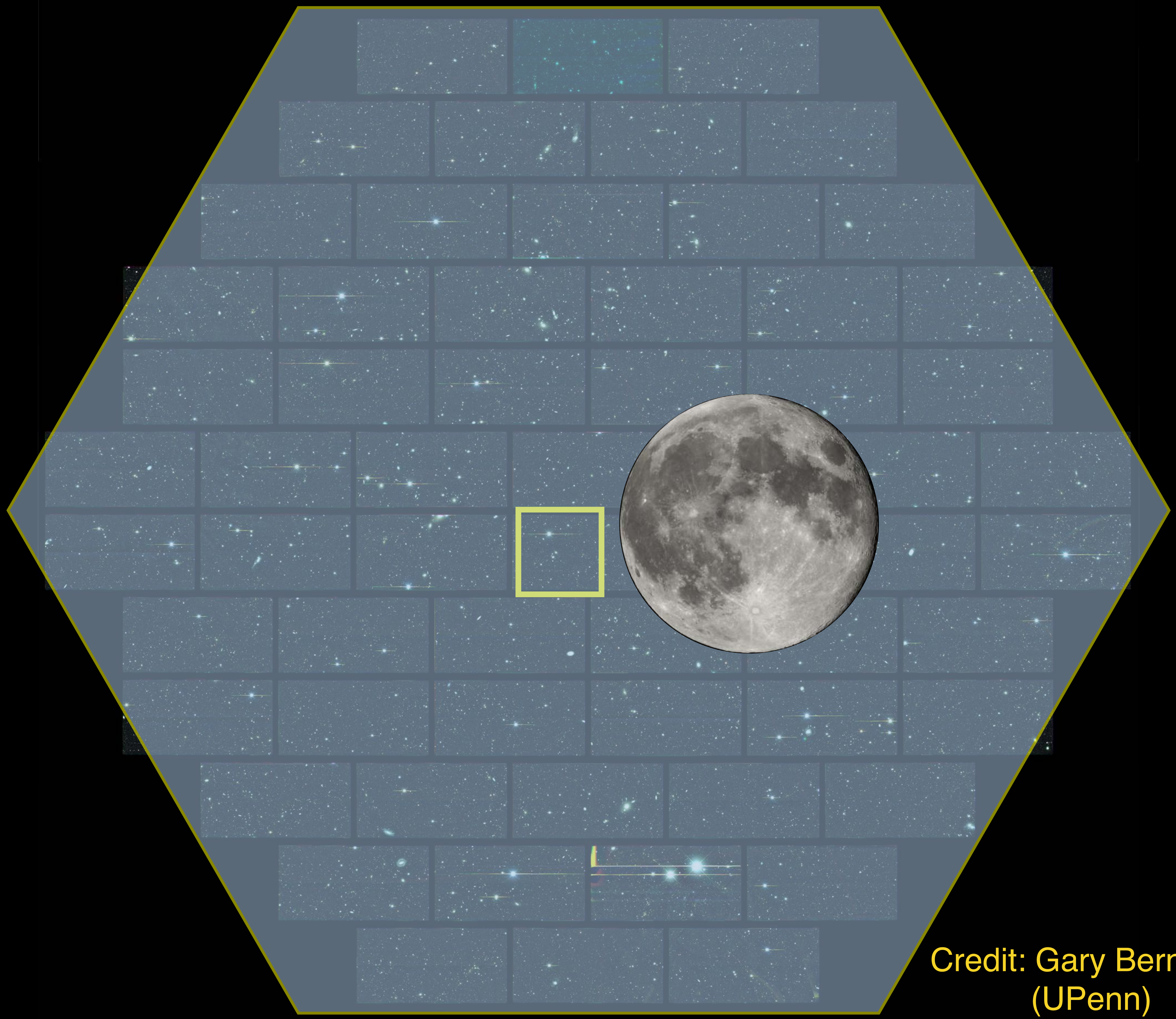

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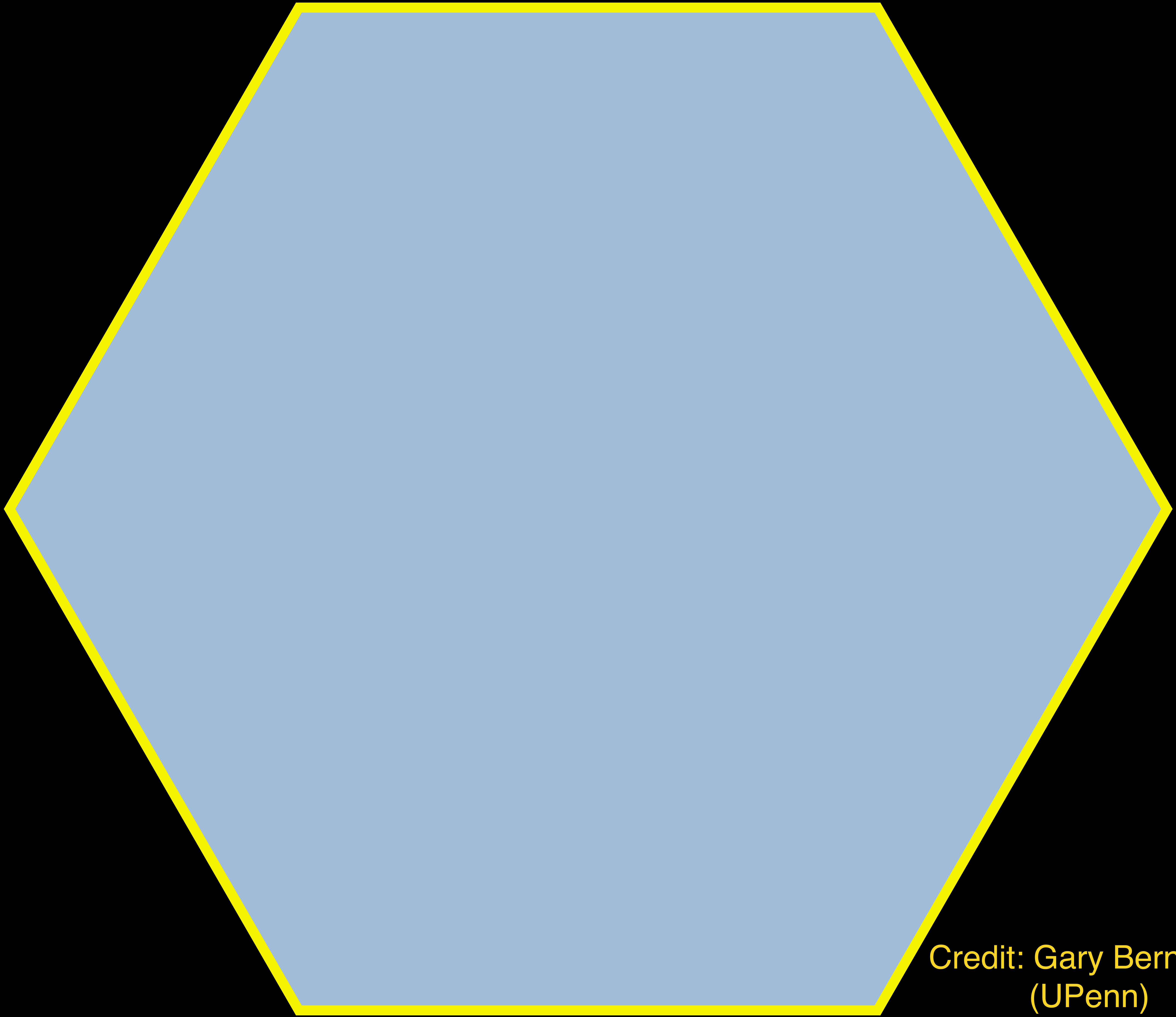

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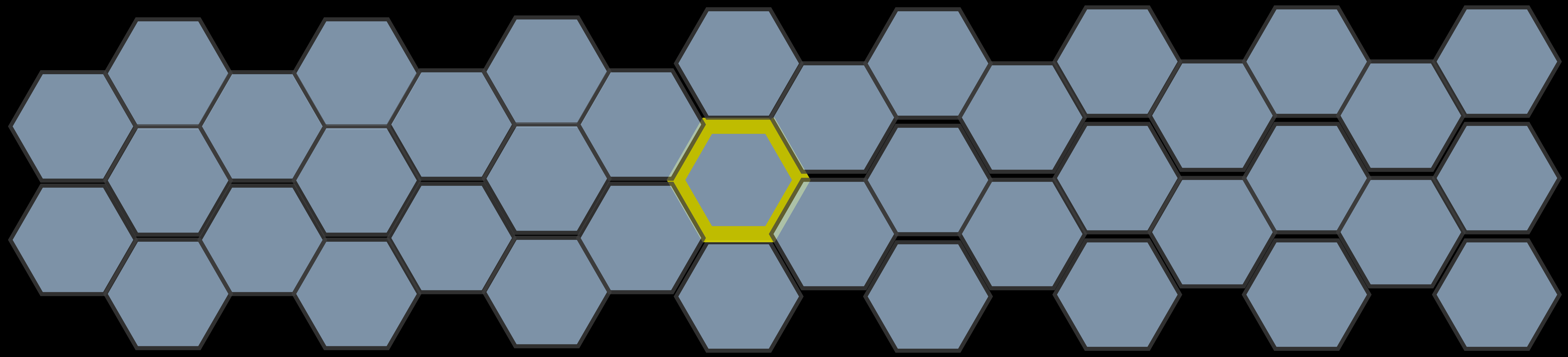

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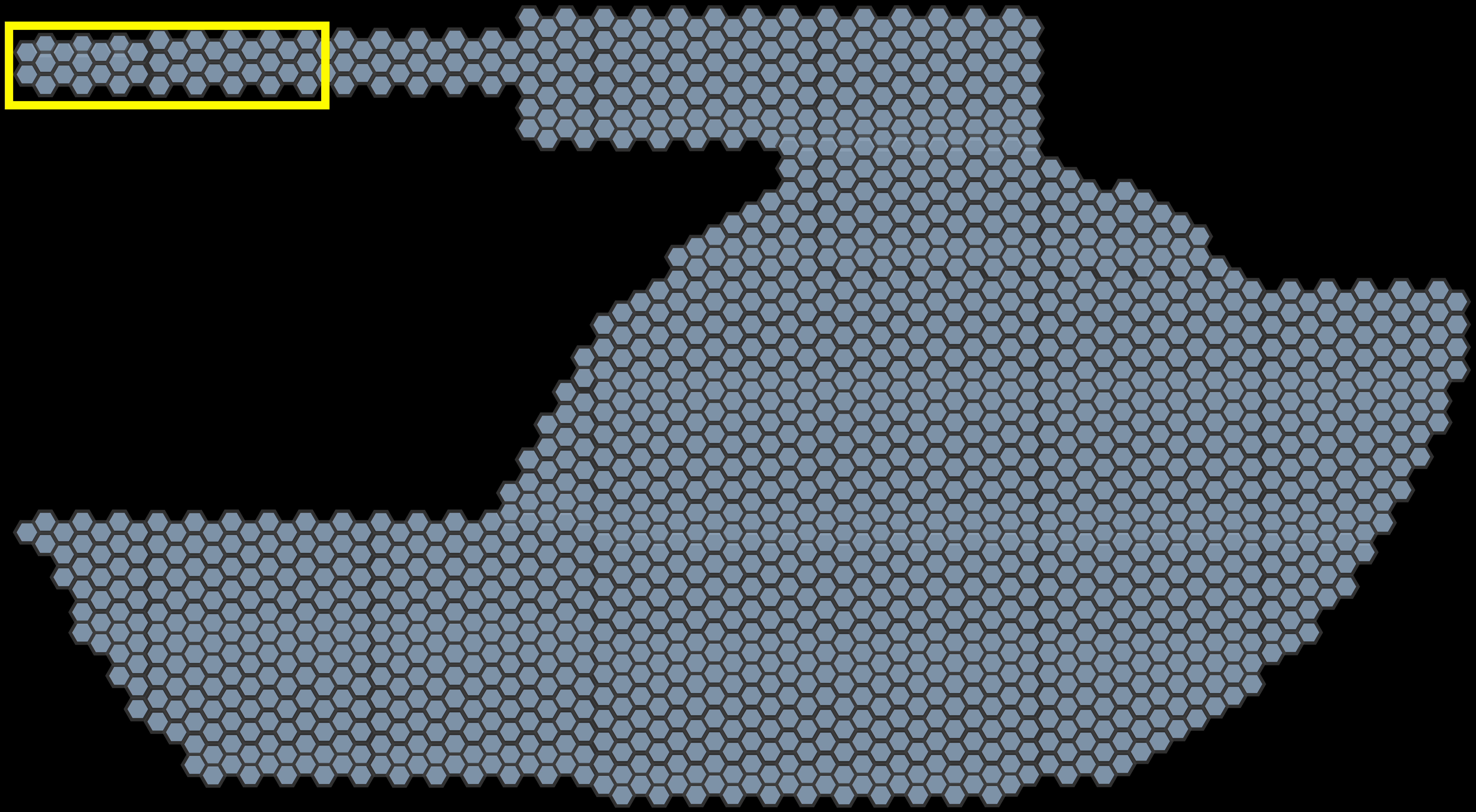

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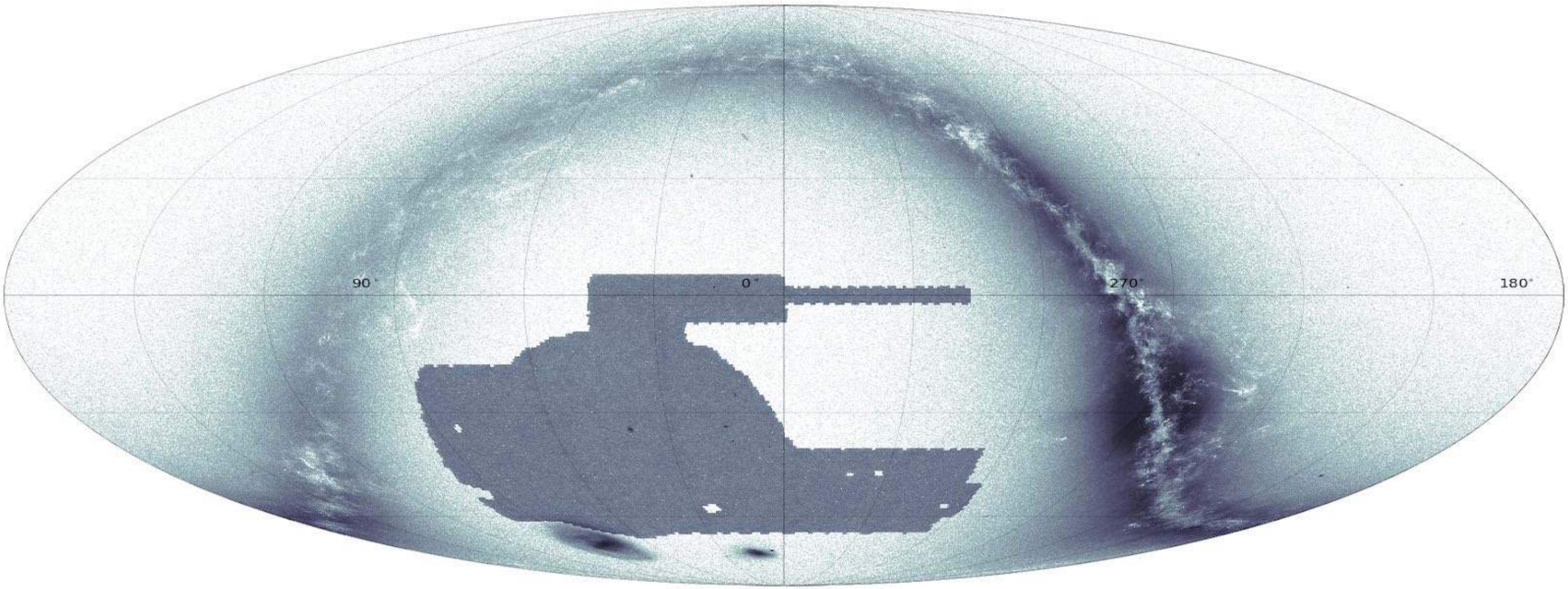
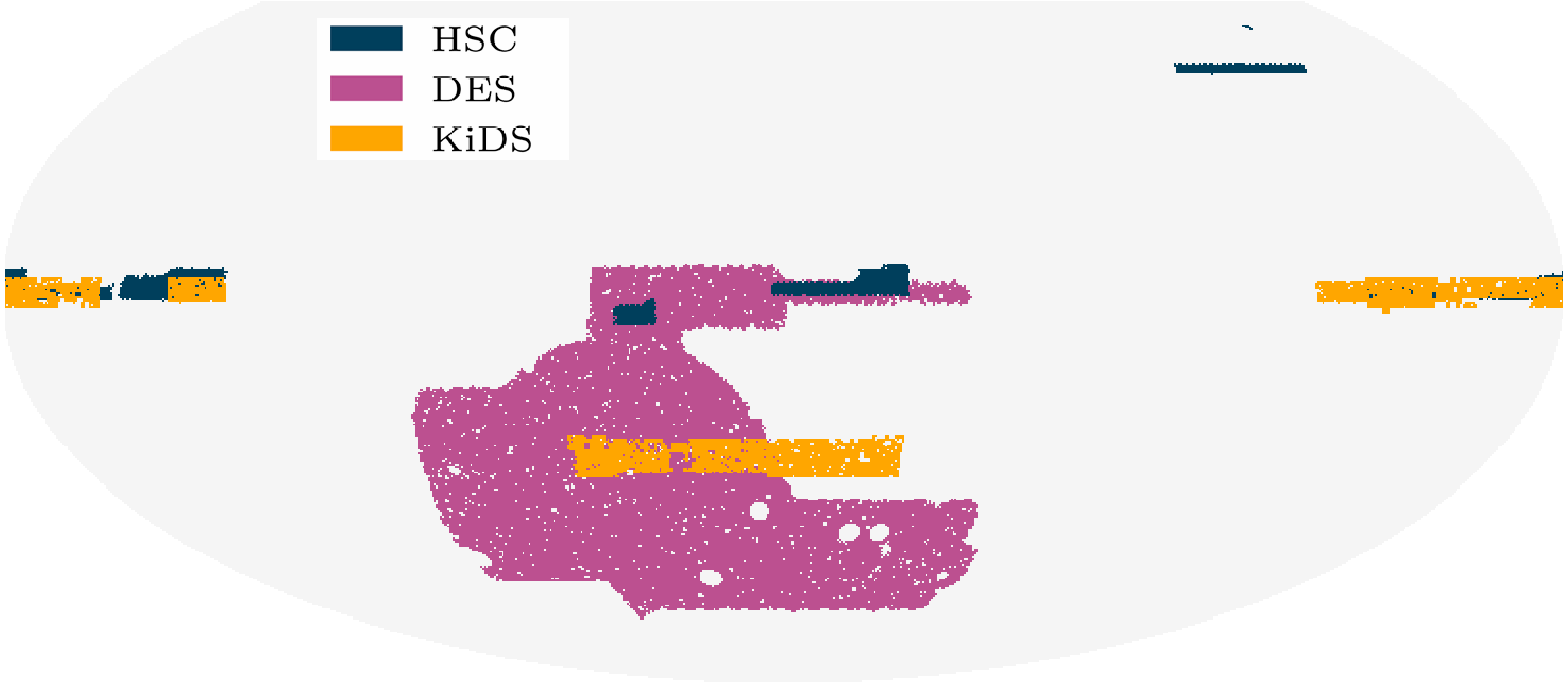
The Dark Energy Survey (DES)

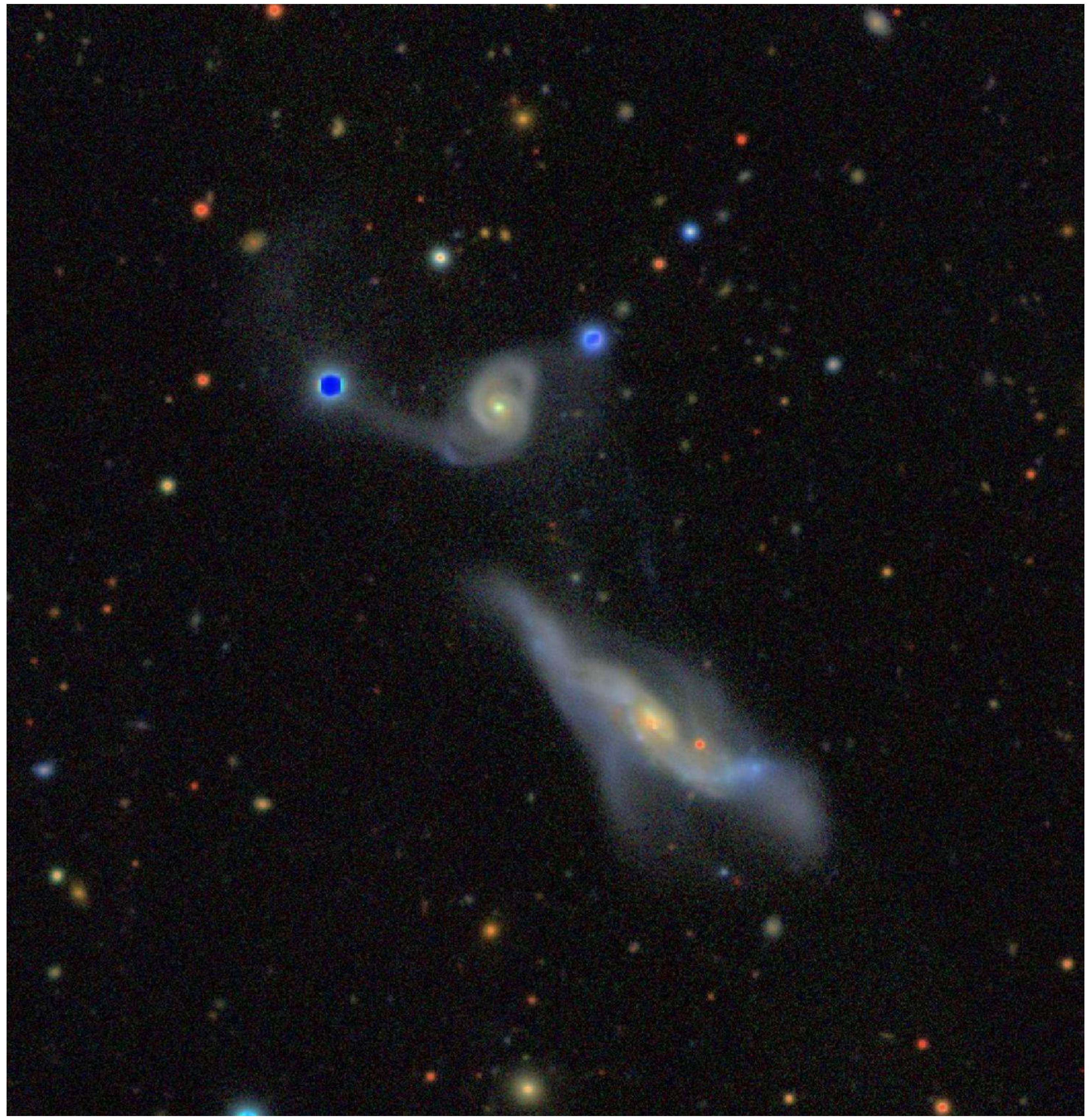


Photometric surveys for weak lensing: Stage III Surveys

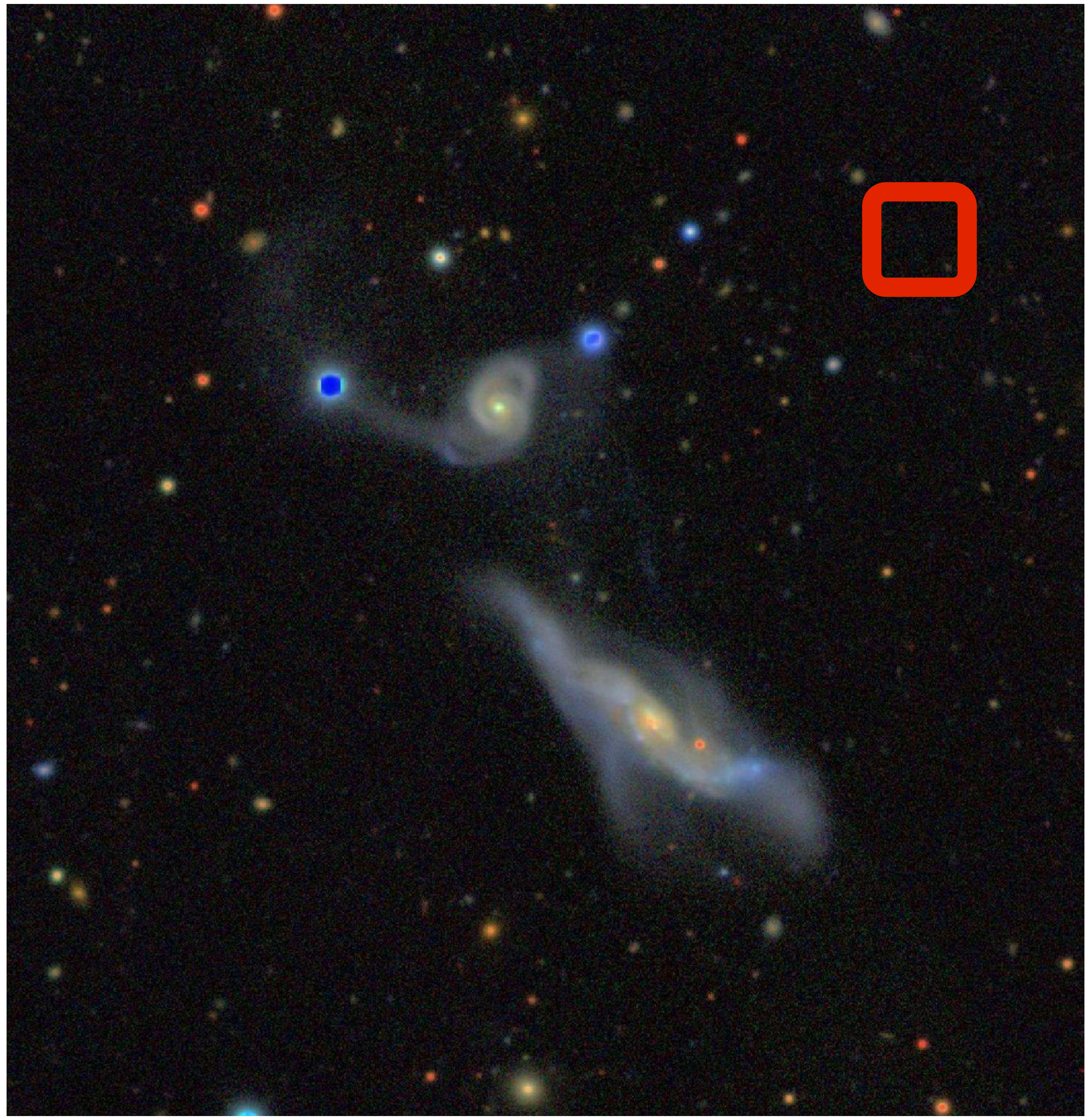
	Survey	Area (deg^2)	Source density [$arcmin^{-2}$]	Redshift range	Observing Status
Stage III	DES Y3	4,143	5.59	0.2 - 1.3	Completed
	KiDS-1000	773	6.17	0.1 - 1.2	Completed
	HSC Y3	416	15	0.3 - 1.5	Ongoing



Detecting galaxies



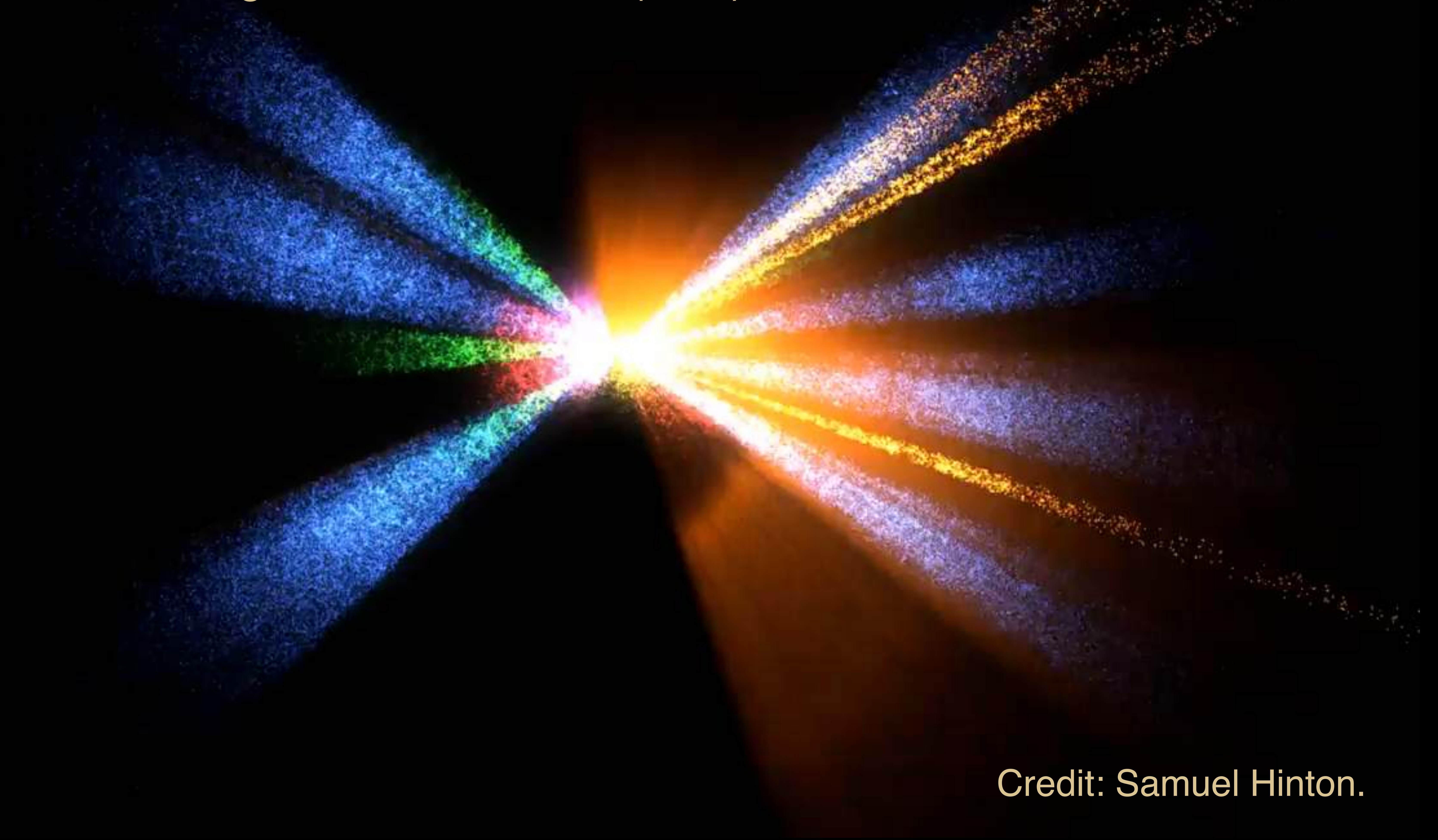
Detecting galaxies



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.

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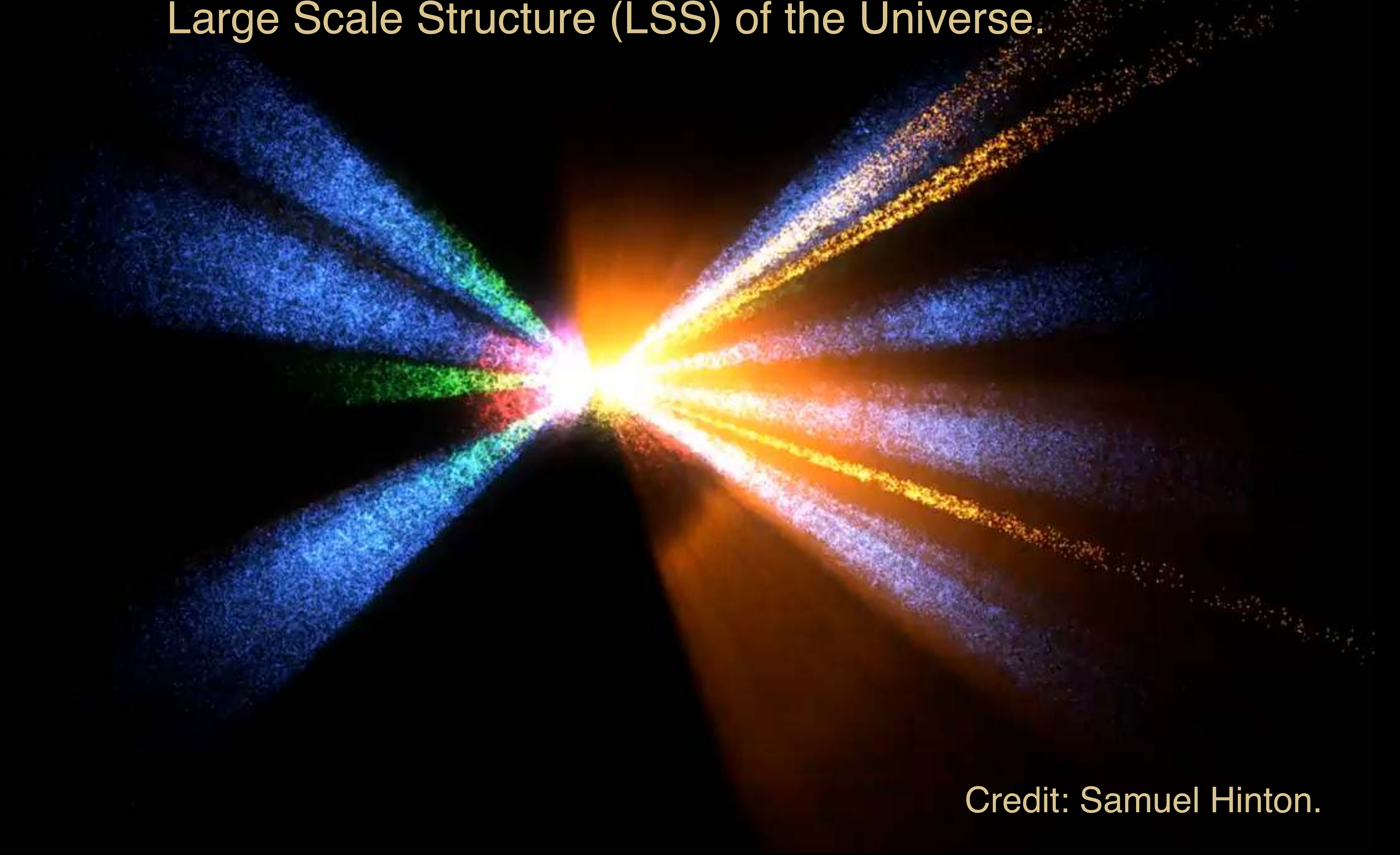


Credit: Samuel Hinton.

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.

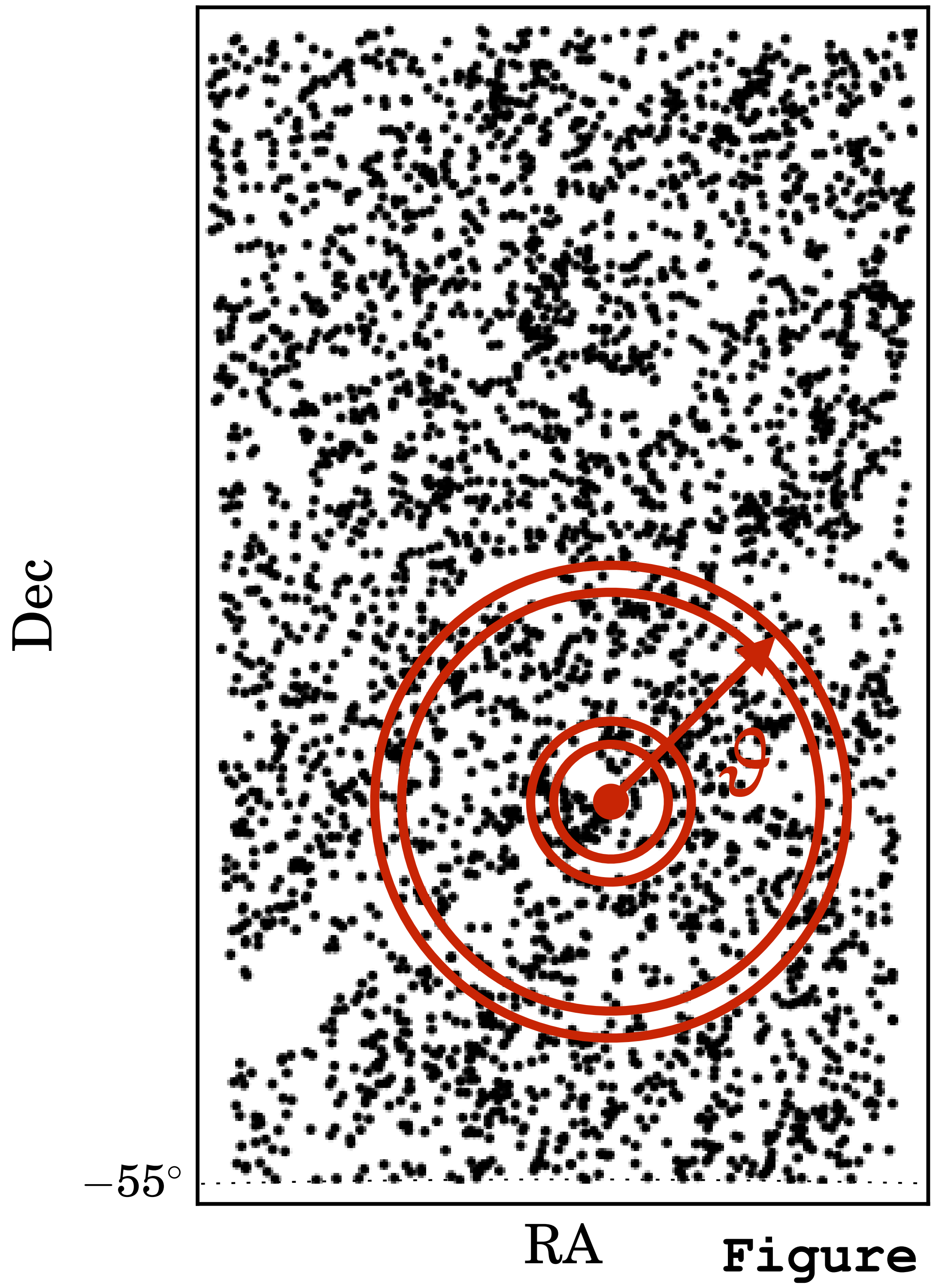
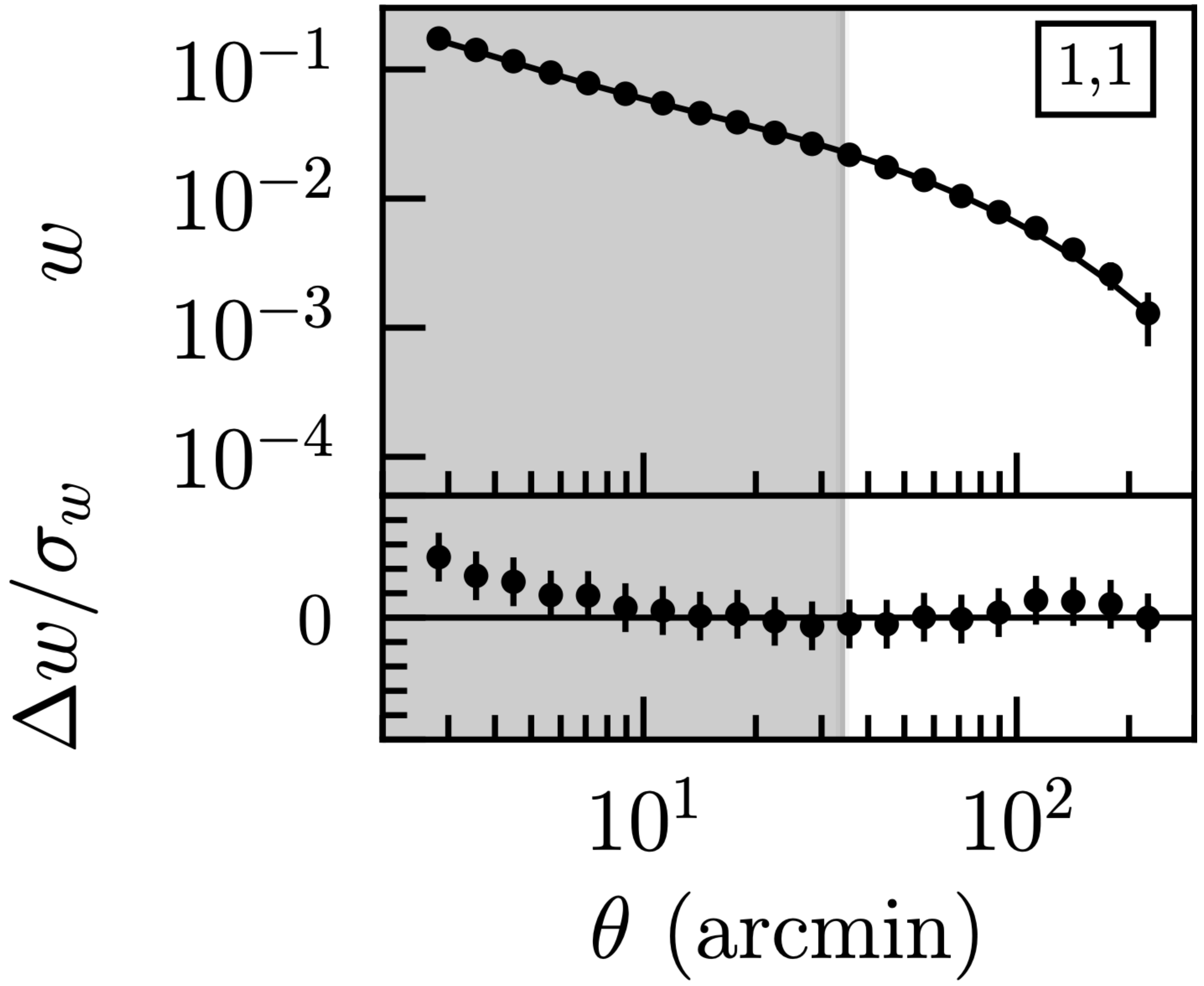
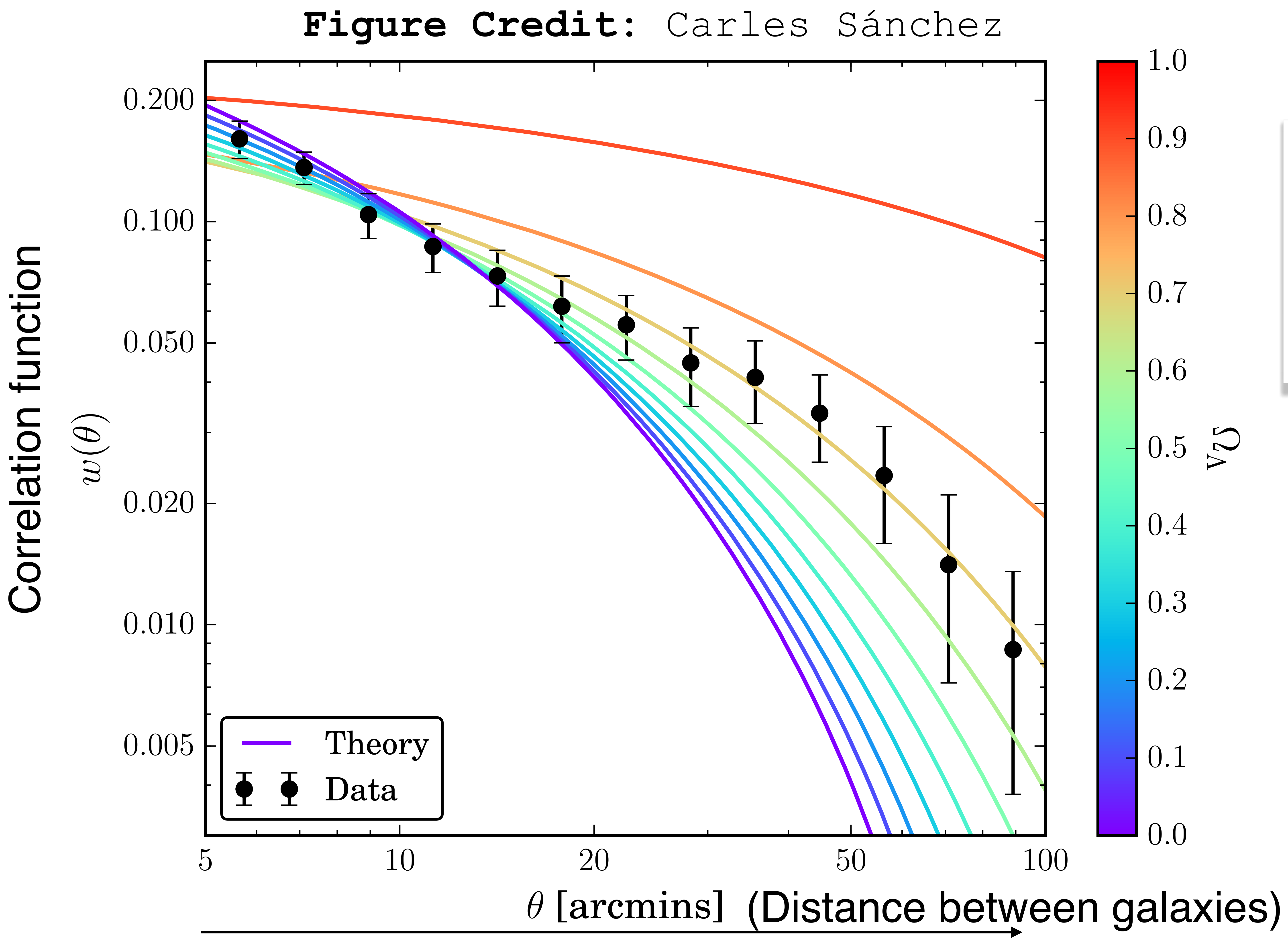


Figure Credit:
Carles Sánchez



DES Y3 measurements:
Rodríguez-Monroy et al. (2022)

Modeling two-point correlation functions…



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

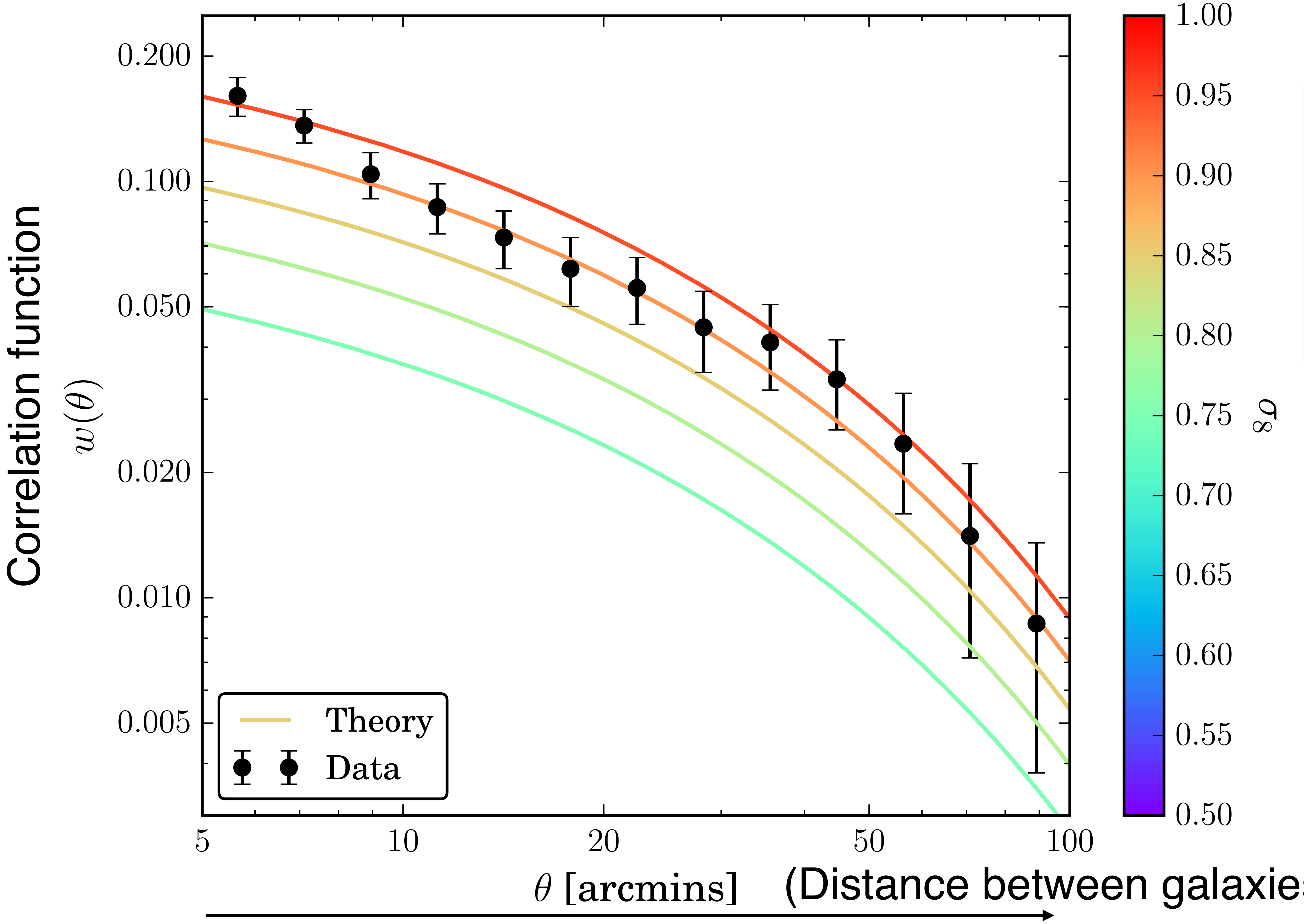
LSS kernel

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

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

Modeling two-point correlation functions…

Figure Credit: Carles Sánchez



(Distance between galaxies)

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

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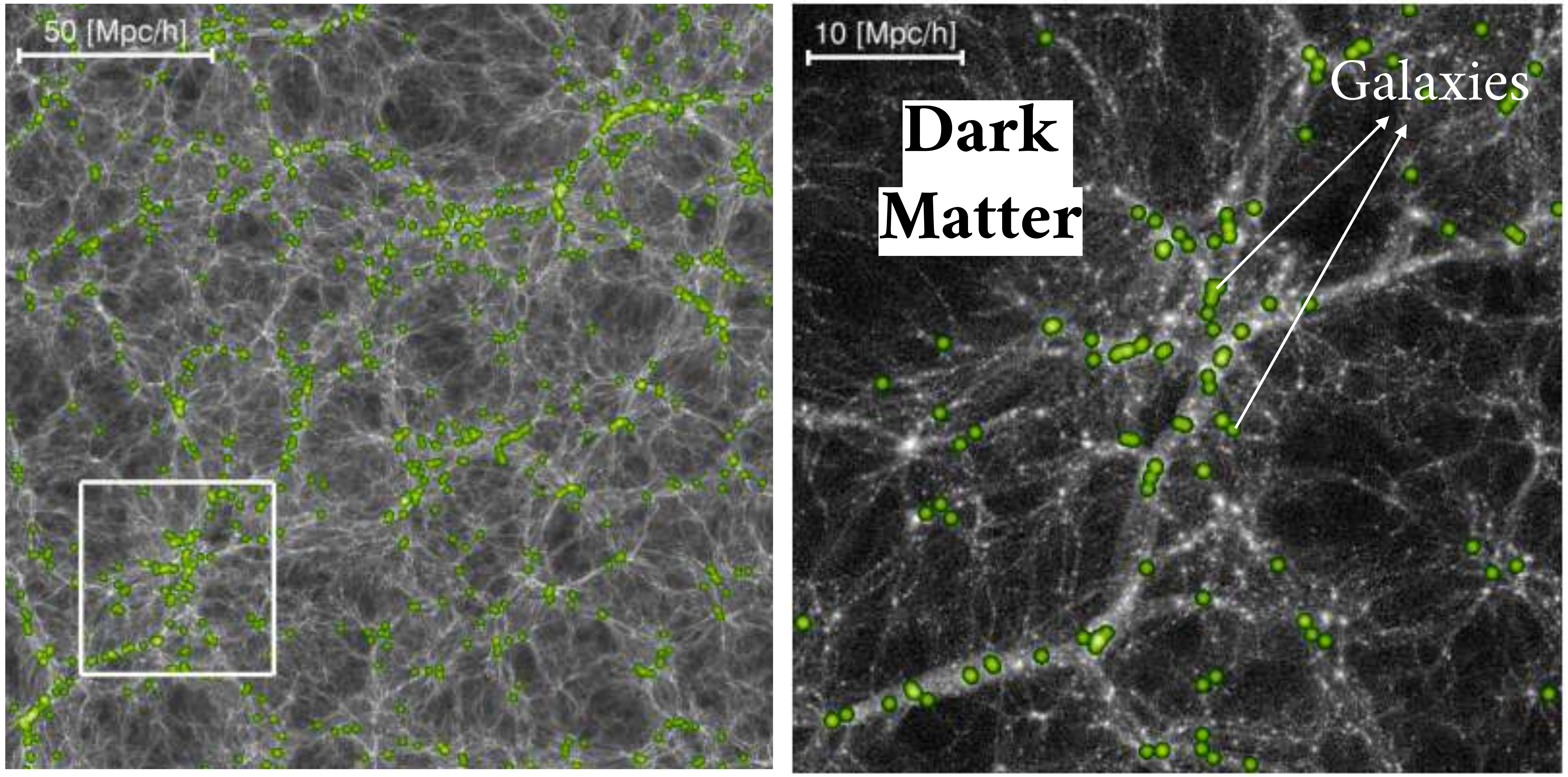
It is sensitive to the matter power spectrum (through the galaxy bias)

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.

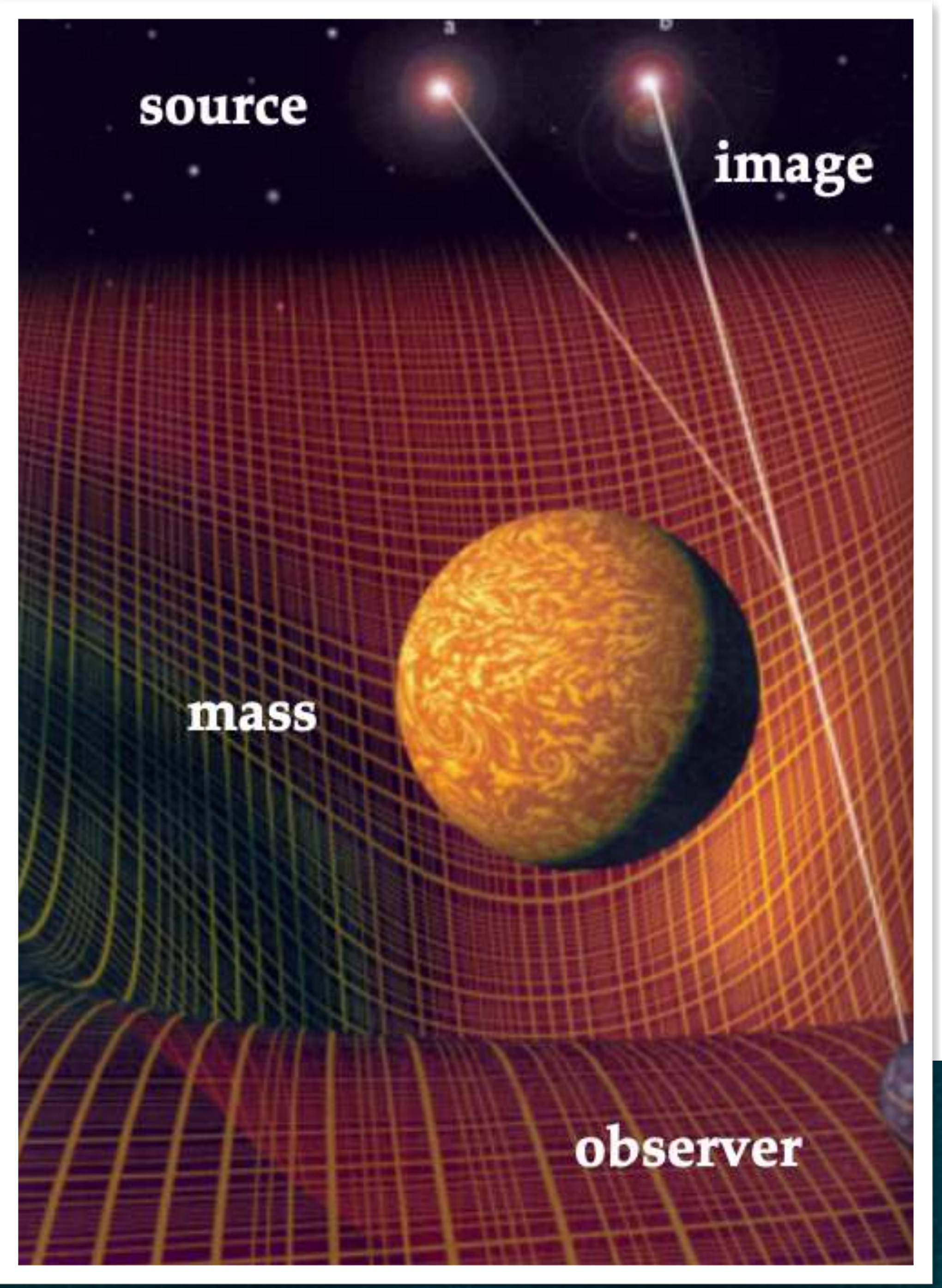
$$\xi_{gg}(r) = b^2(r)\,\xi_{\delta\delta}(r) \qquad P_{gg}(r) = b^2(r)\,P_{\delta\delta}(r)$$



From Orsi et al. (2009)

Gravitational lensing

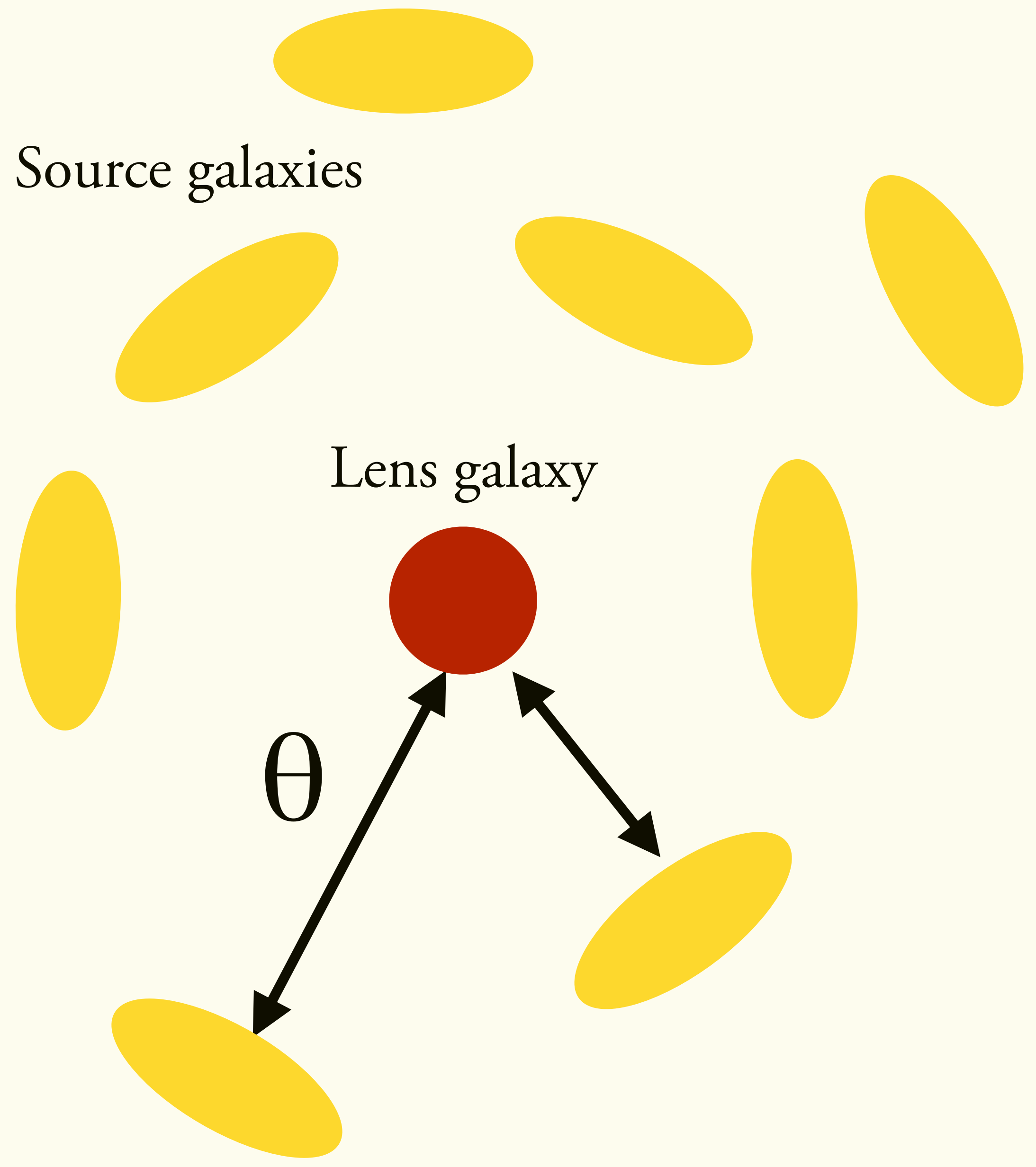
- **Strong gravitational lensing:** If the bending produces multiple images of the galaxy and/or arcs.
- **Weak gravitational lensing:** If the bending is small, the image of galaxies are distorted, stretched and magnified in small amounts. The distortion can be quantified with **shear** (shape) and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

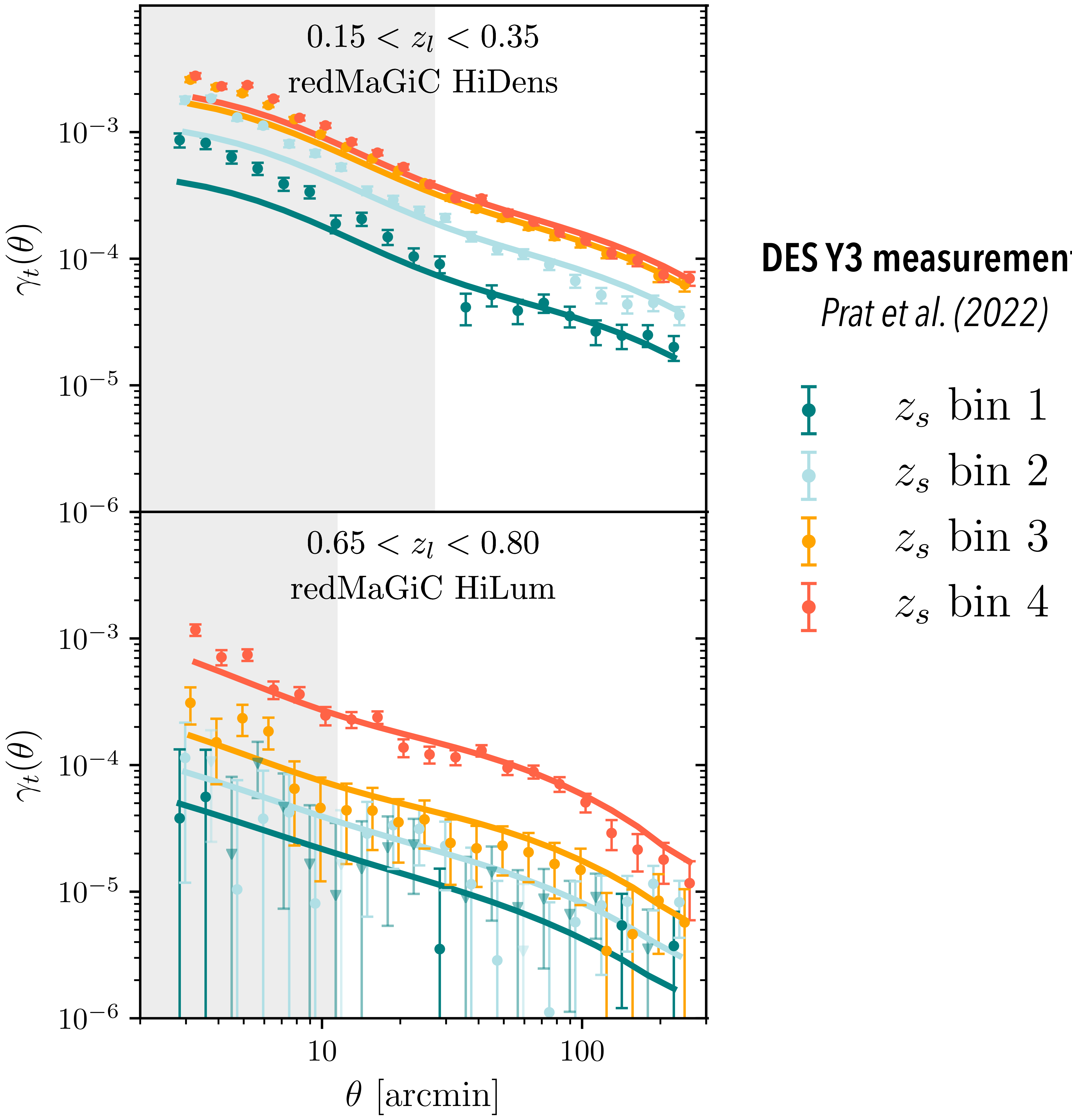


Galaxy-galaxy lensing

Galaxy-galaxy lensing: lens-source correlation

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





DES Y3 measurements:

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Weak gravitational lensing two-point correlation functions

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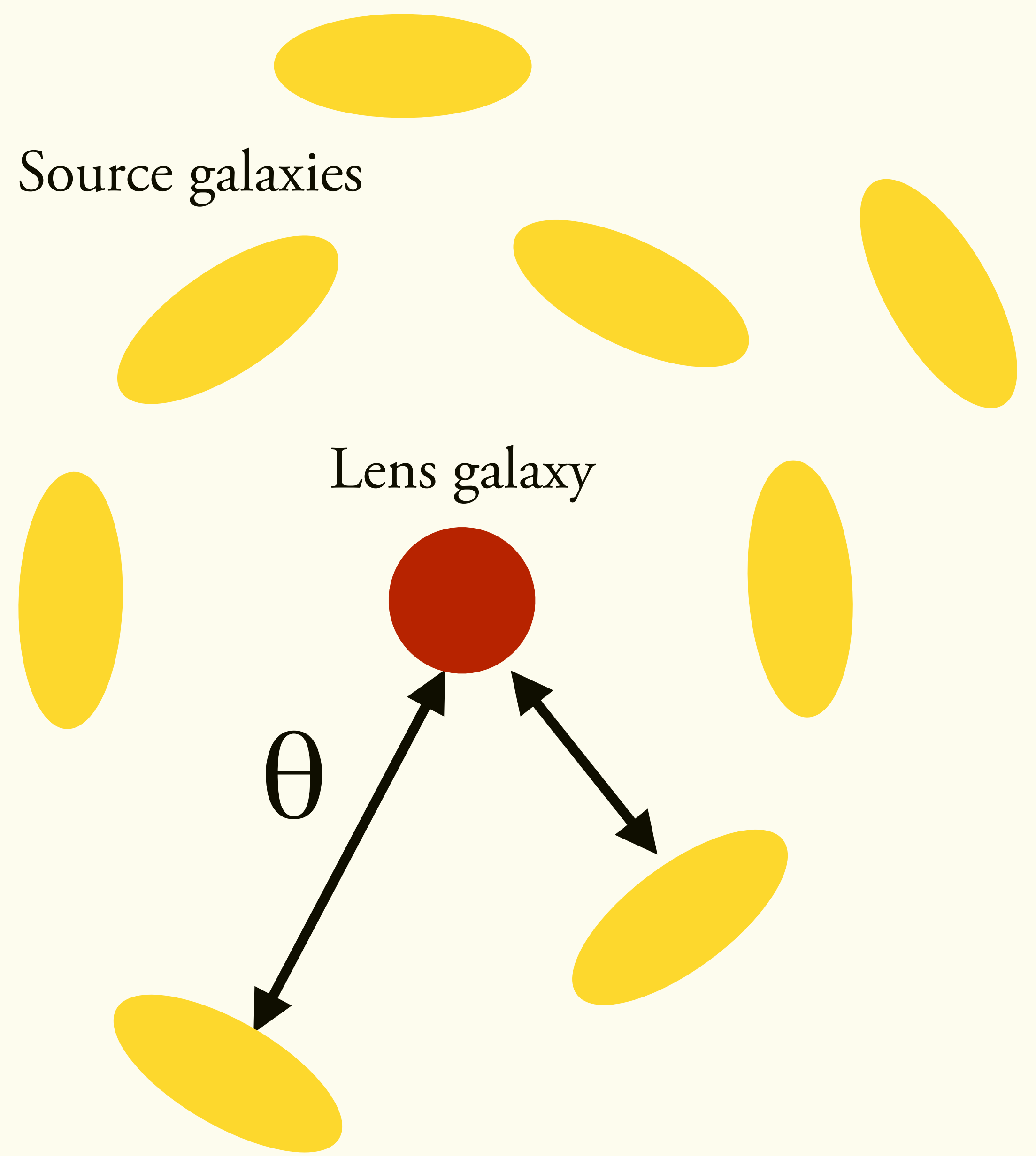
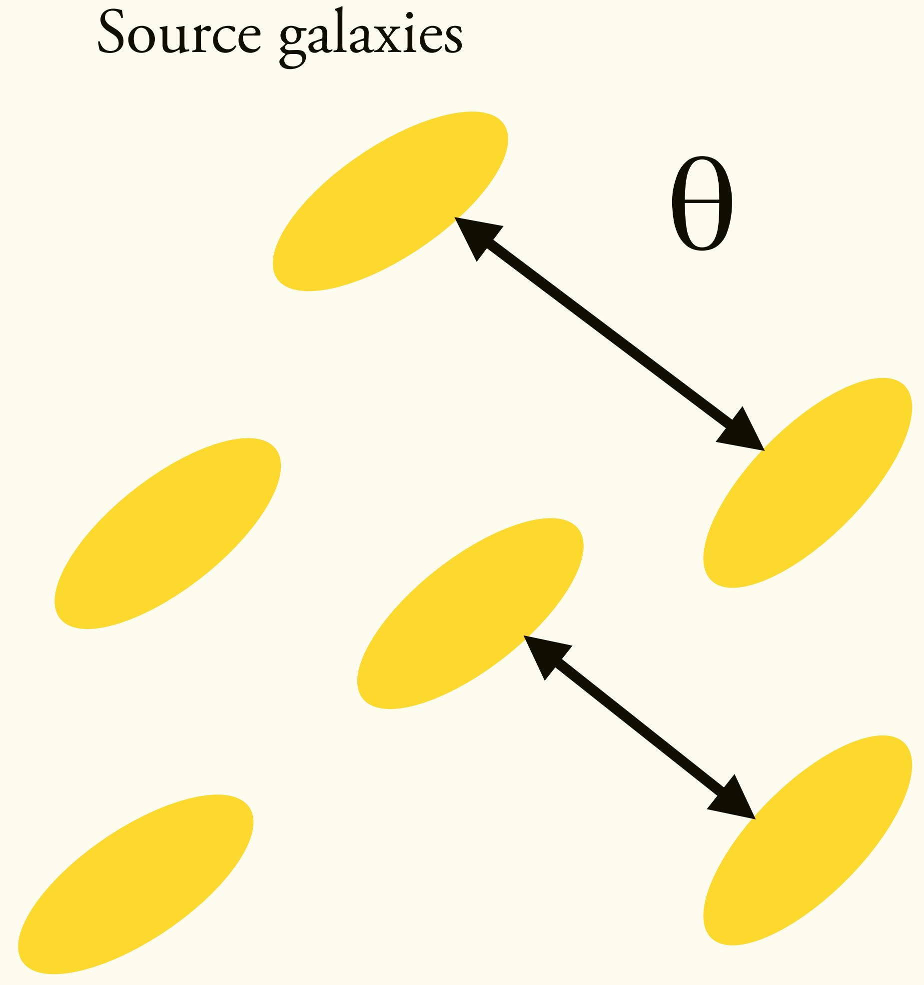
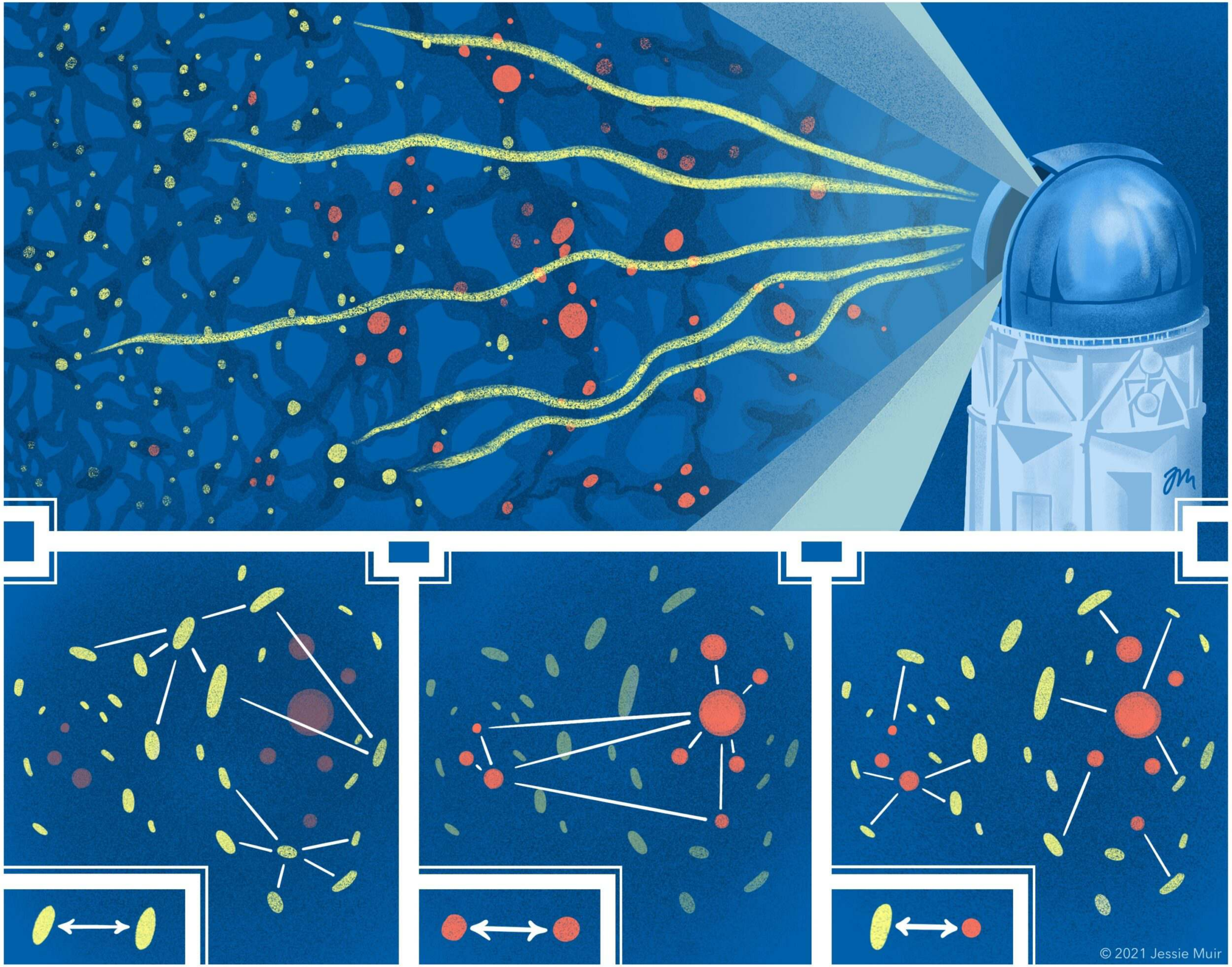


Cosmic shear: source-source correlation

Coherent distortion of galaxy shapes from large-scale structure.



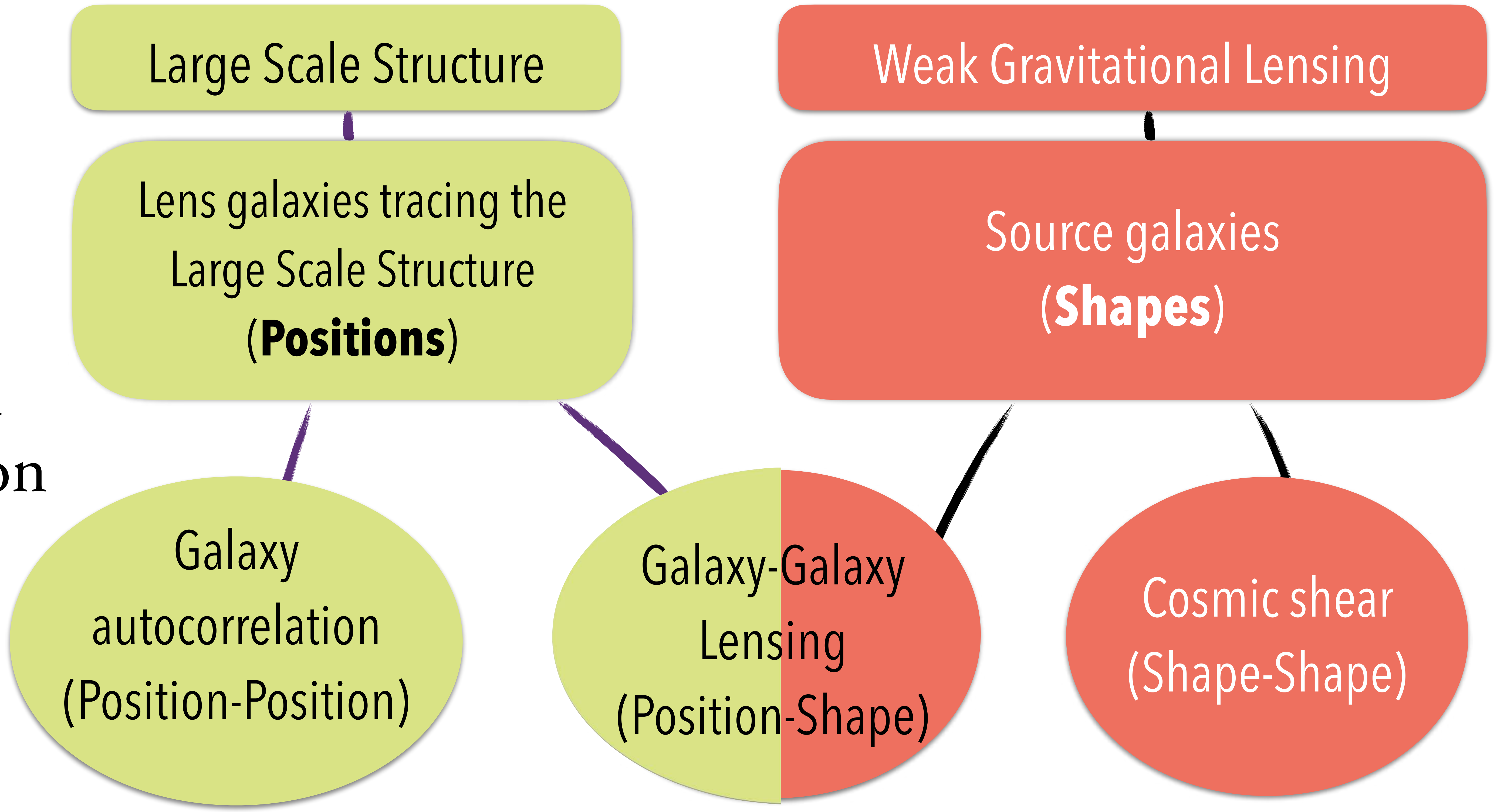
3x2pt:
a synergetic and robust combination of weak lensing and large-scale structure measurements



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.



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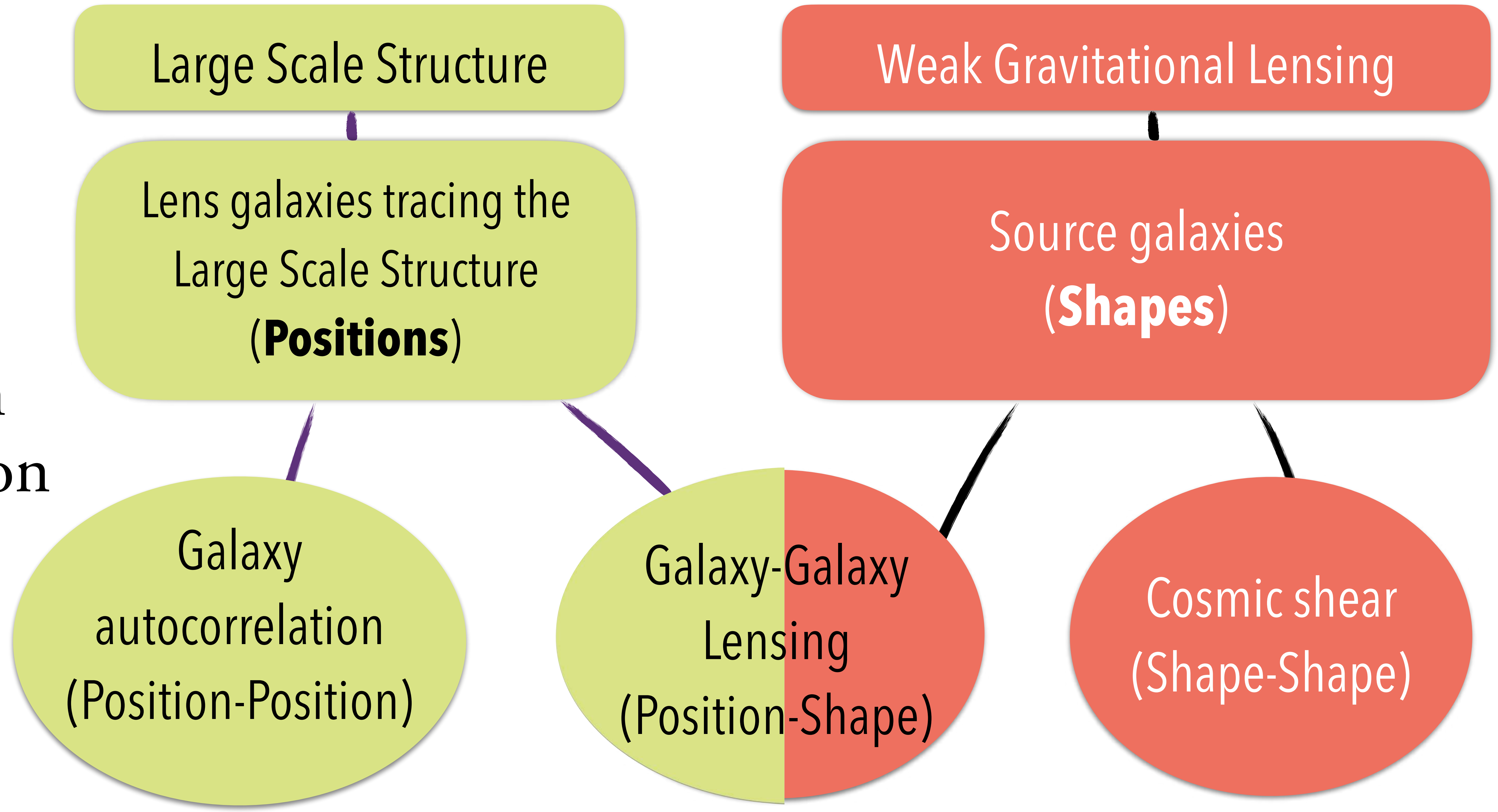

$$\xi_{gg} = \langle \delta_g \, \delta_g \rangle \propto b^2 \, \langle \delta_m \, \delta_m \rangle$$

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

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

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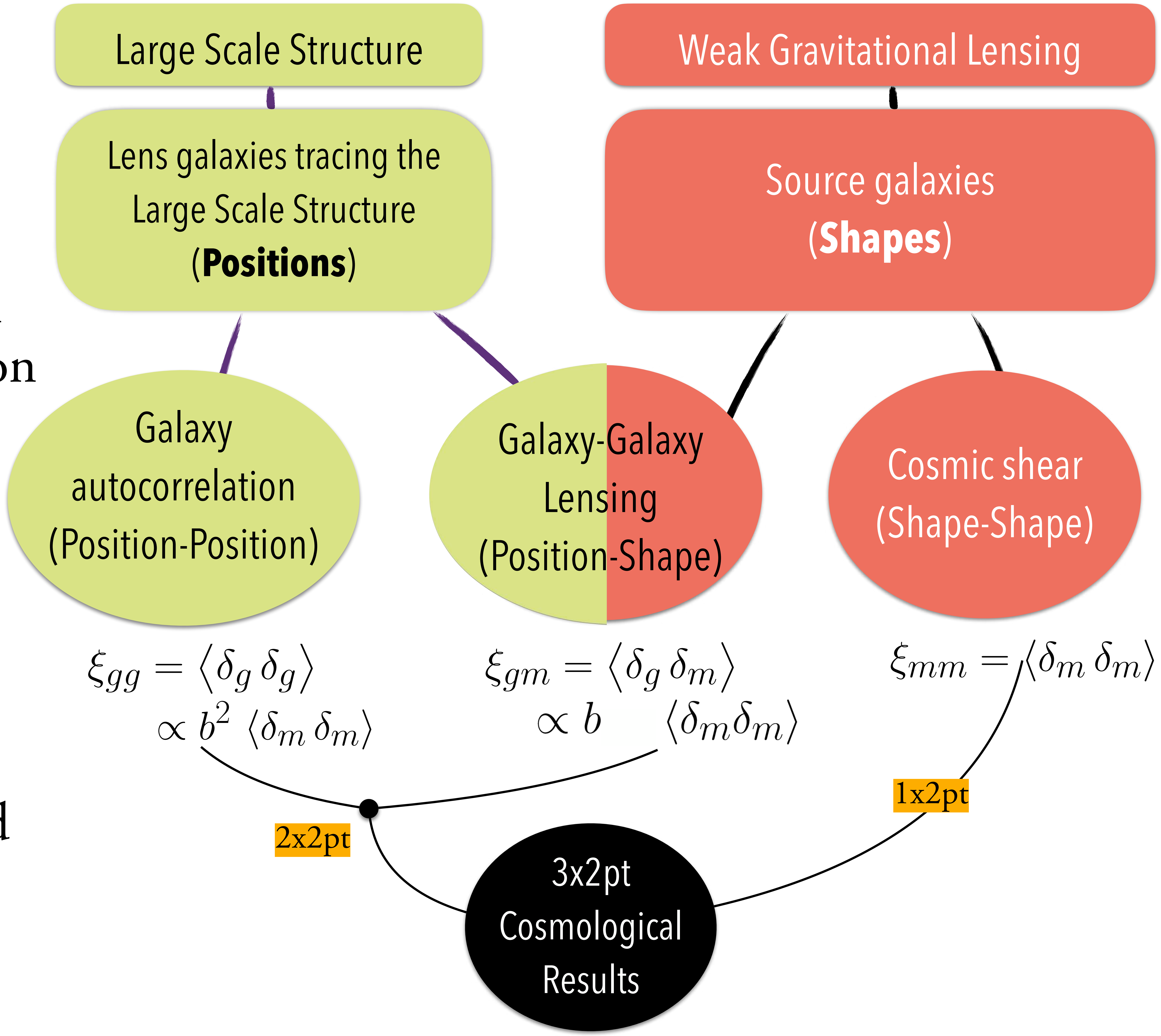

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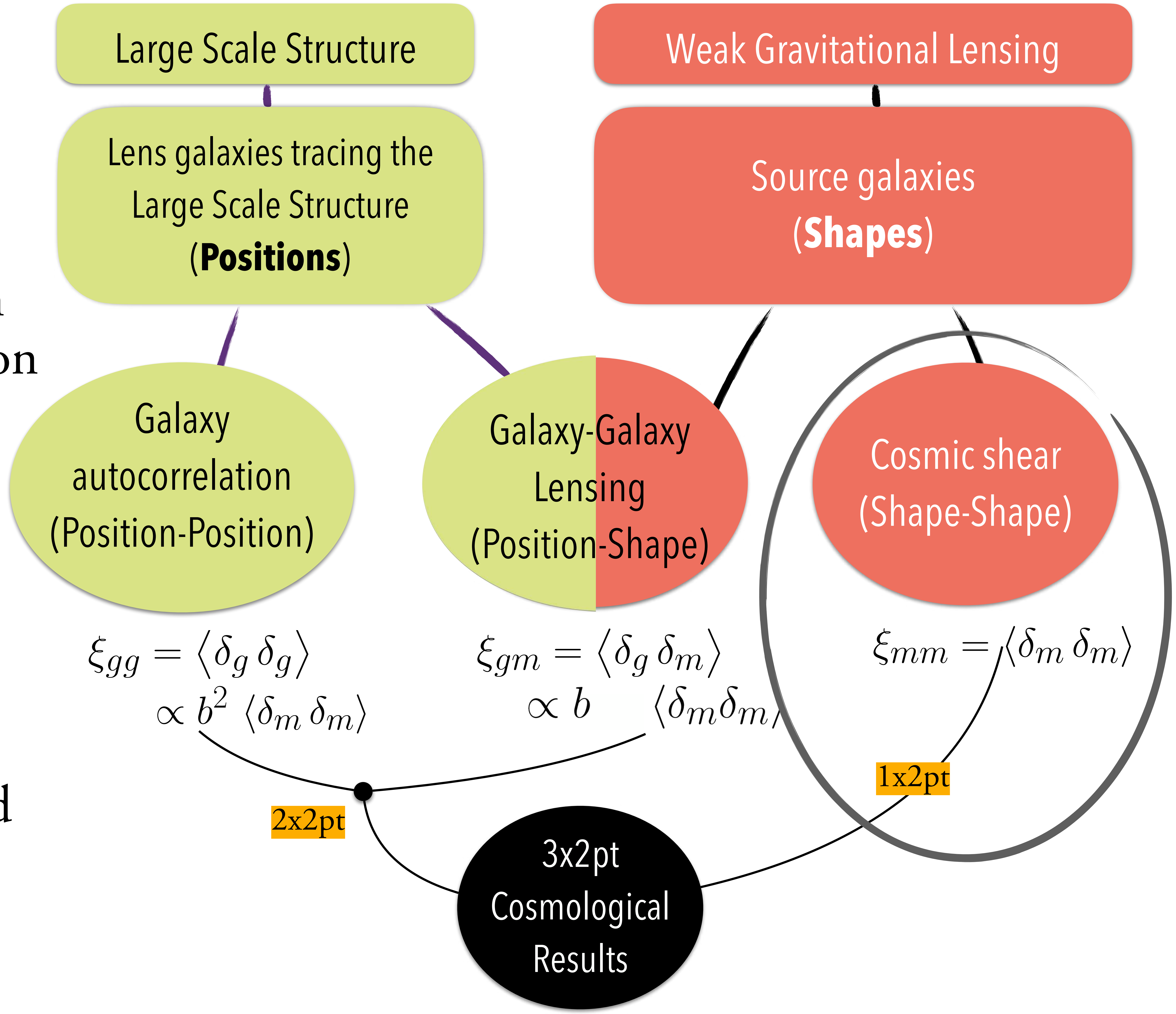
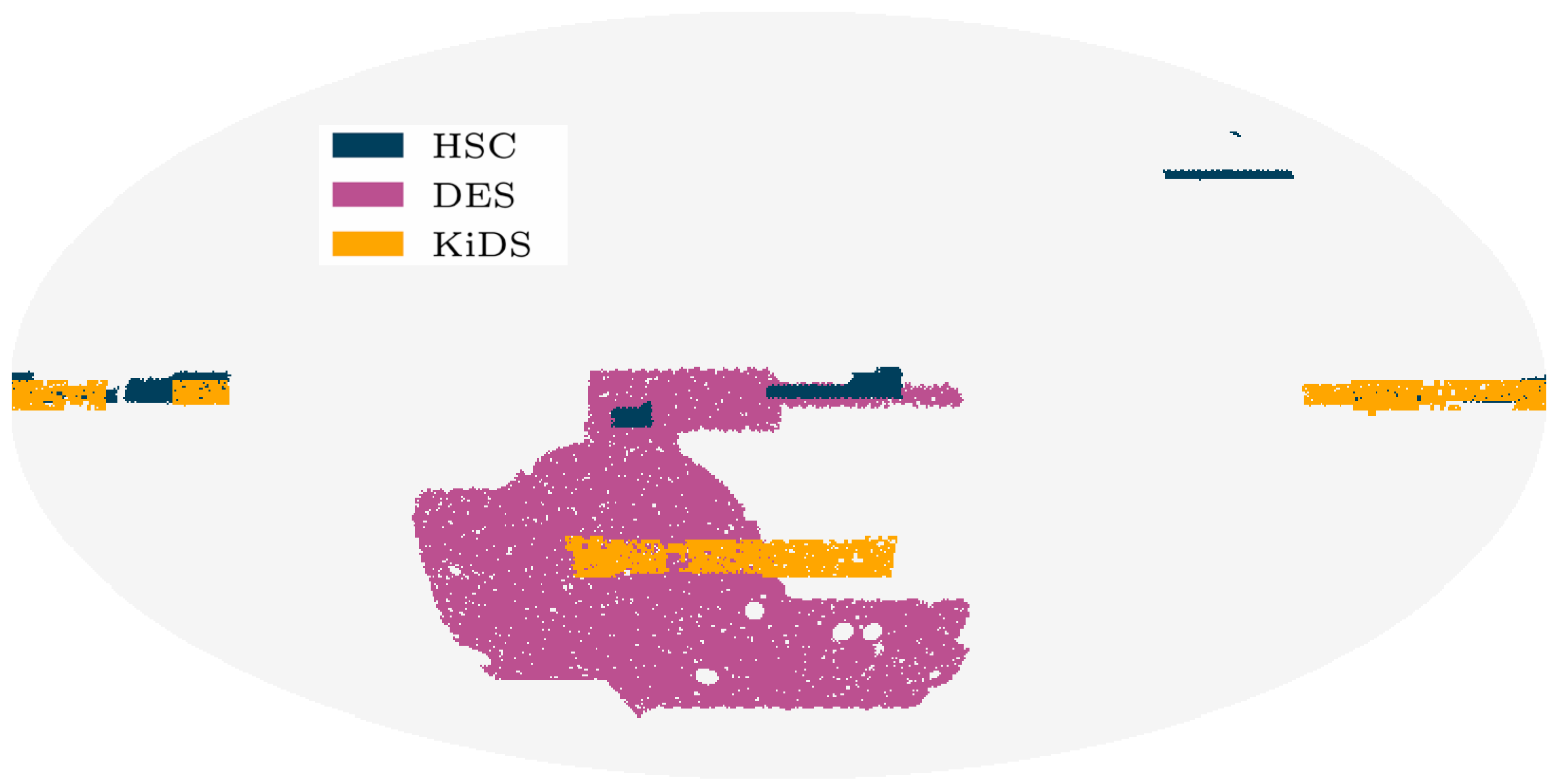


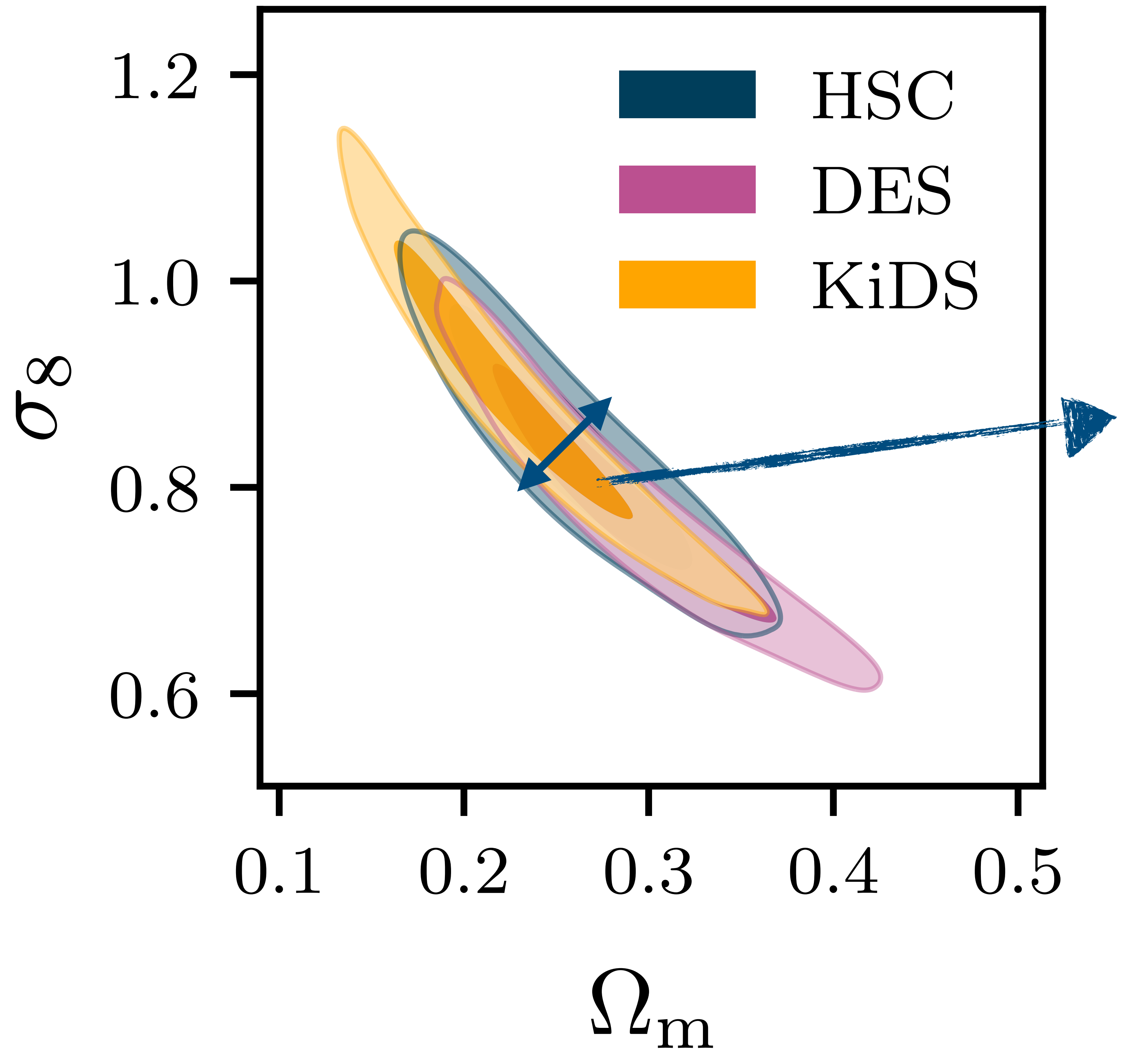
Agreement between surveys: *cosmic shear only*

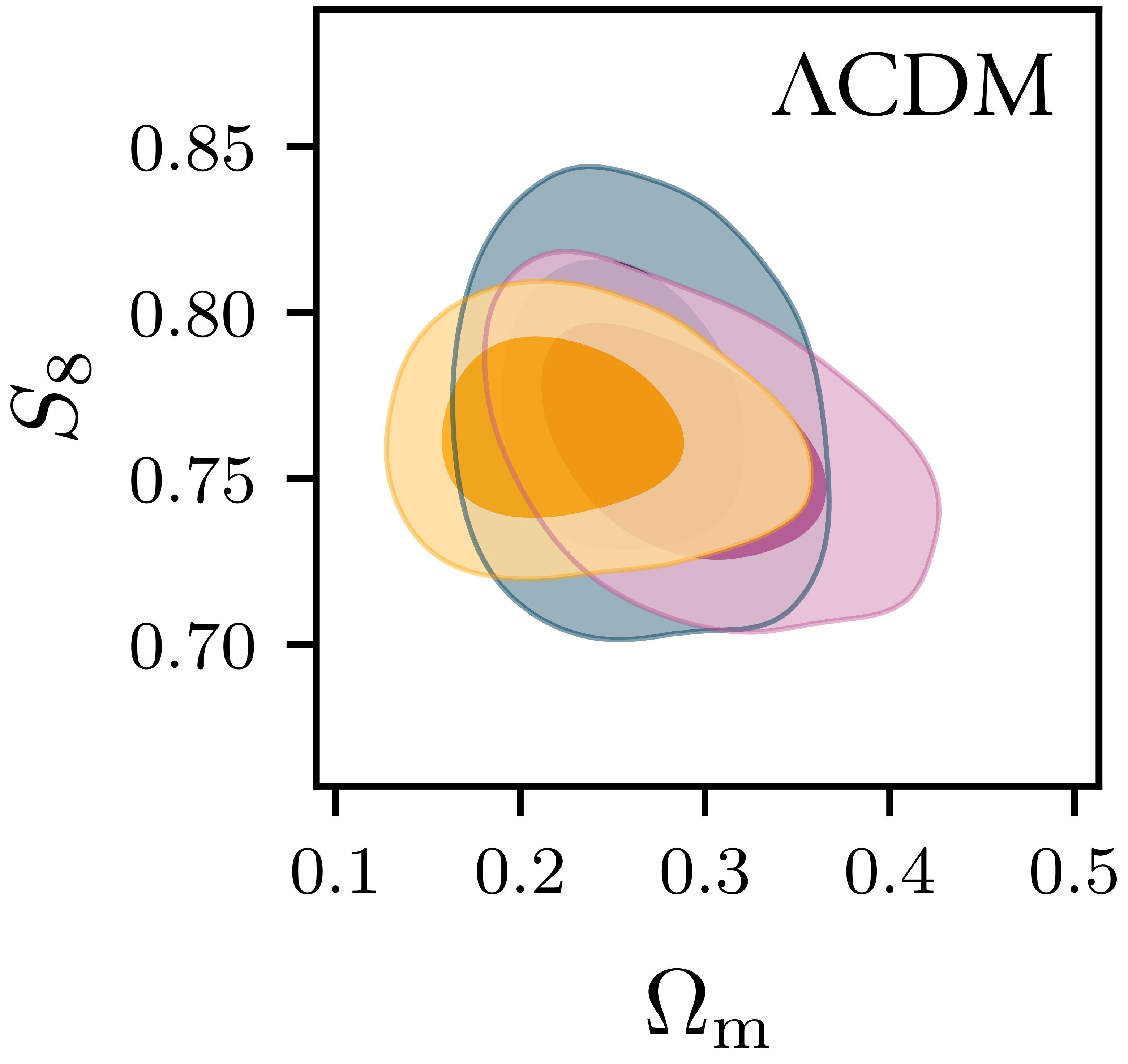
- All cosmic shear results from Stage III surveys are consistent.

$$\sigma_8^2 = \frac{1}{2\pi^2} \int k^2 P(k) \left[\frac{3 j_1(kR)}{kR}\right]^2 dk$$

$$S_8 \equiv \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.5}$$





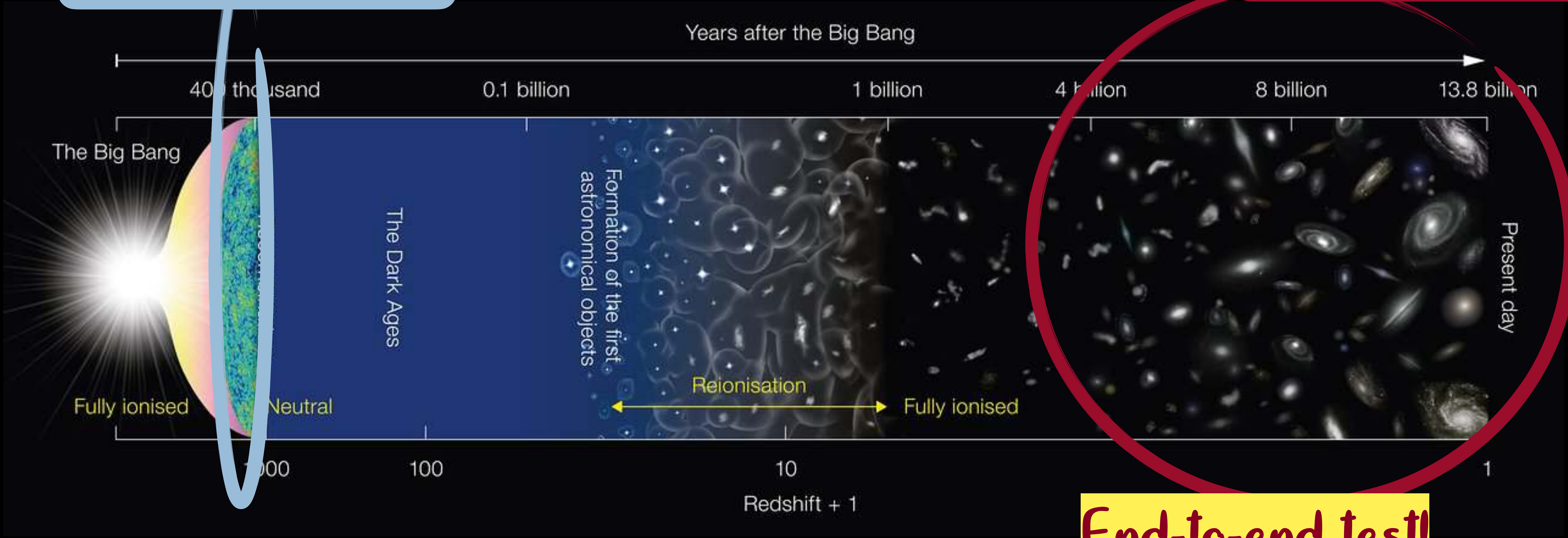


Testing the Standard model of Cosmology: ΛCDM

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

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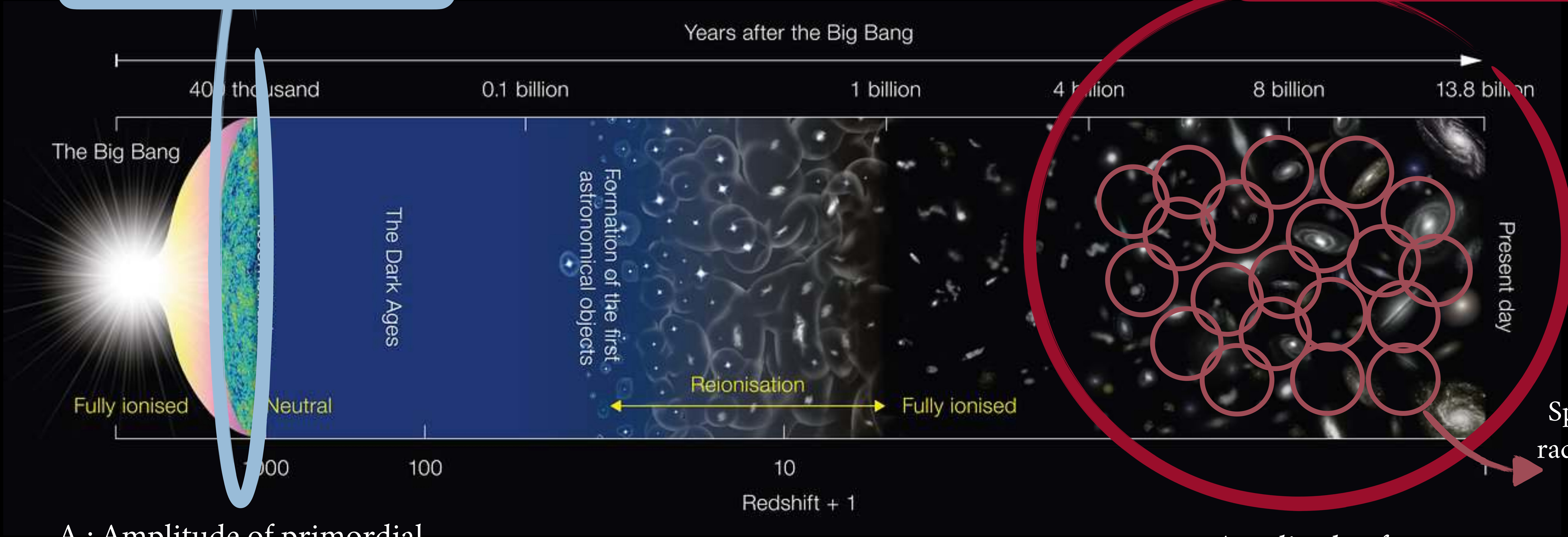


Spheres with radius 8Mpc/h

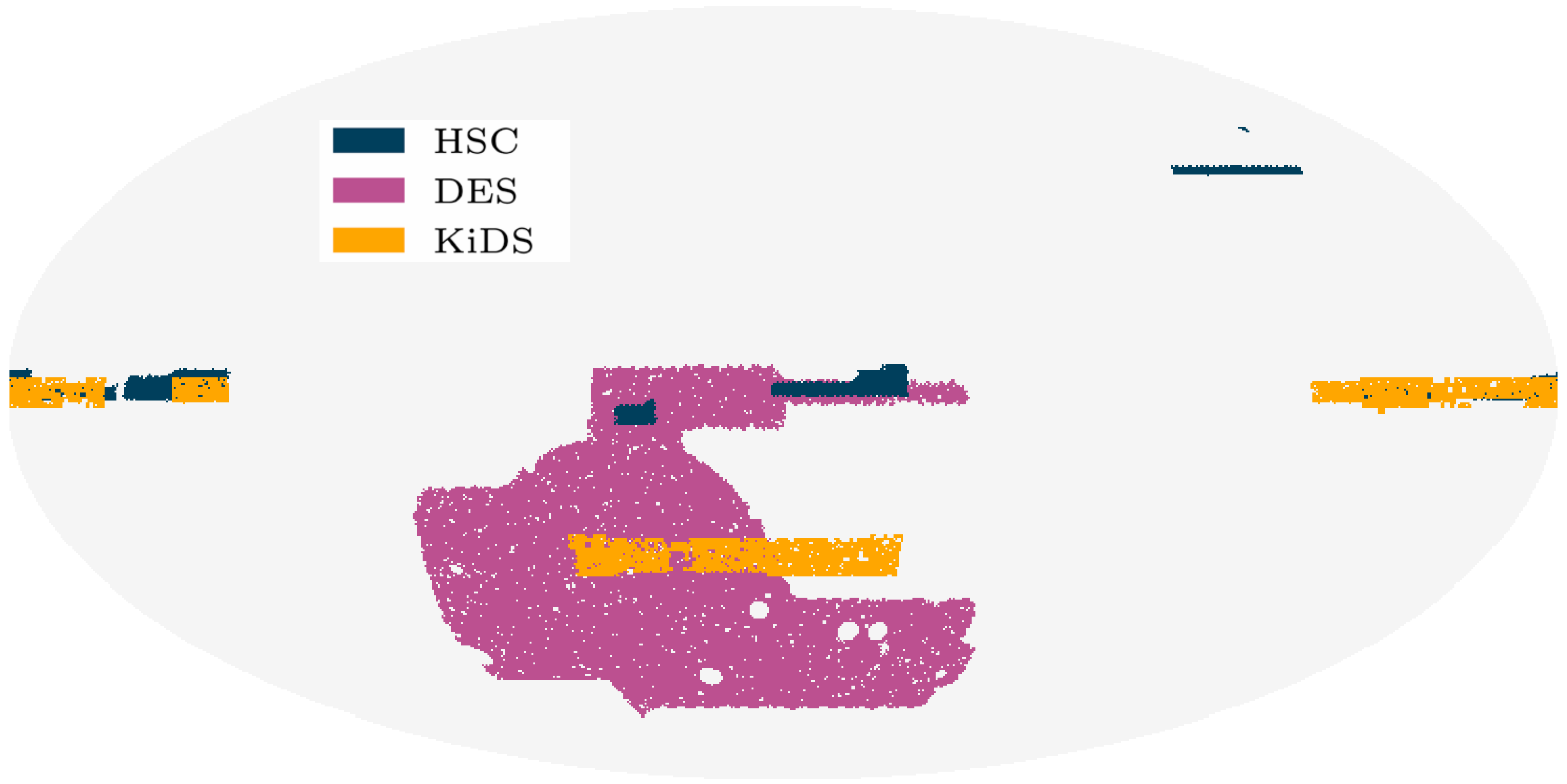
A_s: Amplitude of primordial scalar density fluctuations.

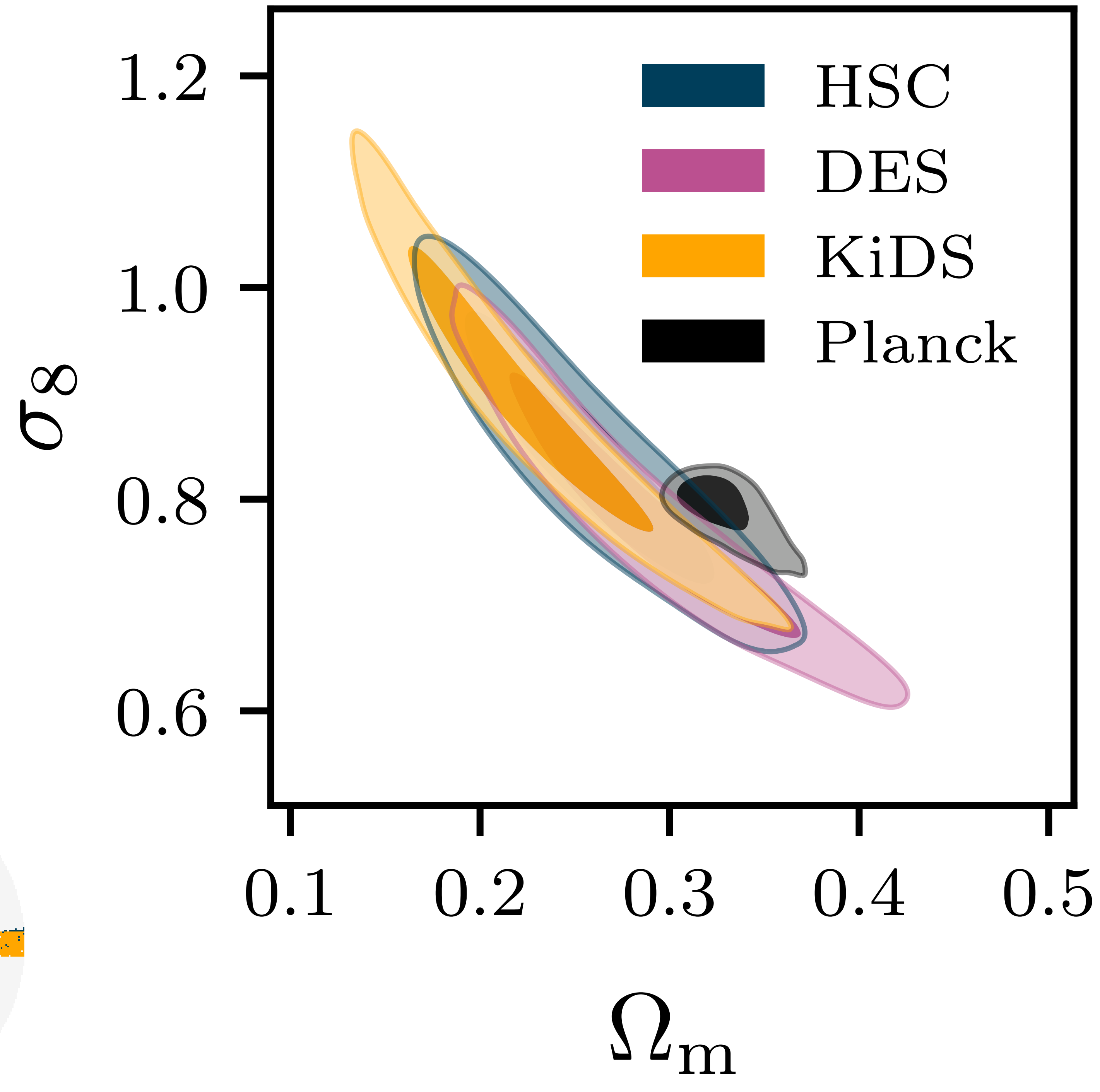
Image credit: NAOJ

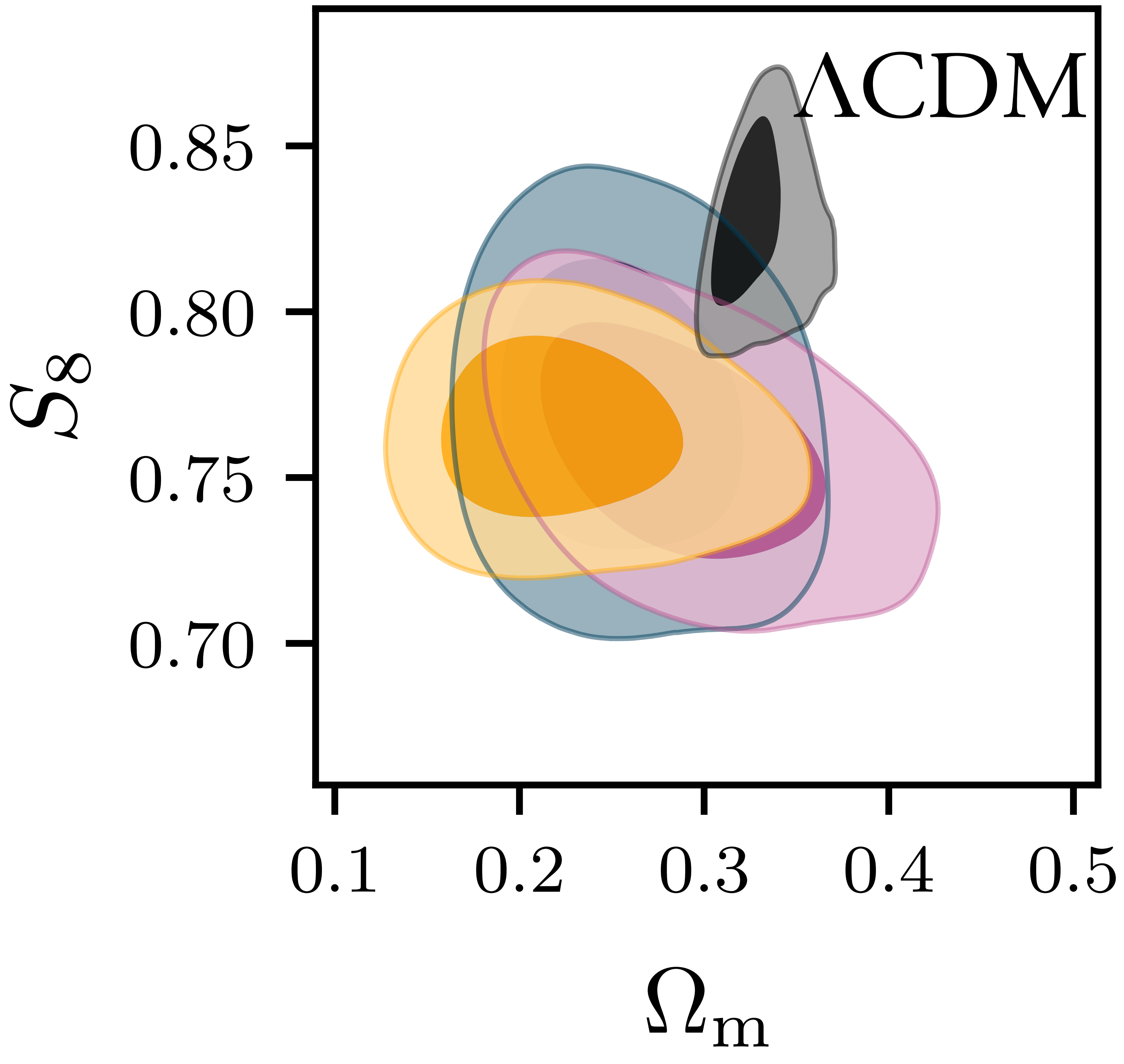
σ_8: Amplitude of mass fluctuations today.

Agreement between surveys: *cosmic shear only*

- All cosmic shear results from Stage III are about 2σ lower than the expected result assuming ΛCDM.





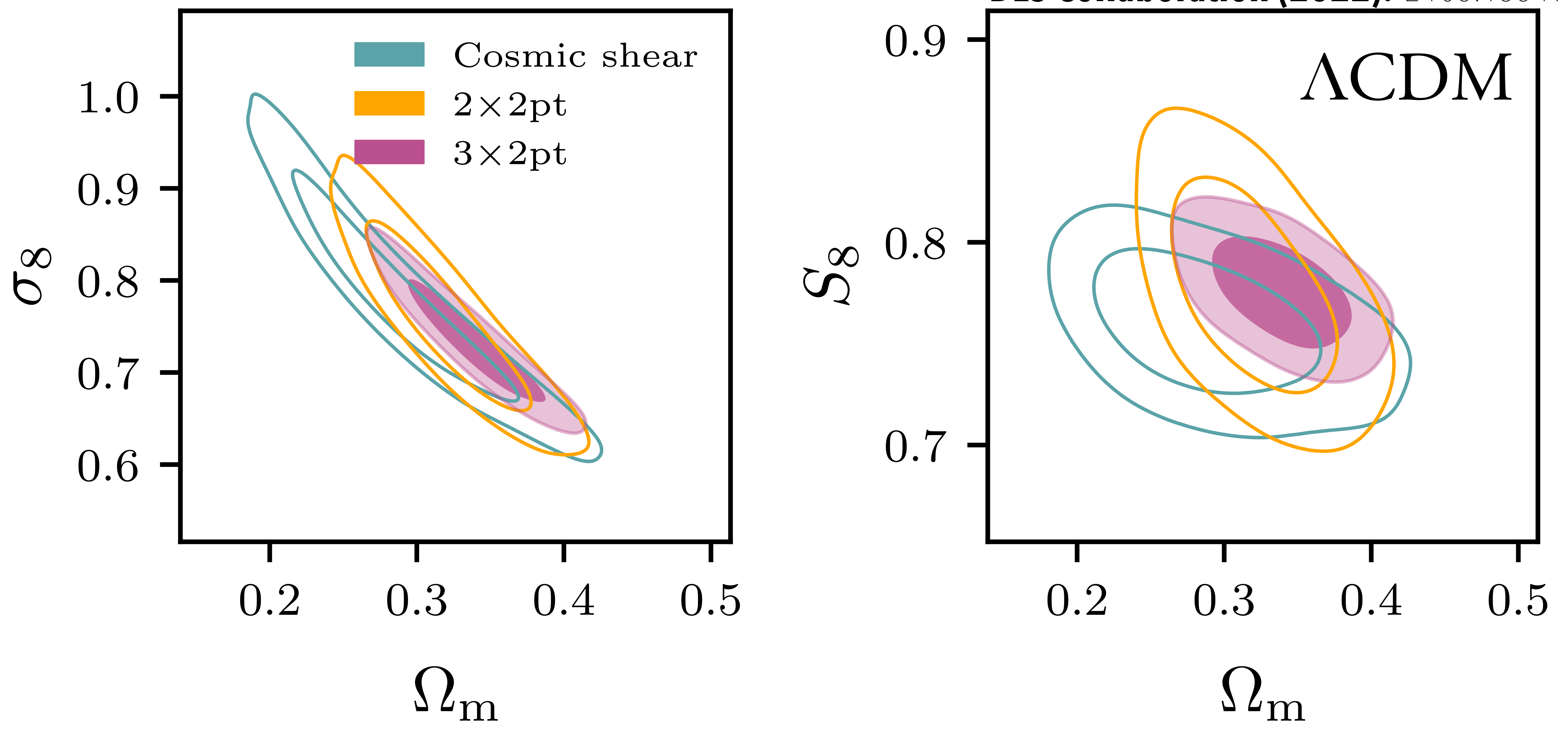


3x2pt combination: DES Y3 results

We find consistency between cosmic shear and 2x2pt.

- Cosmic shear more sensitive to clustering amplitude.
- Galaxy clustering and galaxy-galaxy lensing more sensitive to total matter density.

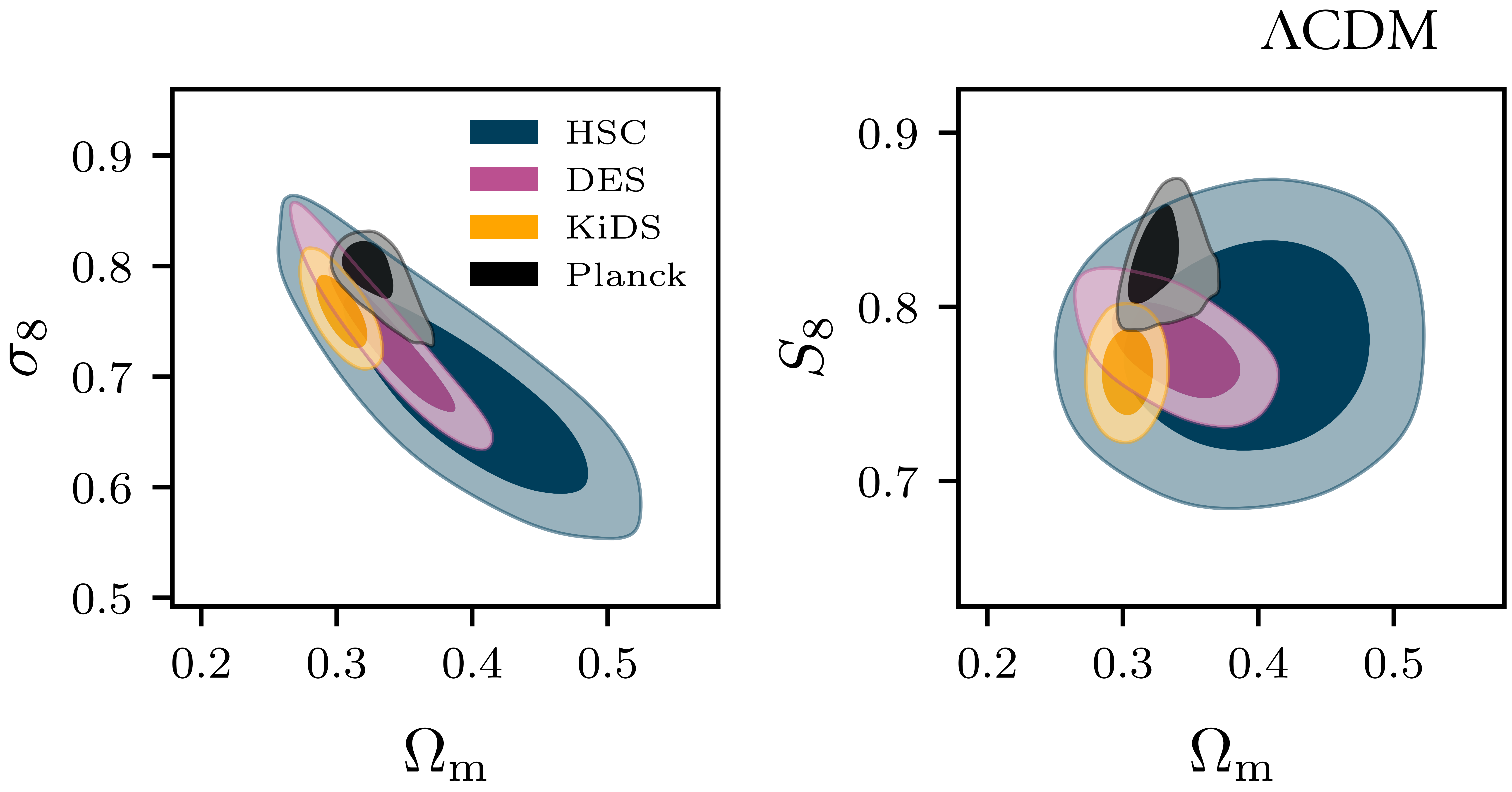
DES Collaboration (2022): 2105.13549



Late time vs early time comparison

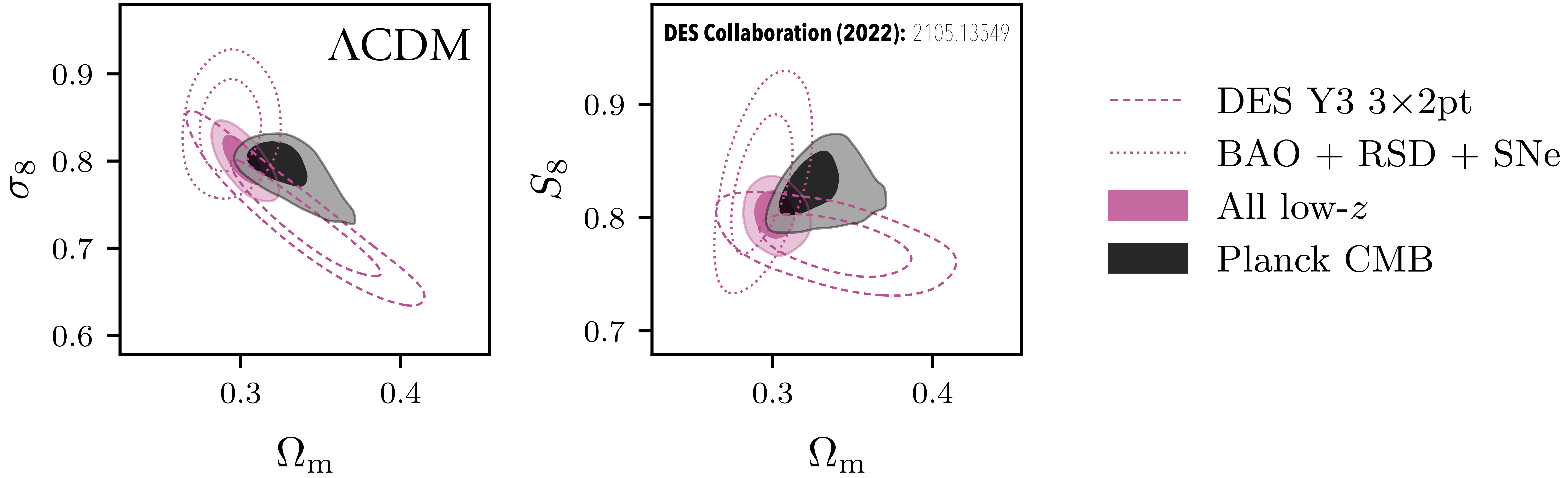
- Planck and DES Y3 are consistent assuming the ΛCDM model (1.5σ), although the clustering amplitude is lower for DES Y3 than Planck.

- KiDS is ~2σ below Planck.



3x2pt in context: *Low redshift Universe constraints*

- In ΛCDM, 3x2pt mostly helps in the σ_8-Ω_m plane.
- When combined with other external redshift probes (*Pantheon SNe IA, BOSS BAO, BOSS RSD*), they are also consistent (0.9σ), with smaller uncertainties.

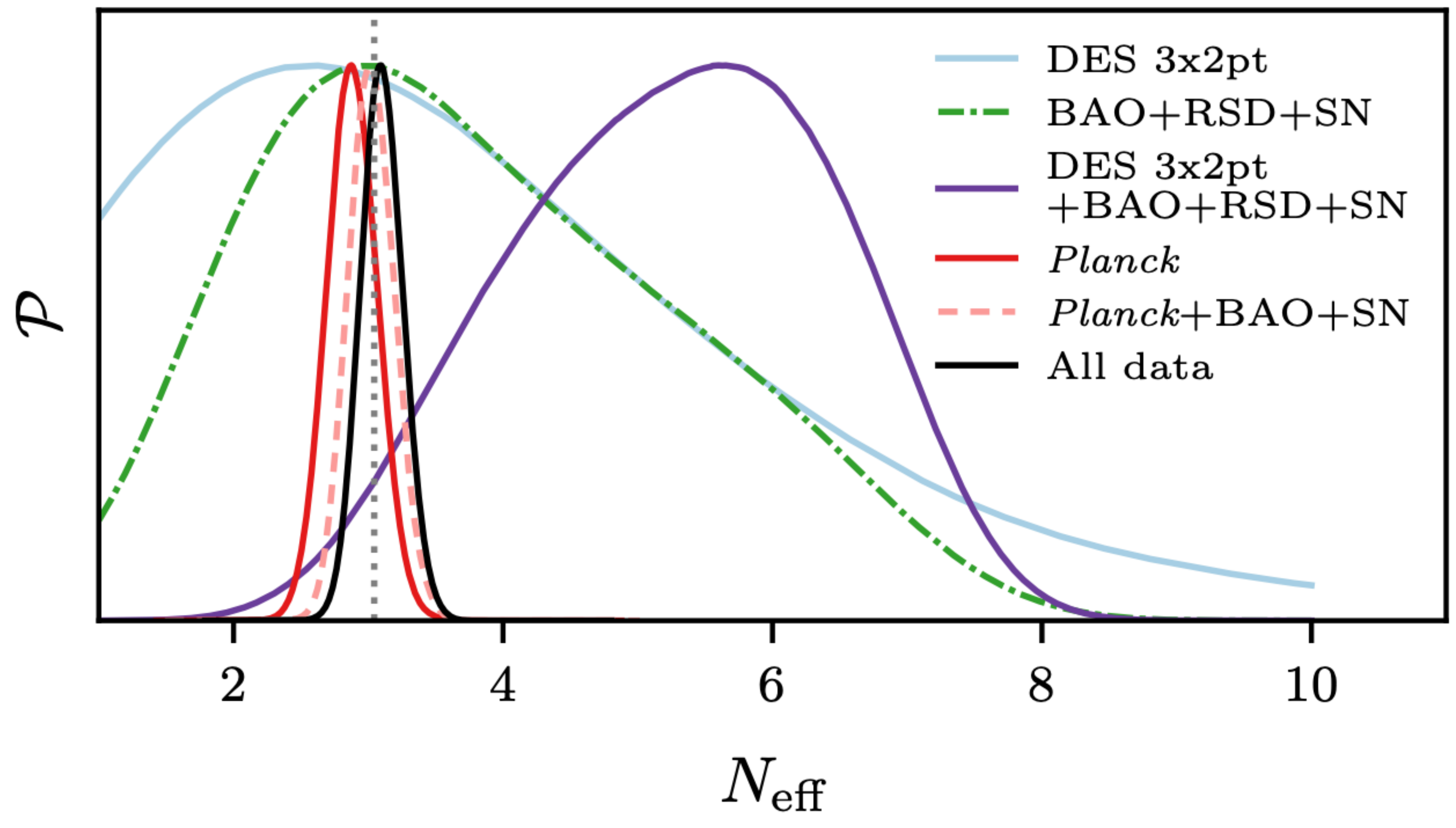


DES Y3 results:

Other extended models

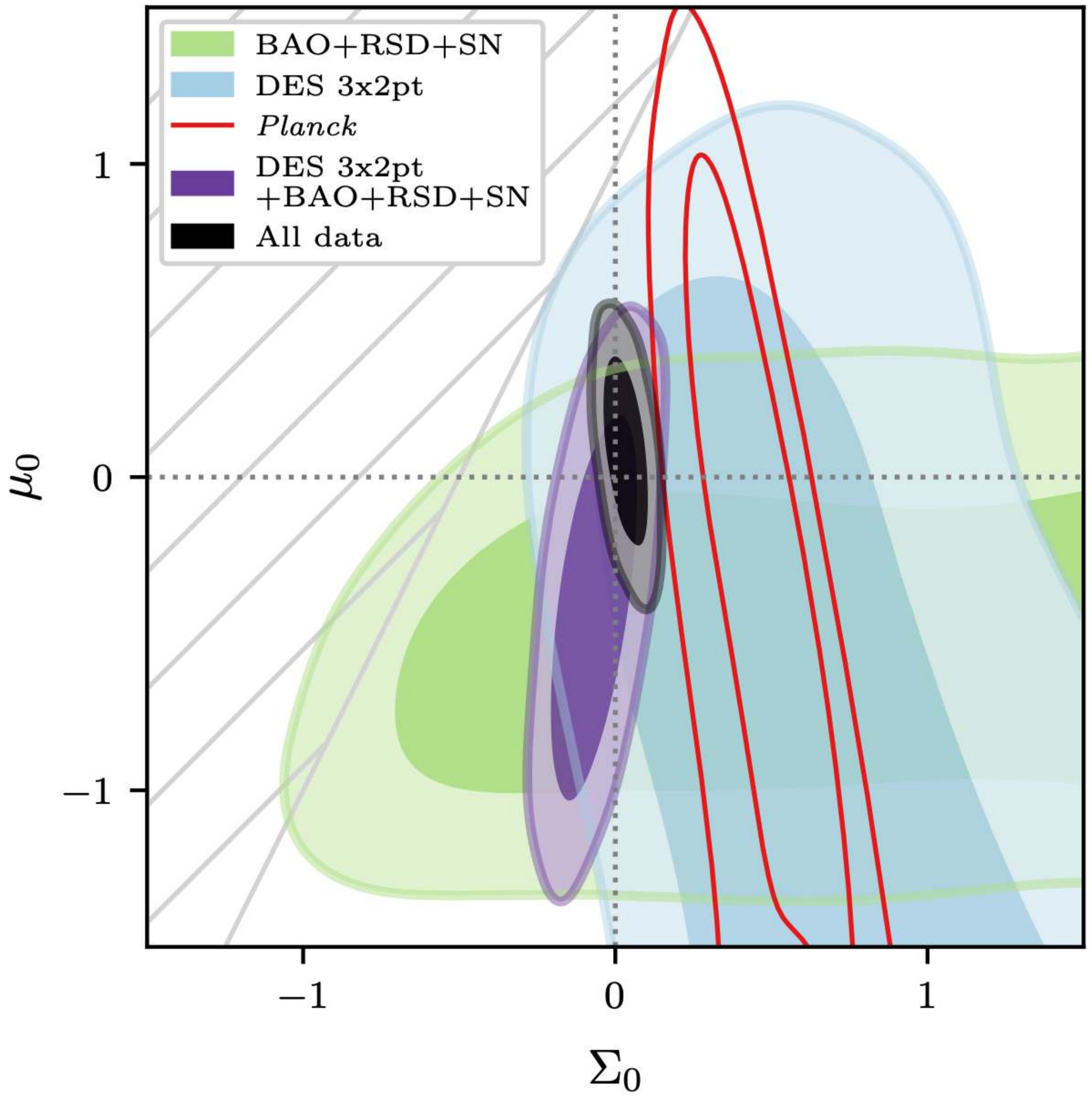
Work led by Jessie Muir and Agnes Ferte

Marginalized posterior on the number of relativistic species.



Modified gravity

DES Collaboration (2022): arXiV: 2207.05766



The Standard Cosmological model is still standing: ΛCDM

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

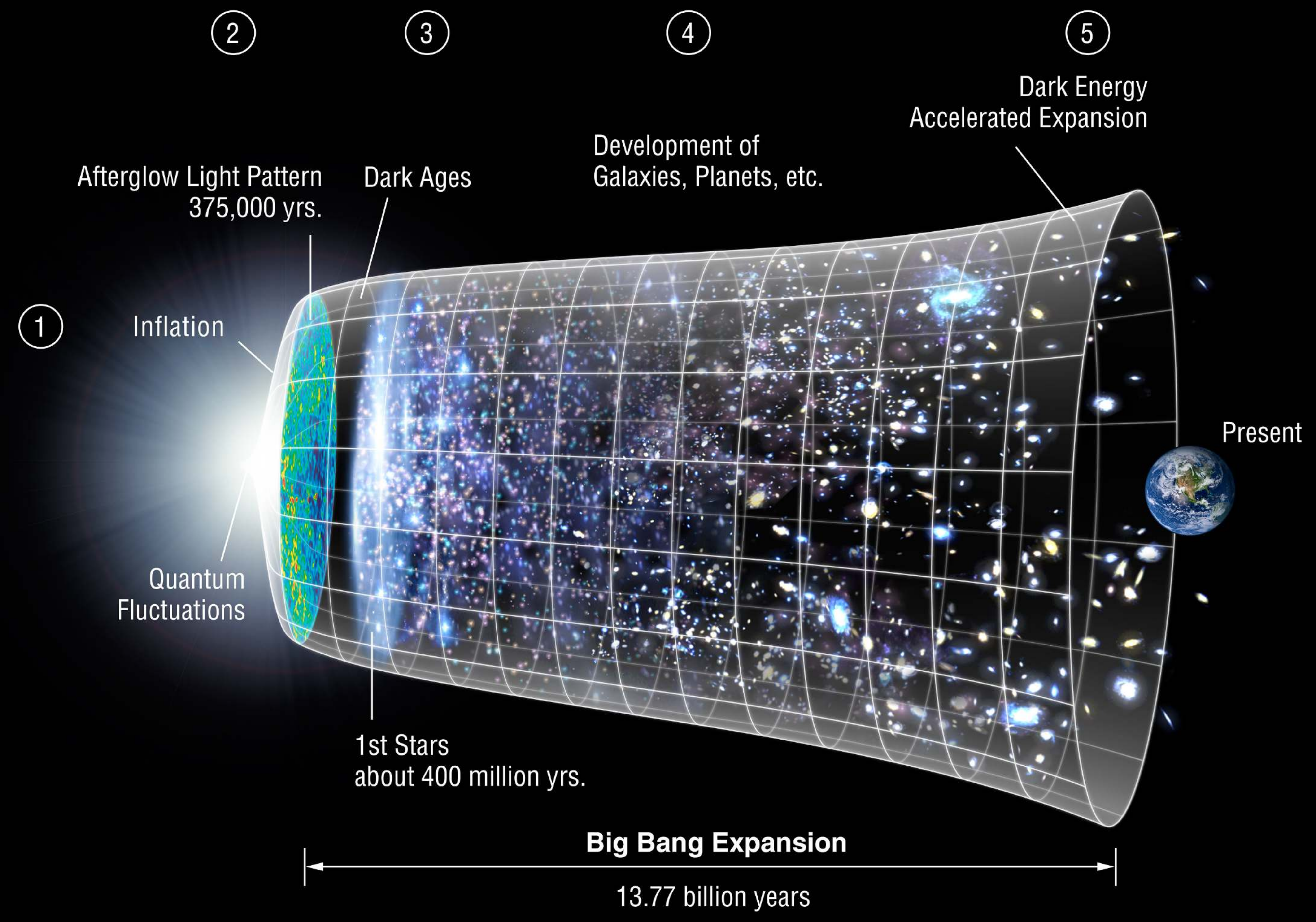


Image Credit: NASA / LAMBDA Archive / WMAP Science Team

However 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.

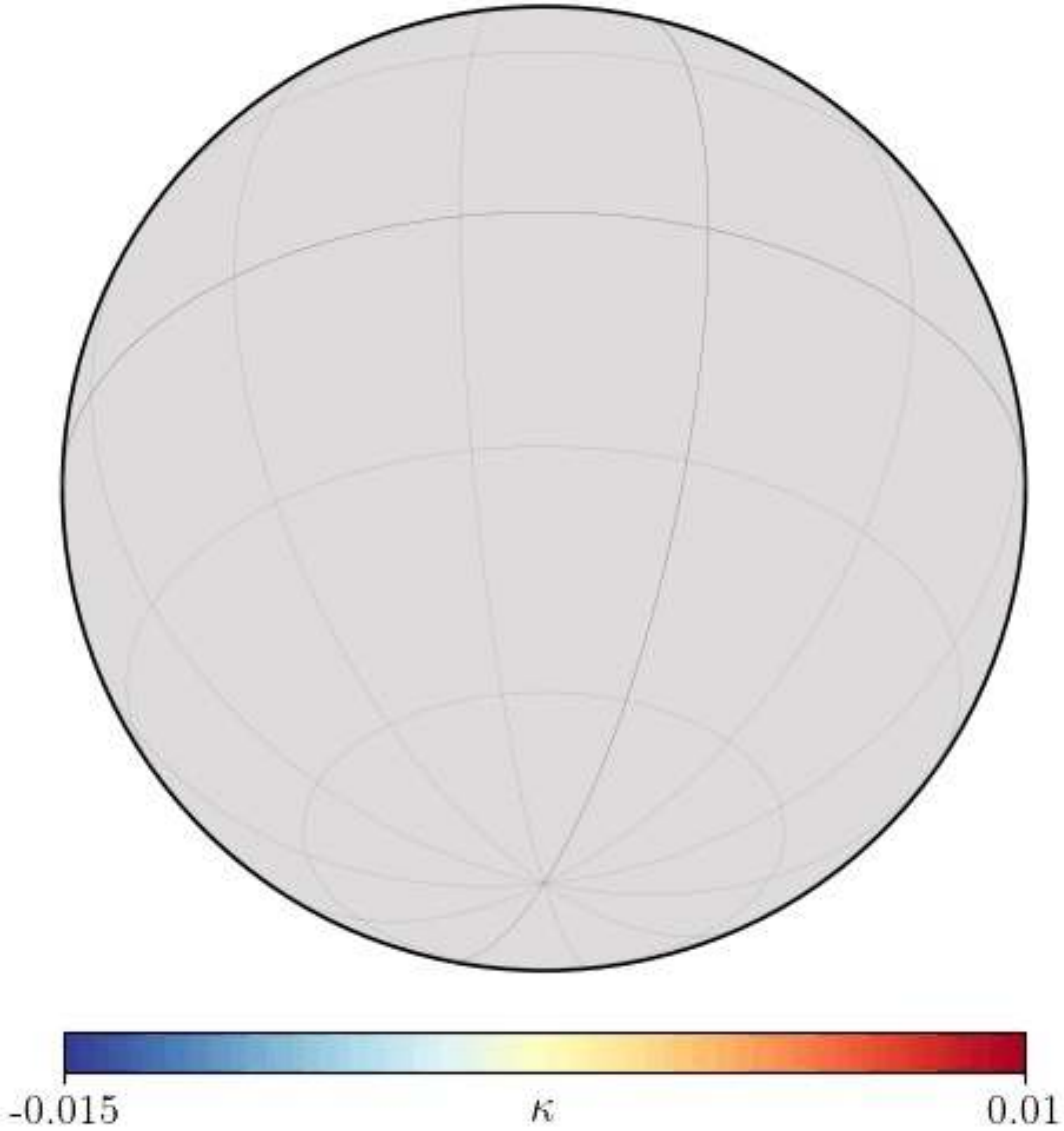
Is **dark energy evolving with time?**

Dark Energy or modified gravity?

How can we do better?

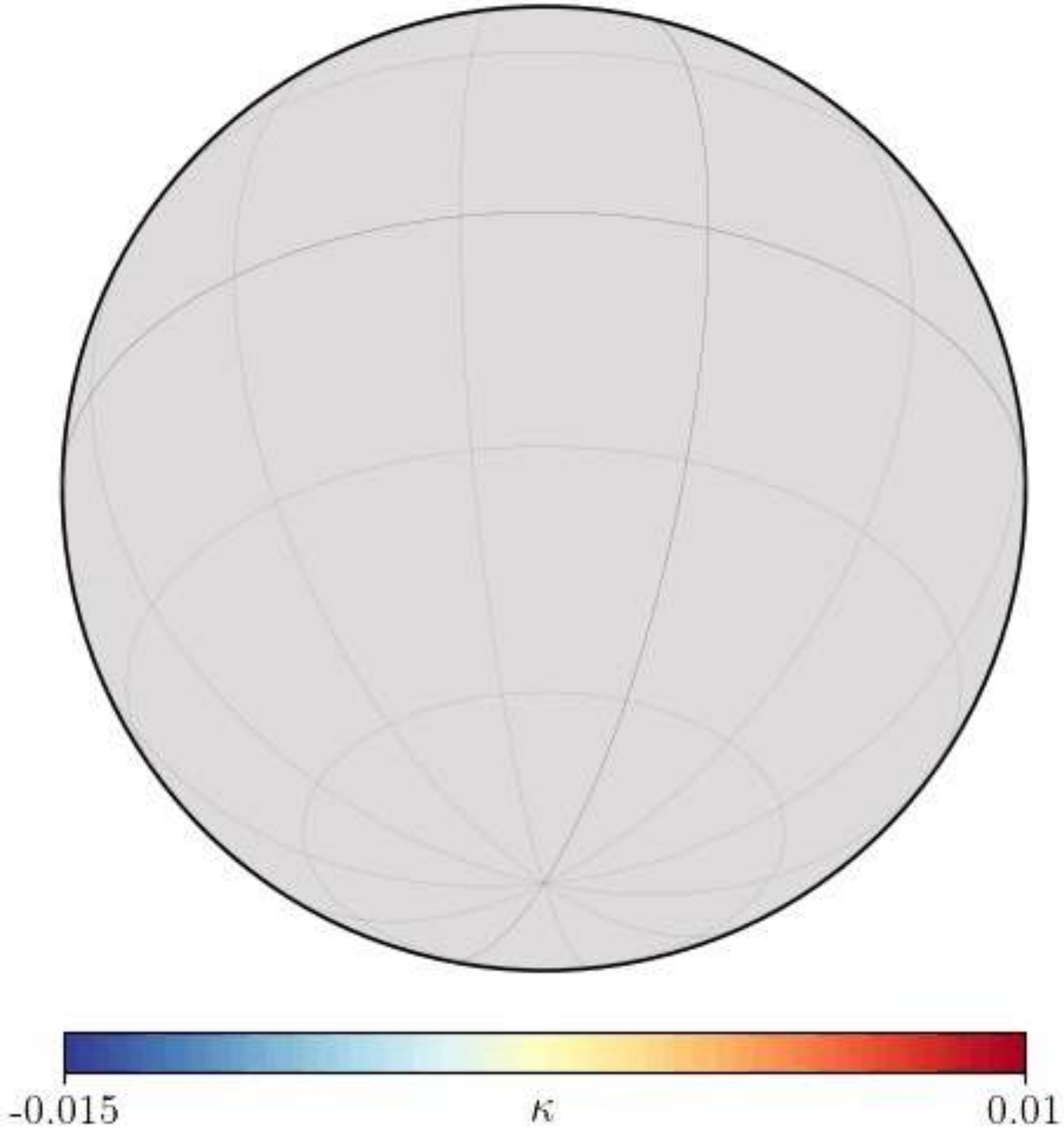
And lessons learned

DES Y6: Stay tuned.. results coming soon



Credit: Chihway Chang, Marco Gatti, Masa Yamamoto, Theo Schutt, and all the DES Y6 shear team!

DES Y6: Stay tuned.. results coming soon

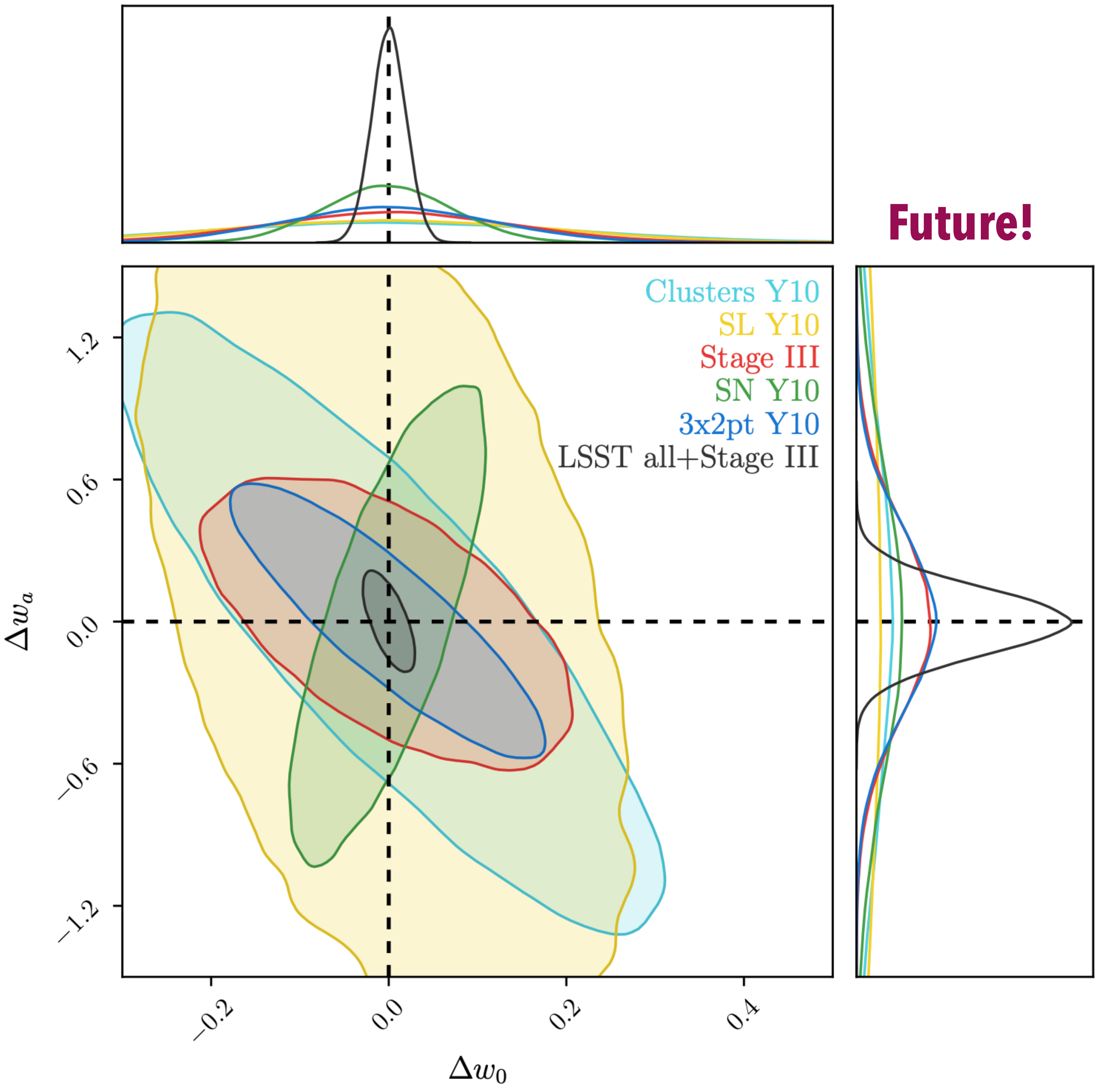


Credit: Chihway Chang, Marco Gatti, Masa Yamamoto, Theo Schutt, and all the DES Y6 shear team!

What's coming?

Exciting times ahead!

- With LSST, we will be able to constrain the equation of state of dark energy very precisely, which determines the evolution of dark energy with time.



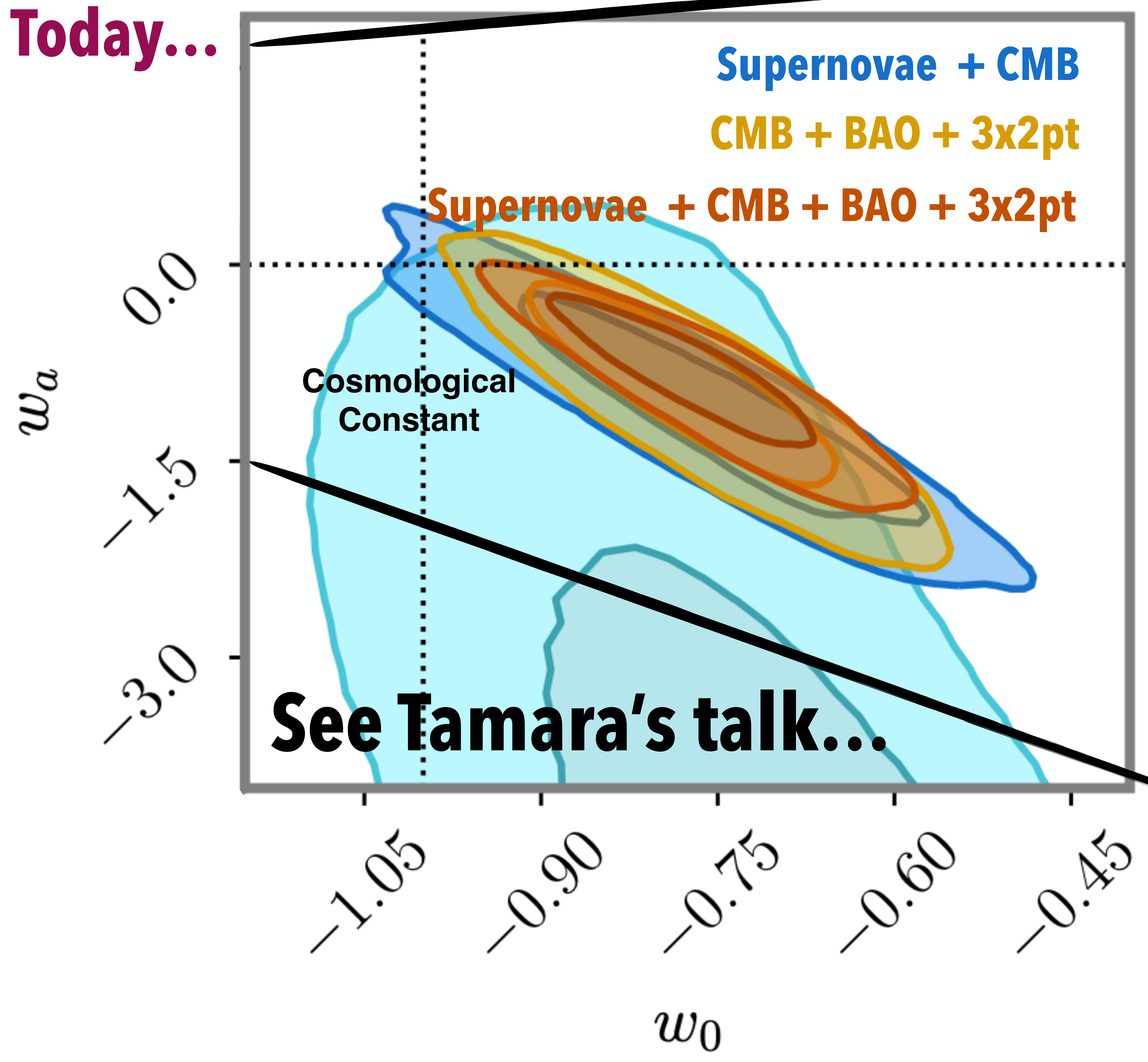
Future!

What's coming?

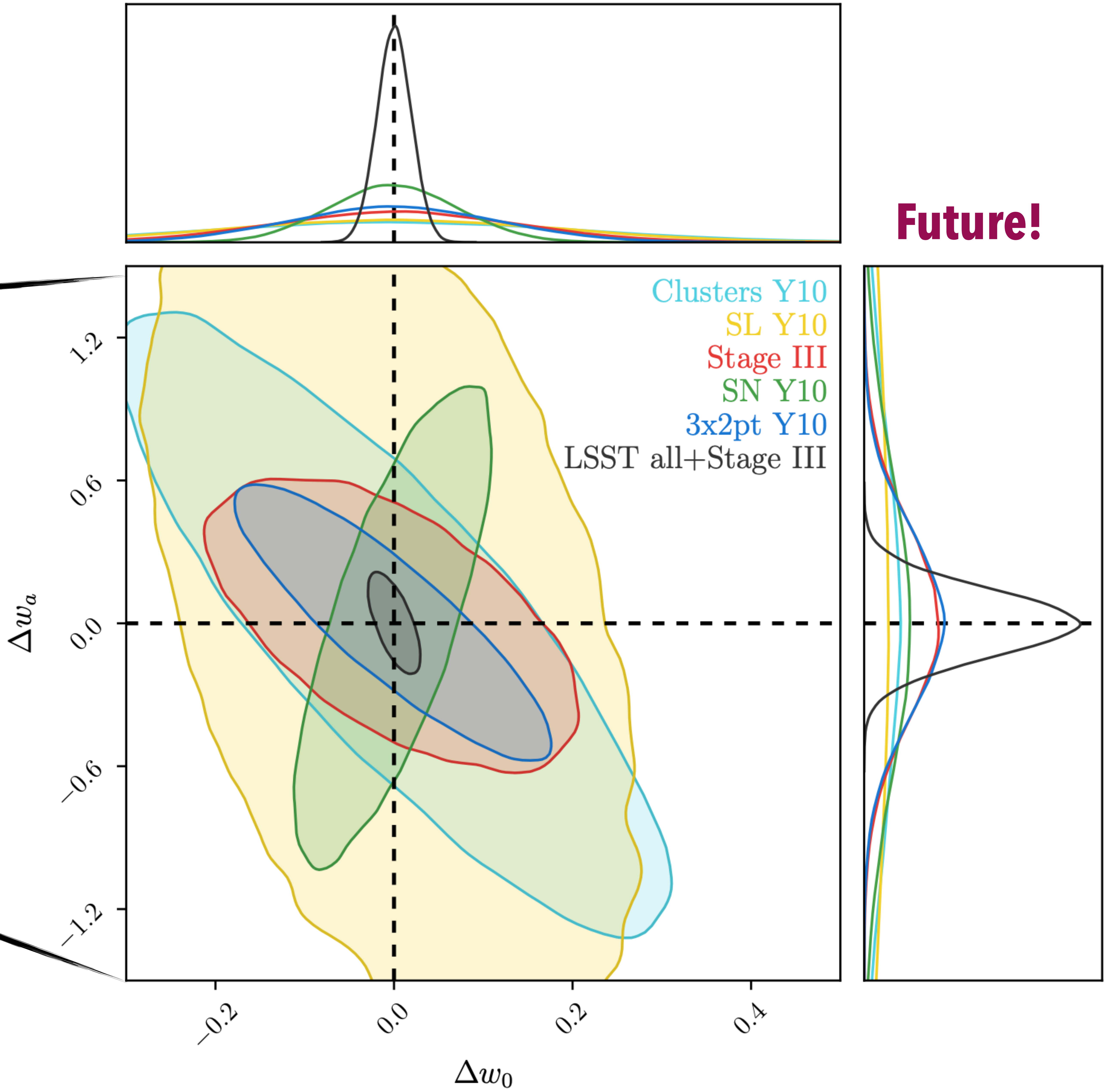
Exciting times ahead!

DES Collaboration: arXiv 2401.02929

Today...



Future!



Limitations of current 3x2pt analyses

Moving forward

- Only using **large scales,** due to not having good enough small scale models due to:
  - Uncertainty in the galaxy-matter connection and non-linear effects
  - 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.
- High dimensional space analysis sampling issues:
  - MCMC's with so many nuisance parameters take a long time.
  - Volume effects

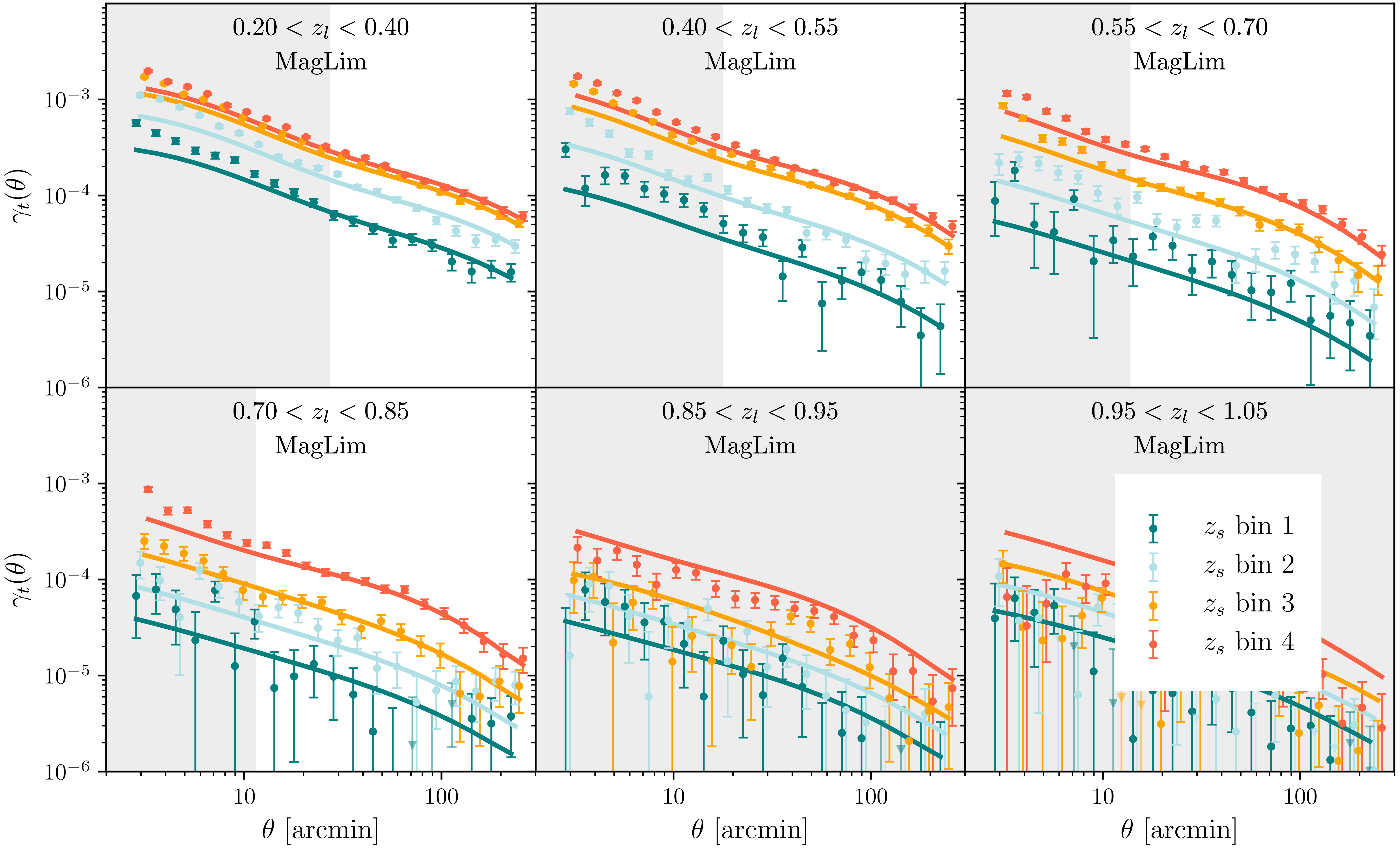
The small scale avenue....

Prat et al. (2022): 2105.13541

Galaxy-galaxy lensing DES Y3: *tangential shear*

- 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



How did we define scale cuts?

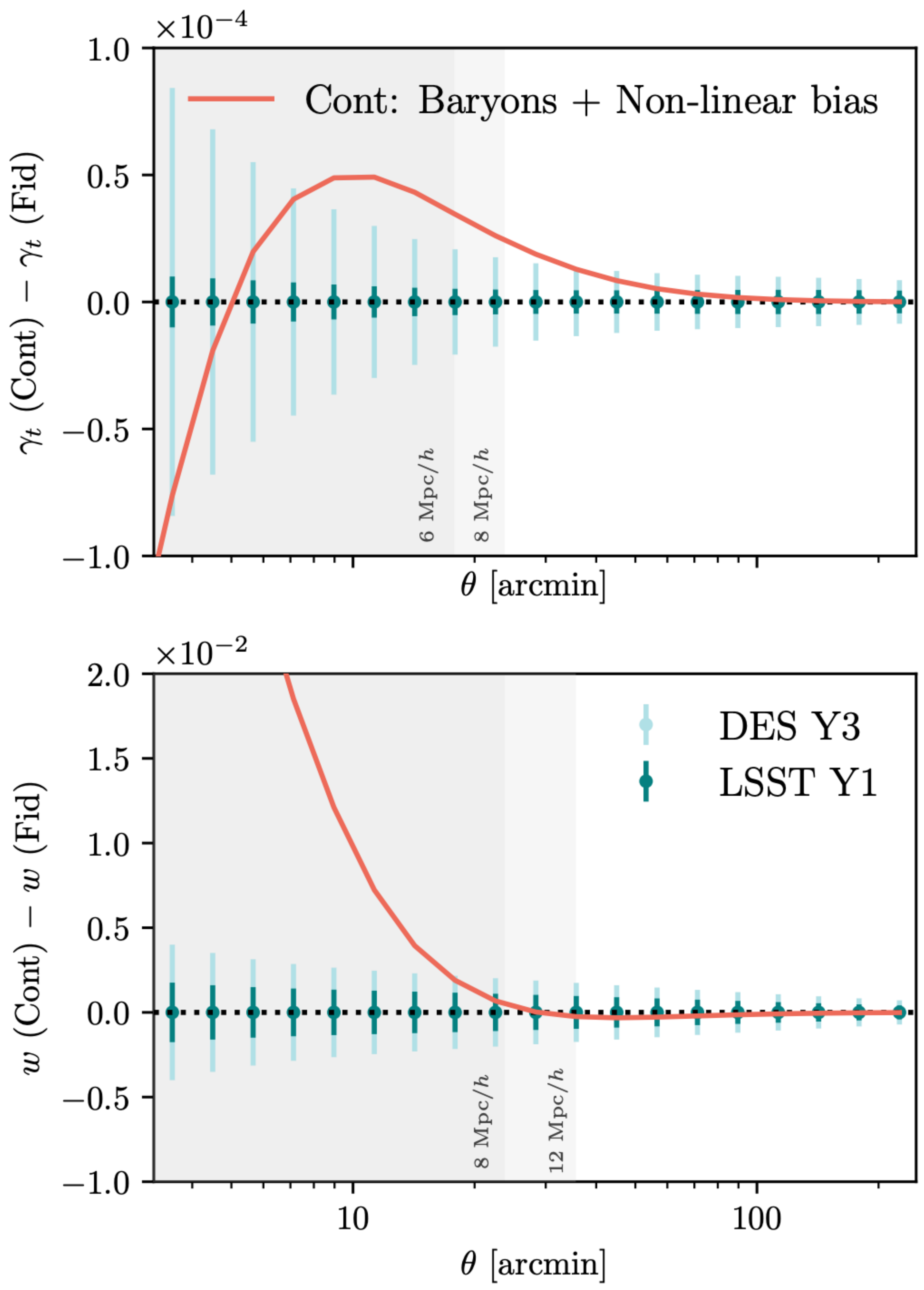
- We contaminate our fiducial model with effects that are not included:
  - Non-linear galaxy bias using perturbation theory (*Pandey et. al 2020, 2008.05991).*
  - Baryonic effects (from OWLS hydrodynamical simulation) to the power spectrum.
- **Criteria:** No more than 0.3 sigma effect in the S_8-Ω_m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

Prat, Zacharegkas et al. (2023): 2212.03734

How much will we loose if we continue cutting scales?

Forecasted scale cuts for LSST Y1

- In a recent analysis we conclude that if we use linear galaxy bias we will need to cut below:
  - **12 Mpc/h for clustering,**
  - **8 Mpc/h cuts for the tangential shear**
    (40 Mpc/h for the tangential shear if not using point-mass marginalization)

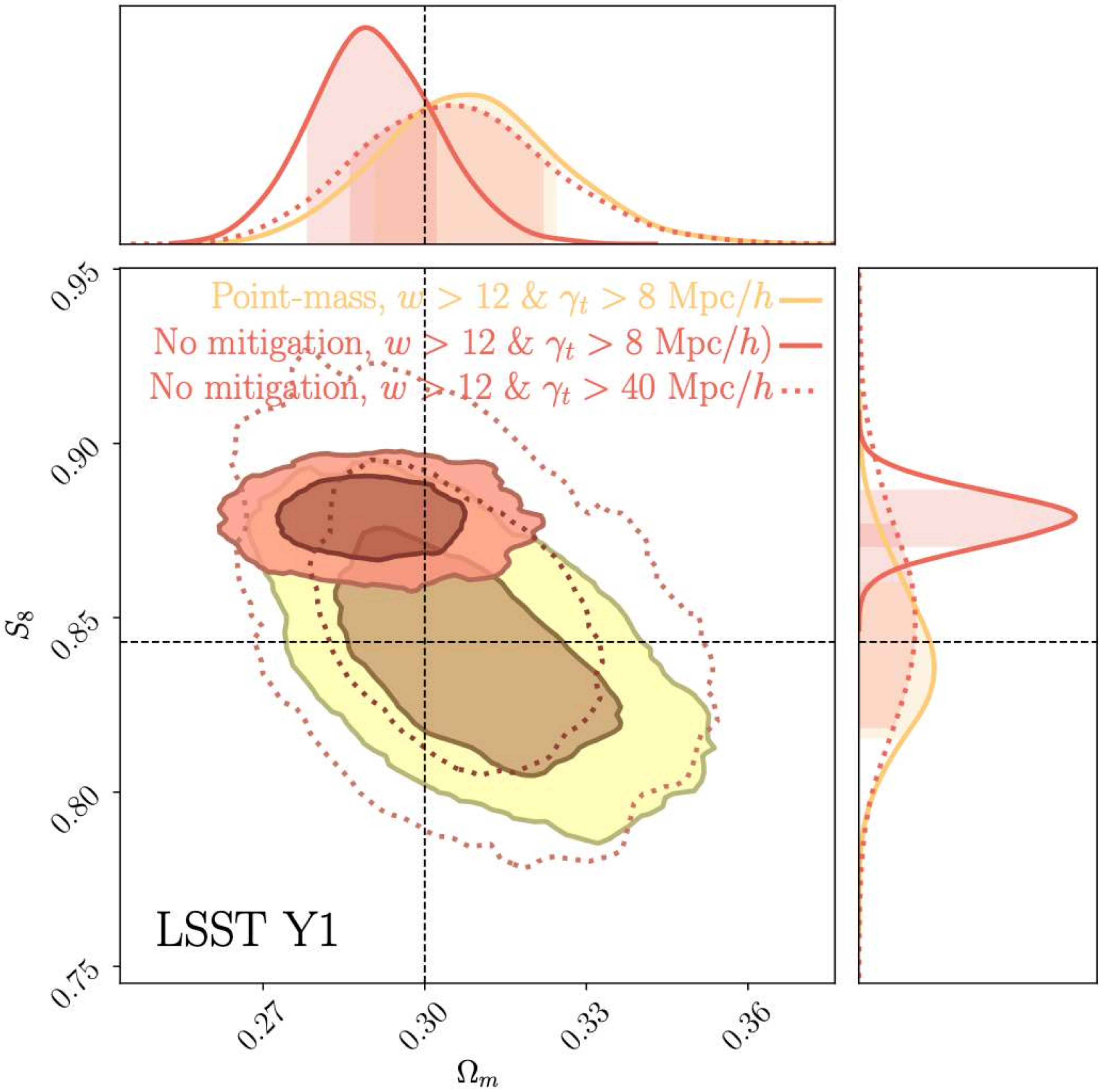


How much will we loose if we continue cutting scales?

Forecasts for LSST Y1

- Quite a lot!
- **For experts:** *Also, 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.*

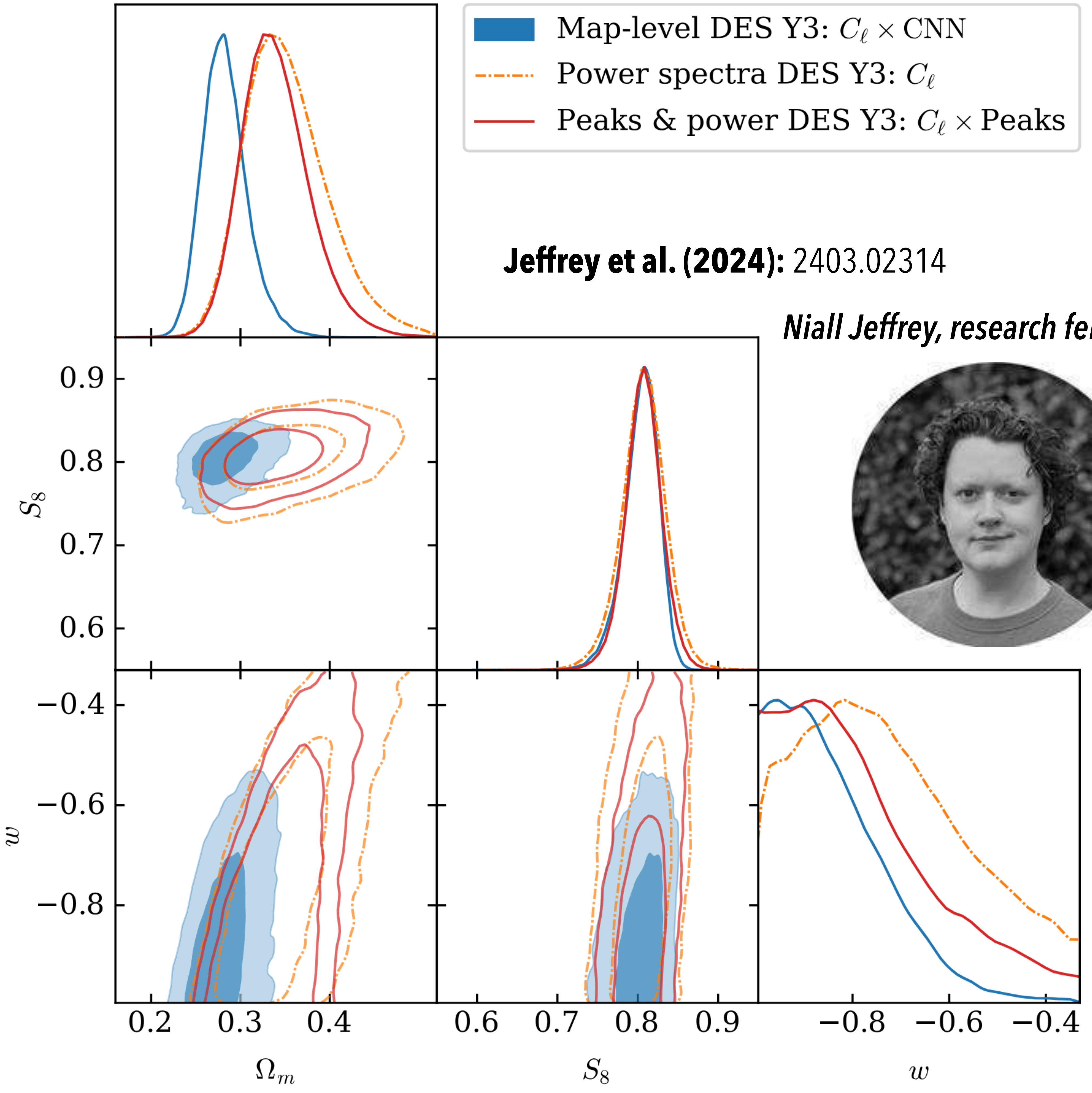
Prat, Zacharegkas et al. (2023): 2212.03734



The beyond 2-point avenue….

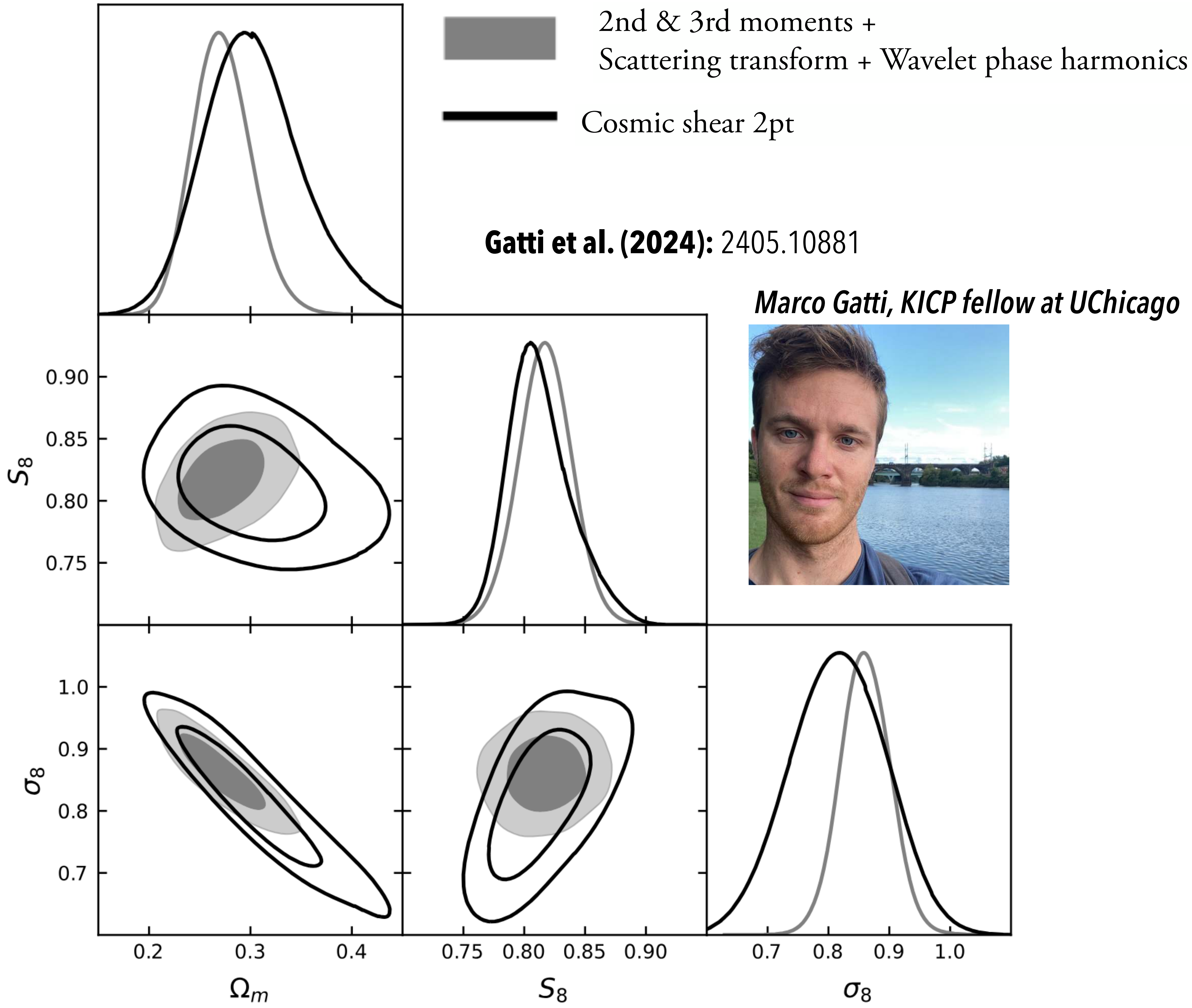
Going beyond 2-point, how much do we gain?

Improvement is on the 2D plane, S_8 is not a good metric to compare methods anymore



Jeffrey et al. (2024): 2403.02314

Niall Jeffrey, research fellow at UCL



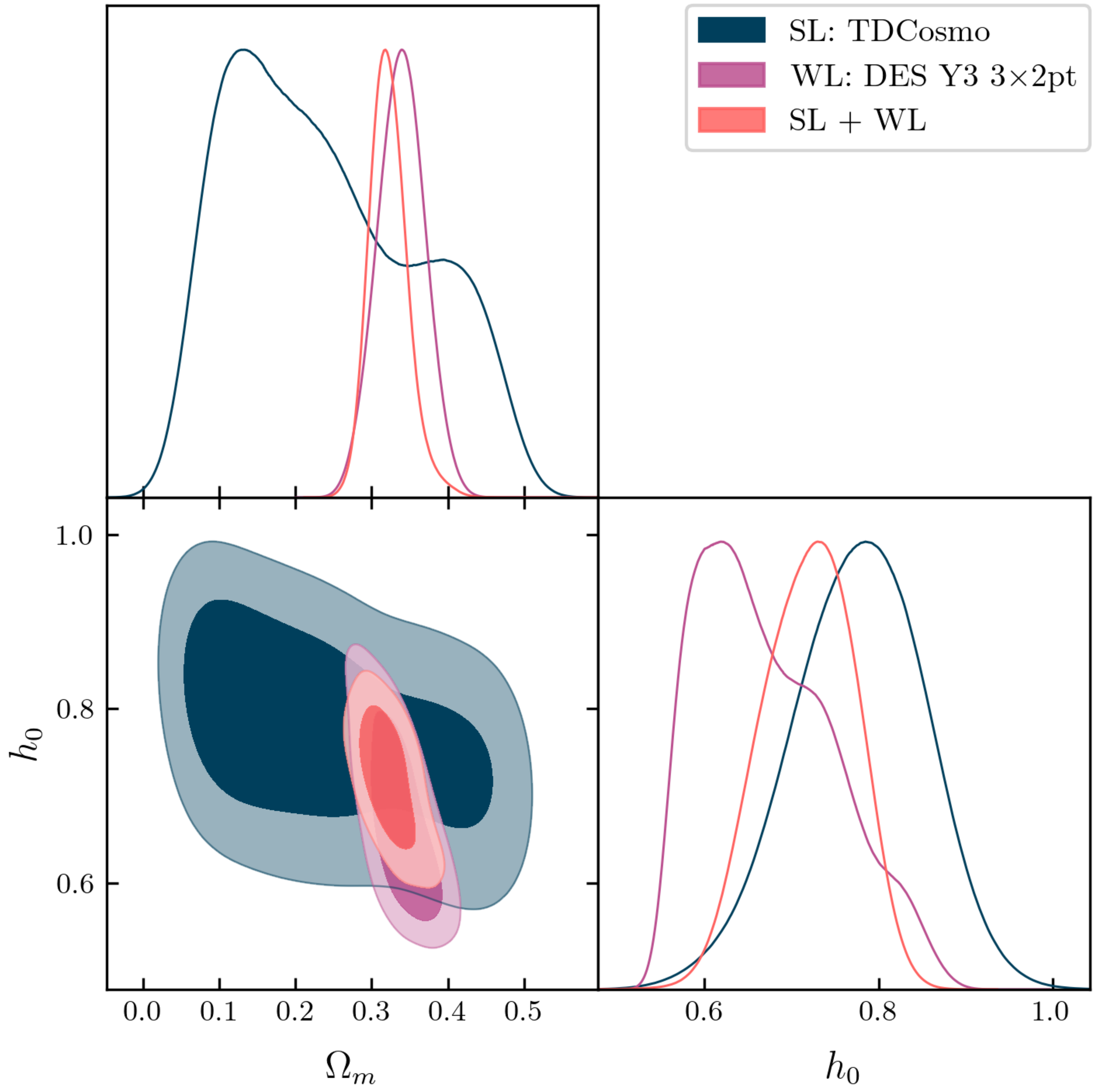
Gatti et al. (2024): 2405.10881

Marco Gatti, KICP fellow at UChicago

The more probes avenue….

Strong Lensing + Weak Lensing

- Strong Lensing (SL) + Weak Lensing (WL) is an example of how we can do better by combing emerging synergetic probes.
- SL is sensitive to H_0, and WL is sensitive to $\Omega_m + \sigma_8$.



TDCOSMO likelihood publicly available in CosmoSIS now thanks to work with Martin Millon (KIPAC) & Simon Birrer (Stony Brook)

The DES Y3 data is public, use it! :)

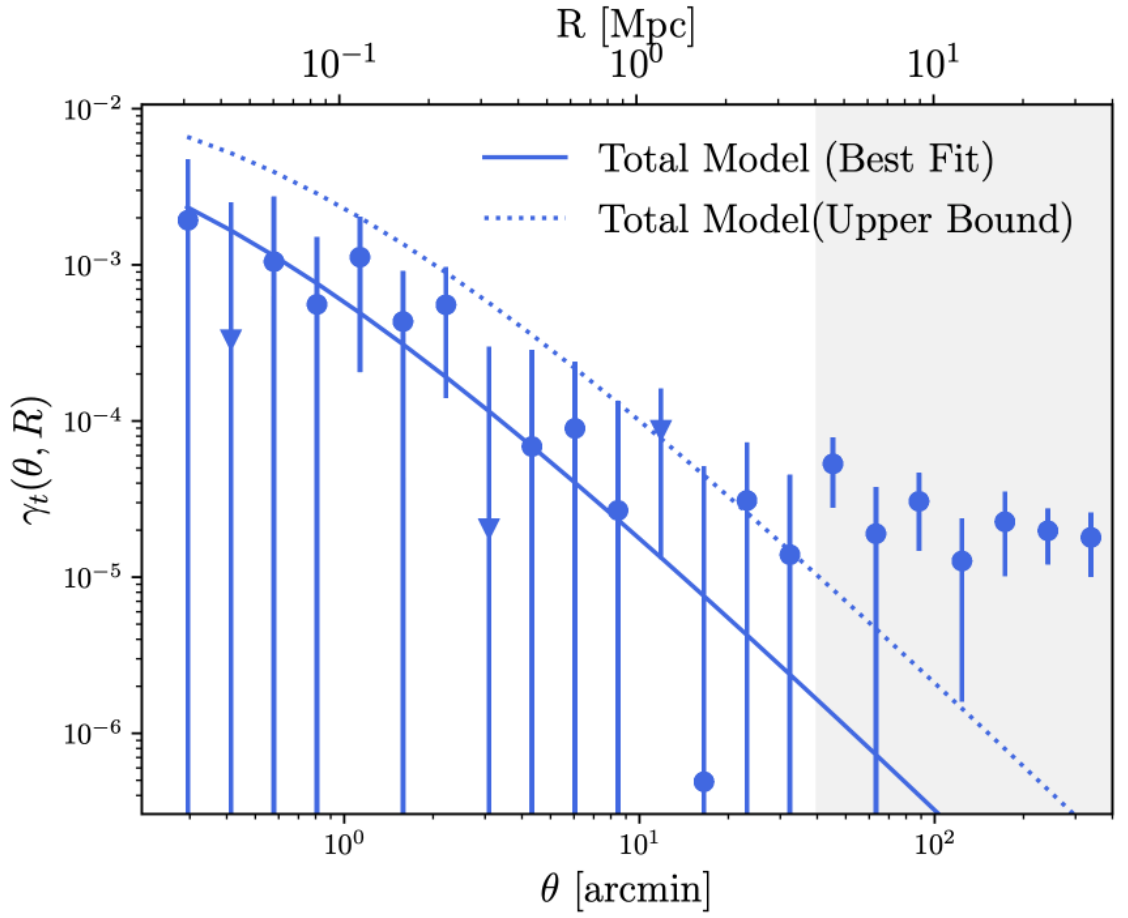
Contact any DES member if you have questions :) You can find it here:

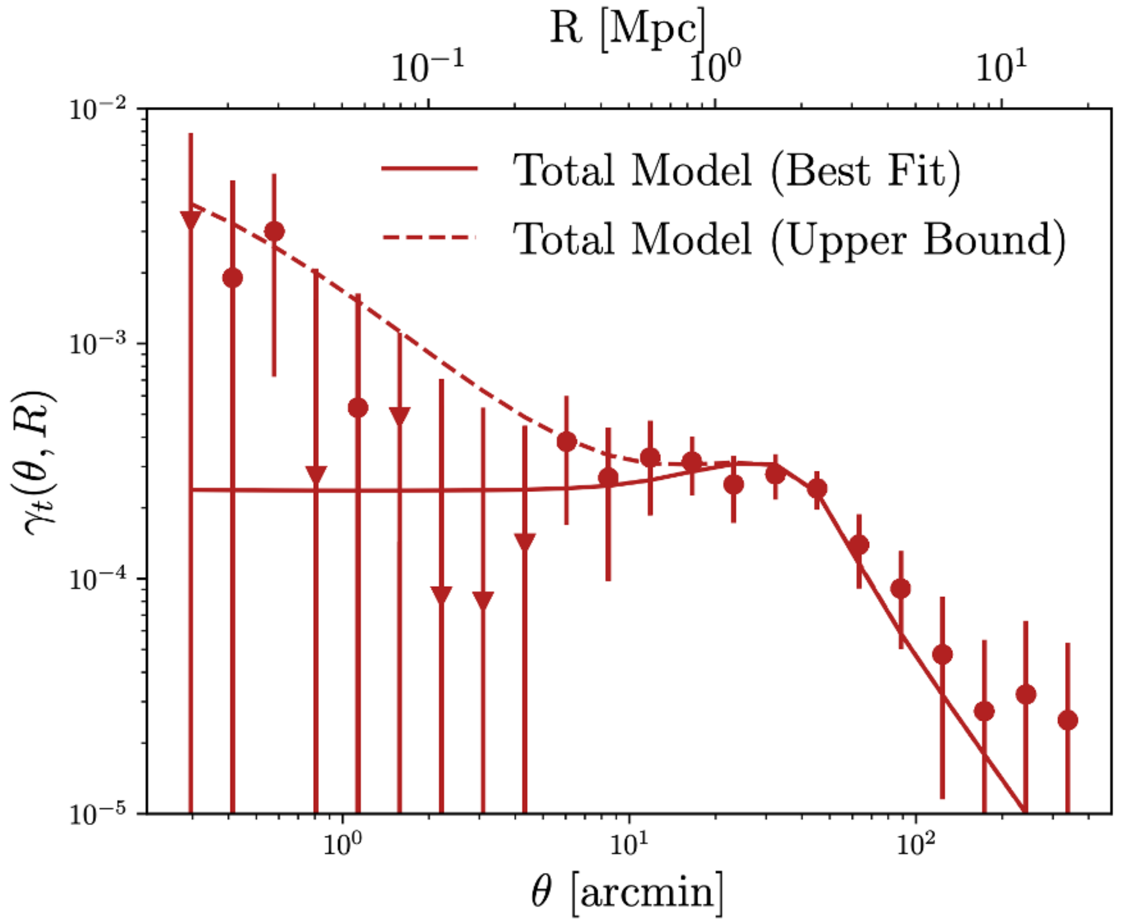
https://des.ncsa.illinois.edu/releases

Examples of things that we can do with this data

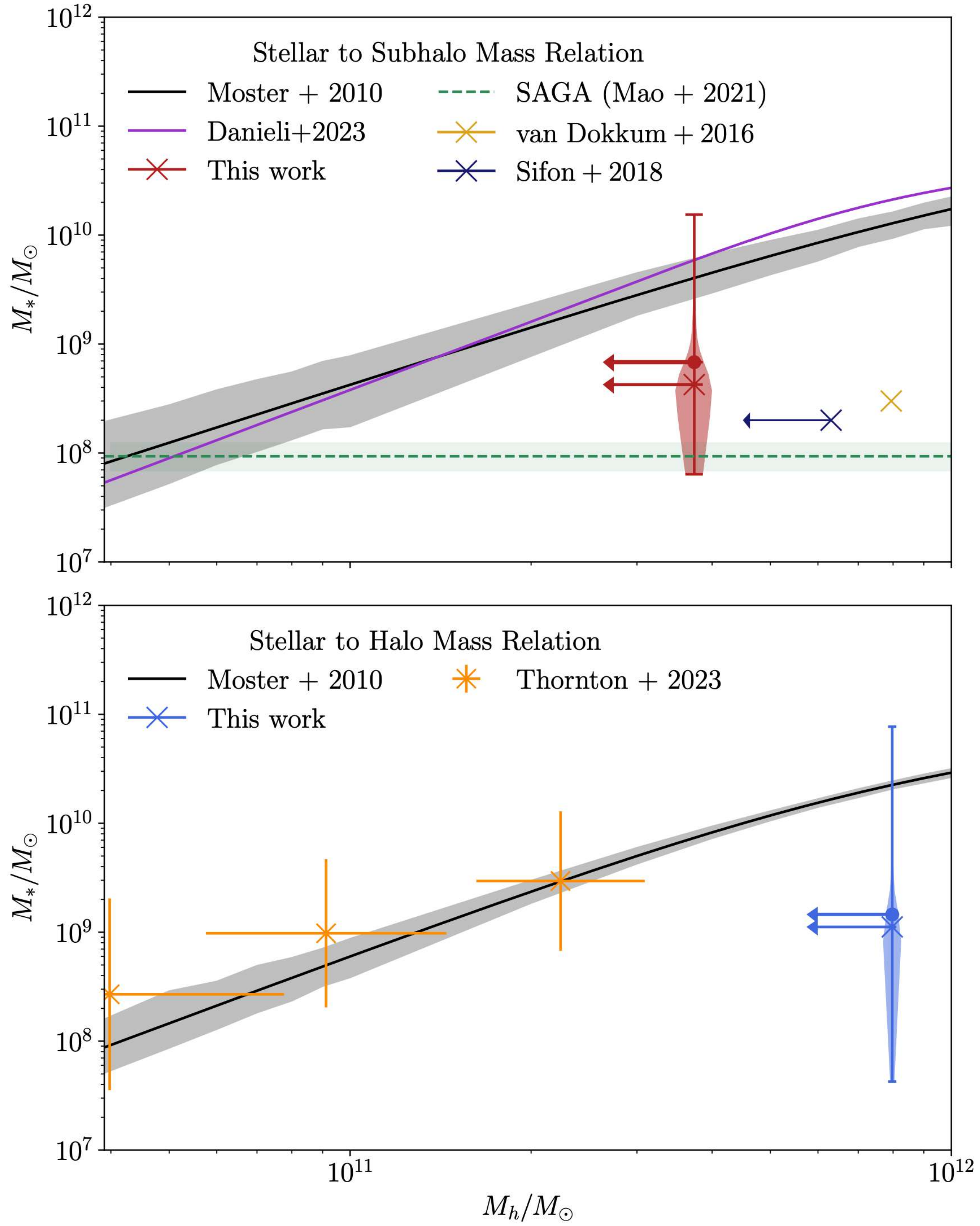
Galaxy-matter with low-surface brightness galaxies (LSBGs)

- We performed a weak lensing study around ~24000 LSBGs galaxies using DES Y3 data and measured the halo mass of such galaxies for the first time.
- Stellar-to-halo mass relation at small masses and for satellite galaxies.





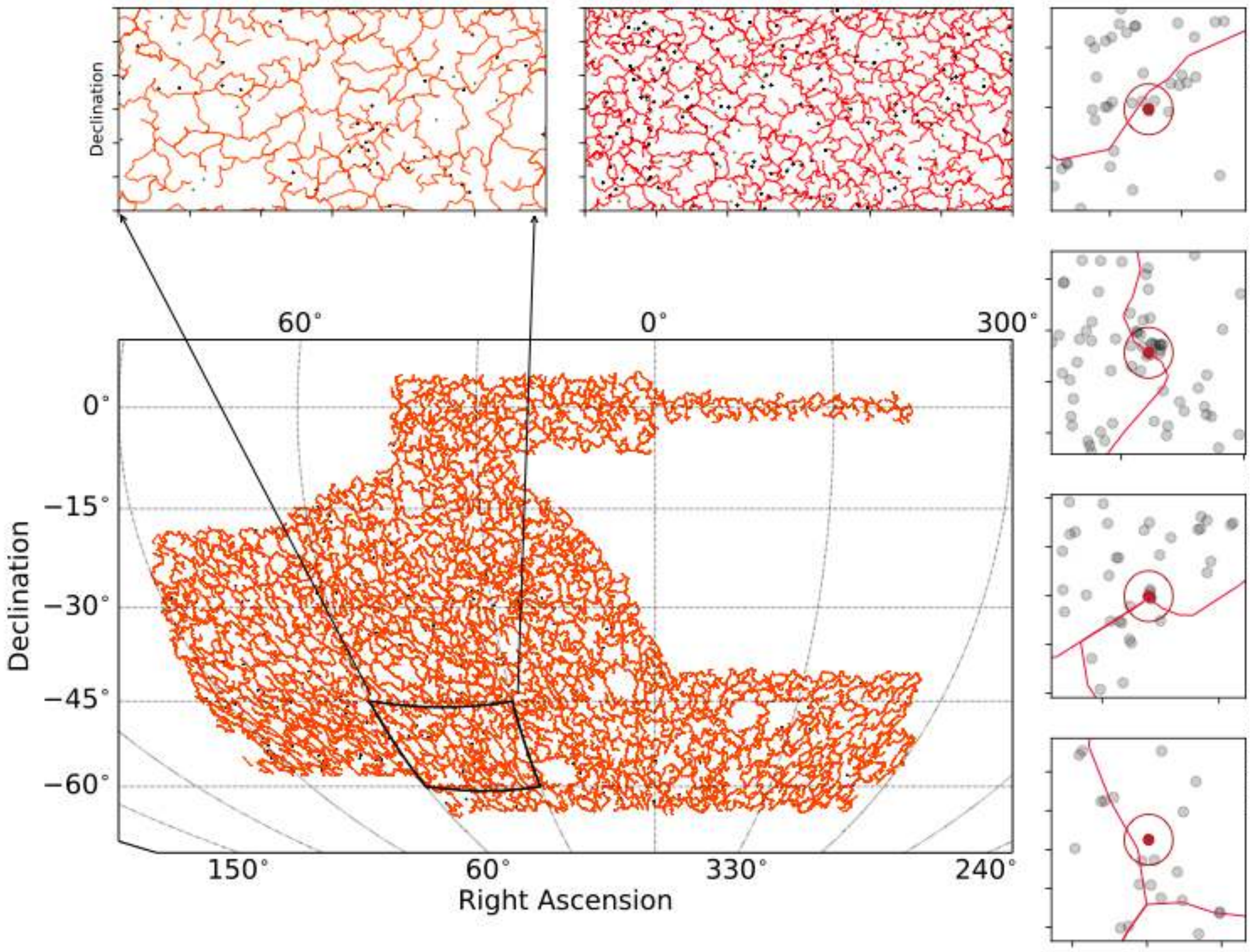
Chicoine, Prat et al. (2024): 2407.19081



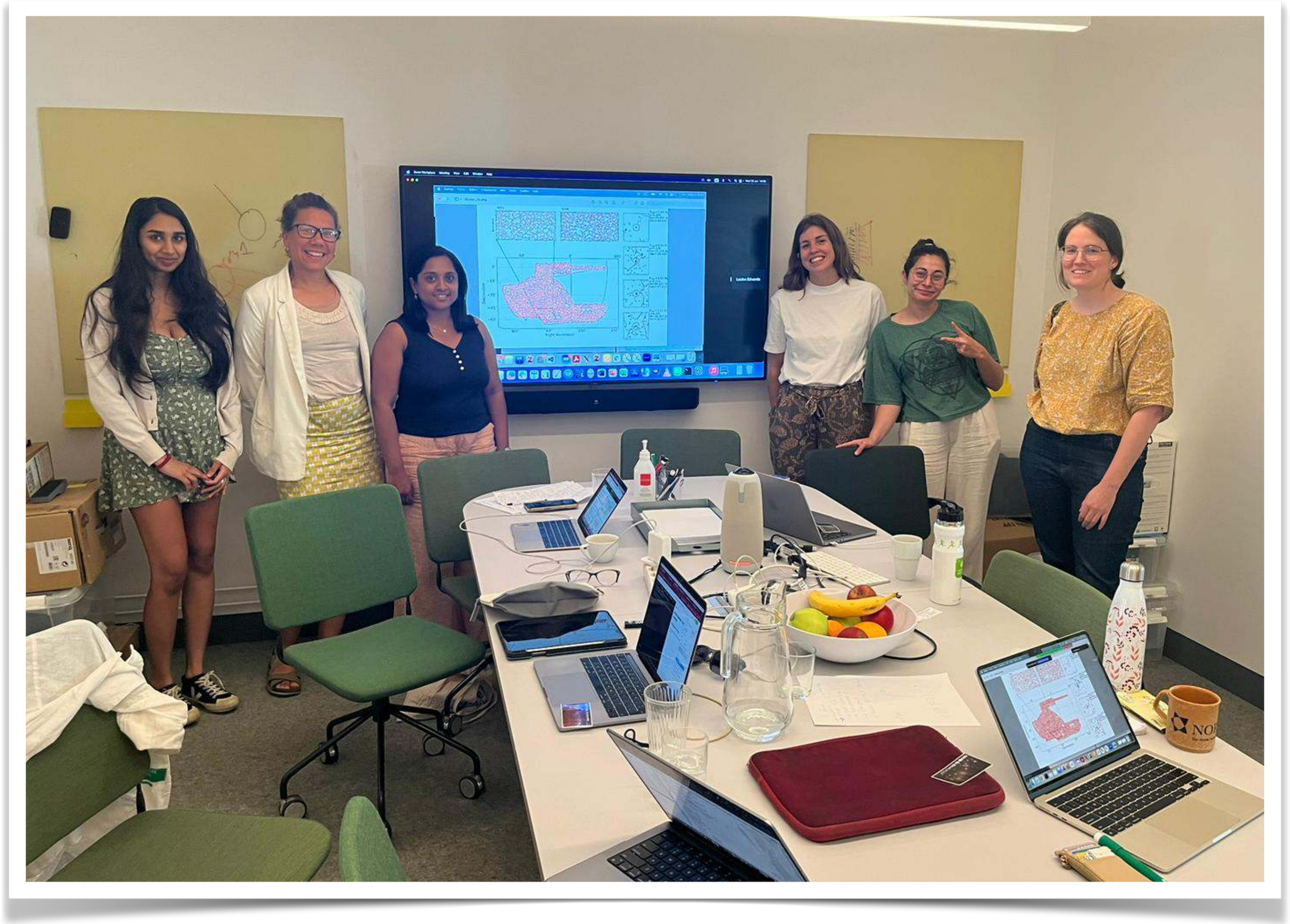
Nathalie Chicoine,
PhD student at University of Pittsburg, previous undergraduate at UChicago

Cosmic filaments and connectivity from DES Y3 data

- The study of the cosmic web offers insights into galaxy formation and evolution.



Preliminary – to be submitted soon



- Geetika Gopidas — Undergraduate Student, California Polytechnic State University, San Luis Obispo.
- Punyakoti Ganeshaiah Veena — Postdoc at University of Genoa, Italy.
- Daniela Galárraga-Espinosa — Fellow at MPA, Germany.
- Louise Olivia Violet Edwards — Associate Professor, California Polytechnic State University, San Luis Obispo.
- Celine Gouin — Permanent researcher at Institut d'Astrophysique de Paris.
- Clotilde Laigle — Astronomer at Institut d'Astrophysique de Paris.

Conclusions and outlook

- We can obtain a lot of cosmological information from galaxy clustering and weak lensing.
- 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. Keep an eye for the DES Y6 results coming this year!
- 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.
- 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 combining with more probes will (hopefully) provide the answers.
- Go use the DES data!

NORDITA
The Nordic Institute for Theoretical Physics

Thanks!

Judit Prat Marti
Nordita fellow at Stockholm University and KTH. October 2024.
X Fundamental Cosmology Sevilla.