THE UNIVERSITY OF CHICAGO

AI in Science
A program of SCHMIDT FUTURES

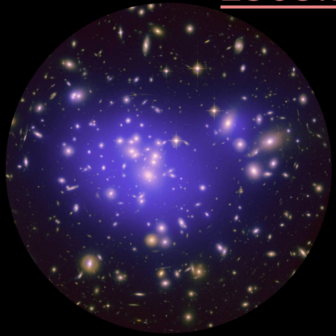
Cosmological constraints from joint analyses of clusters, galaxies, and weak lensing

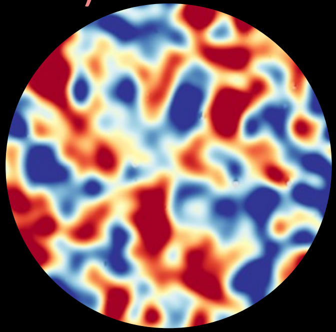
Chun-Hao To

and DES cluster working group

Schmidt Fellow at the University of Chicago

2503.13631 / 2503.13632 (PRD accepted)





Why measure cosmic structure?

- Cosmic structure forms as a result of **gravitational collapse** competing with **the expansion of the universe**.

- Amplitude of cosmic structure depends on
  1. The laws of gravity
  2. The energy content of the universe and their interactions (e.g. dark matter, neutrinos, etc.)

Current status on structure measurement

Cosmic Shear

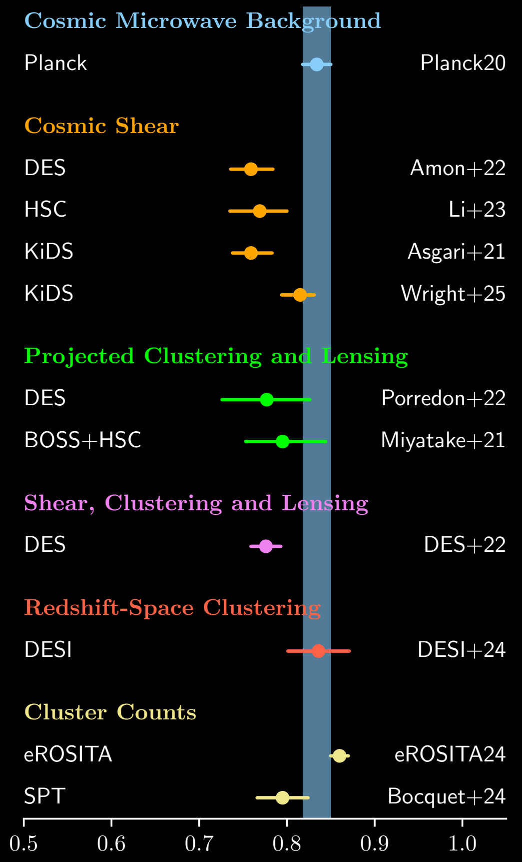
Galaxy clustering + galaxy—galaxy lensing

Cosmic Shear + Galaxy clustering + galaxy—galaxy lensing

Redshift-space clustering

Galaxy cluster abundance

Measurement Model (ΛCDM)



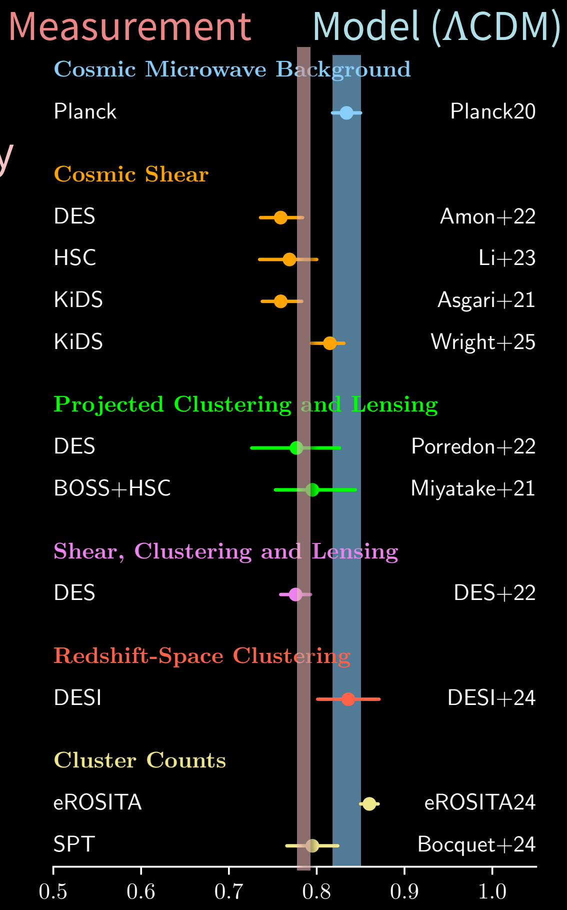
$$S_8 = \sigma_8 \sqrt{\left(\frac{\Omega_m}{0.3}\right)}$$

Amplitude of cosmic structure fluctuation

Current status on structure measurement

- Hints of tension between structure measured in galaxy surveys and the ΛCDM prediction.

→ Systematics or statistical fluctuations or new physics?



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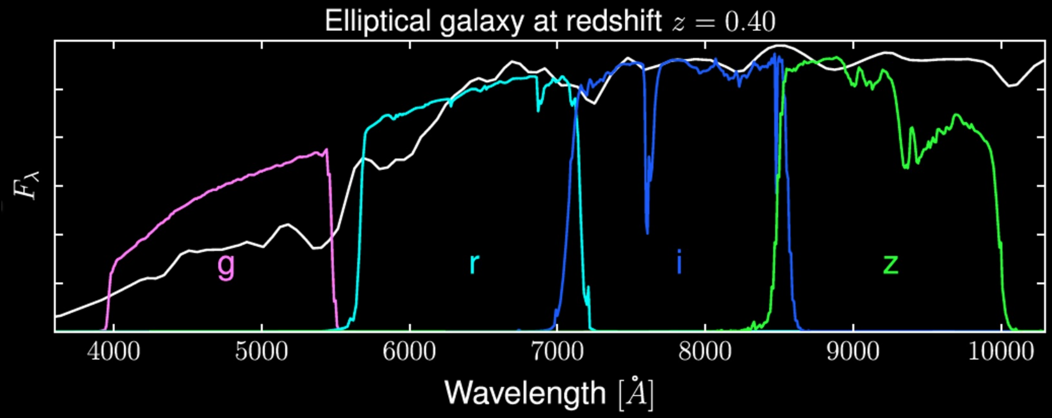
Amplitude of cosmic structure fluctuation

Current status on structure measurement

- Systematics or statistical fluctuations or new physics?
  The **Dark Energy Survey** is uniquely positioned to answer this question.



- 5 color filters used to estimate photo-zs
- **Wide survey**: 5000 sq degrees, ~23 i-magnitude

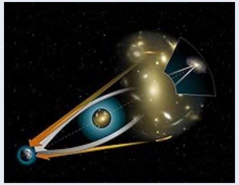
Current status on structure measurement

- Systematics or statistical fluctuations or new physics?

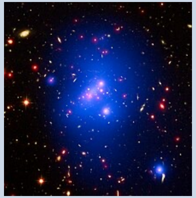
  The **Dark Energy Survey** has multiple probes:
  1. Consistency check between probes
  2. Joint analyses of different probes

Galaxy clustering

Weak lensing



Galaxy clusters



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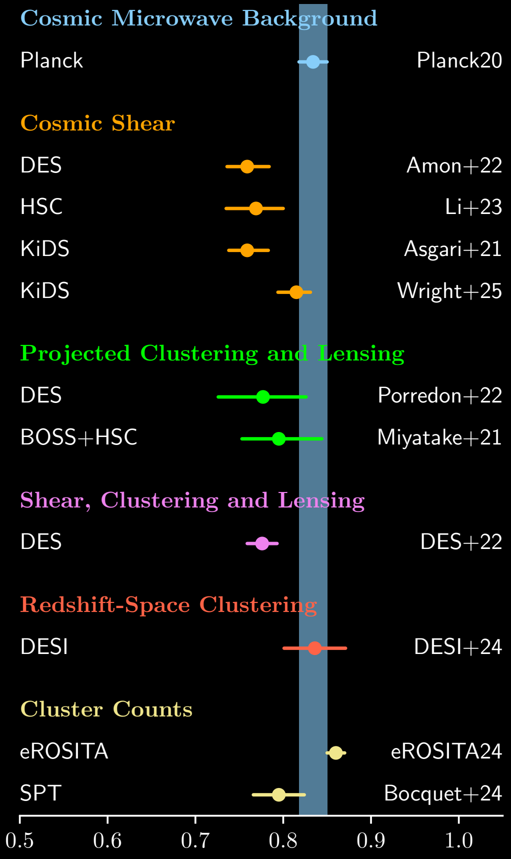

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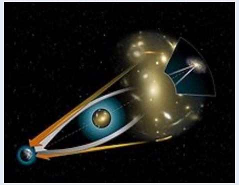

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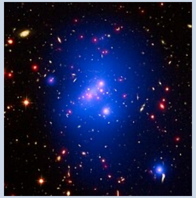

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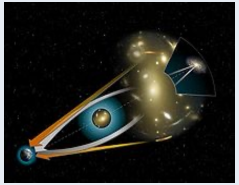

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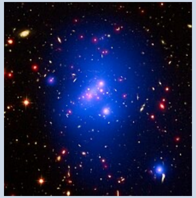
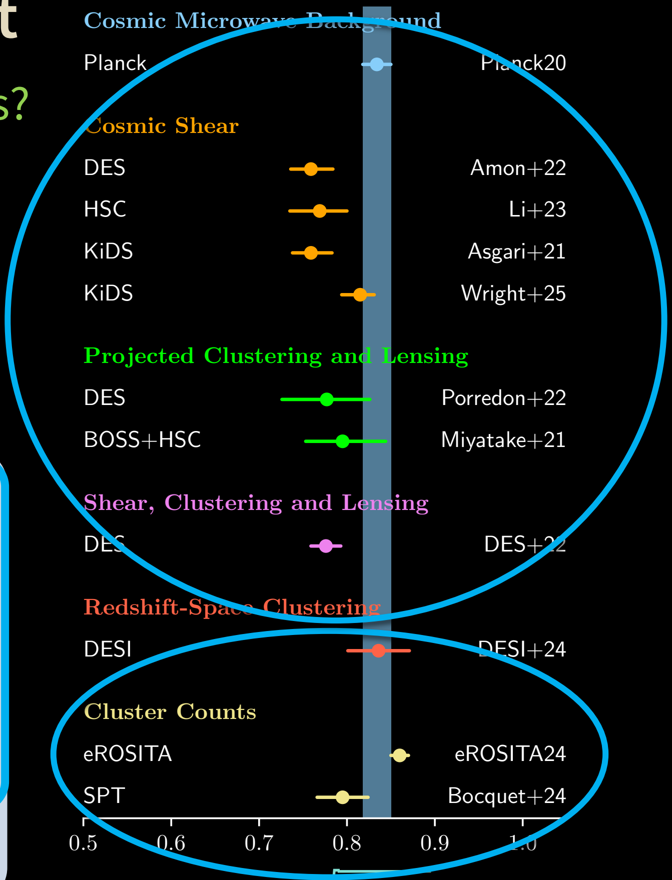


This talk

Measurement Model (ΛCDM)



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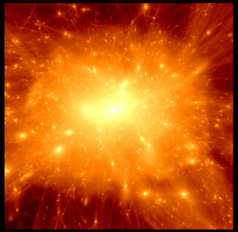
Amplitude of cosmic structure fluctuation

DES Probes of cosmic structure: galaxy clusters

Galaxy clusters: multi-component objects



Dark Matter Halo
→ ~ $5\times10^{14} M_{\odot}$

Red galaxies
~ 2% of the mass

Hot gas
~ 10 % of the total mass

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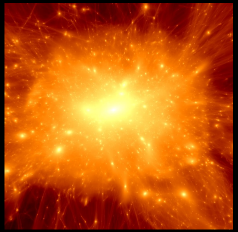

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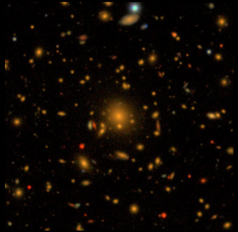

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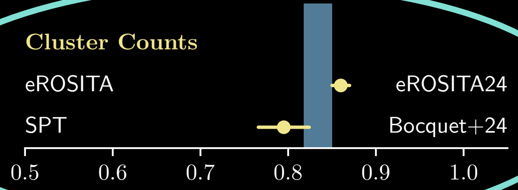

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Amplitude of cosmic structure

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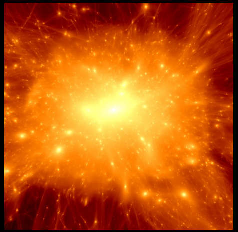

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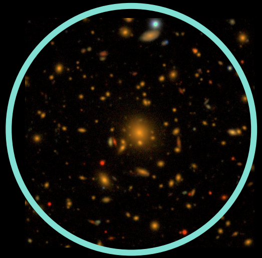

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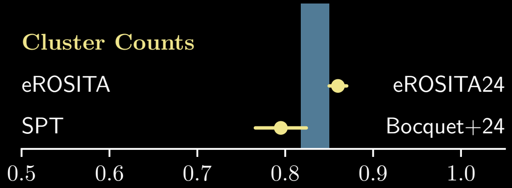

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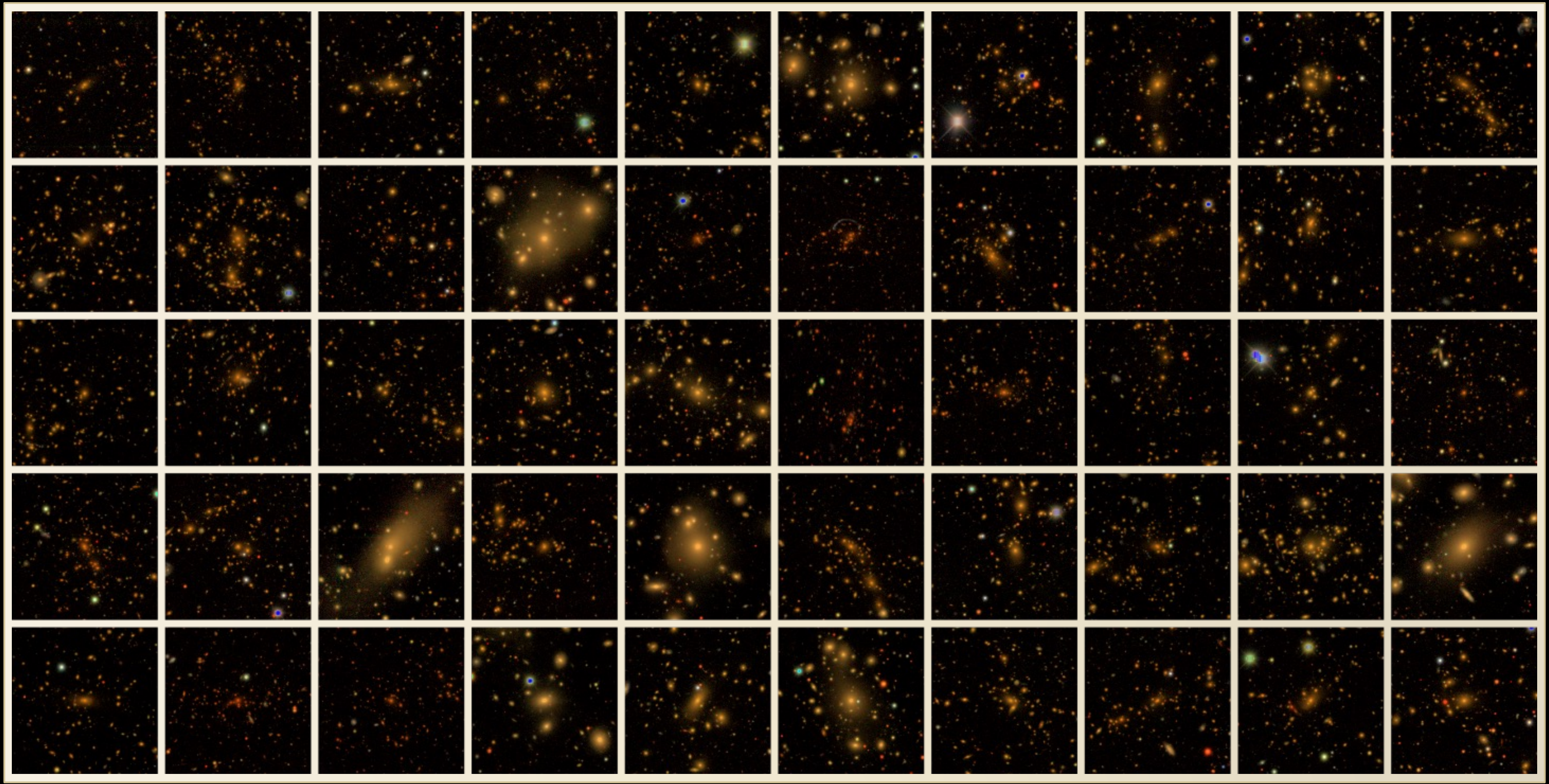
Amplitude of cosmic structure

>16 K optically identified galaxy clusters



How are DES clusters selected?

- Detect overdensities of red-sequence galaxies and assign a membership probability, $\mathrm{p_{mem}}$, to each cluster member candidate.

✓ Mass tracer: richness (λ) = $\sum \mathrm{p_{mem}}$.

DES cluster sample is well validated

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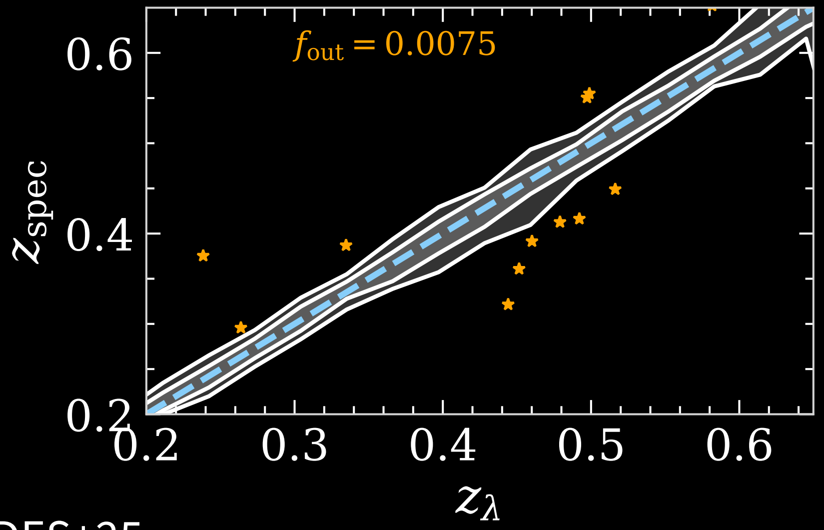

DES+25

DES cluster sample is well validated

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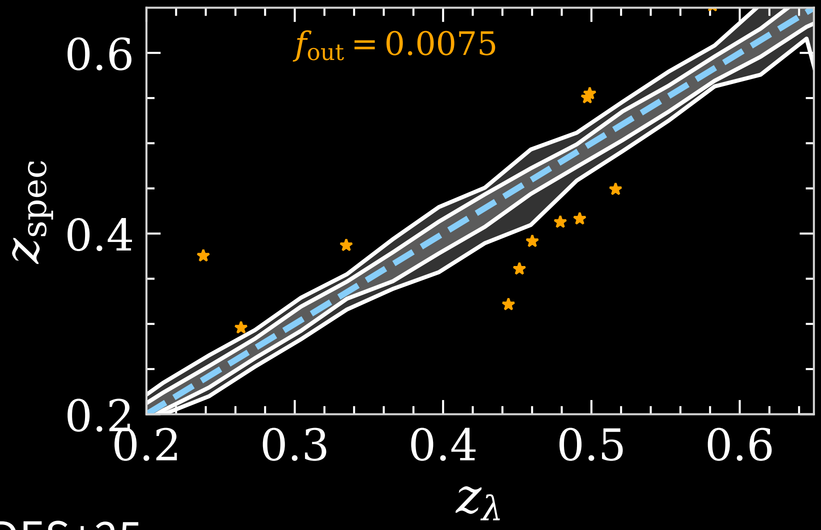
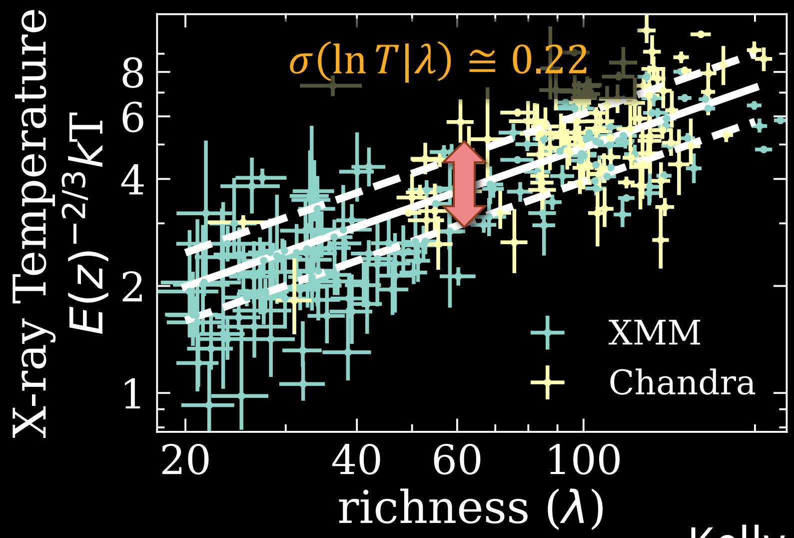
✓ Mass tracer: richness (λ) = $\sum \mathrm{p_{mem}}$.
✓ Sub-percent redshift (z_λ) accuracy.

✓ Selection function is well-validated:
- ➢ X-ray: Kelly+24, Upsdell+ 23
- ➢ Millimeter: Grandis+ 25

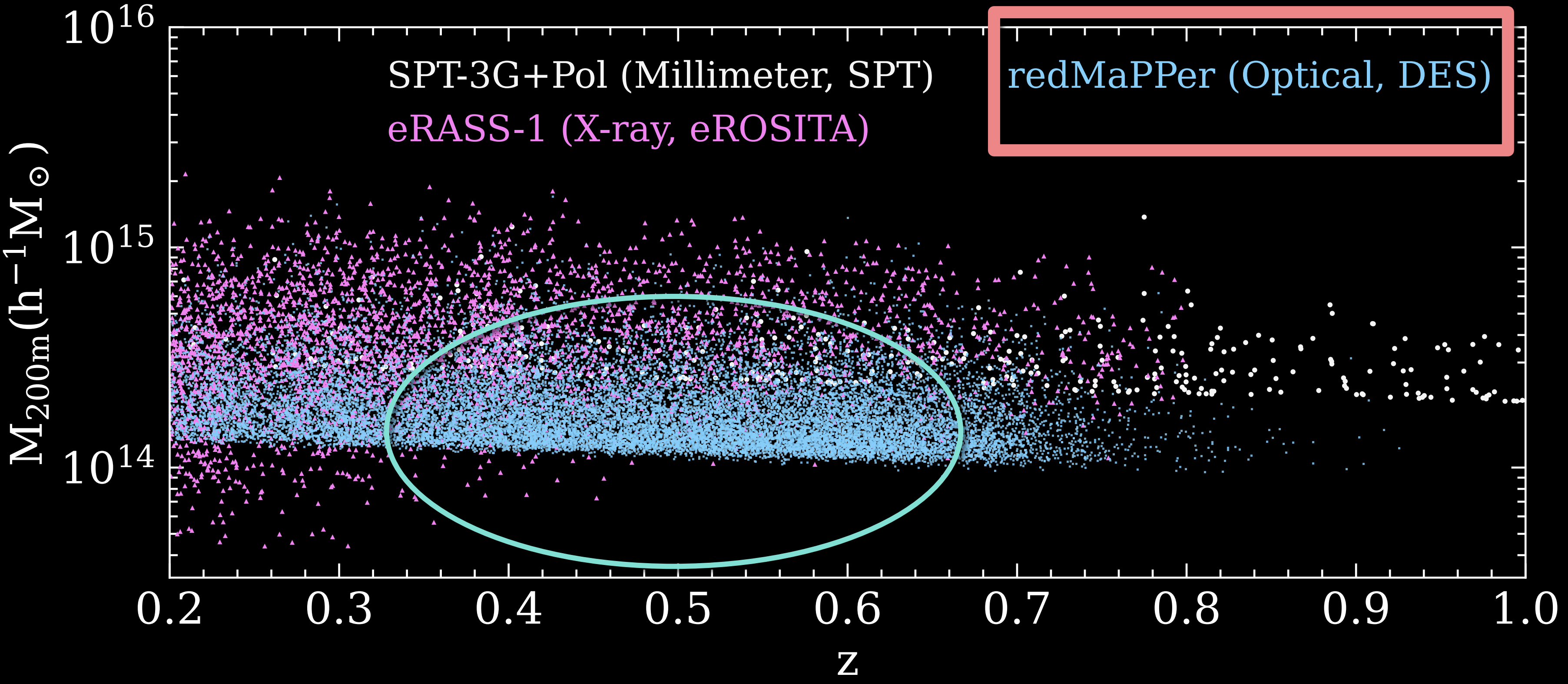


DES+25



Kelly+24

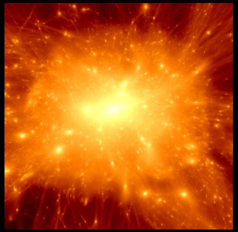
DES clusters probe a unique range of mass and redshift



DES+25

Galaxy clusters as a cosmology probe

Galaxy clusters: multi-component objects



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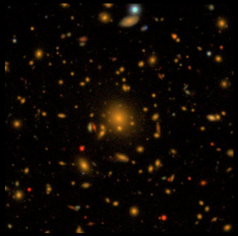

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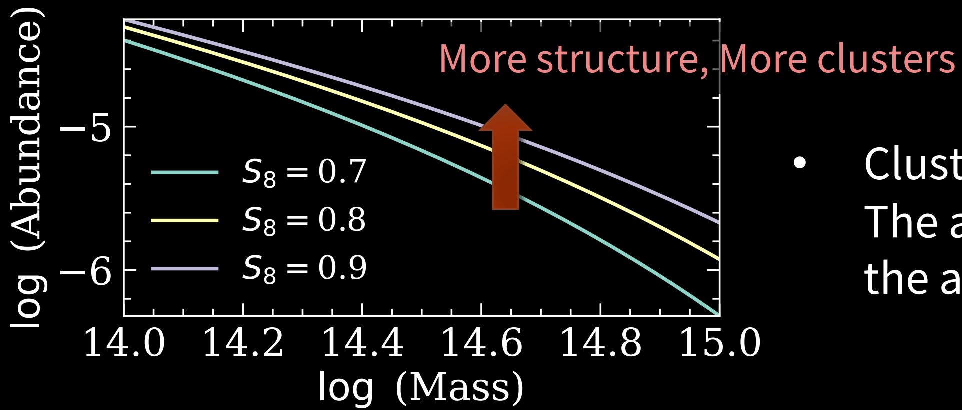
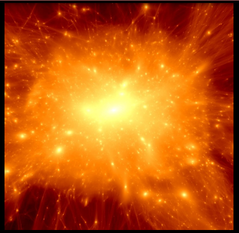


- Cluster abundances:
  The abundance of clusters is sensitive to the amount of structure in the universe.

Galaxy clusters as a cosmology probe

Galaxy clusters: multi-component objects



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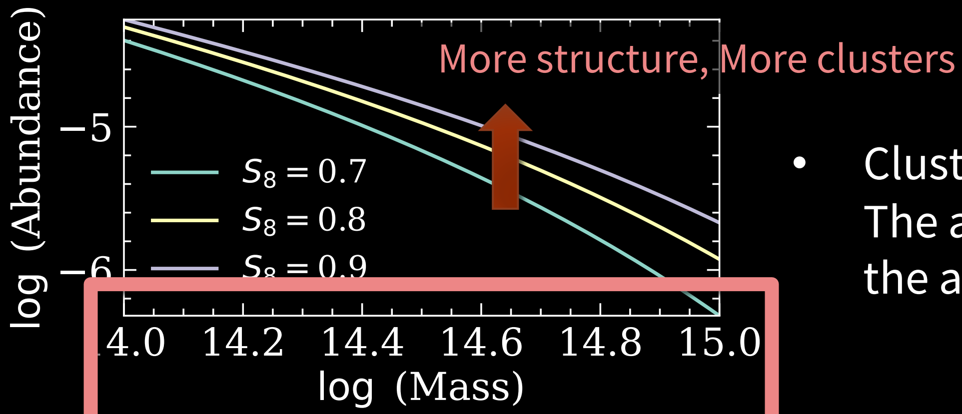

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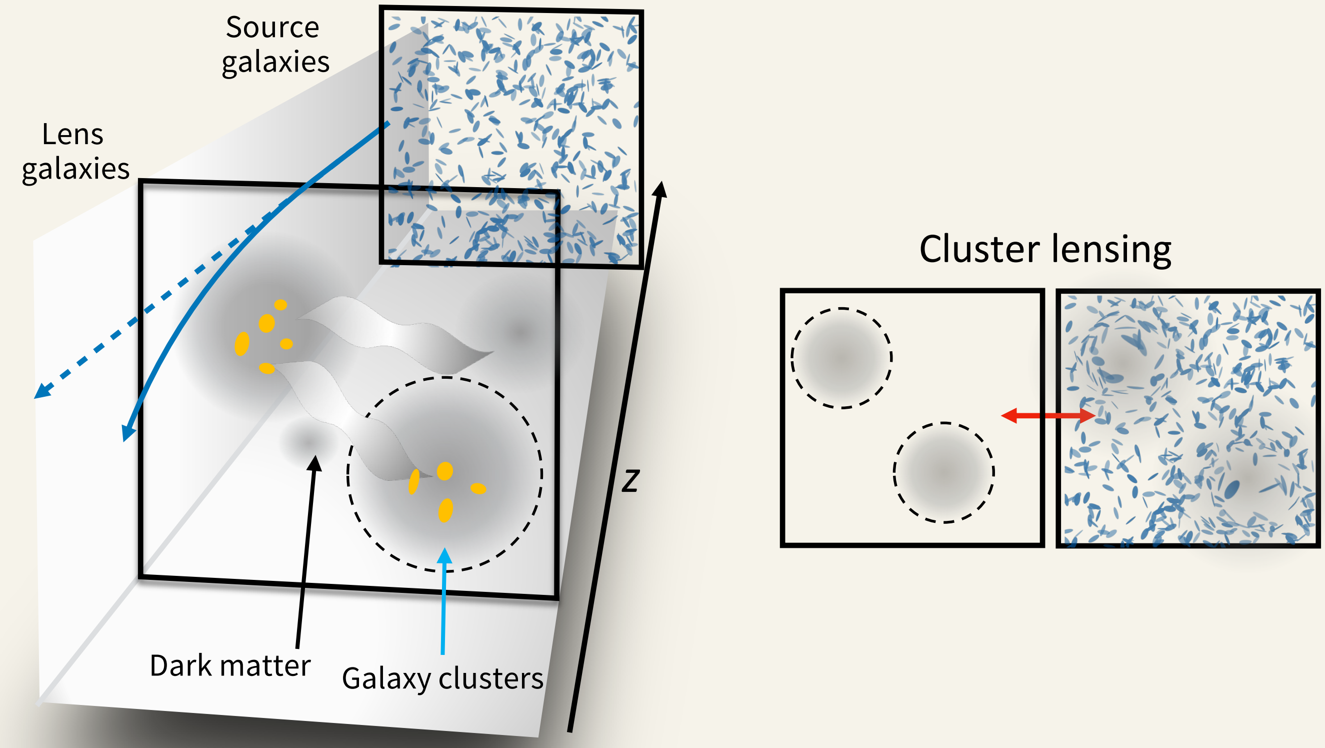
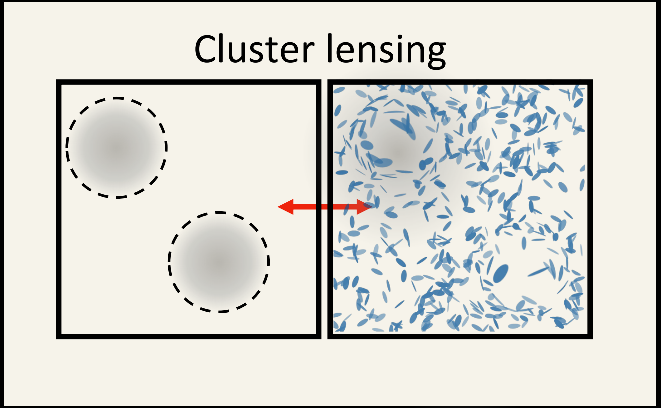
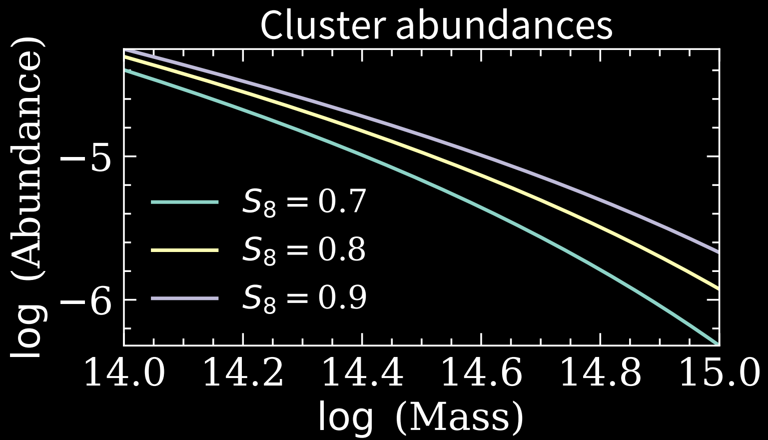
Cluster cosmology: weak lensing mass calibration



Courtesy: Yuuki Omori

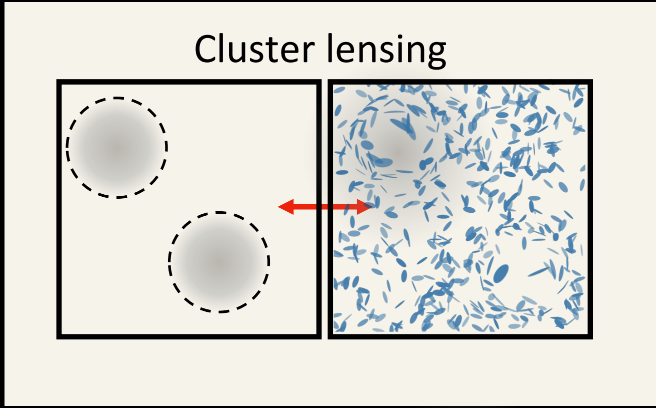
Cluster cosmology: cluster lensing and cluster abundance

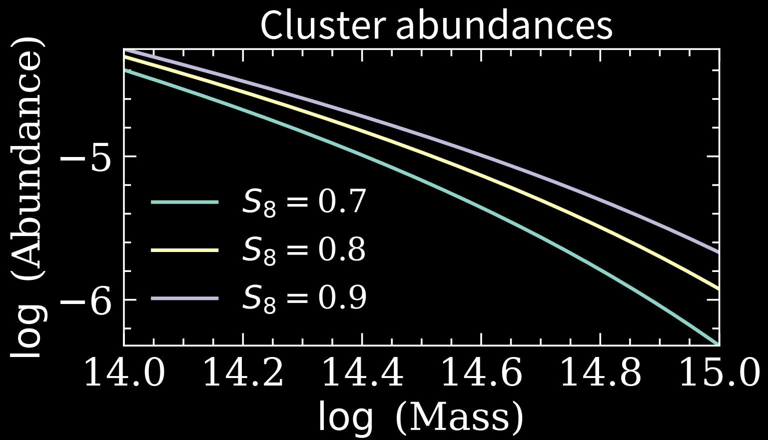


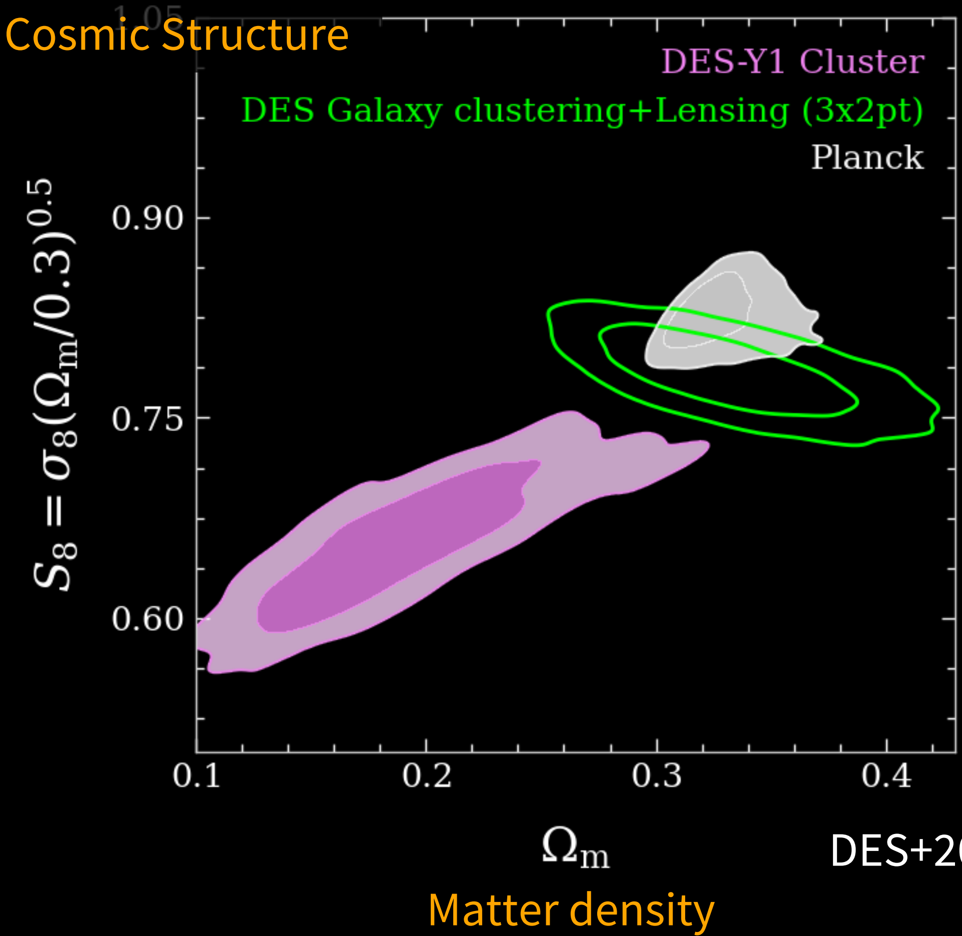


Similar to SPT and eROSITA

Big surprise in the analysis of the first year of DES data

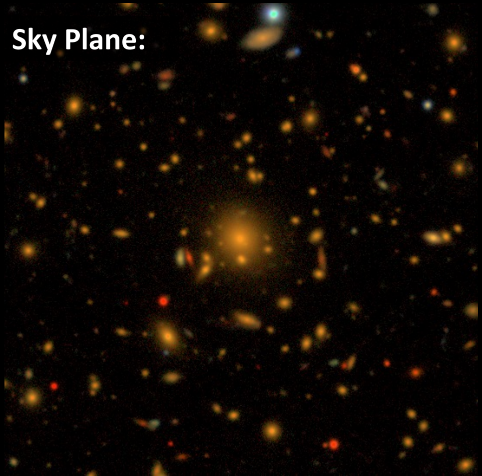






DES+20

Optically selected clusters suffer from projection effect



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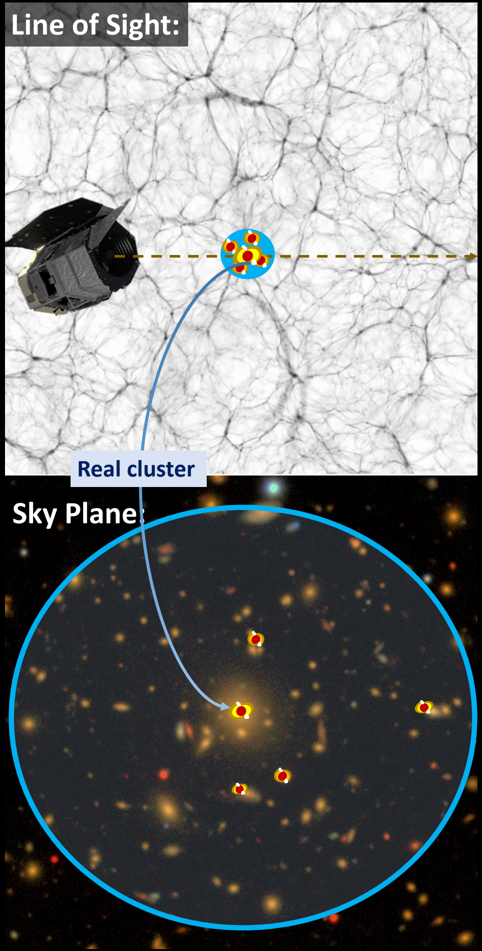

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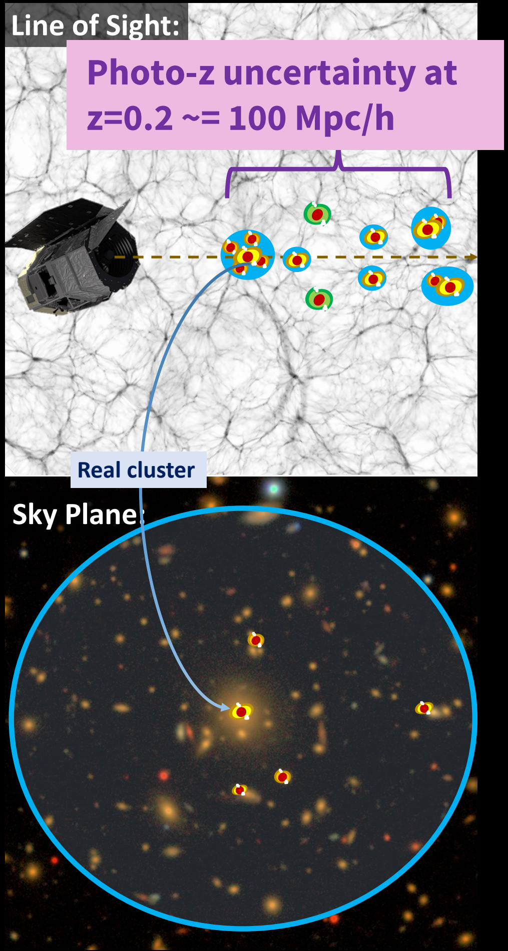

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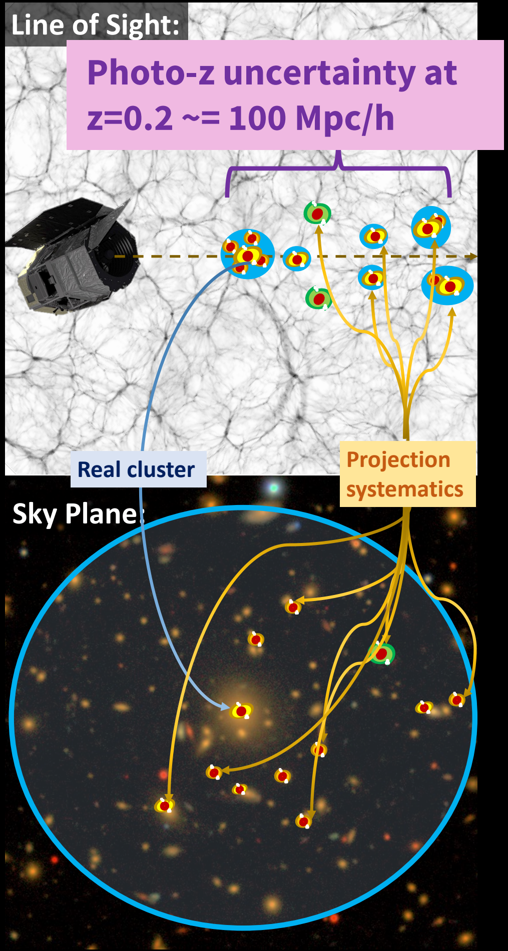
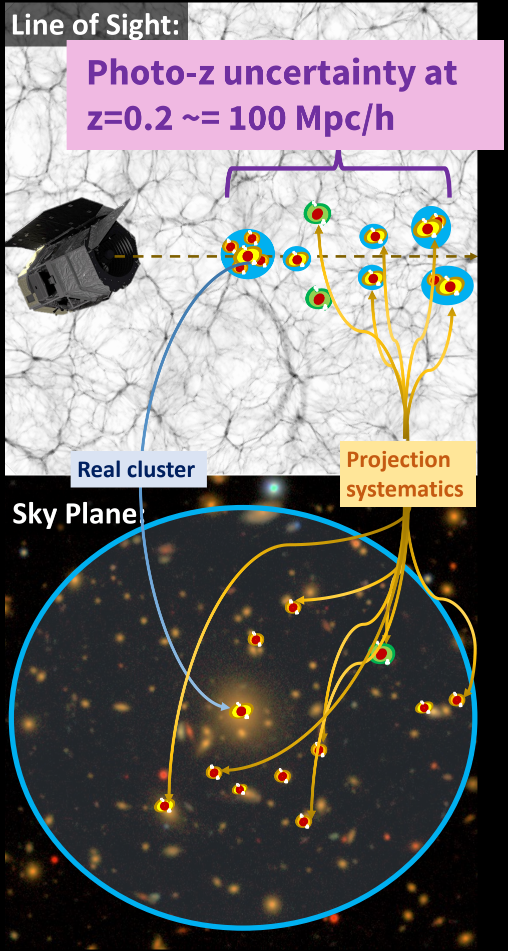


- Optical clusters suffer from the projection effect: Chance alignments of line-of-sight structure.

Optically selected clusters suffer from projection effect



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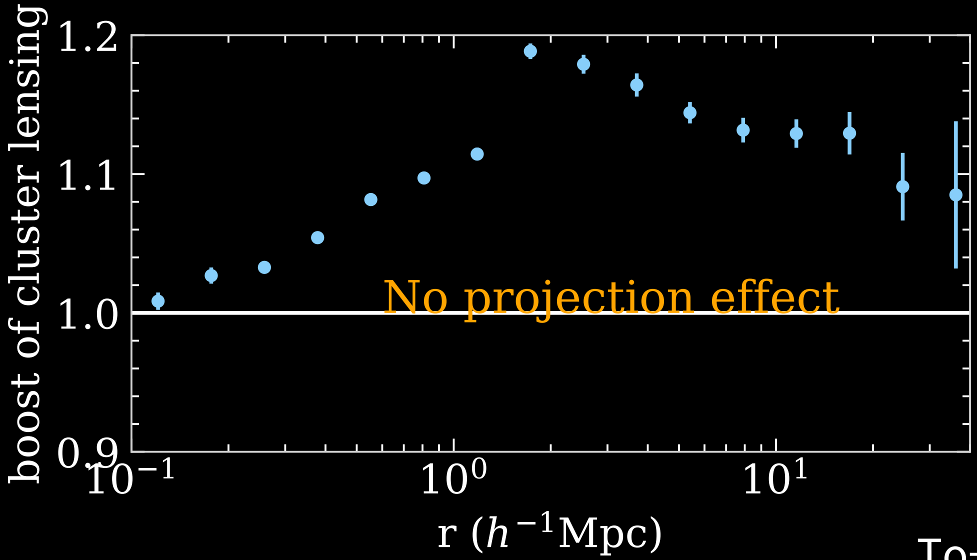
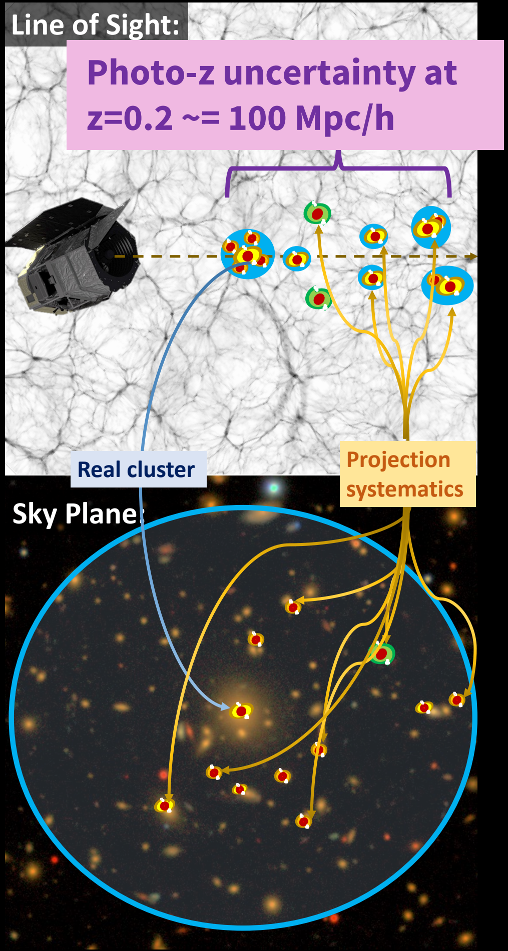
  → Additional modulation on cluster-related correlation functions (To+21, Wu+ 22, Zhang+ 23)



To+ 25

Optically selected clusters suffer from projection effect



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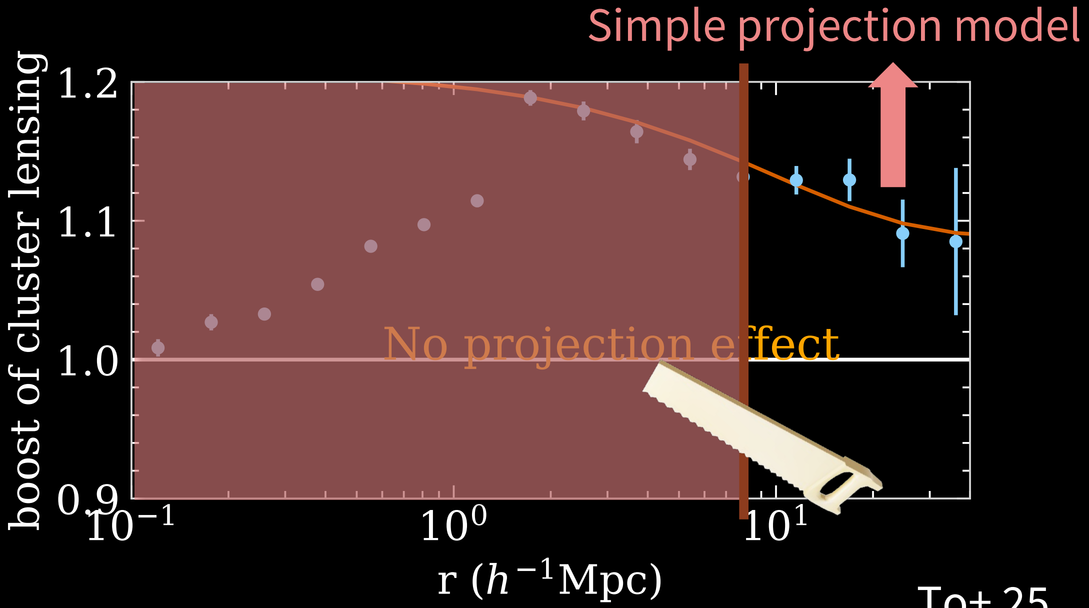


To+ 25

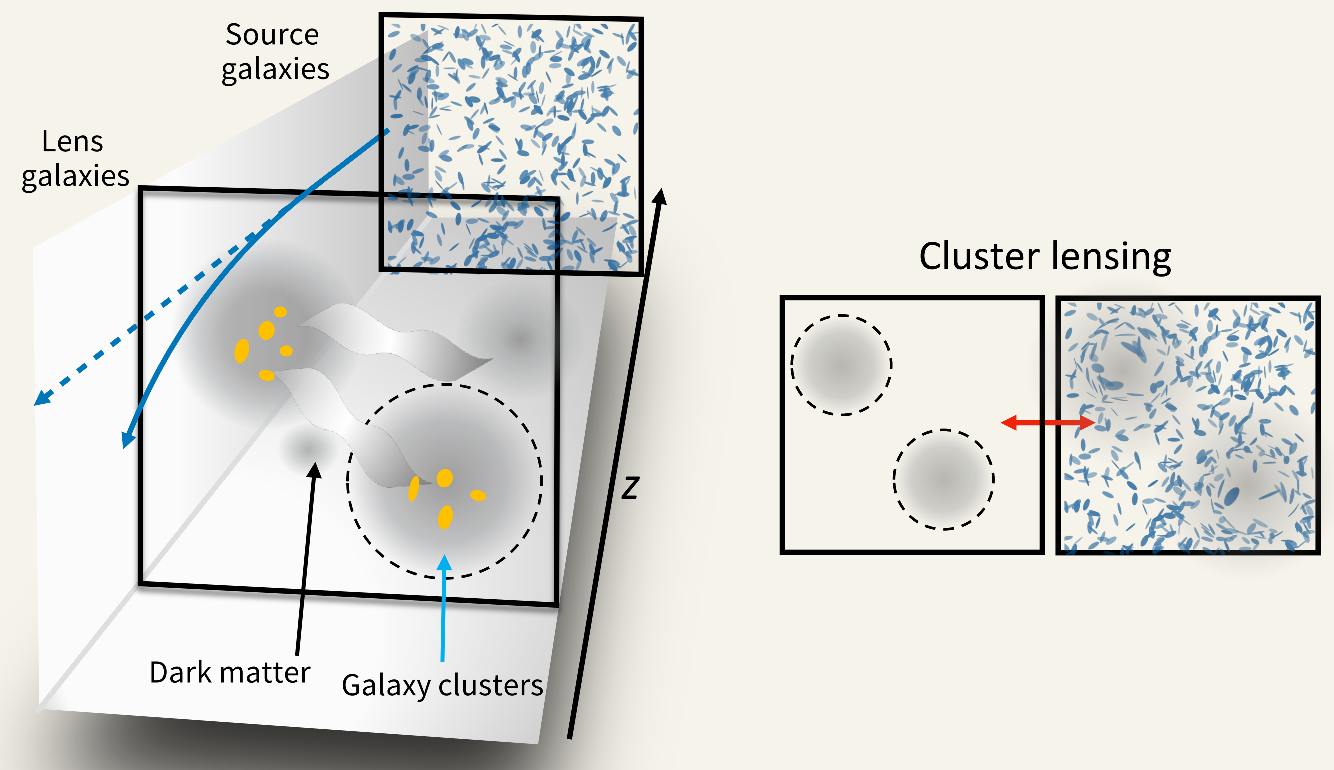
A new paradigm for optical cluster cosmology analysis

- Only large-scale information is used.

  - Benefits:
    - ✓ Simple projection effect model.
    - ✓ Bypass several small-scale systematics.

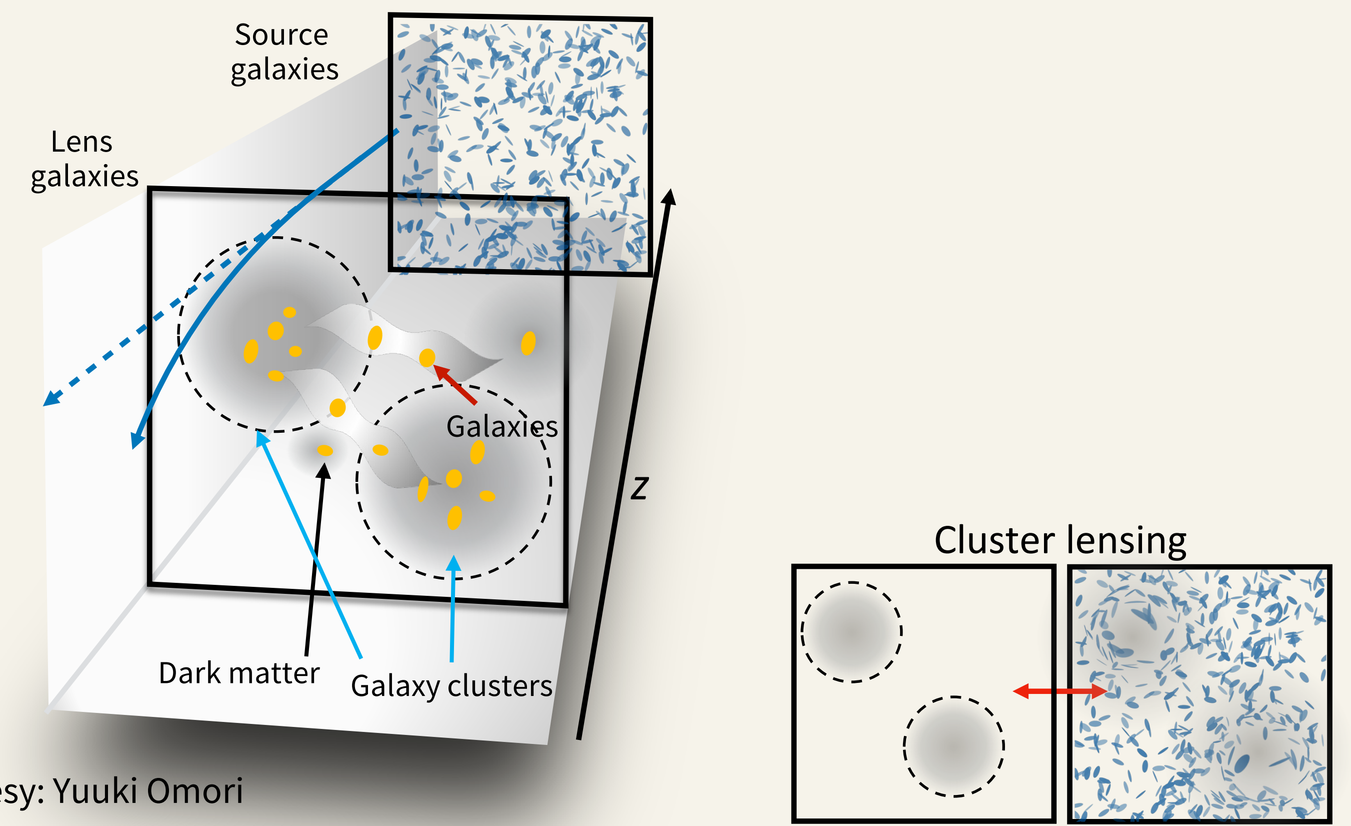
  - Drawbacks:
    - Loss of signal to noise

Cluster cosmology data vector: cluster lensing



Courtesy: Yuuki Omori

Clusters are part of the large-scale structure



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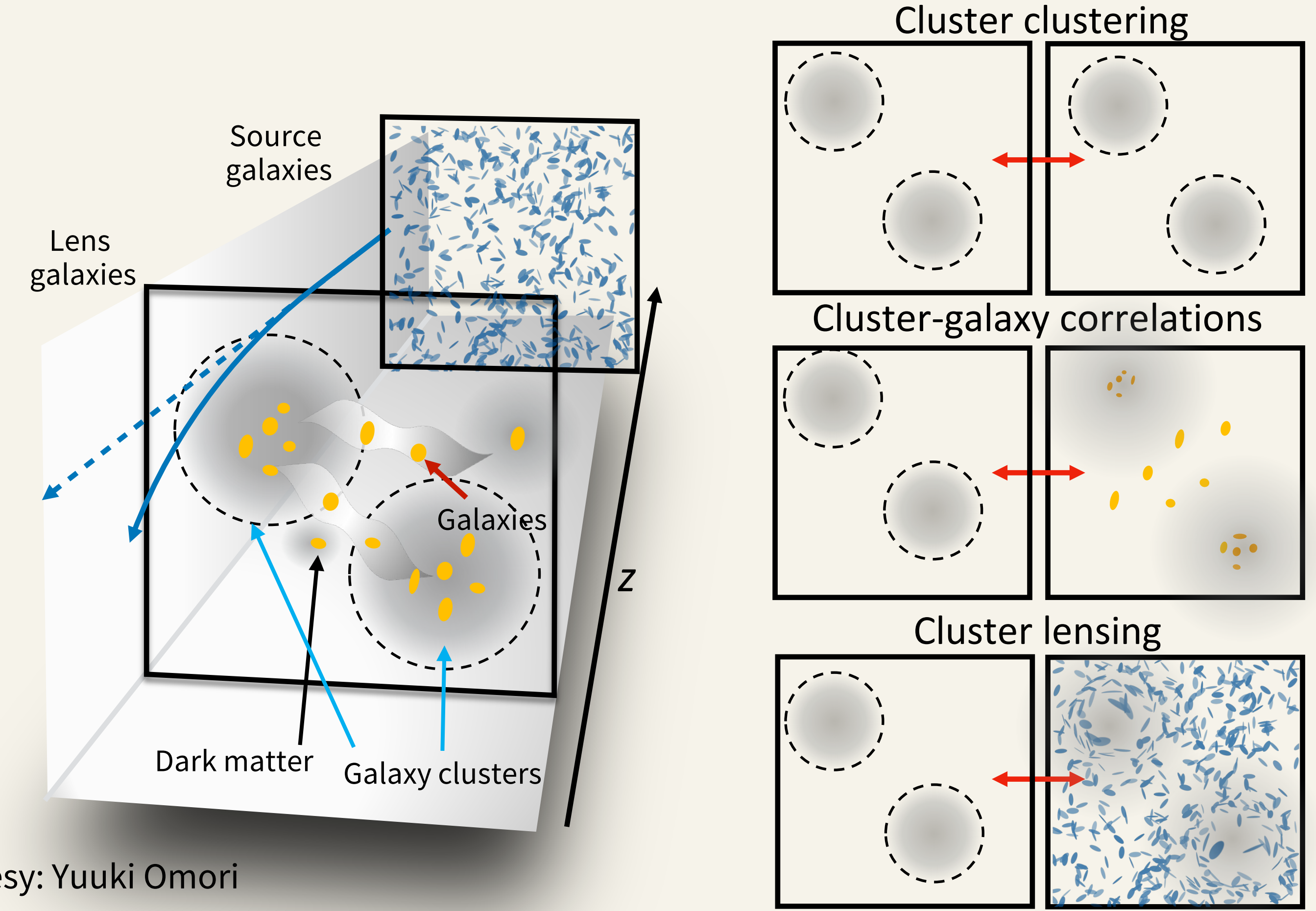
Cluster cosmology data vector: clustering



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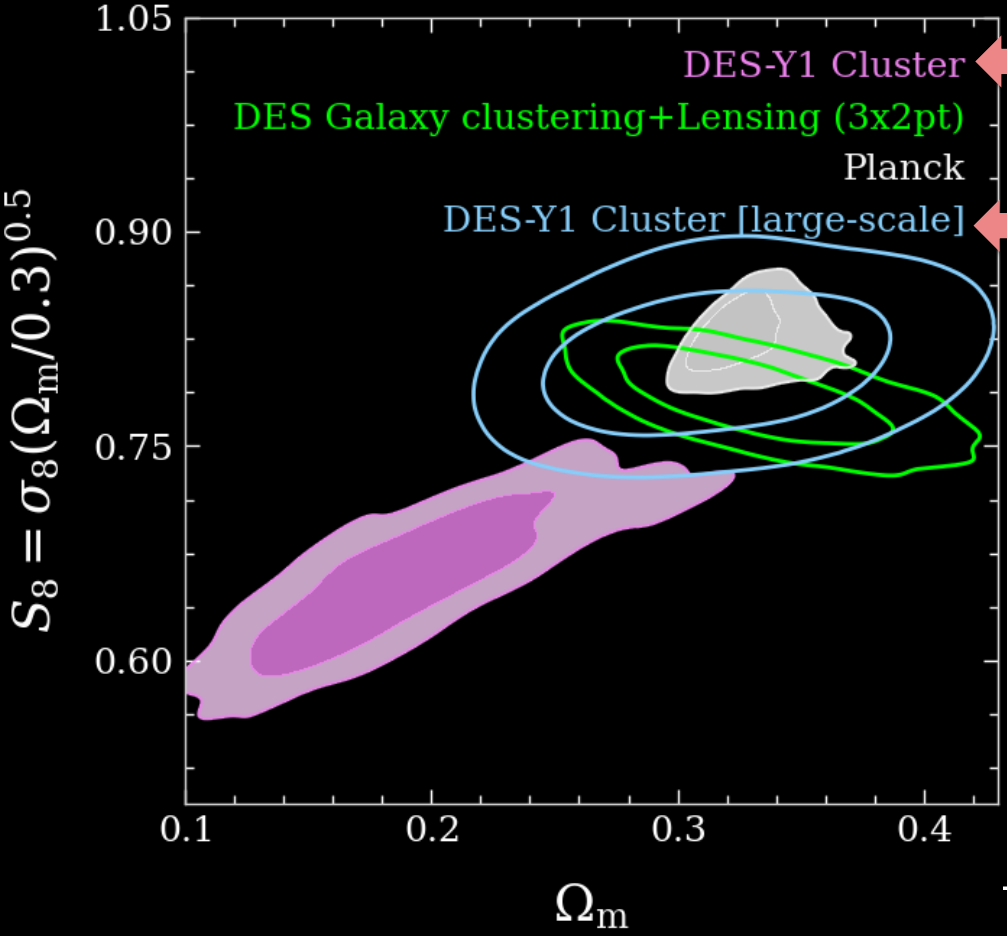
A new paradigm for optical cluster cosmology analysis

- Only large-scale information is used.
  - ➢ Benefits:
    - ✓ Simple projection effect model.
    - ✓ Bypass several small-scale systematics.
  - ➢ Drawbacks:
    - ➢ Loss of signal to noise
      - ✓ rescued by including more correlation functions: cluster clustering, galaxy—cluster correlations and galaxy clustering.

Re-analysis of DES-Y1 results in a consistent cosmology



DES Y1

DES Y1
Large-scale re-analysis

- Avoid several small-scale systematics and have similar constraining power.

To&Krause + 21

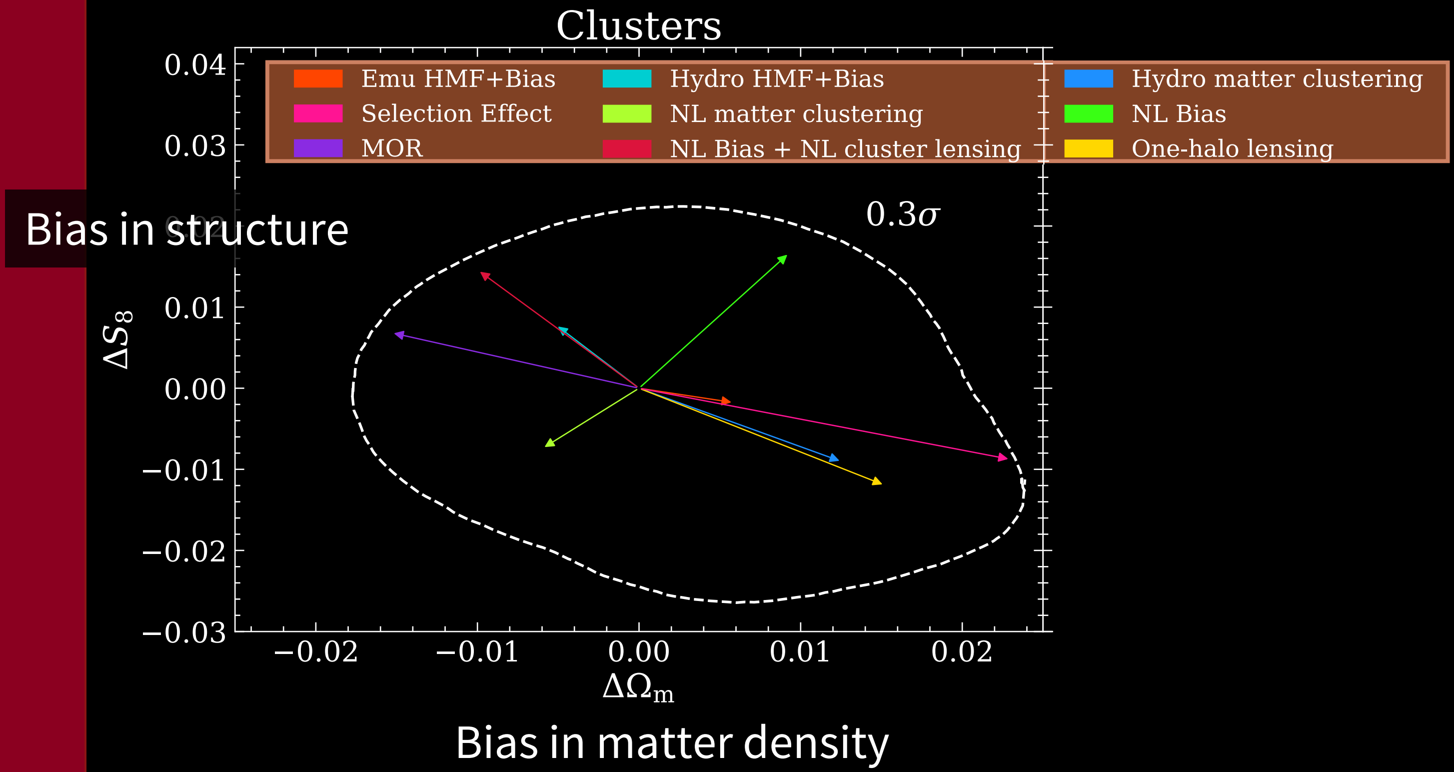
From DES-Y1 to DES-Y6

- Expansion of area by ~3 times.
- Weak lensing noise decreased by ~30%.

- Great statistical power requires great control of systematics!
  - ➢ 19 astrophysical parameters describing connection of measurements and matter fluctuations (linear galaxy bias, intrinsic alignments, mass—observable relations, and projection effects)
  - ➢ 12 observational parameters describing observational systematics (photometric redshift and shear measurement)

A comprehensive test of systematic for cluster cosmology

- None of the **nine** tested systematics will bias our cosmological constraints by more than 0.3 of the statistical uncertainty.



To+ 25

From DES-Y1 to DES-Y6: obstacles

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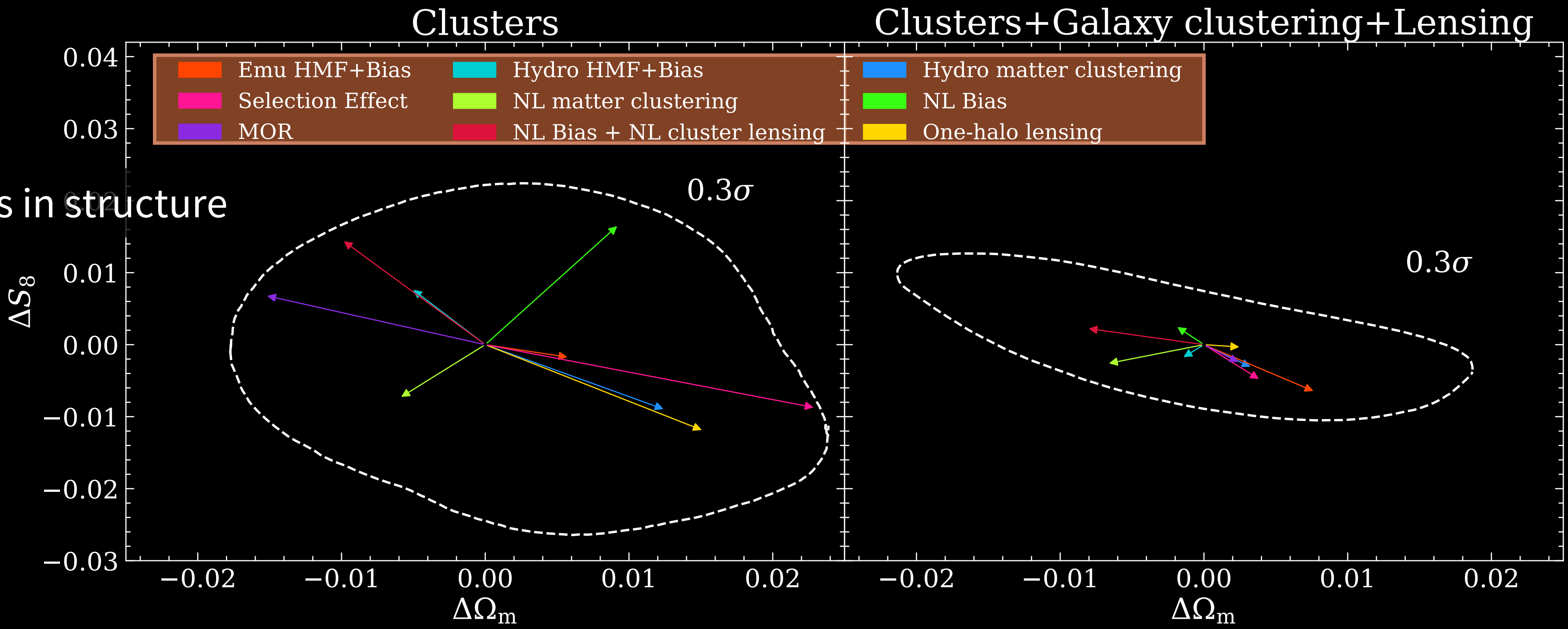

Bias in structure

Bias in matter density

To+ 25

From DES-Y1 to DES-Y6: obstacles

- We have tested the robustness of our model with nine different systematics.
  - ➢ Are there additional systematics?

From DES-Y1 to DES-Y6: obstacles

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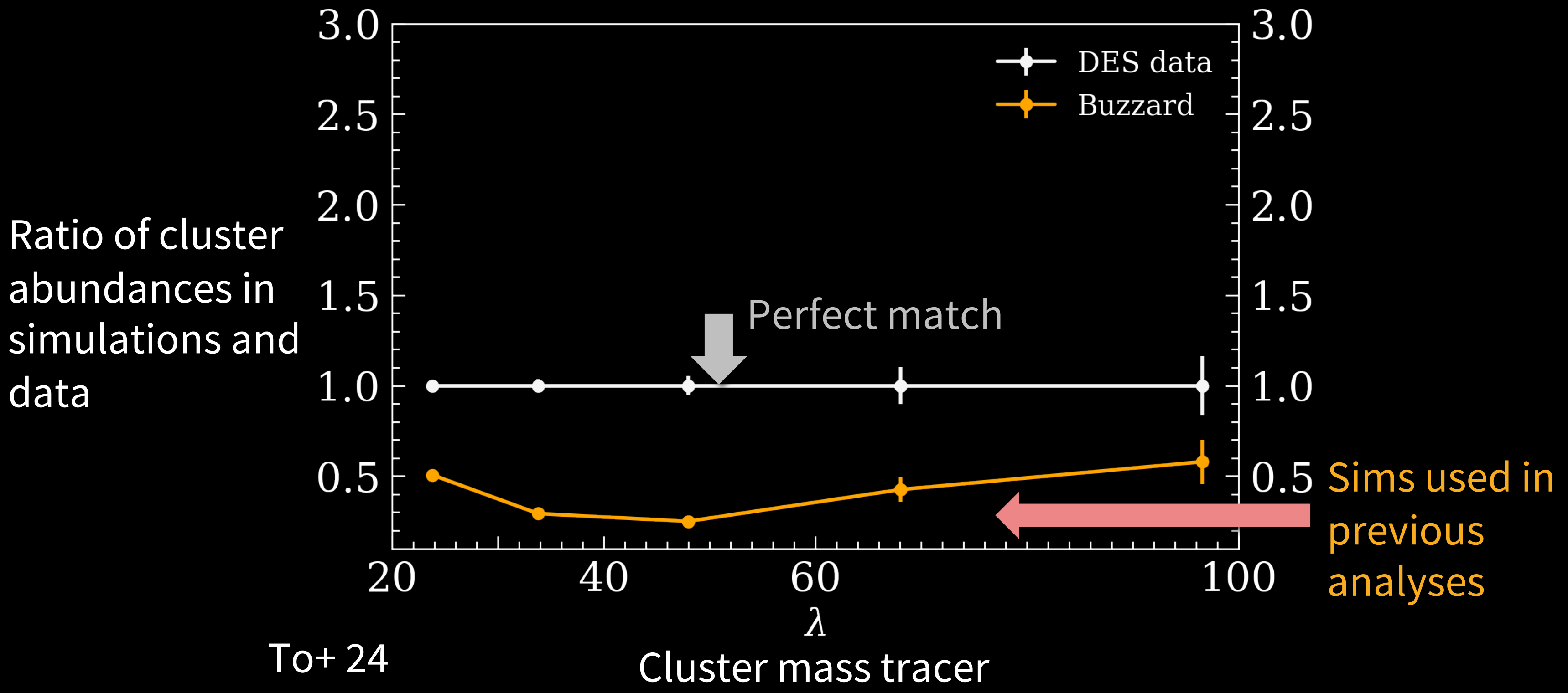
  - ➢ Are there additional systematics?

→ **Simulation validation.**

Simulation validation: Problem

- Cluster abundance in the old simulation is only half of the data.

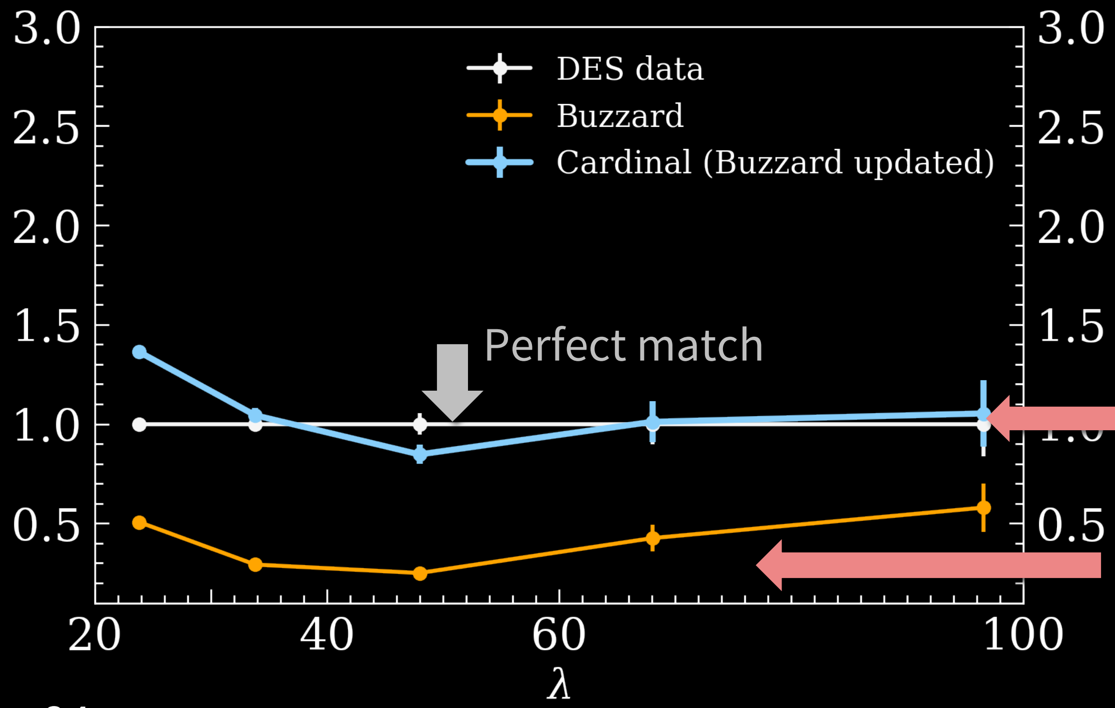


To+ 24

New simulations (Cardinal) solve the long-standing mis-match problem

- This is achieved with 12 major modeling improvements.

Ratio of cluster abundances in simulations and data



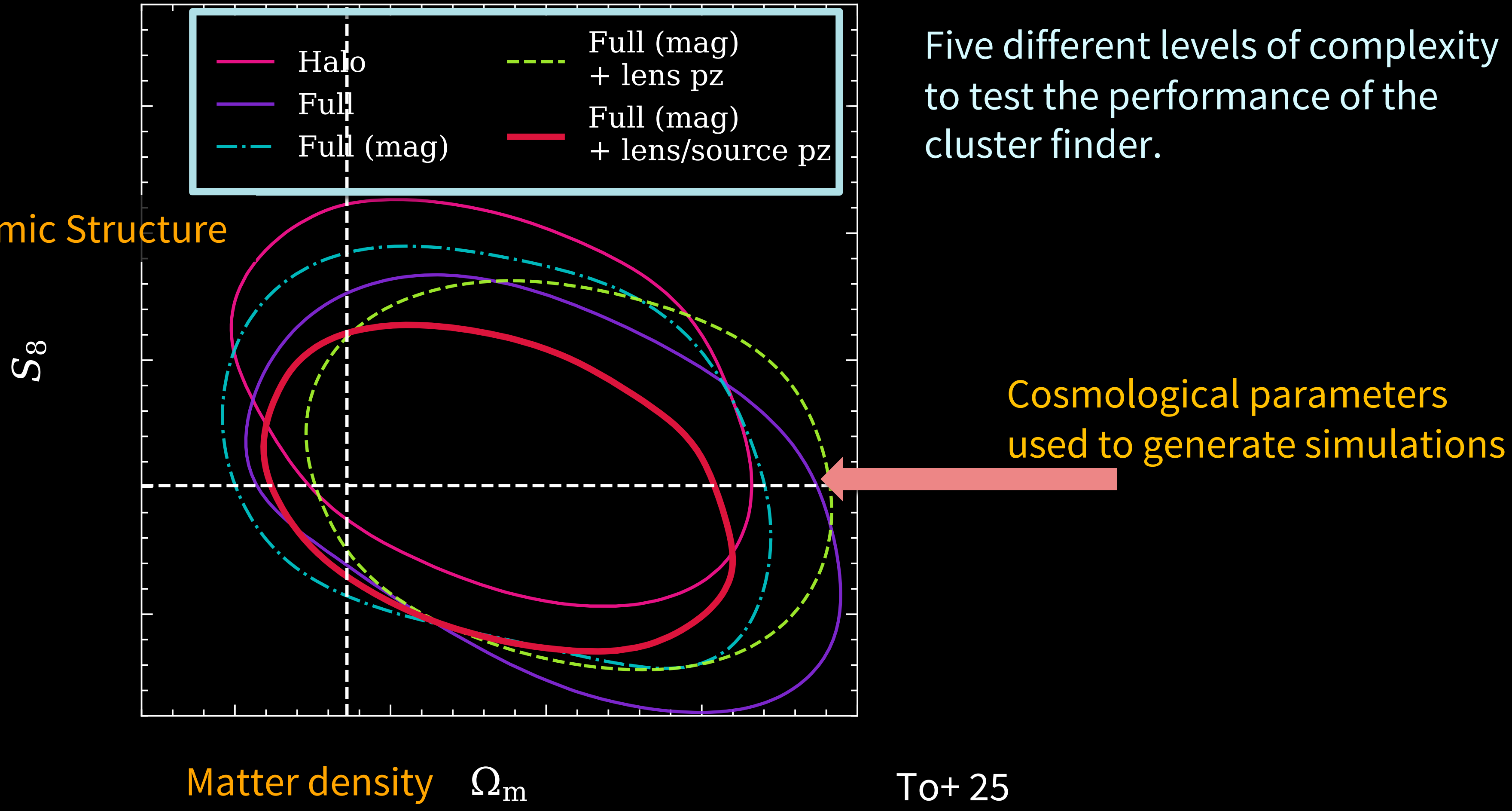
Cluster mass tracer

Updated sims

Sims used in previous analyses

To+ 24

Comprehensive tests of the cluster finding algorithm



Five different levels of complexity to test the performance of the cluster finder.

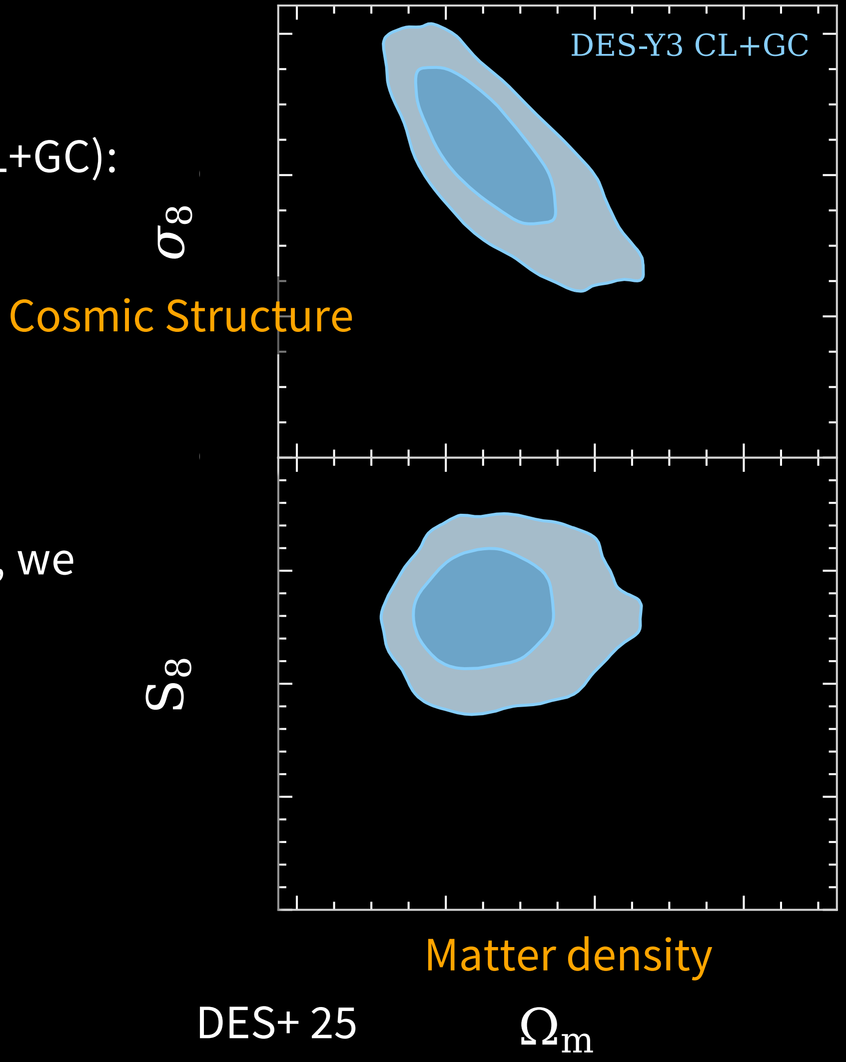
Cosmic Structure

Application on DES-Y3 data

DES Y3 cluster constraints

- DES cluster cosmology constraints (CL+GC):
  - Cluster abundance
  - Cluster lensing
  - Cluster clustering
  - Cluster-galaxy correlations + galaxy clustering
- In addition to **9** modeling systematics, we pass an additional **9** null tests.

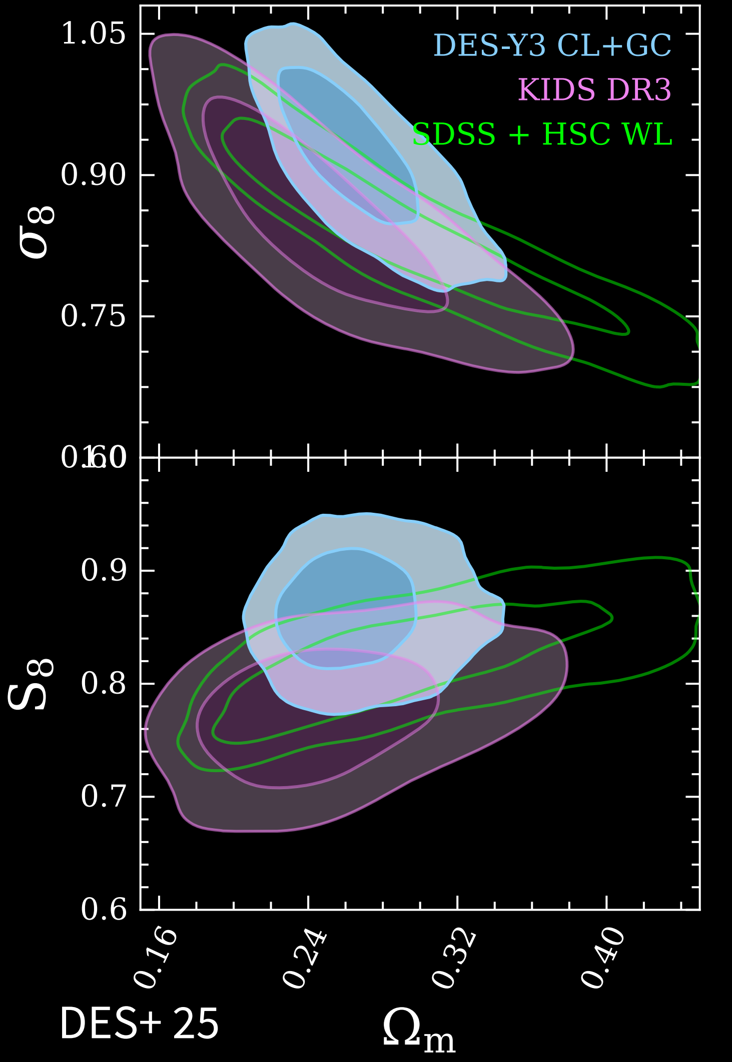
→ We unblind!



DES+ 25

Cluster constraints: optical clusters

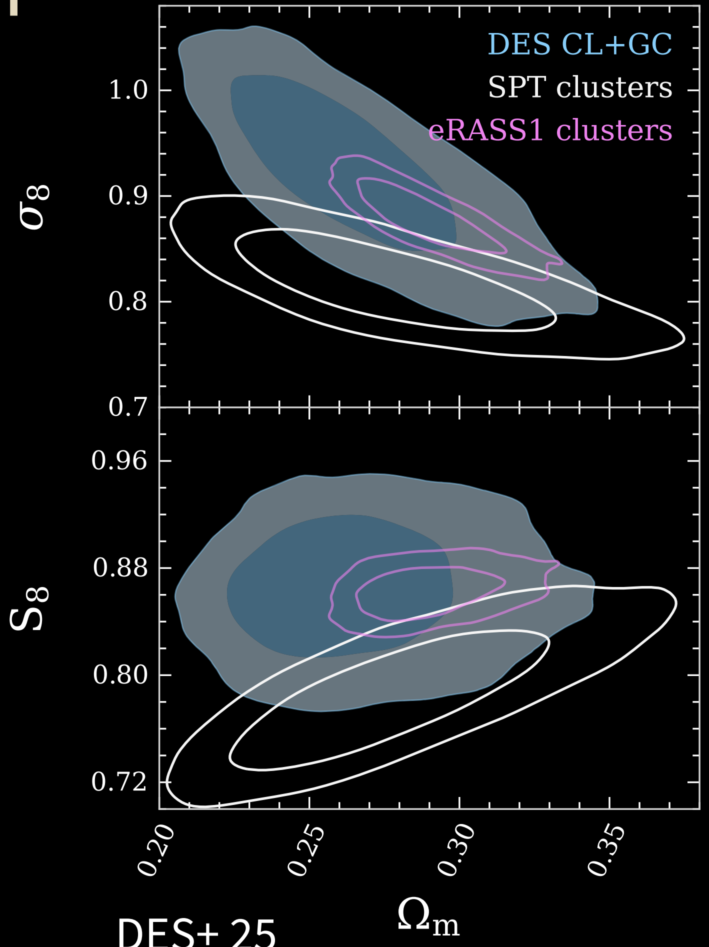
- Cosmology constraints (50% improvements relative to DES-Y1):
  - ➢ $S_8 = 0.86 \pm 0.04$
  - ➢ $\Omega_\mathrm{m} = 0.27^{+0.02}_{-0.03}$
- Constraints is consistent and competitive compared to other optical cluster cosmology result.



DES+ 25

Cluster constraints: Multiwavelength

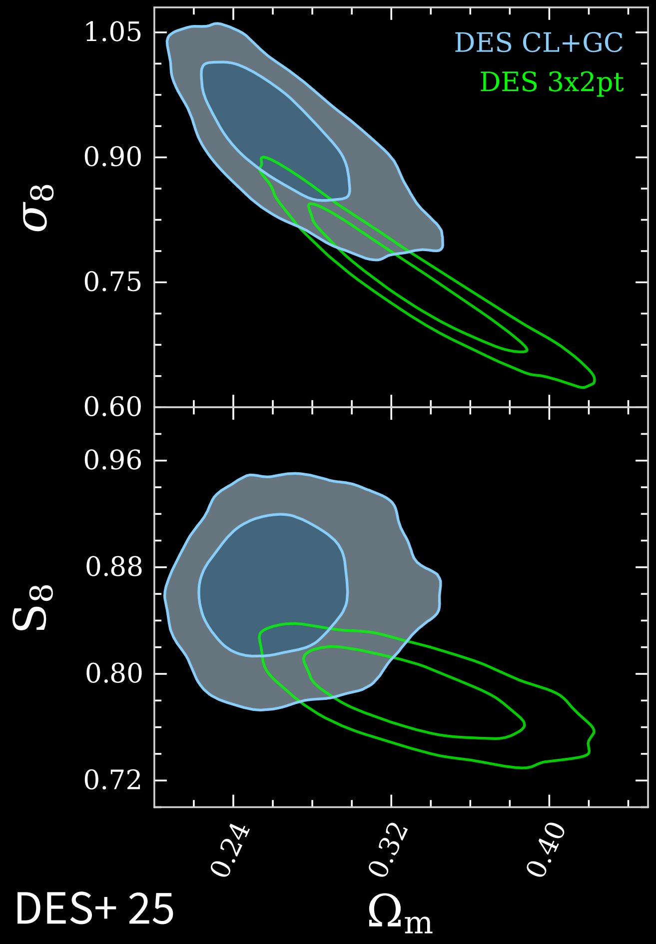
	DES	SPT	eROSITA
Detection	Red galaxies	Hot gas	
Mass and redshift	Low-mass High z	High mass	Low-mass Low z
Analysis method	Large-scale two-point functions	Small-scale cluster lensing	



DES+ 25

Consistency of the individual DES constraints in ΛCDM

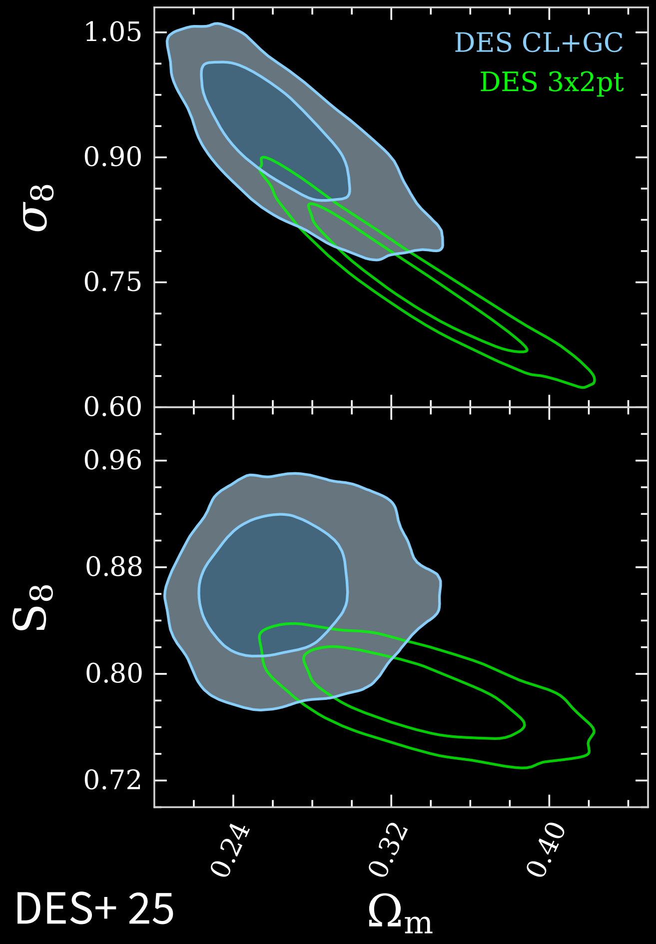
- DES cluster constraints (CL+GC) is consistent with joint analysis of galaxies and weak lensing (3x2pt) under ΛCDM.



DES+ 25

Consistency of the individual DES constraints in ΛCDM

- DES cluster constraints (CL+GC) is consistent with joint analysis of galaxies and weak lensing (3x2pt) under ΛCDM.
- Criteria:
  Consistency of data splits (d1, d2) is quantified by the Posterior Predictive Distribution (PPD) with a criteria PPD (d1|d2)>**0.01**.
  ✓P(cosmic shear | CL+GC, ΛCDM) = 0.04> 0.01
  ✓P(cosmic shear + galaxy-galaxy lensing | CL+GC) = 0.07>0.01



DES+ 25

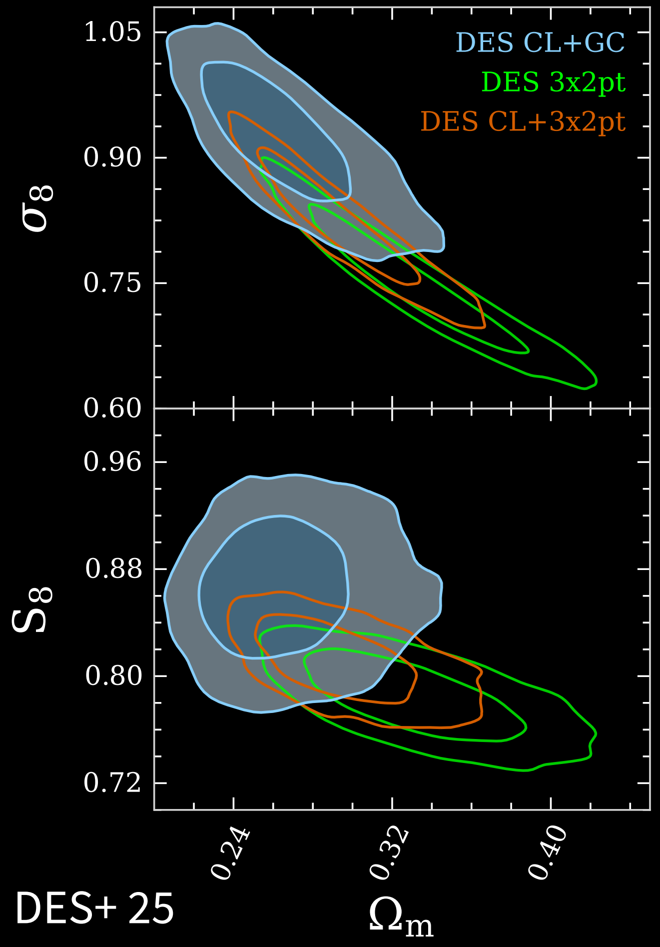
Joint analysis of clusters, galaxies, and weak lensing

- DES **joint analyses** of clusters, galaxies, and weak lensing (CL+3x2pt):

  - $S_8 = 0.81^{+0.02}_{-0.02}$
  - $\Omega_{\rm m} = 0.29^{+0.02}_{-0.03}$

  24% improvements compared to 3x2pt.

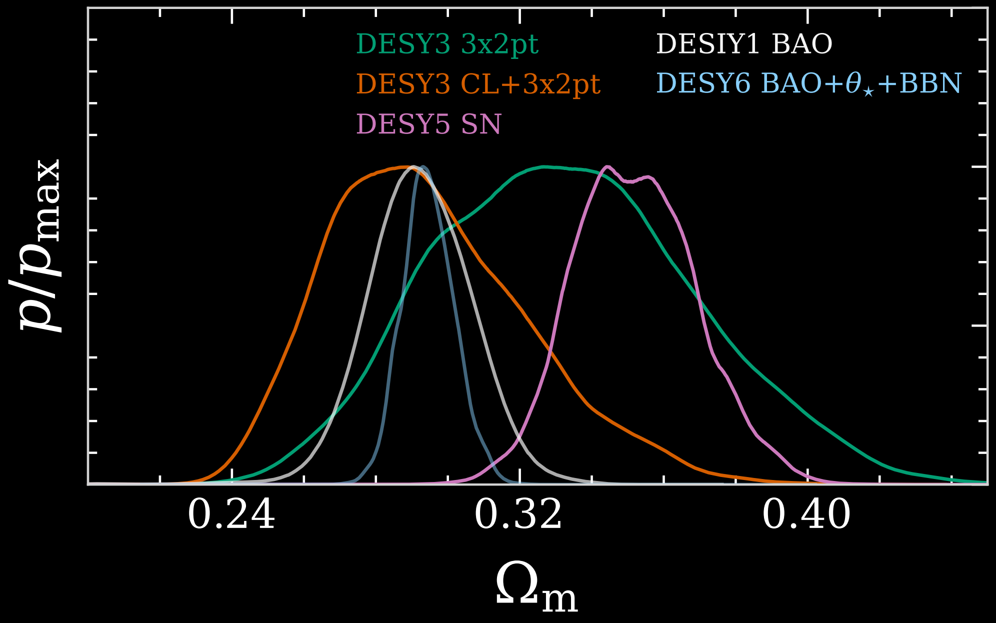
- ΛCDM fit clusters, galaxies, and weak lensing with PPD = 0.53.



DES+ 25

Comparison of matter density from different DES probes

- Under ΛCDM,
  - The matter density of the universe Ω_{m} from CL+3x2pt is consistent with DES and DESI BAO.
  - Ω_{m} from CL+3x2pt is 2.04σ lower from DESY5 SN.

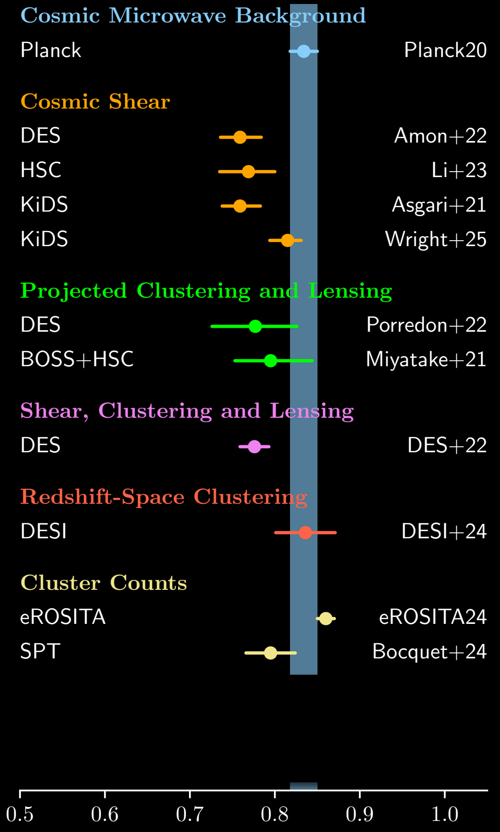


DES+ 25

50

Is the matter distribution in the late-time universe consistent with predictions based on initial conditions constrained by the Cosmic Microwave Background?

Measurement Model (ΛCDM)



$$S_8 = \sigma_8 \sqrt{\left(\frac{\Omega_m}{0.3}\right)}$$

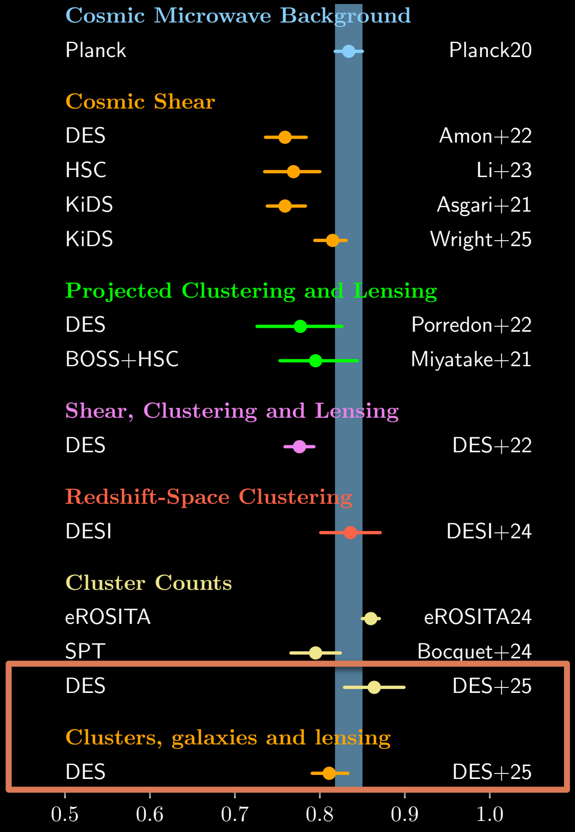
Amplitude of cosmic structure

Is the matter distribution in the late-time universe consistent with predictions based on initial conditions constrained by the Cosmic Microwave Background?

- DES **joint analyses** of clusters, galaxies, and weak lensing (CL+3x2pt) are consistent with ΛCDM predictions based on Planck CMB.

New DES Result

Measurement   Model (ΛCDM)



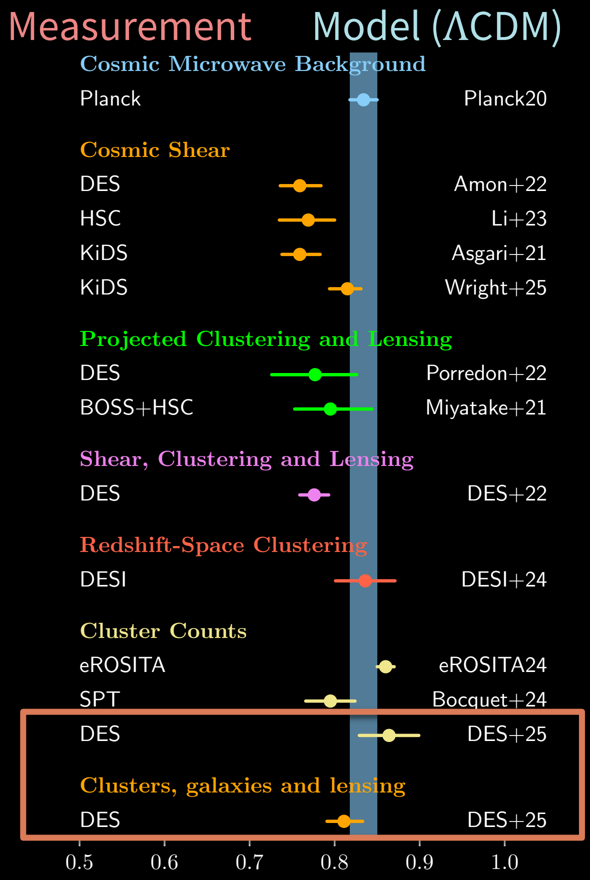
$$S_8 = \sigma_8 \sqrt{\left(\frac{\Omega_m}{0.3}\right)}$$

Amplitude of cosmic structure

Is the matter distribution in the late-time universe consistent with predictions based on initial conditions constrained by the Cosmic Microwave Background?

- DES **joint analyses** of clusters, galaxies, and weak lensing (CL+3x2pt) are consistent with ΛCDM predictions based on Planck CMB.
- Multi-dimensional tension metric: DES CL+3x2pt and Planck are consistent at 0.8 σ level or p=0.6

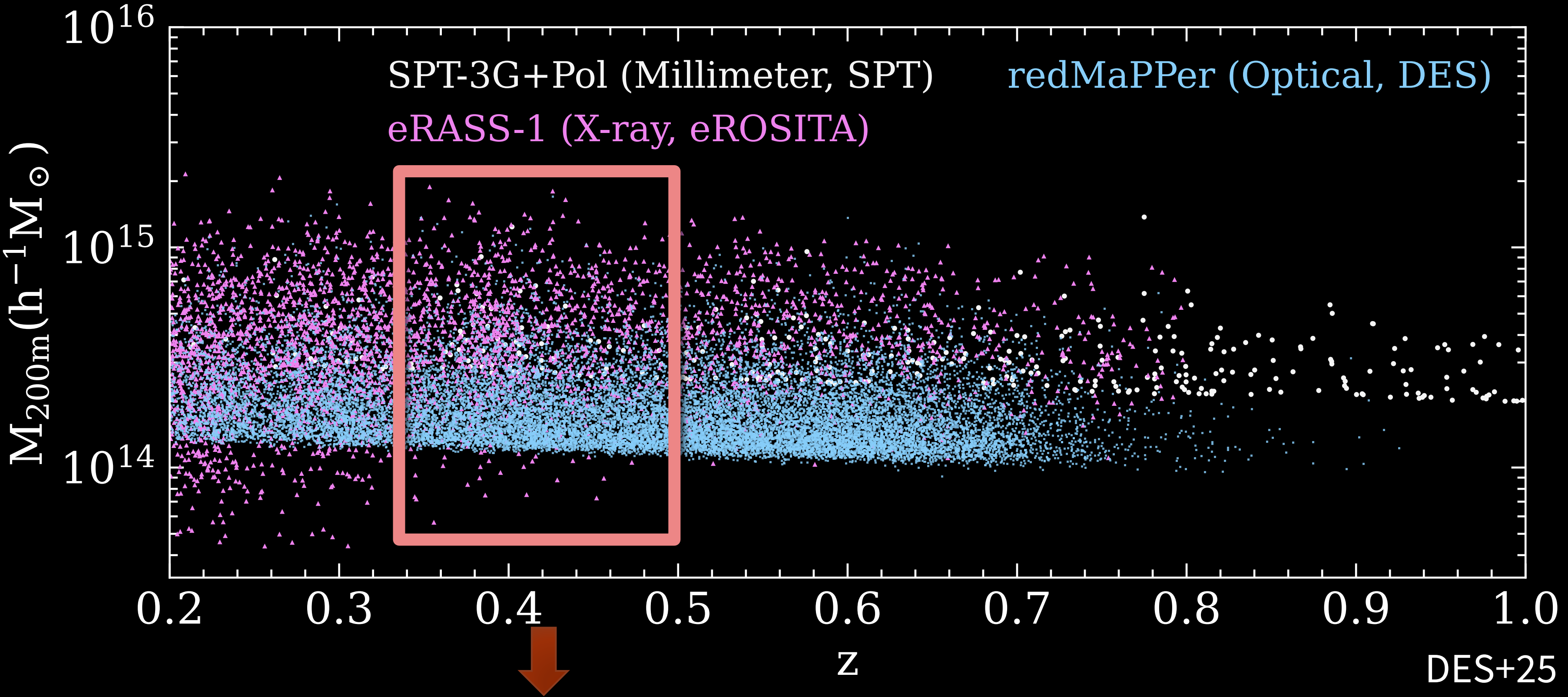
New DES Result



$$S_8 = \sigma_8 \sqrt{\left(\frac{\Omega_m}{0.3}\right)}$$

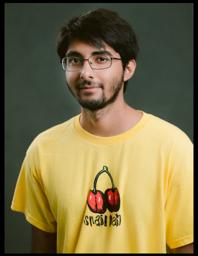
Amplitude of cosmic structure

Outlook: beyond cluster cosmology

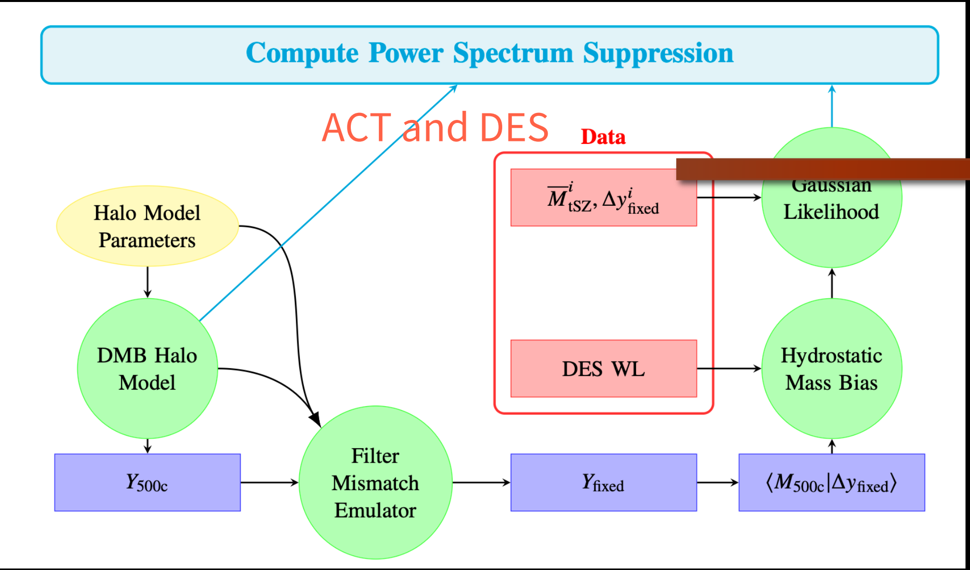


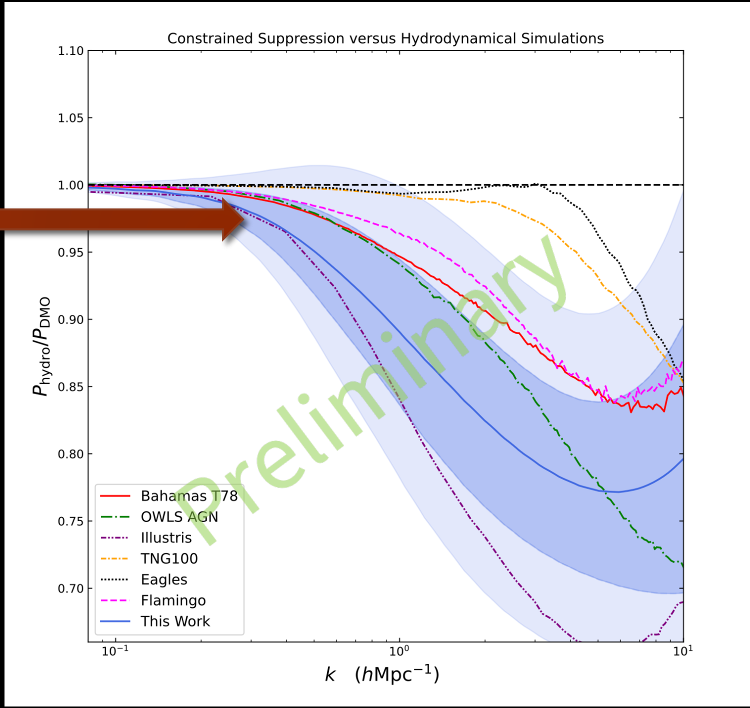
Peak of lensing efficiency for the highest redshift bin in DES WL

Pathfinder study on using the tSZ information around galaxy clusters to study baryonic feedback



Nihar Dalal at OSU

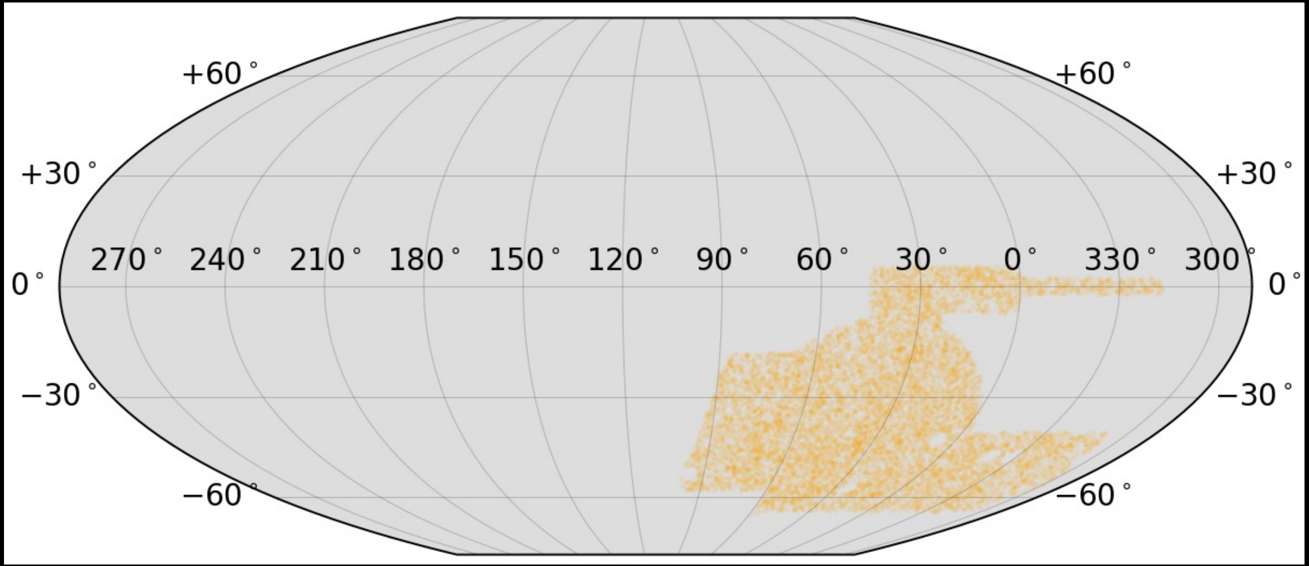




To be submitted in few weeks

Outlook: Clusters used in this analysis

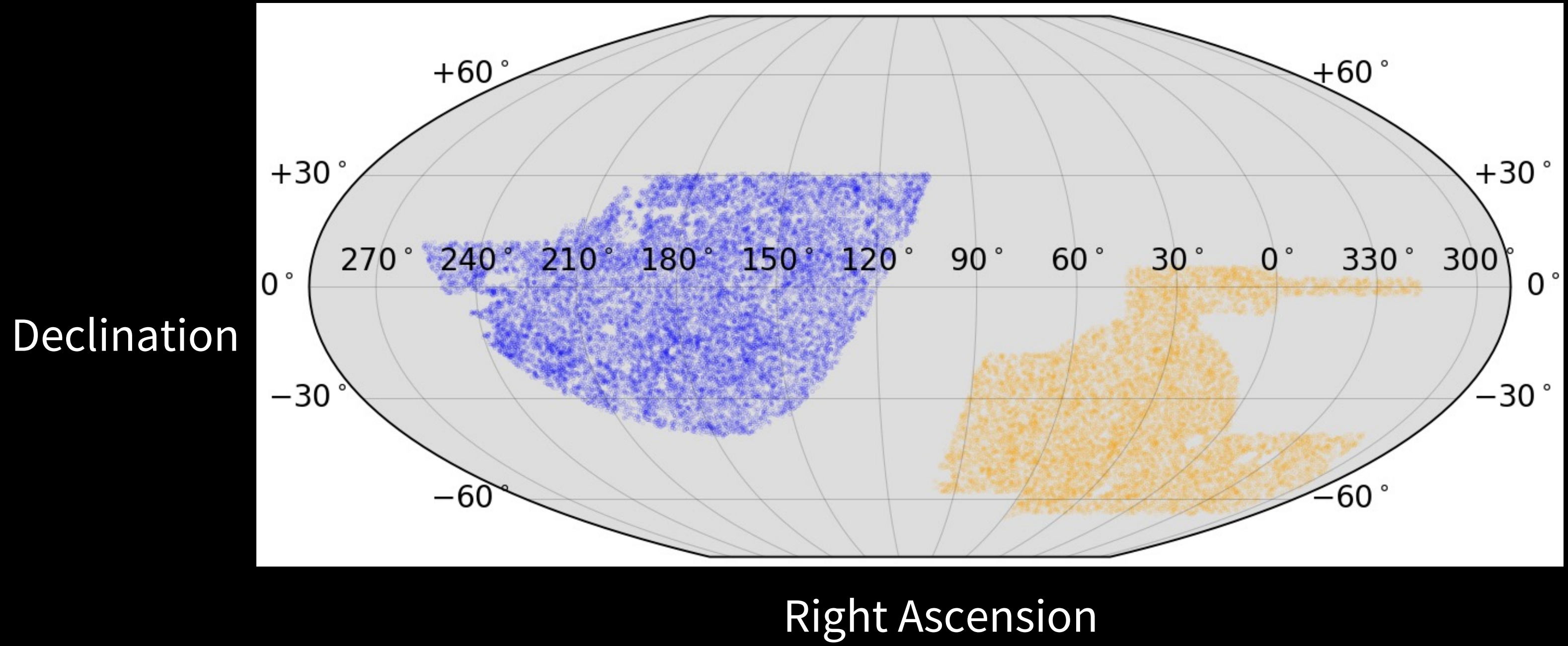
Declination



Right Ascension

DECADE dataset: Lots of clusters on the disk

- Another set of clusters spanning 5000 deg^2 with similar depth.
- Galaxy selection/photometry is processed with the same pipeline.
- Similar quality of weak lensing data as DES-Y3



Conclusions

- We have developed an analysis framework to jointly model three key probes in the Dark Energy Survey:
  Galaxy cluster abundances, galaxy clustering and weak lensing.

- Analysis prioritizes robust inference:
  - ➢ Forgoes small-scale information which is more sensitive to systematics.
  - ➢ Accuracy validated for full DES precision:
    - ✓ Robust against 9 different possible model mis-specifications.
    - ✓ Recover true cosmology in newly developed simulations.

Conclusions

- We have applied this method on DES-Y3 and find
  - Galaxy cluster abundances, galaxy clustering and weak lensing are internally consistent under ΛCDM.
  - Joint analyses of all three probes lead to constraints on the amplitude of cosmic structure consistent with Planck CMB within 1σ.
- We will soon improve the analysis with DES-Y6 and Decade data and conduct a comprehensive test of the cosmological model.
- The associated ~16k cluster samples are publicly available at https://des.ncsa.illinois.edu/releases/y3a2/Y3key-cluster.

Backup slides

Outlook: DES-Y6 analyses

- Combining DES 3x2pt+CL+SN is expected to constrain:

$$\sigma\, w_0 = 0.1$$
$$\sigma\, w_a = 0.5$$