Cosmological constraints from
clusters, galaxies, and weak gravitational lensing

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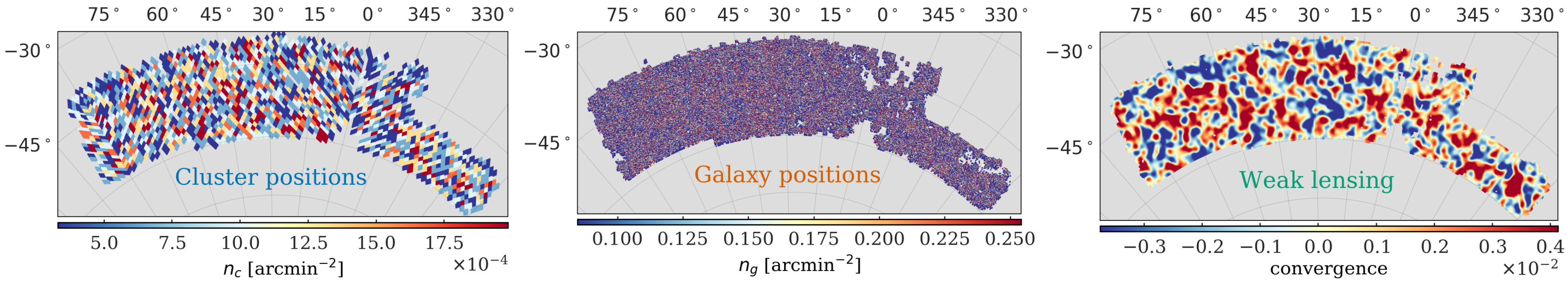
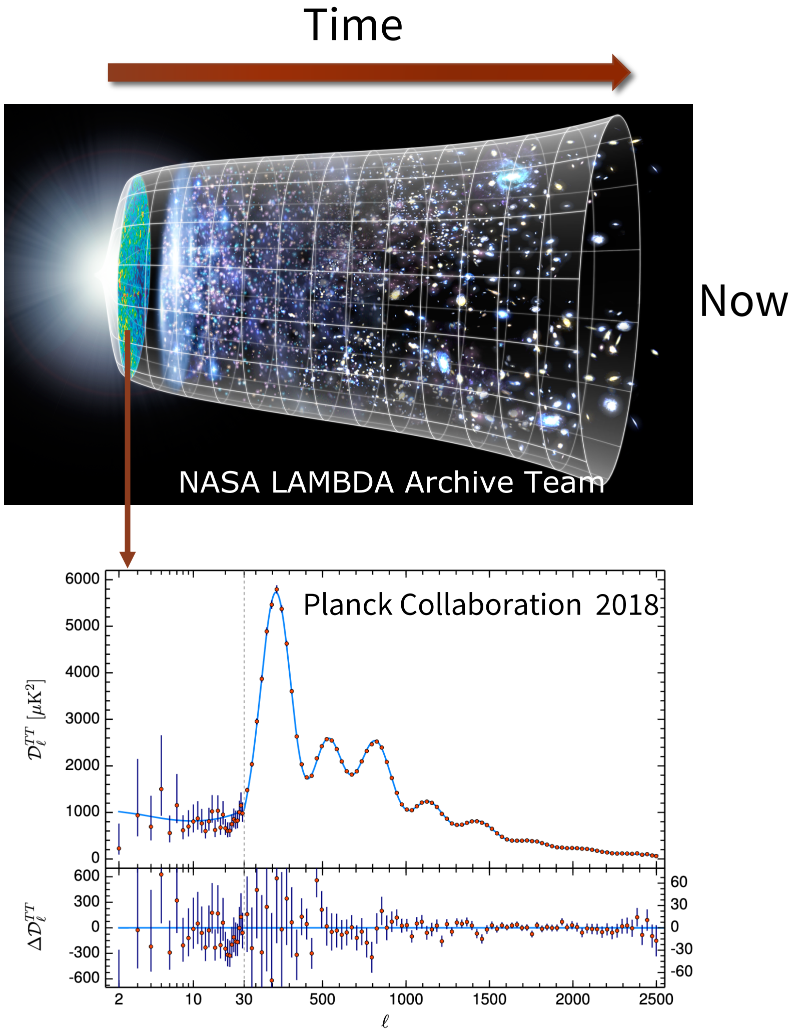


Motivation

- ΛCDM cosmology model:
  6 parameters are sufficient to describe the history of our universe.

- However many mysteries remain:
  - ➢ What is the nature of dark energy and dark matters?
  - ➢ Can the same model describe observations from the early and late universe?

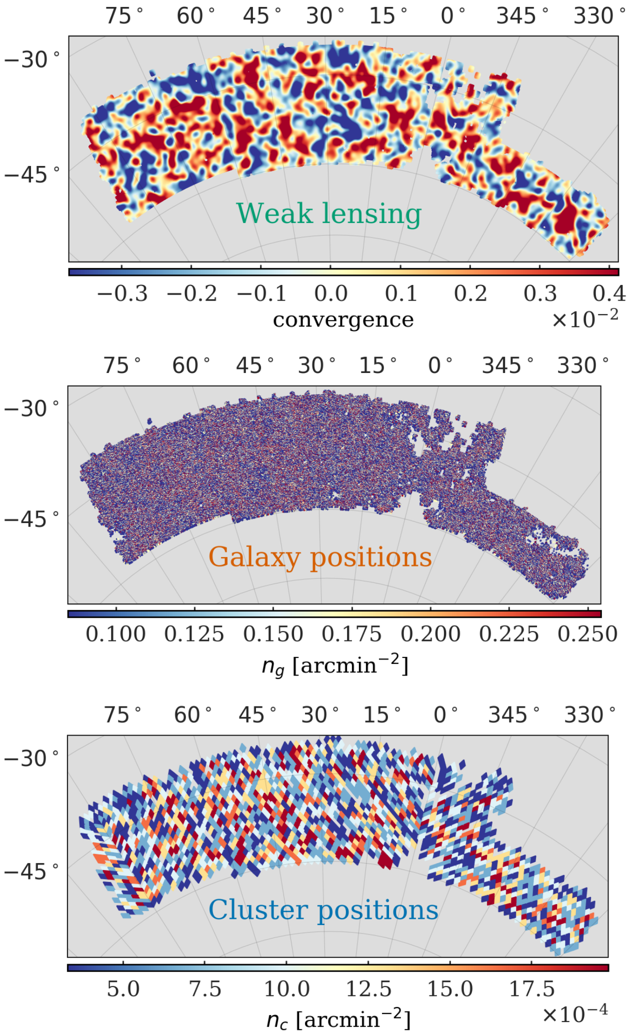
- These questions motivate lots of wide-imaging surveys:
  DES, KIDS, HSC, LSST, etc.



Dark Energy Survey

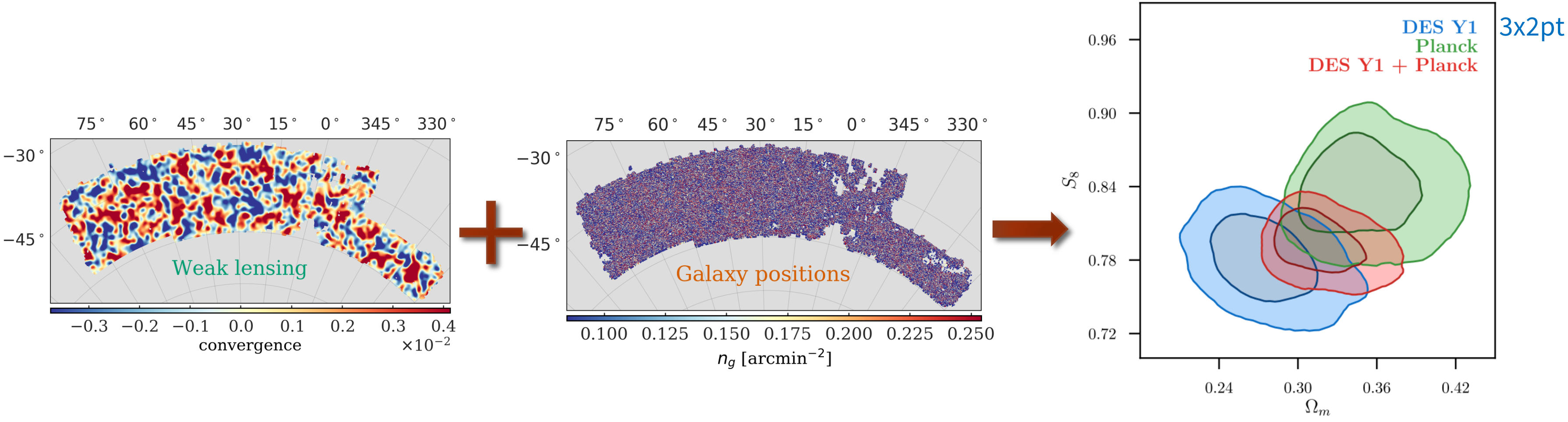
- 5000 sq deg survey in grizY for 5.5 years.
- Status:
  - ➢ Y1: 1500 sq. deg, 40% depth (data released)
  - ➢ Y3: 5000 sq. deg, 50% depth (analysis ongoing)

- Three large scale structure probes:
  - ➢ Weak gravitational lensing
  - ➢ Galaxy positions
  - ➢ Galaxy cluster abundances and positions



Dark Energy Survey

- 3x2pt analysis:
  - 3 two-point correlations derived from two tracer fields: Cosmic shear, galaxy clustering, and galaxy—galaxy lensing.
  - Competitive cosmological constraints compared to CMB.
- Galaxy cluster abundances have not been combined.

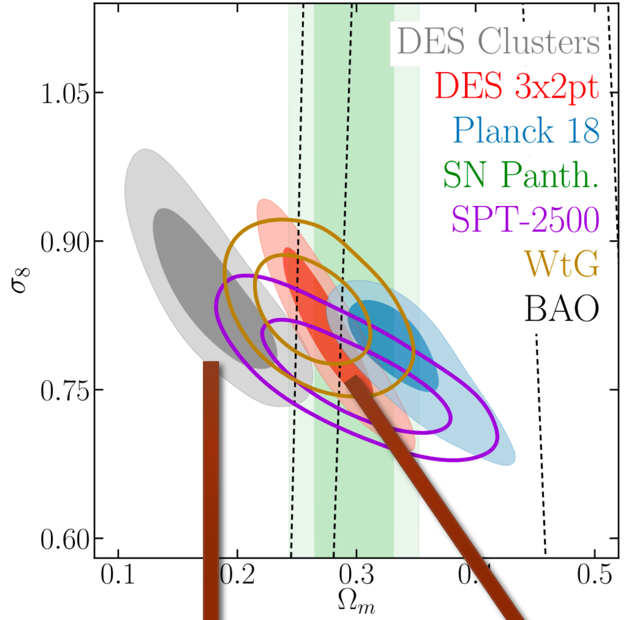


DES Collaboration 2018

Dark Energy Survey: clusters

- Why?
  1. DES cluster abundance and other cosmology probes in DES are in tension.
  2. Analysis approach:
     - ➢ Hard to be combined with other cosmology probes in the same survey.
- We **solve** these two problems simultaneously.

DES Collaboration 2020



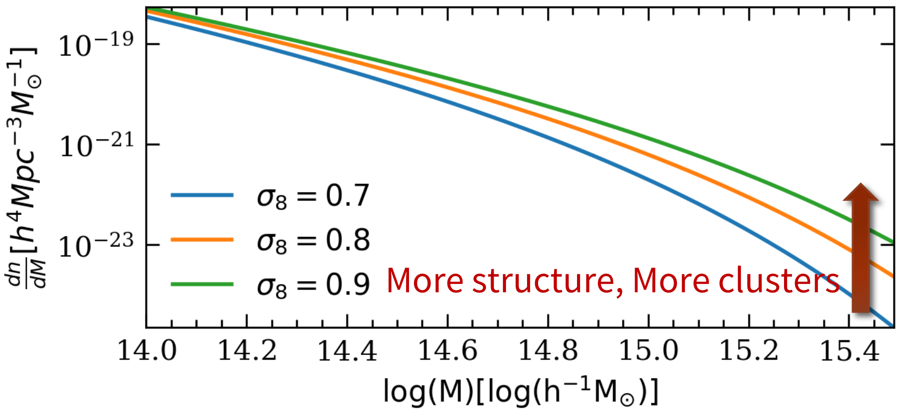
Cluster abundance

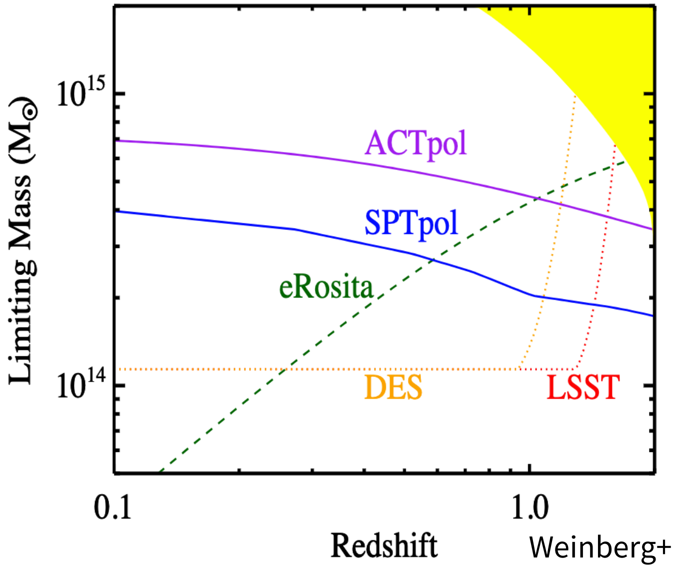
Galaxy clustering + Weak lensing

Same survey: highly correlated.

Why should you care about optical cluster cosmology?

- Why clusters?
  - ➢ More structure → Larger inhomogeneities → More large objects (clusters)
- Why optical?
  - ➢ Low mass → More galaxy clusters → Better weak lensing masses → Better cosmology

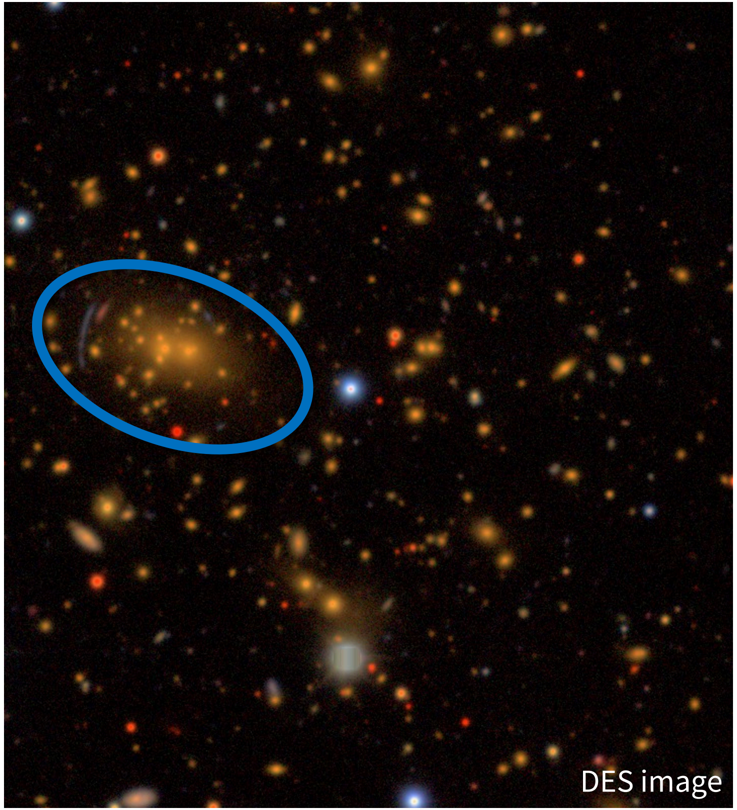




Weinberg+ 2013

Cluster cosmology 101

- Find:
  - redMaPPer algorithm:
    Overdensities of red sequence galaxies.
- Count:
- Weigh:



Cluster cosmology 101

- Find:
  - redMaPPer algorithm:
    Overdensities of red sequence galaxies.
- Count:
  - Number of clusters in bins of the mass proxy (richness λ):
    # of red and bright galaxies
  - Main Challenge: Selection function
- Weigh:

Selection function: (based on observation)

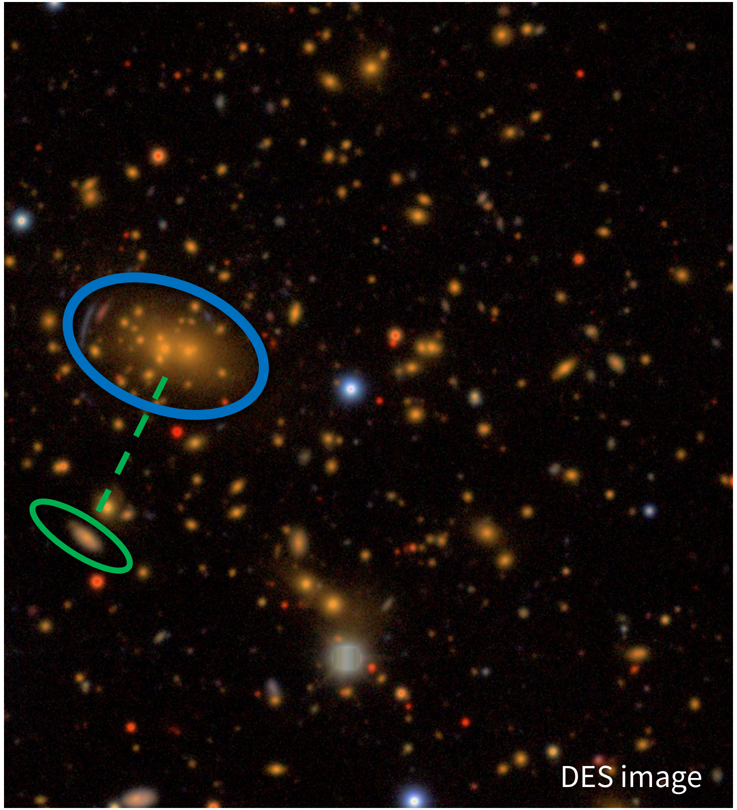
- Completeness:
  Cross match SPT and XCS
  → Complete at $\lambda > 40$
- Purity:
  Follow up 150 clusters with Swift X-ray
  → Pure at $\lambda = 30$

Cluster cosmology 101

- Find:
  - ➢ redMaPPer algorithm:
    Overdensities of red sequence galaxies.

- Count:
  - ➢ Number of clusters in bins of the mass proxy (richness λ):
    # of red and bright galaxies
  - ➢ Main Challenge: Selection function

- Weigh: (difficult)
  - ➢ Weak gravitational lensing.
  - ➢ Relies on small-scale modeling
    → affected by mis-centering, baryonic effects, etc.

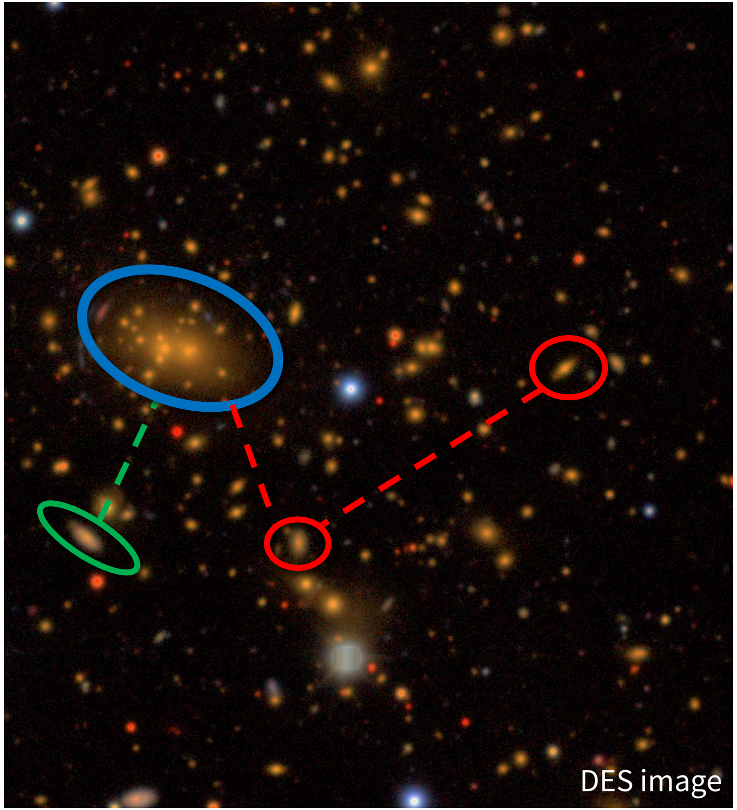


Our approach

- Only use **large-scale information** to weigh the clusters.

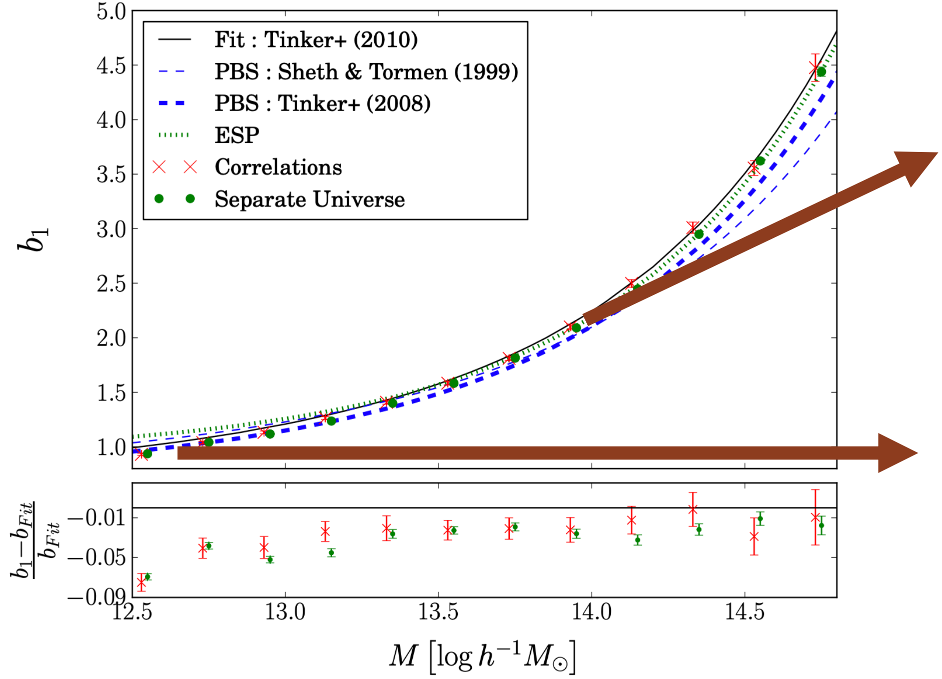
- Measuring cluster mass:
  - Cluster lensing $\propto b_c(M)$
  - Cluster x galaxy $\propto b_c(M) b_g$
    +
    galaxy x galaxy $\propto b_g^2$
  - Cluster clustering $\propto b_c^2(M)$

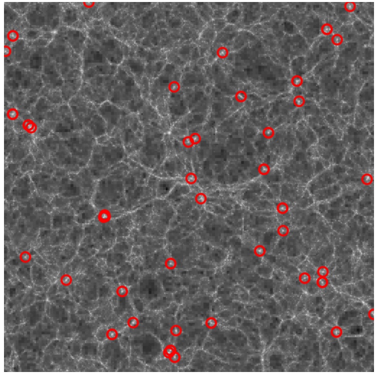
→ Reliable measurements of cluster biases.



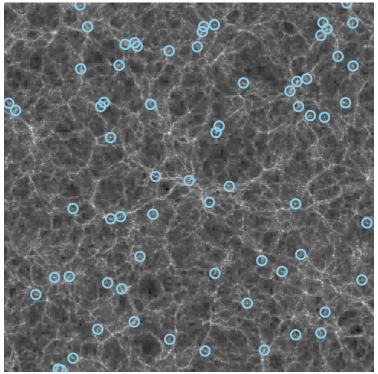
Our approach

- Cluster biases provide information of cluster's mass.





Same number density

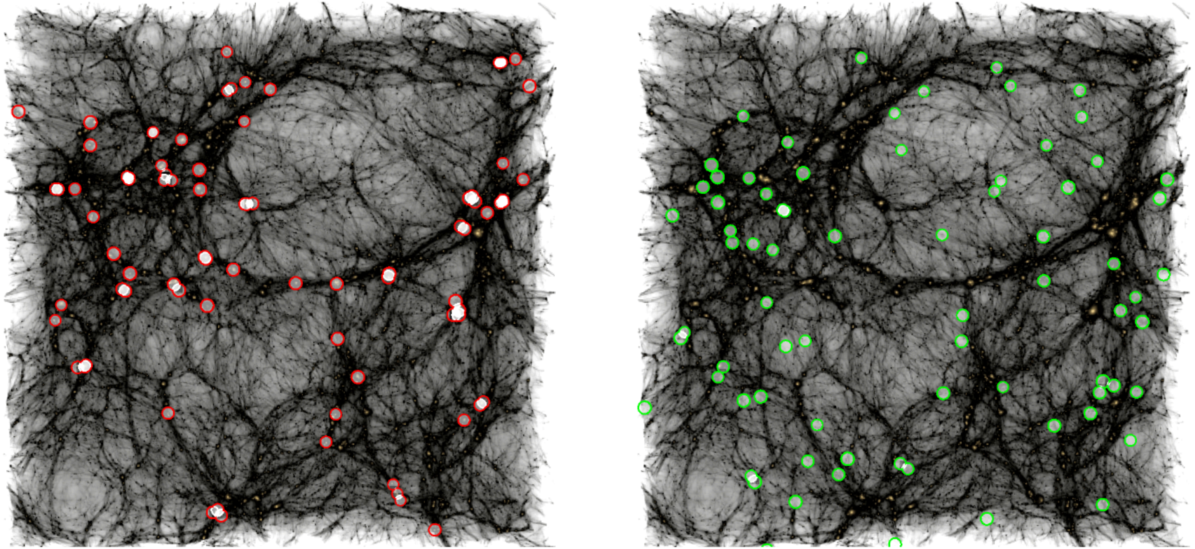


Desjacques et al. 2019

Dark Sky Simulation

Wait a minute

- Cluster bias depends on cluster **mass** and **other local properties of clusters**.
  - ➢ Selecting samples based on properties other than mass will cause a bias on the mass estimation.



Wechsler&Tinker 2018

Wait a minute

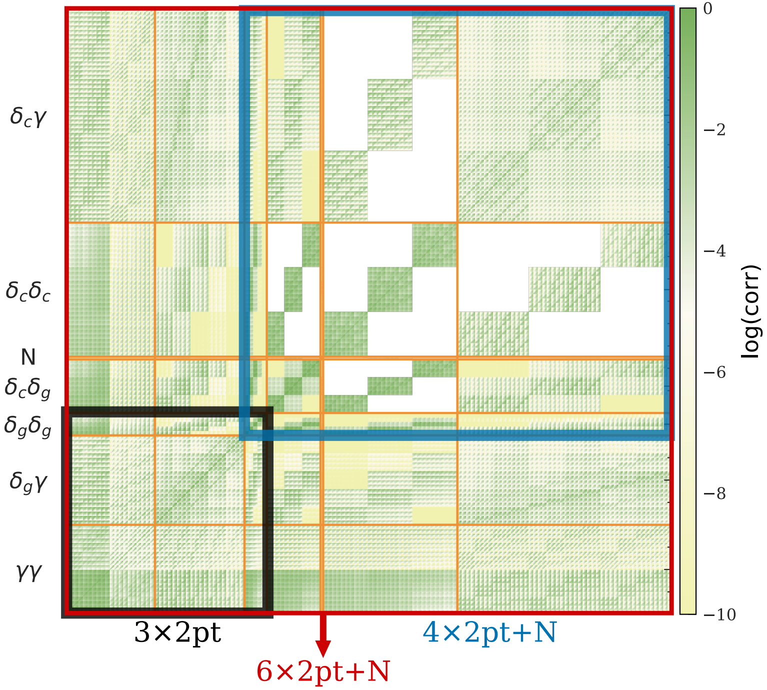
- For redMaPPer cluster cosmology:
  - Whether **richness** and **large-scale correlation functions** at a fix cluster mass are correlated?
    Yes → Additional bias (selection-effect bias).
  - On large-scale, selection effect bias is scale independent.
    → Relatively simple model: normalization and mass dependence [2 free parameters]
    → Is this sufficient? **Simulation validation is needed.**

Summary of our analysis

- 4x2pt+N (cluster) analysis:

Category	Data vector
DES Y1 3x2pt	➢ Galaxy clustering ($\delta_g \delta_g$)
Cluster related two-points	➢ Cluster-galaxy cross correlation ($\delta_c \delta_g$) ➢ Cluster clustering ($\delta_c \delta_c$) ➢ Cluster lensing ($\delta_c \gamma$)
Cluster Abundance	➢ Cluster abundance (N)

- 4x2pt+N (cluster) + 3x2pt (galaxy clustering + weak lensing)
  → 6x2pt+N analysis



Difference from DES Y1 cluster cosmology analysis

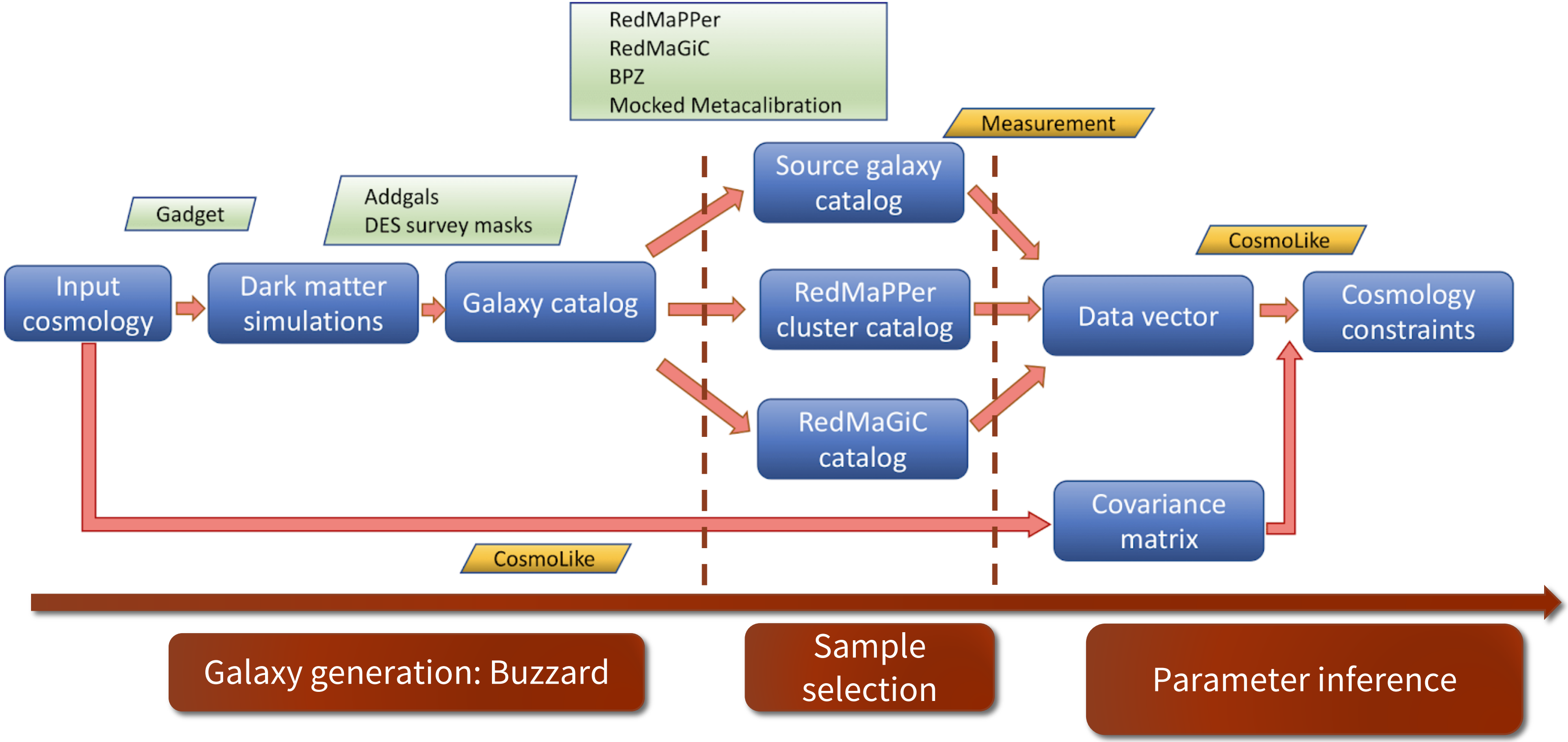
Analysis in comparison		Pros of this analysis
DES Y1 cluster analysis [DES collaboration 2020]	This analysis	
• Small scale	• Large scale, 2-halo regime	Safe from many systematics (e.g. baryonic effects, mis-centering)
• Two step analysis: Weak lensing → mass + N → Cosmology	• One step analysis: Data vector → Cosmology	Easy to be combined with other cosmology probes (e.g. 3x2pt)

The first end-to-end validation of a cluster abundance analysis on catalog-level simulations

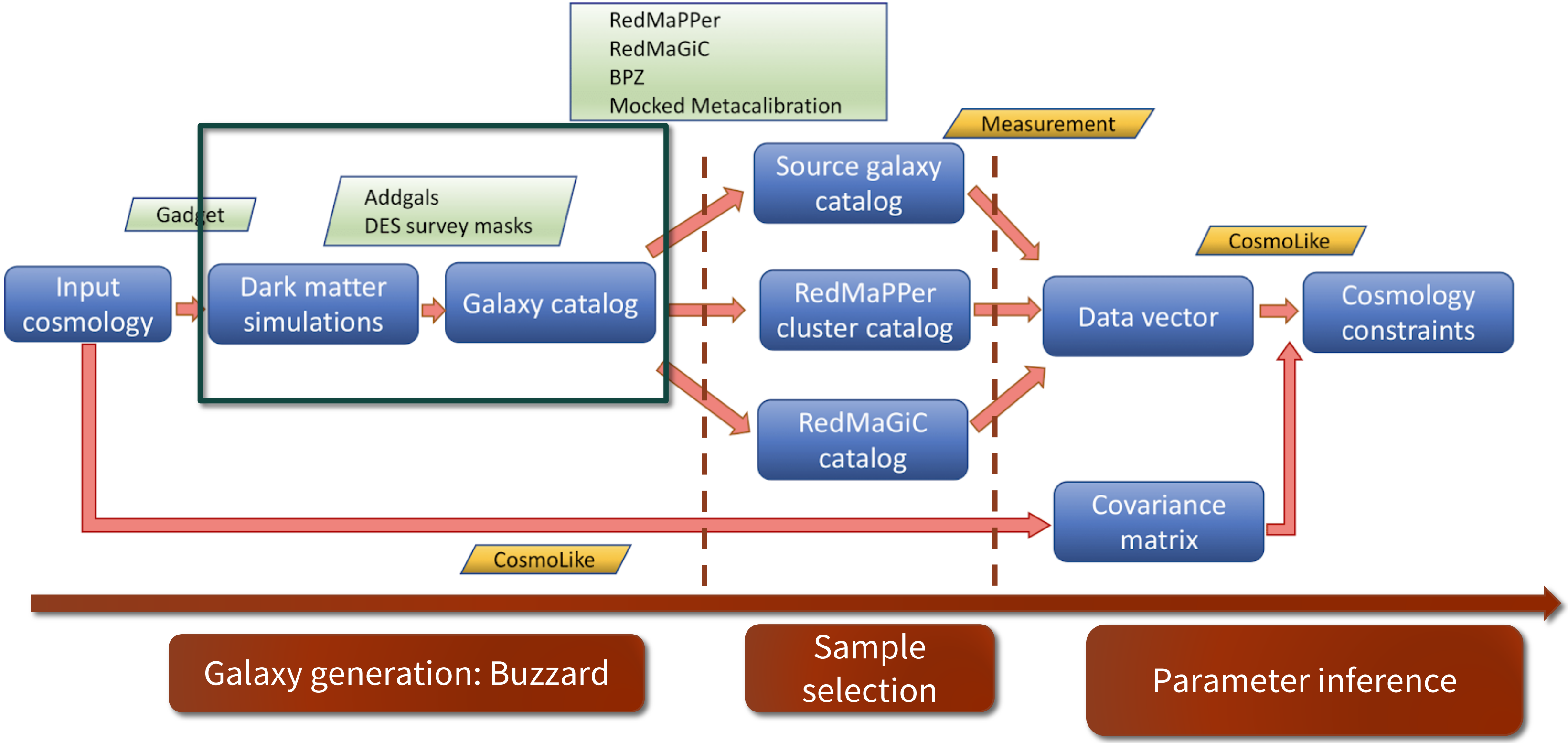
To, Krause et al. 2020a (2008.10757)

- Philosophy:
  Simulated galaxy catalogs are treated as plausible universes

End-to-end simulation tests

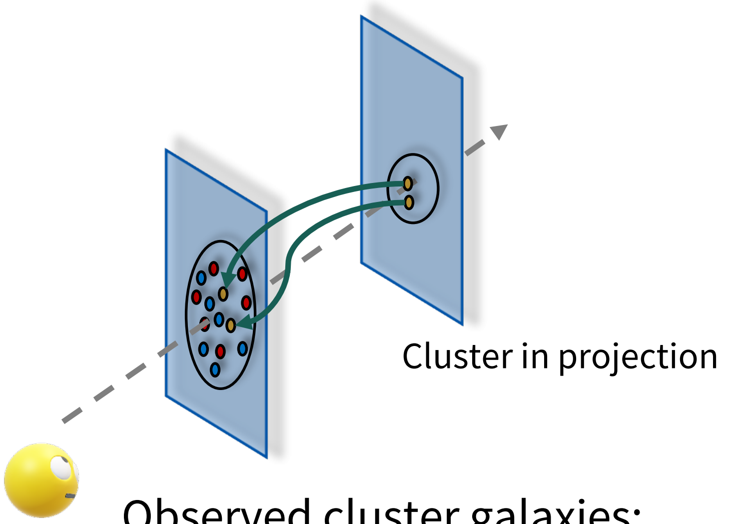


End-to-end simulation tests



Simulation setups

- The projection effect is one of the most important systematics for optical cluster cosmology.

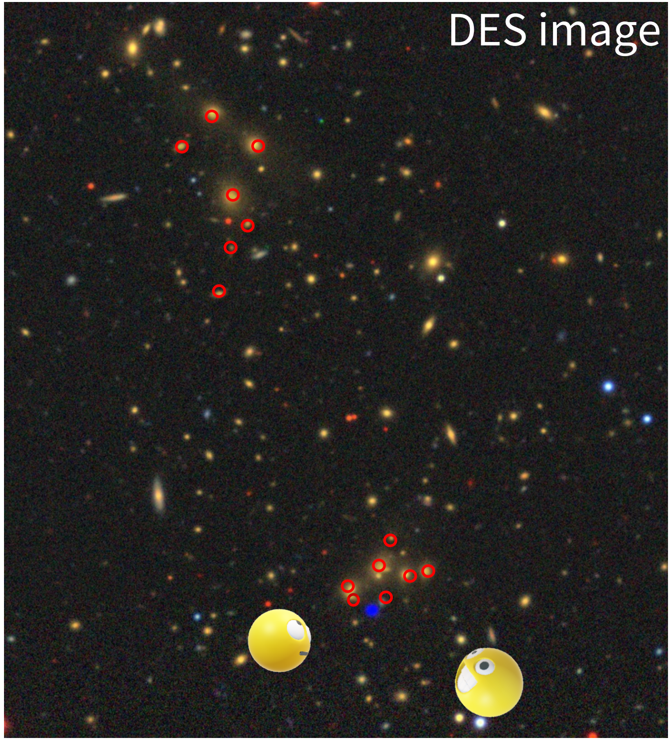


Observed cluster galaxies:

Real cluster galaxies +

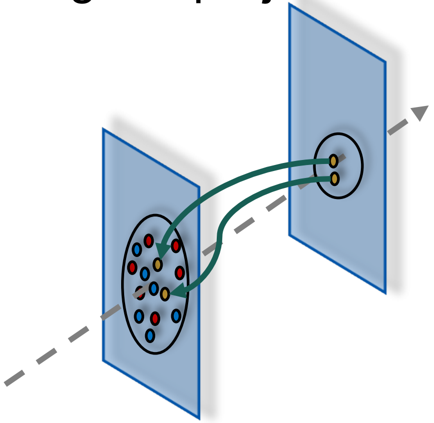
projected galaxies from other clusters +

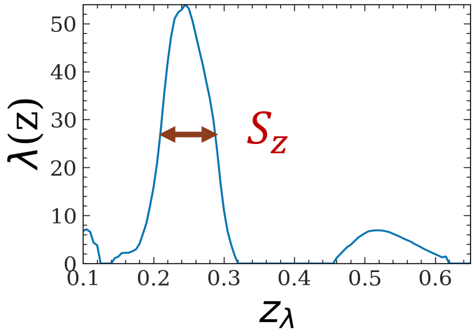
randomly projected galaxies



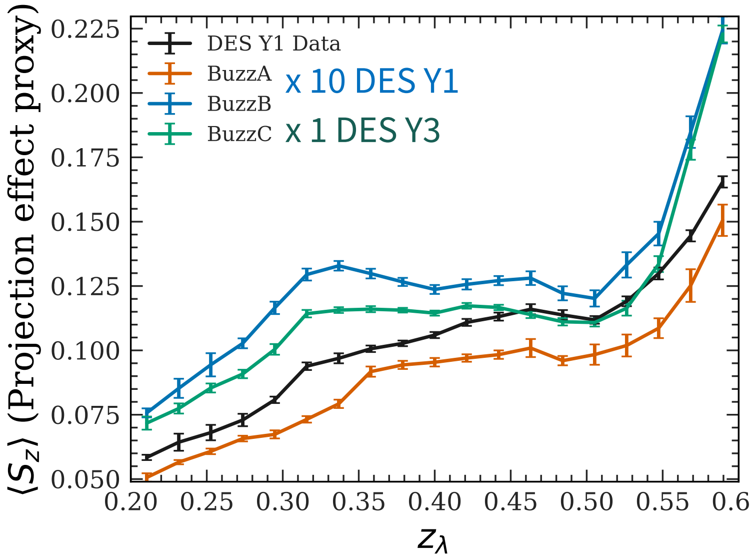
Simulation setups

- We create special versions of the Buzzard simulation.
  → The range of projection effects in simulations well spans the data.





BuzzA: least amount of projection
BuzzB: largest amount of projection



Large-scale selection effect biases in simulations

- Selection effect bias (b_{sel}):
  - Existence of correlations between richness and large-scale correlation functions at a fix cluster mass leads to an addition bias.

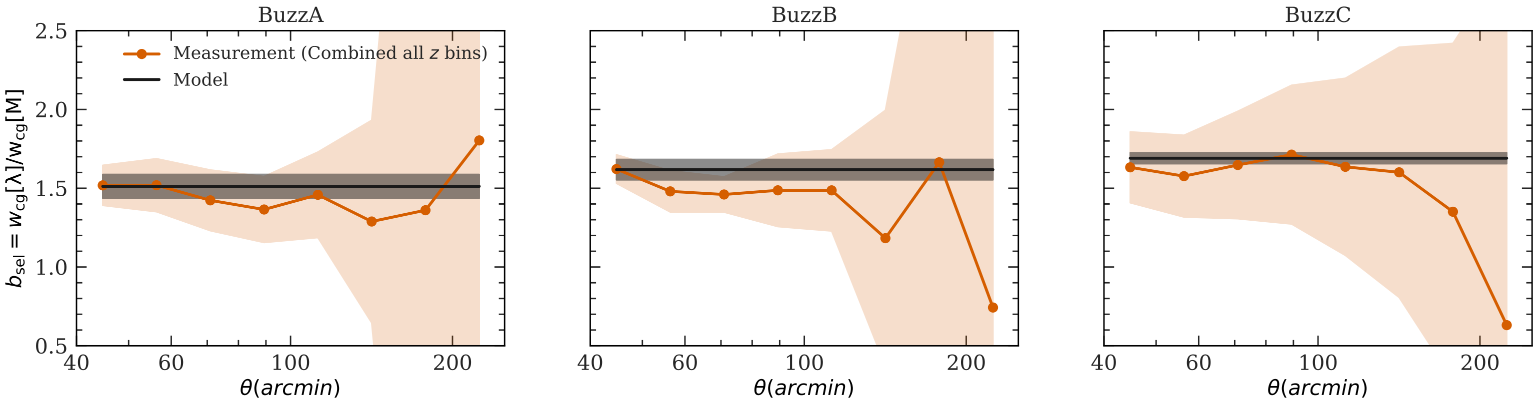
- Measurement in simulation:

  b_{sel} = redMaPPer clusters x galaxies / random halos x galaxies

Large-scale selection effect biases in simulations

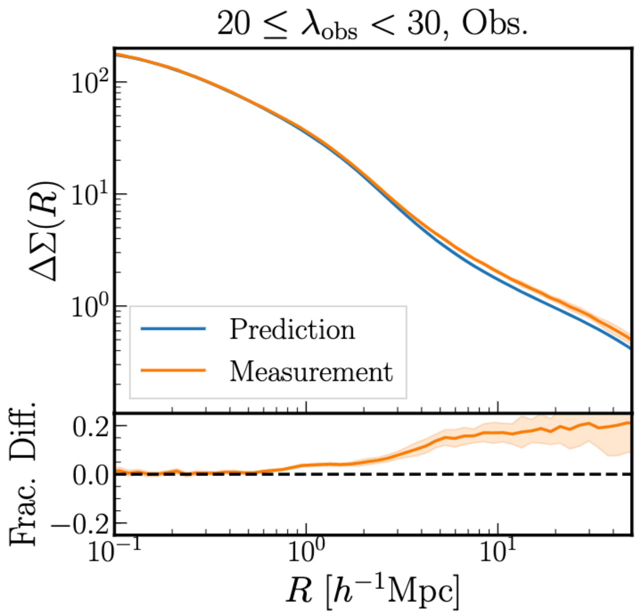
- On large scale, b_{sel} is scale independent.
  - ➢ Relatively simple model: normalization and mass dependence [2 free parameters]

$$b_{sel} = b_{s0} \left(\frac{M}{M_{piv}} \right)^{b_{s1}}$$



Large-scale selection effect biases in simulations

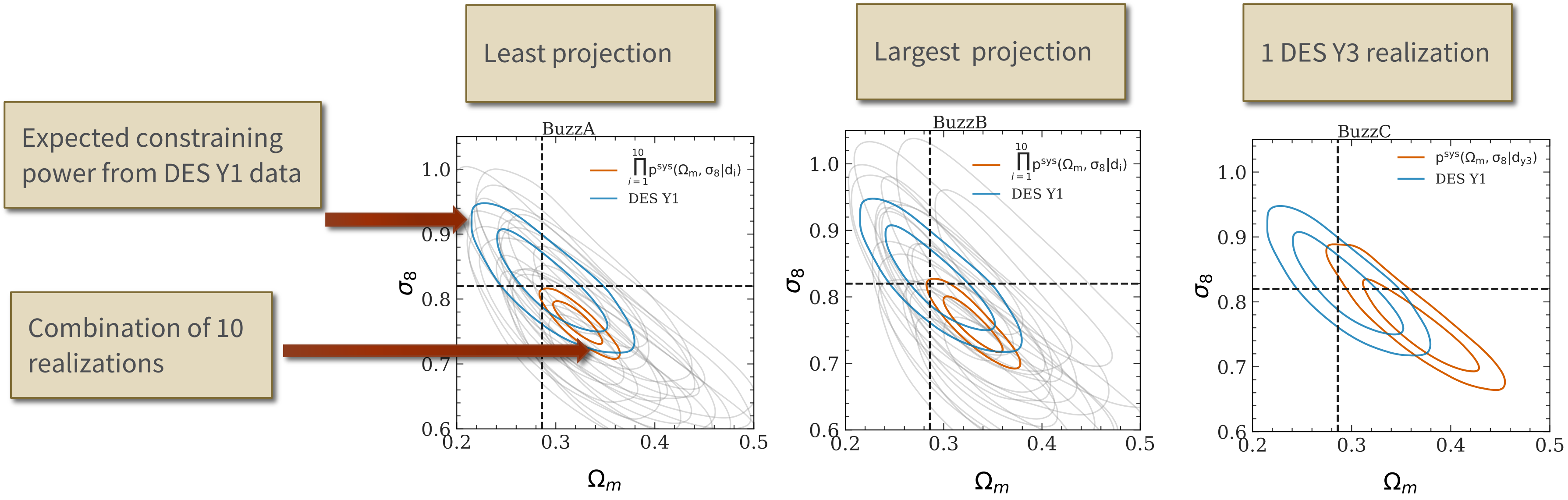
- On large scale, b_{sel} is scale independent.
  → Independently confirmed by other work.
  [different simulation/ different analysis]



Sunayama+ 2020

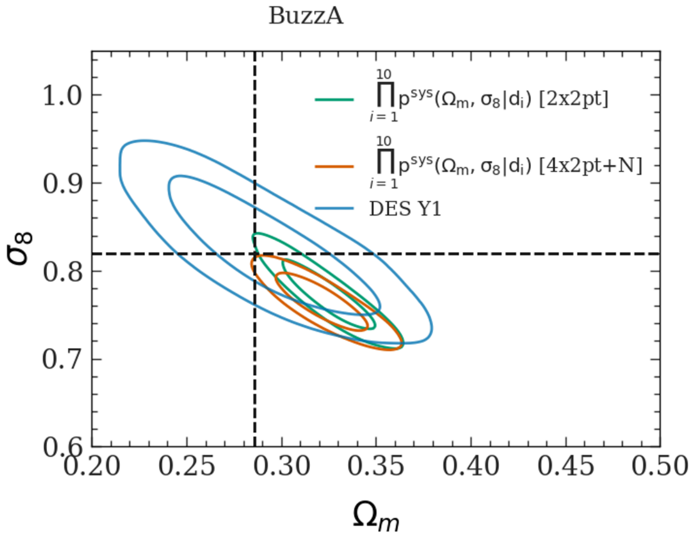
Simulation validation

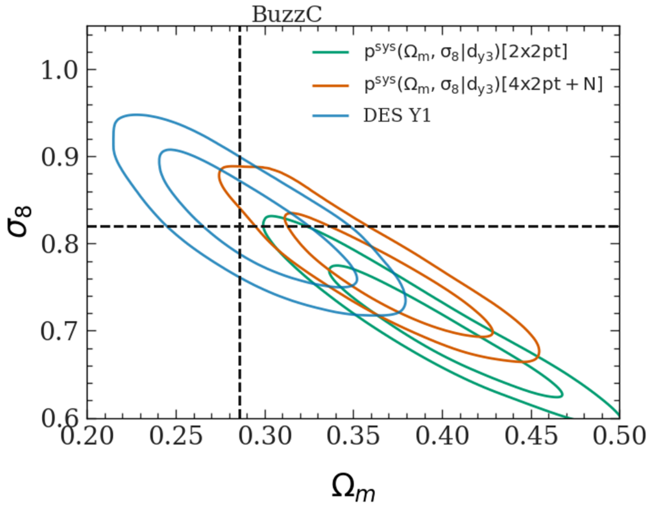
- No significant systematics in the cosmological parameter inferences at DES Y1 accuracy. (Null hypothesis with p-value=3.8%, 7.1% and 2.6% in BuzzA, BuzzB, BuzzC respectively.)
  - ➢Note that different versions (BuzzA and BuzzB) of the Buzzard simulation have the same dark matter distributions → cosmic variances are correlated.



Simulation validation

- Whether the 2σ level discrepancy is due to flaws in the cluster analysis?
  - ➢ 2x2pt (galaxy clustering + galaxy–galaxy lensing) analyses are performed on BuzzA and BuzzC.
- 2x2pt and cluster analysis are consistent
  → The deviation does not come from flaws in the cluster analysis.



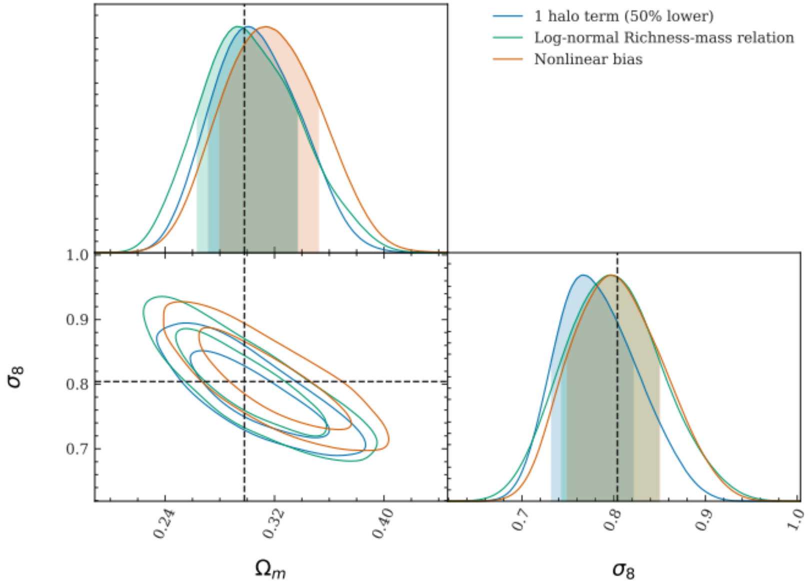


Simulated Likelihood Analysis

- Analyzing systematic-contaminated theory data vector.
- Systematics:

1. Cluster lensing one-halo term is 50% lower than the expected value (DES Collaboration 2020.)
2. Non-linear bias.
3. Functional form of the richness-mass relation.

→ Results robust against these systematics

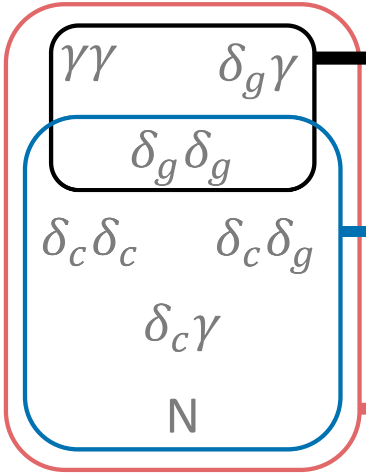


Application on the DES-Y1 data

To, Krause et al. 2020b (in prep.)

- Blind analysis: parameters were randomly shifted during the analysis.

Applications on the DES-Y1 data



3x2pt:

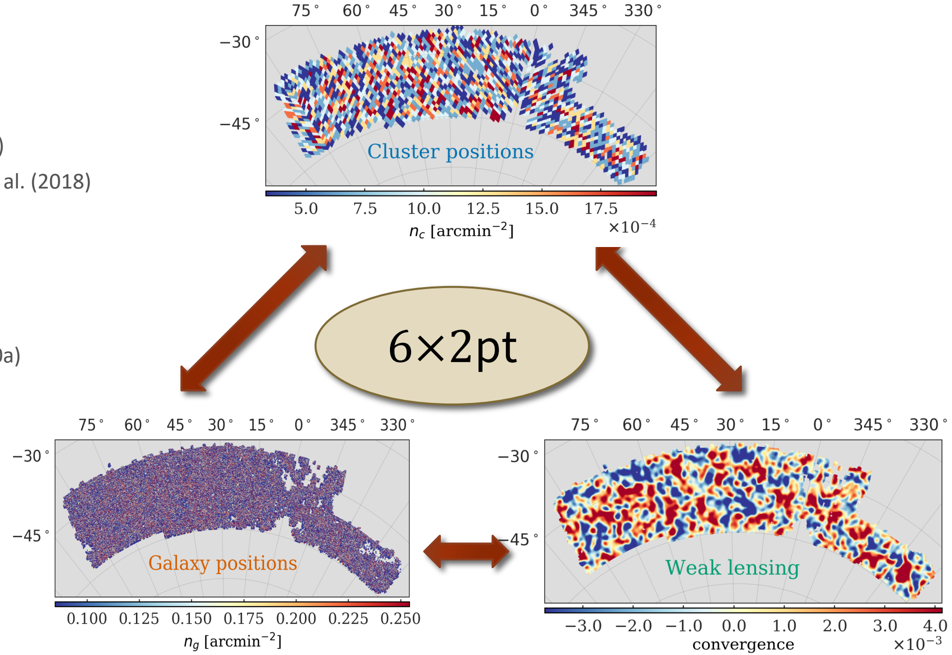
- Method: Krause&Eifler et al. (2017)
- Simulation: MacCrann&DeRose et al. (2018)
- Results: DES Collaboration (2018)

4x2pt+N:

- Method: To&Krause et al. (2020a)
- Simulation: To&Krause et al. (2020a)
- Results: **This work**

6x2pt+N:

- Results: **This work**



Applications on the DES-Y1 data: Cluster cosmology

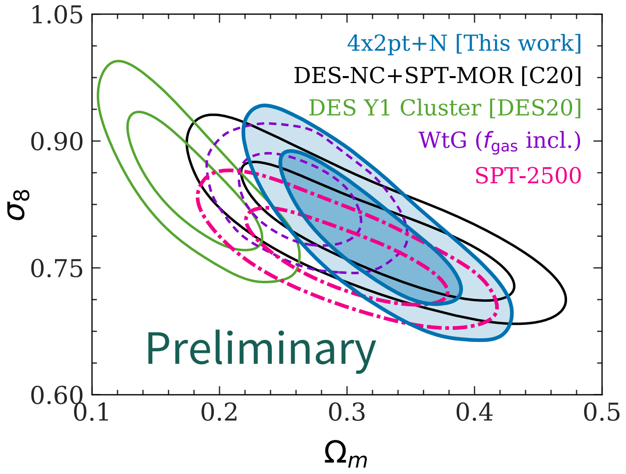
- Our cluster cosmology approach yields competitive cosmological constraints, despite the smallest survey volume.

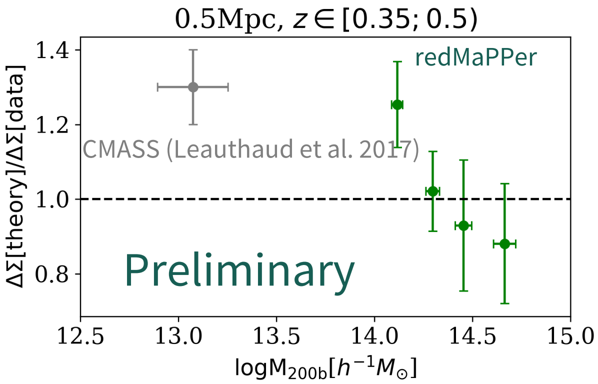
- Comparison between 4x2pt+N and DES Y1 cluster:

  → Modeling of cluster lensing one-halo term is problematic:

  - ❖ Systematics? Or unknown physics?

  → Maybe connected to the "lensing-is-low" problem in CMASS galaxies.





Applications on the DES-Y1 data

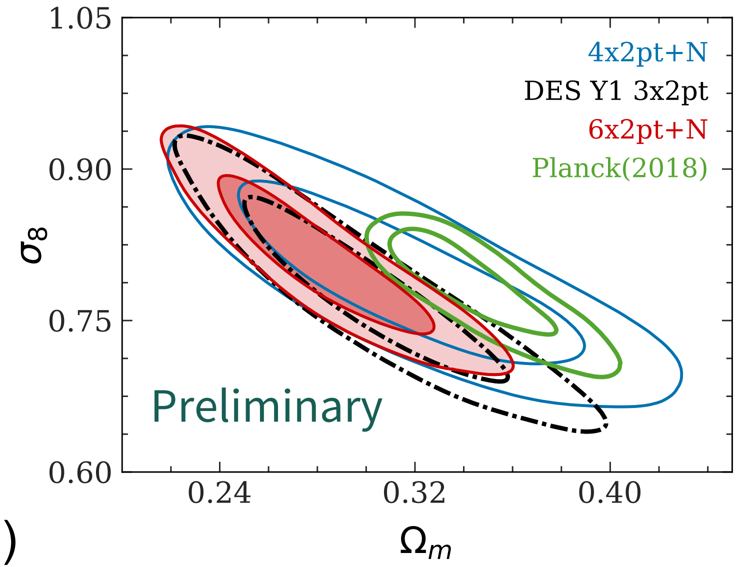
- Cluster analysis and 3x2pt analysis are in tension at 0.024σ

  → strong consistency.

- First joint analysis of cluster abundance and clustering + weak lensing + galaxy clustering in a photometric survey.

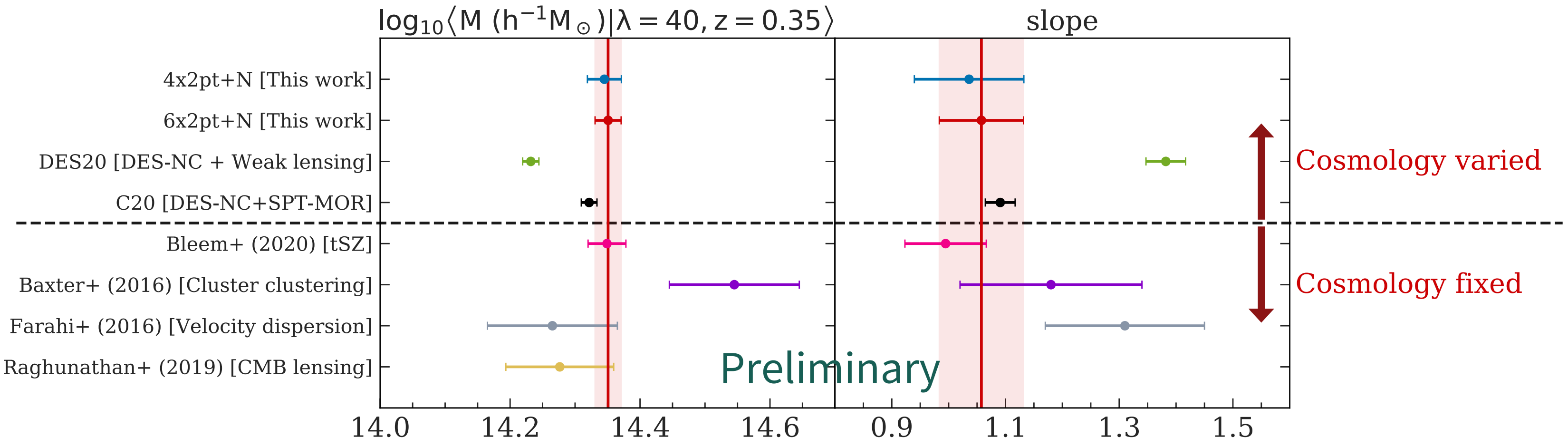
  → 20% improvements on σ_8 and Ω_m.
  → P-value: 0.084 (Good χ^2 with 2xdata)

- Tension between 6x2pt+N and Planck: 1.42σ → No evidence for inconsistency.



Applications on the DES-Y1 data

- Combining clusters with galaxy clustering + weak lensing yields competitive constraints on cluster mass–observable scaling relations.



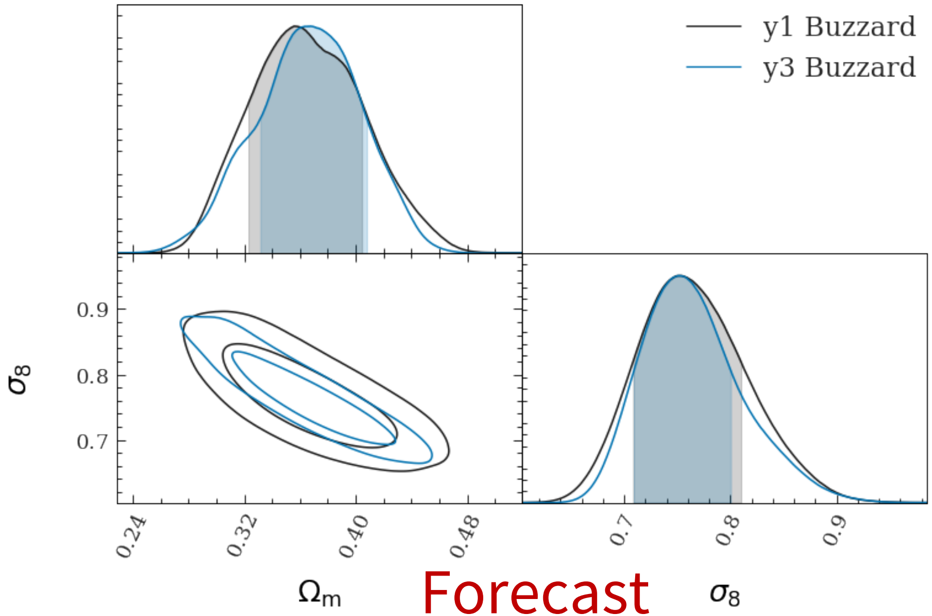
Outlook

Krause, To et al. 2020c (in prep.)

Outlook

If we don't modify the model/scale cut/redshift range:

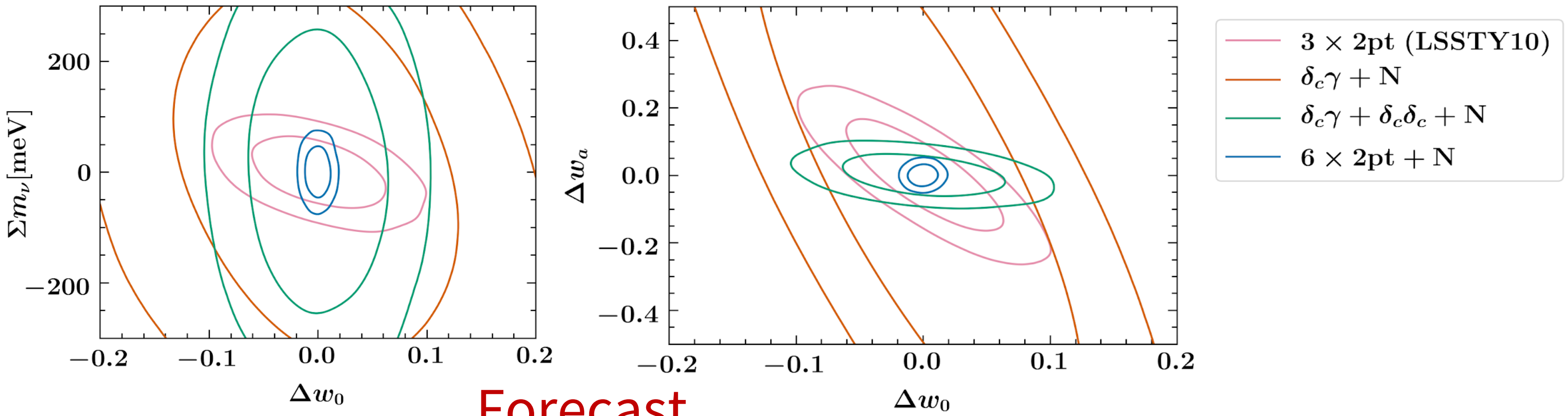
The area of the one sigma contour on Ω_m and σ_8 will decrease by 44% in up-coming DES-Y3 analysis.



Forecast

Outlook

- The developed method is not limited to optically selected galaxy clusters:
  - ➢ For example: LSST Y10 x CMB S4 galaxy clusters.



Forecast

Krause, To et al. 2020c (in prep.)

Conclusion

- We build a large-scale focused cluster cosmology analysis:
  - ✓ Safe from small-scale systematics (mis-centering, baryonic physics).
  - ✓ Yielding competitive cosmological constraints.
  - ✓ Relatively easy to be combined with other cosmology probes.

- We validate the pipeline on three versions of the Buzzard simulations, showing no significant systematics.

- We apply the method on the data: the **first** cosmology analysis from cluster abundance, weak lensing, and galaxy clustering.

- We find that this combination leads to improved constraints on cosmological parameters and mass–observable scaling relations.

Thanks!

Elisabeth Krause, Eduardo Rozo, Hao-Yi (Heidi) Wu, Daniel Gruen, Joe DeRose, Risa Wechsler, and the DES Collaboration