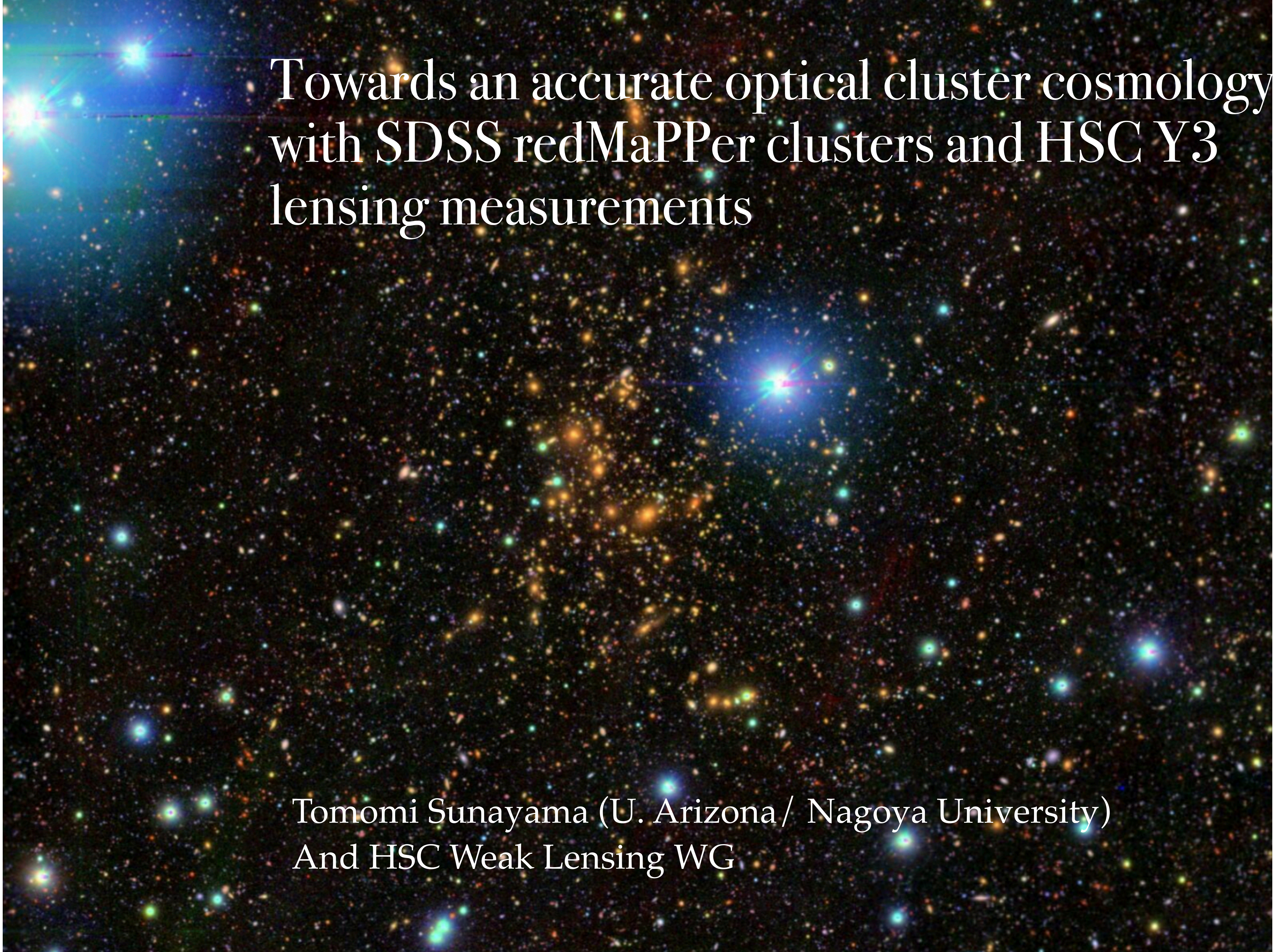
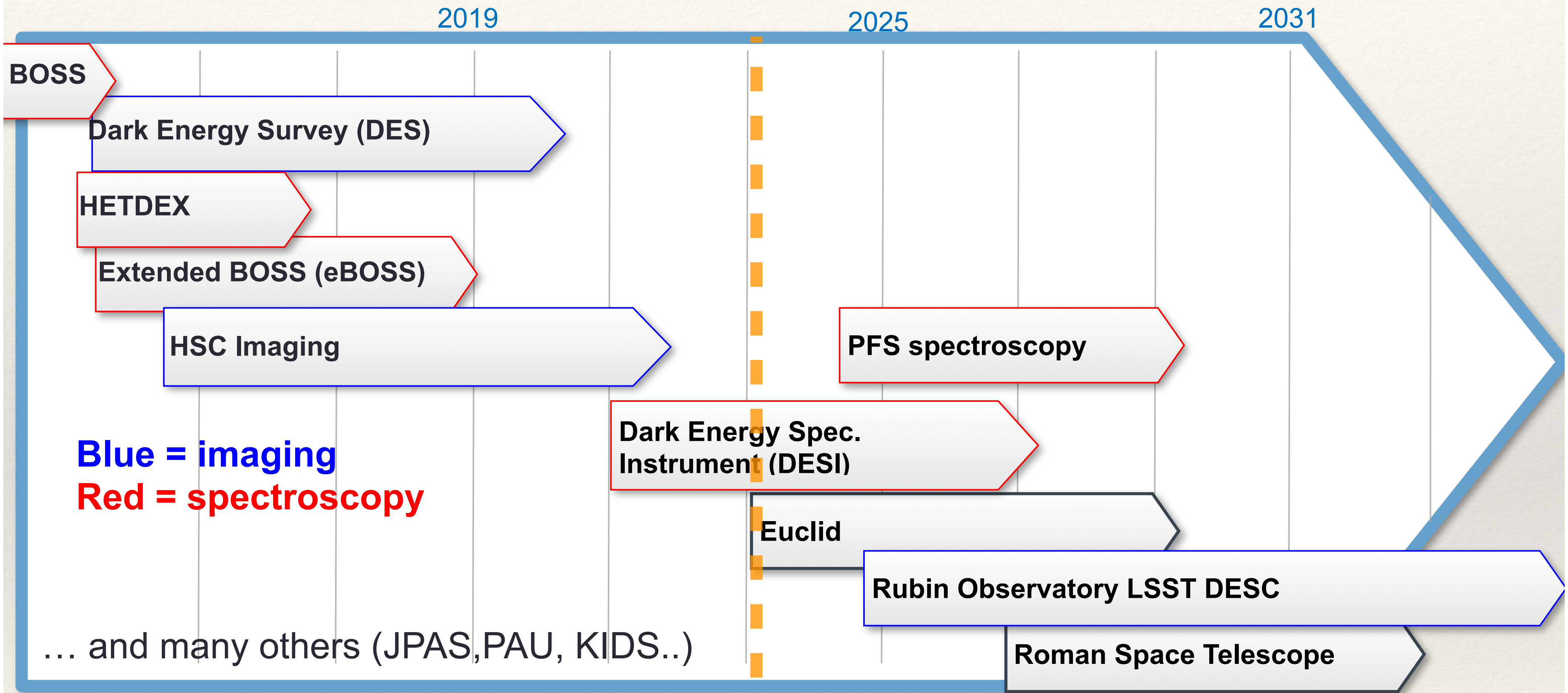


Towards an accurate optical cluster cosmology with SDSS redMaPPer clusters and HSC Y3 lensing measurements

Tomomi Sunayama (U. Arizona/ Nagoya University)
And HSC Weak Lensing WG

Era of Precision Cosmology

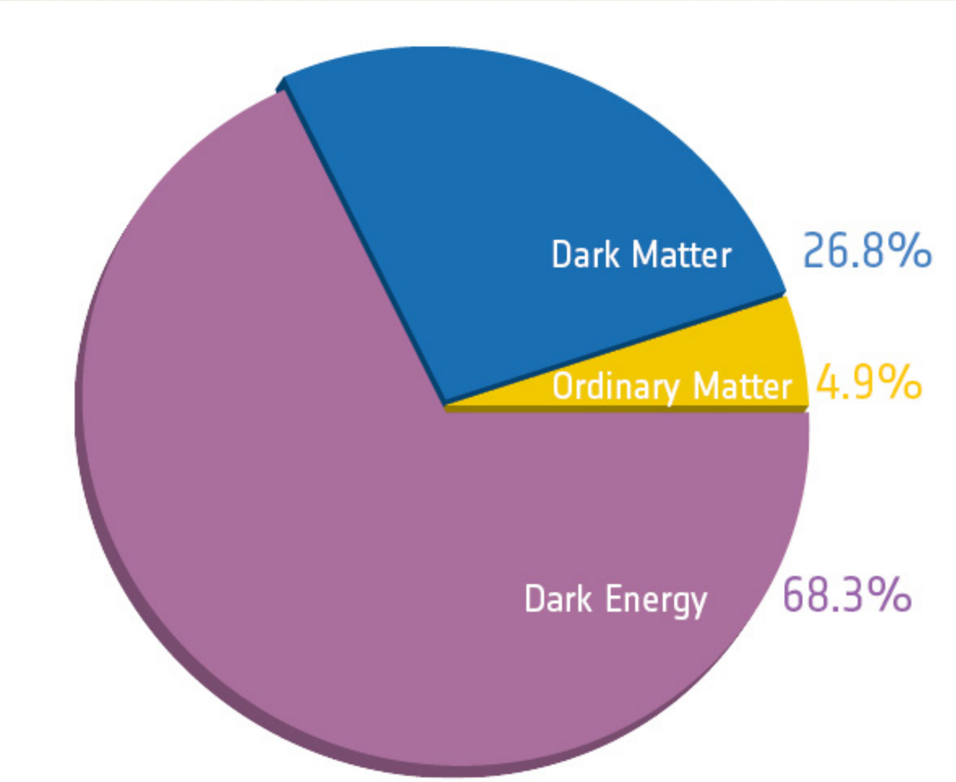


Weinberg et al, Snowmass 2013

- Current and future galaxy surveys will observe larger area and many more galaxies at higher redshift…

Standard Cosmological Model

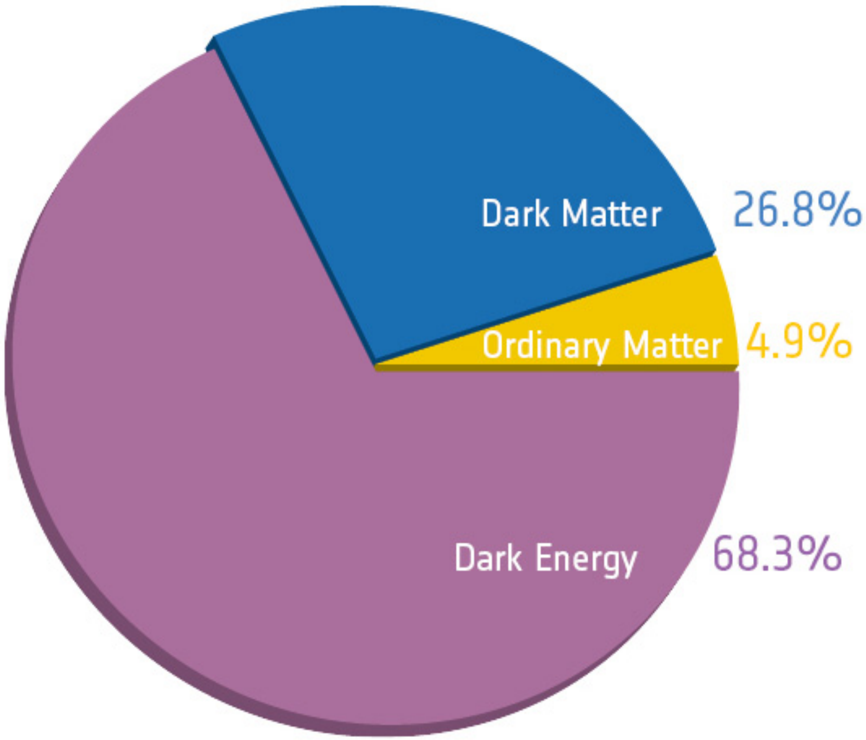
Our Universe can be explained by six parameters (ΛCDM model)



ESA / Planck

- Matter density Ω_m
- Baryon density Ω_b
- Hubble parameter h
- Cosmological constant Λ
- Initial amplitude σ_8 and slope n of power spectrum of fluctuations

Standard Cosmological Model

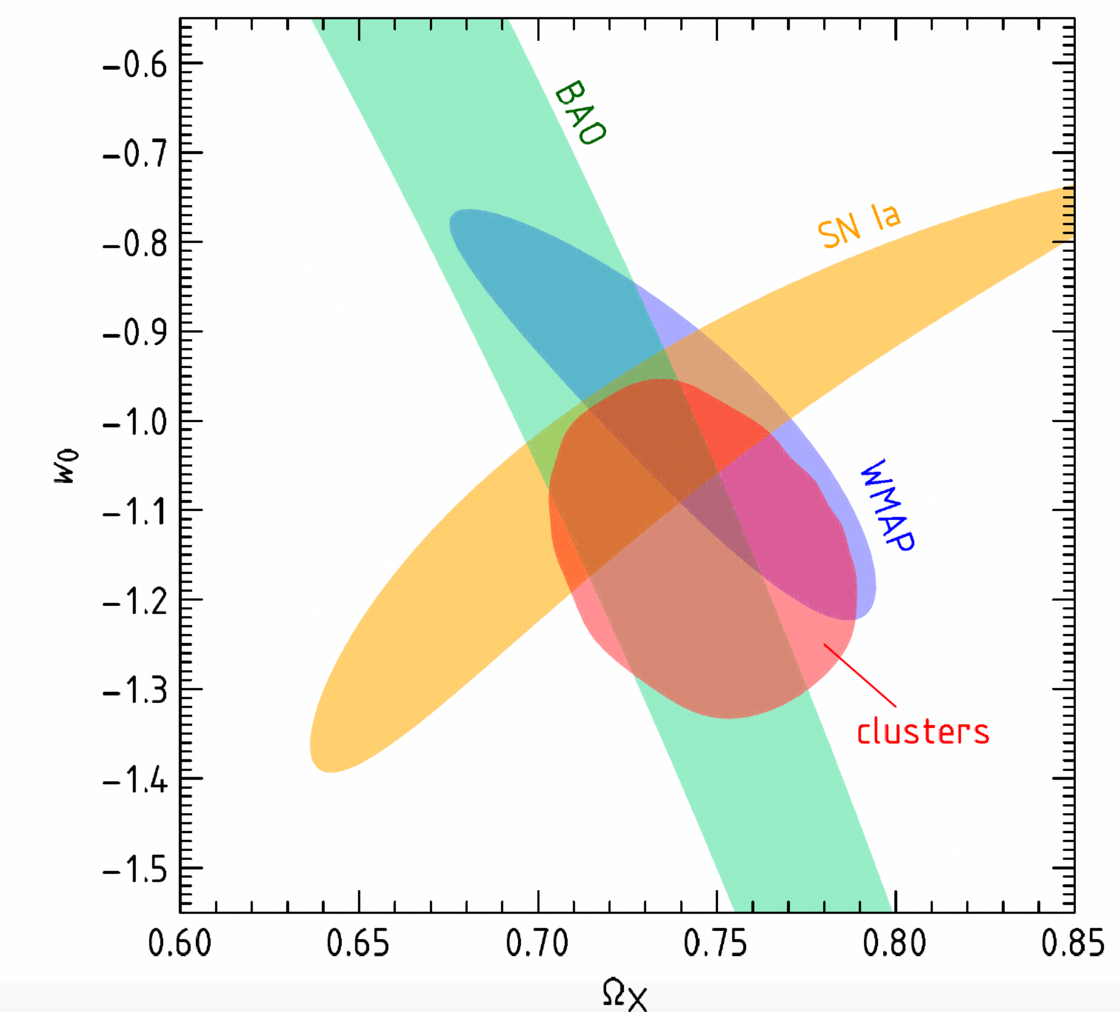


ESA / Planck

- What is the fate of the Universe? — the nature of dark energy
- What is the Universe made of? — the nature of dark matter
- How did the Universe begin? — the nature of primordial fluctuations

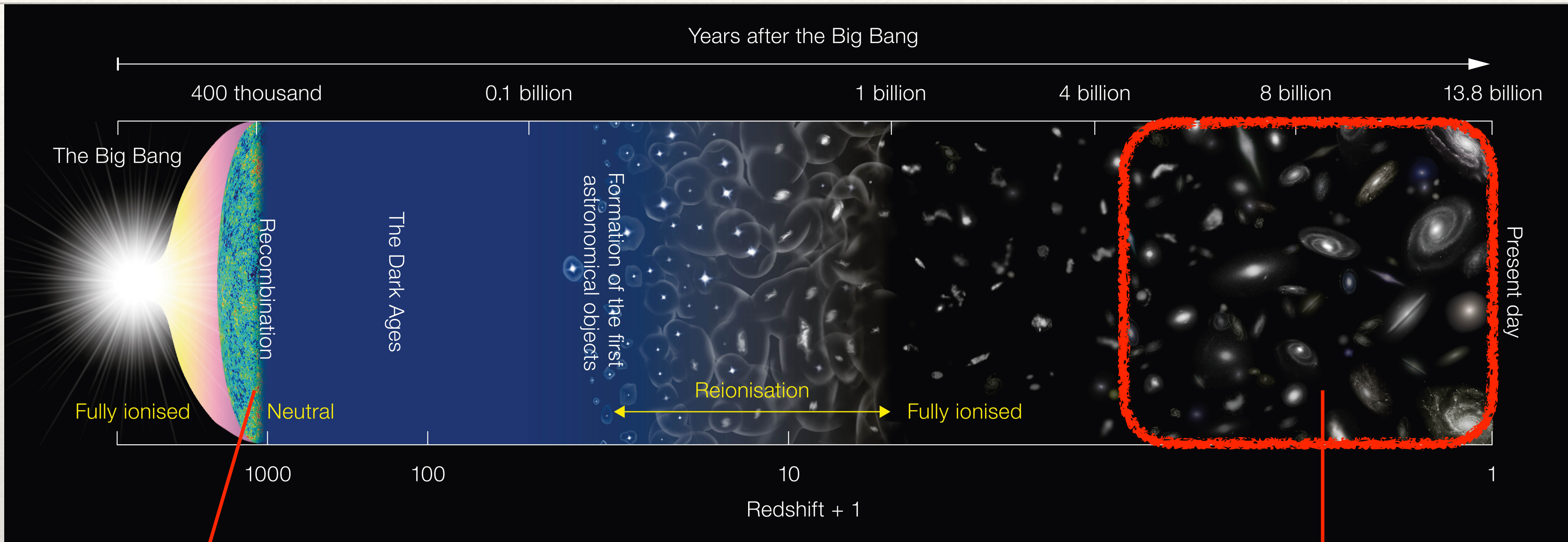
Early 2000s: Concordance Cosmology

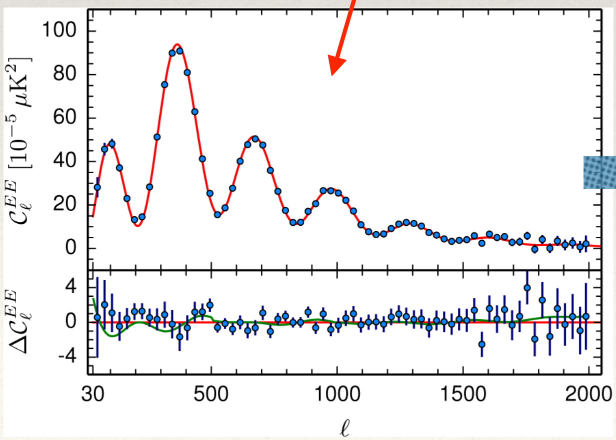
- Different CMB / LSS probes constrain cosmological parameters in a consistent manner



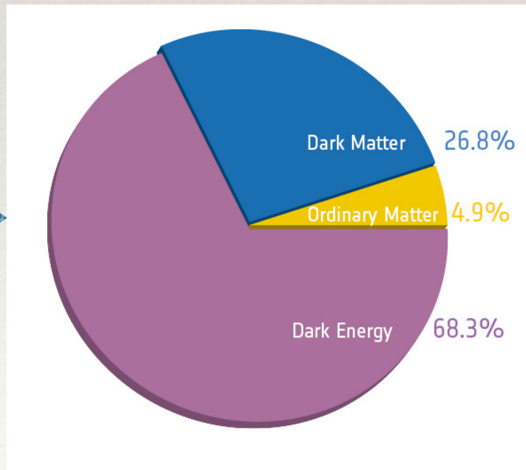
Allen+2011

Does the model describe our Universe consistently?





ESA/Planck



?

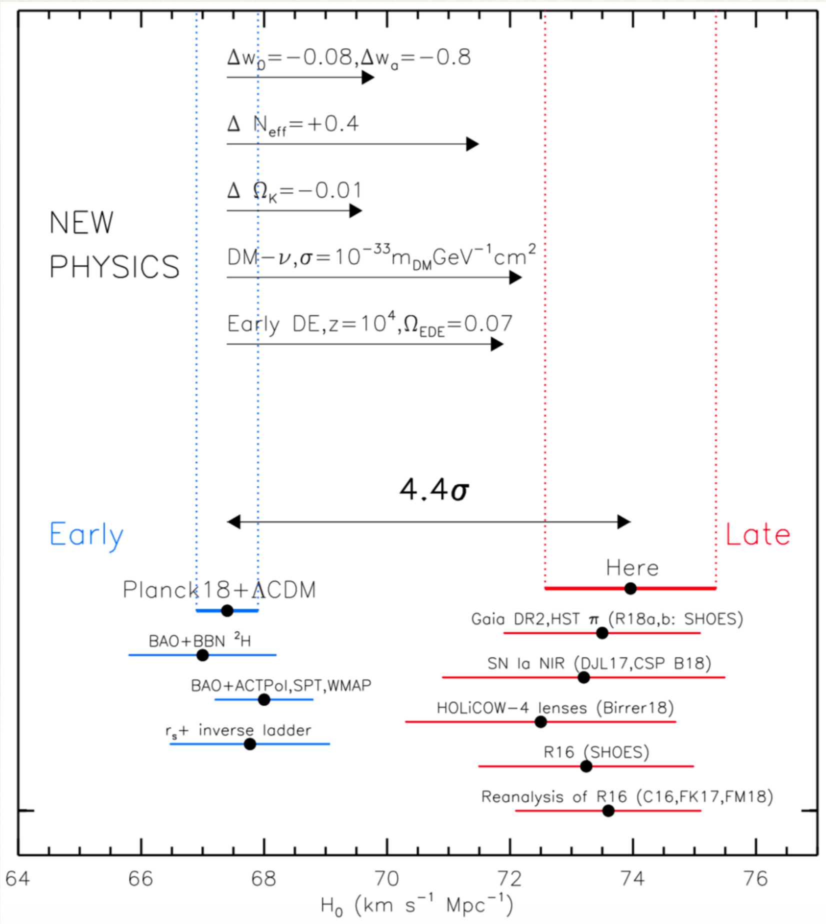
Large scale structure probes

- SNe Ia
- Gravitational Lensing
- Galaxy clusters
- Galaxy clustering

Tensions in Cosmology

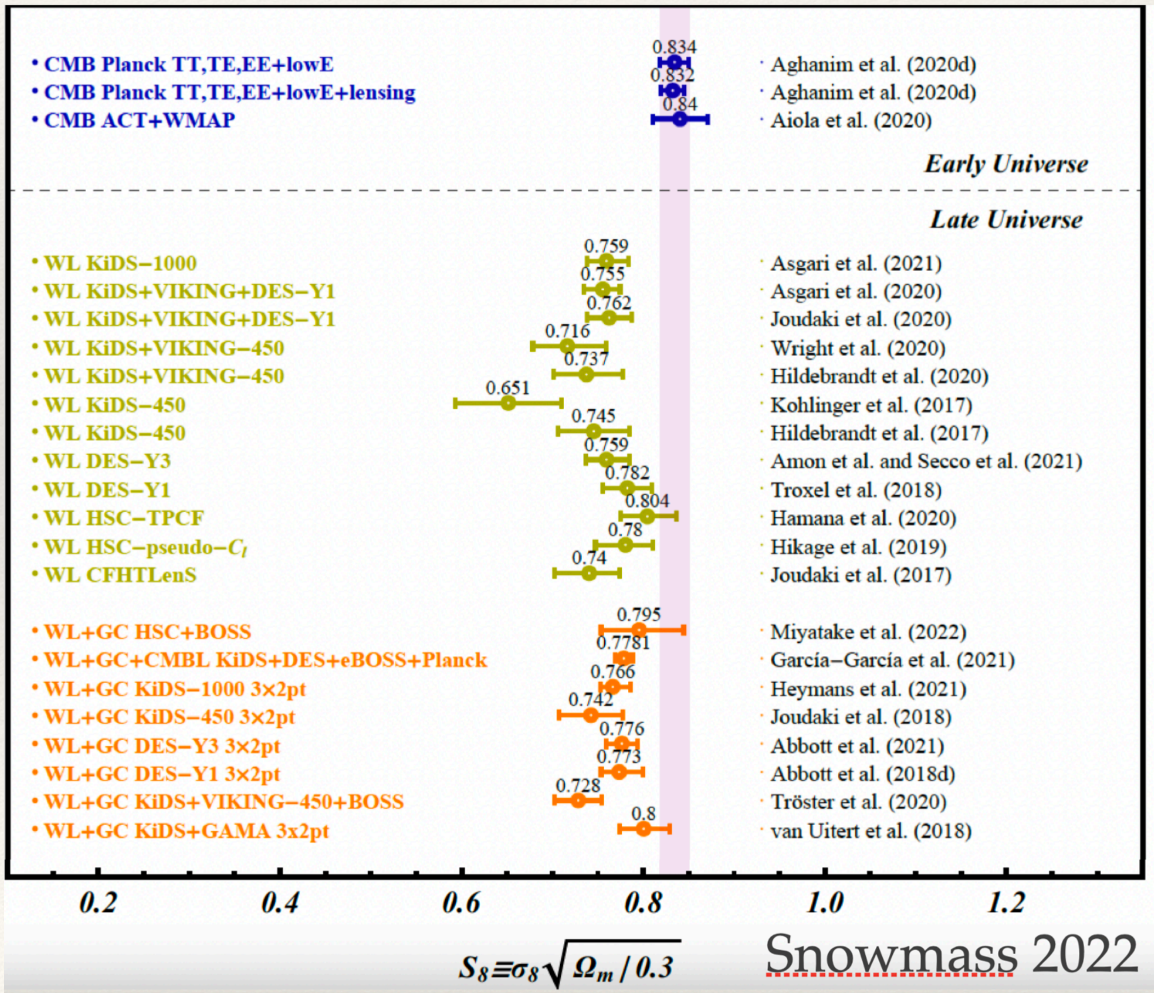
- Tensions in Hubble constant as well as S_8 ("clumpiness").

Expansion rate of the Universe



Riess+,2019

Clumpiness of the density fluctuation

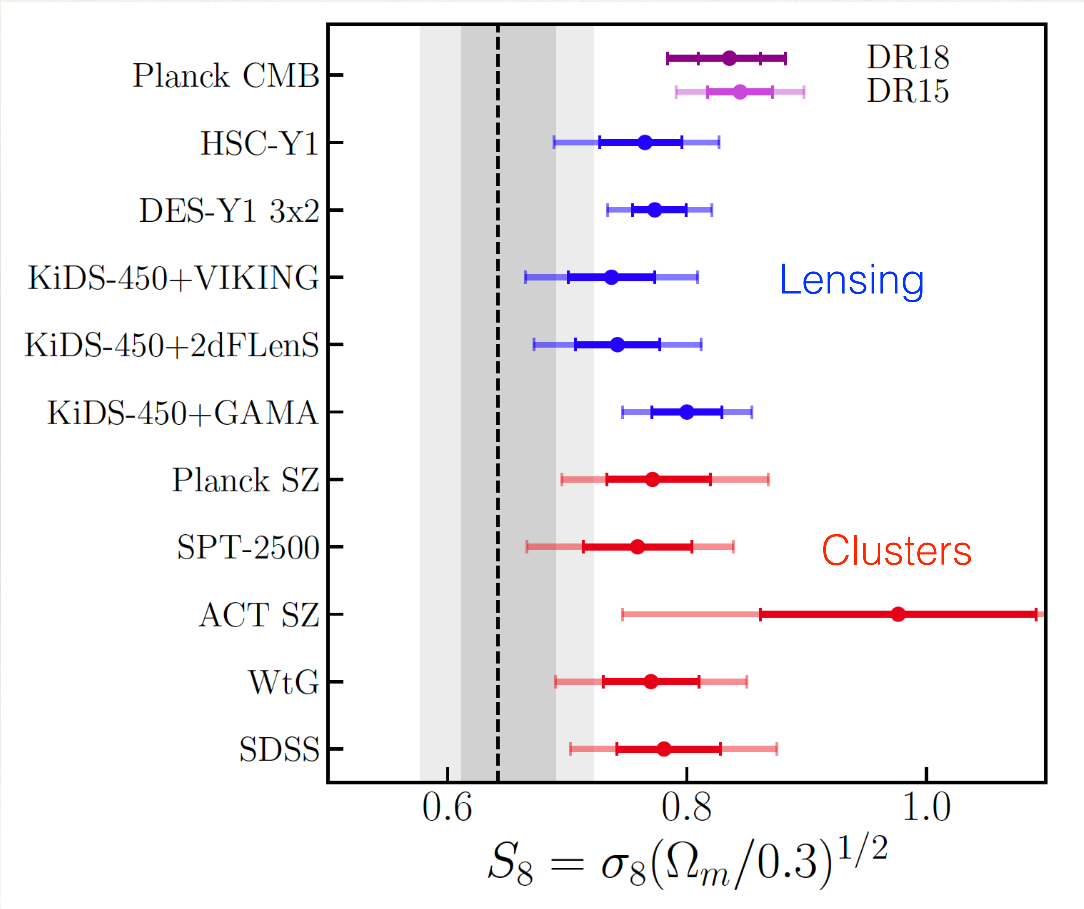


Snowmass 2022

Tension in Optical Cluster Cosmology

- DES Y1 Cluster analysis favored lower S_8 than even late-Universe probes

Clumpiness of the density fluctuation

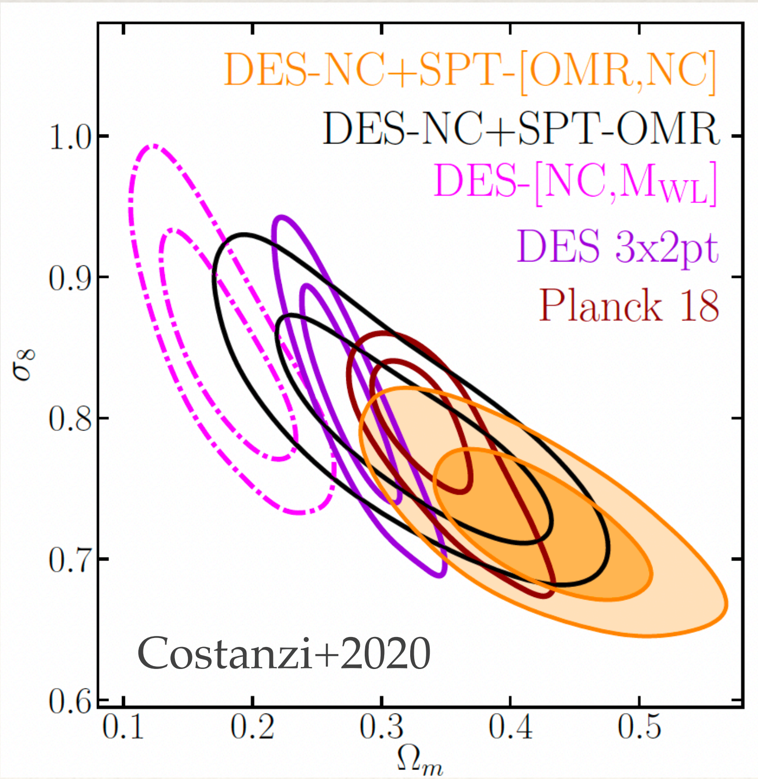


DES Y1 Cluster, 2020

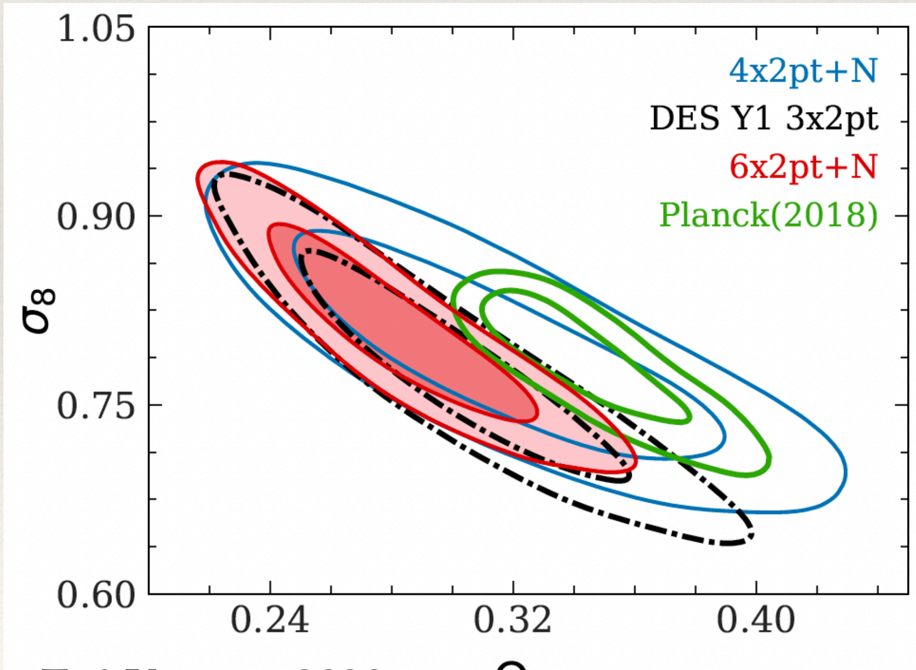
Are optical clusters a good cosmological probe?

- Adding extra data sets to optical clusters give more consistent cosmological result with other probes
- Can we do cluster cosmology only using optical clusters?

Optical + SZ clusters



Clusters + galaxies



To&Krause+2020

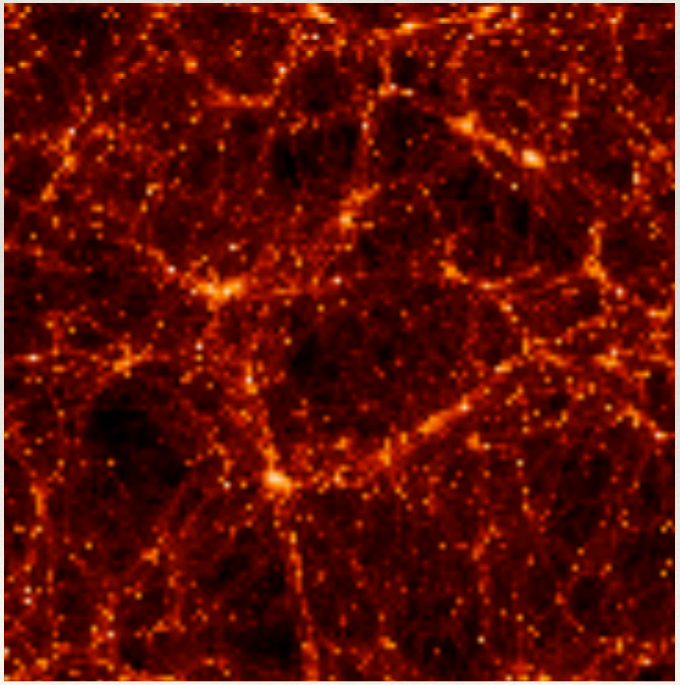
Outline

- (Optical) Clusters as a cosmological probe
- How can we mitigate the issue in optical cluster cosmology?
    - Full-forward modeling of cluster observables
- Cluster Cosmology with SDSS redMaPPer clusters and HSC-Y3 data

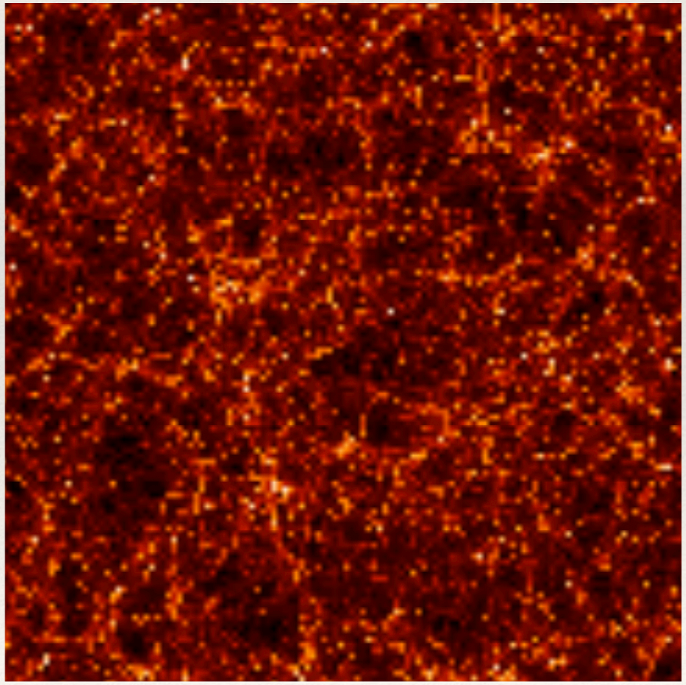
Clusters as a cosmological probe

- Count the number of clusters
- Tail of halo mass function (i.e., number of clusters) is sensitive to cosmological parameters

With Dark Energy



Without Dark Energy



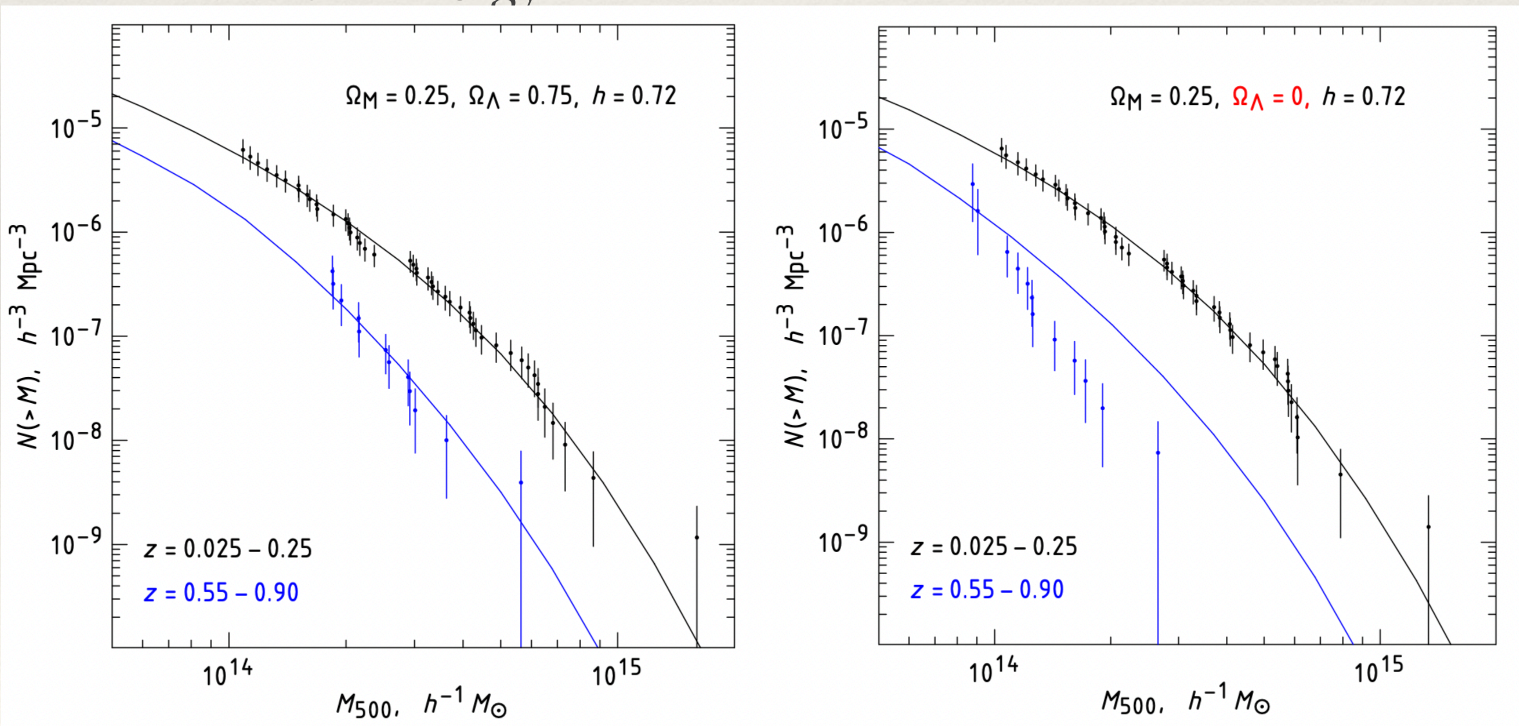
Virgo consortium

Clusters as a cosmological probe

- Count the number of clusters
- Tail of halo mass function (i.e., number of clusters) is sensitive to cosmological parameters

With Dark Energy

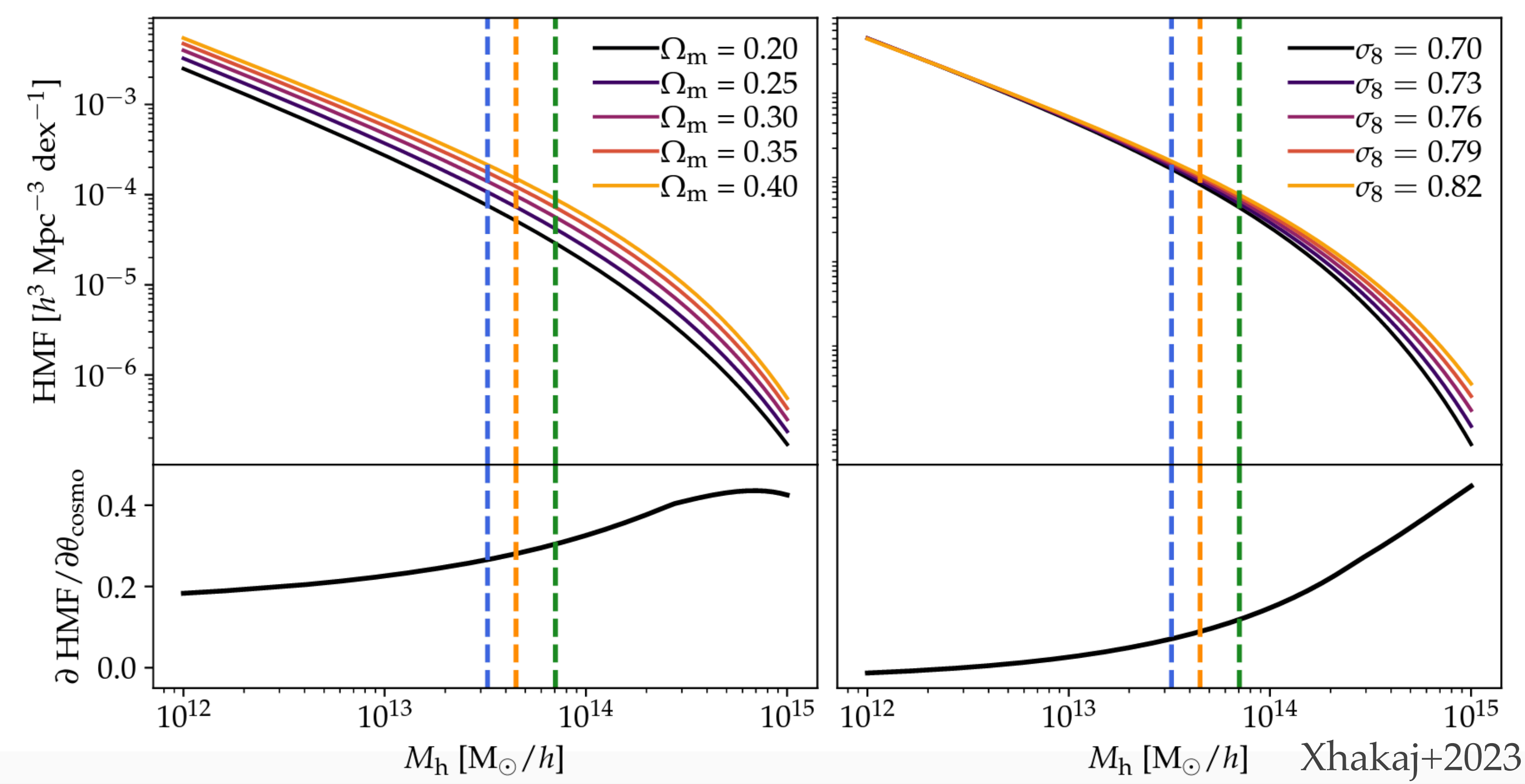
Without Dark Energy



Vikhilinin et al., 2009

Clusters as a cosmological probe

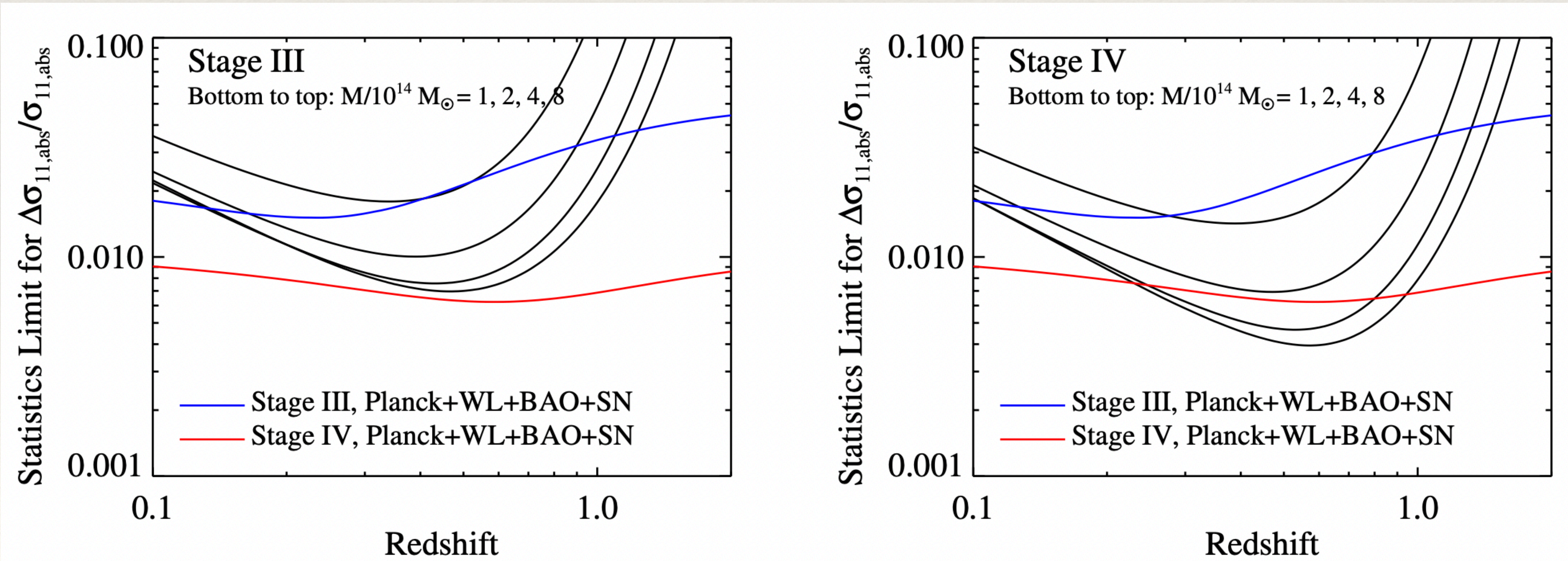
- Background cosmology (i.e., Ω_m) impacts both the number density & evolution
- Clusters form from the highest density peaks in the initial density field
- σ_8 (="clumpiness"): higher σ_8 → more high-density peaks → more clusters



Xhakaj+2023

Clusters can be statistically competitive with other probes…

- Cosmic Visions Report (2016): " The number of massive galaxy clusters could emerge as the most powerful cosmological probe

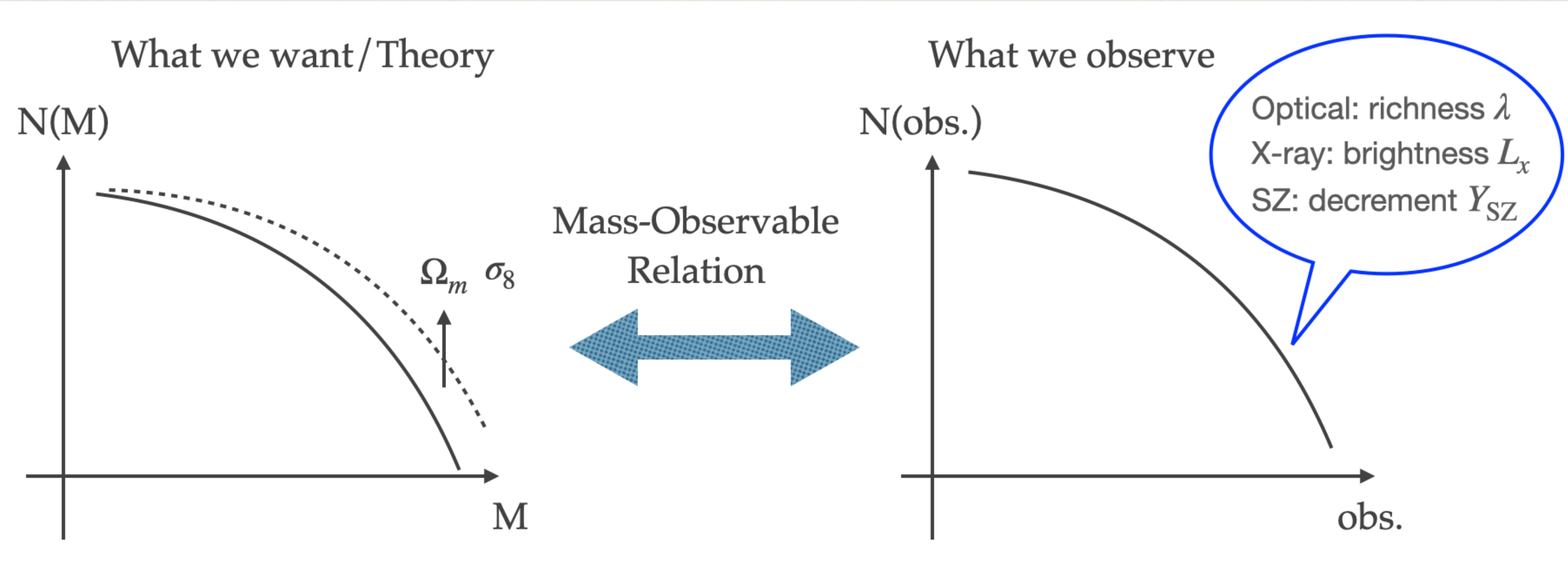


Snowmass2013; Huterer et al.

Challenge in Cluster Cosmology

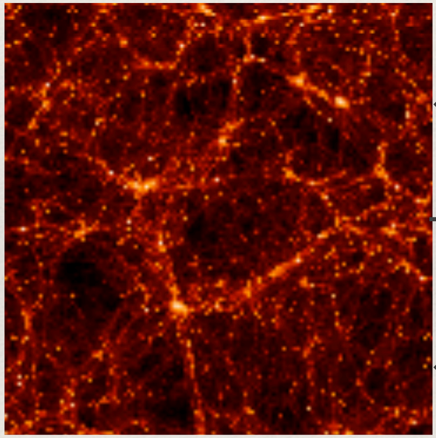
- Cosmic Visions Report (2016): " The number of massive galaxy clusters could emerge as the most powerful cosmological probe if the masses of the clusters can be accurately measured."

- Cluster mass is not a direct observable

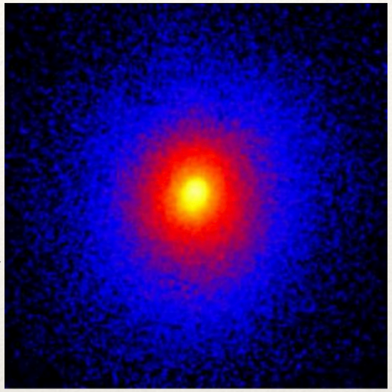


Challenge in Cluster Cosmology

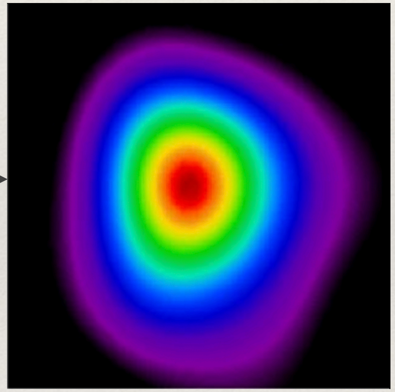
Theory: N-body



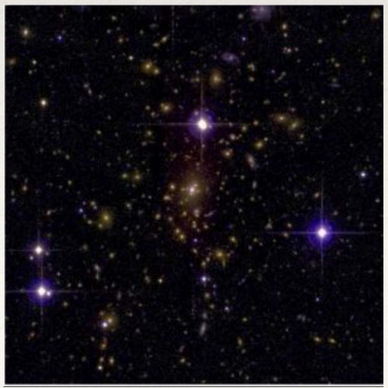
Millennium-II



X-ray
- X-ray brightness (L_x)
- High purity and completeness
- Scatter in mass-L_x
- Mass limit increases with redshift



CMB: Sunyaev-Zel'dovich (SZ) Effect
- SZ decrement (Y_{SZ})
- Redshift independent mass selection threshold
- Limited to massive clusters



Optical
- Number of galaxies (=richness λ)
- High completeness, to relatively low masses
- Susceptible to correlated structure
- Mass measurement from lensing comes free

Small

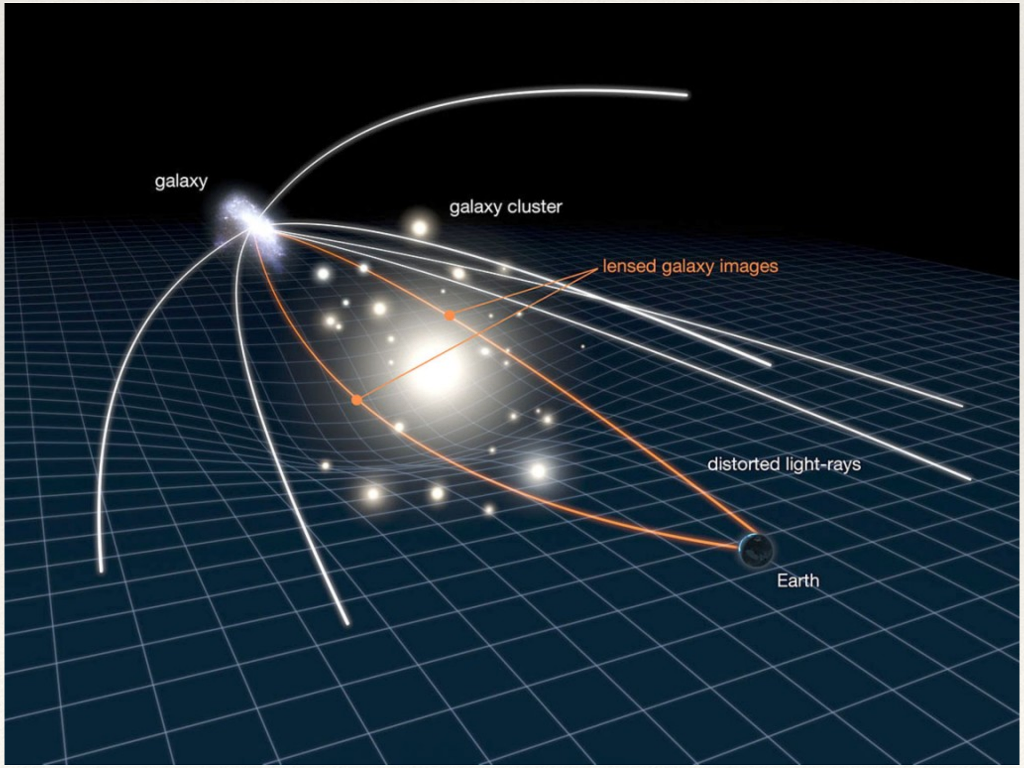
Systematics

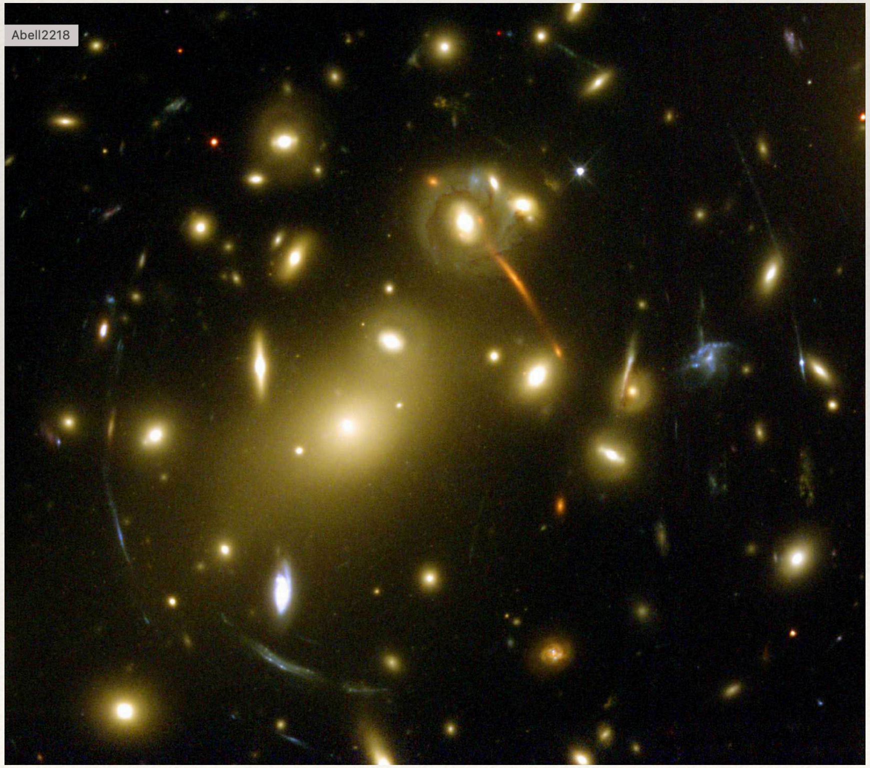
Large

Allen et al., 2011
Mantz et al., 2010

Gravitational Lensing

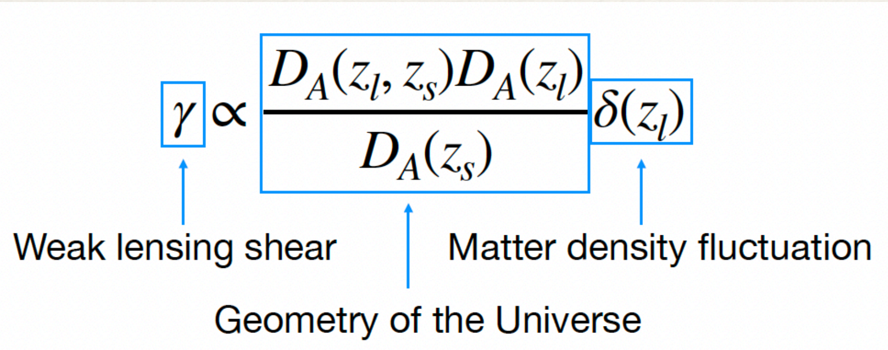
- Gravitational potential due to clusters (=“lens”) bend the light from distant galaxies (=source galaxies) and distort the image of galaxy shapes.

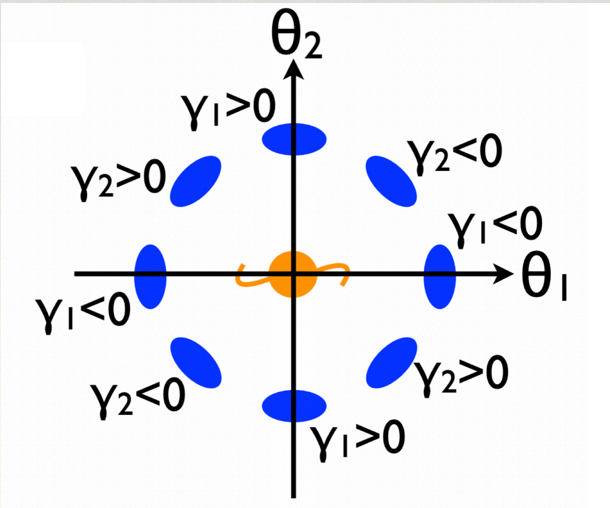


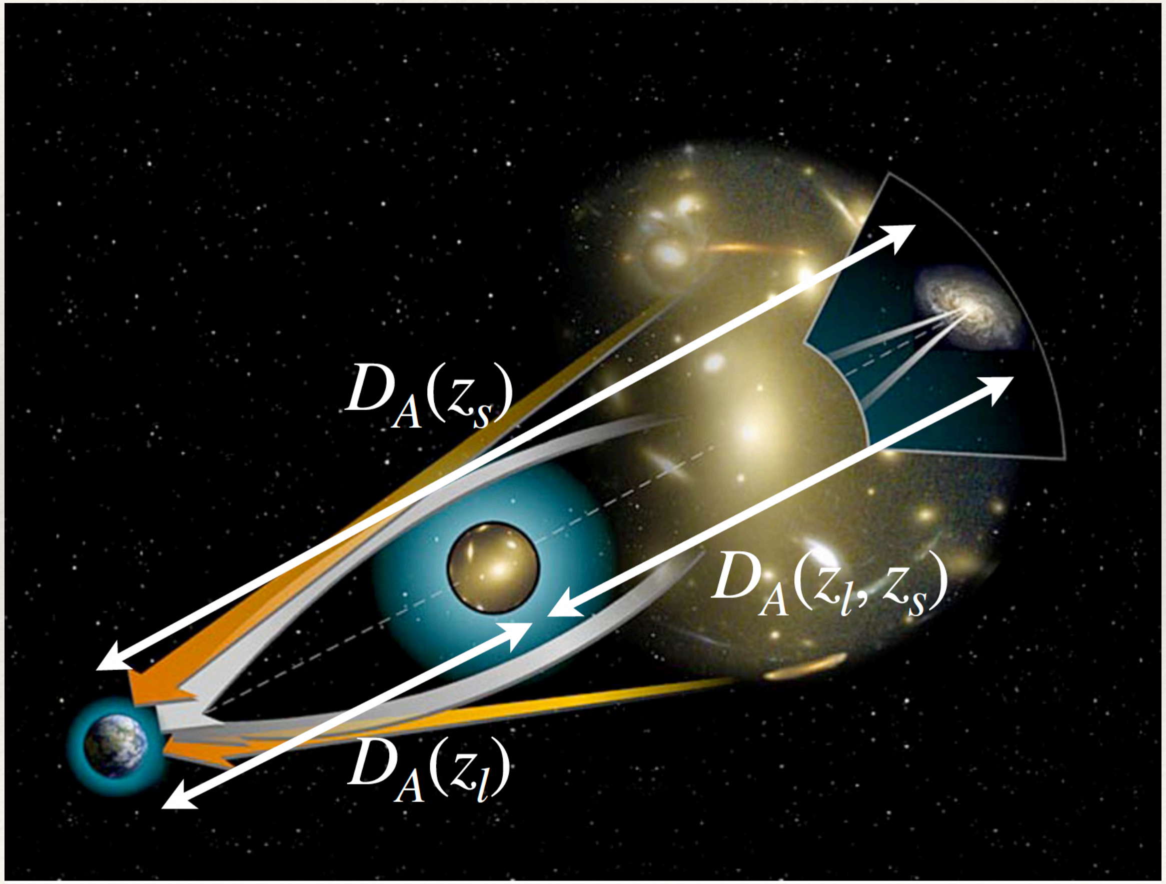


Weak Gravitational Lensing

- Through gravitational lensing, we can infer mass of clusters.

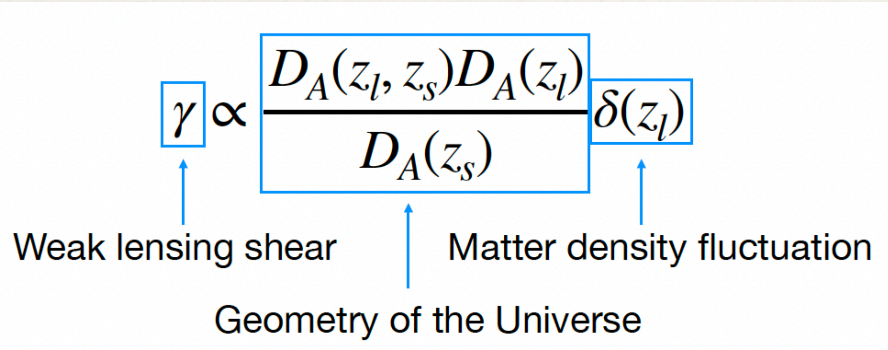


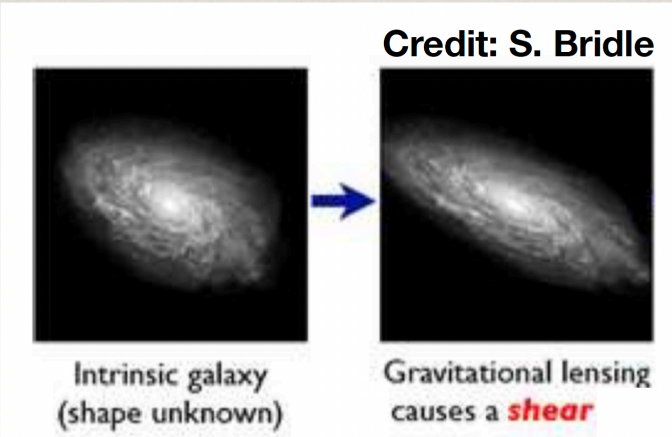


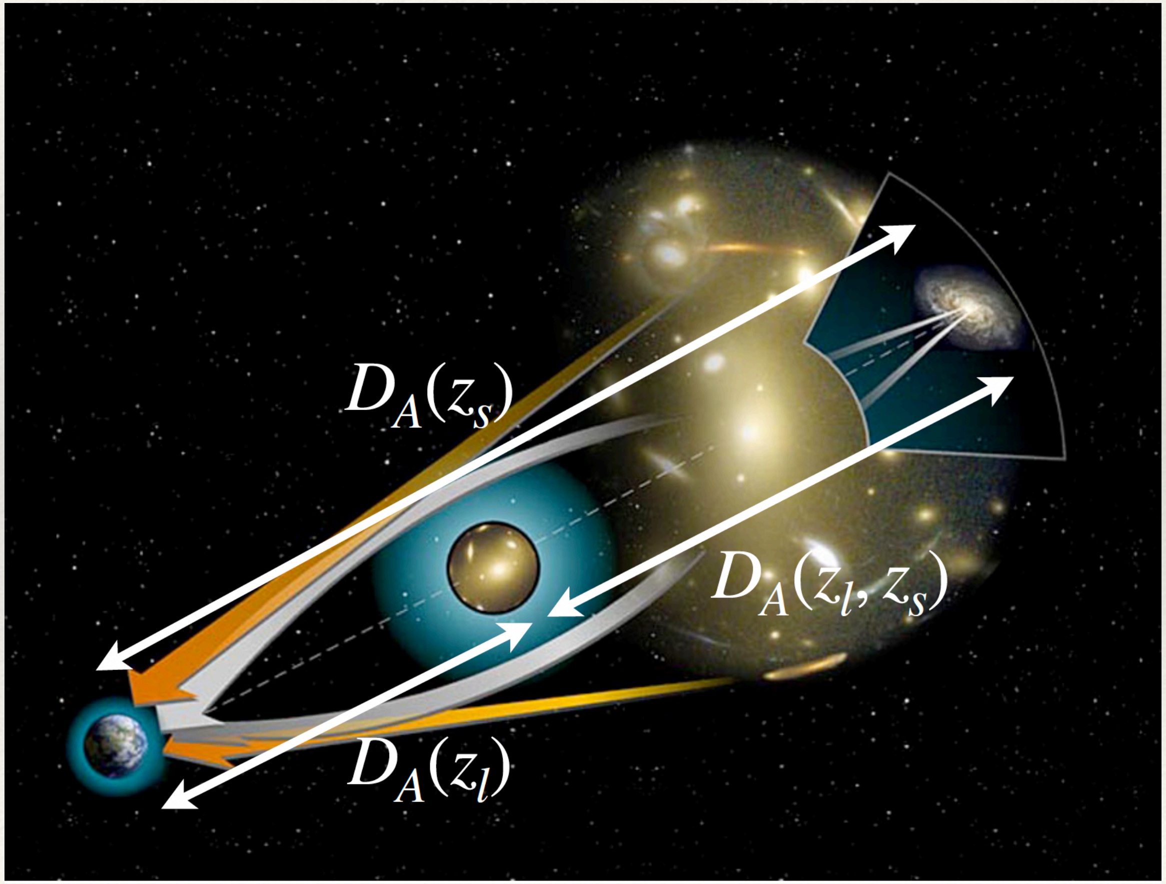


Weak Gravitational Lensing

- Weak gravitational lensing only alters the galaxy shapes slightly; need to stack many clusters to infer mass

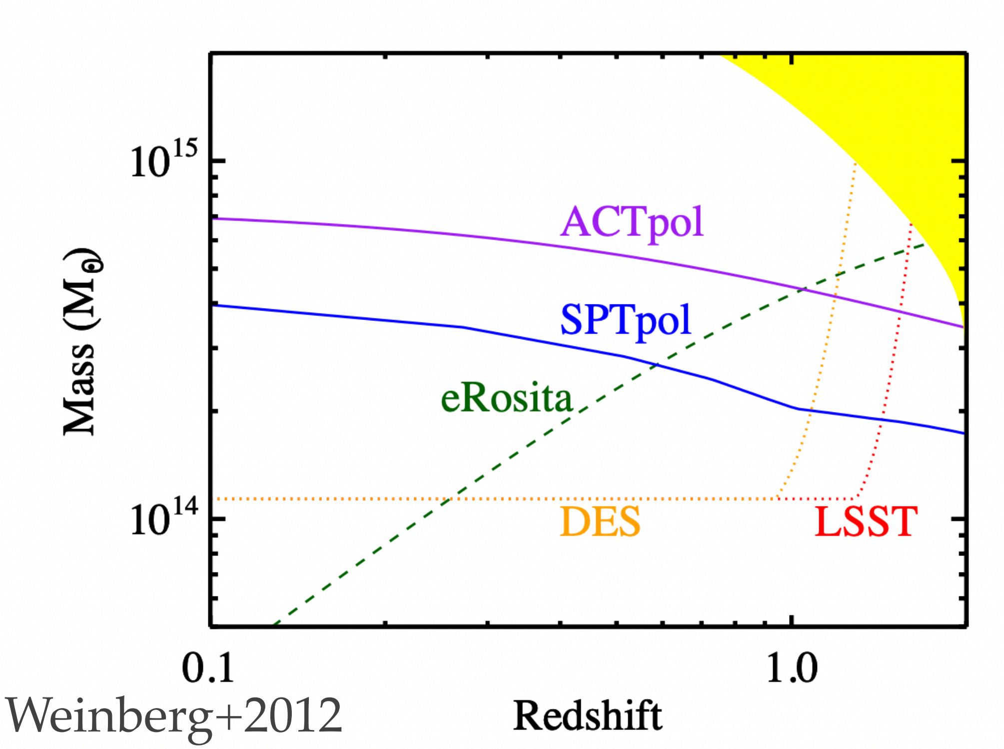




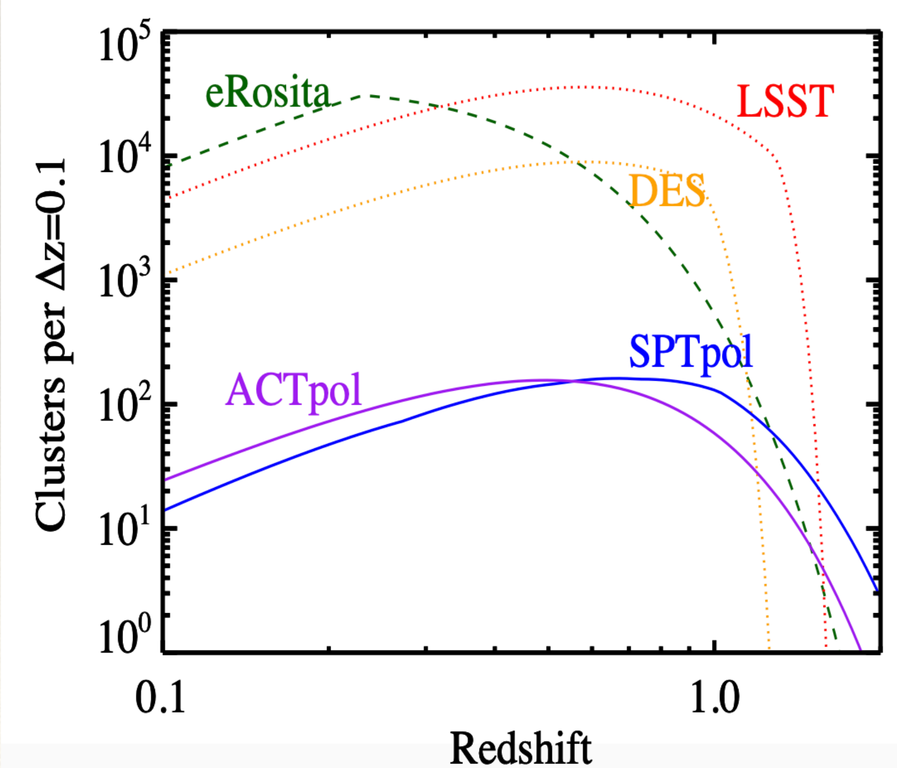


Why optical?

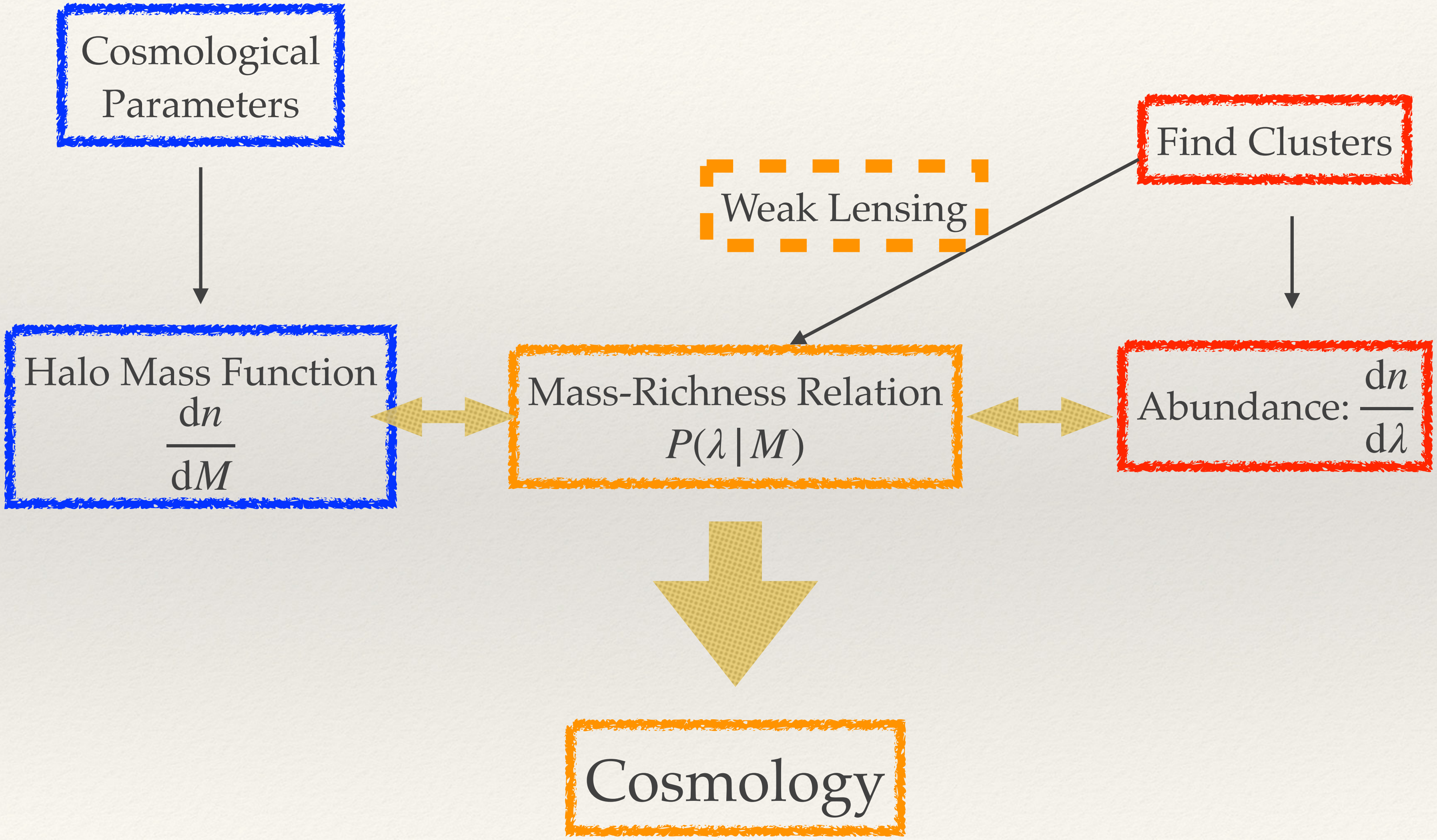
- Optical allows to detect lower mass clusters
- More number of clusters = better weak lensing mass measurement
- Better constraining power on cosmological parameters



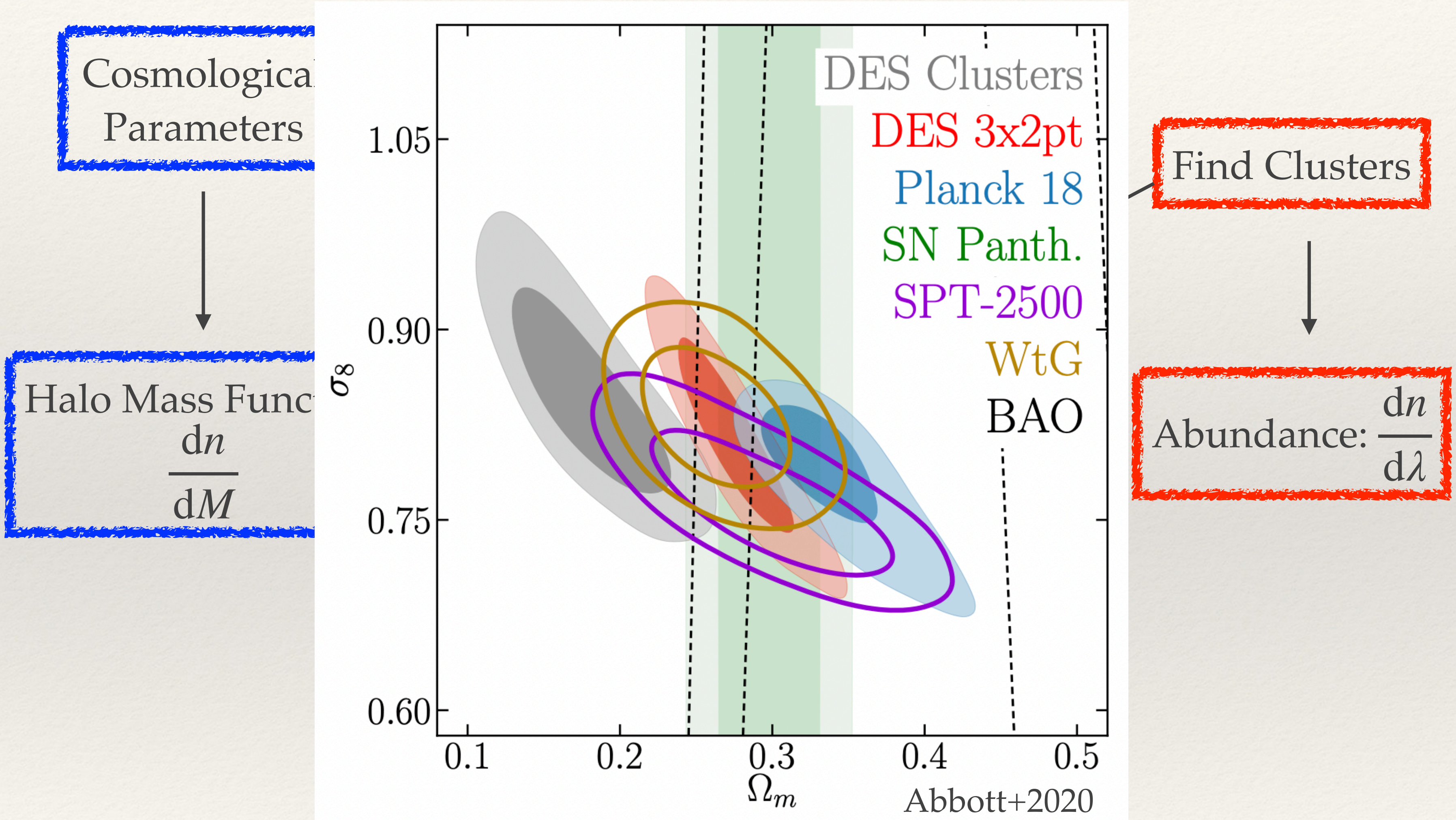
Weinberg+2012



Recipe for Optical Cluster Cosmology



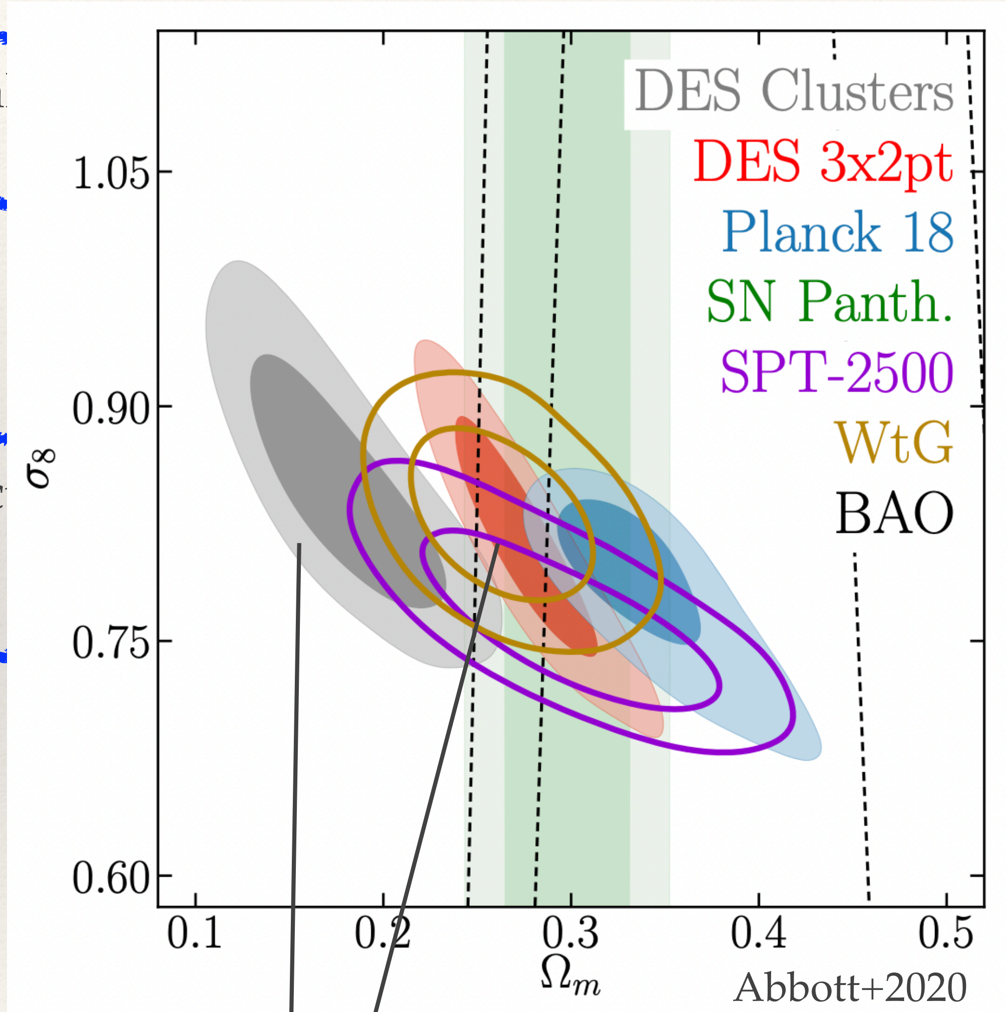
Optical cluster cosmology is in tension



Optical cluster cosmology is in tension

Cosmological Parameters

Halo Mass Function: $\frac{dn}{dM}$

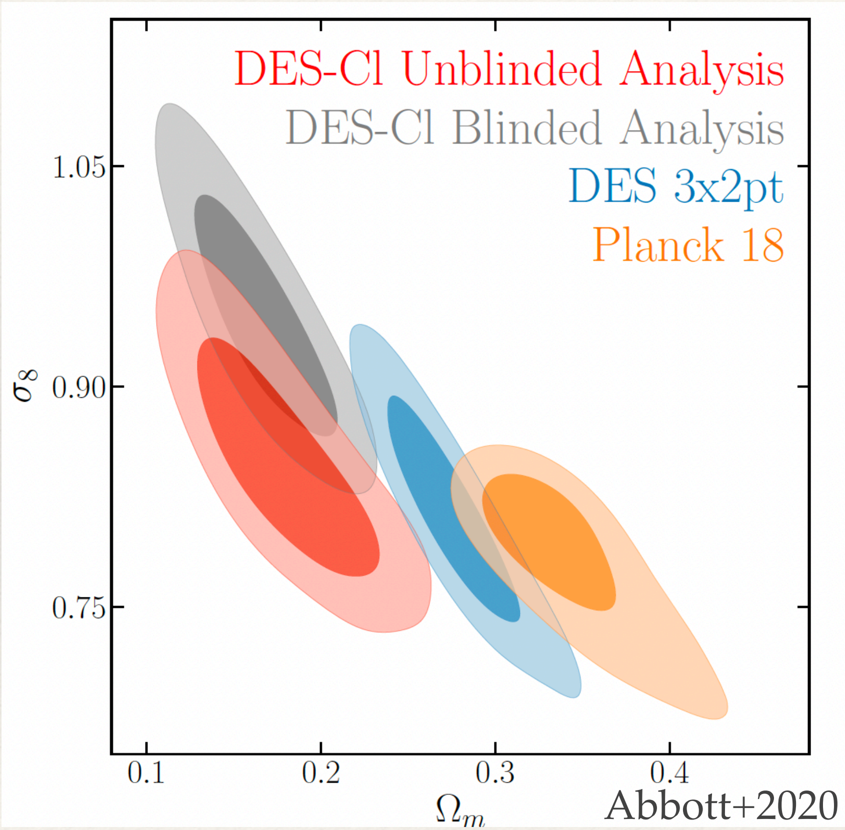


Find Clusters

Abundance: $\frac{dn}{d\lambda}$

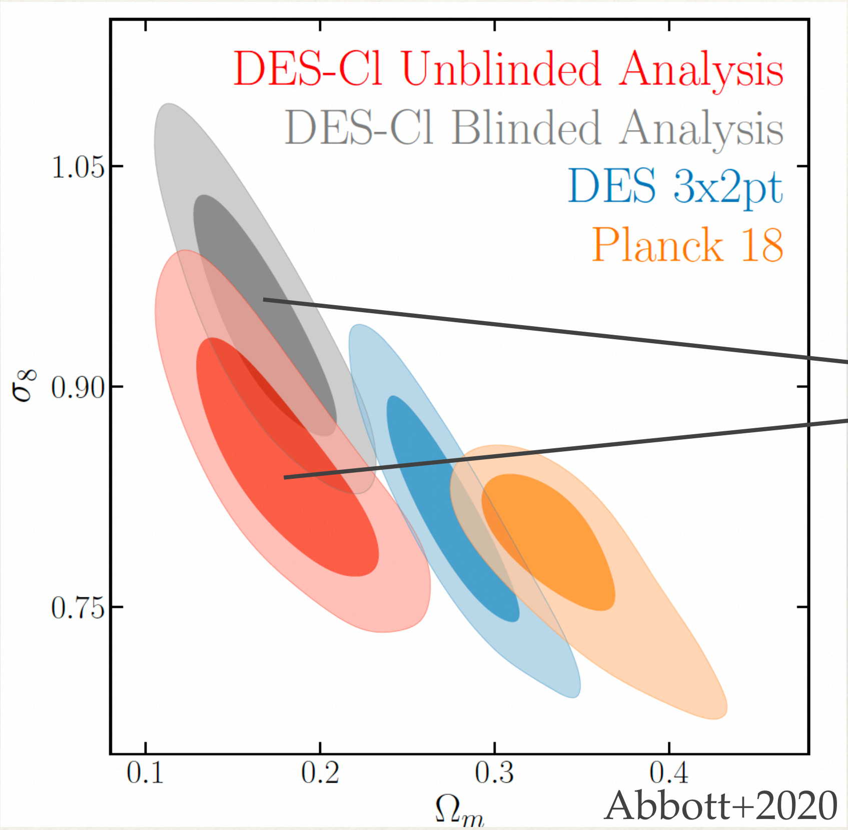
Same data sets = highly correlated

Common systematics for Optical Cluster Cosmology



- **Membership dilutions**
  - Cluster members can be misidentified as source galaxies; dilutes the lensing signal around clusters
  - Can be corrected by the "boost factors"
- **Mis-centering**
  - The assigned center of a cluster can be off-set from the true center
  - Dilutes the lensing signal; subdominant and can be modeled
- **Halo triaxiality**
  - A shape of halos is not spherical but rather triaxial
  - Theoretical systematics can arise by assuming spherical halos in mass measurements; proved to be subdominant from simulations

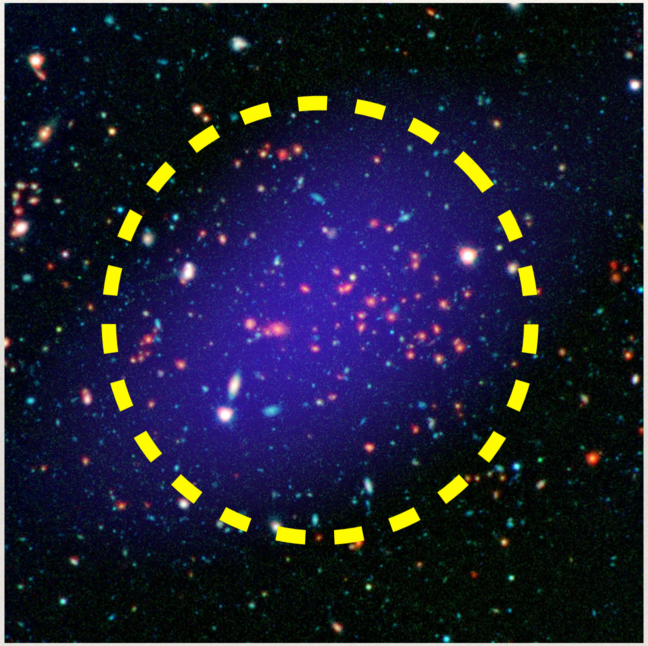
Common systematics for Optical Cluster Cosmology



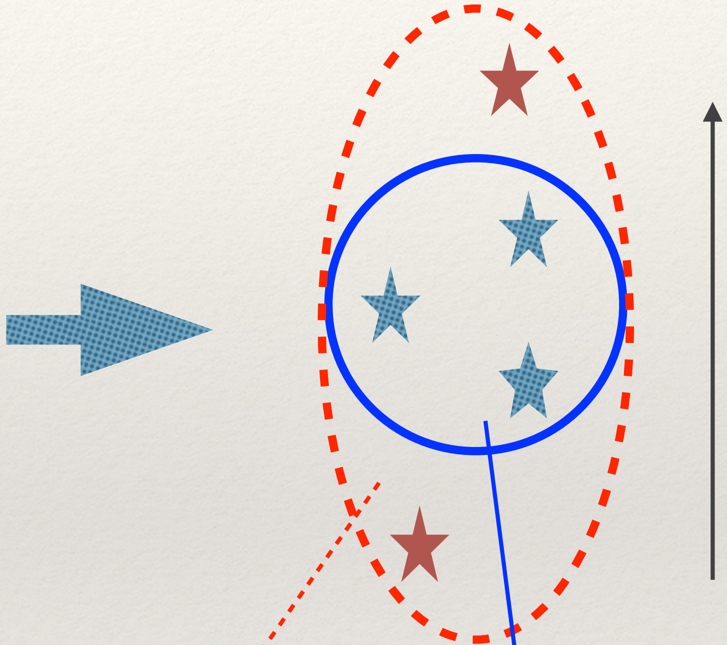
Projection Effects

Projection Effects

- Misidentification of member galaxies along the line-of-sight



WISE/Spitzer



$$P(\lambda^{\rm ob}|M,z) = \int_0^\infty {\rm d}\lambda^{\rm true}\ P(\lambda^{\rm ob}|\lambda^{\rm true},z)P(\lambda^{\rm true}|M,z)\,,$$

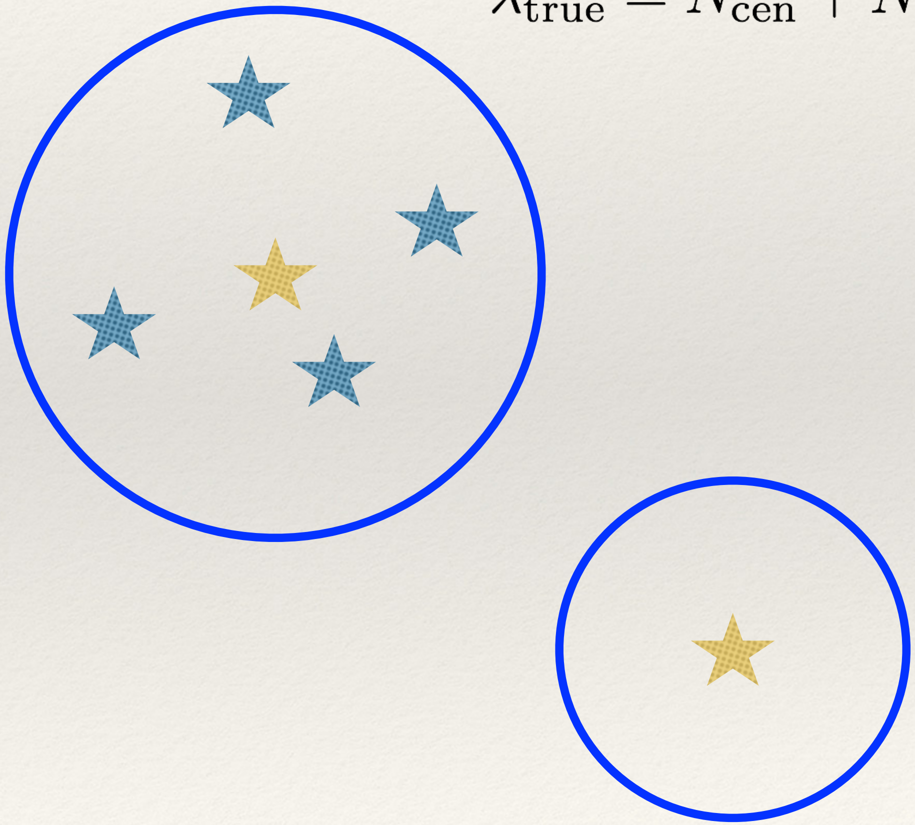
The projection effects alter the mass-richness relation!

Testing Projection Effects: Setups

1. Construct galaxy mock catalogs for red-sequence galaxies using N-body simulation and its halo catalog

“True” cluster samples
richness=# of galaxies in the halo

$$\lambda_{\rm true} = N_{\rm cen} + N_{\rm sat}$$



2. Run the cluster finder on the mock
   - Find over-density regions of red galaxies
   - Determine cluster center and member galaxies in a cylinder
3. Repeat the process iteratively

Testing Projection Effects: Setups

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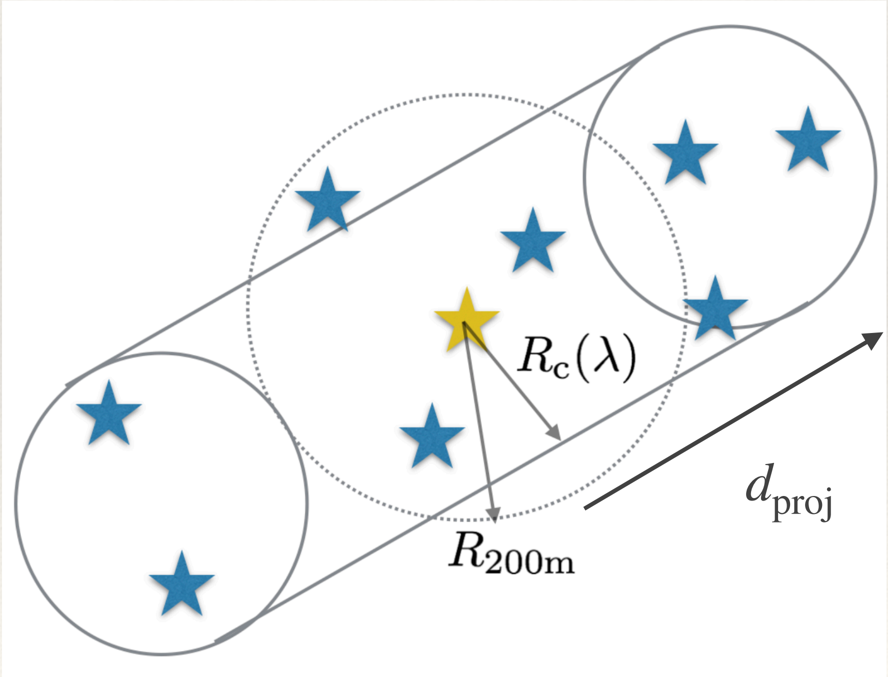


3. Repeat the process iteratively

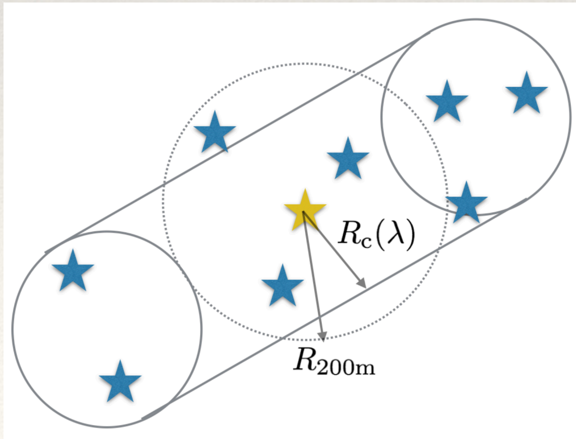
Testing Projection Effects: Setups

1. Construct galaxy mock catalogs for red-sequence galaxies using N-body simulation and its halo catalog
2. Run the cluster finder on the mock
    - Find over-density regions of red galaxies
    - Determine cluster center and member galaxies in a cylinder; assign membership probability
3. Repeat the process iteratively

→ "True" cluster samples richness=# of galaxies in the halo

⇕

→ "Observed" cluster samples: richness=sum of membership probabilities



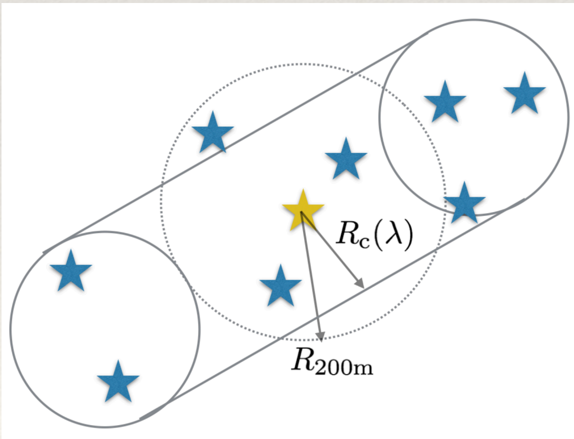
Abundance and Mass-Richness Relation

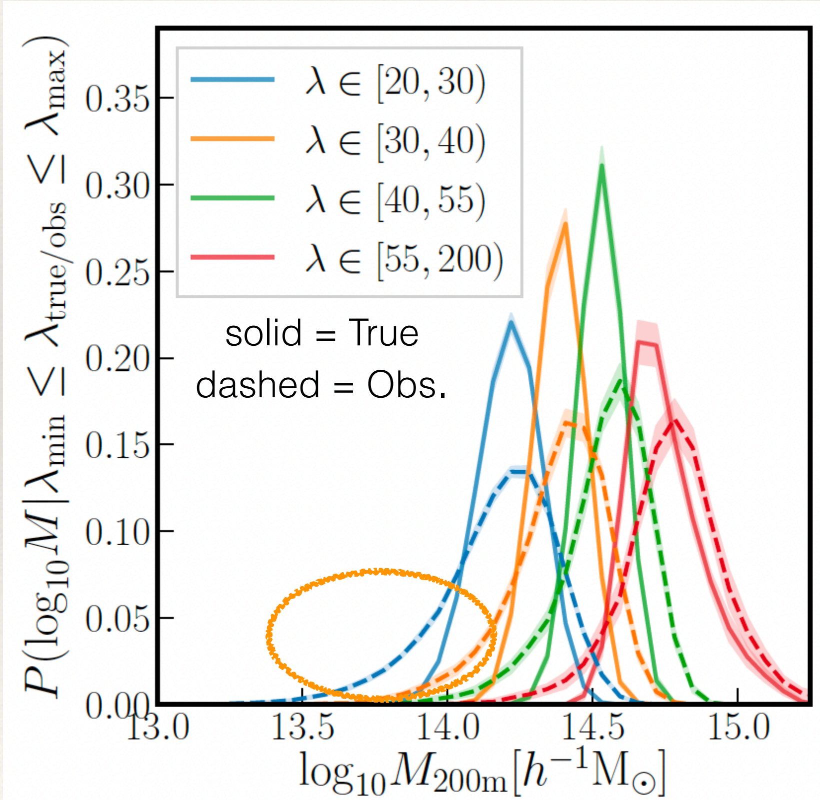
- Due to projection effects, there are more number of lower-mass halos in "observed" cluster samples

- The aperture size is smaller than the actual halo size for massive halos

$$\lambda_{\rm true} = N_{\rm cen} + N_{\rm sat}$$

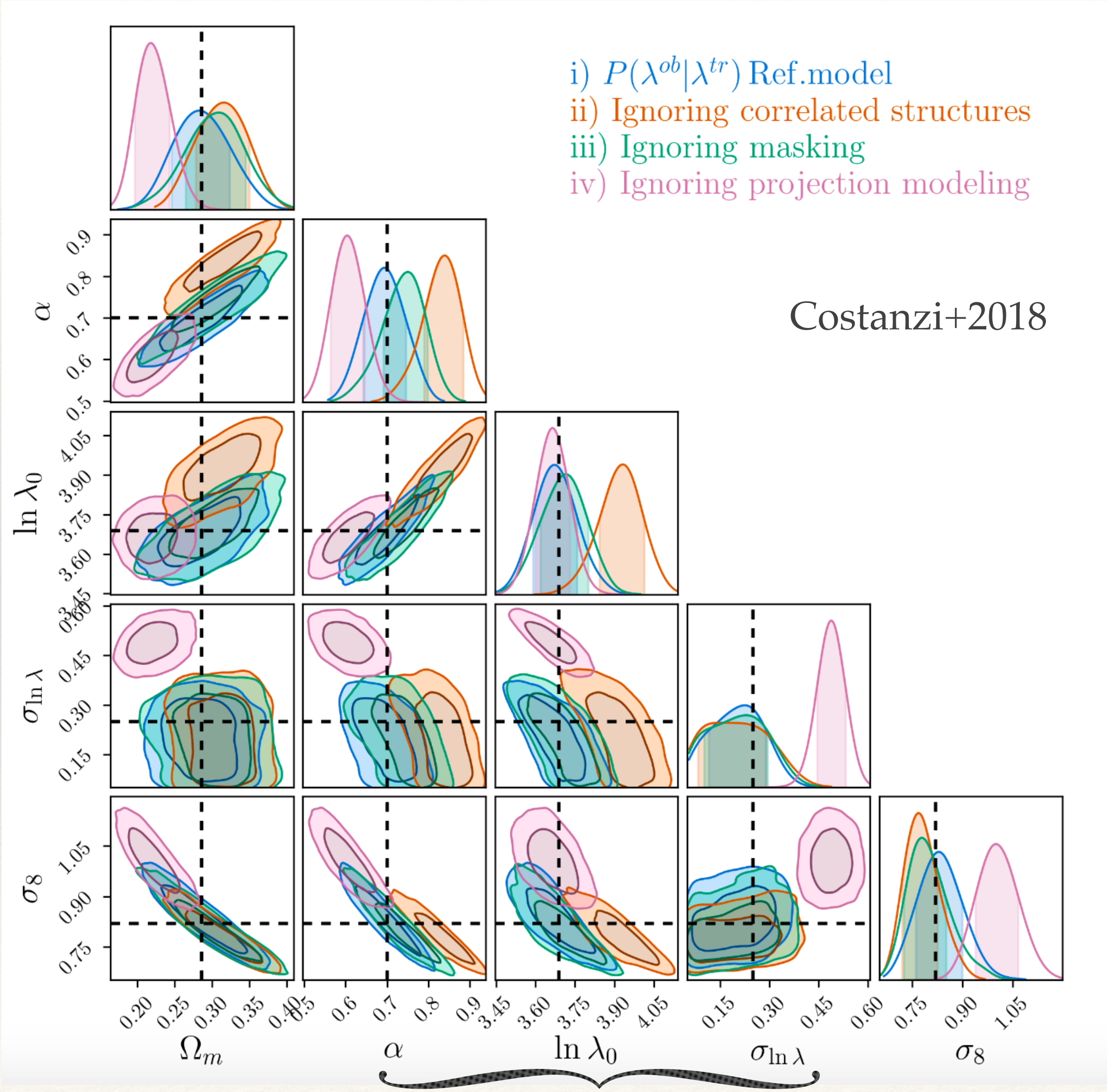
$$\lambda_{\rm obs} = \sum_{R_j < R_c(\lambda)} p_{\rm mem,j}$$





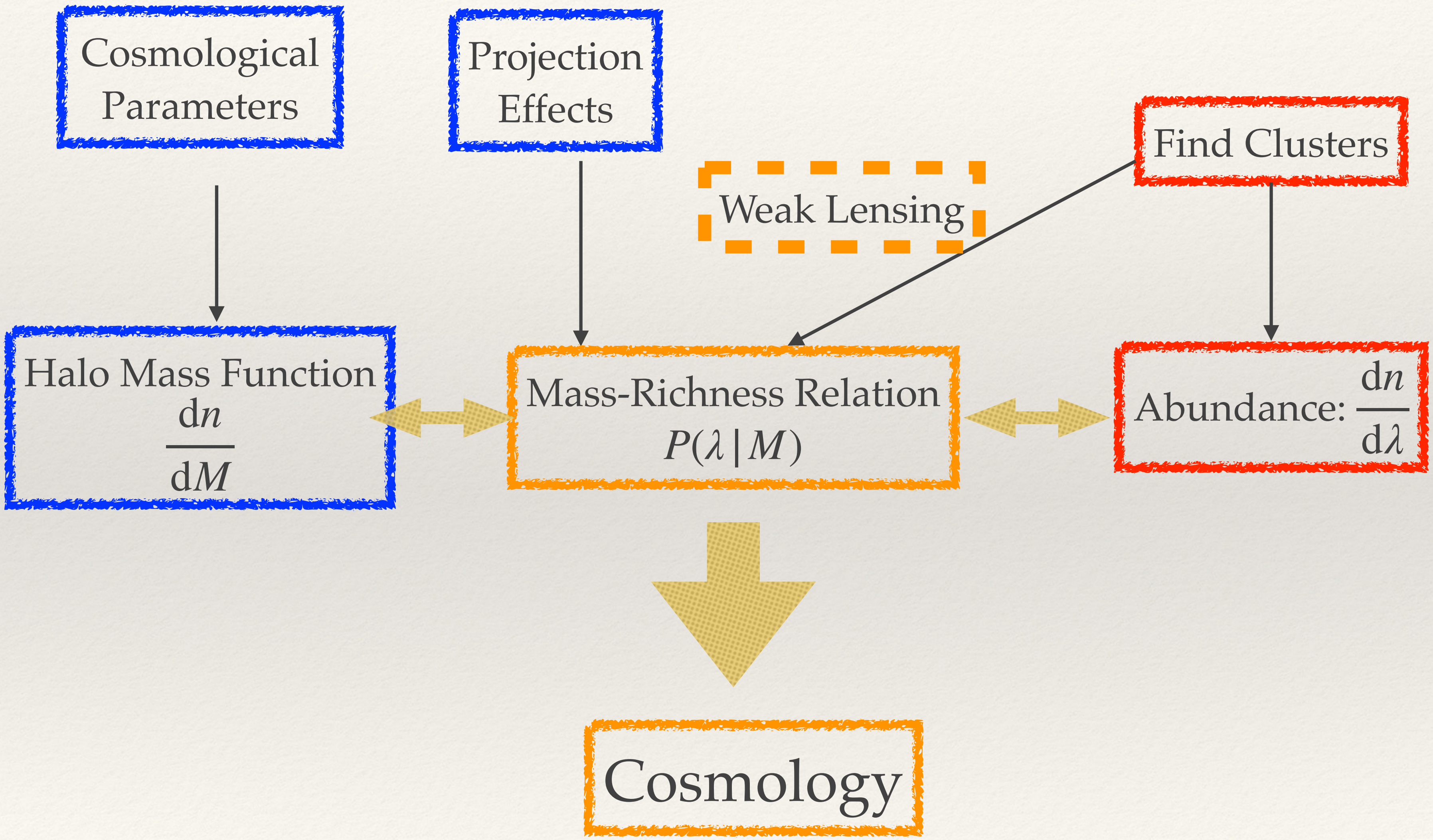
Sunayama+2020

Projection effects can bias cosmology constraints

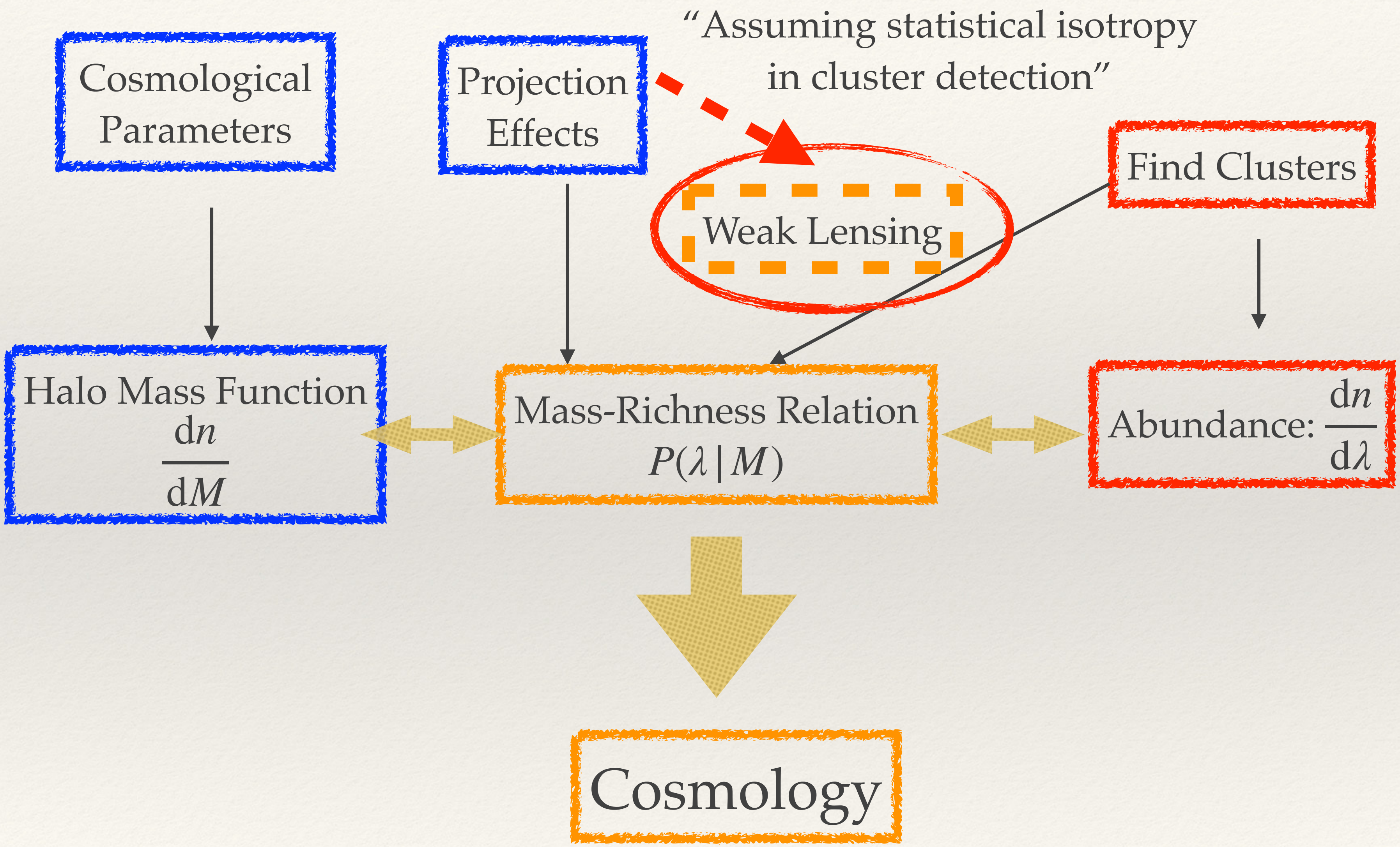


Parameters for mass-richness relation

Recipe for Optical Cluster Cosmology

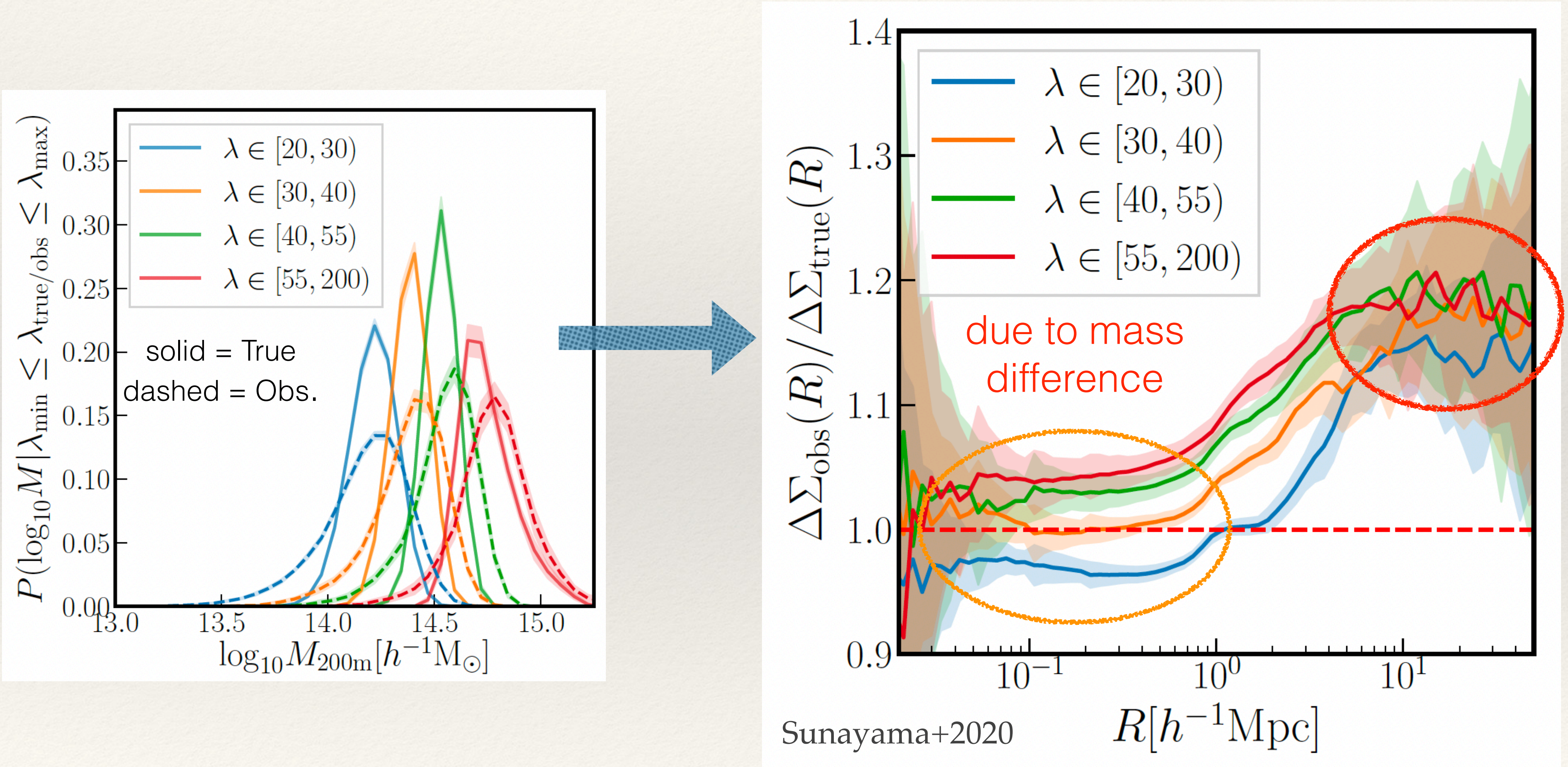


Recipe for Optical Cluster Cosmology



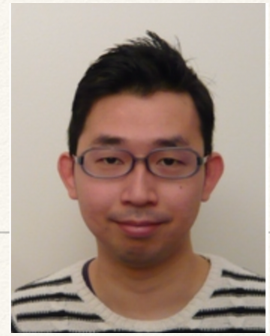
Projection effects beyond Mass-Richness Relation

- The boost on two-halo term cannot be explained by mass difference!



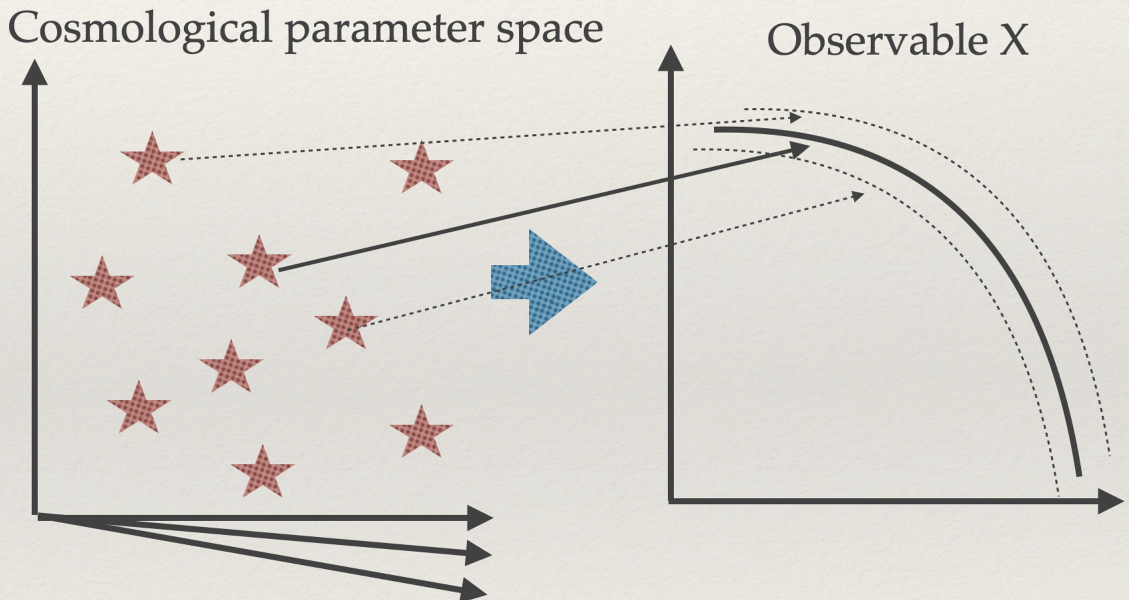
What is the cause of this boost on large scales?

Dark Emulator: accurate prediction of observables



Takahiro Nishimichi (U. Kyoto)

- Building accurate theoretical templates
  - Halo mass function
  - Galaxy-galaxy lensing
  - Galaxy-3D spatial clustering
- "Data driven" sciences with a large suite of simulations
- ~300 simulations for 100 parameter sets (~200TB)

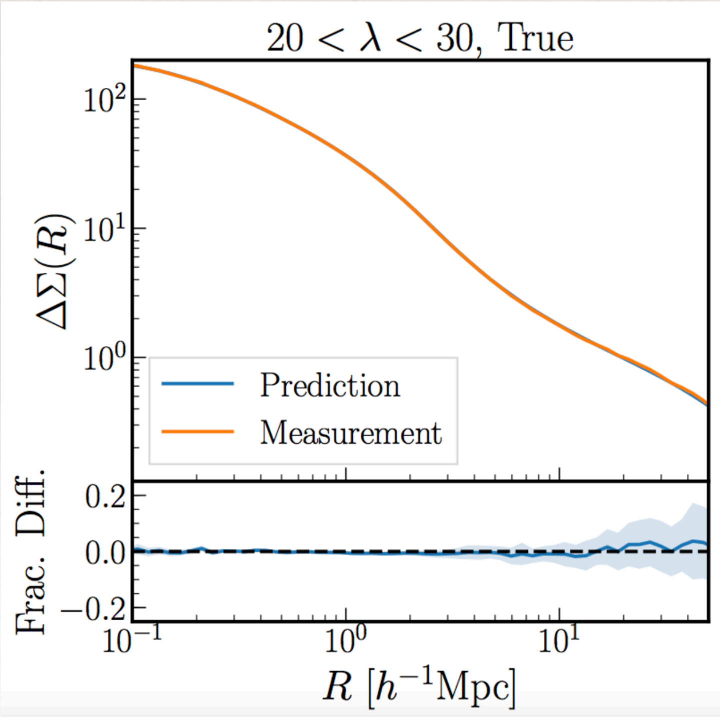


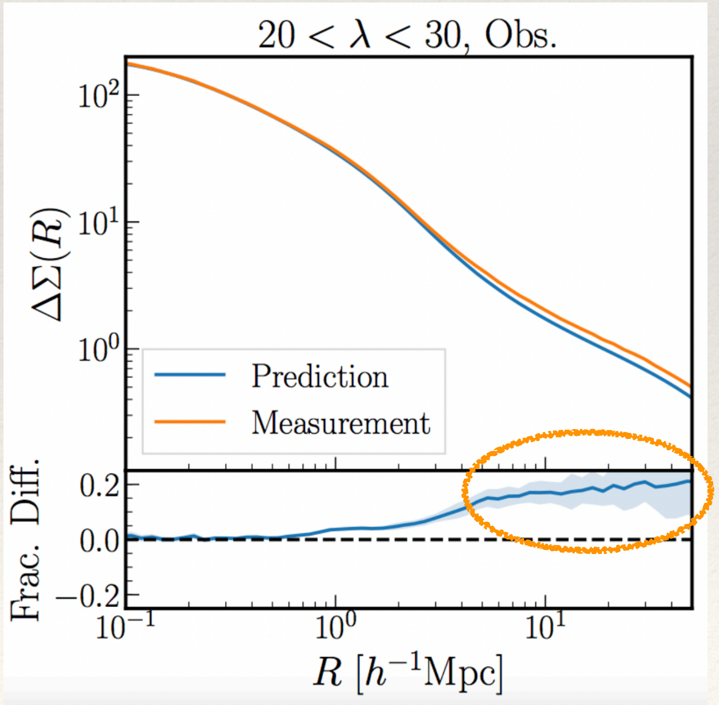
https://dark-emulator.readthedocs.io

Compare the "observed" signals against emulator predictions, *assuming the true underlying cluster mass information!*

Comparison with the emulator

- Dark Emulator (Nishimichi+2018) takes halo masses as input and gives lensing signals as output
- "Obs." Sample shows the boost on two-halo term; anisotropic structure causes the boost on 2-halo term!





Sunayama+2020

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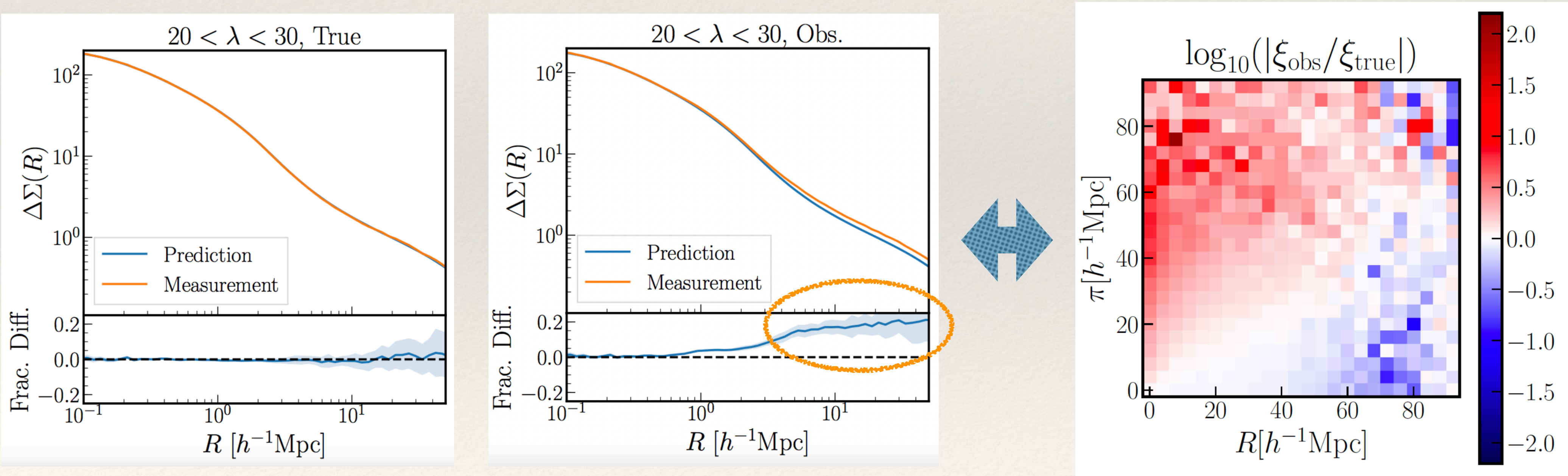
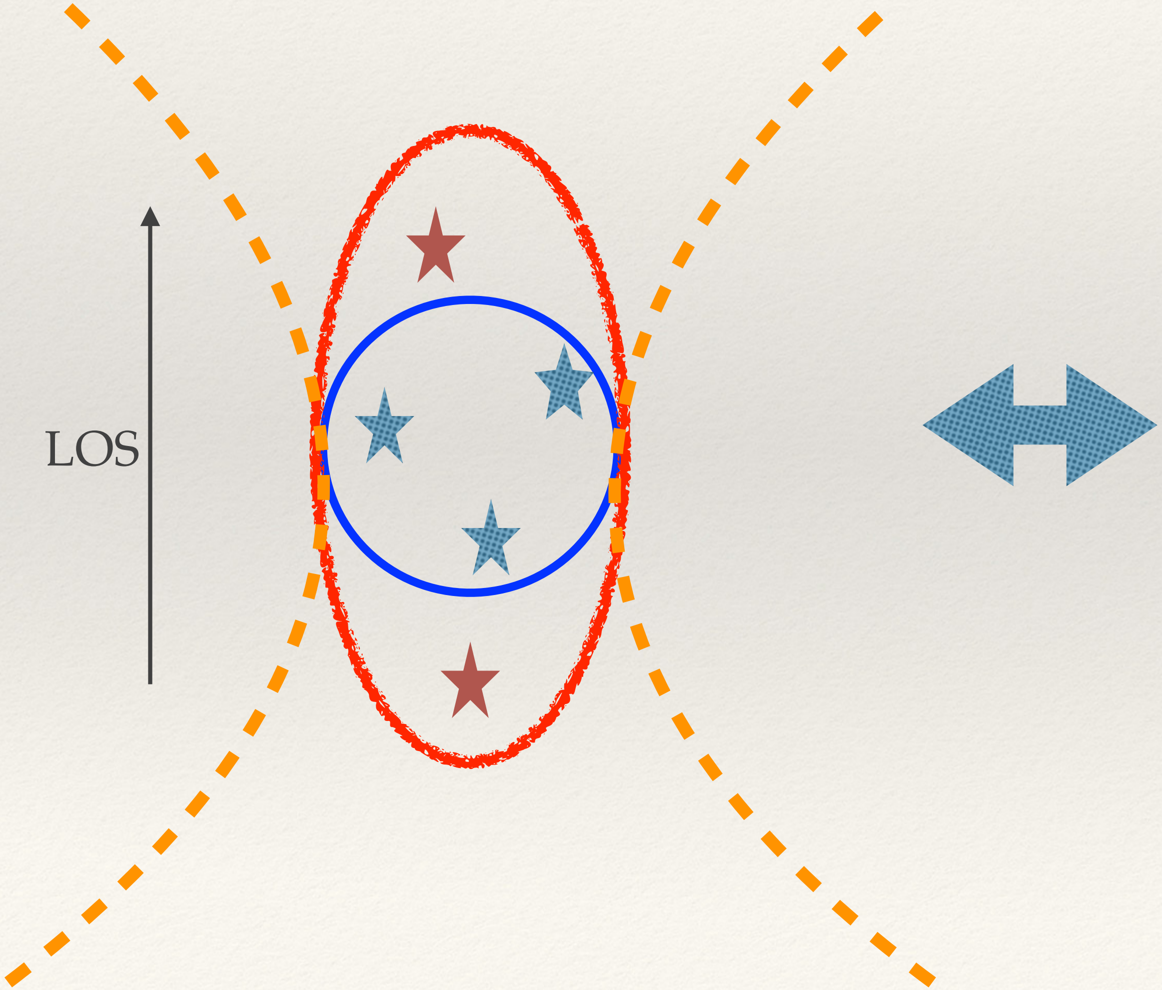
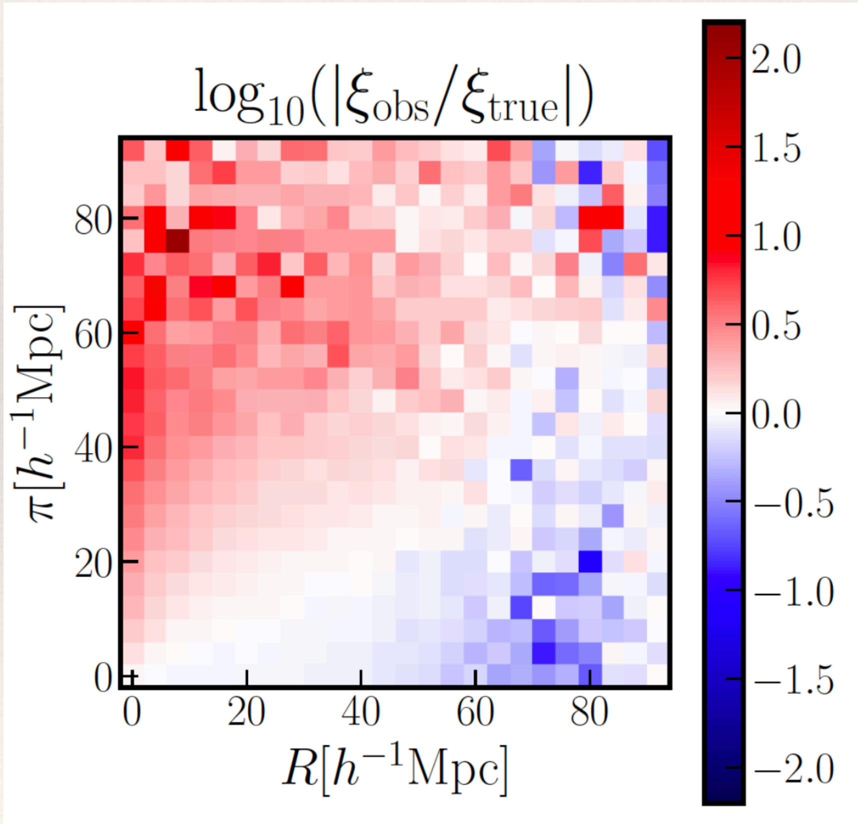


Distribution of clusters is anisotropic

- Cluster finder preferentially identify clusters on aligned filaments along LOS as clusters





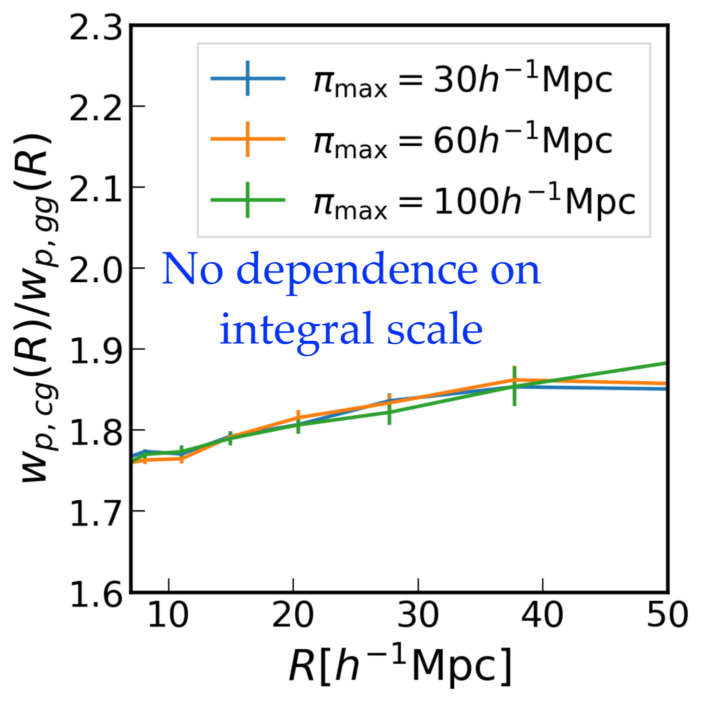
Sunayama+2020

Can we confirm projection effects observationally?

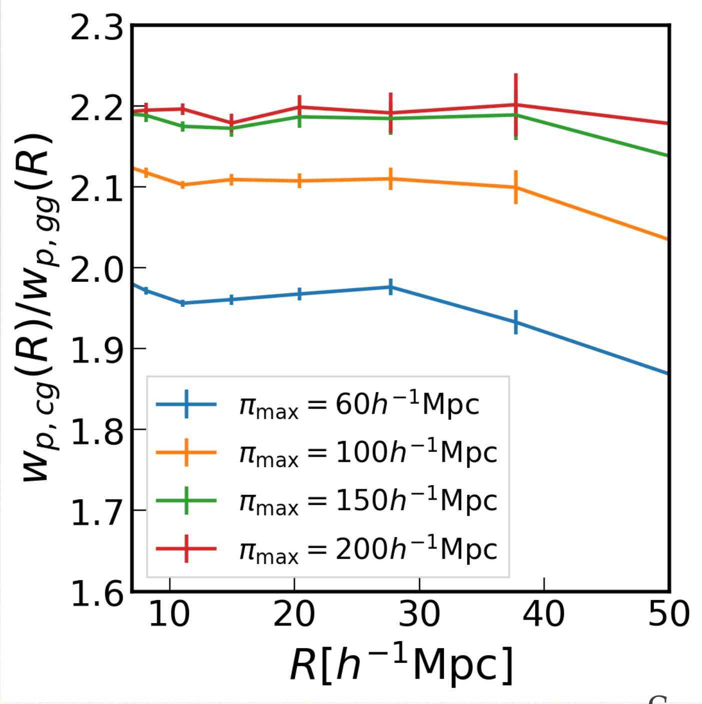
- Increase on amplitude happens only when the integral scale is smaller than the projection length
- Assume that galaxies are more isotropically selected than clusters

$$w_{p,ij}(R) = 2\int_0^{\pi_{max}} d\pi\, \xi_{cc,ij}\left(\sqrt{R^2+\pi^2}\right)$$

"True" clusters: isotropic



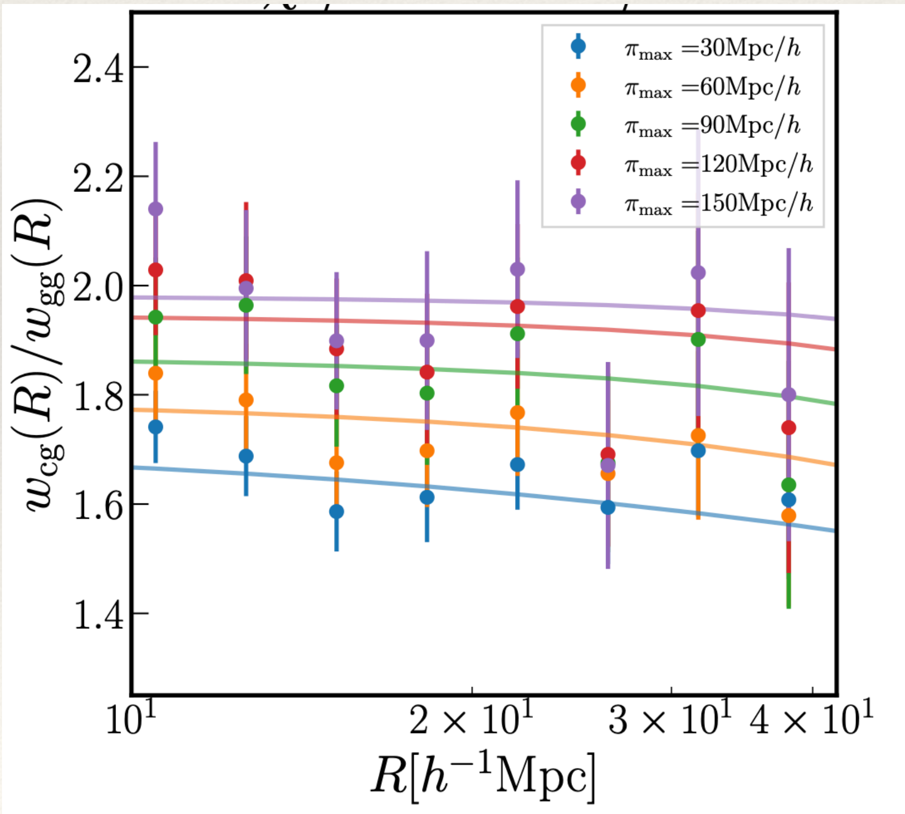
"Observed" clusters: anisotropic



Sunayama 2023

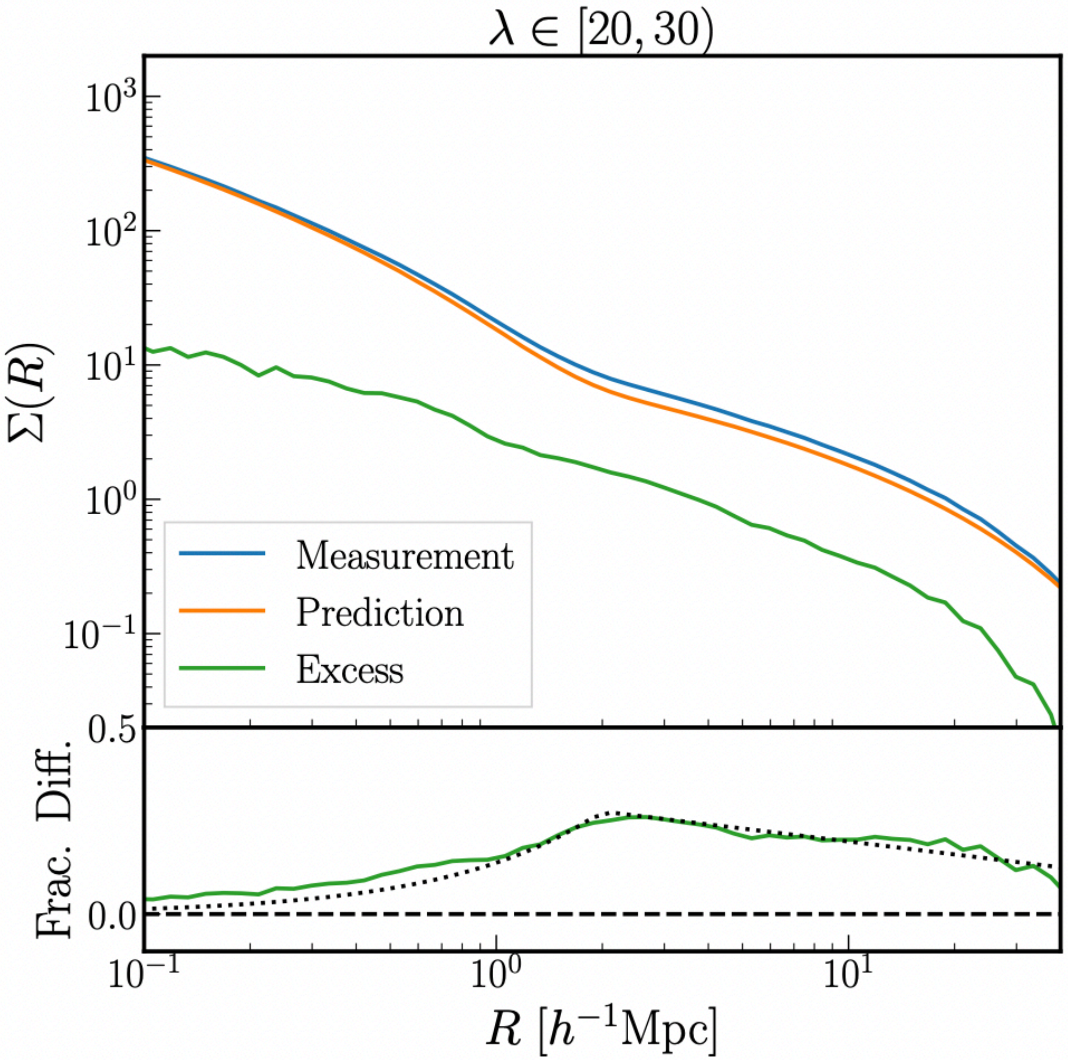
Can we confirm projection effects observationally?

- Using SDSS redMaPPer cluster at 0.1<z<0.33 and measure projected correlation functions with various integral scales
- Observational evidence of clusters being more anisotropic ally distributed than galaxies



Sunayama 2023

Modeling projection effects for cosmology



Model the excess mass as a multiplicative factor

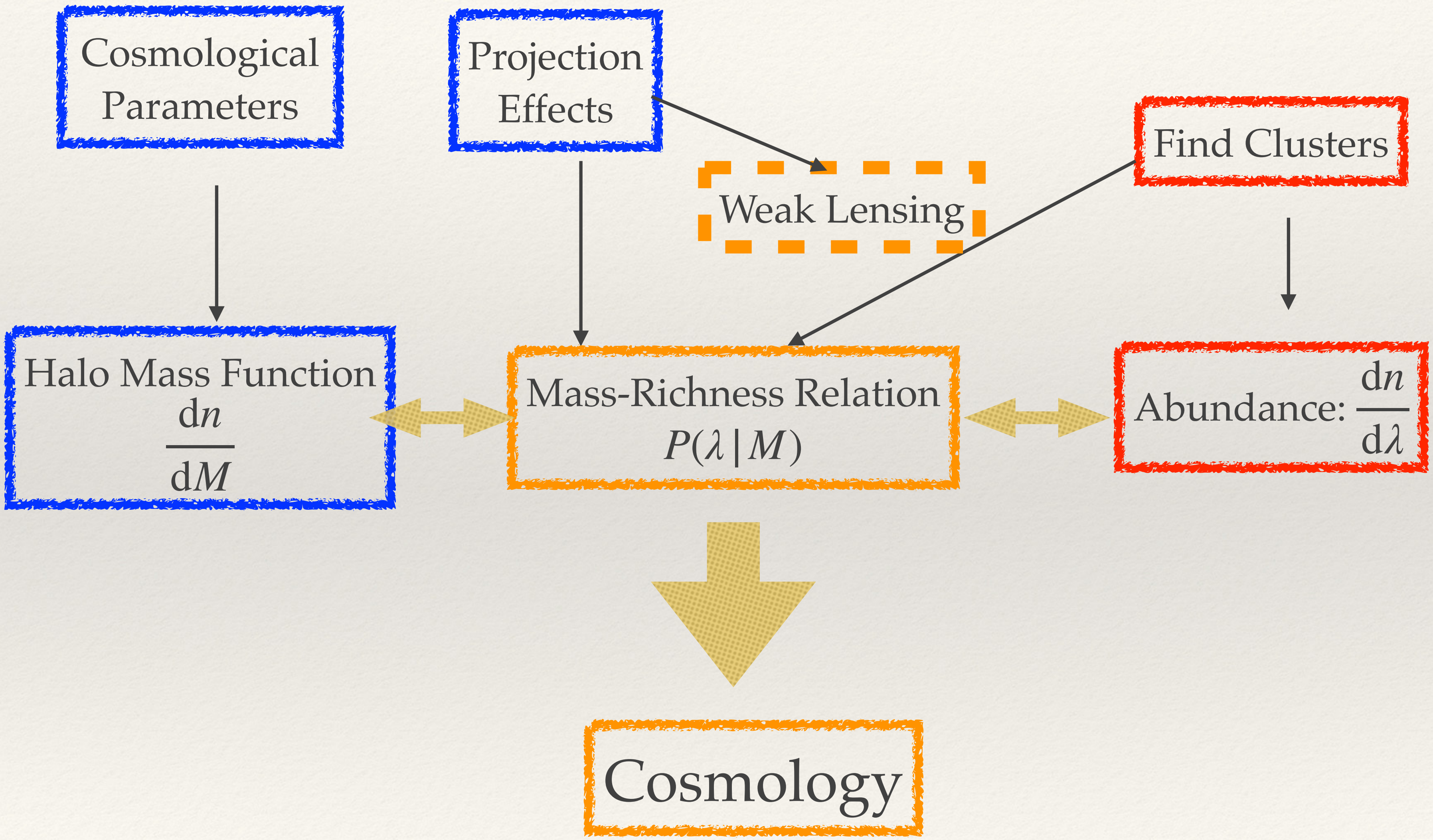
$$\Pi(R) = \begin{cases} \Pi_0 (R/R_0) & \text{for } R \le R_0, \\ \Pi_0 + c \ln(R/R_0) & \text{for } R > R_0. \end{cases}$$

And treat it as effective biases

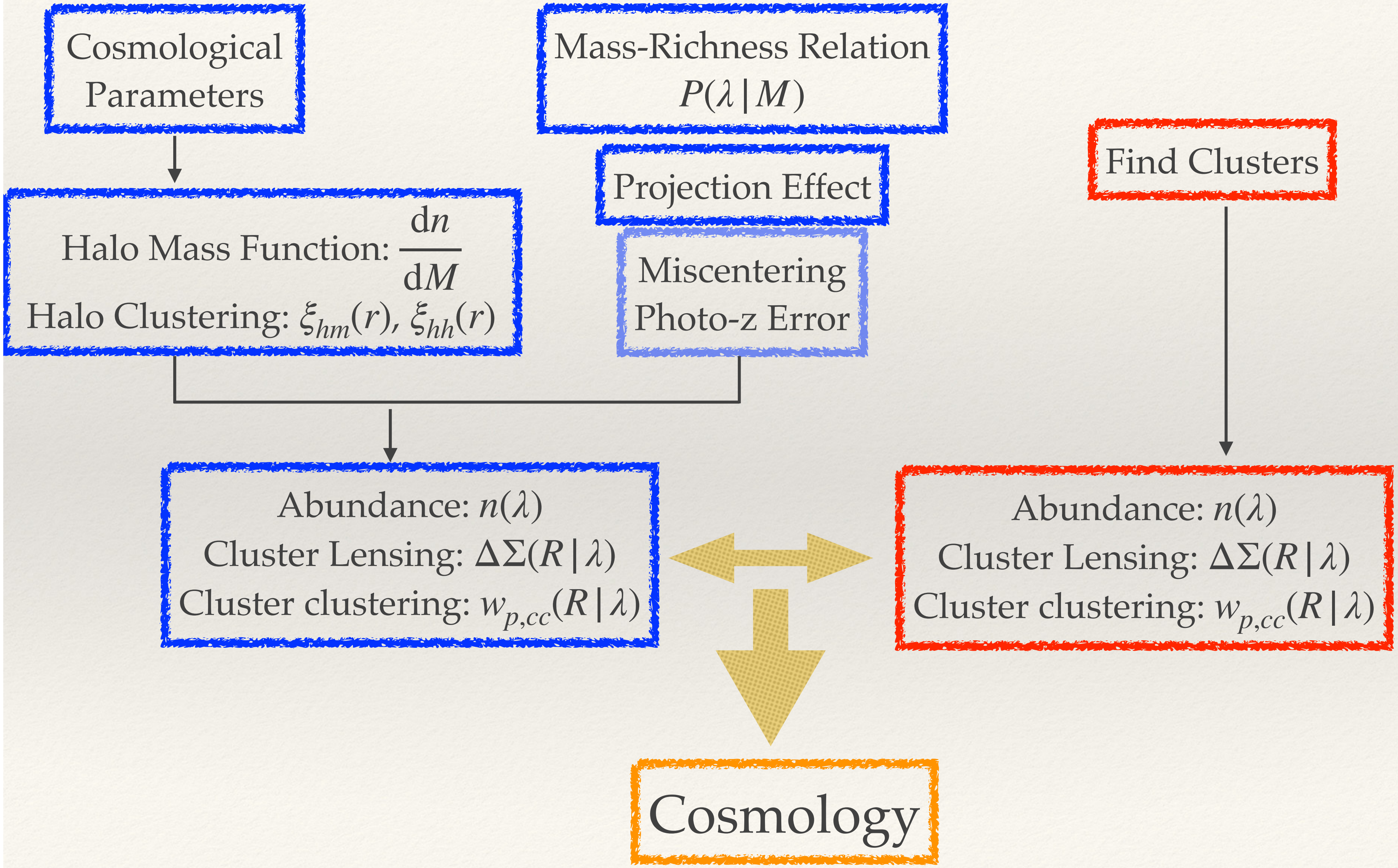
$$\Sigma(R) = \Pi(R)\Sigma^{\rm iso}(R),$$
$$w_{\rm p}(R) = \Pi^2(R) w_{\rm p}^{\rm iso}(R).$$

Park, TS+2022

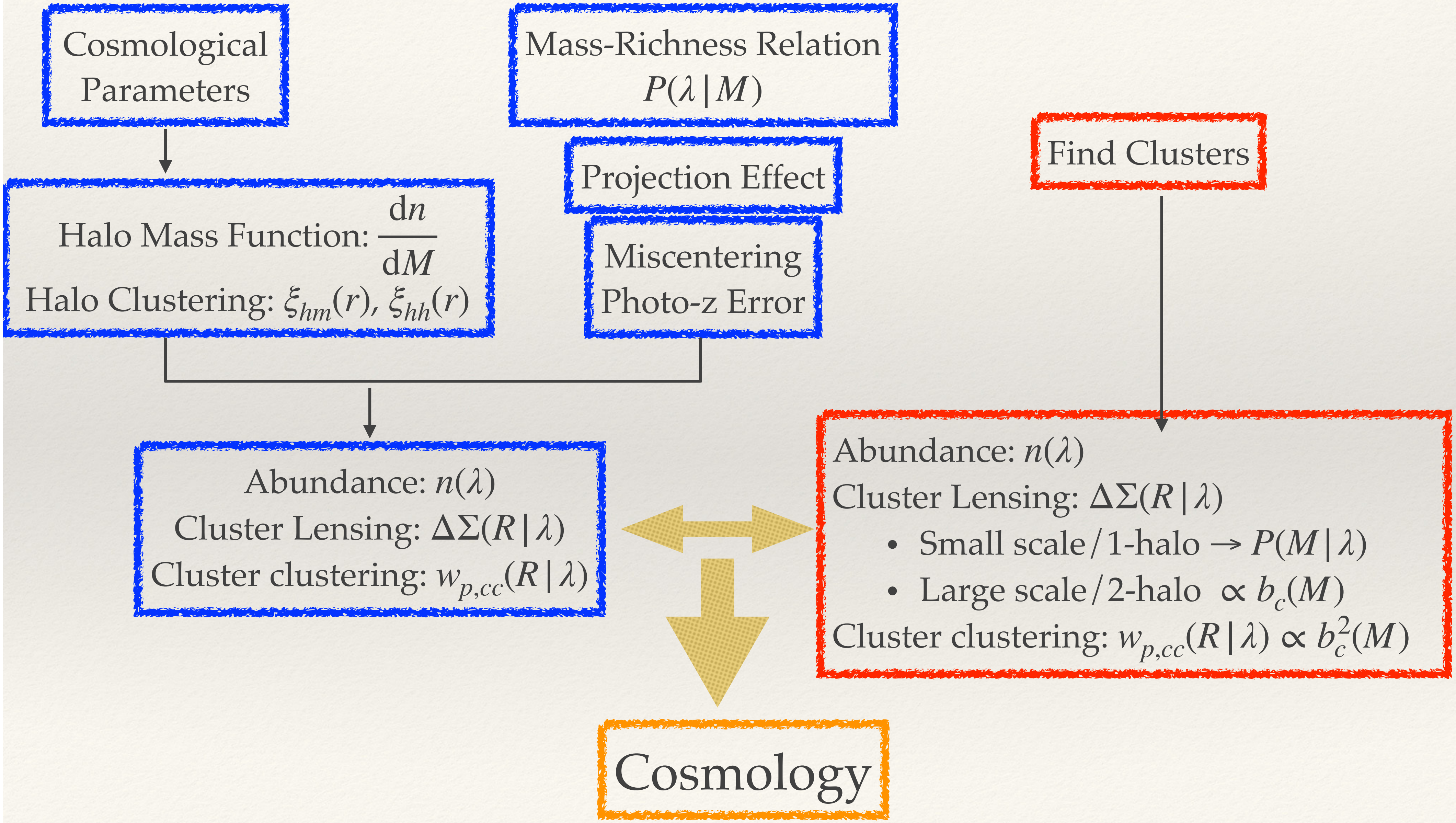
Recipe for Optical Cluster Cosmology



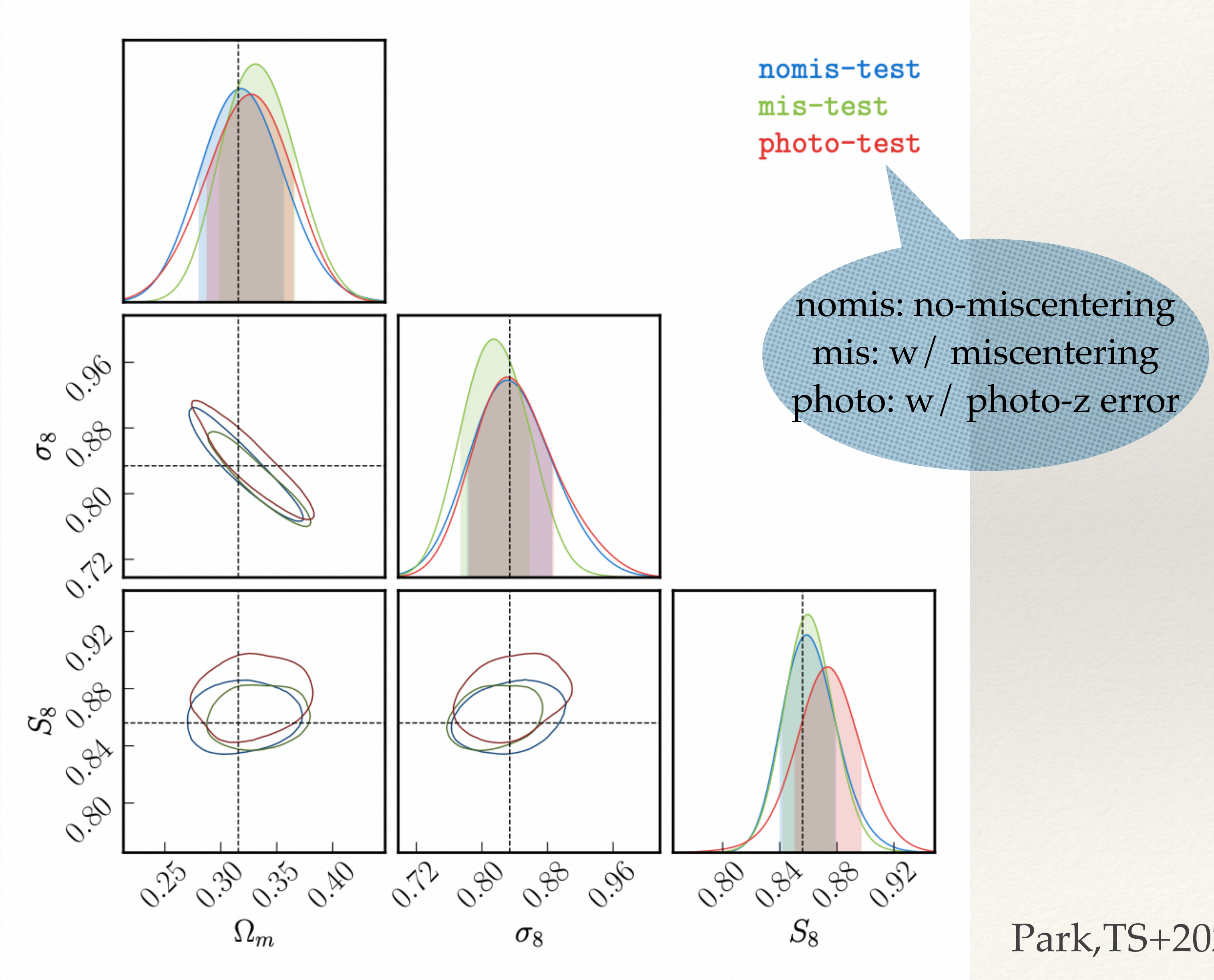
One -Step Full-Forward Modeling



One -Step Full-Forward Modeling



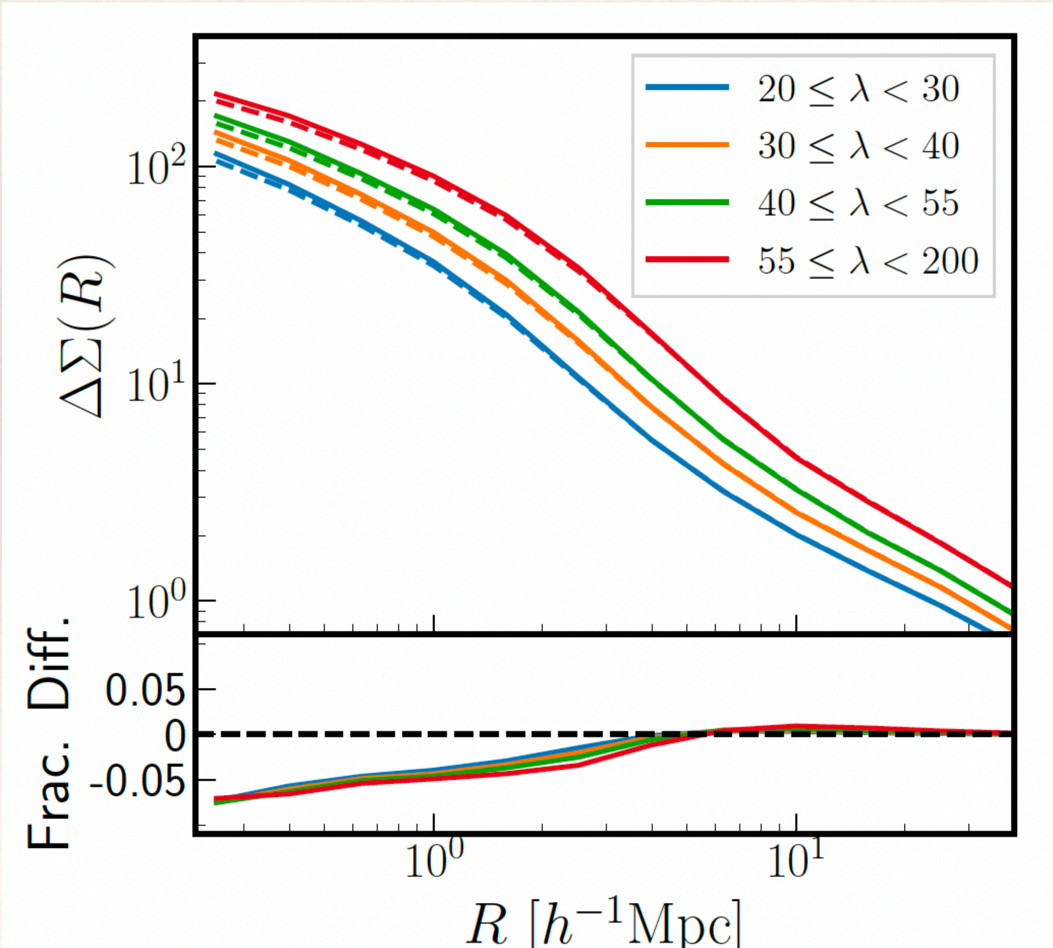
Mock Challenge: Validate the model



Park,TS+2022

Do we need to worry about baryonic effects?

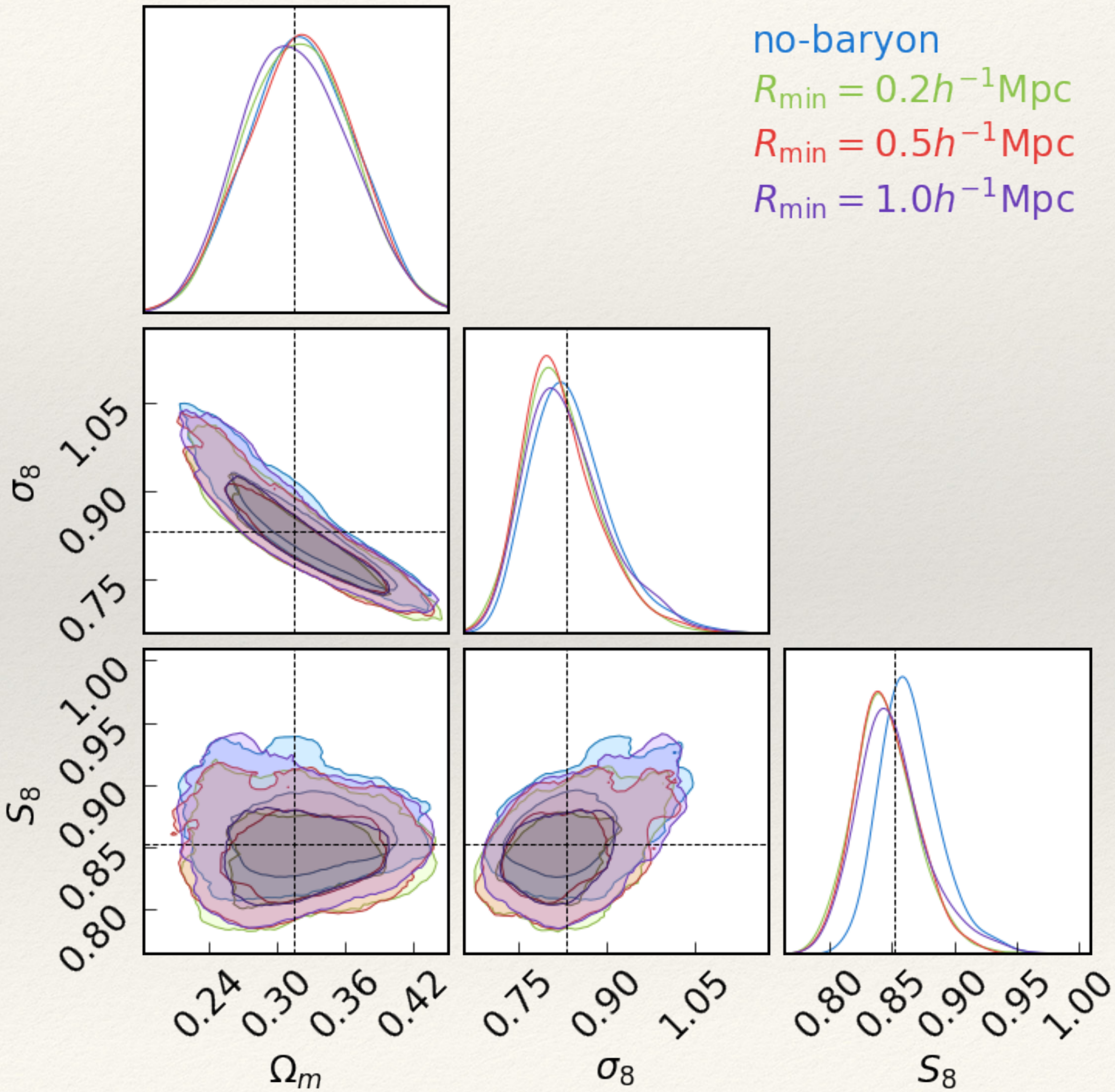
- The baryonic effects constrained from kSZ (Giri&Schneider 2021) and cosmic shear (Arico+2023) suppress power spectra more strongly than the predictions from Illustris-TNG and EAGLE.



Sunayama+2023

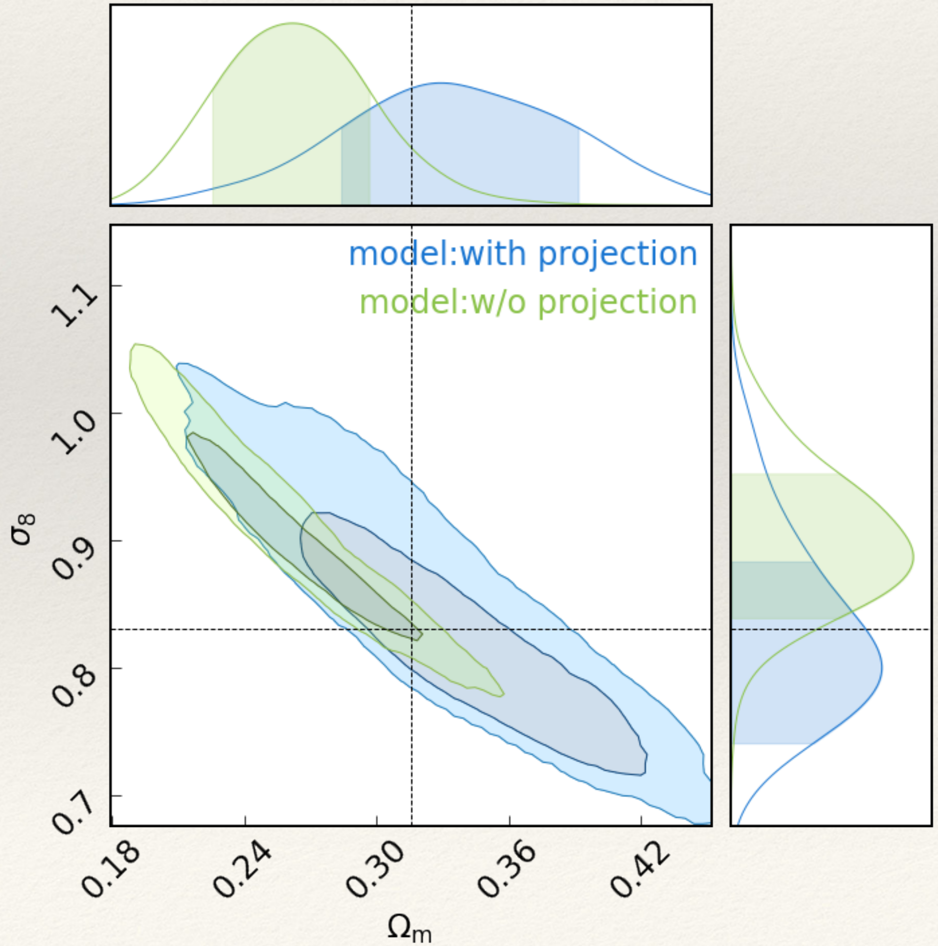
Baryonic effects do not bias cosmology

- We model baryonic effects on lensing signals using *baryonification*
- Cluster cosmology analysis is not biased without modeling baryonic effects on lensing signals



Including projection effects is crucial

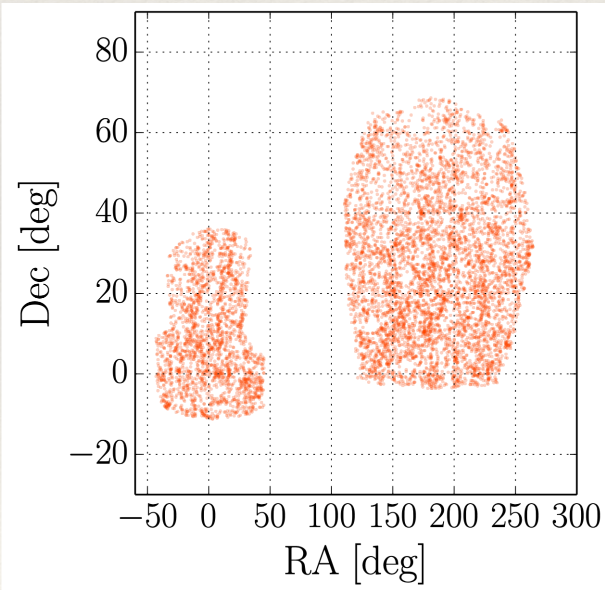
- Ignoring the projection effects can bias the constraints on cosmological parameters



SDSS redMaPPer clusters x HSC WL Measurement

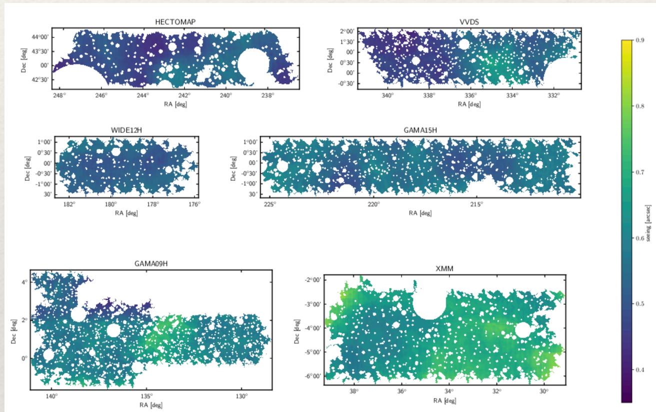
SDSS redMaPPer cluster sample

- Area ~ 8300 deg^2
- z = [0.1, 0.33]
- λ = [20,30],[30,40],[40,55],[55,200]
- In total, ~8000 clusters
- Based on SDSS DR8 photometry



HSC-Y3 shape catalog

- Area ~ 433 deg^2 in total
- <z>~1.2.
- $n_s \sim 16\mathrm{arcmin}^{-2}$



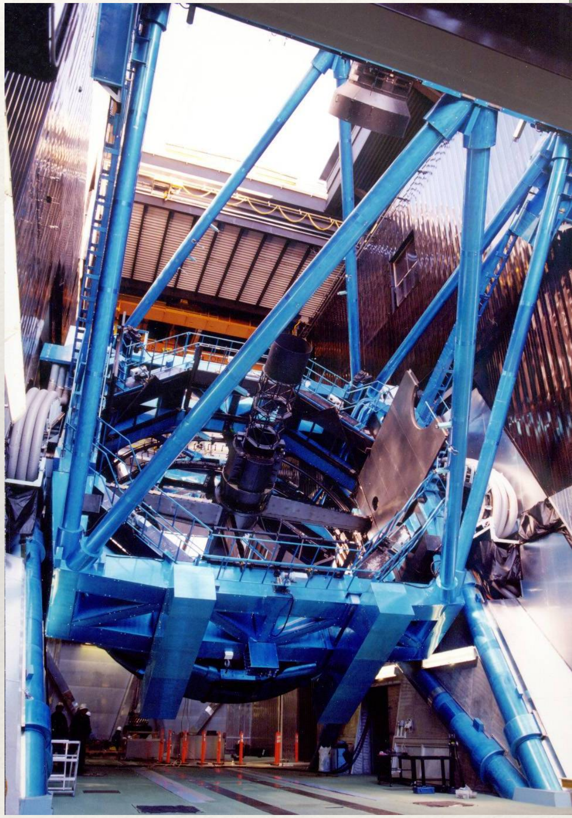
Cluster lensing signal

Cluster abundance

Cluster clustering signal

Subaru Hyper Suprime-Cam (HSC)

- 8.2 m primary mirror
  - ~11 x light collecting power of SDSS
  - Can observe high-z source galaxies
- Superb image quality: PSF~0.6″
  - SDSS~1.0″
  - Better shape measurements
- Large Field-of-View: 1.5°diameter
  - ~7 x full moon
  - Efficiently observe large area of sky



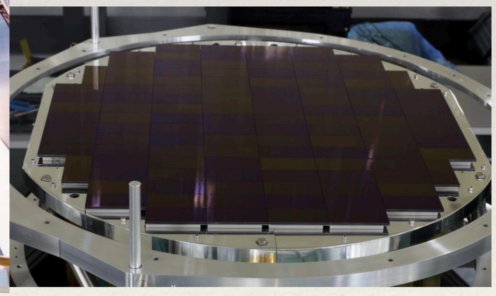
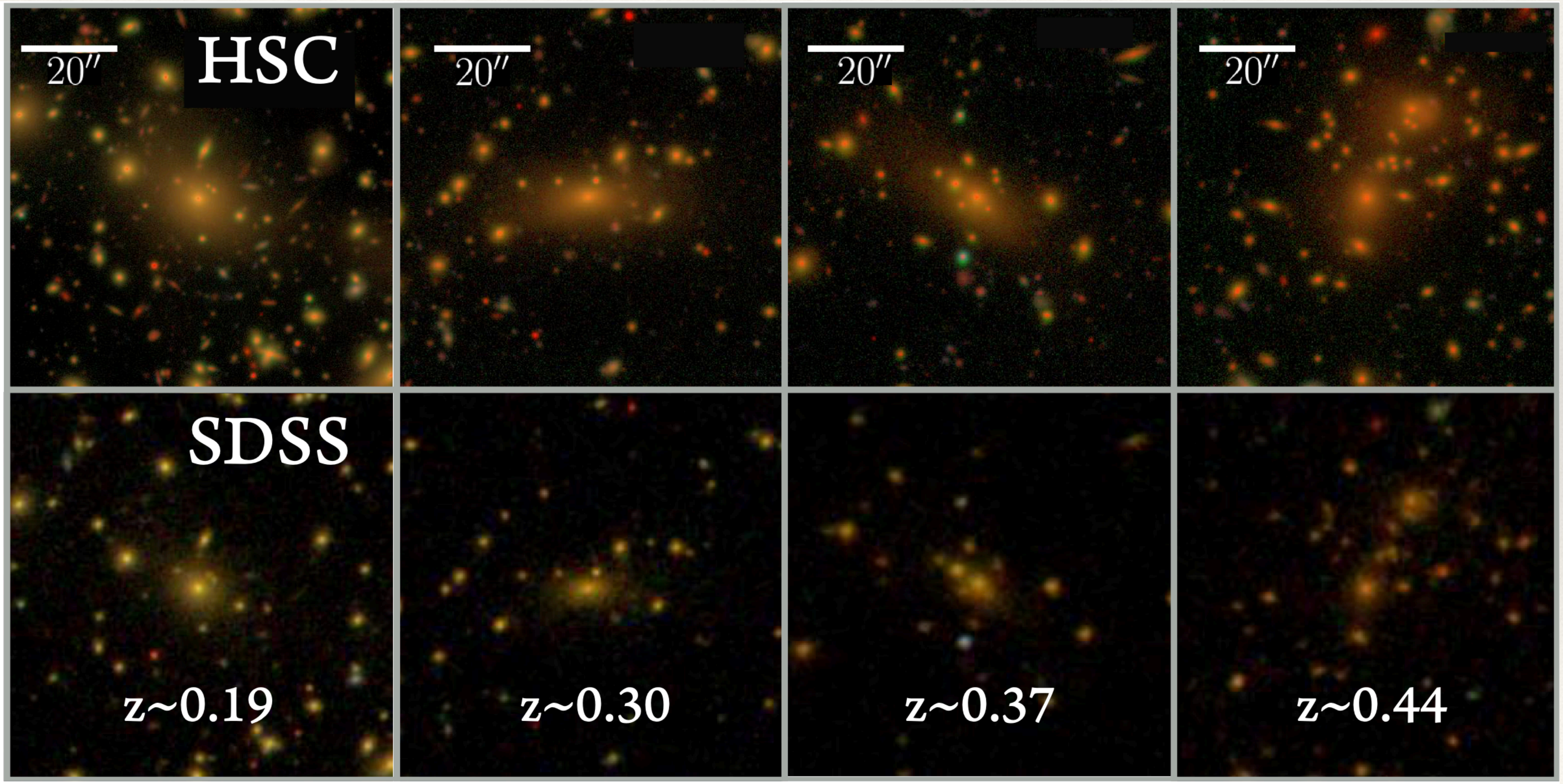


Photo credit: NAOJ, Miyazaki et al. (2018), Komiyama et al. (2018)

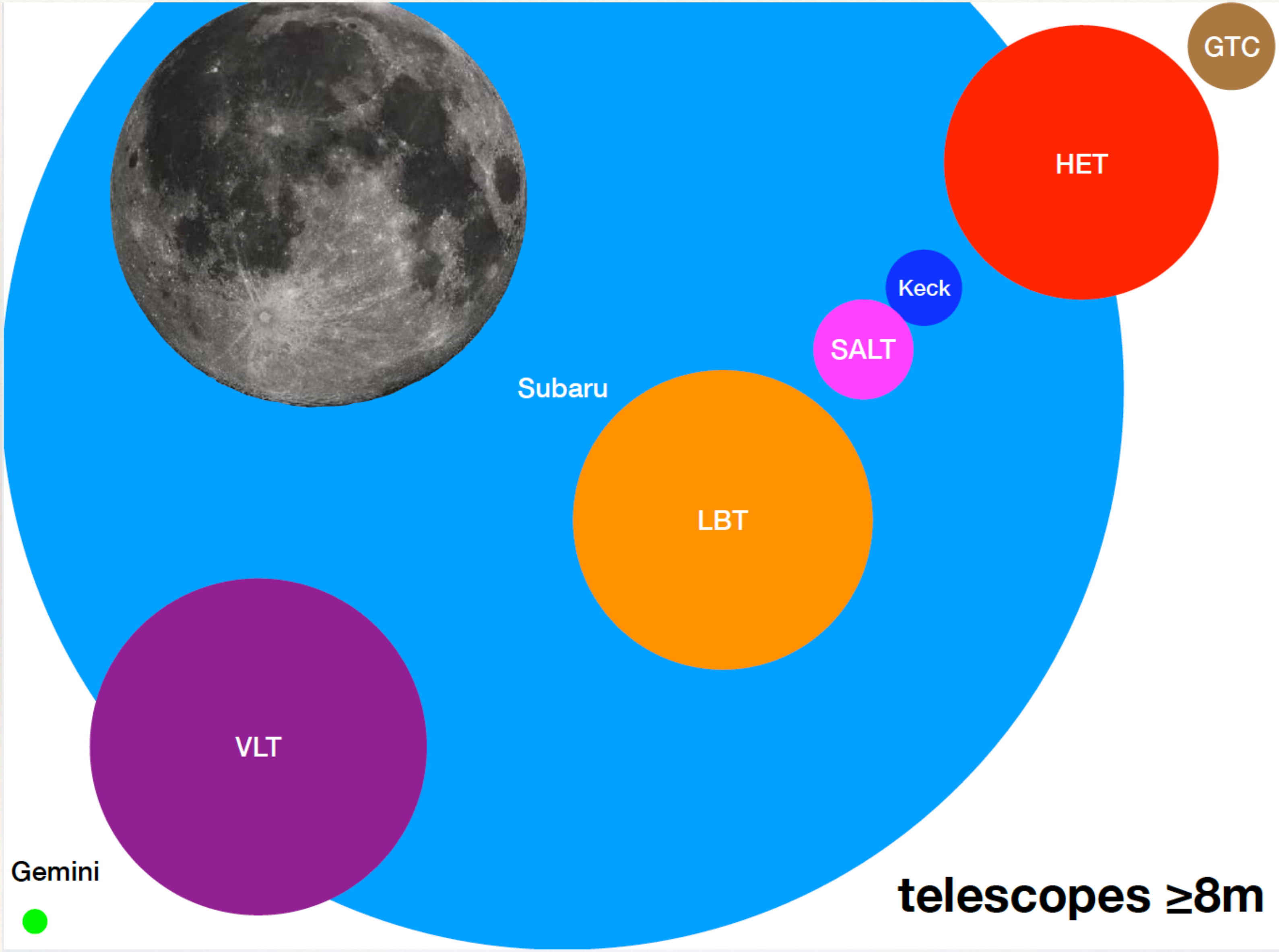
Image quality of HSC

- Superb image quality: PSF~0.6″ → better shape measurement

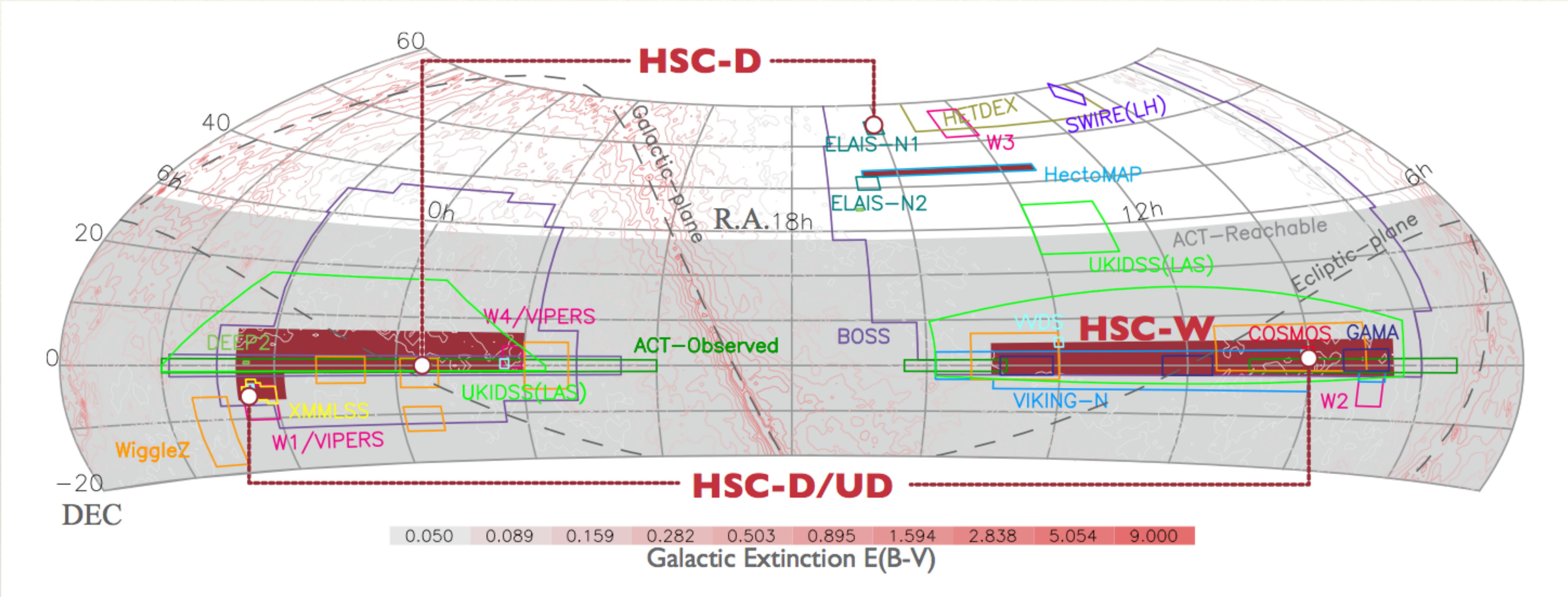


Huang+2017

Subaru Field of View



HSC SSP Survey



- Wide Layer (1200 deg^2, grizy, i_{lim}~26) is designed for weak lensing cosmology (10^8 galaxies).
- Survey started in 2014 and completed at the end of 2021.
- **Third-year data** ~433deg^2.

国立天文台 NAOJ National Astronomical Observatory of Japan

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

PRINCETON UNIVERSITY

中央研究院 天文及天文物理研究所 ACADEMIA SINICA Institute of Astronomy and Astrophysics

Analysis-level blind analysis

- We need to avoid confirmation bias: we might unconsciously correct systematics to match Planck cosmology.
- Analysis-level blinding: When plotting a contour, we **blind the central value and measured signals.**

Nikko Toshogu Shrine, Japan

Internal Consistency Tests

setup label	description	$\mathcal{D}(\boldsymbol{\theta})$, $\mathcal{D}(\mathbf{d})$
fiducial	*baseline analysis* $\mathbf{N}_\mathrm{c} + \mathbf{w}_{\mathrm{p},1-4} + \boldsymbol{\Delta\Sigma}_{1-4}$	21, 68
demp	demp is used to infer the source redshift distribution and for $\boldsymbol{\Delta\Sigma}_{1-4}$ measurement.	21, 68
mizuki	mizuki is used for source sample selection and $\boldsymbol{\Delta\Sigma}_{1-4}$ measurement	21, 68
dNNz	dNNzis used for source sample selection and $\boldsymbol{\Delta\Sigma}_{1-4}$ measurement (same as fiducial)	21, 68
Rmin=0.2	Using the minimum scale cut of $0.2h^{-1}$Mpc for $\boldsymbol{\Delta\Sigma}_{1-4}$	21, 76
Rmin=1.0	Using the minimum scale cut of $1.0h^{-1}$Mpc for $\boldsymbol{\Delta\Sigma}_{1-4}$	21, 64
nonc	$\mathbf{w}_{\mathrm{p},1-4} + \boldsymbol{\Delta\Sigma}_{1-4}$ without $\mathbf{N}_\mathrm{c}$	21, 64
nods	$\mathbf{N}_\mathrm{c} + \mathbf{w}_{\mathrm{p},1-4}$ without $\boldsymbol{\Delta\Sigma}_{1-4}$	21, 28
nowp	$\mathbf{N}_\mathrm{c} + \boldsymbol{\Delta\Sigma}_{1-4}$ without $\mathbf{w}_{\mathrm{p},1-4}$	21, 44
no20to30	$\mathbf{N}_{\mathrm{c},1-3} + \mathbf{w}_{\mathrm{p},1-3} + \boldsymbol{\Delta\Sigma}_{1-3}$ for $\lambda \in [30, 40)$, $[40, 55)$, and $[55, 200)$ but not $\lambda \in [20, 30)$	21, 51
no30to40	the same as above, without the observables for $\lambda \in [30, 40)$	21, 51
no40to55	the same as above, without the observables for $\lambda \in [40, 55)$	21,51
no55to200	the same as above, without the observables for $\lambda \in [55, 200)$	21,51
XMM ($\sim$ 33 deg^2)*	similar to "fiducial", but using the lensing signals of the XMM field alone	21, 68
GAMA15H ($\sim$ 41 deg^2)*	similar to "fiducial", but using the lensing signals of the GAMA15H field alone	21, 68
HECTOMAP ($\sim$ 43 deg^2)*	similar to "fiducial", but using the lensing signals of the HECTOMAP field alone	21, 68
GAMA09H ($\sim$ 78 deg^2)*	similar to "fiducial", but using the lensing signals of the GAMA09H field alone	21, 68
VVDS ($\sim$ 96 deg^2)*	similar to "fiducial", but using the lensing signals of the VVDS field alone	21, 68
WIDE12H ($\sim$ 121 deg^2)*	similar to "fiducial", but using the lensing signals of the WIDE12H field alone	21, 68
dpzs	randomly sampling Δz_ph from the chain provided by Li et al. (2023)	22, 69
dm	using a uniform prior of $\Delta m = \mathcal{U}(-0.05, 0.05)$	22, 69

Internal Consistency Tests

Photo-z

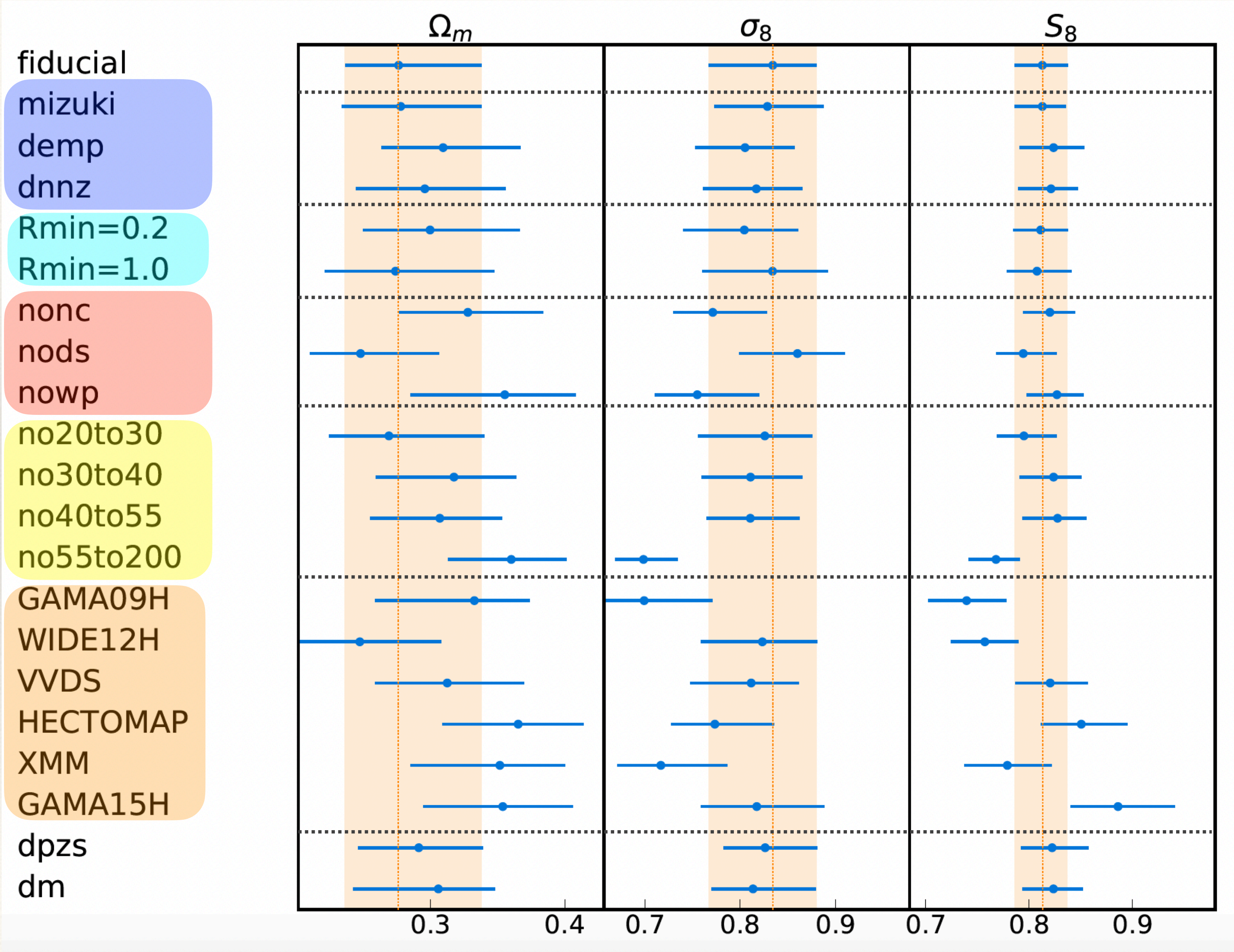
Scale cuts

Observables

Richness bins

Area

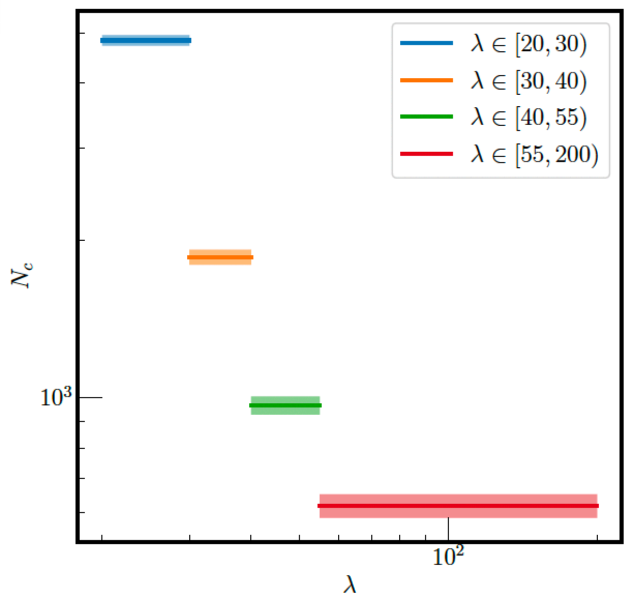
Residual Syetamatics



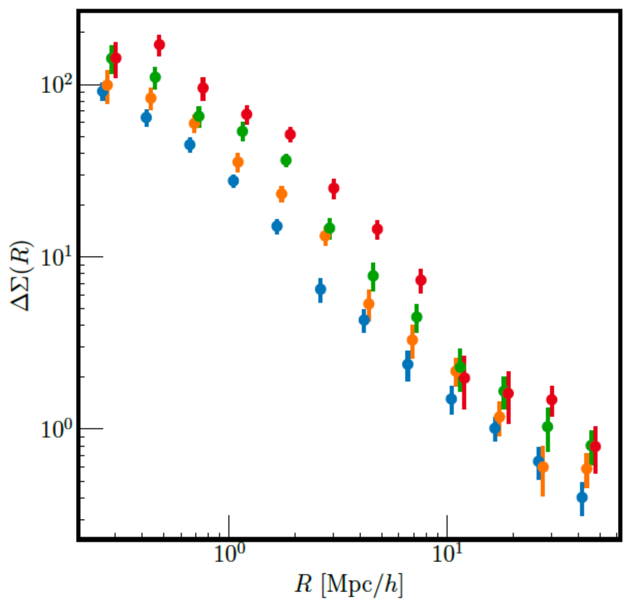
Measuring cluster observables

- We measure cluster abundance and clustering from SDSS redMaPPer clusters and lensing signals using HSC-Y3 source catalog.

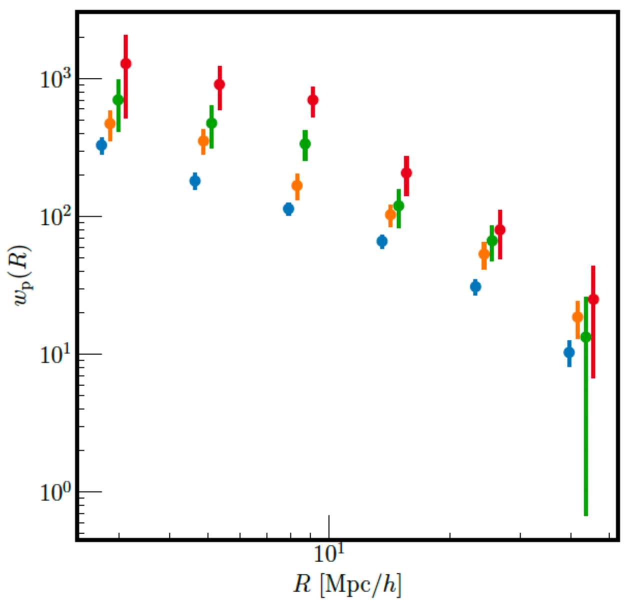
Abundance



Lensing



Clustering

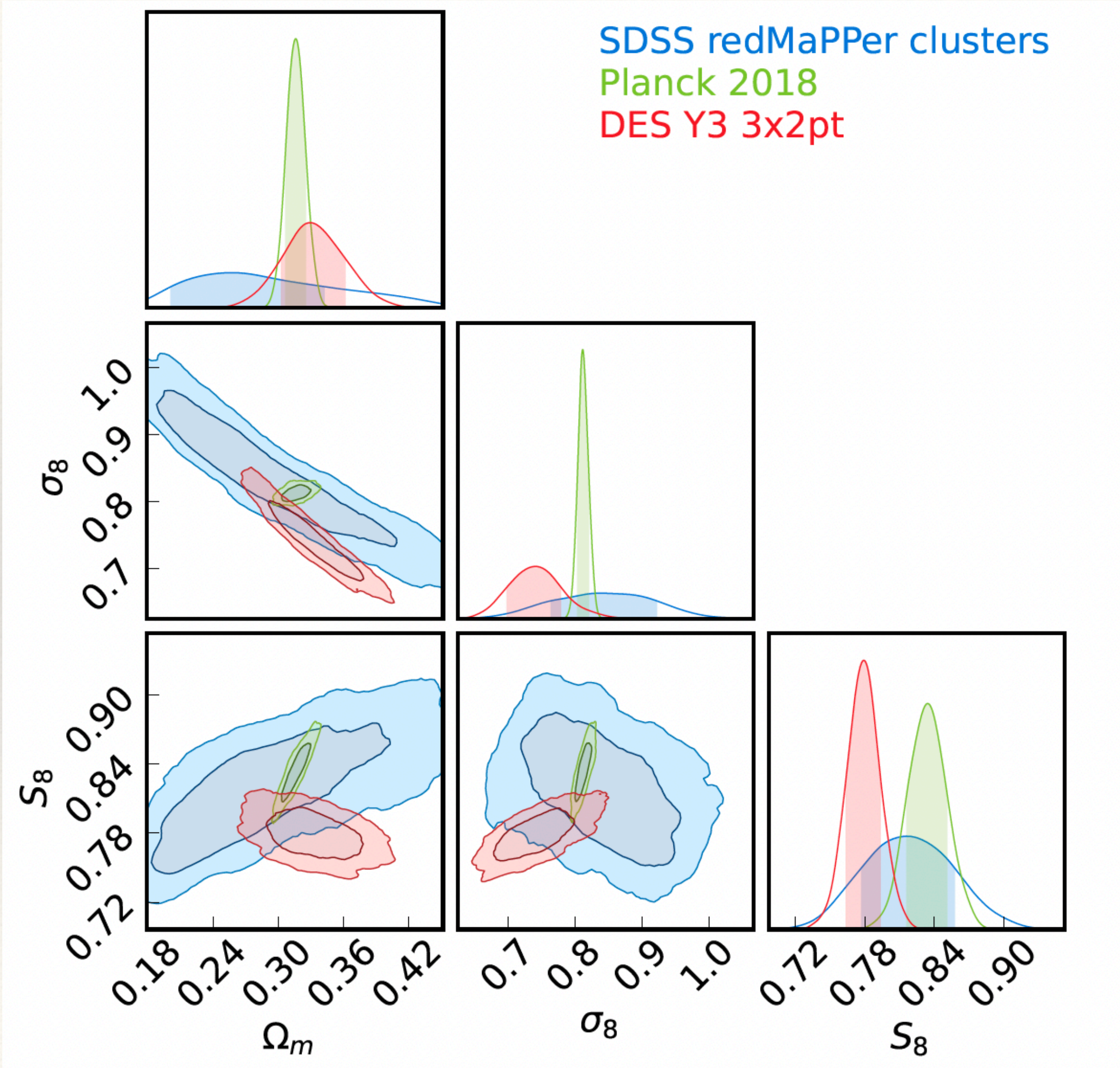


Result: SDSS clusters+HSC lensing

$$\Omega_m = 0.258^{+0.085}_{-0.057}$$

$$\sigma_8 = 0.838^{+0.083}_{-0.074}$$

$$S_8 = 0.816^{+0.041}_{0.039}$$

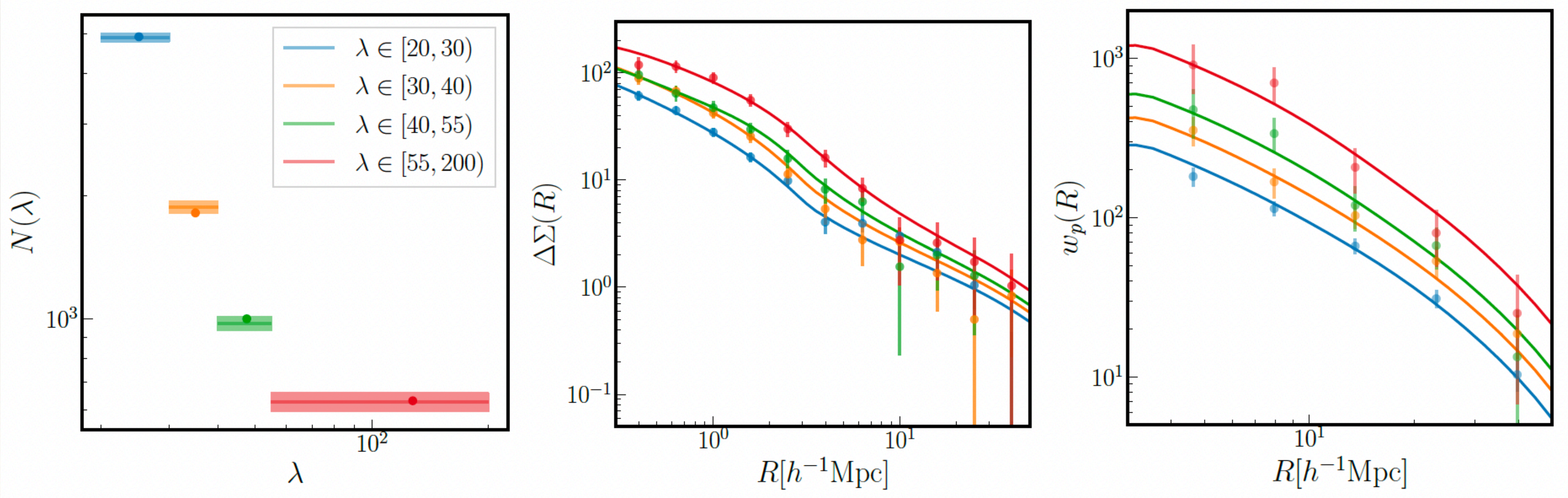


Sunayama+2023:2309.13025

Comparing with the best-fit parameters

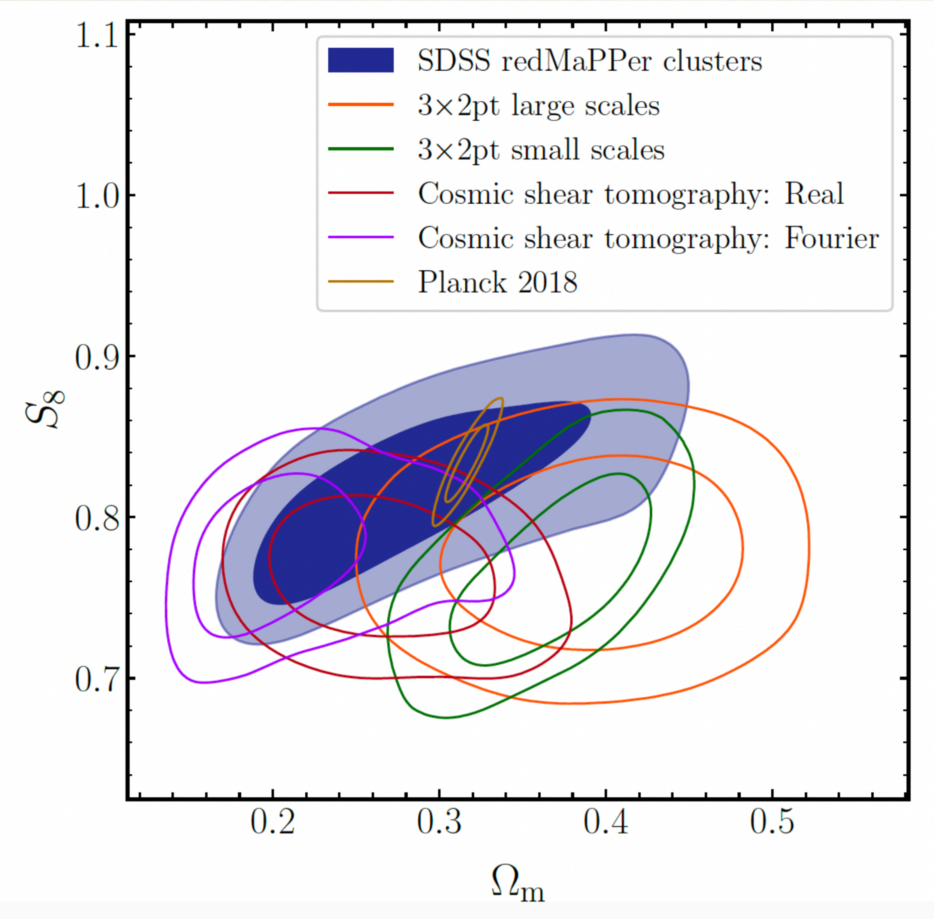
- The measured cluster observables and the best-fit predictions agree well (χ^2/dof = 34.8/47).

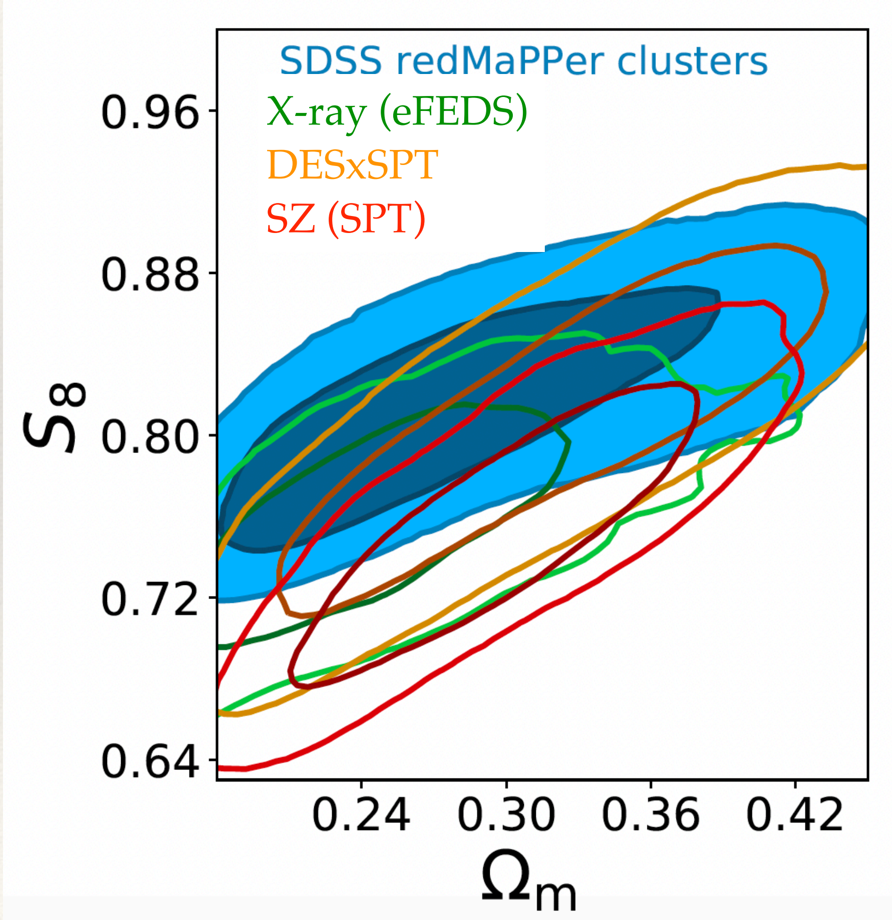
Abundance Lensing Clustering



Comparing to other HSC-Y3/Cluster analyses

- Our results are consistent with other HSC-Y3 and cluster cosmology analyses at the level of 1-sigma on S_8



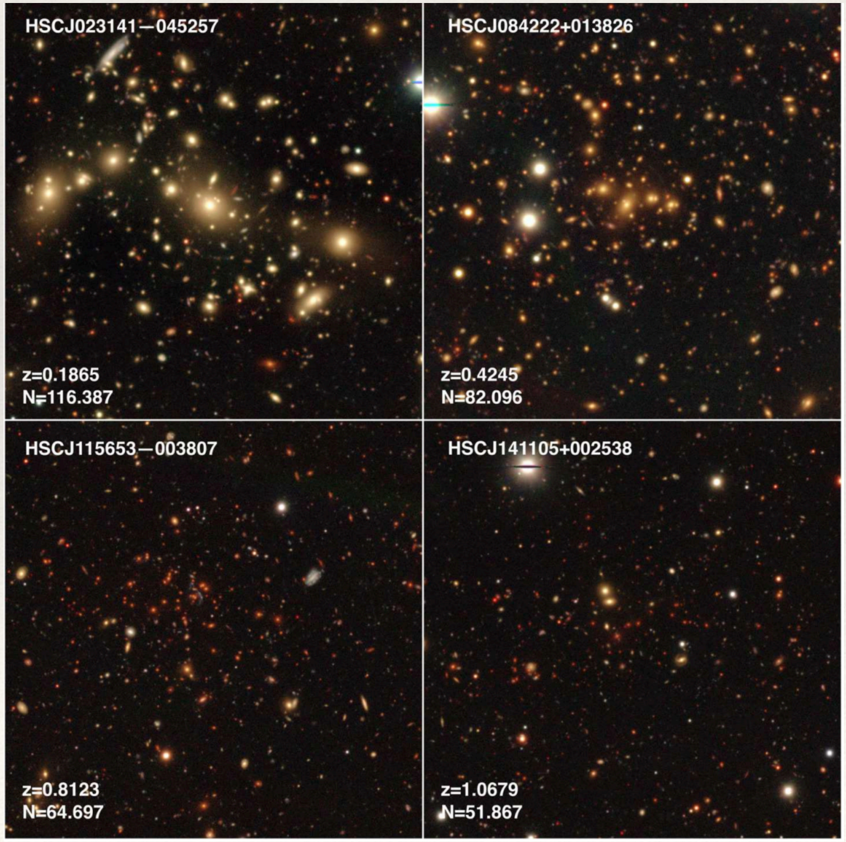


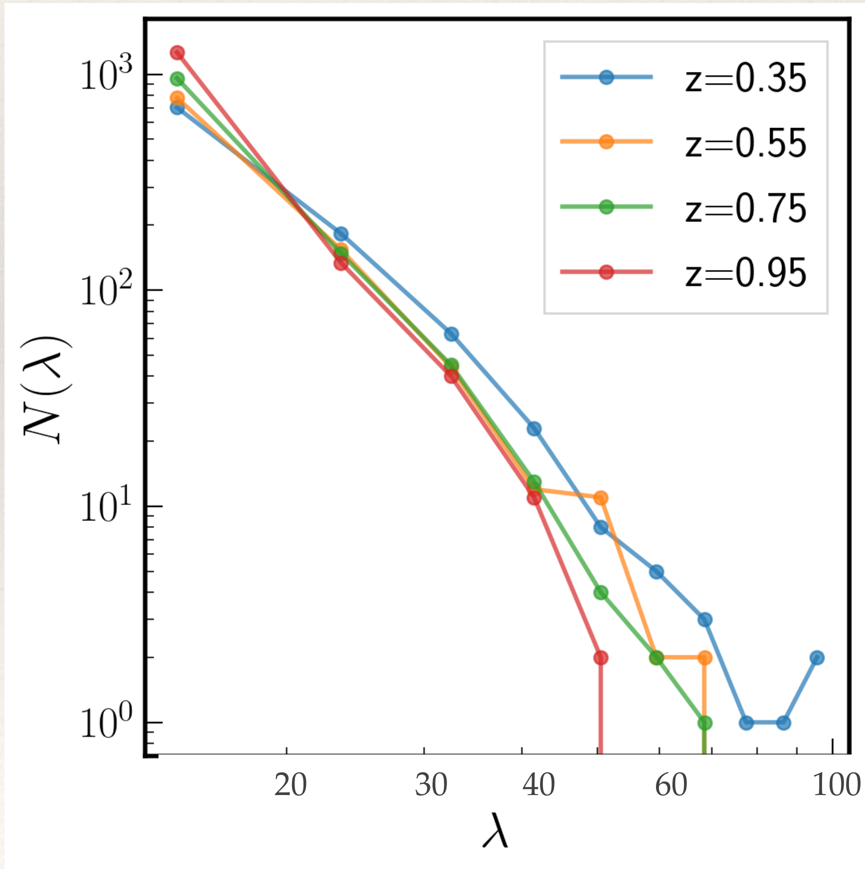
Summary

- This is the first study after DES Y1 cluster analysis to constrain cosmological parameters consistent with other CMB/LSS probes by using only optical cluster observables.
- Optical clusters are susceptible to projection effects, which alter not only the mass-richness relation but also lensing/clustering signals on large scales
- Due to preferential selection of aligned filaments along LOS, the distribution of optical clusters is anisotropic and therefore boosts the amplitude of clustering/lensing on large scales
- Accurate modeling of projection effects is crucial

What's next?

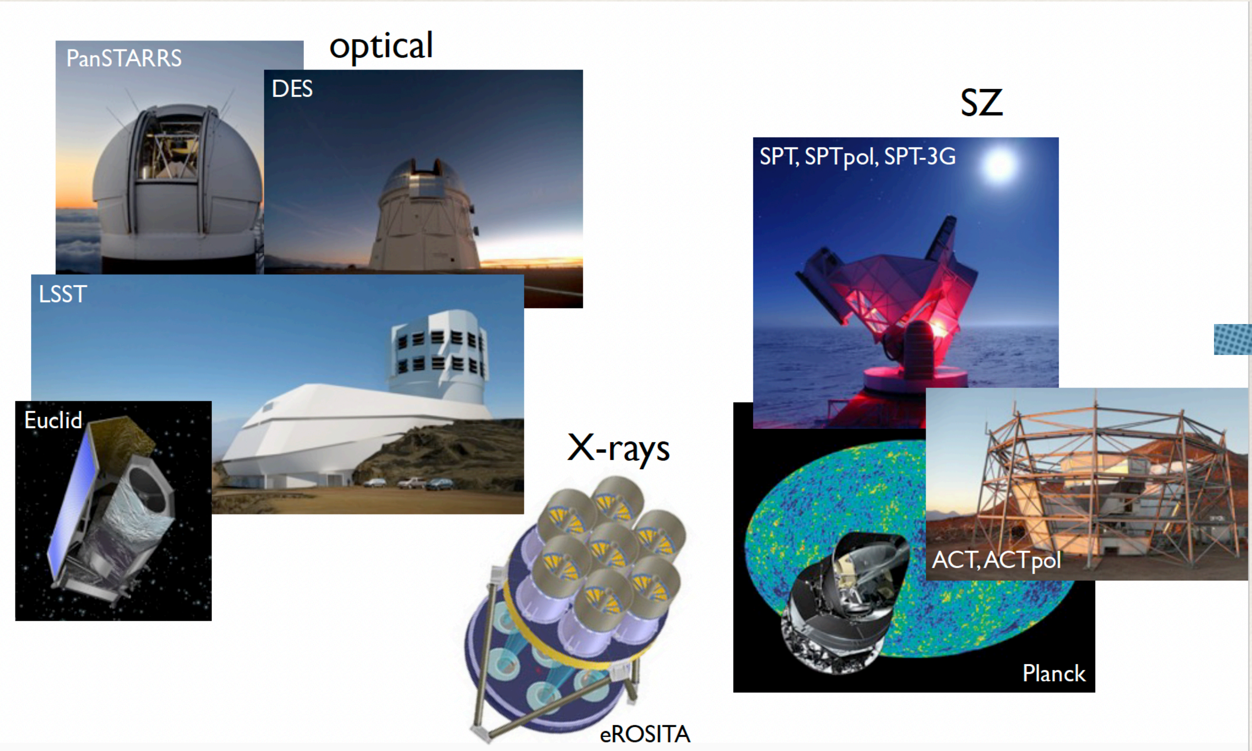
- HSC completed the survey last year, and now people are working on final year catalog (~1200deg^2)
- HSC is much deeper than SDSS: we can track the evolution of galaxy clusters up to $z \sim 1.2 \rightarrow$ better constraint on Ω_m

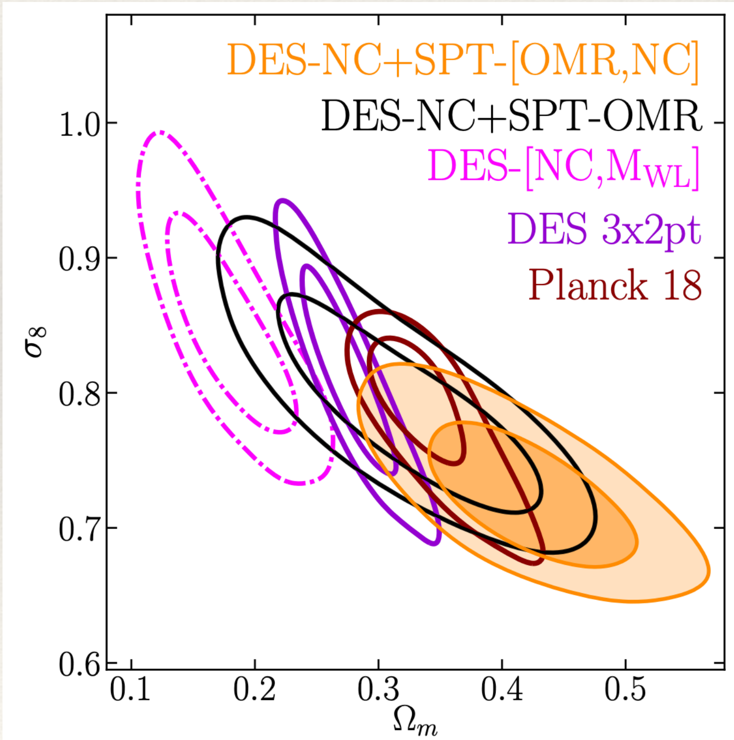




A multi-wavelength approach

- Combining data from different surveys can provide a more comprehensive picture of clusters
- Different data can improve self-calibration of systematics





Costanzi+2020

Optical Cluster Cosmology with DESI

- Spectroscopic data for cluster central galaxies enables us to measure 3D clustering

→ BAO can constrain Ω_m better, RSD can provide kinematic information around clusters and anisotropic structure due to projection effects can be self-calibrated better

→ possibly IA can further improve the precision

- Finding different ways to identify clusters…

→ Using other galaxy properties (such as stellar mass) which are highly correlated with halo mass to identify clusters (e.g., Xhajik+2023)

Thank you!