Weak Lensing Cosmology

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Outline

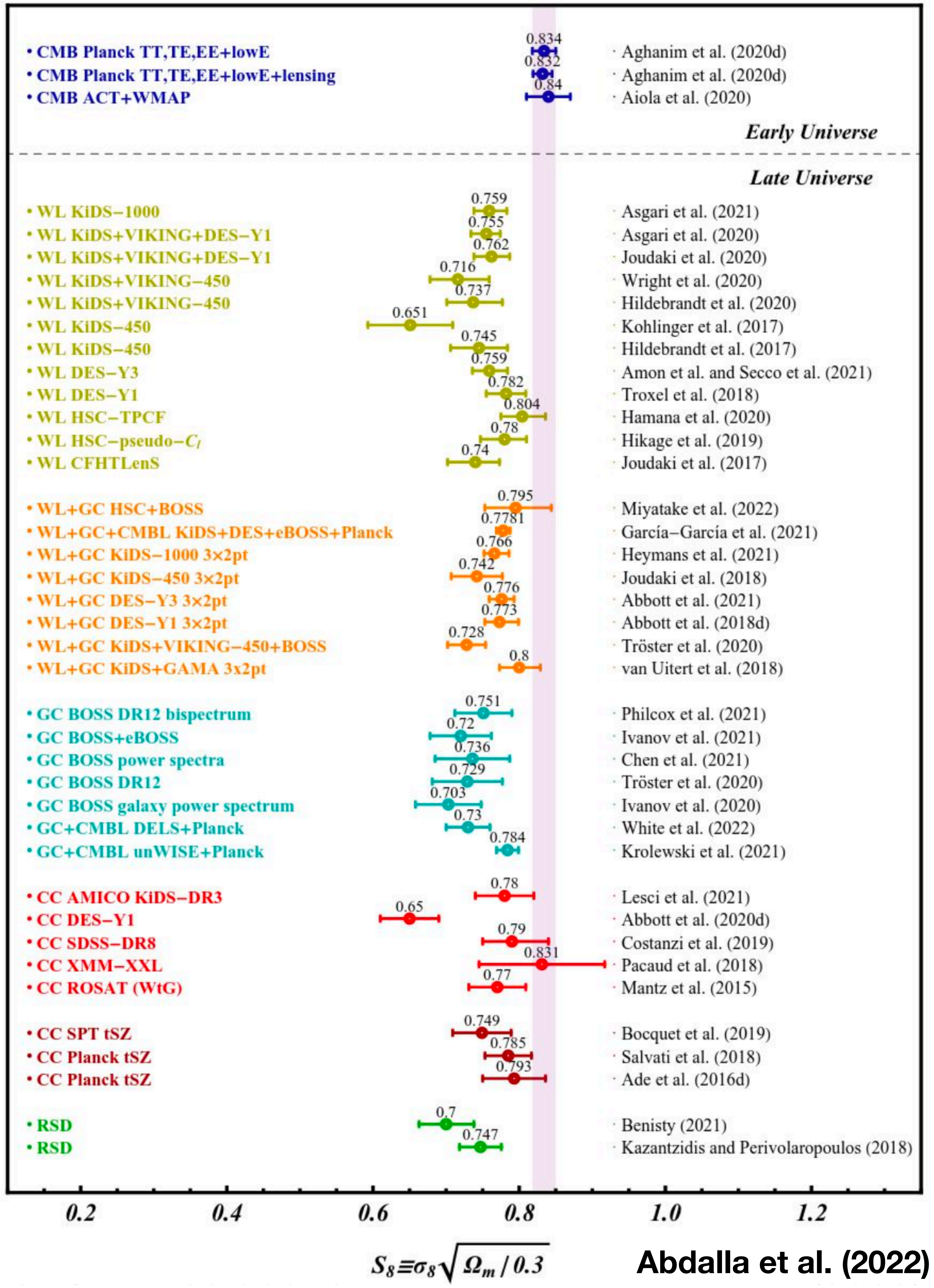
- S_8 tension and weak lensing surveys
- Review of Stage-III survey results (biased towards HSC!)
  - Differences in analysis choices
  - Approaches for systematics
    - Non-linear regime
    - redshift uncertainties
    - intrinsic alignment
    - baryonic effects
- Cosmology with CMB lensing tomography with high-z galaxies

S_8 Tension

$$S_8 \equiv \sigma_8 \sqrt{\Omega_\mathrm{m}/0.3}$$

- σ_8 : Amplitude of linear power spectrum on the scale of 8 Mpc/h
- Ω_m : Energy dense of matter (incl. dark matter)

Most **large scale structure** probes prefer smaller S_8 compared to **CMB**, if we assume ΛCDM.



CMB

Large Scale Structure

Abdalla et al. (2022)

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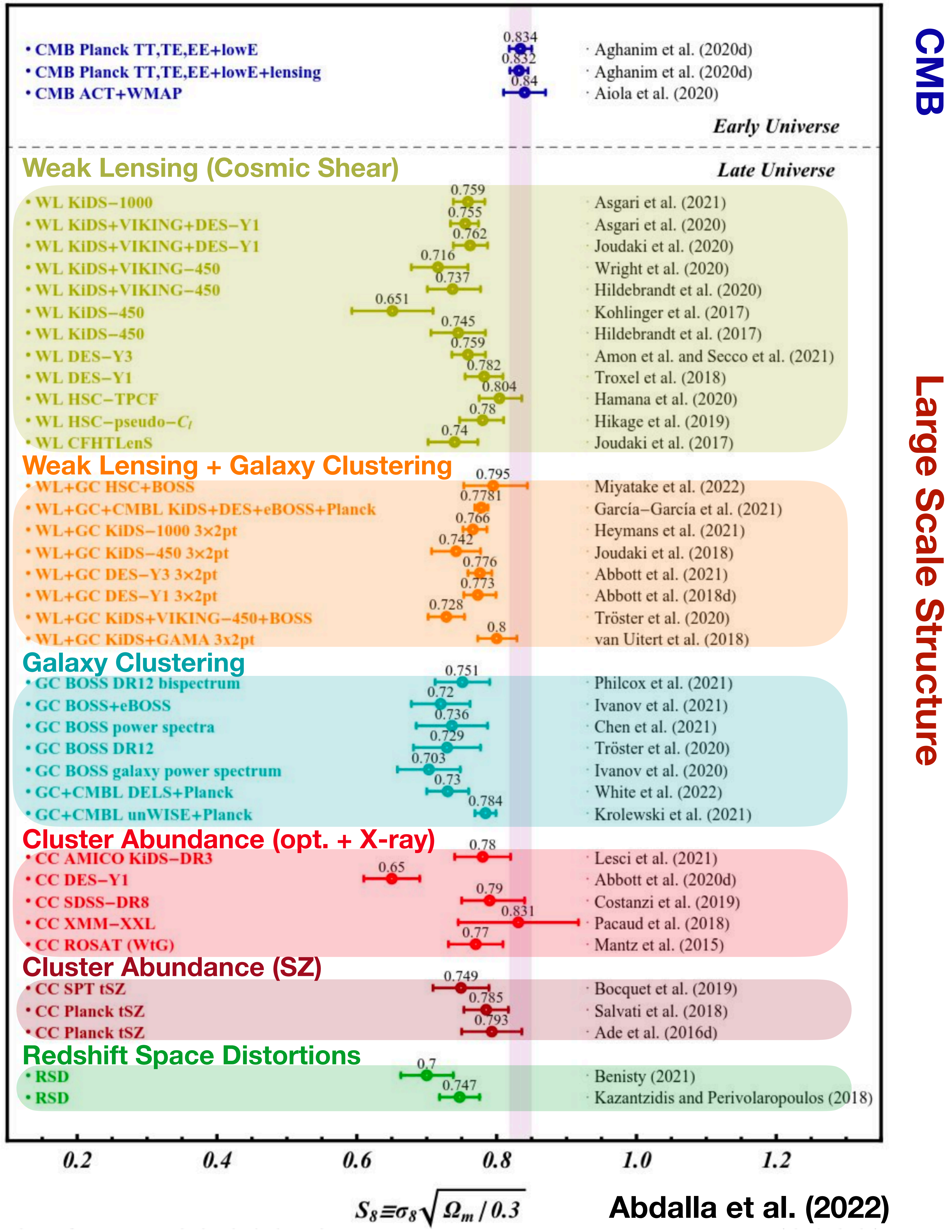

Abdalla et al. (2022)

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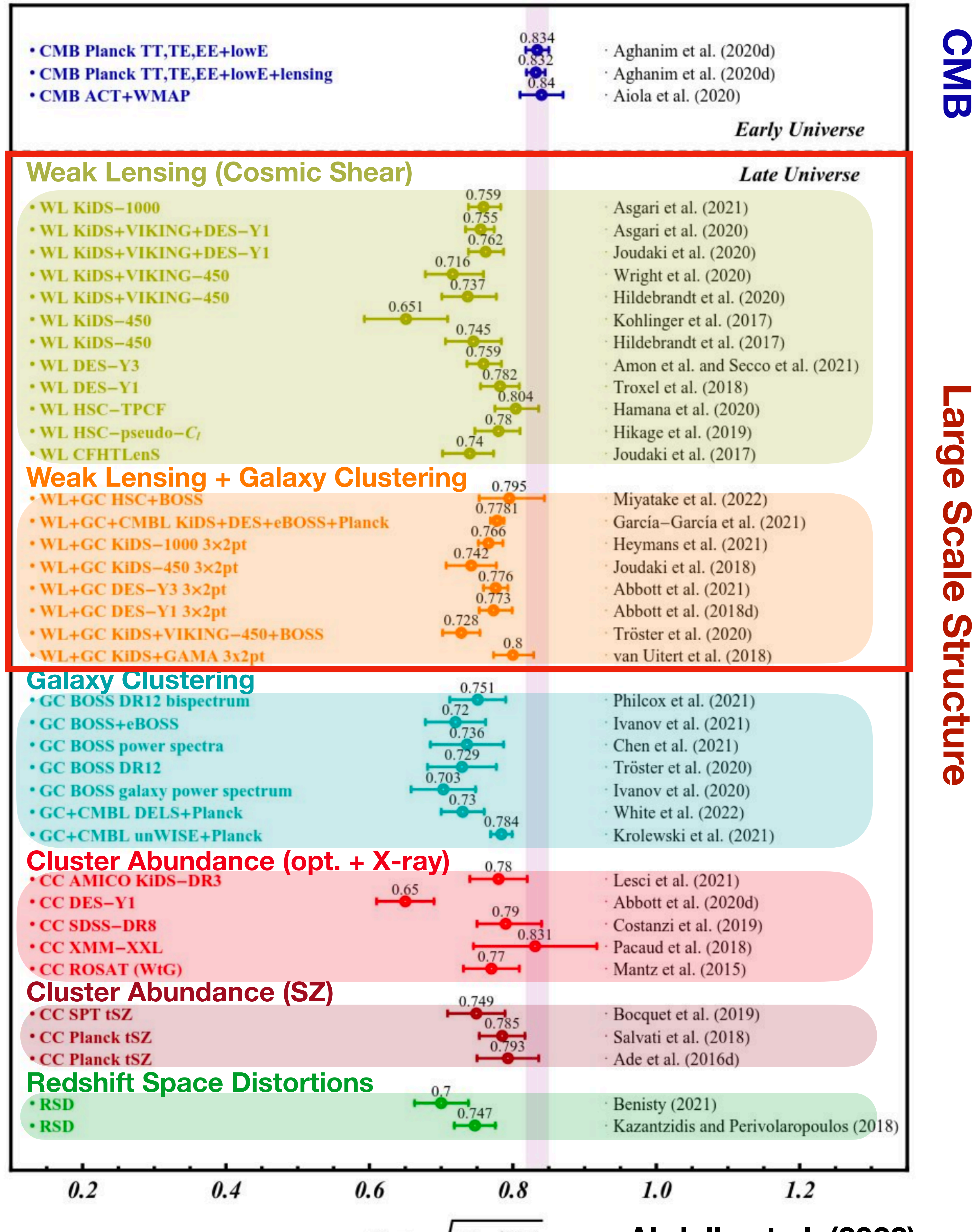
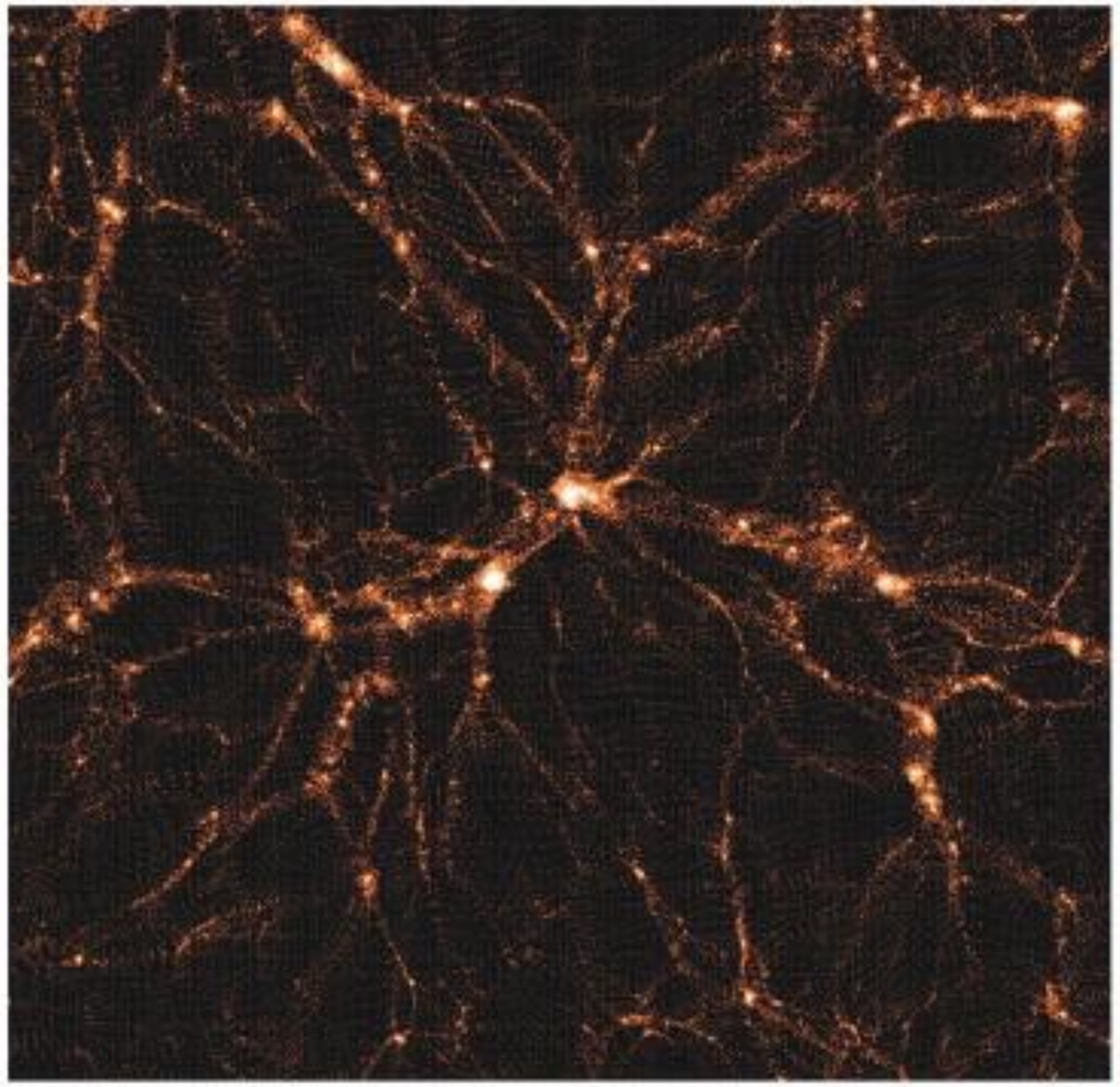


Abdalla et al. (2022)

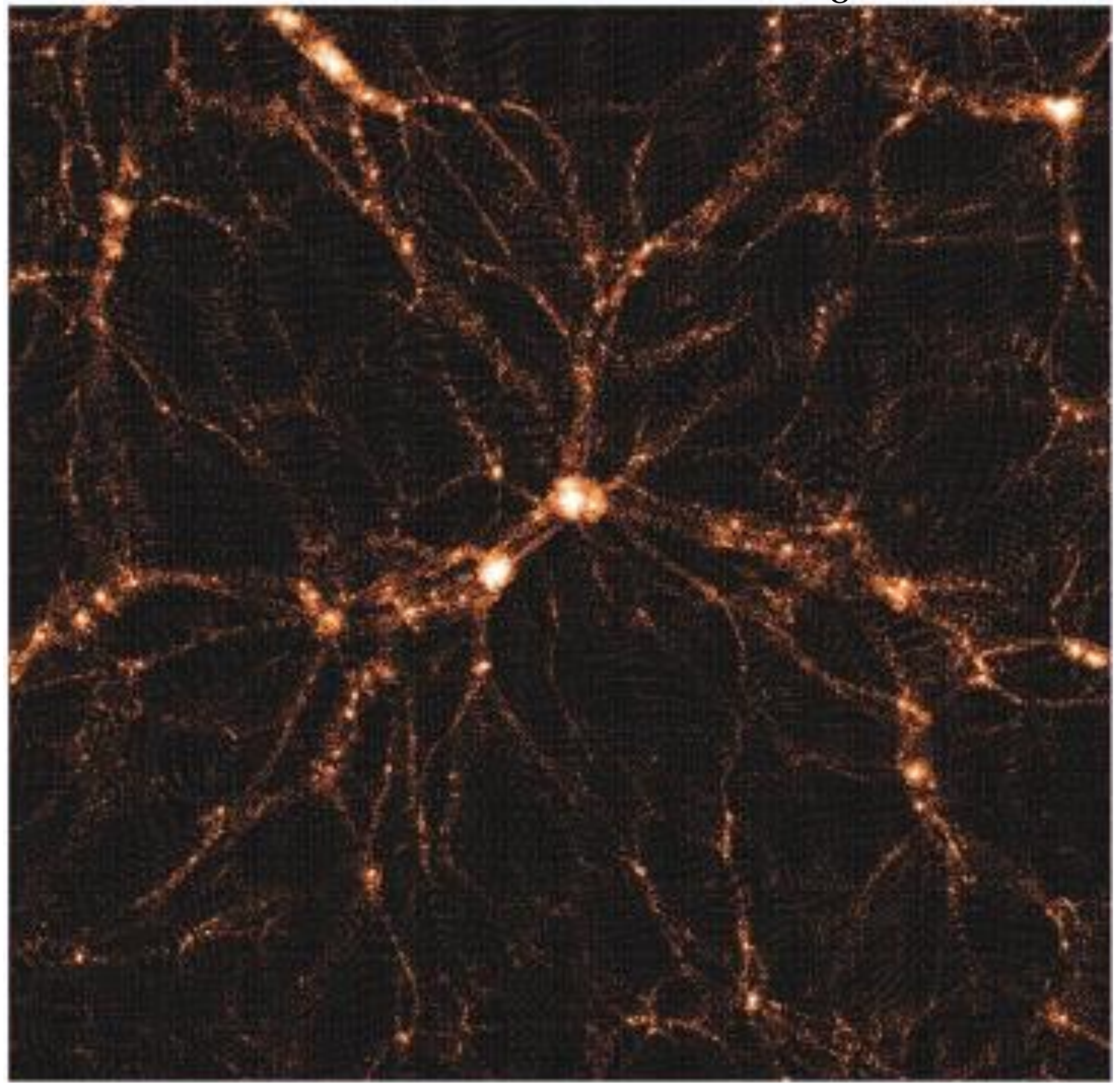
Large Scale Structure

HSC-Y1 cosmic shear: $S_8 = 0.78$



Hikage et al. (2019)

Planck 2020 Primary CMB: $S_8 = 0.83$



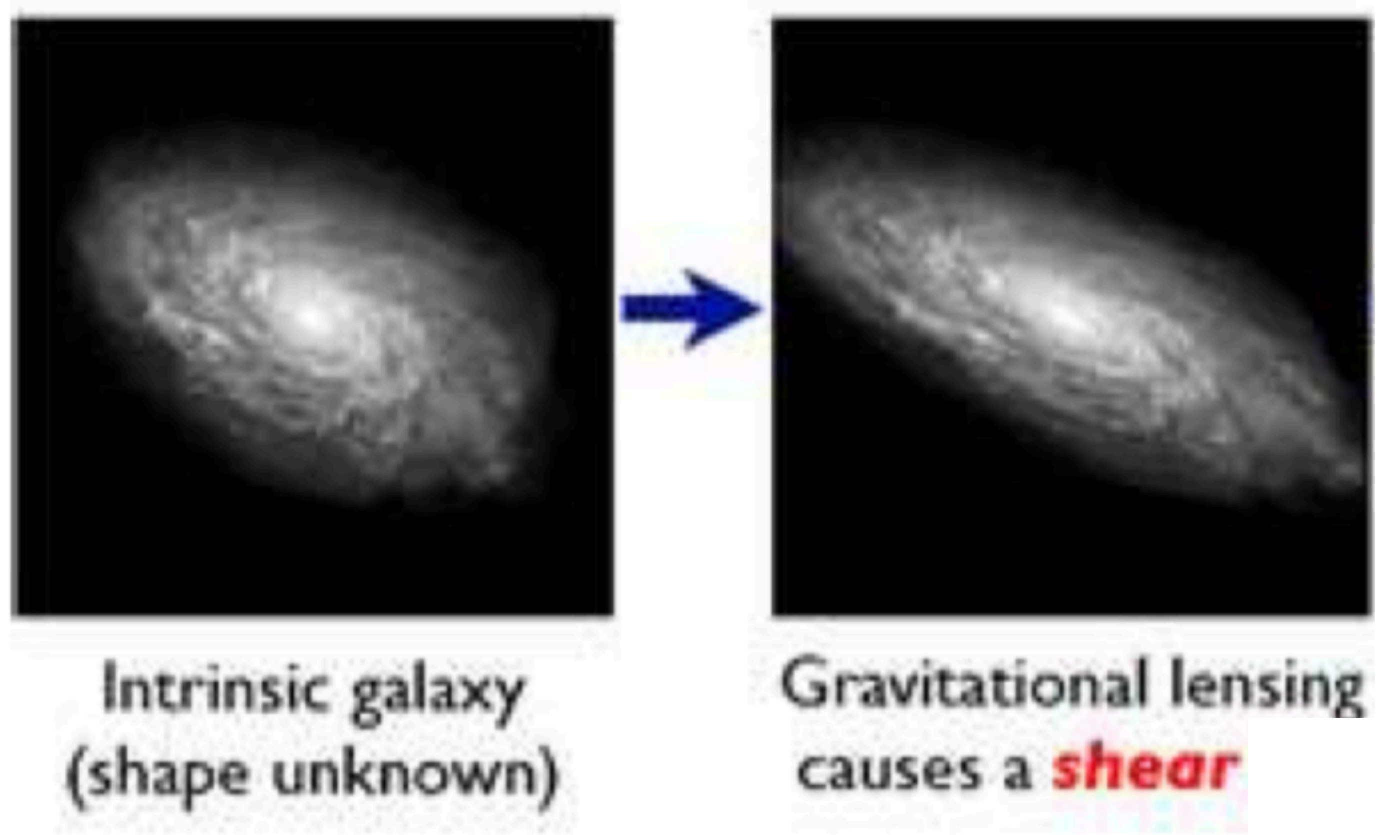
Planck Collaboration (2020)

Credit: T. Nishimichi

We need to measure the difference between LSS above.
Challenge: Most of the matter is dark matter

Weak Gravitational Lensing

Credit: S. Bridle

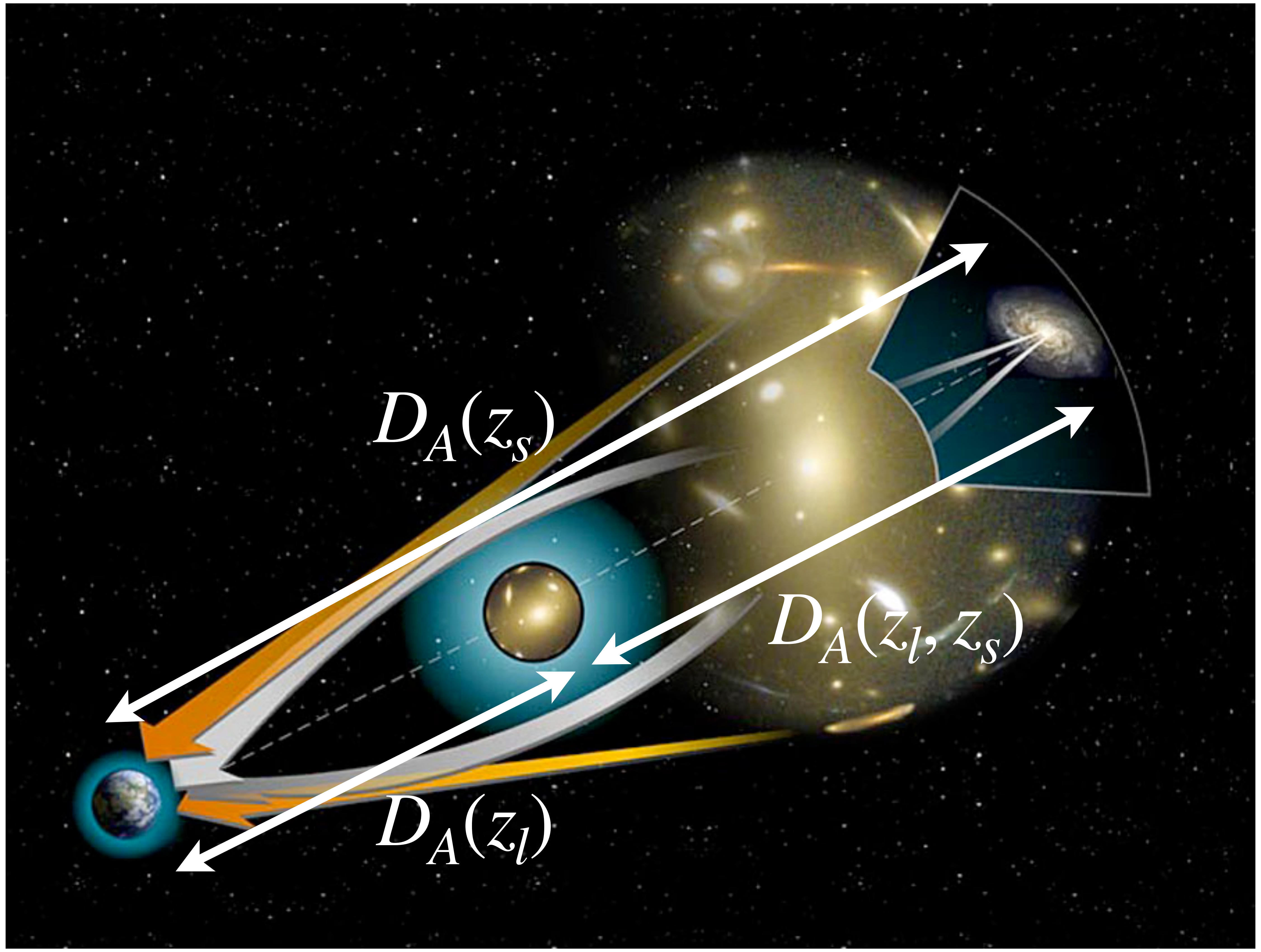


$$\gamma \sim \Omega_m \frac{D_A(z_l, z_s) D_A(z_l)}{D_A(z_s)} \delta_m(z_l)$$

Weak lensing shear

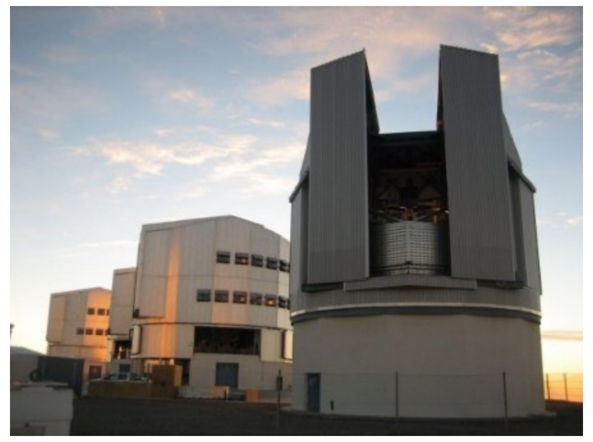
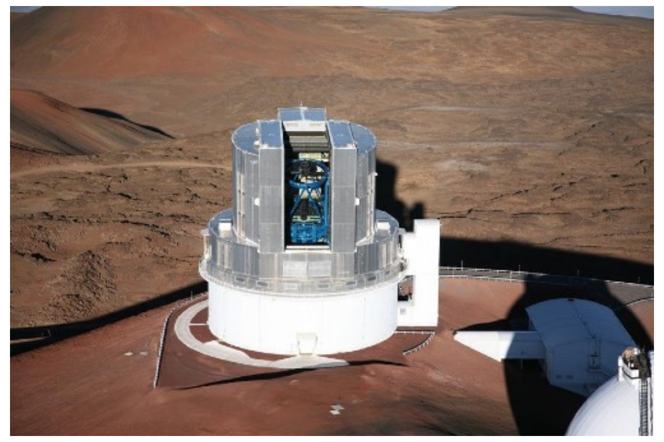
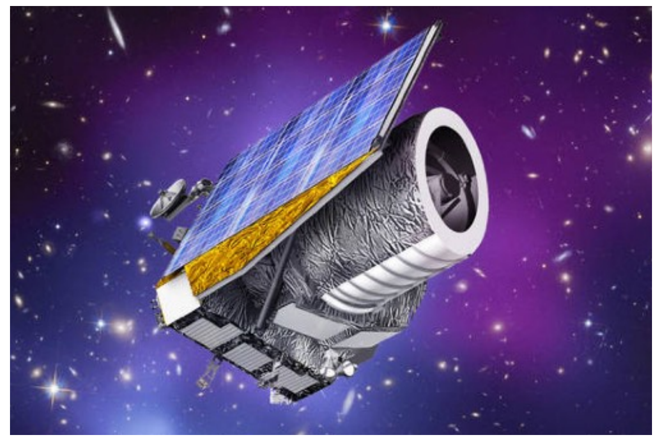
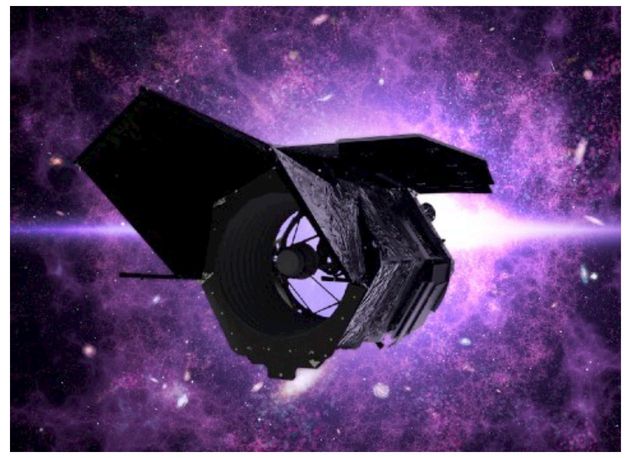
Geometry of the Universe

Matter density fluctuation



Weak lensing enables us to measure matter (incl. dark matter) distributions in the Universe.

Weak Lensing Surveys: Now and Future

	KiDS (Europe)	DES (USA)	Subaru HSC (Japan)	Euclid (Europe)	Rubin Observatory's LSST (USA)	Roman Space Telescope (USA)
						
Primary Mirror [m]	2.6	4.0	8.2	1.2	8.4	2.4
Galaxy Number Density [$arcmin^{-2}$]	11	10	25	30	30	50
Survey Area [sq. deg]	1,500	5,000	1,400	15,000	18,000	2,200

All sky ~41,253 [sq. deg]

2010 2020 2030

Inspired by E. Krause

Credit: ESO, Fermilab/Reidar Hahn, NAOJ, ESA/C. Carreau, Rubin Obs/NSF/AURA, NASA

Weak Lensing Surveys: Now and Future

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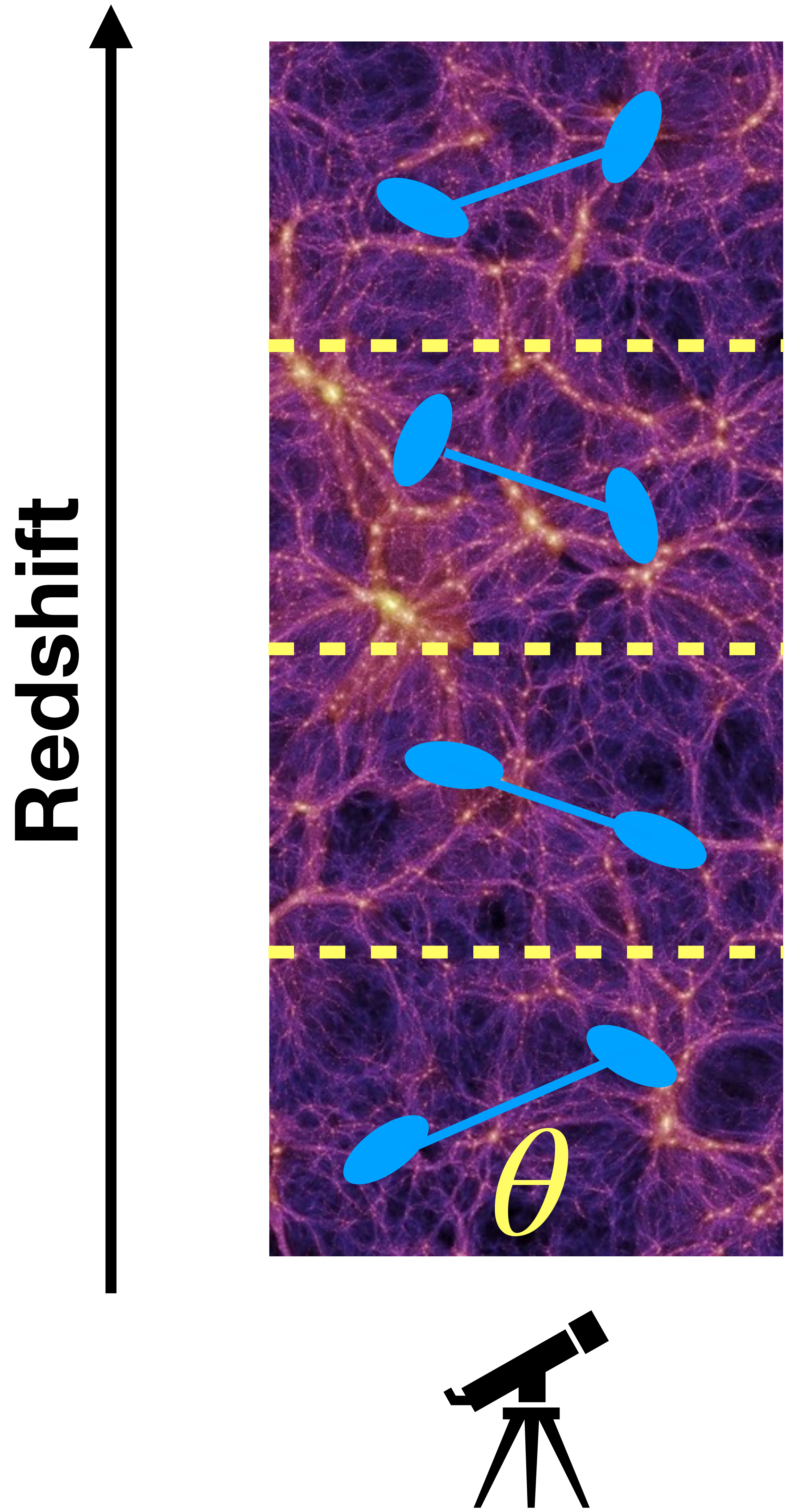
Cosmic Shear



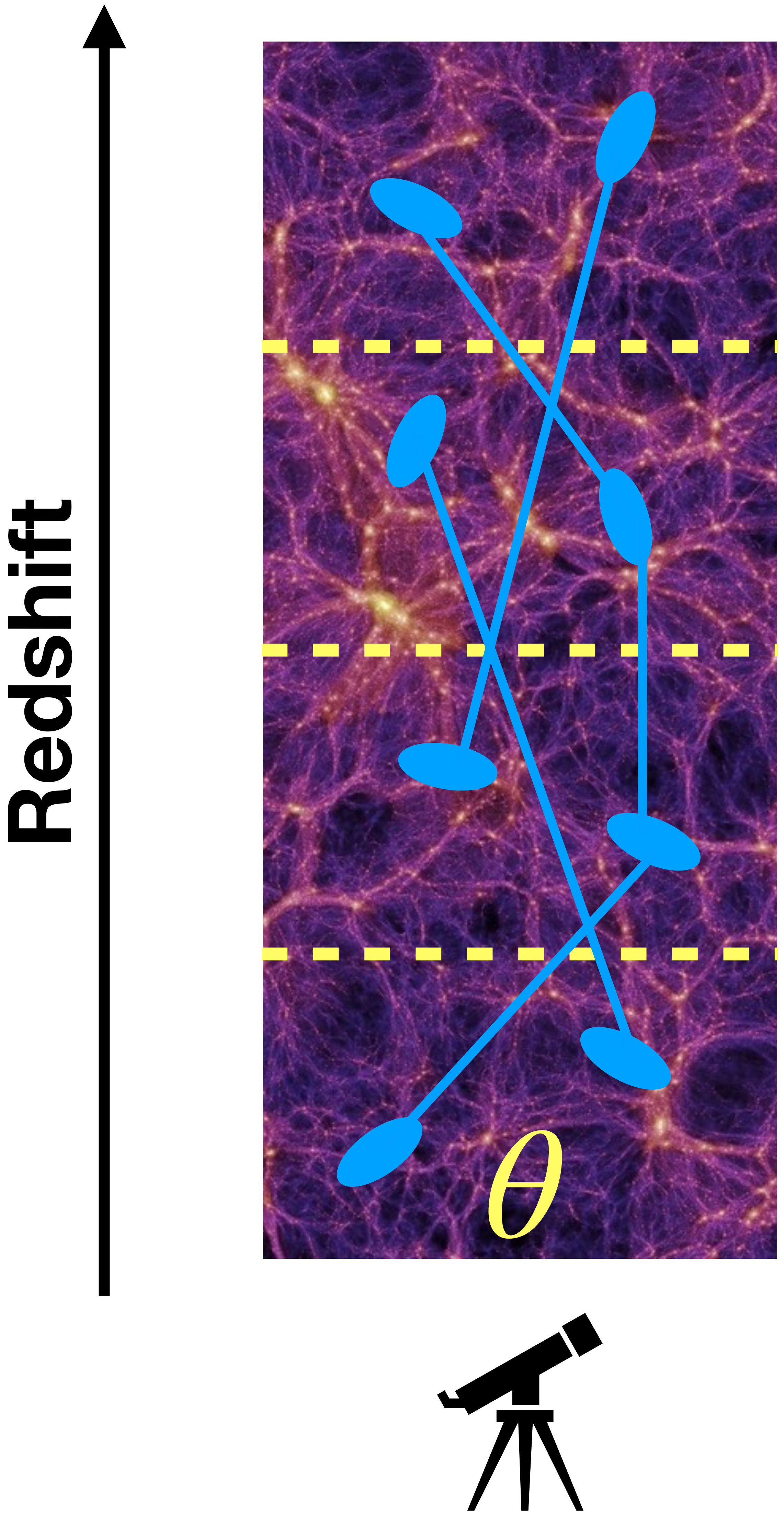
$$\xi_{\pm}(\theta) = \langle \gamma_{+}(\theta')\gamma_{+}(\theta' + \theta)\rangle_{\theta'} \pm \langle \gamma_{\times}(\theta')\gamma_{\times}(\theta' + \theta)\rangle_{\theta'}$$
$$\sim \xi_{\rm mm}(\theta; \sigma_8, \Omega_{\rm m})$$

Note: θ is angular scales (not separation between galaxies)

Correlation can be computed within a redshirt bin

Credit: Millennium Simlations

Cosmic Shear



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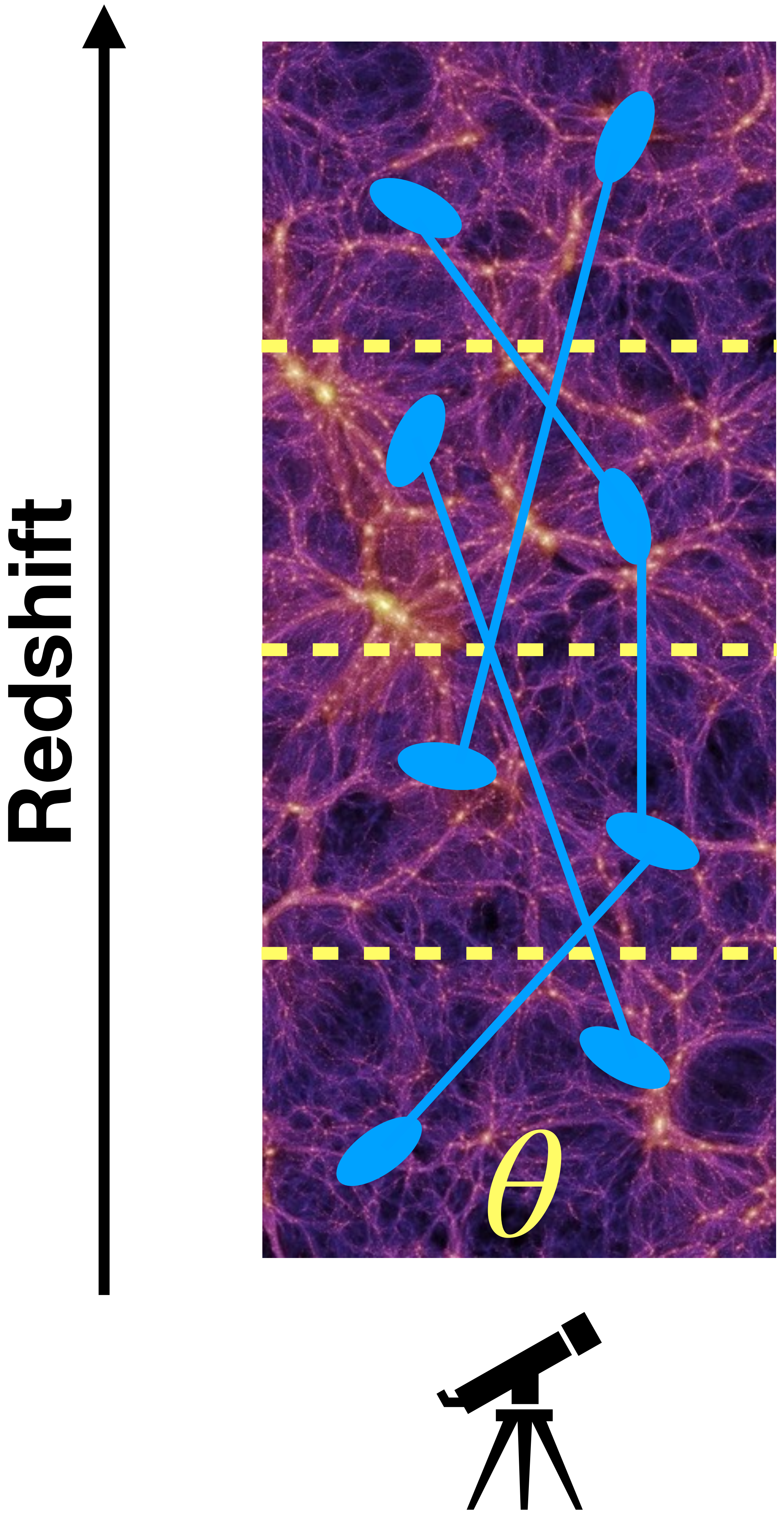

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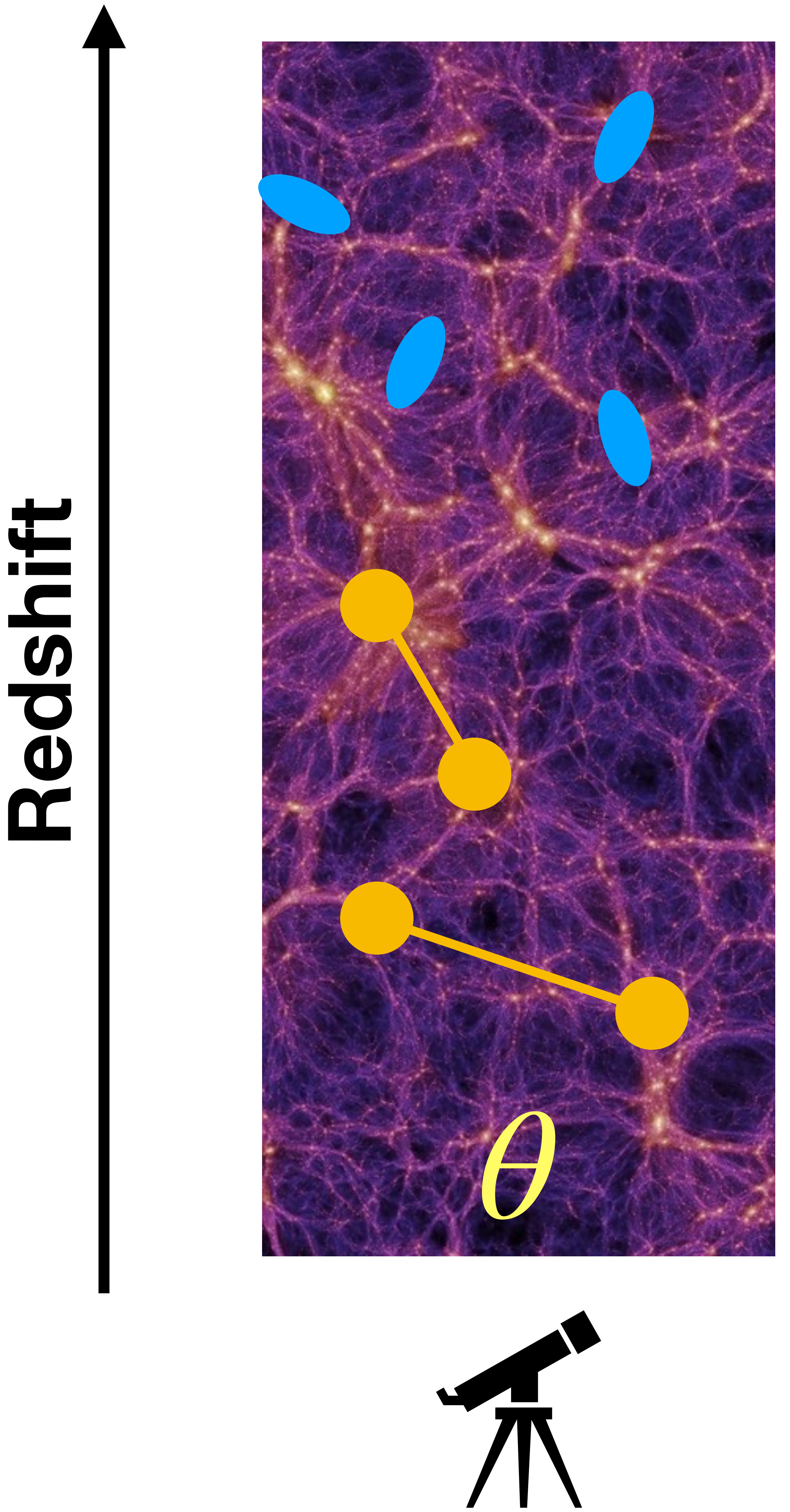
Note: θ is angular scales (not separation between galaxies)

Correlation can be computed within a redshirt bin or across redshift bins

Fourier space measurements $C_{\rm EE}(l), C_{\rm BB}(l)$ are also common now.

Credit: Millennium Simlations

2x2pt: Galaxy-galaxy Clustering and Lensing



(Projected) Galaxy-galaxy clustering

$$w(\theta) \sim \langle \delta_g(\theta')\delta_g(\theta' + \theta)\rangle_{\theta'} \sim b^2 \xi_{\rm mm}(\theta; \sigma_8, \Omega_{\rm m})$$

Linear bias factor

Linear bias approximation: $\delta_g \sim b\delta_m$ (valid at large scales)

Credit: Millennium Simulations

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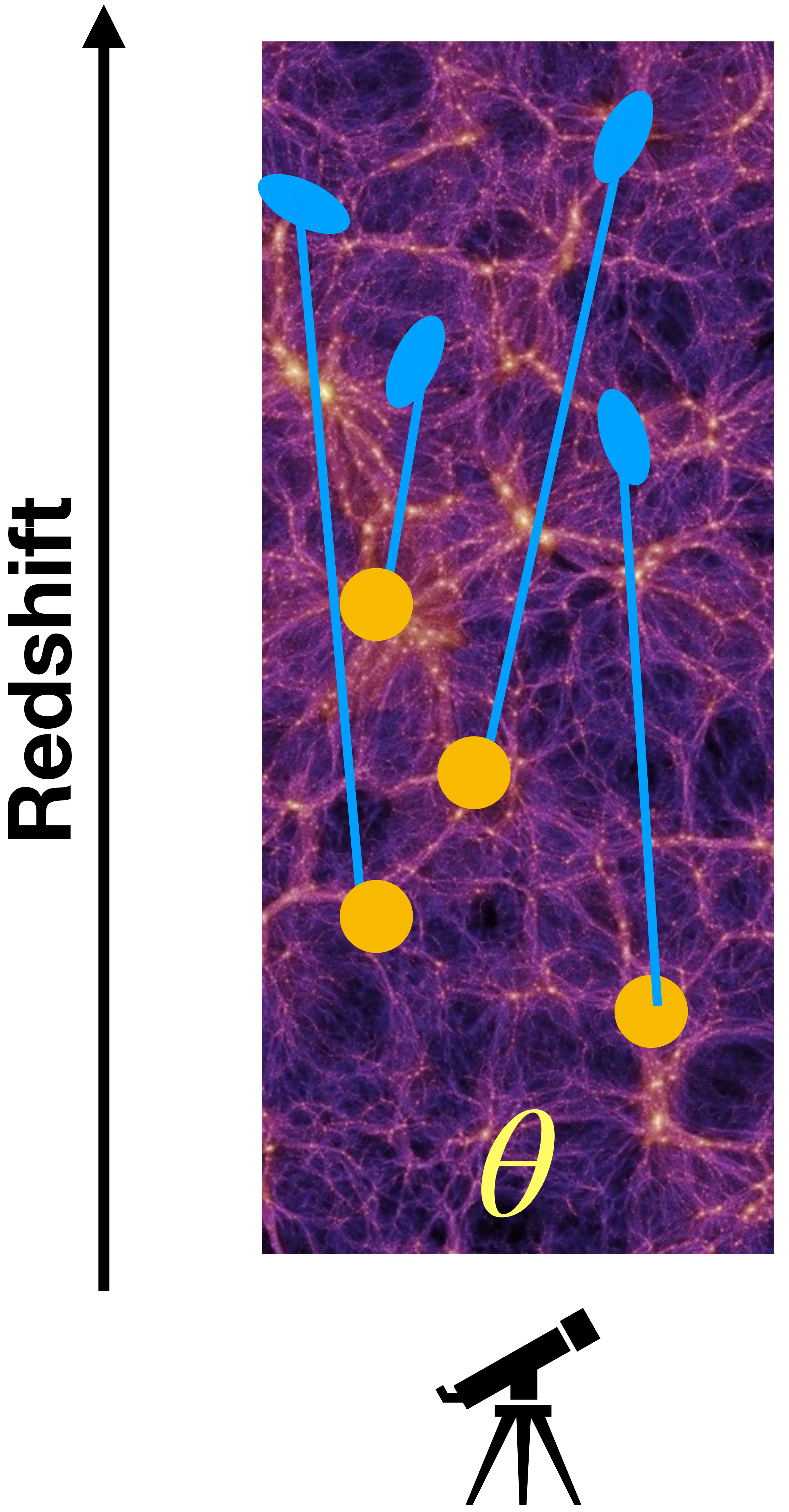

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Galaxy-galaxy lensing

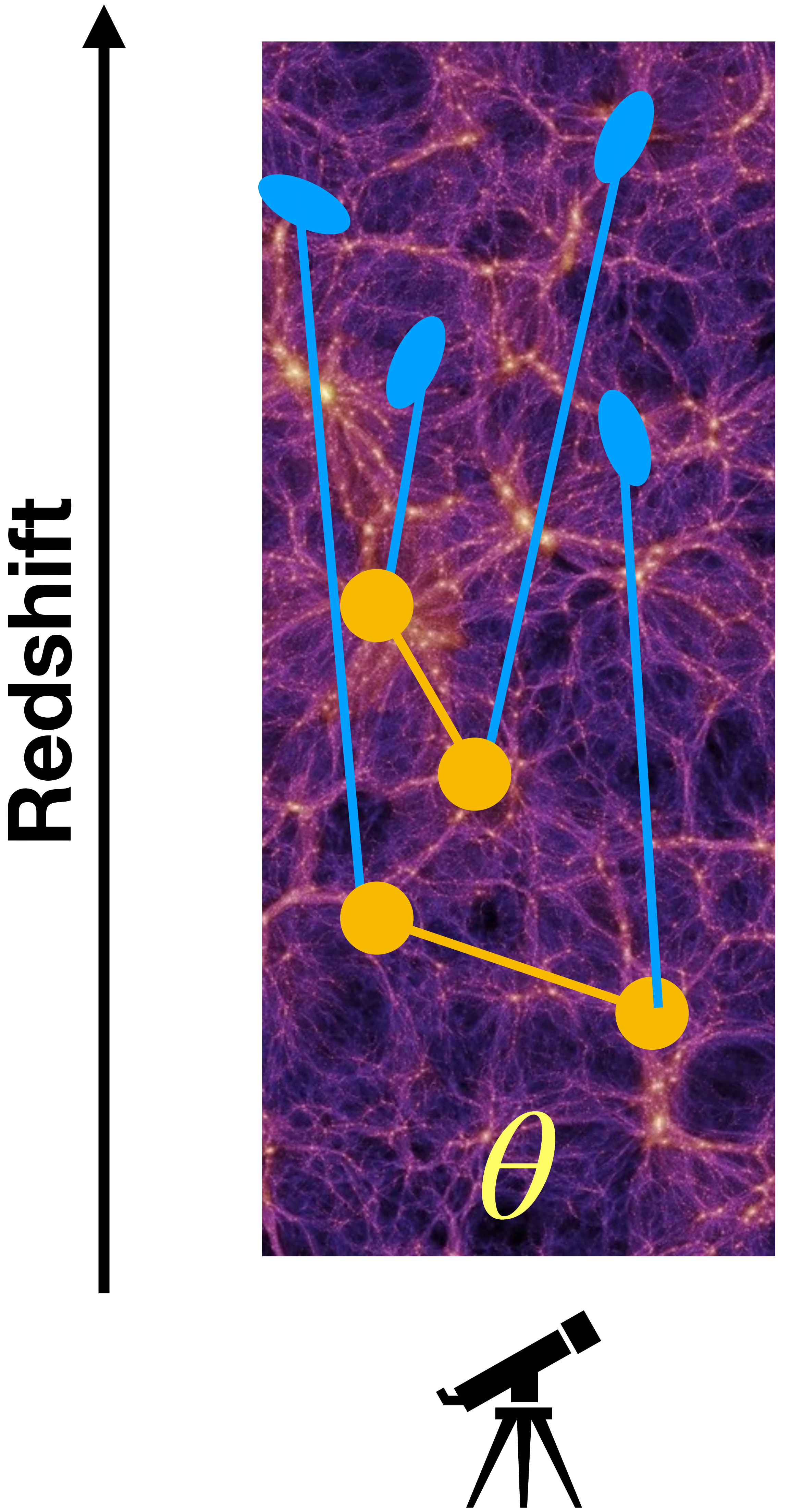
$$\gamma(\theta) \sim \Omega_{\rm m}\Sigma_{\rm cr}(z_l, z_s)^{-1}\langle \delta_g(\theta')\delta_m(\theta'+\theta)\rangle_{\theta'}$$
$$\sim \Omega_{\rm m}\Sigma_{\rm cr}(z_l, z_s)^{-1} b \xi_{\rm mm}(\theta; \sigma_8, \Omega_{\rm m})$$

where

$$\Sigma_{\rm cr} \propto \frac{D_A(z_s)}{D_A(z_l, z_s)D_A(z_l)}$$

Credit: Millennium Simulations

2x2pt: Galaxy-galaxy Clustering and Lensing



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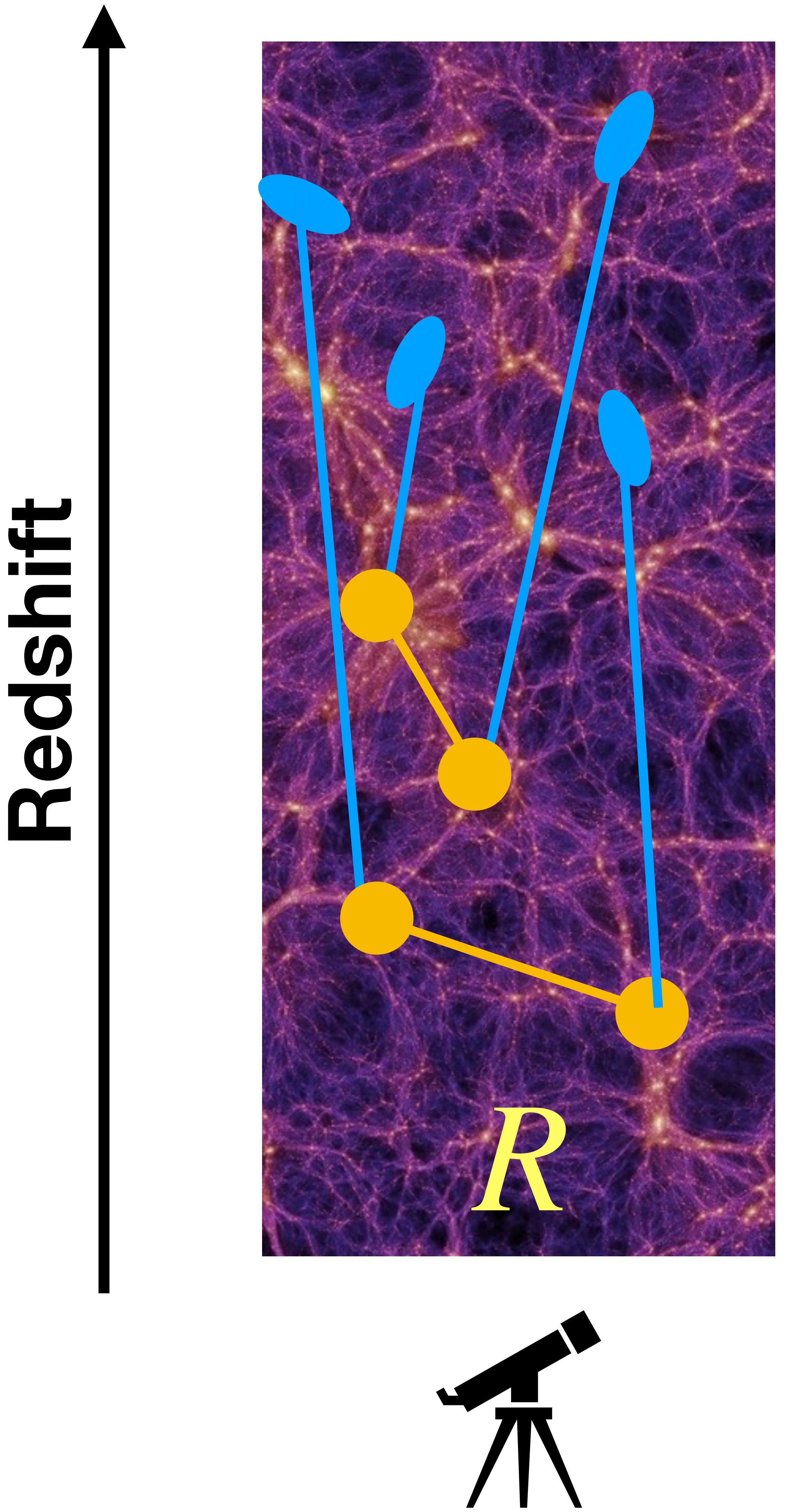
where $\Sigma_{\rm cr} \propto \dfrac{D_A(z_s)}{D_A(z_l, z_s)D_A(z_l)}$

Combination of Galaxy-galaxy clustering and lensing breaks the degeneracy between b and $(\sigma_8, \Omega_{\rm m})$.
Foreground galaxies are called tracers.

Credit: Millennium Simulations

2x2pt: Galaxy-galaxy Clustering and Lensing



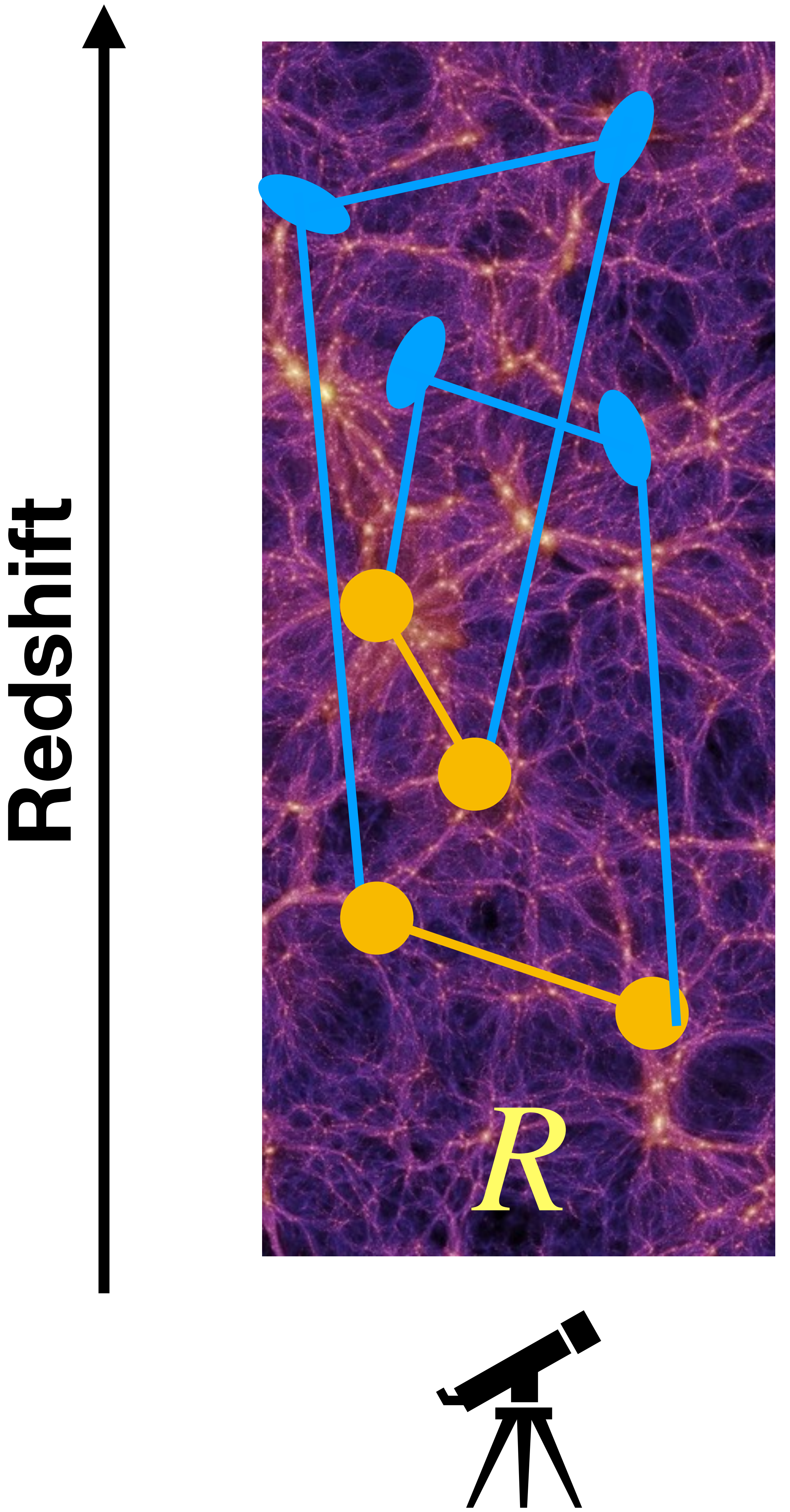
If we have a spectroscopic sample for clustering

$$w_{\rm p}(R) \sim \langle \delta_g(R')\delta_g(R'+R)\rangle_{R'}$$

$$\Delta\Sigma(R) \sim \Sigma_{\rm cr}(z_l, z_s)\gamma(R) = \Sigma_{\rm cr}(z_l, z_s)\langle \delta_g(R')\delta_m(R'+R)\rangle_{R'}$$

Credit: Millennium Simlations

3x2pt: Cosmic Shear + 2x2pt

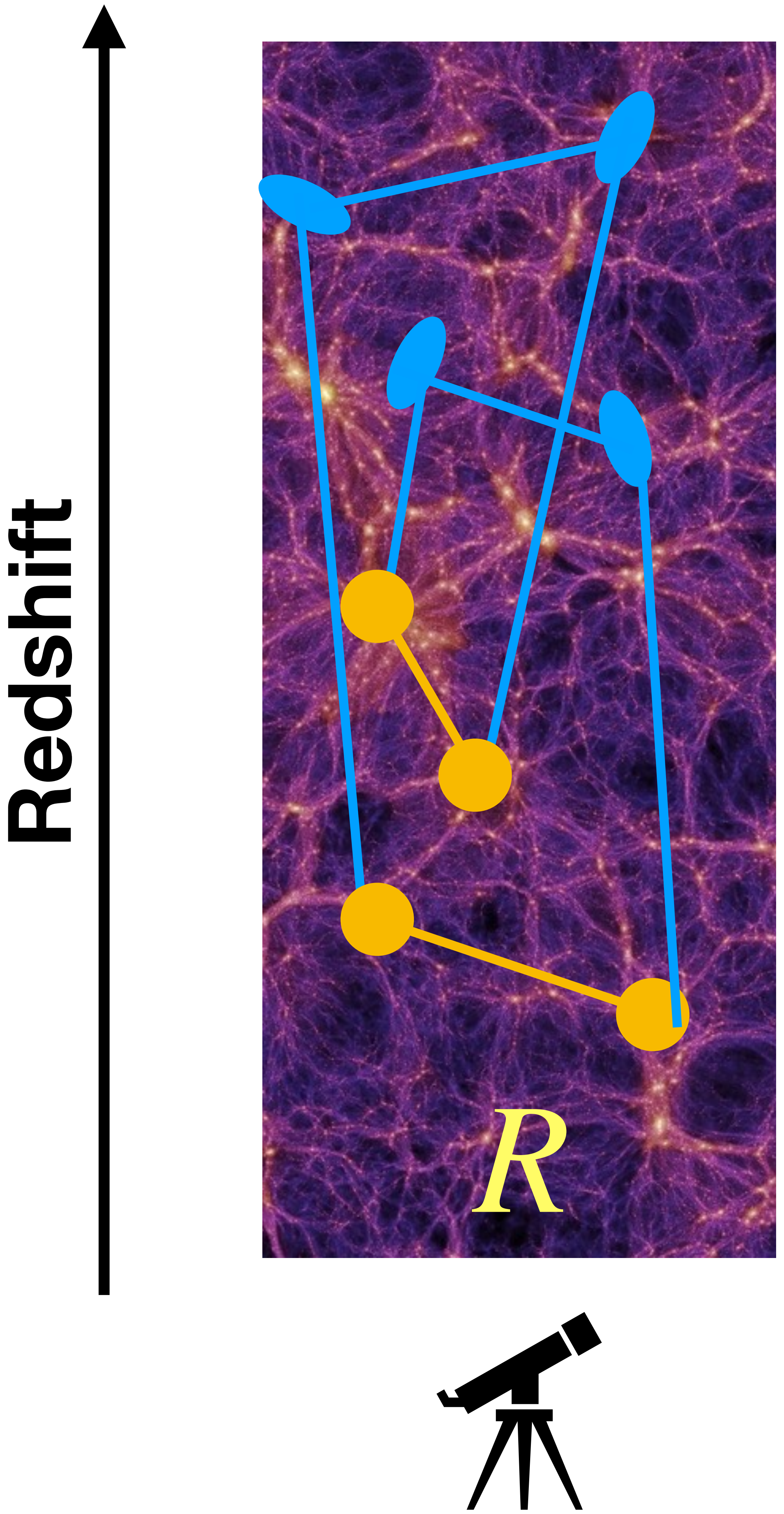


Now we can combine everything :)

$$\xi_{\pm}(\theta), w(\theta), \gamma(\theta)$$

Credit: Millennium Simlations

3x2pt: Cosmic Shear + 2x2pt



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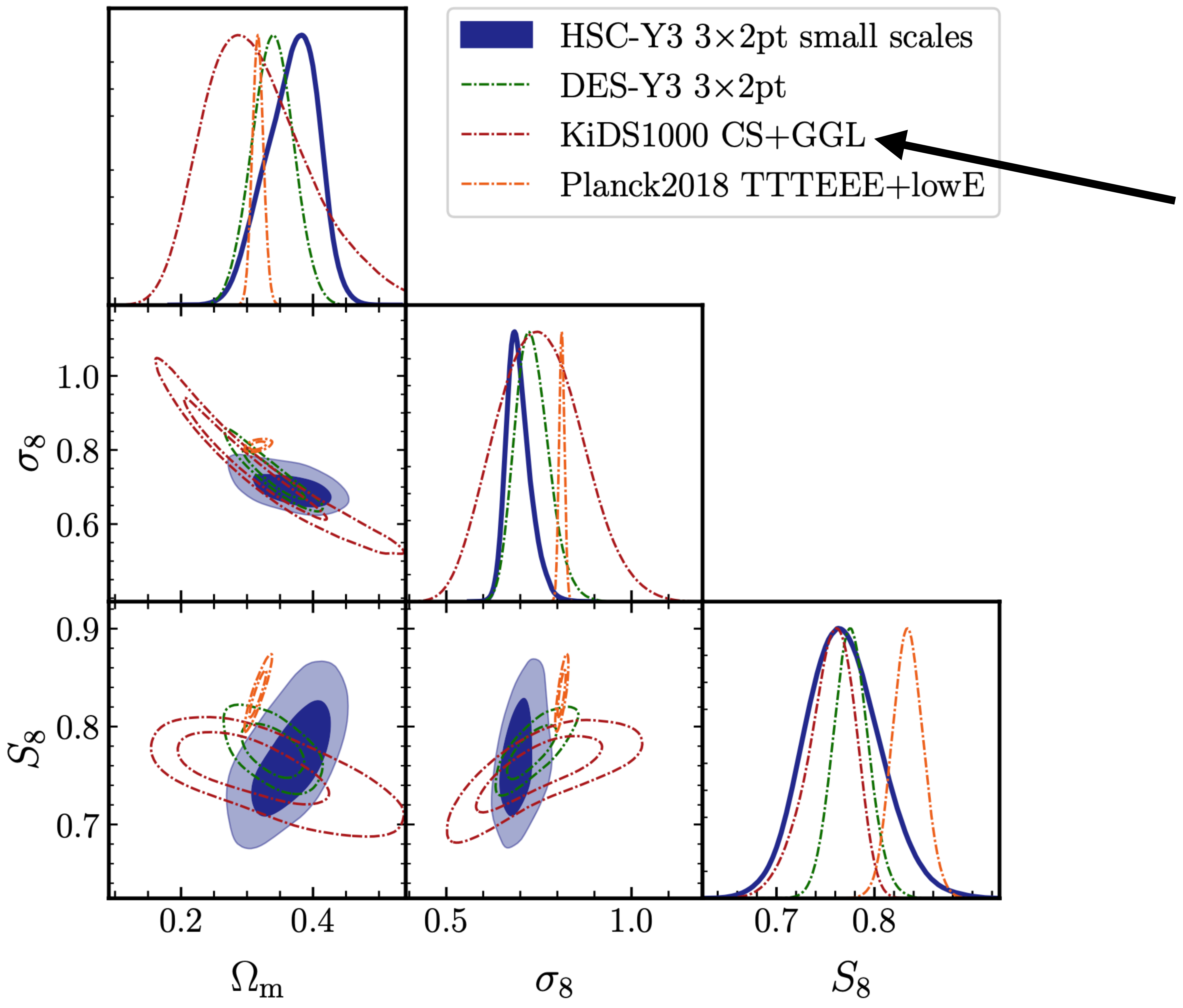
Credit: Millennium Simlations

Latest 3x2pt Analyses of Stage-III Surveys



KiDS 3x2pt is not shown here since the constraint on Ω_m is quite tight due to the use of BAO.

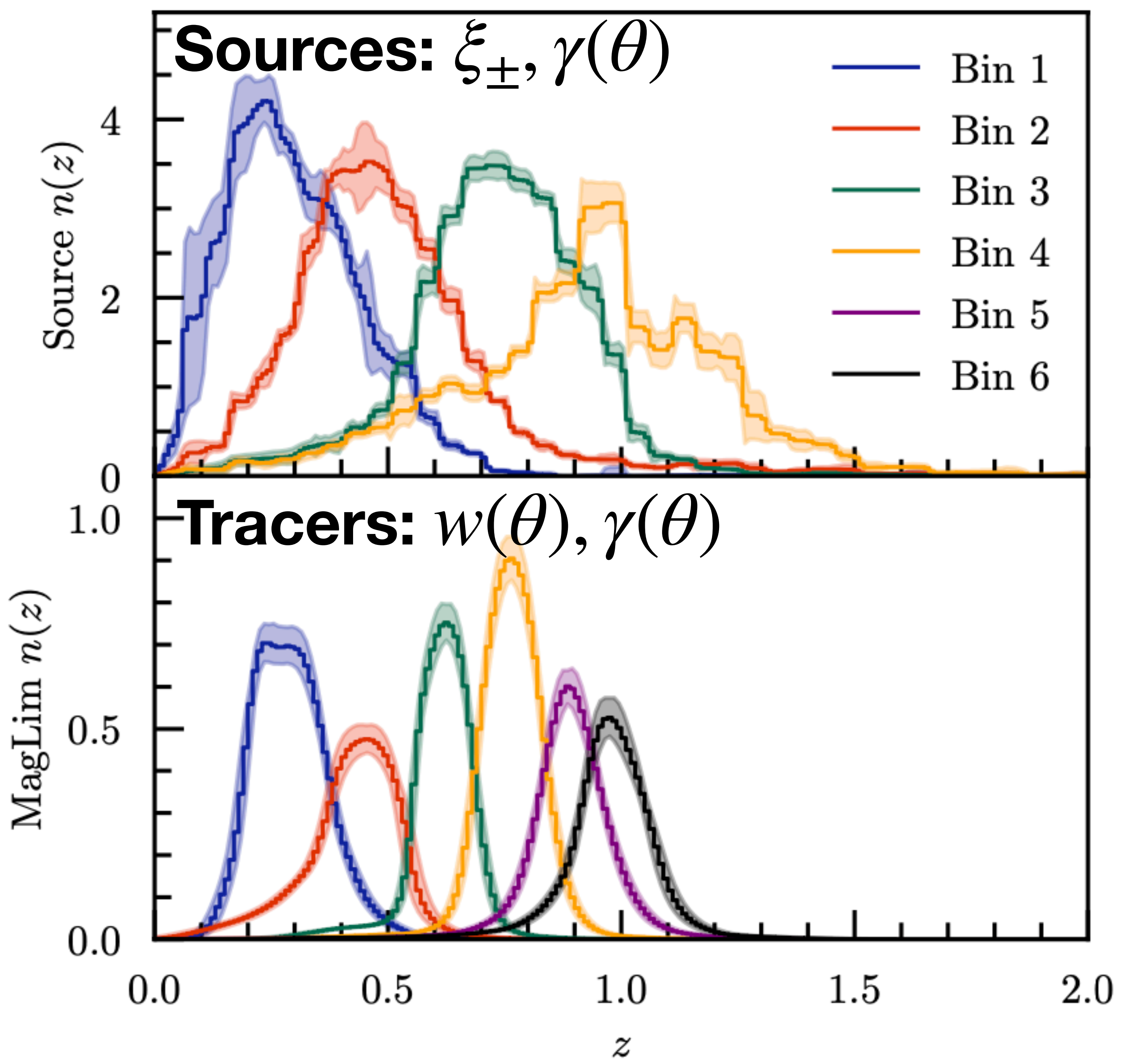
Miyatake et al. (2023)

Analysis Choice: Summary Statistics

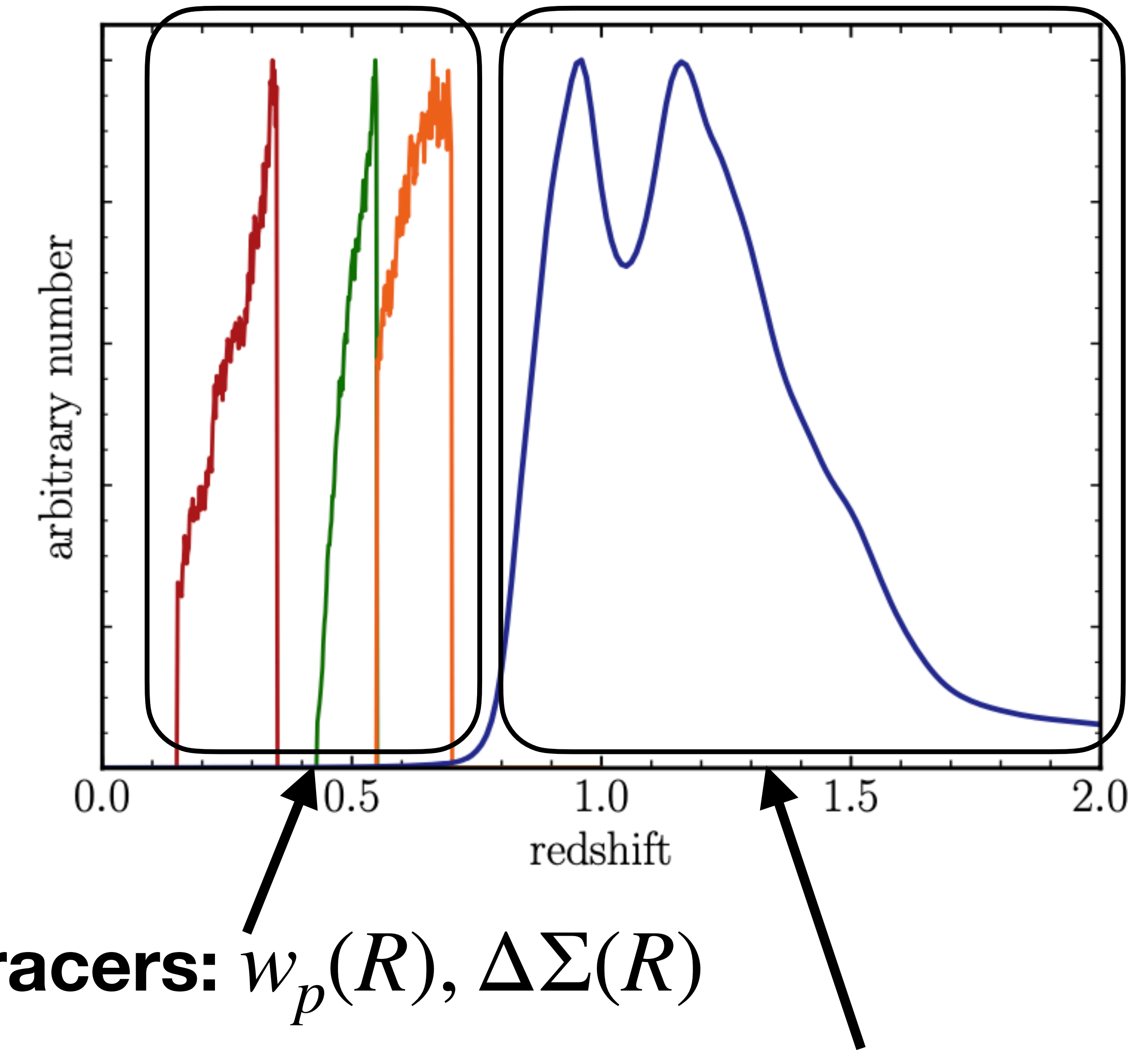
	DES-Y3 **DES collaboration (2022)**	**HSC-Y3** **Sugiyama et al. (2023)** **Miyatake et al. (2023)**	**KiDS-1000** **Heymans et al. (2021)**
Cosmic Shear	Real Space $\xi_{\pm}(\theta)$	Real space $\xi_{\pm}(\theta)$	Fourier Space $C_{\mathrm{EE}}(l)$
Galaxy-galaxy clustering	Projected clustering with photometric galaxies $w(\theta)$	Projected clustering from BOSS $w_{\mathrm{p}}(R)$	3D clustering from BOSS and 2dFLenS $\xi_{\mathrm{gg}}(s, \mu)$
Galaxy-galaxy lensing	Use photometric galaxies as a tracer $\gamma(\theta)$	Use BOSS galaxies as a tracer $\Delta\Sigma(R)$	Use BOSS and 2dFLenS galaxies as a tracer $C_{\mathrm{nE}}(l)$ equiv. To $\gamma(\theta)$

Analysis Choice: Redshift Bins

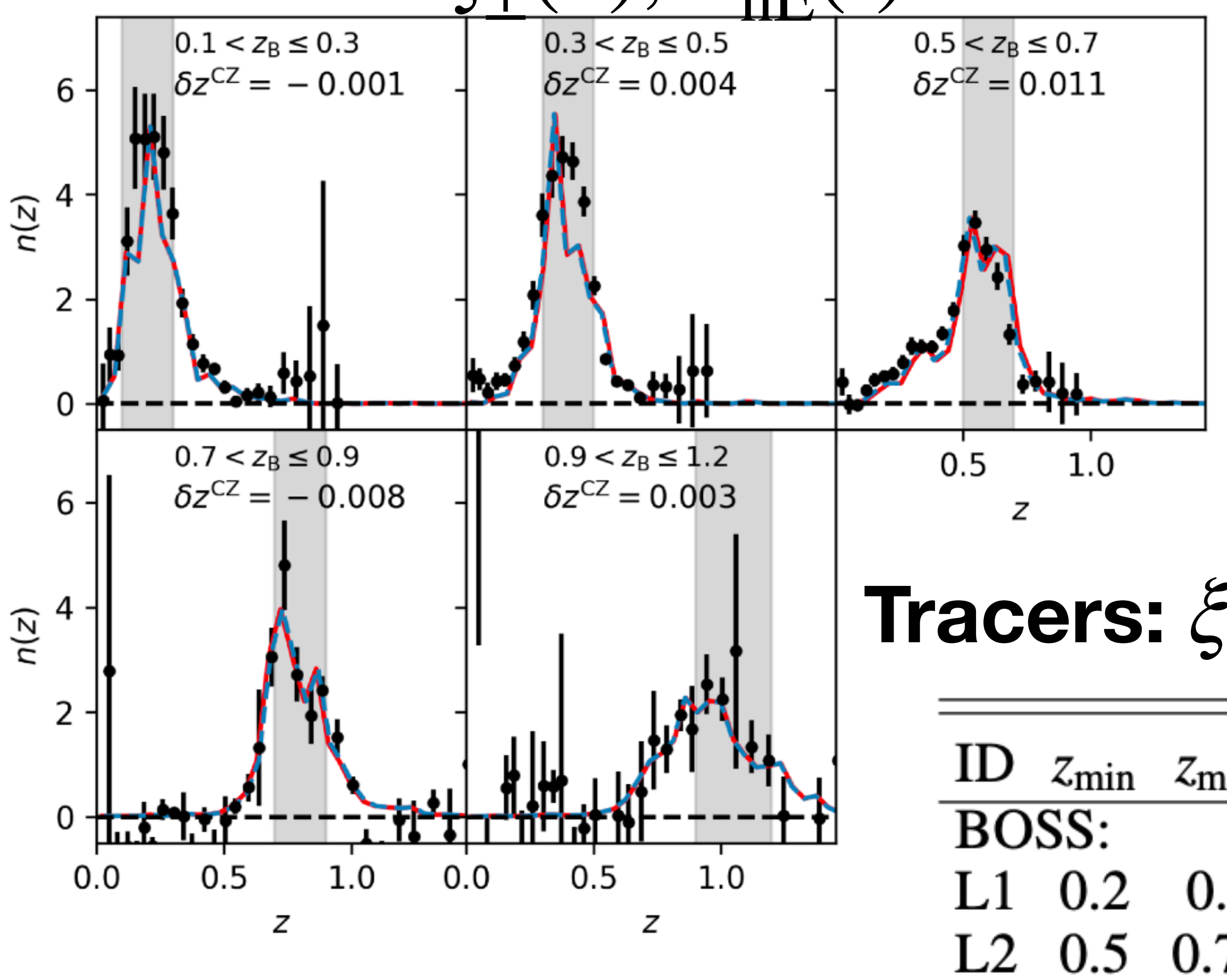
DES-Y3



HSC-Y3



KiDS-1000



Tracers: $\xi_{gg}(s, \mu), C_{\rm nE}(l)$

ID	$z_{\rm min}$	$z_{\rm max}$	Mean z	$n_{\rm eff}$
BOSS:				
L1	0.2	0.5	0.38	0.014
L2	0.5	0.75	0.61	0.016
2dFLenS:				
L1	0.2	0.5	0.36	0.006
L2	0.5	0.75	0.60	0.006

- DES uses lens-source pairs even if there is an overlap in redshift.
- HSC uses sources well separated from lenses. Cosmic shear is measured in a single redshift bin (Cosmic shear only analyses were done using multiple source redshift bins. See Li et al. (2023) and Dalal et al. (2023)).
- KiDS uses lens-source pairs when a source bin is behind a lens bin.

Analysis Choice: Scale Cuts

	DES-Y3 **DES collaboration (2022)**	**HSC-Y3** **Sugiyama et al. (2023)** **Miyatake et al. (2023)**	**KiDS-1000** **Heymans et al. (2021)**
Cosmic shear	ξ_+: ~3 arcmin < θ < ~220 arcmin ξ_-: ~40 arcmin < θ < ~220 arcmin (depends on redshift bin)	ξ_+: 8 arcmin < θ < 50 arcmin ξ_-: 30 arcmin < θ < 150 arcmin	100 < l < 2000 (~5 arcmin < θ < ~100 arcmin)
Galaxy-galaxy clustering	R > 8 Mpc/h	2 Mpc/h < R < 30 Mpc/h	20 Mpc/h < s < 160 Mpc/h (Includes BAO information)
Galaxy-galaxy lensing	R > 6 Mpc/h	3 Mpc/h < R < 30 Mpc/h	l < 300 (θ > ~36 arcmin or R~15 Mpc/h)

HSC uses much smaller scale cuts for clustering and lensing, in which they need to consider non-linear regime.

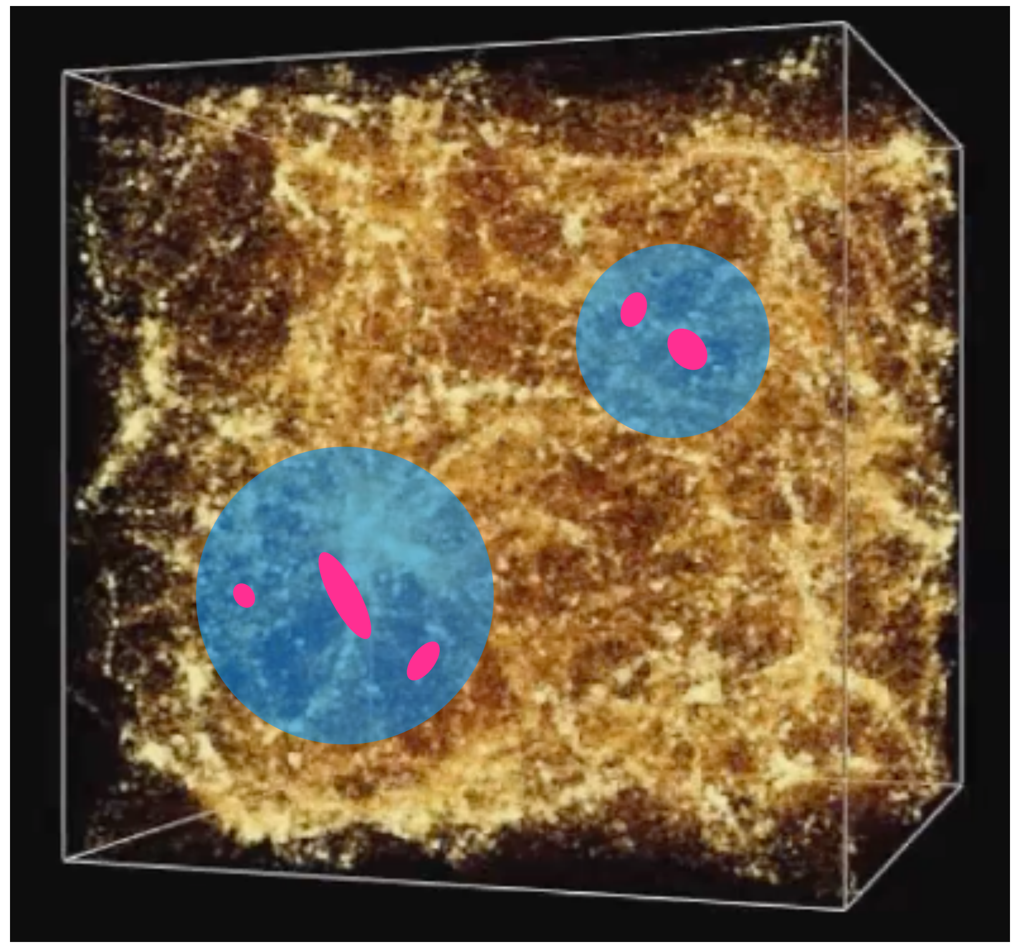
Credit: ESA

Systematics: Non-linear Effect

HSC-Y3 used non-linear scales to gain S/N

Challenges

- Accurate modeling of non-linear regimes
- Proper treatment of uncertainties in galaxy-halo connection



dark matter

dark matter halos

galaxies

Cosmo. Params. $(\sigma_8, \Omega_m, \ldots)$ → $\xi_{hh} = \langle \delta_h \delta_h \rangle$, $\xi_{hm} = \langle \delta_h \delta_m \rangle$ → $\xi_{gg} = \langle \delta_g \delta_g \rangle$, $\xi_{gm} = \langle \delta_g \delta_m \rangle$ → Observables

Projection to 2-d

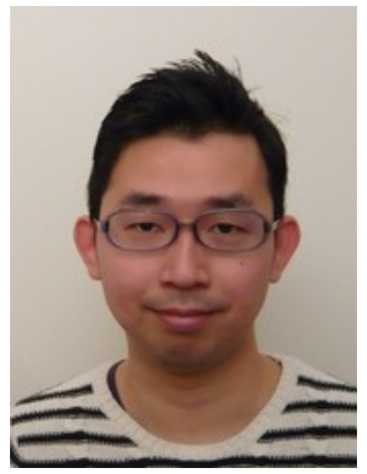
Observables

Observables
Clustering: $w_p(R)$
Weak Lensing: $\Delta\Sigma(R)$

Modeling non-linear regimes
Prediction by **Dark Emulator** achieved a few % accuracy

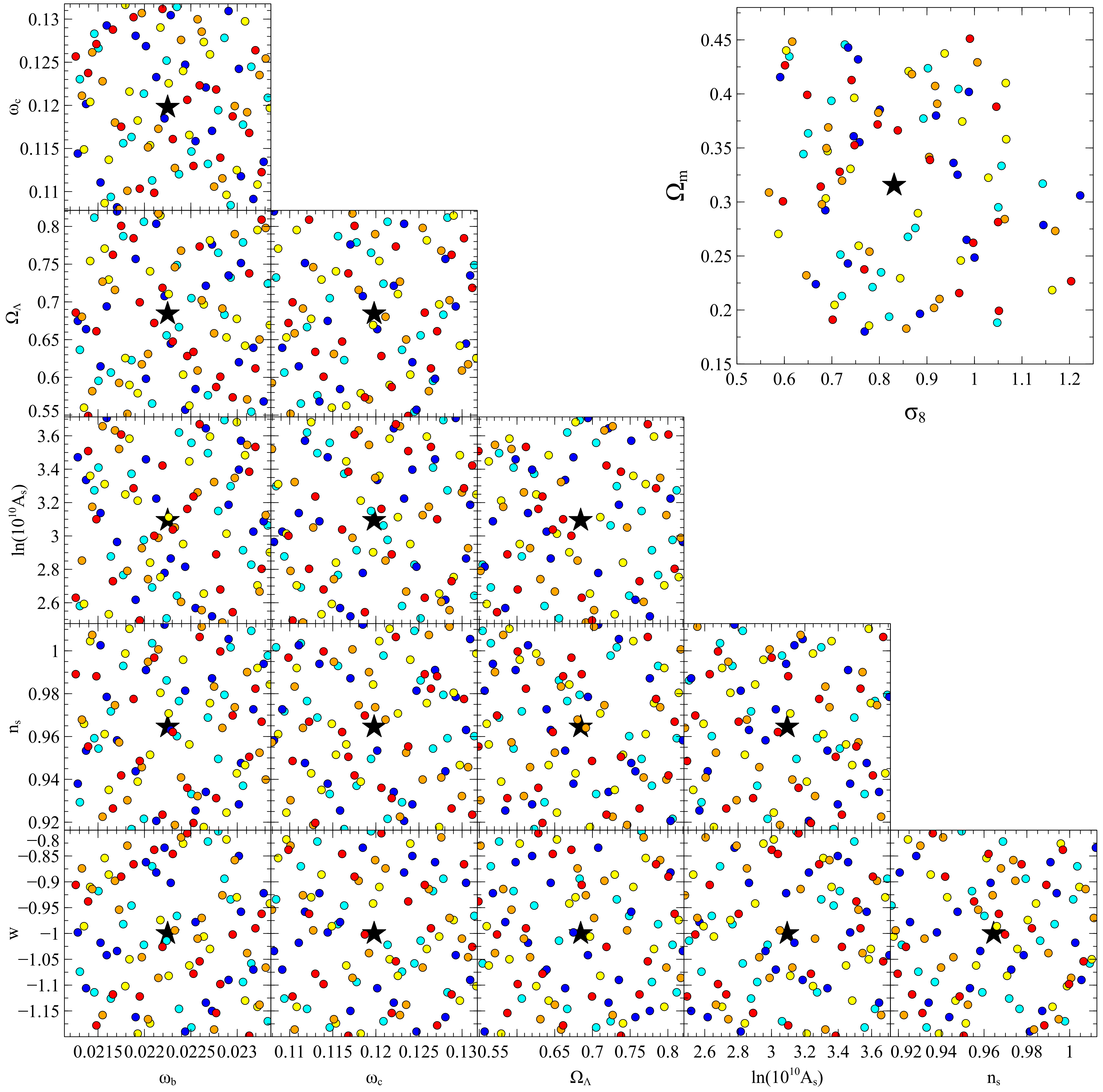
Uncertainties between galaxy-halo connection
Analytical convolution of HOD and marginalize over the HOD parameters

Dark Emulator: accurate non-linear model



T. Nishimichi (Kyoto)

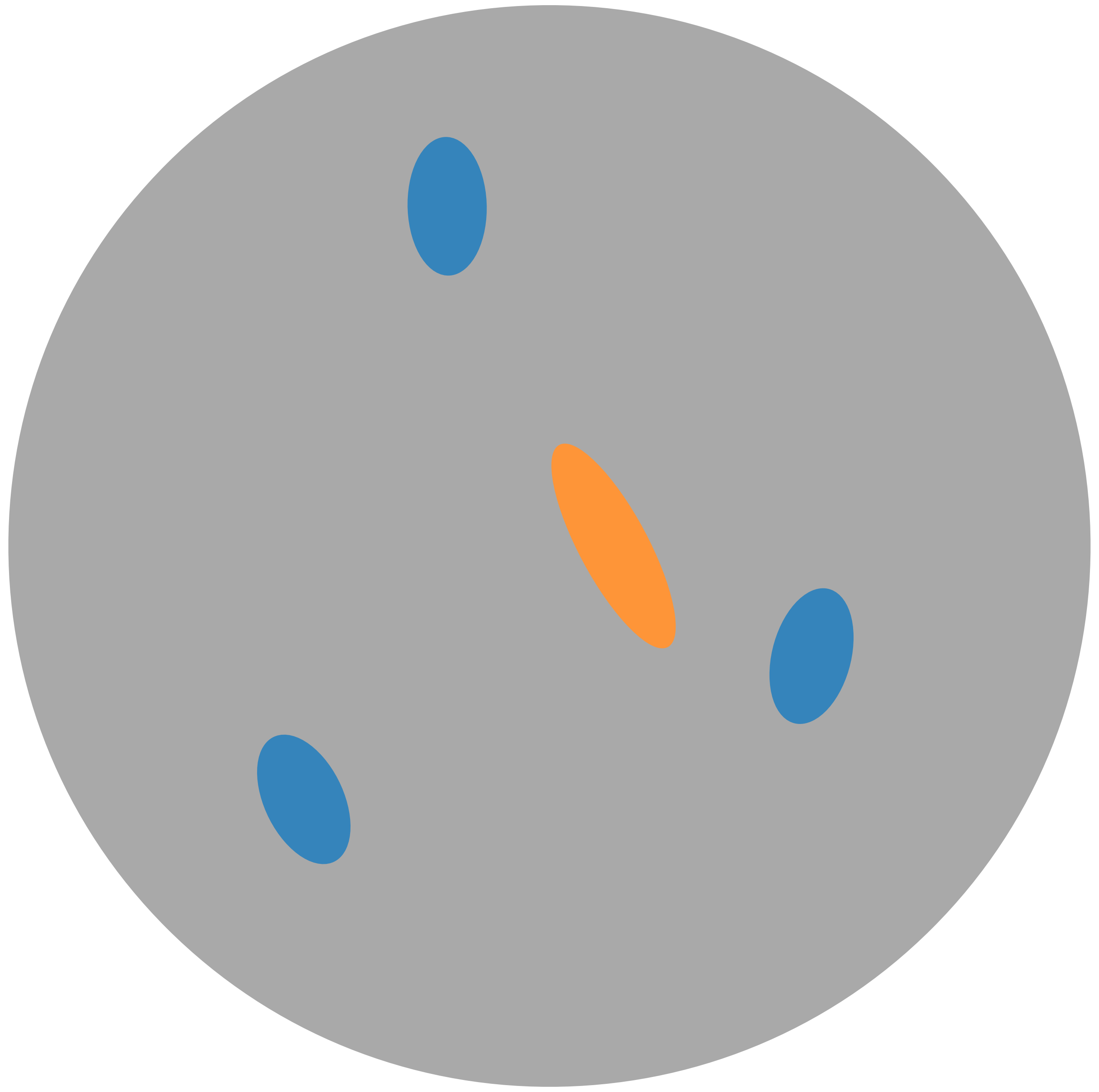
- Run N-body simulations under 101 sets of cosmological parameters.
  $\vec{C} = (\omega_b, \omega_c, \Omega_\Lambda, A_s, n_s, w)$
- Run the Rockstar halo finder.
- Measure correlation functions, i.e., $\xi_{\rm hh}(r; \vec{C})$ and $\xi_{\rm hm}(r; \vec{C})$.
- Interpolate correlation functions across the cosmological parameter sets using PCA and Gaussian process.
- Achieved an accuracy for $\xi_{\rm hh}(r; \vec{C})$ and $\xi_{\rm hm}(r; \vec{C})$ better than 2%.
- **Unique cosmic emulator with halo statistics**

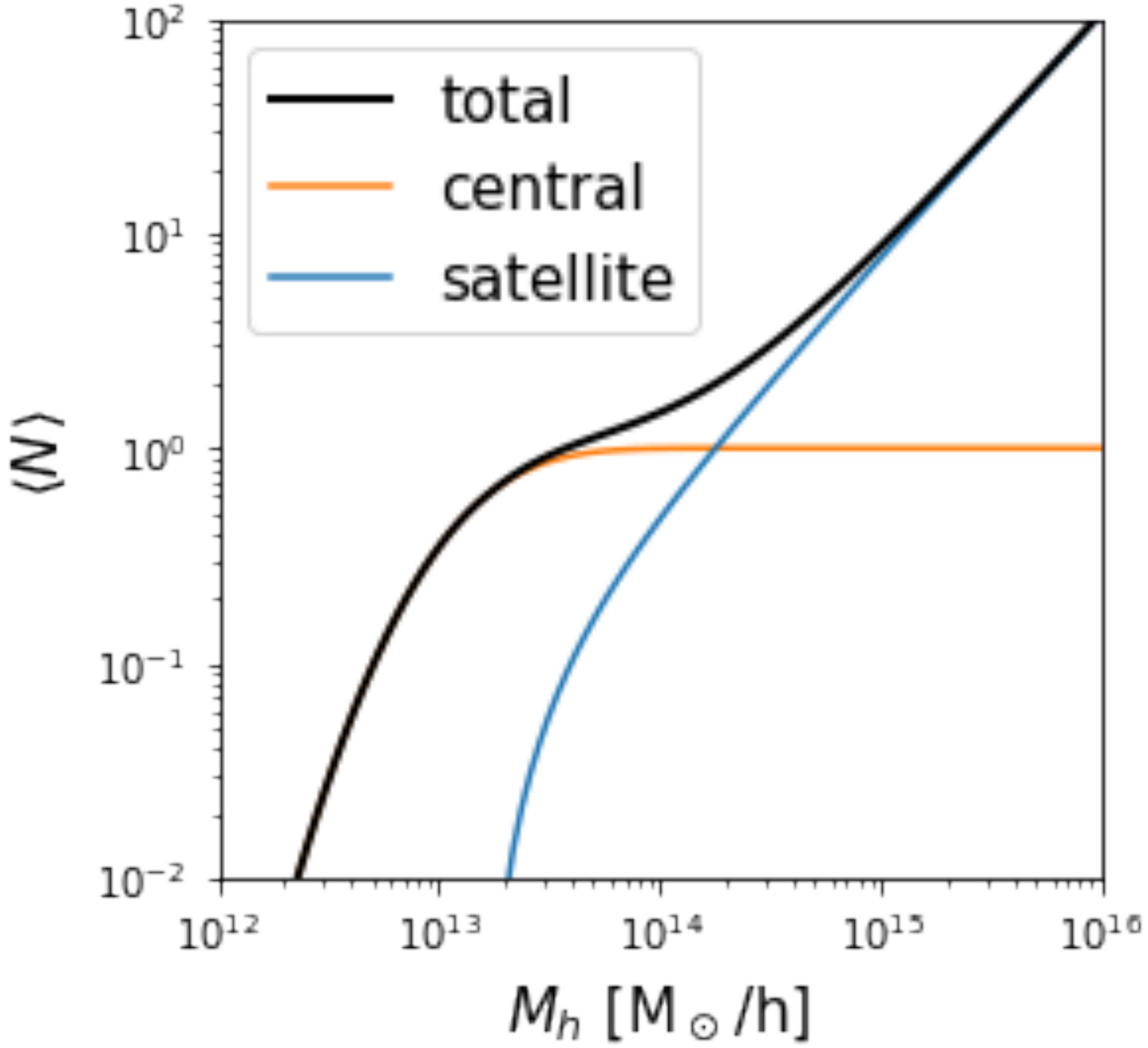


Nishimichi et al. (2019)

Galaxy-halo connection

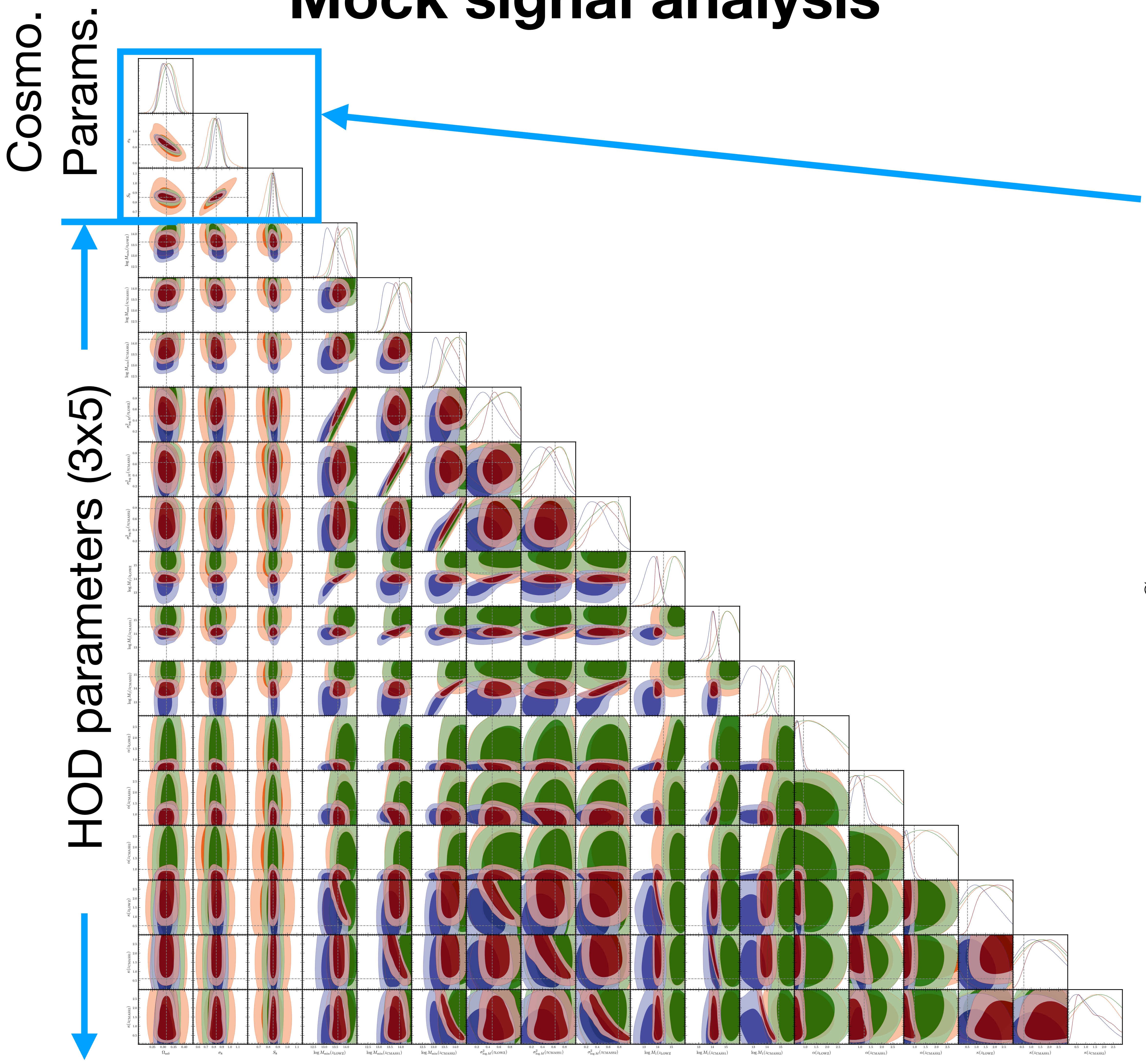
- Use halo occupation distribution (HOD; 5 parameters) to distribute galaxies in a dark matter halo.
- Take into account the uncertainties in galaxy physics by marginalizing HOD parameters.

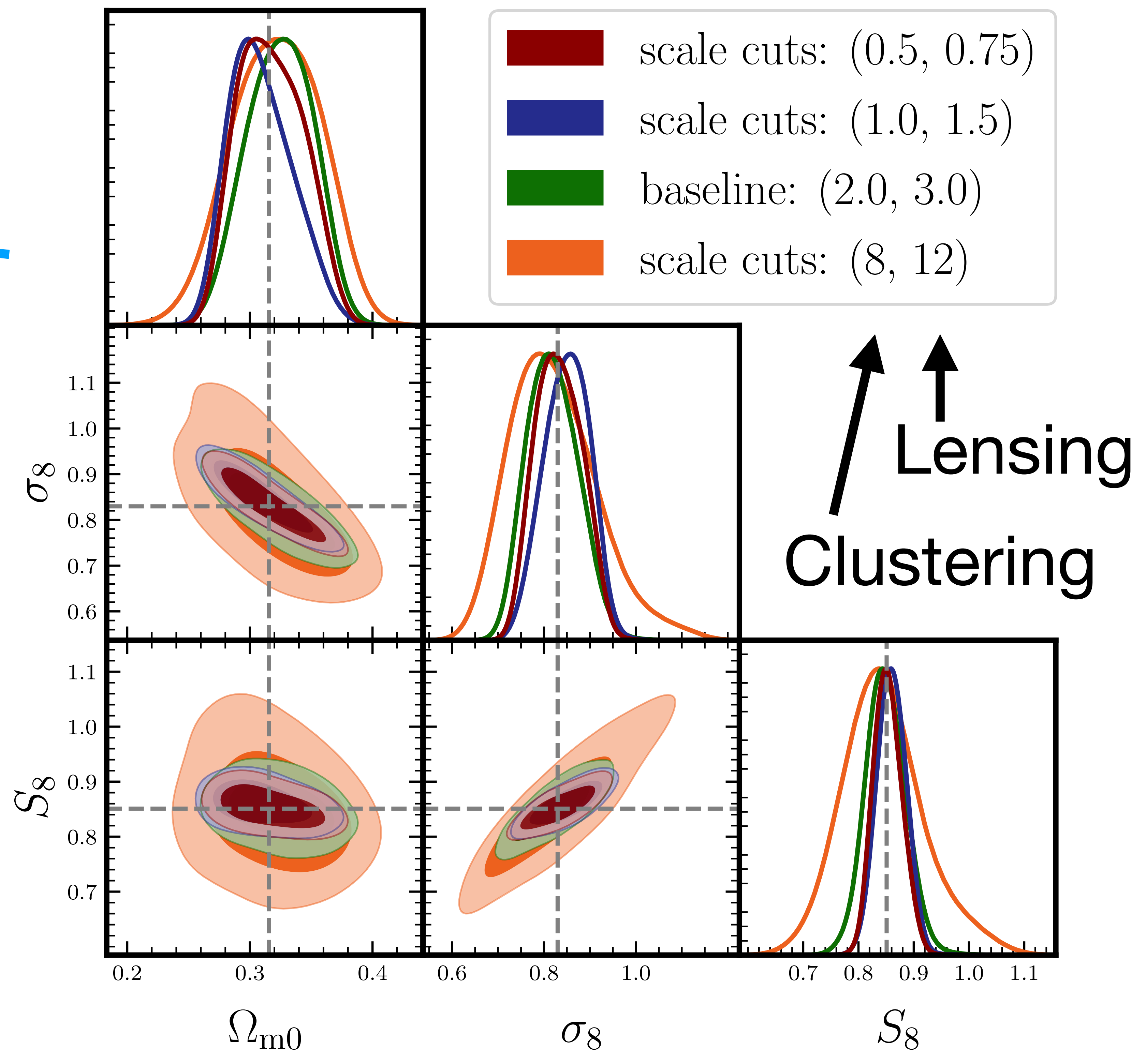




Information Content in Small Scales

Mock signal analysis





We cannot extract information from scales less than ~2 Mpc/h because of the HOD marginalization.

Miyatake et al. (2022a)

Systematics: Redshift Uncertainties

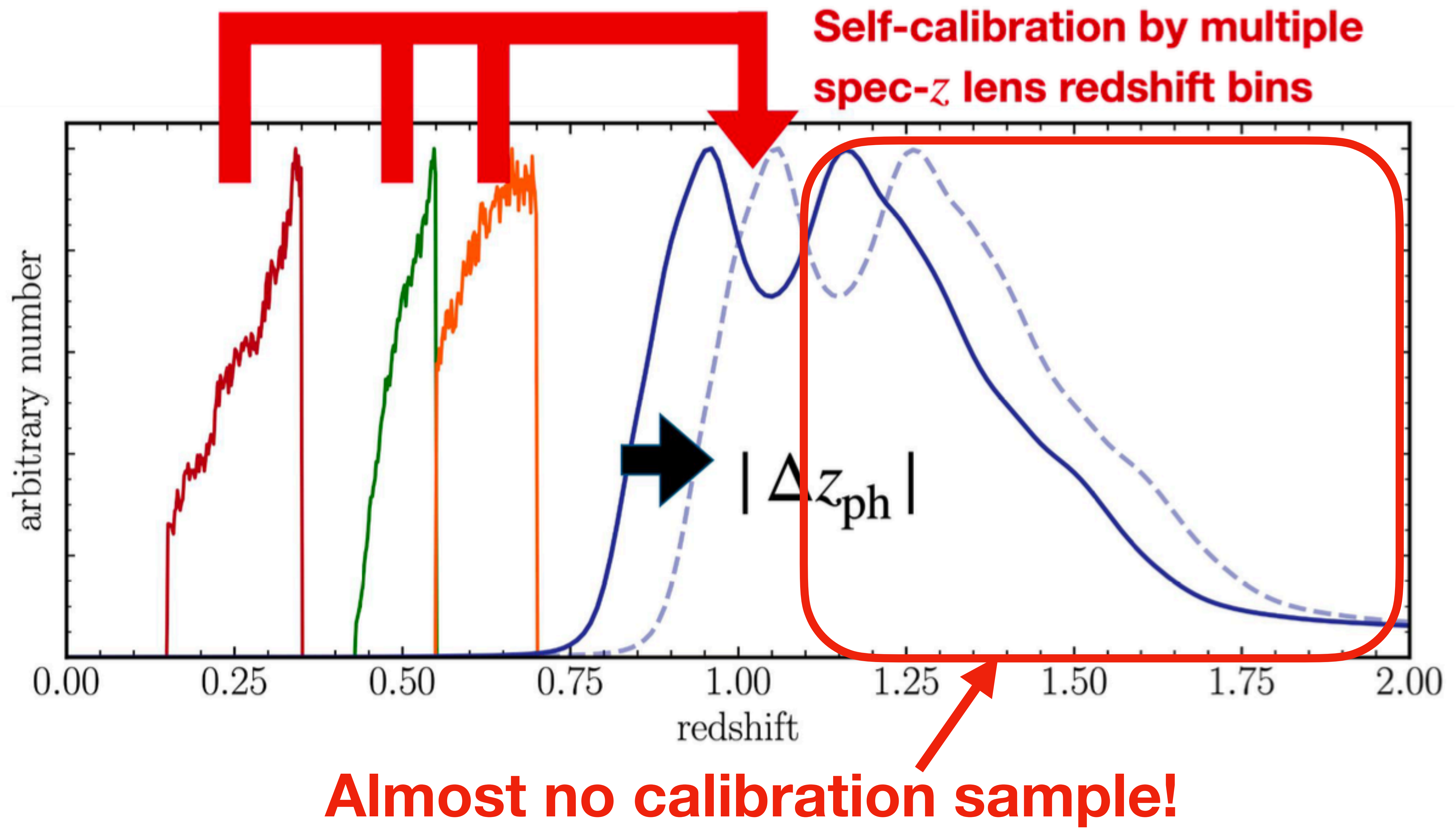
- Bias in a lens or source redshift causes systematic bias in lensing signal.
- When using a spectroscopic sample for lenses, there is no bias in lens redshift.
- For source galaxies, photometric redshift (photo-z) is used, so we should always care about bias.
- When using a spectroscopic sample for lenses we only care about mean of source redshifts.

$$\langle\gamma\rangle = \langle \Sigma_{\rm cr}(z_l, z_s)^{-1}\, \Delta\Sigma(z_l)\rangle$$

$$= 4\pi G(1+z_l)^{-2}\chi_l \left[1 - \chi_l \boxed{\left\langle \frac{1}{\chi_s} \right\rangle}\right] \Delta\Sigma(z_l)$$

An Extreme Case: HSC-Y3

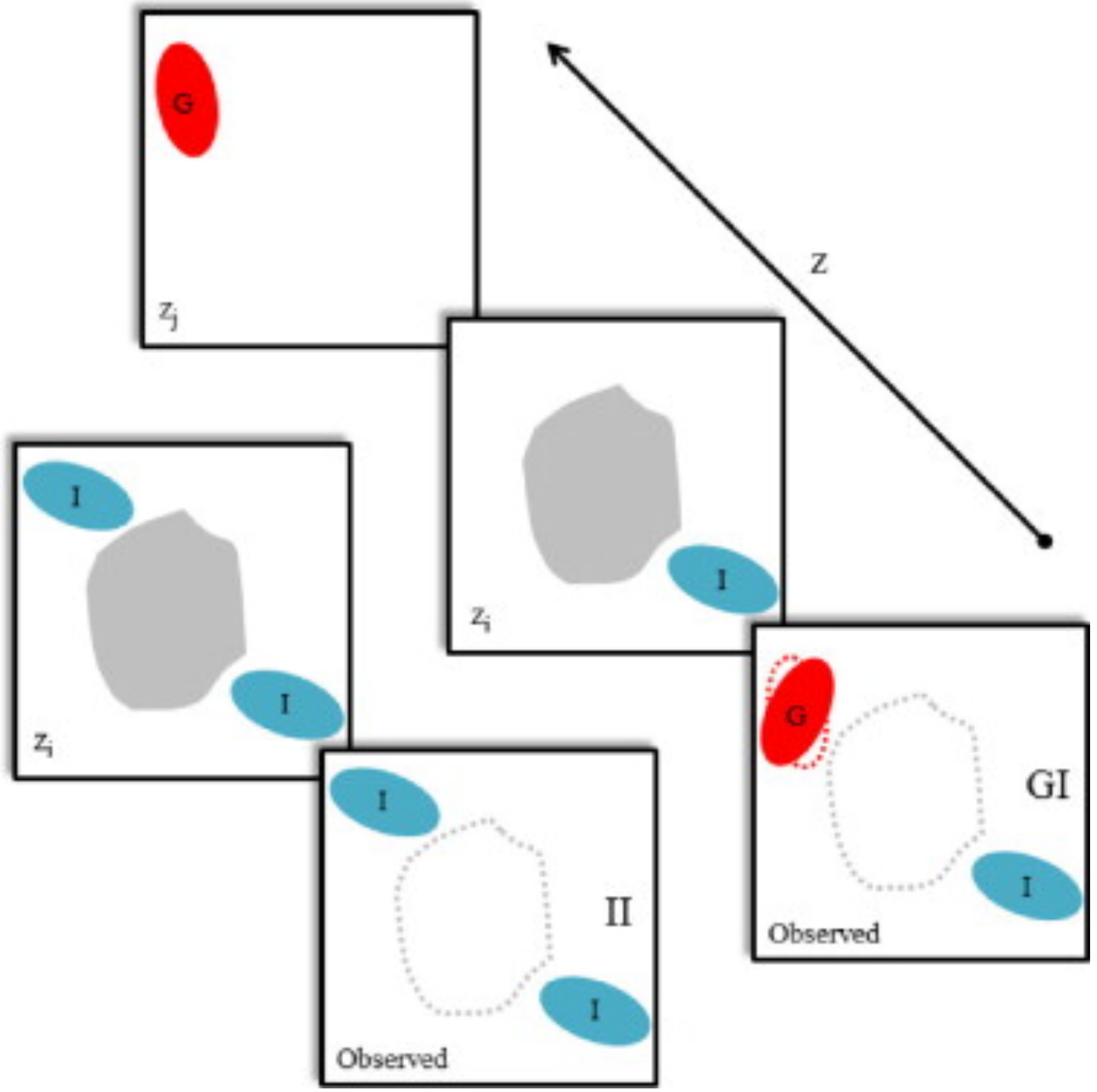
- We had almost no calibration sample except for COSMOS 30-band photo-z at z>1.1.
- We decided to use a flat prior $\Pi(\Delta z_{\rm ph}) = \mathcal{U}(-1,1)$, and self-calibrate by using multiple lens samples (Oguri & Takada, 2011).
- $\Delta z_{\rm ph} = -0.05 \pm 0.09$
- If we fix $\Delta z_{\rm ph}$, our S_8 constraint is shifted by 0.5σ.
- Downside: the error on S_8 is doubled once we use the flat prior.



Miyatake et al. (2023)

Systematics: Intrinsic Alignment

- Intrinsic shape of galaxies is affected by the tidal forces of a dark matter structure.
- There are two terms: II and GI.
- Both II and GI cause a systematic bias in cosmic shear (GI is dominant).
- II causes a systematic bias in galaxy-galaxy lensing.
- There are two models
  - NLA: Assumes galaxies linearly align with the tidal field.
  - TATT: Uses nonlinear perturbation theory to expand the field of intrinsic galaxy shapes interns of the tidal field and matter overdensity.

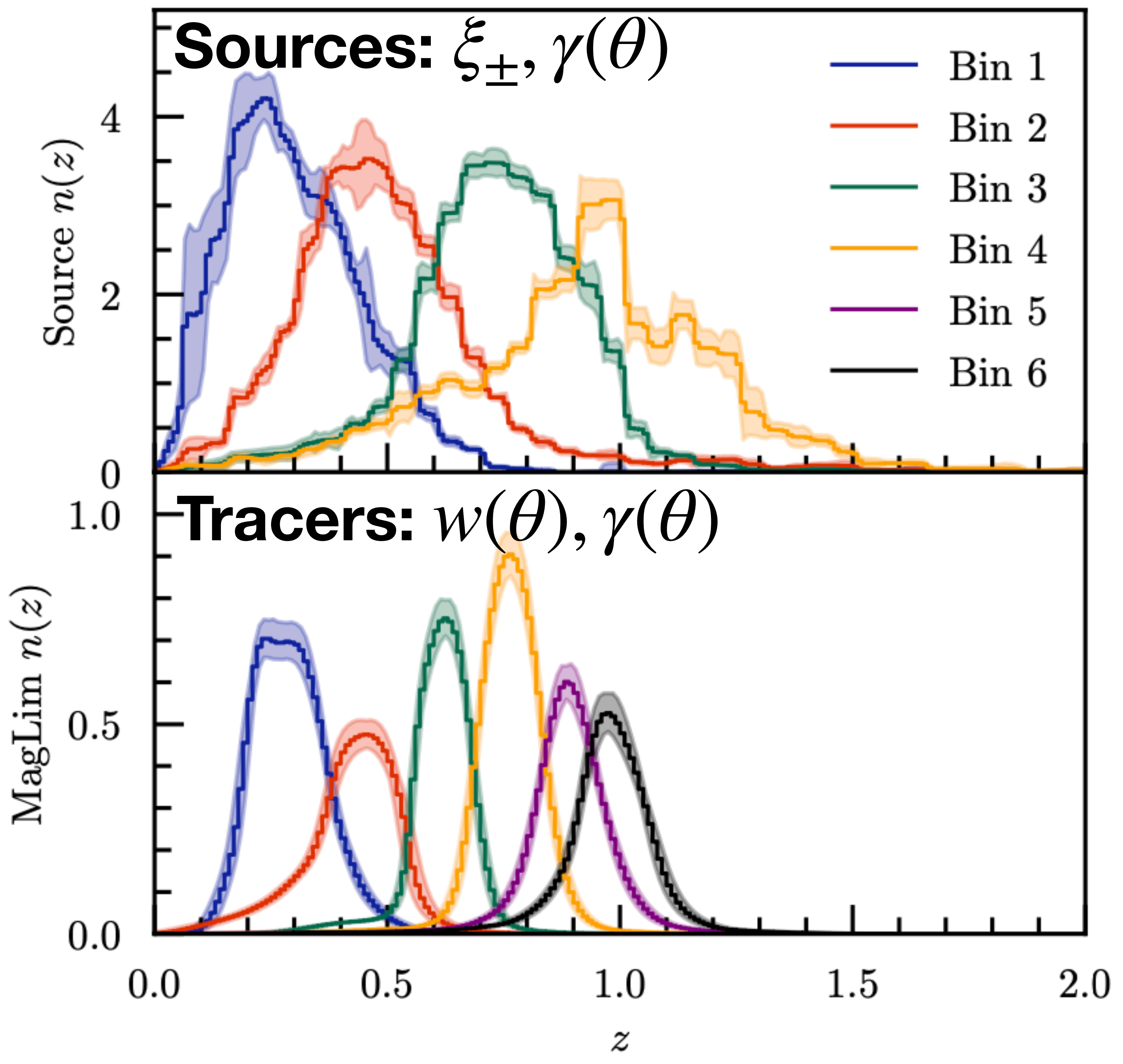


Troxel & Ishak (2014)

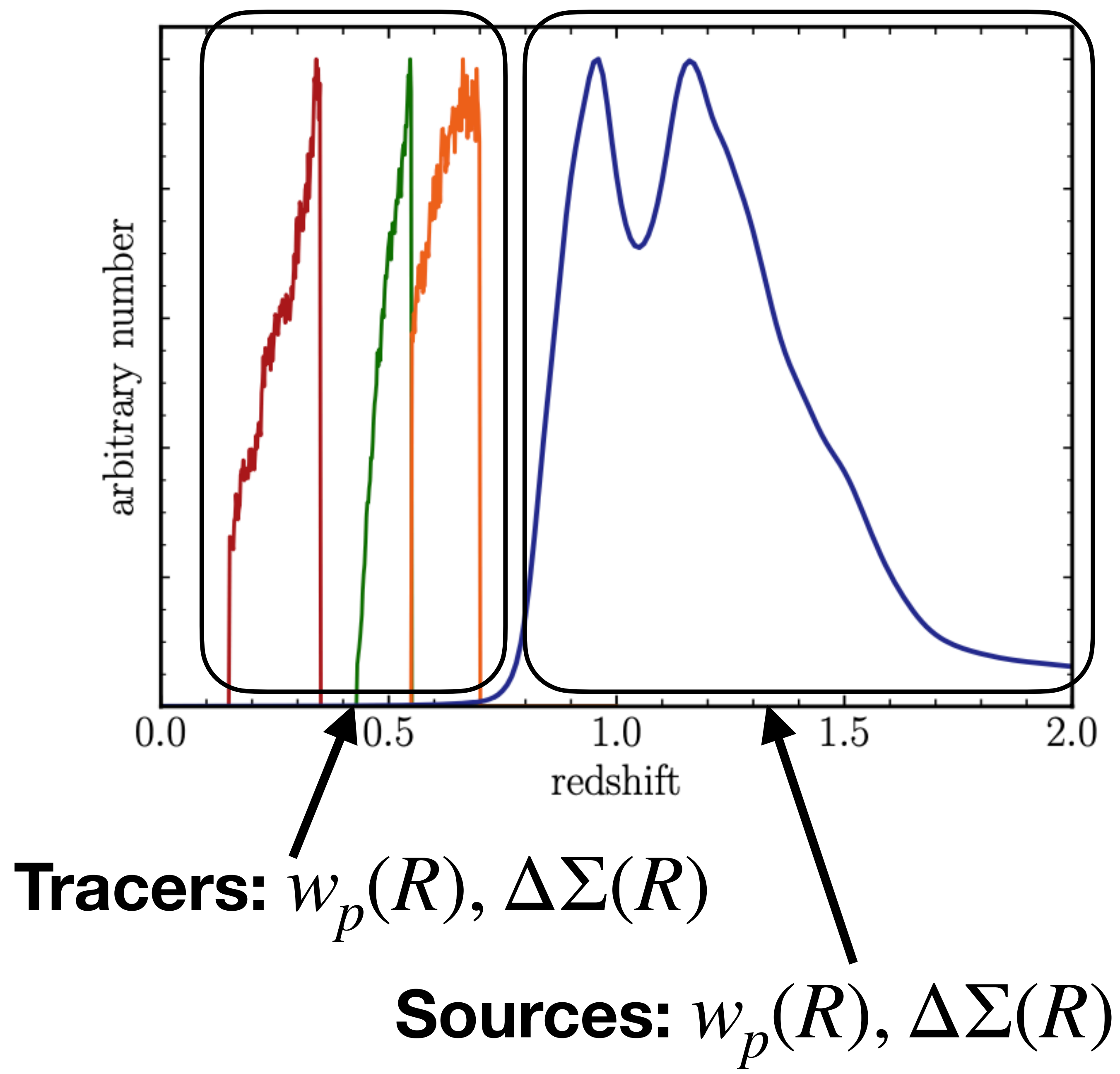
Intrinsic Alignment in Stage-III Surveys

- For cosmic shear, all surveys incorporated IA in their models.
- For galaxy-galaxy lensing, DES and KiDS incorporated IA in their models, but HSC not, due to the use of spectroscopic galaxies as a tracer and conservative selection for source galaxies.

DES-Y3



HSC-Y3



Intrinsic Alignment in Stage-III Surveys

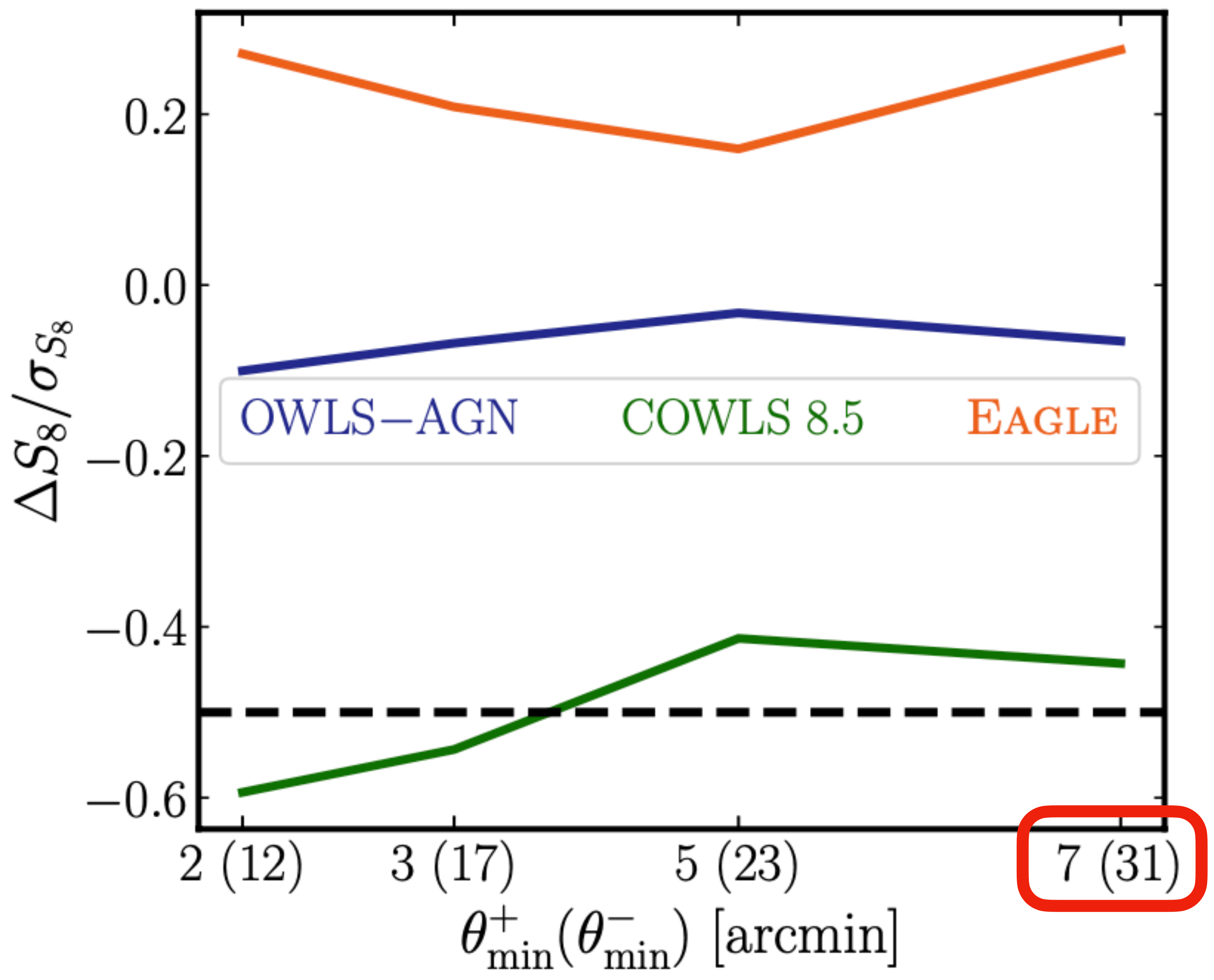
	DES-Y3 DES collaboration (2022)	HSC-Y3 Sugiyama et al. (2023) Miyatake et al. (2023)	KiDS-1000 Heymans et al. (2021)
NLA	No IA detection	No IA detection	3 sigma detection Did not affect S_8 constraint (~0.1σ).
TATT	Fiducial No IA detection	N/A	N/A

Note: HSC tomographic cosmic shear analyses (Dalal et al, 2023; Li et al, 2023) adopted TATT as fiducial, did not detect IA, and S_8 constraints were not affected.

Systematics: Baryonic Effect

- AGN feedback pushes matter away from halo center and modifies small scale signals.
- Scale cut for small scales in cosmic shear measurements is applied to avoid scales affected by AGN feedback.

HSC-Y3 cosmic shear

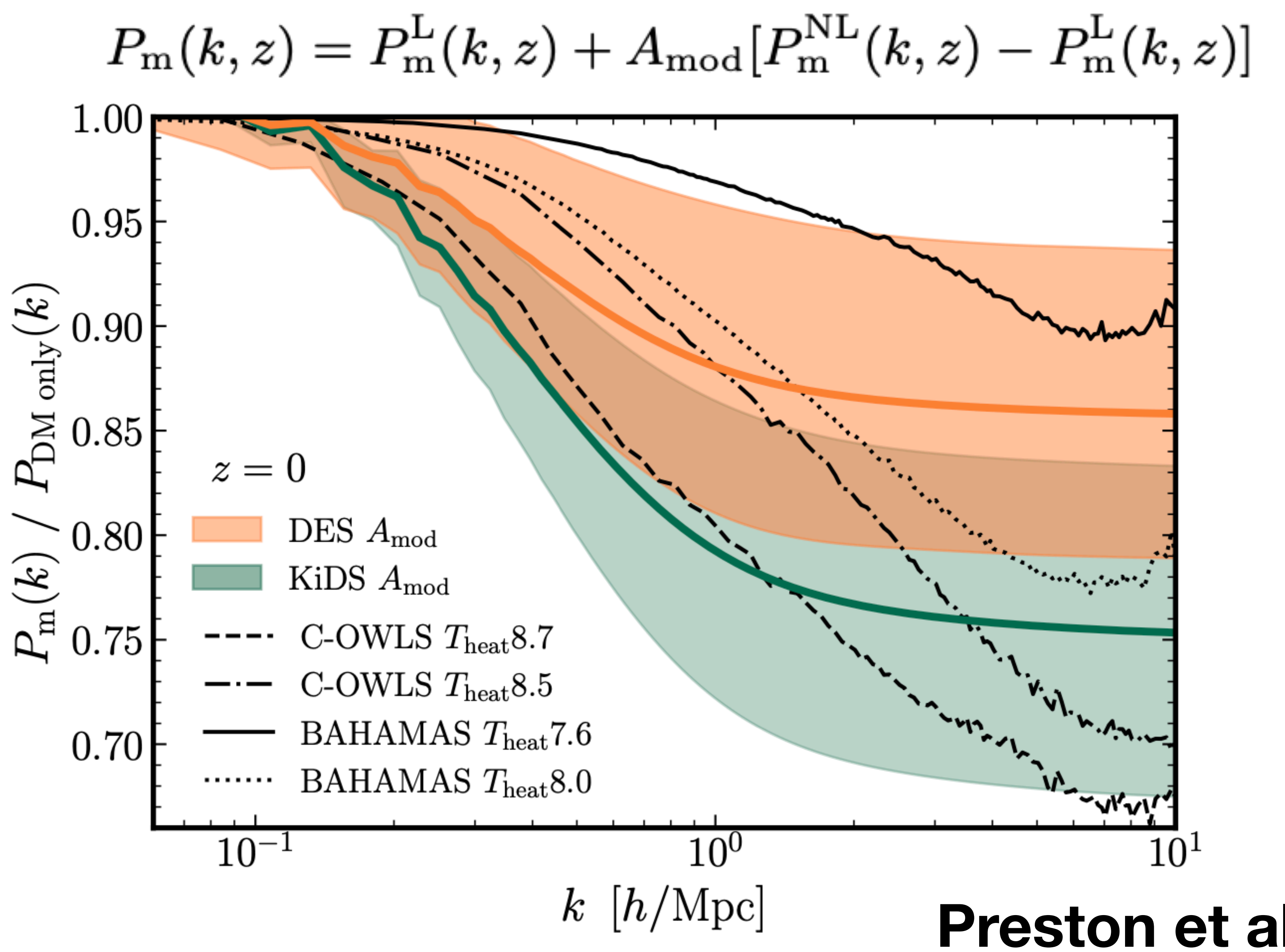


Li et al. (2023)

Baryonic Effect on Cosmic Shear

- To recover Planck S_8 from DES and KiDS cosmic shear including small scales (data points outside of scale cuts), AGN feedback is required to extend to mildly non-linear scale (k~0.2 h/Mpc).

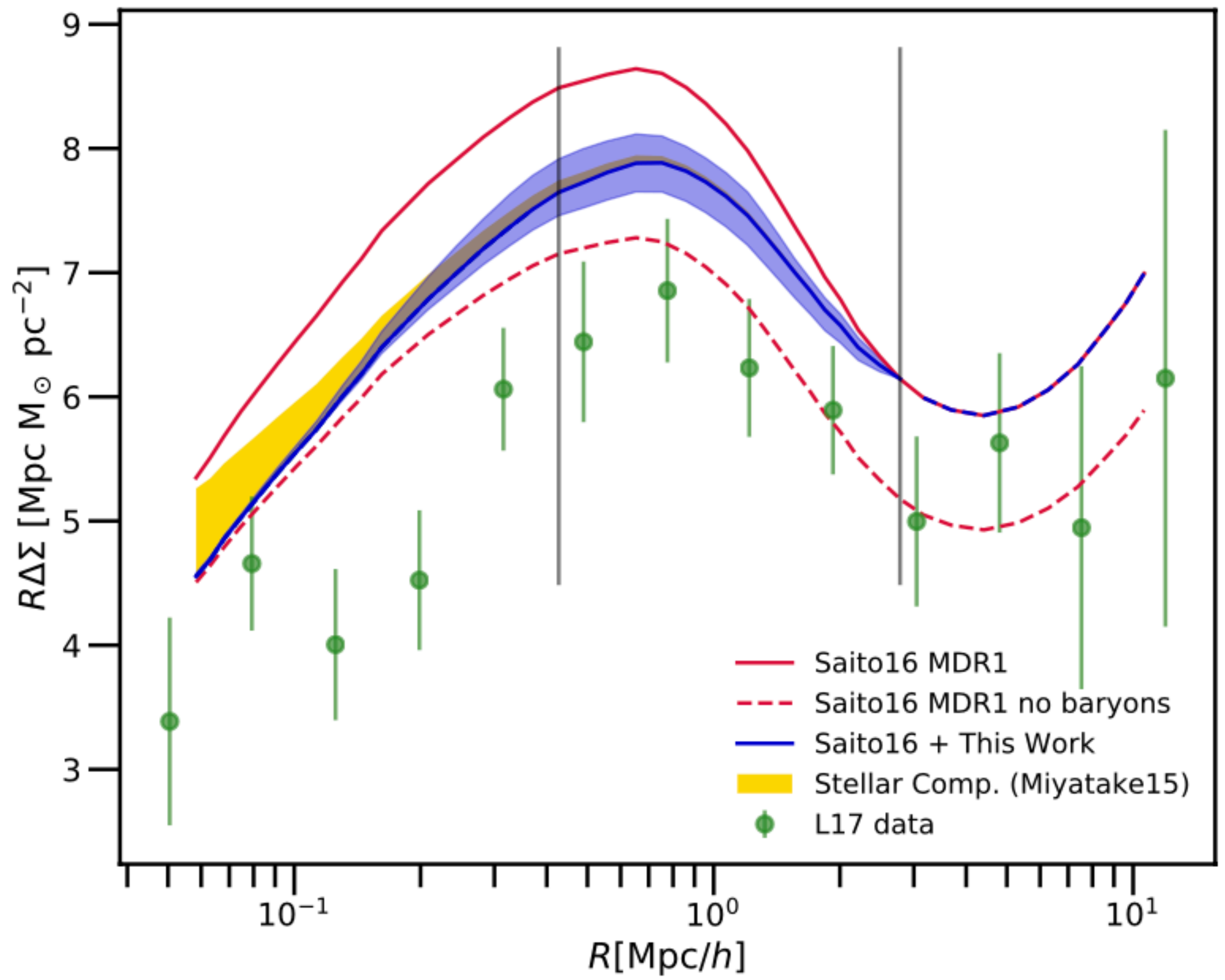
- It may be unrealistic to explain the S_8 tension only by Baryonic effect.



Preston et al. (2023)

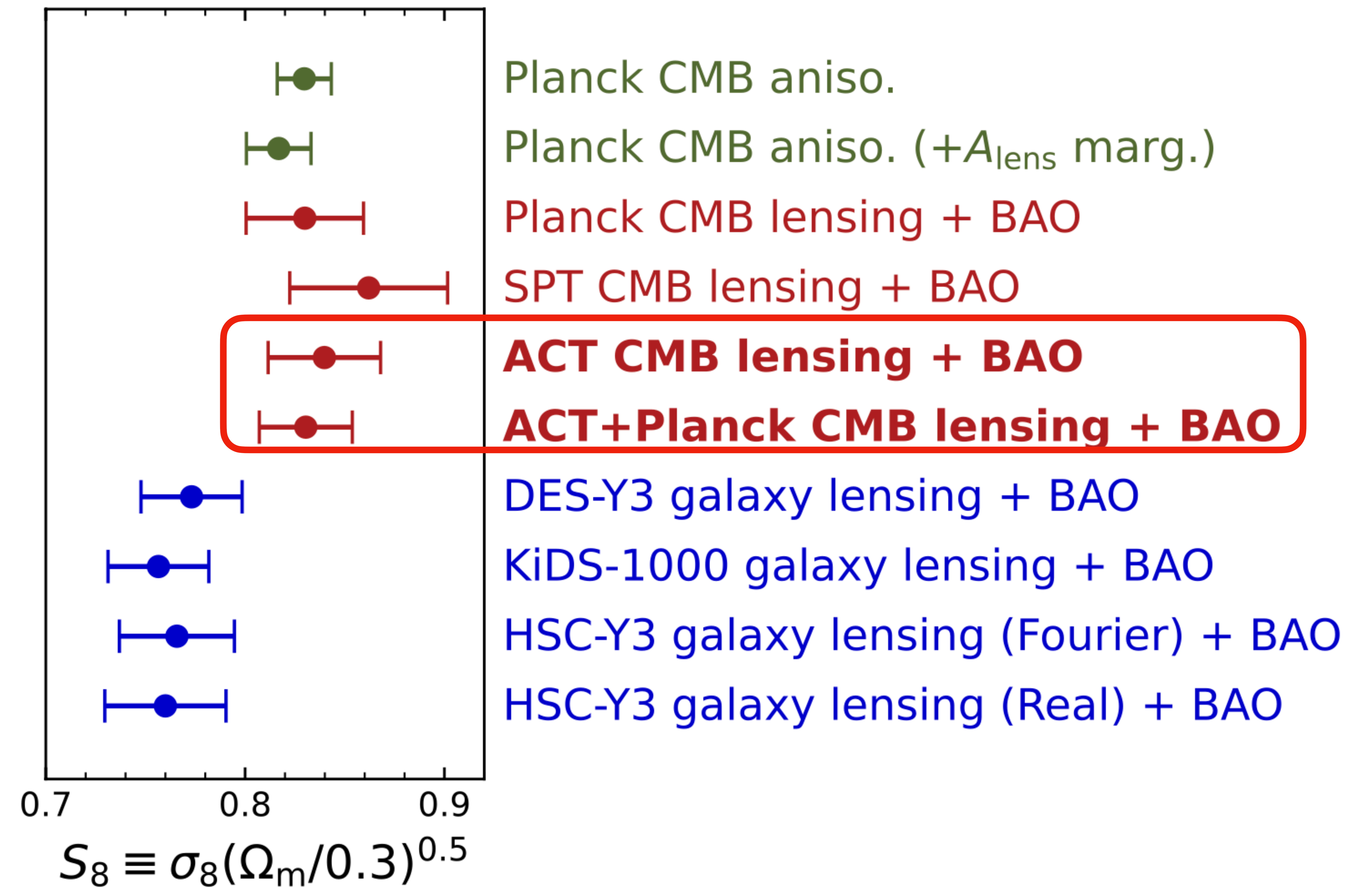
Baryonic Effect on Galaxy-galaxy Lensing

- ACT measured AGN feedback around CMASS sample through kSZ and tSZ signals.
- They also found large AGN feedback up to ~3 Mpc/h in lensing signal.
- HSC-Y3 scale cut (R> 3 Mpc/h) safely avoids the small scales affected by AGN feedback.
- Better to use $\Delta\Sigma(R)$ than $\gamma(\theta)$ to avoid mixing in angular scales.

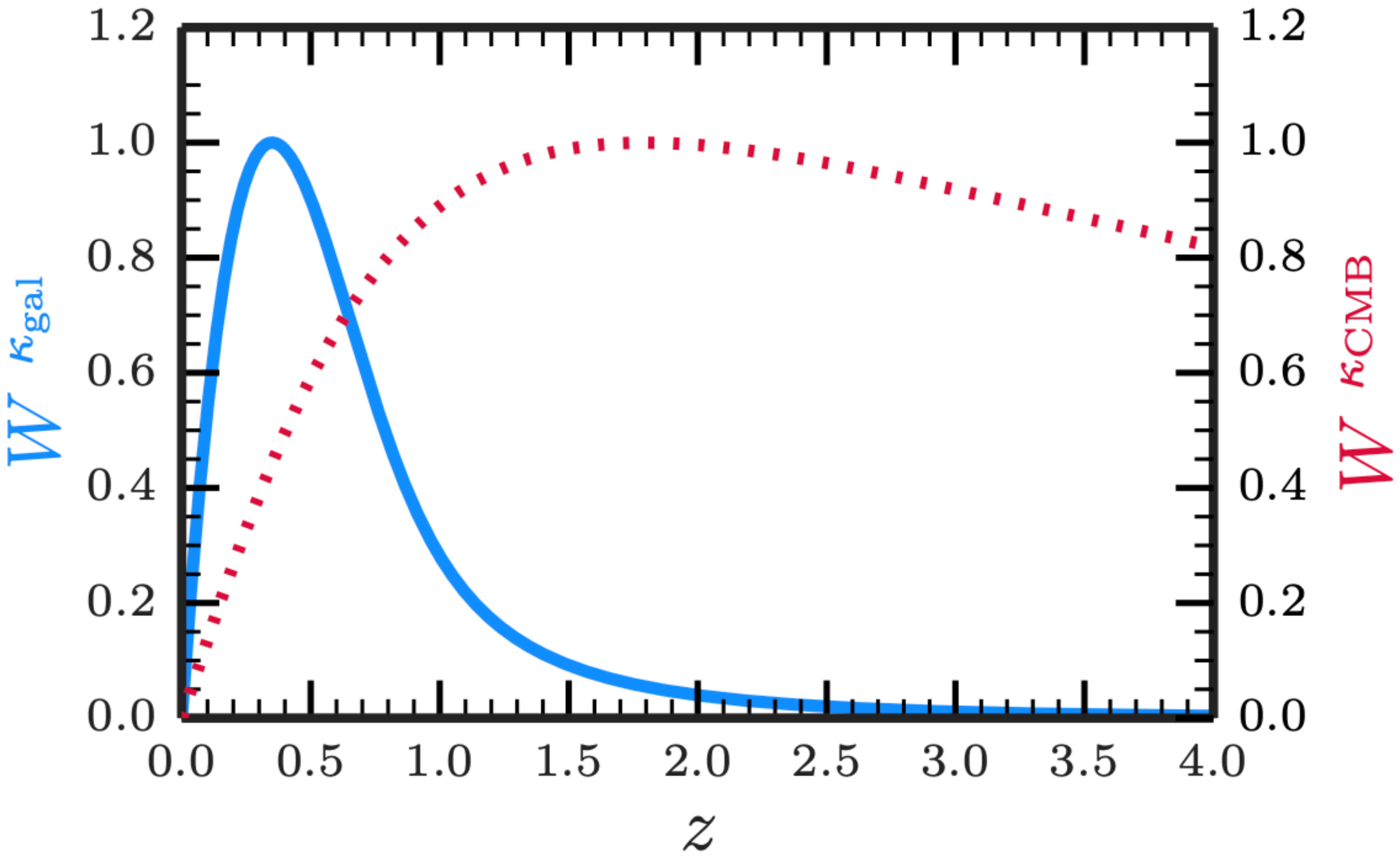


Amodeo et al. (2021)

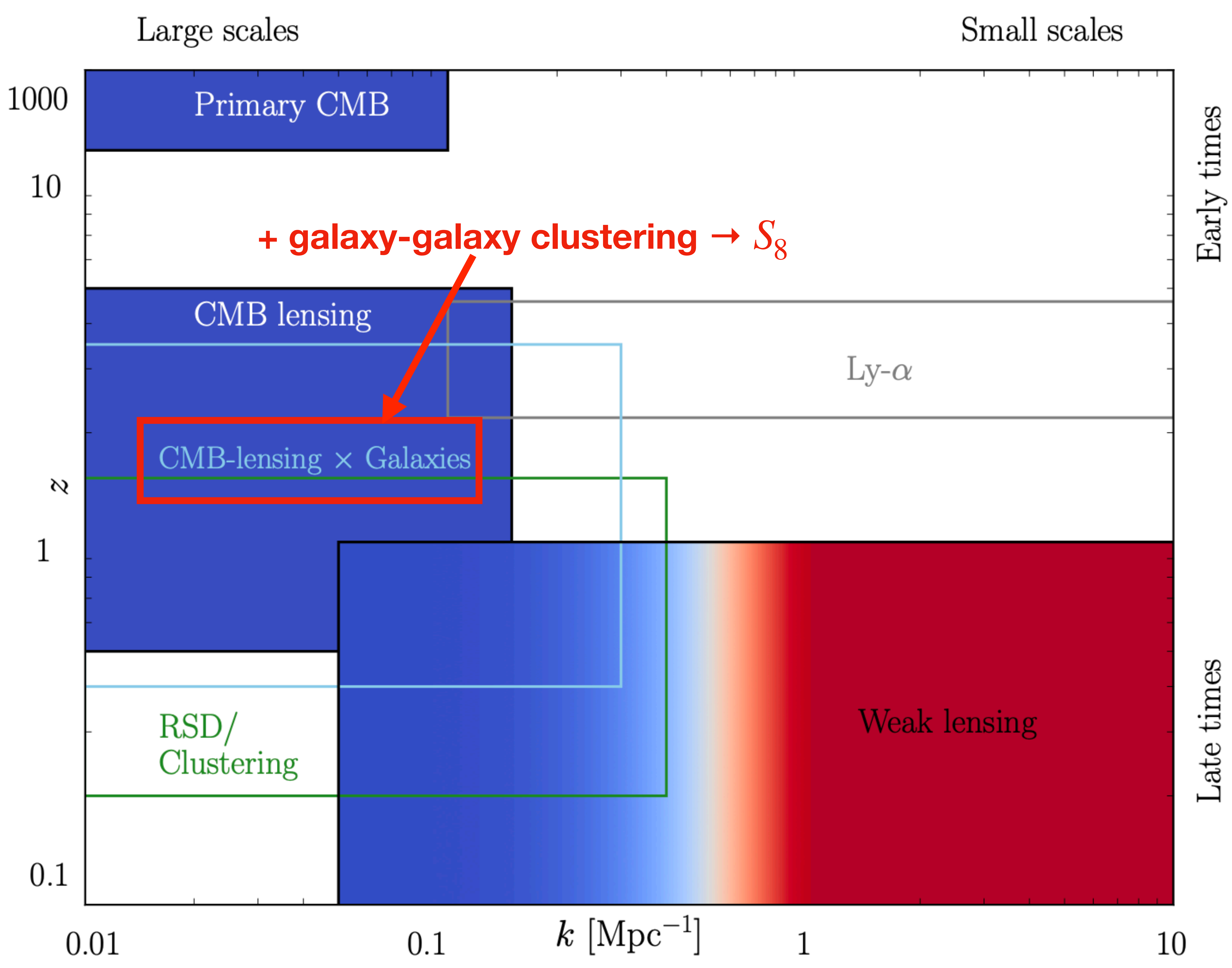
S_8 Tension Updated



Madhavacheril et al. (2023), Qu et al. (2023)



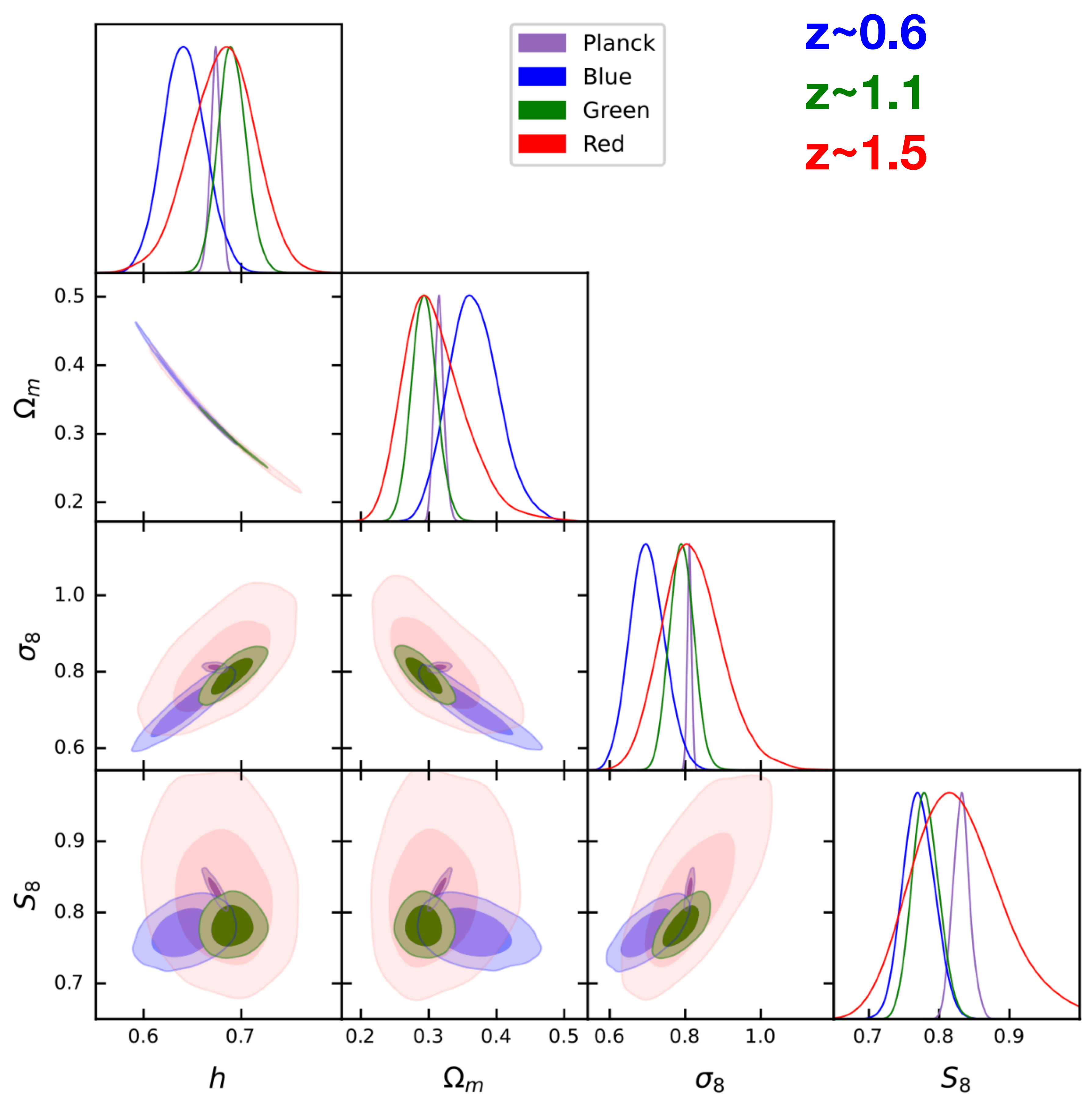
Hand et al. (2015)



Preston et al. (2023)

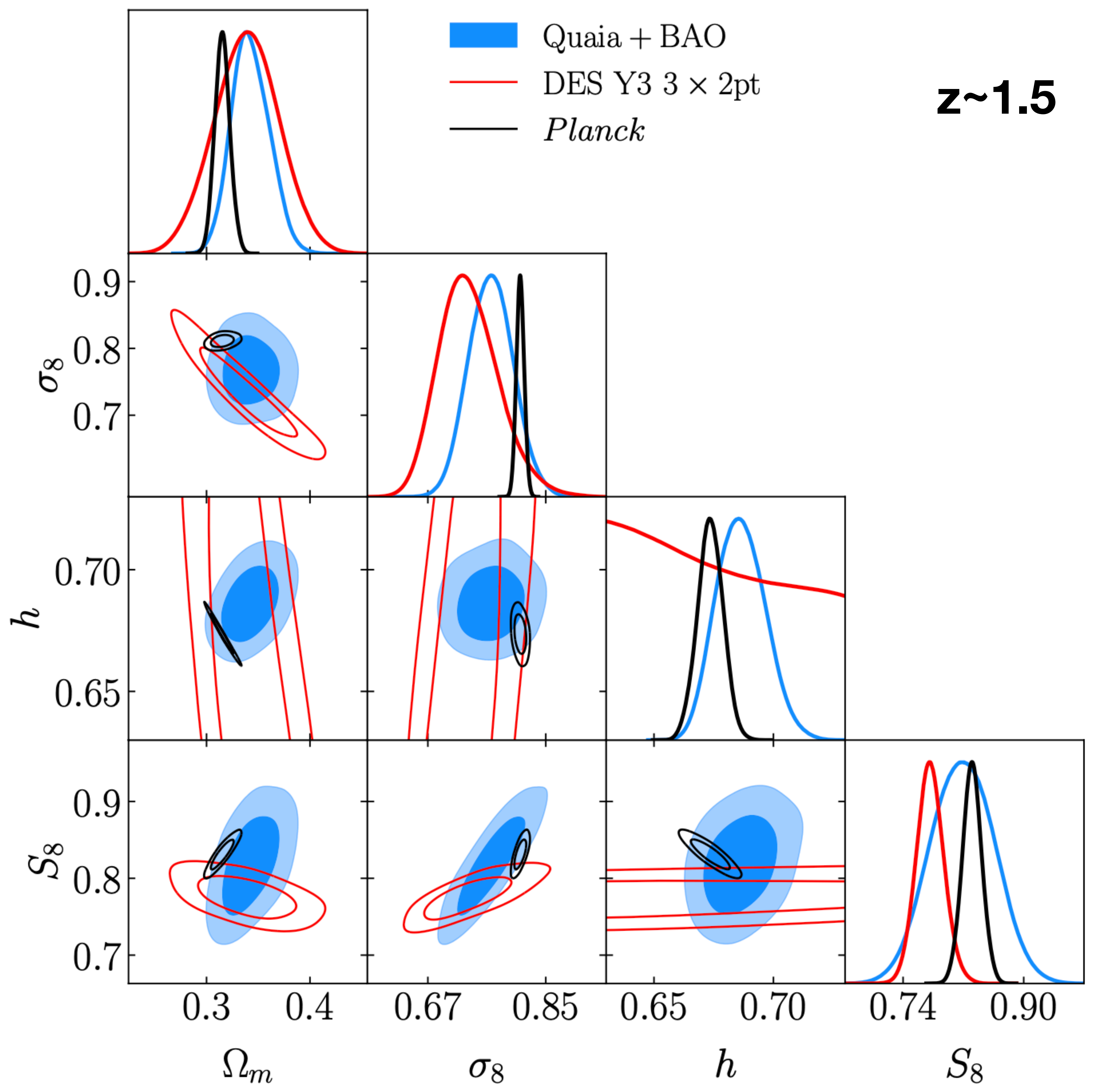
Recent Galaxy x CMB-lensing Studies

unWISE galaxies x Planck



Krolewski (2021)

Gaia-unWISE quasars x Planck

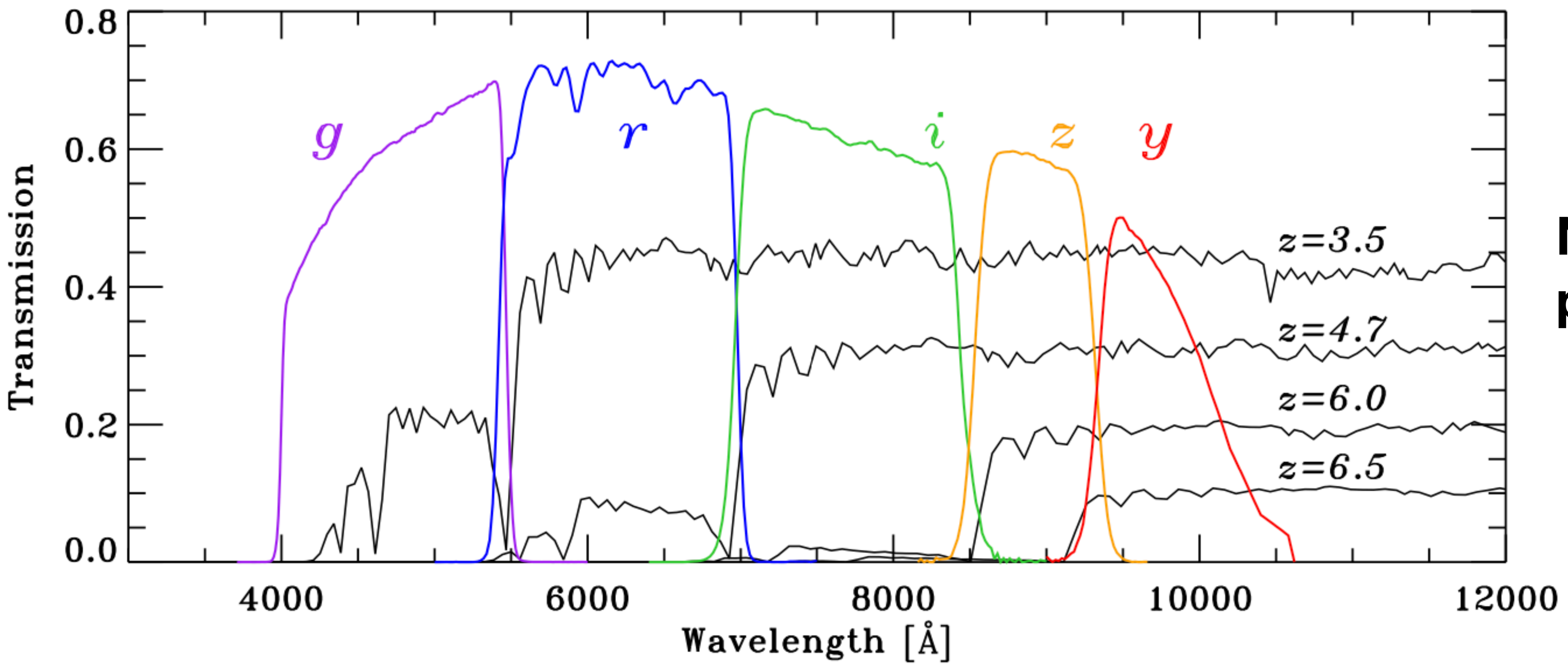


Alonso et al. (2023)

Going beyond $z>2$!

Selecting High-z Galaxies: Dropout Technique

- Broadband photometry can capture the Lyman break at 912Å.
- Selecting distant galaxies with Lyman break is called dropout technique, and these galaxies are called **Lyman break galaxies (LBG)**.

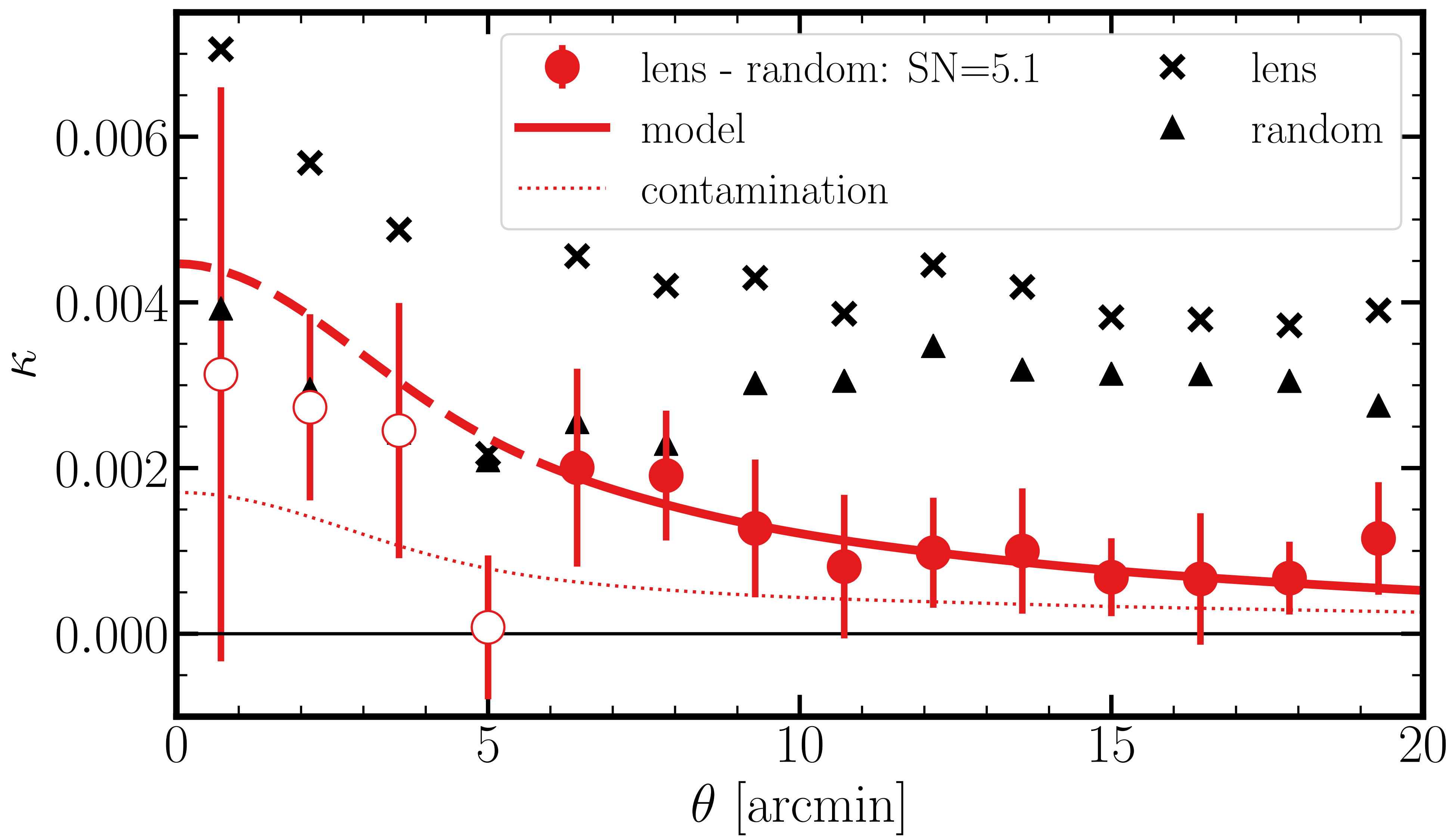


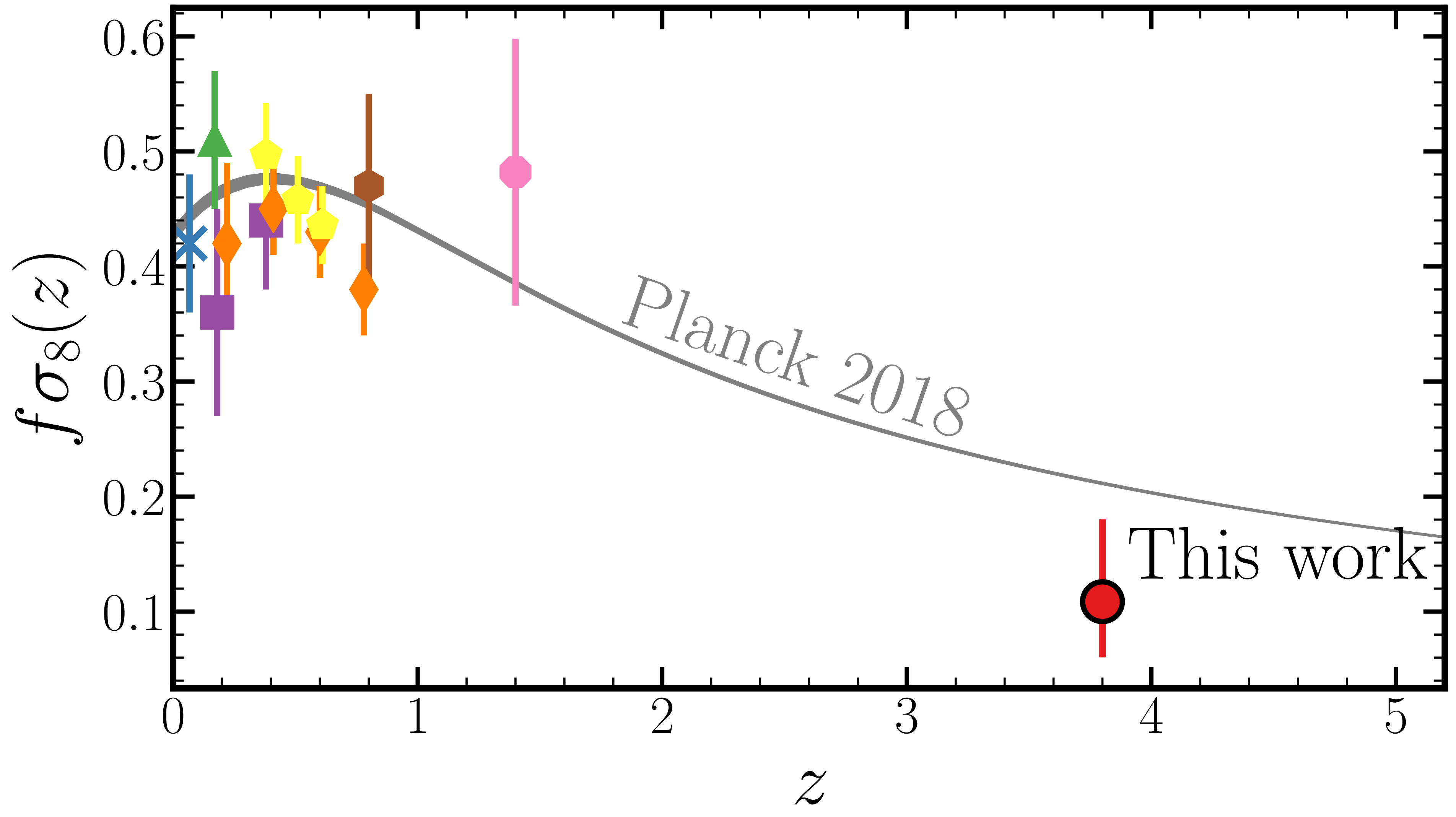
Note: u-dropout provides z~2.5 galaxies

Ono et al. (2018)

LBG x Planck CMB Lensing

- ~1.5M LBG galaxies over 300 deg² of HSC field.
- Stacked Planck lens map behind LBGs
- Contamination from low-z galaxies is quantified by WL measurements with HSC.
- Obtained 3.5σ significance against the contamination signal.





Miyatake et al. (PRL, 2022)

The Future

Near future (in 2-3 years)

- The HSC LBG sample will be tripled with the final HSC data.
- ACT DR6 has a large overlap with HSC. Noise level is 5 x smaller than Planck.

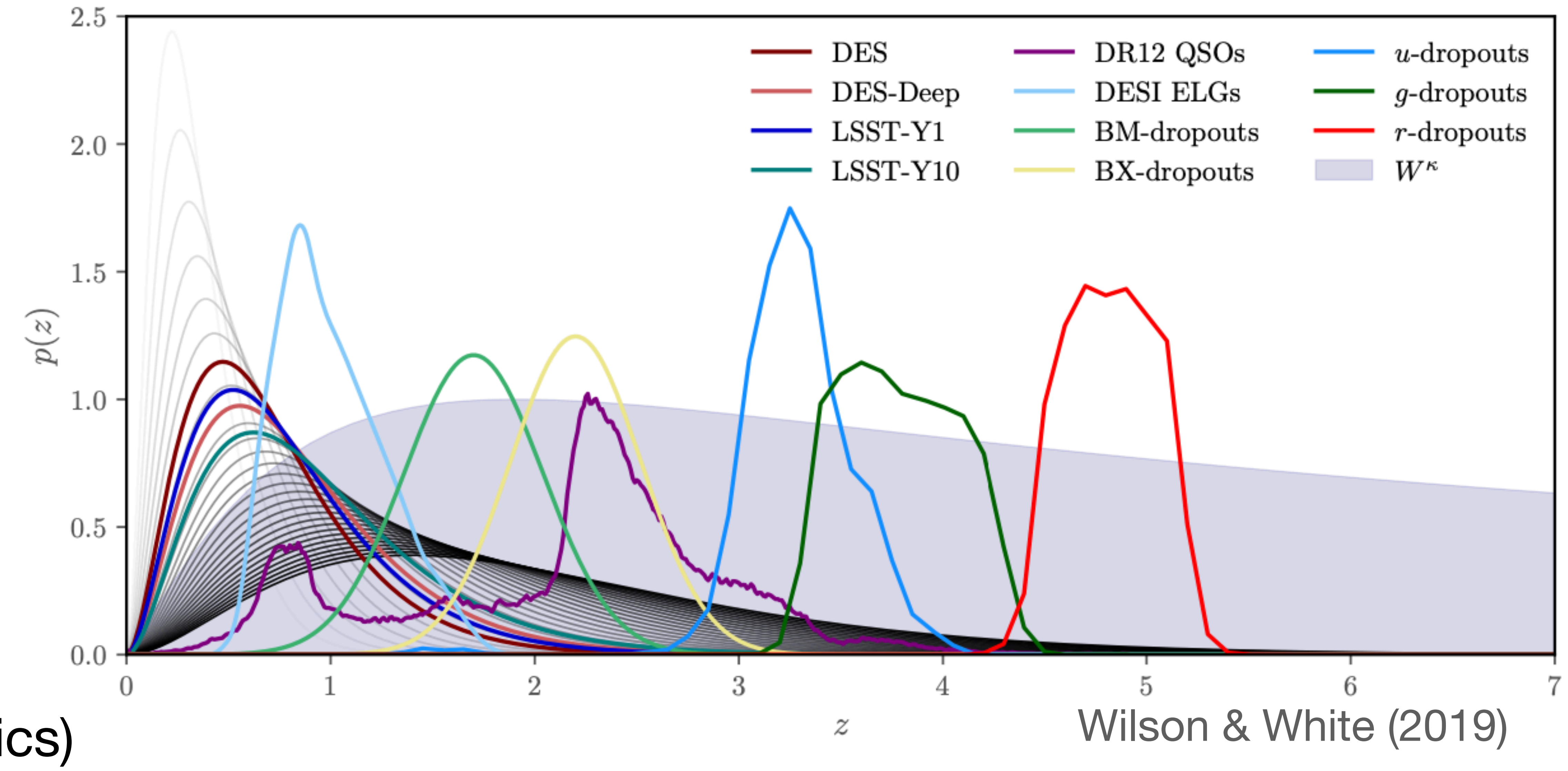
➡ **S/N ~ 15**

Future (beyond 2-3 years)

- More galaxies from upcoming imaging surveys, according to Wilson & White (2019), for Rubin
  - z~3 dropouts: 4×10^7 galaxies
  - z~4 dropouts: 10^8 galaxies
  - z~5 dropouts: 2×10^7 galaxies
- CMB-S4: 30 x smaller noise level compared to Planck.

➡ **S/N ~ 200**

(Can be optimistic since we need to deal with systematics)



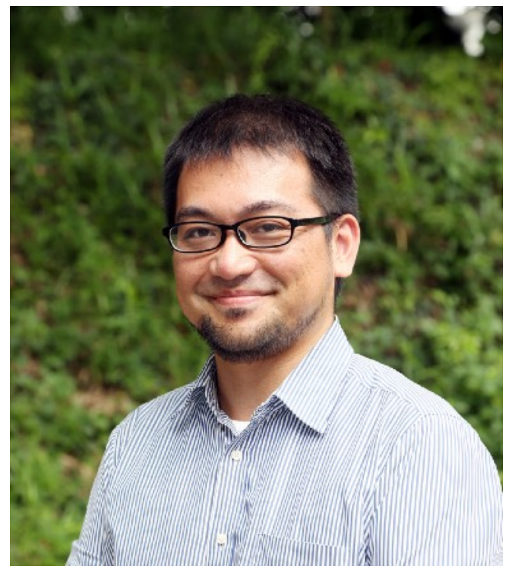
Wilson & White (2019)

Systematics to consider

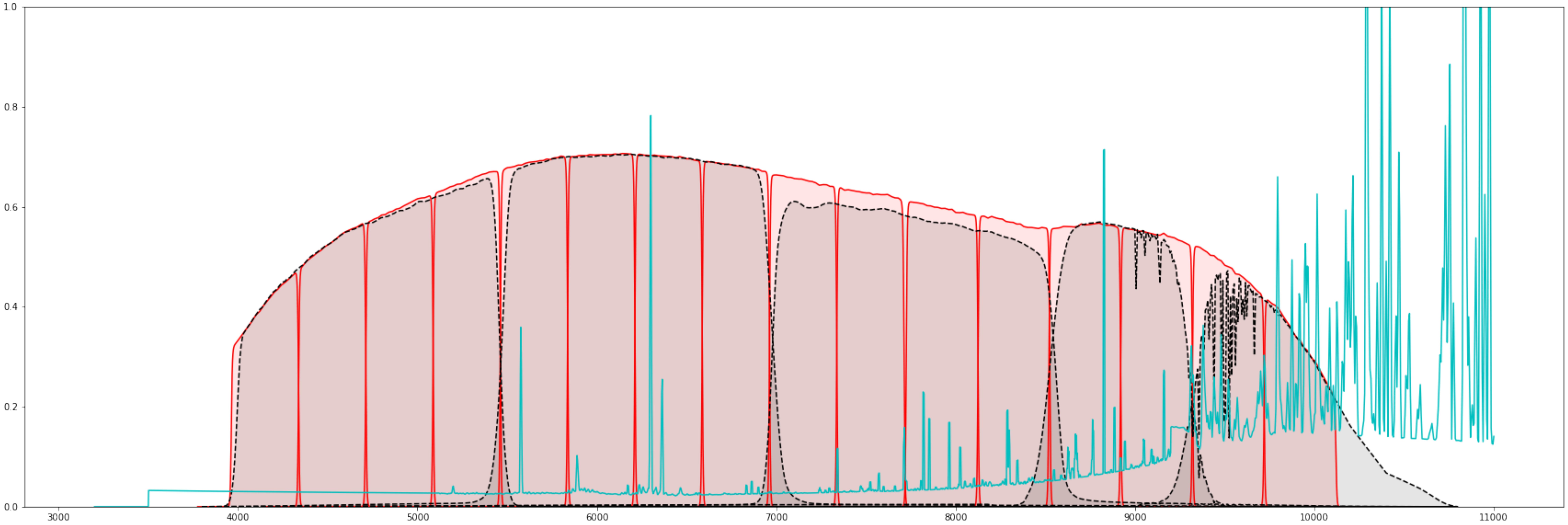
Severeness

- Redshifts/contaminations
  - Majority of contaminations are in low redshift: misidentification of 4000Å break as Lyman break.
  - But the redshift distribution should be measured for precision cosmology.
  - Currently we have ~1000 spec-zs. PFS, MSE and MegaMapper should help. See next slide for a medium-band survey.
  - For the CMB lensing signal, contaminations can be quantified by weak lensing.
- Cosmic Infrared Background (CIB)
  - CIB lowers CMB lensing signal.
- Magnification bias
  - Lens galaxies can be preferentially selected where LSS along the line-of-sight is prominent, which can cause magnification bias in the CMB lensing signal. We checked our measurement is not prone to magnification bias, but it should be revisited to carry out precision cosmology.

HSC Medium-Band (MB) Filters

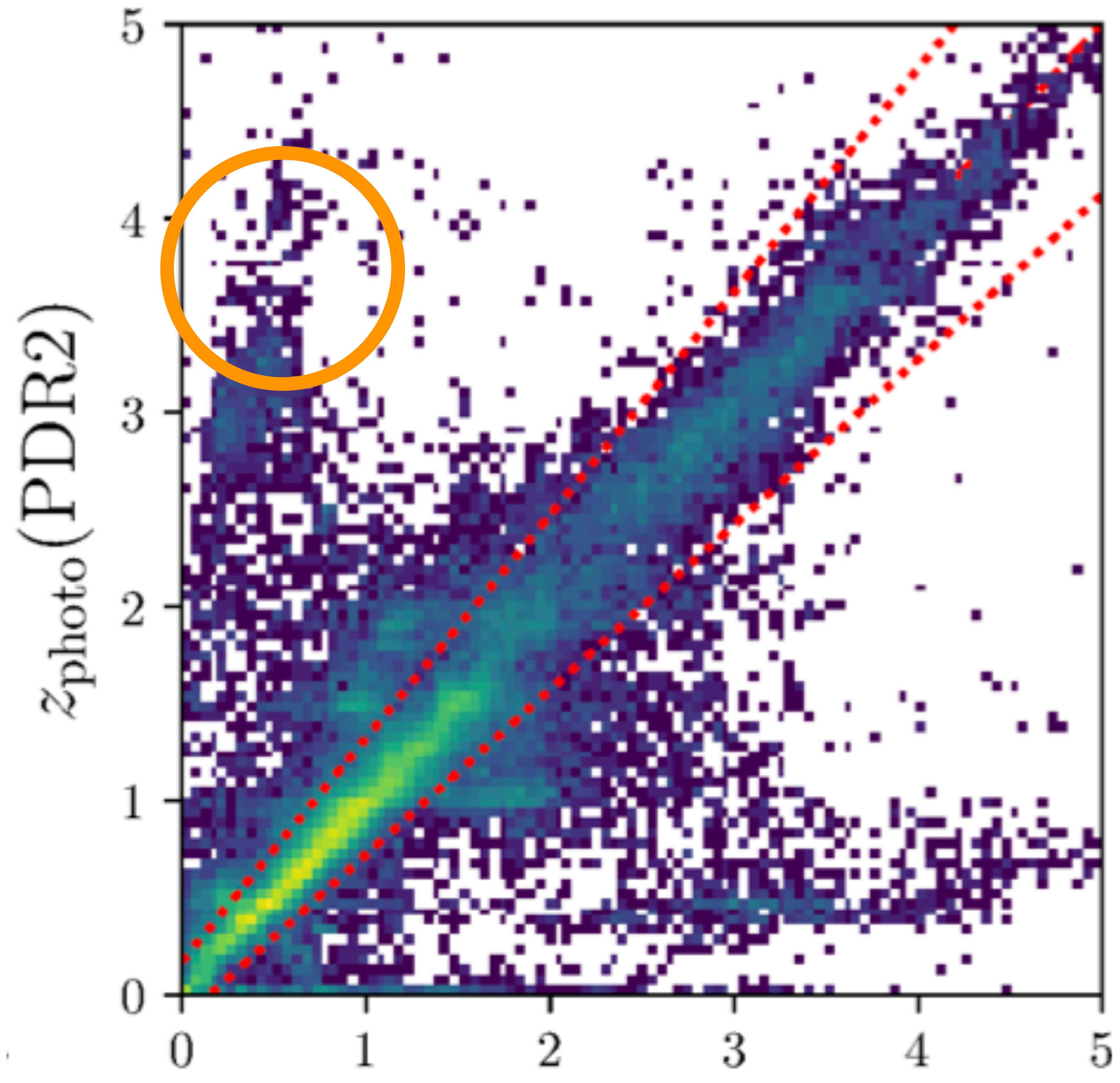


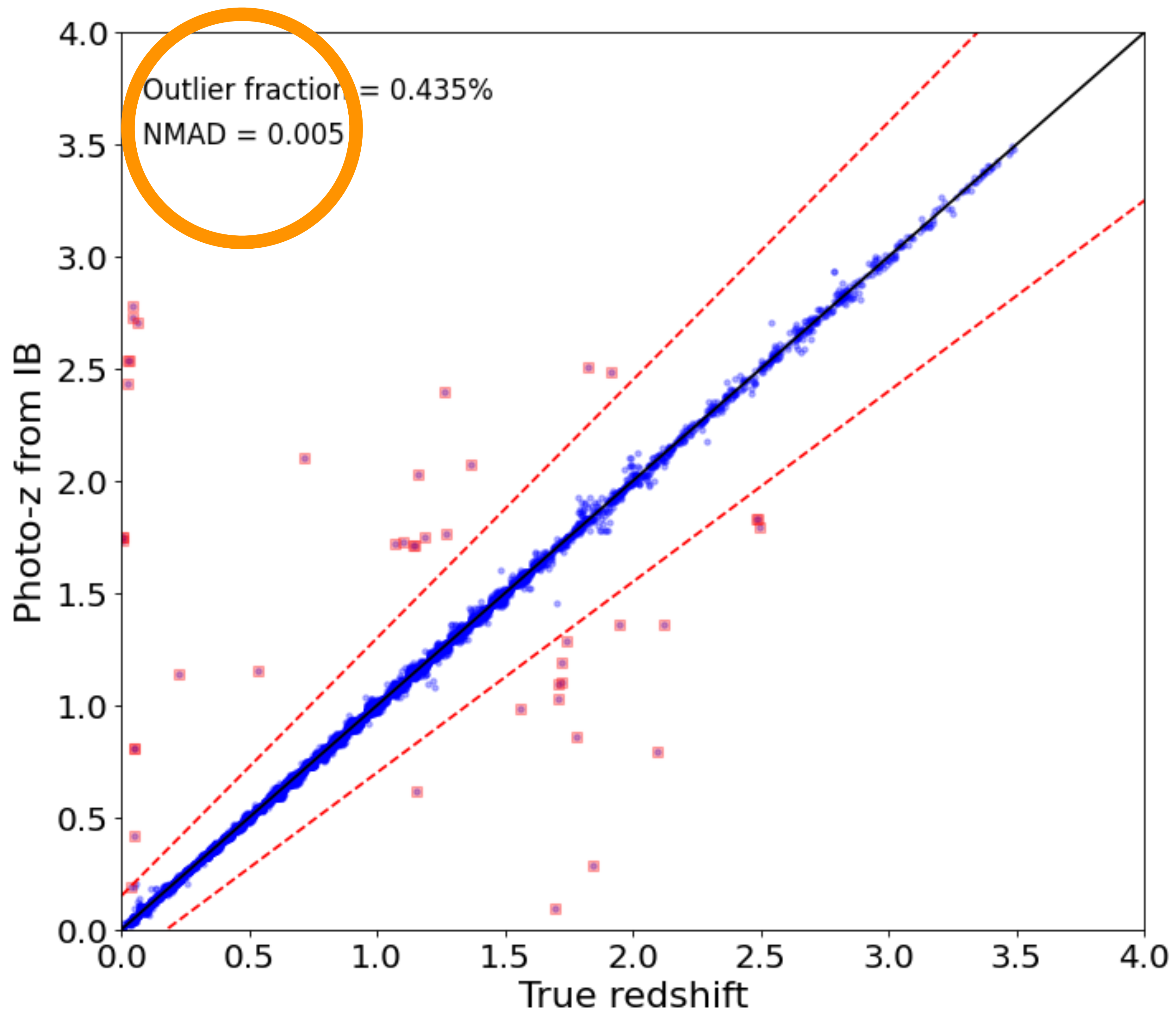
A. J. Nishizawa



- 16 or 20 medium-band (MB) filters that cover 4000-10000Å.
- Fabrication cost is funded (12 filters), and filters will be ready by S25A.

Performance of MB Filters



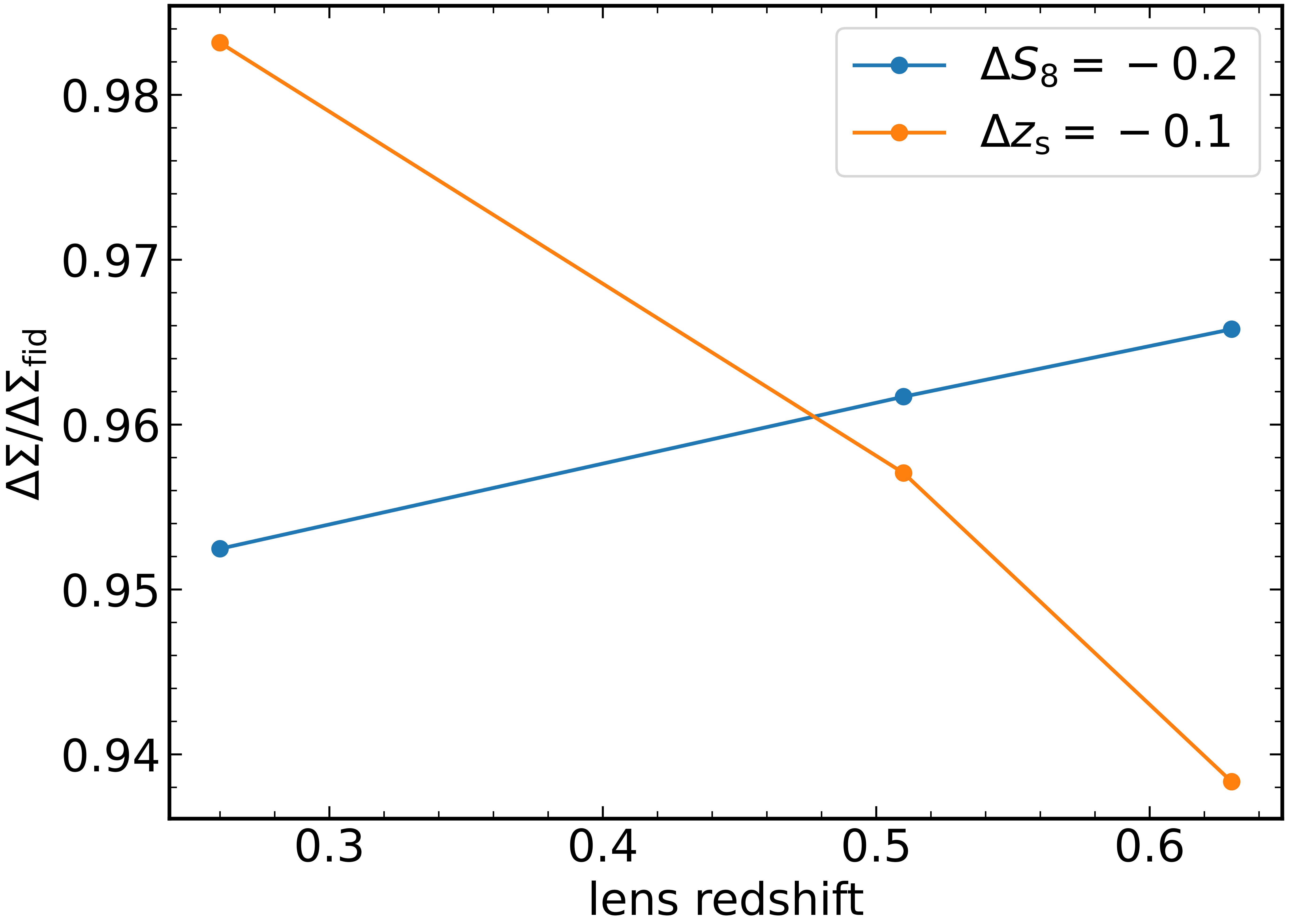


MB filters can be used for calibration to remove contamination.

Summary

- All the stage-III weak lensing surveys released intermediate results
  - Despite of different analysis choices, they consistently exhibit smaller S_8 compared to primary CMB.
  - A number of systematics were carefully tested in their analyses and follow-up studies: non-linear regime, photo-z, intrinsic alignment, baryonic effect.
- ACT lensing showed S_8 consistent with Planck primary CMB.
  - S_8 changes as a function of redshift?
  - In addition to the default science case of Stage-IV weak lensing surveys, where they measure large-scale structure at z<~2, we should to go higher redshift using galaxy-CMB lensing cross correlations!

Backup Slides



$\Delta S_8 = -0.2$
$\Delta z_s = -0.1$
0.98
0.97
0.96
0.95
0.94
$\Delta\Sigma/\Delta\Sigma_{fid}$
0.3
0.4
0.5
0.6
lens redshift