



GION Multi-Wavelength Lightcone Cosmological Simulations: Applications to CMB x LSS Cross-Correlations

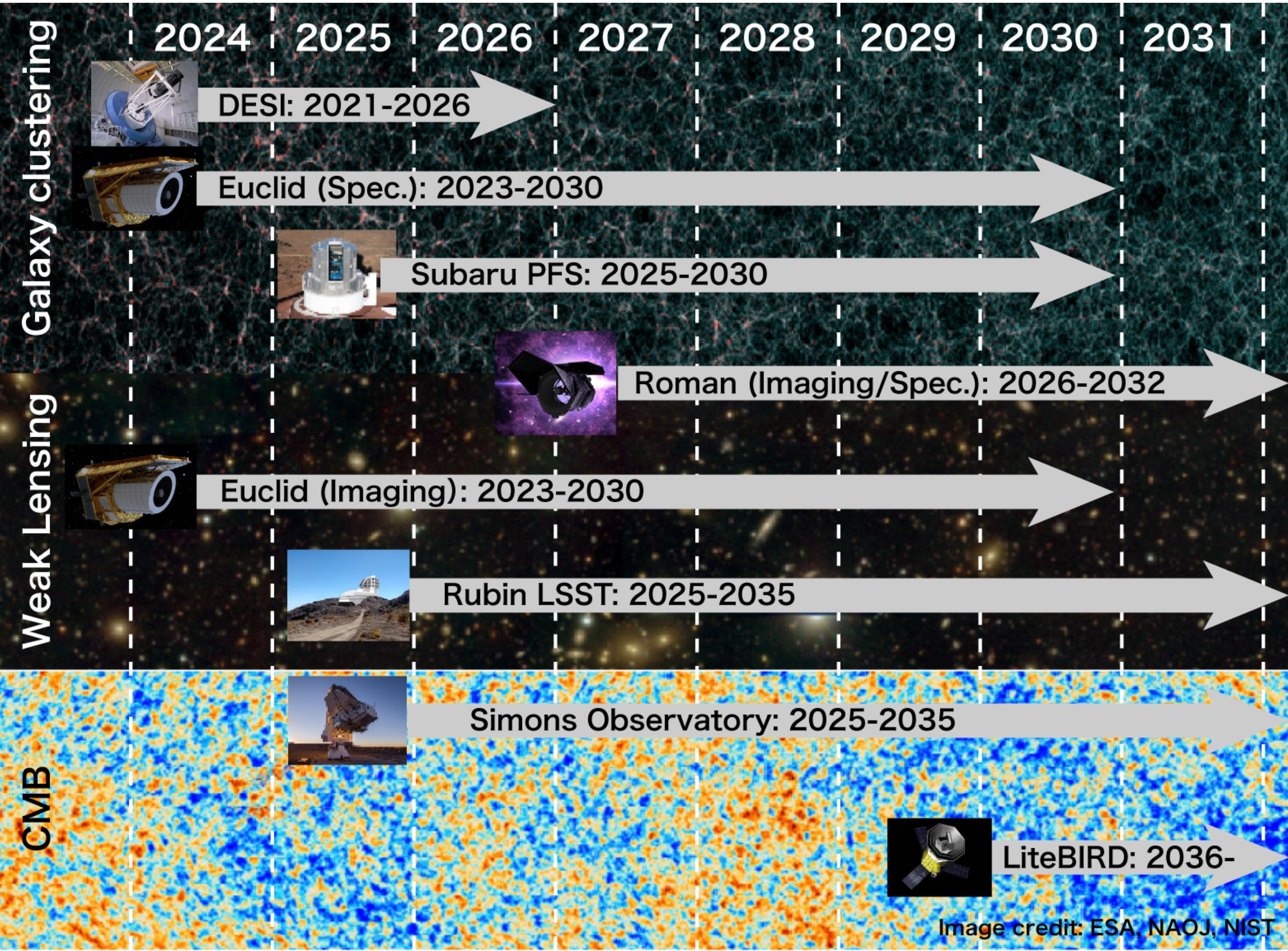
Challenges at the CMB Frontier
Chino, Nagano, Japan
2026/07/03

Ken Osato (Chiba U & RIKEN AIP)

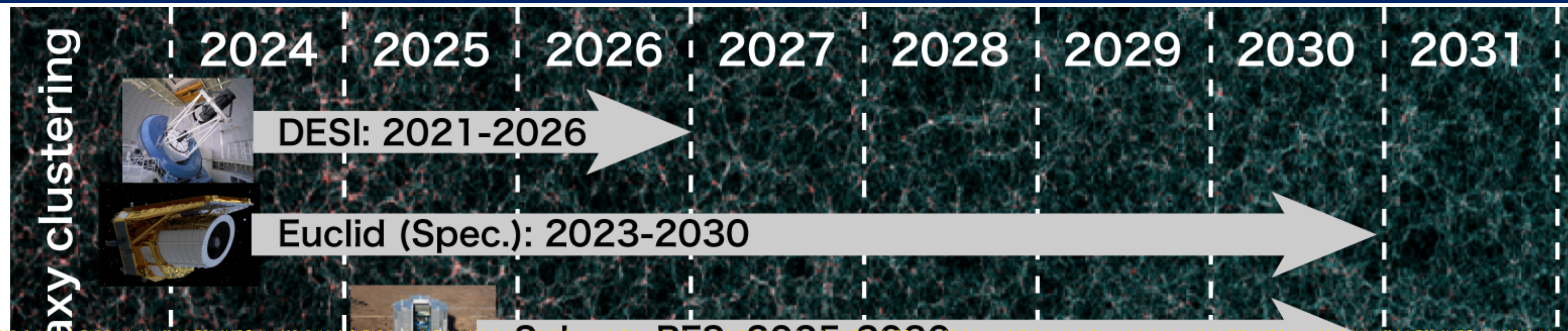
Collaborators:

**Satoshi Tanaka (Hitotsubashi U),
Tomoaki Ishiyama (Chiba U),
Masato Shirasaki (NAOJ/ISM),
Hironao Miyatake (KMI, Nagoya U),
Takahiro Nishimichi (Kyoto Sangyo U)**

Stage-IV Cosmological Surveys



Stage-IV Cosmological Surveys



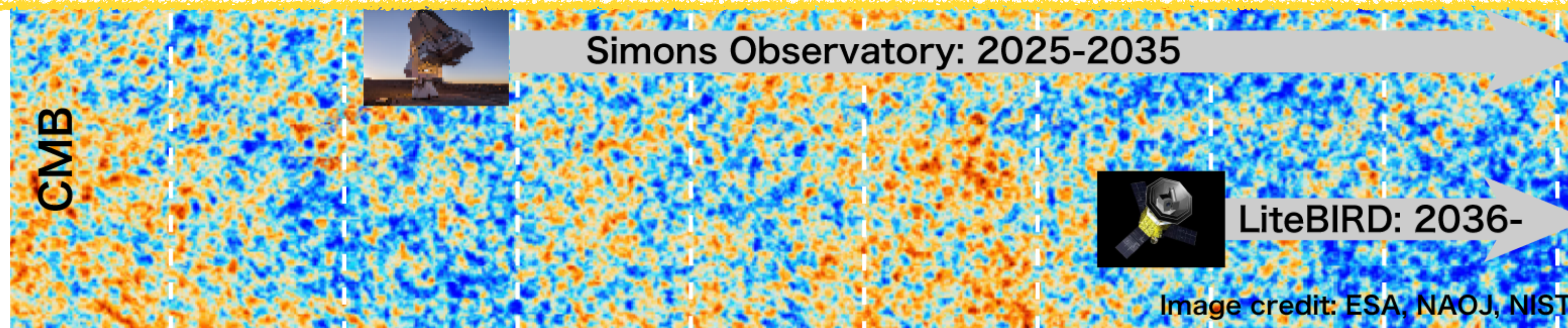
◆ Why are simulations important in cosmological analysis?

1. Predict the cosmological statistics given cosmological model

2. Validate the analysis pipeline

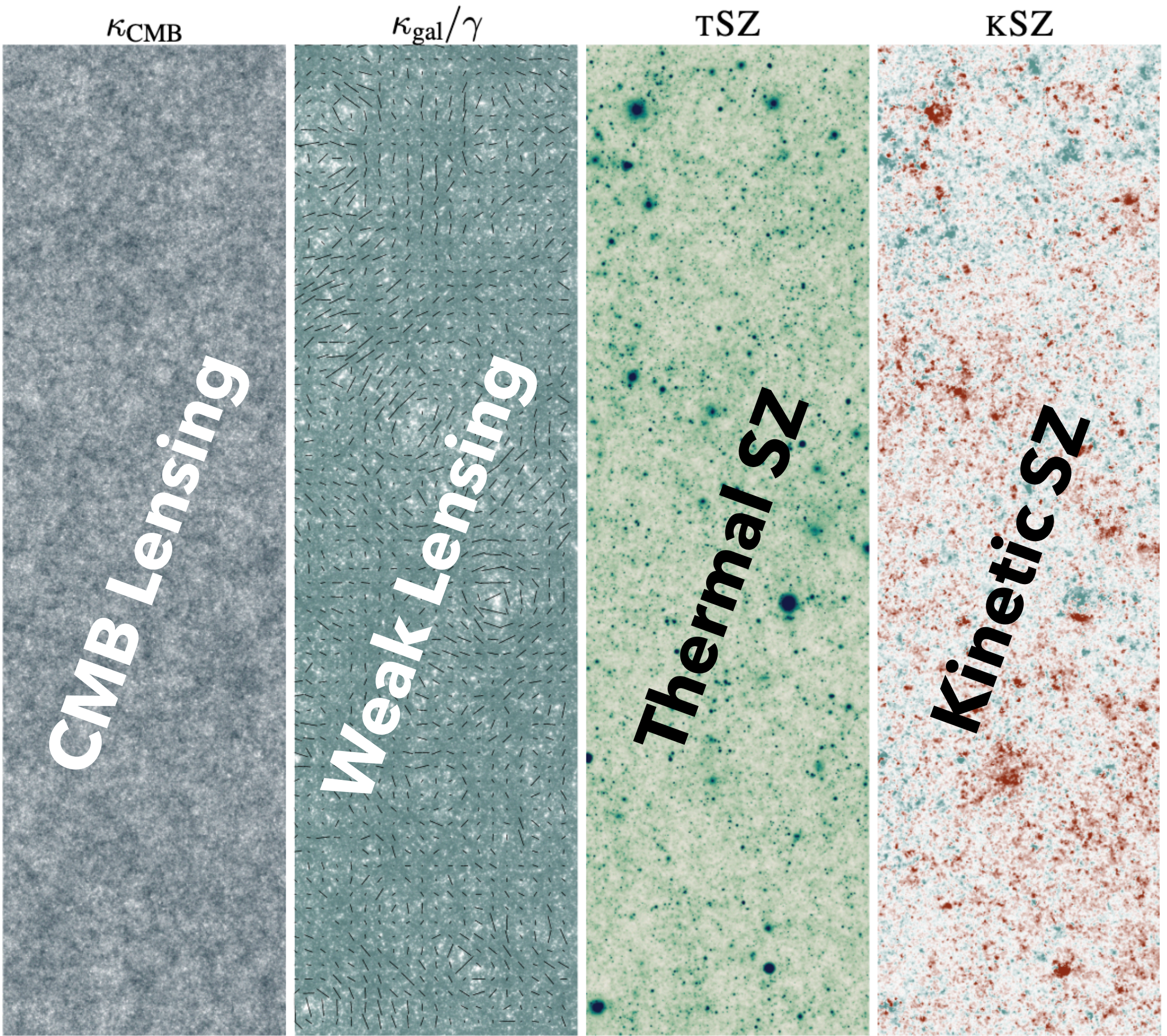
3. Estimate the covariance matrix of cosmological statistics

➡ For Stage-IV (*Euclid, Roman, PFS, ...*), we need *high-resolution* ($M_{h,\min} = 10^{11} \text{ Msun}/h$), *many realizations*, and *correlated multi-wavelength simulations*.

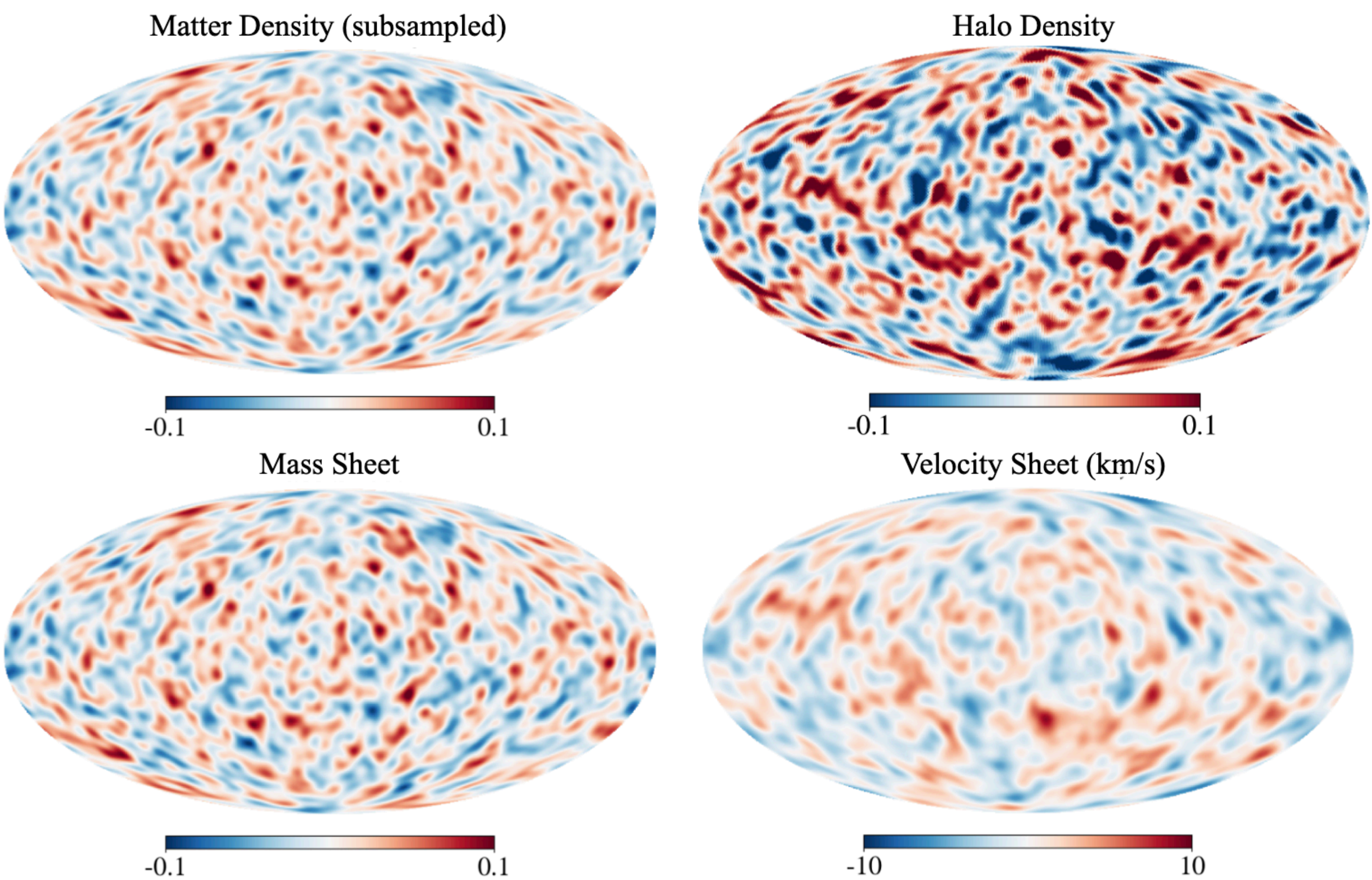


Mock Simulations for Multi-Wavelength Observations

◆ **AGORA simulation** (*Omori, 2023*)



◆ **HalfDome simulation** (*Bayer+, 2024*)



Simulation Campaign with Supercomputer Fugaku

◆Multi-wavelength Cosmological Simulations for Next-generation Surveys

PI: Jia Liu (IPMU); co-PIs: Ken Osato (Chiba), Hironao Miyatake (Nagoya)

720 M CPU-hours x 3 years (AY2023-2025)

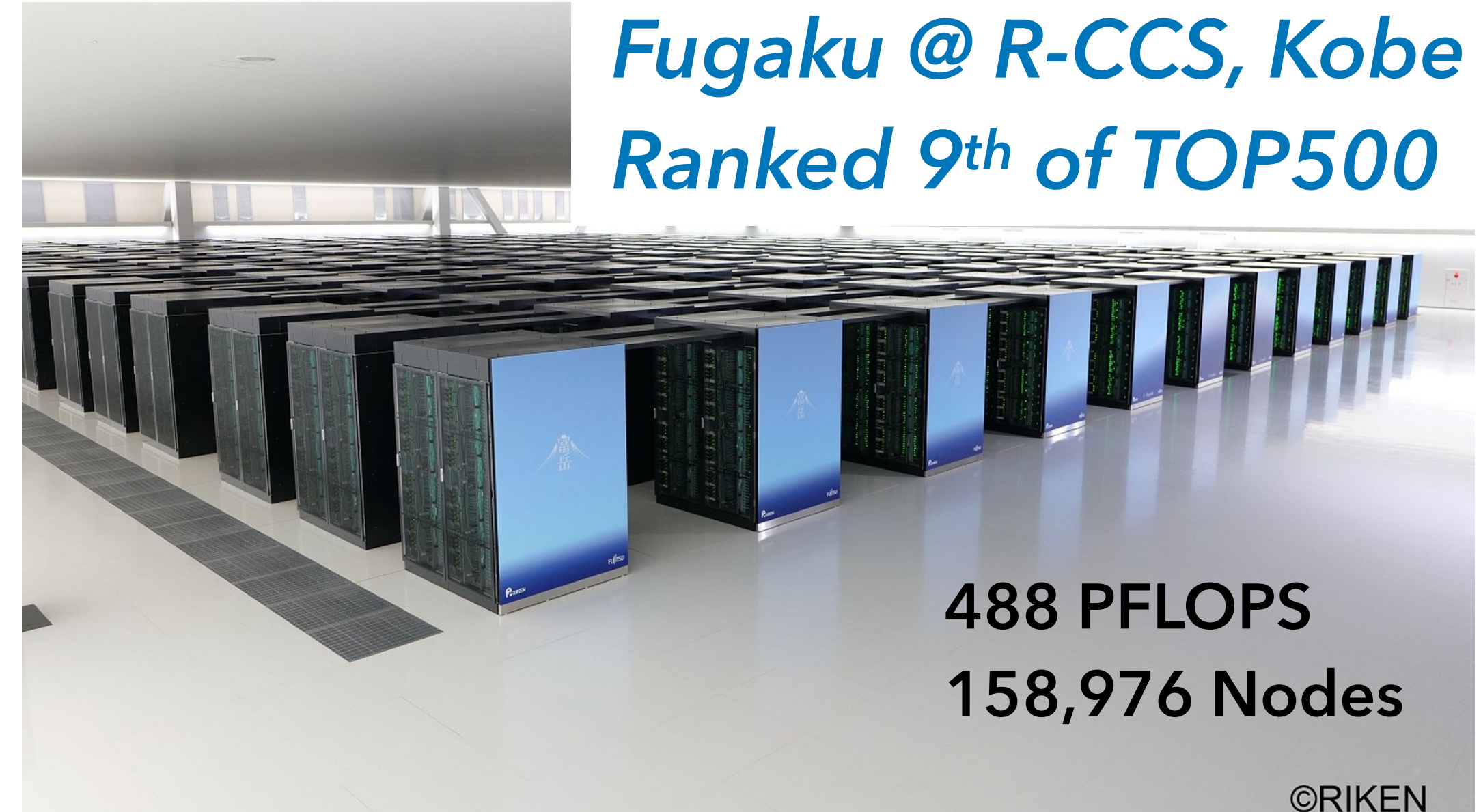
スーパーコンピュータ「富岳」
成果創出加速プログラム

◆Full-sky multi-wavelength mocks from gravity-only N -body simulations:

New N -body code: **GINAKAKU** (*Nishimichi, Tanaka, Yoshikawa, 2026*)

◆Modelled observables

- Weak lensing
- Galaxies (HOD)
- **CMB (lensing, tSZ/kSZ, CIB, radio)**
- X-ray
- and more...



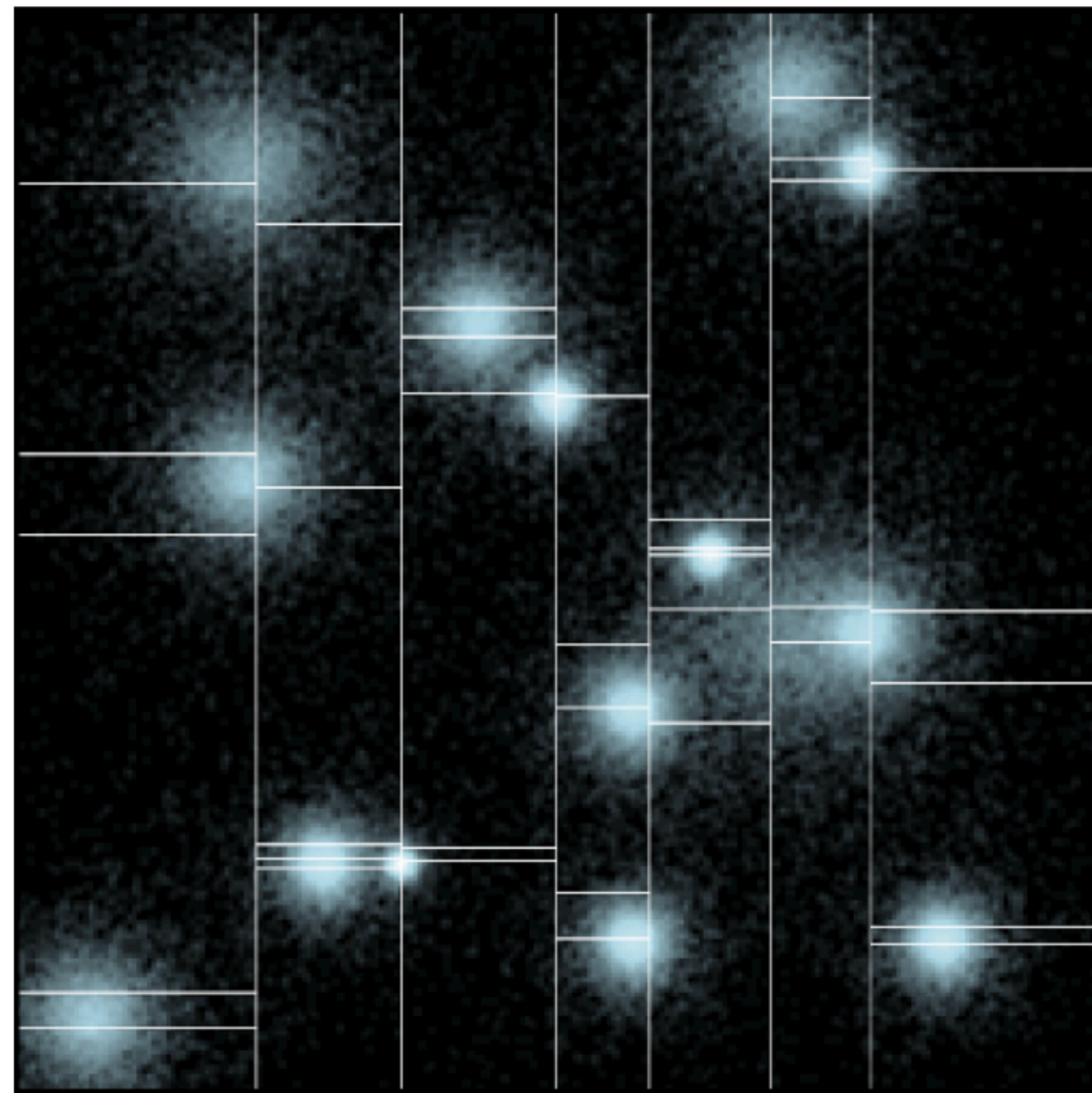
- **Gravitational INtegrator for Kinematical Analysis of dark Universe (GINKAKU)**

(Nishimichi, Tanaka, Yoshikawa; arXiv: 2605.28581)

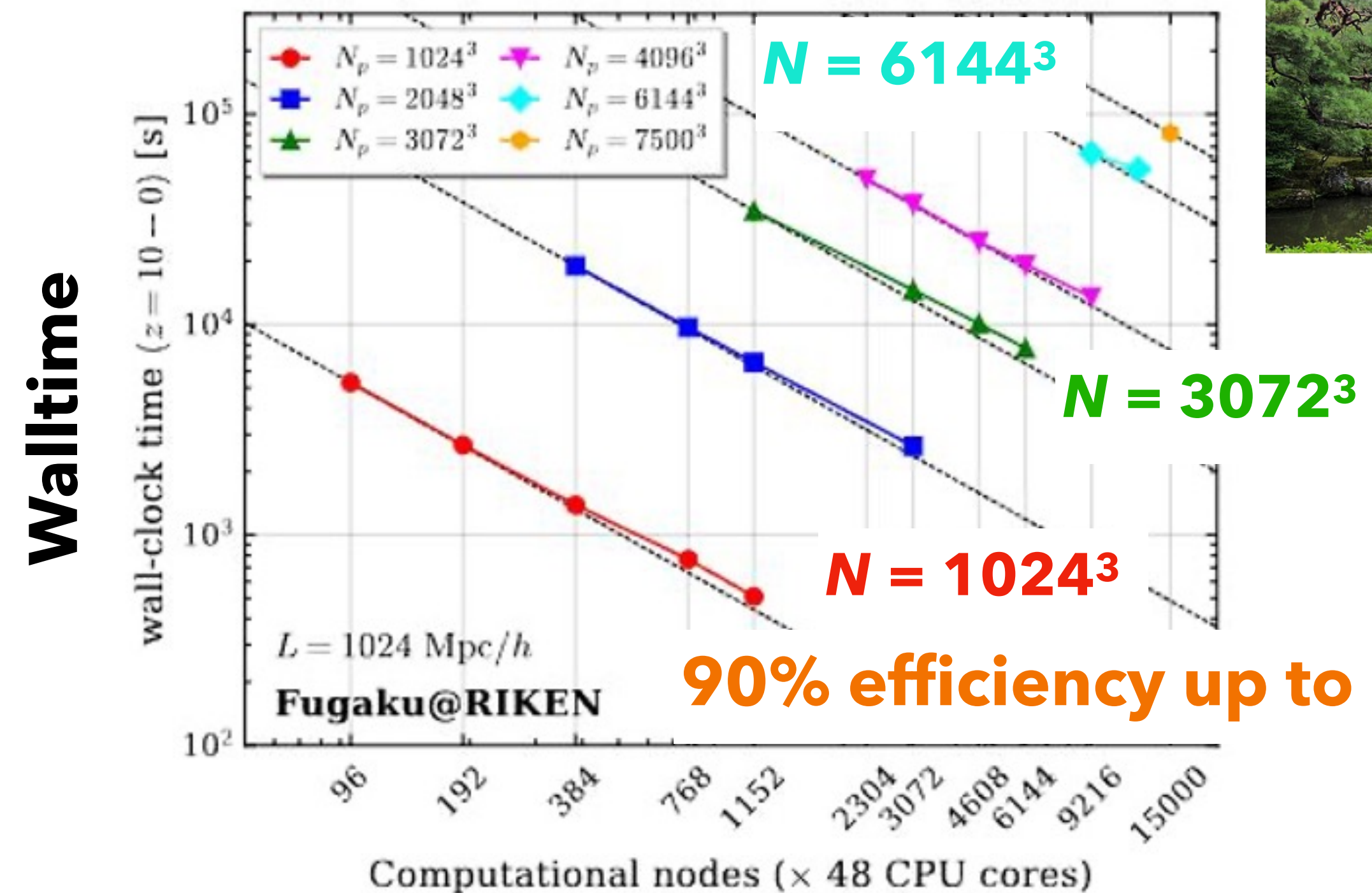
TreePM N-body simulations code implemented based on FDPS *Iwasawa+16, Namekata+18*

Long range: GreeM-based PM *Ishiyama+09, 12* Short range: Phantom-GRAPE *Tanikawa+12, 13*

- **Strong scaling on Fugaku**



Iwasawa+16



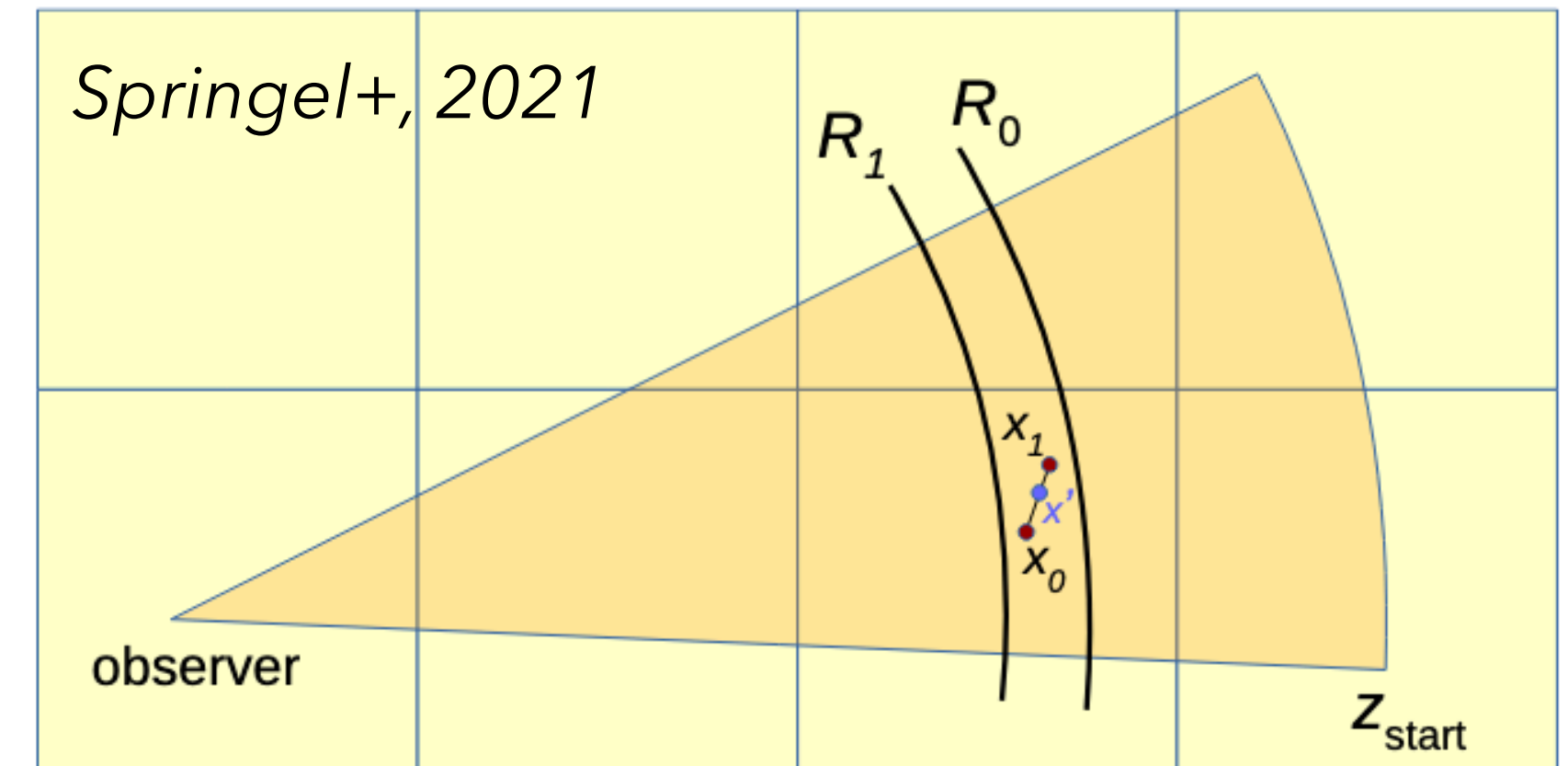
90% efficiency up to 500k CPUs!

Lightcone Simulation

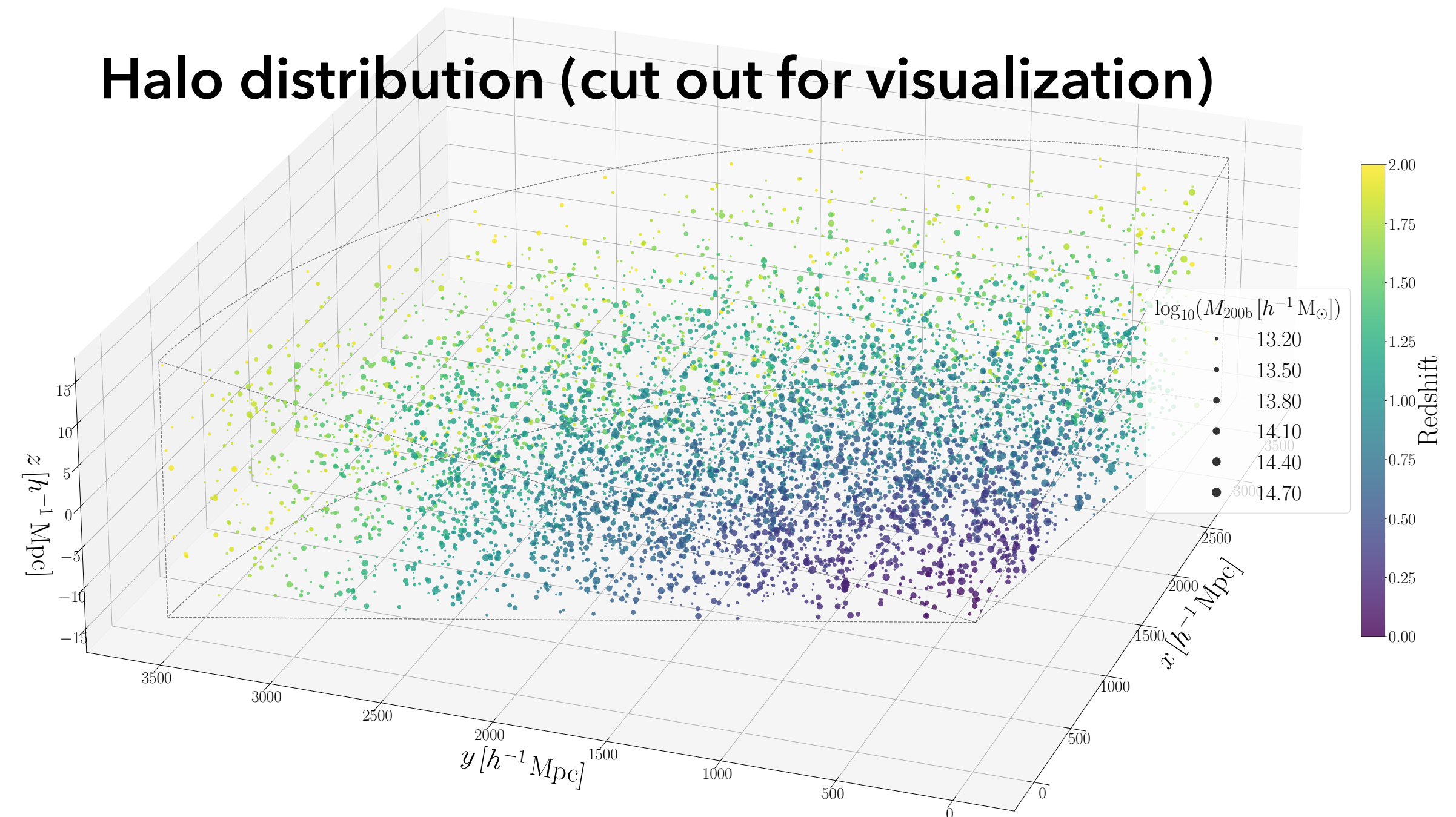
- **Lightcone output** (e.g., *Evrard+02*, *DeRose+19*)
 N -body particles are dumped when they cross the lightcone surface.

➔ **No discontinuity between snapshots**

- **On-the-fly post-processing**
The particles are converted to
 - **Mass shells** for weak lensing
 - **Momentum shells** for kinetic SZ
 - **Halo catalogues** based on MPI-RockstarThe lightcone extends to $z = 5$.



Halo distribution (cut out for visualization)



GION: Ginkaku LightcONe Multi-wavelength Simulation

- GION: Full-sky Multi-wavelength simulations**

Code: GINKAKU, $L_{\text{box}} = 1.5 h^{-1} \text{Gpc}$, $N = 6144^3$, $m_p = 1.3 \times 10^9 h^{-1} M_{\odot}$

Realizations: 10 (Planck 2018 cosmology); 470M CPU hours in total

Initial condition: monofonIC (Michaux+, 2020); 3LPT at $z_{\text{start}} = 24$

Outputs: halo catalogues (MPI-Rockstar; Tokuue, Ishiyama, KO+; 2025)

mass/momentum shells (every 25 Mpc/h, $0 < z < 5$, $N_{\text{side}} = 8192$)

Running simulations and post-processing completed in Mar. 2026.



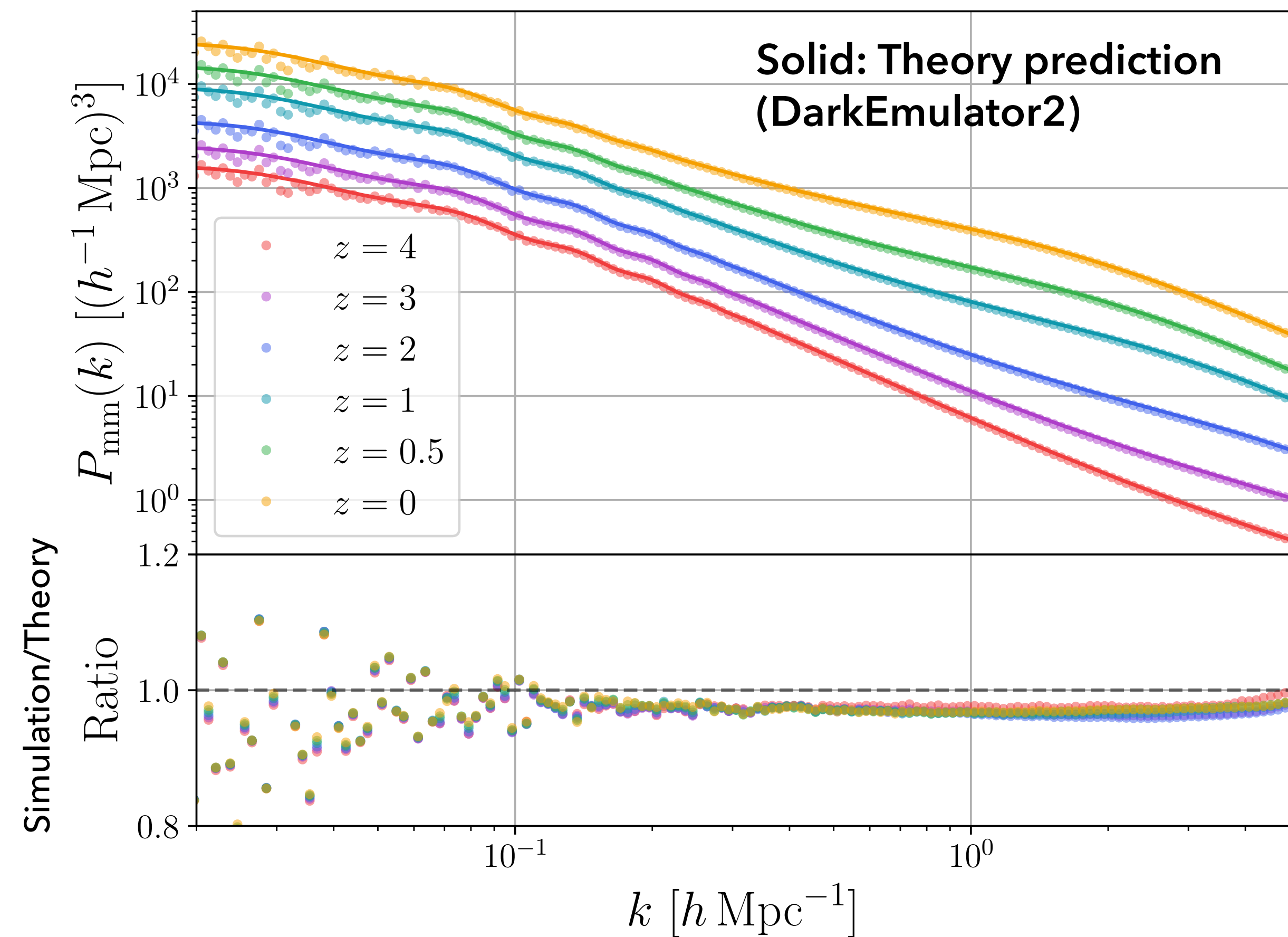
Bayer+, 2024

	Sehgal+ [12, 13]	BAHAMAS [14, 15]	Takahashi+ [16]	MassiveNuS [17]	Buzzard [18]	Websky [19]	Agora [20]	HalfDome (FastPM)	GION TreePM
$L_{\text{box}} (h^{-1} \text{Gpc})$	1	0.4	0.45–6.3	0.512	1.05–4.0	7.7	1	3.75	1.5
N_c	1024^3	2×1024^3	$2048^3 (z=1)$	1024^3	$2048^3 (z=1)$	6144^3	3840^3	6144^3	6144^3
$M_h^{\text{min}} (h^{-1} M_{\odot})$	10^{13}	5×10^{11}	$10^{13} (z=1)$	10^{10}	$10^{13} (z=1)$	1.2×10^{13}	1.5×10^9	6×10^{12}	10^{11}
N_{sim}	1 (500)	11	108	101	30	1	1	11 (+1 f_{NL})	10

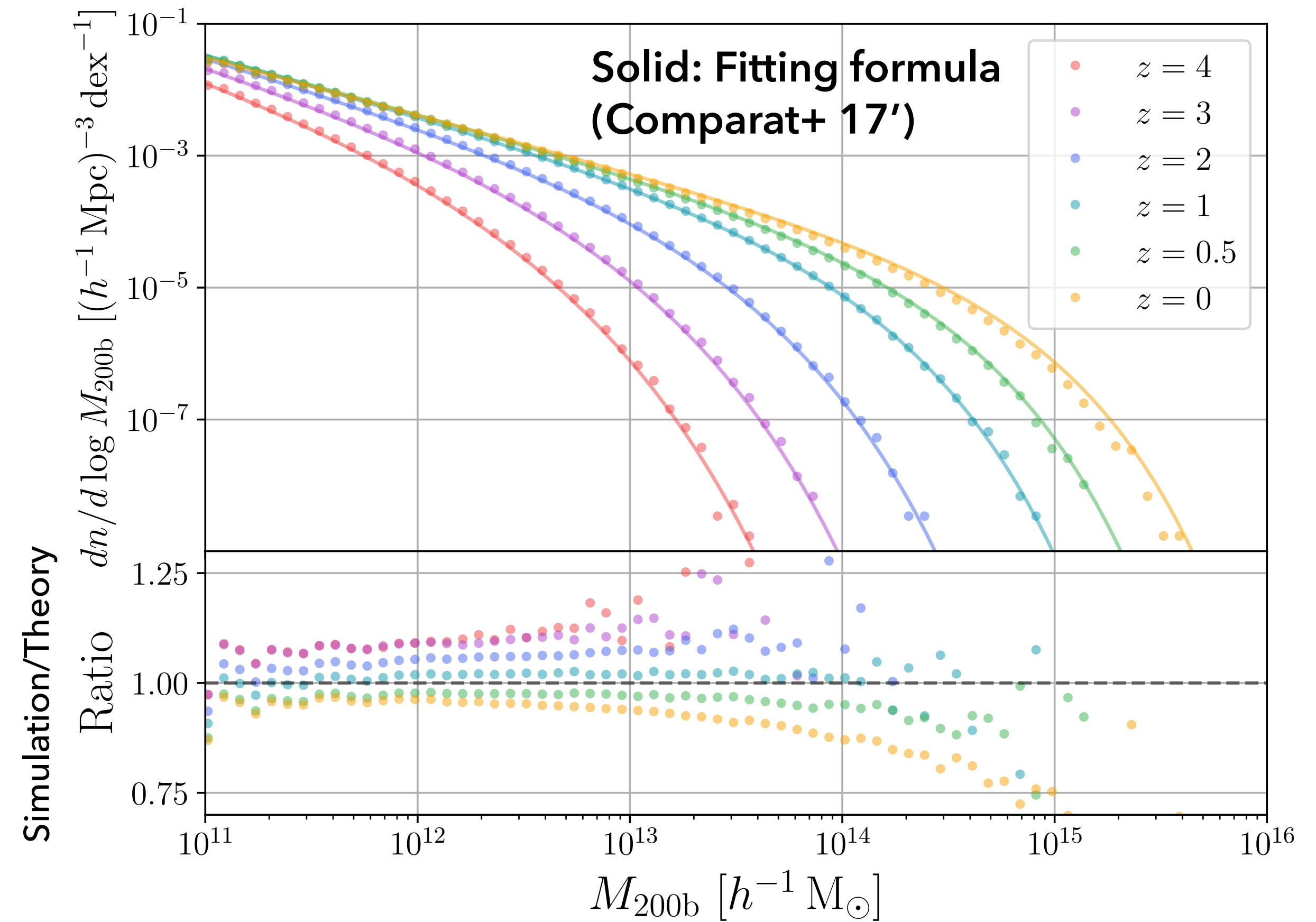
➔ **GION is a unique simulation data sets with multiple realizations and high mass resolution. Ideal for Stage-IV surveys!**

Validation

• Matter power spectrum

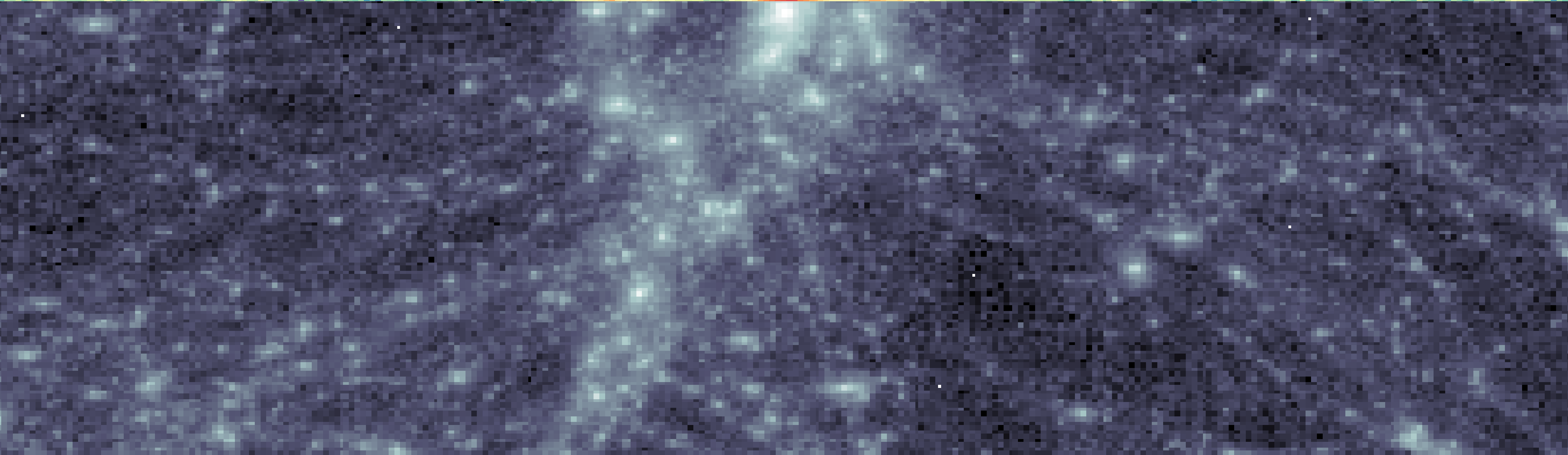
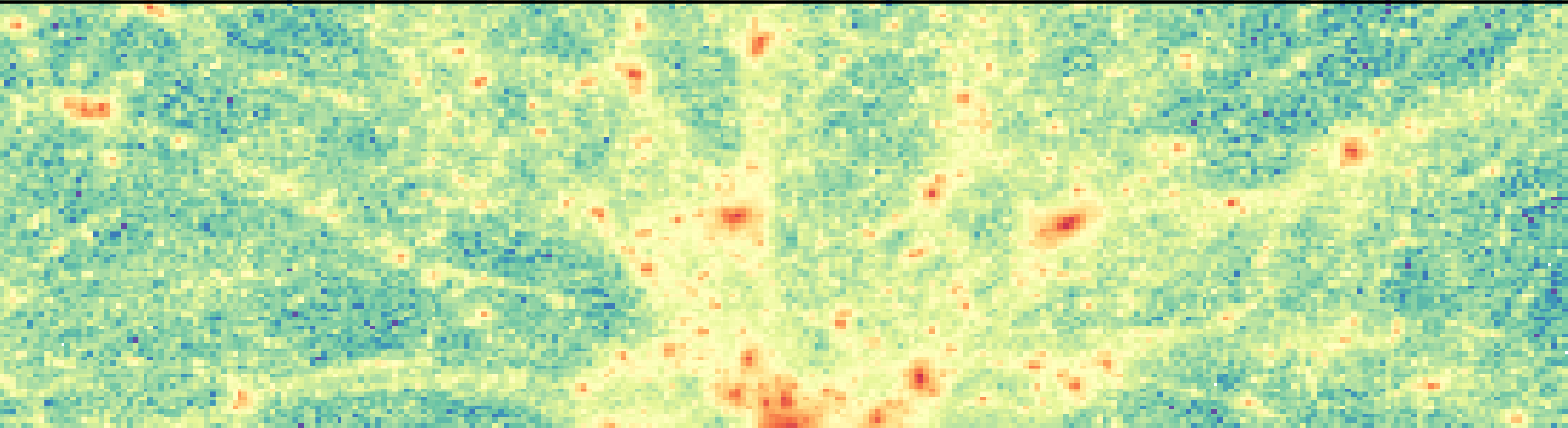


• Halo mass function



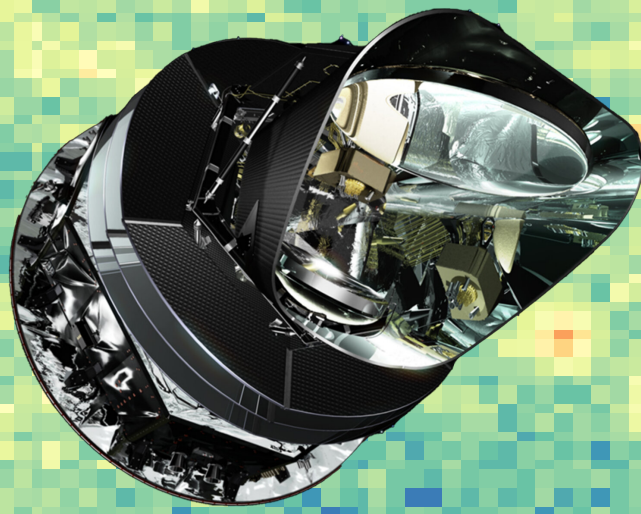
✓ Power spectra and halo mass functions are consistent with models.

Applications in CMB x Large Scale Structures:
Thermal Sunyaev-Zel'dovich effect x Weak lensing



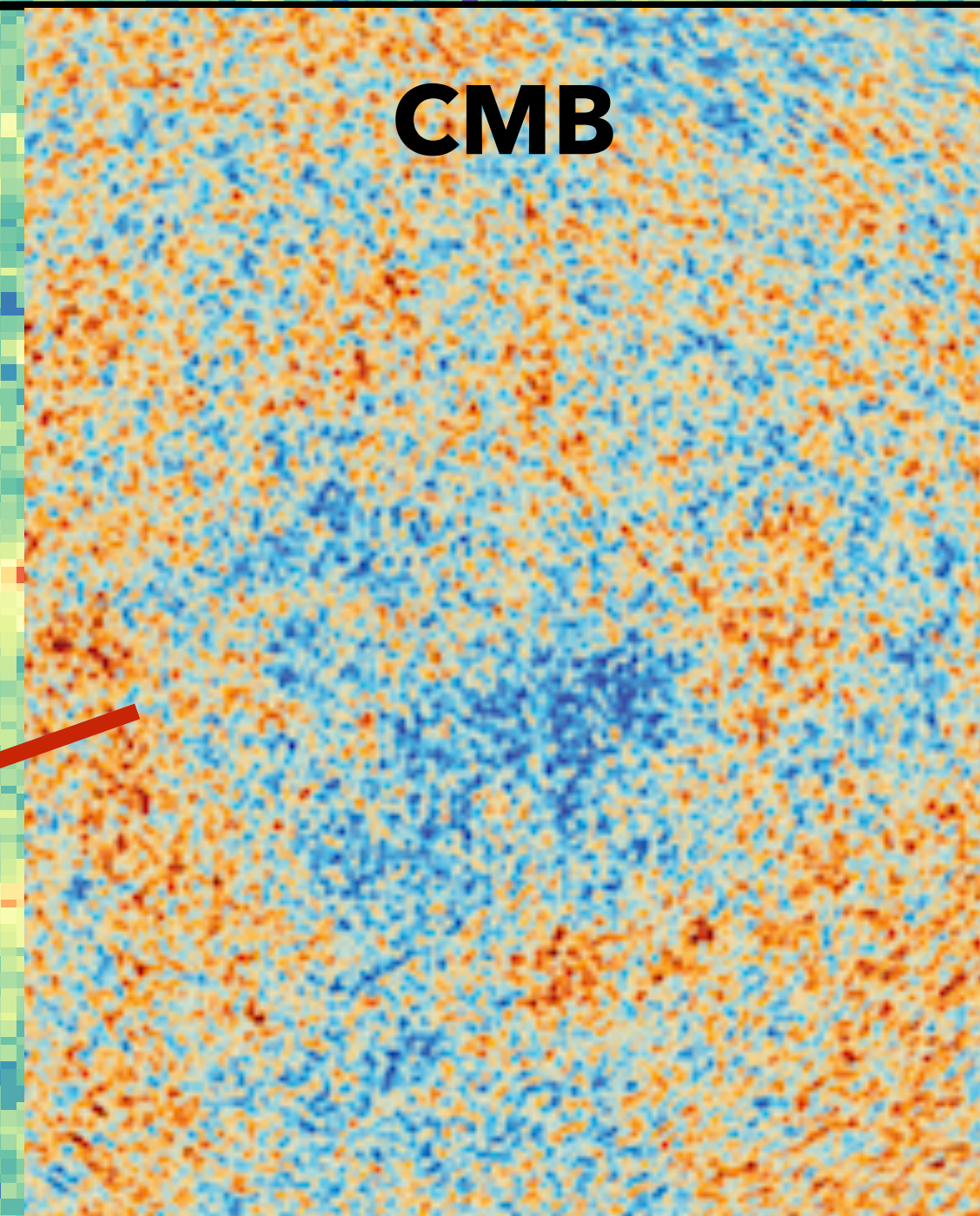
Thermal SZ (tSZ) effect $\frac{\Delta T}{T} = y \left(x \frac{e^x + 1}{e^x - 1} - 4 \right), \quad x = \frac{h\nu}{kT}$

Compton-y $y(\theta) = \frac{\sigma_T k_B}{m_e c^2} \int P_e dl$

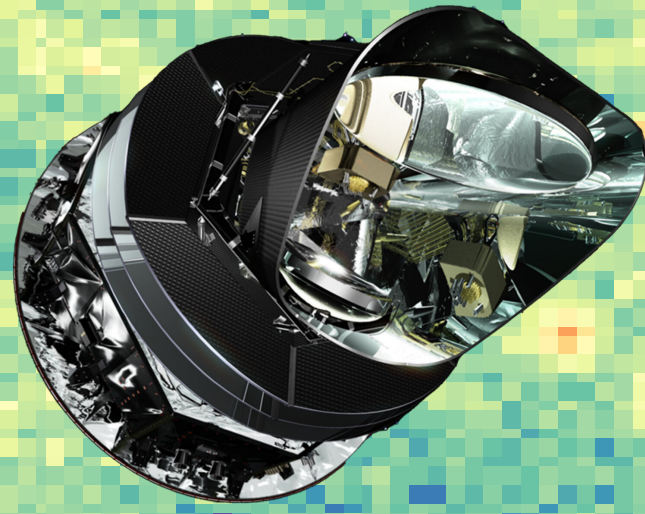


CMB photons get energy through inverse Compton scattering with **hot free electrons**.

CMB



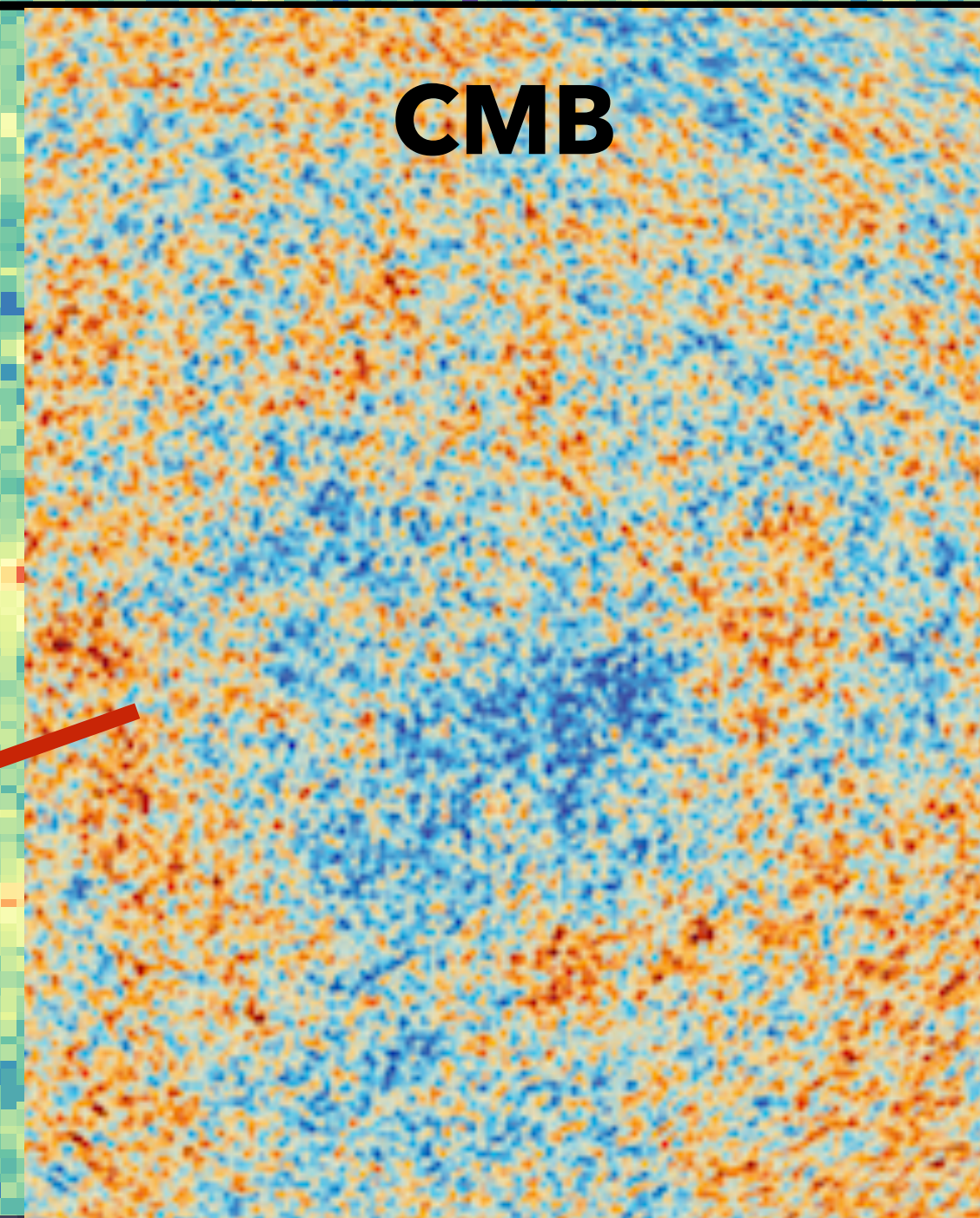
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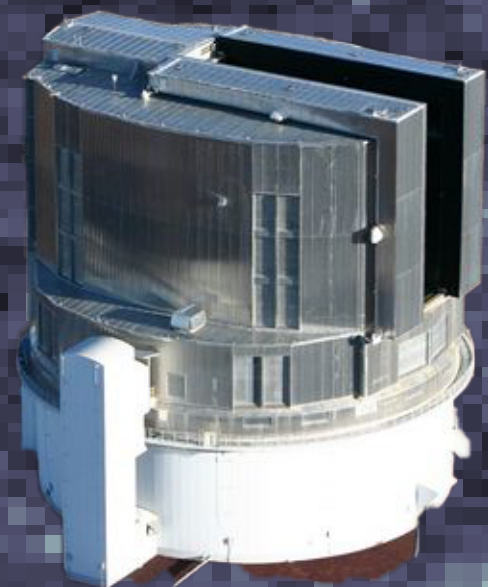
Compton-y $y(\theta) = \frac{\sigma_T k_B}{m_e c^2} \int P_e dl$

CMB photons get energy through inverse Compton scattering with **hot free electrons**.

CMB



Weak lensing (WL) $\kappa(\theta) = \frac{3\Omega_m H_0^2}{2c^2} \int_0^{\chi_s} d\chi \frac{f_K(\chi_s - \chi) f_K(\chi)}{f_K(\chi_s) a(\chi)} \delta(f_K(\chi) \theta, \chi)$



Convergence

True shape



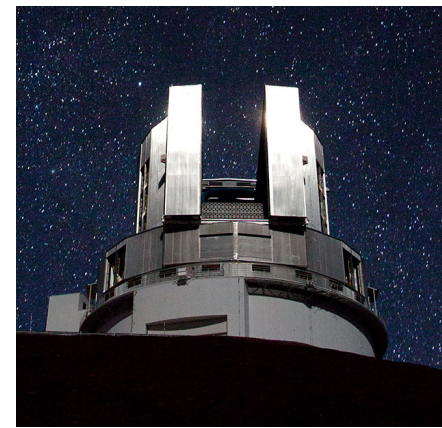
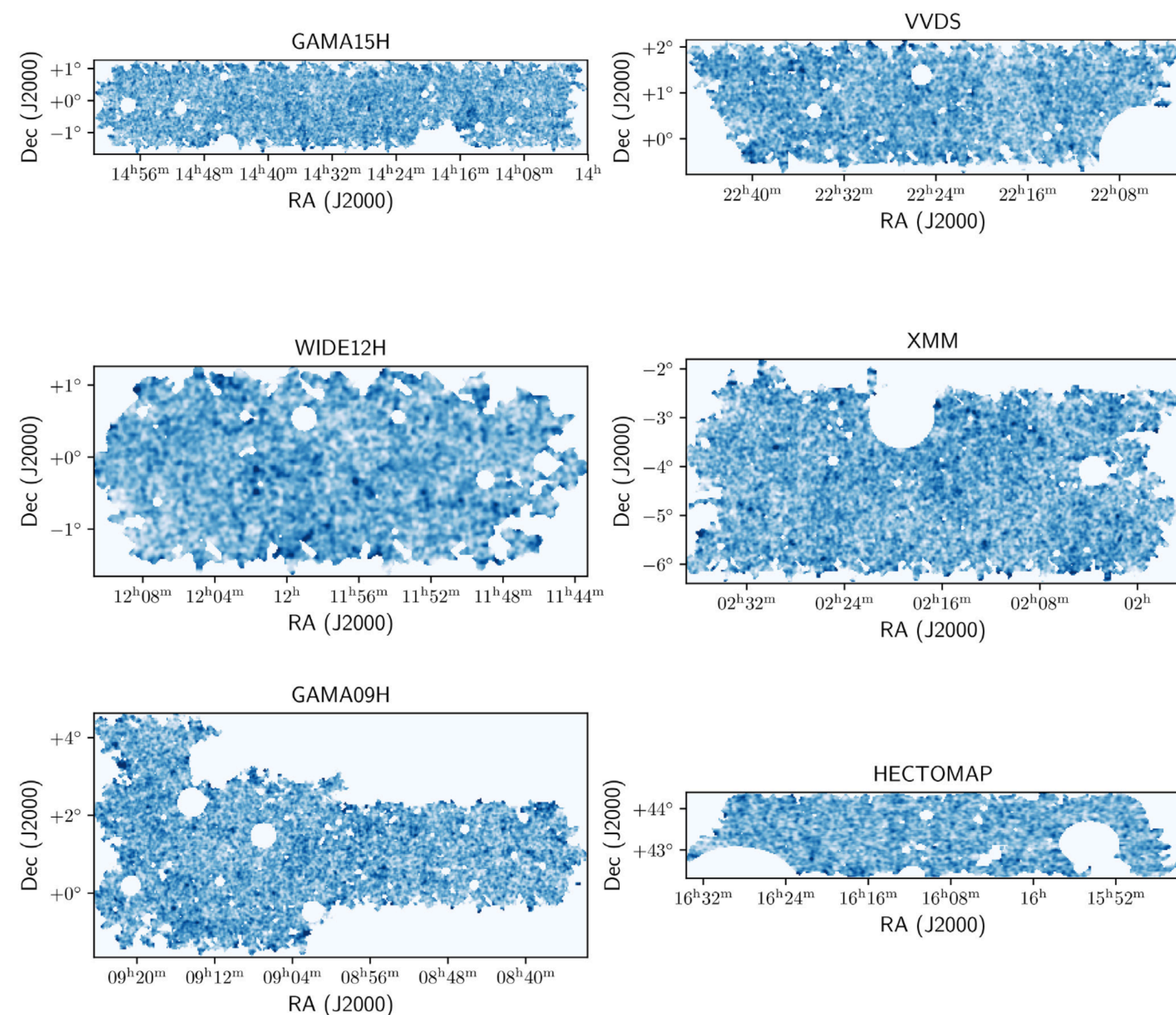
The shapes of galaxies are distorted due to gravitational potential of **intervening matter**.

Observed shape

HSC WL Y1 x *Planck* tSZ

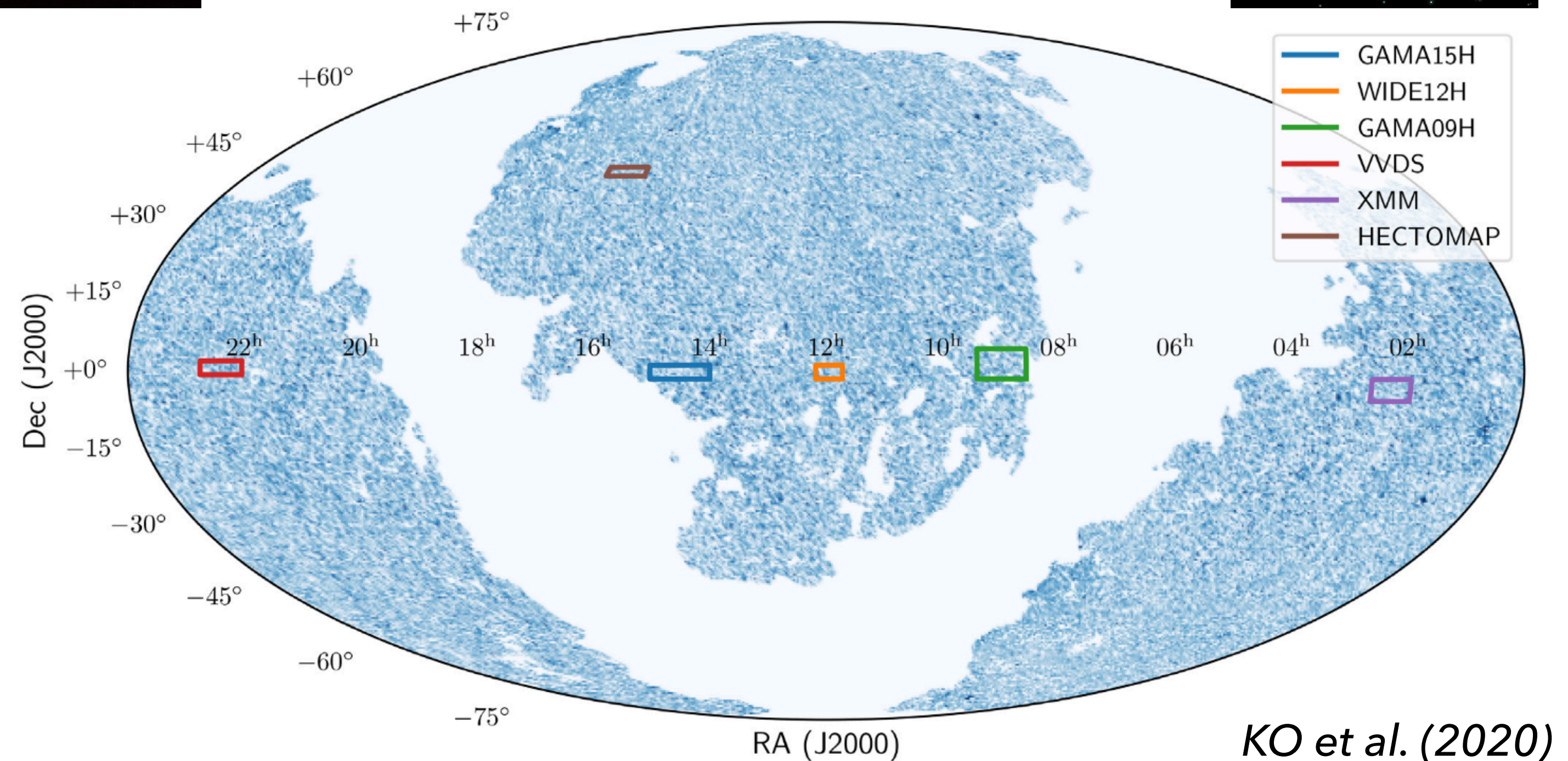
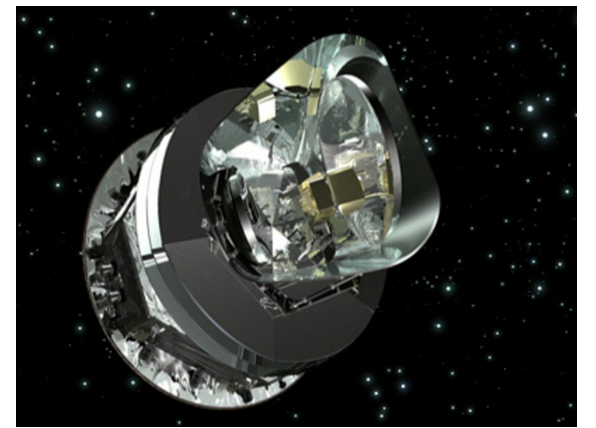
- **HSC WL Y1**

Wide and deep WL survey which covers 136.9 deg² with mean i-band seeing $\sim 0''.58$ and source density $n_{\text{eff}} = 24.6 \text{ arcmin}^{-2}$.



- ***Planck* tSZ map**

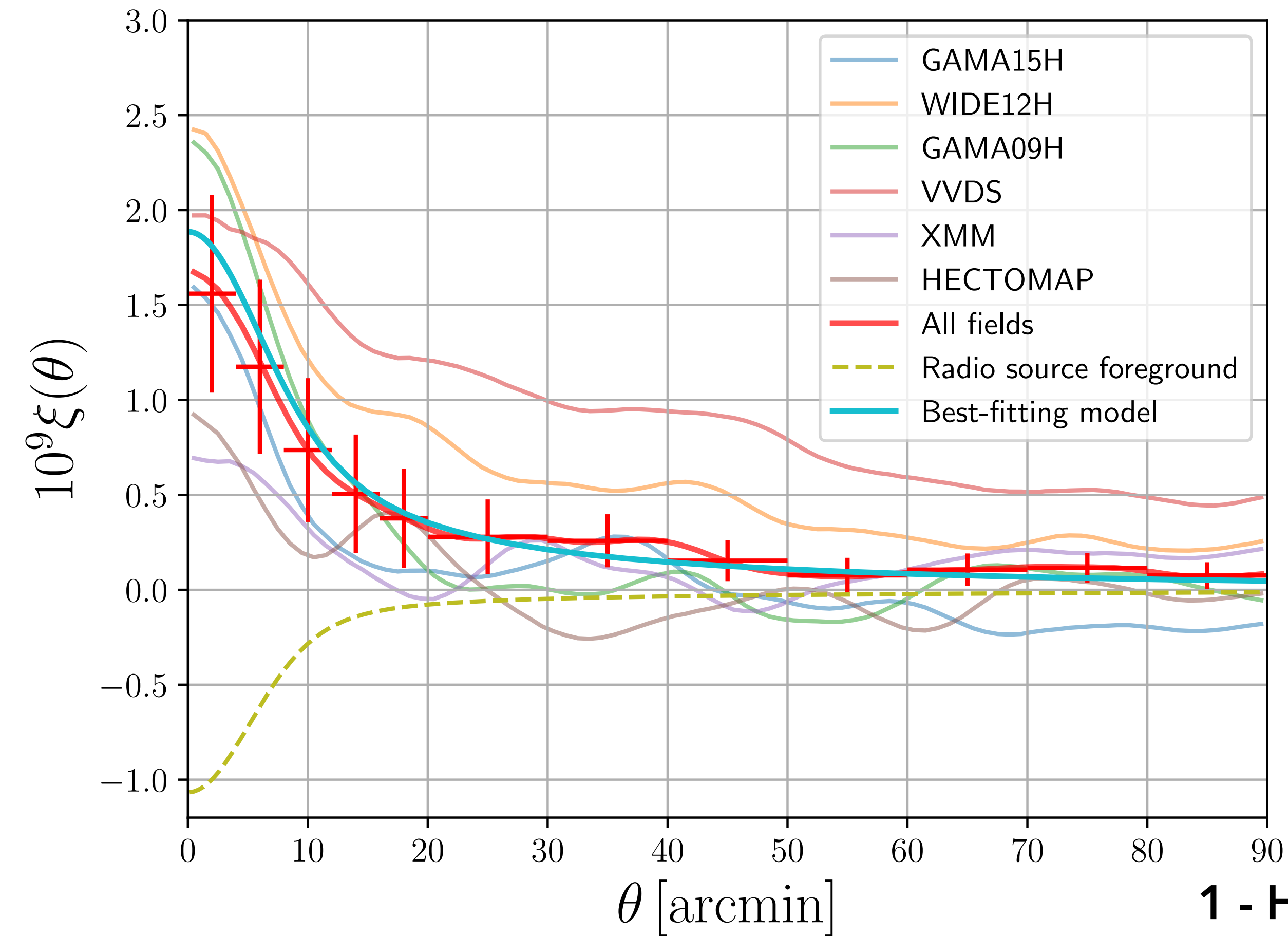
Full-sky with MW and point sources masked. The beam size is 10'.



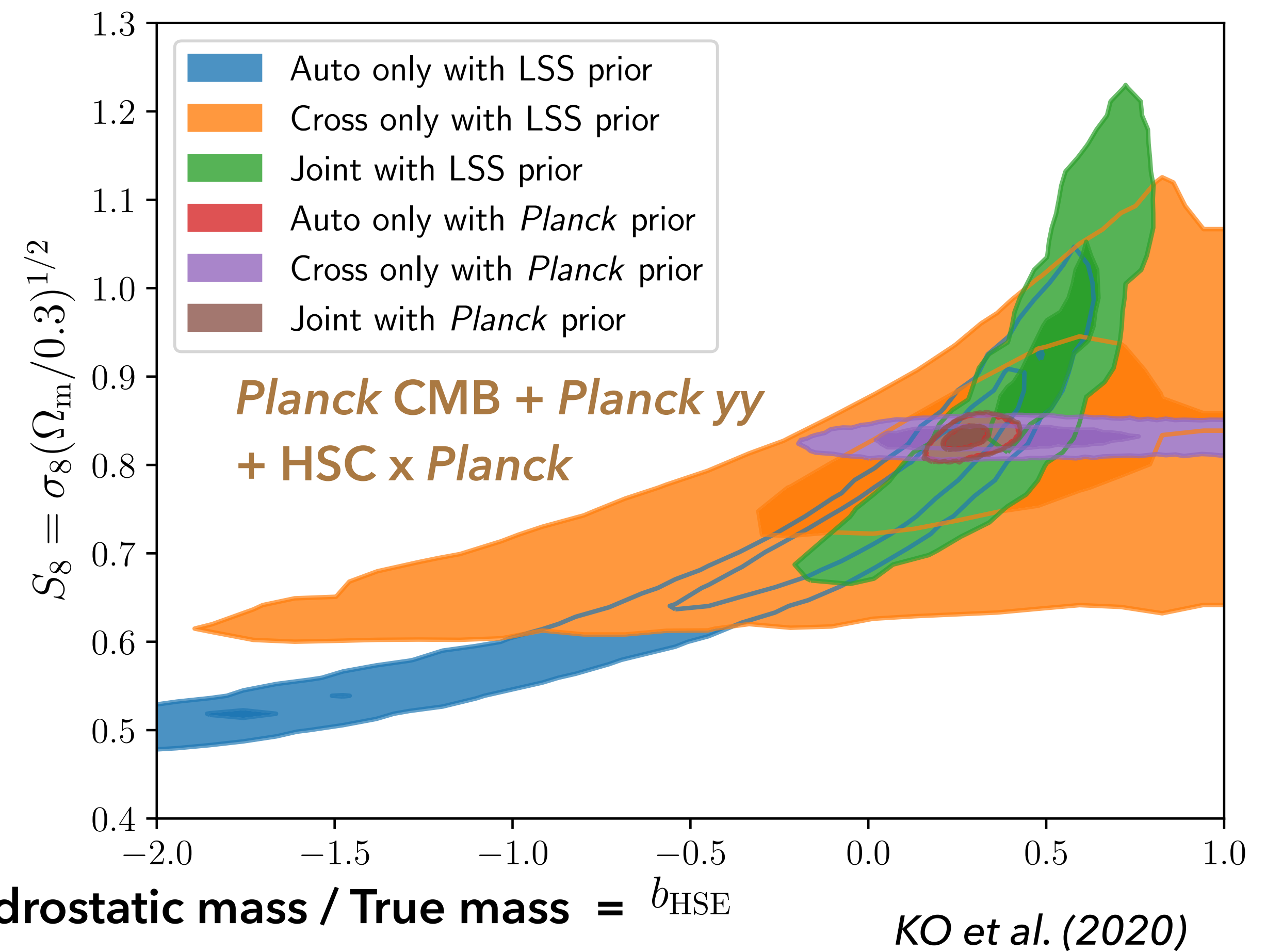
KO et al. (2020)

HSC WL Y1 x *Planck* tSZ

• Cross-correlation function



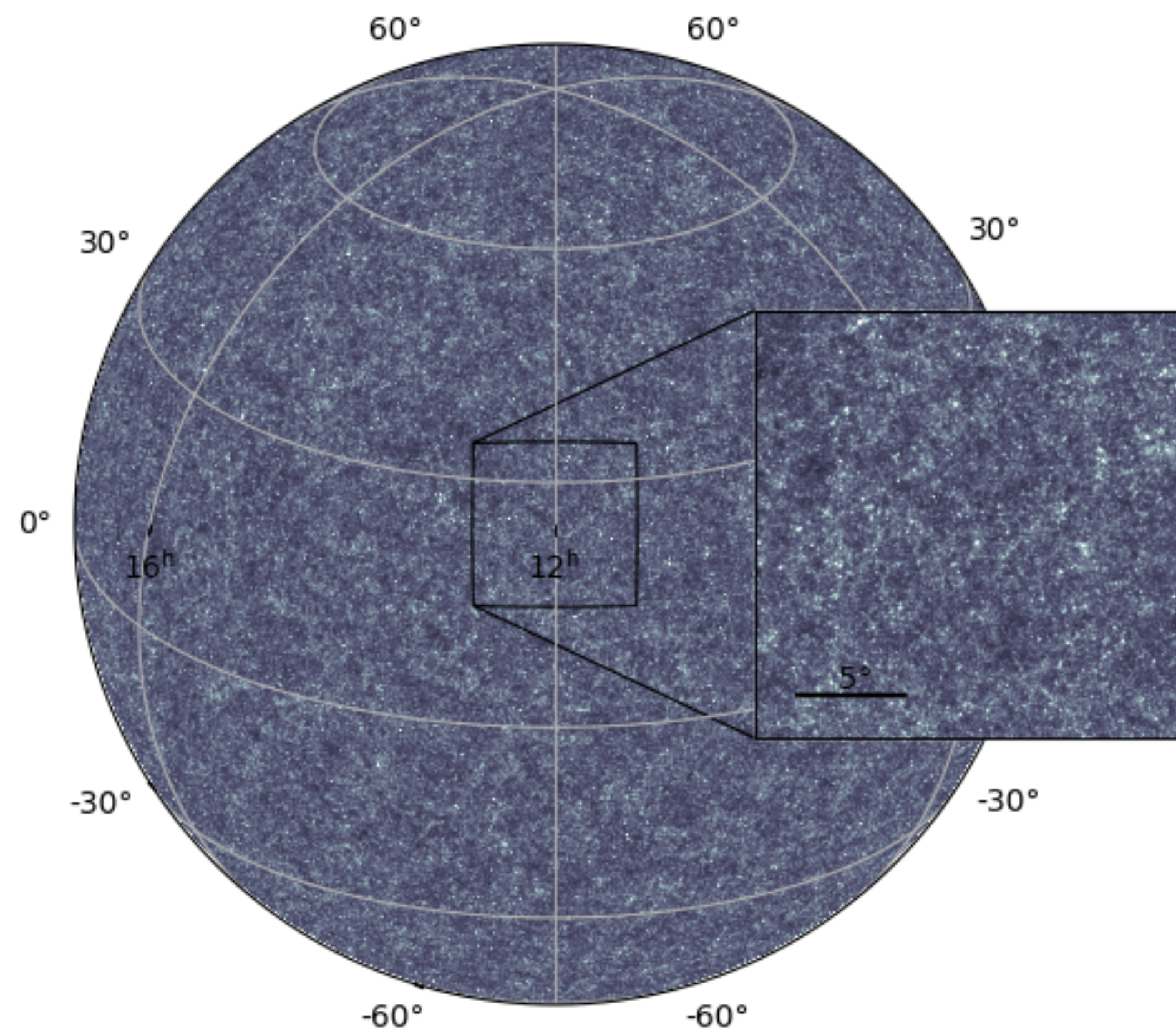
• Constraints on S_8 and mass bias



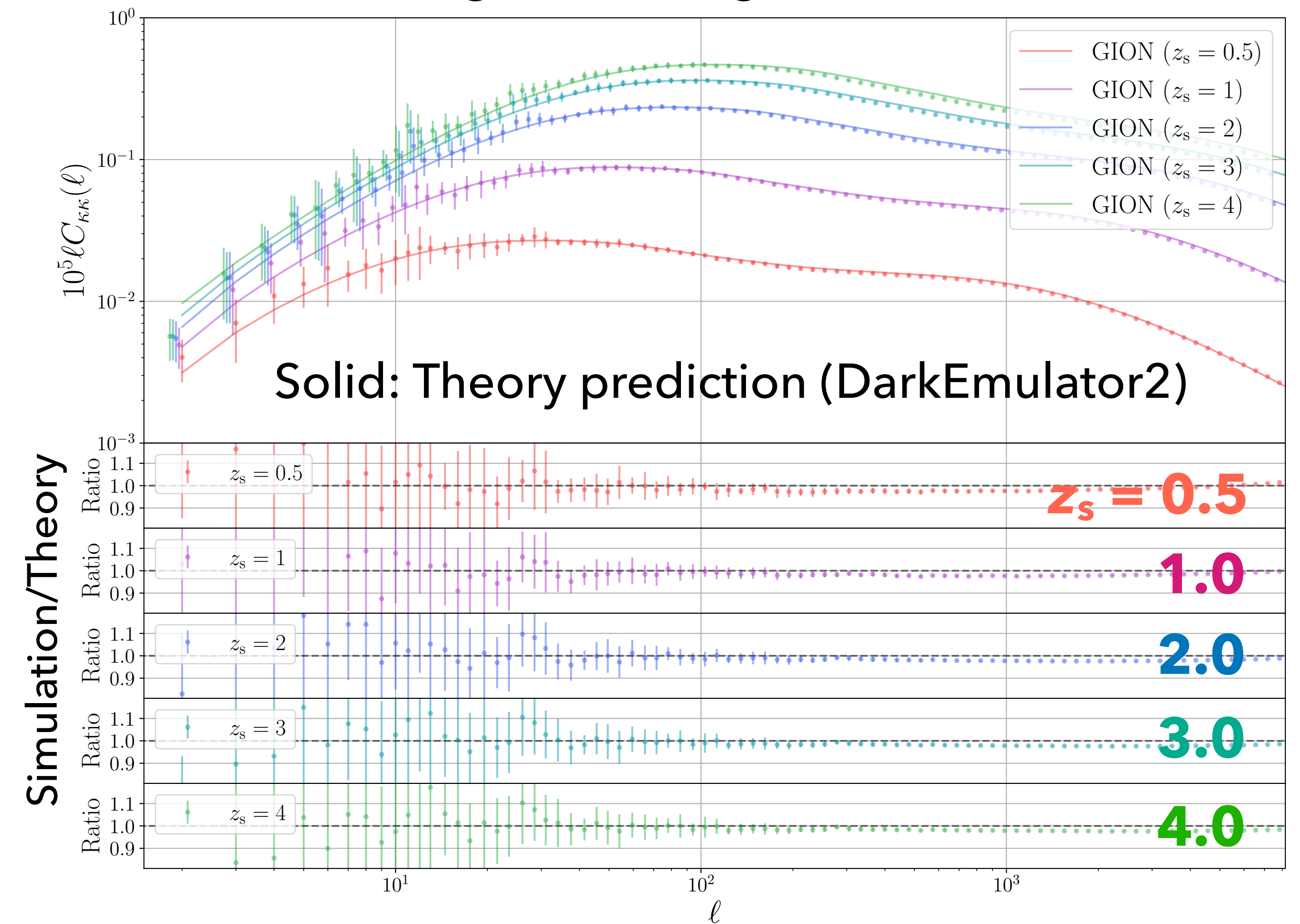
→ Cross-correlation with WL helps break degeneracy of σ_8 and mass bias parameter!

Simulating Weak Lensing

- Mass (convergence) map with $z_s = 1$
➡ Projected mass density map

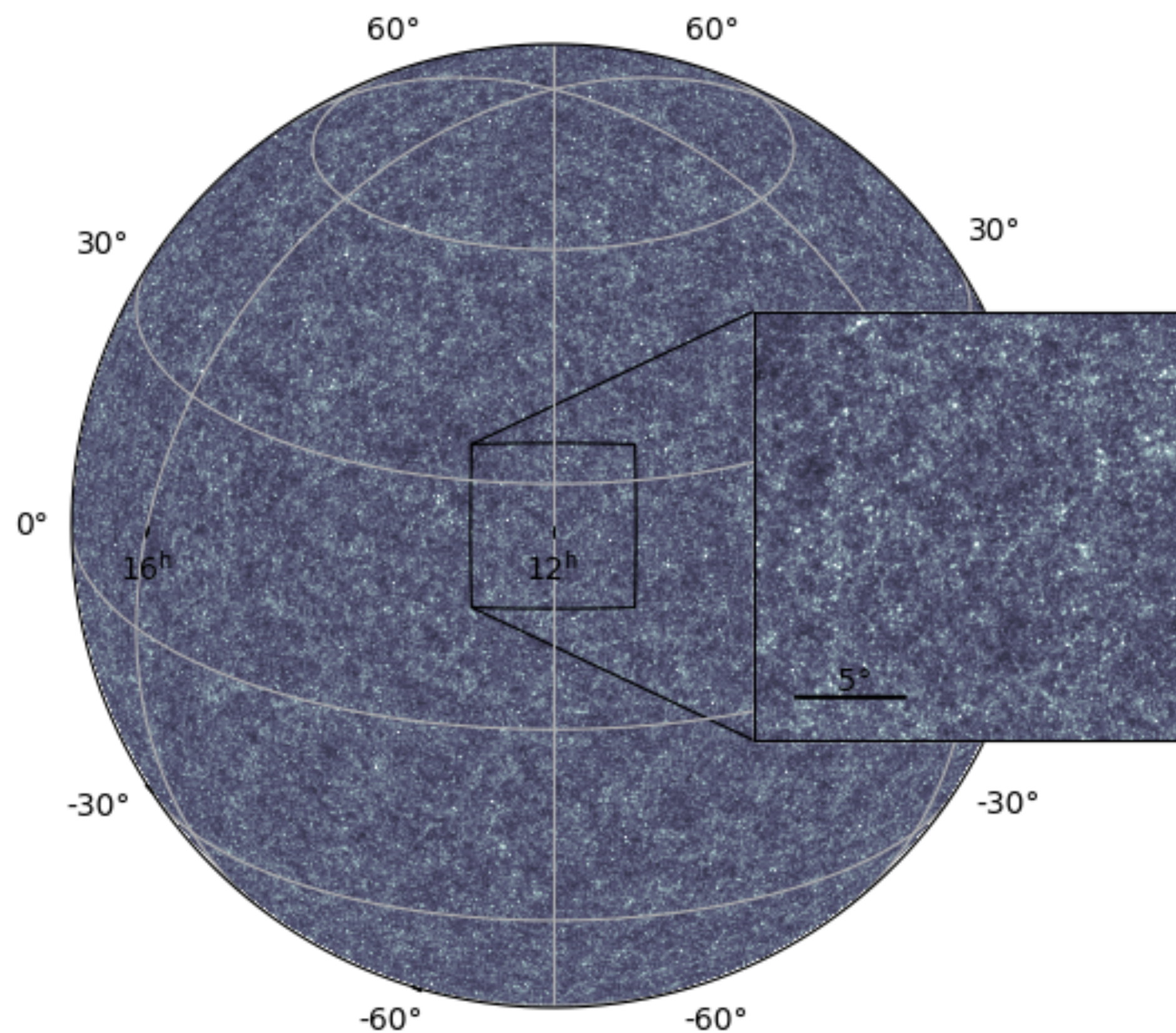


- Angular power spectrum
➡ Encoding cosmological information

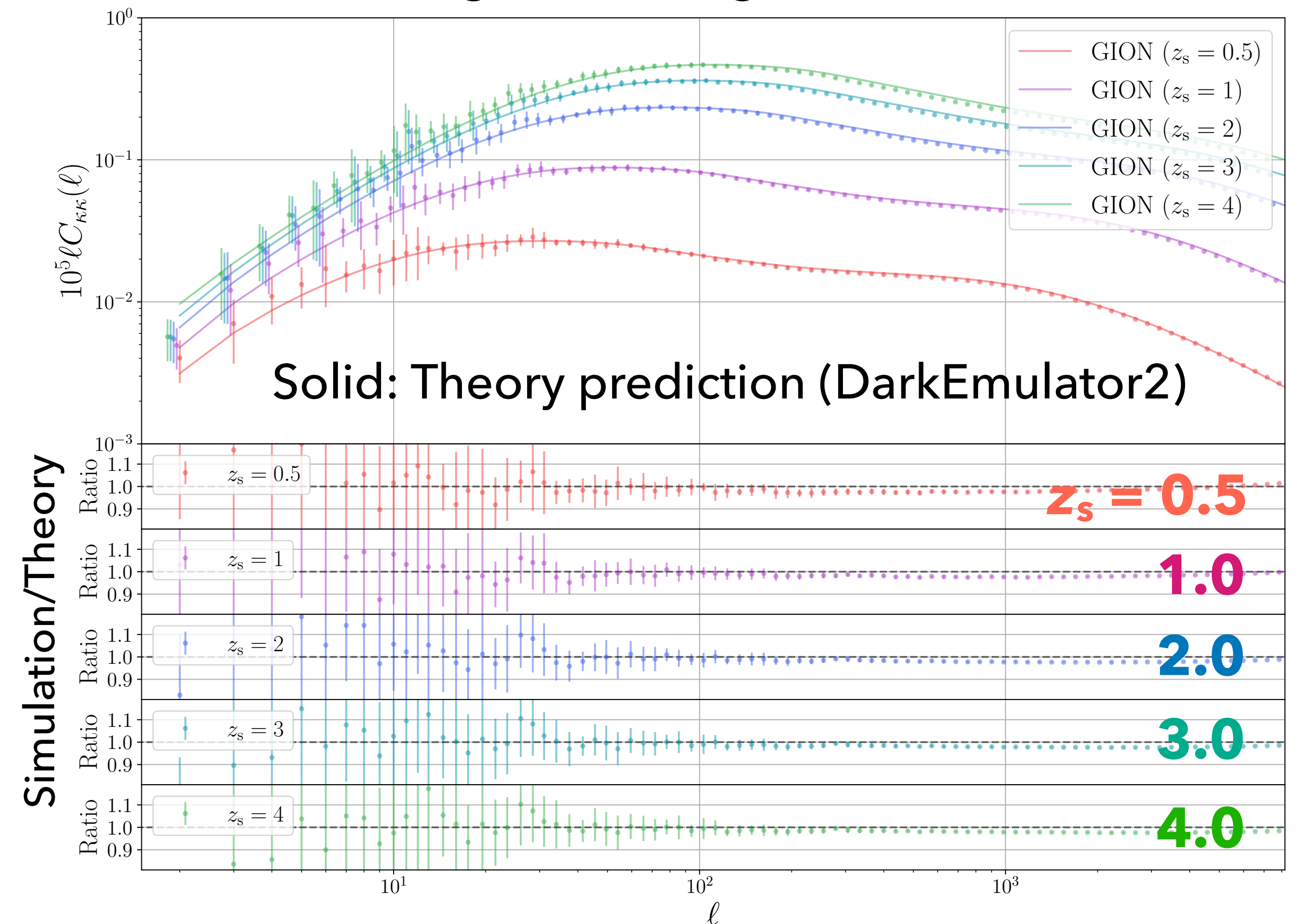


Simulating Weak Lensing

- Mass (convergence) map with $z_s = 1$
➡ Projected mass density map



- Angular power spectrum
➡ Encoding cosmological information



♦ Currently, Born approx. is assumed but ray-tracing simulations (c.f., Ferlito et al., 24) including CMB lensing will be produced.

Analytic Intra-cluster Medium Model

♦ Analytic ICM model in halo (*Ostriker+, 2005; Bode+, 2007; Shaw+, 2010; Flender+, 2016*)

The gas in halos is embedded in the gravitational potential of DM.
The density/pressure profiles are determined from fluid equations.

Total gas pressure gradient

$$\frac{dP_{\text{tot}}(r)}{dr} = -\rho_g(r) \frac{d\Phi(r)}{dr}, \quad P_{\text{tot}} \propto \rho_g^{1.2}$$

Gas density **Potential gradient**

- The amplitudes of density/pressure profiles are determined through energy budget.

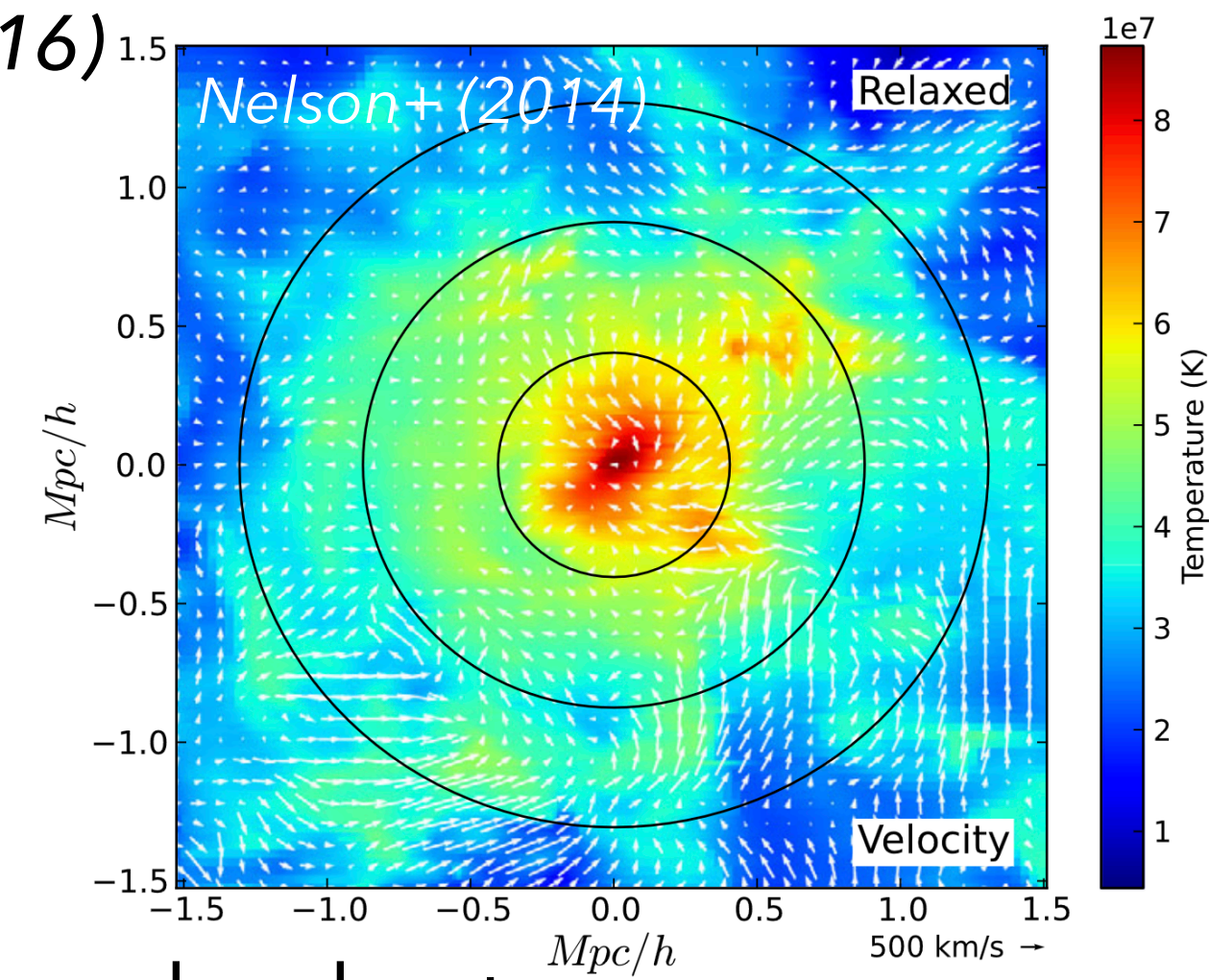
Gas energy

$$E_{g,f} = E_{g,i} + \epsilon_{\text{DM}} |E_{\text{DM}}| + \epsilon_f M_* c^2 + \Delta E_p$$

Gas energy if gas follows NFW **Dynamical friction with DM** **Feedback from SN and AGN** **Work by expansion**

- Non-thermal pressure** (turbulence, magnetic field, etc.) is parametrized according to hydro sim.

$$\frac{P_{\text{nt}}}{P_{\text{tot}}}(r, z) = \alpha_{\text{nt}} f(z) \left(\frac{r}{r_{500}} \right)^{n_{\text{nt}}}, \quad f(z) = \min[(1+z)^{\beta_{\text{nt}}}, (f_{\text{max}} - 1) \tanh(\beta_{\text{nt}} z)]$$

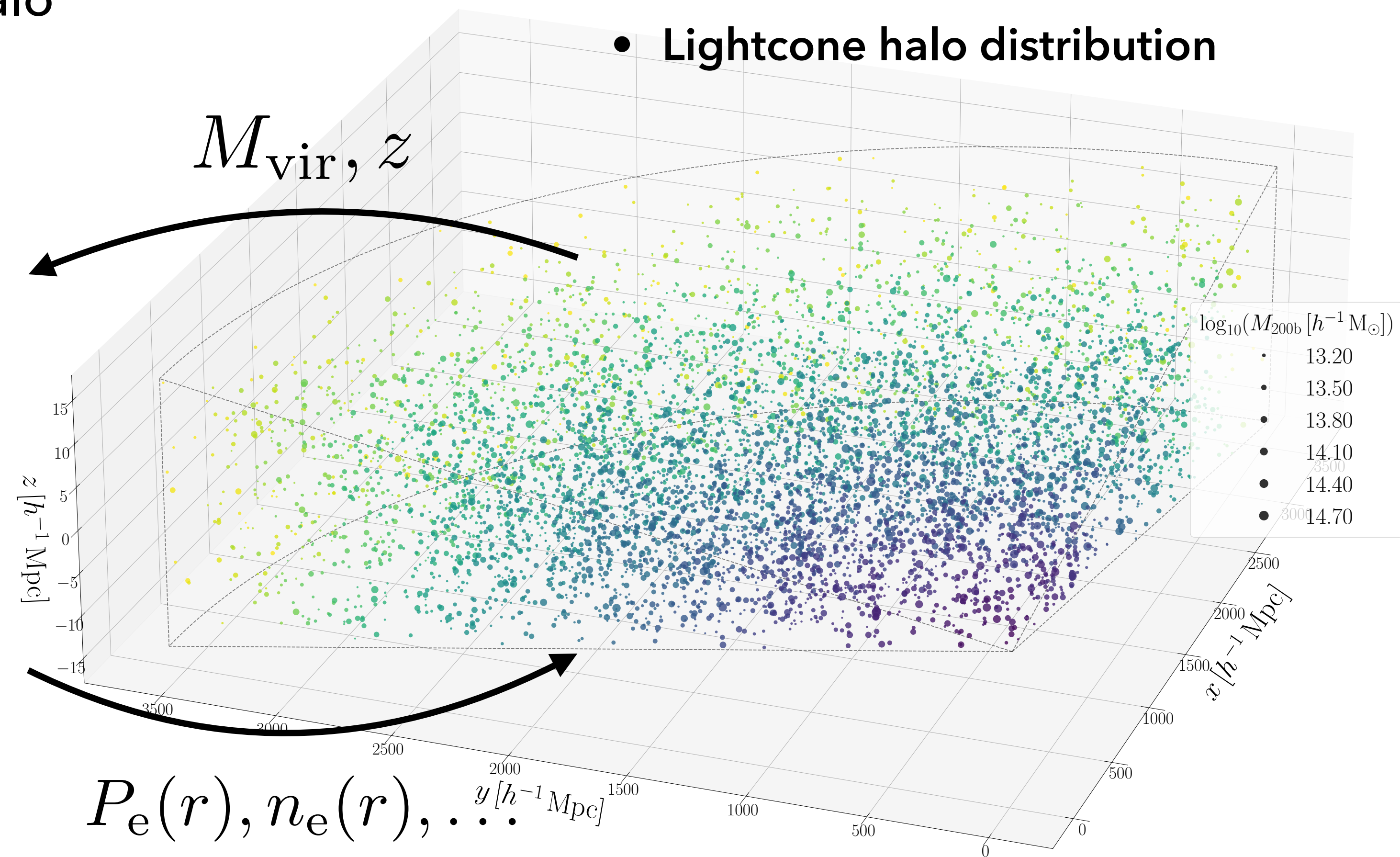
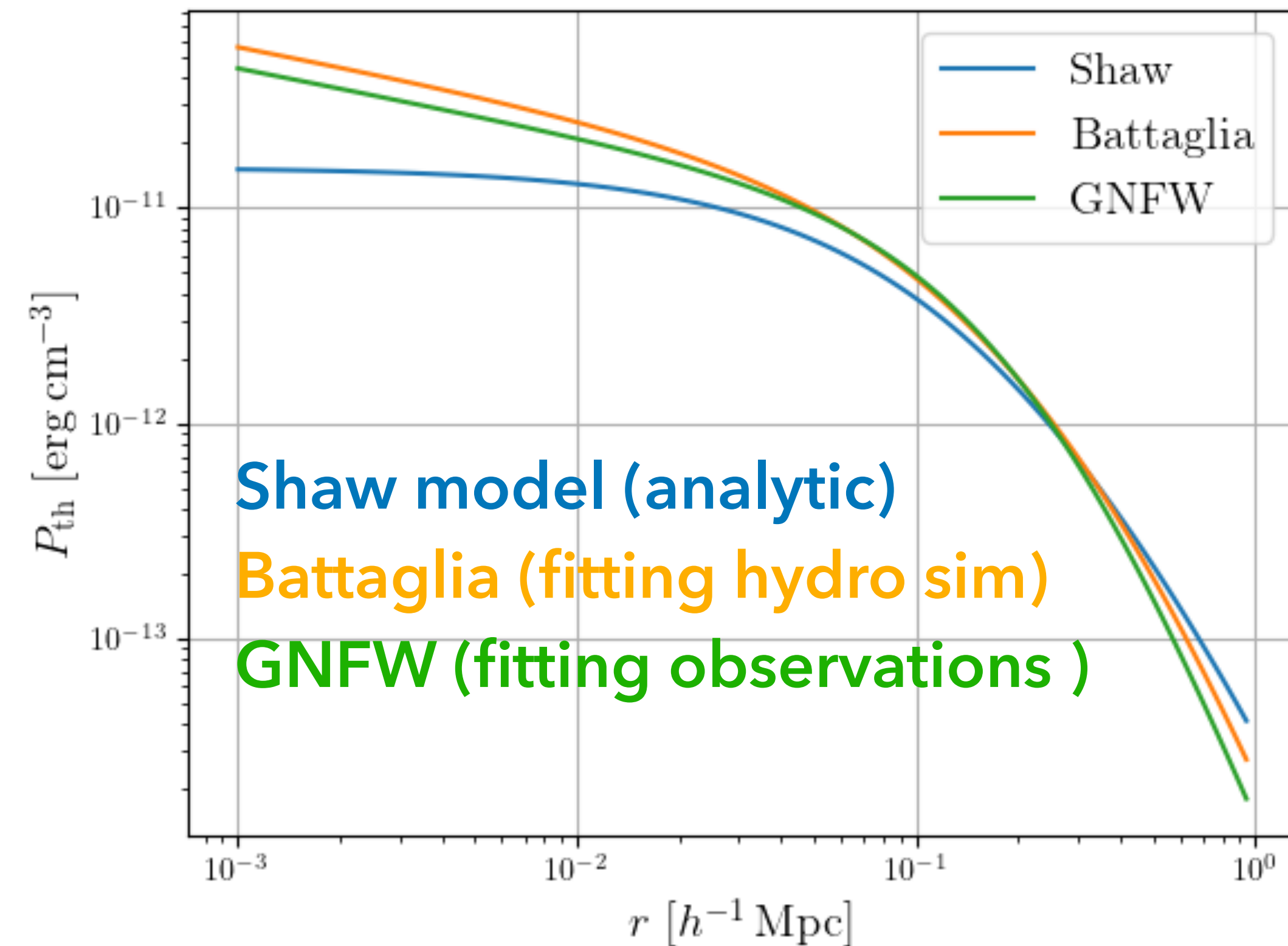


Pasting gas onto dark matter halos

◆ Baryon Pasting (KO & Nagai, 2023)

Solve ICM evolution for each dark matter halo
and paste pressure profile onto the halo

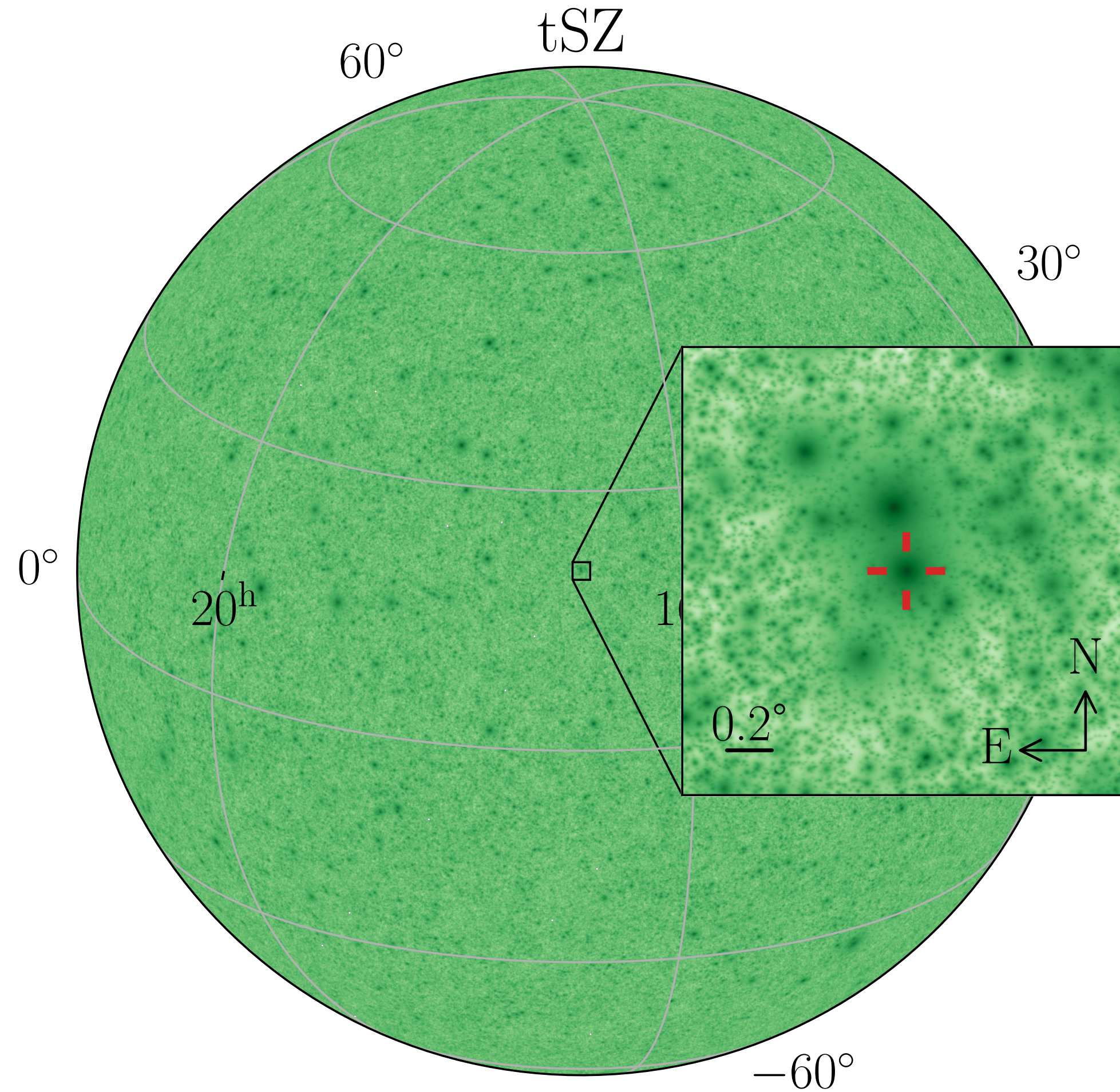
- Electron pressure profile
($M_{\text{vir}} = 10^{14} \text{ Msun}/h, z = 0$)



Correlated tSZ x WL maps

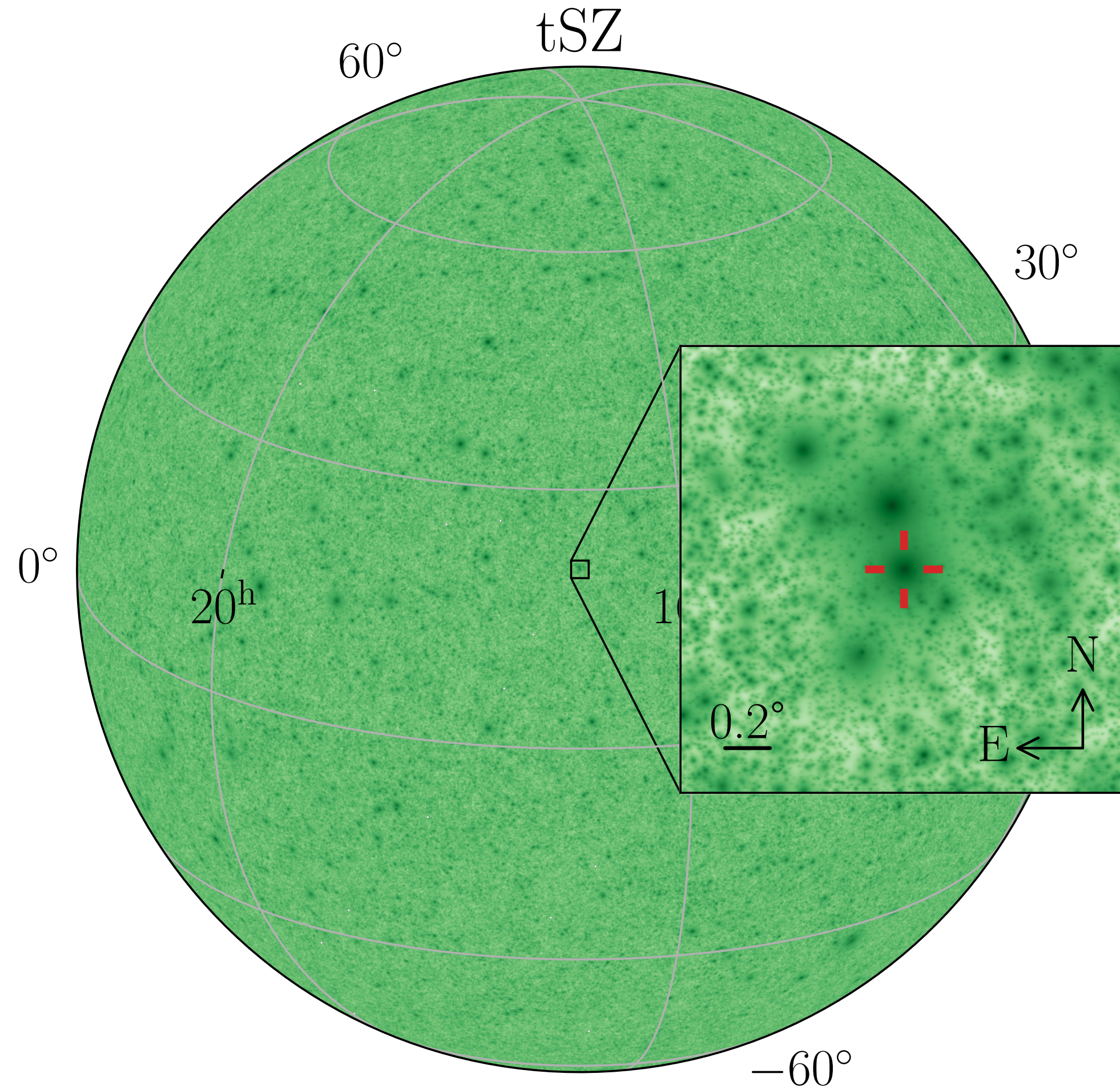
Correlated tSZ x WL maps

- Halo-based pasting (KO & Nagai, 2023)

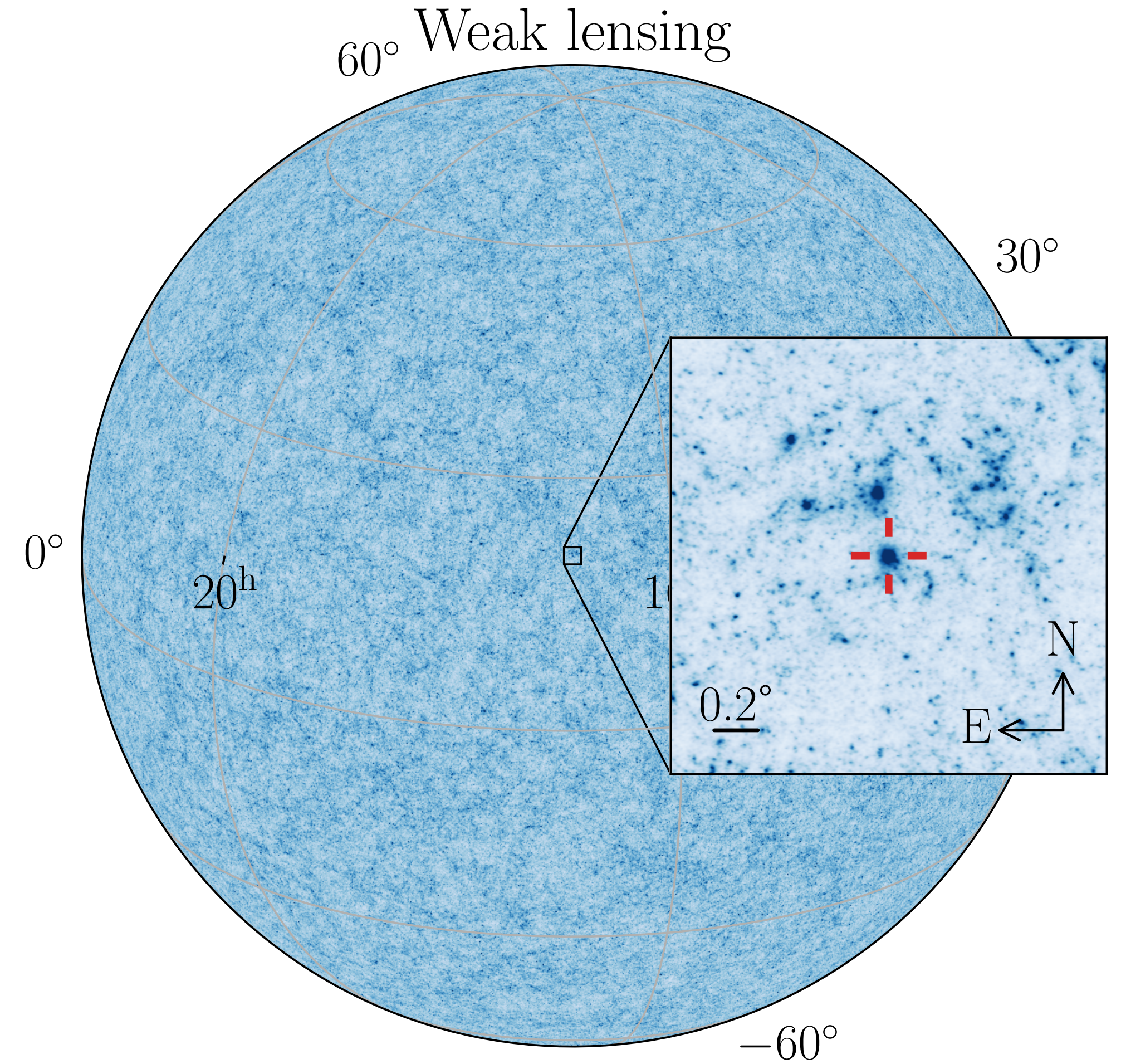


Correlated tSZ x WL maps

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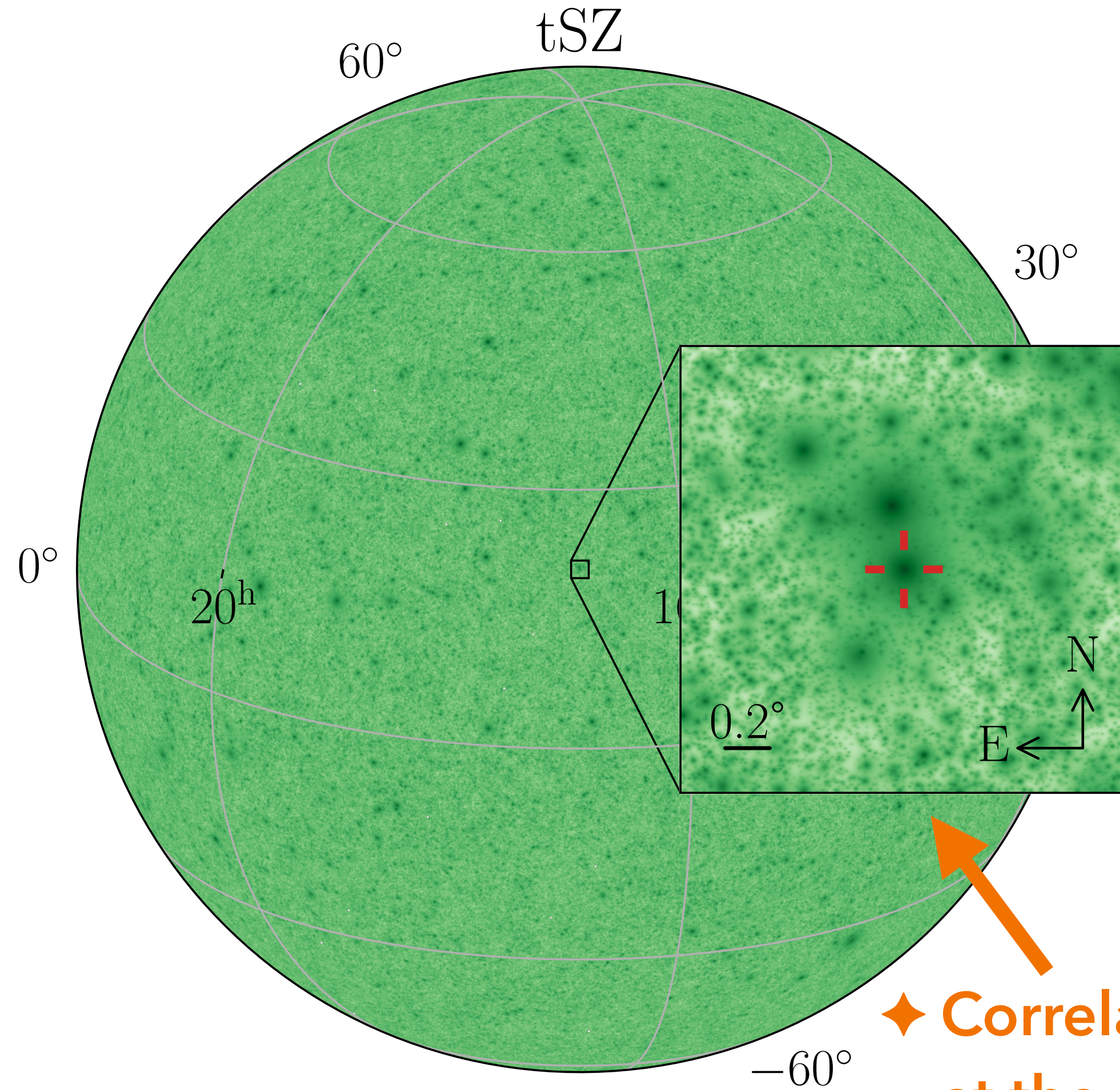


- Born approx WL map



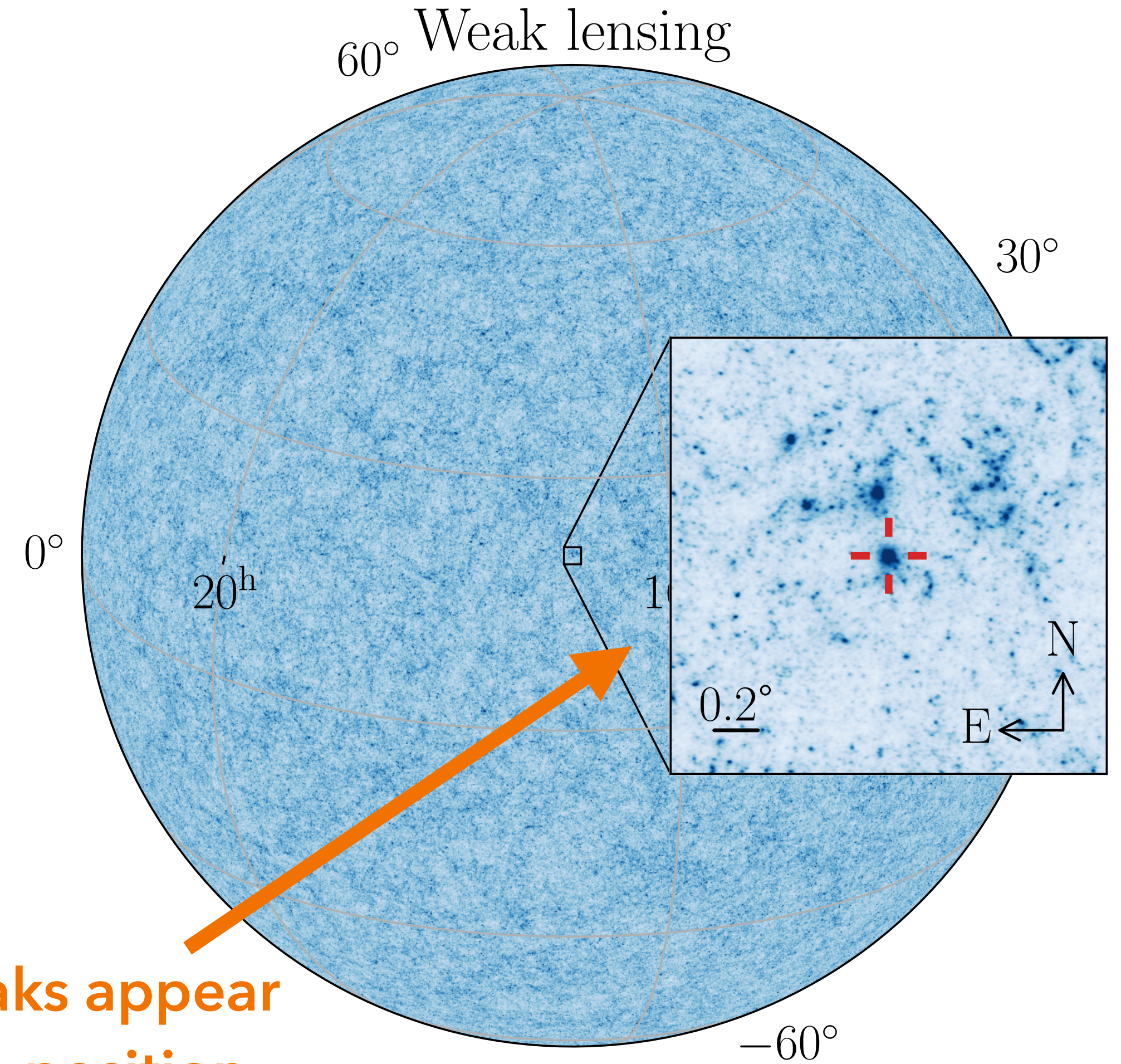
Correlated tSZ x WL maps

- Halo-based pasting (KO & Nagai, 2023)



♦ Correlated sky: Peaks appear at the exactly same position.

- Born approx WL map



tSZ x WL Cross Power Spectrum

- Halo model prediction

$$C^{y\kappa}(\ell) = C_{1h}^{y\kappa}(\ell) + C_{2h}^{y\kappa}(\ell)$$

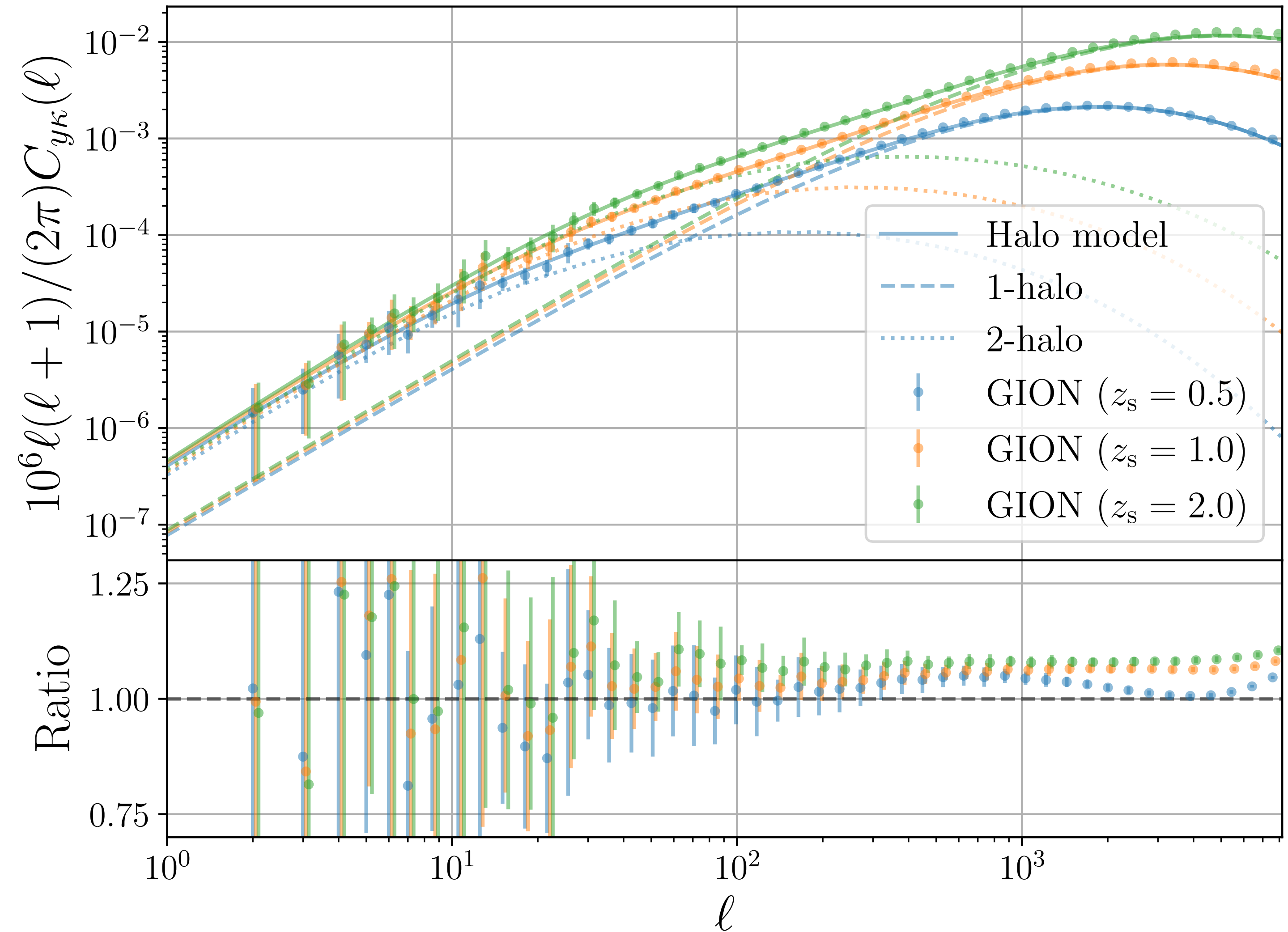
$$C_{1h}^{y\kappa}(\ell) = \int dz \frac{d^2V}{dz d\Omega} \int dM \frac{dn}{dM} \tilde{y}_\ell(M, z) \tilde{\kappa}_\ell(M, z)$$

$$C_{2h}^{y\kappa}(\ell) = \int dz \frac{d^2V}{dz d\Omega} P_m \left(k = \frac{\ell + 1/2}{D_A(z)}, z \right) \times \int dM \frac{dn(M, z)}{dM} \tilde{y}_\ell(M, z) b_h(M, z) \times \int dM \frac{dn(M, z)}{dM} \tilde{\kappa}_\ell(M, z) b_h(M, z).$$

$$\tilde{y}_\ell(M, z) = \frac{4\pi r_s}{\ell_s^2} \left(\frac{\sigma_T}{m_e c^2} \right) \int dx x^2 \underline{P_e(x; M, z)} \frac{\sin(\ell x / \ell_s)}{\ell x / \ell_s},$$

Electron pressure profile

- tSZ x WL Cross-spectrum



Roadmap

GLON basic dataset

- Introducing the overall project
- WL and galaxies, and its cross-correlations (3x2pt)
- Data products: halo catalogues, mass/momentum shells, WL convergence maps
- DR1 (10 cosmo-fixed sims)

CMB

- Lensed CMB
- Secondary anistropies tSZ/kSZ, Radio, CIB

Galaxy

- LRG, ELG, LBG,...
- ML-based populating

WL systematics

- Intrinsic alignment
- Baryonic effects
- Source clustering

X-ray

- Baryon pasting
- Cross-correlations with WL

DR1

DR2

➡ Contact me if you are interested in early access to the data!

Summary

- Simulations are now essential tools for cosmological surveys to validate the analysis pipeline and estimate the covariance matrix of statistics.
- The multi-wavelength all-sky simulation suite (**GION**) is made possible with the efficient N -body code GINKAKU and the massive computing power of Fugaku.
- We demonstrated the use case of WL x tSZ cross-correlations and the simulation suite is useful for other probes of CMB x LSS.
- We finished production runs, the initial datasets are already available. If you are interested in using the data, please contact me.