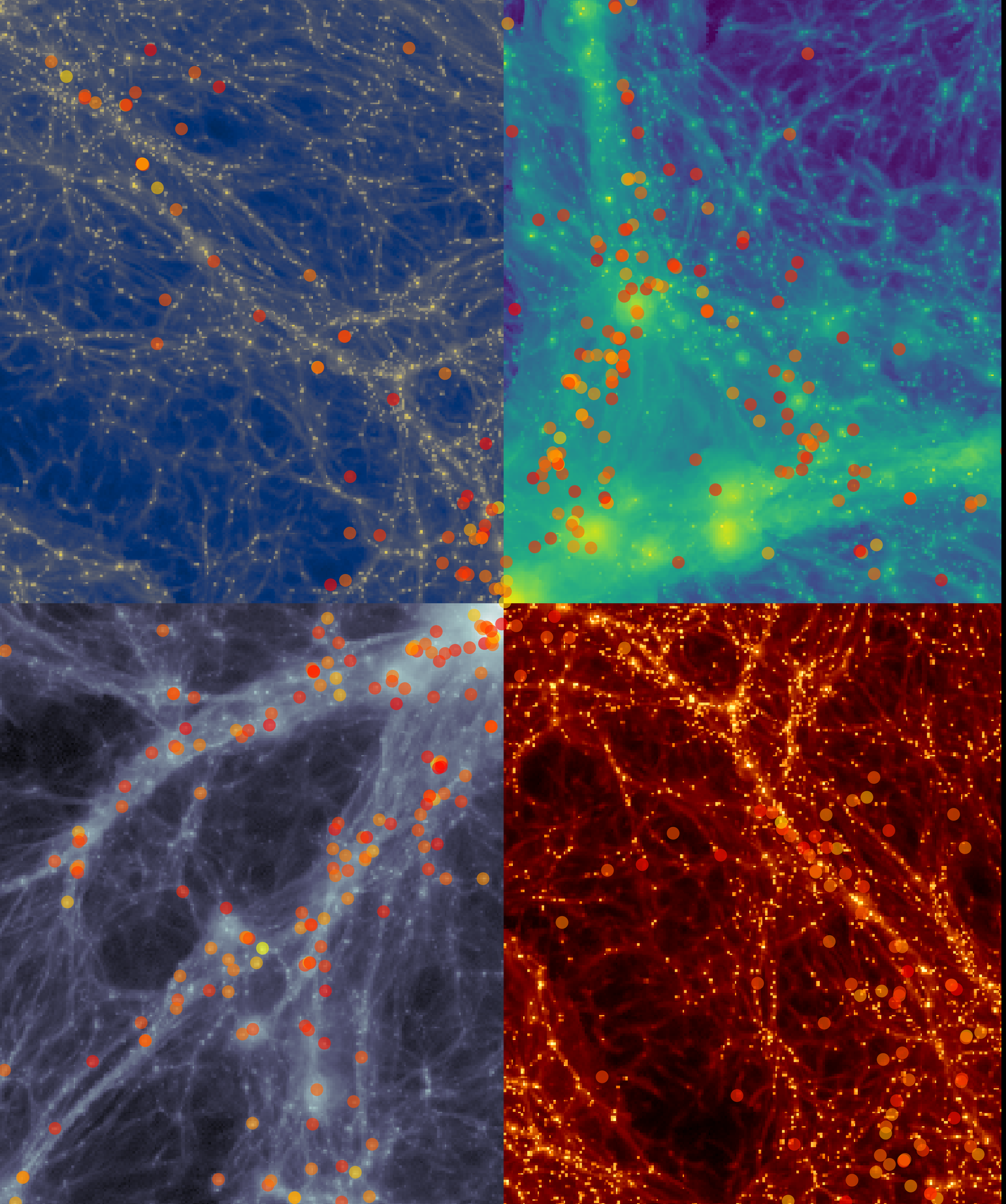


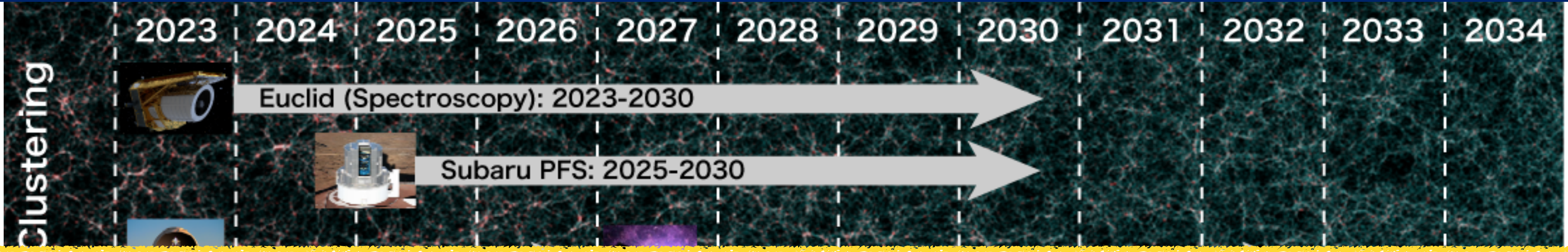
Multi-wavelength Cosmological Simulations for Stage-IV Surveys

10th East Asia Numerical Astrophysics Meeting
Jeju Island, South Korea
2025/09/18

Ken Osato (Chiba U. & RIKEN AIP)

Collaborators: Satoshi Tanaka (Hitotsubashi U.),
Tomoaki Ishiyama (Chiba),
Masato Shirasaki (NAOJ/ISM),
Hironao Miyatake (KMI, Nagoya),
Takahiro Nishimichi (Kyoto Sangyo U),
Sunao Sugiyama (UPenn),
Masahiro Takada (Kavli IPMU, Tokyo)
+ Fugaku Multi-Wavelength Simulation Team

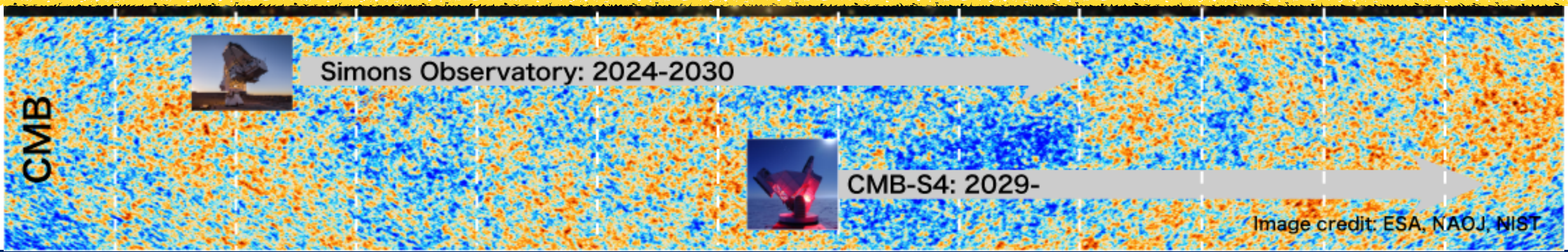
Stage-IV Cosmological Surveys



✦**Why are simulations important in cosmological analysis?**

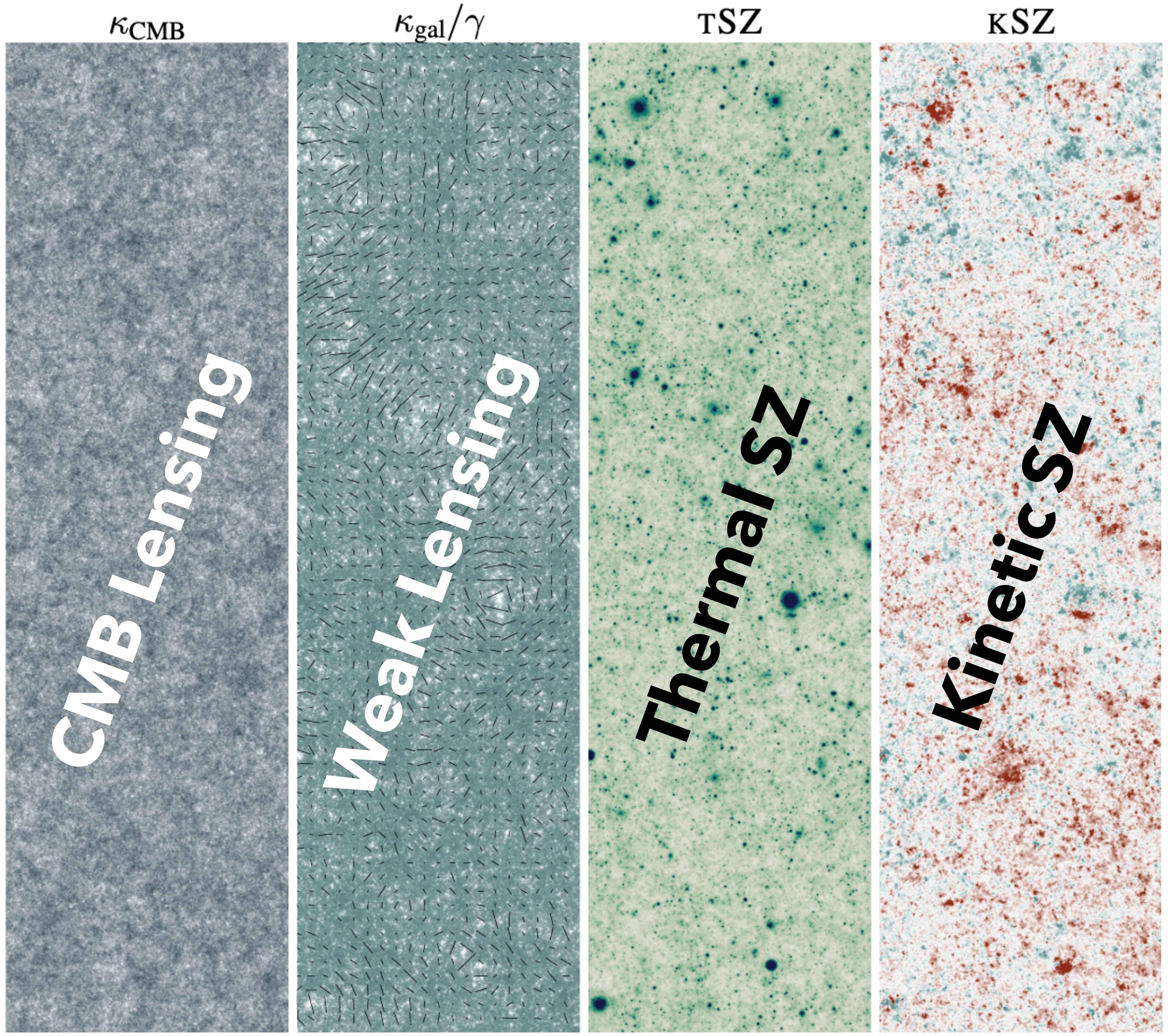
1. Predict the cosmological statistics given cosmological model
2. Validate the analysis pipeline
3. Estimate the covariance matrix of cosmological statistics

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

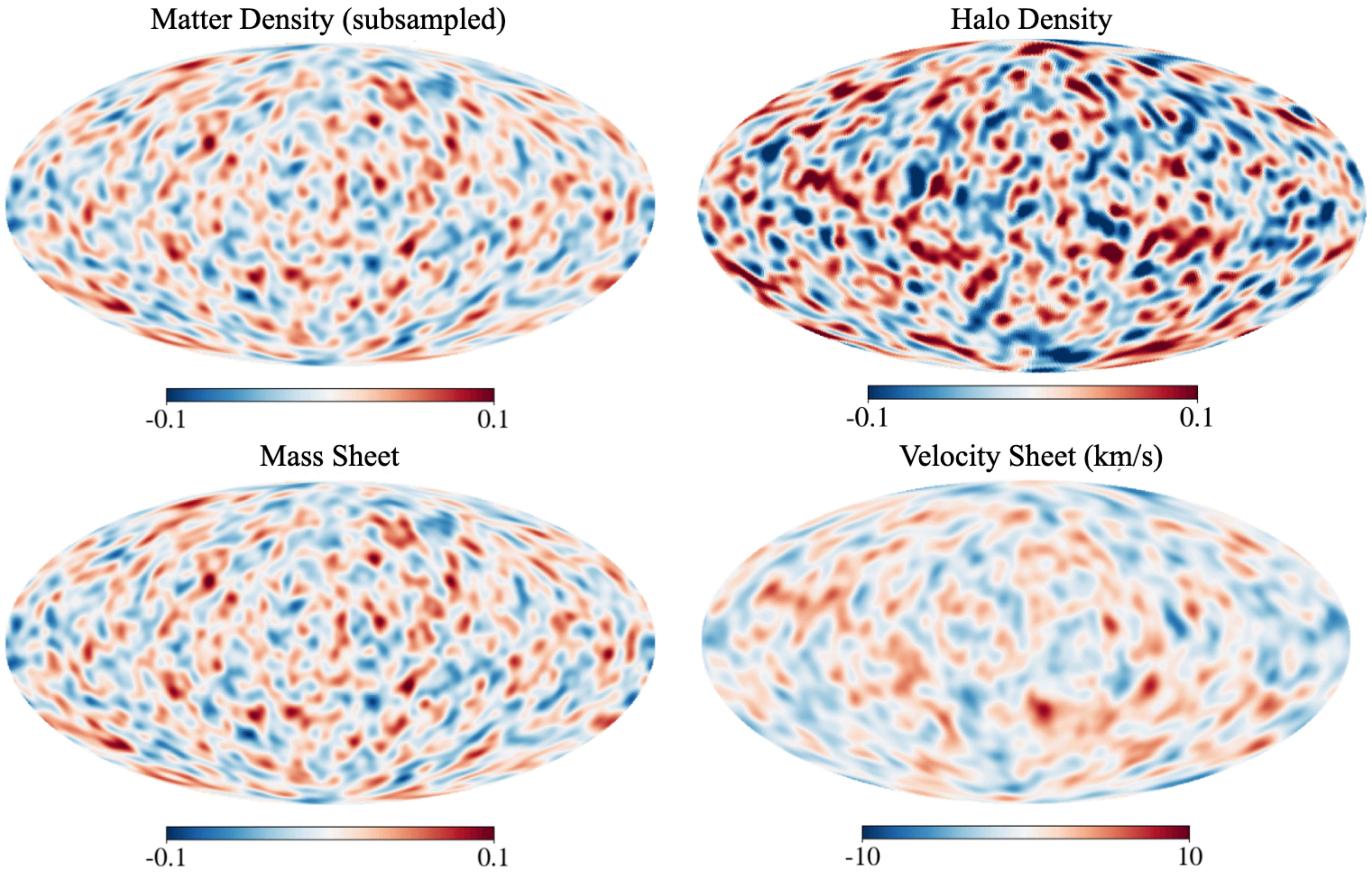


Mock Simulations for Multi-Wavelength Observations

✦ **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-wavelengh mocks from gravity-only *N*-body simulations:**

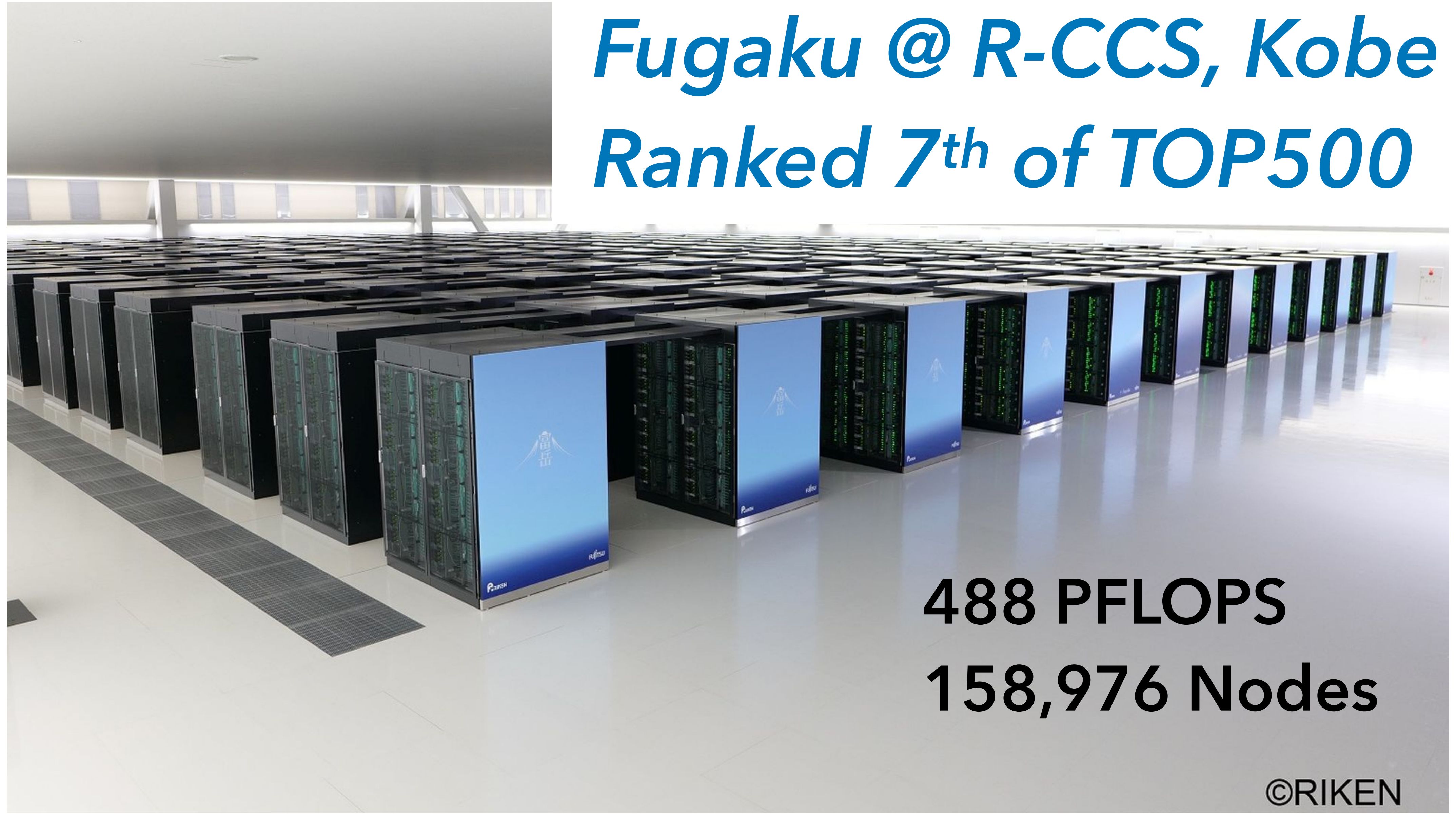
New *N*-body code: GINKAKU *(Nishimichi, Tanaka, Yoshikawa, in prep.)*

✦**Modelled observables**

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

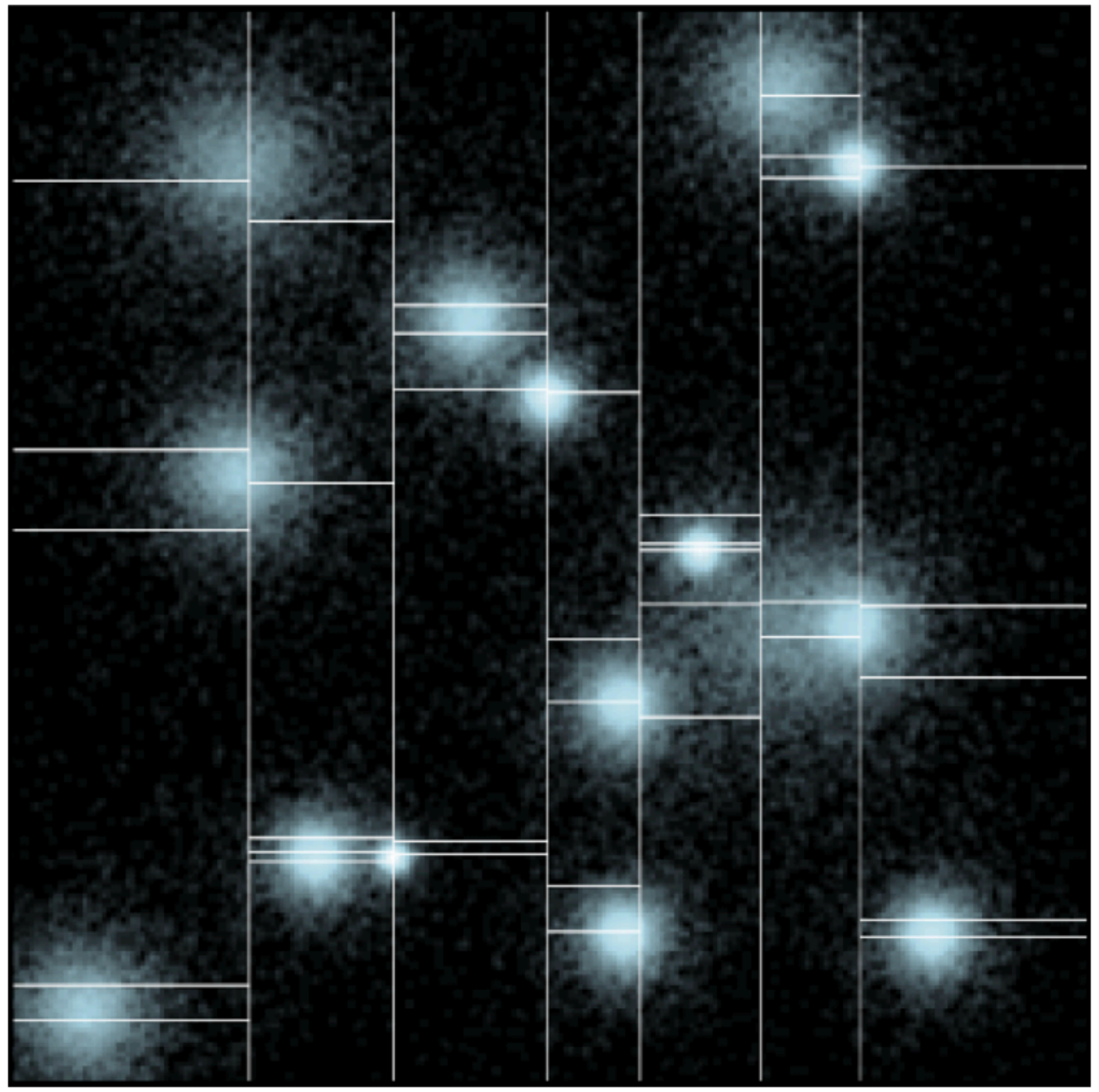
Fugaku @ R-CCS, Kobe

Ranked 7th of TOP500



GINKAKU

- **Gravitational INtegrator for Kinematical Analysis of darK Universe (GINKAKU)**
  (Nishimichi, Tanaka, Yoshikawa in prep.)
  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*



Iwasawa+16

- **Strong scaling on Fugaku**

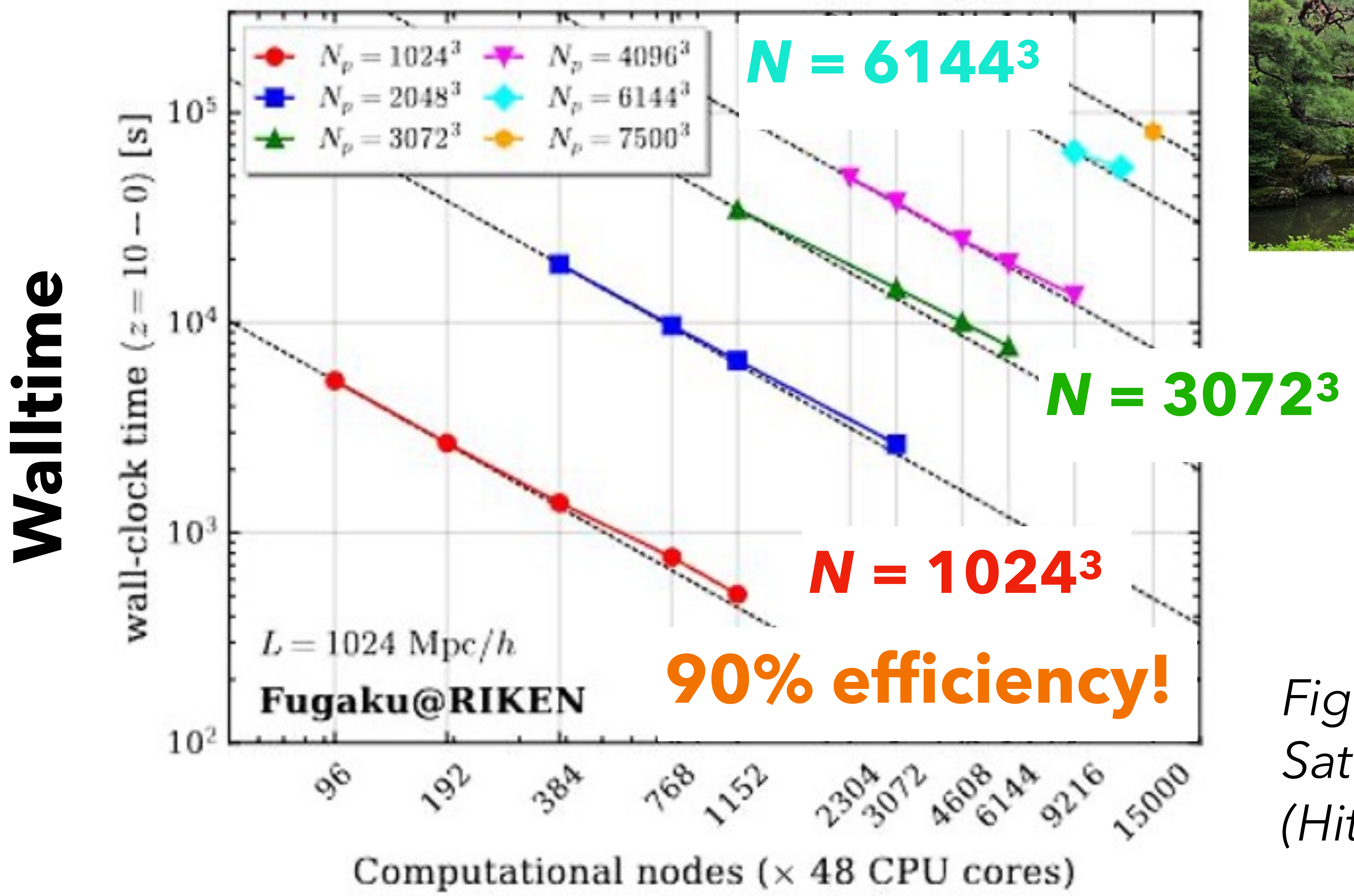
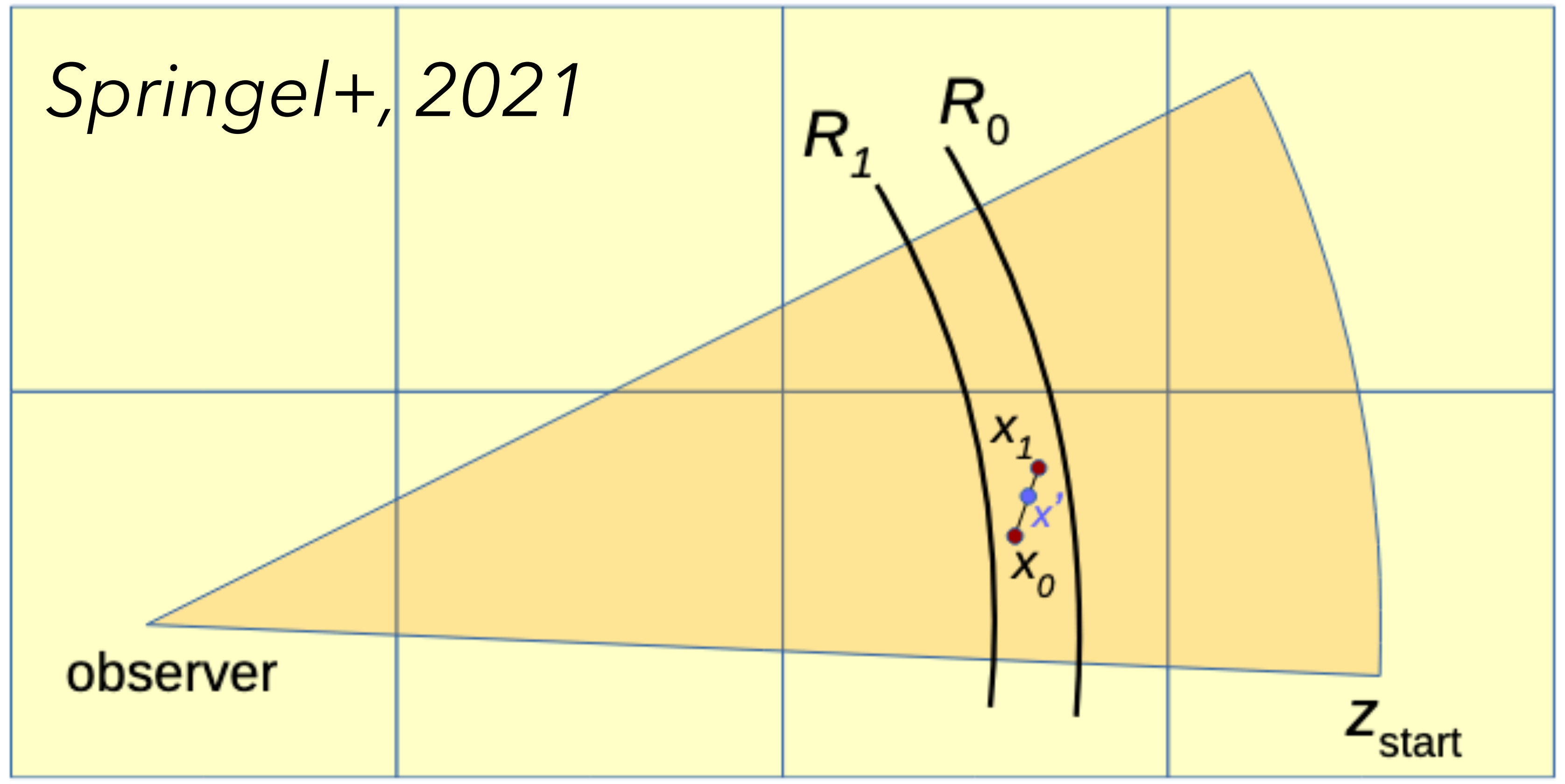


Figure credit:
Satoshi Tanaka
(Hitotsubashi U.)

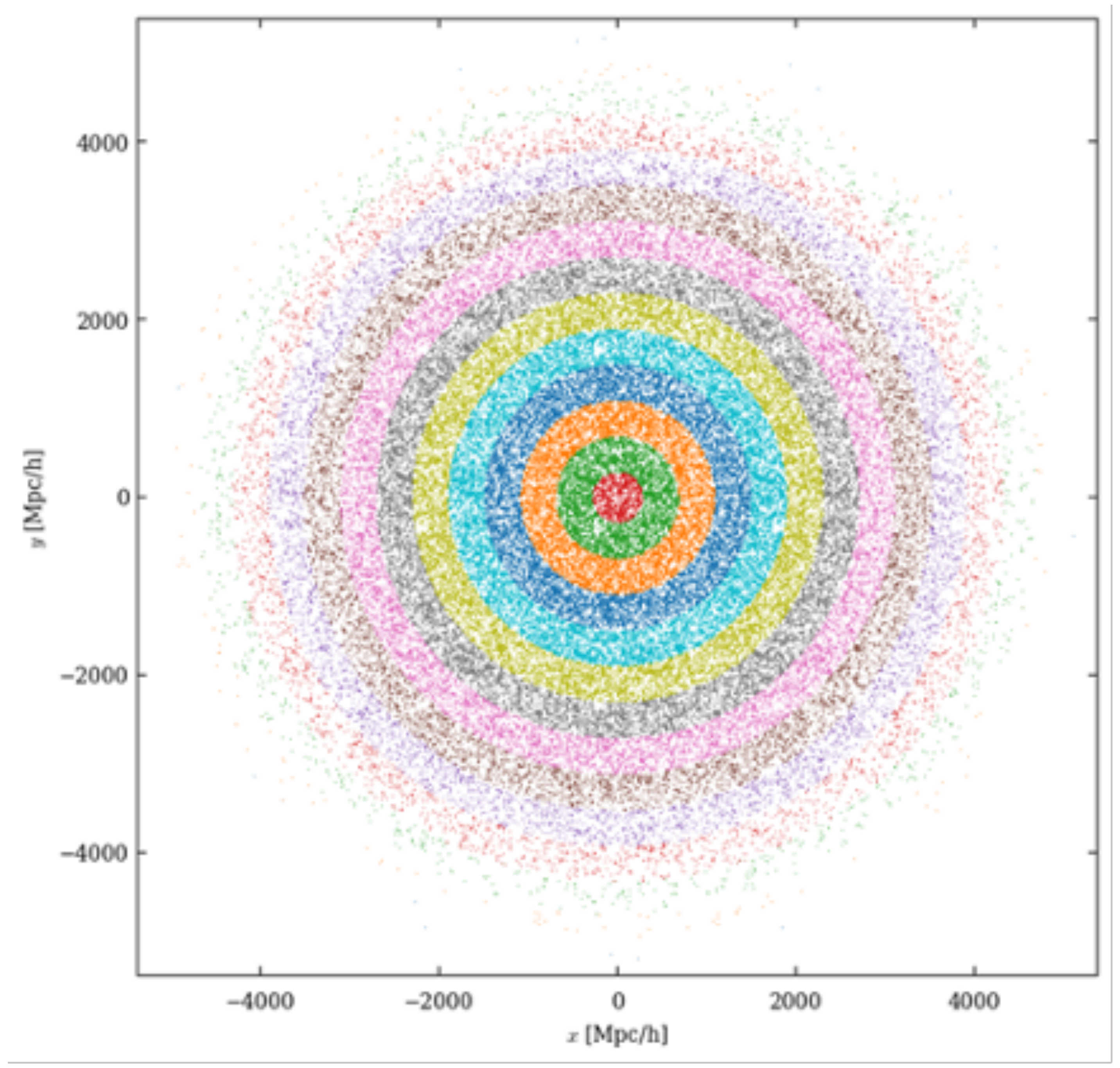
Lightcone Simulation

- **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 halo finding and mass/momentum shell**
  Every time light-cone surface passes by 25 Mpc/*h*, dumped particles are used for halo finding based on MPI-Rockstar and mass/momentum shell creation. Particles are discarded after this step to save the disk.



GINKAKU-Lightcone

- **GINKAKU-Lightcone simulation**

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

  Realization: 15 (Planck 2018 cosmology)

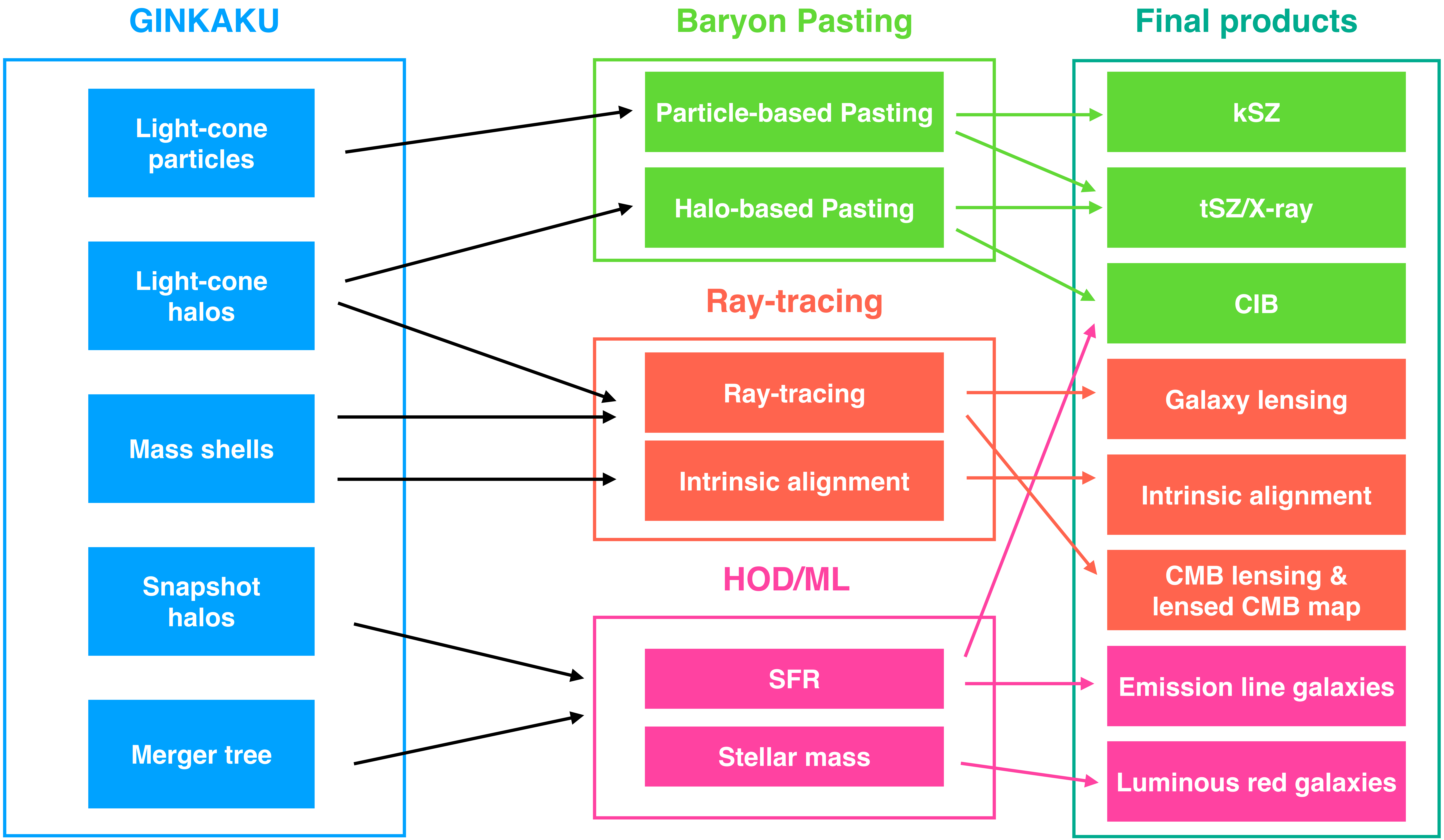
  Initial condition: monofonIC (Michaux+, 2020); 3LPT at $z_{\rm start} = 24$.

  Outputs: halo catalogues (MPI-Rockstar; Tokuue, Ishiyama, KO+; 2025) incl. **halo shapes**, mass/momentum shells (every 25 Mpc/h, $0 < z < 5$, $N_{\rm side} = 8192$)

Bayer+, 2024

	Sehgal+ [12, 13]	BAHAMAS [14, 15]	Takahashi+ [16]	MassiveNuS [17]	Buzzard [18]	Websky [19]	Agora [20]	HalfDome	GINKAKU-Lightcone
$L_{\rm box}$ (h^{-1}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
$M_h^{\rm min}$ ($h^{-1}M_\odot$)	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}
$N_{\rm sim}$	1 (500)	11	108	101	30	1	1	11 (+1 $f_{\rm NL}$)	15 (more)

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


GINKAKU
Light-cone particles
Light-cone halos
Mass shells
Snapshot halos
Merger tree
Baryon Pasting
Particle-based Pasting
Halo-based Pasting
Ray-tracing
Ray-tracing
Intrinsic alignment
HOD/ML
SFR
Stellar mass
Final products
kSZ
tSZ/X-ray
CIB
Galaxy lensing
Intrinsic alignment
CMB lensing & lensed CMB map
Emission line galaxies
Luminous red galaxies

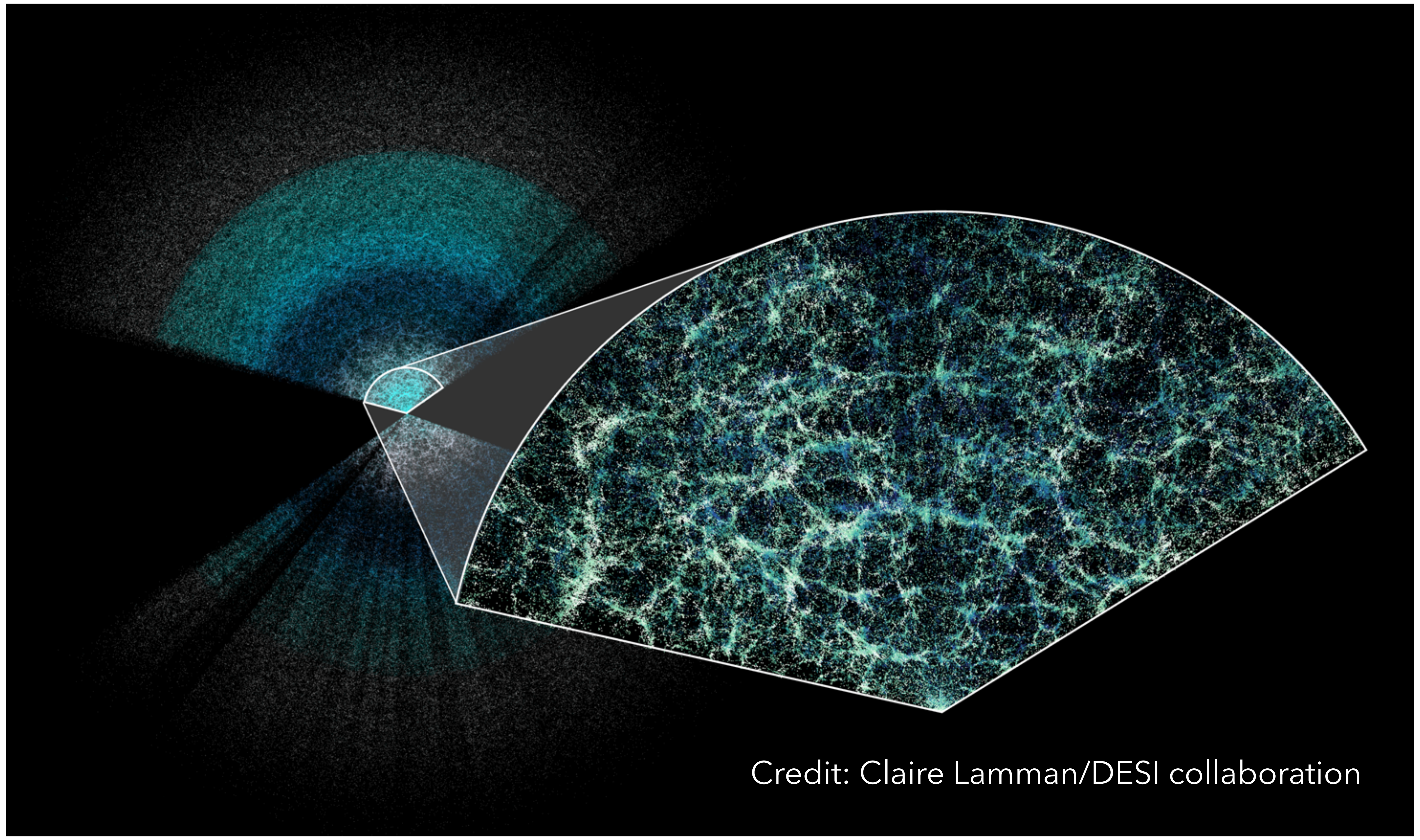
Weak Lensing & Galaxy Clustering

✦ **Galaxy clustering**
- Spectroscopy (*Euclid*, Subaru PFS, *Roman*)

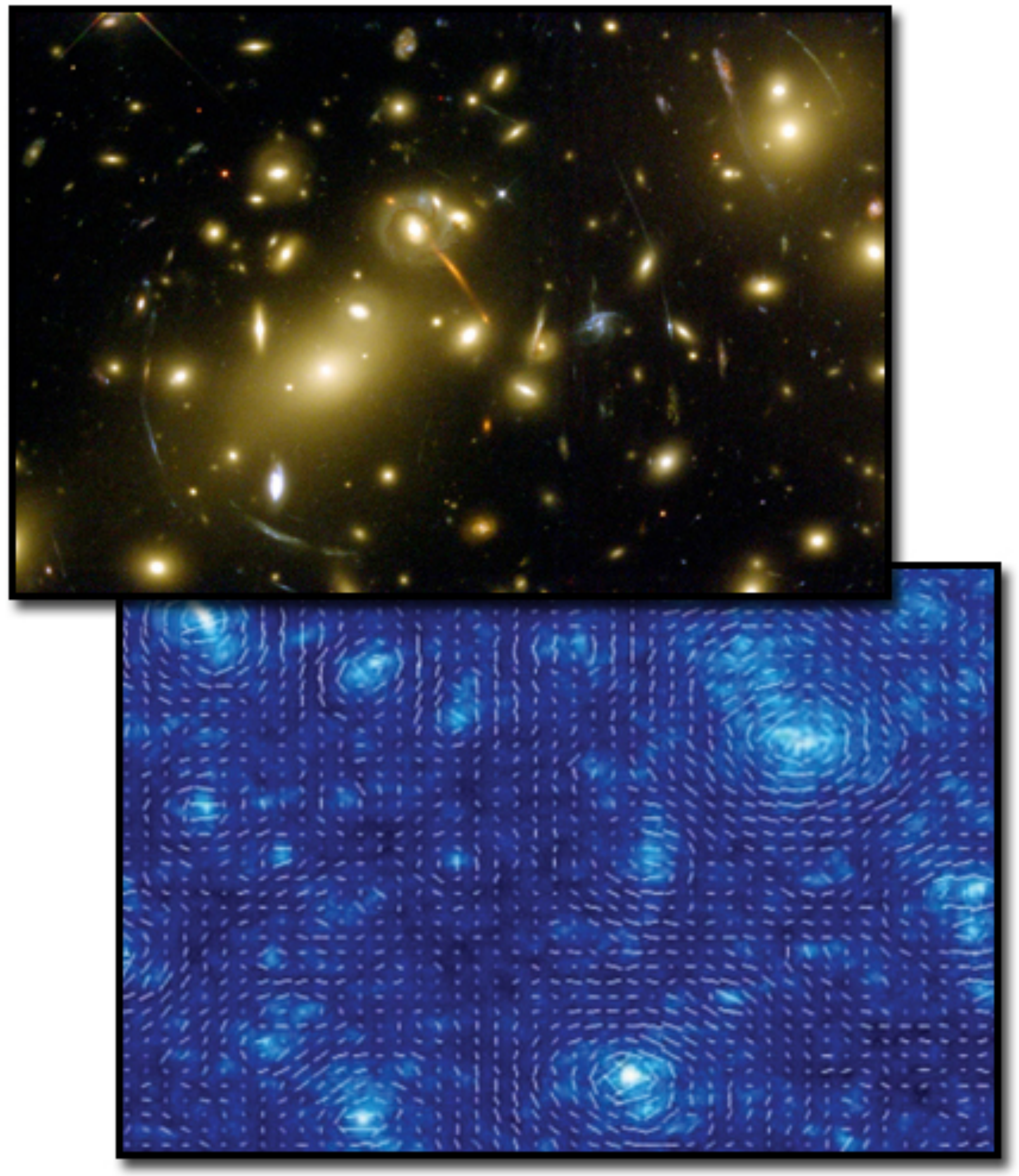
➡ Geometry of the Universe, growth of structures

✦ **Weak Lensing**
- Imaging (*Euclid*, LSST, *Roman*)

➡ Structure formation, galaxy clusters



×



✦ **Galaxy-galaxy lensing (cross-correlation)**

➡ Adding more information to break parameter degeneracy

Simulating Weak Lensing

✦ Multiple plane ray-tracing (Hilbert+09, Ferlito+24): solving ray propagation by approximating matter density fields as density shells

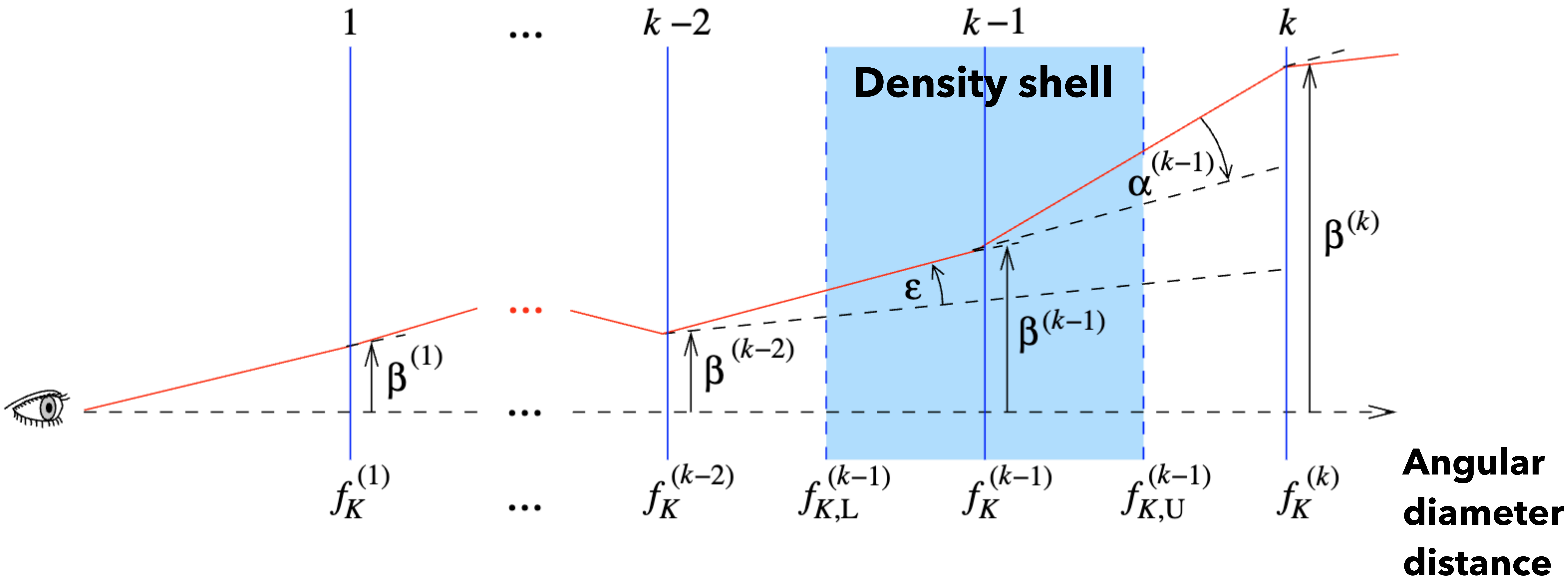


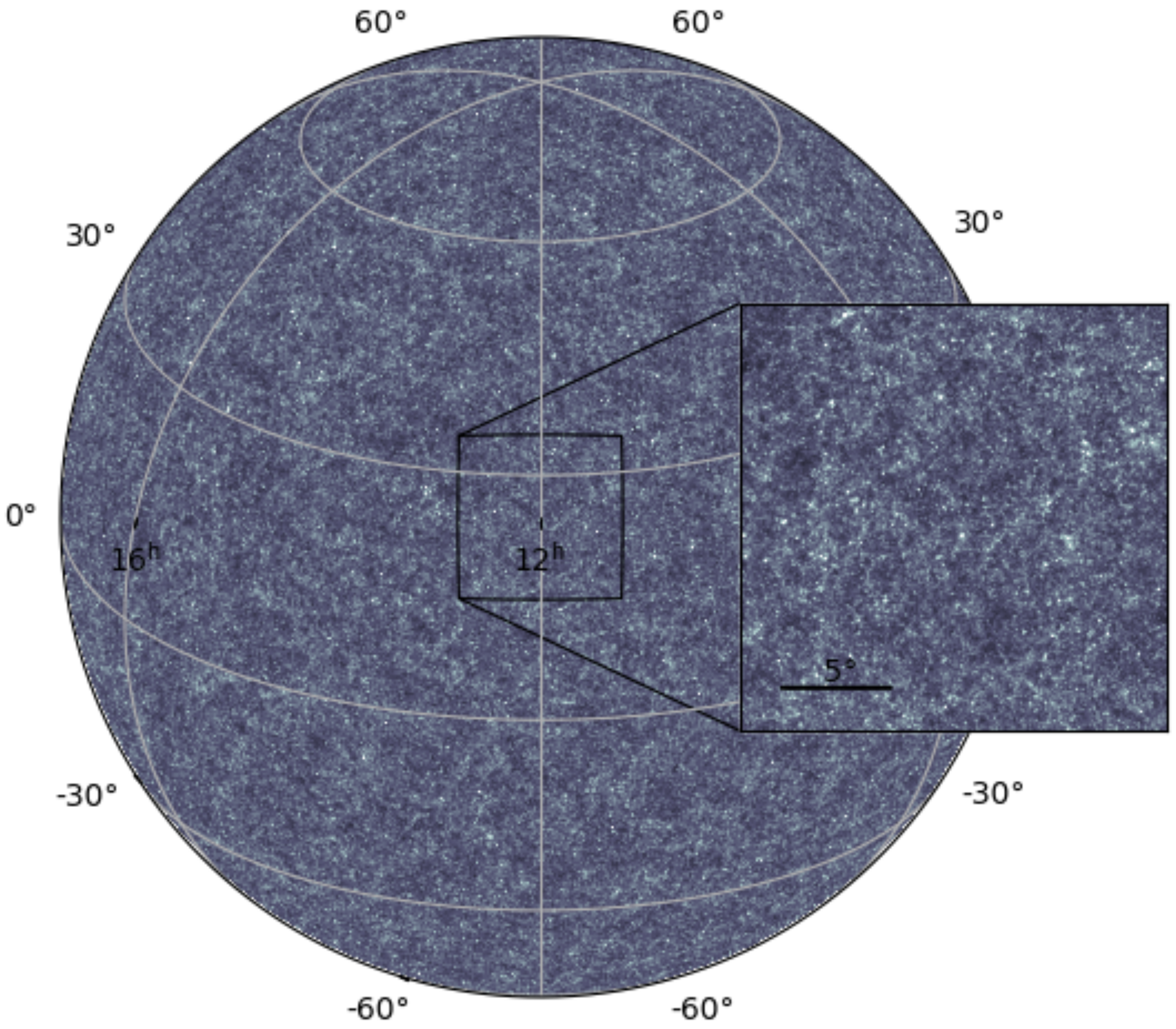
Image position

$$\boldsymbol{\beta}^{(k)} = \left(1 - \frac{f_K^{(k-1)}}{f_K^{(k)}}\frac{f_K^{(k-2,k)}}{f_K^{(k-2,k-1)}}\right)\boldsymbol{\beta}^{(k-2)} + \frac{f_K^{(k-1)}}{f_K^{(k)}}\frac{f_K^{(k-2,k)}}{f_K^{(k-2,k-1)}}\boldsymbol{\beta}^{(k-1)} - \frac{f_K^{(k-1,k)}}{f_K^{(k)}}\boldsymbol{\alpha}^{(k-1)}\left(\boldsymbol{\beta}^{(k-1)}\right).$$

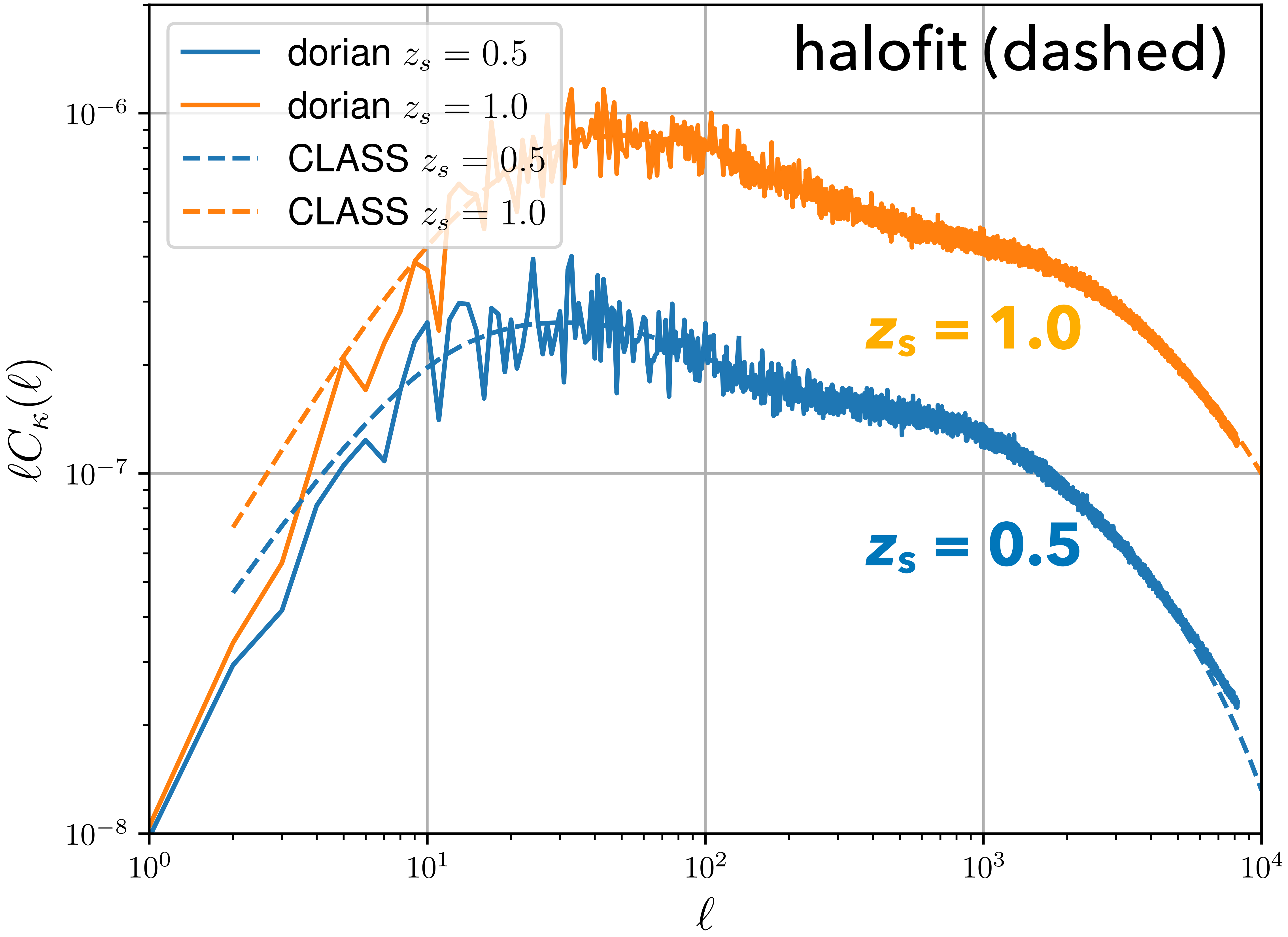
Deflection

Simulating Weak Lensing

- Mass (convergence) map with $z_s = 1$



- Convergence power spectrum



Simulating Galaxy Distribution

✦ **Halo Occupation Distribution (HOD):**
The mean number of galaxies as a function of halo mass.
The most common way to relate galaxies with halo.

- **Central** = gradually growing step-like function
- **Satellite** = power-law function

- **Central HOD**

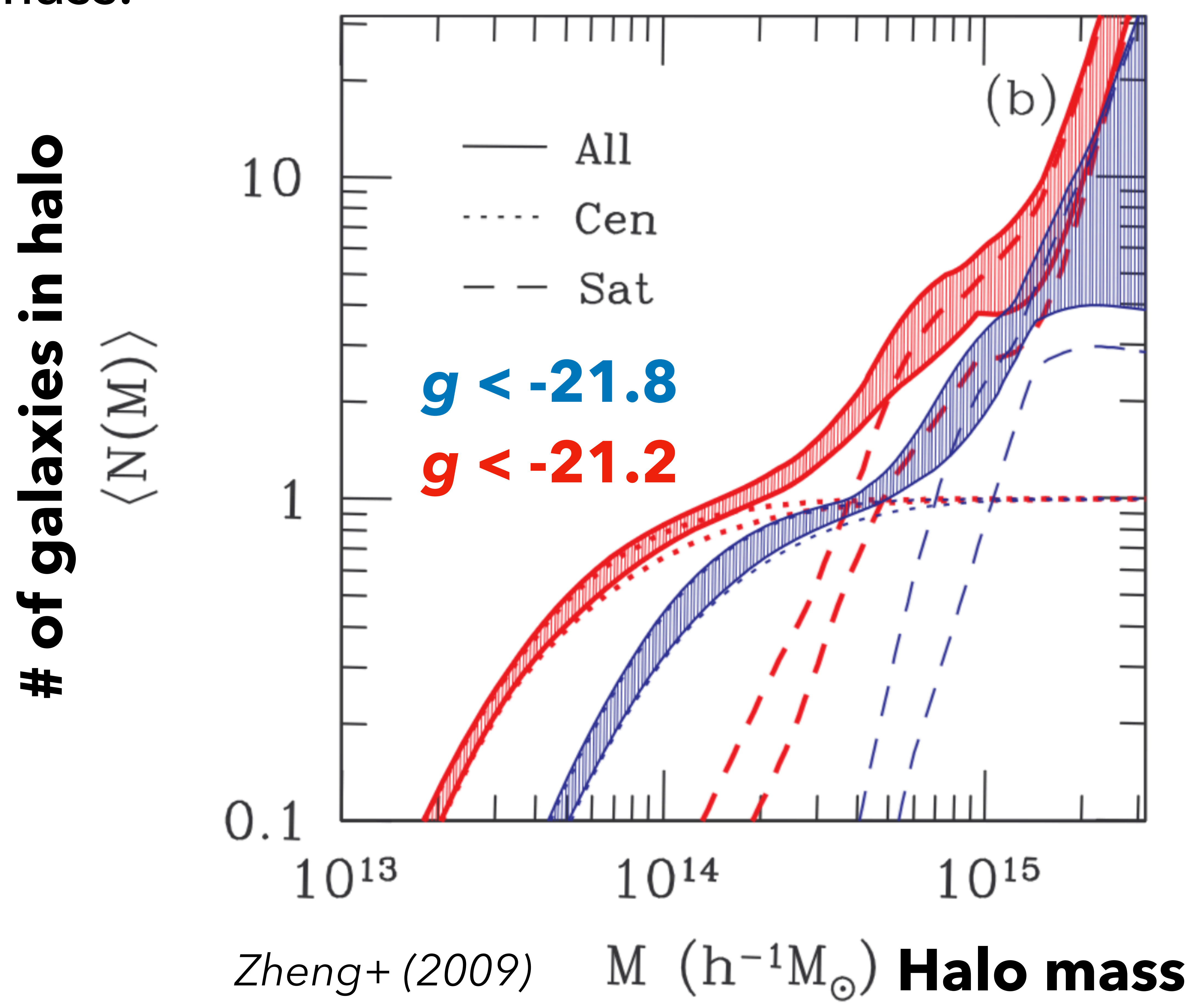
$$\langle N_{\rm cen} \rangle_M = \frac{1}{2}\left[1 + {\rm erf}\left(\frac{\log M - \log M_{\rm min}}{\sigma_{\log M}}\right)\right],$$

- **Satellite HOD**

$$\langle N_{\rm sat} \rangle_M = [(M - M_0)/M_1']^\alpha$$

Kravtsov+ (2004), Zheng+ (2005)

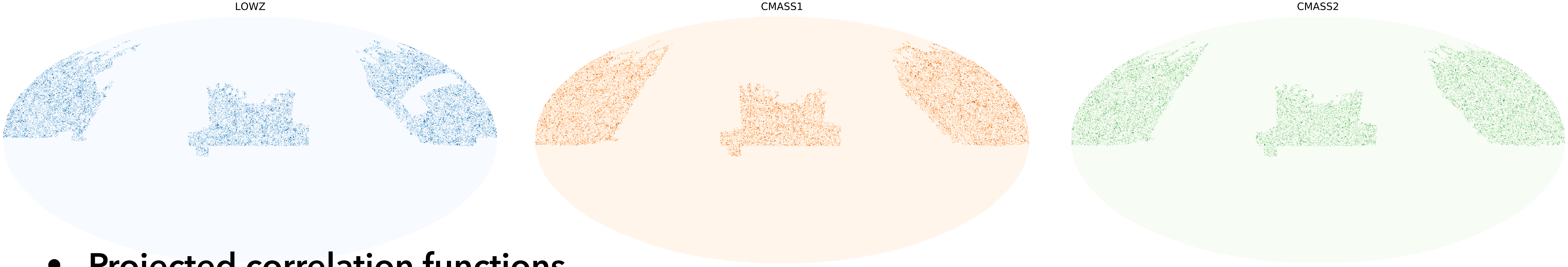
- **HOD of luminous red galaxies**



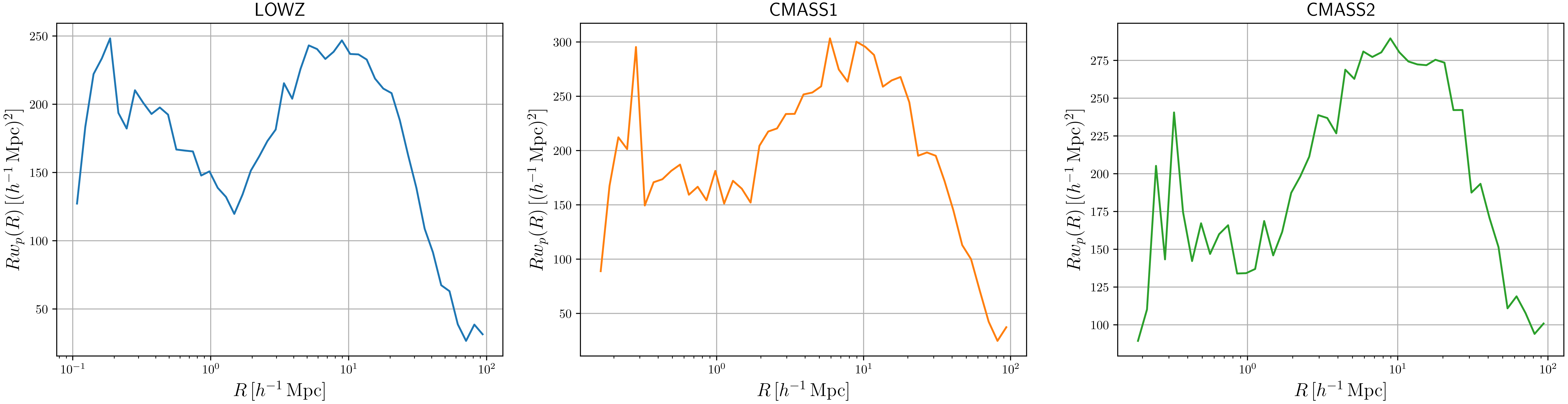
Zheng+ (2009)

Simulating Galaxy Distribution

- **BOSS CMASS/LOWZ galaxies**



- **Projected correlation functions**




Thermal SZ (tSZ) effect $\frac{\Delta T}{T} = y\left(x\frac{e^x+1}{e^x-1}-4\right), \; x = \frac{h\nu}{kT}$
CMB
Compton-y $y(\boldsymbol{\theta}) = \frac{\sigma_{\mathrm{T}} k_{\mathrm{B}}}{m_{\mathrm{e}} c^2} \int P_{\mathrm{e}}\, dl$
CMB photons get energy through inverse Compton scattering with hot free electrons.
Weak lensing (WL) $\kappa(\boldsymbol{\theta}) = \frac{3\Omega_{\mathrm{m}} H_0^2}{2c^2} \int_0^{\chi_s} \mathrm{d}\chi \frac{f_K(\chi_s-\chi) f_K(\chi)}{f_K(\chi_s) a(\chi)} \delta(f_K(\chi)\boldsymbol{\theta}, \chi)$
Convergence
True shape
The shapes of galaxies are distorted due to gravitational potential of intervening matter.
Observed shape

Mock tSZ/kSZ Maps with Baryon Pasting

✦ **Baryon Pasting** (KO & Nagai, 2023):
Paste gas onto halos based on analytic intra-cluster medium model.
Optimized on Fugaku to enable fast production of mock maps, ~ a few hours/map.

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

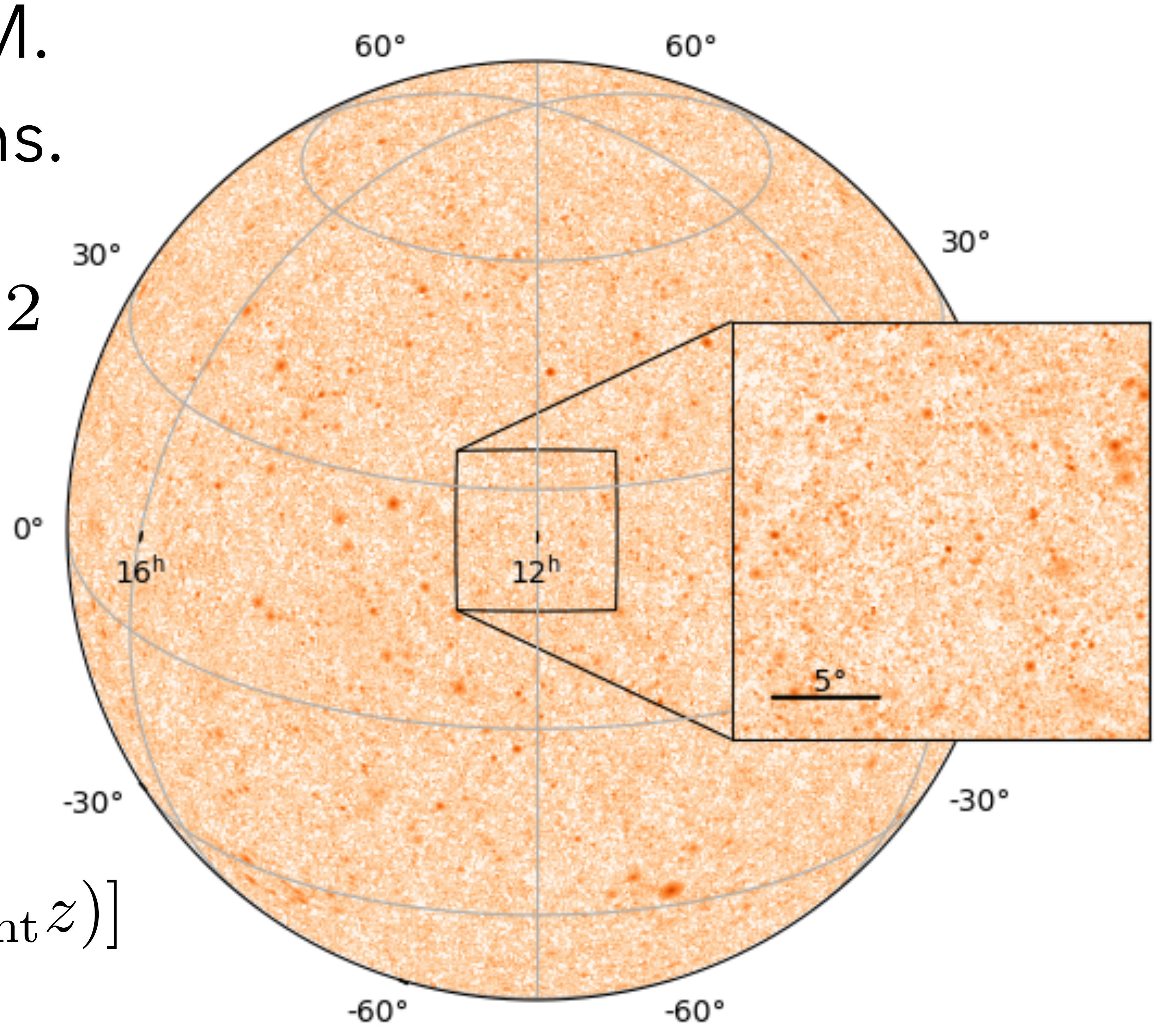
$$\frac{dP_{\rm tot}(r)}{dr} = -\rho_g(r)\frac{d\Phi(r)}{dr}, \quad P_{\rm tot} \propto \rho_g^{1.2}$$

Gas density **Potential gradient**

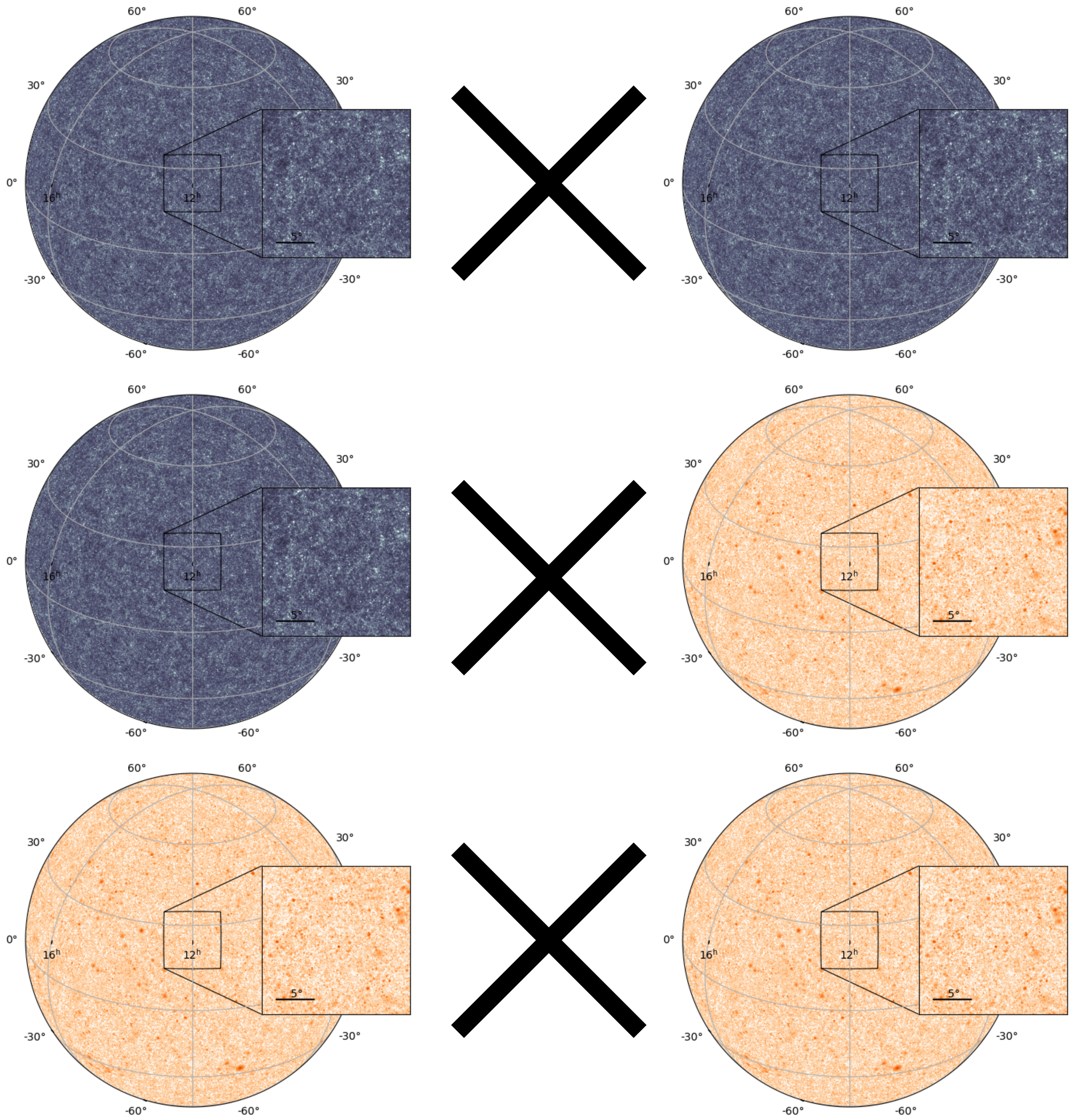
- **Non-thermal pressure** (turbulence, magnetic field, etc.)
  is parametrized according to hydro sim.

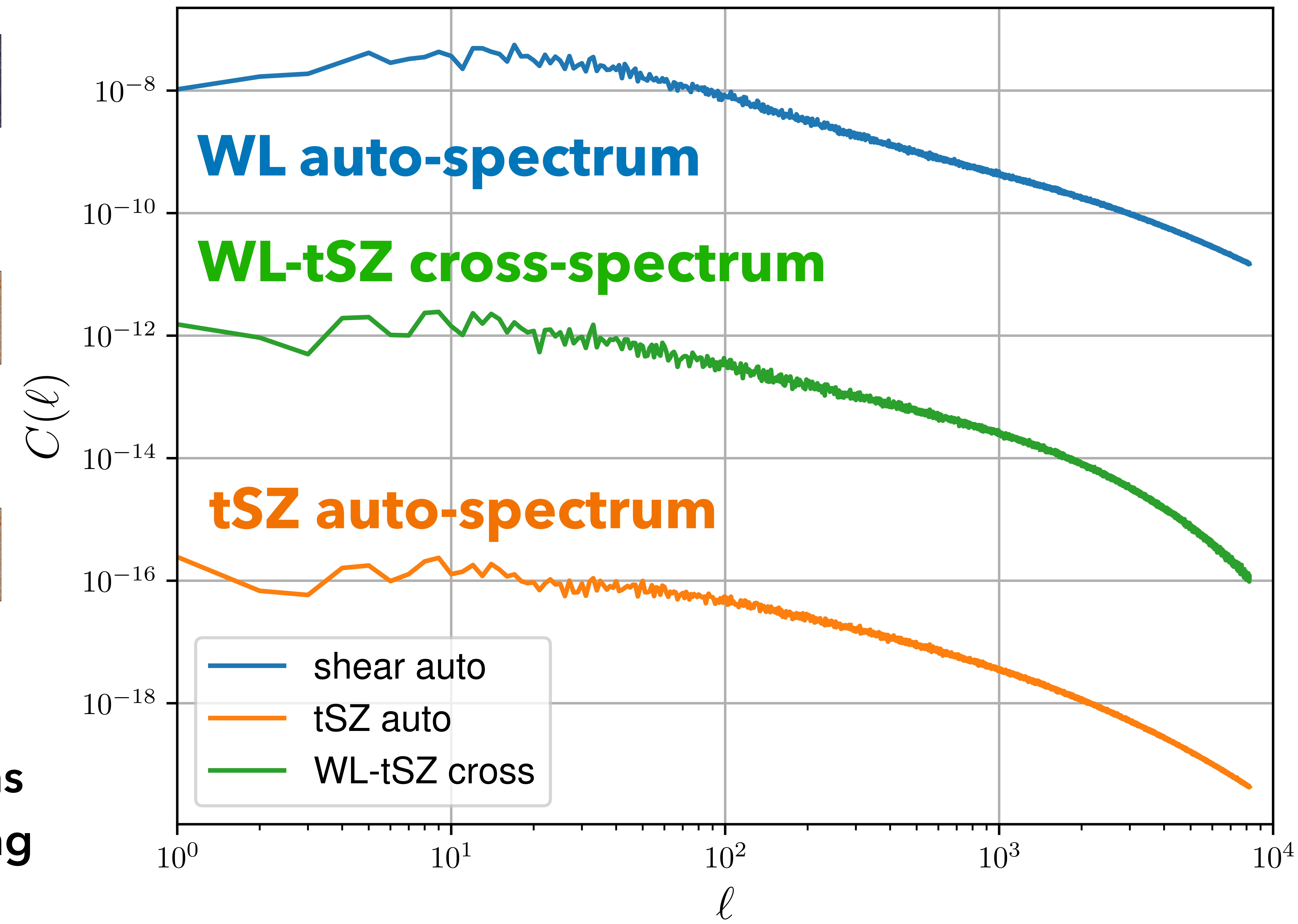
$$\frac{P_{\rm nt}}{P_{\rm tot}}(r,z) = \alpha_{\rm nt} f(z) \left(\frac{r}{r_{500}}\right)^{n_{\rm nt}}, \quad f(z) = \min[(1+z)^{\beta_{\rm nt}}, (f_{\rm max}-1)\tanh(\beta_{\rm nt} z)]$$

tSZ (Compton-*y*)



Measurements of 3x2pt of WL and tSZ





- ✦ **3x2pt analysis:**
  Combination of 3 pairs of correlations extracts more information by breaking parameter degeneracy.

Roadmap

Fugaku All-sky Flagship
- Introducing the overall project
- WL and Galaxies, and its cross-correlations (3x2pt)
- Data products: halo catalogues, mass shells, WL maps, HOD galaxy catalogues
- DR1 (~15 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

2025 (DR1) → **2026 (DR2)**

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

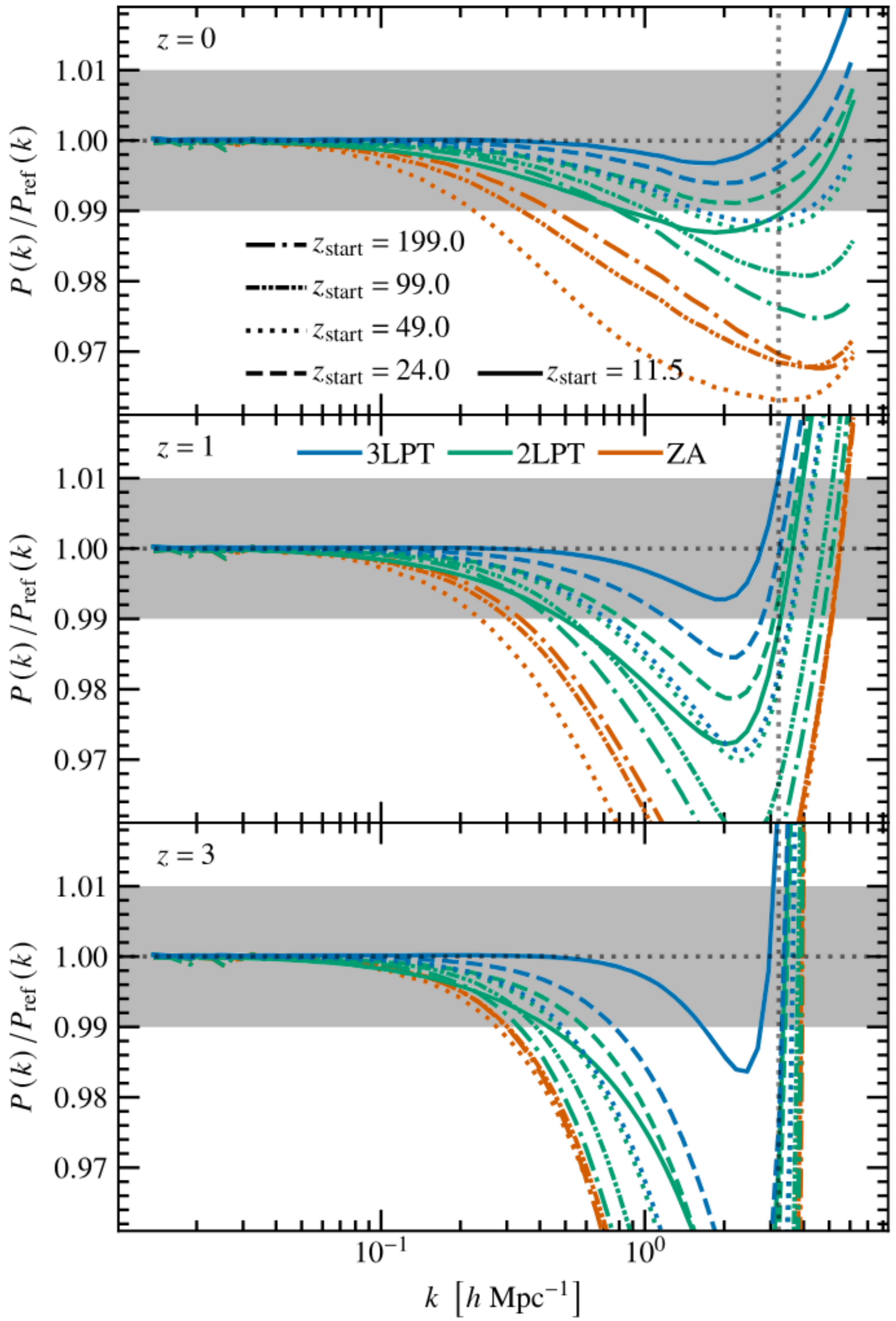
Summary

- 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 is made possible with the efficient *N*-body code GINKAKU and the massive computing power of Fugaku.
- The data products will be publicly released in the near future and this simulation campaign aims to apply the simulation data for Stage-IV cosmological surveys.
- We started production runs, the initial datasets are already available. If you are interested in using the data, please contact me.

Appendix

Starting redshift

- According to Michaux et al. (2021), z_{start} = 11.5 or 24 are consistent with the reference simulation (FCC with z_{start} = 24).
  The resolution for this test: L = 1 Gpc/h , N = 1024^3.



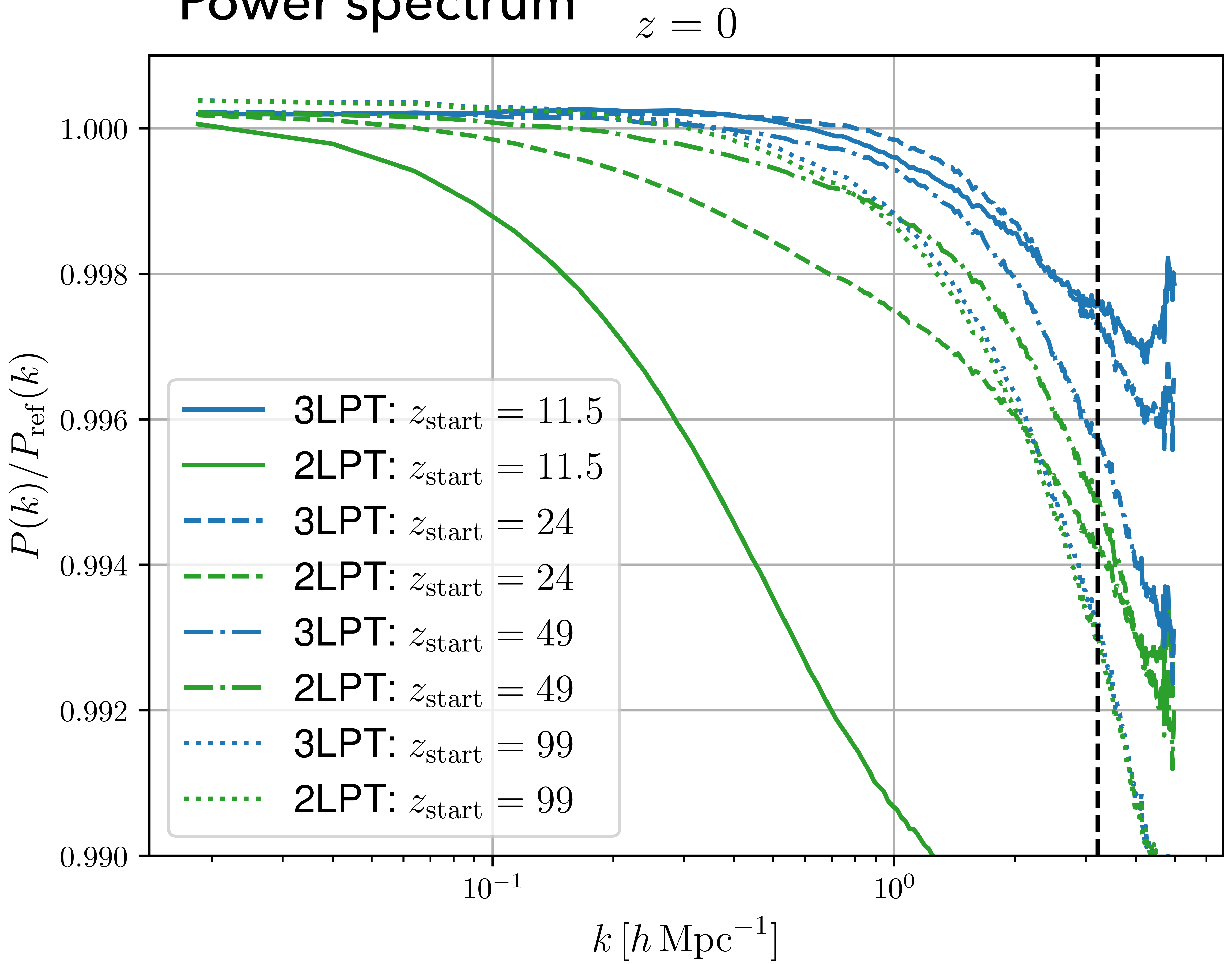
3LPT
2LPT
ZA

Starting redshift

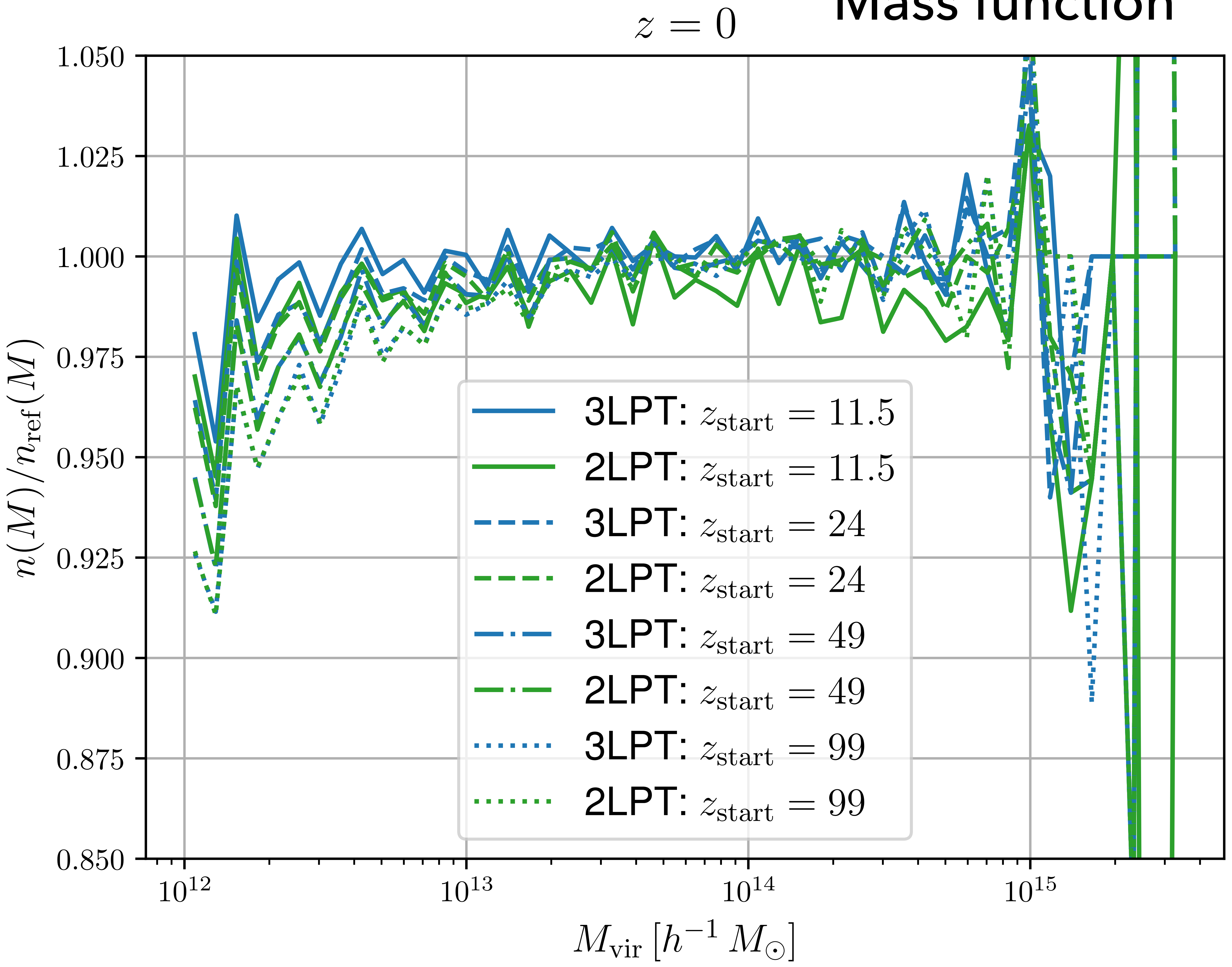
- Initial condition is generated with monofonIC (Michaux+ 2020; Hahn + 2020).

✅ $z_{\rm start}$ = 24 with 3LPT

Power spectrum

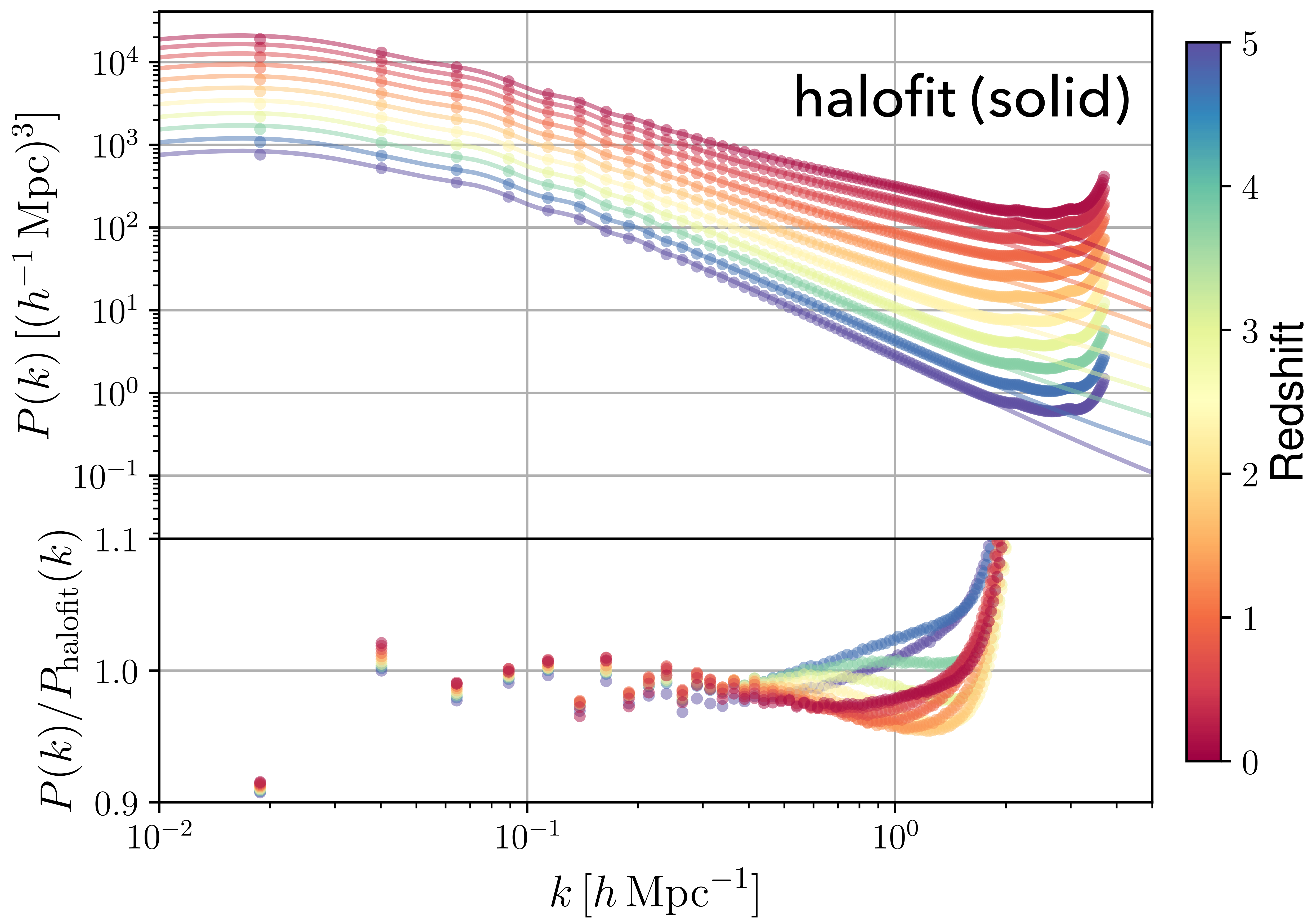


Mass function

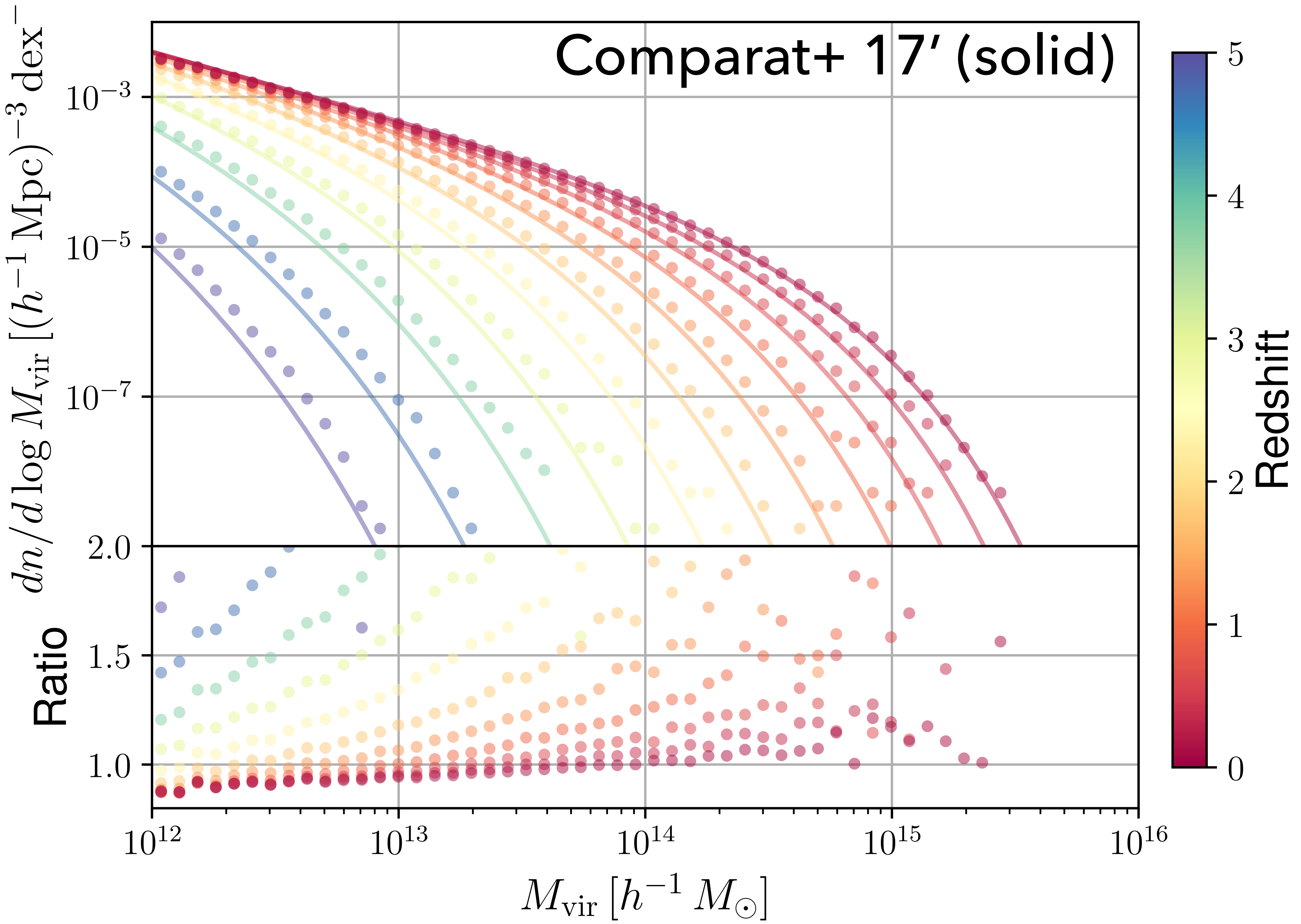


Validation

- **Matter power spectrum**



- **Halo mass function**



Alignments of Halo Shapes

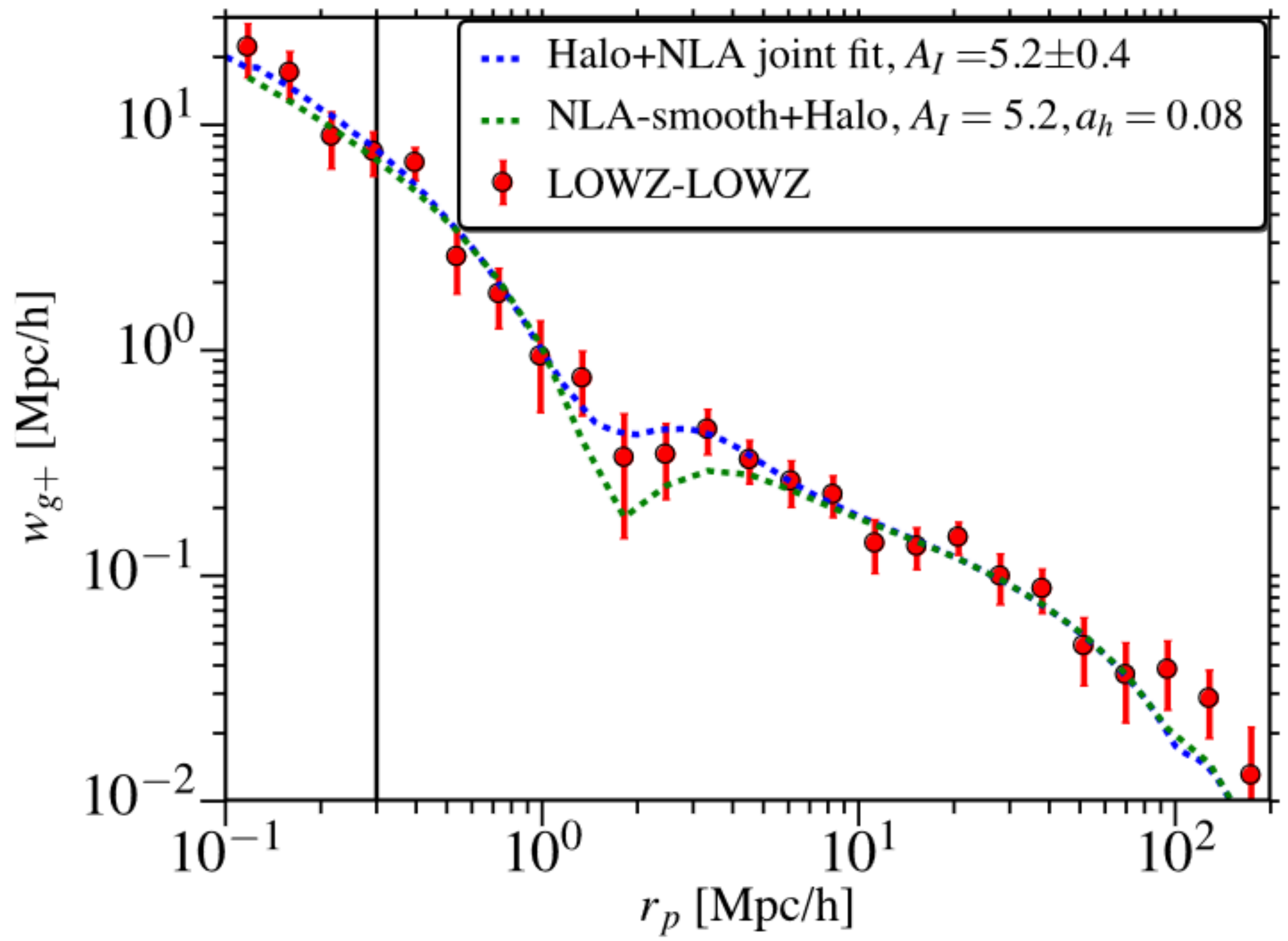
The **tidal field** and/or **tidal torque** align halos. The shapes are correlated with large-scale structures.

$$I_{ij}(\boldsymbol{x}_1) = \sum_p m_p r_{p,i} r_{p,j}$$

Halo shapes are characterized by the inertia tensor.

$$I_{ij}(\boldsymbol{x}_2)$$

Galaxy-shape cross-correlation measured with SDSS sample



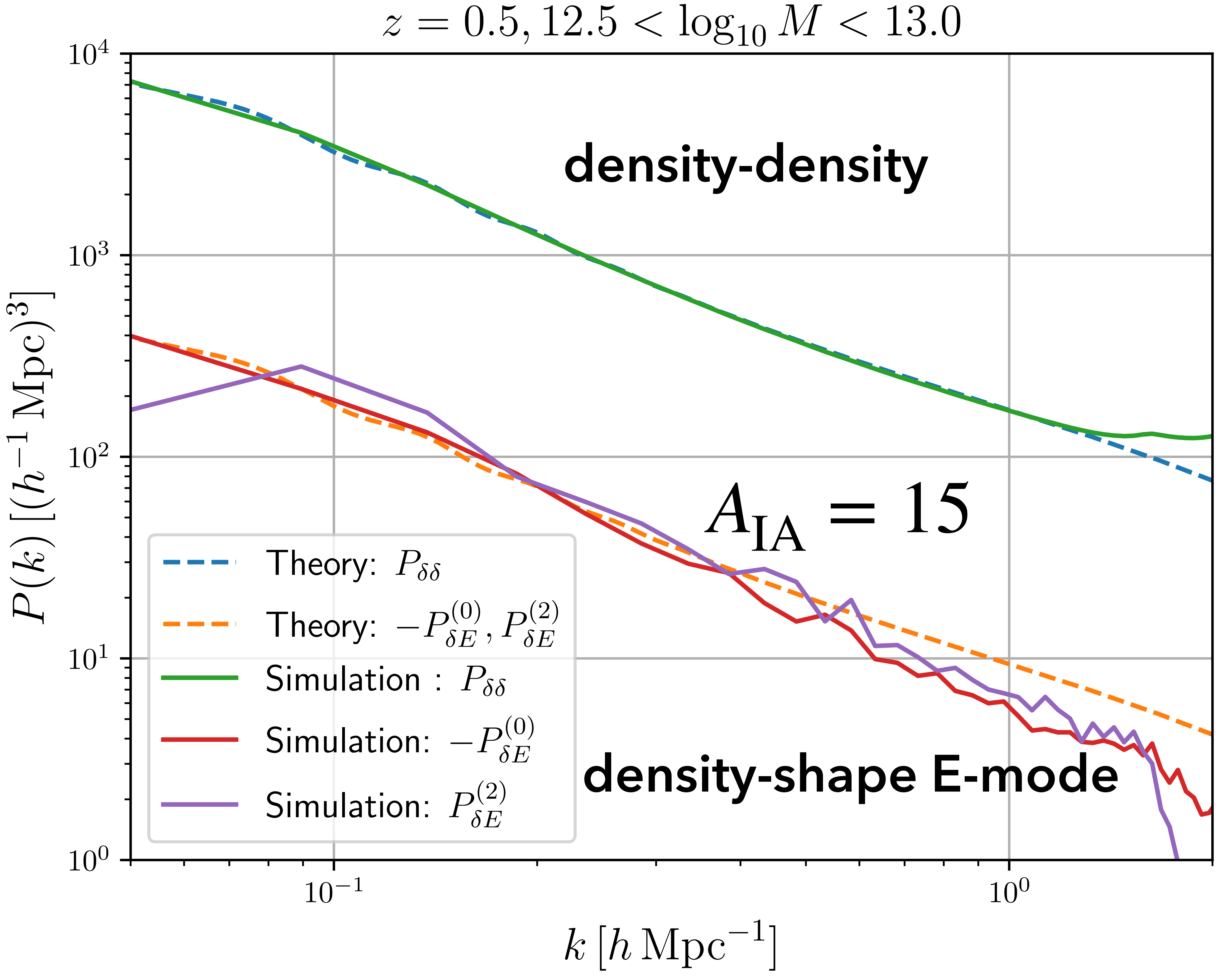
Singh, Mandelbaum, More (2015)

Image credit: Benedikt Diemer

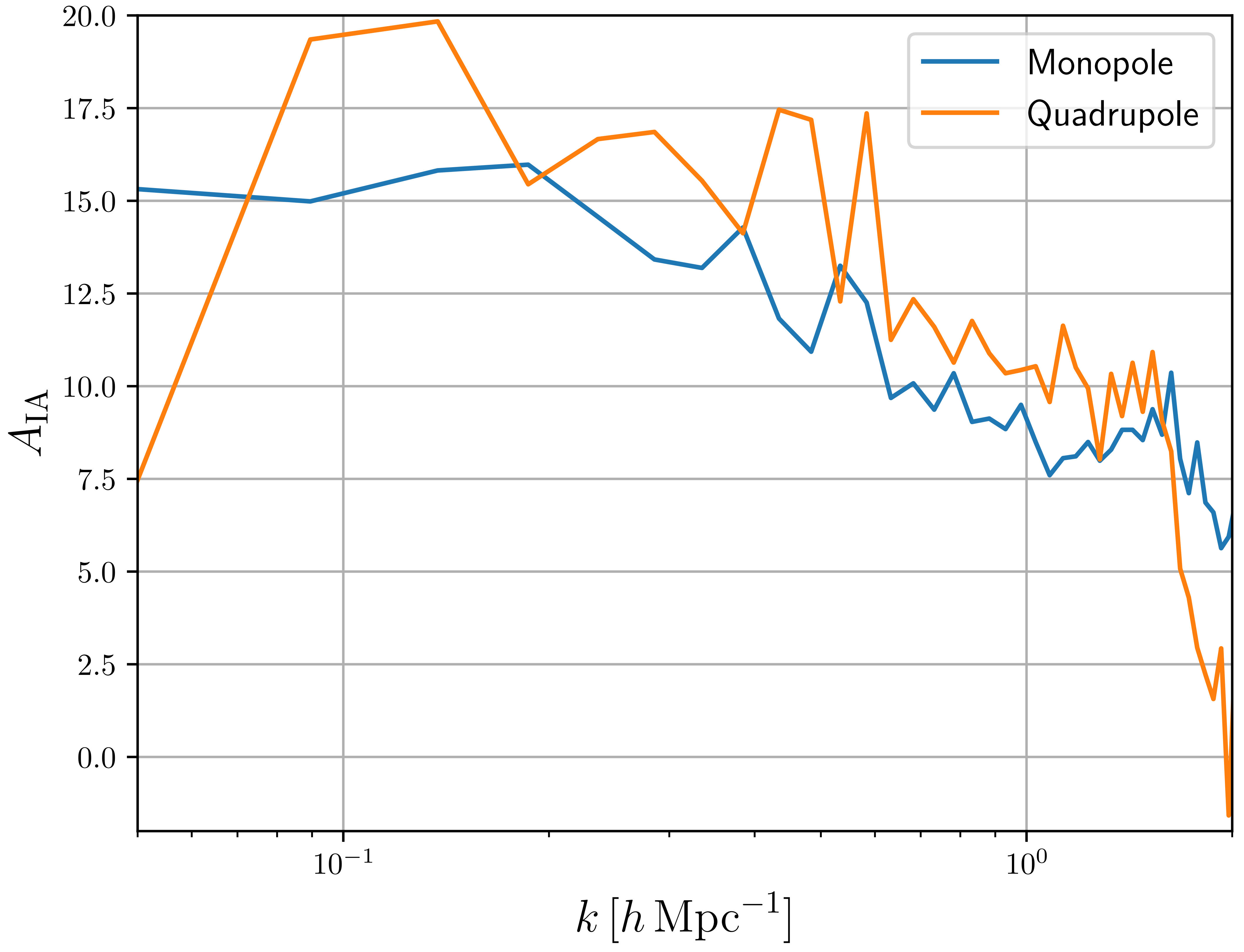
Shape Correlations

✦ Subhalo shapes are computed with the iterative reduced tensor. $I_{ij} = \sum_p m_p \frac{r_{p,i} r_{p,j}}{r_p^2}$

- **Shape-Density cross-spectrum**



- **Amplitude**
  Consistent with Kurita+ (2021)



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

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

Gas density **Potential gradient**

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

Gas energy

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

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.

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

Analytic Intra-cluster Medium Model

✦ **Analytic ICM m**

The gas in halo

The density/pre

Total gas pressu
gradient

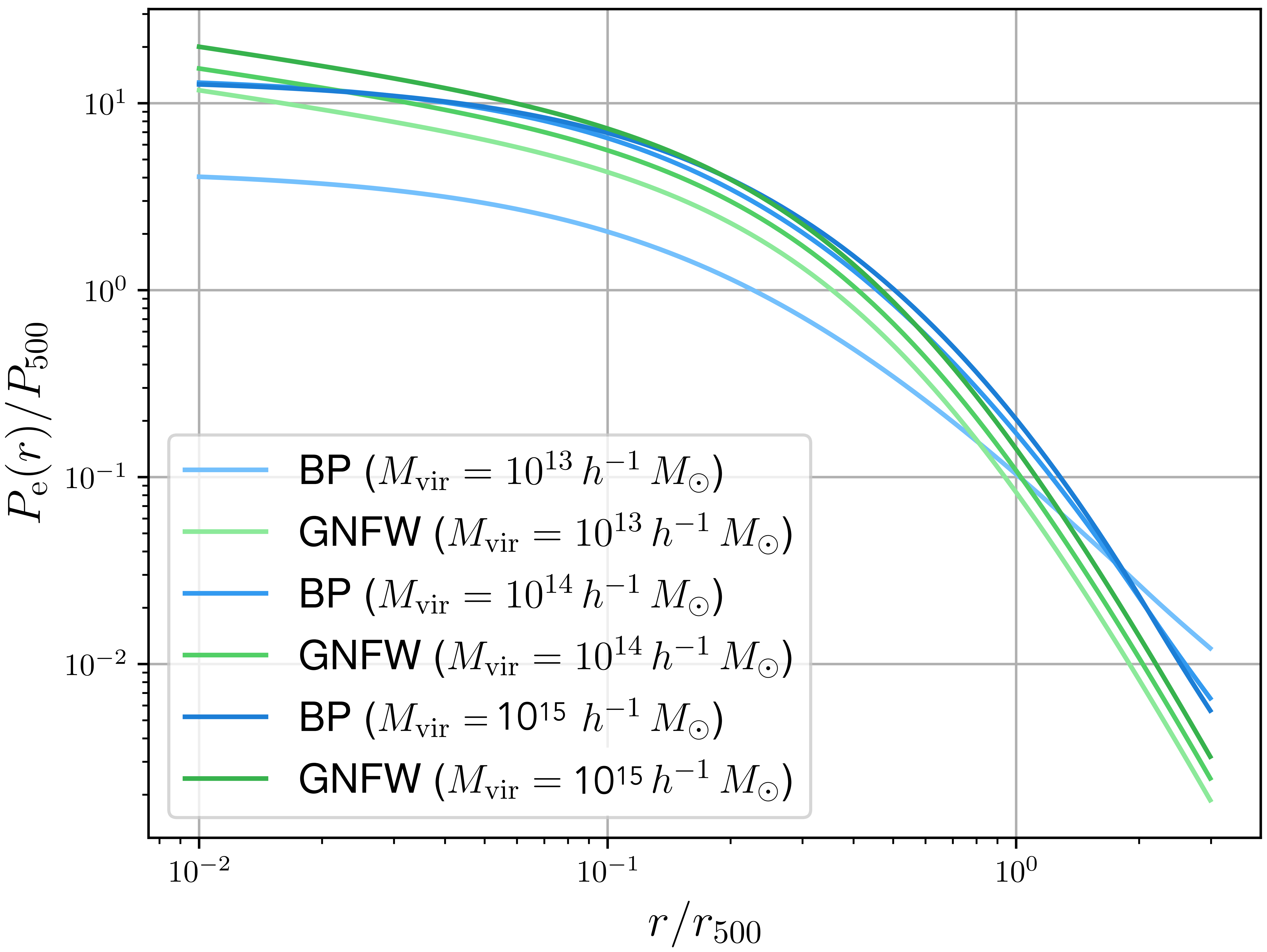
- The amplitude ... budget.

Gas energy ... **by expansion**

- **Non-thermal p** ... rding to hydro sim.

$$\frac{P_{\rm nt}}{P_{\rm tot}}(r,z) \ldots (\beta_{\rm nt} z)]$$

✦**Comparison with Planck GNFW pressure profile**



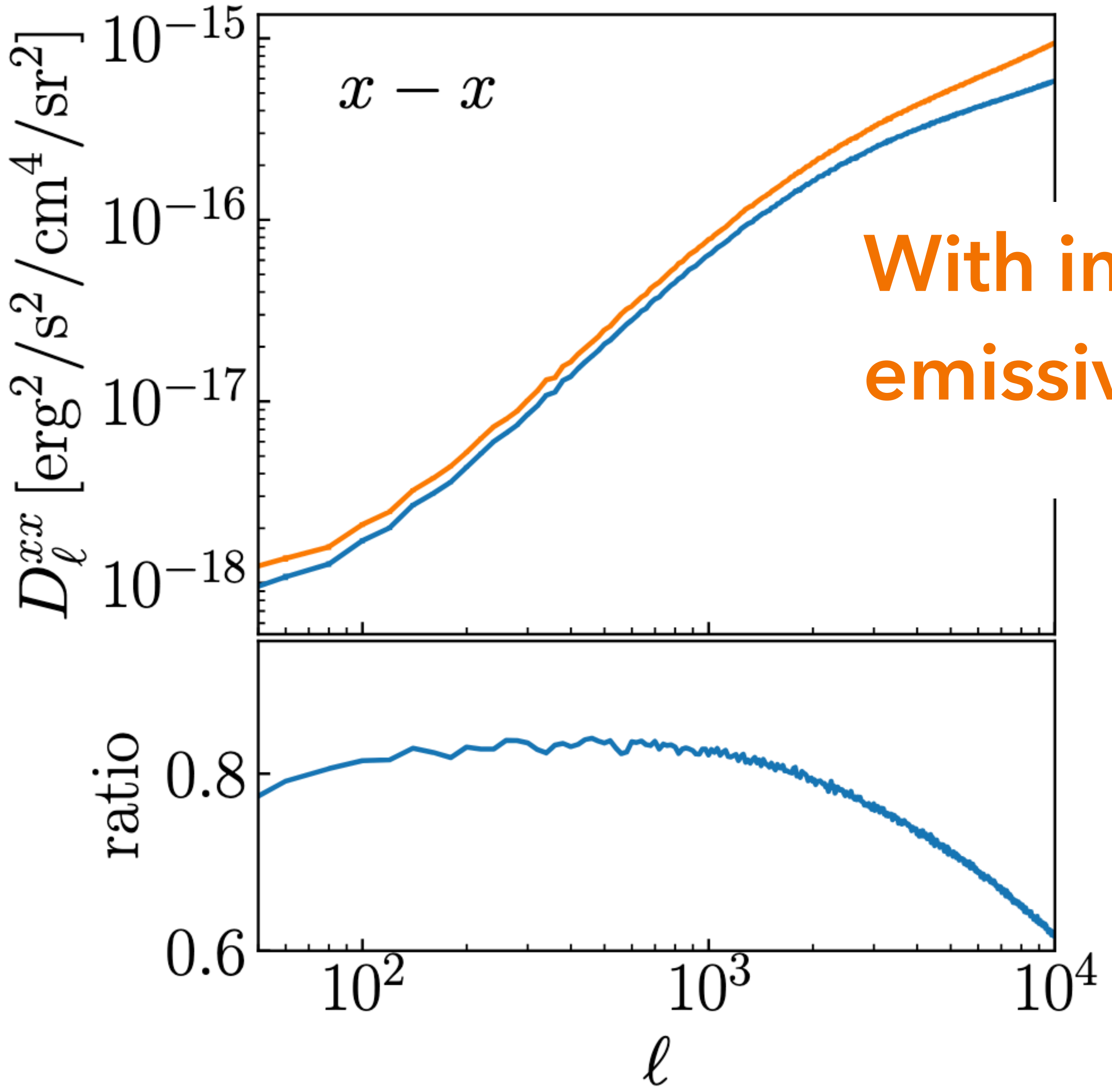
X-ray Modelling with Baryon Pasting

- **X-ray emissivity:**

$$\epsilon_X(r; M_{\rm vir}, z) = \frac{n_H(r; M_{\rm vir}, z) n_e(r; M_{\rm vir}, z)}{4\pi(1+z)^4} \times \int_{E_{\rm min}(1+z)}^{E_{\rm max}(1+z)} \underline{\Lambda(T(r; M_{\rm vir}, z), Z, E)} dE \quad (12)$$

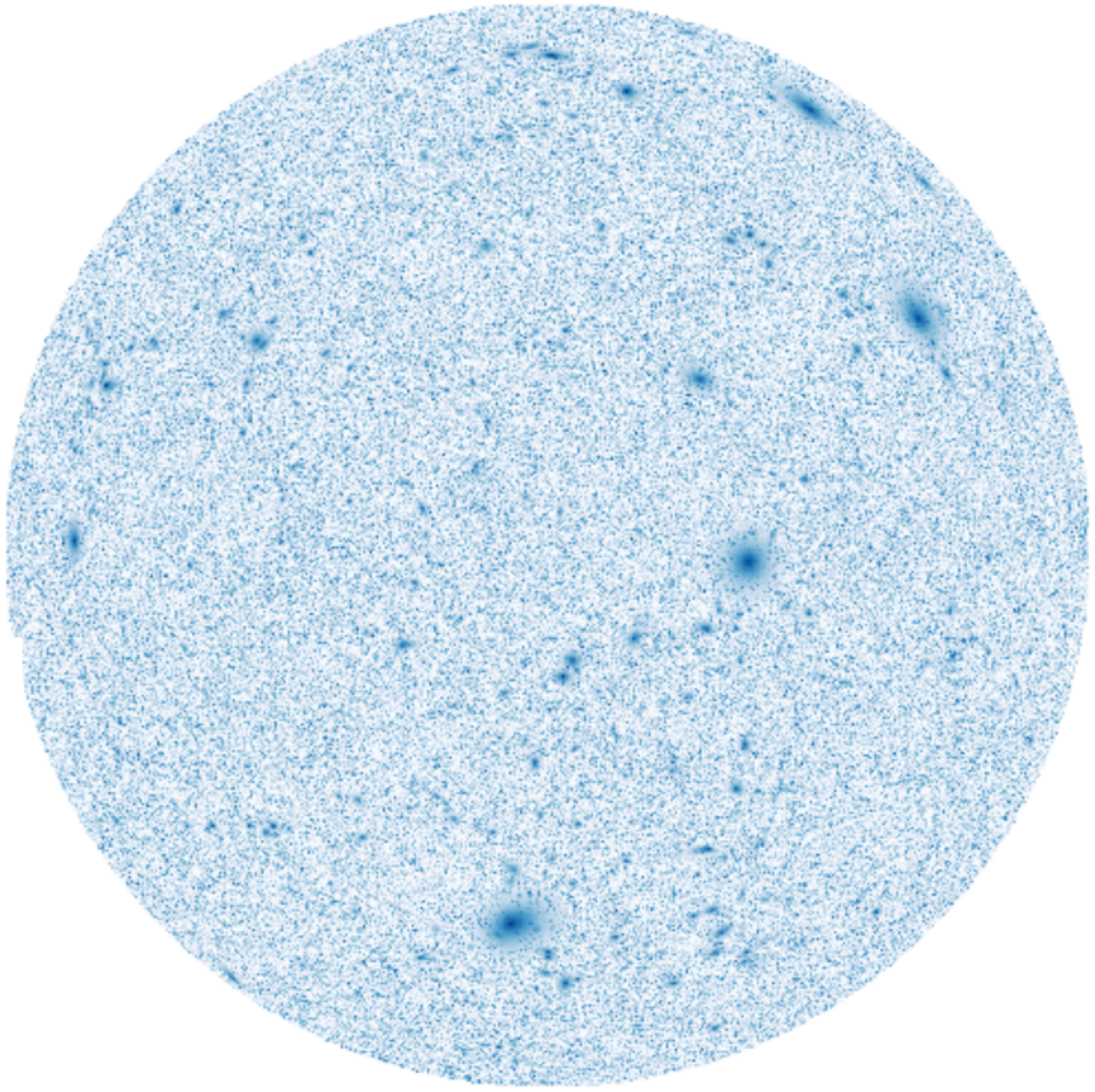
Cooling function precomputed with plasma code APEC

- **Power spectrum**



With intrinsic scatter in X-ray emissivity profile

X-ray Surface Brightness Map



Lau, Nagai, Farahi, Ishiyama, Miyatake, KO, Shirasaki (2024)