宇宙大規模構造エミュレータとニュートリノの影響

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NUMERICAL COSMOLOGY W/ SUBARU

観測データ

↓

銀河の統計量

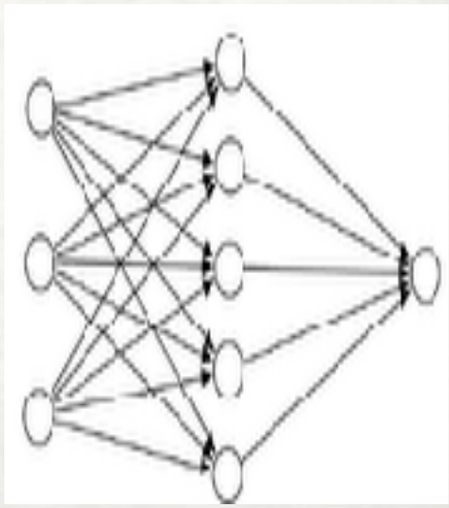
↑ Forward modeling　**ここはよく分からない**

ハローの統計量

↑ Forward modeling　**機械学習**

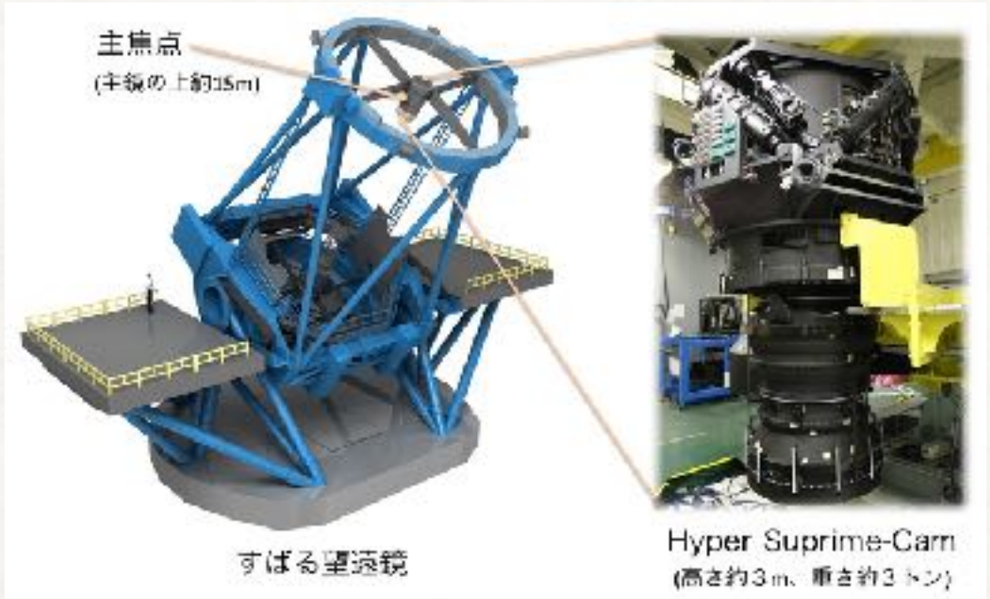
宇宙論パラメタ

- Direct sampling of LSS joint PDF unfeasible
- Analysis based on statistical measures (dimension reduction)
- forward modeling + MCMC
- Gravity only simulation is only an approximation
  - Model what we can
  - Marginalize over uncertainties in what we do not simulate (i.e., baryonic effects, small scale effects below resolution limit…)
- **No deep learning needed**
  - e.x., how P(k) depends on Ω_m

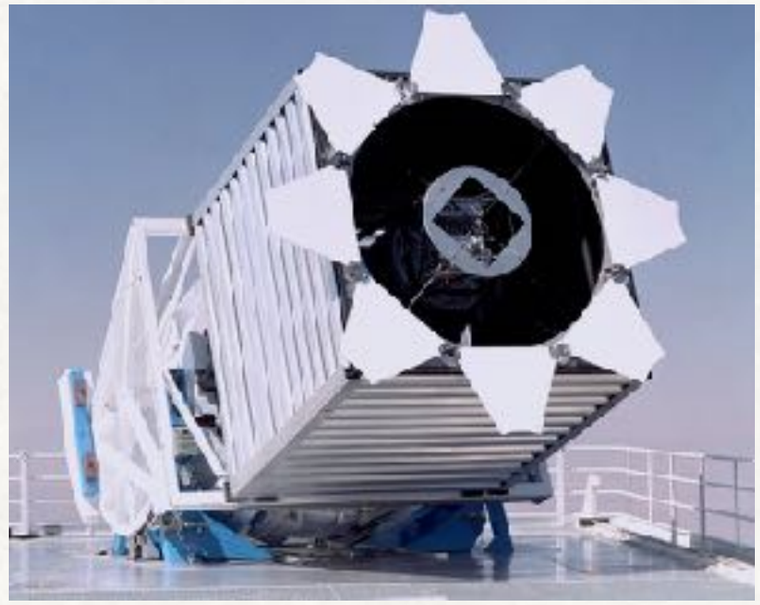


WHAT WE WANT TO (HAVE TO) DO

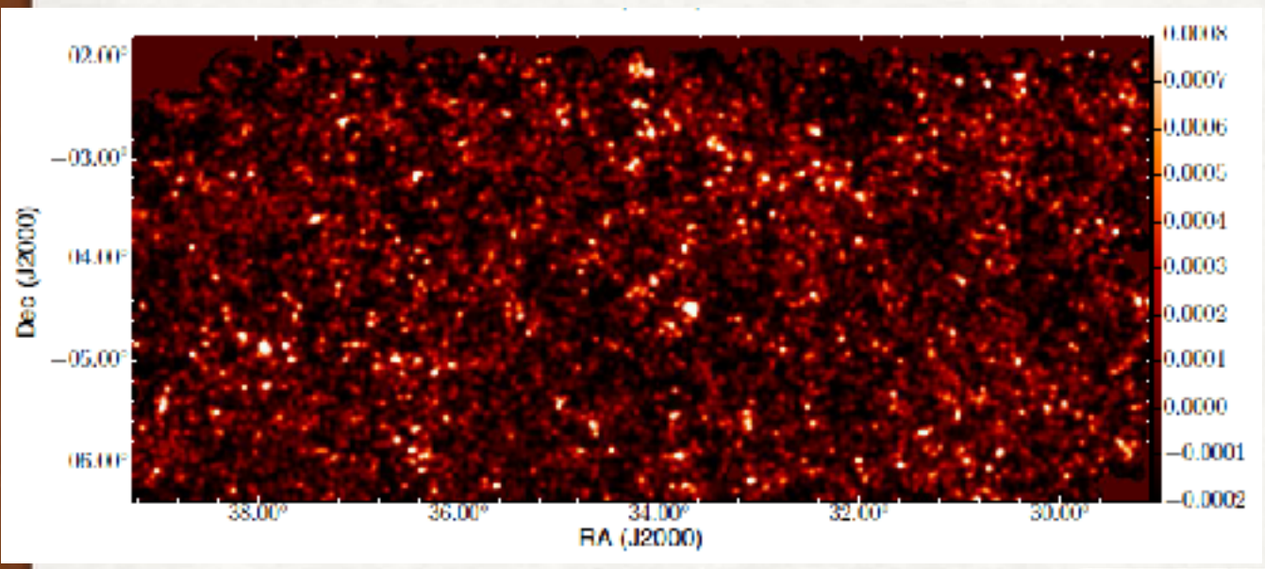
Hyper Suprime Cam (HSC)



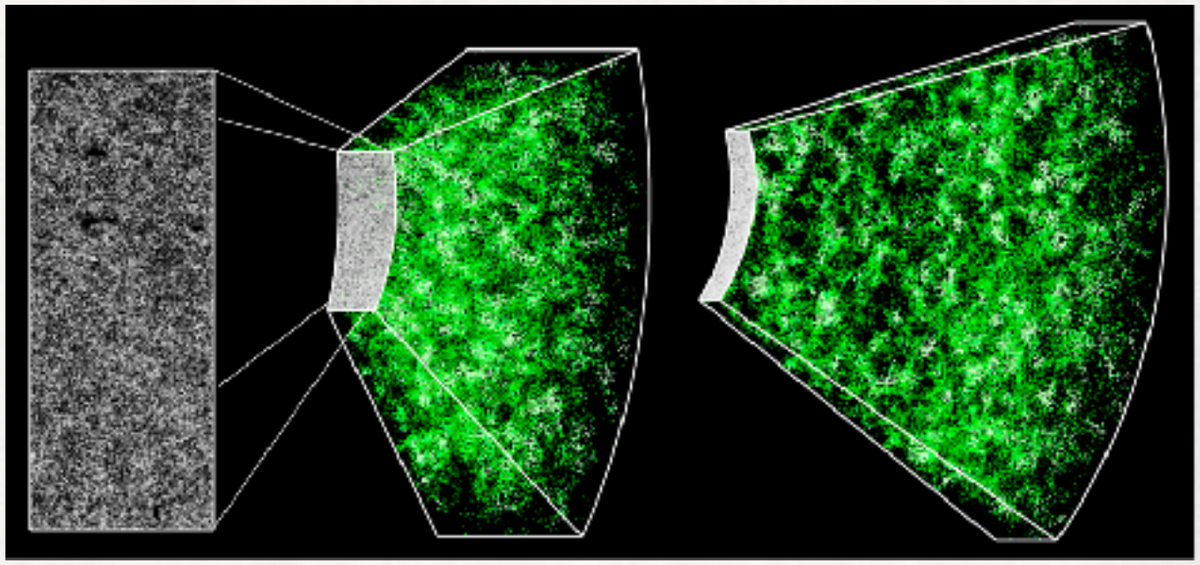
Sloan Digital Sky Survey



Weak lensing: convergence κ (Oguri+'17)



Galaxy redshift survey: overdensity δ_g



$\langle \kappa\, \kappa \rangle$

Free from bias —> Hikage+'18

$\langle \delta_g\, \kappa \rangle$ $\langle \delta_g\, \delta_g \rangle$

Degeneracy between bias and cosmology?
—> Miyatake, TN+ in prep

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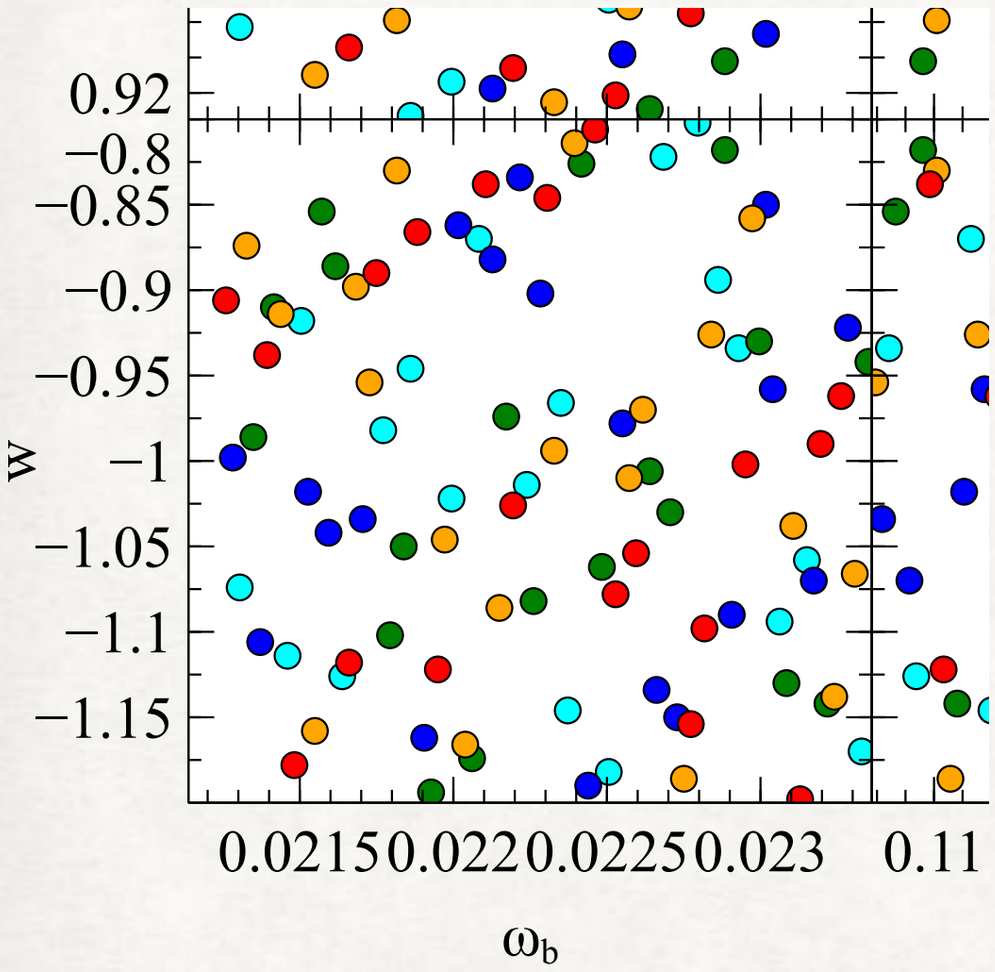
DARK QUEST PROJECT

DARK QUEST SIMULATIONS

TN+'18 (arXiv:1811.09504)



Circles: 100 parameter sets to be covered

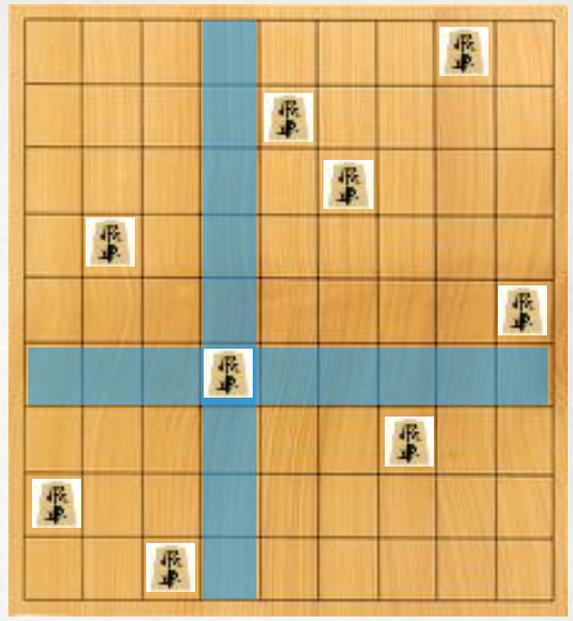
Centered at Planck 2015

$\omega_b = \Omega_b h^2$: ±5%	$\ln(10^{10} A_s)$: ±20%
$\omega_c = \Omega_c h^2$: ±10%	n_s: ±5%
Ω_Λ: ±20%	w: ±20%

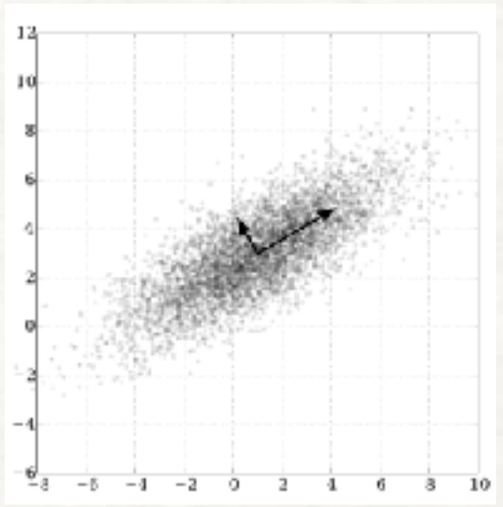
DQ 1: to be made public after HSC cosmology analyses (~early this year)

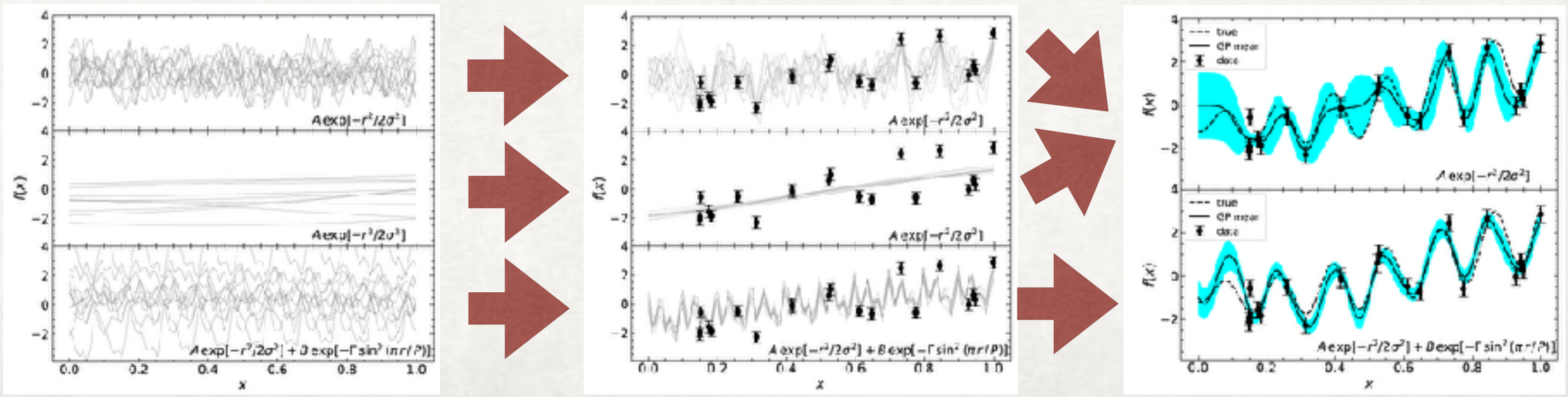
- Ensemble of N=2048^3 sims
  - 2 base resolutions
    - L = 1 Gpc/h and 2 Gpc/h
  - 100+1 6D-wCDM models
    - 28 HR (14 LR) fiducial runs
    - 1 run at every 100 LHD sample
- density on 1024^3 grid points
- Rockstar halos + postprocess
  - Subhalos excluded
  - Spherical density profile (40 bins from 10kpc/h to 5Mpc/h)

EMULATOR STRATEGY



- Efficient sampling
  - Latin Hypercube designs
- Dimension reduction by
  - Fitting when a good fitting form is known/available
  - Principal Component Analysis
  - Data vector size: 50,000 -> 20
- Learning/prediction with Bayes
  - Gaussian Process Regression

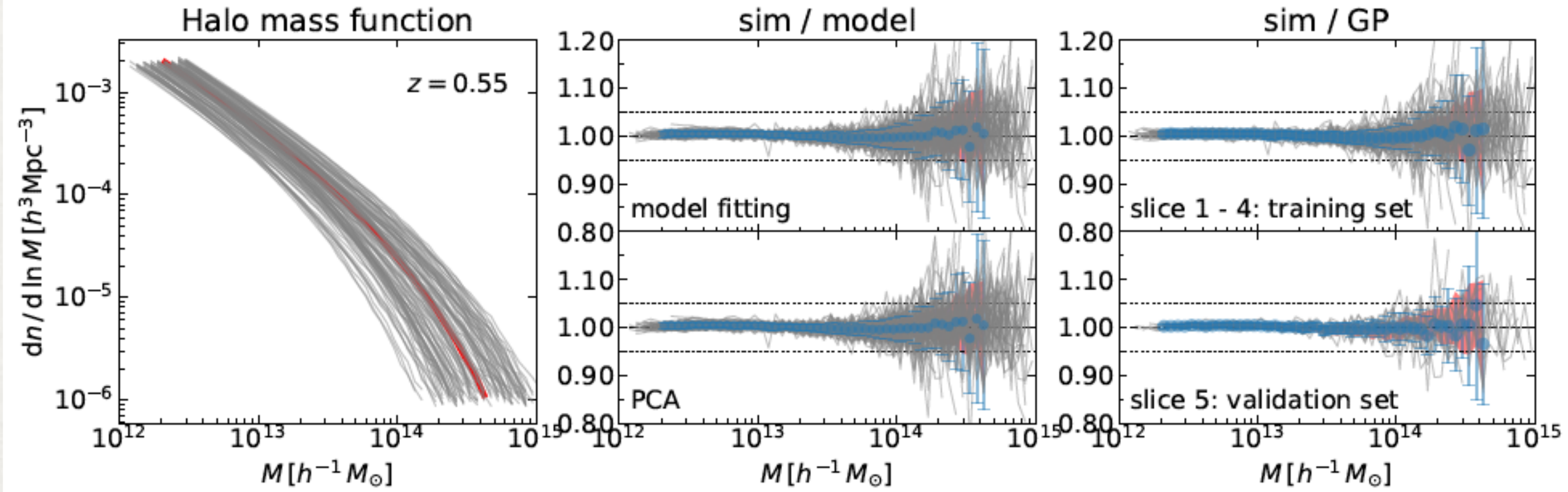




CROSS VALIDATION TEST EXAMPLE

TN+'18 (arXiv:1811.09504)

Example plot at z = 0.55



Spread in HMF among the 100 models

Gaussian Process Regression

Upper: Model fitting w/ Sheth-Tormen type function (2 free parameters)

Training set

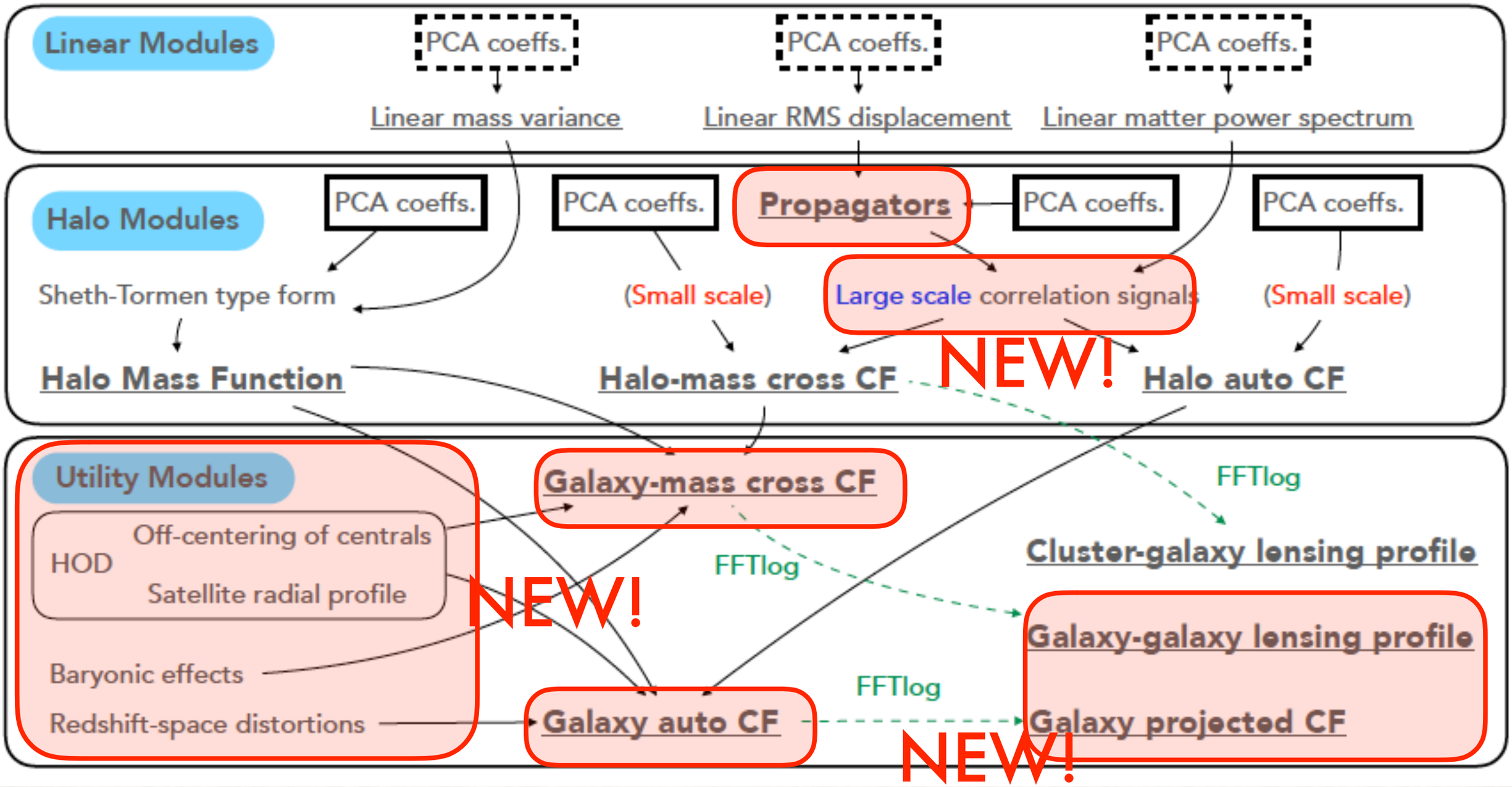
Lower: Compress the 42 (=2 x 21 redshifts) coefficients into 6 PCs

Validation set

Red shades: scatter of 28 fiducial runs

EMULATOR IMPLEMENTATION

TN+'18 (arXiv:1811.09504)

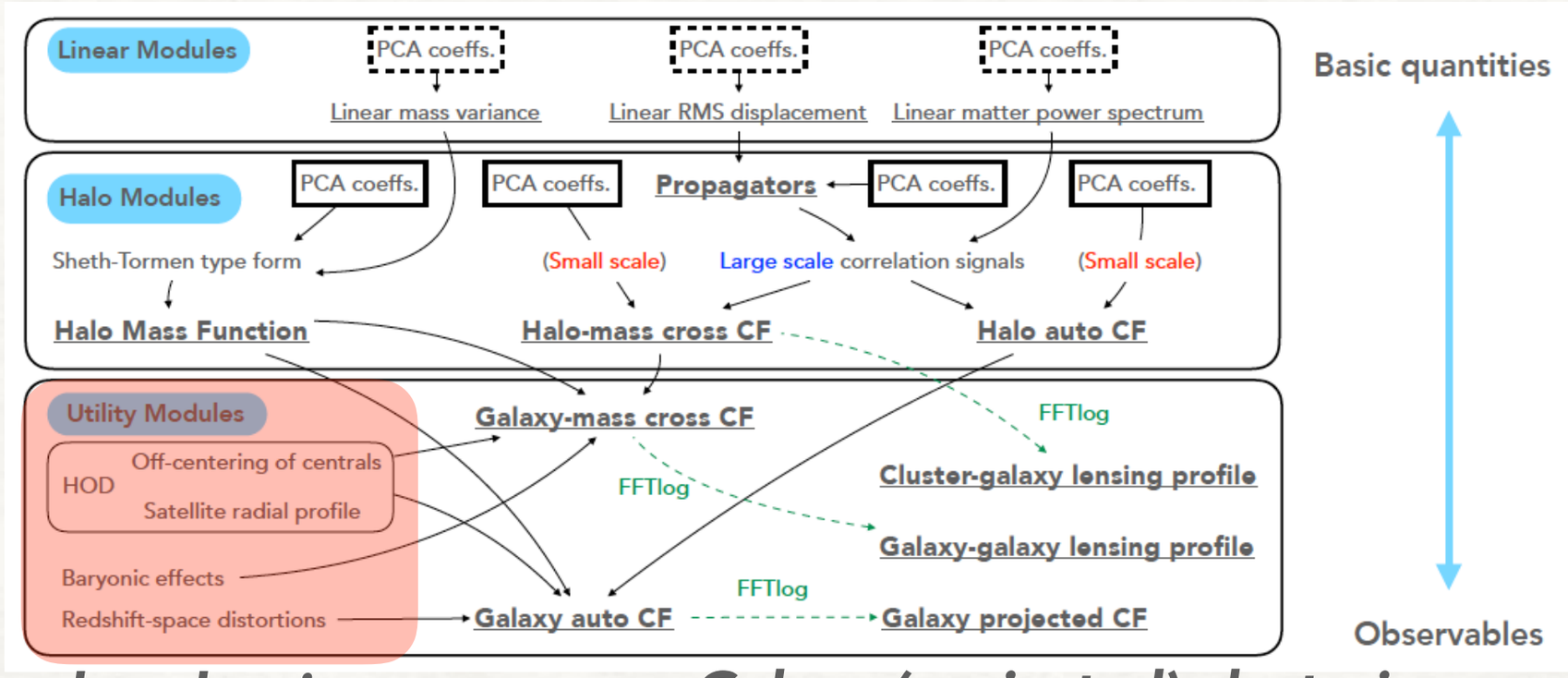


- Combine different modules to work together
- Utility modules can deal with different recipes to populate galaxies

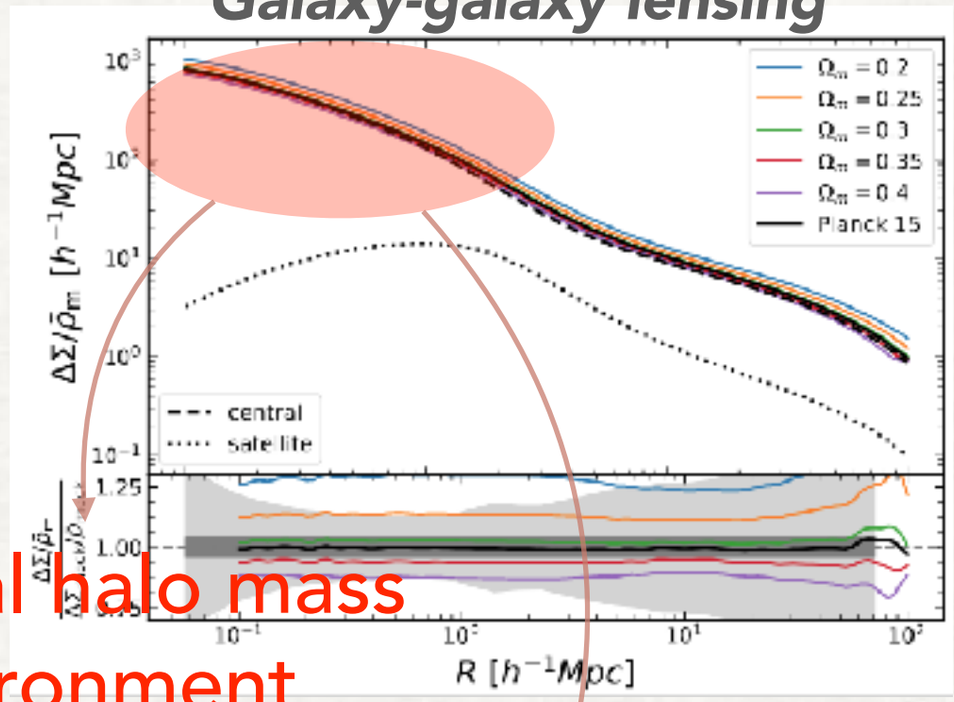
ANALYSIS PLAN

TN+'18 (arXiv:1811.09504)

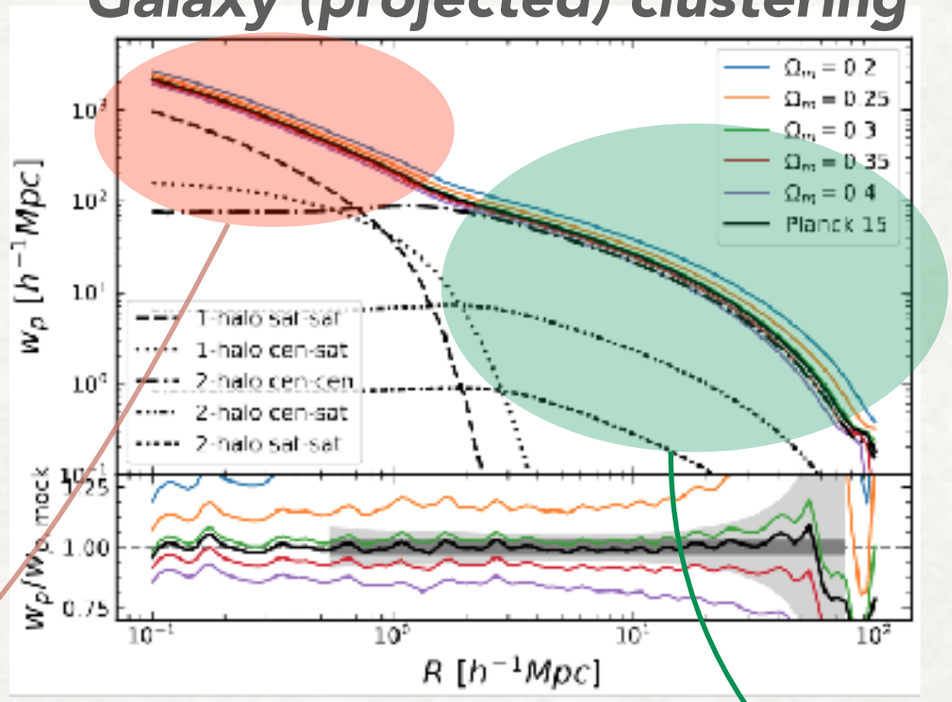
Put here (as) many (as you want) nuisance parameters to account for unknowns



Galaxy-galaxy lensing



Galaxy (projected) clustering



Typical halo mass

Environment

Distribution of galaxies around cluster center

(Theory) → Large-scale bias → Cosmology!

DARK EMULATOR: WHAT IT CAN DO

TN+'18

OVERVIEW

```
In [18]: import darkemu

In [19]: emu = darkemu.base_class()
```

```
initialize cosmo_class
Initialize xilin emulator
initialize xinl emulator
Initialize pklin emulator
initialize propagator emulator
Initialize sigma_d emulator
initialize cross-correlation emulator
initialize auto-correlation emulator
Initialize hmf emulator
Initialize sigmaM emulator
```

$$(\omega_{\rm b}, \omega_{\rm c}, \Omega_{\rm de}, \ln(10^{10}A_{\rm s}), n_{\rm s}, w)$$

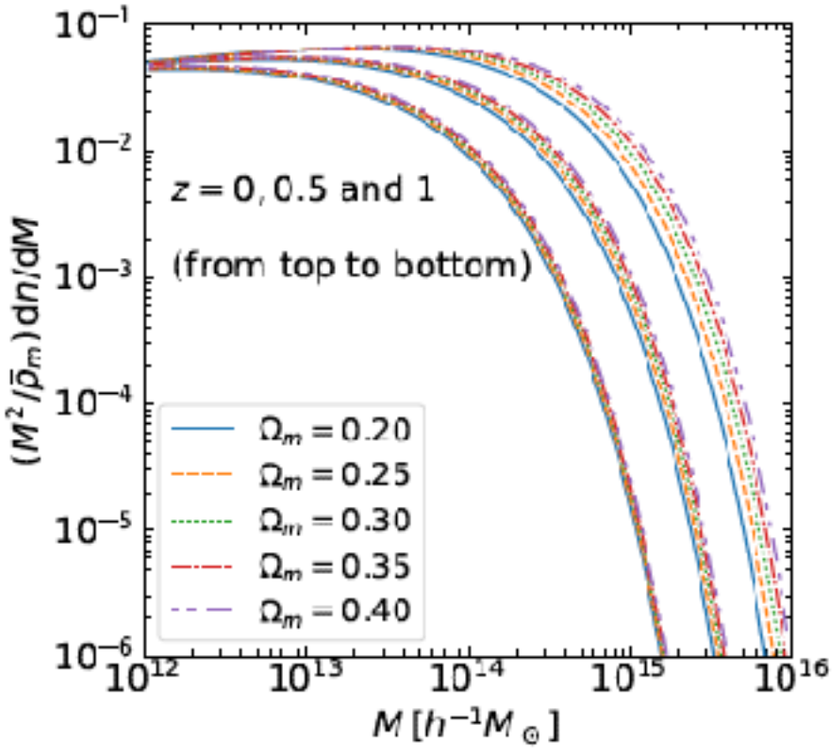
```
In [14]: cparam = np.array([0.02225,0.1198,0.6844,3.094,0.9645,-1.])
         emu.set_cosmology(cparam)
```

```
emu.get_nhalo(massbins[ii],massbins[ii+1],1.,z)
```

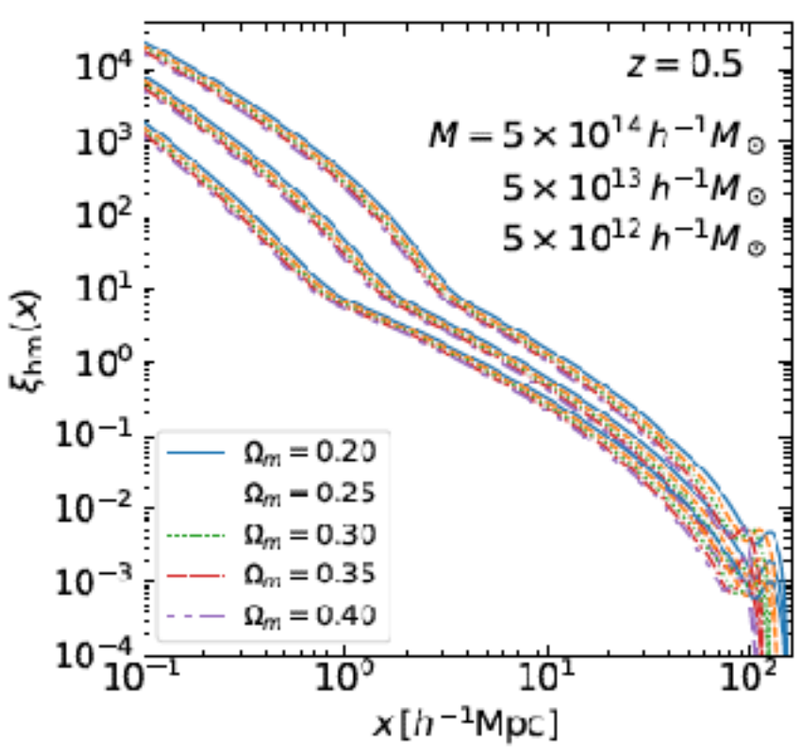
```
emu.get_xicross_mass(rs,Mh,z)
```

```
emu.get_xiauto_mass(rs,Mh,Mh,z)
```

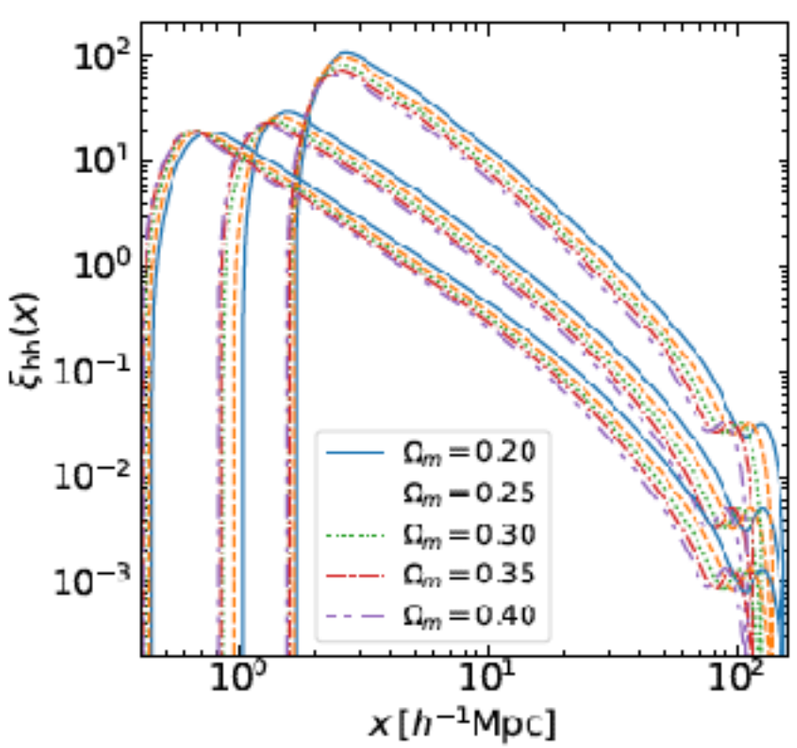
Halo mass function



Halo-Matter Cross CF



Halo-Halo Auto CF



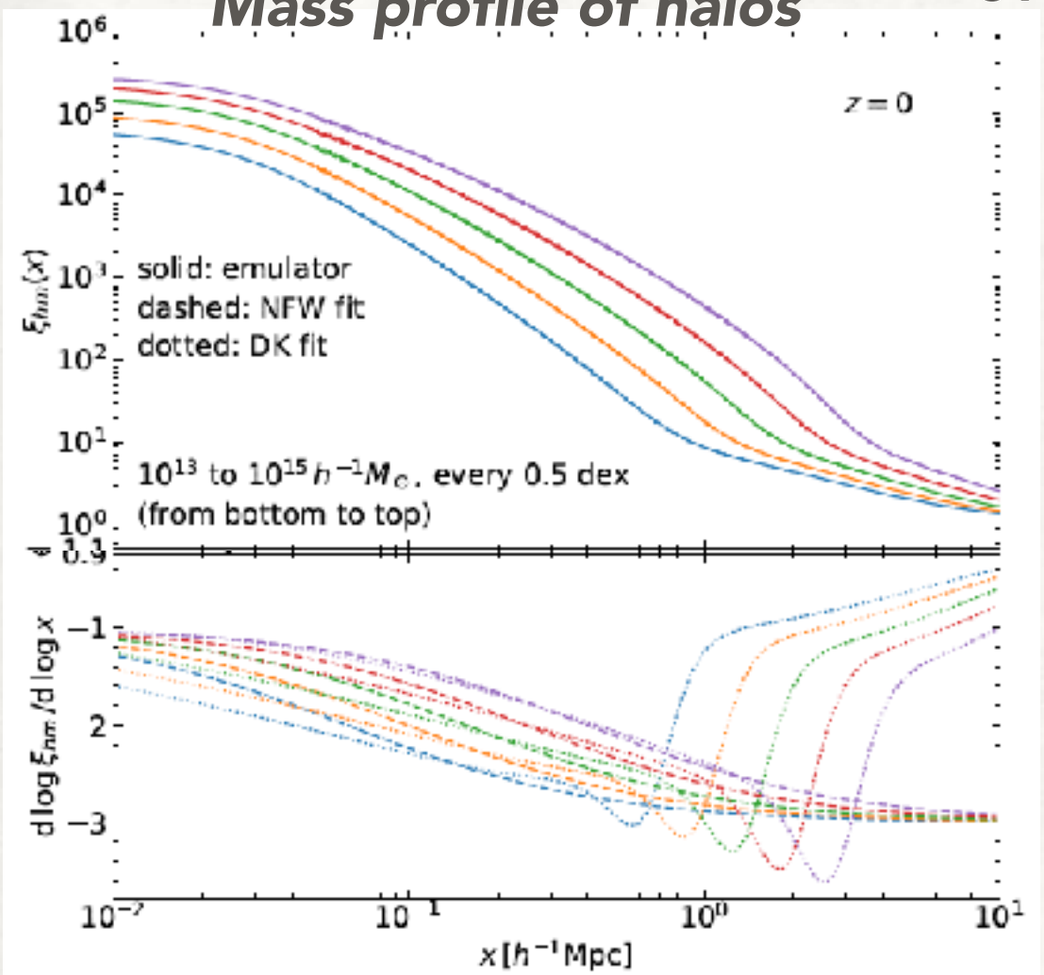
1 curve ~ 100 mili secs on a typical laptop computer

DARK EMULATOR: WHAT IT CAN DO

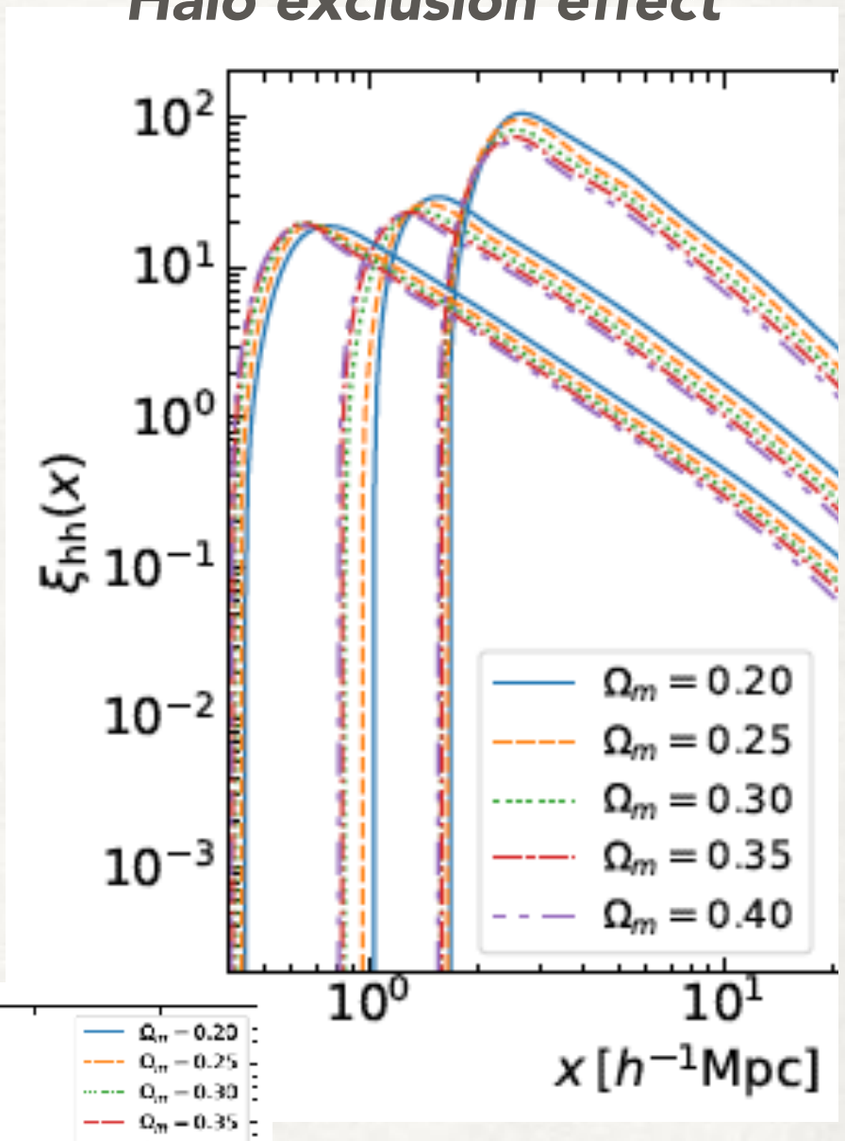
TN+'18

SMALL SCALES

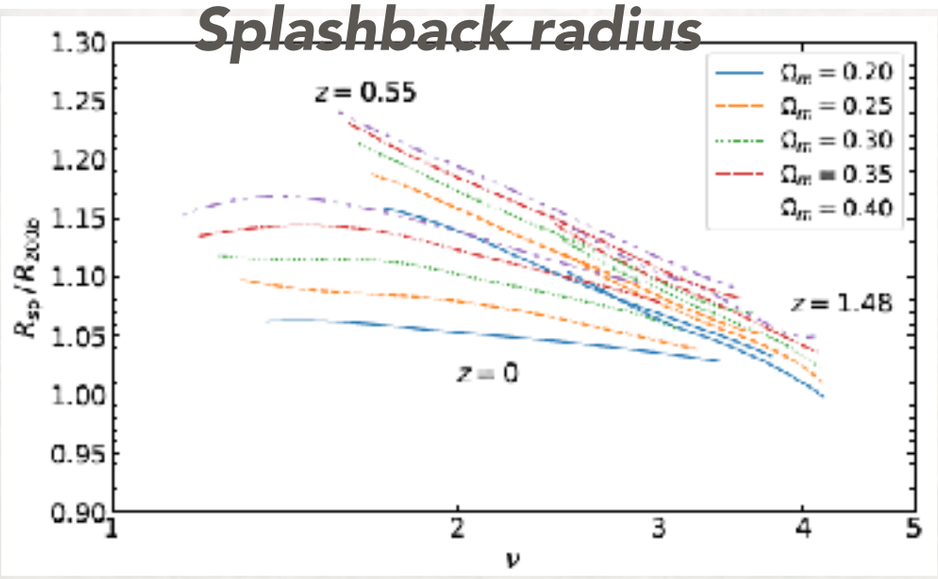
Mass profile of halos



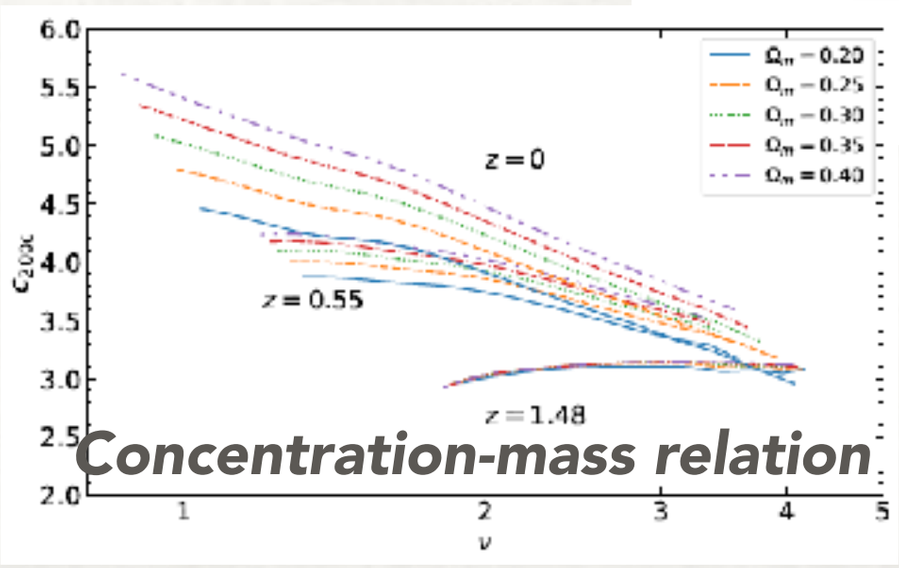
Halo exclusion effect



Splashback radius



Concentration-mass relation



COSMOLOGY CHALLENGE

EFFECTIVE FIELD THEORY APPROACHES

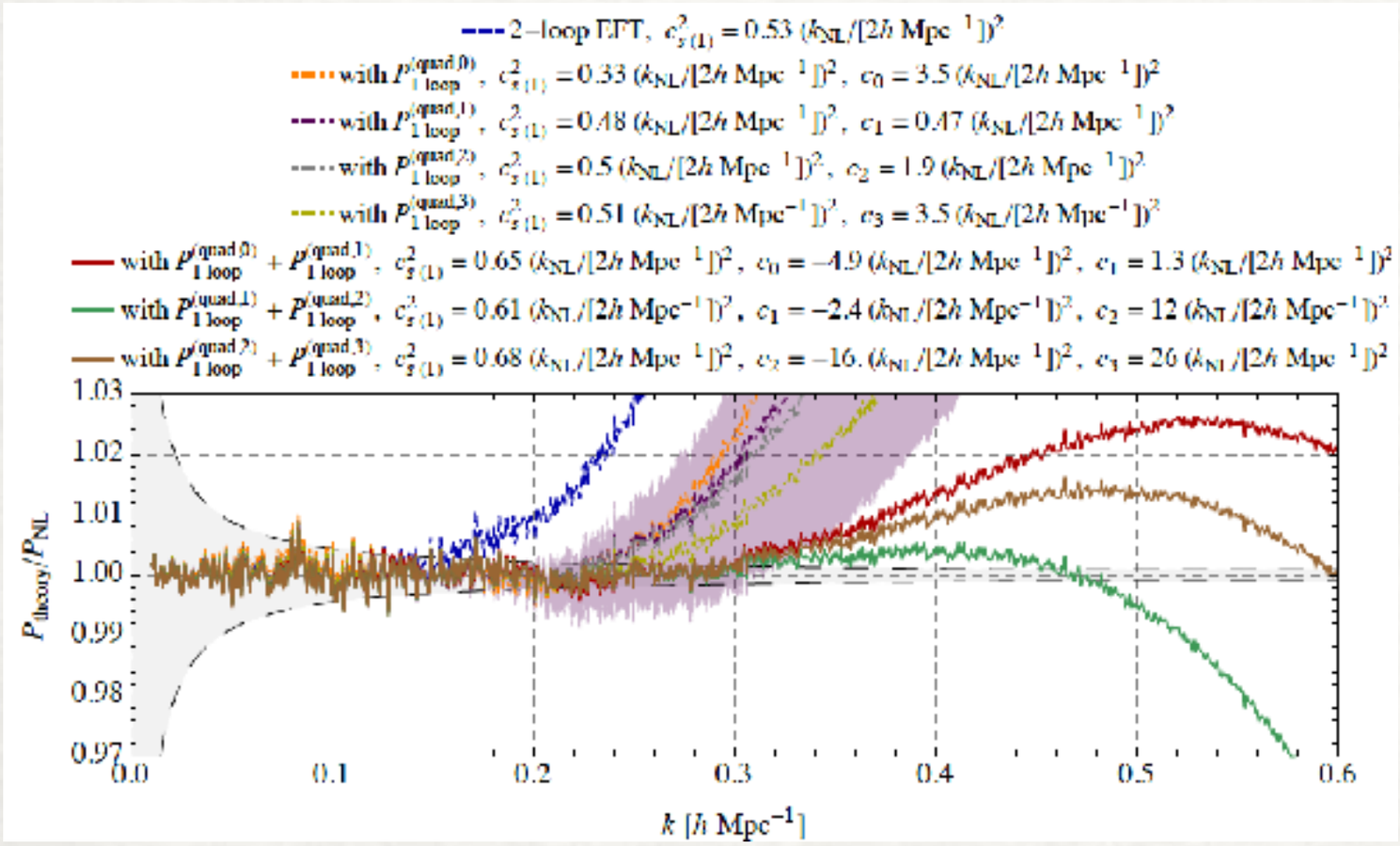
continuity + **Euler** + **Poisson** eqs.

Baumann+'12, Carrasco, Herzberg, Senatore'12 …

$$\frac{\partial \delta}{\partial t} + \frac{1}{a}\nabla \cdot [(1+\delta)\boldsymbol{v}] = 0,$$

$$\frac{\partial \boldsymbol{v}}{\partial t} + H\boldsymbol{v} + \frac{1}{a}(\boldsymbol{v}\cdot\nabla)\boldsymbol{v} = -\frac{1}{a}\nabla\phi - \frac{1}{\rho_{\rm m}}\frac{1}{a}\nabla\tau_{ij}$$

$$\nabla^2\phi = 4\pi\mathcal{G}\bar{\rho}a^2\delta.$$



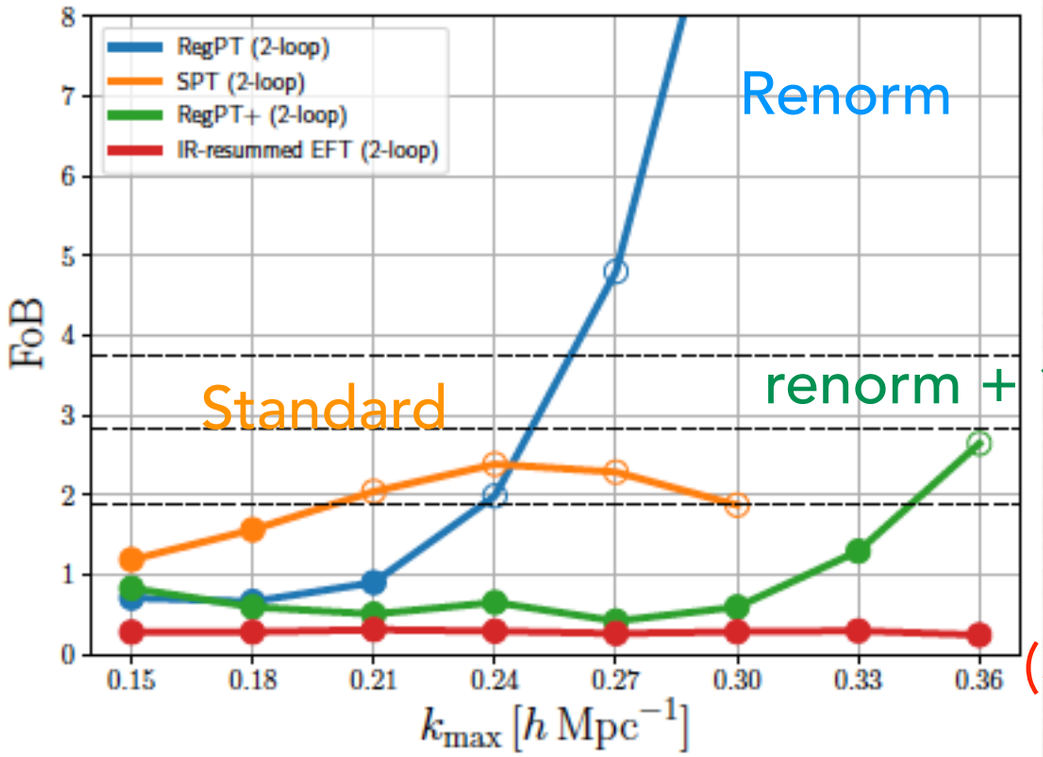
Foreman, Perrier, Senatore'16

- Neglecting the stress tensor would be a reasonable approximation for a CDM-dominated universe at least at early times
- EFT estimates the functional form for the corrections from viscosity and anisotropic stress in an empirical manner
- Introduce free parameters and determine them by simulations

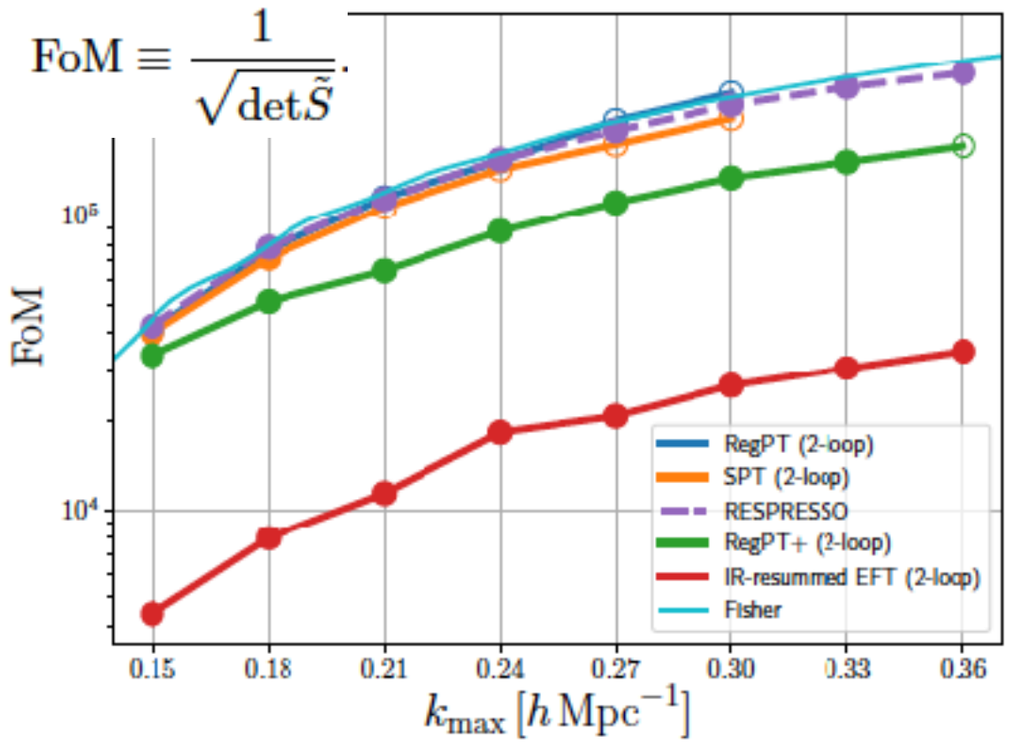
COSMOLOGY CHALLENGE

Osato, TN, Bernardeau, Taruya '18 (arXiv:1810.10104)

$$\mathrm{FoB} = \left[\sum_{\alpha,\beta} \delta\theta_\alpha \left(\bar{S}\right)^{-1}_{\alpha\beta} \delta\theta_\beta \right]^{1/2}$$



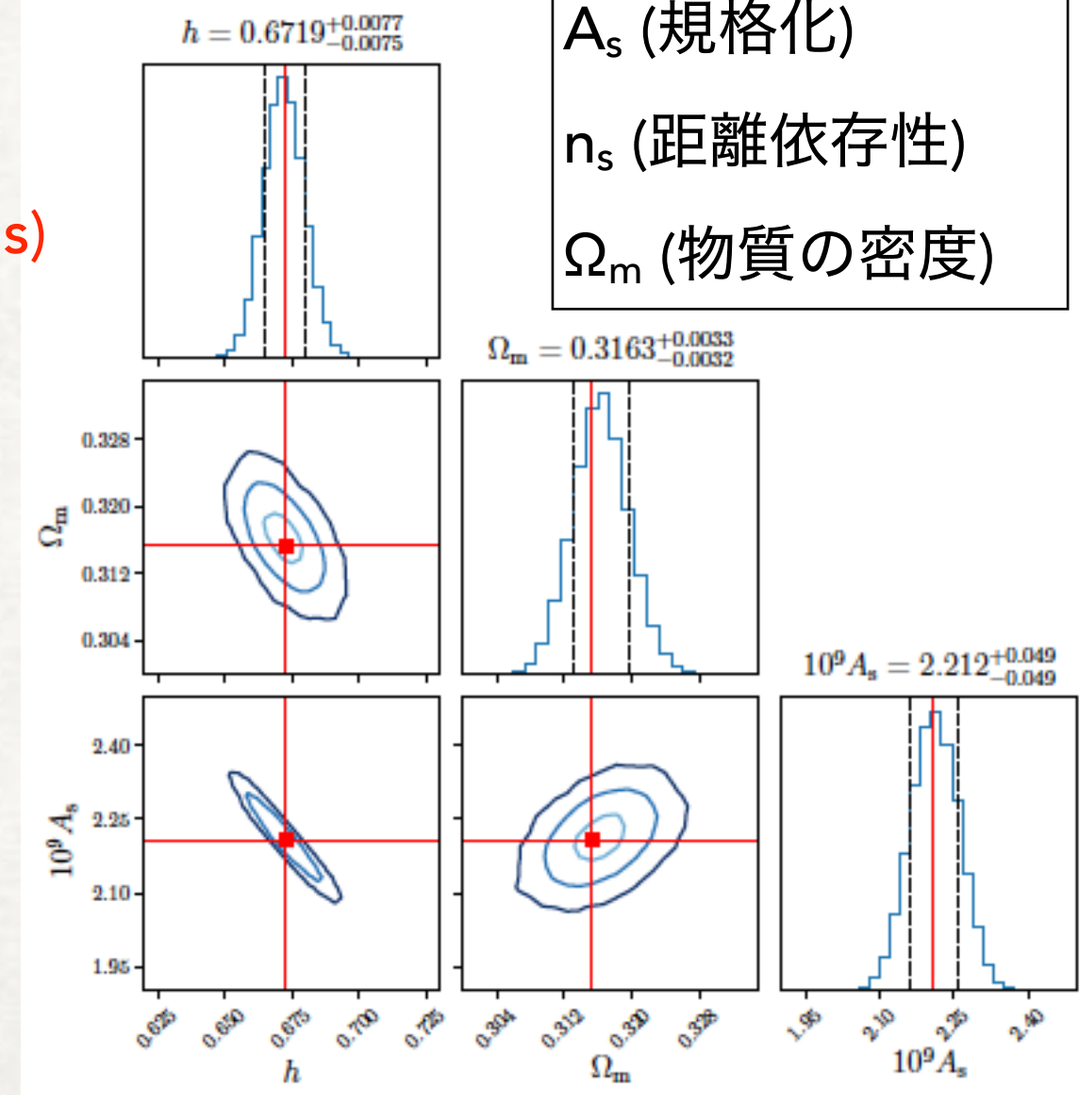
- N=2048^3, L=1024Mpc/h
- 10 realizations with suppressed variance
- Matter power in real space



A_s (規格化)

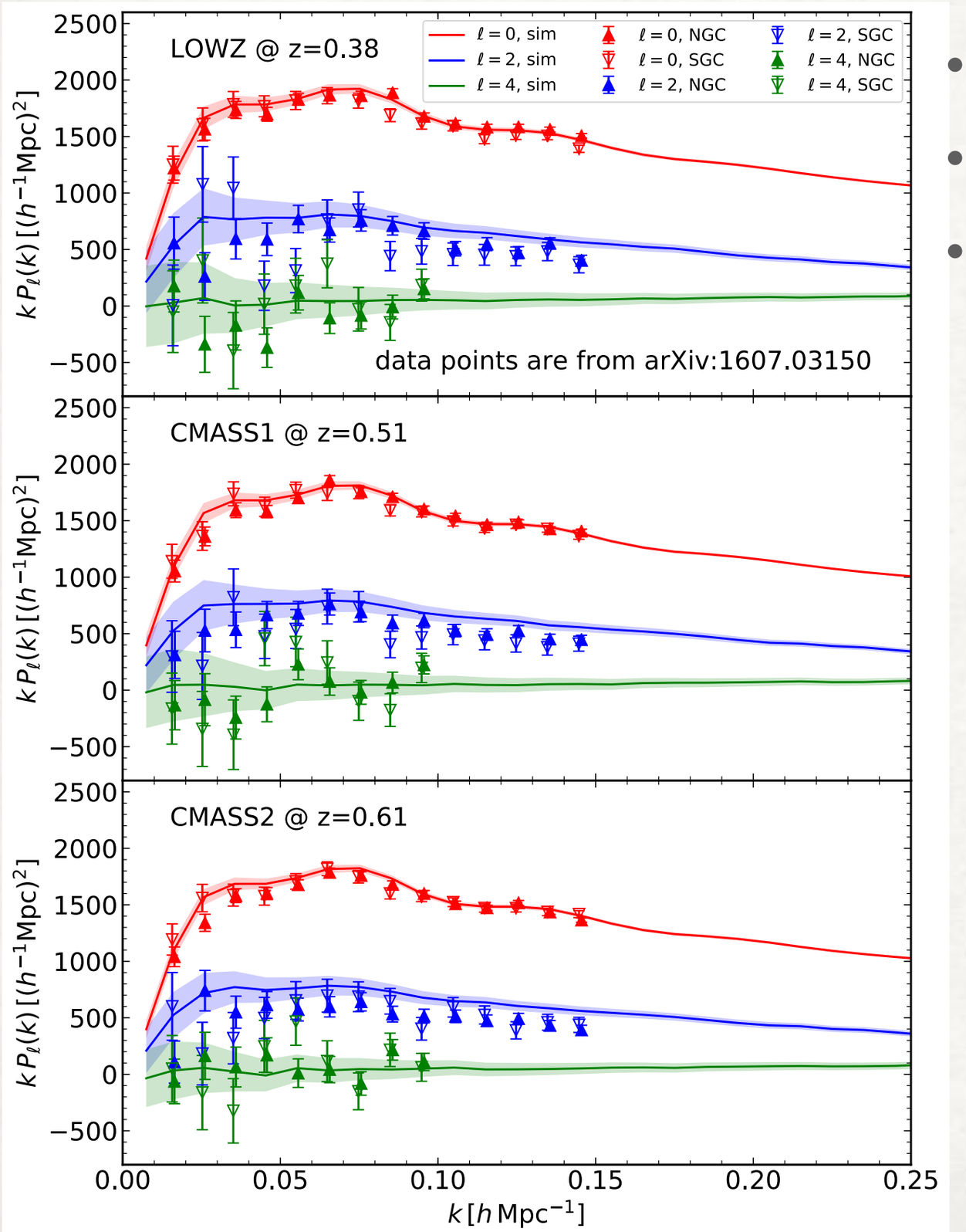
n_s (距離依存性)

Ω_m (物質の密度)



COSMOLOGY CHALLENGE (CONTINUED)

TN, Takada, Senatore, Zaldarriaga++ in prep



- **N=3072^3, L=3840Mpc/h**
- 24 realizations done
- Sub halos in redshift space
  - http://www-utap.phys.s.u-tokyo.ac.jp/~nishimichi/data/PTchallenge/

PRELIMINARY

COSMOLOGY CHALLENGE (CONTINUED)

- **Distribute galaxies and analyze the data as a mock catalog**
  - Standard HOD with different assumptions
    - Different satellite profiles
    - Off-centering of ``central" galaxies
    - Residual RSD in projected correlation function
    - Baryonic effects by modifying the mass profile around halos
  - Assembly bias by introducing a second parameter
  - —> (Almost) ready for HSC g-g lens + BOSS clustering analysis

MASSIVE NEUTRINOS

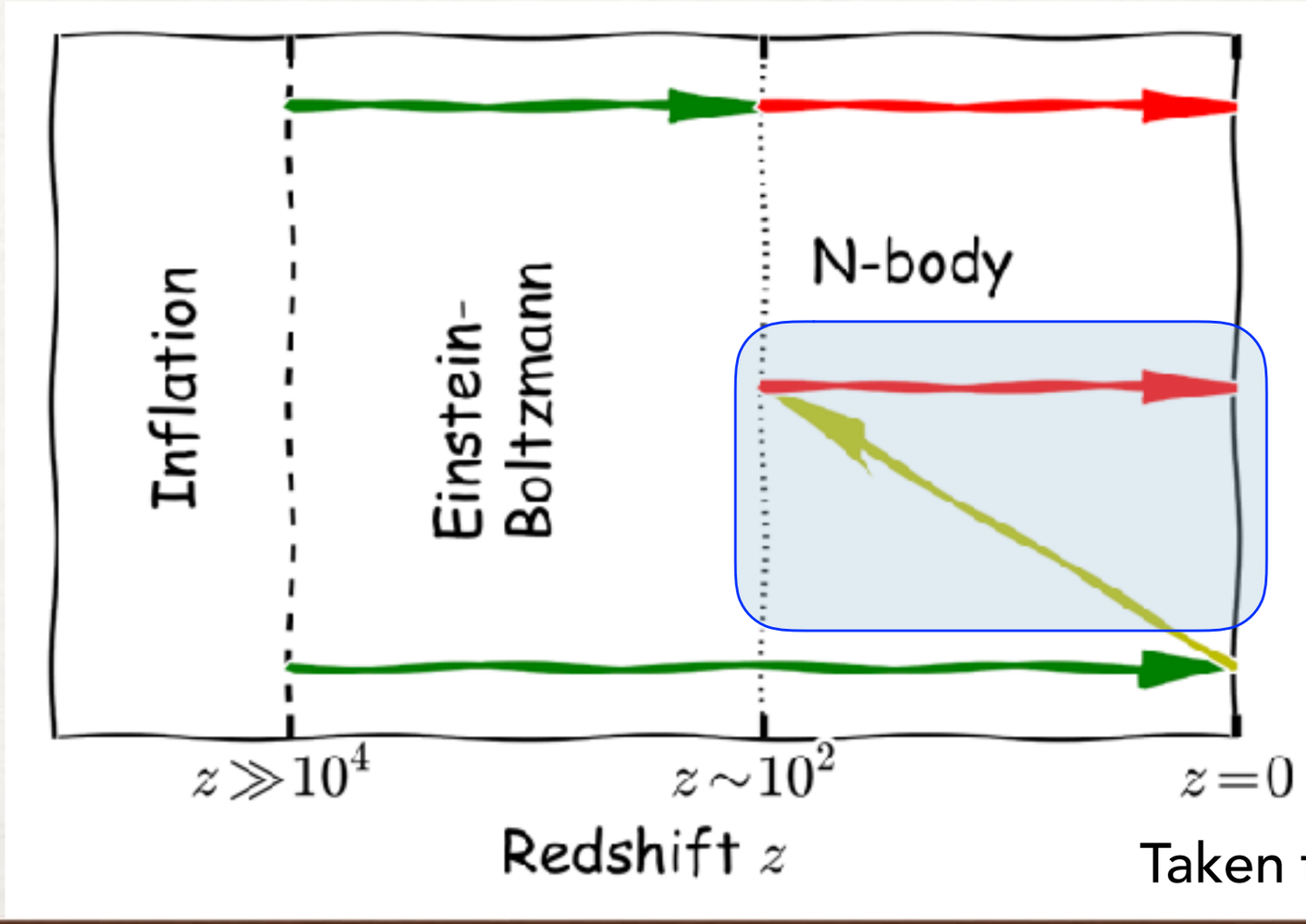
HOW TO TREAT NEUTRINOS

- Neutrinos cannot cluster on small scales due to free-streaming

  —> neutrino PT stays in linear regime (as long as they are light)

  —> short-range force (to other fluid) negligible

- Neutrinos were relativistic at early epoch
- Would like to add other relativistic sources for consistency



Ignore massive and massless neutrinos, photon and metric PT

Taken from Fildler+'17 (arXiv:1702.03221)

CODE DEVELOPMENT

- Neutrinos cannot cluster on small scales due to free-streaming

  —> neutrino PT stays in linear regime (as long as they are light)

  —> short-range force (to other fluid) negligible

- Add linear neutrino PT to PM force in Gadget2
- Added other sources for more consistency:

  Linearized newtonian growth equation for transfer function

Massive neutrino
Massless neutrino
Photon
Metric

$$\frac{\mathrm{d}^2 T_{cb}(k)}{\mathrm{d}(\ln a)^2} + \left[1 + \frac{\mathrm{d}\ln \mathcal{H}}{\mathrm{d}\ln a}\right] \frac{\mathrm{d}T_{cb}(k)}{\mathrm{d}\ln a} = \frac{3}{2}\left[\Omega_{cb}(a) T_{cb}(k) + S_{\mathrm{other}}(k)\right]$$

Expansion history

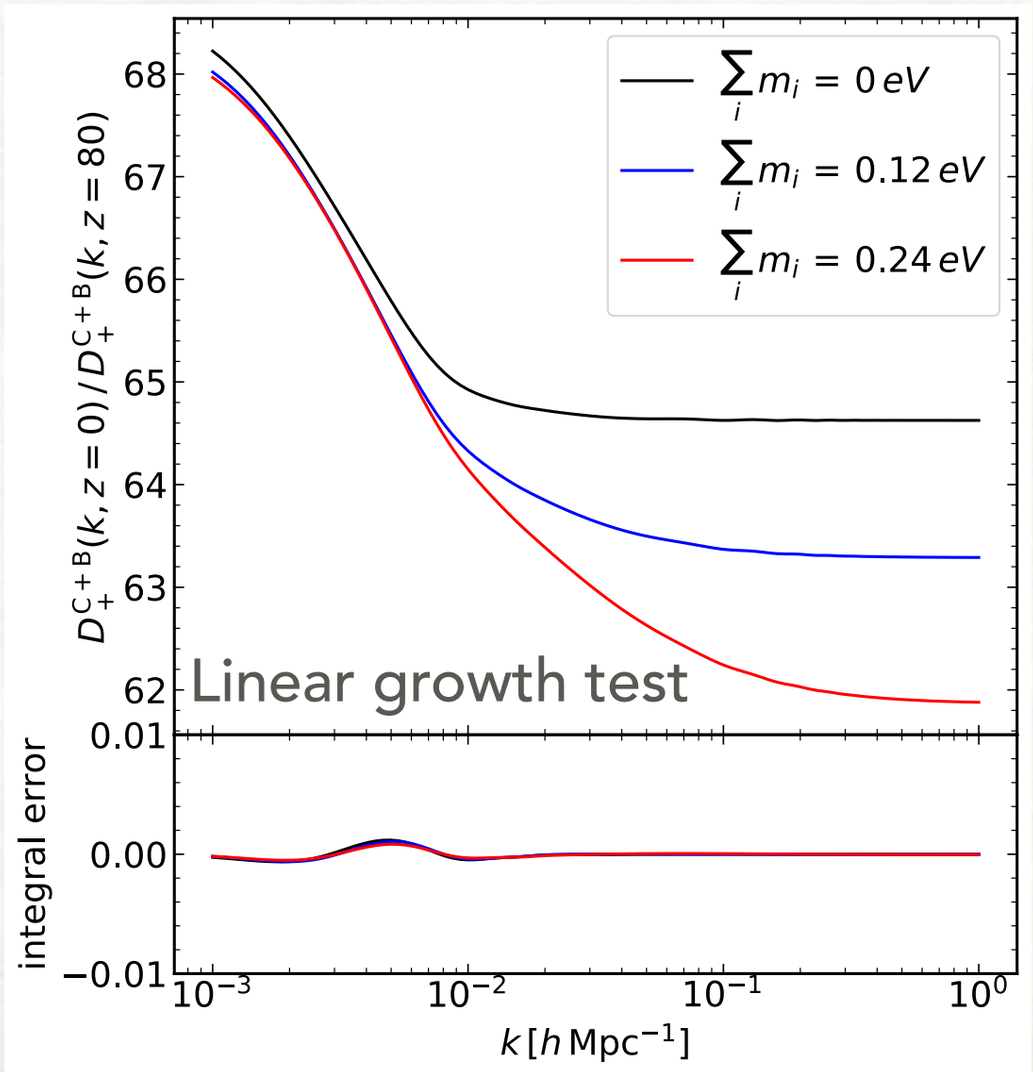
External sources

Transfer function for CDM+baryon fluid

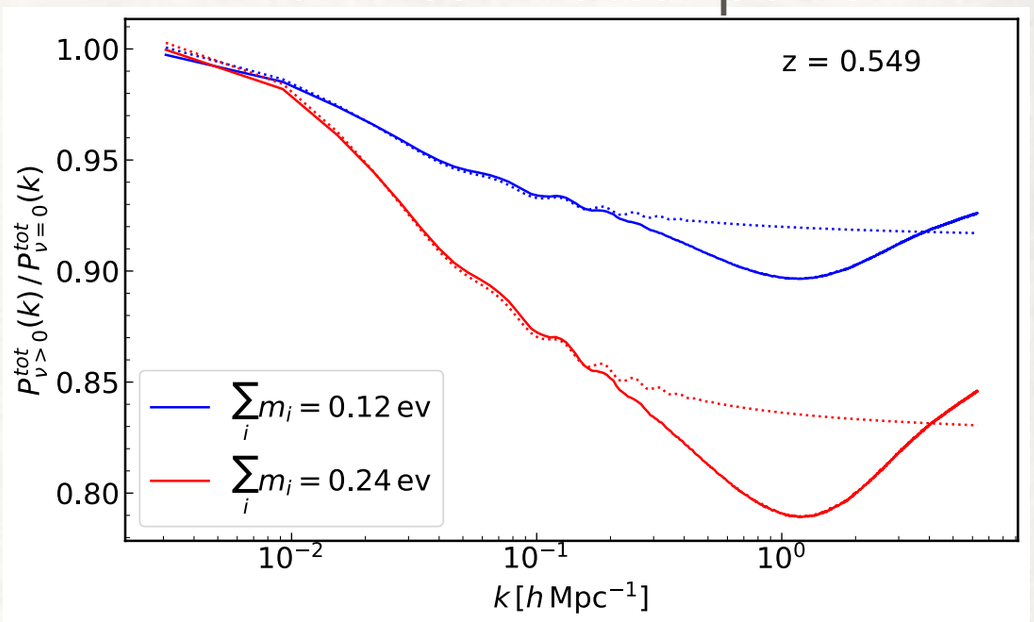
- Prepare tabulated transfer function $S_{other}(k,a)$ & $H(a)$ by CAMB
  - Gadget modified for arbitrary S and H.

EARLY RESULTS

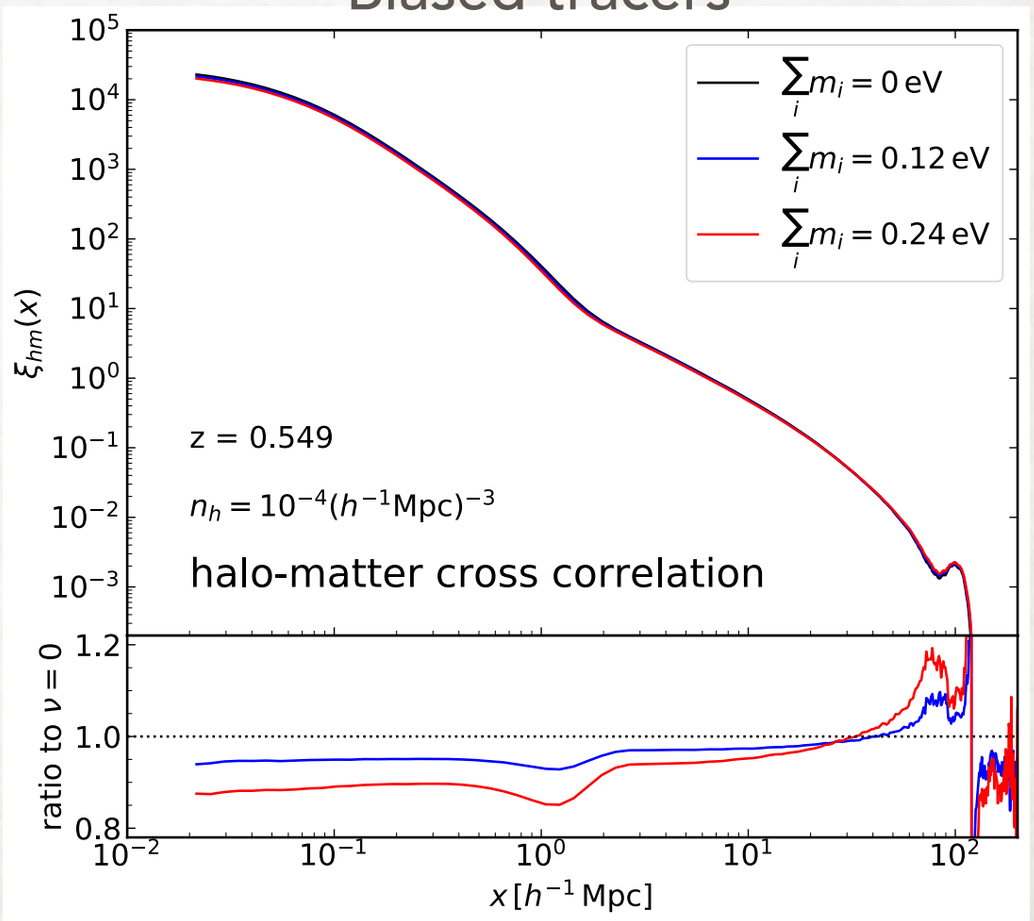
- Our product runs
  - CDM+baryon: 2048^3 particles
  - Neutrinos (+others): 4096^3 grid
  - To be joined into emulator!



Nonlinear matter power



Biased tracers



SUMMARY

- Emulator
  - Efficient sampling + dimension reduction + gaussian process
  - A few to several % accuracy achieved
  - Ready for practical application to HSC data
- Cosmology challenge
  - Assessing the ultimate accuracy on cosmological parameters with analytic and numerical approaches
  - New set of big mock catalogs available
- Massive neutrinos
  - Implemented in to the PM force with linear approximations
  - Other relativistic sources taken care at the same time
  - Analysis underway for biased tracers