むすんで、うみだす。
KYOTO SANGYO UNIVERSITY
Faculty of SCIENCE
Kyoto Sangyo University





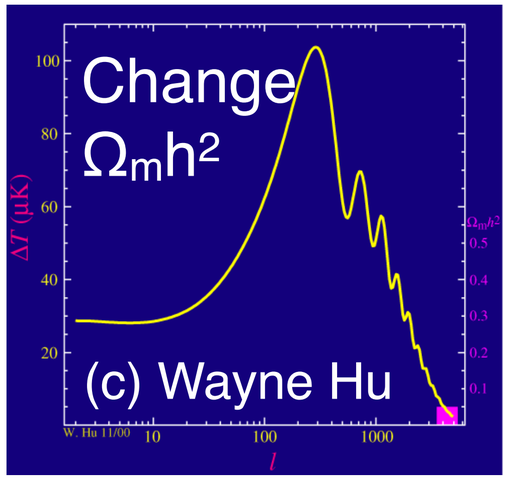
The Dark Quest Project for Large-Scale Structure Cosmology

Takahiro Nishimichi
(Kyoto Sangyo University)

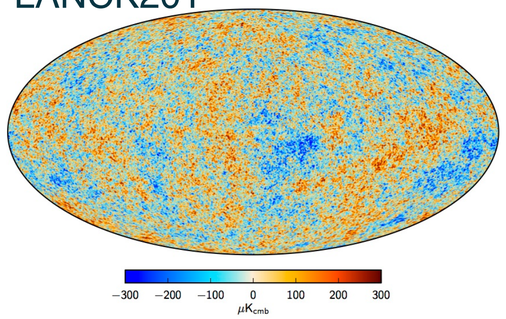
References:
TN+ ApJ 884 (2019) 29
TN+ PRD 102 (2020) 123541
Kobayashi+ PRD 102 (2020) 063504
Kobayashi+ PRD 105 (2022) 083517
Miyatake+ PRD 106 (2022) 083519
Miyatake+ PRD 106 (2022) 083520
Miyatake+ PRD 108 (2023) 123517
Cuesta-Lazaro+ MNRAS 523 (2023) 3219
TN, Tanaka, Yoshikawa (to appear soon)
Tanaka, TN, Kobayashi (to appear soon)

The 11th KIAS Workshop on Cosmology and Structure Formation; Oct. 28th 2024 @ Hilton Gyeongju

Objectives



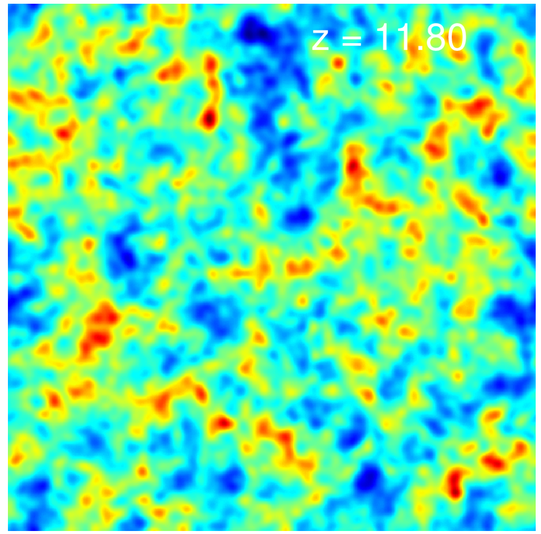
PLANCK201



Gravit

Ingredient





- ~Initial state
  - Photon temperature/ polarization
- Linear regime
  - Linear theory

Tests of cosmological models

"Vanilla" ΛCDM fine?
Tensions?

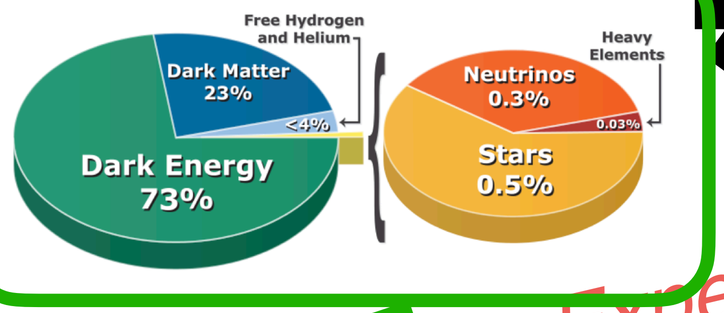
- Final state
  - Galaxy number density/projected total matter density
- Quasi-linear to nonlinear regime
  - Perturbation theory
- *N*-body simulations for smaller scales?
- Consistent framework for various observables?

Computational cost, curse of dimensionality

Takahiro Nishimichi (Kyoto Sangyo Univ.)

The forward model

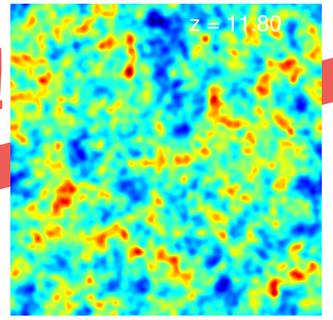
Cosmological Parameters (6 numbers)



(4,096^3 numbers)

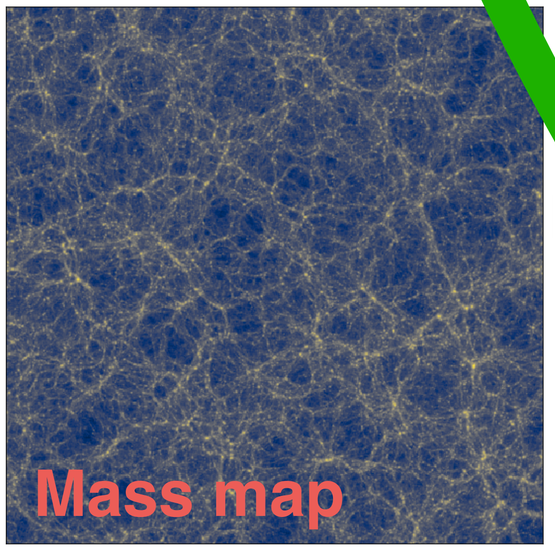
Initial condition generation

Expensive!

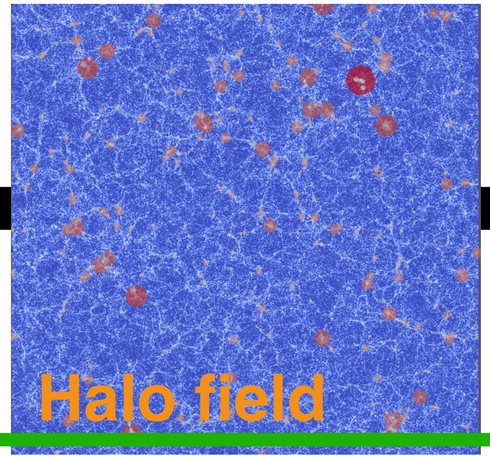


Emulate!

(3 x 2,048^3 numbers)

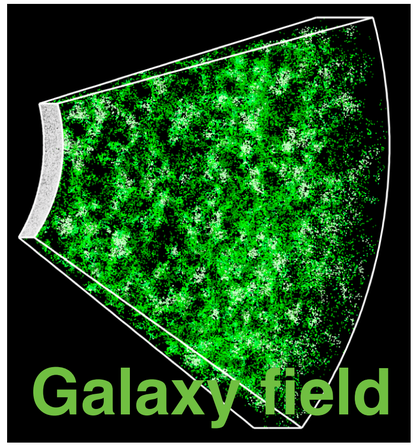


(~10^4 numbers)



Summary statistics

(~10^2 numbers)



Galaxy sample characteristic (~10 numbers)

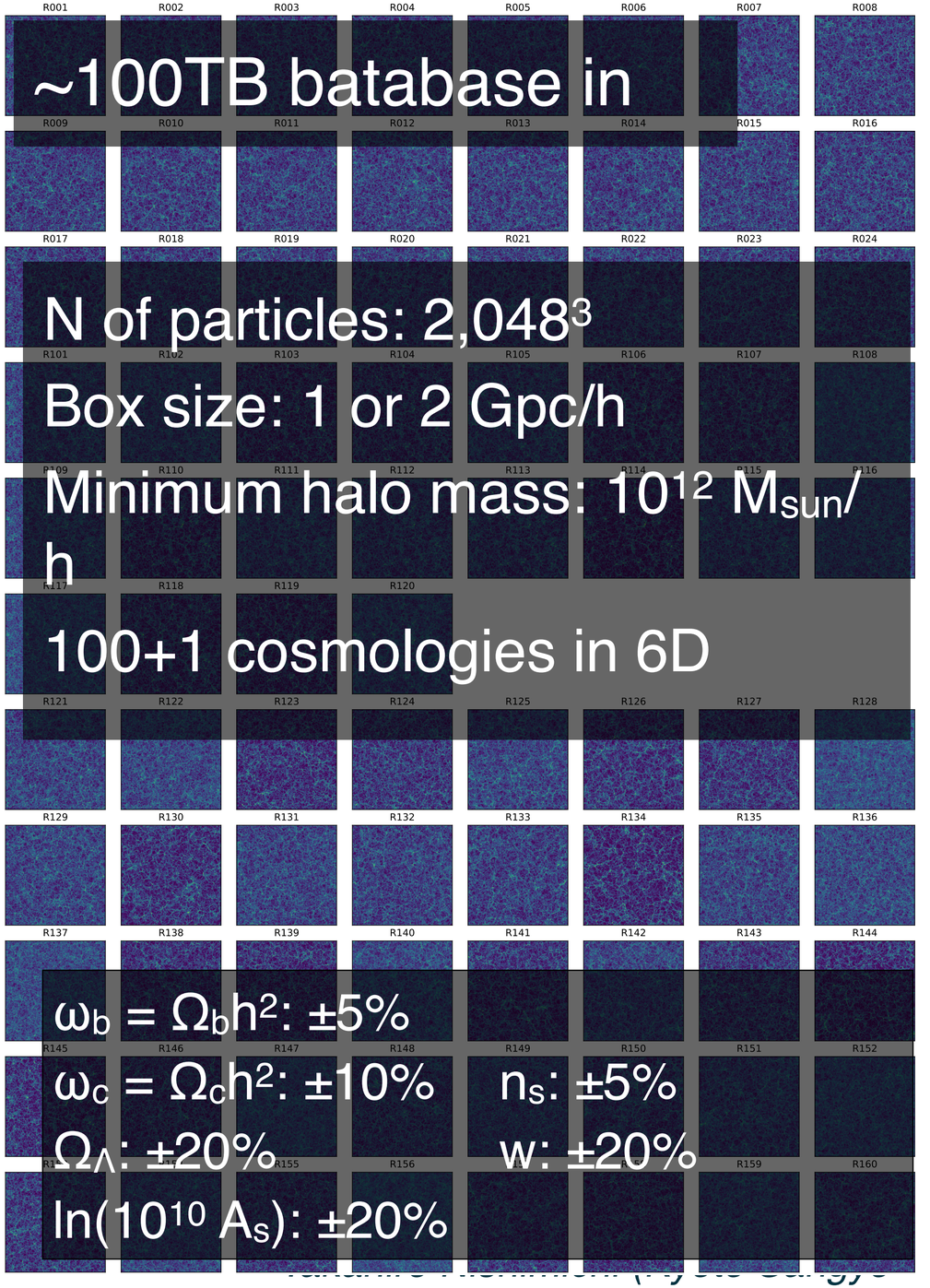
Dark Quest I. TN+, ApJ 884 (2019) 29

- 2048^3-body sims @ 101 wCDM cosmologies by Gadget2 (Springel`05)
- “DarkEmulator” 2021 3/19 public release
  - 2—4% accuracy for LRG-like galaxies
- Project Webpage

  https://darkquestcosmology.github.io/
- Maintained on GitHub
- Documentation: readthedocs

```
pip install dark_emulator
```

```
conda install -c nishimichi dark_emulator
```



Univ.)

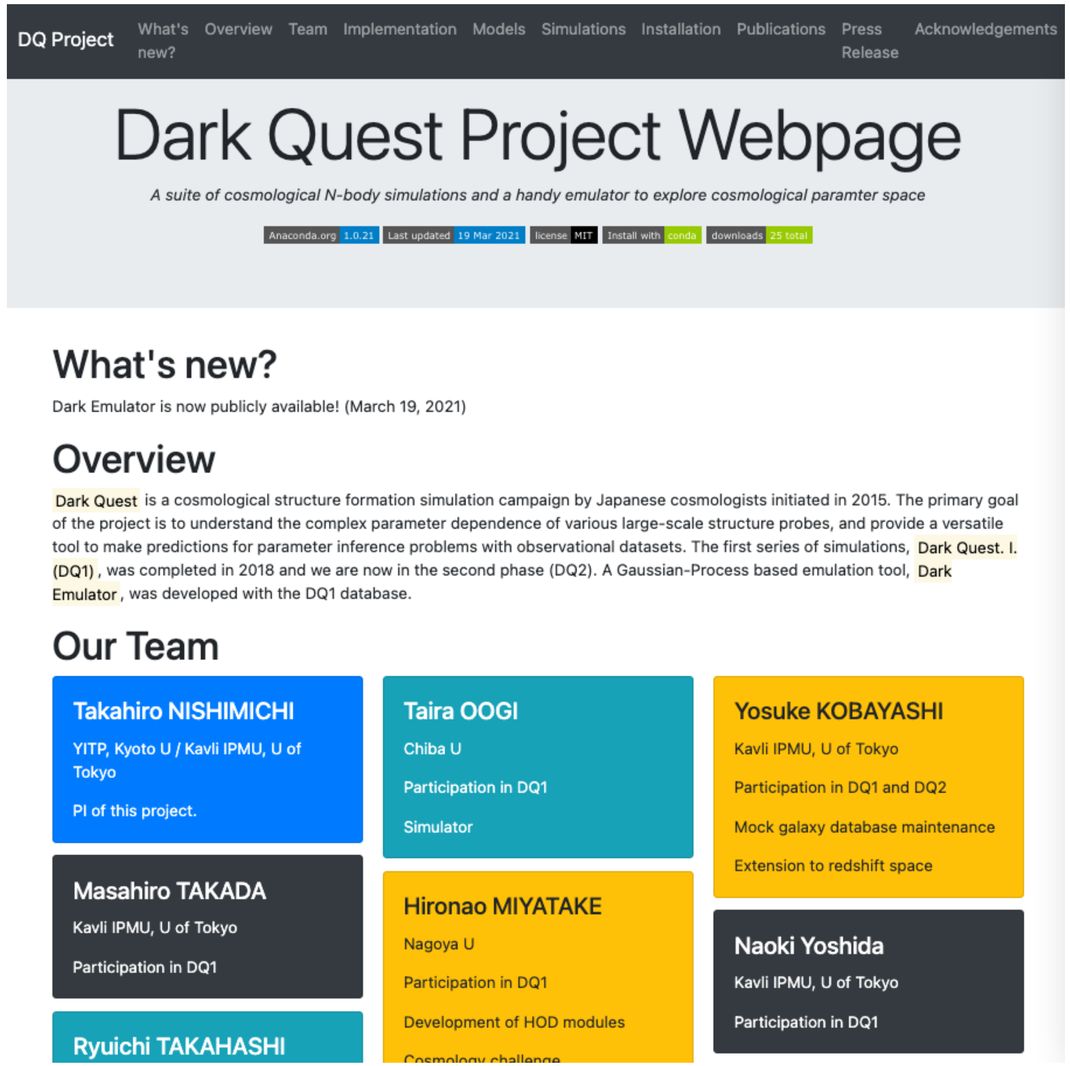
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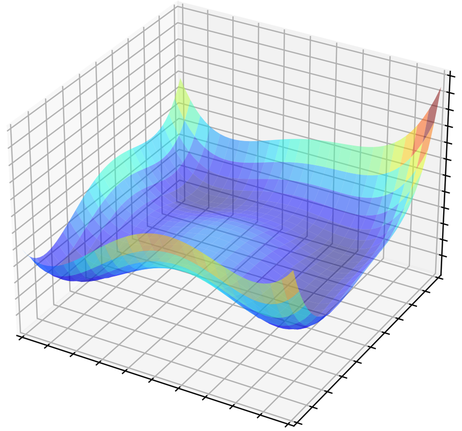
```
conda install -c nishimichi dark_emulator
```



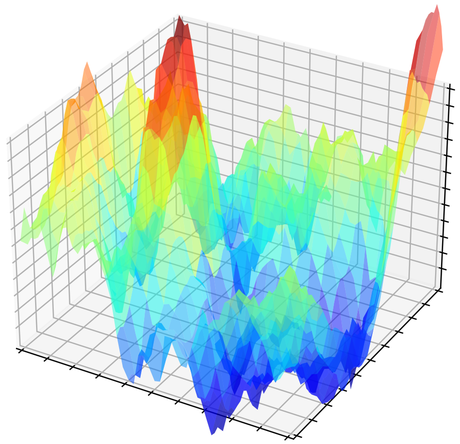
19,086 downloads (Oct 27

Takahiro Nishimichi (Kyoto Sangyo Univ.)

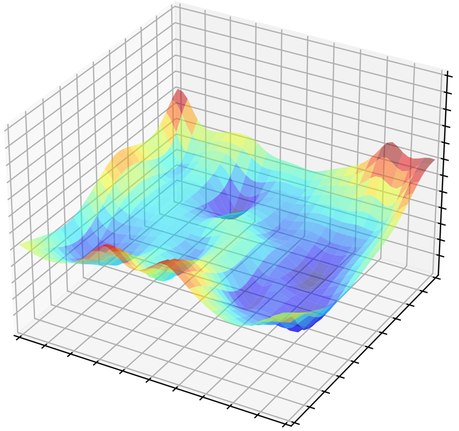
ground truth



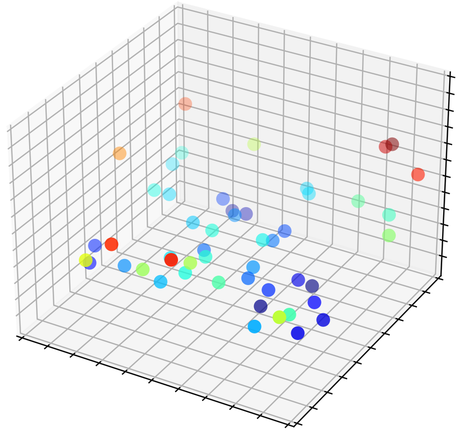
draw from prior



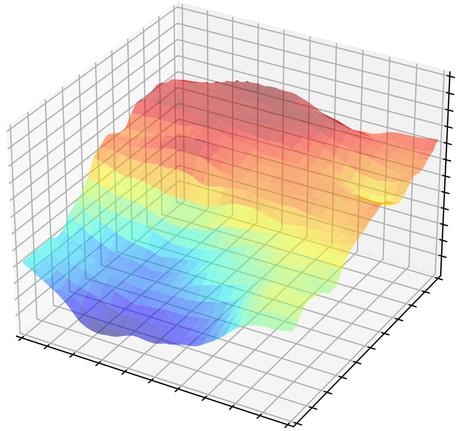
posterior mean



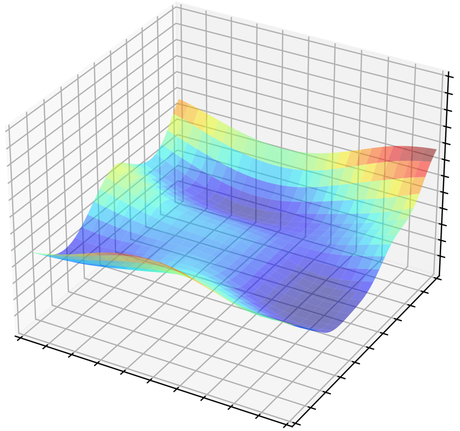
data



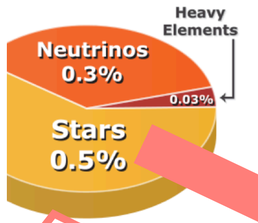
(w/ optimization)



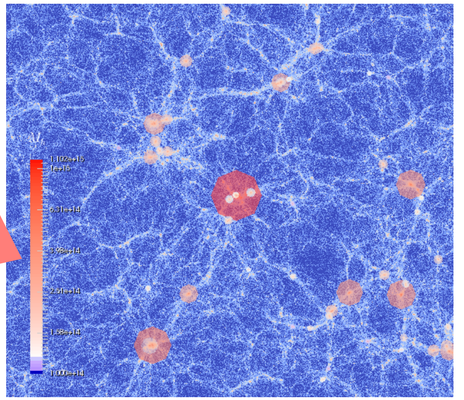
(w/ optimization)



Halo stats
(~10^4 numbers)



Emulate!



laptop

Hypercube design (Ba, Myers,

training & validation set)

reduction by weighted PCA

~10-D

endently

cess regression

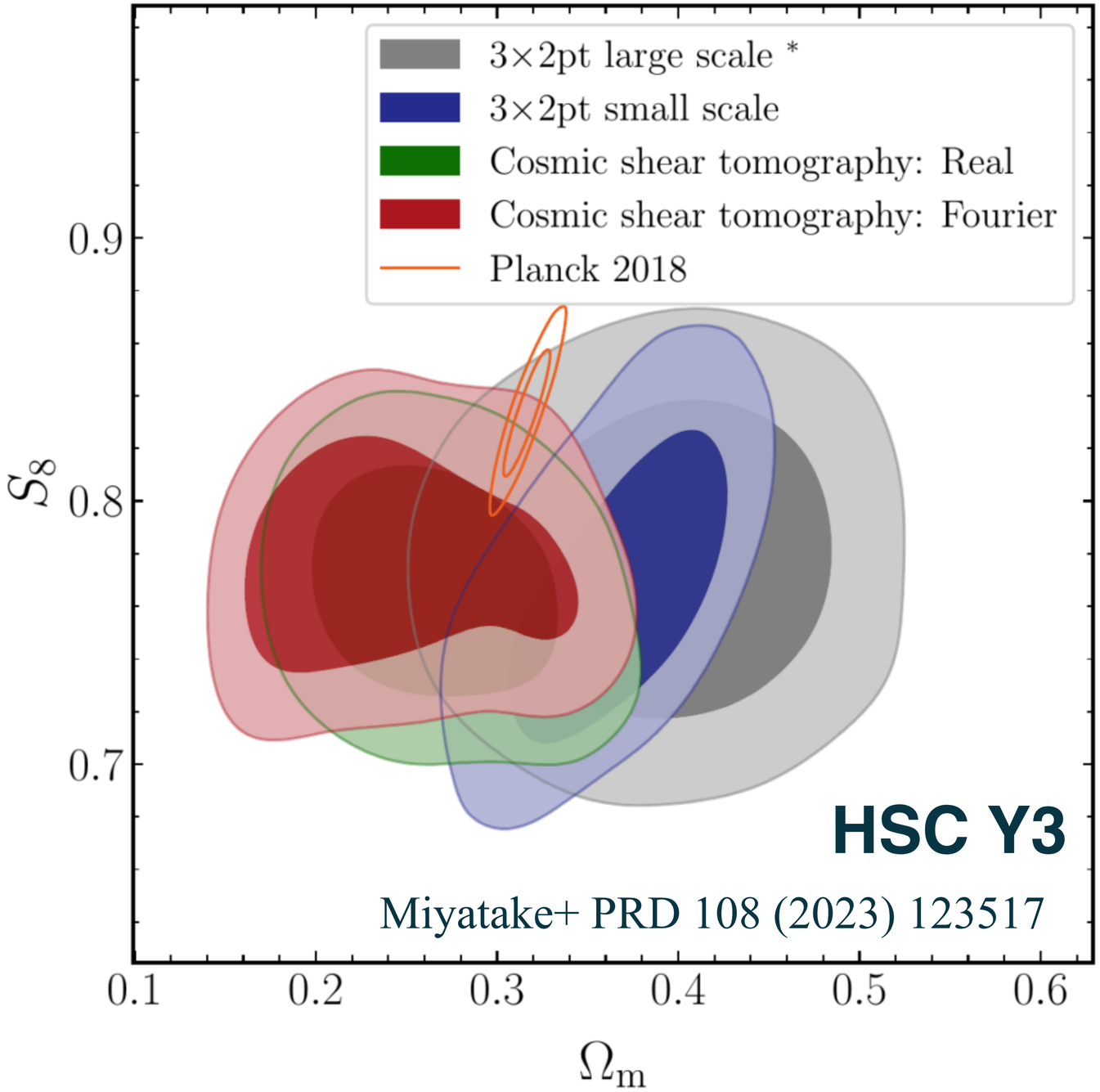
Nishimichi (Kyoto Sangyo Univ.)

$$P(t_{N+1}\,|\,\mathbf{t}_N) \propto \exp\left[-\frac{1}{2}\left[\mathbf{t}_N\ t_{N+1}\right]\mathbf{C}_{N+1}^{-1}\begin{bmatrix}\mathbf{t}_N\\ t_{N+1}\end{bmatrix}\right] \quad \begin{aligned}\hat{t}_{N+1} &= \mathbf{k}^T\mathbf{C}_N^{-1}\mathbf{t}_N\\ \sigma^2_{\hat{t}_{N+1}} &= \kappa - \mathbf{k}^T\mathbf{C}_N^{-1}\mathbf{k}.\end{aligned}$$

ɔaru HSC Y1

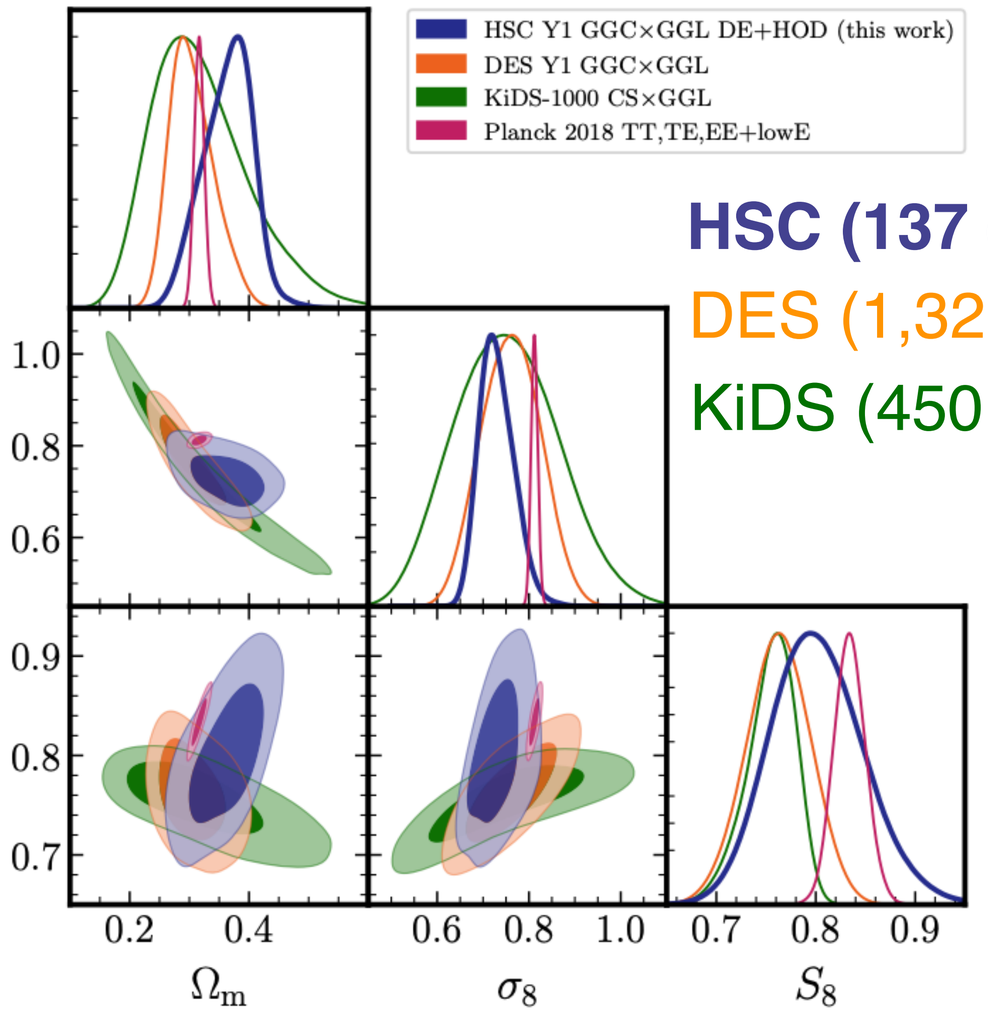
Miyatake+ PRD **106** (2022) 083520

Comparison with other WL surveys



HSC Y3

Miyatake+ PRD 108 (2023) 123517



HSC (137 deg²)

DES (1,321 deg²)

KiDS (450 deg²)

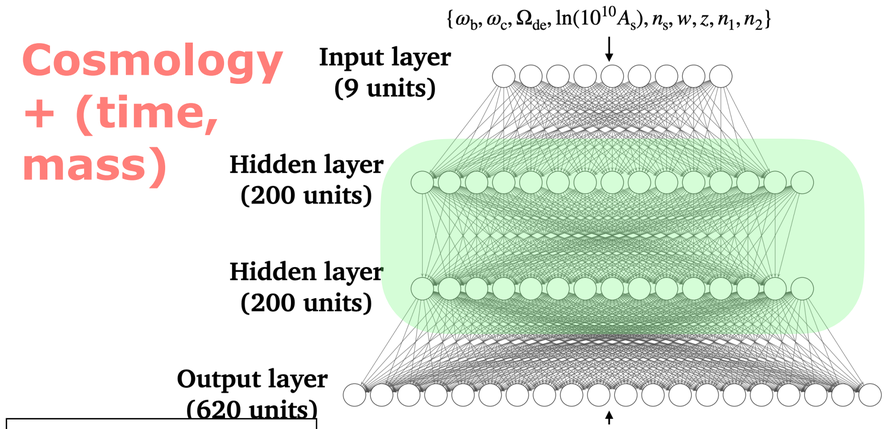
Takahiro Nishimichi (Kyoto Sangyo Univ.)

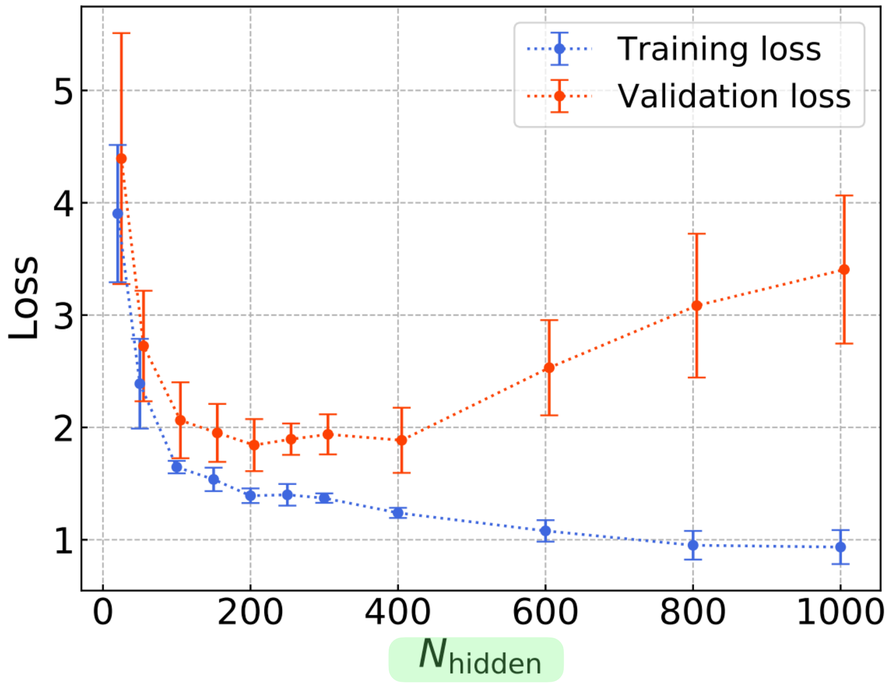
Redshift space

Kobayashi, TN+, PRD **102** (2020) 063504

Cuesta-Lazaro+ MNRAS 523 (2023) 3219

- GP works for multiple inputs, but not straightforward for *multiple output problems*
- The previous GP implementation was a bit ad hoc
  - Choice of weights in PCA
  - GP hyperparameter optimization not stable, required many trials with different initial guesses
- Neural networks can naturally handle these
- Shallow architectures (a few to several hidden layers) with many neurons are enough
- *Autograd* capability implemented w/ JAX
  - Efficient optimization and inference





gyo
niv.)

“Full shape” analysis w/ emulator

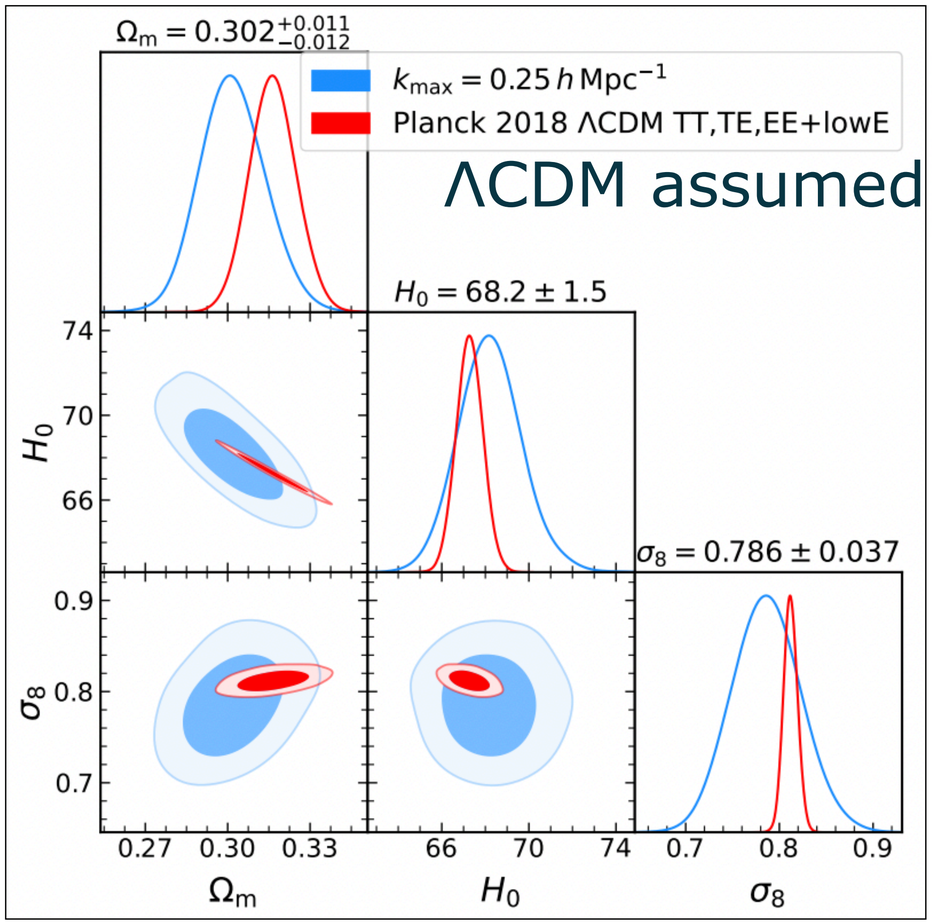
Kobayashi, TN+, PRD 105, 083517 (2022)

Full-shape cosmology analysis of SDSS-III BOSS galaxy power spectrum using emulator-based halo model: a 5% determination of σ_8

Yosuke Kobayashi[1,2],* Takahiro Nishimichi[3,2], Masahiro Takada[2],† and Hironao Miyatake[4,2]



Arizona —> Kyoto S. U.



Kobayashi+ (Emulator) :	$\sigma_8 = 0.786^{+0.036}_{-0.037}$	$\Omega_m = 0.301^{+0.012}_{-0.011}$	$H_0 = 68.2 \pm 1.4$
Princeton (Philcox+21):	$\sigma_8 = 0.737^{+0.040}_{-0.044}$	$\Omega_m = 0.312^{+0.011}_{-0.012}$	$H_0 = 68.5^{+1.1}_{-1.3}$
Berkeley (Chen+21):	$\sigma_8 = 0.738 \pm 0.048$	$\Omega_m = 0.305 \pm 0.01$	$H_0 = 68.5 \pm 1.1$

Exactly the same data vector & similar priors

※ BOSS DR12 multipoles updated by Buetler & McDonald

arXiv:2106.06324

See also
- D’Amico+ (1909.05271)
- Tröster+ (1909.11006)

for similar full shape analyses

- Roughly consistent with EFT-based analyses
- No tension with Planck!

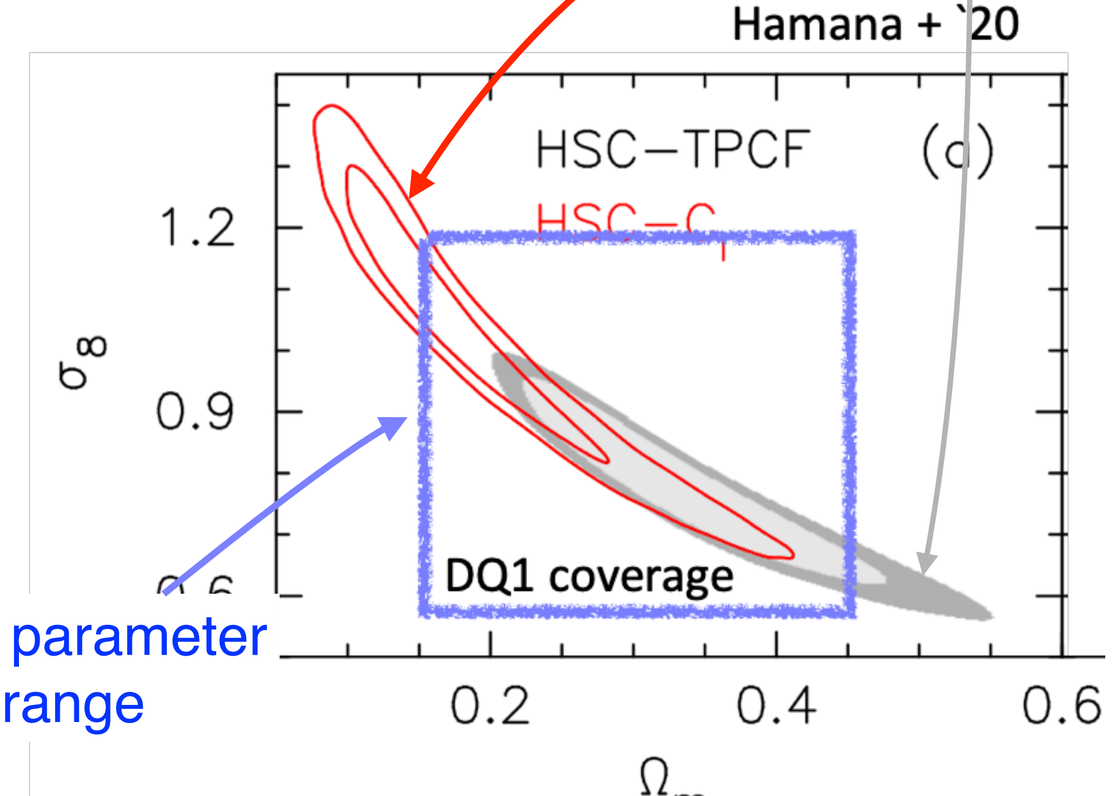
Takahiro Nishimichi (Kyoto Sangyo Univ.)

Dark Quest 2

New!!

Parameter	range	fiducial parameter
$\Omega_{\rm m}$	[0.05, 0.62]	0.3156
$\omega_{\rm c}$	[0.01, 0.3]	0.1198
M_ν	[0.0, 0.5]	0.06
$\Omega_{\rm K}$	[-0.1, 0.1]	0
$n_{\rm s}$	[0.916, 1.012]	0.9645
σ_8	[0.47, 1.23]	0.831
h	[0.5, 0.9]	0.674
w_0	[-1.5, -0.5]	-1
w_a	[-0.5, 0.5]	0
$\omega_{\rm b}$	[0.015, 0.03]	0.02225
$\Omega_{\rm de}$	[0.4125, 0.9385]	0.6843
$\ln(10^{10}A_{\rm s})$	[1.0412, 5.7548]	3.0911
S_8	[0.6, 0.95]	0.85233

Subaru HSC Y1 (cosmic shear) constraints



DQ1 parameter range

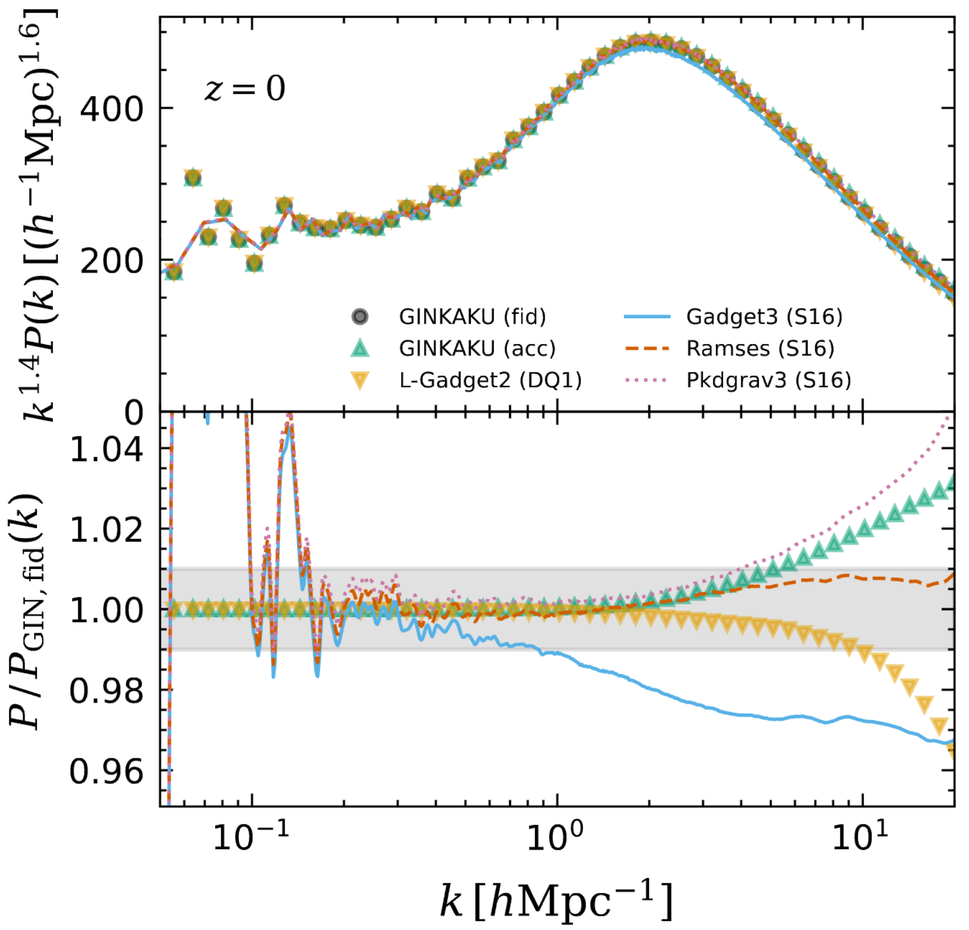
GINKAKU (Gravitational INtegrator for Kinematical Analysis of dark Universe)

TN, Tanaka & Yoshikawa in prep

銀閣



- New N-body code based on FDPS (framework for developing Particle Simulators; Iwasawa+`16, Namekata+`18)
  - Long range: Particle-Mesh, based on GreeM (Ishiyama+`09,`12)
  - Short range: Barnes-Hut Tree (Barnes & Hut`86), w/ cutoff for “S2” shaped particles
  - Accelerated by SIMD (Phantom-GRAPE; Tanikawa+`12,13)
  - Massive ν implementation based on Linear Response (Ali-Haimoud & Bird`13)
- Excellent scaling on modern supercomputers
- Extensive convergence study and comparison
  - Comparison with the “Code Comparison Project” by A. Schneider et al. 2016

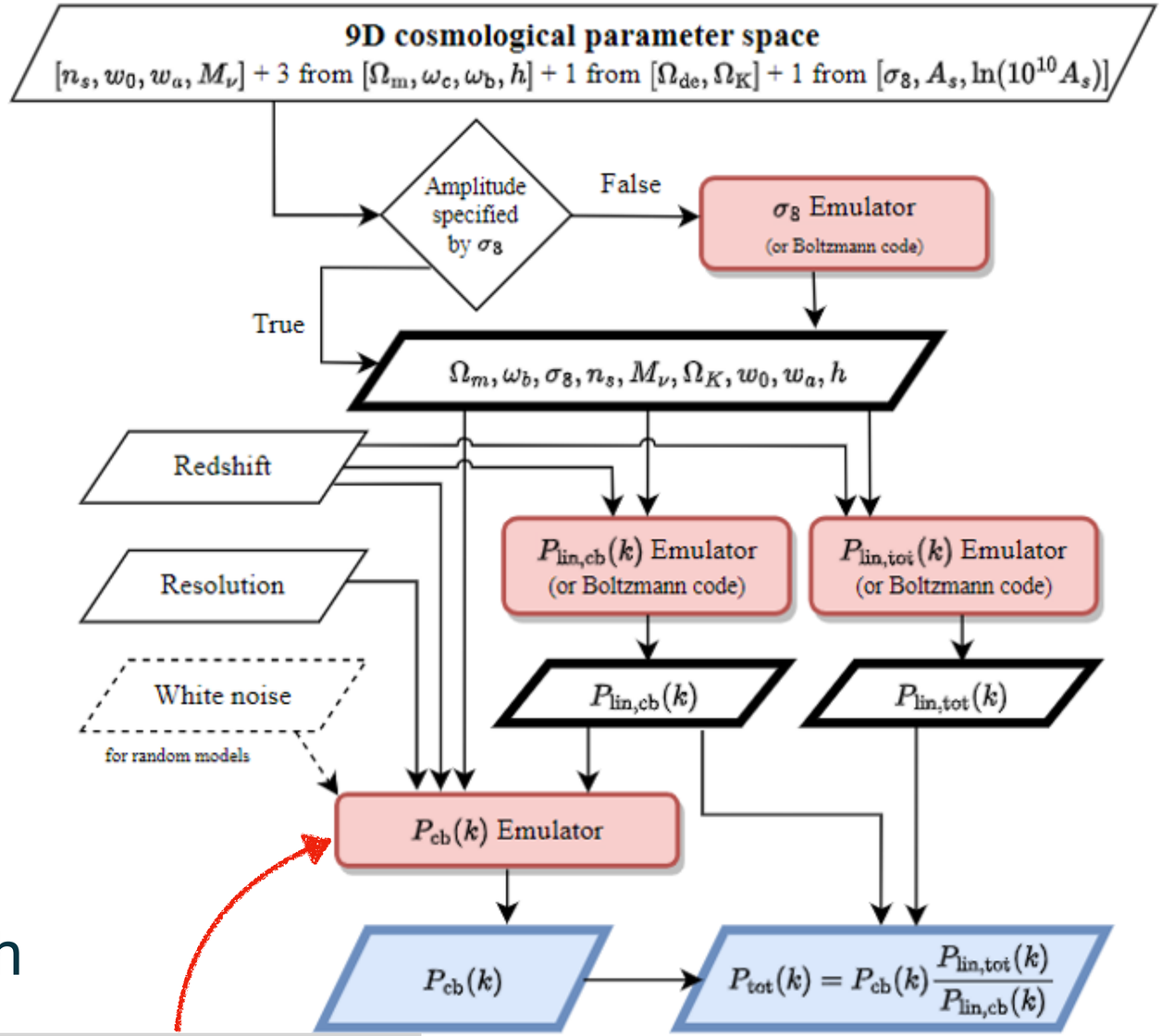


DarkEmulator2 pipeline

TN, Tanaka, Yoshikawa to appear soon

Tanaka, TN, Kobayashi to appear soon

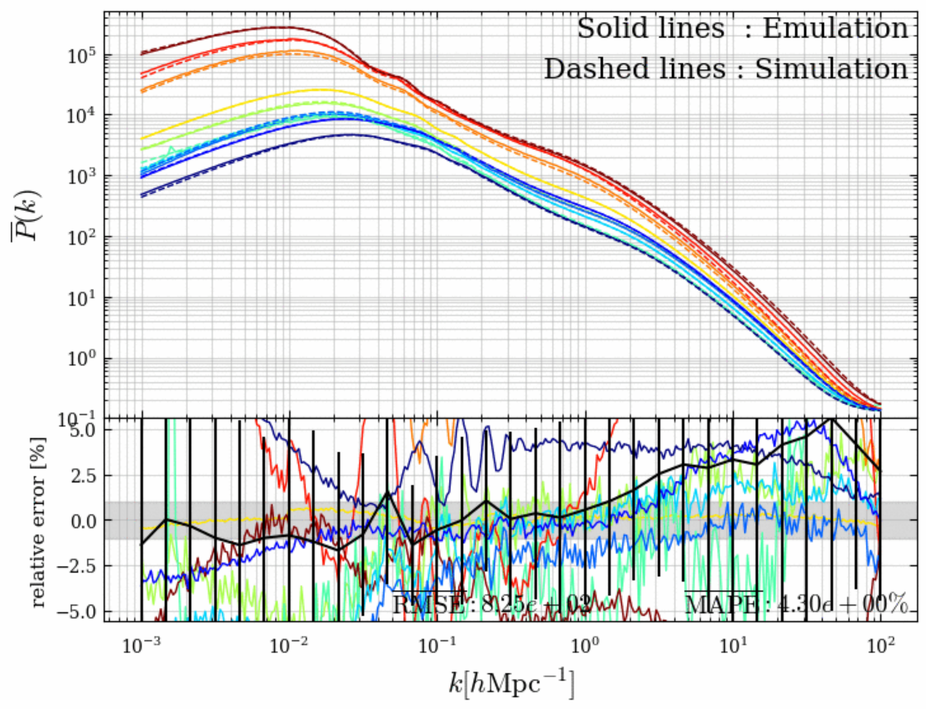
- Better generalization capability and update the resolution limit?
- Let's make a full use of the *flexibility* of NN architecture
  - Mixed-resolution simulation data
    - **Let the network learn the resolution dependence**
  - Linear P(k) as additional input
  - Automatic hyper-param tuning with CMA-ES (Covariance Matrix Adaptation Evolution Strategy)
- New simulation campaign is ongoing with a more efficient simulator "GINKAKU"

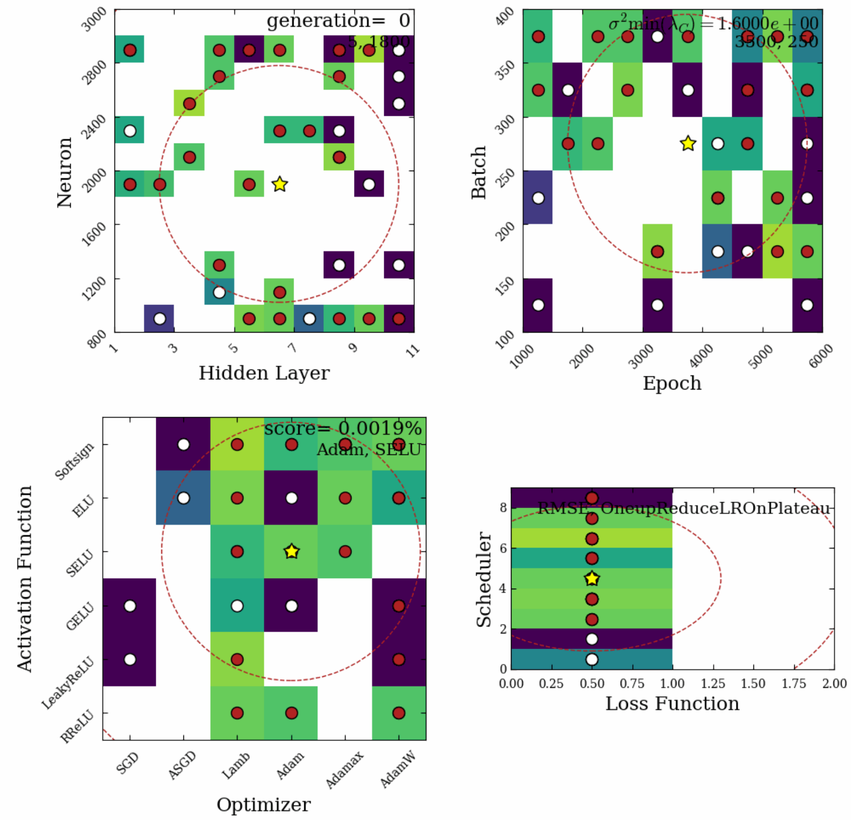


Main part here

Univ.)

ML architecture auto optimization w/ CMA-ES





Covariance Matrix Adaptation Evolution Strategy

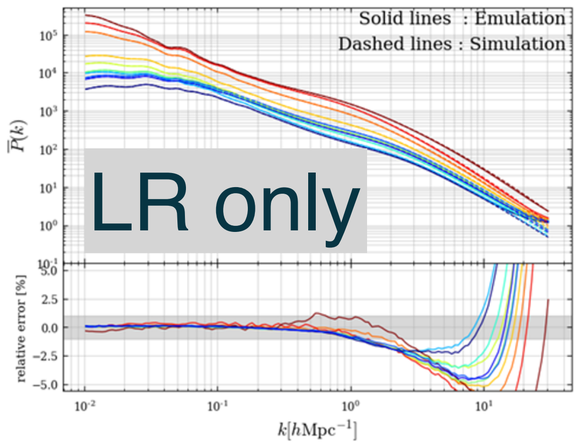
Hansen & Ostermeier `96

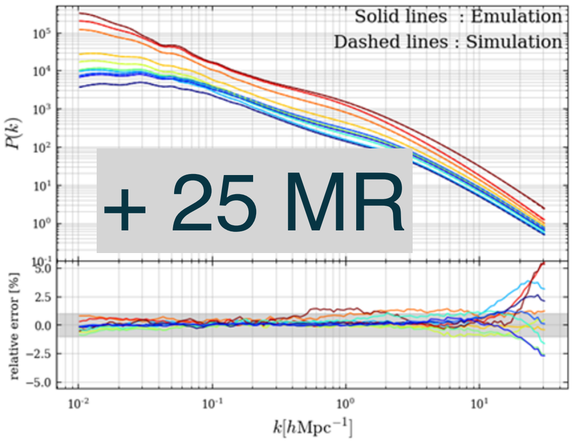
- Wide & slightly deeper network optimal after ~20 generations of evolution
  - ~5 hidden layers with ~1000 neurons each
  - Activation function: GeLU (Gaussian Error Linear Unit)
  - Optimizer: Adam

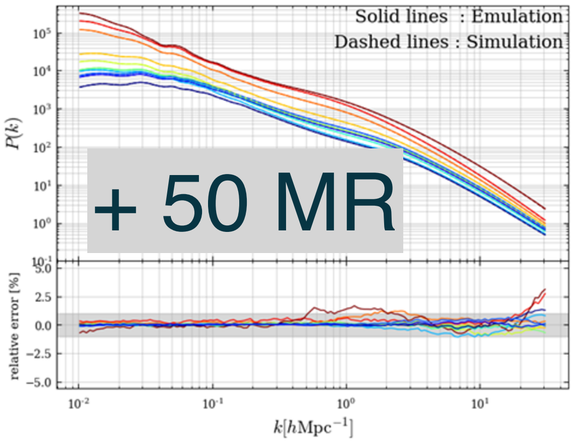
Preliminary

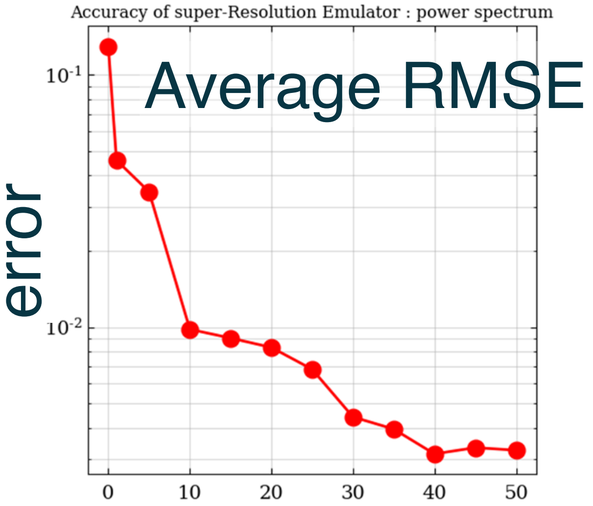
Takahiro Nishimichi (Kyoto Sangyo Univ.)

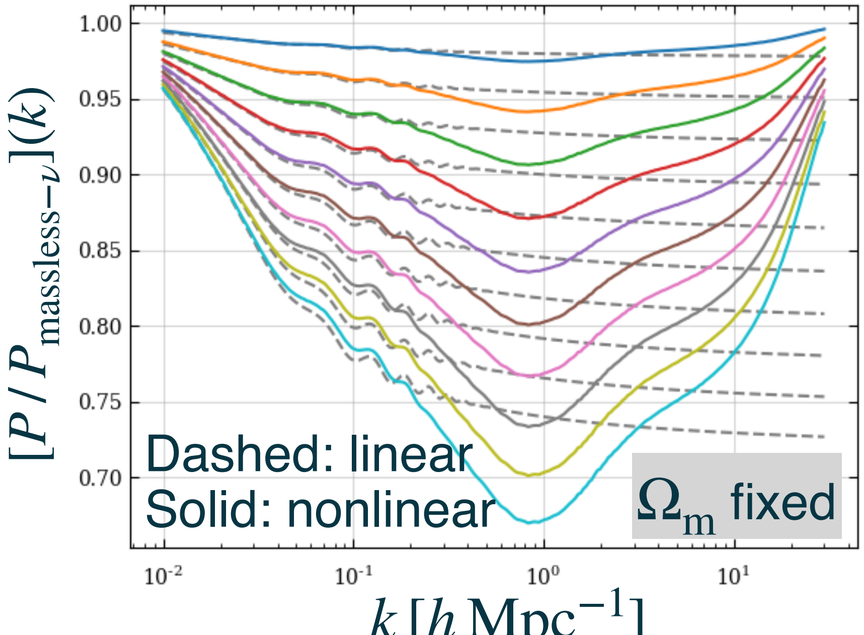
Early results: Matter power spectrum











Preliminary

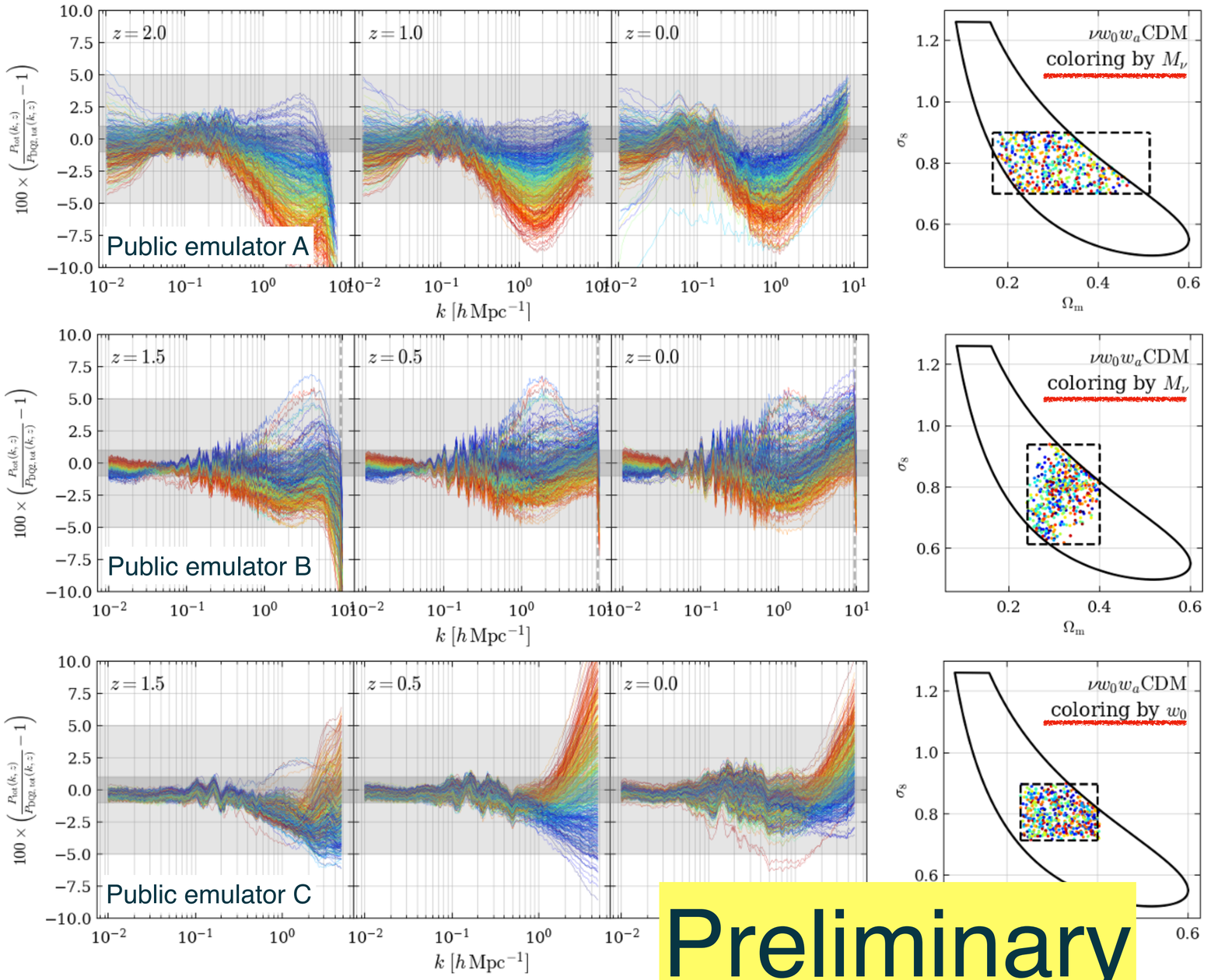
- LR+MR vs MR testsets
  - LR: 1000 cosmologies
- A small number of high resolution simulations very helpful

Takahiro Nishimichi (Kyoto Sangyo Univ.)

Early results

- Matter power spectrum really converged in the community?
- Comparison with 3 unnamed emulators at 500 random points within the mutual parameter coverage
- The difference with our emulator is correlated with some of the cosmological parameters
- Extension to halos to follow

DE2 evaluated for the MR setting



Preliminary

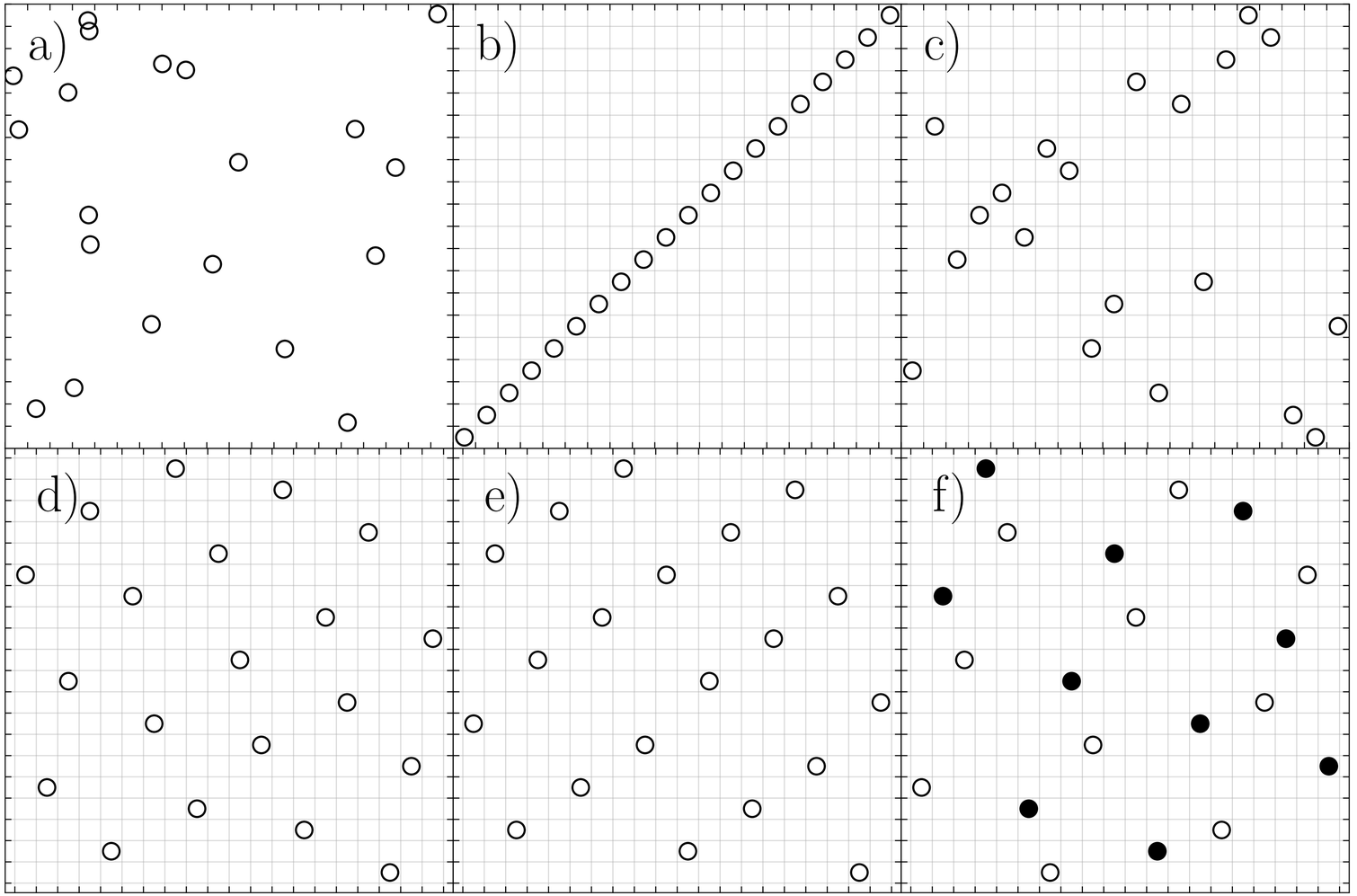
Summary

- Emulator is a promising solution for “simulation-based inference”
  - Efficient sampling + ML (or Bayes)
  - *The methodology itself is applicable to any summary statistics*
- ***DarkEmulator*** is now in action!!
  - 3x2pt analysis from HSC Y1/Y3 and SDSS BOSS
  - Full-shape analysis on SDSS BOSS
- **DQ2** ongoing
  - New simulation code GINKAKU
  - Make full use of the flexibility of neural net
  - *Nonlinear matter power spectrum really converged in the community?*

Appendix

Takahiro Nishimichi (Kyoto Sangyo Univ.)

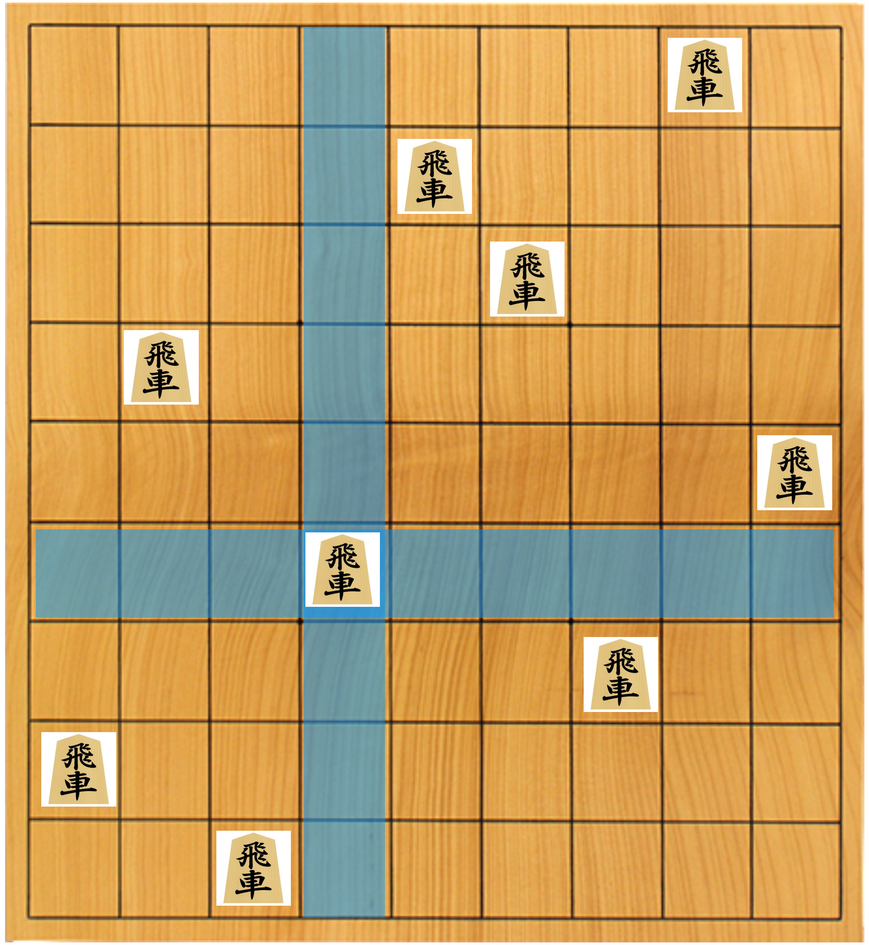
Design of experiments



- Curse of dimensionality
- Filling up multi-D space is a nontrivial task
- Important properties
  - Space-filling
  - Projective properties
  - Granularity

Takahiro Nishimichi (Kyoto Sangyo Univ.)

Design of experiments

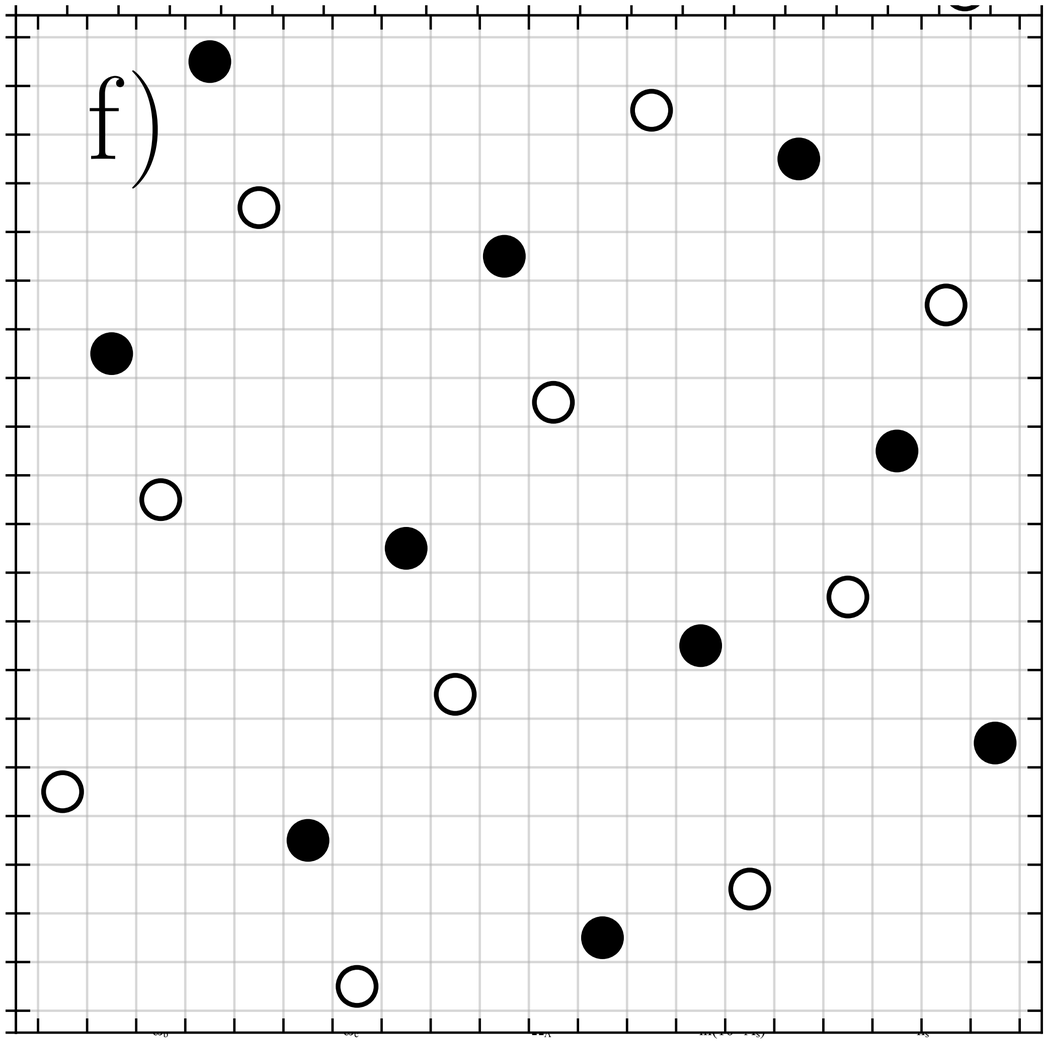


Divide into k segments/ dimension and sample k points instead of k^n

- Latine Hypercube Designs
  - One and only one in every row and column
  - Good projection properties
  - Space-fillingness ensured by maximizing the minimum distance between the points

Takahiro Nishimichi (Kyoto Sangyo Univ.)

Design of experiments



- Sliced LHD (Ba, Myers, Brenneman ’15)
  - Each symbol forms an LHD
  - All the points together form an LHD
  - Space filling property ensured by minimizing a total cost function

Cost function for all the *within the t-th*

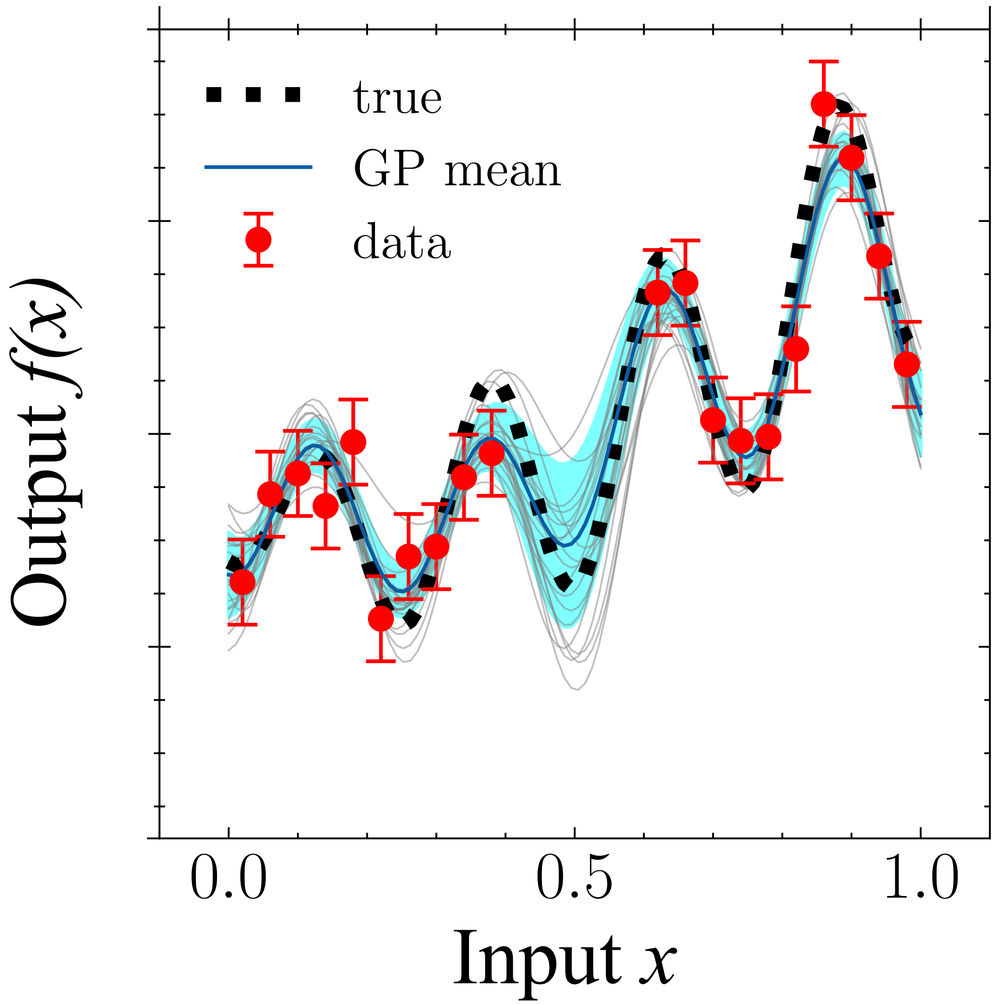
$$\Phi(\mathbf{X}_N) = \frac{1}{2}\left(\phi_{\text{all}} + \frac{1}{m}\sum_{t=1}^{m}\phi_t\right),$$

$$\phi(\mathbf{X}_N) = \left(\frac{2}{N(N-1)}\sum_{i\neq j}\frac{1}{d^r(\mathbf{x}^{(i)},\mathbf{x}^{(j)})}\right)^{1/r}$$

Takahiro Nishimichi (Kyoto Sangyo Univ.)

Regression→Gaussian Process

- Assume that the target function follows a multi-variate normal distribution
- Specify the mean (usually set to zero) and covariance function (parametrized)
- *Optimize* the parameters (controlling the typical amplitude and smoothness of the curve) to the available data
- Make predictions by considering the conditional probability given data
- GP acts as a *prior*



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Regression→Gaussian Process

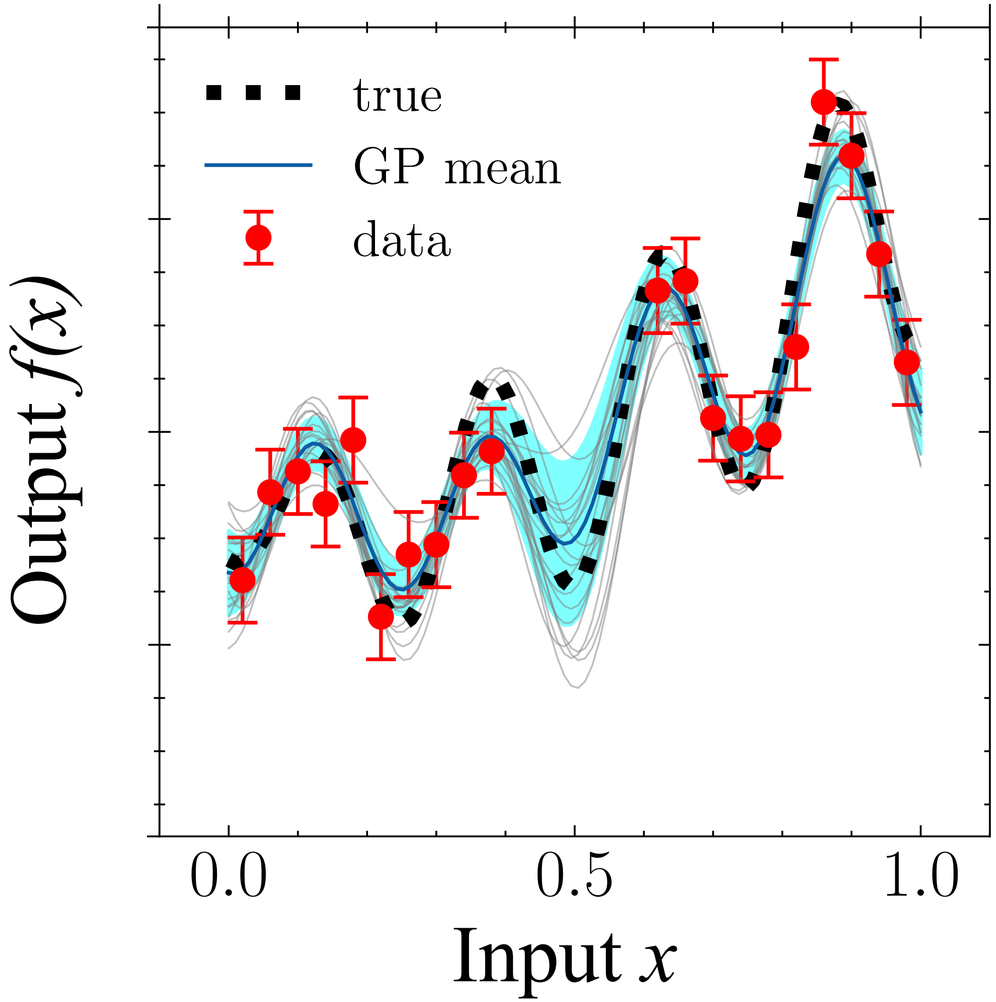
Everything is analytically calculable thanks to the Gaussian assumption

Conditional distribution given *N* data points

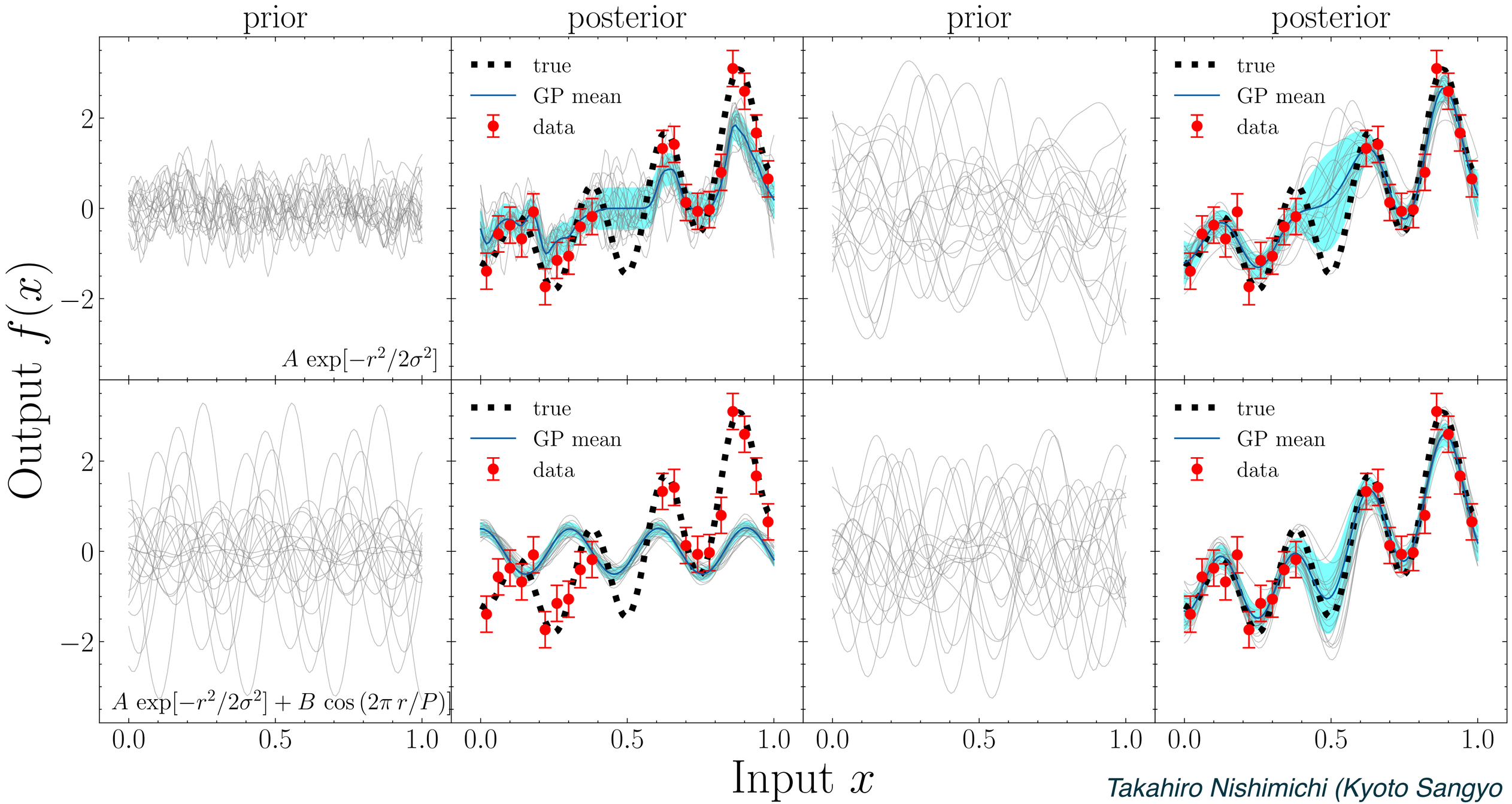
$$P(t_{N+1} \,|\, \mathbf{t}_N) \propto \exp\left[-\frac{1}{2}\left[\mathbf{t}_N \; t_{N+1}\right] \mathbf{C}_{N+1}^{-1} \begin{bmatrix} \mathbf{t}_N \\ t_{N+1} \end{bmatrix}\right].$$

Expectation value and uncertainty

$$\begin{aligned} \hat{t}_{N+1} &= \mathbf{k}^T \mathbf{C}_N^{-1} \mathbf{t}_N \\ \sigma^2_{\hat{t}_{N+1}} &= \kappa - \mathbf{k}^T \mathbf{C}_N^{-1} \mathbf{k}. \end{aligned}$$



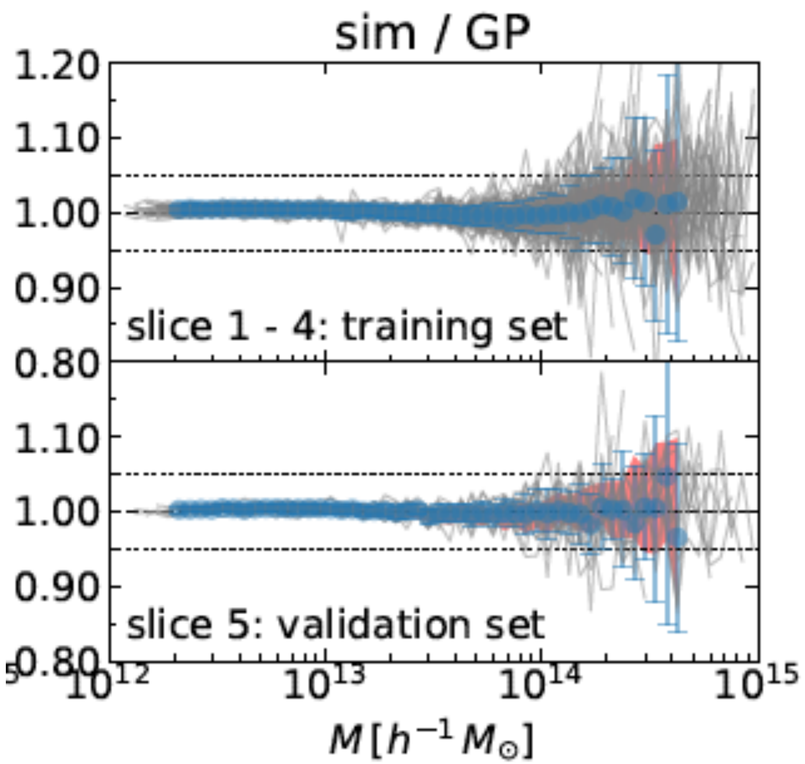
Takahiro Nishimichi (Kyoto Sangyo Univ.)



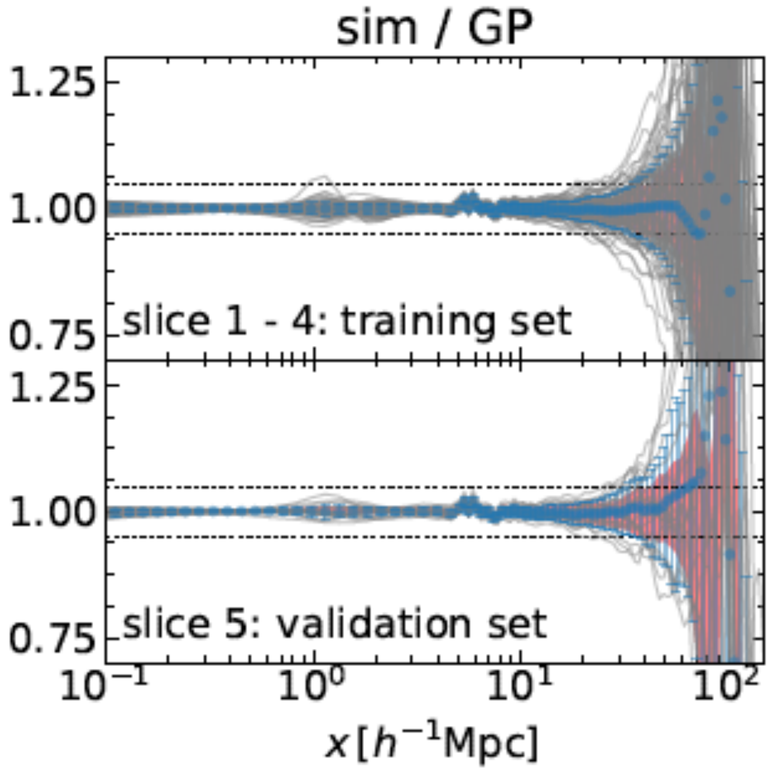
Takahiro Nishimichi (Kyoto Sangyo Univ.)

Performance of DarkEmulator

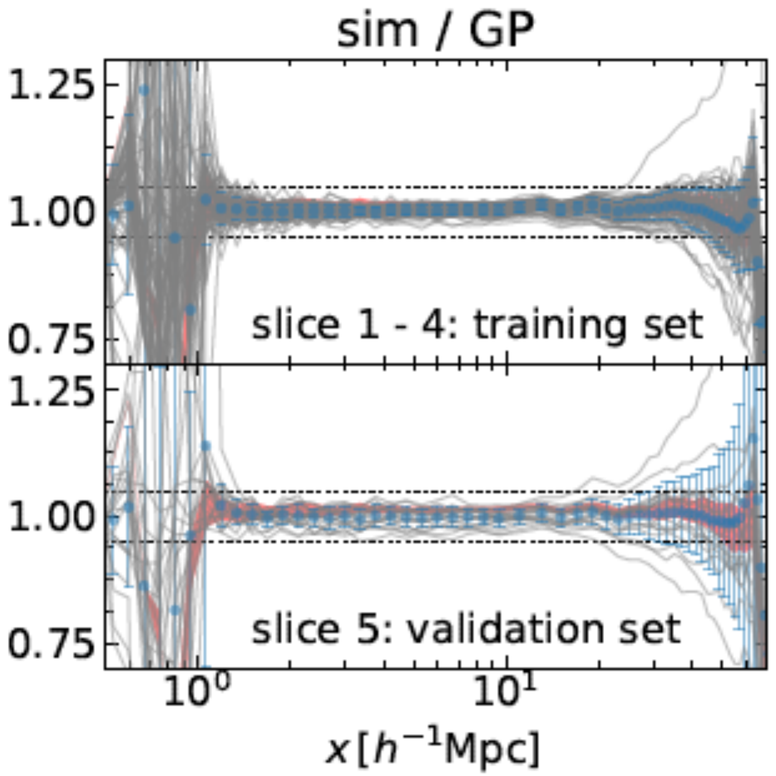
Halo mass function



Halo-matter cross CF



Halo-halo auto CF



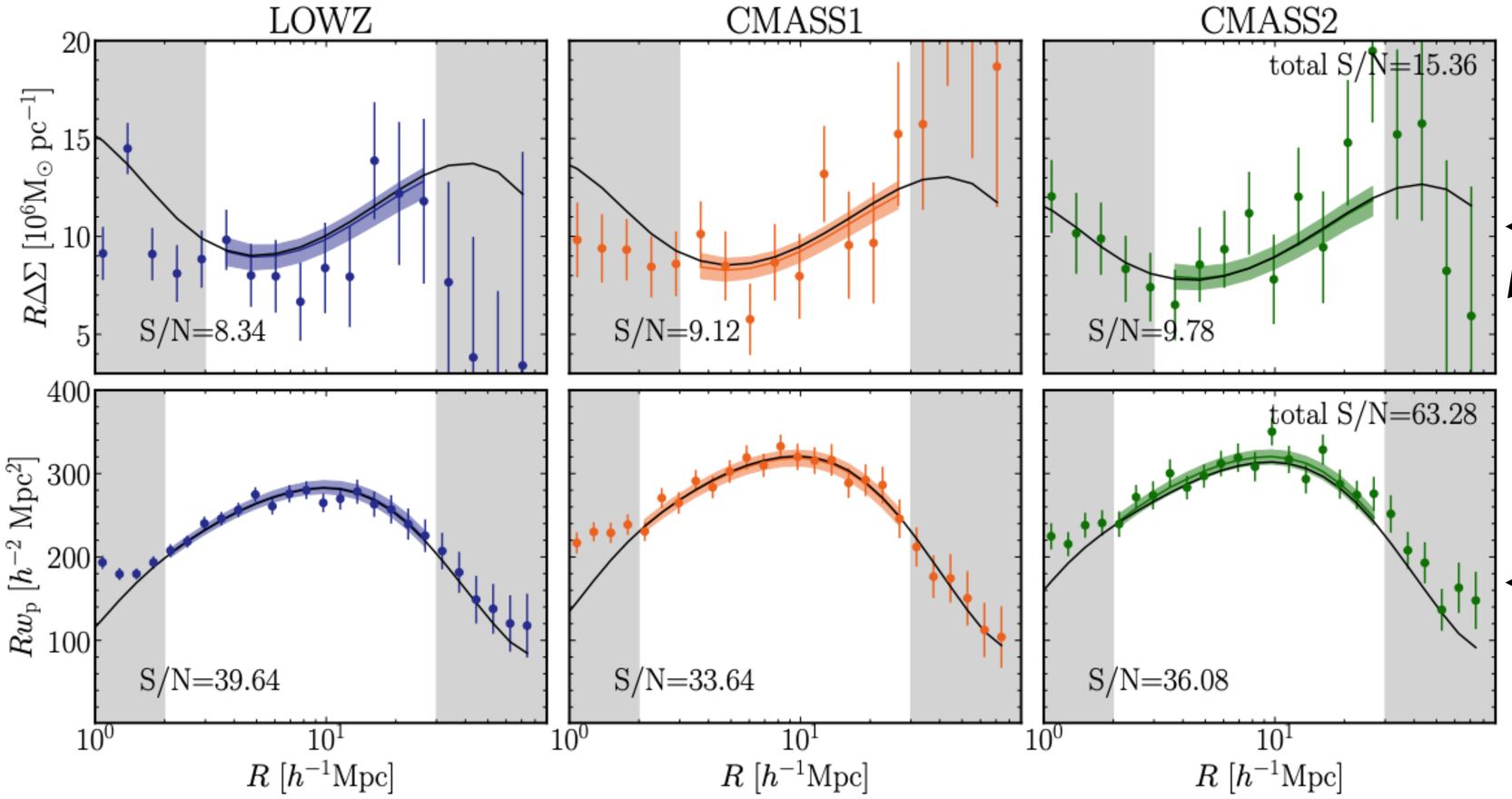
Typical accuracy: 2 - 4%

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DarkEmulator vs Subaru HSC Y1

Miyatake+ PRD **106** (2022) 083520

- HSCxSDSS 2x2 pt (lensing + clustering) analysis
  - Break the degeneracy between galaxy-halo connection and cosmology



HSC Y1:

- 4M galaxy shapes
- $z_s > 0.75$
- 140 deg^2 (~10% of final)

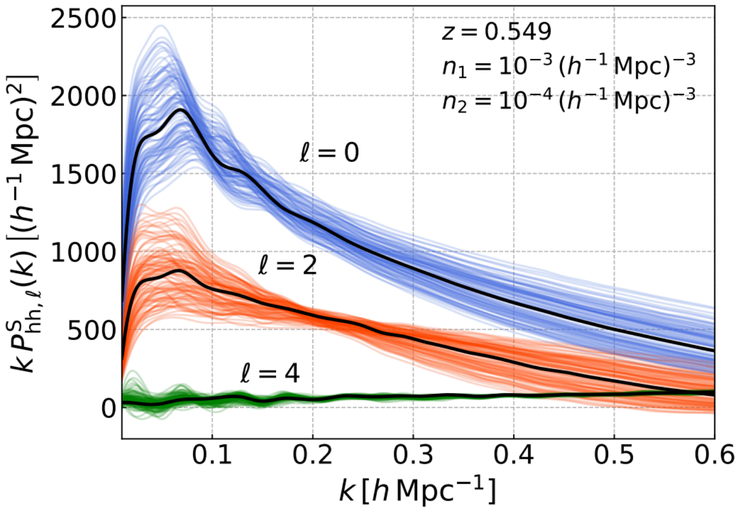
SDSS BOSS DR11:

- 0.3M galaxies w/ redshift
- $0.15 < z_l < 0.7$
- 8,300 deg^2

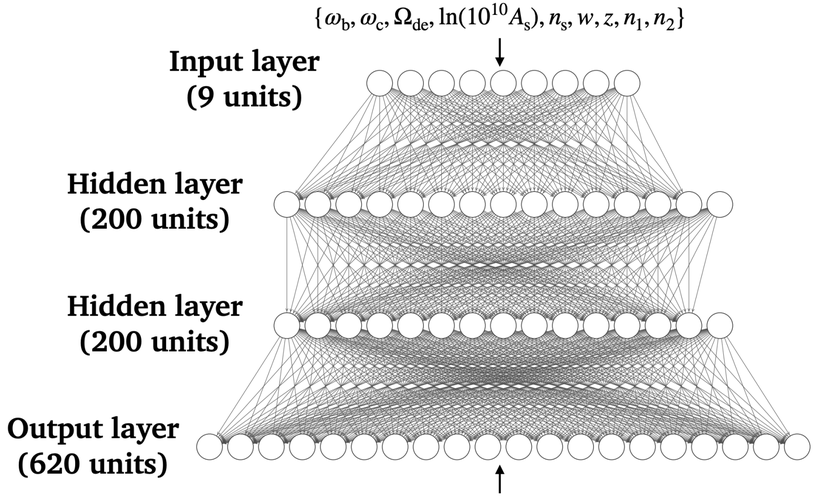
Takahiro Nishimichi (Kyoto Sangyo Univ.)

Redshift space

Kobayashi, TN+, PRD 102, 063504

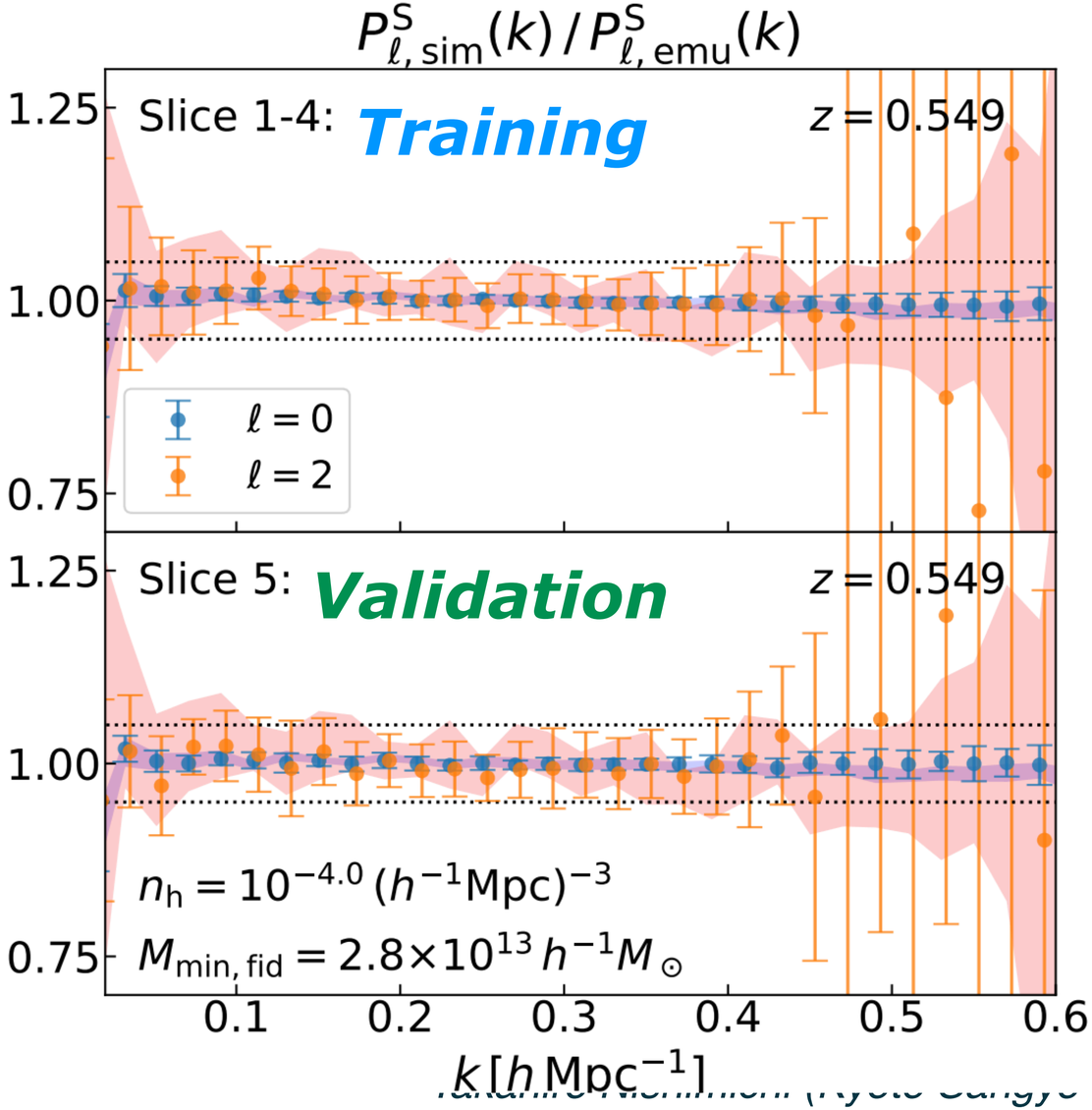


Cosmology + (time, mass) 9



Redshift-space Clustering of halos P(k,μ): 620

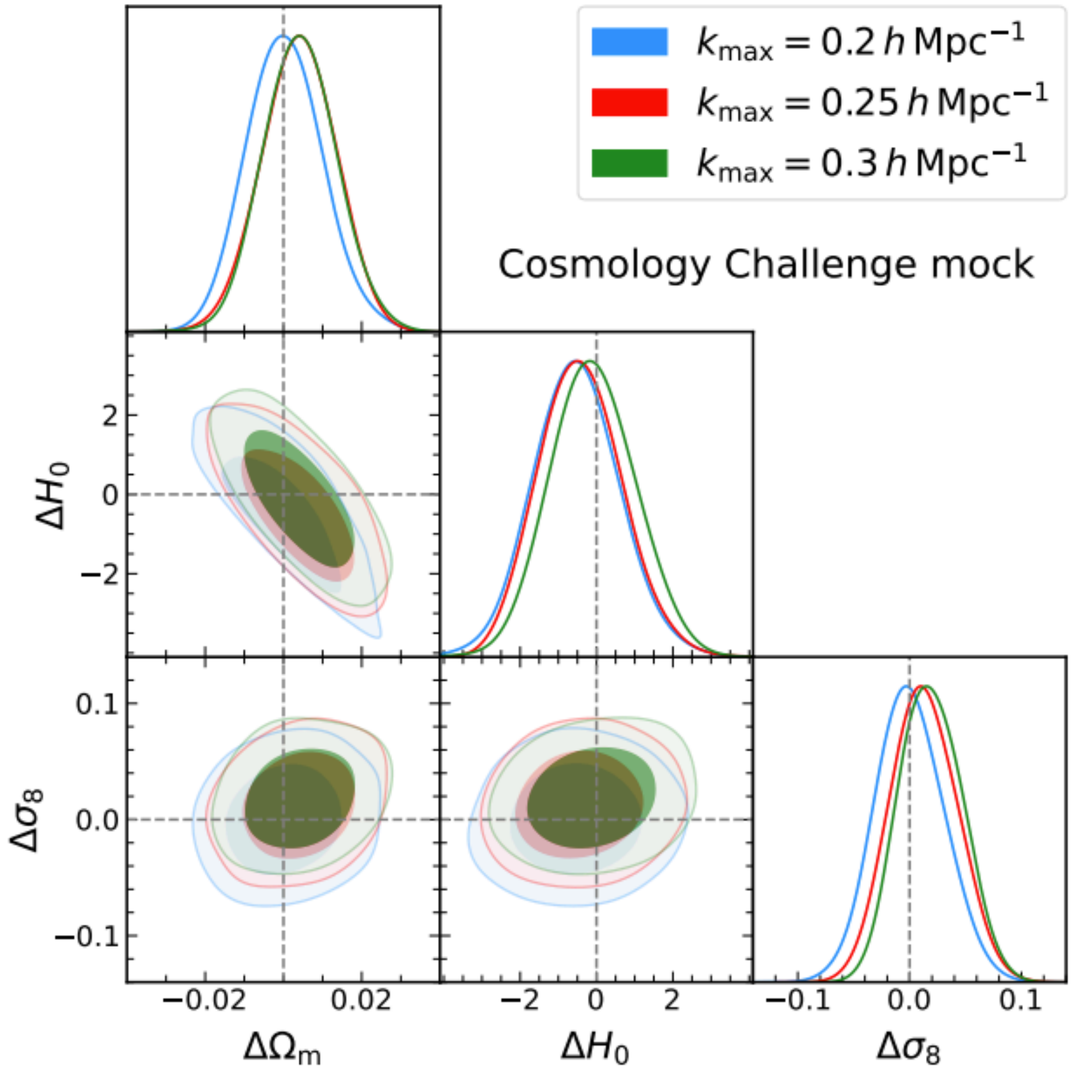
Feedforward Neural Network

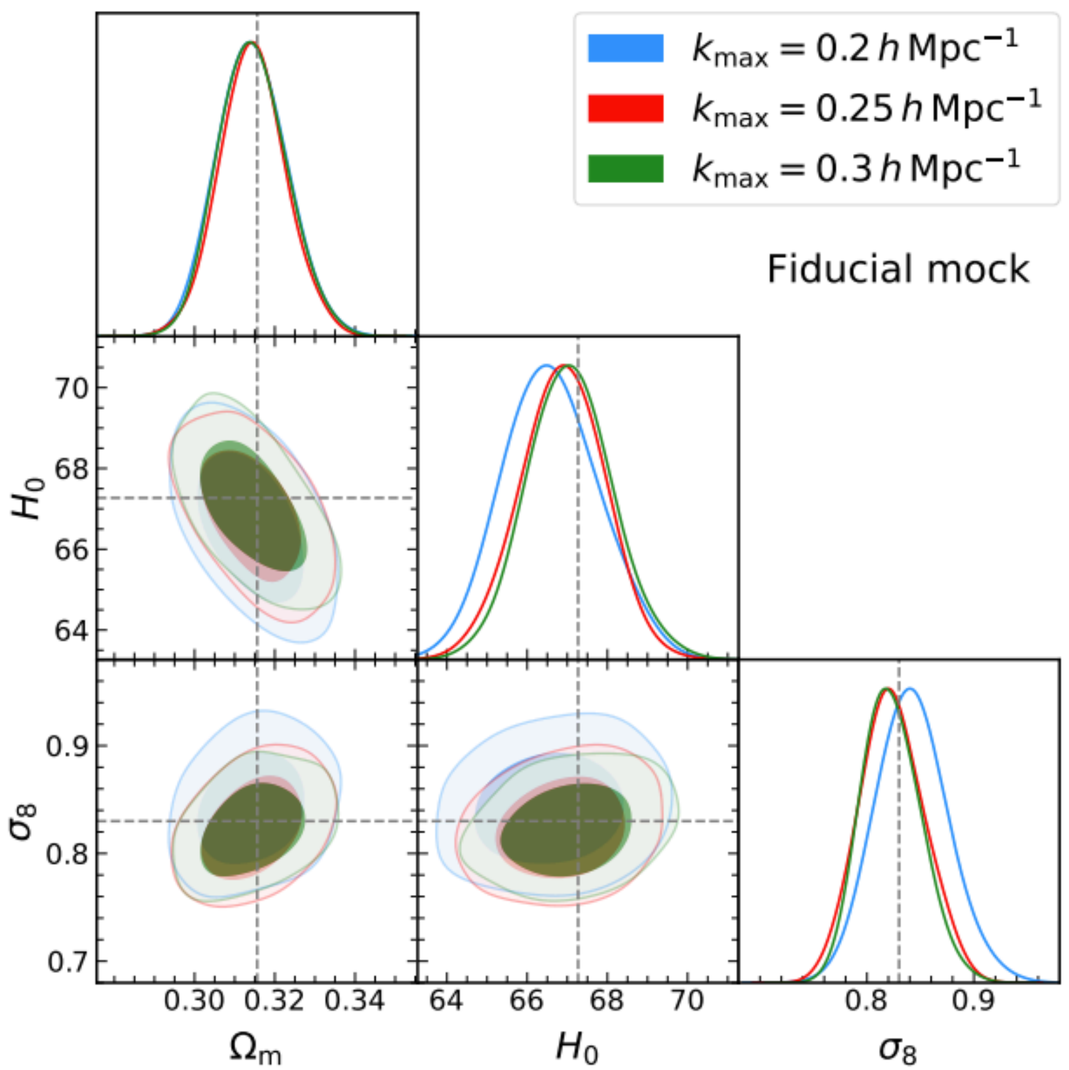


Univ.)

Validation studies for full-shape RSD

Kobayashi, TN, Takada, Miyatake arXiv:2110.0

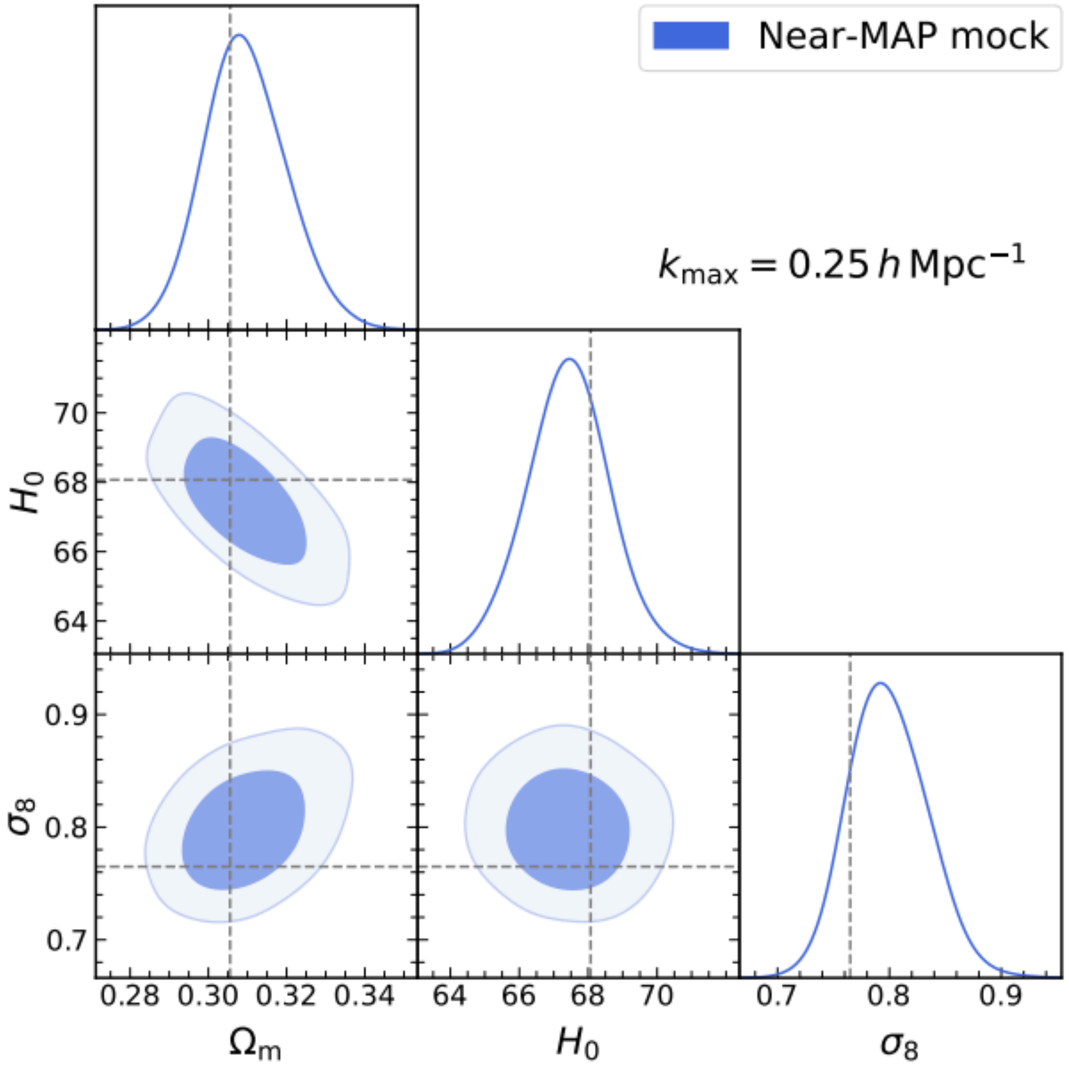


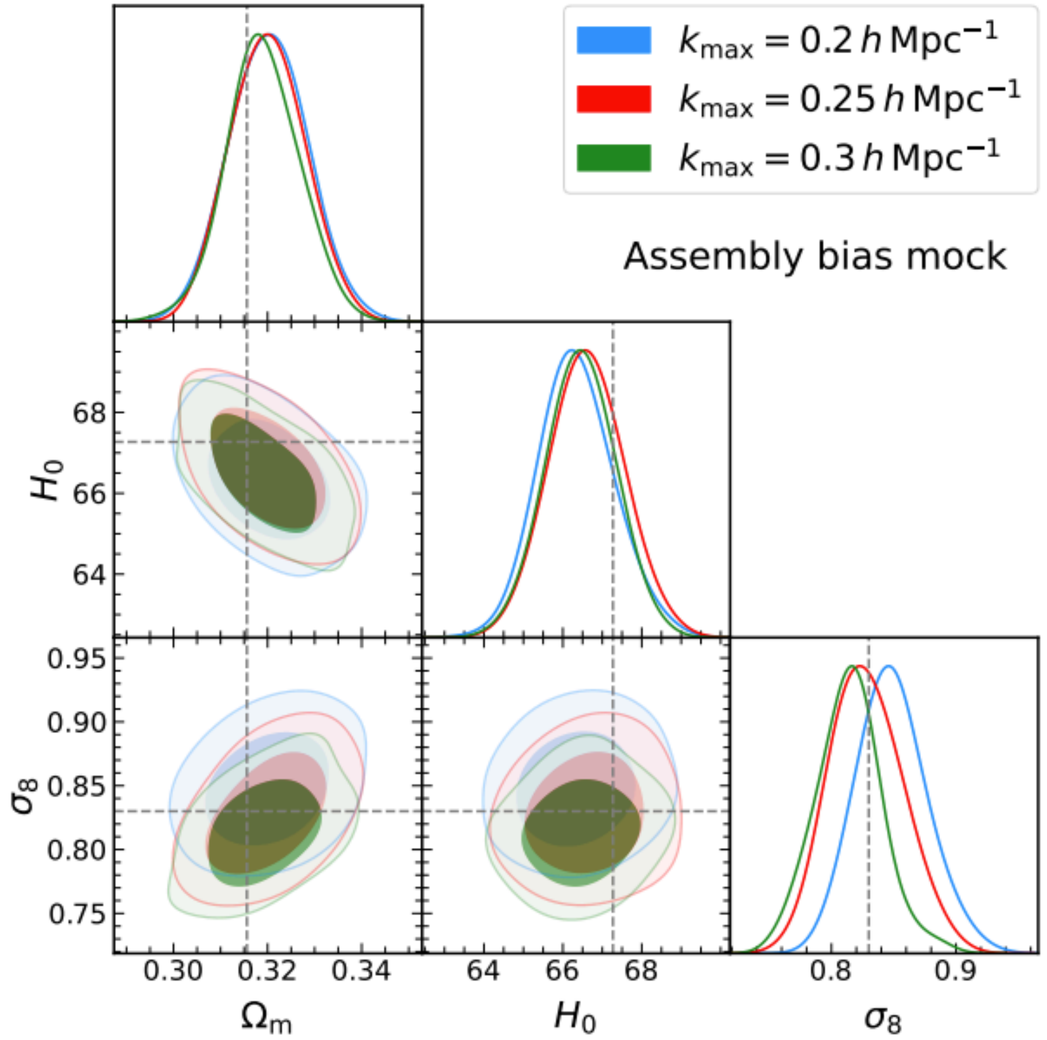


Sangyo Univ.)

Validation studies for full-shape RSD

Kobayashi, TN, Takada, Miyatake arXiv:2110.0

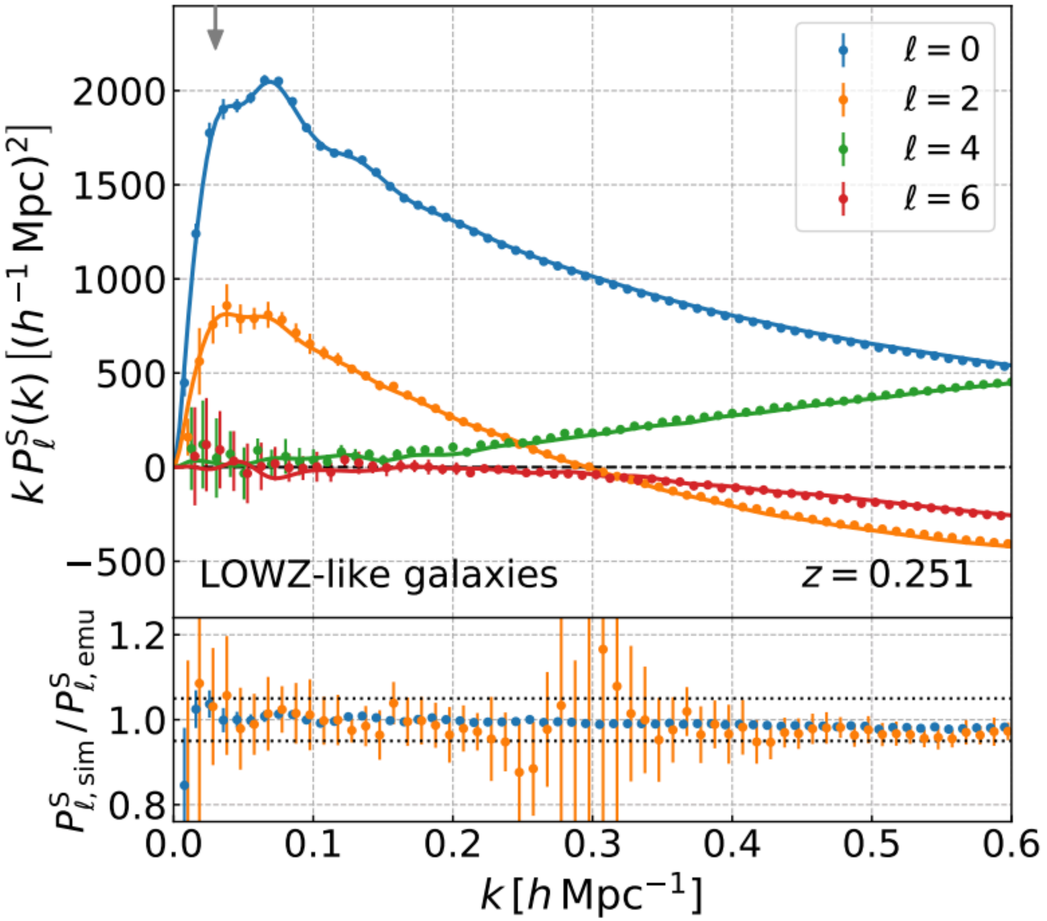


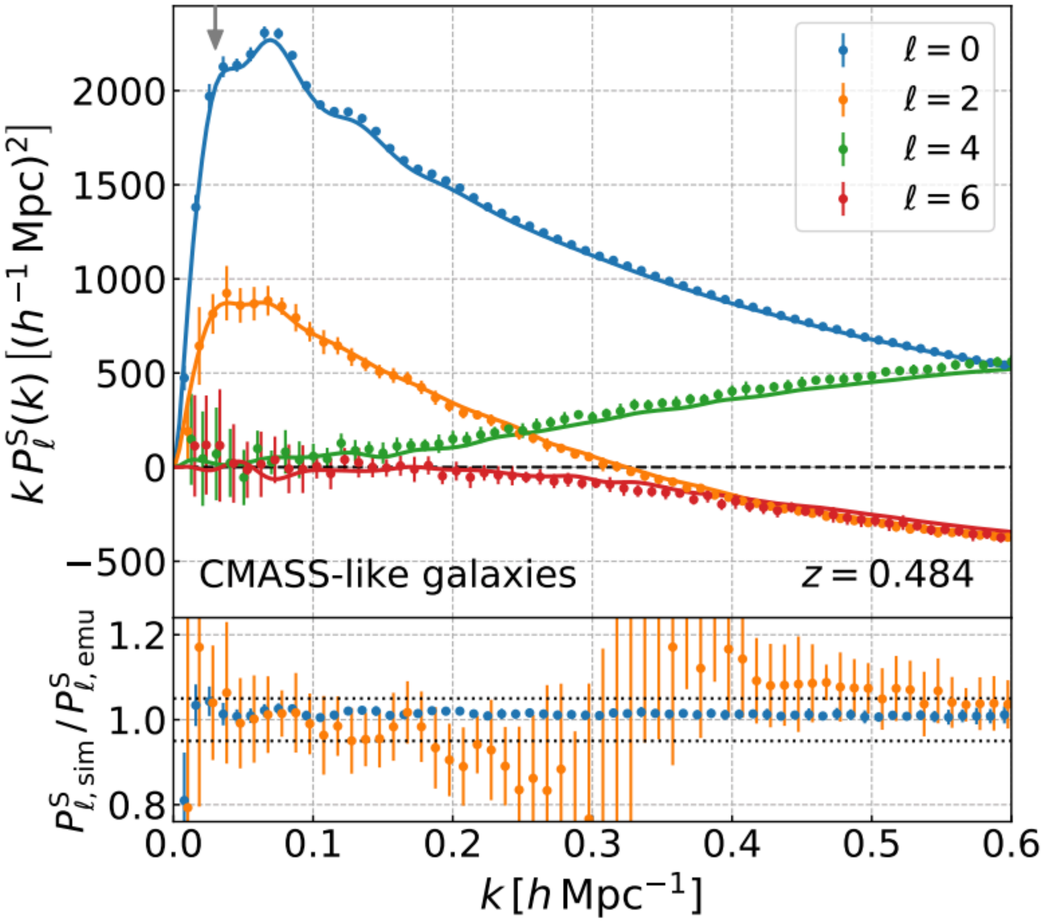


Takahiro Nishimichi (Kyoto Sangyo Univ.)

Tests for RSD emulator performance

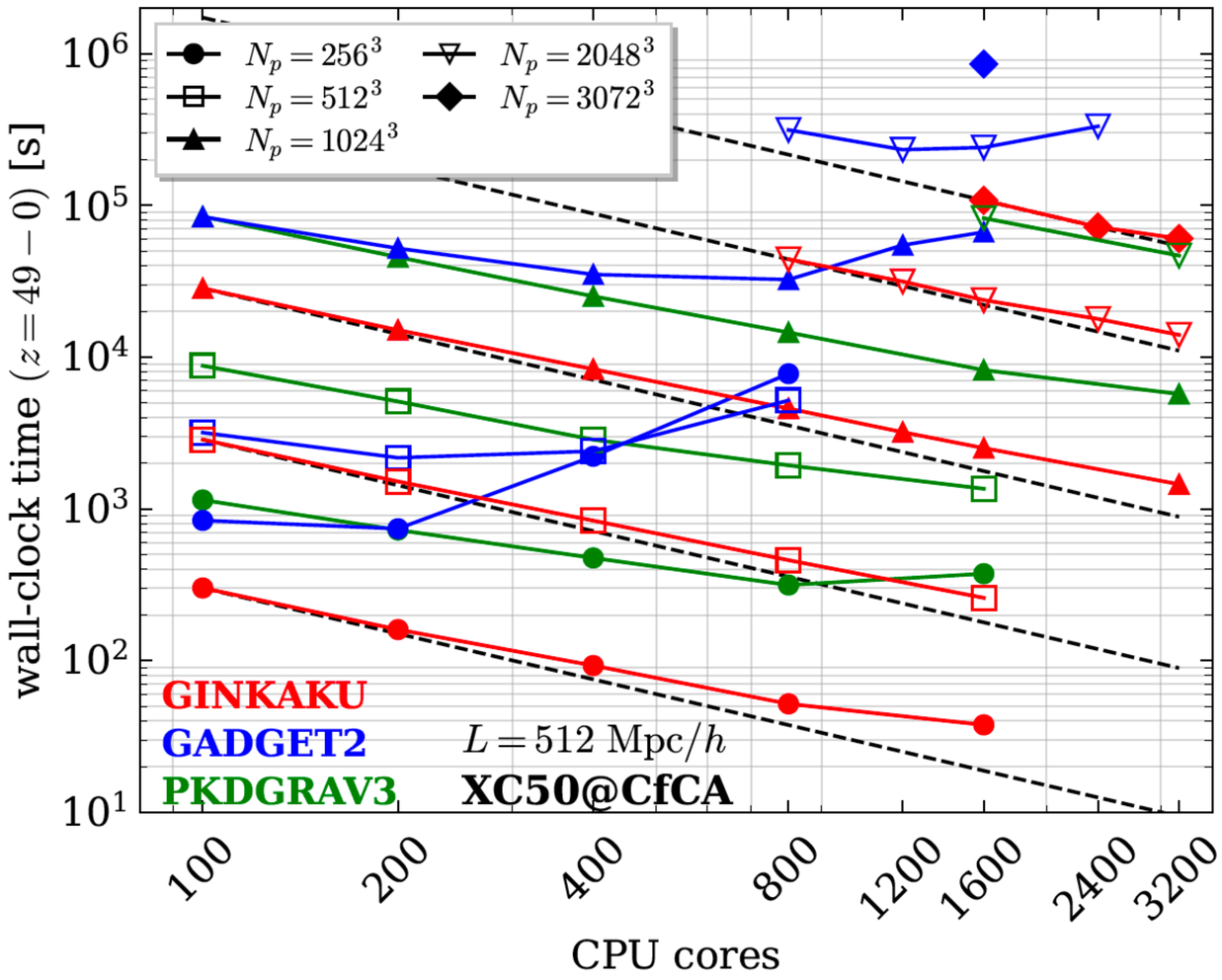
Kobayashi, TN, Takada, Takahashi, Osato arXiv:2005.0

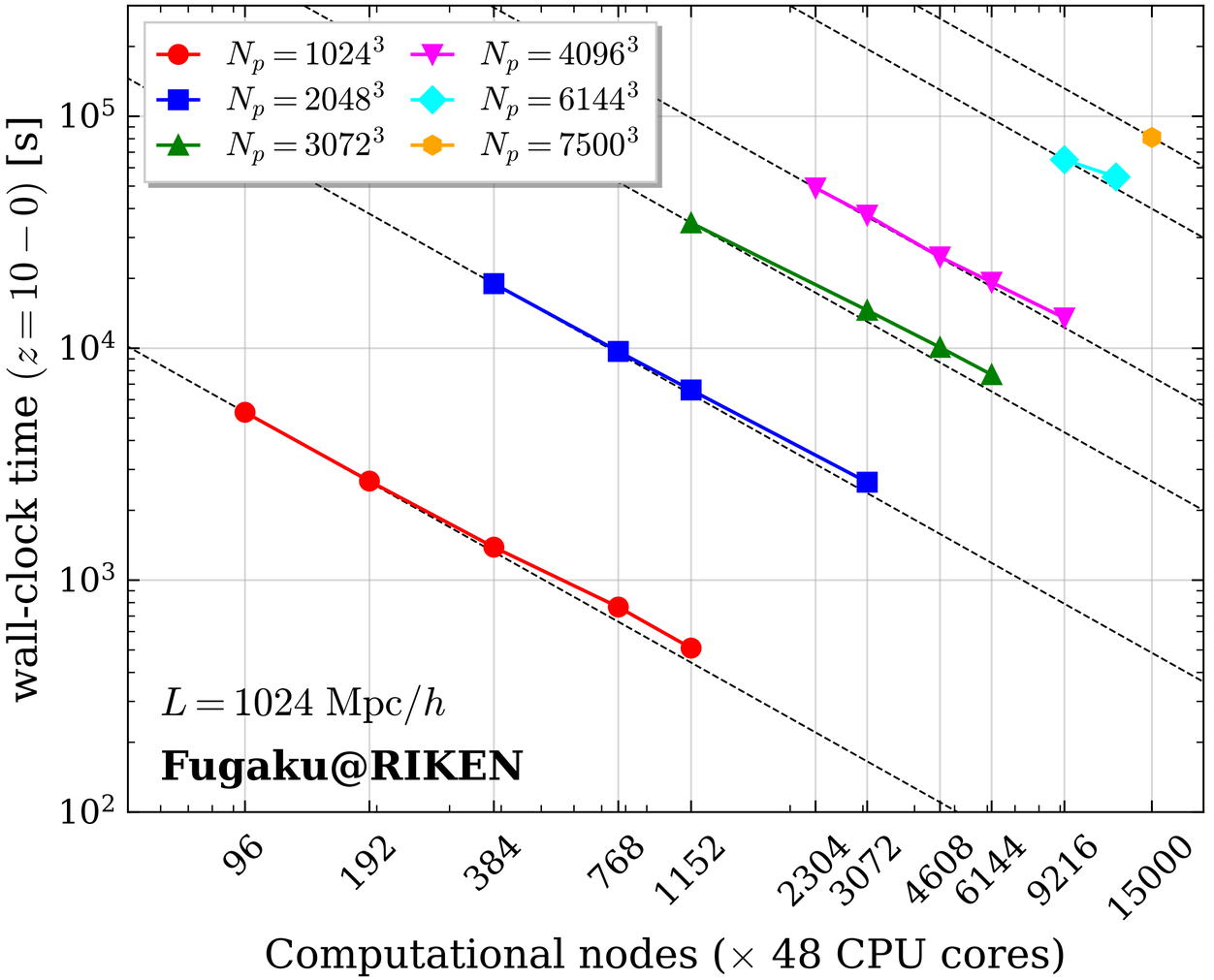




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Performance

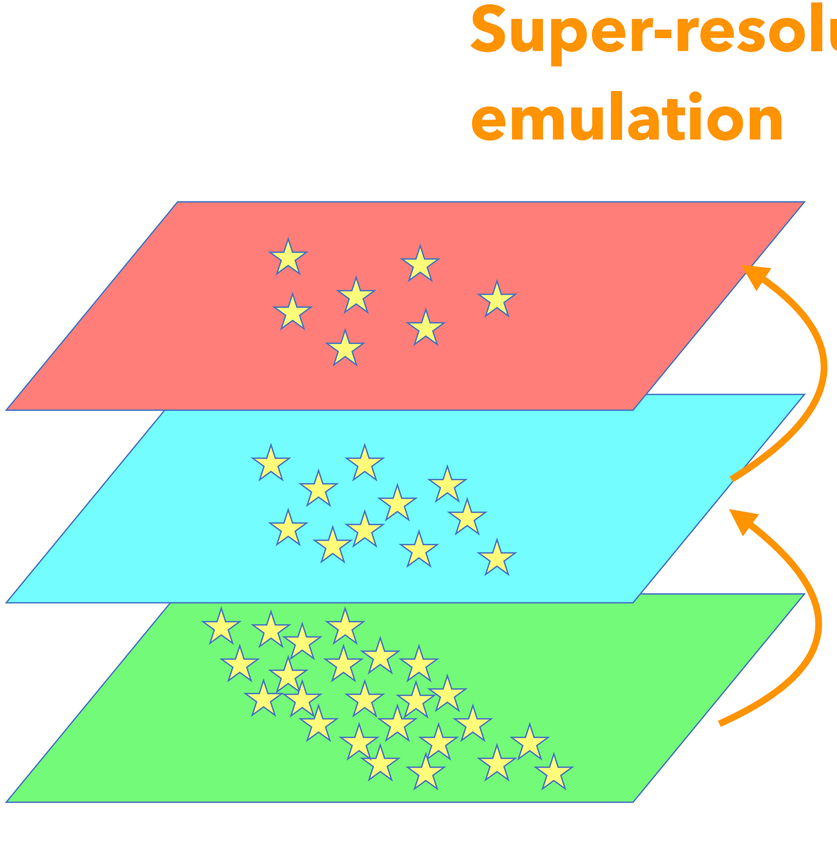




Takahiro Nishimichi (Kyoto Sangyo Univ.)

Mixed-resolution training data

Resolution (cost)



Super-resolution emulation

Test with the best-resolution simulations

40 models w/ $N = 3000^3$

Optimized sampling based on the distance metric

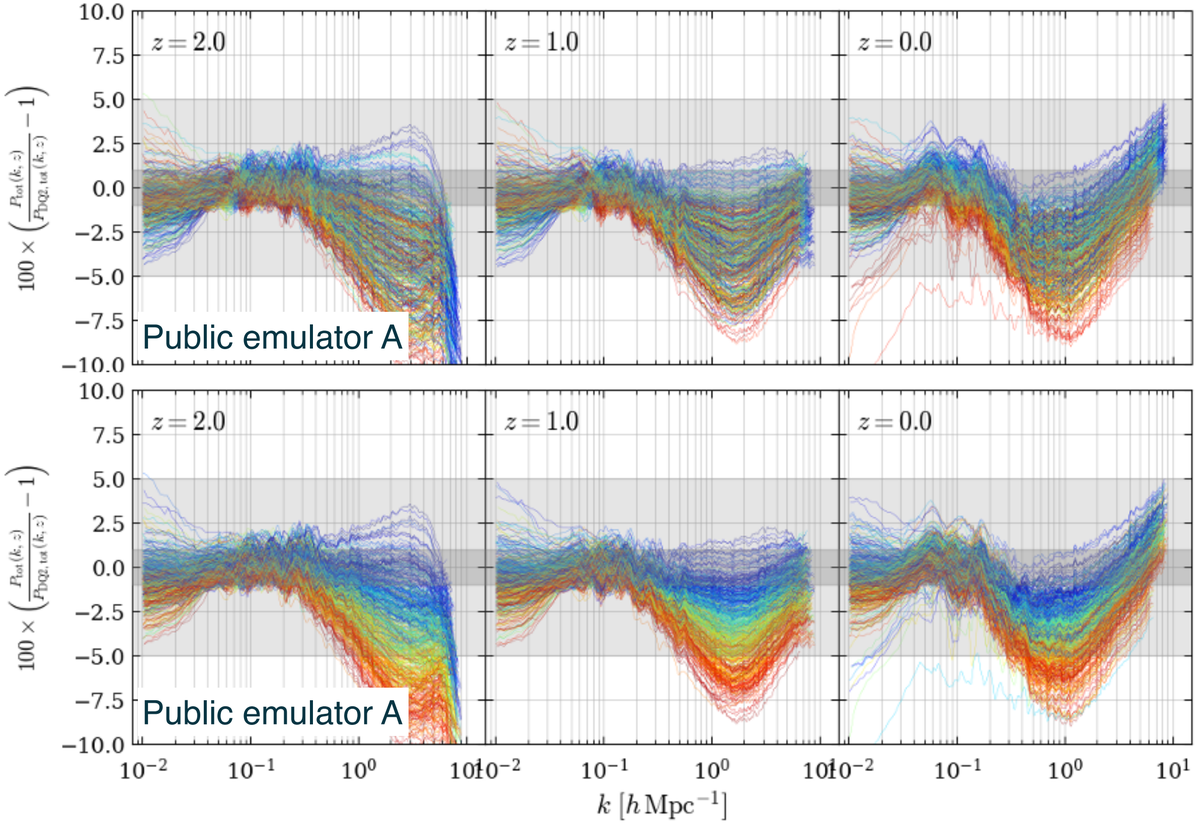
100 models w/ $N = 2048^3$

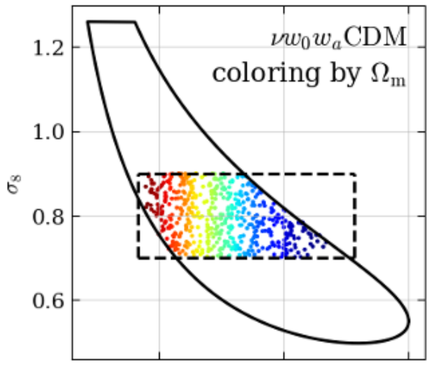
Brute-force, dense sampling (***pilot simulations***)

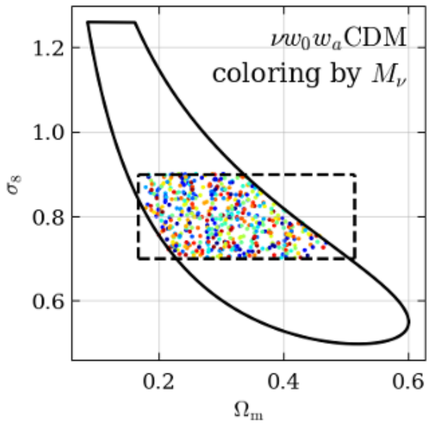
1000 models w/ $N = 1024^3$

Takahiro Nishimichi (Kyoto Sangyo Univ.)

Comparison w/ public emulator A







Color coded by

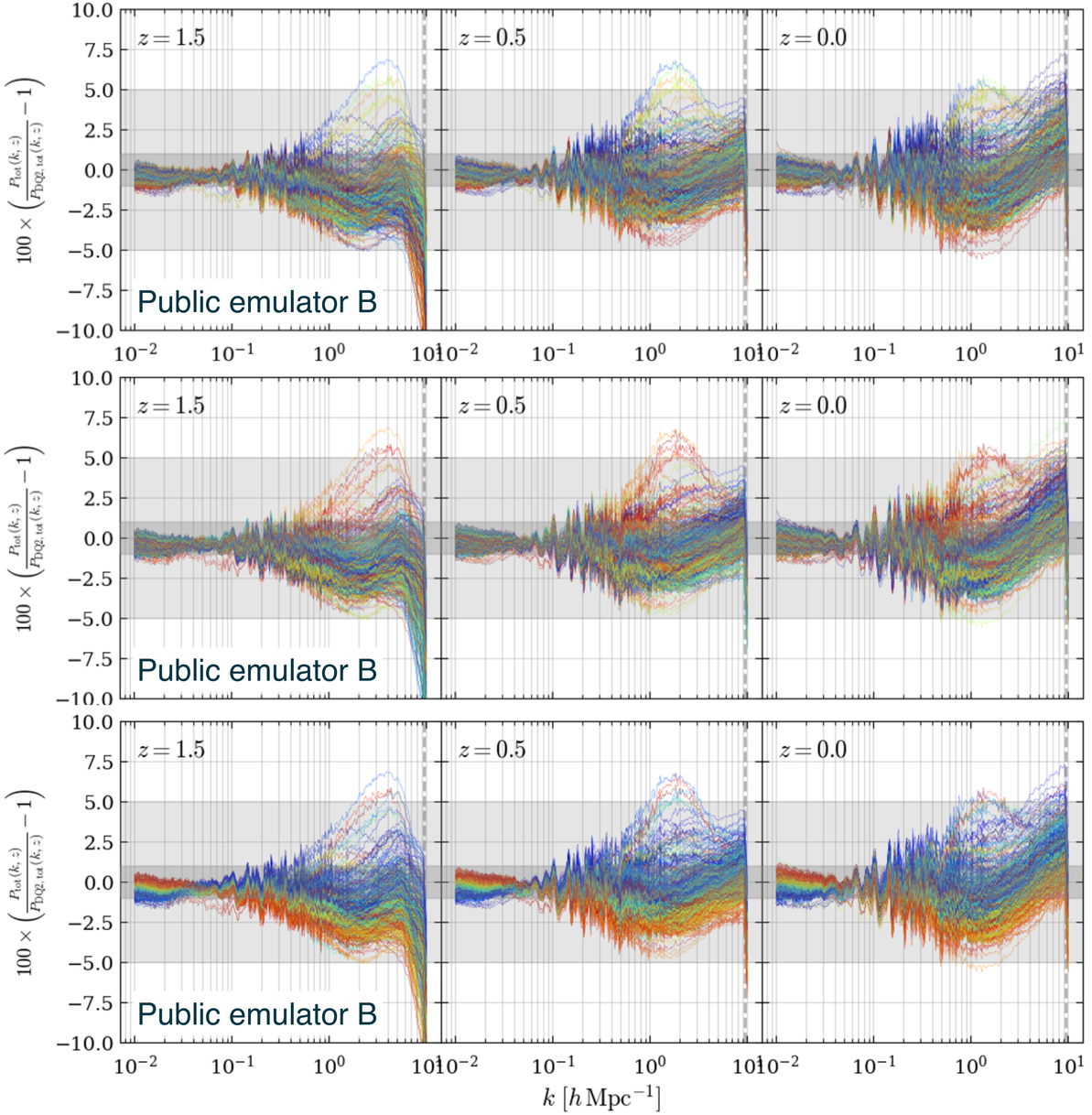
$\Omega_{\rm m}$

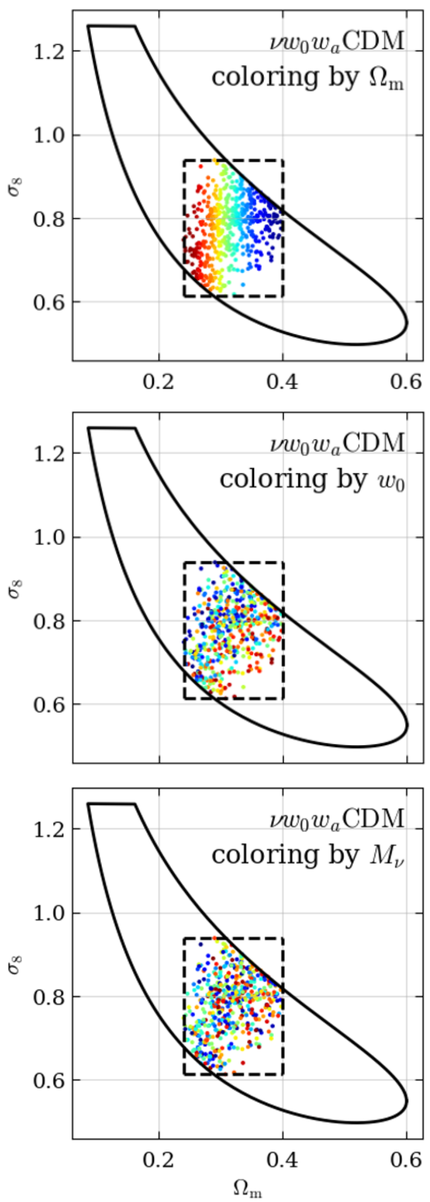
M_ν

Preliminary

Takahiro Nishimichi (Kyoto Sangyo Univ.)

Comparison w/ public emulator B





Color coded by

$\Omega_{\rm m}$

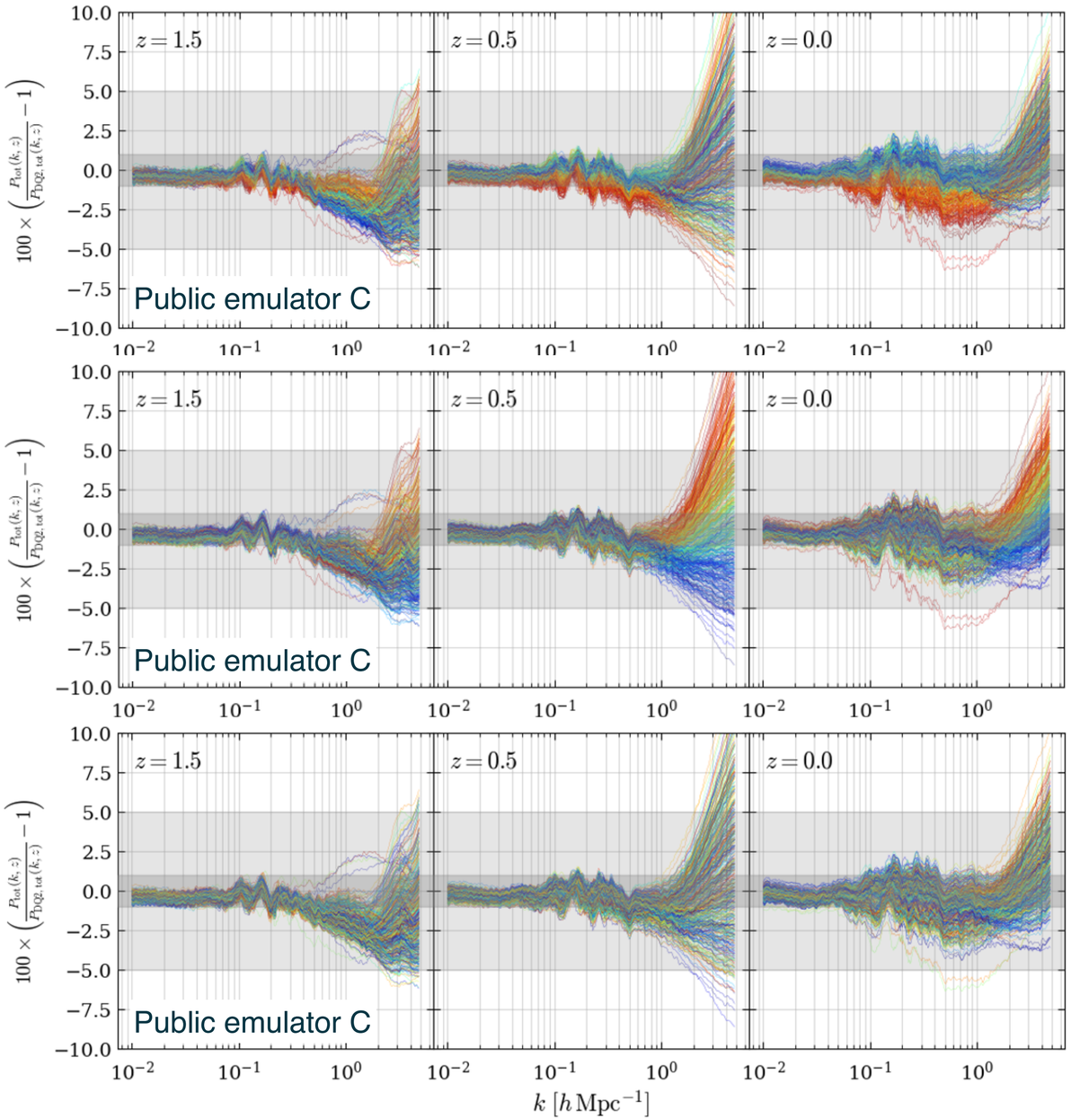
w_0

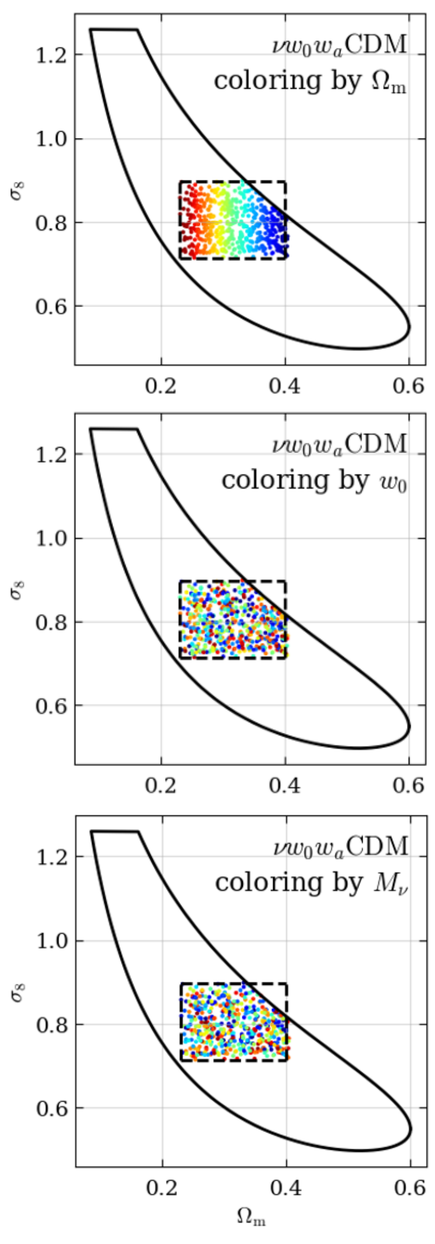
M_ν

Preliminary

Takahiro Nishimichi (Kyoto Sangyo Univ.)

Comparison w/ public emulator C





Color coded by

$\Omega_{\rm m}$

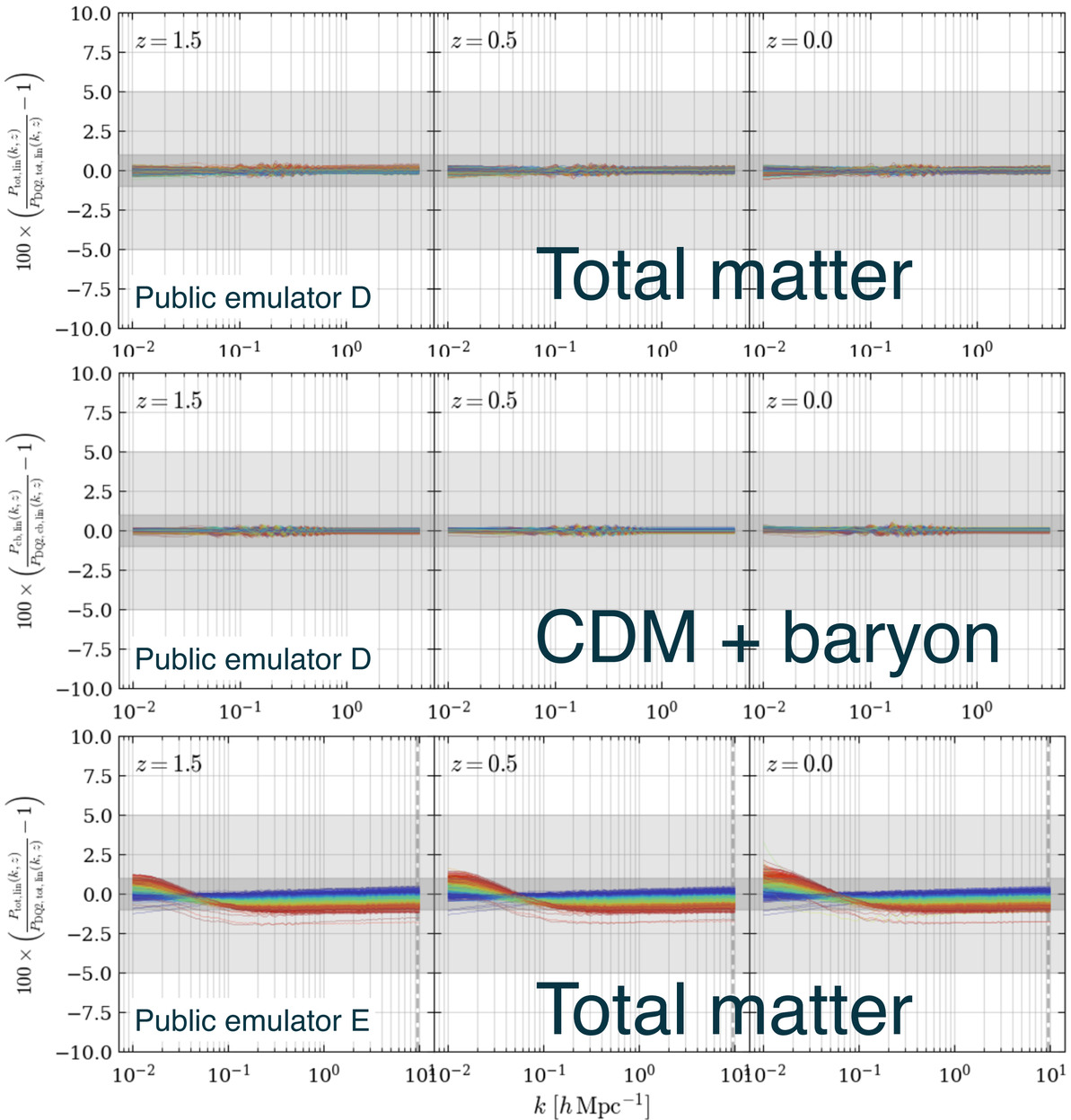
w_0

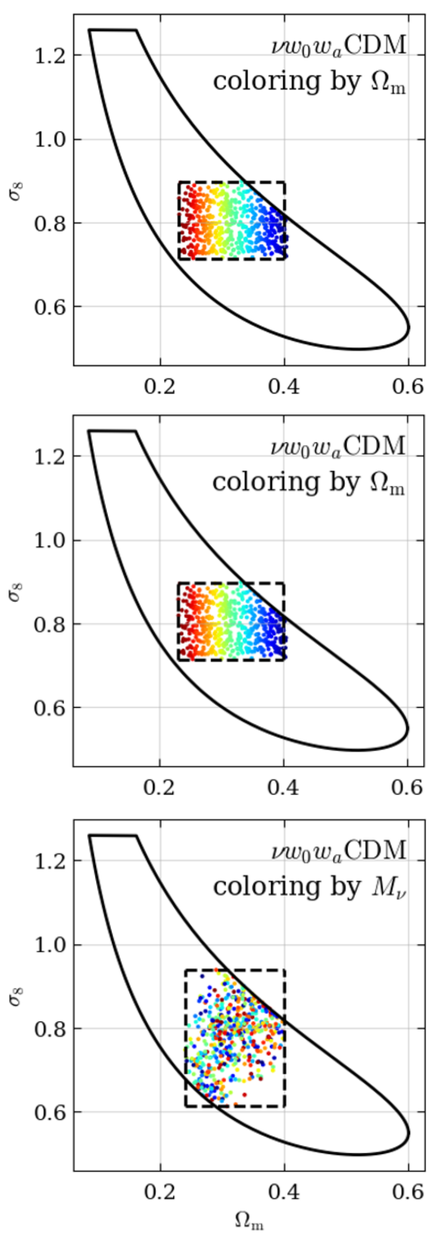
M_ν

Preliminary

Takahiro Nishimichi (Kyoto Sangyo Univ.)

Linear emulator comparison





Color coded by

Ω_{m}

Ω_{m}

M_ν

Preliminary

Takahiro Nishimichi (Kyoto Sangyo Univ.)

Speed of DarkEmulator II

- Total time to evaluate 500 cosmologies at 3 redshifts (i.e., 1500 curves)

Emulator	Time [sec.]
DarkEmulator2	8.44
DarkEmulator2 (w/o P_lin	over 5000
EuclidEmulator2	509.68
baccoemu	19.85
Mira-Titan Universe IV	1.56
PkANN	4.87
HMcode (Mead+16, 20)	612(LCDM), 1747(kvw0wa CDM)

- Winner: Mira-Titan Universe IV
- Ours & baccoemu follow
- HMcode is slow just because it calls CAMB for the linear P(k)

Preliminary

Takahiro Nishimichi (Kyoto Sangyo Univ.)