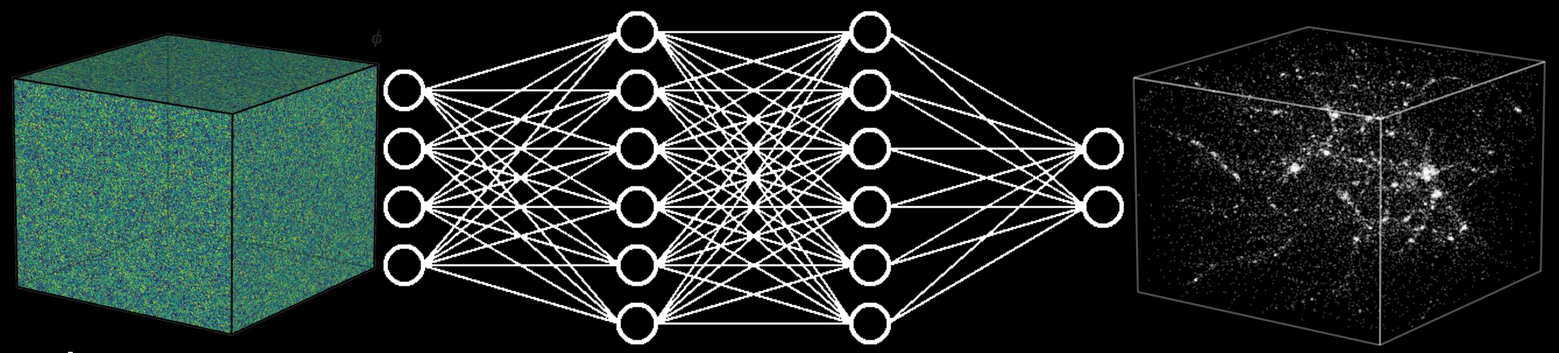
Field-level Emulation of Cosmic Structure Formation with Cosmology and Redshift Dependence

Drew Jamieson
Postdoc, MPA

MAX-PLANCK-INSTITUT FÜR ASTROPHYSIK



arXiv:2206.04594
arXiv:2206.04573
arXiv:2303.13056
arXiv:2307.09134
arXiv:2312.09271
arXiv:2408.07699

Collaborators

Peng Cheng Laboratory: Yin Li
Flatiron Institute: Shirley Ho, David Spergel, Francisco Villaescusa-Navarro, Renan Alves de Oliveira, Siyu He
Carnegie Mellon: Aarti Singh, Vaibhav Jindal, Albert Liang
Stockholm University: Ludvig Doeser, Jens Jasche
University of Edinburgh: Marcos Pellejero
DIPC: Raúl Angulo

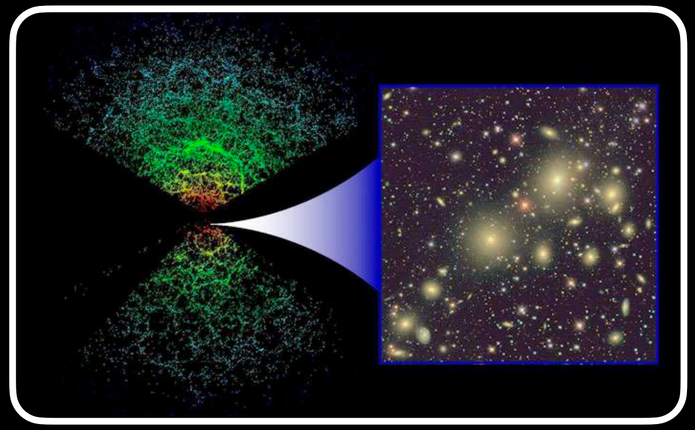
Map2Map with style parameters:
https://github.com/eelregit/map2map
https://github.com/dsjamieson/map2map_emu

What is a field-level emulator for LSS?

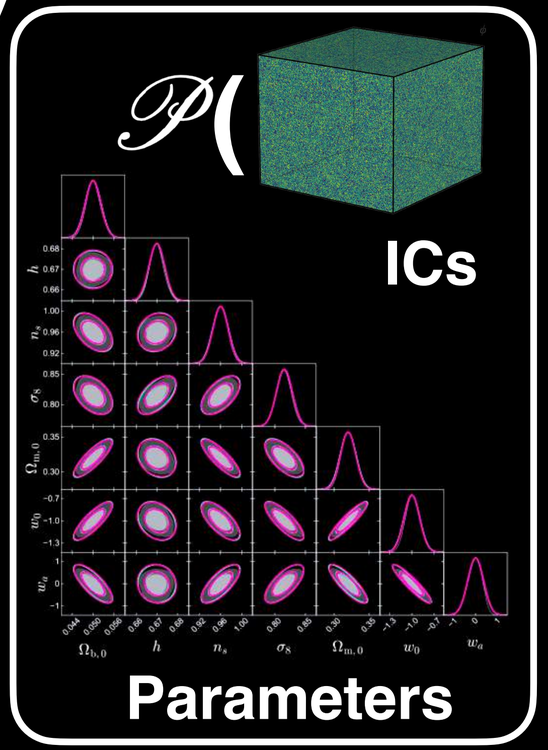
Surveys



Data



Comparison & Inference



Constraints

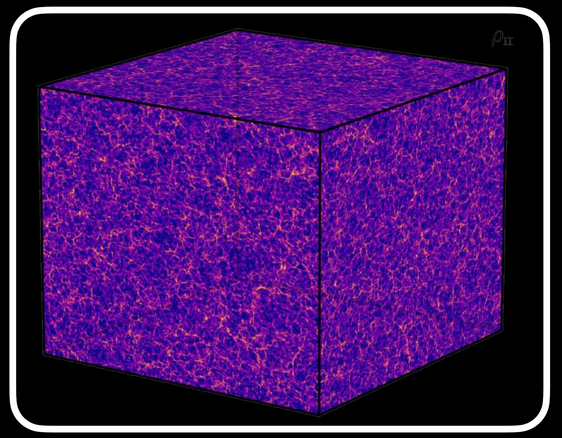
Model

$$\Lambda\mathrm{CDM} + \text{extensions}$$

$$f_{\mathrm{NL}} \qquad \Omega_K$$

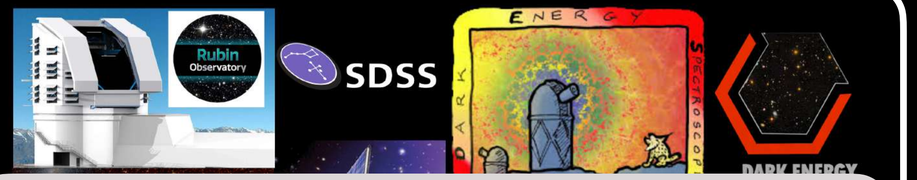
$$M_\nu \qquad w_0 + w_1 a$$

Forward-model prediction



What is a field-level emulator for LSS?

Surveys



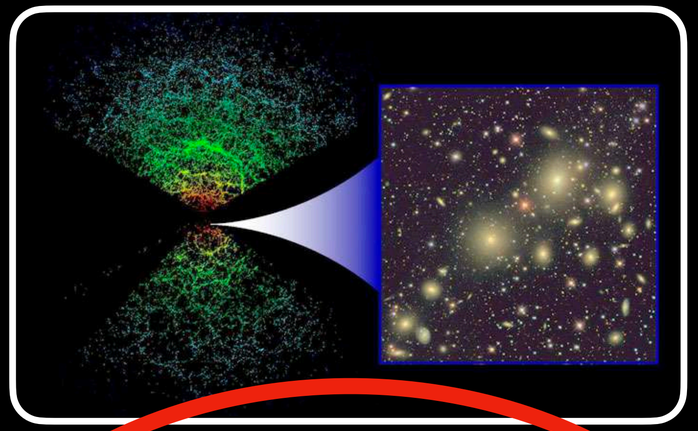
Accelerate with machine learning

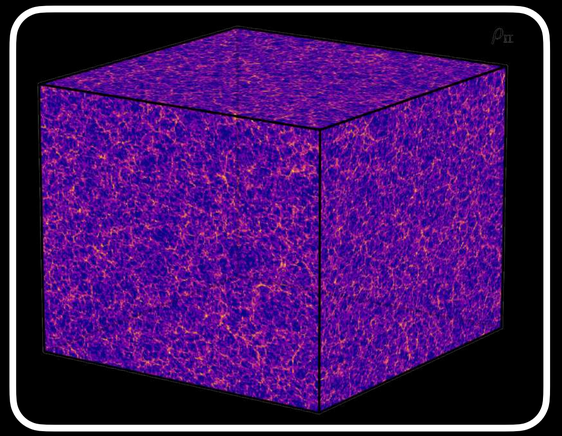
$f_{\rm NL}$ Ω_K

M_ν $w_0 + w_1 a$

Model

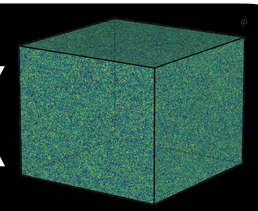
Data



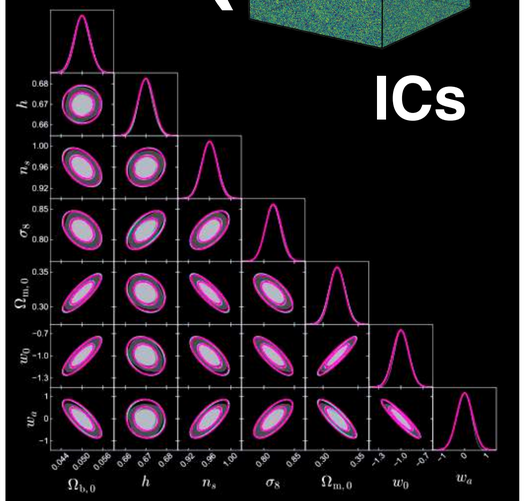


Forward-model prediction

Comparison & Inference

$\mathscr{P}($ 

ICs

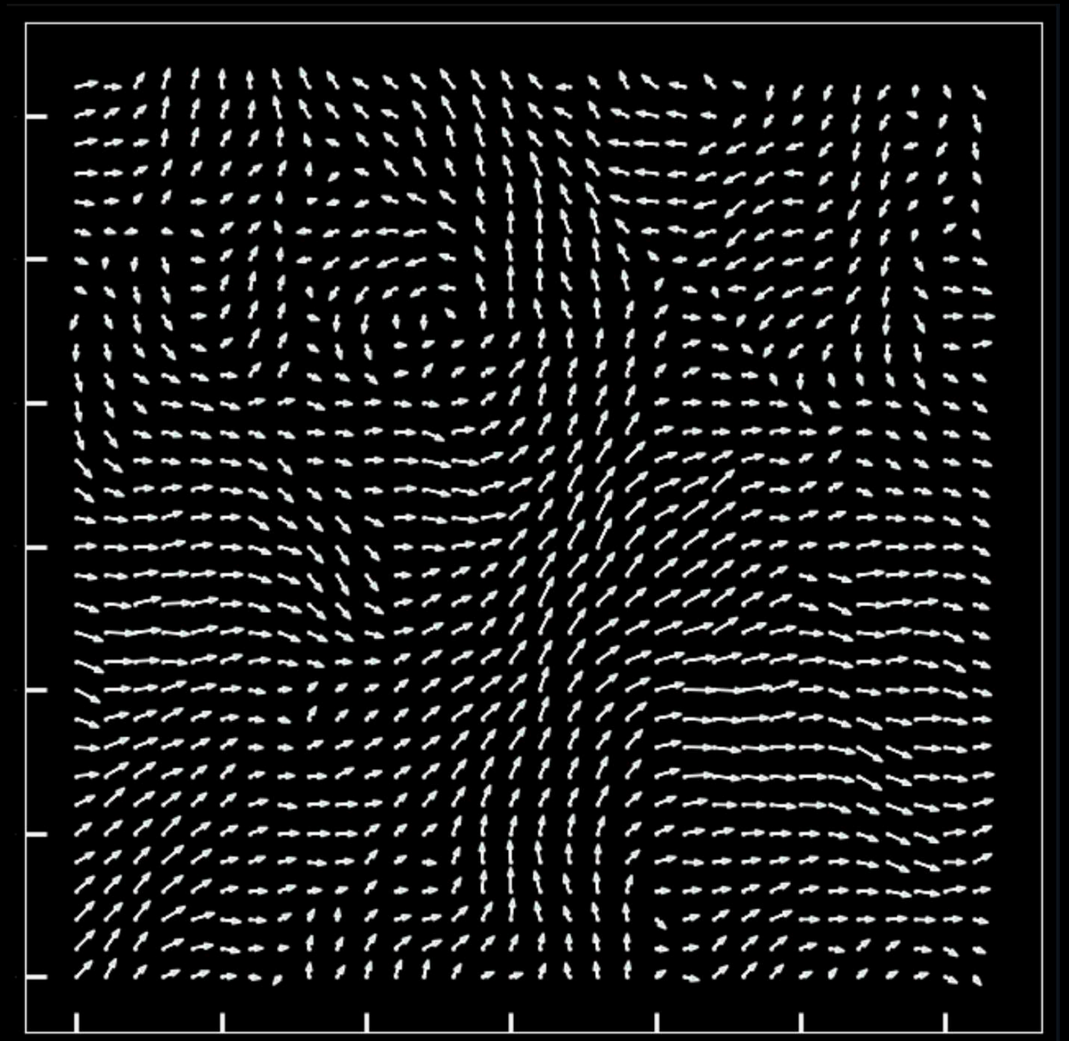


Parameters

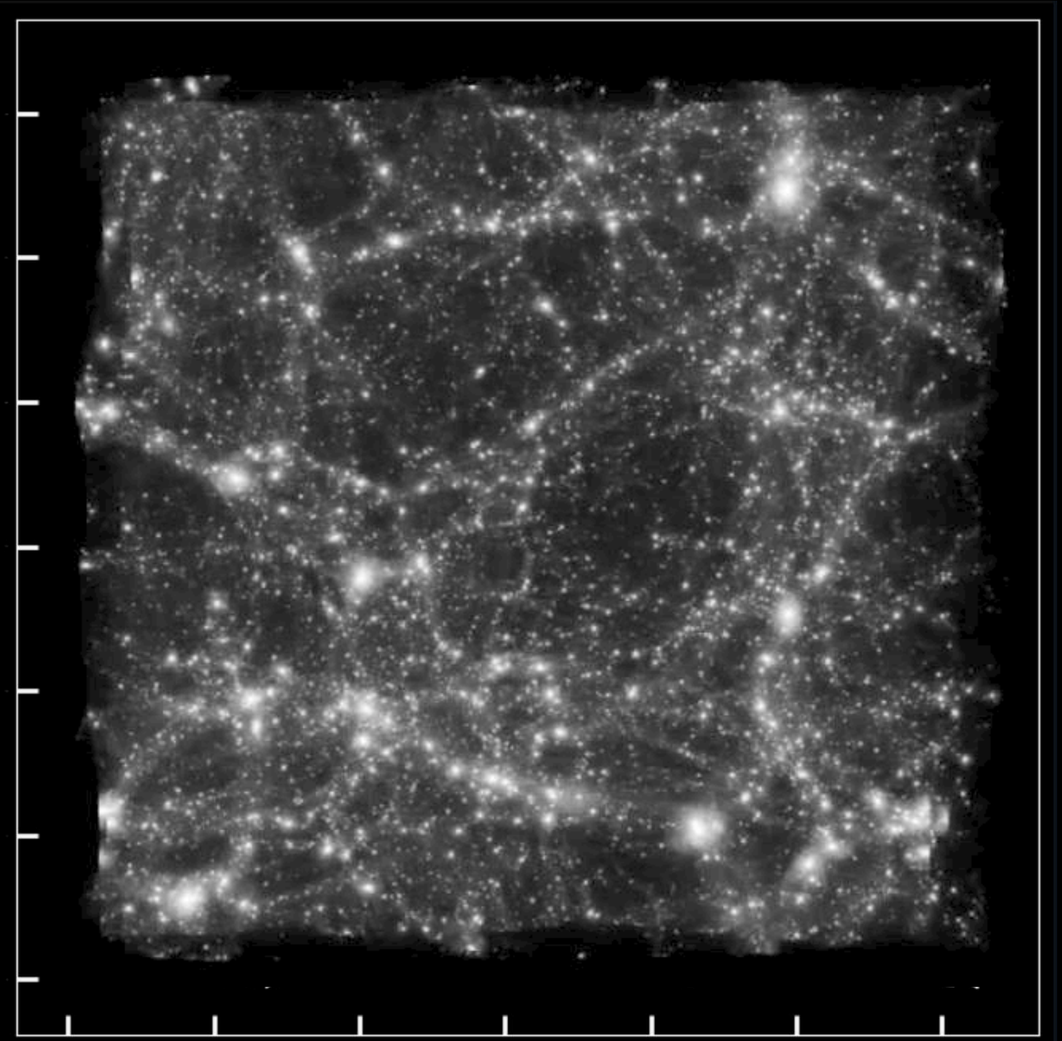
Constraints

N-body simulations

Linear



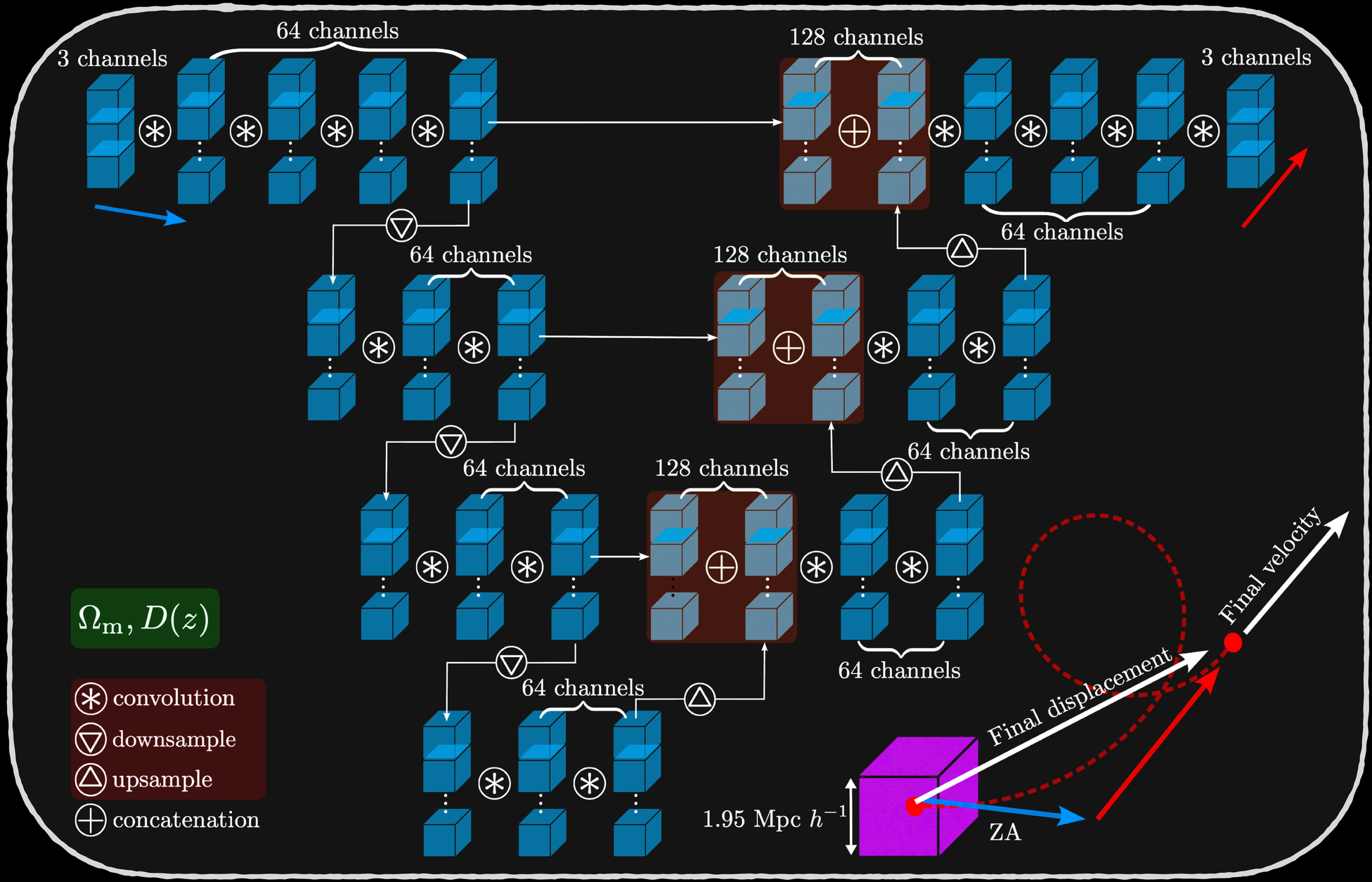
Nonlinear



Map2Map

Map2Map: https://github.com/eelregit/map2map

- U-Net/V-Net design
- 4 convolutional layers
- Receptive field: 190 Mpc/h
- Preserves ZA on large scales
- Input ZA field at z=0
- Output nonlinear field at redshift z



How to capture the cosmology dependence?

Style vs. content

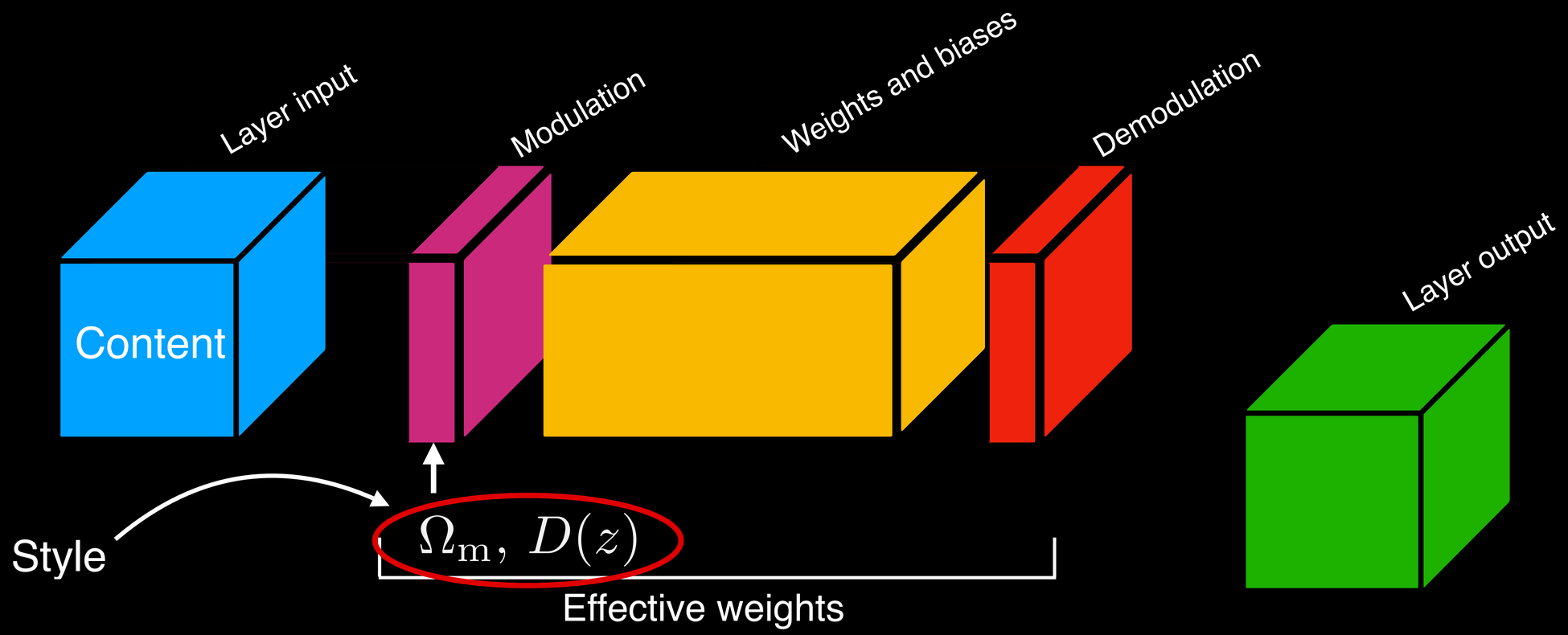
Gatys, Ecker, Bethge arXiv:1508:06576
Karras, Laine, Aittala, Hellsten, Lehtinen, Aila arXiv:1912.04958

Content | Style | Results



Cosmology dependence

StyleGAN2: http://arxiv.org/abs/1912.04958



- Based on StyleGAN2: https://github.com/NVlabs/stylegan2
- $\Omega_{\rm m}$ is a style parameter input for every convolutional operation
- Model learns to interpolate predictions of LSS for different cosmologies

arXiv > astro-ph > arXiv:2408.07699

Astrophysics > Cosmology and Nongalactic Astrophysics

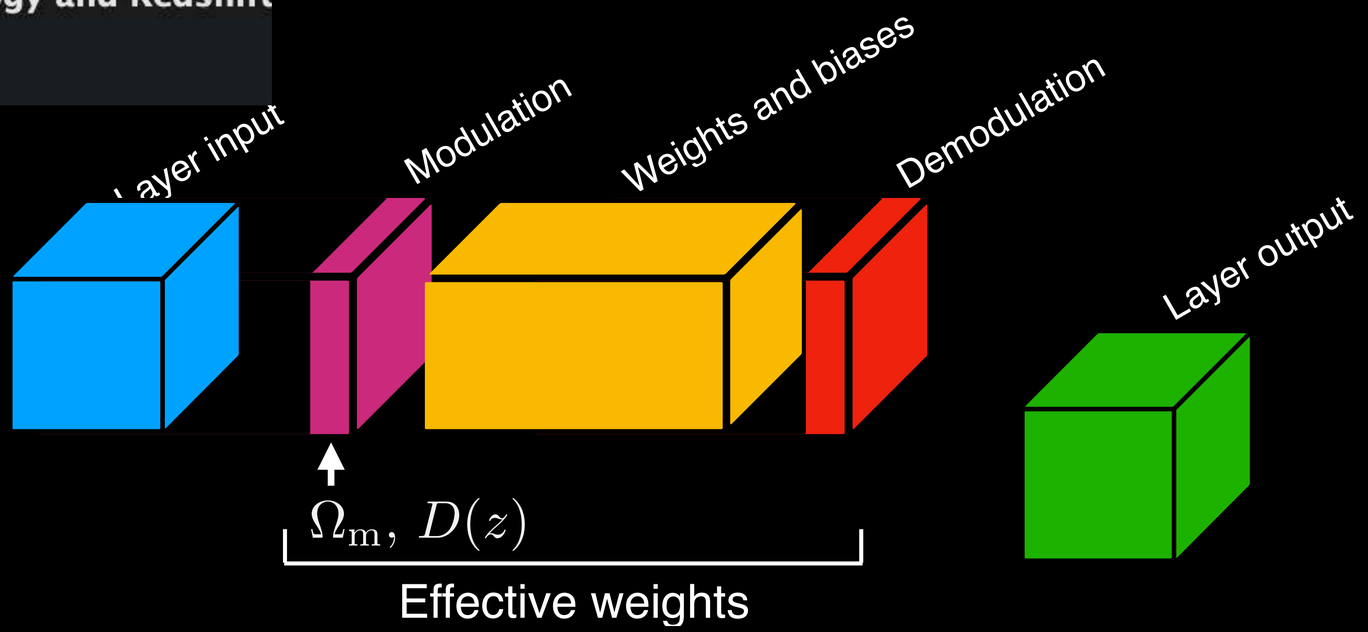
[Submitted on 14 Aug 2024]

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Drew Jamieson, Yin Li, Francisco Villaescusa-Navarro, Shirley Ho, David N. Spergel

Do not need a velocity model!

$$\vec{v} = \dot{\vec{\Psi}} = \frac{\partial \vec{\Psi}}{\partial D} \frac{\mathrm{d}D}{\mathrm{d}t}$$



Evaluate velocities during training and add to loss

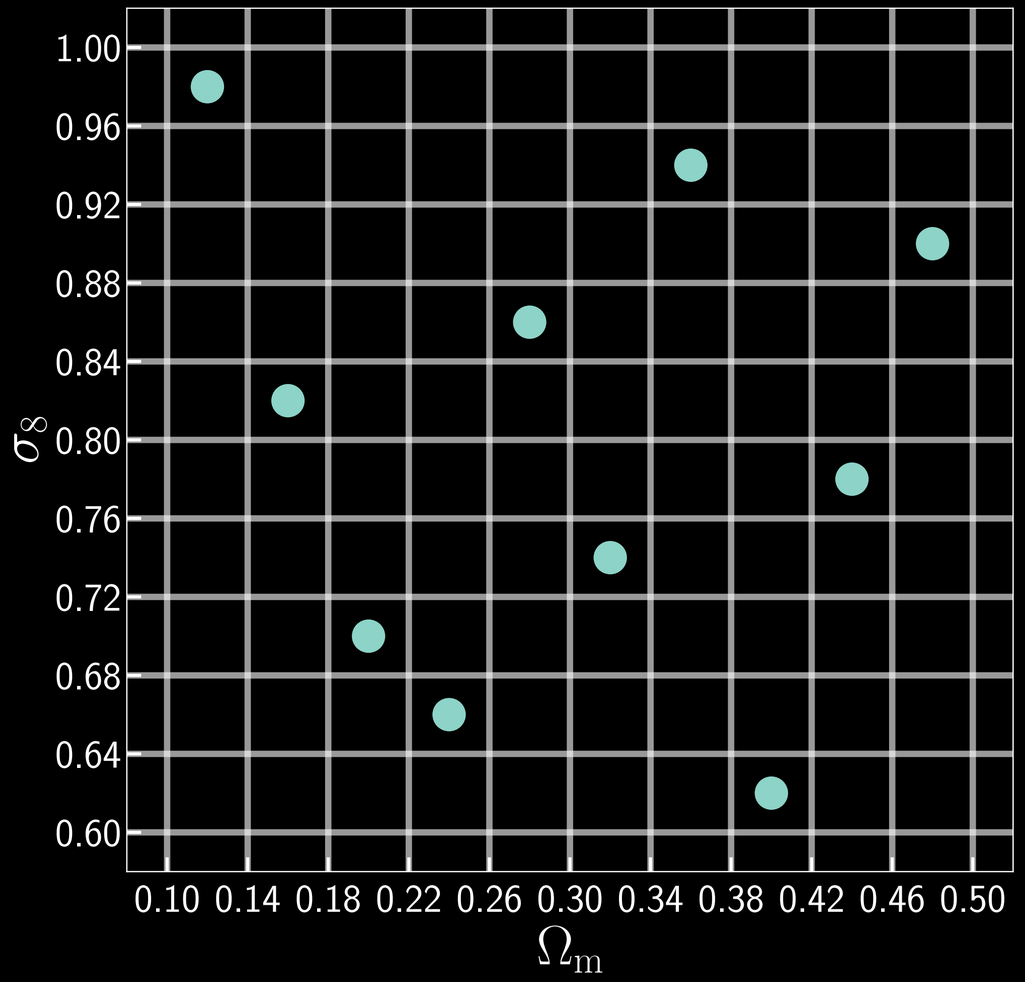
$$\mathrm{loss} = \log(\sum \mathrm{displacement\ error}^2) + \log(\sum \mathrm{density\ error}^2) + \log(\sum \mathrm{velocity\ error}^2) + \log(\sum \mathrm{momentum\ error}^2)$$

Training Data: Quijote Latin Hypercube

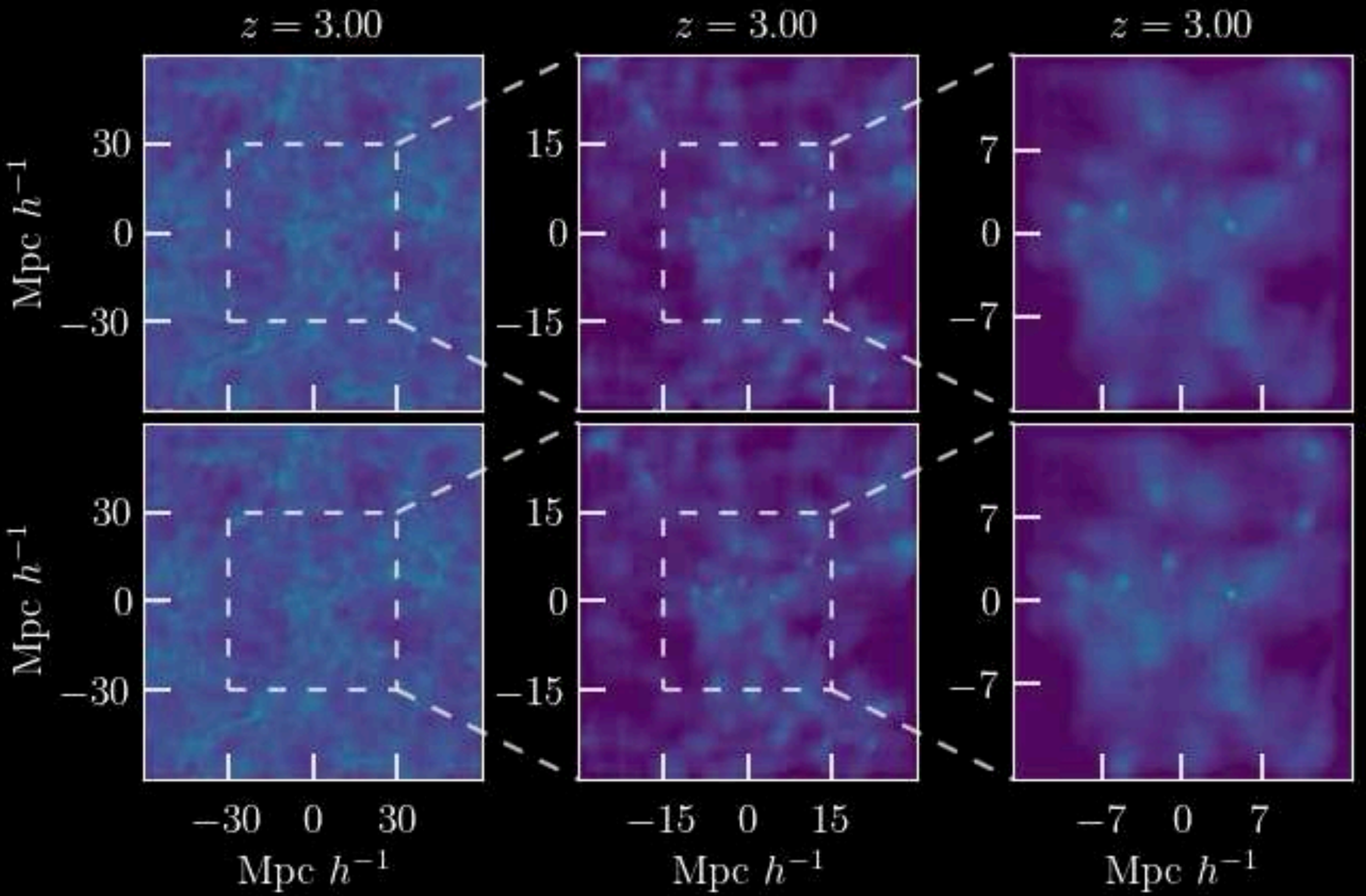
Villaescusa-Navarro et al. arXiv:1909:05273

- 2000 simulations
- 512^3 particles 1 Gpc/h box
- Latin hypercube sample of 5 parameters

Ω_m	$0.1 - 0.5$
Ω_b	$0.03 - 0.07$
h	$0.5 - 0.9$
n_s	$0.8 - 1.2$
σ_8	$0.6 - 1.0$



Cosmology and time dependence



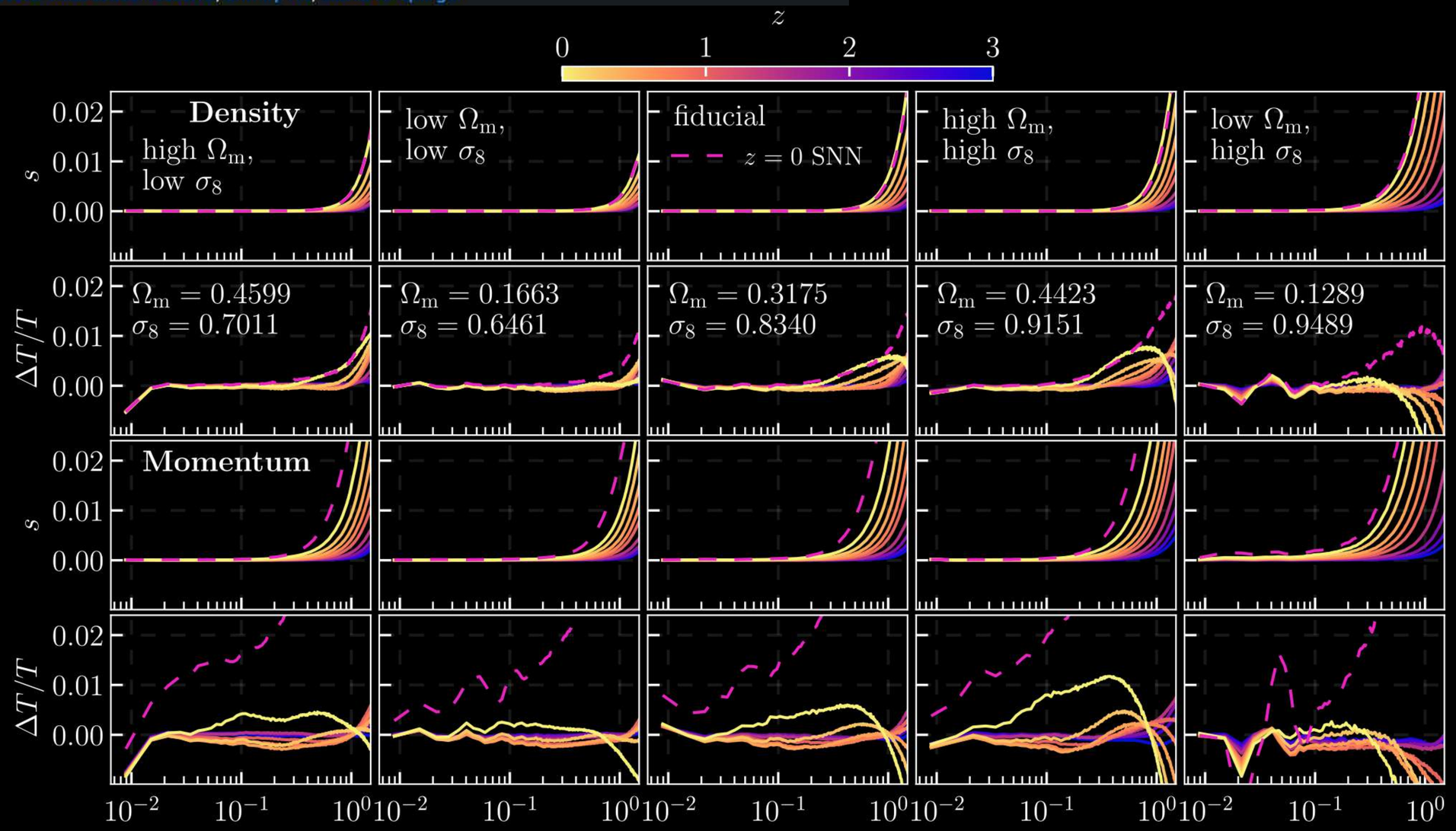
arXiv > astro-ph > arXiv:2408.07699

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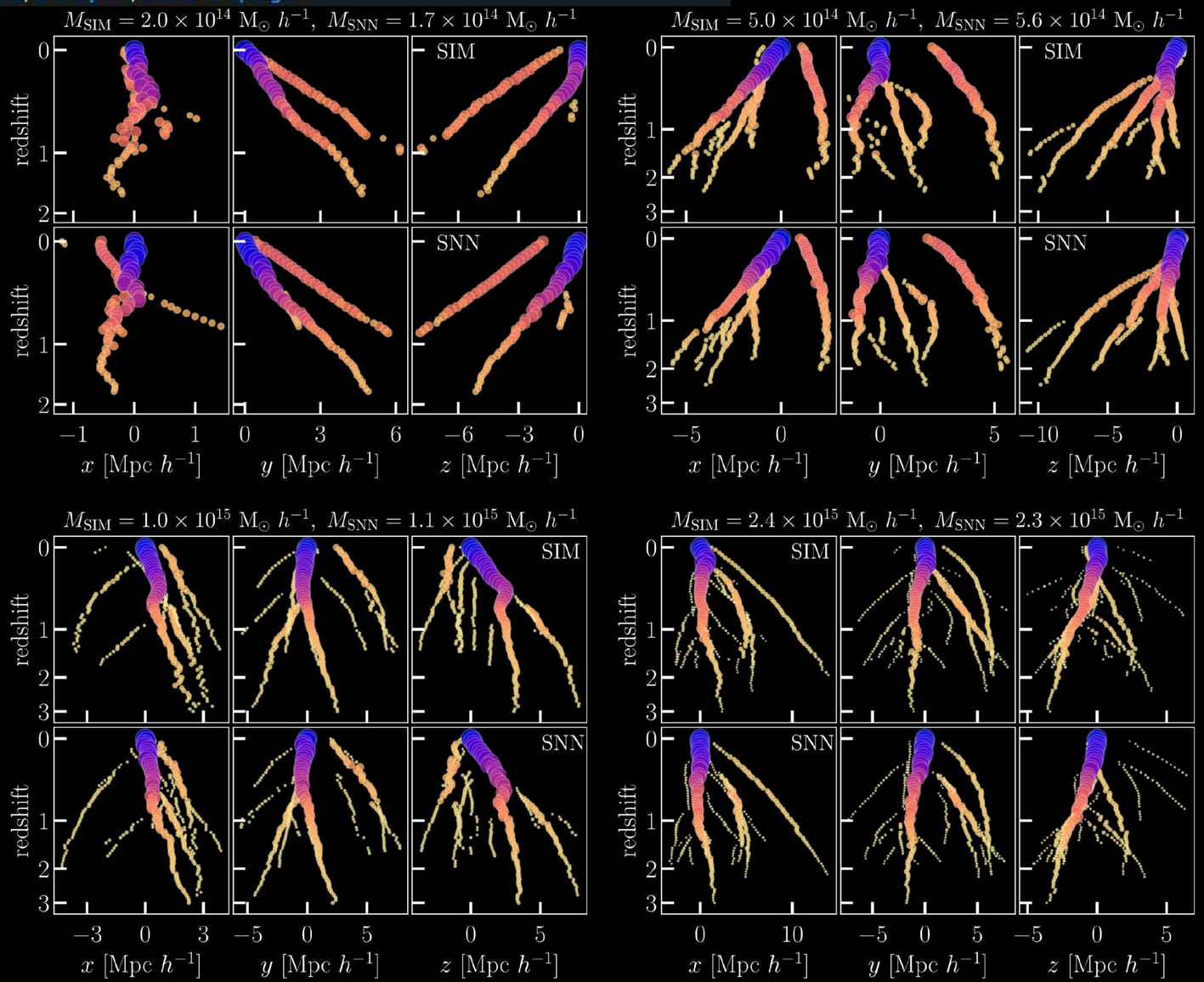
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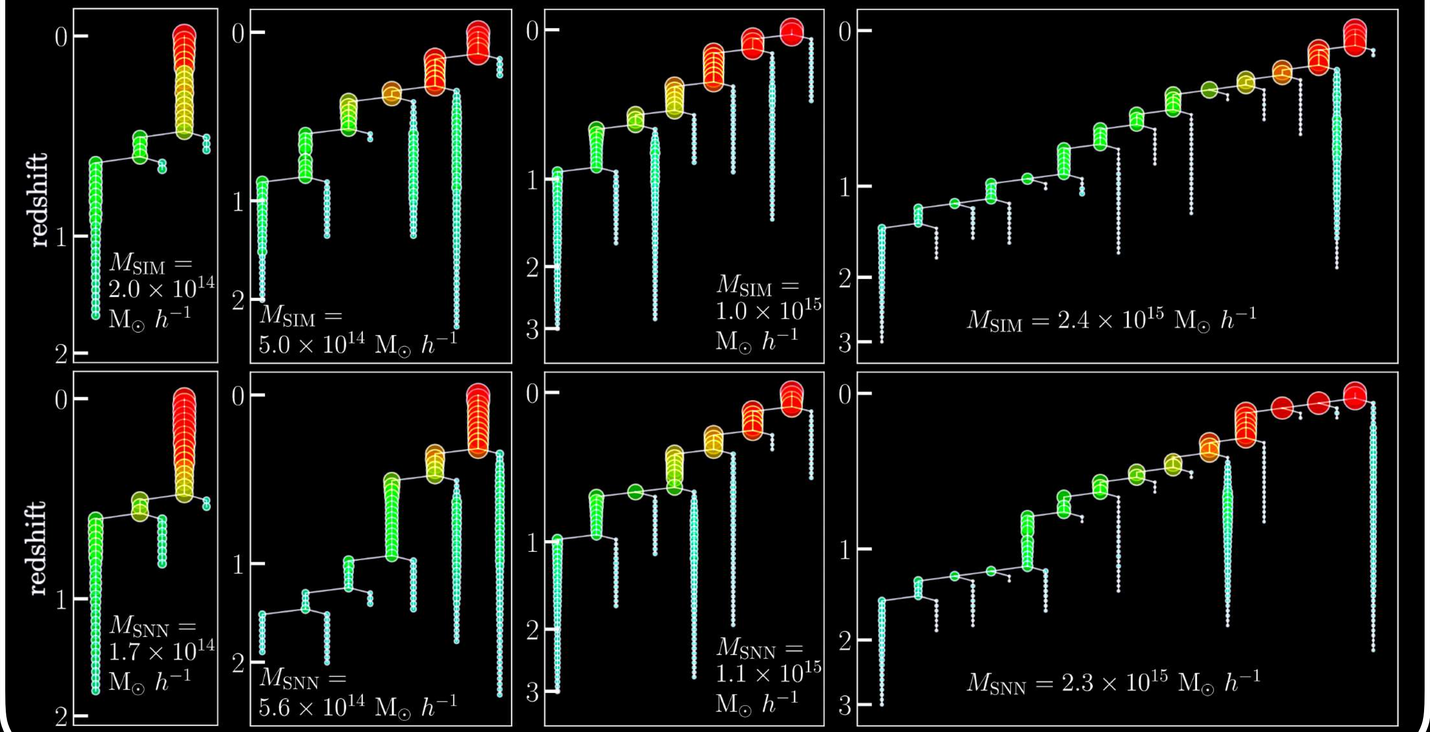
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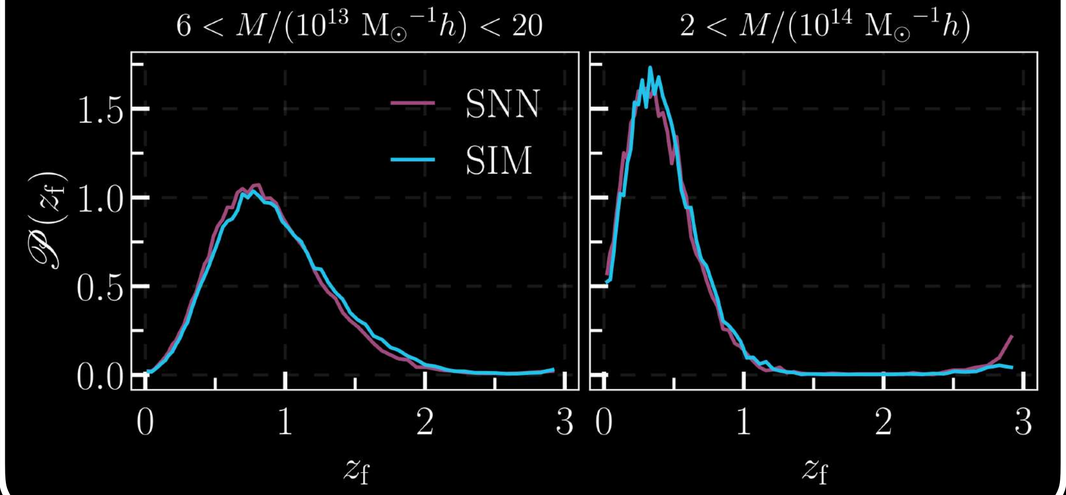
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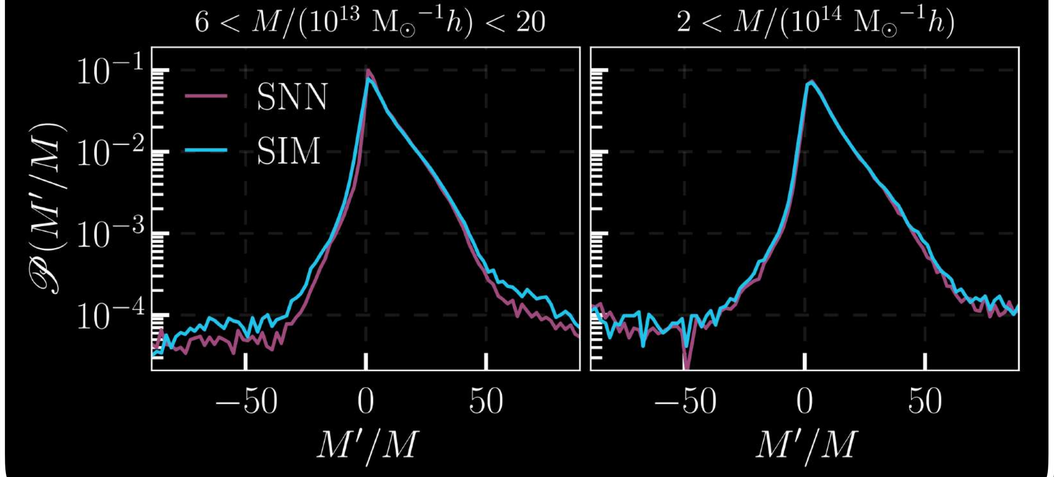
Individual Merger Trees



Formation Redshift



Mass Accretion



Conclusion:

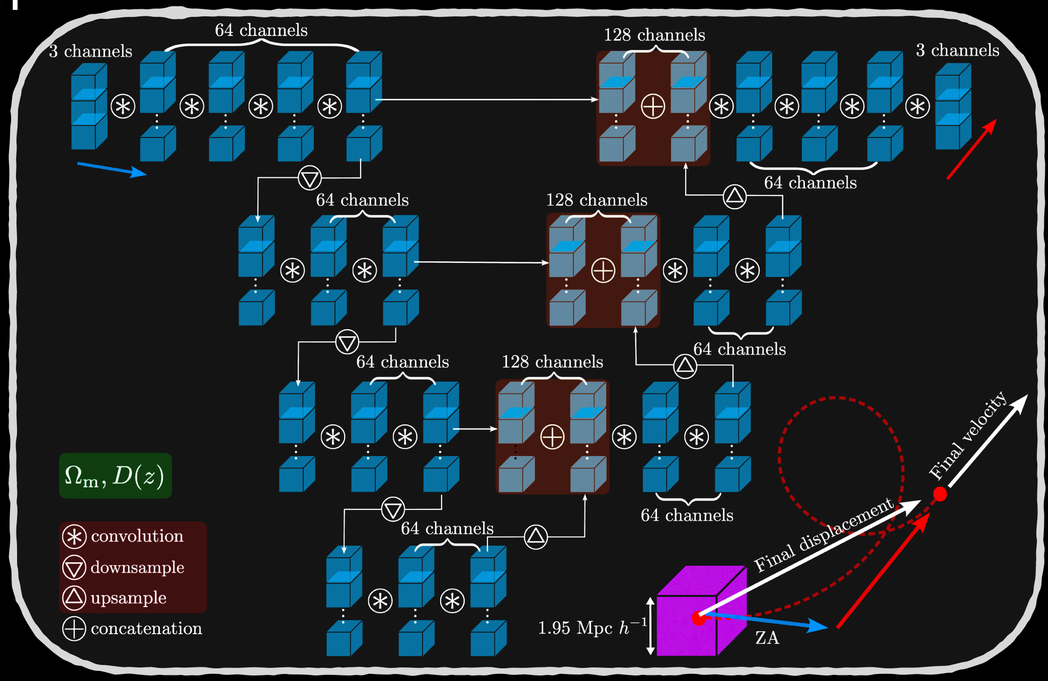
https://github.com/eelregit/map2map
https://github.com/dsjamieson/map2map_emu

- Emulator is fast and accurate in the nonlinear regime
- Differentiable, can sample over cosmology and ICs
- Models the phase space of N-body at the field level
- Models the redshift dependence of structure formation

arXiv:2206.04594 arXiv:2307.09134
arXiv:2206.0457 arXiv:2312.0927

Outlook

- Additional parameters: $\Omega_K, M_\nu, w(z), \ldots$
- Super-resolution?
- Baryons?
- Lightcones?



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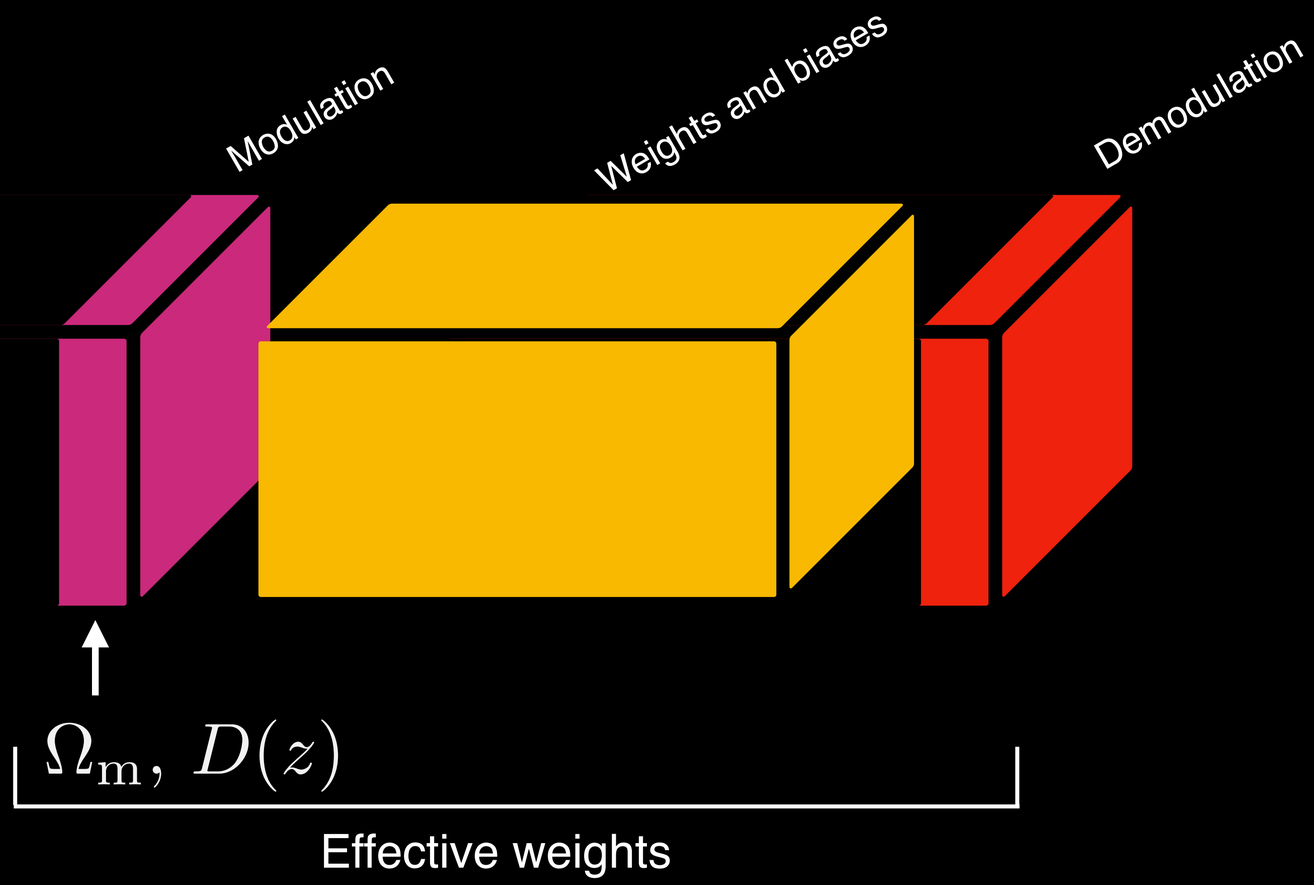
arXiv > astro-ph > arXiv:2408.07699

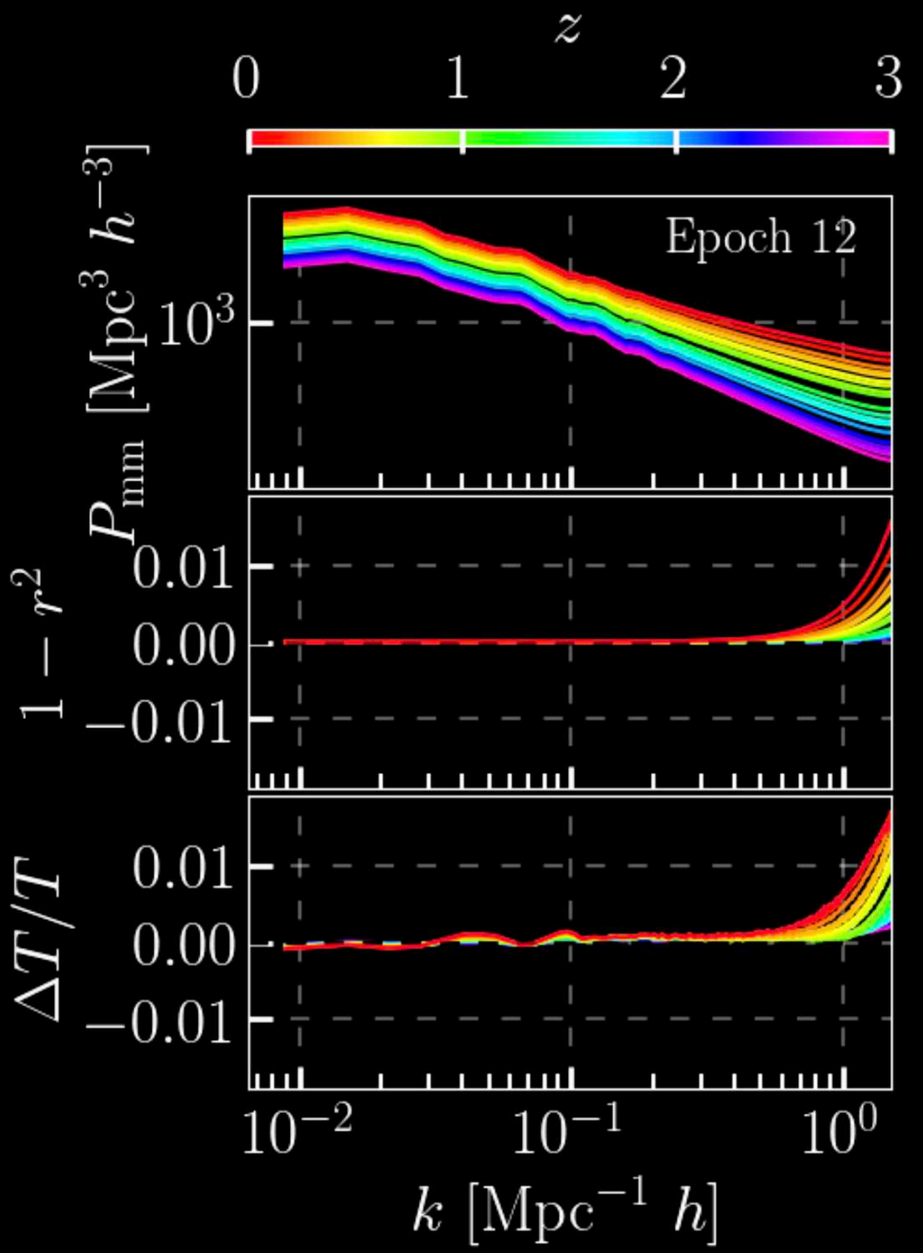
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Field-level Emulation of Cosmic Structure Formation with Cosmology and Redshift Dependence

Drew Jamieson, Yin Li, Francisco Villaescusa-Navarro, Shirley Ho, David N. Spergel





Why Convolutional Neural Networks?

- Linear theory capture global information

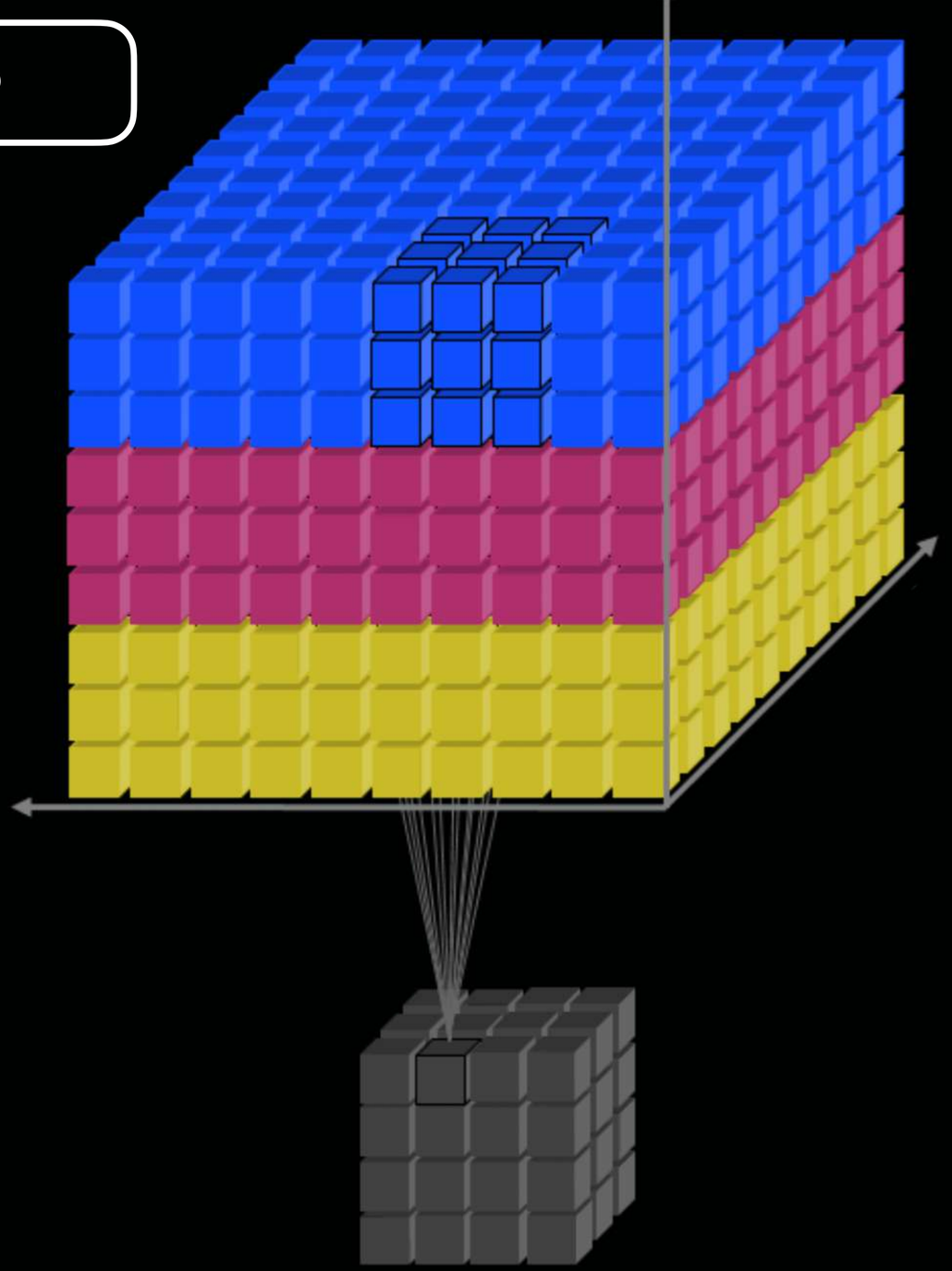
  → Poisson equation

- Nonlinearity is sensitive to local environment

- Convolutions combine neighborhood information

- Multiple convolutions probe difference scales

  → Mode coupling



How serious is the σ_8 error dependence?

arXiv > astro-ph > arXiv:2307.09134

Astrophysics > Cosmology and Nongalactic Astrophysics

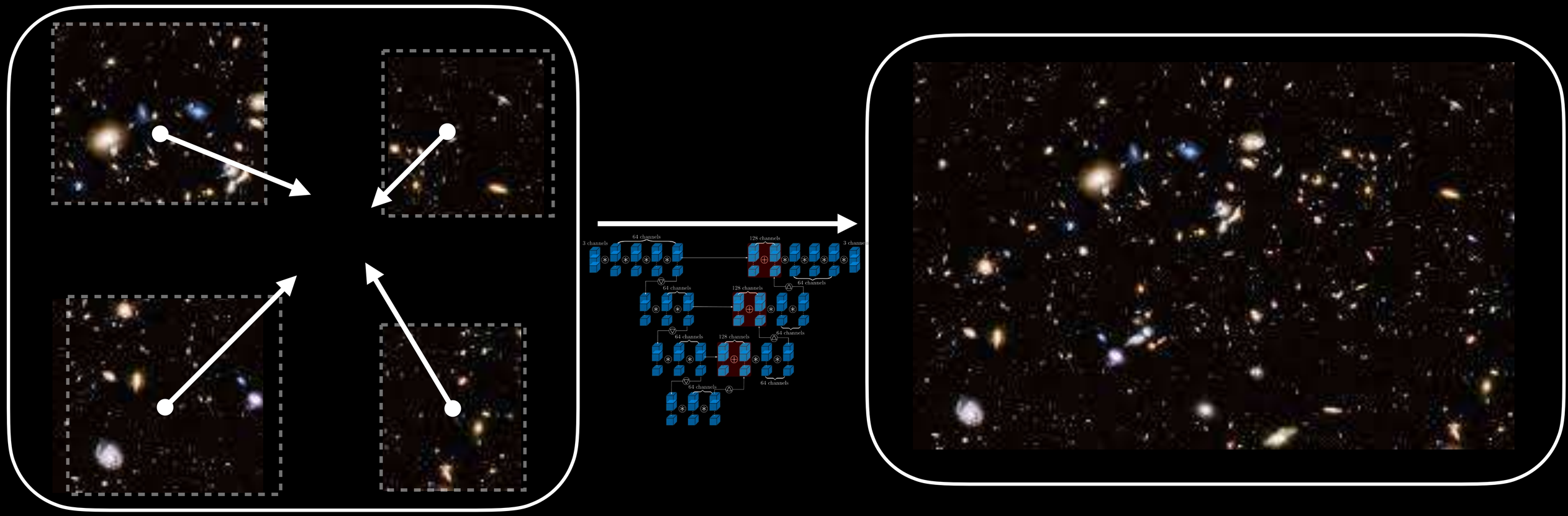
[Submitted on 18 Jul 2023 (v1), last revised 21 Jul 2023 (this version, v2)]

Hybrid-bias and displacement emulators for field-level modelling of galaxy clustering in real and redshift space

Marcos Pellejero Ibanez, Raul E. Angulo, Drew Jamieson, Yin Li

Biased galaxy field in Lagragian space:

$$\delta_g = b_1\delta + b_2(\delta^2 - \langle\delta^2\rangle) + b_{s^2}(s^2 - \langle s^2\rangle) + b_\nabla\nabla^2\delta$$



arXiv > astro-ph > arXiv:2307.09134

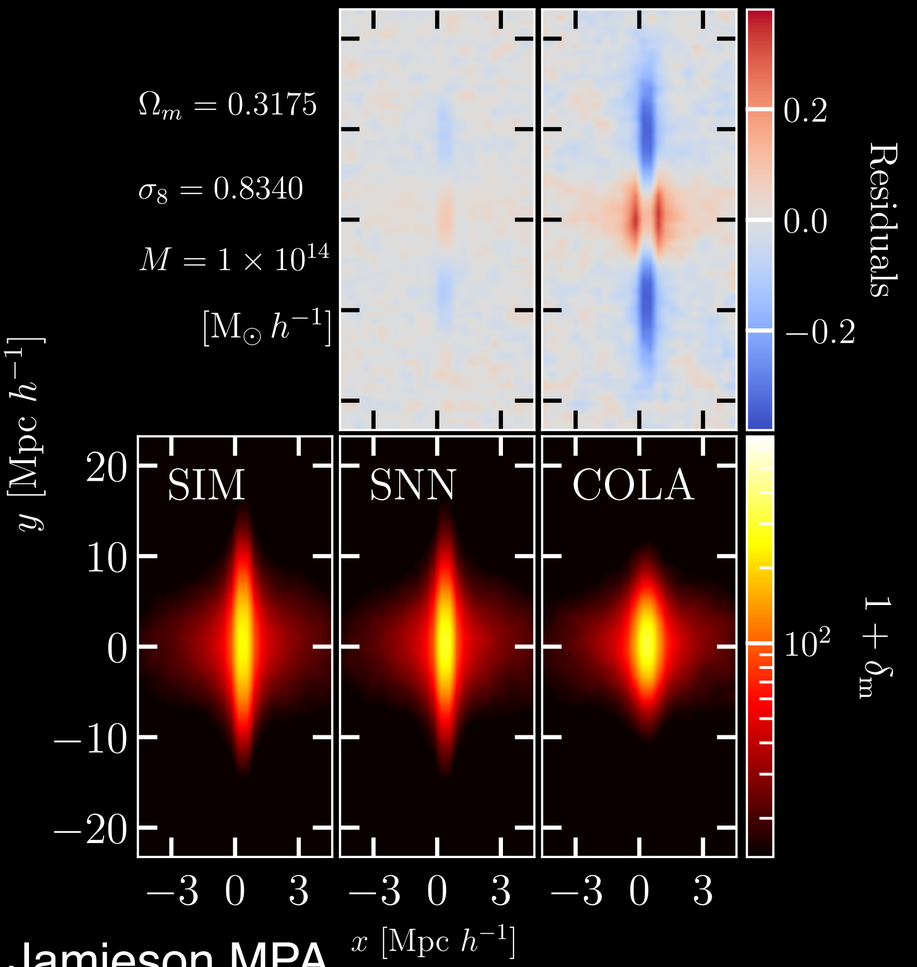
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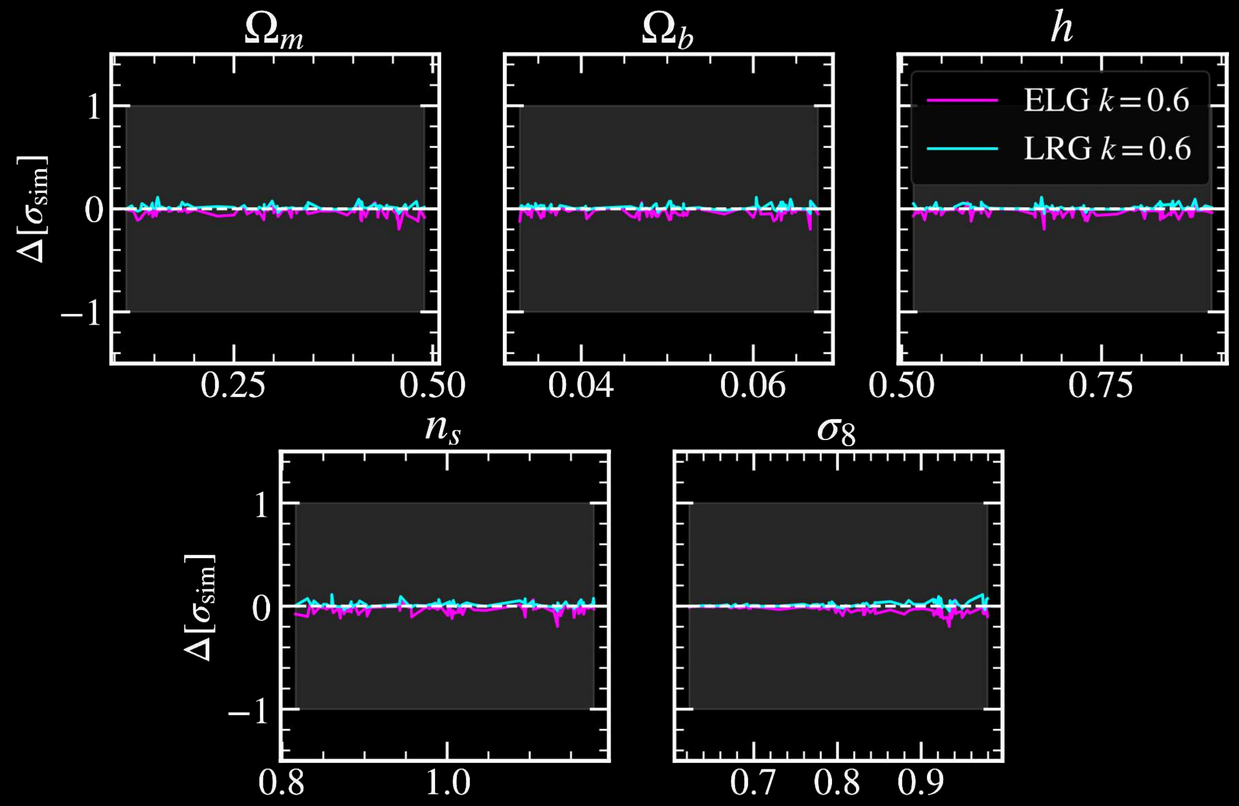
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Hybrid-bias and displacement emulators for field-level modelling of galaxy clustering in real and redshift space

Marcos Pellejero Ibanez, Raul E. Angulo, Drew Jamieson, Yin Li

Redshift space

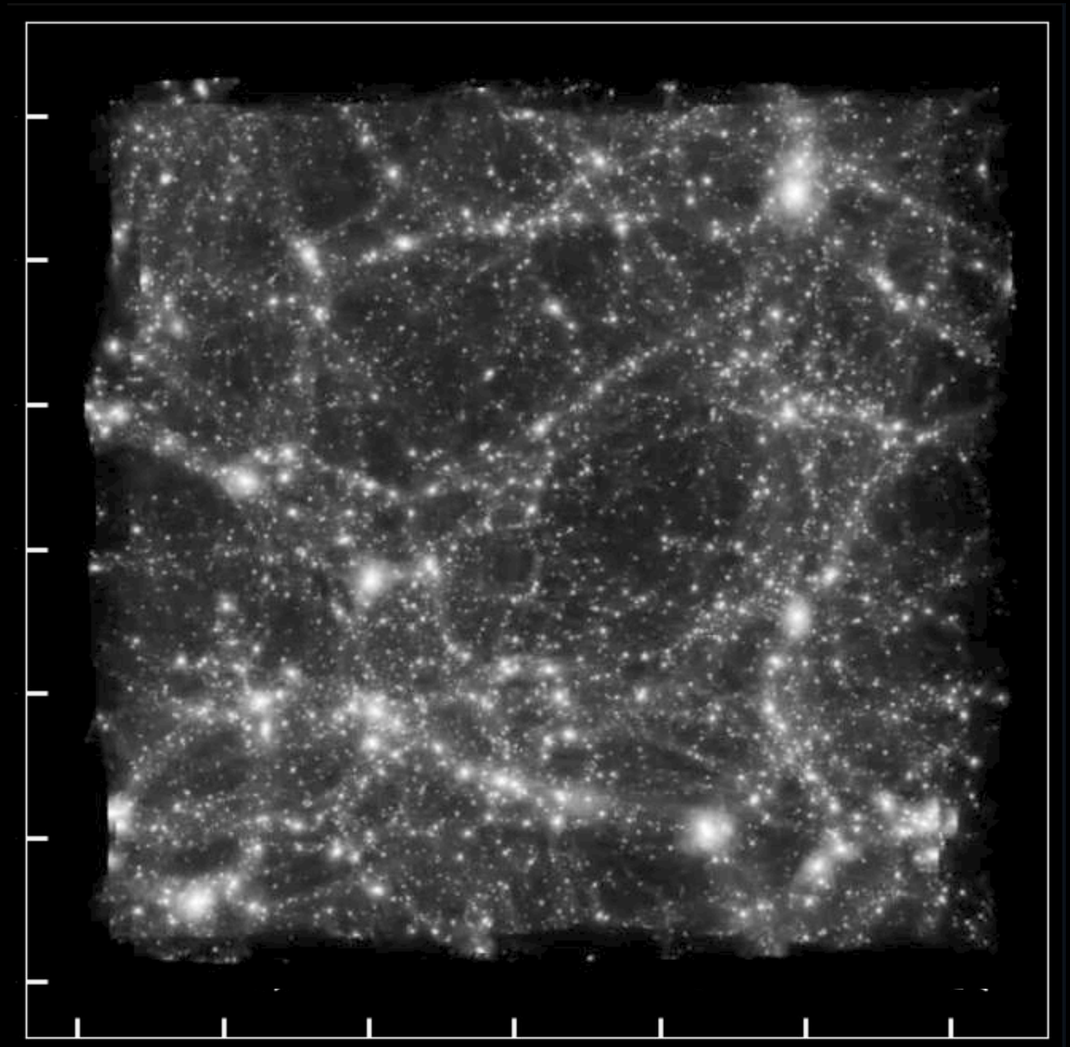




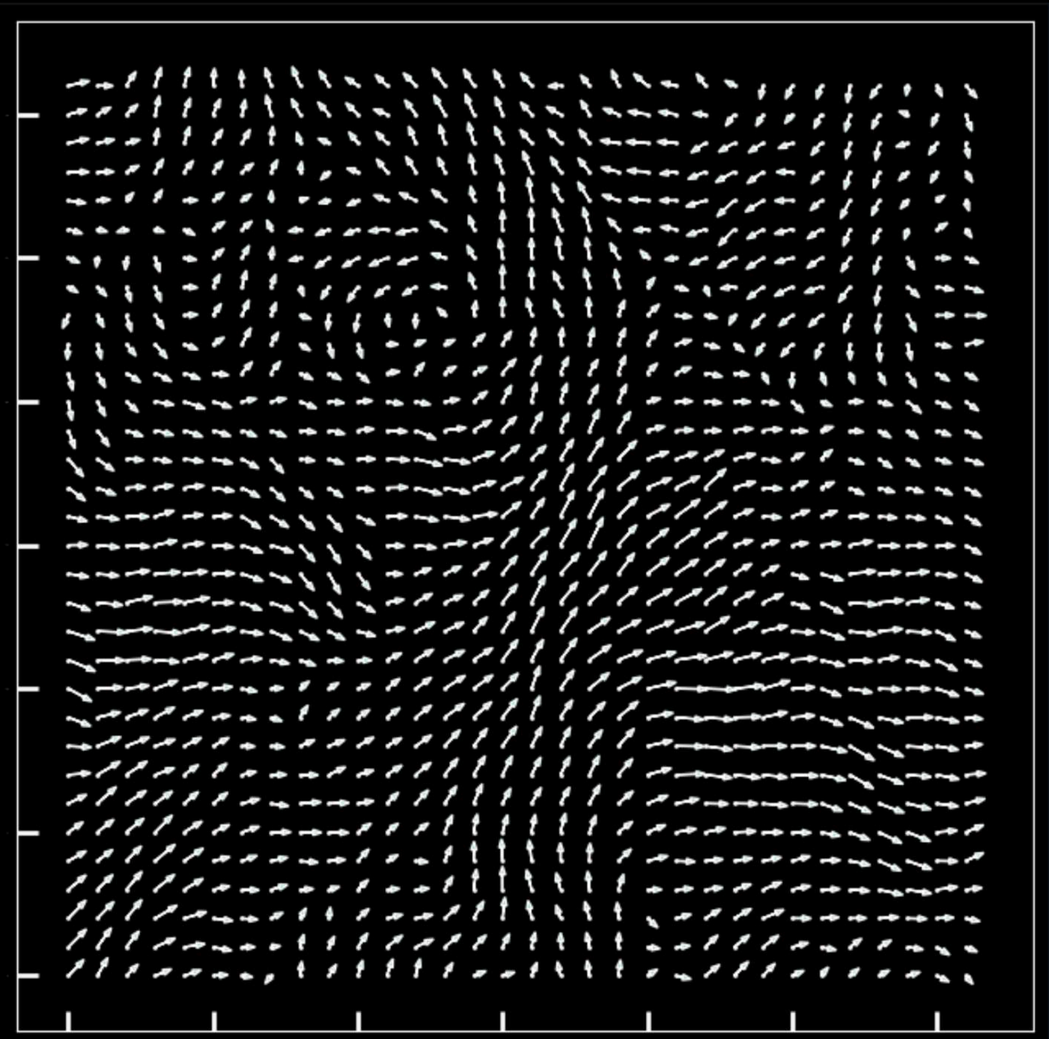
Redshift space and noise parameters absorb the σ_8 dependence

Adding redshift dependence

Can it learn the initial conditions?



?



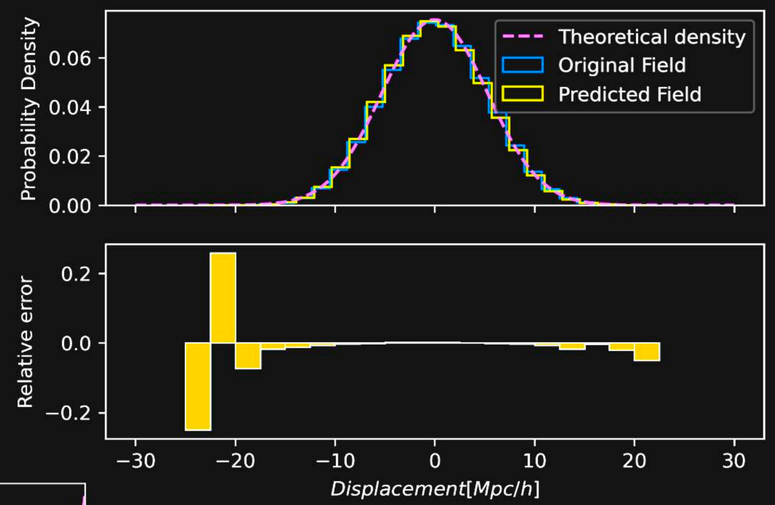
arXiv > astro-ph > arXiv:2303.13056

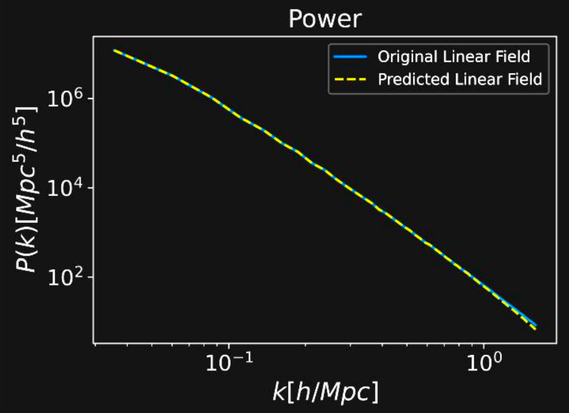
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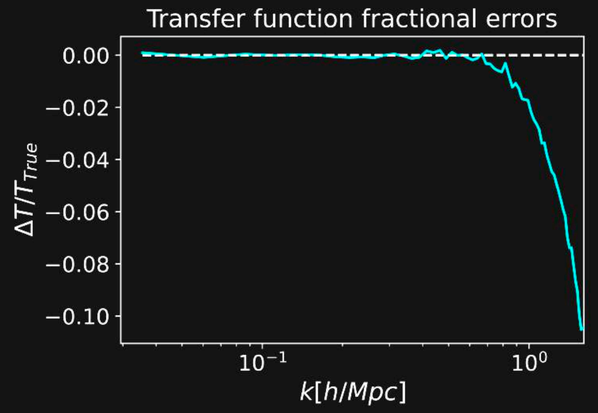
[Submitted on 23 Mar 2023]

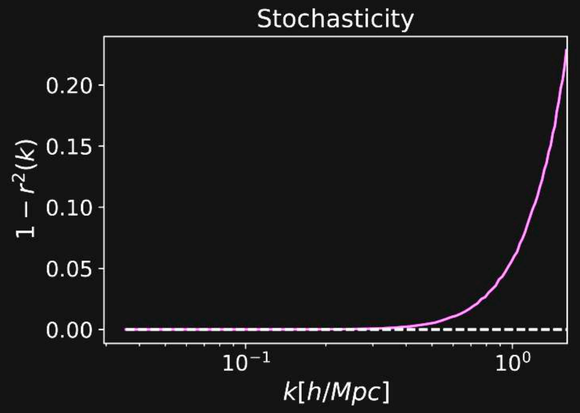
Predicting the Initial Conditions of the Universe using Deep Learning

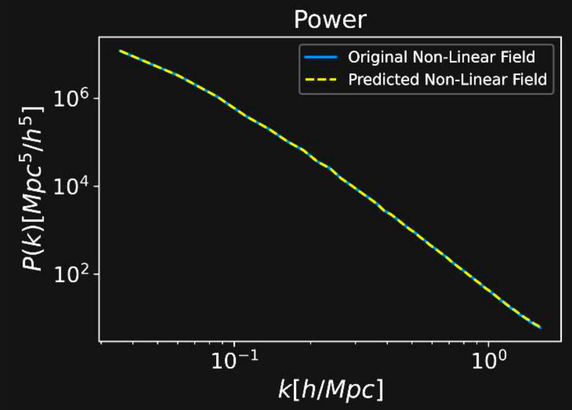
Vaibhav Jindal, Drew Jamieson, Albert Liang, Aarti Singh, Shirley Ho

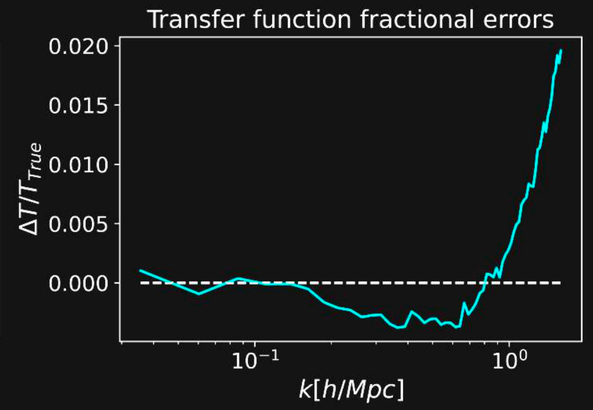


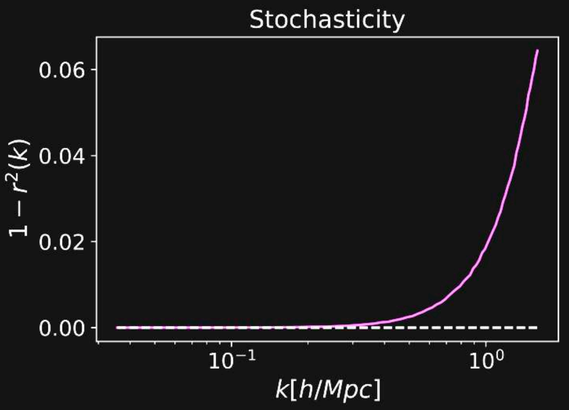












arXiv > astro-ph > arXiv:2312.09271

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[Submitted on 14 Dec 2023]

Bayesian Inference of Initial Conditions from Non-Linear Cosmic Structures using Field-Level Emulators

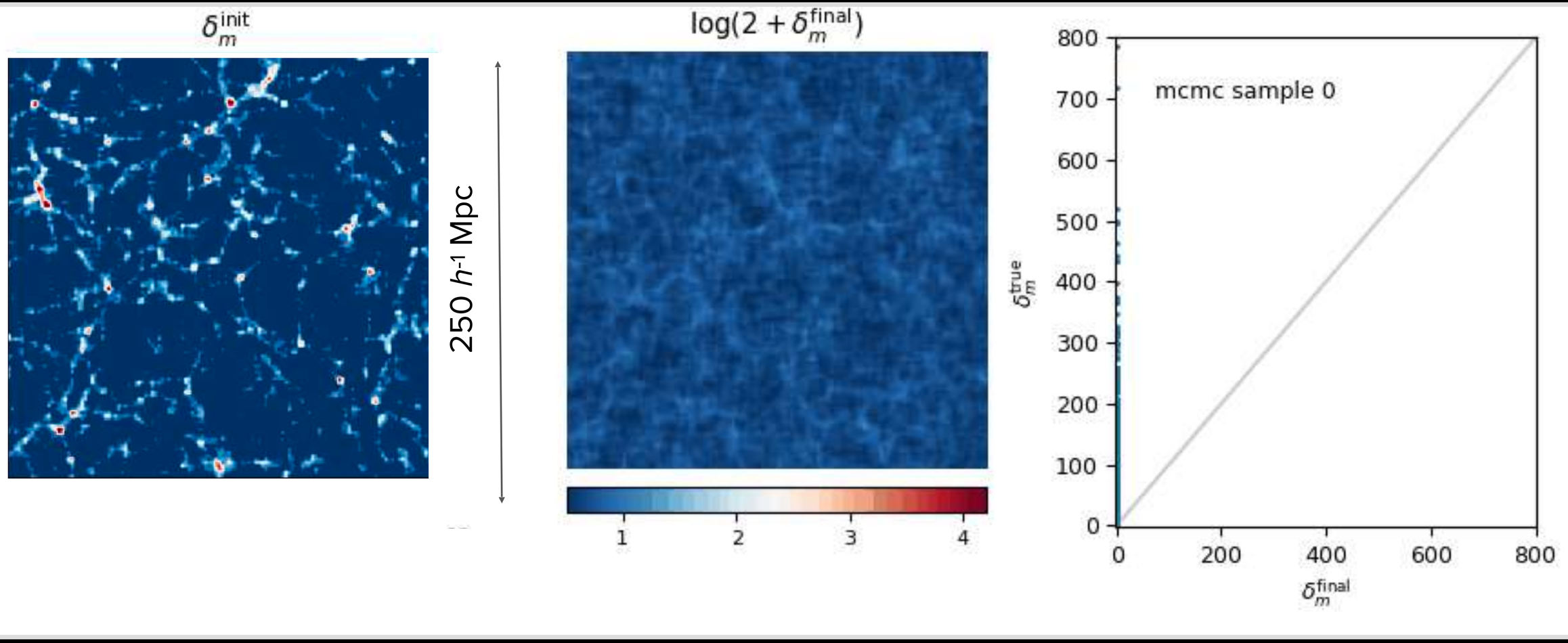
Ludvig Doeser, Drew Jamieson, Stephen Stopyra, Guilhem Lavaux, Florent Leclercq, Jens Jasche

Ludvig Doeser



BORG

Jasche, Wandelt arXiv:1203.3639



Drew Jamieson MPA

KIAS, 01.11.2024

arXiv > astro-ph > arXiv:2312.09271

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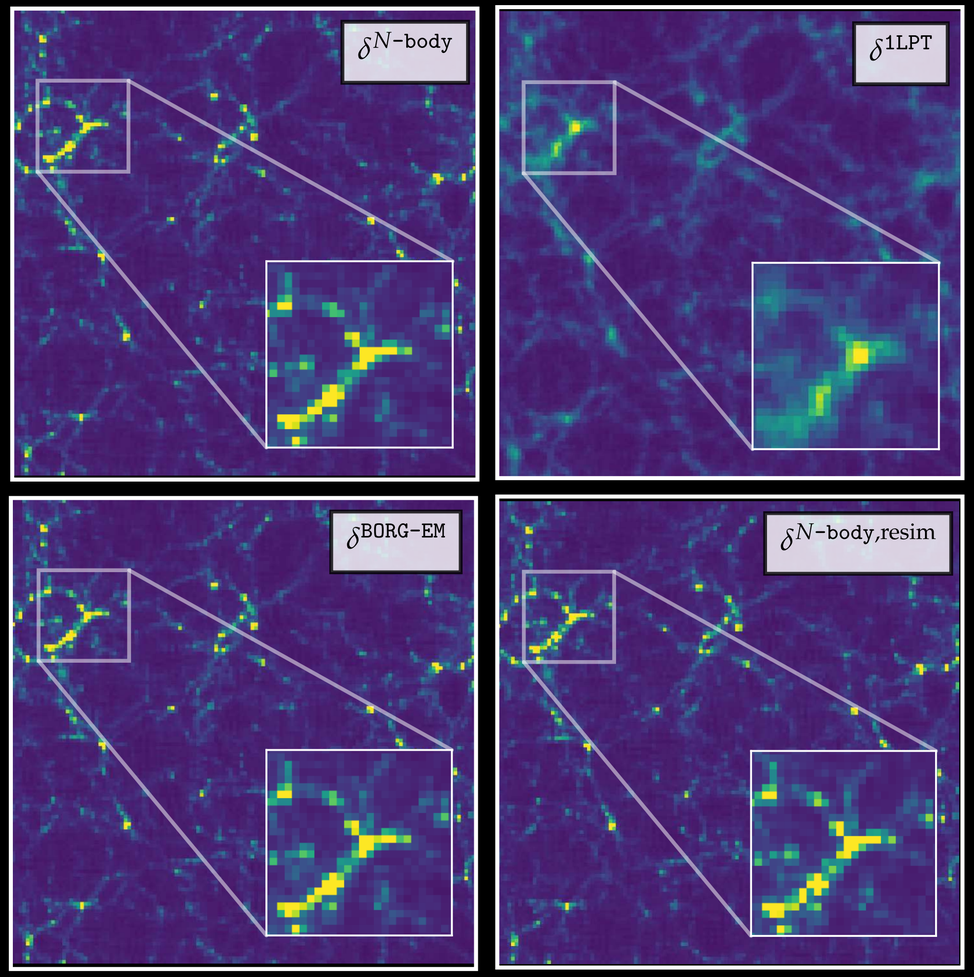
[Submitted on 14 Dec 2023]

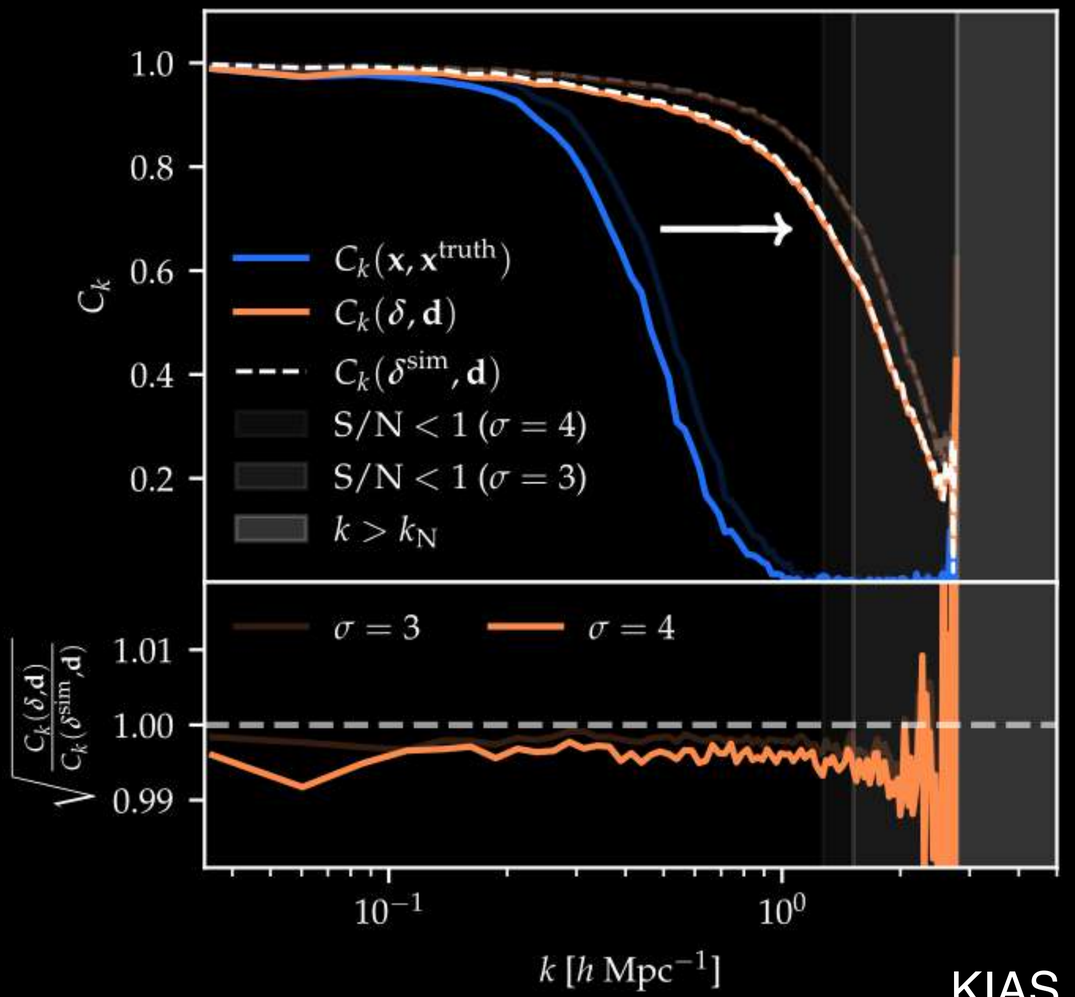
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Ludvig Doeser, Drew Jamieson, Stephen Stopyra, Guilhem Lavaux, Florent Leclercq, Jens Jasche

Ludvig Doeser







Drew Jamieson MPA

KIAS, 01.11.2024

Is it learning physics?

arXiv > astro-ph > arXiv:2206.04573

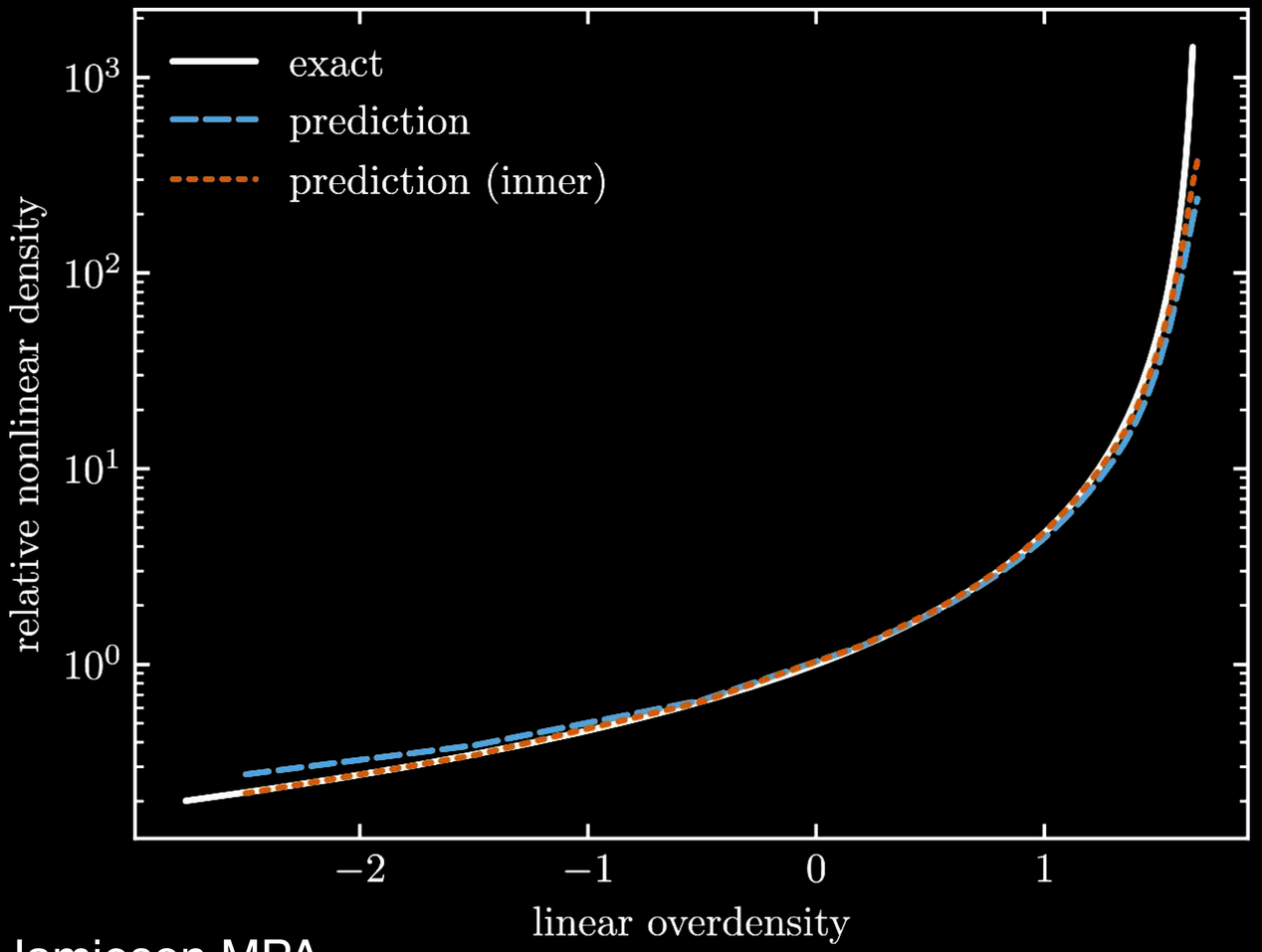
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[Submitted on 9 Jun 2022 (v1), last revised 14 Jun 2022 (this version, v2)]

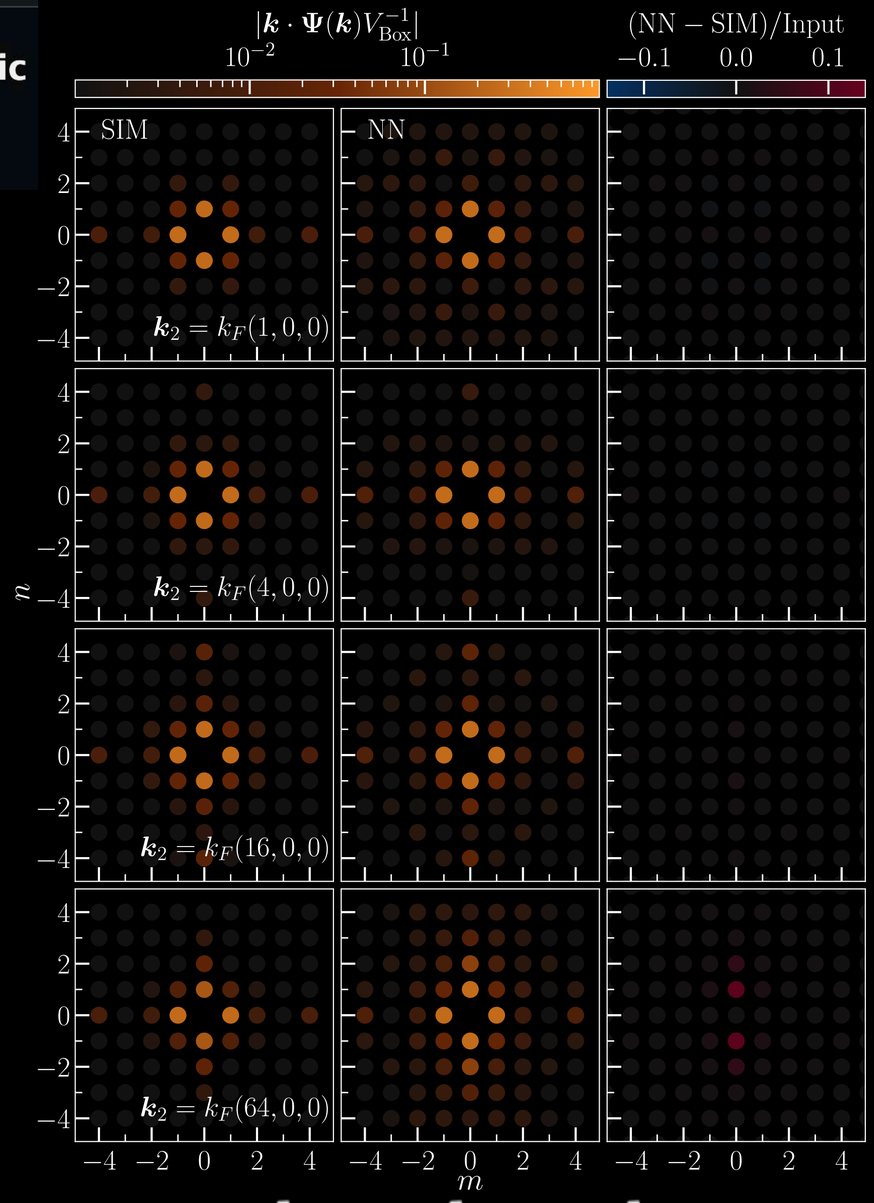
Simple lessons from complex learning: what a neural network model learns about cosmic structure formation

Drew Jamieson, Yin Li, Siyu He, Francisco Villaescusa-Navarro, Shirley Ho, Renan Alves de Oliveira, David N. Spergel

Spherical evolution



Mode coupling



$$\boldsymbol{k} = m\boldsymbol{k}_1 + n\boldsymbol{k}_2$$

arXiv > astro-ph > arXiv:2206.04594

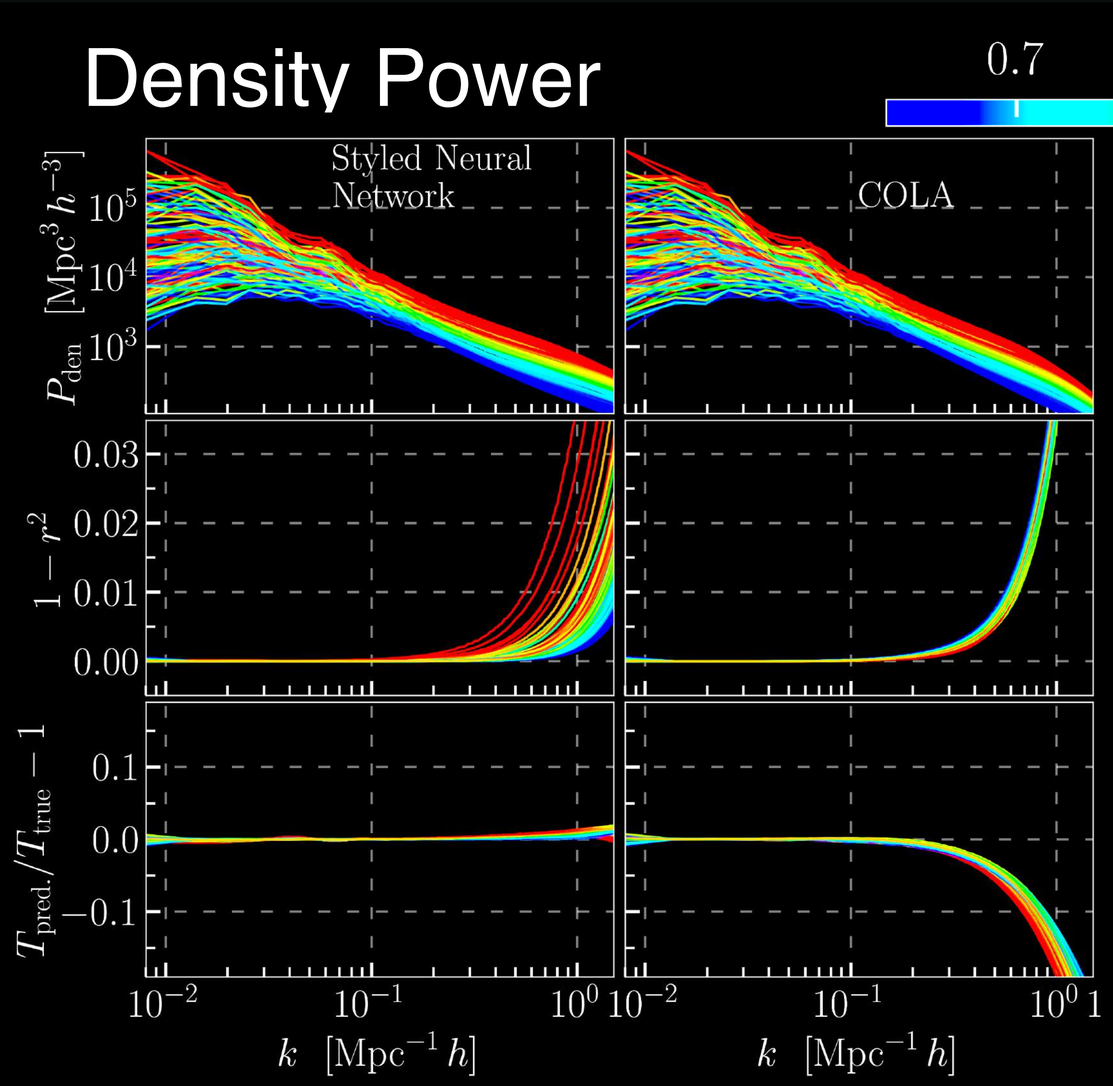
Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 9 Jun 2022 (v1), last revised 14 Jun 2022 (this version, v2)]

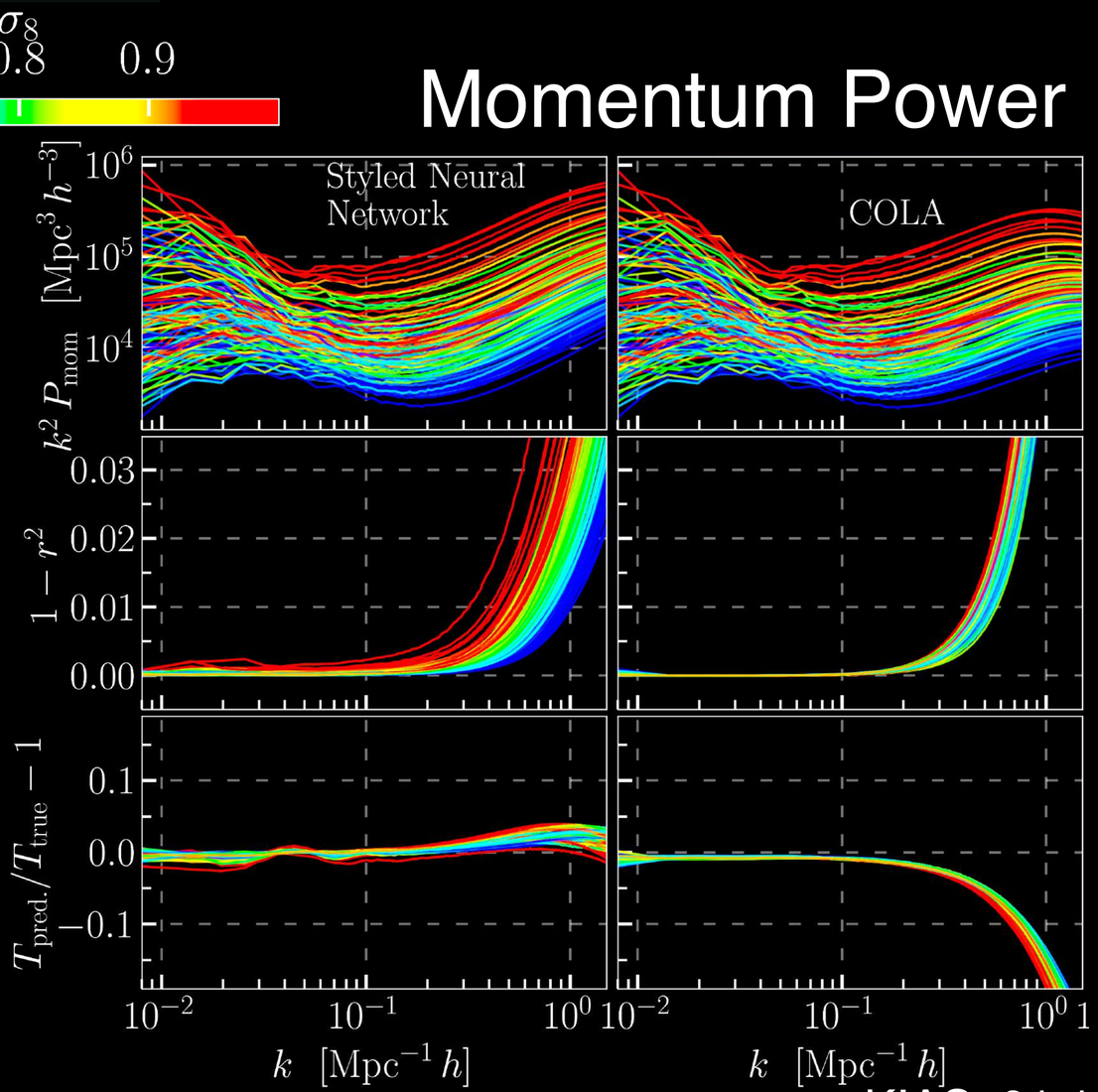
Field Level Neural Network Emulator for Cosmological N-body Simulations

Drew Jamieson, Yin Li, Renan Alves de Oliveira, Francisco Villaescusa-Navarro, Shirley Ho, David N. Spergel

Density Power



Momentum Power



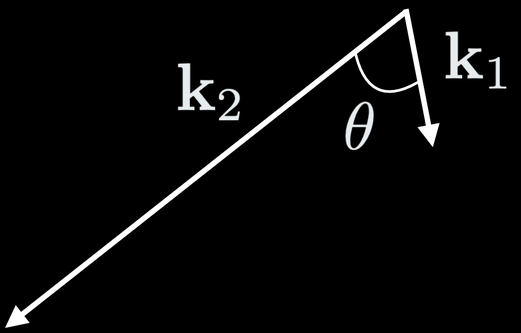
arXiv > astro-ph > arXiv:2206.04594

Astrophysics > Cosmology and Nongalactic Astrophysics

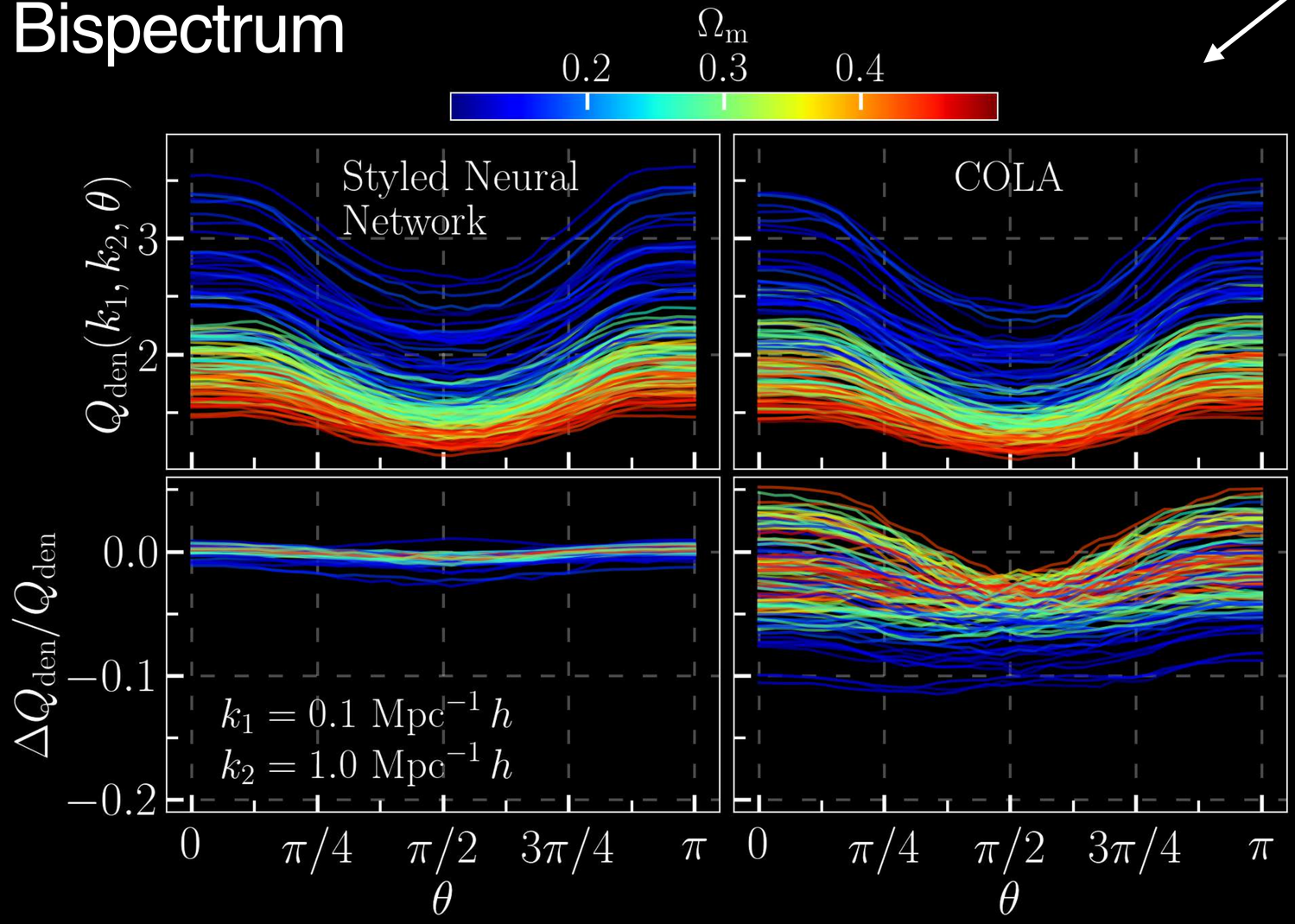
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Field Level Neural Network Emulator for Cosmological N-body Simulations

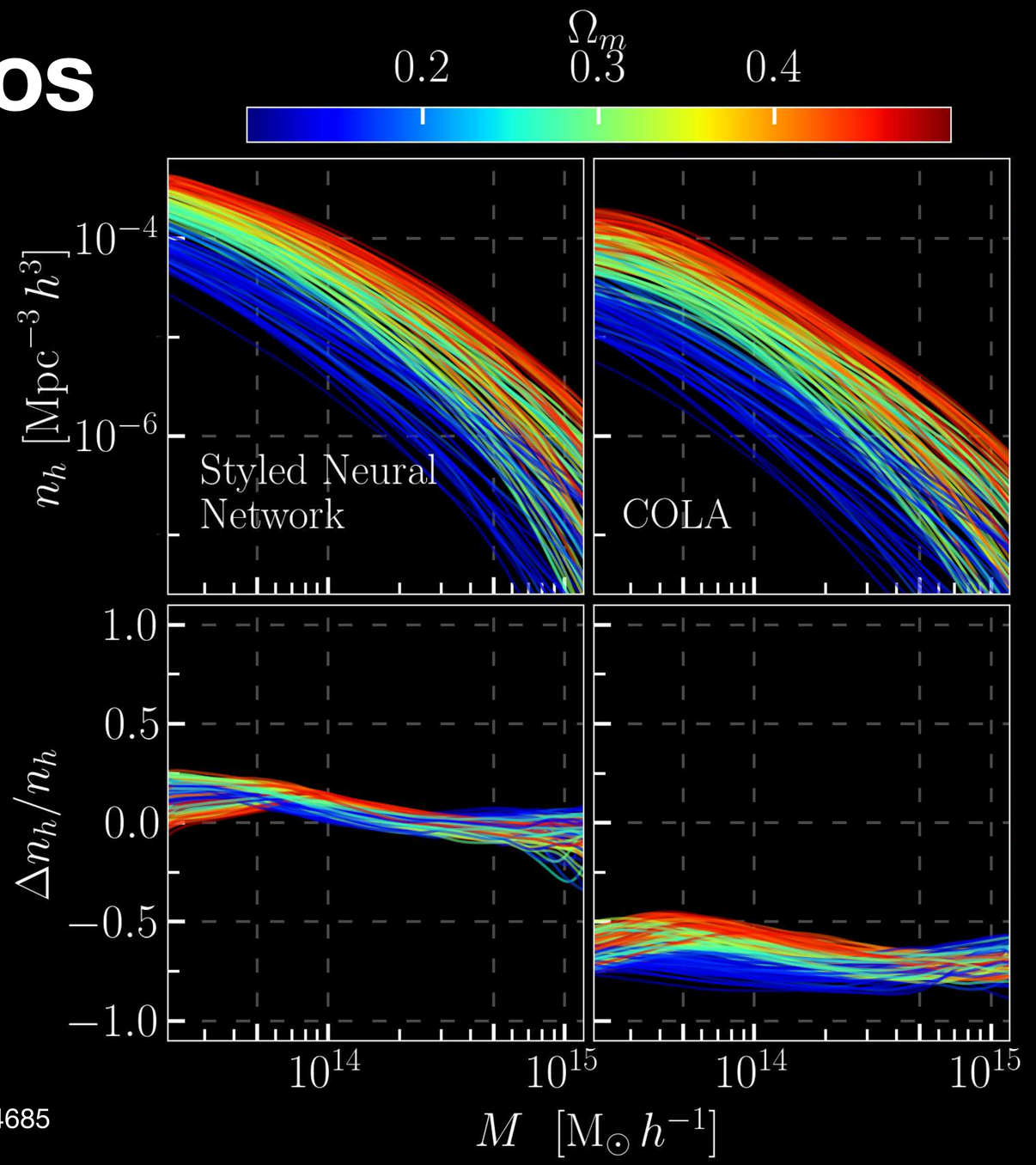
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Density Bispectrum



Results: Halos



For abundance matching with COLA
see Izard, Crocce, Fosalba arXiv:1509.04685

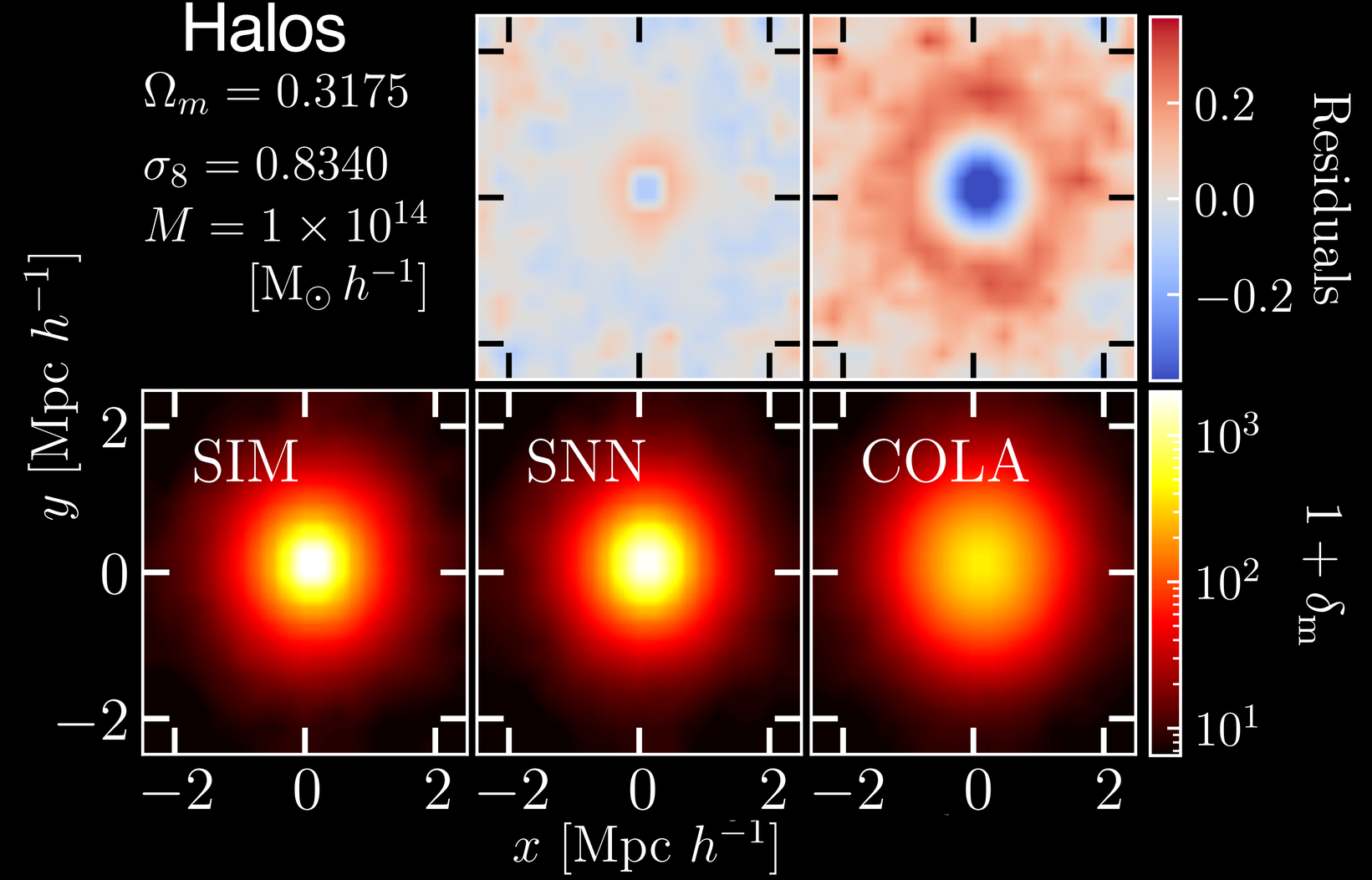
arXiv > astro-ph > arXiv:2206.04594

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Field Level Neural Network Emulator for Cosmological N-body Simulations

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Learn the map from linear theory to nonlinear, N-body evolution

Input the Zeldovich approximation displacement field on uniform grid

Output nonlinear displacements after N-body evolution

Model evaluation: $(128 + 96)^3$ particles + padding = 0.7375 seconds

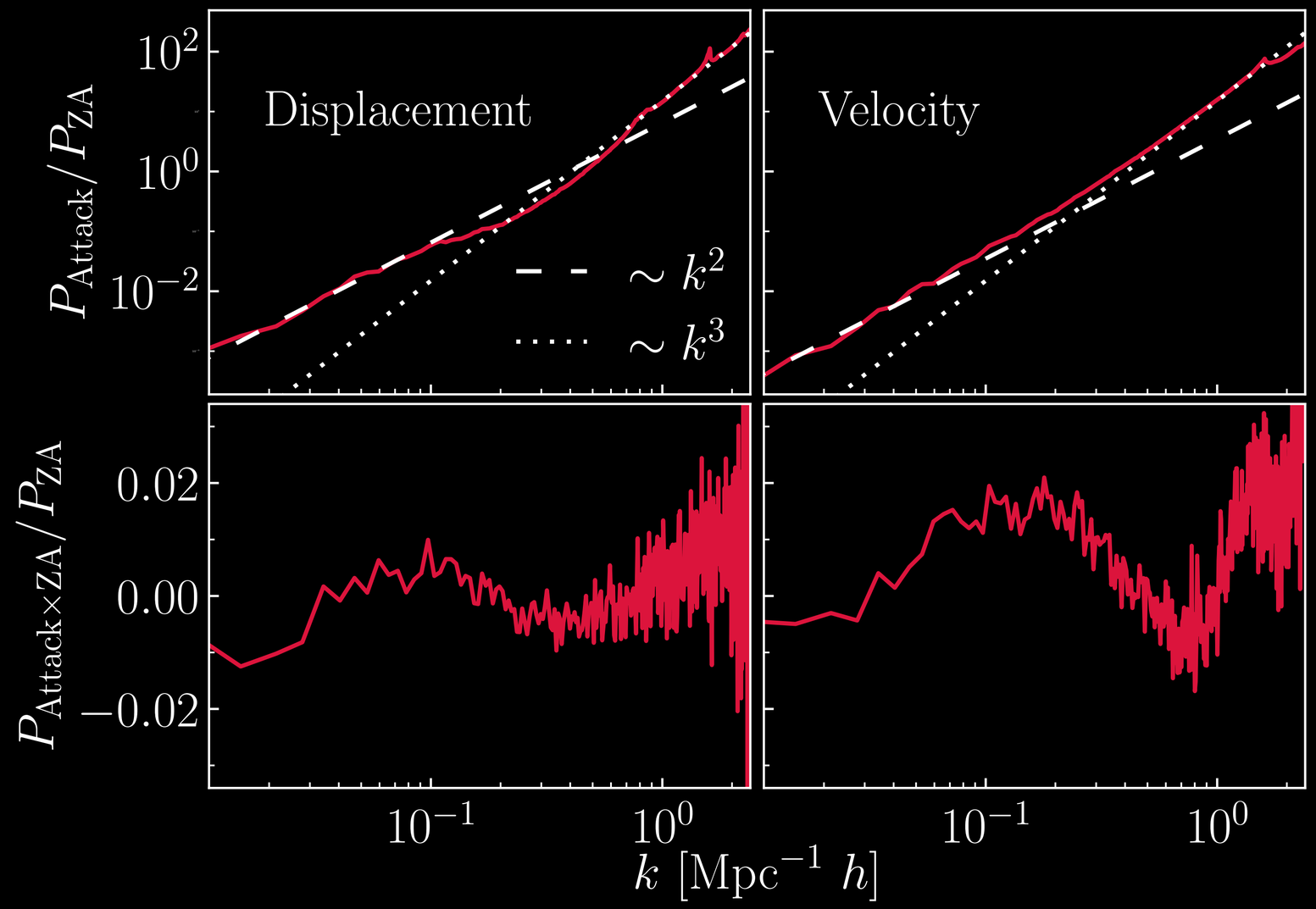
Number of CNN parameters: 3,347,078

Number of style parameters: 5132

$$\text{loss} = \log(\sum \text{displacement error}^2) + \log(\sum \text{density error}^2)$$

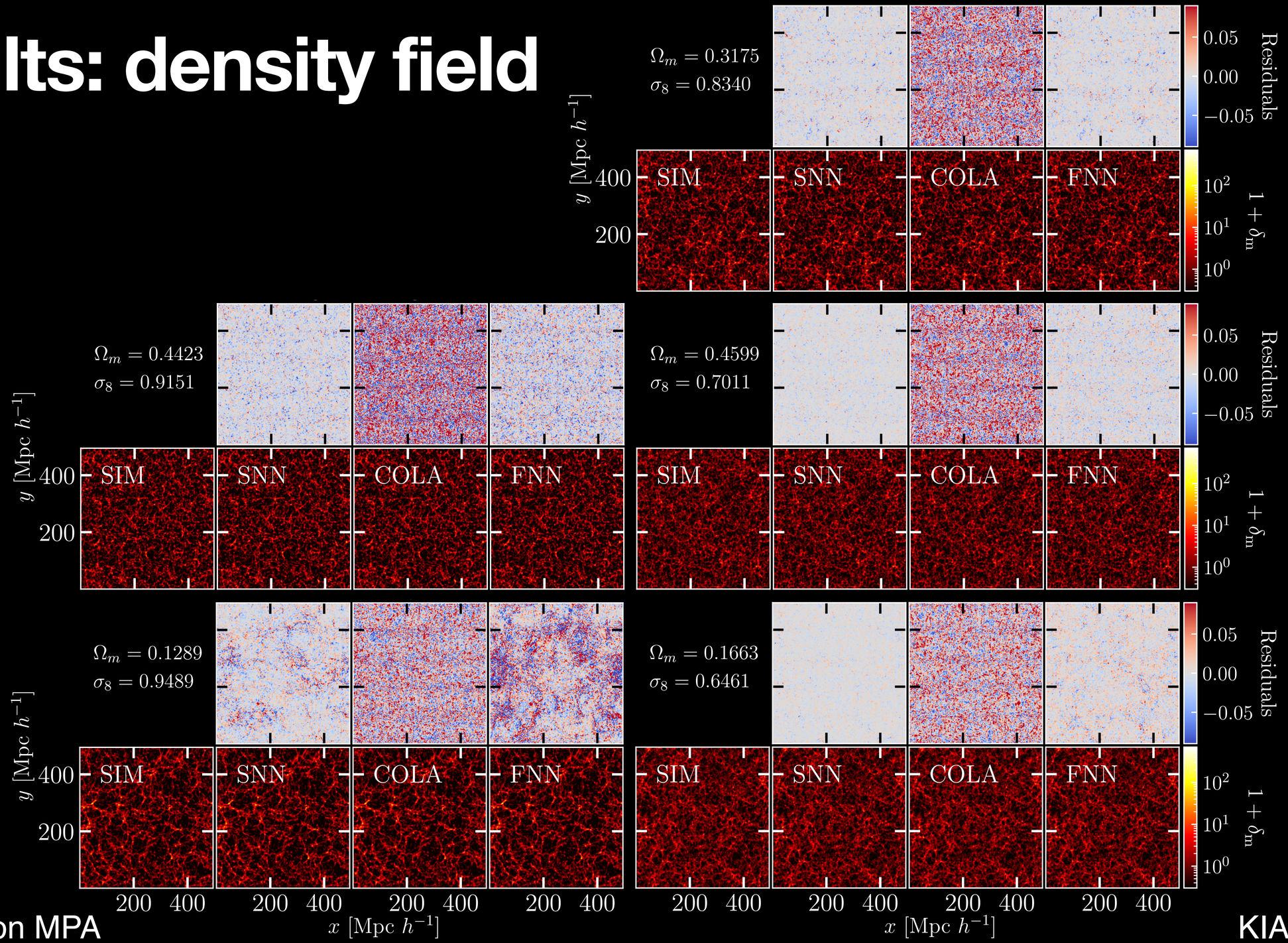
Adversarial attack

- Fast gradient sign attack
- Take sign of gradient of loss wrt input
- Multiply by small constant and add to original input
- New input is a nearly worst case scenario
- Preferentially adds power to small scales

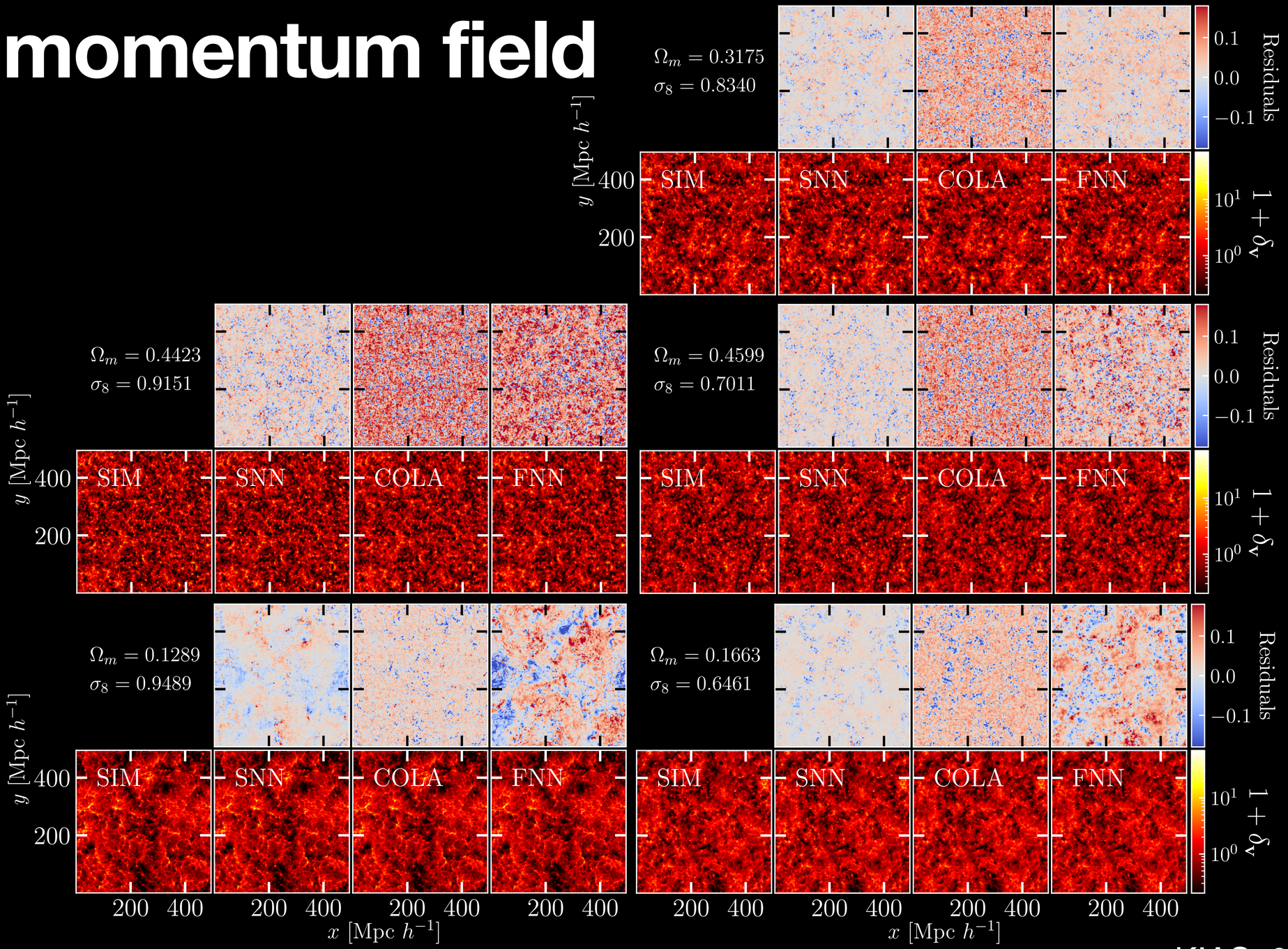


Attack field is an extremely unlikely configuration of initial Gaussian field

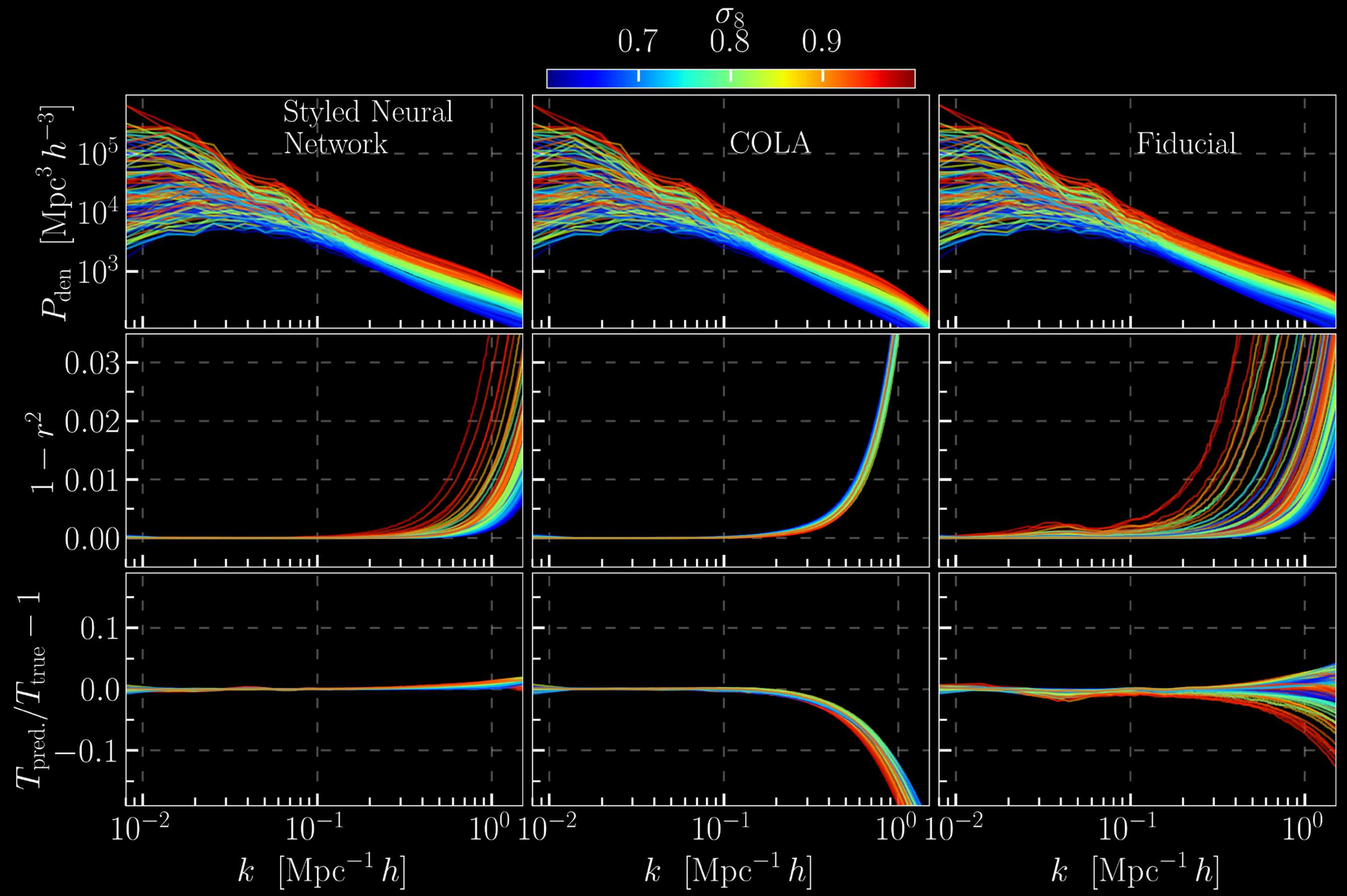
Results: density field



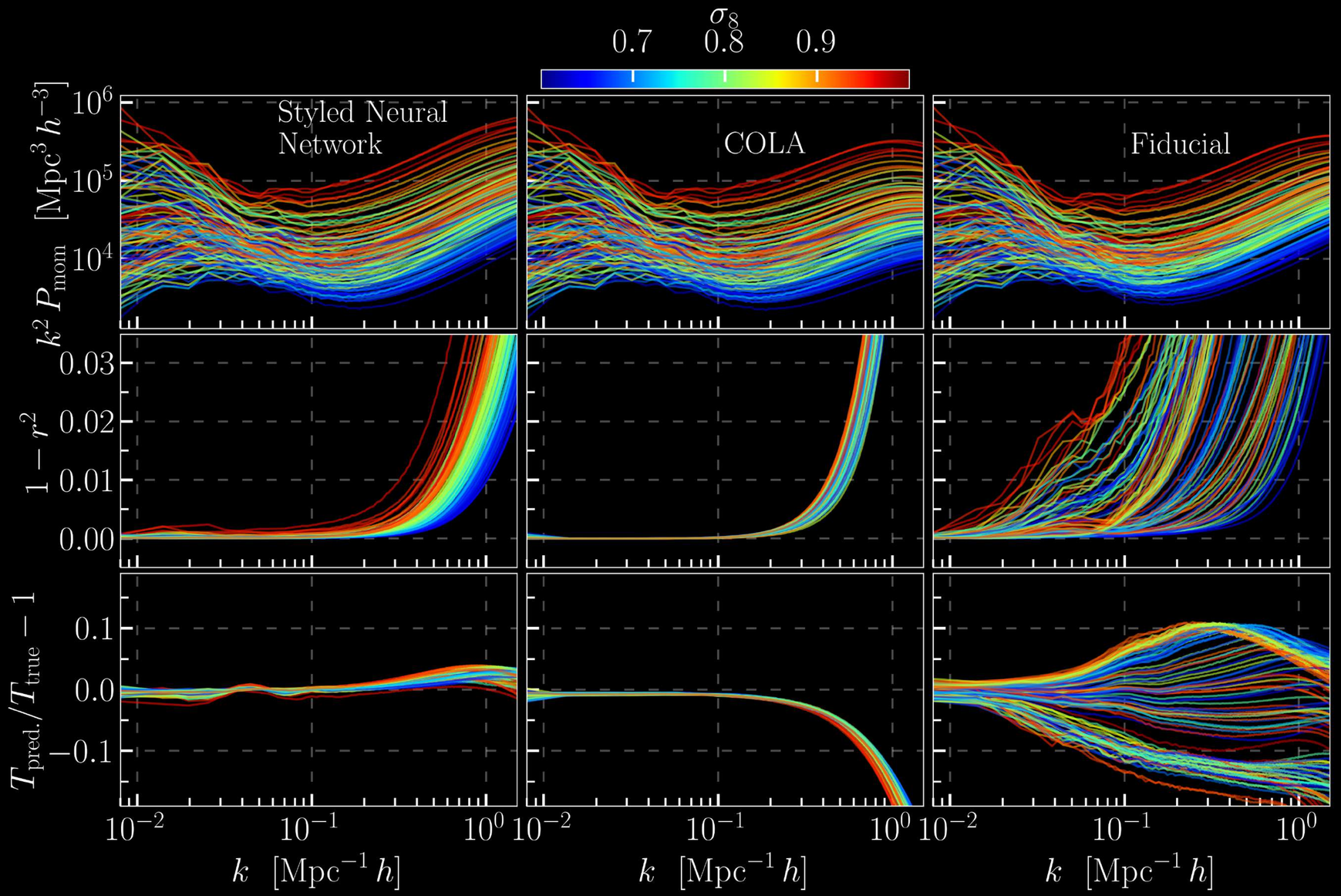
Results: momentum field



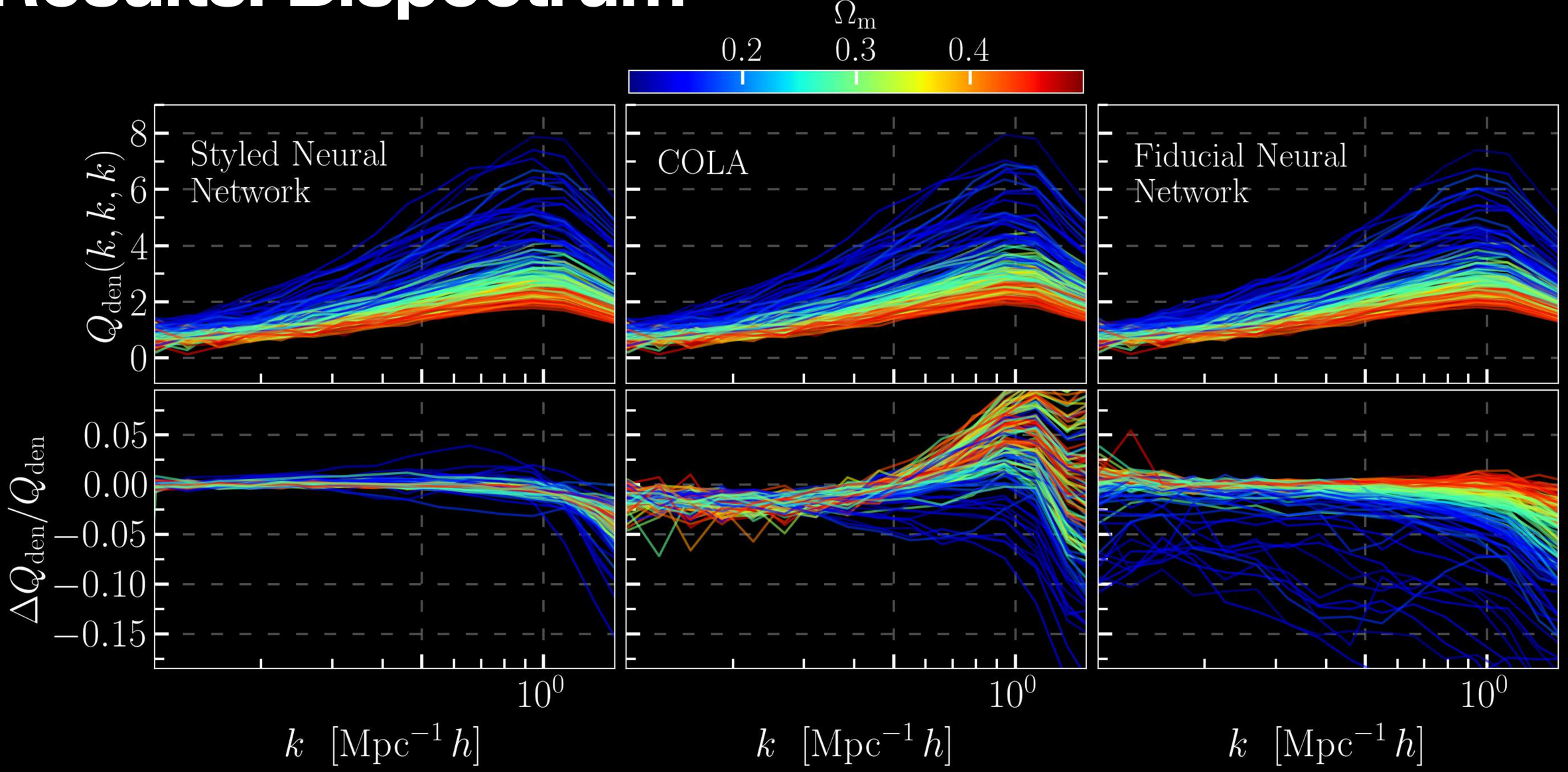
Results: density power spectrum



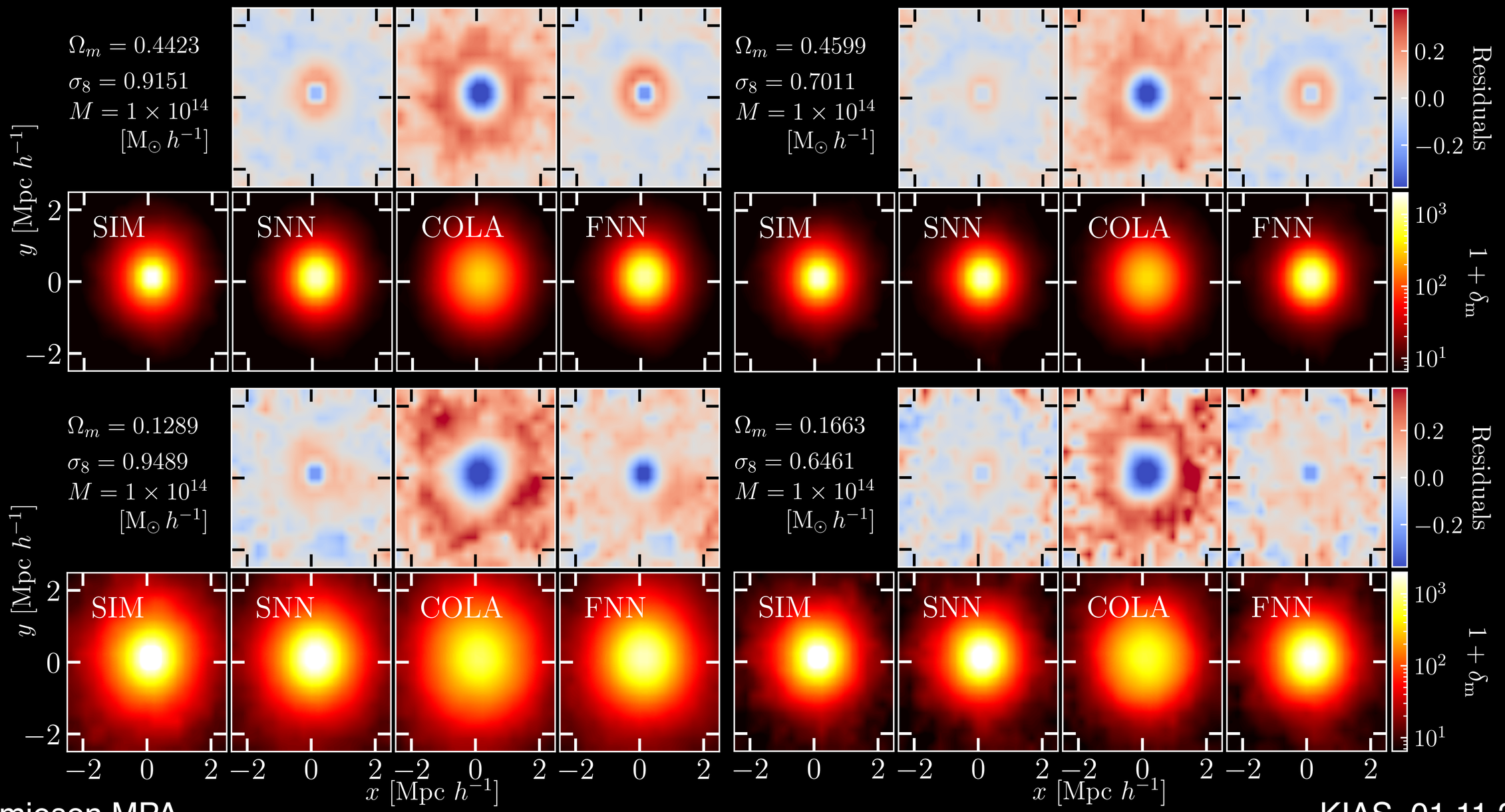
Results: momentum power spectrum



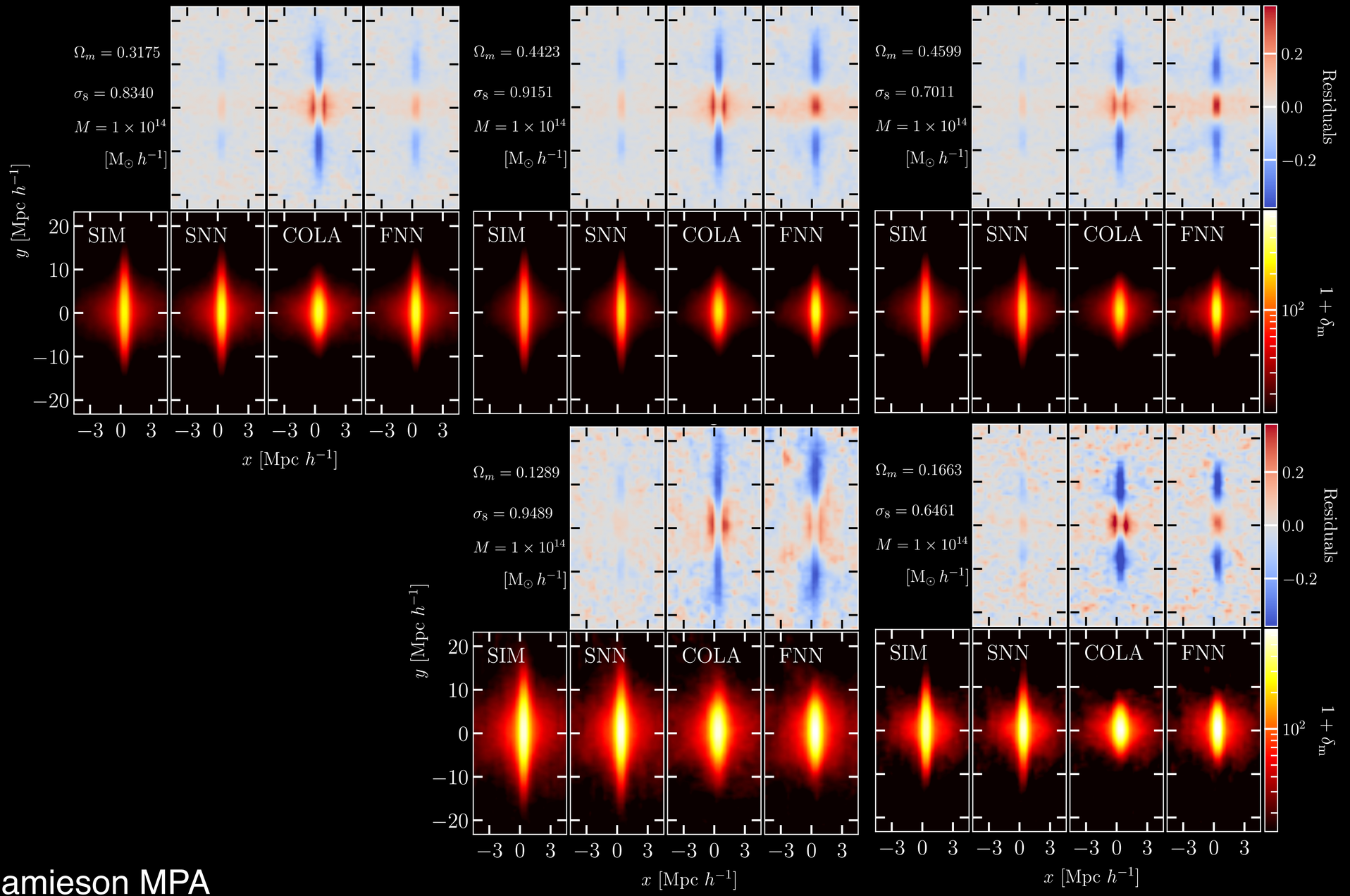
Results: Bispectrum



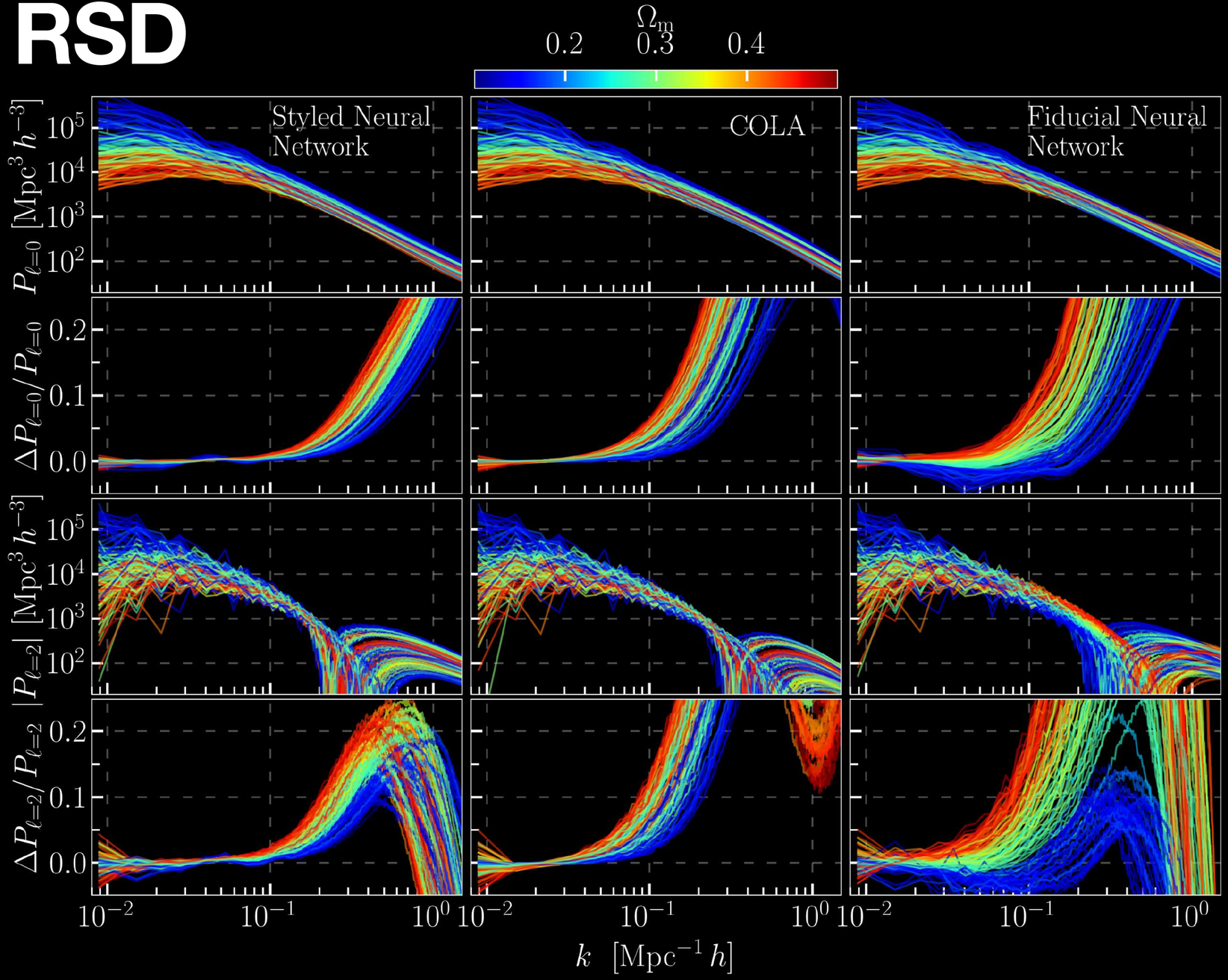
Results: Halos



Results: RSD Halos



Results: RSD


Ω_m
0.2
0.3
0.4
Styled Neural Network
COLA
Fiducial Neural Network
$P_{\ell=0}$ [Mpc^3 h^{-3}]
$\Delta P_{\ell=0}/P_{\ell=0}$
$|P_{\ell=2}|$ [Mpc^3 h^{-3}]
$\Delta P_{\ell=2}/P_{\ell=2}$
k [Mpc^{-1} h]

Modelling simulations with neural networks

Simulations

- Linear theory captures the global features of structure formation
- Nonlinear corrections should be dominated by local information
- Initial conditions are on a uniform grid (Lagrangian space): 3D image of voxels with 3 “channels” (coordinates)

Convolutional Neural Networks

- Convolutions are nearest-neighbour operations in real space: **begins with local information**
- Multiple layers correspond to different scales in Lagrangian space

Emulating large-scale structure formation at the field level with styled neural networks

Drew Jamieson
Postdoc, MPA

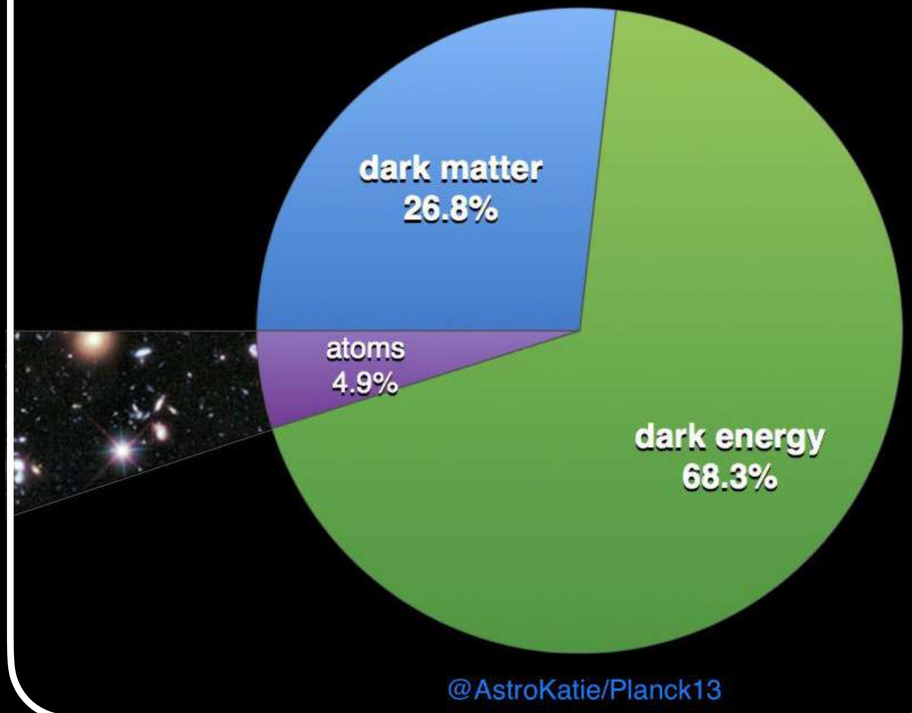
arXiv:2206.04594
arXiv:2206.04573
arXiv:2303.13056
arXiv:2307.09134
arXiv:2312.09271
arXiv:2408.07699

Map2Map with style parameters:
https://github.com/eelregit/map2map
https://github.com/dsjamieson/map2map_emu

Collaborators:
Peng Cheng Laboratory: Yin Li
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Carnegie Mellon: Vaibhav Jindal, Albert Liang, Aarti Singh
Stockholm University: Ludvig Doeser, Jens Jasche
University of Edinburgh: Marcos Pellejero
DIPC: Raúl Angulo

Cosmology

Contents of the Universe:



Early Universe:

- One scalar source of fluctuations
- Gaussian random field
- Nearly scale-invariant power

