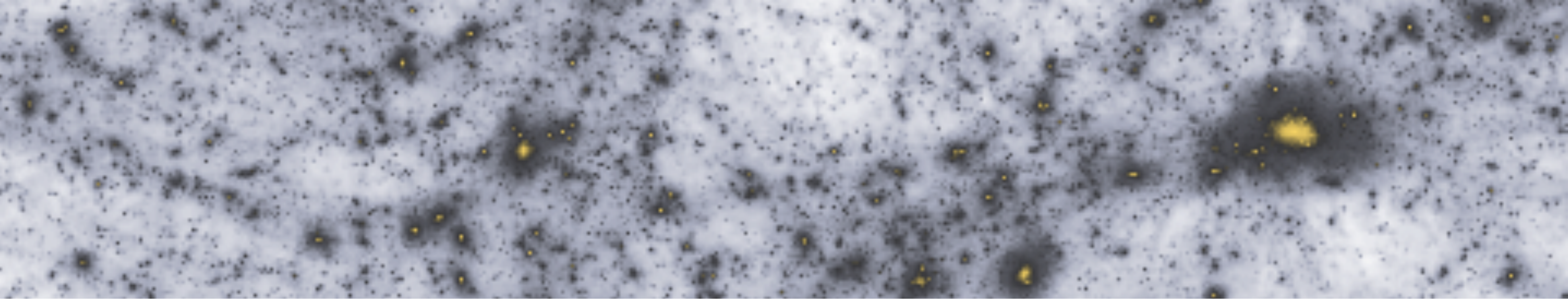

Deep learning insights into cosmological structure formation

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Cosmology From Home, 5 — 16 July 2021

MAX PLANCK INSTITUTE
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Outline

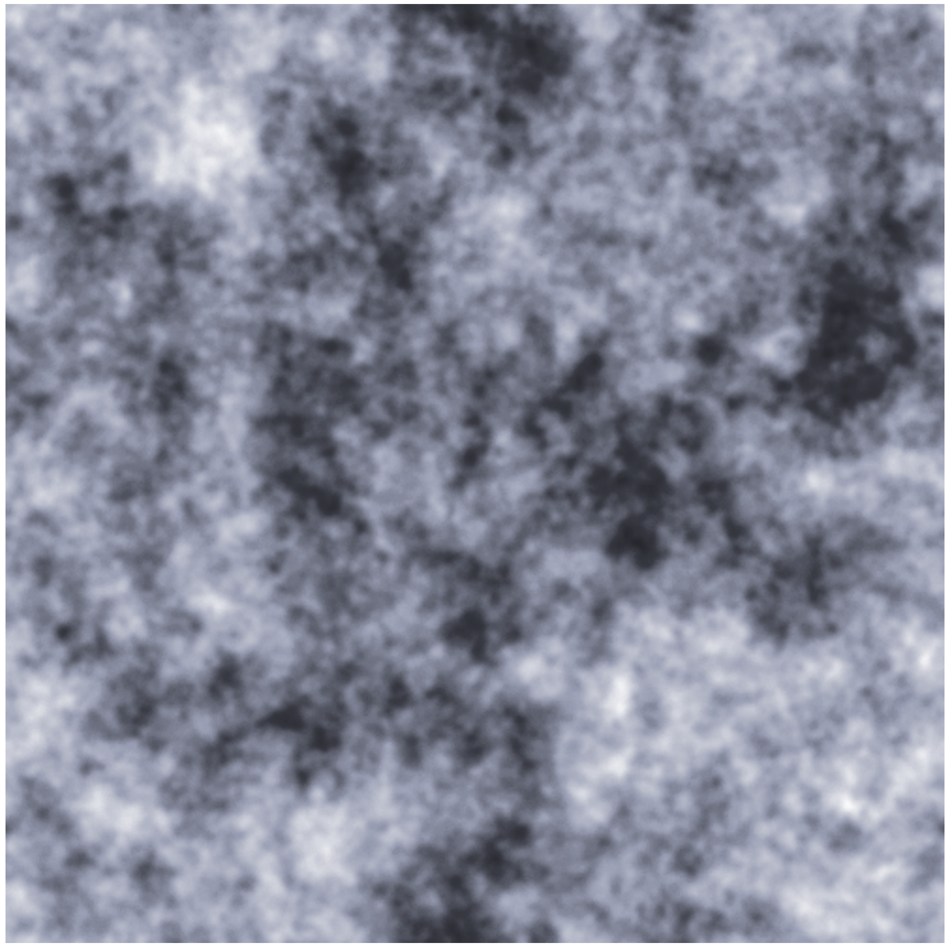
1. Train a deep learning algorithm to learn mapping between initial conditions and final cosmic structures from N-body simulations

2. Develop techniques to physically interpret the learnt mapping

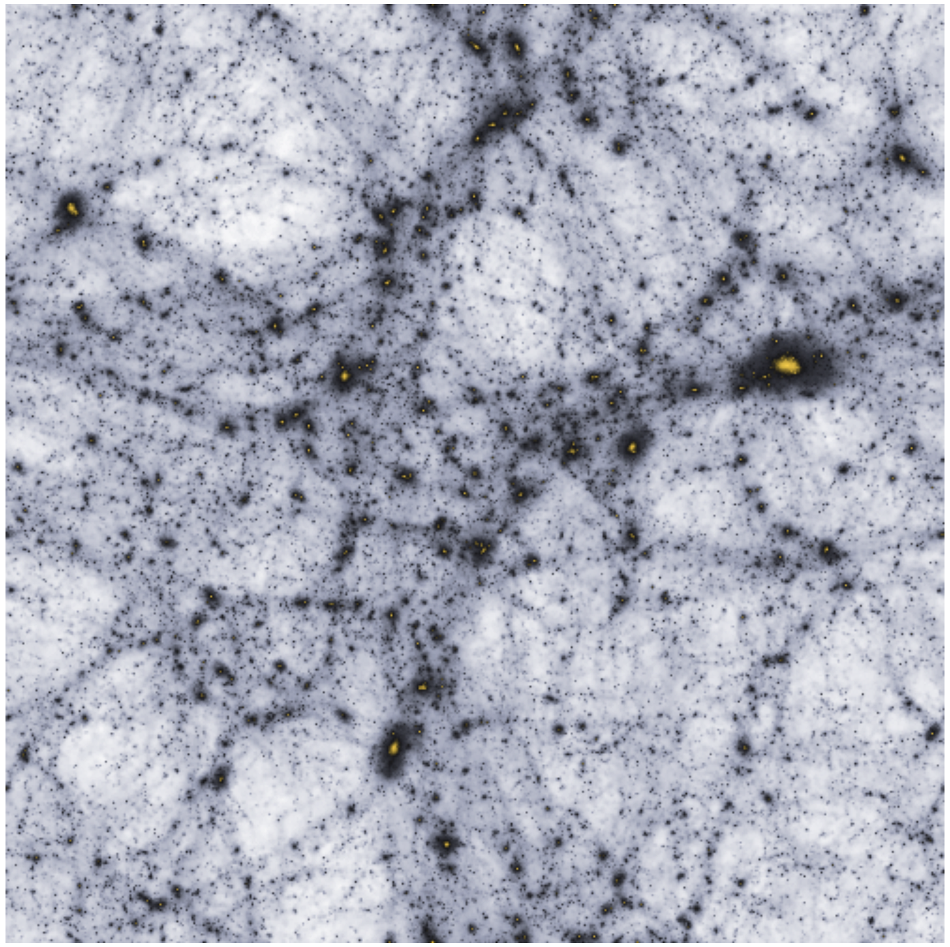
3. Gain new knowledge about the underlying physics of cosmological structure formation

Cosmological structure formation

ΛCDM model successfully describes evolution of matter in Universe

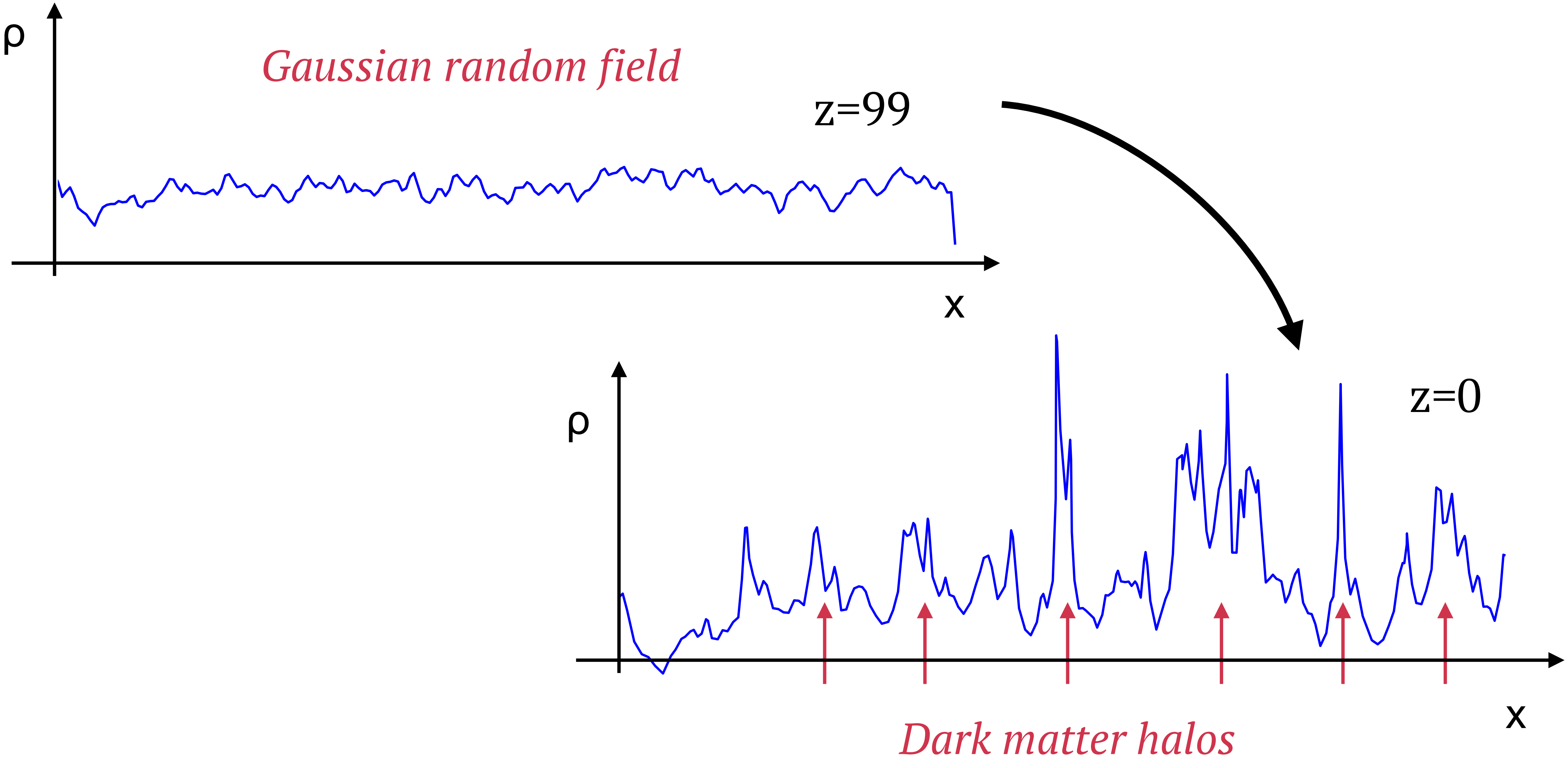


Perturbations in the density of matter at early times



Today's large-scale structure

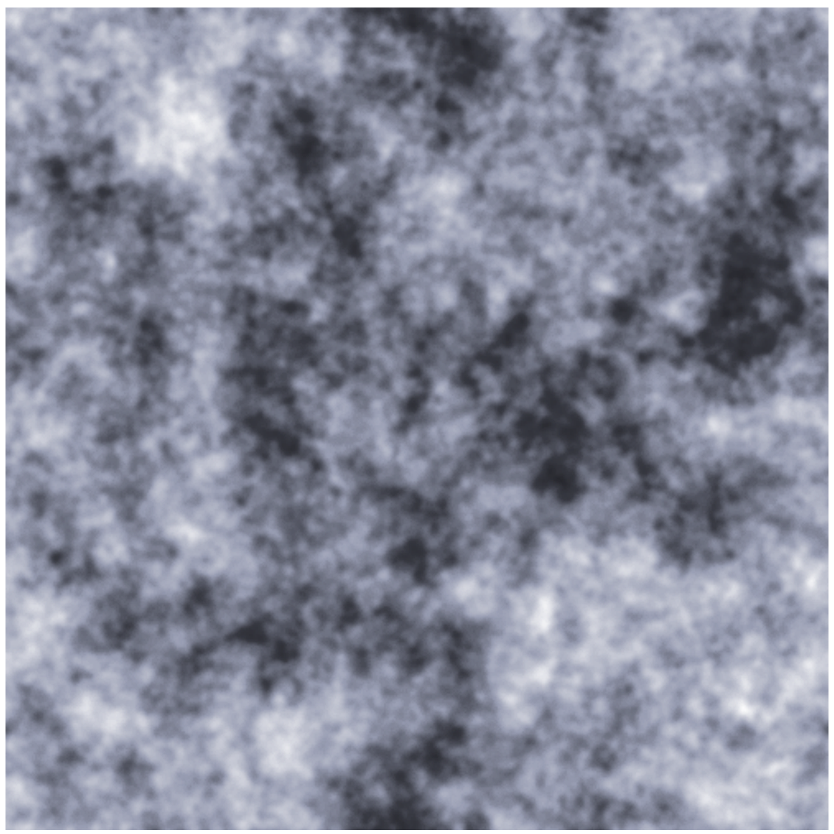
Dark matter halo formation

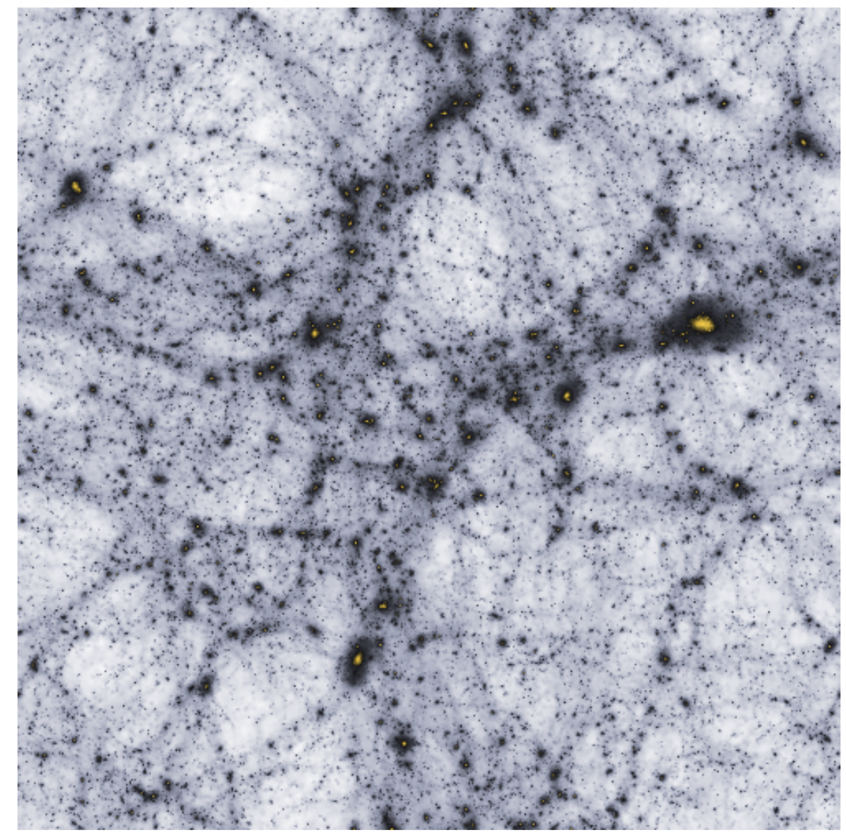


- **N-body simulations:** most accurate method but difficult to *physically interpret*
- **Analytic models:** provide *qualitative* understanding due to limited model complexity

Insights into dark matter halo collapse from ML?

Approach: Train ML algorithm to learn mapping between initial conditions and dark matter halos from N-body simulations

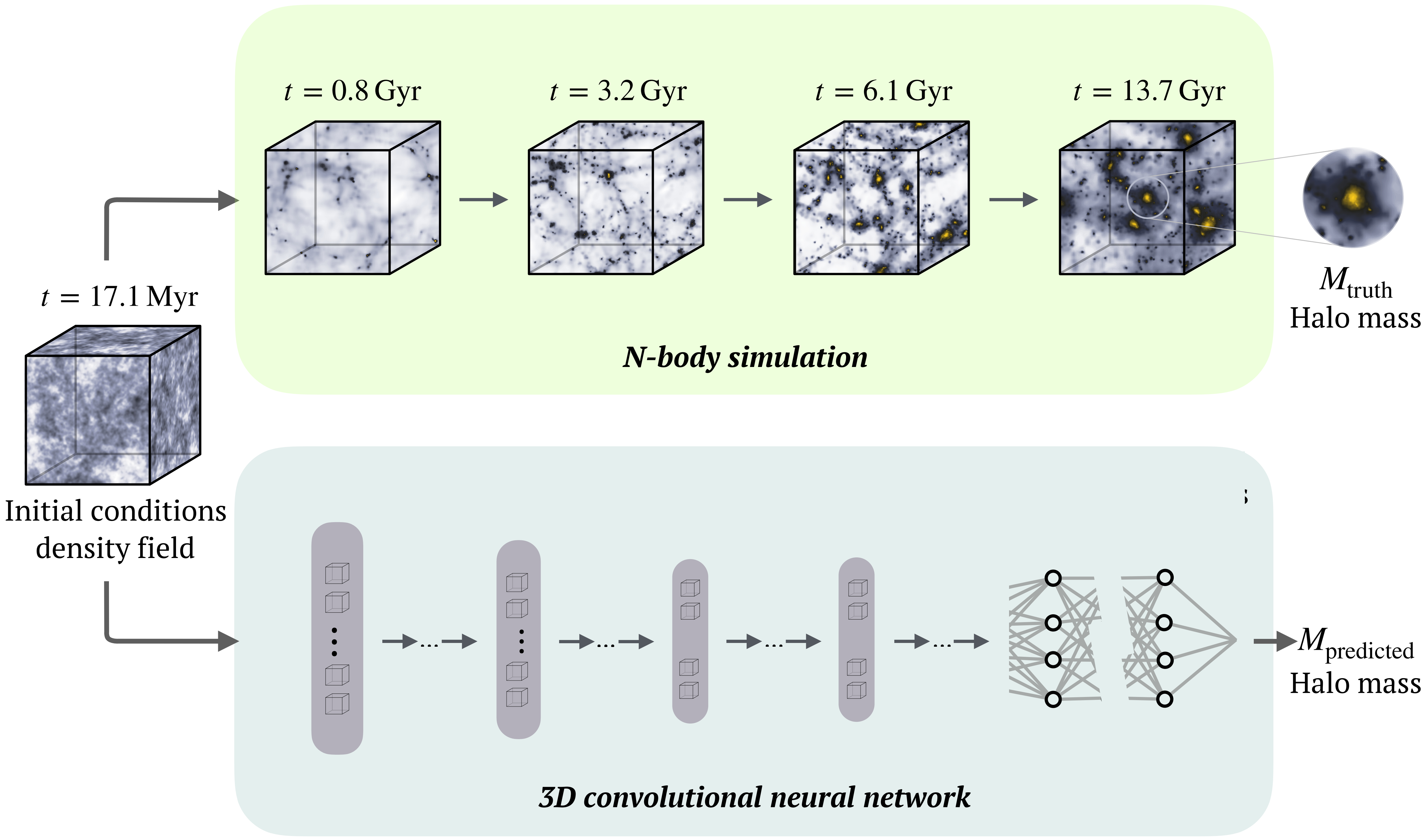




Aim: gain new physical insights into dark matter halo formation

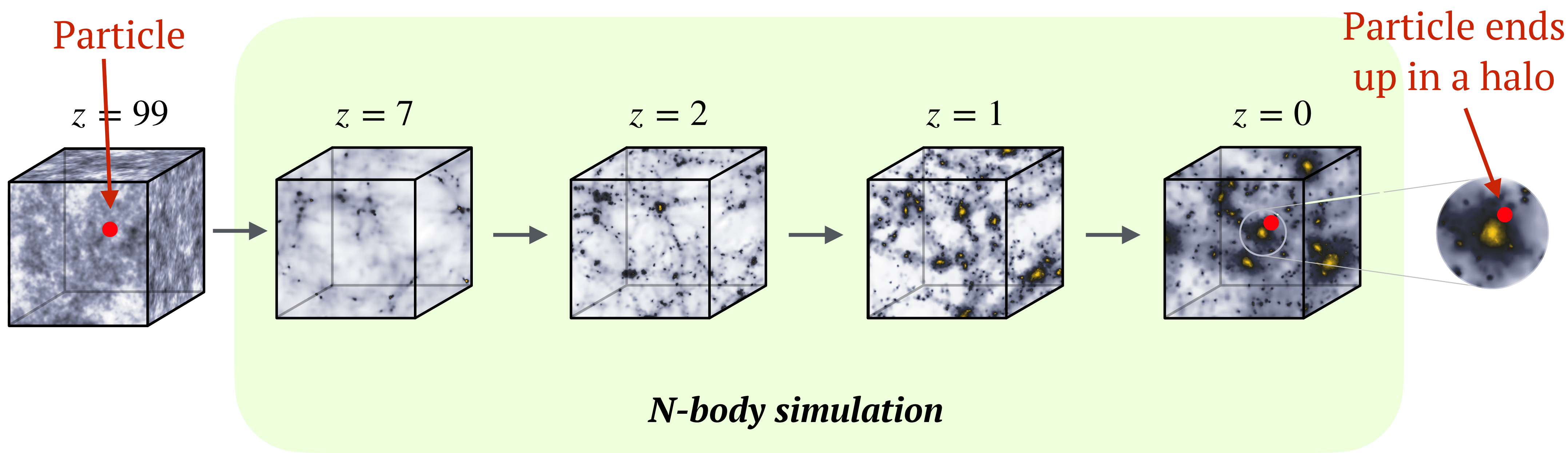
Lucie-Smith, Peiris, Pontzen, Nord, Thiyagalingam (2020)
Lucie-Smith, Peiris, Pontzen (2018, 2019)

A deep learning (DL) approach to halo formation



Lucie-Smith, Peiris, Pontzen, Nord, Thiyagalingam (2020)

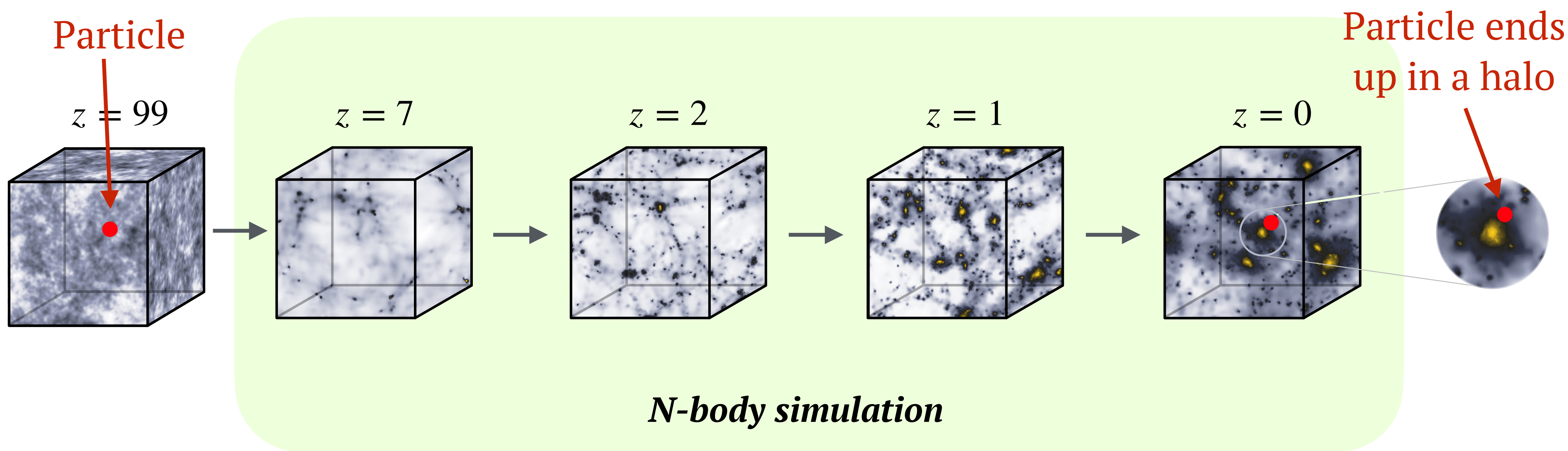
ICs-to-halo mass mapping for every particle



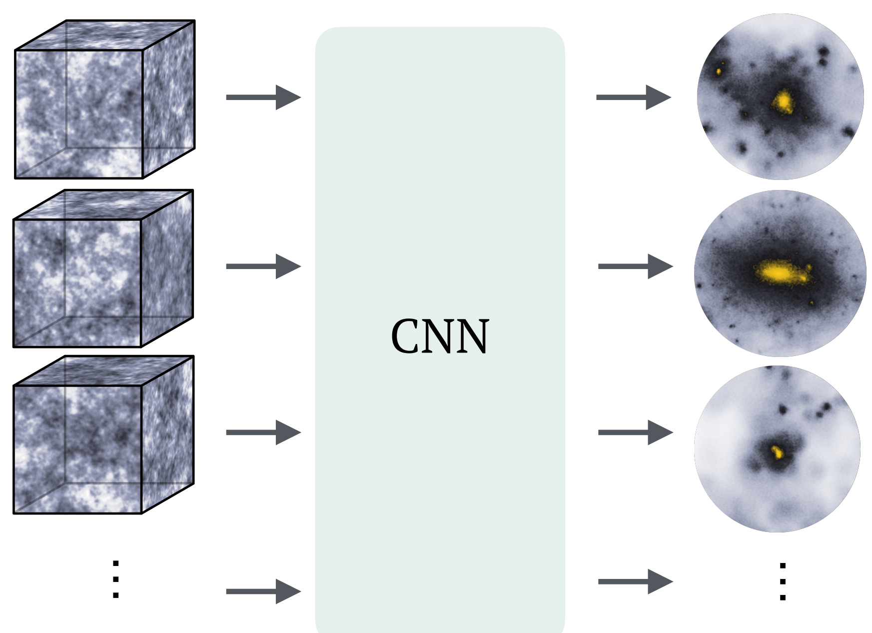
Input:
Initial density field centred on particle's position

Output:
Mass of halo to which particle belongs at $z = 0$

Construct ICs-to-halo mass mapping for every particle



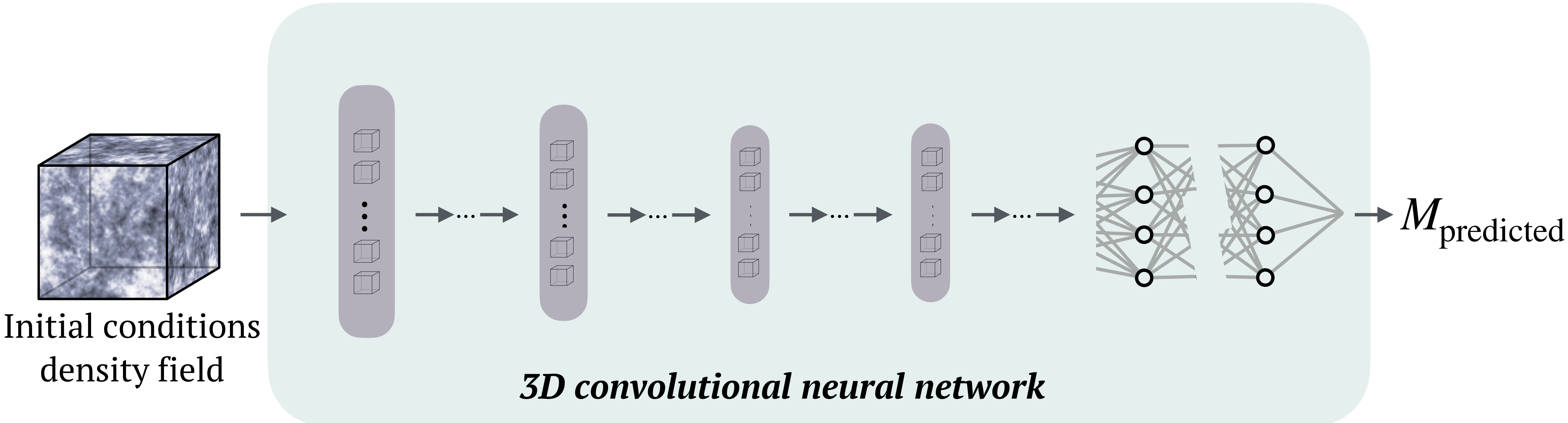
Input:
Initial density field centred on particle's position



Output:
Mass of halo to which particle belongs at $z = 0$

By training network on many particles across many simulations, model learns to identify aspects of initial density field relevant to final halo mass

Why convolutional neural networks?



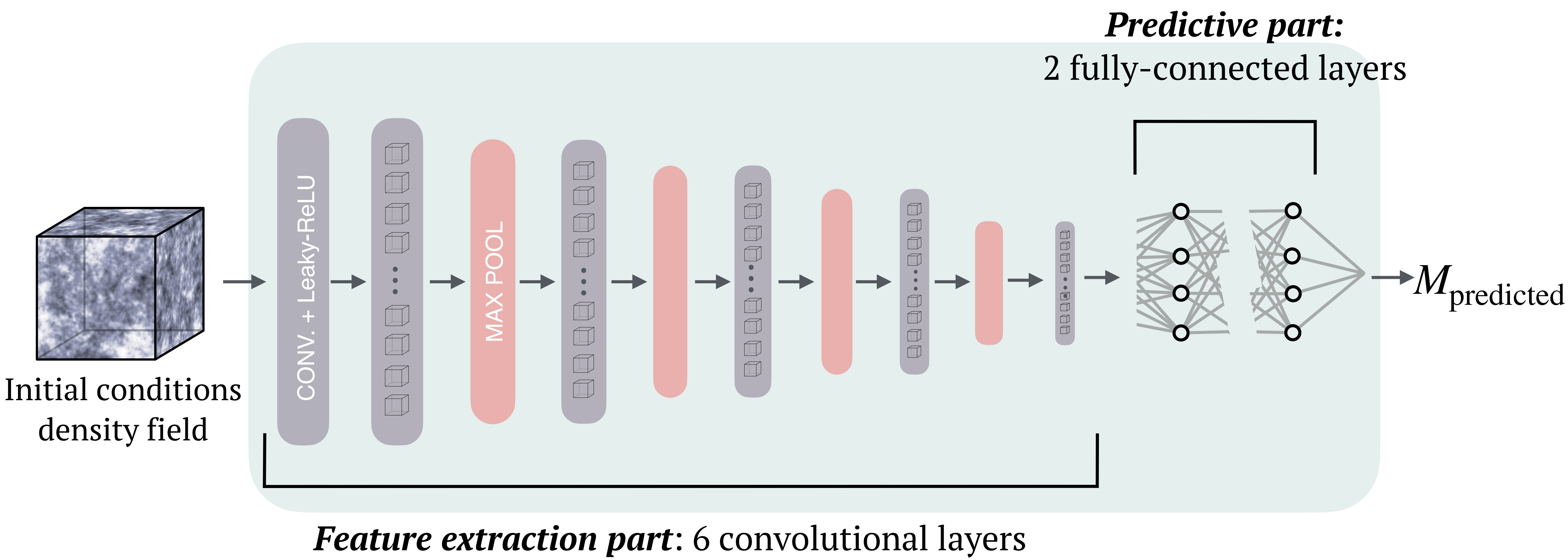
Advantages:

- no *featurization:* CNN learns directly from ICs "raw data"
- CNN identifies which ICs features are relevant for halo mass

Disadvantages:

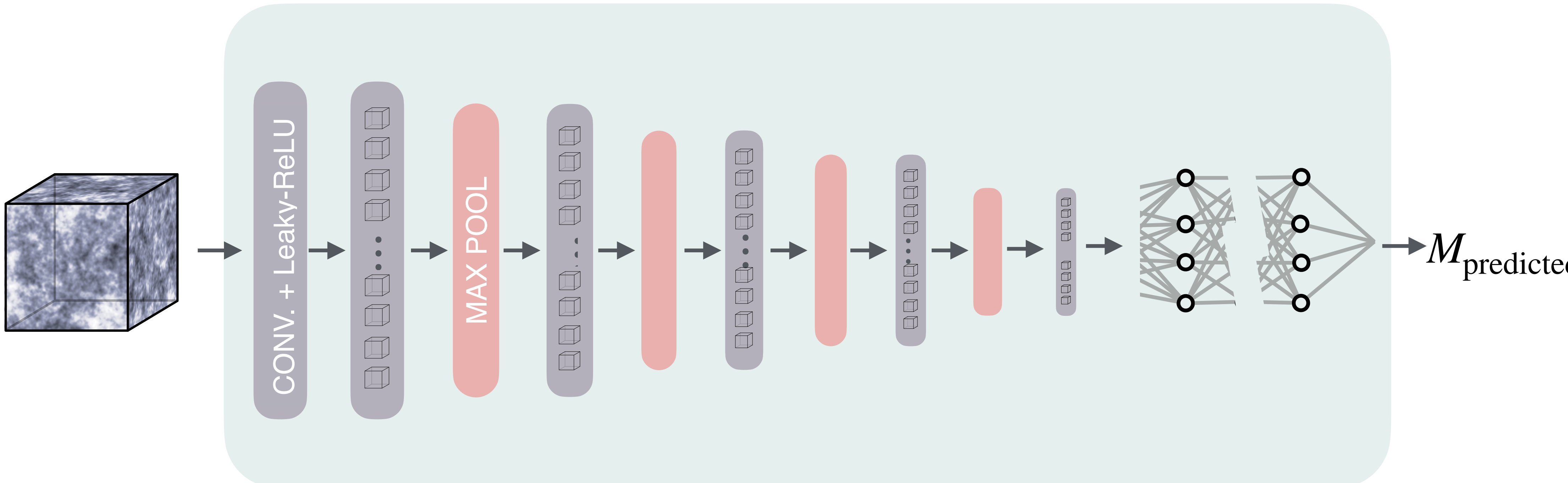
- DL algorithms are "black-box" algorithms
- ***how do we extract physical knowledge from a DL algorithm?***

The CNN model



- Input convolved with kernels, s.t. each kernel detects a specific feature
- Features extracted hierarchically: low-level to high-level features

Training the CNN model



Find the set of parameters $\vec{w}$ that minimise the loss function:

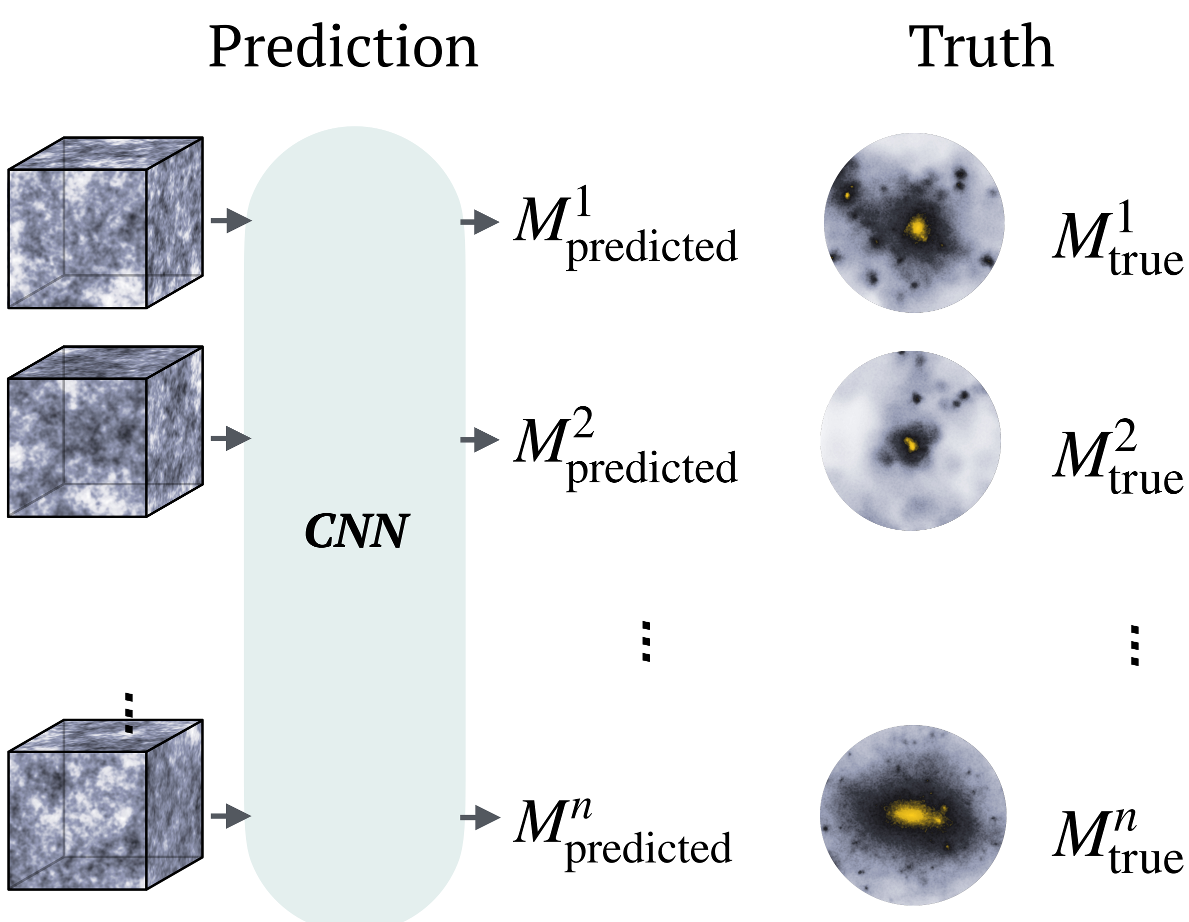
$$\text{Loss} = \mathscr{L}_{\text{pred}}(M_{\text{true}}(x), M_{\text{predicted}}(x, w)) + \mathscr{L}_{\text{reg}}(w)$$

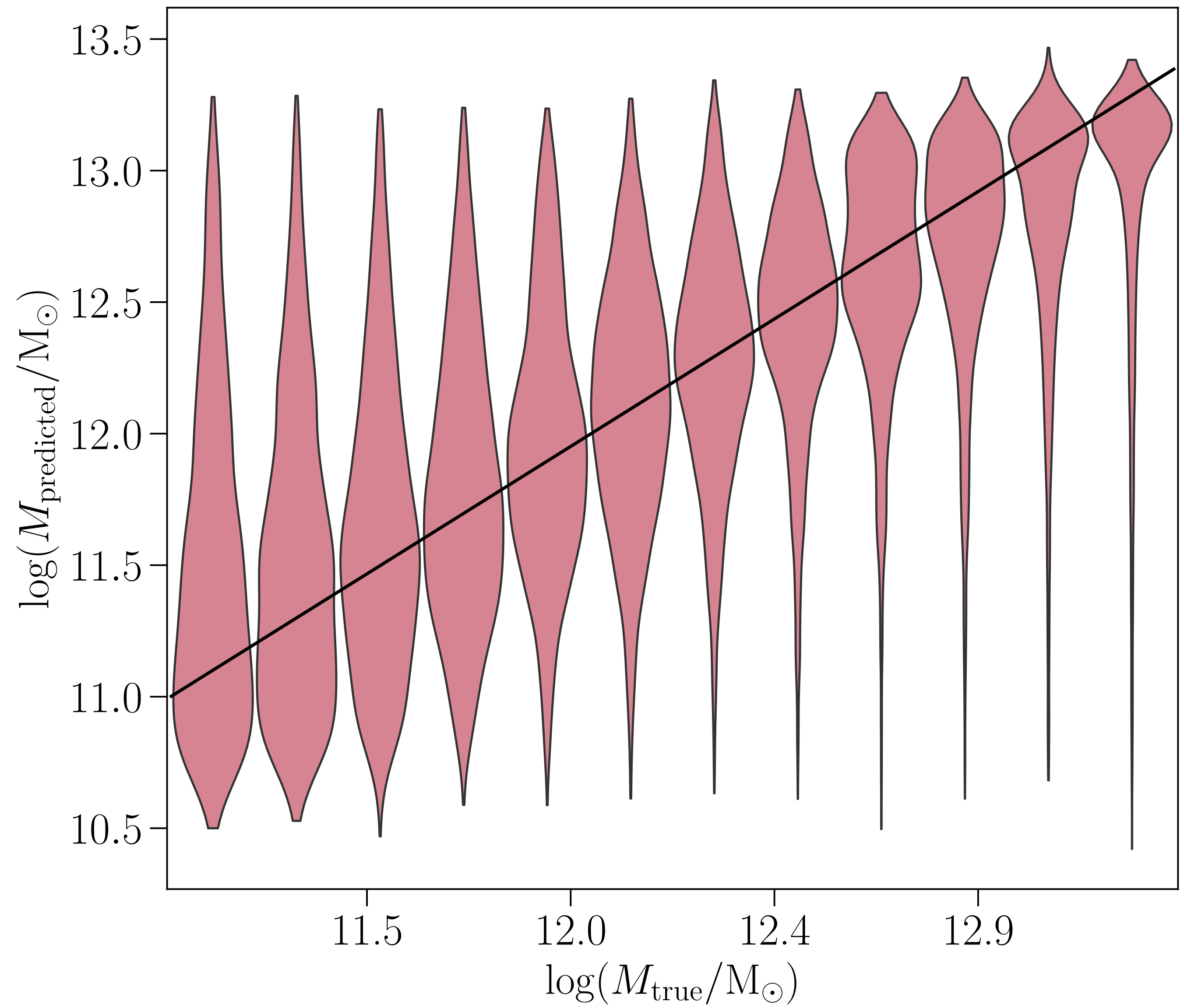
Predictive term:
Negative log of a Cauchy likelihood

Regularization term:
Priors on the weights to
(i) regularise network & reduce overfitting
(ii) compress the model (sparsity)

Halo mass predictions from the initial conditions

Test model on dark matter particles from independent simulations





Lucie-Smith, Peiris, Pontzen, Nord, Thiyagalingam (2020)

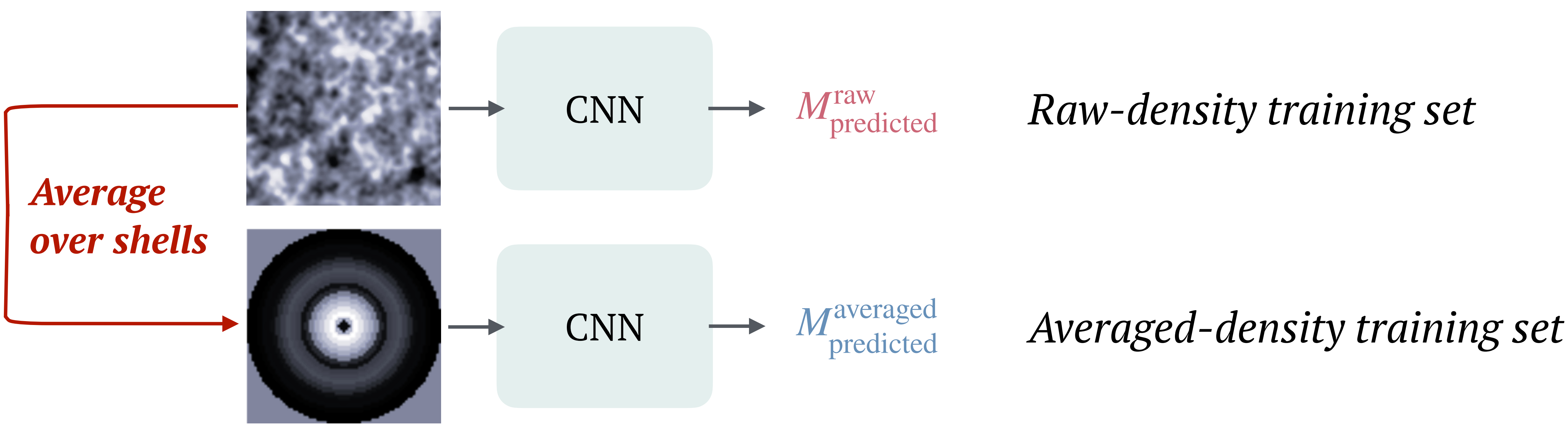
Interpreting the DL model

Interpretability technique:

1. Remove part of the information carried by inputs & re-train model
2. Measure the resulting change in the model's performance.

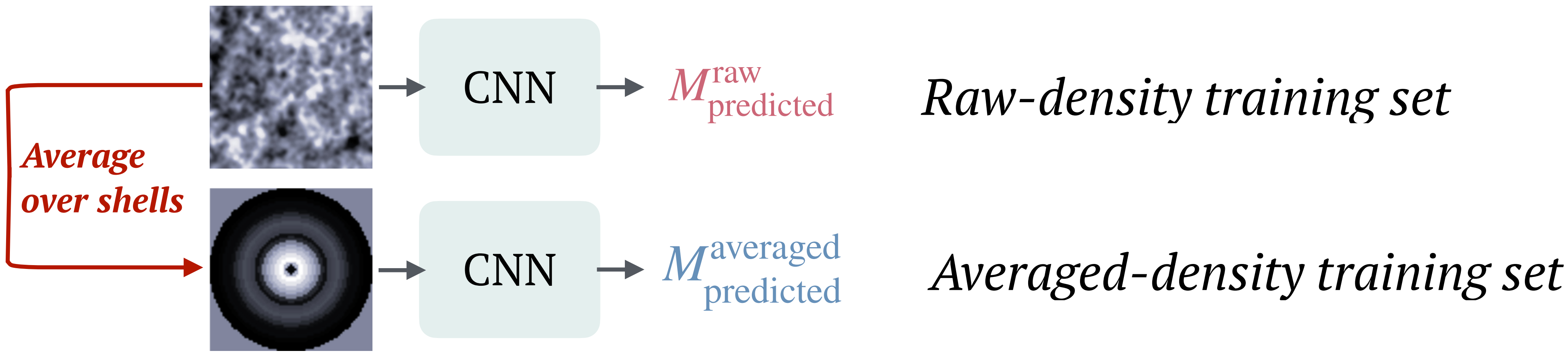
Application:

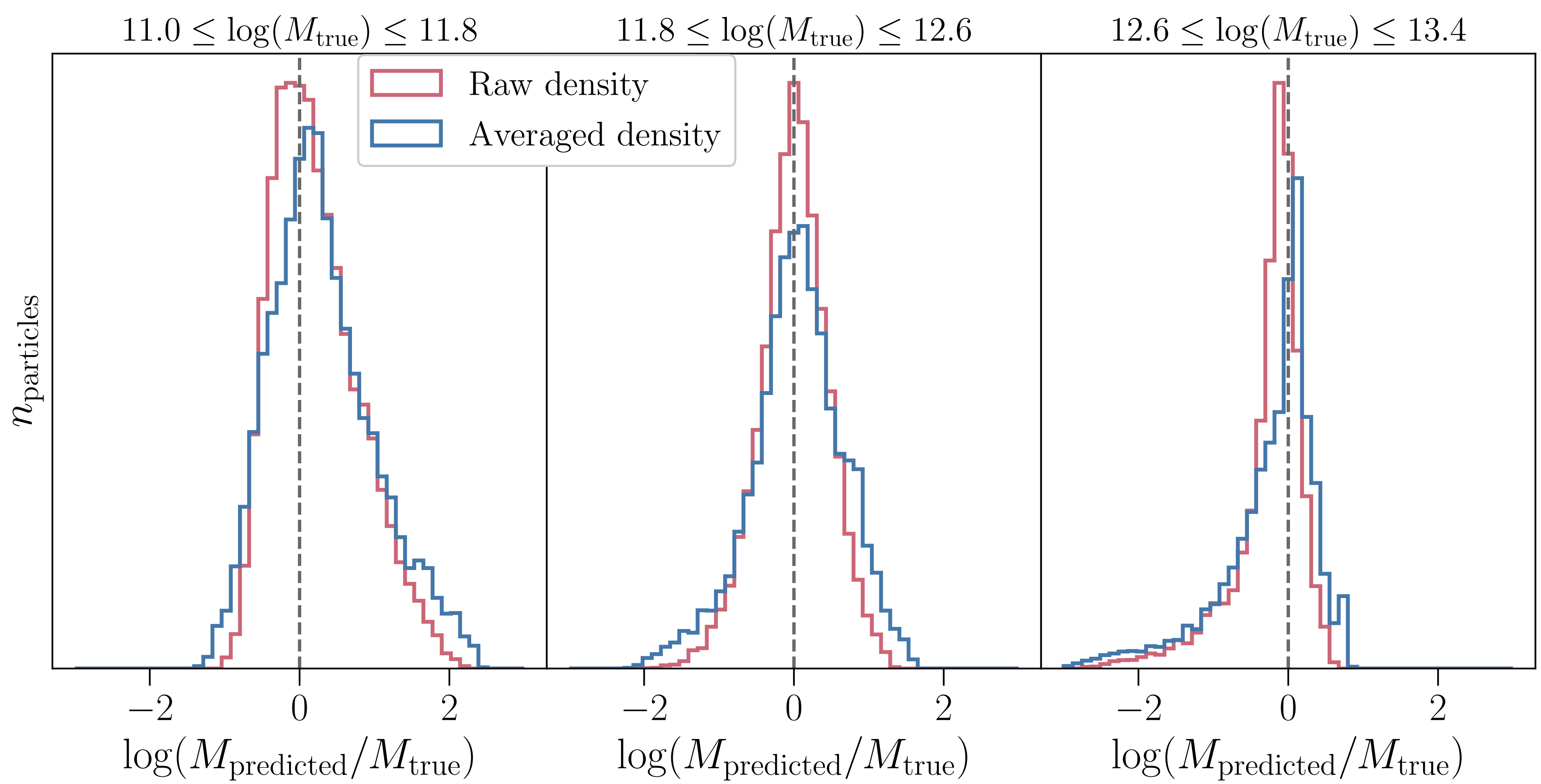
1. Remove anisotropic information from the initial density field



Lucie-Smith, Peiris, Pontzen, Nord, Thiyagalingam (2020)

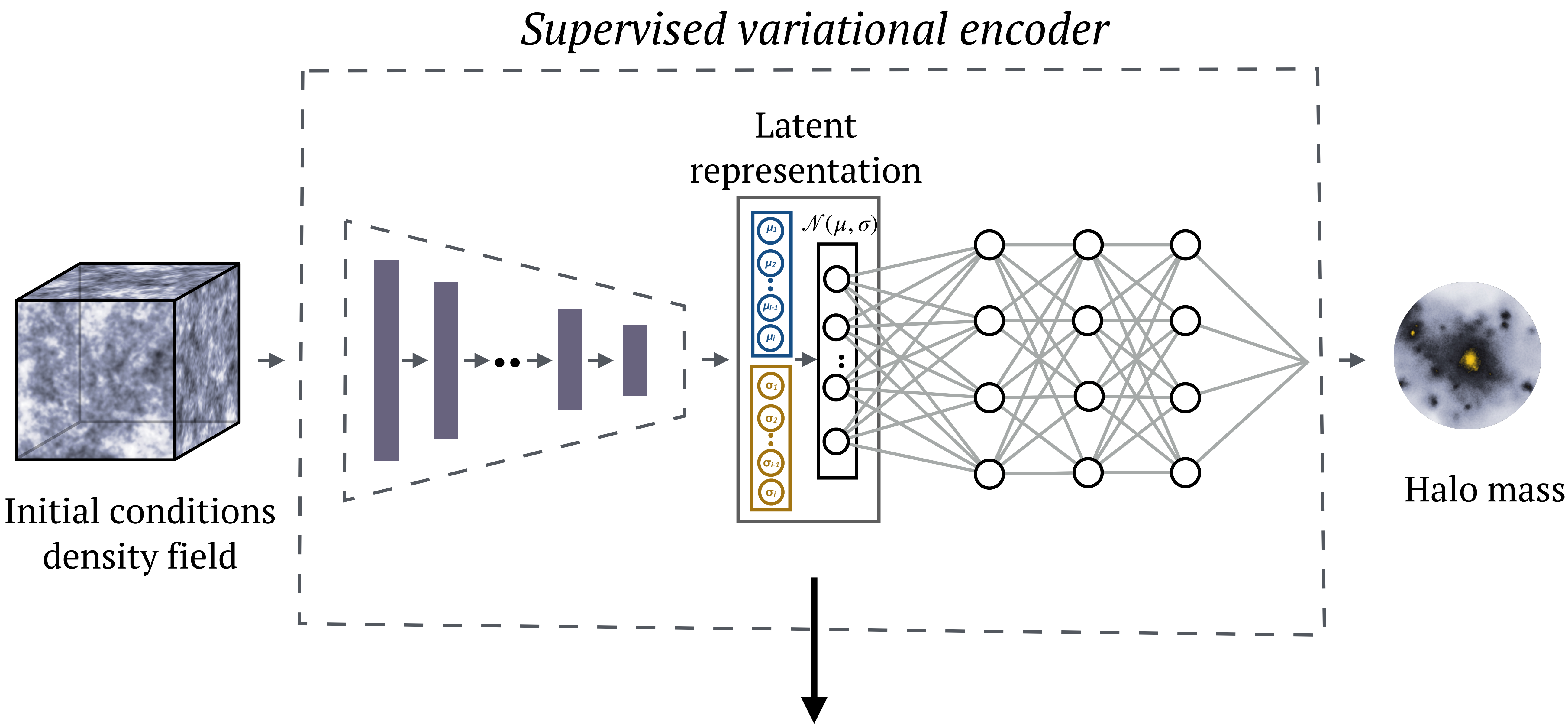
Interpreting the learnt mapping between ICs and halos





Anisotropic information plays no role in establishing final halo masses

Work in progress: knowledge extraction



Latent variables encode most relevant aspects of initial conditions about final halo masses

Iten et al. (2018; arXiv:1807.10300)
Lucie-Smith, Peiris, Pontzen, Nord, Thiyagalingam(in prep)

Conclusions

- Interpretable DL framework enabled new insights into role of anisotropic information in initial density field in establishing final halo masses
- **Work in progress:** employing "supervised variational encoder" to extract new physical knowledge about cosmological structure formation
- **Future work**: application to other properties of halos & other cosmic structures such as voids

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arXiv:2011.10577