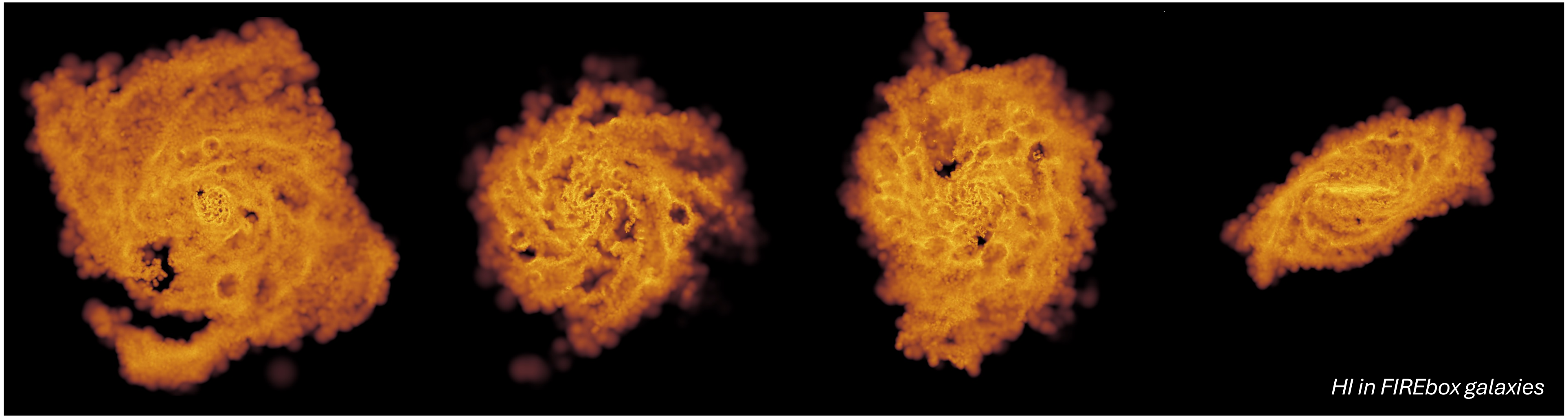
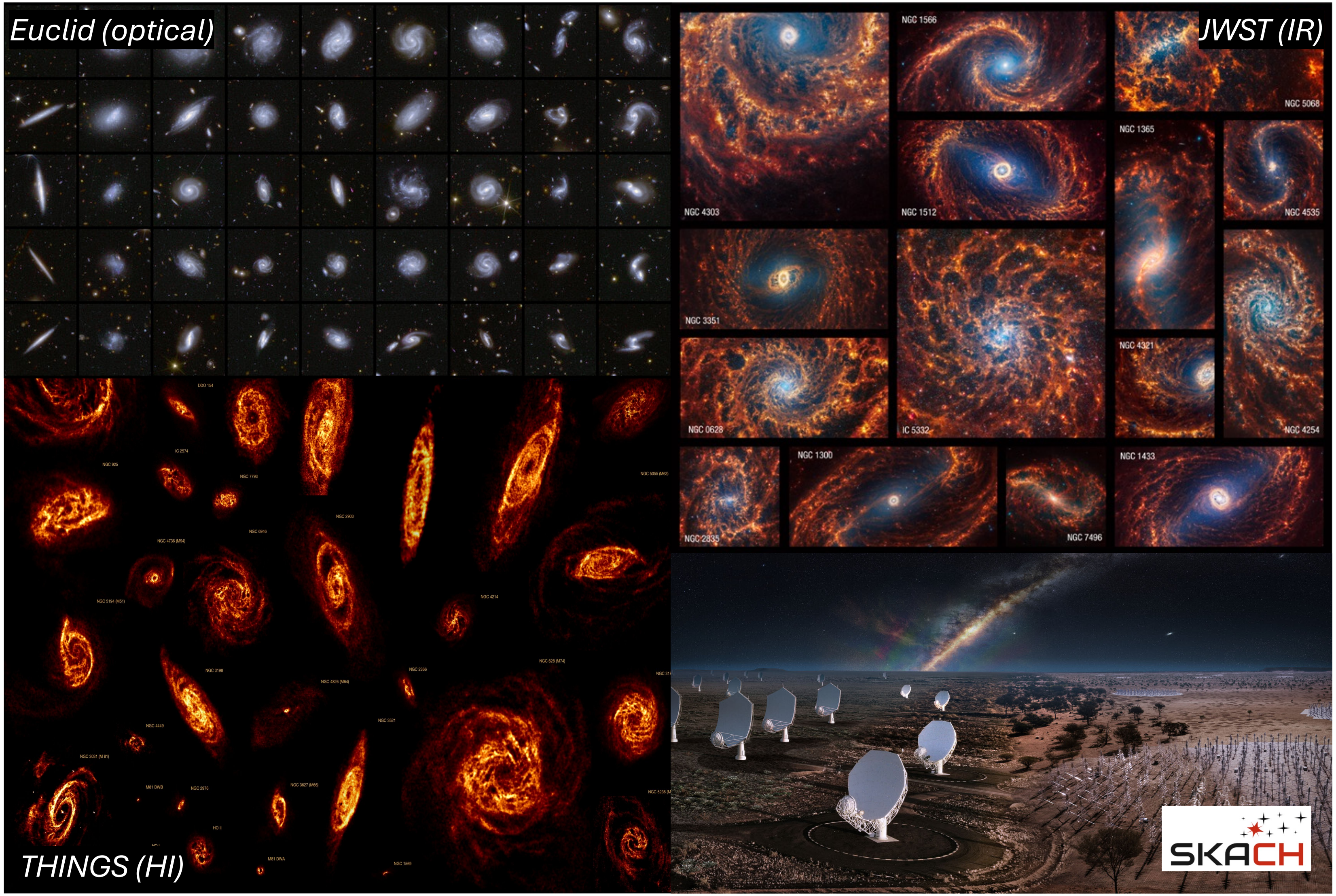
EMBER-2: towards implicit emulators for FIRE-based galaxy-formation simulations

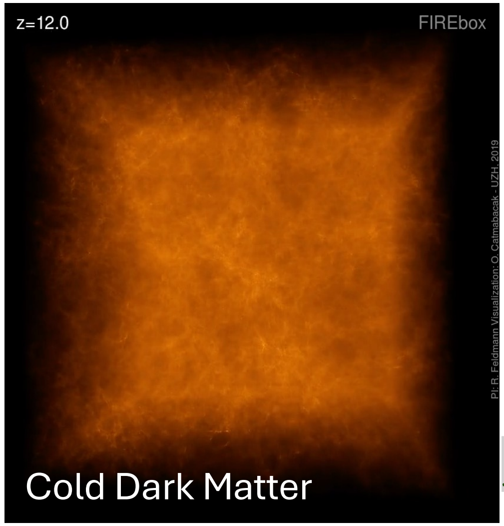


Mauro Bernardini


Euclid (optical)
JWST (IR)
NGC 1566
NGC 5068
NGC 4303
NGC 1512
NGC 1365
NGC 4535
NGC 3351
NGC 4321
NGC 0628
IC 5332
NGC 4254
NGC 2835
NGC 1300
NGC 7496
NGC 1433
THINGS (HI)
SKACH

Current challenges of numerical modeling

Gravity



$$\frac{df}{dt} = \partial_t f + v\partial_r f - \partial_r \Phi \partial_v f = 0$$

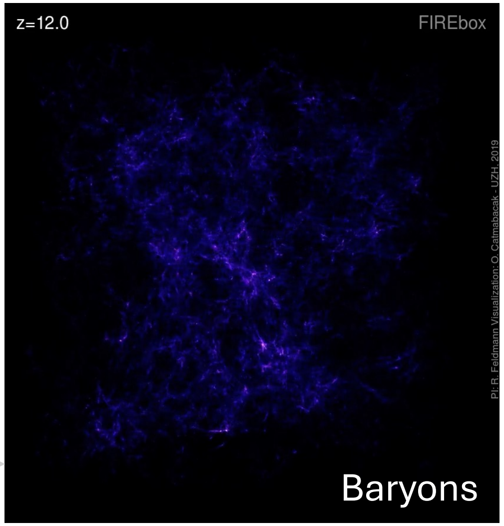
$$\Delta\Phi = 4\pi G \int f dv$$

Hydrodynamics

$$\partial_t \rho + \nabla \cdot (\rho v) = 0$$

$$\partial_t (\rho v) + \nabla \cdot (\rho v \otimes v + P) = 0$$

$$\partial_t (\rho e) + \nabla \cdot (\rho e + P) v = 0$$



„cheap“ ML „costly“

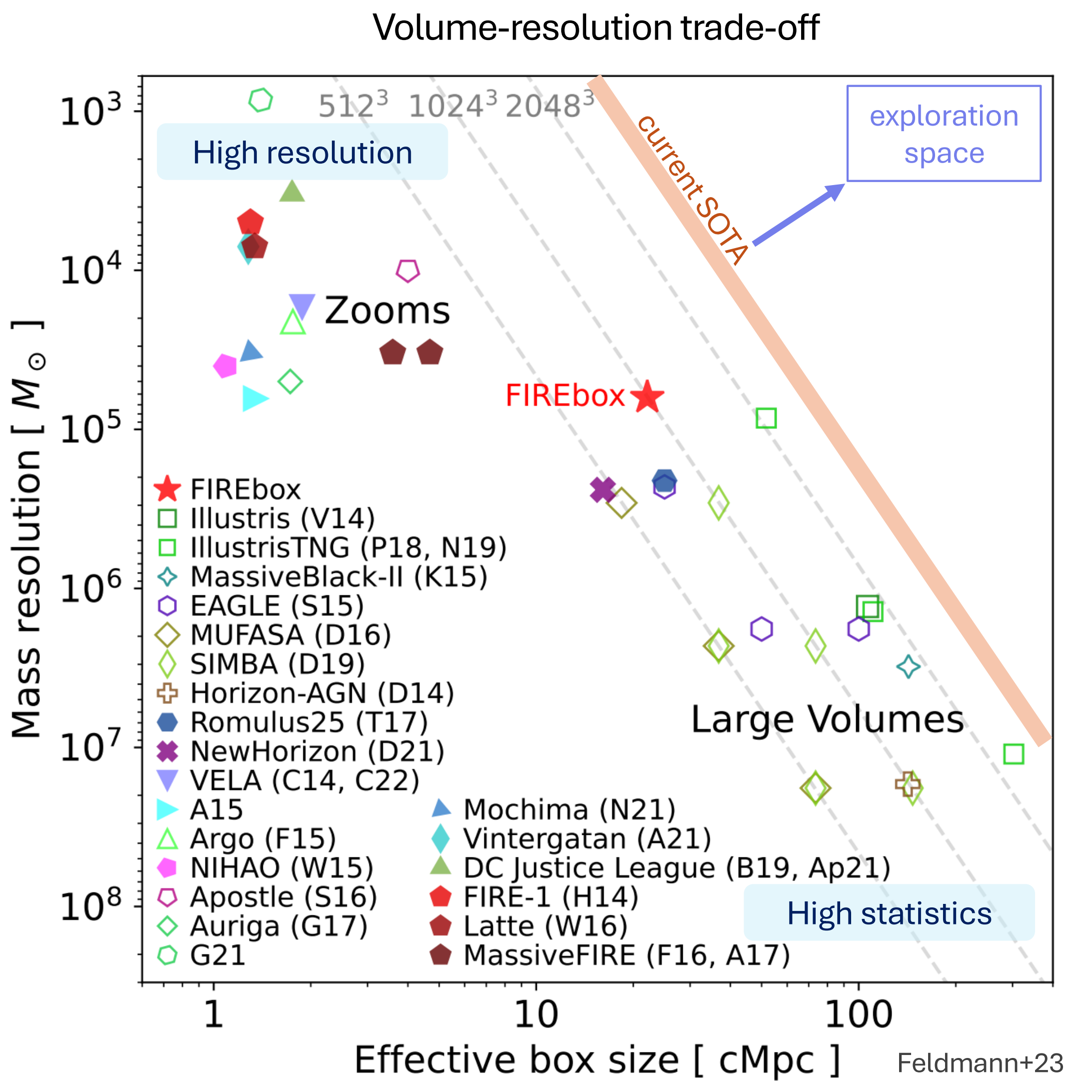
Feldmann+23

„uncertain“

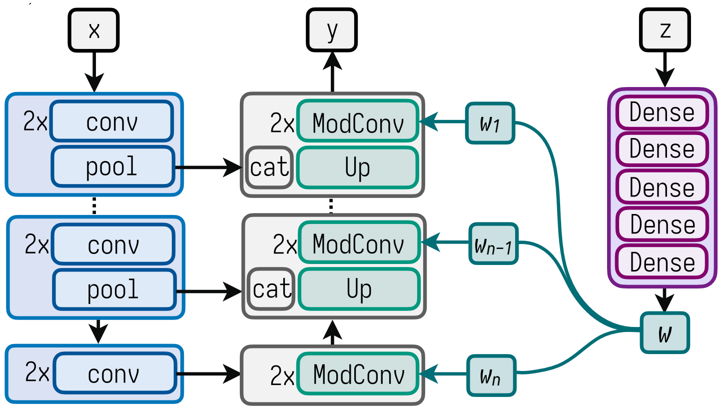
Gas cooling	Interstellar medium	Star formation	Stellar feedback	Supermassive black holes	Active galactic nuclei	Magnetic fields	Radiation fields	Cosmic rays
Atomic/ molecular/ metals/ tabulated network	Effective equation of state/ multiphase	Initial stellar mass function/ probabilistic sampling/ enrichment	Kinetic/ thermal/ variety of sources from stars, supernovae	Numerical seeding/ growth by accretion prescription/ merging	Kinetic/ thermal/ radiative/ quasar model radio mode	Ideal MHD/ cleaning schemes/ constrained transport	Ray tracing/ Monte Carlo/ moment based	Production/ heating/ anisotropic diffusion/ streaming
Stellar physics				BH + AGN		MHD		

Vogelsberger+20

Simulation costs!



Bernardini+25a



Architecture:

- StyleGAN-2 inspired NN
- Emulates gas fields from dark matter maps
- Across large redshift range (0-6)
- Fully convolutional, thus scalable

Designed for:

(1) Domain translation
(2) Resolution / Volume upscaling } *This talk!*
(3) Field-level emulation conditioned on different astrophysical models

→ ***Caveat***: *No physics-constraints in the model; purely data-driven!*

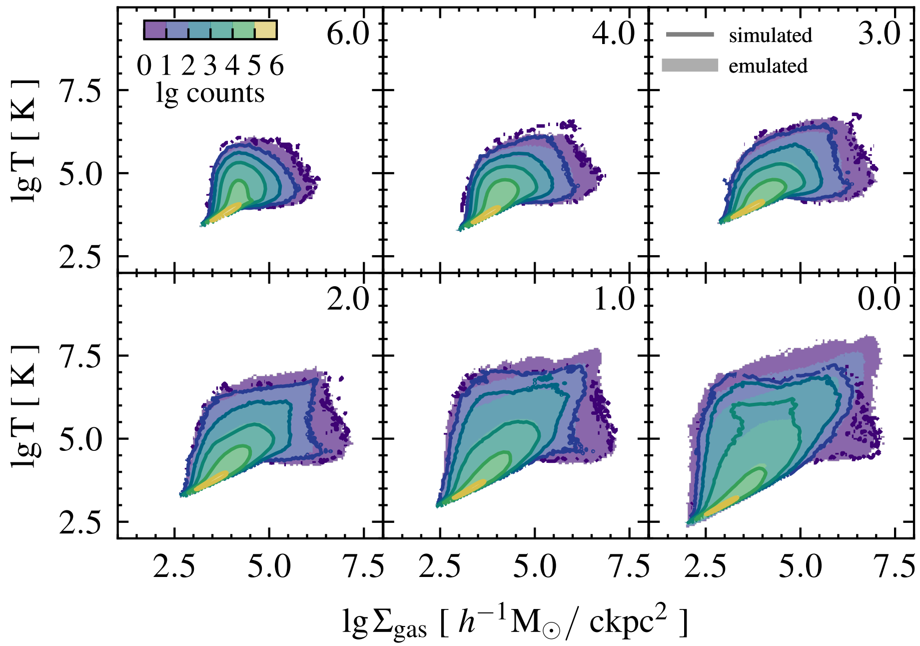
Website: `maurbe.github.io/ember2`

EMBER *dark matter → baryons*

Key idea: Train to emulate **baryon** from **dark matter** maps

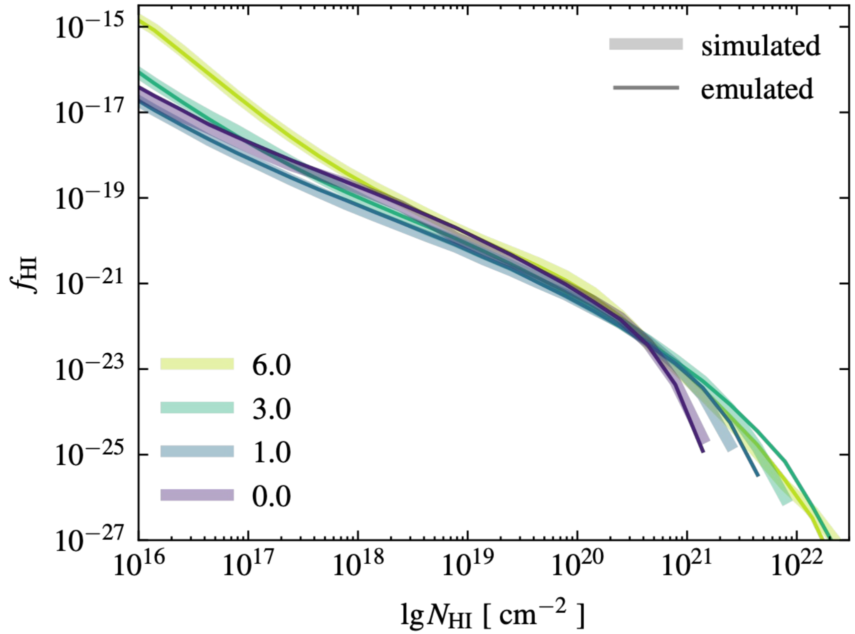
$$f : (\Sigma_{\rm dm}, v_{\rm dm}) \rightarrow (\Sigma_{\rm gas}, v_{\rm gas}, T_{\rm gas}, \Sigma_{\rm HI})$$

Phase-diagram



Bernardini+25a

HI CDDF



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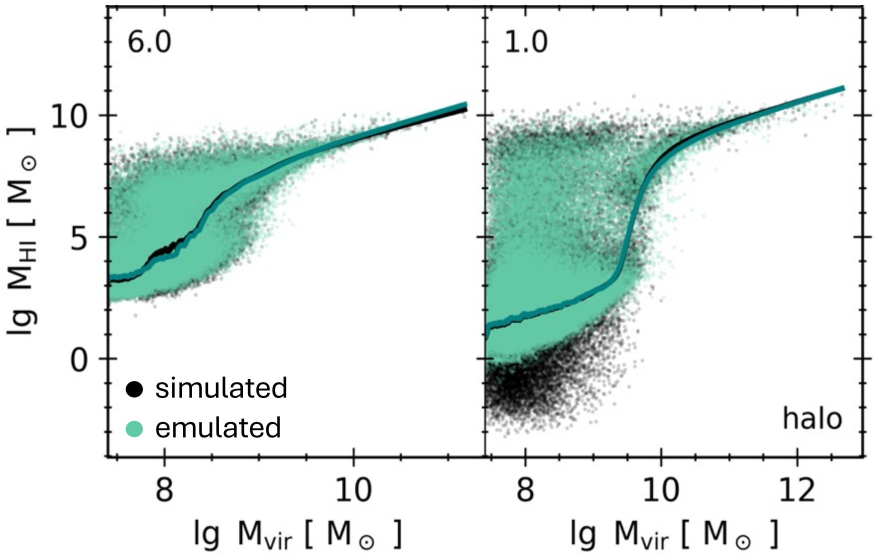
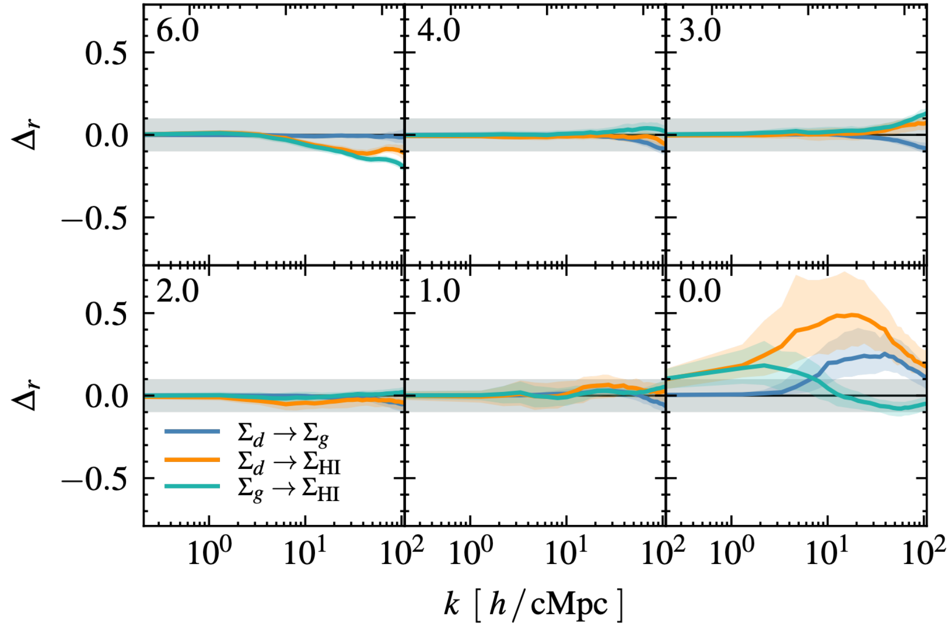
HM-HI relation (halo-based)

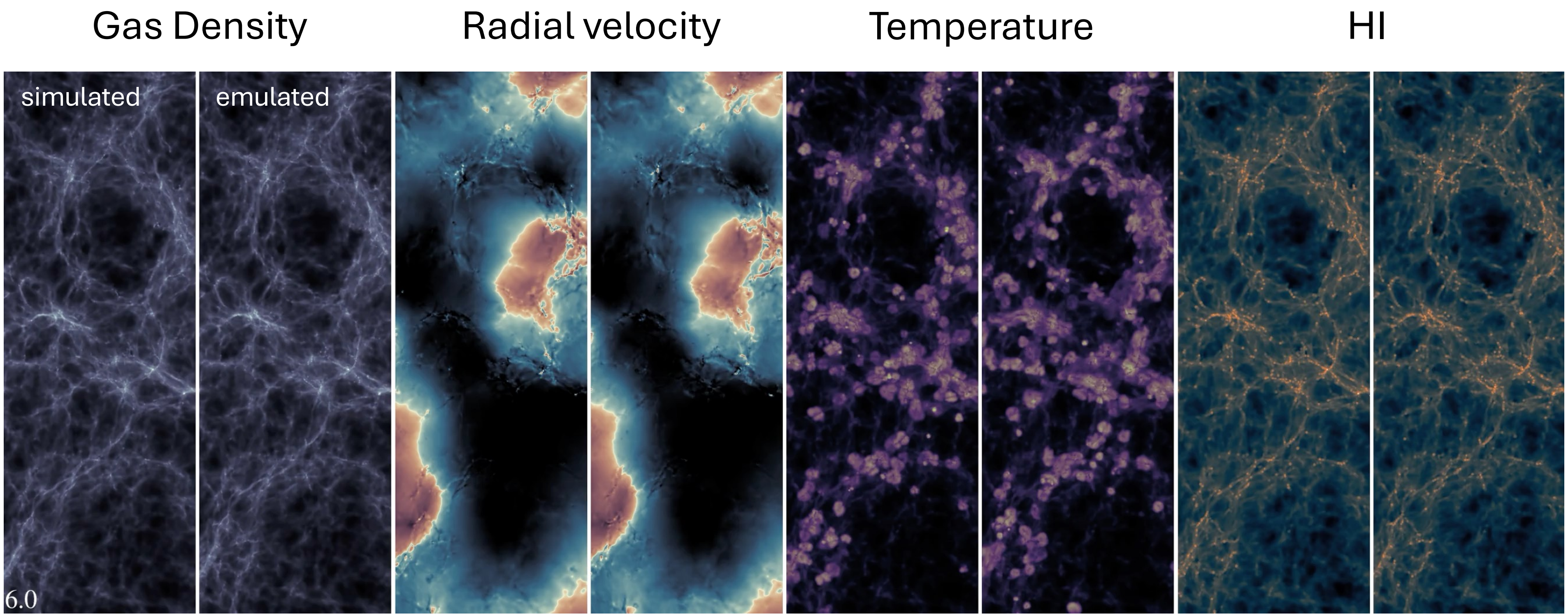


Cross-correlations

Bernardini+25a

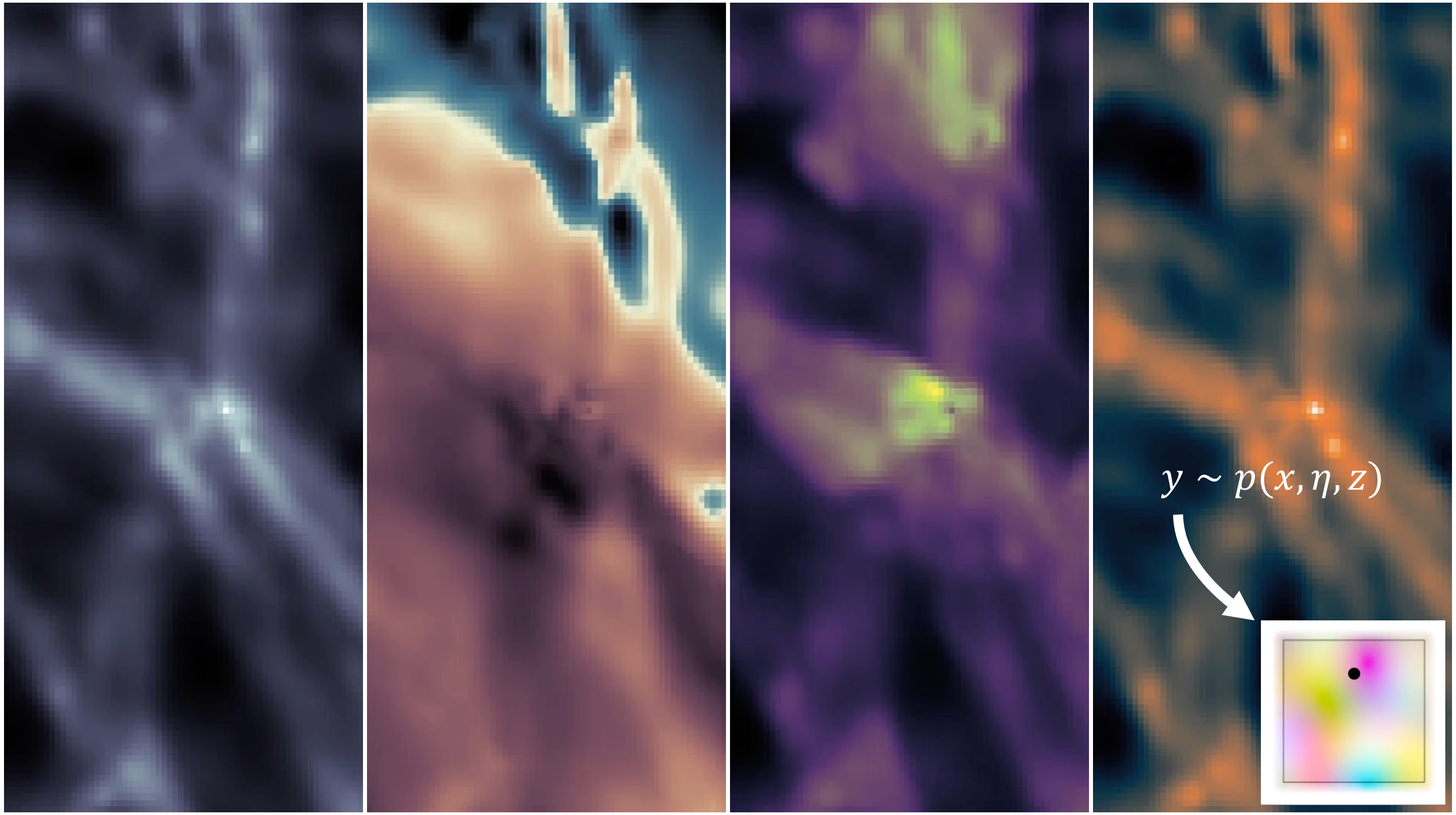


EMBER *dark matter → baryons*



Bernardini+25a

EMBER *dark matter → baryons*

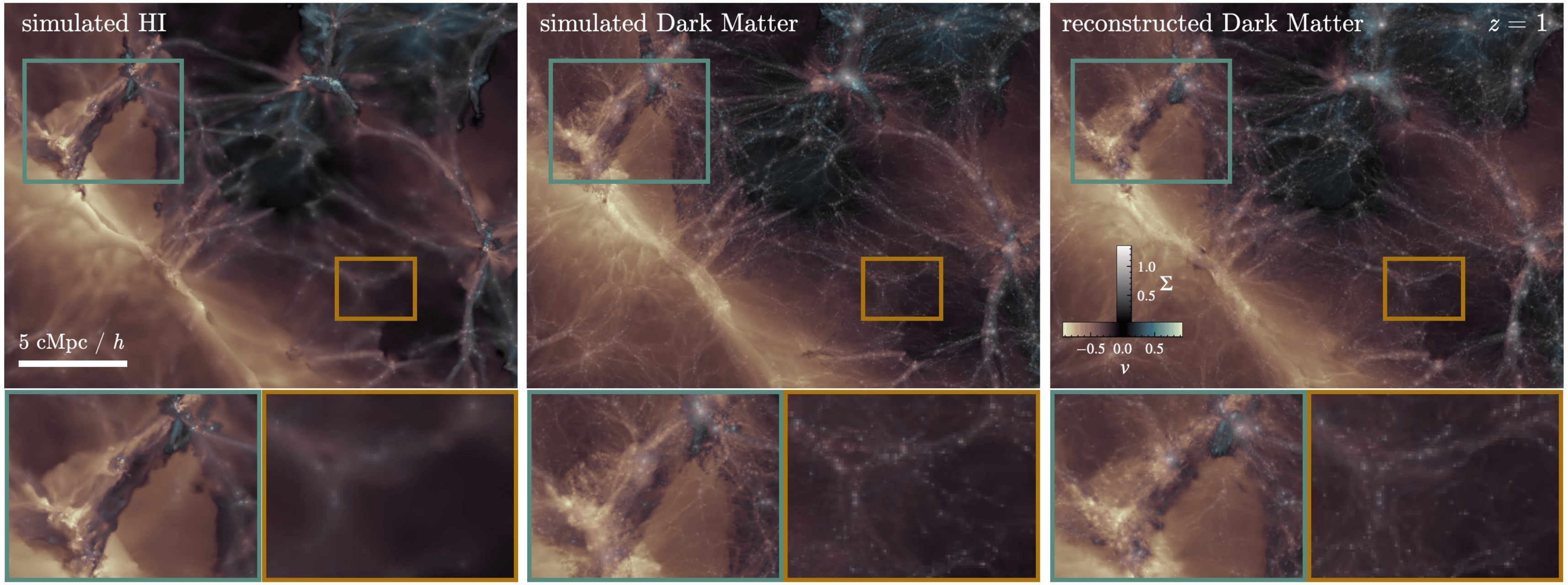


EMBER: *HI → dark matter*

Key idea: Train to predict **dark matter** from **HI** maps

$$f : (\Sigma_{\mathrm{HI}}, v_{\mathrm{HI}}) \rightarrow (\Sigma_{\mathrm{dm}}, v_{\mathrm{dm}})$$

Bernardini+25b



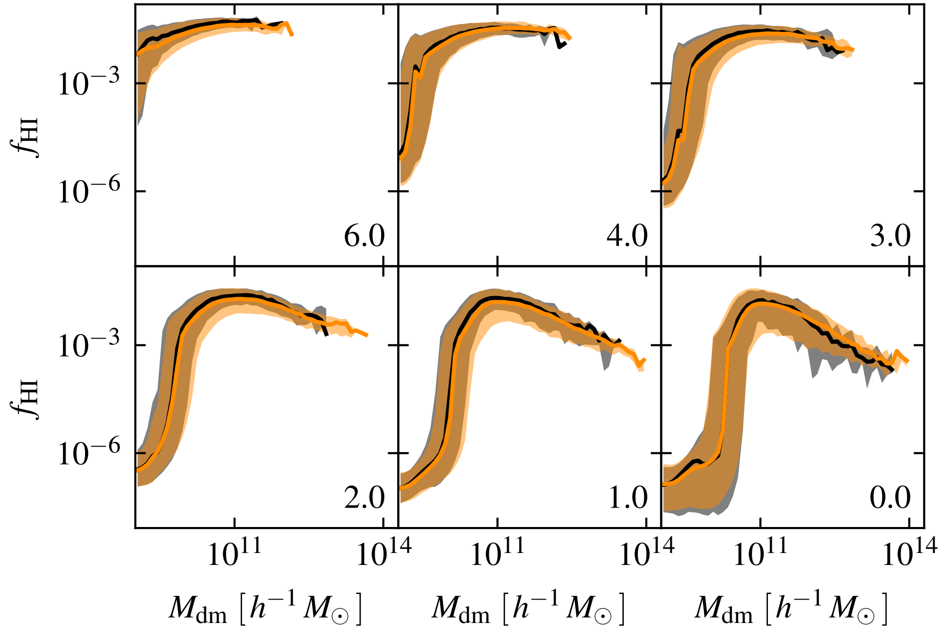
→ Can be integrated into downstream analysis pipelines of HI observations

EMBER *HI → dark matter*

Key idea: Train to predict **dark matter** from **HI** maps

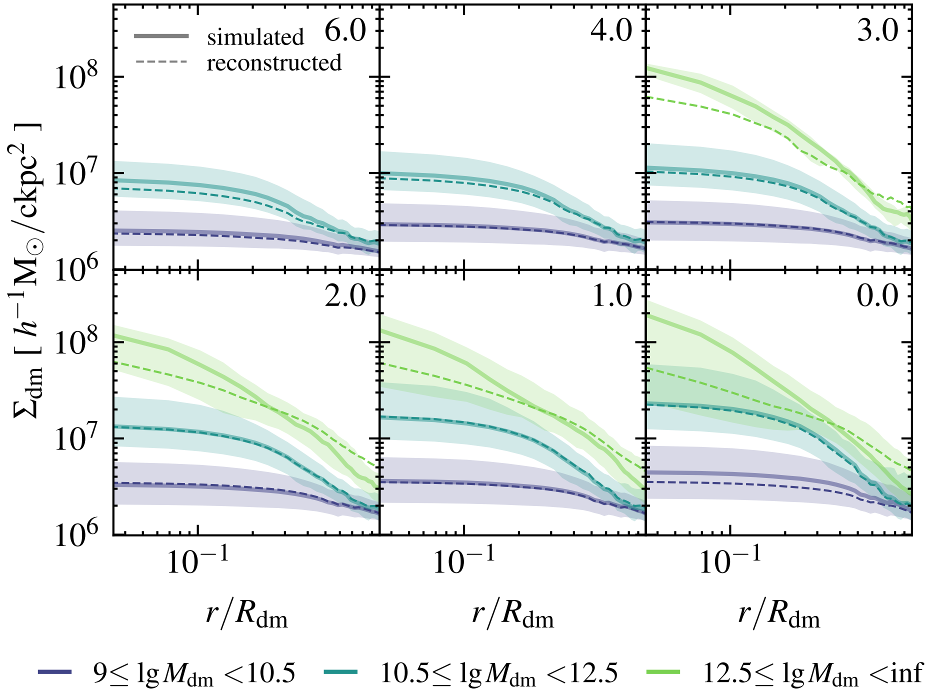
$$f : (\Sigma_{\mathrm{HI}}, v_{\mathrm{HI}}) \rightarrow (\Sigma_{\mathrm{dm}}, v_{\mathrm{dm}})$$

HI-DM fractions



Radial profiles

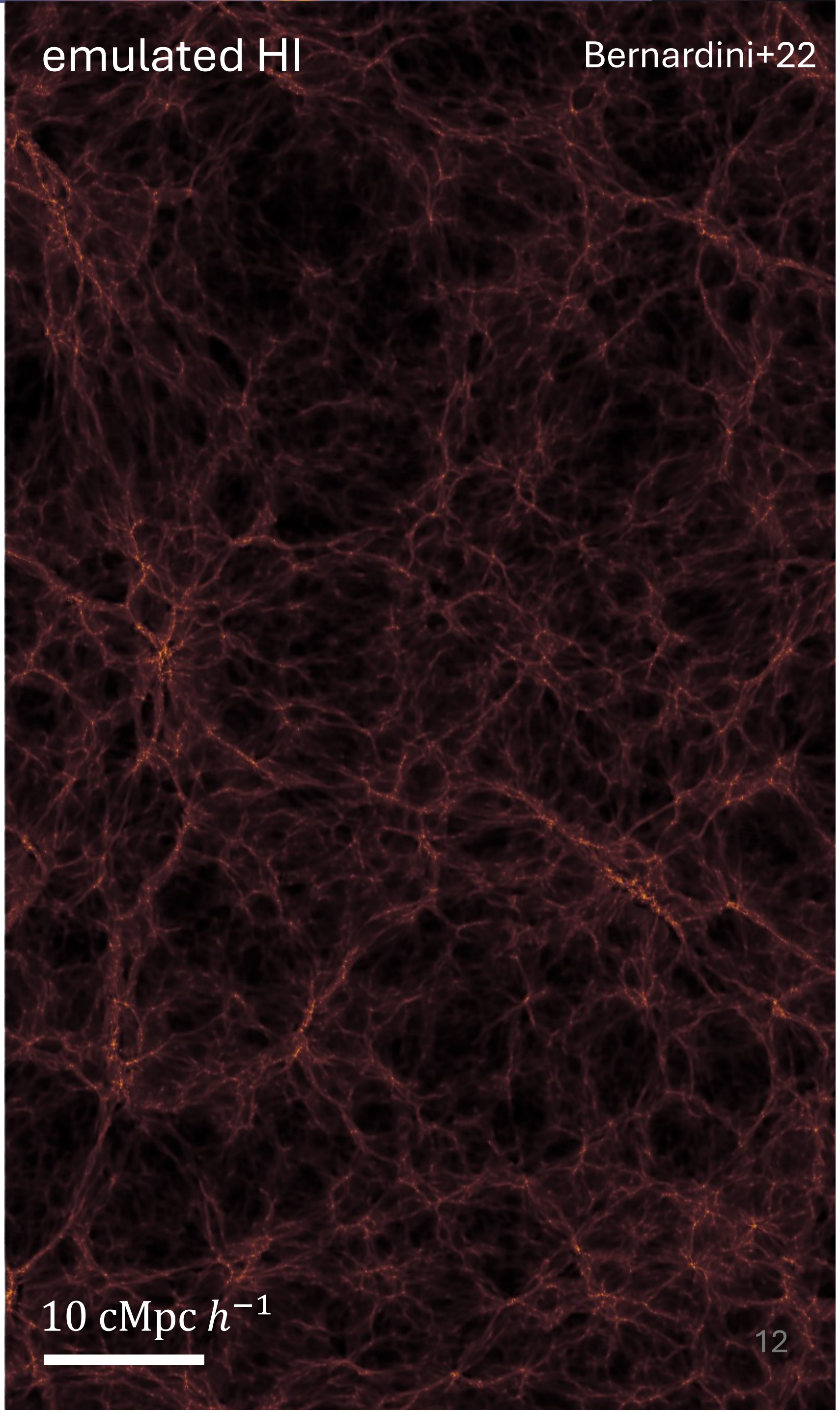
Bernardini+25b



EMBER *upscaling simulation outputs*

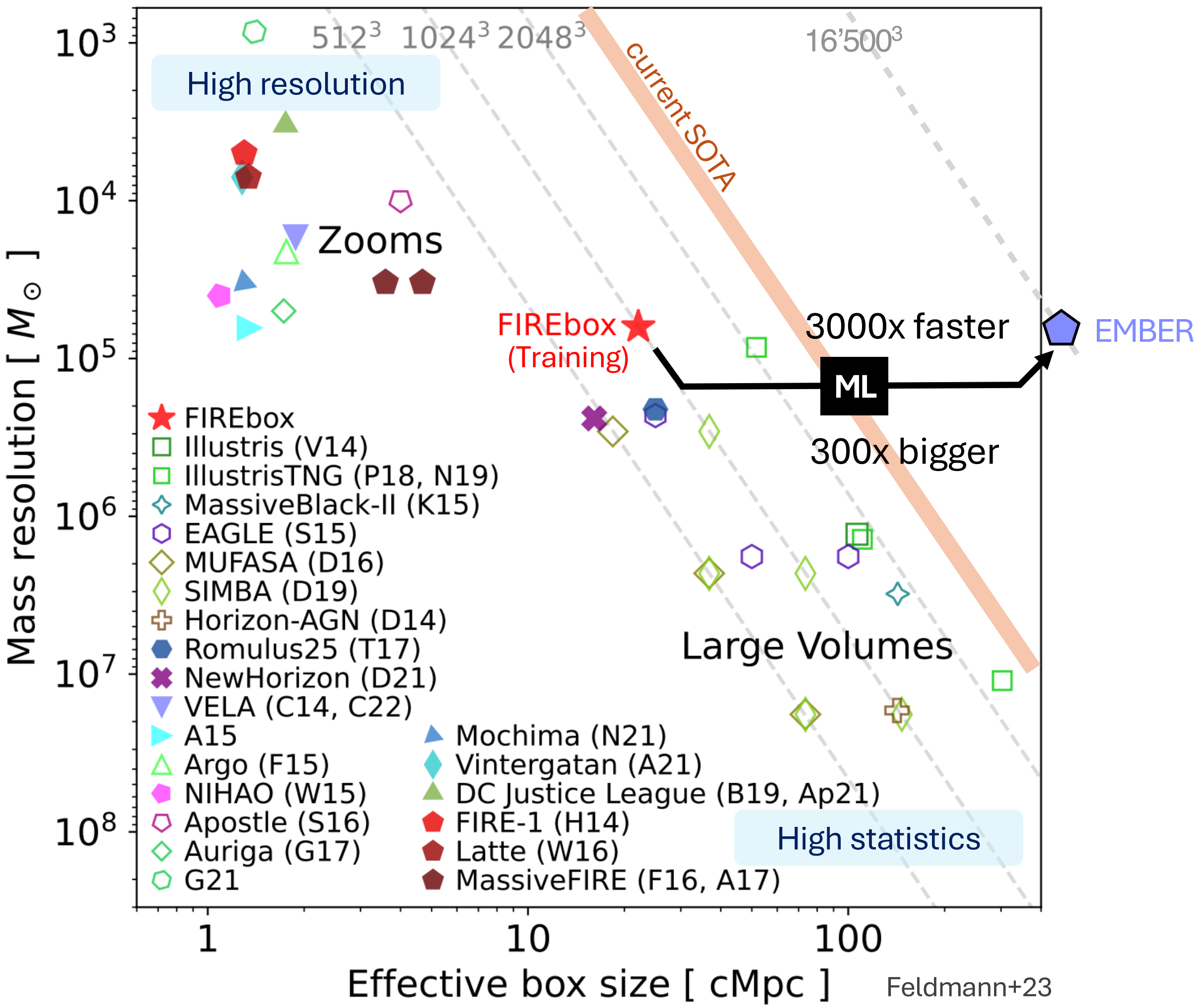
Training:
- Training on small high-resolution volumes and high-resolution zoom-in simulations
- Degrading the input dark matter resolution
- Training on paired maps of **low-res DM → high-res baryon**
- Upscalable due to fully convolutional nature

Application:
- „Emulate" high resolution baryon fields onto much larger volumes (here 300x)



Simulation costs!

Volume-resolution trade-off



Feldmann+23

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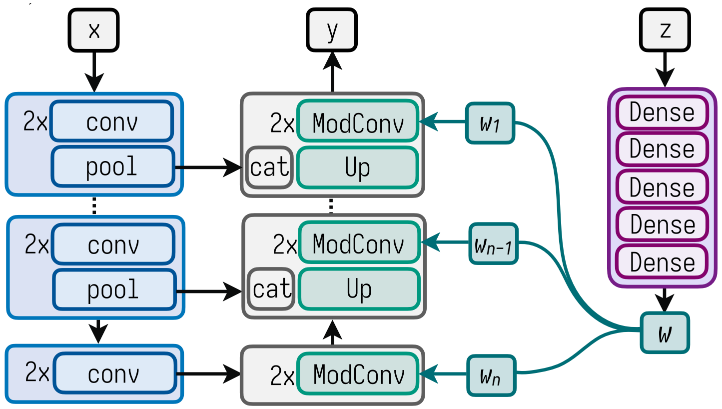

Designed for:

(1) Domain translation ✅

(2) Resolution / Volume upscaling ✅

Based on:
Bernardini+22 (2110.11970
Bernardini+25a (2502.15875)
Bernardini+25b (to appear)

Thank you!

Website: `maurbe.github.io/ember2`