Dall-E: "The cosmic web in the style of a cubist painter"

picasso:

Painting intra-cluster gas on gravity-only simulations

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Context

- **Simulations needed for cluster cosmology (SBv2, §6.1.4)**
  - Halo mass function calibration
  - Covariances between observables
  - Analysis calibration (e.g. cluster detection, systematic calibrations, …)
  - → **Need realistic synthetic maps / catalogs**
- **Two kinds of cosmological simulations:**
  - Hydrodynamic (include baryonic physics, but slow and uncertain)
  - Gravity-only / G-O (fast, but no baryons)

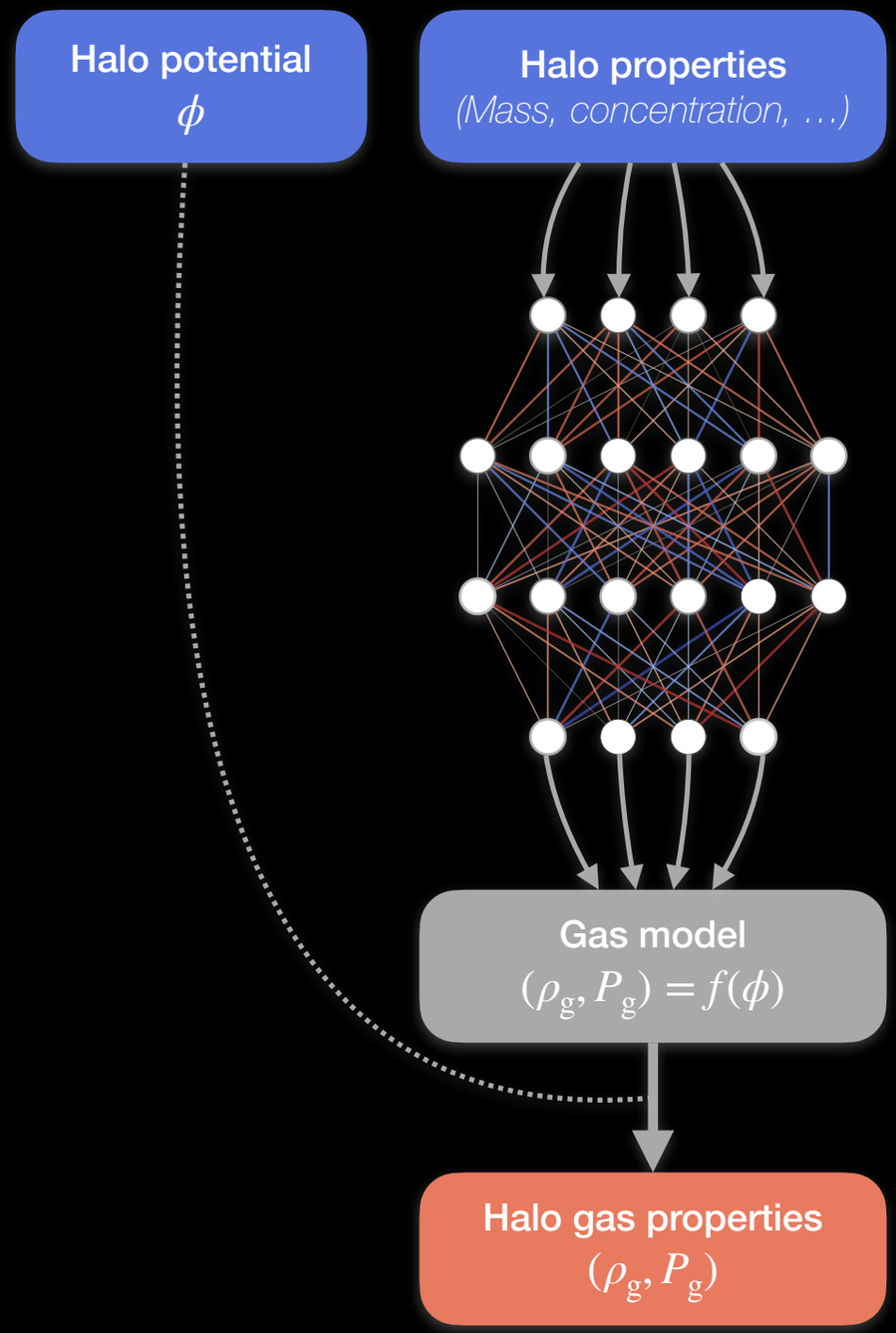
→ **Need post-processing to create observables from G-O**

- In particular intracluster gas for SZ effects
- Examples: Websky (Stein20); AGORA (Omori24); HalfDome (Bayer+24), …

This work: New analytical+ML model to “paint” intracluster gas

The `picasso` model

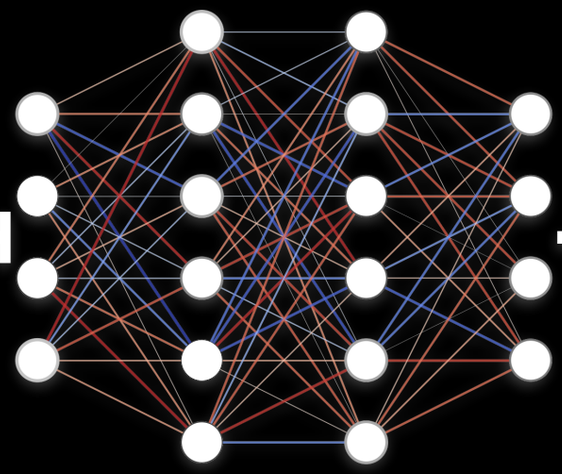
- What is `picasso`?
  - ML-powered model to “paint” gas on gravity-only halos
  - From halo properties, predicts analytical mapping between halo potential and gas thermodynamics
  - Trained on pairs of gravity-only / hydrodynamic simulations
- Strengths:
  - Flexible:
    - → Can be trained to accurately & precisely reproduce different observables from hydro simulations
    - → Can be trained on new hydrodynamic simulations
  - Scaleable:
    - → Can take minimal inputs (halo catalog) or take advantage of full particle information
  - Fast, GPU-accelerated, differentiable (JAX)



The picasso model… more detailed

Halo properties vector $\vartheta_{\rm halo}$

- Halo mass M_{200c}
- Concentration c_{200c}
- Dynamical state
- Morphology
- Mass accretion history



Gas model parameters
$\vartheta_{\rm gas}$

Halo potential distribution
(r, ϕ)

Can be particles, 3D grid, profile, …

Analytical gas model:

- Gas density:
  $\rho_{\rm g} = f(\phi, r \mid \vartheta_{\rm gas})$
- Gas total (thermal + kinetic) pressure:
  $P_{\rm tot} = f(\phi, r \mid \vartheta_{\rm gas})$
- Gas non-thermal pressure fraction:
  $f_{\rm nt} = f(r \mid \vartheta_{\rm gas})$
- Gas thermal pressure:
  $P_{\rm th} = (1 - f_{\rm nt})\, P_{\rm tot} = f(\phi, r \mid \vartheta_{\rm gas})$

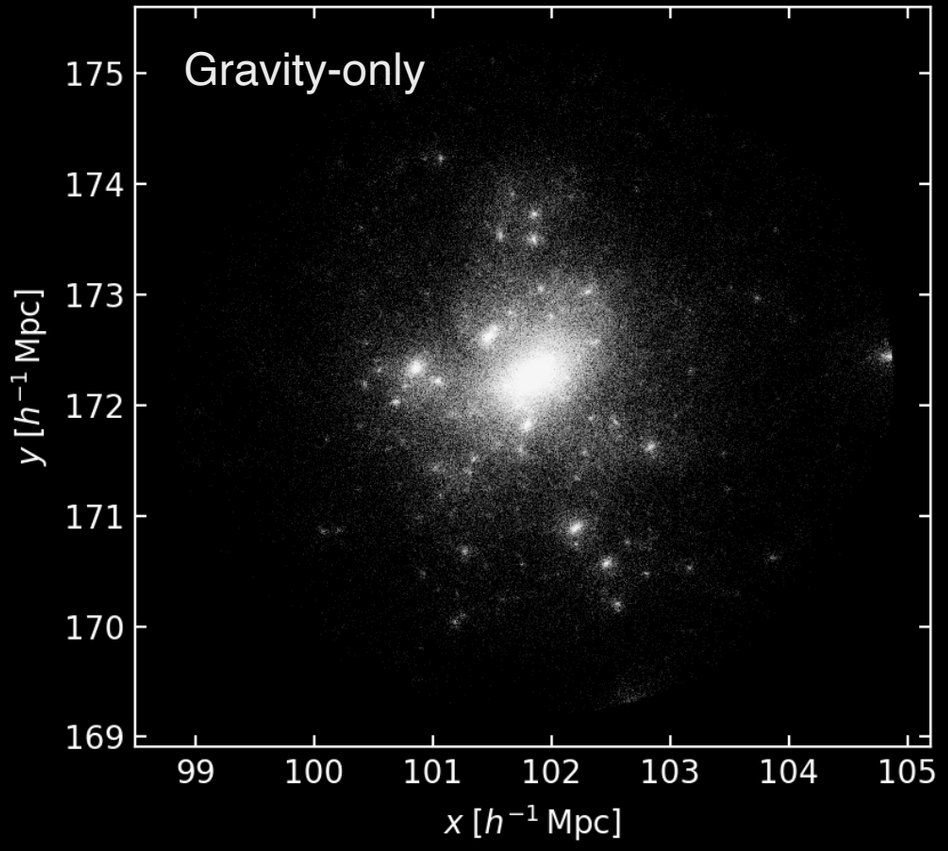
Halo gas properties
$(\rho_{\rm g}, P_{\rm tot}, f_{\rm nt}, P_{\rm th})$

Model training

- Trained on pair of gravity-only & hydrodynamic simulations
  - $L = 576\ h^{-1}\,\mathrm{Mpc}\ ;\quad m_{\mathrm{DM}} \sim 10^{9}\ h^{-1}\,M_{\odot}$
  - Halo masses $M_{500c} > 10^{13.5}\ h^{-1} M_{\odot}$ → ~10,000 halos

→ **Training:**

  - Forward model gas properties of G-O halos
  - Train to reproduce properties of hydro counterparts: $(\rho_{\mathrm{g}},\ P_{\mathrm{tot}},\ f_{\mathrm{nt}},\ P_{\mathrm{th}})$



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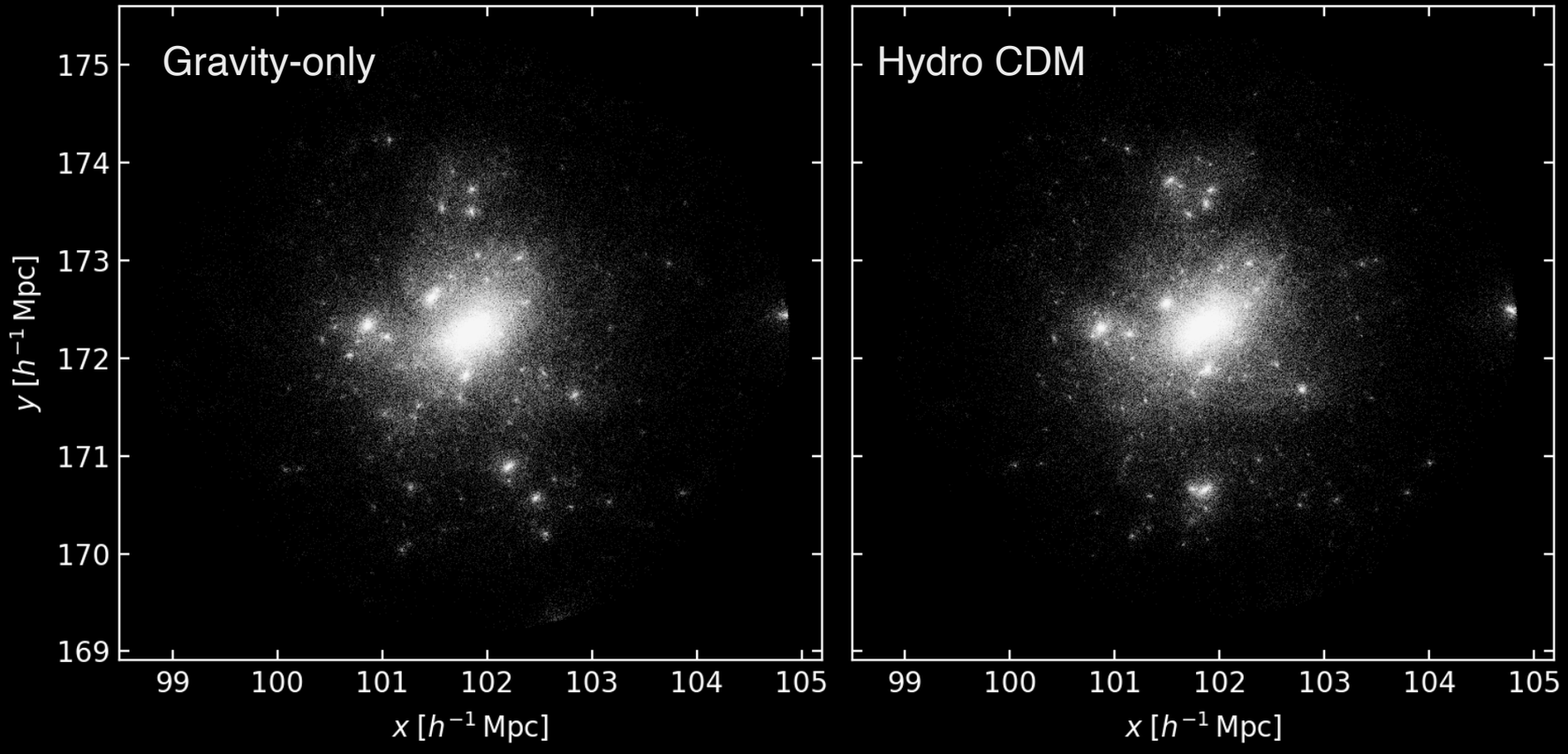

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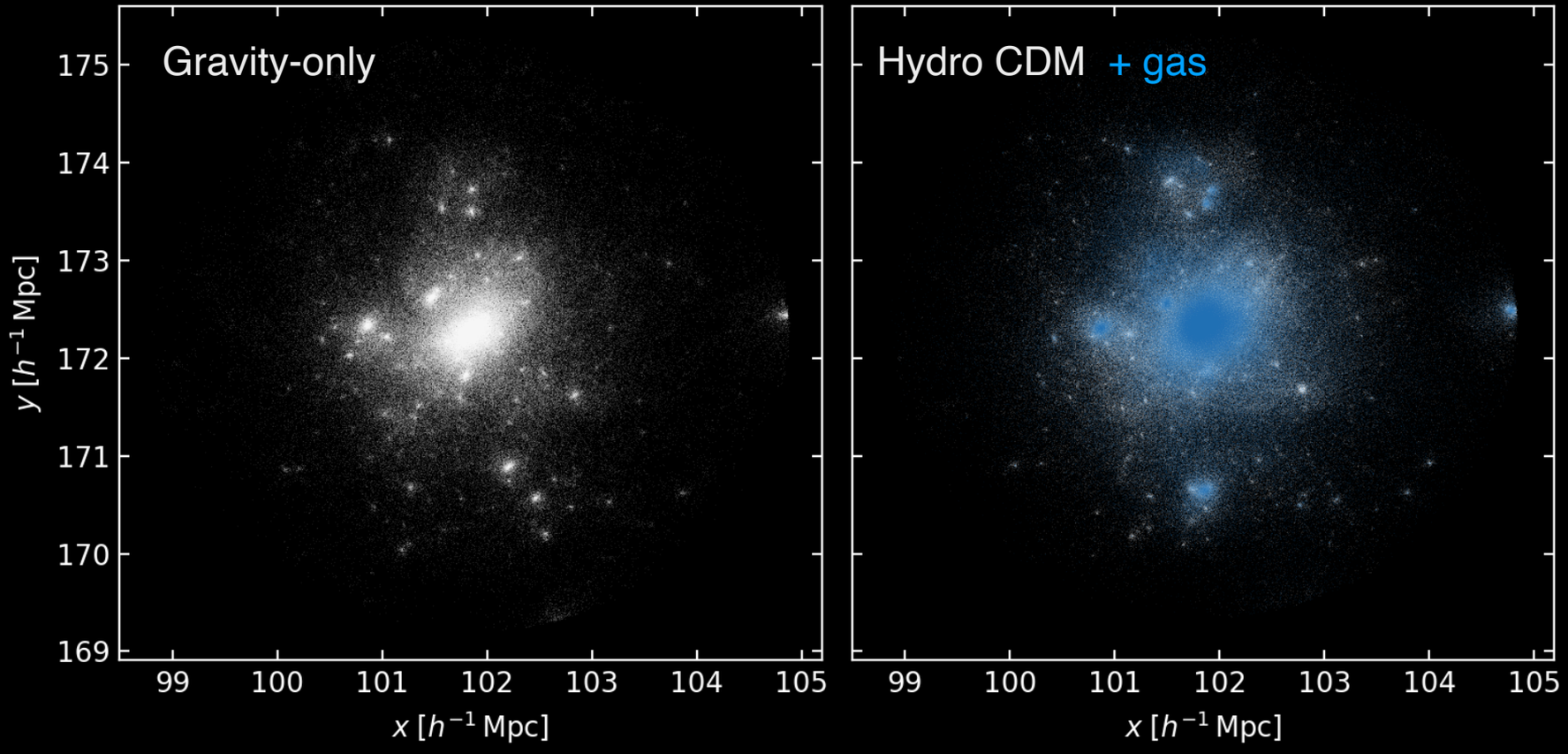
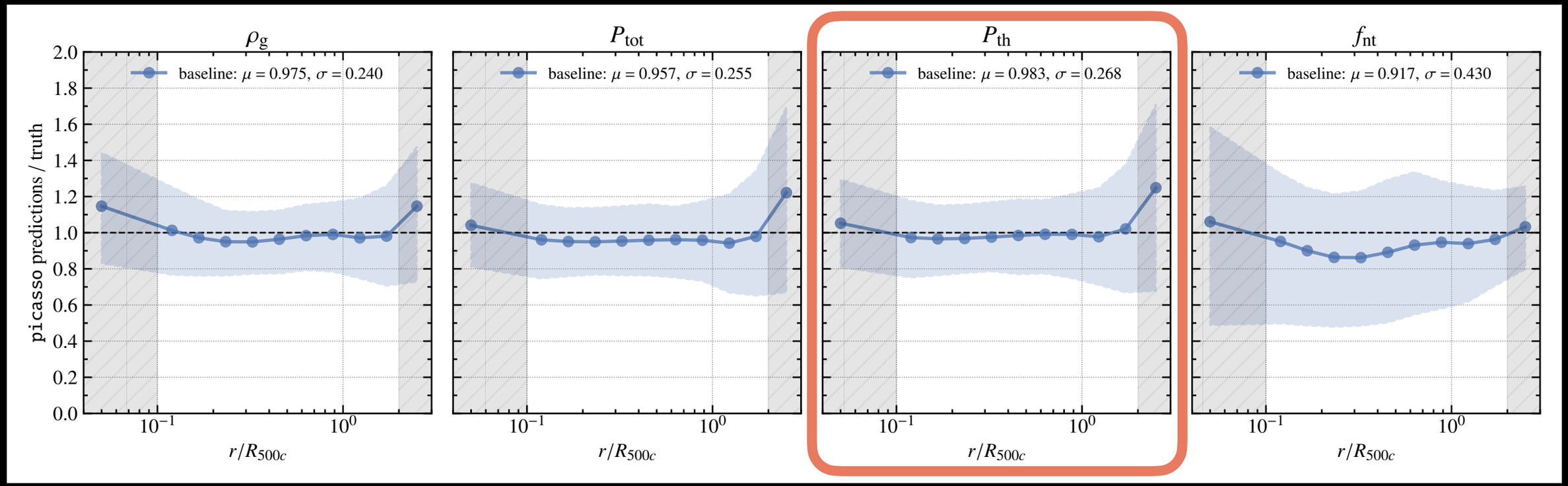


Baseline model results

- Baseline model:
  - Train to reproduce results from non-radiative hydro run (no subgrid models)
  - Full input vector
- Results: for the training range ($r \in [0.1, 2] \times R_{500c}$),
  - Few-% accuracy on main property of interest ($P_{\rm th}$)
  - Scatter similar to “pasting” methods (Kéruzoré+23)

  → Low expected impact on cosmology!

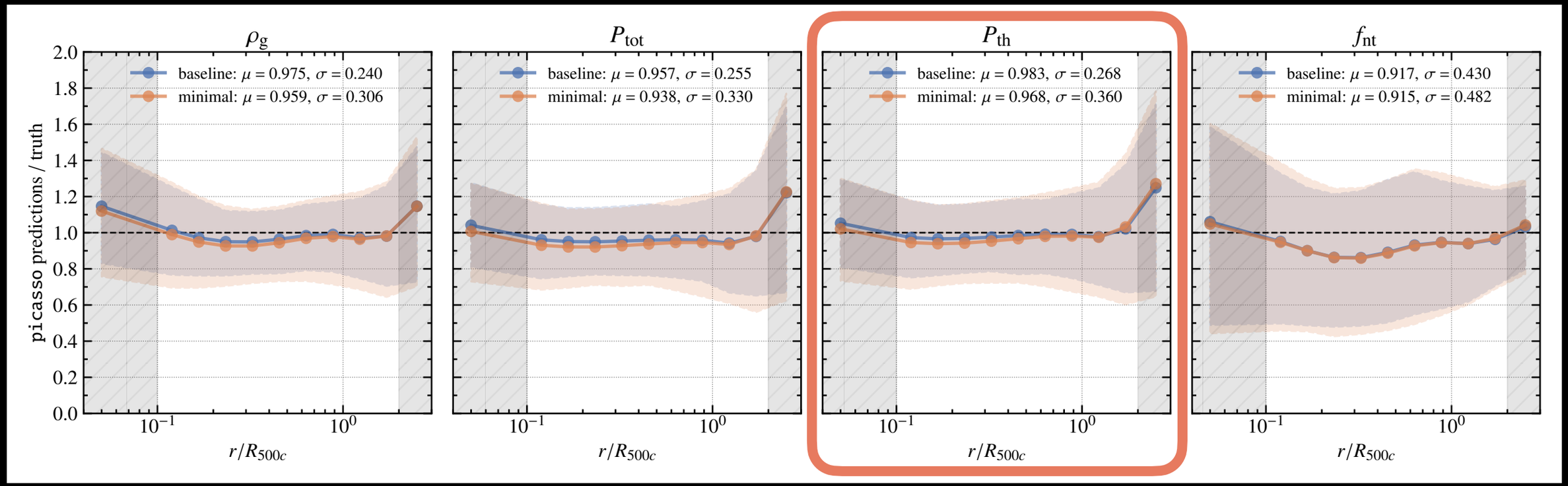
Testing set: halos not seen in training



Minimal model results

- Minimal model:
  - Non-radiative hydro run (no subgrid models)
  - Minimal input vector (M_{200c}, c_{200c})
- Results:
  - Bias similar to baseline, scatter slightly degraded
  - → Promising: can be used from minimal inputs

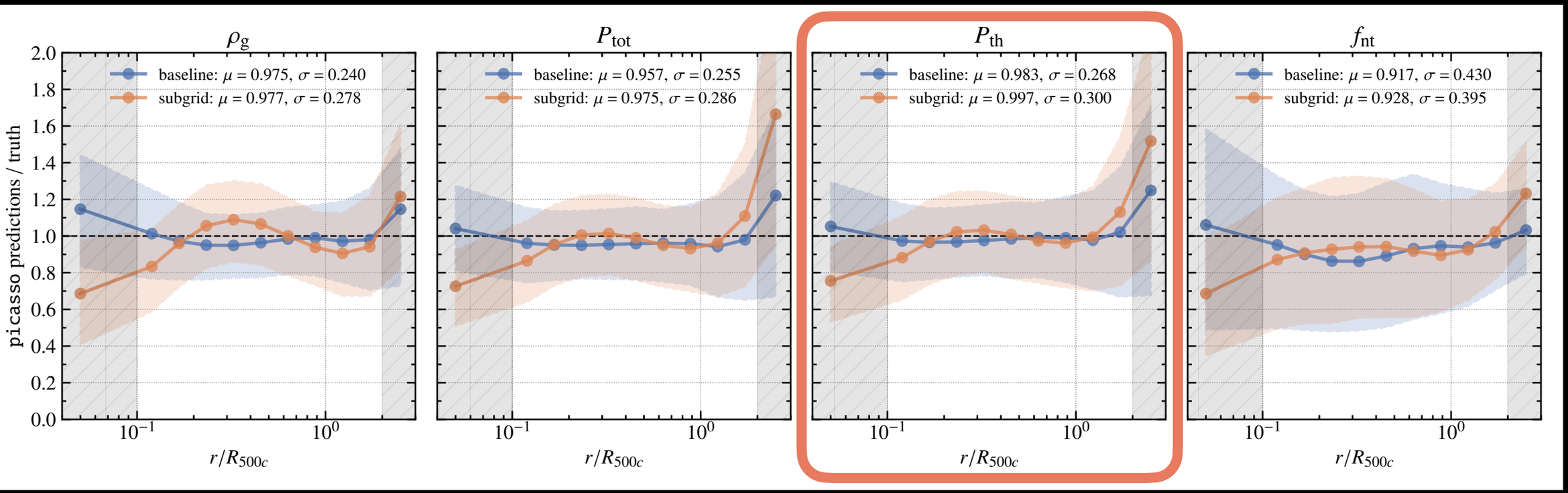
Testing set: halos not seen in training



Subgrid model results

- Subgrid model:
  - Train on **full-physics hydrodynamic simulation**
  - Full (baseline) input vector
- Results:
  - Bias slightly worse and not constant with radius (still few-% at $r > 0.2R_{500c}$)
  - Scatter slightly degraded
  - → Promising! But further model investigation required

Testing set: halos not seen in training



Conclusions

- New gas model combining analytical model and AI/ML
  - Fast, GPU-enabled, differentiable
  - Flexible
- Promising first results:
  - High accuracy & precision on non-radiative hydrodynamic sims
  - Slightly degraded on full-physics hydrodynamics → to be improved
- What's next?
  - Code + model (including trained models) to be published in ~weeks
  - Release of tSZ maps from G-O simulations: Last Journey, OuterRim
    - Paired with ongoing ANL work → multi-wavelength suites

      Radio sources (G. Campitiello), CIB (M. Mallaby-Kay), kSZ, galaxies (DiffSky team), (CMB-)Lensing
    - Interested in possible integrations to Data Challenges!
  - Continuous retraining as new hydrodynamic simulations are run