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ICSC Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

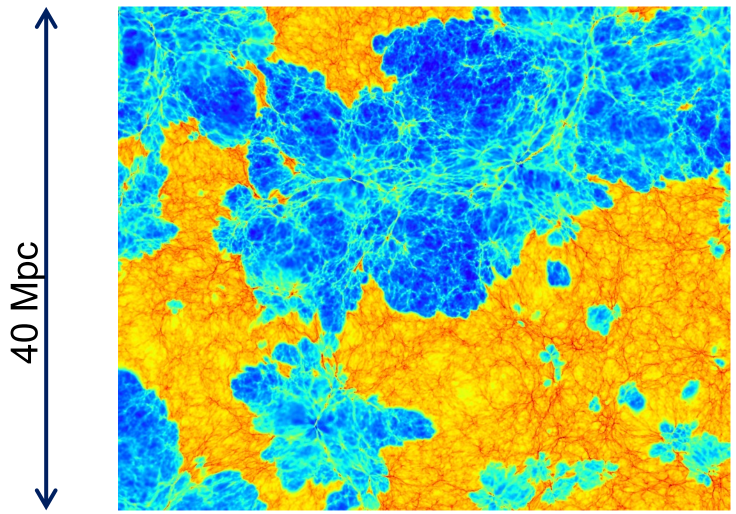
Modelling Hydrogen Distribution in the post-reionization Universe

Matteo Viel – SISSA

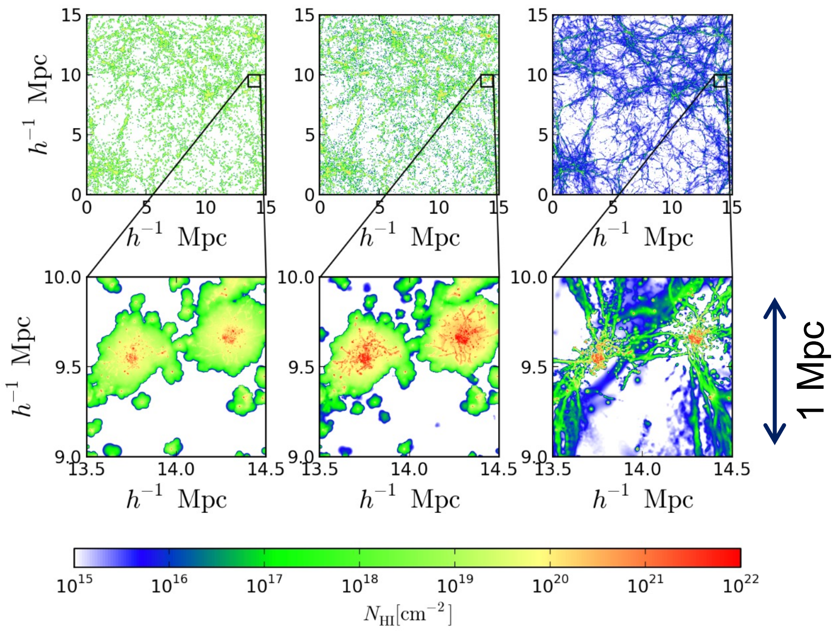
Spoke 3 General Meeting, Elba 5-9 / 05, 2024

Scientific Rationale

- HI (Atomic/Neutral Hydrogen) outside and inside galaxies. Modelling is challenging, huge variety of scales involved, redshifts, environments, physical effects (including radiative transfer).
- Atomic processes: Lyman-α scattering and 21cm electron spin-flip transition



Sherwood Relics collaboration (G3 Puchwein+23 (w MV) - HI distribution including radiative transfer on GPU to simulate patchy reionization



Villaescusa—Navarro (w MV) 2014, 2018
HI distribution in haloes

- ➢ Probing cosmological structure formation processes
- ➢ Probing the cold gas phase and its relation with galaxy formation
- ➢ Address fundamental physics questions like nature of Dark Matter, Neutrinos, Dark Energy

Technical Objectives, Methodologies and Solutions

- Lyman-α forest: Code developement: G3→G4 and AREPO to simulate the low-density IGM [eventually physics could be incorporated into OpenGADGET – this is mainly cooling.c routine + interface with GPUs ATON code for Radiative Transfer].

- Intensity Mapping: Code devolopement: HIP-POP. Populating the DM haloes with HI to produce realistic mocks ready for pipeline testing (e.g. foreground removal/cross-correlation analysis).

- Combination of the two above with Machine Learning techniques to 1) increase resolution; 2) learn sub-grid physics; 3) learn how to marginalize over sub-grid physics; 3) emulation and fast generation of hydro sims/maps.

Timescale, Milestones and KPIs

HIP-POP	Description	Target	KPIs
M8	We generated mock catalogs with Pinocchio (input for the code). We tested the HIP-POP code on them, to mock a light cone (full sky) and Meerkat patch.	Compute the Cls (power spectrum in harmonic space) - generate first maps	First testing of the pipeline (without instrumental noise) - github repository created
M9	Further validation of the code by using different setup of ICs - cosmo parameters	Compute Cls for the different cases, validate HI profile within haloes, validate HI population (different methods). Tests of CPU/memory consumption and scalability	Release of the code on github With example/small data set provided
M10	Scientific validation	Perform scientific runs applied to several physical setup (different scales,redshifts, experiment) including cross-correlations	Publication presenting the code

Accomplished Work, Results

- Modelling of the low-density IGM and post-reionization – about 75M CPUhrs since 2017

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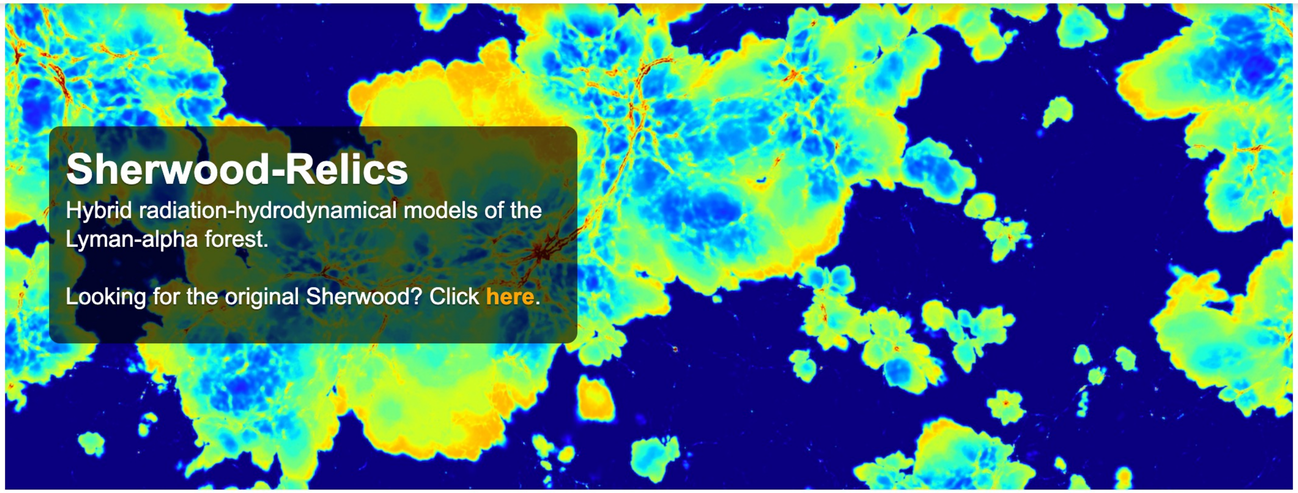

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Unveiling dark matter free streaming at the smallest scales with the high redshift Lyman-alpha forest

Vid Iršič,[1,2,*] Matteo Viel,[3,4,5,6,7] Martin G. Haehnelt,[1,8] James S. Bolton,[9] Margherita Molaro,[9] Ewald Puchwein,[10] Elisa Boera,[5,6] George D. Becker,[11] Prakash Gaikwad,[12] Laura C. Keating,[13] and Girish Kulkarni[14]

[1]*Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom*
[2]*Cavendish Laboratory, University of Cambridge, 19 J. J. Thomson Avenue, Cambridge CB3 0HE, United Kingdom*
[3]*SISSA—International School for Advanced Studies, Via Bonomea 265, 34136 Trieste, Italy*
[4]*INFN—National Institute for Nuclear Physics, Via Valerio 2, I-34127 Trieste, Italy*
[5]*IFPU, Institute for Fundamental Physics of the Universe, via Beirut 2, 34151 Trieste, Italy*
[6]*INAF, Osservatorio Astronomico di Trieste, Via G. B. Tiepolo 11, I-34131 Trieste, Italy*
[7]*ICSC—Centro Nazionale di Ricerca in High Performance Computing, Big Data e Quantum Computing, Via Magnanelli 2, Bologna, Italy*

Constraints on:

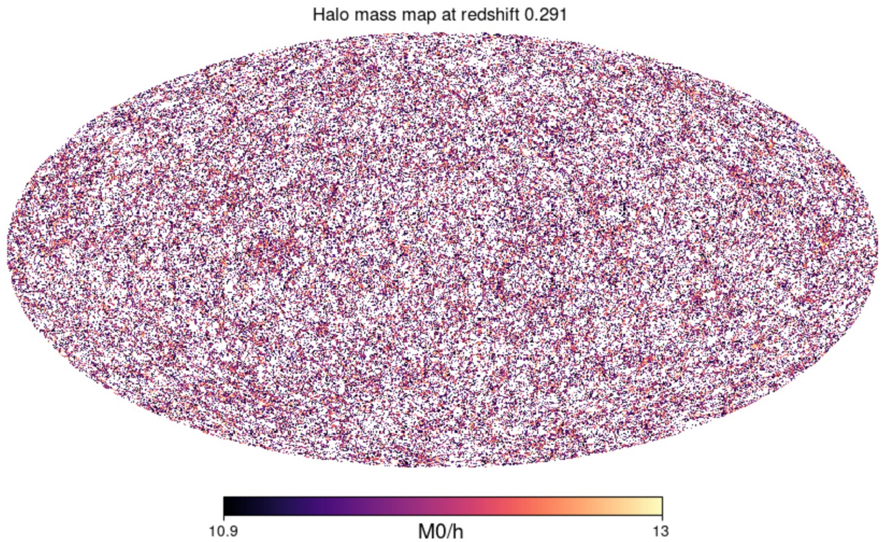
- Gas thermal state
- And its pressure
- And a possible warm dark matter signature at z=4-5

Accomplished Work, Results

- HIP-POP HIProbe-POPulator code developed with Marta Spinelli (work started in 2020, with early contributions from Tiago Castro and Emiliano Munari)
- Currently development branch is https://github.com/spinemart/HIP-POP/tree/Matteo_develop
- Main branch maintained by Marta Spinelli https://github.com/spinemart/HIP-POP

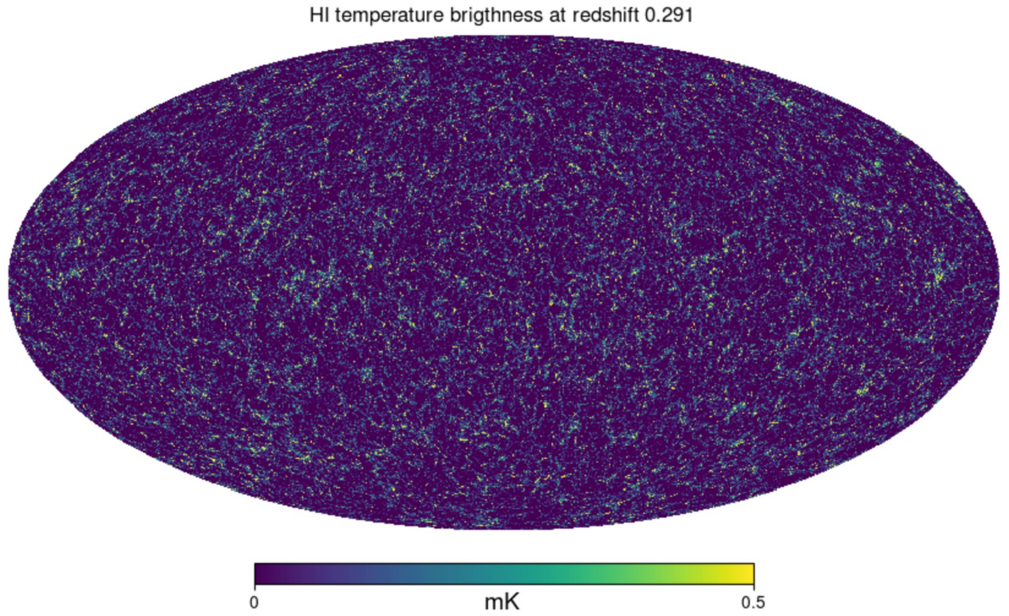
- 1. Lightcone created with PINOCCHIO CODE (minimum halo mass is 10^{10}Msun/h) catalogs are copied in lapoderosa (OATS) and Ulysses (SISSA) – total size about 75 Gbytes - 1 Gpc/h box 2048^3 size – σ_8 = 0.9 Ω_m=0.25 flat Universe

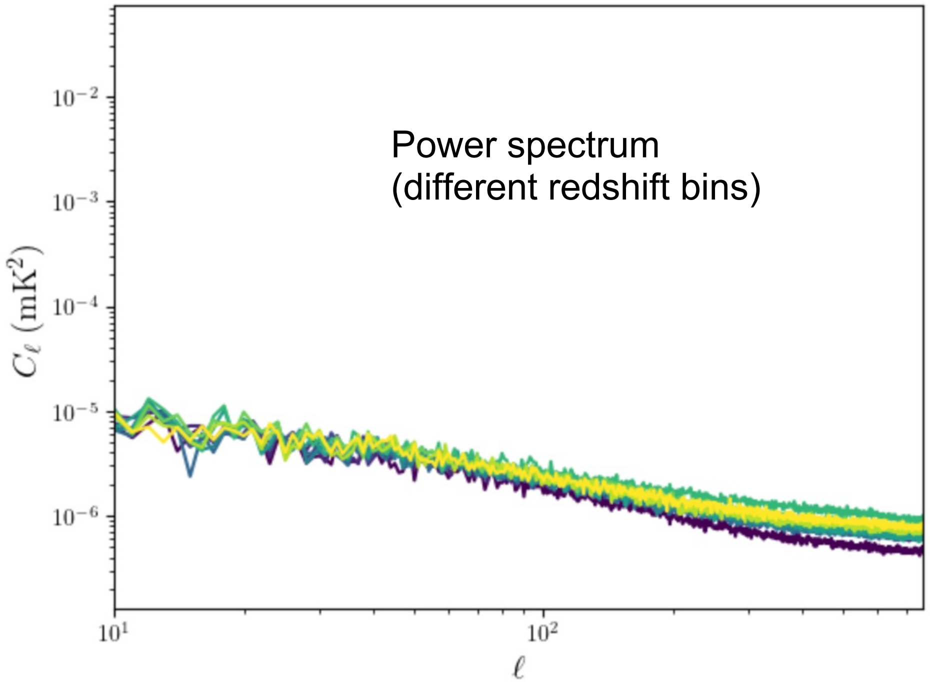
Marta Spinelli



Accomplished Work, Results

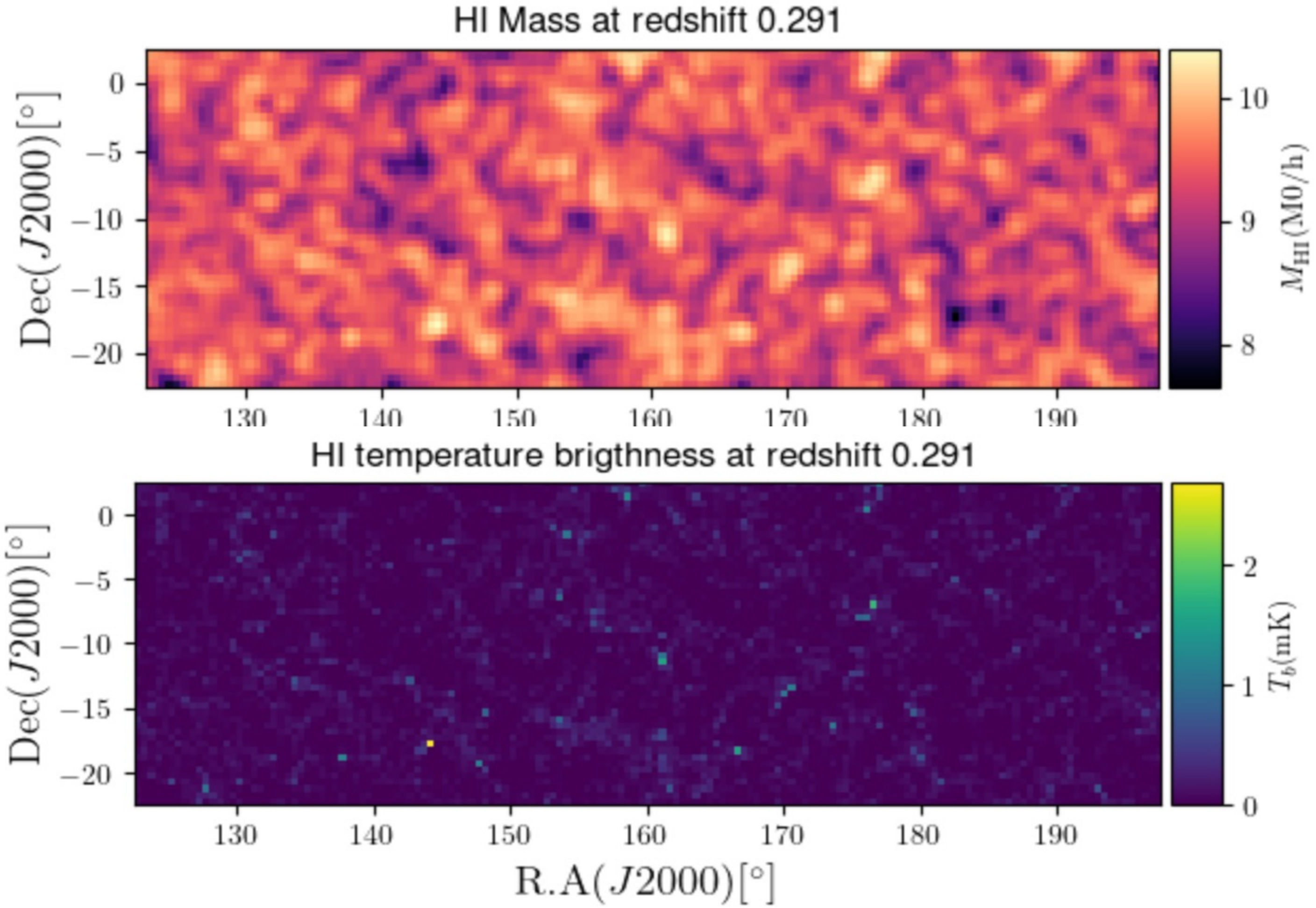
- From haloes to 21cm intensity with M_HI vs M_halo relation





Accomplished Work, Results

- From 21cm intensity maps to actual mock MeerKAT like data



- ➢ To be cross-correlated with galaxies
- ➢ To be used for foreground blind challenges
- ➢ To check effect of beam/scanning strategy and its impact on parameter estimation

Accomplished Work, Results

- Lagrangian Deep Learning: learning physical maps from initial displacement fields
https://github.com/maurorigo/JERALD

Mauro Rigo
SISSA PhD student
Supervisors: Trotta and Viel

jaxLDL: JAX implementation of Lagrangian Deep Learning

- Installation
- Testing
- Documentation

jaxLDL is the JAX implementation of the code performing Lagrangian Deep Learning, a machine learning method to paint baryons and related quantities on top of N-body only simulations.

The package is based on JAX and mpi4jax, and it uses MPI to implement parallel Cloud-In-Cell (CIC) painting and interpolation algorithms as well as parallel forward and backward Fourier transforms via FFTW.

- ➢ Generative model to produce maps and to learn effective description of subgrid physics.
- ➢ Fast Particle Mesh N-body solver + hydro simulations
- ➢ Displacement fields modelled with an effective potential

Accomplished Work, Results

- New work: JAX implementation, parallelized, faster 5-6 orders of magnitude compared to full hydro for a reference simulation, extended to HI

Dark matter particles from approximate N-body simulations are moved via a displacement field S_θ:

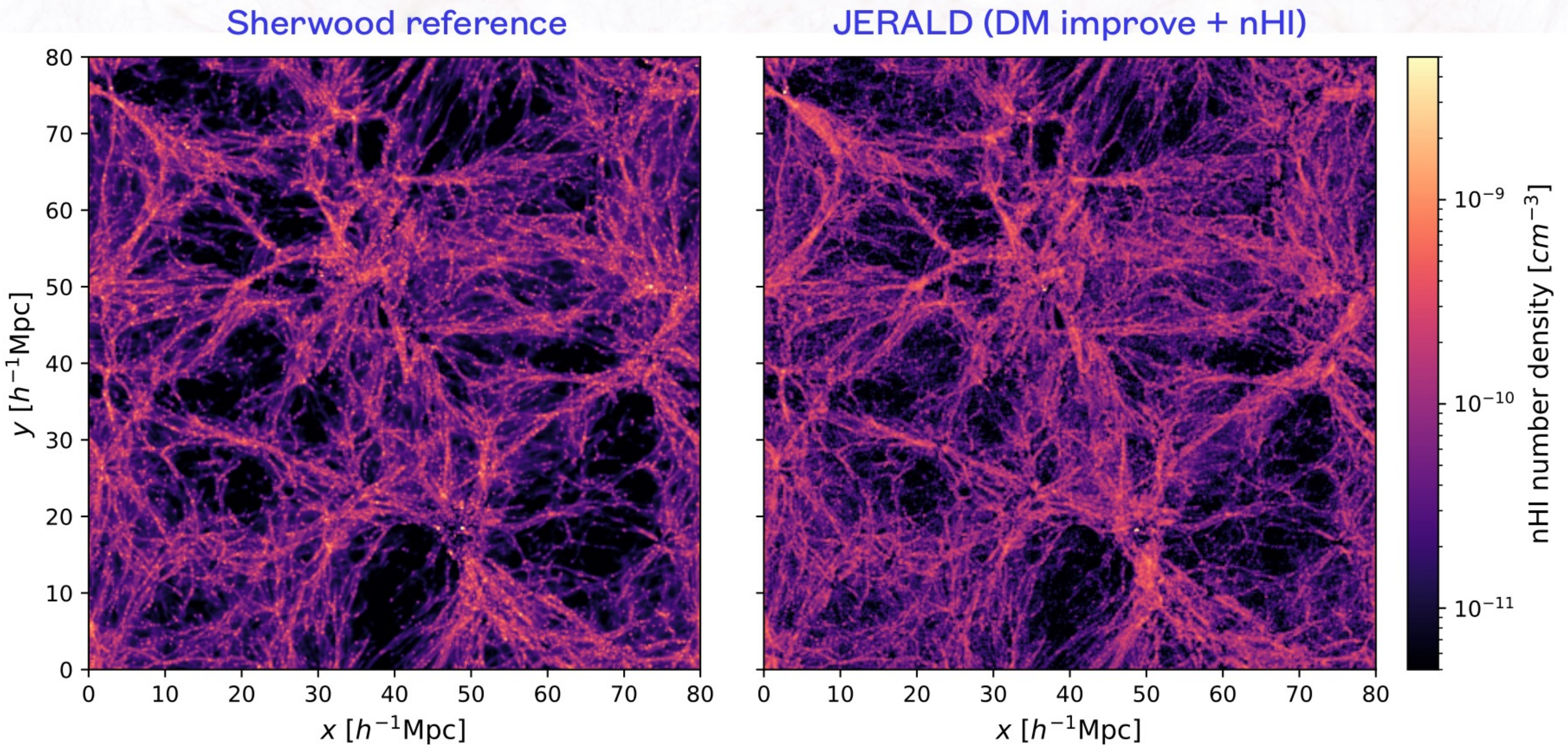
$$X' = X + S_\theta \quad , \quad S_\theta = \nabla U_\theta(\delta(X))$$

The parameters θ are trained by matching the output density $\delta_{\text{model}}(X')$ with a target map δ_{target} through a L1 or L2 loss:

$$\mathscr{L} = \frac{1}{N_{\text{pixel}}} \| \delta_{\text{model}} - \delta_{\text{target}} \|^p$$

Optionally, a non-linearity can be added after the displacements to model phenomena that cannot be modelled via matter transport:

$$\delta_{\text{model}} = \text{ReLU}(b_1\, \delta(X')^\mu + b_0)$$



Pre-training is important
Somehow tricky the non-linear transform to model HI (needs fine tuning)

Next Steps and Expected Results

- Implementation of magnetic fields effects into G3-G4 (in the ICS)
- HIP-POP development, improvement of performances, user friendly interface (M8-M9-M10)|
- JERALD application to HI → public repository