Fast Simulation of Post-Reionization Cosmological Neutral Hydrogen based on the Halo Model

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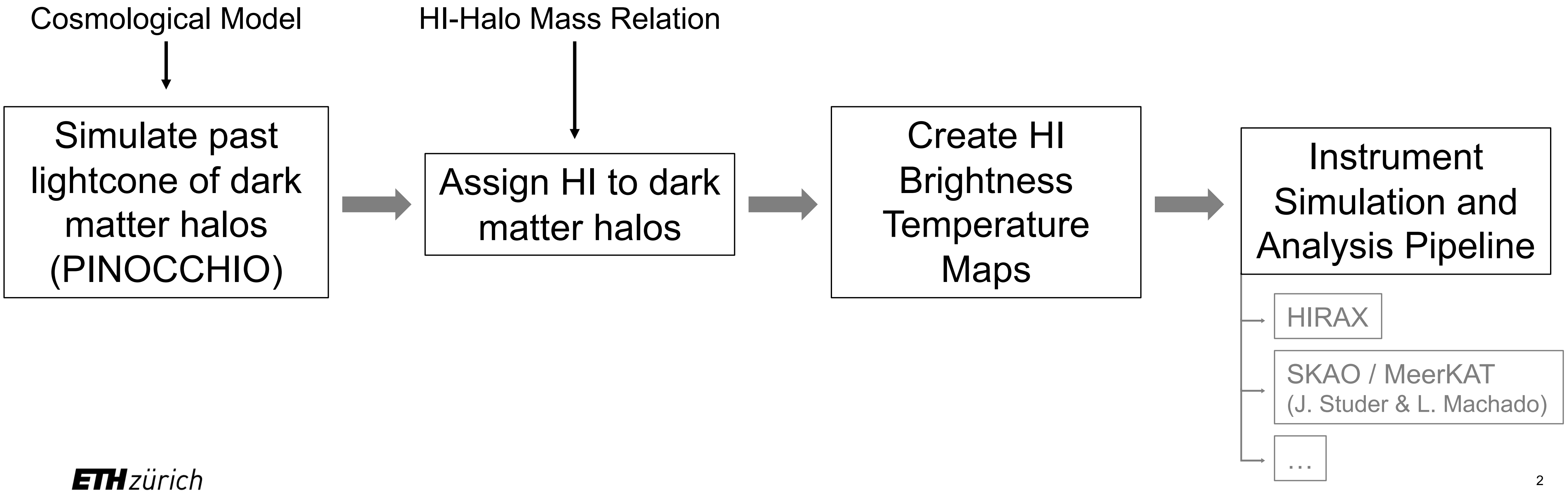
Image Credit: SARAO, Heywood et al. (2022) / J.C. Muñoz-Mateos

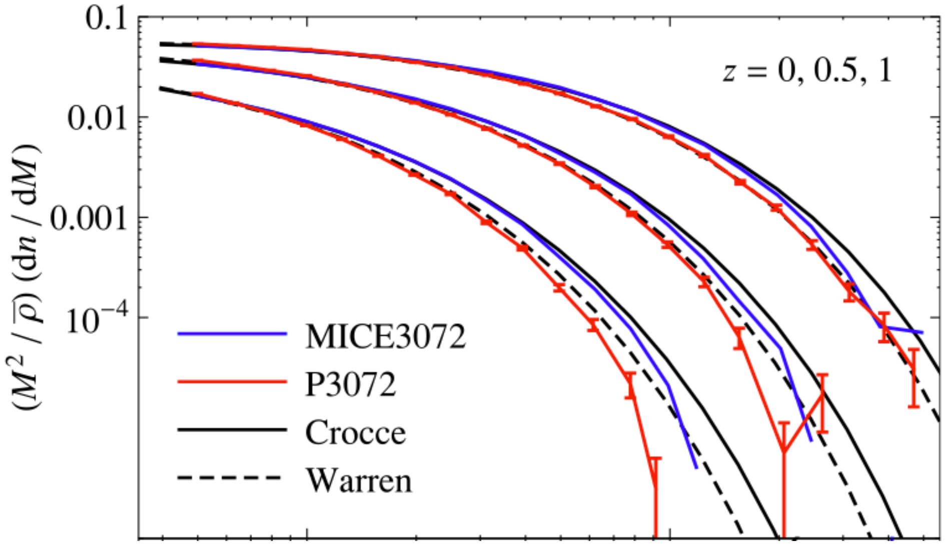
Overview

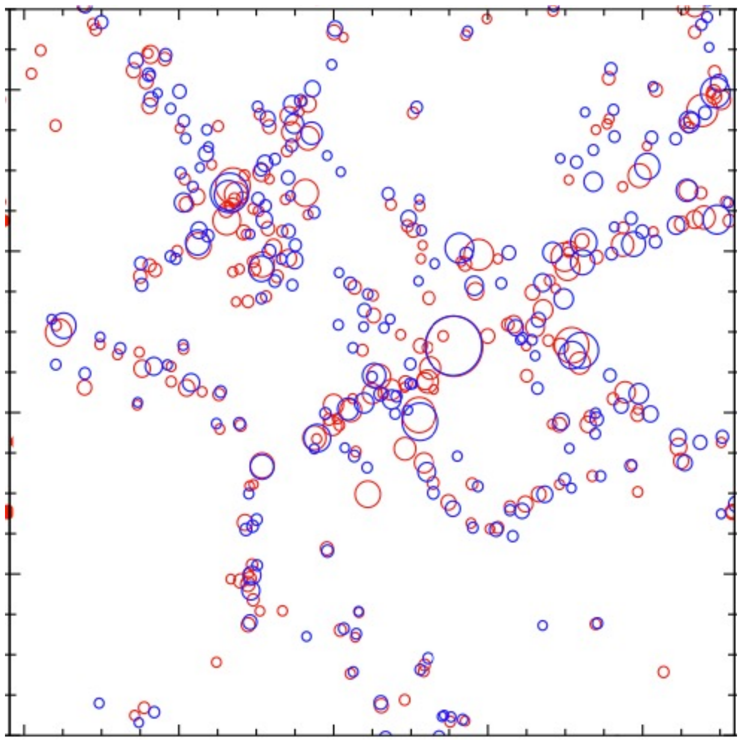
- Fast and large volume simulations of neutral hydrogen (HI) distribution for post-reionization ($z \lesssim 6$) 21 cm intensity mapping experiments
  - Assumption: Most HI resides inside of dark matter halos
- Test instrument simulations and analysis pipelines to measure the HI emission



PINOCCHIO: Dark Matter Halo Simulation

- Monaco et al. (2002, 2013), Taffoni et al. (2002), Munari et al. (2017)
- Lagrangian Perturbation Theory
- Collapsed points grouped into halos, hierarchical growth
- Catalogue of dark matter halos
- Much faster than N-body





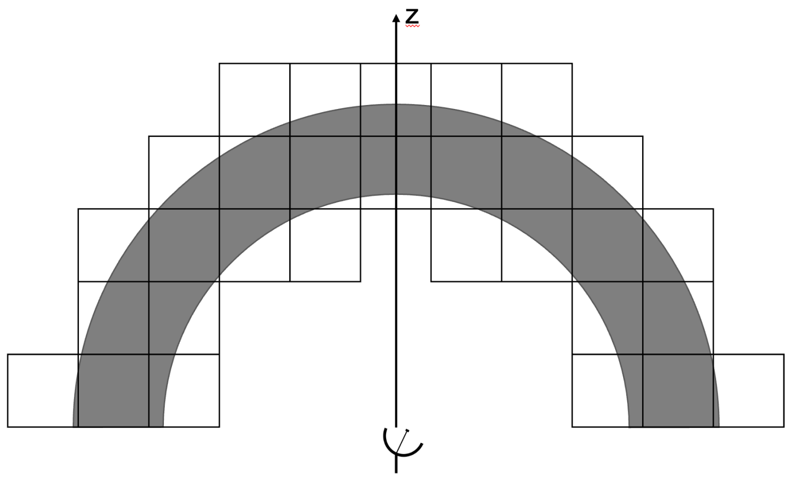
Monaco et al. 2013

Current Setting of DM Simulations

- 1 Gpc/h box size
- 6700^3 simulation particles
- ≥ 10 particles per halo ↔ ≥ $4.3 \times 10^9\ M_\odot$

→ 2 – 3% HI mass missing

- Lightcone settings:
  - Frequency range: 700 – 800 MHz ↔ Redshift 0.77 – 1.03
  - Declinations between -15° and -35°
  - 40 box replications



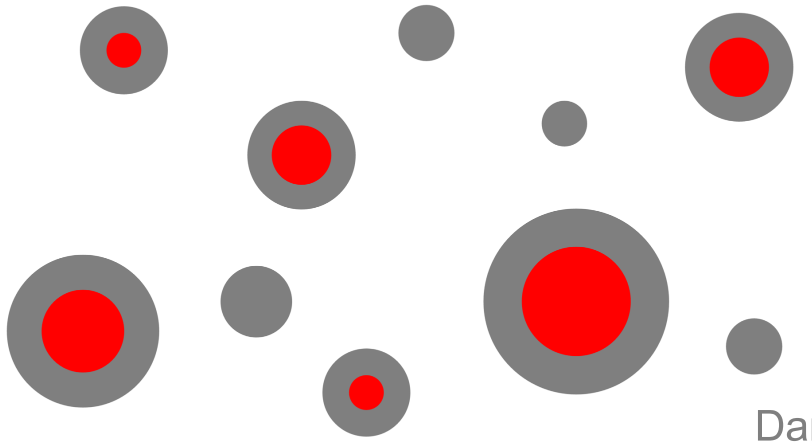
- Ran on Piz Daint with MPI parallelization
  - 2400 nodes with 12 cores each
  - 150 TB RAM, 40’000 CPU h runtime

Halo Model for Cosmological HI

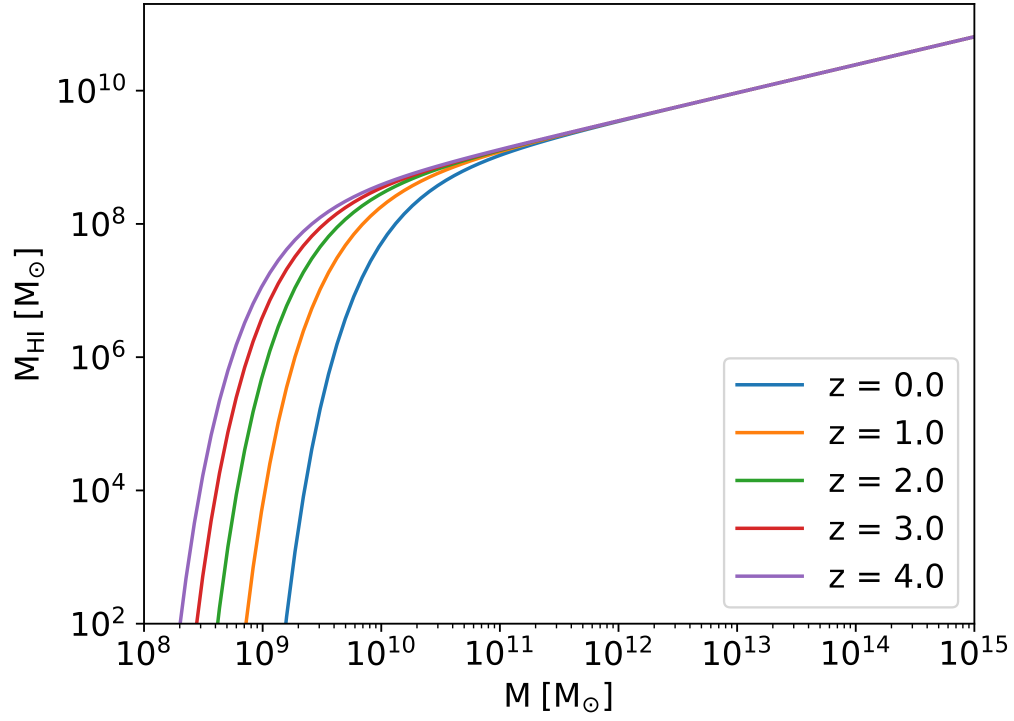
<u>HI-halo mass relation fitted to observations:</u>

$$M_{\mathrm{HI}}(M,z) = \alpha f_{\mathrm{H,c}} M \left(\frac{M}{10^{11} h^{-1} \mathrm{M}_{\odot}}\right)^{\beta} \exp\left[-\left(\frac{v_{\mathrm{c},0}}{v_{\mathrm{c}}(M,z)}\right)^{3}\right]$$

Padmanabhan et al. 2017



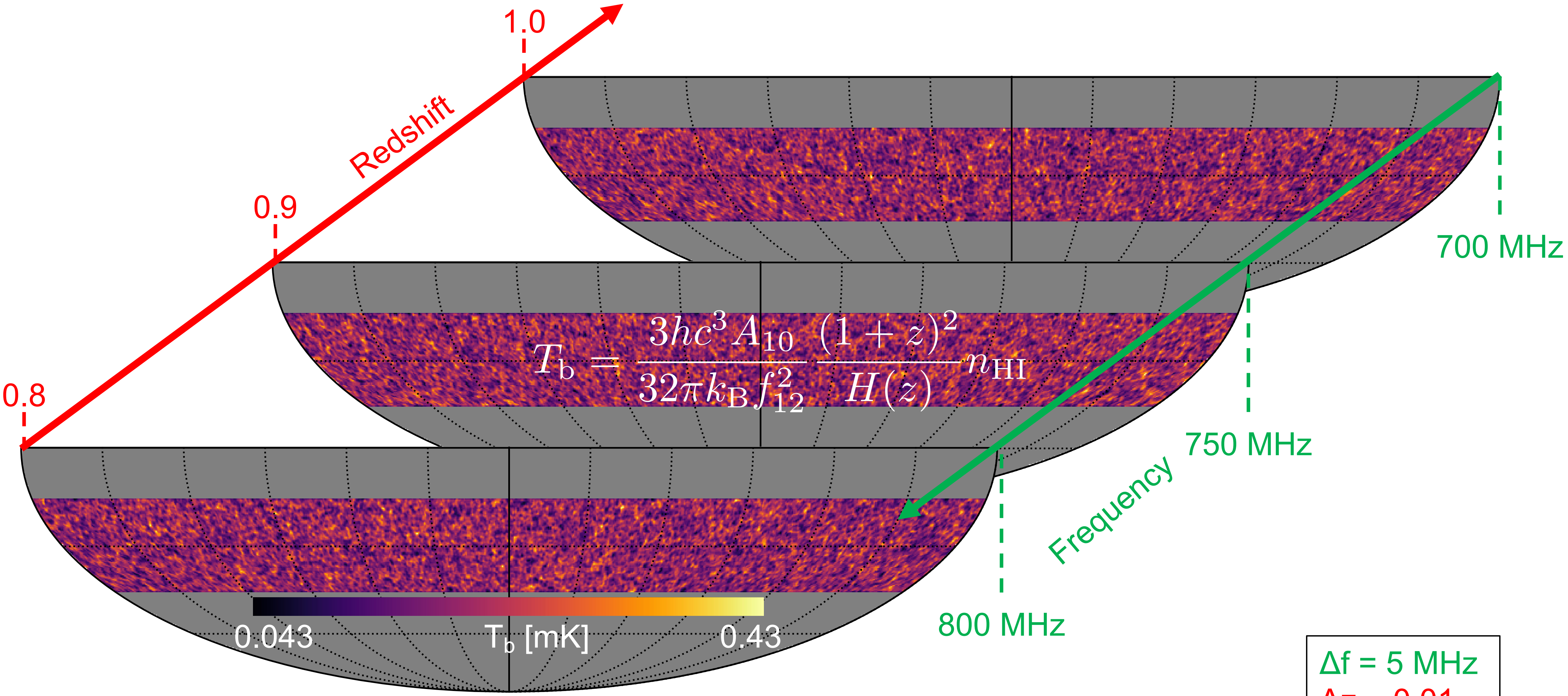
Dark Matter
Neutral Hydrogen



- More massive halos contain more HI
- **But:** Many more small halos than large ones
  → Important not to neglect small halos

- 2 – 3% loss over considered redshift range

Brightness Temperature Maps

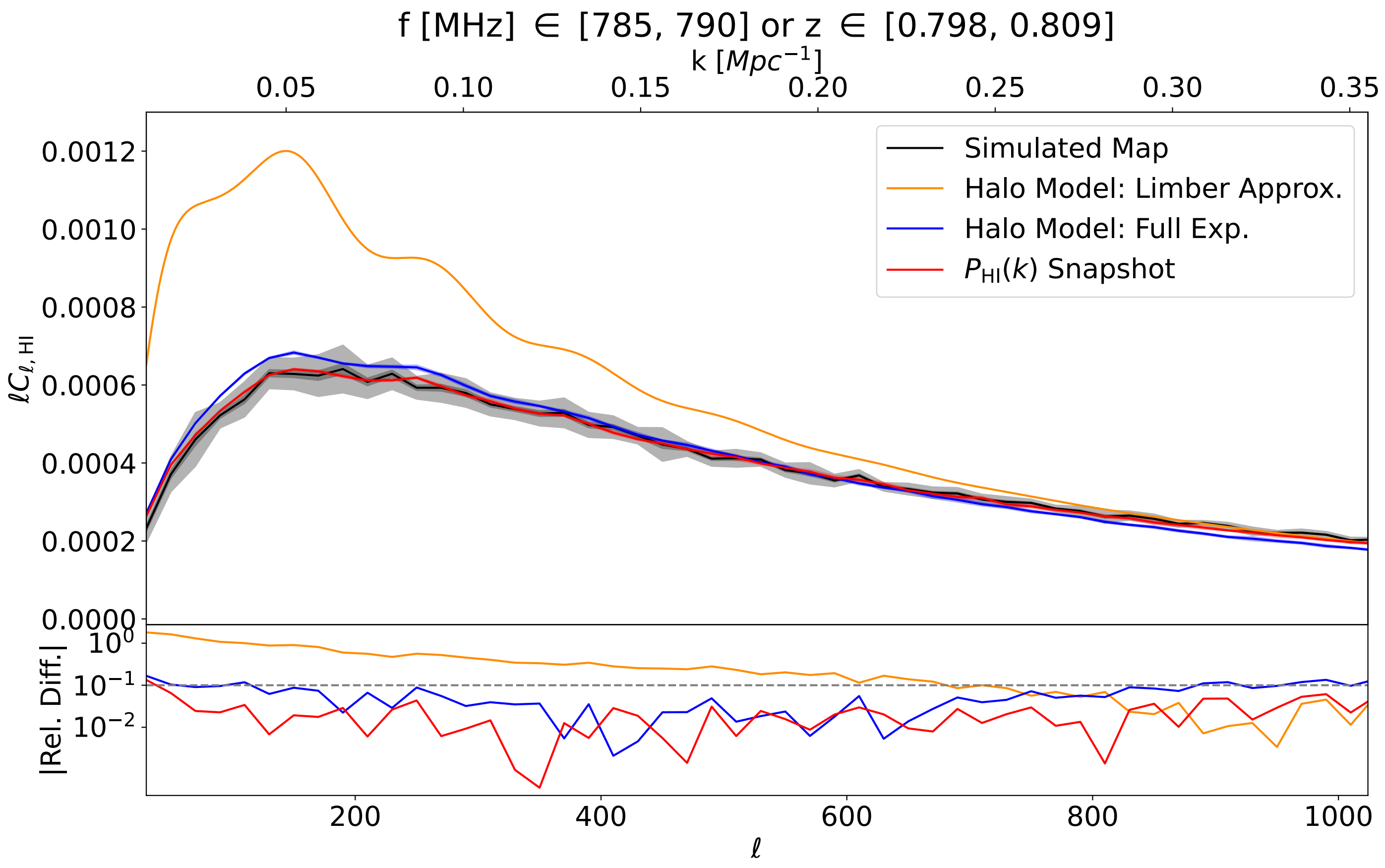


$$T_\mathrm{b} = \frac{3hc^3 A_{10}}{32\pi k_\mathrm{B} f_{12}^2} \frac{(1+z)^2}{H(z)} n_\mathrm{HI}$$

Δf = 5 MHz
Δz ~ 0.01

HI Angular Power Spectrum

Refregier et al. 2017



Limber Approximation:

$$C_{\ell,HI} \approx \int dz \frac{c}{H(z)} \frac{W^2(z)}{r(\chi(z))^2} P_{\rm HI}\left(\frac{\ell+1/2}{r(\chi(z))}, z\right)$$

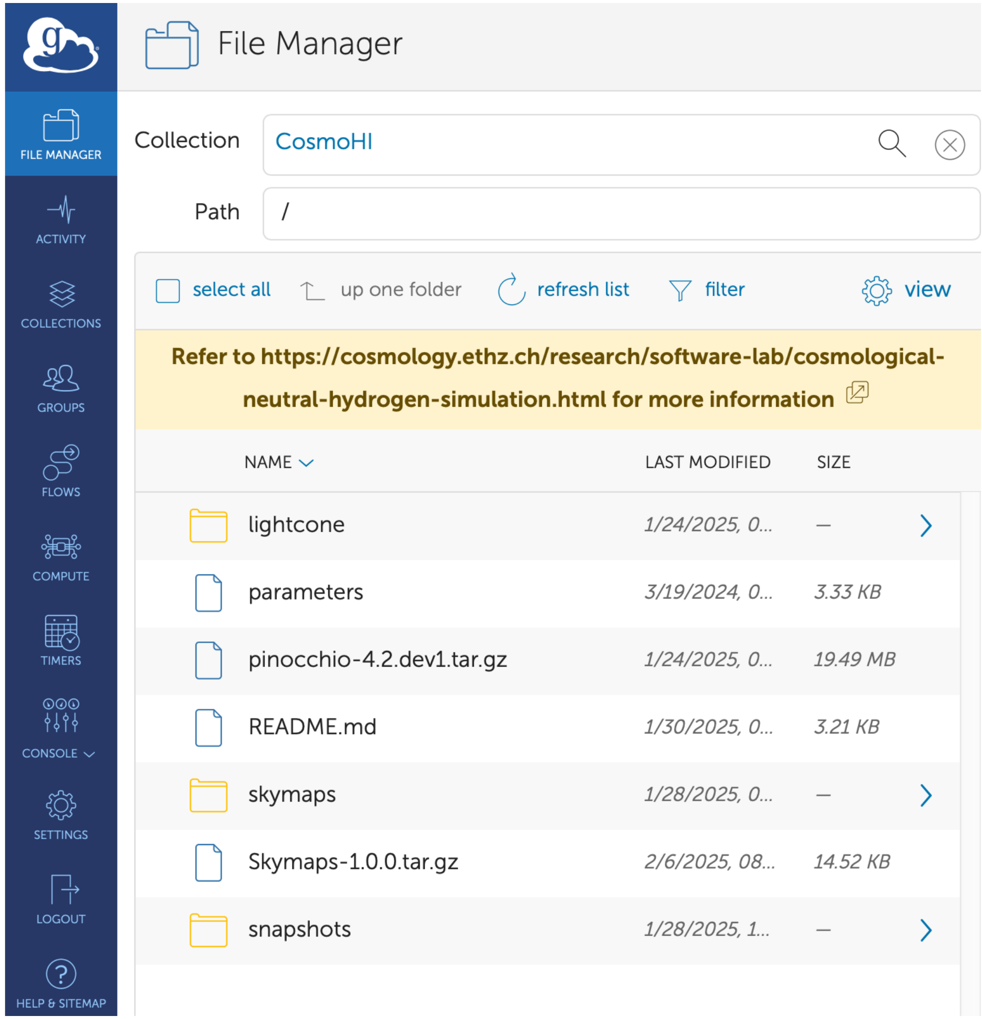
Full Expression:

$$C_{\ell,HI} = \frac{2}{\pi} \int k^2 dk \int_0^\infty d\chi\, W(\chi) j_\ell(k\chi) \sqrt{P_{\rm HI}(k, z(\chi))}$$
$$\times \int_0^\infty d\chi'\, W(\chi') j_\ell(k\chi') \sqrt{P_{\rm HI}(k, z(\chi'))}$$

Data Availability

- Data documentation on our group website https://cosmology.ethz.ch/research/software-lab/cosmological-neutral-hydrogen-simulation.html

- Fast data transfer via Globus
  - **./snapshots:** DM halo box snapshot catalogues at z = 0.8, 0.9 and 1
  - **./lightcone:** DM halo past light cone catalogue from z = 0.77 – 1.03
  - **./skymaps:** DM mass and HI mass / brightness temperature HEALPix maps



Summary

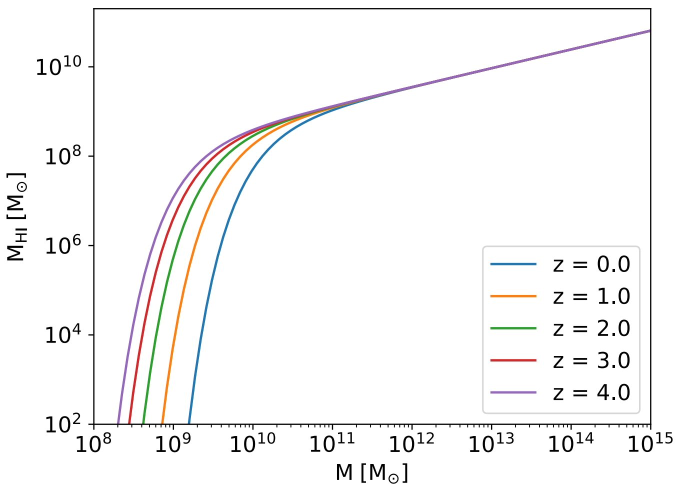
- Simulation pipeline of HI distribution for intensity mapping
- Theoretical predictions of power spectrum
  - Halo Model in PyCosmo 2.2.0: pip installable and documented
    https://cosmology.ethz.ch/research/software-lab/PyCosmo.html

- Outlook:
  - Apply it to HIRAX, SKAO, MeerKAT, …
  - Cross-correlations with other probes
  - Vary cosmology and astrophysics (HI-Halo mass relation)
  - Consider foregrounds, noise and RSD

Hitz et al. (2025) https://arxiv.org/abs/2410.01694

Backup Slides

HI Mass Loss



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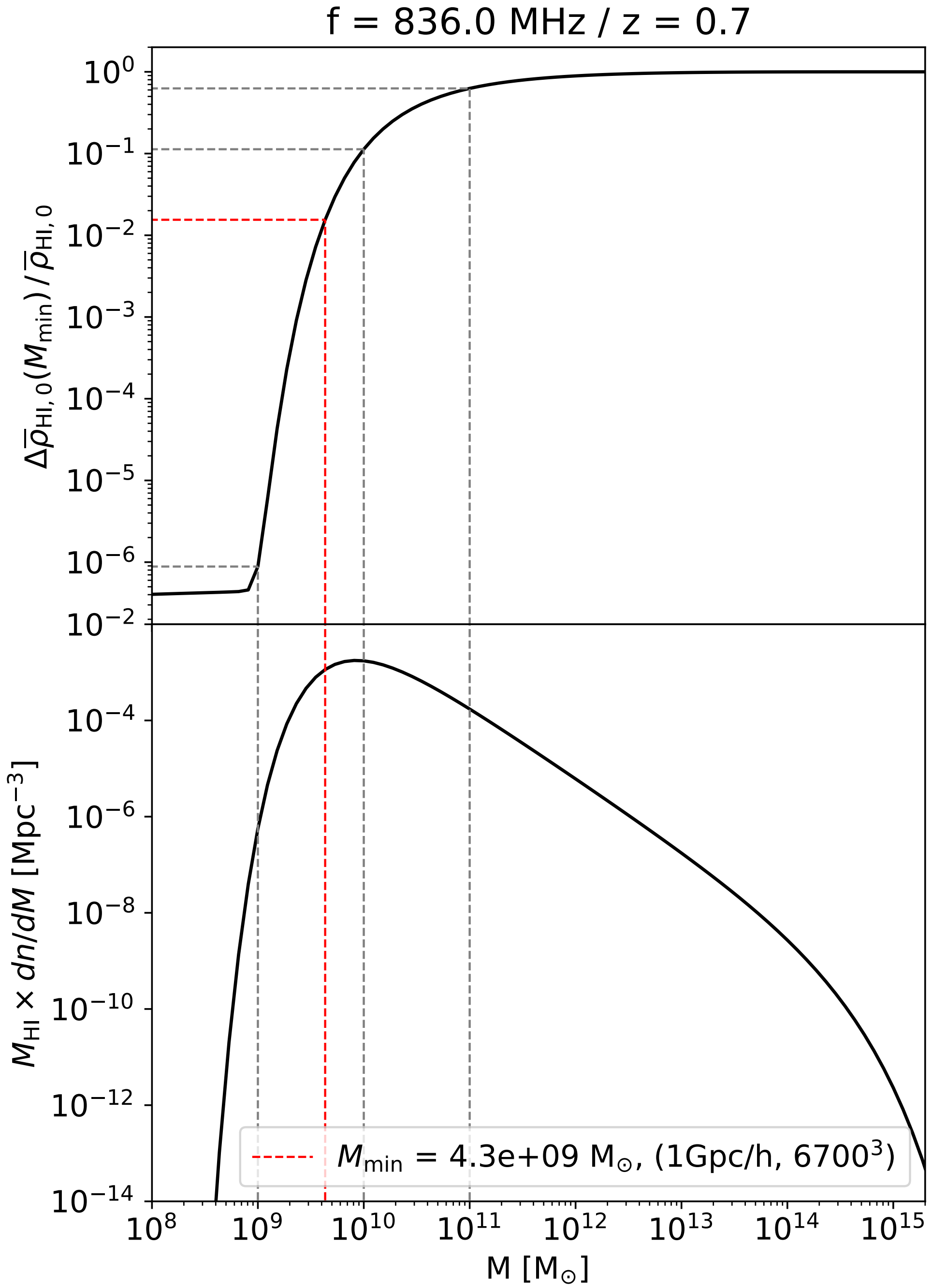
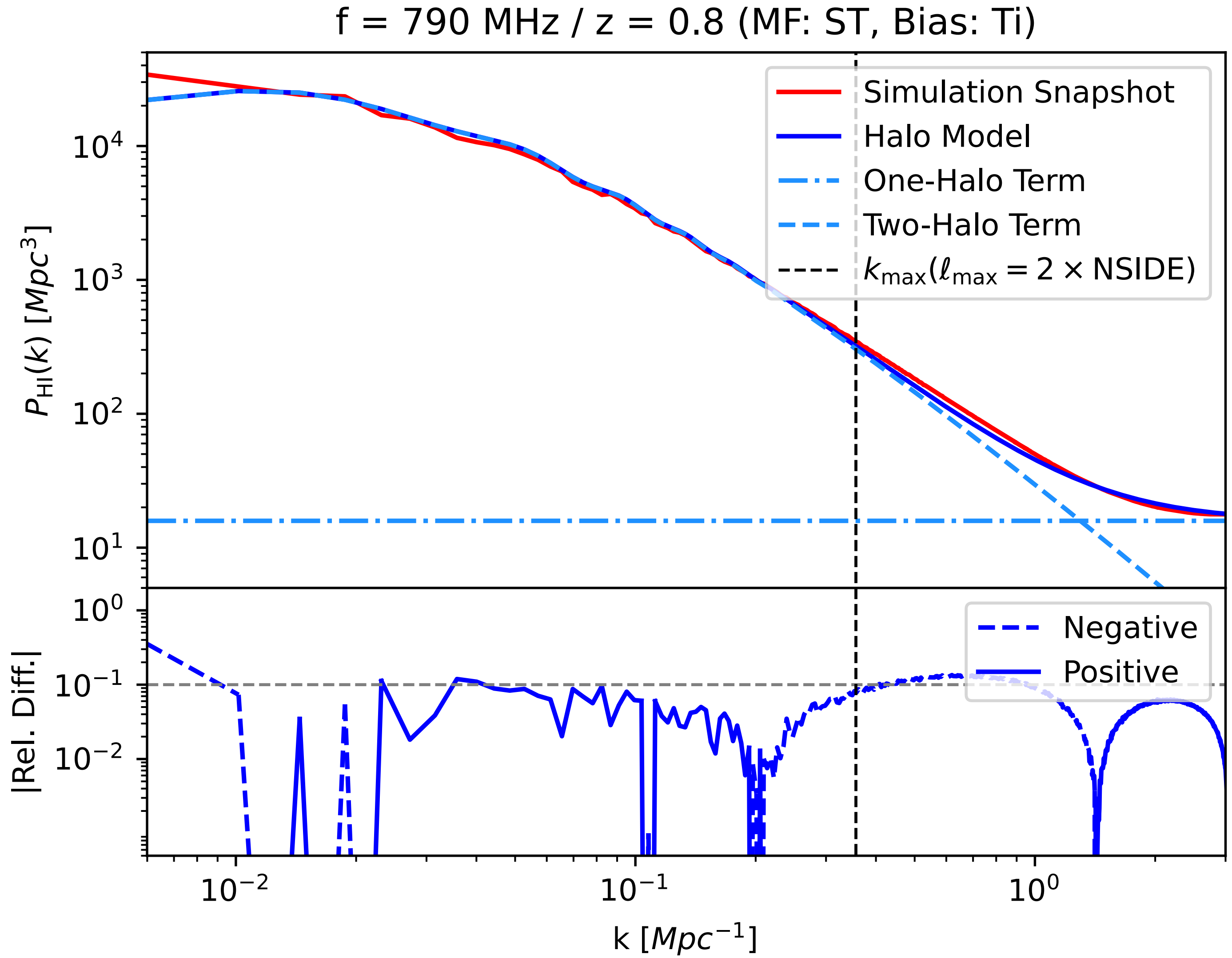
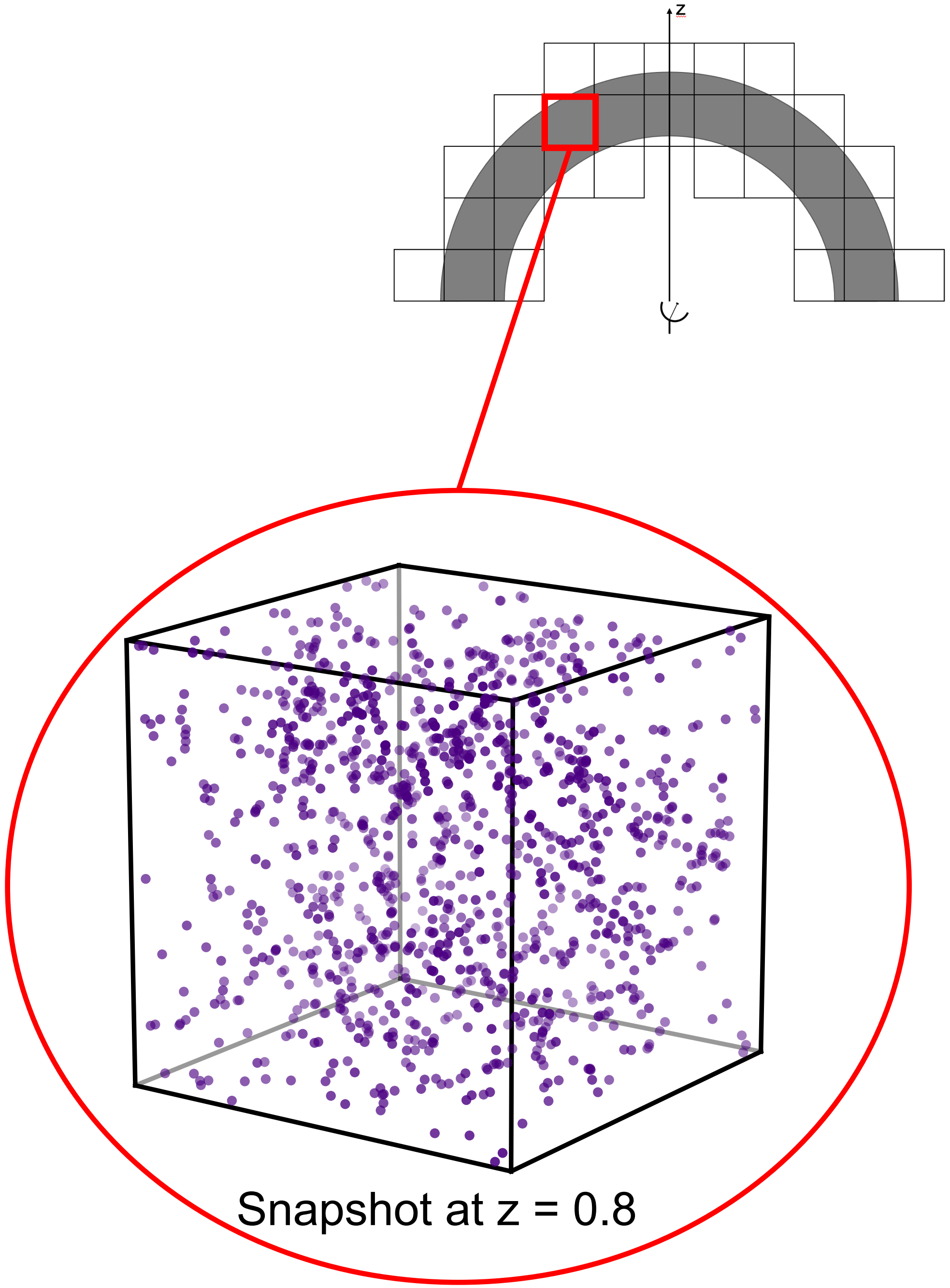


HI Power Spectrum





PyCosmo HI Halo Model

- Fundamental assumption: All matter in the universe is arranged in halos of different sizes and masses

$$P_{\mathrm{HI}}(k) = P_{\mathrm{1h,HI}}(k) + P_{\mathrm{2h,HI}}(k)$$

$$\rightarrow P_{\mathrm{1h,HI}} = \frac{1}{\bar{\rho}_{\mathrm{HI}}^2} \int dM \, \frac{dn(M,z)}{dM} M_{\mathrm{HI}}^2(M) |u_{\mathrm{HI}}(k|M)|^2$$

$$\rightarrow P_{\mathrm{2h,HI}} = P_{\mathrm{lin}}(k) \left[\frac{1}{\bar{\rho}_{\mathrm{HI}}} \int dM \, \frac{dn(M,z)}{dM} M_{\mathrm{HI}}(M) \, b(M) |u_{\mathrm{HI}}(k|M)| \right]^2$$