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

Pascal Hitz
ETHZ Cosmology Group†

SKA Cosmology SWG Meeting Nice 05.11.2024

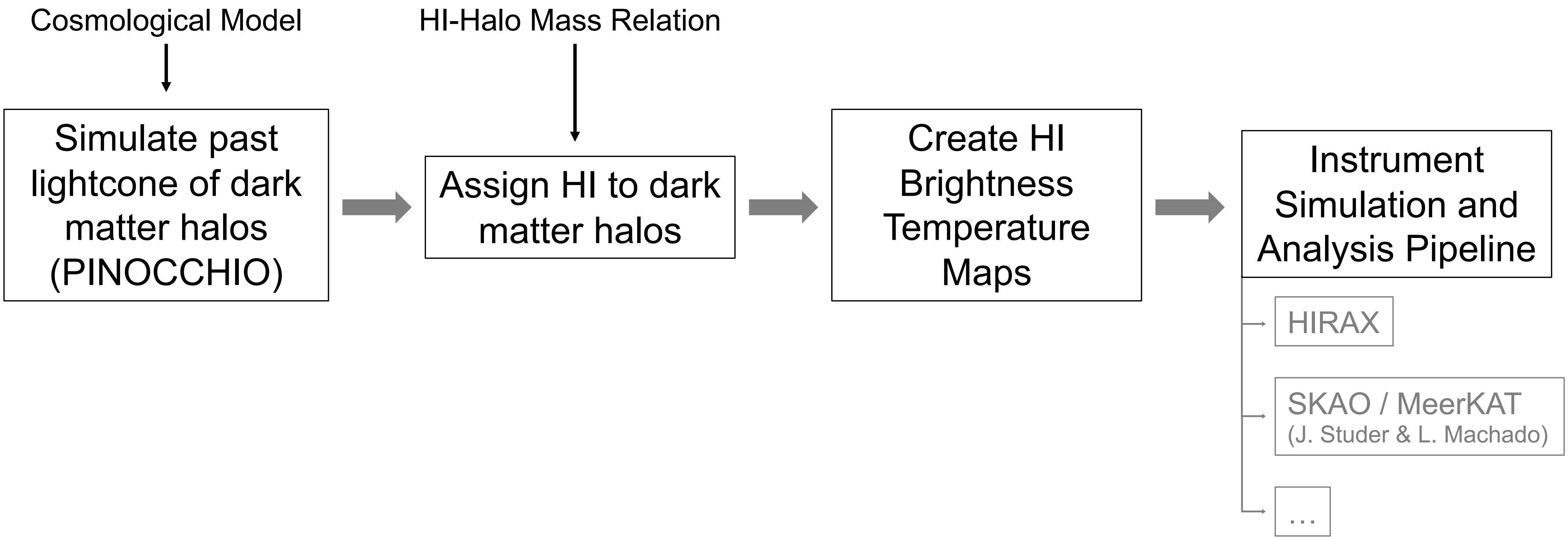
† Alexandre Refregier, Pascale Berner, Devin Crichton, John Hennig

ETH zürich

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

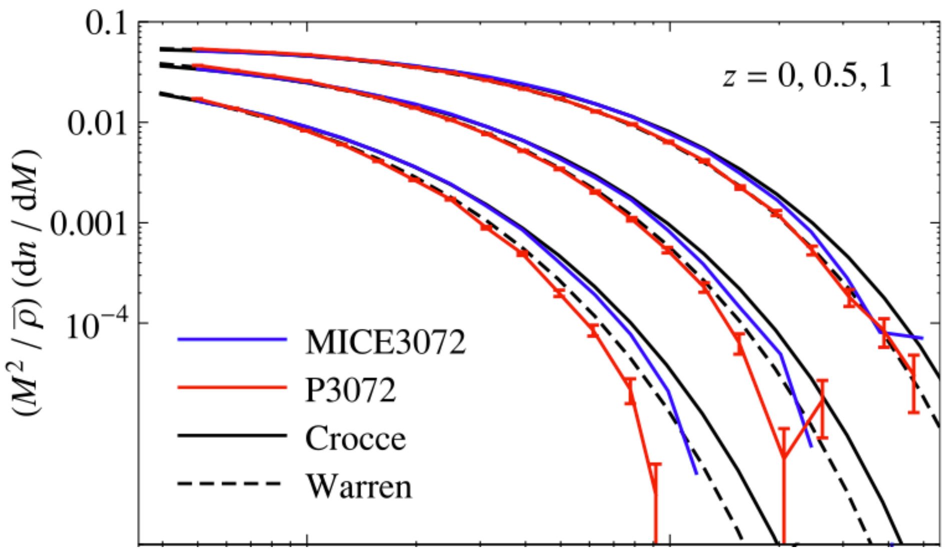
Overview

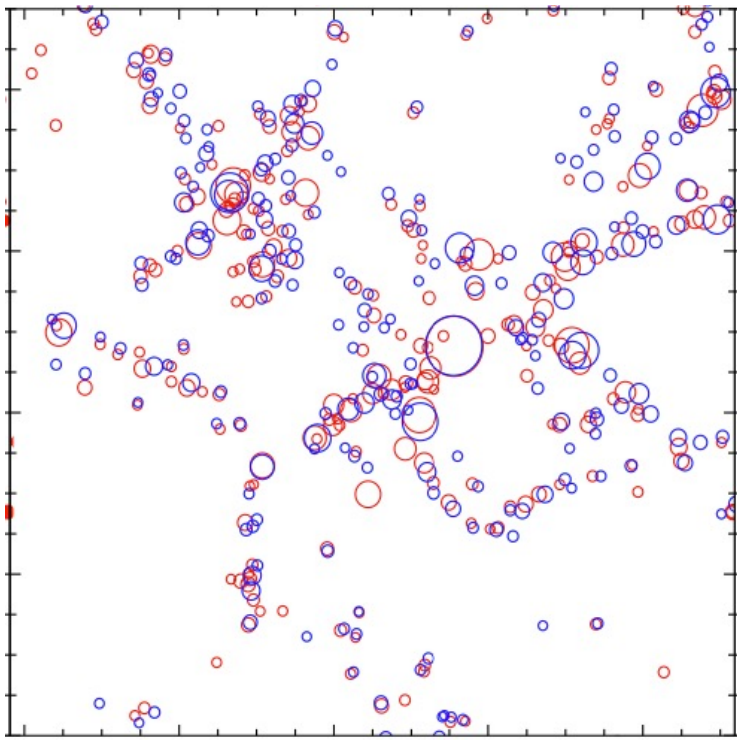
- Fast and large volume simulations of neutral hydrogen (HI) distribution
- Test instrument simulation and analysis pipeline to measure the HI emission



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
- Catalog of dark matter halos
- Much faster than N-body





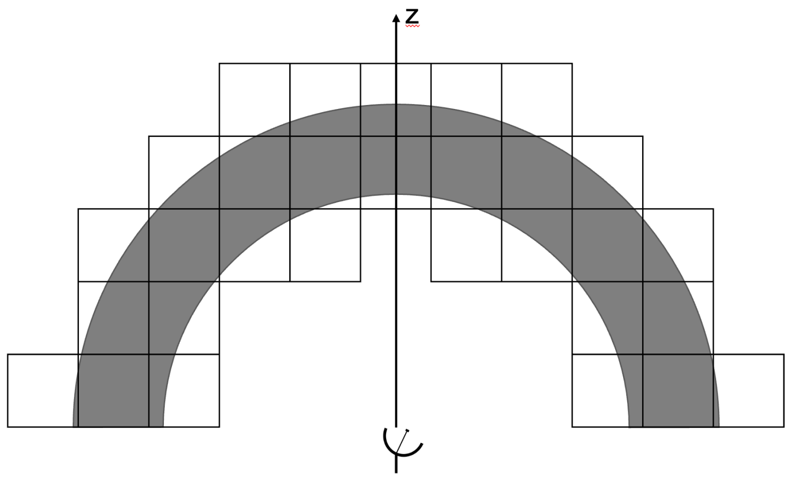
Monaco et al. 2013

Current Setting of DM Simulations

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

→ 1.5 – 3% HI mass missing

- Lightcone settings:
  - Frequency range: 700 – 800 MHz ↔ Redshift 0.78 – 1.03
  - Declinations between -15° and -35°
- Ran on Piz Daint with MPI parallelization
  - 2400 nodes with 12 cores each
  - 150 TB RAM, 40’000 CPU h runtime

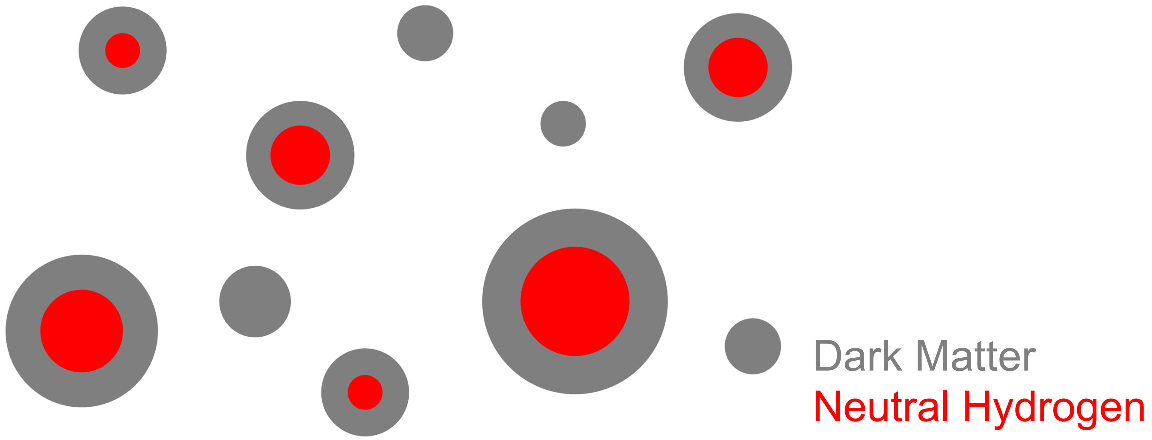


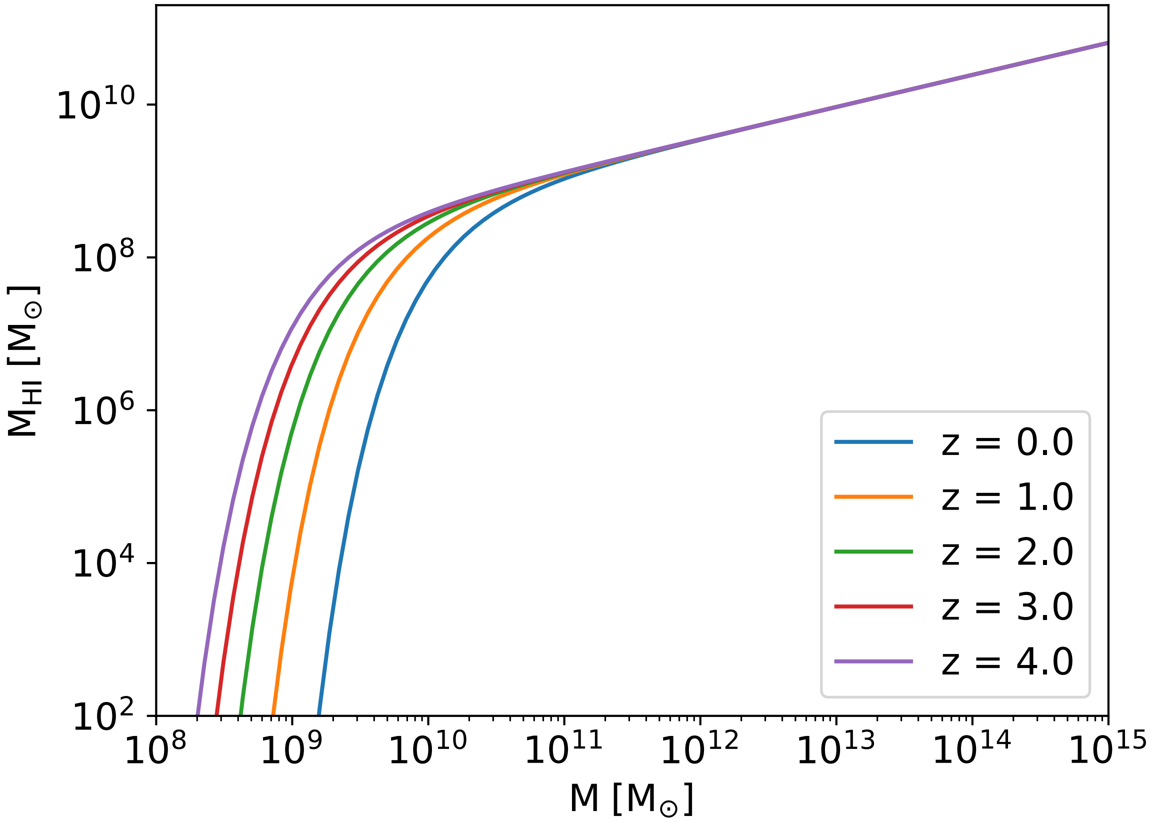
Halo Model for Cosmological HI

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

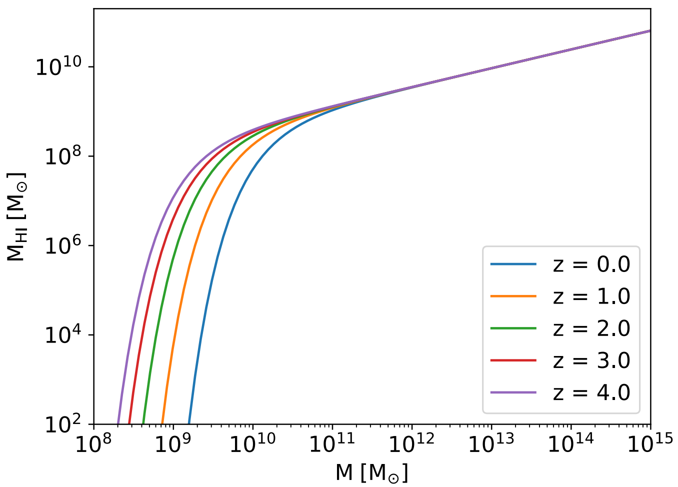
$$M_{\mathrm{HI}}(M,z) = \alpha f_{\mathrm{H,c}} M \left(\frac{M}{10^{11} h^{-1} \mathrm{M}_\odot}\right)^{\beta} \exp\left[-\left(\frac{v_{\mathrm{c},0}}{v_{\mathrm{c}}(M,z)}\right)^{3}\right]$$

Padmanabhan et al. 2017





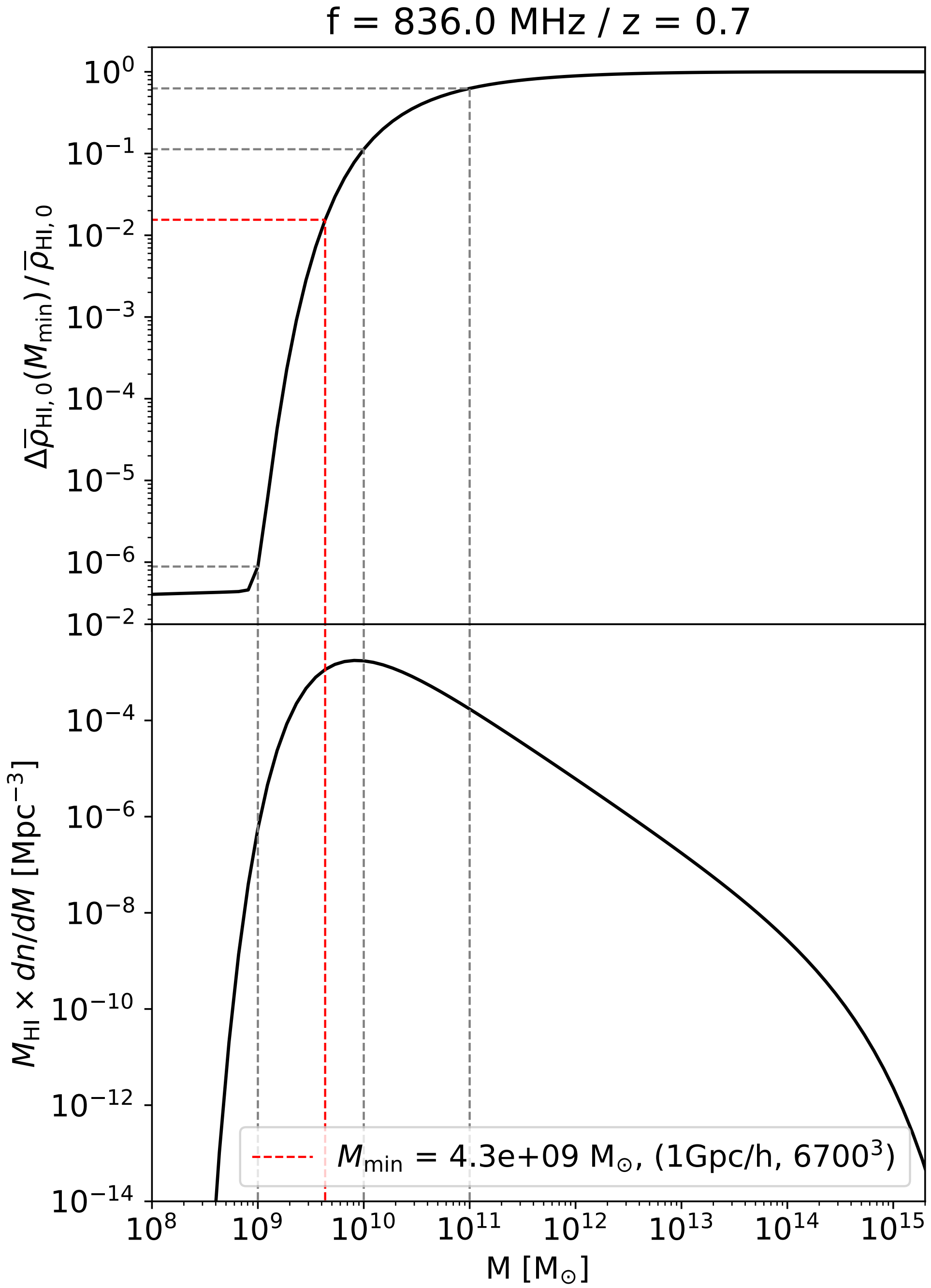
HI Mass Loss



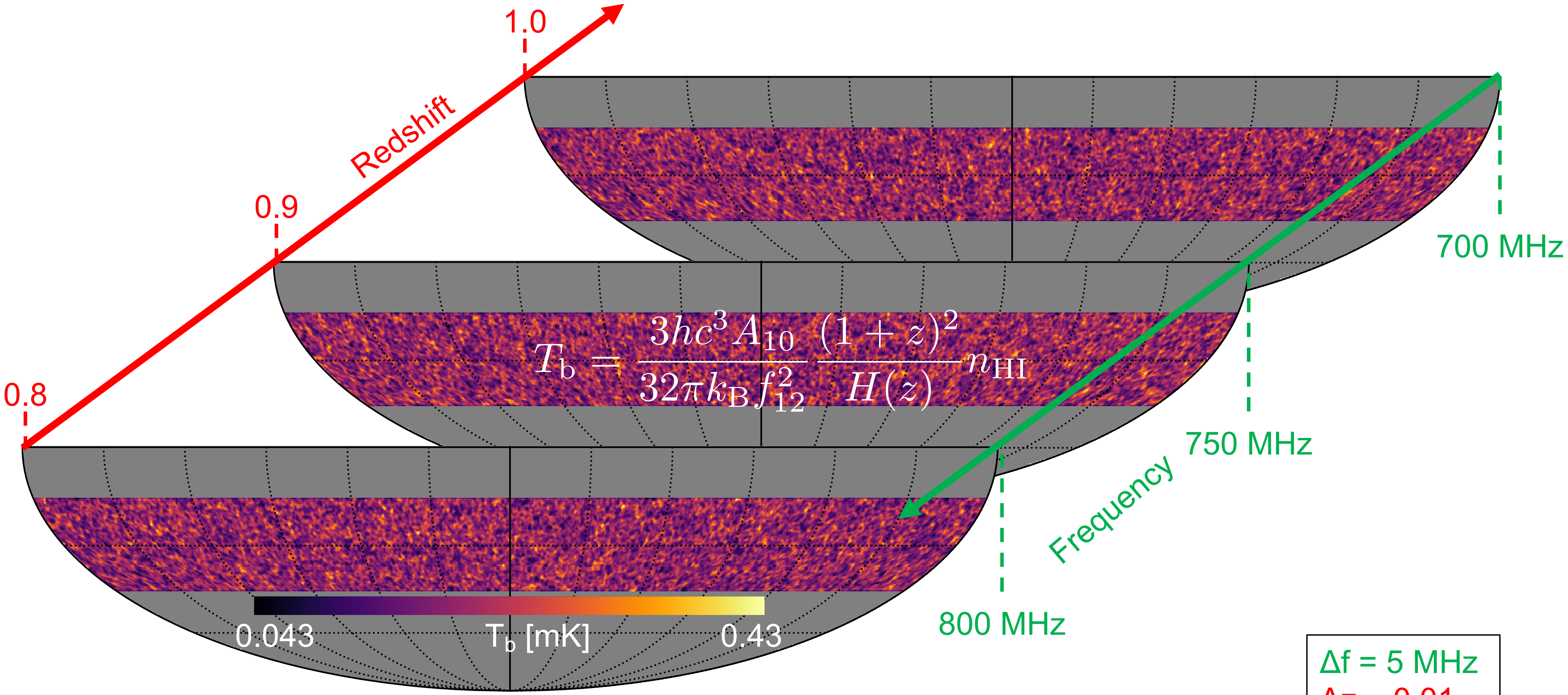
- More massive halos contain more HI
- **But:** Many more small halos than large ones

➔ Important not to neglect small halos

- 1.5 – 3% loss over considered redshift range

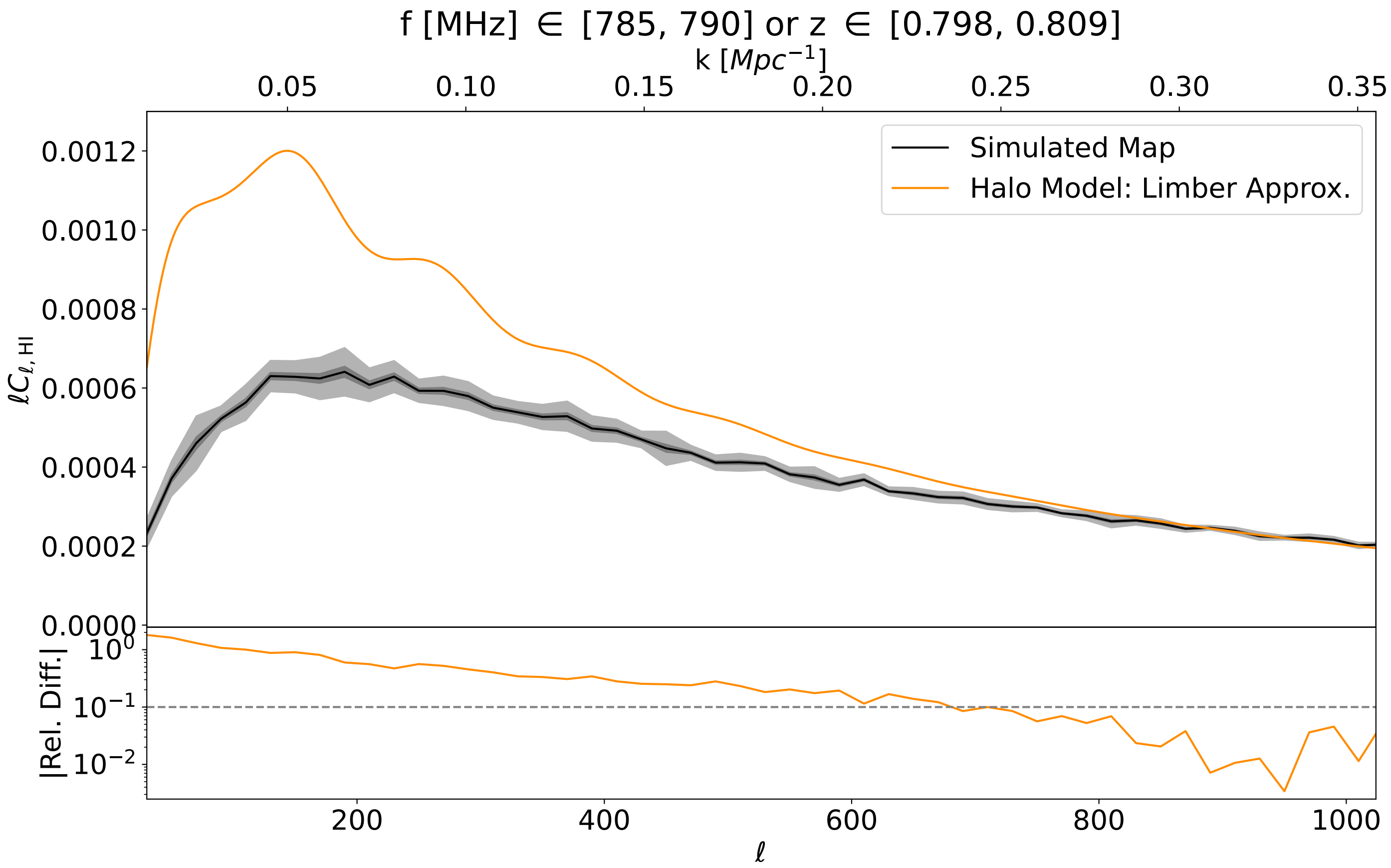


Brightness Temperature Maps



Δf = 5 MHz
$\Delta z \sim 0.01$

HI Angular Power Spectrum



Simulation:

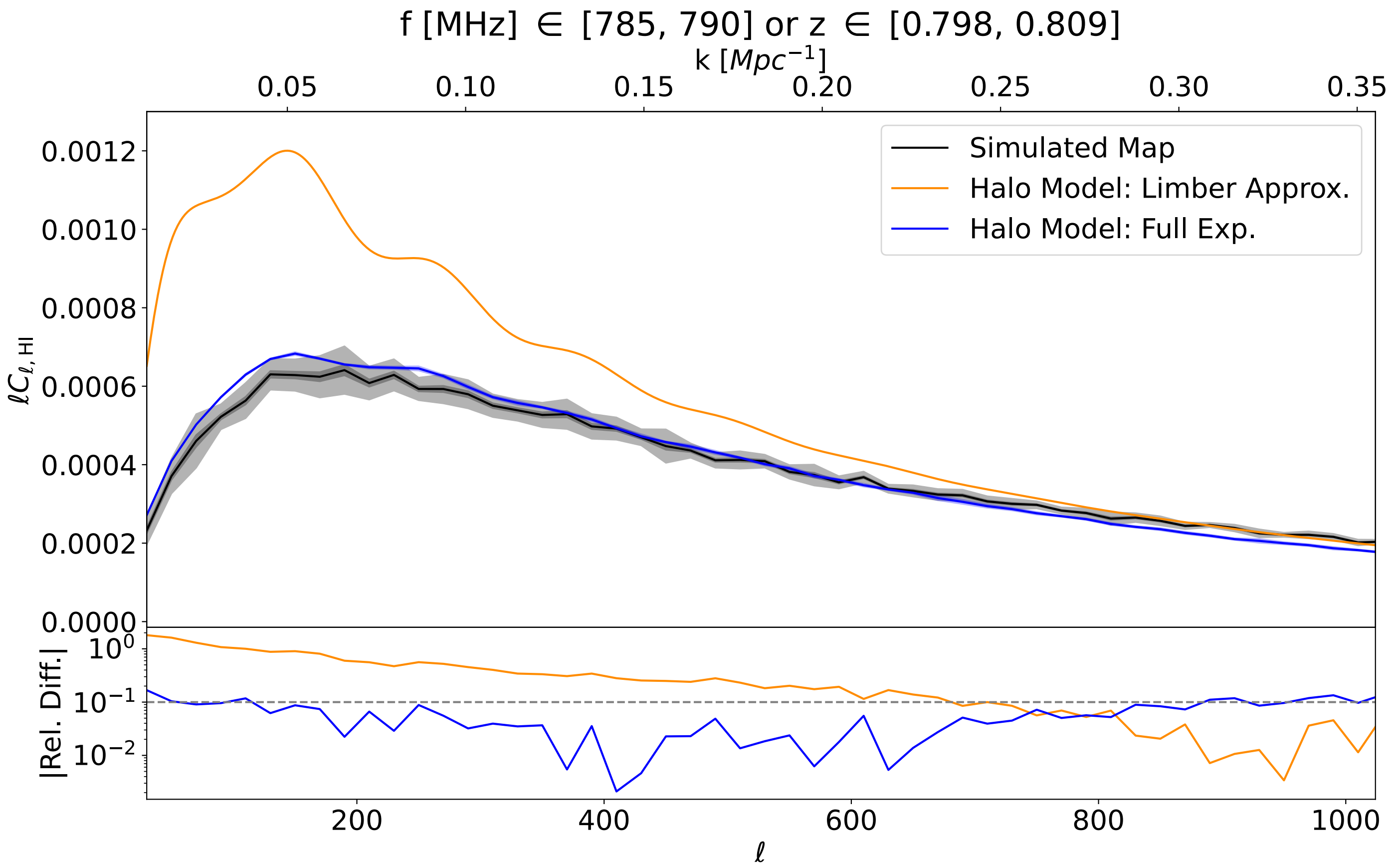
$$\delta_{HI} = (T_{HI} - \bar{T}_{HI})/\bar{T}_{HI}$$
$$\langle \delta_{HI,\ell m} \delta^*_{HI,\ell' m'} \rangle = \delta^D_{\ell\ell'} \delta^D_{mm'} C_{\ell,HI}$$

Limber Approximation:

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

Refregier et al. 2017

HI Angular Power Spectrum



Simulation:

$$\delta_{HI} = (T_{HI} - \bar{T}_{HI})/\bar{T}_{HI}$$

$$\langle \delta_{HI,\ell m} \delta^*_{HI,\ell' m'} \rangle = \delta^D_{\ell\ell'} \delta^D_{mm'} C_{\ell,HI}$$

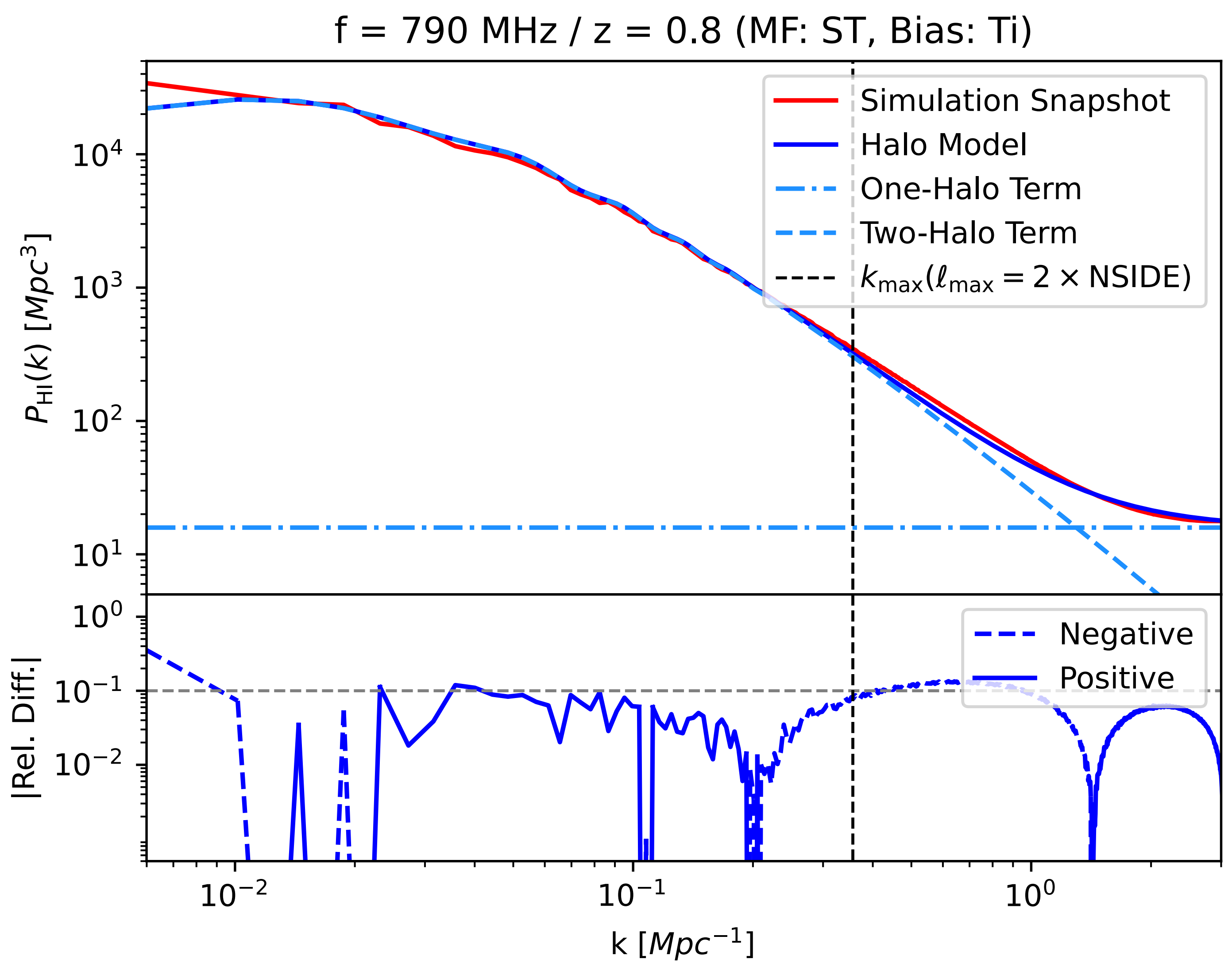
Limber Approximation:

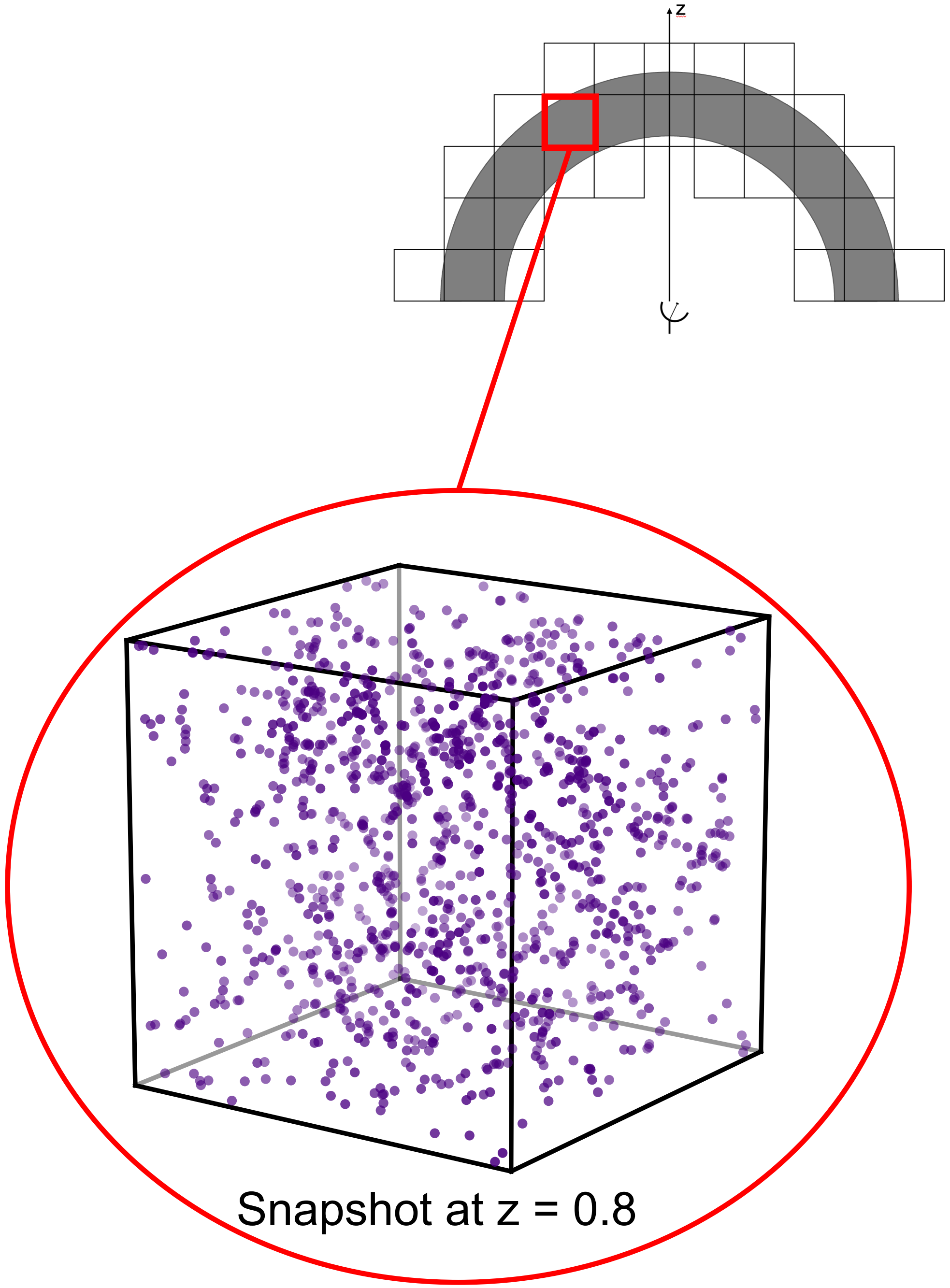
$$C_{\ell,HI} \approx \int dz \frac{c}{H(z)} \frac{W^2(z)}{r(\chi(z))^2} P_{\mathrm{HI}}\left(\frac{\ell + 1/2}{r(\chi(z))}, z\right)$$

Full Expression:

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

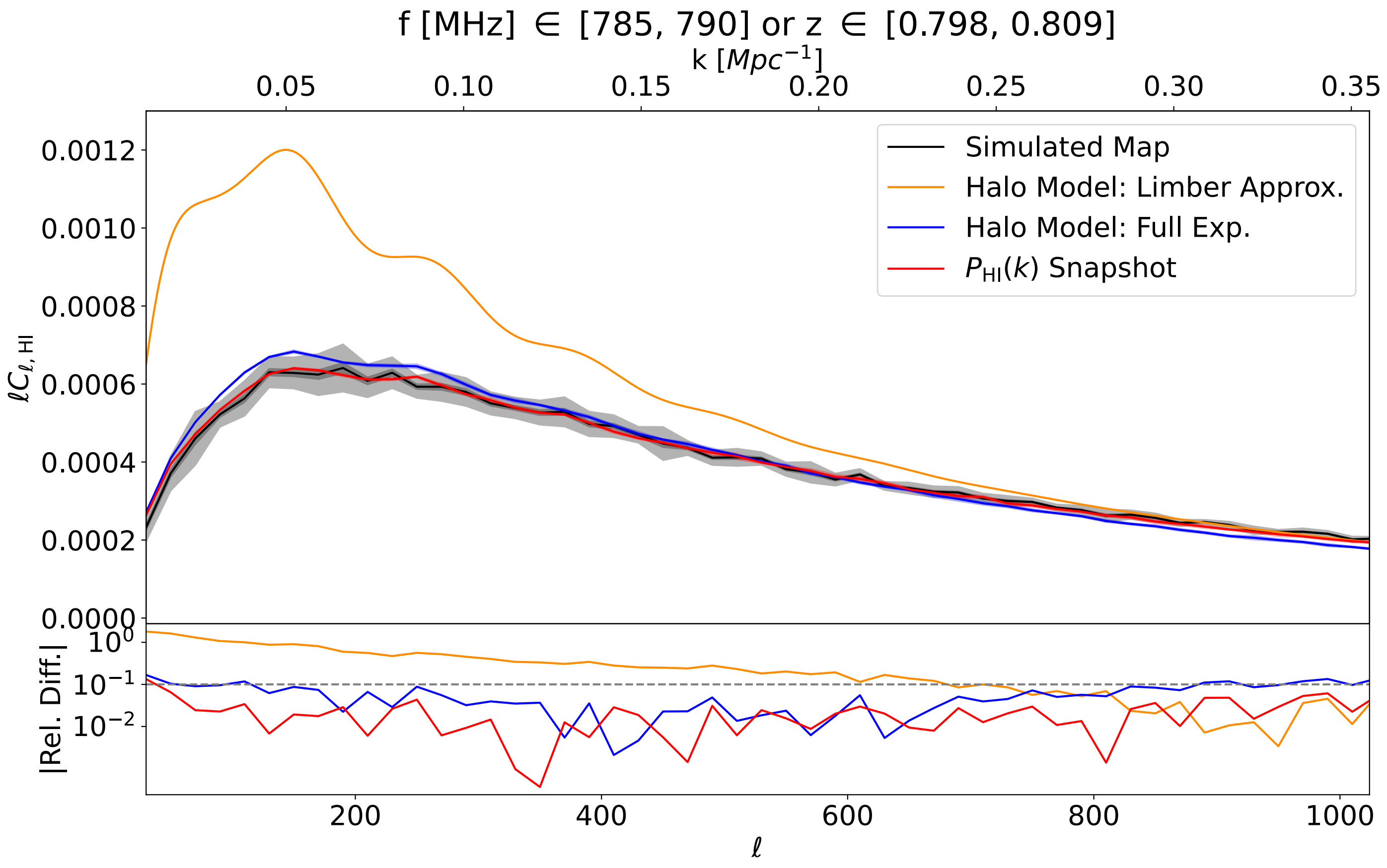
HI Power Spectrum





ETH zürich

HI Angular Power Spectrum

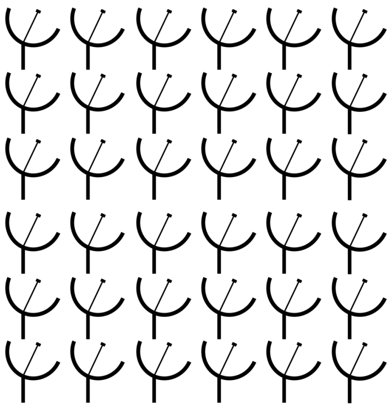


Full Expression:

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

- : $P_{\mathrm{HI}}(k,z)$ from halo model
- : $P_{\mathrm{HI}}(k,z)$ from snapshot

Instrument Simulation and Analysis Pipeline

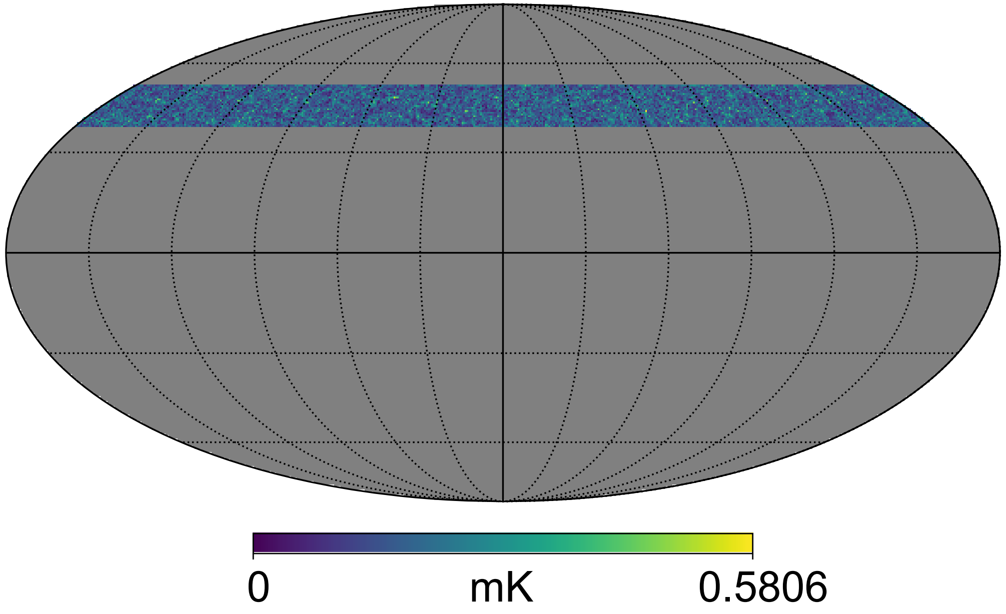


Number of dishes: 36 (6 x 6 grid)
Operating mode: Drift-scan
Dish diameter: 6 m
Dish separation: 6 m
Primary Beam Type: Gaussian
Telescope Latitude: 45°

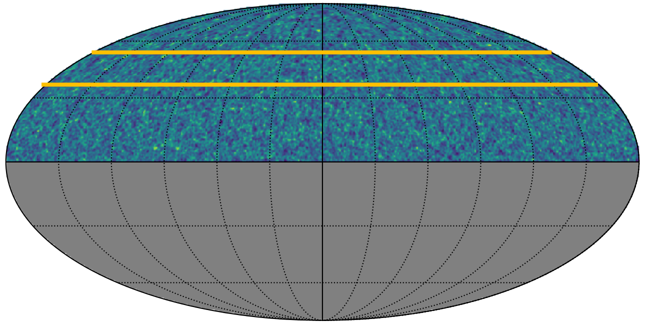
Simplified HIRAX array configuration

Construct instrument model → Generate synthetic data: Visibilities → Map Making →

Recovered Map



↓



→ Angular Power Spectrum

Angular Power Spectrum

Summary

- Simulation pipeline of HI maps for intensity mapping
- Theoretical predictions of power spectrum
- Apply it to HIRAX, SKAO, MeerKAT, …
- Future developments:
  - Vary cosmology and astrophysics (HI-Halo mass relation)
  - Consider foregrounds, noise and RSD
  - Cross-correlations with other probes

Hitz et al. (2024) https://arxiv.org/abs/2410.01694

PyCosmo HI Halo Model

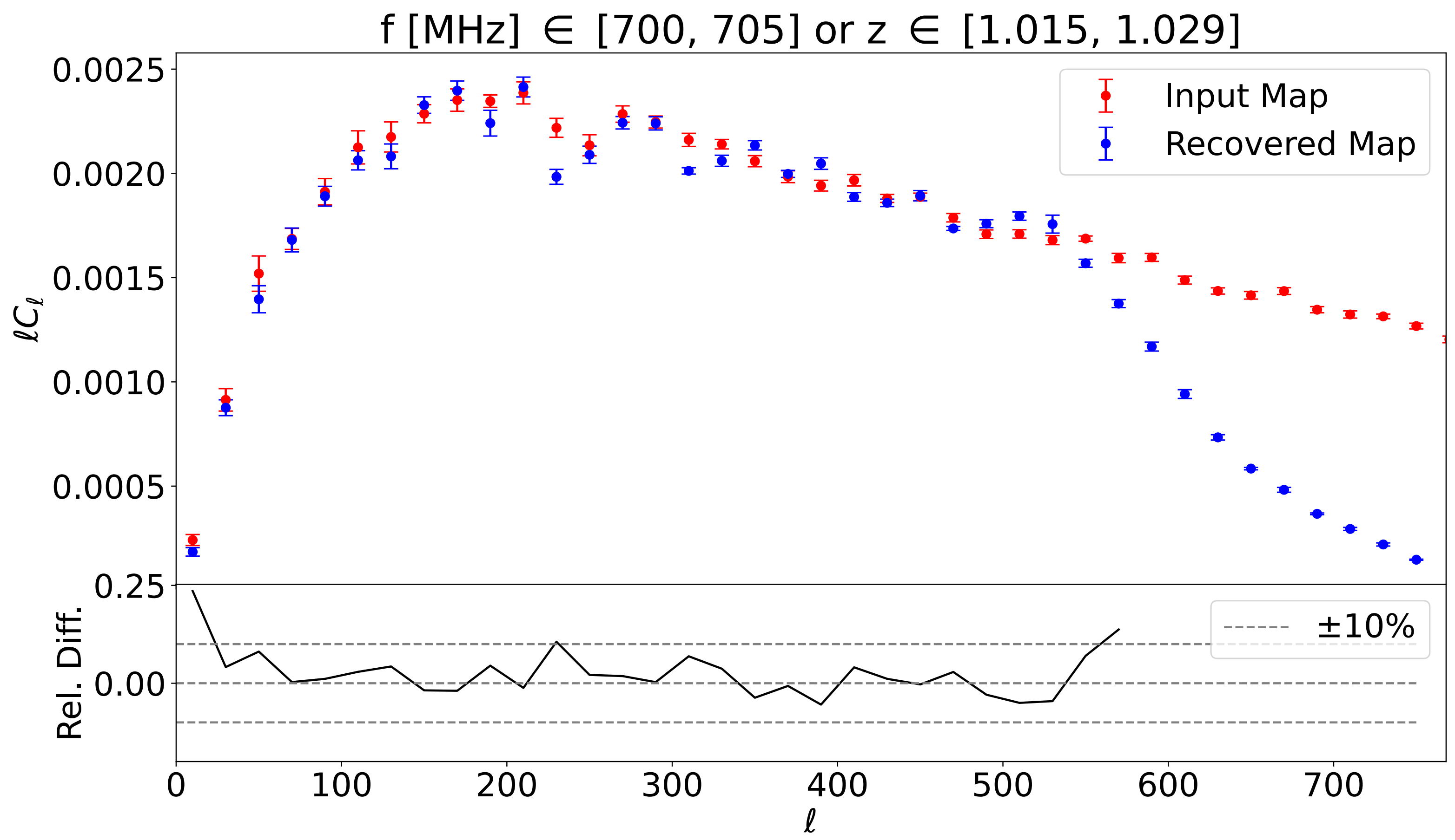
- Fundamental assumption: All matter in the universe is arranged in halos of different sizes and masses

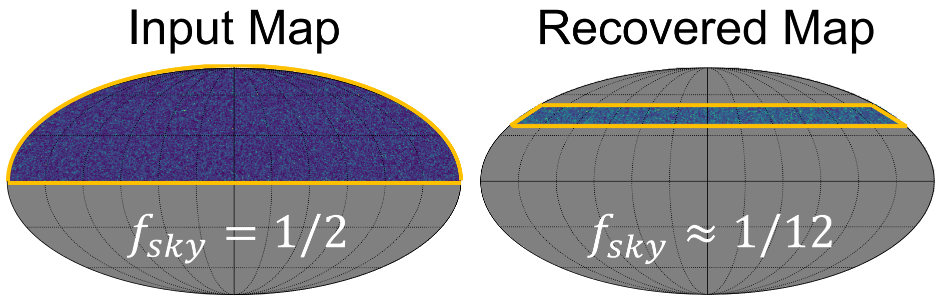
$$P_{\mathrm{HI}}(k) = P_{1\mathrm{h,HI}}(k) + P_{2\mathrm{h,HI}}(k)$$

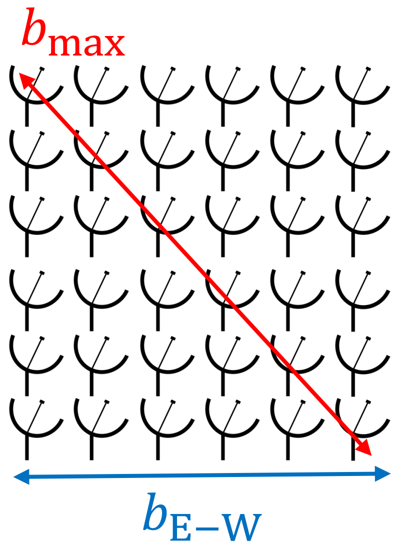
$$P_{1\mathrm{h,HI}} = \frac{1}{\bar{\rho}_{\mathrm{HI}}^2} \int dM \, \frac{dn(M,z)}{dM} M_{\mathrm{HI}}^2(M) |u_{\mathrm{HI}}(k|M)|^2$$

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

Recovered HI Angular Power Spectrum







$$\ell \sim \frac{2\pi f}{c} b$$

$\ell_{\max}(700 \text{ MHz}) \sim 620$

$\ell_{\mathrm{E-W}}(700 \text{ MHz}) \sim 440$