SKACH

SKAO

Fast Simulation of Cosmological Neutral Hydrogen with a Halo Model Approach

Pascal Hitz
ETHZ Cosmology Group† in collaboration with FHNW Group ††

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† Alexandre Refregier, Pascale Berner, Devin Crichton, John Hennig, Luis Fernando Machado Poletti Valle, Joël Mayor, Marta Spinelli, Jennifer Studer

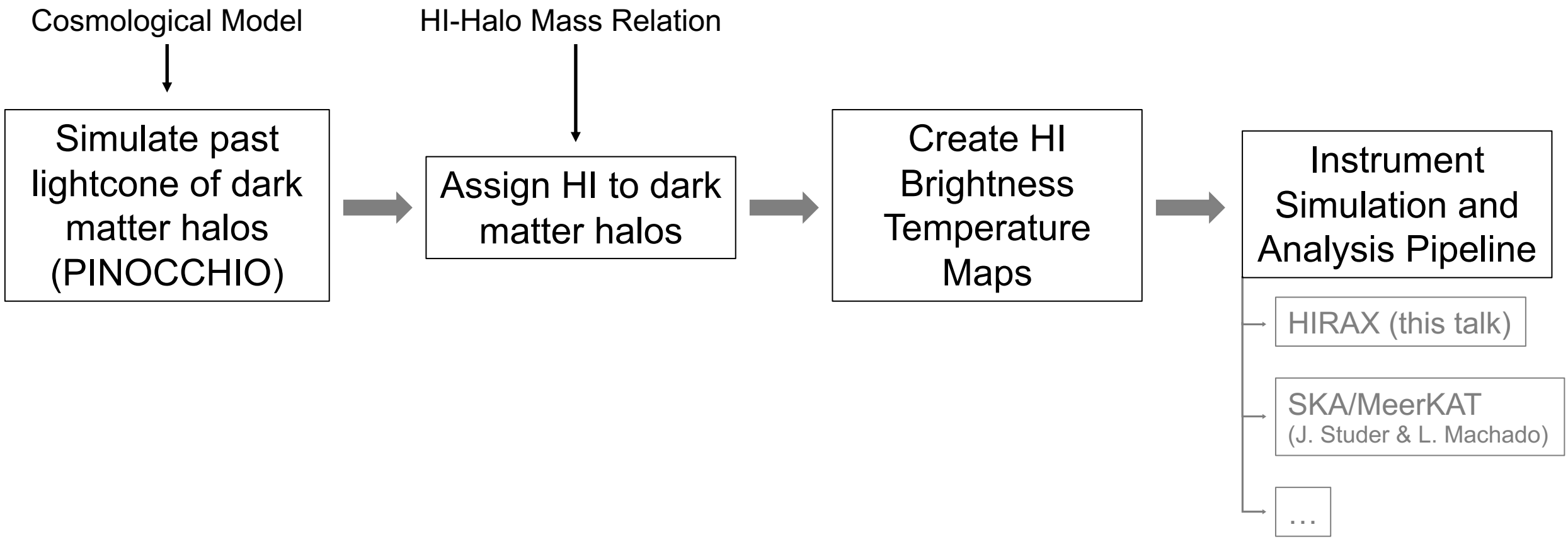
††André Csillaghy, Simon Felix, Lukas Gehrig, Filip Schramka, Rohit Sharma, Vincenzo Timmel

ETH zürich

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

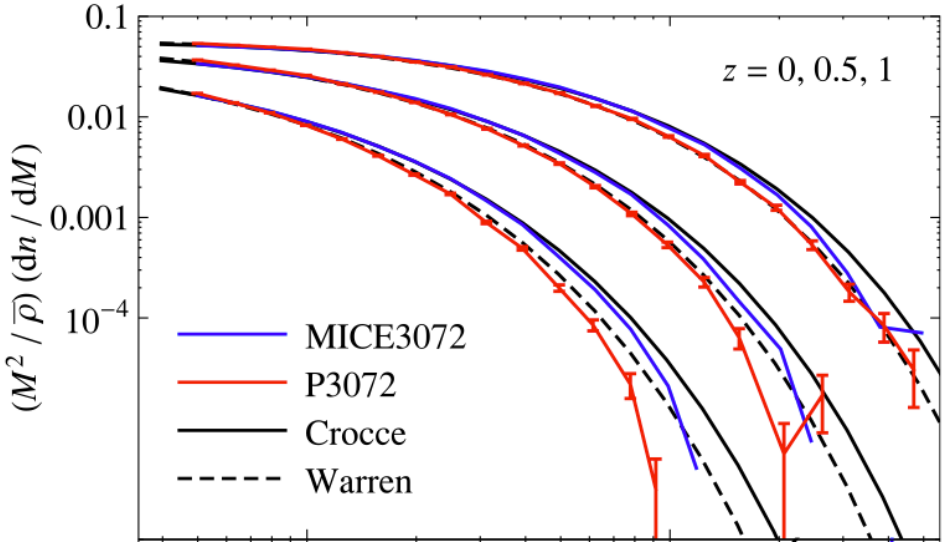
Overview

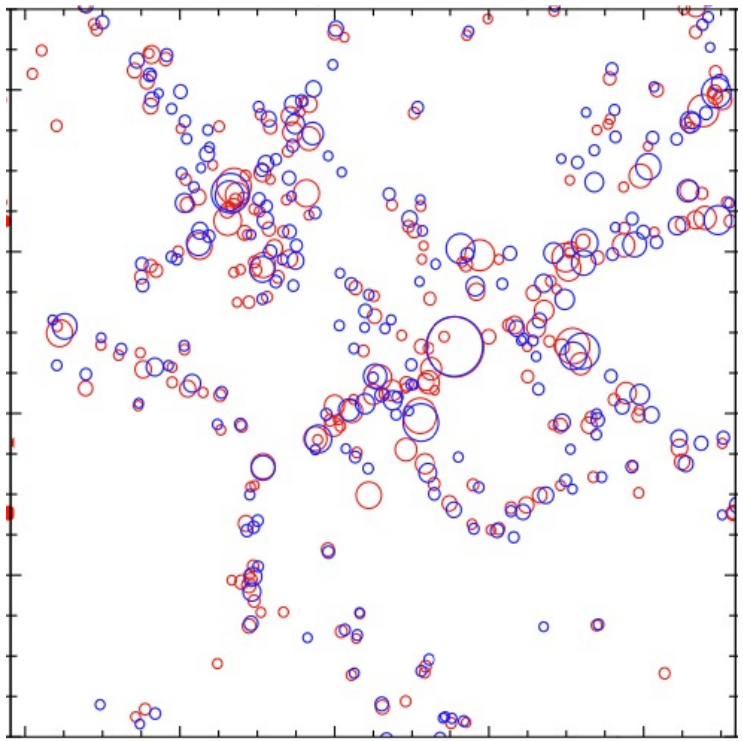
- Fast and large volume simulations of neutral hydrogen (HI) distribution
- Test instrument simulation and analysis pipeline to measure the HI emission



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

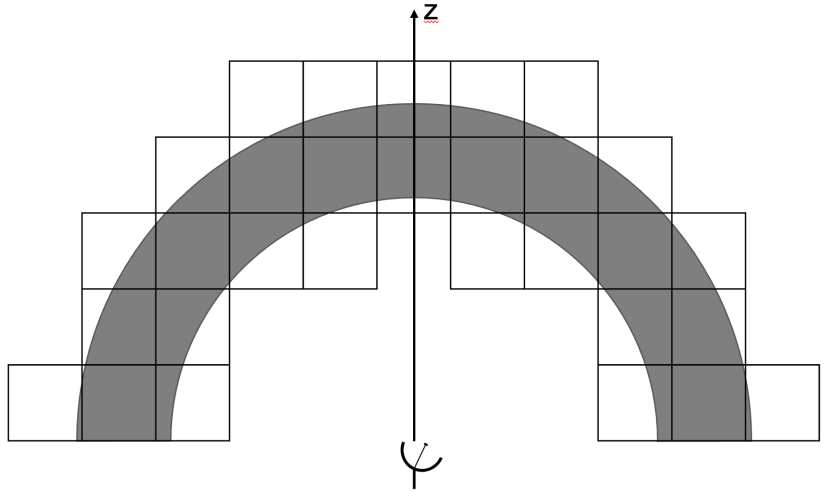
Current Setting of DM Simulations

- 500 Mpc/h box size
- 2048^3 simulation particles
- ≥ 10 particles per halo ↔ ≥ $1.27 \times 10^{10}\ M_\odot/h$

→ 20 – 30% HI mass missing

- Lightcone settings:
  - Frequency range: 700 – 800 MHz ↔ Redshift 0.77 – 1.03
  - Half sky

- Euler Cluster of ETHZ (CPU) with MPI parallelization
  - 1032 cores over 39 nodes
  - 2.75 TB RAM, 332 CPU h runtime

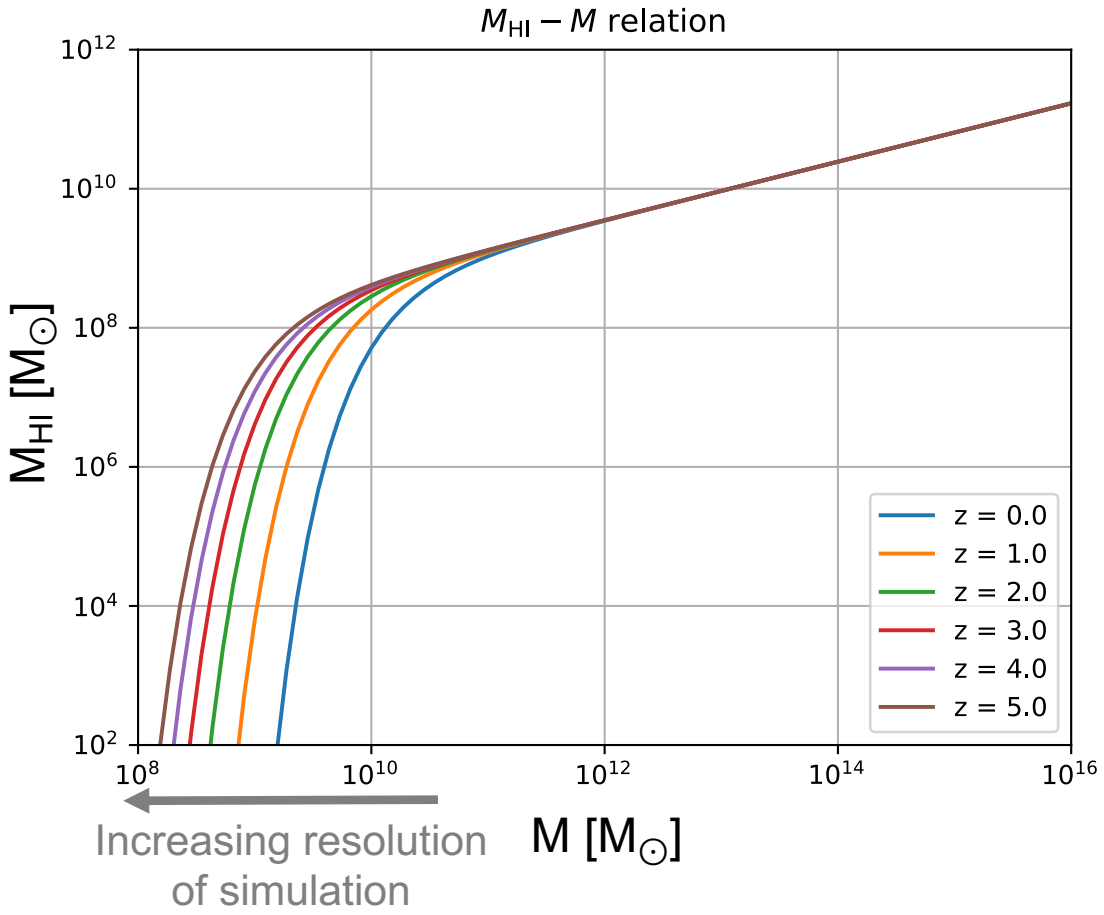


Halo Model for Cosmological HI

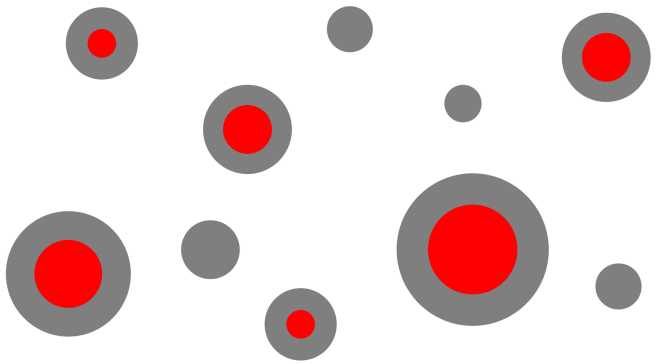
<u>HI-halo mass relation fitted to observations:</u>

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

Padmanabhan et al. 2017



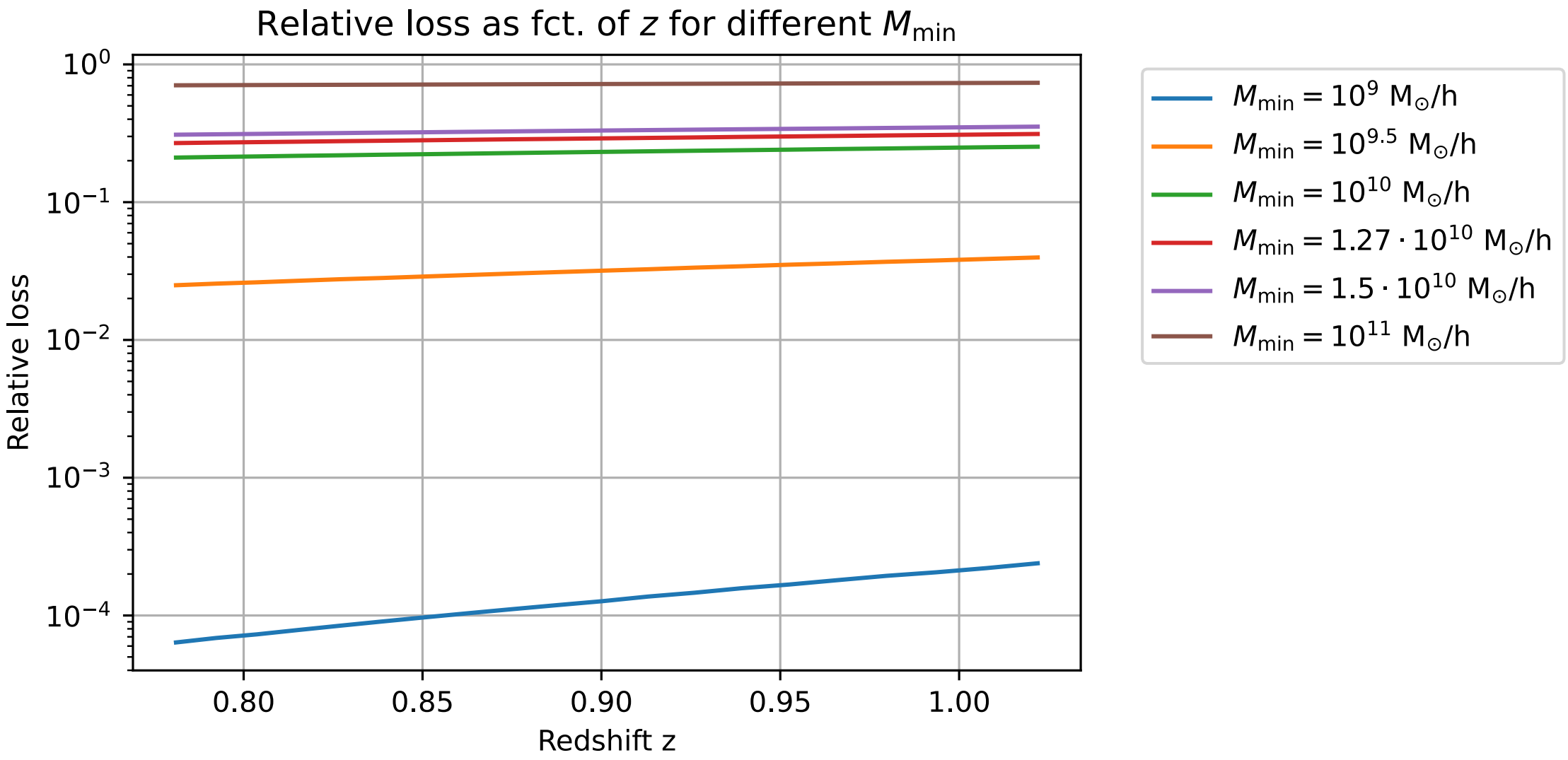
Dark Matter
Neutral Hydrogen



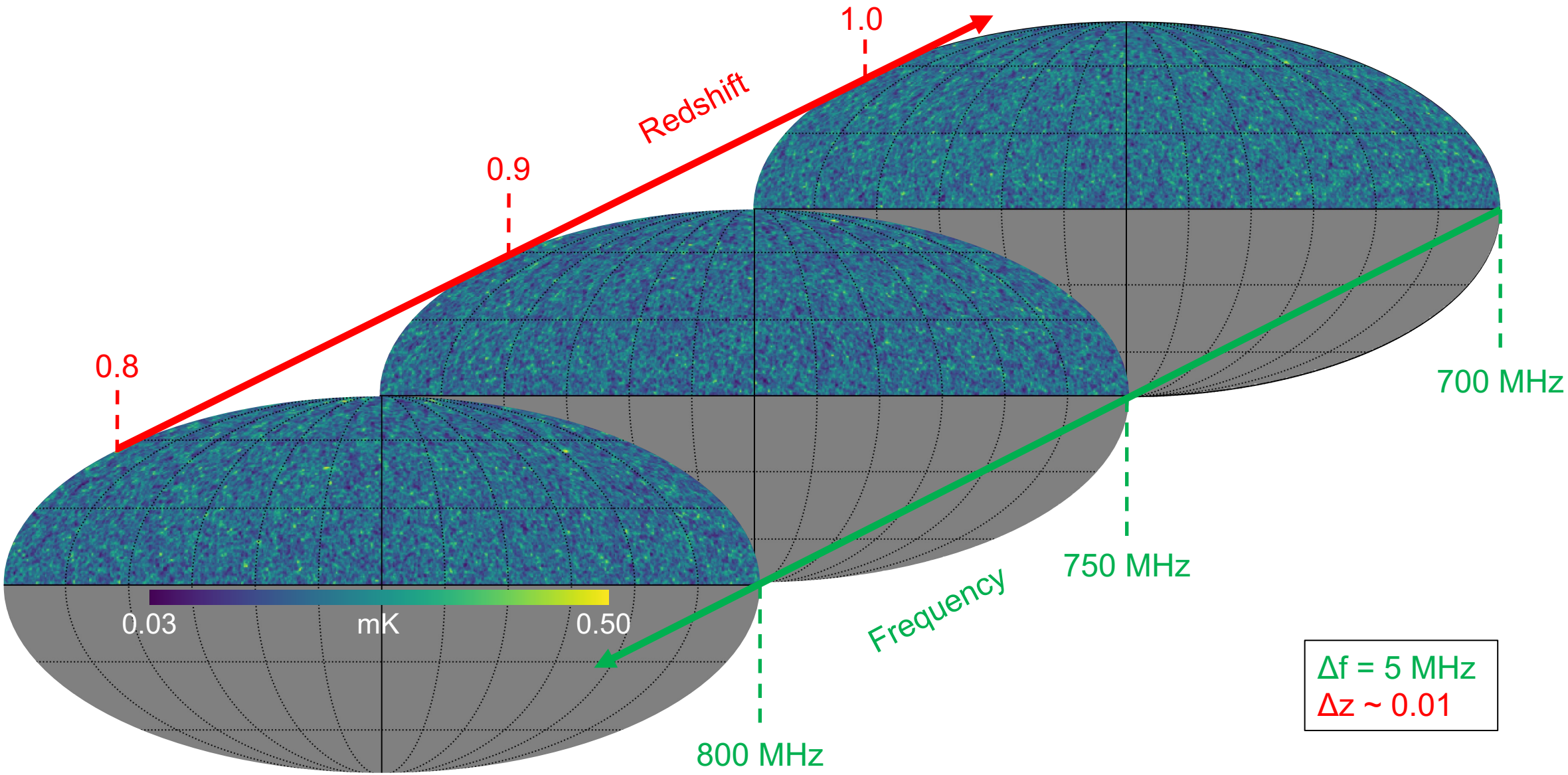
- More massive halos contain more HI
- **But:** Many more small halos than large ones

➔ Important not to neglect small halos.

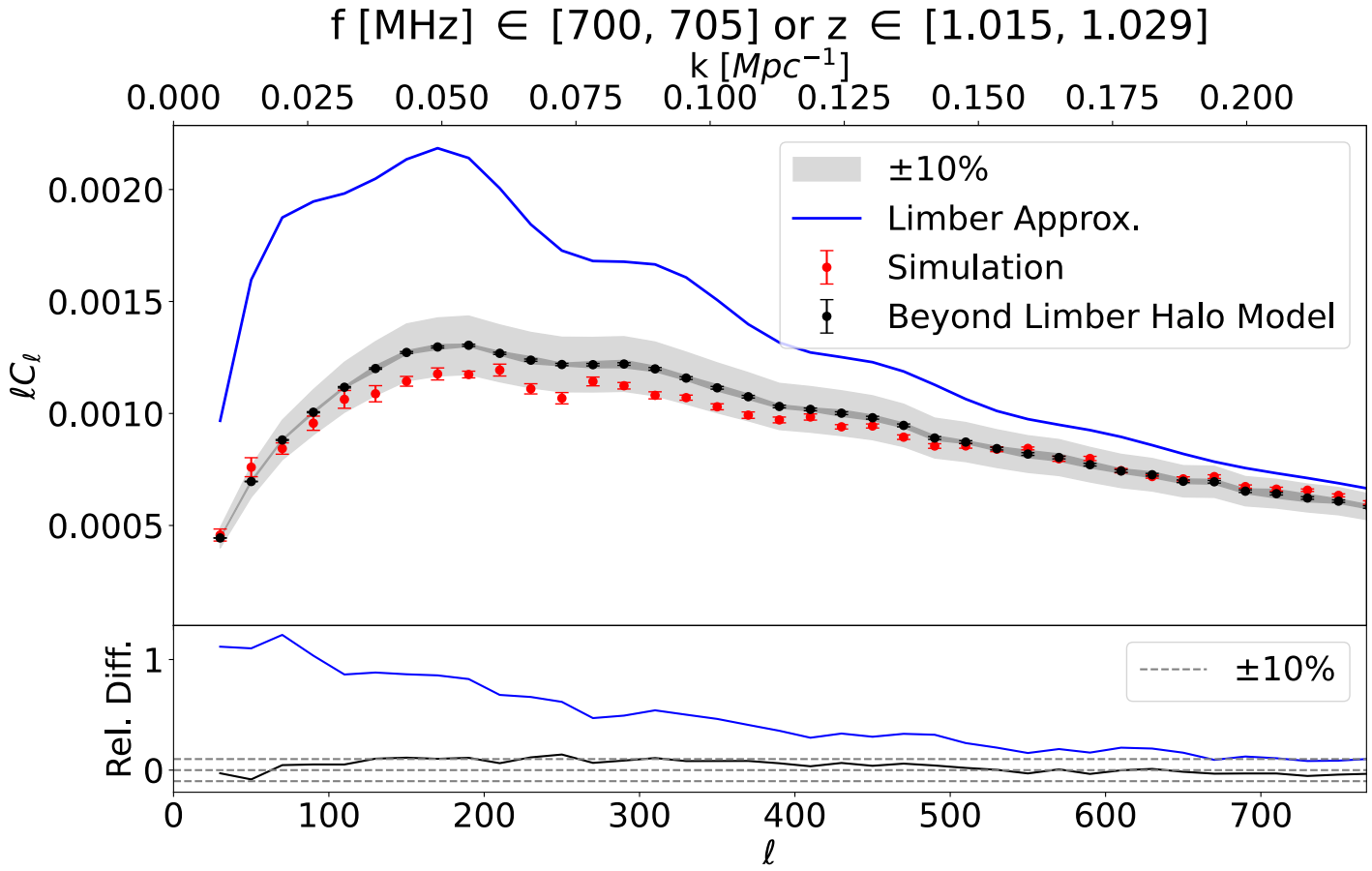
Relative Loss of Total HI Mass



Brightness Temperature Maps



HI Angular Power Spectrum



Simulation:

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

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

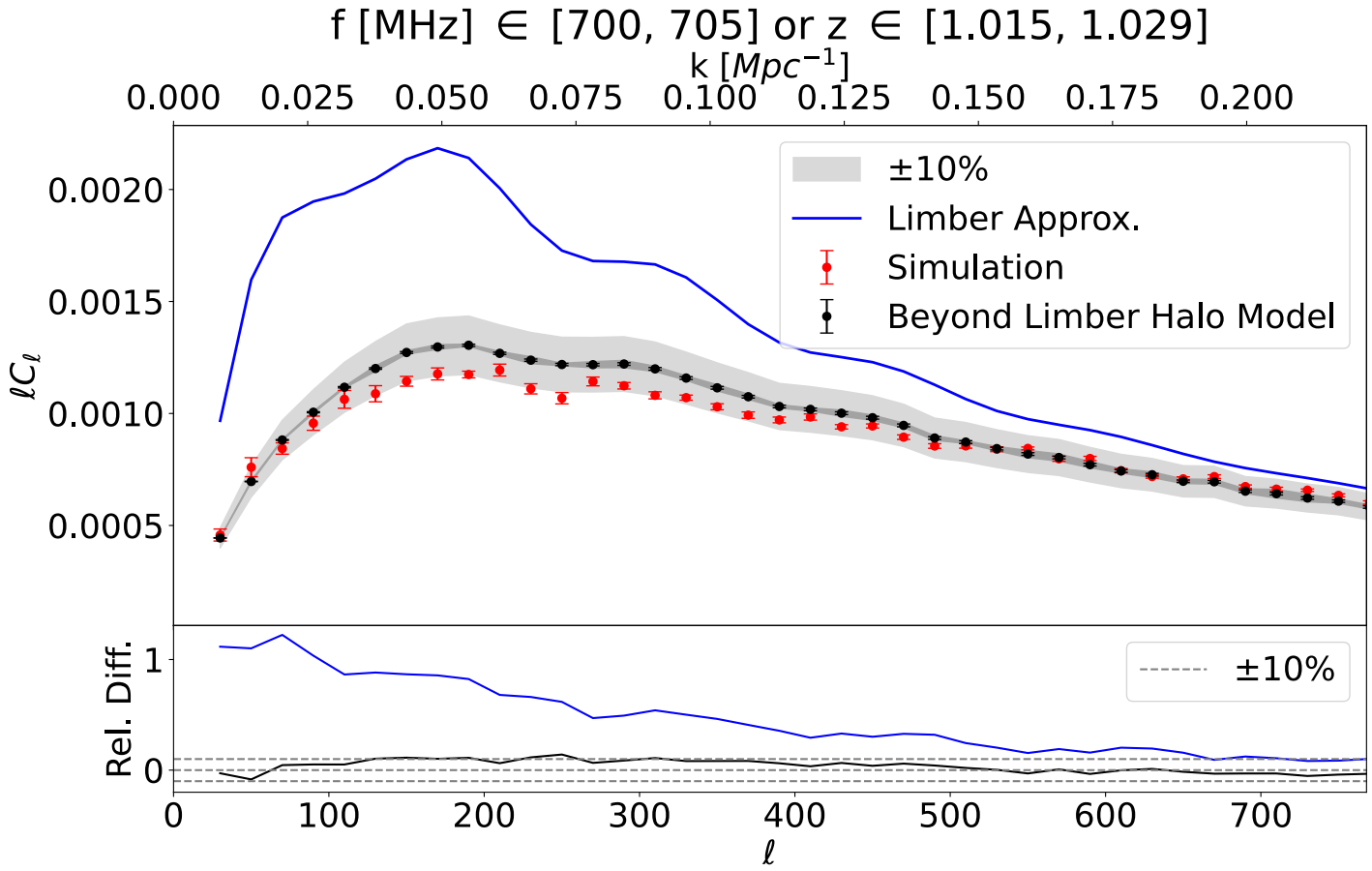
Limber Approximation:

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

PyCosmo

Refregier et al. 2017

HI Angular Power Spectrum



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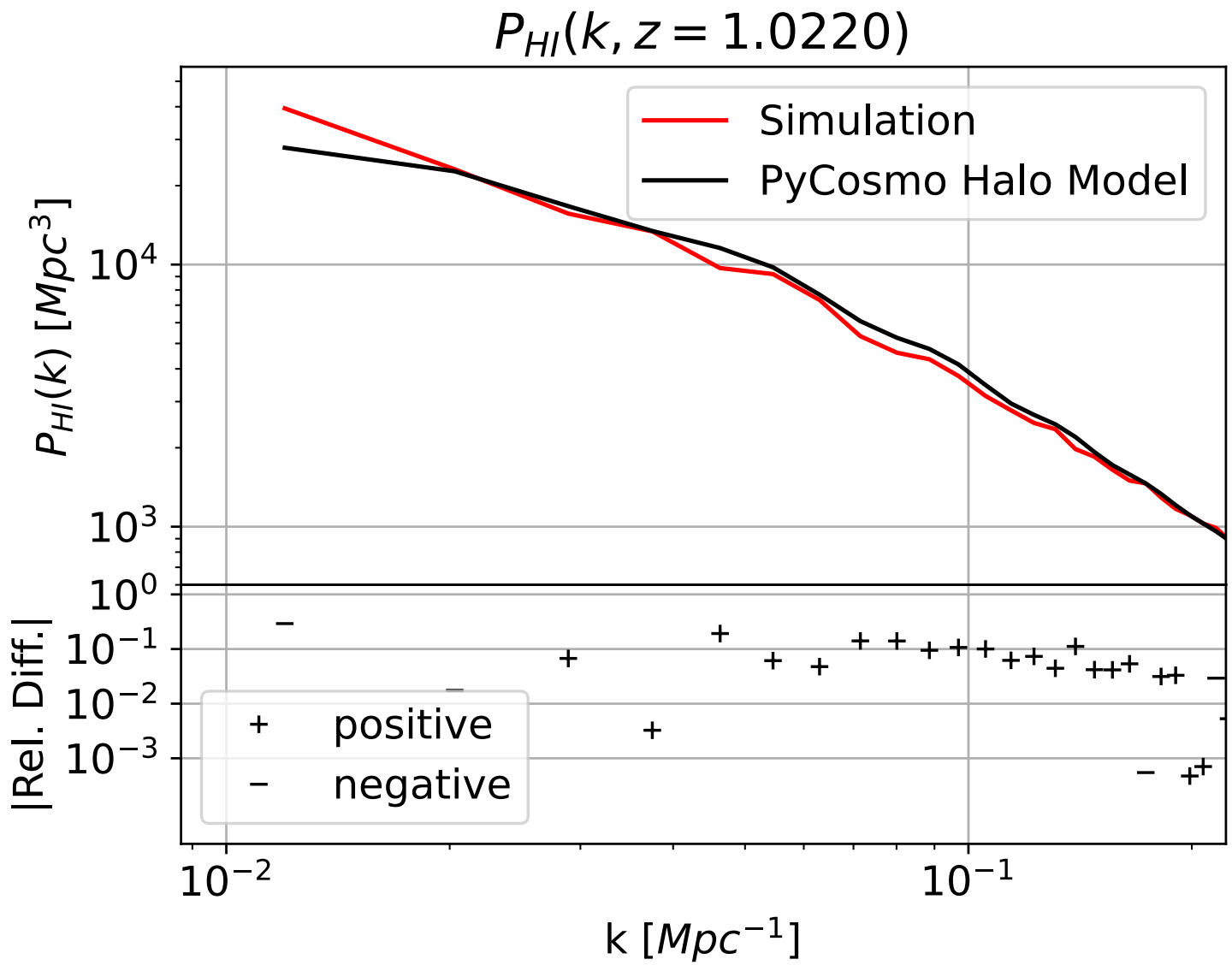
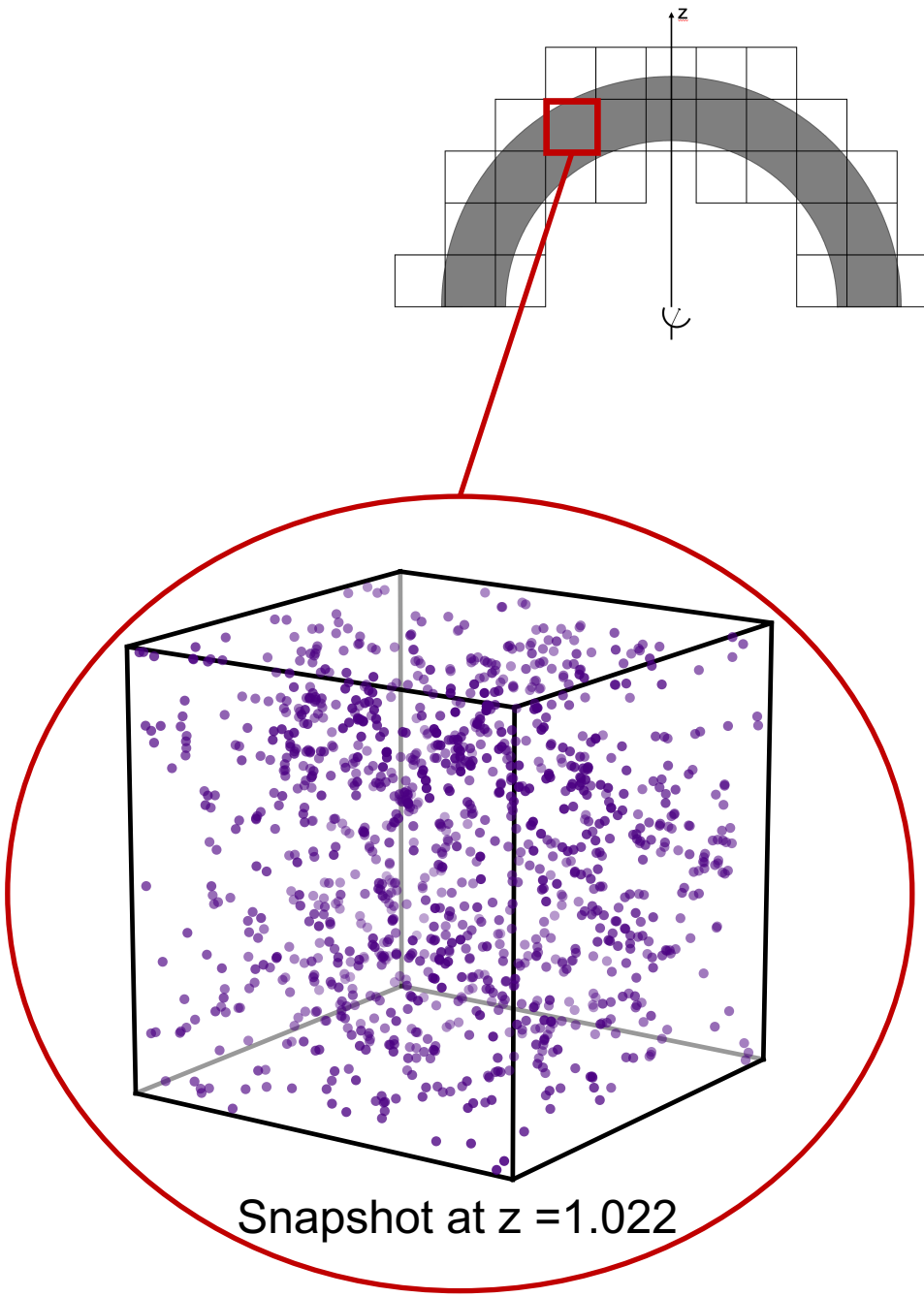
Full Expression:

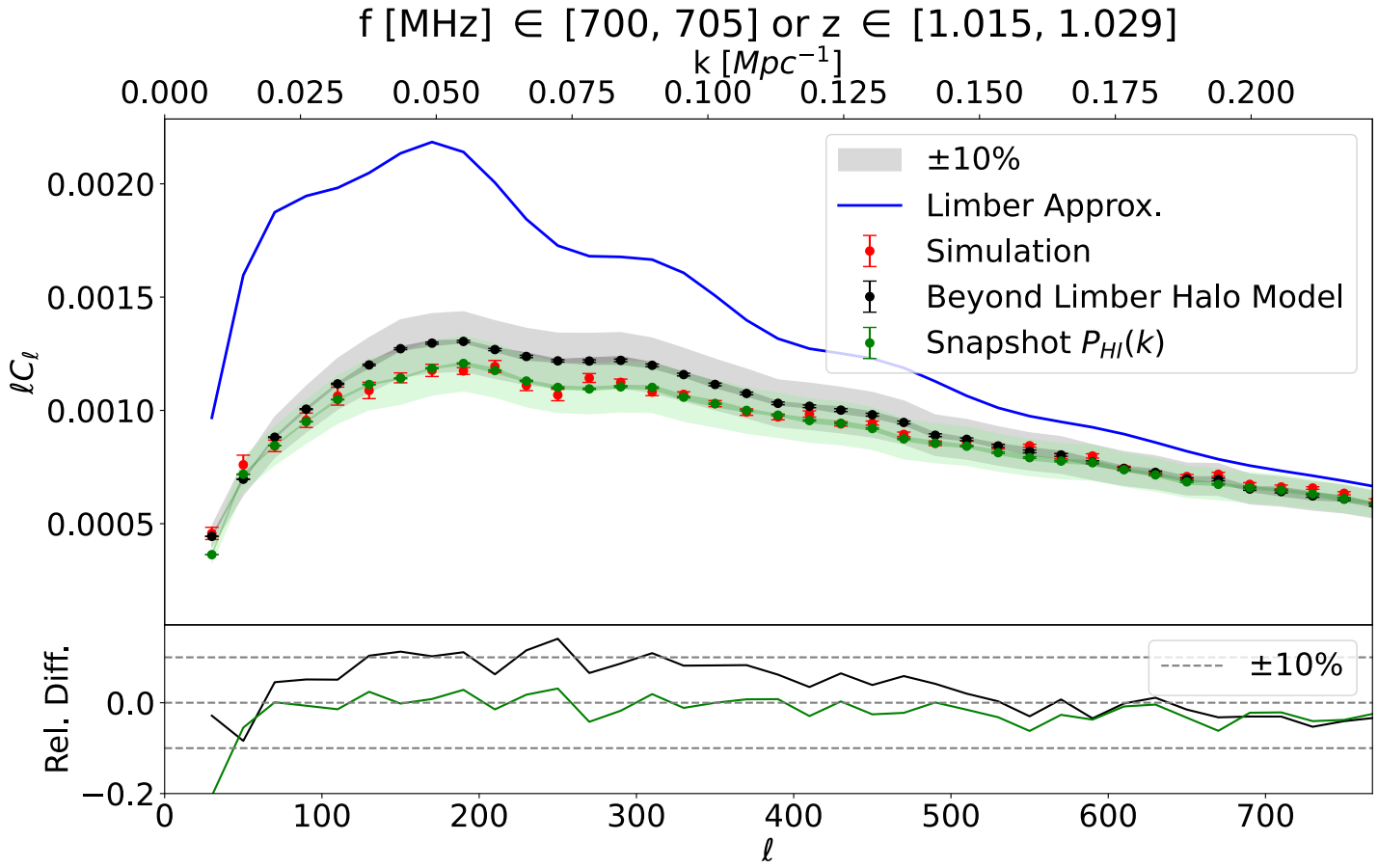
$$C_{\ell,HI} = \frac{2}{\pi} \int k^2 dk \int_0^\infty d\chi\, W(\chi) j_\ell(k\chi) \sqrt{P_{HI}(k, z(\chi))} \times \int_0^\infty d\chi'\, W(\chi') j_\ell(k\chi') \sqrt{P_{HI}(k, z(\chi'))}$$

HI Power Spectrum





HI Angular Power Spectrum



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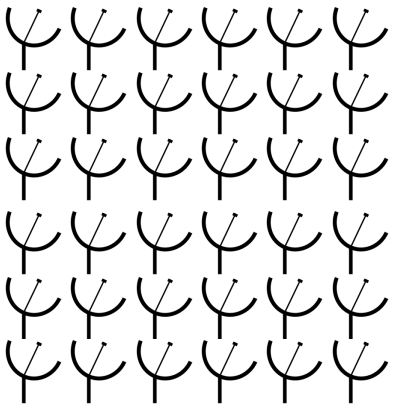
Instrument Simulation and Analysis Pipeline

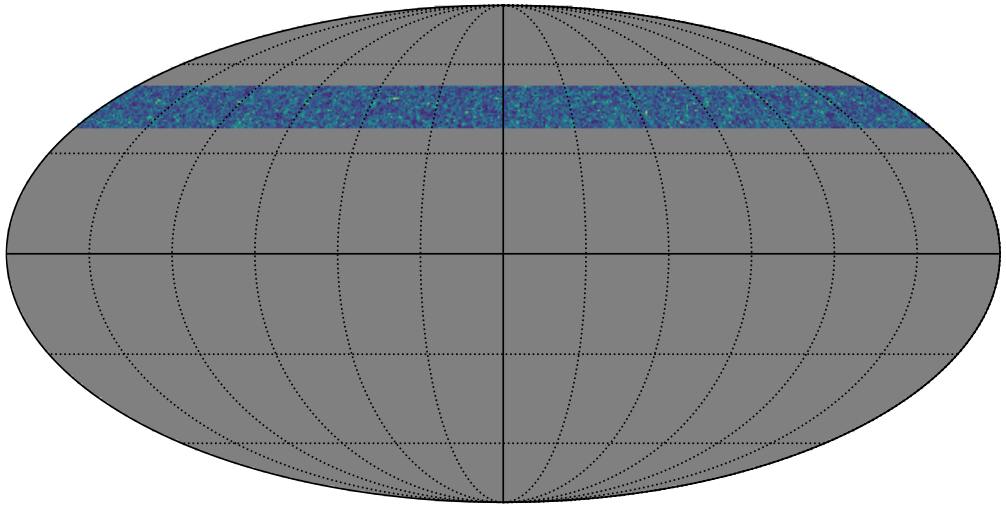


Number of dishes:	36 (6 x 6 grid)
Operating mode:	Drift-scan
Dish diameter:	6 m
Dish separation:	6 m
Primary Beam Type:	Gaussian
Telescope Latitude:	45°

Simplified HIRAX array configuration

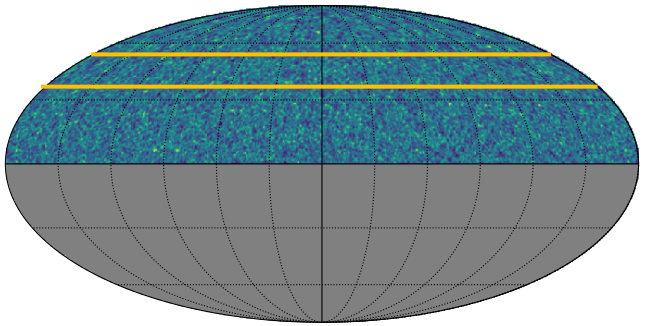
Construct instrument model → Generate synthetic data: Visibilities → Map Making

Recovered Map



0 mK 0.5806

Angular Power Spectrum



Angular Power Spectrum

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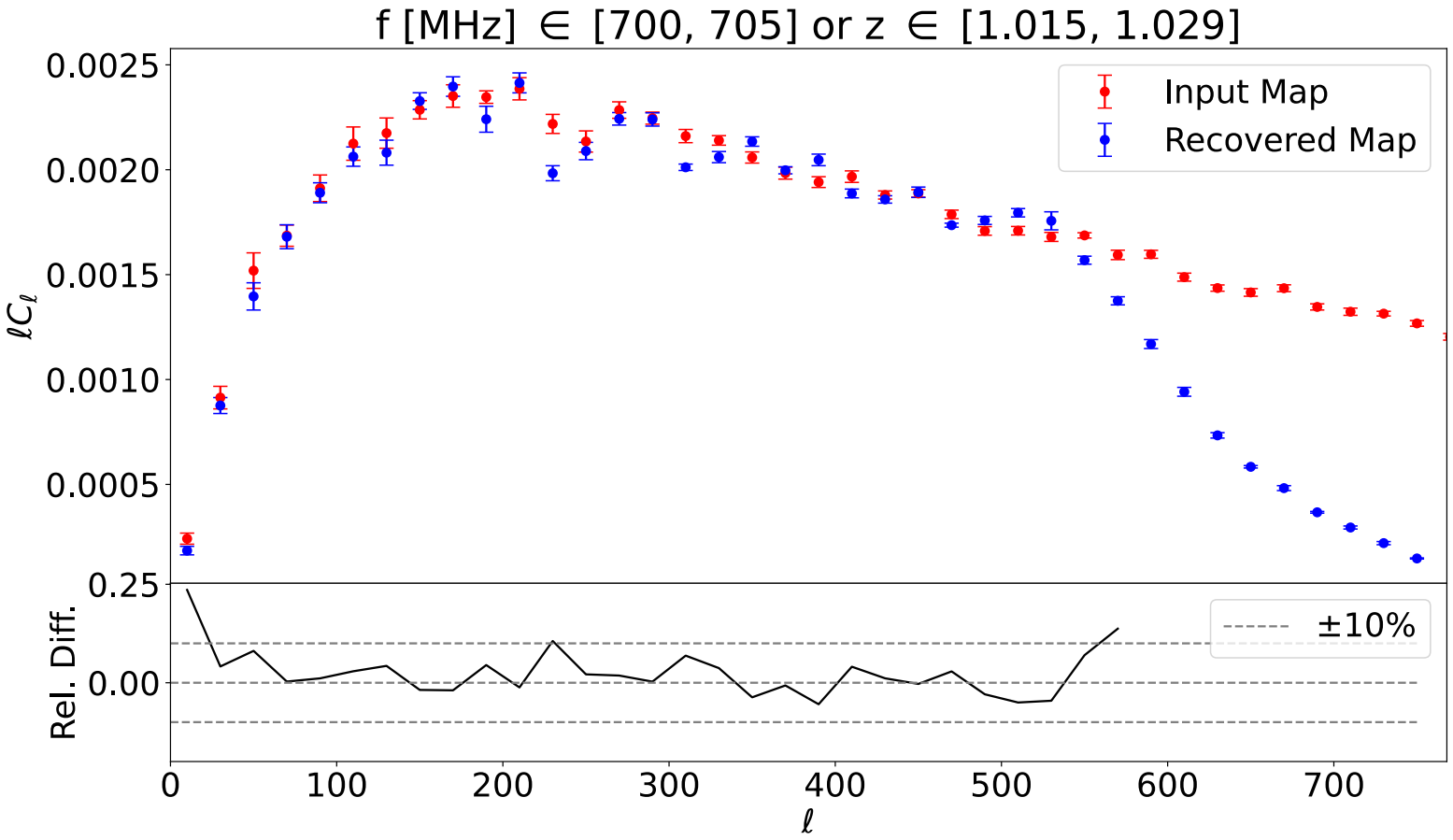
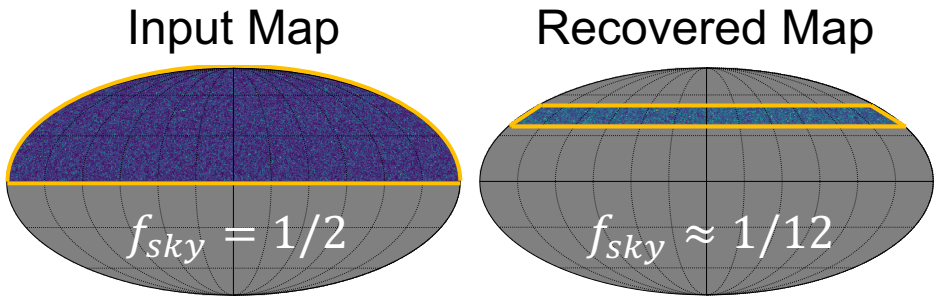
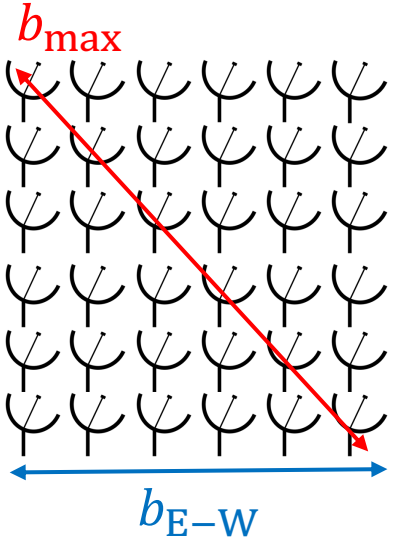
Recovered HI Angular Power Spectrum







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

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

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

Summary

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

Hitz et al. (in prep.)

Backup Slides

PyCosmo HI Halo Model: Angular Power Spectrum

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

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

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

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