SKACH

SKAO

# Non-Gaussian Simulation of Post-Reionization Cosmological Neutral Hydrogen based on a Halo Model Approach

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Swiss SKA Days 04.09.2024

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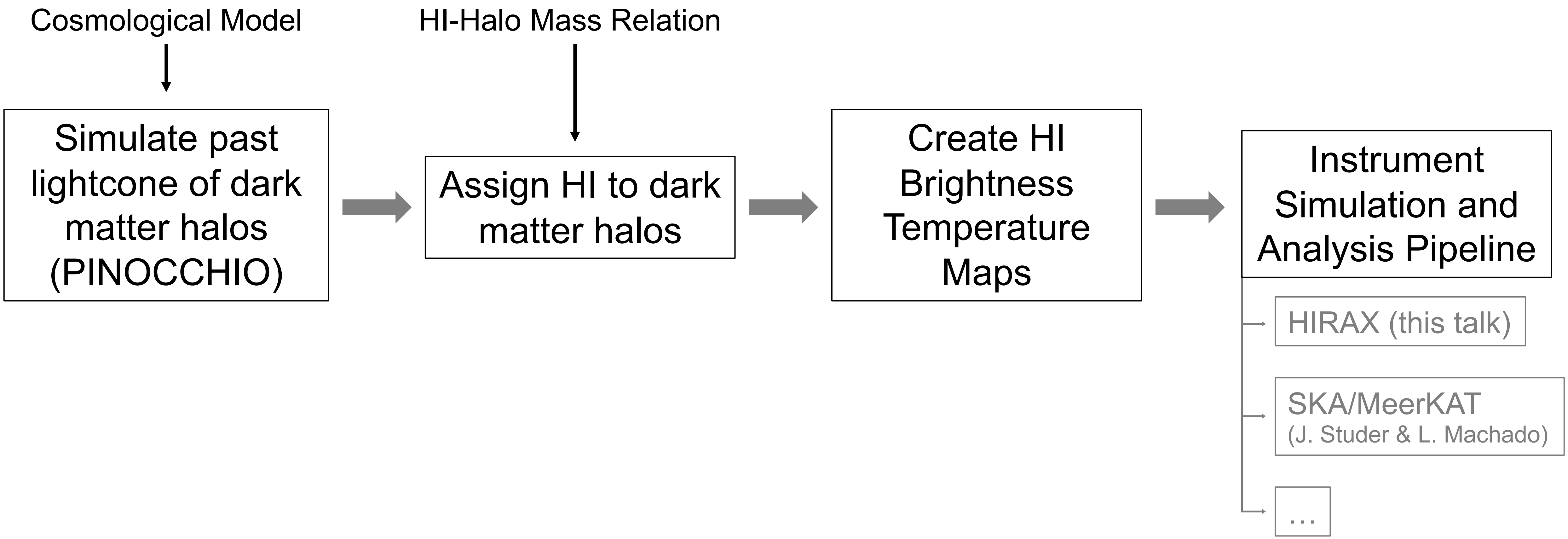
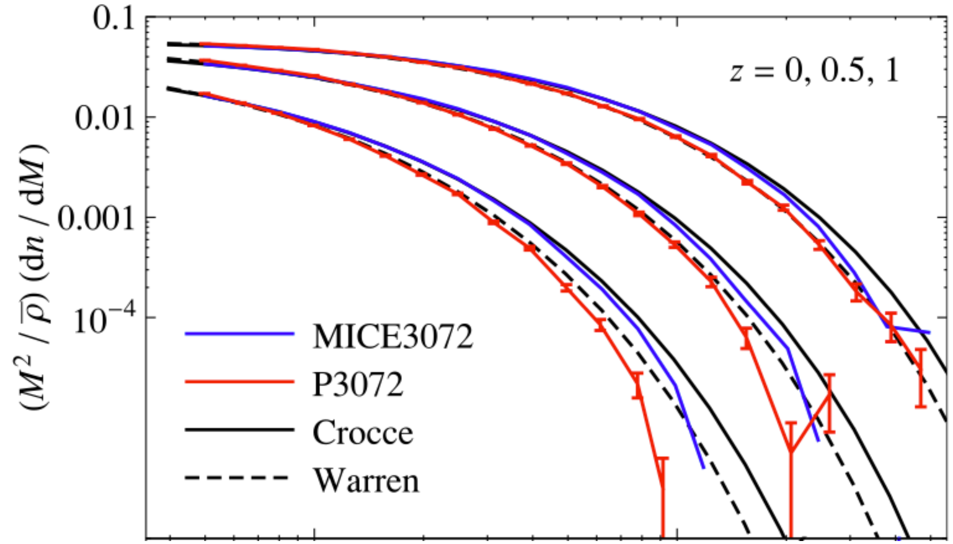
# Overview

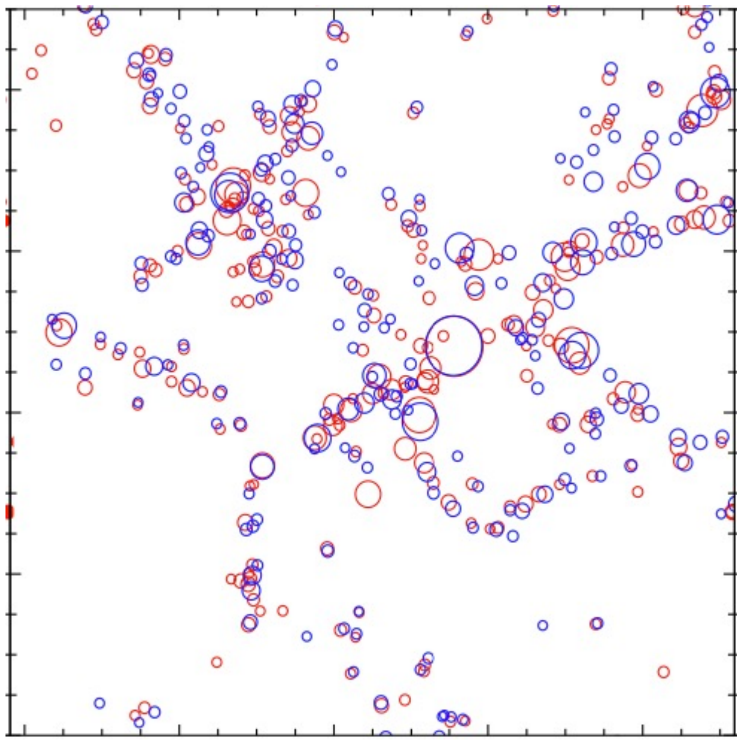
- Fast and large volume simulations of neutral hydrogen (HI) distribution
- Test instrument simulation and analysis pipeline to measure the HI emission



# 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



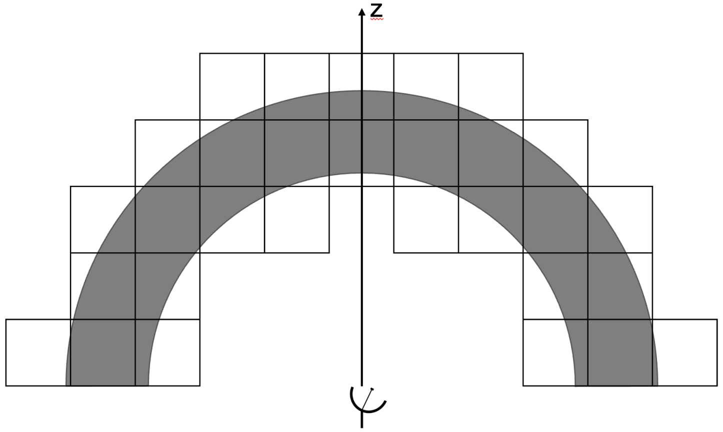
Monaco et al. 2013

# Current Setting of DM Simulations

- 1 Gpc/h box size ~~(500 Mpc/h)~~
- $6700^3$ simulation particles ~~($2048^3$)~~
- ≥ 10 particles per halo ↔ ≥ $4.3 \times 10^9\, M_\odot$ ~~($1.89 \times 10^{10}\, M_\odot$)~~

→ 1.5 – 3% HI mass missing ~~(20 – 30%)~~

- Lightcone settings:
  - Frequency range: 700 – 800 MHz ↔ Redshift 0.77 – 1.03
  - Declinations between -15° and -35° ~~(Half-Sky)~~




- Ran on Piz Daint with MPI parallelization
  - 2400 nodes with 12 cores each ~~(39 nodes with in total 1032 cores on Euler Cluster of ETHZ)~~
  - 150 TB RAM, 40’000 CPU h runtime ~~(2.75 TB RAM, 332 CPU h runtime)~~

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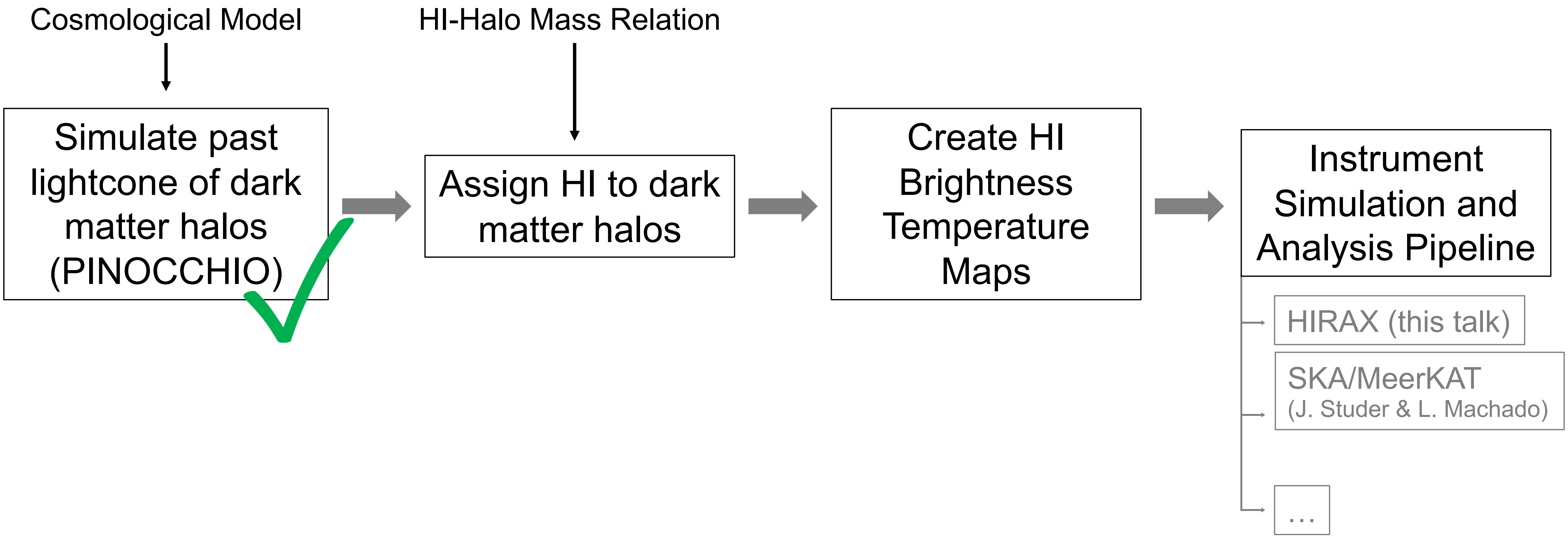
Cosmological Model
HI-Halo Mass Relation
Simulate past lightcone of dark matter halos (PINOCCHIO)
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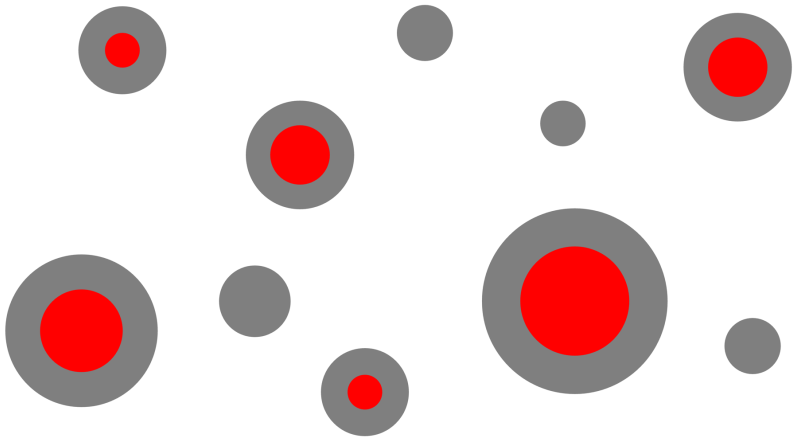
Create HI Brightness Temperature Maps
Instrument Simulation and Analysis Pipeline
HIRAX (this talk)
SKA/MeerKAT
(J. Studer & L. Machado)
…

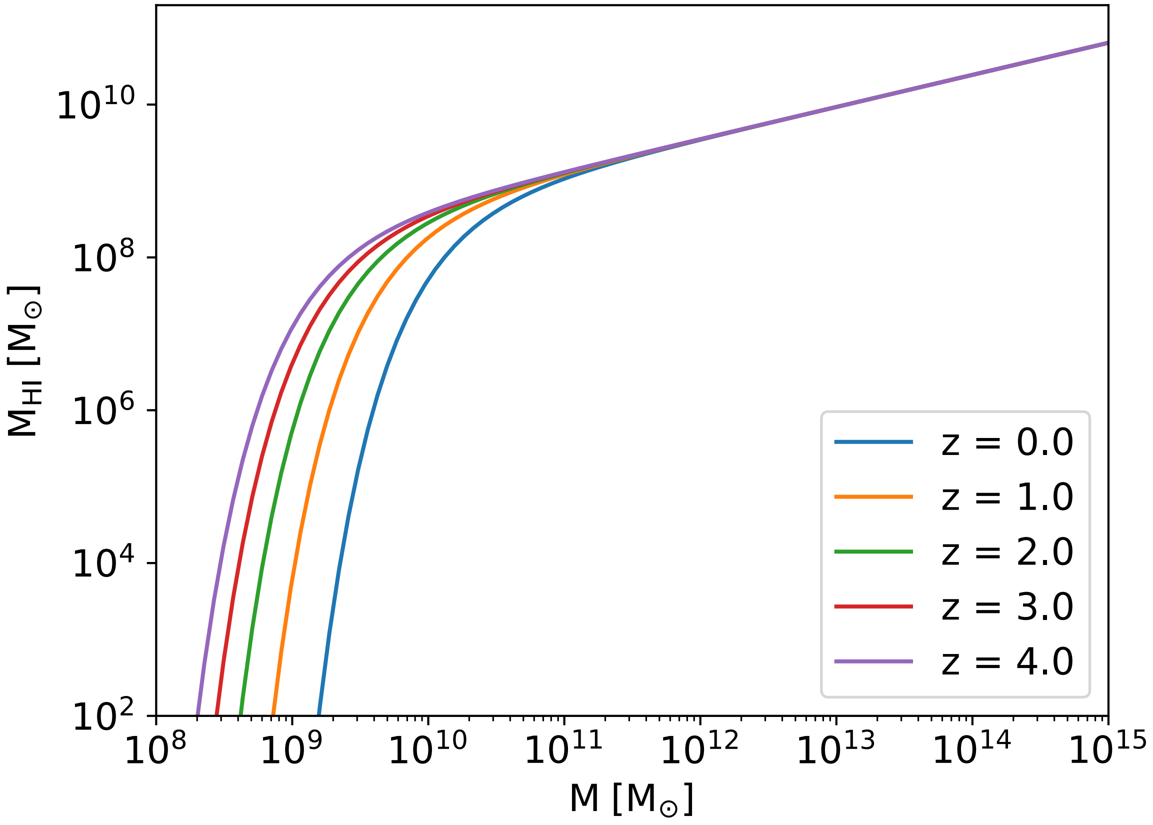
# Halo Model for Cosmological HI

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

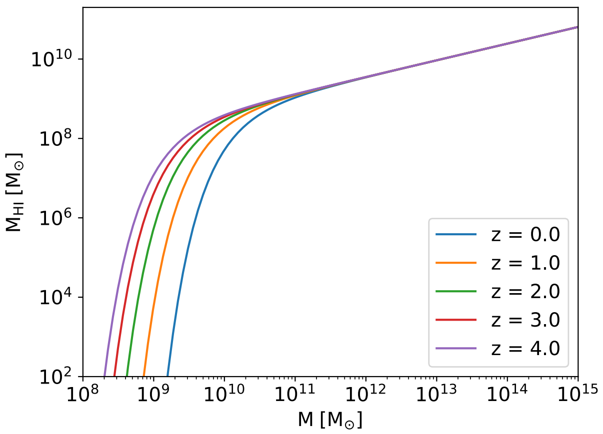
$$M_{\rm HI}(M,z) = \alpha f_{\rm H,c} M \left(\frac{M}{10^{11}h^{-1}{\rm M}_\odot}\right)^{\beta} \exp\left[-\left(\frac{v_{\rm c,0}}{v_{\rm c}(M,z)}\right)^{3}\right]$$

Padmanabhan et al. 2017



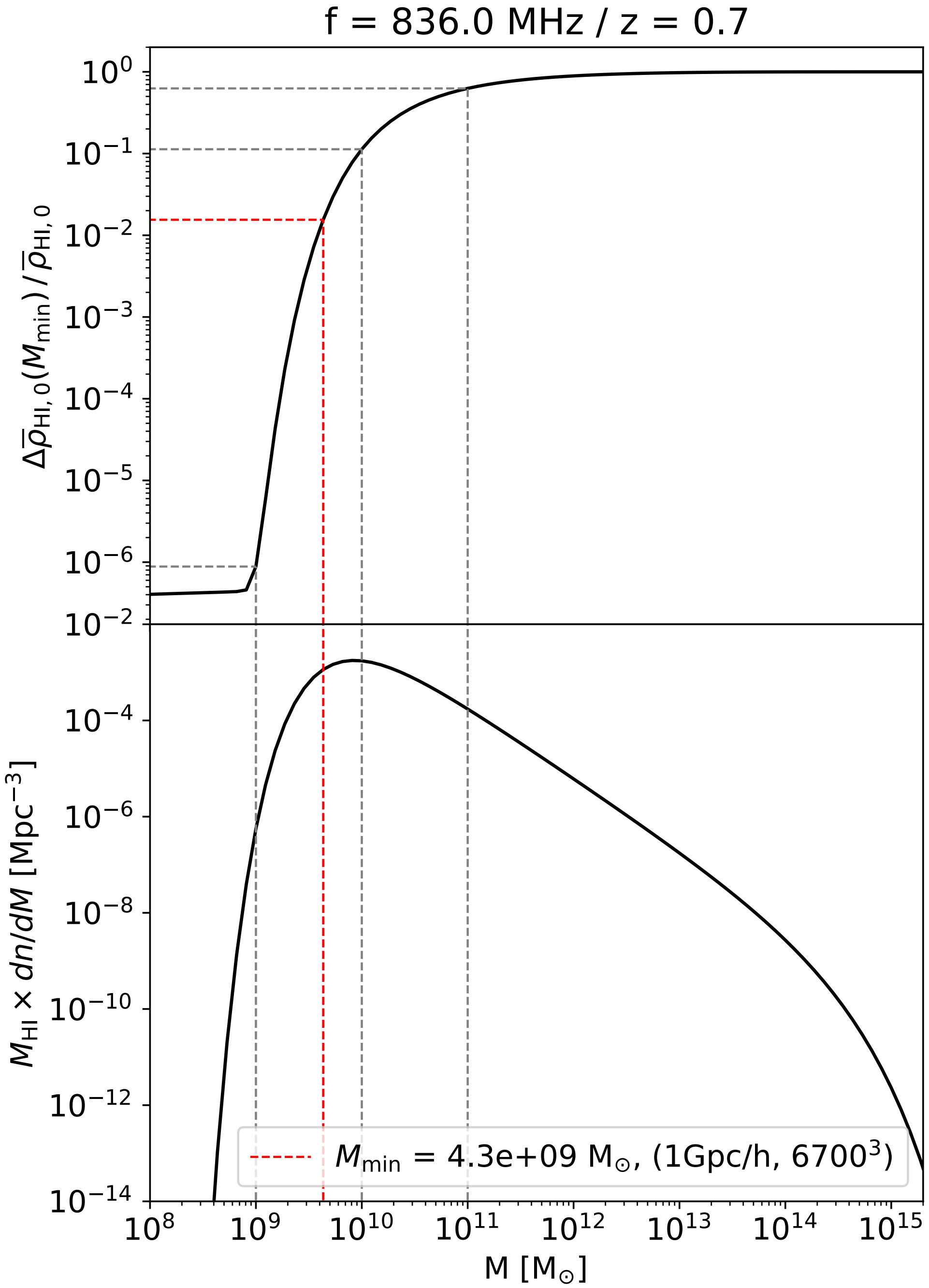
# HI Mass Loss




- 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.



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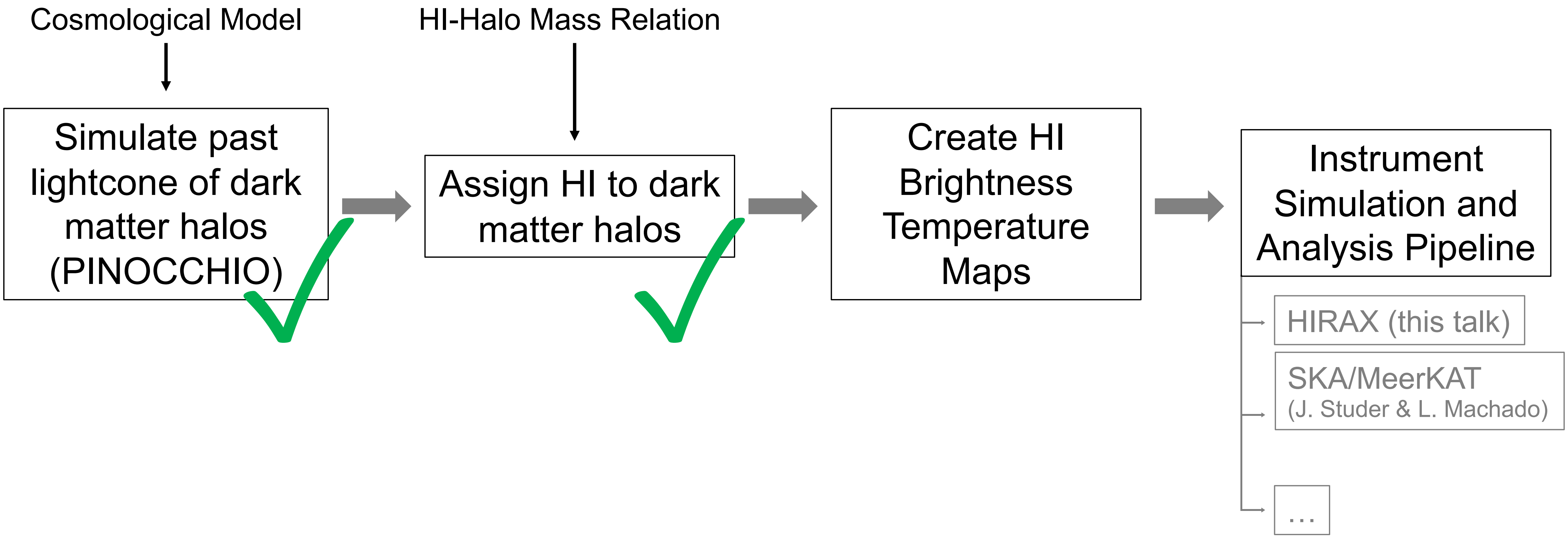
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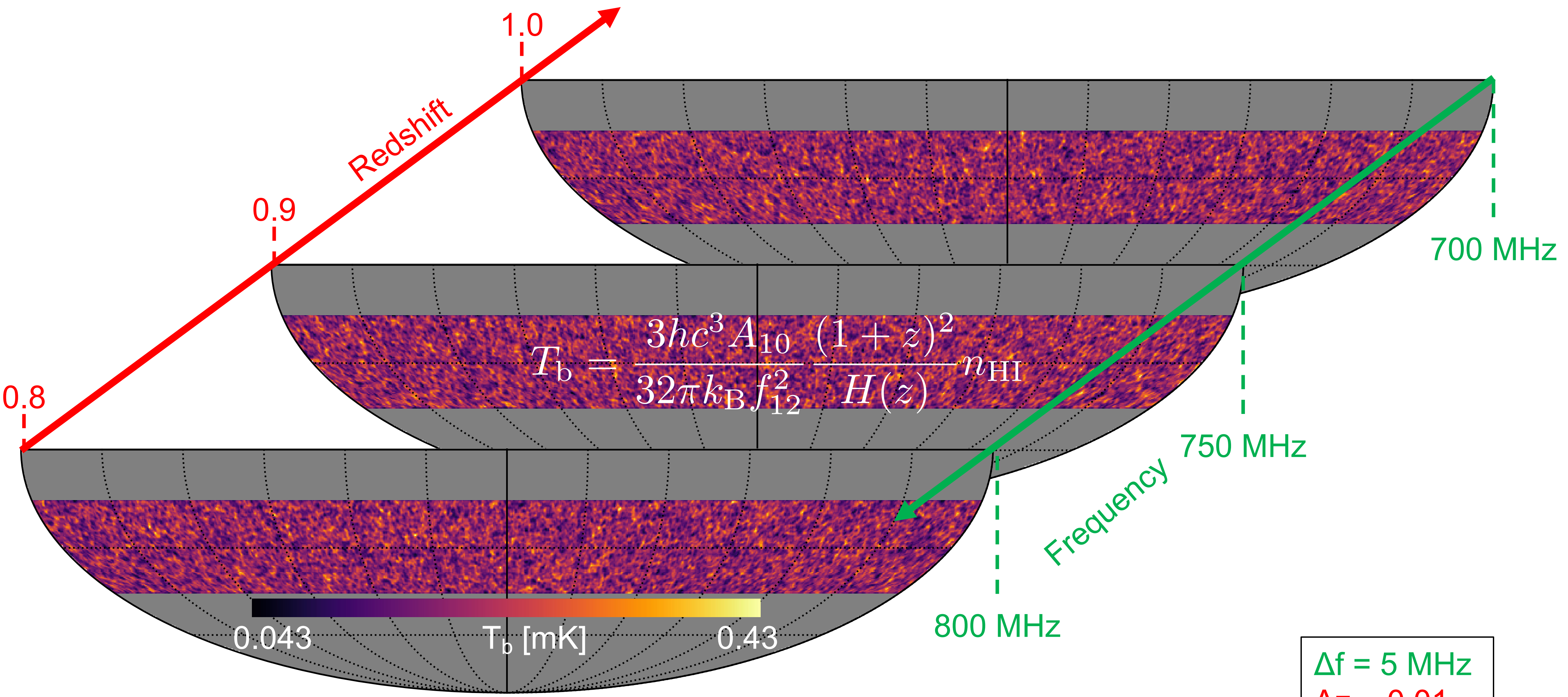
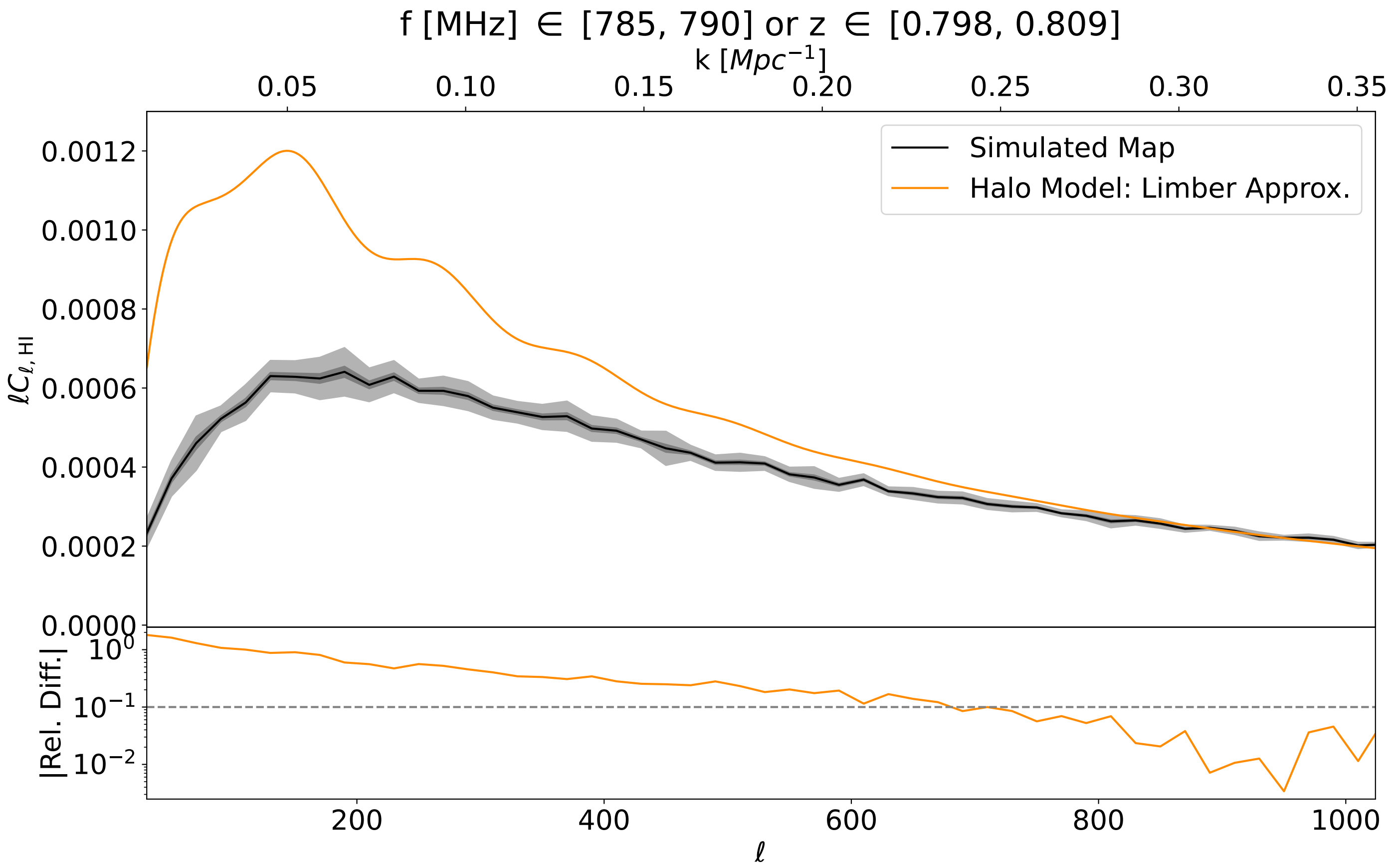
# Brightness Temperature Maps




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

Δf = 5 MHz
Δz ~ 0.01

# HI Angular Power Spectrum




Simulation:

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

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

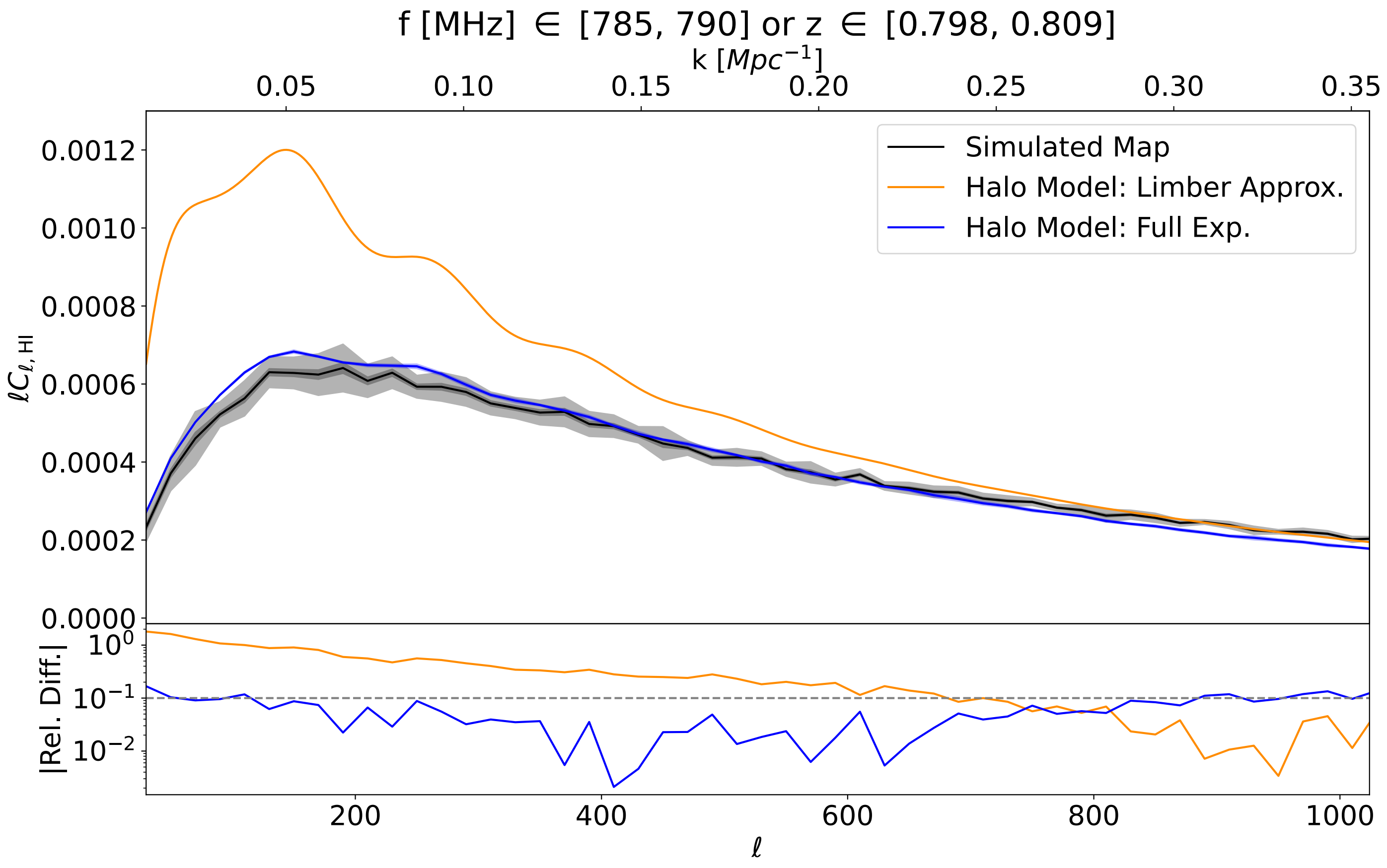
Limber Approximation:

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

PyCosmo

Refregier et al. 2017

# HI Angular Power Spectrum

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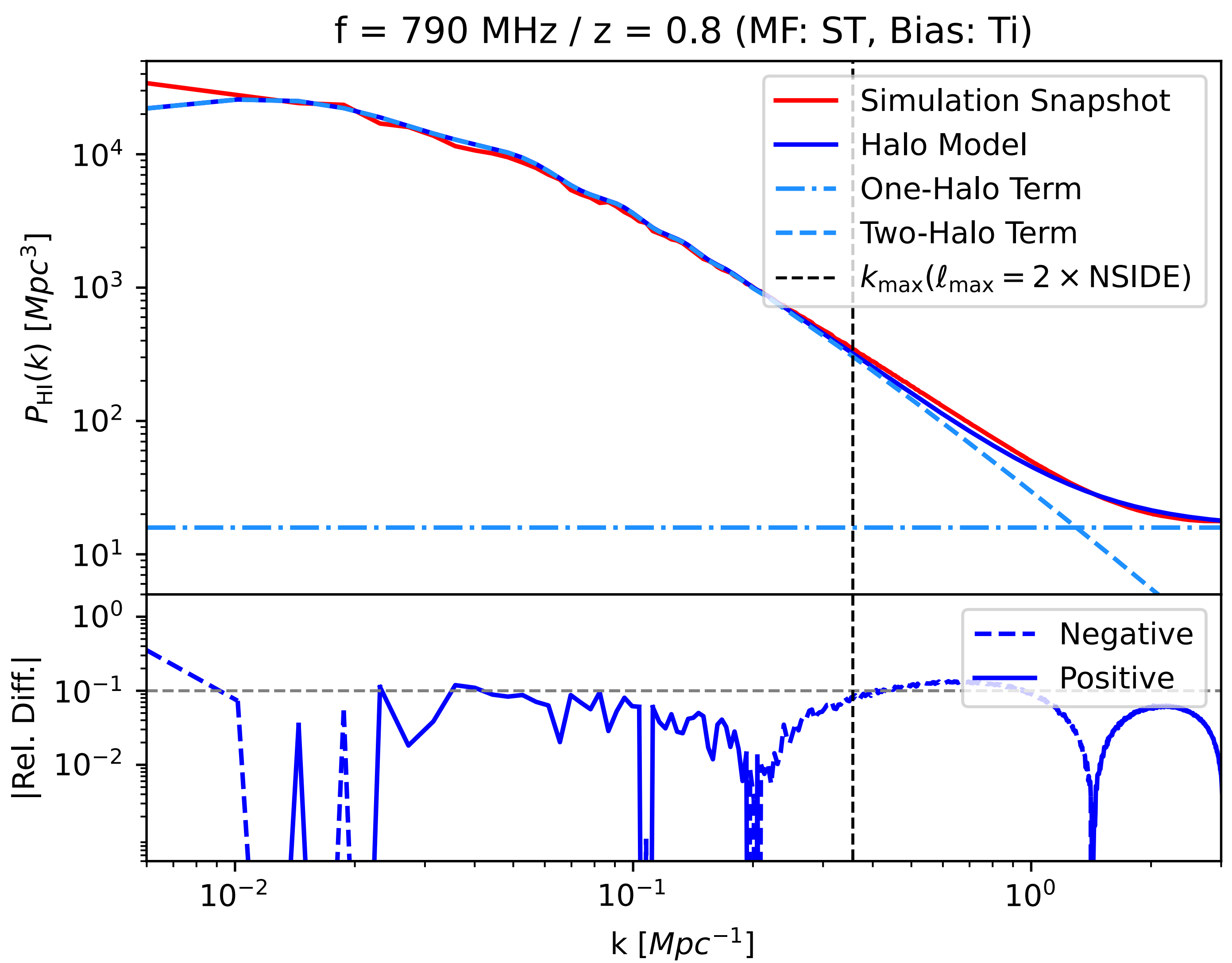
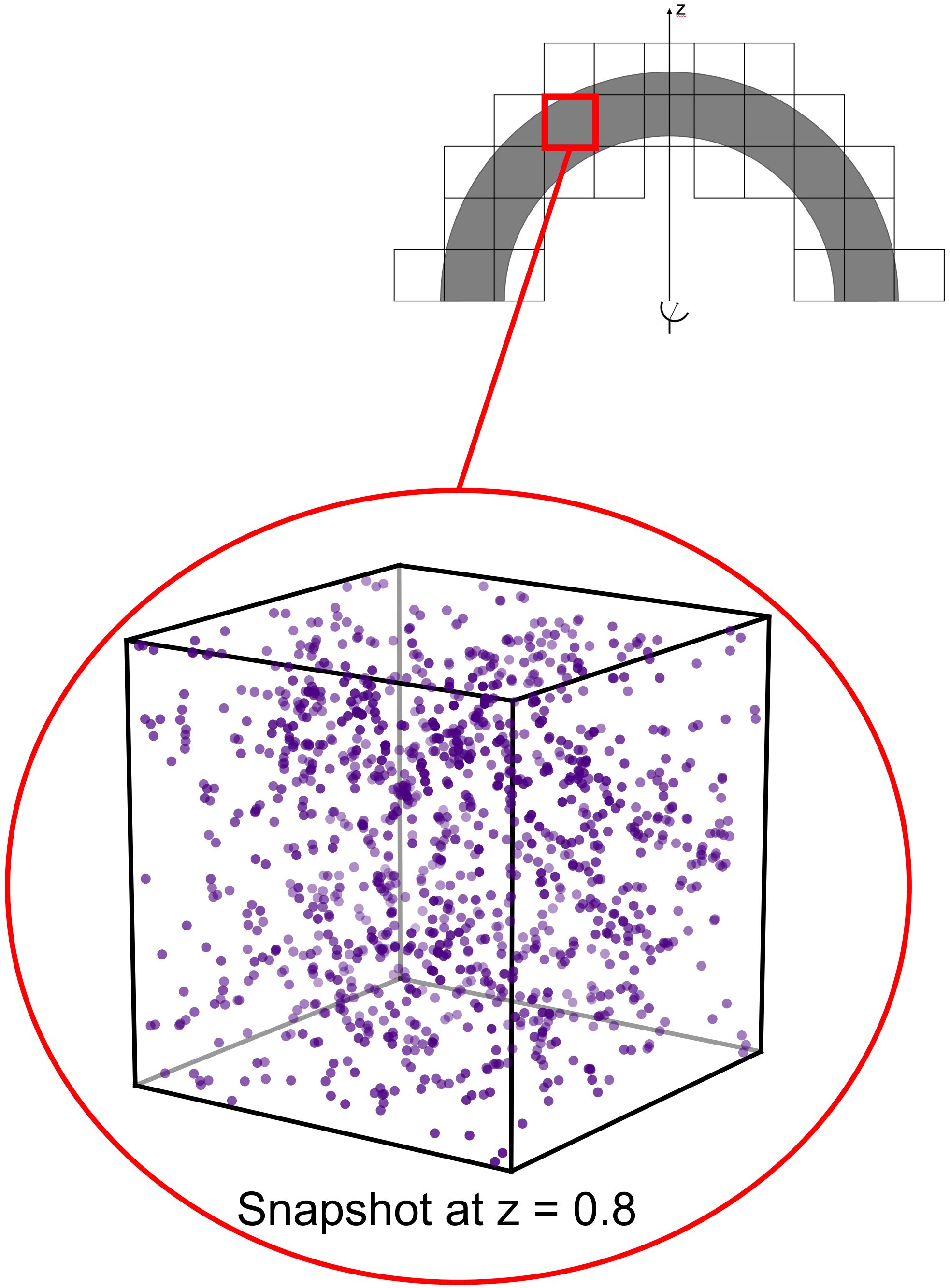
Full Expression:

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

# HI Power Spectrum

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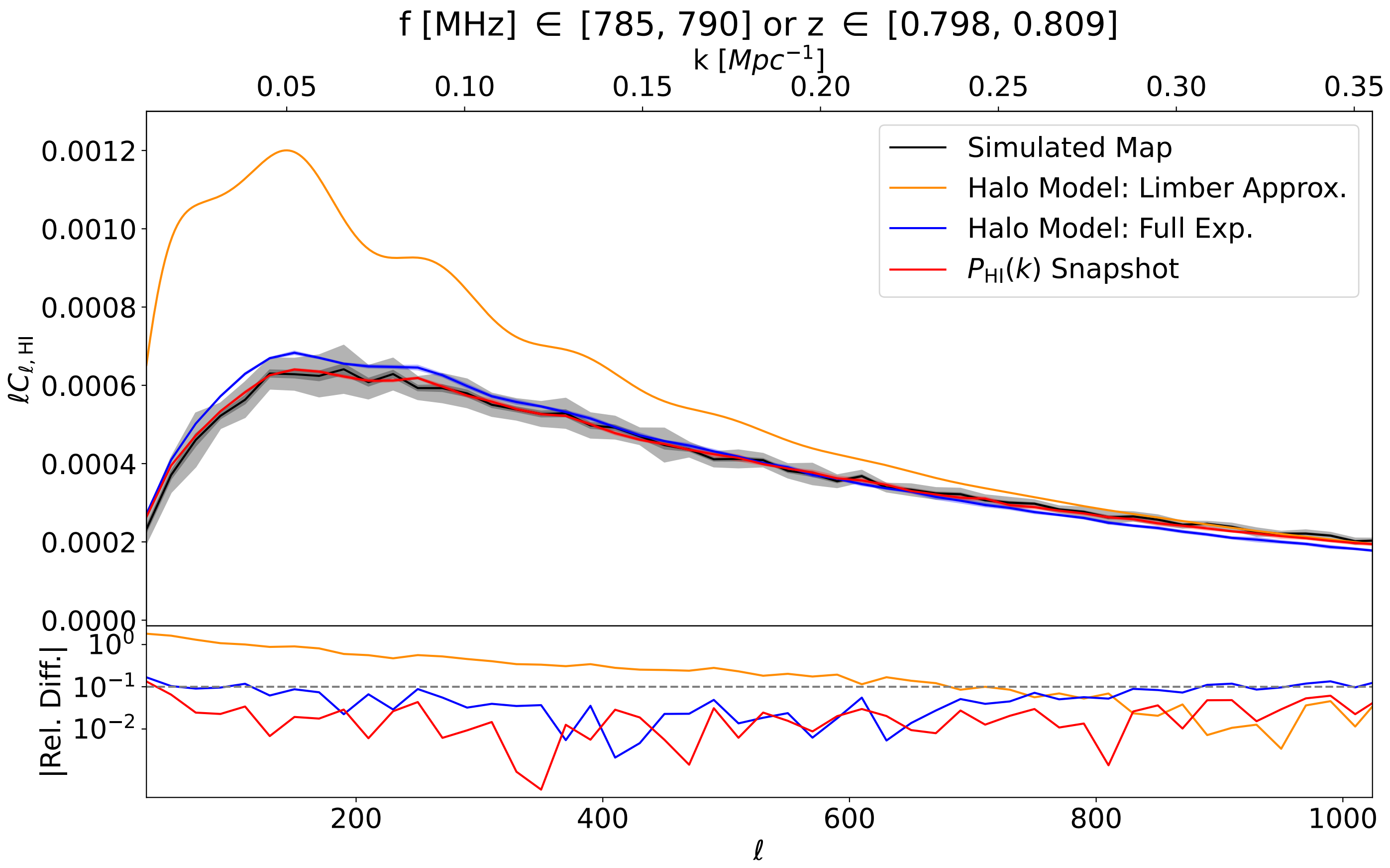
# HI Angular Power Spectrum

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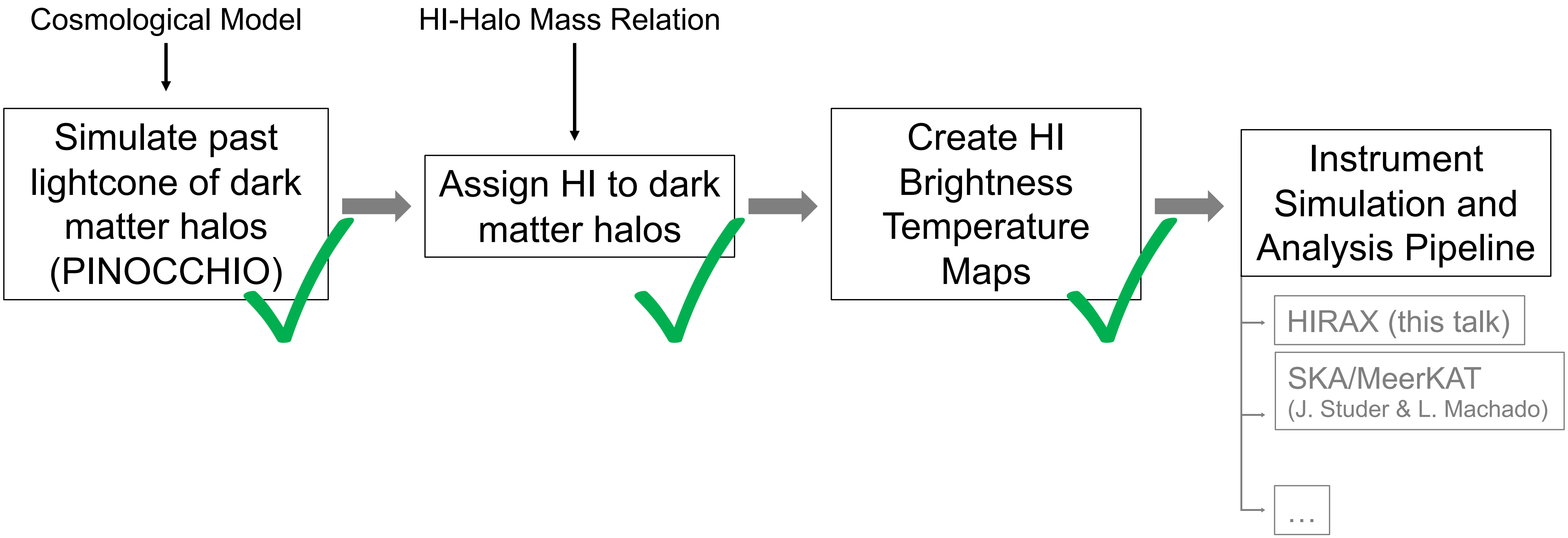
$$\times \int_0^\infty d\chi'\, W(\chi') j_\ell(k\chi')\sqrt{P_{\rm HI}(k, z(\chi'))}$$

: $P_{\rm HI}(k, z)$ from halo model

: $P_{\rm HI}(k, z)$ from snapshot

# Overview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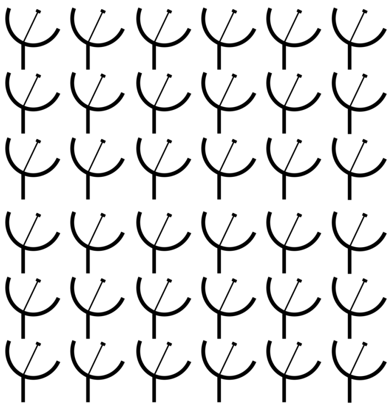
# Instrument Simulation and Analysis Pipeline

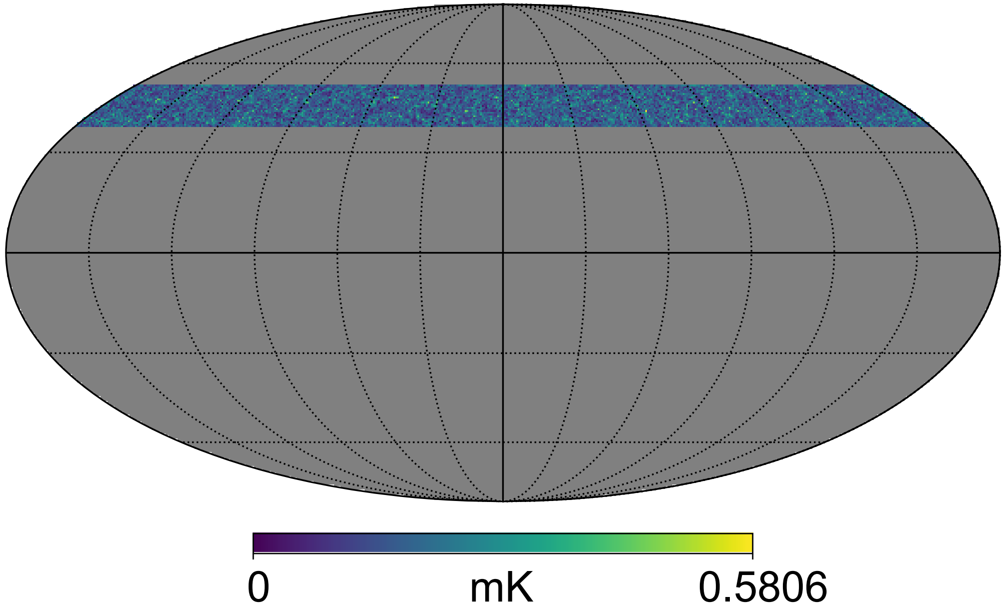


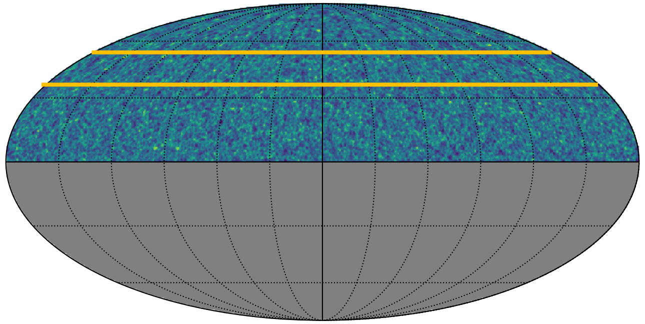
| | |
|---|---|
| Number of dishes: | 36 (6 x 6 grid) |
| Operating mode: | Drift-scan |
| Dish diameter: | 6 m |
| Dish separation: | 6 m |
| Primary Beam Type: | Gaussian |
| Telescope Latitude: | 45° |

Simplified HIRAX array configuration

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

Recovered Map

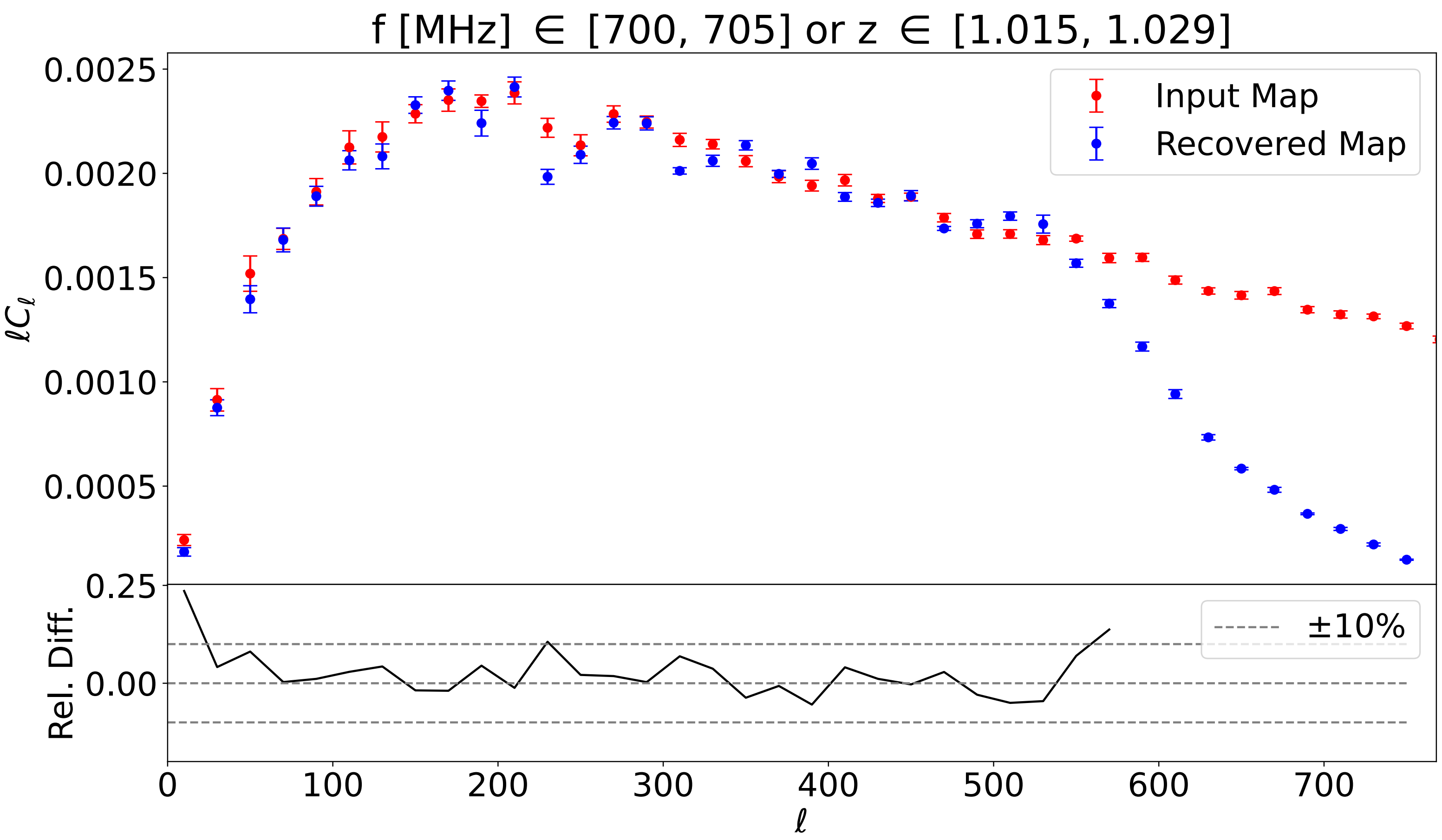


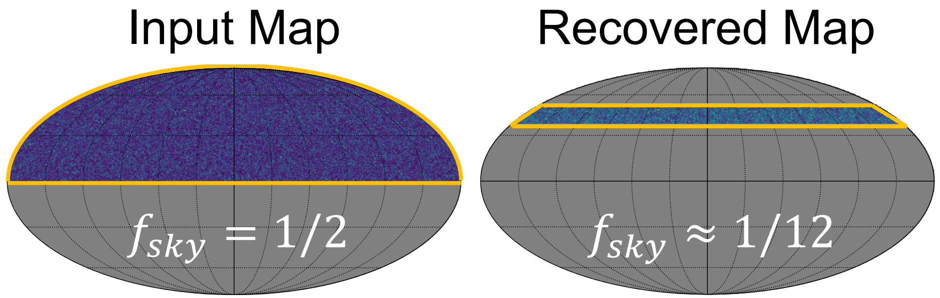



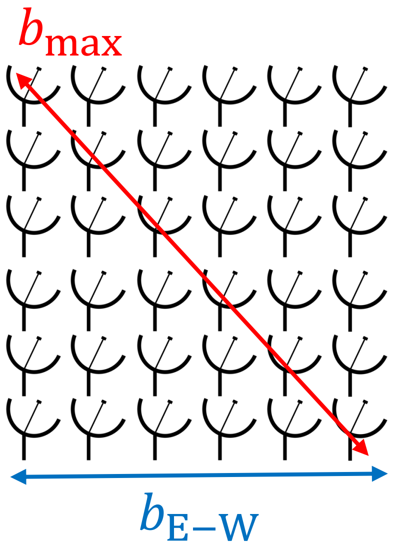
Angular Power Spectrum

Angular Power Spectrum

# Recovered HI Angular Power Spectrum




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

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

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

# Summary

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

Hitz et al. (in prep.)

# PyCosmo HI Halo Model

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

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

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

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