Fast Generation of 21cm Emission Maps for Intensity Mapping

Pascal Hitz and ETHZ Cosmology Group†
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† Alexandre Refregier, Devin Crichton, Marta Spinelli, Pascale Berner, Jennifer Studer

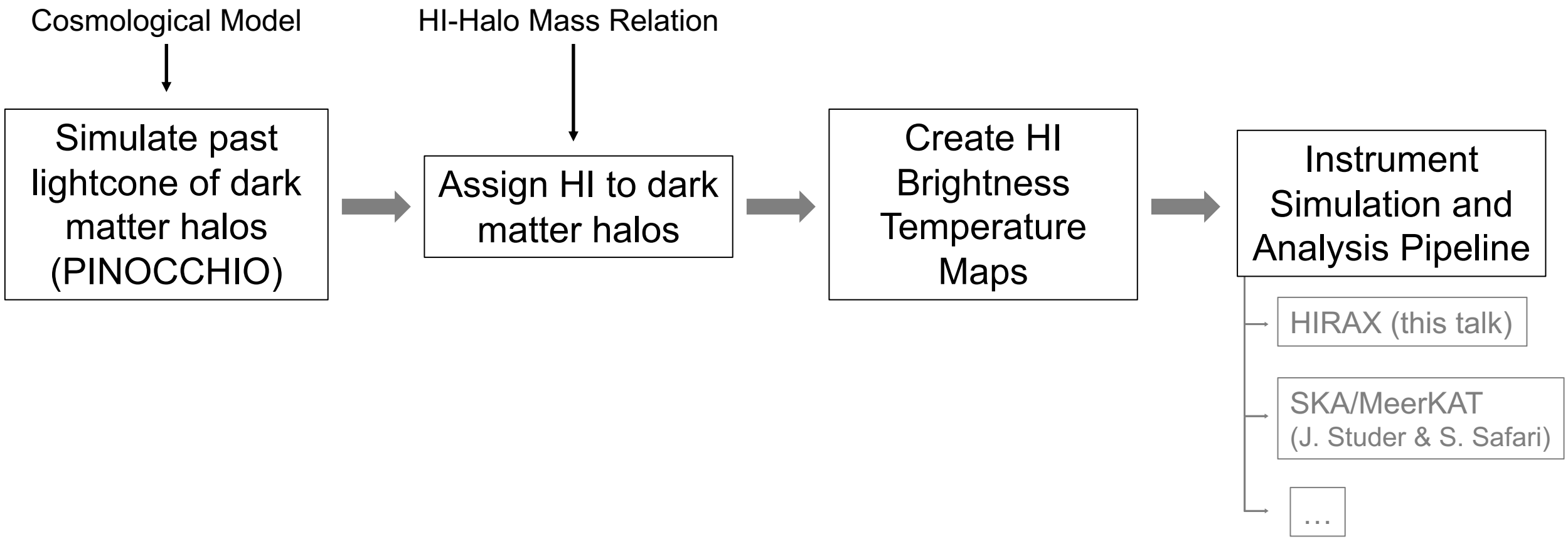
SKAO

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



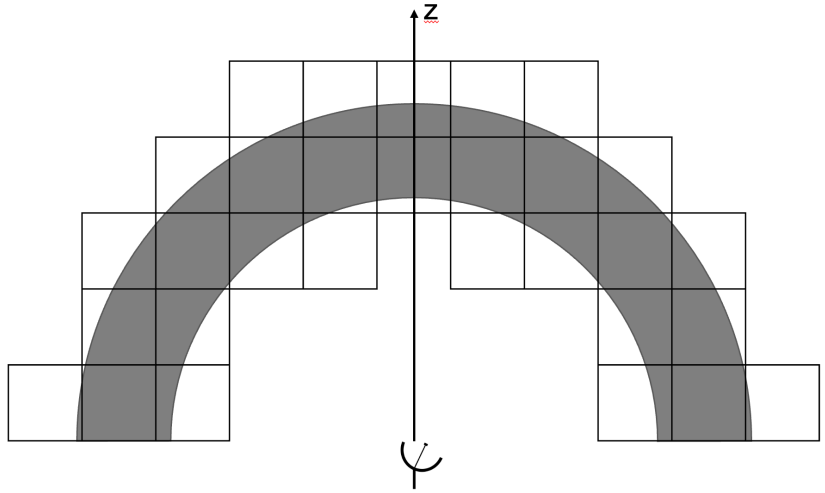
Current Setting of DM Simulations

- 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

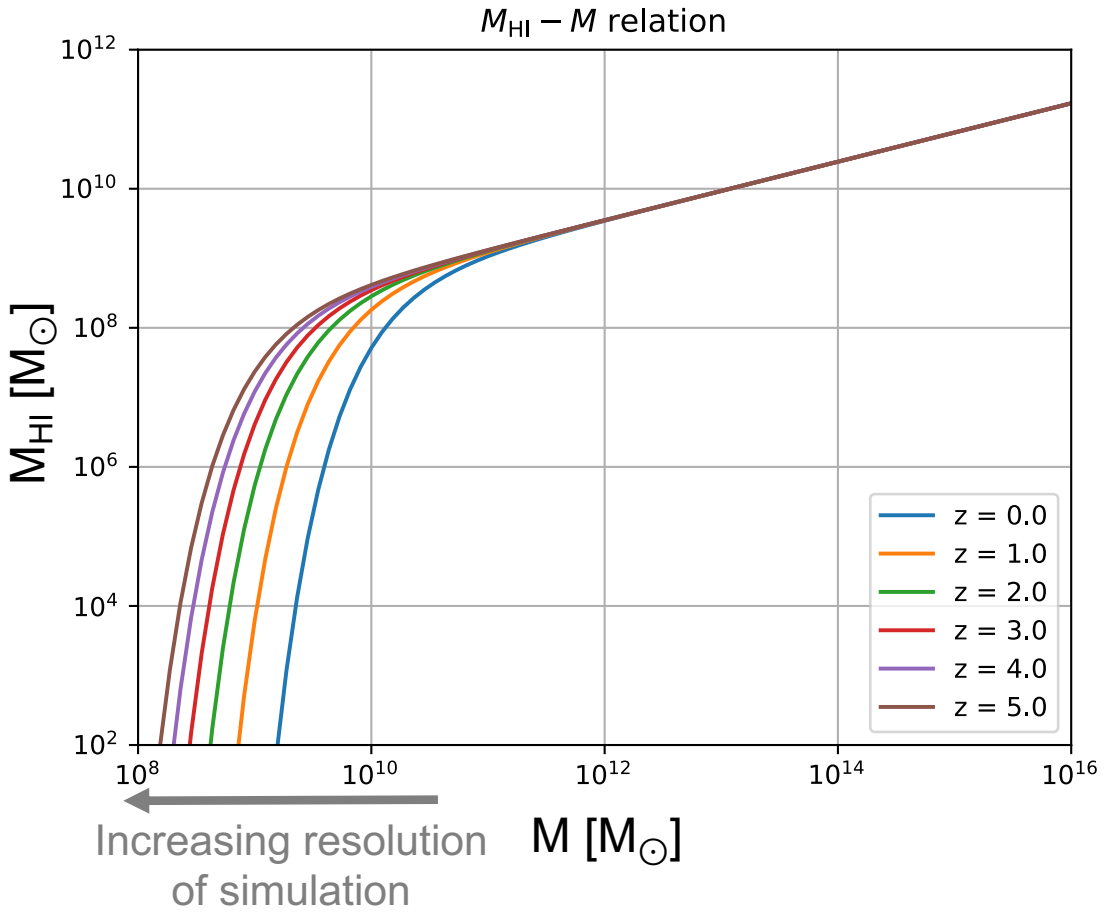


Halo Model for Cosmological HI

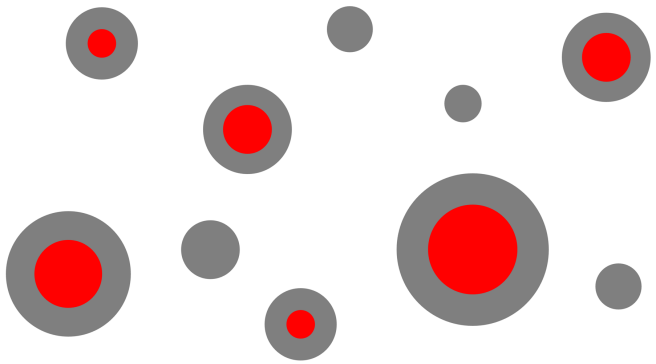
<u>HI-halo mass relation fitted to observations:</u>

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

Padmanabhan et al. 2017



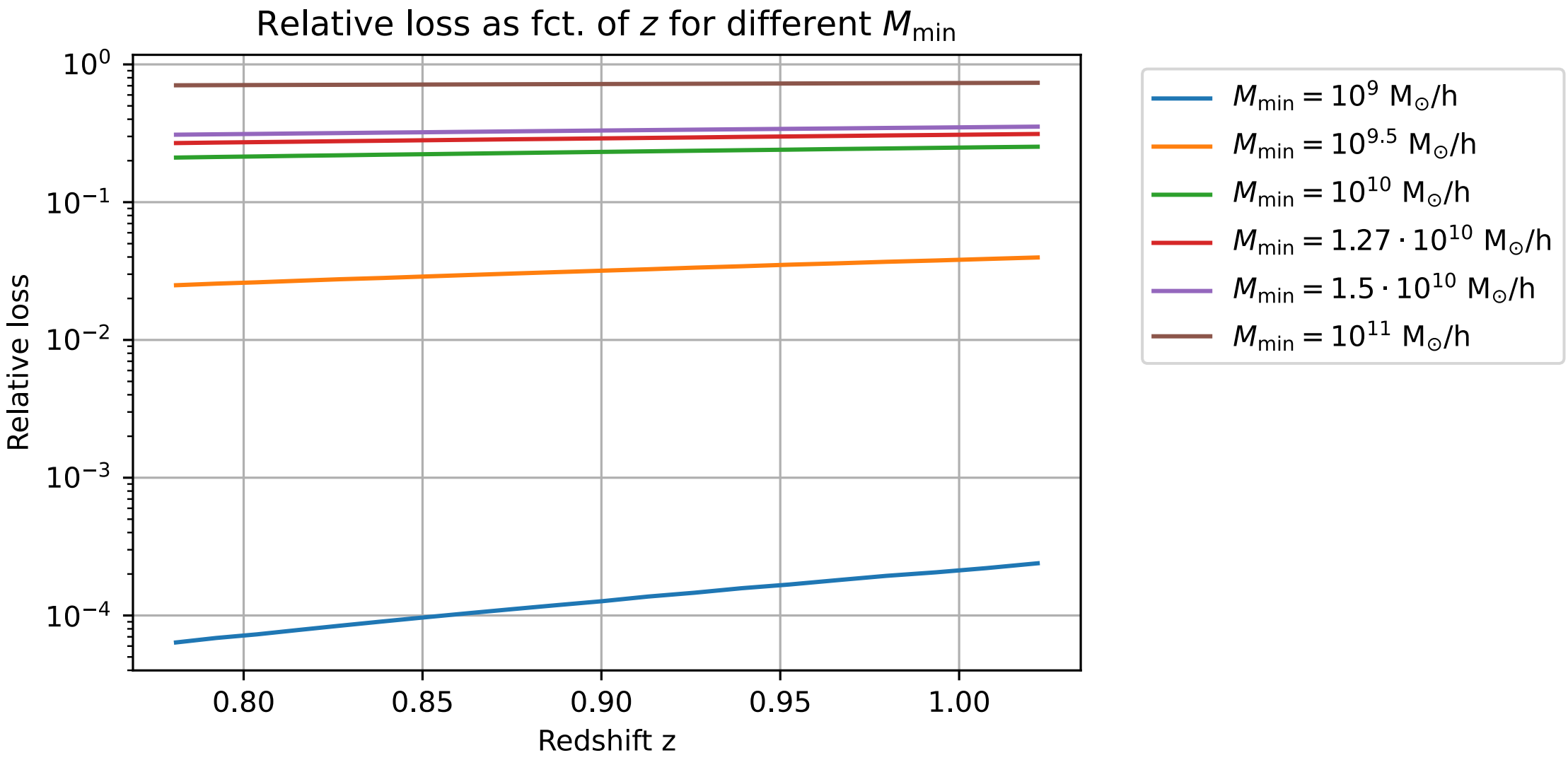
Dark Matter
Neutral Hydrogen



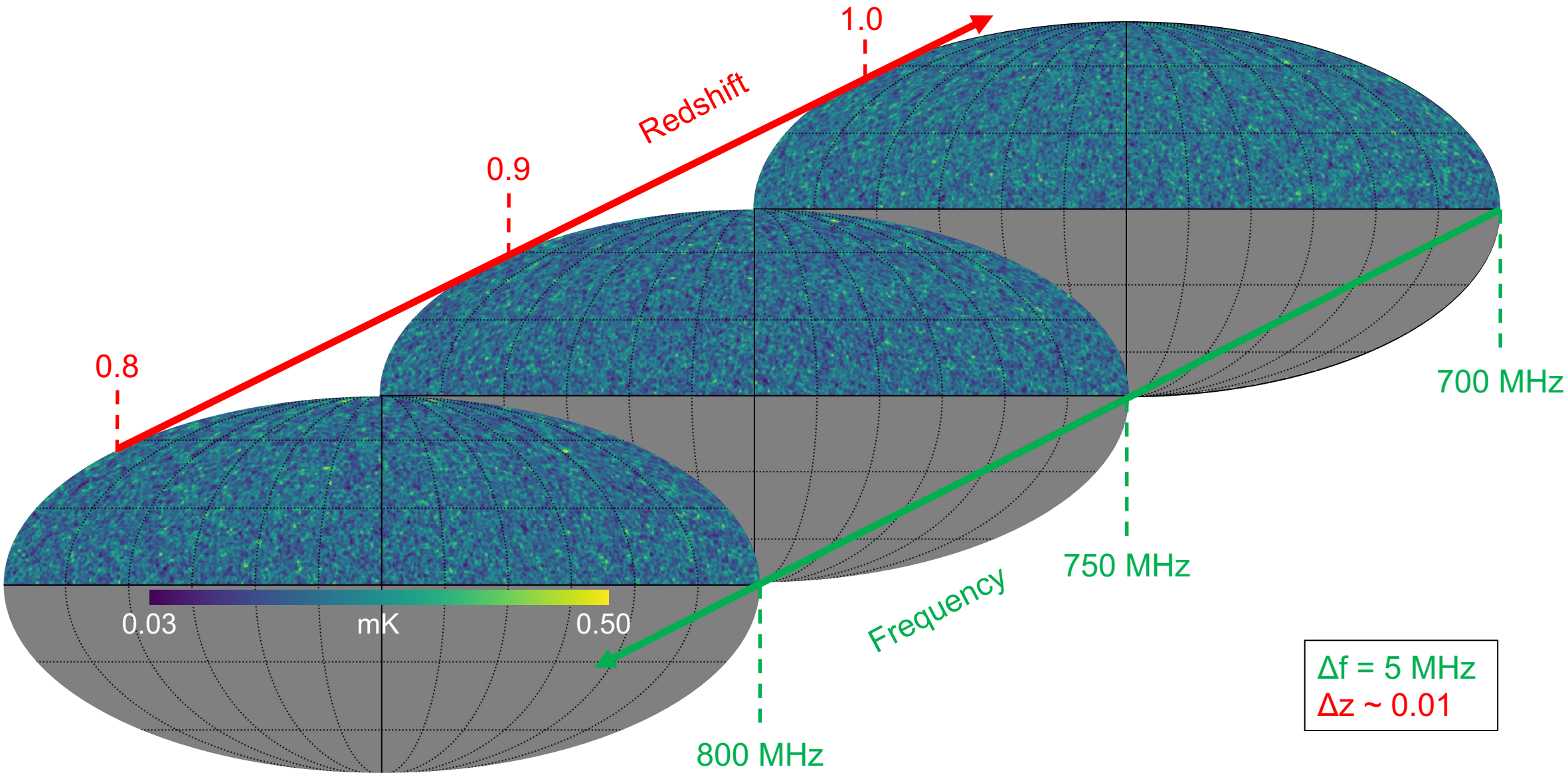
- More massive halos contain more HI
- **But:** Many more small halos than large ones

➔ Important not to neglect small halos.

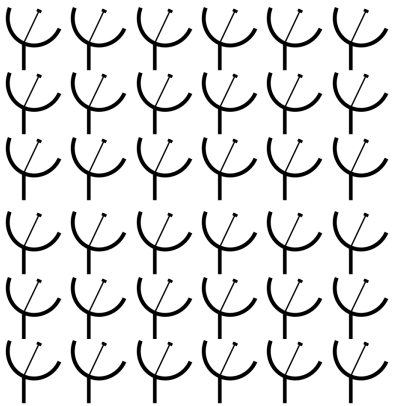
Relative Loss of Total HI Mass



Brightness Temperature Maps



Instrument Simulation and Analysis Pipeline



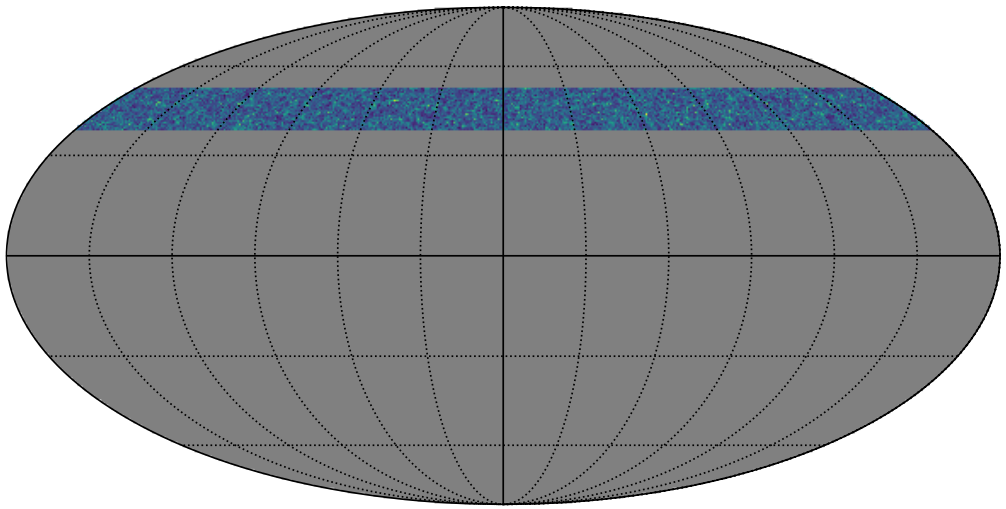
Number of dishes:	36 (6 x 6 grid)
Operating mode:	Drift-scan
Dish diameter:	6 m
Dish separation:	6 m
Primary Beam Type:	Gaussian
Telescope Latitude:	45°

Simplified HIRAX array configuration

↓ *driftscan*

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

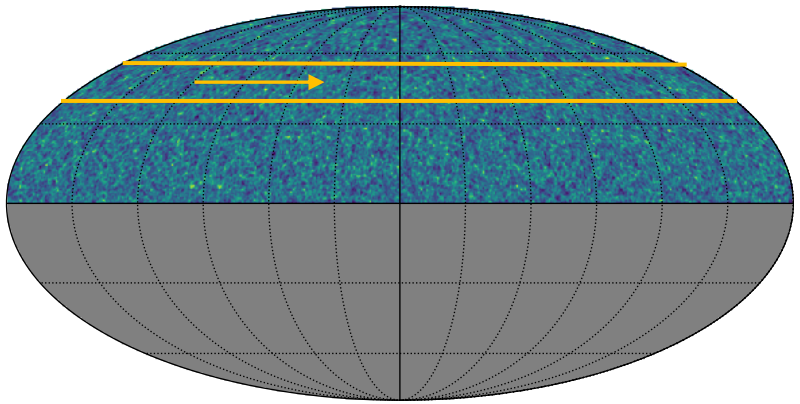
Recovered Map



0 mK 0.5806

↓

Angular Power Spectrum



→ Angular Power Spectrum

ETH zürich

Analysis Method: *m-mode* Formalism

$$V_{ij}(\varphi) = \langle F_i F_j^* \rangle = \int \left[B_{ij}^T(\hat{\boldsymbol{n}};\varphi) T(\hat{\boldsymbol{n}}) + Polarisations \right] d^2\hat{n} + n_{ij}(\varphi)$$

Spherical Harmonics Transform

$$V_{ij}(\varphi) = \sum_{l,m} [B_{ij;lm}^T(\varphi) a_{lm}^T + Polarisations] + n_{ij}(\varphi)$$

$$V_{ij;m} \equiv \int \frac{d\varphi}{2\pi} V_{ij}(\varphi) e^{-im\varphi}$$

$$V_{ij;m} = \sum_{l} [B_{ij;lm}^T a_{lm}^T + Polarisations] + n_{ij;m}$$

Vector-, Matrix-Notation

$$\boldsymbol{v} = \mathbf{B}\boldsymbol{a} + \boldsymbol{n}$$

SVD-based data compression

$$\bar{\boldsymbol{v}} = \bar{\mathbf{B}}\boldsymbol{a} + \bar{n}$$

Moore-Penrose pseudo-inverse

$$\hat{\boldsymbol{a}} = \bar{\mathbf{B}}^{+}\bar{\boldsymbol{v}}$$

Inverse Spherical Harmonic Transform

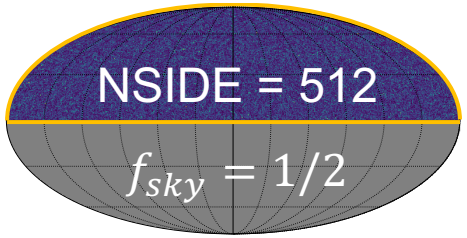
Recovered Map

T:	Brightness Temp.
B_{ij}^T:	Beam Transfer Functions
n_{ij}:	Noise

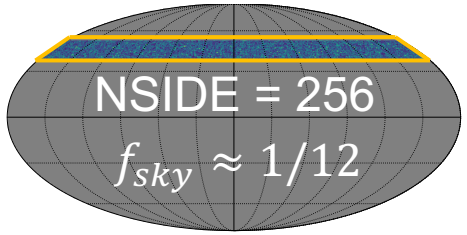
Shaw et al. 2015

HI Angular Power Spectrum

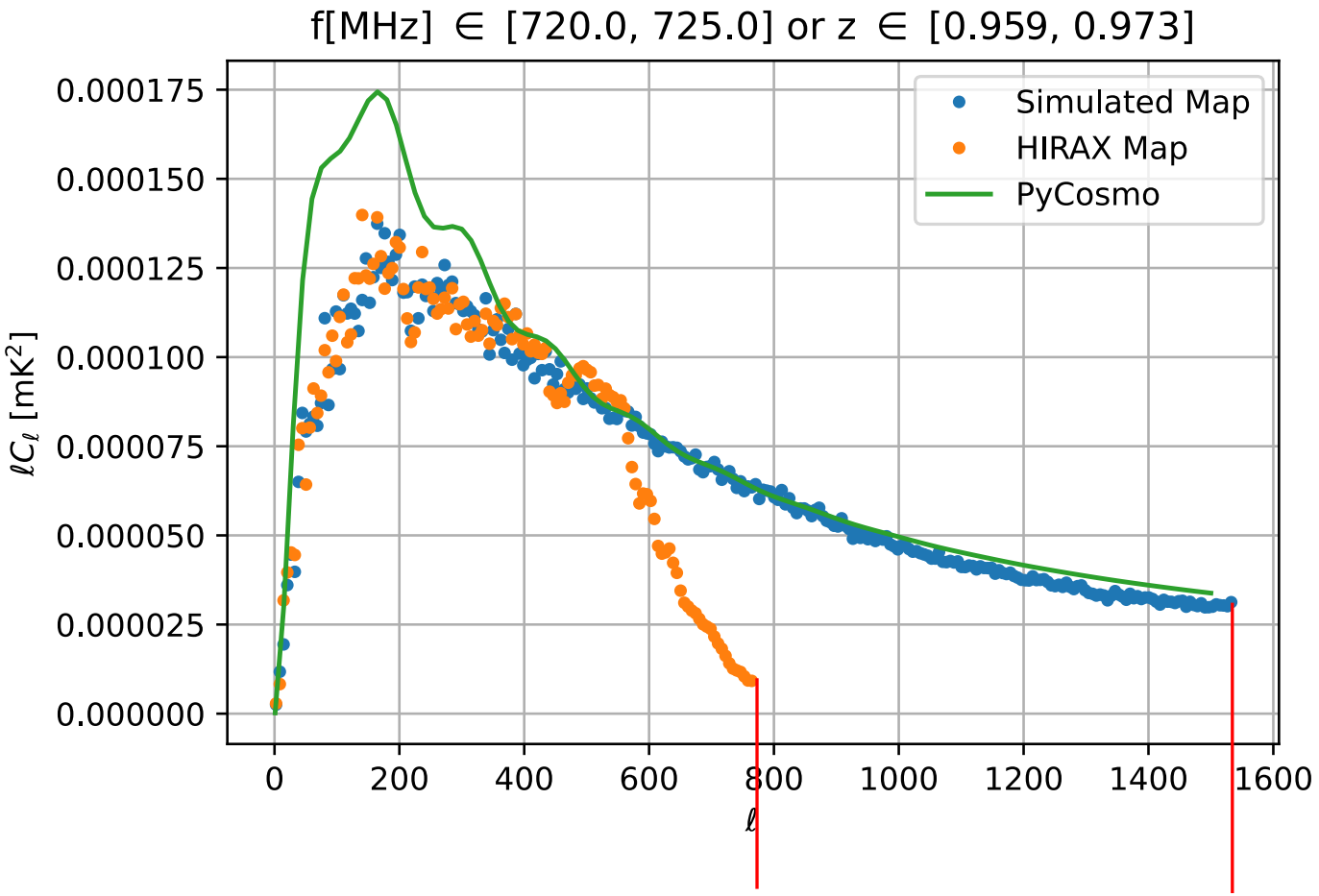
- Simulated Map

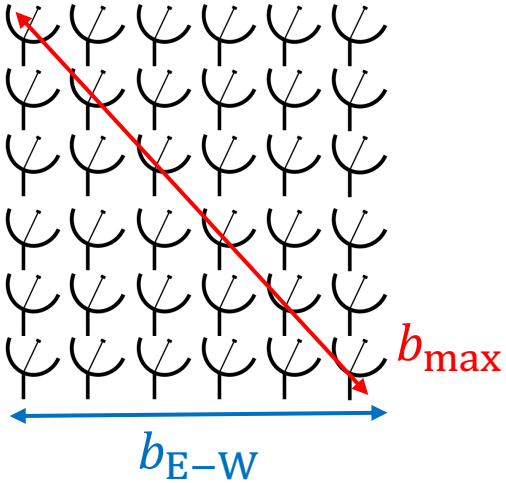


- HIRAX Map



- PyCosmo:
  Theoretical prediction
  Refregier et al. 2017





$$\ell \sim \frac{2\pi}{\lambda} b$$

$$\ell_{\max}(720\ \mathrm{MHz}) \sim 640$$

$$\ell_{\mathrm{E-W}}(720\ \mathrm{MHz}) \sim 450$$

Summary

- Simulation pipeline of HI maps for intensity mapping
- Apply it to HIRAX and SKA/MeerKAT
- Future developments:
  - Increasing resolution
  - Extend theoretical predictions
  - Vary HI-Halo mass relation
  - Consider foregrounds, noise and RSD

Hitz et al. (in prep.)