Forward Modeling of 21cm Intensity Mapping: Updates from ETHZ and FHNW

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SKACH Winter Meeting, 22/01/2024

ETH Zürich: Alexandre Refregier, Devin Crichton, John Hennig, Pascal Hitz, Jennifer Studer, Joel Mayor

FHNW: André Csillaghy, Simon Felix, Rohit Sharma, Vincenzo Timmel, Lukas Gehrig

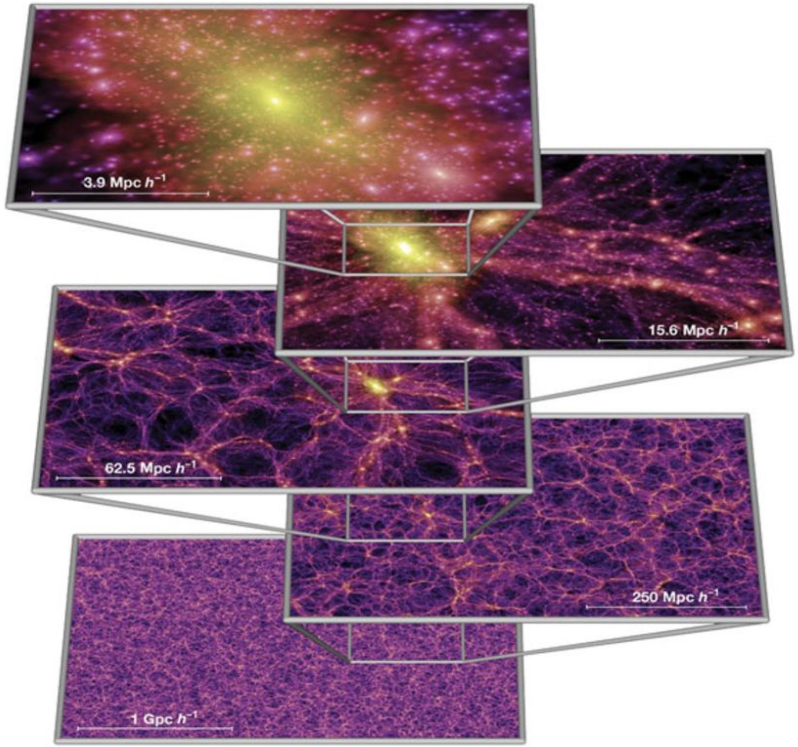
Image Credits: https://skach.org/

Motivation: Cosmology

- Era of precision Cosmology
  - CMB: Planck
  - Stage IV Surveys: DESI, LSST, PFS
- Nature of Dark Matter and Dark Energy

- Promising probe: **HI Intensity Mapping**
  - Complement spectroscopic galaxy surveys (z < 2)
  - Explore Cosmic Dawn / EoR

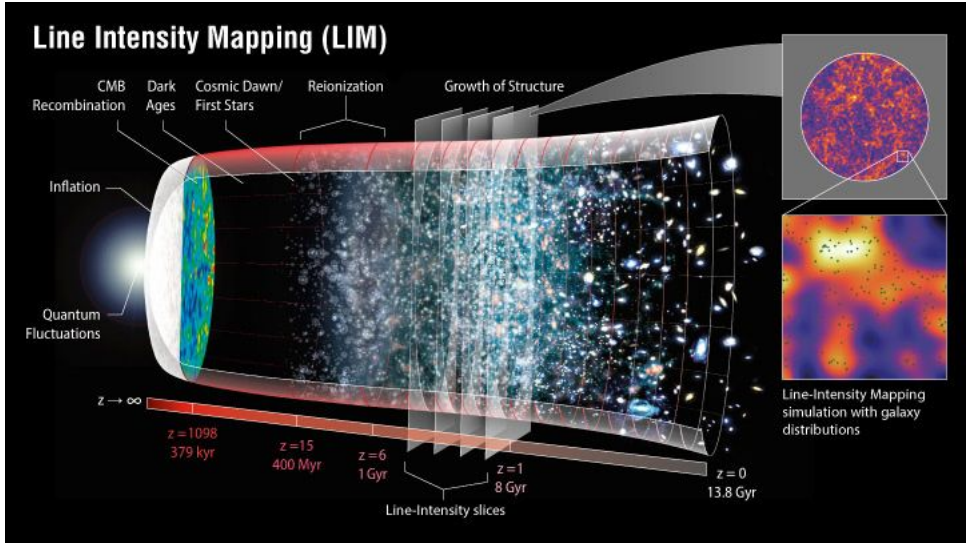
- Our focus: post-EoR IM, for **LSS**
  - SKA-Mid, HIRAX

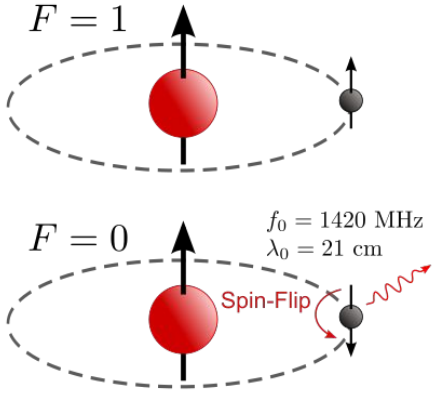


Springel+2005

Motivation: HI Intensity Mapping

- HI is a **biased tracer of DM** density fluctuations in post-EoR Universe ($z < 6$)
- HI Intensity Mapping => reconstruct DM density field
- Efficient survey: large cosmological volumes with redshift information
- High spectral (thus redshift) **resolution**

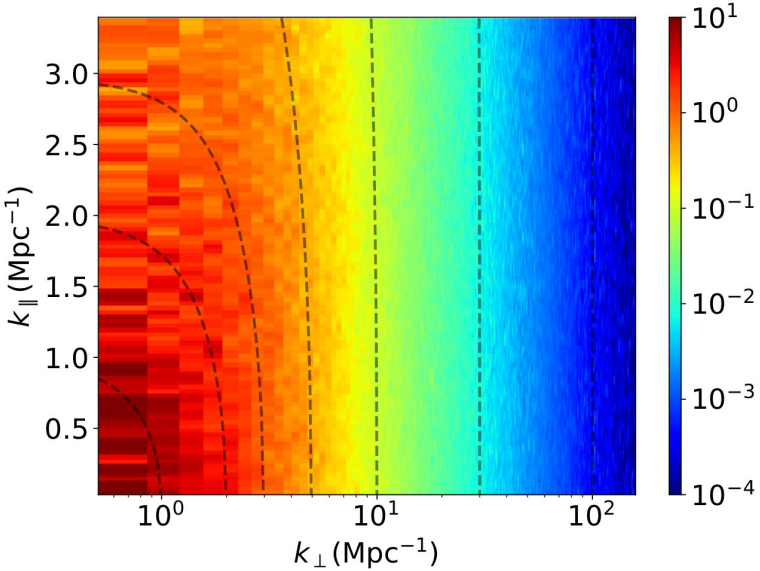


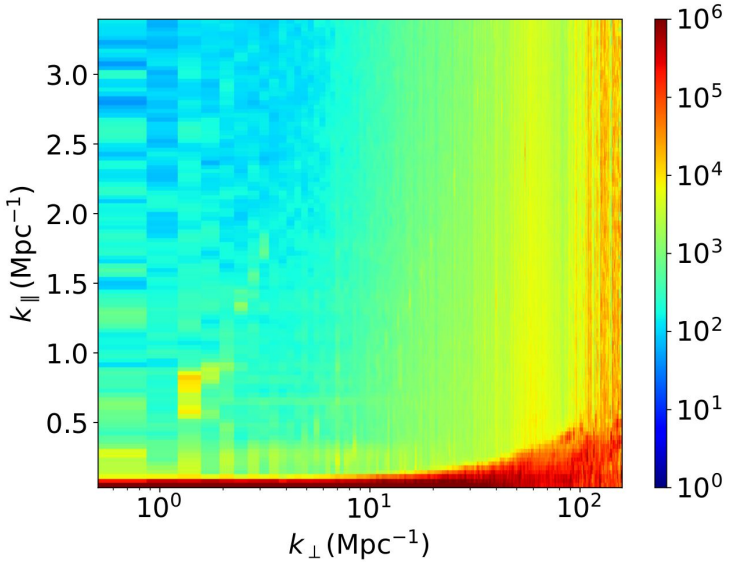


https://lambda.gsfc.nasa.gov/education/graphic_history/intensitymapping.html

https://commons.wikimedia.org/w/index.php?curid=5739956

Challenge: Systematics



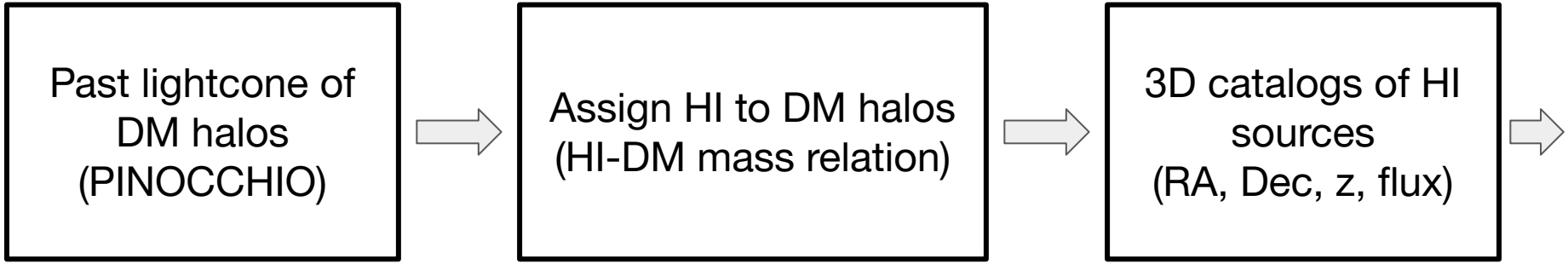


- Systematics (instrument + foregrounds) dominate 21 cm signal
- <u>Goal:</u> Forward model pipeline of HI visibilities + images

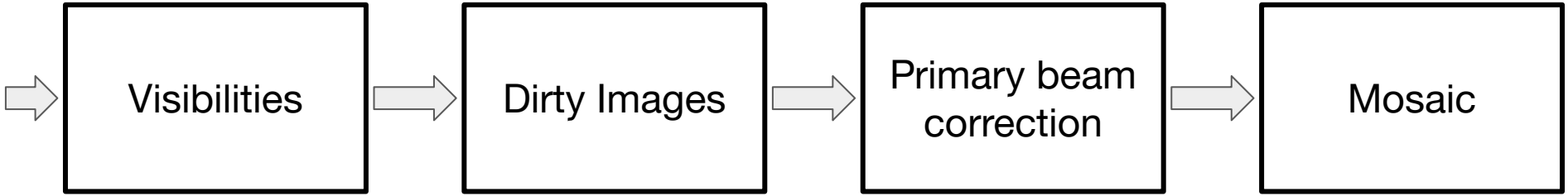
Sourabh+2021

Forward Modeling Pipeline

1) Sky Model (credit: Pascal Hitz)



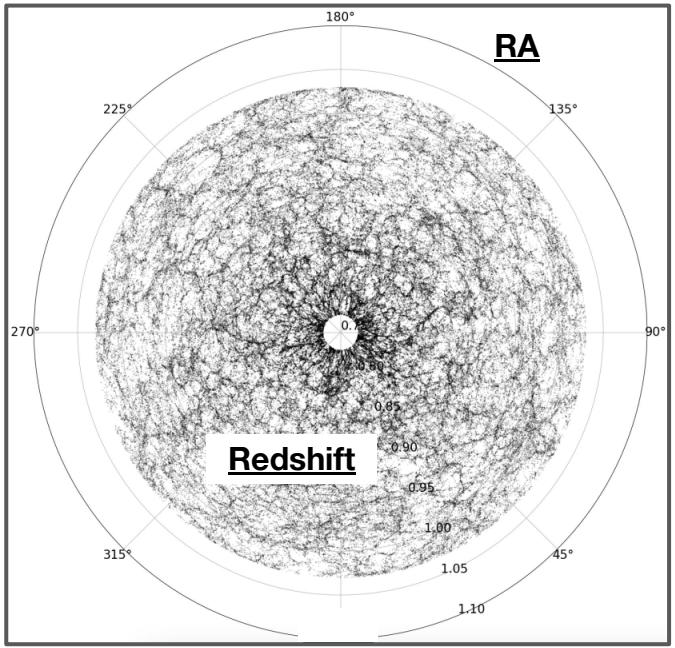
2) Instrument Simulation



Sky Model: Past Lightcone of DM Halos

PINOCCHIO: approximate DM simulation

- Lagrangian Perturbation Theory (LPT)
- Faster than NBody
- Output: past lightcone catalog of DM halos



Current configuration (Planck18 Cosmology):

- 2048^3 particles
- 500 Mpc/h boxsize
- $0.77 < z < 1.03$ (21cm: 700 - 800 MHz)
- Half-sky opening
- Halos: > 10 particles (minimal halo mass: $1.27 * 10^{10}$ Msun/h)

Currently: increasing size/resolution on Piz Daint (John Hennig)

Monaco+2002, 2013
Munari+2017

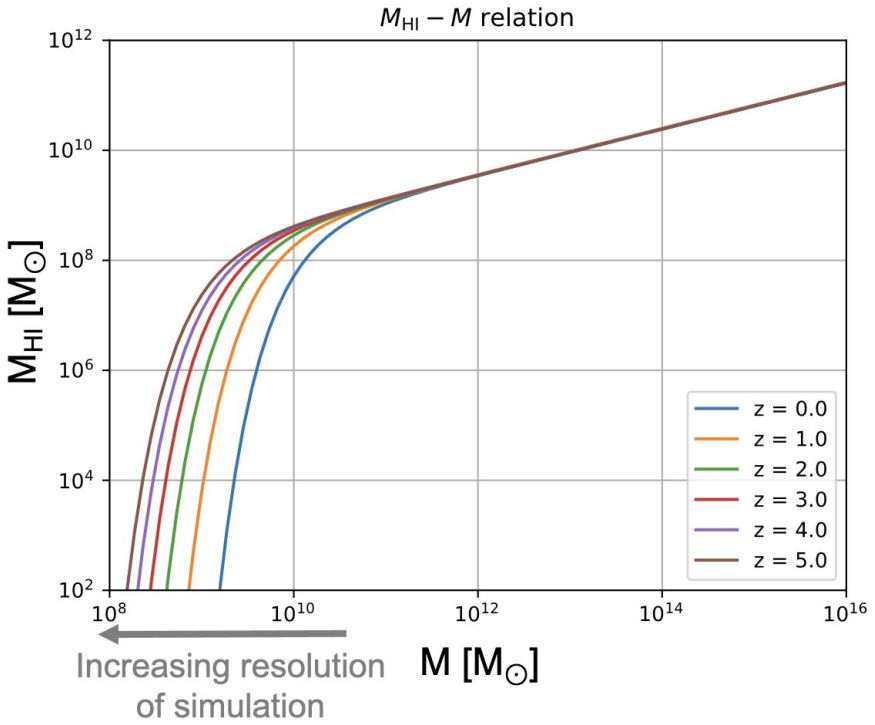
Sky Model: Painting HI with Halo Model

HI-DM Mass relation:

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

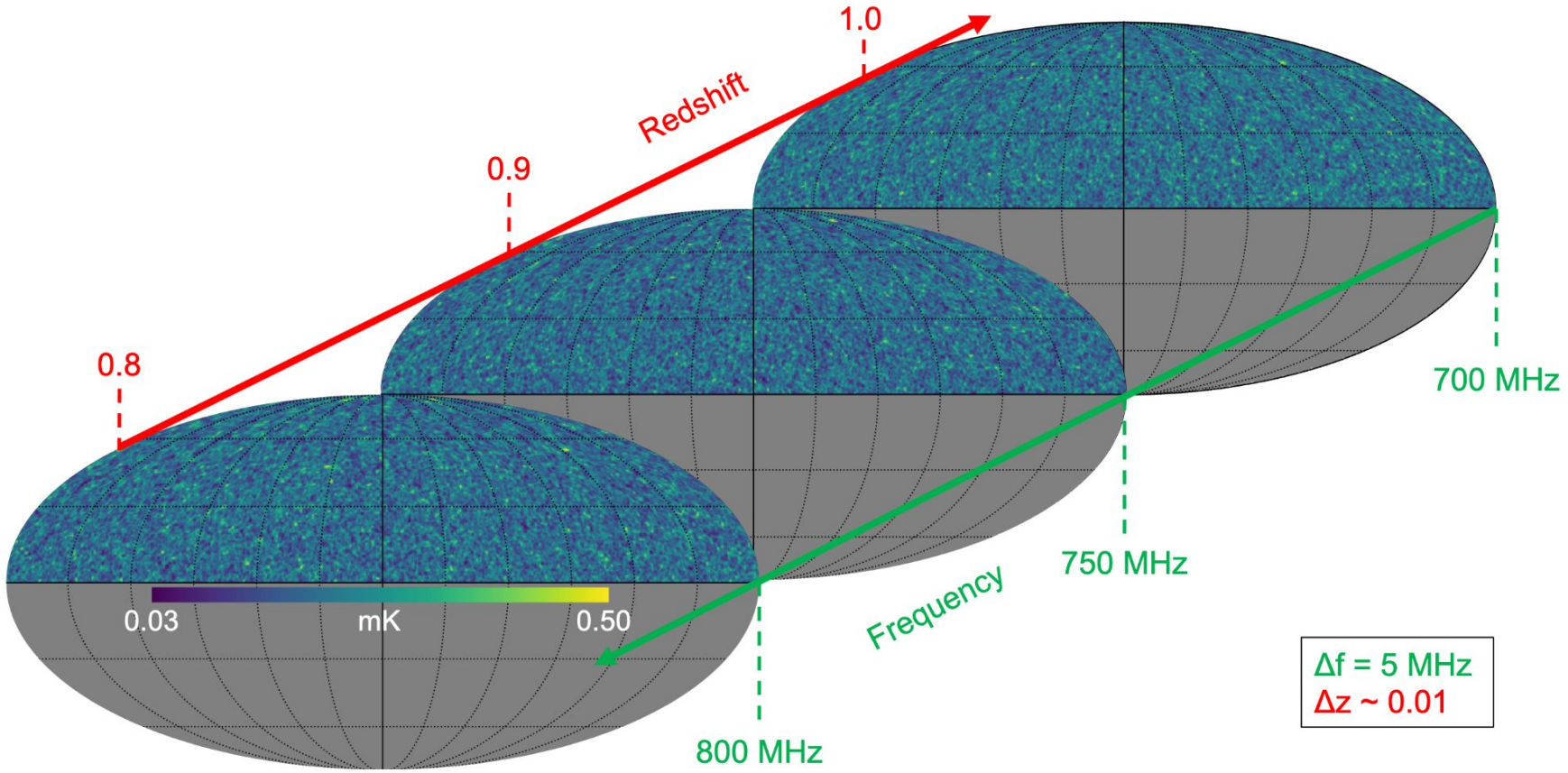
- Small halos have significant HI content
- Need **high resolution** to capture most HI mass

- Current resolution: missing ~ 15% of HI
- Goal: miss a few % of HI mass



Padmanabhan+2017

Sky Model: Resulting Catalogs



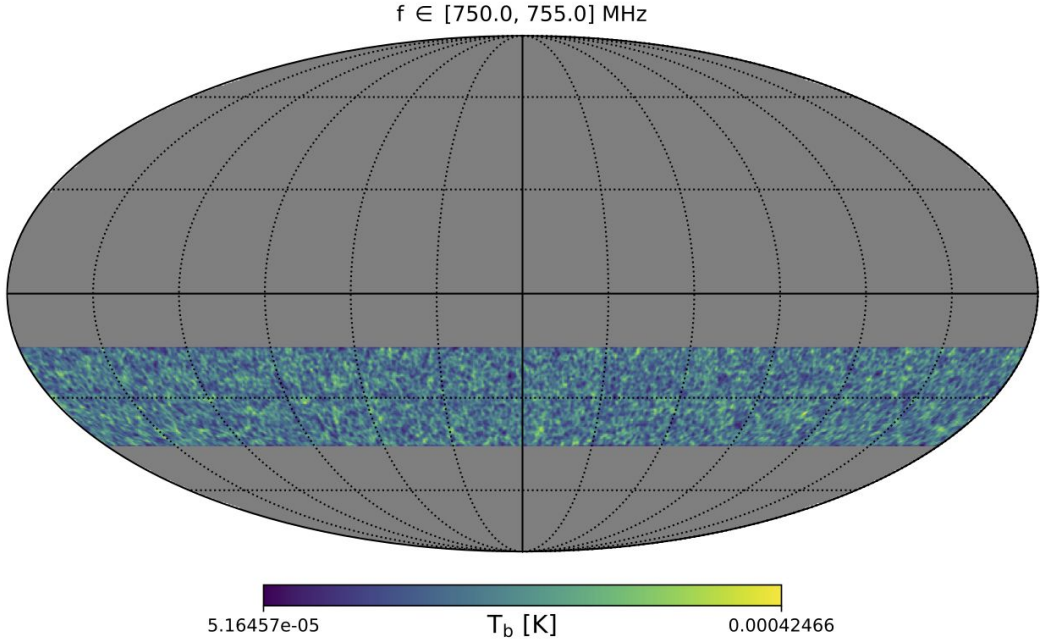
Sky Model: Recent Updates

<u>Latest run:</u>

- 1 Gpc/h boxsize, 6000^3 particles
- -15° > Declination > -45°
  - Custom code for declination stripes
  - Motivated by HIRAX observations
- Minimal halo mass: $6 * 10^9$ Msun/h
  - Missing 10% of HI mass

<u>Next planned simulation:</u>

- 1 Gpc/h boxsize, 8000^3 particles
  - Hopefully will succeed within allocated node hours



Instrument Simulation with Karabo

Power spectra

Options:
OSKAR,
RASCIL (WIP)

Input:
HI Source Catalog
(RA, Dec, z)

Interferometer

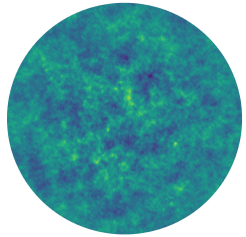
Choose telescope, frequency channels, time steps, UV distance ranges

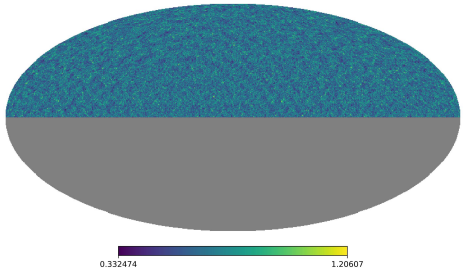
Complex Visibilities

Imager

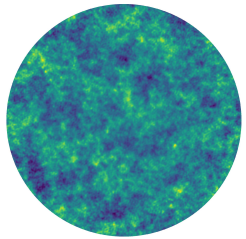
Options:
OSKAR,
RASCIL

Dirty Images, PSF



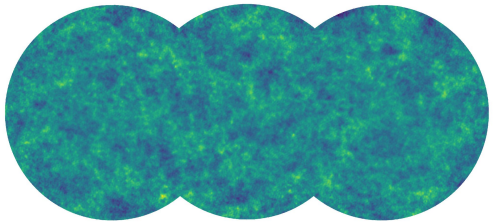


Primary
Beam
Correction



Mosaic

Mosaic of Pointings



Karabo Package (FHNW)

- Support for several workflows
  - Catalog loading + filtering, interferometry, imaging, mosaicking, source detection…
- User-friendly abstraction layer on top of OSKAR, RASCIL, Bluebild, PyBDSF
- Dask support for HPC via dask-mpi and dask-distributed

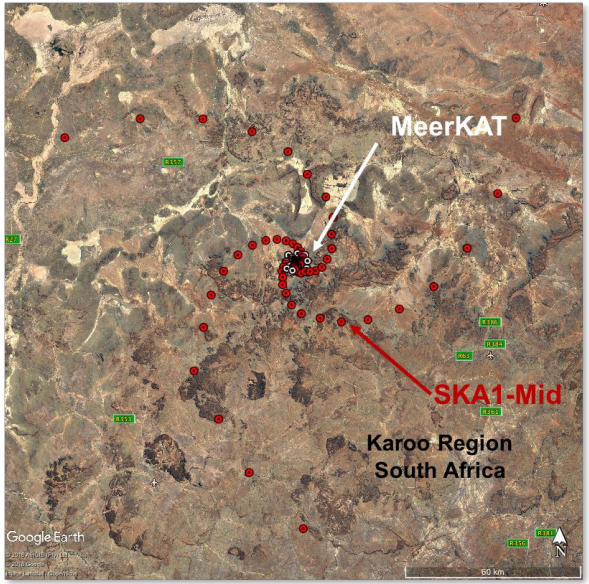
<u>Current efforts:</u>

- Include RASCIL as interferometry simulator
- Improve Dask support

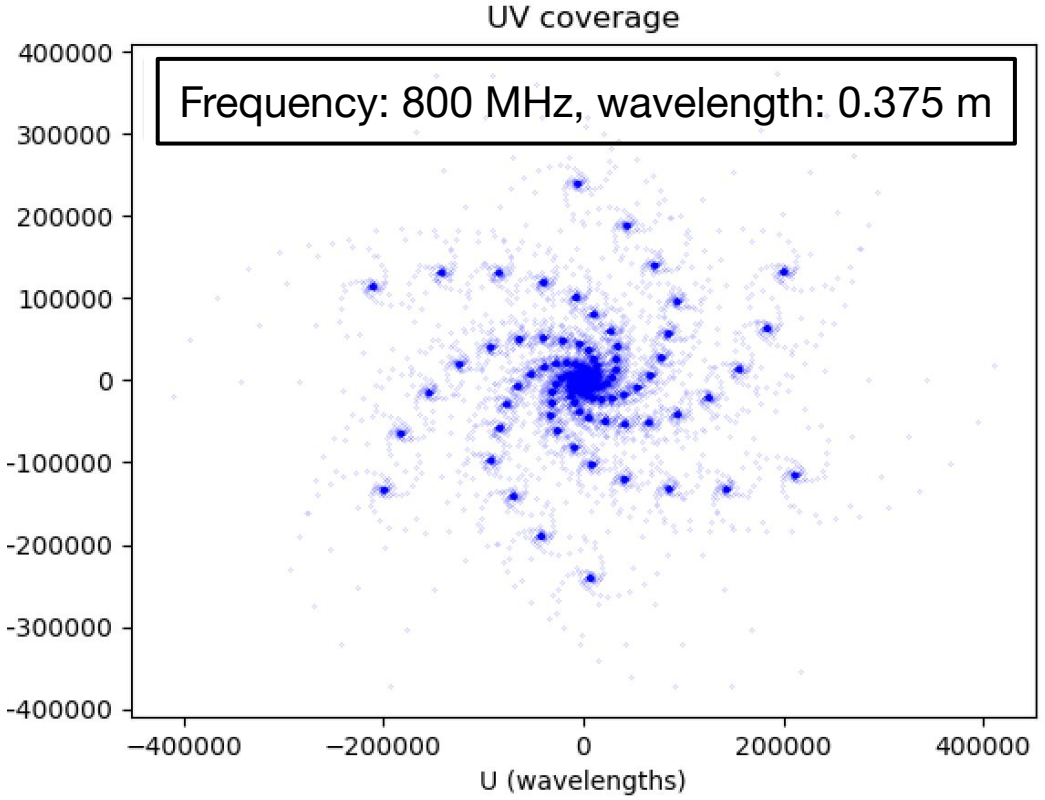
Check out the code: https://github.com/i4Ds/Karabo-Pipeline

Telescope Configuration: SKA-Mid

- Core: 50% of dishes within 2km radius
- 3 arms out to ~150 km

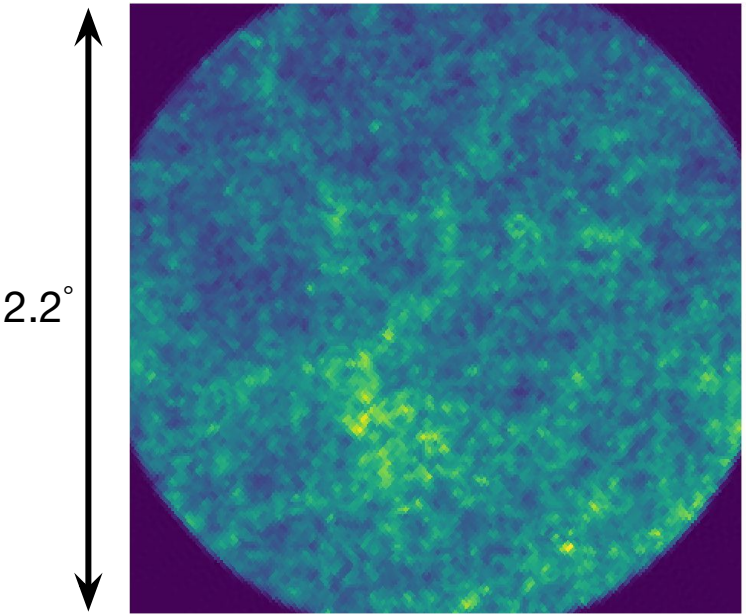


Credit: SKAO Website



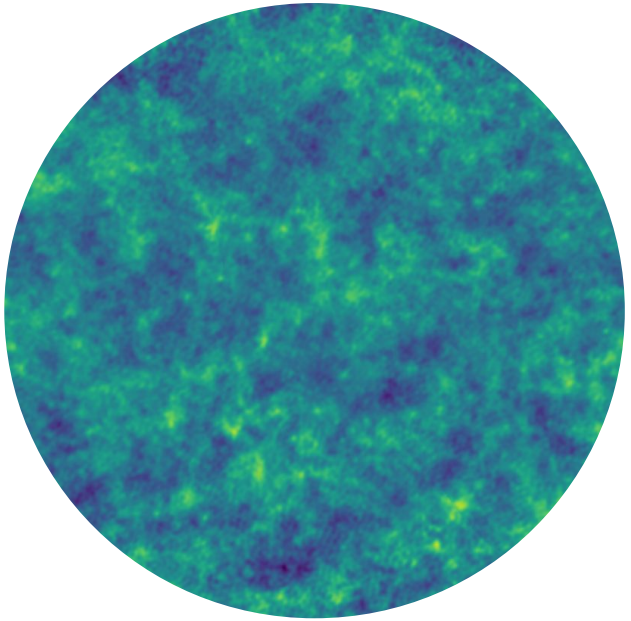
Example: from Sky to Dirty Image

Input Sky Model, projected
(HEALPix flux map with NSIDE = 4096)



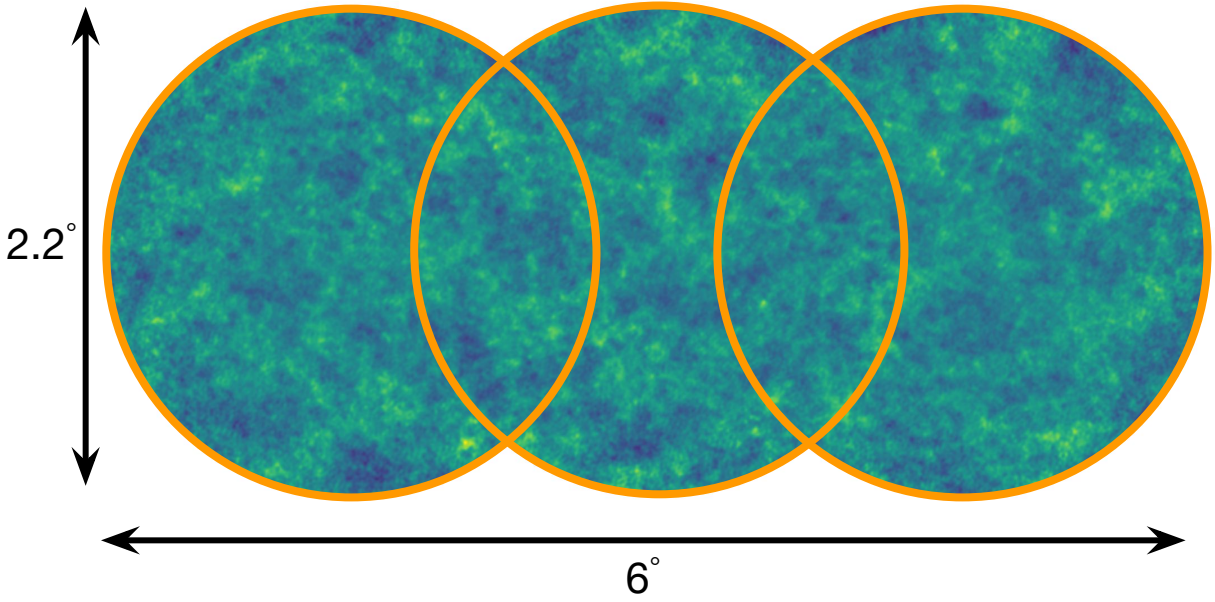
Pointing Centered at RA,
Dec = 20°, -30°

Dirty Image, projected, after
primary beam correction



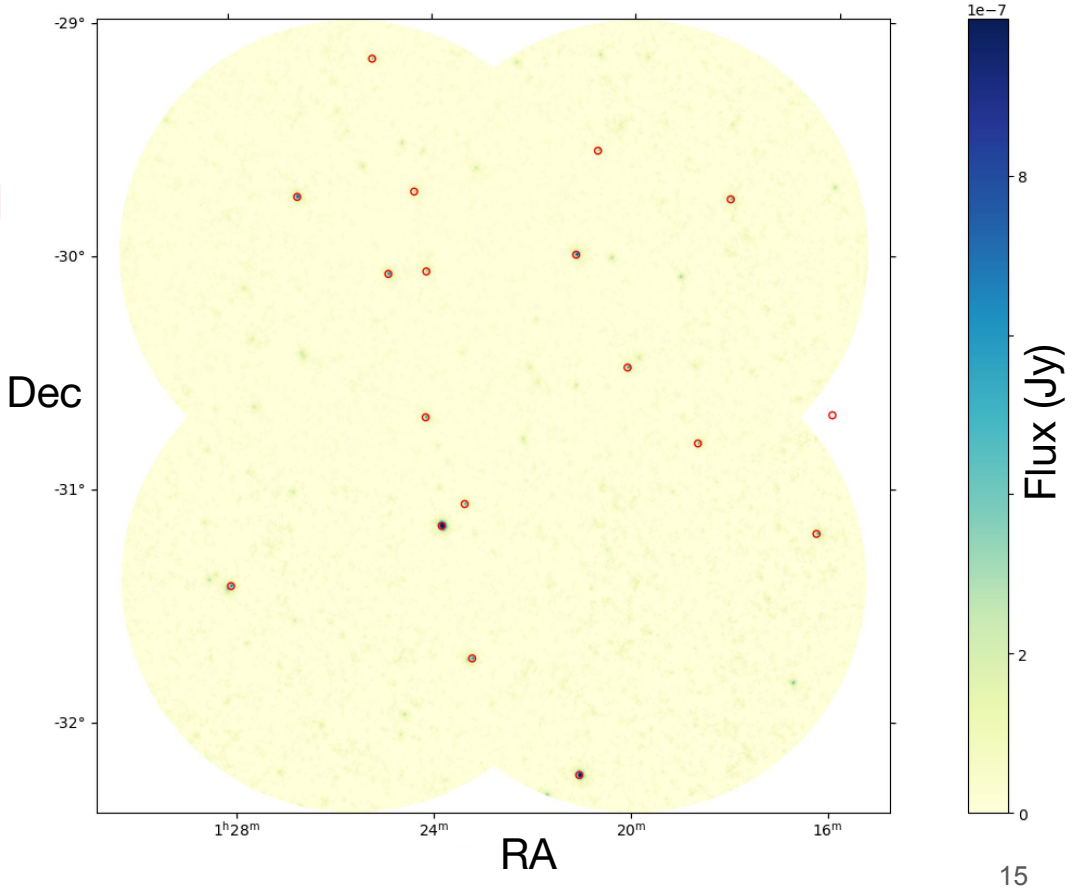
Results: Pointing Mosaics

- FWHM of Primary Beam at mid frequency: 1.8°
- Summed over 20 frequency channels (700 - 800 MHz, bandwidth = 5 MHz)



Results: Pointing Mosaics

- 4 pointings, each diameter = 1°
- Bright input sources marked in **red**
- Reproducible using OSKAR or RASCIL as backends
- Currently: parallelization of visibility calculation and imaging



HIRAX: Hydrogen Intensity and Real-time Analysis eXperiment

- Interferometric array up to 1024 6m dishes operating at 400-800 MHz
- Scalable array built in stages: 2 (qualification), 8, 128, 256 (funded) then expand to 1024 and operate full array for 4 years
- SARAO Karoo site co-located with SKAO in South Africa
- Dishes stationary and tiltable
- 15,000 deg2 Neutral Hydrogen survey with redshifts between 0.8 and 2.5

HIRAX Updates

High precision metrology

- Laser tracker
- Photogrammetry
- Radio reflectometer

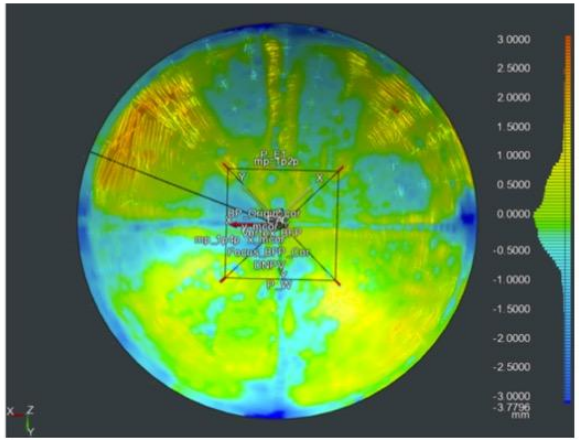



Fig 2.

Fig 3.


Fig 4.


Fig 5.

Outlook

Current

- Simulate higher resolution catalogs
- Integrate RASCIL interferometer simulation into Karabo
- Optimize interferometry and imaging code with Dask

Future

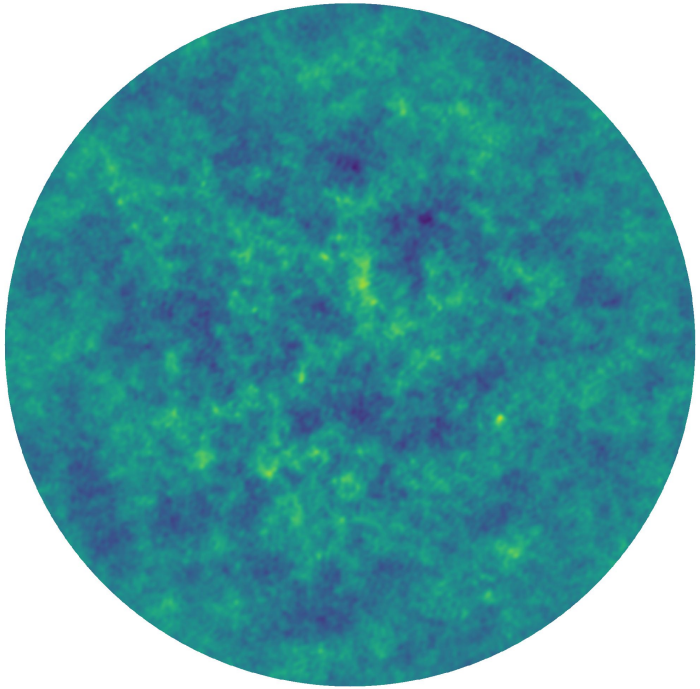
- Include extended sources + foregrounds
- Self-consistent cross-correlation studies (spectroscopic galaxy surveys)
- Include deconvolution (e.g., WS-CLEAN) into pipeline

Reach out if you are interested!

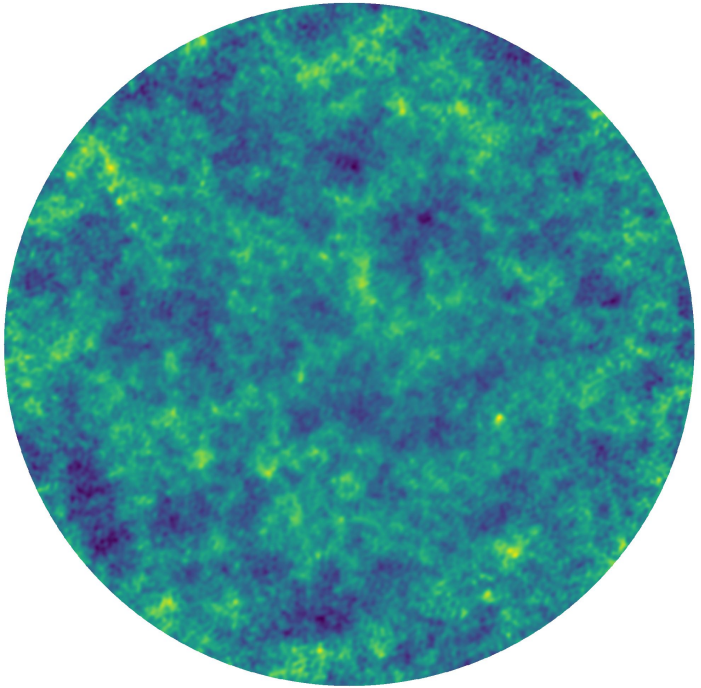
Backup Slides

Primary Beam Correction

Final Dirty Image, without primary beam correction



Final Dirty Image, with primary beam correction



Tomography: z slices in HI maps