Cosmology with the Square Kilometre Array

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Part Three

Simulate the signal - Understand the telescope

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Acknowledgments & References

The content of these slides is inspired by various lectures given by different experts in SKA Cosmology.
I would like to thank for letting me steal here and there:

Phil Bull (QMUL), Stefano Camera (UniTo), Alkistis Pourtsidou (Edinburgh), Laura Wolz (UNIMAN)

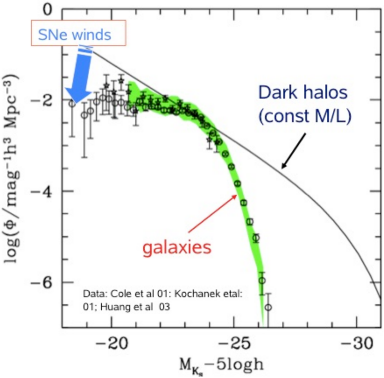
SKA specific material can be found at: `https://www.skatelescope.org` or `https://www.skaobservatory.org/`.

See also: Advancing Astrophysics with the Square Kilometre Array, `https://pos.sissa.it/215/`

Not only Dark Matter

- dark matter halo mass function converted into a luminosity function assuming a fixed mass-to-light ratio
- compare with a measured luminosity function
- this over-predict the number of both faint and luminous galaxies

Feedback processes are fundamental for baryons:
SN feedback and AGN feedback

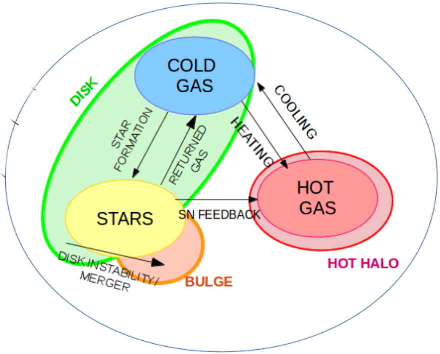


Benson et al. (2003)

Adding Baryons (over-simplified version)

Galaxy evolution: complex interplay of physical processes on wide range of scales and times with cold gas crucial piece of the puzzle

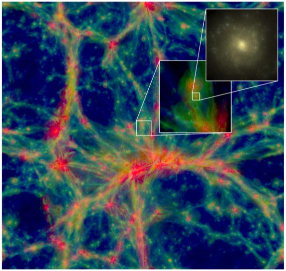
- potential wells of collapsing structures ⇒ trapped gas is heated
- cooling and accretion onto the central regions
- cold gas main components: atomic and molecular hydrogen, HI and H2
- H2 ⇒ stars ⇒ SN feedback
- the presence of AGN slows down gas accretion (AGN feedback)



Courtesy of A. Zoldan

Hydro vs semi-analytical

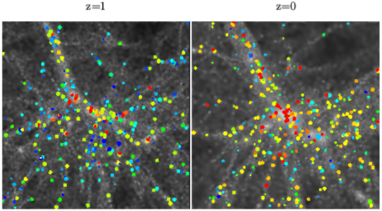
EAGLE simulation



Hydrodynamic simulations:

- explicit gas hydrodynamics;
- follow particle distribution;
- sub-grid physics;
- computationally demanding (small cosmological volumes).

Coldberg & Diaferio

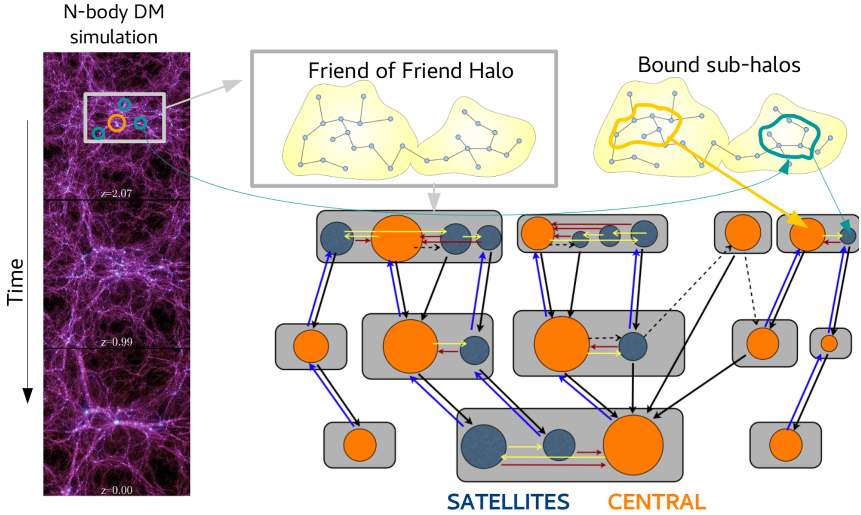


Semi-analytic models:

- do not follow the particle dynamics;
- same sub-grid physics;
- fast computation (large cosmological volumes).

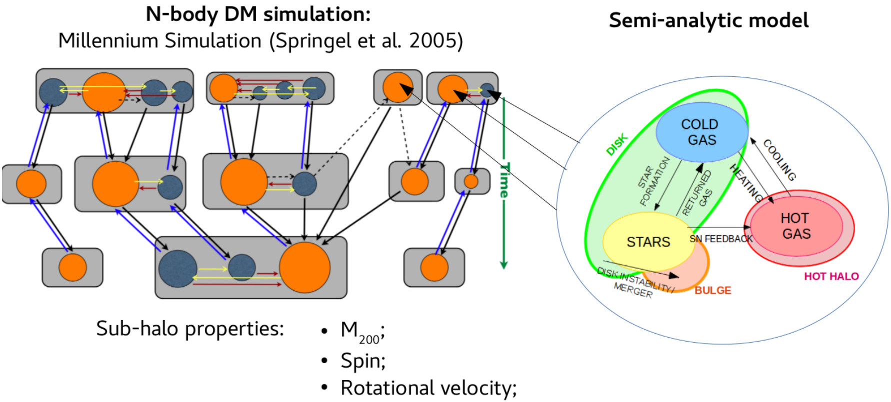
courtesy of A.Zoldan

An example from SAMs



credit: A.Zoldan

An example from SAMs



credit: A. Zoldan

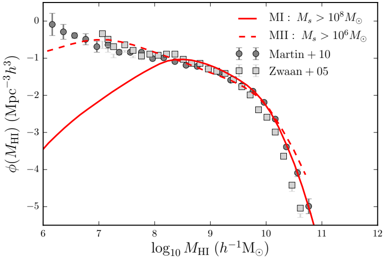
The GAlaxy Evolution and Assembly (GAEA)

- both on Millennium I and II
  more "cosmological" *vs.*
  better resolution
  (500 h^{-1} Mpc, 100 h^{-1} Mpc)

- explicit treatment of cold gas partition in atomic (HI) and molecular (H2)
  (Xie et al. 2017)

- Tested and upgraded during the years: e.g. De Lucia &. Blaizot 2007, De Lucia et al. 2014, Hirschmann et al. 2016, Xie et al. 2017, Zoldan et al. 2017

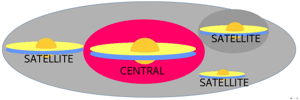
SF efficiency tuned to match the HI mass function at $z = 0$



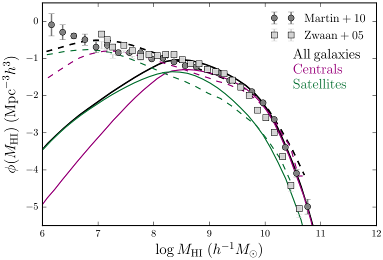
Role of centrals and satellites

Centrals dominate from intermediate to high HI masses

Satellites dominate for low HI masses



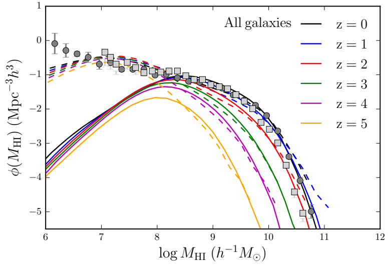
— MI – – MII

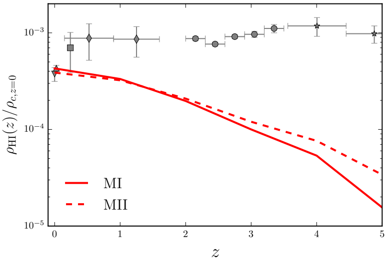


Redshift evolution

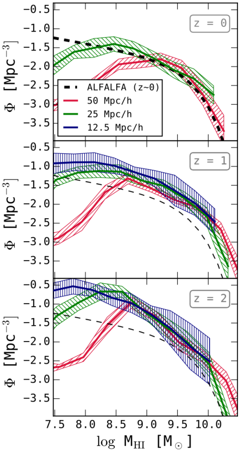
How does the HI content evolve with redshift?

- hierarchical growth of structures, switch between $z = 0$ and $z = 1$ due to AGN feedback
- tuned to match $\Omega_{\rm HI}$ in the local universe
- SAMs often predict decrease with redshift

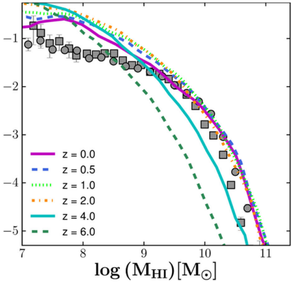




Redshift evolution: other results



Davé et al. (2017)

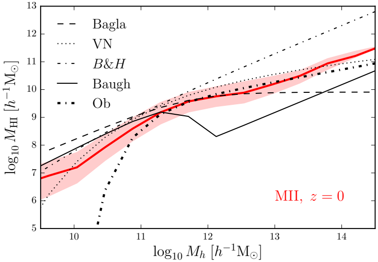


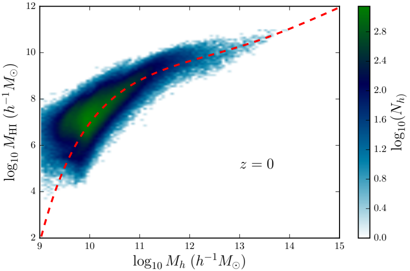
Popping et al. (2014)

HI halo mass function

Total HI content M_{HI} of a halo of mass M_h: $M_{\mathrm{HI}}(M_h)$

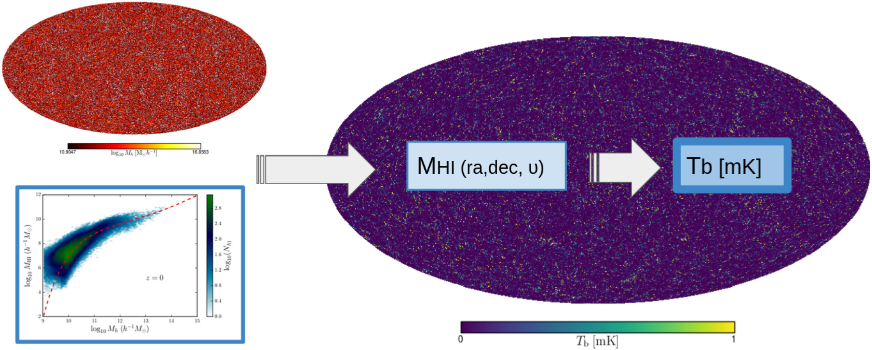
- a fundamental ingredient of the halo model (Chen et al. (2021)) and to build mock 21 cm maps
- GAEA vs some literature
- $z = 0$: fit a functional form with: low mass cut-off + power law with an inflection point (due to AGN feedback: Baugh et al. 2019)





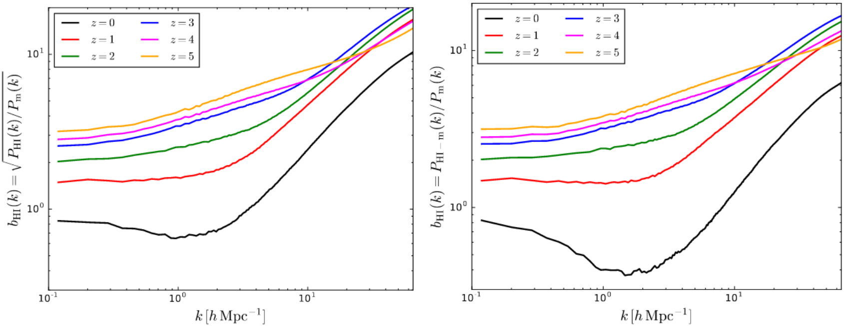
A semplification

How to get big volumes for large-scale studies?
Combining SAMs and fast halo catalogues
(LPT: e.g. Pinocchio, Monaco et al. (2002))



arXiv:2107.10814

Power spectrum and bias

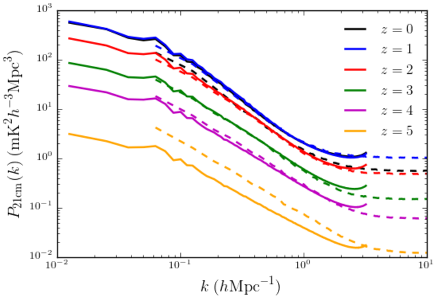


Villaescusa-Navarro et al. (2018)

21cm power spectrum

$$P_{21\mathrm{cm}}(z,k) = \bar{T}_b^2 x_{\mathrm{HI}}^2 \left[b_{\mathrm{HI}}^2 \left(1 + \beta^2\mu^2\right)^2 P_m(z,k) + P_{\mathrm{SN}} \right]$$

e.g. Kaiser (1987), Bacon et al (2019)



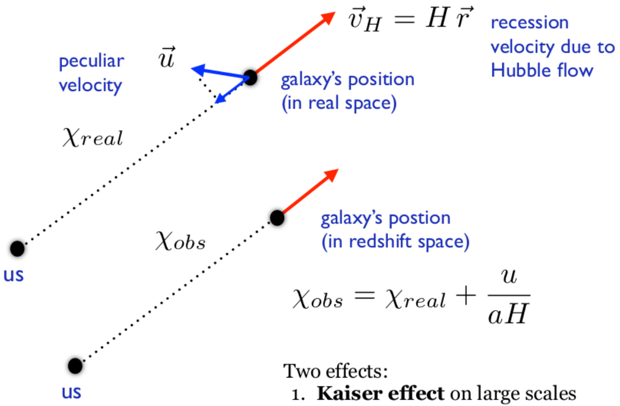
x_{HI}: abundance of neutral hydrogen

b_{HI}: HI bias

$\beta^2\mu^2$, with $\beta \equiv f/b_{\mathrm{HI}}$
Redshift Space Distortions

Shot Noise from small scales

Redshift Space



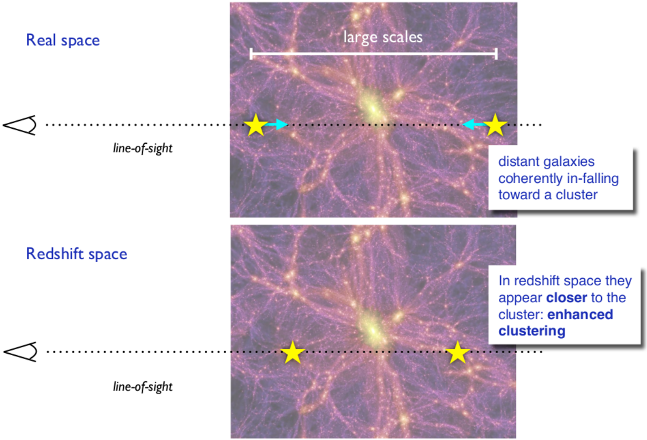
$$\chi_{obs} = \chi_{real} + \frac{u}{aH}$$

Two effects:

1. **Kaiser effect** on large scales
2. **Finger-of-God effect** on small scales

courtesy of E. Sefusatti

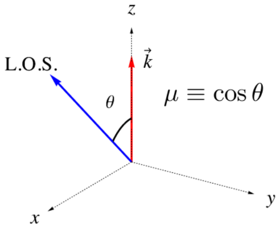
Kaiser effect



courtesy of E. Sefusatti

Kaiser effect on the Power Spectrum

- in real space $P_m(k)$ is isotropic
- in redshift space is not (clustering is enhanced along the line-of-sight)
- we are interested in HI so a biased tracer $P_{\rm HI}(k) = b_{\rm HI} P_m(k)$

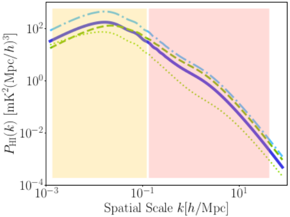


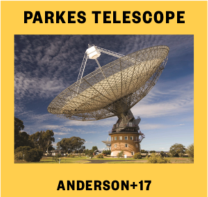
$P_s(\mathbf{k}) = P_s(k, \mu) = (b_{\rm HI} + f\mu^2)^2 P_m(k)$

Multipole expansion: $P_\ell = \int d\mu P_s(k, \mu) \mathcal{L}_\ell(\mu)$

21 cm Power Spectrum: how to

courtesy of Laura Wolz





From single dishes to radio arrays

- the resolution of single dish telescopes scales as $\lambda/D_{\rm dish}$
- can we ask for sub-arcsecond resolution?
- you can go big (GBT $D_{\rm dish} = 100{\rm m}$) but not too big (a square kilometer array telescope would be a bit too much..)

Way out:

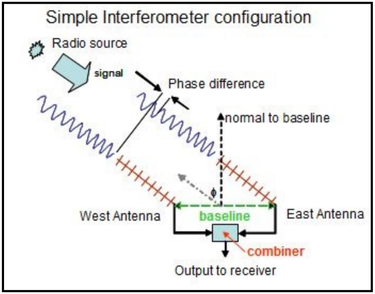
combine the views of a group of dishes/antennae spread over a large area and operate them together

courtesy of A. Pourtsidou

Key points of interferometers

courtesy of P. Bull

- Phase delay depends on array geometry (baseline length)
- Interferometers see the whole sky (weighted by a beam)
- Each baseline measures a single Fourier mode of the (antenna-weighted) intensity on the whole sky
- The longer the baseline, the sharper the view!



https://sites.google.com/site/radioastronomydm2/interferometry

Array layout

courtesy of P. Bull

baseline length (distance between antennas) connected to the scale I can measure:
- Short baselines $\leftrightarrow$ large scales
- Long baselines $\leftrightarrow$ small scales (high resolution)

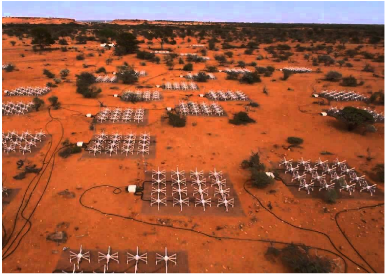
- For large arrays: we care about the number density of long vs. short baselines.
  - Higher density $\leftrightarrow$ higher sensitivity per mode
- Optimise: Where do you need most sensitivity?
  - Small objects (e.g. jets) $\rightarrow$ more long baselines (sparse array)
  - Large scales $\rightarrow$ more short baselines (dense array)
  - Detect galaxies $\rightarrow$ balanced baseline distribution

Array layout

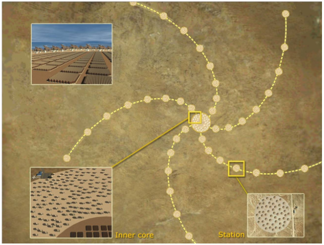
courtesy of P. Bull

Sparse array
e.g. JIVE/EVN

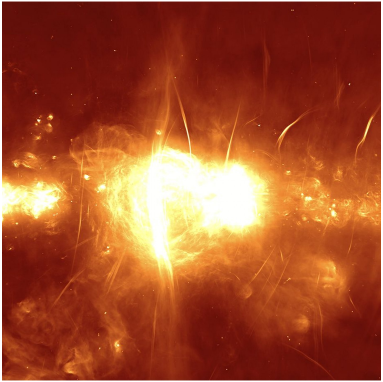
Dense array
e.g. MWA



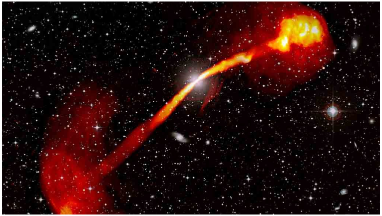
Balanced array
e.g. SKA-MID



MeerKAT 64 dishes



Heywood et al. (2019)



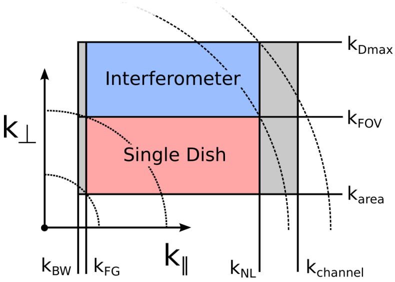
Condon et al. (2021)

From single dishes to radio arrays, and back!

- Interferometer
  $\lambda/D_{\rm min} \lesssim \delta\theta \lesssim \lambda/D_{\rm max}$
- Single-dish (also called autocorrelation)
  we can see angular size larger than $\delta\theta \gtrsim \lambda/D_{\rm dish}$

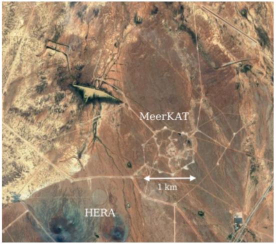
Plan for Intensity Mapping

use 64 MeerKAT dishes as a collection of single-dishes looking at the same patch in the sky



Bull et al. (2015)

Intensity Mapping with MeerKAT



MeerKLASS

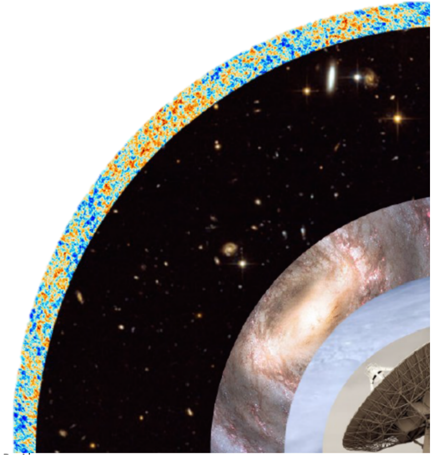
- larger area,
  more integration time
- IM for Cosmology
- *Radio Continuum*
  HI galaxies

Science Verification Data

Antennas	All 64 MeerKAT dishes
Observation mode	Single-dish
Frequency range	0.856-1.712 GHz
Frequency resolution	0.2 MHz
Time resolution	2s
Exposure time	1.5hr x 7 scans
Target field	WiggleZ 11hr field ($10^\circ \times 30^\circ$)

Wang et al. (2021)

Challenges with Intensity Mapping observations



credit: D. Alonso

- HI IM signal
- Foregrounds
- Earth
  - Atmosphere, RFI
- Instrument
  - Beam
  - Noise

Noise and sensitivity

courtesy of P. Bull

Receiver noise

- Radio receivers measure signal + **thermal noise**
- Noise comes from electronics, the sky, the ground...
- Total noise temperature is the **system temperature**

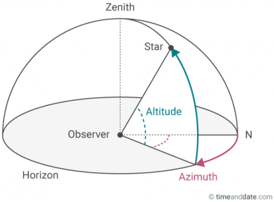
Reducing noise

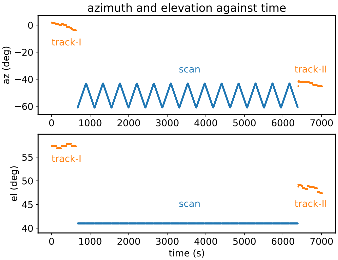
- Lower system temperature = less noise
- Can **average the signal** over time – noise averages down
- Can also average the signal over **frequency**; wider *bandwidth* = more photons = lower noise

Radiometer equation

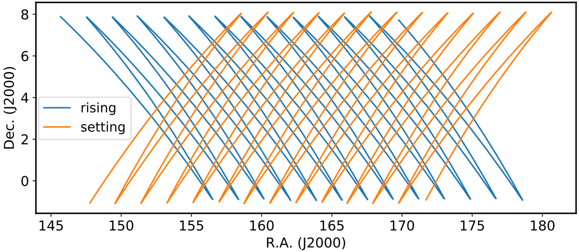
$$\sigma_{\rm T} \approx \frac{T_{\rm sys}}{\sqrt{\delta\nu\, t_{\rm obs}}} \approx \frac{\textit{Thermal noise temperature}}{\textit{Number of “samples”}}$$

MeerKLASS scanning strategy



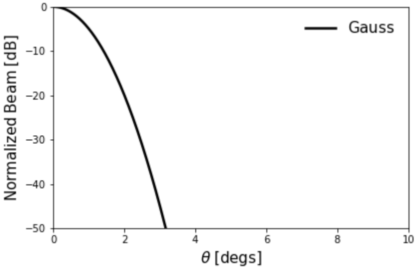


MeerKLASS scanning strategy

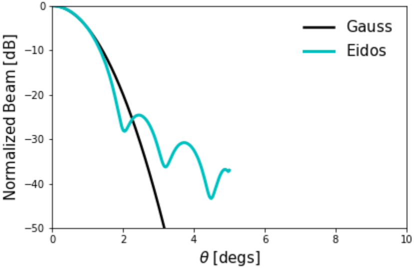


Wang et al. (2021)

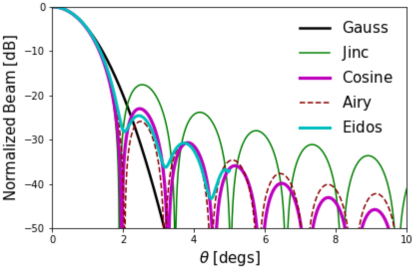
A realistic beam



A realistic beam

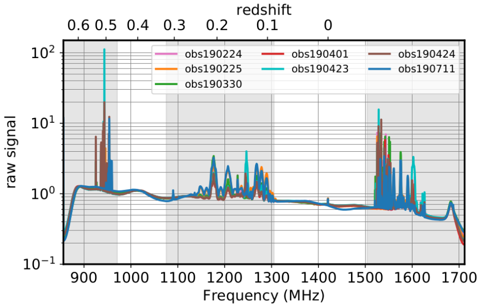


A realistic beam



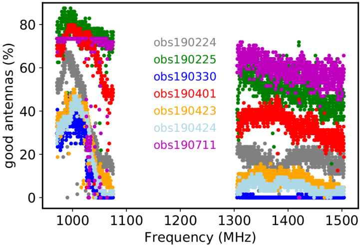
Radio Frequency Interference (RFI)

RFI is everywhere, even in the Karoo desert



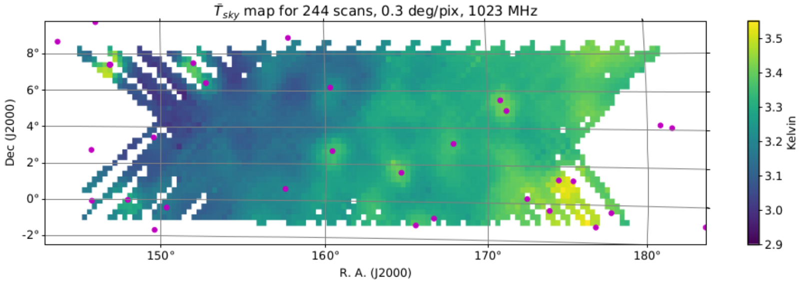
- contamination from satellites
- much worse in the future?

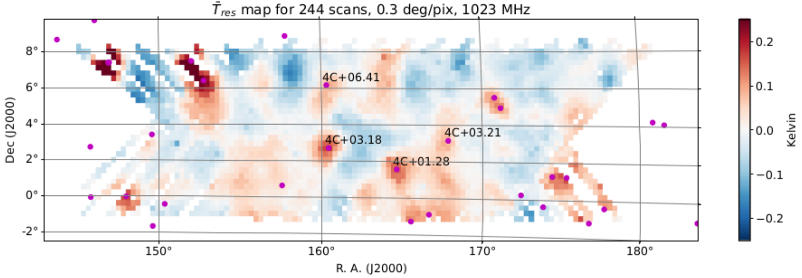
- RFI flagging steps
- discard data



Wang et al. (2021)

Where we stand





Instrumental effects

- Need a realistic beam modeling
  (side-lobes, frequency evolution, more accurate deconvolution)
- Scanning strategies
  (non homogeneous noise, need for real space convolution, polarization leakage)
- RFI
  (impact on cleaning, impact on signal interpretation)