Cosmology with HI intensity mapping: the SKA view

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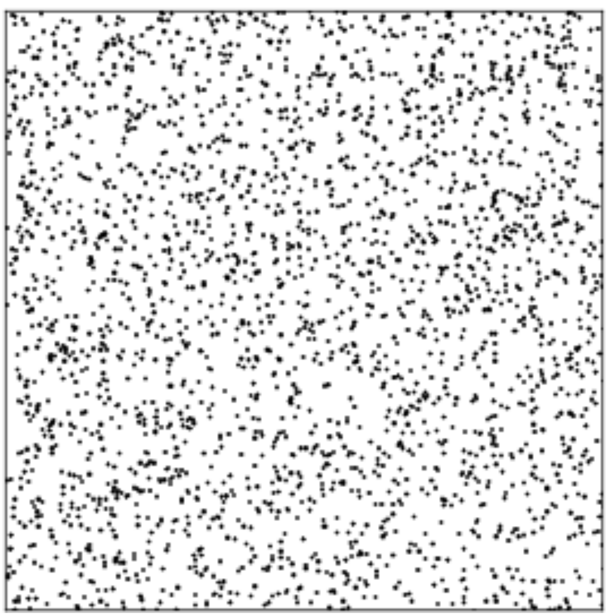
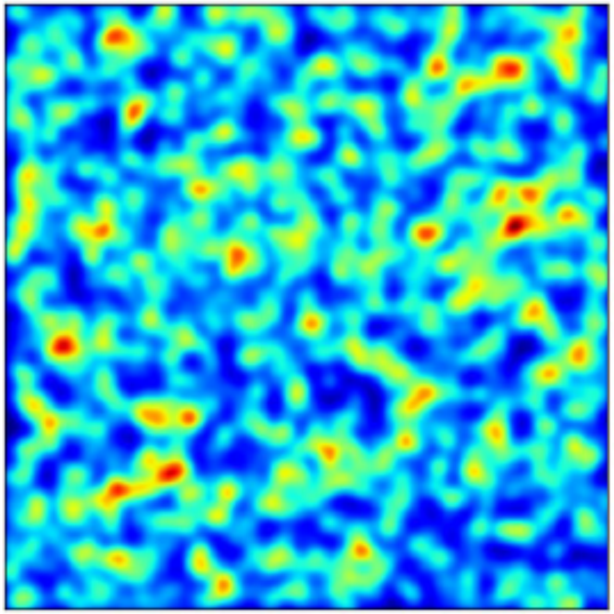
Intensity mapping?

- Look at the total intensity for a given emission line in a large 3d pixel (angle and frequency)
- Pixel will have joint emission from multiple galaxies



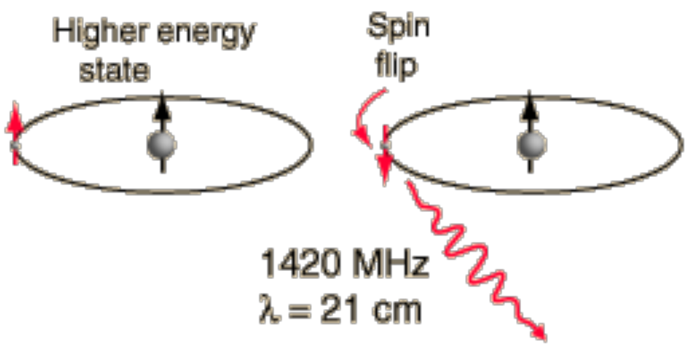
galaxies



Intensity map

What lines to use?

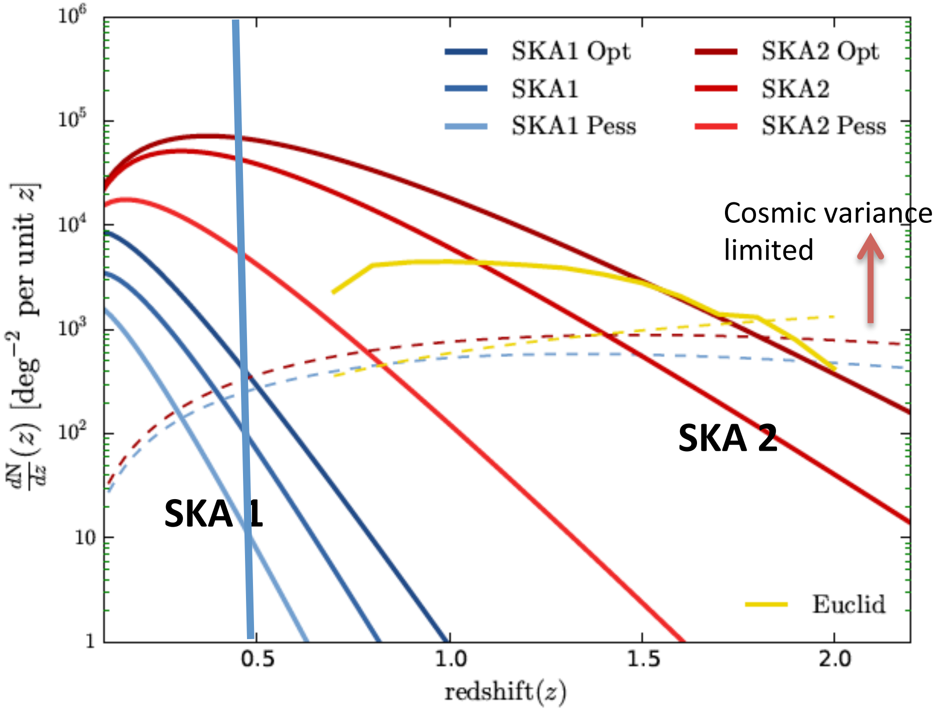
- HI (21 cm signal – 1.4 GHz)
- CO (1-0) (115 GHz, 2.61 mm)
- CII (1.9 THz, 157.7 um)
- Lya (121.6 nm)
- At z>6, HI signal dominated by IGM emission
- At z<3 (e.g. Cosmology), HI inside galaxies…



HI IM: advantages

- Easy to observe from Earth
- Not contaminated by other lines
- Good tracer of dark matter
- Cheap way to observe large volumes – detecting HI galaxies requires high resolution and sensitivity (see right)
- Allows to probe the really low HI mass regime…

Very demanding to do cosmology with HI galaxy surveys…

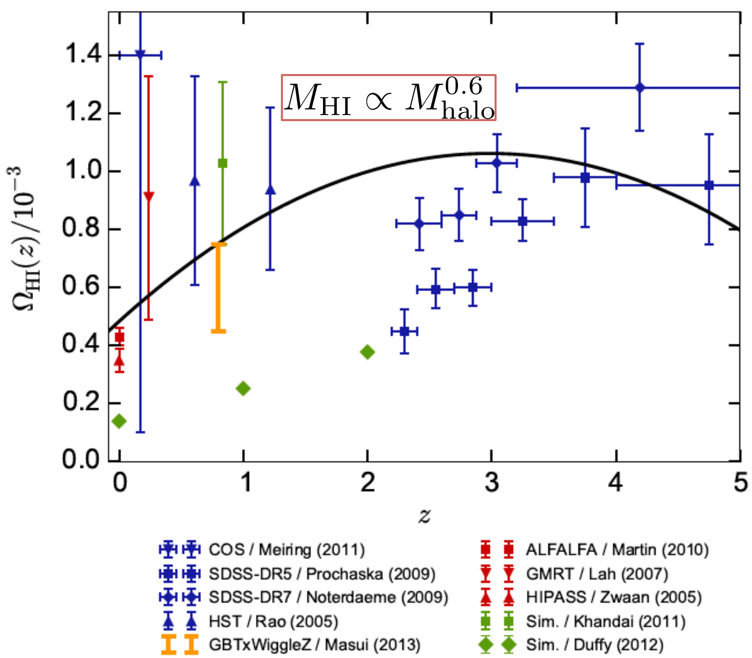


See Santos et al., http://arxiv.org/abs/1501.03990

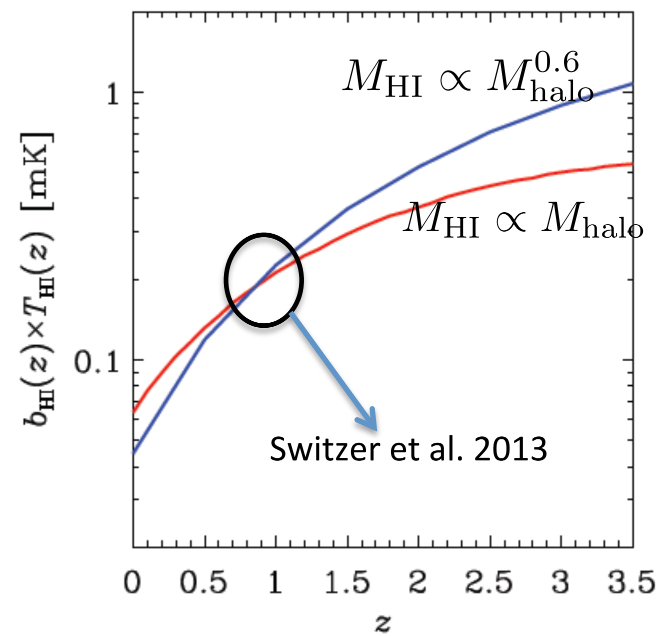
SKA1 ~ 10^7 galaxies over 5,000 deg^2
SKA2 ~ 10^9 galaxies over 30,000 deg^2

The HI signal

- Our signal is a sum over many galaxies (one "pixel" of (1 deg)^{2}x(5 MHz) ~ 10^5 Mpc^3 contains ~ 10^4 HI galaxies at z~1!
- Use Halo mass function
- Assume a function for **$M_{HI}(M_{halo},z)$** to calculate the HI density
- Power spectrum depends on the product of total temperature (HI density) and bias



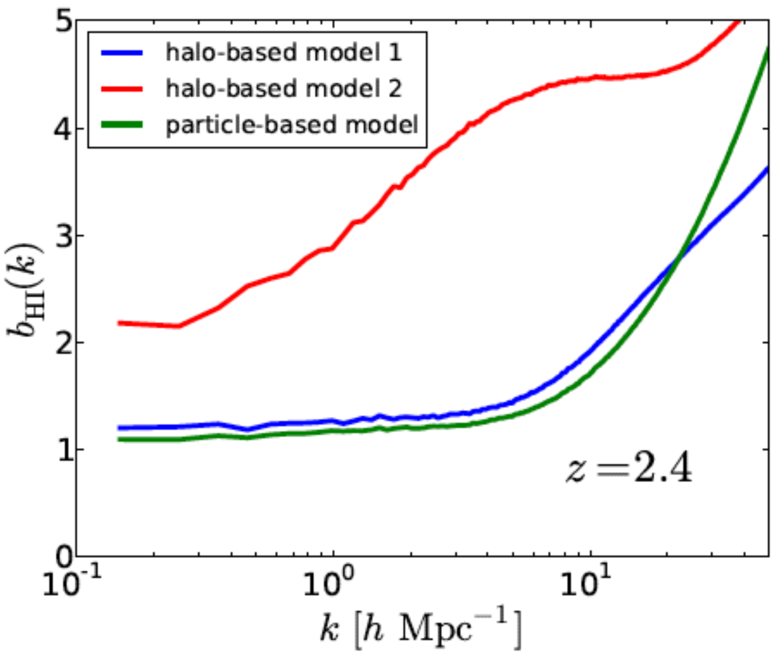
Bull et al. 1405.1452

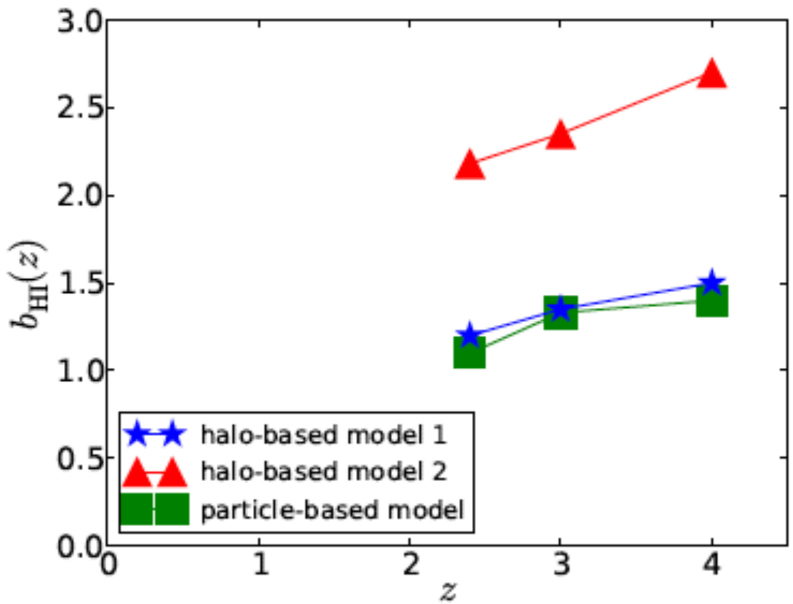


Santos et al. 1501.03989

HI bias

- For cosmological applications, crucial for bias to be scale independent
- DLA systems seem to indicate a larger bias at high z (e.g. HI in higher mass halos)
- (Villaescusa-Navarro et al 2014, Bagla et al. 2010, Padmanabhan et al. 2015…)



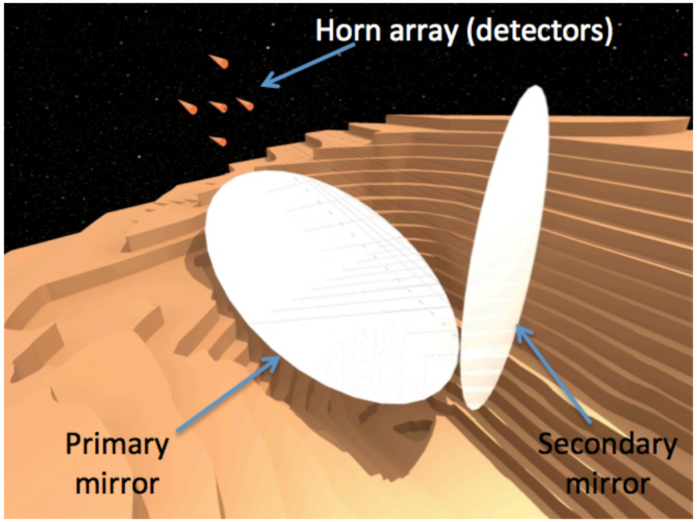


Simulations from Villaescusa-Navarro et al. (2014)

Experiments: dish surveys

- Angular scales > λ/D_{dish}
- Each pointing gives you 1 pixel on the sky
- Brightness sensitivity does not depend on dish size
- Good to scan large areas of the sky

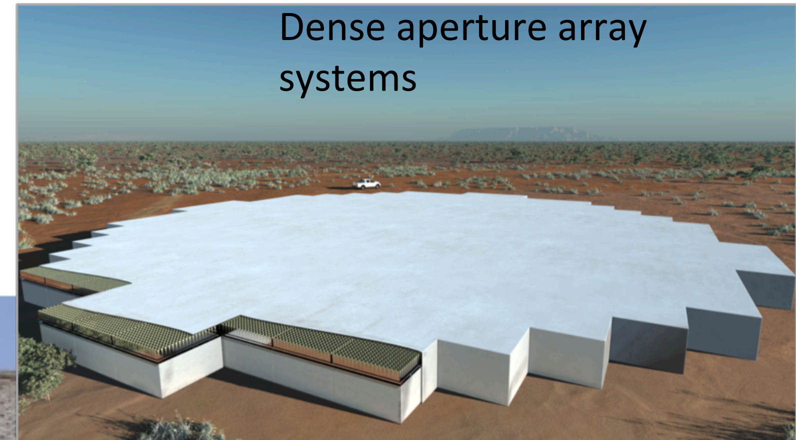
- GBT (Chang et al.)
- **Parkes**



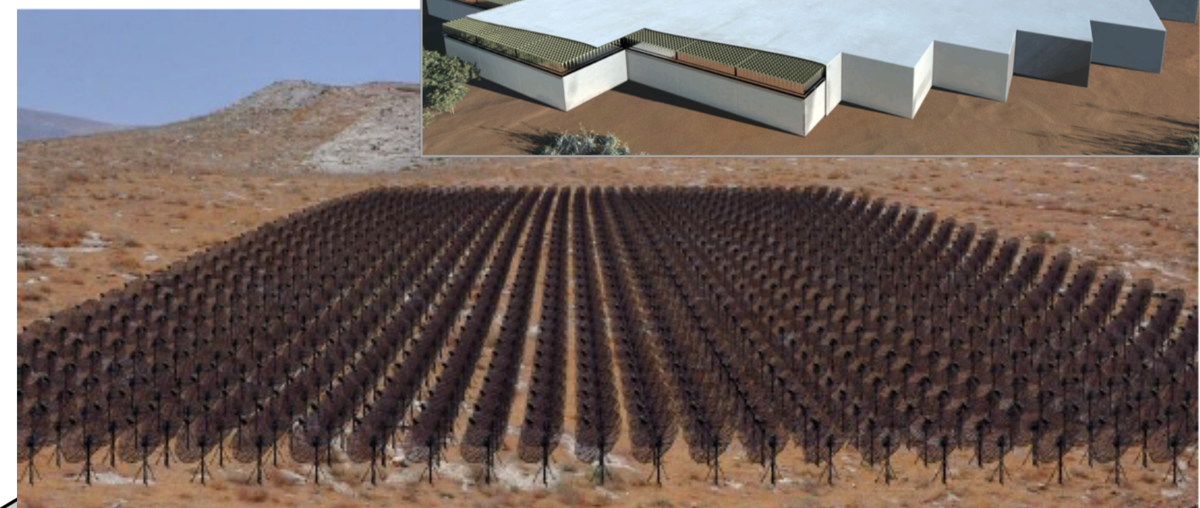
BINGO (Battye, et al., http://arxiv.org/abs/1209.1041)

Experiments: interferometers

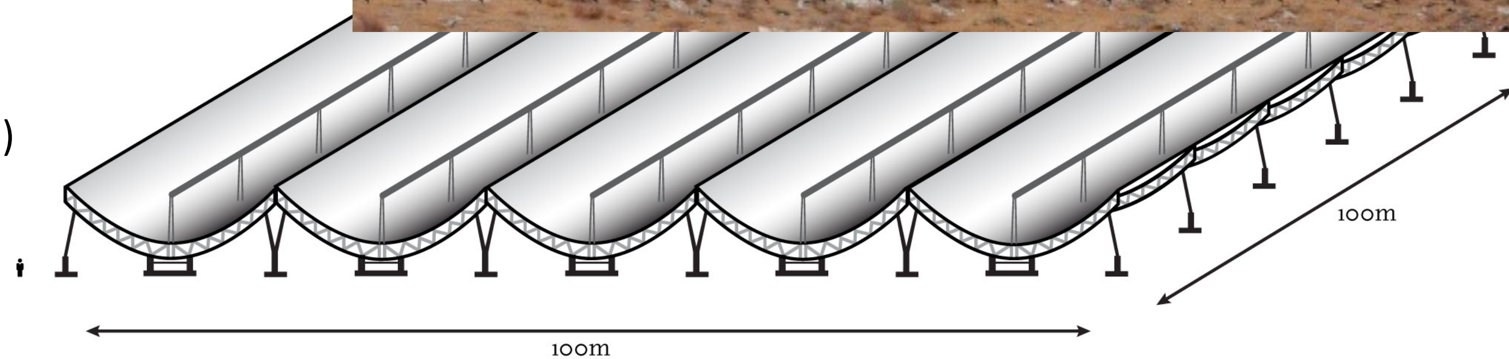
- λ/b_{max} < angular scales < λ/b_{min}
- Provide higher resolution
- Hard to do "full sky" surveys…



HIRAX (South Africa)
~ 1000, 5 m dishes
400 – 800 MHz (0.8 < z < 2.5)



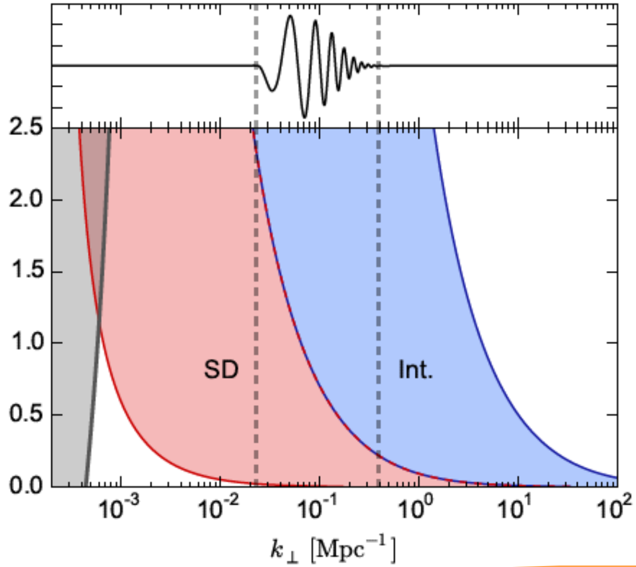
- CHIME (Canada)
- Tianlai (China)



SKA1 as an intensity mapping "machine"

MeerKAT -> SKA1-MID (~200 dishes by 2023)

- Interferometer: baselines not small enough to probe BAO scales and above
- Main idea: use each dish in "single observation mode"
- Save interferometer data for calibration
- Proposal to provide calibrated auto-correlations has been approved by the SKA office
- SKA1 survey: 30,000 deg^2, 10,000 hours, 0.35 – 1 GHz

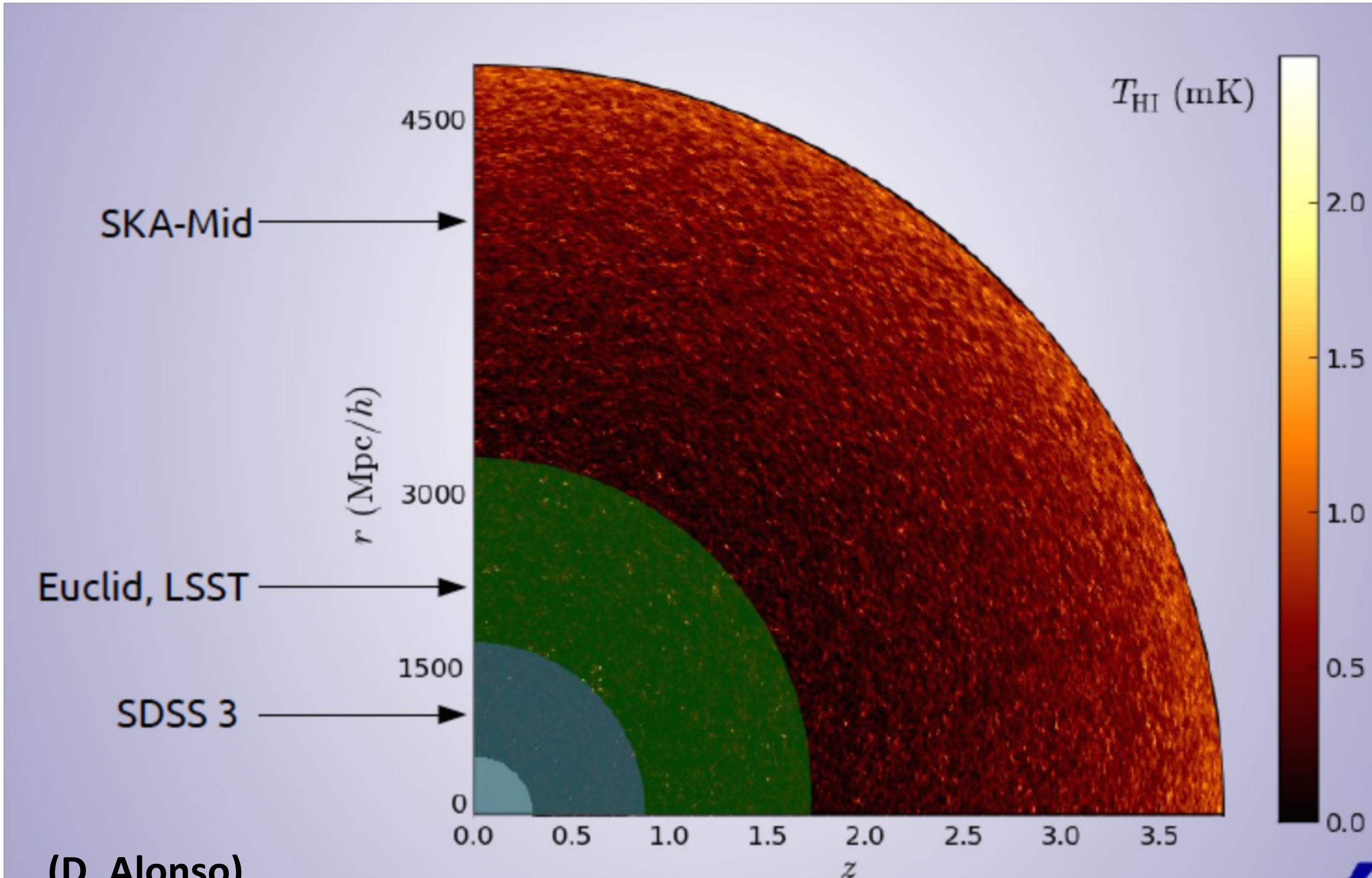


Note: SKA1 "re-baselining" decisions…

- SKA1-MID:
  - South Africa
  - 64 MeerKAT dishes + 133 15m dishes
  - 0.35 – 1.76 GHz (for band 1 + 2)
- SKA1-LOW
  - Australia
  - 131,072 antennas
  - 454 stations
  - 50 – 350 MHz

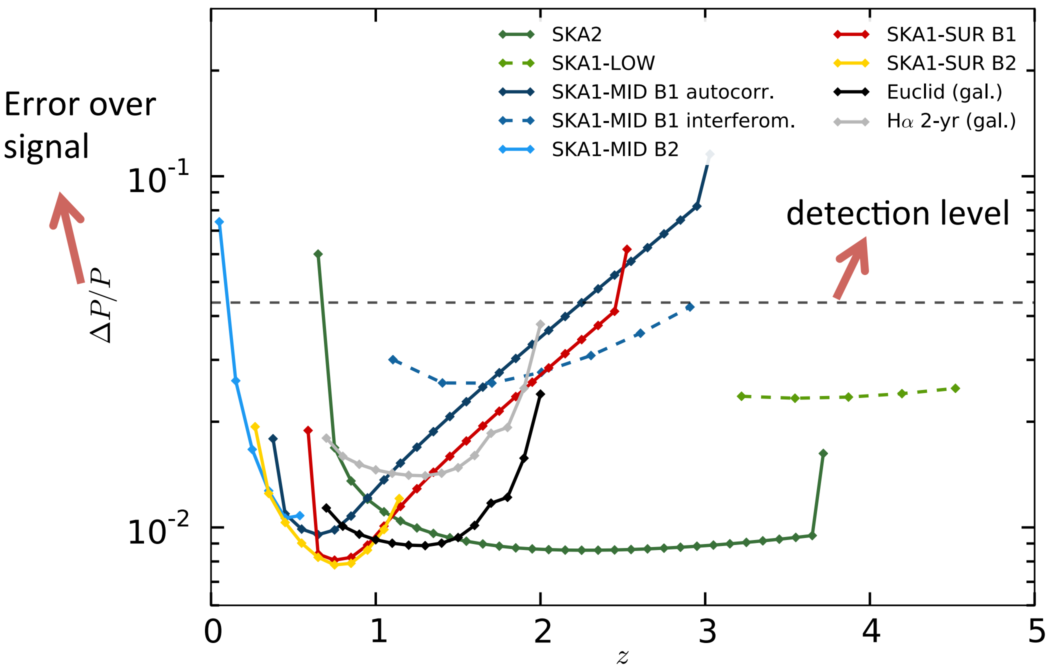
SKA1-MID: Cosmology with HI IM

- Competitive with largest redshift surveys on BAO scales
- Huge available volume

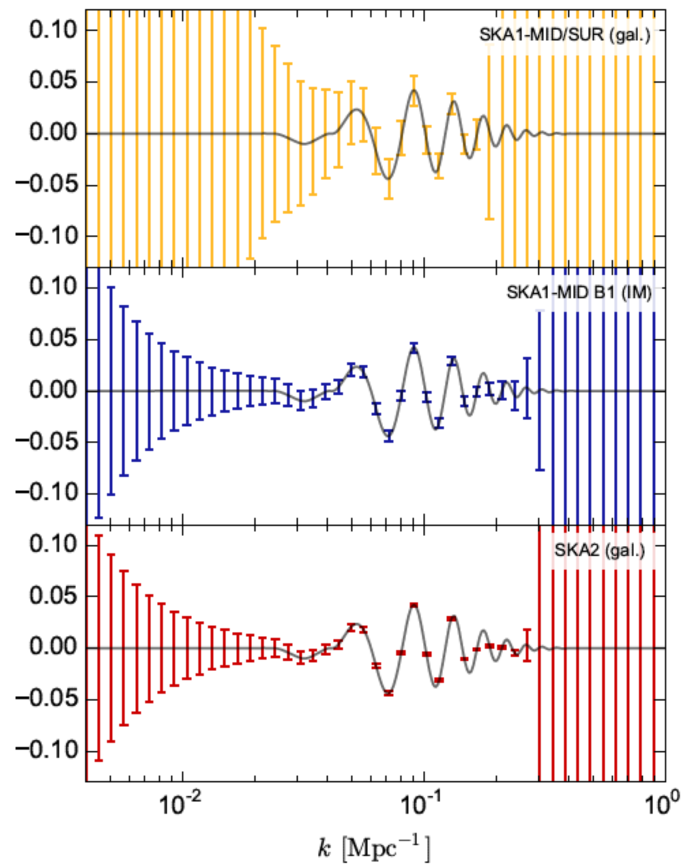


(D. Alonso)

BAO with a SKA1 HI intensity mapping survey



Combined redshifts up to z ~ 3.0

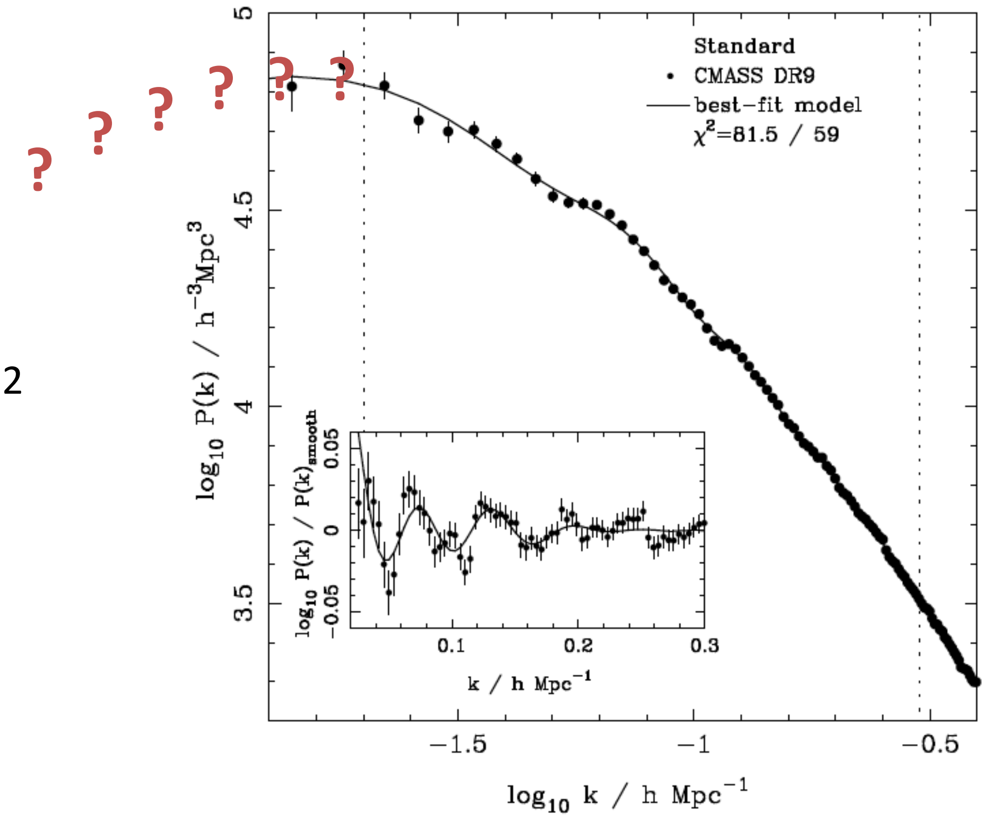


- Intensity mapping will make SKA1 very competitive for BAO constrains
- Note: SKA2 will surpass any of these surveys

Bull et al. 1405.1452
M. Santos, et al., SKA chapter, 1501.03990

What about really large scales?

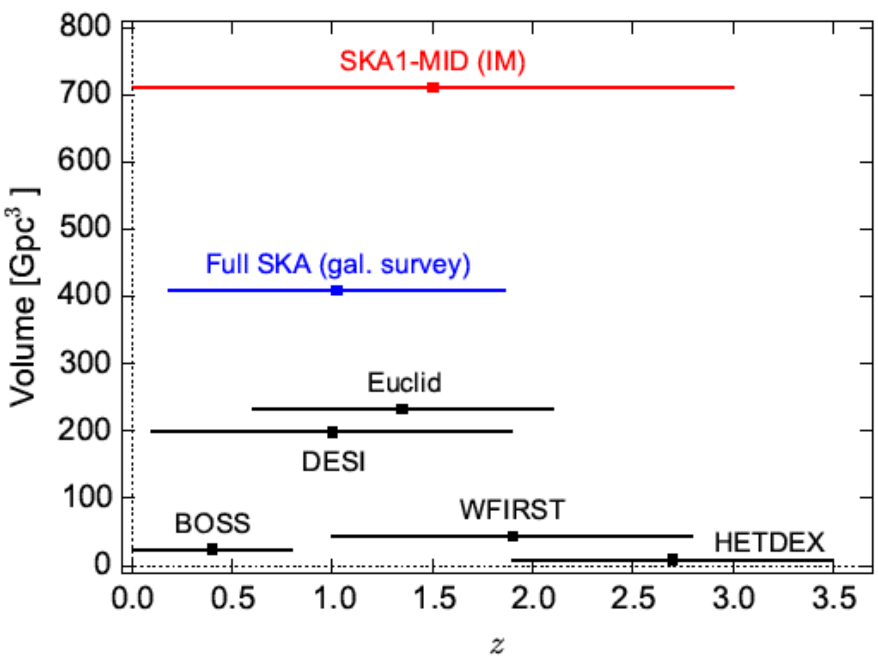
- Scales near or above the horizon (at z=2 -> k_H ~ 1.0×10^{-3} h/Mpc)
- "Smoking gun" for new physics?
- Linear fluctuations!
- No measurement yet…

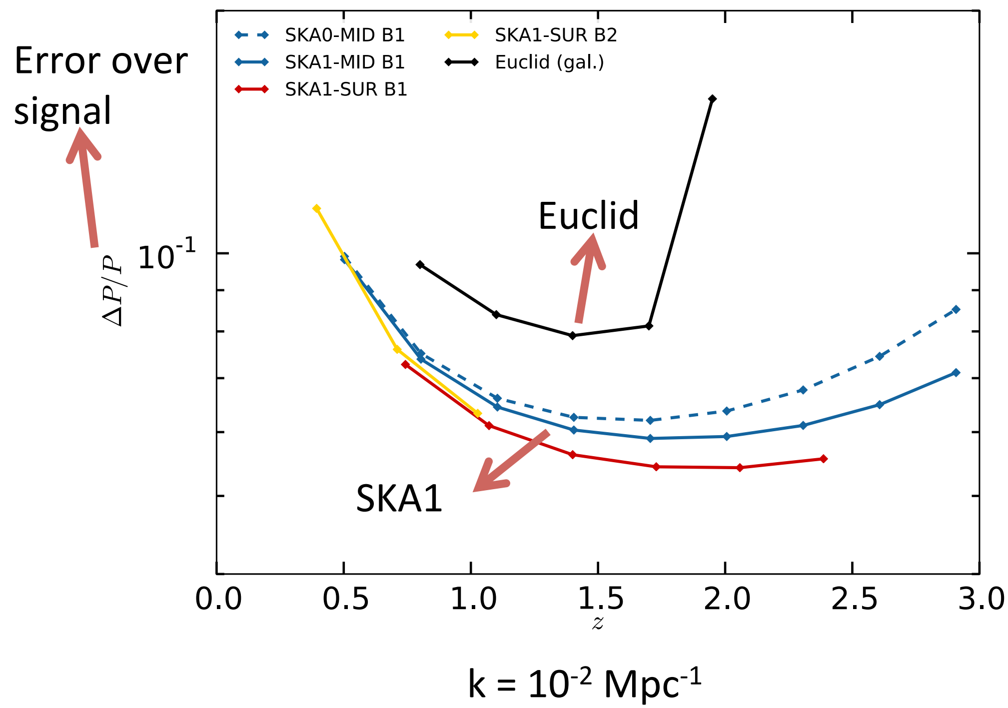


BOSS survey:
Anderson et al., MNRAS, 2012
Smallest **k ~ 0.03 h/Mpc**

(see Stefano Camera talk)

Probing very large scales with a SKA1 HI intensity mapping survey

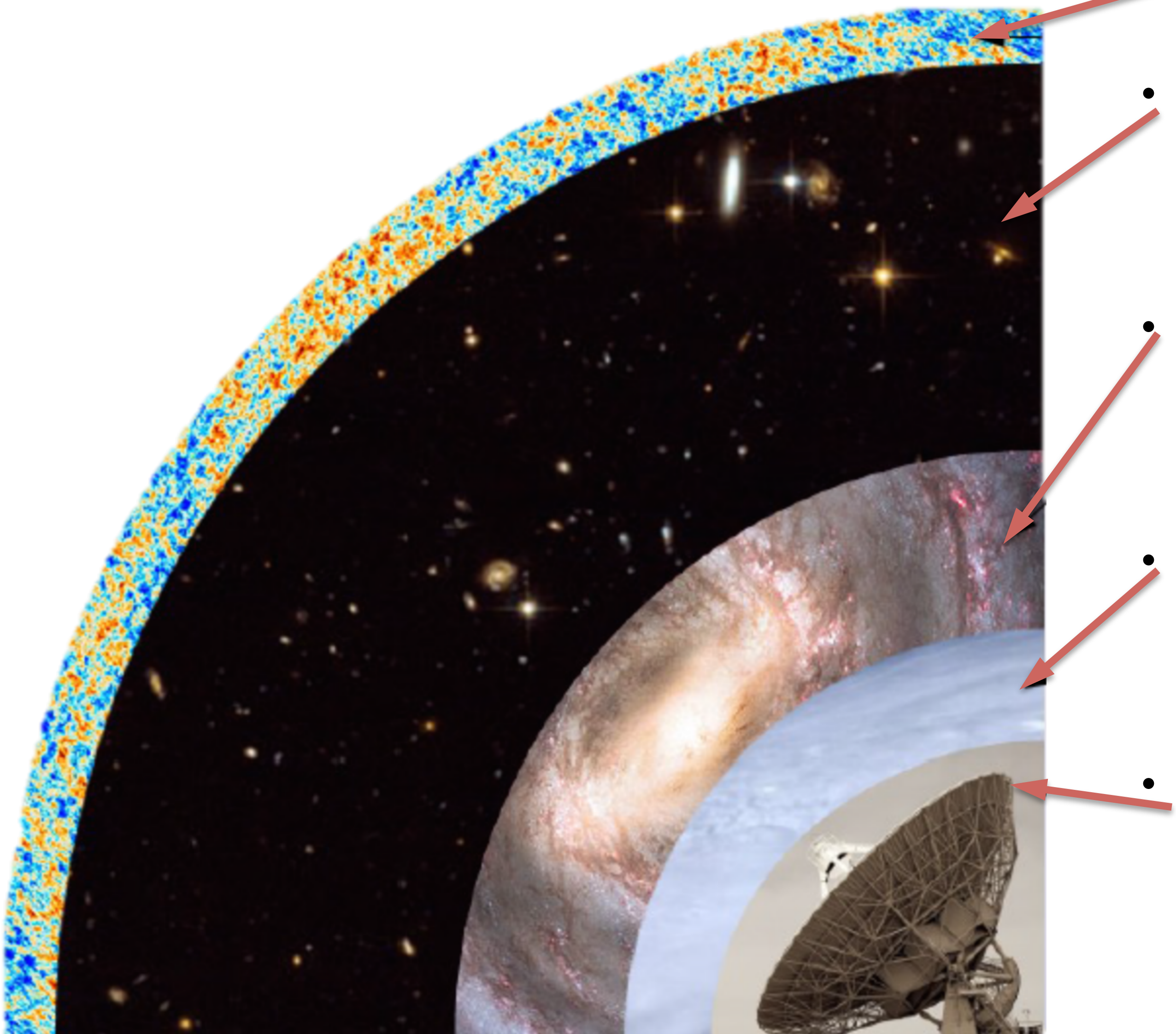




- SKA top ranked science case: *"Map the 3D matter distribution on the largest scales and deepest redshifts ever - in order to obtain transformational constraints on primordial non-Gaussianity and to perform the first tests of gravity on super-horizon scales."*

See Santos et al., 2015, PoS(AASKA15), SKA chapters

Challenges with IM observations…



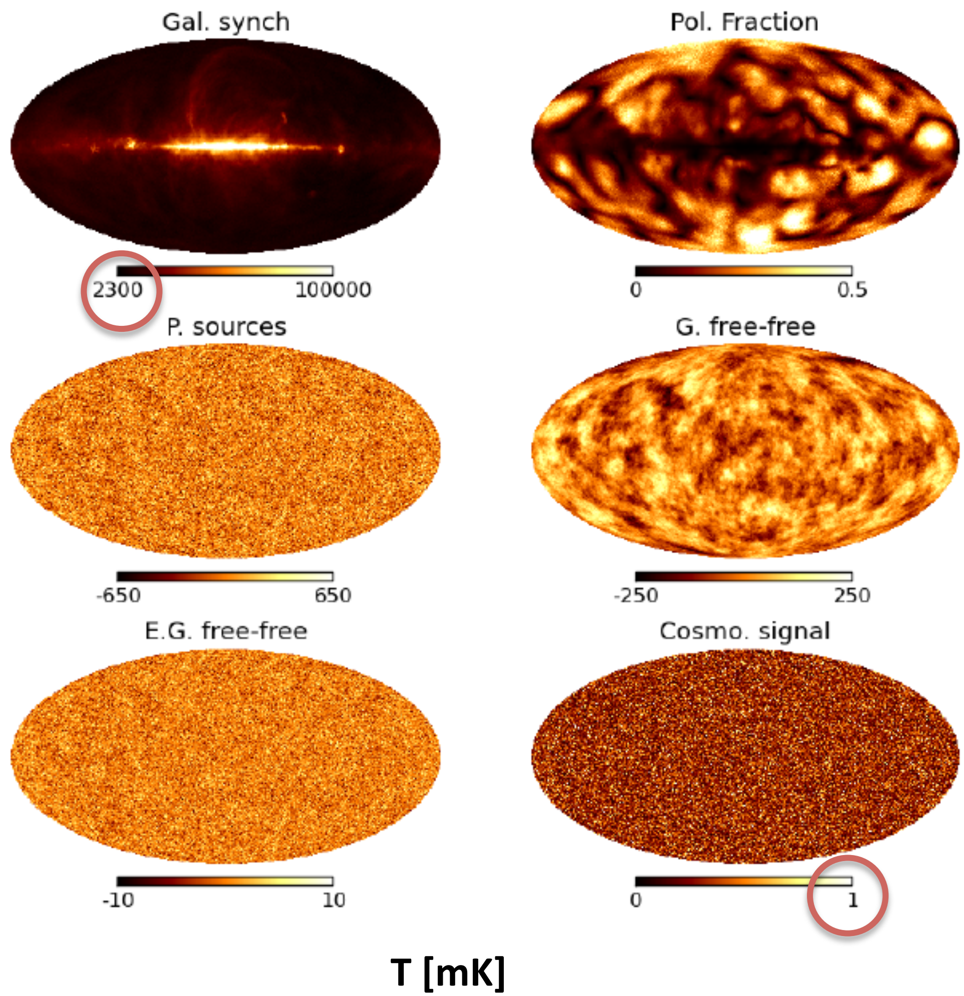
- HI IM signal
- Extragalactic foregrounds:
  - Point sources
  - E.G. free-free

  (might be a background)
- Galactic foregrounds:
  - **Synchrotron (I,Q,U)**
  - Free-free
  - Dust
- Earth:
  - Atmosphere: clouds, H2O, Ionosphere
  - RFI
- Instrument:
  - Spillover
  - Gain fluctuations
  - Beam fluctuations
  - **Polarization leakage**

D. Alonso

Challenges with IM observations…

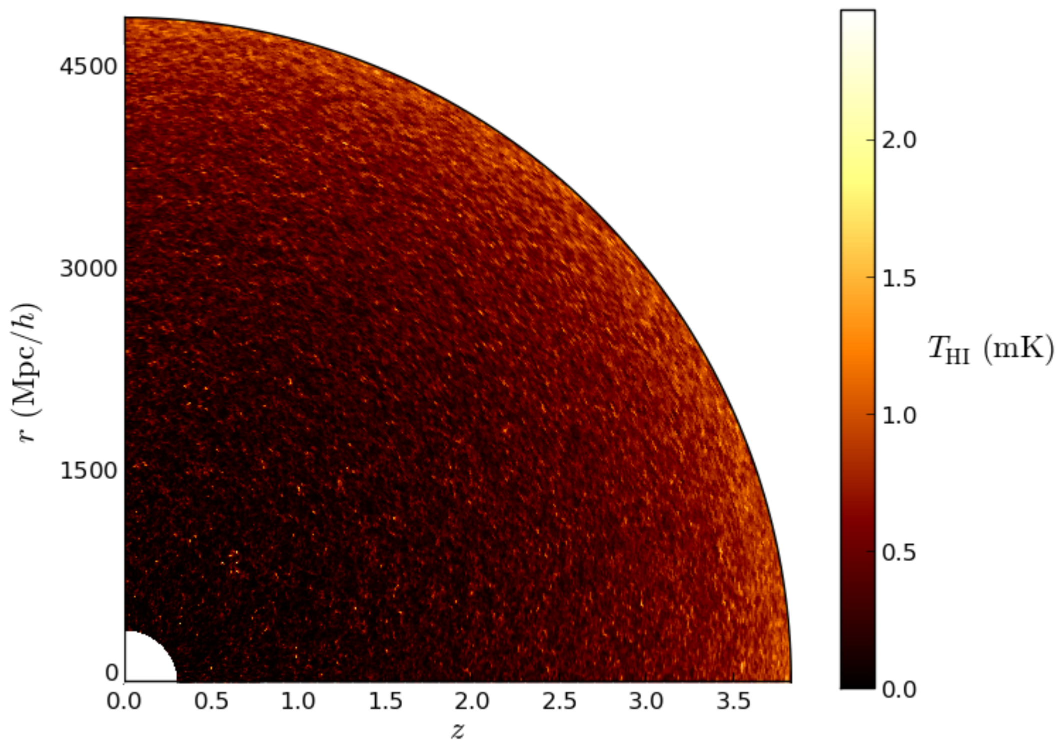
- Need to remove everything else that falls in our pixel!
- Main contaminant: galactic synchrotron (about 1000 times stronger)
- Other lines (OH, CH) not a concern
- **Note**: ionosphere not really a problem at these frequencies…



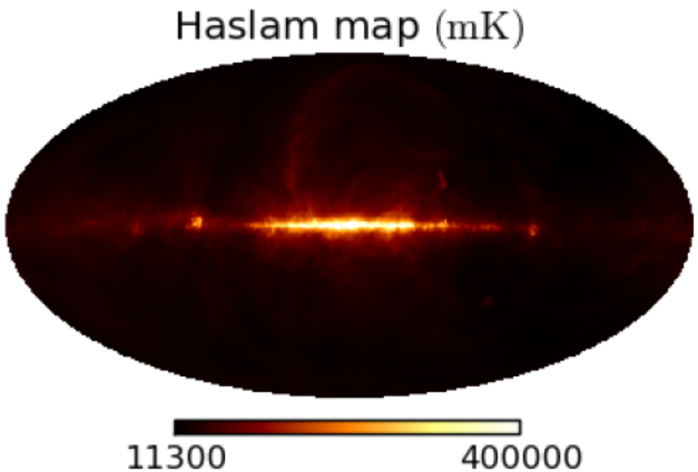
Alonso, Ferreira and Santos, 2014, arXiv:1405.1751
Simulations: http://intensitymapping.physics.ox.ac.uk/CRIME.html

Fast simulations for intensity mapping

- Mock simulated observations crucial to test foreground cleaning methods
- Cosmological signal:
  - Generate lognormal density and radial velocities.
  - Compute 3D HI mass grid.
  - Interpolate to pixel maps and implement RSDs.

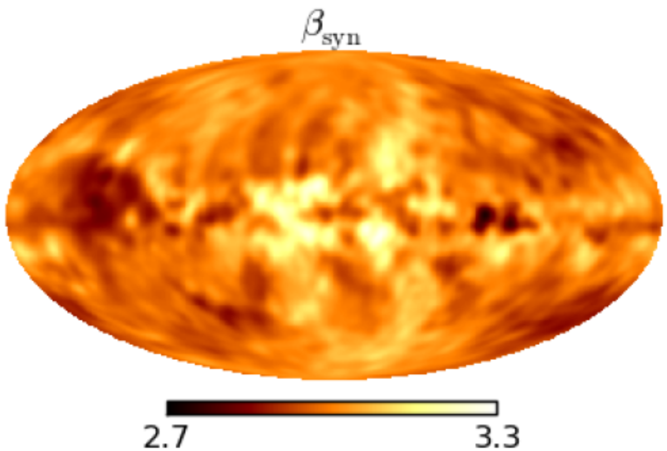


Fast simulations: galactic synchrotron



+

Planck



Delabrouille et al. 2013 (PSM)

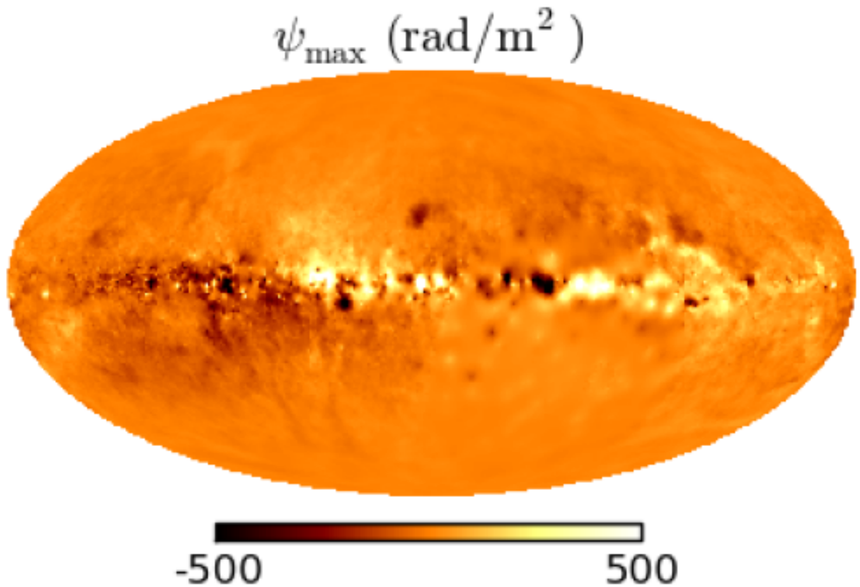
+ Small scale fluctuations

$$T_{\rm sync}(\nu, \hat{\mathbf{n}}) = T_{408}(\hat{\mathbf{n}}) \left(\frac{\nu_H}{\nu}\right)^{\beta(\hat{\mathbf{n}})} + \Delta T_{\rm SCK}(\nu, \hat{\mathbf{n}})$$

Gaussian distribution using model from Santos, Cooray, Knox 2003

Fast simulations: polarized synchrotron

- Approximations using a single Faraday screen
- Calibrated with simulations based on models of n_{CR}, n_e, B_{gal} (Waelkens et al. 2009, HAMMURABI)
- Very fast!
- More observations needed…



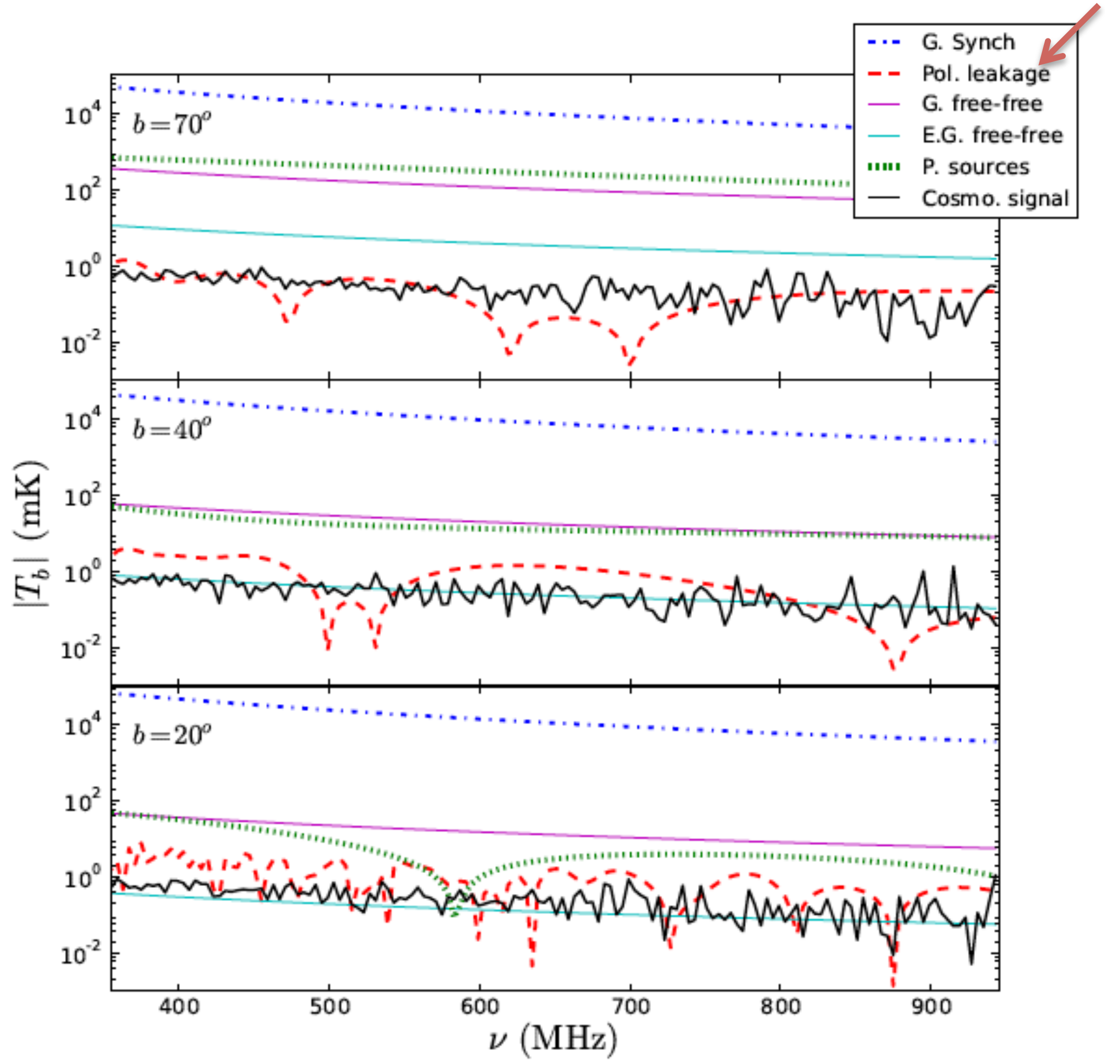
Oppermann et al. 2012

$$T_{\rm leak}(\nu,\hat{\mathbf{n}}) = \epsilon_P T^Q_{\rm syn}(\nu,\hat{\mathbf{n}})$$

Alonso, Ferreira and Santos, 2014, arXiv:1405.1751

Foreground cleaning

- Foregrounds are smooth across frequency while signal fluctuates (e.g. Santos et al. Apj, 2005, Wang et al. ApJ 2006)
- Instrumental effects:
  - Beam convolution
  - Polarization leakage
  - Noise
- Most problematic: polarization leakage, beam frequency dependence…
- Cross-correlation with other surveys will useful



Red alert: polarisation leakage

Blind foreground subtraction

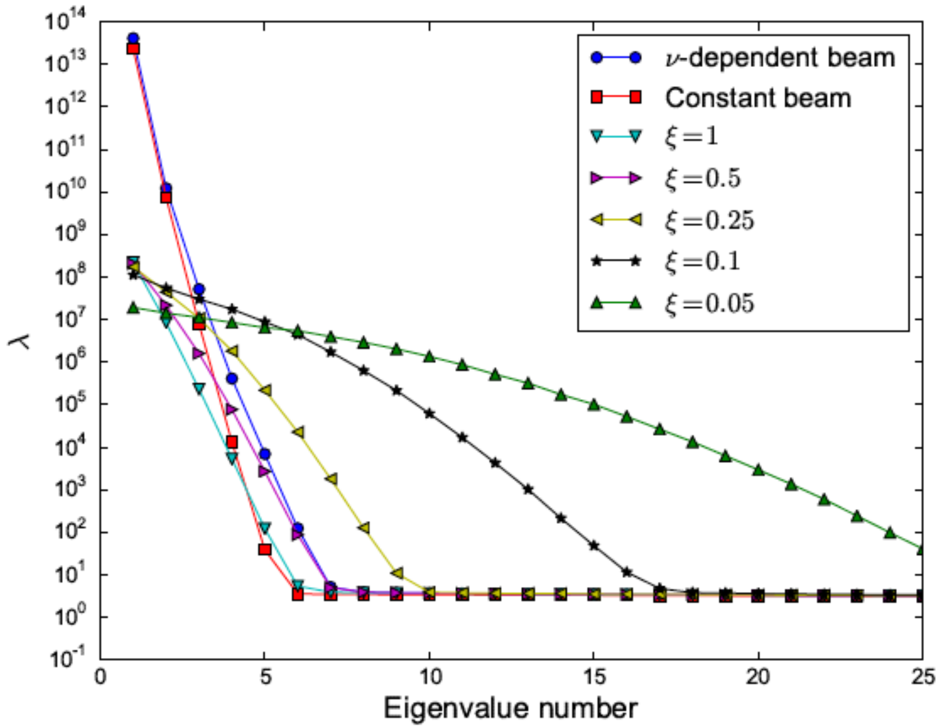
- Tested 3 different methods for IM:
  - **LOS fitting**: choose ad-hoc smooth functions. Usually polynomial fitting in log-log space.
  - **PCA**: uncorrelated sources maximizing the variance. Diagonalize ν-covariance and subtract principal eigenvectors.
  - **ICA**: independent sources maximizing the variance. Find independent sources by maximizing non-Gaussianity. (See Wolz et al. ArXiv: 1310.8144 for a first application to IM). Equivalent to PCA for Gaussian foregrounds.
- Specs: 5 foregrounds, SKA1-MID setup, Gaussian noise, frequency dependent primary beam, 400 < ν < 800 MHz

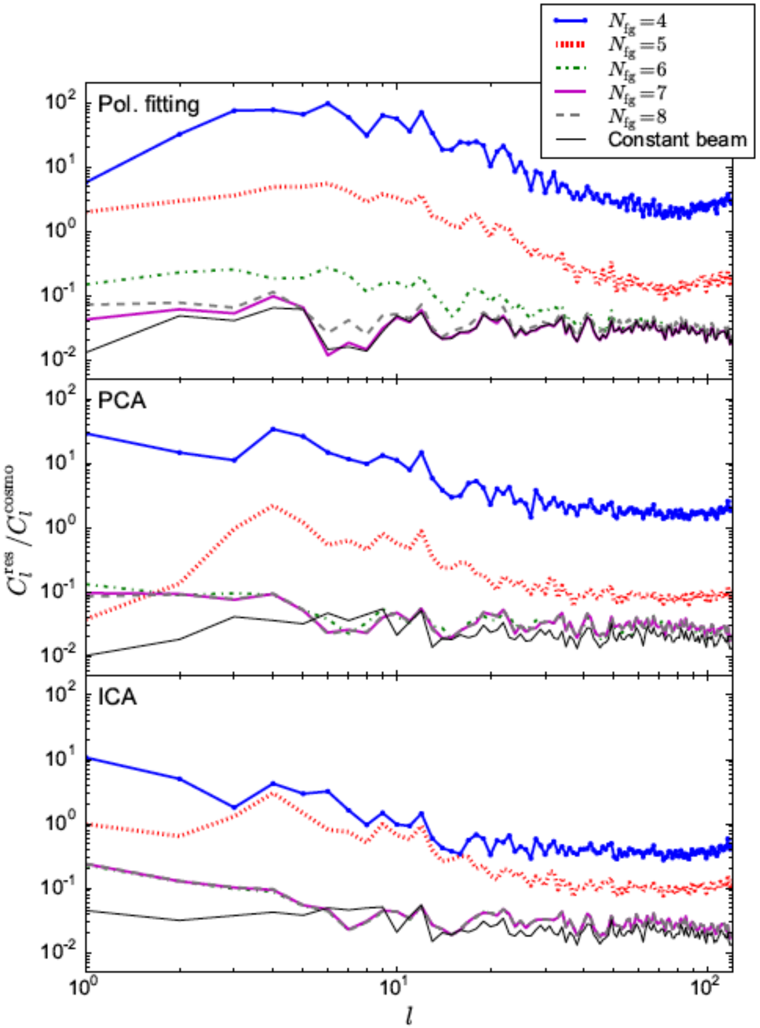
(See also: Gleser et al. 2008, Liu et al. 2009, Ricciardi et al., 2010, Harker et al. 2009, Hyvärinen et al. 1999, Chapman et al. 2012, Wolz et al. 2013, Chapman et al. 2013)

Alonso, Bull, Ferreira & Santos. ArXiv:1409.8667

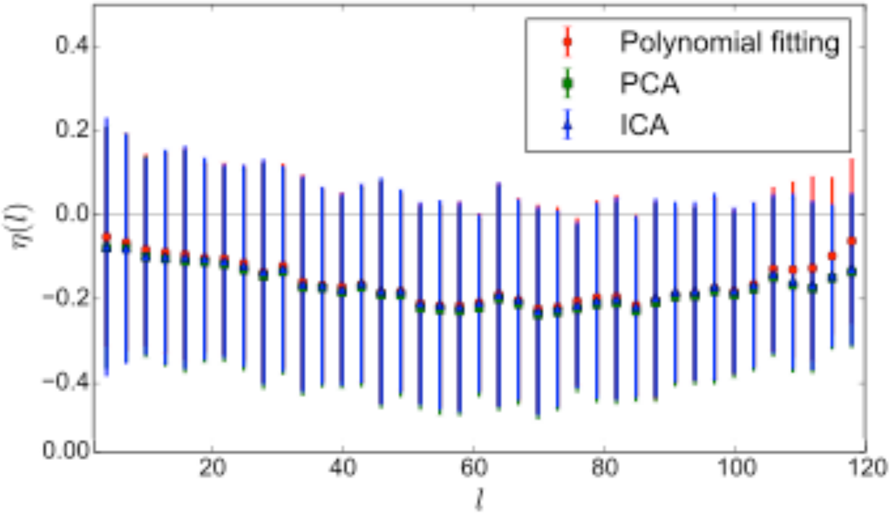
Blind foreground subtraction

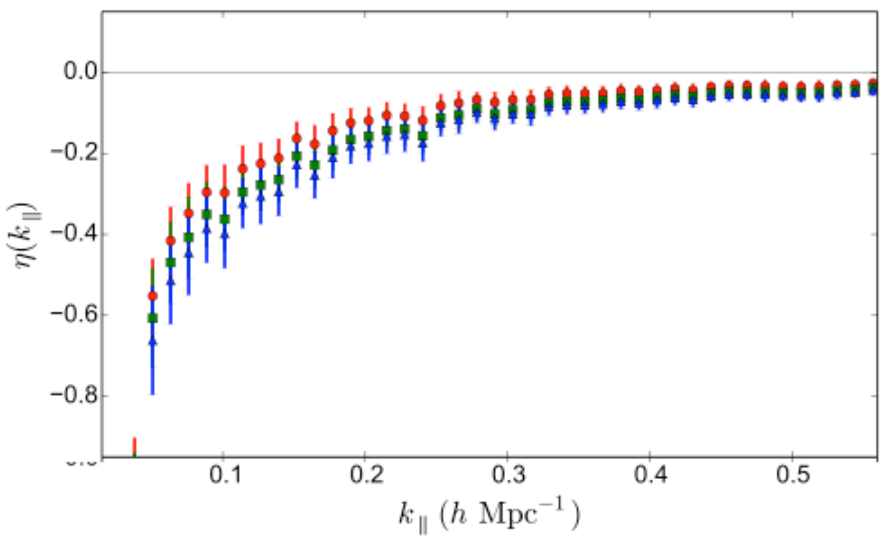
- Foregrounds degrees of freedom…





Blind foreground subtraction





- Bias of the recovered power spectrum

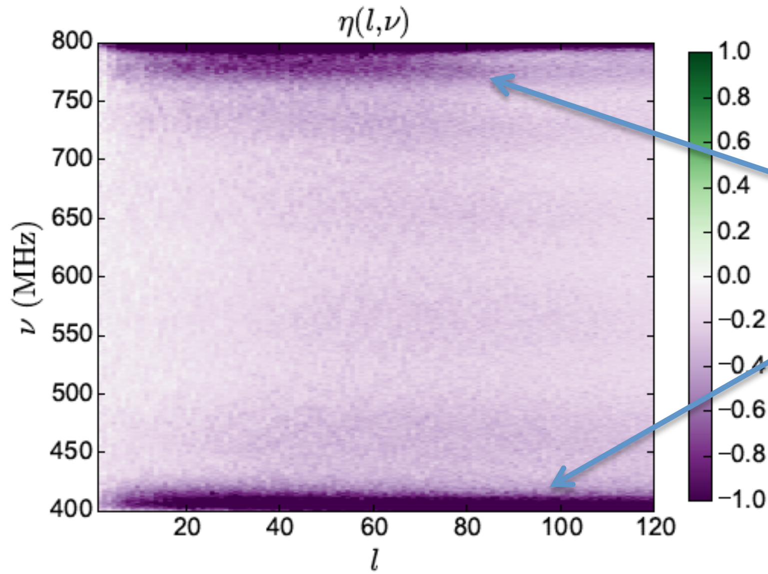
$$\eta \equiv \frac{\langle P_{\mathrm{clean}} - P_{\mathrm{cosmo}} \rangle}{\mathrm{error}}$$

  - Angular scales (bias ~ 20%)
  - Radial scales (Significantly larger contamination on large scales - dominated by foregrounds)

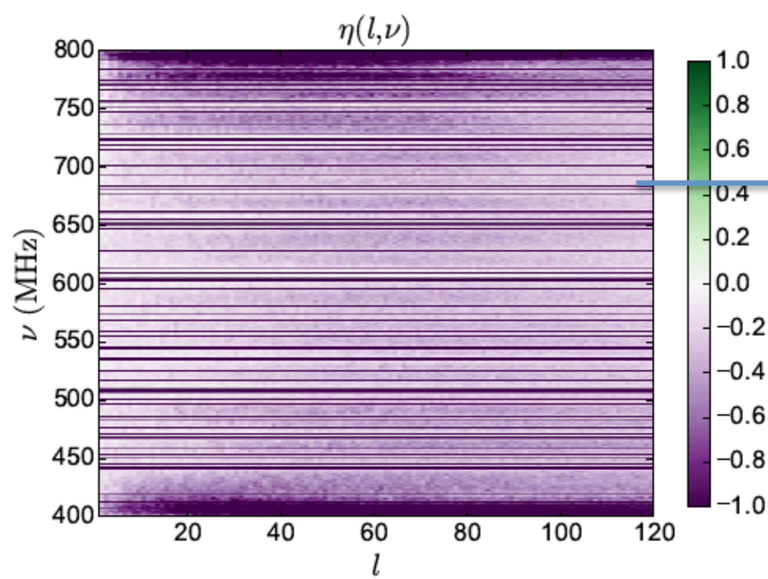
Overall: equivalent results found for all methods

Alonso, Bull, Ferreira & Santos. ArXiv:1409.8667

Blind foreground subtraction



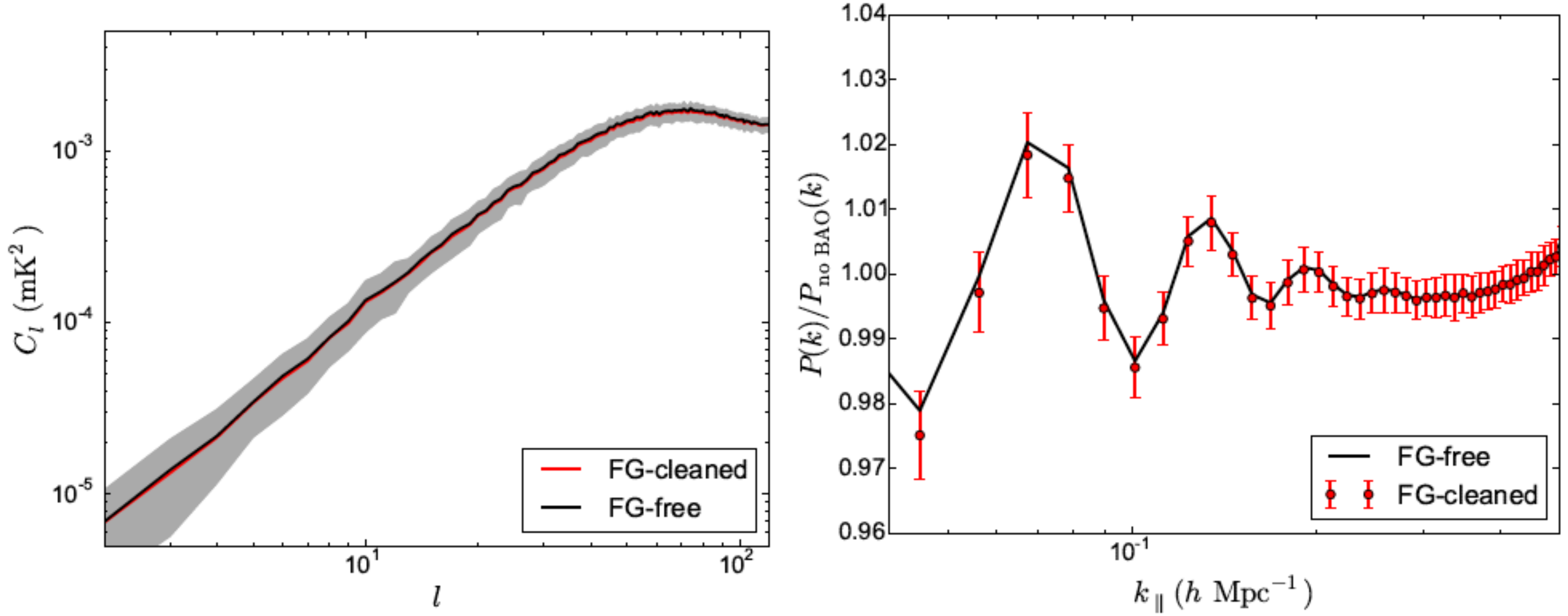
- Edge effects



- 20% RFI flagging

Blind foreground subtraction

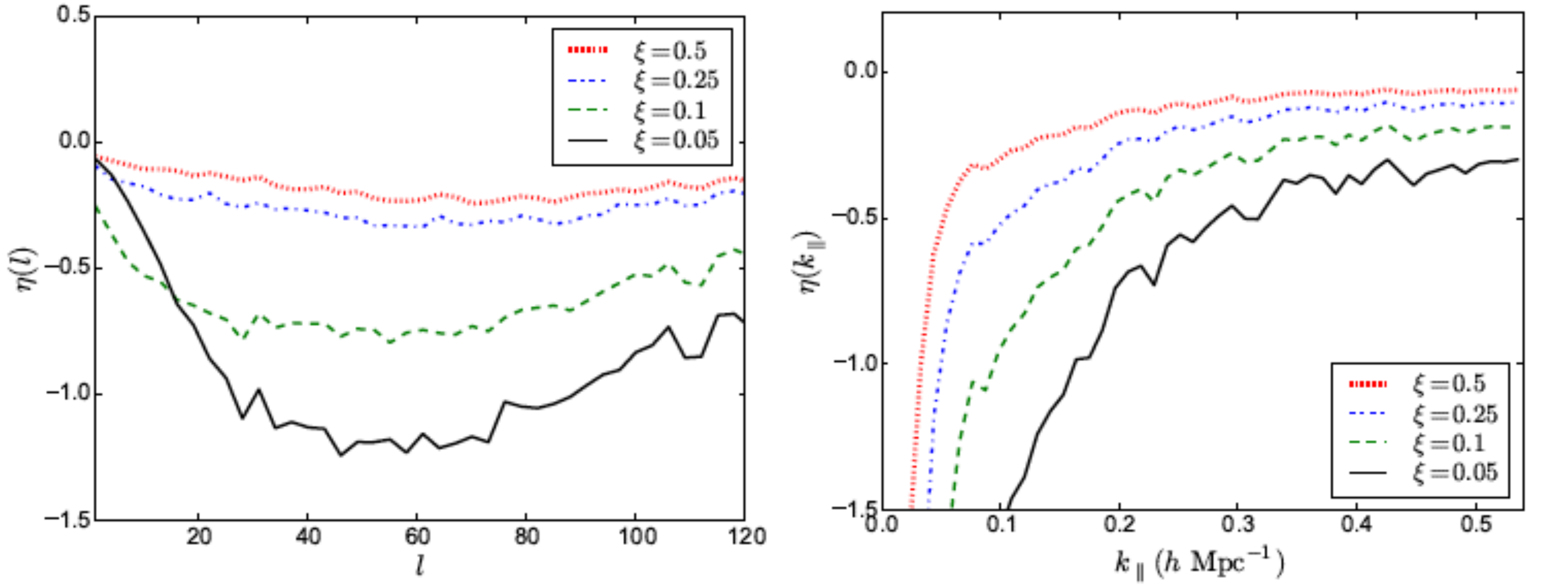
- Features such as BAO recovered with no bias…
- **Crucial to look at features to "believe" in the signal!**



Alonso, Bull, Ferreira & Santos. ArXiv:1409.8667

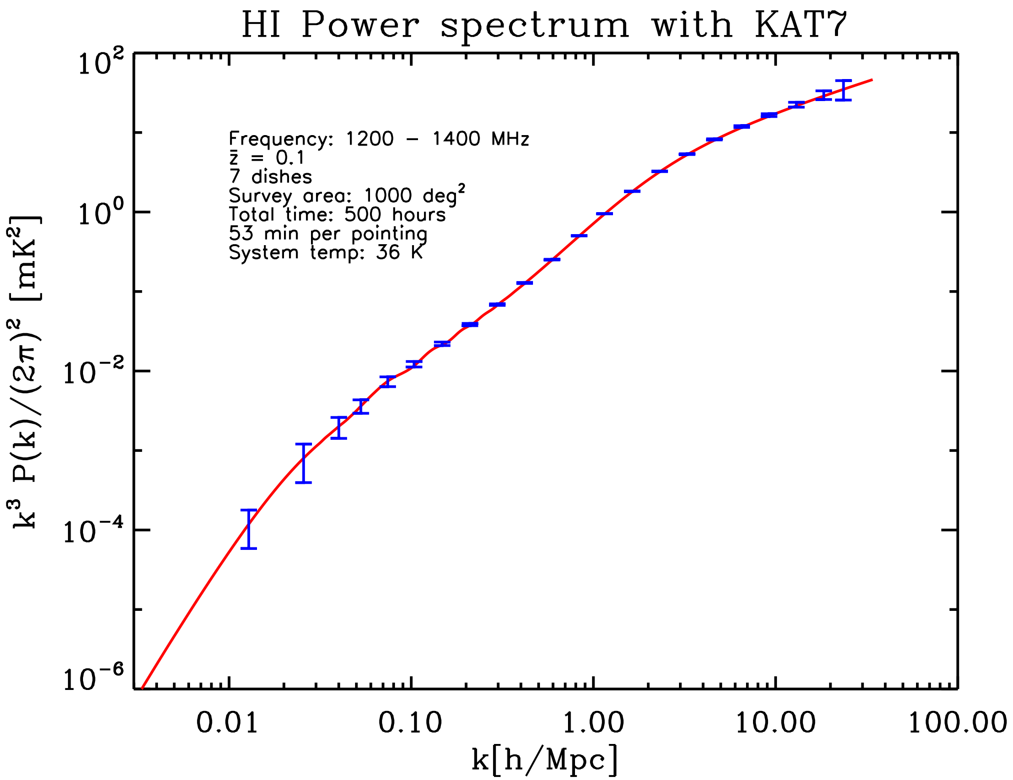
Blind foreground subtraction

- Polarized foregrounds:
  - Leakage can generate non-smooth foregrounds
  - Significant signal loss for $\xi \sim 0.1$ (compatible with galactic polarized emission models)
  - Solutions? Design an instrument with low leakage (< 0.2%). Calibrate the leakage (e.g. figure out it's frequency dependence). Find a better cleaning method…



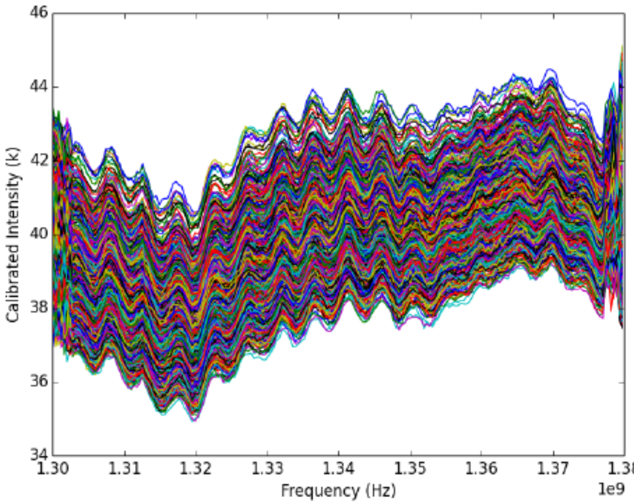
KAT7 tests…

- Important to test these auto-correlation techniques with data as soon as possible
- First detection will also be important to "calibrate" Ω_{HI}
- Currently performing tests with KAT7 (a pathfinder for MeerKAT with 7 dishes, in South Africa).
- Further tests with MeerKAT by early 2016 (10 dishes) including mapmaking techniques to deal with 1/f noise

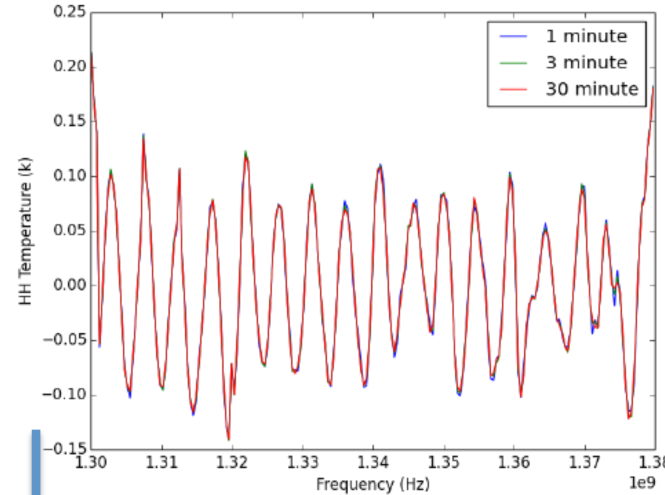


500 hours…

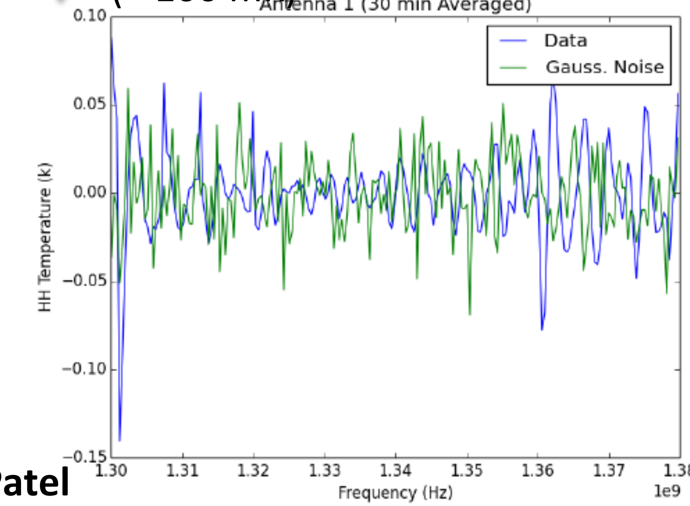
KAT7 foreground cleaning



Initial data. Drift scan. 1 dish. 30 min.
1 sec time stamps. 80 MHz band
(~ 40,000 mK)



After removing the smooth
components – sinusoidal residual
(~ 100 mK)



Fit a “sine wave” like template.
Final result “noise like” after 30
min. integration.
(~ 30 mK – noise/HI signal should
be ~ 1 mK)

P. Patel

Summary

- SKA1 can provide competitive constraints on standard cosmology, in particular using HI intensity mapping techniques
- But real strength is in probing very large scales: tests of homogeneity/relativistic corrections/ primordial non-Gaussianity with HI intensity mapping
- "Single dish" survey with SKA1 is the only solution for this **(but maybe also, the best solution**?!)
- Calibration issues not as demanding as for EoR (because it's higher frequency and primary beam is smaller)
- Current foreground cleaning methods work similarly well. **However all of them will have problems dealing with "wiggle like" contamination**
- Calibration looks achievable up to 30 min integration with KAT7 (about what we need per pointing)
- Expect final constraints from KAT7 by end of 2015 and with MeerKAT in 2016, then SKA1-MID…