21cm Cosmology: MeerKAT and the SKA

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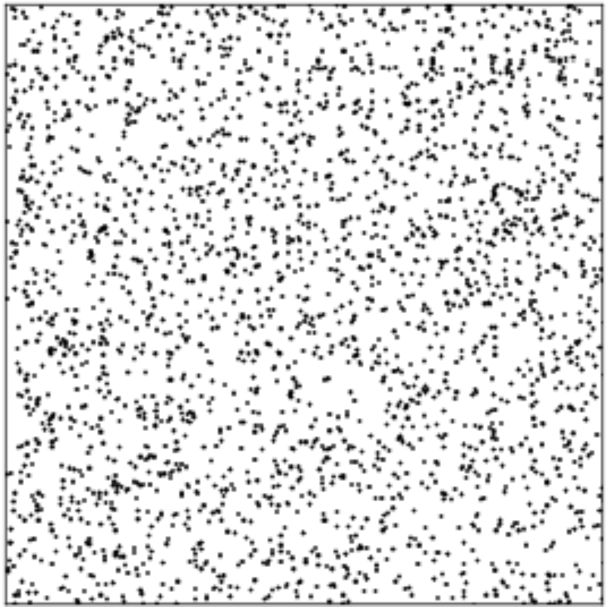
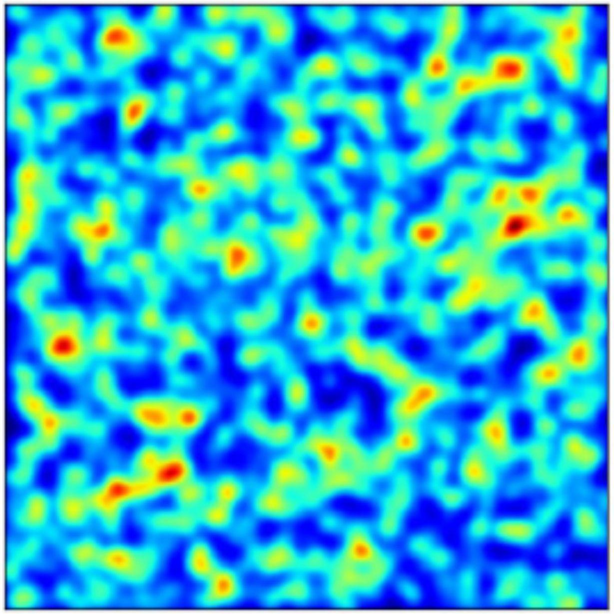
UWC ASTROPHYSICS
SKA AFRICA
SQUARE KILOMETRE ARRAY

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

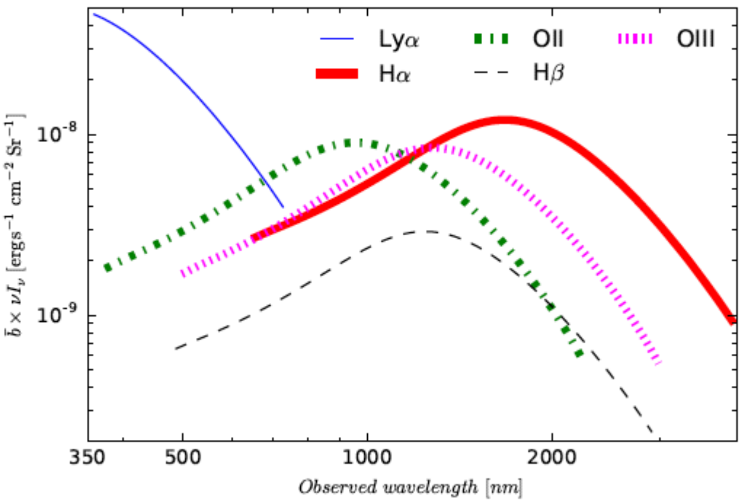


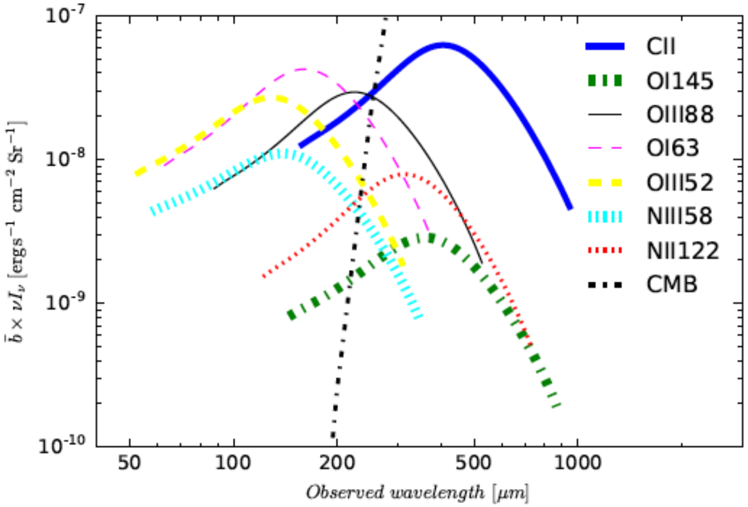
galaxies

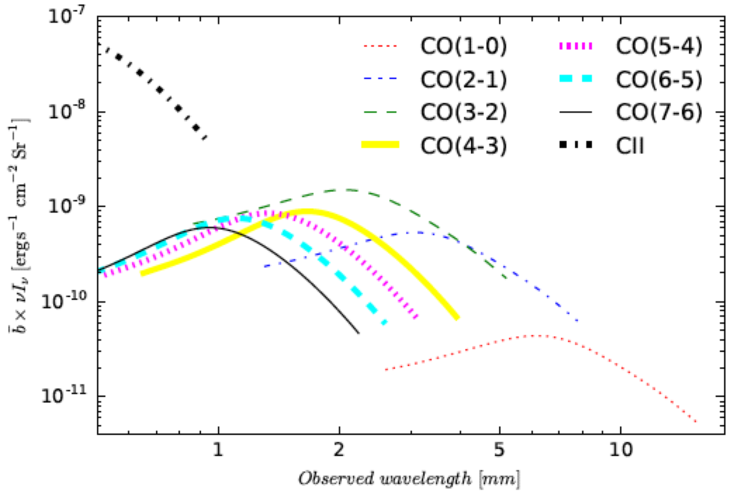


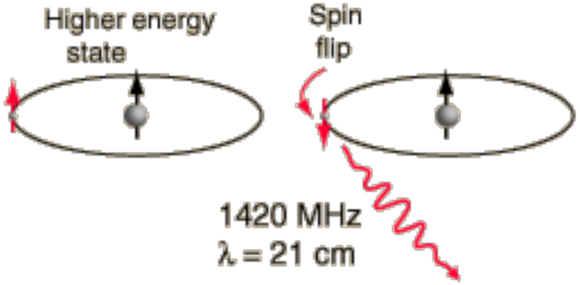
Intensity map

Which lines to use?







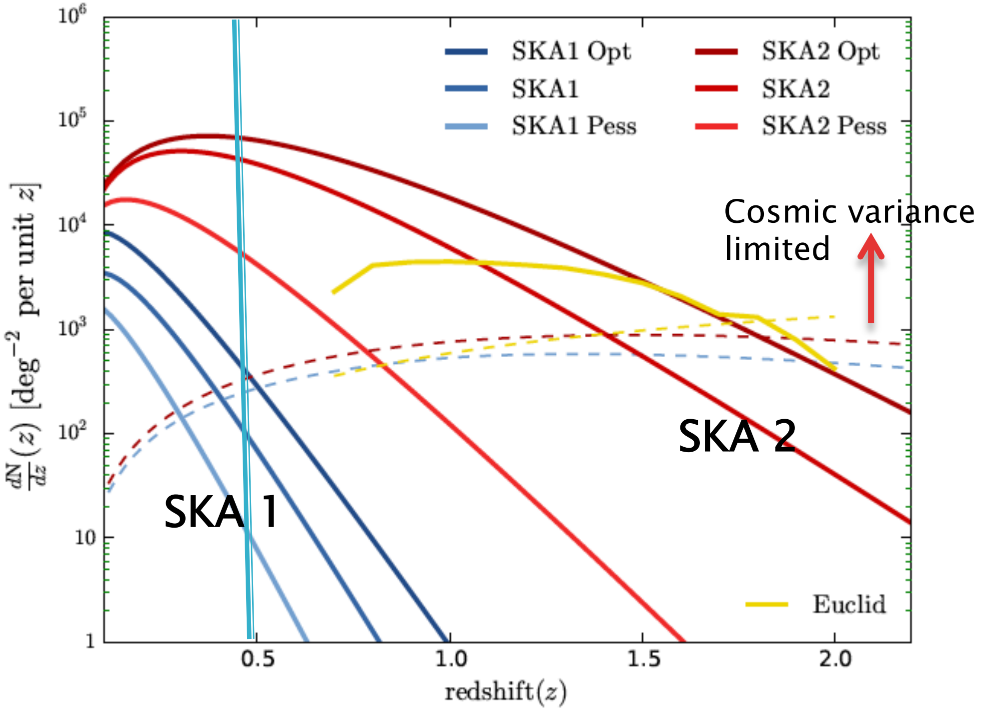


- HI (21 cm signal – 1.4 GHz)
- At z>6, HI signal dominated by IGM emission
- At z<3 (e.g. Cosmology), HI inside galaxies…

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…

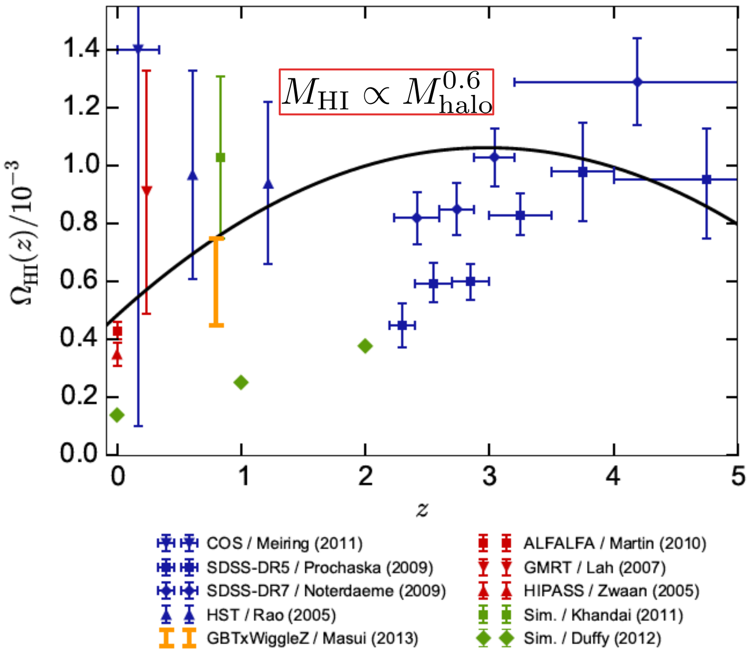


See Santos et al., http://arxiv.org/abs/1501.03990

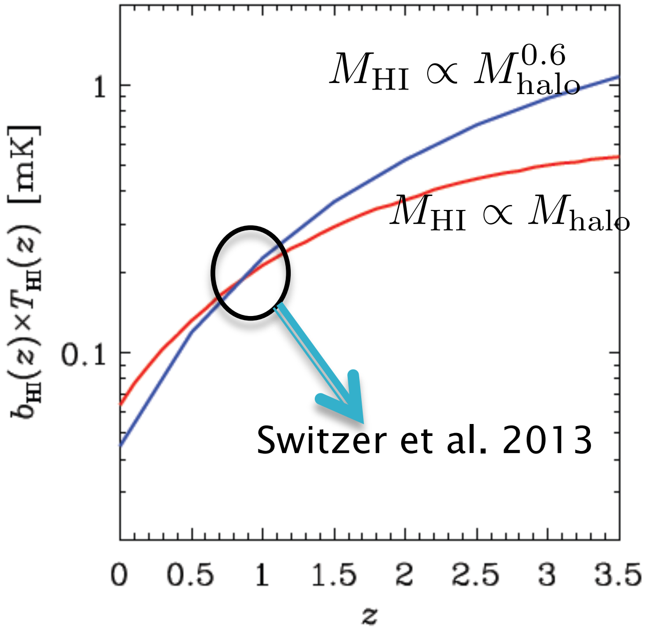
SKA1 ~ 10^7 galaxies over 5,000 deg^2
SKA2 ~ 10^9 galaxies over 30,000 deg^2

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

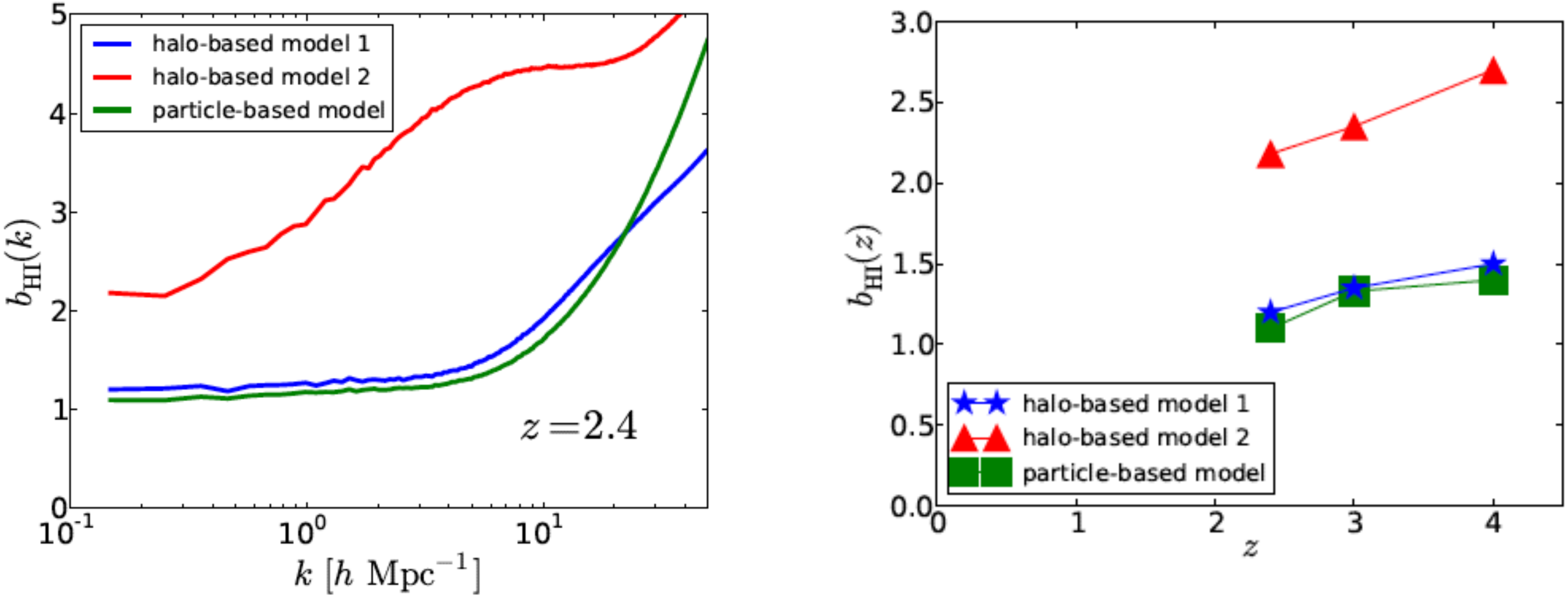


Switzer et al. 2013

Santos et al. 1501.03989

HI bias

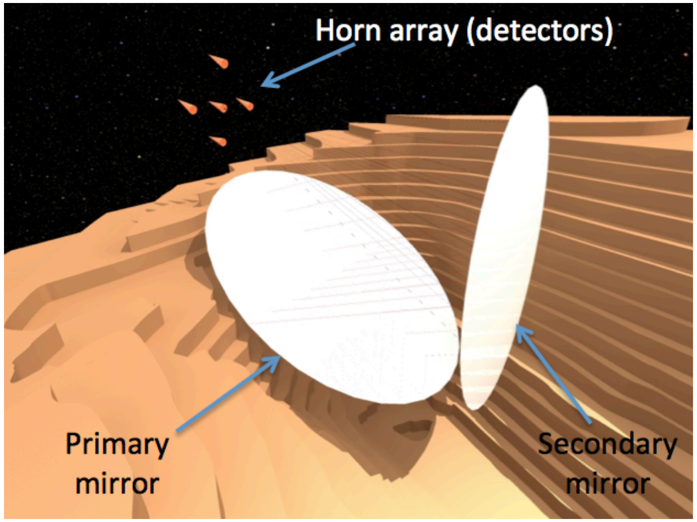
- For cosmological applications, crucial for bias to be scale independent
- DLA systems seem to indicate a larger bias at high z (e.g. HI in higher mass halos)
- (Villaescusa-Navarro et al 2014, Bagla et al. 2010, Padmanabhan et al.



Simulations from Villaescusa-Navarro et al. (2014)

How to measure it? – dish surveys

- Each pointing gives you 1 pixel on the sky
- Brightness sensitivity does not depend on dish size
- Good to observe large areas of the sky (crucial for Cosmology)

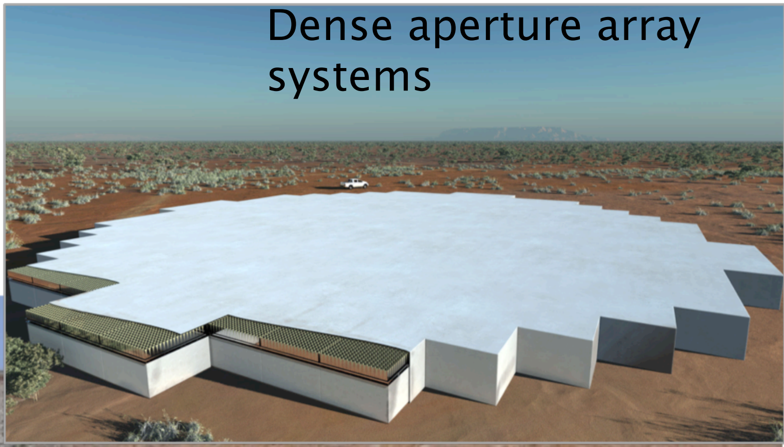


BINGO (Battye, et al., http://arxiv.org/abs/1209.1041)

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

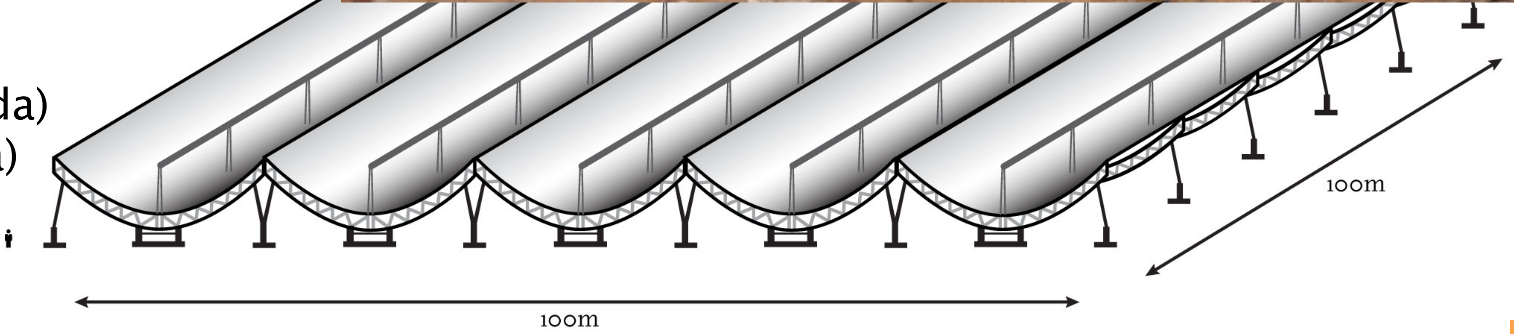
How to measure it? – interferometers

- Provide higher resolution
- Misses the large scales…


Dense aperture array systems

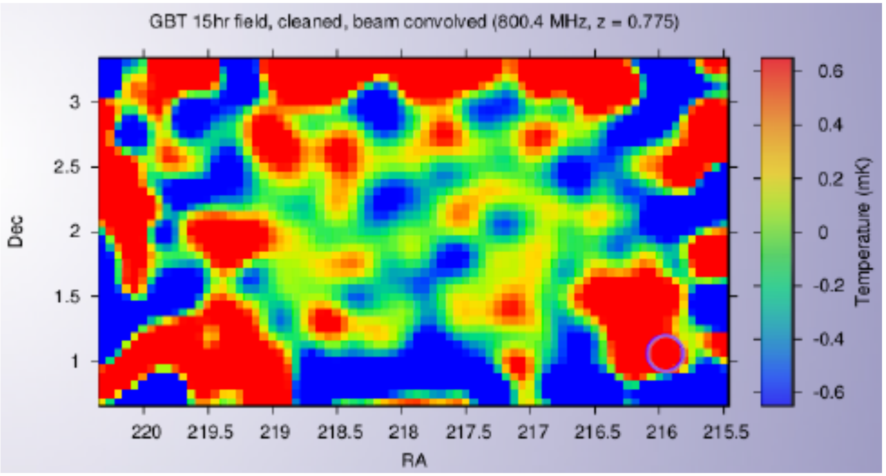
HIRAX (South Africa)
~ 1000, 5 m dishes
400 – 800 MHz ($0.8 < z < 2.5$)

- CHIME (Canada)
- Tianlai (China)



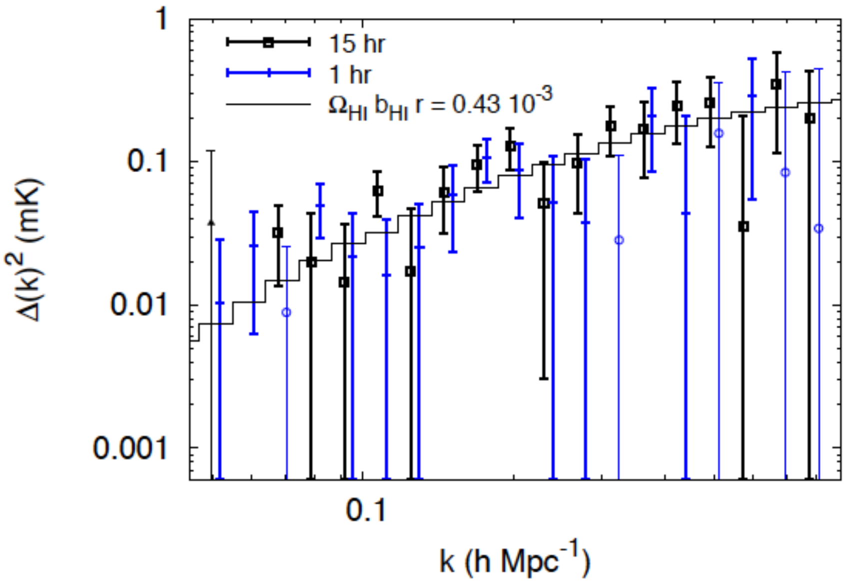
Current measurements…

- GBT: HI map at z~0.8 (noise/systematics dominated)



Masui, et al., ApJ 2012,
Chang et al., Nature 2010

- Detection: GBT cross-correlation with Wigglez



GBT (Switzer et al., 2013): Ω_{HI}bias $\sim 0.6 \times 10^{-3}$ at z~0.8

Crucial to have more detections, even if at low z…

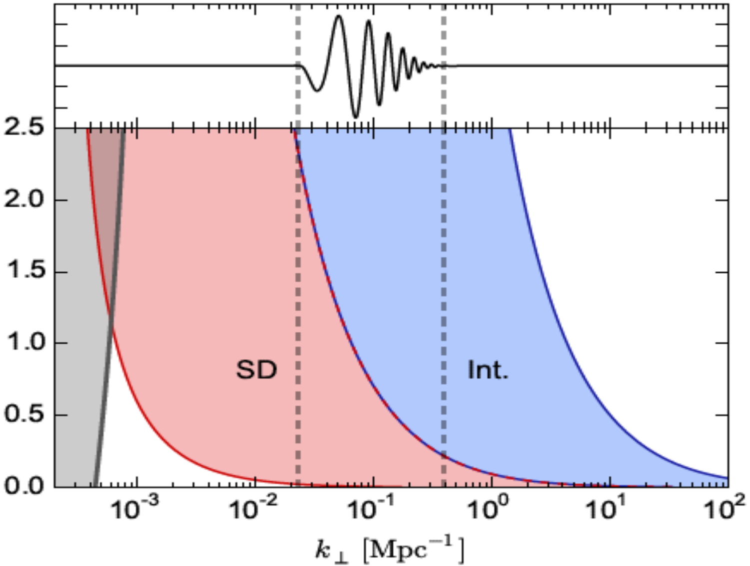
Stay tuned for MeerKAT 8/16!

SKA1 as an intensity mapping "machine"

- Interferometer: baselines not small enough to probe BAO scales and above (maximum scale set by smallest baseline!)
- Main idea: use each dish in "single observation mode"
- Save interferometer data for calibration
- SKA1-MID HI intensity mapping survey will turn SKA into a state of the art cosmological machine
- Only way to really go after the unexplored very large scales (specially in combination with LSST)
- Proposal to provide calibrated auto-correlations has been approved by the SKA office

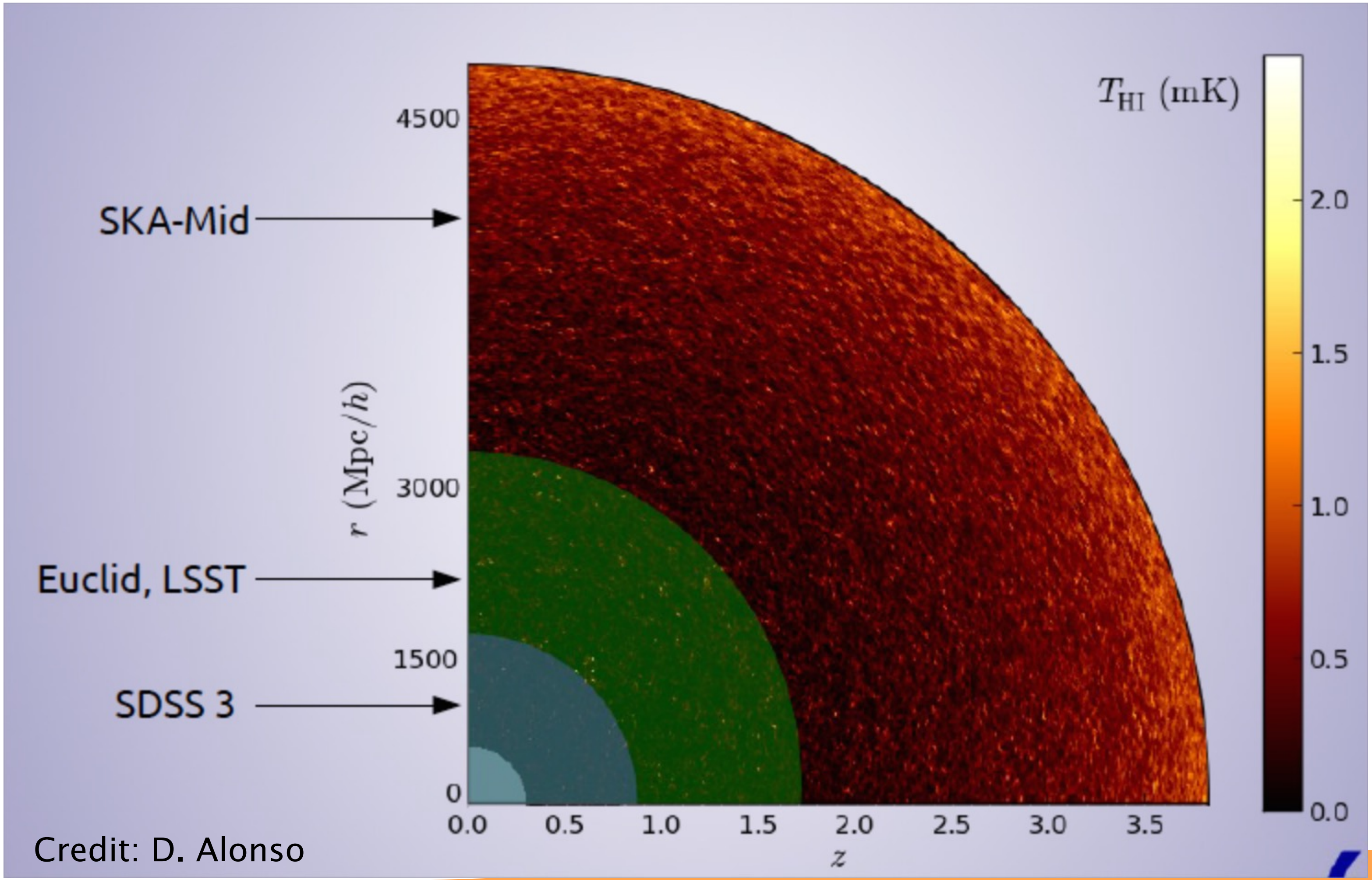
(see Santos et al. 1501.03989)

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



SKA1-MID: Cosmology with HI IM

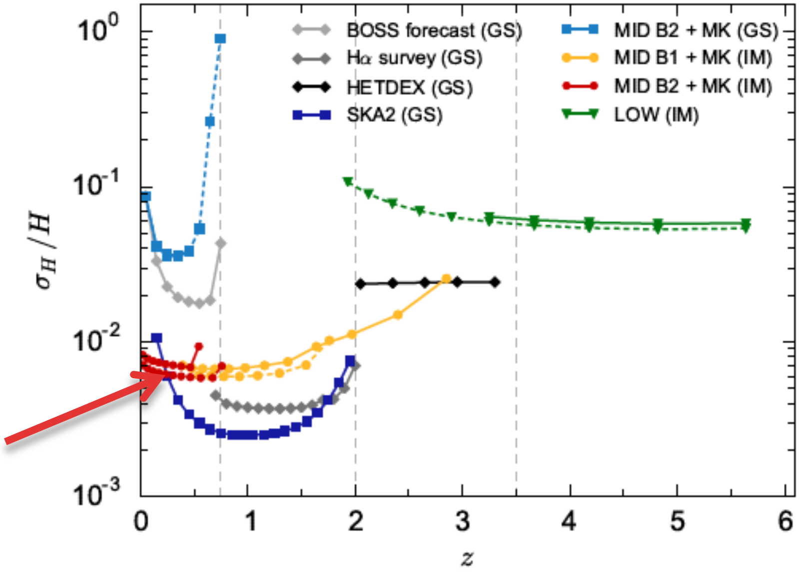
- Competitive with large redshift surveys for "precision cosmology"
- Huge available volume/low resolution – ideal for large scale tests



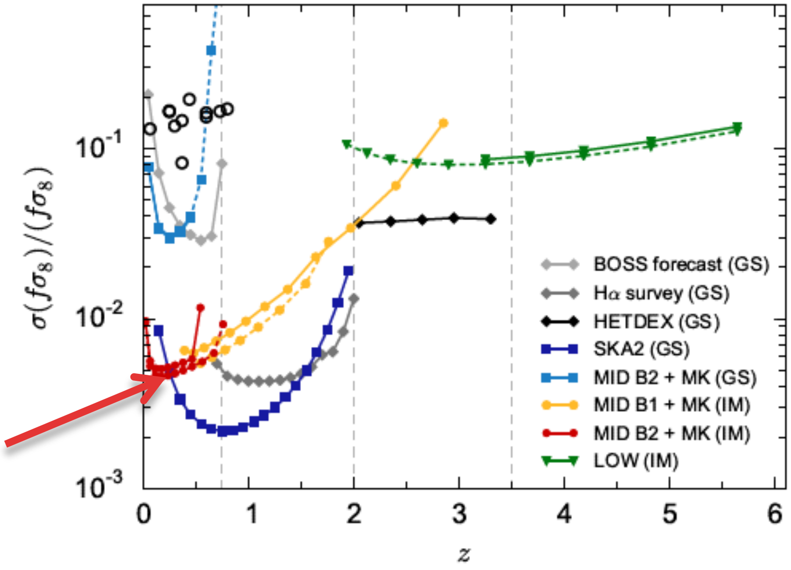
Credit: D. Alonso

High precision cosmology with SKA1-MID HI intensity mapping survey

Hubble rate



Growth rate

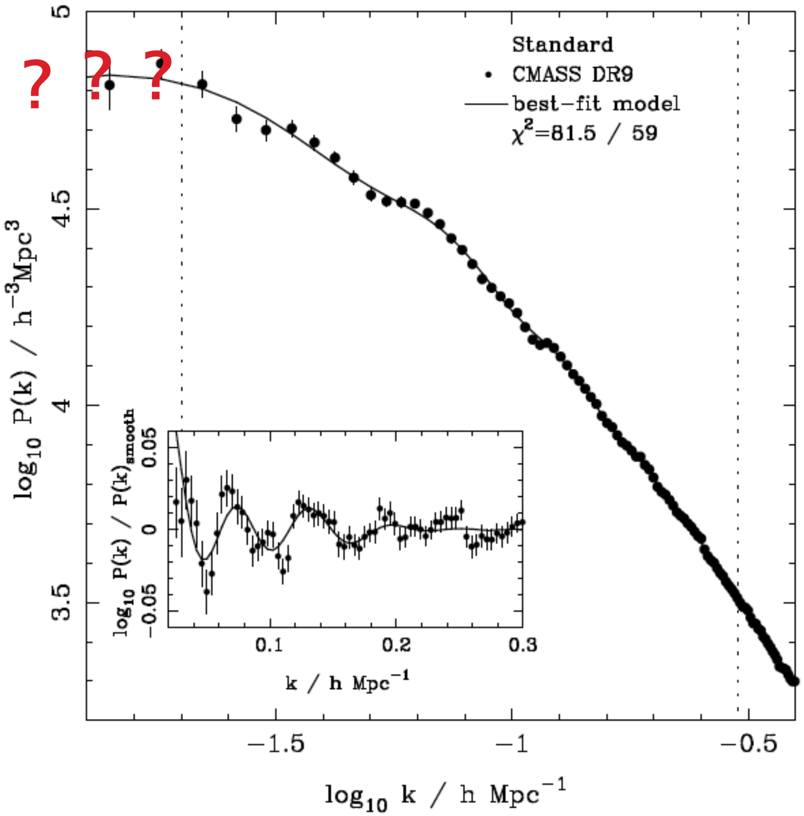


P. Bull, arXiv:1509.07562, 2015

- Use SKA1-MID band 2 ($z < 0.8$)
- Low z measurements will be unmatched and surpass contemporary spectroscopic galaxy surveys such as DESI and Euclid in terms of constraints on modified gravity parameters

What about really large scales?

- Scales near or above the horizon (at $z=2 \rightarrow k_H \sim 1.0\times10^{-3}$ h/Mpc)
- "Smoking gun" for new physics?
- Require general relativistic corrections:
  - Lensing magnification
  - Local terms (Doppler, Sachs-Wolfe type contributions)
  - Integrated terms (time delays, ISW…)
- No measurement yet…



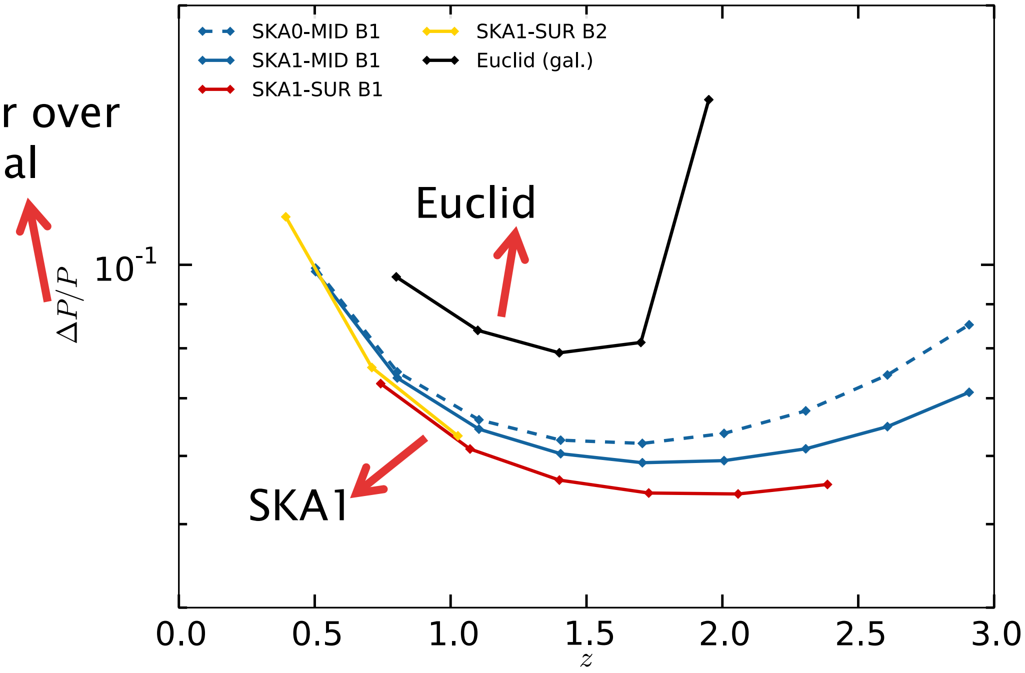
BOSS survey:
Anderson et al., MNRAS, 2012
Smallest k ~ 0.03 h/Mpc

Probing very large scales with a SKA1 HI intensity mapping survey

- Use band 1 ~ $0.5 < z < 3.0$
- ~ 20,000 deg^2
- Probe HI signal across large redshift range
- Probe homogeneity and primordial fluctuations
- Primordial non-Gaussianity:

$$\phi_{NG} = \phi + f_{NL}\left(\phi^2 - \langle\phi^2\rangle\right)$$

- Planck: $f_{NL} < 8$
- SKA: $f_{NL} < 2$ (Camera, Santos, Ferreira and Ferramacho, PRL, 2013)



Error over signal

Defeating cosmic variance with the multi-tracer technique – a breakthrough for Cosmology?

- Most large scale effects rely on measuring the bias of the tracer relative to dark matter:

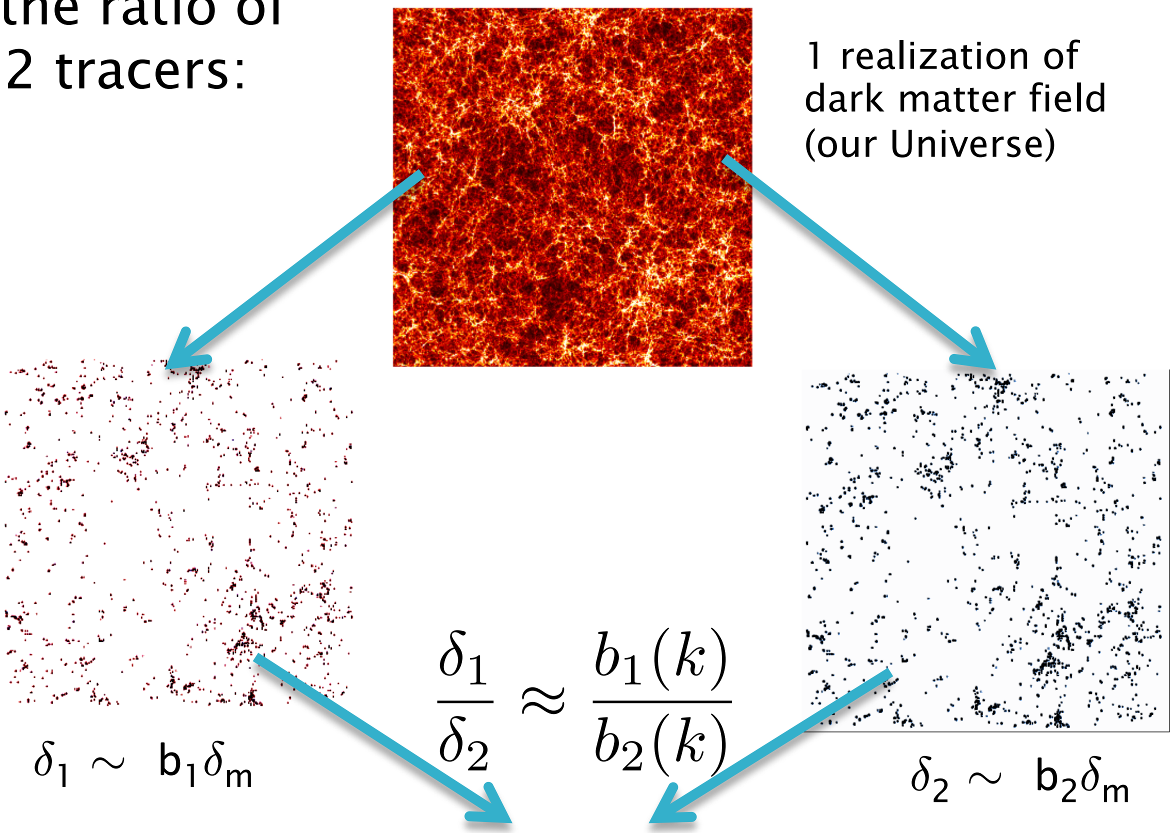
What we measure

$$P_G(k) = \overset{?}{\boxed{b(k)}} P_m(k)$$

- On large scales we will only have a few measurements of $P_G(k)$ -> large error (cosmic variance)…

The multi-tracer technique explained

- Look at the ratio of bias for 2 tracers:



1 realization of dark matter field (our Universe)

Galaxy survey 1 (with bias b_1)

Galaxy survey 2 (with bias b_2)

$\delta_1 \sim b_1\delta_m$

$\delta_2 \sim b_2\delta_m$

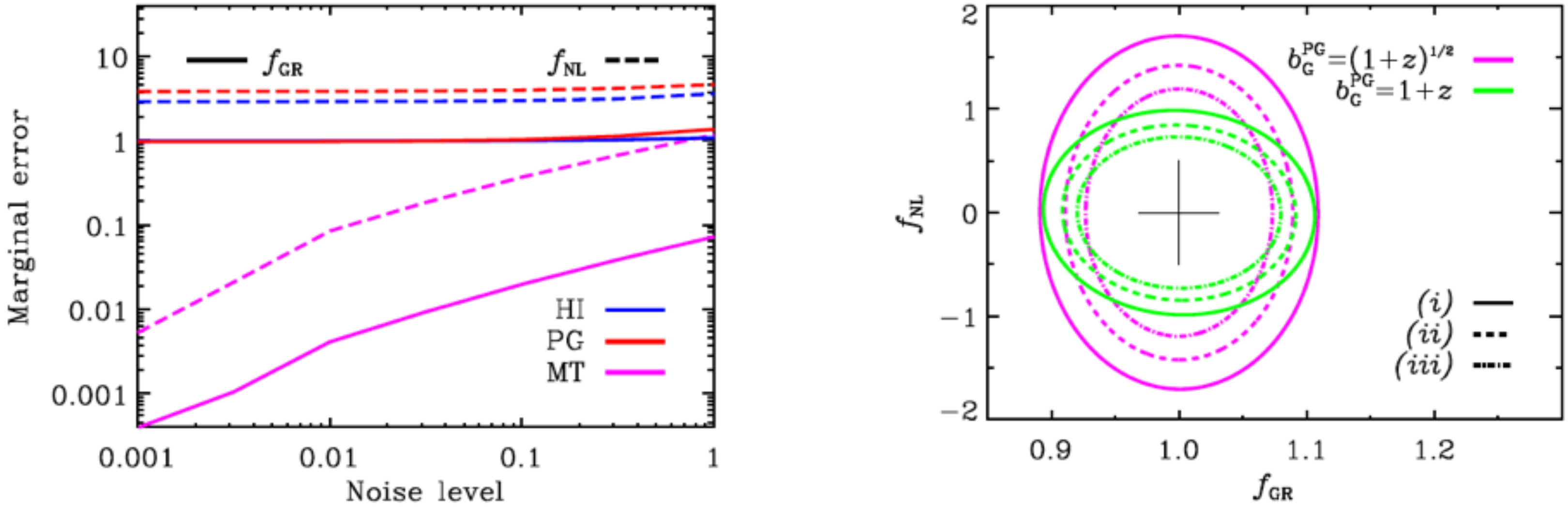
$$\frac{\delta_1}{\delta_2} \approx \frac{b_1(k)}{b_2(k)}$$

Divide the two maps to measure directly b1/b2 (plus shot noise) – no cosmic variance!

Seljak, PRL 2009

SKA1-MID HI intensity mapping and the multi-tracer technique

(see D. Alonso talk)



Fonseca et al., ApJ Letters, 2015
Alonso et al., PRD, 2015

- Combining a HI intensity mapping survey using SKA1-MID with Euclid or LSST will detect fNL < 1 as well as GR corrections!
- A powerful test of GR on large scales!
- A nice way to “fight” systematics

MeerKLASS: MeerKAT Large Area Synoptic Survey

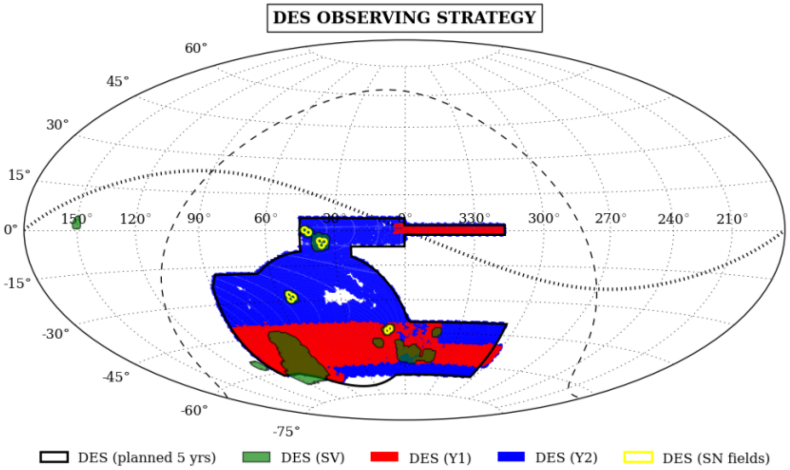
- Aim: Cosmology (IM/continuum) and lots of other stuff
- Current thinking: ~4,000 deg^2 down to ~ 6 uJy continuum (most sensitive radio survey on these scales)
- MeerKAT final specifications delivers excellent survey speed (large primary beam, low noise)
- Lower resolution makes it harder for continuum deep surveys
- Lots of other large sky science requires multi-wavelength data which is not available on full sky (for now)
- A crucial step in preparation for SKA1-MID large sky surveys
- Can start preliminary observations as early as 2017! (with 32 dishes and some tests with 16 dishes this year)

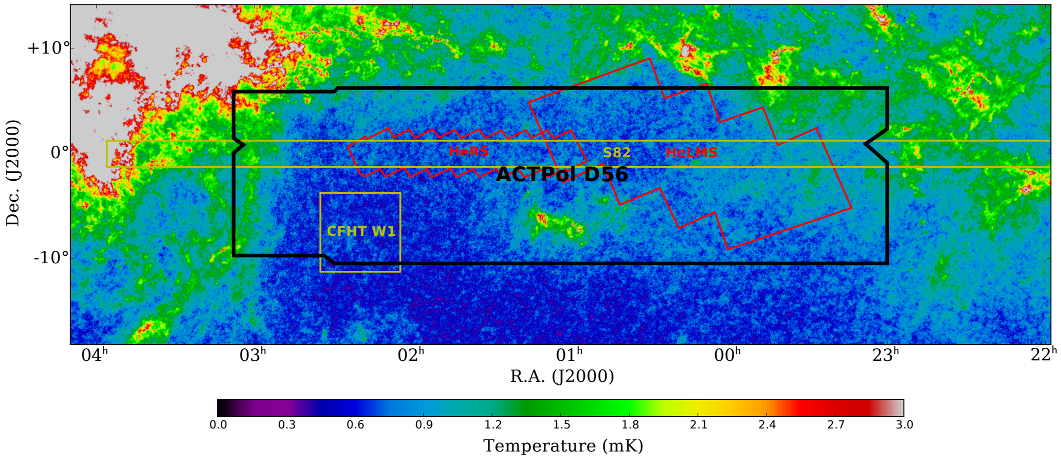
What science can we do?

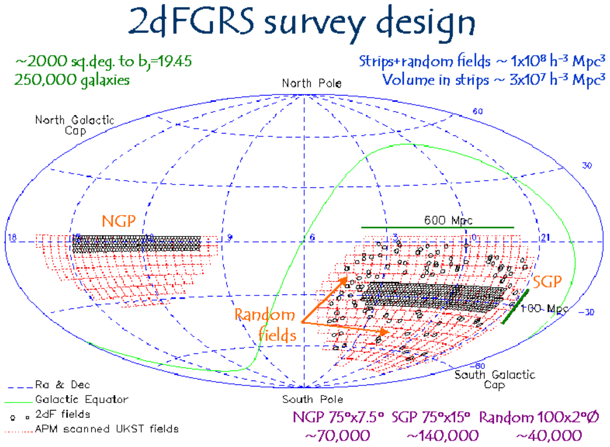
- Cosmology!
  - Continuum survey
  - HI intensity mapping
  - (and cross-correlations with multi-wavelength data)
- A large statistical investigation of galaxy clusters
- Study of radio halos and relics in clusters
- Probe the AGN and SFG populations up to large masses
- Statistical measurements of the HI mass function at the high end
- Find the rarest high-redshift AGN which can be used to probe the epoch of reionization through 21-cm absorption studies
- Produce a rotation measure map across a large patch of the sky
- Detect thousands of sources which can be used to investigate associated HI absorption systems
- Transient searches
- ____add your science here____

Survey specs

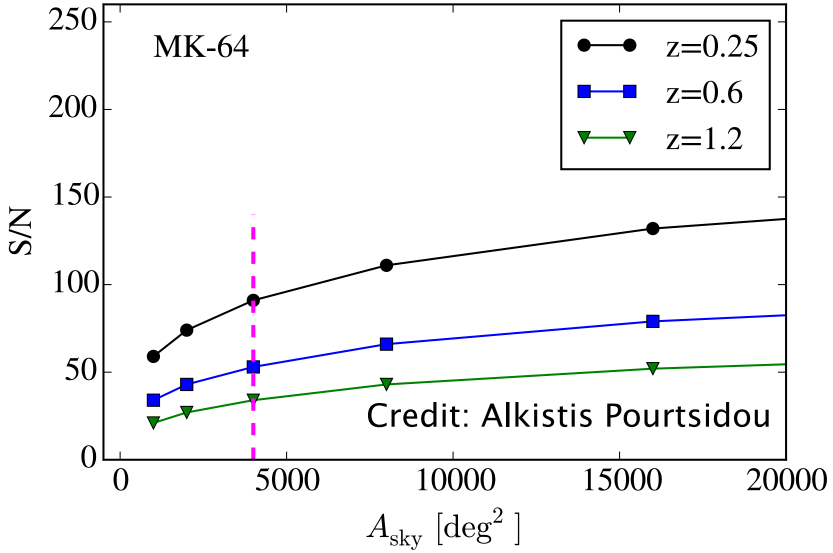
- Choose a sky patch with lots of multi-wavelength data coverage: DES, 2df, KIDS+VIKING, ACT, SPT, Herschel…
- On-the-fly scanning: increased telescope stability across the sky patch, much more time efficiency because of less overheads
- Survey ~ 4,000 deg^2 every day? Useful for transient science
- L-band/UHF band? UHF better for redshifts, probing very large scales and and cluster science, L-band gives more S/N for BAO/RSDs and higher resolution for continuum…
- ~ 4,000 hours and ~ 4,000 deg^2 -> ~ 6 uJy rms in continuum for L-band





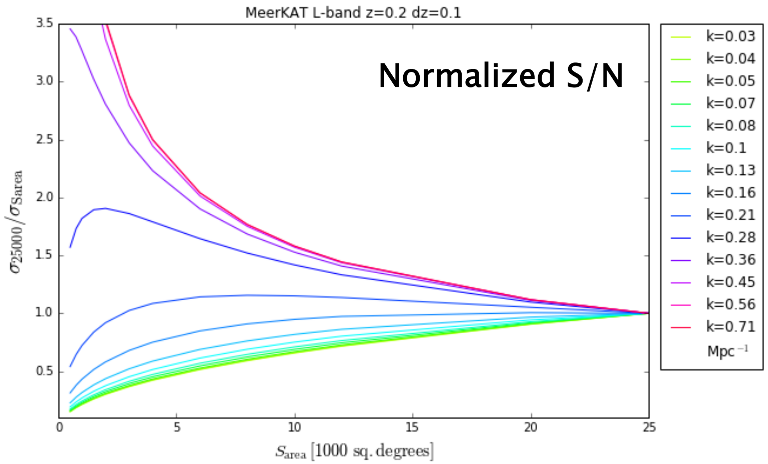


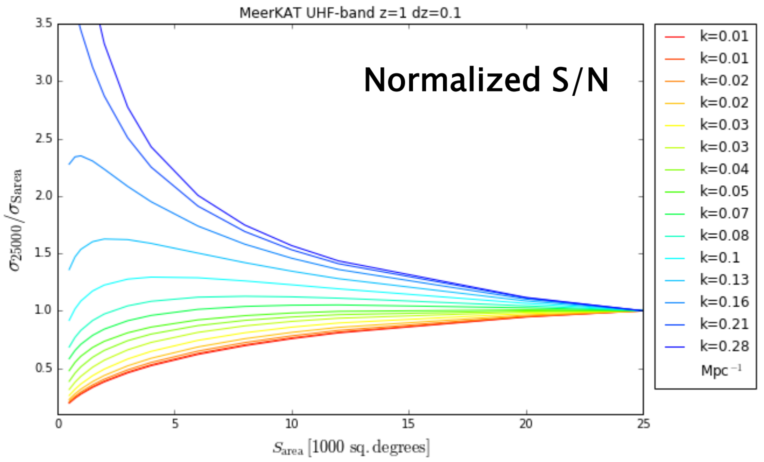
First detections with MeerKAT...



Credit: Alkistis Pourtsidou

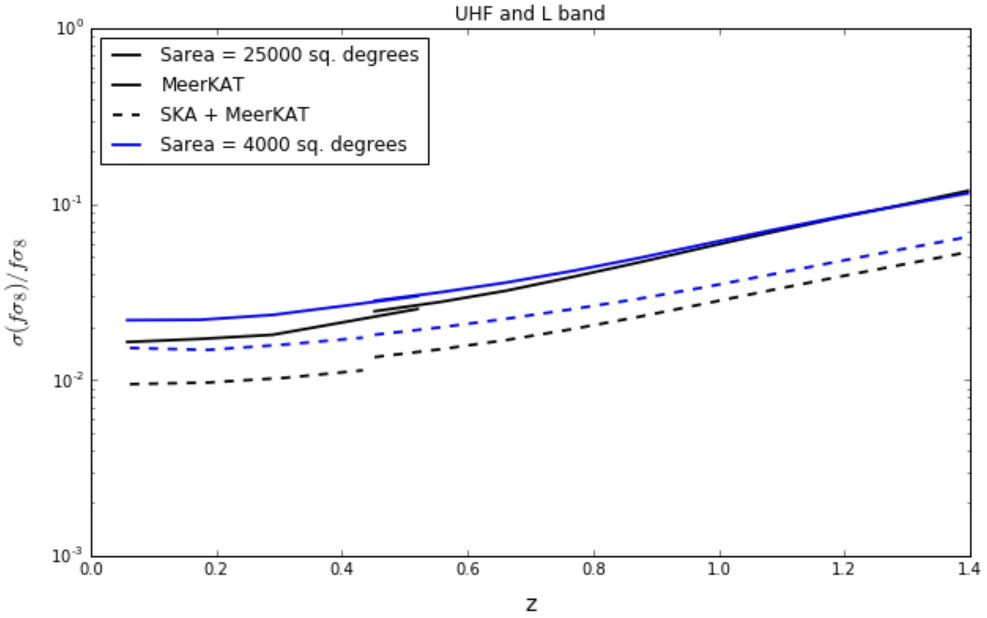
- Nominal survey: 4,000 hours.
- ~ 4,000 deg^2 area seems a good compromise
- Better S/N on L-band but smaller z...





Credit: Amadeus Witzemann

Redshift Space Distortions with MeerKAT!

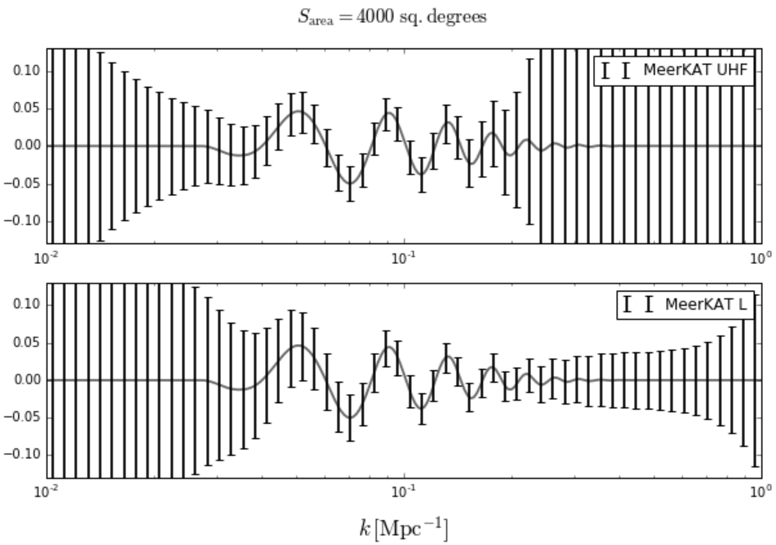


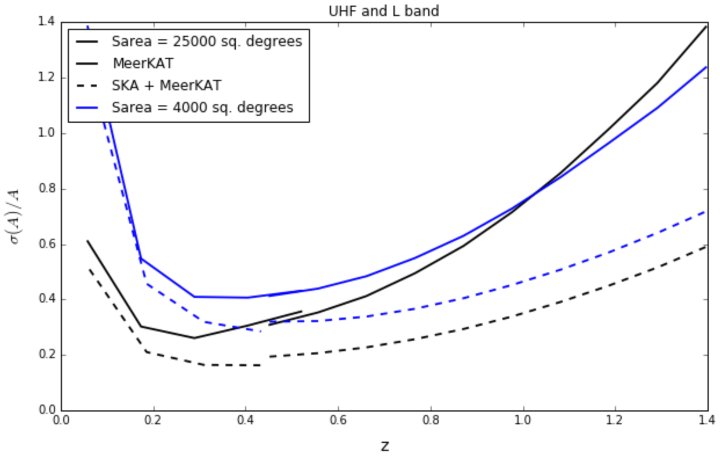
Credit: Amadeus Witzemann

- Constraints on growth rate will surpass the BOSS survey and be unmatched at low z on near future
- Results will allow to detect deviations from General Relativity!

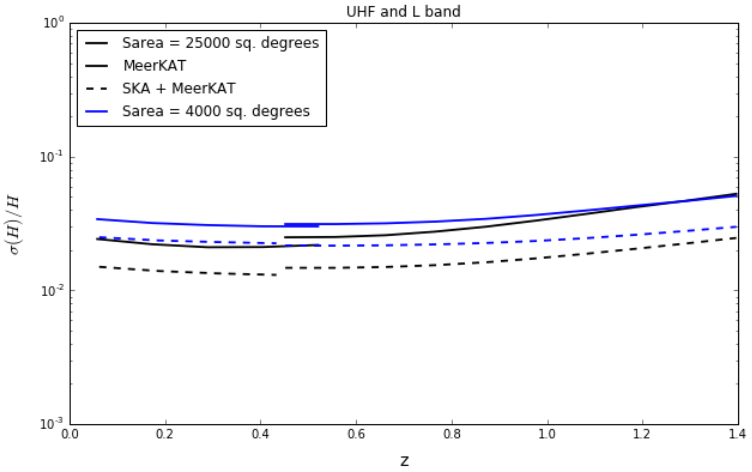
BAO with MeerKAT

- Possibly the first detection of baryon acoustic oscillations using the intensity mapping technique…
- A probe of dark energy
- Right: BAO wiggles
- (4,000 hours)





- Total BAO amplitude (error/signal)

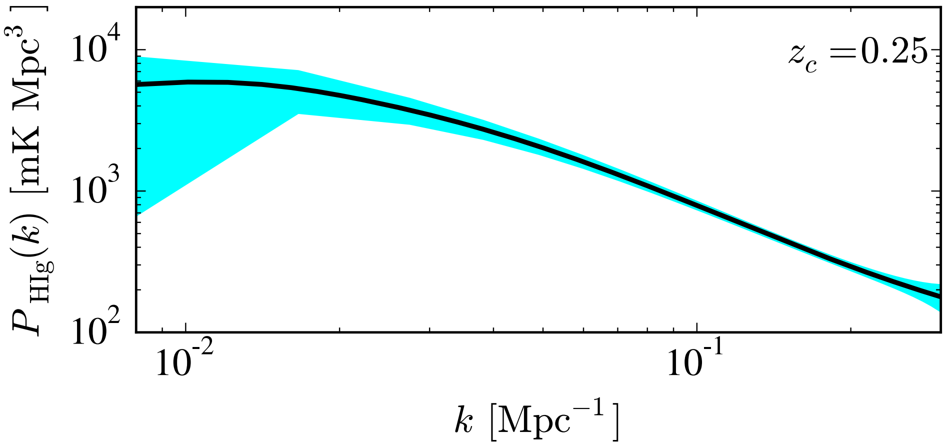


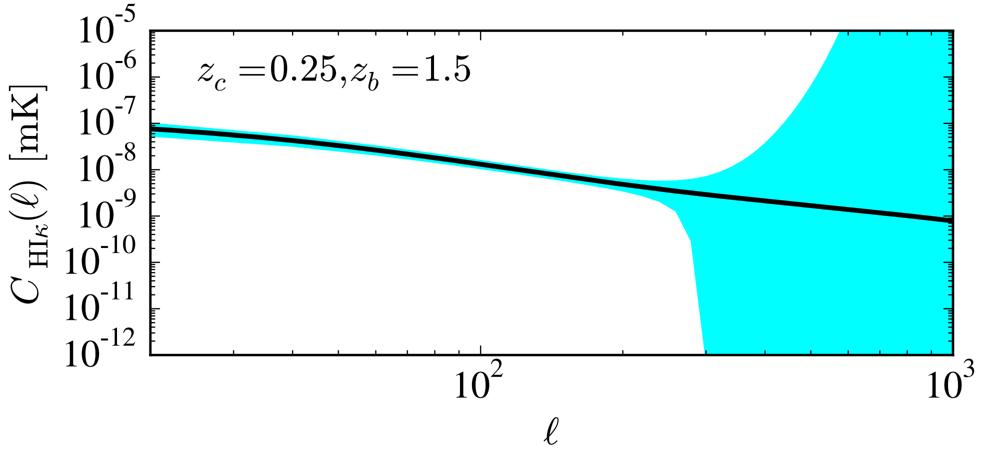
- Hubble rate (error/signal)

Credit: Amadeus Witzemann

Cross-correlating with other surveys

- One possibility: use DES (~ 5,000 deg^2, photometric redshifts up to z ~1, 5 bins)
- Great way to deal with foregrounds and systematics!
- Use DES galaxies as background sources to detect cross-correlation between the HI density field and lensing!
- Top: cross-correlation with galaxies
- Bottom: cross-correlation with lensing
- Precursor science for LSST/SKA!

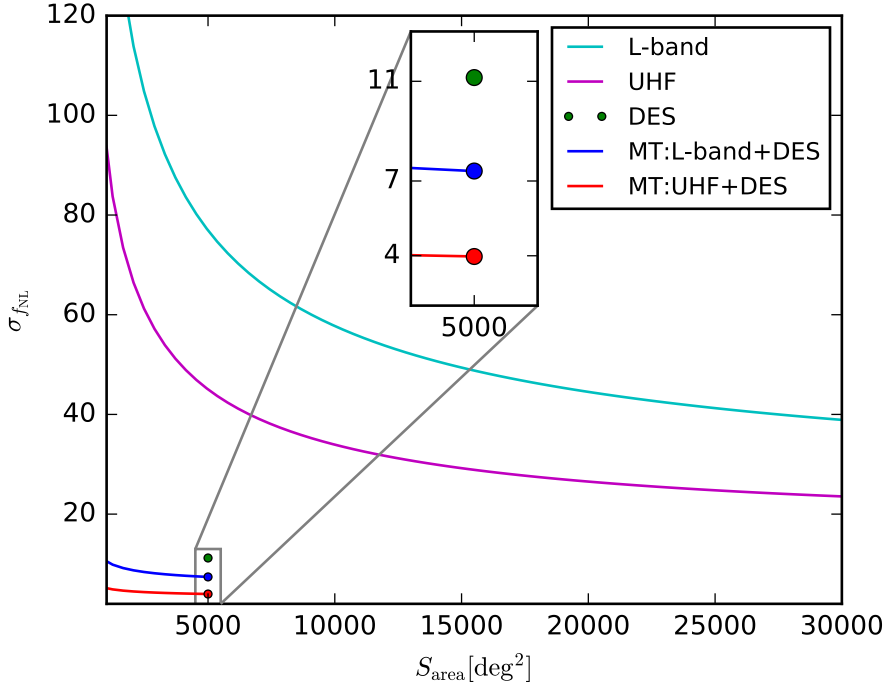




Credit: Alkistis Pourtsidou

Probing the nature of primordial fluctuations with MeerKAT

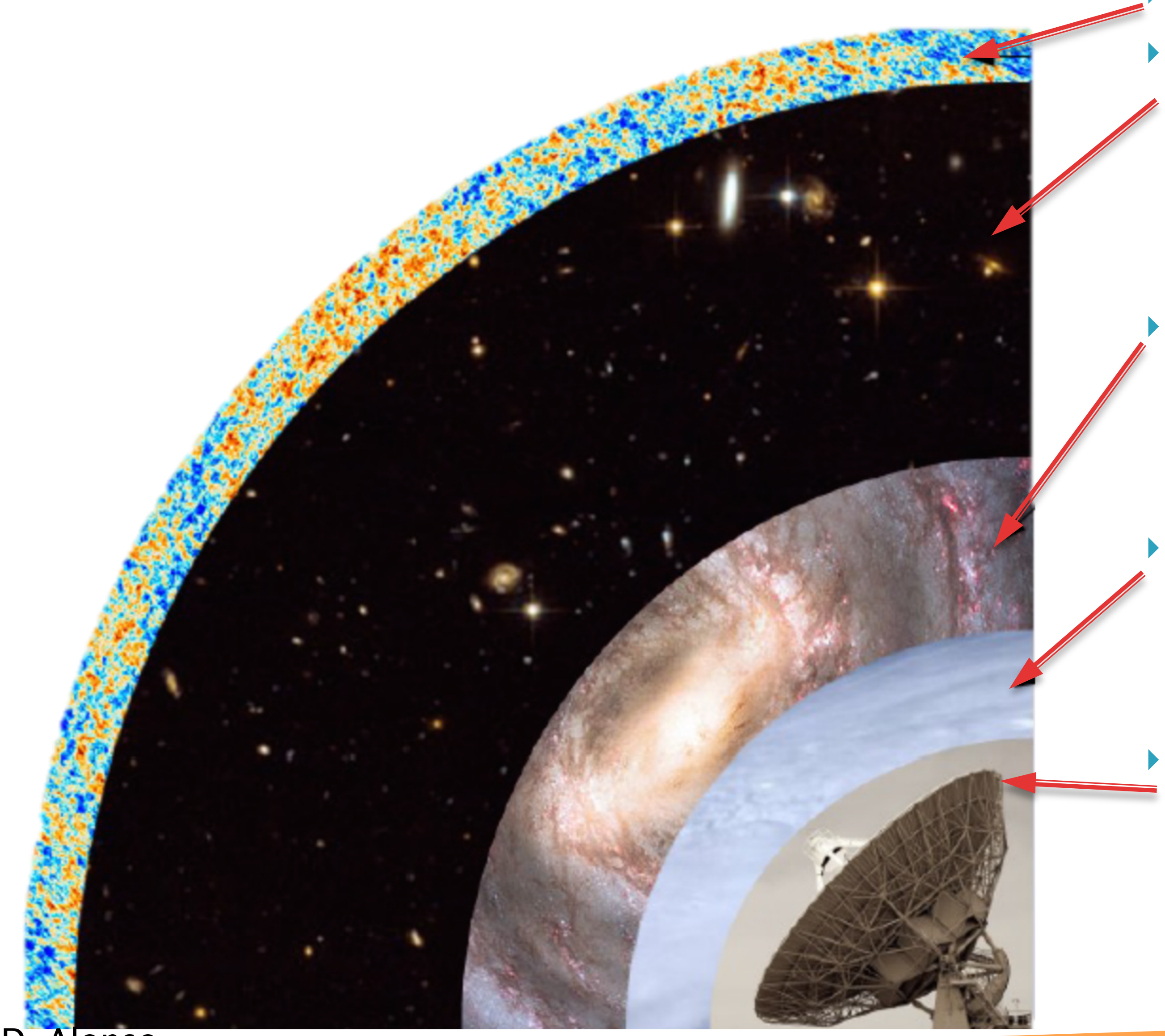
- Are they Gaussian?
  - $f_{NL}=0$ – yes
  - $f_{NL}\neq 0$ – No
- Look for clustering effect on large scales – bias
- Use the multi-tracer technique with DES to “kill” cosmic variance!
- Results:
  - L-band: $f_{NL}< 7.3$
  - UHF-band: $f_{NL}< 3.6$
  - **(Planck ~ 6.5)**



Fonseca et al.

(see Fonseca et al., ApJ Letters, 2015 – SKA+LSST: fNL< 0.5)

Challenges with IM observations…



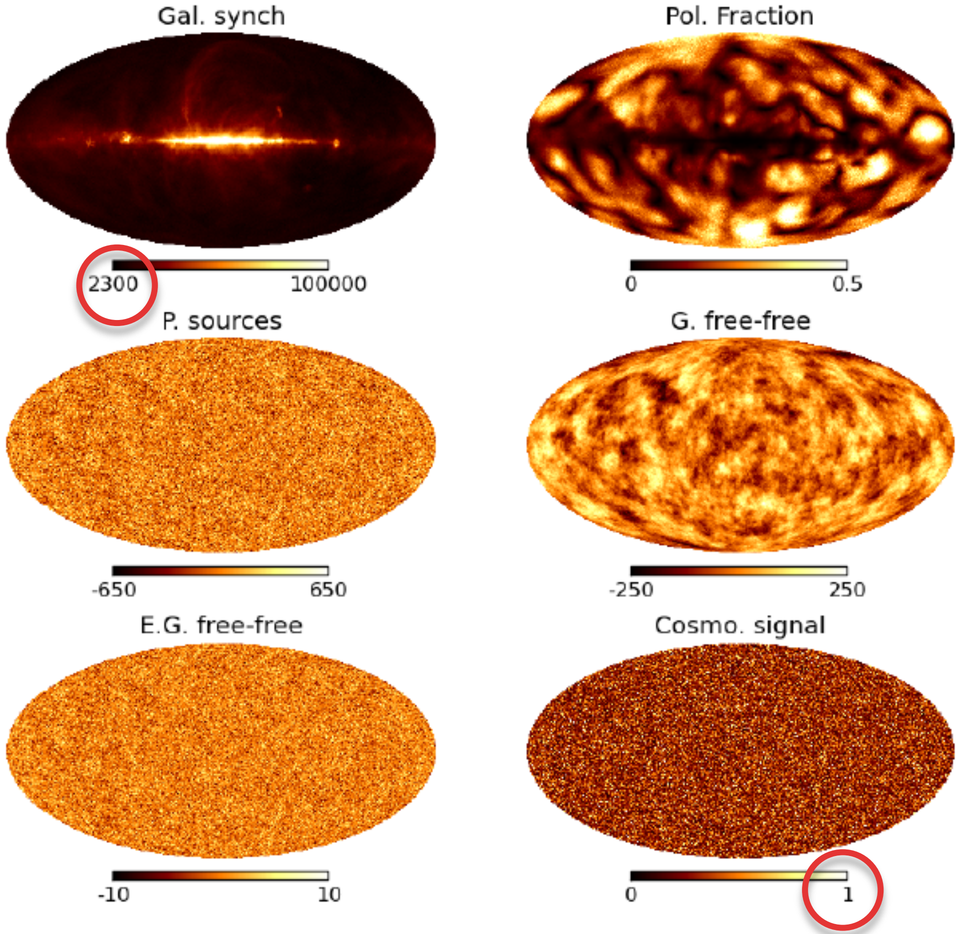
- HI IM signal
- Extragalactic foregrounds:
  - Point sources
  - E.G. free-free

  (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…

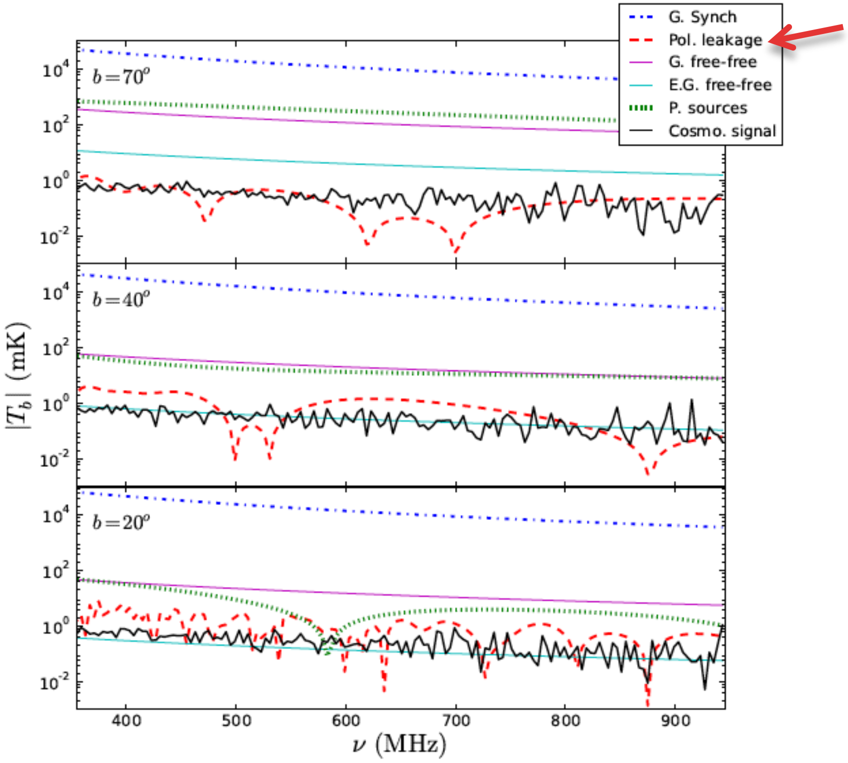


T [mK]

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

Foreground cleaning…

- Take advantage of extra information: foregrounds are smooth across frequency while signal fluctuates
- Results show that signal can be extracted with great accuracy (*Alonso, et al., MNRAS 2014*)
- However: fluctuations in the instrument will make these much more difficult!
- Tests currently being done with KAT7 and soon with MeerKAT!

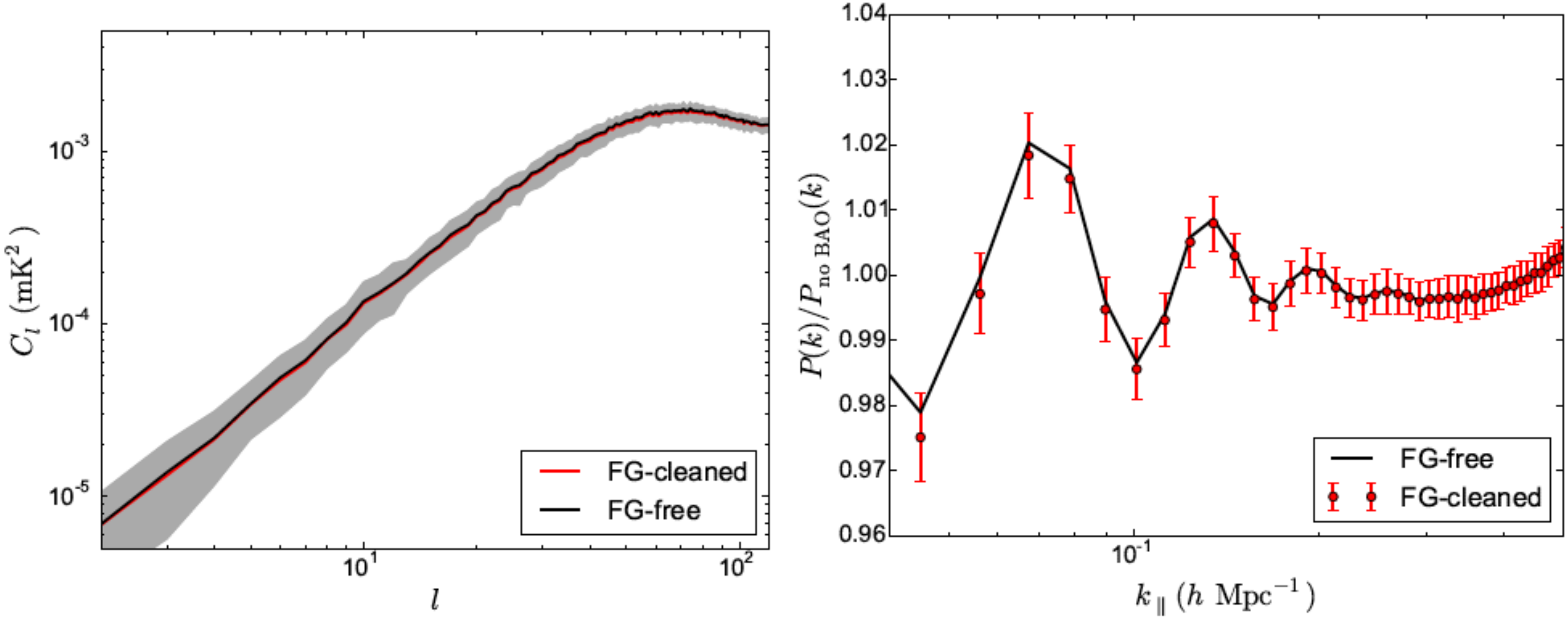


Foregrounds frequency dependency

- Methods: Polynomial fitting (Gleser et al. 2008, Liu et al. 2009), CCA (Ricciardi et al., 2010), Wp smoothing (Harker et al. 2009), FastICA (Hyvärinen et al. 1999, Chapman et al. 2012, Wolz et al. 2013), GMCA (Chapman et al. 2013), GNILC (Olivari et al.), Bigot-Sazy et al.

BAO after foreground cleaning

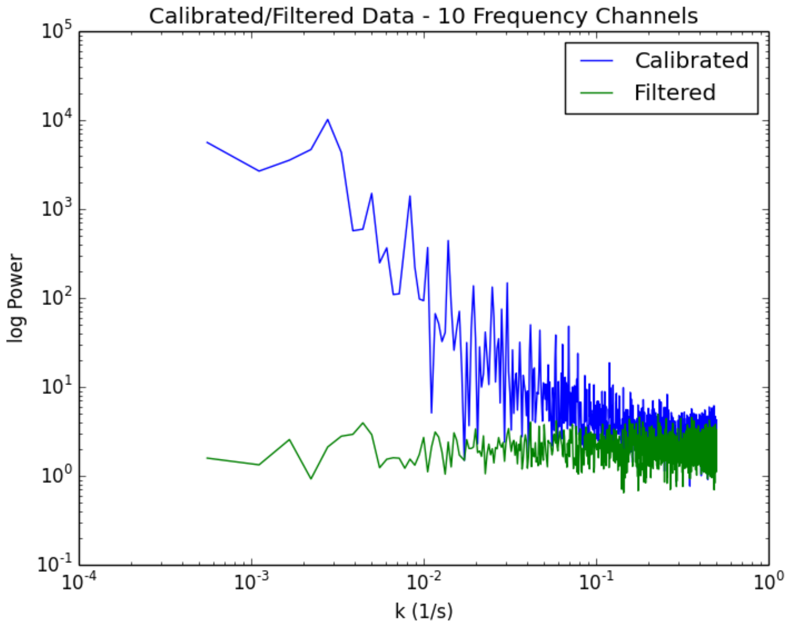
- Features such as BAO recovered with no bias
- **Very robust to contaminations...**

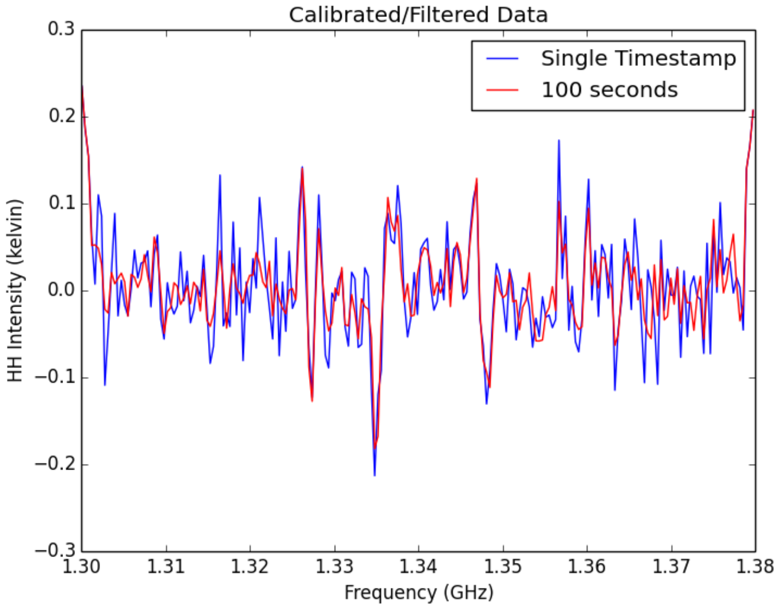


Alonso, Bull, Ferreira & Santos. ArXiv:1409.8667

Tests with KAT7…

Credit: Prina Patel (with thanks to Sean Passmoor and the KAT office team!)

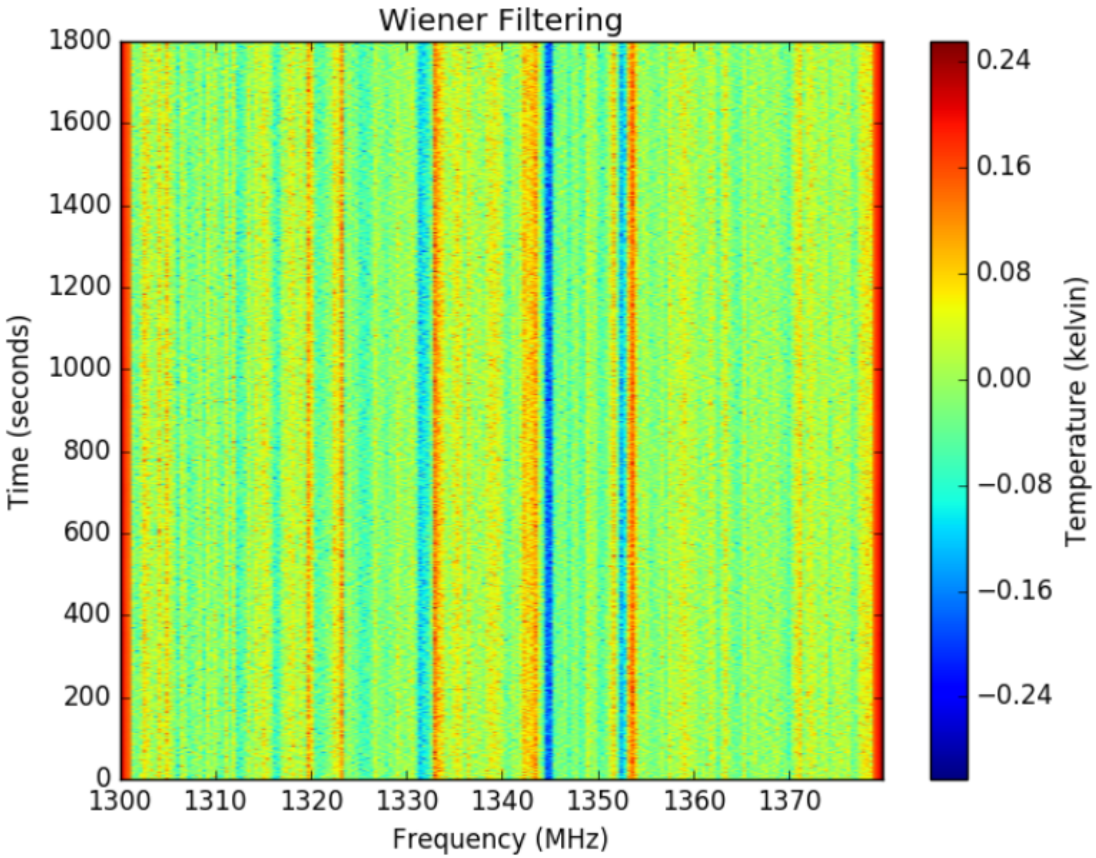




- Power spectrum of the time stream (drift scan) before and after filtering a smooth component in frequency

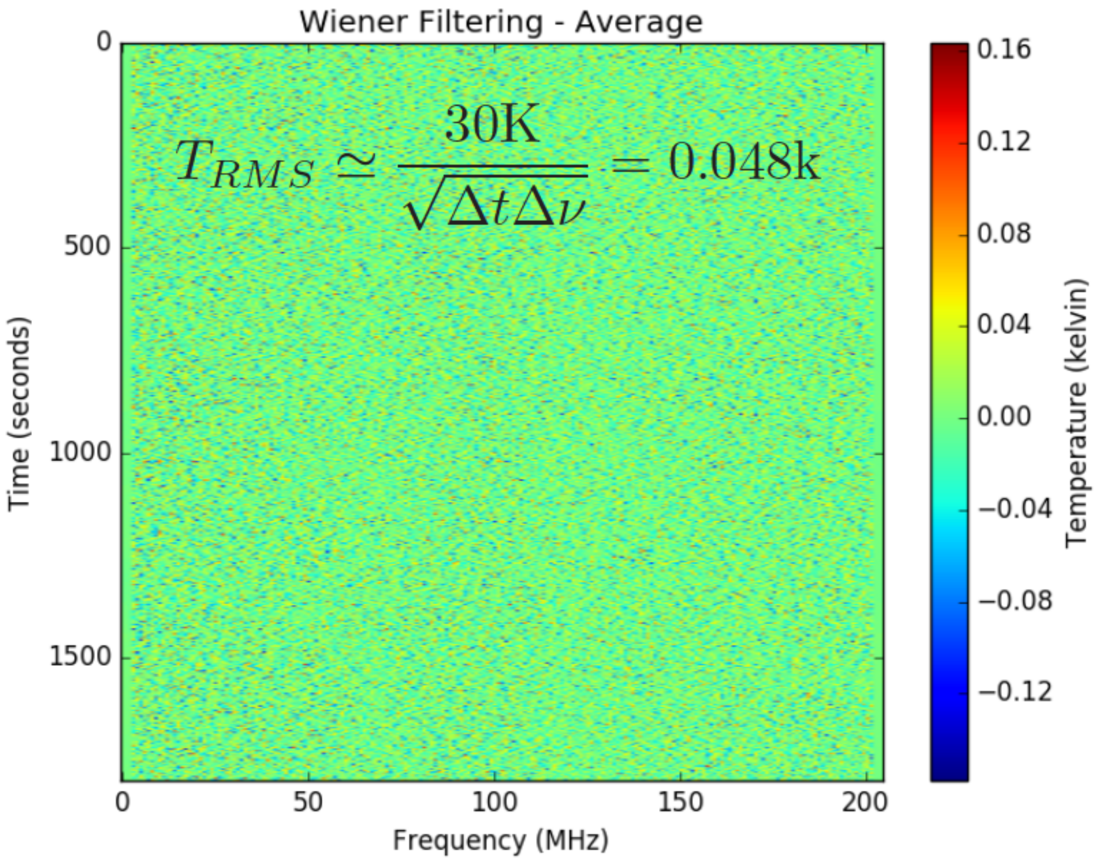
- Residuals in intensity after smooth frequency component is removed -> residuals probably due to the primary beam…

Wiener Filtering:



Leaves a very distinct signature in frequency that appears very constant in time

Prina Patel



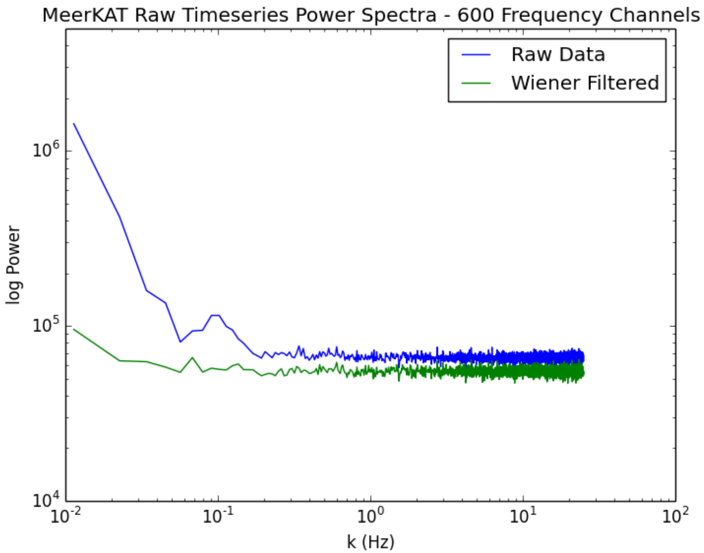
$$T_{RMS} \simeq \frac{30\mathrm{K}}{\sqrt{\Delta t \Delta \nu}} = 0.048\mathrm{k}$$

Subtract off this very constant pattern and you're left with noise like residuals (but rms level is below the expected signal)

Observations with MeerKAT…

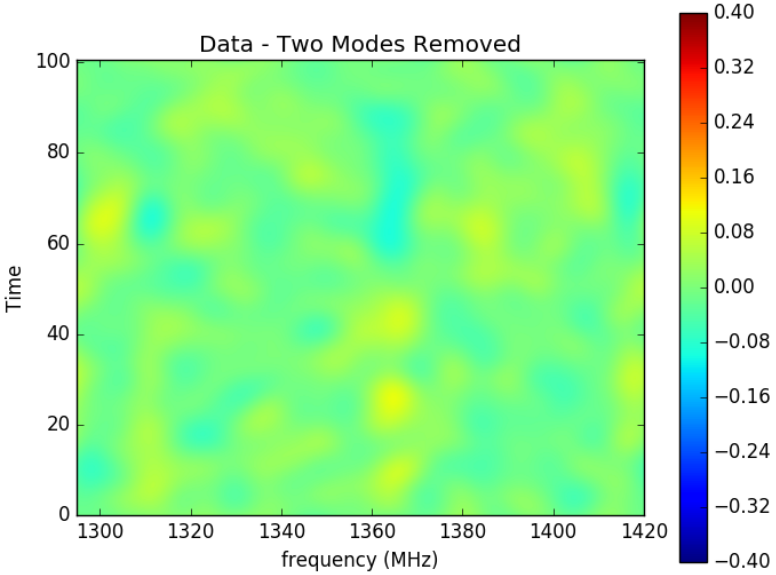
- 1 single dish
- 100 seconds observations of South Celestial Pole
- 50 Hz time sampling…

(with thanks to Adriaan
Peens-Hough and the
MeerKAT engineering team)



Prina Patel

- 1/f knee around 1 sec.
- Filtering in frequency moves the knee to ~ 20 sec.



Jon Sievers

- SVD analysis
- Data looks as white noise after top 2 modes removed…

MeerKAT: IM obsevation pipeline

- Stable noise injection available for every dish (noise diode is stabilized to achieve $< 0.04\%$ RMS computed over 20 minute intervals)
- Fast time sampling and fast noise switching if needed
- Scanning stable up to 5 deg/min but possible to go up to 2 deg/sec
- Use sky model for further calibration (pulsars?) – we have the interferometer data!
- Cross-correlate maps between different dishes…

Conclusions

- The HI intensity mapping signal will provide an unique (and transformational) window on Cosmology (from dark energy to Gravity and the primordial Universe):
- The HI intensity mapping technique will allow MeerKAT to deliver state of the art cosmological constraints: first detections of the signal? (2017!), BAO in HI – dark energy, RSDs – modified gravity, primordial non-Gaussianity…
- Preliminary tests with MeerKAT shows low 1/f noise after cleaning. Noise diodes should provide stable calibration up to 20 min. at least. System will allow fast scanning across the sky. Target: 4,000 deg^2
- However, the coupling between the bright sky and instrument fluctuations will present several challenges (in particular for the primary beam)…