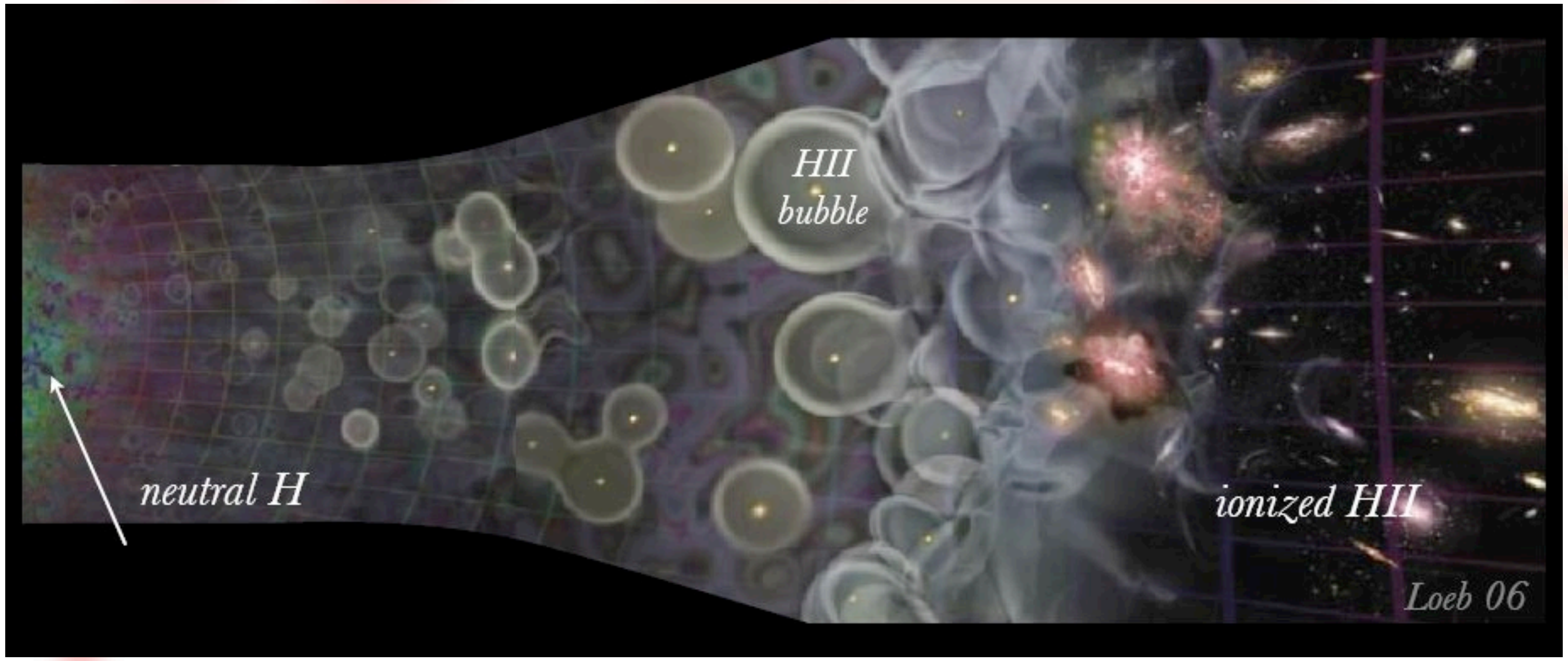


International Centre for Radio Astronomy Research

SKA EoR Experiments

Array design and challenges

Cathryn Trott
DECRA Fellow - Curtin Institute of Radio Astronomy

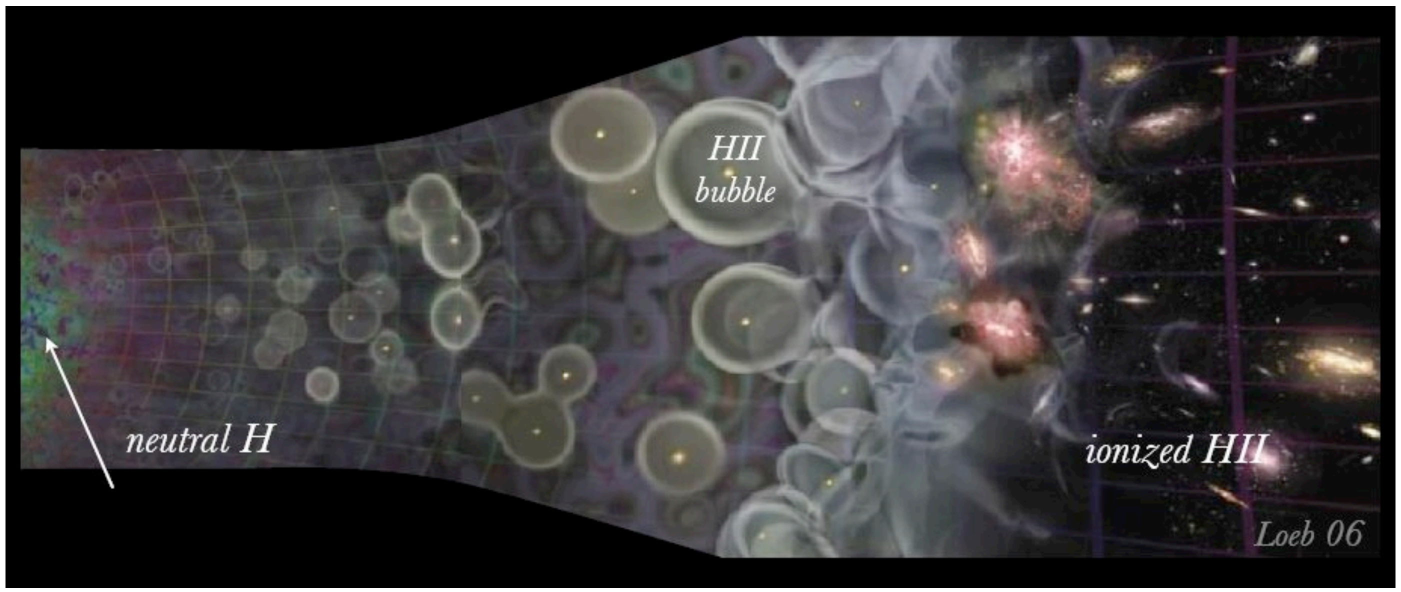
CAASTRO ALL-SKY ASTROPHYSICS

Curtin University

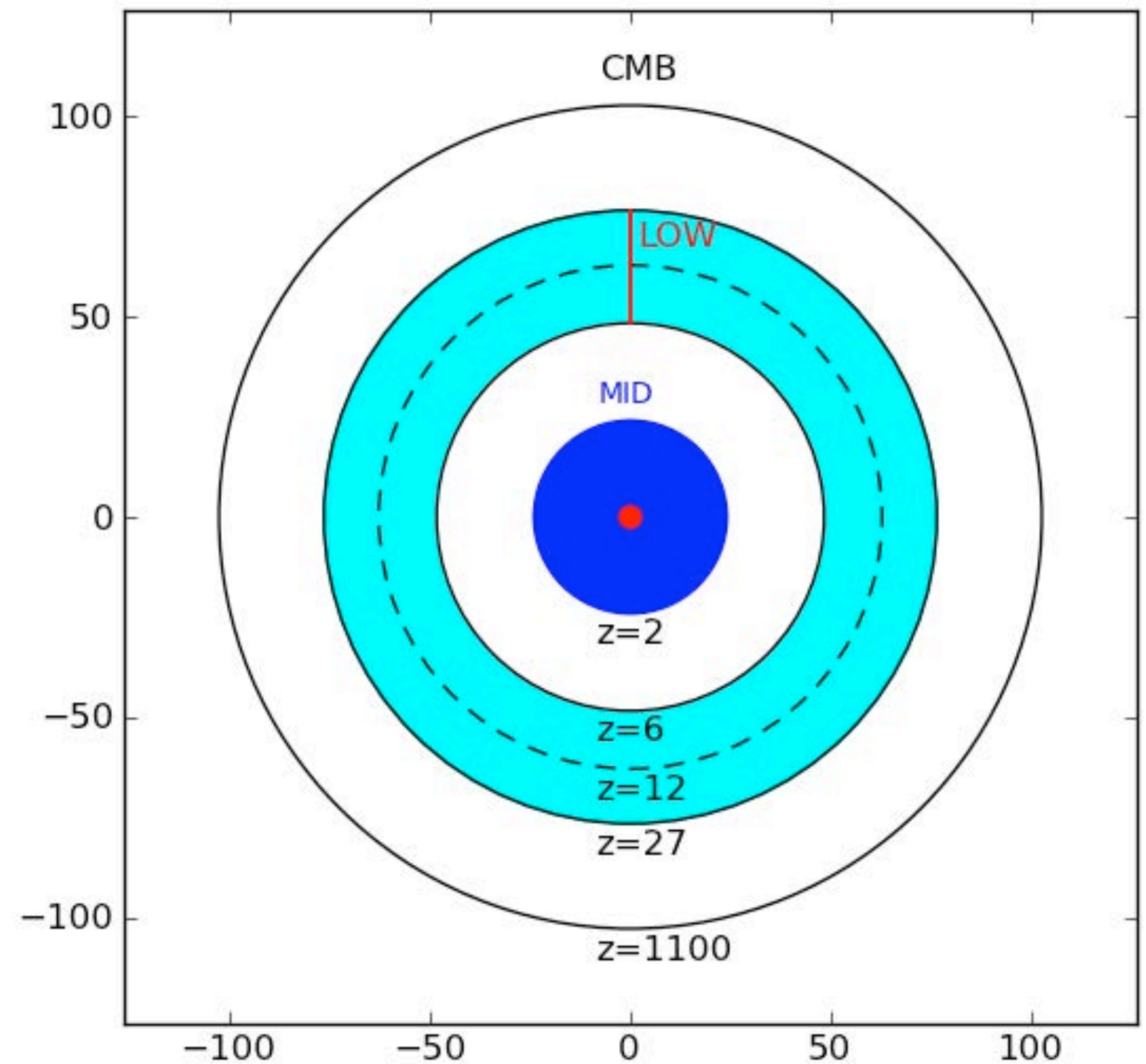
The University of Western Australia

The Square Kilometre Array

Epoch of Reionisation - Primary SKA-Low science



The SKA was conceived for detailed exploration of the Epoch of Reionisation



Pritchard+CD/EoR SWG (2015)

Unexplored space:

book-ended by CMB Thompson scattering (z=11) and z=6 quasar spectra

EoR versus Cosmic Dawn

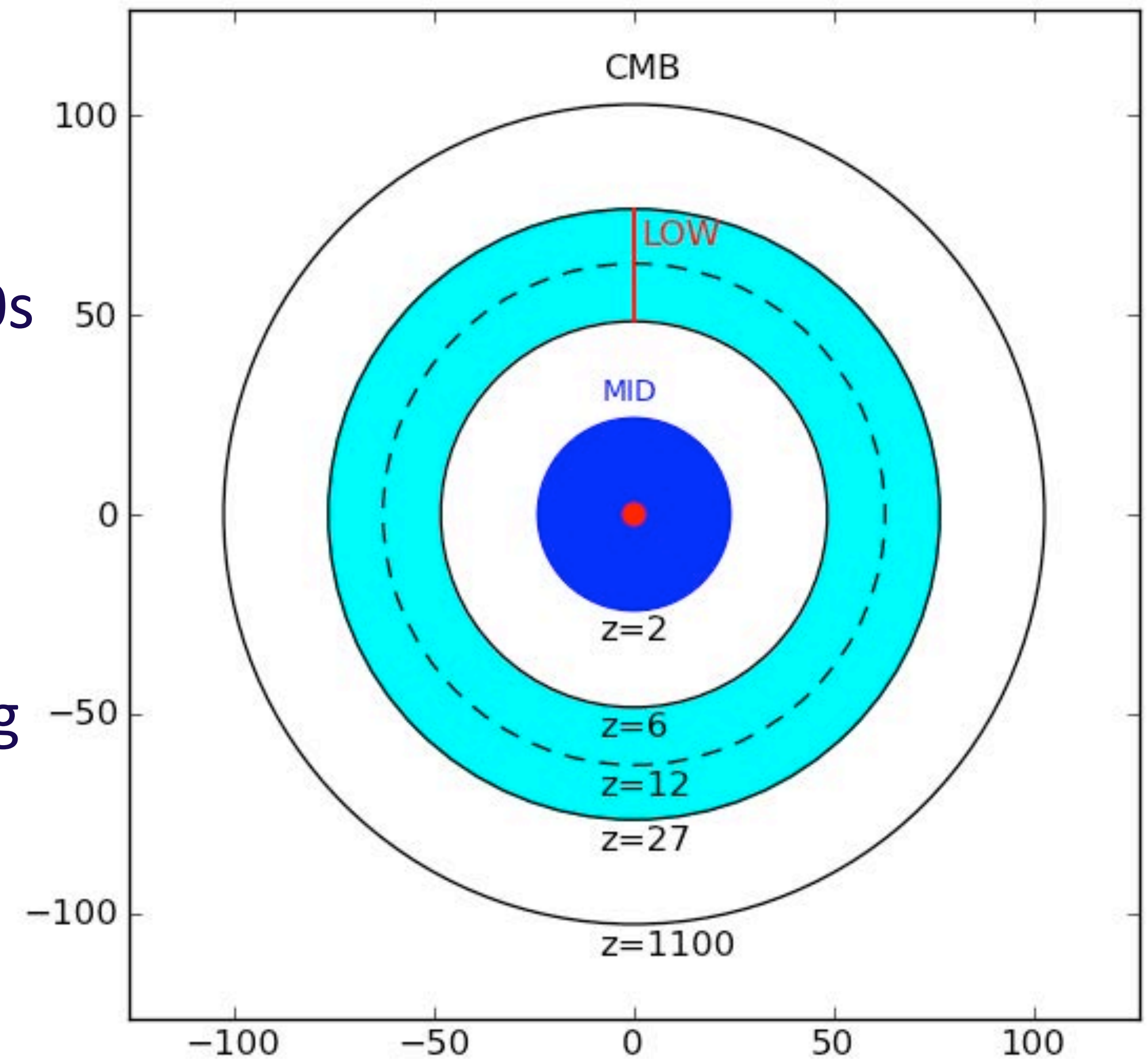
Cosmic Dawn

z ~ 12 -> 28

Growth of structure; high sky temp. (1000s K); completely unchartered territory

Epoch of Reionisation

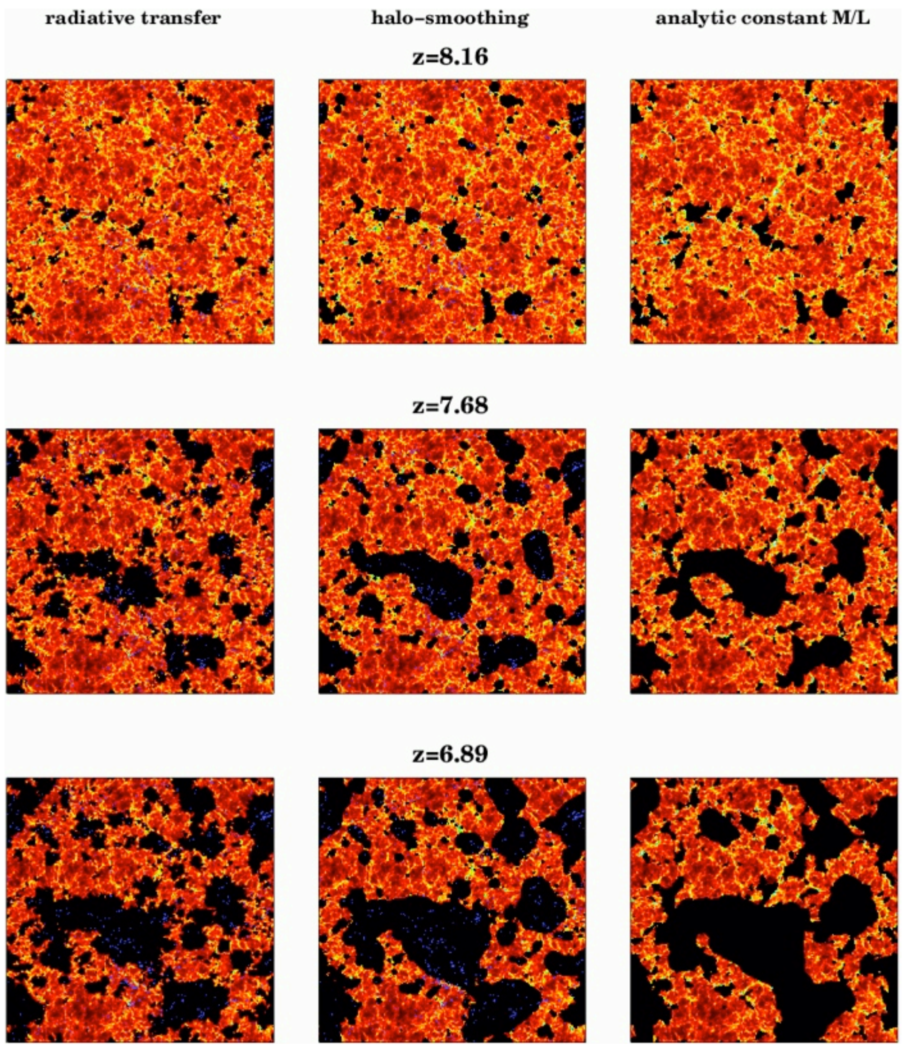
book-ended by CMB Thompson scattering (z=11) and z=6 quasar spectra; lower sky temp. (100s K); chartered by relatively unexplored (MWA, LOFAR, PAPER...)



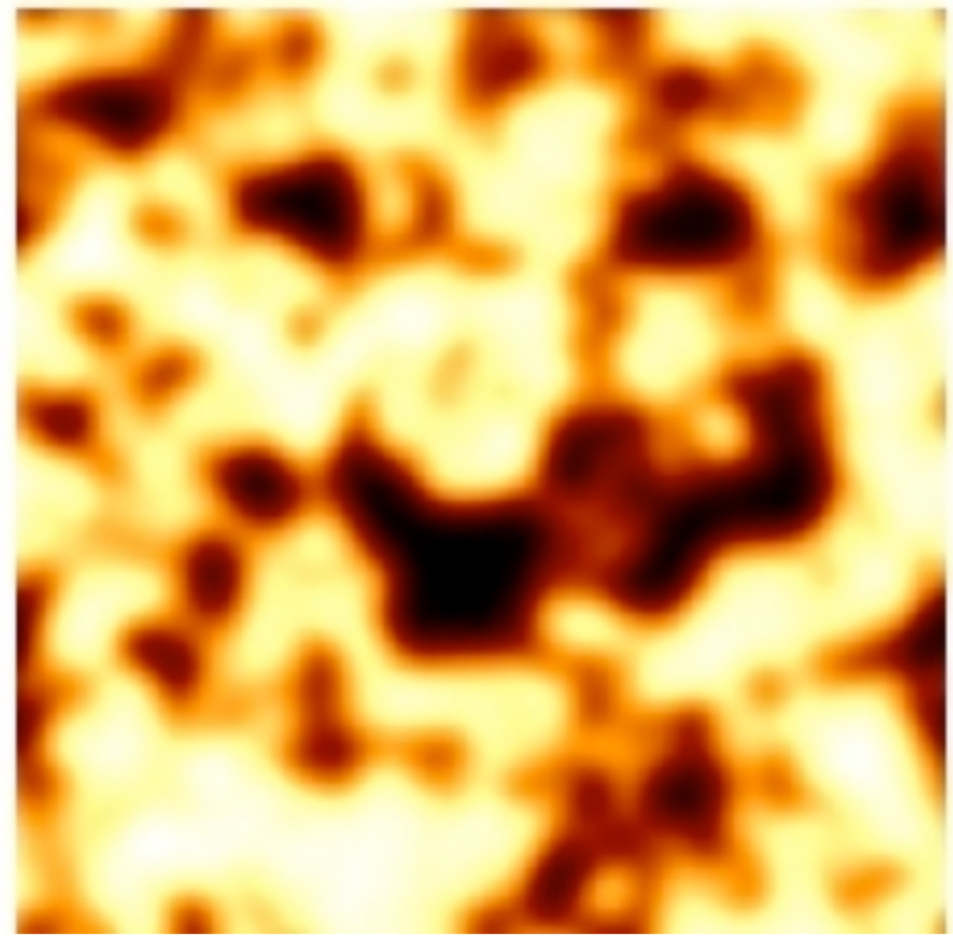
Pritchard+CD/EoR SWG (2015)

SKA-Low primary science

Fluctuations in the brightness temperature of HI gas in the early Universe



Scale and evolution encode *cosmological* and *astrophysical* information



Zahn+ (2006)

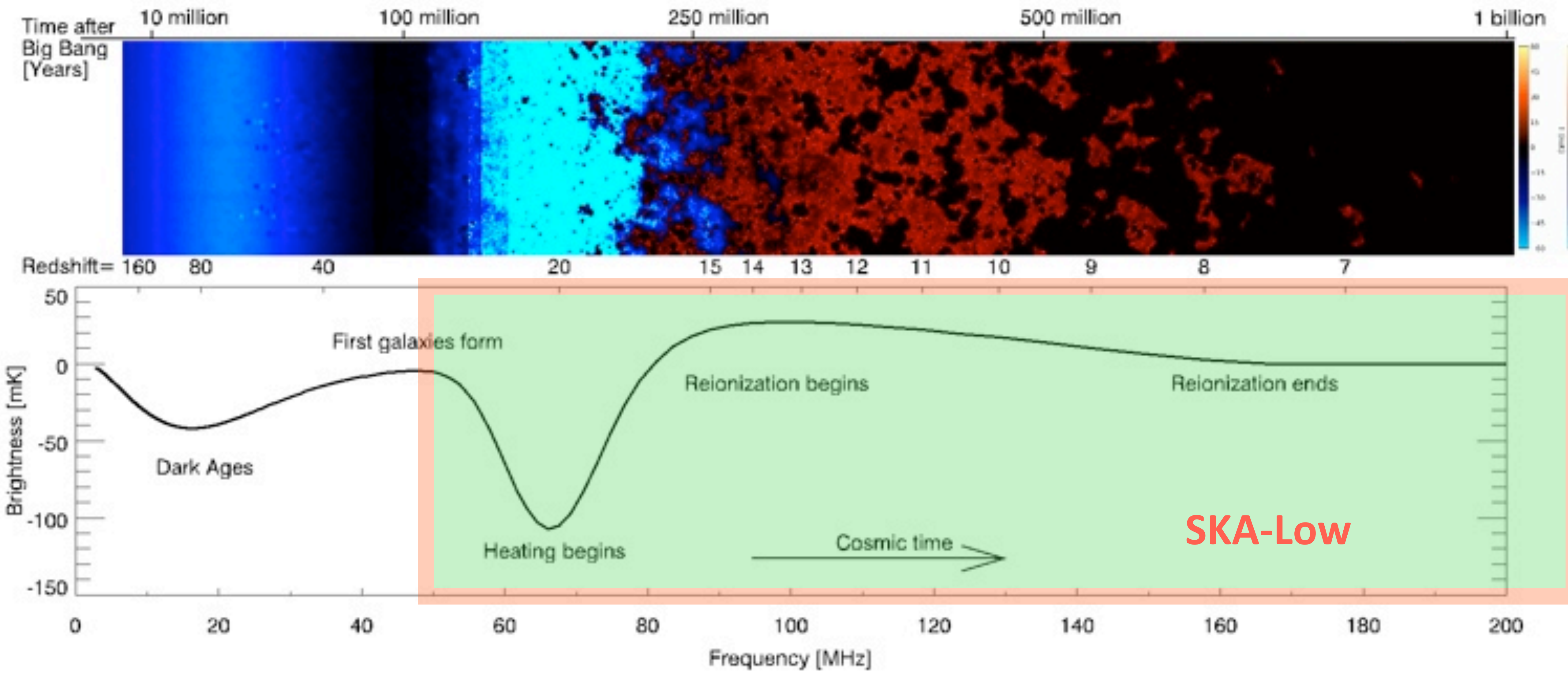
$$\delta T_B = 27 x_{HI}(1+\delta_b)\left(\frac{T_S - T_{\rm CMB}}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2}\left[\frac{\partial_r v_r}{(1+z)H(z)}\right]^{-1} \mathrm{mK}$$

Outline

- SKA EoR experiments
- SKA-Low Baseline Design and re-baselining
- Challenges
    - Foregrounds
    - Confusion noise
    - Station calibration
    - Ionospheric calibration

The early Universe

Cosmic time →



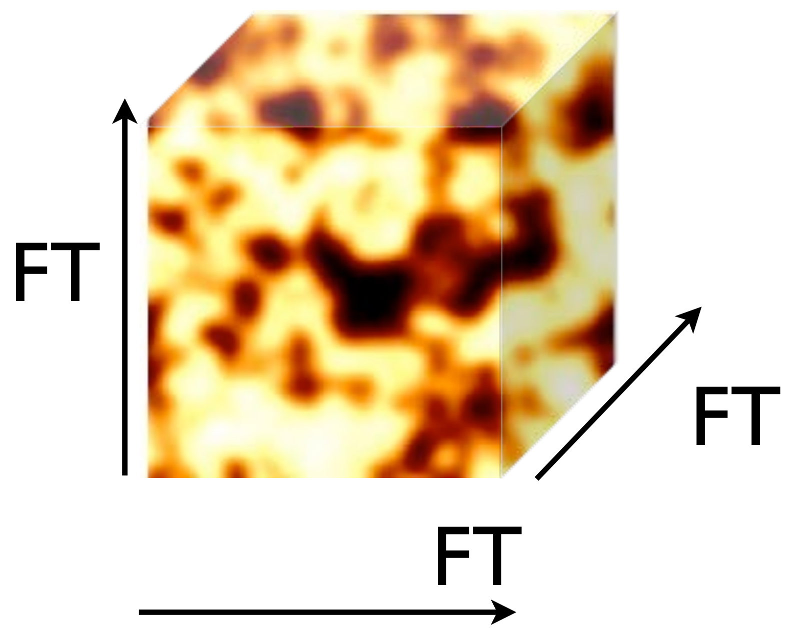
Pritchard & Loeb (2001)

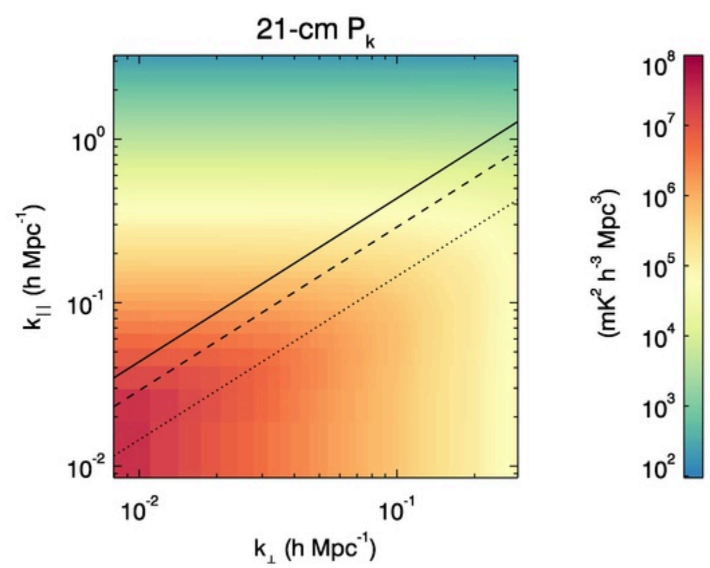
Mean brightness temperature (model)

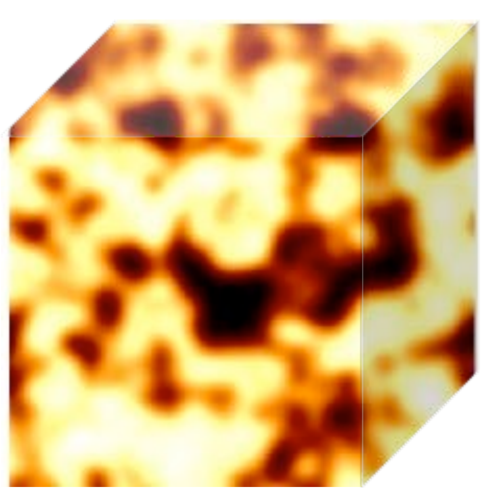
$$1 + z \simeq \frac{v}{c}$$

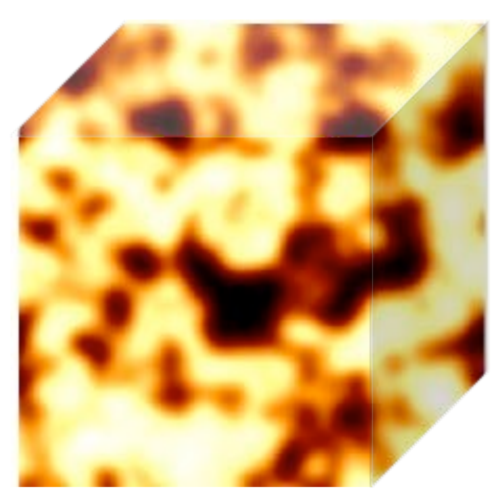
SKA EoR experiments

Science Goal	SWG	Objective	SWG Rank
1	*CD/EoR*	Physics of the early universe IGM - I. Imaging	1/3
2	*CD/EoR*	Physics of the early universe IGM - II. Power spectrum	2/3
3	*CD/EoR*	Physics of the early universe IGM - III. HI absorption line spectra (21cm forest)	3/3









SKA EoR experiments

Science Goal	SWG	Objective	SWG Rank
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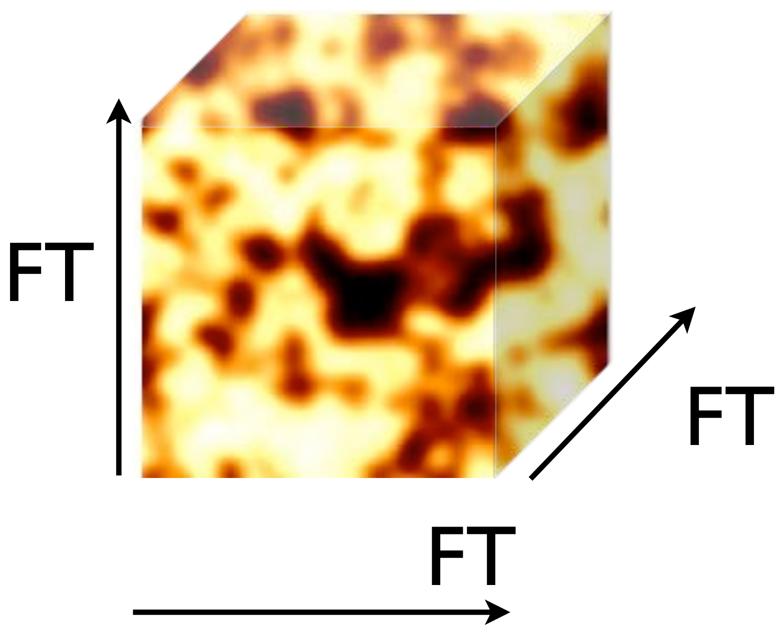
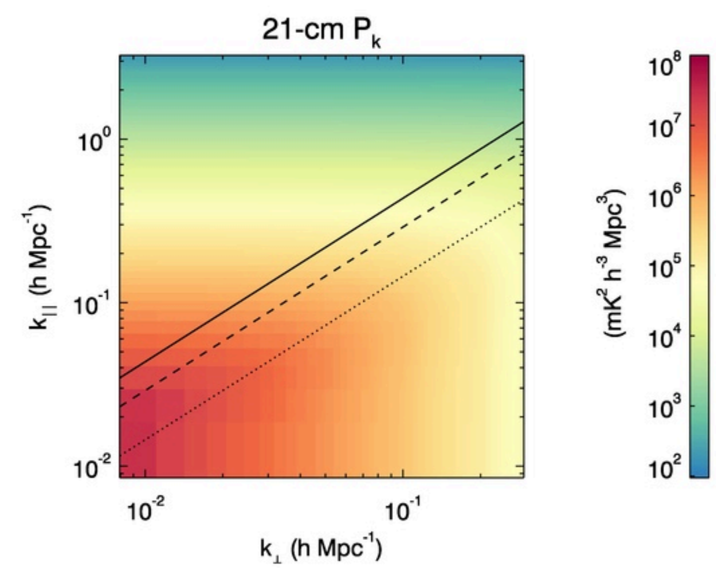
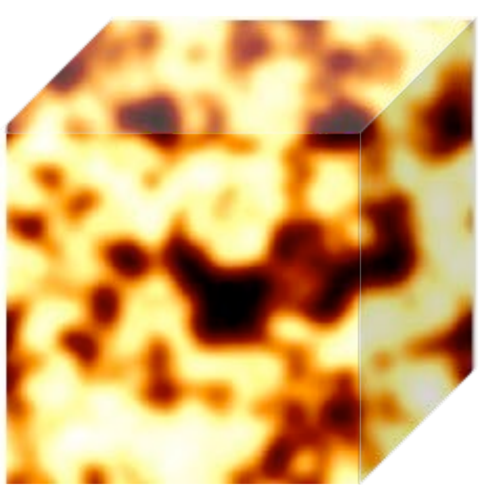
3	*CD/EoR*	Physics of the early universe IGM - III. HI absorption line spectra (21cm forest)	3/3

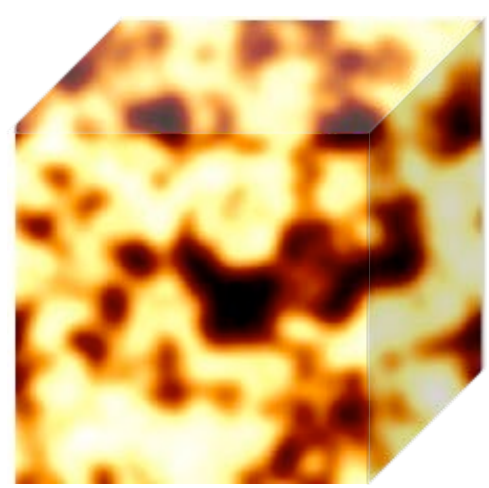




Power spectrum

- integrates signal for each spatial scale
- lower signal-to-noise ratio
- retains scale information
- yields "cosmic-scale" information



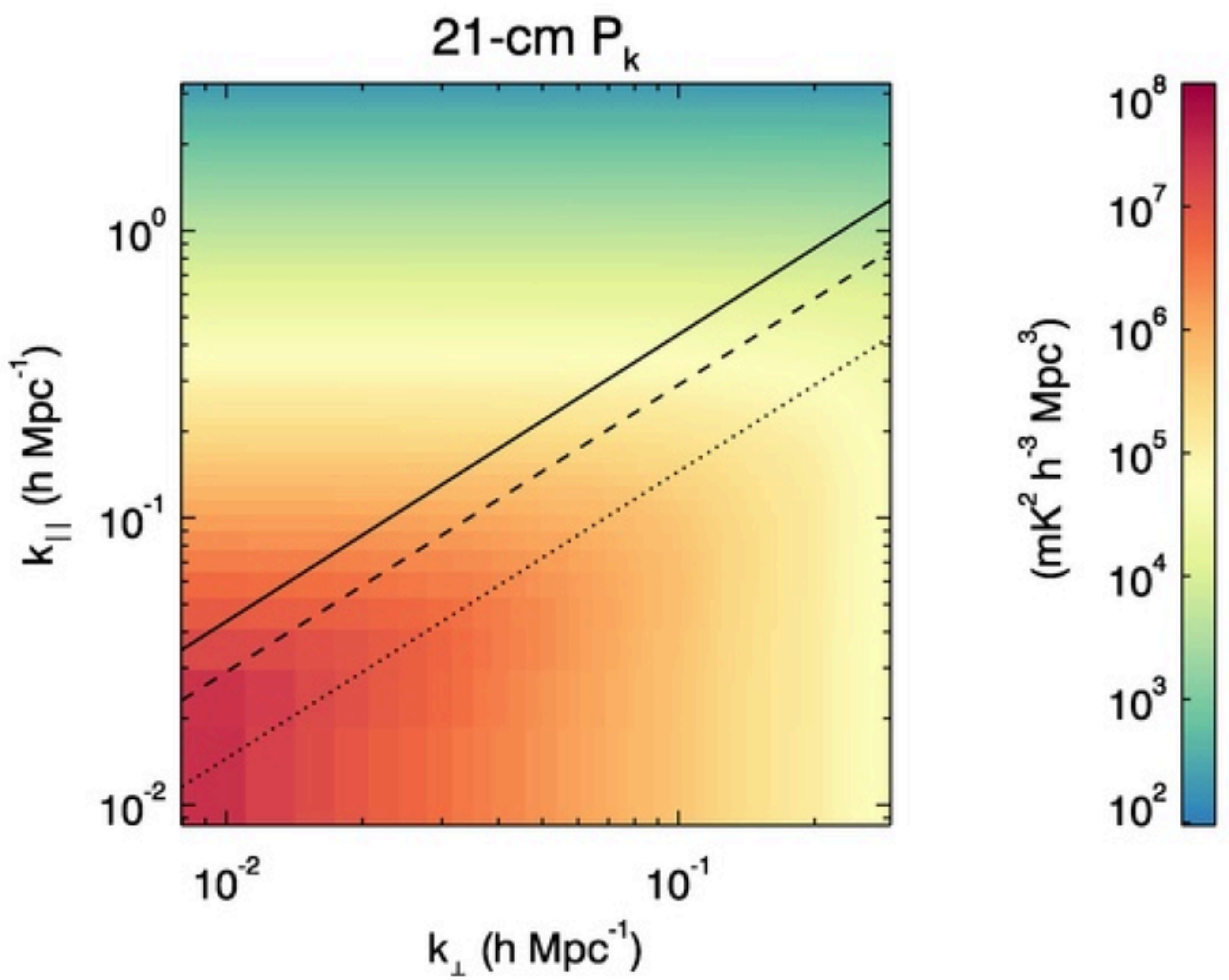


HI tomography (imaging)

- direct imaging of brightness temperature fluctuations
- provides "local" structural information
- **weak signal requiring SKA-scale sensitivity**

The second moment: 2D power spectral density

Line-of-sight wavenumber: spatial power



Angular wavenumber: spatial power →

$$\langle \widehat{T}_b(\mathbf{k})^* \widehat{T}_b(\mathbf{k}') \rangle = (2\pi)^3 \delta(\mathbf{k} - \mathbf{k}') P_T(k_\perp, k_{||}),$$

[K^2] [m^{-3}] [$m^3.K^2$]

SKA EoR experiments

Science Goal	SWG	Objective	SWG Rank
1	*CD/EoR*	Physics of the early universe IGM - I. Imaging	1/3
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3	*CD/EoR*	Physics of the early universe IGM - III. HI absorption line spectra (21cm forest)	3/3

	Science	Details
Imaging/tomography	Direct imaging of HI structures; z=6-28	100 sq. deg.; 5000/Nbeams hours; 200MHz BW; z=6-28; $\Delta\nu$=0.1MHz
Power Spectrum	2D and 1D power spectra of T_B fluctuations	Deep: 1,000 sq. deg. (100h per field) Shallow: 10,000 sq deg. (10h per field)
HI Absorption	Narrow HI systems along LOS to z~6 radio sources	1,000h integrations toward select z=6 radio sources. Study small scale HI distribution.

SKA EoR experiments

Science Goal	SWG	Objective	SWG Rank
1	*CD/EoR*	Physics of the early universe IGM - I. Imaging	1/3
2	*CD/EoR*	Physics of the early universe IGM - II. Power spectrum	2/3
3	*CD/EoR*	Physics of the early universe IGM - III. HI absorption line spectra (21cm forest)	3/3

	Chapters	Challenges
Imaging/tomography	Mellema et al.; Wyithe et al.	Instrument calibration; surface brightness sensitivity; good lines-of-sight; beam models
Power Spectrum	Koopmans et al.; Pritchard et al.; Mesinger et al.; Subrahmanyan et al.	Foregrounds; sample variance; polarization leakage
HI Absorption	Ciardi et al.	Identifying high-z sources (z=10); S/N for broad systems; contamination by spatially-coincident T fluctuations

SKA EoR chapters - from Koopmans overview

8.1 SKA1 and 2 Science High-lights

Some high-light science results expected to be largely unique for SKA1 (and 2) are (in random order; related chapters in this volume are indicated at the end of each bullet point):

- Direct imaging of ionized regions and HI fluctuations on scales of arcminutes and larger during the *Epoch of Reionization* and *Cosmic Dawn* — Mellema et al.; Whyithe et al.
- Probing many aspects of cosmology/cosmography out to the highest possible redshifts (i.e. = 27 in case of SKA1) — Pritchard et al.
- Enabling one to probe $k \sim 1000\,\mathrm{Mpc}^{-1}$ scales via 21-cm absorption, probing mini-halos even out of reach of JWST — Ciardi et al.
- Direct study of the state of the IGM in the first billions years of the Universe – Ahn et al.; Subrahmanyan et al.
- Unique studies (i.e. CD) beyond the *Epoch of Reionization* which will remain out of reach of most of not all other (planned) facilities in particular the first (PopIII stars and X-ray heating sources) – Mesinger et al., Semelin et al.
- Probing the impact of bulk-flows during the later *Dark Ages* and the *Cosmic Dawn* allowing physics during the *Dark Ages*and CMB to be probed in a unique manner – Maio et al.
- Strong synergy with intensity mapping of the CO, CII, Ly-alpha lines, as well as the kS-Z effect and NIR/X-ray emission, as well as with many other (planned) facilities in space and on the ground — Chang et al., Jelic et al.

SKA-Low Baseline Design: 910 35m stations

256 log-periodic dipoles = 1 35m station
Core: 865 stations (densest in centre)
Arms: 45 stations (spiral)

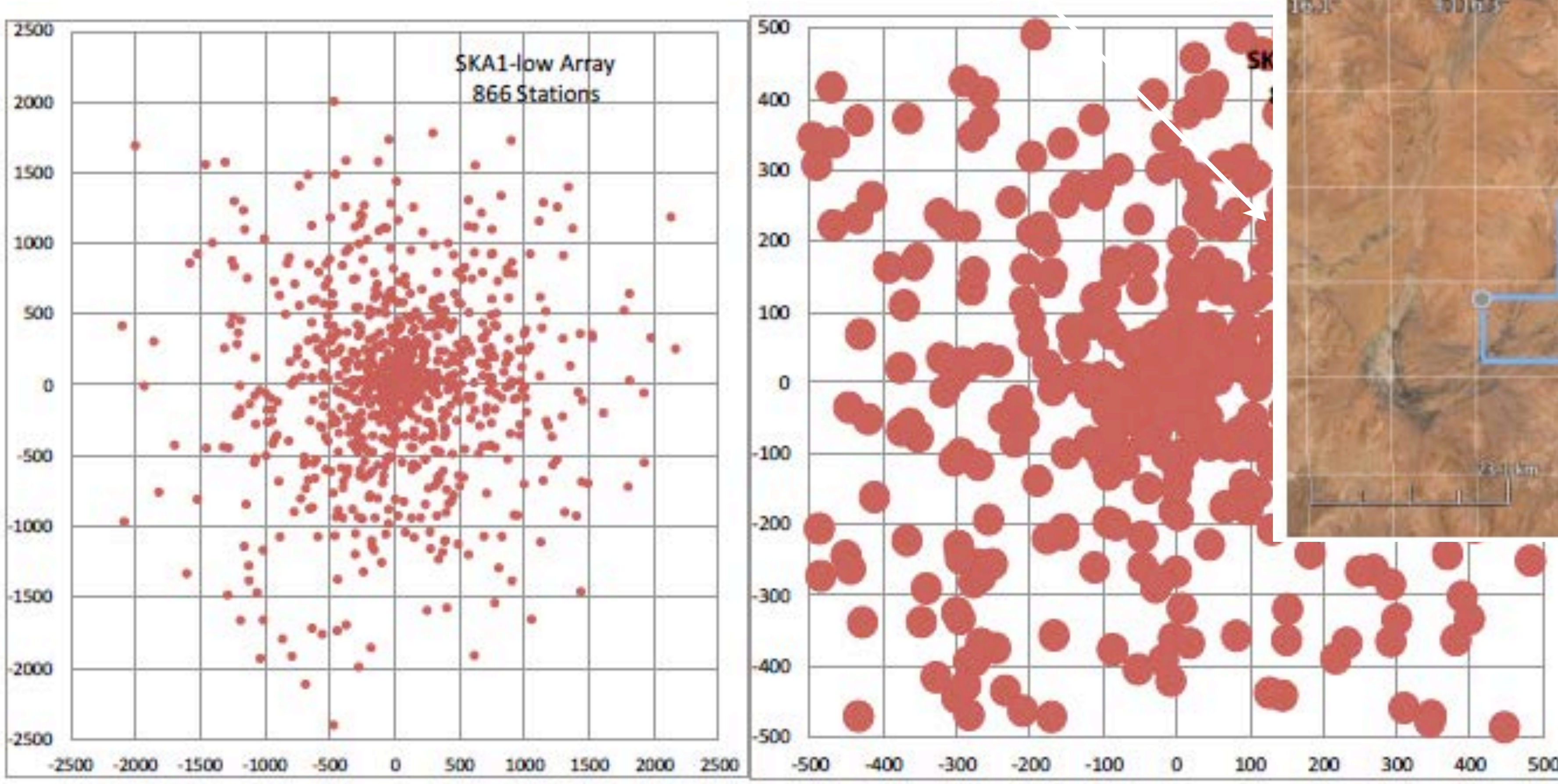
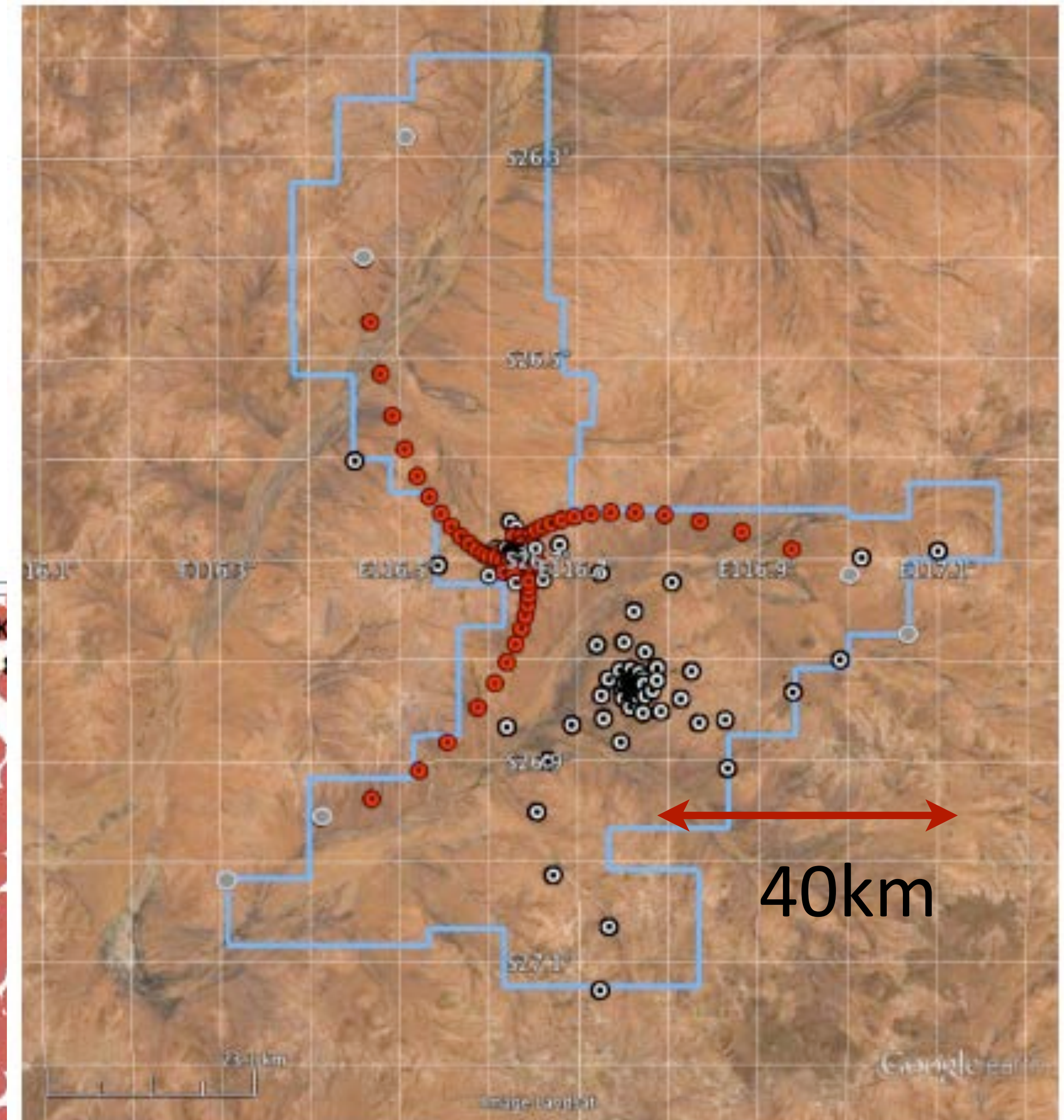


Figure 4 The SKA1-low configuration in the core (35-m diameter stations).



Braun (2014)

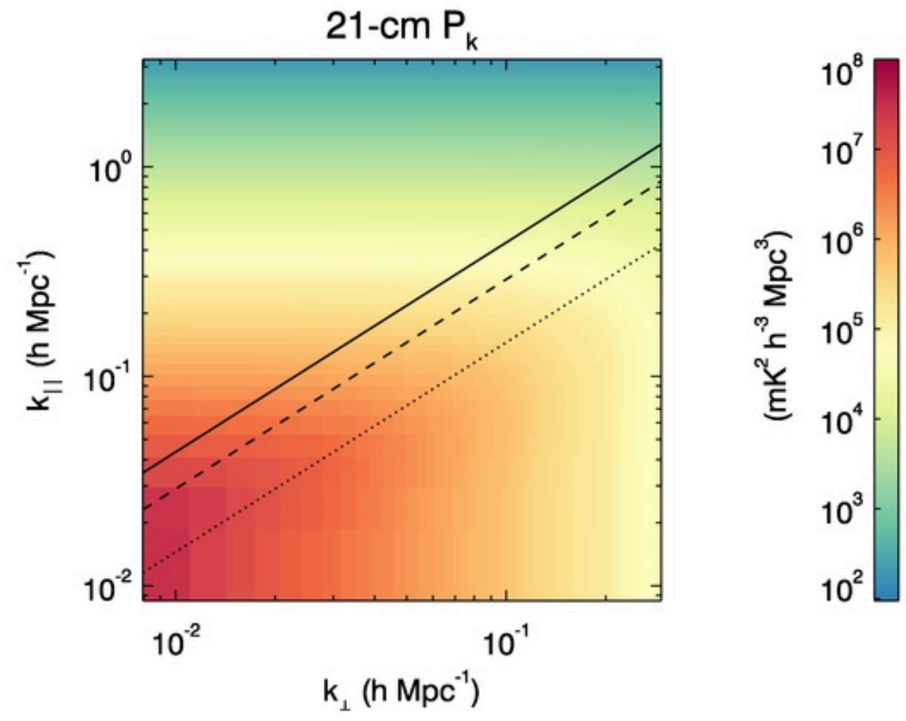
Why this configuration?

Configuration driven by EoR core science:

- High surface brightness sensitivity over scales of arcmin.-deg. (core <3000m) --> imaging extended structure, power spectrum
- Calibration via spiral arms (**not** an imaging array)
- EoR science will *not* use long baselines

- 35m stations --> primary beam ~5 deg @ 150 MHz (image individual HII bubbles)

- (50 MHz) 5λ - 500λ
- (150 MHz) 15λ - 1500λ
- (350 MHz) 40λ - 2500λ



5 deg ~10λ

10 arcmin ~500λ

Re-baselining: 512 stations (467 core, 45 arms**)

SKA1-Low:

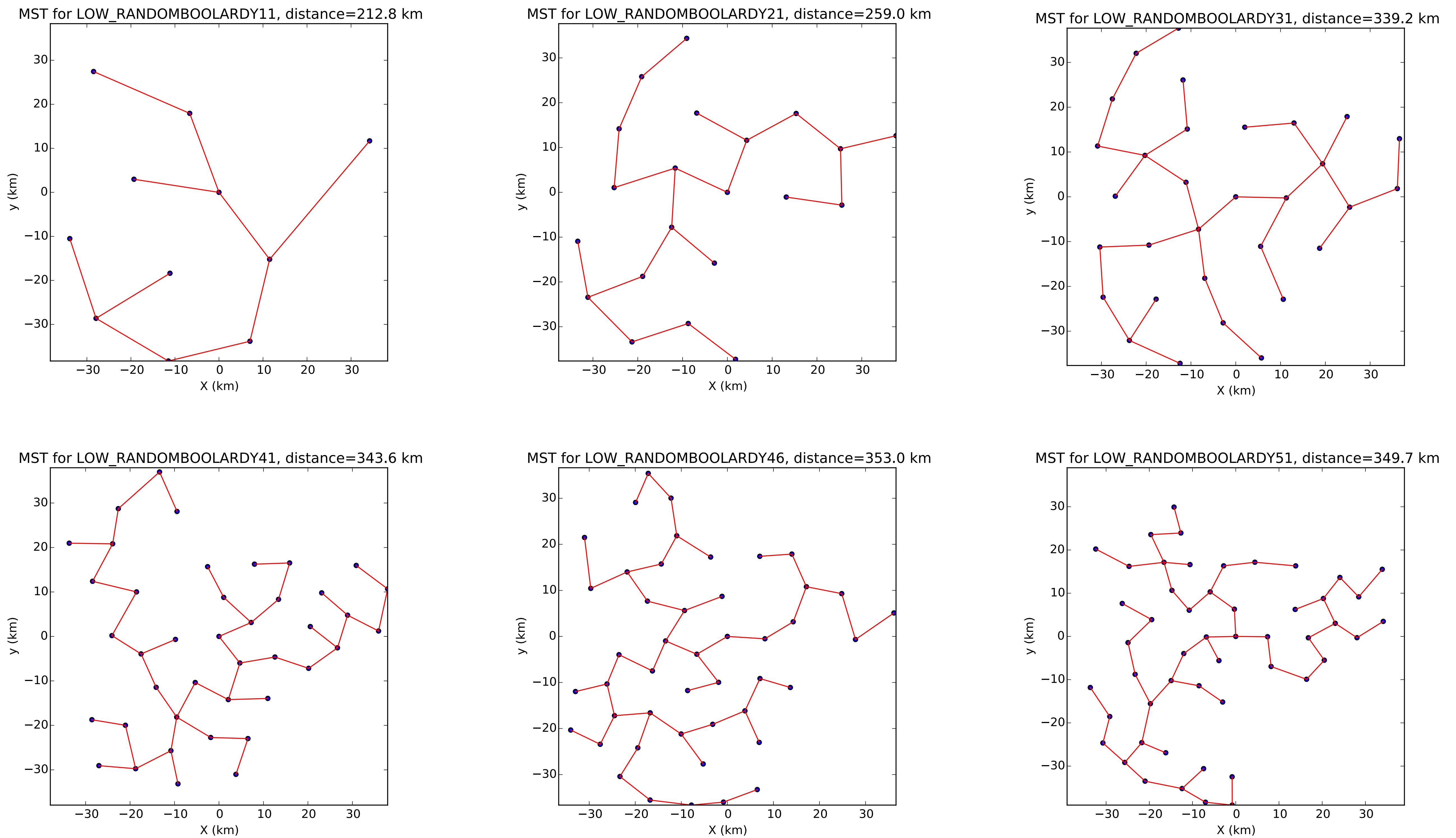
1. 512 stations of 256 antennas shall be built.
2. The telescope build shall be staged to mitigate calibration risks (See the SEAC report, SKA-BD-17-13e, for motivation). Stage 1 will deploy and utilise the remote stations to demonstrate successful calibration, followed by Stage 2, the full build out of the core.
3. The longest baselines shall be ~ 80km.
4. The remote stations shall be distributed more uniformly in Boolardy Station than in Baseline Design V1.
5. The antennas shall be of the current log-periodic design. The full frequency range

   shall be 50 – 350MHz.
6. The maximum number of spectral channels transmitted from the SKA1-Low correlator to SDP-Low shall be 65,536. The maximum bandwidth will remain as specified in Level 1 requirements, version 5.

Cornwell (2015)

Re-baselining: configurations being considered

Courtesy Tim Cornwell, SKA System Architect



Challenges: complicated instrument

- Beam model: pseudo-random distribution of dipoles in each station leads to different individual beams
- Polarization: how will polarization leakage affect the science? How well can we perform polarization calibration? (and how?)
- Large fractional bandwidth: can we really observe effectively between 50-250 MHz simultaneously --> instrument beam size varies by factor of six.

- Open questions:
  - How do we understand each station primary beam?
  - How do we calibrate the polarization?

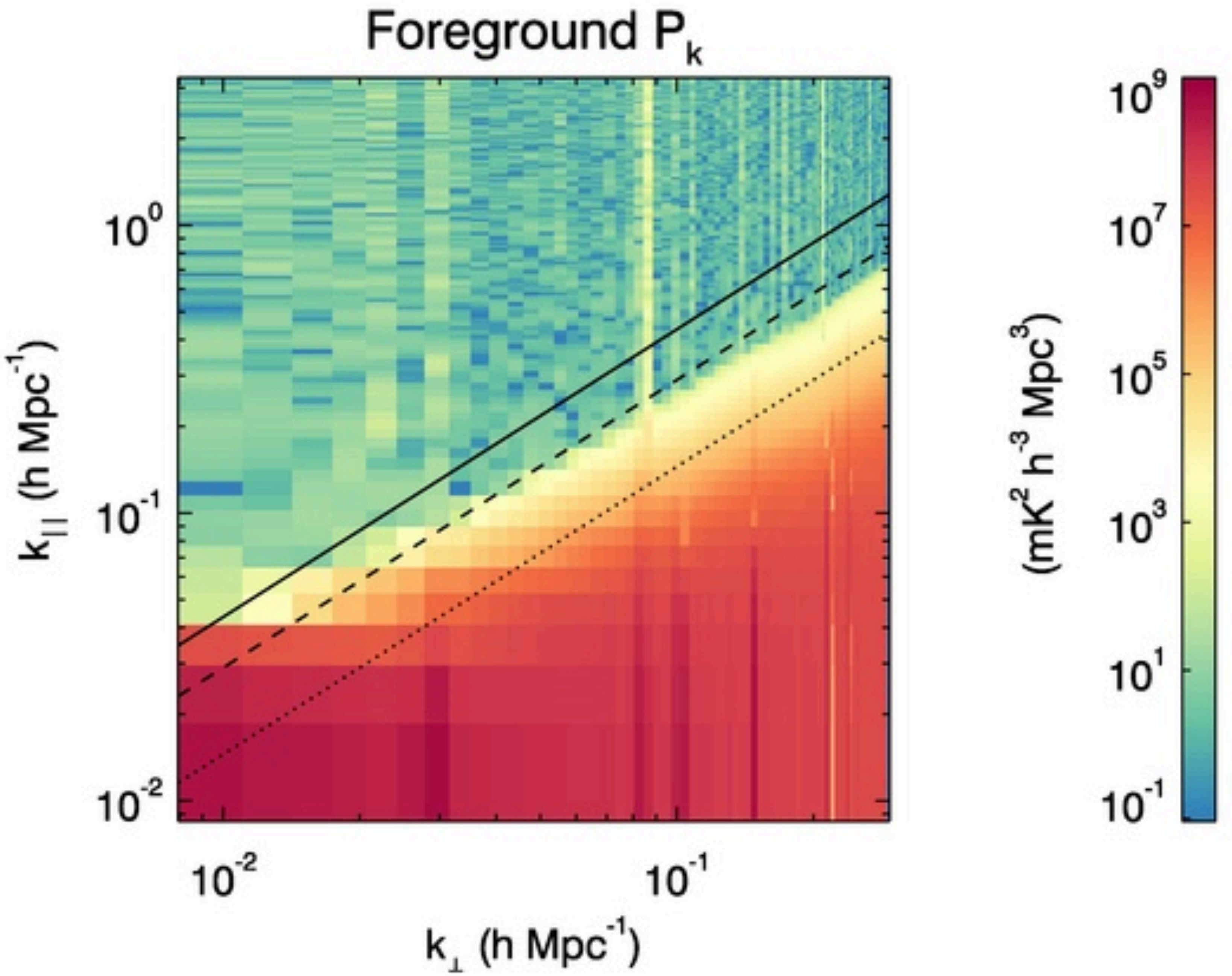
Challenges: sensitive array

- Foreground contamination primary systematic limiting EoR science (sample variance limit on large angular scales)
- Sensitive array leads to confusion-limited data in core in ~10s seconds
- Spiral arms provide angular resolution to resolve confused sources and subtract sky model

- Open questions:
  - How do we calibrate individual stations of 256 dipoles?
  - How do we calibrate the ionosphere?

Foreground structure in k-k space

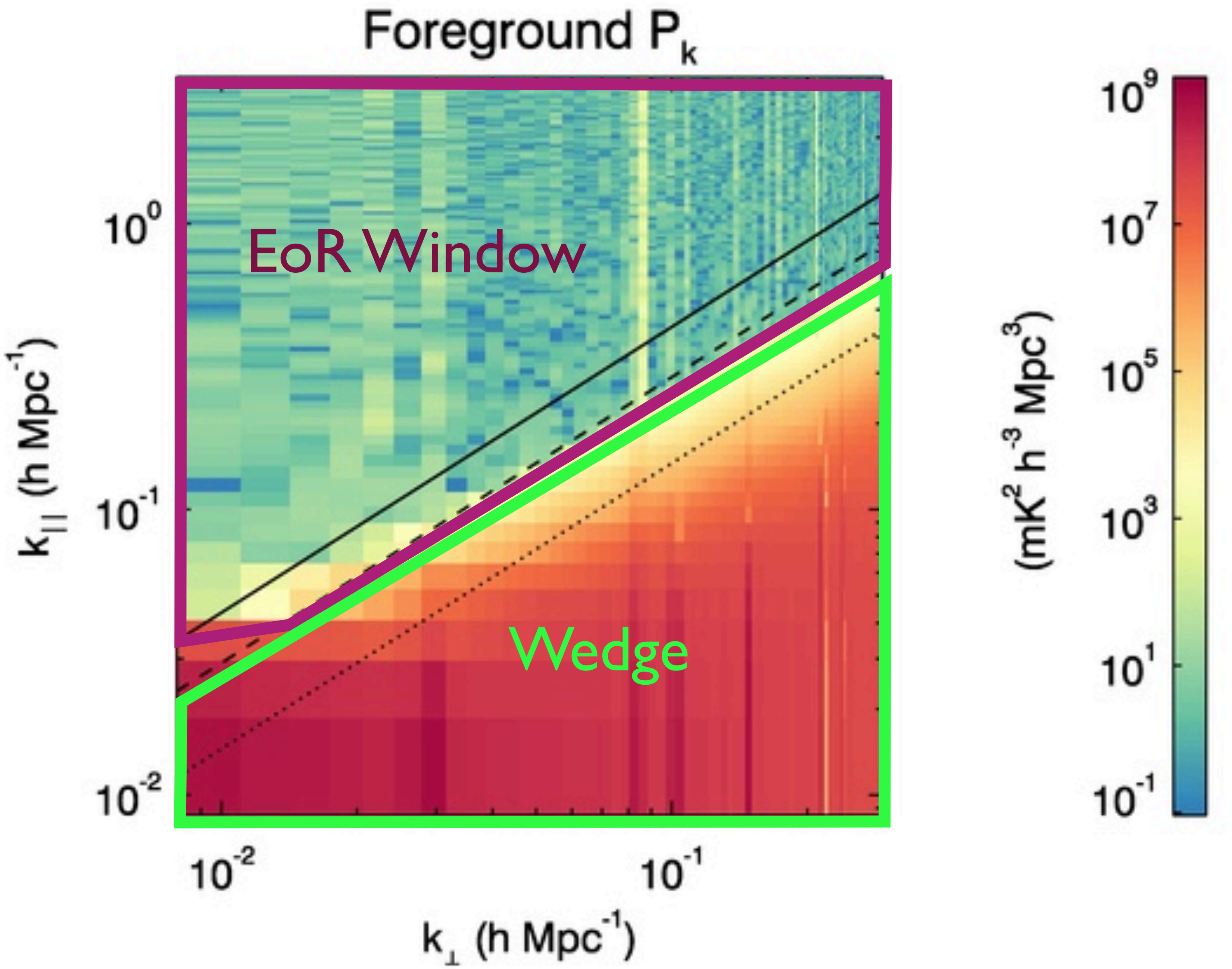
$$P(k) = P_{21}$$



Morales+ (2009); Trott, Wayth & Tingay (2012); Thyagarajan+ (2013); Vedantham+ (2012)

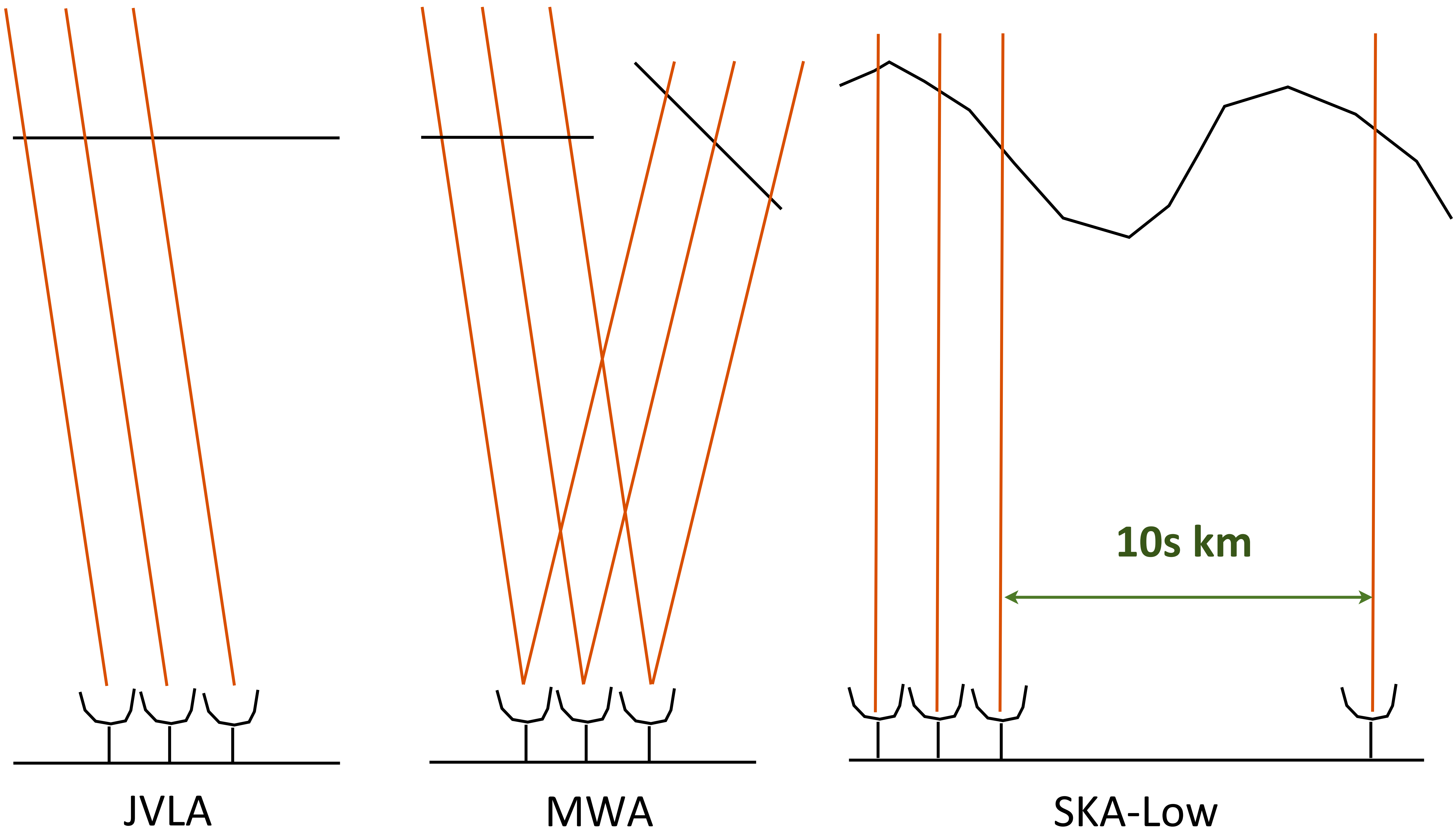
Foreground structure in k-k space

$$P(k) = P_{21}$$

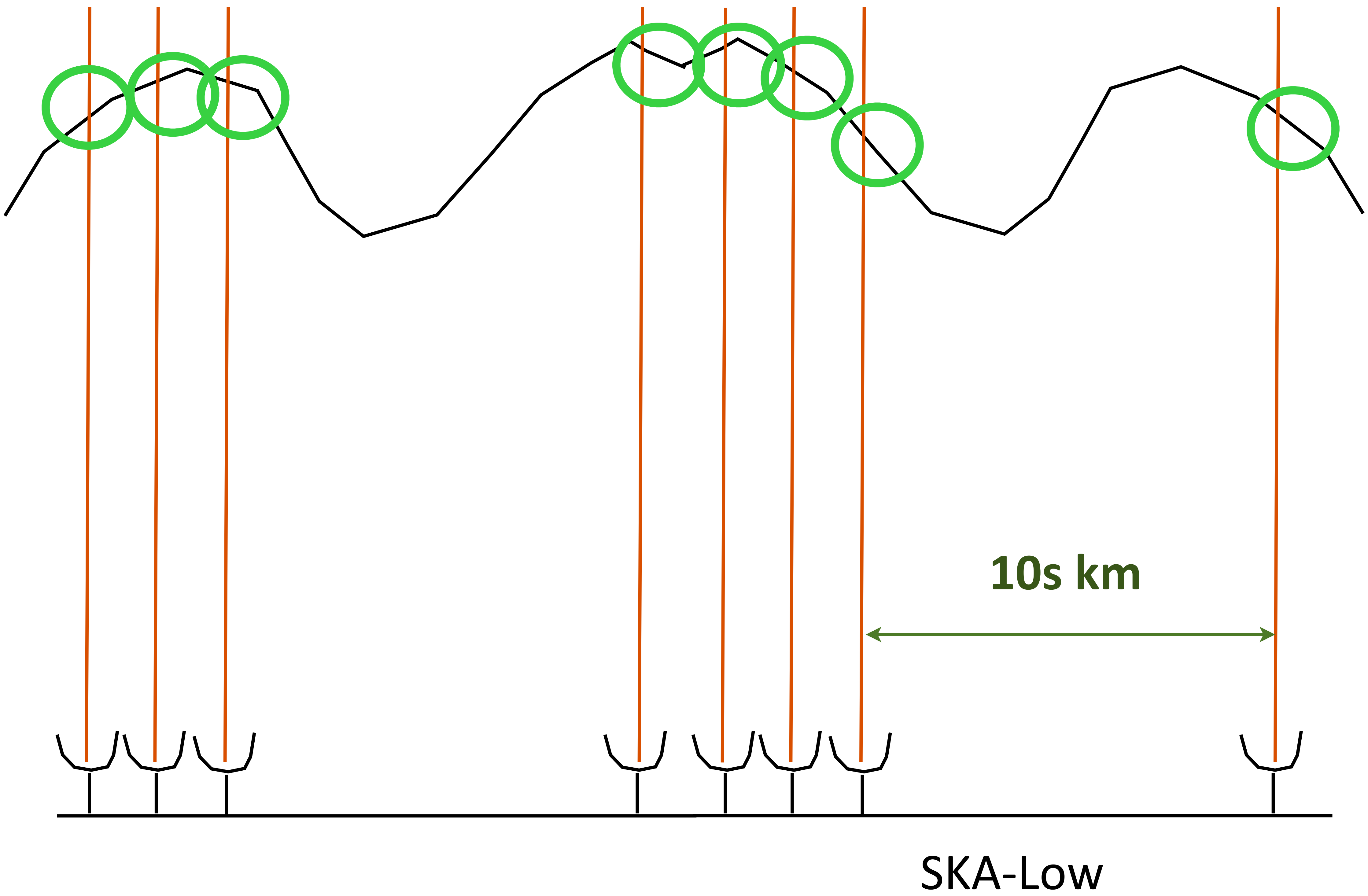


Morales+ (2009); Trott, Wayth & Tingay (2012); Thyagarajan+ (2013); Vedantham+ (2012)

Ionosphere: time- and position-dependent phase screen

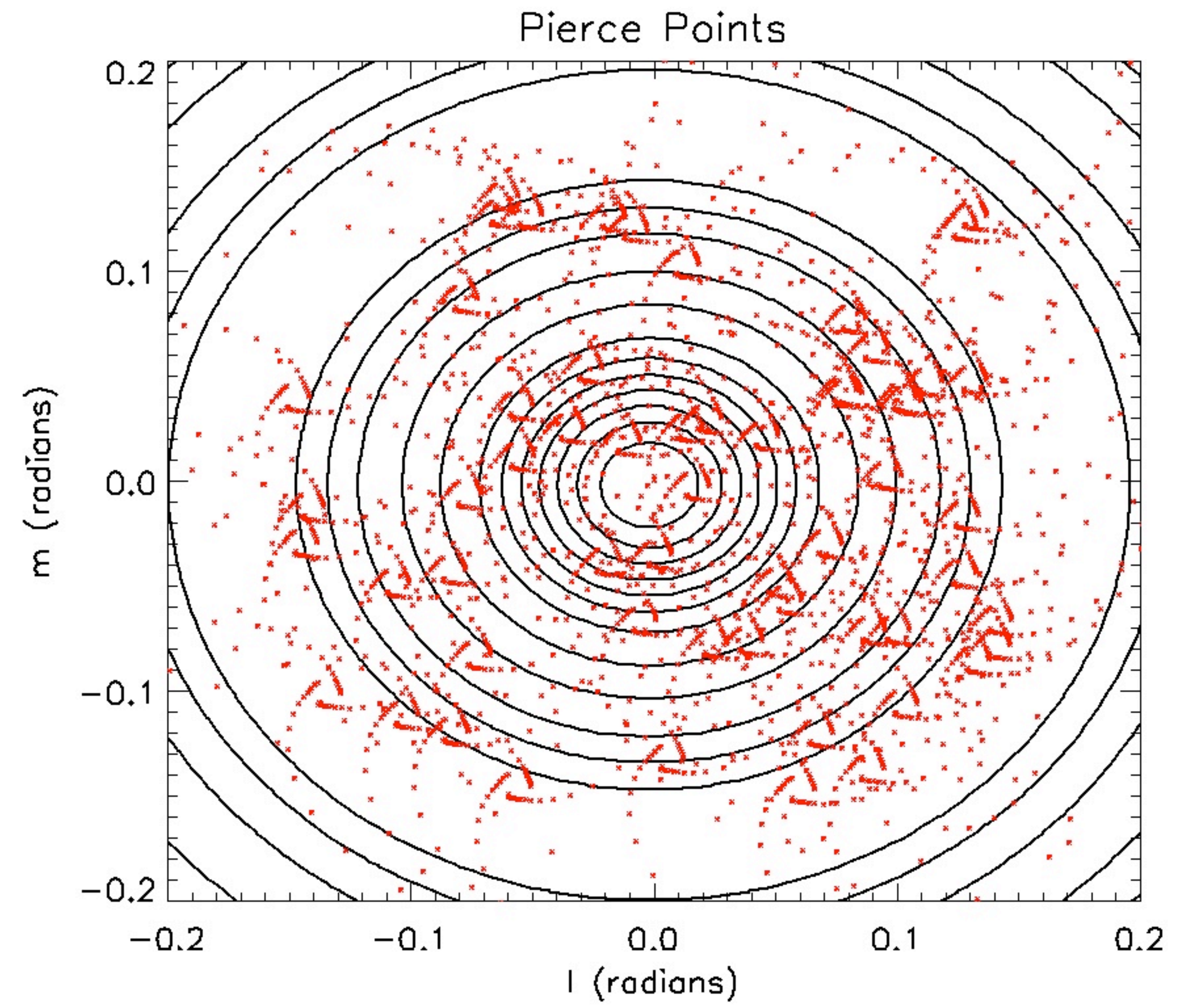


Ionosphere: pierce points to extragalactic sources



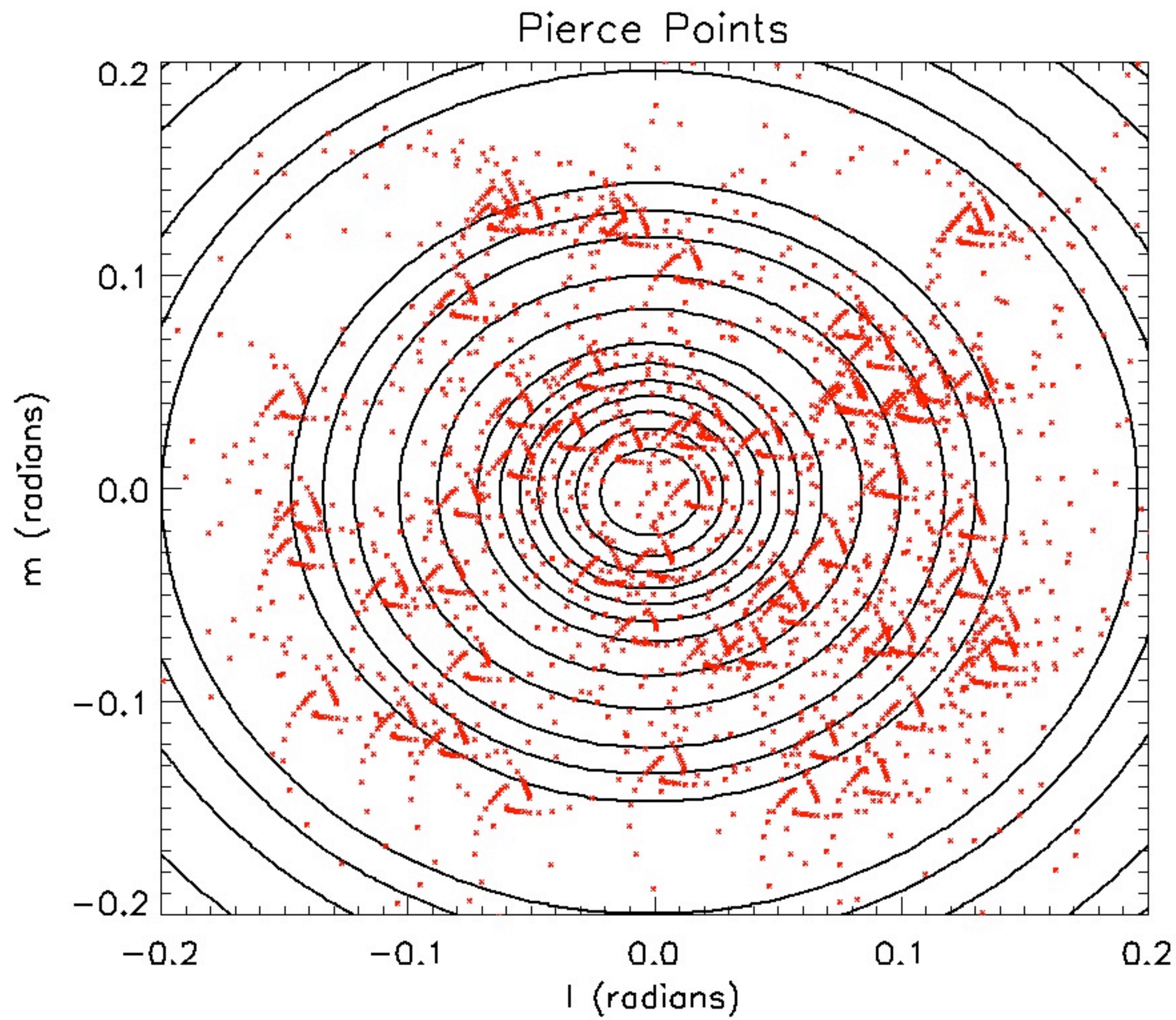
Calibration: estimating ionospheric model parameters

Pierce points towards 60 calibrators (>1 Jy) overlaid on ionospheric model (Zernike basis)



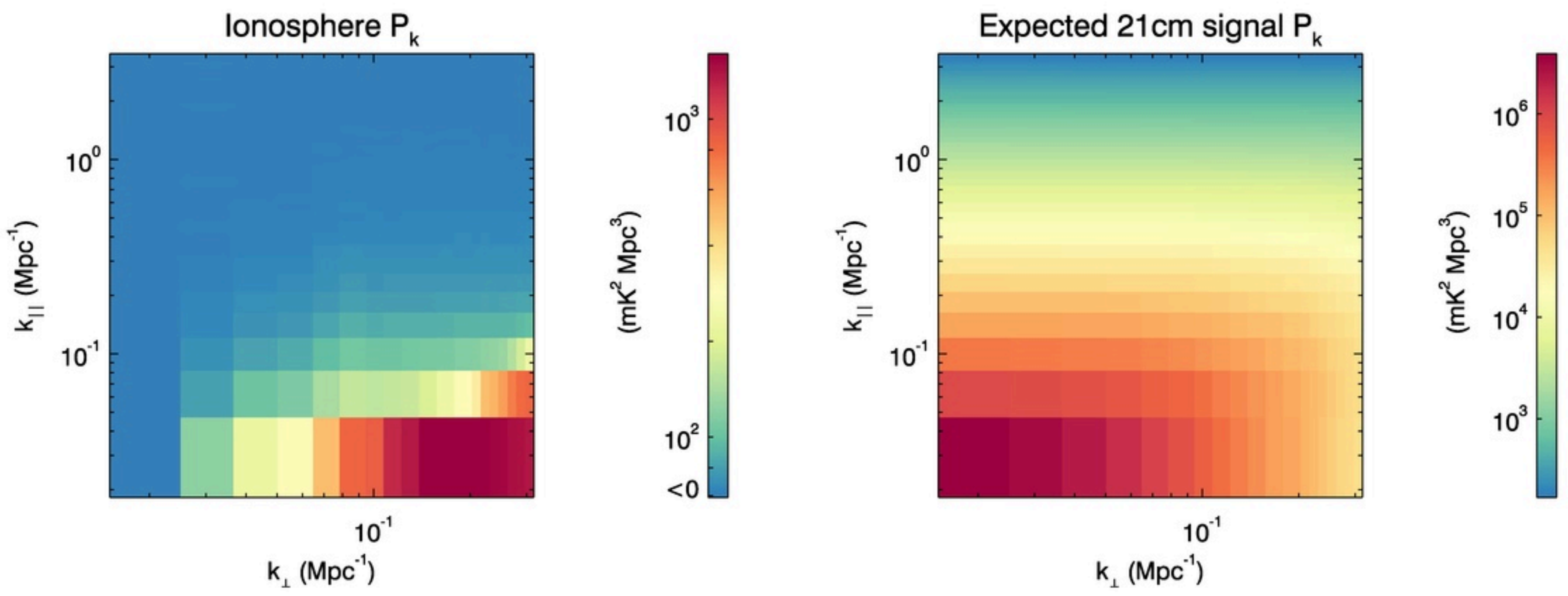
Calibration: estimating ionospheric model parameters

Fisher analysis of ability of a given baseline configuration to *estimate* ionospheric model parameters



Calibration: impact on EoR power spectrum

Ionospheric model*: sinusoidal phase screen
λ = 5 degrees, amplitude, Δθ = 20 arcsec

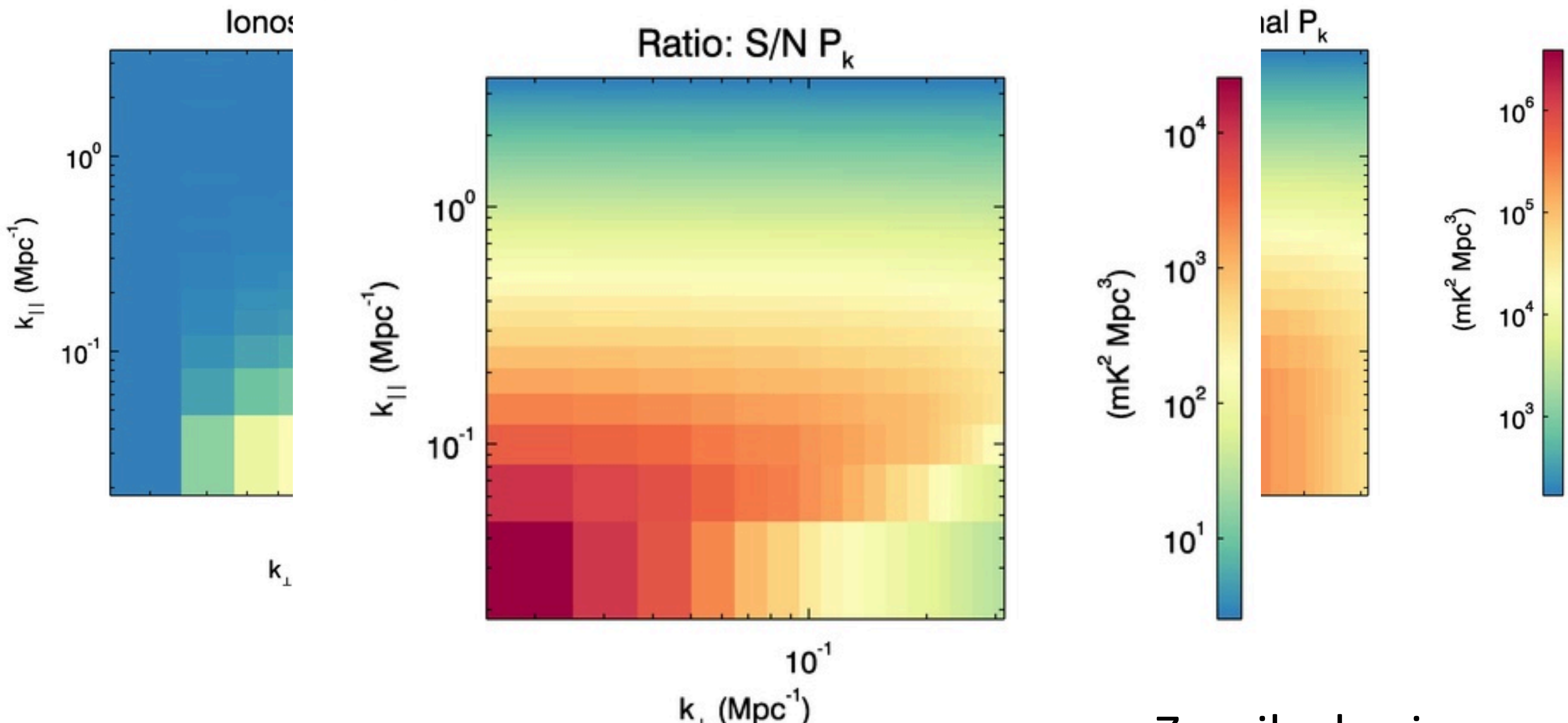


Zernike basis

*Loi+ (2015)

Calibration: impact on EoR power spectrum

Ionospheric model*: sinusoidal phase screen
λ = 5 degrees, amplitude, Δθ = 20 arcsec



Zernike basis

*Loi+ (2015)

Calibration: impact on EoR power spectrum

Ionospheric model*: sinusoidal phase screen
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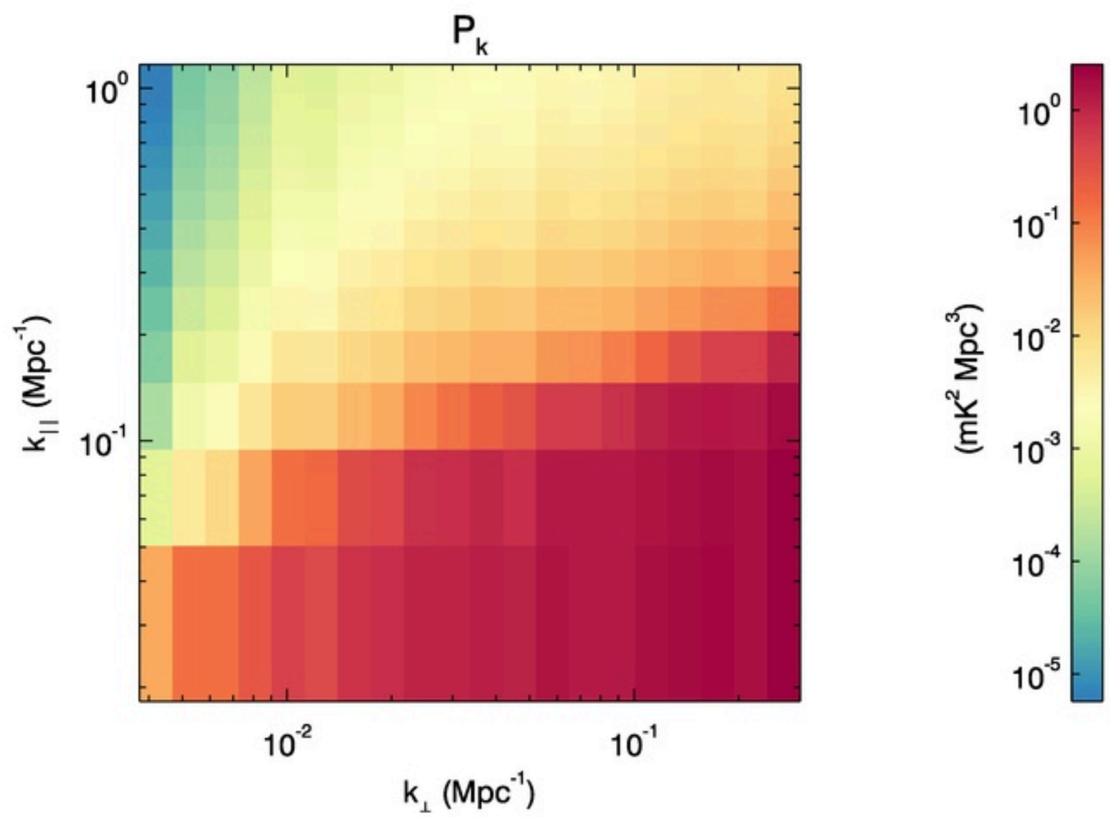
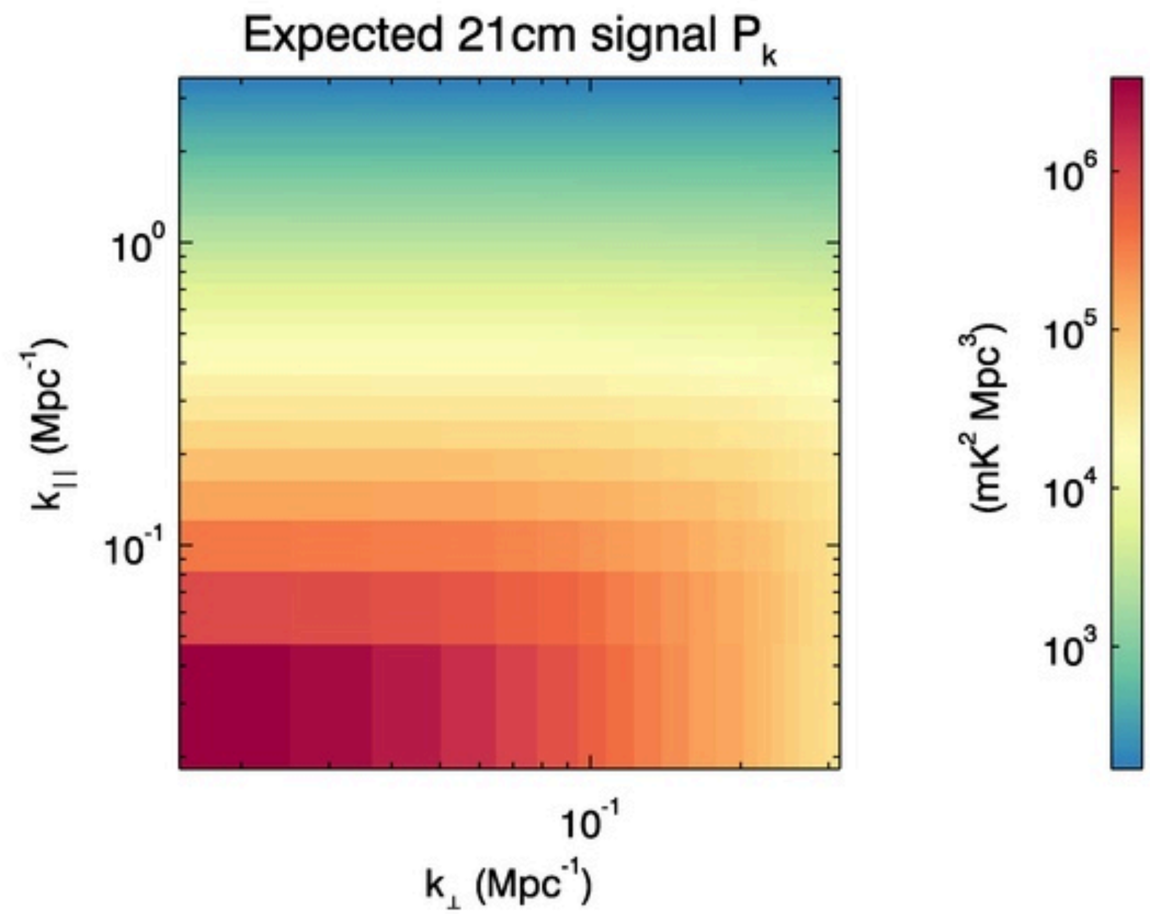


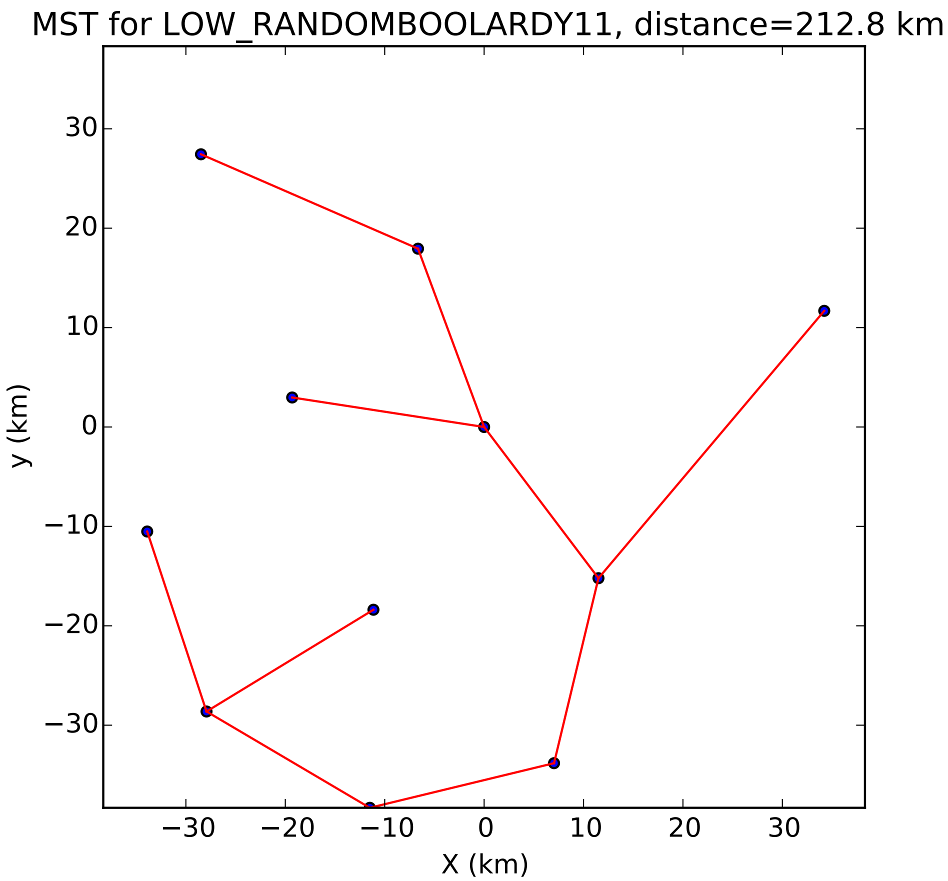
Cosine basis

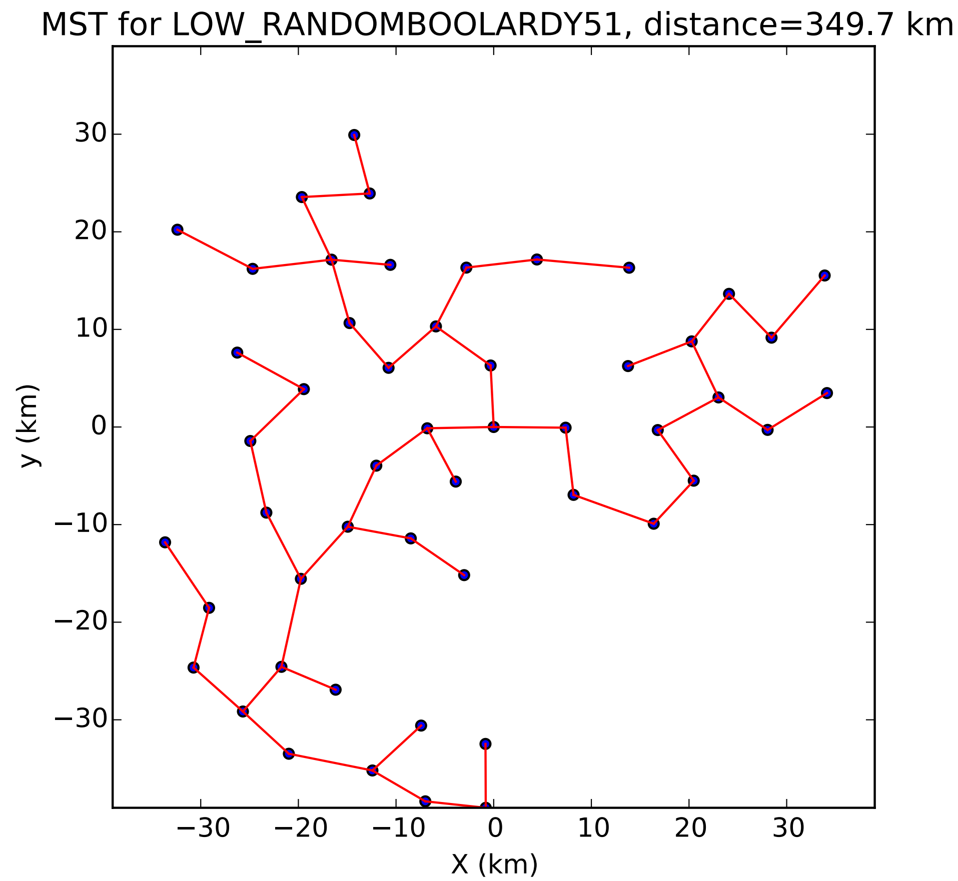


*Loi+ (2015)

Calibration: impact on EoR power spectrum

Compute ability to calibrate ionospheric parameters for different array configurations



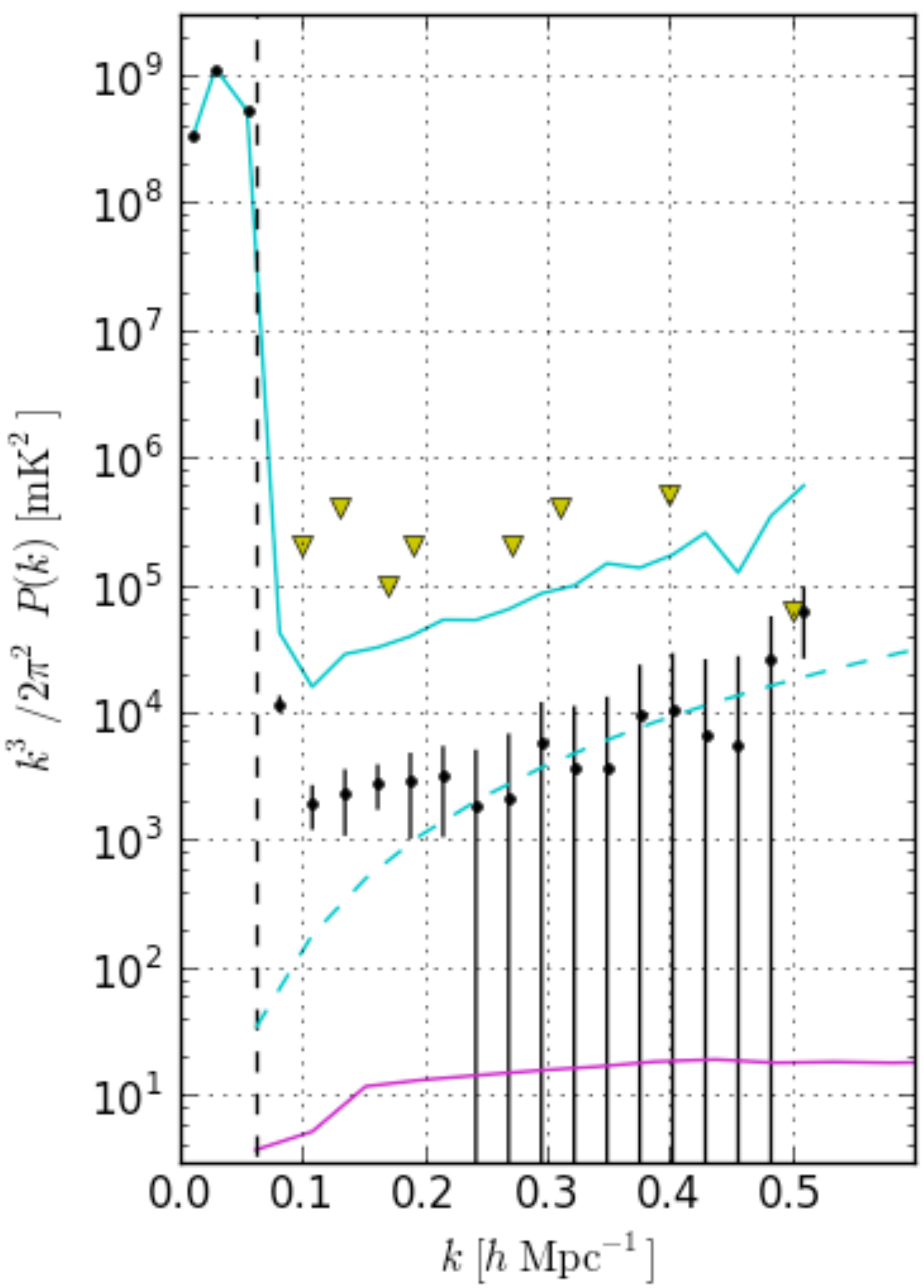


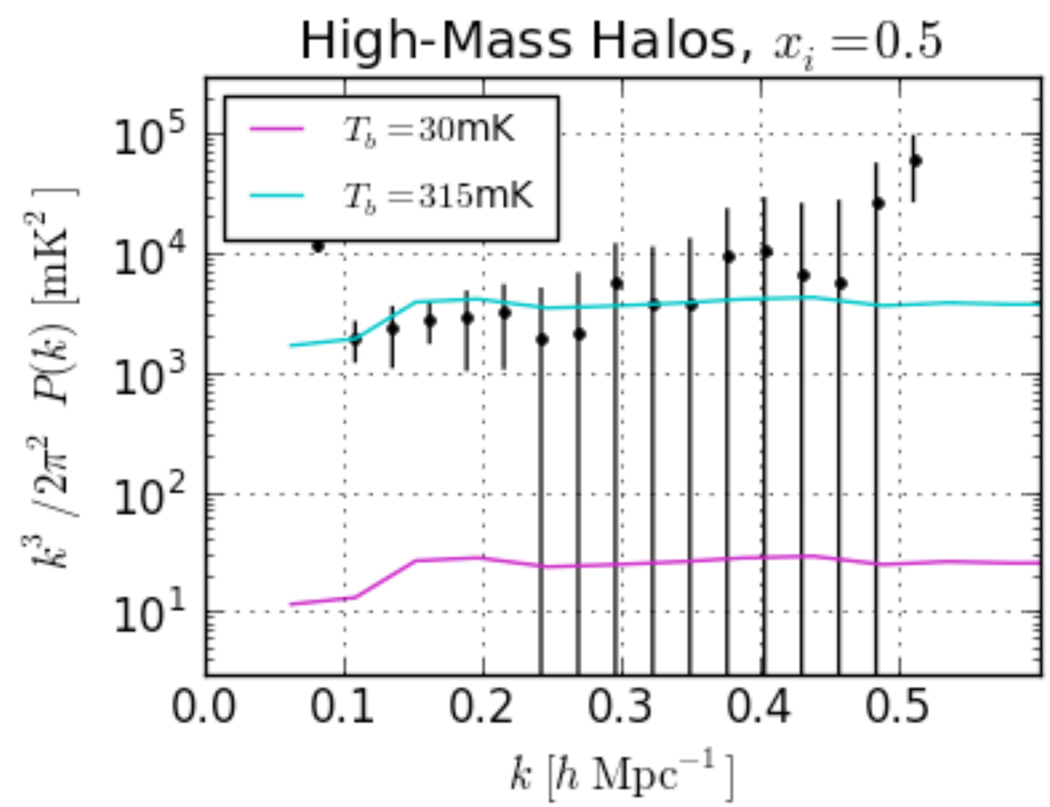
Summary

- Primary EoR science with SKA-Low unaffected by re-baselining, but hours-per-experiment will increase
- Potential mitigation of loss of sensitivity by allowing multi-beaming (divide instrument bandwidth)
- Ionospheric calibration and confusion noise motivating use of 60-80km baselines, but methods for calibrating the instrument not well-defined.

What information can the power spectrum provide?

Example: IGM heating at z=7.7 PAPER Parsons+ (2013)





PAPER limits:

<|T_B|> < 315 mK (2σ) (absorption)

<|T_B|> = 400 mK (no IGM heating)

<|T_B|> = 30 mK (large x-ray heating)

⟶ consistent with non-zero heating

SKA-Low primary science

Credit: CAASTRO/Swinburne Productions

A photon travels from the early Universe, is stretched by cosmological expansion, and arrives at our telescopes in a sea of nuisance signals

SKA-Low primary science

Credit: CAASTRO/Swinburne Productions

A photon travels from the early Universe, is stretched by cosmological expansion, and arrives at our telescopes in a sea of nuisance signals