SKA-low: Science Requirements from "a" Community Perspective

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- EoR/Cosmic-Dawn Science Requirements
- Implications on the Design of SKA-1
- Contentious or Consensus?

Partly based on: "Reionization and the Cosmic Dawn with the Square Kilometre Array", Mellema, Koopmans et al. (2013), to appear in Experimental Astronomy

Motivation

"Reionization and the Cosmic Dawn with the Square Kilometre Array",
Mellema, Koopmans et al. (2013), to appear in Experimental Astronomy

- Writing of the above WP was motivated by the dramatic change in our understanding of the EoR since the SKA Science Book in 2004.

  - CMB scattering optical depth z_{EoR}~10 rather z_{EoR}~20, bringing the Cosmic Dawn into reach of ground-based radio telescope.
  - First discoveries of objects in the EoR: drop-outs, Ly-alpha emitters, QSOs, GRBs, SNae.
  - New physical phenomena: e.g. HI bulk-flows at high-z
  - Much improved simulations (larger and more complete physics).

- Guided by the latest results, we wrote an updated EoR and Cosmic Dawn science case and asked, given (although limited) input from current experiments, what the SKA-low design should be in order to study the CD/EoR to do both <u>power-spectra AND tomography</u>

Science Drivers

- "Dark Ages":

  z = 40-200: Most likely only accessible from space/moon via total power measurements using single receivers.

- "Cosmic Dawn"

  z ~ 25 - 15: Formation of the first stars/galaxies that heat/couple the IGM mostly; impact on gas/spin-temp. T_b fluctuations will be a mixture of density and spin-T fluctuations. Maybe there is impact by bulk-flows from recombination in this redshift range.

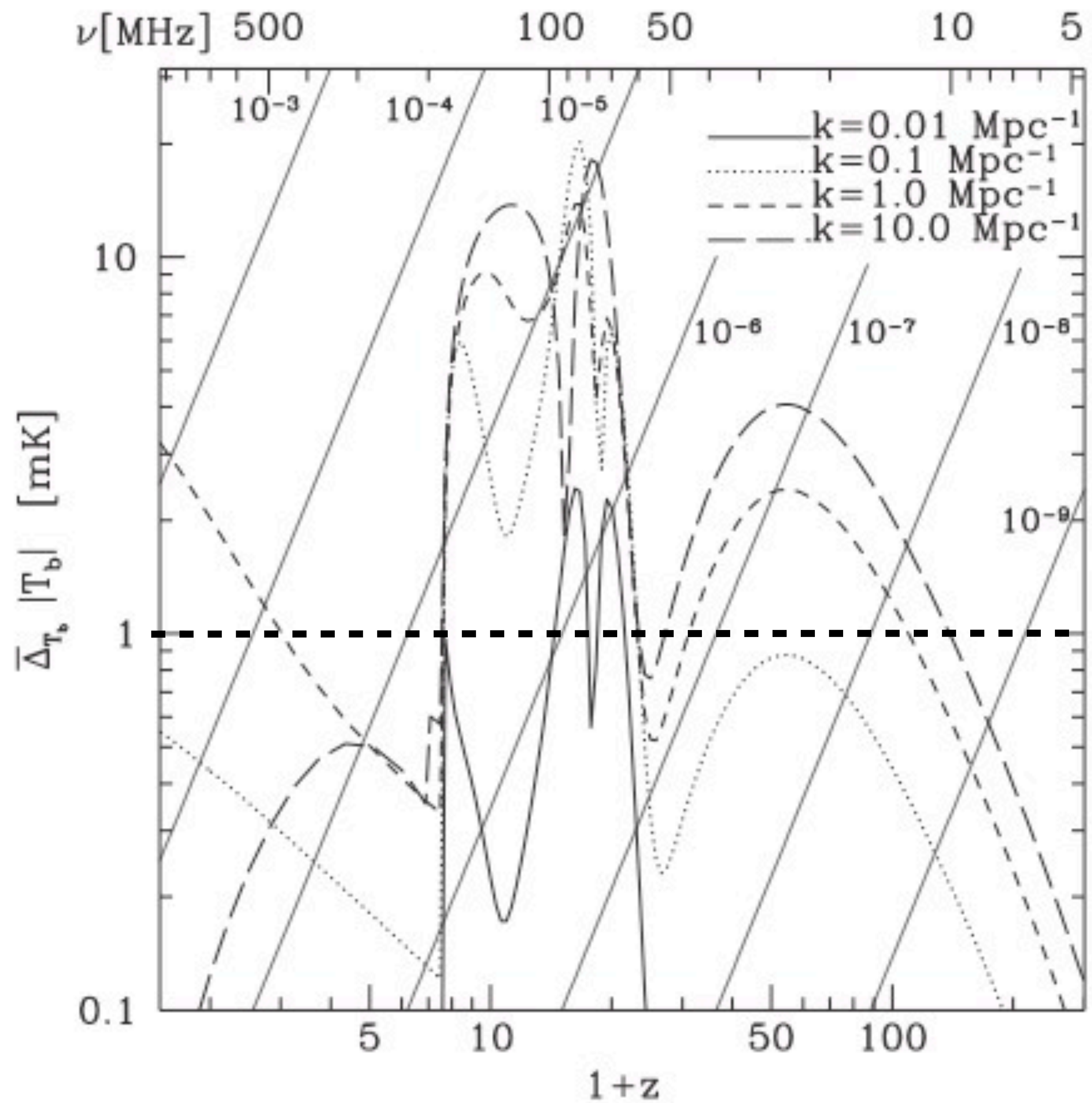
- Reionization:

  z ~15 - 5: Ionizing bubbles grow around first stars/galaxies and percolate. T_b is set by density fluctuations and ionized bubbles mostly.

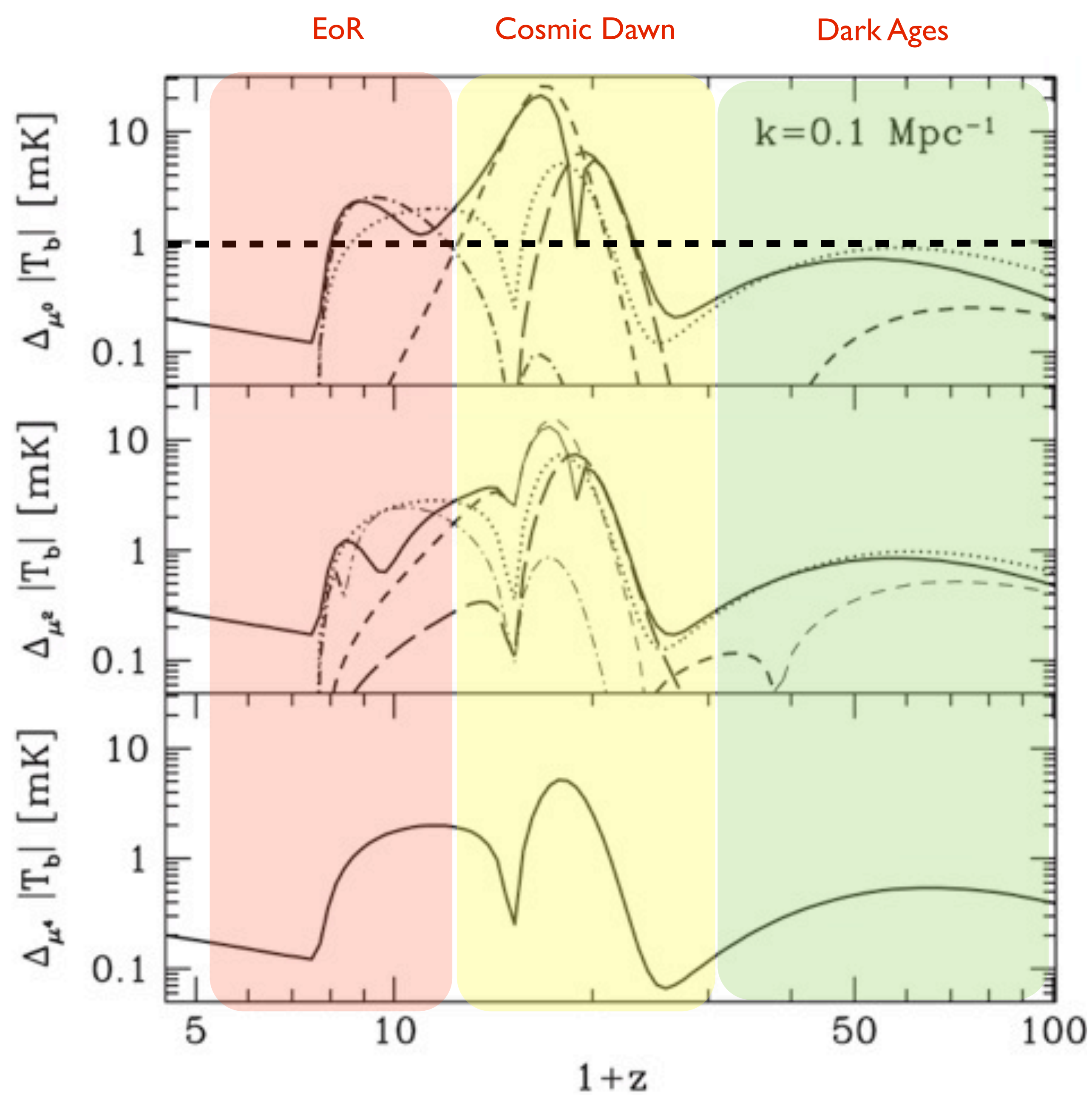
[See Science Talks Yesterday]

Science Drivers

Intensity Fluctuations



Intensity Fluctuations



Pritchard & Loeb 2009; see also Santos et al. 2008, 2010, 2011

Top-level Science Requirements

- Redshift/Freq. Range:
  - z~25-6 - trace the Cosmic Dawn prior to EoR and the EoR till full reionization (z~5-6) [motiv.: CMB-pol, G-P].
- Angular scales for power-spectrum & tomography:
  - arcminute - degrees - Allow PS measurement on degree scales over the full freq. range and tomography on degree scale at z=25 and on all scales >5' at z=10.
- Brightness temperature:
  - dT_b ~ 1 mK rms between bubbles; ~10 mK on/off bubbles [set by state-of-the art simulations plus CMB/G-P limits]

In good agreement with

THE SQUARE KILOMETREARRAY DESIGN REFERENCE MISSION: SKA PHASE 1

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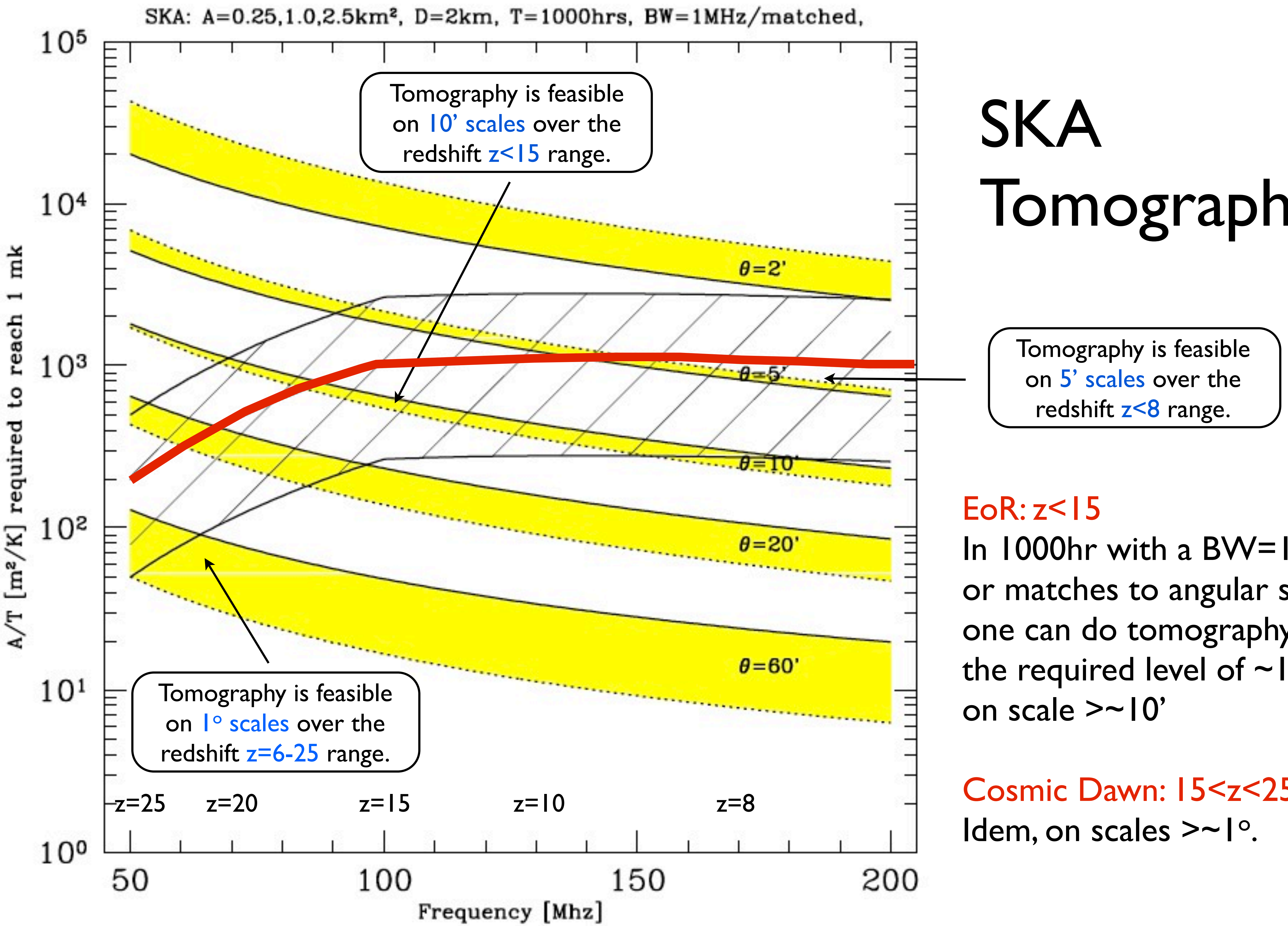
Requirements for the design of SKA-low

From "Reionization and the Cosmic Dawn with the Square Kilometre Array", Mellema, Koopmans et al. (2013), to appear in Experimental Astronomy

1. An absolute minimal frequency range 54–190 MHz; an optimal frequency range 54–215MHz and a wide frequency range of 40–240 MHz.
2. A frequency resolution of ~1 KHz [HI absorption/RFI/calibration/noise-estim.].
3. A physical collecting area A_{coll}> 1 km^{2}x (ν_{opt}/100MHz)$^{-2}$ for ν_{opt} < 100 MHz and at least 1 km^2 for ν_{opt}>100 MHz.
4. An optimal frequency (ν_{opt}; corresponding to a l=2 size of a receiver dipole) around 100 MHz.
5. A core area with a diameter of < 5 km with most collecting area (~75%) inside the inner 2 km.
6. A set of longer baselines (10–20% of the core collecting area) up to ~100 km for calibration, ionospheric modeling and for building a detailed sky model.
7. A station size of order 35m which corresponds to a 2.5–10 degree field-of-view from 200MHz down to 50 MHz.

SKA Tomography



EoR: z<15

In 1000hr with a BW=1MHz or matches to angular scales, one can do tomography to the required level of ~1mK on scale >~10'

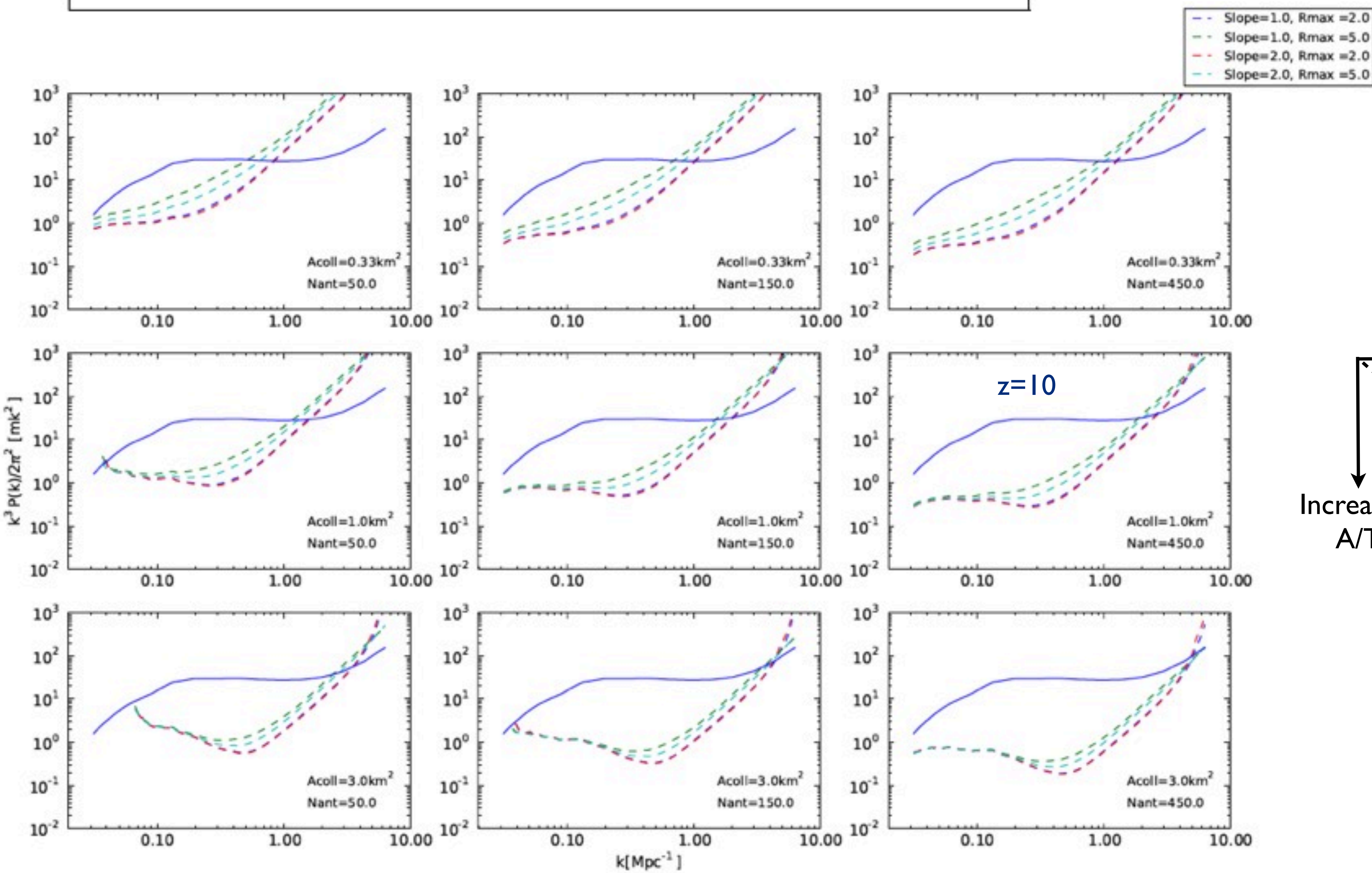
Cosmic Dawn: 15<z<25

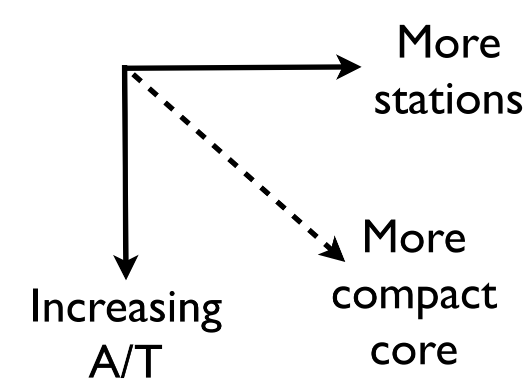
Idem, on scales >~1°.

SKA Power-Spectrum Sensitivity for Single Beam

$$\Delta^2_{\rm Noise} = \left(\frac{2}{\pi}\right) k^{3/2} \left[D_c^2 \Delta D_c \times \Omega_{\rm FoV}\right]^{1/2} \left(\frac{T_{\rm sys}}{\sqrt{B t_{\rm int}}}\right)^2 \left(\frac{A_{\rm core} A_{\rm eff}}{A^2_{\rm coll}}\right)$$

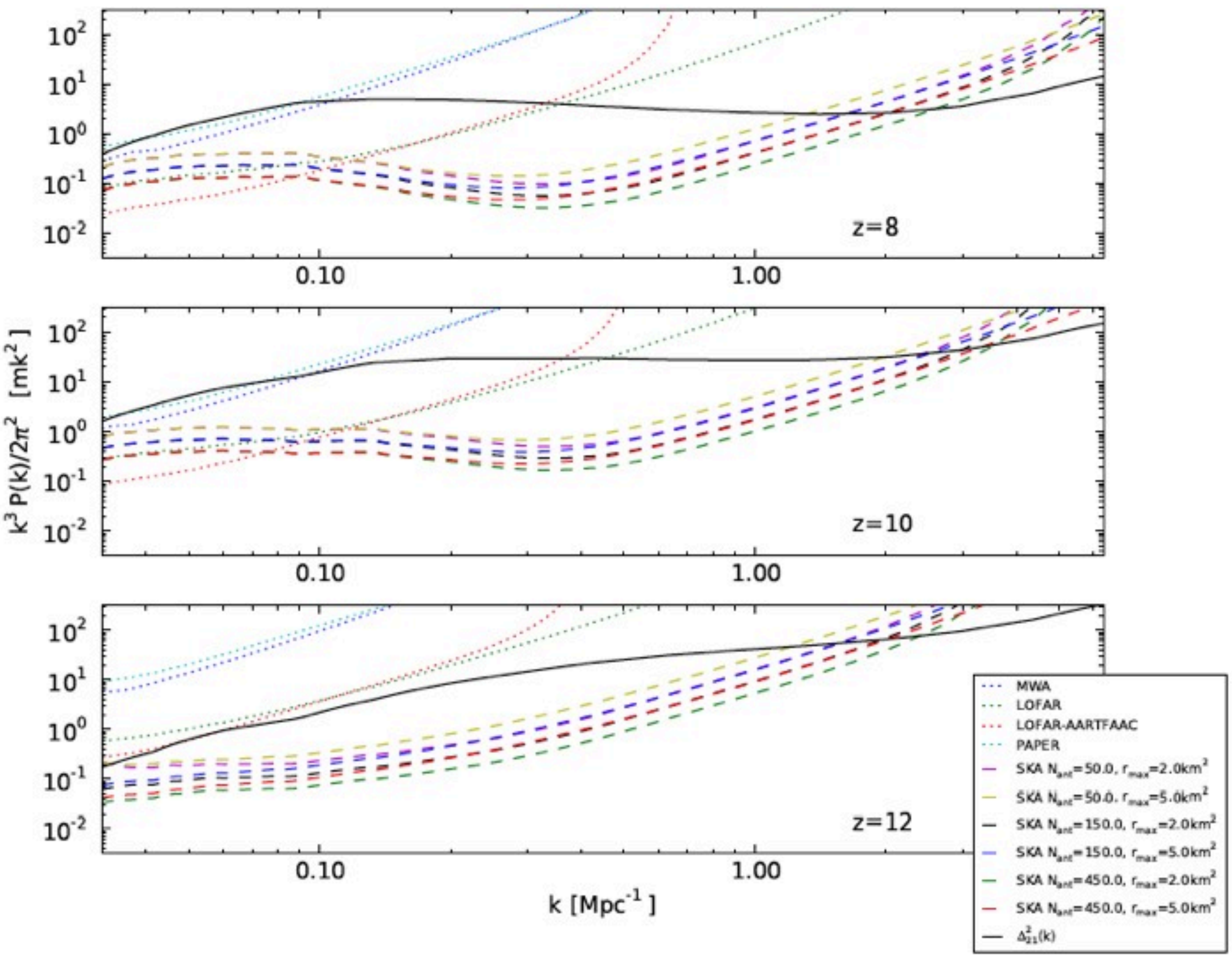
Different core diameters and station densities





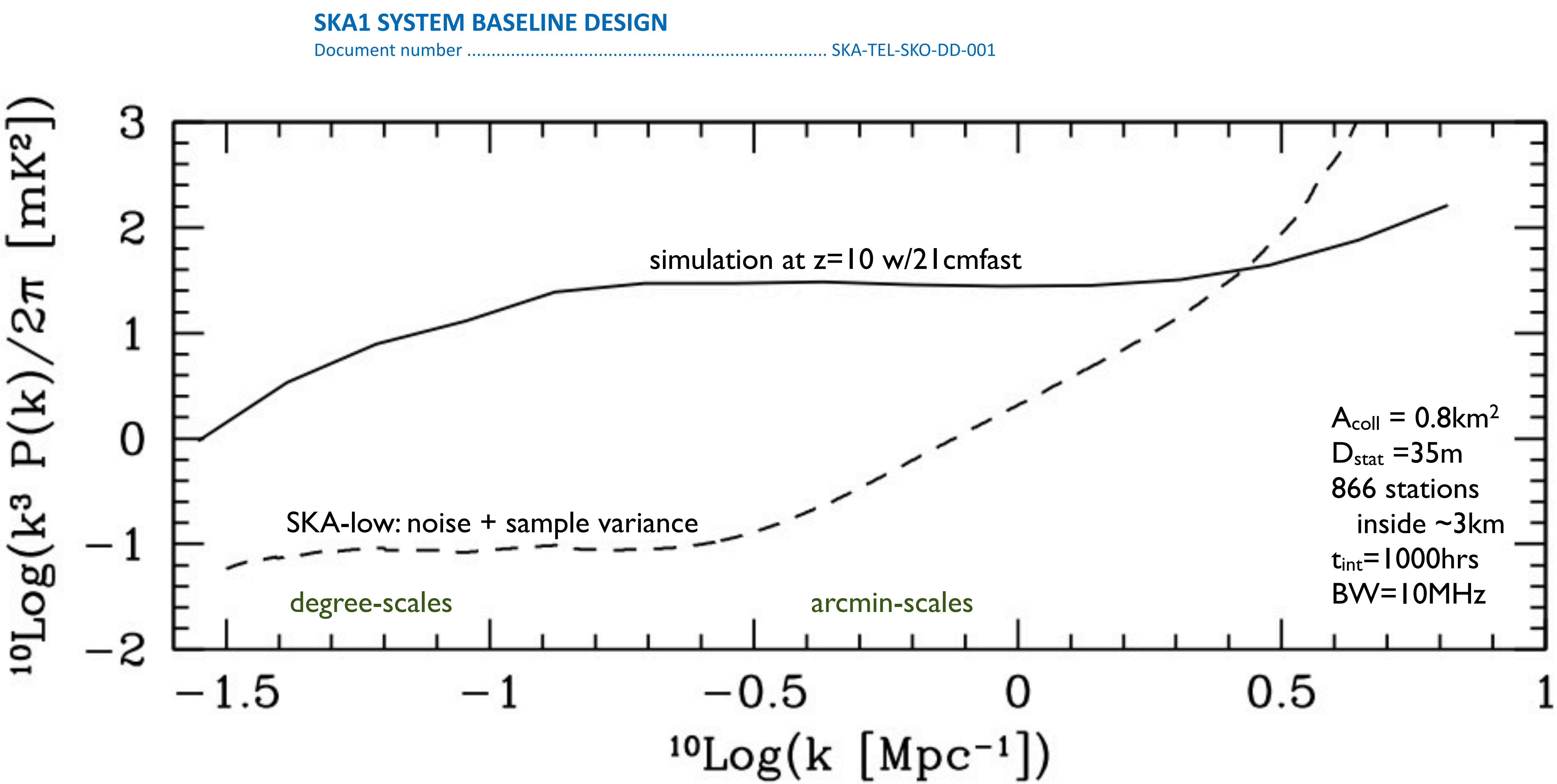
SKA versus Current Arrays

$$\Delta^2_{\rm Noise} \propto \left(\frac{A_{\rm core}\sqrt{A_{\rm eff}}}{A^2_{\rm coll}}\right) \propto \left(\frac{A_{\rm core}}{N^2_{\rm stat}A^{3/2}_{\rm eff}}\right) \propto \left(\frac{A_{\rm core}}{\sqrt{N_{\rm stat}}A^{3/2}_{\rm coll}}\right).$$



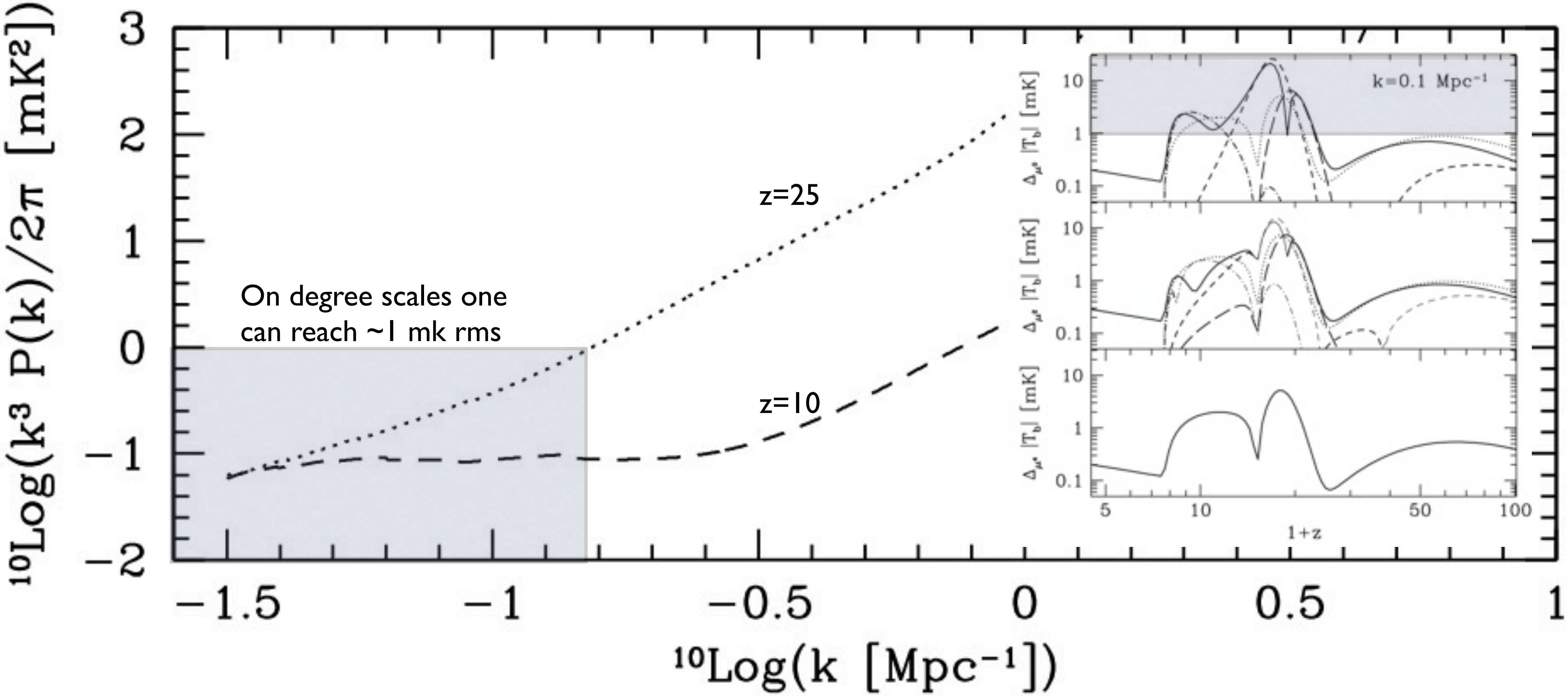
Measuring the EoR HI-T_b Power-Spectrum at z=10

Assuming the current SKA baselines design



HI detection at z=25 with SKA-low

At z=25, one can reach an errors << 1mK on scales of ~1 degree within 1000hrs and BW=10MHz, using the current (March 2013) baseline design.



Impact on the Design of SKA-low

FoV/Station size

- CD/EoR simulations suggest that scales ~1' to ~1 degree can show dT_b~1mK fluctuations. Limiting the sample variance and loss in structure in tomography requires at least FoV>>1 degree.

- A larger FoV/smaller station for fixed A_{coll}, leads to a better uv-coverage, which helps instantaneous calibration.

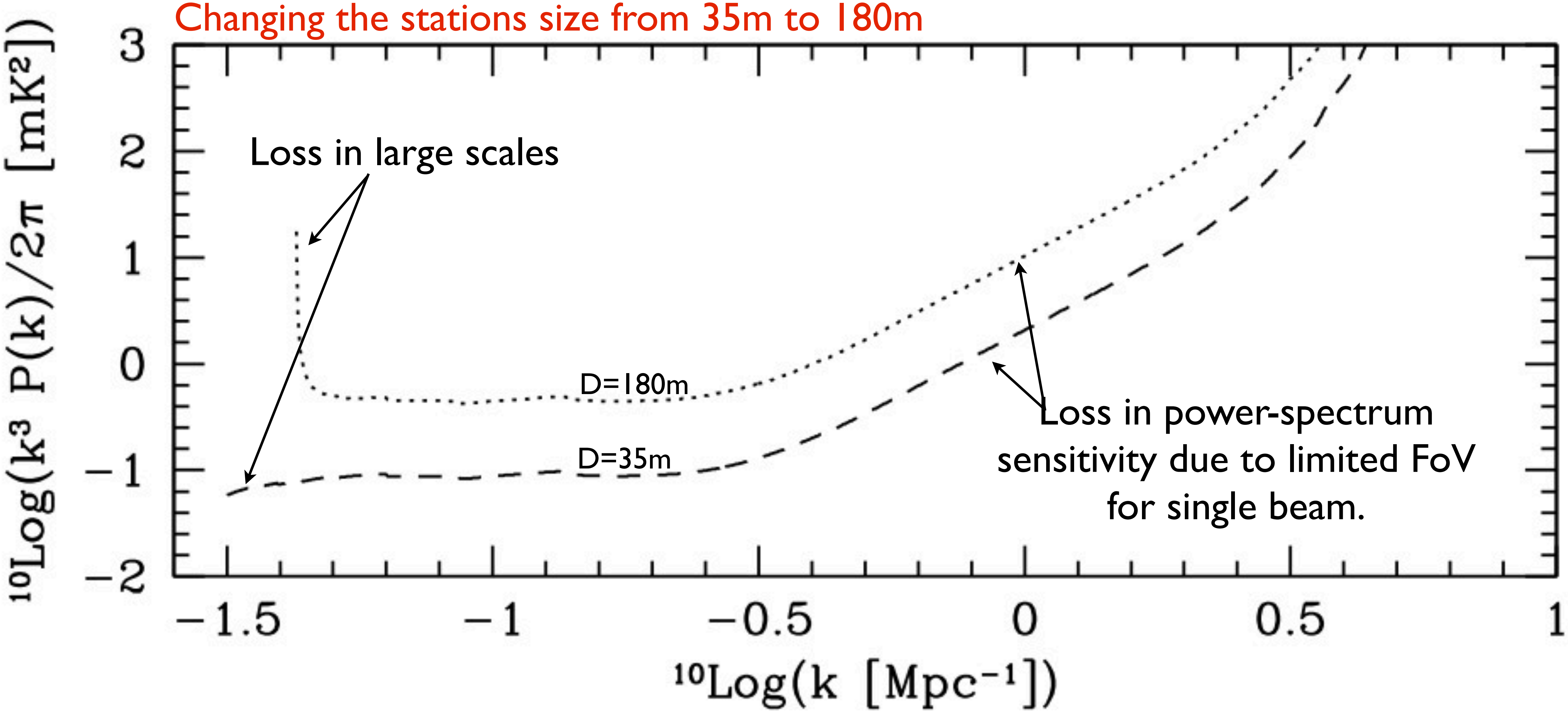
- A too large FoV/too small station, might lead to a sky that is only calibratable around bright sources => analogy with MC-AO systems!

- Multi-beaming can only partly recover scales > station beam, but can build up power-spectrum sensitivity on scale inside the beam and do tomography.

- Too many small stations cost much more correlator/computing power

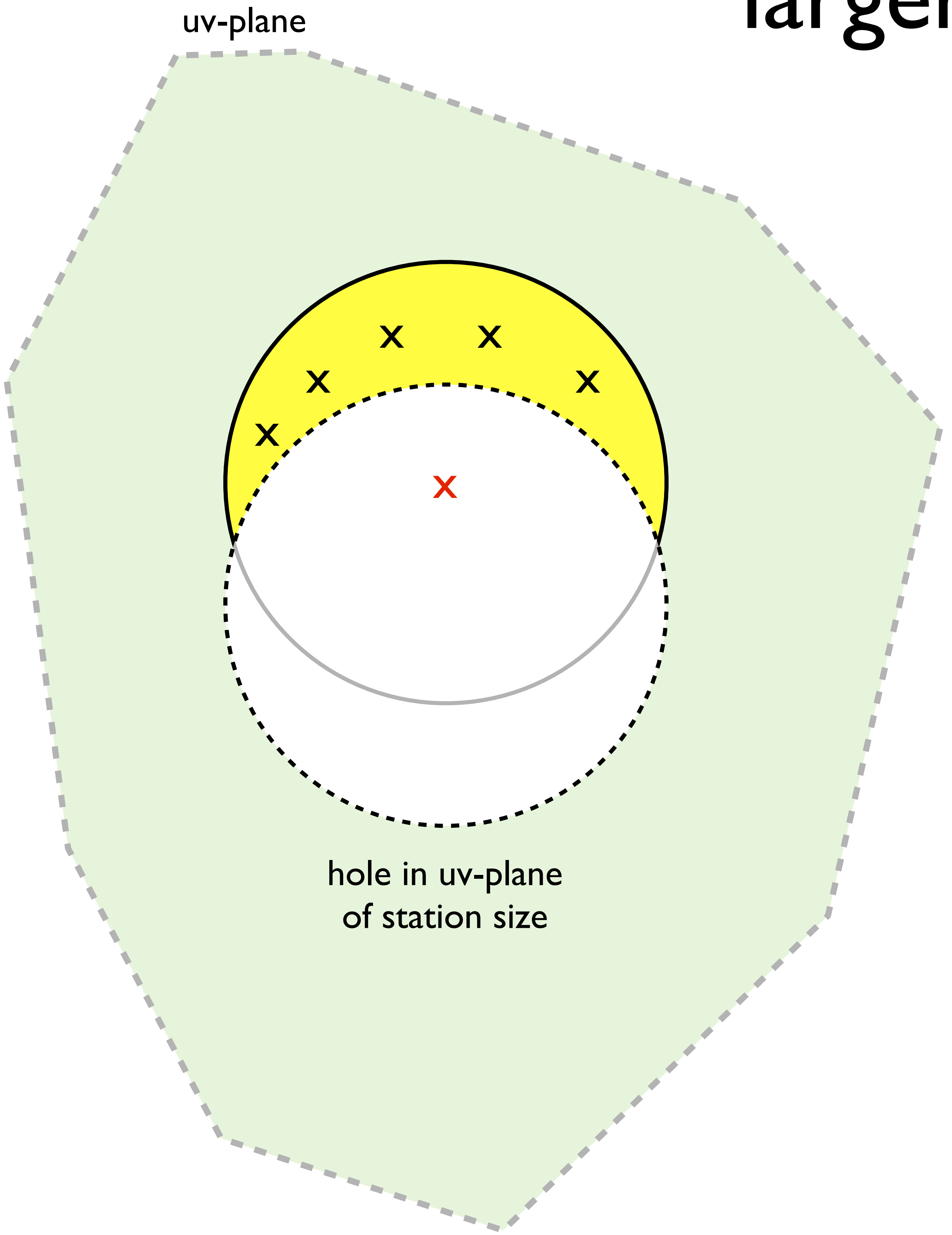
Impact on the Design of SKA-low

Changing the stations size from 35m to 180m



Loss in sensitivity for a single beam station is a factor ~(180/35)~5; Multi-beaming with ~25 beams can recover the PS-sensitivity loss for ~25x less station correlations. However, scales > 1 degree are harder to recover, if at all, and at a cost of sensitivity.

Multi-beaming comes at a cost for scale larger than the station beam



If we want to know scales larger than the primary beam, we basically want to know points (x) that are inside the hole in the uv-plane.

Since visibilities contain information about the true uv-plane inside a circle of station size around them, only visibilities (x) in the yellow crescent contain this information.

This crescent shaped area decreases rapidly as x moves closer to the zero-spacing and hence information is lost on large scales.

It's an extrapolation/deconvolution process, notoriously ill-posed.

SCIENCE REQUIREMENTS

Long Baselines

- Calibration using long baselines reduces model degeneracies. The sky is "simpler" at long baselines, whereas the science is at short baselines. Hence the danger of covariance between calibration and EoR parameters is reduced

- Information content in uv plane is much larger when going from say 3 km diameter array to a 45 km diameter array; by factor $(D^2_{core} \times (4+N_{stat,outer})/(4D^2_{core}) \sim 1 + (1/4) \times N_{stat,outer} \sim 10\times$. Much more if uv-planes are filled.

- Modeling of high-DR slightly resolved sources improves dramatically. One is sensitive to FWHM/sqrt[S/N] for any source. Especially bright sources need exquisite modeling

- Confusion "noise" on short baselines can be reduced by subtracting sources observed at higher spatial resolution prior to MW-FG removal.

- An imprint of the array equal to the FoV of a core station allows the ionosphere to be modeled in 3D through 3D tomography.

Contentious or Consensus?

- A/T ~ 1000 m^2/K >100MHz, down to ~150 m^2/K @ 50MHz:

  i.e. A_{coll}=1km^2 Consensus? Tomography needs it, but power-spectra maybe not.

- ν_{low} = 50 MHz lower frequency limit

  Consensus? Many new interesting physics might take place starting at z~25; risk is high but reward is high as well.

- D_{stat} = 35 meter station size:

  Too small for calibration? Seems sweet-spot for FoV and computational effort. Can multi-beaming make up loss in FoV if D>>35m? Should stations outside core be larger?

- Baselines up to 100 km:

  Really needed or can calibration and compact-FG be done with same baselines that provide EoR science? Can be understand the sky/ionosphere well enough with limited information content in the core? Information content is small on short baselines. i.e. short-baseline problems are more visible on long-baselines.