SKA1-AA-low: CD/EoR Science, Requirements and Request for (no/some) Change

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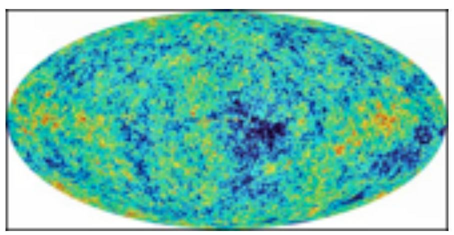
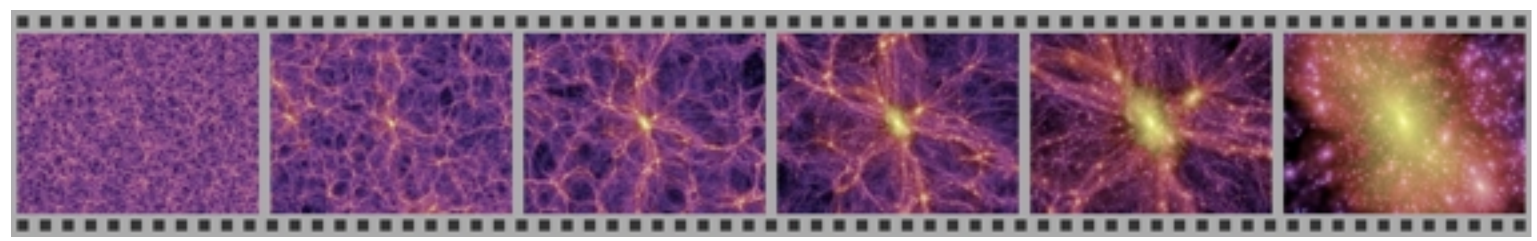
- Cosmic-Dawn/EoR Science Requirements
- Implications on the design of SKA(-1)
- Rf(no)C of the current baselines design

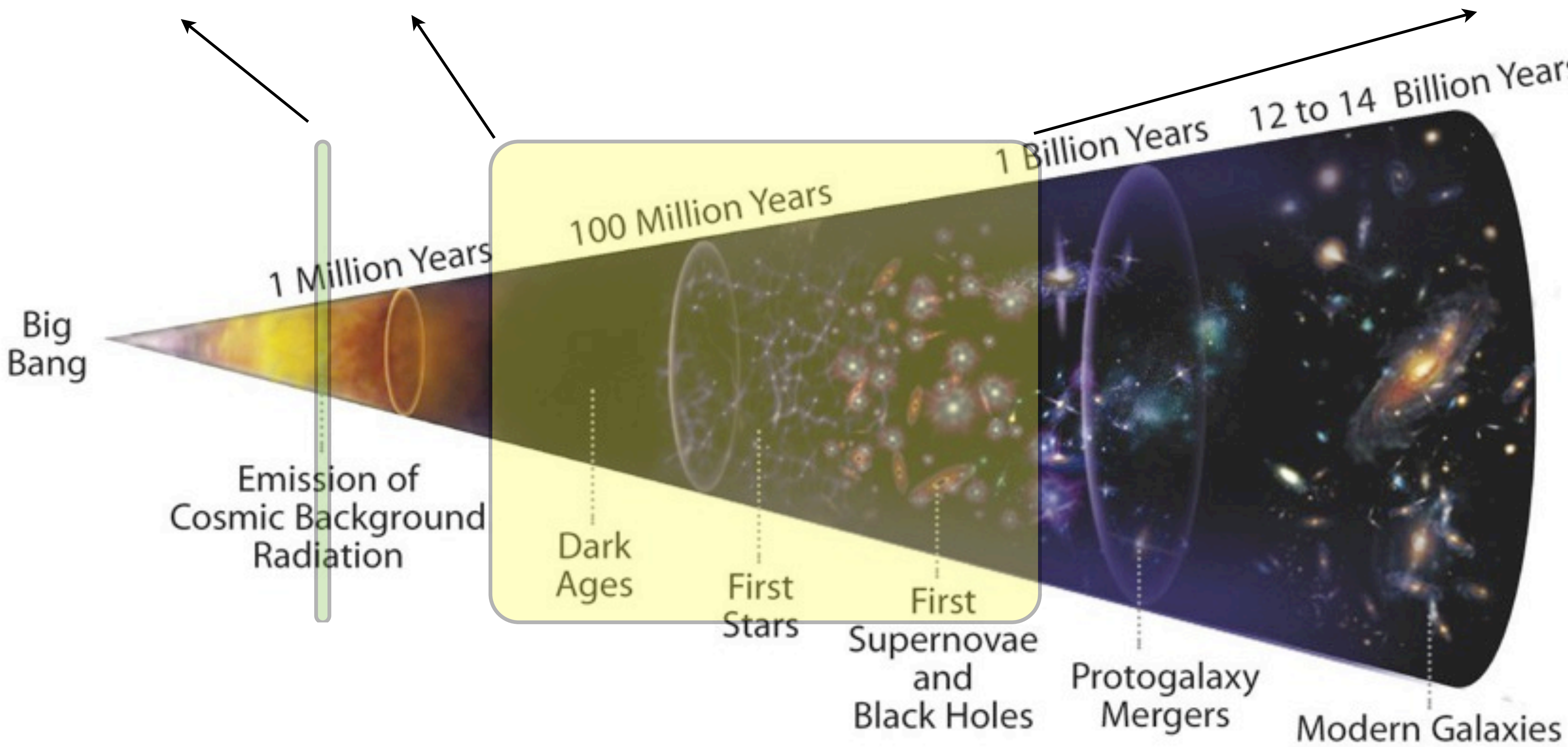
Dark Ages, Cosmic Dawn & EoR

CMB displays a single moment of the Universe. Its initial conditions at ~400,000 yrs

HI emission from the Dark Ages, Cosmic Dawn & EoR traces an evolving "movie" of baryonic structure formation. ($<10^9$ yrs)







Short Summary of Constraints on the EoR

Most evidence points at substantial reionization (still) occurring at $z<10$, but its cause/source is unknown: better tracers are needed (i.e. HI itself)

- Scattering optical depths from CMB observations

  Ionized medium causes CMB polarization: $z_{eor} \sim 10$

- High-z galaxies

  IR drop-outs give SFR/LF to z~10: SFR rises fast below z~10 but there are not enough UV photons to re-ionize the Universe >>> Puzzle!

- High-z QSOs

  Gunn-Peterson troughs suggest ~10% neutral HI at z~7, i.e. the end of reionization occurs close to the highest z QSO/galaxies that we observe

- High-z GRBs

  GRBs traces massive star formation. Currently rare events, but z~8.2 GRB has been seen and could be a direct tracer of the SFR.

- Temperature of the IGM

  Extrapolation of the high-z IGM temperature suggest late reionization

Changes in our understanding of the CD/EoR eras, since 2004

- Since the SKA Science Book (2004) a dramatic change in our understanding of how the CD/EoR has unfolded (*) *"Reionization and the Cosmic Dawn with the SKA"*, Mellema, Koopmans et al., 2013, Exp. Ast.

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

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

What makes SKA special?

It allows study of the Cosmic Dawn & Tomography of the EoR!

Space/Moon based Interferometers
~2030

SKA/ELT/JWST
~2020

Present day Telescopes
2013

Dark Ages

- DM power-spectrum evolution
- DM annihilation physics
- Baryonic Bulk Flows
- Physics of Gravity/GR

Cosmic Dawn

- Appearance of first stars (PopIII?)
- Ly-α radiation field
- Impact of Baryonic Bulk Flows
- First X-ray heating sources

Reionization

- Reionization by stars & mini-quasars
- IGM feedback (e.g. metals)
- PopIII - PopII transition
- Emergence of the visible universe

Hydrogen Brightness Temperature

The quantity that can be measured with SKA along a given line of sight is given by:

$$\boxed{\delta T_b} = \frac{T_S - T_R}{1+z}\left(1 - e^{-\tau_\nu}\right)$$

$$\approx \frac{T_S - T_R}{1+z}\tau$$

Cosmology

$$\boxed{\begin{aligned} &\approx 27 x_{\mathrm{HI}}\,(1+\delta_b)\left(\frac{\Omega_b h^2}{0.023}\right)\left(\frac{0.15}{\Omega_m h^2}\,\frac{1+z}{10}\right)^{1/2} \\ &\times \left(\frac{T_S - T_R}{T_S}\right)\left[\frac{\partial_r v_r}{(1+z)H(z)}\right]\ \mathrm{mK}, \end{aligned}}$$

Ionization

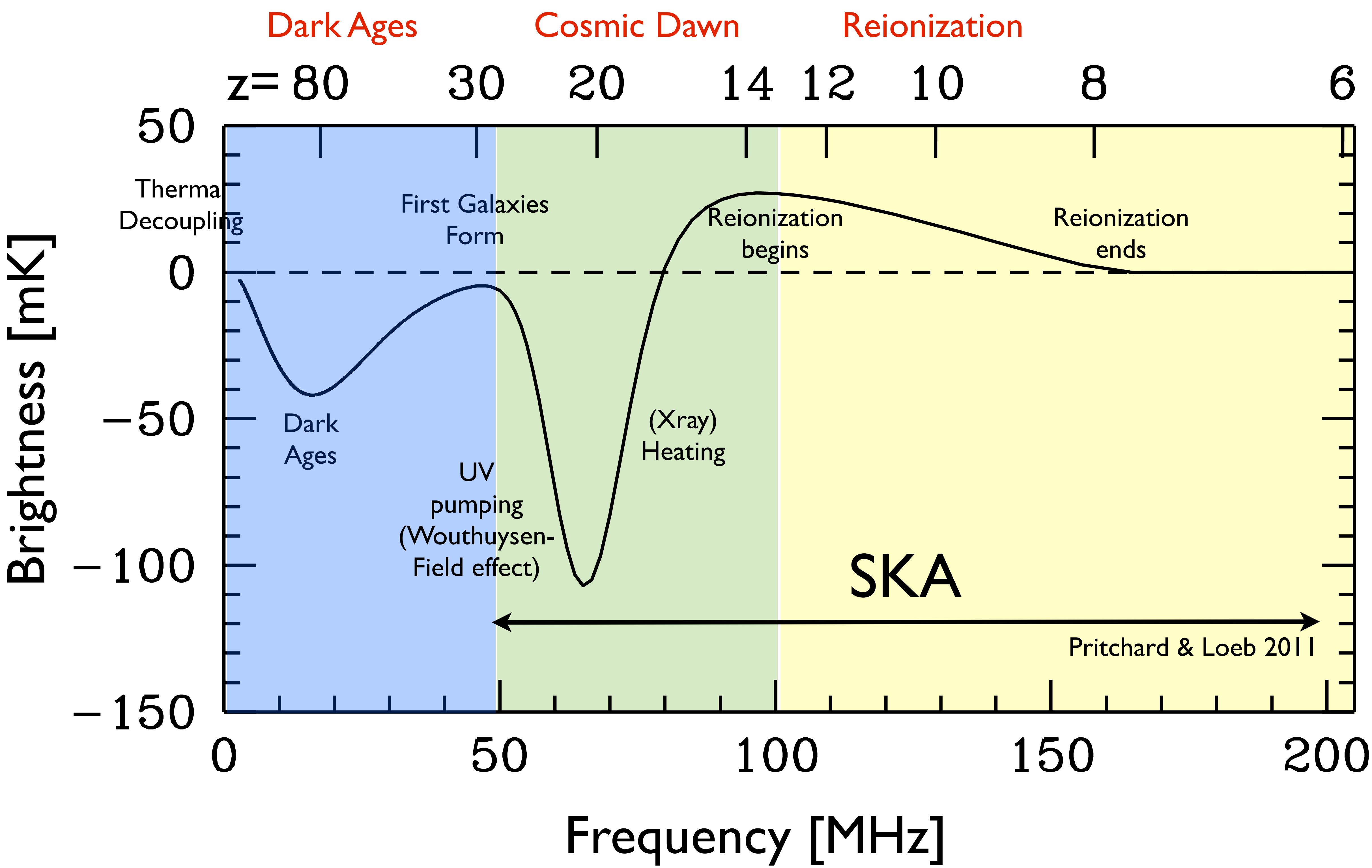
(G)astrophysics

Peculiar velocities/Bulk-flows

The HI 21-cm intensity is set by a complex interplay between cosmology and (g)astrophysics.

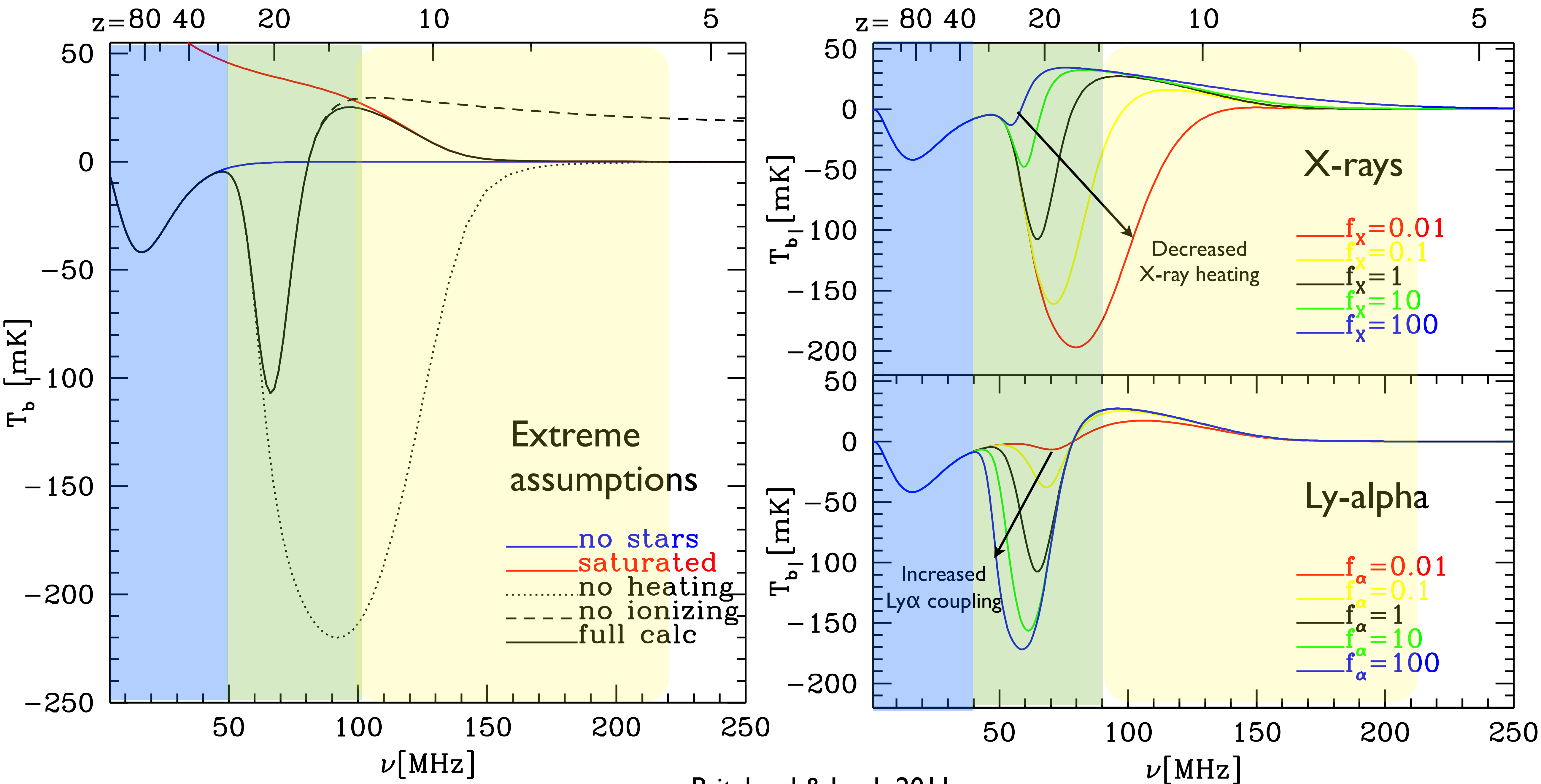
Hydrogen Brightness Temperature

Global Signal



Hydrogen Brightness Temperature
Global Signal

The history of T_b can vary; hence measuring T_b as function of redshift/time, provides a handle on SF, Ly-α coupling (WF), (X-ray) heating, etc.

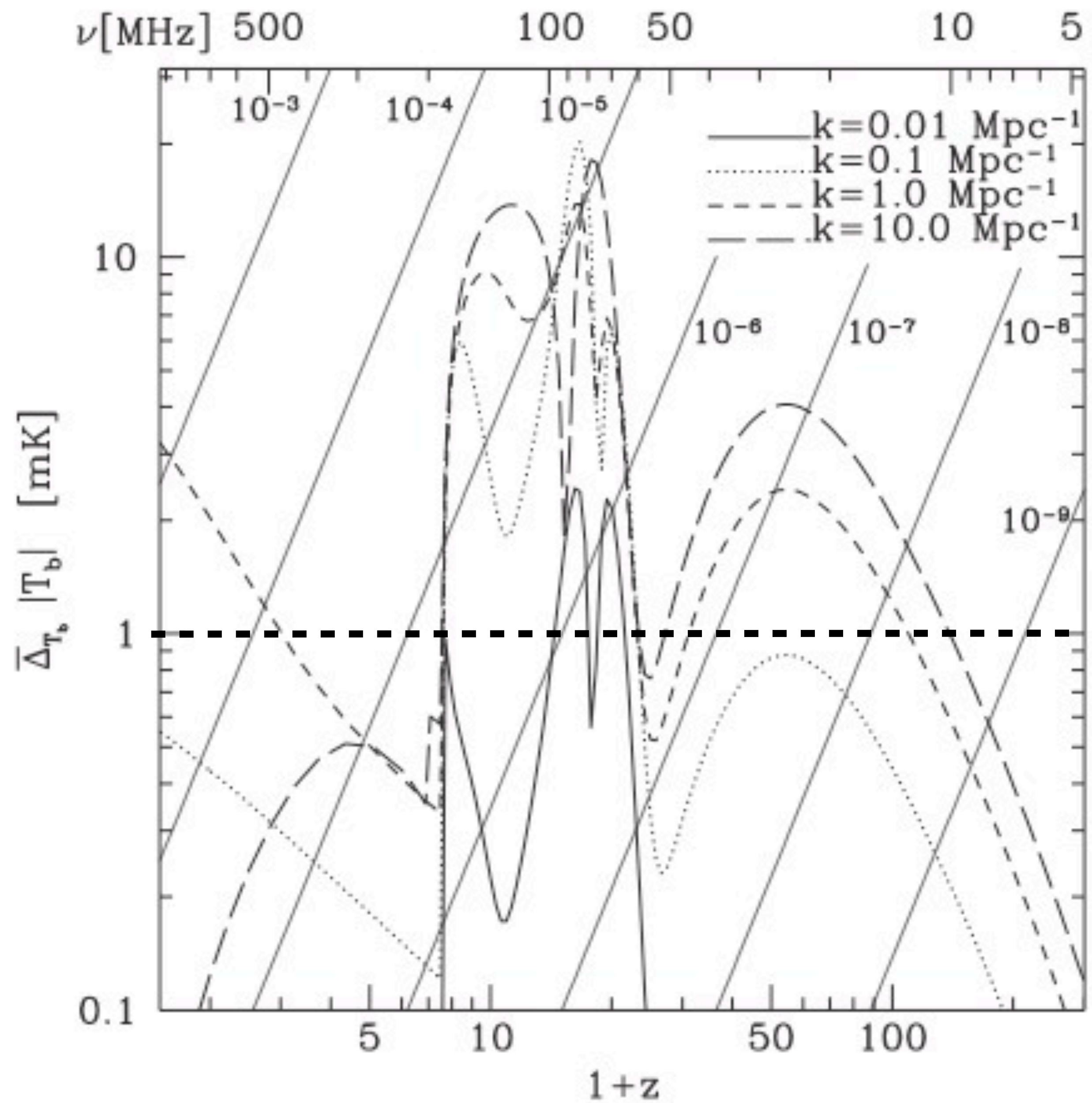


Pritchard & Loeb 2011

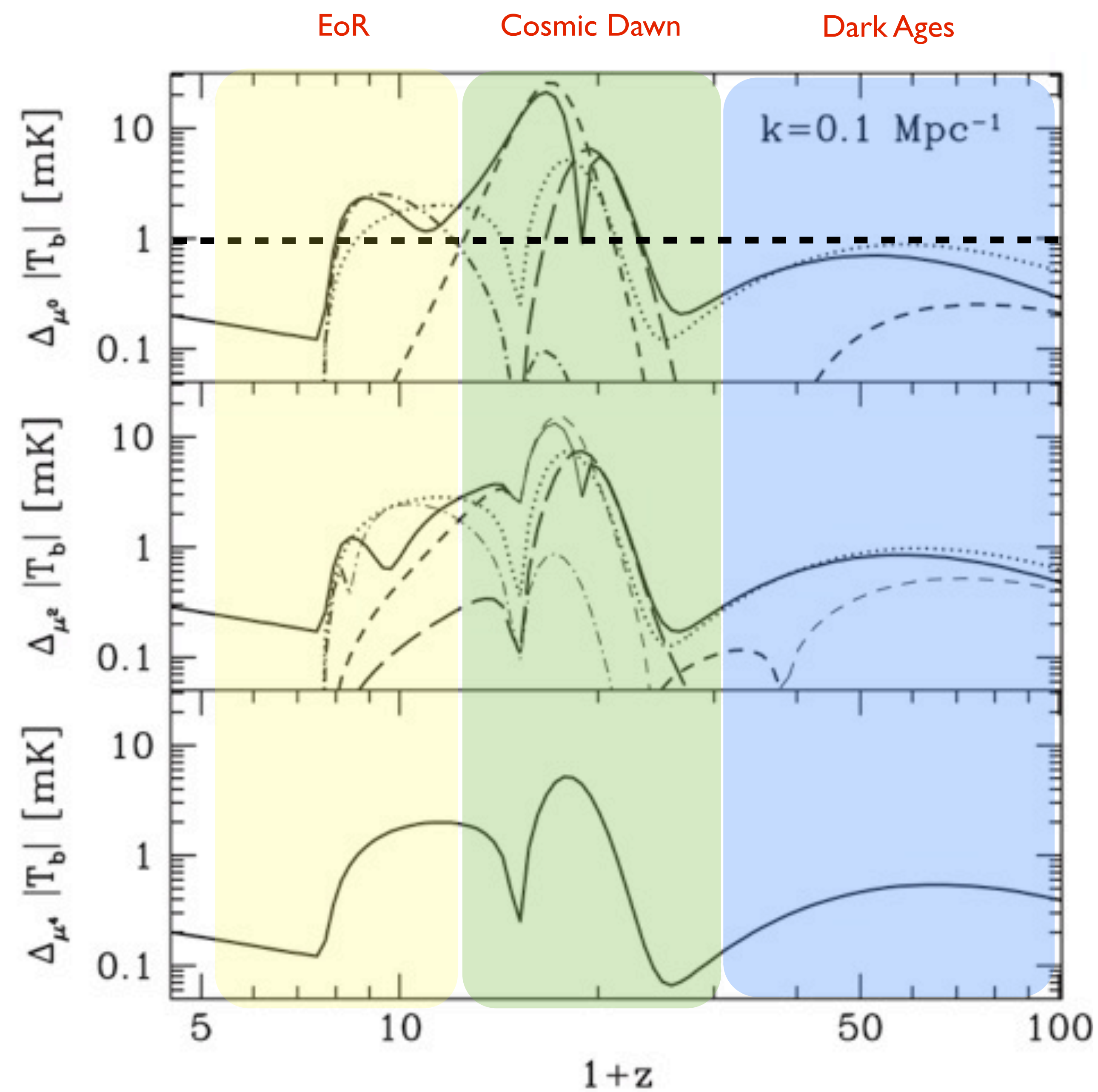
Hydrogen Brightness Temperature

Power-Spectrum

Intensity Fluctuations



Intensity Fluctuations

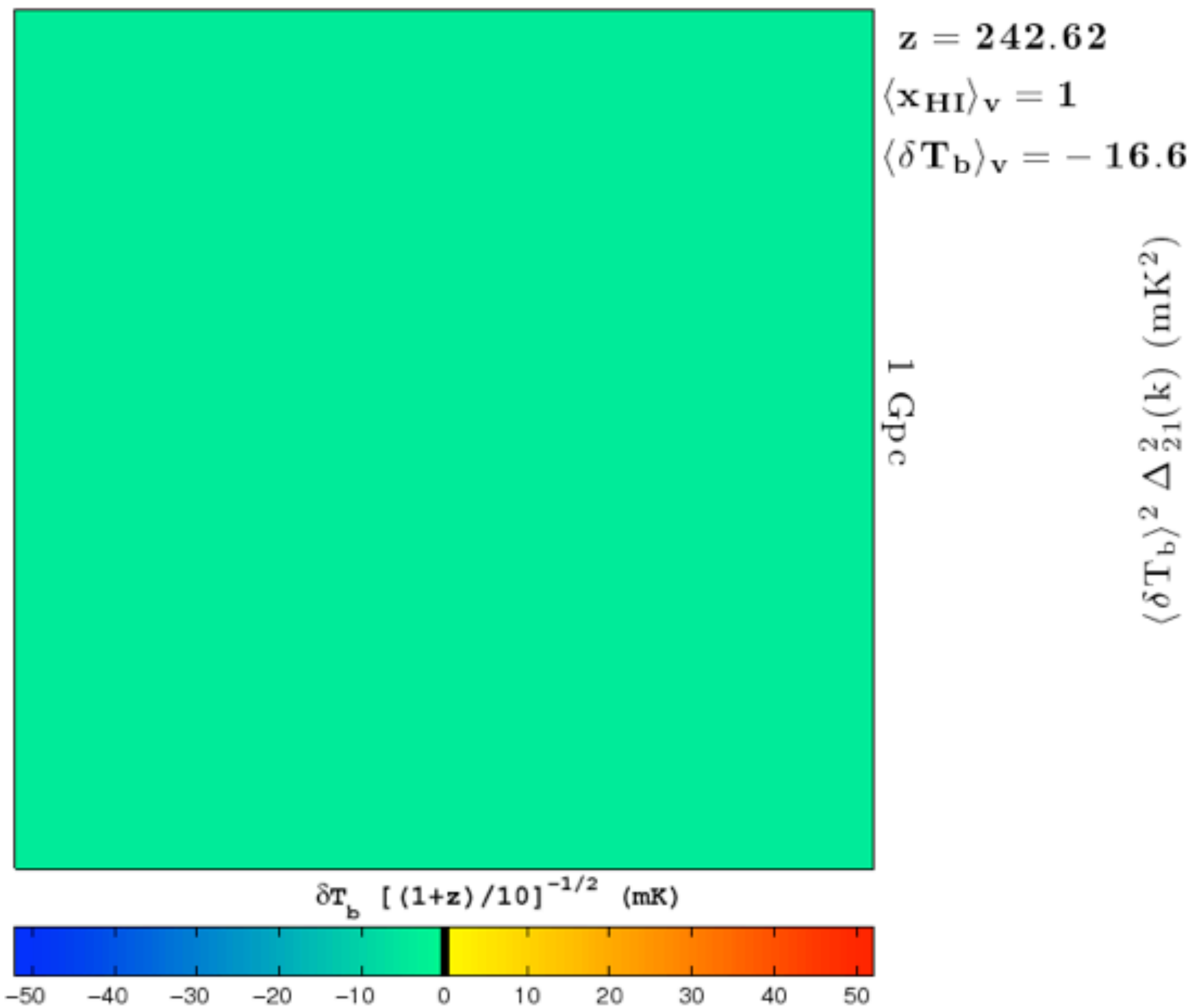


Pritchard & Loeb 2009; see also Santos et al. 2008, 2010, 2011

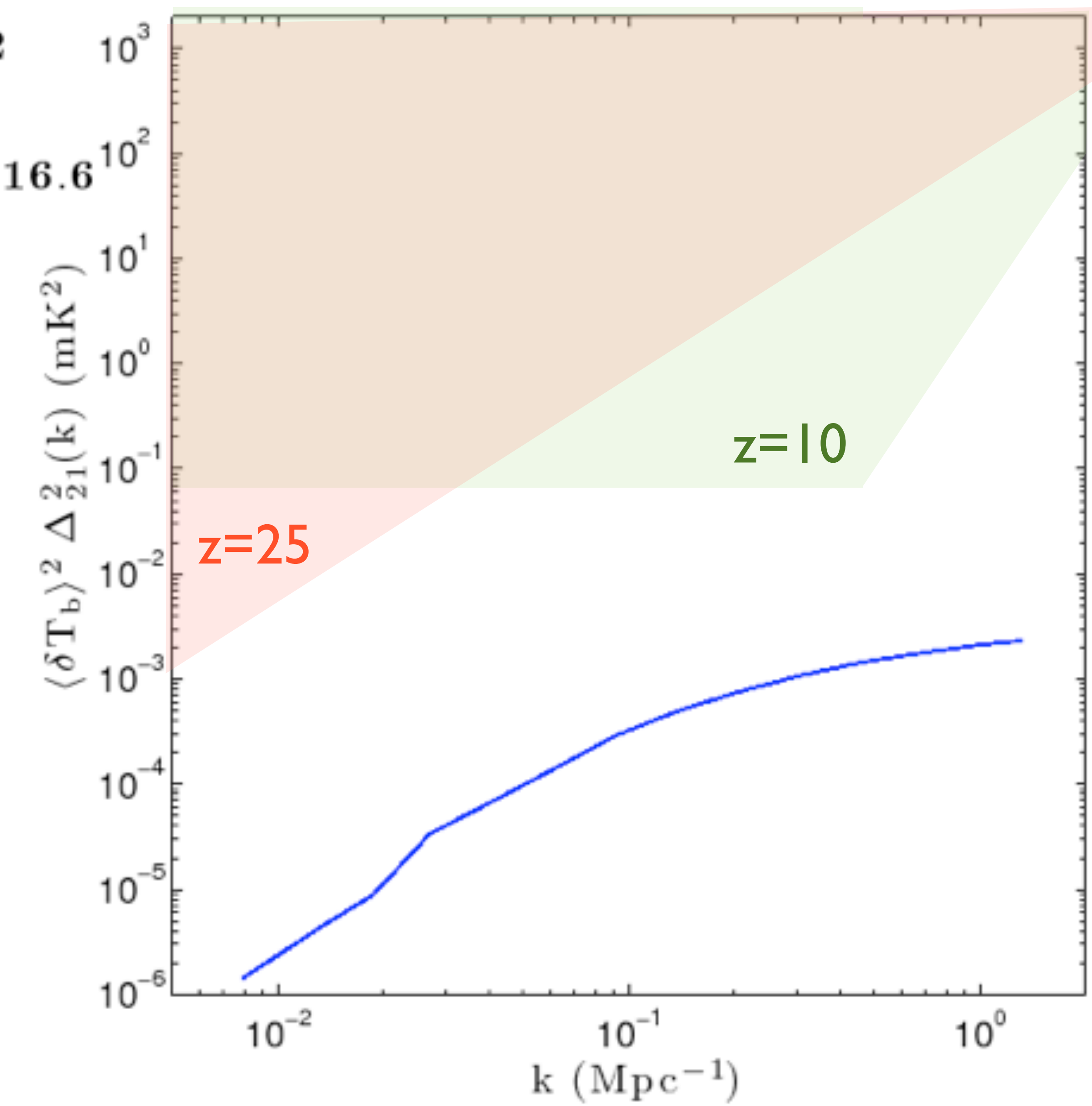
Hydrogen Brightness Temperature

Tomography & Power-spectrum

Credit: Mesinger



Rough detection box for SKA



Sensitivity limits are scale dependent but Δ^2_{noise}~few mK^2 is where current instruments aim for in ~1000 hrs. SKA can go to Δ^2_{noise}~0.1 mK^2

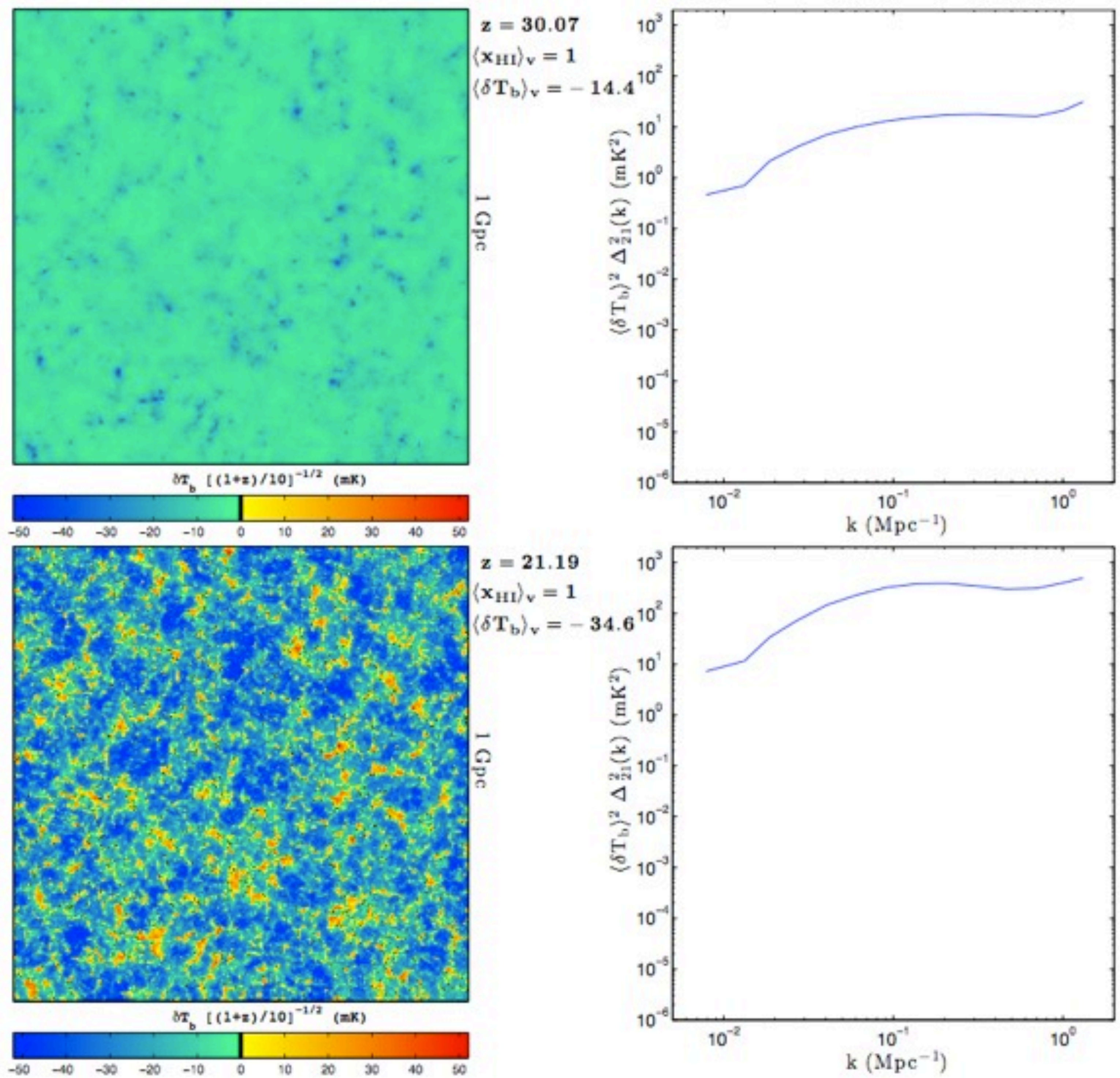
Hydrogen Brightness Temperature

Tomography & Power-spectrum

Cosmic Dawn

The first stars form in ~10^8 M_{sun} haloes and start coupling the spin temperature (locally) to the cold gas temperature (W-F). After some time X-ray sources(?) heat the gas and cause the spin-temperature to rise again.

At high-z HI is seen in absorption with fluctuations sourced by baryonic density fluctuations. Some time later locally the gas is heated by X-rays and locally couples to the spin-temp. causing patches in absorption and emission, sourcing T_b fluctuations.



Mesinger 2010

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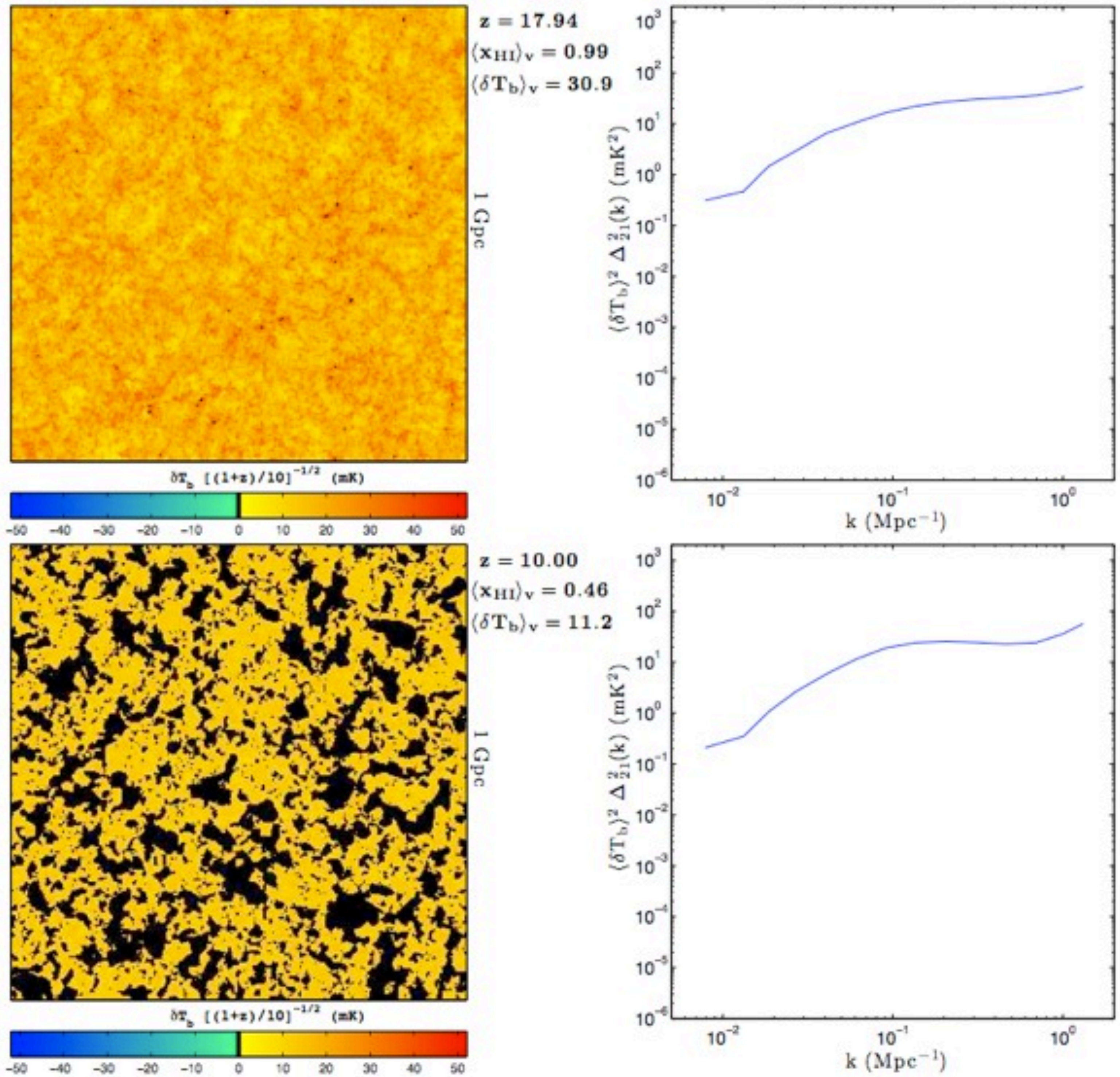
Hydrogen Brightness Temperature

Tomography & Power-spectrum

Reionization

After a while X-ray heating is completed and HI is only seen in emission and is still mostly neutral. Fluctuations are sourced again by density fluctuations and peculiar velocities.

Finally ionization sets in and causes bubbles to occur. The strong contrast between bubbles and neutral patches is another sources of T_b fluctuations.



Mesinger 2010

SKA1: Transformational or not?

For SKA1 to be *transformational* and not a statistical HI detection instrument like its pathfinders MWA, PAPER, LOFAR, GMRT, it should be able to:

(1) Study the Cosmic Dawn (to z~25) via tomography on large scale and via power-spectra on smaller scales.

(2) Enable tomography on all scales (few arcmin-degrees) during the full Epoch of Reionization (z~6-15).

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].

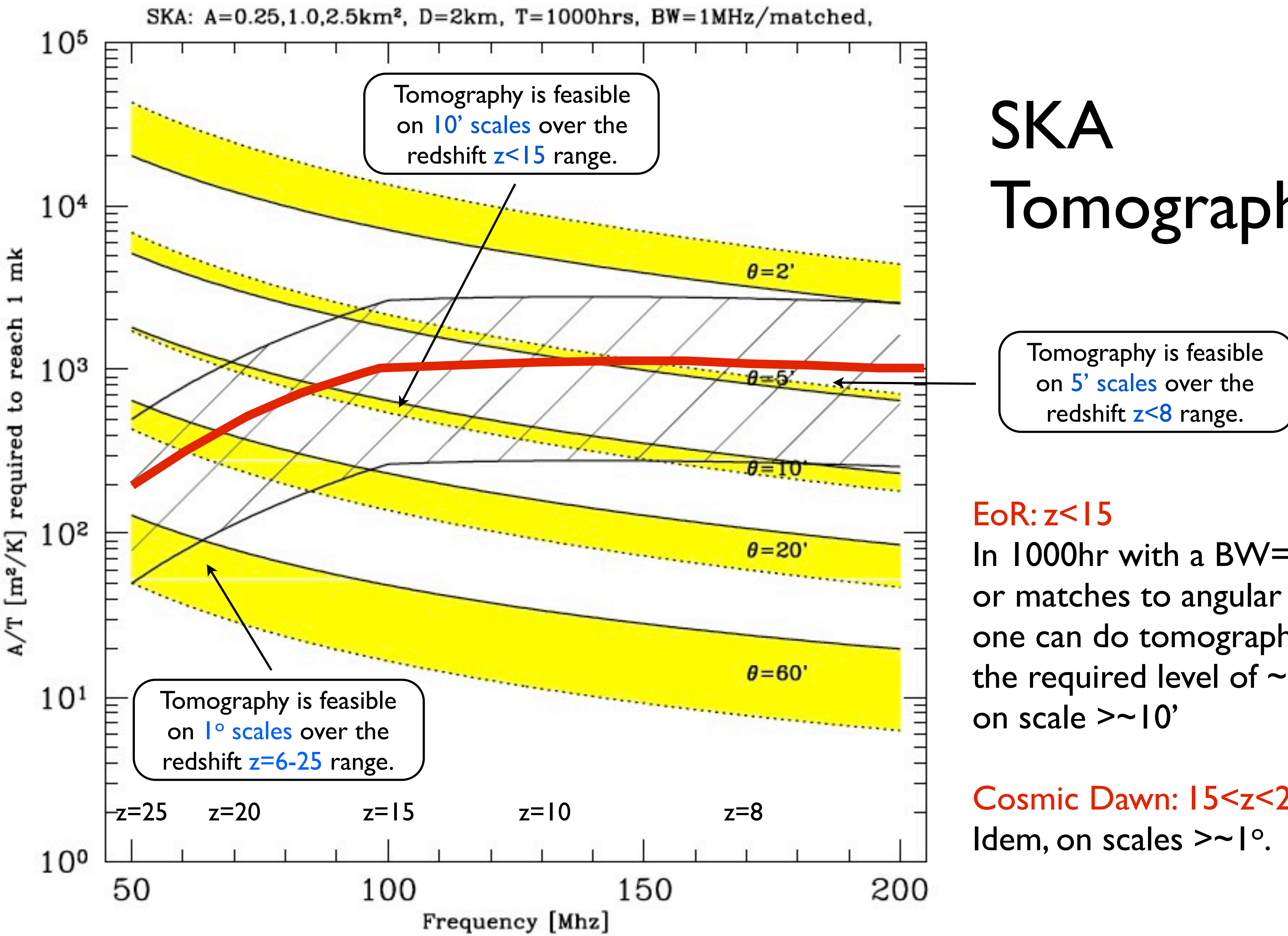
- Angular scales for power-spectrum & tomography:
  - arcminute - degrees - Allow PS measurement on degree scales over the full freq. range and tomography on degree scale at z=25 and on all scales >5' at z=10.

- 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 excellent agreement with

THE SQUARE KILOMETREARRAY DESIGN REFERENCE MISSION: SKA PHASE 1

Document number SCI-020.010.020-DRM-002
Revision........ 3
Author .... SKA Science Working Group
Date 2012-05-28
Status .... Requirements Baseline



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

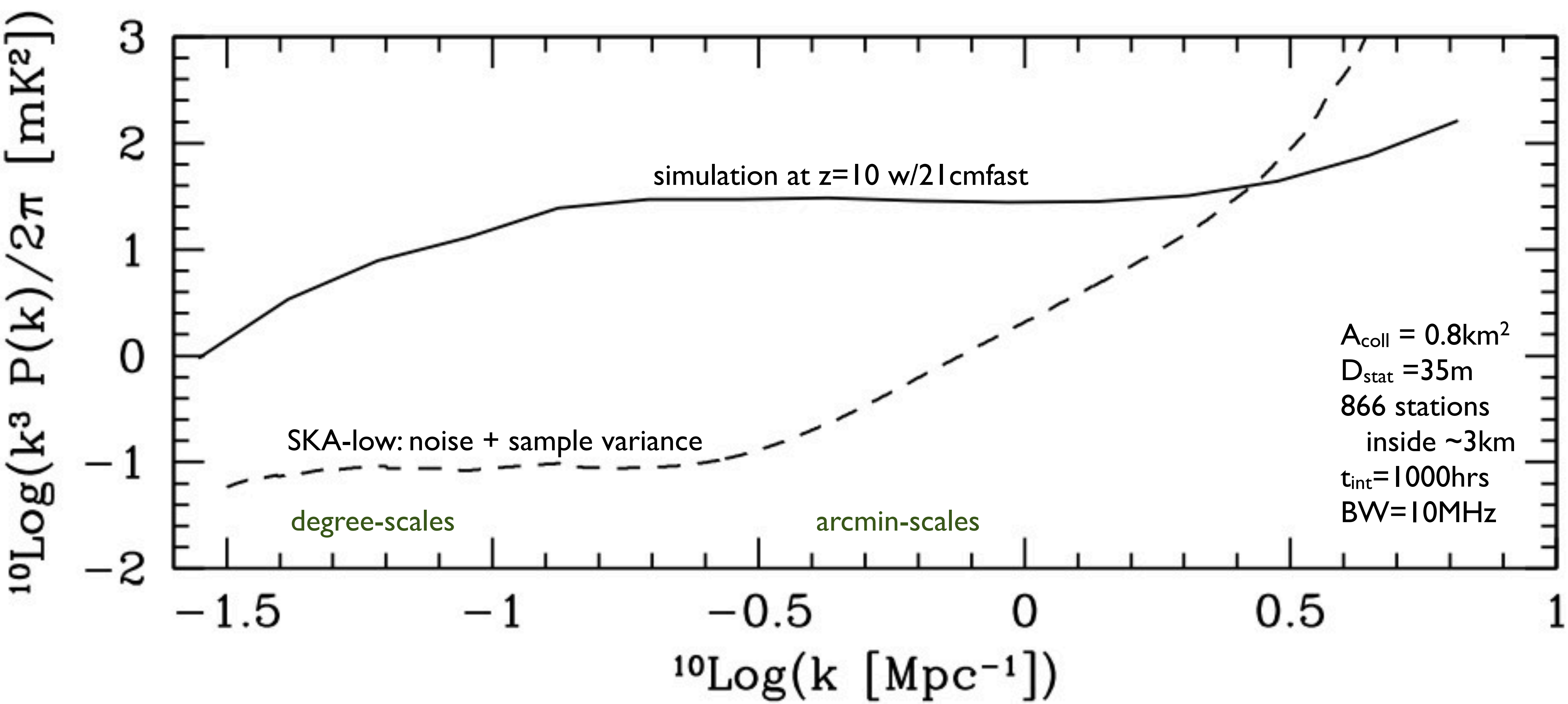
Idem, on scales >~1°.

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

Assuming the current SKA baseline design

SKA1 SYSTEM BASELINE DESIGN

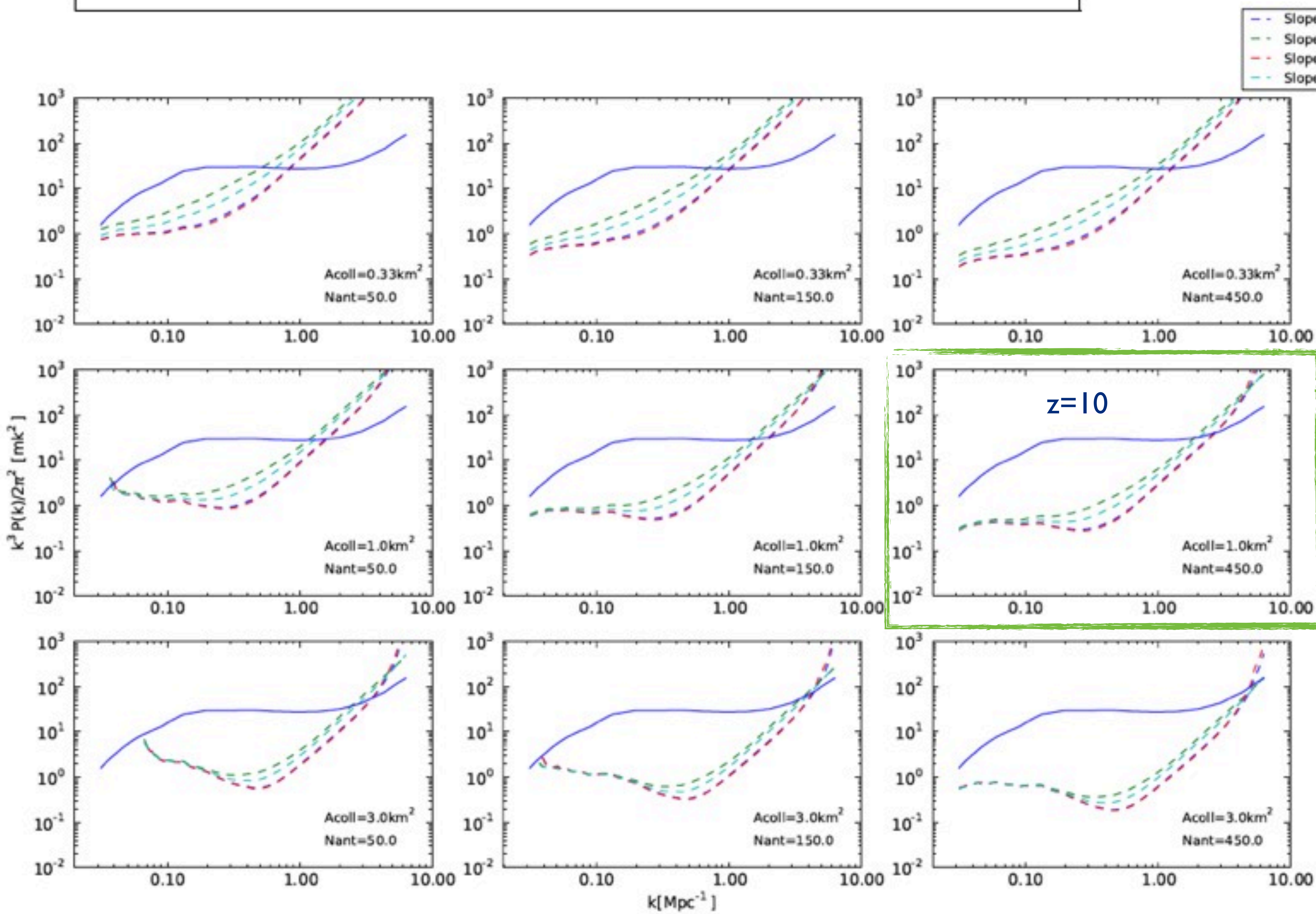
Document number SKA-TEL-SKO-DD-001

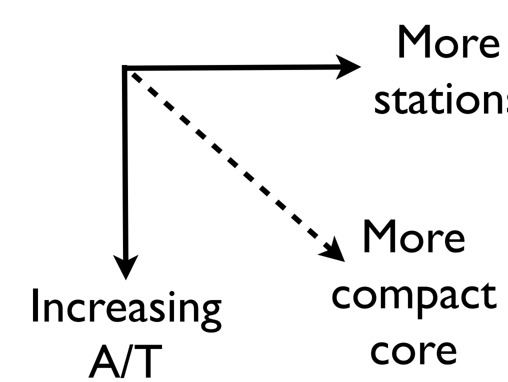


SKA Power-Spectrum Sensitivity for Single Beam

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

Different core diameters and station densities





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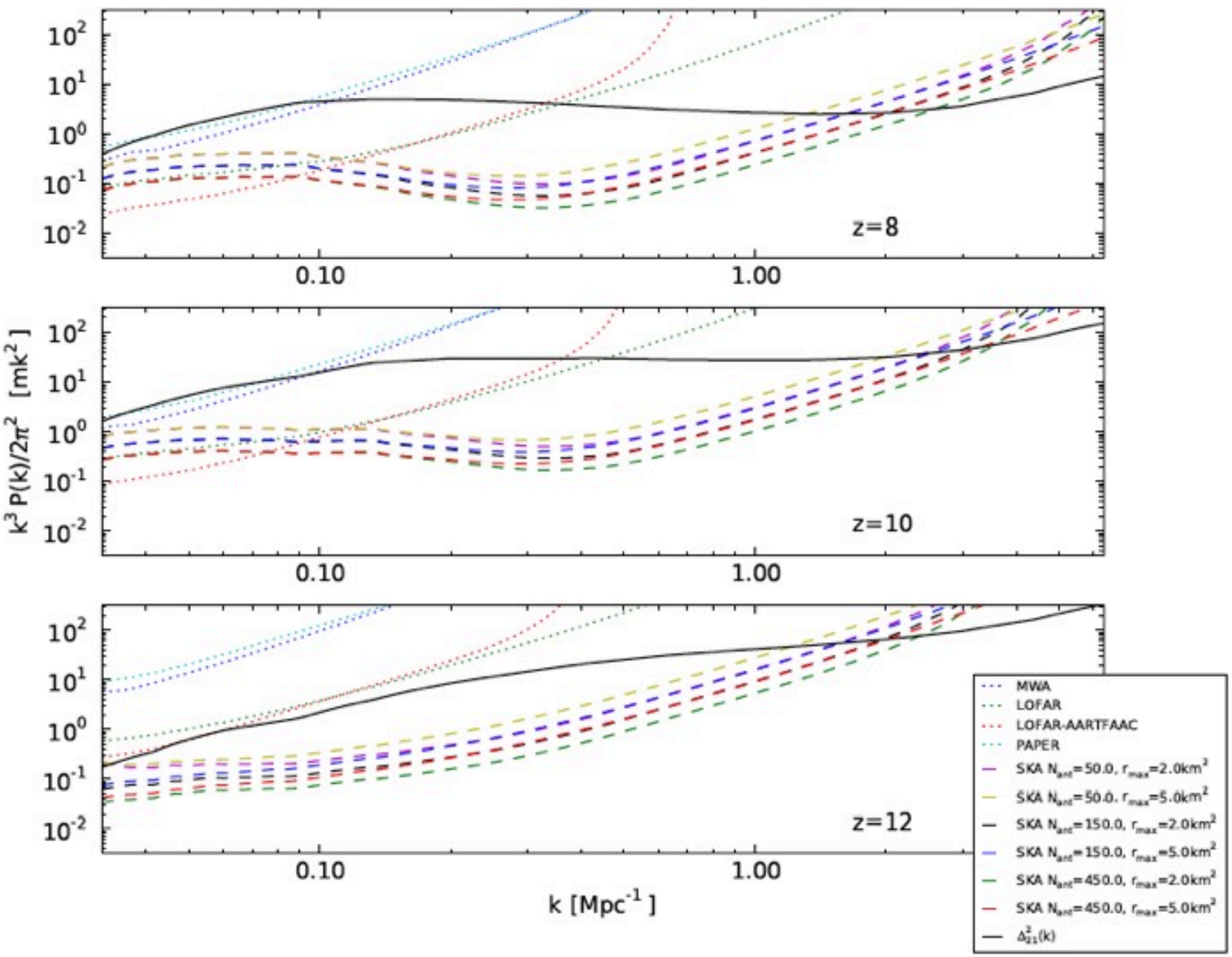
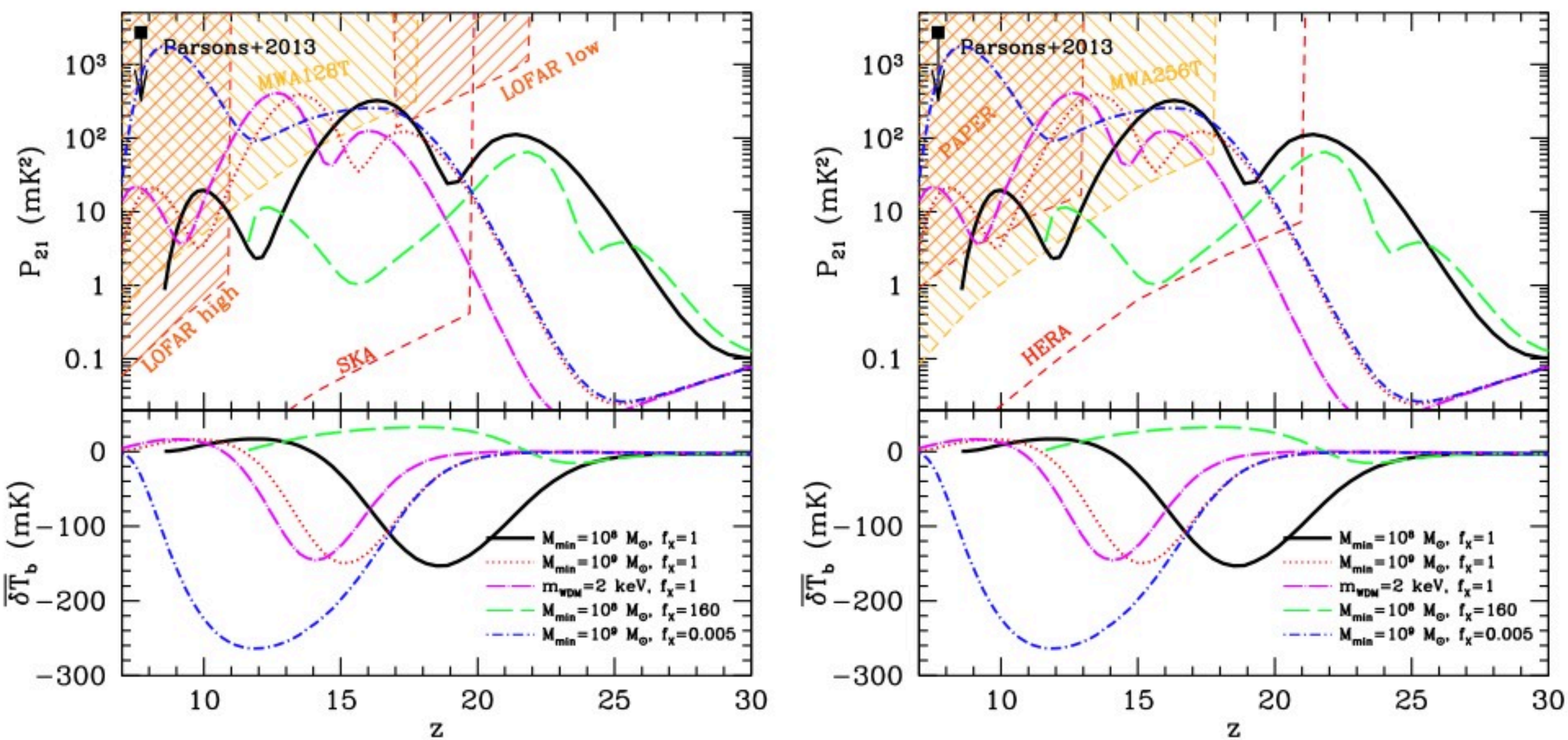
SKA versus Current Arrays

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



SKA1-AA-low Power-spectrum sensitivity
(current baselines design)

Sensitivity of SKA1 versus pathfinders (2000hrs)



Mesinger et al. 2013

SKA1-AA-low Power-spectrum sensitivity
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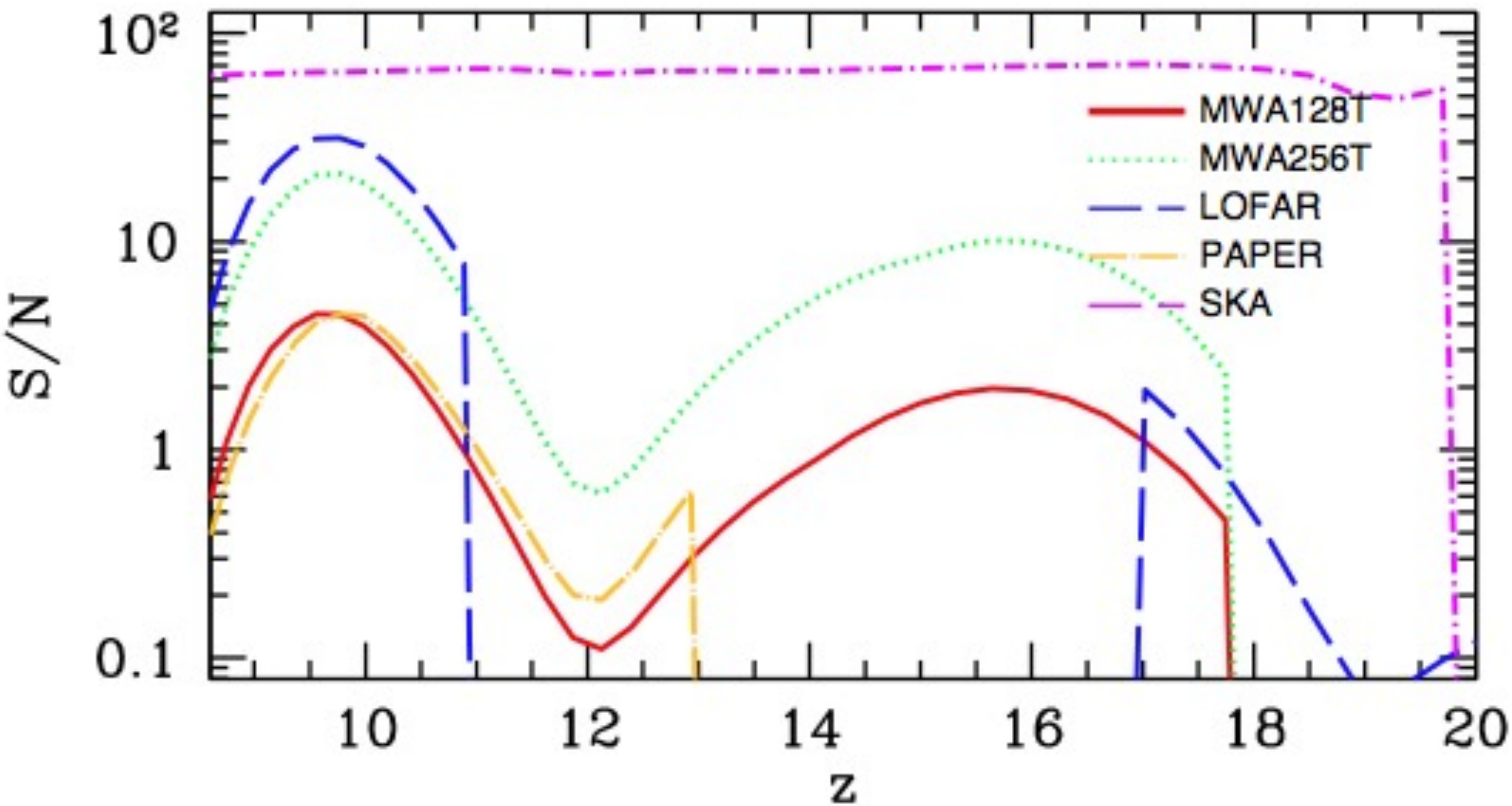
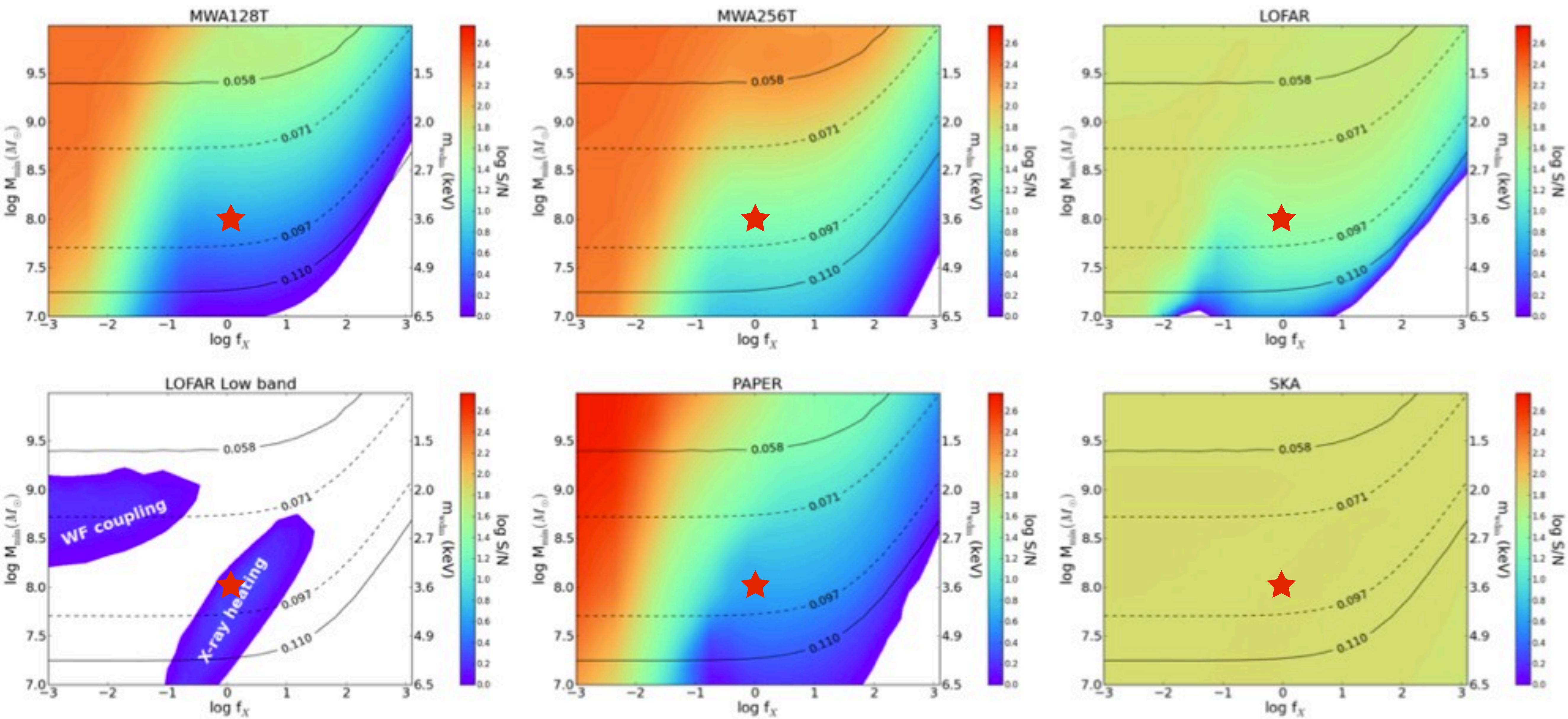
Sensitivity of SKA1 versus pathfinders (2000hrs)



SKA1-AA-low Power-spectrum sensitivity
(current baselines design)

S/N for different heating and halo models (nominal $M_{min}=10^8\ M_{sun}/f_X=1$ model is a red star)



S/N>100 with SKA1 for all models

Mesinger et al. 2013

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

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 $(D^2_{core} \times (4+N_{stat,outer})/(4D^2_{core}) \sim 1 + (1/4) \times N_{stat,outer} \sim 10$x. Much more if uv-plane is filled.

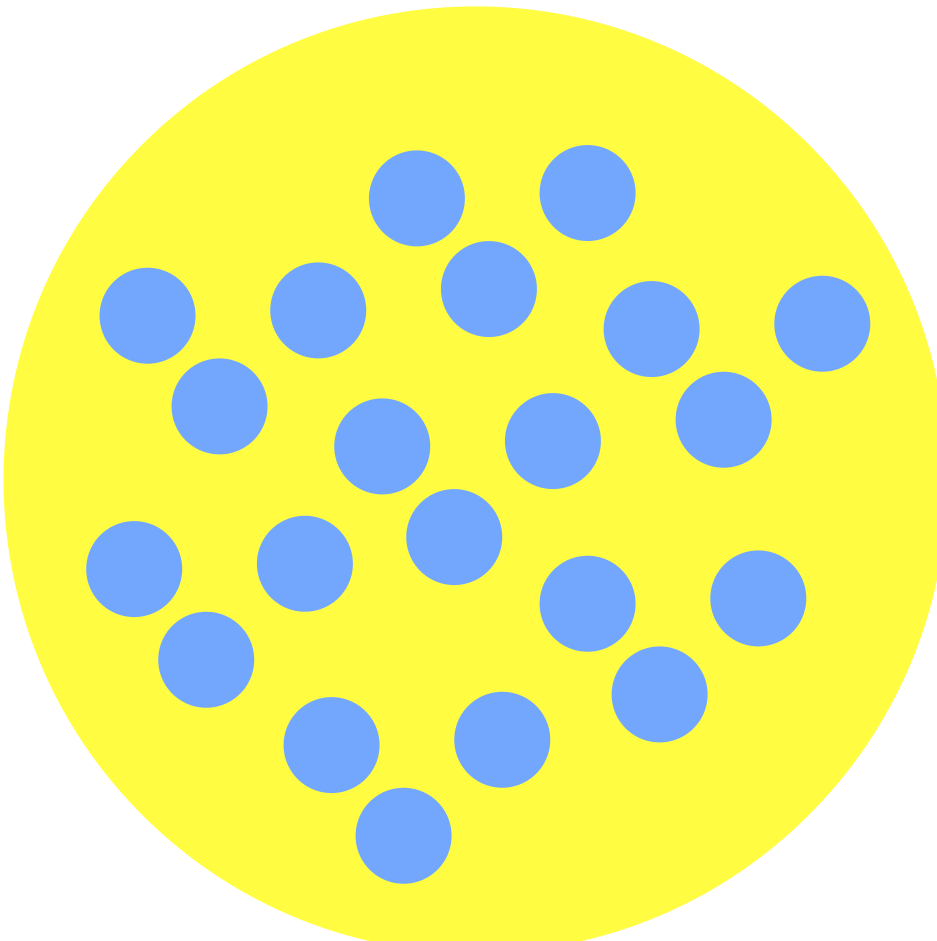
- Modeling of high-DR slightly resolved sources improves dramatically. One is sensitive to FWHM/sqrt[S/N] for any source. Especially bright sources need exquisite modeling

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

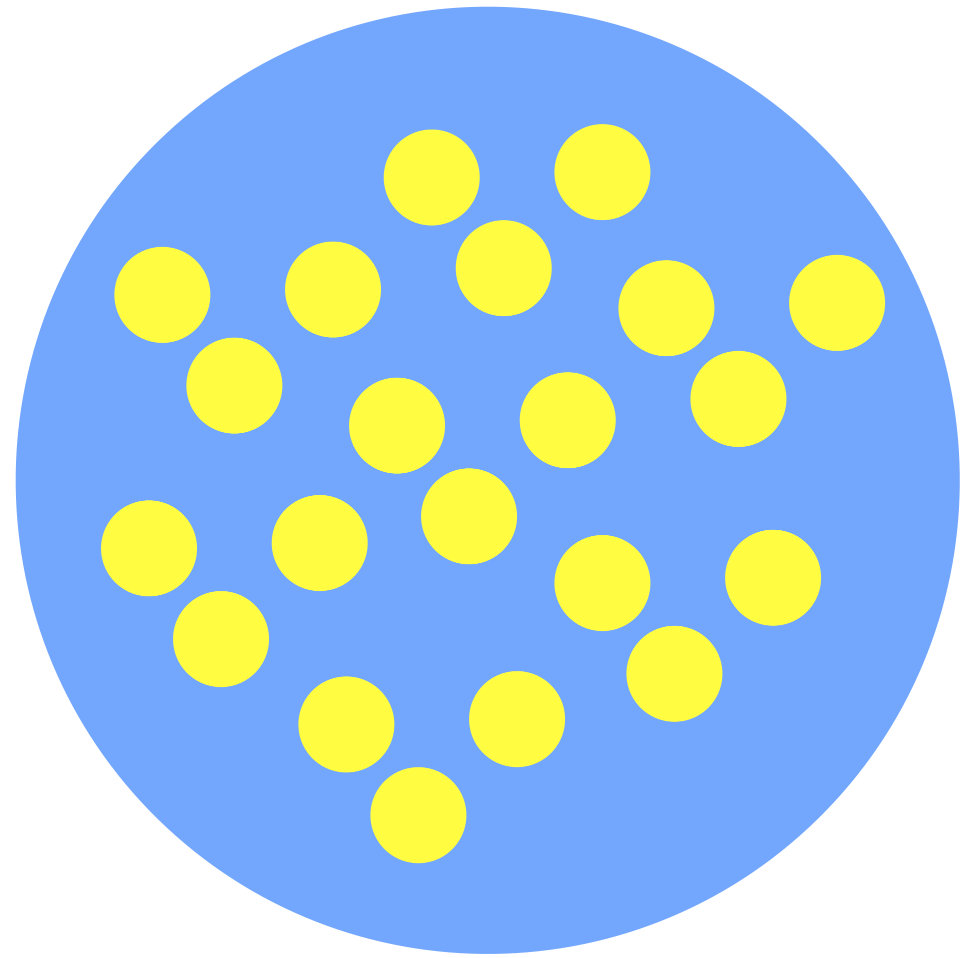
- An imprint of the array equal to the FoV of a core station allows the ionosphere to be modeled in 3D through 3D tomography.

UV-plane Information Content per Channel

uv-space



sky



Maximum # of independent pieces of information = $(D_{core}/D_{stat})^2$
[This is true even for >>1 visibility per uv-cell]

Maximum # of independent pieces of information = $(D_{core}/D_{stat})^2$
$= (\lambda/D_{stat})^2/(\lambda/D_{core})^2$
[you can map the full sky, but it will be correlated!]

The sky does <u>not</u> contain more information than the uv-plane (i.e. its Fourier conjugate)

[i.e. the Nyquist–Shannon sampling theorem]

Current Baseline Design provides:

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

  i.e. A_{coll}=1km^2 Consensus. Tomography needs it, although power-spectra maybe not, but SKA1 should take the next steps beyond current pathfinders in 10 years!

- ν_{low} = 50 MHz lower frequency limit

  Consensus. Many new interesting physics seems to take place starting at z~25; risk is higher but reward of detection is very high as well.

- D_{stat} ~ 35 meter station size in the core

  Seems sweet-spot for FoV and computational effort. Multi-beaming can not make up loss in FoV if D>>35m. (non-EoR) Stations outside core could be larger.

- Baselines up to ~90 km:

  Needed for calibration and compact-FG using different baselines than those for EoR science. Understand the sky/ionosphere. Information content is small on short baselines. i.e. short-baseline problems are more visible on long-baselines.

Request for (no) Change

Overall (see RfC document + science assessment workshop outcome) the CD/EoR ST is content with the current BLD, but requests some minor modifications/changes and also makes several other recommendations.

- No RfC in frequency range, resolution or optimal frequency
  Required to cover the CD/EoR eras.

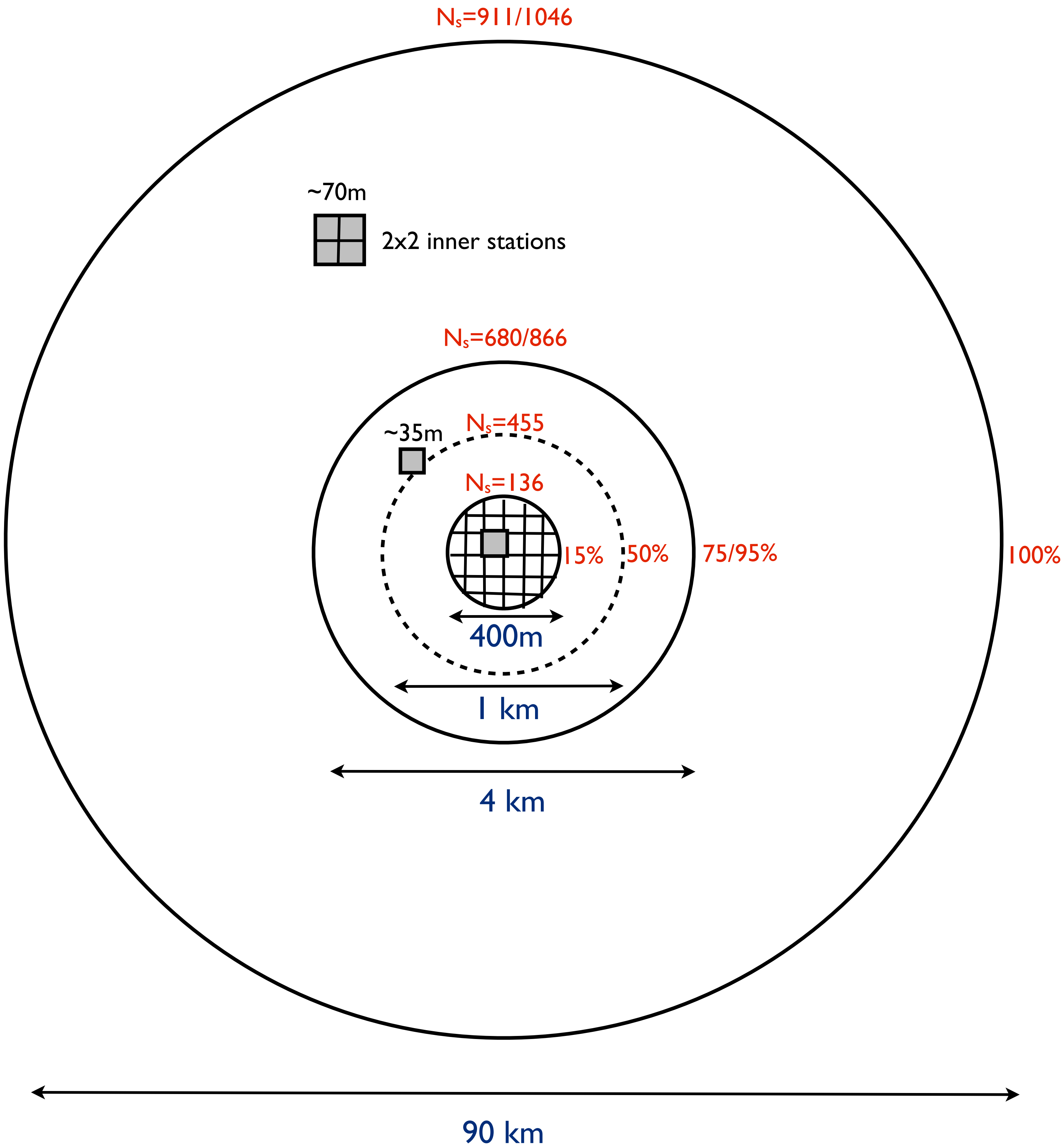
- No RfC in A_{eff} as function of radius, apart from maybe minor rearragments
  Required to reach 1-mK Tb levels from 5’ to 1° (from z=6 to z=25)

- No RfC on long baselines of 90 km
  Required for sky, instrument and ionospheric calibration.

- Recommends to put central D=400m core on a regular grid (redundancy/FFT).
  Enables rapid calibration, saves time/comput. costs, possibly enables FFT-type telescope

- Recommends signal fibers to central bunker for flexible beam forming and correlation
  Enables flexible beam-forming as function of experiment/freq./etc.

General Geometry SKA1-AA-low



- Filled inner R=200m core with elements on a regular grid
- "Stations" of 35m out to R=2km (50% <1km, 75%/95% <2 km)
- Larger (2x2 or 3x3?) clusters of 35m stations out to R=45 km
- Elements and stations in core placed on regular/repeating grid for redundancy/FFT-type processing
- Maximize instantaneous uv-cover. inside the core as much as possible
- Signals of each element in the core goes to a central bunker for hierarchical beam-forming (freq., case, baseline dependent)
- Stations <2 km for CD/EoR science and >2km mostly for sky, instrument and ionospheric calibration
- Freq. coverage 50-250+ MHz.

What is detrimental to CD/EoR studies and should certainly *not be done* for SKA1.

- Reduce A_{eff} (or A/T) in the core significantly below the current baseline design: SKA(1) would reduce to a power-spectrum instrument and tomography during the EoR will be difficult if not impossible. CD studies will become hard.

- Reduce the frequency coverage or shift to higher frequencies: The Cosmic Dawn starts at z~25-30, i.e. ~50MHz; not going to those freq. will close that window for SKA(1). No other instrument can do this in the future.

- Reduce long baselines to <90 km: Experience with LOFAR has shown that longer baselines (~100km) are extremely powerful for creating a sky model, for calibration, for ionospheric corrections and for diagnosing the overall system performance and data-quality.

- Do beam-forming "on-site" and build "the beam" in to the hardware system/layout of the receiver elements: Severely limits the flexibility in the system to adjust to novel/future science cases.

Thank you!