Galaxy Formation, Cosmology, and the Epoch of Reionization with the SKA

Jonathan Pritchard
Co-chair EoR-SWG
UK-SKA-SC

Imperial College London

https://www.skatelescope.org/shared-sky/

collaborative painting from Aboriginal Yamaji Artists

SKA Science Priorities

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
4	*Pulsars*	Reveal pulsar population and MSPs for gravity tests and Gravitational Wave detection	1/3
5	*Pulsars*	High precision timing for testing gravity and GW detection	1/3
13	*HI*	Resolved HI kinematics and morphology of ~10^10 M_sol mass galaxies out to z~0.8	1/5
14	*HI*	High spatial resolution studies of the ISM in the nearby Universe.	2/5
15	*HI*	Multi-resolution mapping studies of the ISM in our Galaxy	3/5
18	*Transients*	Solve missing baryon problem at z~2 and determine the Dark Energy Equation of State	=1/4
22	*Cradle of Life*	Map dust grain growth in the terrestrial planet forming zones at a distance of 100 pc	1/5
27	*Magnetism*	The resolved all-Sky characterisation of the interstellar and intergalactic magnetic fields	1/5
32	*Cosmology*	Constraints on primordial non-Gaussianity and tests of gravity on super-horizon scales.	1/5
33	*Cosmology*	Angular correlation functions to probe non-Gaussianity and the matter dipole	2/5
37 + 38	*Continuum*	Star formation history of the Universe (SFHU) – I+II. Non-thermal & Thermal processes	1+2/8

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HI: Local ISM measurements			
Cradle of Life/Magnetism/Transients			
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Extra galactic astronomy is a huge part of the SKA science case

SKA is an HI machine

Track evolution of HI from present day to 100 Myr after Big Bang (z=27)

21cm line 1420/(1+z) MHz

SKA-LOW 50-350MHz z=3-27

SKA-MID Band 1: 350-1050MHz z=0.35-3
Band 2 950-1760 MHz z=0-0.5

SKA-SUR Band 1: 350-900MHz z=0.6-3
Band 2: 650-1670 MHz z=0-1.2

Epoch of Reionization/Cosmic Dawn

SKA-LOW targets EoR signal at 50MHz-250MHz

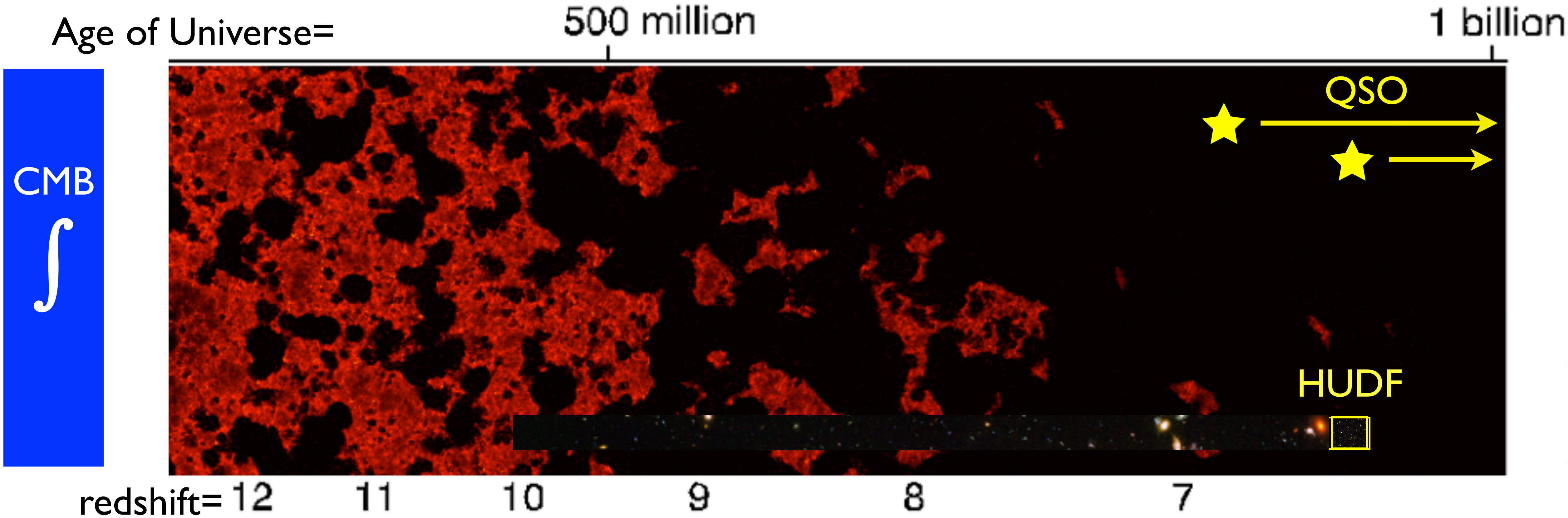
Western Australia.

Log-periodic dipoles

Chair: Leon Koopmans

UK:
Jonathan Pritchard
Fil Abdalla
Ilian Iliev
Emma Chapman
Anna Bonaldi
Mike Jones
Pratika Dayal

Reionization



Existing observations leaves much unanswered

Possible hints of neutral hydrogen at z~7, e.g. z=7 QSO, LAE/LBG ratio

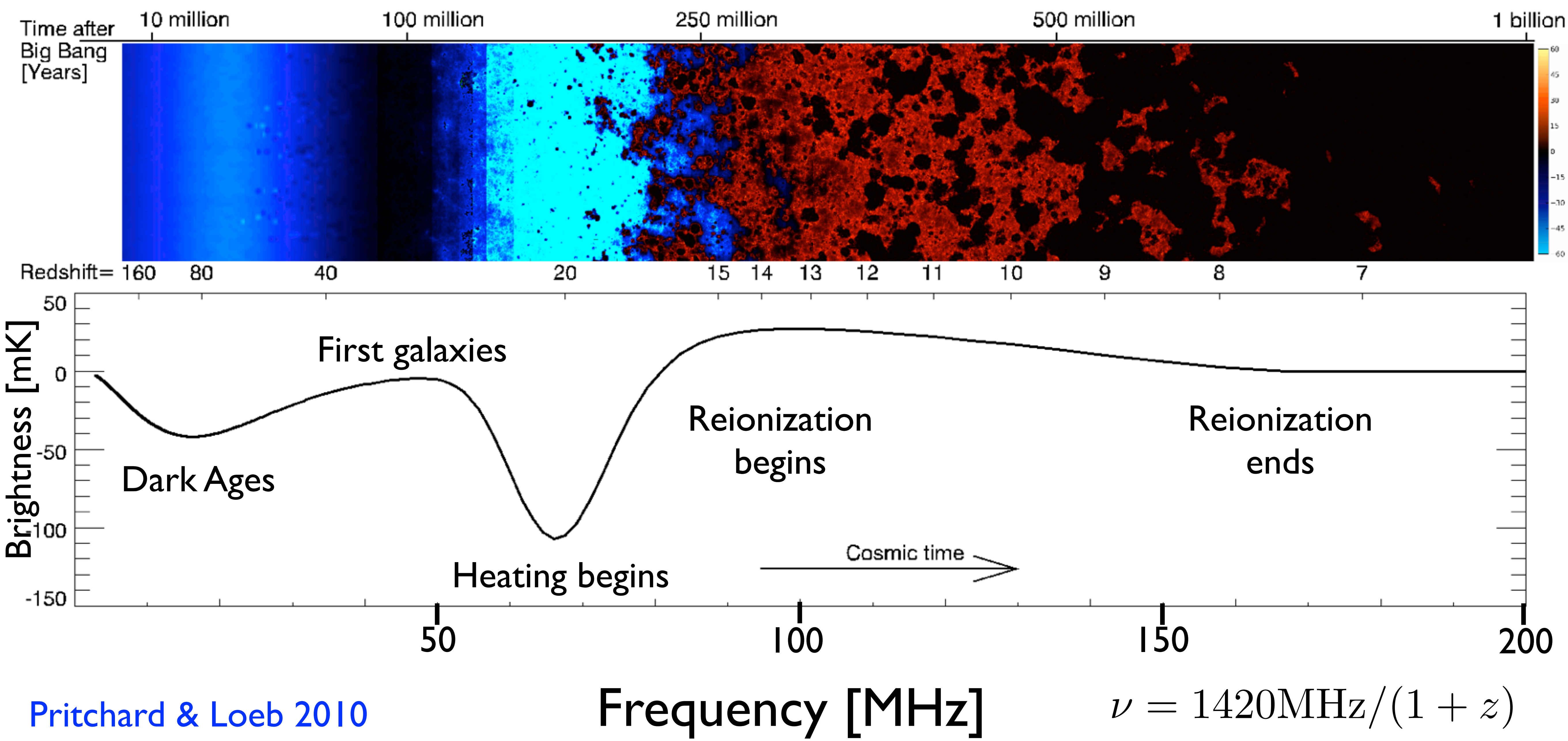
By 2020: possible advances...

1) Planck polarisation could constrain redshift and duration of reionization
2) HST+JWST will have observed bright end of luminosity function to z~12
   (faint end will still be incomplete; connection to ionizing photons may still be unclear)
3) Little advance in QSO (more at z~7) - wait for Euclid in 2020 to push to z~8
4) LAE surveys into EoR will be more advanced (HSC) - maybe clustering => patchy reionization?

SKA will map out details of reionization and cosmic dawn

Epoch of Reionization & Cosmic Dawn

- 21 cm fluctuations contain wealth of information
  - Lyman alpha fluctuations => star formation rate and first galaxies
  - Temperature fluctuations => X-ray sources and first black holes
  - Neutral fraction fluctuations => topology of reionization
  - Density fluctuations => cosmology



$\nu = 1420\text{MHz}/(1+z)$

Pritchard & Loeb 2010

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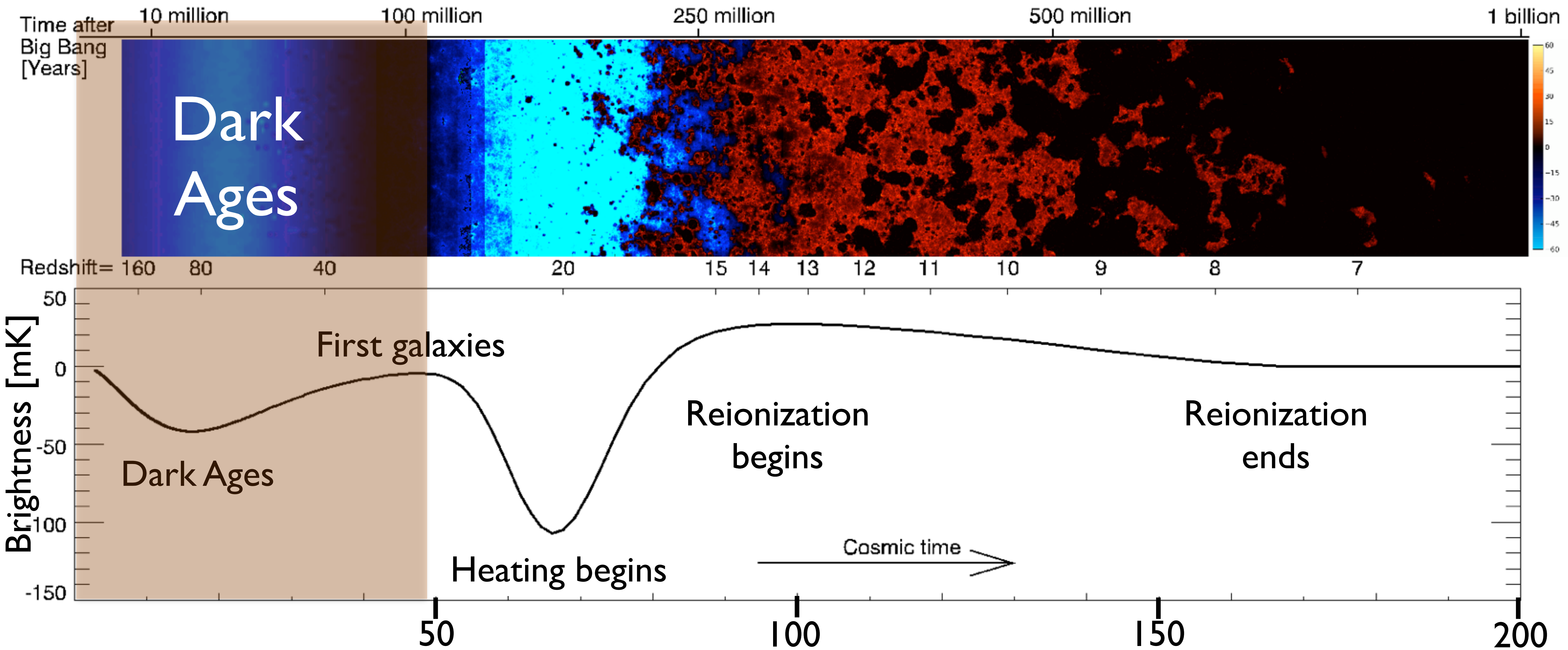

Pritchard & Loeb 2010

Frequency [MHz]

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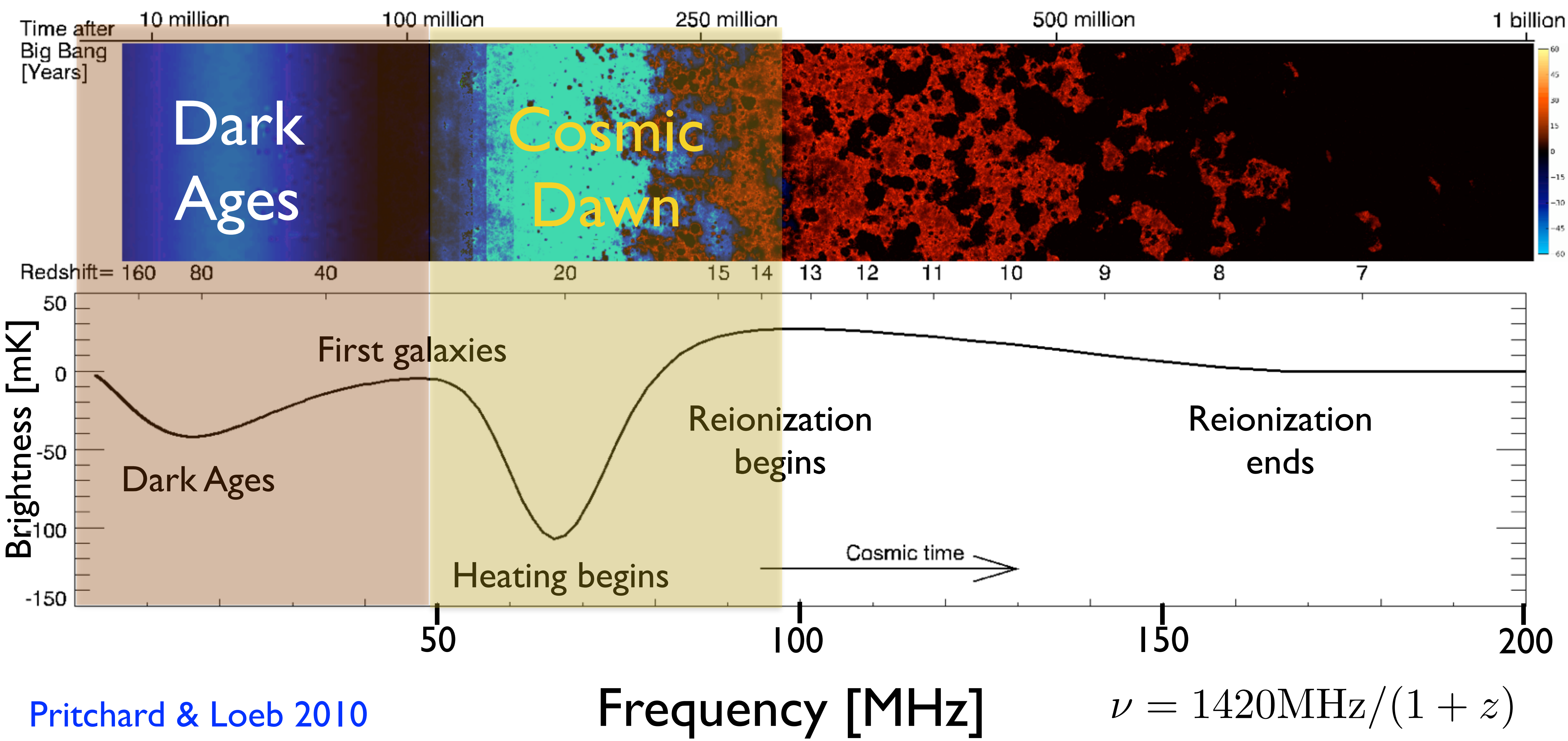

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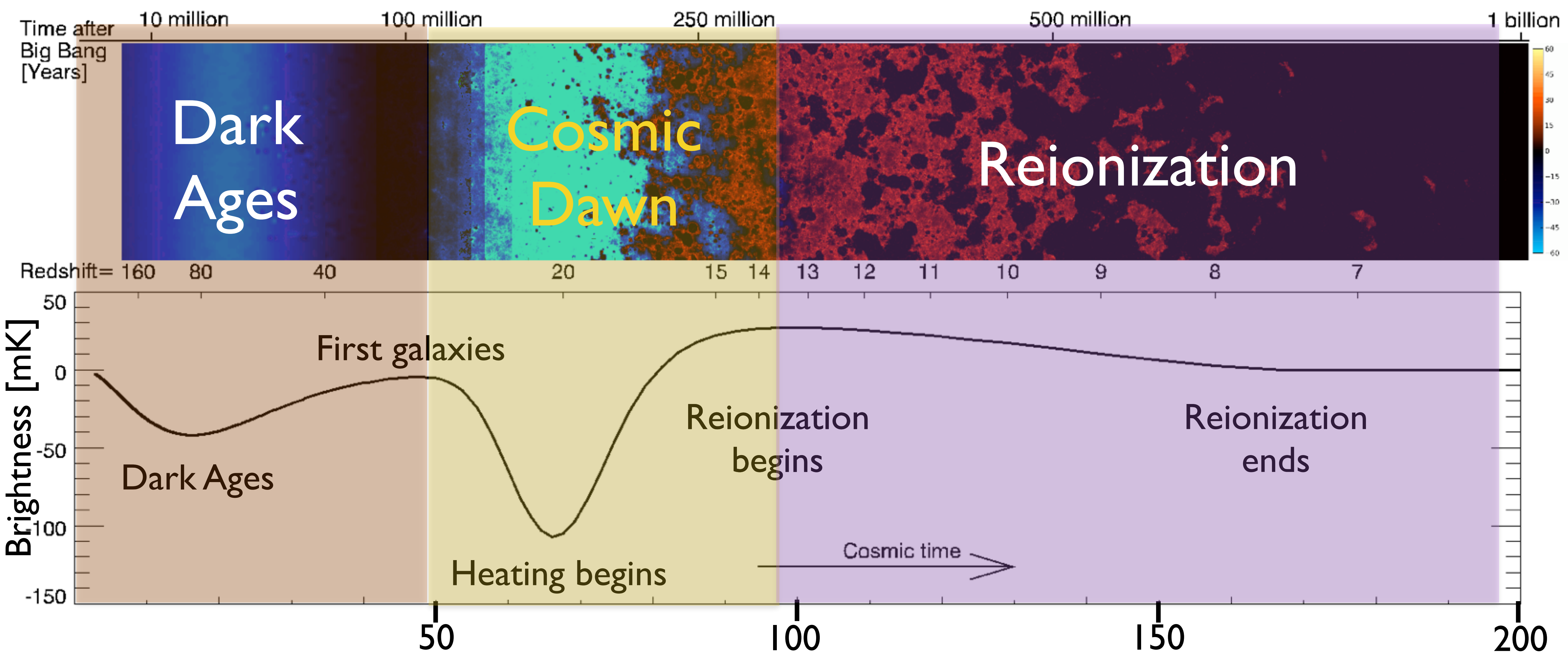

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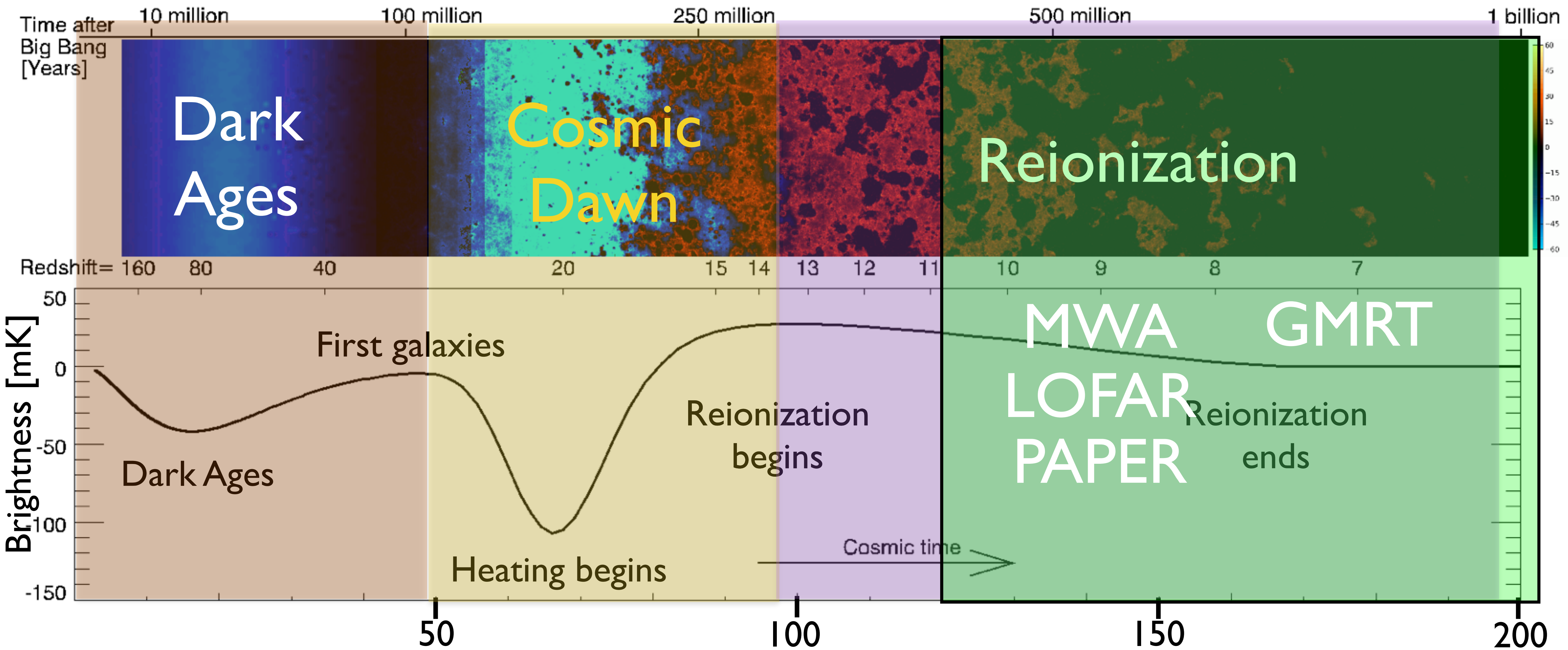

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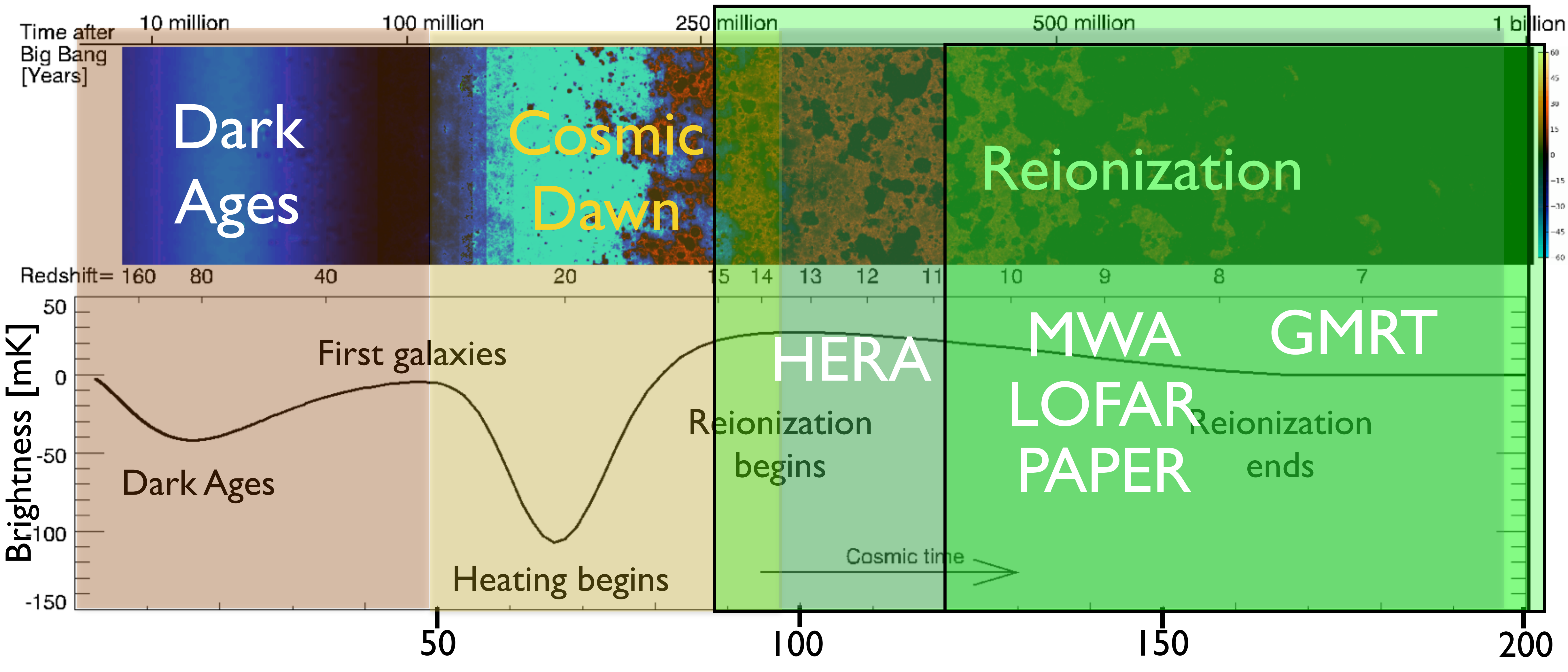

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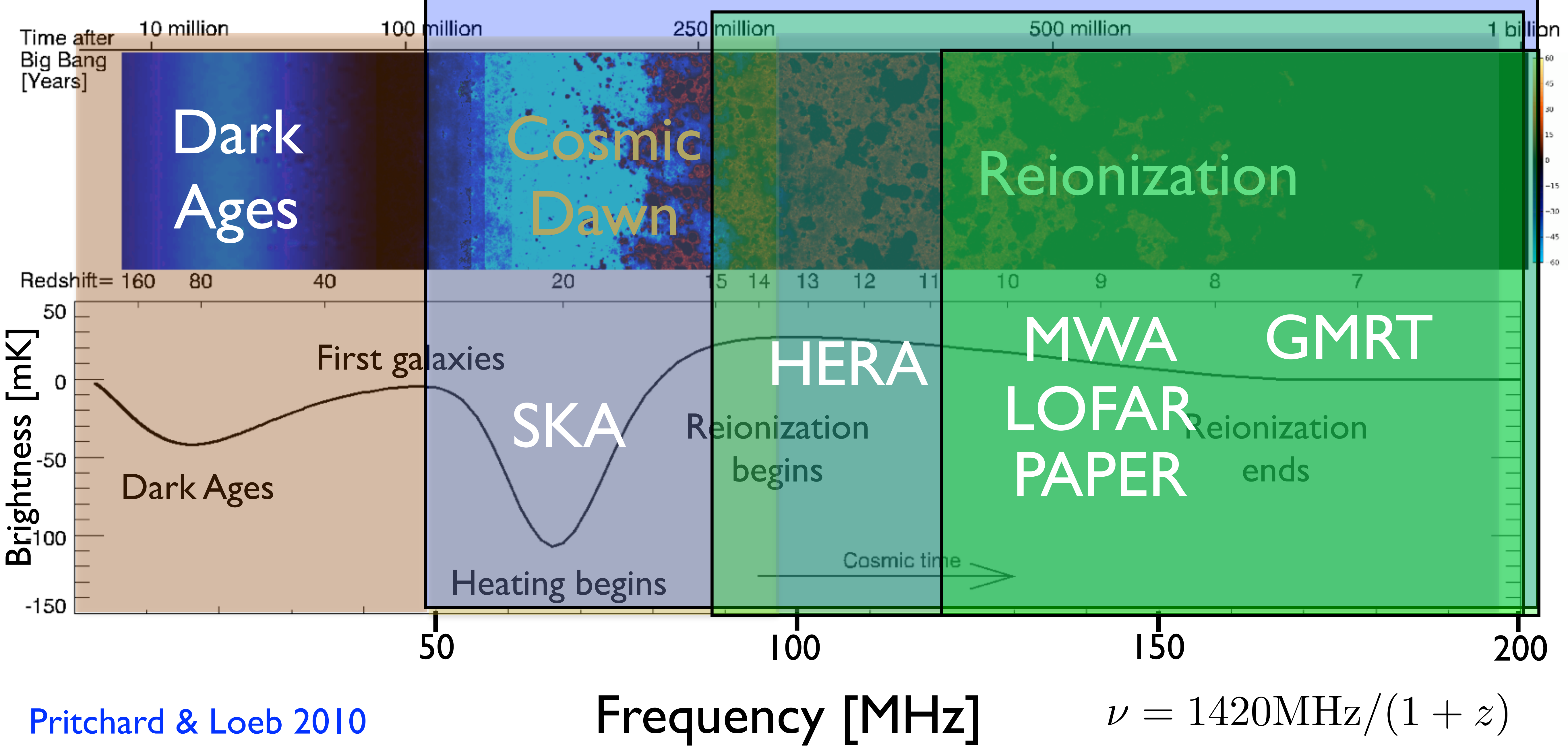

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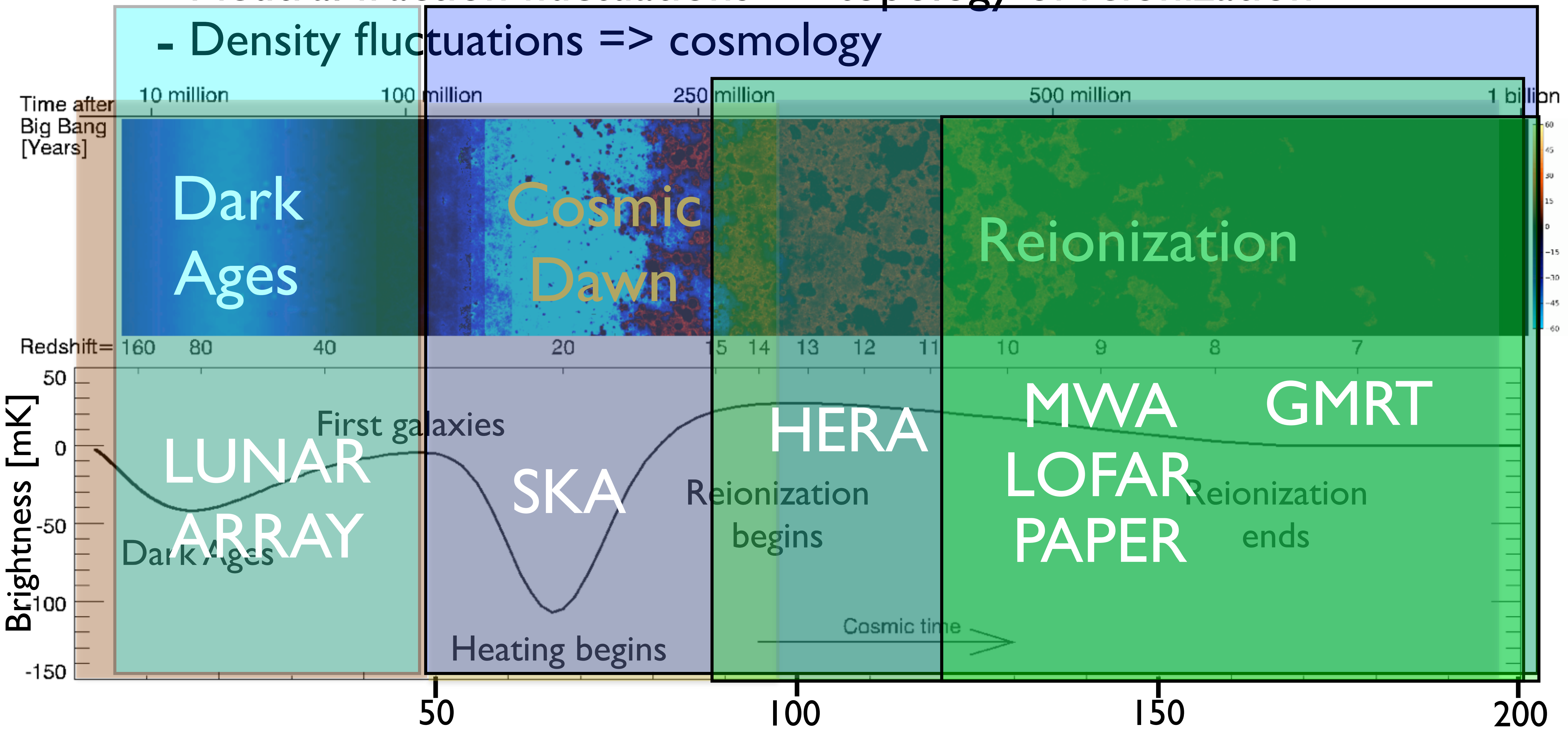


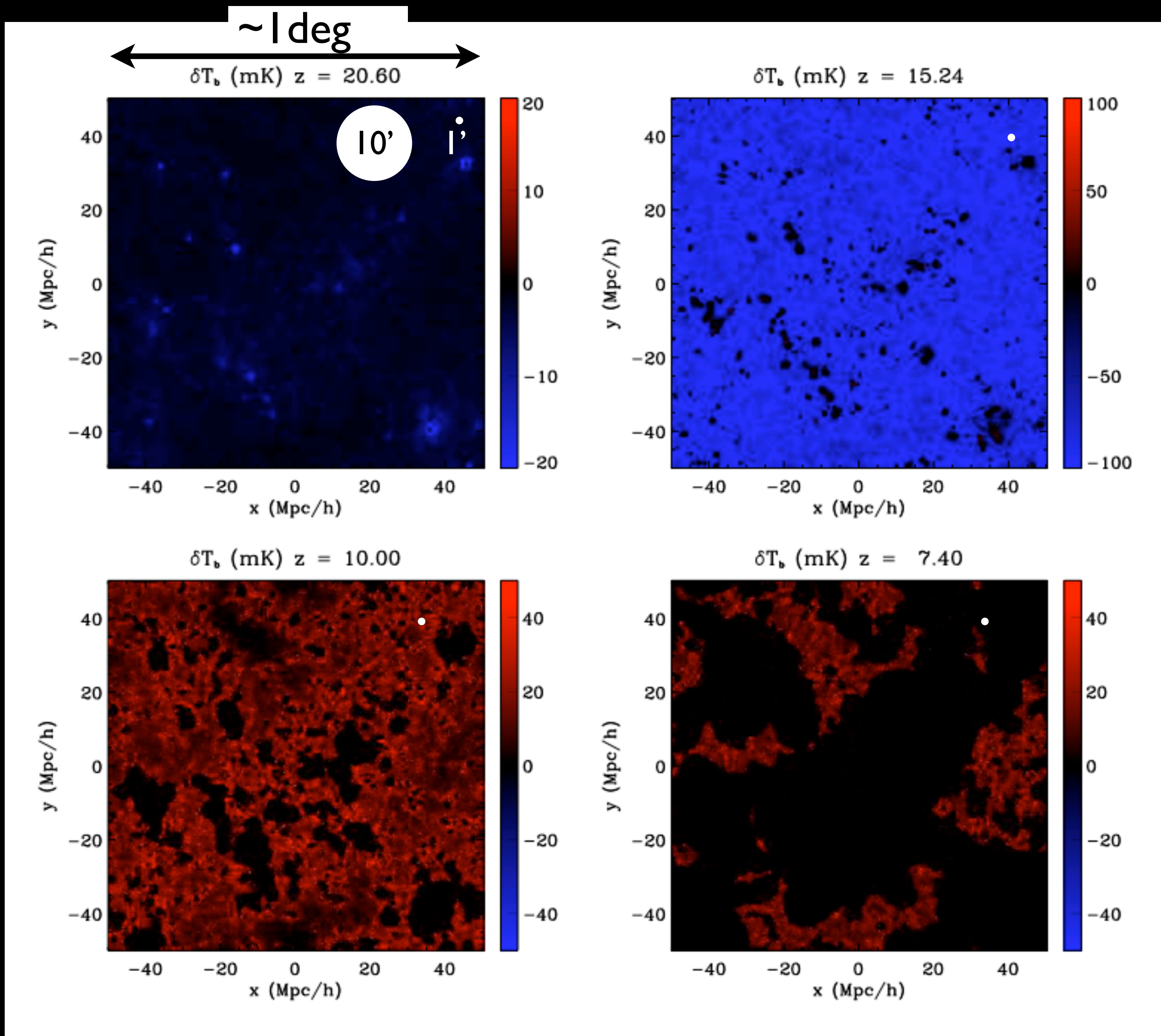
Pritchard & Loeb 2010

$\nu = 1420\text{MHz}/(1+z)$

SKA will image reionization

SKA will be first instrument with sensitivity for imaging
=> map topology of reionization

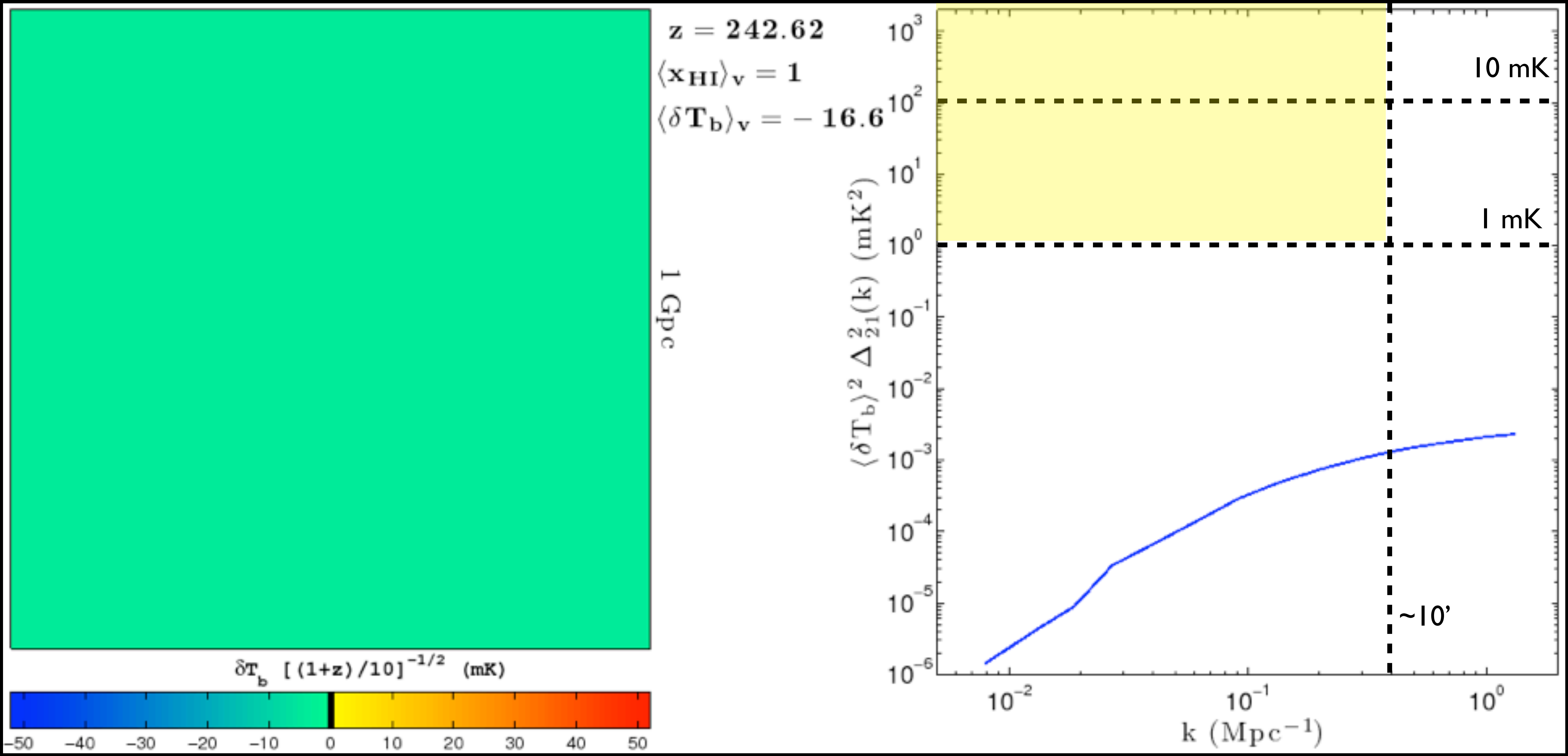
Mellema+ 2013



SKA FOV~ 20deg^2

Evolution of the power spectrum

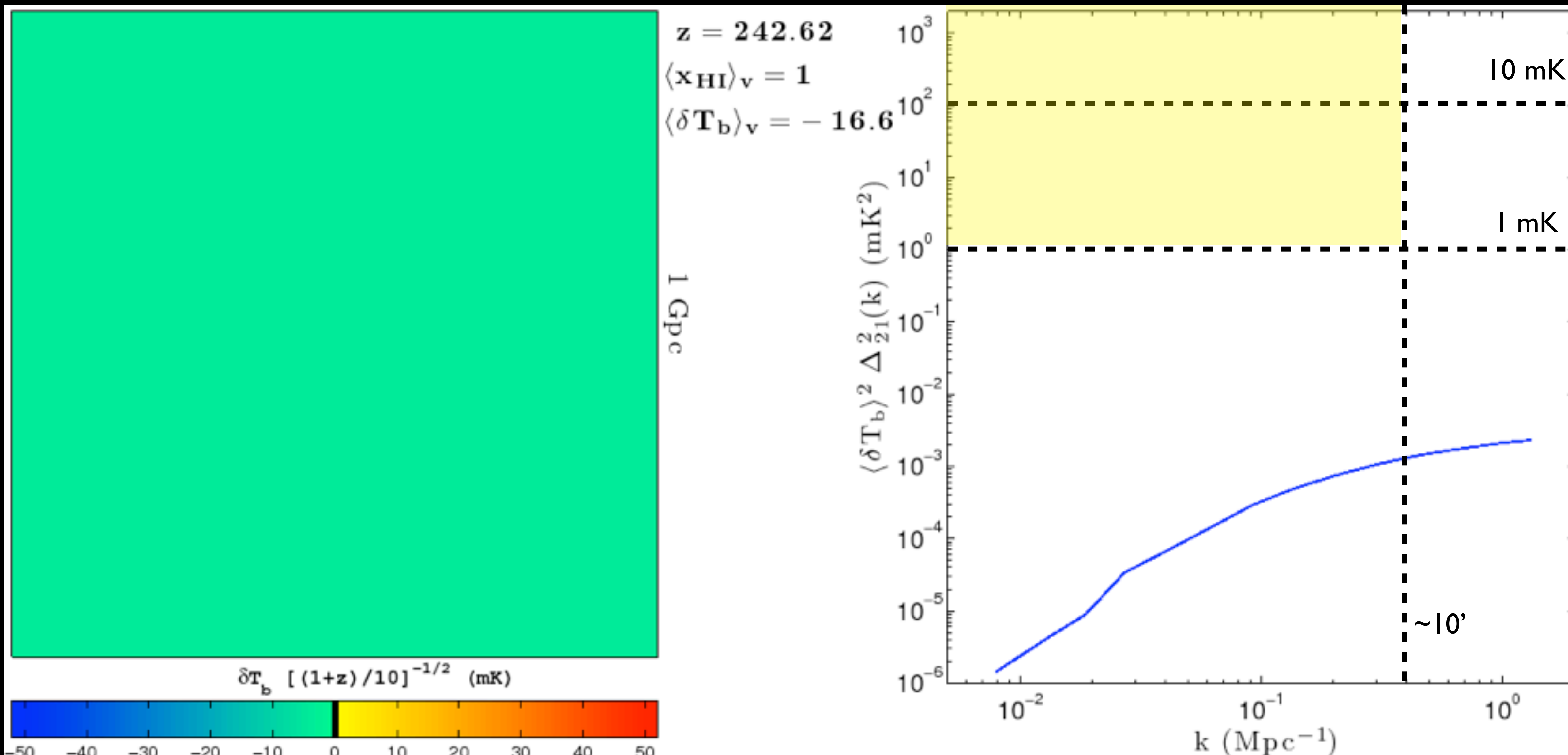
Mesinger+ 2010



Measure power spectrum from z=27 to z~6
=>traces onset of star formation and IGM heating

Evolution of the power spectrum

Mesinger+ 2010



Measure power spectrum from z=27 to z~6

=>traces onset of star formation and IGM heating

EoR overview

Key Science:
Map neutral hydrogen in IGM at z=6-27
(Universe 100MYr-1GYr old)

1) 3D imaging of ionized regions during reionization

2) Power spectrum measurements to constrain X-ray emission and SFR of first galaxies via spin-temperature fluctuations

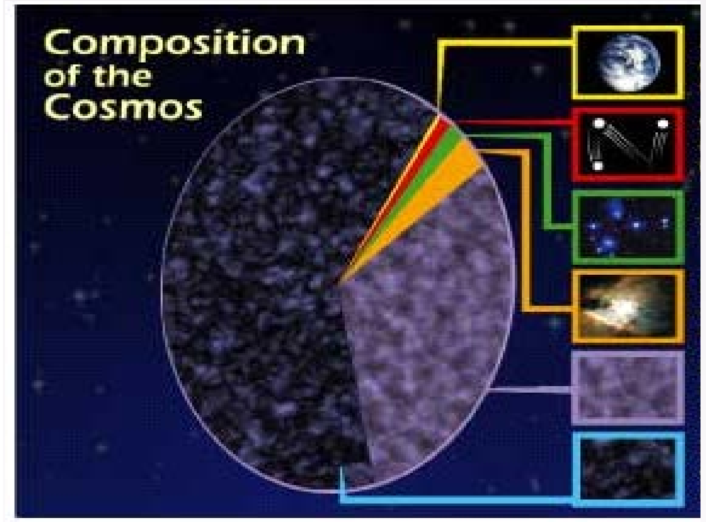
3) 21cm forest towards radio bright high-z sources e.g. Quasars probes small scale structures

4) Cosmology from density field, weak lensing, thermal history

Cosmology

Chair: Roy Maartens (Cape Town)

Fil Abdalla (UCL)
Matt Jarvis (Oxford)
Mike Brown (Manchester)
David Bacon (Portsmouth)
Jonathan Pritchard (Imperial)
…



Heavy elements 0.03%

Neutrinos 0.3%

Stars 0.5%

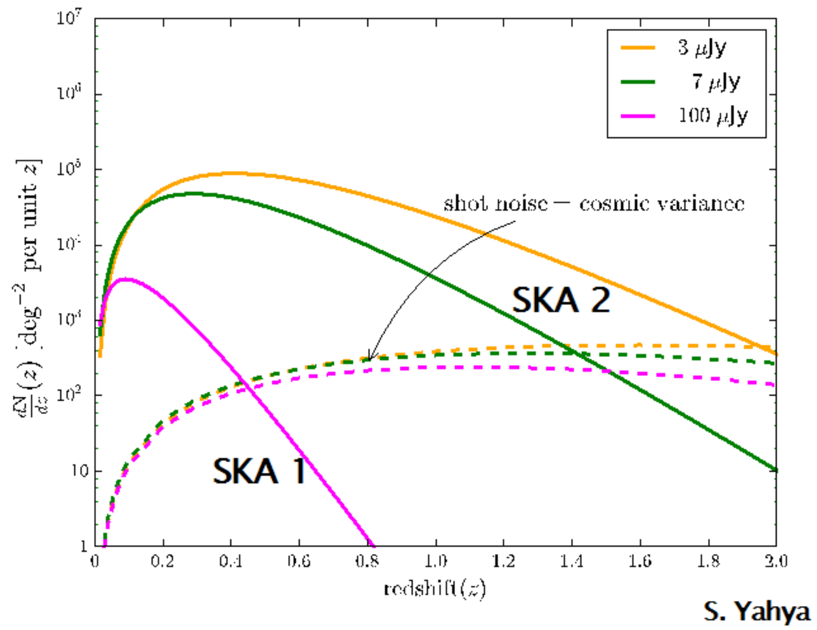
H + He gas 4%

Dark matter 20%

Dark Energy 75%

Surveys for Cosmology

HI GALAXY REDSHIFT SURVEY
•SKA1 – $z<0.5$
•SKA2 – $z<2$

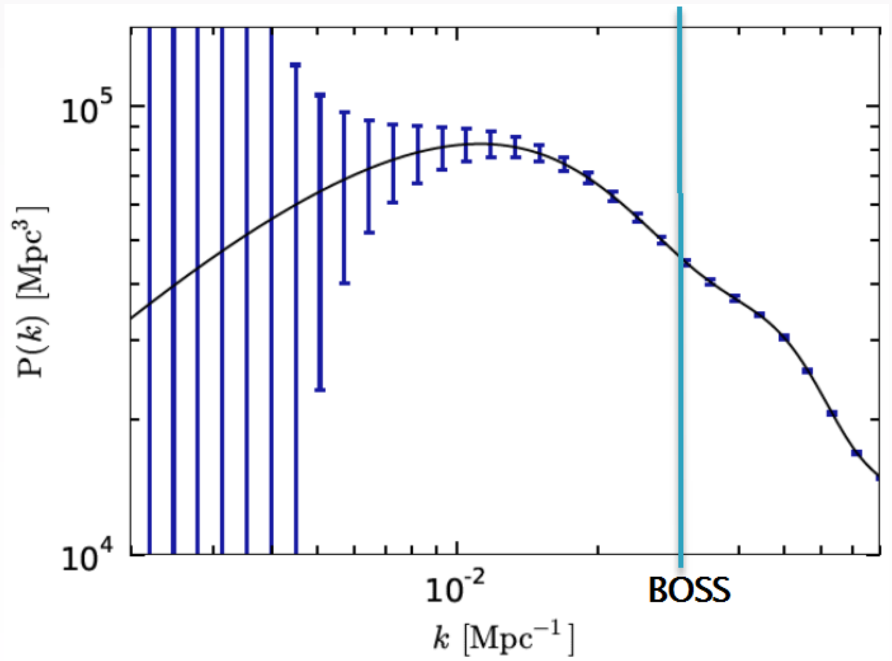


SKA1 ~ 10^7 galaxies over 5,000 deg^2
SKA2 ~ 10^9 galaxies over 30,000 deg^2

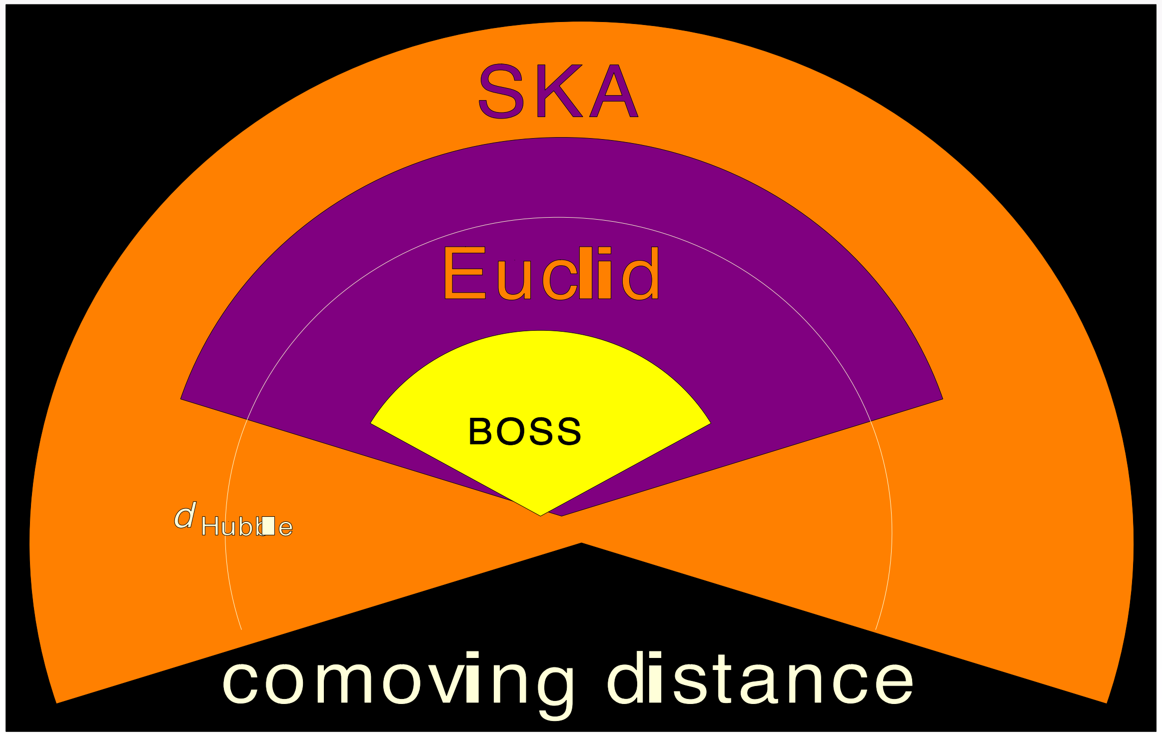
CONTINUUM SURVEY

•SKA1 – 100 million galaxies, 30000 deg^2
•SKA2 – 2 billion galaxies, 30000 deg^2

HI INTENSITY MAPPING SURVEY
•SKA1 – 30000 deg^2 , $z<3$
•SKA2 – 30000 deg^2 , $z<5$



See: Bull, Ferreira, Patel, Santos, 2014 (arXiv: 1405.1452)



following slides adapted from Abdalla

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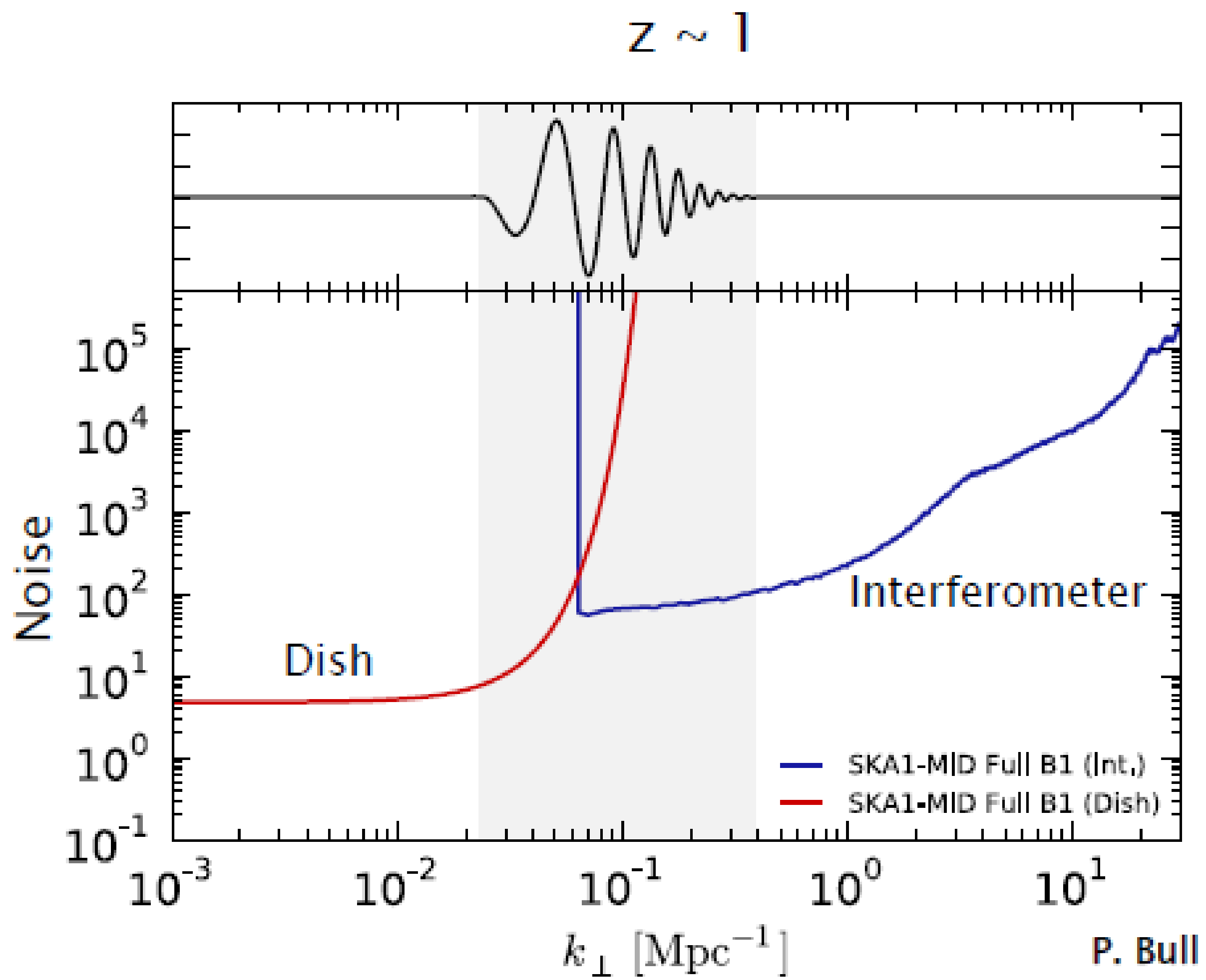
SKA1 auto-correlations

- Problem: not enough short baselines (need ~ 20 m for BAO)
- Solution: use each dish as a single telescope (auto-correlation)
- "Like 254 GBT dishes but with less resolution"
- Save the interferometer data (complement small scales)

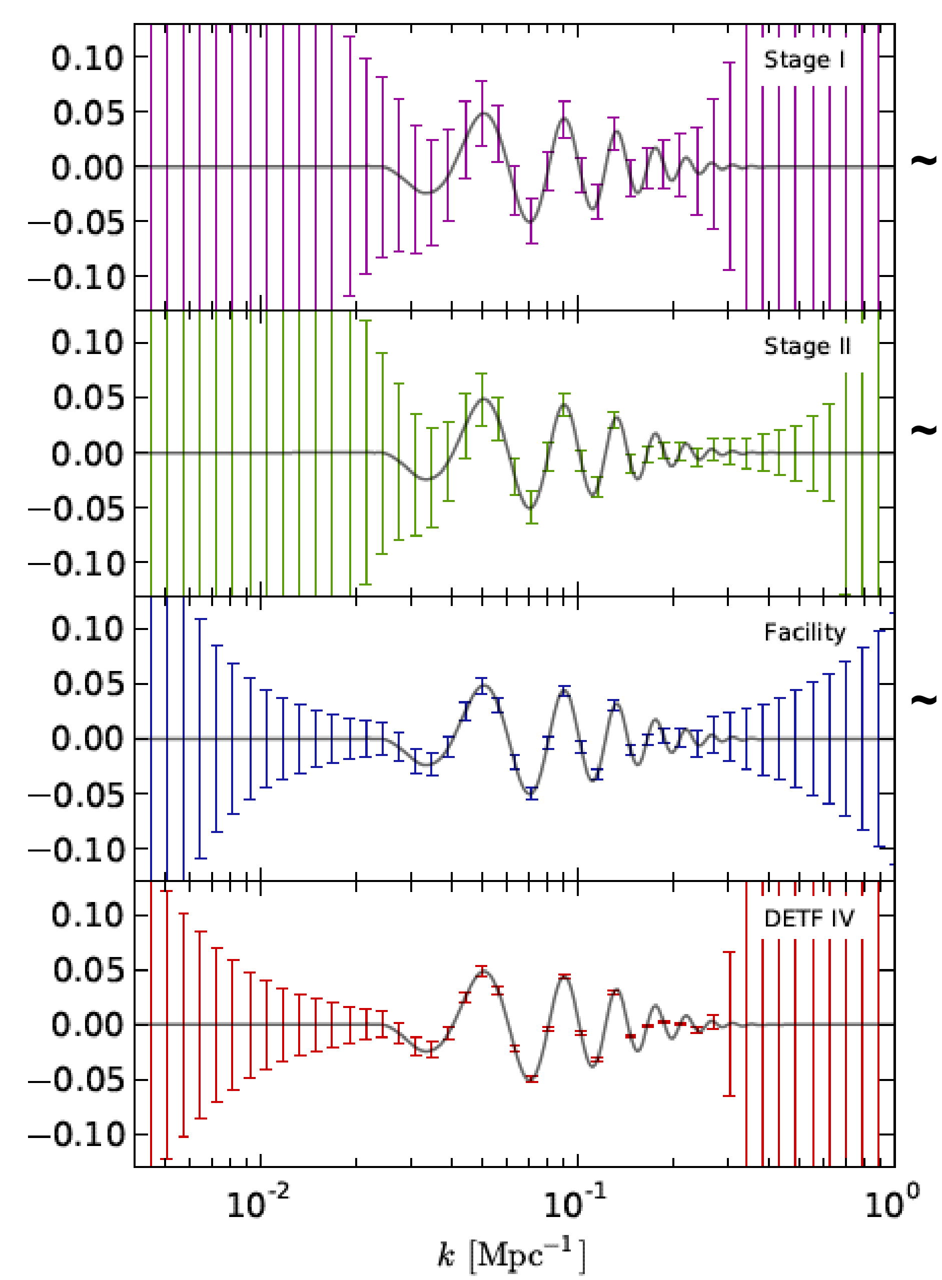


Scales probed by SKA1 (15m dishes)

Cosmological probes

Imperial College London

BAO



~ BINGO

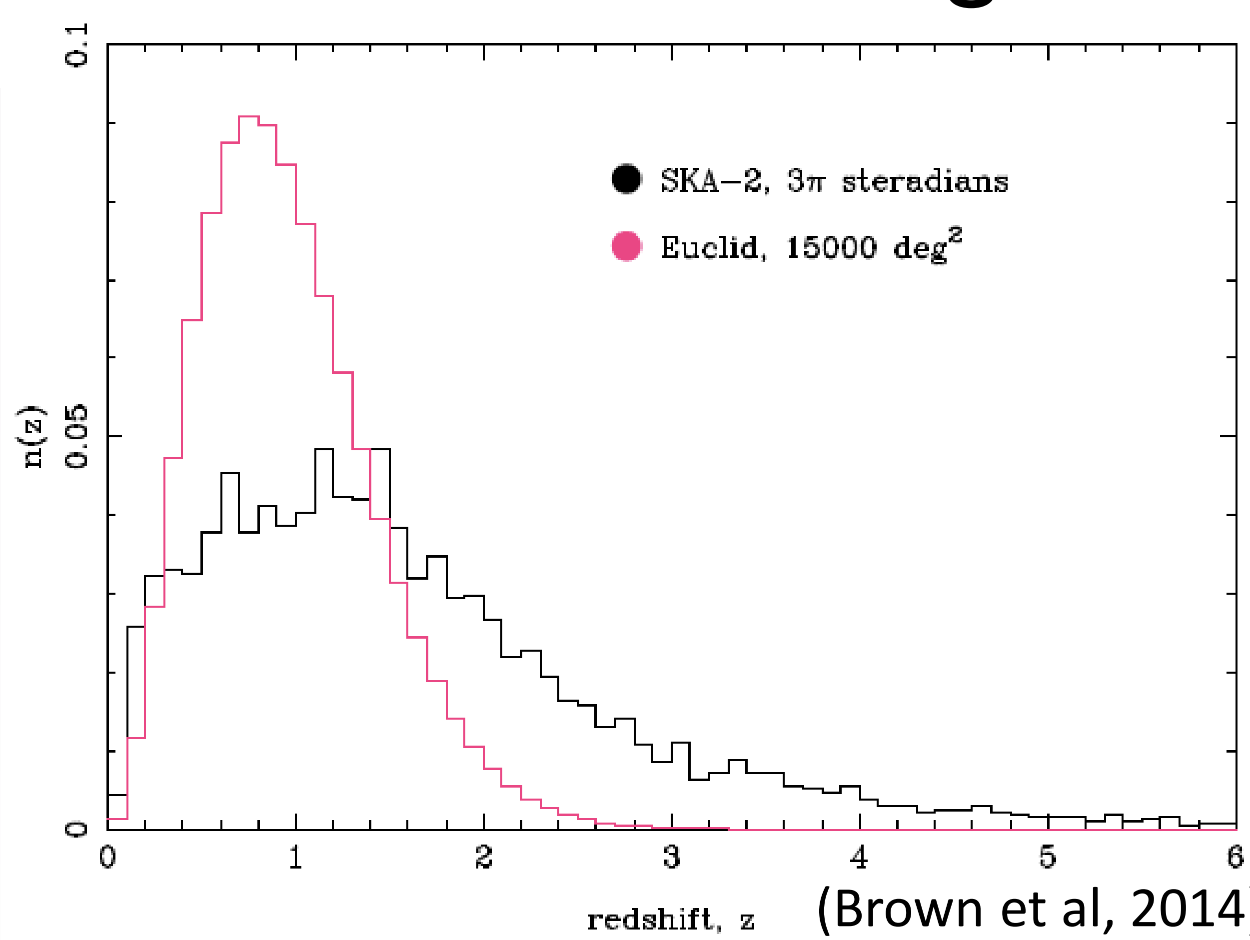
~ MeerKAT

~ SKA1-Mid base (up to z ~ 2.0)

~ Euclid

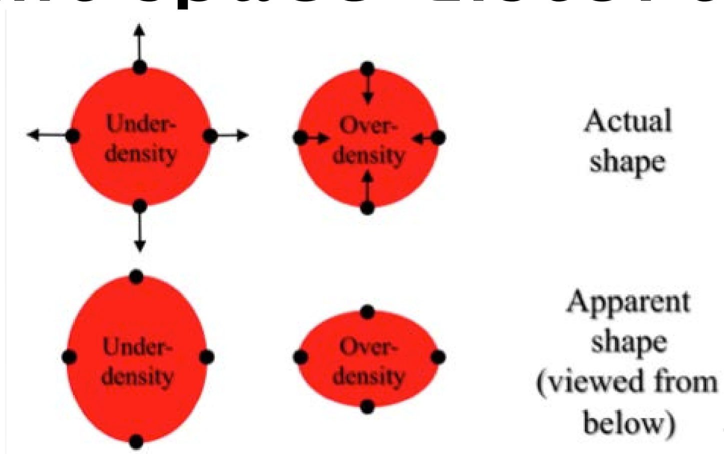
(Bull et al, 2014)

Radio weak lensing



(Brown et al, 2014)

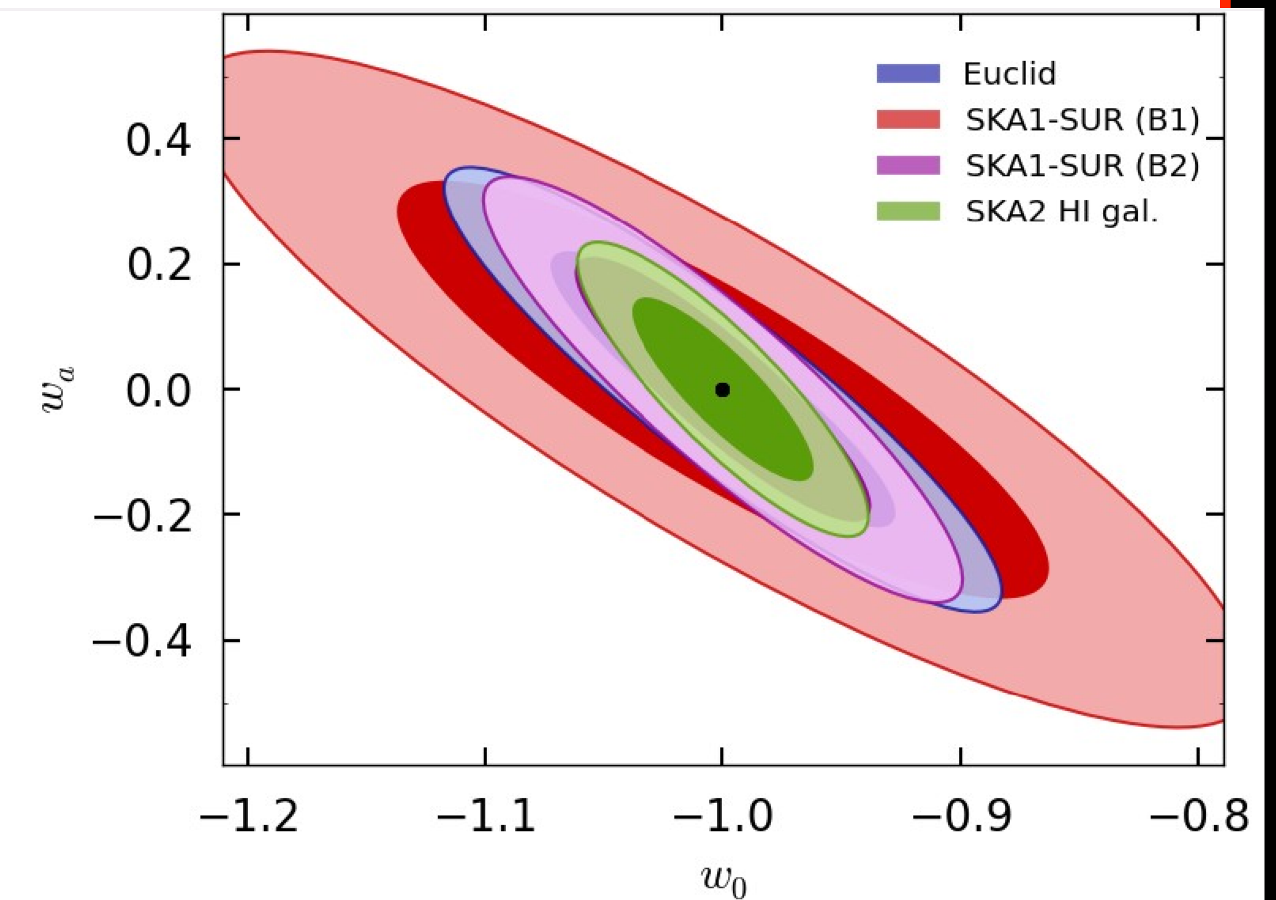
Redshift space distortions



Cosmology summary

SKA1:

1) HI Intensity mapping survey
   - BAO & RSD up to z~3
   - constraints on DE and curvature
   - probe largest scales - Non-Gaussianity, modified gravity
2) HI galaxy redshift survey
   precise RSD to z<0.5
3) Continuum survey
   - 1st large-scale weak lensing survey in radio
   - test isotropy of the Universe
   - tight constraints on non-Gaussianity



(Bull et al, 2014) See also Gong-bo Zhao talk

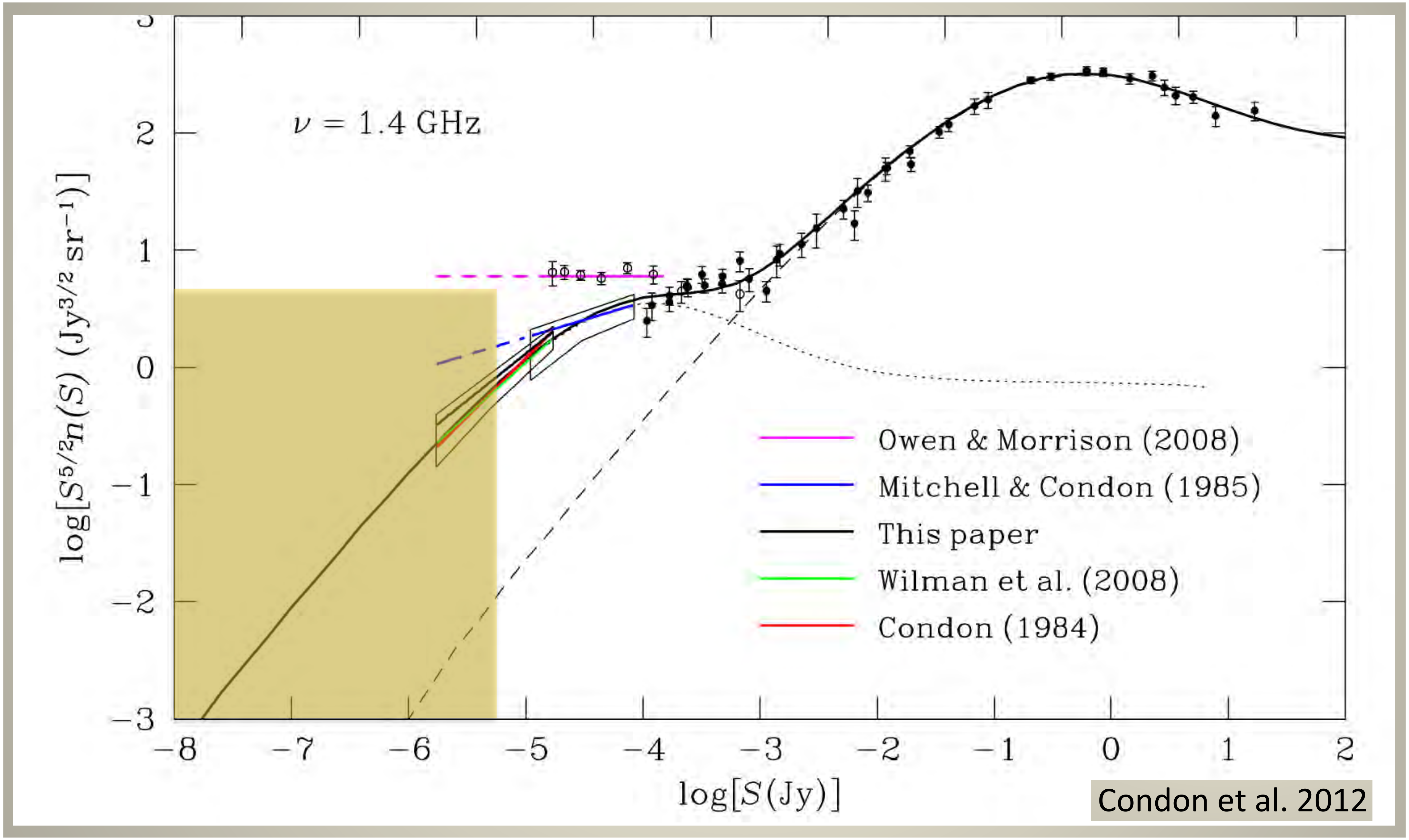
SKA2:

- HI redshift survey (billion galaxy survey) will be state of art
- Radio lensing competative with optical e.g. Euclid

General:

- Radio gives different systematics to optical/IR

Continuum surveys



Condon et al. 2012

HI & Galaxy evolution: Matt Bothwell

Continuum Science: Rob Beswick, Philip Best, Elias Brinks, Matt Jarvis, Mark Sargent, Richard Schilizzi, Elizabeth Stanway

following slides adapted from Jarvis

AGN and Star formation history

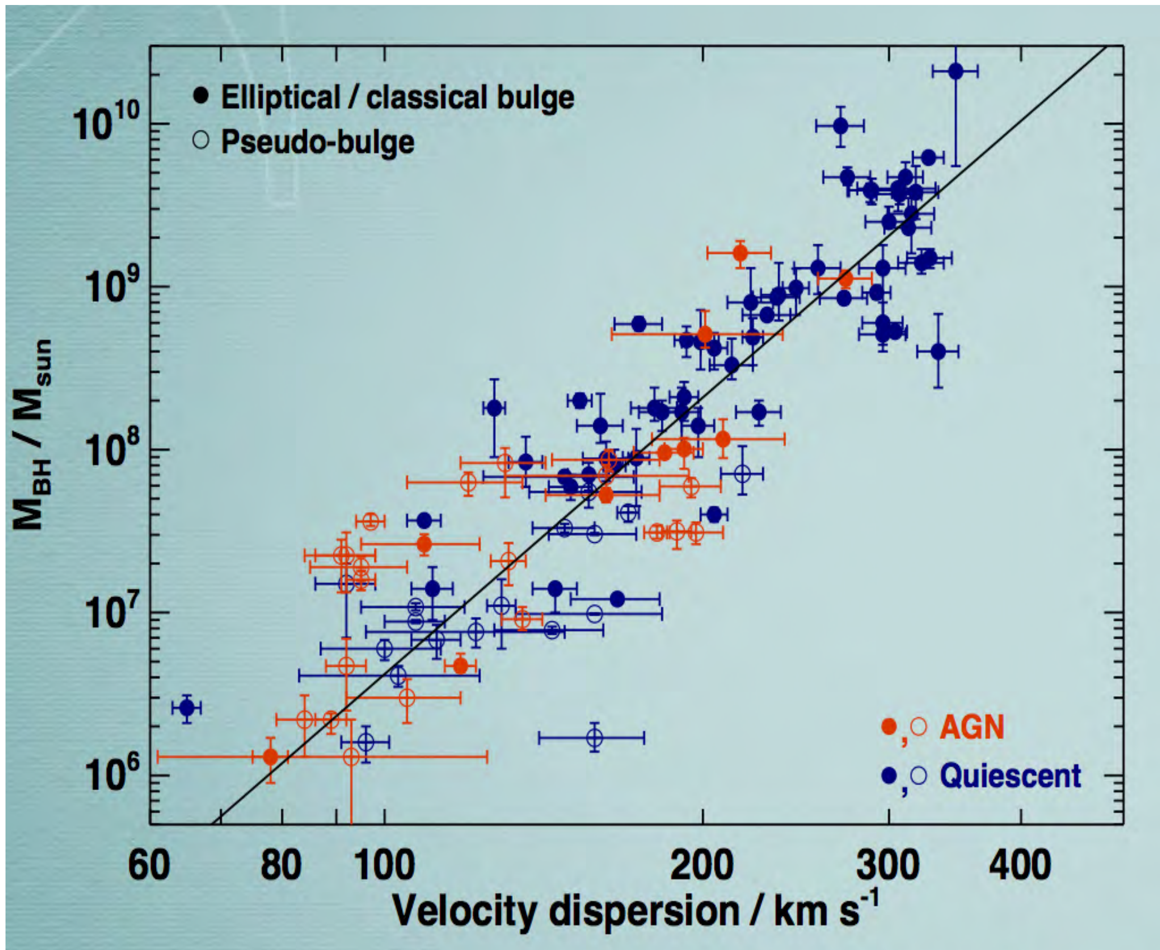


Fig. from Woo et al. 2013

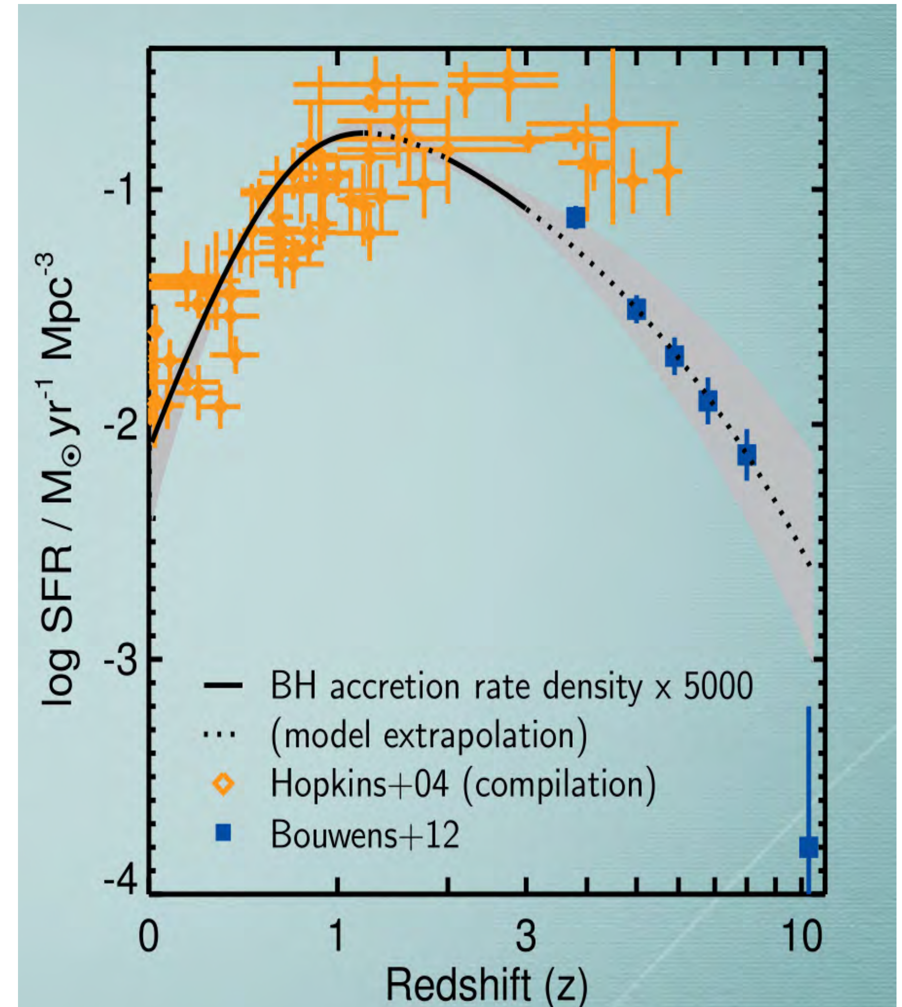


Fig. from Kormendy & Ho 2013

Study interplay between AGN-galaxy growth e.g. feedback

At nJy sensitivity detect normal star forming galaxies

Lradio-SFR correlation avoids issues of other tracers e.g. dust

Resolved HI images

Imperial College London

Key HI Science

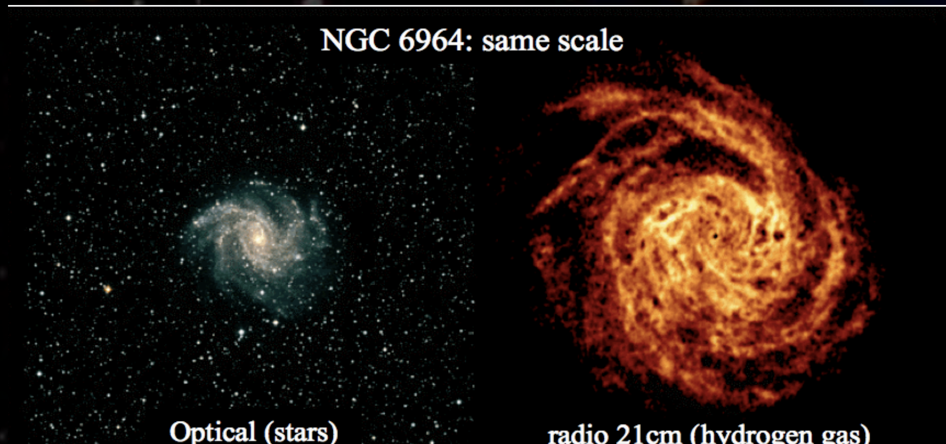
- **HI and galaxy evolution**

  Resolved studies of HI emission in and around galaxies out to z ~ 1, i.e. from Now to ~8 Gyr ago. Current work is out to z=0.2.
  Pathfinders will cover this redshift range, but will not resolve galaxies.
  Unresolved statistical studies (emission & absorption) beyond 8 Gyr

  Will provide, for large part of the life span of the Universe, information about the cold-gas in galaxies and their environment for multi-wavelength, multi-archive studies of galaxies evolution.

- Star formation declined factor 10 over this period

  WHY???



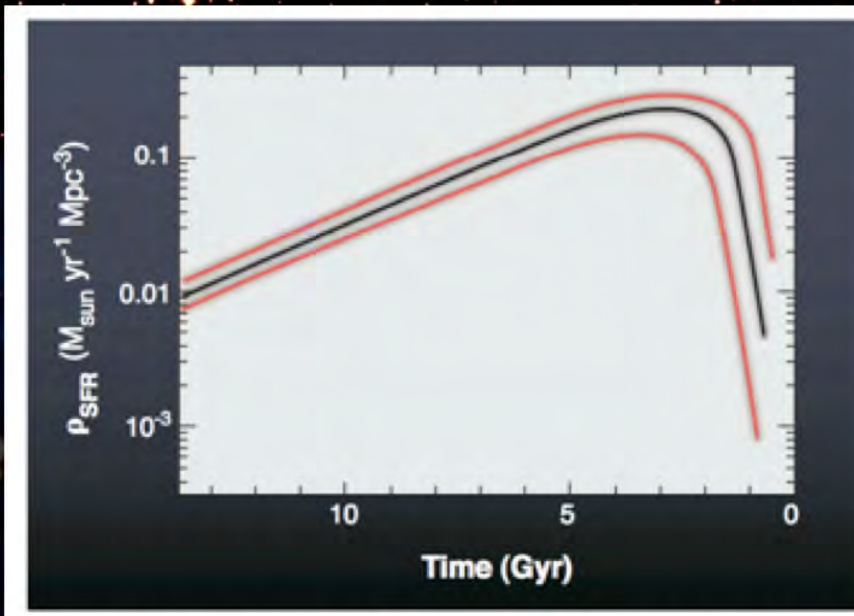


Fig. 2. A simple representation of our current knowledge of the rise and fall of globally averaged star-formation activity over the 13.7 billion years of cosmic history.

Stolen from Tom Oosterloo

HI/Continuum summary

SKA with sub-arcsec resolution resolves galaxies in continuum & HI at $z<1$; count them out to higher redshift

Trace evolution of star formation back to EoR without dust obscuration issues

Connect galaxies to LCDM in detail e.g. HoD modeling $z<4$

Tracing neutral hydrogen pins down origin of gas used for SF (with ALMA get neutral-H > molecular-H > SF)

Multi-wavelength data critical. Huge mutual benefits from combining HI & continuum with Euclid & LSST (VISTA-MOST)

Clusters, strong lensing, …

Rebaselining constraints

EoR:
- 50-250MHz key to see cosmic dawn & reionization
- few arcmin resolution & mK sensitivity

Cosmology:
- high sensitivity & survey speed at <1.2GHz key
- ~0.5 arcsec resolution needed for radio weak lensing, RG separation into types for use as different bias tracers

HI/Continuum:
- High sensitivity on 1-10 arcsec scales at <1420MHz
- MID somewhat better than SUR since angular resolution & sensitivity matter more than FoV for deep fields
- HI would prefer a single band covering 650-1420MHz (break in MID bands)

Conclusions

SKA will trace galaxy formation across cosmic time

- HI & Continuum resolved images of galaxies z<1
- HI & Continuum surveys to z~<3 - 4
- 21 cm imaging during reionization z~6 - 12
- 21cm fluctuations during cosmic dawn z~12 - 27

SKA-LOW opens a new window into early Universe
- trace star-formation history, X-ray sources, reionization

SKA-MID & SKA-SUR enable large area surveys excellent for cosmology - dark energy, non-Gaussianity, curvature
- HI spectroscopic+continuum survey for BAO, RSD & lensing
- 21cm intensity mapping for BAO & largest scales

nJy sensitivity enables continuum surveys that see normal star-forming galaxies to trace AGN-galaxy connection & SF history

Resolved HI images at z<1 connect galaxies to LCDM & DM halos

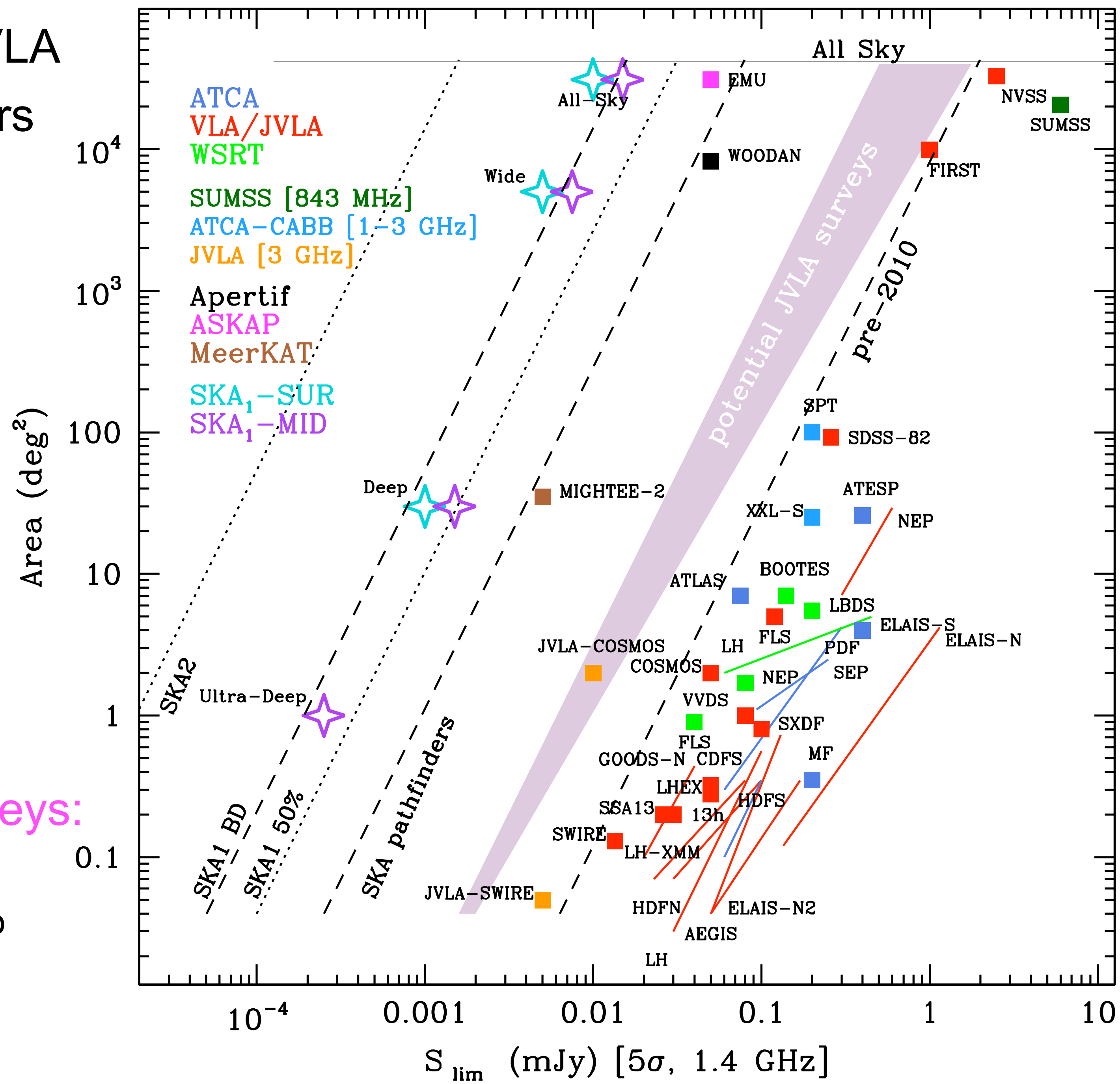
Fin

- **SKA1:** factor 30x over JVLA
  factor 5x over pathfinders

- **All-Sky** (2 yr) → 3π
- **Wide** (1 yr) → 5000 deg^2
- **Deep** (2000^h) → 30 deg^2
- **Ultra Deep** (“) → 1 deg^2

- **SKA1-SUR** Surveys:
  - Resolution: ~2-3 arcsec
  - Rms noise: 2, 1, 0.2 uJy/b

- **SKA1-MID** *High-res* Surveys:
  - Resolution: ~0.6-3 arcsec
  - Rms noise: 3, 1.5, 0.3 uJy/b
    + 0.05 uJy/b



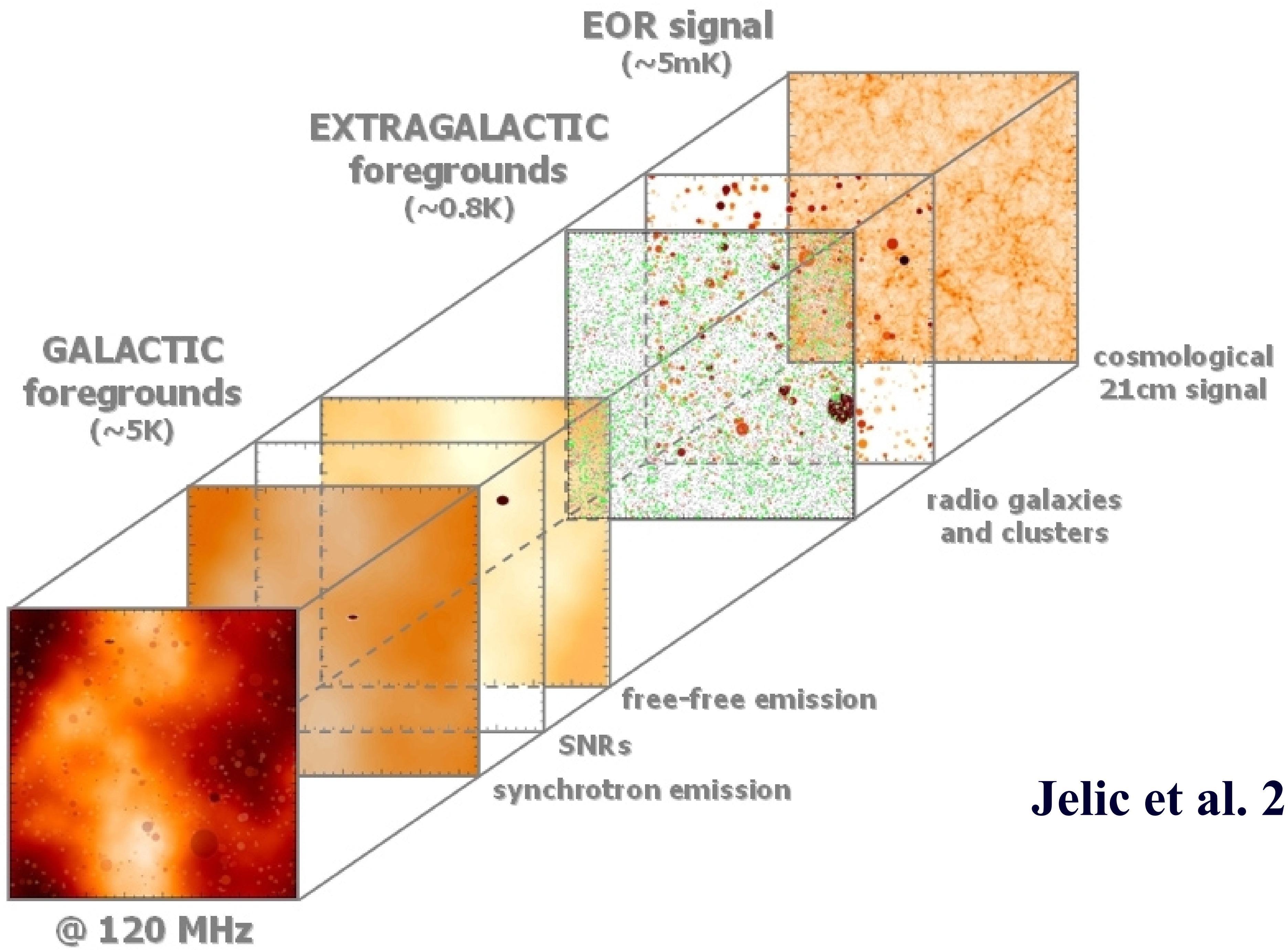
Increasing area

Increasing sensitivity

I. Prandoni - Radio Continuum Science

Foreground removal

Foregrounds ~ 10^3 signal



Jelic et al. 2008

Foreground removal challenging, but exploiting spectral smoothness of foregrounds seems effective
Various techniques e.g. ICA, GMCA, … Chapman+ 2013

X-ray heating and histories