Intensity Mapping with 21cm Observations

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CCA Intensity Mapping Workshop
20 February 2019

Intensity mapping in a nutshell

~4500 hours
VLA detects ~1% of CO-emitting galaxies

~1500 hours
COMAP maps intensity fluctuations across field

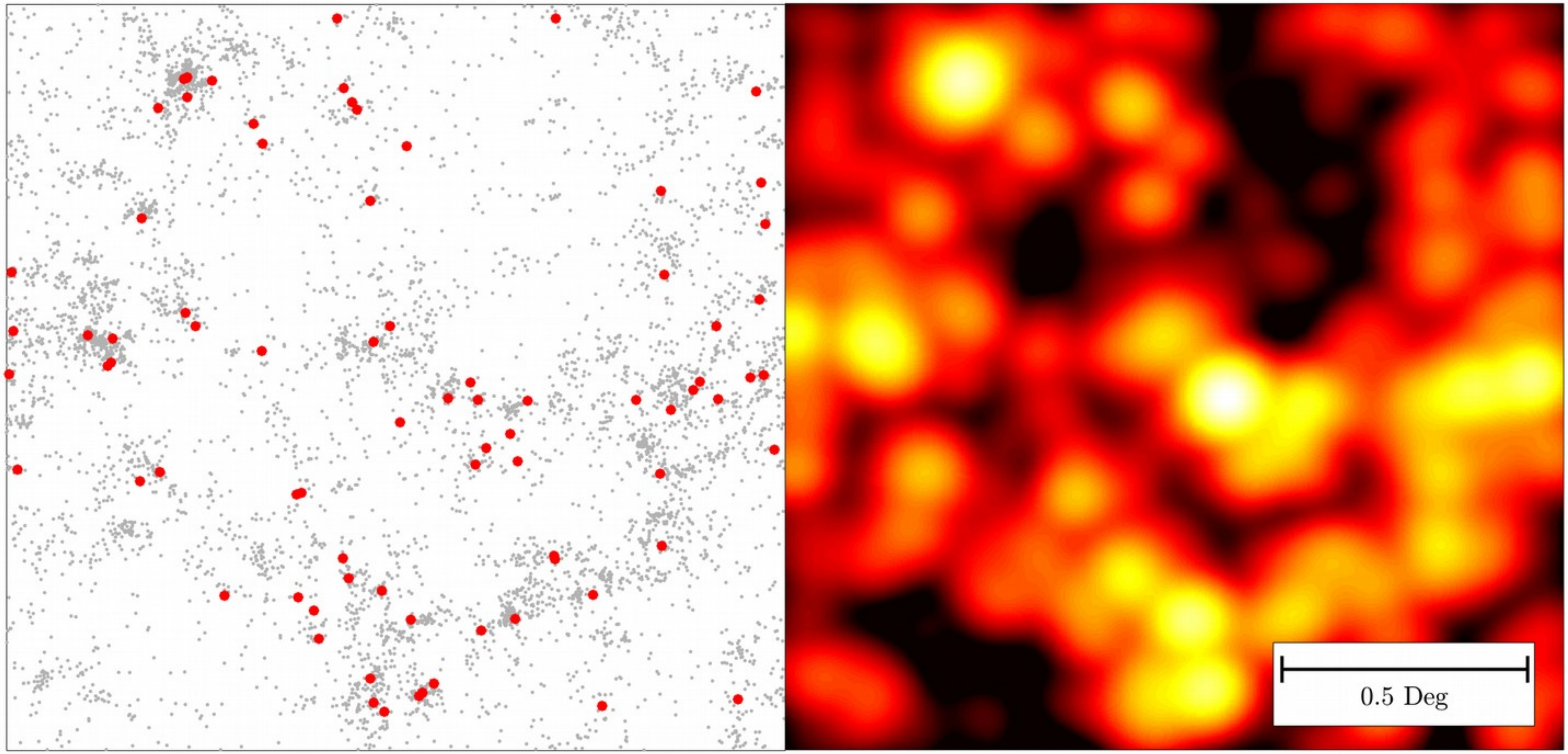
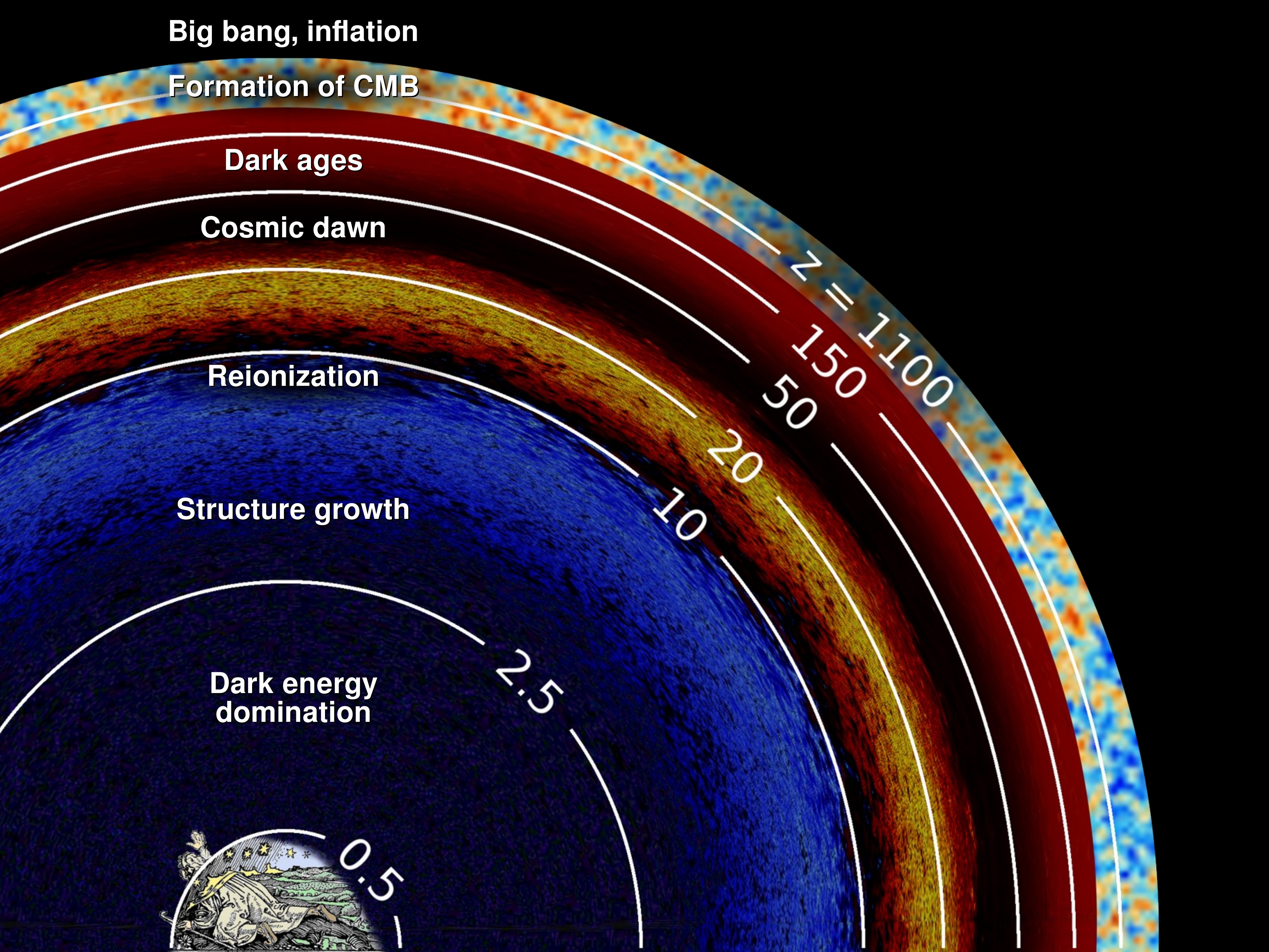


Image: P. Breyesse

Use intensity mapping to map 3D specific intensity from line emission and obtain statistical properties of the emitting objects



Big bang, inflation
Formation of CMB
Dark ages
Cosmic dawn
Reionization
Structure growth
Dark energy domination
z = 1100
150
50
20
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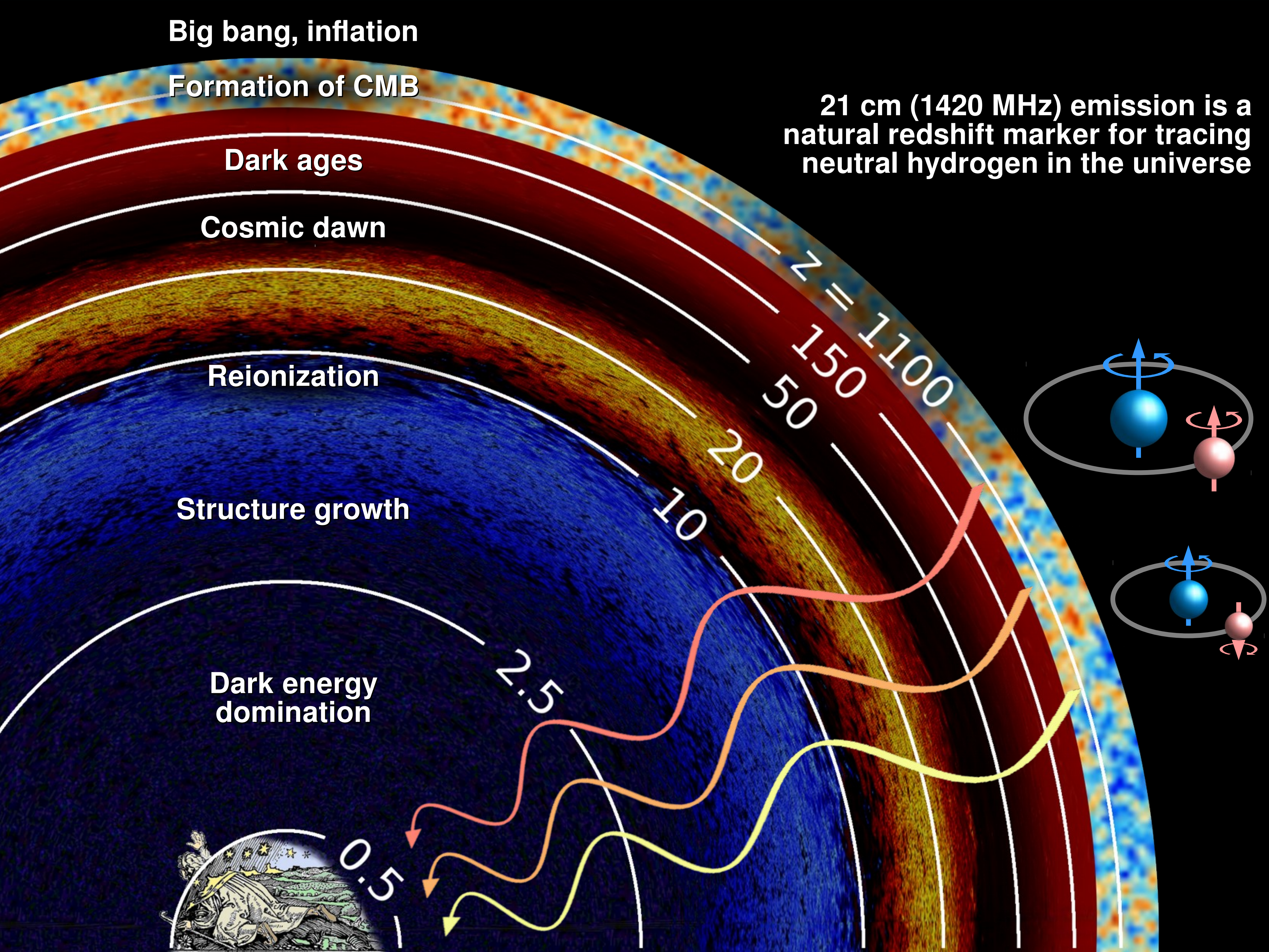
2.5
0.5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21 cm (1420 MHz) emission is a natural redshift marker for tracing neutral hydrogen in the universe
z = 1100
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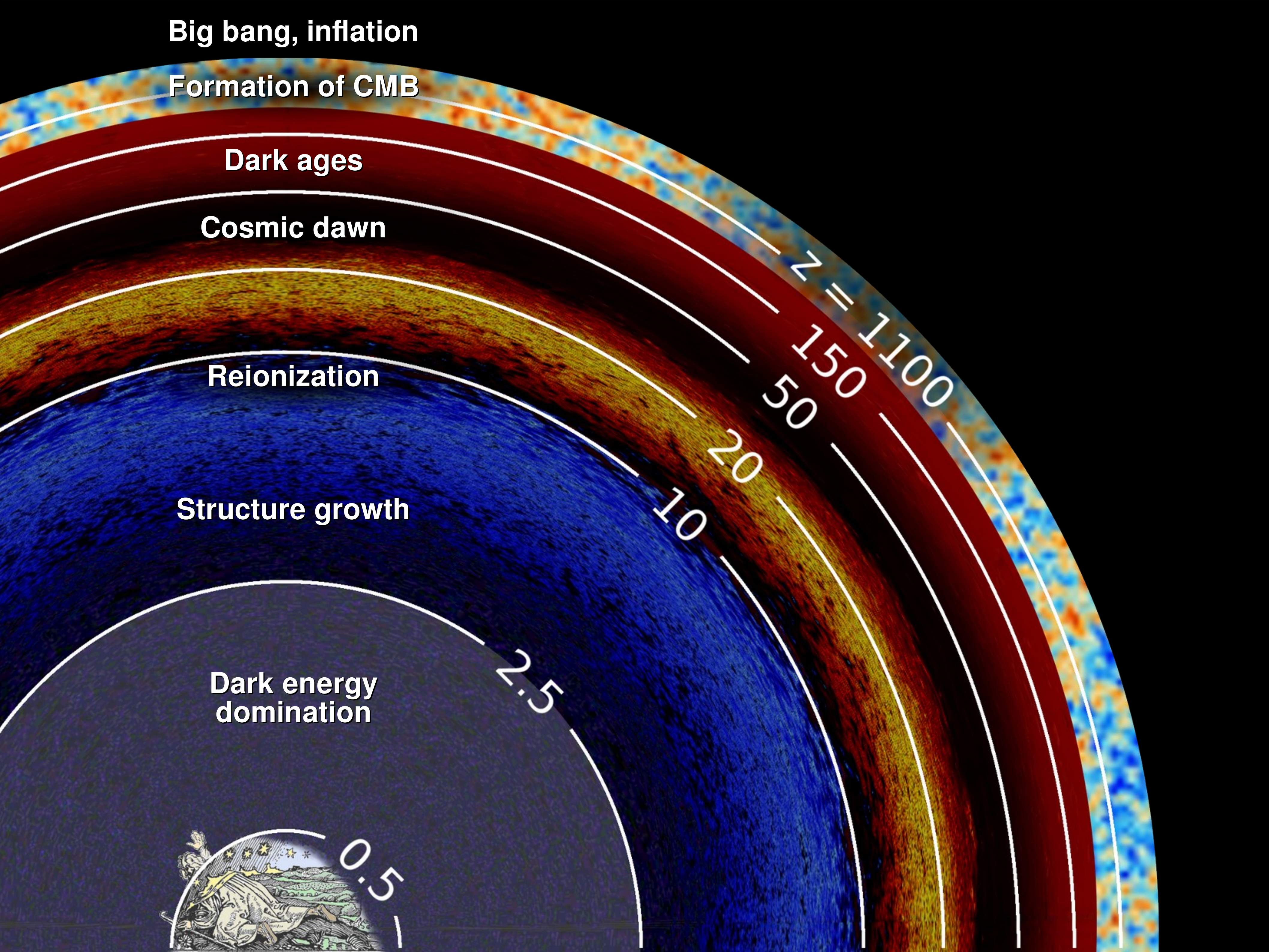
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Baryon acoustic oscillations

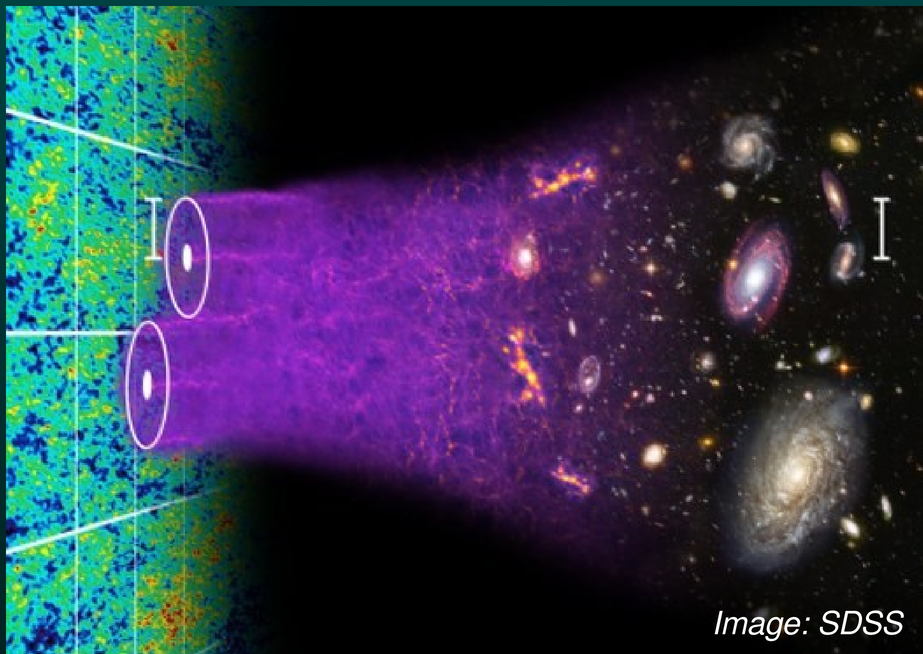
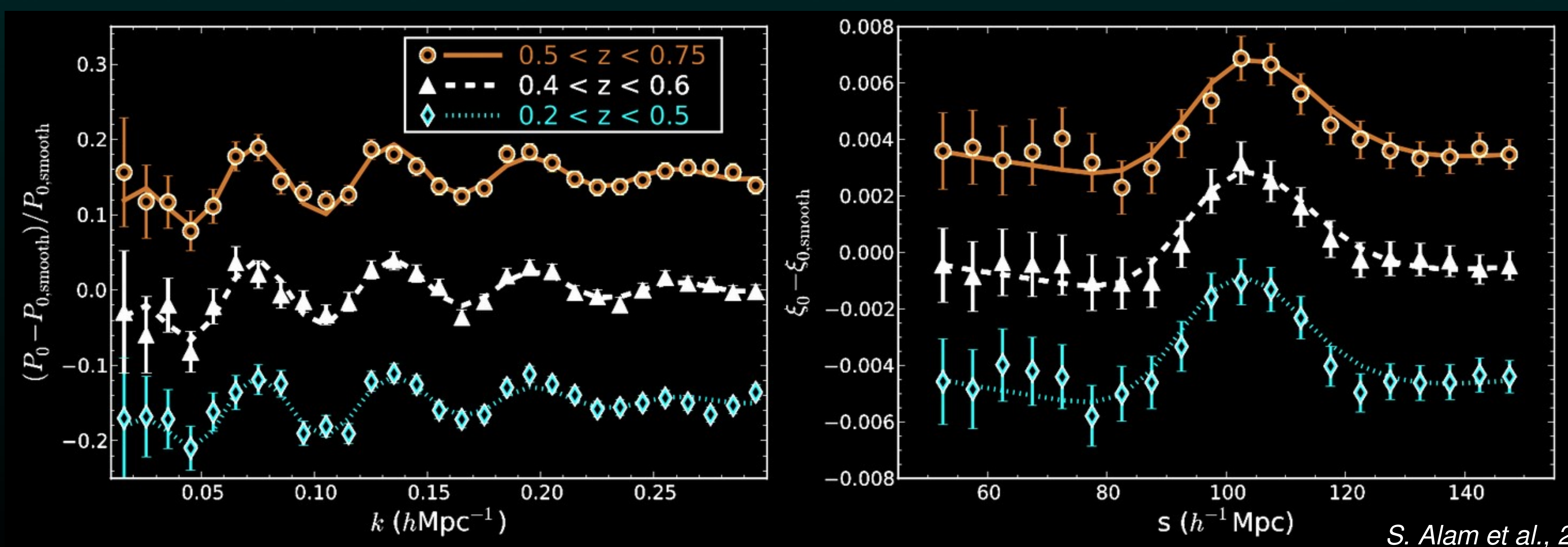


Image: SDSS

Galaxy positions "remember" acoustic waves from the early universe: sound horizon sets characteristic 150 Mpc scale

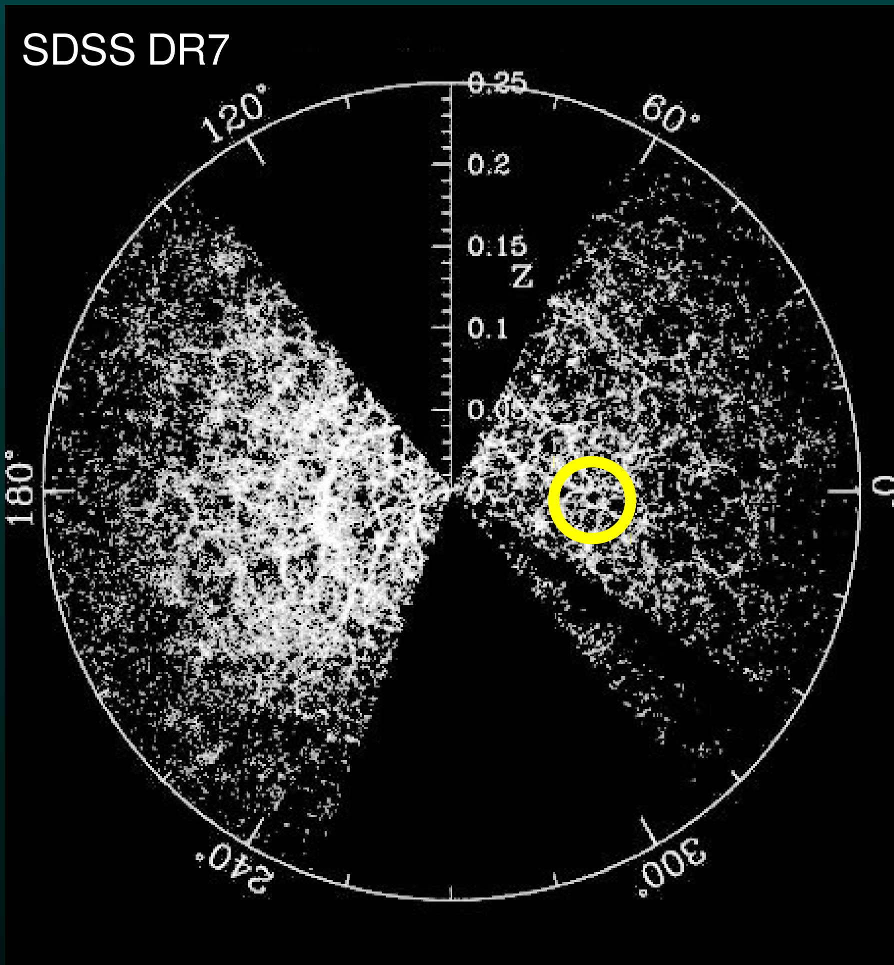
Measure galaxy positions → should see ripples in the power spectrum, peak in the correlation function

DR12 release from SDSS-III shown below, redshift range 0.2 < z < 0.75



S. Alam et al., 2016

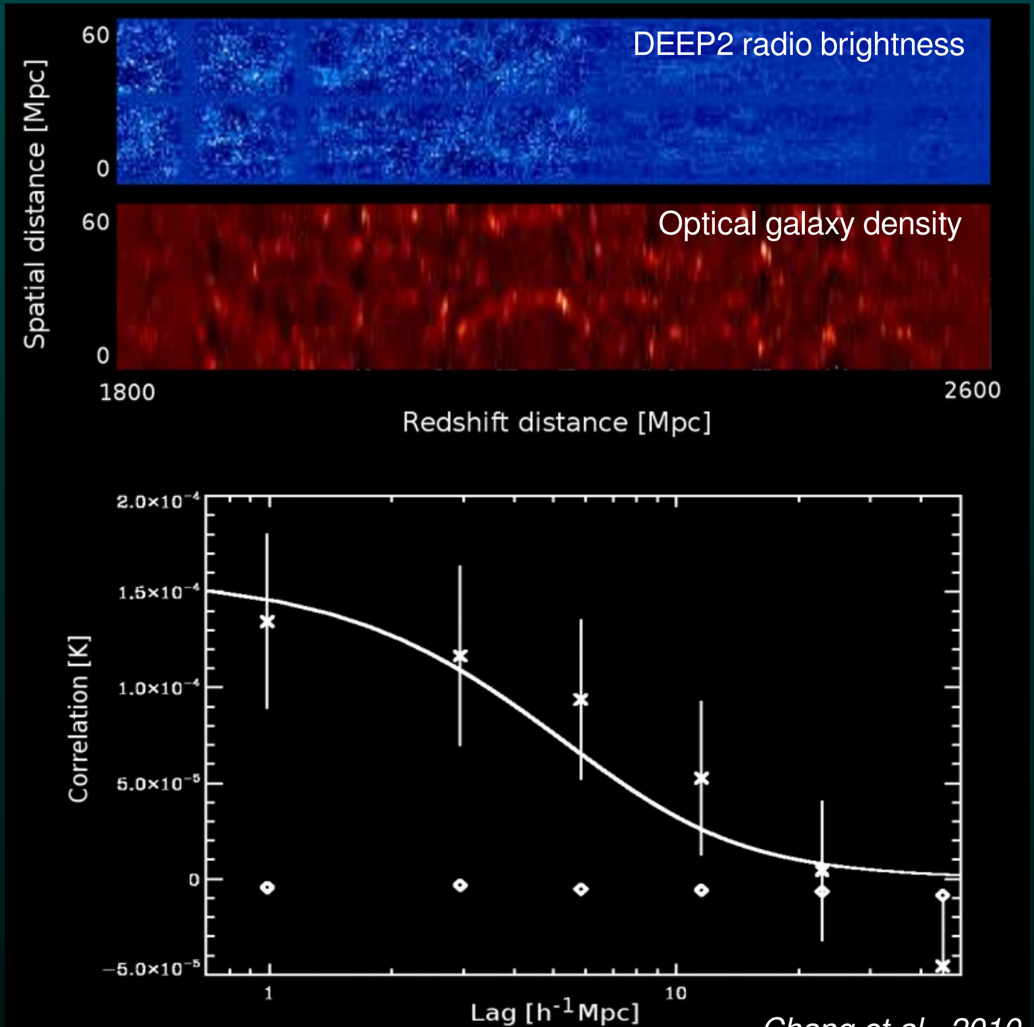
BAOs with hydrogen intensity mapping



We want large volumes (large sky, large *z* range) for precision cosmology

...but counting individual galaxies is hard, and getting to high redshifts is challenging

150 Mpc scale is big (degree scale)



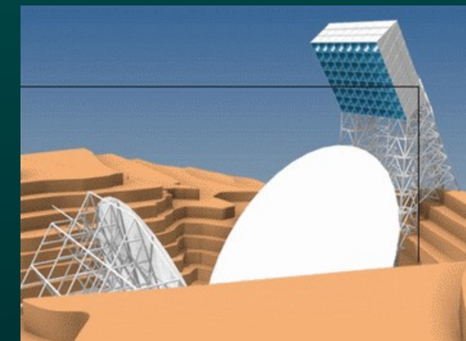
Chang et al., 2010

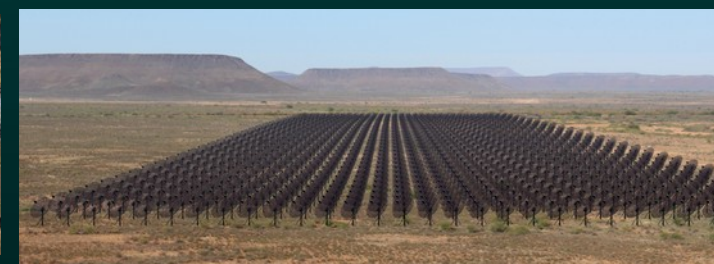
Throw away resolution: use HI intensity mapping to measure matter distribution AND obtain redshift information.

Use BAO peak as a standard ruler to chart the universe's expansion history, probe dark energy.

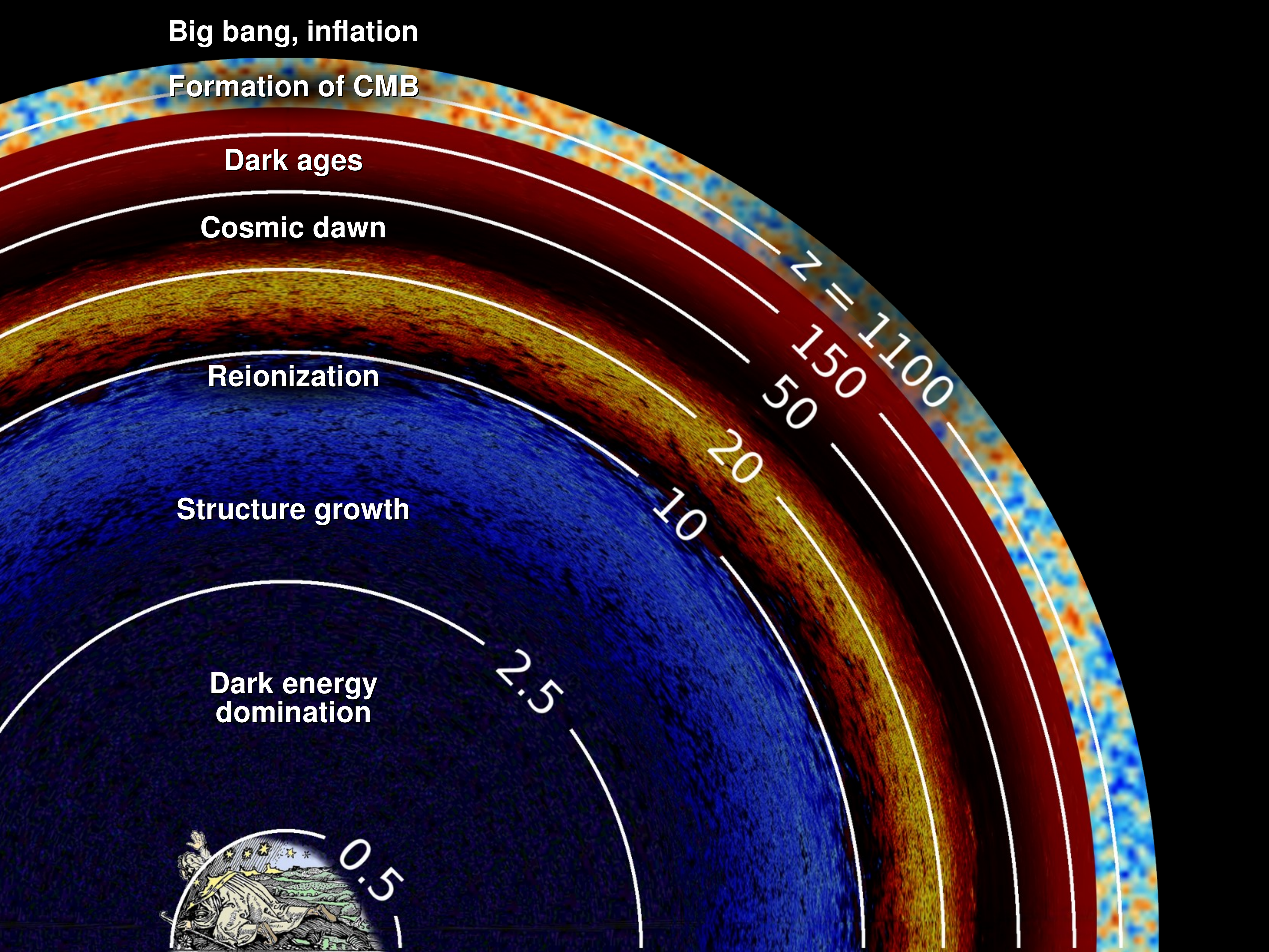
Experiments at $z < 2.5$





	MeerKAT	**Tianlai**	**BINGO**	**GBT**	**CHIME**	**HIRAX**
Site	Karoo	Xinjiang	Brazil	Green Bank	DRAO, Canada	Karoo
Type	Dish array	Cylinder+dish	Multi-feed dish	Single dish	Cylinder array	Dish array
Freq (MHz) ***z* range**	580 – 1670 $0 < z < 1.45$	400 – 1500 $0 < z < 2.5$	960 – 1260 $0.13 < z < 0.48$	670 – 910 $0.53 < z < 1.12$	400 – 800 $0.8 < z < 2.5$	400 – 800 $0.8 < z < 2.5$
FOV	1°	NS x 3°	15°	15 arcmin	100° x 1°–2°	5° – 10°
Resolution	10 arcsec	14 arcmin	40 arcmin	15 arcmin	14 – 32 arcmin	6 – 12 arcmin
Coll. area	9000 m^2	10,000 m^2	>500 m^2	9300 m^2	8000 m^2	28,000 m^2
Coverage	4000 deg^2	North	3000 deg^2	2 x DEEP2 + ?	North	South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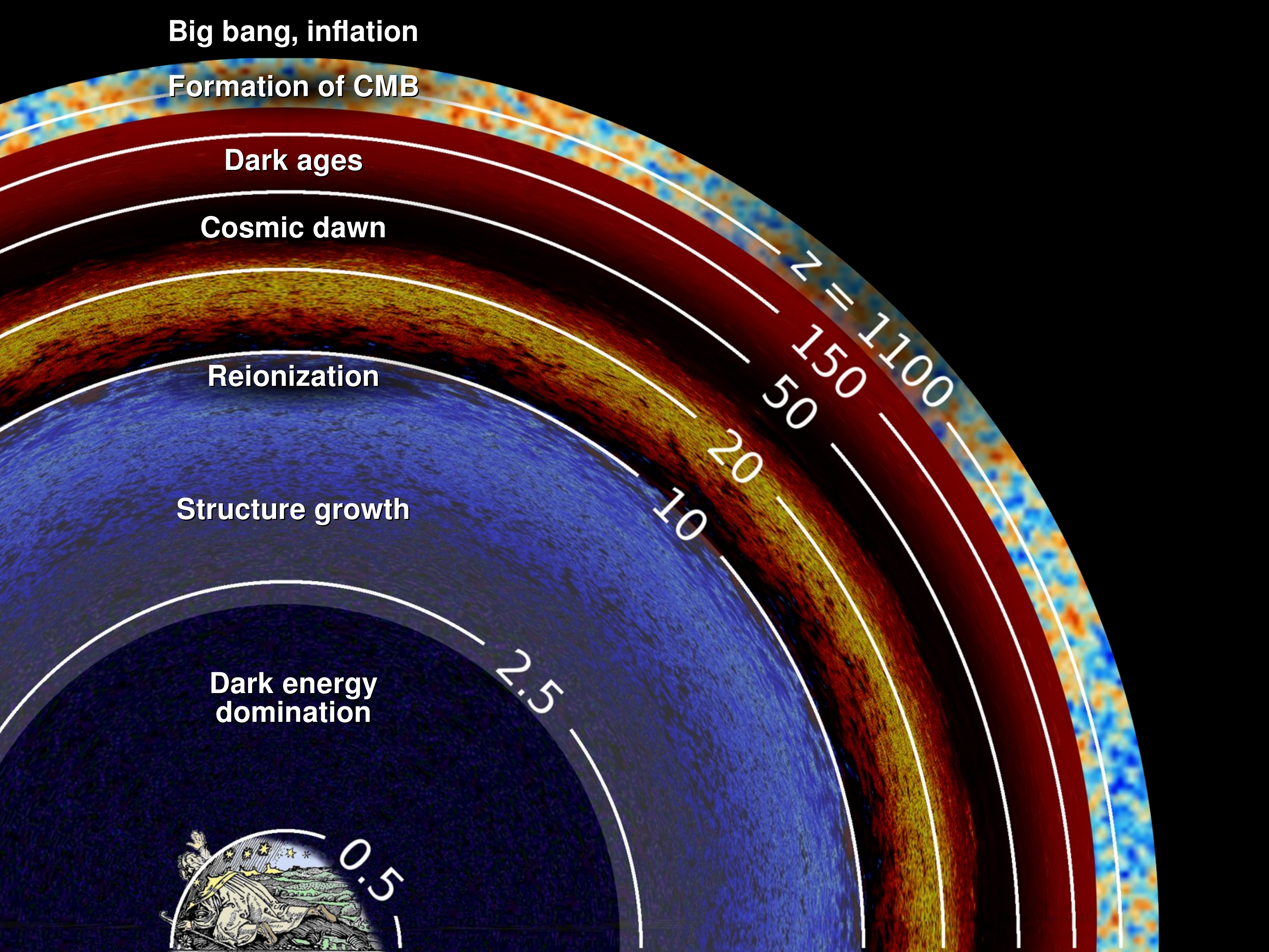

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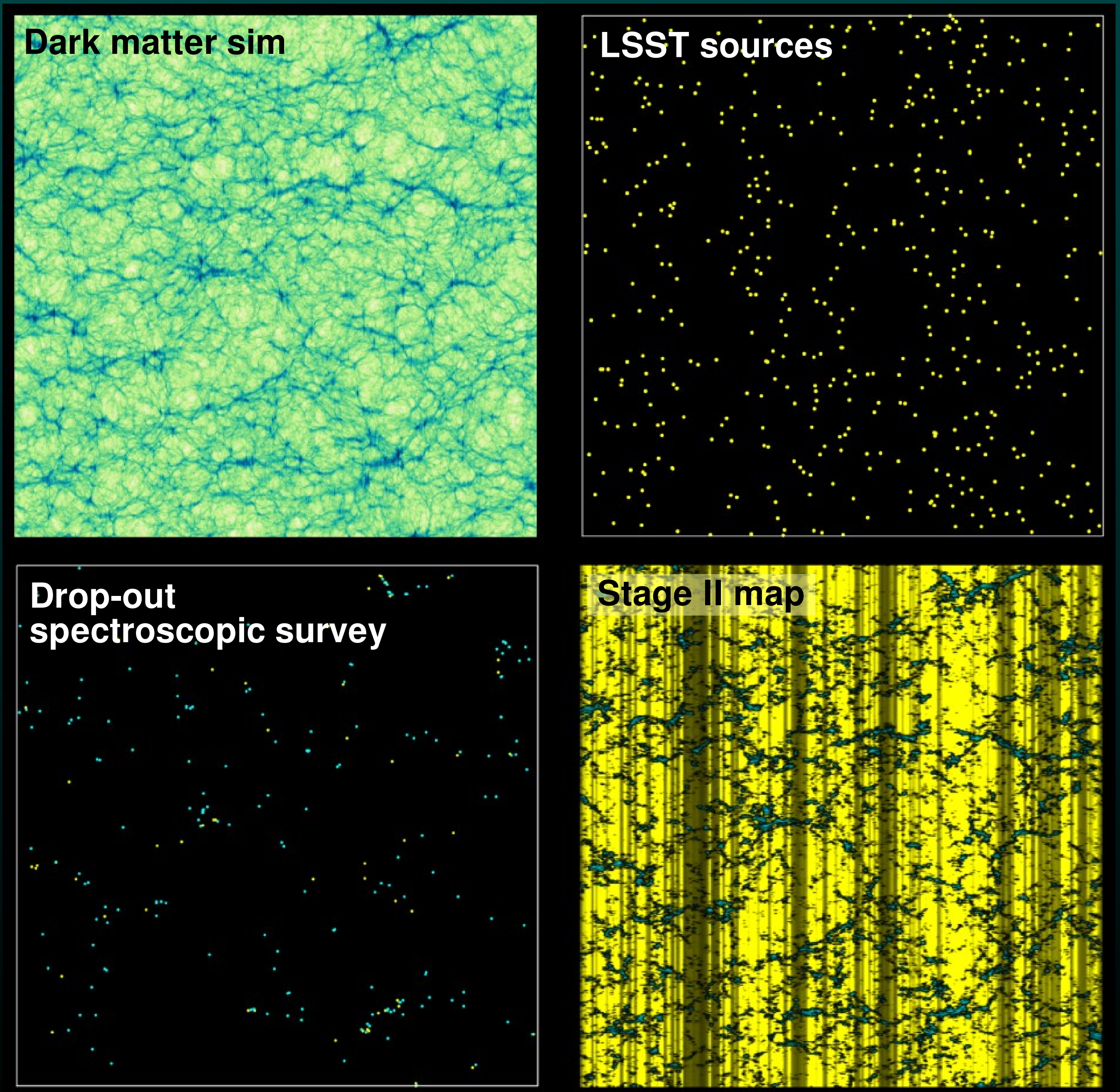
Pre-acceleration, post-reionization era



Cosmic Visions 21cm Collaboration

Extend characterization of universe's expansion history to this era

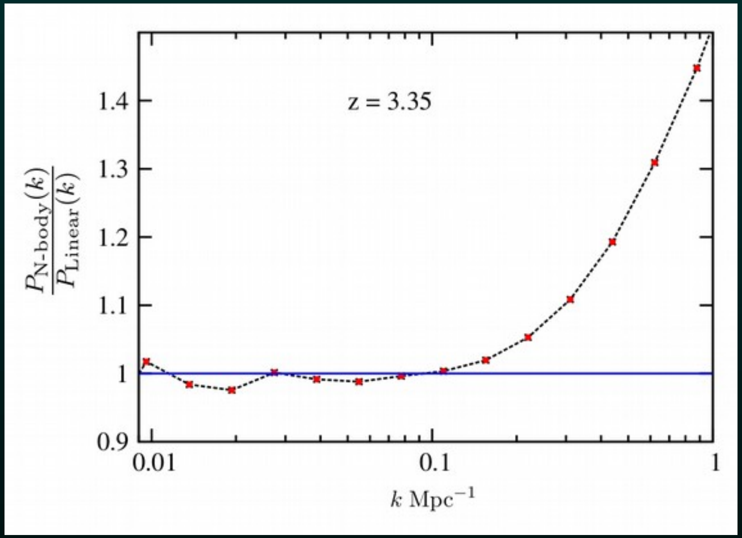
Constrain inflationary relics via primordial power spectrum features

Improved constraints on primordial non-Gaussianity

Experiments at 2 < z < 10

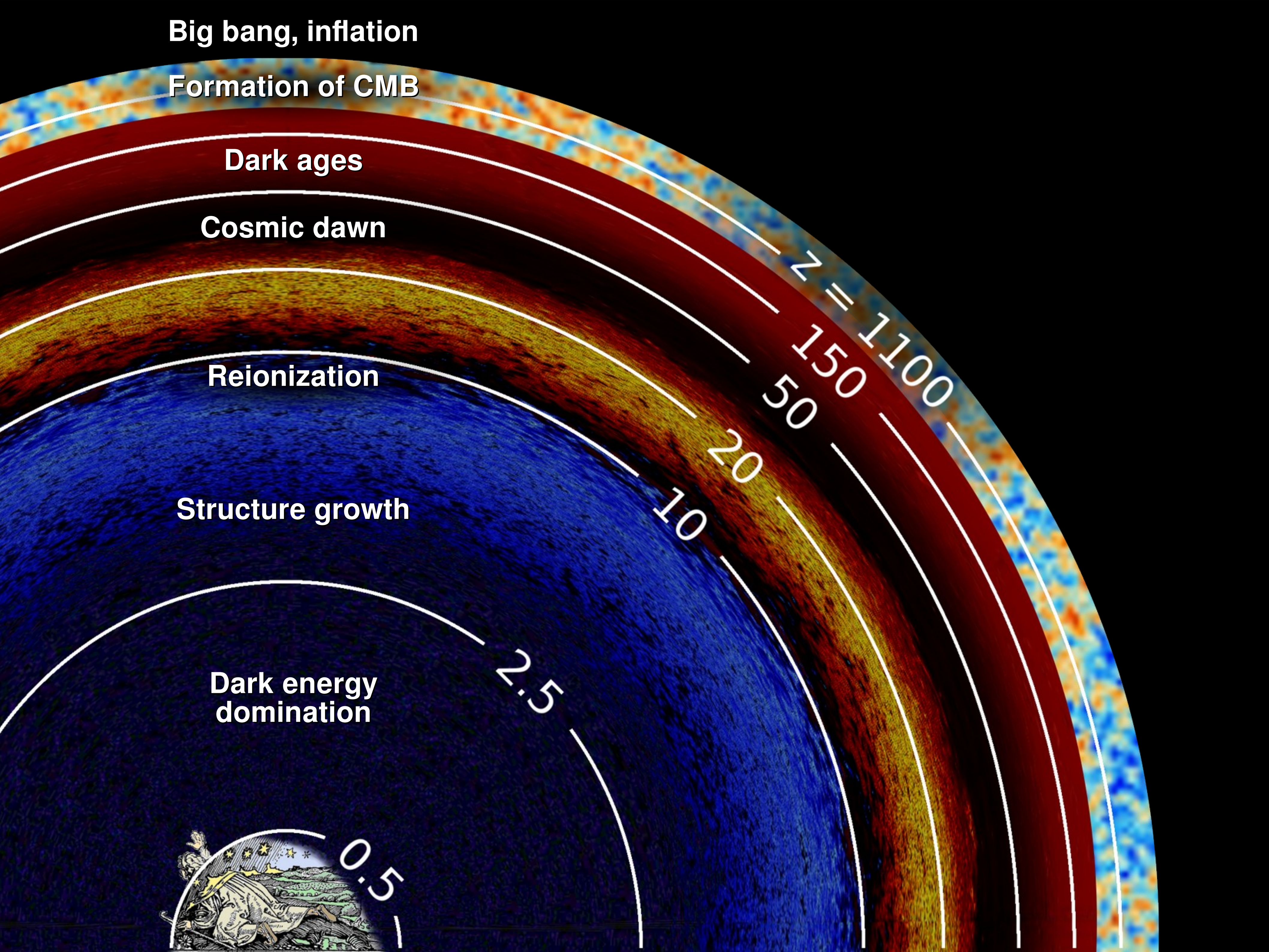
- No dedicated HI experiments spanning $2 < z < 5$
  – Lots of experiments in this range for other line emission
  – Several HI experiments at $z > 5$ (coming up in a few slides)

- A couple experiments in the redshift gap:
  – GMRT @ $z = 3.37$ (325 MHz)
  – Ooty Wide Field Array @ $z = 3.35$ (327 MHz)



Density fluctuation PS ratio: N-body vs linear

- Future and proposed experiments:
  – SKA-LOW @ $3 < z < 27$ (50 – 350 MHz)
  – Cosmic Visions Dark Energy Stage II experiment @ $2 < z < 6$ (200 – 500 MHz)



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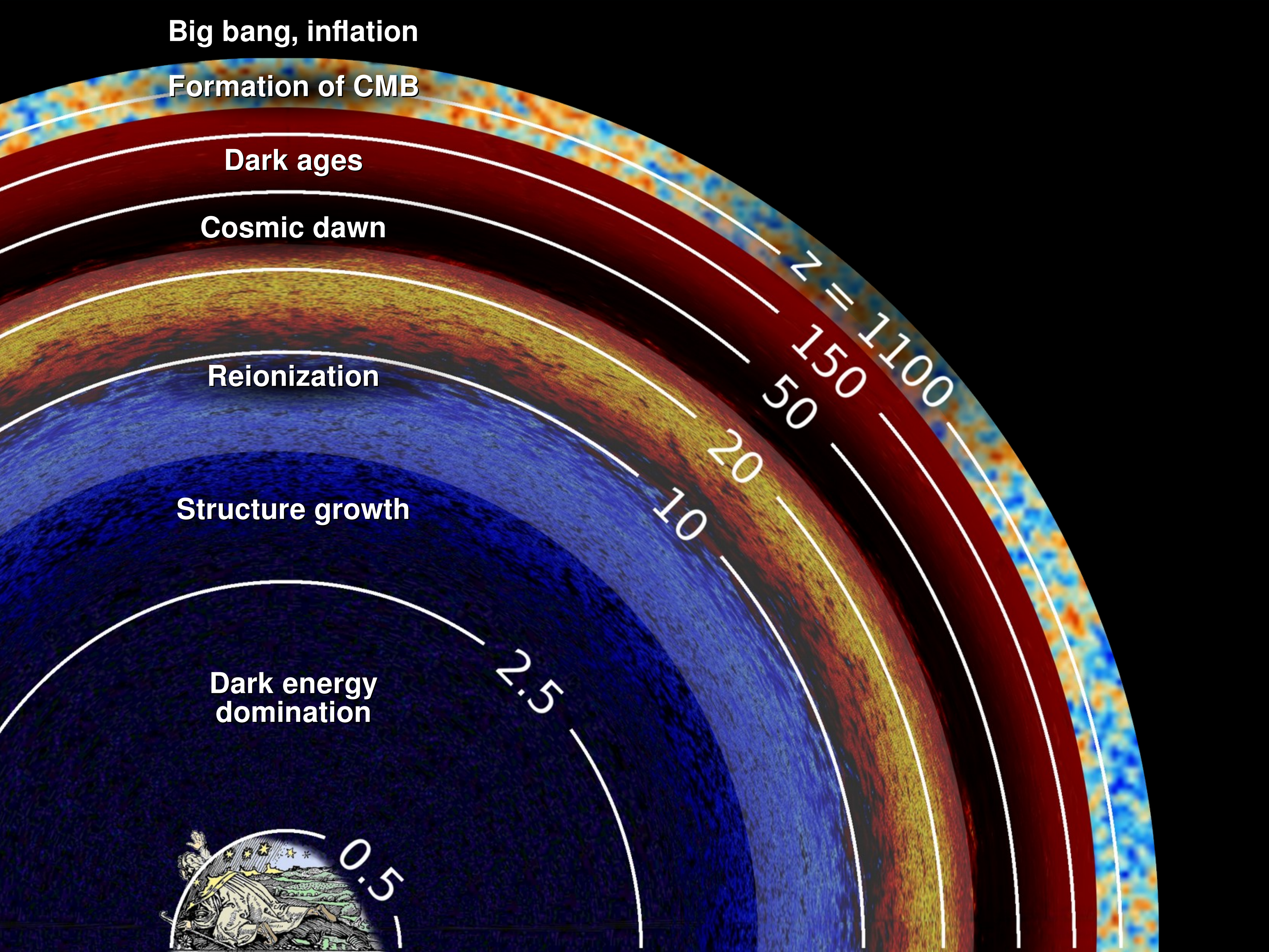

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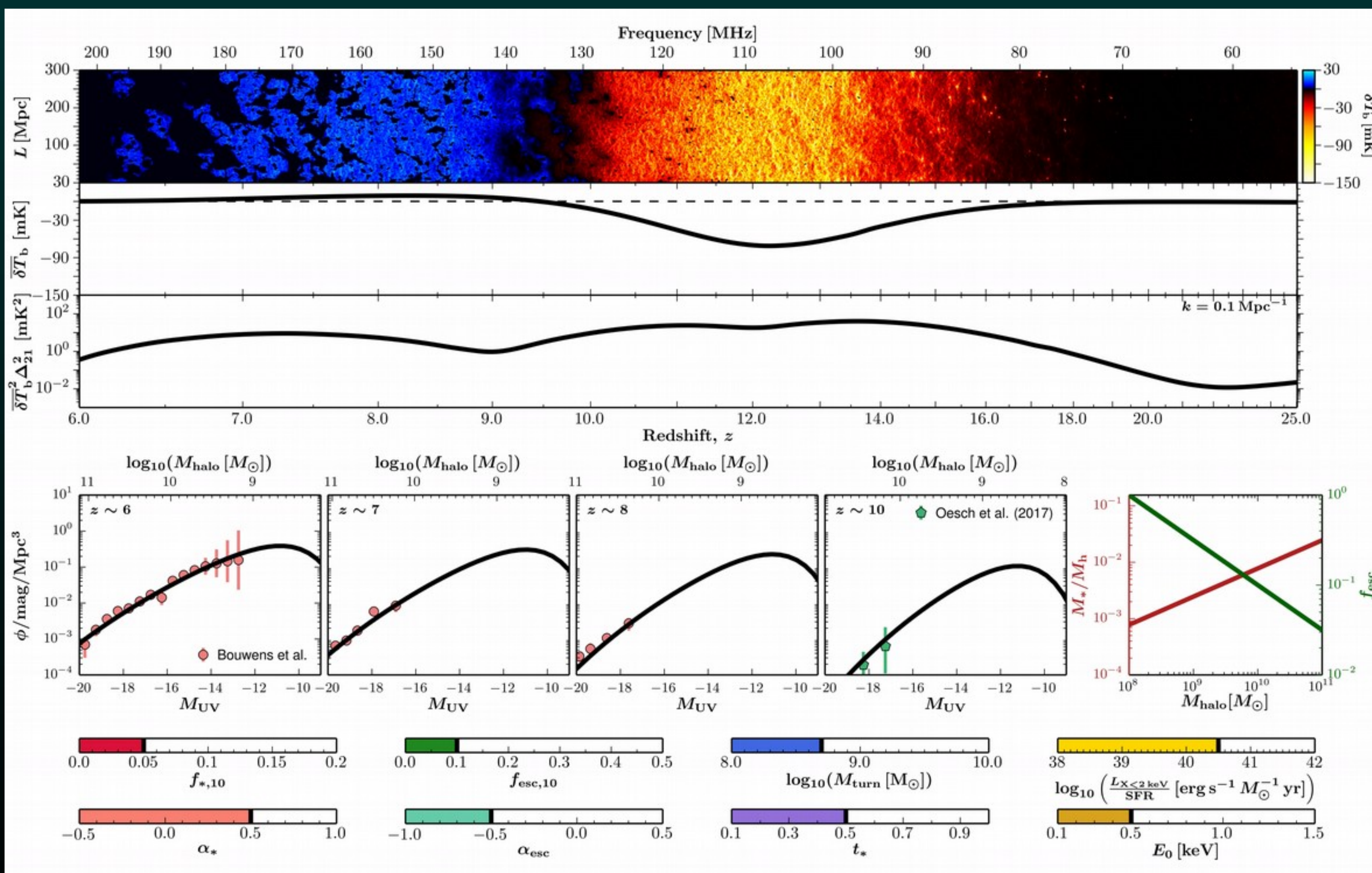
Reionization and cosmic dawn

- First luminous objects create patchy structure containing a 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

Credit: J. Pritchard

- Multiple observables and constrainable parameters – see e.g. 21CMMC



Ultimate dream: image fluctuations

Globally averaged brightness temperature

Fluctuation power spectrum amplitude

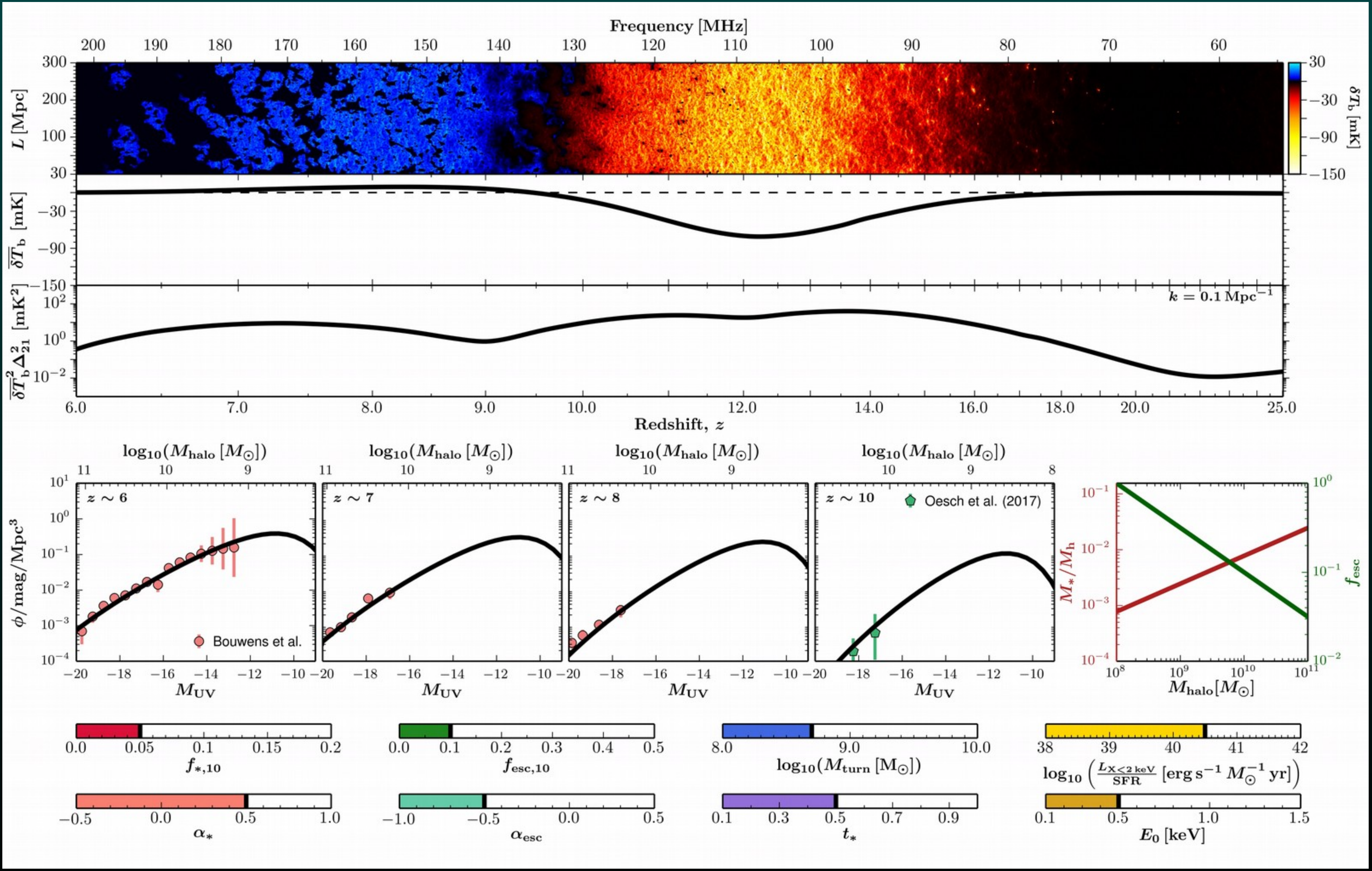
Luminosity functions, stellar mass per halo mass, escape fraction

Astrophysical parameters

Image: J. Park et al.

Images: 21CMMC team

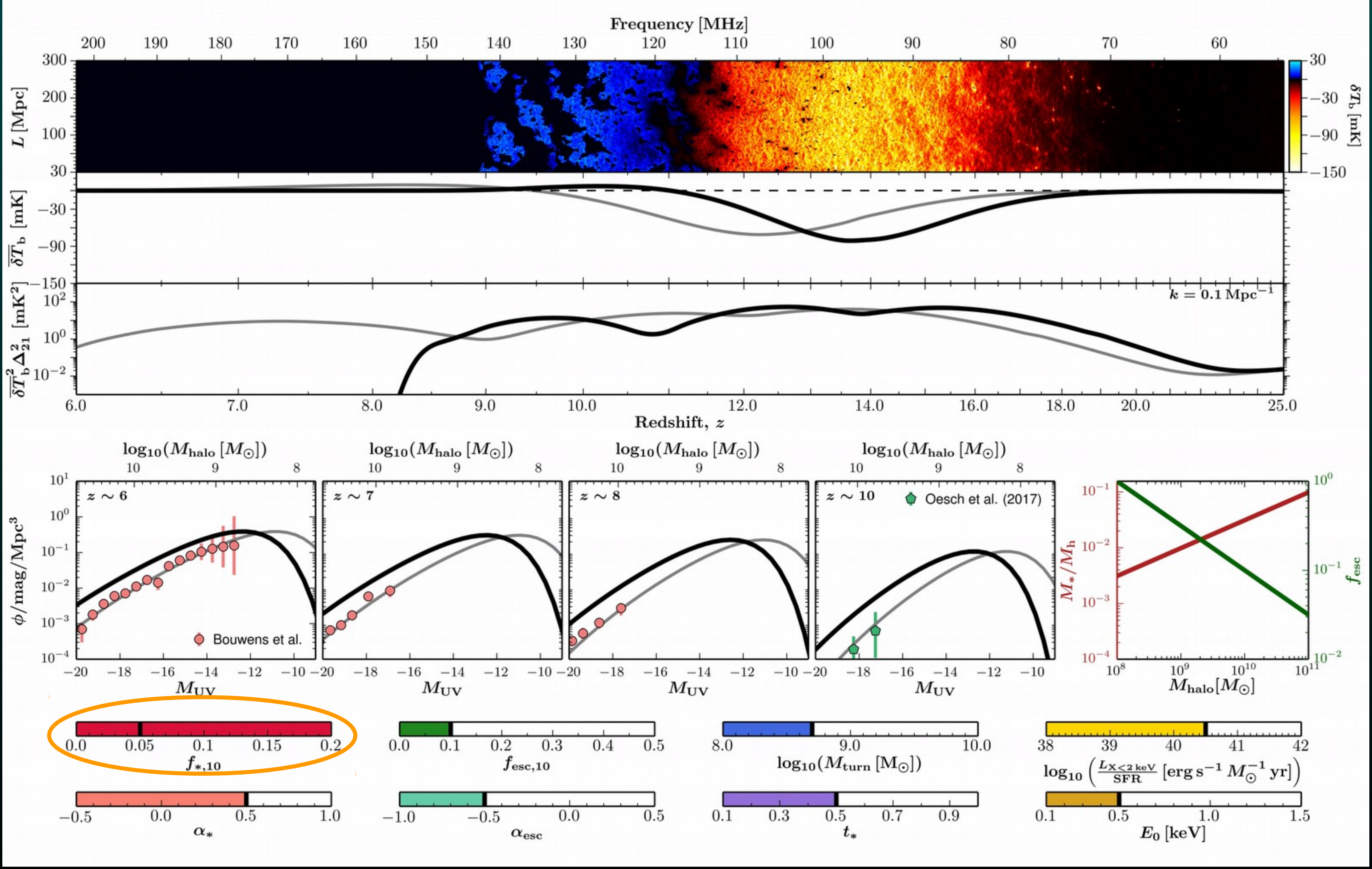
Example observables and parameters



Nominal parameters

Example observables and parameters

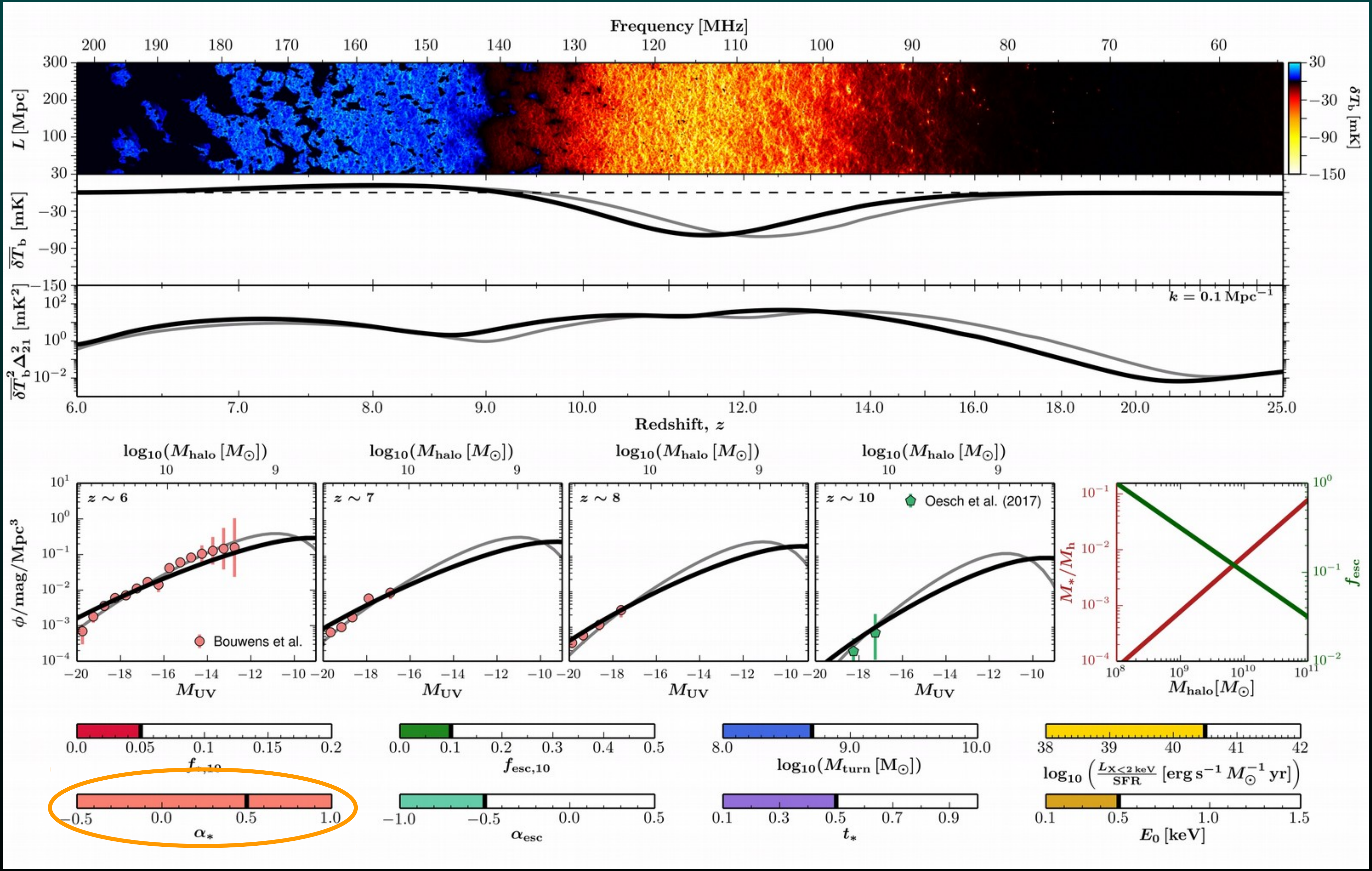
Images: 21CMMC team



Fraction of galactic gas in stars at high-z

Example observables and parameters

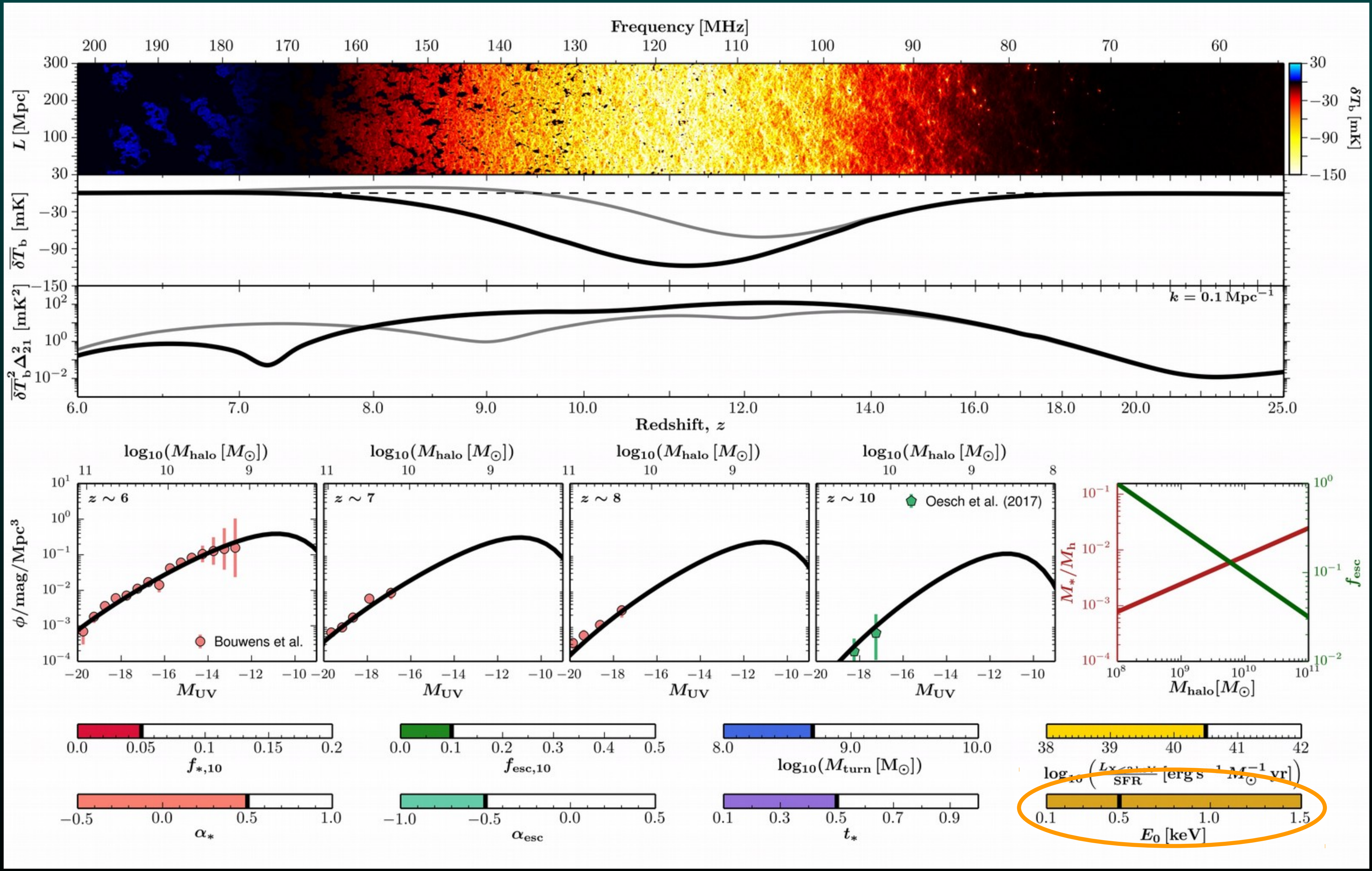
Images: 21CMMC team



Power law scaling of gas fraction with halo mass

Example observables and parameters

Images: 21CMMC team



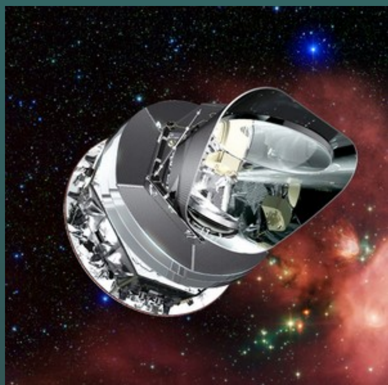
Minimum X-ray photon energy capable of escaping galaxy

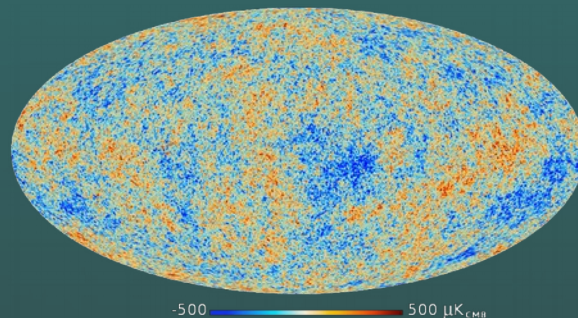
Experiments at 5 < z < 27

	GMRT	MWA	HERA	OVRO-LWA	LOFAR
Site	Khodad	Murchison	Karoo	Owens Valley	Netherlands
Type	Dish array	Dual-pol dipoles	Dish array	Crossed dipoles	Dipoles
# elements	30	2048 (128 tiles)	350	288	18+18+8 stations
Freq (MHz)	150 – 1500	70 – 300	50 – 250	27 – 85	30 – 240
***z* range**	$z < 8.5$	$4 < z < 19$	$5 < z < 27$	$16 < z < 50$	$5 < z < 50$
FOV	3°	15 – 50°	9°	Full hemisphere	1.3 – 19.5°
Resolution	20 arcsec	~few arcmin	25 arcmin	9 – 23 arcmin	0.3–1031 arcsec, 150 MHz
Coverage	North	South	1440 deg^2	North	North

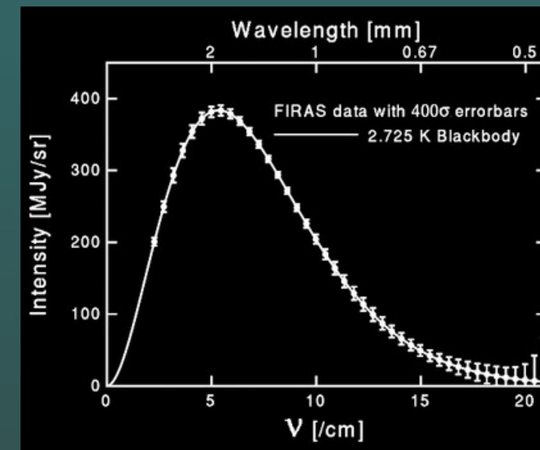
Fluctuations vs global signals

Planck, WMAP, etc

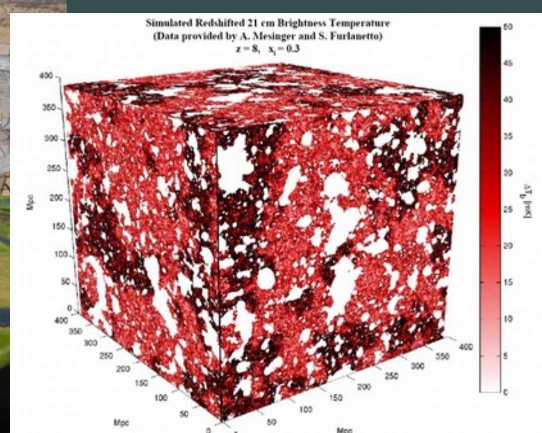




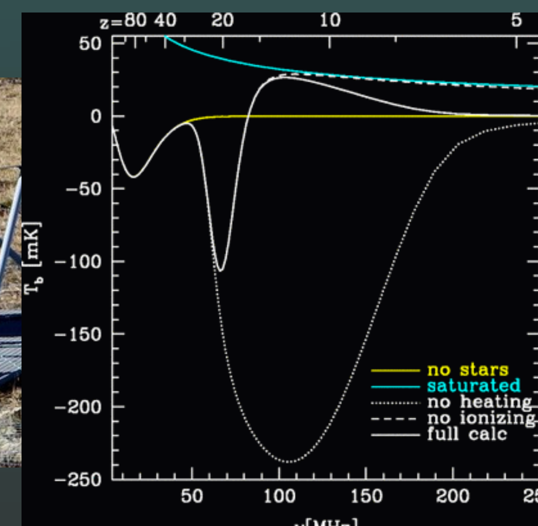
COBE/FIRAS



HERA, LOFAR, etc



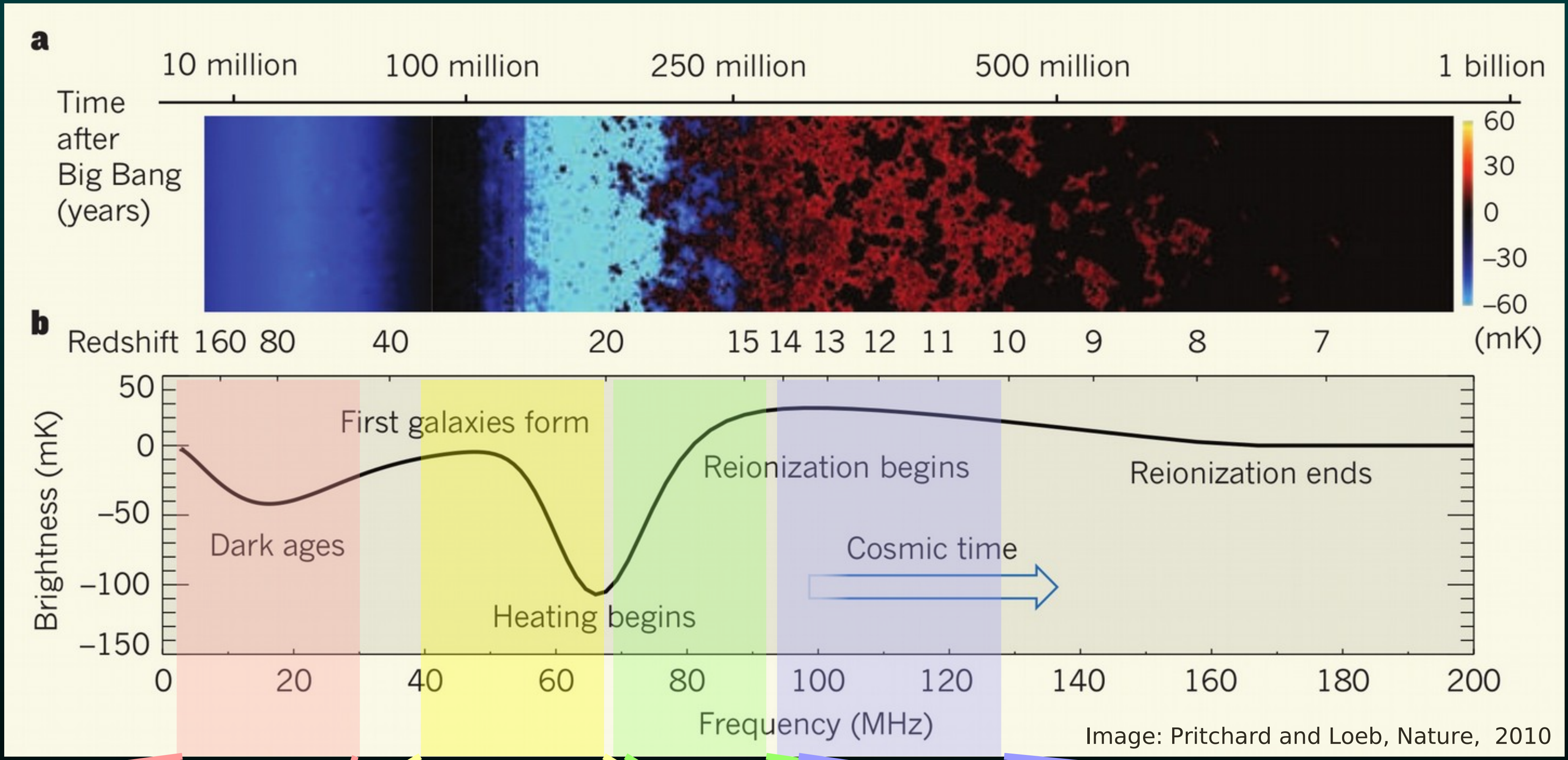
Global 21cm experiments



21cm signal evolution is a “thermometer” that can probe heating processes and energy injection in the early universe, depends on neutral hydrogen fraction and spin/kinetic temperature coupling

Global 21cm signal evolution

$$\delta T_b \propto x_{HI}\,(1+z)^{1/2}\,(T_s - T_{CMB})\,/\,T_s$$



HI gas kinetic temp (T_K) below T_{CMB}. Collisions couple T_K and T_S at first. Later, CMB photons drive $T_S \rightarrow T_{CMB}$.

First stars form, Lyα photons couple T_K and T_S via Wouthuysen-Field mechanism

Heating by X-rays, gamma rays from first sources drives T_K above T_{CMB}

Reionization erases HI signal

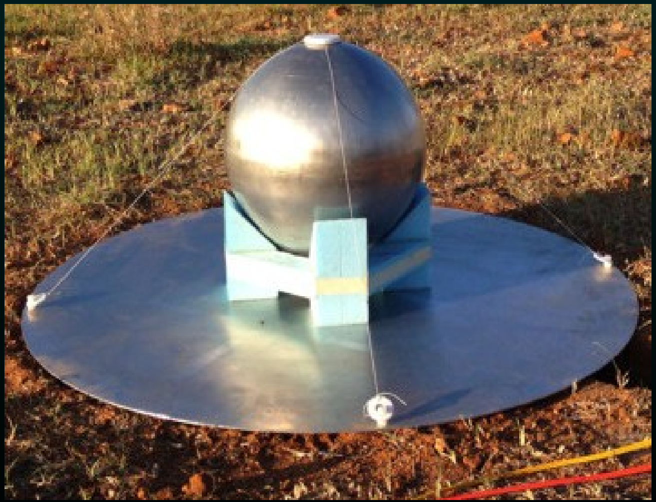
Global 21cm experiments

EDGES
50 – 200 MHz
Murchison Radio Obs.

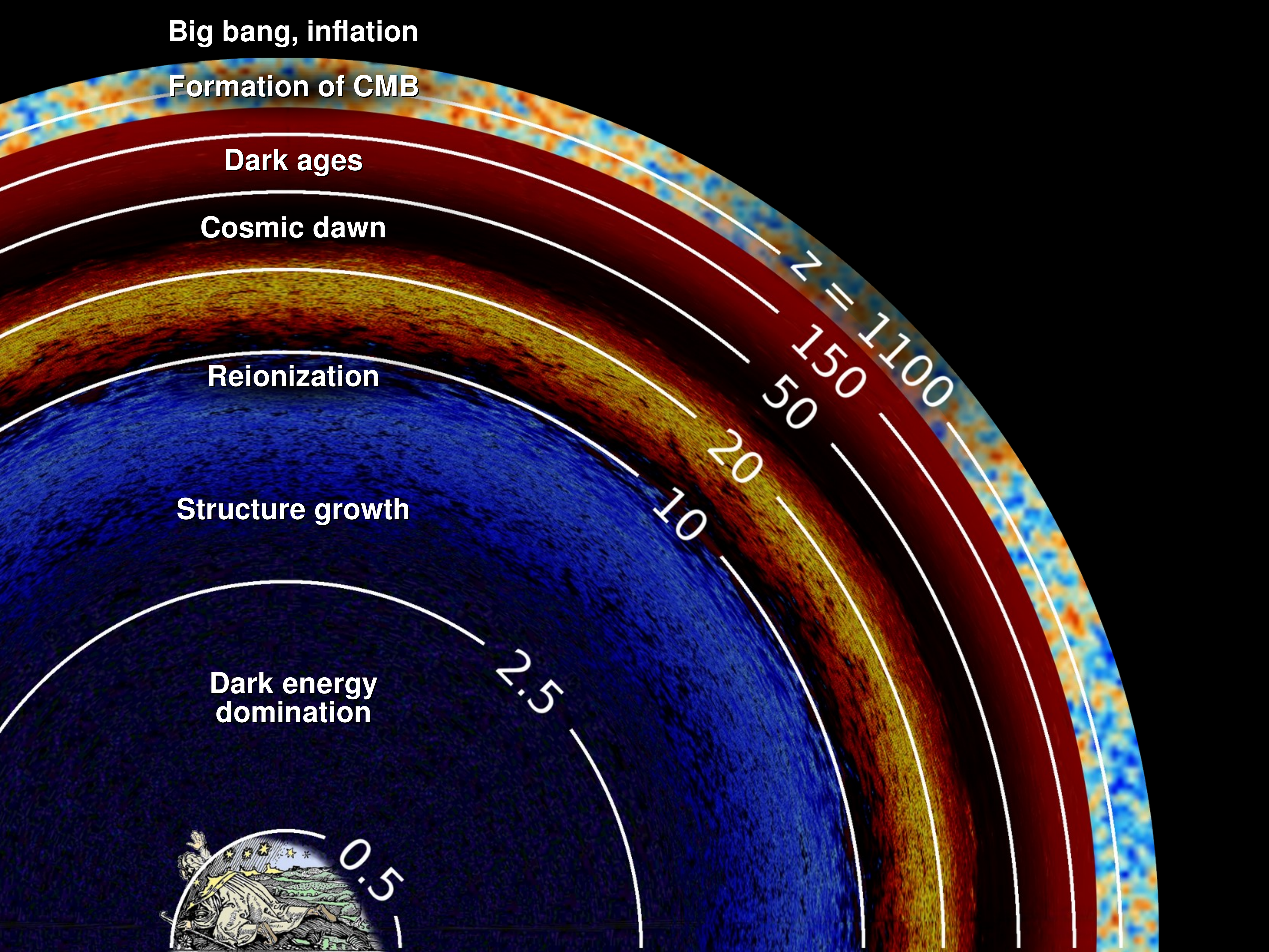
PRI^{Z}M
30 – 200 MHz
Marion Island

LEDA
30 – 88 MHz
Owens Valley

SARAS2
87.5 – 175 MHz
Gauribidanur Obs., India



CTP
60 – 120 MHz
Green Bank + ...



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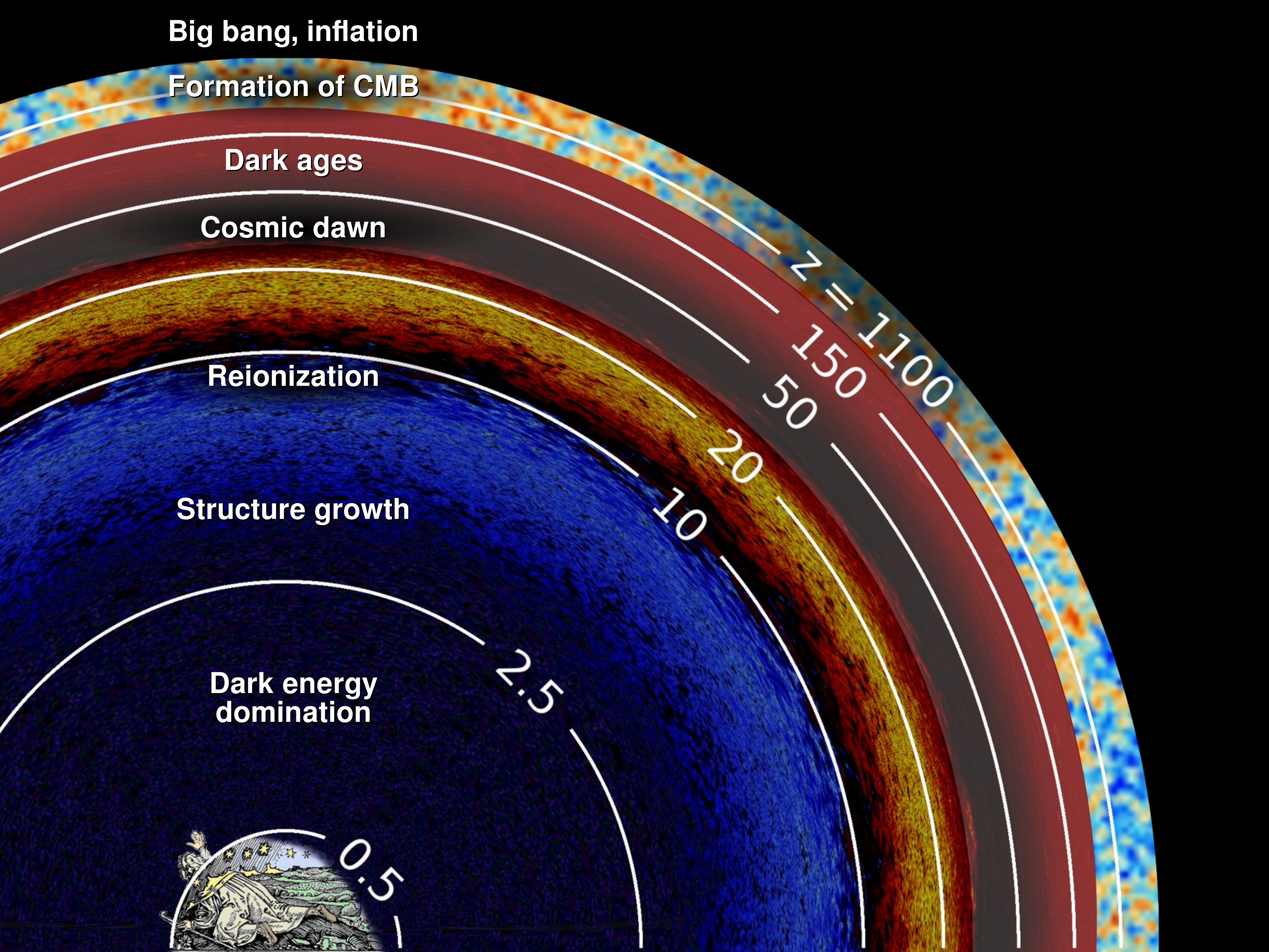
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The final frontier: dark ages

$$\delta T_b \propto x_{HI} (1+z)^{1/2} (T_s - T_{CMB}) / T_s$$

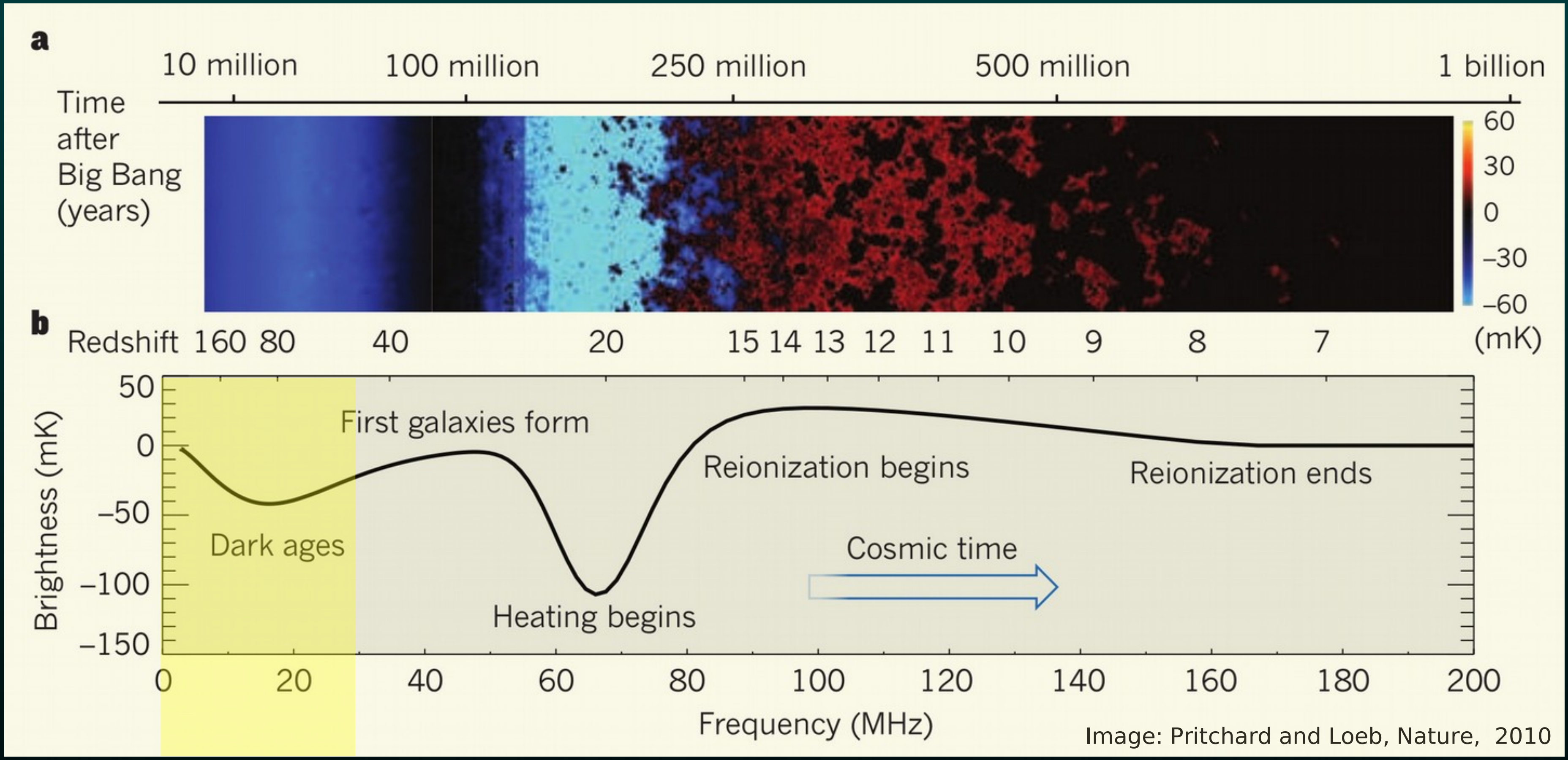


Image: Pritchard and Loeb, Nature, 2010

What lurks down here...?

Most experiments operate here and above.

The dream: lay groundwork for exploring dark ages

Ultimate dream: image the fluctuations

The state of the art at low frequencies

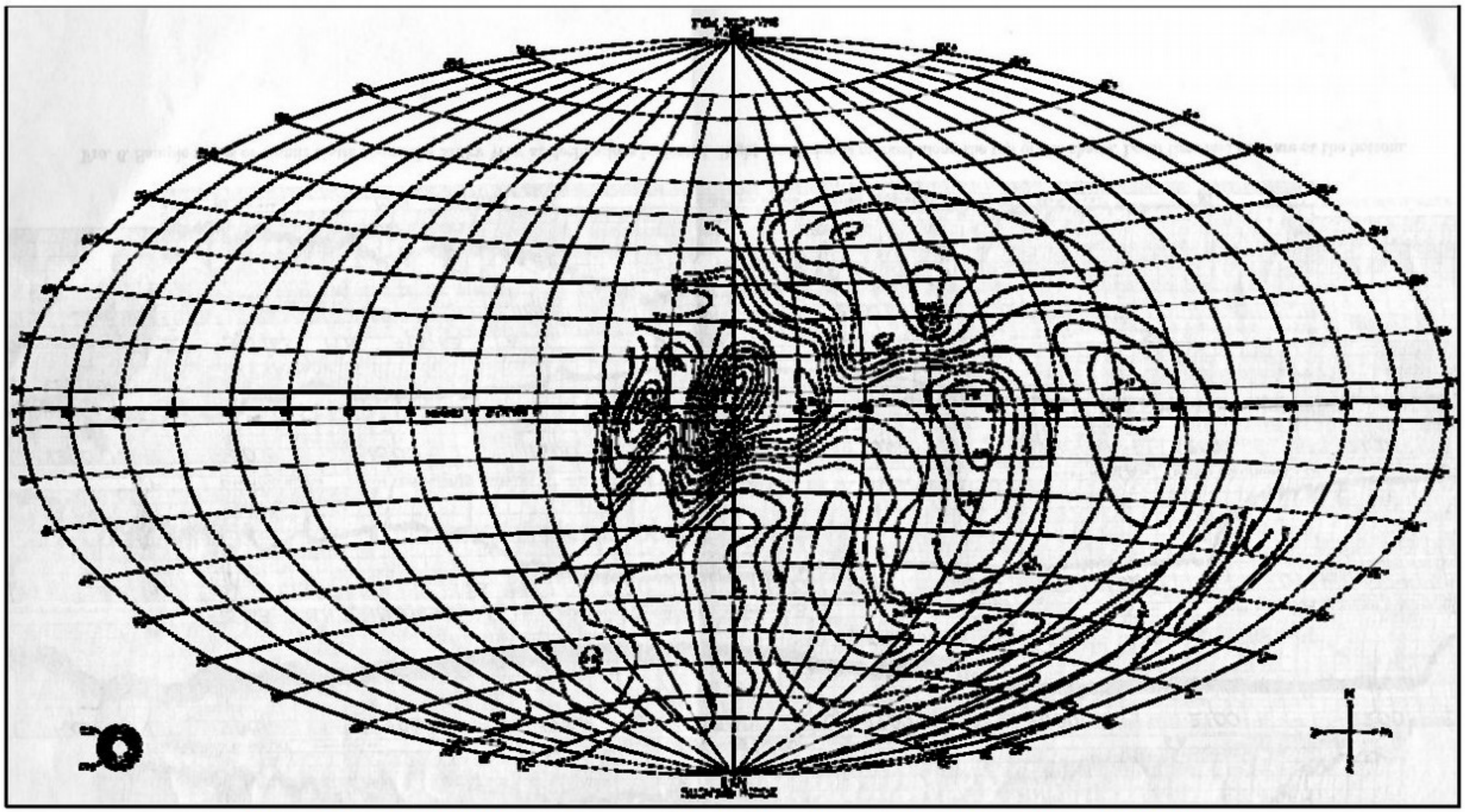
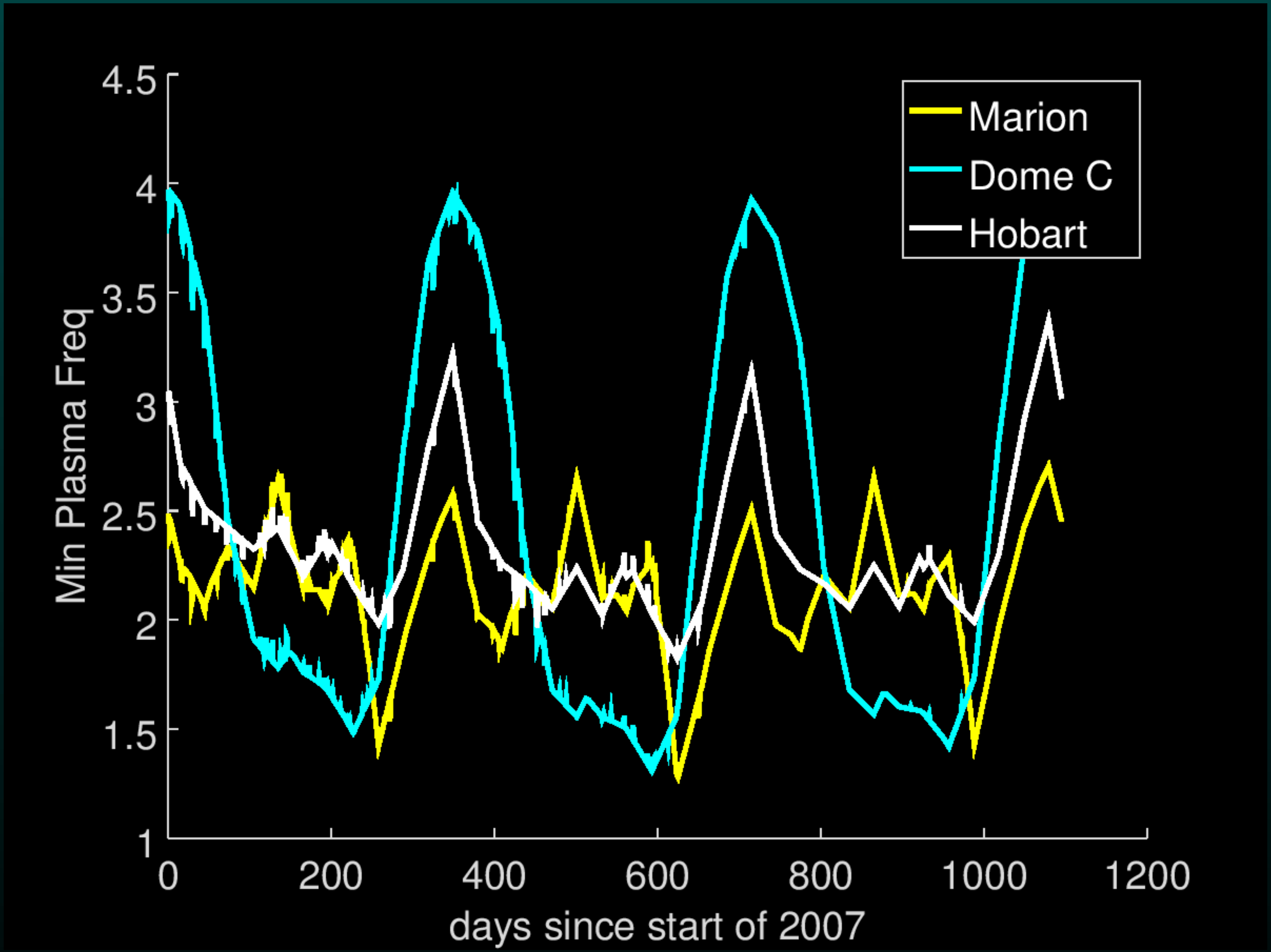


Figure 11: A 2.085 MHz contour map of galactic radio emission (after Reber, 1968: 10).

Experiment	Frequency	Resolution	Year
Grote Reber	2.1 MHz	~5 deg	1968
RAE-B satellite	4.7 MHz	~10 (??) deg	1978
DRAO	22 MHz	1.1–1.7 deg	1999
LWA	36.5 MHz	15 arcmin	2017

Will the ionosphere let us see through?

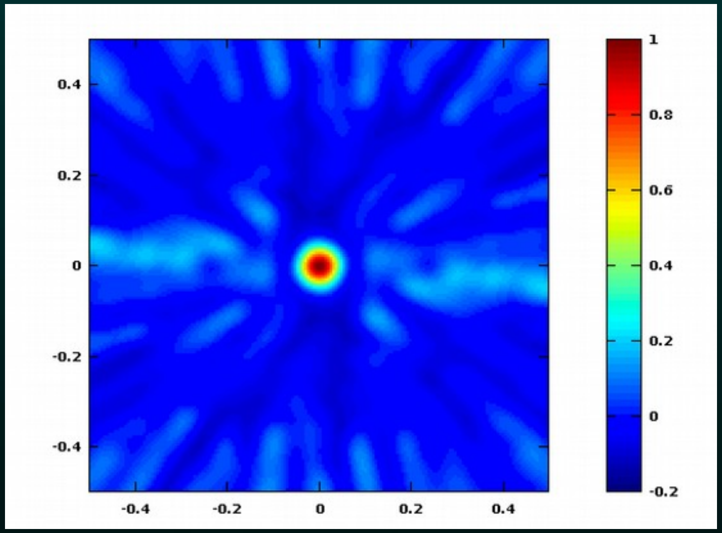


IRI model prediction: plasma frequency down to ~1.5 MHz during last solar minimum, next one is coming up...

Exploratory low frequency measurements

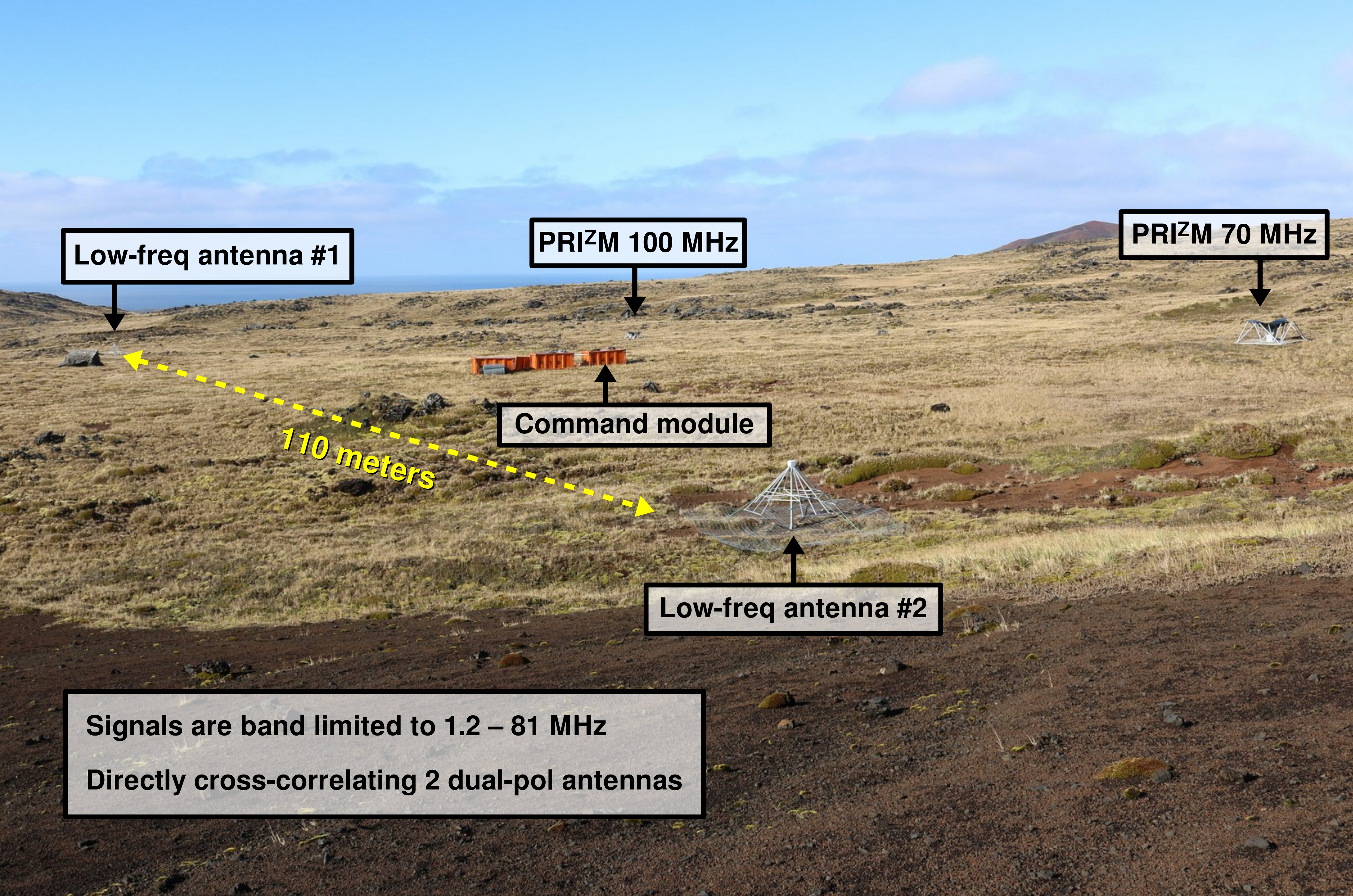
- Marion Island: 2000 km from South Africa and Antarctica, exceptionally radio quiet
- Infrastructure: 9 huts around island perimeter, convenient ring-like layout for imaging
- The plan: deploy antennas at huts, save lowest 10–20 MHz baseband, correlate offline

~25 km

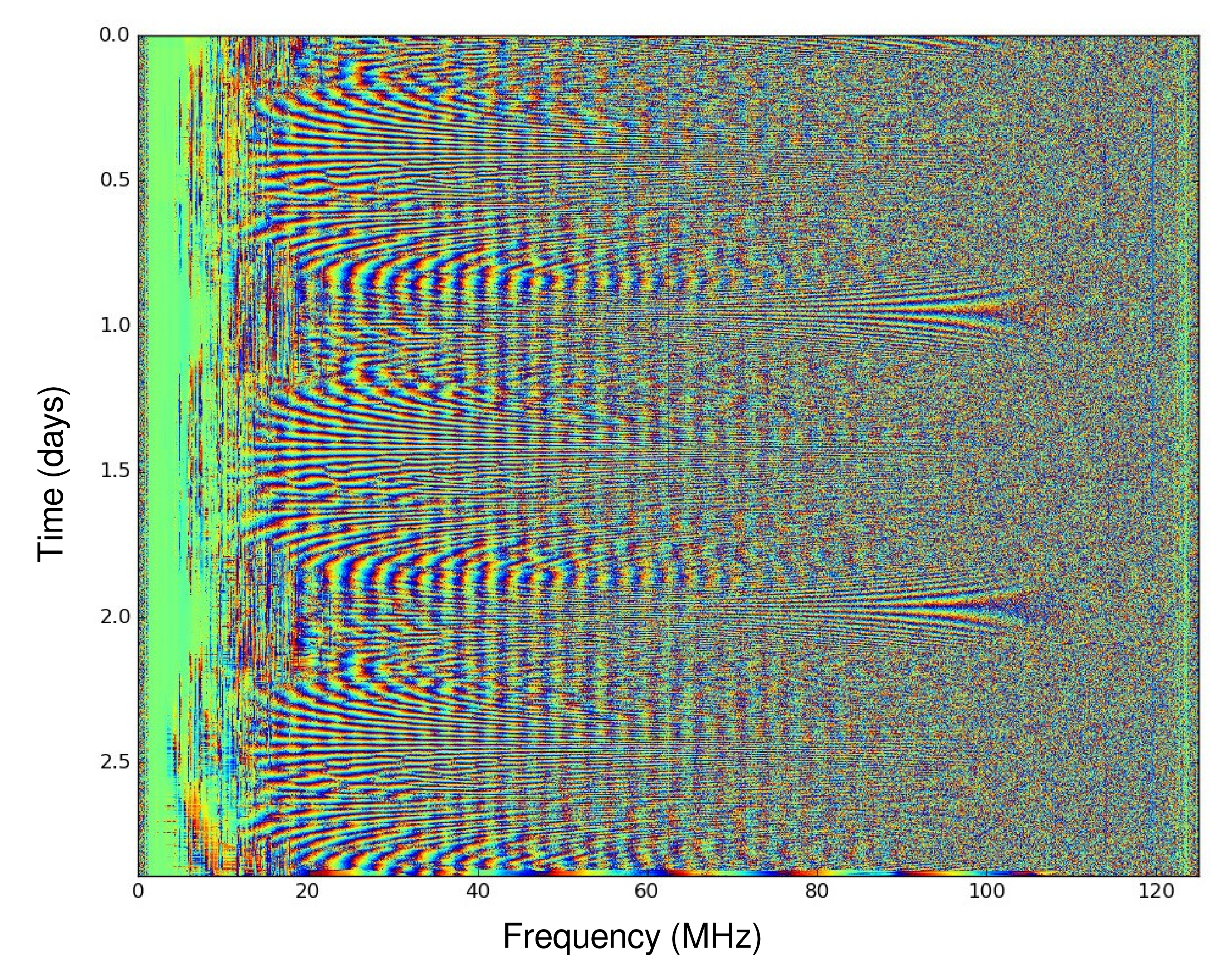


8' FWHM synthesized beam @ 5 MHz

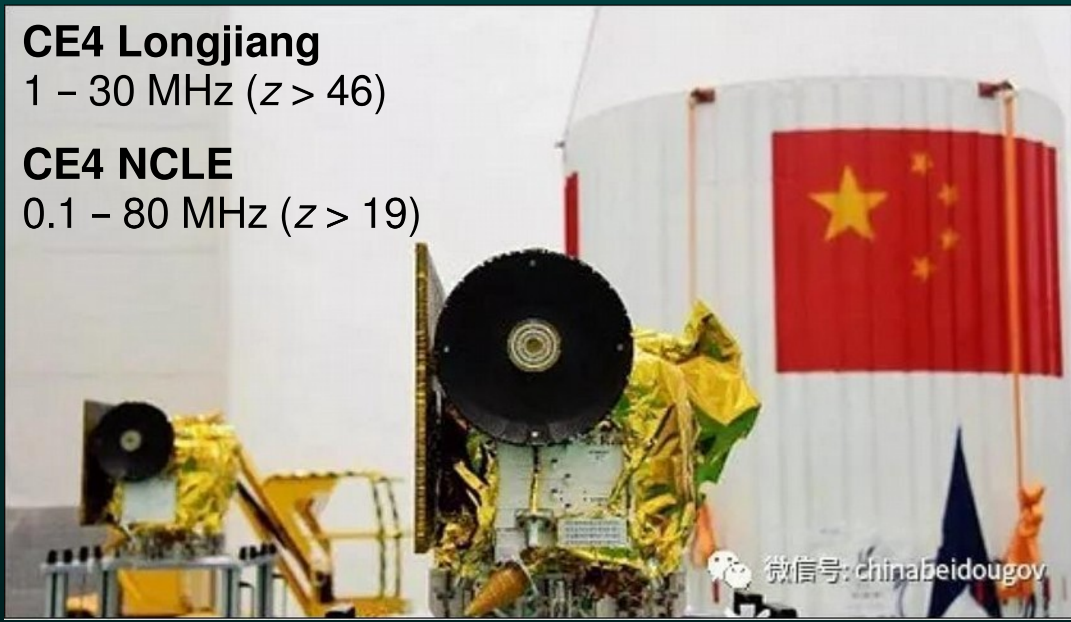
Two-element pathfinder

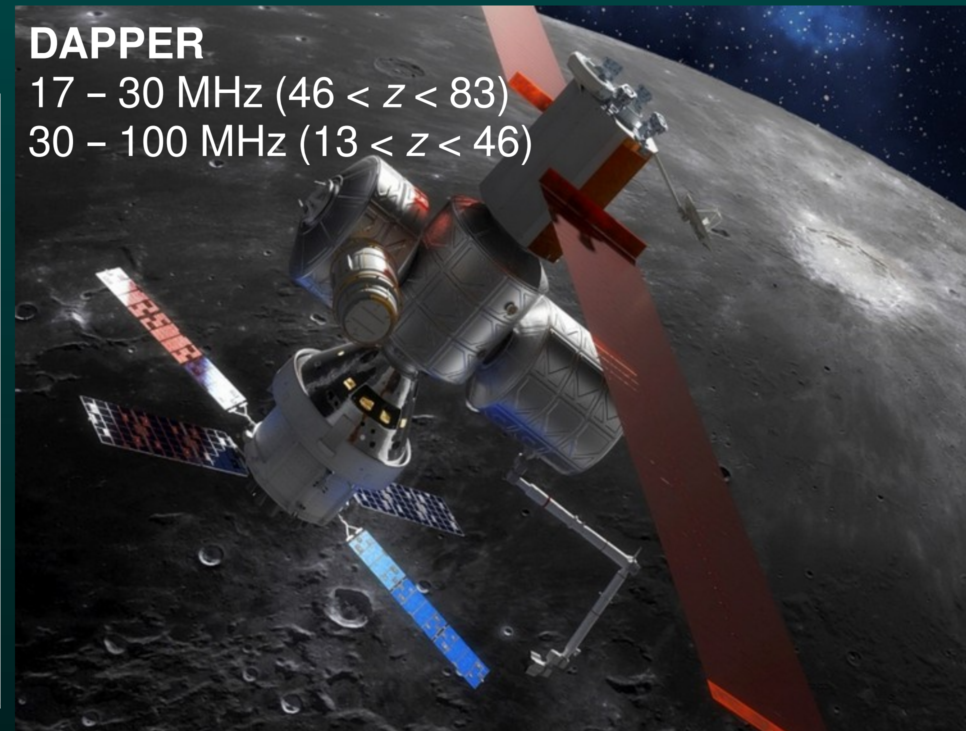


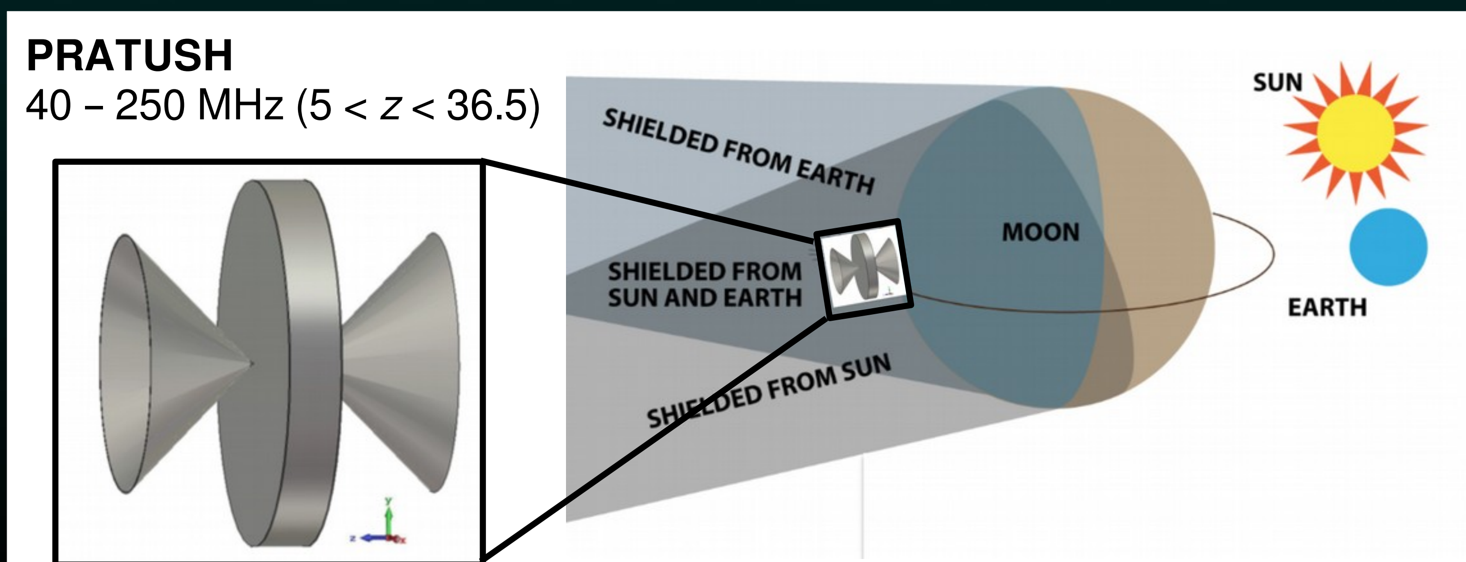
First fringes from low freq antennas



Exploring low frequencies from lunar orbit

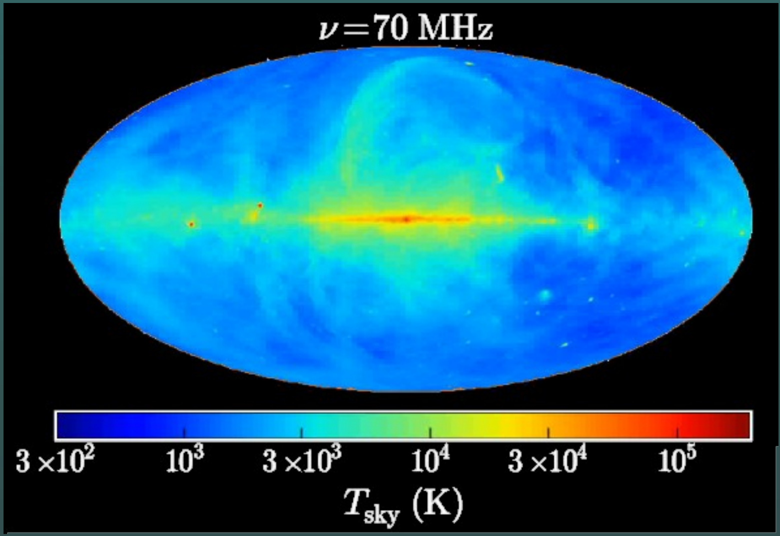




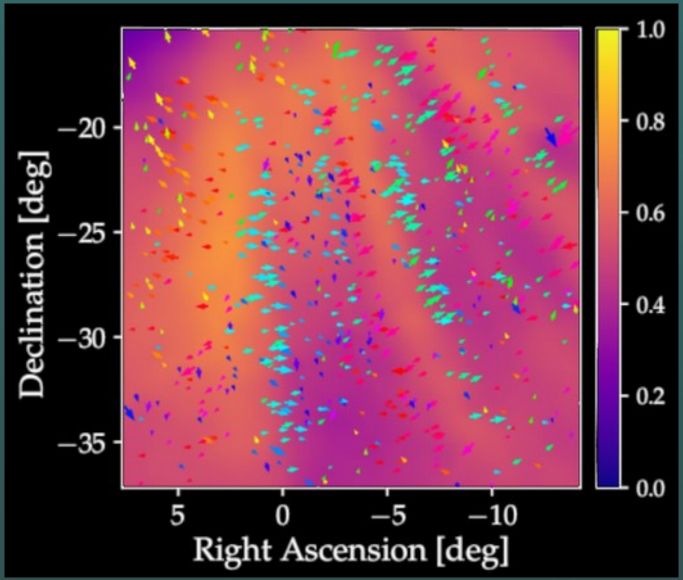


Experimental challenges

Foregrounds
4–5 orders of magnitude brighter



Ionosphere
refraction and attenuation

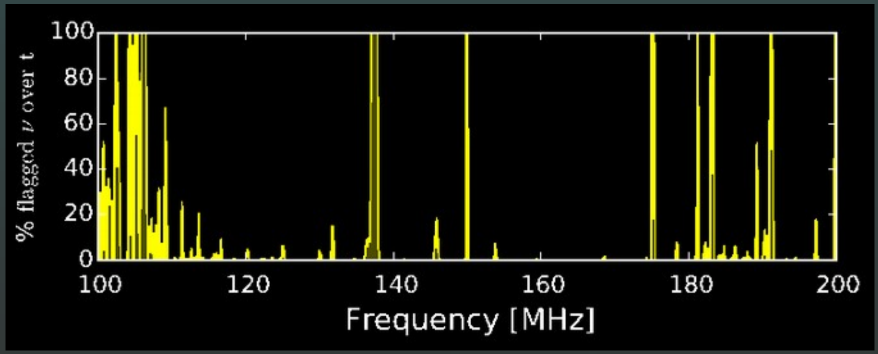


C. Jordan et al. 2017

Instrumental systematics
calibration, coupling to foregrounds, etc.

D. Jacobs

Radio-Frequency Interference



S. Kohn

Summary & future prospects

- Lots of new exciting opportunities in redshifted 21-cm observations, can probe a huge comoving volume

- Lots of experimental efforts:
  – Structure growth and dark energy domination at $z < 2.5$
  – Post-reionization era at $2 < z < 10$
  – Reionization and cosmic dawn at $5 < z < 27$
  – Dark ages at $z > 27$

- Technical challenges include foregrounds, ionosphere, RFI, instrumental effects and calibration – we'll hear more about these in later talks