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ORIGINAL ARTICLE

Peering into the dark (ages) with low-frequency space interferometers

Using the 21-cm signal of neutral hydrogen from the infant universe to probe fundamental (Astro)physics

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Abstract
The Dark Ages and Cosmic Dawn are largely unexplored windows on the infant Universe ($z \sim 200$–10). Observations of the redshifted 21-cm line of neutral hydrogen can provide valuable new insight into fundamental physics and astrophysics during these eras that no other probe can provide, and drives the design of many future ground-based instruments such as the Square Kilometre Array (SKA) and the Hydrogen Epoch of Reionization Array (HERA). We review progress in the field of high-redshift 21-cm Cosmology, in particular focussing on what questions can be addressed by probing the Dark Ages at $z > 30$. We conclude that only a space- or lunar-based radio telescope, shielded from the Earth's radio-frequency interference (RFI) signals and its ionosphere, enable the 21-cm signal from the Dark Ages to be detected. We suggest a generic mission design concept, CoDEX, that will enable this in the coming decades.

Keywords 21-cm cosmology · Dark ages · Cosmic dawn · Epoch of reionization · Space or lunar-based radio telescopes

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Peering into the Dark (Ages) with low-frequency space interferometers

Léon Koopmans
(Kapteyn Astronomical Institute)

Based on a white paper for ESA's Voyage 2050

What can “21-cm Cosmology” tell us?

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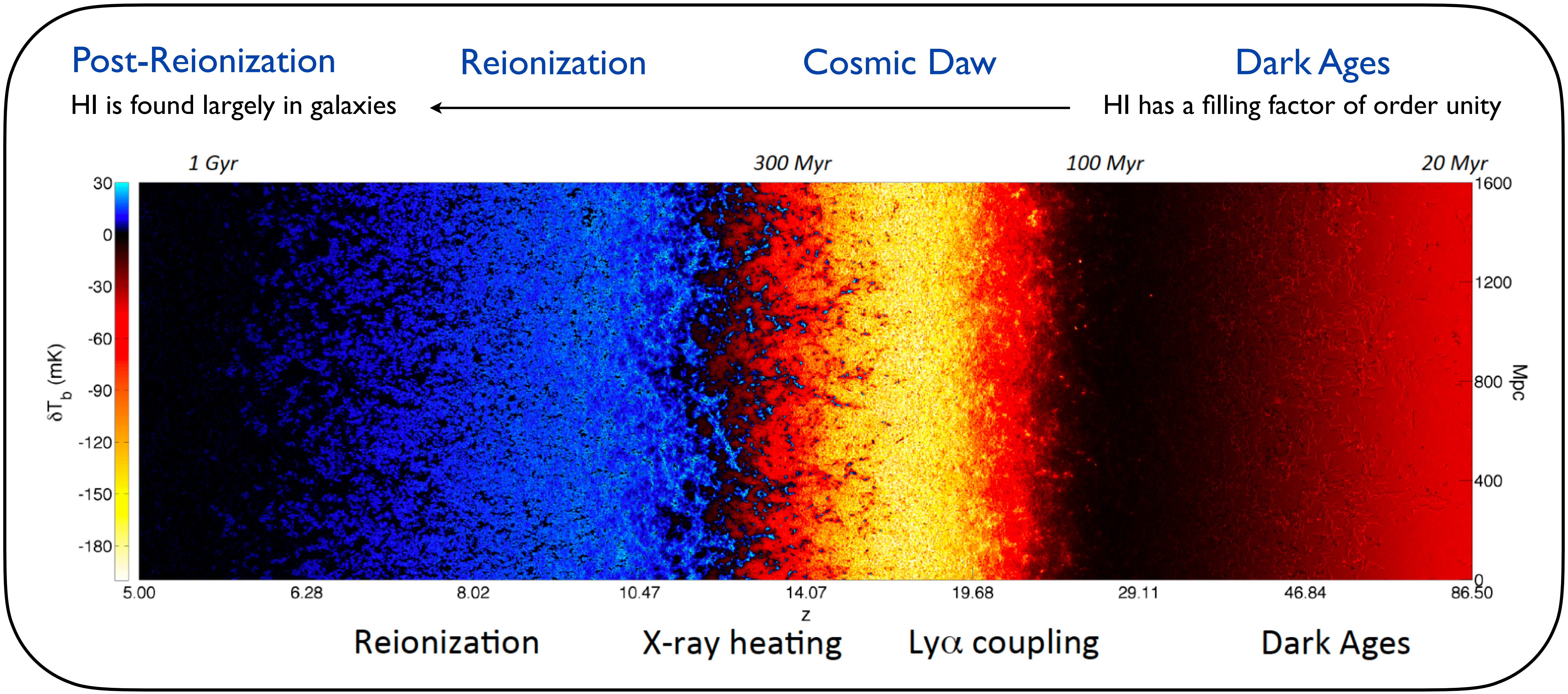
The tomography of HI emission/absorption is a treasure trove of information for (astro)physics, cosmology & fundamental physics.



Credit figure: Mesinger

What can “21-cm Cosmology” tell us?

The first radiating sources (stars/remnants/quasars) heat/ionise neutral hydrogen

Alvarez et al. 2009

Combining structure formation in the ΛCDM paradigm with baryonic physics (hydro-dynamics), feedback, heavy-element enrichment and radiative transfer allows us model the evolution of neutral hydrogen, but …

… many processes are poorly known…

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What can “21-cm Cosmology” tell us?

The brightness of the 21-cm signal (in Kelvin; Rayleigh-Jeans regime) that can be measured with radio telescopes is given by:

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

Cosmology

Ionization

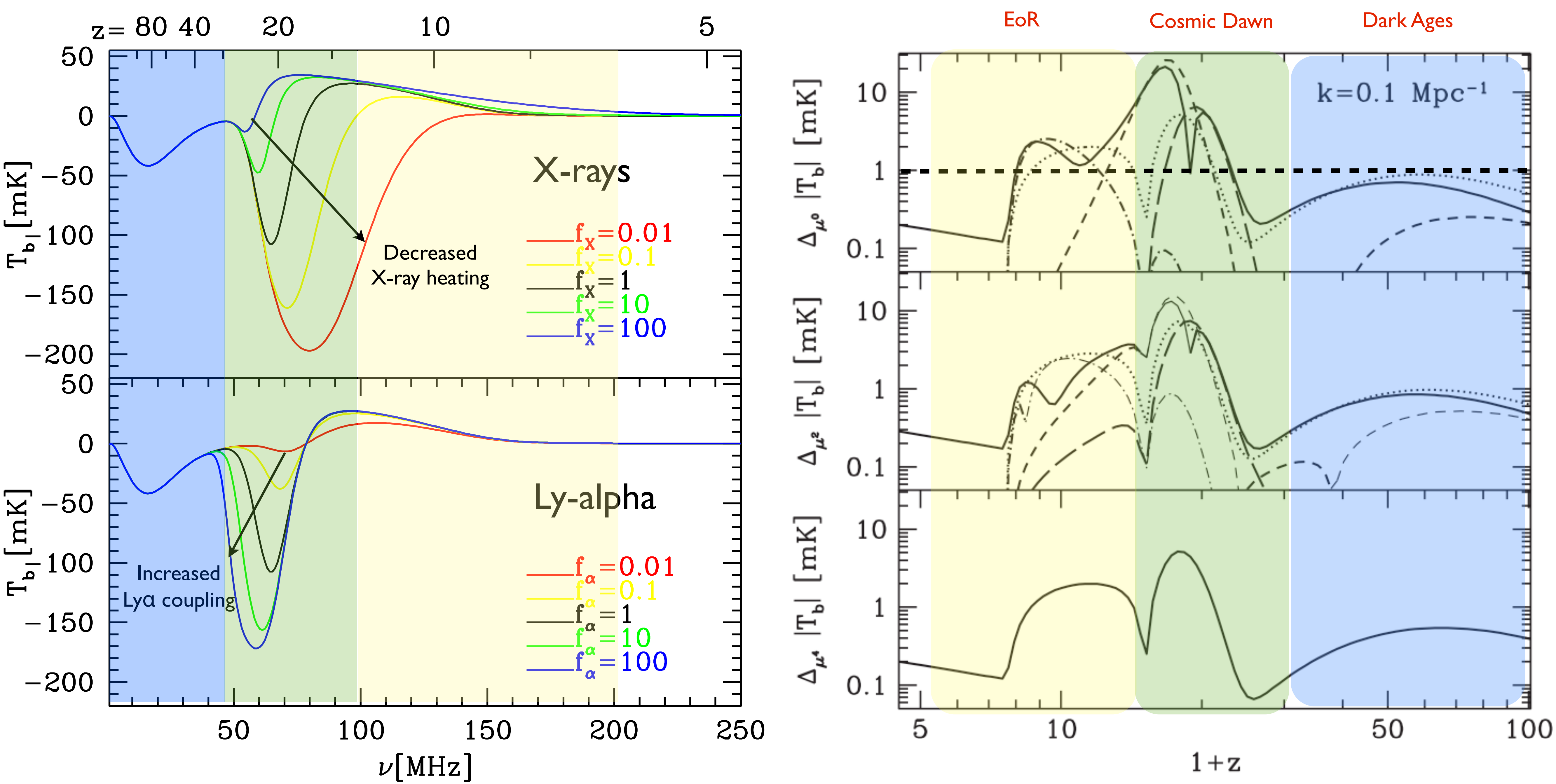
(G)astrophysics

Peculiar velocities/Bulk-flows

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

What can "21-cm Cosmology" tell us?

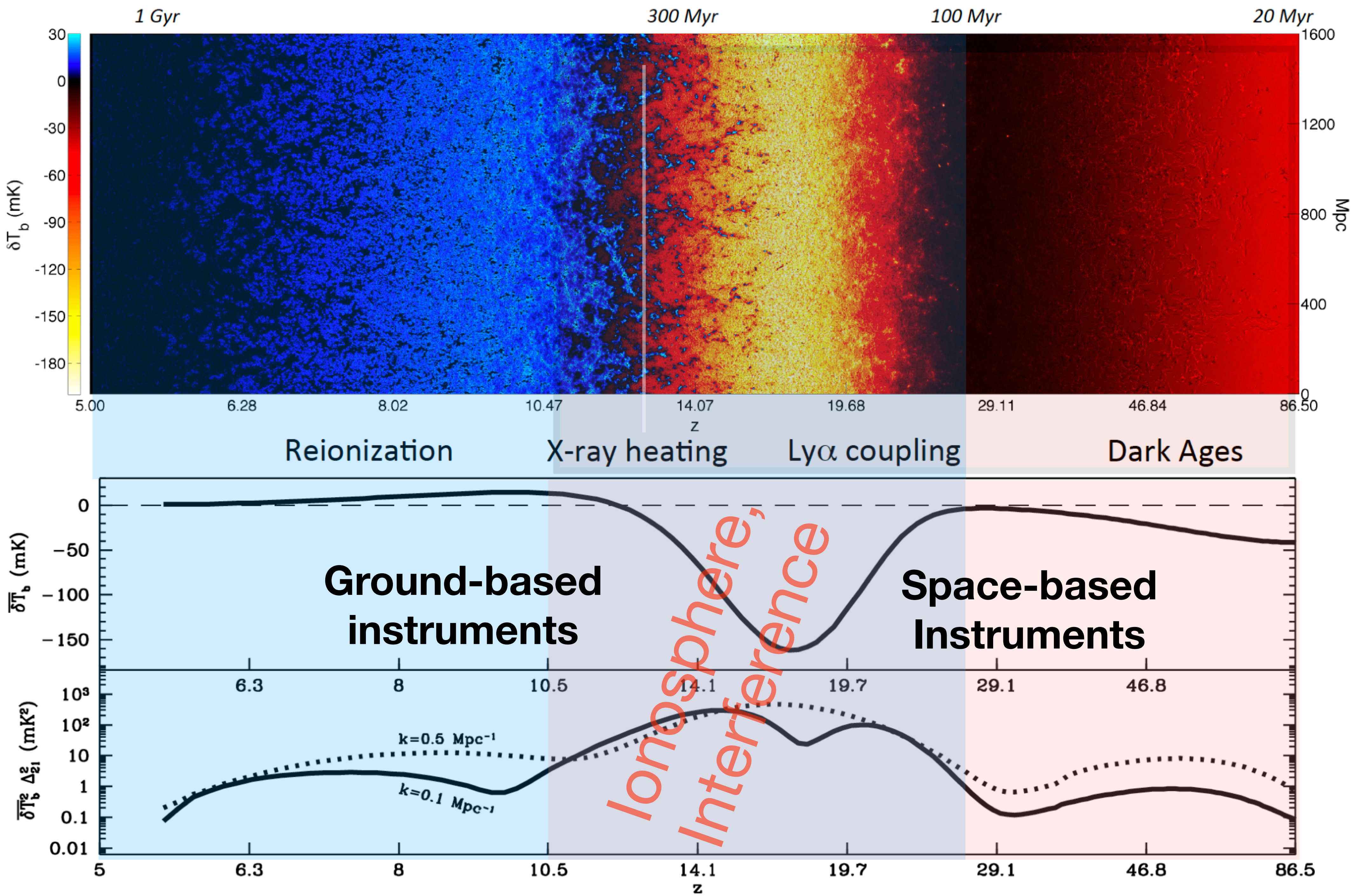
Global Signal (left) and Intensity Fluctuations (right)



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

What can “21-cm Cosmology” tell us?

Between z~200* and z~6**, neutral hydrogen is a key tracer of fundamental physical processes (early stages) and unique astrophysical processes (later stages)

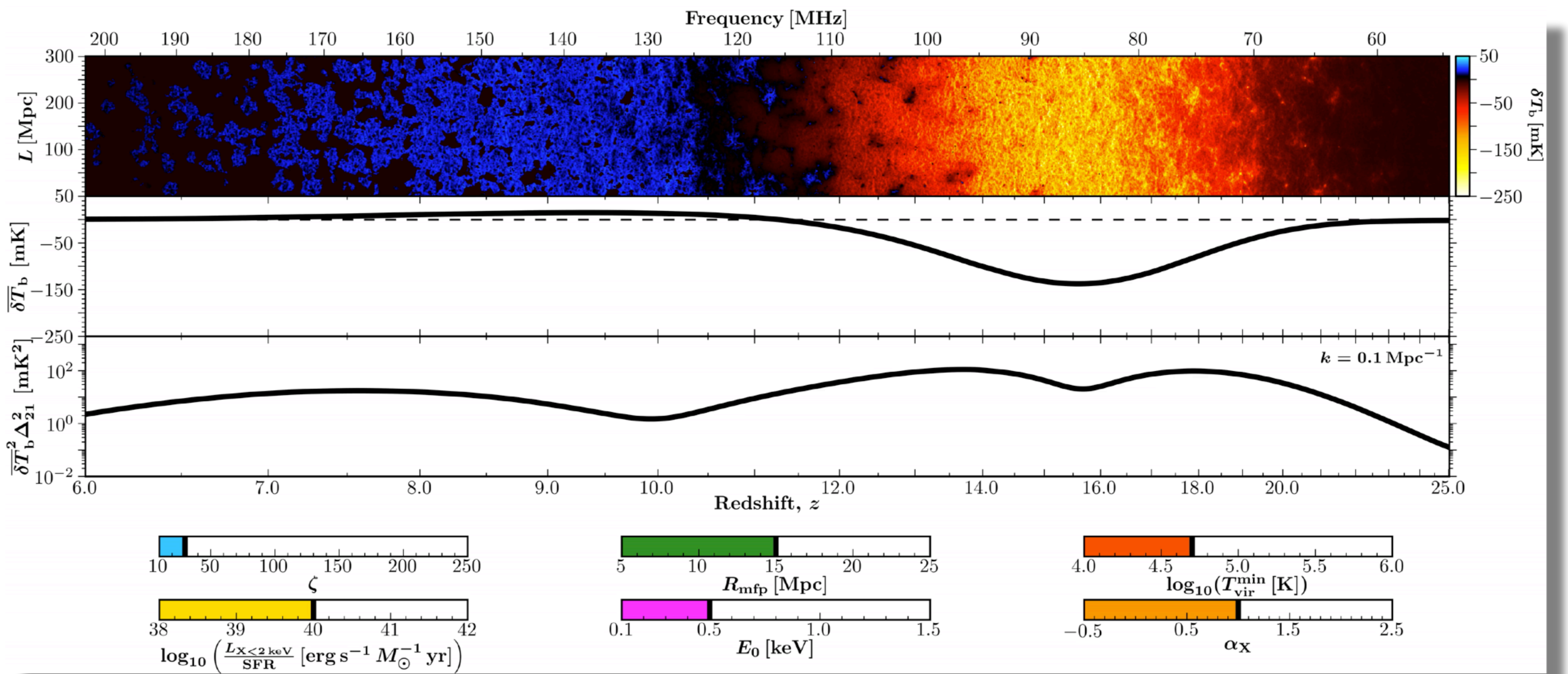


* spin & CMB-temperature decouple; ** universe is reionized

What can “21-cm Cosmology” tell us?

Numerical Models

Many “ingredients” in the 21-signal models are effective descriptions of the underlying complex physical processes (sub-grid physics) that we hope to connect to these processes on smaller (galaxy/stellar) scales.



Credit movie: Mesinger & Greig

What can “21-cm Cosmology” tell us?

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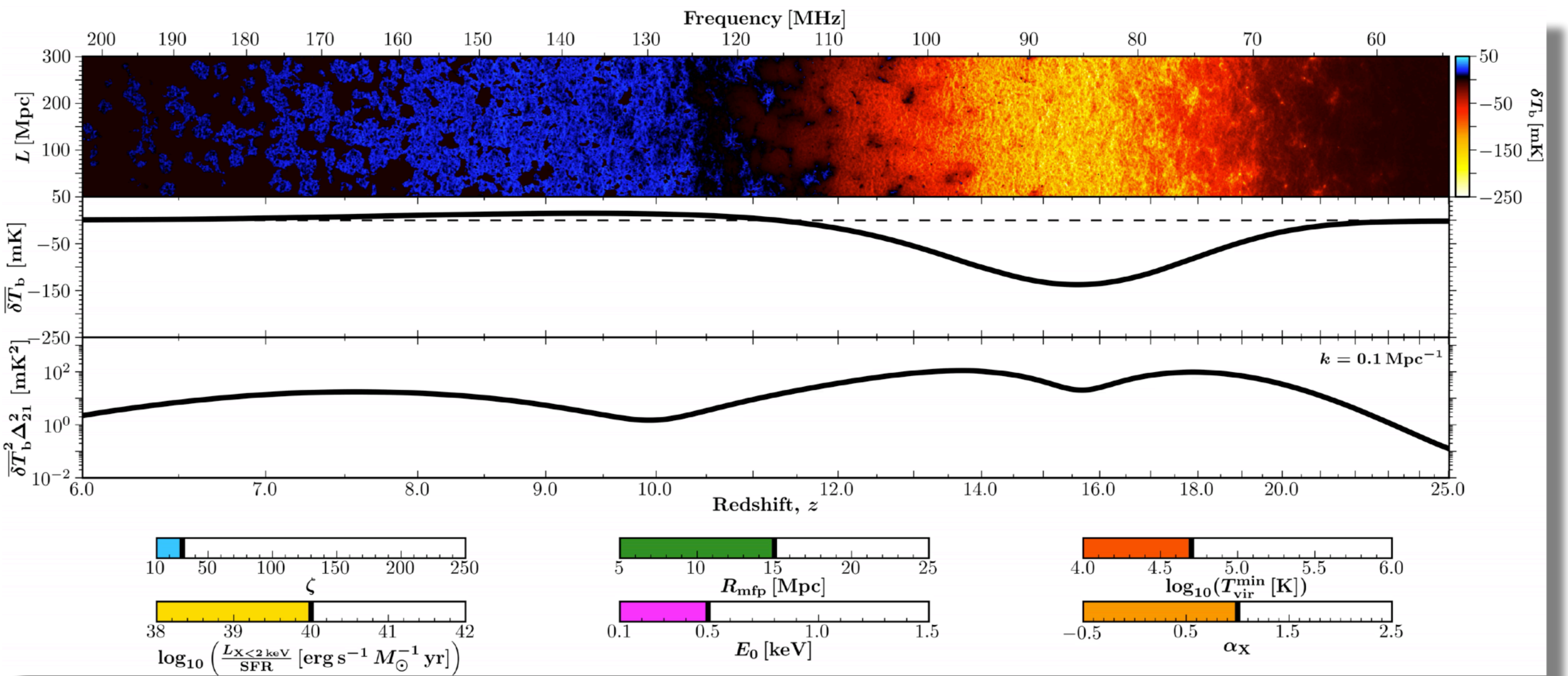
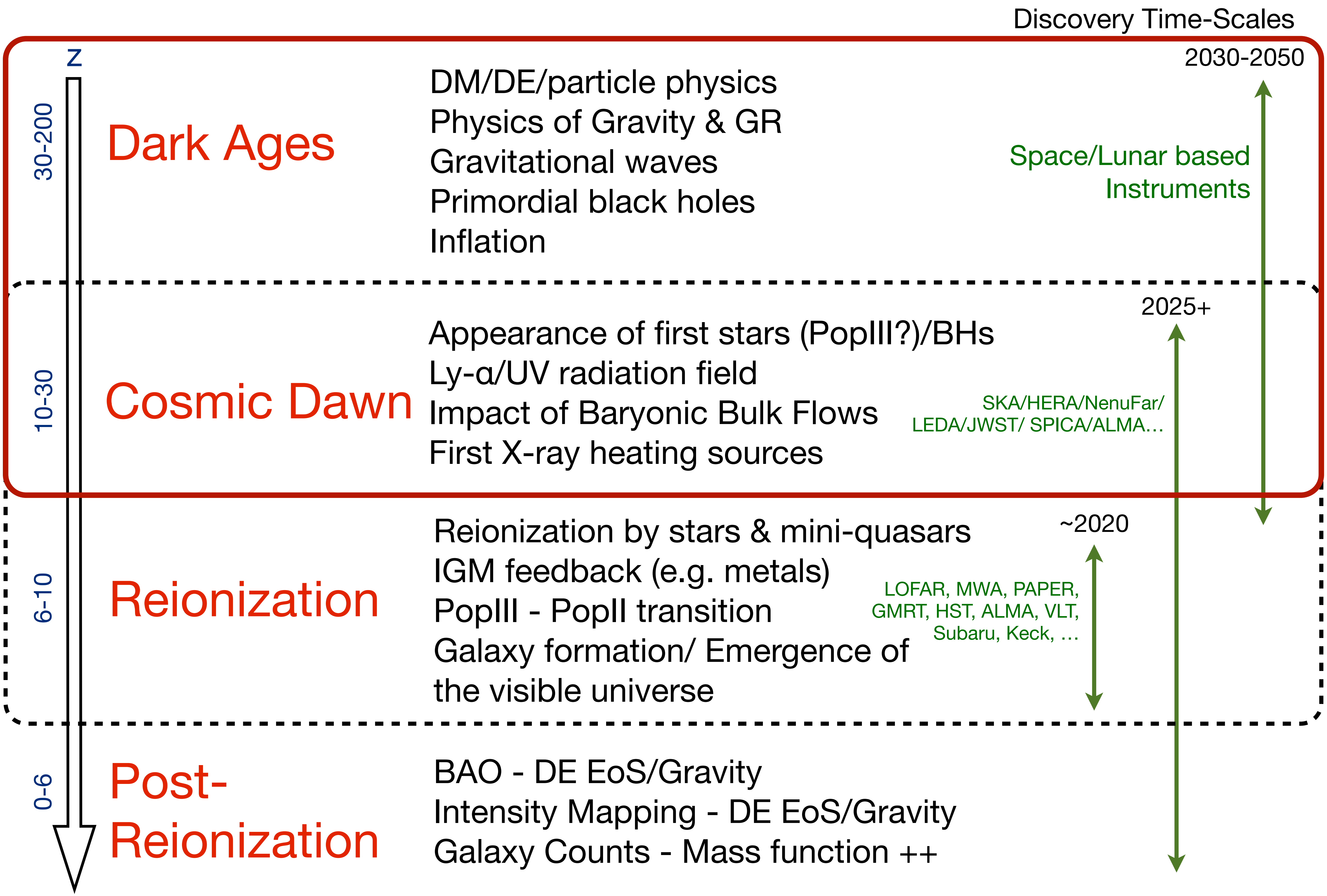


Credit movie: Mesinger & Greig

What can "21-cm Cosmology" tell us?

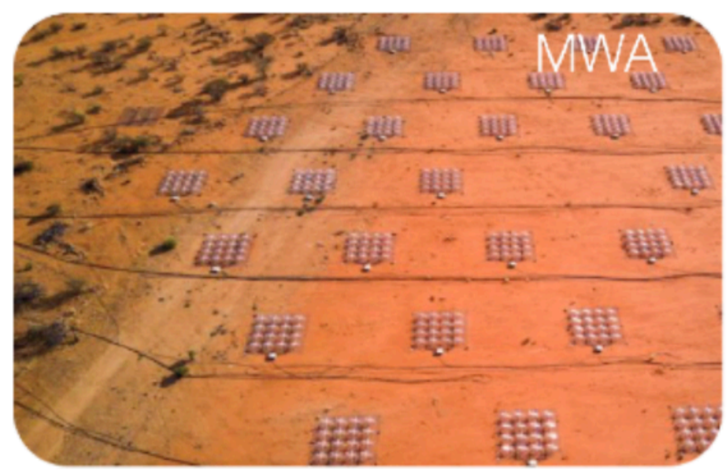


Why go to space for 21-cm Cosmology?

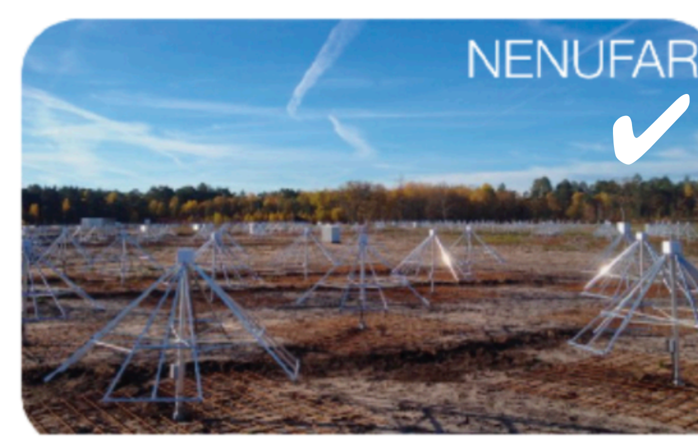
Ground-based interferometry experiments

Globally (*China, India, South Africa, US, Australia, Netherlands, France, etc.*) many efforts are underway to **detect the 21-cm signal from z~6 to z~25 with ground-based interferometers** — *experiments are extremely hard!*

Past/Current instruments focussing mostly on z<10



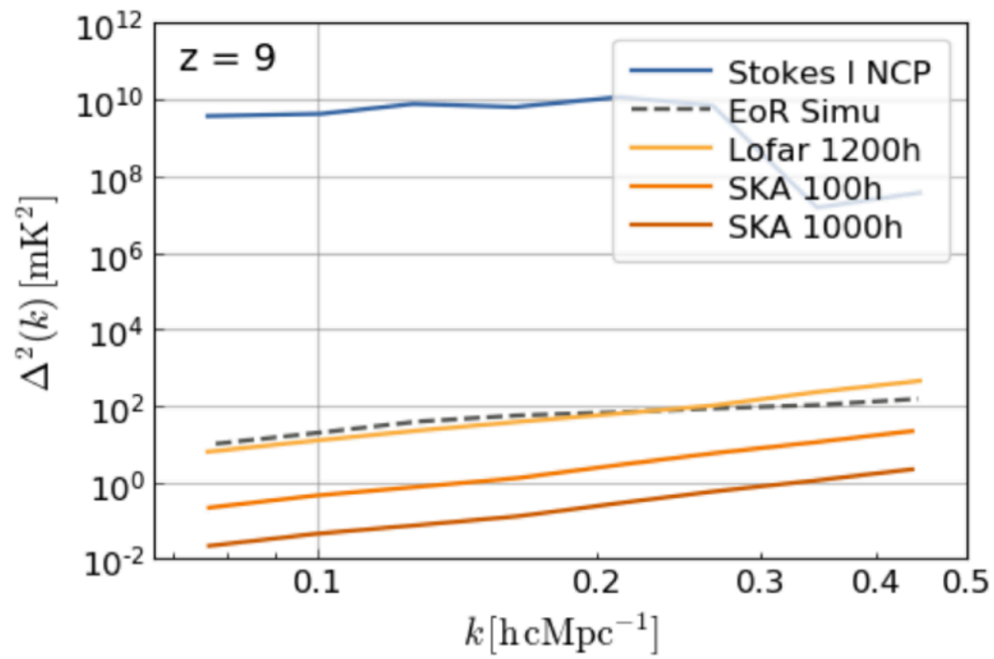
Upcoming instruments in coming decade focussing mostly on z~6-25



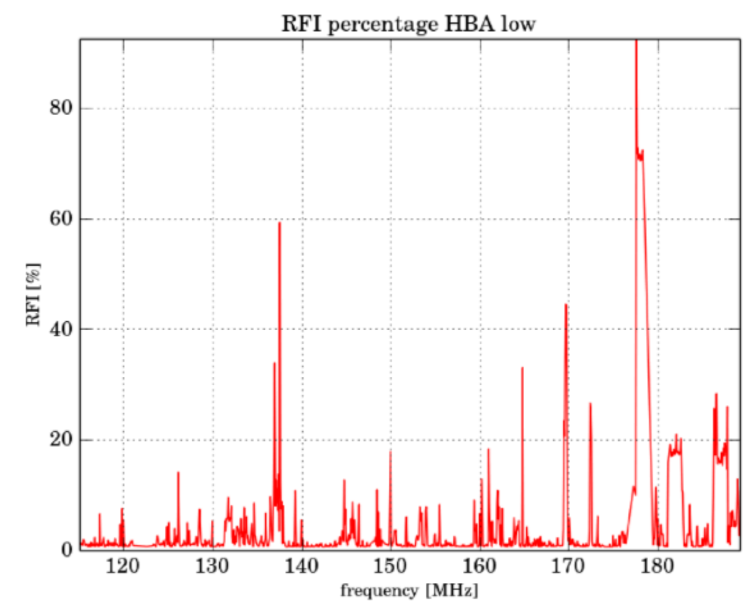
Ground-based interferometry experiments

Some challenges to detect the 21-cm signal are unique to earth-based interferometers (ionosphere) or worse (RFI, instrument stability) on earth.

Foregrounds

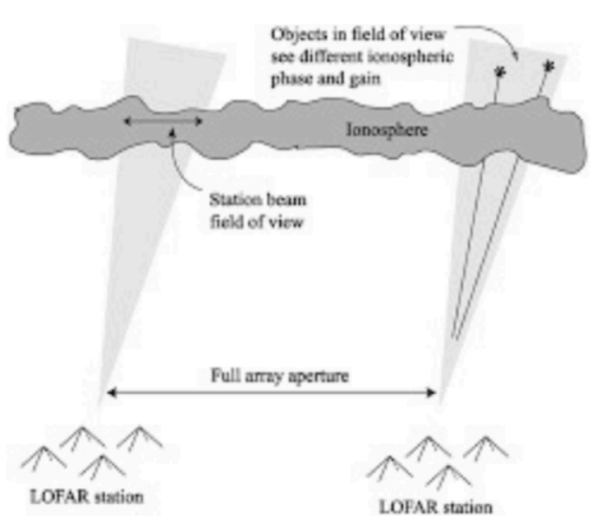


Radio Frequency Interferance (RFI)



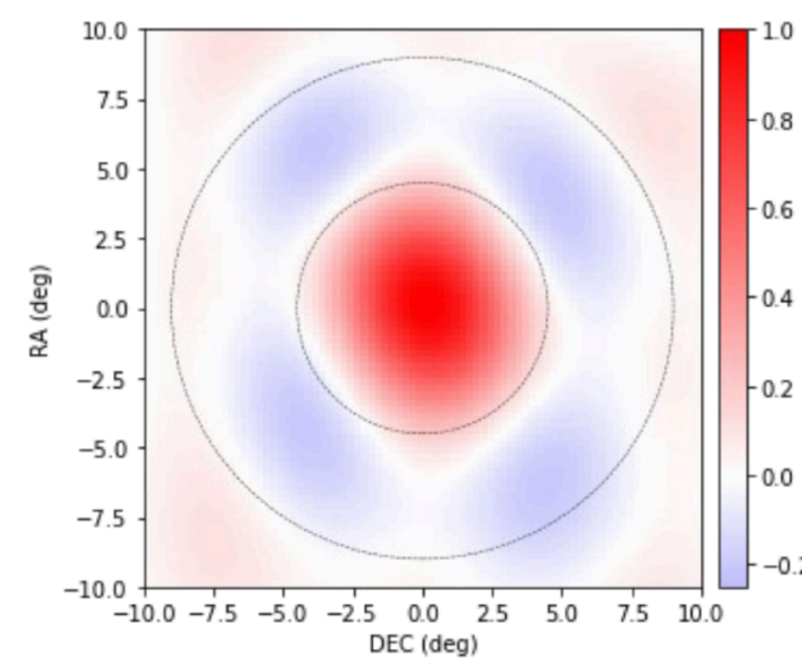
Credit: A. Offringa

Ionosphere



Credit: S. Van der Tol

Primary beam Stability



Ground-based interferometry experiments

Current experiments (incl. LOFAR) are getting closer to the 21-cm signal in the EoR, but are far removed from a detection in the Cosmic Dawn and Dark Ages, let along image it.

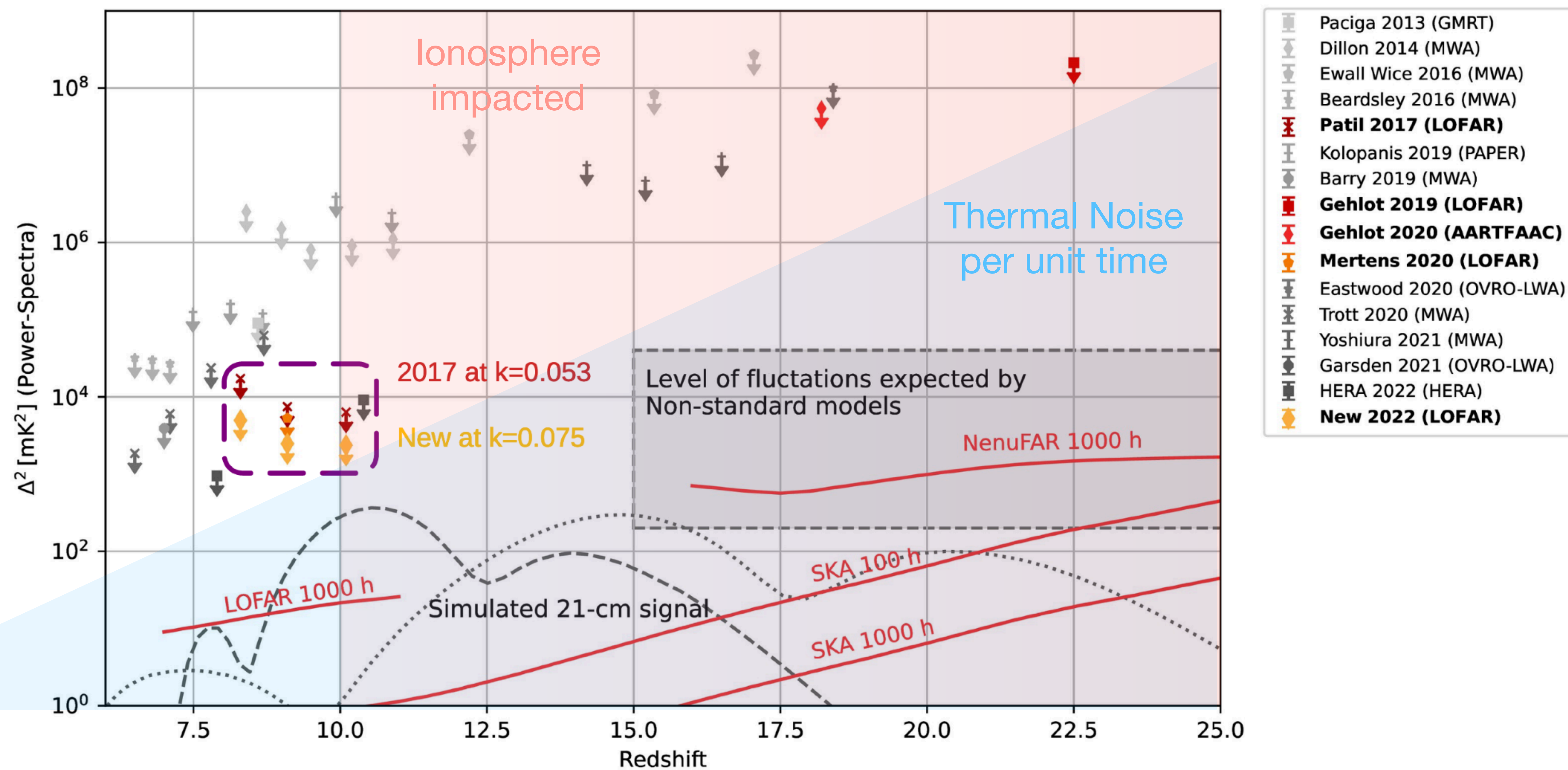
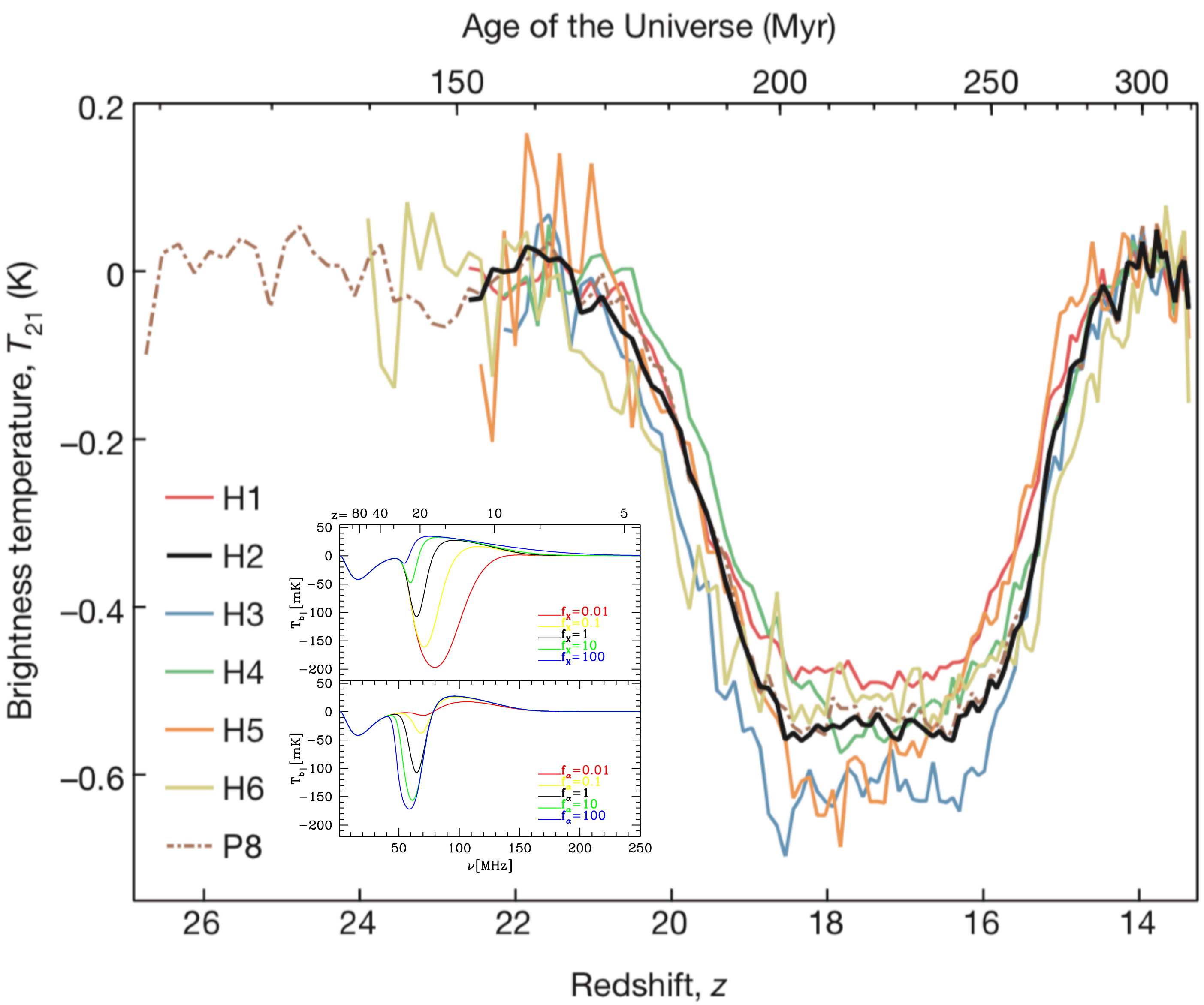
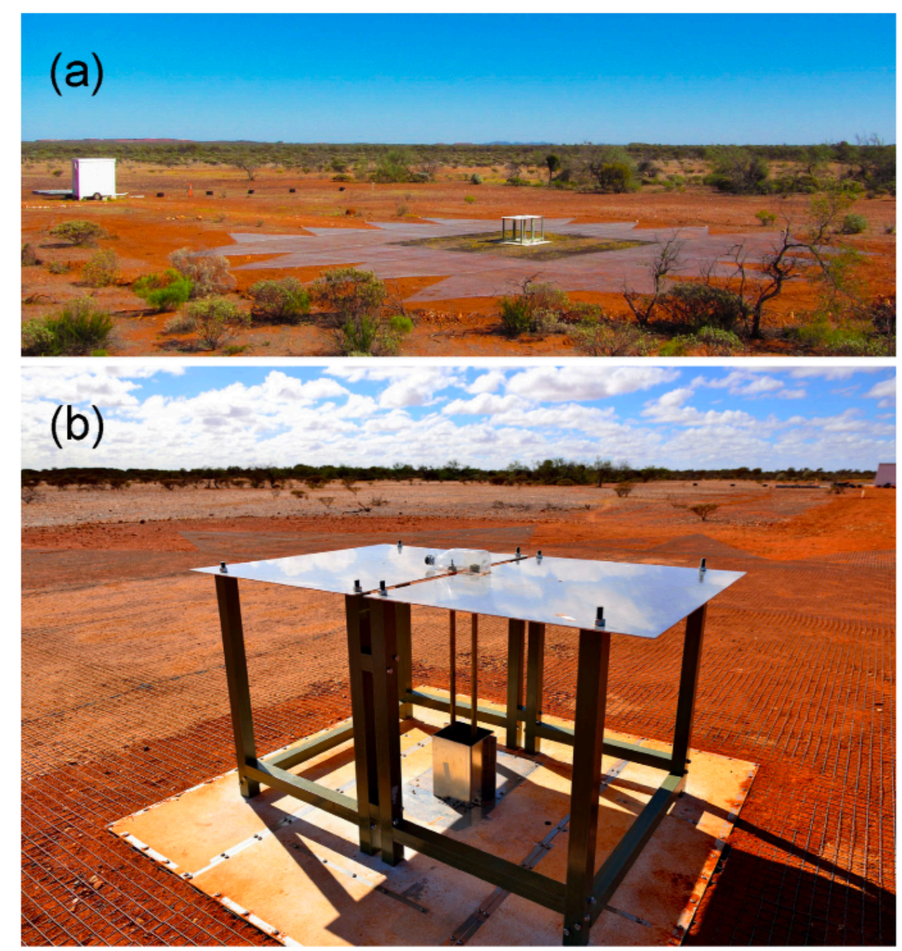


Figure: credit Florent Mertens

Ground-based global experiments

In 2018 a detection of the global 21-cm signal of neutral hydrogen was claimed by the EDGES team. Not the same as what interferometers do, but just as exciting.



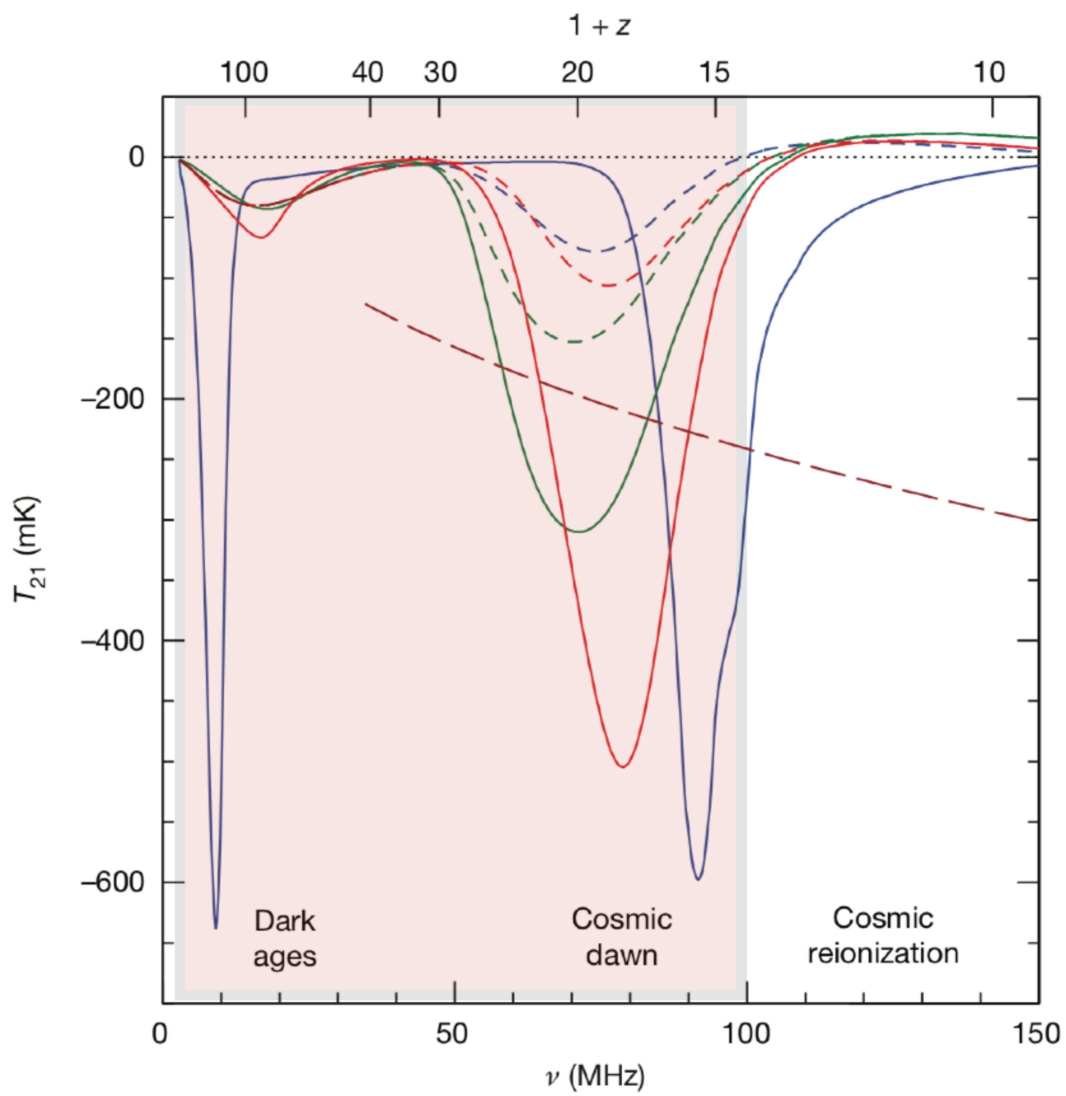


Bowman et al. 2018 (Nature)

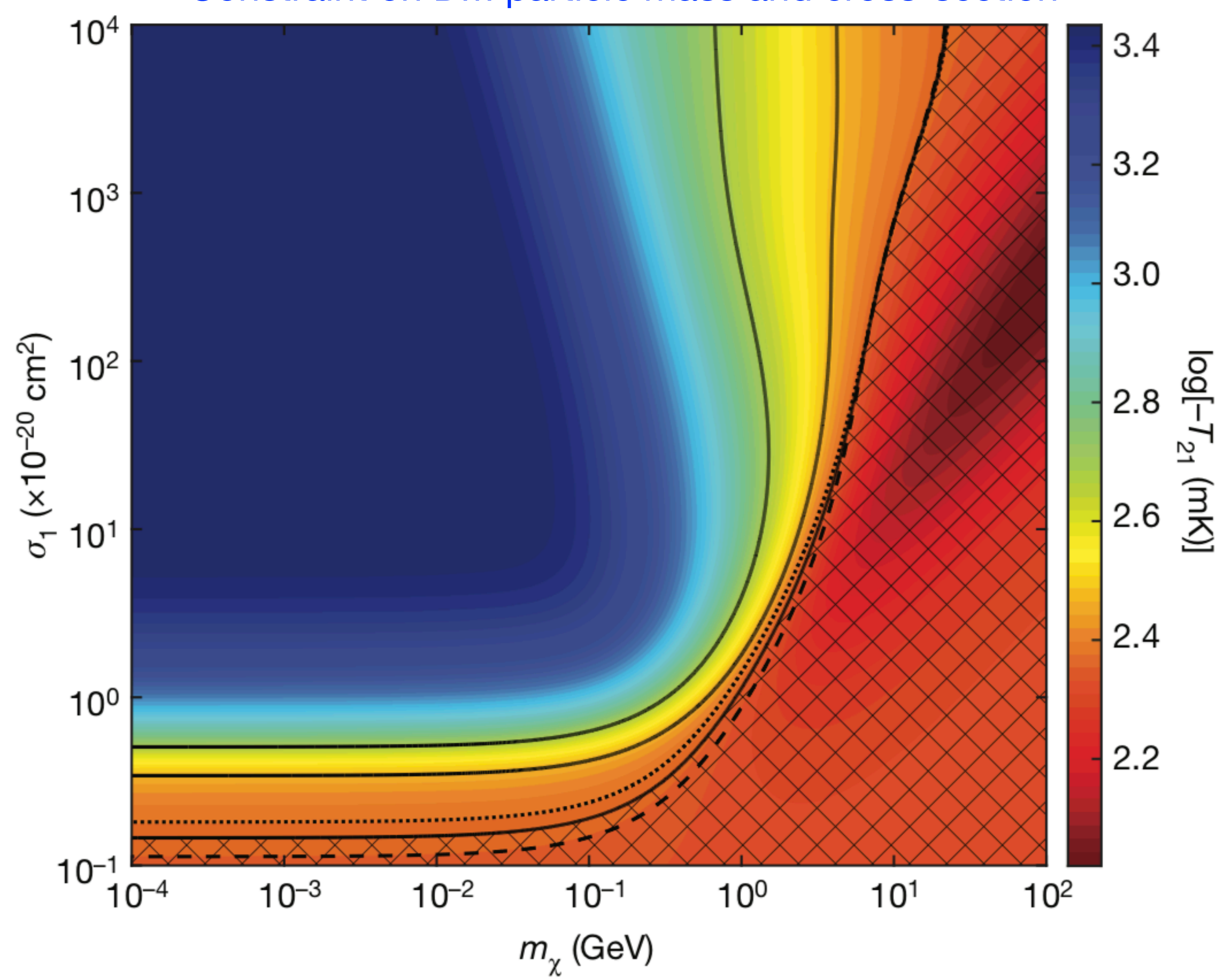
Ground-based global experiments

If genuine, it requires some "exotic" physics, e.g. the cooling of baryons by scattering off dark matter to explain the depth of the signal (-600mK).

Global-signal models; some affect the Dark Ages



Constraint on DM particle mass and cross-section

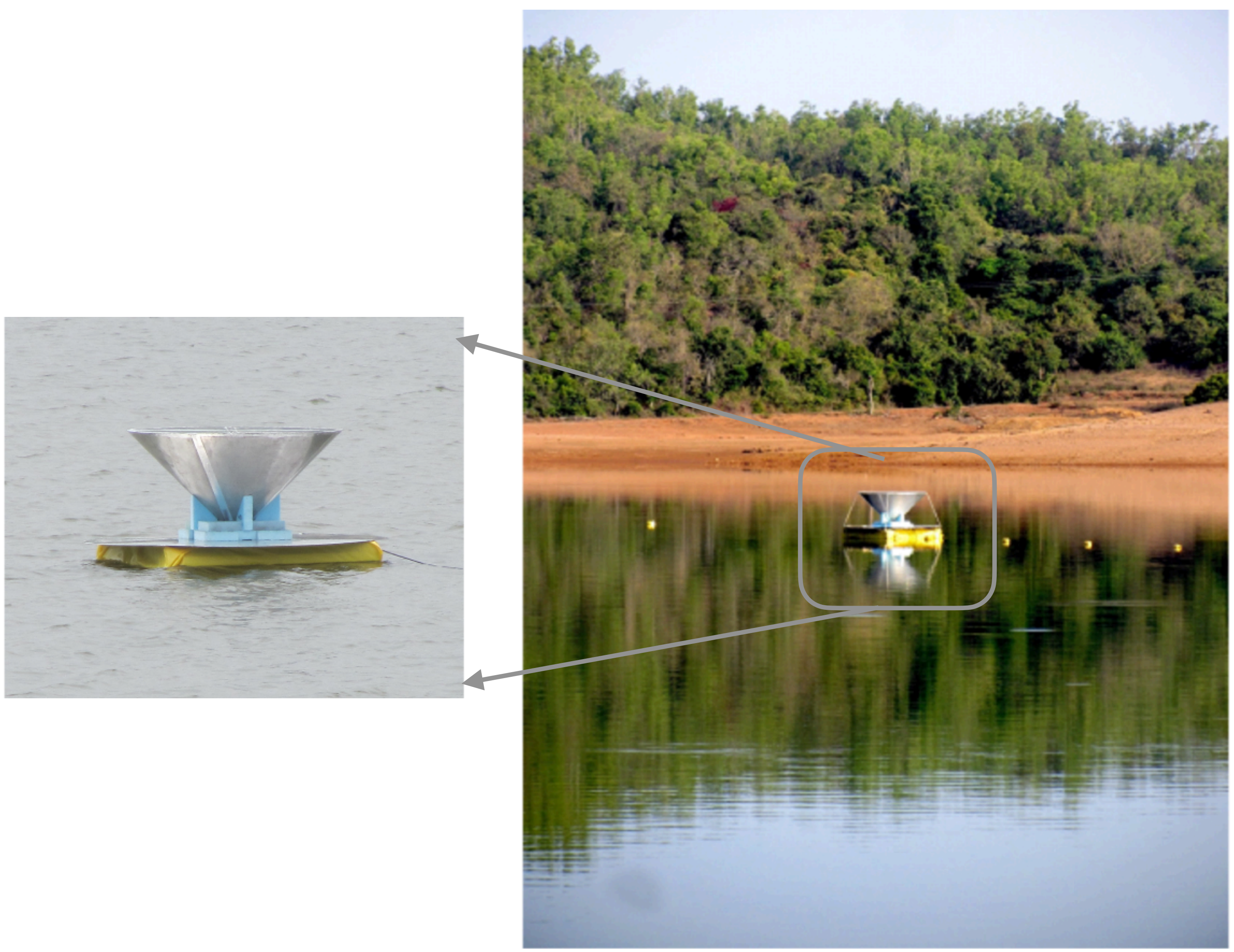


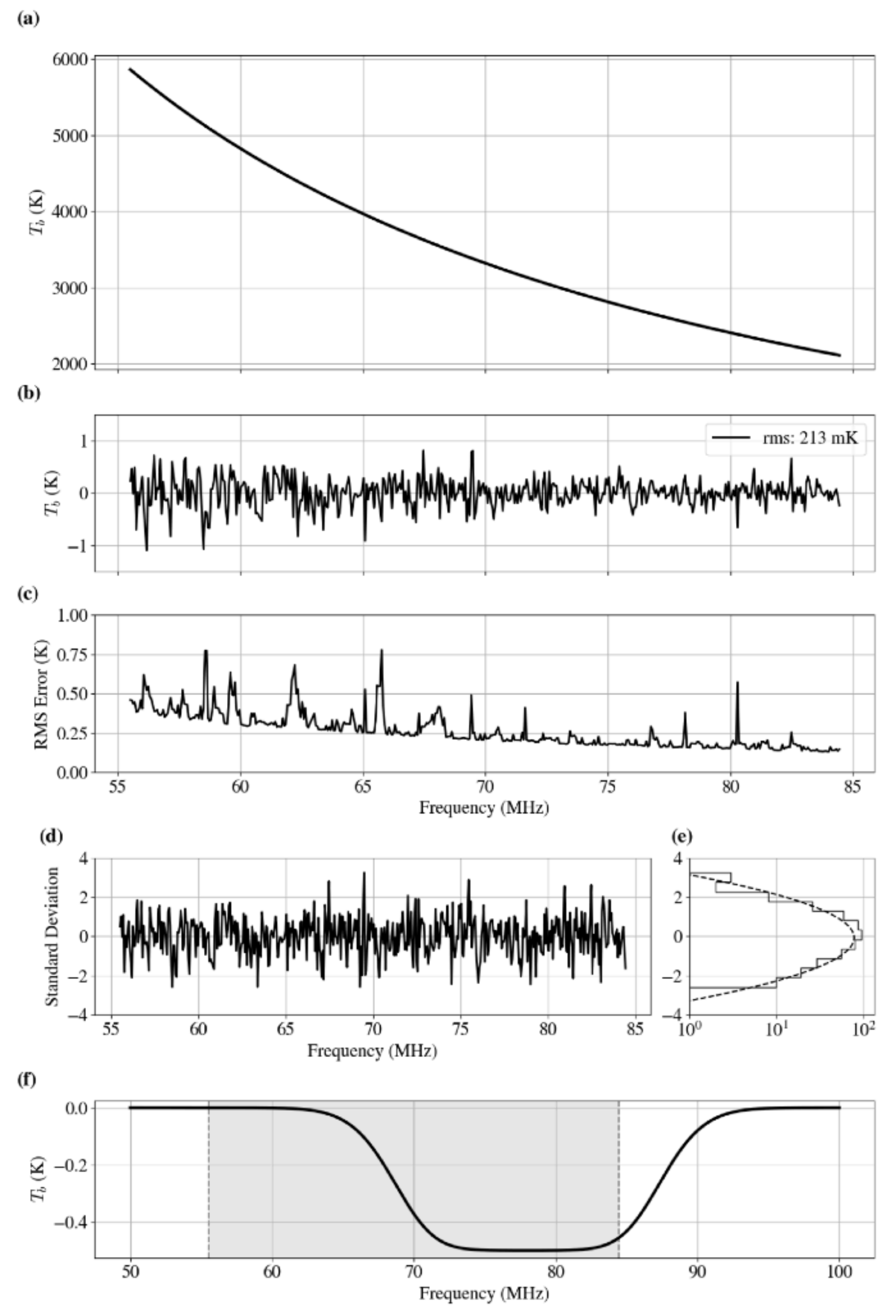
Barkana 2018 (Nature)

Ground-based global experiments

On the other hand, the SARAS3 experiment (India) fails to see this signal, although the frequency coverage is limited and significance is not yet very high (~3σ).

A global 21-cm signal detection requires spectral smoothness of $<10^{-4}$ over tens of MHz !





Singh et al. 2022 (Nature)

Challenges facing 21-cm observations from the Earth's surface

- Foregrounds — (extra)Galactic emission exceeds the 21-cm signal by 3-6 orders of magnitude (from z~6-200)

- Interference signal: human-made radio-frequency signals strongly out-power the 21-cm signal at many frequencies

- Instrumental stability: the "gains" of the receivers vary with time, frequency, direction. There is mutual coupling and multi-path propagation due to complex environment.

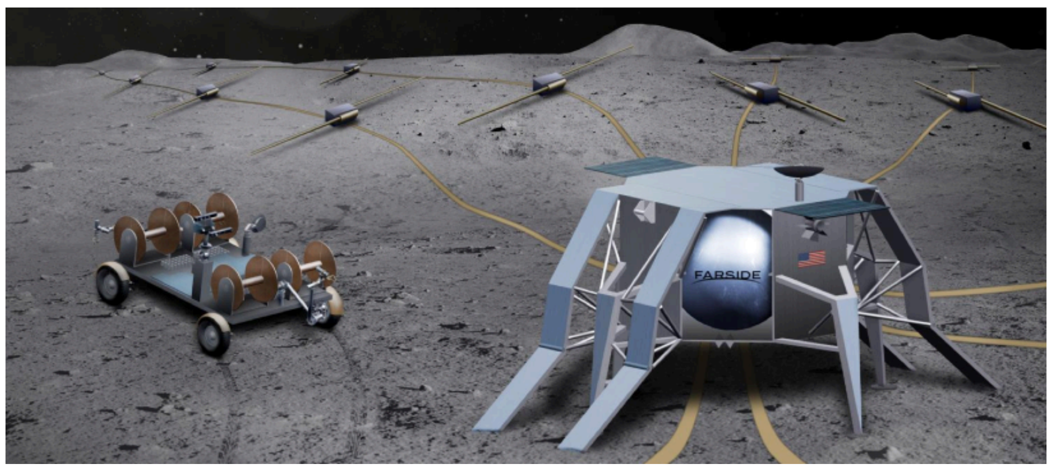
- Ionosphere: causes phase and amplitude errors in the data as function of baseline, time, frequency and direction.

Most challenges are largely mitigated in space, in particular far away from Earth (L2), in lunar orbit or on the lunar far-side:
No ionosphere, >80dB RFI suppression, stable environment

Some ongoing initiatives for space missions/ experiments — US, China, India

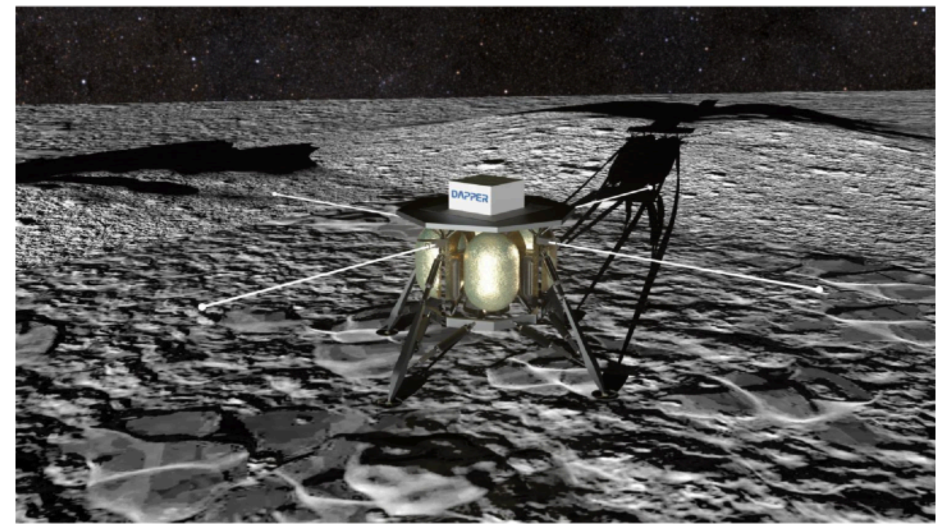
US FARSIDE PI: Burns

Probe-class Concept



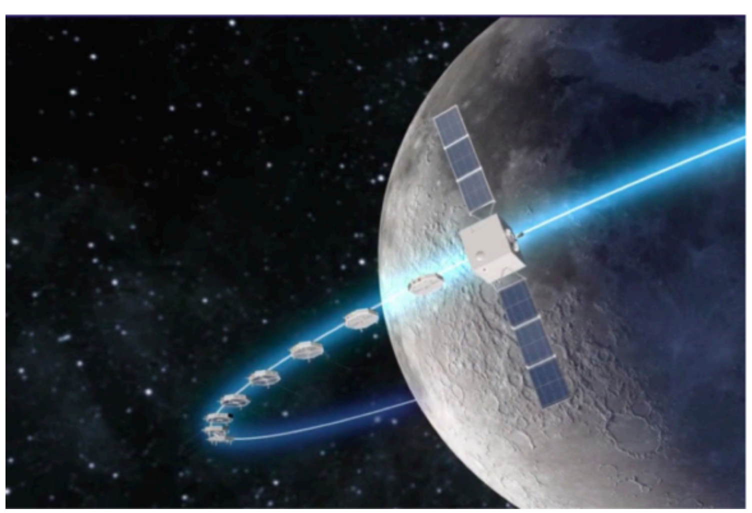
128 dual polarisation antennas deployed across a 10 km area on the lunar far side (Dark Ages: z>36)

US DAPPER PI: Burns



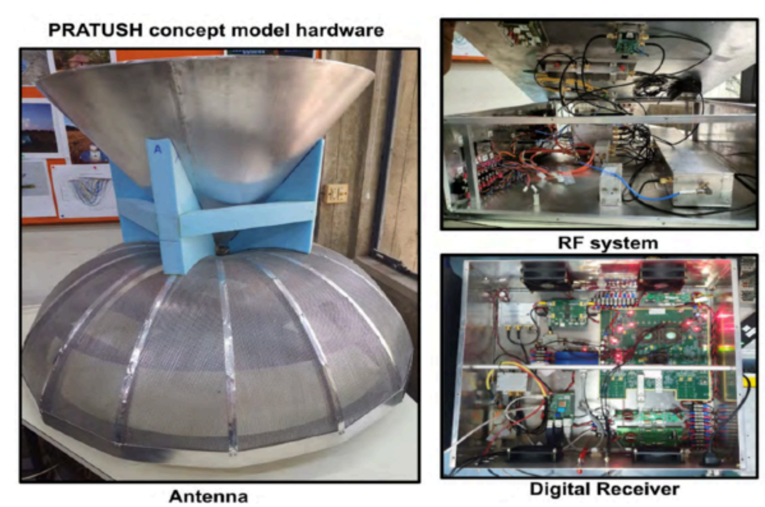
Di-pole receiver in orbit to measure the global 21-cm signal (z~83-36)

China DSL PI: Chen



Series (6-8) of tri-pole receivers in lunar orbit to measure the global 21-cm signal and do interferometry

India PRATUSH PI: Singh



Mono-pole receiver in orbit to measure the global 21-cm signal


September 1992

A feasibility study under coordination of ir. M.P. Nieuwenhuizen

ALFIS

TU Delft
Delft University of Technology

Faculty of Aerospace Engineering

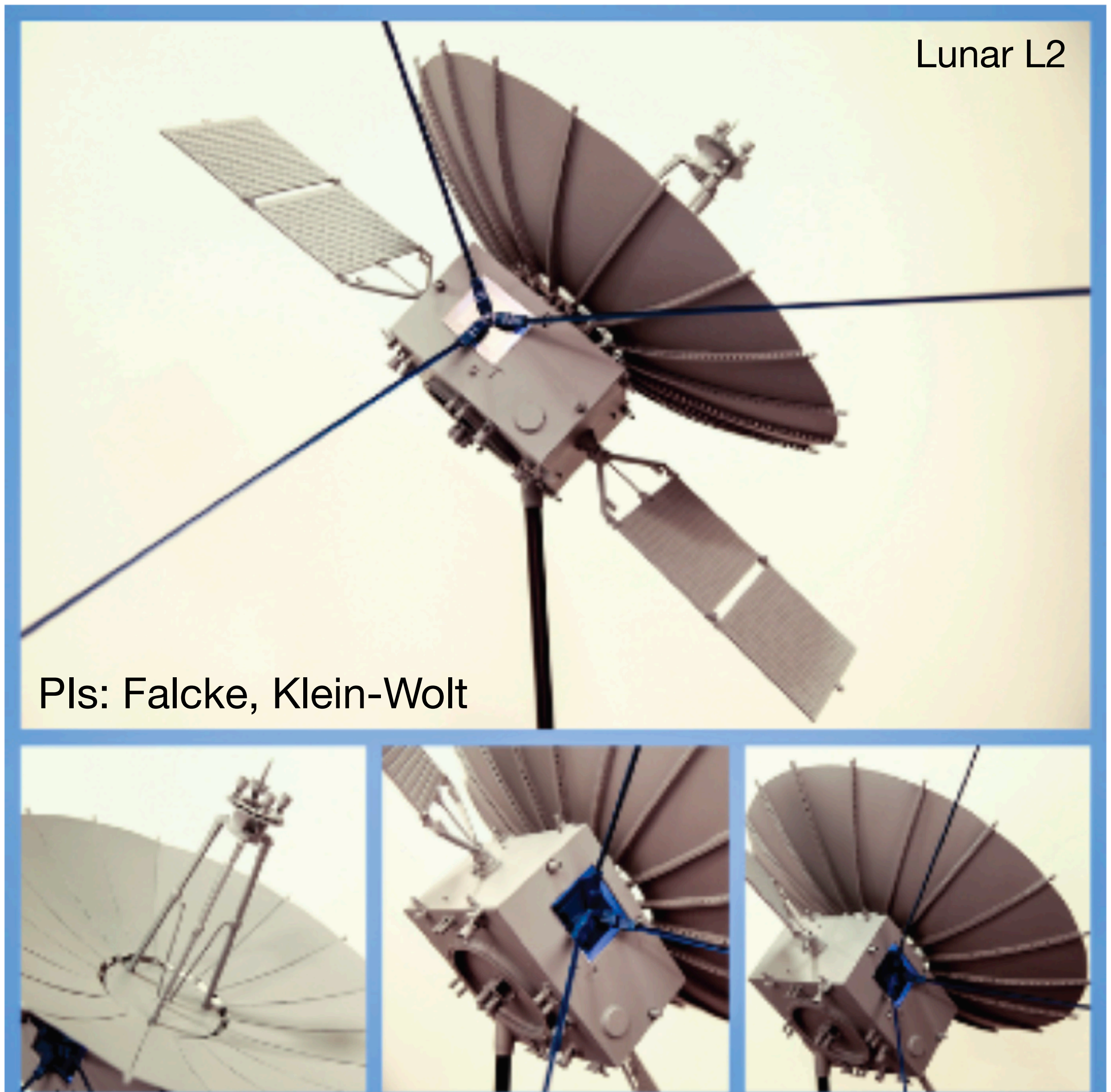
What about initiatives in NL/Europe?

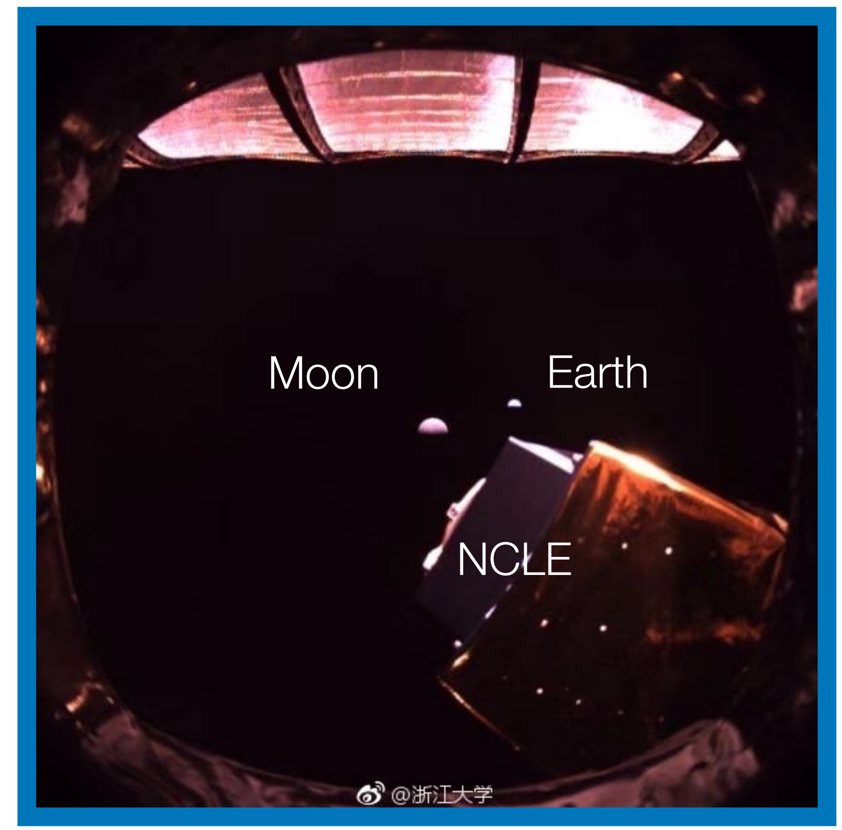
Many past proposals: ALFIS, DARIS, SURO,
LRX, OLFAR going back 30 years (not just 21-cm science)

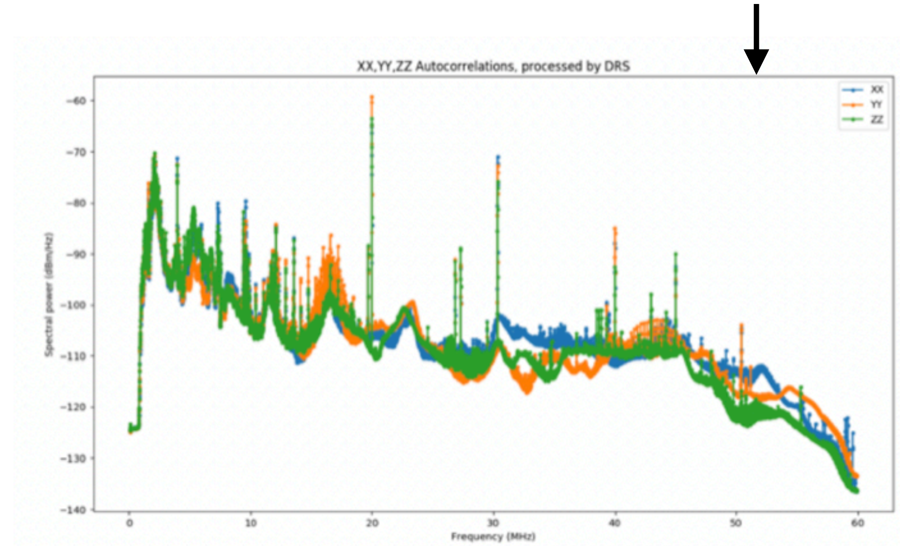
Credit image: George Miley

Netherlands-China Low-Frequency Explorer (NLCE)

Launched in May 2018; part of Chang-e'4; global 21-cm observations (z>~15);
(see upcoming talk by Sukanth Karapakula)







The holy grail:

Probing the Dark Ages?

Observing the 21-cm signal from the Dark Ages ($z>30$) allows us to test fundamental physics on par with the CMB but as function of Cosmic Time!

Space-based 21-cm Cosmology: Fundamental (astro)Physics

Ground-based instruments can not reach the Dark Ages or even the early Cosmic Dawn, due to ionosphere, RFI, and sensitivity.

Current space-based instruments are still pilots and largely focus on the global 21-cm signal (requires single receiver).

For a power-spectrum or tomographic detection a large collecting area lunar/space-based interferometer is essential.

Fundamental Key Questions that a space/lunar-based low radio-frequency mission can address via the 21-cm signal

The standard model of physics plus the standard Cosmological model *exactly* predict the 21-cm signal of neutral during the Dark Ages: “simple" linear theory. During the Cosmic Dawn (g)astrophysics is added.

Fundamental physics

Dark Ages (z~30-200)

- Physics of gravity
- Gravitational waves
- Dark Matter & Dark Energy
- Particle physics (e.g. WIMPs, axions, neutrinos)
- Primordial black holes
- Inflationary physics
- Non-Gaussianity
- Baryon-Dark-matter interactions
- ...

Cosmic Dawn (z~10-30)

- First stars (Pop III/II)
- Formation of first galaxies
- Stellar remnants/HMXRBs
- Seeds of SMBHs
- Synthesis of metals and enrichment of the IGM
- Molecular cooling
- ...

Foundational astrophysics

Astrophysical Lunar Observatory (ALO)

(see talk on Wednesday by Christiaan Brinkerink)

- Concept for a low-frequency radio telescope on the lunar surface (pole/far-side)
- Science payload on EL3 landers
- Both global 21-cm signal receivers (pole/far-side) and array for 21-cm power-spectrum/ tomography observations (lunar far-side)
- Covering Cosmic Dawn <u>and</u> Dark Ages redshifts (z>~15), needing >10^4 hours of integration.


European Large Logistics Lander (concept)


esa

ASTROPHYSICAL LUNAR OBSERVATORY

CDF Study Report

Assessment of an Astrophysical Lunar Observatory on the farside of the Moon

esa

Astrophysical Lunar Observatory

concurrent design facility

CDF-219(A)
October 2021

Summary

- The **21-cm signal is the *only* tracer of the Dark Ages and potentially the only tracer of the early Cosmic Dawn**. Only space-based interferometers can characterise this signal from z~15 to z~50 and beyond (below ionospheric cutoff).
- Detection of the 21-cm signal from the Dark Ages enables **fundamental (astro-) physical processes** to be studied — DM/DE, inflation, GWs, first stars, etc.

- Detection requires **A_{eff}=0.1, 1, 10, 100 km^2 (depending on science case)** in a compact configuration: feasible in space with lightweight material array, swarms of micro-satellites, etc. TRL levels reasonably high, but development needed.
- Enabling **detections from Earth is excluded by the ionosphere, human-generated RFI and a relatively unstable environment**: a space-based mission is necessary.
- The **lunar orbit/far-side or deep space** provide excellent environments. On the lunar surface one could piggy-back on other exploratory missions).

- **ALO/NLCE** encode these concepts and science motivations. Missions are **scalable** with **science from day one**. Building on **many earlier concepts and pilots** (ALFIS, DARIS, SURO, LRX, OLFAR, and NCLE, resp.). Also **enables other science** (e.g. exoplanets) and connects to global efforts (e.g. US, China, India)