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21-Cosmology of the Dark Ages, with the Astrophysical Lunar Observatory

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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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21 cm Cosmology Workshop, July 17-21, China

What can "21-cm Cosmology" tell us?

The CMB Radiation versus the High-z 21-cm Signal

=

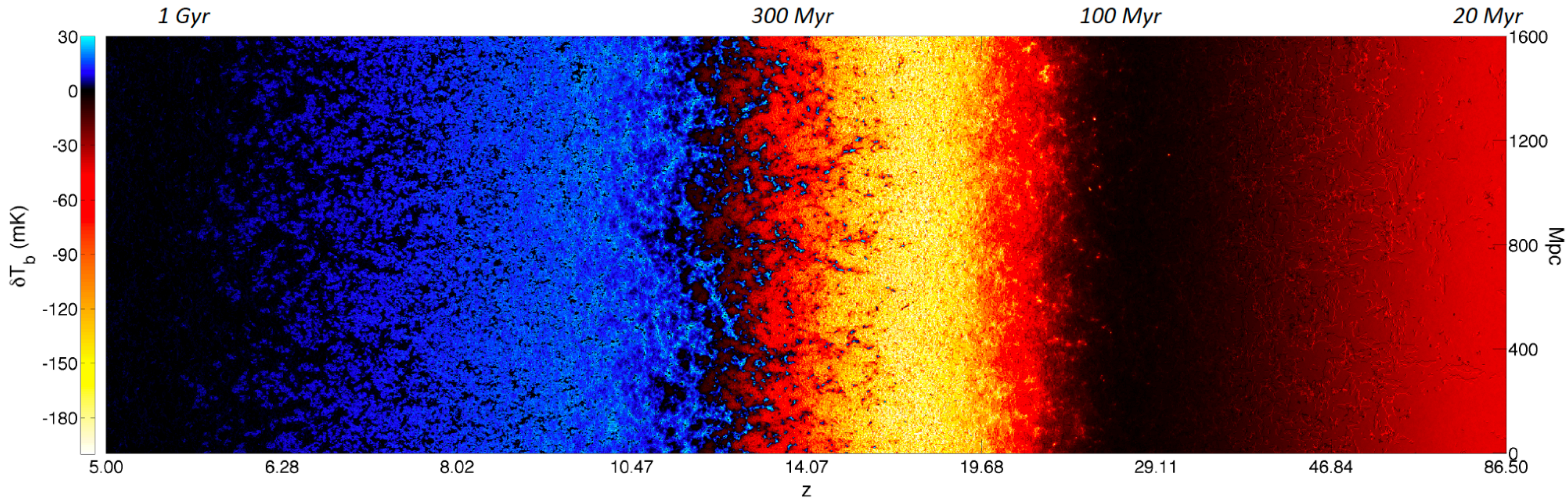
A still photograph versus a feature film

What can “21-cm Cosmology” tell us?

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

Post-Reionization | Reionization | Cosmic Daw | Dark Ages

HI is found largely in galaxies ← HI has a filling factor of order unity



Reionization | X-ray heating | Lyα coupling | Dark Ages

Credit figure: Mesinger

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:

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

Cosmology

Ionization

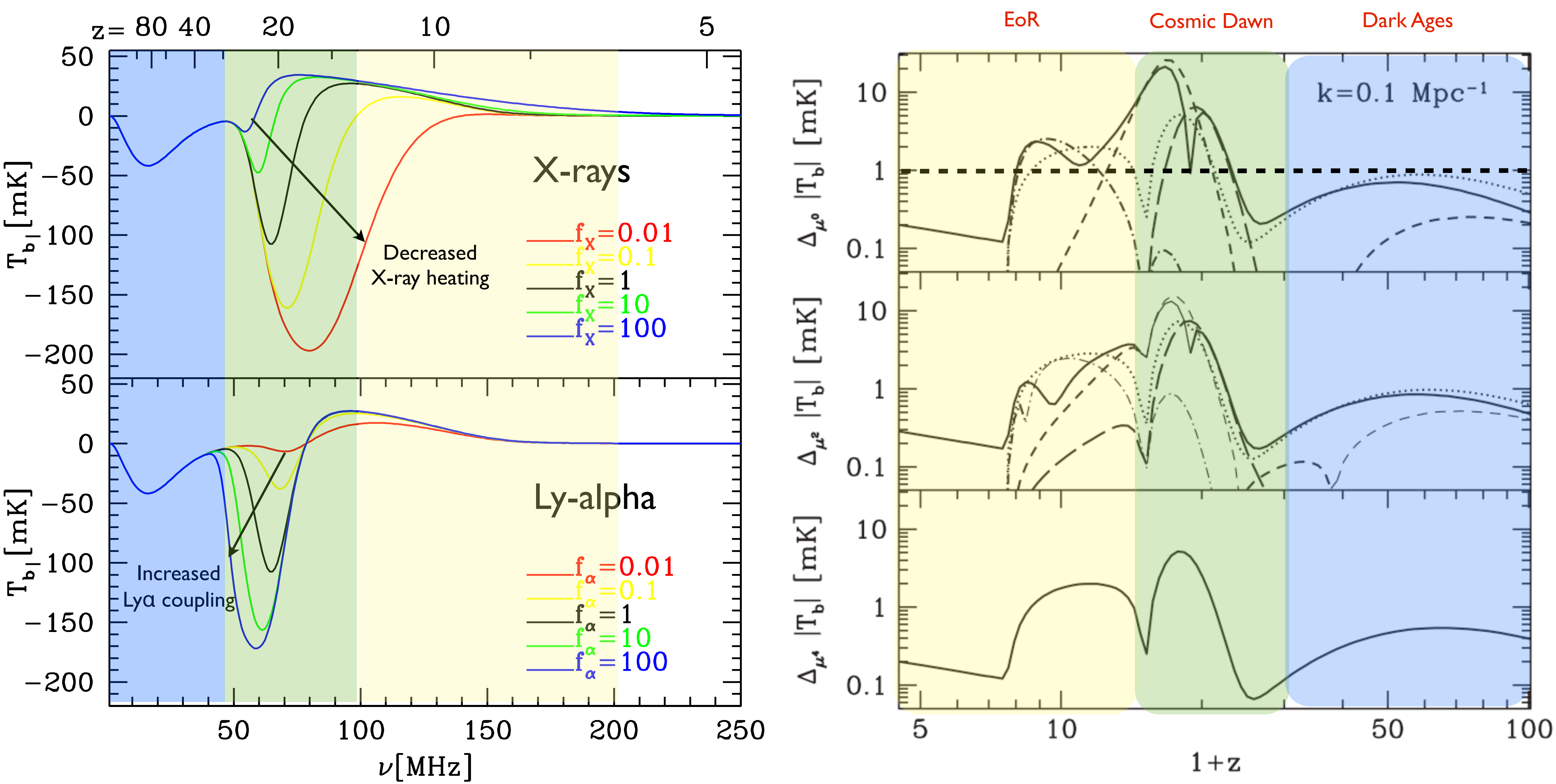
(G)astrophysics

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?

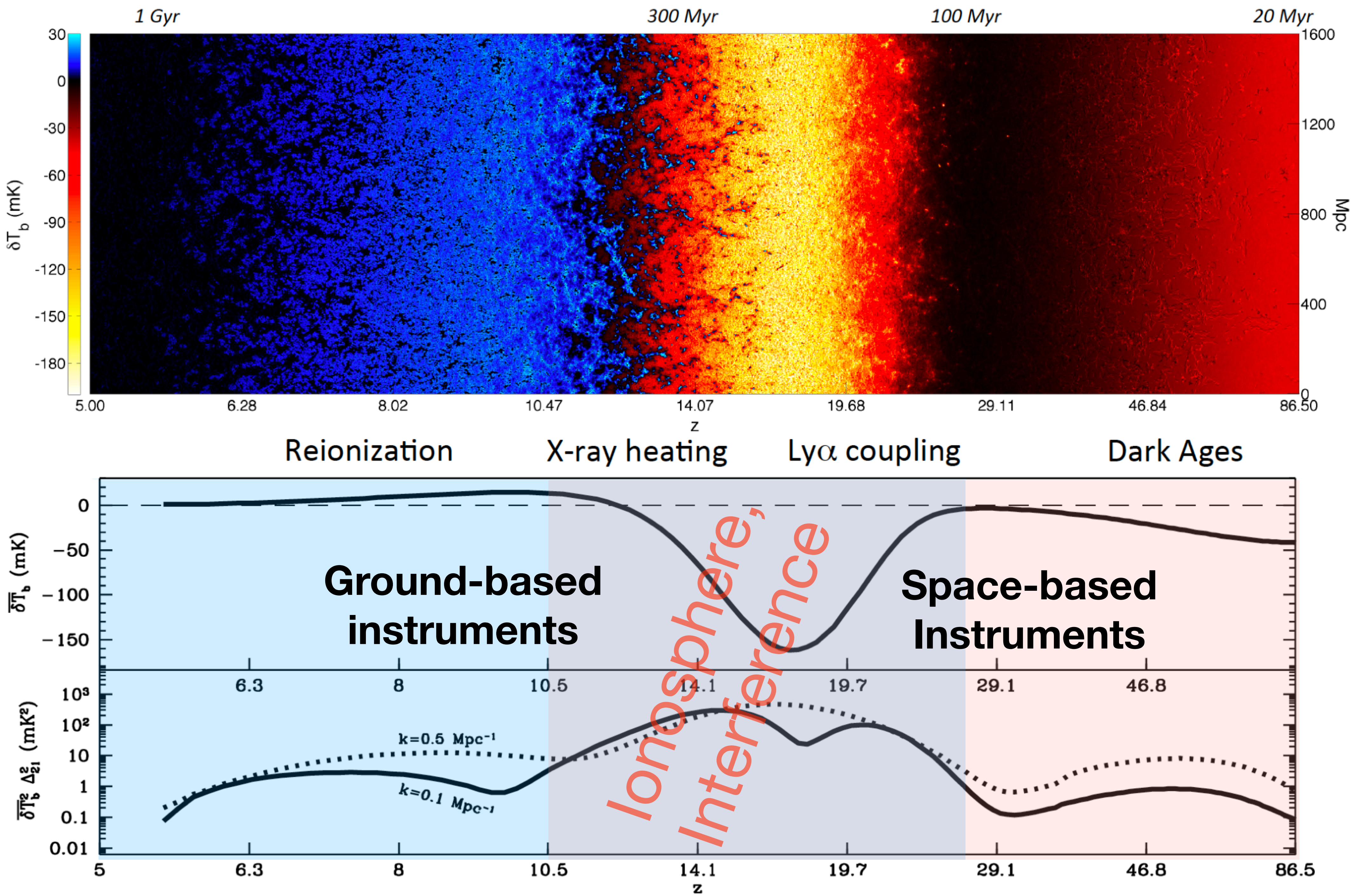
Global Signal (left) and Intensity Fluctuations (right)



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)

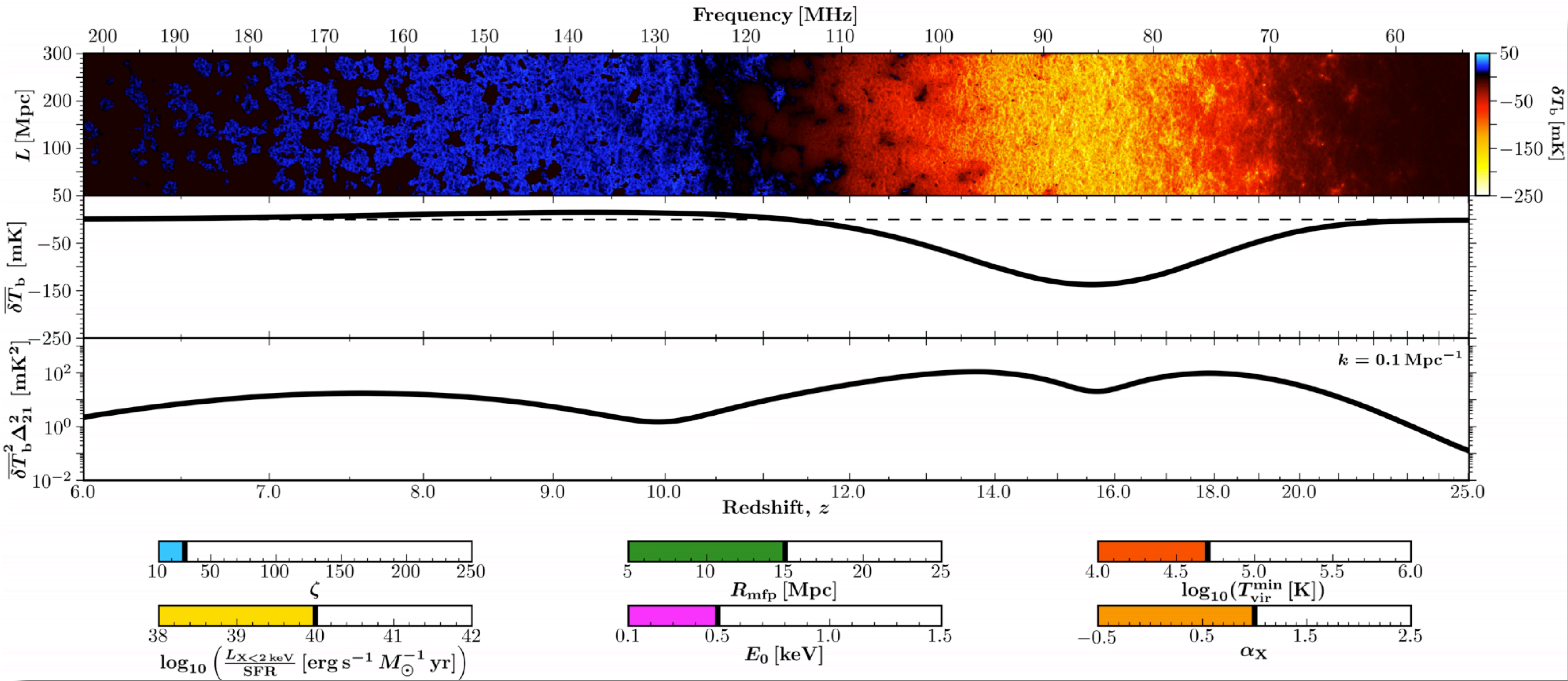


* Spin & CMB-temperature decouple; ** universe is reionized

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?

Numerical Models

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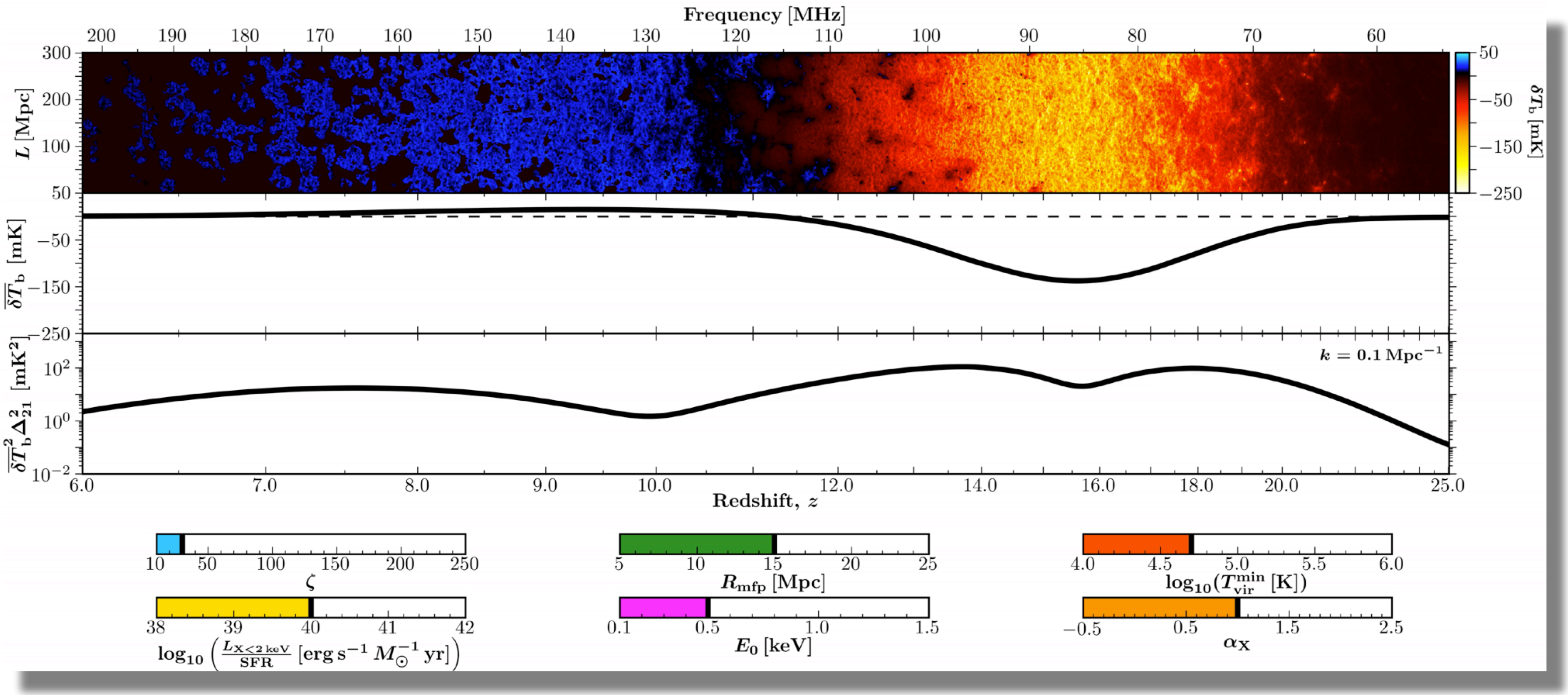
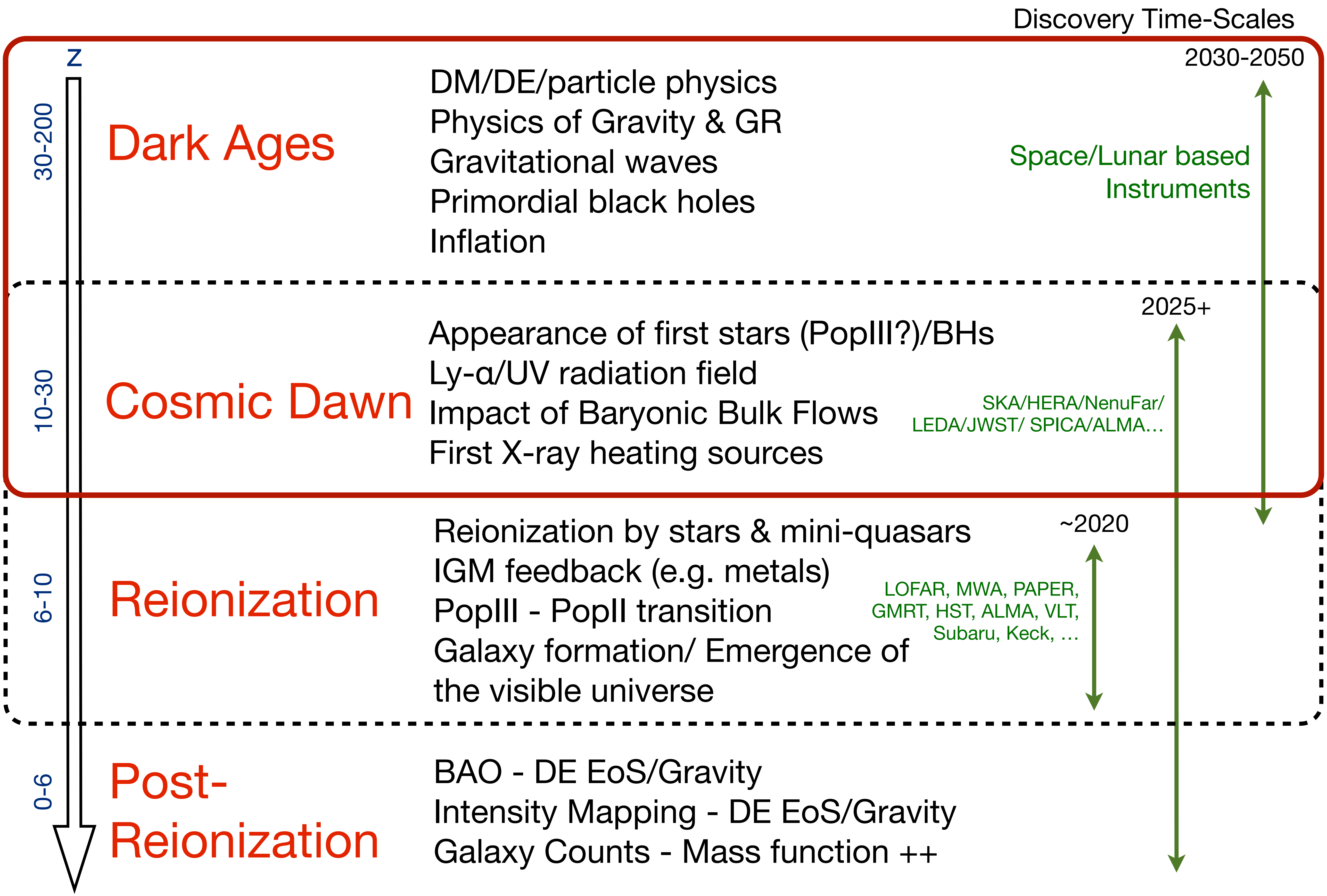


Credit movie: Mesinger & Greig

What can “21-cm Cosmology” tell us?



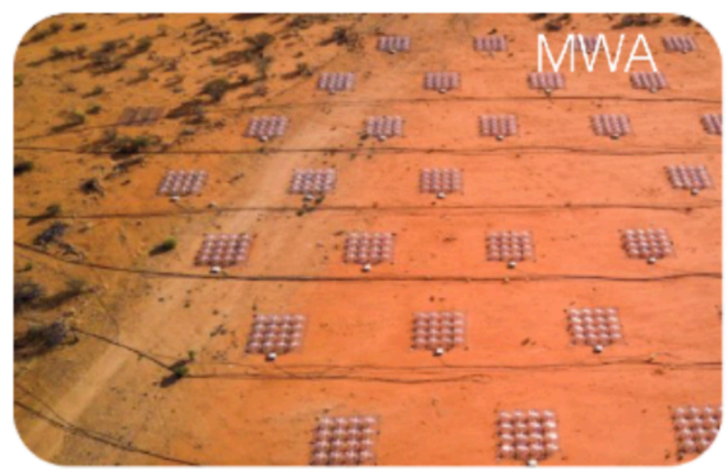
Why go to space for 21-cm Cosmology?

Observing the 21-cm signal at (z>>10) is very hard!!

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

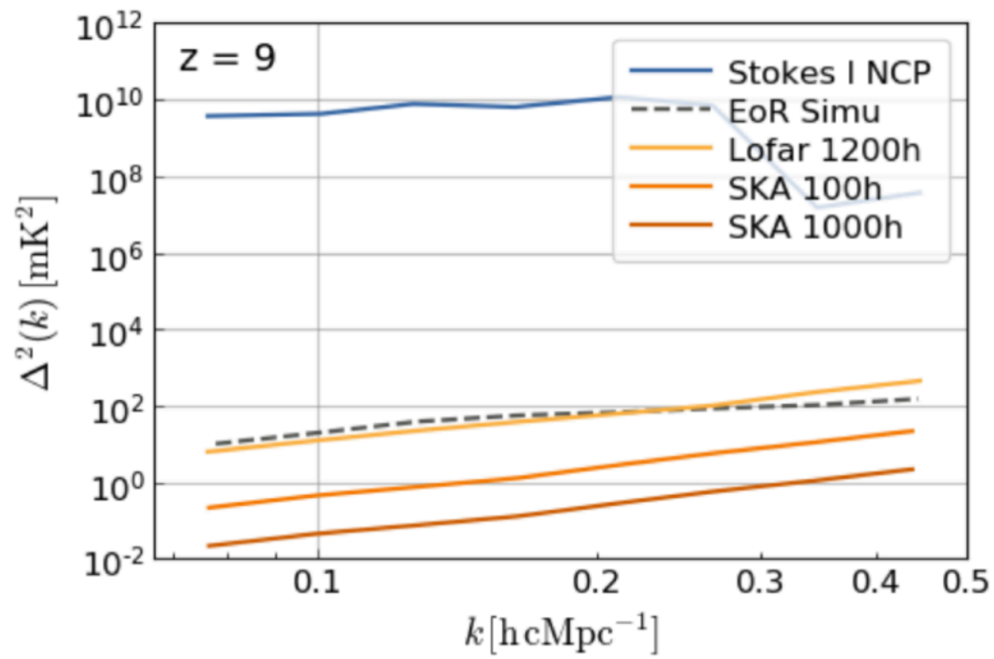


Upcoming instruments in coming decade focussing mostly on z~6-25

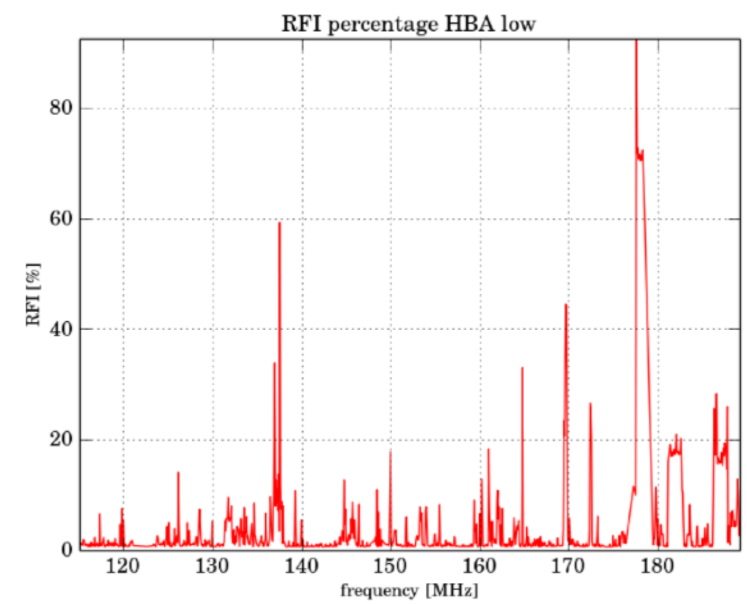
Ground-based interferometry experiments

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

Foregrounds

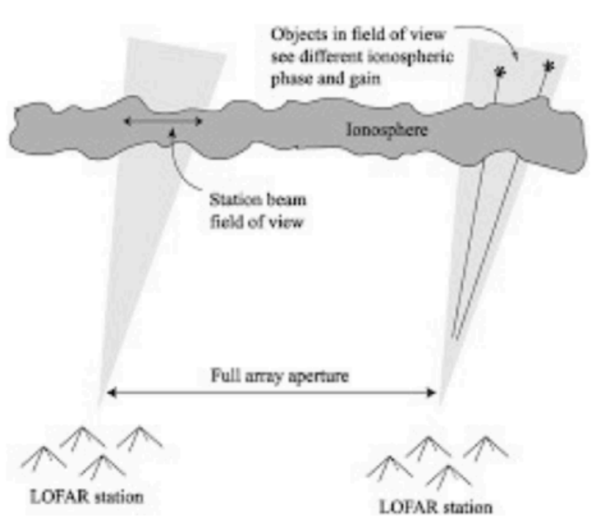


Radio Frequency Interferance (RFI)



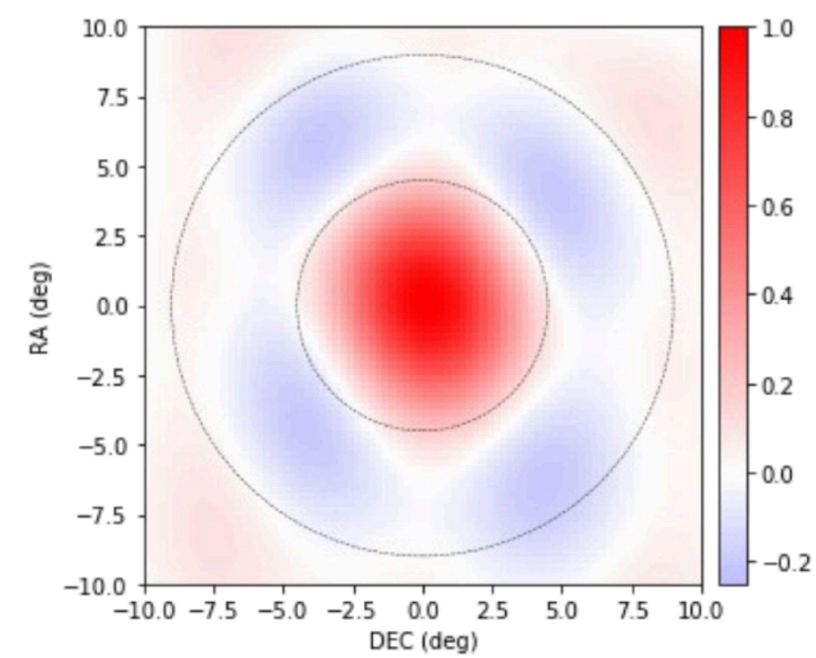
Credit: A. Offringa

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.

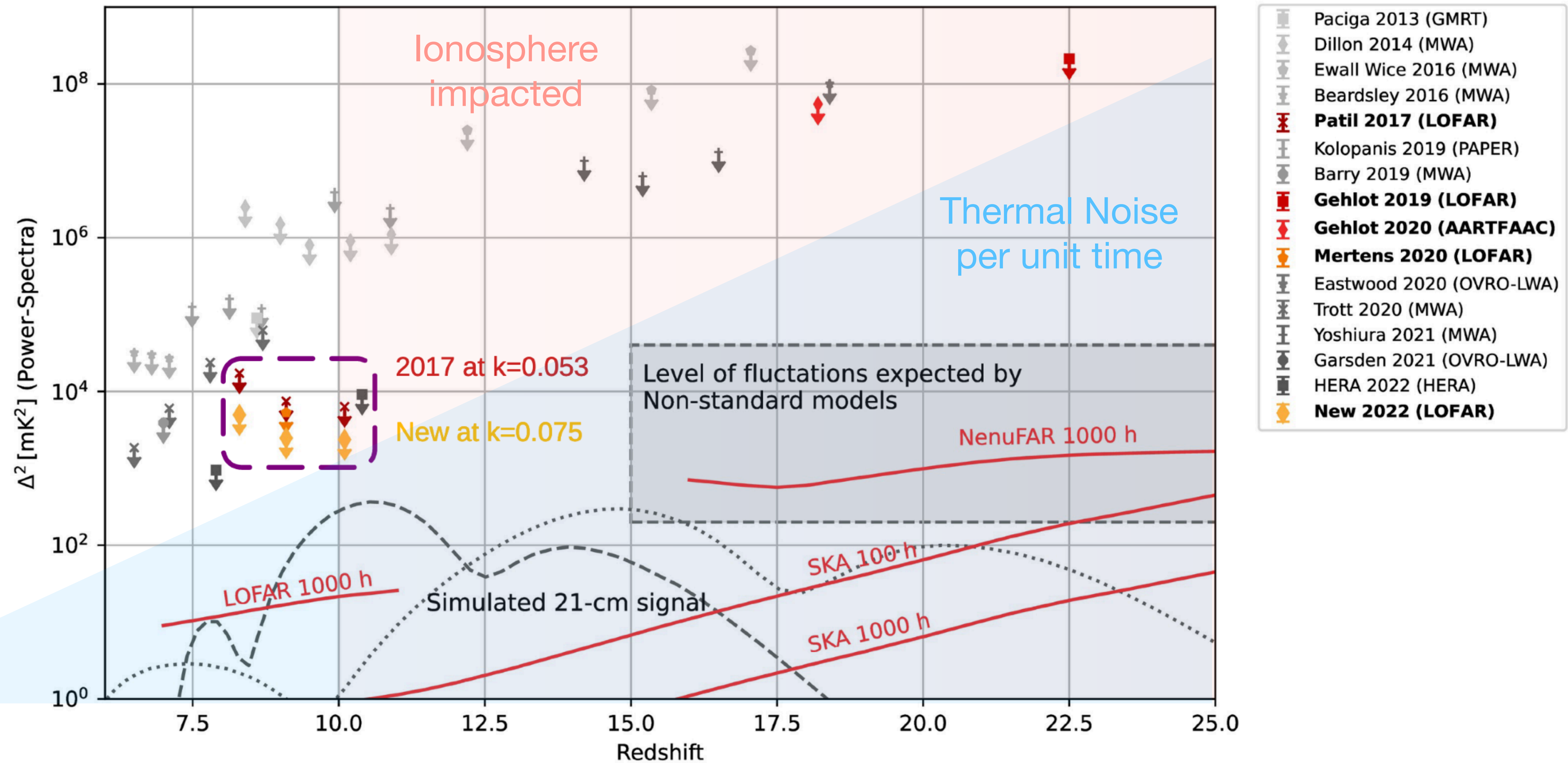
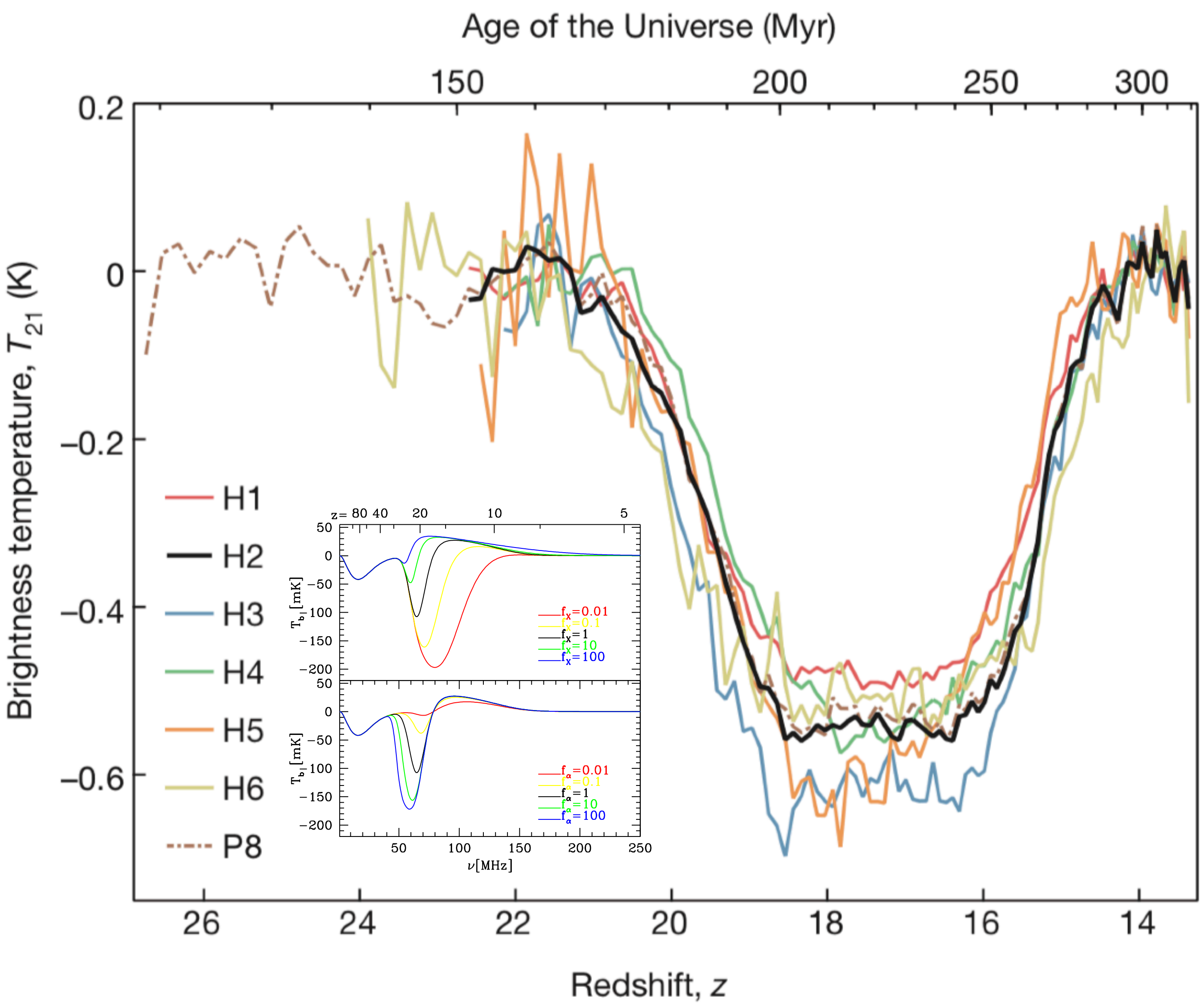
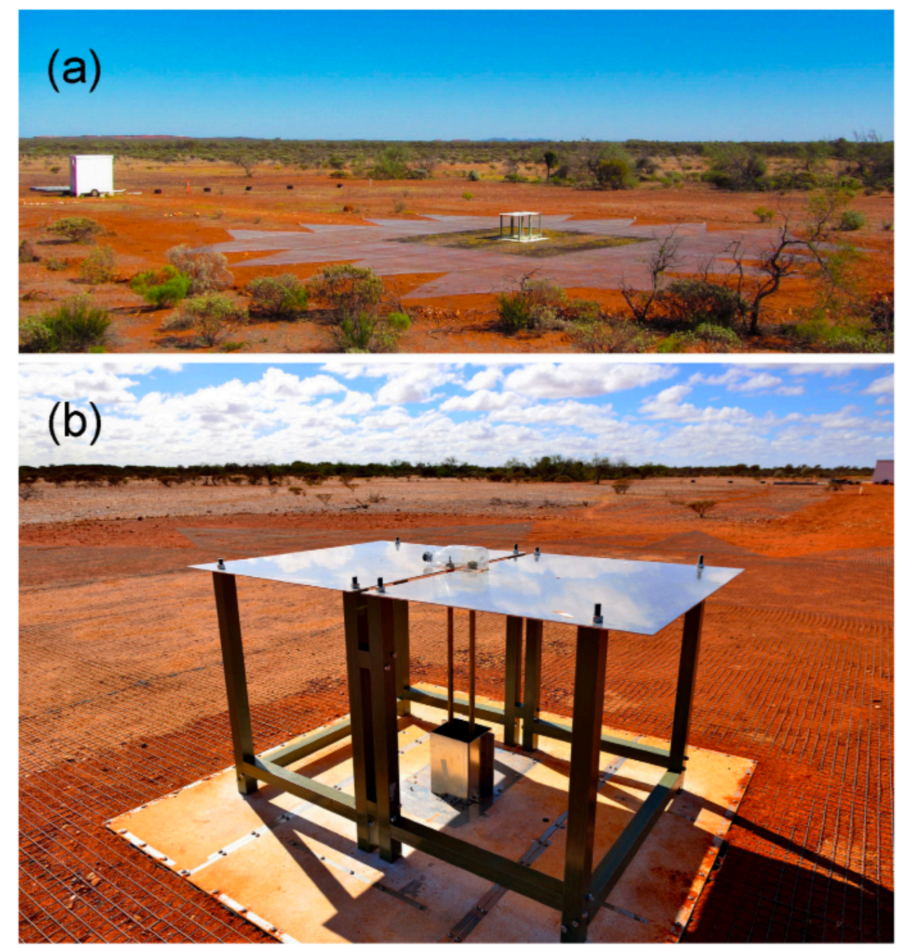


Figure: credit Florent Mertens

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.



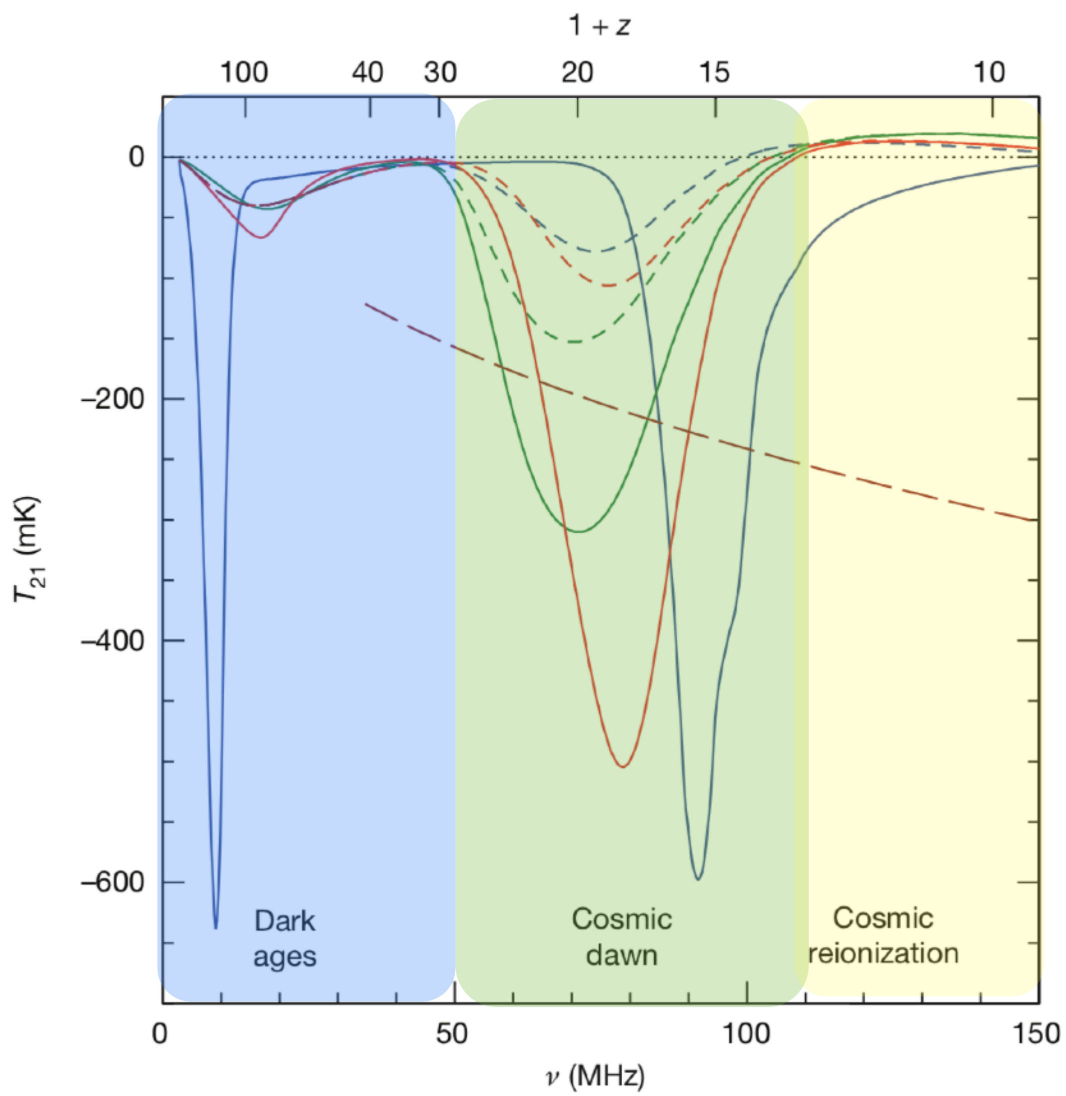


Bowman et al. 2018 (Nature)

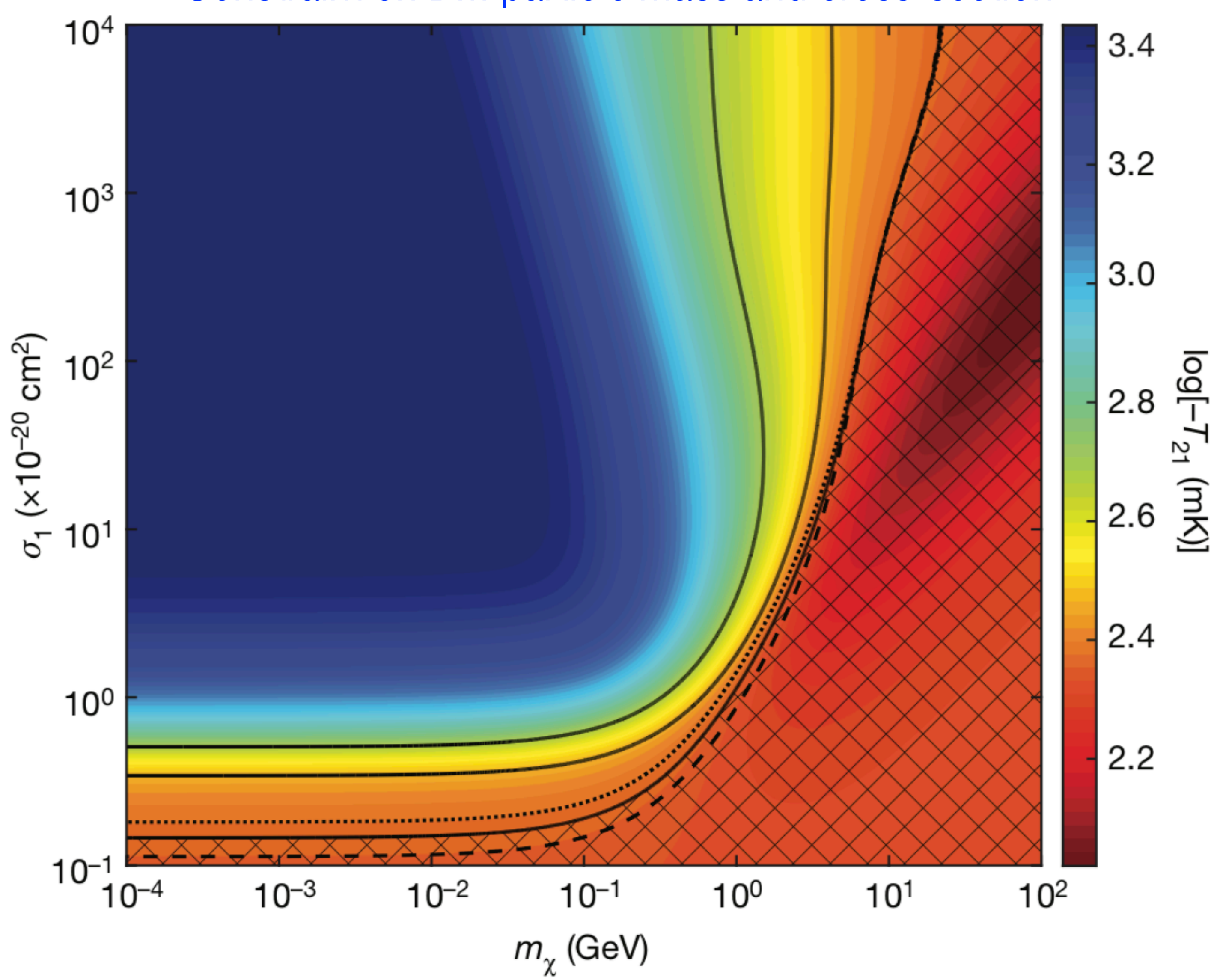
Ground-based global experiments

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

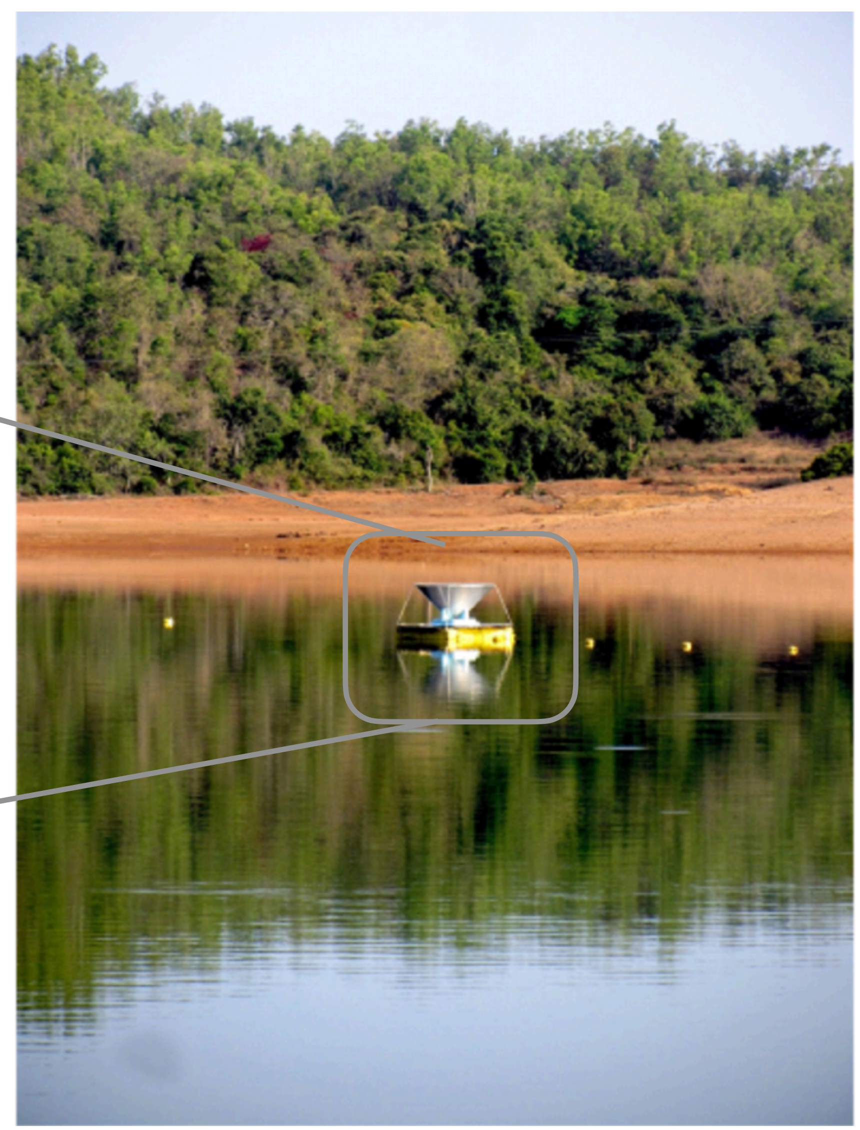


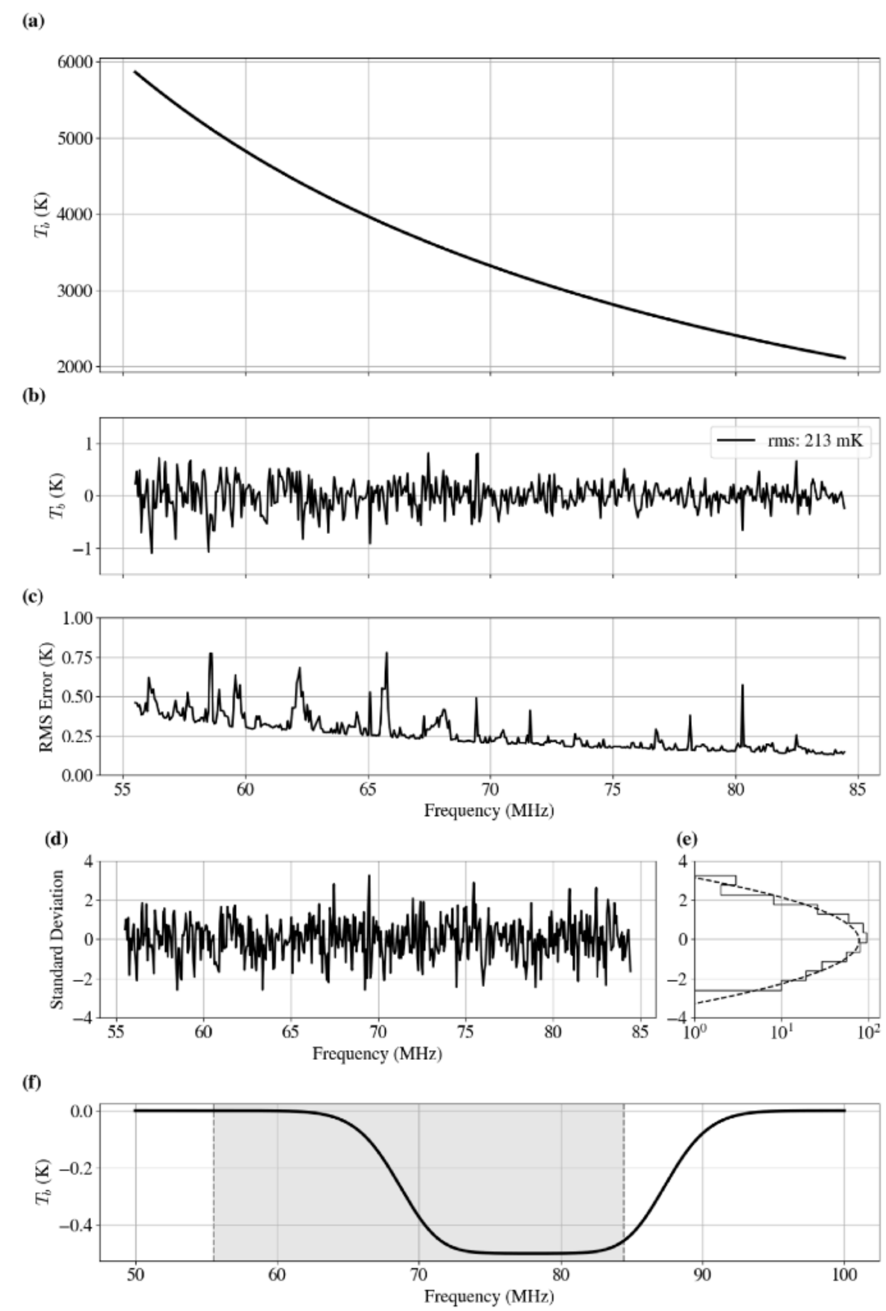
Barkana 2018 (Nature)

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

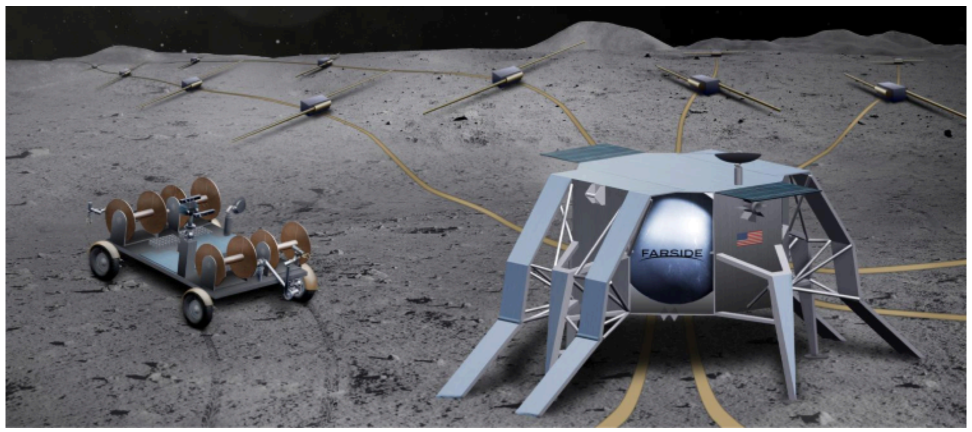
- Instrumental stability: the "gains" of the receivers vary with time, frequency, direction. There is mutual coupling and multi-path propagation due to complex environment.

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

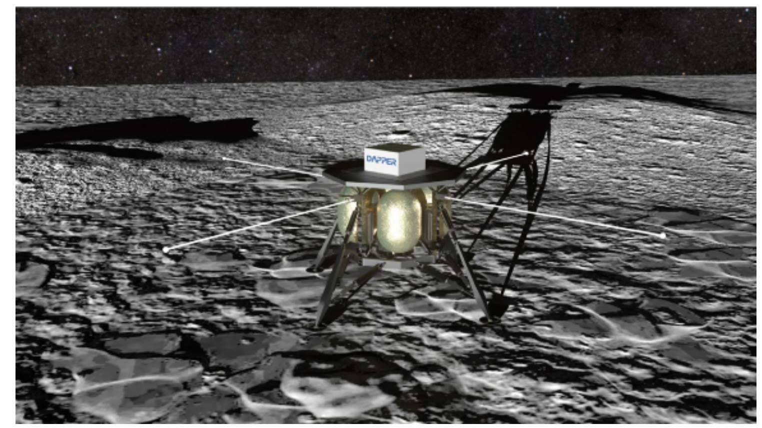
Most challenges are largely mitigated in space, in particular far away from Earth (L2), in lunar orbit or on the lunar far-side:
No ionosphere, >80dB RFI suppression, stable environment

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

DAPPER/ROLSES/LuSEE/FARSIDE PI: Burns

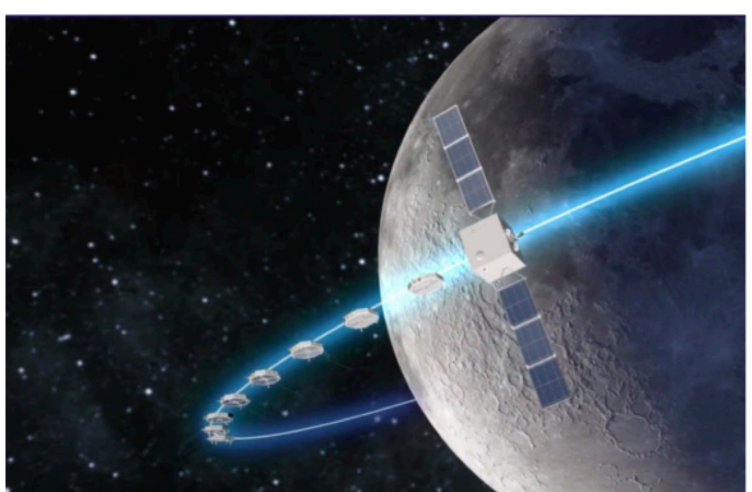


128 dual polarisation antennas deployed across a 10 km area on the lunar far side (Dark Ages: z>36)



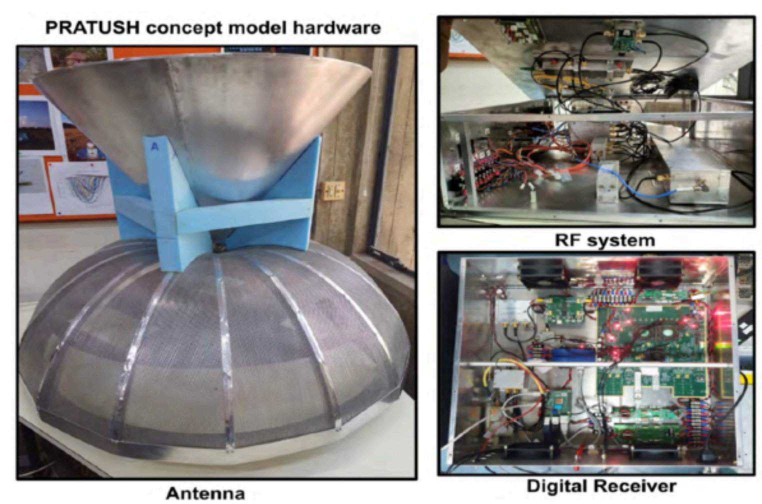
Di-pole receiver in orbit to measure the global 21-cm signal (z~83-36)

DSL PI: Chen



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

PRATUSH PI: Singh



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

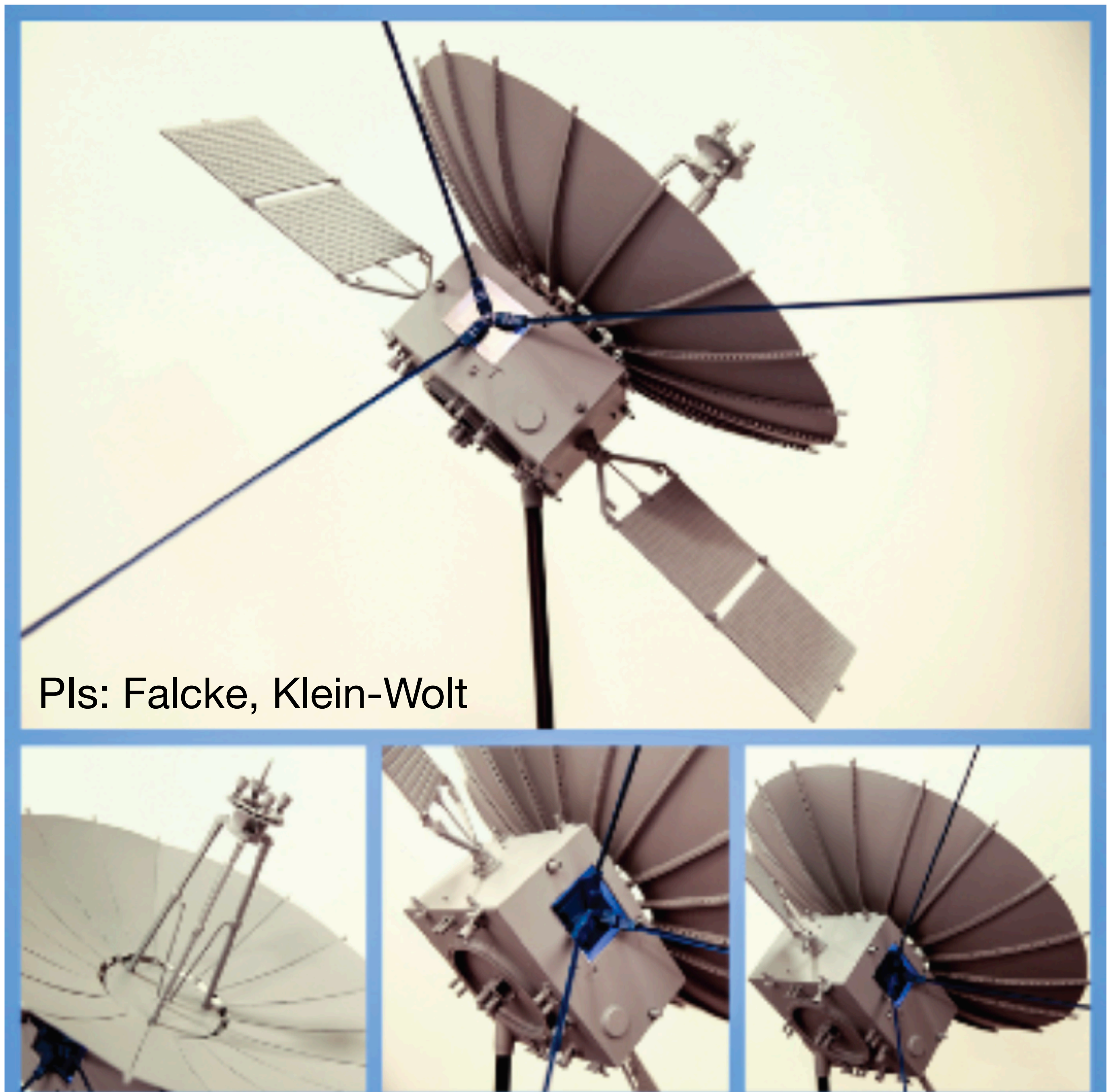
What about initiatives in NL/Europe?

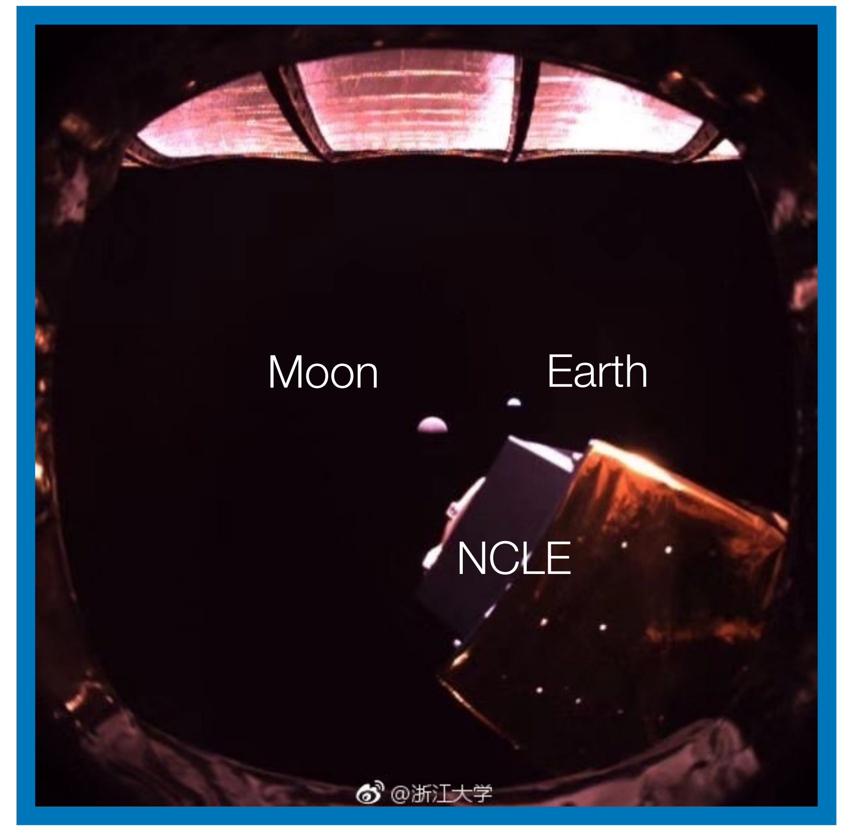
Many past proposals: ALFIS, DARIS, SURO, LRX, OLFAR going back 30 years (not just 21-cm science) and one realised system: NCLE (in lunar L2)

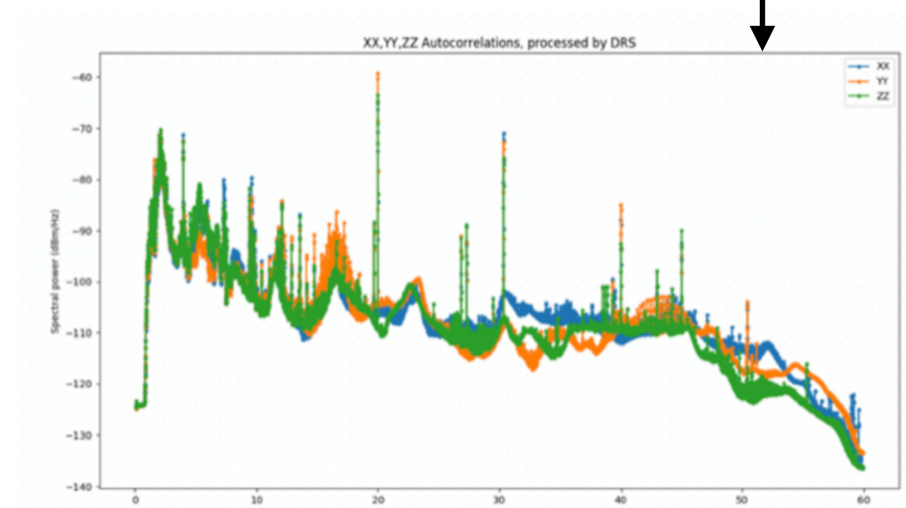
Credit image: George Miley

NCLE — a pilot experiment in lunar L2 between China and the Netherlands

Launched in May 2018; part of Chang-e'4; commissioning ongoing; tripole role-out planned for mid-Nov 2019







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!

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

ALO — Astrophysical Lunar Observatory

What is needed for a detection of the early Cosmic Dawn and Dark Ages?

Basic Objectives

- Enable a 10-sigma statistical detection of the 21-cm signal during the Dark Ages
- Enable direct imaging of the 21-cm signal during (early) Cosmic Dawn

Basic Requirements

- Space-based interferometer
- Collecting areas of 0.1-1-10-100 km^2
- All/half-sky field of view
- High filling factor (i.e. compact array)
- Large bandwidth covering 1-100MHz
- More than 5-yr lifetime

Potential Mission Concepts

- Large free-floating inflatable structures
- Swarm of free-floating/connected (small) satellites
- Array of di/tri-poles on lunar surface
- Allow scalability

Potential locations

- Lunar surface: far-side or poles
- Lunar orbit
- “Deep” space (e.g. Sun-Earth L4,5)

Astrophysical Lunar Observatory (ALO)

- 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.

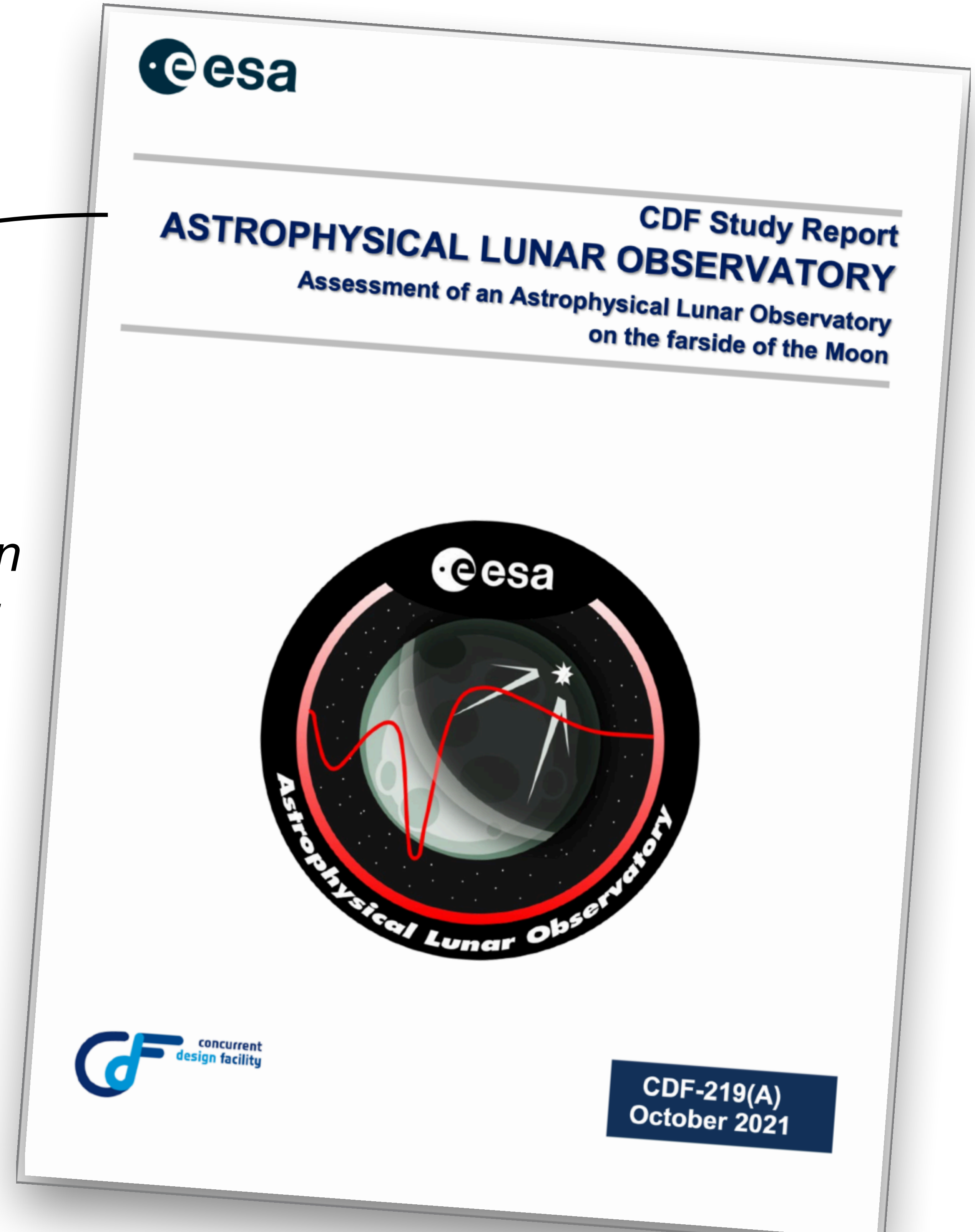

European Large Logistics Lander (concept)

Astrophysical Lunar Observatory (ALO)

Concurrent Design Facility study conducted with ESA over the summer of 2021

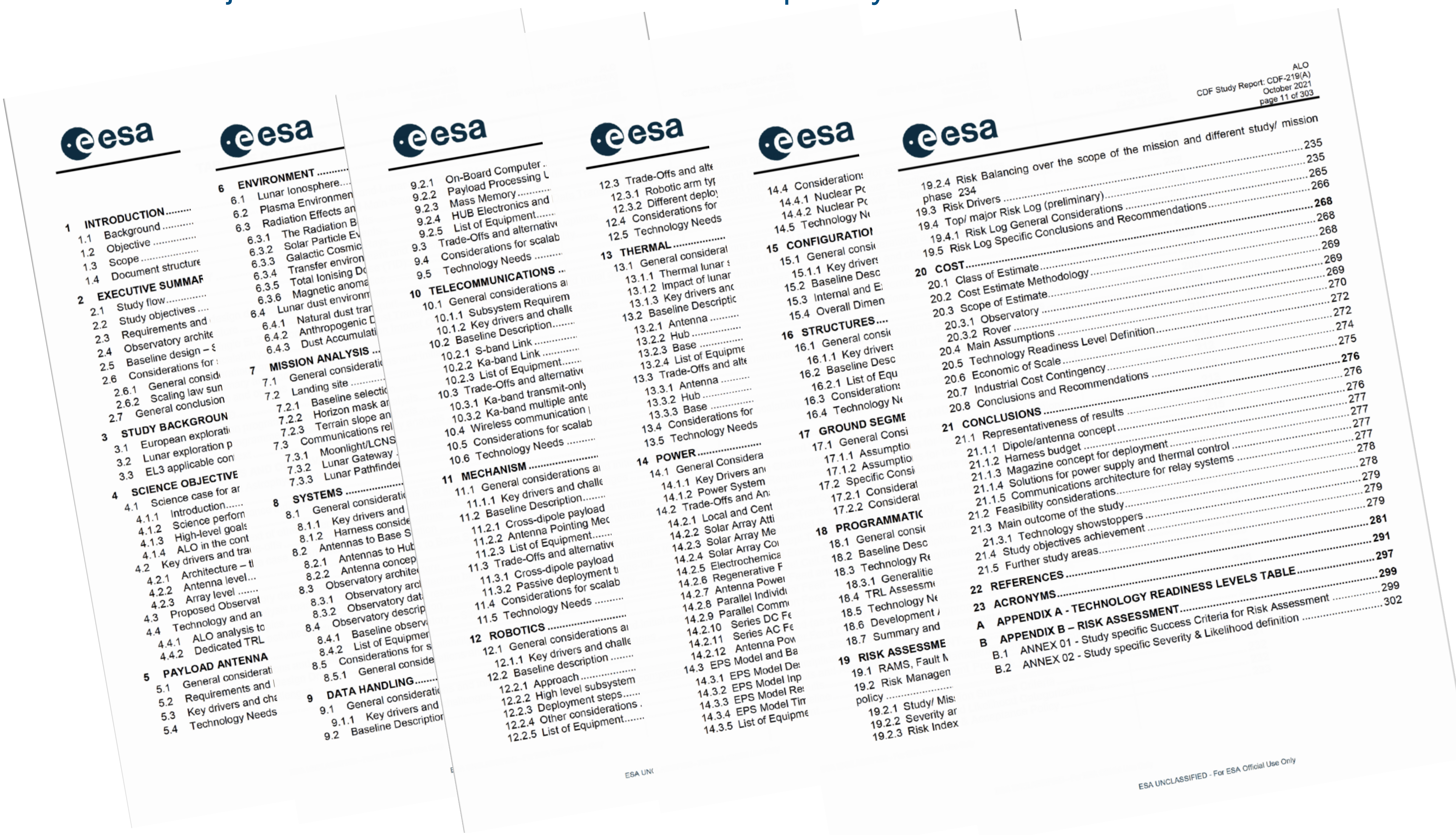
"The Astrophysical Lunar Observatory (ALO) mission is notionally the 3rd mission concept being studied in the context of the European Large Logistic Lander (EL3) project, currently in phase A/B1 aiming at program subscription at ESA Ministerial Council in 2022"

internal pre-phase A or Level-0 assessment studies



Astrophysical Lunar Observatory (ALO)

A in-depth study over the course of several months involving the joint science team and an interdisciplinary team of ~40 from ESA


ALO
CDF Study Report: CDF-219(A)
October 2021
page 11 of 303

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The basic idea behind ALO

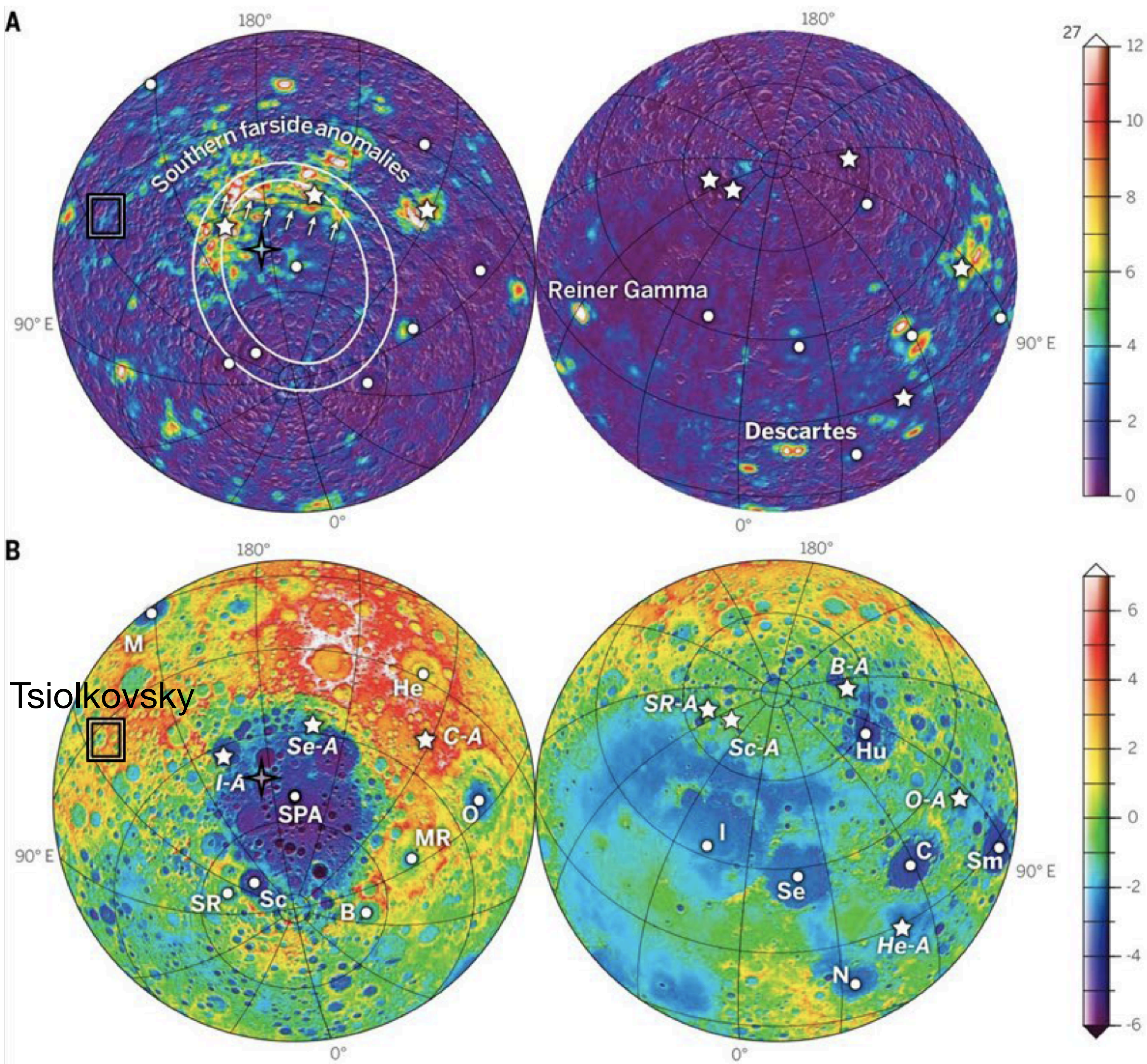
A discovery mission to observe the Dark Ages ($z>30$ to ~200) and the late Cosmic Dawn ($z\sim15$-30) using the 21-cm line of neutral hydrogen.

Neither era of the Universe has been explored by any instrument to this date. A unique mission.

Requires a very large-area low-frequency space-based interferometer.

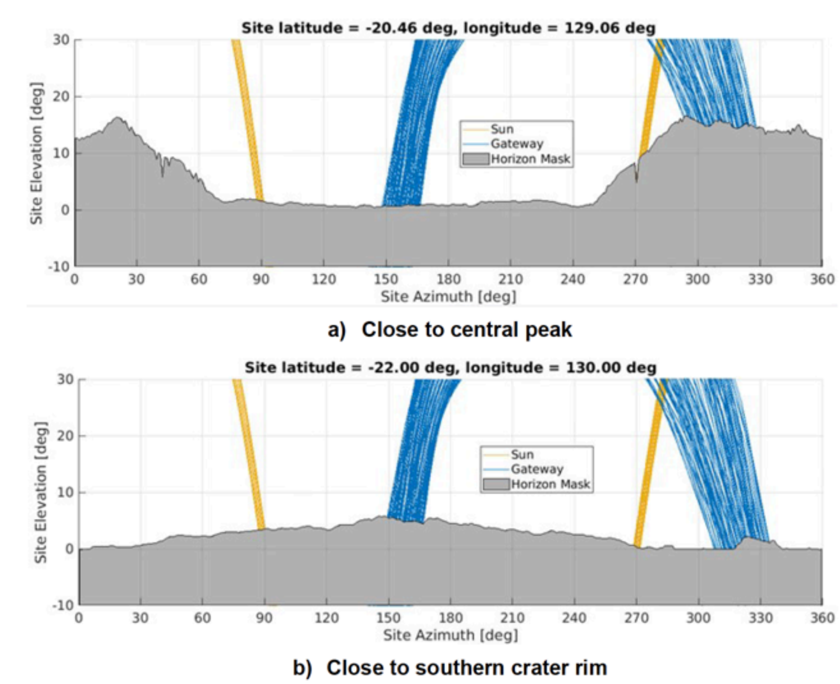
Enables ESA to play a leading role in 21-cm cosmology.

Astrophysical Lunar Observatory (ALO)



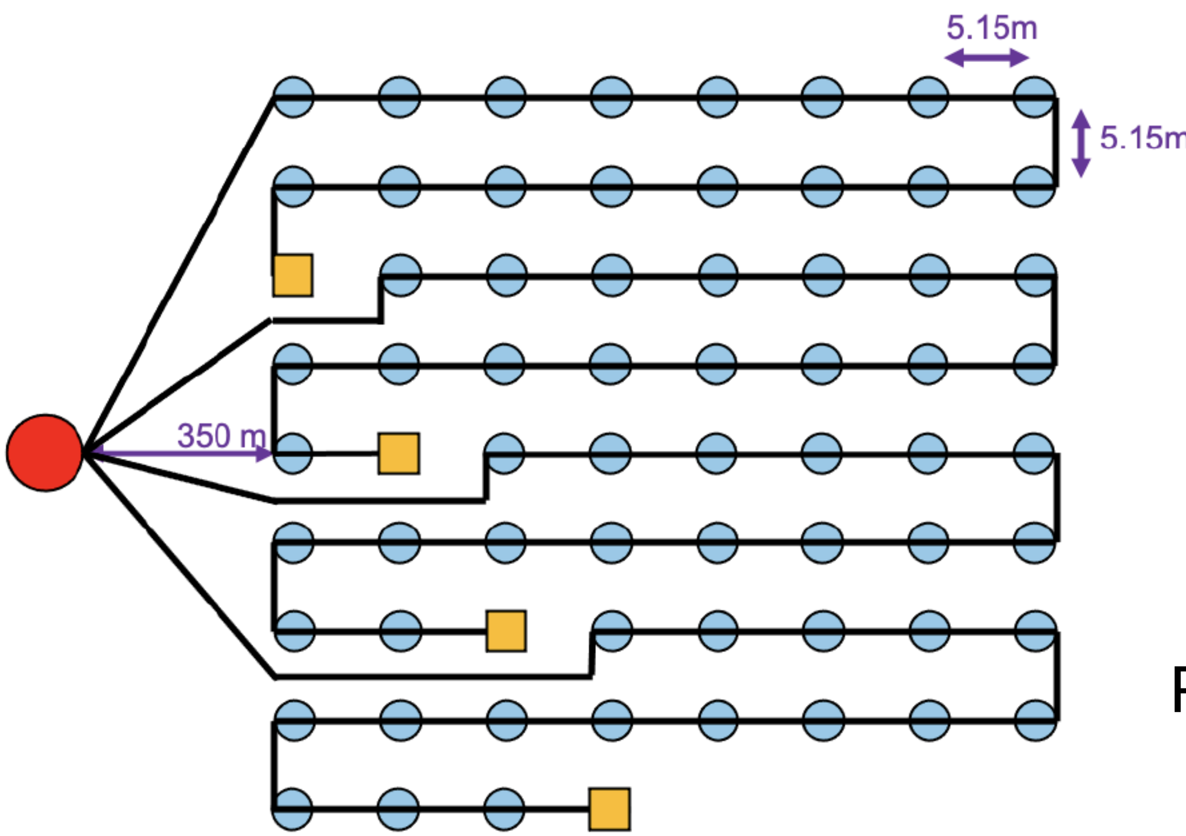
• Tsiolkovsky

- Location on the lunar poles or far side (e.g. Tsiolkovsky) shielded from lunar/earth RFI, mid-latitude for improved uv-coverage and sufficient for solar power.
- Observe mostly during lunar day and small part during lunar night.

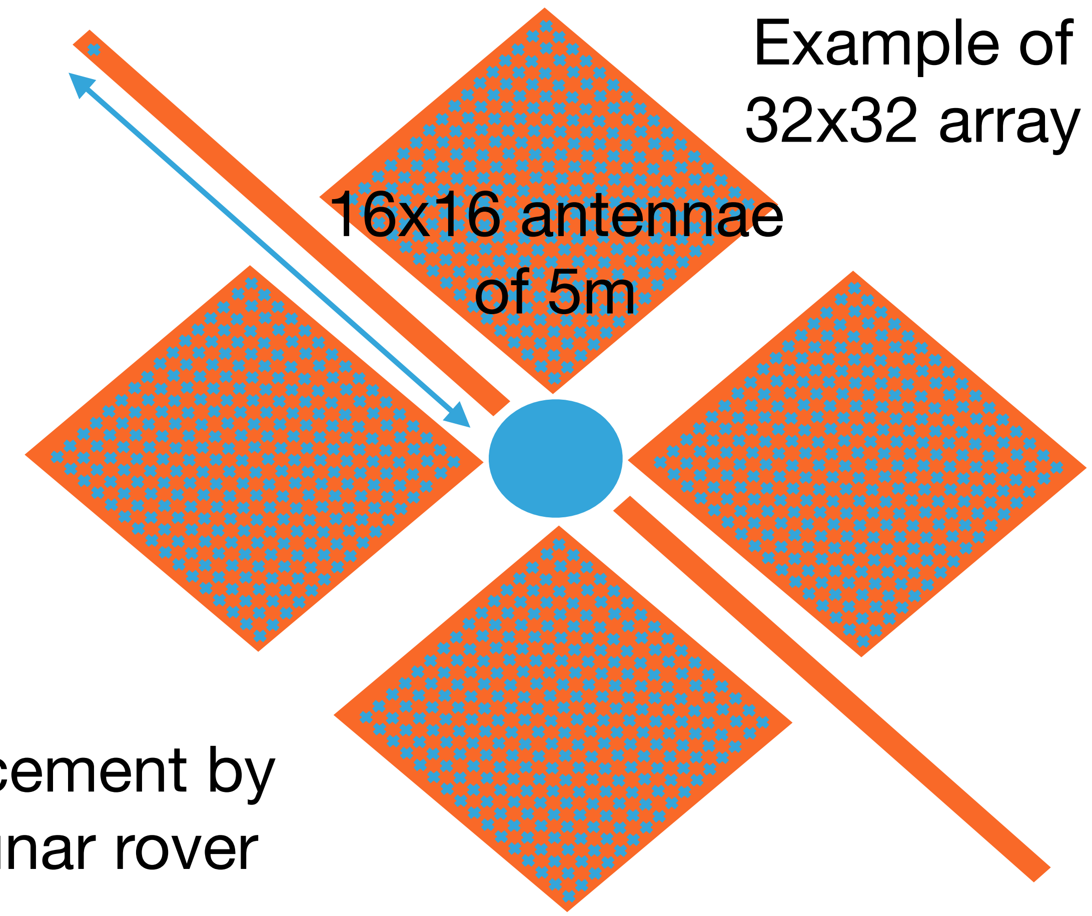


Astrophysical Lunar Observatory (ALO)

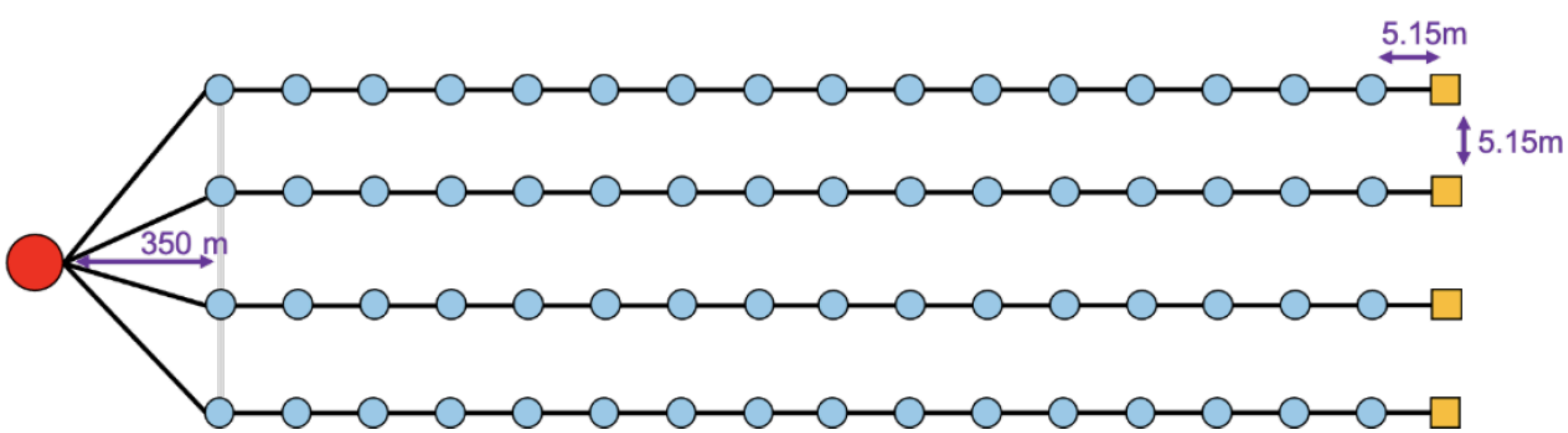
Basic concept of NxN array (power-spectrum)
with 4 outriggers (global signal)



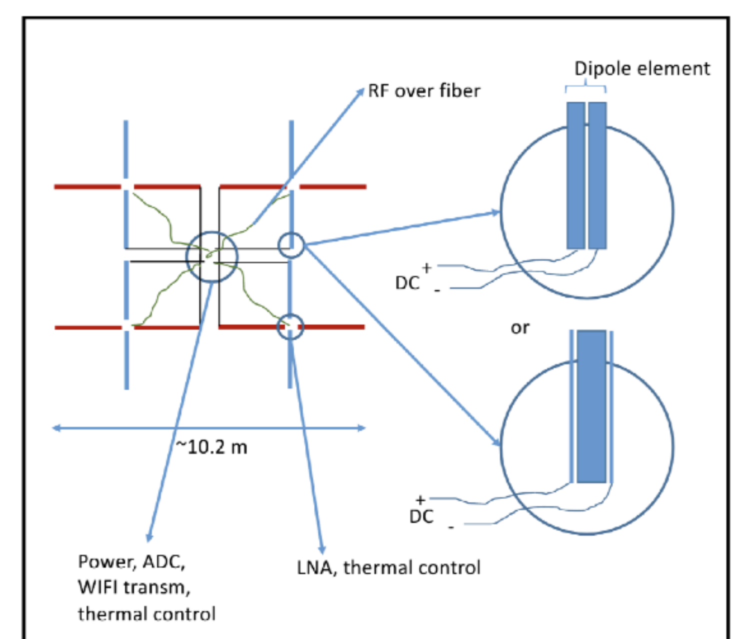
Example of
32x32 array



Placement by
a lunar rover

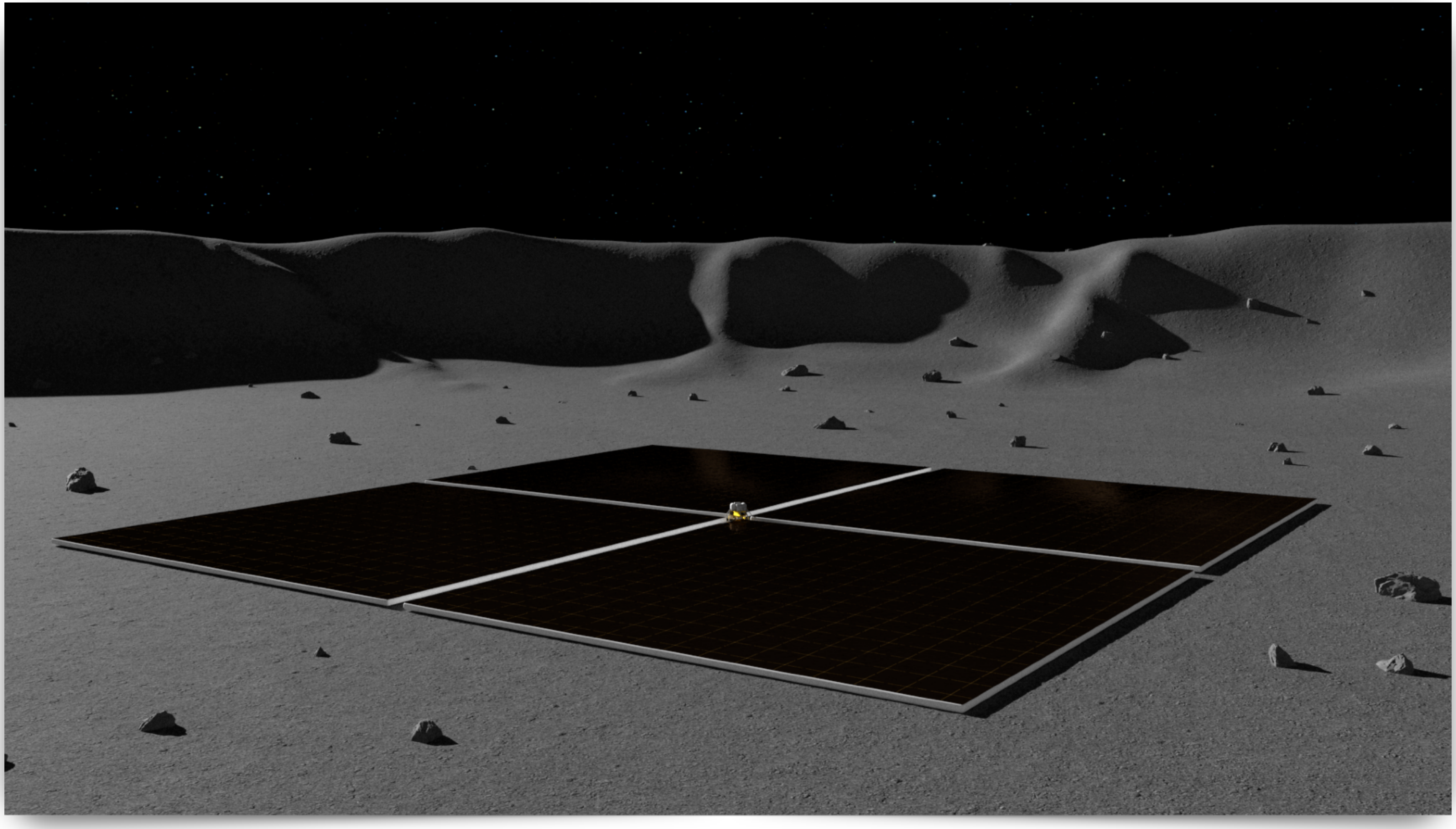


(red: lander, blue: antennas, yellow: magazines)



Astrophysical Lunar Observatory (ALO)

A conformal grid-like array (allowing for a spatial FFT correlation), shielded from (other) activities on the lunar surface, with up to four outrigger global 21-cm receivers placed at a distance.



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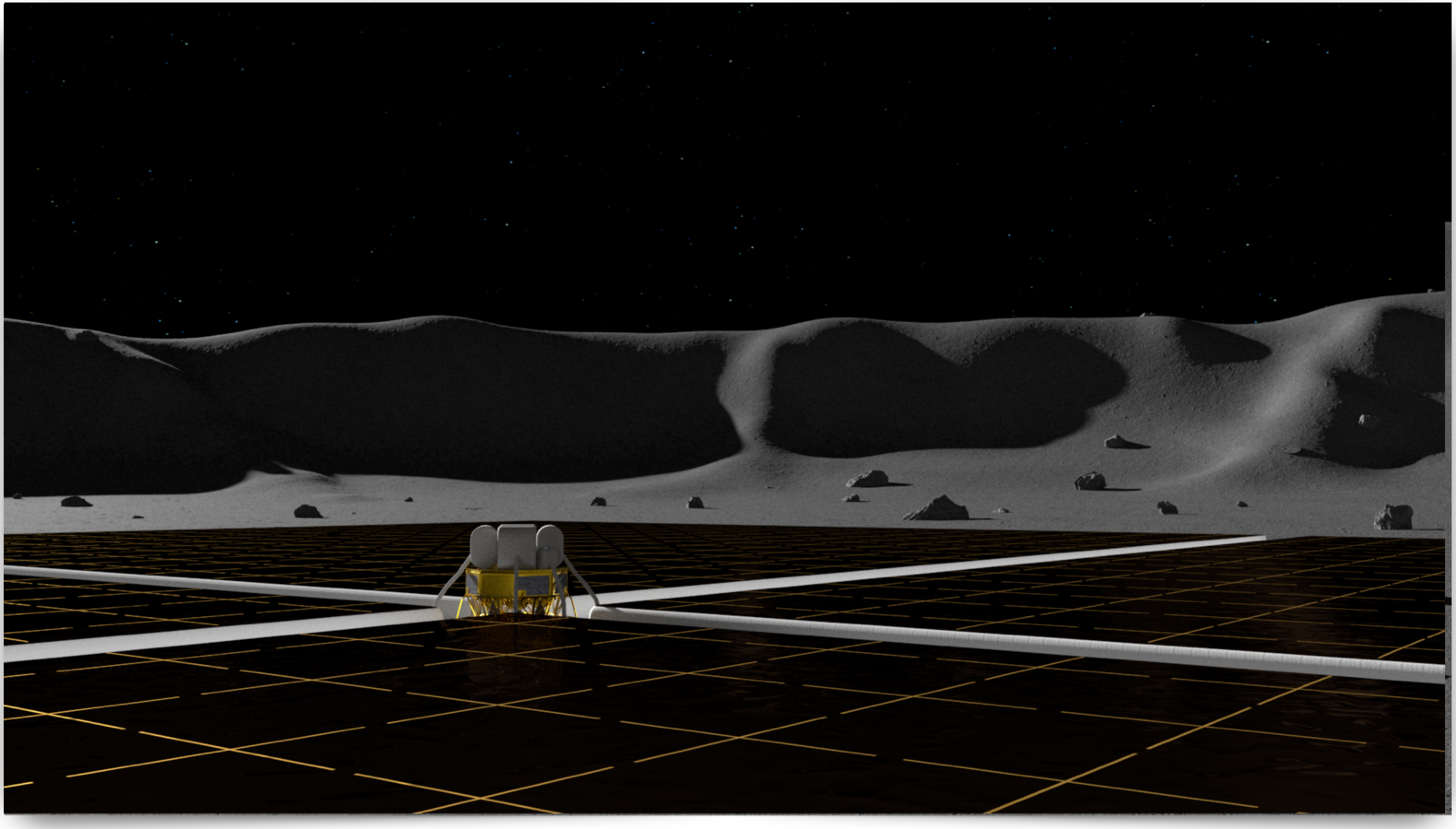

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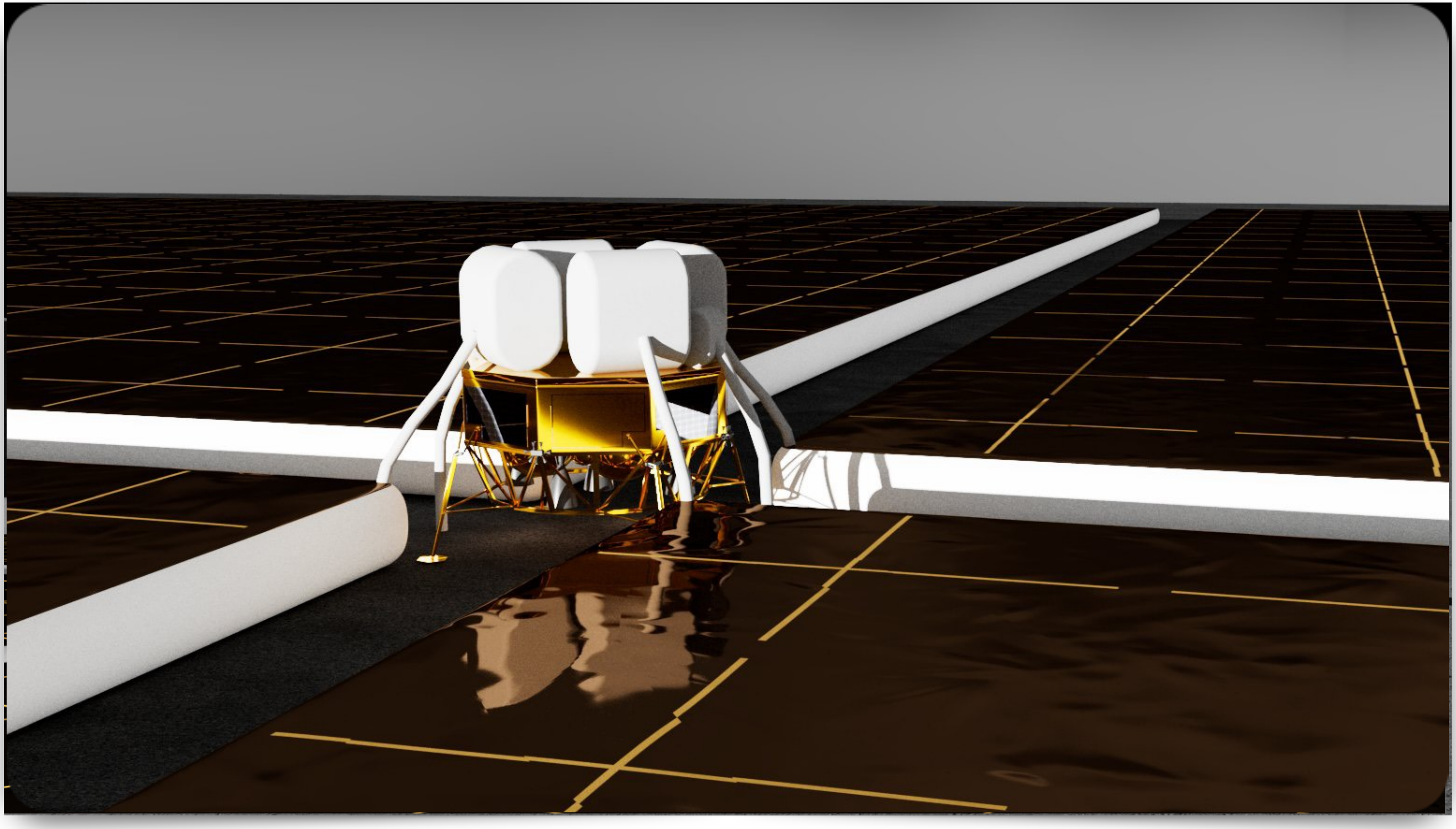
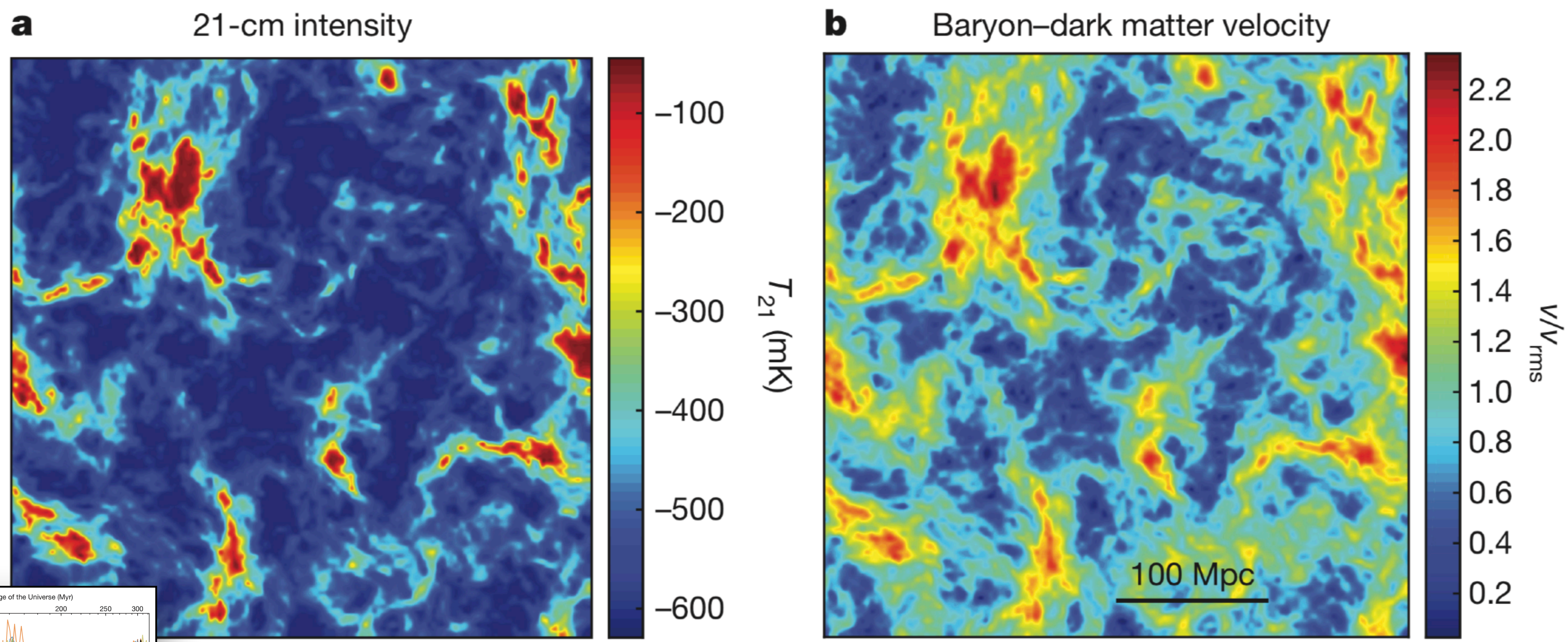


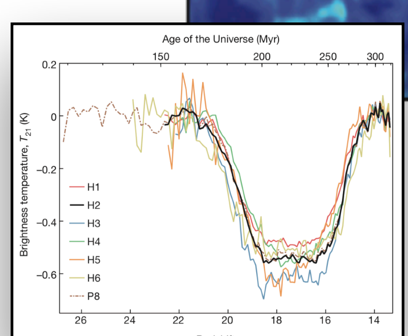
What does ALO aim for?

Power-spectrum measurements & Global 21-cm signal
of the Dark Ages and Cosmic Dawn

ALO can directly image the Cosmic Dawn

ALO is able to directly image the 21-cm signal during the Cosmic Dawn and provide crucial information of very fundamental physical process (e.g. DM-baryon interaction in this case) unlike a statistical (e.g. power-spectrum) detection, and observe the Dark Ages.





Barkana 2018

The Astronomical Lunar Observatory

Power-spectrum sensitivity (standard model; 10^4 hrs)

	Nr. of antennas	Dark Ages Power Spectra (DA)	Cosmic Dawn Power spectra (DP)
Other science	**4 x 4**	S/N << 1	S/N > 1 for z = 20, k from 0.003 to 0.1
	8 x 8	S/N << 1	S/N > 1 for z = 22, k from 0.003 to 0.1
	16 x 16	S/N << 1	S/N > 1 for z = 22, k from 0.003 to 0.2
21-cm Cosmology	**32 x 32**	S/N << 1	S/N > 1 for z = 25, k from 0.003 to 0.1
	64 x 64	S/N << 1	S/N > 1 for z = 27, k from 0.003 to 0.1
	128 x 128	S/N < 1	S/N > 1 for z = 28, k from 0.003 to 0.1
	1024 x 1024	S/N ~ 10 for z = 50, k from 0.002 to 0.2	S/N ~ 10 for z = 28, k from 0.003 to 1

Interferometers are extremely flexible instruments: ALO is a scalable experiment that can start small and grow over time and do science from day one.

The Astronomical Lunar Observatory

Global 21-cm Signal Sensitivity (standard model)

Pilot for array if on earlier EL3 (e.g on poles)

Faster signal detection

Better control of systematics

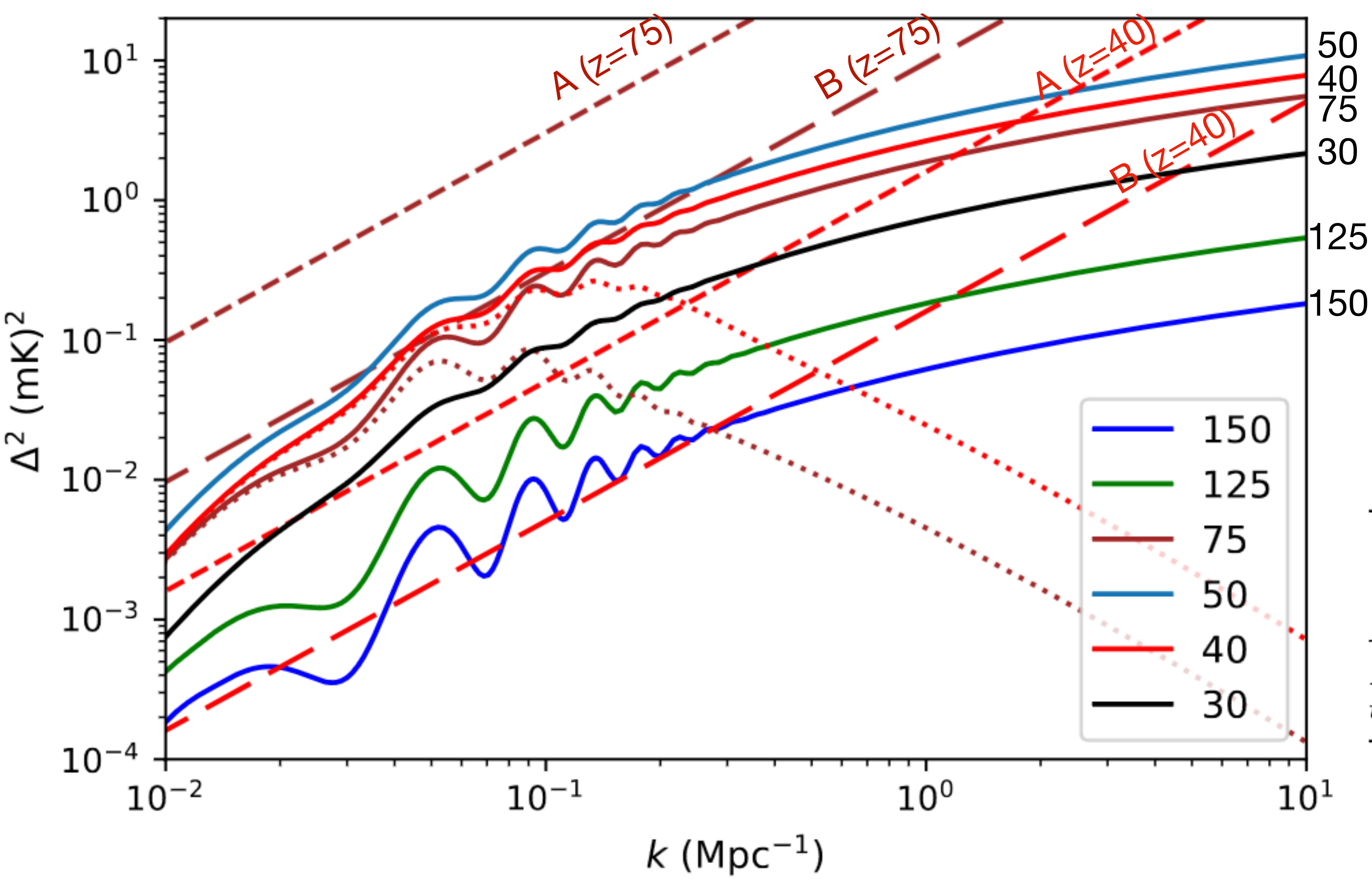
Different designs?

Different locations

Nr. of antennas	Global Dark Ages signal (DA)	Global Cosmic Dawn signal (CD)
1	For z = 80 (17.5 MHz), bandwidth 10 MHz, deltaT = 10 mK: t_int = 2000 hours.	For z = 20 (70 MHz), bandwidth 1 MHz, deltaT = 10 mK: t_int = 17 hours.
2	For z = 80 (17.5 MHz), bandwidth 10 MHz, deltaT = 10 mK: t_int = 1400 hours.	For z = 20 (70 MHz), bandwidth 1 MHz, deltaT = 10 mK: t_int = 12 hours.
3	For z = 80 (17.5 MHz), bandwidth 10 MHz, deltaT = 10 mK: t_int = 1150 hours.	For z = 20 (70 MHz), bandwidth 1 MHz, deltaT = 10 mK: t_int = 10 hours.
4	For z = 80 (17.5 MHz), bandwidth 10 MHz, deltaT = 10 mK: t_int = 1000 hours.	For z = 20 (70 MHz), bandwidth 1 MHz, deltaT = 10 mK: t_int = 8.5 hours.

Astrophysical Lunar Observatory (ALO)

Power-spectrum sensitivity for 16 (4x4), 1024 (32x32), 16384 (128x128) receivers:
Compact (f=1) array, 5m dipoles, BW=10MHz, 10^4h integration, half-sky



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	Configuration			
	D	C	B	A
$A_{\rm coll}$ [km^2]	100	100	10	10
$t_{\rm int}$ [hrs]	10,000	1,000	10,000	1,000

[Note an array of 128x128 5x5m dipoles has "only" A_{eff}=0.4km^2 at 30MHz;
Larger A_{eff} than the SKA-low core and 100x SKA-low's FoV at 50MHz]

Summary

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- 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 **DA detections from Earth is excluded by 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** encodes 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)