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



**CDF Study Report**  
**ASTROPHYSICAL LUNAR OBSERVATORY**  
Assessment of an Astrophysical Lunar Observatory  
on the farside of the Moon



CDF-219(A)  
October 2021

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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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Bharat Gehlot<sup>7</sup> · Leonid Gurvits<sup>13</sup> · Vibor Jelic<sup>14</sup> · Marc Klein-Wolt<sup>11</sup> ·  
Joseph Lazio<sup>15</sup> · Daan Meerburg<sup>16</sup> · Garrelt Mellema<sup>17</sup> · Florent Mertens<sup>1,18</sup> ·  
Andrei Mesinger<sup>19</sup> · André Offringa<sup>4</sup> · Jonathan Pritchard<sup>20</sup> · Benoit Semelin<sup>18</sup> ·  
Ravi Subrahmanyam<sup>21</sup> · Joseph Silk<sup>22,23</sup> · Cathryn Trott<sup>24</sup> · Harish Vedantham<sup>4</sup> ·  
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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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# *What can “21-cm Cosmology” tell us?*

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

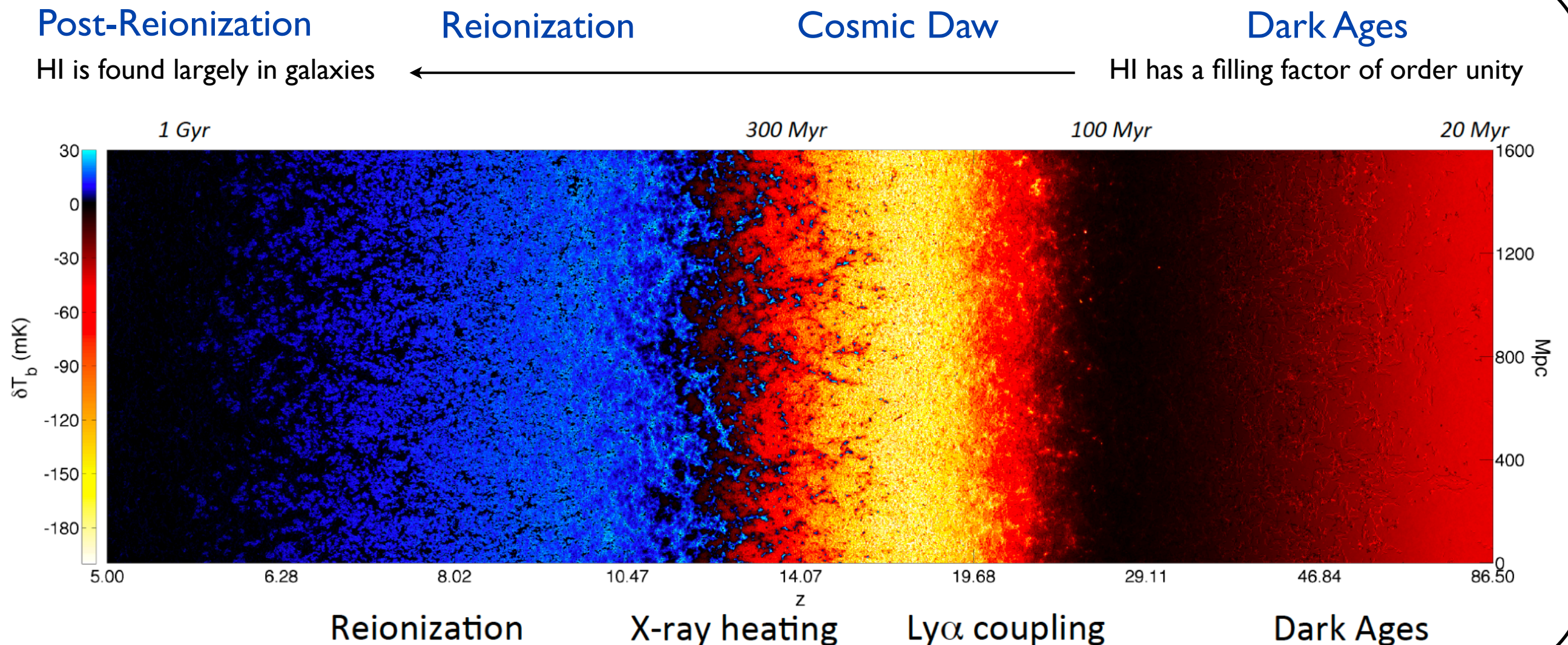
*=*

*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.



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:

$$\begin{aligned}
 \boxed{\delta T_b} &= \frac{T_S - T_R}{1 + z} (1 - e^{-\tau_\nu}) \\
 &\approx \frac{T_S - T_R}{1 + z} \tau
 \end{aligned}$$

Cosmology

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

Ionization

(G)astrophysics

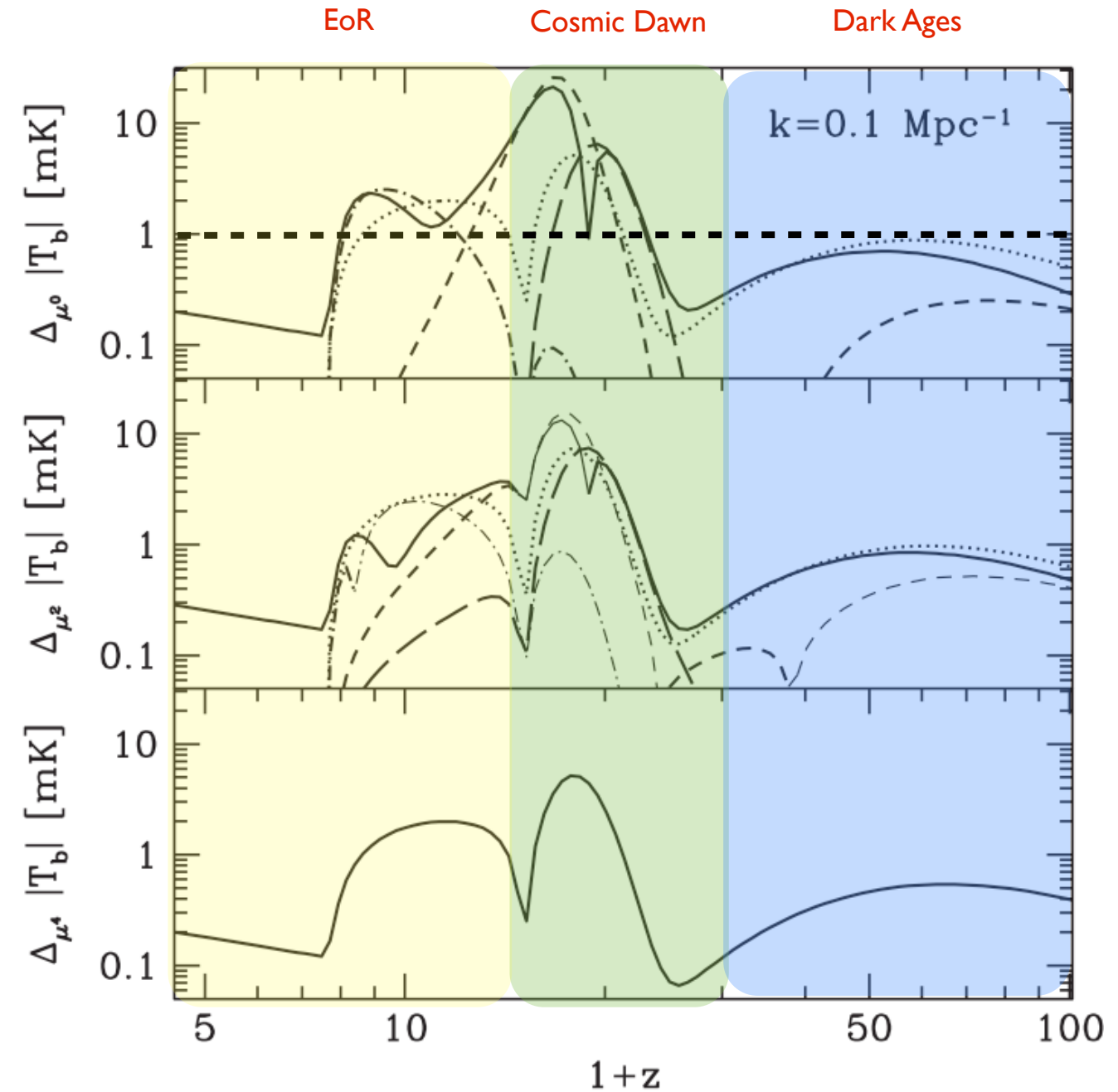
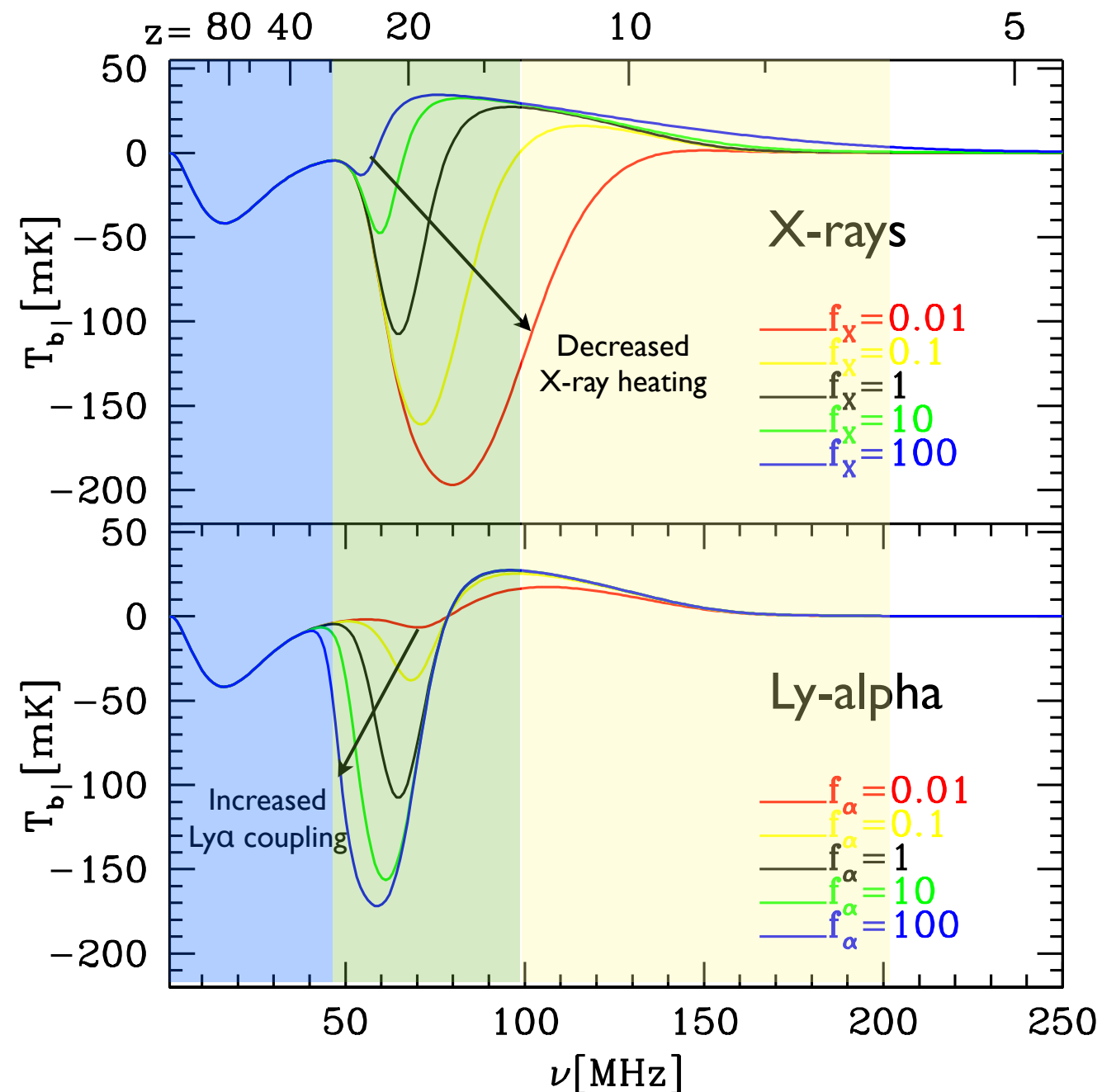
Peculiar velocities/Bulk-flows

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



# What can “21-cm Cosmology” tell us?

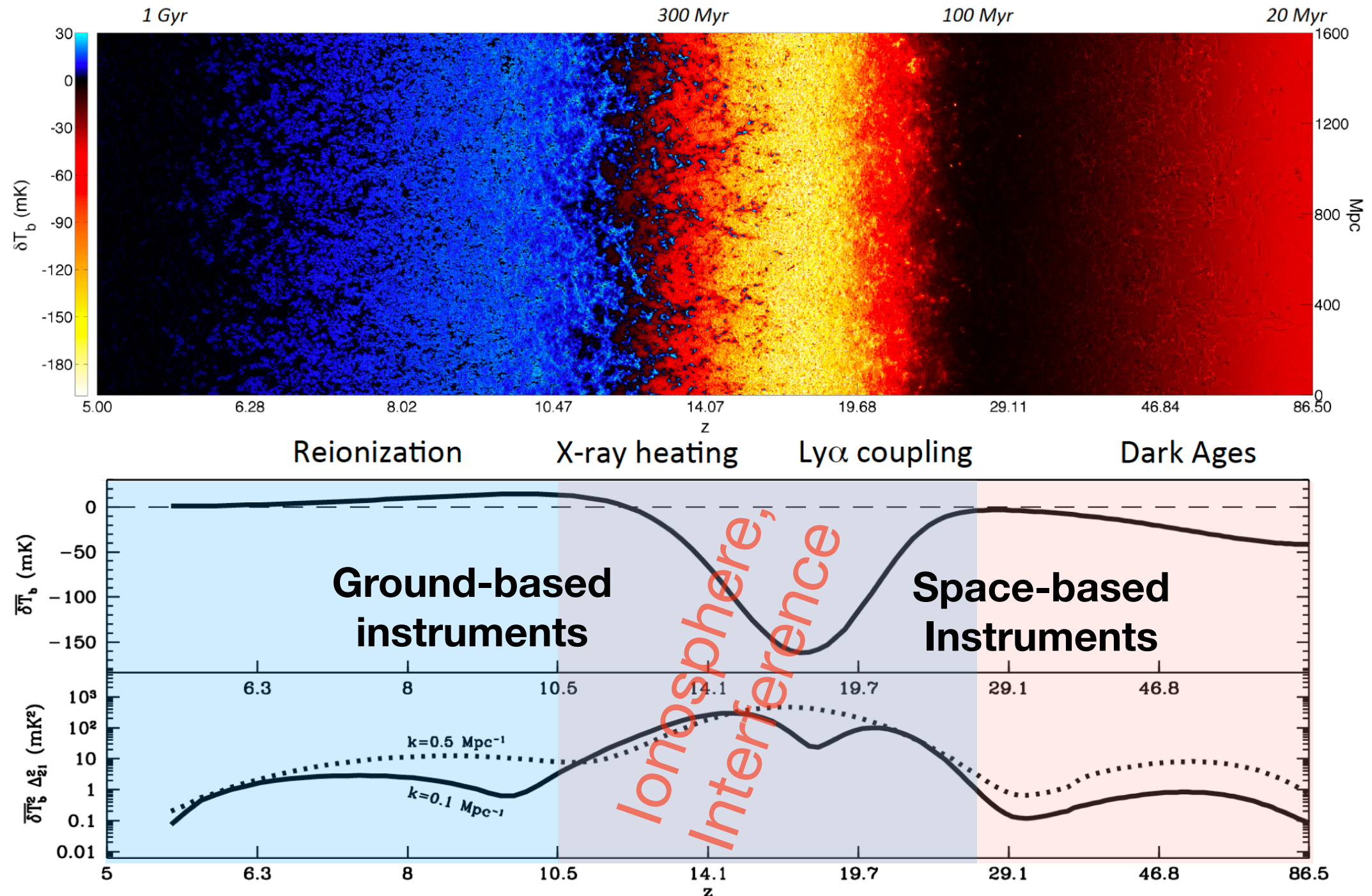
## Global Signal (left) and Intensity Fluctuations (right)



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

# What can “21-cm Cosmology” tell us?

Between  $z \sim 200^*$  and  $z \sim 6^{**}$ , neutral hydrogen is a key tracer of fundamental physical processes (early stages) and unique astrophysical processes (later stages)



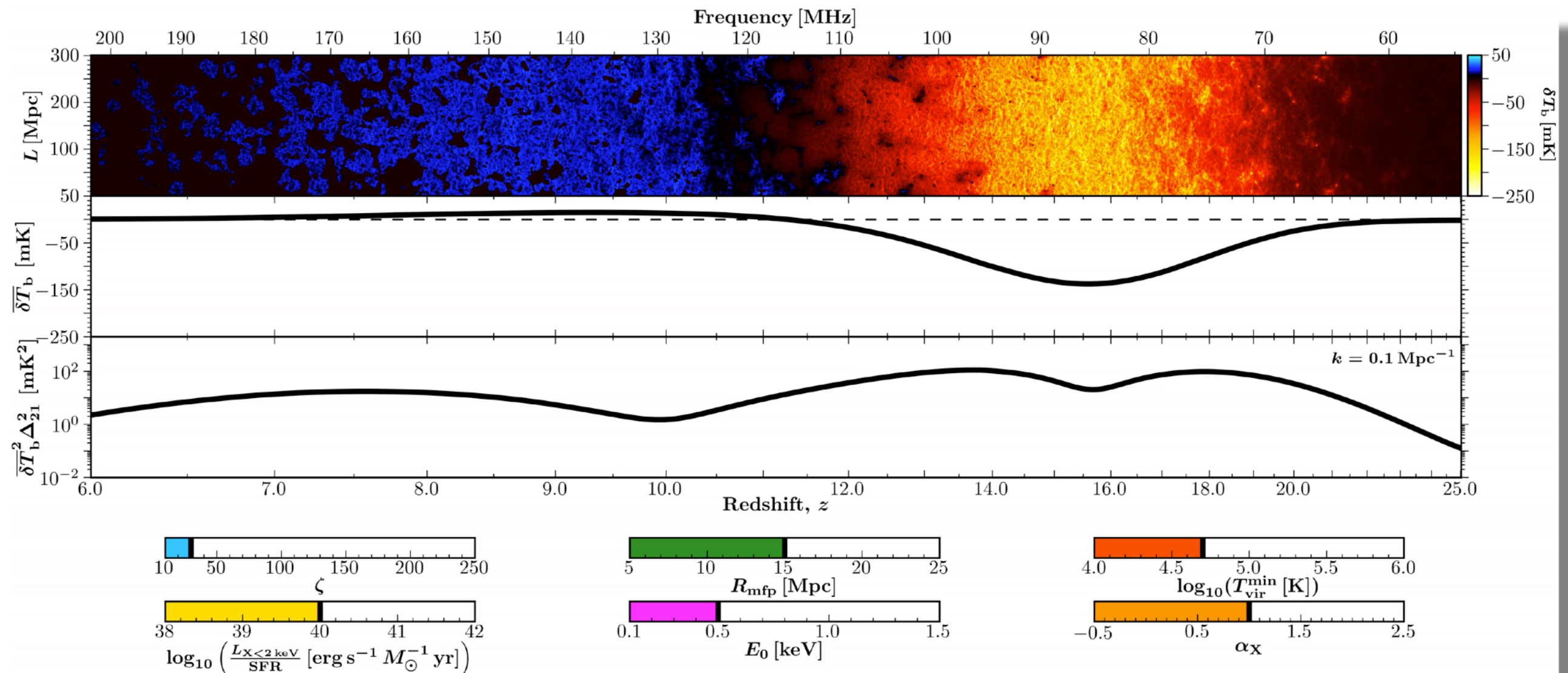
\* Spin & CMB-temperature decouple; \*\* universe is reionized



# 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.

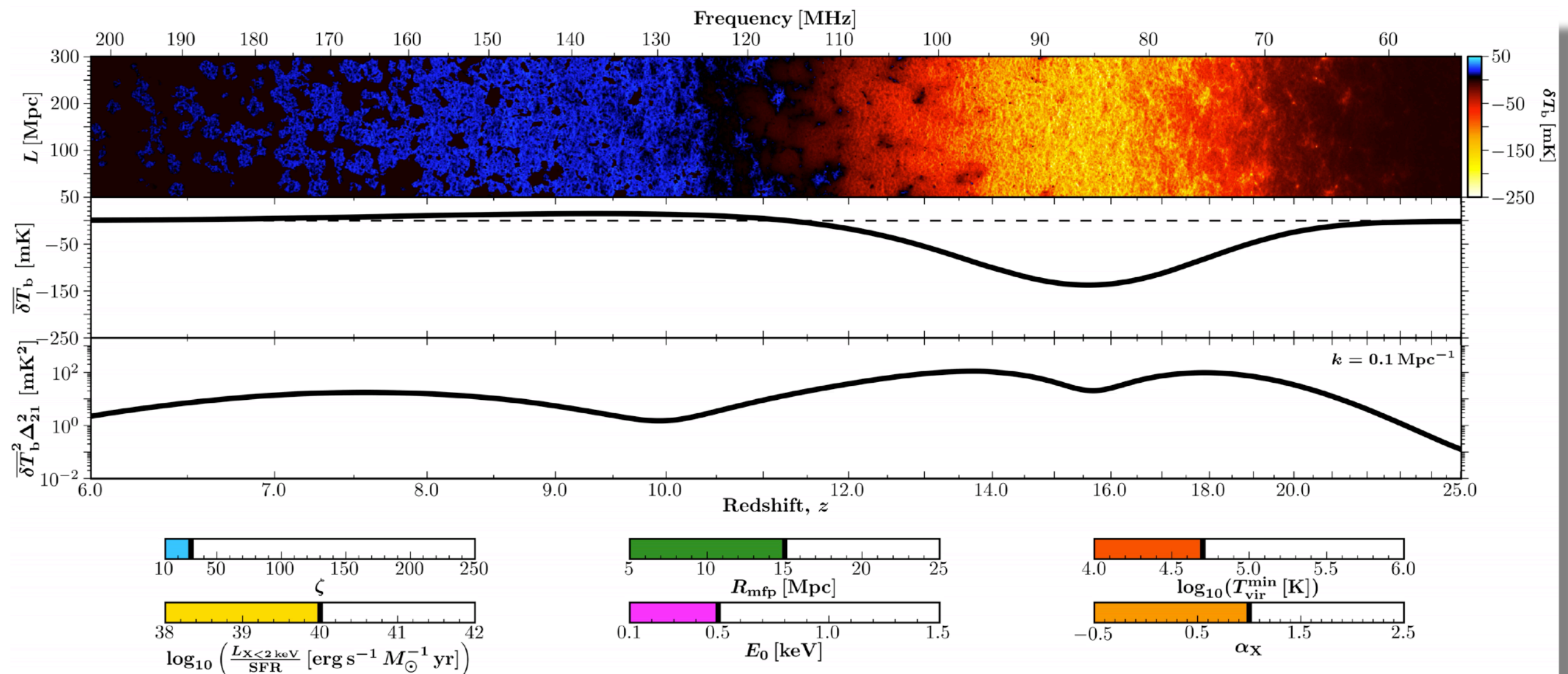


Credit movie: Mesinger & Greig

# What can “21-cm Cosmology” tell us?

## Numerical Models

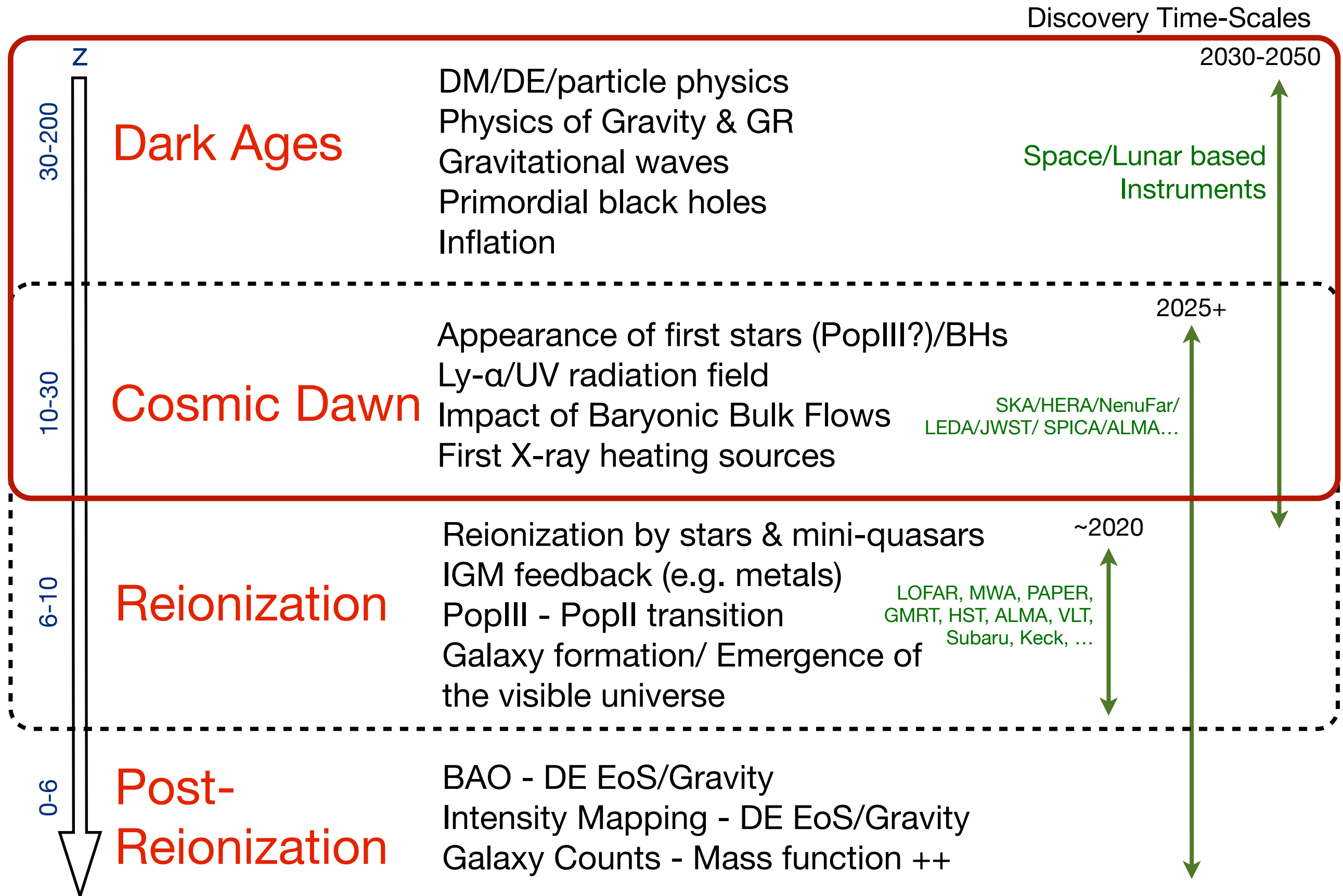
Many “ingredients” in the 21-signal models are effective descriptions of the underlying complex physical processes (sub-grid physics) that we hope to connect to these processes on smaller (galaxy/stellar) scales.



Credit movie: Mesinger & Greig



# What can “21-cm Cosmology” tell us?





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# *Why go to space for 21-cm Cosmology?*

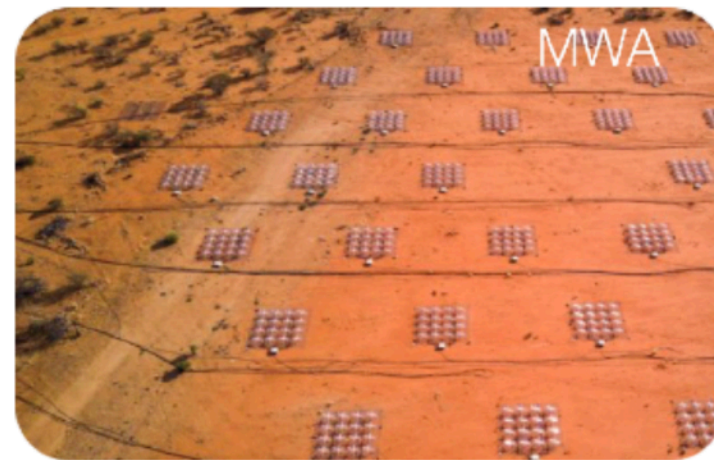
Observing the 21-cm signal at ( $z \gg 10$ ) is very hard!!



# 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  $z \sim 6$  to  $z \sim 25$**   
**with ground-based interferometers** — *experiments are extremely hard!*

Past/Current  
instruments  
focussing  
mostly on  $z < 10$



Upcoming  
instruments  
in coming  
decade  
focussing  
mostly on  
 $z \sim 6-25$

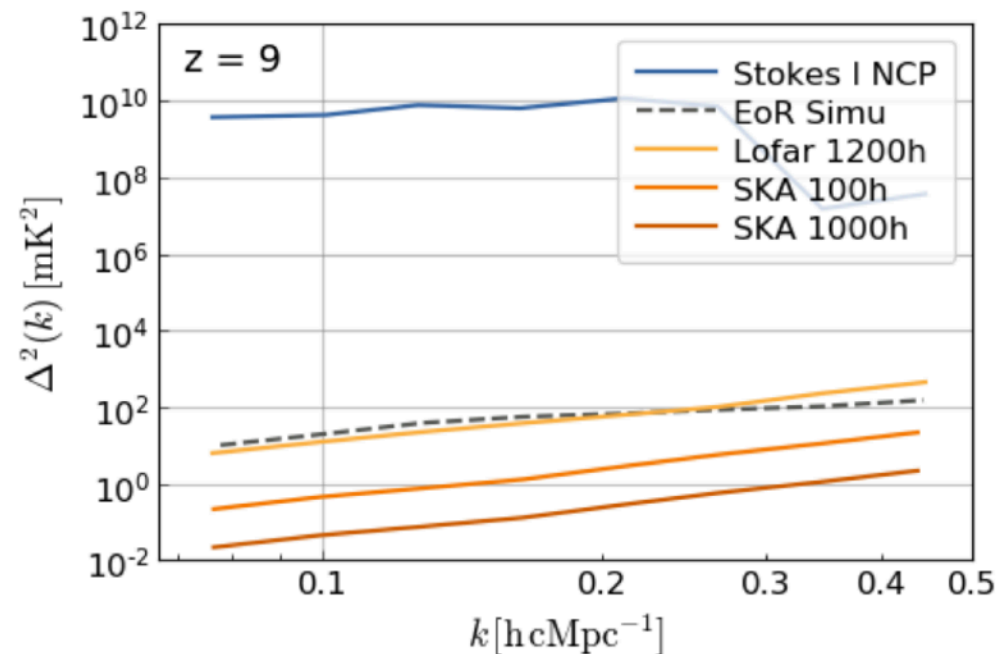




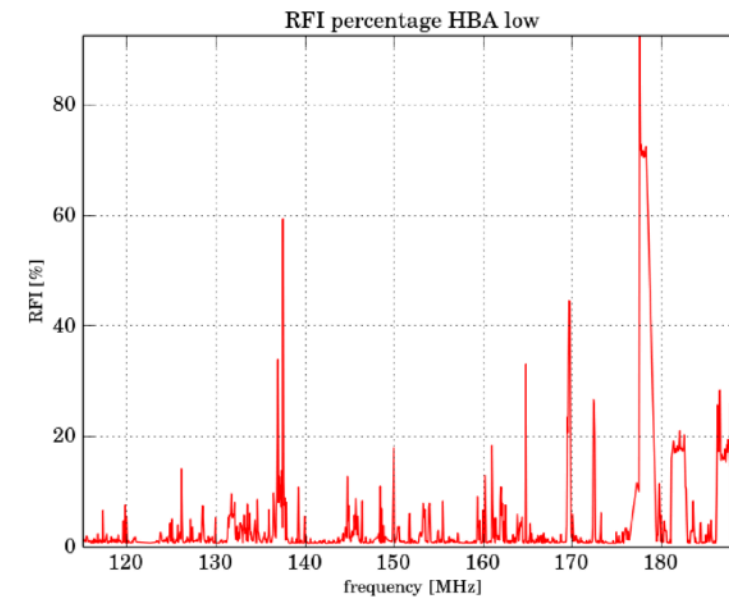
# Ground-based interferometry experiments

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

## Foregrounds

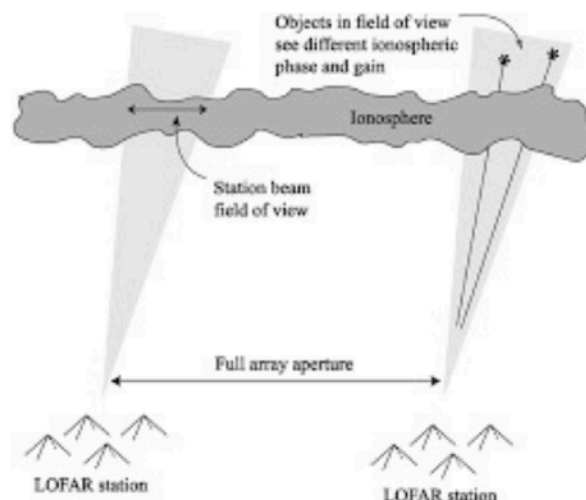


## Radio Frequency Interference (RFI)



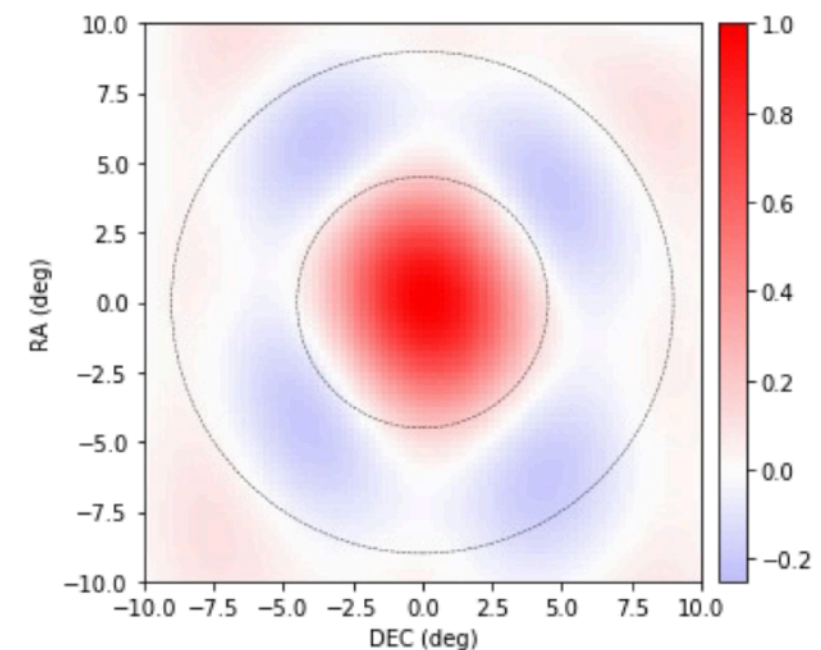
Credit: A. Offringa

## 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 alone image it.

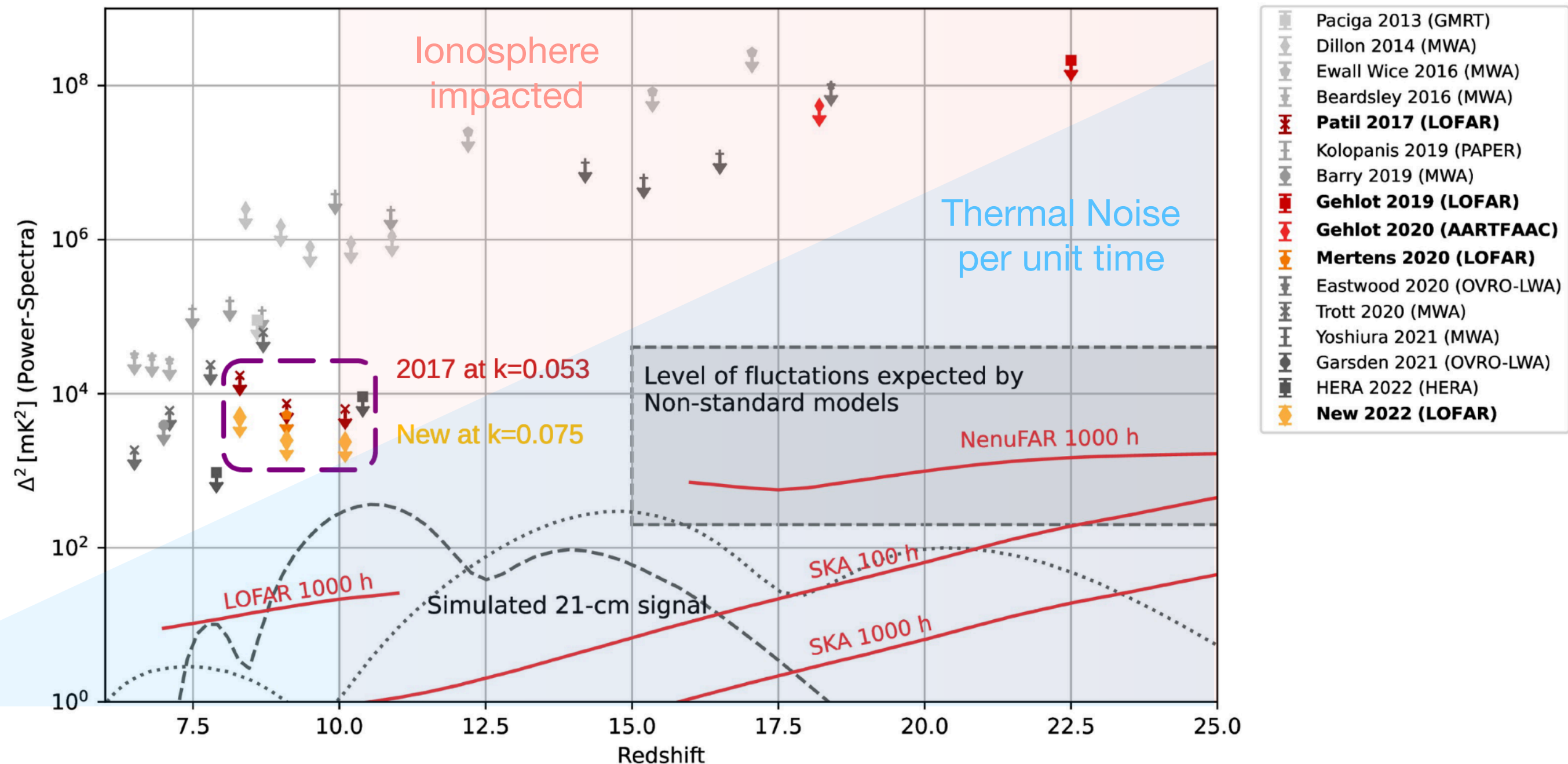
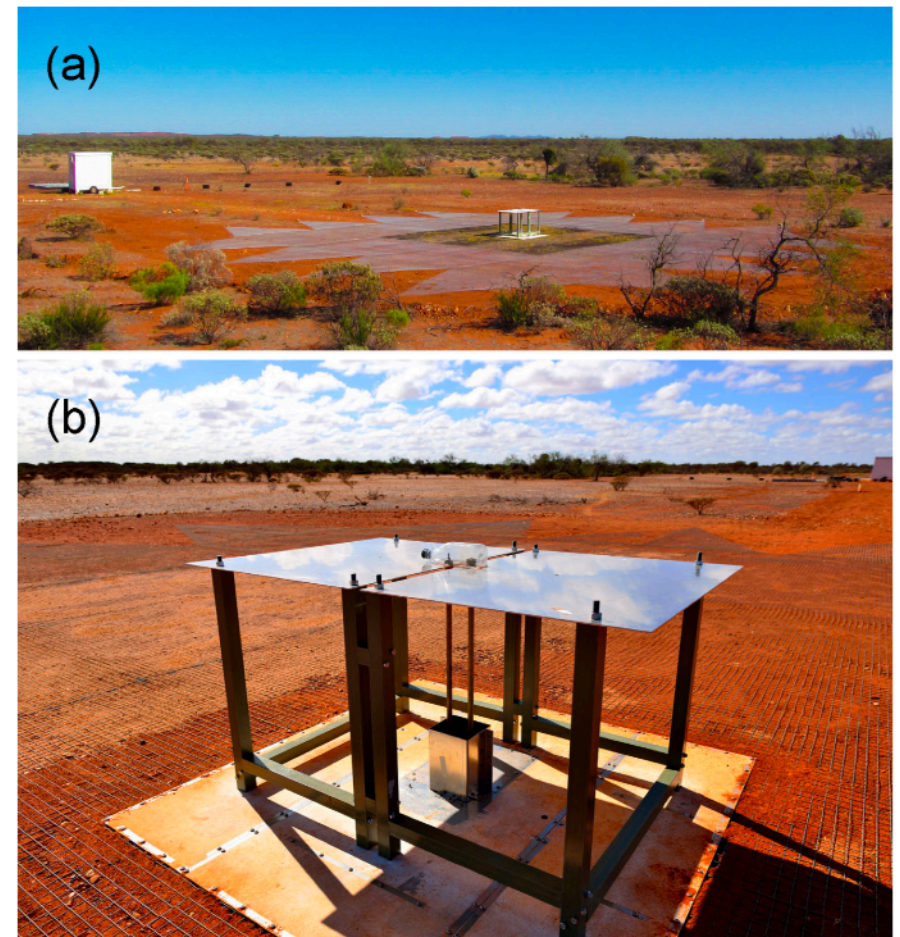
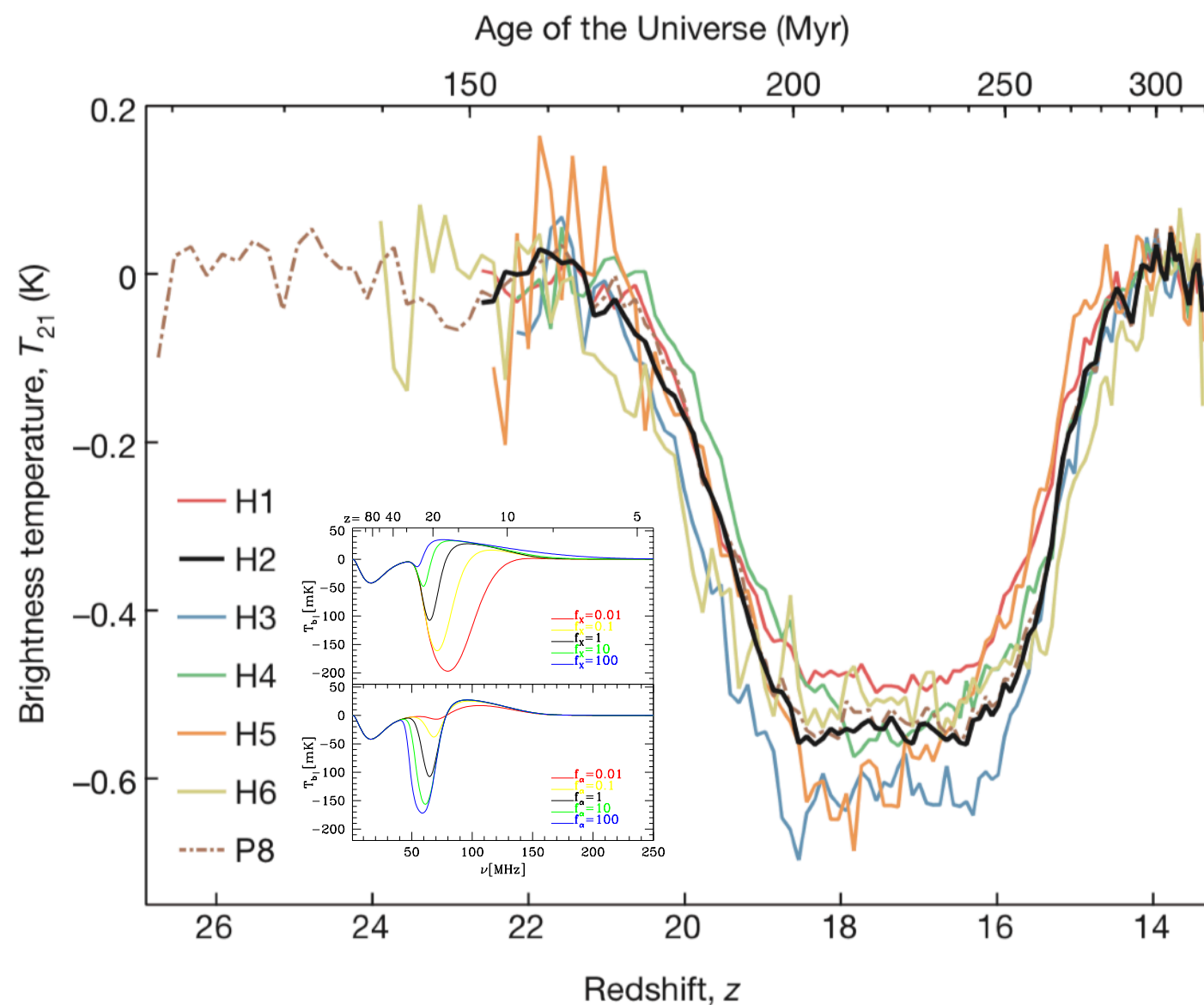


Figure: credit Florent Mertens

# 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.

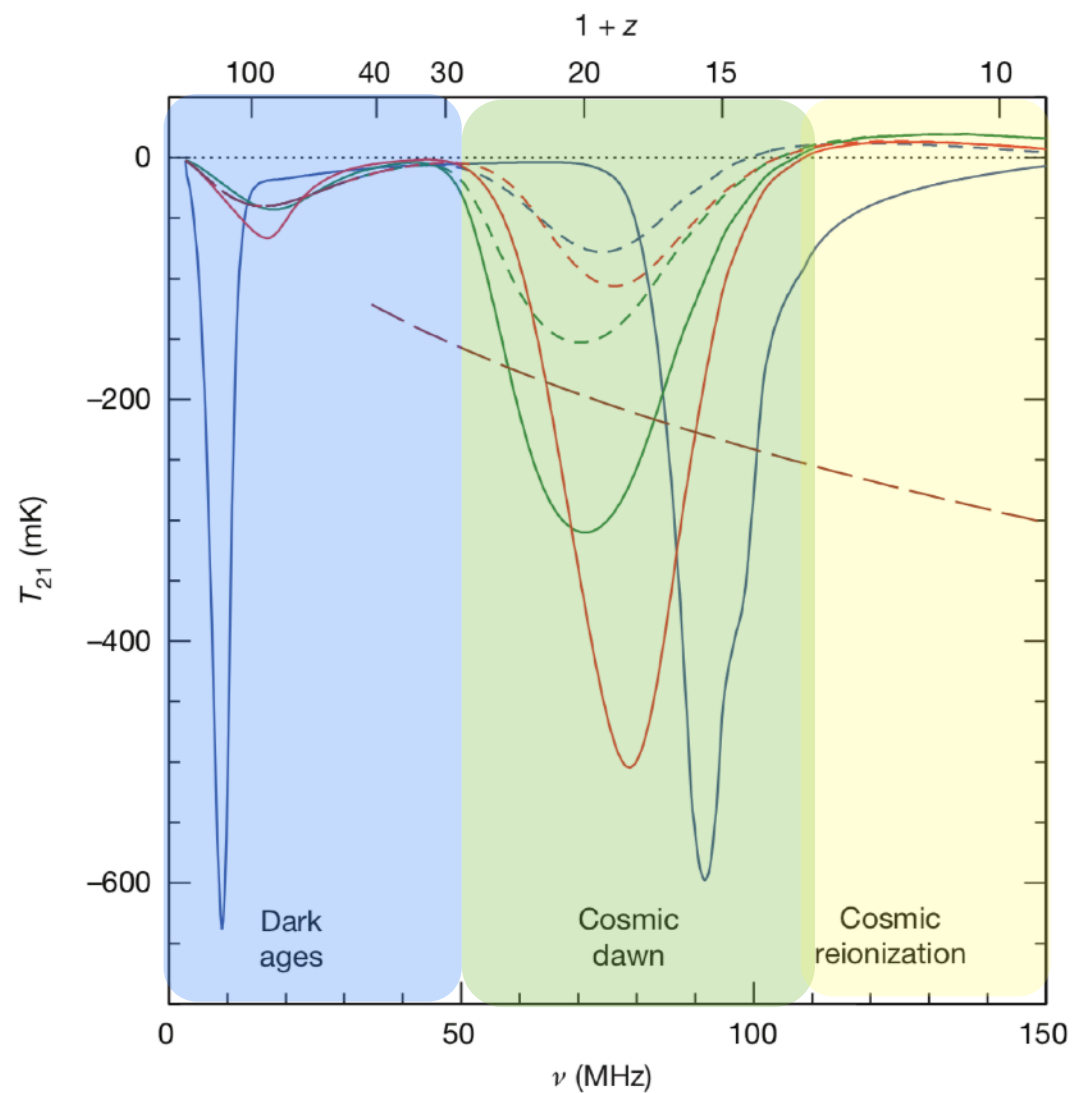


Bowman et al. 2018 (Nature)

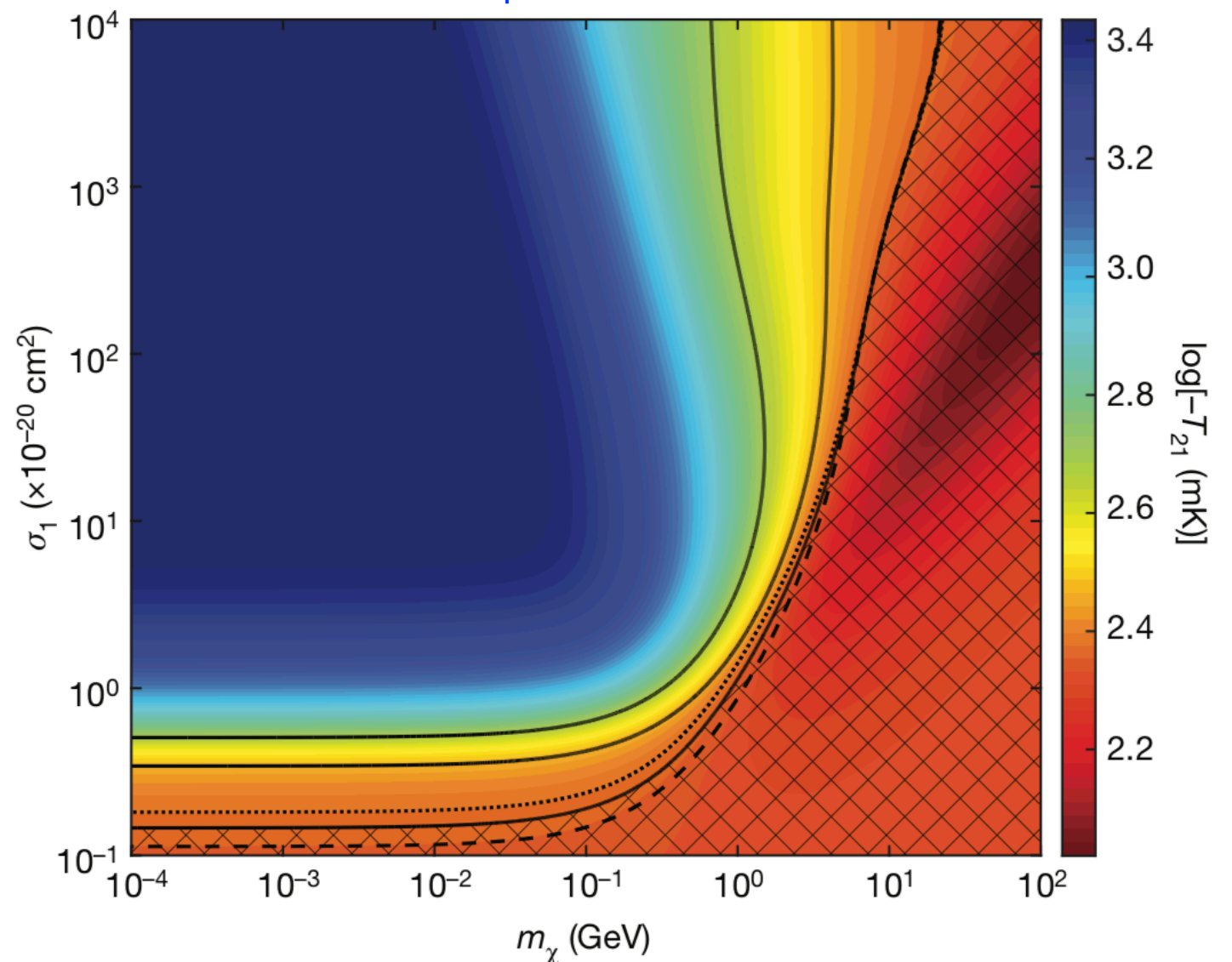
# Ground-based global experiments

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



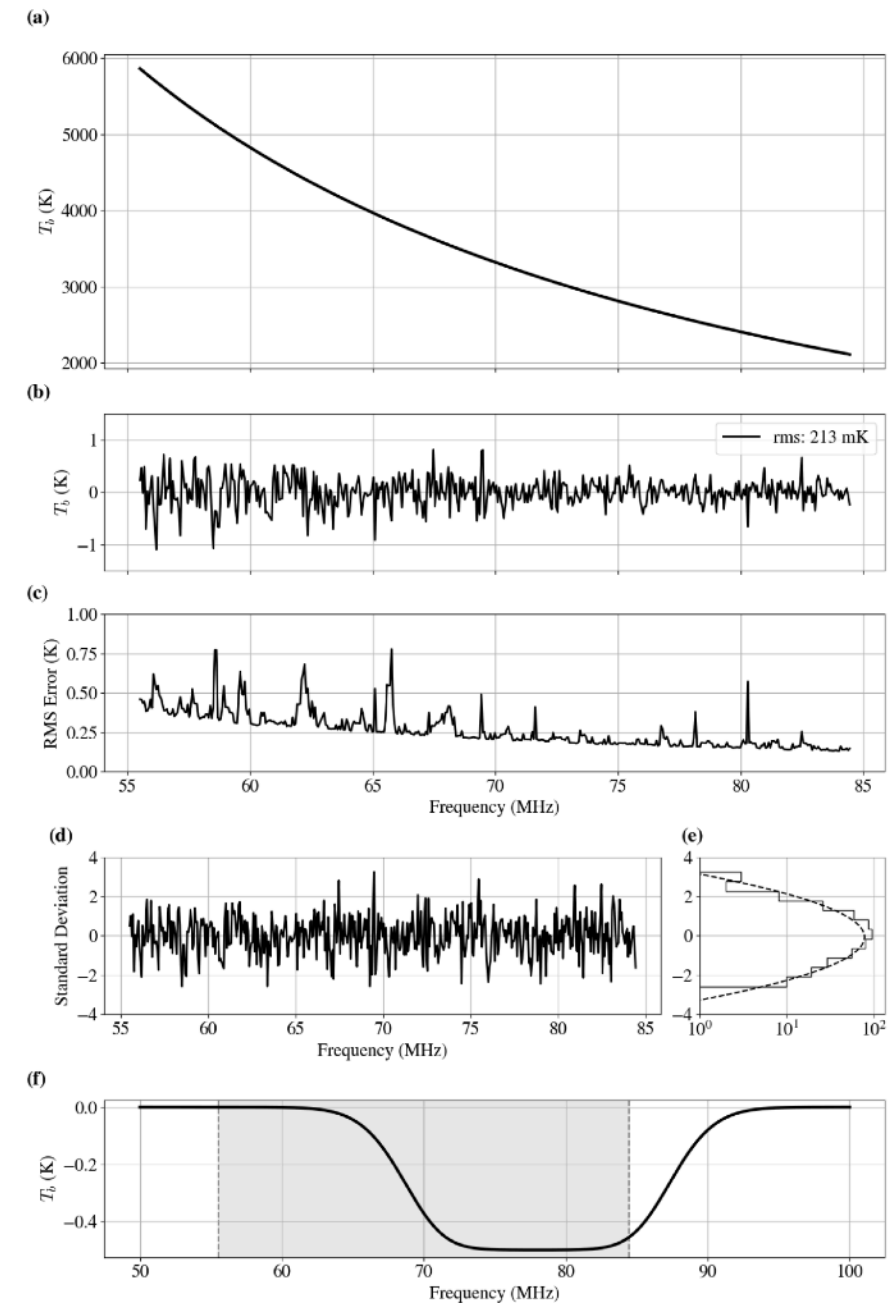
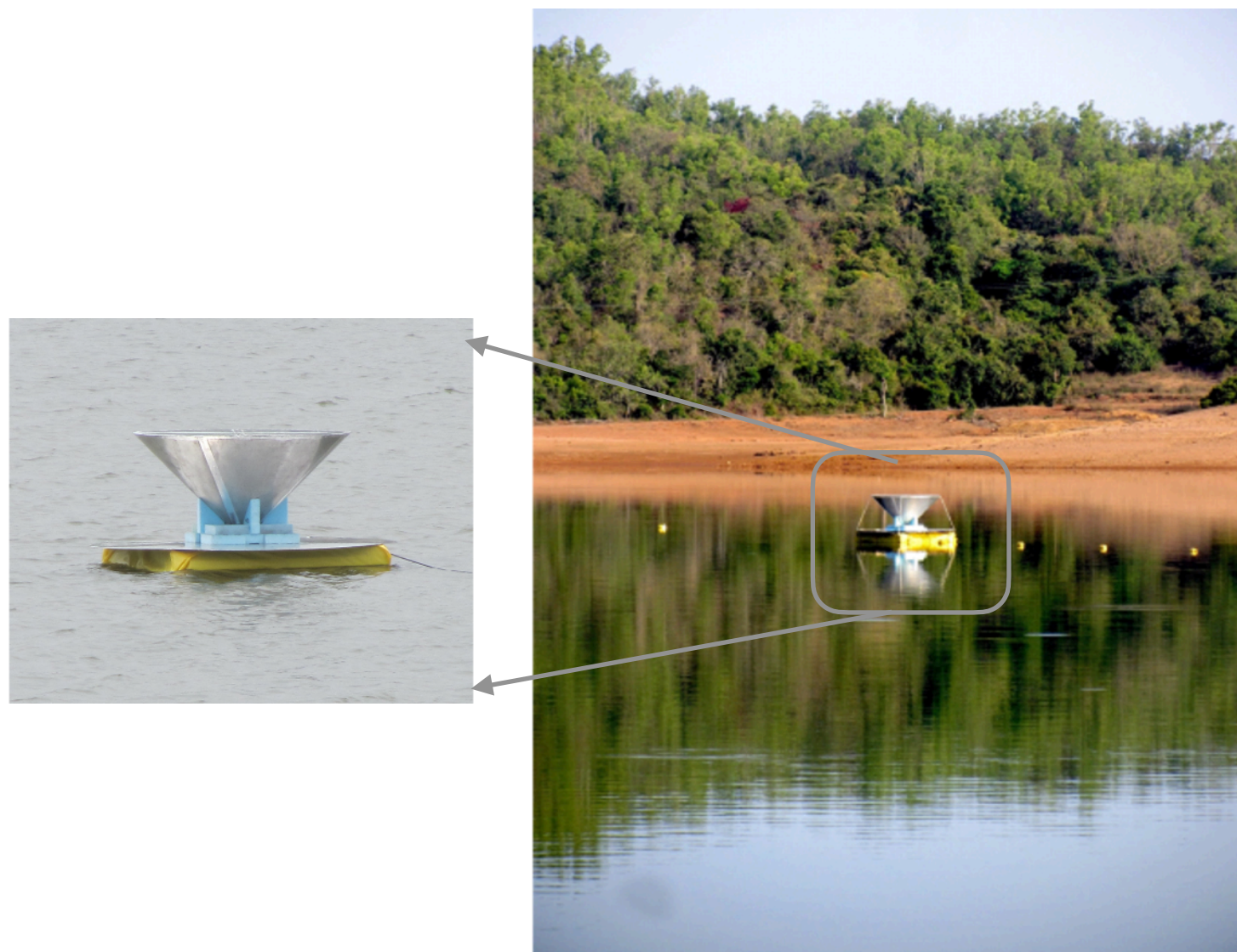
Barkana 2018 (Nature)



# 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 ( $\sim 3\sigma$ ).


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  $z \sim 6$ -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.

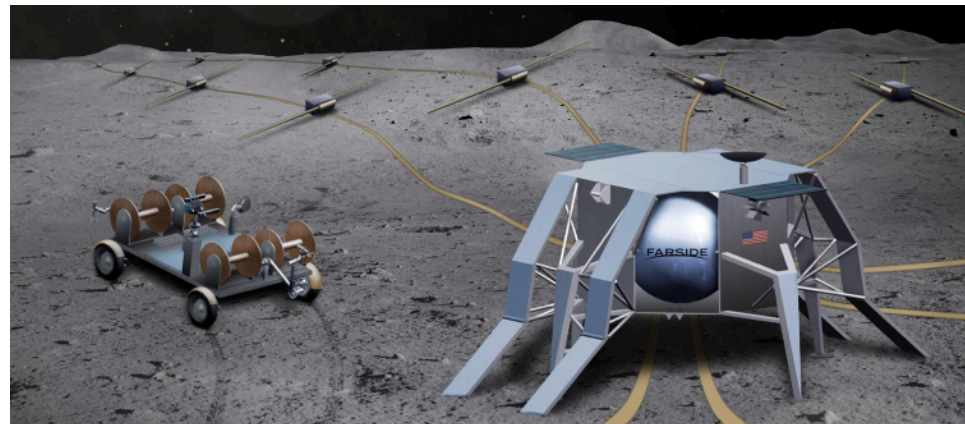


Most challenges are largely mitigated in space, in particular far away from Earth (L2), in lunar orbit or on the lunar far-side:  
**No ionosphere, >80dB RFI suppression, stable environment**

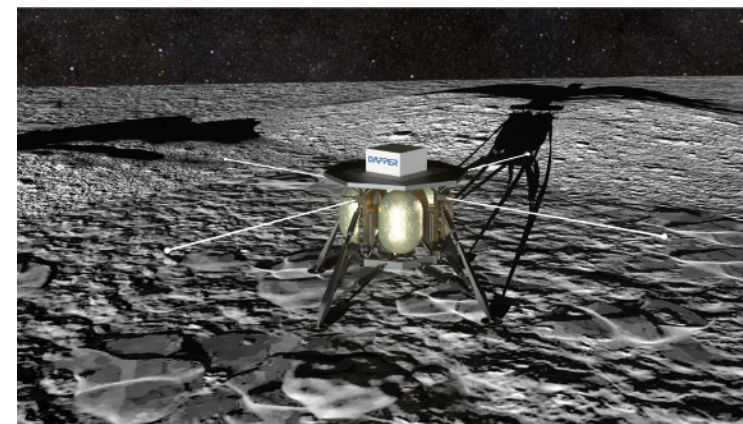


# Many ongoing initiatives for space missions/ experiments — US, China, India

## DAPPER/ROLSES/LuSEE/FAR SIDE PI: Burns



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



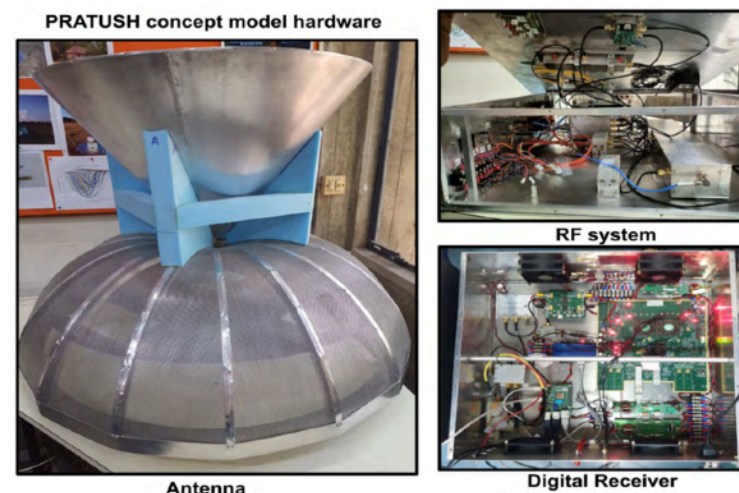
Di-pole receiver in orbit to measure the  
global 21-cm signal ( $z \sim 83-36$ )

## 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



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



# *What about initiatives in NL/Europe?*

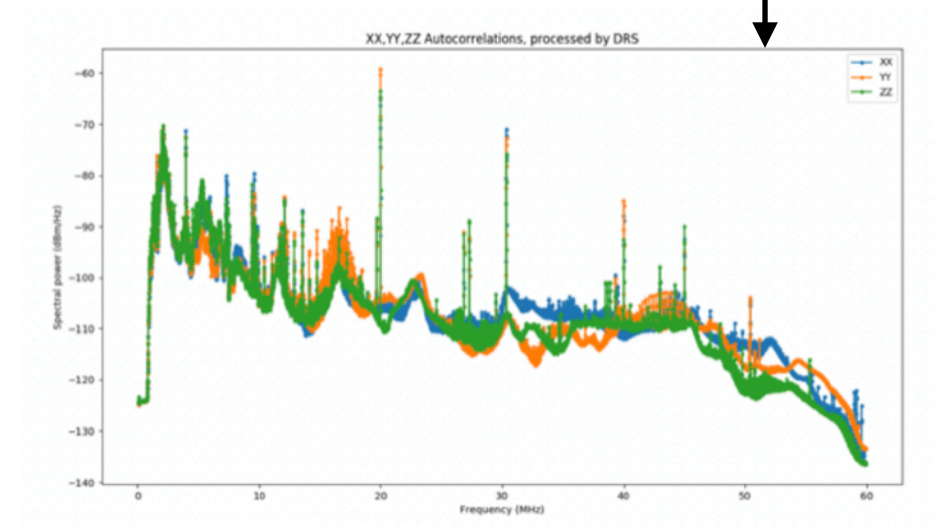
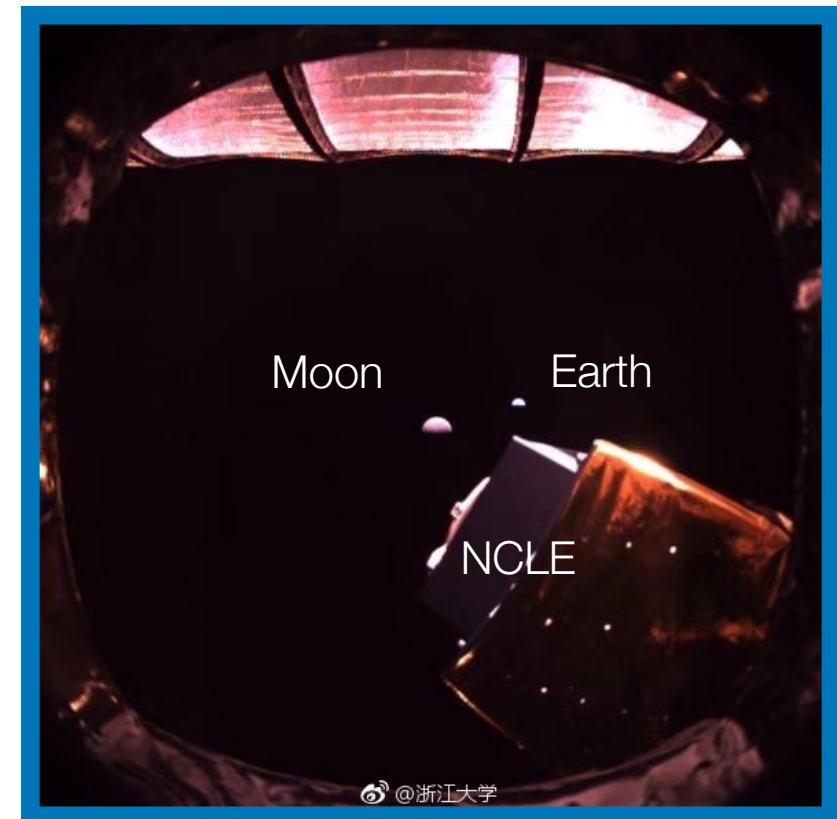
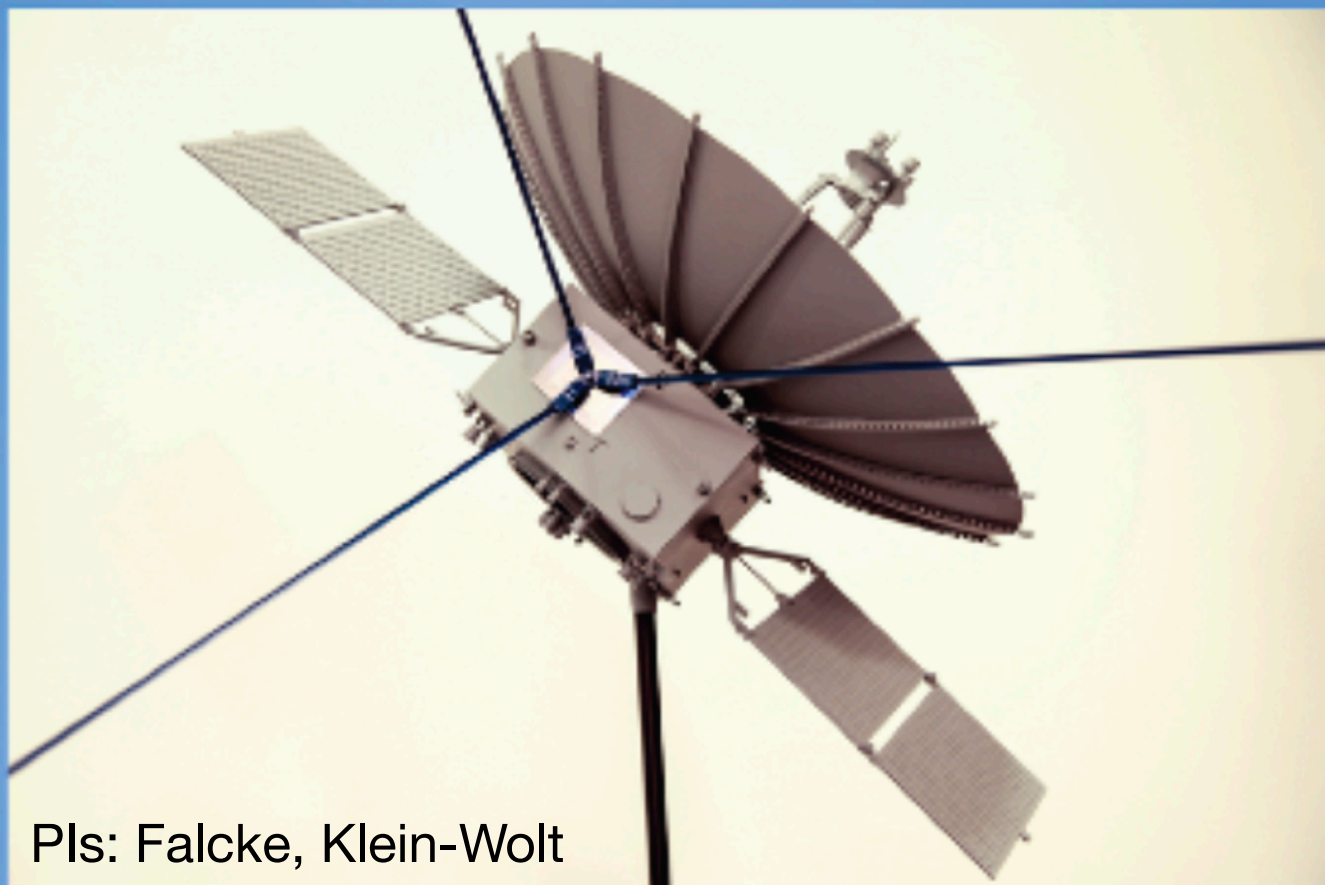
Many past proposals: ALFIS, DARIS,  
SURO, LRX, OLFAR going back 30  
years (not just 21-cm science) and one  
realised system: NCLE (in lunar L2)

**TU Delft**  
Delft University of Technology

Faculty of Aerospace Engineering

# 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







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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 ( $z \sim 30-200$ )

- 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 ( $z \sim 10-30$ )

- 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<sup>2</sup>
- 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

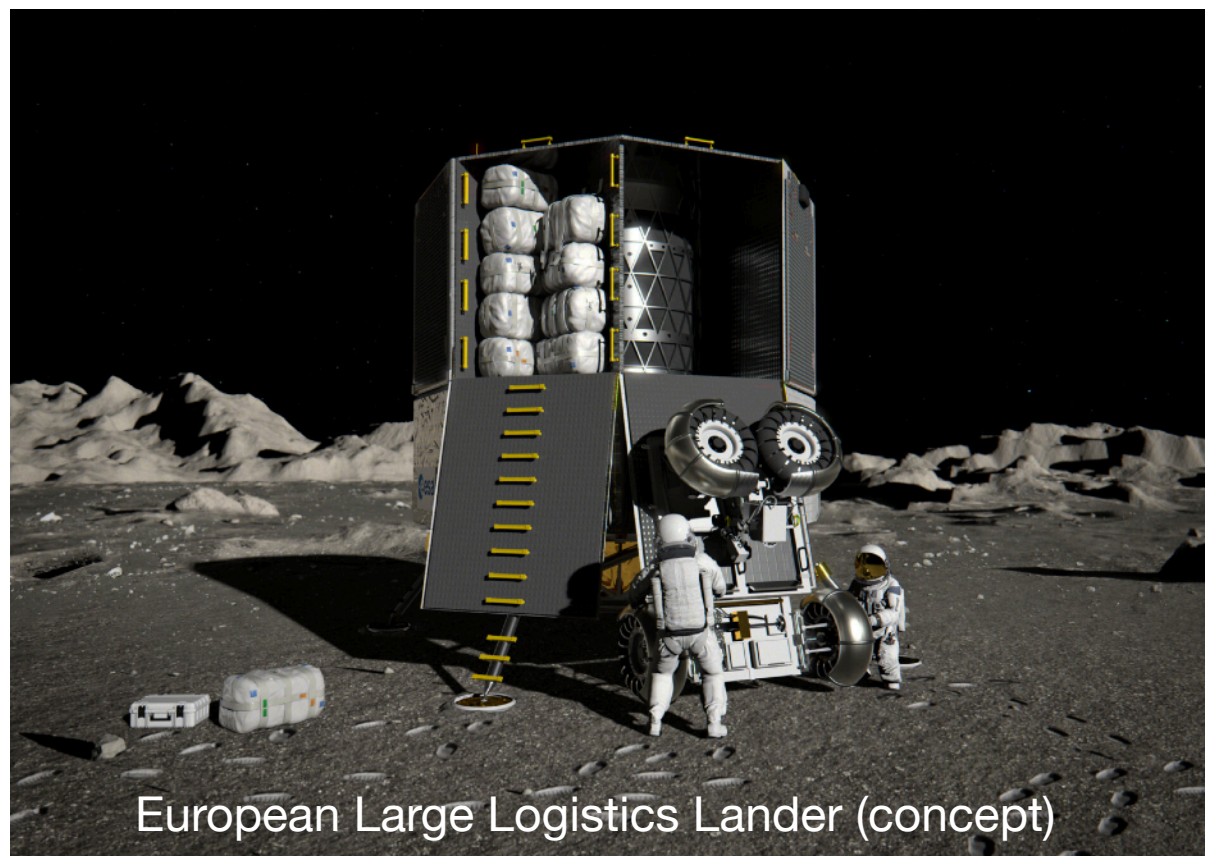
## Potential locations

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

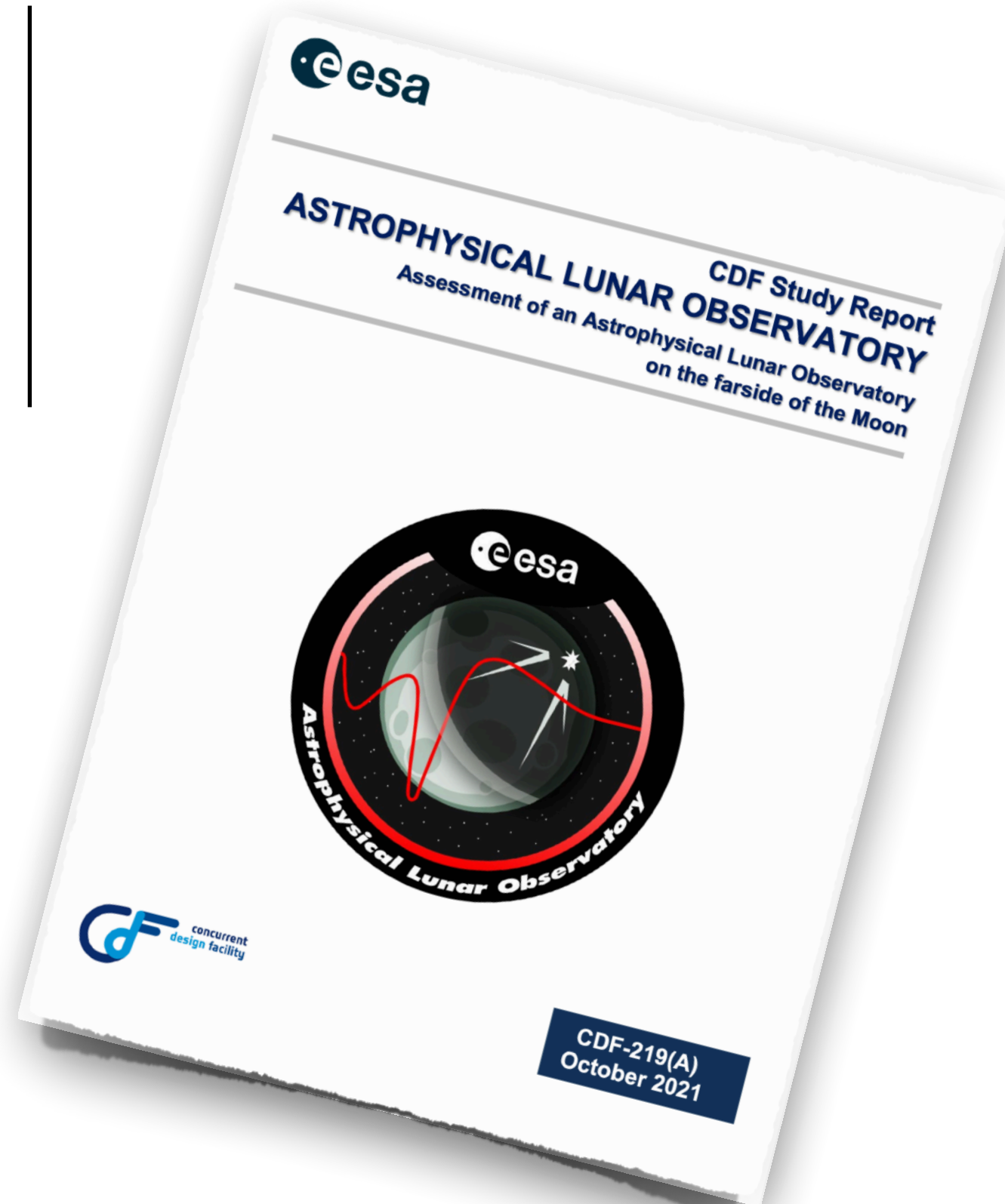


# Astrophysical Lunar Observatory (ALO)

- 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 and Dark Ages redshifts ( $z > \sim 15$ ), needing  $>10^4$  hours of integration.



European Large Logistics Lander (concept)



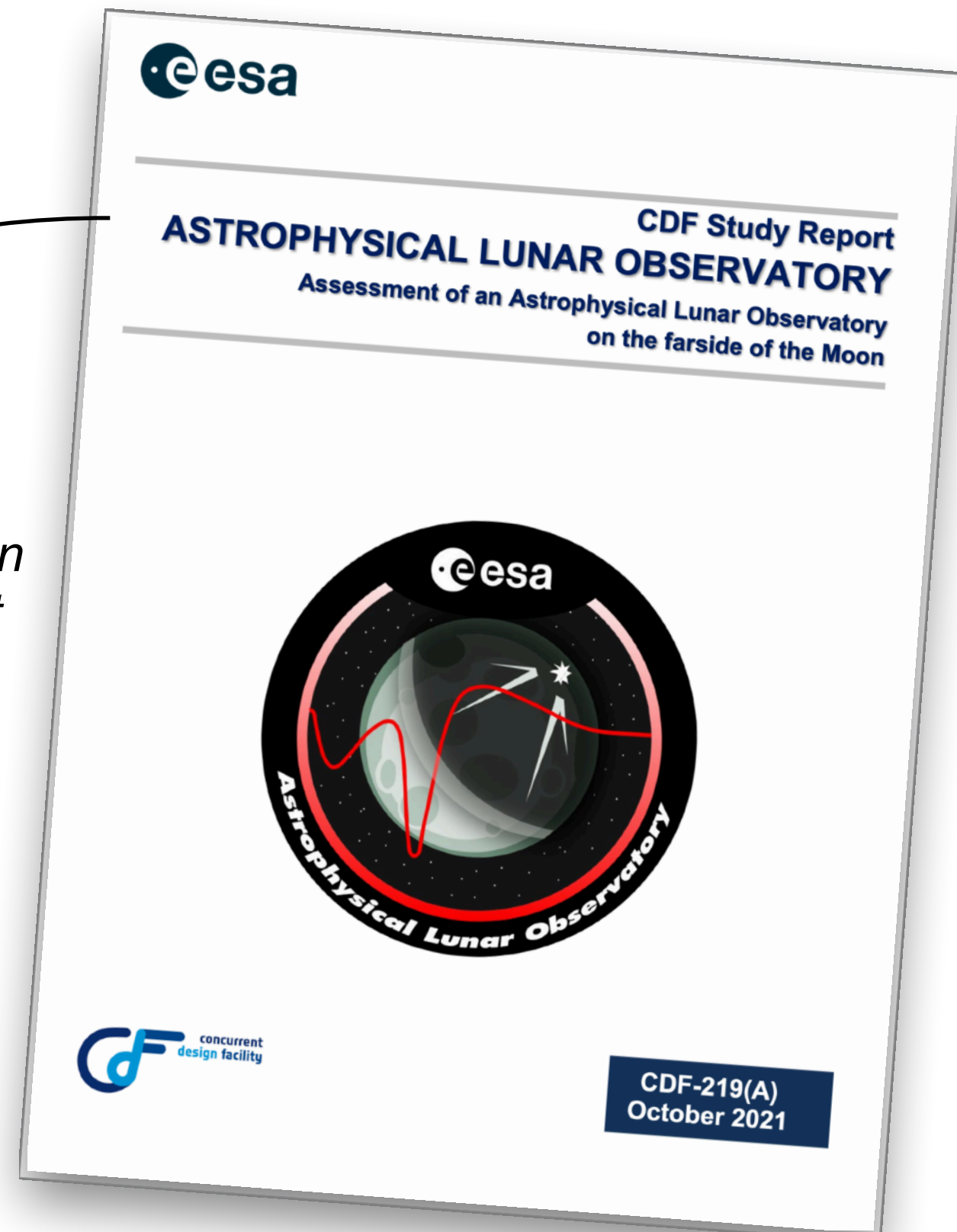
# Astrophysical Lunar Observatory (ALO)

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



## 1 INTRODUCTION

- 1.1 Background
- 1.2 Objective
- 1.3 Scope
- 1.4 Document structure

## 2 EXECUTIVE SUMMARY

- 2.1 Study flow
- 2.2 Study objectives
- 2.3 Requirements and
- 2.4 Observatory architecture
- 2.5 Baseline design –
- 2.6 Considerations for
- 2.6.1 General consid
- 2.6.2 Scaling law sun
- 2.7 General conclusion

## 3 STUDY BACKGROUND

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- 3.2 Lunar exploration p
- 3.3 EL3 applicable con

## 4 SCIENCE OBJECTIVE

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- 4.1.2 Science perform
- 4.1.3 High-level goals
- 4.1.4 ALO in the cont
- 4.2 Key drivers and tra
- 4.2.1 Architecture – tl
- 4.2.2 Antenna level
- 4.2.3 Array level
- 4.3 Proposed Observat
- 4.4 Technology and an
- 4.4.1 ALO analysis to
- 4.4.2 Dedicated TRL

## 5 PAYLOAD ANTENNA

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- 5.3 Key drivers and cha
- 5.4 Technology Needs



## 6 ENVIRONMENT

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- 6.2 Plasma Environment
- 6.3 Radiation Effects an
- 6.3.1 The Radiation B
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- 6.3.3 Galactic Cosmic
- 6.3.4 Transfer environ
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- 6.4.1 Natural dust tra
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- 7.2.3 Terrain slope an
- 7.3 Communications rel
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- 7.3.2 Lunar Gateway
- 7.3.3 Lunar Pathfinder

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- 8.1.2 Harness consid
- 8.2 Antennas to Base S
- 8.2.1 Antennas to Hut
- 8.2.2 Antenna concep
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- 8.3.1 Observatory arc
- 8.3.2 Observatory dat
- 8.4 Observatory descrip
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- 8.5 Considerations for s
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- 9.2 Baseline Descriptio



- 9.2.1 On-Board Computer
- 9.2.2 Payload Processing L
- 9.2.3 Mass Memory
- 9.2.4 HUB Electronics and
- 9.2.5 List of Equipment
- 9.3 Trade-Offs and alternativ
- 9.4 Considerations for scalab
- 9.5 Technology Needs

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- 10.1.1 Subsystem Requirem
- 10.1.2 Key drivers and challe
- 10.2 Baseline Description
- 10.2.1 S-band Link
- 10.2.2 Ka-band Link
- 10.2.3 List of Equipment
- 10.3 Trade-Offs and alternativ
- 10.3.1 Ka-band transmit-only
- 10.3.2 Ka-band multiple ante
- 10.4 Wireless communication
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- 10.6 Technology Needs

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- 11.2.2 Antenna Pointing Mec
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- 11.3 Trade-Offs and alternativ
- 11.3.1 Cross-dipole payload
- 11.3.2 Passive deployment ti
- 11.4 Considerations for scalab
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- 13.2 Baseline Descripti
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- 13.2.3 Base
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- 13.3.1 Antenna
- 13.3.2 Hub
- 13.3.3 Base
- 13.4 Considerations for
- 13.5 Technology Needs

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- 14.2 Trade-Offs and An
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- 14.2.3 Solar Array Me
- 14.2.4 Solar Array Coi
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- 14.2.7 Antenna Power
- 14.2.8 Parallel Individ
- 14.2.9 Parallel Comm
- 14.2.10 Series DC Fe
- 14.2.11 Series AC Fe
- 14.2.12 Antenna Pow
- 14.3 EPS Model and Ba
- 14.3.1 EPS Model De
- 14.3.2 EPS Model Inp
- 14.3.3 EPS Model Re
- 14.3.4 EPS Model Tir
- 14.3.5 List of Equipme



- 14.4 Consideration:
- 14.4.1 Nuclear Pc
- 14.4.2 Nuclear Pc
- 14.5 Technology Ne

## 15 CONFIGURATION

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- 16.4 Technology Ne

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- 17.1.2 Assumptio
- 17.2 Specific Consi
- 17.2.1 Considerat
- 17.2.2 Considerat

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- 18.2 Baseline Desc
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- 18.3.1 Generalitie
- 18.4 TRL Assessm
- 18.5 Technology Ne
- 18.6 Development
- 18.7 Summary and

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- 19.1 RAMS, Fault N
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- 19.2.1 Study/ Mis
- 19.2.2 Severity ar
- 19.2.3 Risk Index



- 19.2.4 Risk Balancing over the scope of the mission and different study/ mission phase
- 19.3 Risk Drivers
- 19.4 Top/ major Risk Log (preliminary)
- 19.4.1 Risk Log General Considerations and Recommendations
- 19.5 Risk Log Specific Conclusions and Recommendations

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- 20.1 Class of Estimate
- 20.2 Cost Estimate Methodology
- 20.3 Scope of Estimate
- 20.3.1 Observatory
- 20.3.2 Rover
- 20.4 Main Assumptions
- 20.5 Technology Readiness Level Definition
- 20.6 Economic of Scale
- 20.7 Industrial Cost Contingency
- 20.8 Conclusions and Recommendations

## 21 CONCLUSIONS

- 21.1 Representativeness of results
- 21.1.1 Dipole/antenna concept
- 21.1.2 Harness budget
- 21.1.3 Magazine concept for deployment
- 21.1.4 Solutions for power supply and thermal control
- 21.1.5 Communications architecture for relay systems
- 21.2 Feasibility considerations
- 21.3 Main outcome of the study
- 21.3.1 Technology showstoppers
- 21.4 Study objectives achievement
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## 22 REFERENCES

## 23 ACRONYMS

- A APPENDIX A - TECHNOLOGY READINESS LEVELS TABLE
- B APPENDIX B – RISK ASSESSMENT
- B.1 ANNEX 01 - Study specific Success Criteria for Risk Assessment
- B.2 ANNEX 02 - Study specific Severity & Likelihood definition

# The basic idea behind ALO

A **discovery mission** to observe the Dark Ages ( $z > 30$  to  $\sim 200$ ) and the late Cosmic Dawn ( $z \sim 15-30$ ) using the 21-cm line of neutral hydrogen.

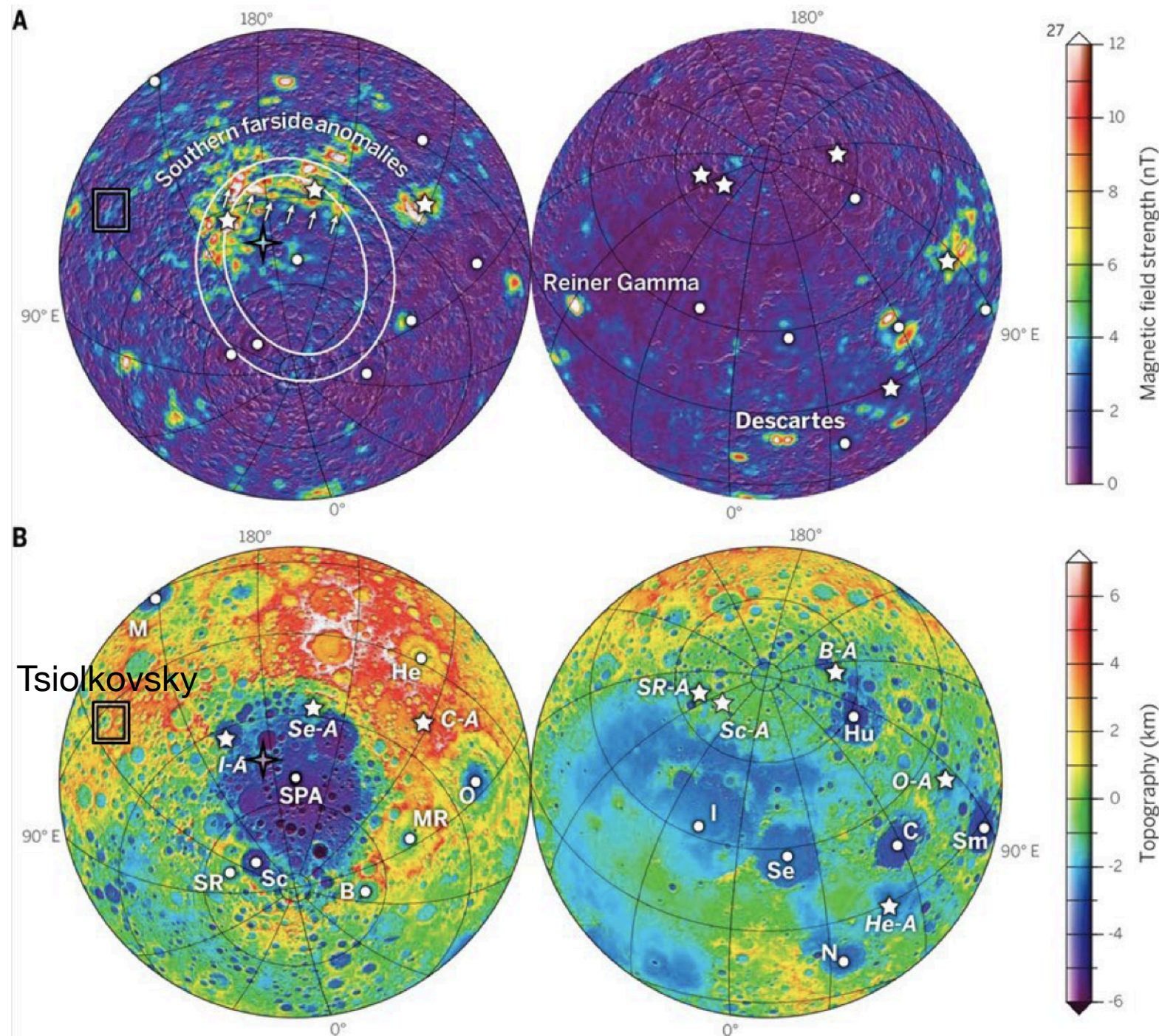
*Neither era of the Universe has been explored by any instrument to this date. A unique mission.*

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

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

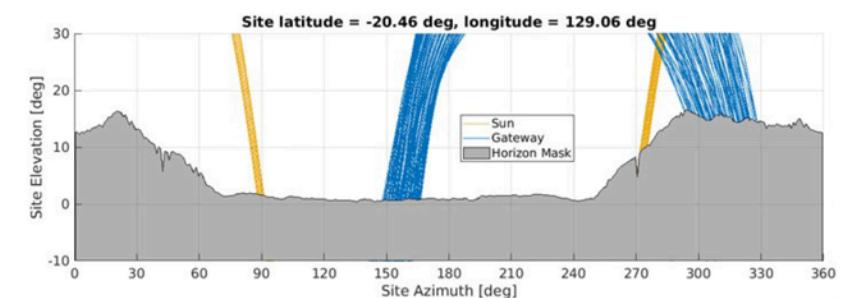


# Astrophysical Lunar Observatory (ALO)

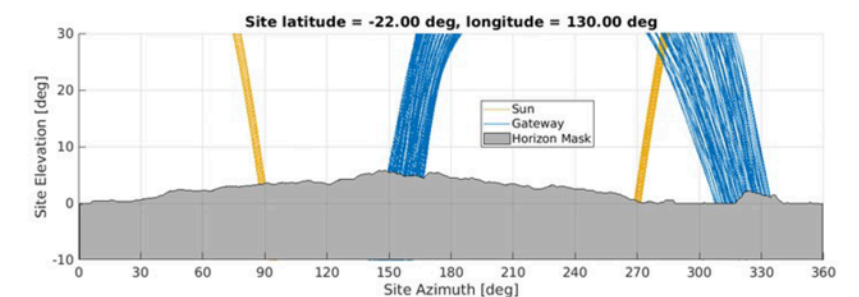


- Tsiolkovsky

- 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.



a) Close to central peak

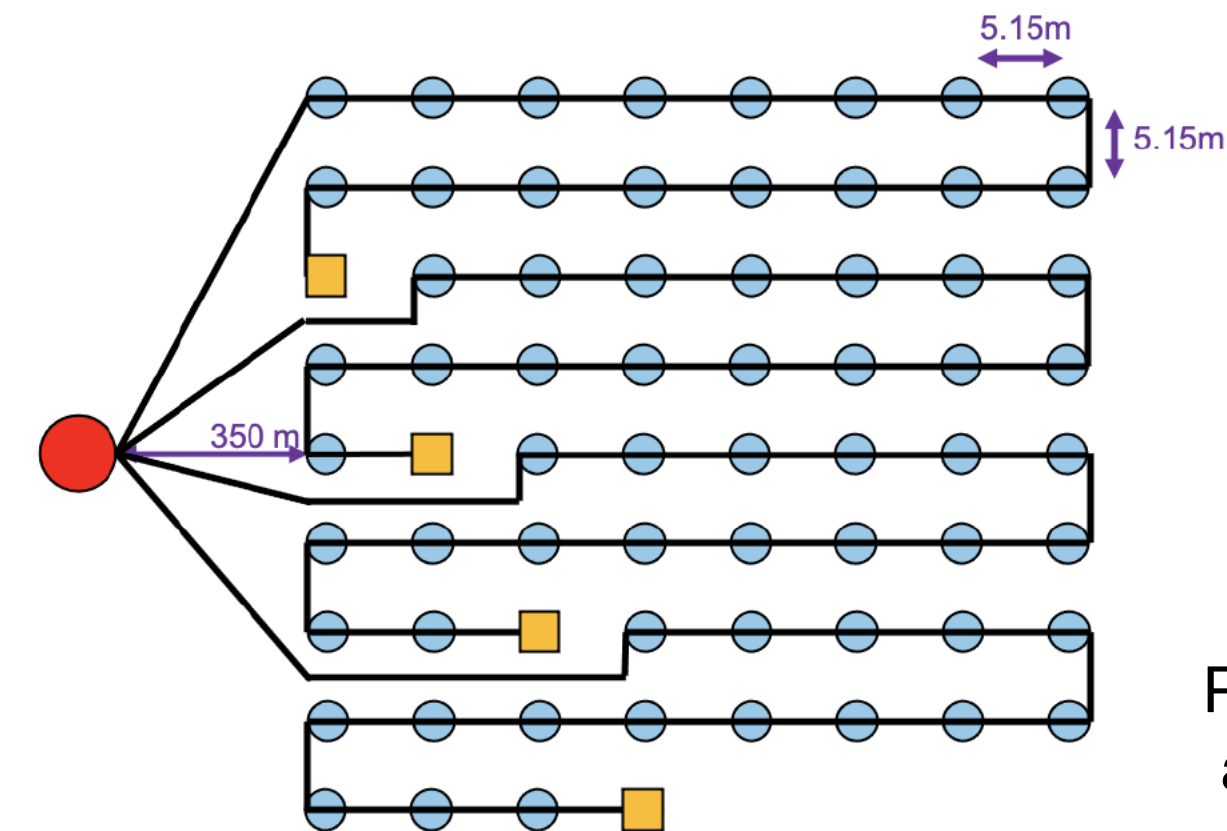


b) Close to southern crater rim



# Astrophysical Lunar Observatory (ALO)

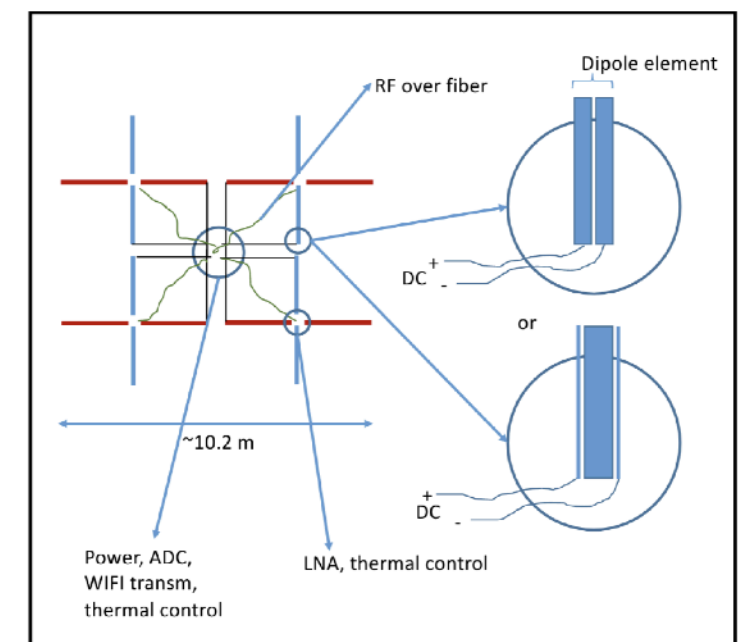
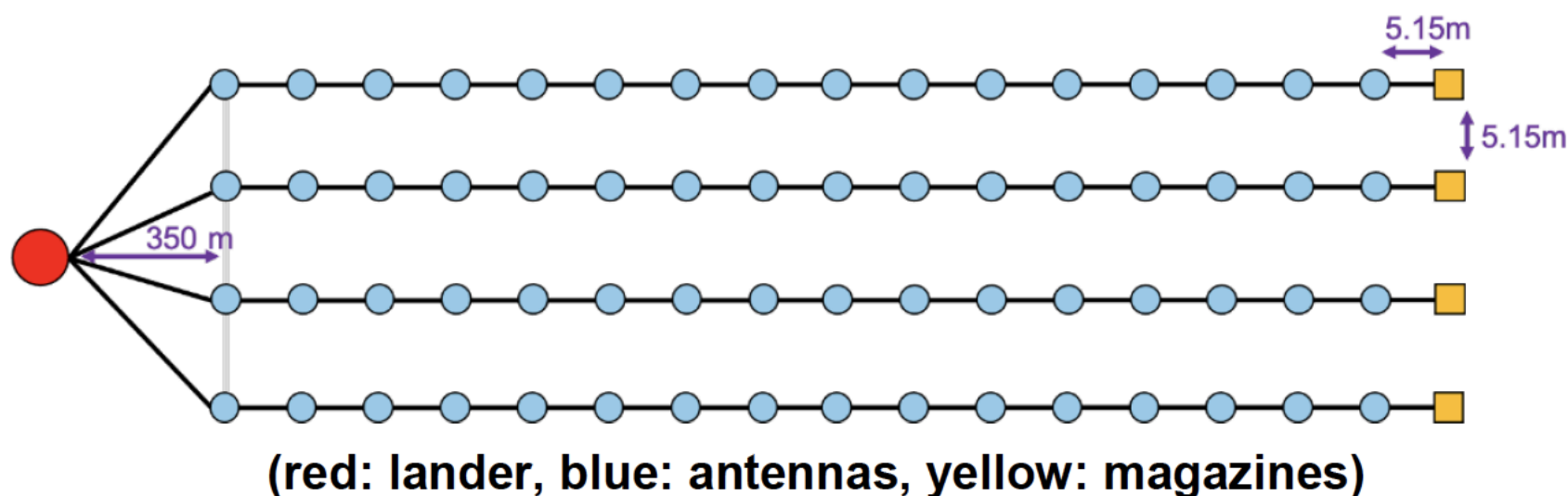
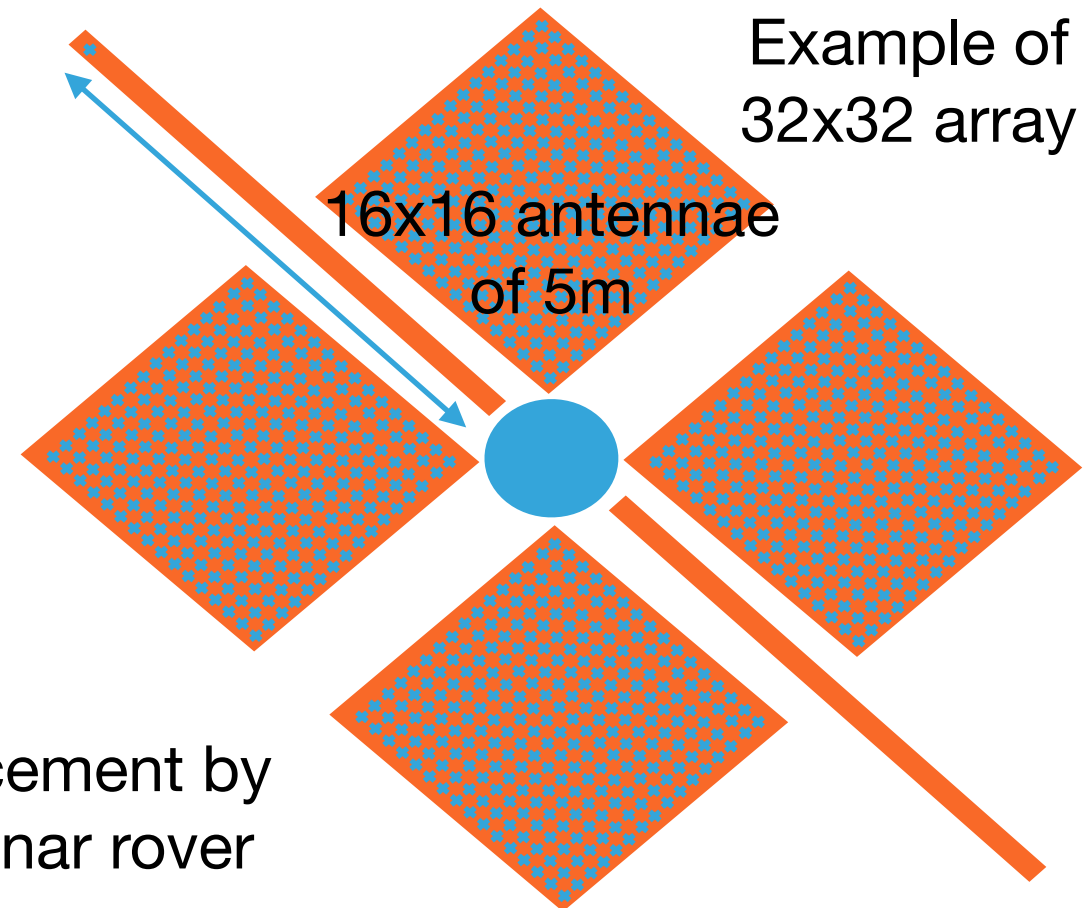
# Basic concept of NxN array (power-spectrum) with 4 outriggers (global signal)



## Placement by a lunar rover

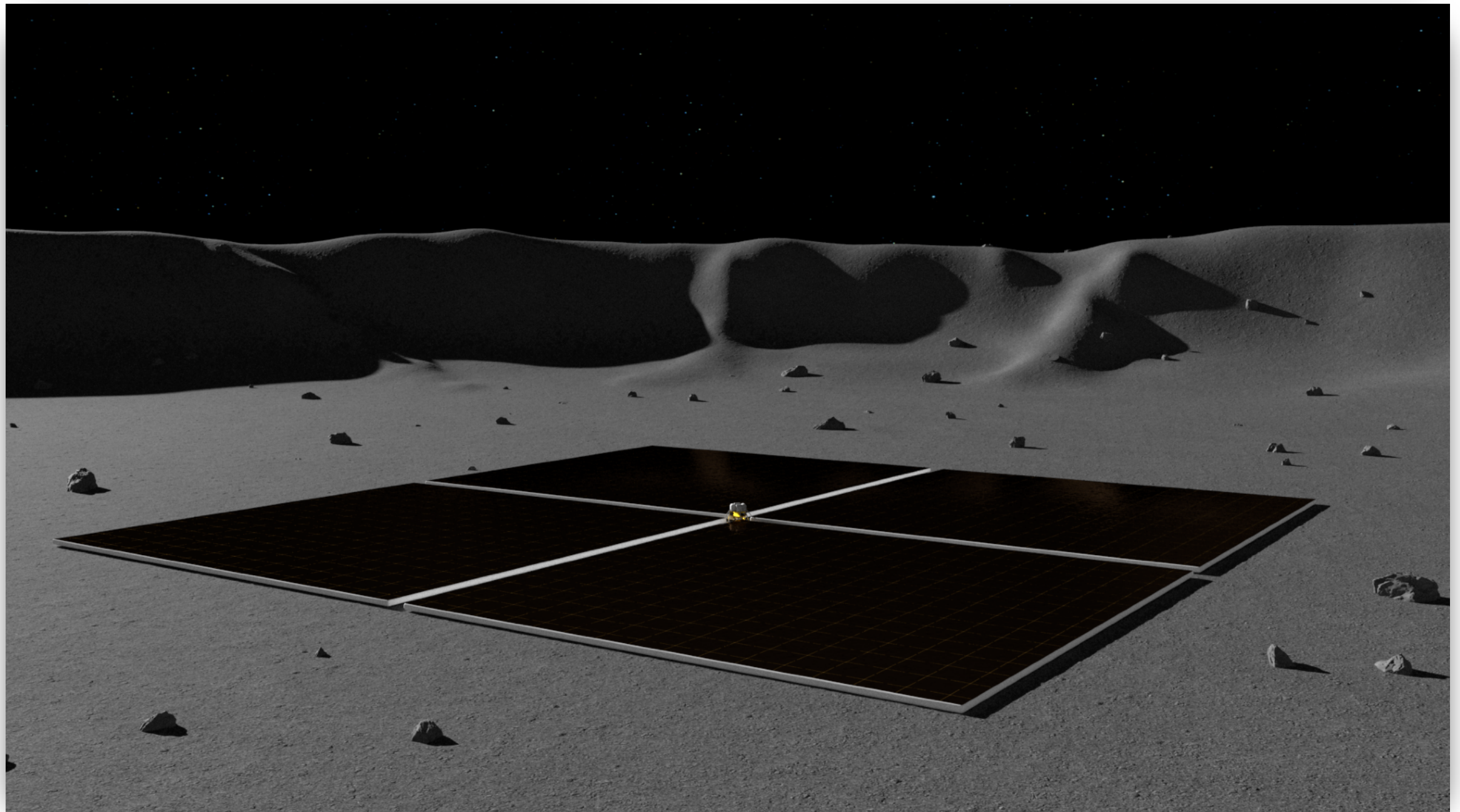
## Example of 32x32 array

16x16 antennae  
of 5m



# Astrophysical Lunar Observatory (ALO)

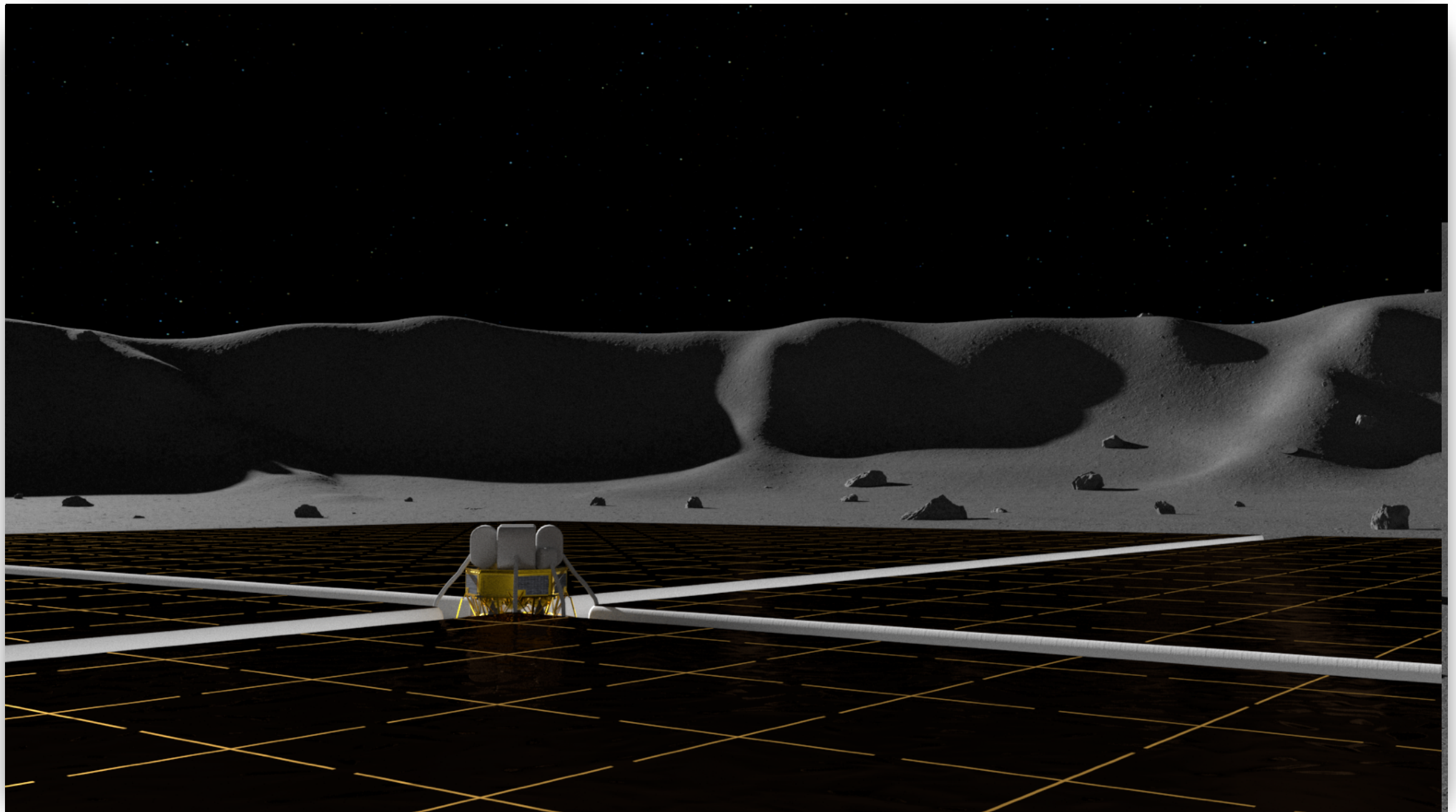
A conformal grid-like array (allowing for a spatial FFT correlation), shielded from (other) activities on the lunar surface, with up to four outrigger global 21-cm receivers placed at a distance.





# Astrophysical Lunar Observatory (ALO)

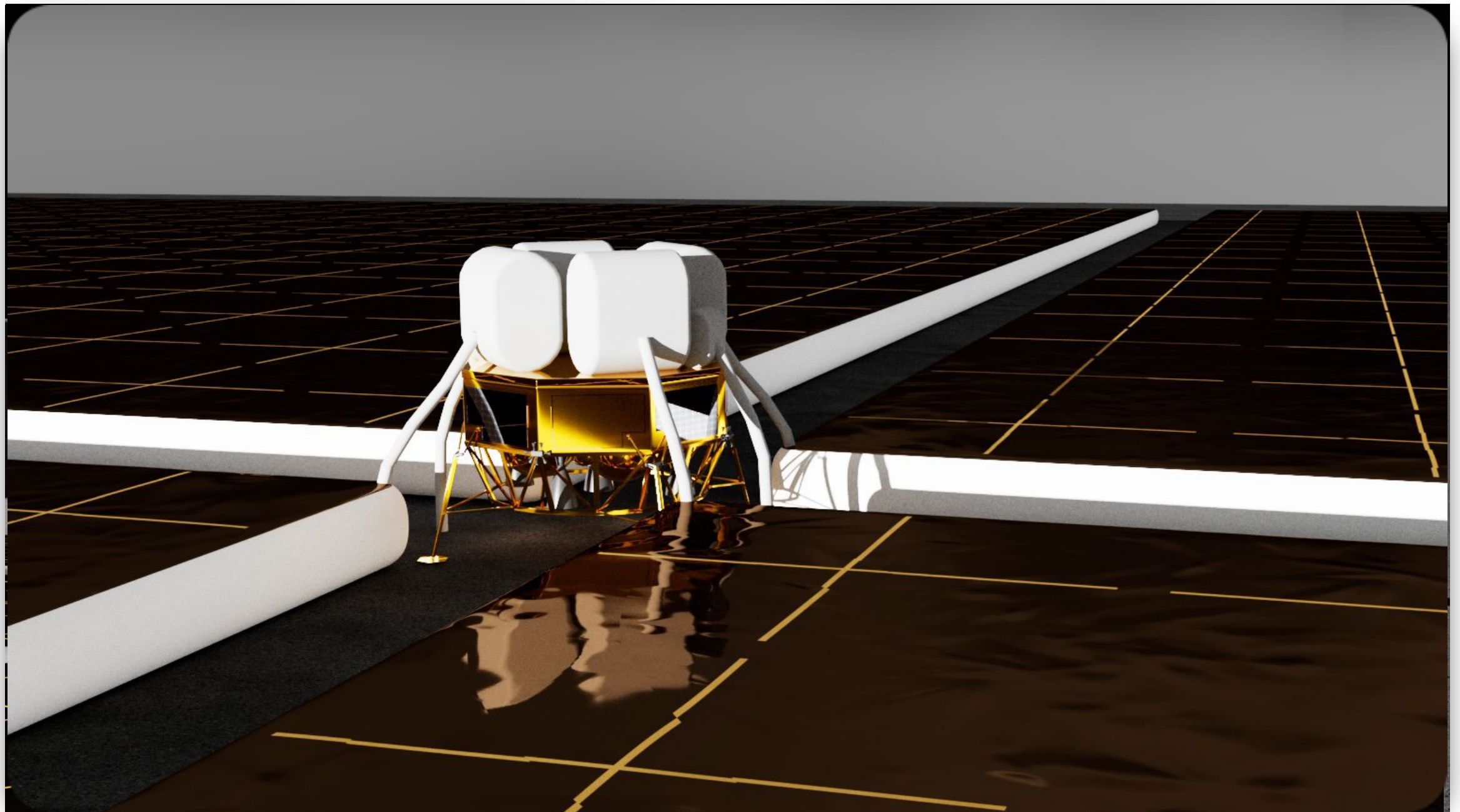
A conformal grid-like array (allowing for a spatial FFT correlation), shielded from (other) activities on the lunar surface, with up to four outrigger global 21-cm receivers placed at a distance.





# 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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and natural sciences

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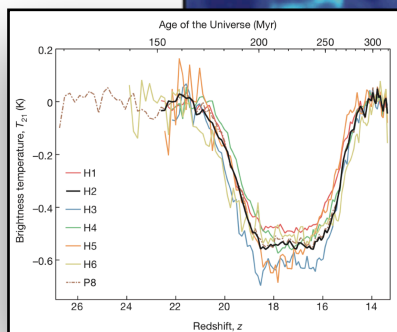
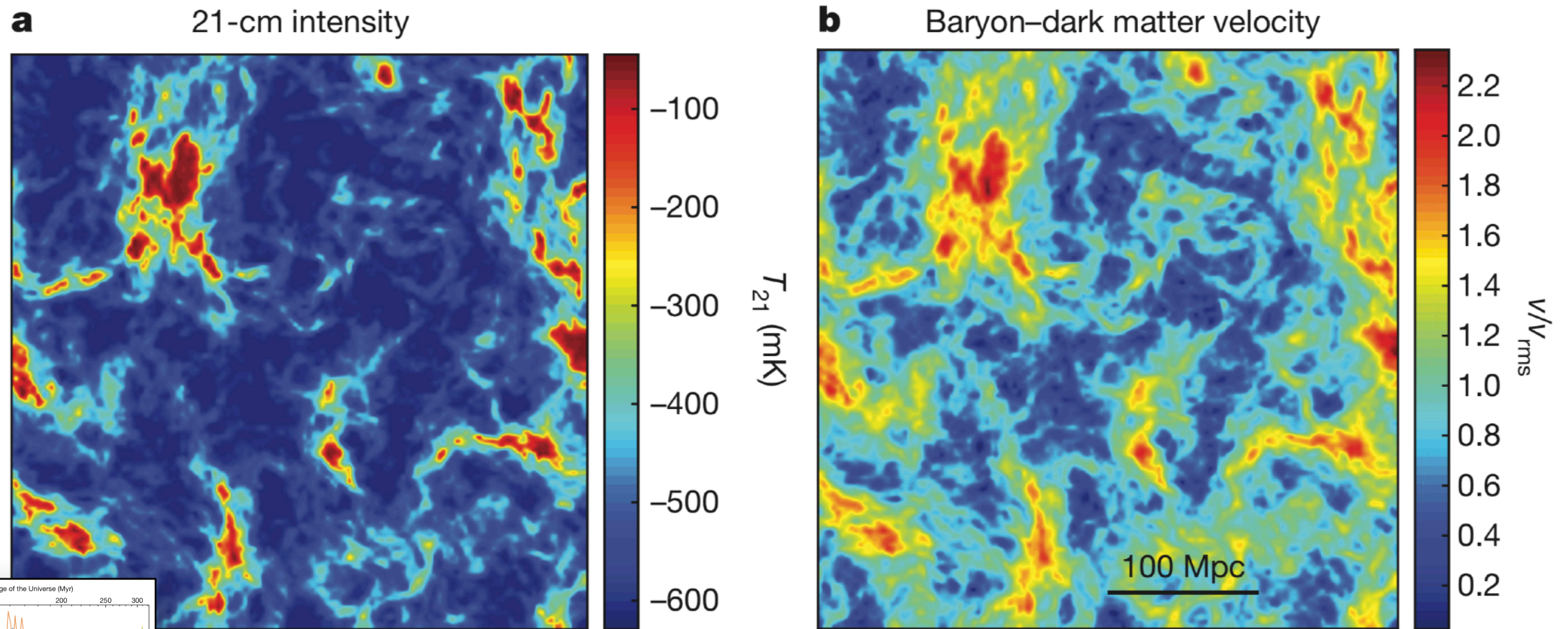
# *What does ALO aim for?*

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.



# 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 $\ll$ 1	S/N > 1 for $z = 20$ , $k$ from 0.003 to 0.1
	8 x 8	S/N $\ll$ 1	S/N > 1 for $z = 22$ , $k$ from 0.003 to 0.1
	16 x 16	S/N $\ll$ 1	S/N > 1 for $z = 22$ , $k$ from 0.003 to 0.2
21-cm Cosmology	32 x 32	S/N $\ll$ 1	S/N > 1 for $z = 25$ , $k$ from 0.003 to 0.1
	64 x 64	S/N $\ll$ 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 $\sim$ 10 for $z = 50$ , $k$ from 0.002 to 0.2	S/N $\sim$ 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

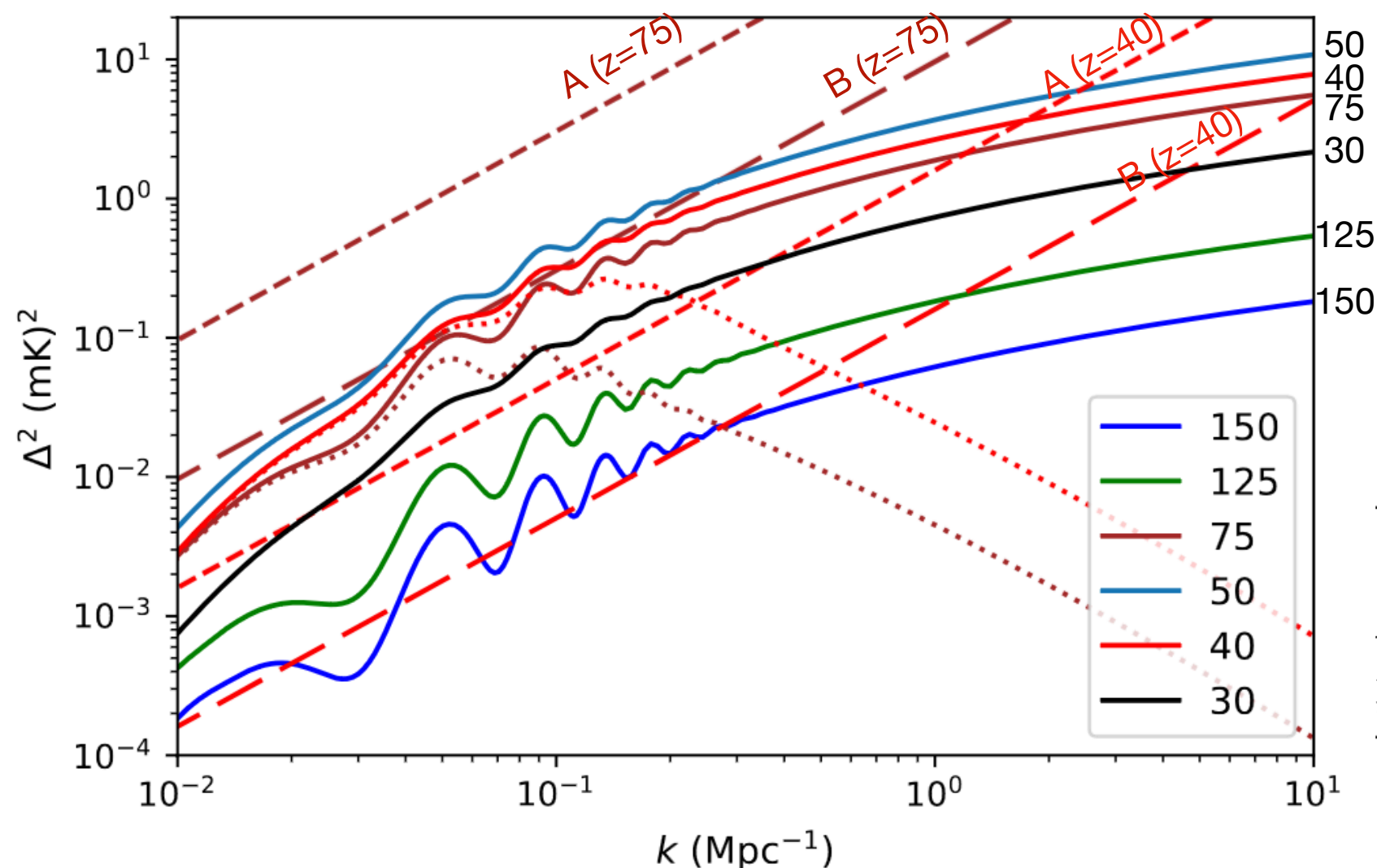
Different designs?

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<sup>4</sup>h integration, half-sky



Mondal & Barkana 2023

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

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



- 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  $z \sim 15$  to  $z \sim 50$  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  **$A_{\text{eff}} = 0.1, 1, 10, 100 \text{ km}^2$  (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)