Toward a Lunar far-side radio observatory

Science goals, ESA CDF study results, and the ALO TT

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RADBOUD RADIO LAB

Radboud University

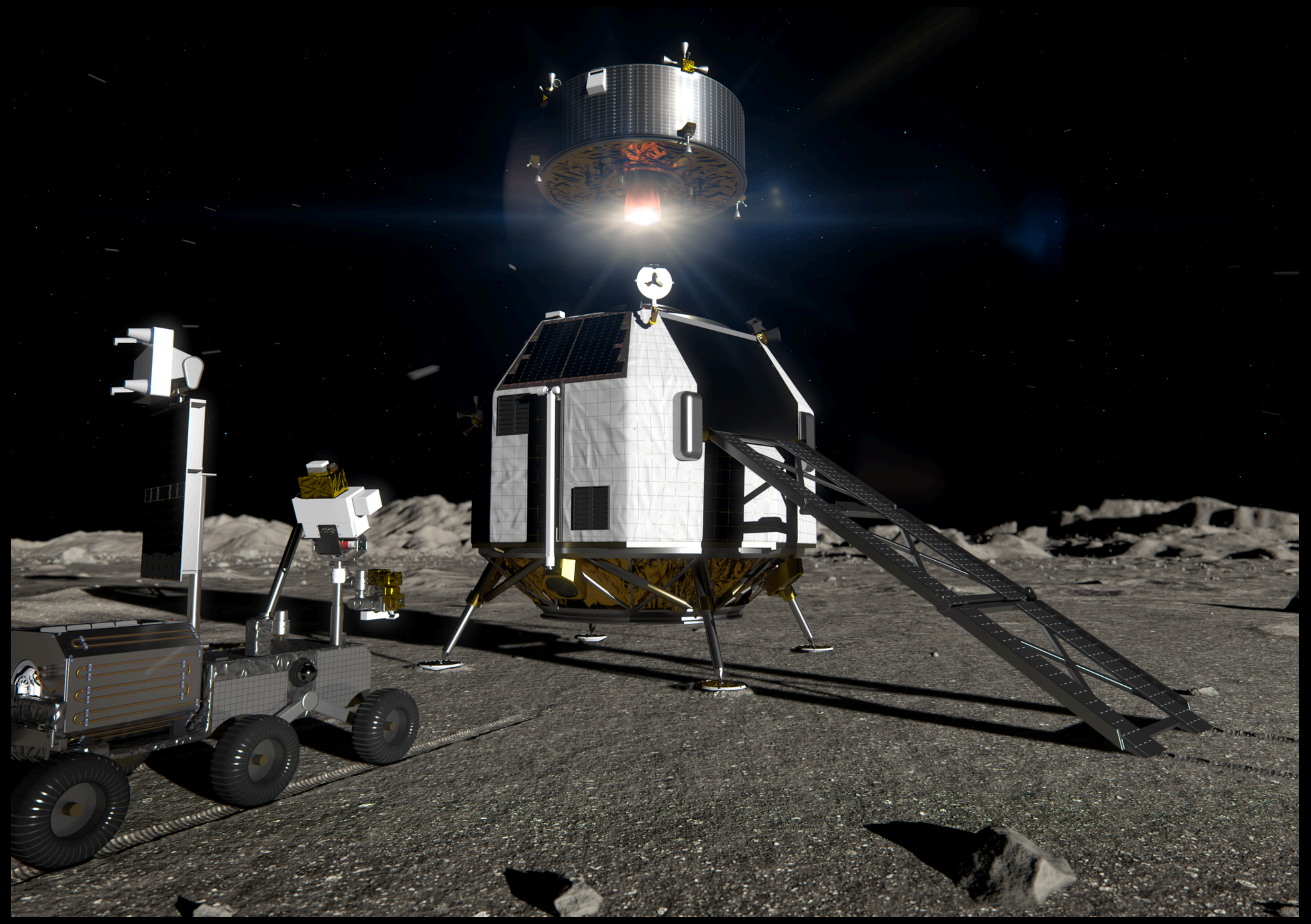
Centre for Astronomical Instrumentation

The European Large Logistics Lander

- EL3 aim is to develop an independent way to deliver payloads to the Lunar surface. Decision to pursue development will be made at the ministerial meeting, Nov 2022

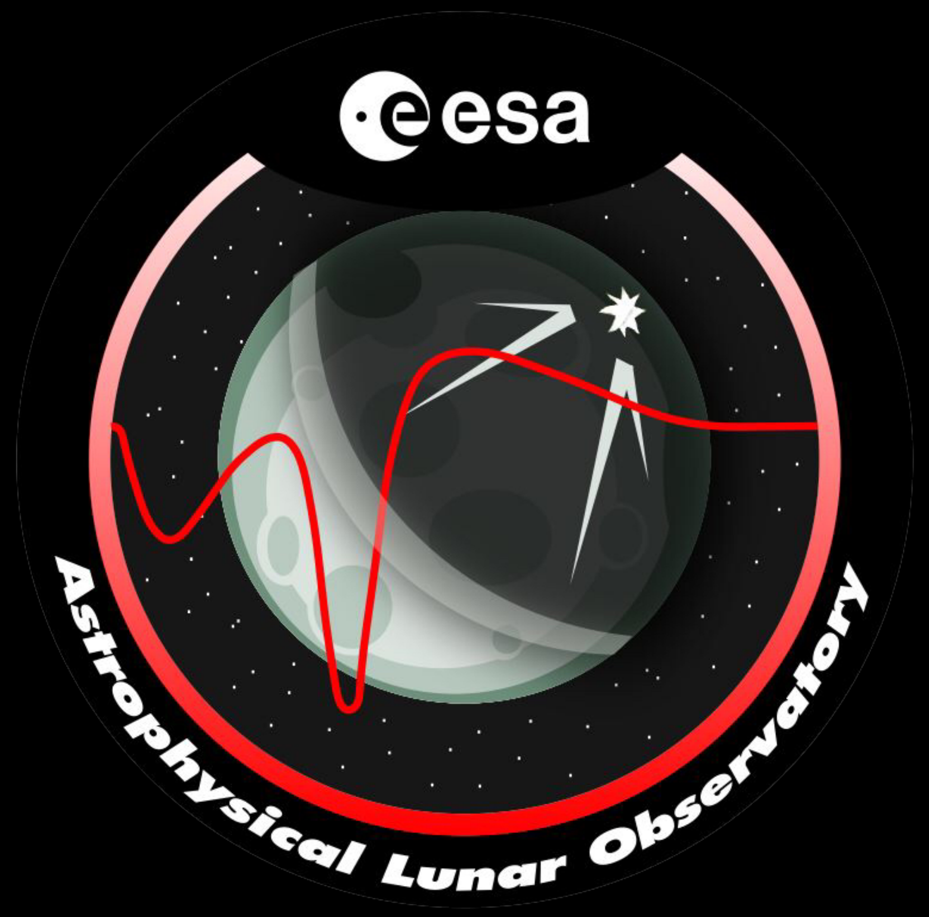
- Currently, various use case for the platform are being developed: e.g., in-situ resource utilisation, infrastructure development, radio astronomy

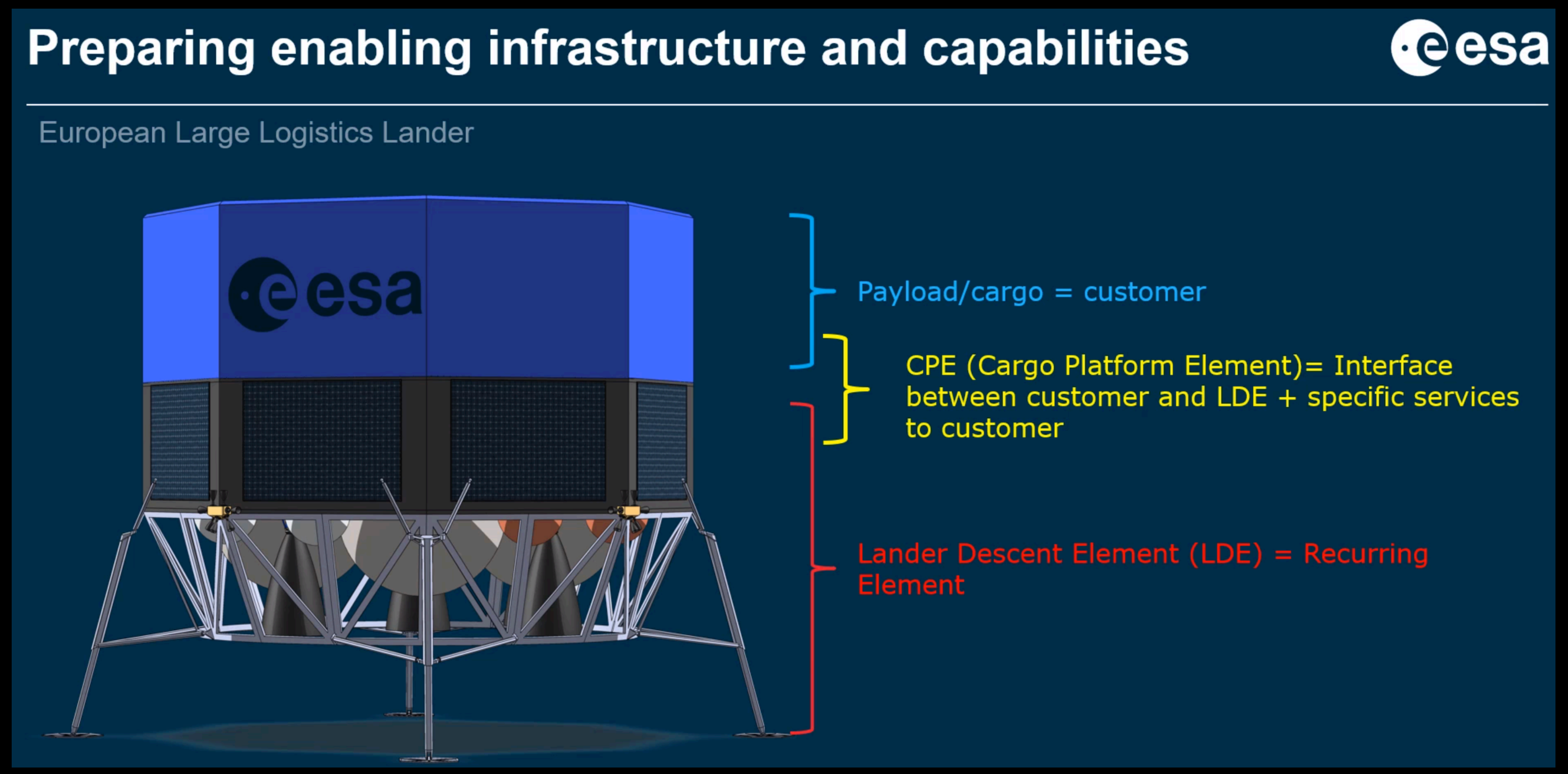
- The topical team on radio astronomy is studying how we can make use of the Lunar far side for this discipline



What is ALO?

- Astrophysical Lunar Observatory: a many-element low-frequency radio interferometer on the Lunar far side, to be delivered by EL3
- Currently being defined in more detail by the ALO Topical Team, consisting of ~65 scientists and engineers from various research institutes and commercial partners, with ESA as client
- Precursor instrument (PRE-DEX) has finished concept design study





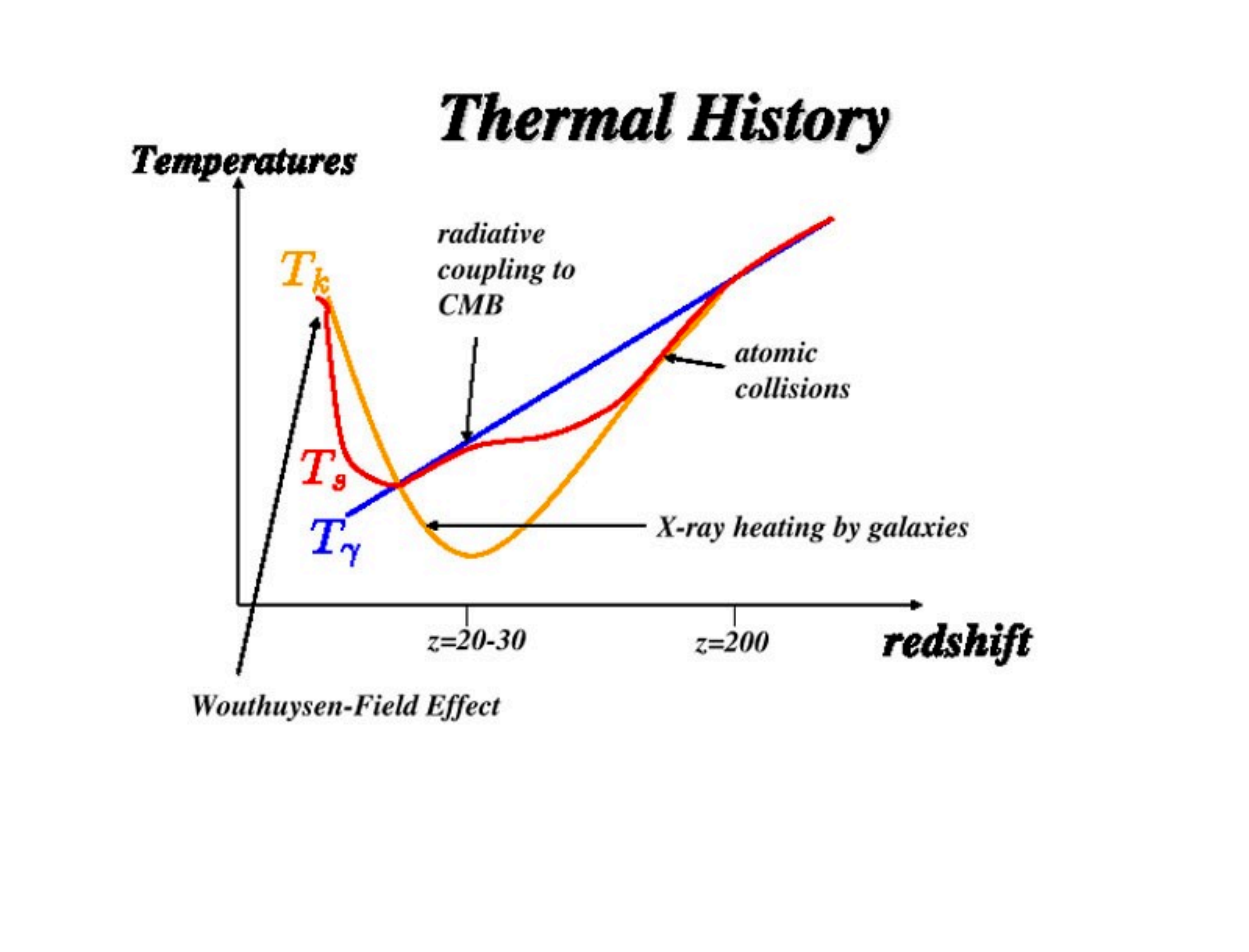
ALO Science Goals I

z=200 to z=30:
Dark Ages

z=30 to z=6:
Cosmic Dawn

ALO Science Goals II

- Top science goal for ALO: neutral hydrogen cosmology in the redshift range from ~200 to ~16 (Dark Ages and initial phase of Cosmic Dawn)
- Capture global signal as well as power spectrum at different redshift slices

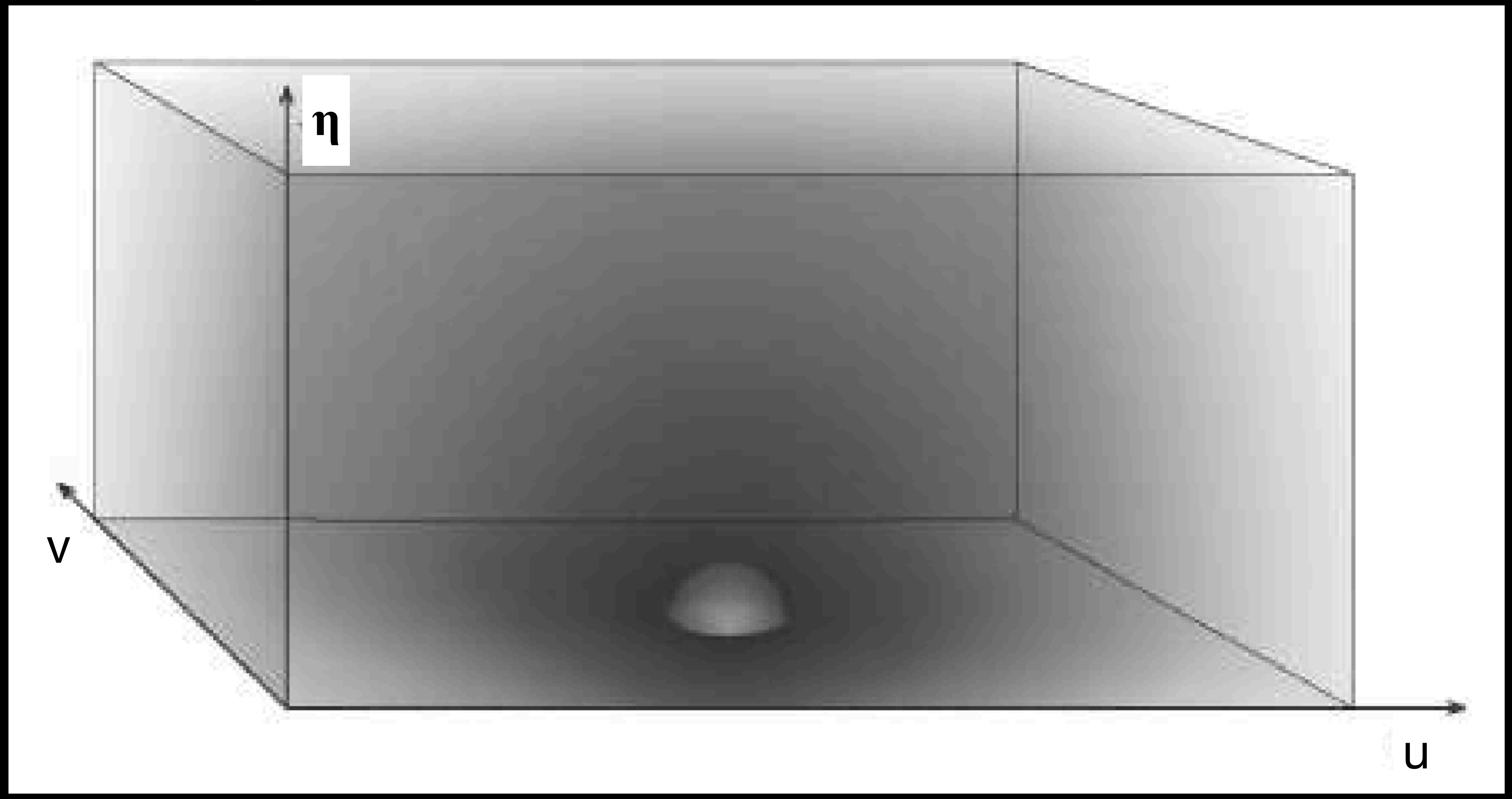


Loeb 2006

Power Spectrum Measurement

- Measurement of spatial power spectrum involves measurement of Fourier modes of hydrogen emission in 3 dimensions: 1 spectral (‘depth’), 2 spatial (directions on the sky).

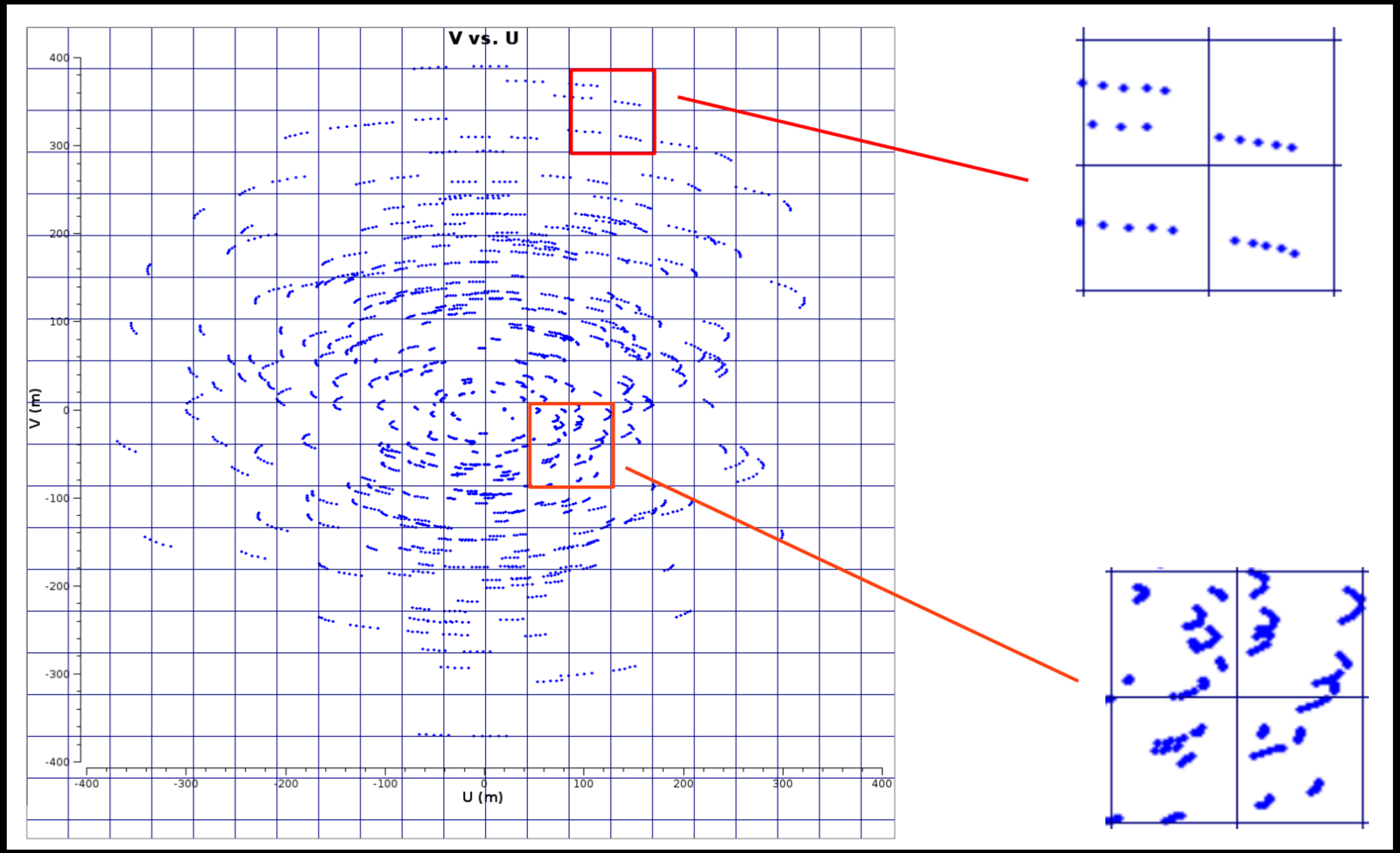
- Detectability of neutral hydrogen density fluctuations drops RAPIDLY with increasing redshift: important to maximise sensitivity at particular angular scales on the sky.



Morales & Hewitt 2004

Science-derived properties I

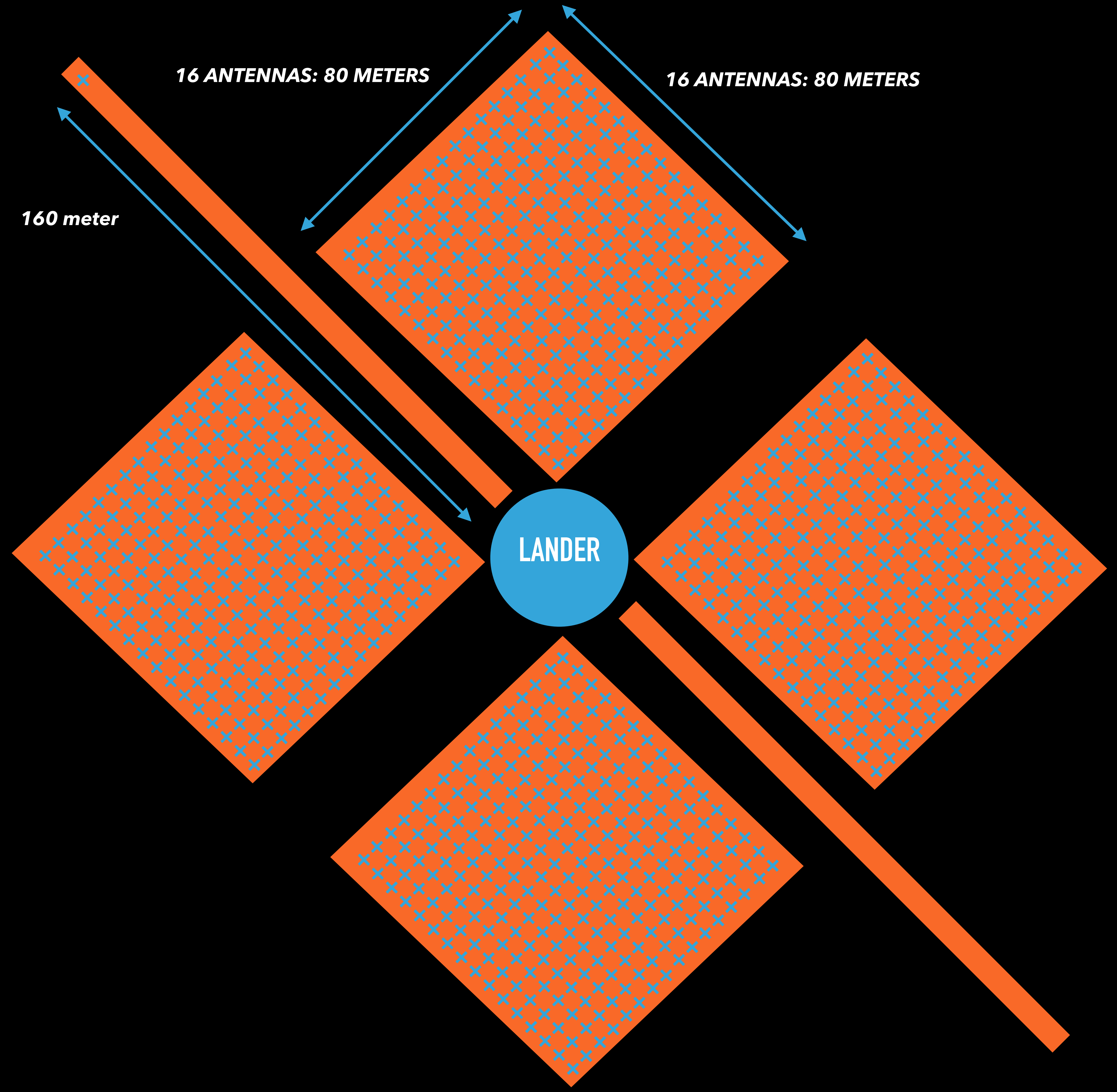
- uv-cell size is determined by FoV (~1 radian)
- View on sky rotates -> changing visibility for each uv-point and frequency bin. But we can only use coherent measurements, so limit on integration time.
- Short baselines: long dwell times in uv-cells, gridded array: ‘redundant’ measurements.



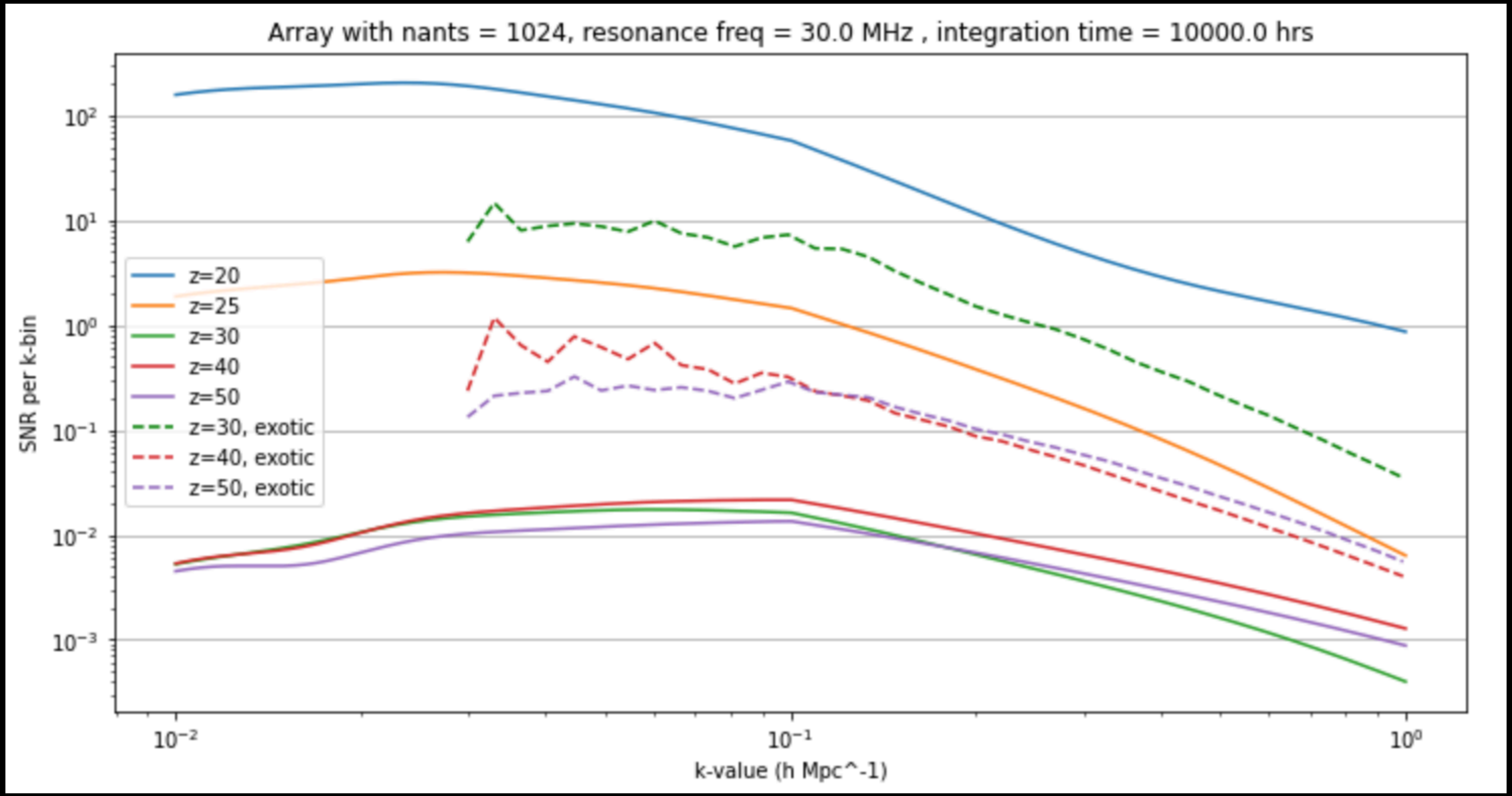
R. Paladino

Science-derived properties II

- Total number of antennas: 32 x 32, to meet sensitivity requirements for discerning different physics models for the Dark Ages
- Antenna size: several meters (to be chosen in the current concept design activity), dual polarisation
- Antennas to be placed close together in a regular grid: an ‘FFT telescope'



Motivation for array size and sensitivity



32x32 is the smallest array that enables us to distinguish ‘standard’ physics models from DM-enhanced interaction models

ALO top-level system requirements

Mass

1500 kg total, 1024 antennas: ~1 kg/ant

Power budget

~few Watts per antenna

Temperature range

~100 to 390 K (-173 to 117 C) at surface

Sensitivity

7×10^{-20} W/m^2/Hz (1 - 100 MHz range)

Data rate

250 Ms/s @ ~6 bits per sample for each antenna, ~20 Mbit/s aggregate (after integration)

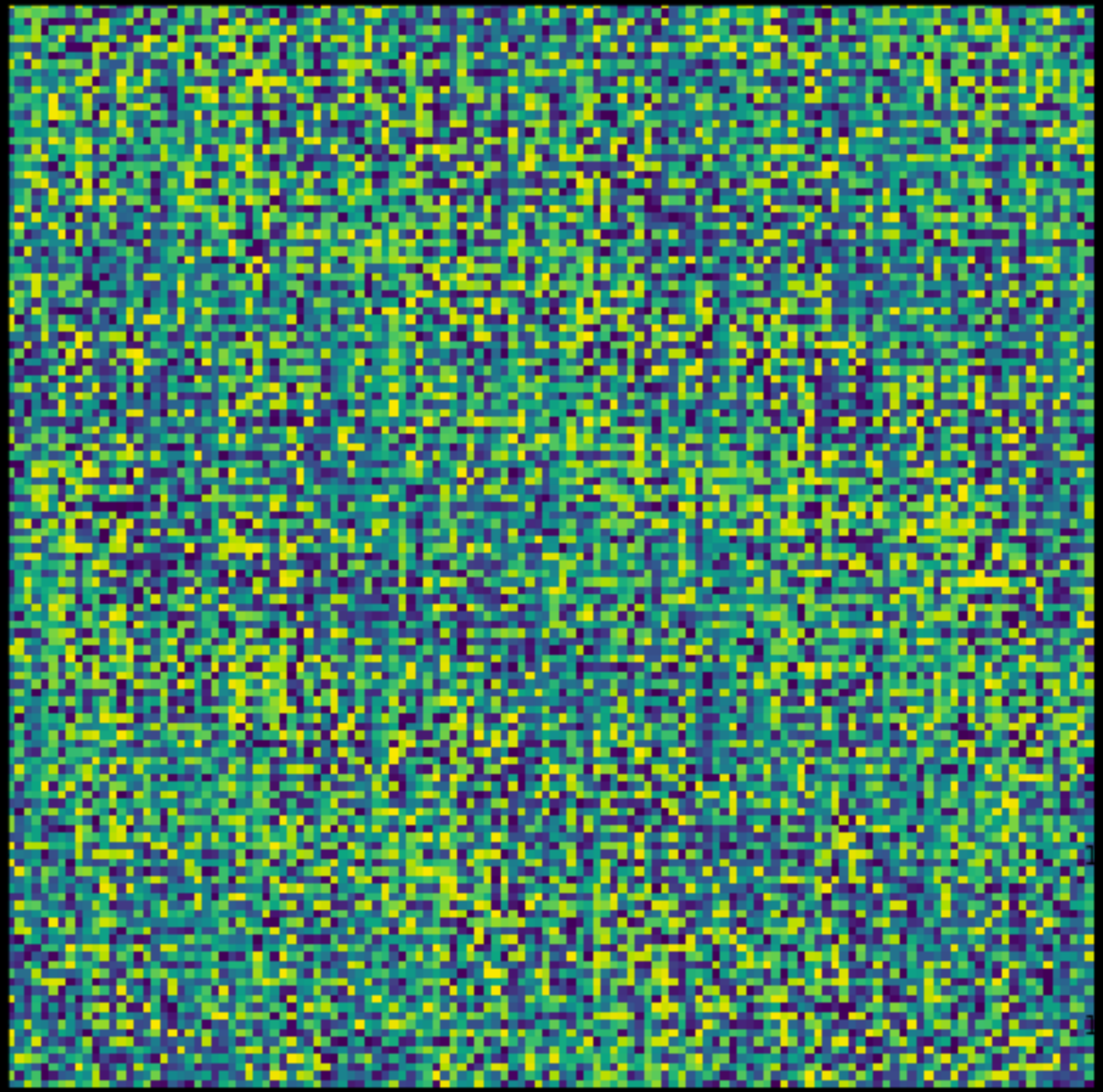
Data processing

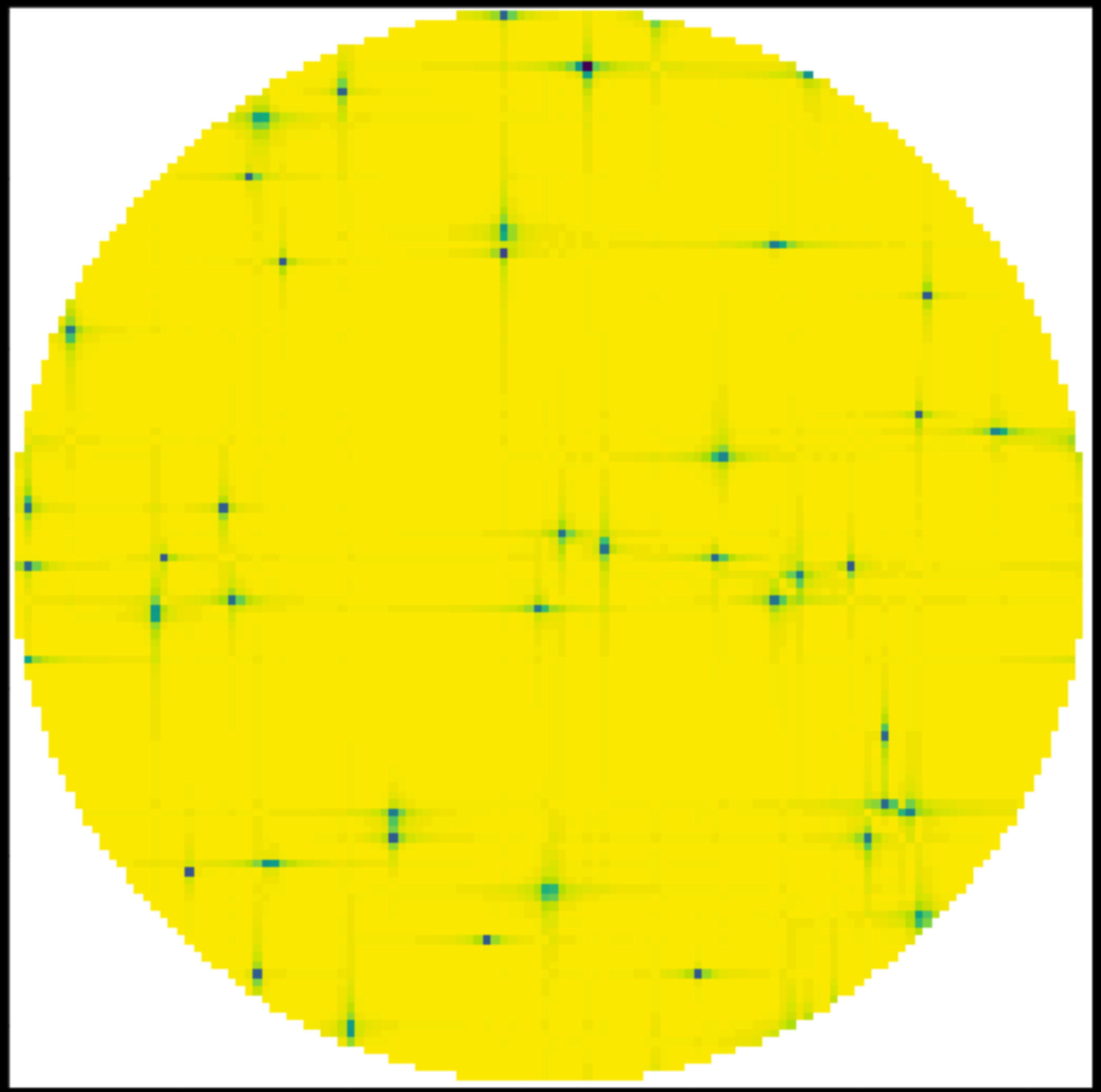
2.6 Gflops/s per antenna (FFT), 20 Tflops/s for grid processing

Measurement data of ALO

No direct correlation per baseline, but array-wide FFT imaging: large impact on processing requirements!

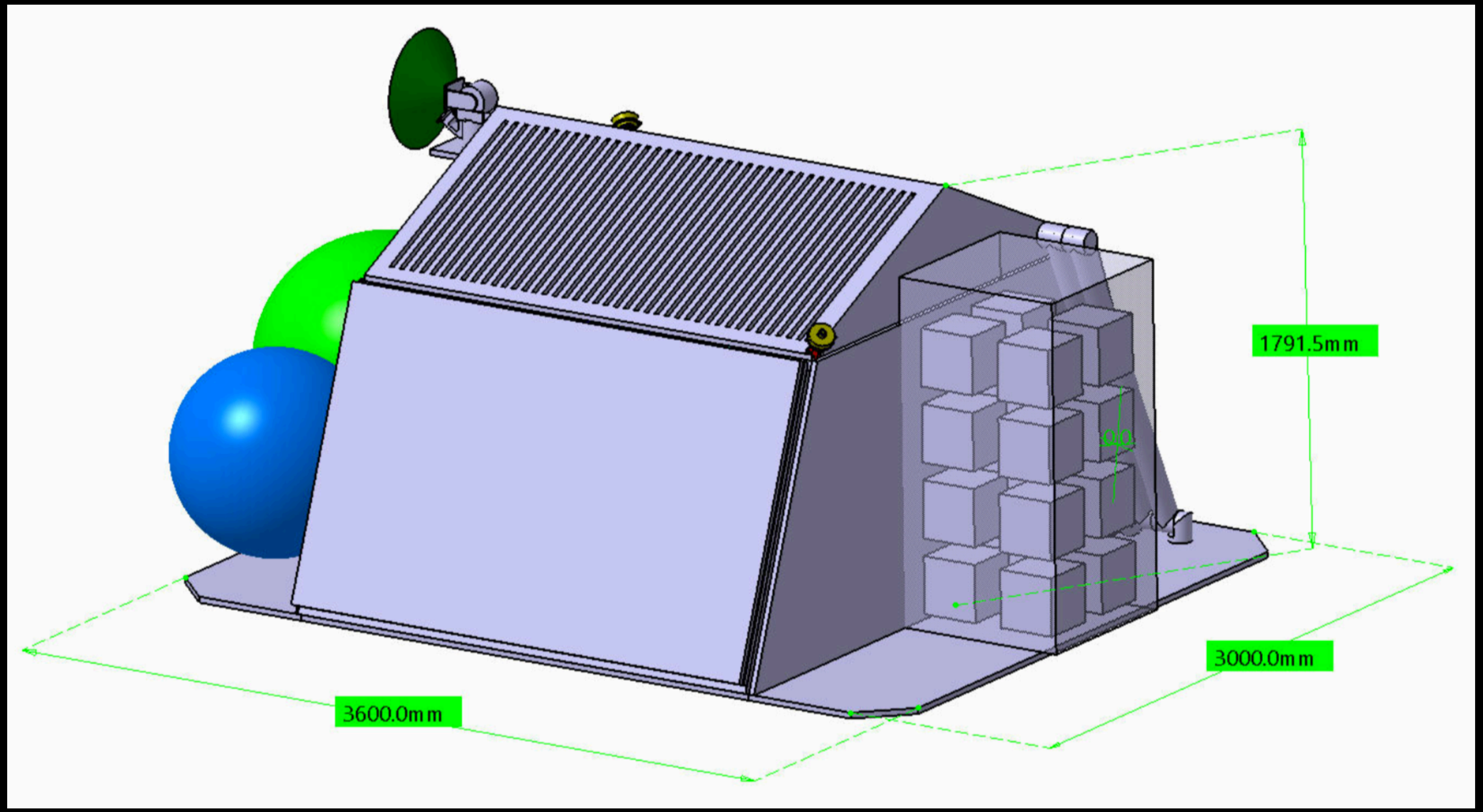
Limited sky resolution and sidelobe structure make proper sky modelling and array calibration extra important

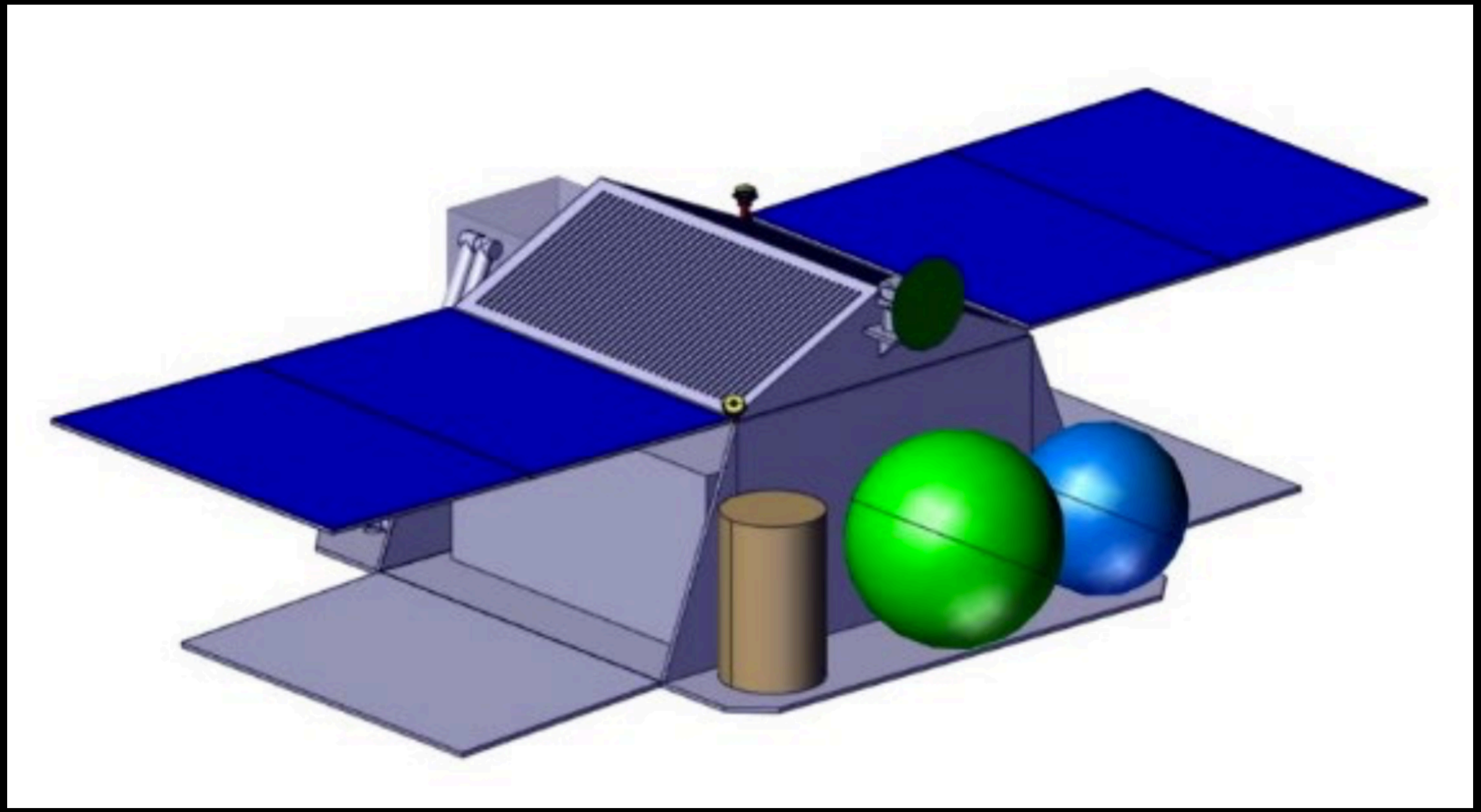




Outcome of CDF study

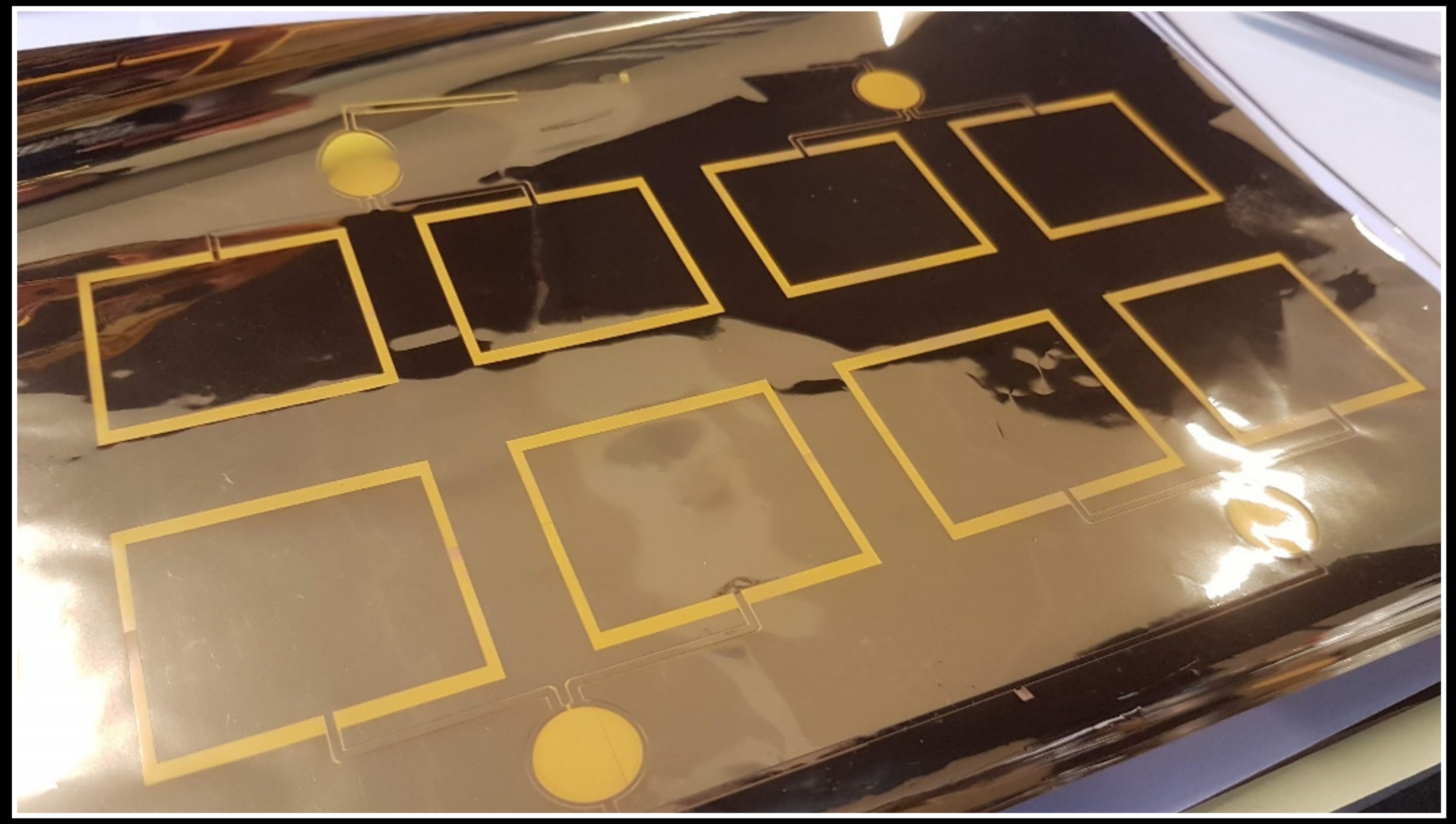
- With current tech, max scale of system for 1 lander: 4x4 antennas. Significant mass reduction needed in antenna hardware, deployment system, power/data harnessing for 32x32 array.
- Reduction in power consumption needed: ~2W per antenna is the goal
- Modular approach fits array design: multiple ‘hubs’ with their own locally organised antenna subarrays (+power, data…)

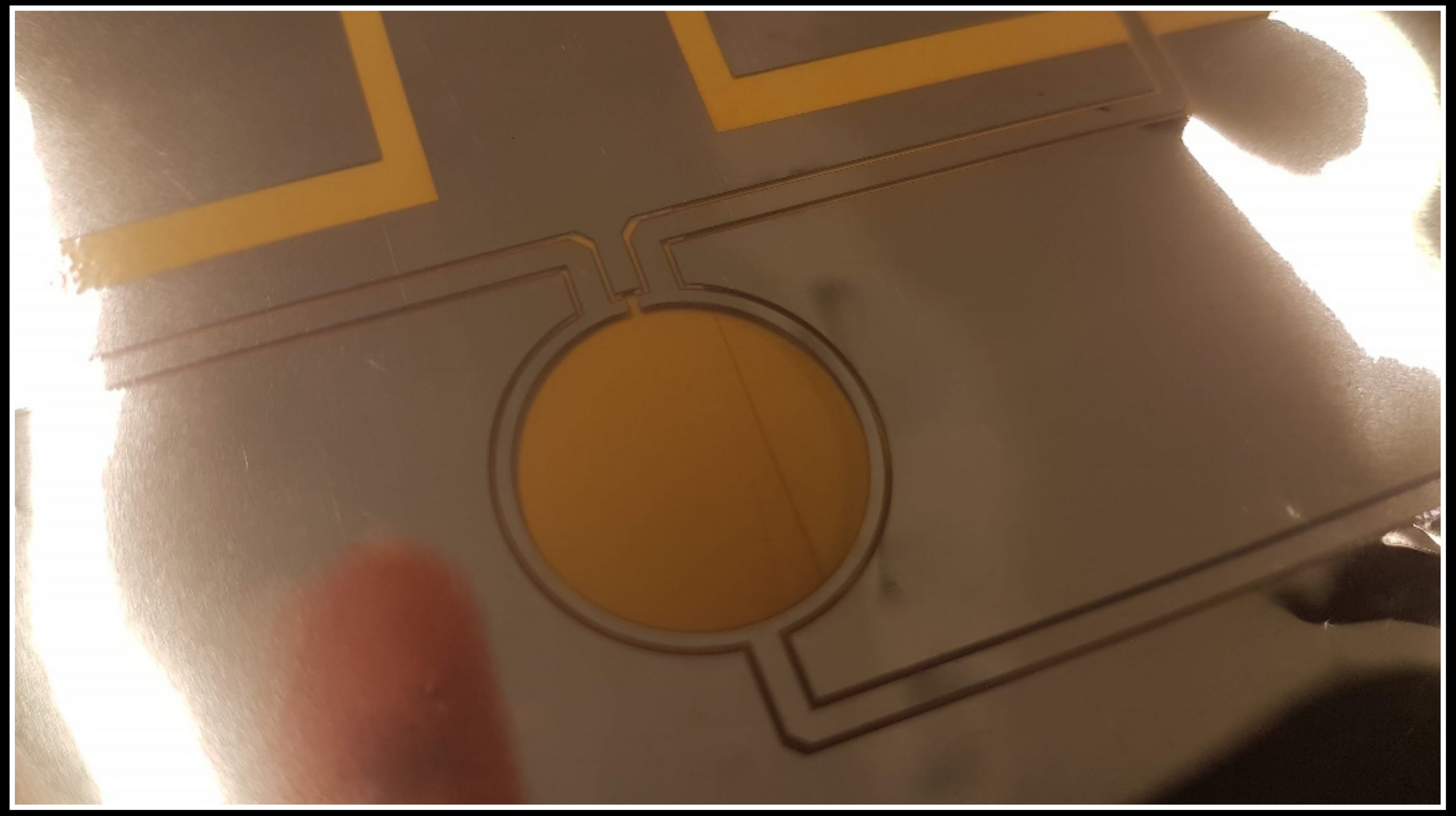




Necessary tech development

- Low-mass antennas: unrollable/inflatable structures
- Harnessing: local power generation, wireless data transmission
- LNA survivability: large temperature range electronics, protection using regolith or shade structures
- Performance monitoring and calibration: internal and external





M. Bentum, N. Vertegaal, TU/E

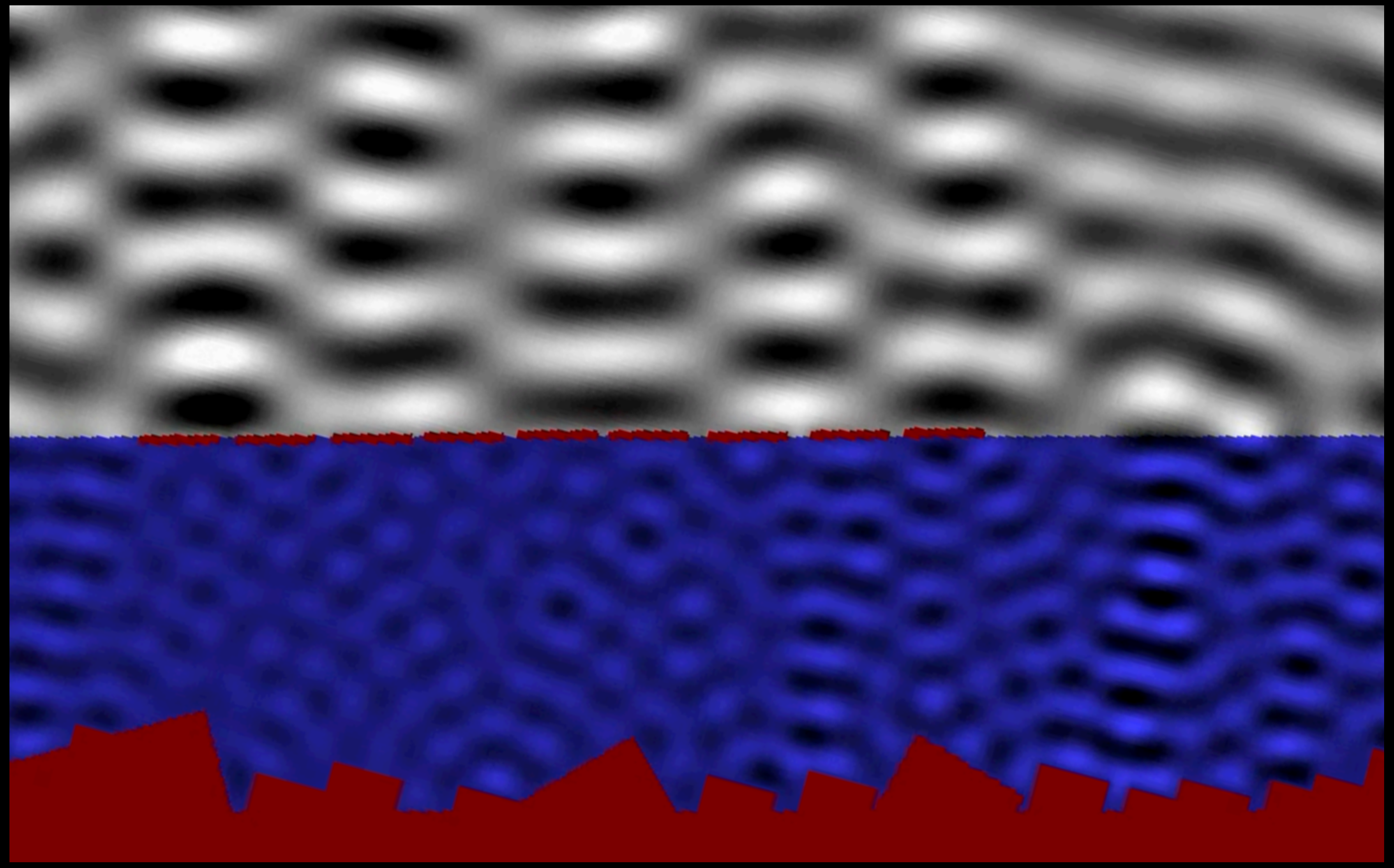
Effects to worry about I

Influence of Lunar regolith:

No ground plane means a risk of ‘multi-path’ array illumination

Severity depends on Lunar regolith dielectric profile (absorption vs reflection, roughness scales)

Can we recognise this effect adequately in our observations?

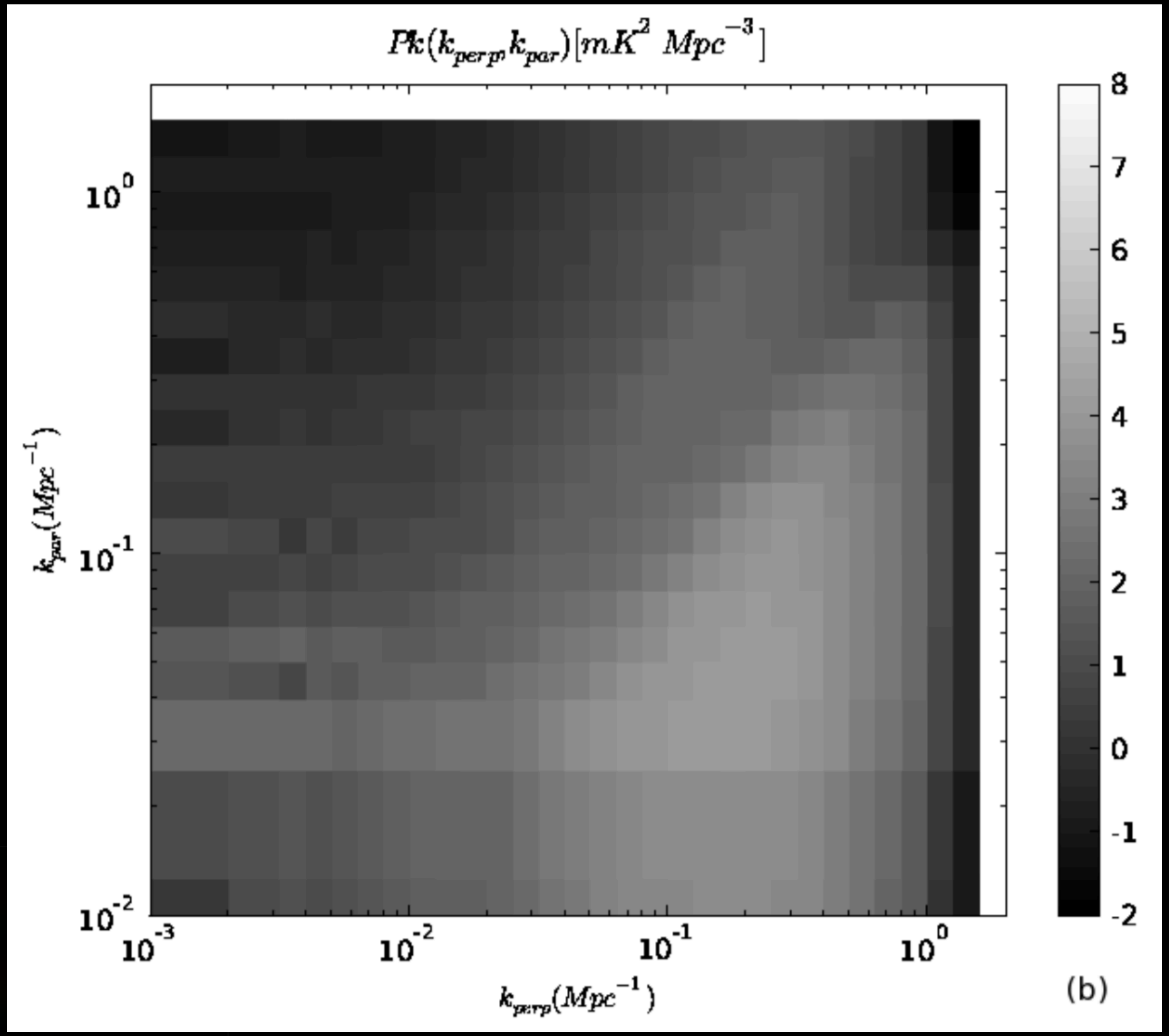


Snapshot of simplified subsurface reflection scenario

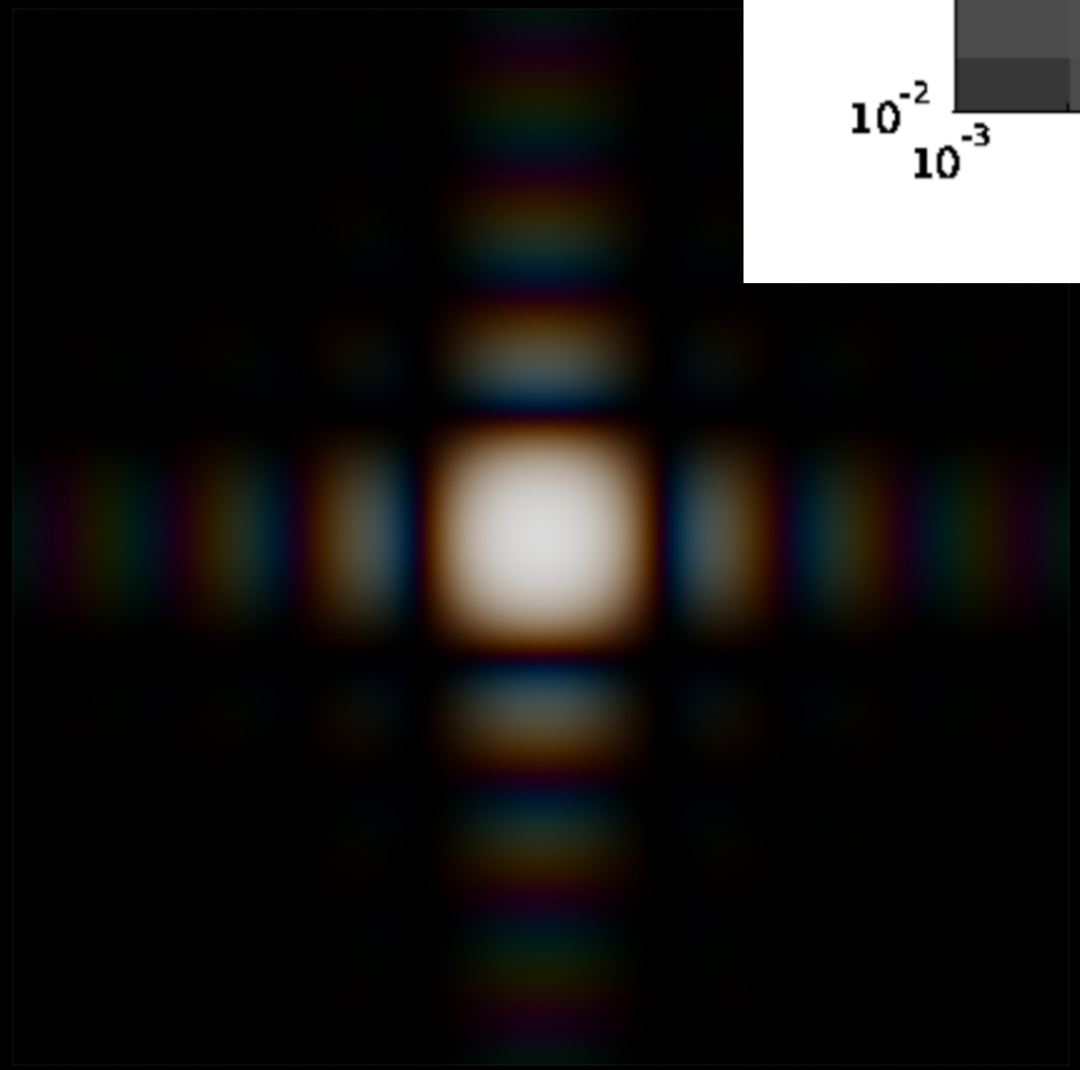
Effects to worry about II

Chromaticity of antennas and array: frequency-dependent beam shapes and angular resolution

Small errors in sky model mimic the signal we are trying to measure by adding frequency structure



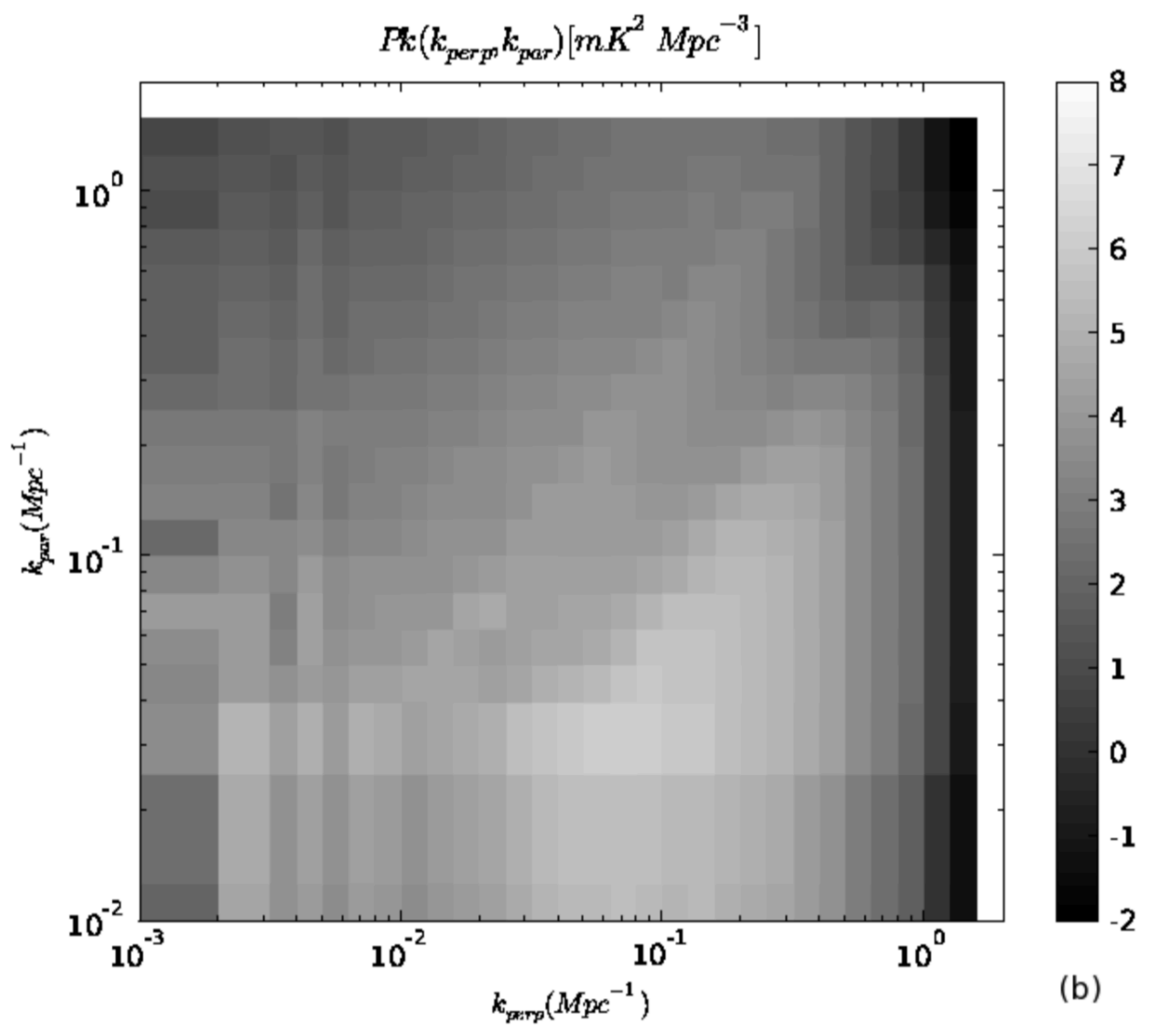
Datta et al. 2010



Effects to worry about III

Antenna gains need to be exquisitely calibrated: ~0.05% antenna gain error allowed!

Antenna heterogeneity makes this problem worse



Datta et al. 2010

Current activities of the ALO TT

Identification of necessary technology development for ALO currently underway:

Antennas: low-mass, printed?

Power distribution: local hub power?

Clock synchronisation: central to hubs?

Deployment: inflatable or unrollable structures?

Data transmission: RF or optical? Fiber or free-space?

Calibration: external and/or internal?

Data processing: how to tackle foreground removal?

Interested? Please get in touch!