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A Designer's Guide to Lunar Far-Side Interferometer Array: Power Spectrum Measurement and Cosmological Constraints in the Dark Ages

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The Cosmic Dark Ages and the 21-cm Signal

- From recombination (z~1100) to the formation of first stars and galaxies (z~30)
  - No luminous sources
  - HI constitutes the bulk of baryonic content of the Universe
  - The 21-cm signal from HI becomes main tracer of matter density distributions
- A pristine probe of the initial conditions of the Universe
  - No complex radiation, ionization, feedback...
  - Primordial non-Gaussianity, inflation, particles physics etc.

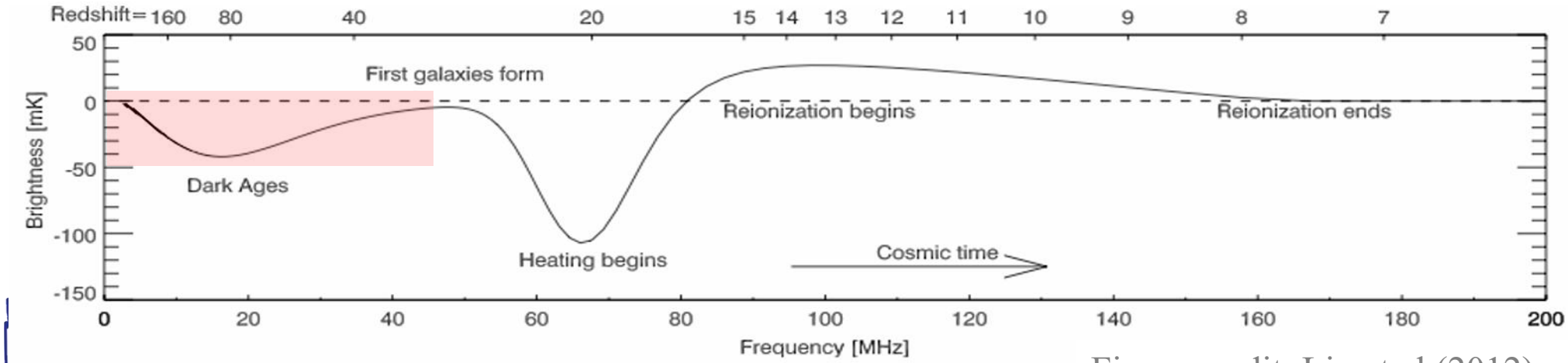


Figure credit: Liu et al (2012) arXiv 1211.3743

Scientific Potentials of the Cosmic Dark Ages

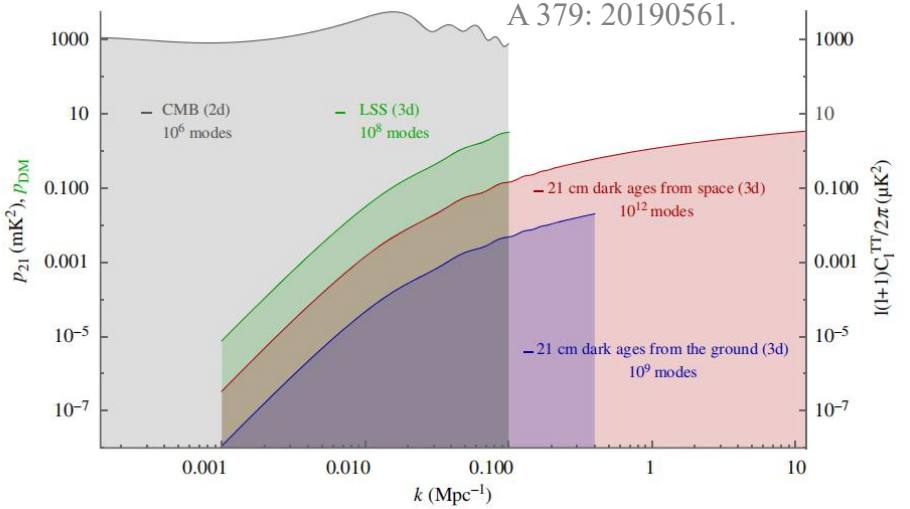
Access to small but still linear scales

- Structure formation still at an early stage
  - Linearity holds up to very small scales of $\geq 10\ \mathrm{Mpc}^{-1}$
- Compare to other probes
  - CMB: $\sim 0.1\ \mathrm{Mpc}^{-1}$ due to Silk damping
  - LSS: $\sim 1\ \mathrm{Mpc}^{-1}$ due to nonlinearities
- Testing theories that have a small-scale deviation from ΛCDM

Cosmological Constraint

- Large Fourier volume
  - Wide transverse scale coverage
  - Observable redshift span $\Delta z \approx 150$
- Probe of inflationary and early universe parameters

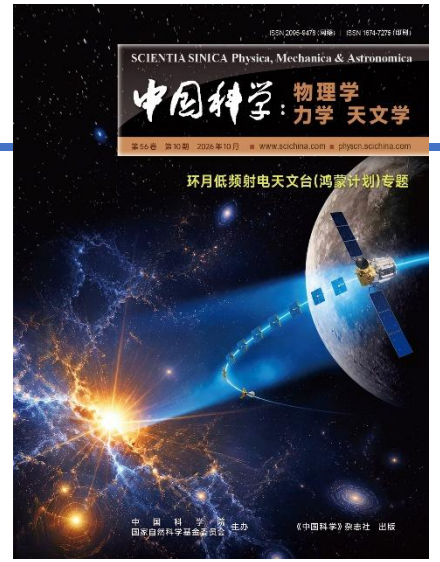
Figure credit: Silk J. 2021. *Phil. Trans. R. Soc.* A 379: 20190561.



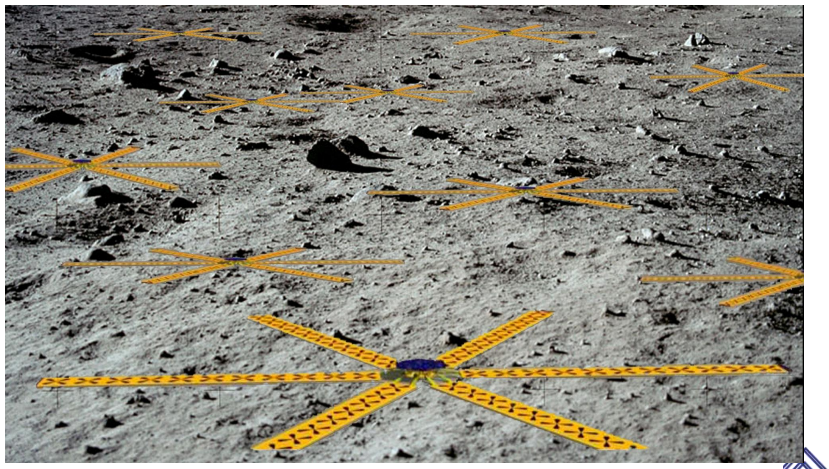
A Lunar Far-Side Interferometer Array

- The redshifted Dark Ages signal: 7-46 MHz
  - The last EM window yet to be opened in astronomy
  - Earth's ionosphere absorbs and refracts in this band
  - Terrestrial RFI contaminates the signal
- Lunar far-side interferometer
  - No ionosphere and shielded from RFI
  - Ongoing lunar-based projects:
    - CoDEX, FarView, ROSS/DALI…
    - DSL/Hongmeng Project

To achieve different scientific goals, how should we strategize the design of the lunar intereferometer array?



DSL/Hongmeng Project



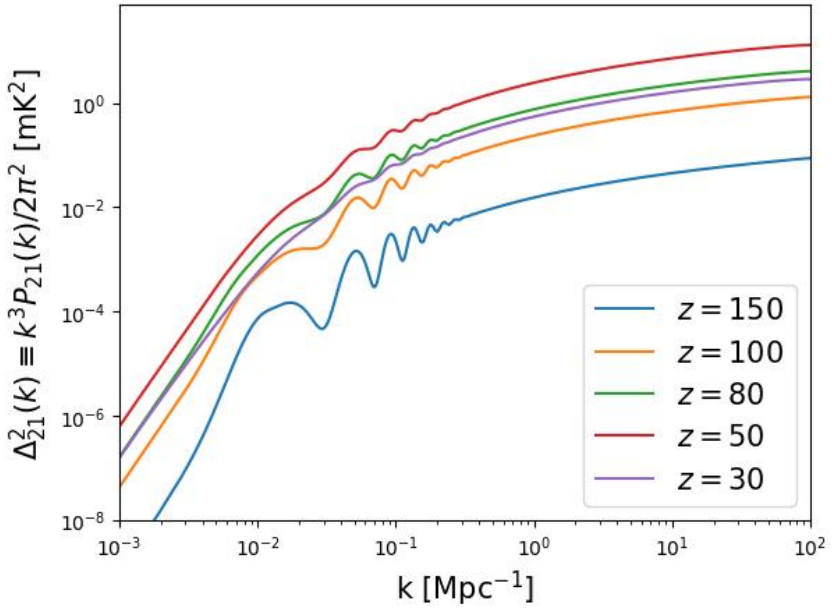
FarView Concept Design

https://lunar.colorado.edu/lowfreq/

The 21-cm Power Spectrum

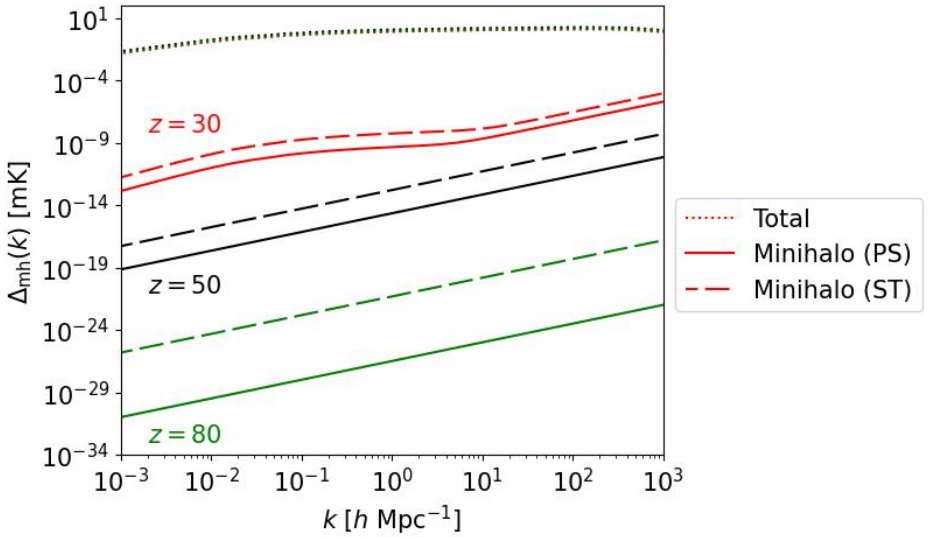
CAMB computes the 21-cm power spectrum

$$P_{21}(k,\mu) = (\delta\overline{T}_b)^2\left[P_{\mu^0} + \mu^2 P_{\mu^2} + \mu^4 P_{\mu^4}\right]$$



Impact of Minihalos

- Sparse but present during the later stage of the Dark Ages
- Halo model approach with both Press-Schechter and Sheth-Tormen mass function
- Minihalo contribution is negligible



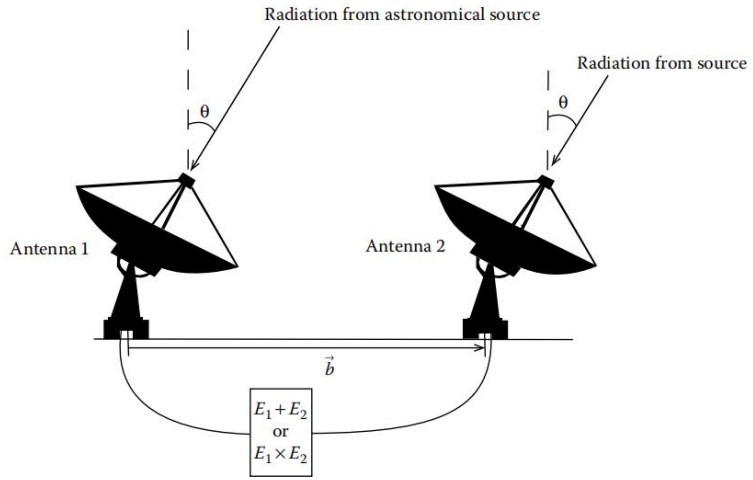
Goal #1: Measuring at a Selected Small-Scale

- Baseline length $D \rightarrow$ Which scale/$k_\perp$ can be probed
- Baseline density $n_b(D) \rightarrow$ Sensitivity at $k_\perp$
  - $S/N\,(k_\perp) \sim \sqrt{N(k_\perp)} \times P_{21}(k_\perp) \times n_b(k_\perp)$

Binning in k-space

Signal

Baseline density



Example baseline density distributions of a single circular arrays with randomly distributed antennas

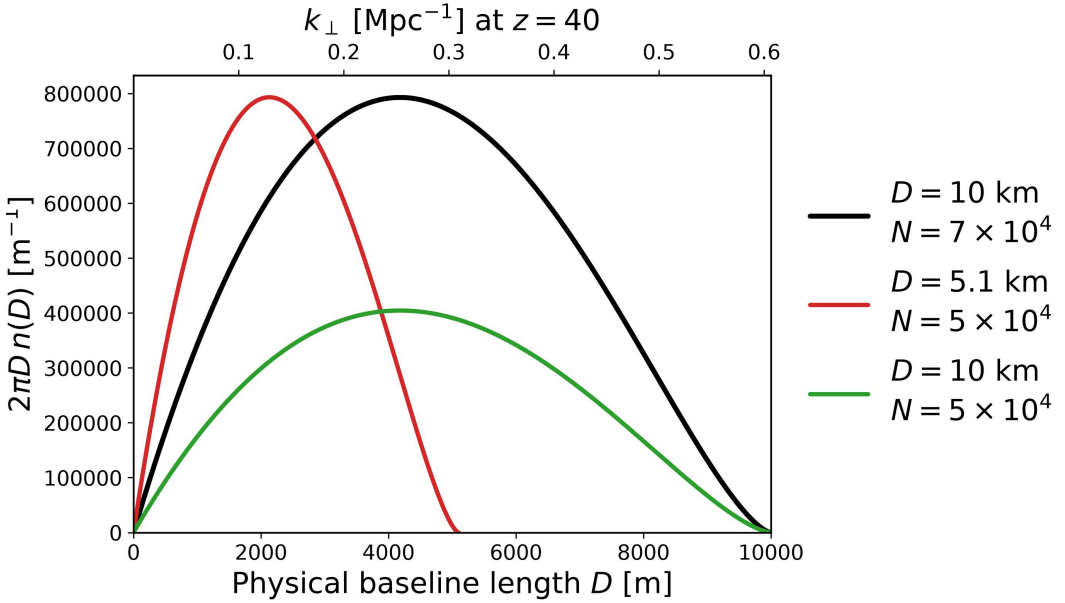
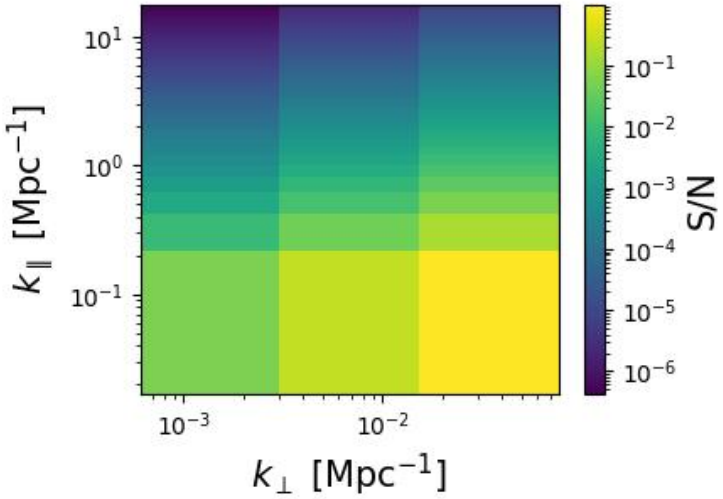


Figure credit: Marr, Snell, and Kurtz *Fundamentals of Radio Astronomy: Observational Methods*, CRC Press (2013).

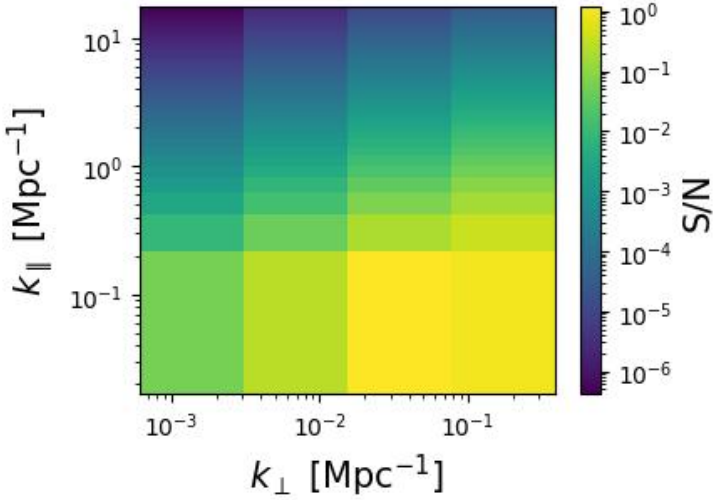
Detection with a Single Array (and Its Limitations)

S/N forecast for 21-cm power spectrum at $z = 40$

- Extending the same architecture to smaller scales requires rapidly increasing resources
- The high-$k_\perp$ reach does not automatically translate into an efficient measurement



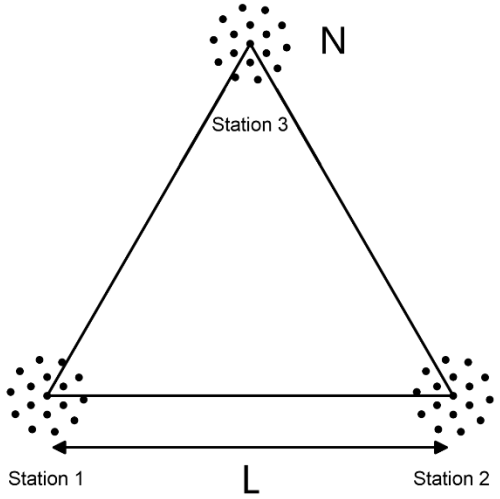
Compact
$D_{\max} = 3.6$ km
$N_{\text{ant}} = 10^5$
$t_{\text{tot}} = 6 \times 10^4$ hrs

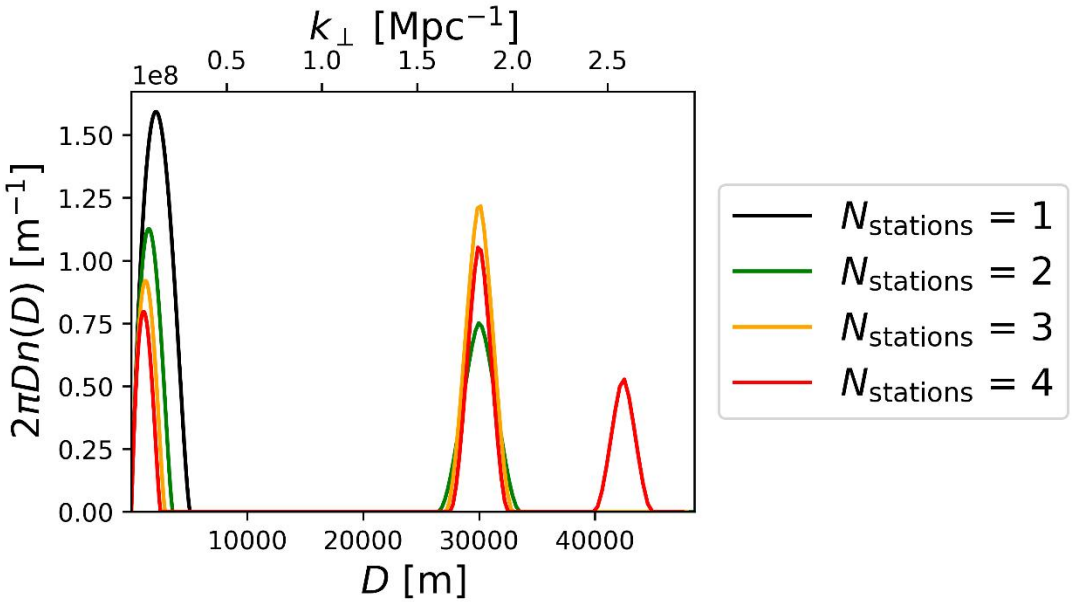


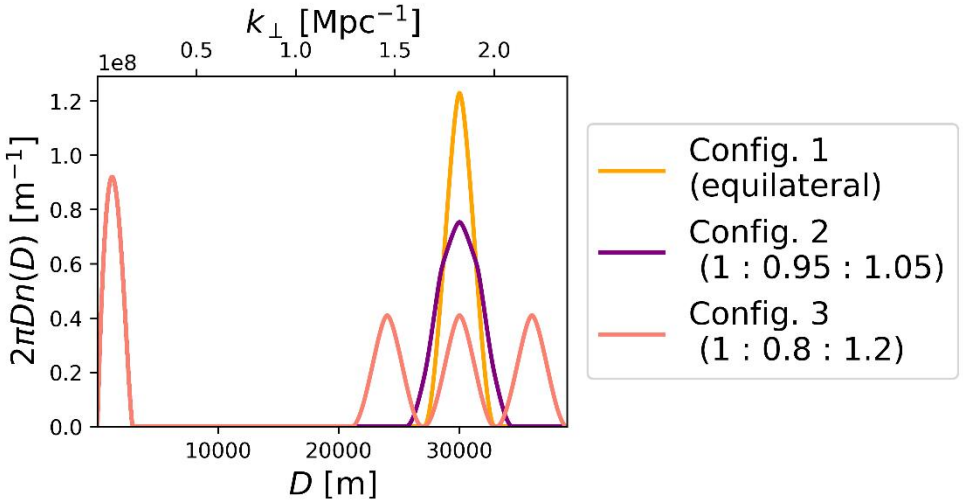
Sparse
$D_{\max} = 10$ km
$N_{\text{ant}} = 2 \times 10^5$
$t_{\text{tot}} = 10^5$ hrs

A More Economic Alternative: Multi-Station

- Cross-station baselines: long and dense
  - Station separation $L \rightarrow$ target small scales
  - Number density of cross-baselines $\sim N^2$
  - Flexibility in peak location and width

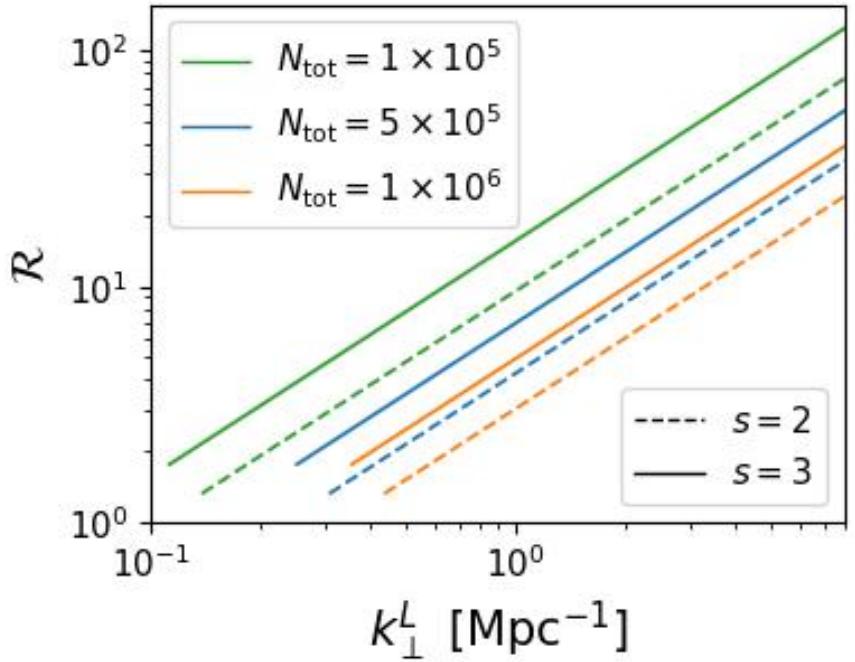






Improvement over Single-Array

- With equal amount of resources
  - Greater gain at smaller target scale
  - Greater gain with fewer resources
  - $\mathcal{R} = 10$ or 16 at $k_\perp = 1$ and $z = 40$



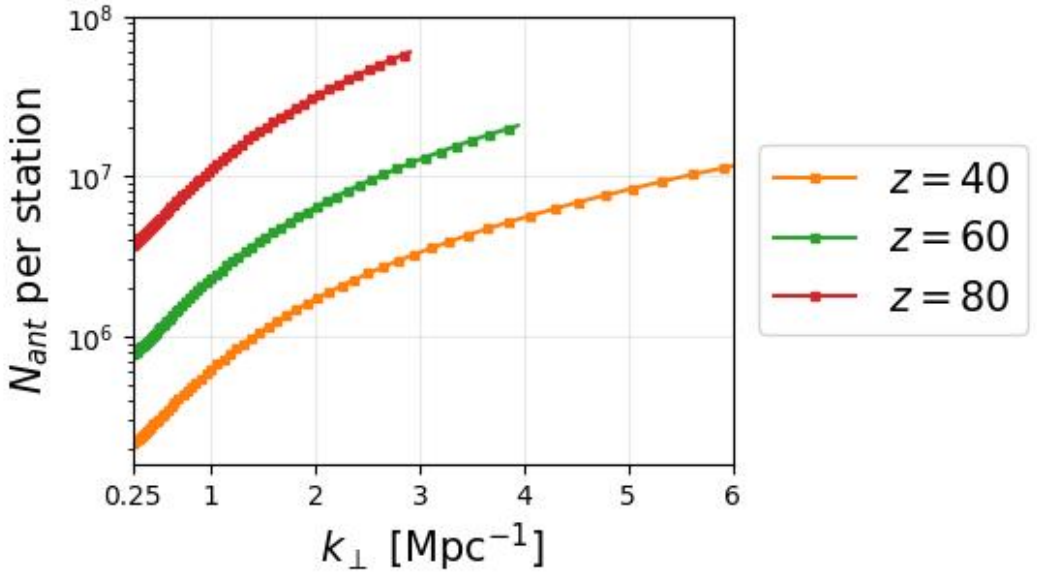
- Requirement curve

$$N_{\text{ant}} = \mathcal{S}^{-2/3}\left(S/N\right)^{2/3}\left[P_{21}(k_\perp, z)\xi(z)\right]^{-2/3}$$

Stations

Target Sensitivity

$r(z)$, $H(z)$ … etc.



Goal #2: Parameter Constraint

Fisher information formalism

$$F_{ij} = \sum_z \sum_k \left(\frac{\partial P_{21}(k,z)}{\partial p_i}\right)\left(\frac{\partial P_{21}(k,z)}{\partial p_j}\right)\frac{1}{\delta P_{21}^2(k,z)}$$

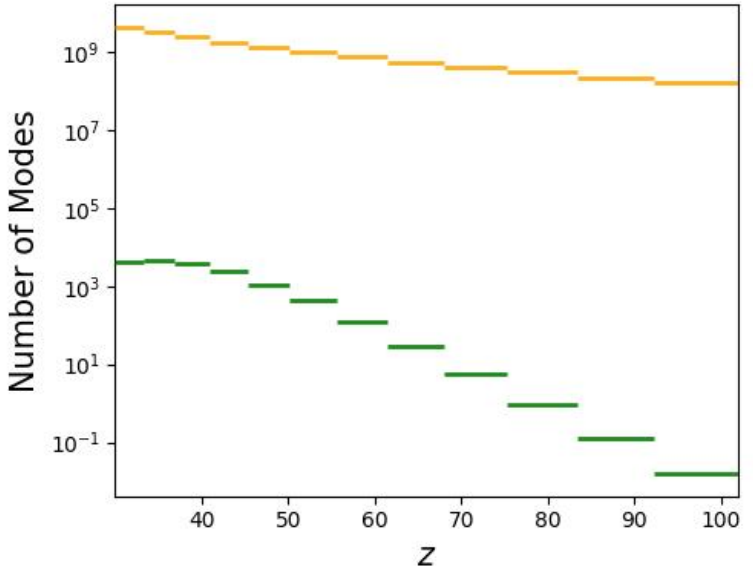
How is Fisher information distributed along the z and $k_\perp$ direction?

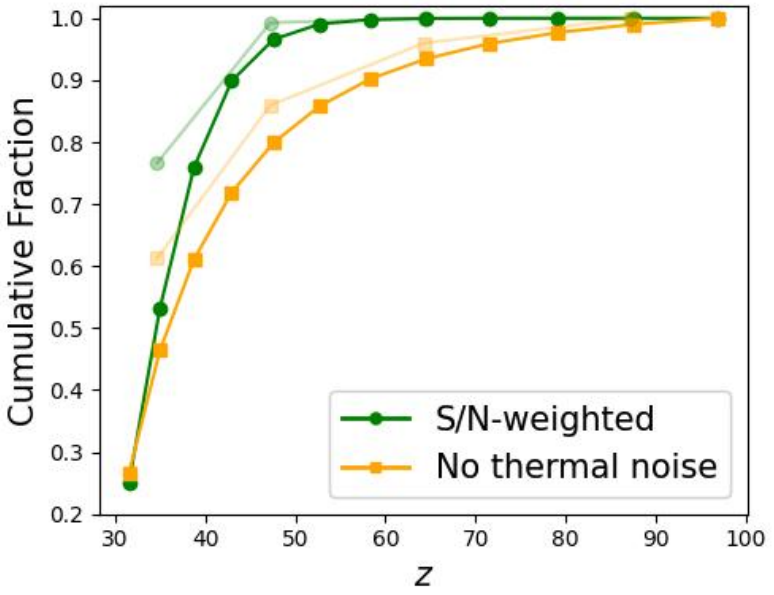
How is Information Distributed in z-Space?

- "Dark Ages can access 10^{12} Fourier modes"
  - In comparison: CMB: $\sim 10^6$; LSS: $\sim 10^8$
- Effective #modes in a redshift bin

$$N_{\text{modes}}(z) \equiv \sum_k (P_{21}/\delta P_{21})^2$$

- At high-z, thermal noise dominates and erodes the accessible modes
- For a near-term array of 10^6 antennas and $t = 10^5$ hrs
  - Total models $\sim 3 \times 10^4$
  - 50% at $z \lesssim 36$ and 90% at $z \lesssim 50$





How is Information Distributed in $k_\perp$-Space?

Information Density

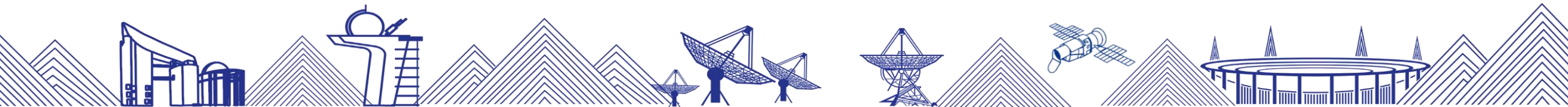
$$\frac{dI_k(p)}{d\ln k_\perp} \sim k_\perp^2 \times \left(\frac{\partial P_{21}}{\partial p}\right)^2 \times n_b(k_\perp)^2$$

Phase space factor

Parameter's response

Baseline density

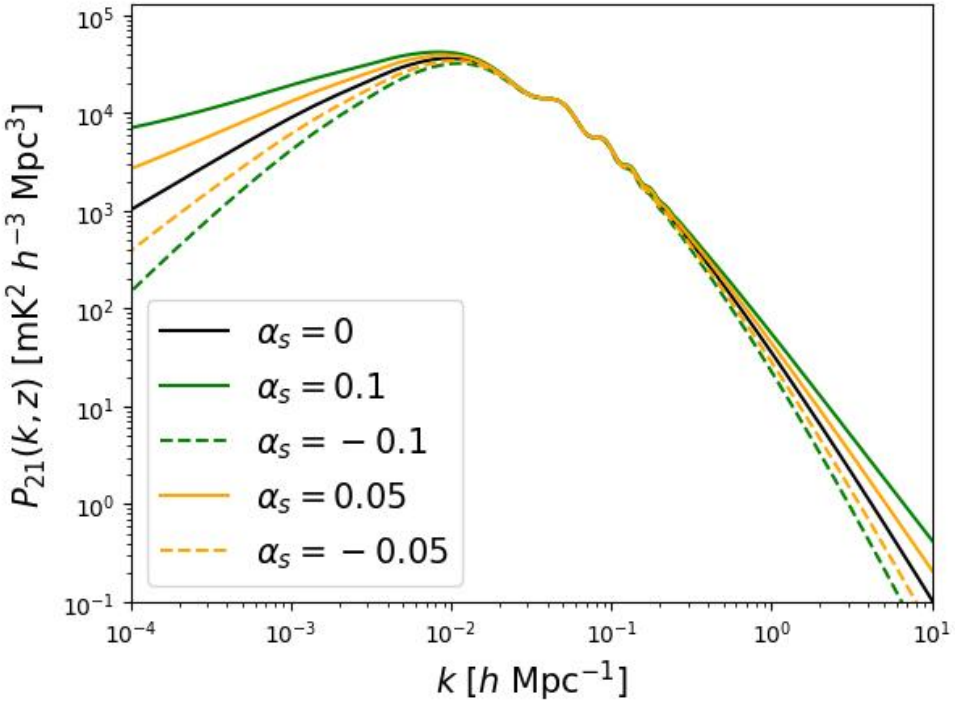
To maximize Fisher information: a joint optimization of array configuration and parameter response, which may sometimes may compete with each other



Case Study: Constraining α_s

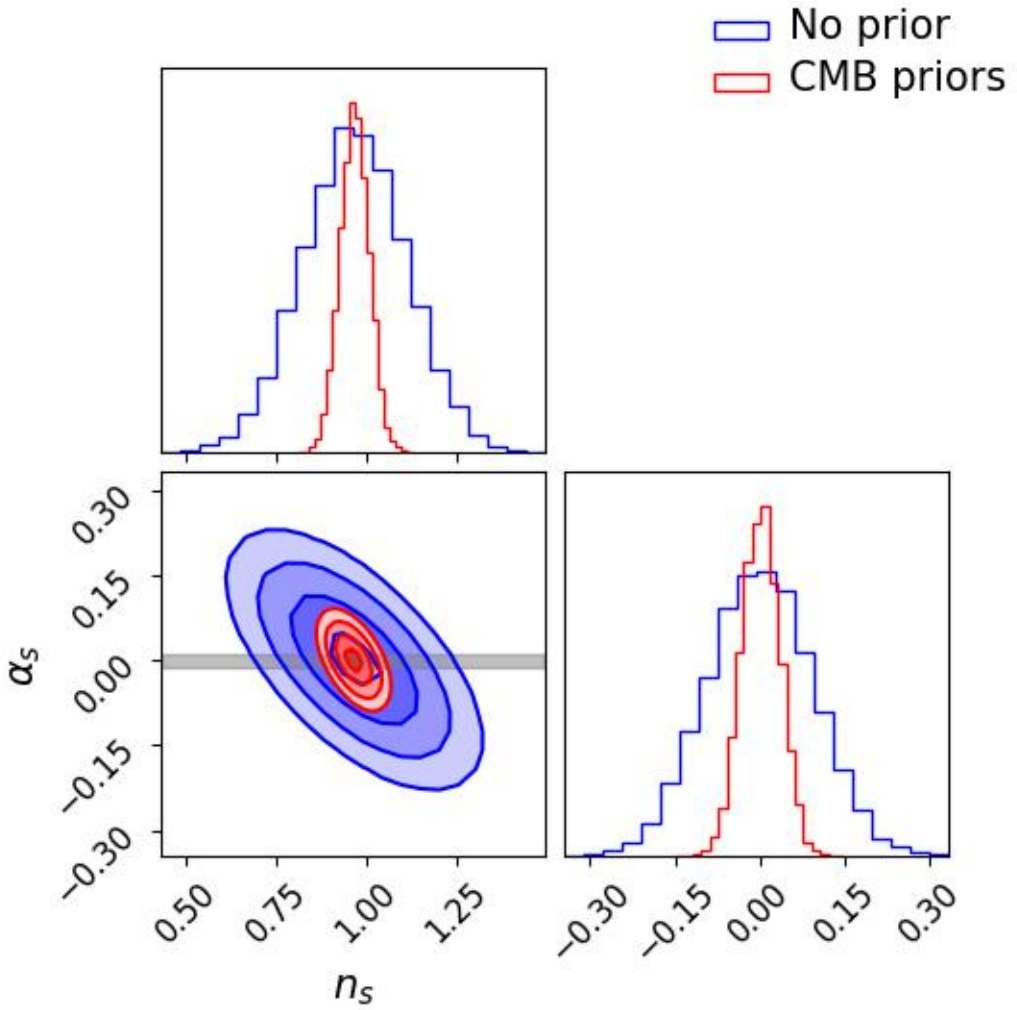
- The running of the spectral index of the primordial power spectrum $\alpha_s \equiv dn_s/d\ln k$
  - Important probe of inflationary models: standard slow-roll or exotic ones?
  - Planck 2018 constraint: $\sigma(\alpha_s) = 0.012$ or 0.0067
- Why Dark Ages might offer better constraint?
  - Large survey volume
  - May map out the full "lever arm"

Model	α_s
Scale-invariant R^2 inflation	$\sim 10^{-2}$
Multi-natural (sinusoidal)	-0.06 to 0.08
Multi-natural (η-function)	-0.013 ± 0.009
Linear potential + oscillations	~ 0.05
Quadratic potential + oscillations	~ 0.10
Multifield natural	$\sim -5 \times 10^{-3}$



Constrains from Using a Single Array

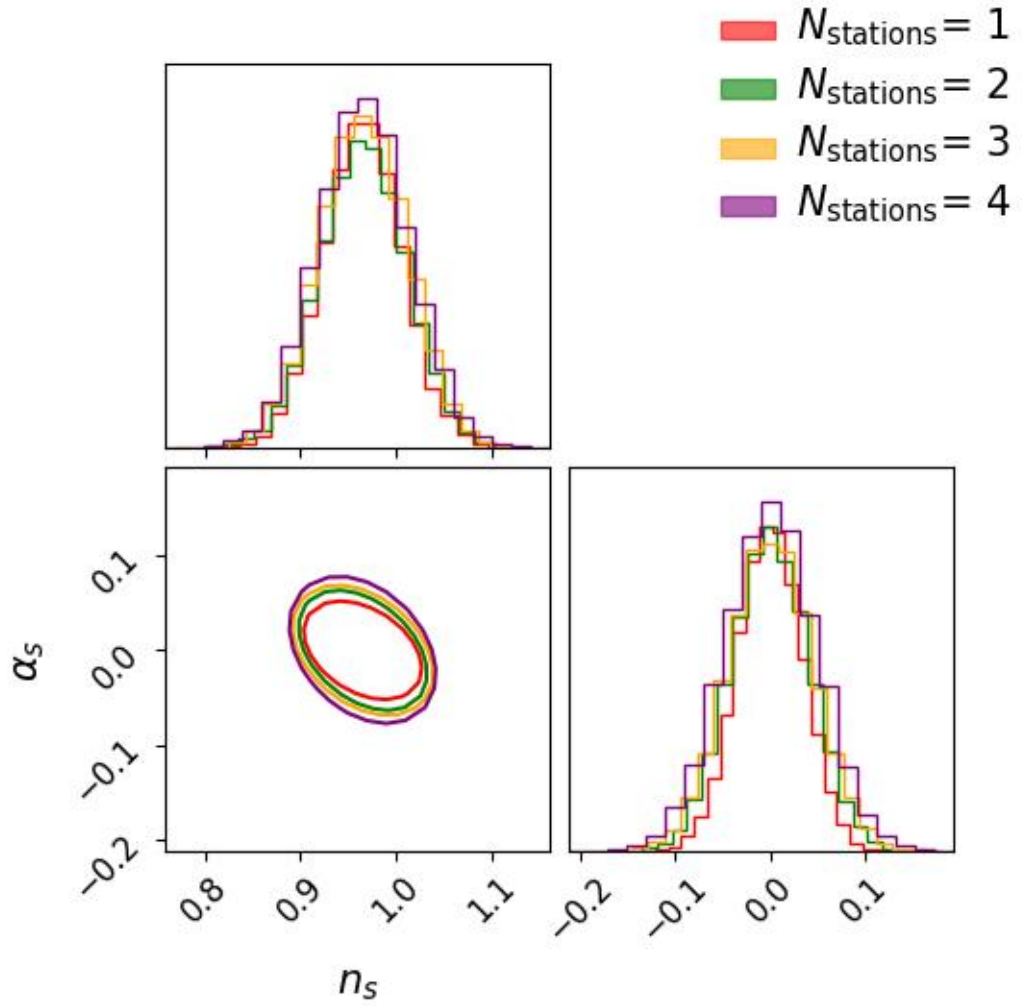
- Fisher forecast on $\sigma(\alpha_s)$ assuming a near-term lunar far-side array:
  - Diameter 5.1 km (k_{max}~0.4 Mpc^{-1}) and 10^6 antennas, 100,000 hrs integration time, covers $30 \leq z \leq 100$
  - $\sigma(\alpha_s) = 0.034$



Constrains from Multi-Array

- Splitting into several sub-arrays
  - Each station placed at the vertex of a regular polygon of side length L
- Constraints remain similar to that of the single array
  - Slightly worsens as #stations increases
  - Changing L has little impact

L [km]	1	2	3	4
5	0.034	0.039	0.041	0.044
10		0.041	0.045	0.049
20		0.041	0.047	0.051
100		0.041	0.047	0.052



Not Quite as Expected?

- Why is $\sigma(\alpha_s)$ not as tight as expected, despite the large amount of resources invested?
- Claim #1: large survey volume
  - The number of accessible modes is eroded at high-z by thermal noise
- Claim #2: mapping out the "lever arm"
  - As one goes to smaller scales, the response grows as

$$\frac{dI_k(p)}{d\ln k_\perp} \sim k_\perp^2 \times \left(\frac{\partial P_{21}}{\partial p}\right)^2 \times n_b(k_\perp)^2$$

$$\partial P_{21}/\partial \alpha_s \sim P_{21}[\ln(k_\perp/k_0)]^2$$

  - For a single array: cannot offset the dilution of baselines
  - For a multi-station array:
    - Adding a narrow peak at small scales vs. discarding info from middle scales
- To constrain α_s: prefers a compact single array; should concentrate on low redshift end

Summary and Conclusion

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- The Dark Ages 21-cm signal offers two major scientific opportunities
  - Precision measurements on small scales
  - Constraining on primordial physics and inflationary parameters
- What design requirements do these goals impose on a lunar far-side array? What measurement precision can a near-future array achieve?
- To measure the power spectrum at a target scale: distribute the collecting area among multiple stations provides orders of magnitude better S/N and more flexibility
- Cosmological constraints
  - Derive the distribution of accessible information in z and $k_\perp$ directions
  - Showcase with the running of the spectral index how this framework can be used to analyze and optimize the array design aiming to constrain a certain parameter of interest