The Precision Array for Probing the Epoch of Reionization (PAPER)

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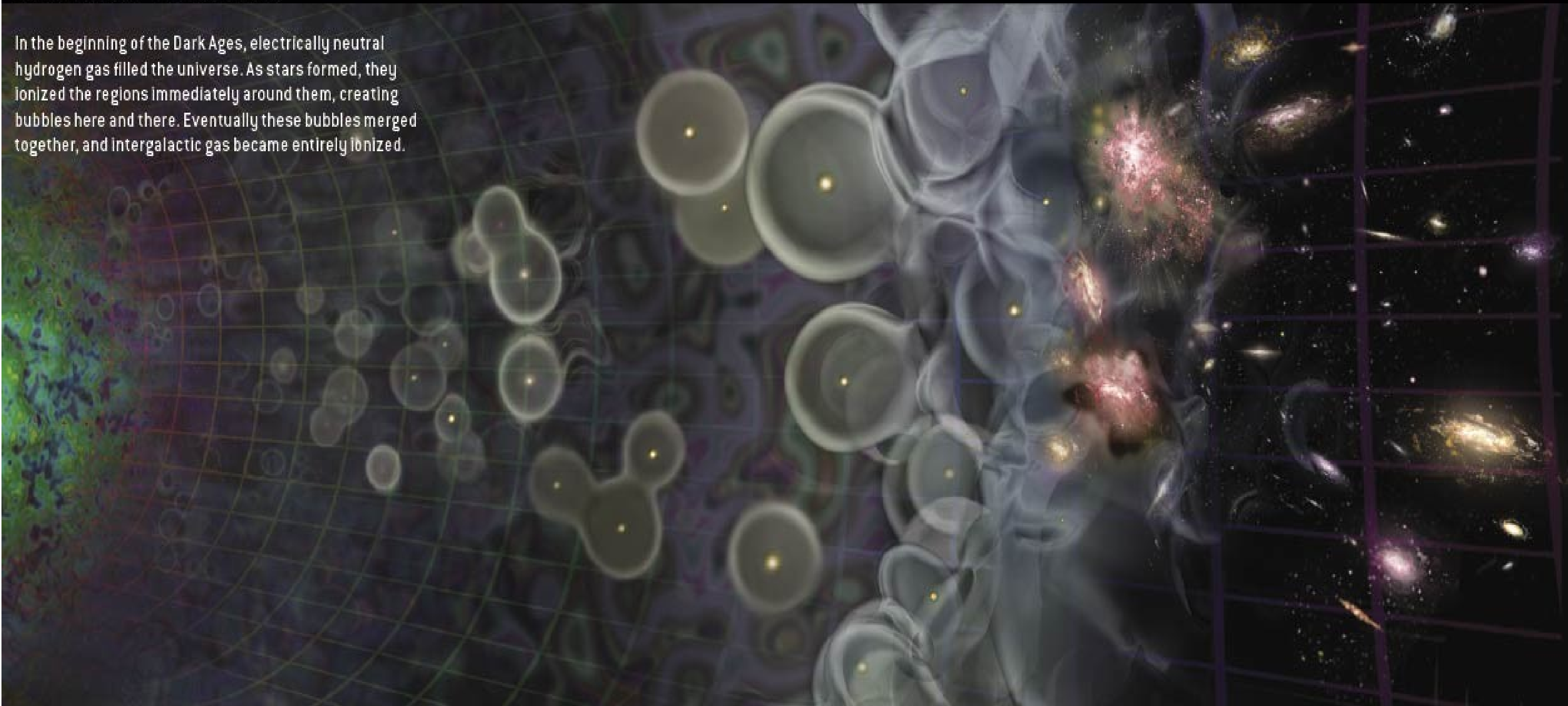
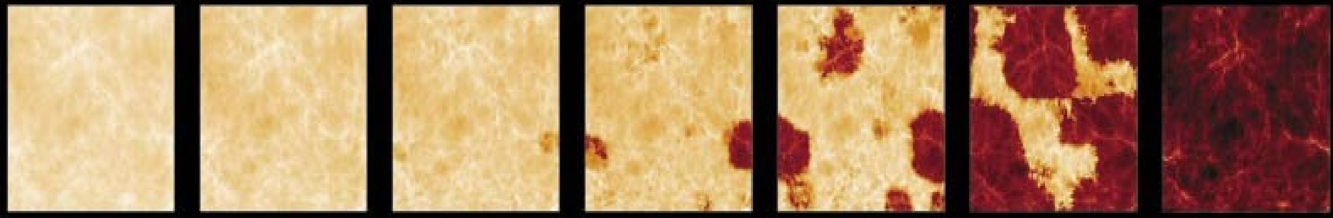
LIGHTING UP THE COSMOS

In the beginning of the Dark Ages, electrically neutral hydrogen gas filled the universe. As stars formed, they ionized the regions immediately around them, creating bubbles here and there. Eventually these bubbles merged together, and intergalactic gas became entirely ionized.



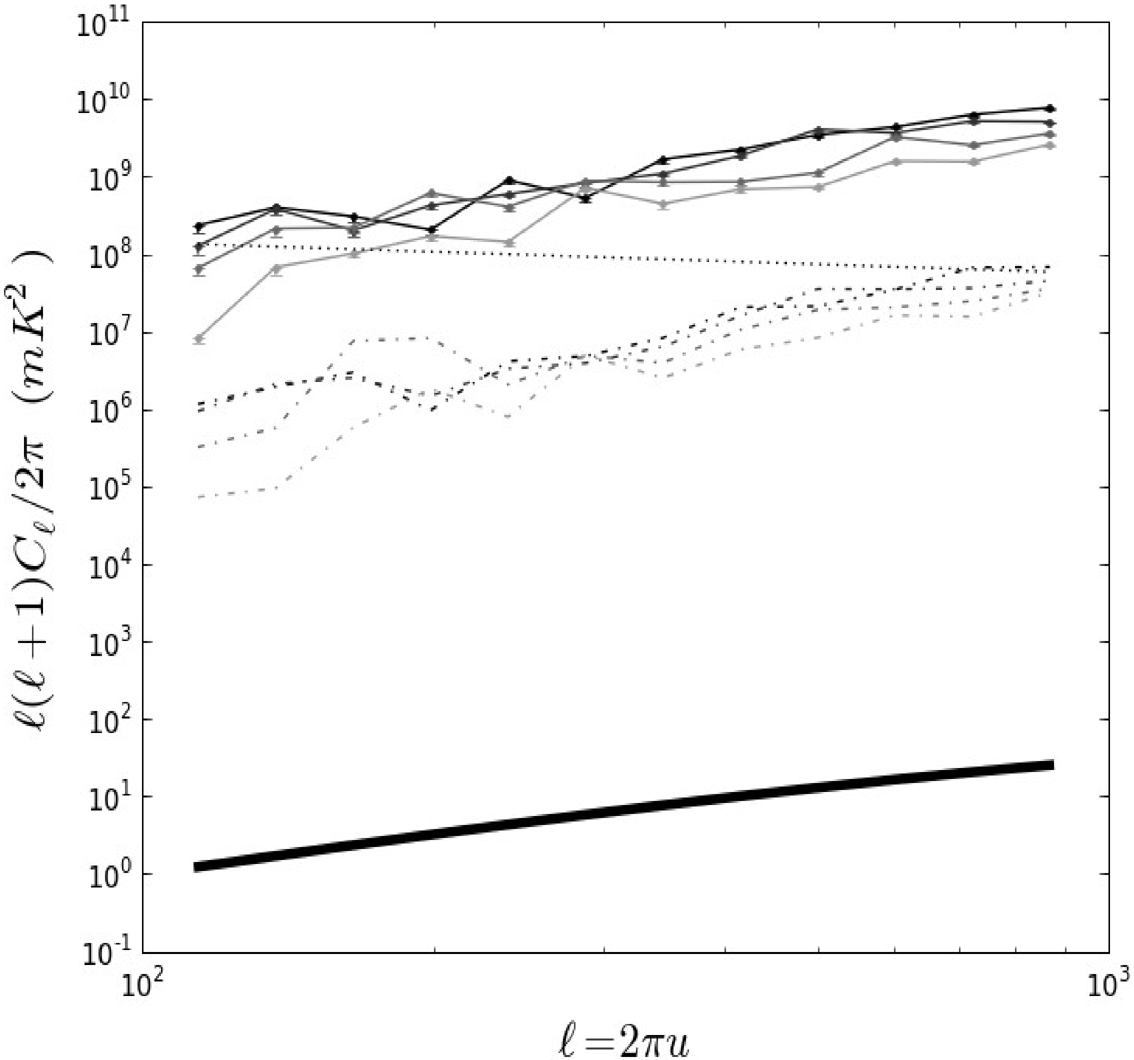
Time:	210 million years	290 million years	370 million years	460 million years	540 million years	620 million years	710 million years
Width of frame:	2.4 million light-years	3.0 million light-years	3.6 million light-years	4.1 million light-years	4.6 million light-years	5.0 million light-years	5.5 million light-years
Observed wavelength:	4.1 meters	3.3 meters	2.8 meters	2.4 meters	2.1 meters	2.0 meters	1.8 meters
	All the gas is neutral. The white areas are the densest and will give rise to the first stars and quasars.	Faint red patches show that the stars and quasars have begun to ionize the gas around them.	These bubbles of ionized gas grow.	New stars and quasars form and create their own bubbles.	The bubbles are beginning to interconnect.	The bubbles have merged and nearly taken over all of space.	The only remaining neutral hydrogen is concentrated in galaxies.



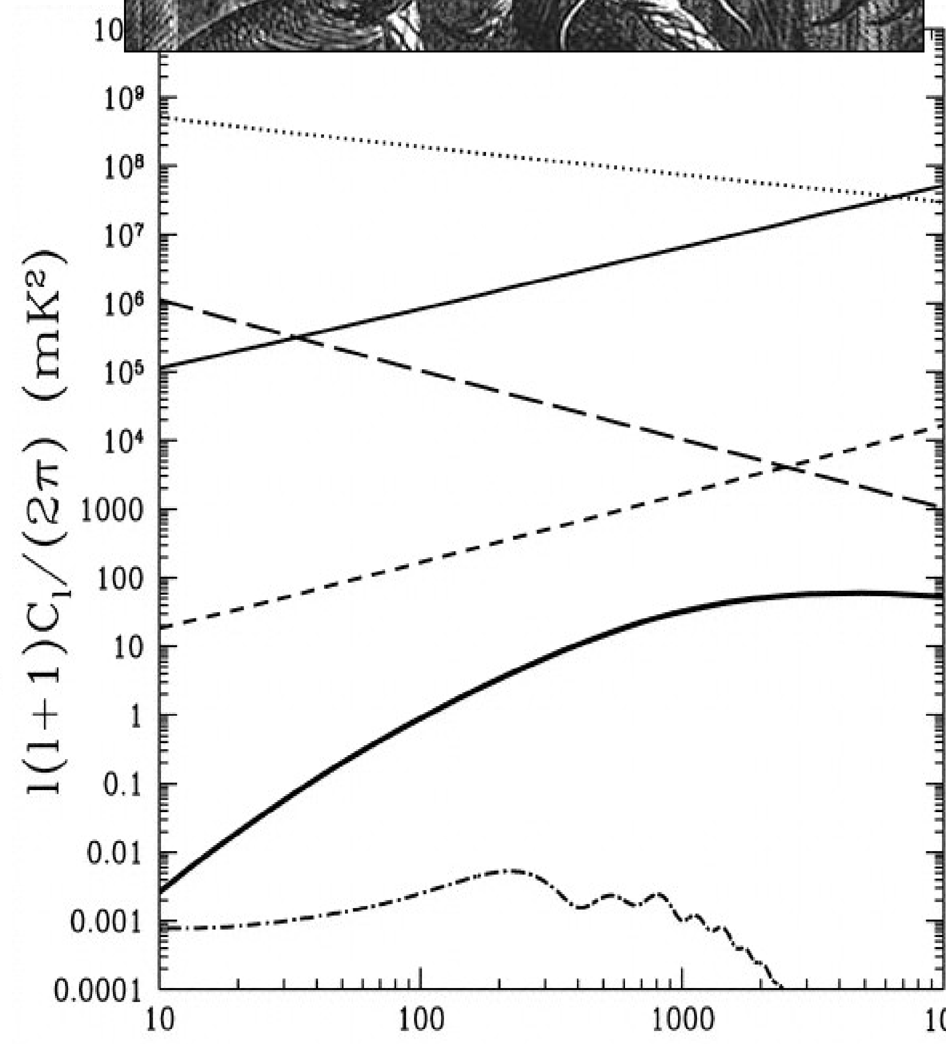
Simulated images of 21-centimeter radiation show how hydrogen gas turns into a galaxy cluster. The amount of radiation (*white is highest; orange and red are intermediate; black is least*) reflects both the density of the gas and its degree of ionization: dense, electrically neutral gas appears white; dense, ionized gas appears black. The images have been rescaled to remove the effect of cosmic expansion and thus highlight the cluster-forming processes. Because of expansion, the 21-centimeter radiation is actually observed at a longer wavelength; the earlier the image, the longer the wavelength.

JEAN-FRANCOIS PODEVIN (*illustration*); STEVEN FURLANETTO, AARON SOKASIAN AND LARS HERNQUIST *Harvard University* (*simulations*)

Power Spectra and Foregrounds

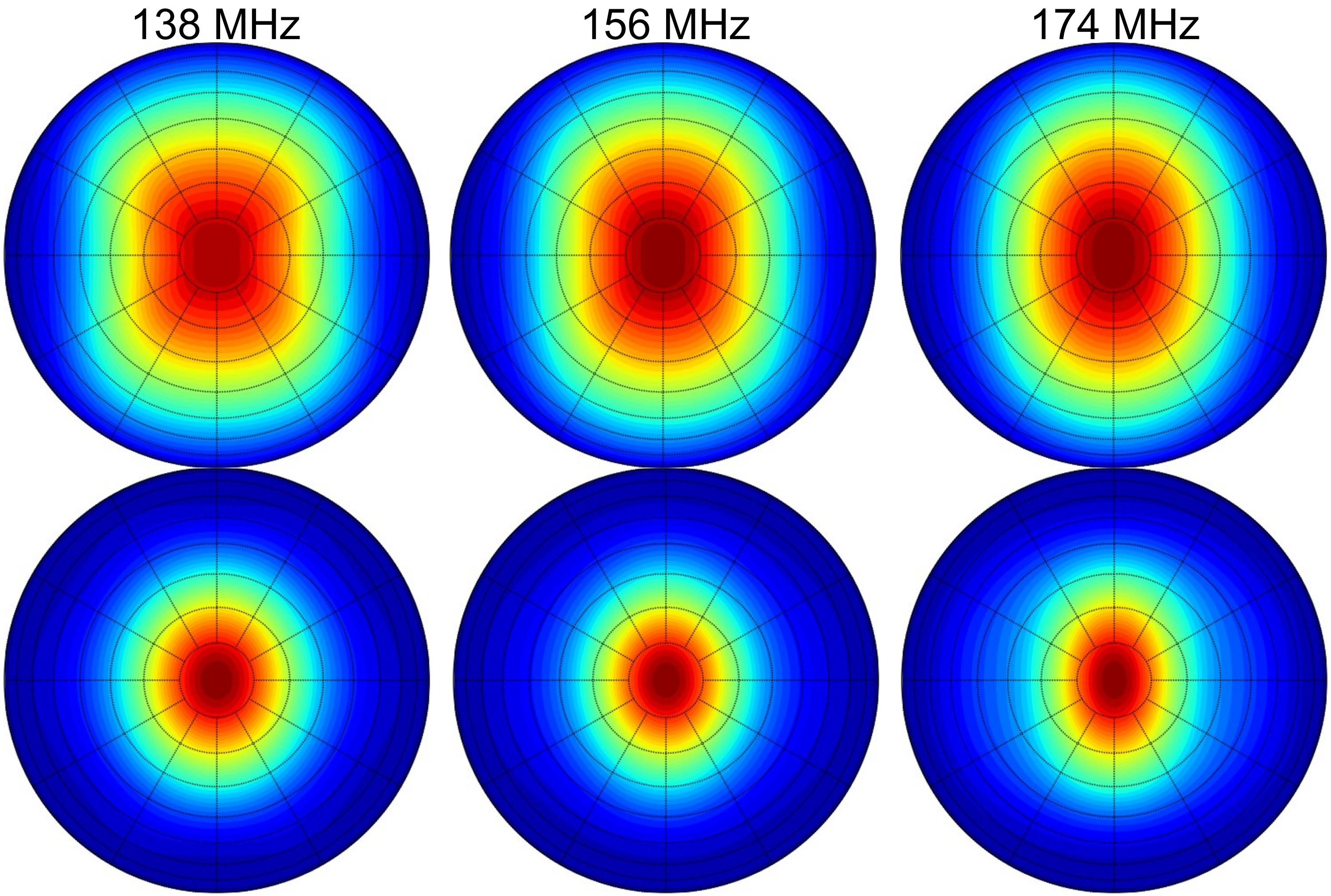


PGB-8 Power spectra at 146.6, 155.7, 164.5, and 173.3 MHz (top to bottom w/ error bars), from 4 fields near RA=12:00,DEC=40:00.
Point source dominated, starting to see synchrotron at lower frequencies, wavemodes



Santos et al. (2005)

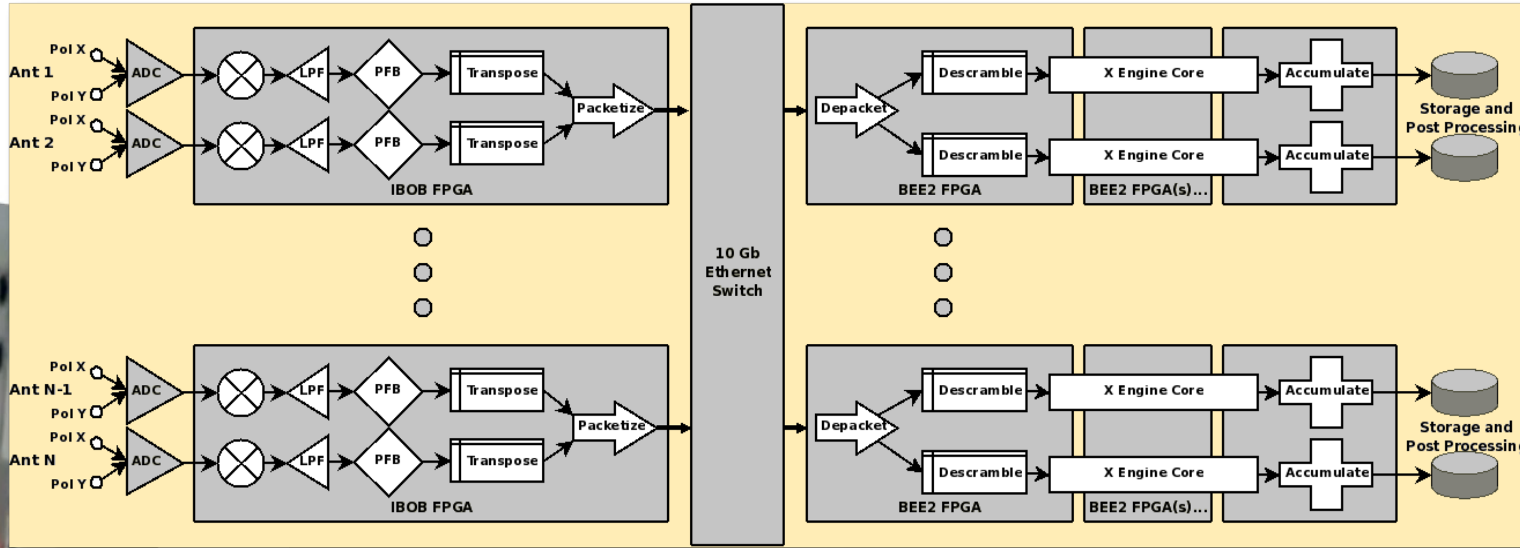
Modeling Beam of Dipole + Flaps

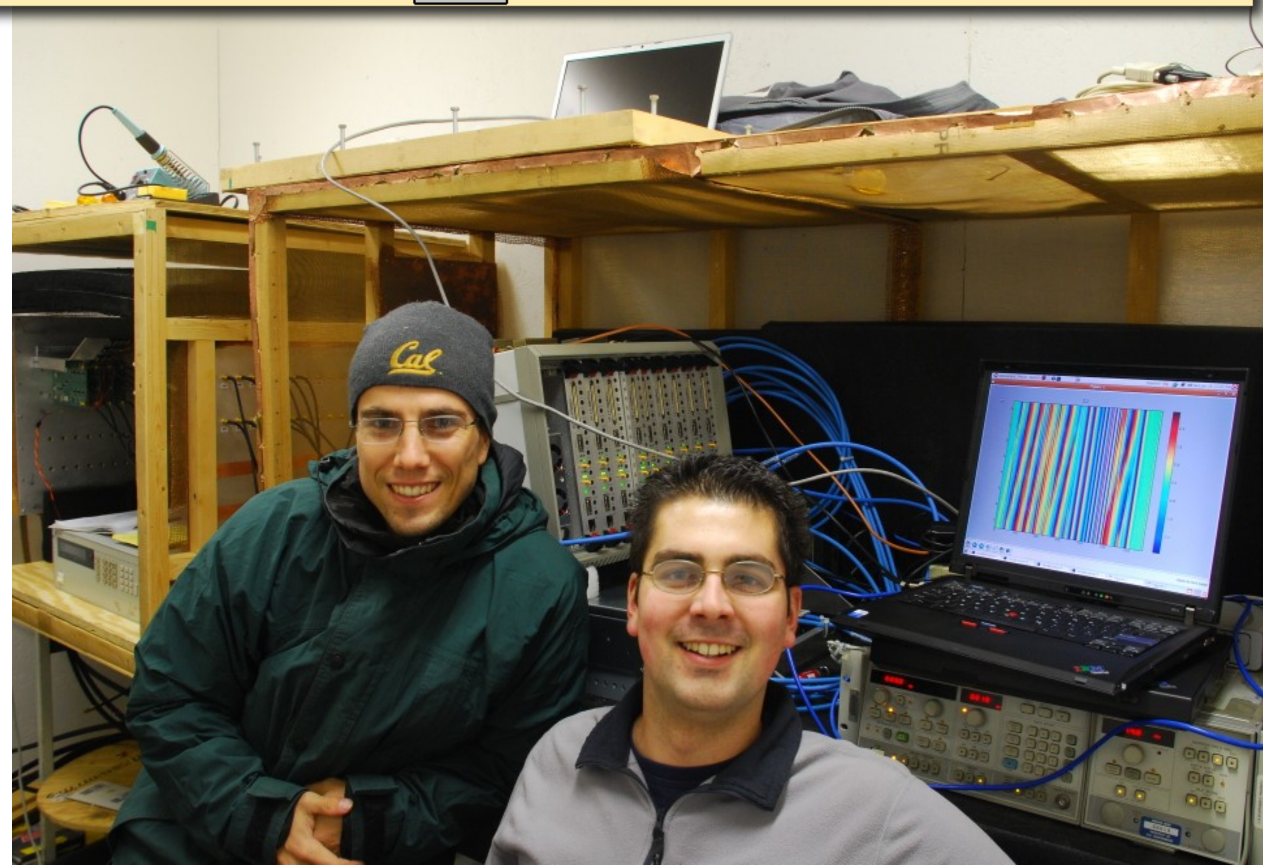


$$a_\nu(\hat{s}) = \sum_{k=0}^{7} \nu^k \left[\sum_{\ell=0}^{8} \sum_{m=0}^{\ell} a_{\ell m}(k) Y_{\ell m}(\hat{s}) \right]$$

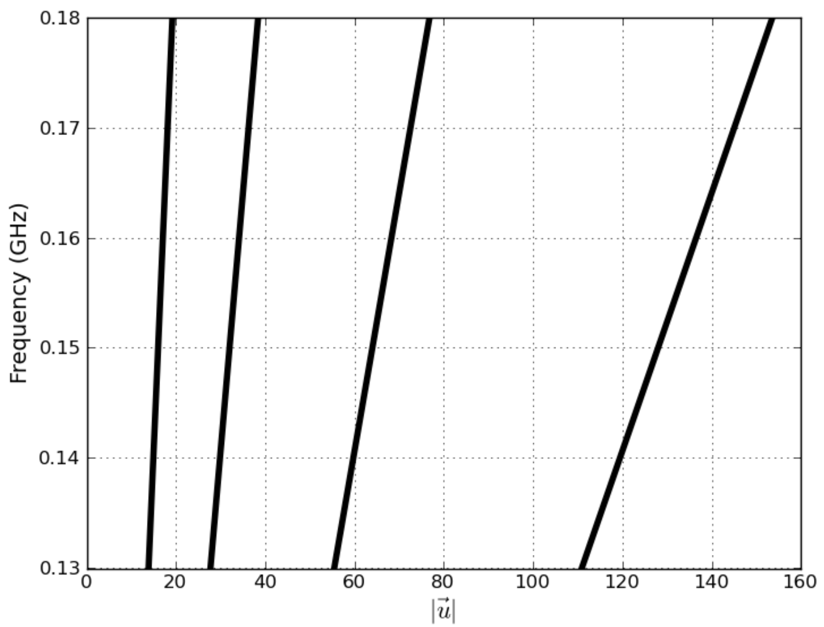
40dB zenith to horizon, 60 degree FWHM
Smooth spatially and vs. frequency

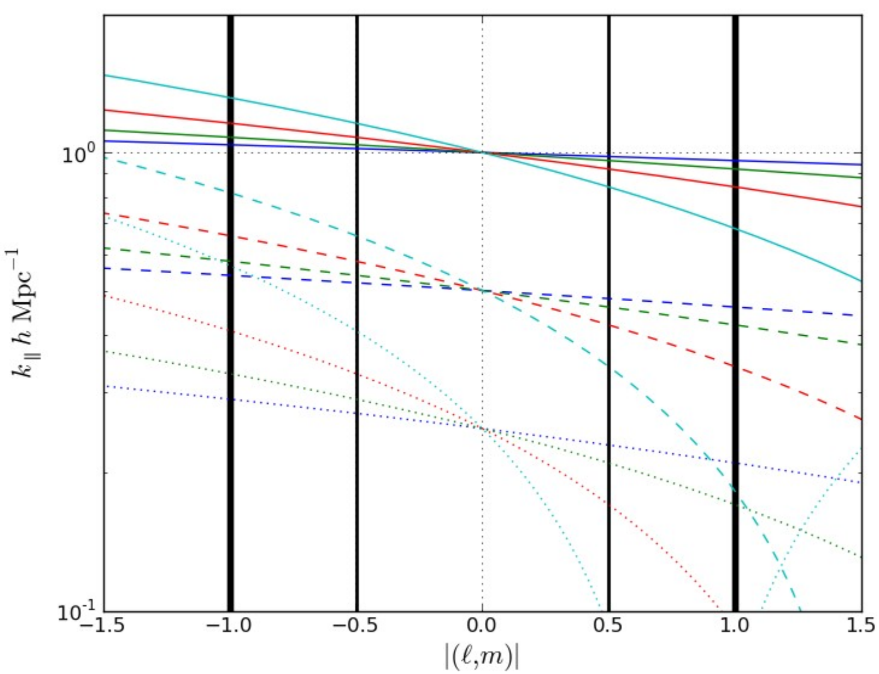
PAPER/CASPER Packetized Correlator

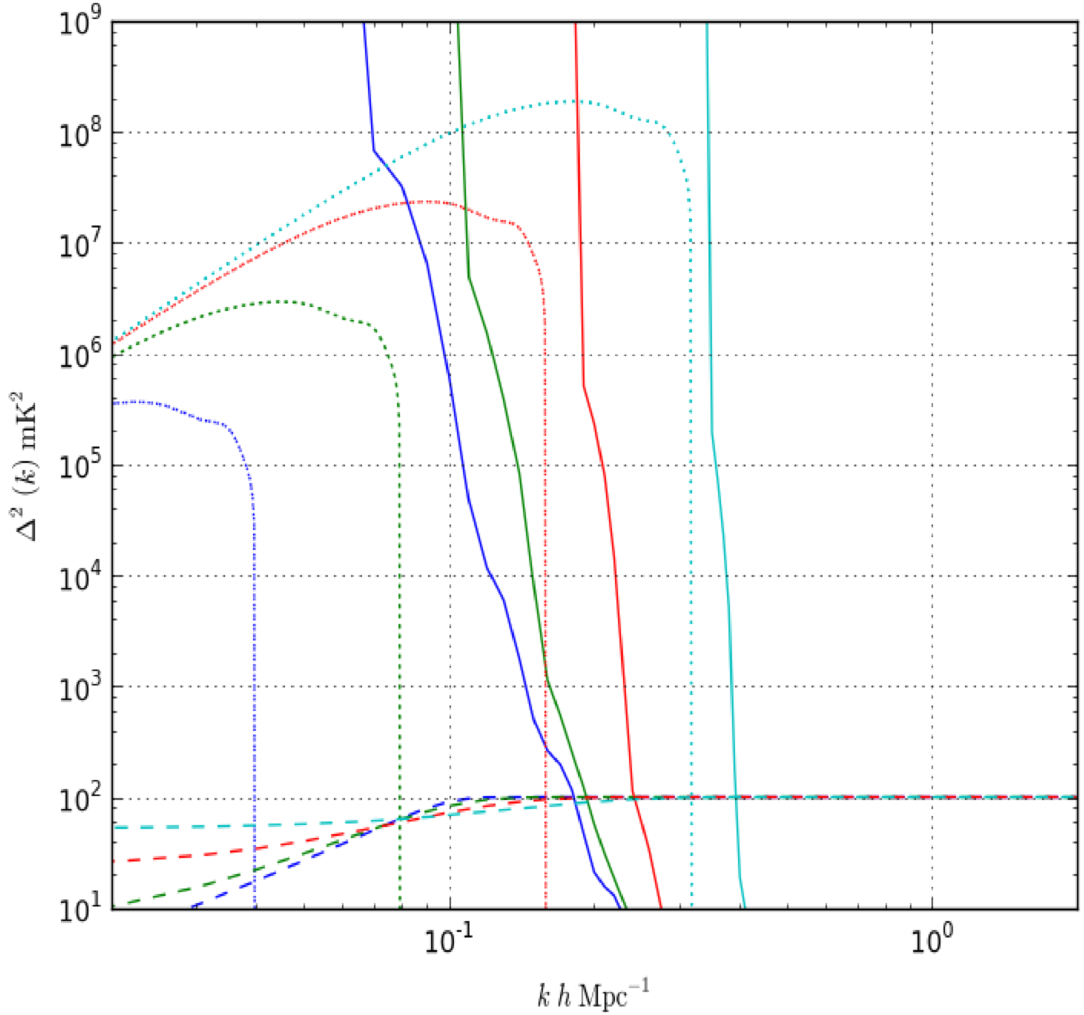




Using Delay Transform to Evade Foregrounds

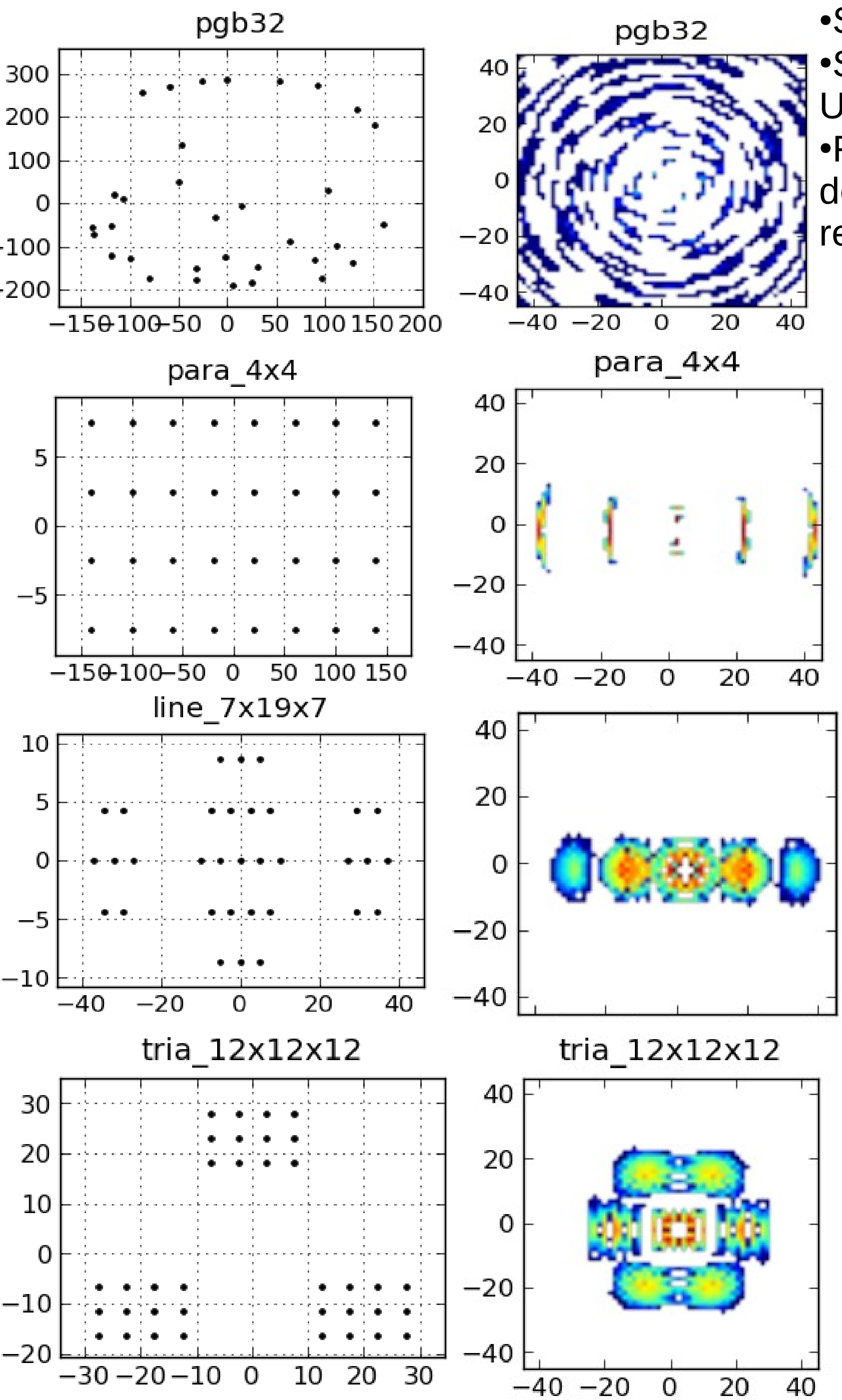




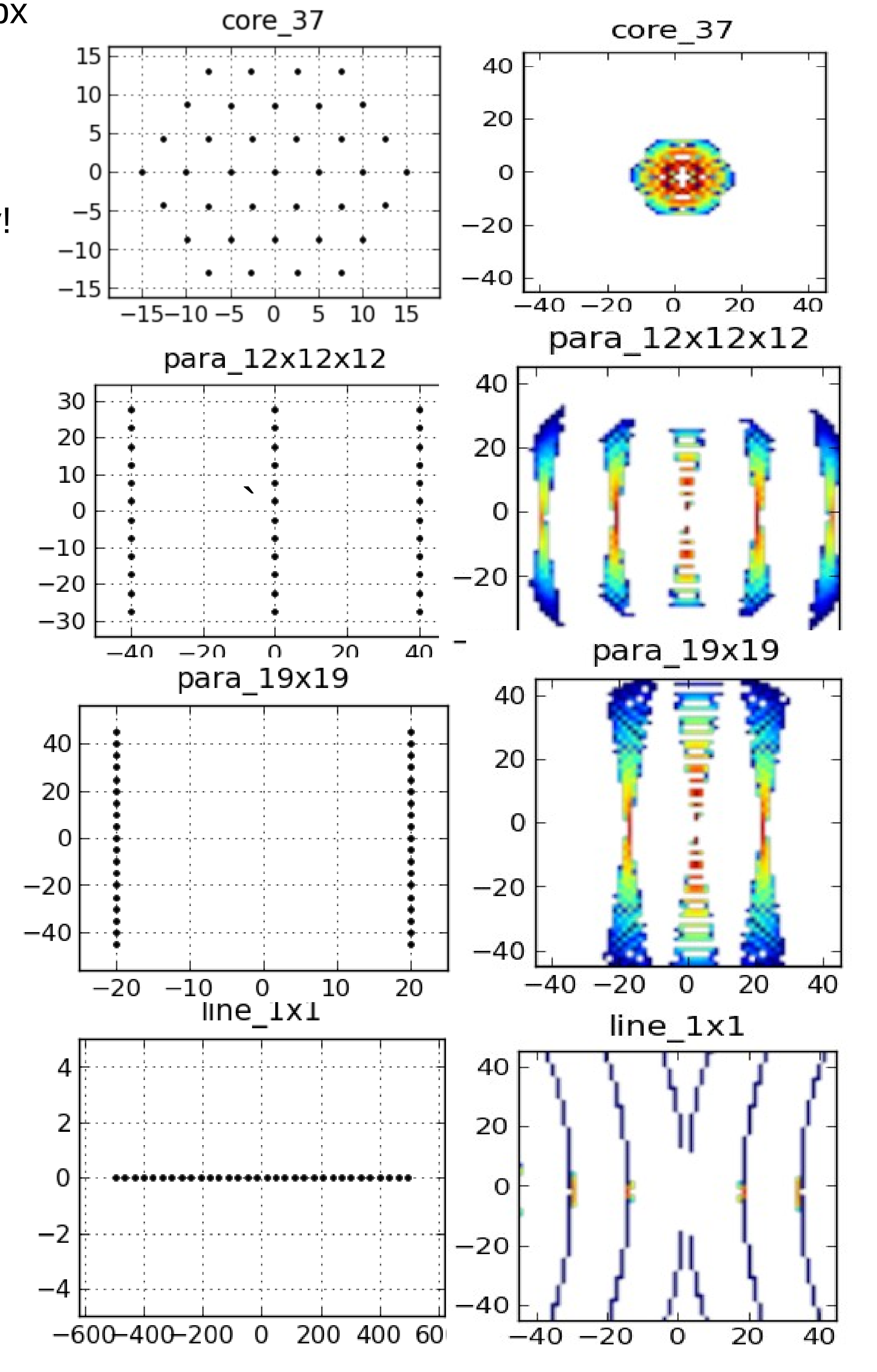


- Point sources/synchrotron are spectrally smooth
- If primary beam smooth spatially/spectrally, then delay transform of foregrounds tightly confined to group-delays above the horizon
- At delays beyond the horizon, non-smooth spectra ("sidelobes" of EoR) come to dominate
- Delay-space is very nearly k-space

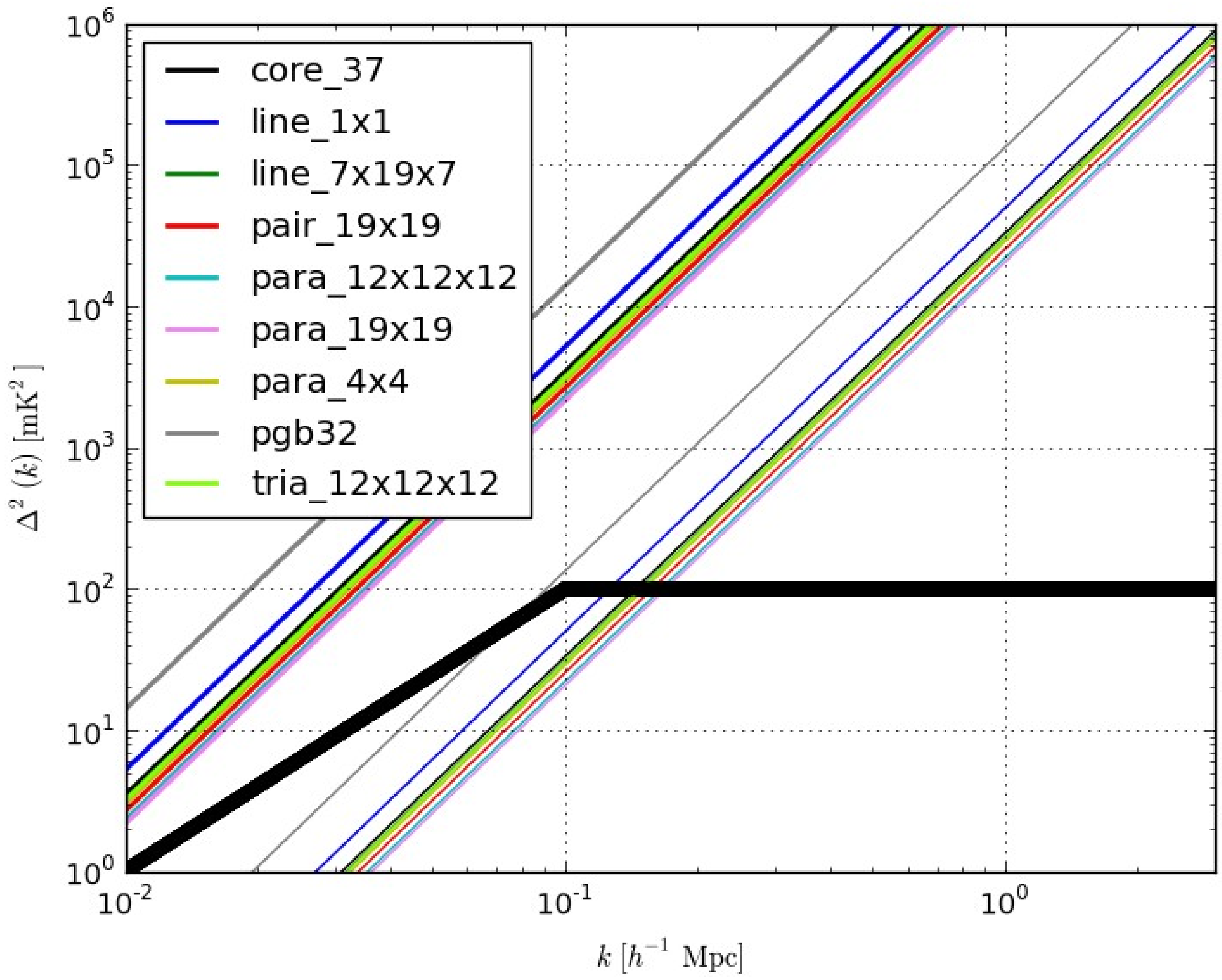
PAPER Configuration Studies



- SNR α Nsamp in 1 UV px
- SNR α Nsamp$^{1/2}$ across UV pixels
- For SNR-limited $\Delta^2(k)$ detection redundancy, redundancy, redundancy!



PAPER Sensitivity



- 32 antennas (9 configs)
- Upper (dark) = 1 day obs
- Lower (light) = 60 day obs
- High-redundancy configs have 10x sensitivity of minimum-redundancy config
- Short (≤ 30 wavelength) baselines have adequate sensitivity at k=0.2 to k=0.3 and avoid smooth spectrum foregrounds.

Hydrogen Epoch of Reionization Array

HERA-I: detect the reionization signal and measure a few of its most general properties, such as the power spectrum, over a limited range of spatial scales and cosmic redshifts. **The HERA-I program is currently being actively pursued in the United States, spearheaded by Murchison Widefield Array (MWA) and Precision Array to Probe the Epoch of Reionization (PAPER), which are testing alternative approaches.**

HERA-II: detailed characterization of the power spectrum. Requires ~0.1 square km of collecting area. Mid-decade design decision.

HERA-III: direct imaging of neutral hydrogen during EoR. Requires ~1 square km of collecting area. Ntural candidate for long-wavelength Square Kilometer Array.

Summary

- Antennas: tiles vs. '(very) cheap parabolas'.
- Config: power spectrum vs. imaging have opposing requirements (min/max redundancy)
- Data storage: if at all possible, store visibilities
- Calibration (total and polarized intensity): more to explore, but techniques exist
- Interference: looks manageable
- DSP (large-N correlators and interconnect): looks manageable (but keep it simple)