Epoch of Reionization

Recent Results from PAPER
And Future Plans

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Overview

- Motivation
- The HERA Road Map
- PAPER
- Results and Analysis
- HERA II
- Lessons Learned

The First Billion Years

A Schematic Outline of the Cosmic History

S.G. Djorgovski et al. & Digital Media Center, Caltech

Some Interesting Questions

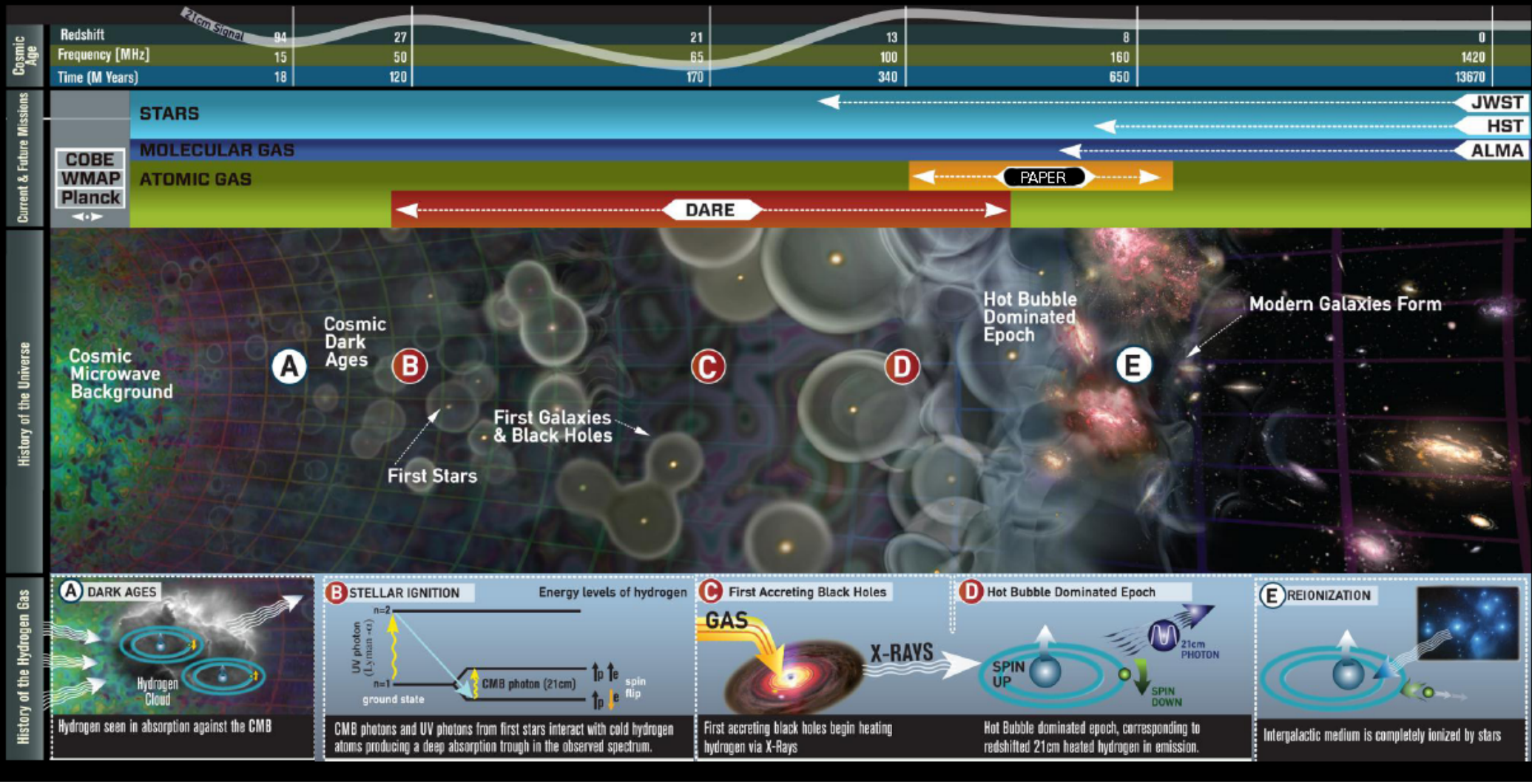
When did the first stars form?

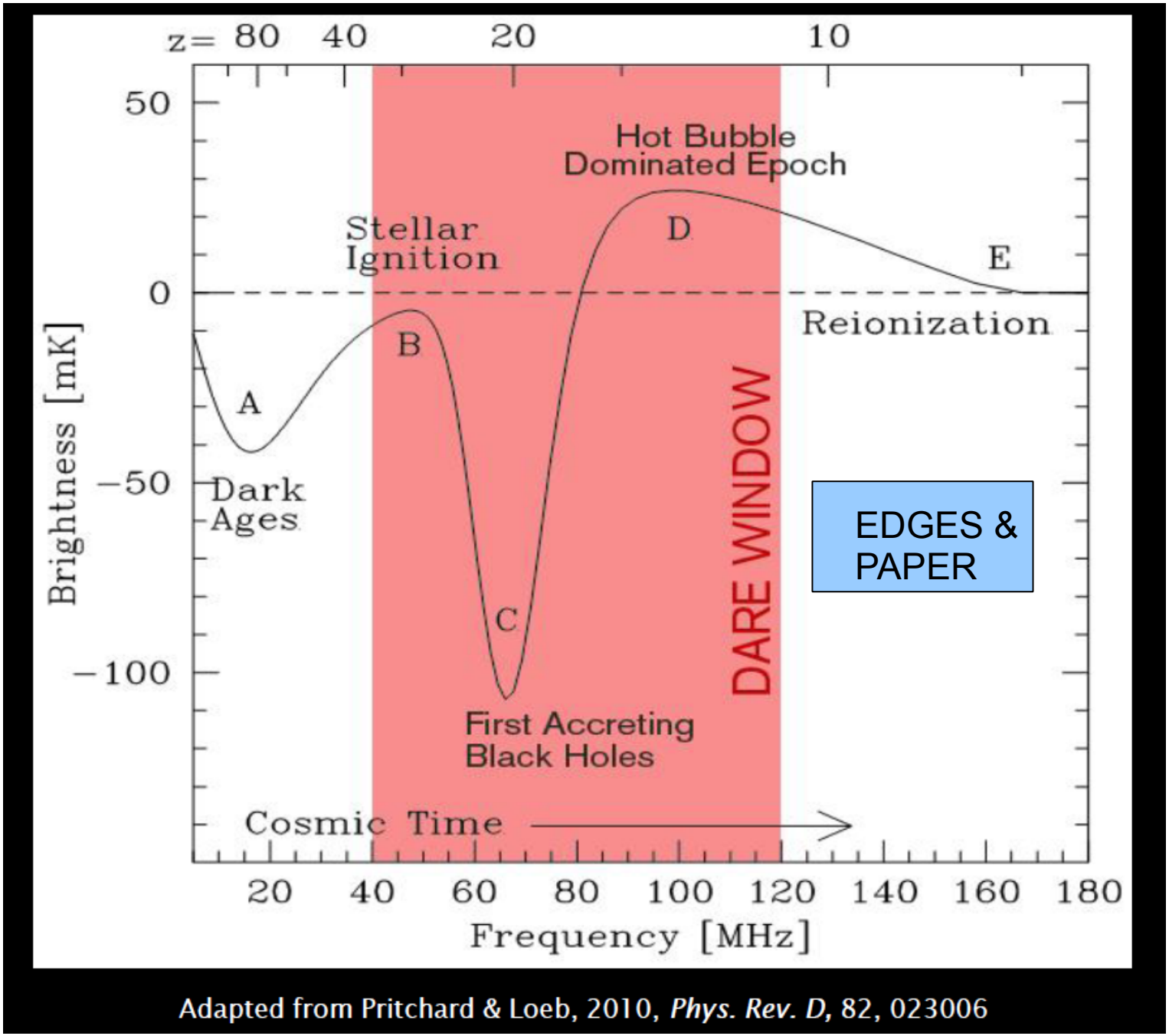
When did the first accreting black holes form?

When did the hot-bubble EoR begin?

What surprises did the end of the Dark Ages hold?

The History of Hydrogen





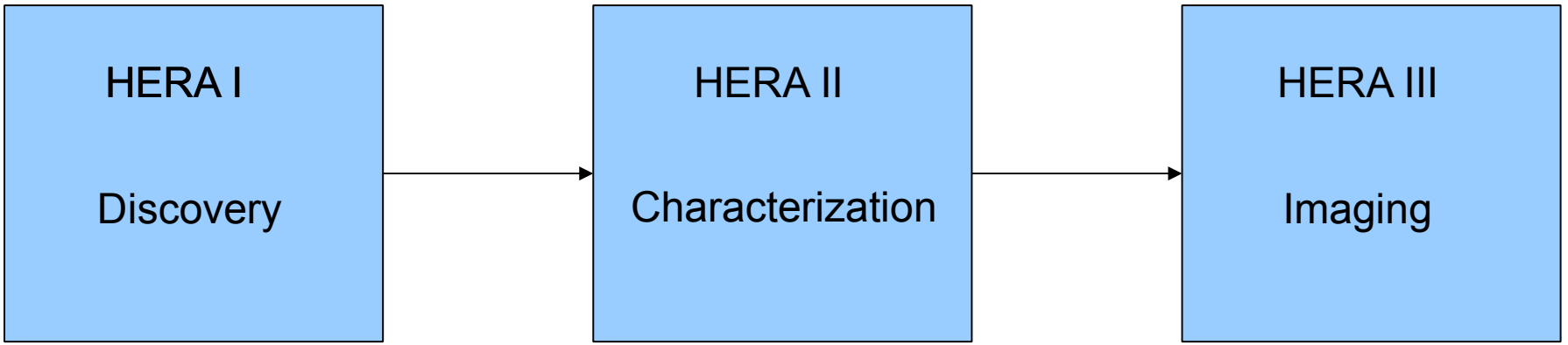
Adapted from Pritchard & Loeb, 2010, *Phys. Rev. D*, 82, 023006

What is HERA?

The Hydrogen Epoch of Reionization Array

- HERA is NOT a project, but a road map toward EoR Science.
- Promulgate a phased approach to big science through logical progression of useful activities:
  - HERA I – detection
  - HERA II – characterization
  - HERA III – imaging

HERA as a Science Road Map



PAPER
MWA
LOFAR
EDGES
DARE

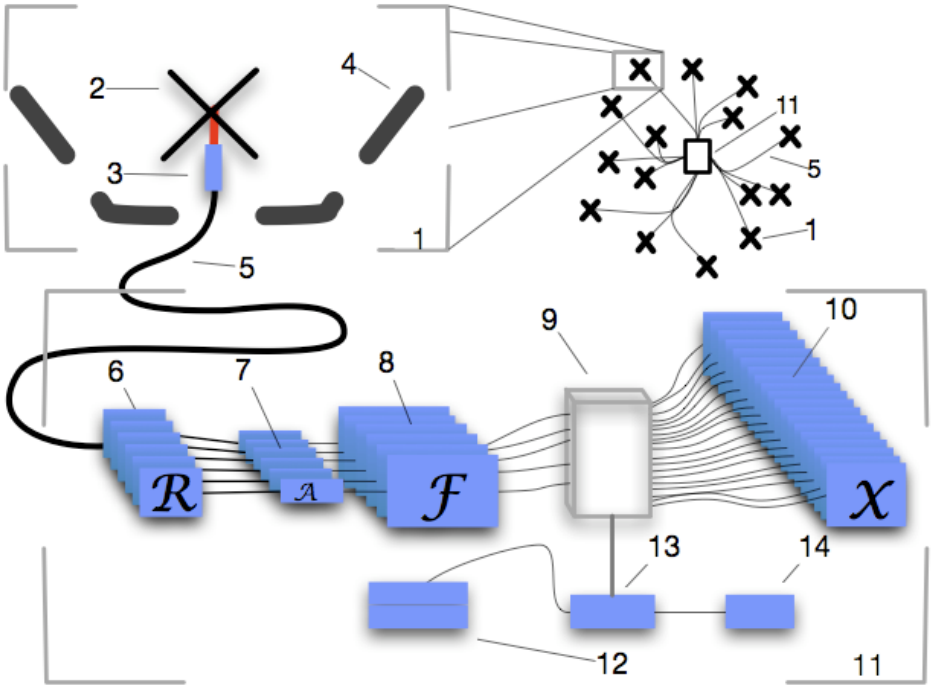
Instrument Proposed

SKA

What Sets PAPER Apart?

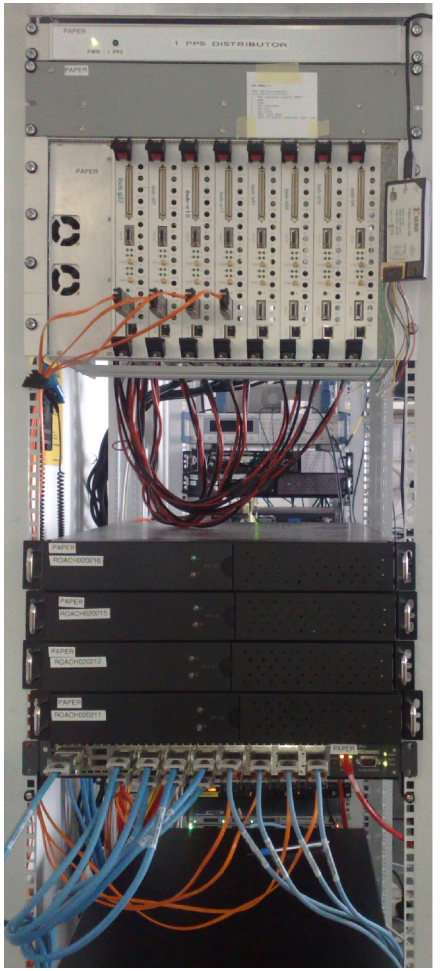
- Focused experiment
- Small dedicated team
- Lots of students
- Learn-as-you-go
- Body of Knowledge
- Calibration is key
- Two arrays
- Tap NRAO expertise
- Hardware optimized for EOR

PAPER Hardware



1. Array element
2. Sleeved dipole
3. Balun
4. Ground screen
5. Coaxial cable
6. Receivers
7. Attenuators

8. F-engine
9. Packet switch
10. X-engine
11. Hut
12. Laptop
13. Interface
14. Storage



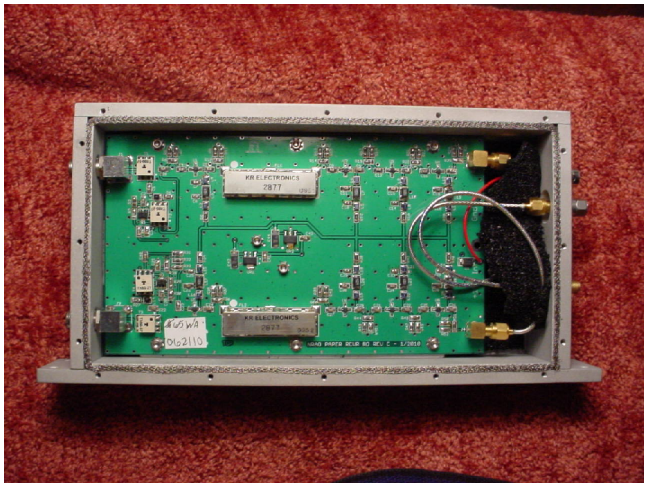
a)

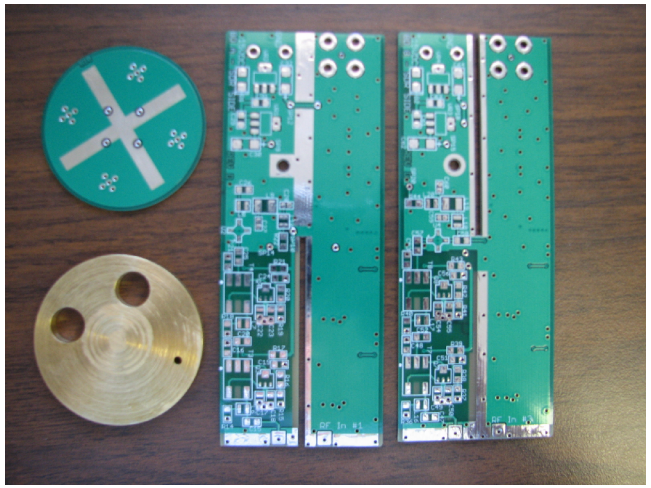
ROACH Based Correlator

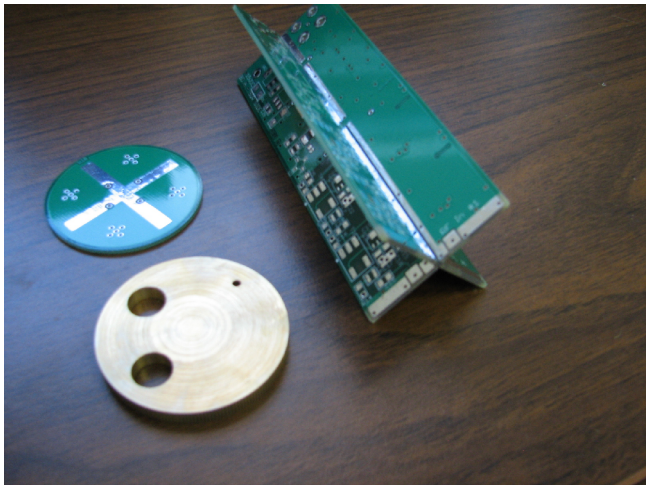
b)

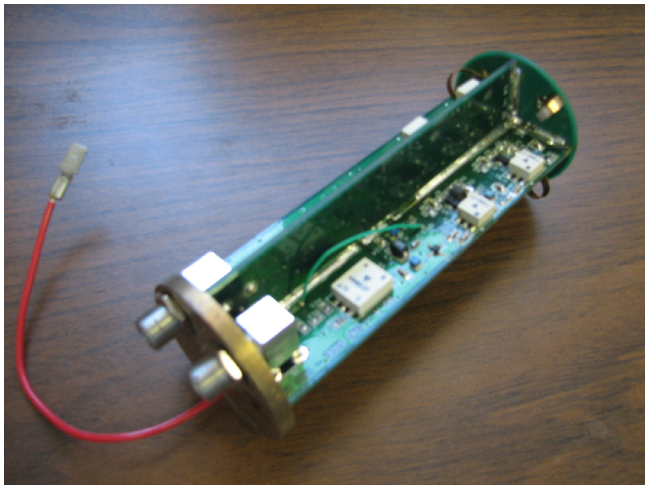
ROACH Board

PAPER Hardware









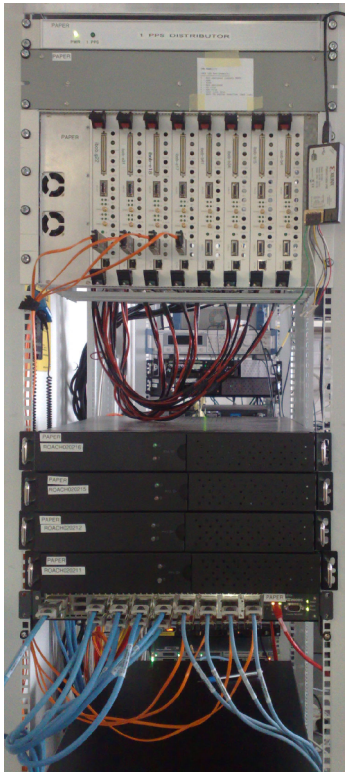
PAPER-32 in Green Bank, WV

PAPER-128 in South Africa

PAPER

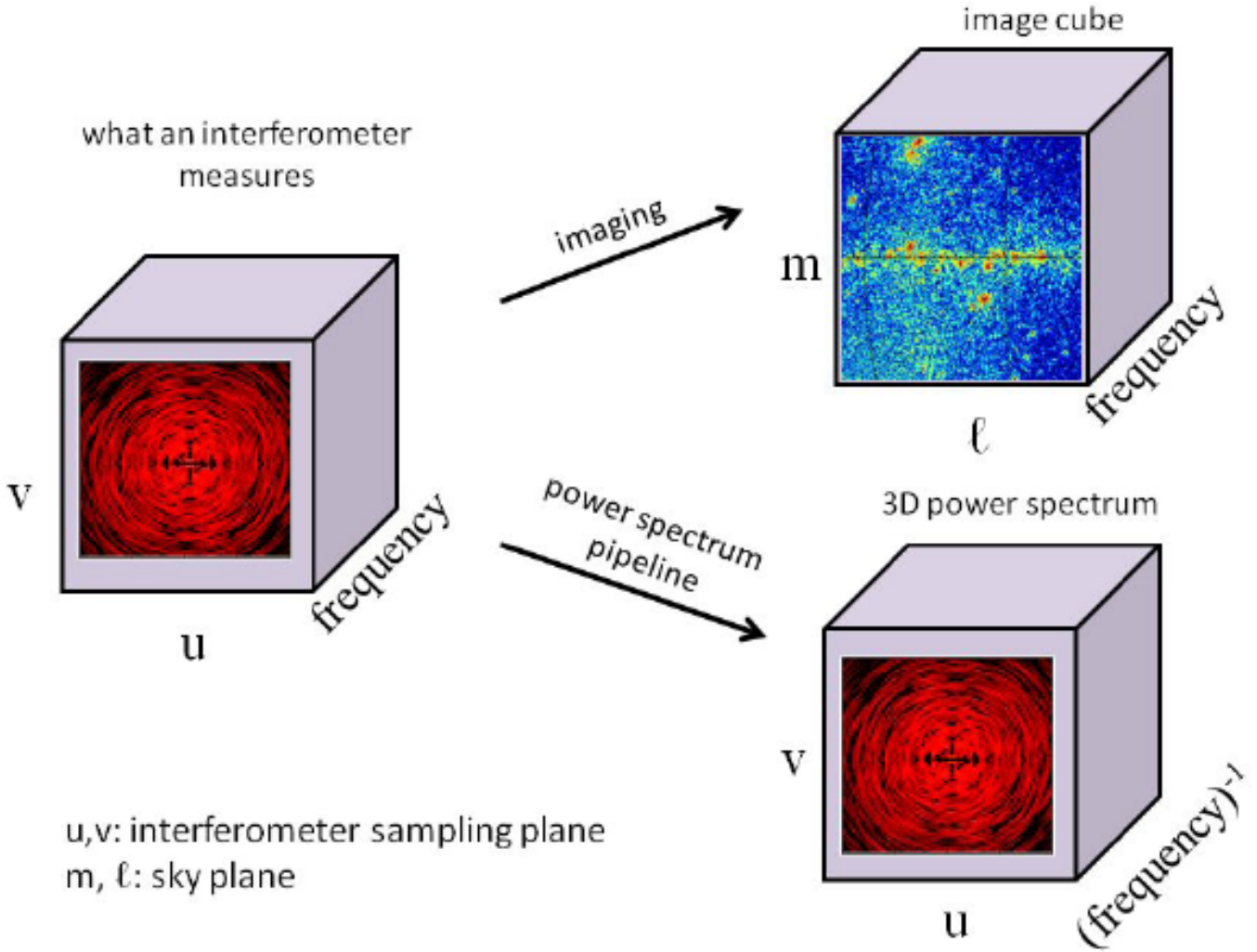
Receiver Rack

Antenna Assembly in South Africa



Correlator

Fourier Measurements

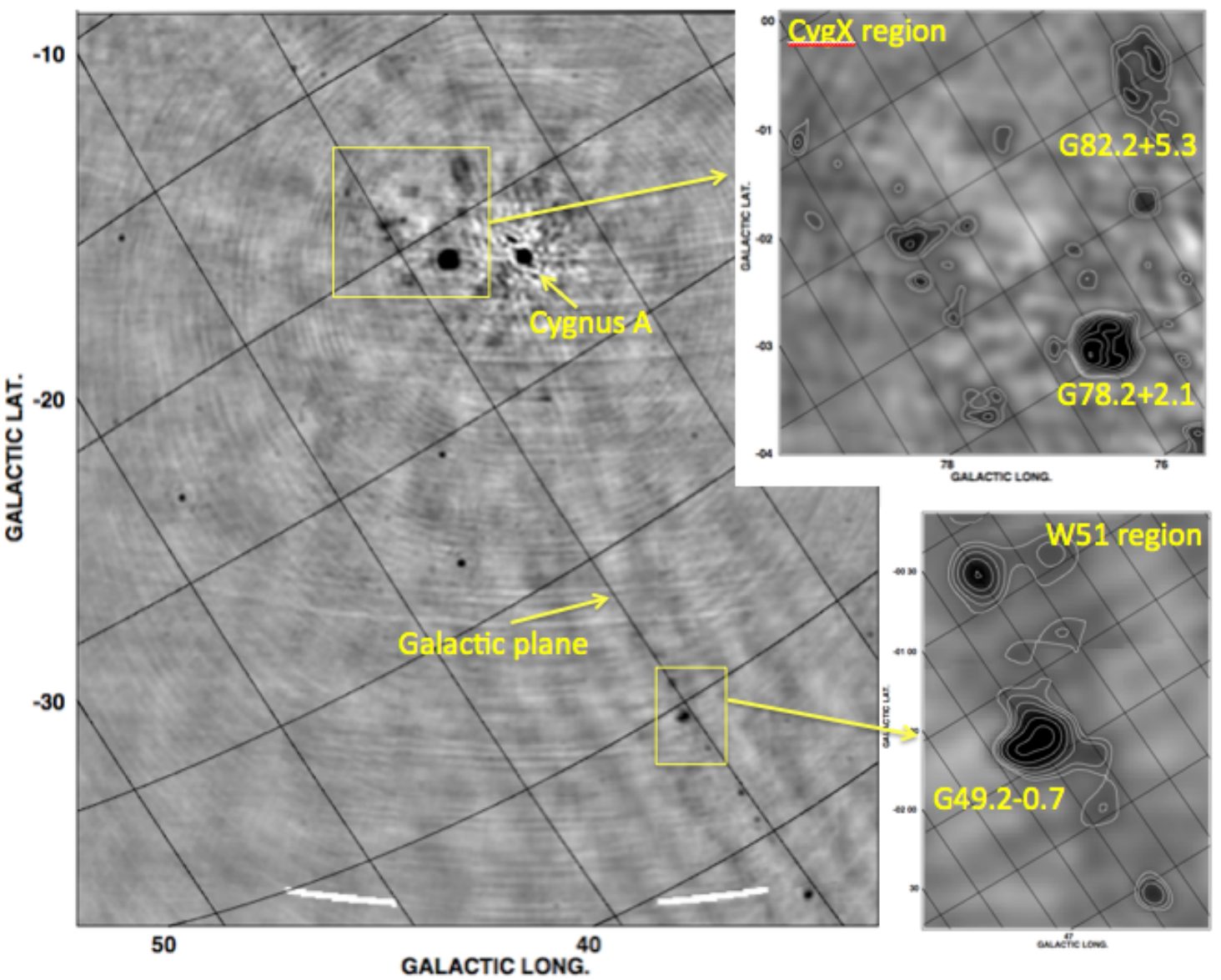


u,v: interferometer sampling plane
m, ℓ: sky plane

PSA-32 in South Africa

Minimum Redundancy Array

PGB32 Image Using AIPS / CASA



Northern Sky around Cygnus A
AIPS: 1 hour PGB-32, 28 MHz BW,
Weakest sources about 4 Jy

Image produced using standard wide-field imaging and self-calibration methods

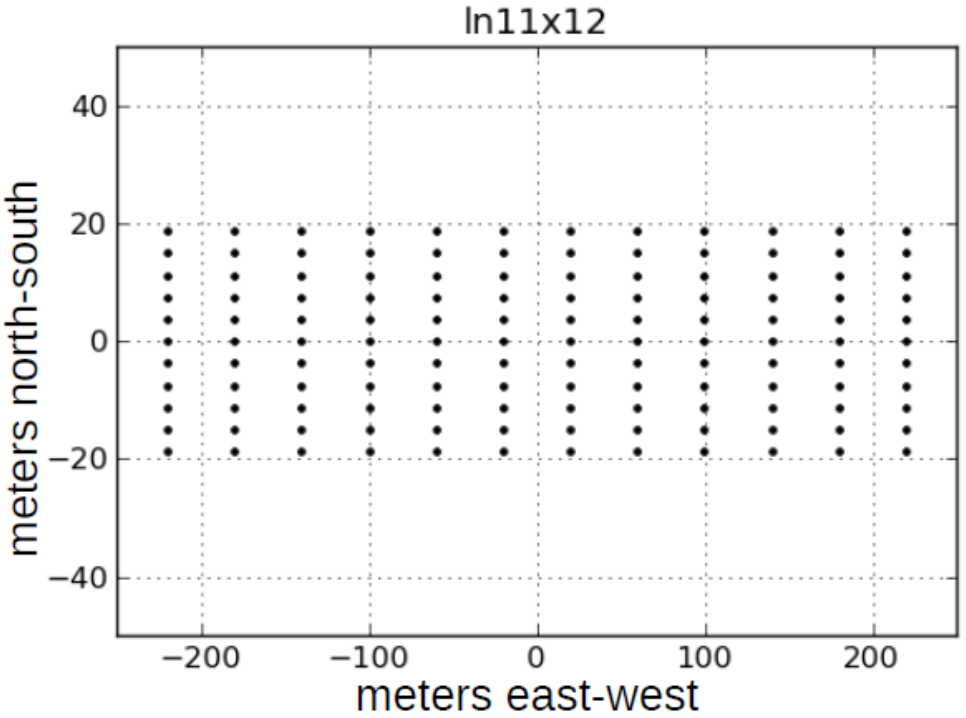
Power Spectrum Measurement Array in Green Bank

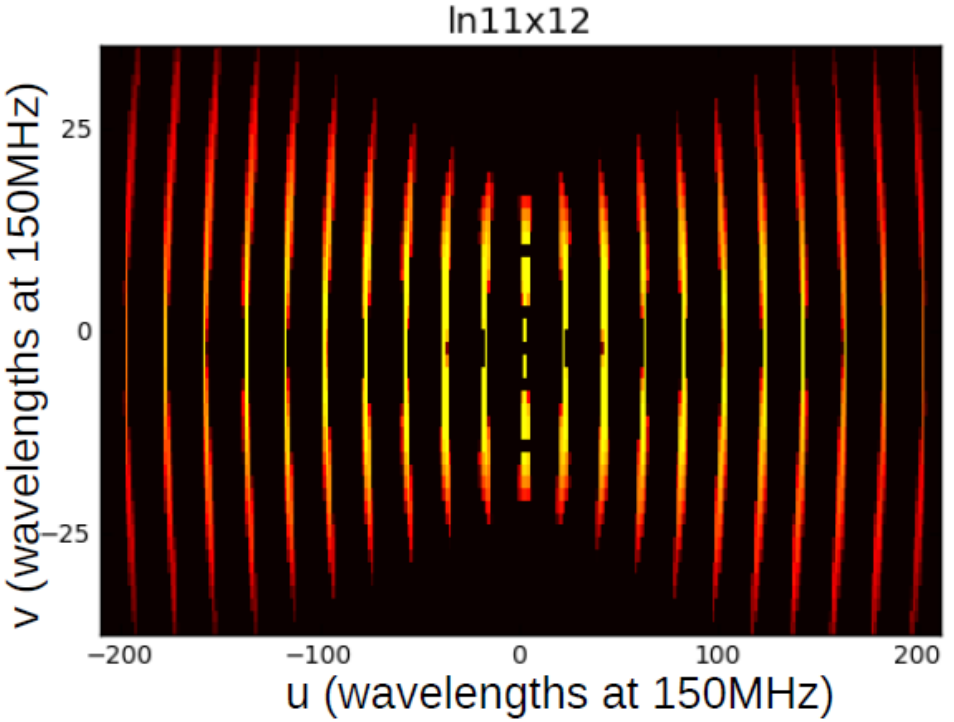
Maximum baseline redundancy

Linear arrays of elements placed in a maximum baseline redundancy configuration to increase sensitivity over a range of wave numbers.

Technology frontier – study of instrumental effects such as cross coupling among the the array elements.

PAPER-128
Maximum-Redundancy Configuration

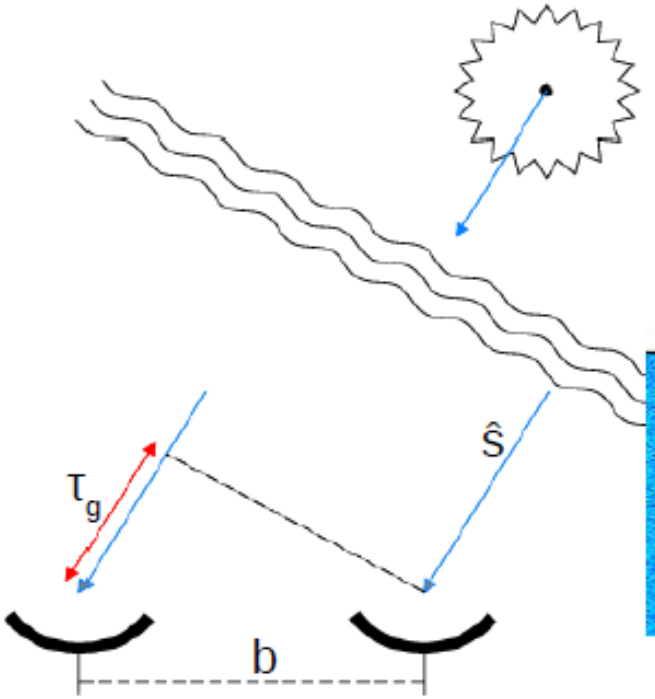


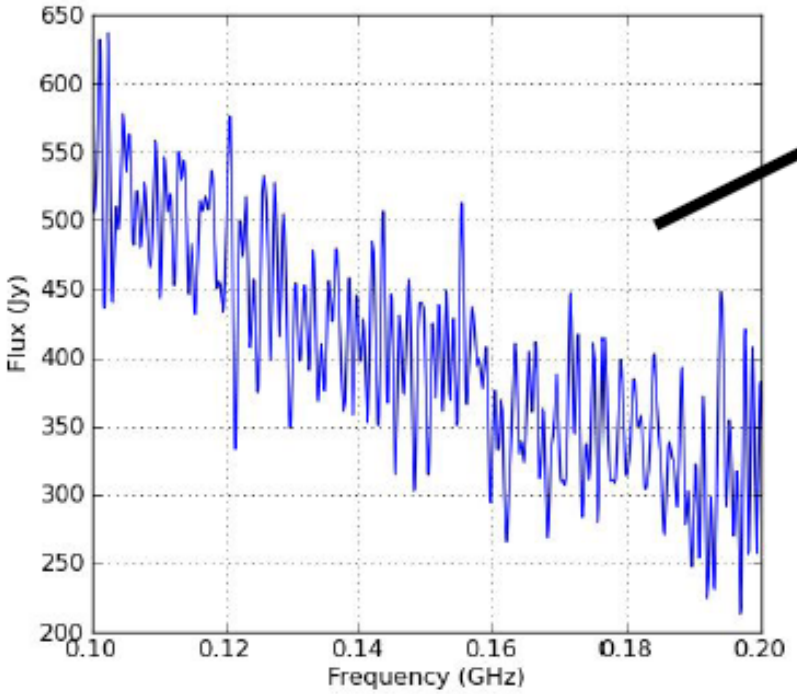


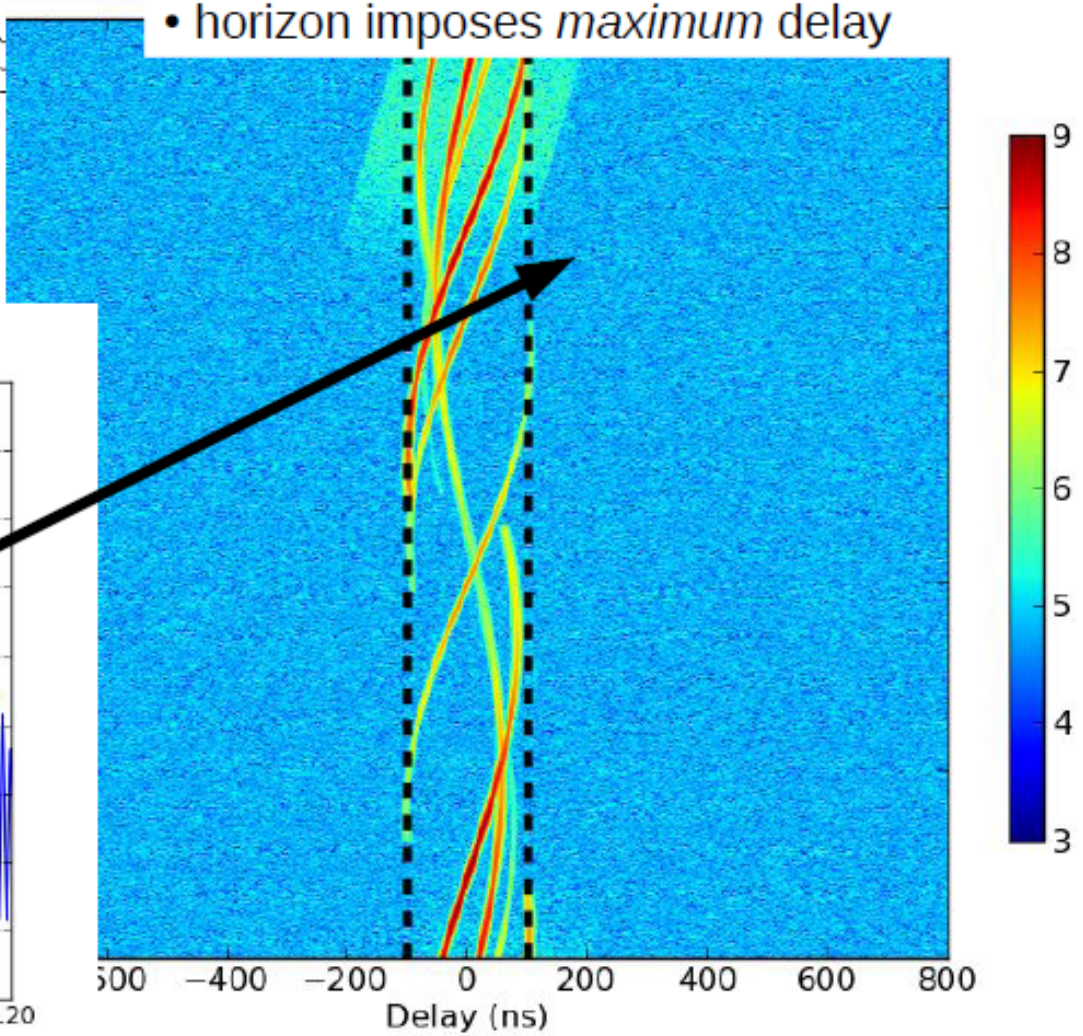
- power-spectrum sensitivity builds linearly with redundant UV sampling
- rows build redundancy through earth-rotation synthesis

Using Delay Transform to Evade Foregrounds

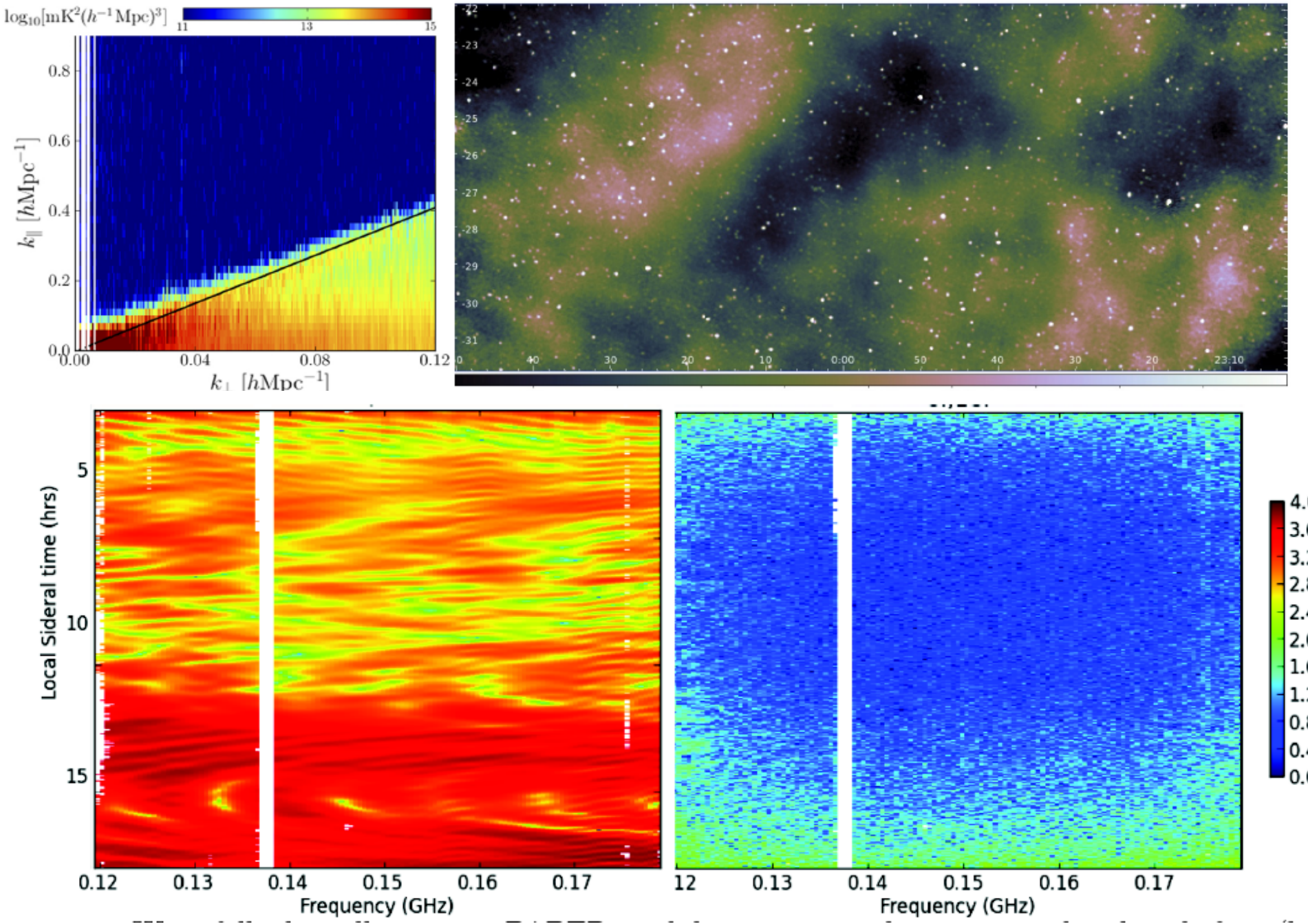
- delay: Fourier transform of frequency
- point source appears at geometric delay $\tau_g = b \cdot \hat{s}$
- smooth-spectrum flux confined near τ_g
- horizon imposes *maximum* delay





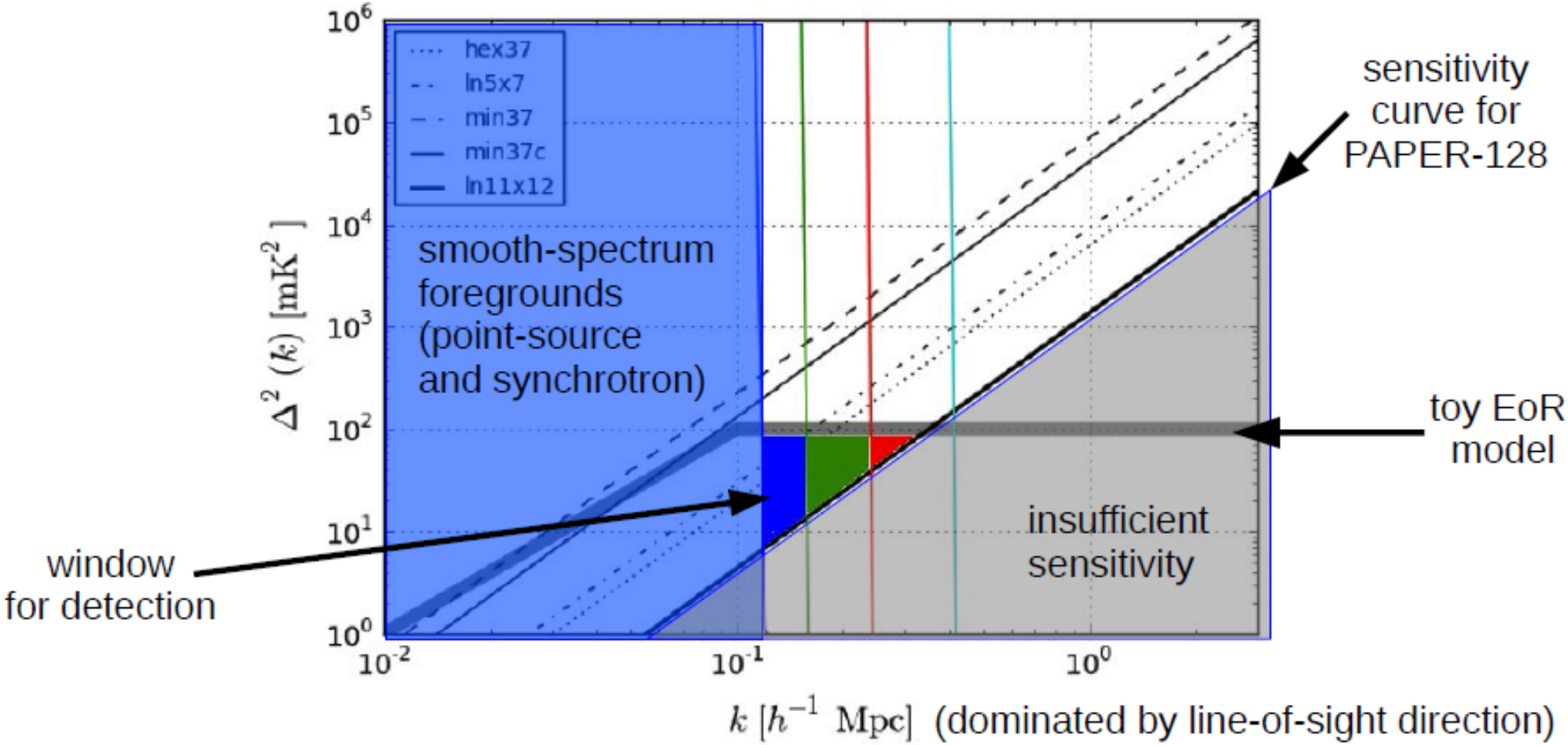


Removing Foreground by Signal Processing

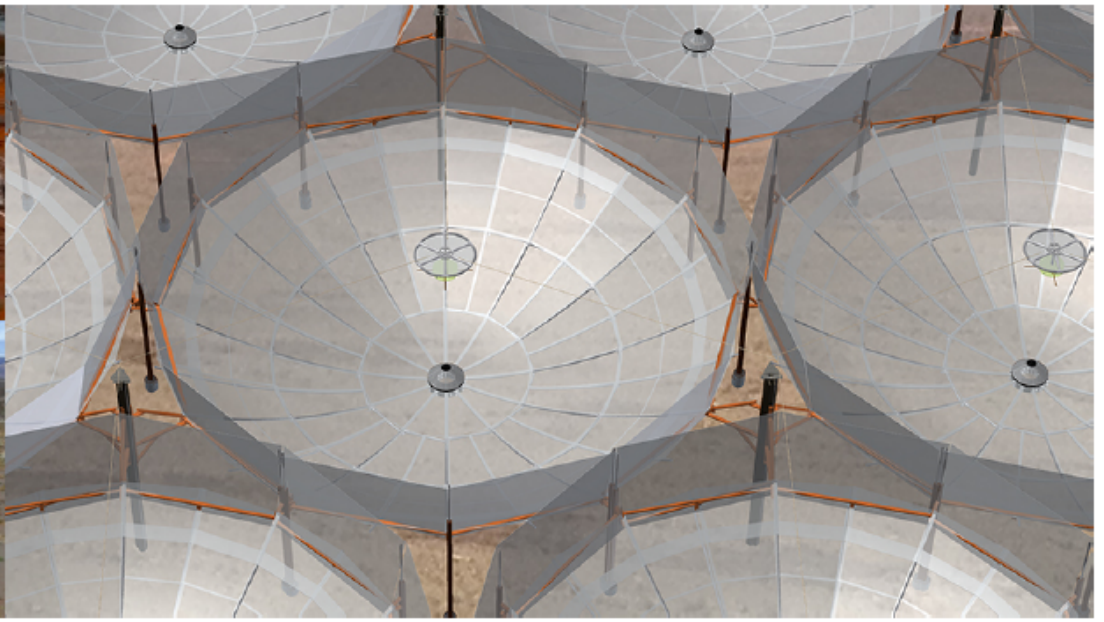


Sensitivity and Approach for Detecting EoR

- 128 antennas, 4-month (elapsed time) observation
  - 6 sidereal hours used
- maximum-redundancy antenna configuration
  - repeated, coherent measure of select UV pixels
  - 10x SNR improvement
- per-baseline approach to measuring power spectrum
  - explicit frequency-dependence of interferometer response
  - delay-transform (discussed later) isolates smooth-spectrum emission
  - foreground isolation depends on baseline length



Moving Toward HERA II



Lessons Learned

- Confidence in instrument and calibration method
- Low RFI environment is essential.
- Explore power spectrum measurement methods
- Ionosphere plays a minor role
- Develop optimized array configurations
- Understand sensitivity (no EoR detection, yet!)
- The NRAO and SA infrastructures are an important asset!
- A phased approach is highly desirable.