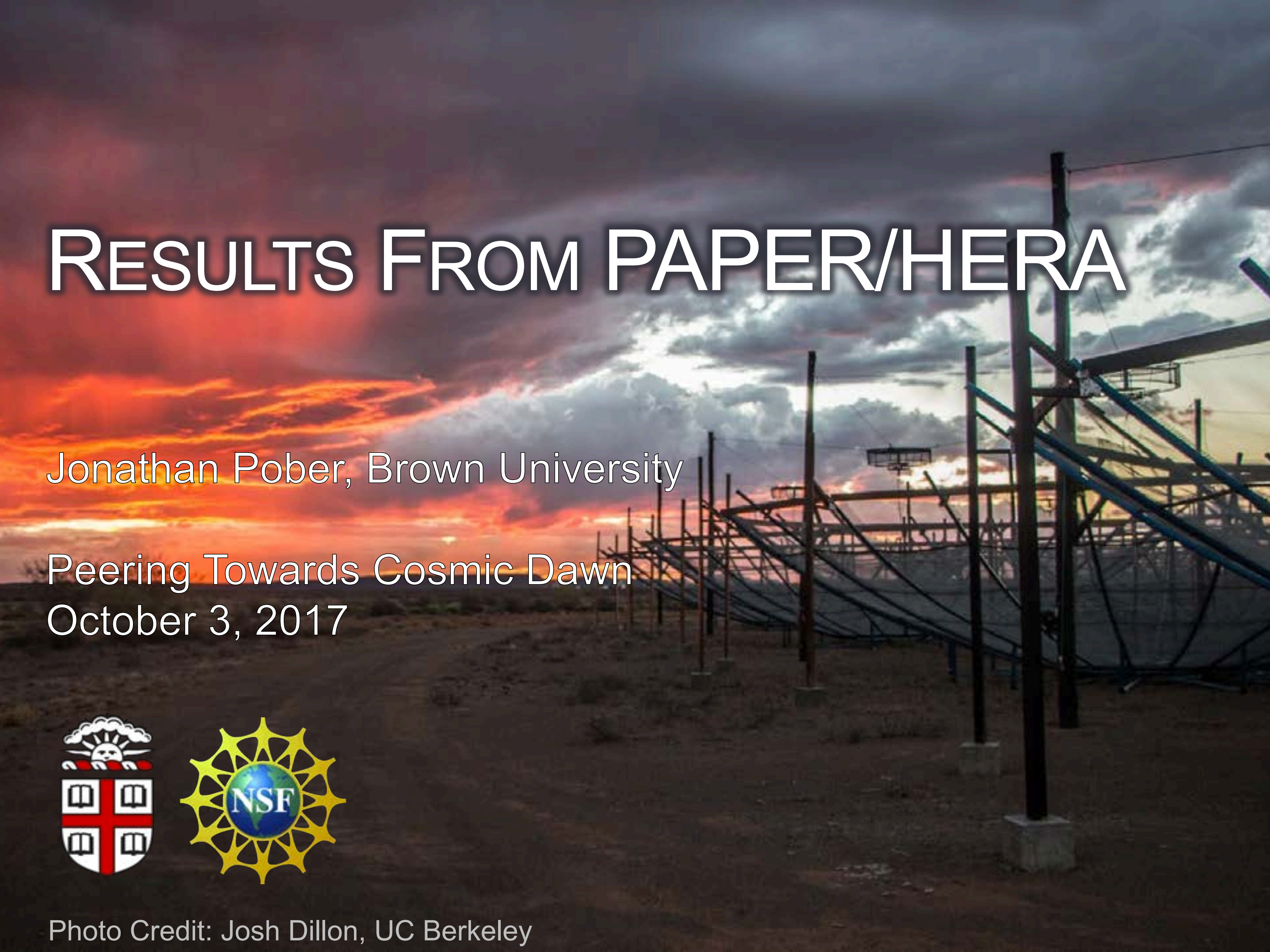


RESULTS FROM PAPER/HERA

Jonathan Pober, Brown University

Peering Towards Cosmic Dawn
October 3, 2017

Photo Credit: Josh Dillon, UC Berkeley

Outline

- About PAPER and HERA
- Key design tests with PAPER
  1. Non-imaging configuration
  2. Redundancy (for analysis; calibration next talk)
  3. Short baselines
  4. Small antenna elements
  5. Large instantaneous bandwidth
- Designing HERA
  - Building on PAPER
  - Open questions for HERA

The Donald C. Backer Precision Array for Probing the Epoch of Reionization (PAPER)

U. Pennsylvania
- James Aguirre
- Saul Kohn

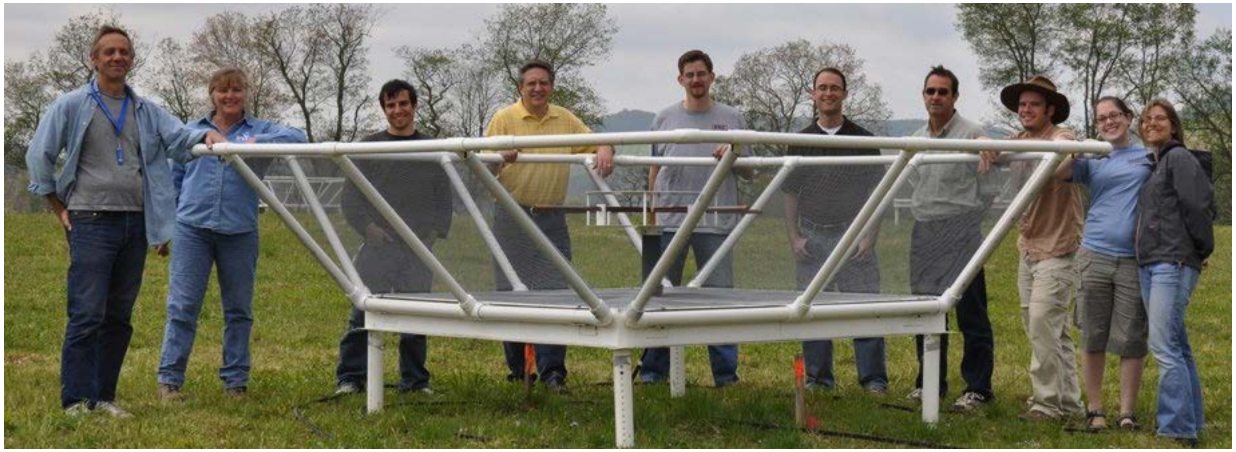
Brown U.
- Jonathan Pober
- Josh Kerrigan

UC Berkeley
- Aaron Parsons
- Zaki Ali
- Dave DeBoer
- Josh Dillon
- Adrian Liu
- Carina Cheng

U. Virginia / NRAO
- Rich Bradley
- Chris Carilli
- Pat Klima

Arizona State U.
- Daniel Jacobs
- Matt Kolopanis

SKA South Africa
- Gianni Bernardi
- Rhidima Nunhokee

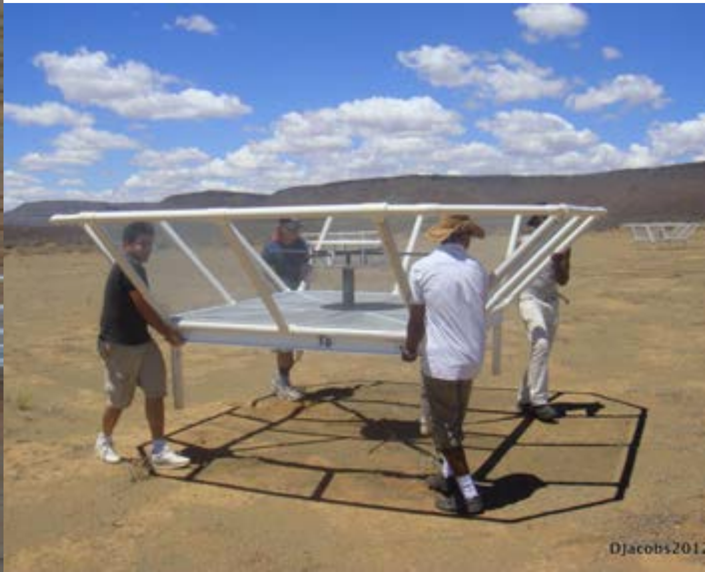



Kgalagadi
Southern
Johannesburg
Mpumalanga
North West
Swaziland
Karas
Kimberley
Free State
KwaZulu-Natal
Northern Cape
D'Urban
Lesotho
Karoo Astronomy Reserve
Carnarvon
South Africa
Eastern Cape
Western Cape
Port Elizabeth
Stellenbosch
Cape Town

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

- **One goal**: detect the power spectrum of 21 cm emission from the EoR

- Reconfigurable & scalable
- Unique test-bed for EoR-focused analysis

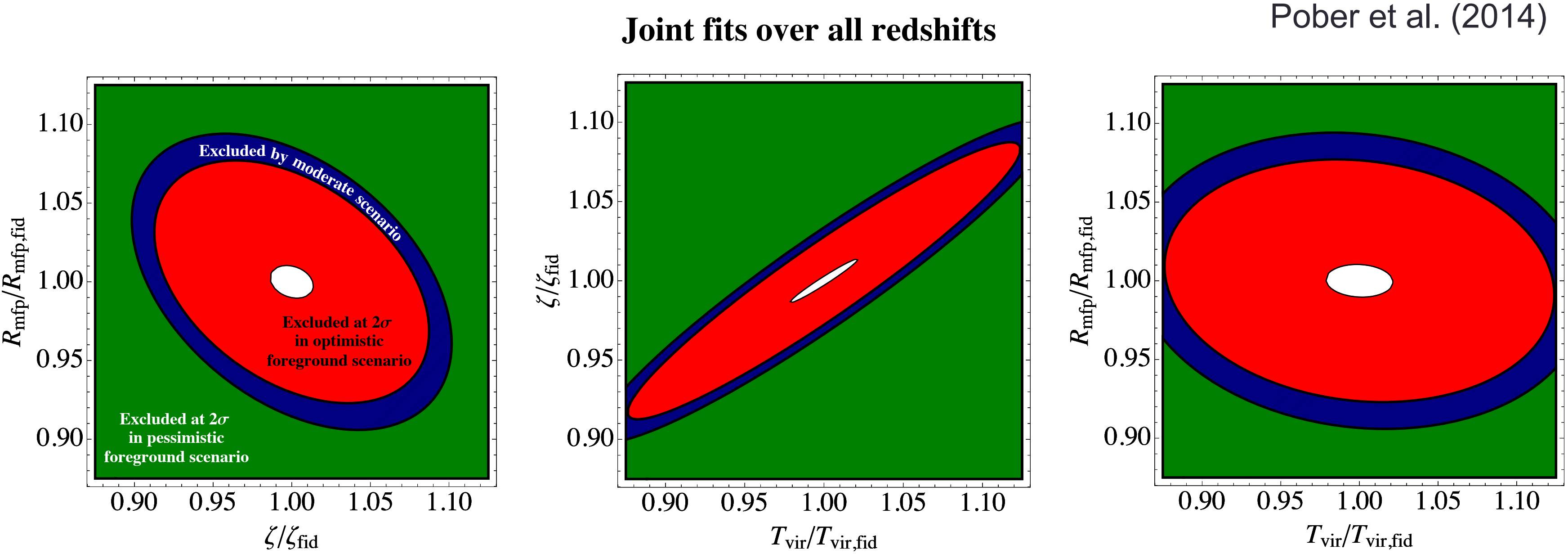


Why the Power Spectrum?

- Allows averaging over *k* modes
  - Imaging requires SNR 1 per pixel/voxel
  - Power spectra can be binned in *k* space
  - → better SNR → smaller instrument → less expensive

- Powerful science tool!

Pober et al. (2014)



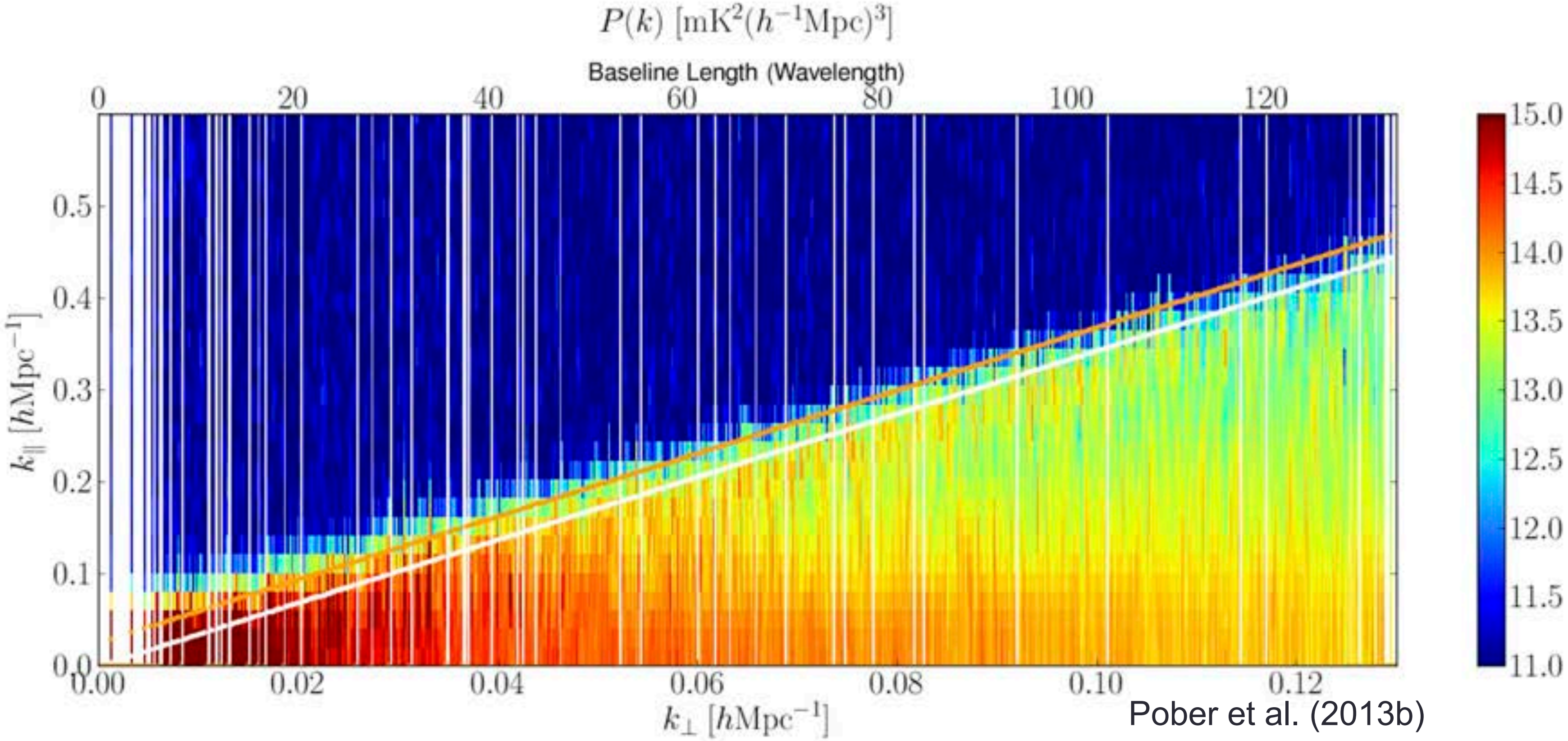
WHAT DID WE TRY WITH PAPER?

And What Did We Learn?

(1) Non-Image Based Approach

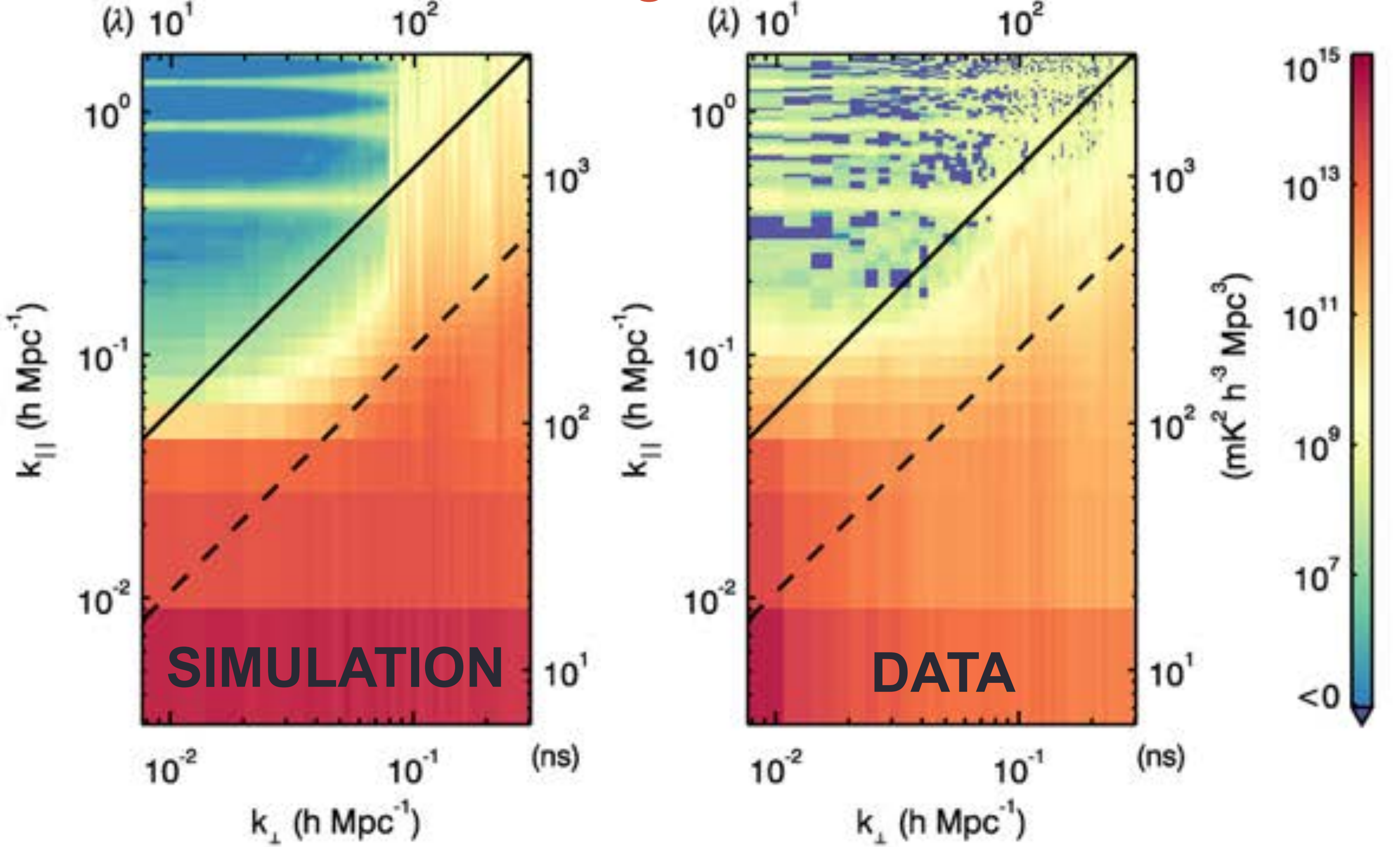
- Interferometers introduce spectral structure into otherwise smooth-spectrum foregrounds
- Stronger effect on long vs. short baselines → “the wedge”
- Generic feature regardless of analysis style (can be mitigated)

PAPER Measurements: “Delay Spectrum”



Pober et al. (2013b)

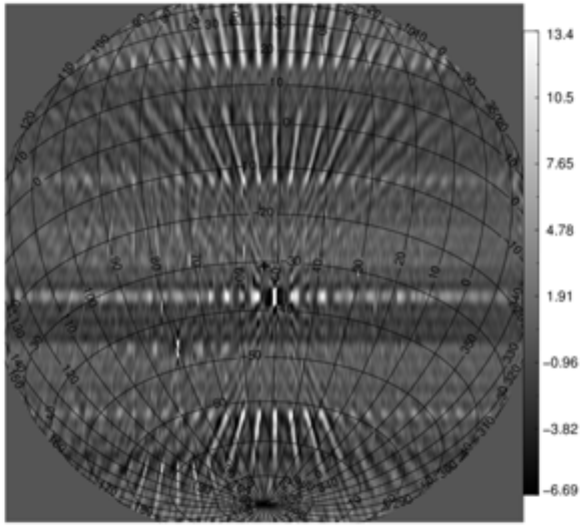
MWA Wedge: Simulation & Data



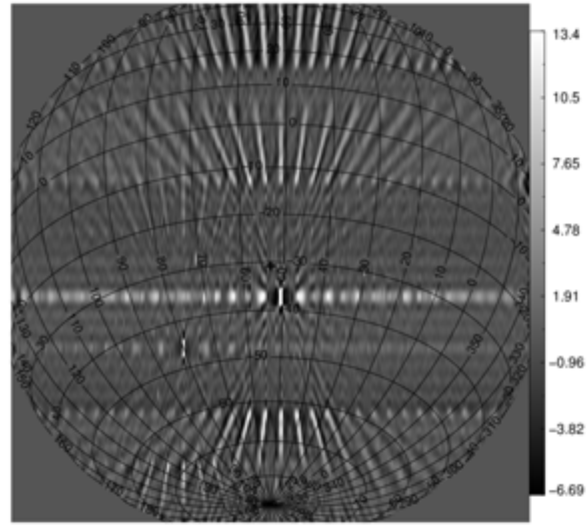
Foreground Avoidance

- PAPER pioneered the *foreground avoidance* approach: minimize bleed from the wedge to higher *k* modes (Parsons et al. 2012b)
- Powerful techniques available if signal recovery from within the wedge isn't the goal (e.g. delay filter)
- *Big* sensitivity hit (factor of ~5 at EoR frequencies), but can drastically ease calibration requirement
  - If you can subtract foregrounds, subtract foregrounds – but not mutually exclusive! Try both on the same data set.

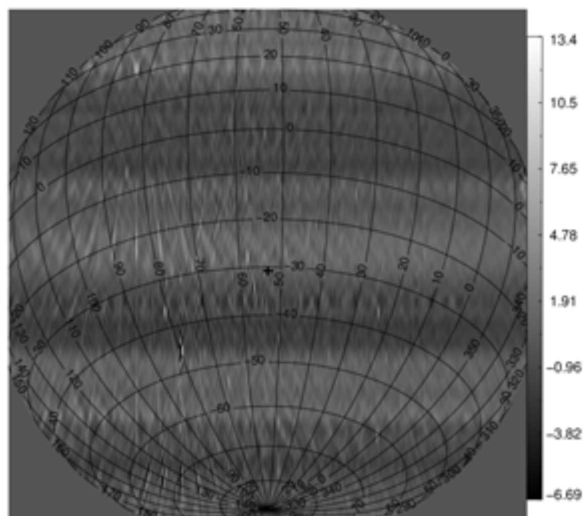
Foreground Subtraction with PAPER



(a) Dirty

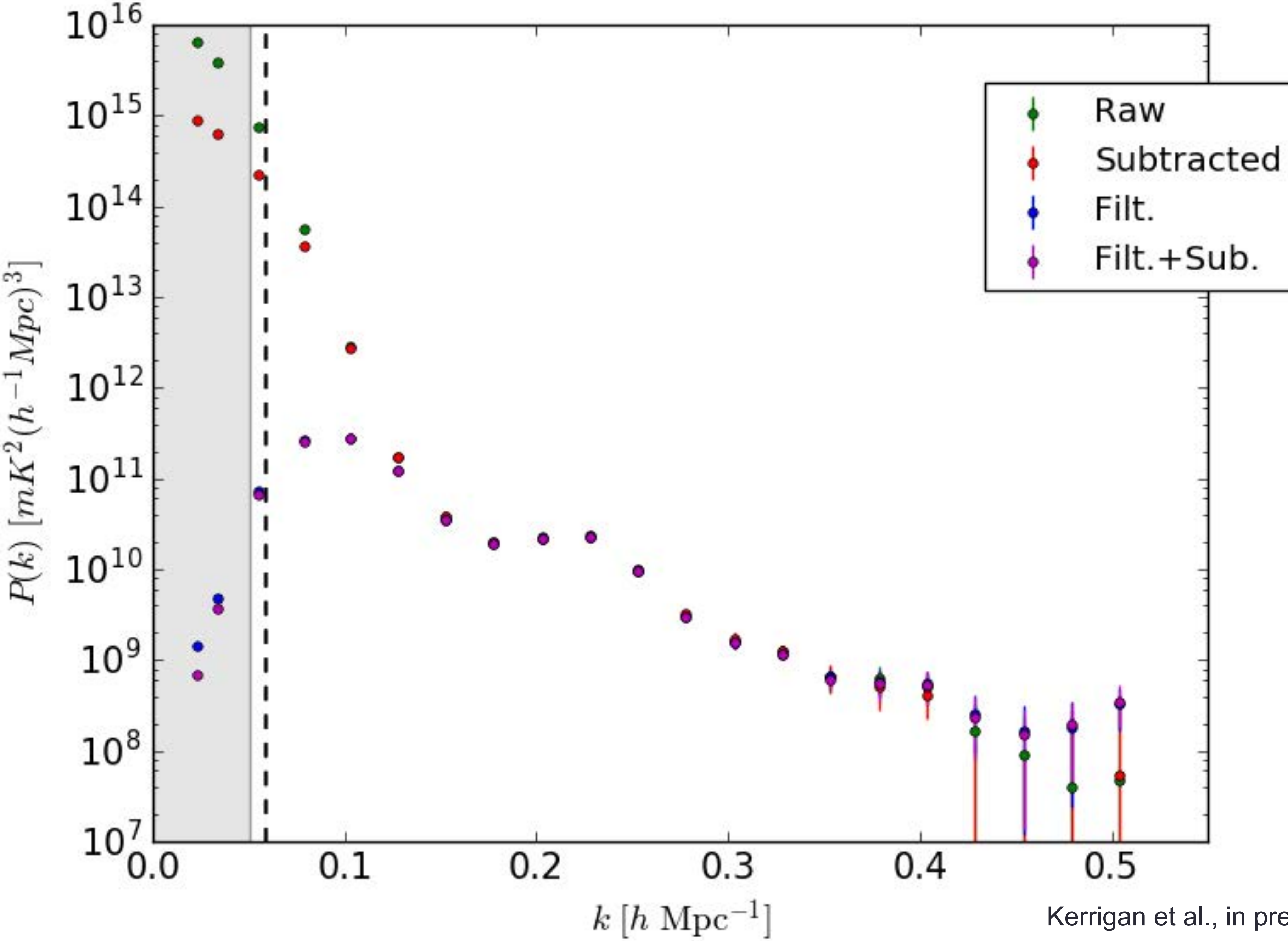


(b) Model

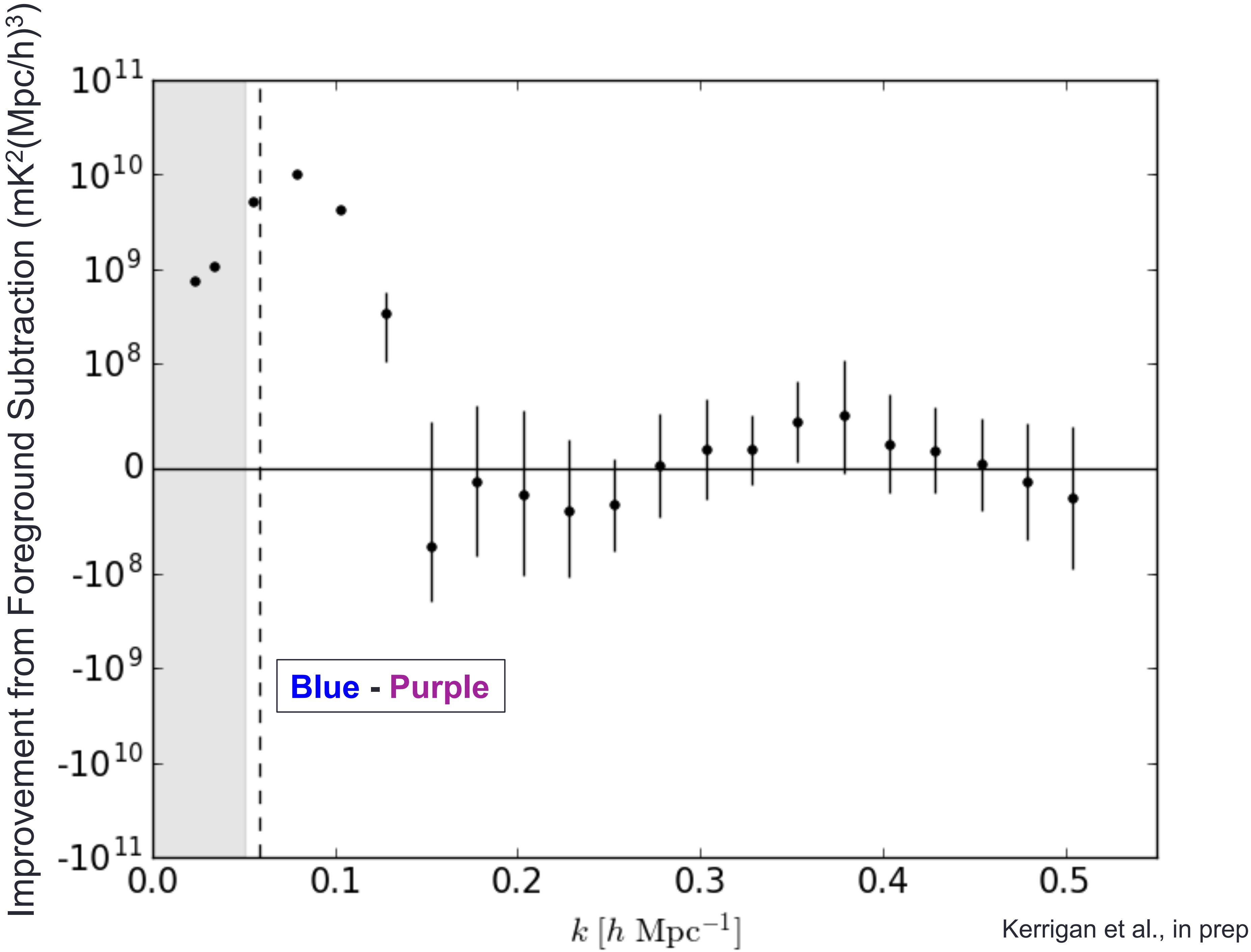


(c) Residual

Joshua Kerrigan

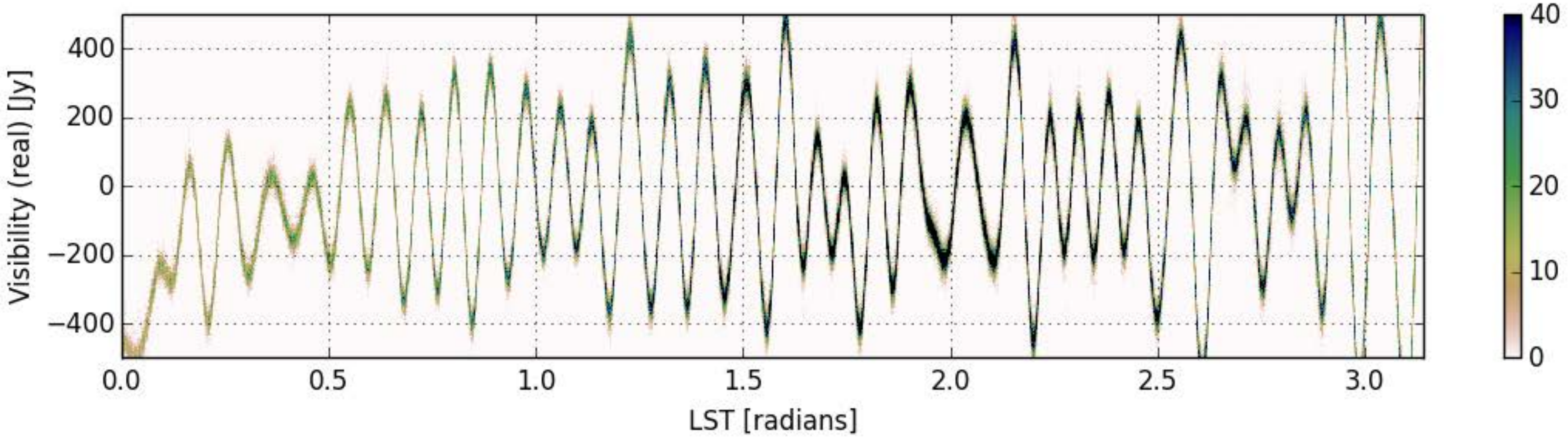


Kerrigan et al., in prep


Improvement from Foreground Subtraction (mK²(Mpc/h)³)
10^11
10^10
10^9
10^8
0
-10^8
-10^9
-10^10
-10^11
0.0
0.1
0.2
0.3
0.4
0.5
k [h Mpc^-1]
Blue - Purple
Kerrigan et al., in prep

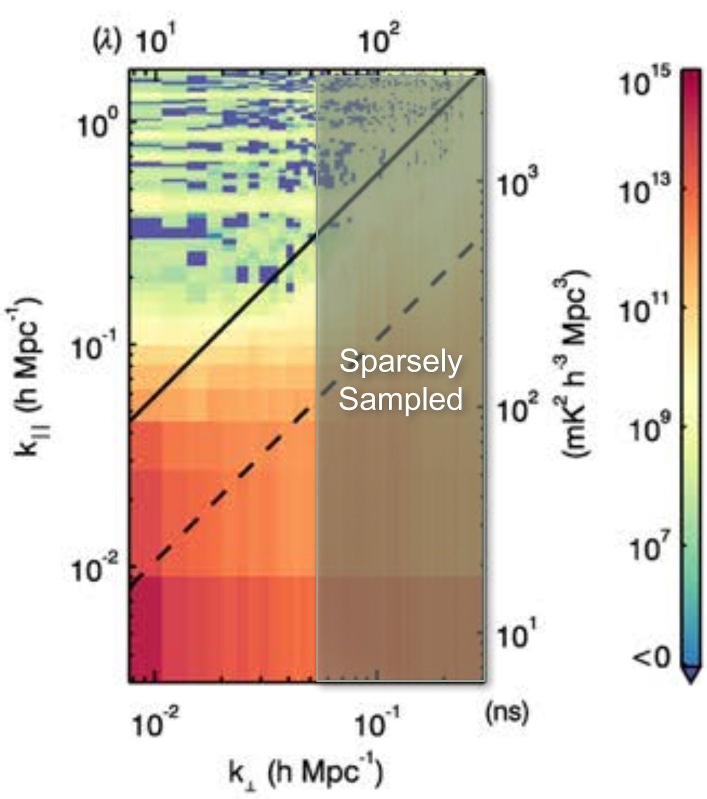
(2) Redundancy

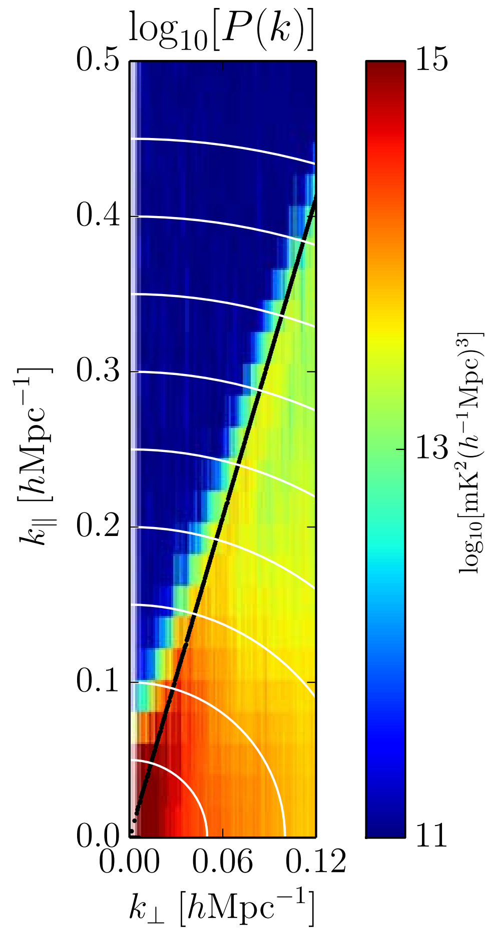
- Redundancy helps analysis
- Statistically independent samples of same mode provide:
  - Sensitivity boost (Parsons et al. 2012a)
  - Axis for jack-knifing and bootstrapping
  - Statistical weights (inverse covariance)
  - Real time diagnostics
- For PAPER, calibration a secondary bonus



(3) Short baselines

- Short baselines have most intrinsic sensitivity to EoR and least foreground contamination
- Long baselines are potentially:
  - More corrupted by the ionosphere
  - Sources of calibration error (e.g. Barry et al. 2016, Ewall-Wice 2017)
  - Computationally expensive





(4) Small elements

- Philosophy: avoid introducing spectral structure in foregrounds at all costs!
- Small elements minimize spectral structure in response
- Actually overspec-ed!
- PAPER is sensitivity starved, bigger dishes could still meet spectral smoothness needs

(4) Small elements

- Philosophy: avoid introducing spectral structure in foregrounds at all costs!
- Small elements minimize spectral structure in response
- Actually overspec-ed!
- PAPER is sensitivity starved, bigger dishes could still meet spectral smoothness needs
- **A PHILOSOPHY IS NOT A SPECIFICATION**

(5) Large (100 MHz) instantaneous bandwidth

- Invaluable lever arm for foreground constraints
  - Helps with delay filtering

- Scientifically motivated
  - Reionization redshift predications have come down significantly in the last 10 years!

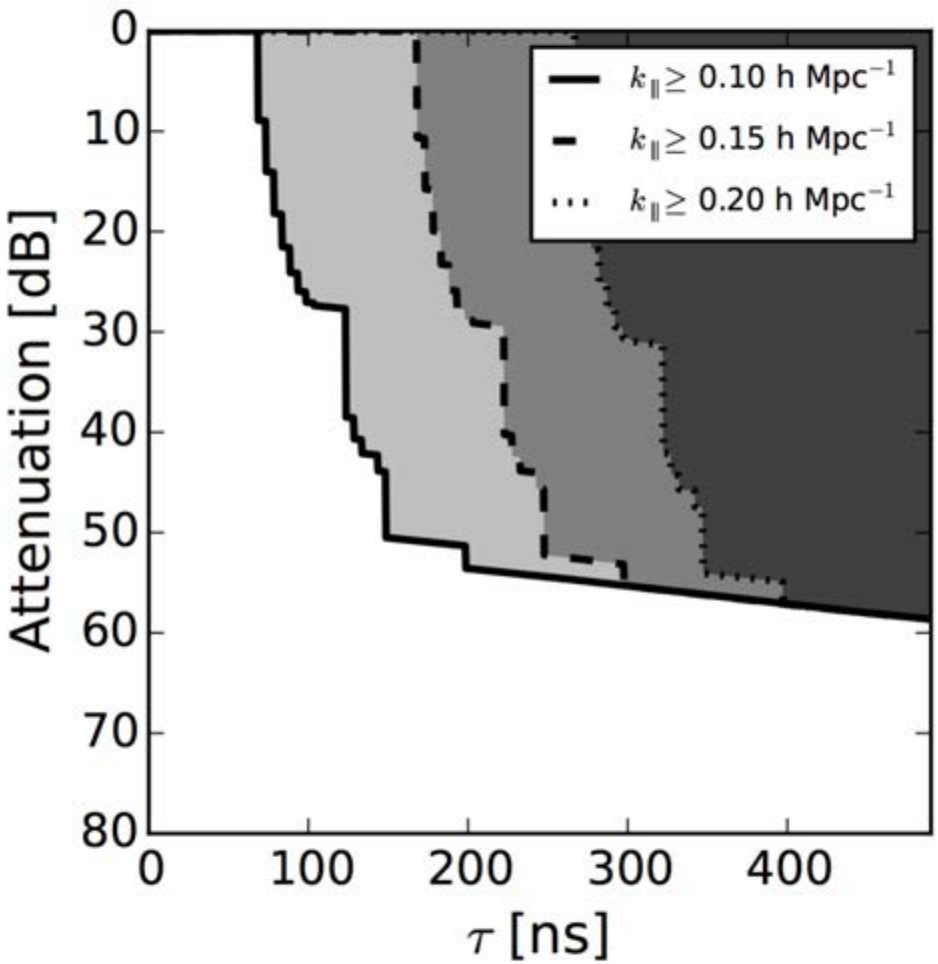
DESIGNING HERA

What could we do better?

Increase Sensitivity

- …but not at the expense of spectral smoothness

A Specification for Spectral Smoothness



- Short focal length minimizes frequency structure in dish response
- Not just a philosophy: specification on the attenuation of reflections as a function of delay necessary to make an EoR detection at a given *k* mode
- Derived from interferometric simulations using models of both instrument beams and foregrounds

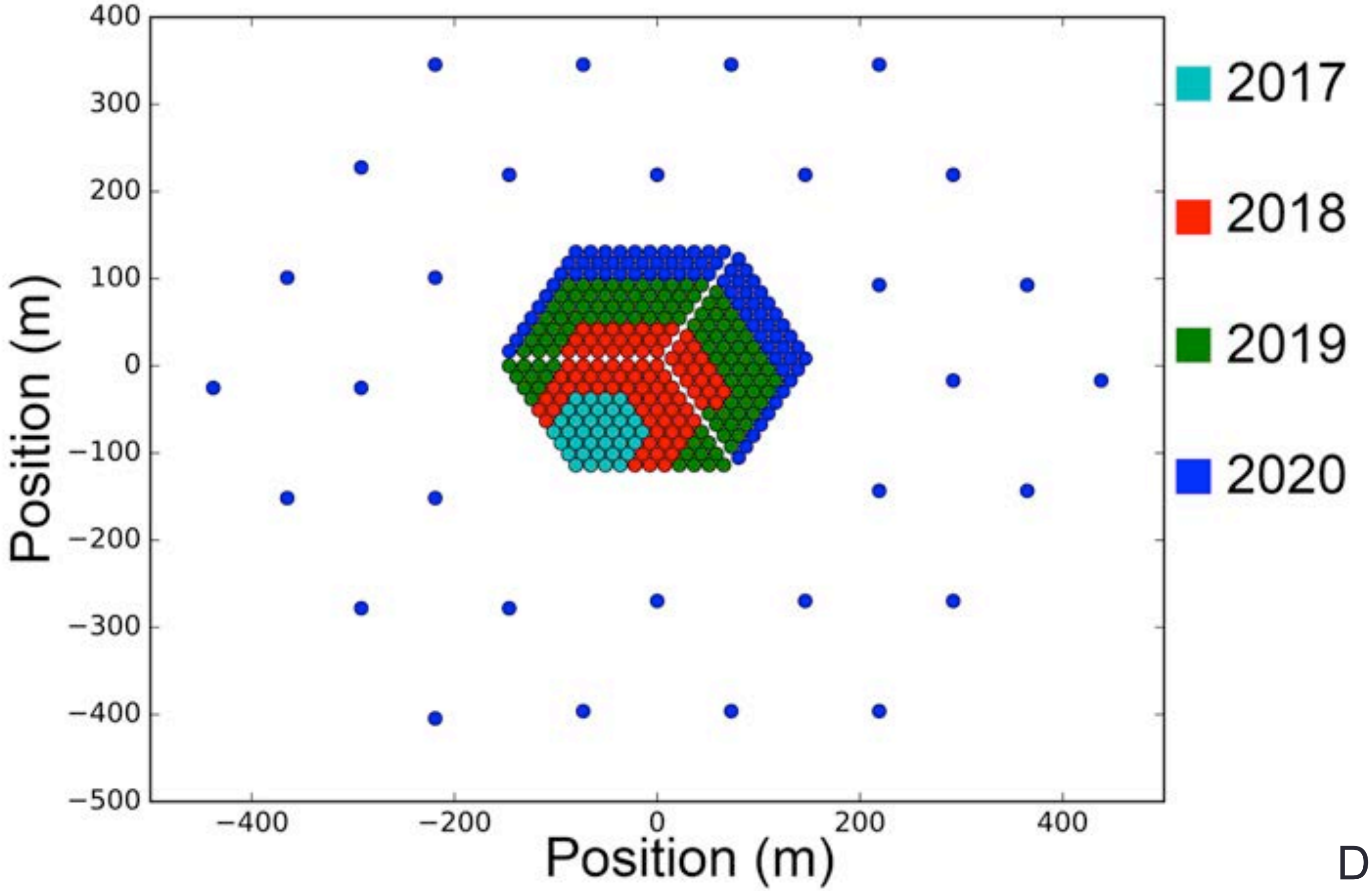
Thyagarajan et al. (2016); DeBoer et al. (2016)

Increase Bandwidth

- …but not at the expense of spectral smoothness
- Target bandwidth: 50 – 250 MHz (z ~ 5 – 27)
  - Epoch of X-ray heating studies (e.g. Ewall-Wice et al. 2016)
    - Supported by Moore Foundation (not optional)
  - Null test for post-reionization signal (Pober et al. 2016)
- Feed selection in ~ two weeks

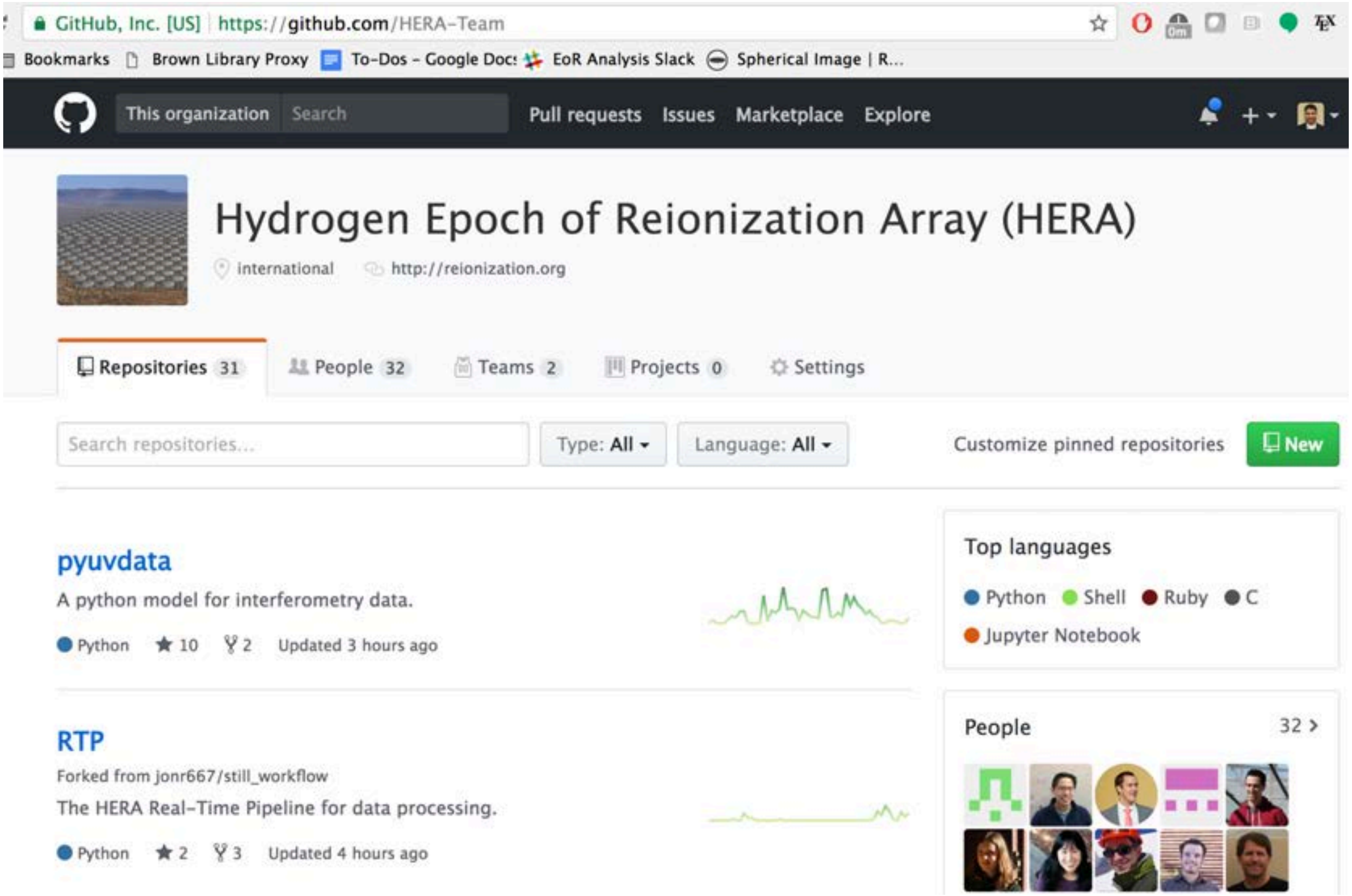
Increase Resolution

- …but not at the expense of surface brightness sensitivity and calibration



Dillon & Parsons (2016)

Increase Software Sophistication



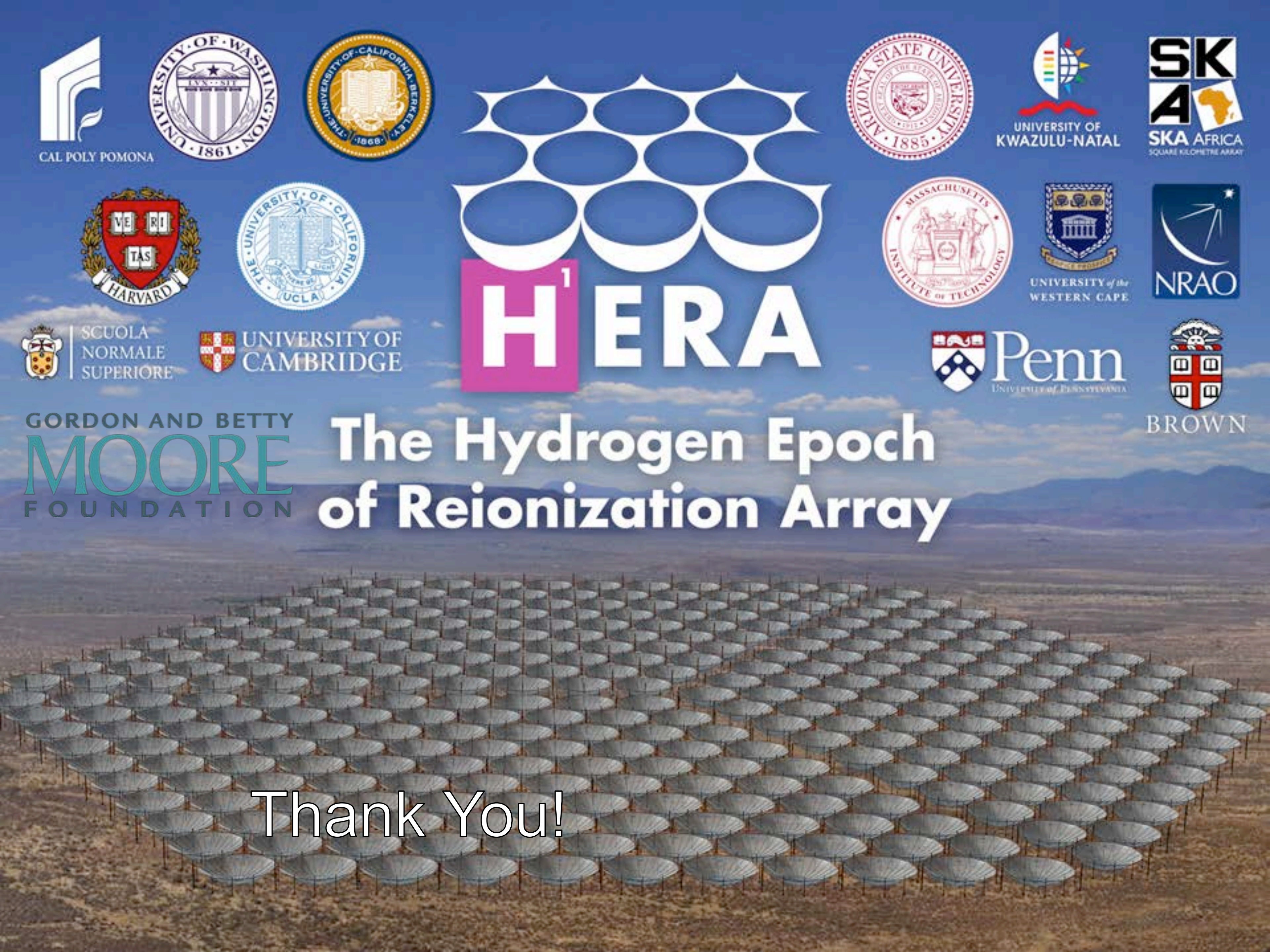
pyuvdata

- Python object for representing interferometric data
  - Supports MIRIAD, uvfits, measurement sets, FHD custom savefiles
  - Documented
  - Unit tested
  - Peer reviewed: http://dx.doi.org/10.21105/joss.00140
  - Now supports calibration solutions, full-polarization primary beams

- Set of software best practices for *all* HERA-Team project code
  - Real-Time Pipeline, Quality Metrics, Monitor & Control, Calibration, Librarian, Simulation, Power Spectrum

Testing HERA

Developing new specifications with simulations and in situ measurements (Neben et al. 2016, Thyagarajan et al. 2016, Ewall-Wice et al. 2016b, Patra et al. 2017)


CAL POLY POMONA
UNIVERSITY OF WASHINGTON 1861
UNIVERSITY OF KWAZULU-NATAL
SKA AFRICA
SQUARE KILOMETRE ARRAY
HARVARD
UCLA
UNIVERSITY of the WESTERN CAPE
NRAO
SCUOLA NORMALE SUPERIORE
UNIVERSITY OF CAMBRIDGE
HERA
Penn
UNIVERSITY of PENNSYLVANIA
BROWN
GORDON AND BETTY MOORE FOUNDATION
The Hydrogen Epoch of Reionization Array
Thank You!