LEDA[†] Project and 21 cosmology

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† Large Aperture Experiment to Detect the Dark Ages

Outline

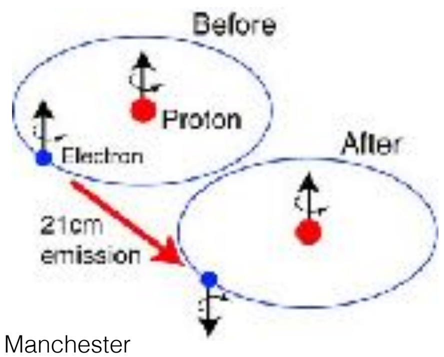
- 21cm cosmology
    - Observable
    - Evolution
- LEDA
    - Telescope
- Current Projects
    - Global signal
    - Sky distribution (power spectrum)
    - Problems
- Developed Technologies
    - Software

Dark Ages

- After recombination (~ 400,00 years, z=1100) before first stars
- There exists -
  - Cosmic Microwave Background (CMB)
  - Neutral Hydrogen (HI)
  - (Dark matter)
- 21cm cosmology is about relative temperatures
  - HI kinetic, and CMB blackbody
    - Collisional coupling due to high density gas + CMB
    - Compton scattering of CMB photons off residual electrons
- Another temperature to consider
  - HI Spin temperature (21-cm)

Spin Temperature

- Electron in HI ground state has two hyperfine levels
  - Energy difference is 21cm



U. Manchester

- Temperature: electrons in high vs. low state
  (G. Field, 1958)
- Something "sets" the spin temperature
- Spectral line against CMB
  - Source = CMB, absorber = HI spin
  - Emission too
- Absorption/emission depends on spin temperature
- Dark Ages

HI temperature
CMB temperature
Spin Temperature

All in equilibrium due to collisional coupling

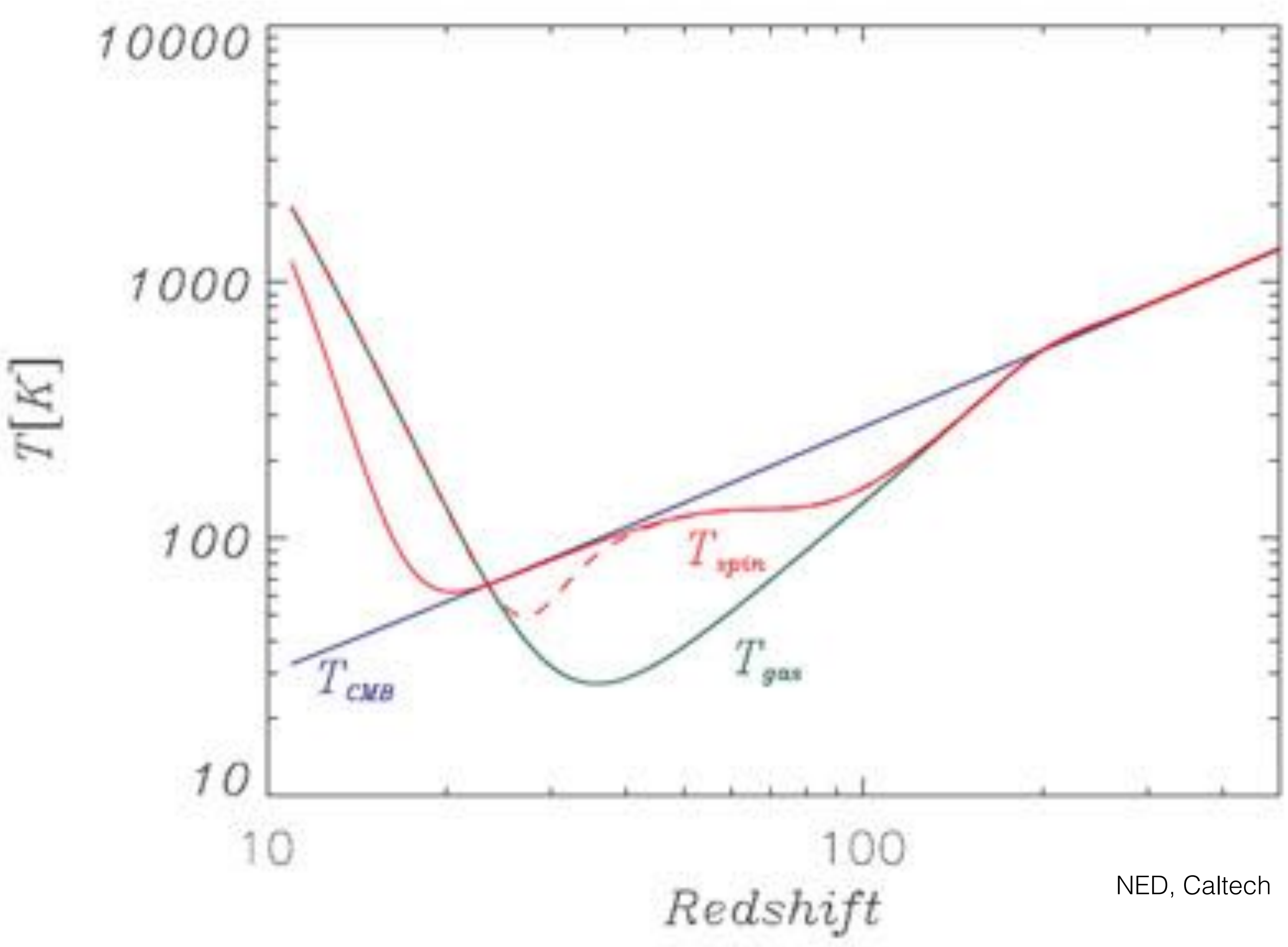
21 cm cosmology

- Equilibrium does not last
  - Cooling, expansion
  - Ignition of first stars
    - UV photons, X-Rays
- All set spin temperature

  => *spin temperature probes cosmic evolution*
- View brightness temperature of redshifted 21 cm line over long time scales (low frequencies)

21 cm cosmology

- First thoughts on temperature changes

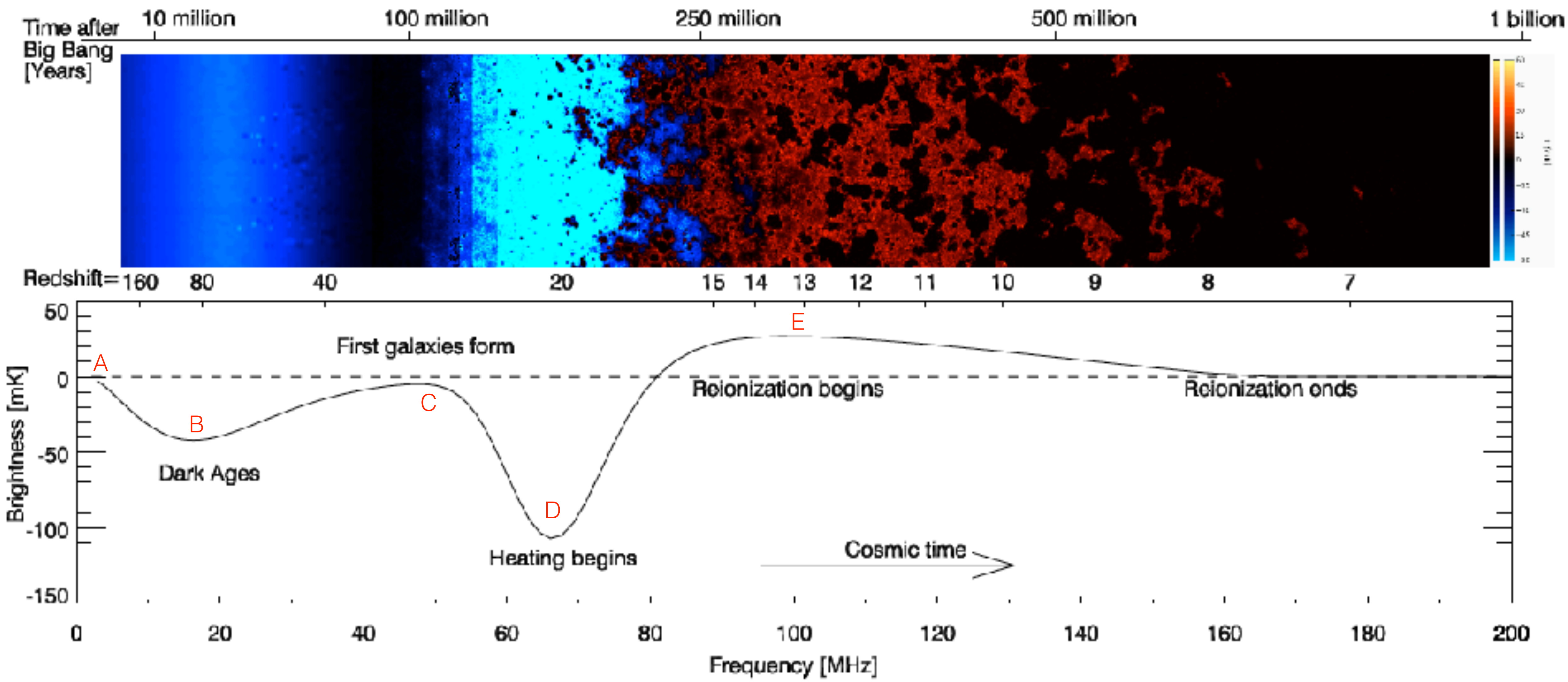


NED, Caltech

- CMB and HI expand and cool
- Spin temperature wanders
- Different models predict different wanderings

21 cm cosmology

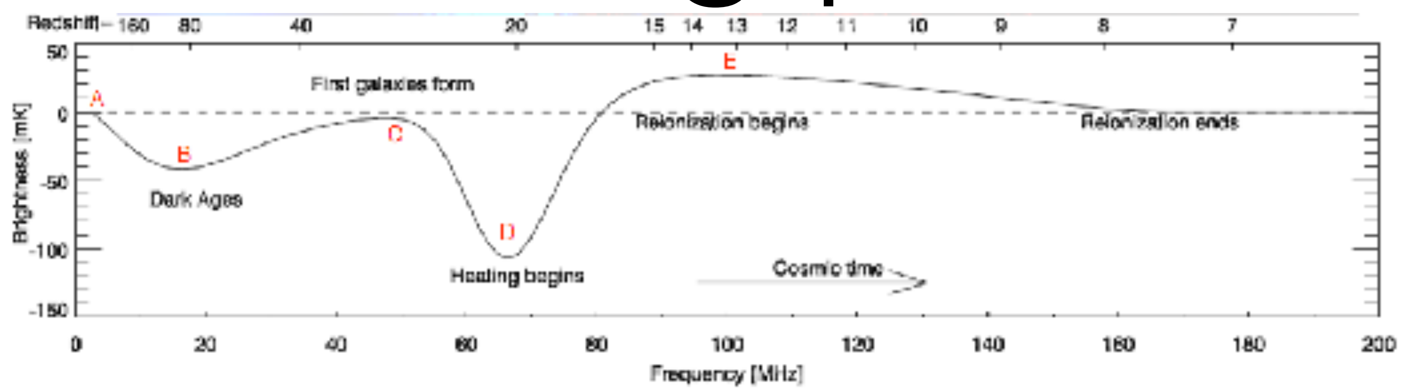
One possible scenario



Pritchard, Loeb, *21-cm cosmology in the 21st Century*, 2012 (red letters are mine)

Five key turning points, A, B, C, D, E

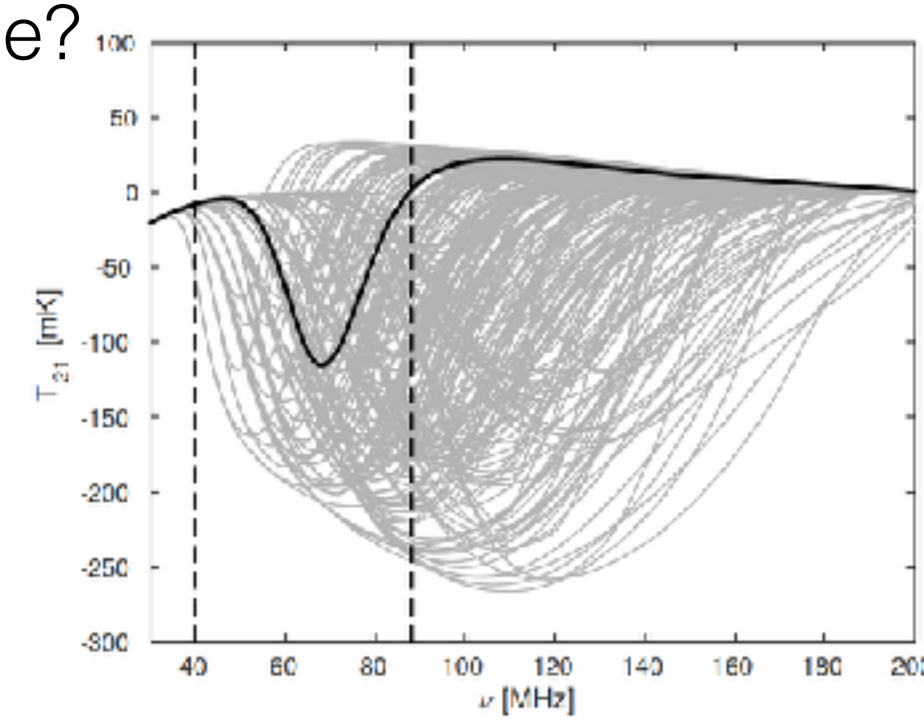
Turning points



- A - gas decouples from CMB
- B - spin decouples from gas (collision), couples to CMB (radiation)
- C - Lyα decouples spin from CMB (Wouthuysen-Field Effect), spin drops to gas temperature
- D - X-ray heating begins, spin coupled to gas, both increase
- E - reionization, HI decreases, signal dies

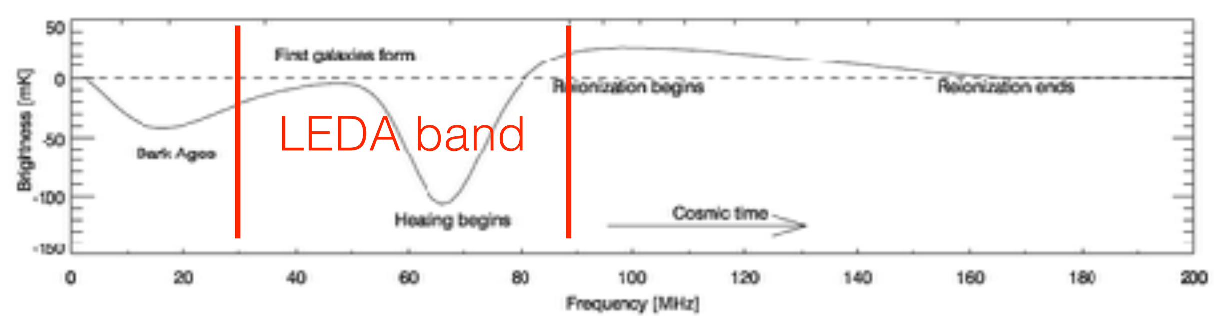
Variation in model parameters

- Do we know when X-rays start?
- How hard/soft?
- What is their extent of influence?
- Where do they come from?
  X-ray binaries? Supernova?



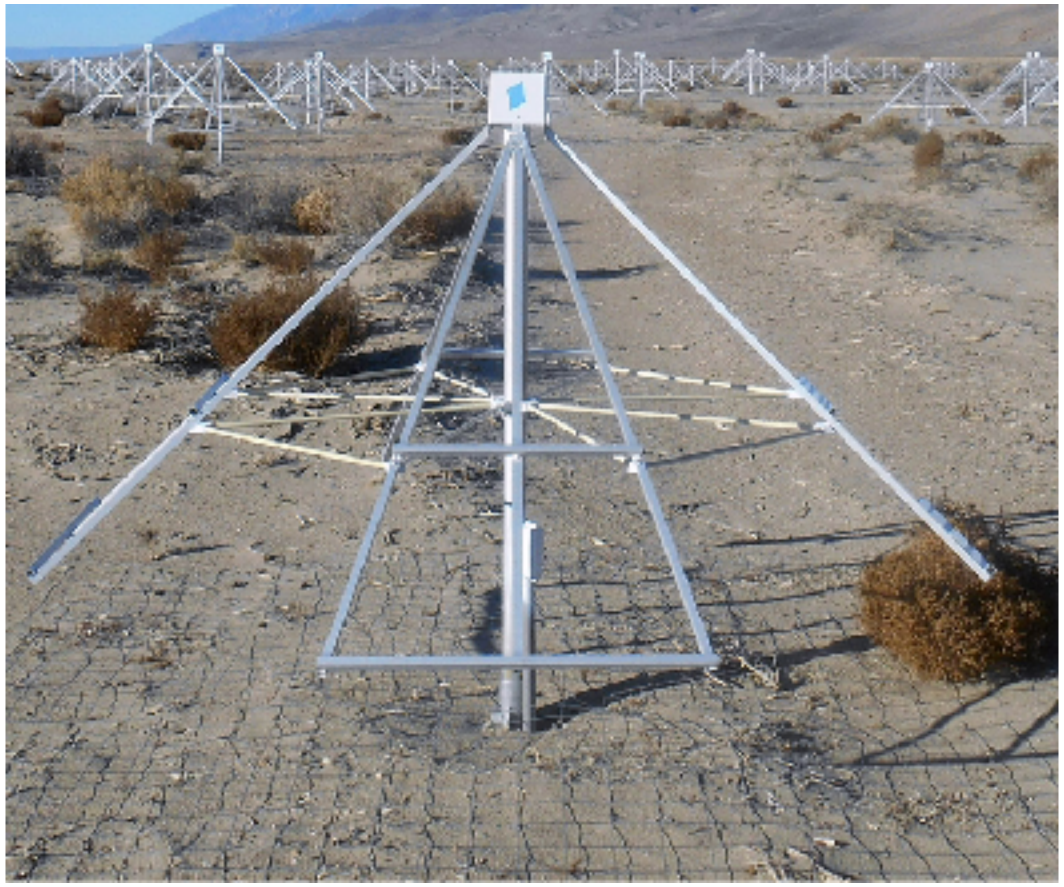
Cohen et. al, *Charting the Parameter Space of the Global 21-cm Signal*, 2016

D. Price et al. *Design and characterization of the Large-Aperture Experiment to Detect the Dark Ages (LEDA) radiometer systems*, in prep.



LEDA

- LEDA Cosmic Dawn Project (PI: Lincoln Greenhill, CfA)
- Facilities (Joint CalTech/CfA Managed, CalTech owned)
  - OVRO-LWA Interferometer, Owens Valley, CA
  - Based on LWA, 256 stands, 512 antennas 500m baseline, 30-87 MHz
  - Compute:
  - 16 FPGAs (ROACH)
  - 22 GPUs on 11 computers, 100 TF/s
  - High speed (40Gb) Ethernet
  - Dumps ~400 MB/s (35 TB/day possible)
  - In-house correlator and calibration/imaging pipeline (xGPU and RTS)



OVRO-LWA stand. Amanda Kocz

LEDA

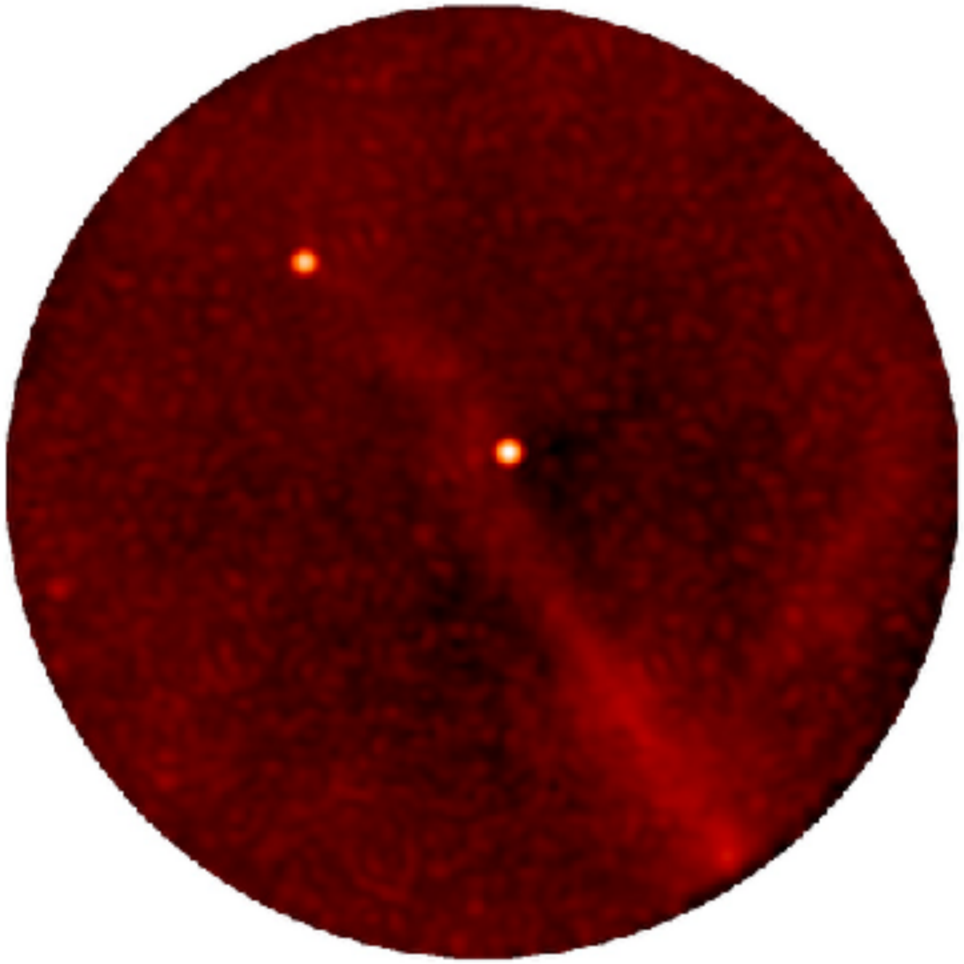
Other LEDA Group interests

- All sky transient monitor
  - CalTech ahead (LIGO)

- Extra-solar space weather
  - Observe pulsars through solar corona
    - Beam forming
    - Determine magnetic field
  - Partner with U. Michigan, NASA

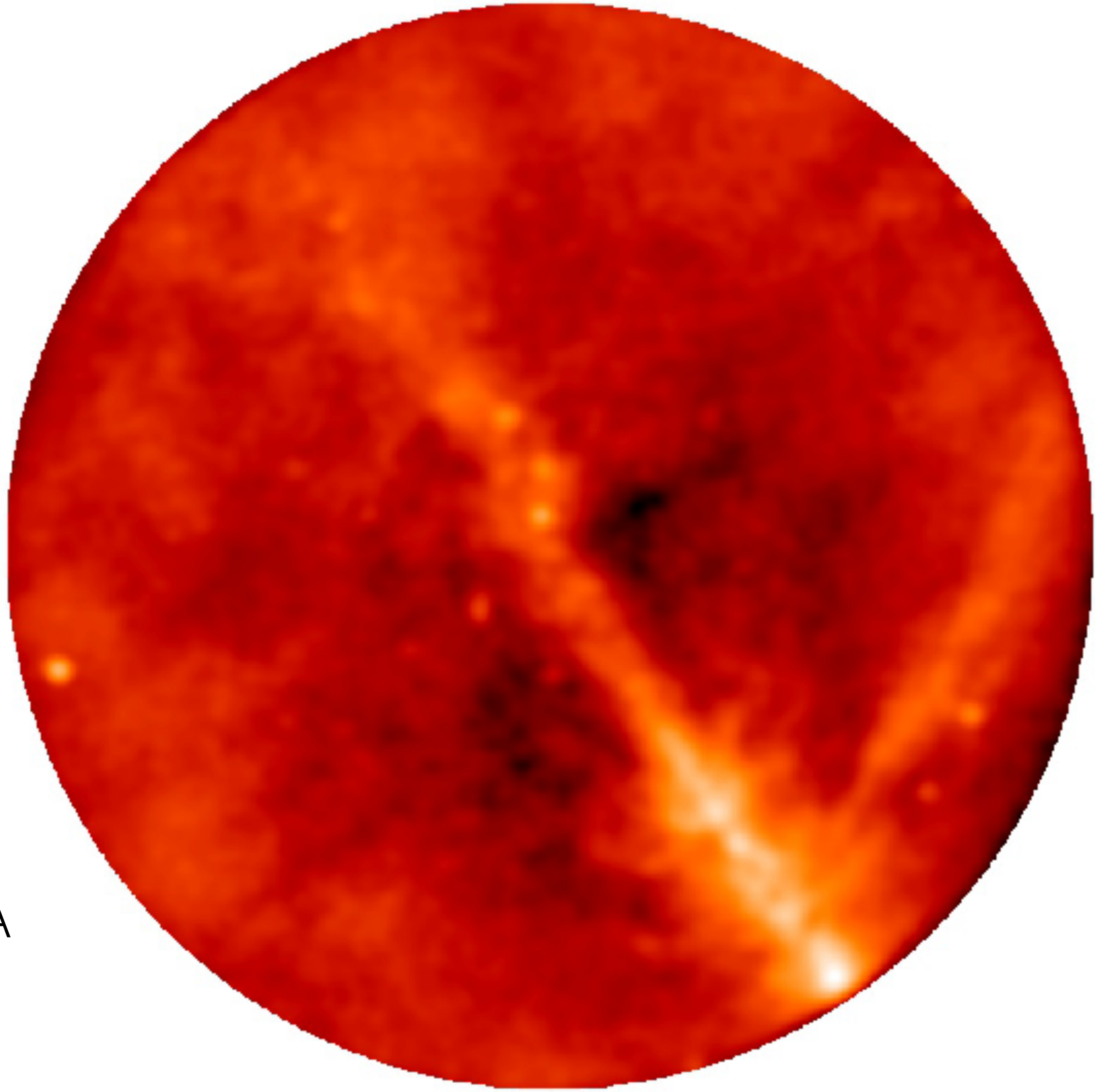
Solar corona - Wikipedia

- New Technologies



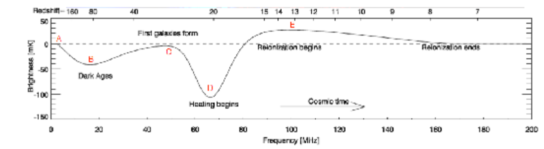
Observation of Cyg A and Cas A

47 MHz, 180 degree FoV

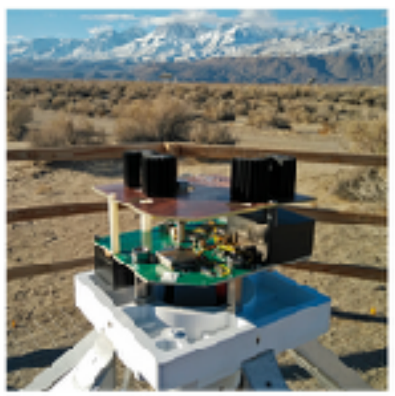


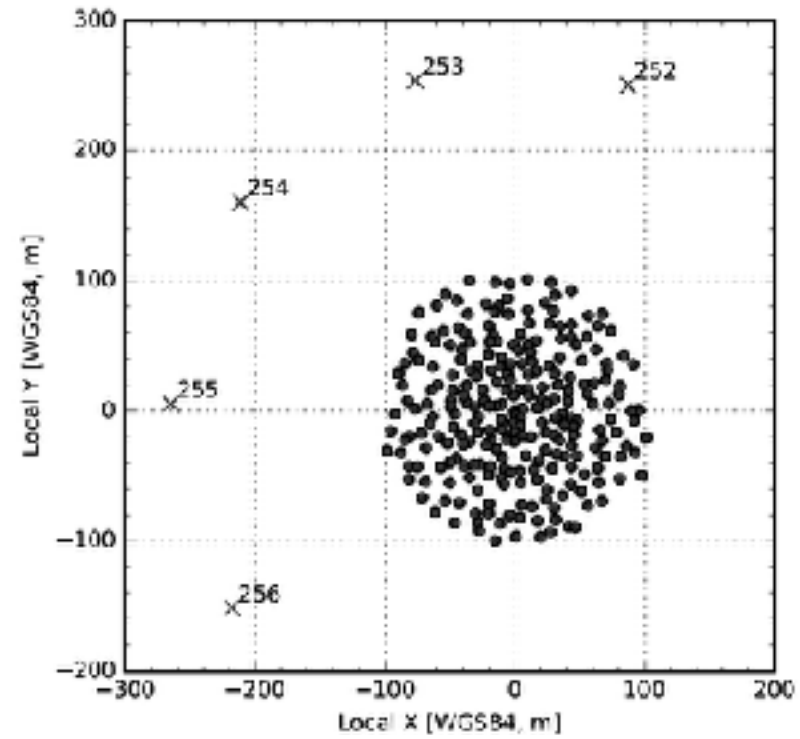
Cyg and Cas peeled out

21 cm Global Signal

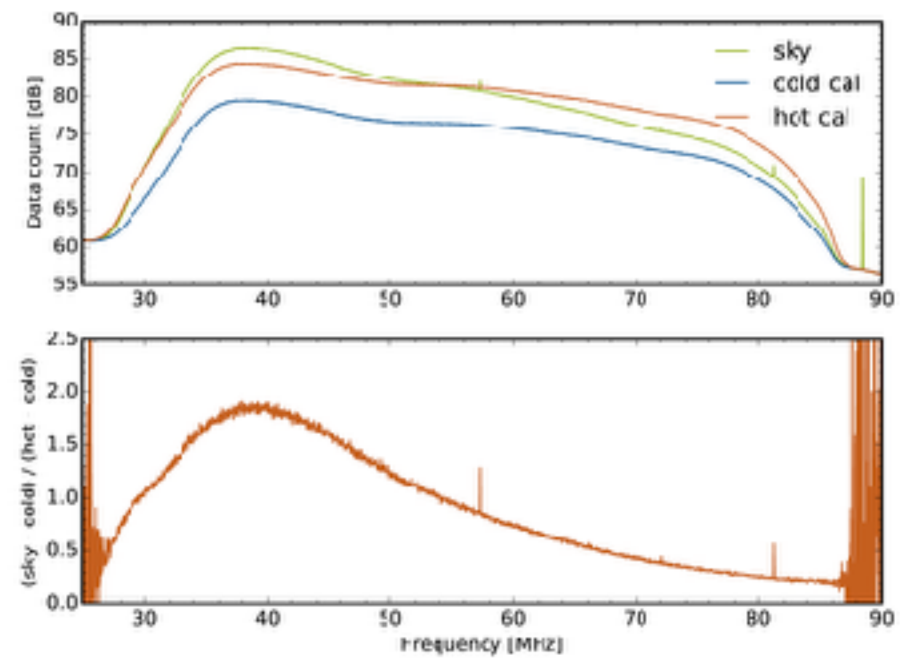


- 5 dual-polarization antennas with radiometry attached





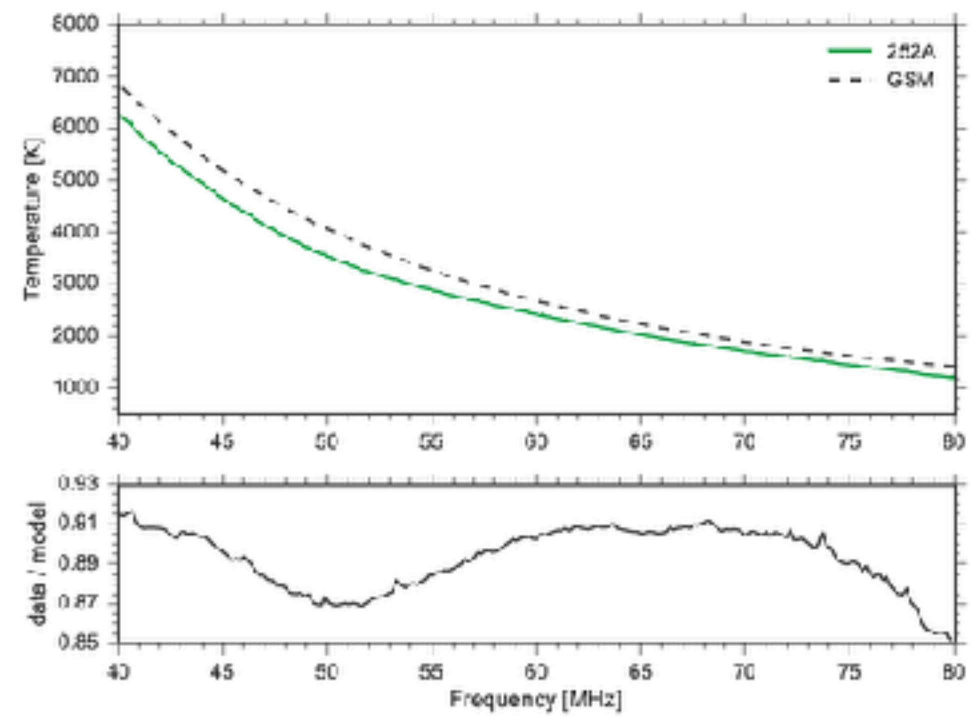
- Recording continuously
  ~ 0.5 GB /day
- Three-state switching calibration
  Cold/hot diodes + sky
- RFI excised with Offringa thresholding algorithm



D. Price et al. *Design and characterization of the LEDA radiometer systems*, in prep.

Radiometry

- Our spectrum consistent with GSM2008



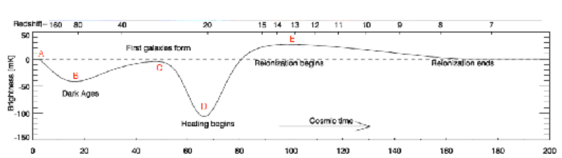
- Spectral Index consistent with other work

Reference	Decl. (deg)	Freq. (MHz)	α
Costain (1960)	+52.16	38-178	-2.37±0.04
Purton (1966)		13-100	-2.38±0.05
Andrew (1966)	+52.16	10-38	-2.43 ± 0.03
Rogers & Bowman (2008)	-26.5	100-200	-2.5 ± 0.1
Patra et al. (2015)	+13.6	110-175	-2.30 to -2.45
Mozdzen et al. (2017)	-26.7	90-190	-2.5 to -2.6
This work	+37.24	40-80	-2.28 to -2.38

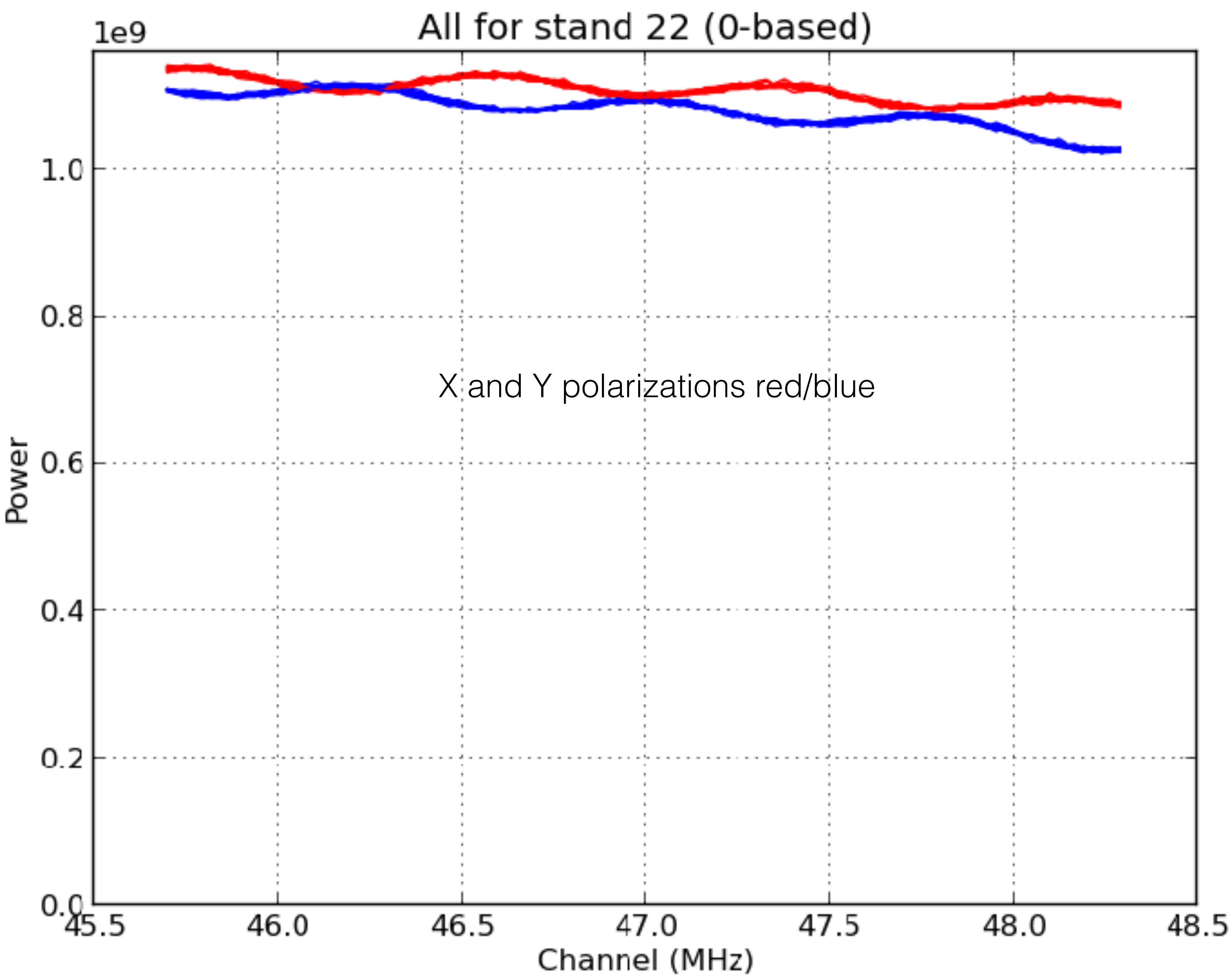
D. Price et al. *Design and characterization of the LEDA radiometer systems*, in prep.

The Signal

- How to extract the (very weak) 21cm signal?
- Like CMB analysis, get rid of foregrounds
  - Compact sources, galactic synchrotron, free-free …
- Bayesian/MCMC method -
  - Foreground spectrum as 7th order polynomial in log(ν)
  - simplified (but plausible) Gaussian model of the 21-cm emission
  - Bernardi et al., *Bayesian constraints on the global 21-cm signal from the Cosmic Dawn*, 2016
- Reached 470mK RMS on 20min integration. Need 400 hrs.

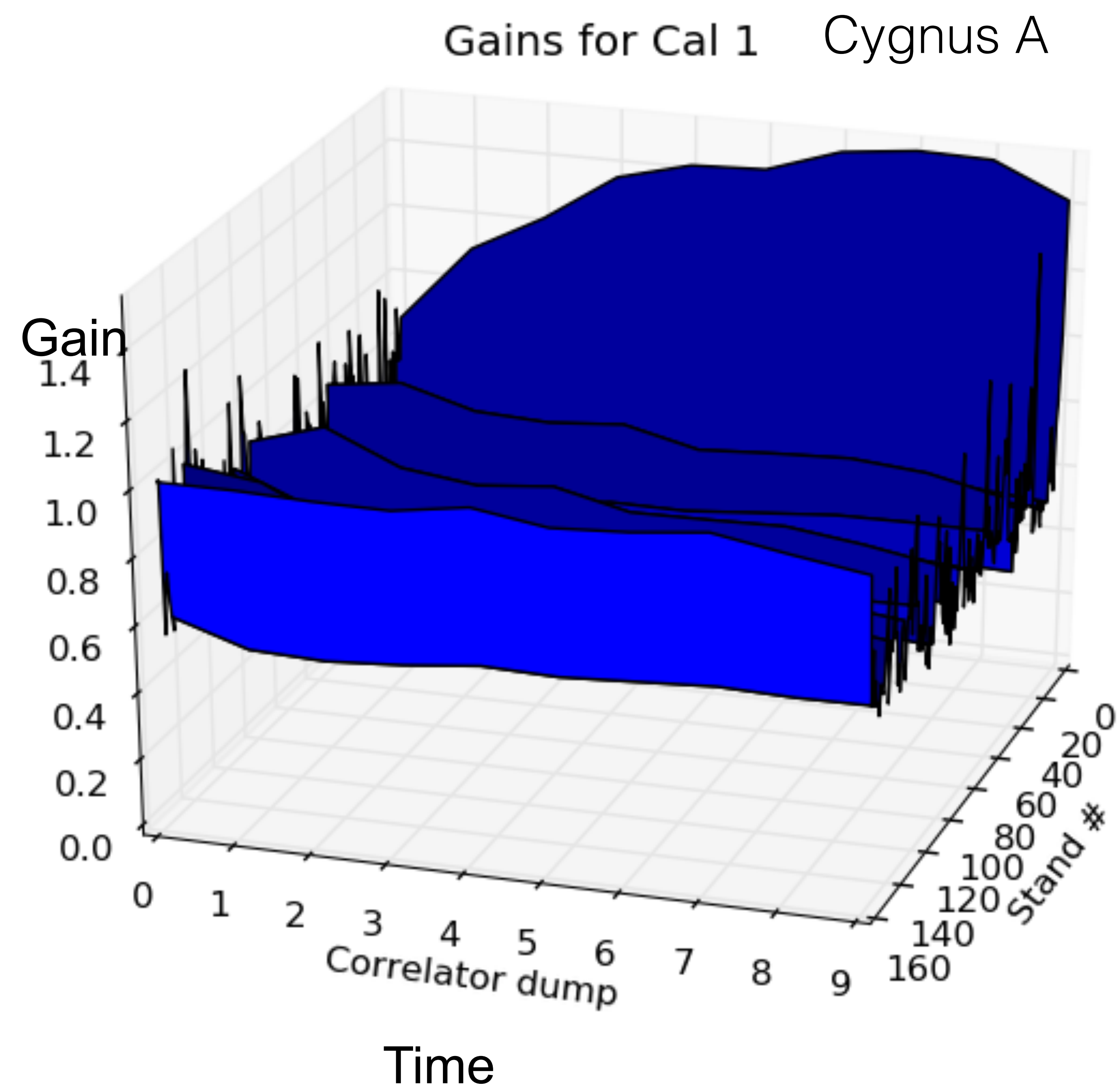


- Problems: Ionosphere, Ripples, Antenna gain pattern, RFI


All for stand 22 (0-based)
1e9
1.0
0.8
0.6
0.4
0.2
0.0
Power
45.5
46.0
46.5
47.0
47.5
48.0
48.5
Channel (MHz)
X and Y polarizations red/blue

Antenna gain pattern

- Drift scans
- Calibrate with RTS
- Dump gains for source
  - Over time
  - Over antenna



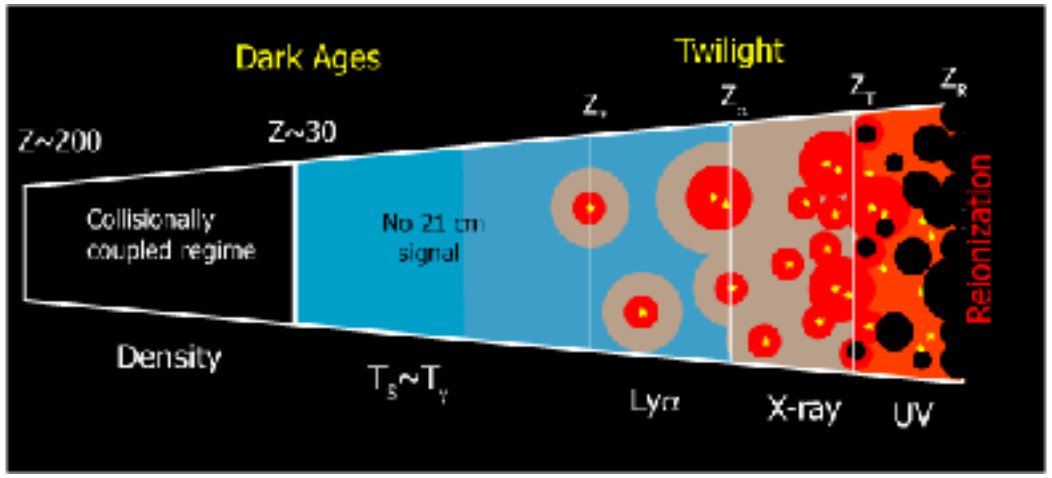
- RFI:
  - attempting Nita/Gary spectral kurtosis estimator (can discuss if time)

Harvard-Smithsonian Center for Astrophysics

LEDA

Power Spectrum

- Interferometry, different foreground technique
- The distribution of 21 cm is not uniform as universe develops
- Development of structure -> ionized bubbles. Swiss Cheese.



J. Pritchard

- We want distribution of 21 cm over the sky and over time
- Over sky
  - Interferometry: Visibilities give power at angular scales

Power Spectrum

- Over time, use redshift
  - Frequency axis is time
- Hang on - frequency axis is *frequency*
- Interesting things happen if FFT along frequency axis
  - An interferometer accesses the three-dimensional power spectrum of 21 cm EoR emission by measuring variation perpendicular to the line of sight using samples provided by different baselines in the uv-plane, and variation parallel to the line of sight using the Fourier transform of frequency data (Parsons et al. 2012)

  Foregrounds end up in a different place in the Fourier Transform (involves Delays - can discuss if time)
- This leads to “The Wedge” in ($k_\perp$, $k_\parallel$) space.
  - k => Fourier modes
  - $k_\parallel$: time $k_\perp$: over sky

The Wedge

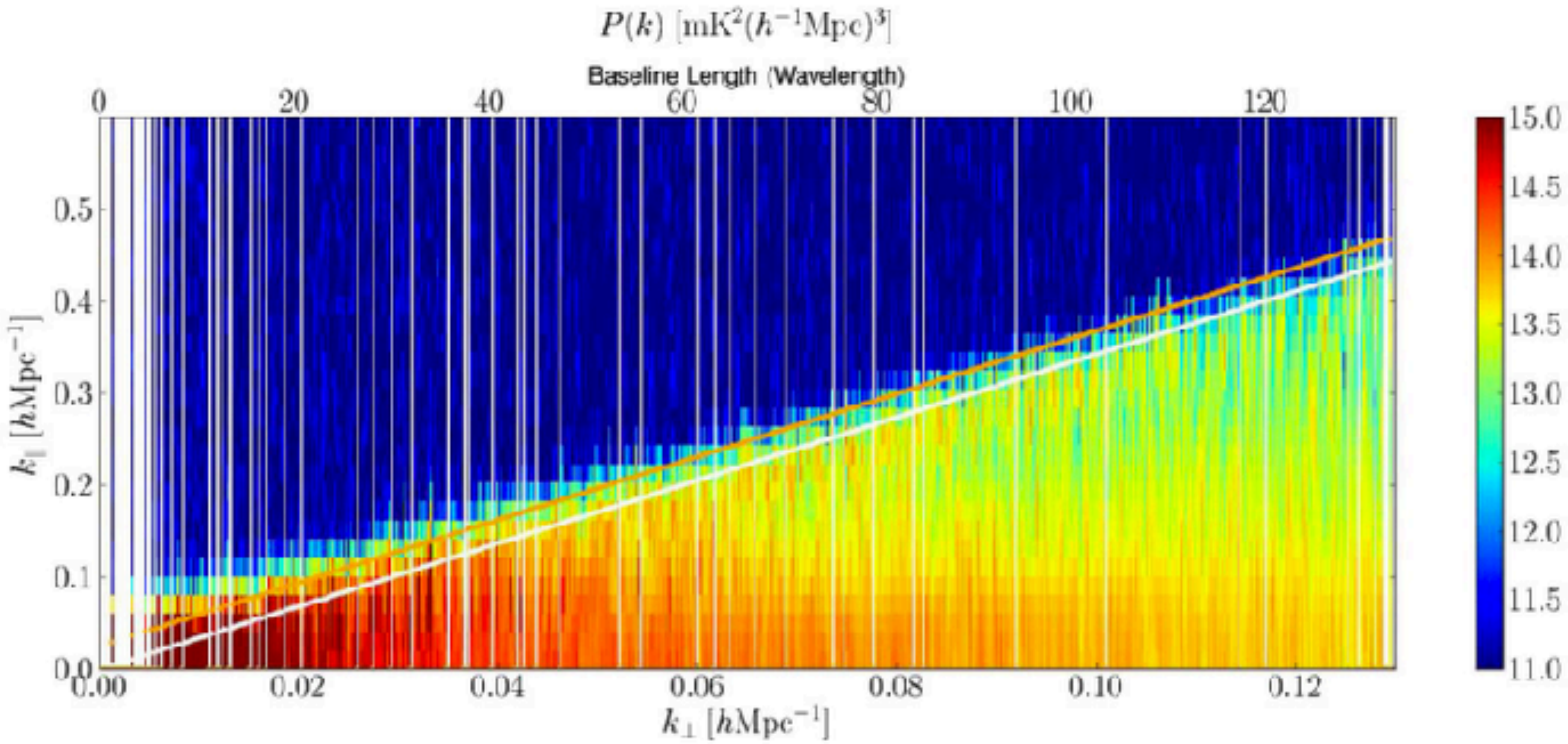


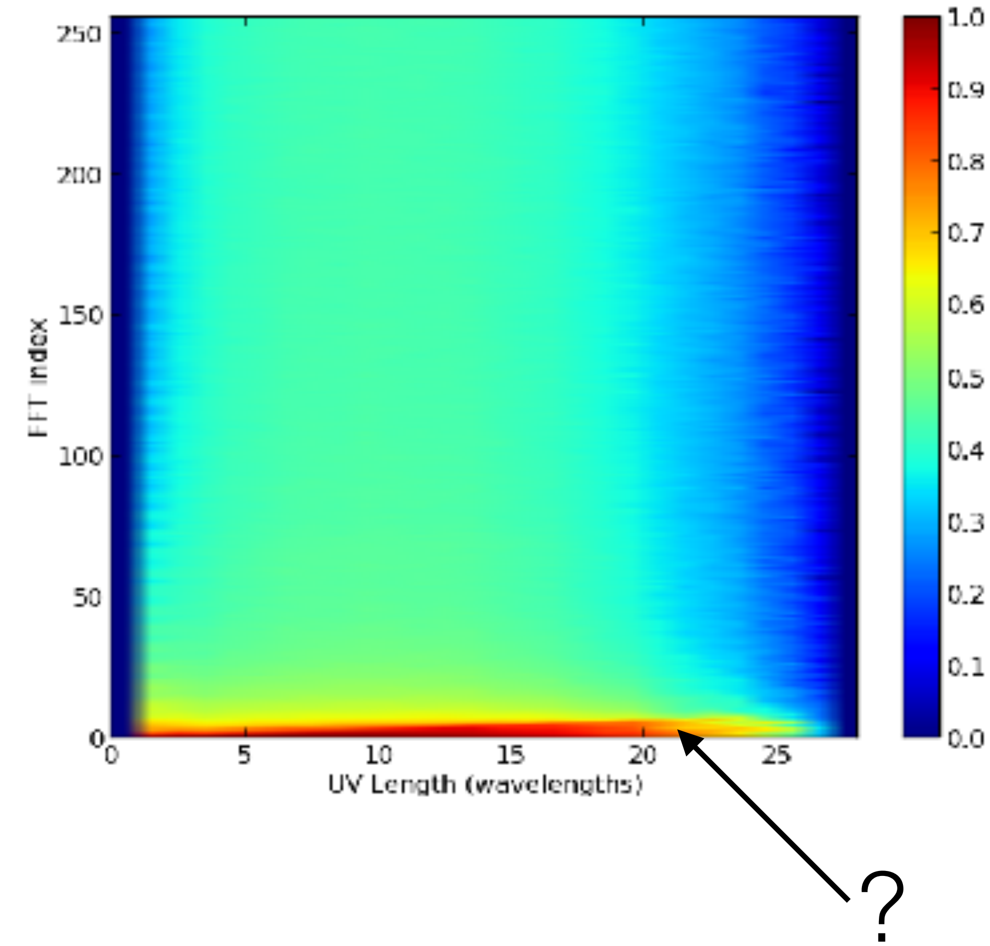
Figure 3. Two-dimensional power spectrum of the 4 hr of data analyzed. The wedge-like nature of the foreground emission is clear. The white line marks the horizon limit and the orange line is 50 ns beyond. The color scale is logarithmic and the units are mK^2(h^{-1} Mpc)^3. The binning is described in the text.
(A color version of this figure is available in the online journal.)

OPENING THE 21 cm EPOCH OF REIONIZATION WINDOW:MEASUREMENTS
OF FOREGROUND ISOLATION WITH PAPER
- Pober et. al, ApJ 768:L36, 2013

My Wedge

- Easy to FFT visibilities
- Need longer integration
- Better calibration (better data hygiene)
- Calibration to include:
  -ionospheric effects,
  -antenna gain pattern, fixes
- Calibration is key.
- "The Impact of Modeling Errors on Interferometer Calibration for 21 cm Power Spectra" - A. Ewall-Wice
- Aim: Determine limits of current LEDA hardware/software

10MHz



Other 21cm Projects

- EDGES (single antenna), AU
- MWA, AU
- LWA, US
- LOFAR, EU
- GMRT, India
- SKA, SA/AU
- PAPER, SA/US
- HERA, SA (redundant baselines)
- CalTech OVRO-LWA
  - Mike Eastwood, m-modes

ICRAR

EDGES

NCRA India

GMRT

SKA SA

HERA

Technologies

- xGPU
  - Correlator
  - possible upgrade into ALMA

  Clark et al., *Accelerating Radio Astronomy Cross-Correlation with Graphics Processing units*, 2011

- RTS
  - Calibration and Imaging
  - Uses GPUs

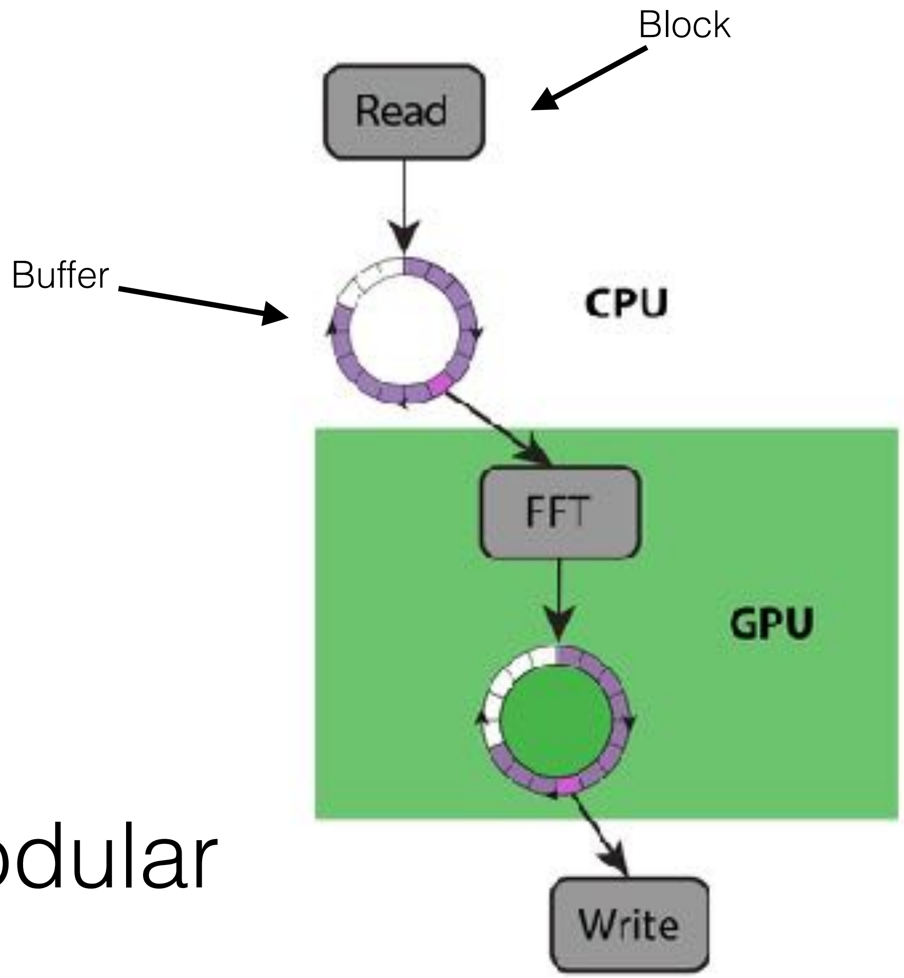
  Mitchell et al. *Real-Time Calibration of the Murchison Widefield Array*, 2008 [developed at CfA]

- BiFrost
  - New

  Barsdell et al., *Bifrost: a Python/C++ Framework for High-Throughput Stream Processing in Astronomy*, in prep.

Bifrost†

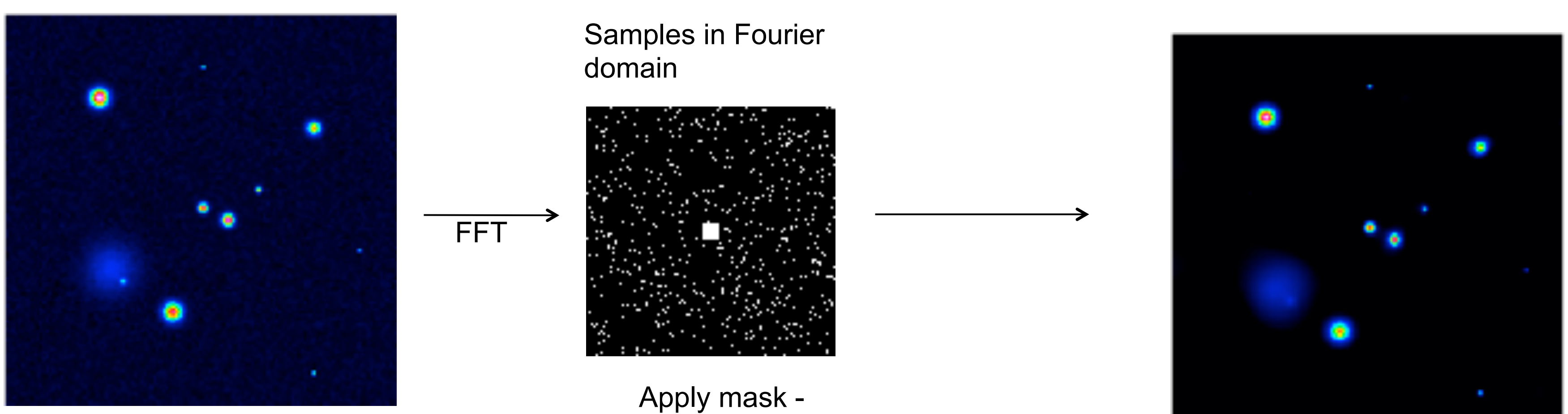
- Antecedent: PSRDADA
- Integrates:
  - Stream data processing
  - Multiprocessing
  - GPU processing
  - CPU/GPU memory spaces
  - Python/C++
- High Performance, scalable, modular
  - Blocks and buffers
- Python, numpy data types native
- Deployed on Sevilleta-LWA for beam forming



† In Norse mythology, Bifröst is a burning rainbow bridge that reaches between Midgard (Earth) and Asgard, the realm of the gods.

Compressed Sensing

- Deconvolution
    - and of diffuse/extended structure
- Does not use PSF
- Match visibilities to an image in some domain (e.g. wavelets) in which the image is sparse
- Iterate using techniques like rate variation, thresholding, different norms … to convergence



Test Image

Conclusions

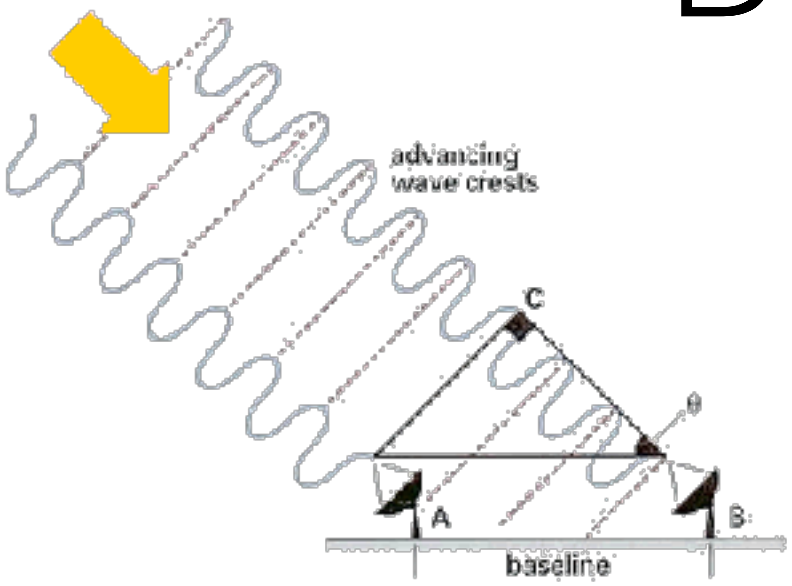
- Recap
    - 21cm cosmology
    - LEDA
    - Global signal
    - Power spectrum - the wedge
    - Technologies
- Future
    - Calibration is key - continue pushing
    - RFI Excision
    - Gain Patterns
    - Power Spectrum

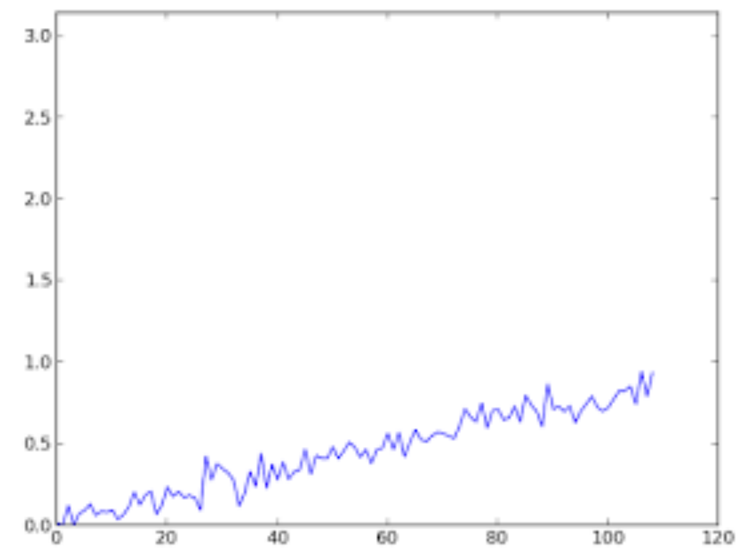
You've reached the end

No you haven't

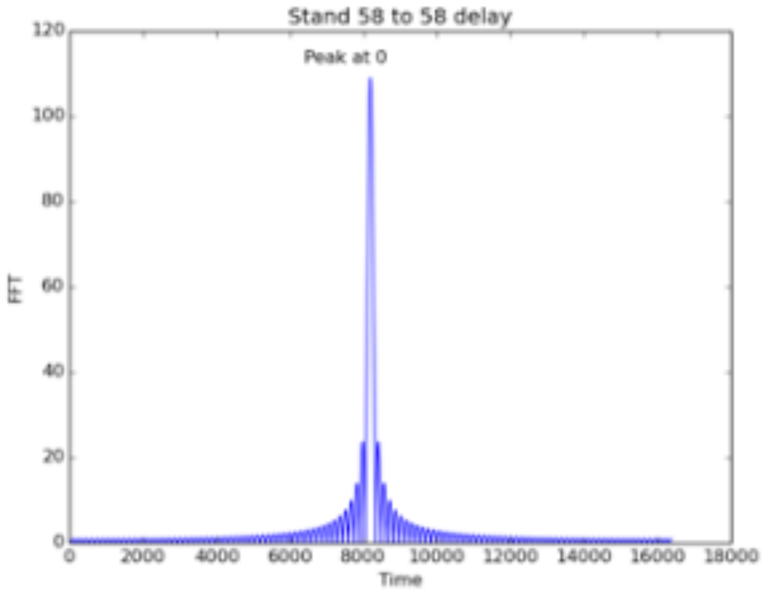
LEDA

Delays

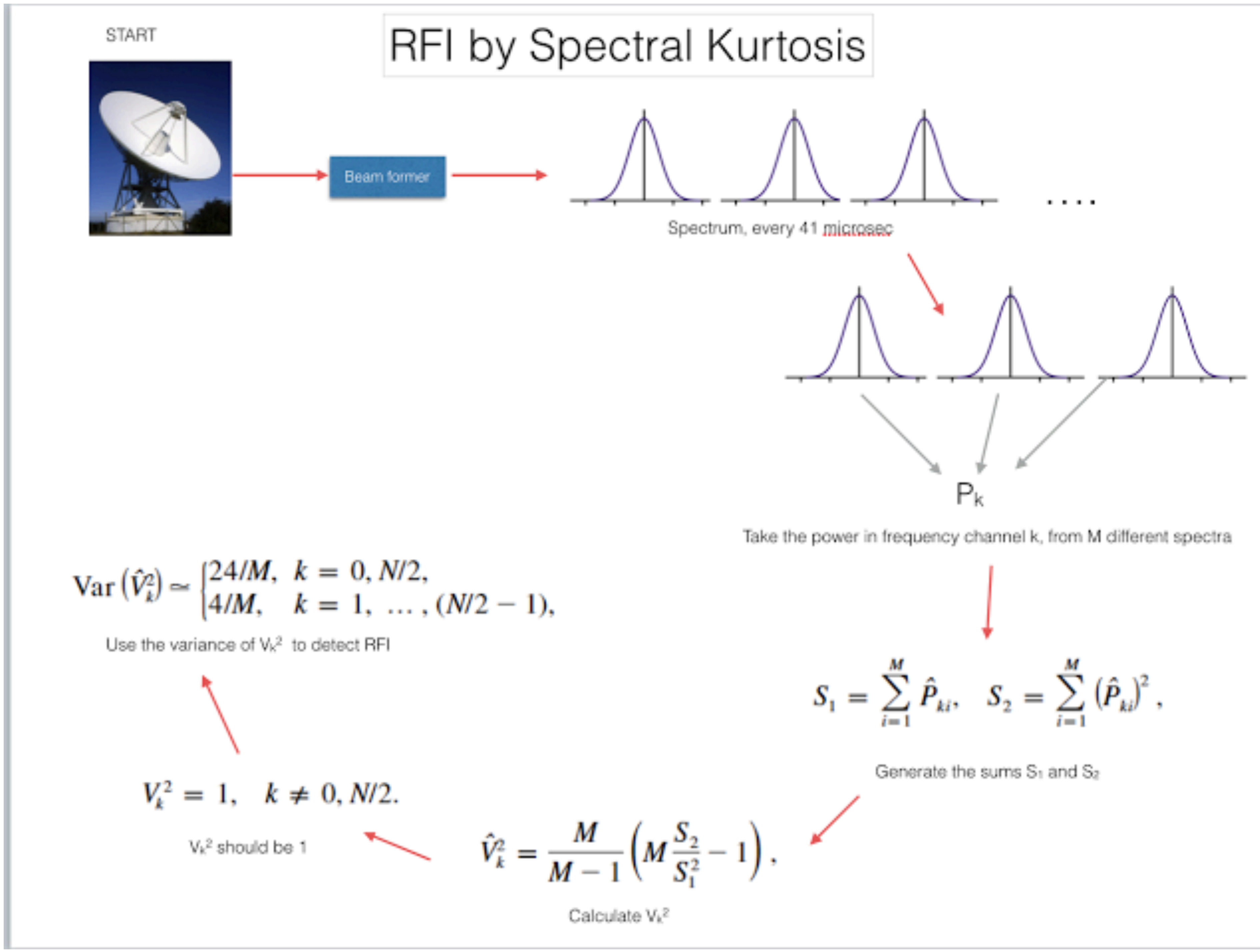




- Across frequency, for 1 source,
  phase of correlated signal changes linearly
- phase = k f + $phase_0$ (cf. a x + b)
- visibilities are $e^{k f + phase0}$
- Fourier transform is a delta function

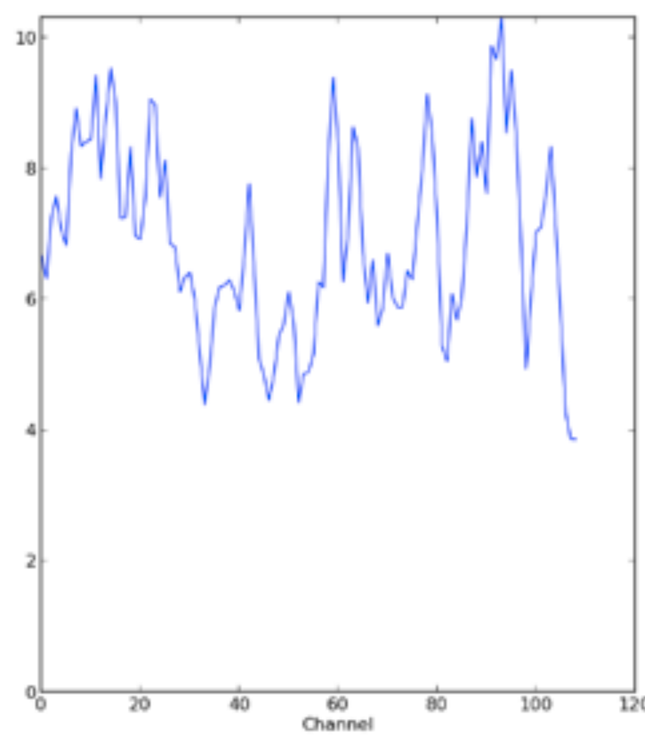


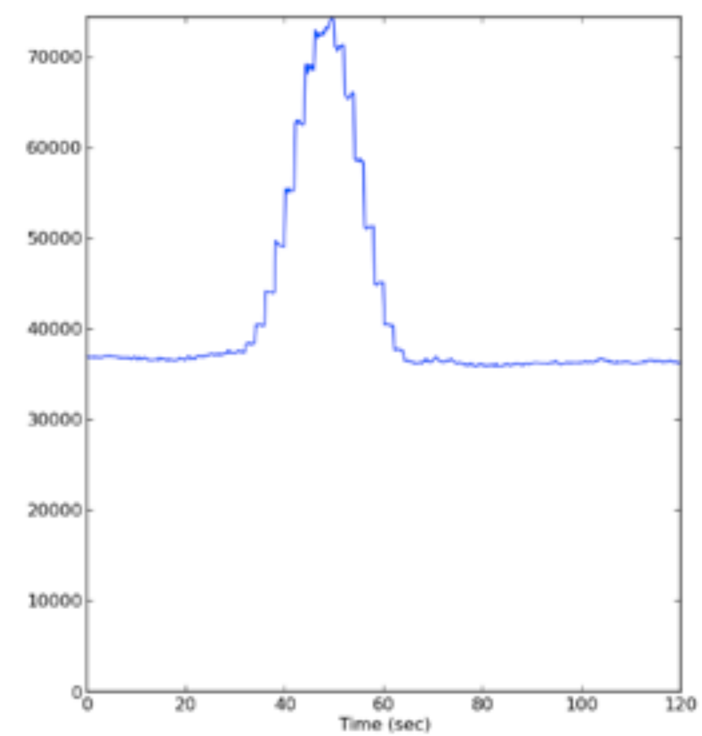
Spectral Kurtosis Estimator



Beam-Former commissioning

Beam sweep over Cygnus A





Beam sweep raw data vs. time