Beam Mapping of LWA using Pulsar Holography

Akshatha K Vydula
Ph.D. Candidate
Arizona State University

Prof. Judd Bowman
Prof. Danny Jacobs

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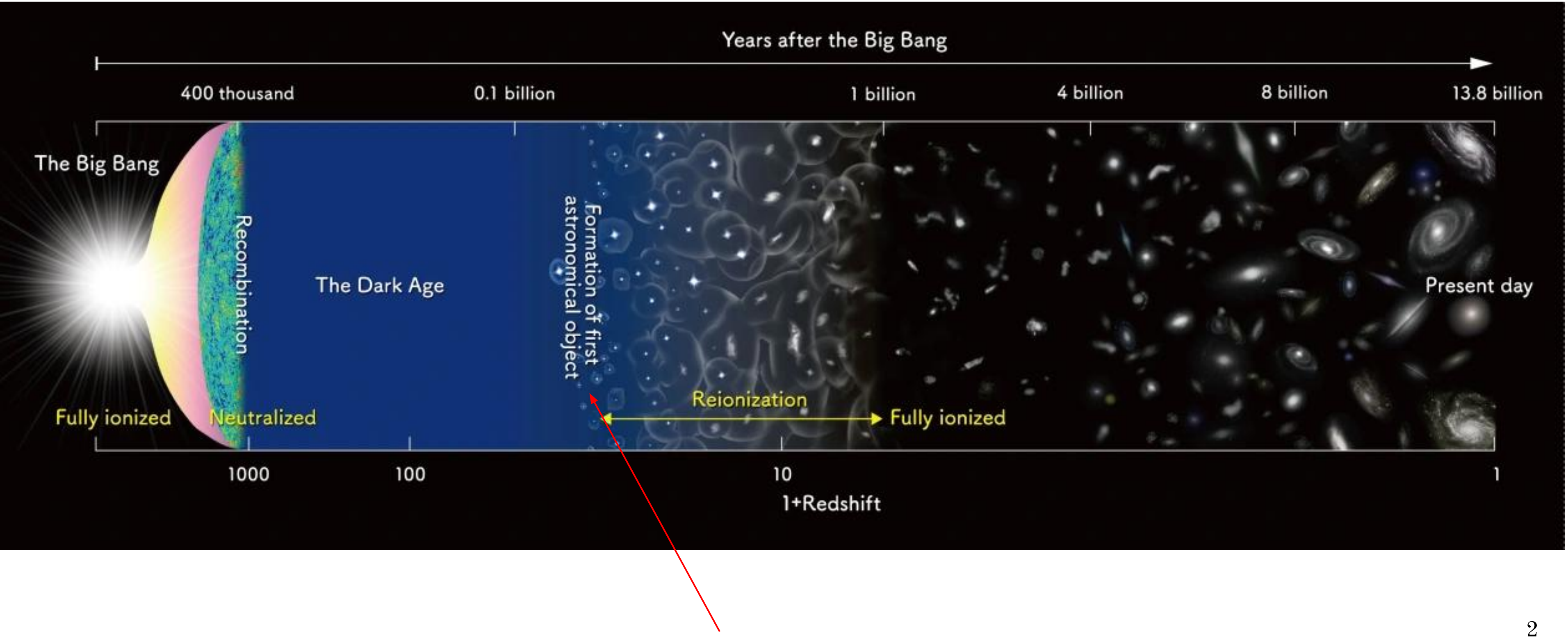
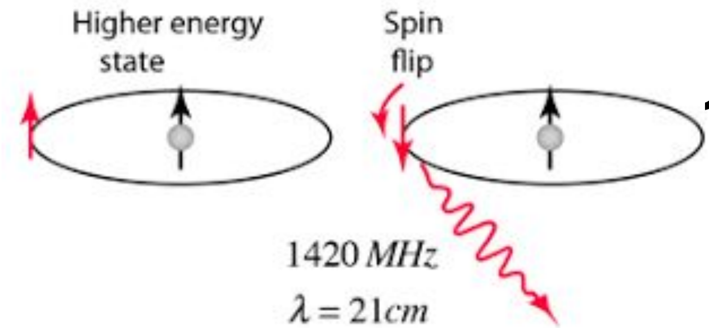
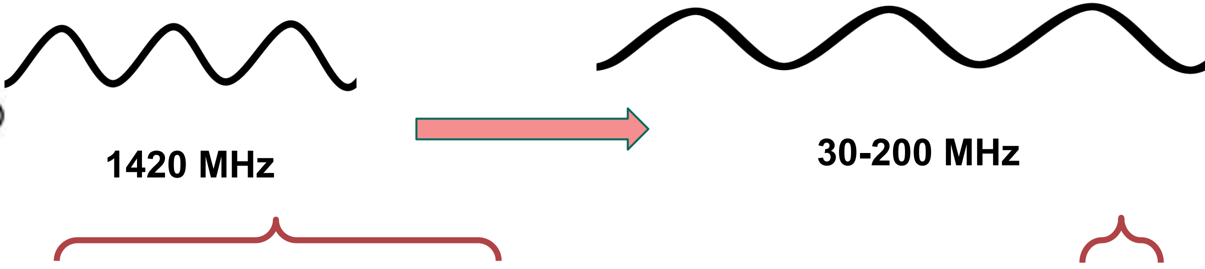
History of the Universe

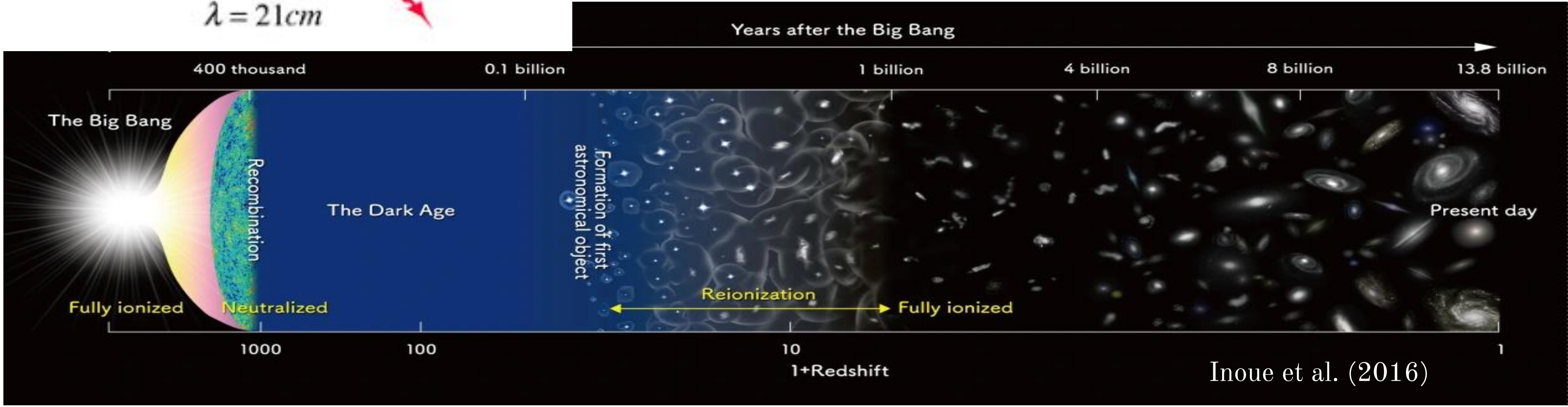
Inoue et al. (2016)



21 cm signal

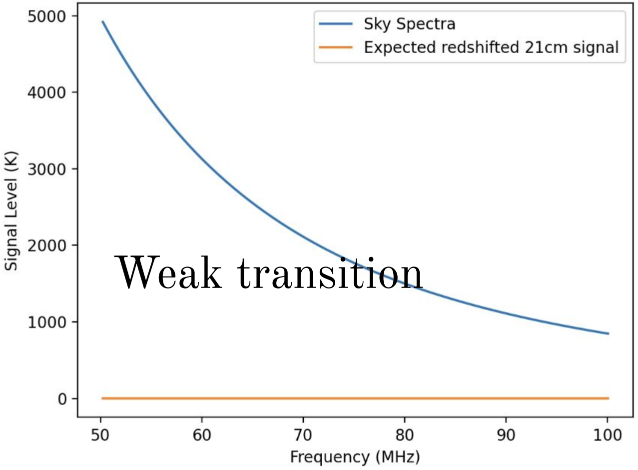


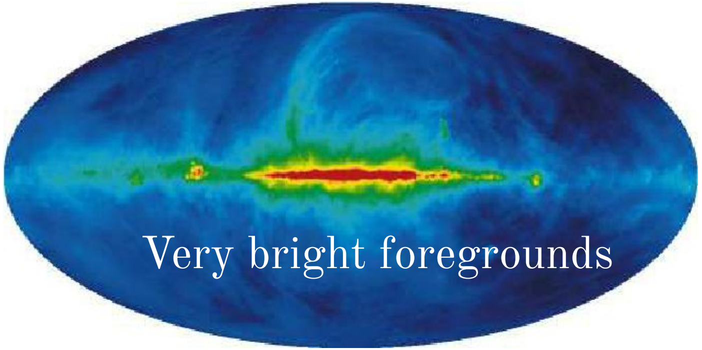


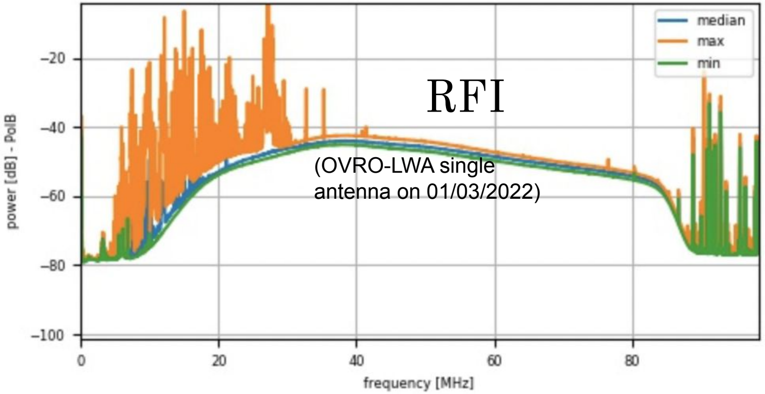


Inoue et al. (2016)

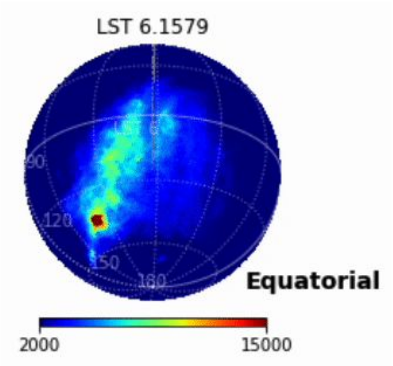
Challenges



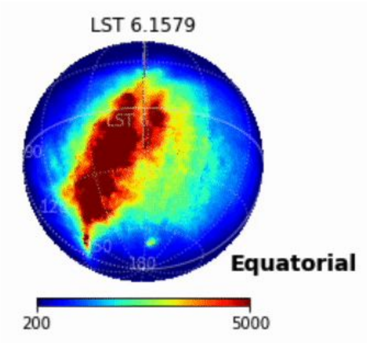




Instrumental beam effects



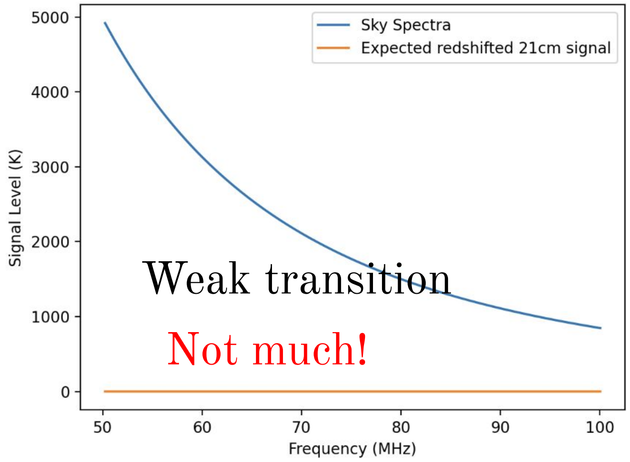
Sky

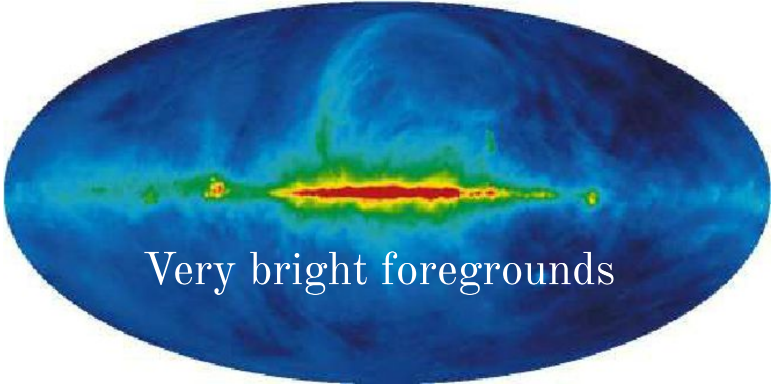


Beam
Convolved

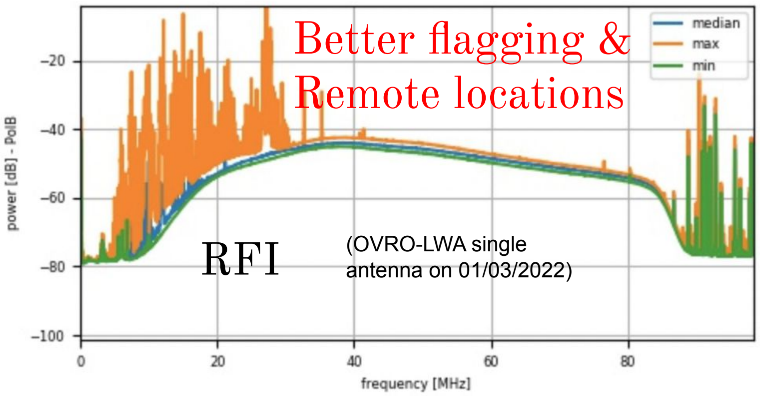
Harker(2011), Haslam(1982), Hellbourg (OVRO), Bowman(2018)

Possible solutions?



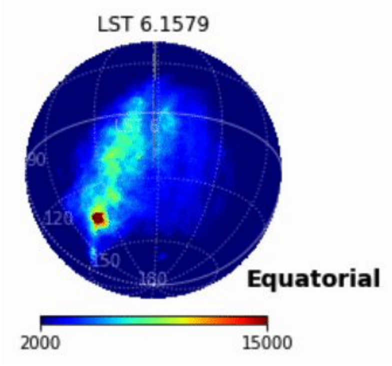


Better sky mapping and calibration

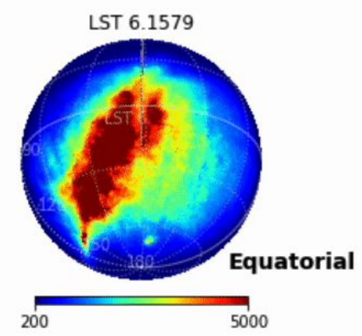


Instrumental beam effects

Better beam mapping (0.1% accuracy)



Sky



Beam Convolved

Harker(2011), Haslam(1982), Hellbourg (OVRO), Bowman(2018)

Beam Calibration

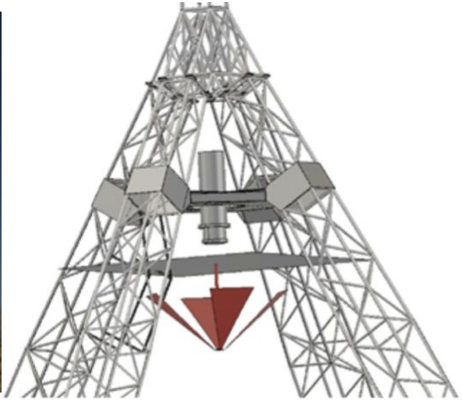
- 2D map the sky within the beam
- Involves mapping all the known sources in the sky:
  - better sky model $\Rightarrow$ better calibration solutions
- Gets complicated because it requires:
  - Point sources
  - High angular resolution to distinguish faint sources
  - Catalogs are incomplete and have uncertainties

Beam Errors!

Proposed Solution: Beam mapping using pulsar holography.

Target Instrument

- Owens Valley Long Wavelength Array (OVRO-LW
  - Upgrading to 352 antennas.
  - Frequency: 13 to 88 MHz
- 40 m dish with LWA feed
  - ~1km from OVRO-LWA
  - LWA feed at the prime focus



Credits: Jacobs (2021)[NSF]

Placeholder Instruments

- VLA 4 band (placeholder for 40 m):
  - Frequency Range: 70 to 82 MHz
- LWA-1 and LWA-SV (placeholder for OVRO-LWA):
  - Located near VLA center and ~75 km from the center
  - 288 broadband dipole antennas.
  - Frequency Range: 10 to 88 MHz

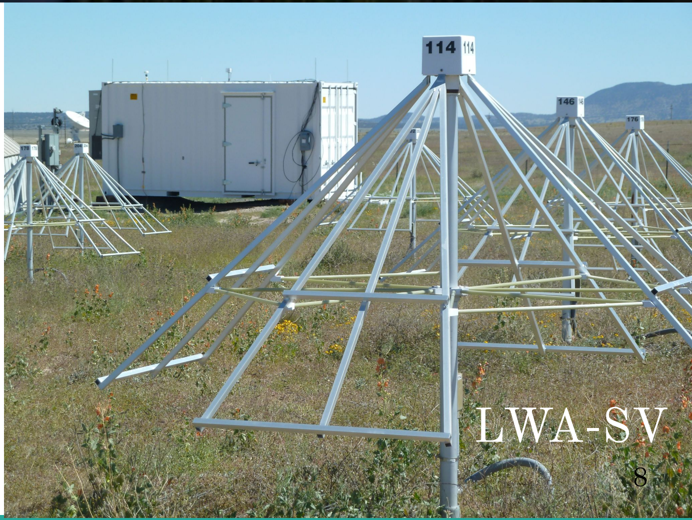


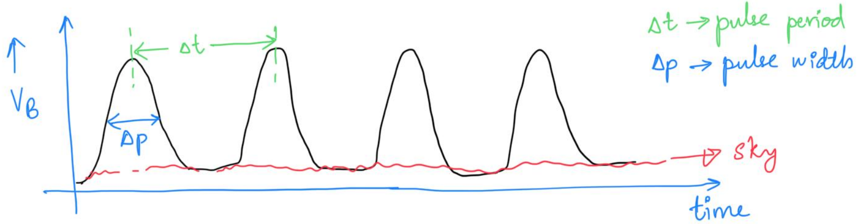
Image Source:[National Radio Astronomy Observatory]

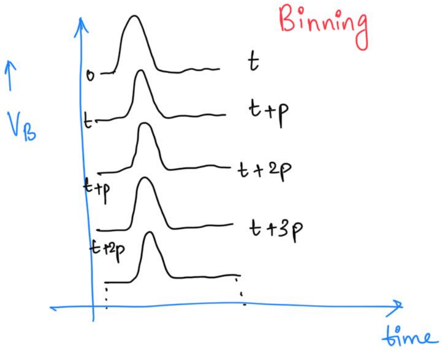
Data: VLA and LWA-1 + LWA-SV (eLWA)

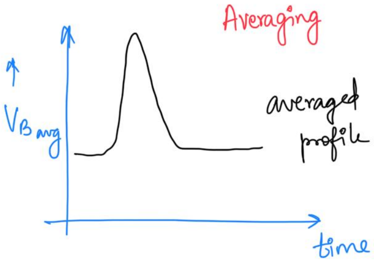
Source: Google Satellite images

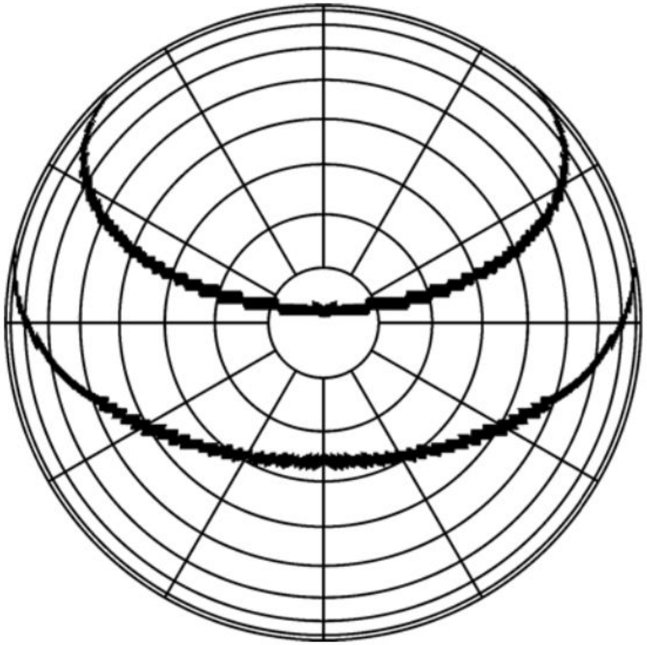
Technique in a nutshell

1. Diff b/w pulsar off and on → Remove effects from the sky
2. Simultaneous observation of pulsar: tracking through VLA & drifting through LWA's beam
3. Use VLA's known beam to calibrate LWA's beam









Pober et al (2012)

Sensitivity Analysis

- Ability of an antenna to detect the weakest radio source
- SEFD, System Equivalent Flux Density ~ System Temperature

SEFDs we currently know:

LWA dipole	1 MJy
LWA1 station	4.68 kJy
VLA dish	50 kJy

Correlation mode	$\tau_{acc}(s)$	Sensitivity (Jy)
Single LWA dipole & Single VLA dish	200	3.952
256 element LWA & Single VLA dish	200	0.270
256 element LWA & 26 VLA dishes	20	0.155

Pulsar selection

1. Bright radio pulsars
2. Visible during the day

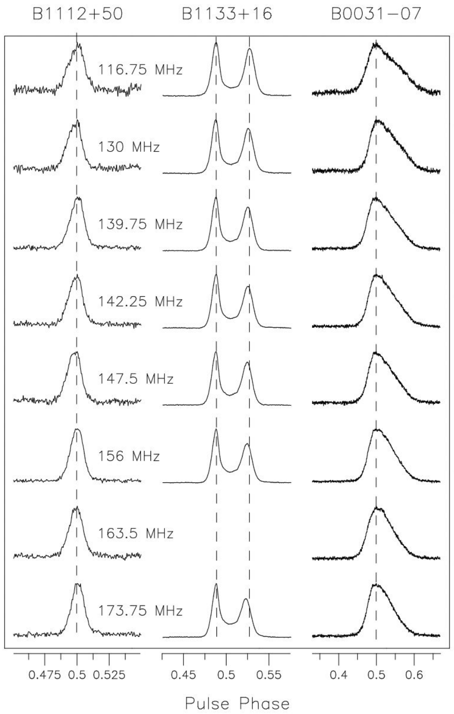
From ATNF Catalog:

B1133+16

RA: 11:36:03.1198

Dec: +15:51:14.183

Source flux at 80MHz: 4730 ± 2370 mJy

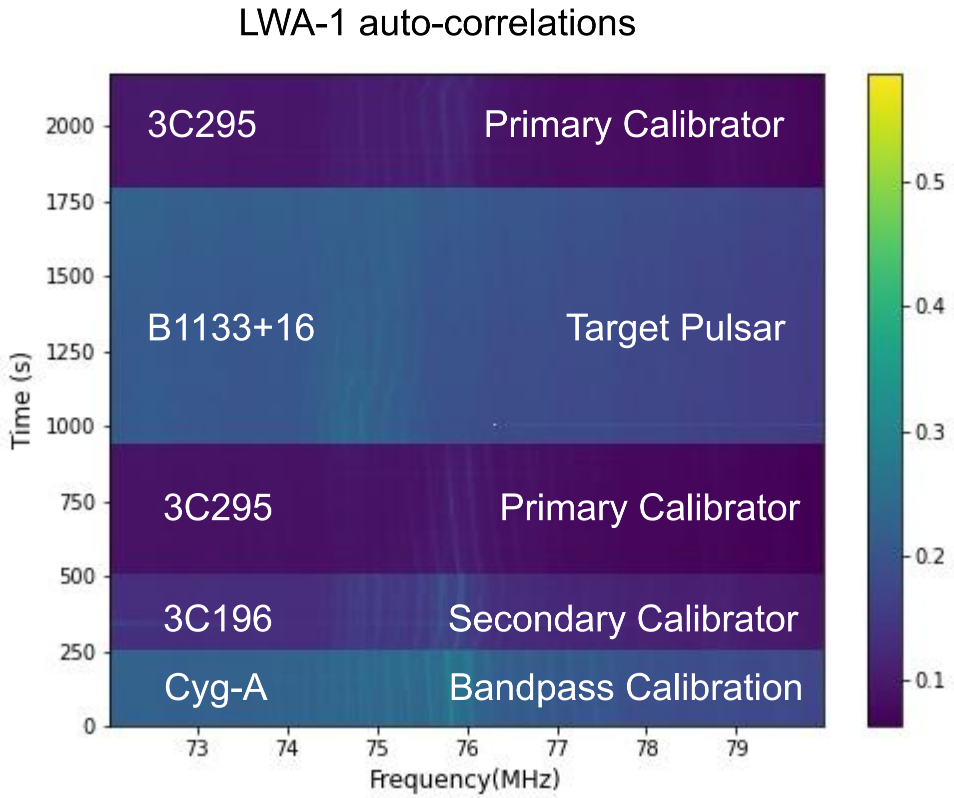


As seen by LOFAR and LWA

Karuppusamy (2018), Stovall (2015)

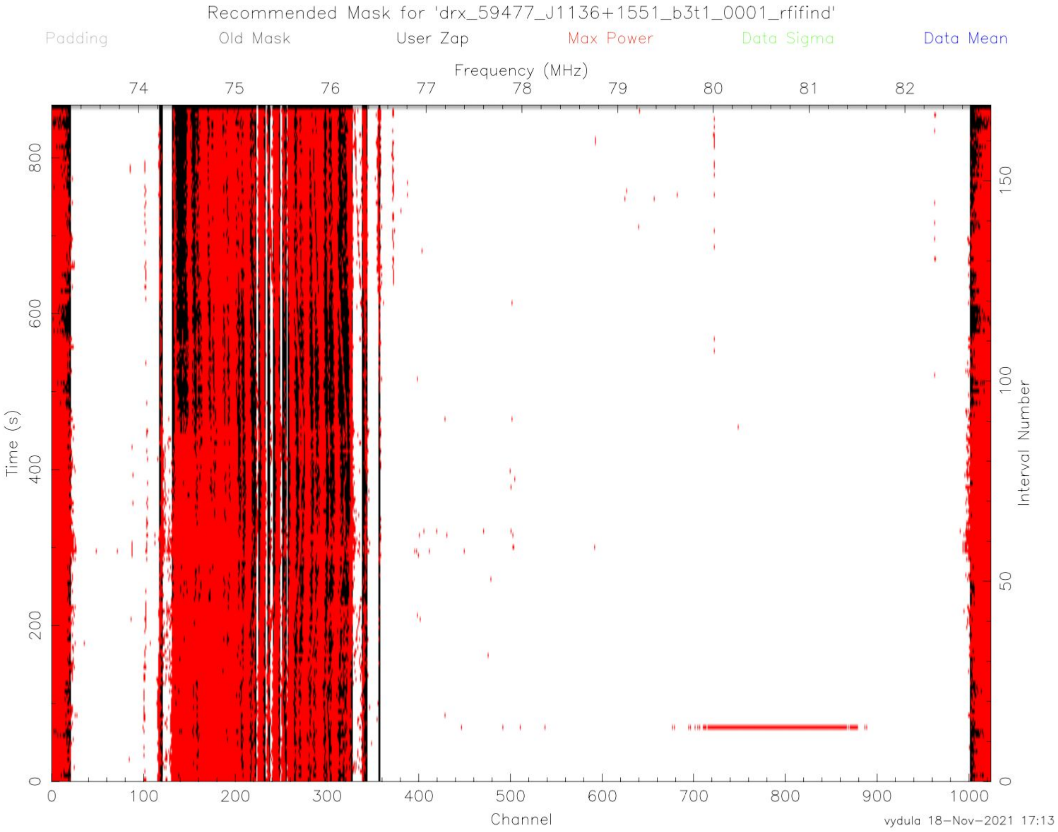
First set of data

- First observation: on Sep 20, 2021 (eLWA)
- ~ 14 minutes on the target
- Frequency range: 72 MHz to 82.9MHz



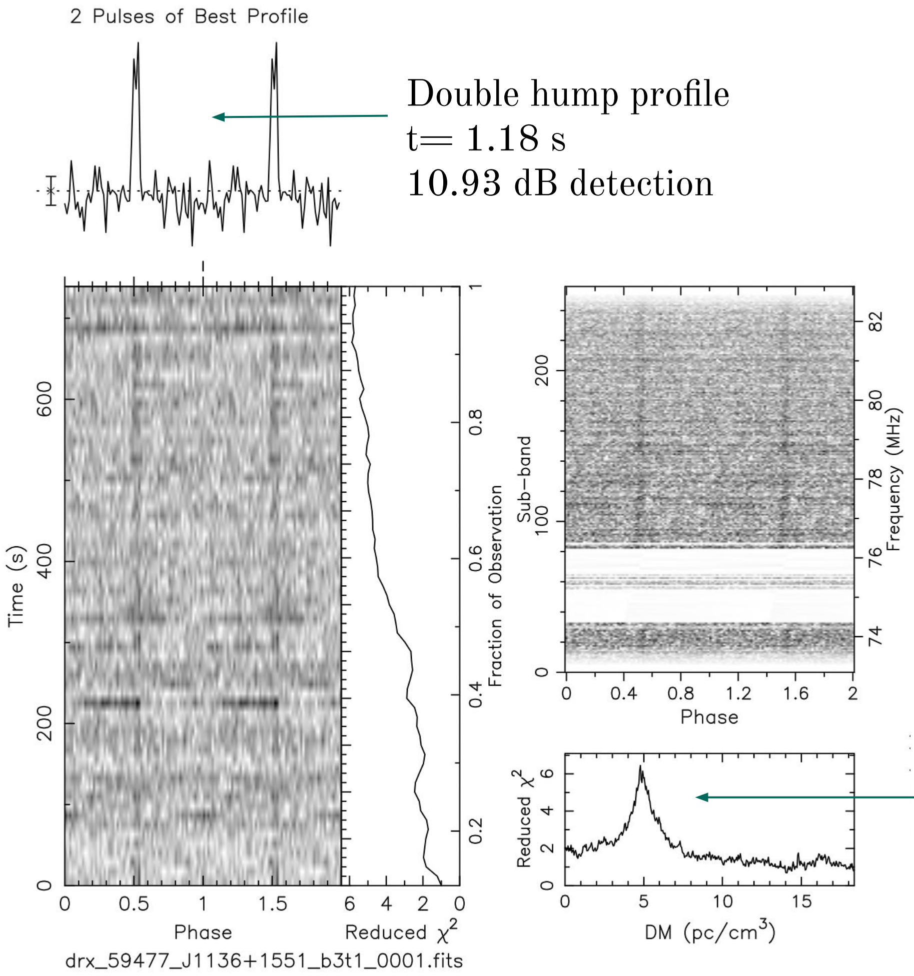
PRESTO RFI flagging

- Parameters used:
  - Integrate 5sec to find rfi and save masks (Still a detection with 1sec integration)



PRESTO: PulsaR Exploration and Search TOolkit

PRESTO detection



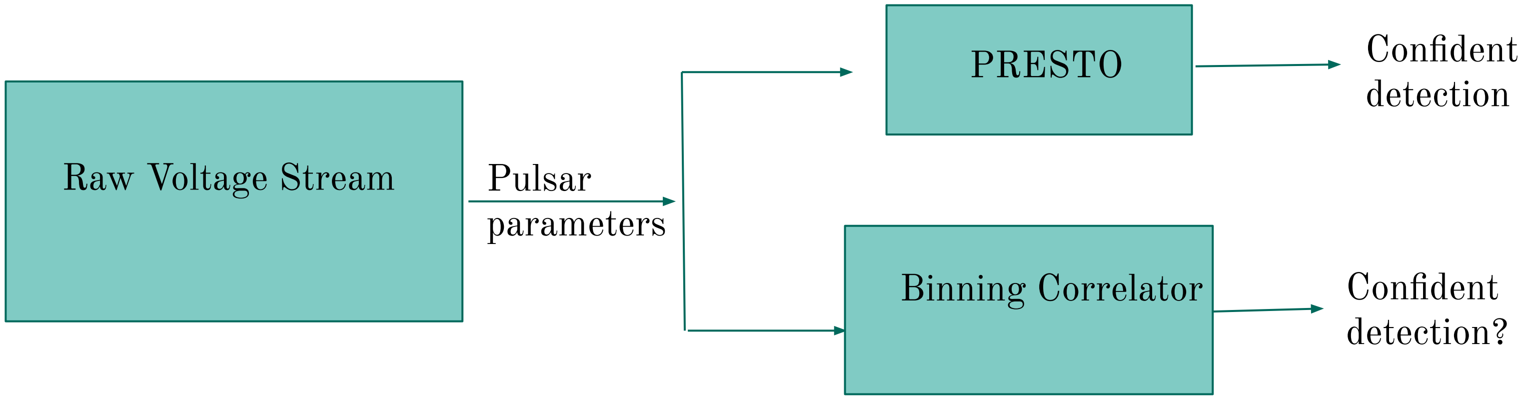
Double hump profile
t= 1.18 s
10.93 dB detection

DM= 4.84

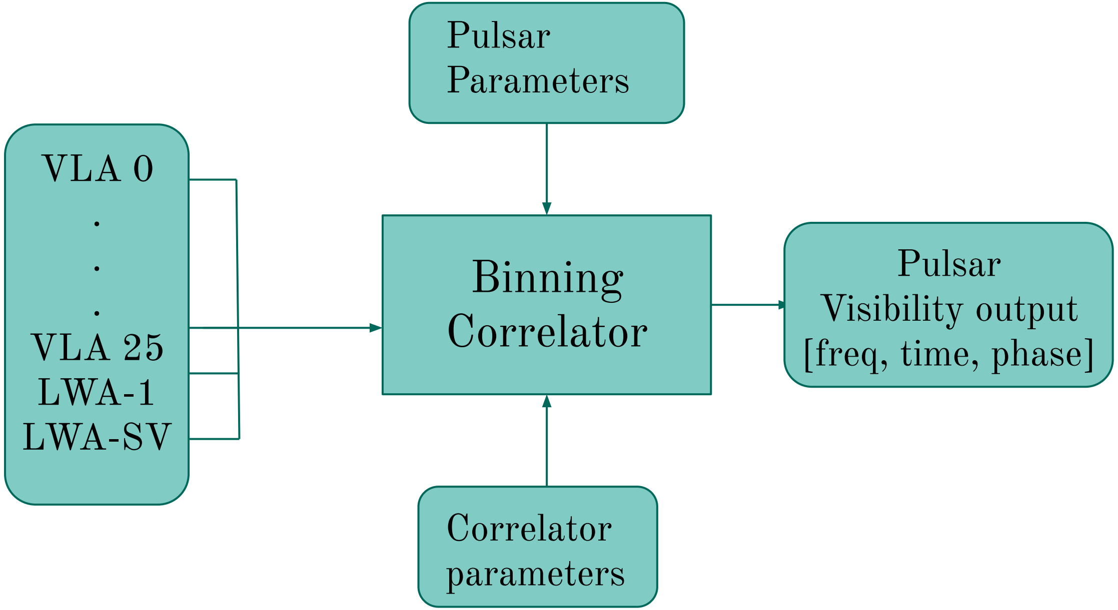
PRESTO: PulsaR Exploration and Search TOolkit

How well does the Binning Correlator work?

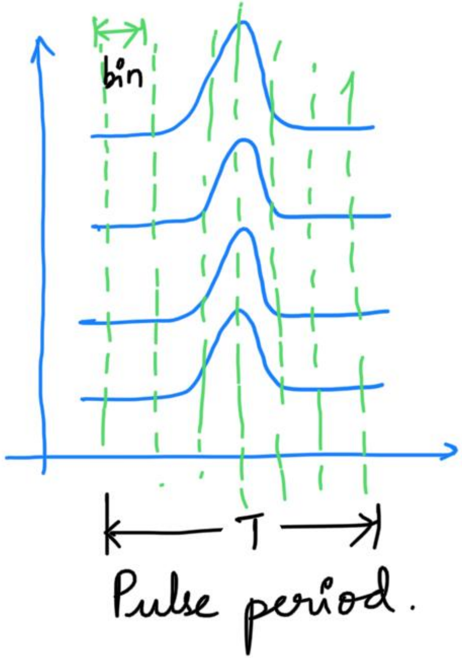
eLWA Binning correlator: part of LWA software library for Pulsar detections



Binning Correlator

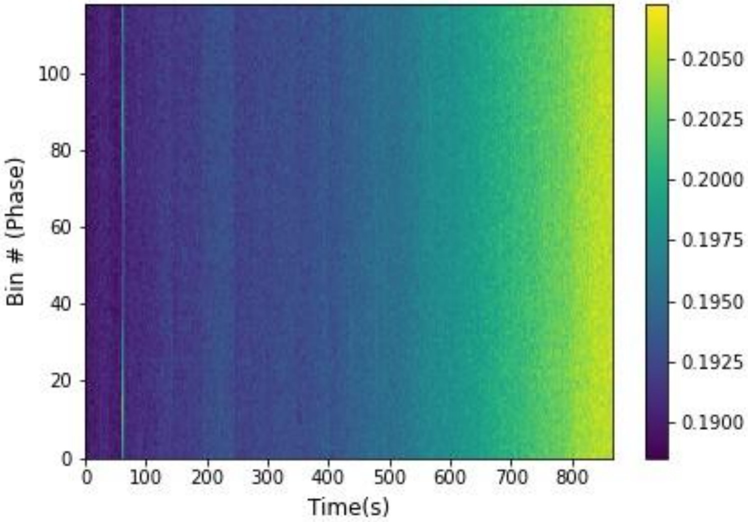


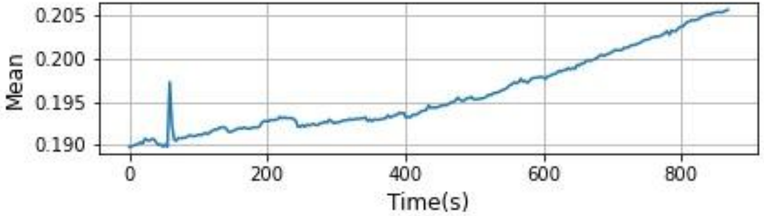
Sub-integration time: 10 ms



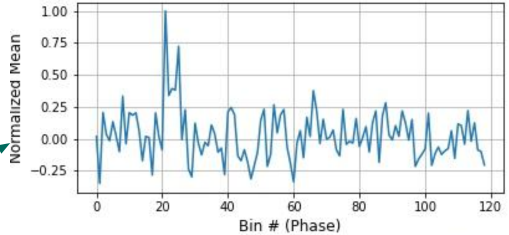
- Pulsar parameters: DM, period, RA, DEC etc
- Correlator parameters: Integration time, Channel BW, Center freq etc
- No. of bins = Pulse period/ sub-integration time (119 for B1133+16)

LWA-1 auto-correlation products

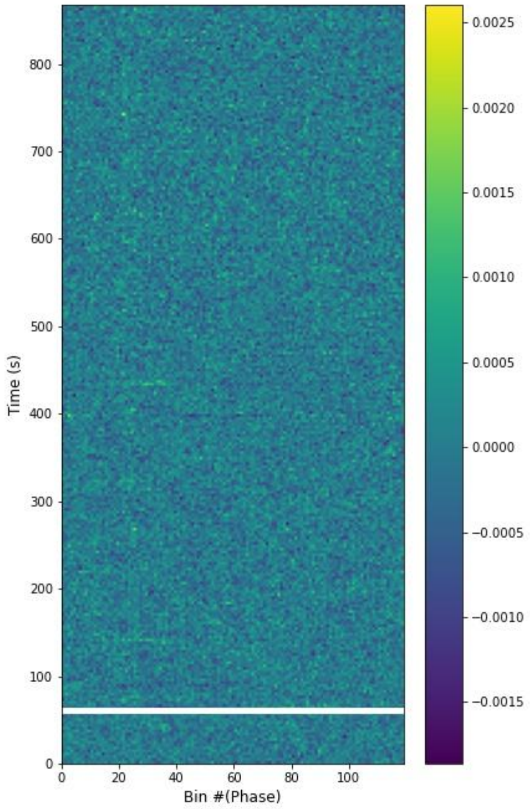




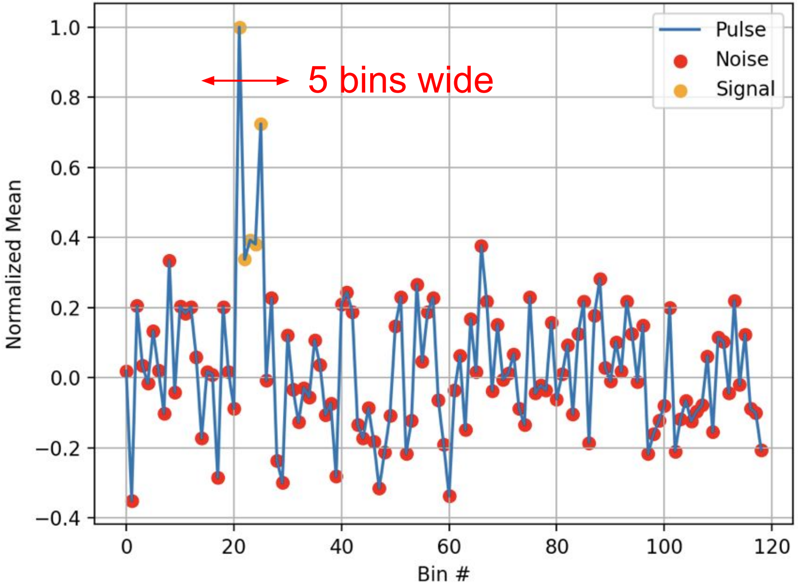
Median subtracted, averaged profile



Time vs bins waterfall



Signal-to-Noise Ratio Analysis



Detected SNR for LWA-1:

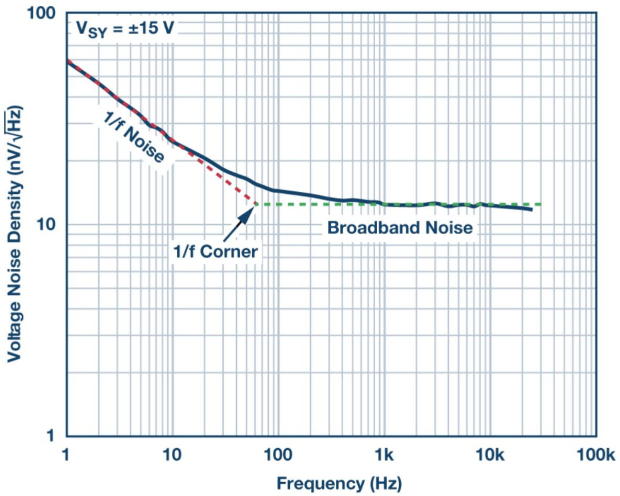
- Binning Correlator: 9.02 dB
- PRESTO: 10.93 dB

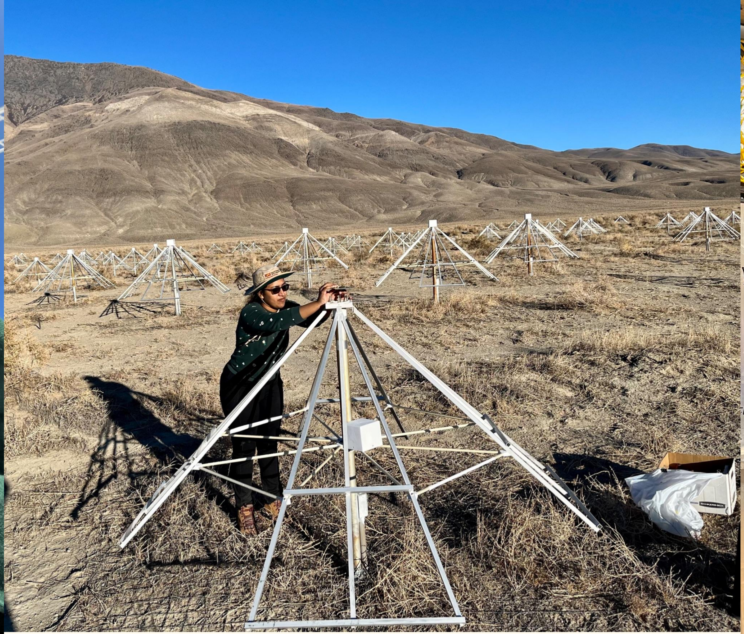
Expected SNR for LWA-1:

- Signal Level: 4730 ± 2370 mJy
- SNR: $11.69^{+1.76}_{-3.02}$ dB

Conclusions & Open Questions

- Sensitivity limitations of 40m dish
- Limited by integration time:
  - 1/f noise → infinite integration can't help with sensitivity → what's the limit?
  - Gain variability, temperature fluctuations, weather conditions over long integration times
- Pulsars aren't enough. Combination of pulsars and bright sources
  - Redoing the analysis with fresh VLA+LWA data for a bright source/bright pulsar
  - Adding incoherent sources
- Improving performance of binning correlator (BW mismatch, hardcoded integration time 10ms etc)





OVRO Bishop CA, Nov-2021, Jan 2023

Thank You!