21cm Cosmology: Efforts with EDGES, OVRO-LWA and DSA-2000

Nivedita Mahesh

David and Ellen Lee Postdoctoral Fellow

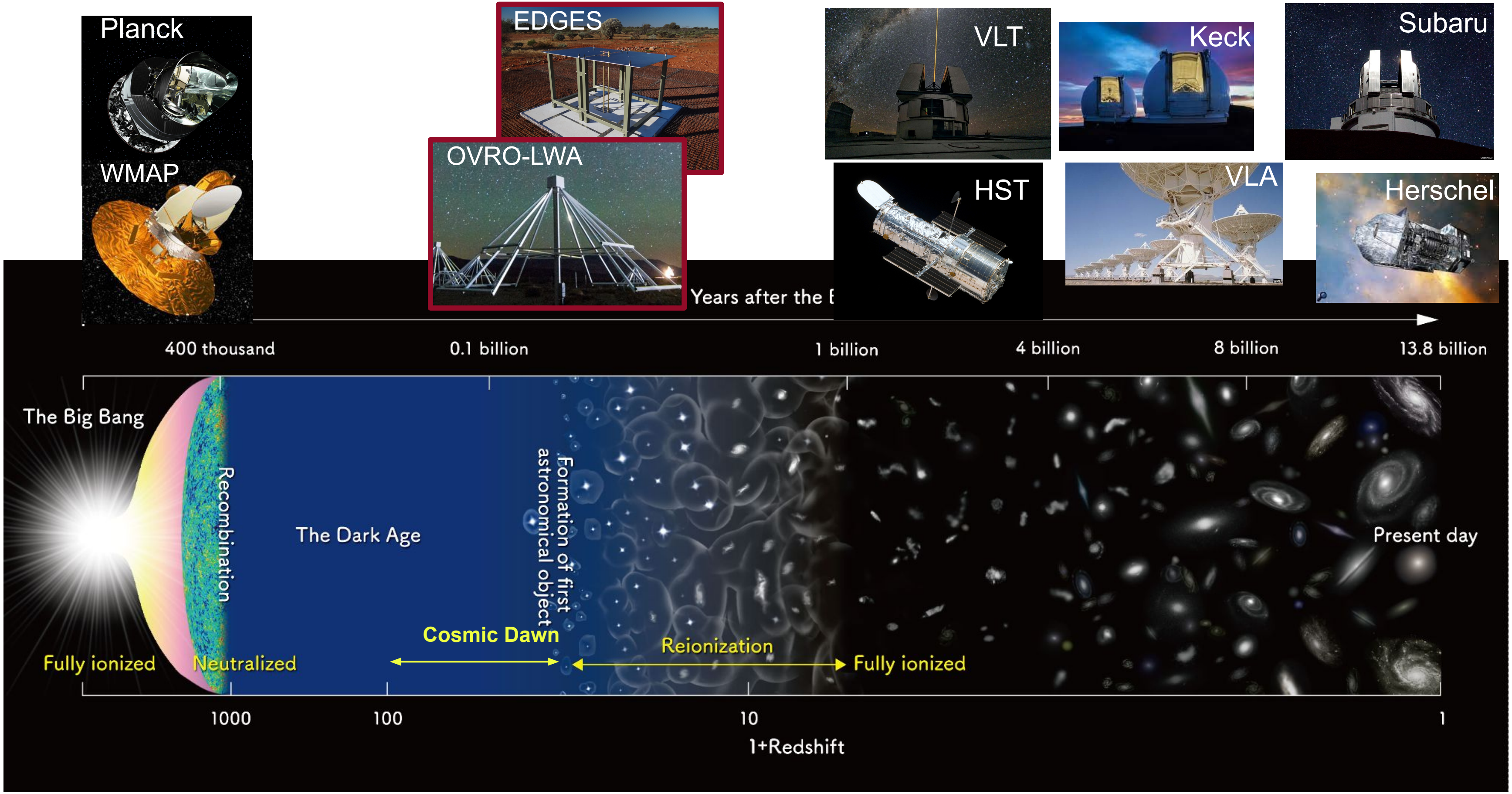
California Institute of Technology

BCCP/Cosmology Seminar, UC Berkeley April 2024

Caltech

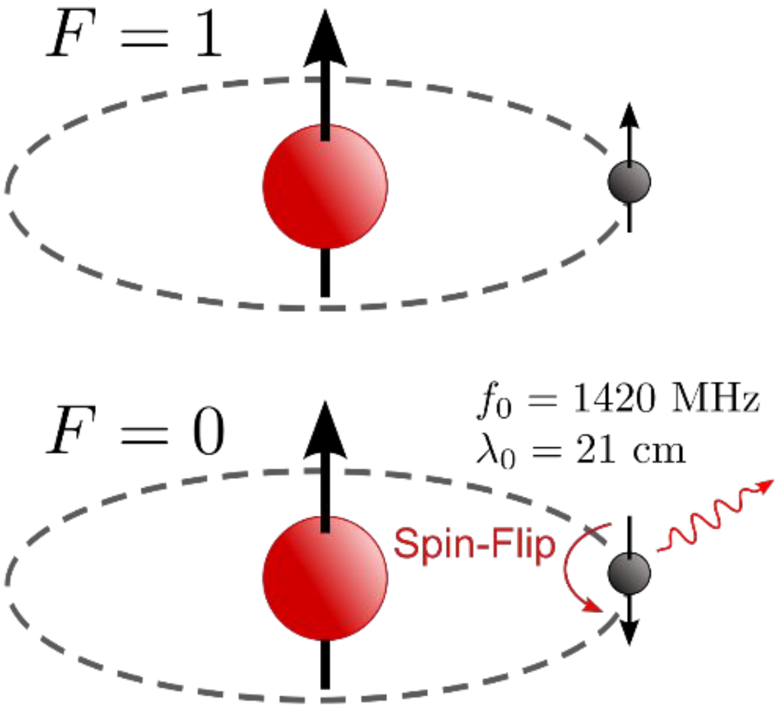
ASU

Probing the Cosmic Dawn



Using the most ubiquitous matter present - Hydrogen!

Hydrogen atom & its spin axis



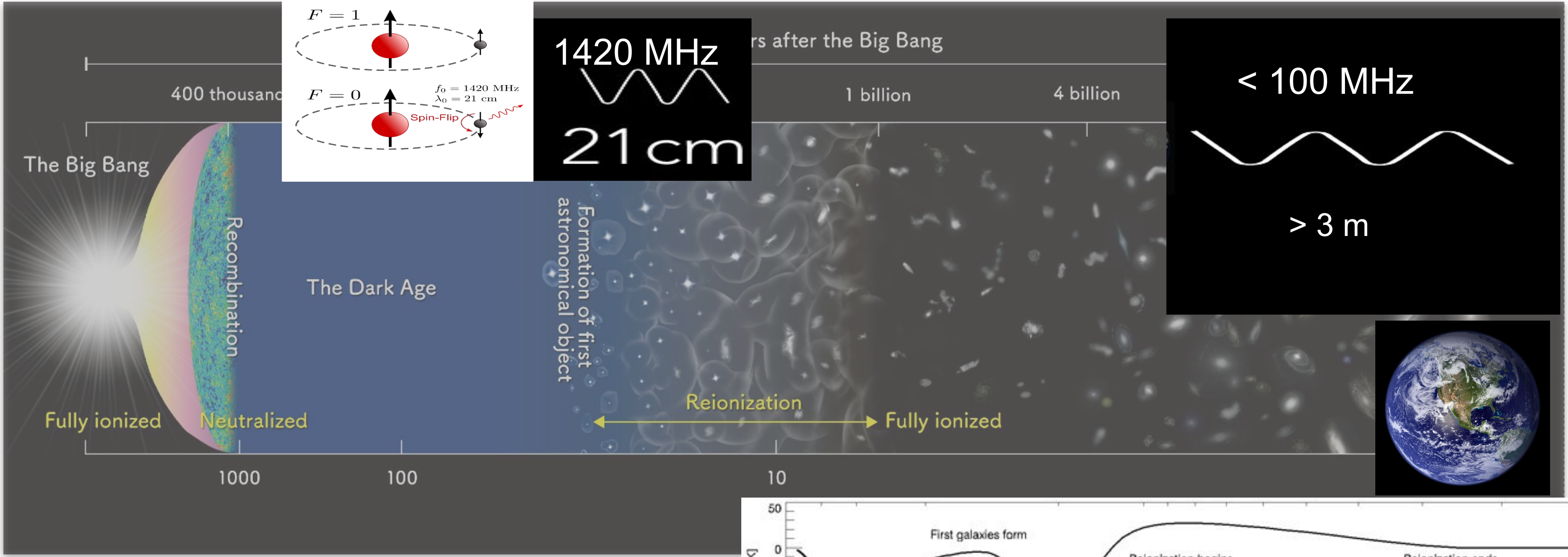
Prior to reionization ⇒ Cosmic dawn Neutral Hydrogen is plenty!

What is the signal?

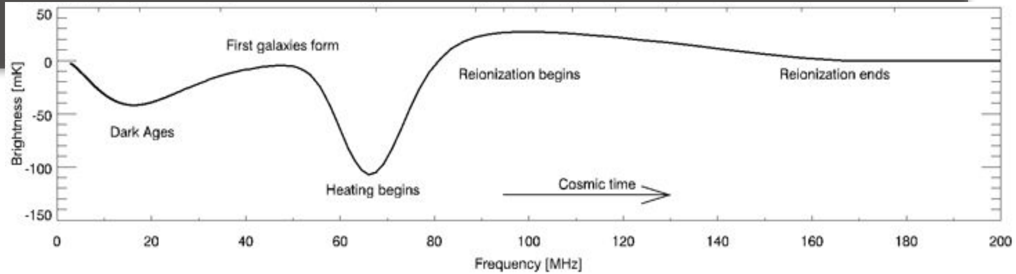
Emission due to spin flip transition

- When the spin axis changes from aligned to anti-aligned
- Produces radiation at 1.42 GHz

Hydrogen’s signal is redshifted into radio frequencies.



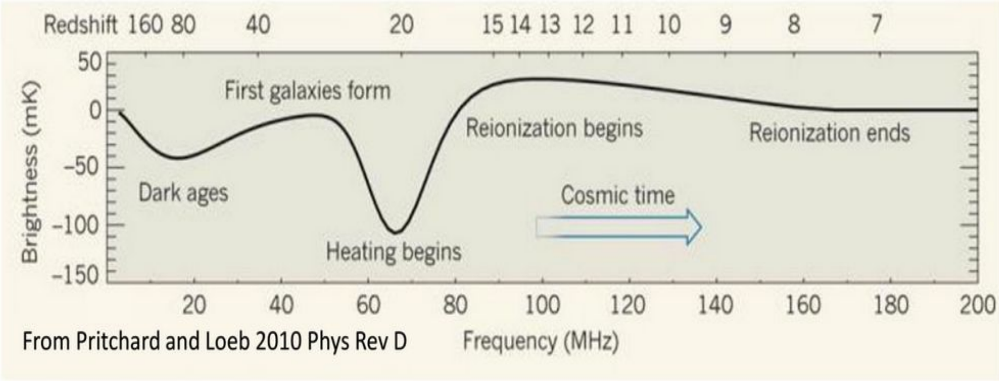
few mK! →



Two approaches to measure the redshifted 21cm

1.) <u>Measure sky averaged signal</u>

- Signal sensing element/antenna
- $T_b \propto (T_S/T_{cmb} - 1)\, X_H$

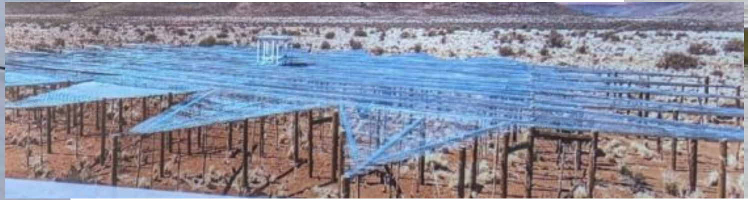


EDGES - Western Australia

SARAS - India

MIST - McGill Arctic center

REACH - South Africa

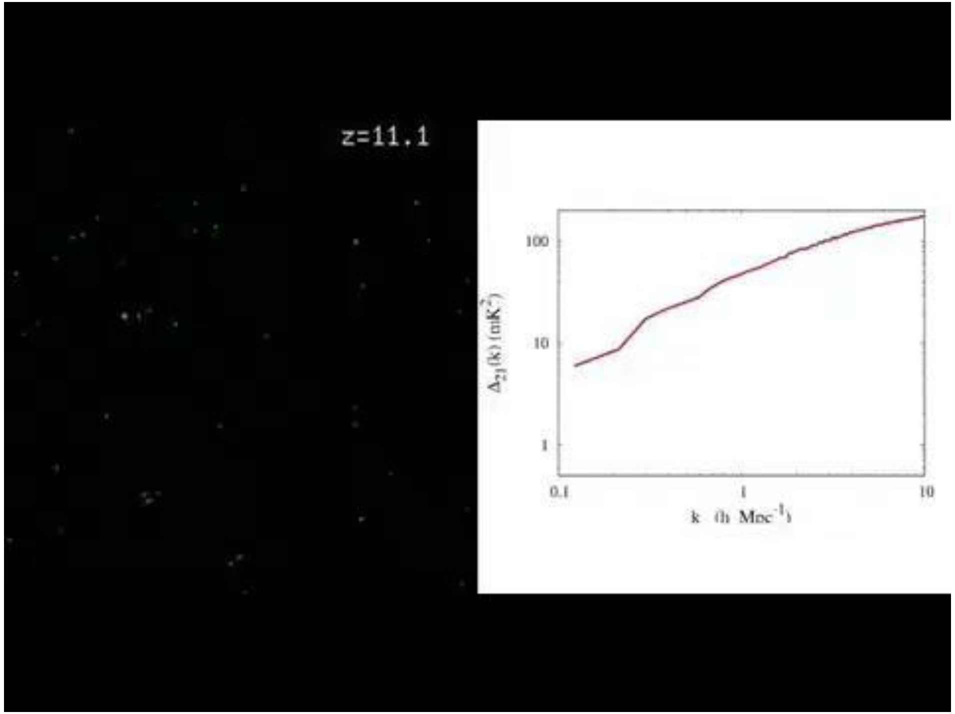


Two approaches to measure the redshifted 21cm

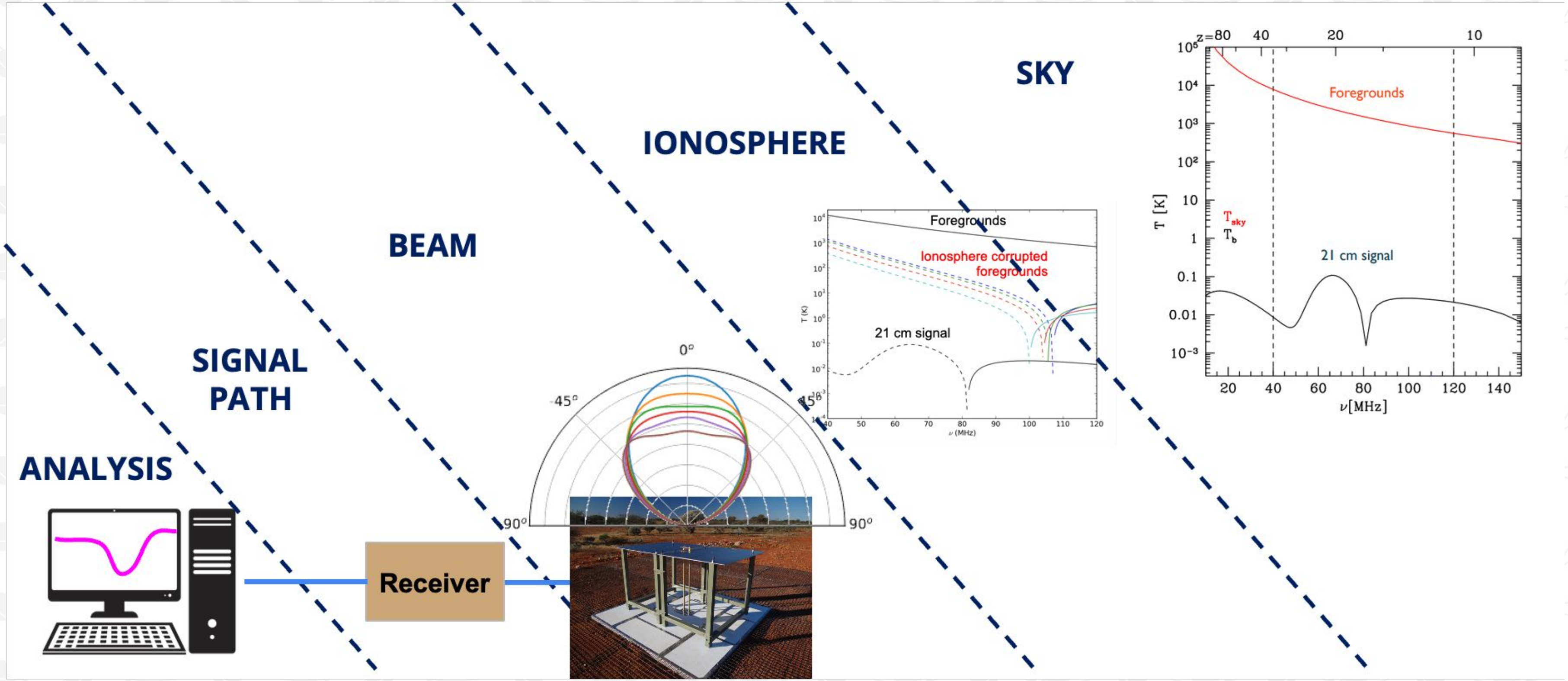
2.) Statistical detection - Power spectrum

- Using interferometers / radio arrays
- Measuring the change in brightness temp along the line of sight ***and on the plane of the sky***

Credit: McQuinn



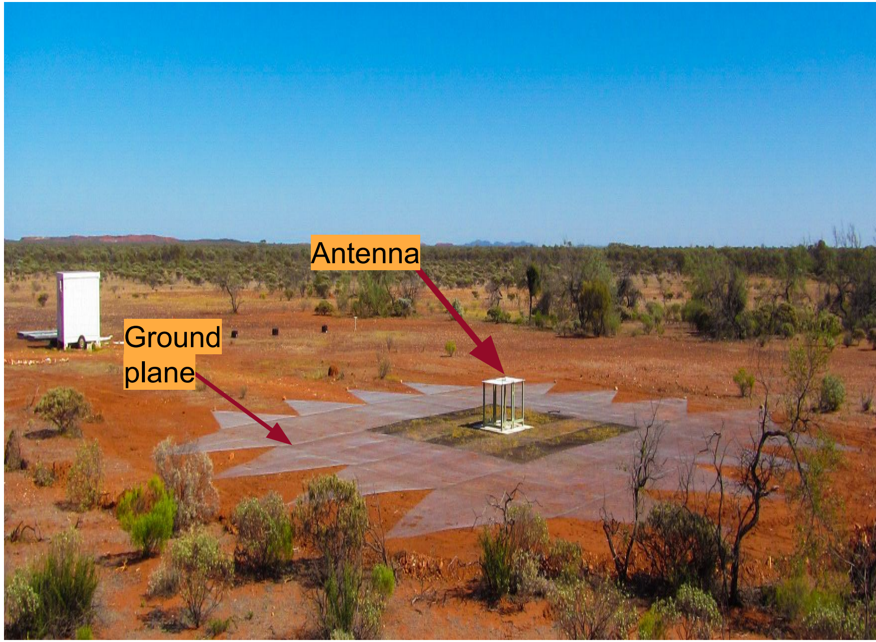
Main observational challenges with 21cm observations



EDGES a single dipole in Western Australia

- **E**xperiment to **D**etect the **G**lobal **E**oR **S**ignature
- Science goal: search for the global 21-cm from Cosmic Dawn and EOR
- Sensing element: antenna (horizontal dipole) over a ground plane
- Operates over: 50-200 MHz
  - Lowband: 50 -100 MHz (Cosmic Dawn)
  - Highband: 100 - 200 MHz (EoR)
  - Midband: 60-120 MHz (confirming Cosmic Dawn)
- Receiver is below the ground
- Two calibration schemes:
  - Switching (field)
  - Absolute calibration (lab)

EDGES Low band antenna in Australia



The EDGES Team

PIs

Alan Rogers

Judd Bowman

Colin Lonsdale

Engineers

Titu Samson

John Barrett

Ken Wilson

Researchers

Raul Monsalve

Steven Murray

Peter Sims

Rigel Capallo

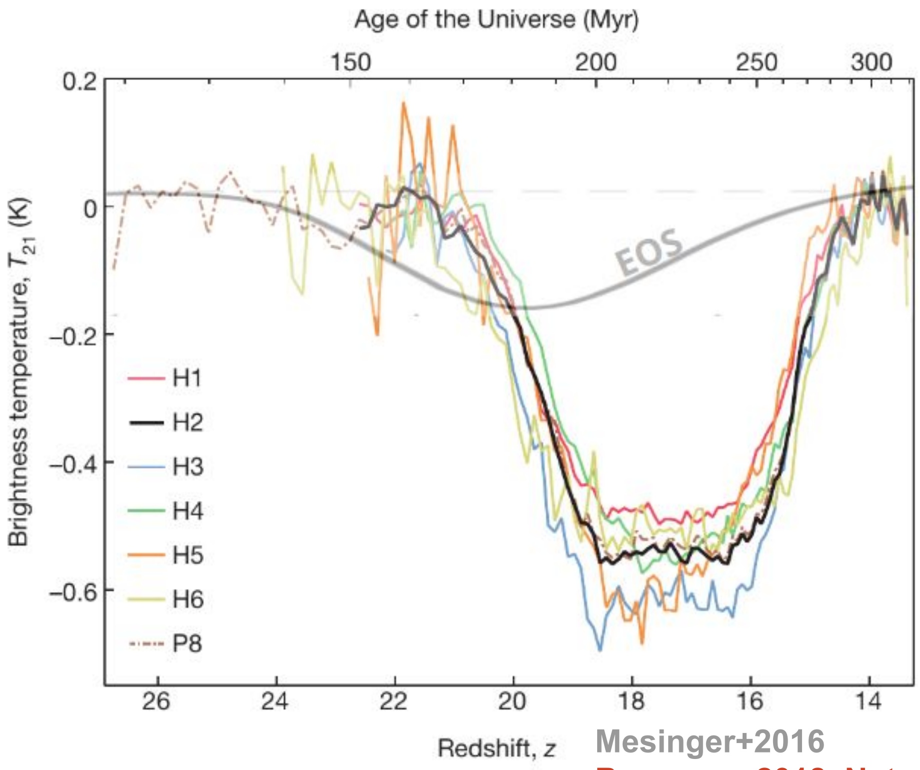
Nivedita Mahesh

PhD

Akshatha Vydula

Evidence of the first stars

- Surprising depth, timing and shape.
- Possible indication of:
  - Excess radio background (eg. Fialkov & Barkana 2019)
  - DM-baryon interactions
    - eg. Millicharged DM (eg. Barkana 2018, Liu+2019, Berlin+2018)
  - High-z black holes (eg. Ewall-Wice+2018)
  - Soft-photon emission from light dark matter (eg. Fraser+2018)
  - Early Dark Energy (eg. Hills & Baxter 2018)
- **... or does it suffer from systematics?** (eg. Hills+2018, Sims+2020, Singh+2020)



Mesinger+2016

Bowman+ 2018, Nature

SARAS 3 (Singh+2022) claims non-detection!

New EDGES data processing pipeline

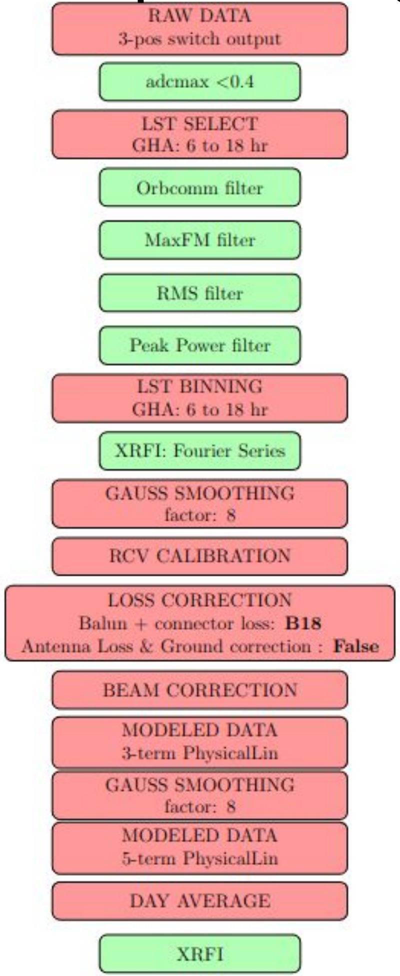
Nivedita Mahesh, Steven G Murray, Judd Bowman, Alan EE Rogers, Raul Monsalve, Peter Sims, ***In prep***

*EDGES collaboration has developed a **new, open-source** data processing pipeline with repos to processes all the way from raw field data to final products for various analyses*

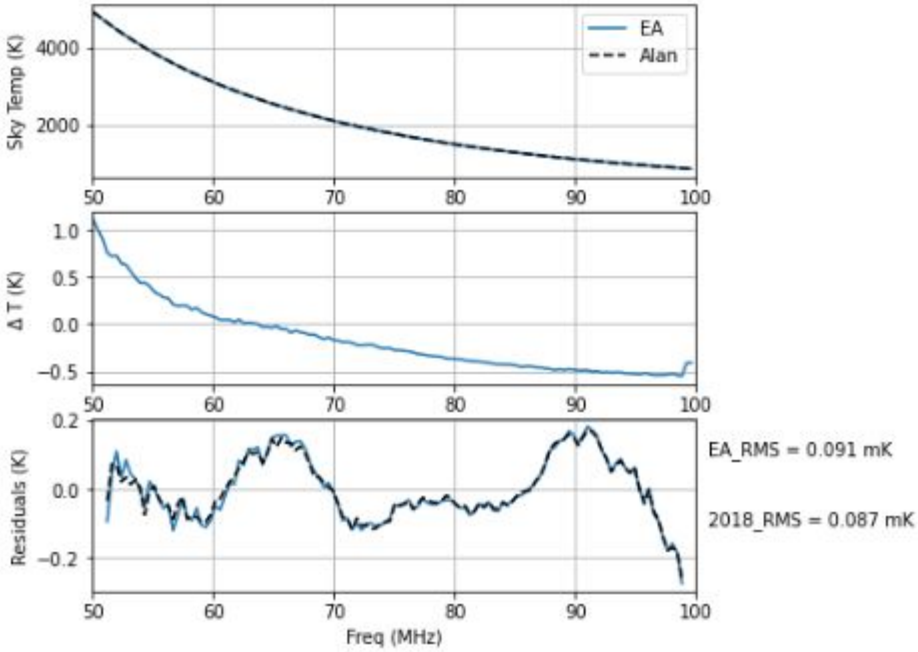
Why did we spend countless hours understanding, improving and building upon the 10000+ lines of the 2018 legacy C pipeline?

- Need for an independent processing pipeline to keep us honest
  - Provides modularity and full traceability
  - Allows simple switching of analysis choices & techniques
- Independently process the same EDGES low-band data
- Understand the impact of different data processing choices at various stages of the analysis
  - Forward modelling effects on the inferred astrophysical & cosmological parameters
  - Enable future Bayesian frameworks for more fidelity in inference
- Will accompany EDGES-3
- We want to develop interoperable tools for this growing community.

Reproducing Bowman et al. 2018 with edges-analysis



Using the same dataset and the same analysis choices as 2018



LST binned analysis

Motivation :

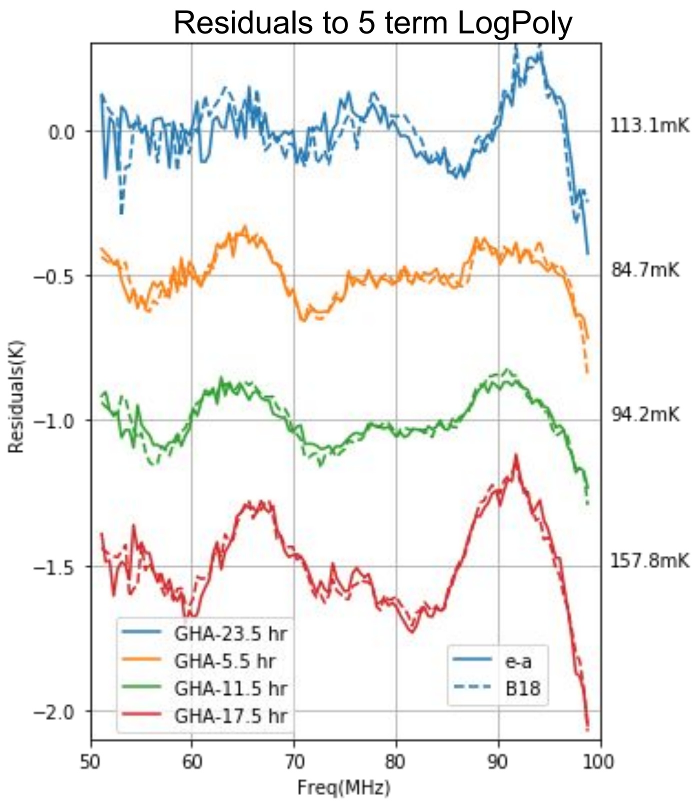
- Test the global nature of the signal (Liu+2013, Tauscher+2016)
- More information & degrees of freedom

Simultaneous LST bin fits:

- The HPBW of edges beam ~ 75 deg ⇒ 5hr
- Data binned into 4 bins of 5 hours each with 1 hr between bins
- Different foreground models for each bin
- Estimate same absorption model for all bins

Four GHA bins:

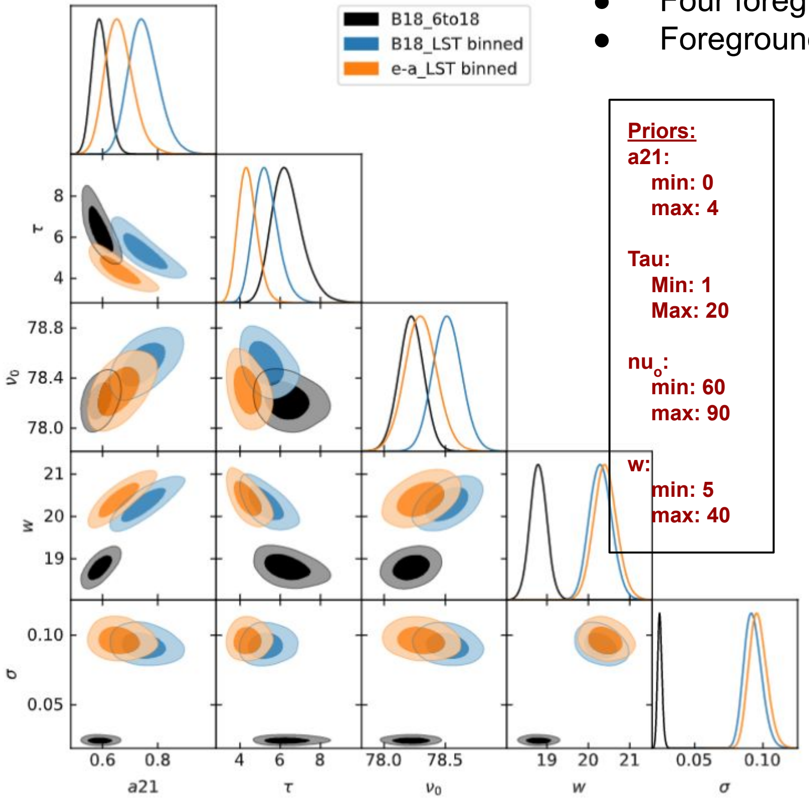
- 21 - 2 hr
- 3 - 8 hr
- 9 - 14 hr
- 15 - 20 hr



B18 & edges-analysis results agree @ the binned data level too

edges-estimate: Simultaneously fitting four 5 hour GHA bins

- One absorption model for the four data bins
- Four foreground models for the four data bins
- Foreground model - 5 term Logpoly



Priors:
a21:
min: 0
max: 4

Tau:
Min: 1
Max: 20

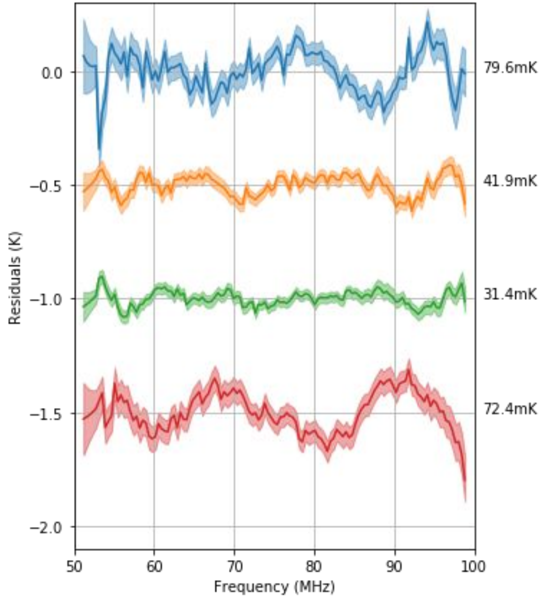
nu_o:
min: 60
max: 90

w:
min: 5
max: 40

Consistent (B18) estimates of the absorption parameters

Foreground estimates

GHA centers(hr)	T_{75} (K)	Beta
23.5	4463	-2.45
5.5	2370	-2.54
11.5	1642	-2.57
17.5	2380	-2.52



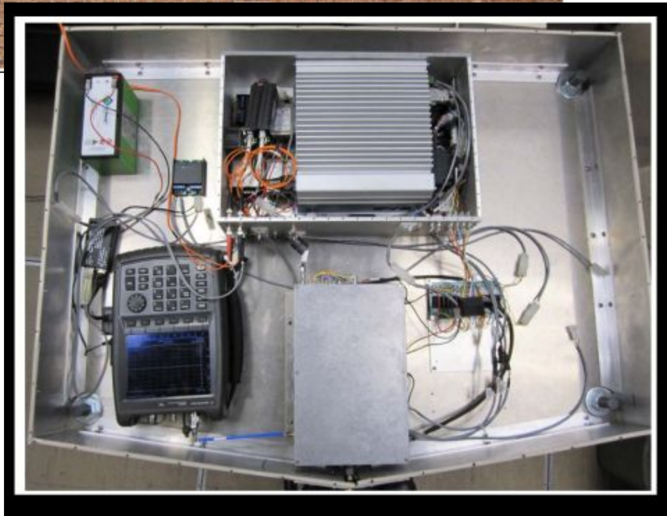
RMS of the residuals in each GHA bin has reduced by atleast half

New Data: EDGES-3, Rotated EDGES-2, Mid-Band,...

(Re-)Analysis with the new pipeline, convergence on what the data tells us in different cuts.

Future of EDGES

EDGES-3



Upgrades:

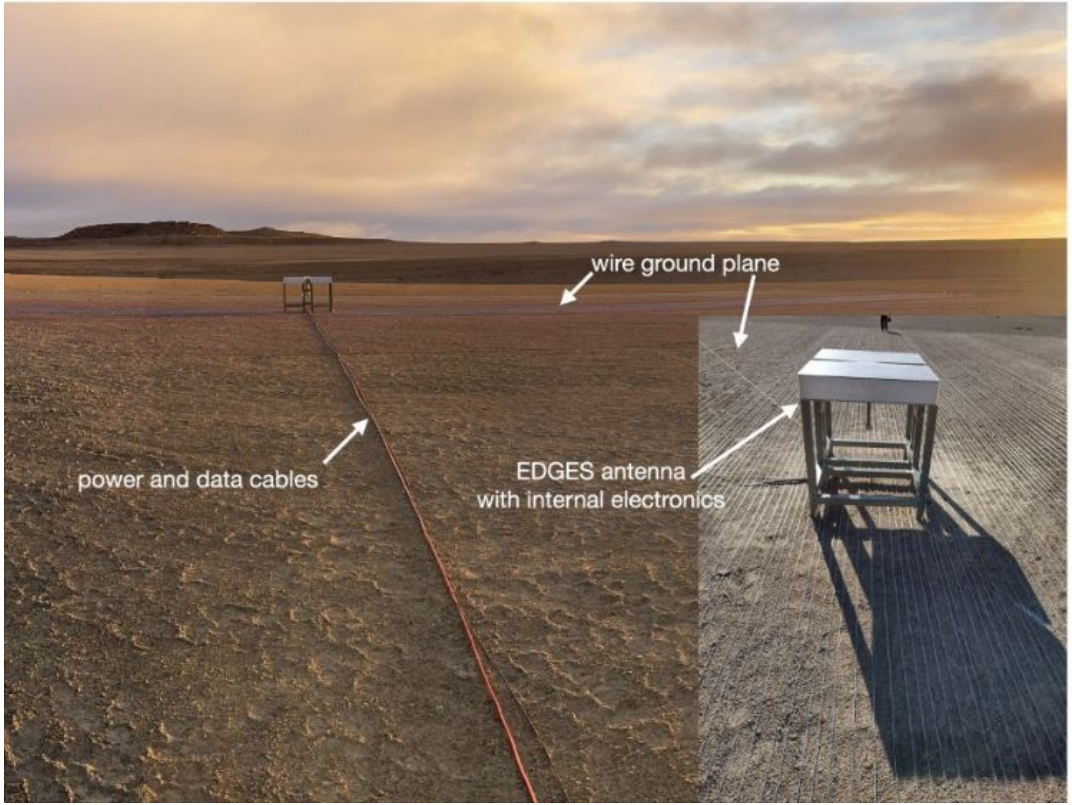
1. Receiver embedded in antenna
    a. No balun loss
2. In-situ/real-time calibration
3. Less chromatic beam
   (larger 50x50m ground plane)
4. Fat dipole optimized for 60 - 160 MHz

Status:

- Tests in Devon Island (Portable model)
- In Australia: EDGES-3 actively collecting data since Nov 2022.

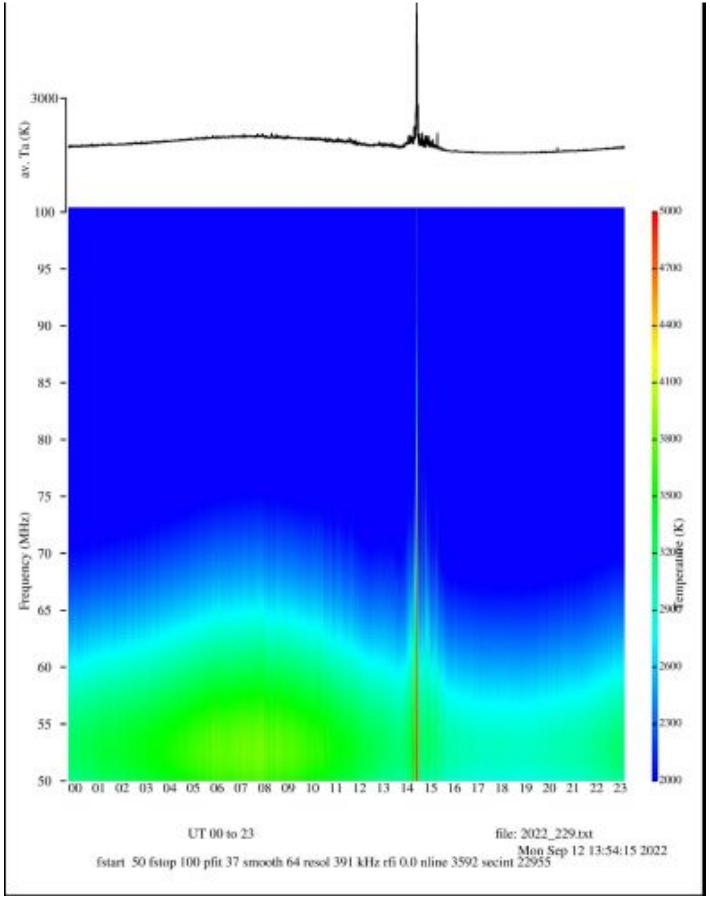
EDGES-3 Devon Island Deployment

- Devon Island is the largest uninhabited island in the world, at 75^0N in the Canadian Arctic - generally free of RFI
- Team of three from Haystack hitched a ride with five members of the Haughton Mars Project, led by Pascal Lee
- 50 x 25 m ground plane was constructed using ~ 9 km of meandering copper wire.
- Total time on island was 25 days, only able to obtain 12 days of usable data.
- Expedition was in August, thus the sun was always up



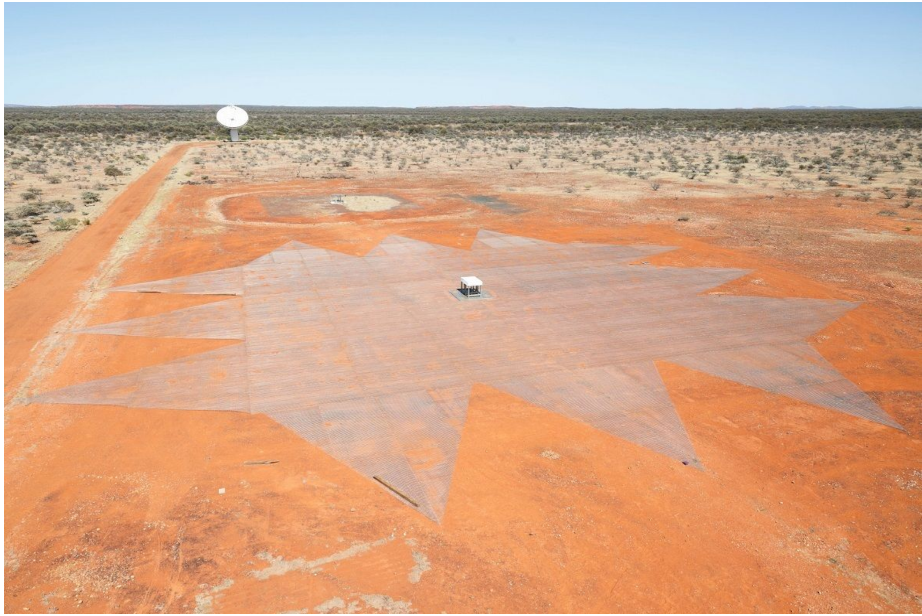
Lessons learnt from Devon island

- Sun extremely active currently
- Sporadic-E caused FM stations (and perhaps power line noise) to contaminate data from ~ 2000 km away.
- Temperature control is extremely important for VNA functionality.
- Meandering copper wire functions sufficiently as a ground plane.
- Currently unexplained RFI at low end (50 to 60 MHz)



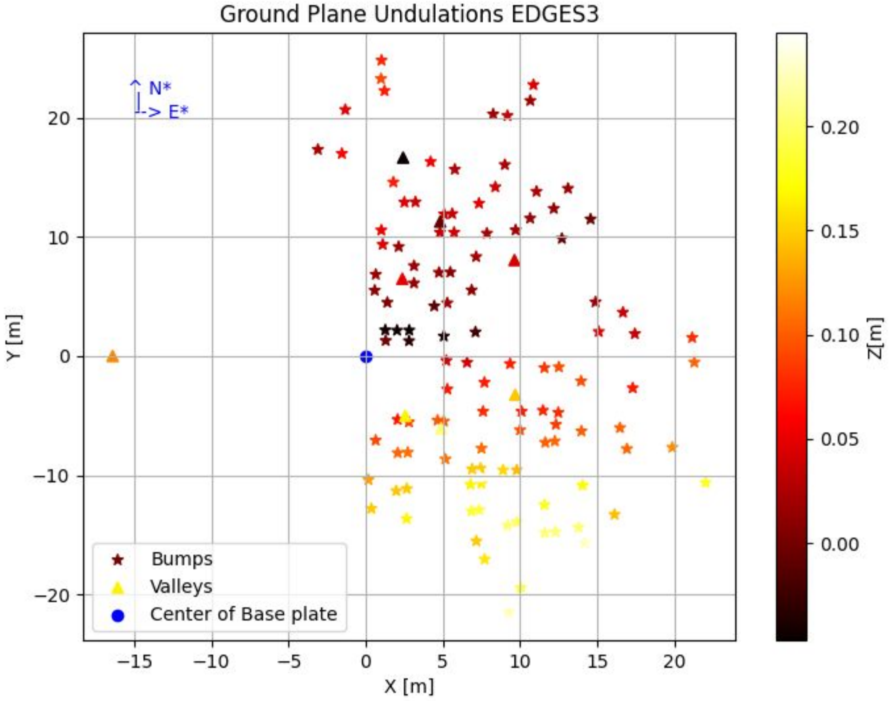
EDGES-3 Australian Deployment

- Located at Inyarrimanha Ilgari Bundara, the CSIRO Radio-astronomy Observatory in WA
- Permanent deployment completed in November 2022.
- A 48 x 48 m welded mesh ground plane was installed, with EDGES-3 on a baseplate in the center.
- Has been on sky since November 25th, and data continues to come in daily.



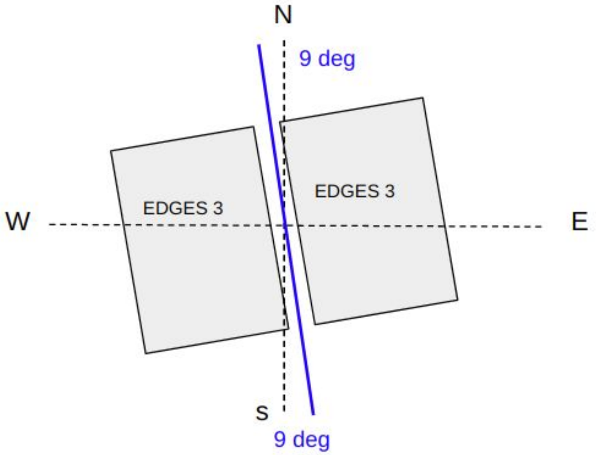
EDGES 3 Australia - Upgrades and Maintenance - Feb 2024

Ground Plane survey to measure undulations using theodolite for EDGES-3



EDGES 3 Australia - Upgrades and Maintenance

Orientation, tilt and roll of EDGES-3



Roll Measurement	Repeats	Offset (cm)	Roll (deg)	Tilt Measurement	Repeats	Offset (cm)	Tilt (deg)
Parallel to excitation Southside	1st	0	0	Perpendicular to excitation East side	1st	1.8	0.61
	2nd	0.1	0.034		2nd	2.1	0.72
	3rd	0.1	0.034		3rd	2.6	0.89
Parallel to excitation Northside	1st	0.3	0.10	Perpendicular to excitation West side	1st	2.6	0.89
	2nd	0	0		2nd	2.7	0.92
	3rd	0.2	0.068		3rd	2.65	0.92

The roll is almost non-negligible.
The maximum tilt is about ~1 deg.
The baseplate slopes from N to S in terms of tilt.

EDGES 3 Australia - Upgrades and Maintenance

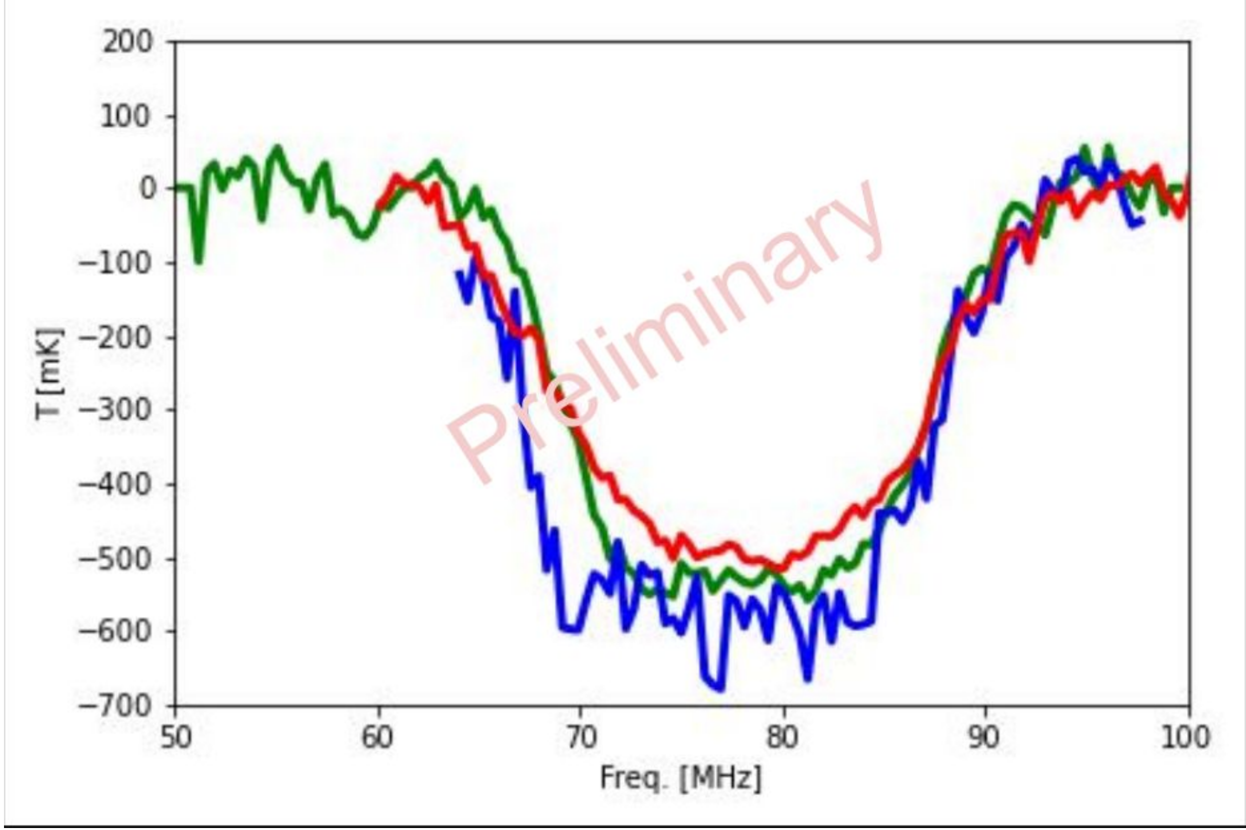
Installation of Receiver-1 to low2-45

Preliminary analysis of the EDGES 3 data

Bowman et.al. 2018

Devon Island

MRO EDGES-3

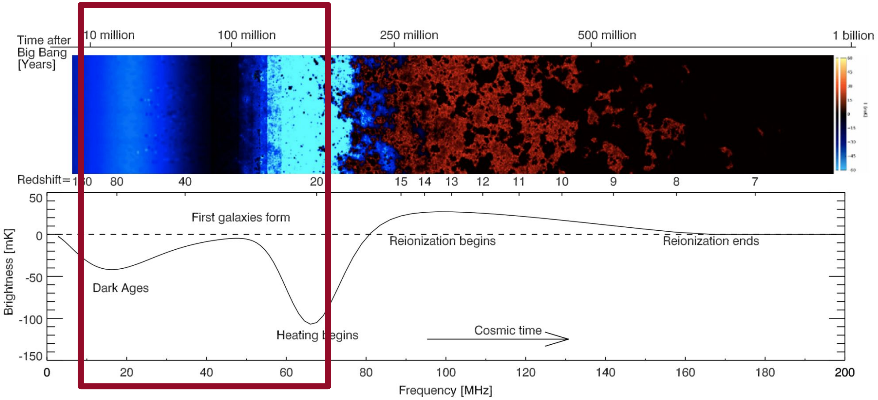


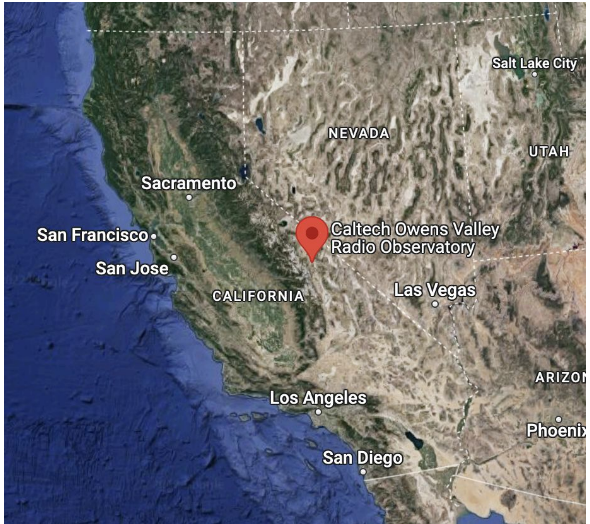
EDGES Summary

- Lots of work done by the EDGES collaboration to increase our confidence in our instrument.
- Analysis moving in a forward-modelling direction.
  - Developed an open source edges pipeline in python
  - **Reproduced!!** the 2018 processed spectra using the same dataset and analysis choices
  - Now for all the interesting analysis to come: Forward model all the significant processing choices, LST binned analysis, Process data from different EDGES configurations
- Lots of data still to process and understand, including EDGES-3

What is the OVRO-LWA?

- Owens Valley Radio Observatory (OVRO) Long Wavelength Array in California
- 352 Dual-polarization widefield dipole antennas
- Fully cross-correlated
- 12-85 MHz
- Currently in its “Stage III” of operations





The OVRO-LWA Stage III Team

Caltech / OVRO / JPL
Gregg Hallinan (PI)
James Lamb
David Woody
Mark Hodges
Morgan Catha-Garrett
Andres Rizo
Corey Posner
Casey Law
Rick Hobbs
Larry D'Addario
Jack Hickish
Yuping Huang
Kathryn Plant
Ruby Byrne
Ivey Davis
Jun Shi
David Hodge
Vinand Prayag
Marin Anderson (PS)
Andrew Romero-Wolf (co-PI)
Nivedita Mahesh
Greg Hellbourg
Xander Hall
Charlie Harnach
Nikita Kosogorov
Emily Kuhn

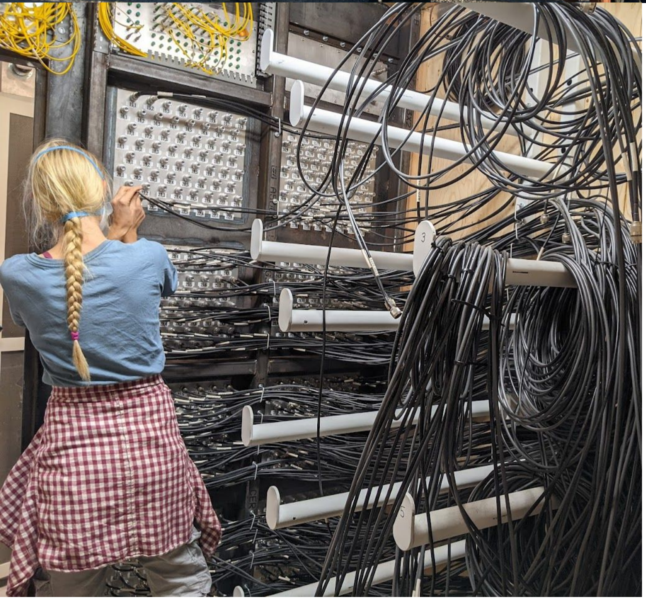
University of New Mexico
Greg Taylor
Jayce Dowell

New Jersey Institute of Technology (NJIT)
Dale Gary (co-PI)
Bin Chen
Sherry Chhabra (NRL)
Gelu Nita
Brian O'Donnell
Surajit Mondal

Arizona State University
Judd Bowman (co-PI)
Danny Jacobs
Katherine Elder
Matthew Kolopanis
Akshatha Vydula
Amy Zhao

National University of Ireland, Galway (NUIG)
Aaron Golden
Dúalta Ó Fionnagáin

Rice University
Andrea Isella (co-PI)
Jason Ling
Ramon Wrzosek
Deekshit Vedula




LWA
MU
L.F.C.

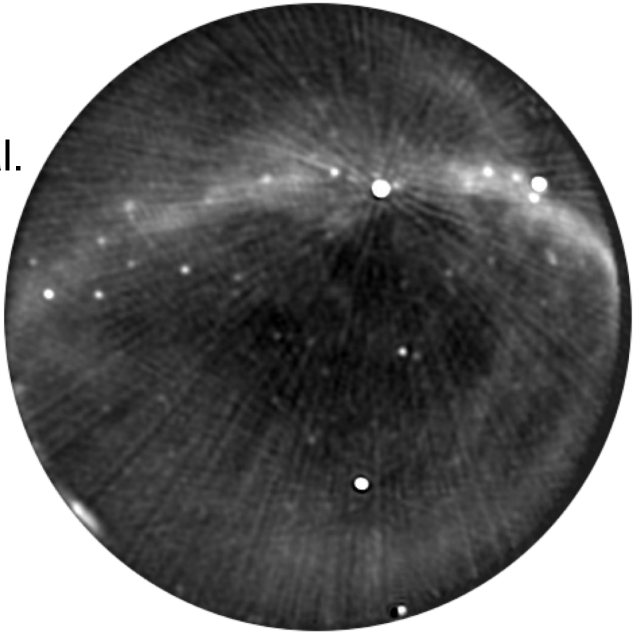
Stage I

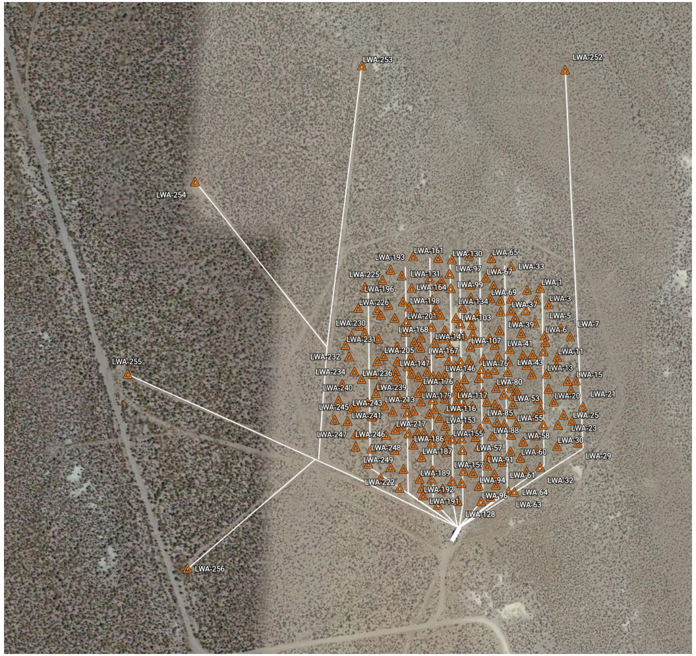
<u>2013-2014</u>

251 antennas

5 outriggers

LEDA correlator (Kocz et al. 2015)





Stage II

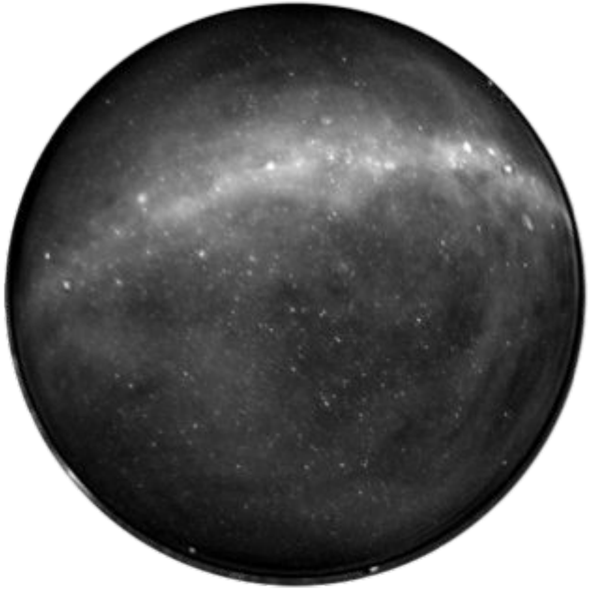
<u>2015-2020</u>

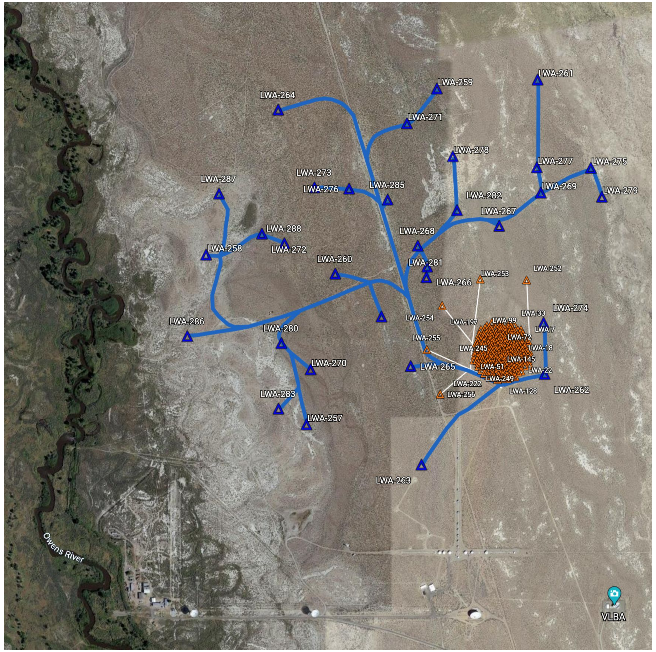
283 antennas

Addition of 32 fiber-fed outrigger antennas

Longest baseline extended to 1.5 km

Custom fiber-link board





Stage III

Funded by NSF Major Research Infrastructure (MRI): $2.4 million

<u>2023 - present</u>

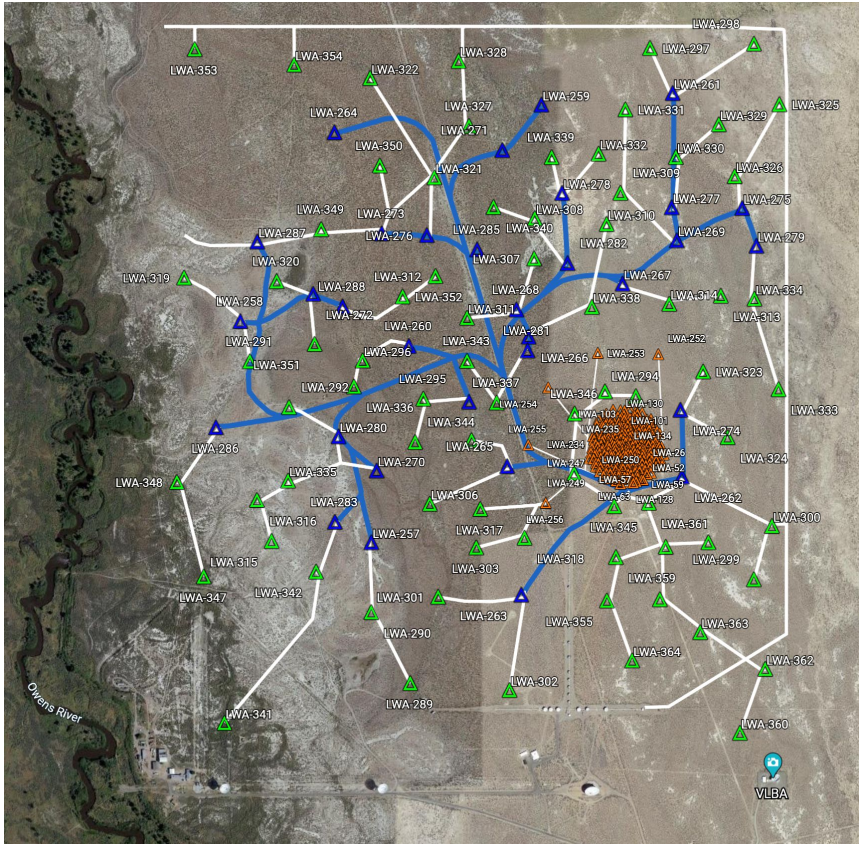
352 antennas

Longest baseline extended to 2.4 km

Complete overhaul of the analog and digital backend

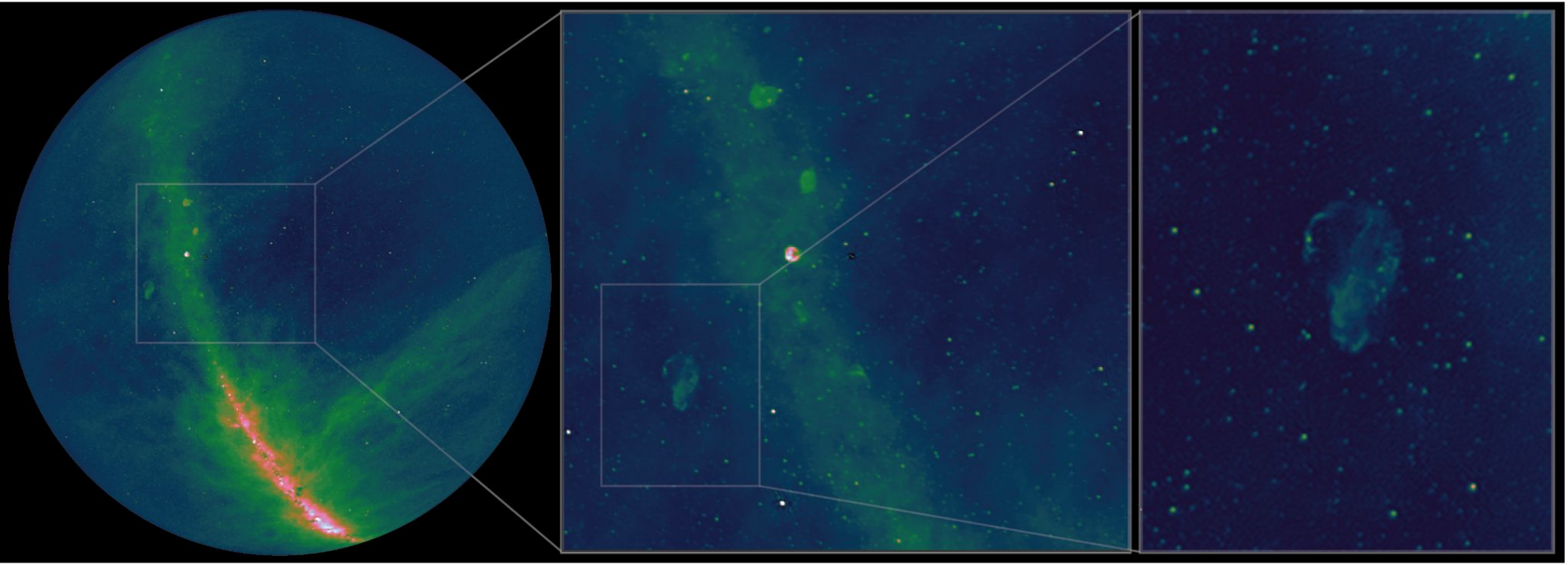
Fully cross-correlated

Currently undergoing science commissioning



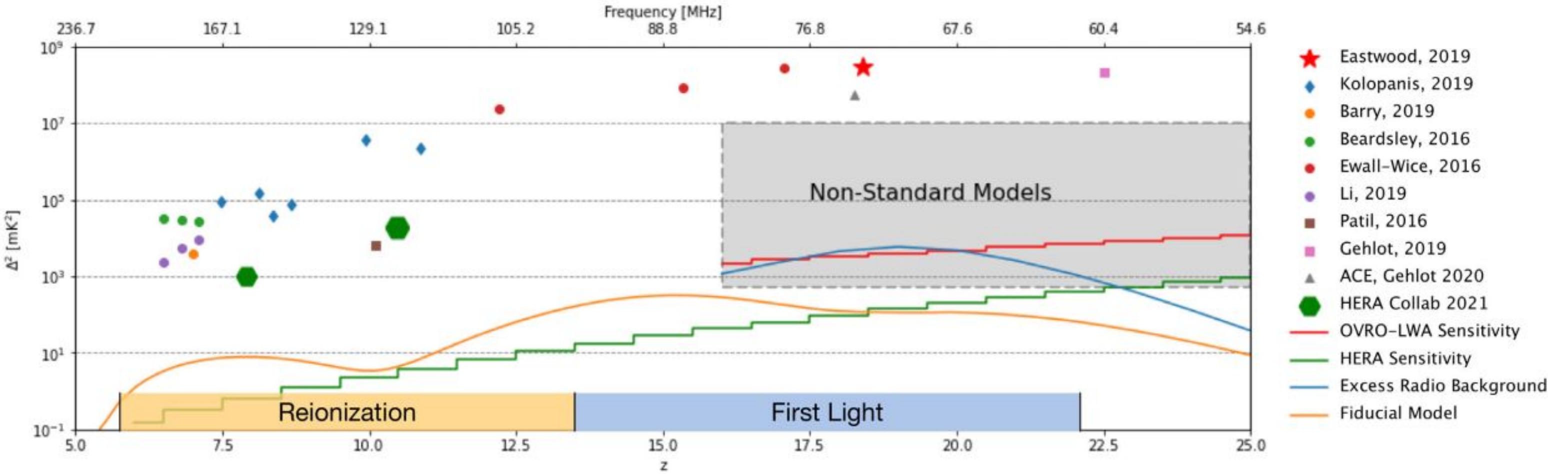
Stage III Preliminary Results

High-band: 63.5 MHz (45 MHz b/w) – ~2h LST



10 seconds (left) and 10 minutes (center and right) ; Source: Gregg Hallinan

We have this incredible array to improve on 2019 upper limits!

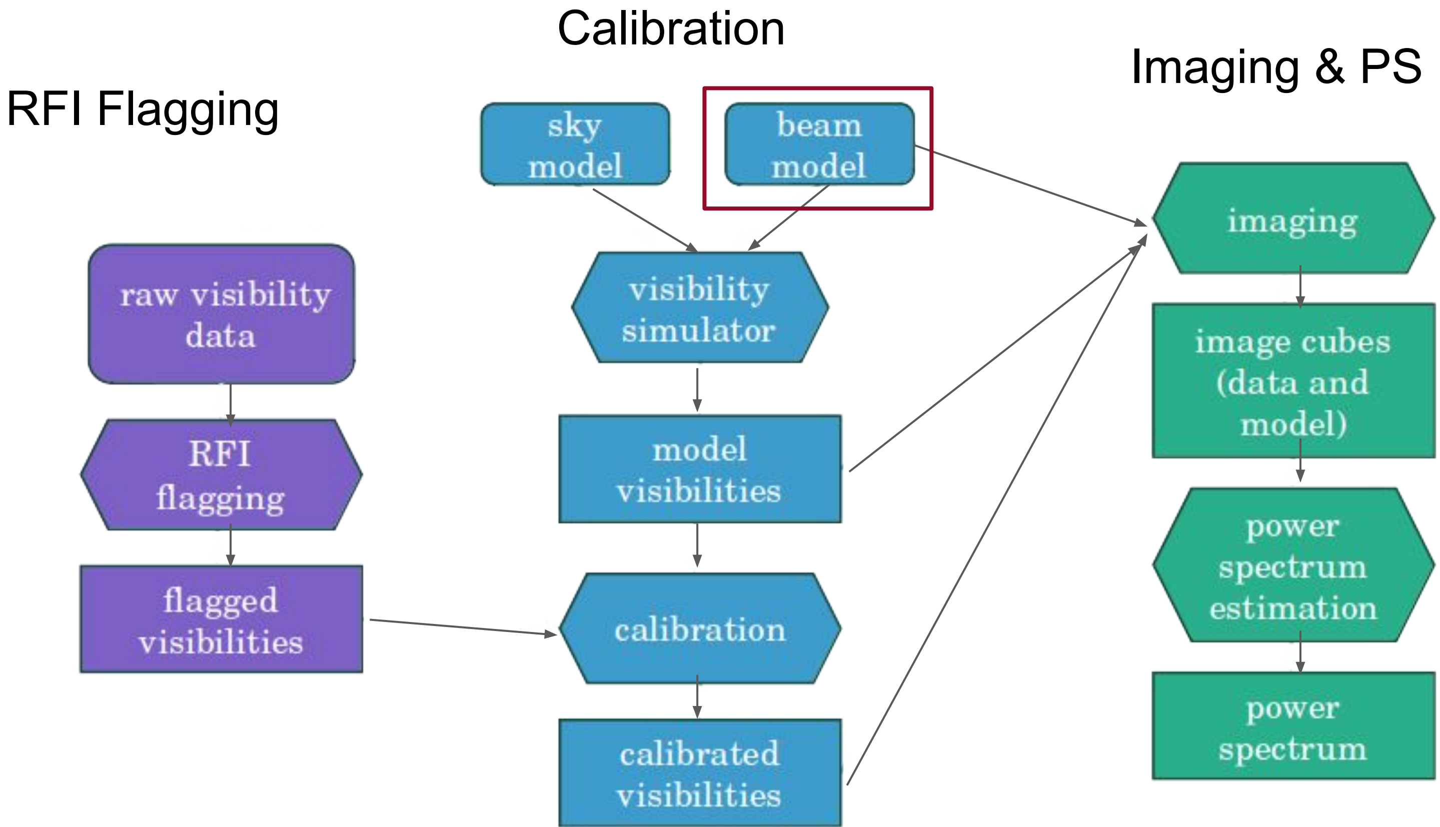


Ref: Bowman, Jacobs++

- ***Objective*** : achieve noise-limited performance for the first time with the recently upgraded and expanded OVRO-LWA.
- For most existing arrays, observing the 21 cm signal in the Cosmic Dawn band is a post-hoc science goal.
- Upgraded OVRO-LWA is designed from the ground up and optimized for the CD band
- Upgrades have been targeted at reducing crucial spectral systematics that fundamentally limit all 21 cm instruments.

OVRO-LWA Cosmology Pipeline

Team :
ASU- Judd Bowman, Danny Jacobs, Matthew Kolopanis, Katherine Elder
Caltech - Gregg Hallinan, Ruby Byrne, Xander Hall, Nivedita Mahesh



Why do we care about the Beam?

Galactic and extragalactic foregrounds are 10^4 - 10^5 >> Redshifted 21 cm from Cosmic Dawn

The statistical detection can be via:

- Foreground removal
- Foreground avoidance

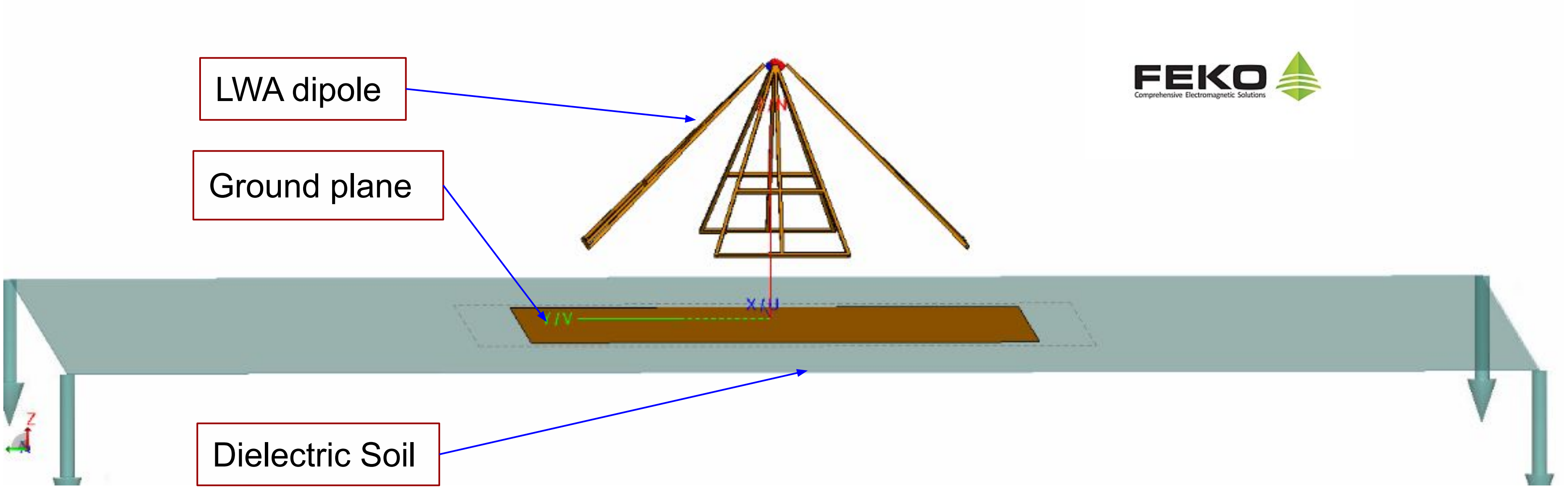
Effectiveness of either approach is limited by the beam convolved sky

Source peeling leads to residuals ~ level of signal of interest if the knowledge of the beam limited
Beam convolves the foreground to higher k-modes reducing the window of cosmological detection

TLDR; I am my own problem

How do we obtain knowledge of the beams?

Via EM modelling



Soil is modeled with a σ = 0.0013 S/m and ϵ_r = 3.7 (Spinelli+ 2022).
Long term plan: install hygrometer and collect soil data to be input for simulations

Need - Realistic beam in the array.

1.) Add complexity to the models: More antennas to the simulation; but in small sections

⇩

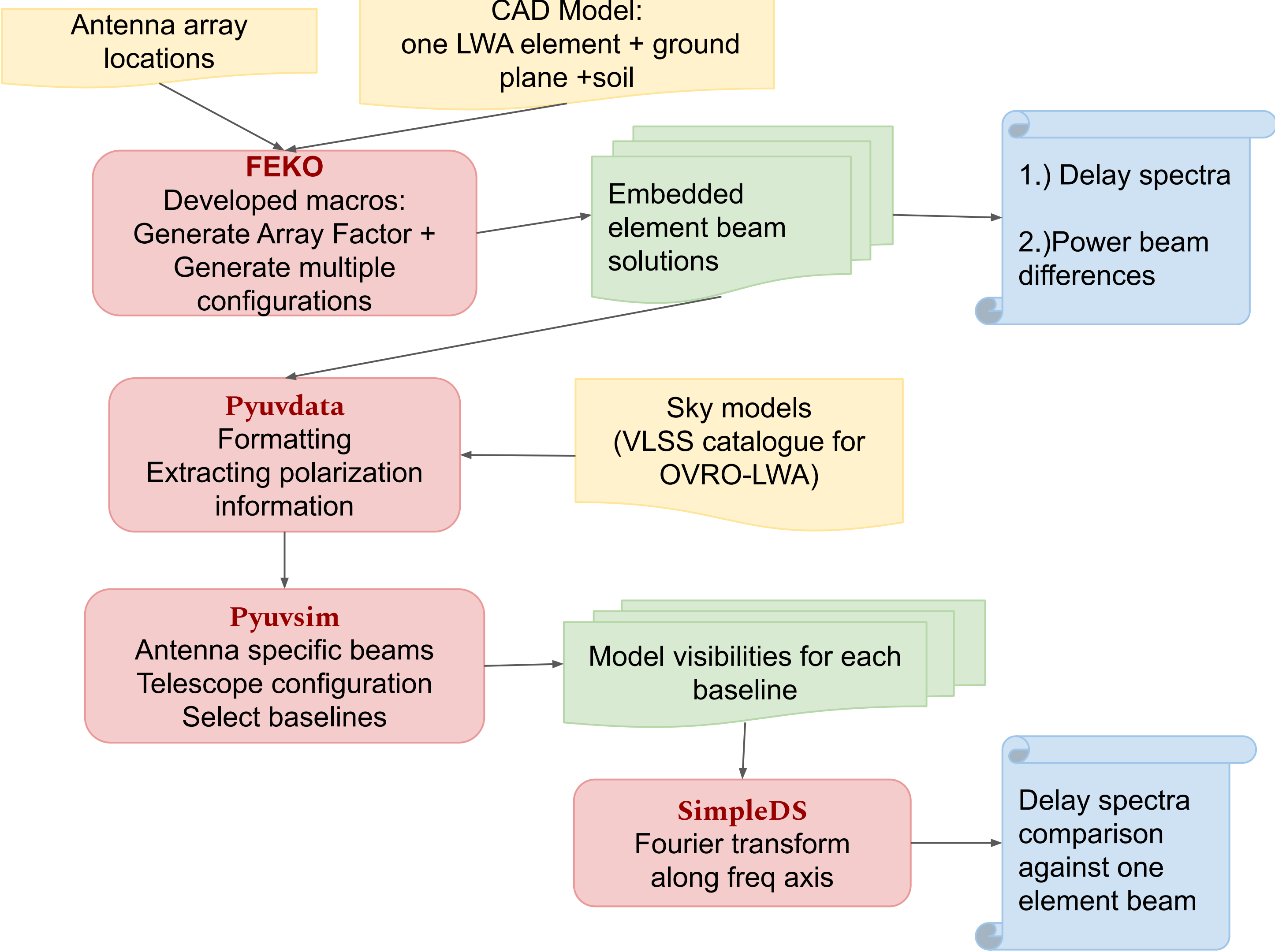
2.) Quantify the effect on a given beam.

3.) Converge on the simulation that captures the effect in the array

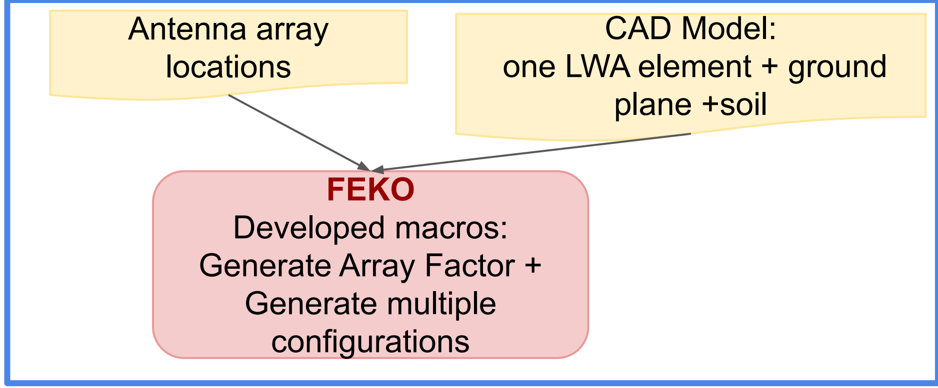
4.) Model the beam as: Primary beam + differential beam ⇒ to be used in the analysis pipeline

Assessing Beam & Mutual coupling:

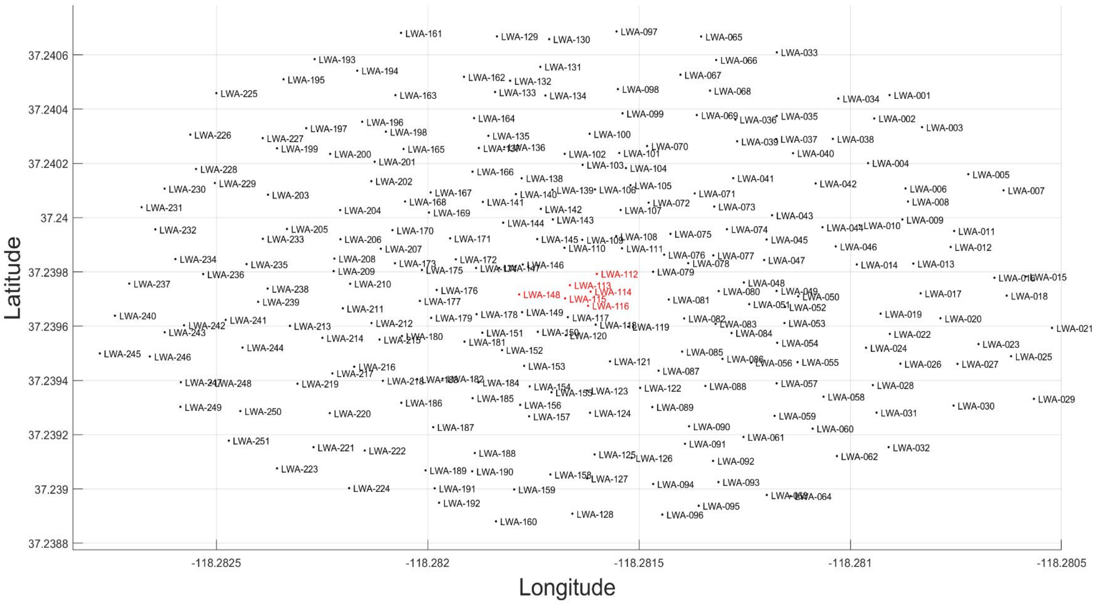
OVRO-LWA Science cases

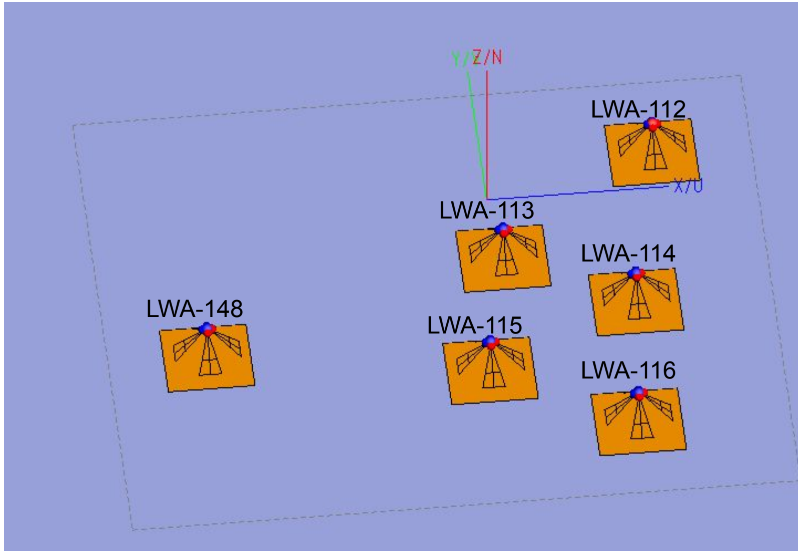


Step 1: Modeling a section of the array & solving for the beams



OVRO-LWA core

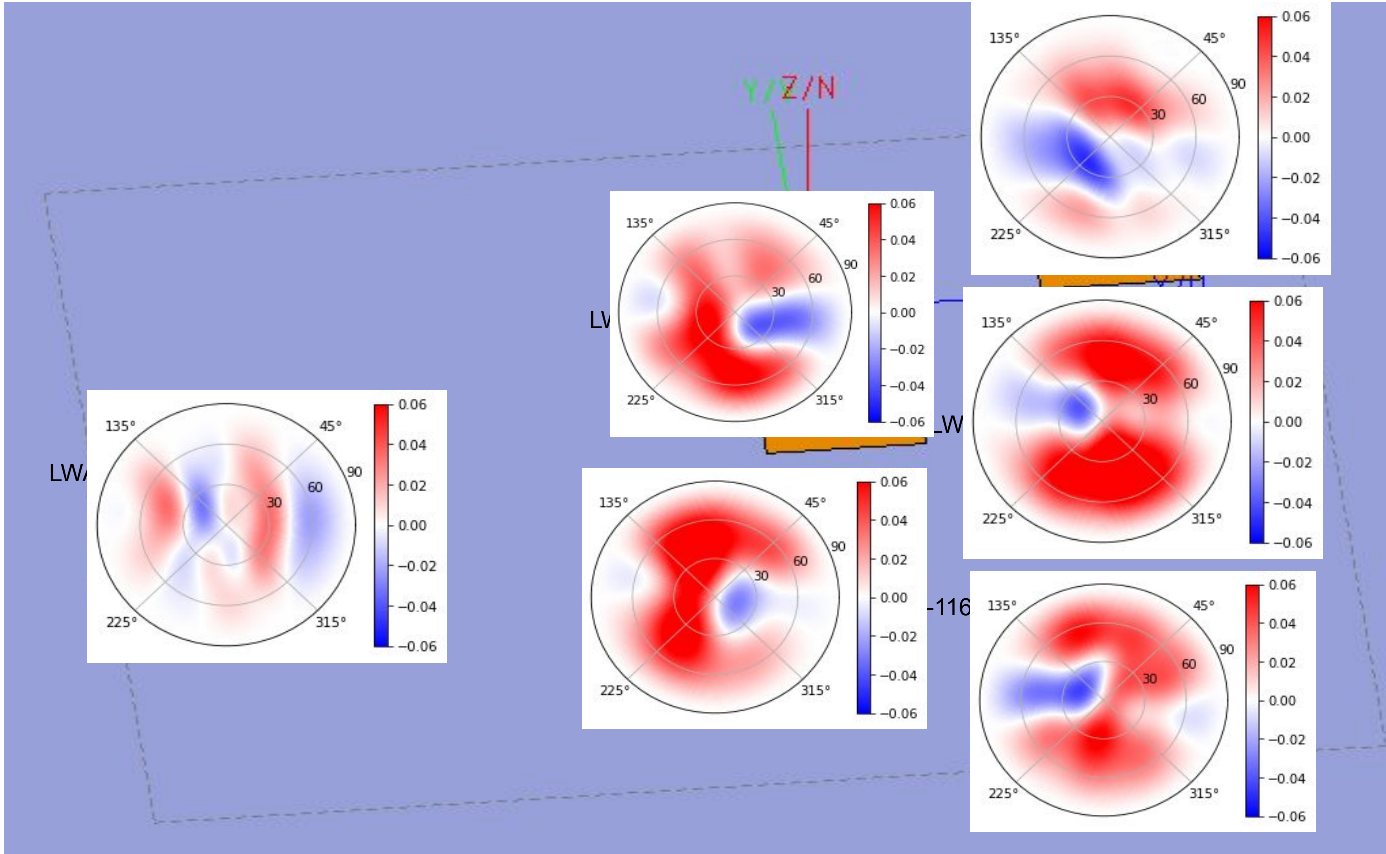




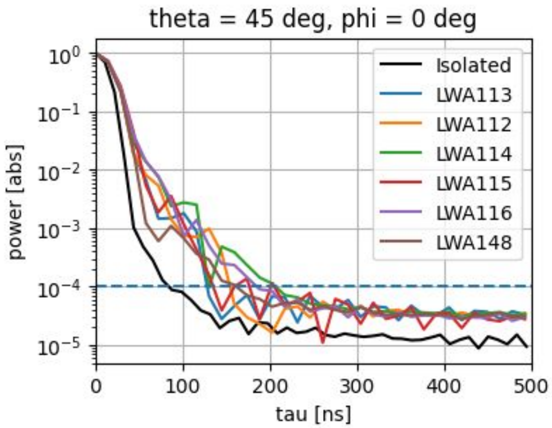
Step 2a: Analyse embedded element beams; power beam differences

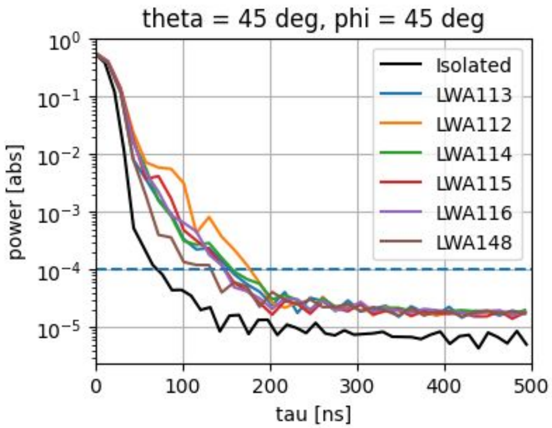
@ 20 MHz

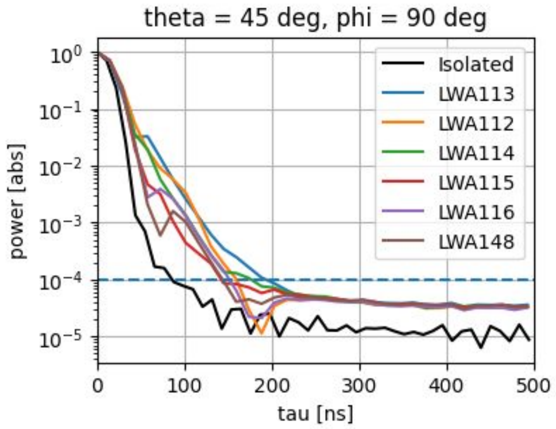
- Each embedded beam is subtracted from the Isolated beam
- Upto 6% deviations
- With the innermost dipole seeing the max deviation
- Outermost the least



Step 2a: Delay spectra analysis on the beam

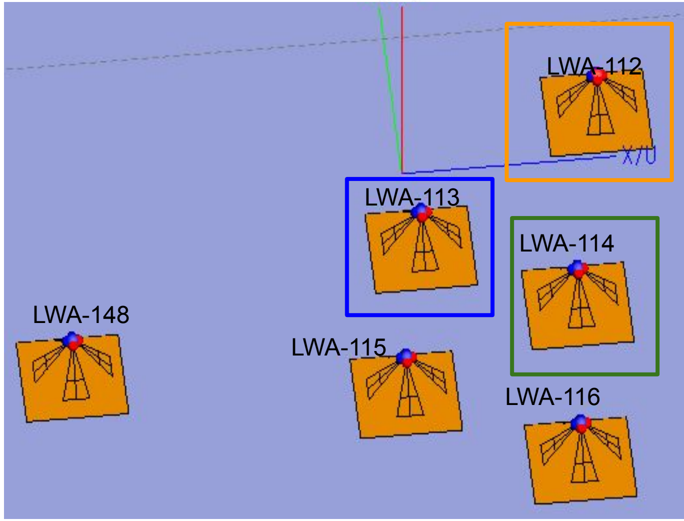






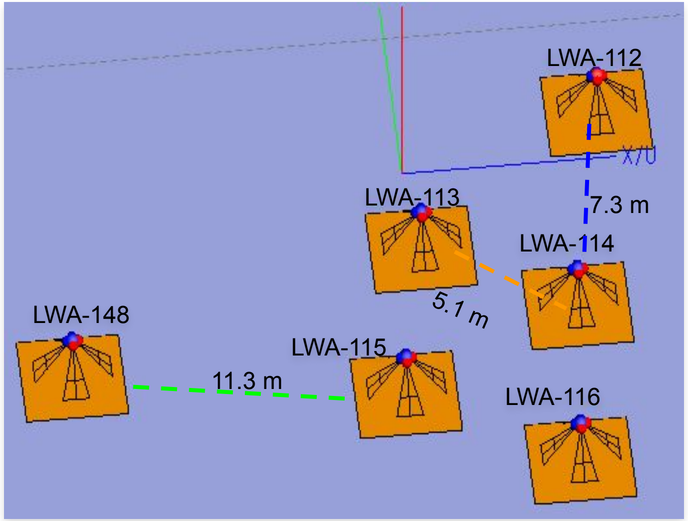
Isolated dipole: The power is suppressed by 10^{-4} @ delays > 100ns -or- baselines> 60 m

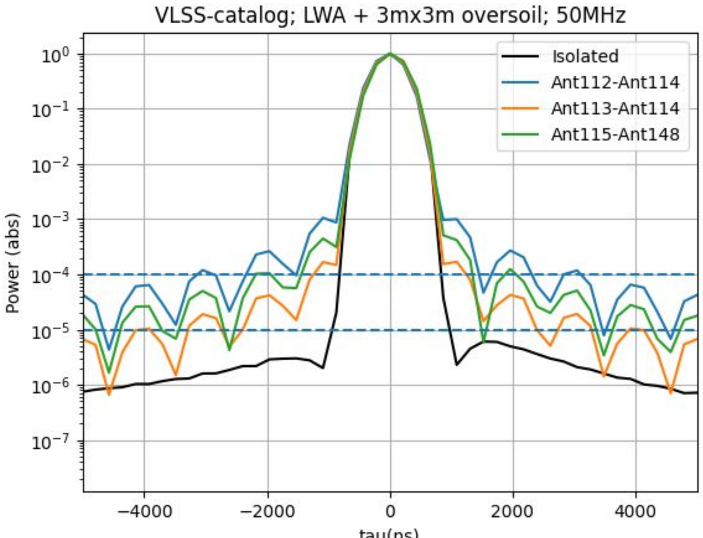
Mutually coupled dipoles: The desired suppression is @ delays >200 ns -or- baselines > 120 m



Step 3: Delay spectra analysis of the model Visibility

- Generated model visibilities with pyuvsim and embedded beam solutions for 3 baselines
  - Used the specific beam for each antenna in the baseline
- The embedded elements increased the power by >10x at all delay modes compared to the isolated beam





OVRO-LWA summary

- 21 cm measurements with the OVRO-LWA will probe Dark Ages, Cosmic Dawn, and X-Ray Heating
- Eastwood et al. 2019 developed a first limit on the signal with Stage II
- Forthcoming results will generate deeper 21 cm limits
  - Improved uv coverage and long baselines
  - Systematic-resistant signal backend
  - State-of-the-art data analysis

Beam Modeling efforts

- A pipeline in place to assess the effects of OVRO-LWA beams.
- Shown preliminary results of simulating large-ish(?) chunks of the LWA array; Capturing mutual coupling.
- Generated model visibilities using sky models to quantify the beam effects more realistically.

<u>Next steps</u>

- *Comparison against data:* Model visibilities Vs. Field visibilities
- Add more antennas and come up with an analytical formulation of the mutual coupling.
- Incorporate the beams into the main calibration & data processing pipelines in memory and time efficient way

Late time Cosmology with DSA-2000 as HI IM experiment

Nivedita Mahesh, Caltech
Phil Bull, University of Manchester

Inputs & discussions: Ruby Byrne, Gregg Hallinan, Liam Connor, Danny Jacobs

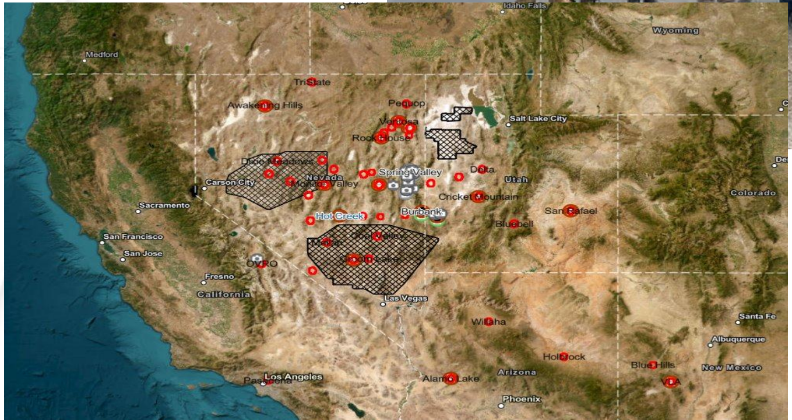
DSA-2000

A world-leading radio survey telescope and multi-messenger discovery engine

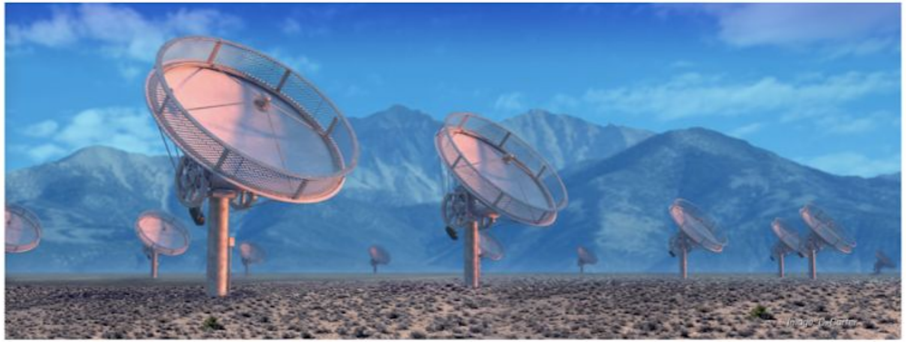
- ~2000 x 5m dishes (19 x 15 km)
- Spring Valley, Nevada
- Frequency: 0.7 - 2 GHz band
- Spatial resolution: 3.3 arcseconds
- **Highly optimized for surveys**

- **First light: 2027, key surveys: 2028 – 2033**

- Design: Funded by Schmidt Sciences
- Construction costs: $188M



Why 21-cm Intensity mapping with the DSA-2000?



The DSA-2000 can overcome the challenges of other 21 cm intensity mapping experiments

- Excellent sensitivity
- Extremely calibratable
- Resilient to foreground contamination

Other Helpful Design Features

- Relatively spectrally smooth frequency response
  - Supports foreground mitigation
  - Enhances calibratability
- Spillover protection
  - Reduces system temperature
  - Provides beam stability
- Fully steerable dishes
  - Eases beam characterization requirements
- RFI environment and mitigation

What cosmological observables can we look for?

$$C^S \sim T_b^{\,2}\,(b_{Hi} + f\mu^2)^2 \exp(-k^2\mu^2\sigma^2_{NL})\, D^2(z)\, P(k, z=0)$$

$\propto \Omega_{Hi}$

Hi density function

Bias factor

$\propto \Omega_M H(z)^{-2}$

Matter density function, Growth rate

Non linear dispersion

Linear growth factor

BAO scales, P(k) turnover (cunnington 2022)

We begin our exploration of the capabilities of DSA as an IM experiment by forecasting constraints on a few key observables

Fisher forecasting Framework in RadioFisher (Bull et. al. 2015)

Accessible transverse scales : DSA as an interferometer & DSA as a dish experiment

For SD

D_{dish} = 5 m,

S_{area} = 32,000 deg^2

For interferometer:

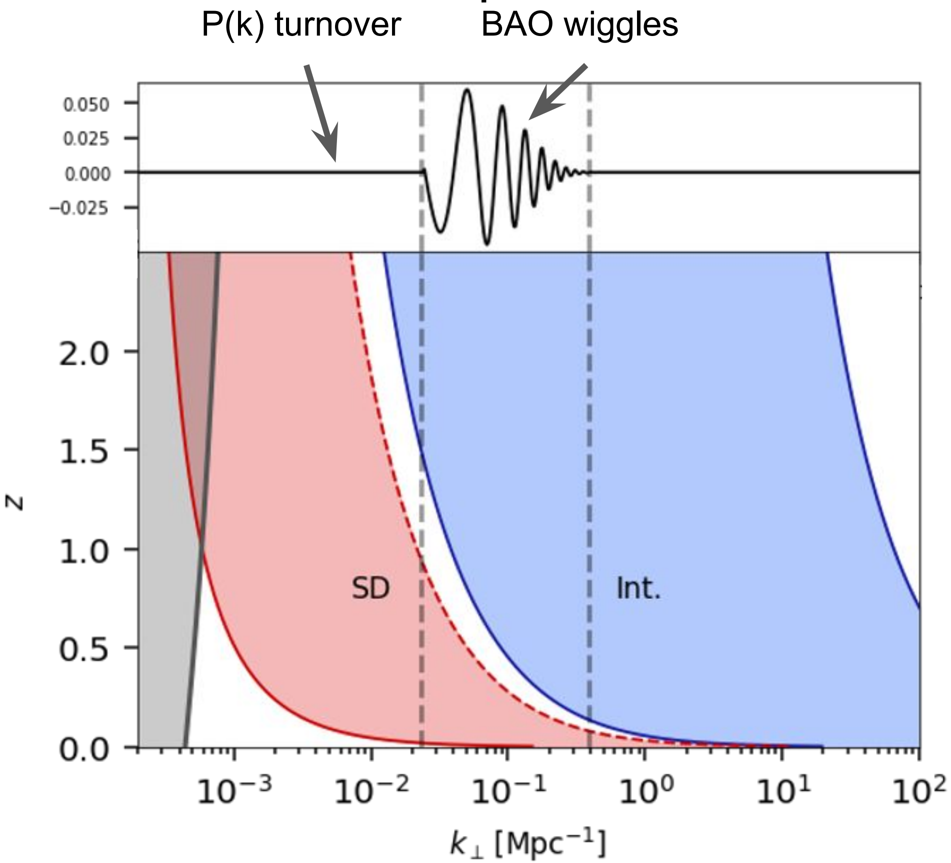
D_{min} = 8.8 m,

D_{max} = 16000 m

shaded gray region superhorizon scales,

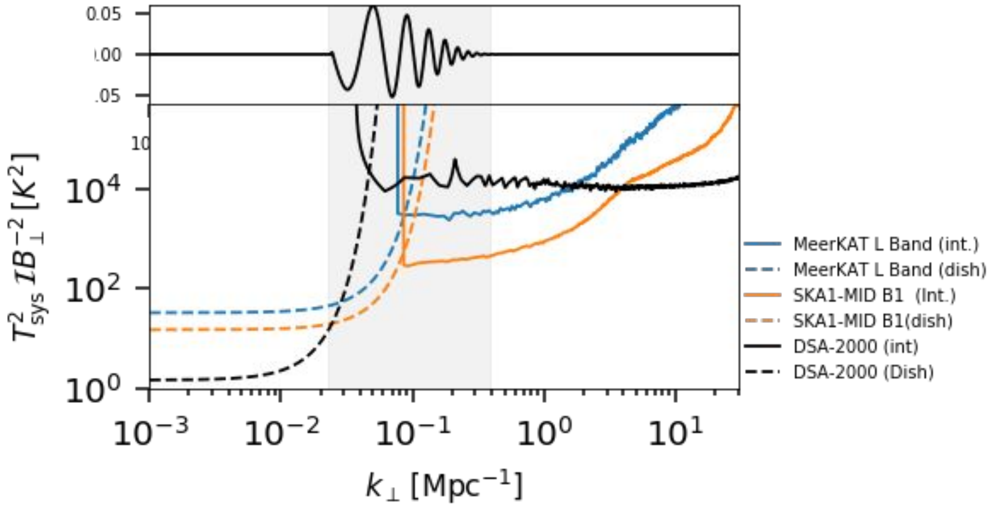
$k < k_H = 2\pi / r_H$

z ≥ 1, the baselines can probe all the relevant k scales for the BAO feature

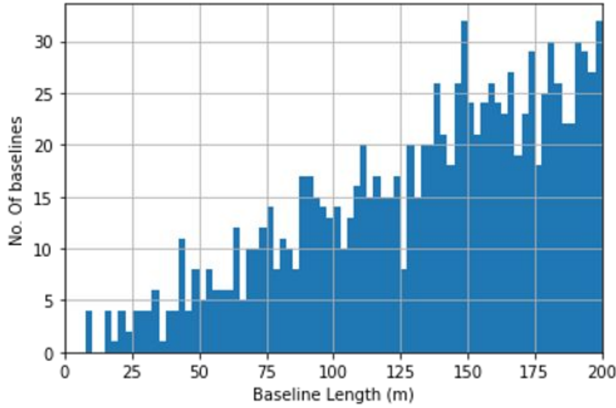


Noise sensitivity vs $k_\perp$ (angular scales)

- High noise indicates the array is very sparse.
- Encouraging: can get very short baselines, and cover the whole BAO feature at these frequencies
- But the layout needs to have more of a core, or a few clustered sites, to get the baseline density needed at these scales
- ==> Huge errors bars on the BAO constraints



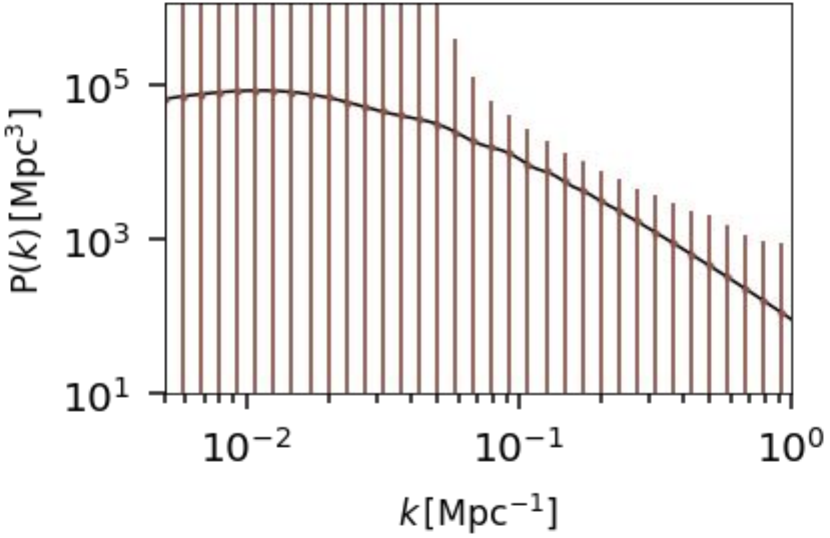
- Zoomed into d<200m reveals very few baselines of order 20 at the desired scales



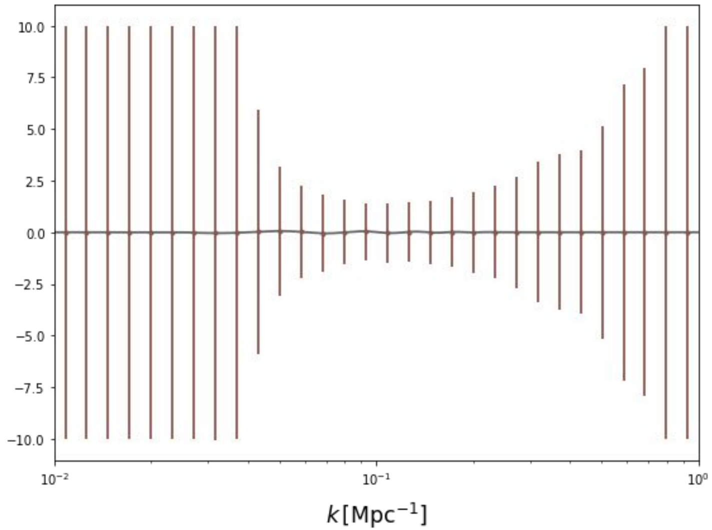
Constraints on BAOs & P(k) with current array layout

ttot = 2800 hr

Forecast constraints on P(k)



Forecast constraints on BAO wiggles



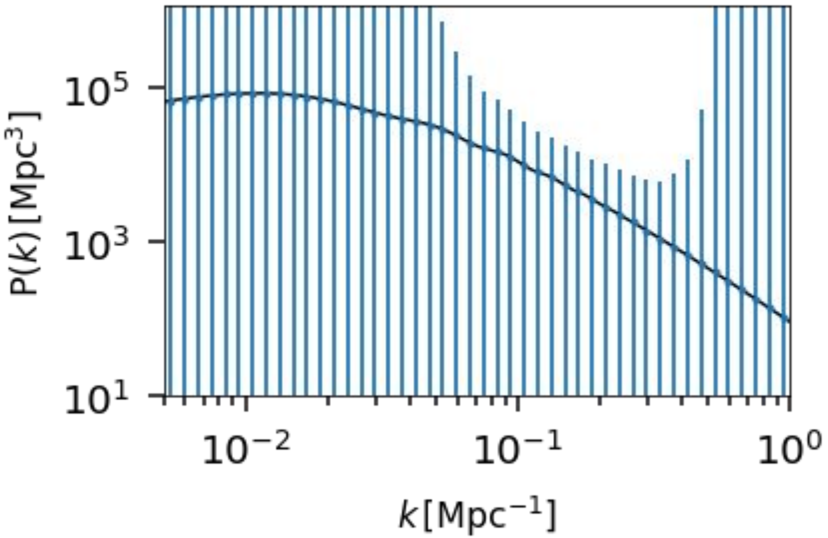
P(k, z=0) from CAMB (lewis et. al. 2000)

Constraints on BAOs & P(k) with current array layout

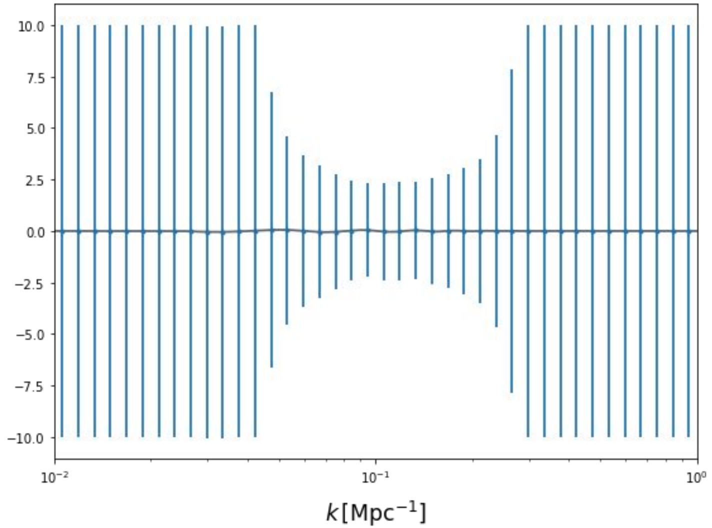
More realistically → considering k_{NL} & 3dB wedge

ttot = 2800 hr

Forecast constraints on P(k)



Forecast constraints on BAO wiggles

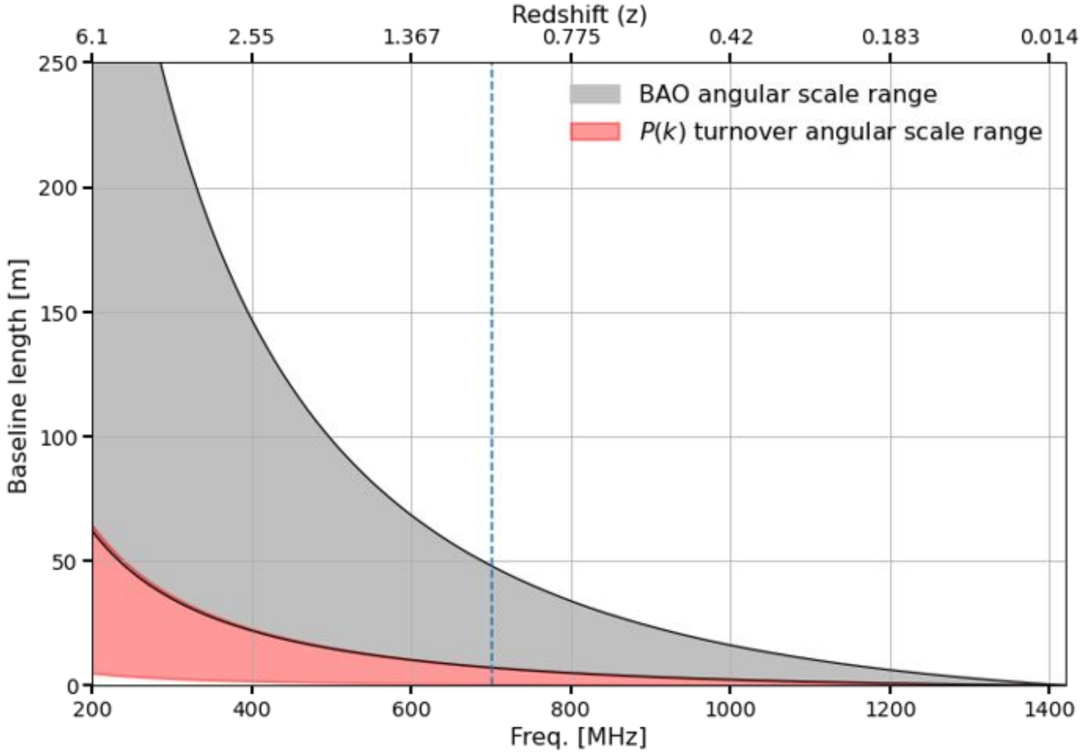


What are the desired baselines for the desired angular scales?

	$K_{min}(Mpc^{-1})$	$K_{max}(Mpc^{-1})$
P(k) turnover	0.0024	0.03
BAO	0.03	0.2

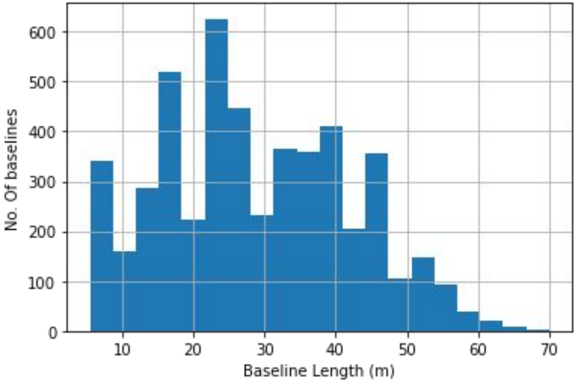
$$d_{\min,\max} = \frac{\{K_{\min,\max} r\lambda\}|}{2\pi}$$

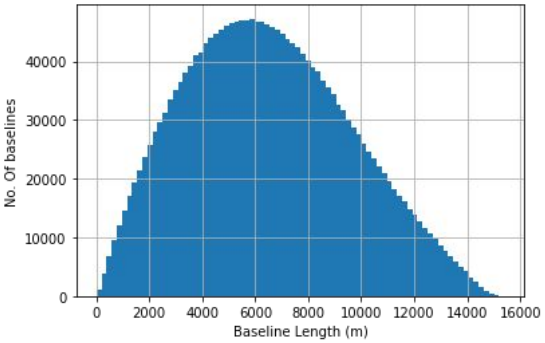
Thus for z ≅1 we need more
d<50m for BAO constraints
d<20m for P(k) turnover constraints

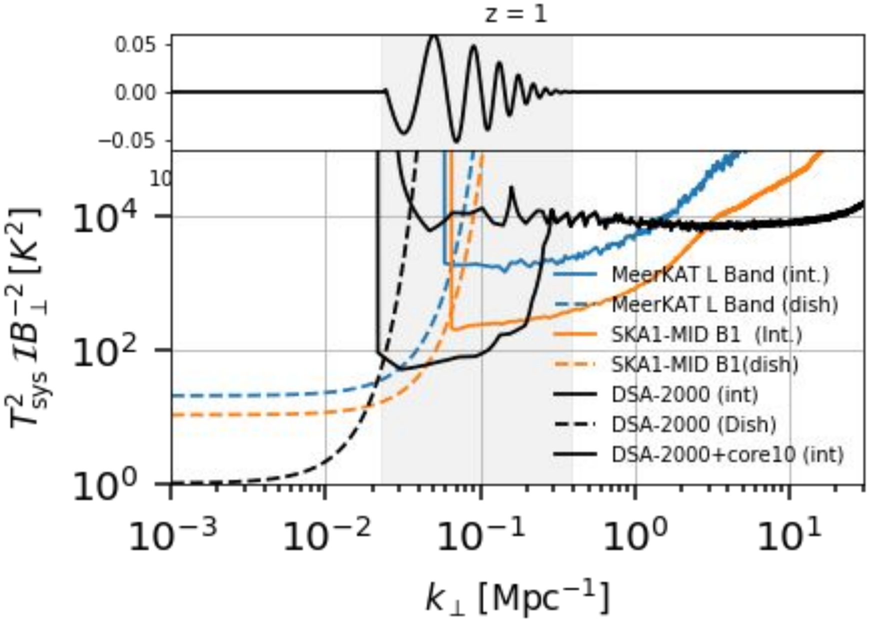


Noise sensitivity with an added core

Core specs: (10 x 10 antennas, Dmin = 5.5m)

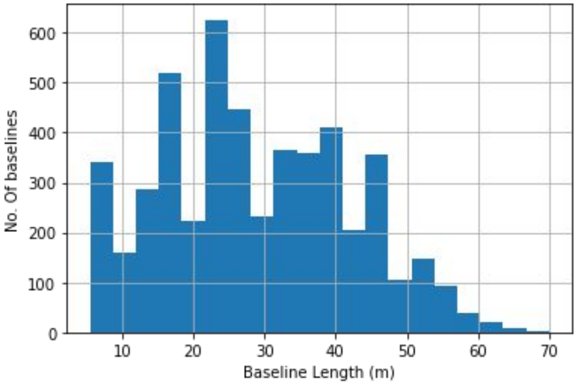


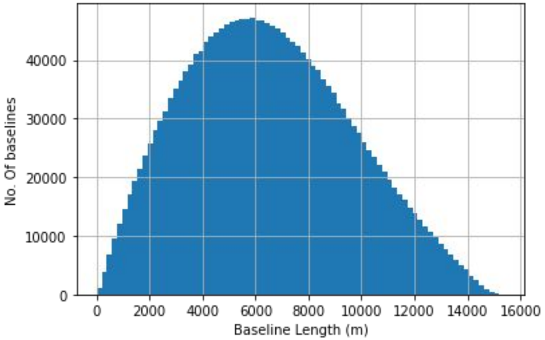


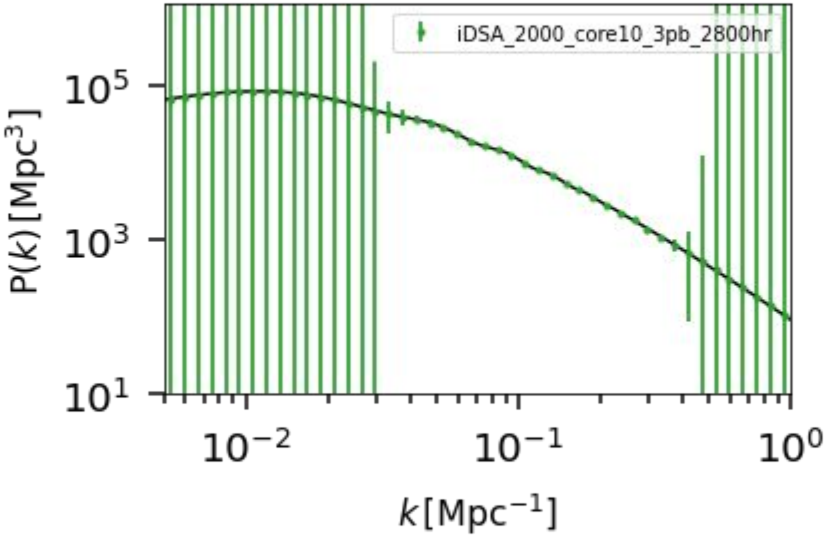


Fractional errors on P(k) with an added core

Core specs: (10 x 10 antennas, Dmin = 5.5m)

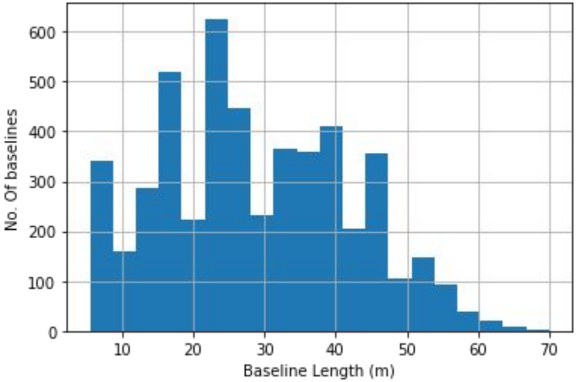


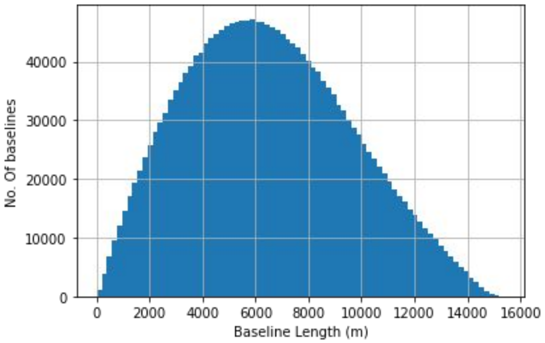


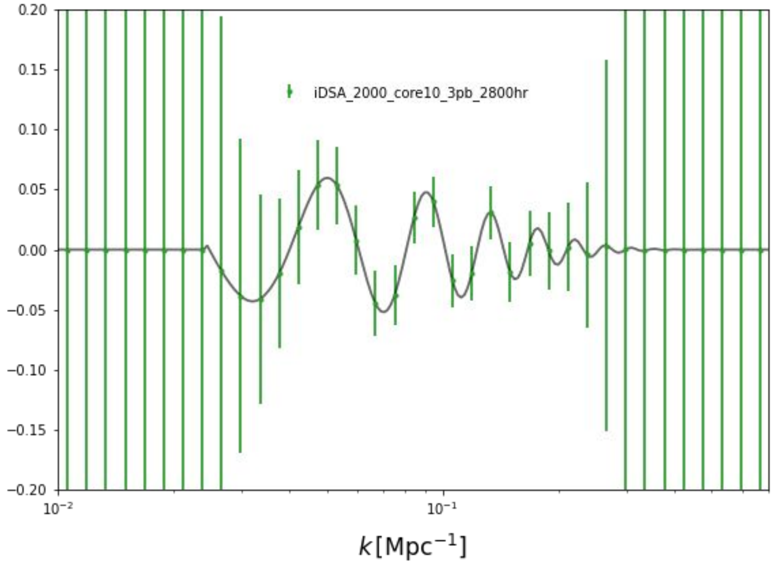


BAO constraints with an added core

Core specs: (10 x 10 antennas, Dmin = 5.5m)

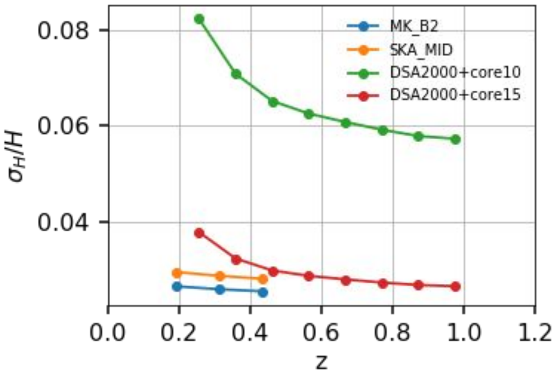




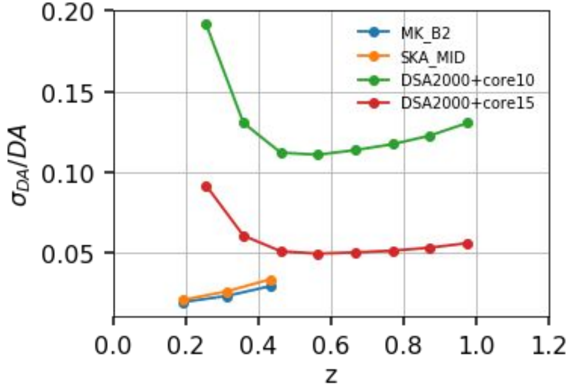


Constraints on Expansion, Growth, Acoustic Peak, Ω_{Hi}

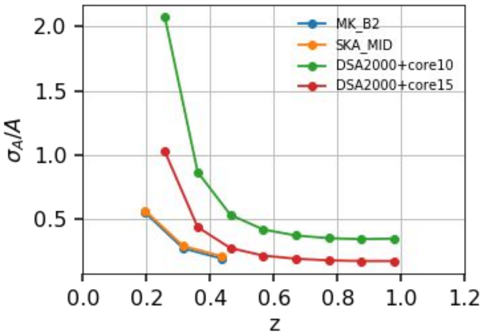
Expansion rate from radial scales



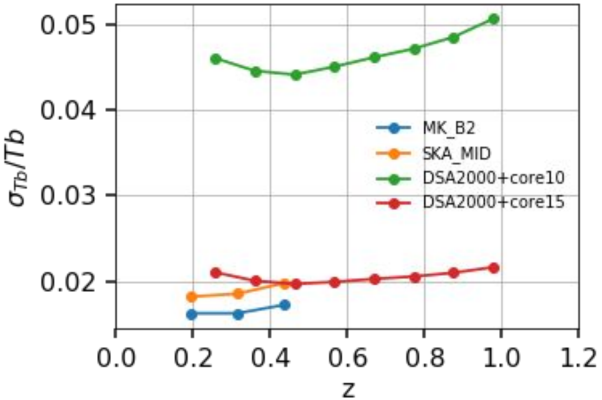
geometry/expansion of the Universe from transverse scales



Detectability of BAOs



$\sigma T_b/T_b \propto \sigma\Omega_{Hi}/\Omega_{Hi}$



Summary

- DSA 2000 extremely powerful (exquisite calibration, lower systematics, foreground reduction)
- Fisher forecasted a few Cosmological observables - Test the IM capabilities
- For interesting cosmology from Hi IM we need a core
- Constraints improve quickly with just ~100 antennas

Open Questions

- 5-10% more antennas (trade offs?)
- Or is it more feasible to push freq_low to 500 MHz?
- Operate in Single dish mode - Need a plan for calibration

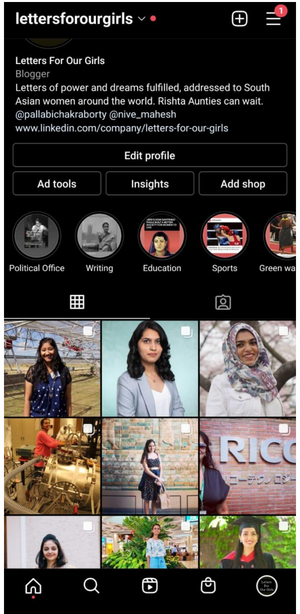
Letters for our Girls

Mission Statement:

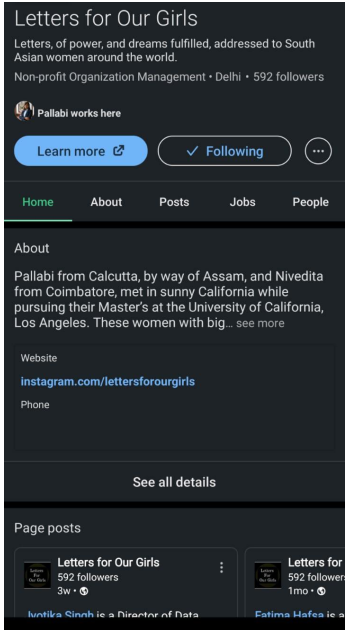
Our mission is to demystify different careers, humanize South Asian women professionals, and inspire our girls to explore. We believe that if girls are able to form authentic relationships with real professionals, they will be able to see in them, themselves.

Letters For Our Girls

Instagram page



LinkedIn Page



What value are we bringing?

- Highlight and appreciate the accomplishments of South Asian women
- Show that role models aren't far from home
- Navigate the similar challenges & Learn from women before us
- Breaking stereotypes
- Demystifying the next steps
- Highlighting career possibilities they had never imagined
- Genuine words of reality - reduce self doubts & increase confidence
- Learning the ropes - to be able to put to use.
- ***All said & done - Inspiration is a thrill!***

Thank you for inviting me!

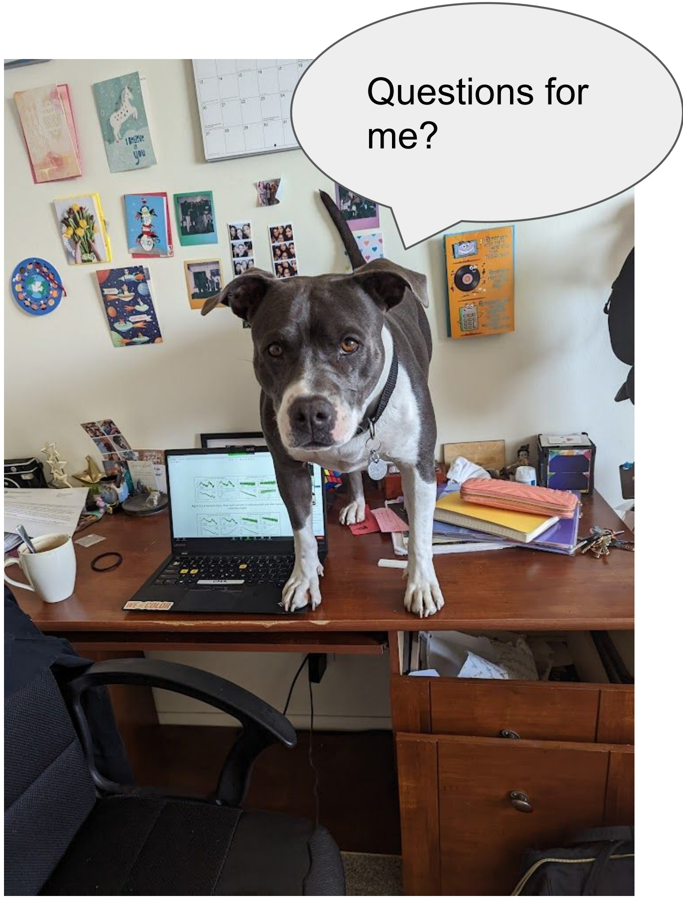
QUESTIONS?

EDGES Open-source pipeline: edges-collab

Contact info: nmahesh@caltech.edu

Nivedita Mahesh

@nivedita_mahesh



EXTRAS