# The Upgraded OVRO-LWA

**LWA Users Meeting 2023**

**June 2, 2023**

**Ruby Byrne (on behalf of the OVRO-LWA team)**

# *What is the OVRO-LWA?*

- Owens Valley Radio Observatory (OVRO) Long Wavelength Array
- Located near Big Pine, California
- Fully cross-correlated and all-sky field of view
- 352 antennas spaced over ~2.5 km
- 12-85 MHz (3072 channels)
- Currently in its “Stage III” upgrade
- *Goal is to adapt the LWA antenna to all-sky imaging at several arcminute resolution*

# 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
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Ivey Davis
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Vinand Prayag
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Andrew Romero-Wolf (co-PI)
Nivedita Mahesh
Greg Hellbourg
Xander Hall
Charlie Harnach
Nikita Kosogorov
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University of New Mexico
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Jayce Dowell

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

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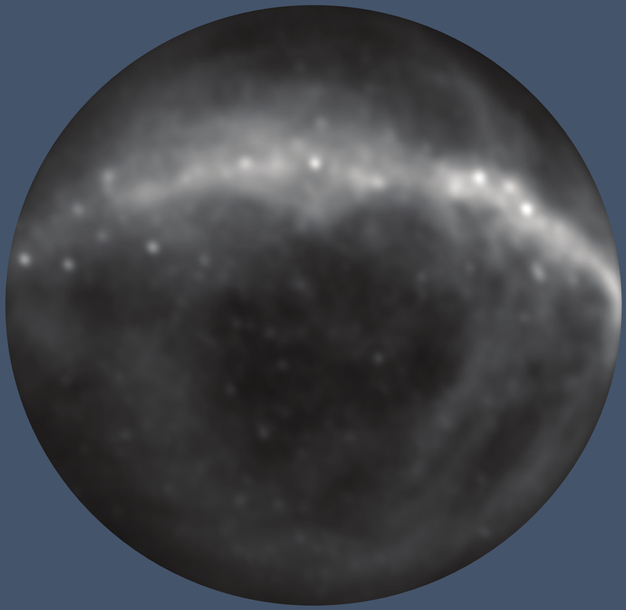
Danny Jacobs
Katherine Elder
Matthew Kolopanis
Akshatha Vydula

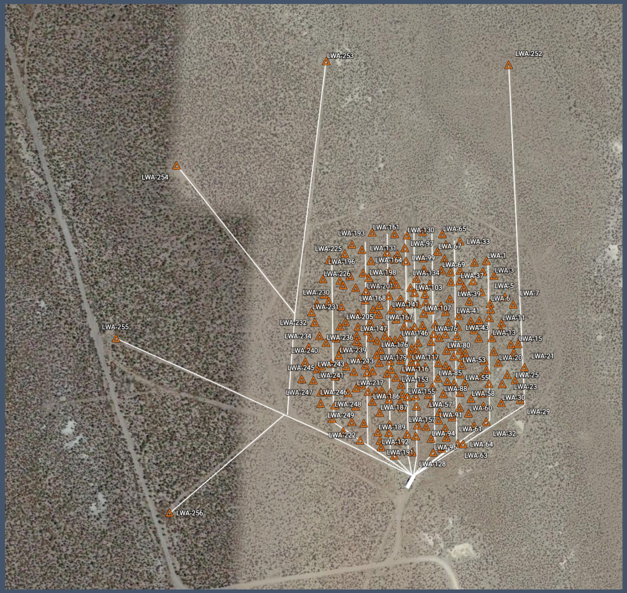
National University of Ireland, Galway (NUIG)
Aaron Golden
Dúalta Ó Fionnagáin

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

# The OVRO-LWA: Stage I

- 2013-2014
- 251 antennas
- 5 outriggers
- LEDA correlator (Kocz et al. 2015)

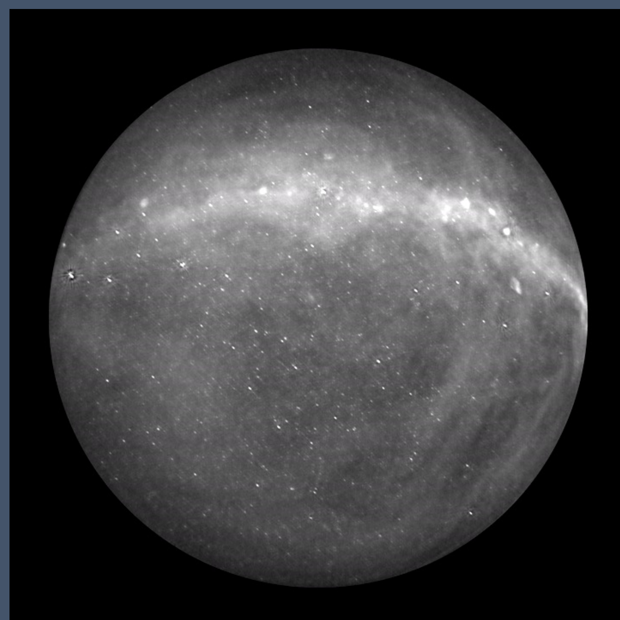


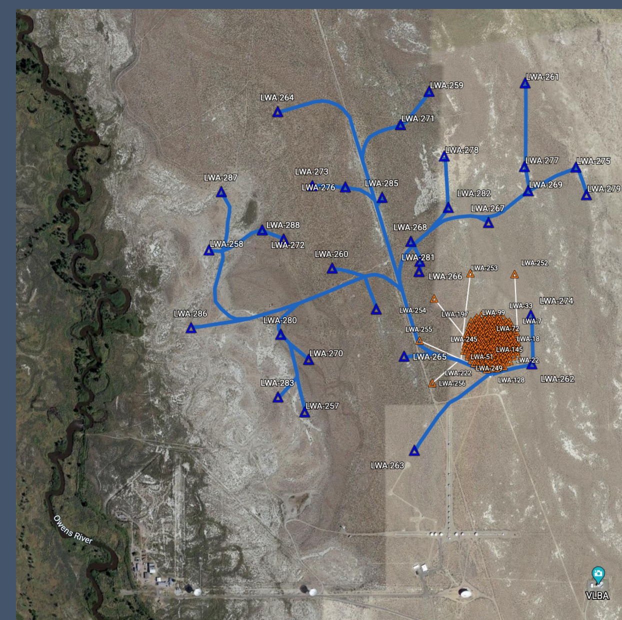


Source: Gregg Hallinan, Marin Anderson and Morgan Catha

# The OVRO-LWA: Stage II

- 2015-2020
- 283 antennas
- Addition of 32 fiber-fed outrigger antennas
- Longest baseline extended to 1.5 km
- Custom fiber-link board



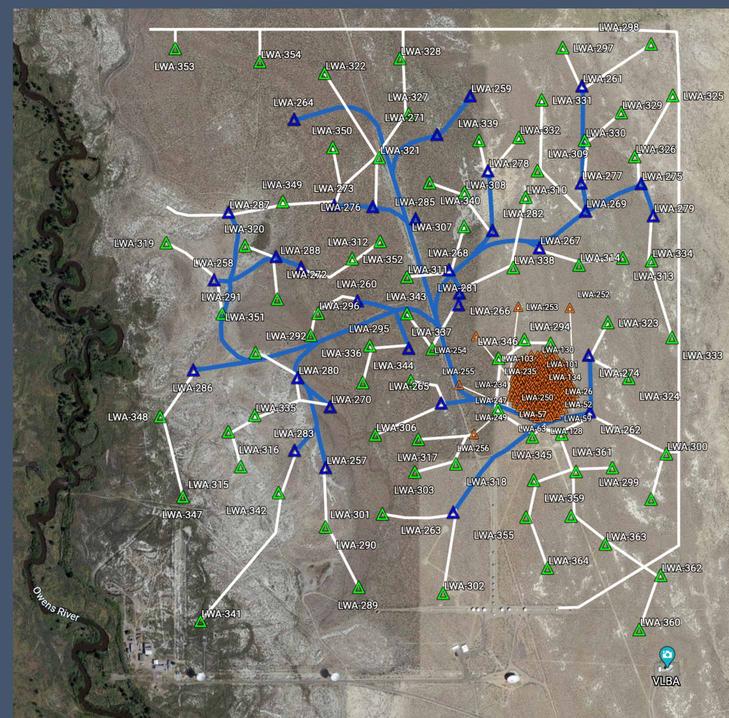


Source: Gregg Hallinan, Marin Anderson and Morgan Catha

# The OVRO-LWA: Stage III

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

- 2021-present
- 352 antennas
- Longest baseline extended to 2.4 km
- Complete overhaul of the analog and digital backend
- New data analysis backend and pipeline (Cal-Im) with 5PB of storage



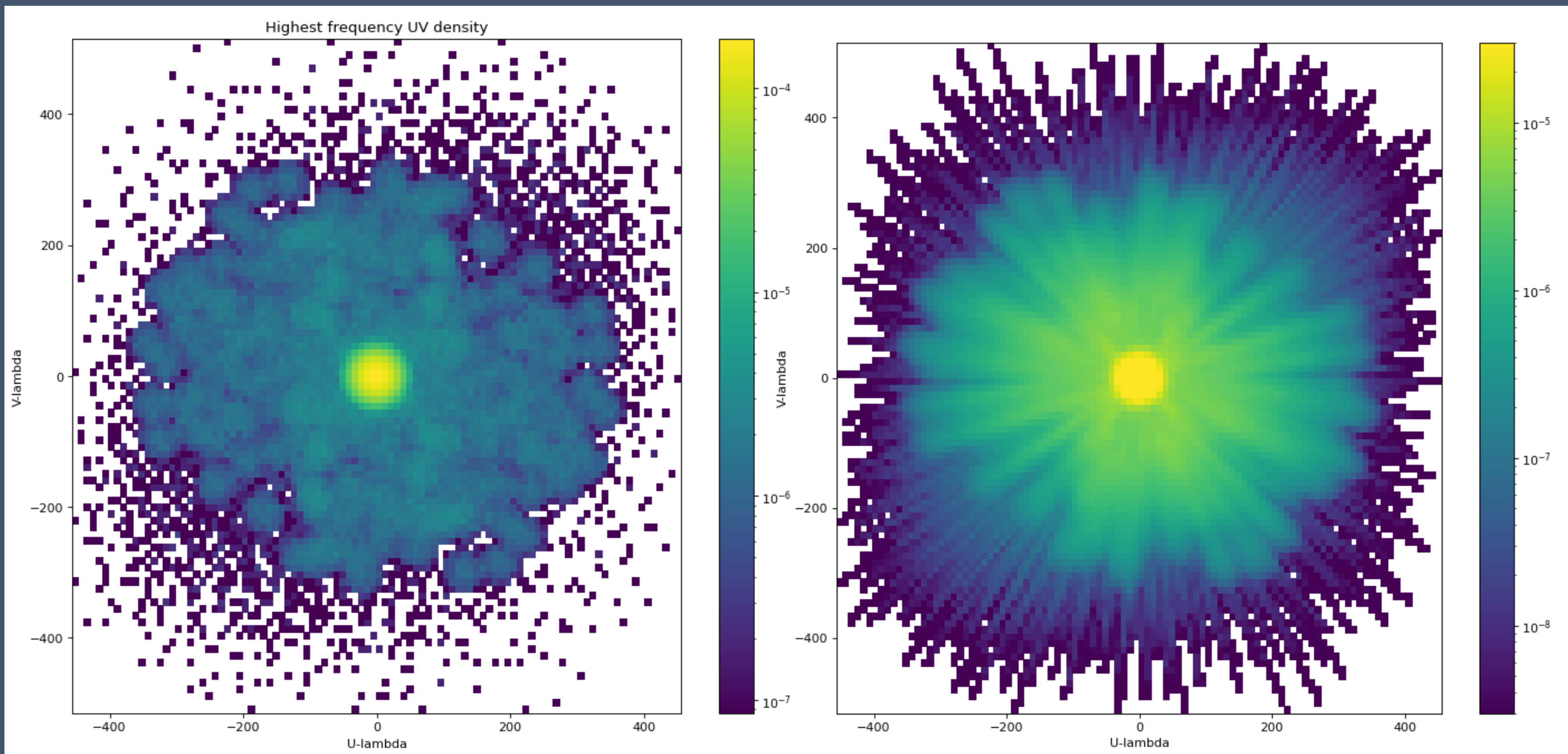

Source: Marin Anderson and Morgan Catha

# OVRO-LWA Stage III Antenna Installation

- 69 additional fiber-fed outrigger antennas
- 16 km of additional trenching
- New junction boxes
- Newly designed fiber link boards

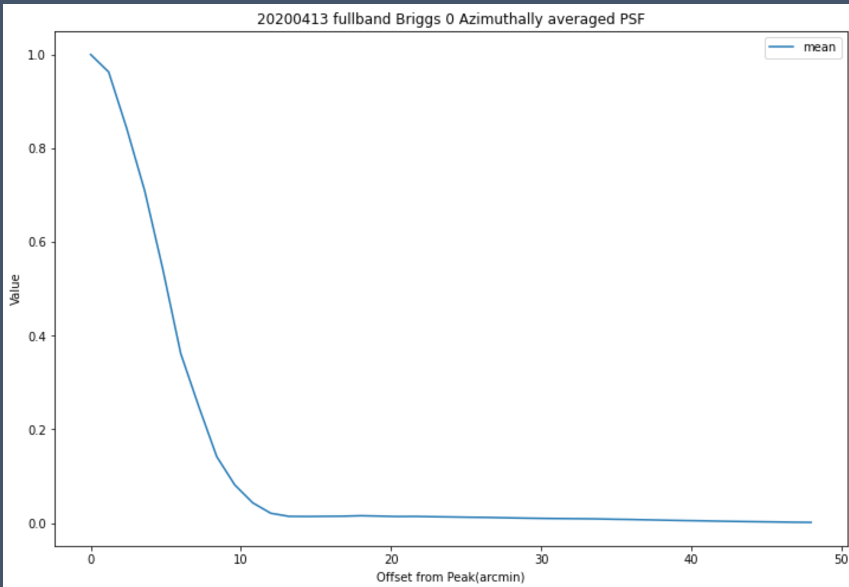

Credit: Morgan Catha

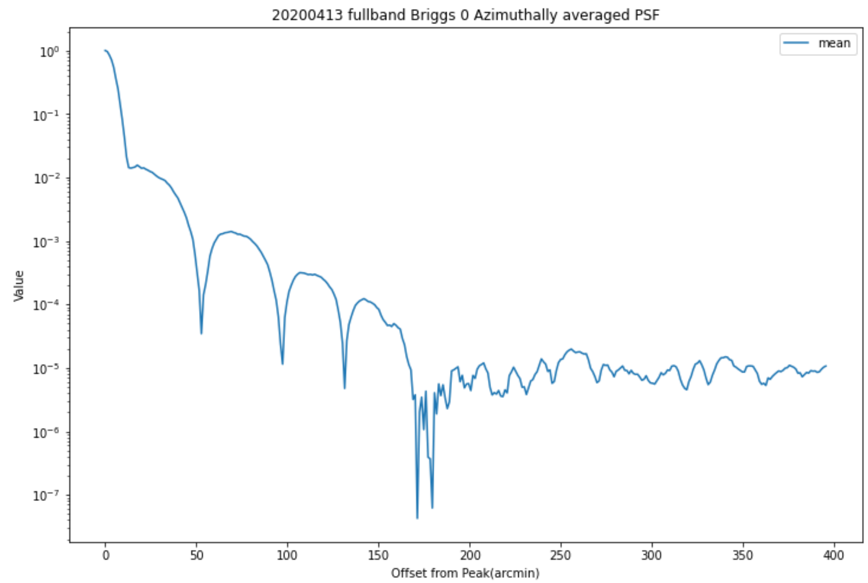
# Stage III PSF Performance




Source: Yuping Huang

# Stage III PSF Performance

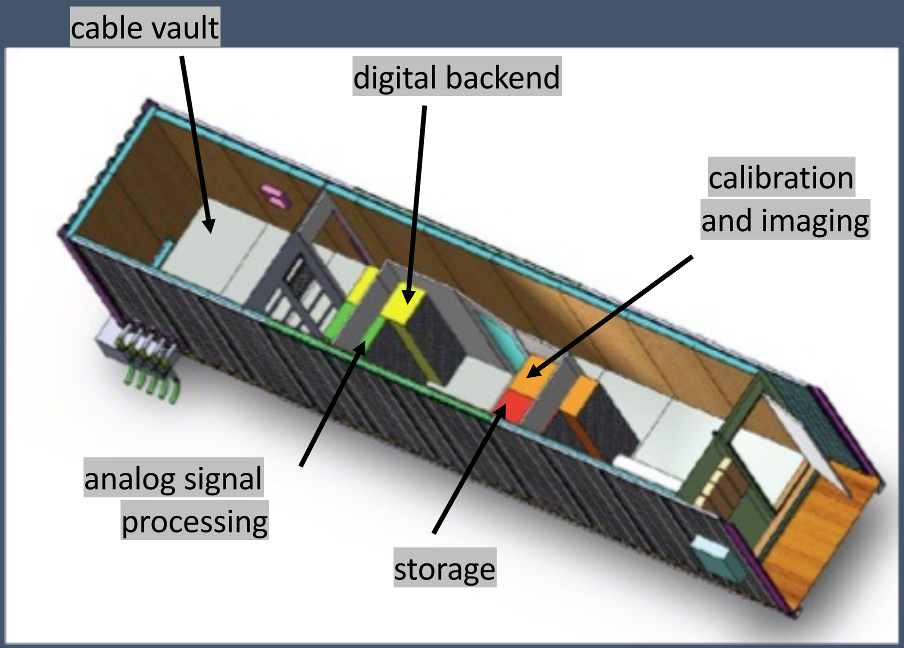



Source: Yuping Huang

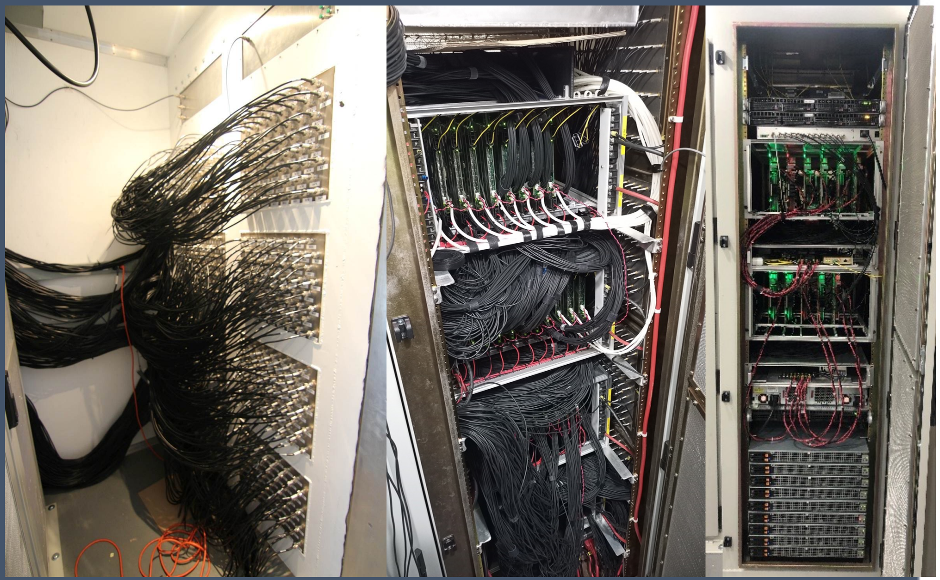
# Signal Backend

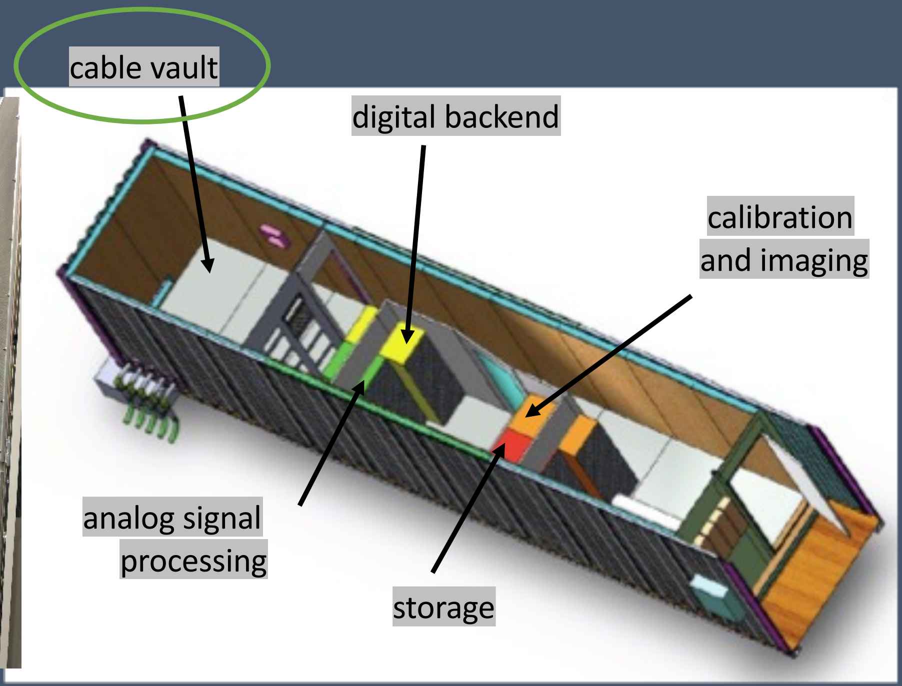
- All data processing is on-site




Source: Gregg Hallinan

# Cables, cables, cables

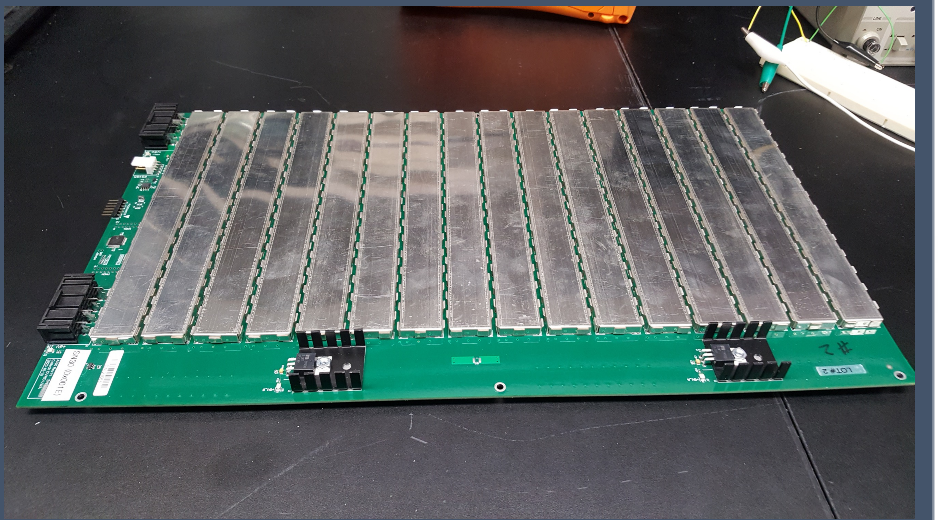




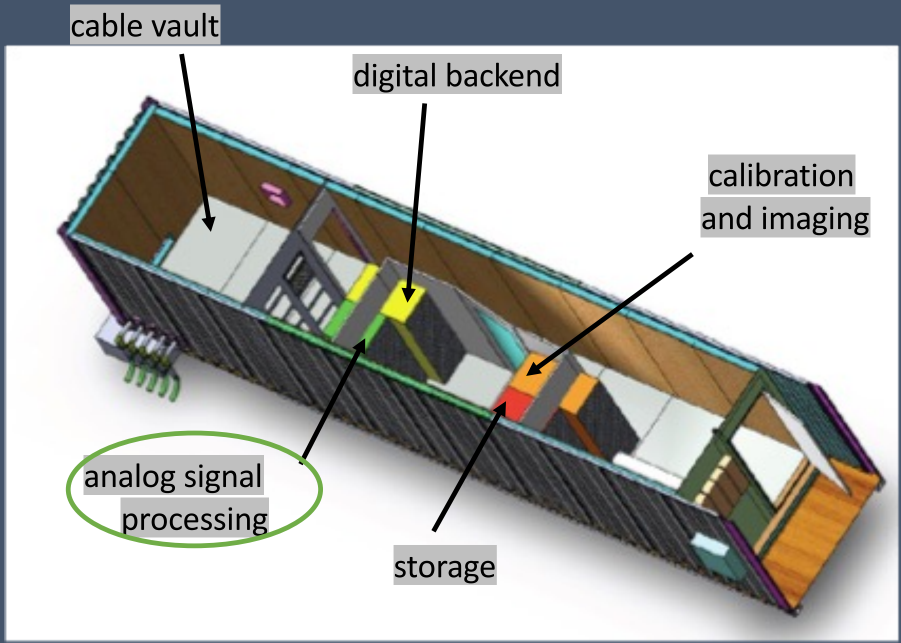

Source: Gregg Hallinan

# Analog Receiver

- Custom redesigned analog receiver boards developed by Larry D'Addario

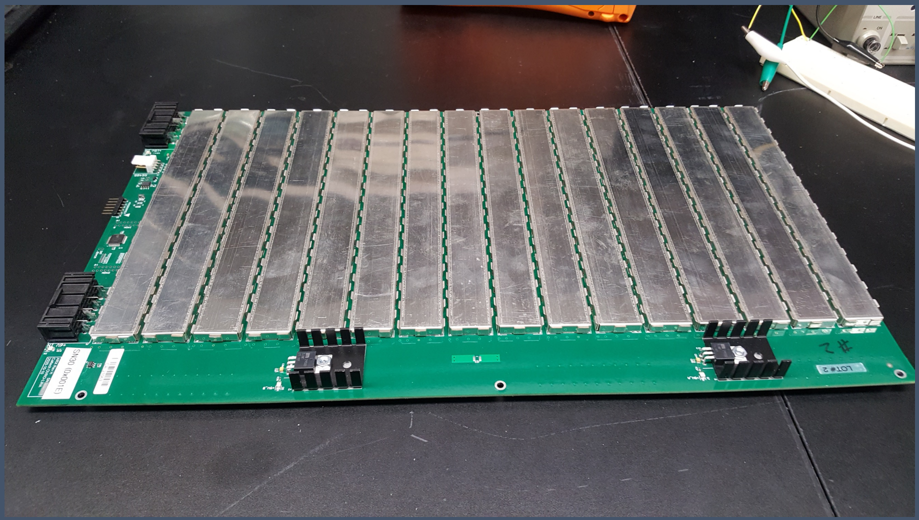


Source: Larry D'Addario

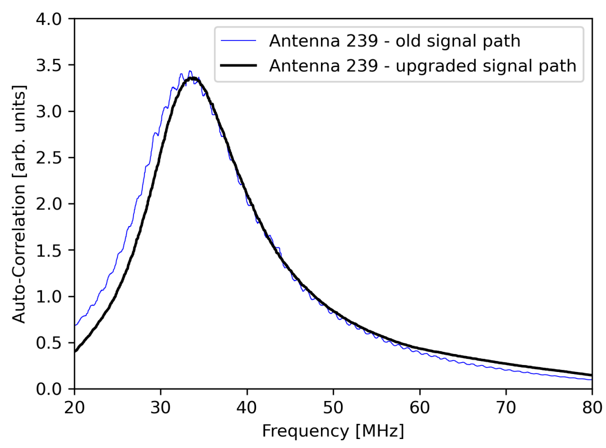


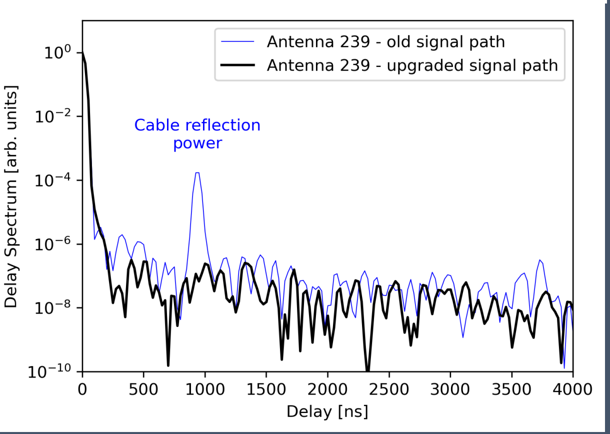

Source: Gregg Hallinan

# Analog Receiver



Source: Larry D'Addario



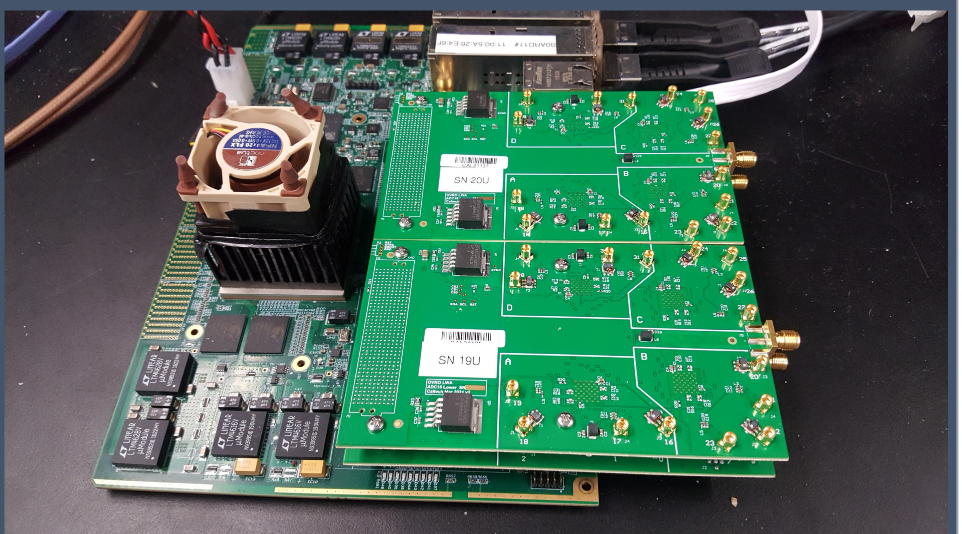




Source: Katherine Elder, Judd Bowman

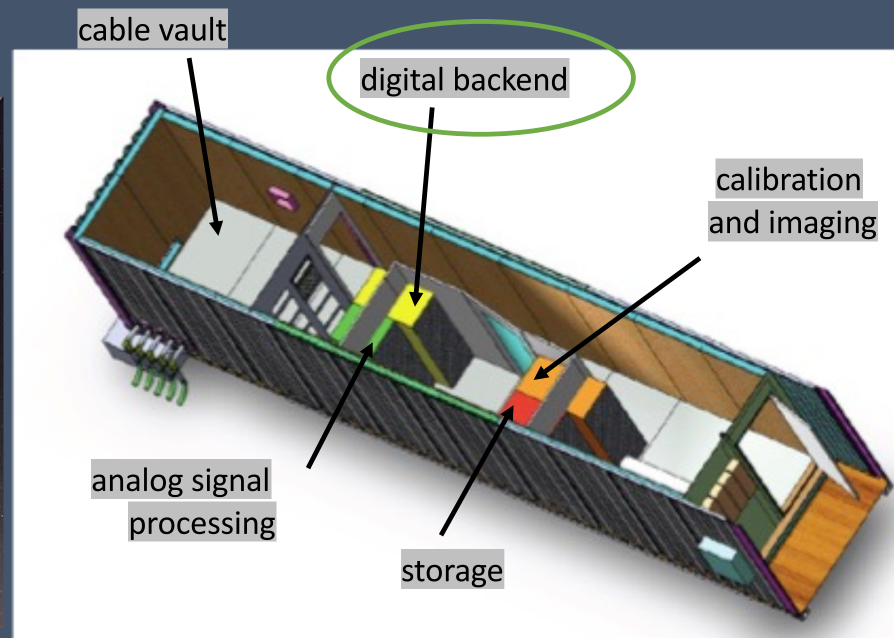
- 120 dB signal path isolation
- Improved performance at low frequencies
- Greatly reduced common mode noise, intermod products
- Reduced reflections

# Digitization and Channelization

- Custom ADCs (Larry D'Addario, Jack Hickish)

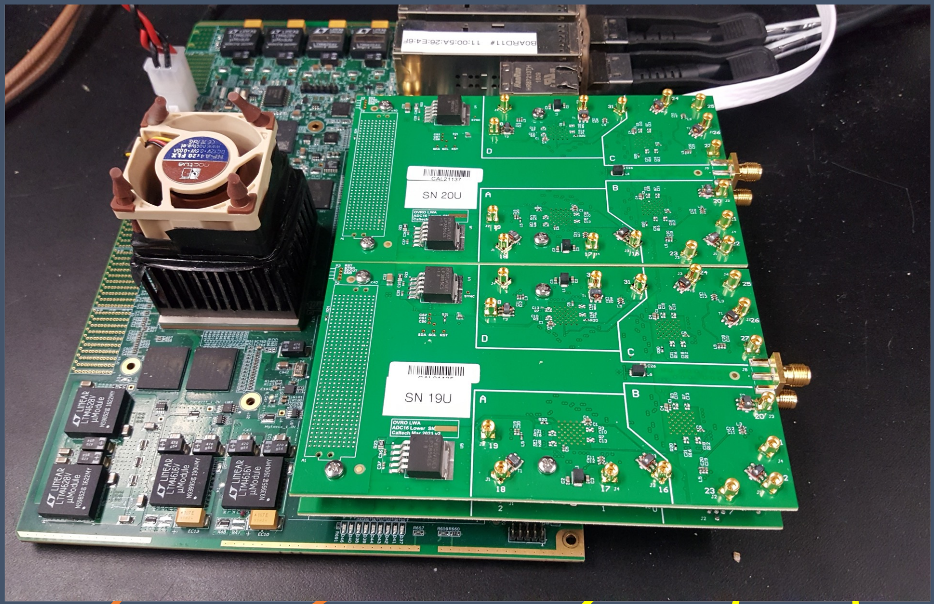



Source: Jack Hickish




Source: Gregg Hallinan

# Digitization and Channelization



SNAP2

Kintex Ultrascale 115

Custom ADC boards
Enabling 64x 10-bit ADCs
(ADS5296A)

Developed by Larry D'Addario

64 analog RF inputs
(coax)

1GbE
control

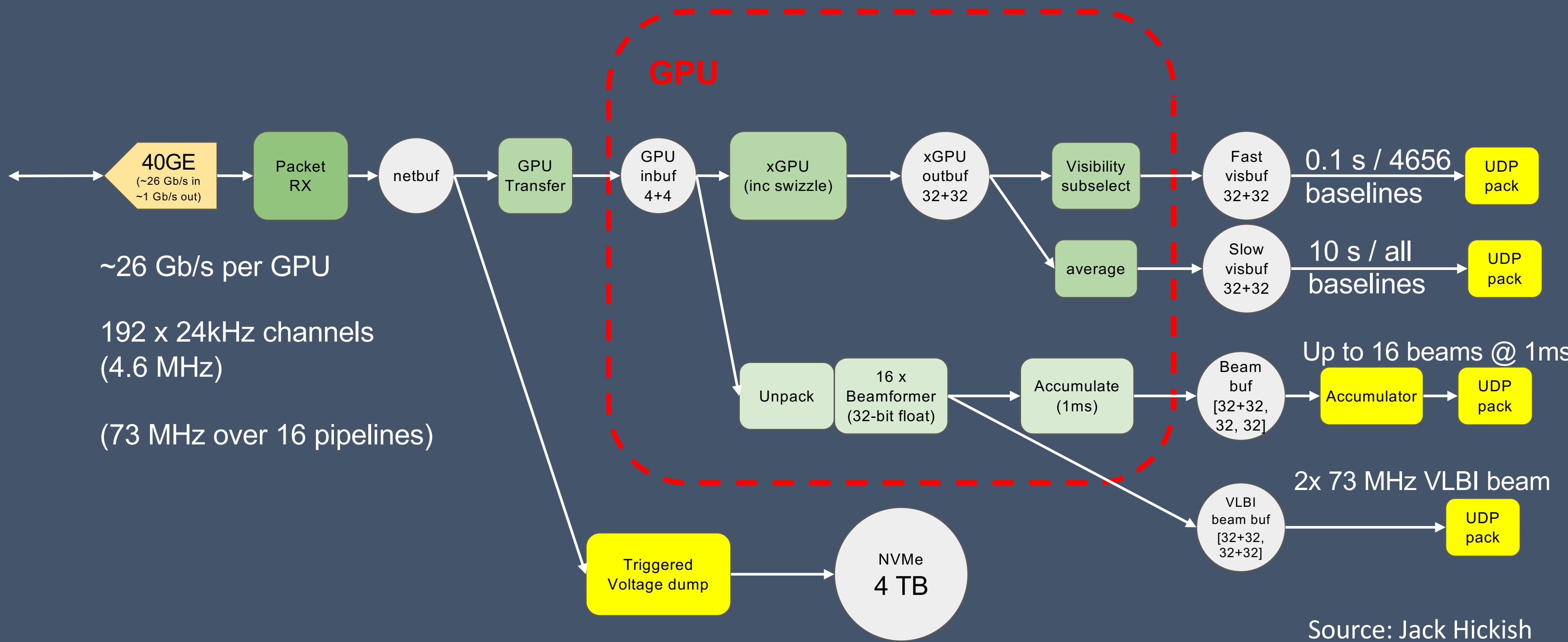
Cosmic Ray
Triggers / data

40 Gb Ethernet output
(4+4 bit; channelized @ 24kHz)

**Credit: Jack Hickish**

# All-singing, All-dancing Digital Back-end

**GPU: 16 x NVIDIA GeForce RTX 2080 Ti**



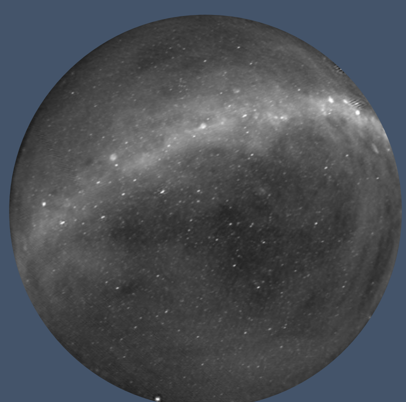

Source: Jack Hickish

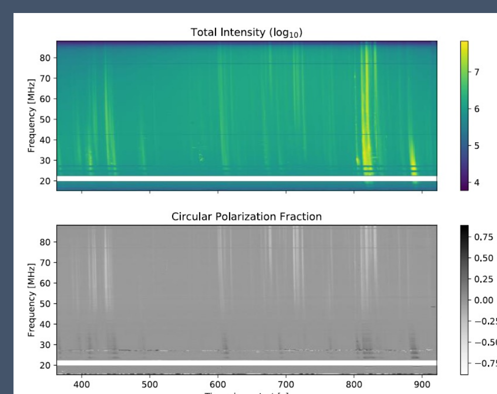
# All-singing, All-dancing Digital Back-end

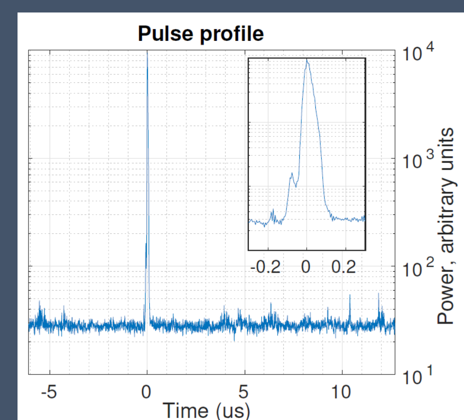
**Simultaneous…**

- 704-input full cross-correlation
- 96-input full cross-correlation
- 12 independently steerable beams
- 2x VLBI beams
- Cosmic-ray detection
- Voltage buffer

10 s → 0.1 s → 1 ms → 1 ns

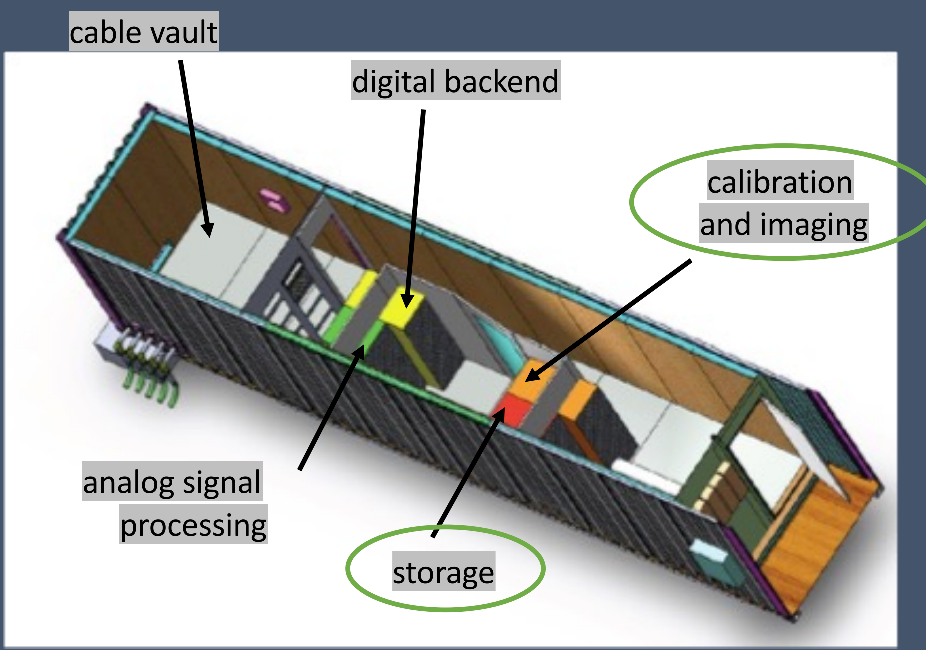




# Cal/Im Cluster

- New computing cluster and storage system dedicated to OVRO-LWA data
- 528 cores
- 5.6 TB of RAM
- 5 PB of storage




Source: Gregg Hallinan

# Science Cases

1. All-sky imaging
2. Extrasolar space weather
3. Exoplanets
4. Solar dynamic imaging
5. Gravitation wave/FRB event follow-up
6. Cosmic Rays
7. Cosmic Dawn

# Science Cases

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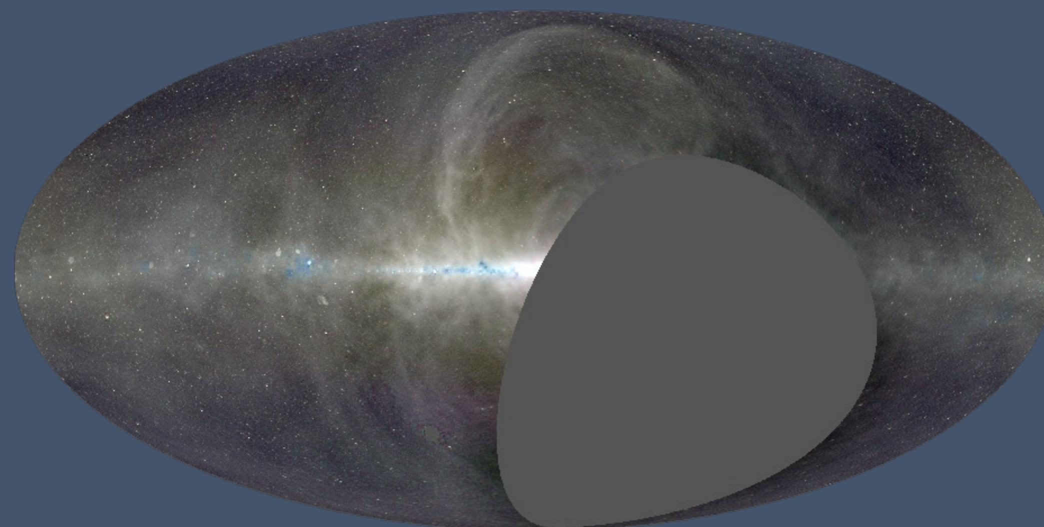
# All-Sky Imaging with m-Mode Analysis

- m-mode analysis with Tihkonov regularization (Eastwood et al. 2018, 2019; technique based on Shaw et al. 2014, 2015)
- Stage III
  - 1000-hour integrations with upgraded array
  - Incorporating physical beam models
  - Fully polarized



m-mode mapping result from the OVRO-LWA Stage II
Source: Eastwood et al. 2018

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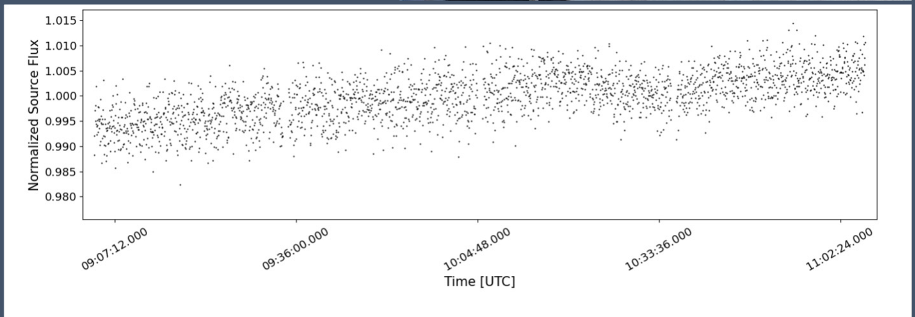
# Monitoring Extrasolar Space Weather with Flarescope (Ivey Davis)

- Small optical telescope at Palomar Observatory
- Coordinated with single beam from OVRO-LWA
- Automated observing
  - Dedicated to small sample of nearby, sun-like stars
  - Looking for white-light component of flares from coronal mass ejections (CMEs) and solar energetic particle events (SEPs)
- 0.5m aperture
  - 13’ x 13’ FOV
  - 0.7”/px
  - ~1s kinetic cycle time
- mmag precision
  - 5 min integration time
  - Objects brighter than 10th mag in *g’* band



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# Detection of Explanet Auroral Emission

Type II/III radio bursts

Auroral radio emission

Source: Chuck Carter & Caltech/KISS

- Search for time-variable Stokes V emission
- Leveraging all-sky m-mode analysis imaging pipeline

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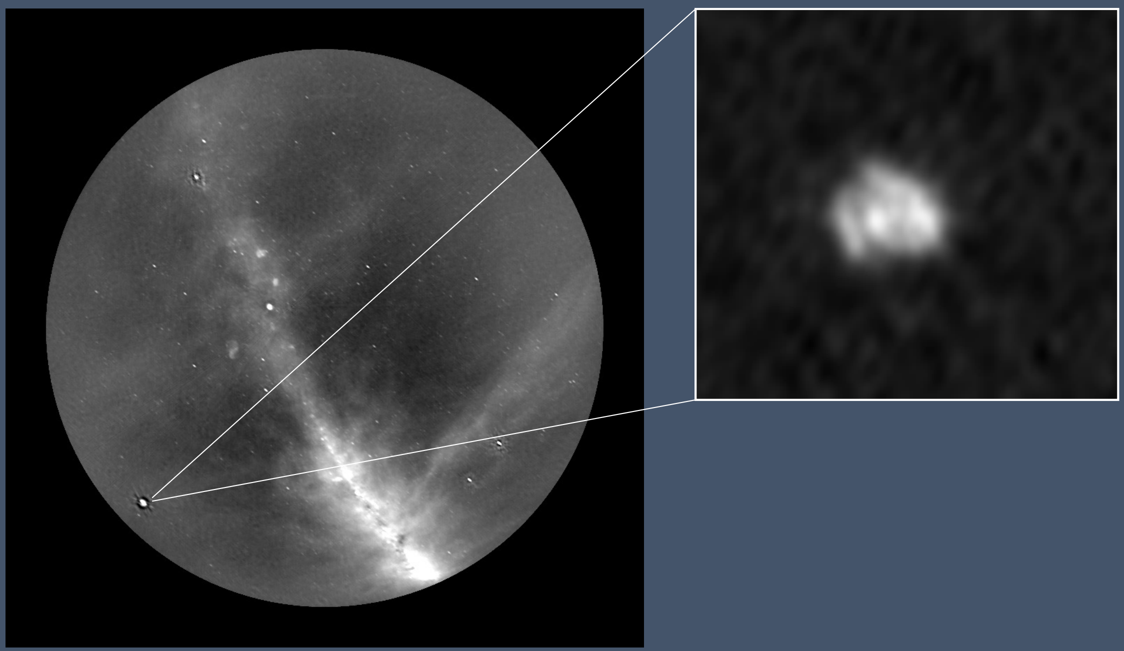
# Solar Monitoring



results from the OVRO-LWA Stage II
Source: Chhabra et al. 2021

- Continuous daytime monitoring of the Sun
- Three timescales:
  - Dedicated solar beam – 1 ms
  - Selected baselines – 100 ms
  - Full cross-correlation – 10s

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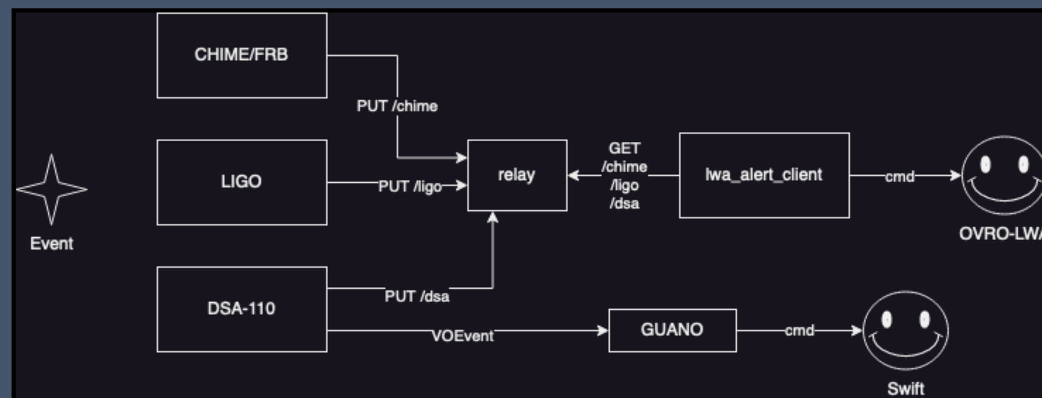
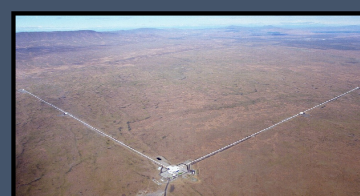
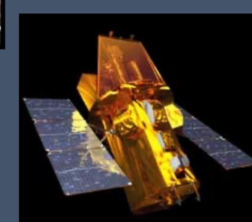
# Triggered Observing with the OVRO-LWA

(Casey Law)

- Event
  - LIGO NS merger
  - CHIME FRB
  - DSA-110 FRB
- Response
  - 8x8 TB voltage (retroactive all-sky ms imaging)
  - low-latency power beam
  - high-energy all-sky buffer and repointing
- ovro-alert: Code for astronomical alerts at OVRO (https://github.com/ovrocaltech/ovro-alert)





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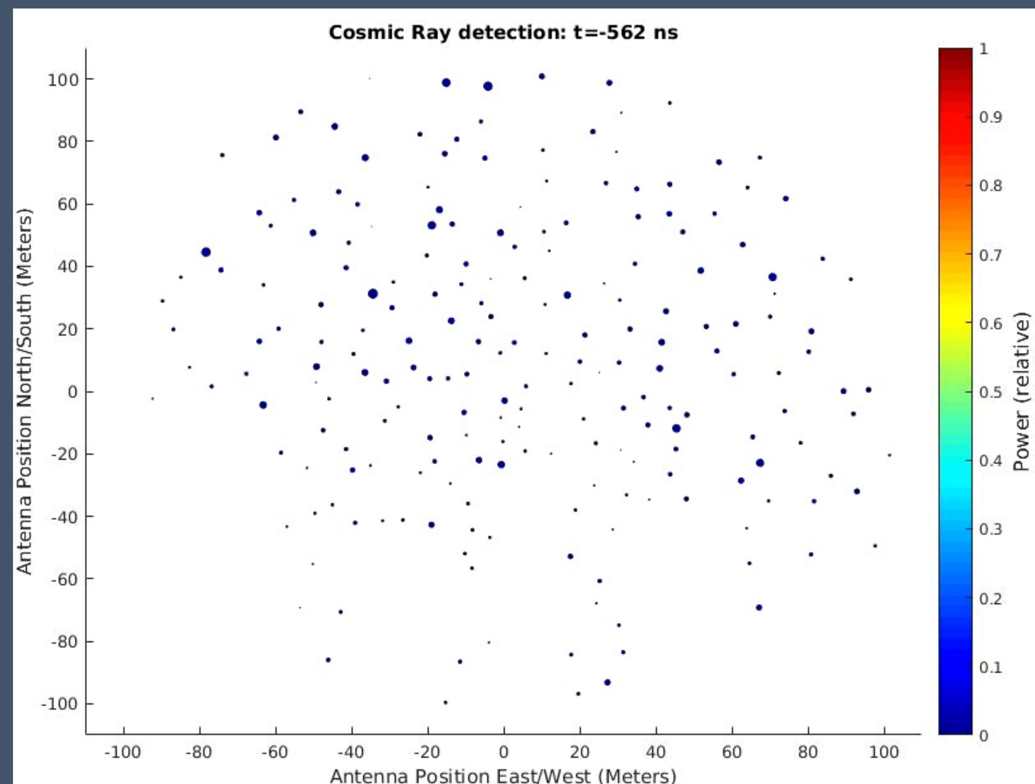
# Cosmic Ray Detection

- Radio-only detection of cosmic-rays demonstrated with Stage II
- Continuous monitoring with Stage III (Kathryn Plant)
- 8000 events per year will be detected with Stage 3 array in the energy range $10^{16.5} – 10^{18}$ eV
- $X_{max}$ = 20g/cm$^2$ per event




results from the OVRO-LWA Stage II
Source: Monroe et al. 2019

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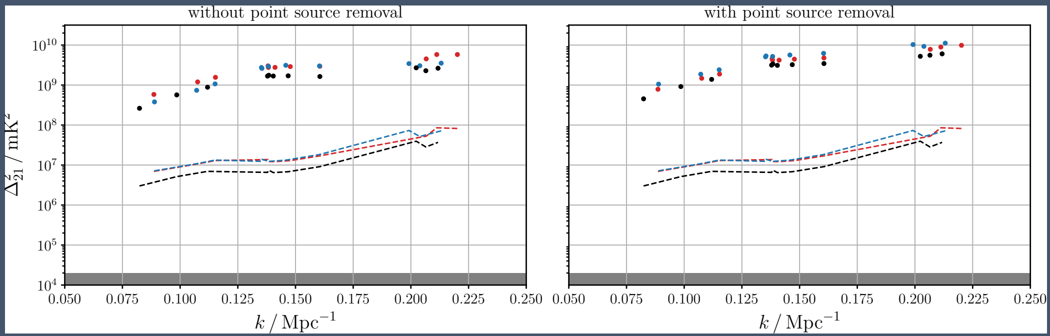
# 21 cm Constraints on the Cosmic Dawn

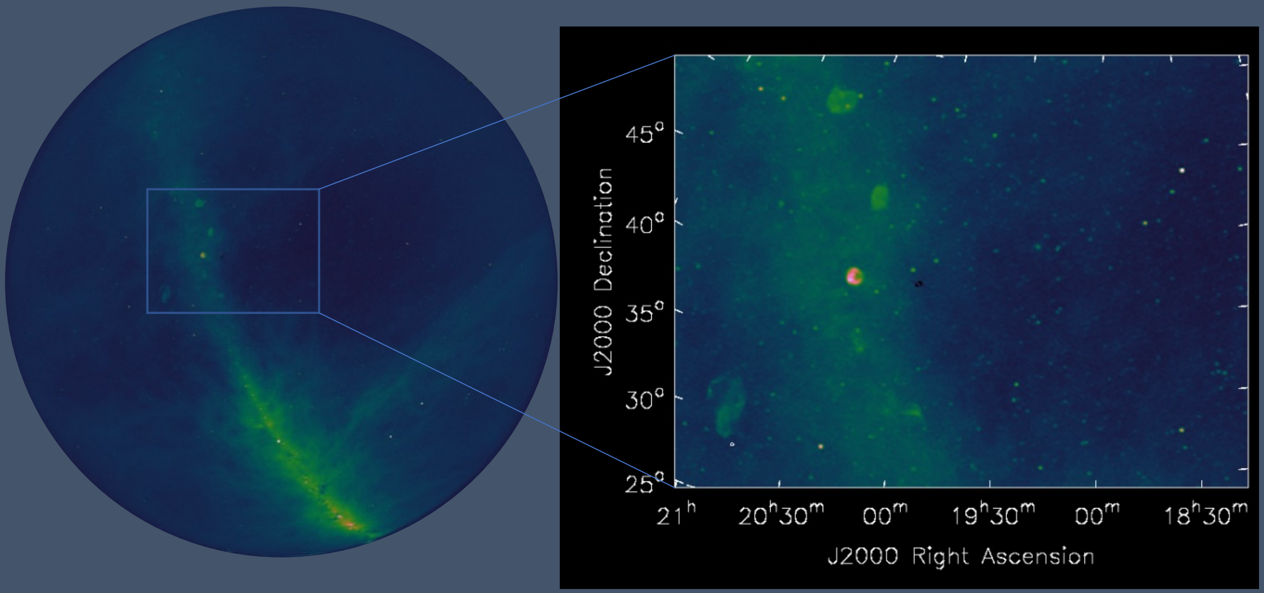
- Non-constraining limit on the 21 cm power spectrum from Stage II: $\Delta_{21} < 10^4$ mK at $z \approx 18.4$
- New 21 cm pipeline with Stage III focused on systematics mitigation
  - Signal path isolation to mitigate cross-talk
  - Reduced signal reflection
  - Precision beam mapping and calibration
  - State of the art analysis pipeline




results from the OVRO-LWA Stage II
Source: Eastwood et al. 2019

# *Where are we now?*

- Currently wrapping up commissioning Stage III and bringing the last outrigger antennas online
- Success making high-fidelity images with just 10 seconds of data!
- Longer integrations and upgraded analyses are forthcoming




Preliminary OVRO-LWA Stage III imaging results
Source: Gregg Hallinan

# Conclusions

- Massive upgrade to the OVRO-LWA with Stage III
  - Now 352 antennas
  - Baselines up to 2.4 km
  - Improved signal processing backend
- Lots of science underway:
  - All-sky imaging
  - Extrasolar space weather
  - Exoplanets
  - Solar dynamic imaging
  - LIGO follow-up
  - Cosmic Rays
  - Cosmic Dawn