Fine Structure in Jovian Decametric Emission: LWA1 Observations

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Long Wavelength Array (LWA1), Socorro, NM

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The LWA1 Array

A collaboration of the following institutions: U. New Mexico, Virginia Tech, Los Alamos NL, JPL, and the Naval Research Lab.

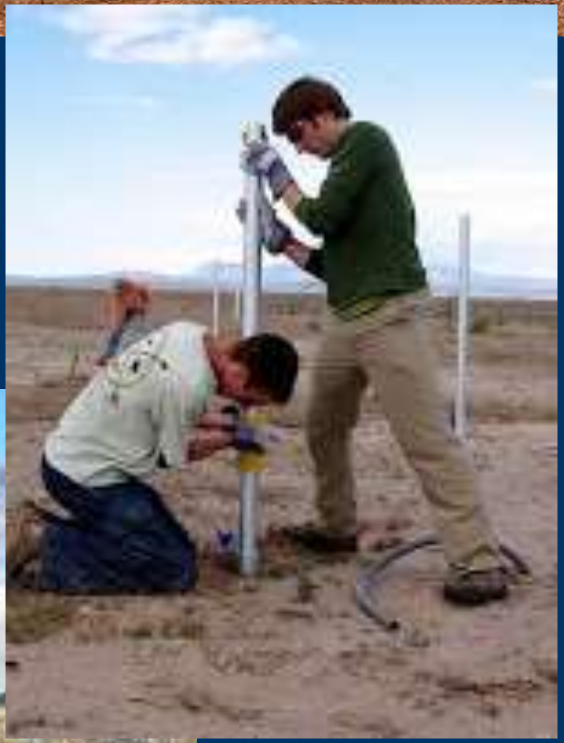
Recent additions: Caltech, Harvard, NRAO and Air Force Research Lab

From Imai et al., 2013

Why the LWA Array?

[from S. W. Ellingson, IEEE, 2005]

- f < 100 MHz "under-explored" in astronomy
- Ionosphere turbulence (opaque below 10 MHz)
- Filled aperture antennas are impractical



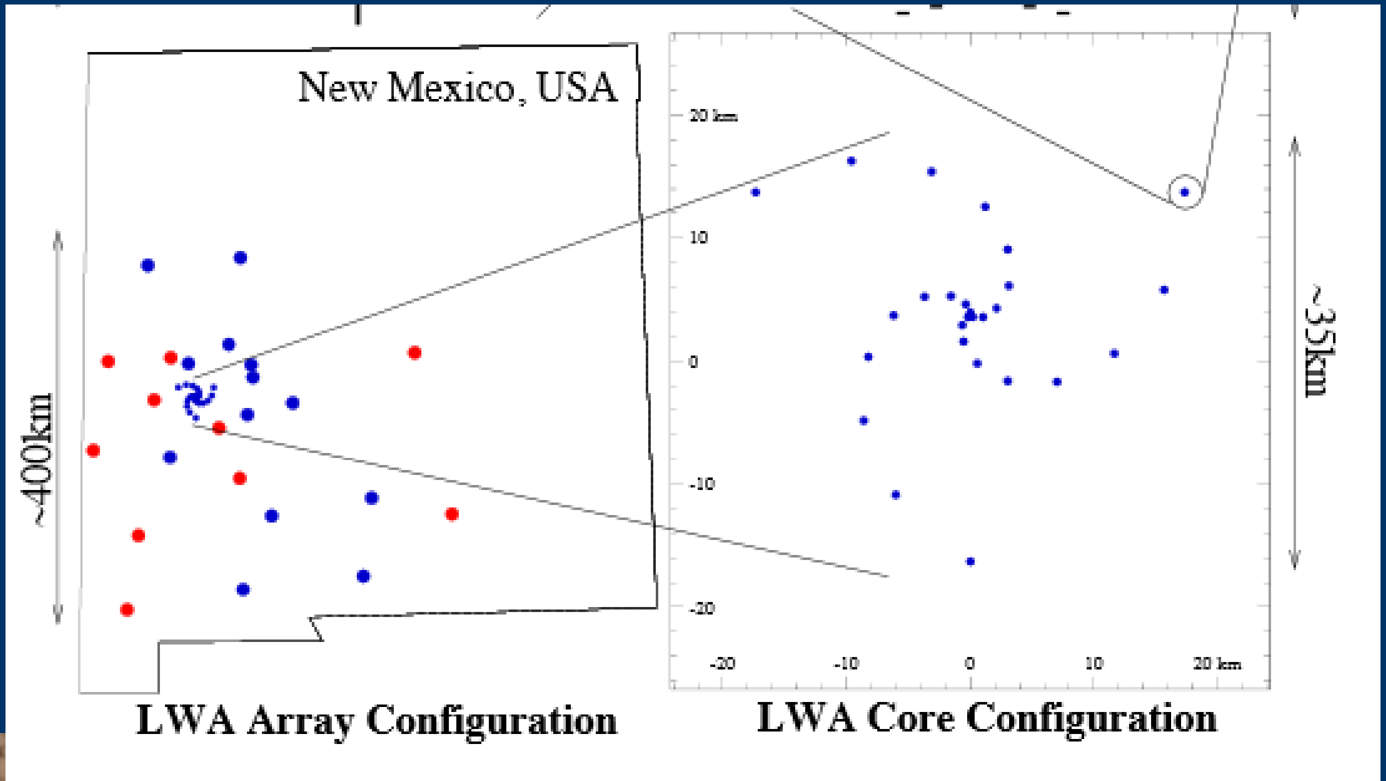
Why a revived interest?

- Technology allowed mitigation of the ionospheric turbulence giving sub-arcminute resolution
- Cost and technology improved
- Interesting astrophysical questions

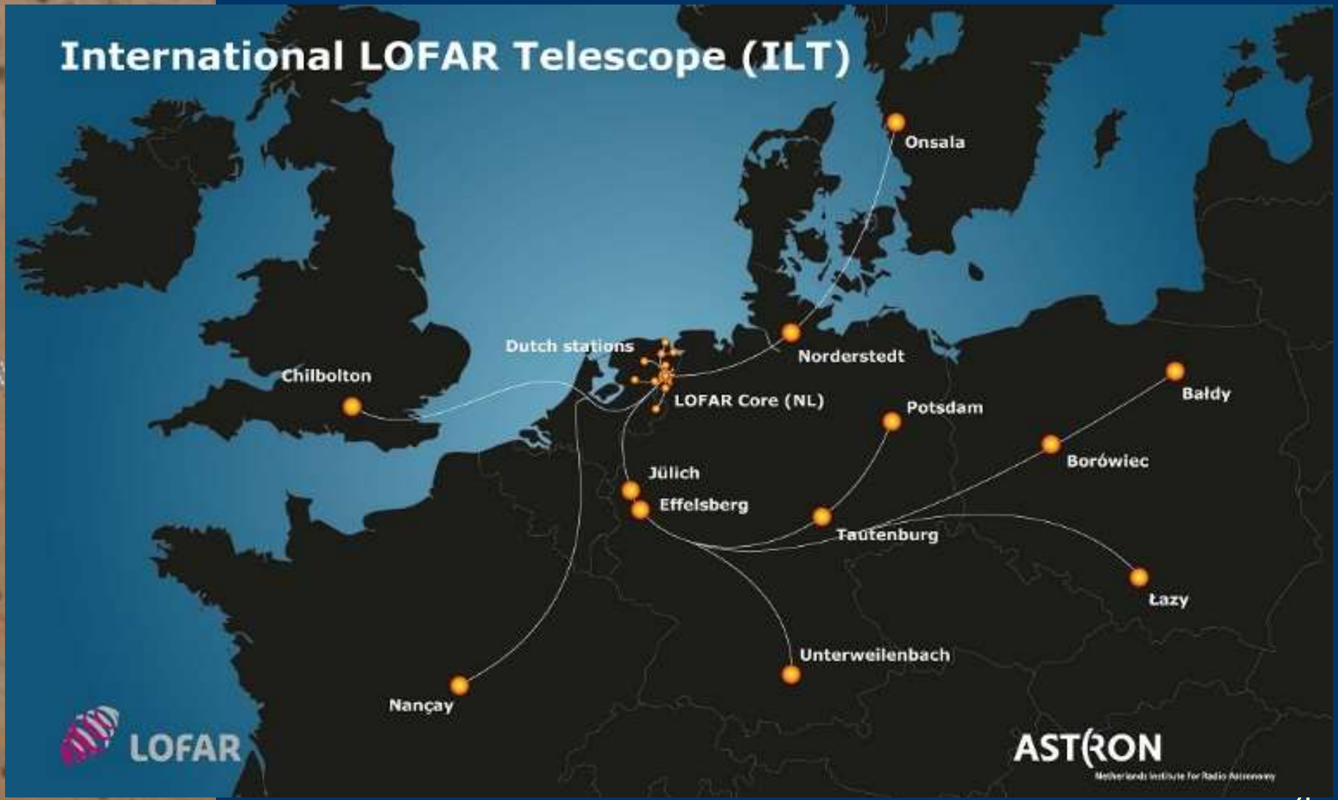
A New Era in Radio Astronomy

Three new arrays

- Long Wavelength Array (LWA), New Mexico, USA
- Low Frequency Array (LOFAR), Netherlands and Europe, 10-240 MHz
- Murchison Wide-Field Array (MWA), Western Australia, 80-300 MHz



Murchison Wide-Field Array (MWA)



The LWA1 Array

Basic Statistics (from Ellingson, IEEE, 2013)

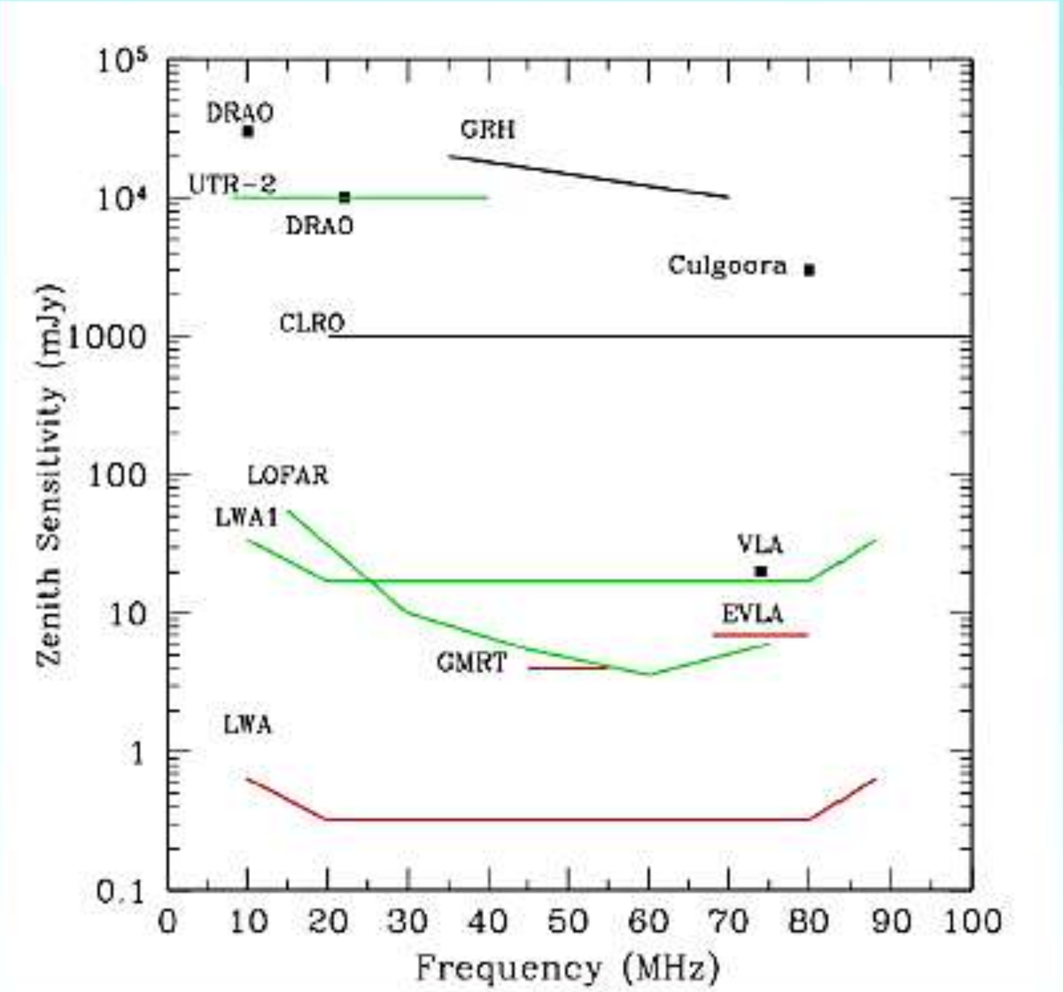
Location	Socorro, NM, near the VLA
Bandwidth	10-88 MHz
Antennas	256 crossed-dipoles (sky noise dominated)
Beams	4 independently-steerable 2 tunings per beam
Polarizations	Dual linear
Bandwidth	< 16 MHz x 2 tunings X 4 beams
Beam FWHM	< 3.2° × [(74 MHz)/ν]
Instrument Sensitivity	6 kJy zenith System Equiv. Flux Density [1 Jy = 10^{-26} W/m^2/Hz]
Beam Sensitivity	≈ 8 Jy (5σ) for 1 s, 16 MHz, Z = 0 (inferred from SEFD)

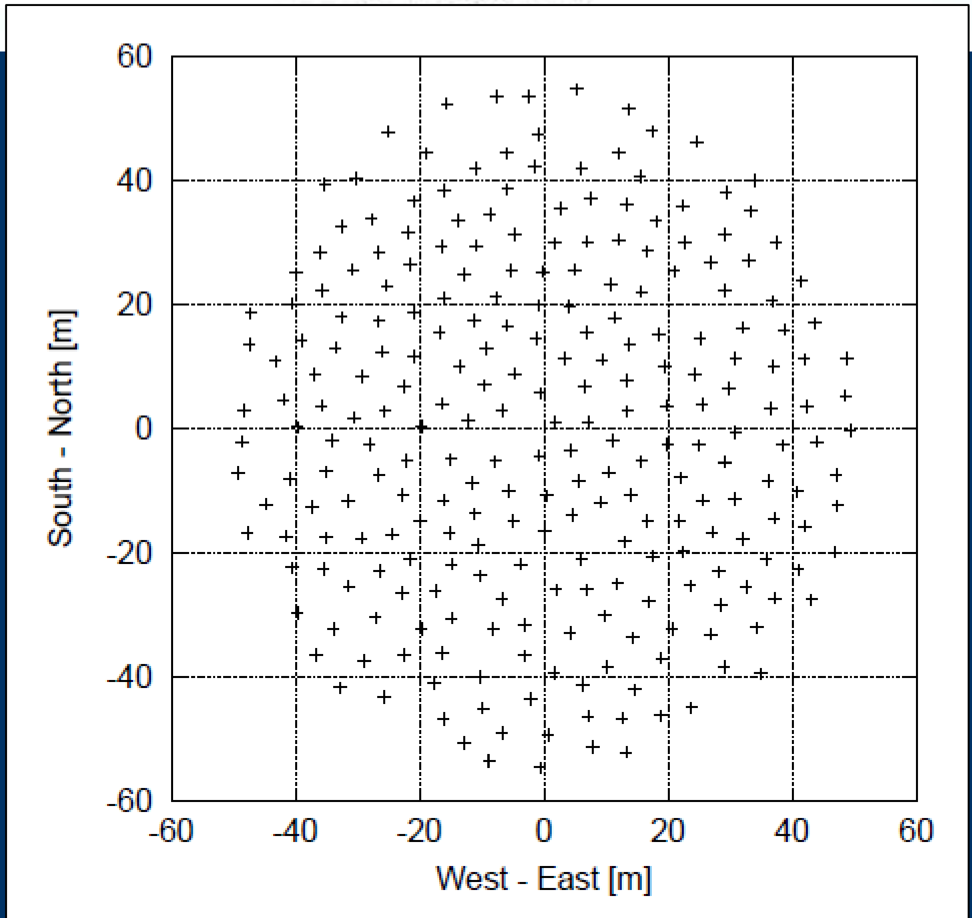
Array Geometry

256 Antenna stands, 100 m x 110 m elliptical footprint + 2 outrigger antennas for calibration

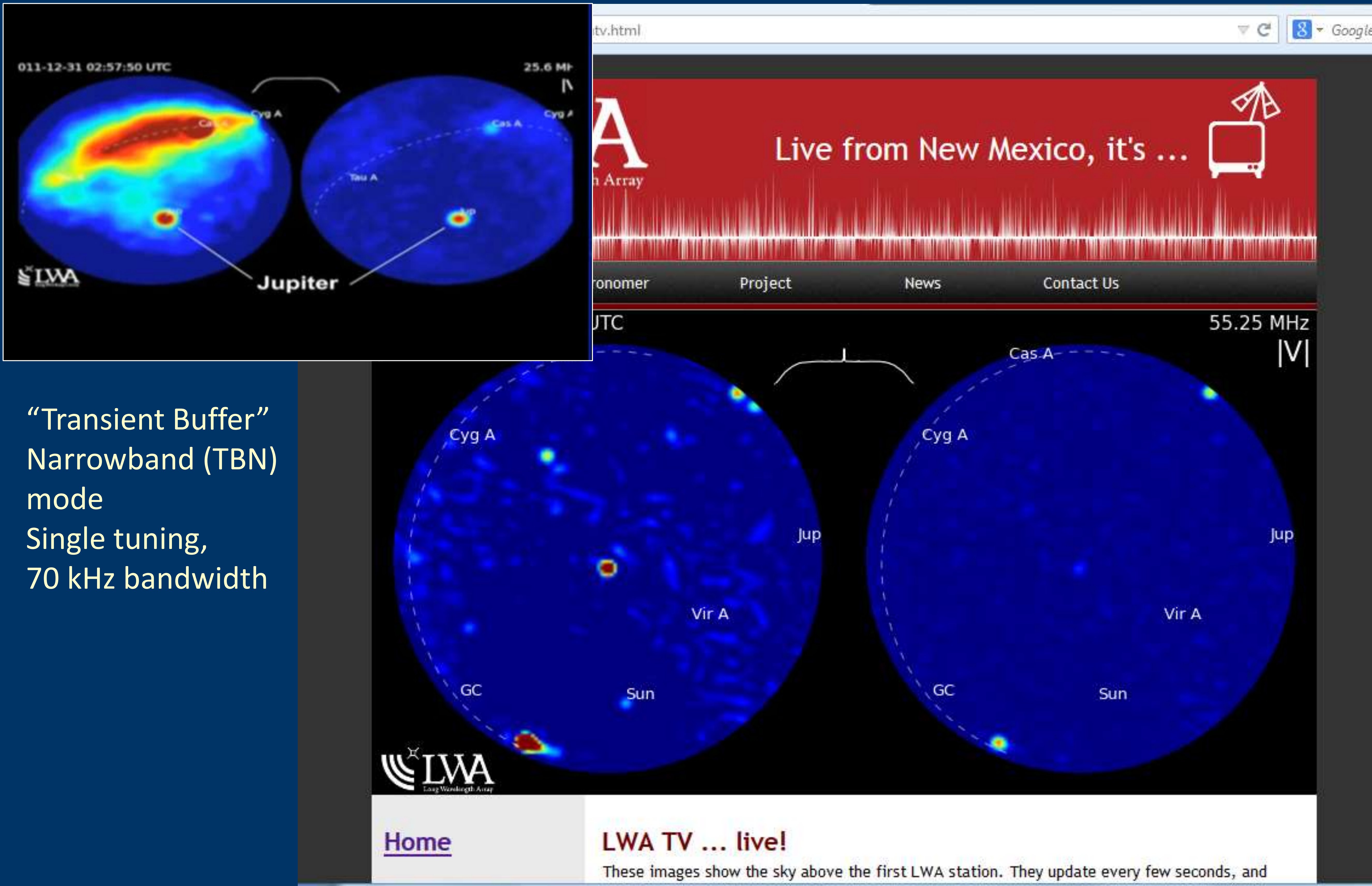
Pseudo-random arrangement – to suppress aliasing

COMPARING THE LWA TO OTHER INSTRUMENTS





The LWA TV – All-sky View

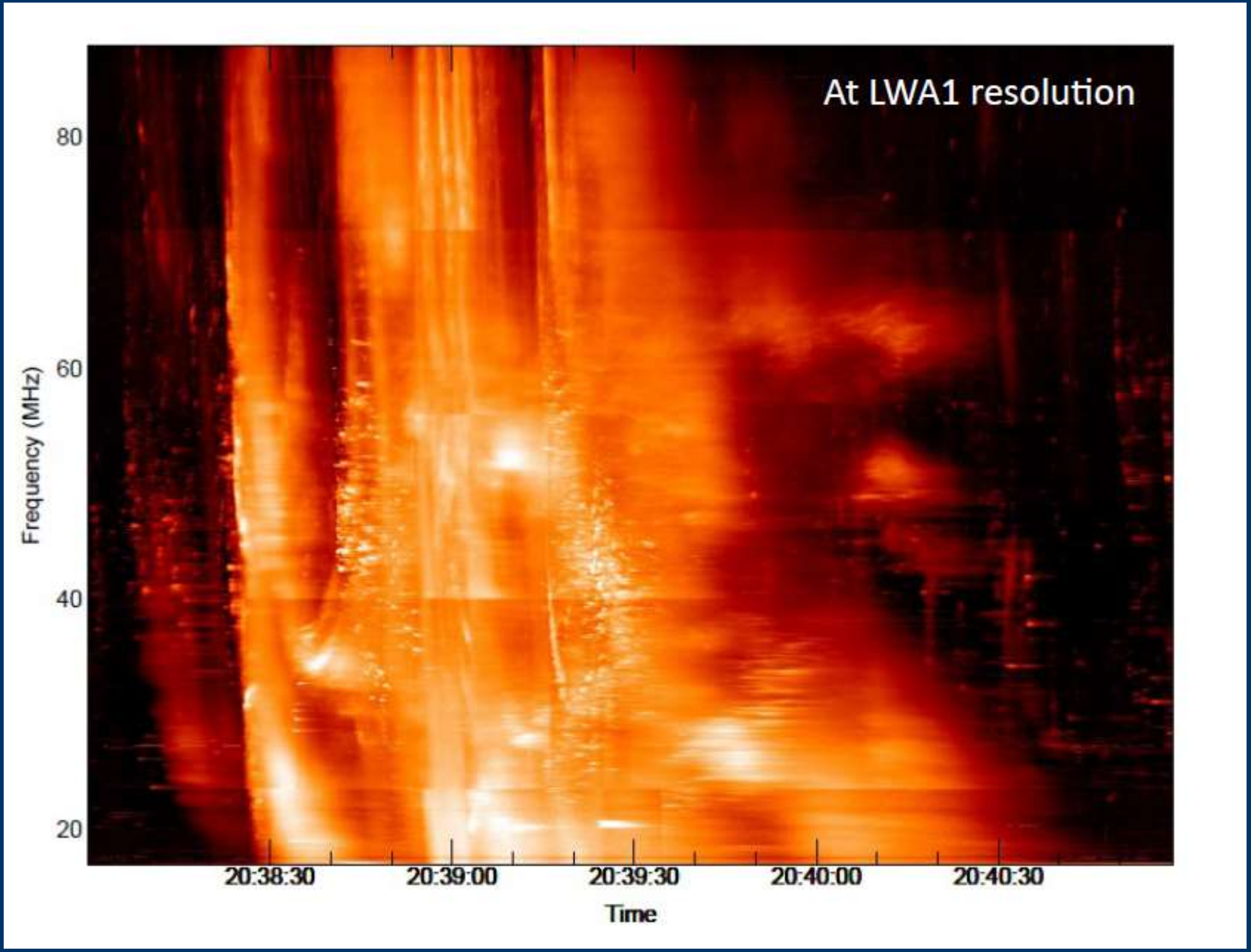


"Transient Buffer" Narrowband (TBN) mode

Single tuning,

70 kHz bandwidth

Solar Radio Emission

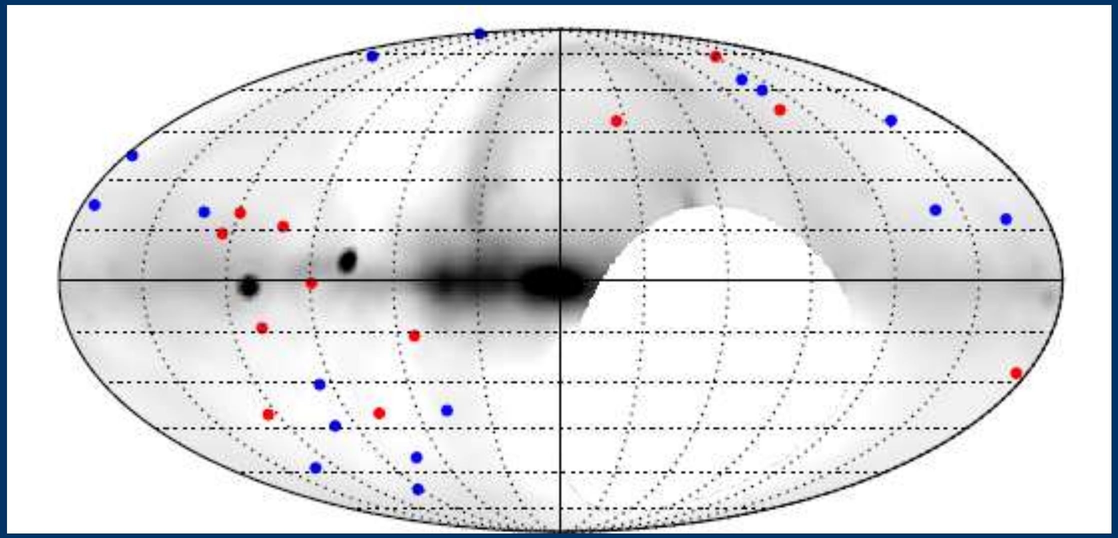


From Stephen White, AFRL

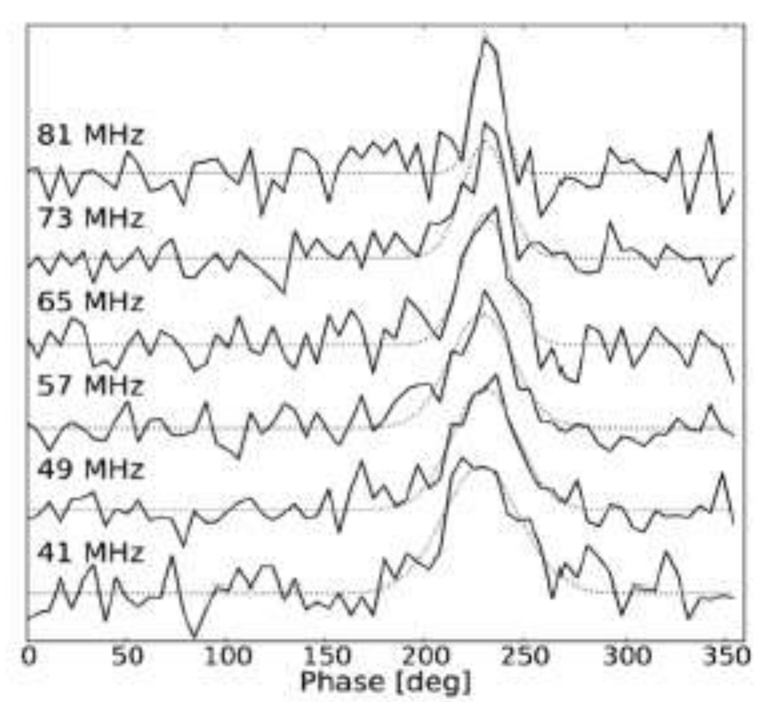
Other LWA Research

Transients (28 detections)
The Early Universe
The Galaxy
Pulsars (38 discoveries so far)
Fireballs and Meteors
Solar
Jupiter
Supernova Remnants
Ionosphere
ISM
Exoplanets (hot Jupiters)
GRBs (Gamma Ray Bursts)

Radio Transients

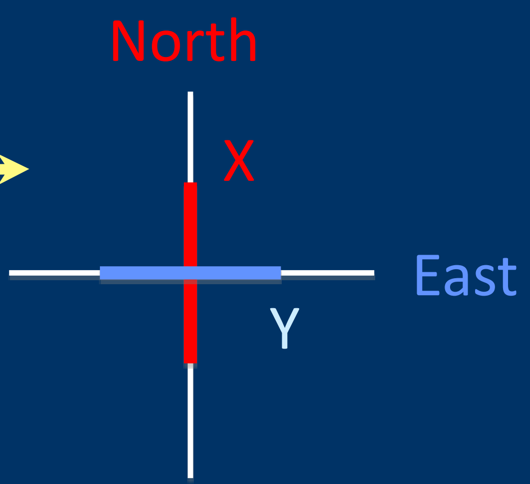


Obenberger et al. 2014



Millisecond Pulsar J2145-0750 with LWA1
Dowell et al. 2013; ApJL 775, L28

Data Reduction and Analysis



Basis change to r, l

$$r = \frac{(x + iy)}{\sqrt{2}}$$

$$l = \frac{(x - iy)}{\sqrt{2}}$$

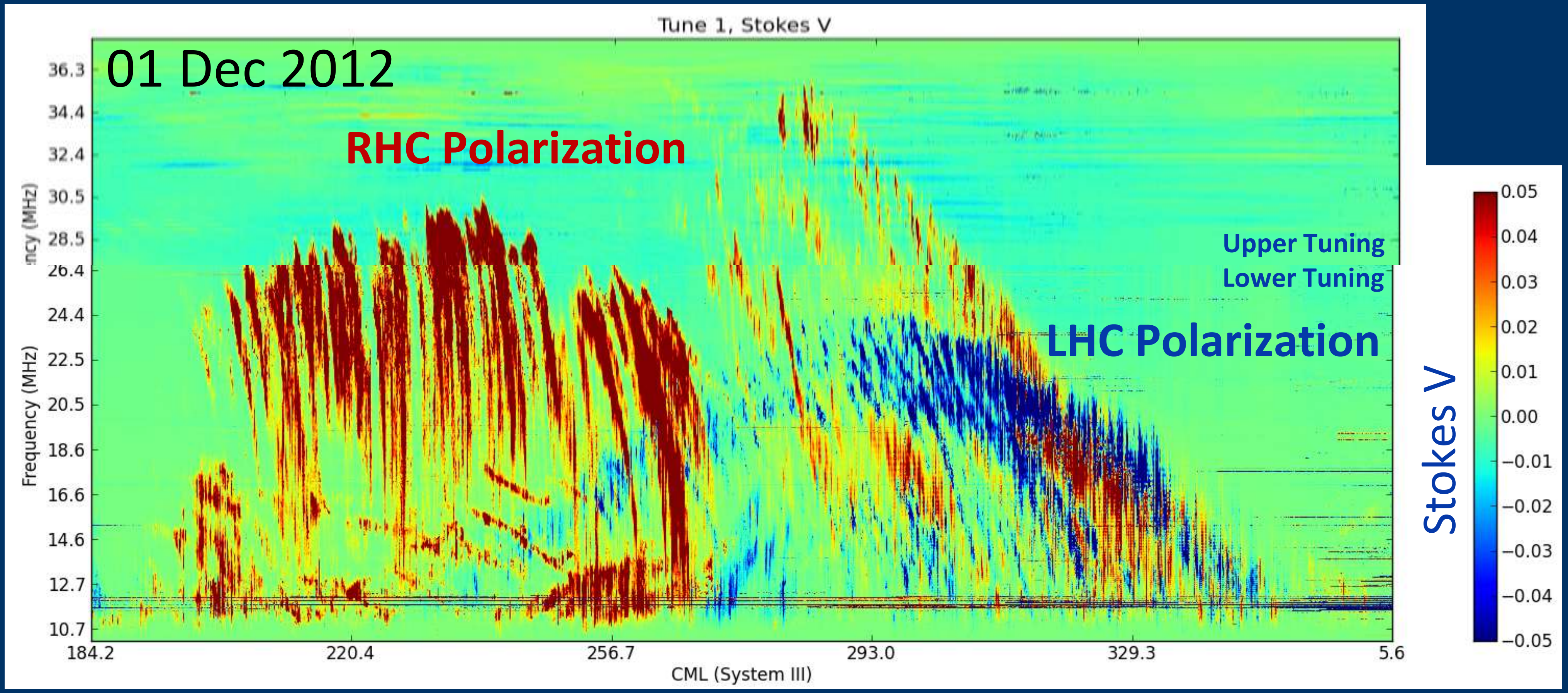
Use Fourier transforms to convert to frequency spectra

Convert to Stokes *V*

$V=R^2-L^2$

Output

Jupiter Spectra

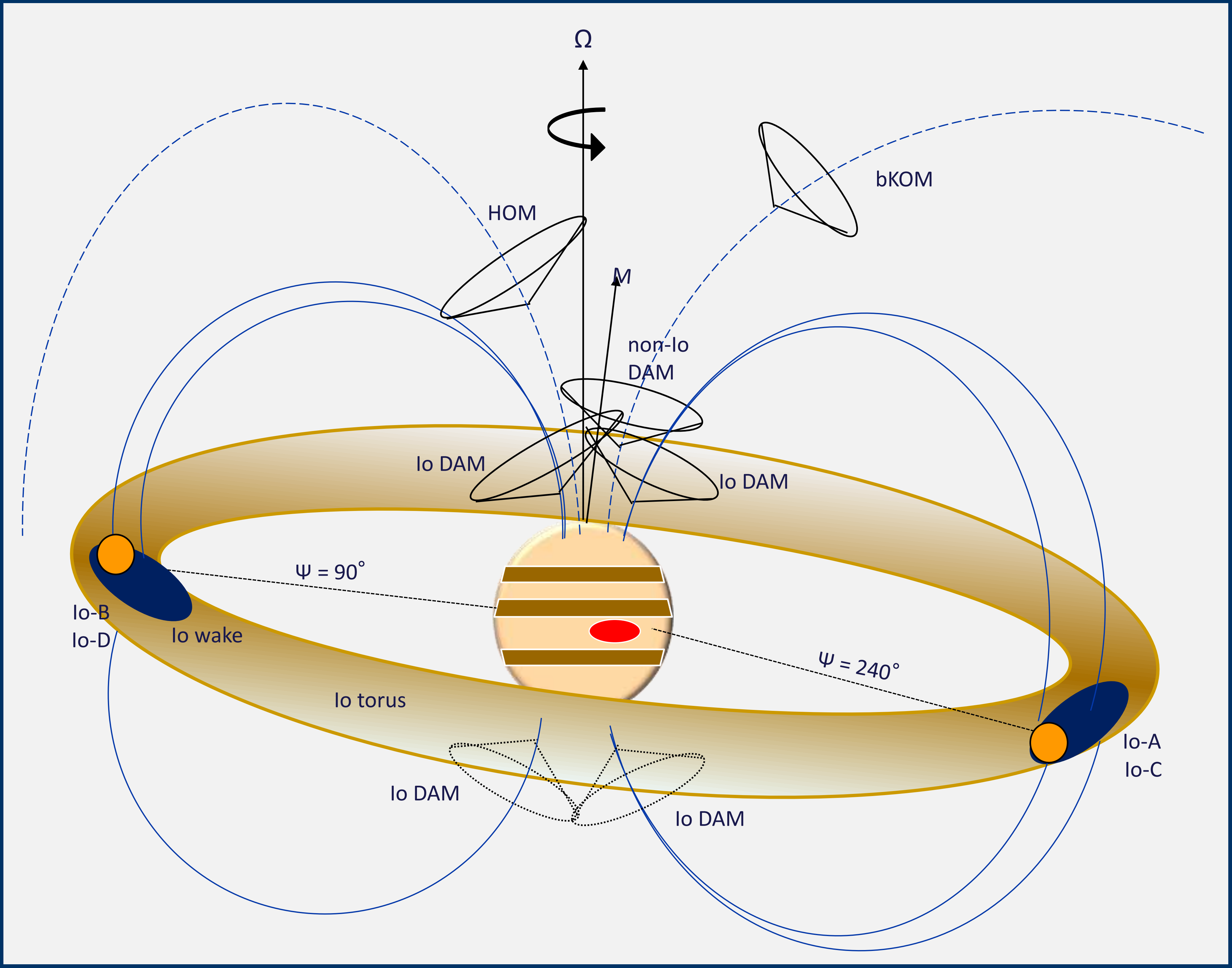


LWA1 Instrument

- Excellent observing conditions
- Fine Temporal & Spectral Resolution: 0.25 ms and 10 kHz

However,
Data Volume: up to ~1 TB/hour
LWA has 45 Data Recorder Storage Units (DRSUs) = ~ 500 TB total

Jupiter Radio Emission Overview



bKOM – broadband kilometric emission (auroral origins)

HOM – hectometric emission (auroral)

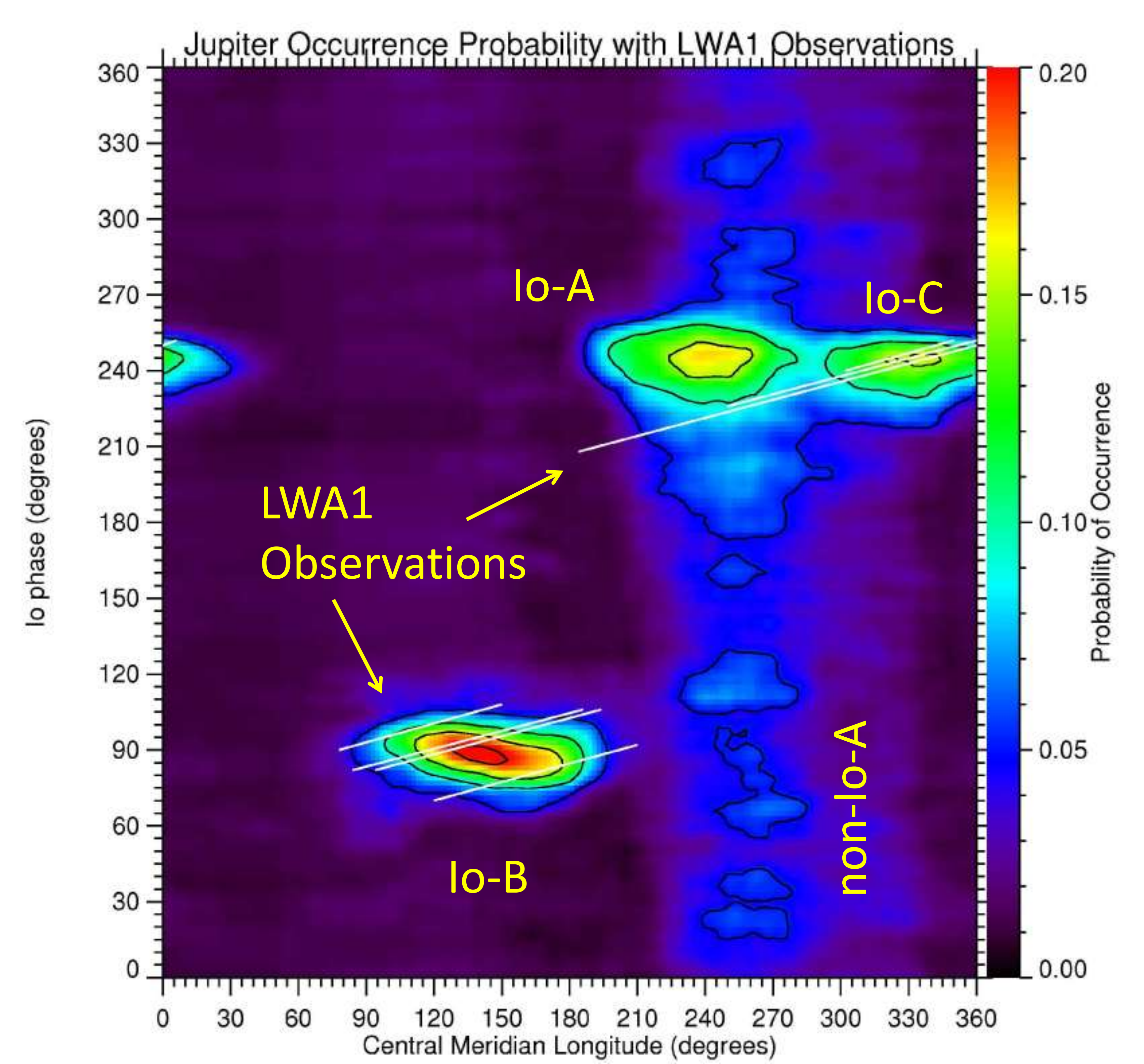
Non-Io-DAM – auroral decametric (related to HOM)

Io-DAM – decametric emission tied to Io flux tube and Io torus

DAM Occurrence Probability Maps

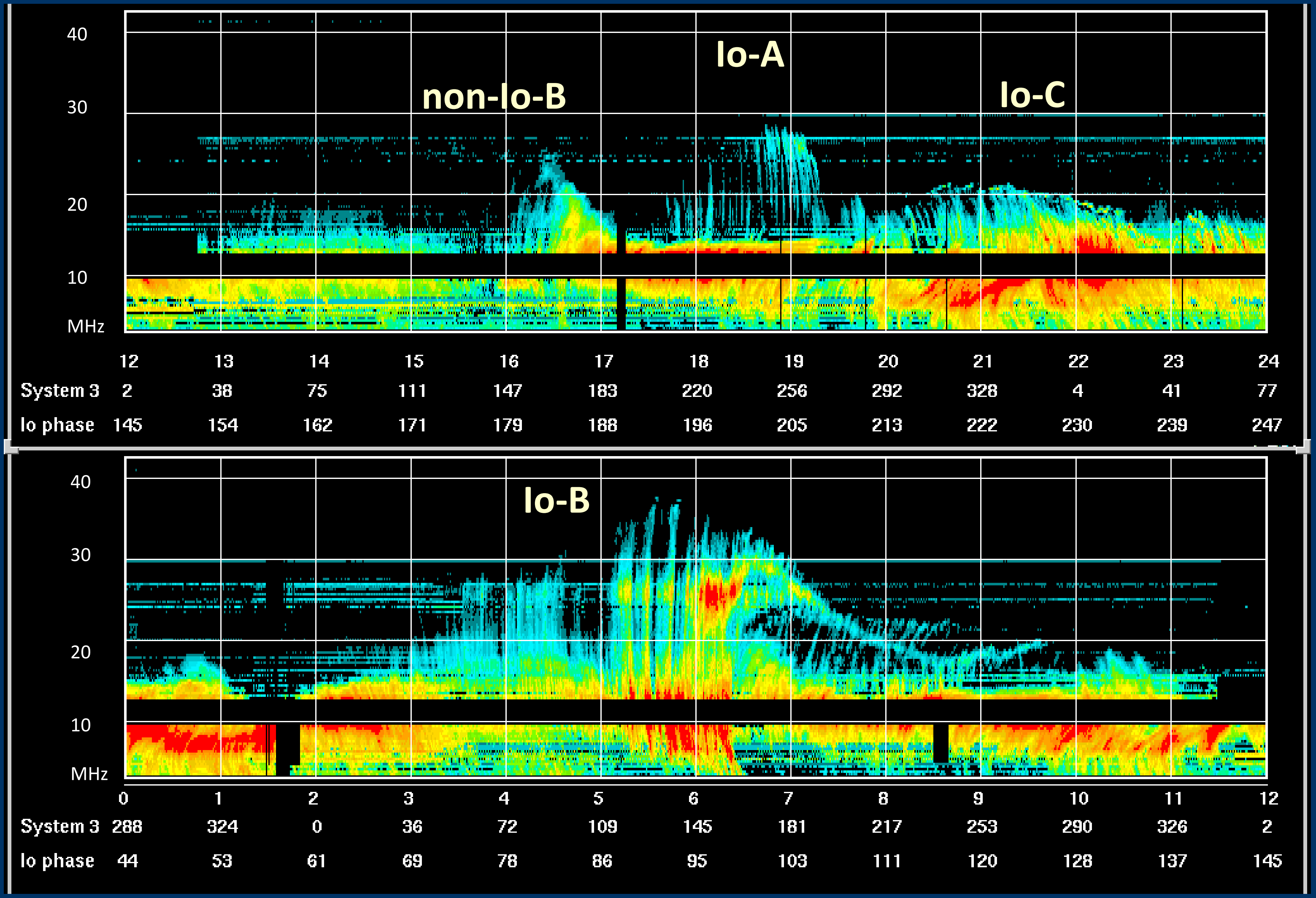
<u>Background</u>
50 years of University of Florida Radio Observatory (UFRO) data

<u>Initial LWA1 Observations</u>
Mar 2012 – Mar 2013

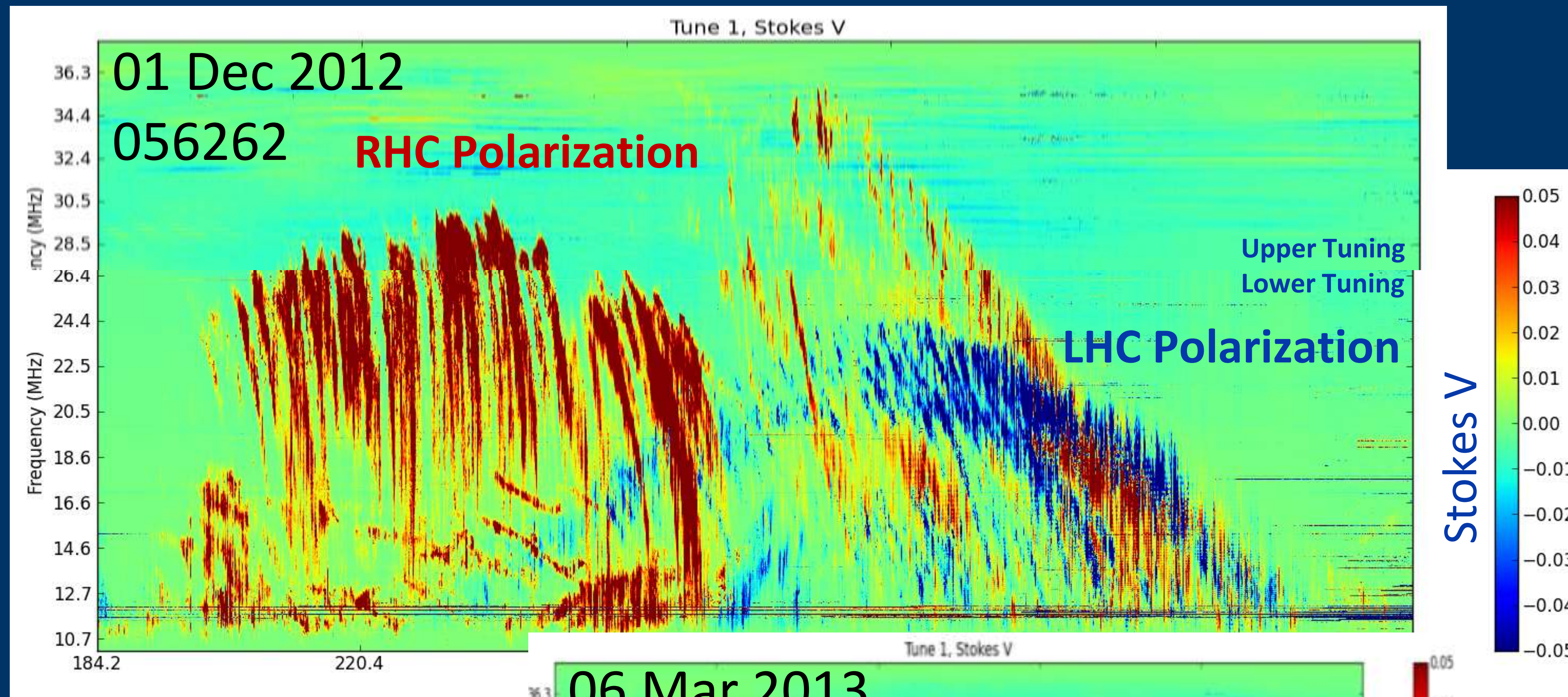


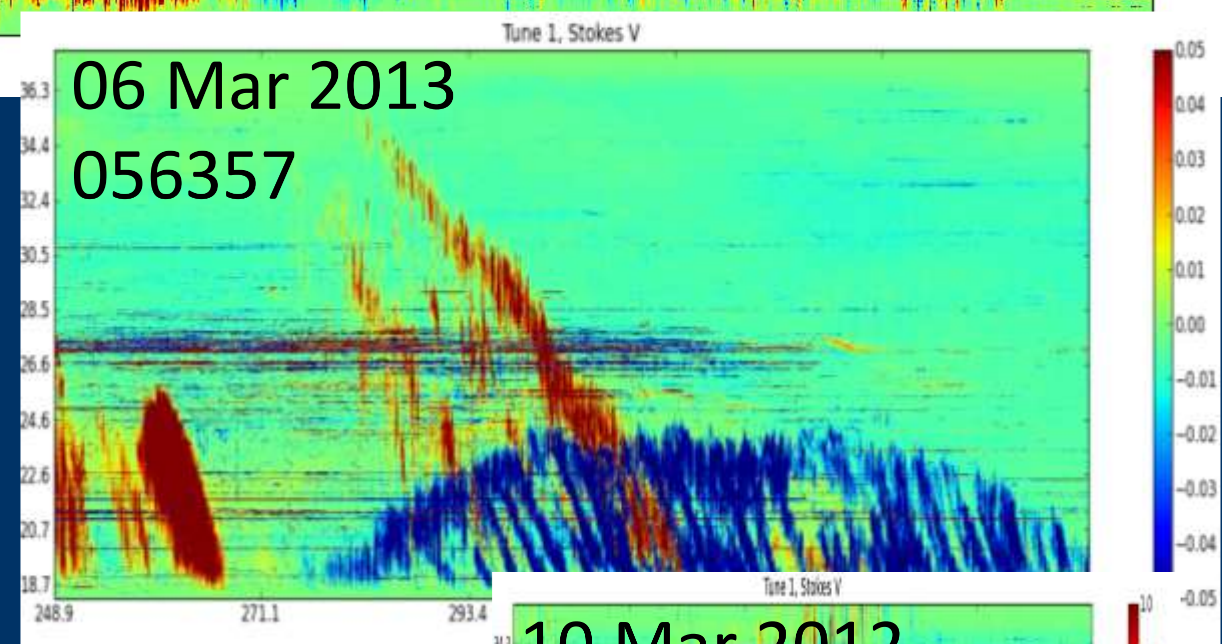
Voyager Observations (for comparison)

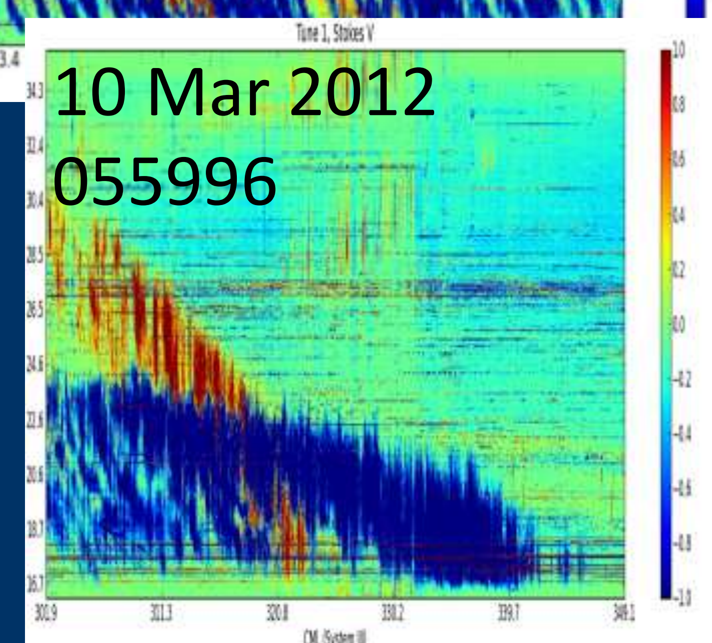
July 16, 1979



Io-A, Io-C Observations







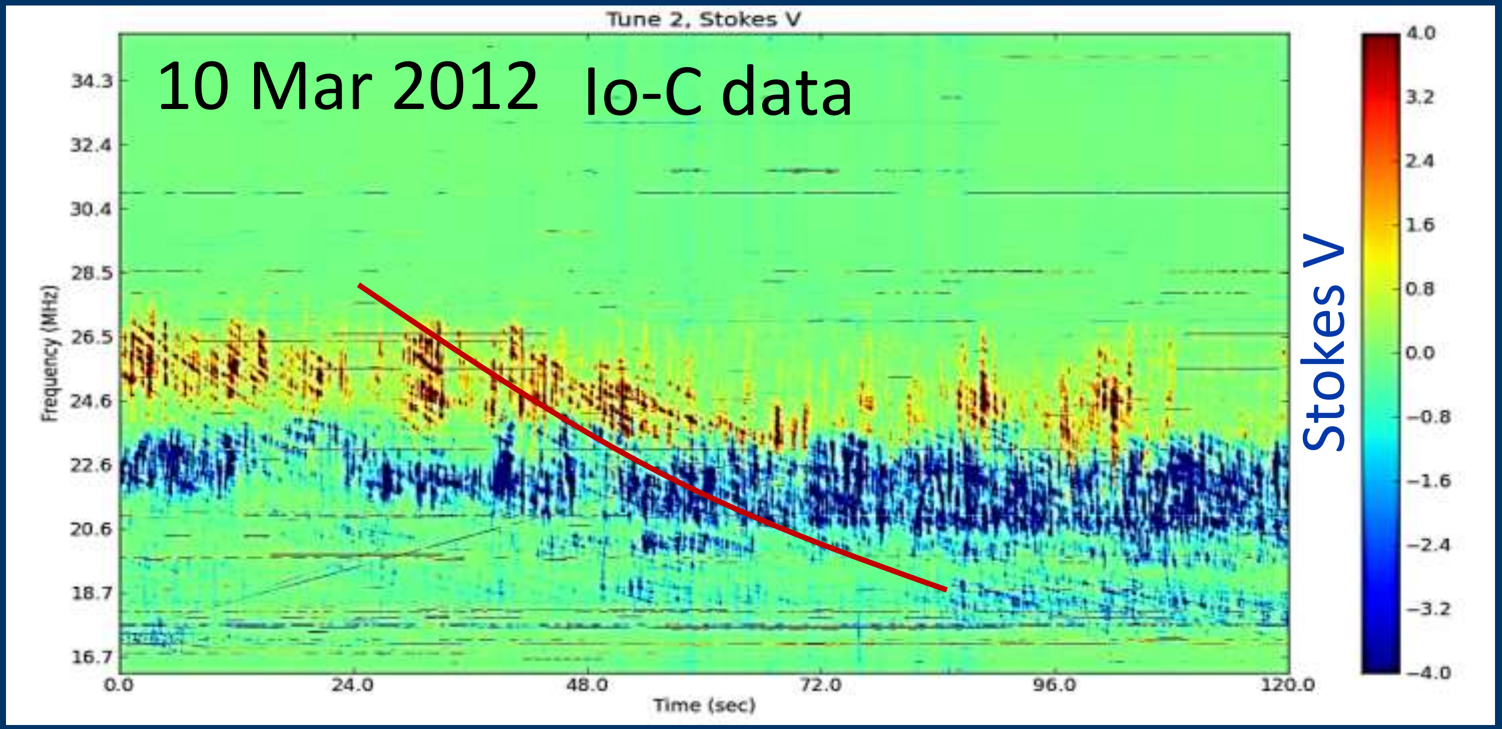
LWA1 Instrument

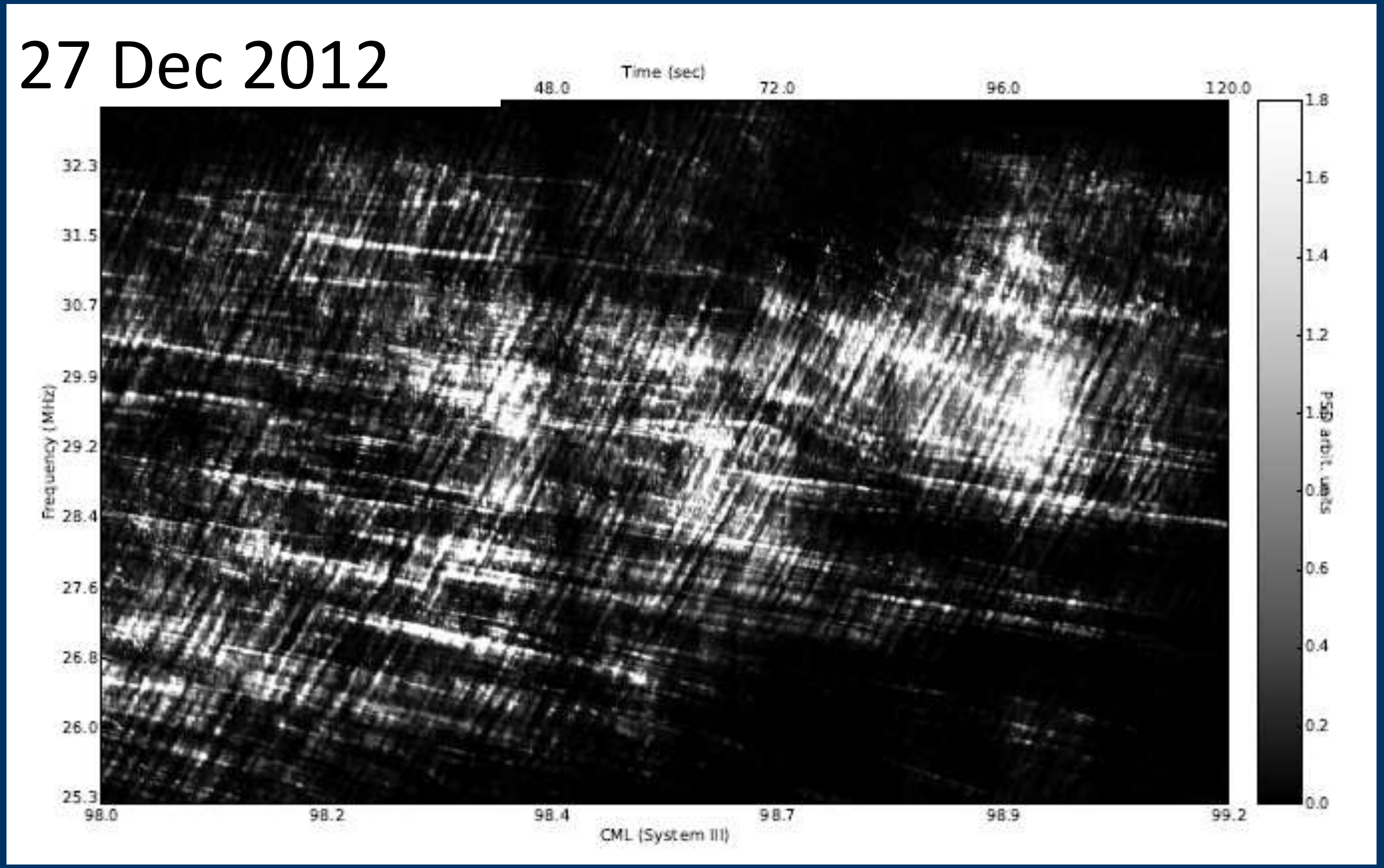
- Excellent observing conditions
- Excellent Temporal & Spectral Resolution showing fine structures in Jovian decameter emissions
- Remarkable Consistency of the Io-A/C Emission Structure

- RH and LH polarizations – good test of the CMI theory
- Are RX and LO modes coming from the same hemisphere?

Io-A/C Modulation Lanes

- Modeled as interference through the Io plasma torus (Imai et al., 1992, 1997)
- Modulation Lanes continuity argues for RH and LH emission from the SAME hemisphere



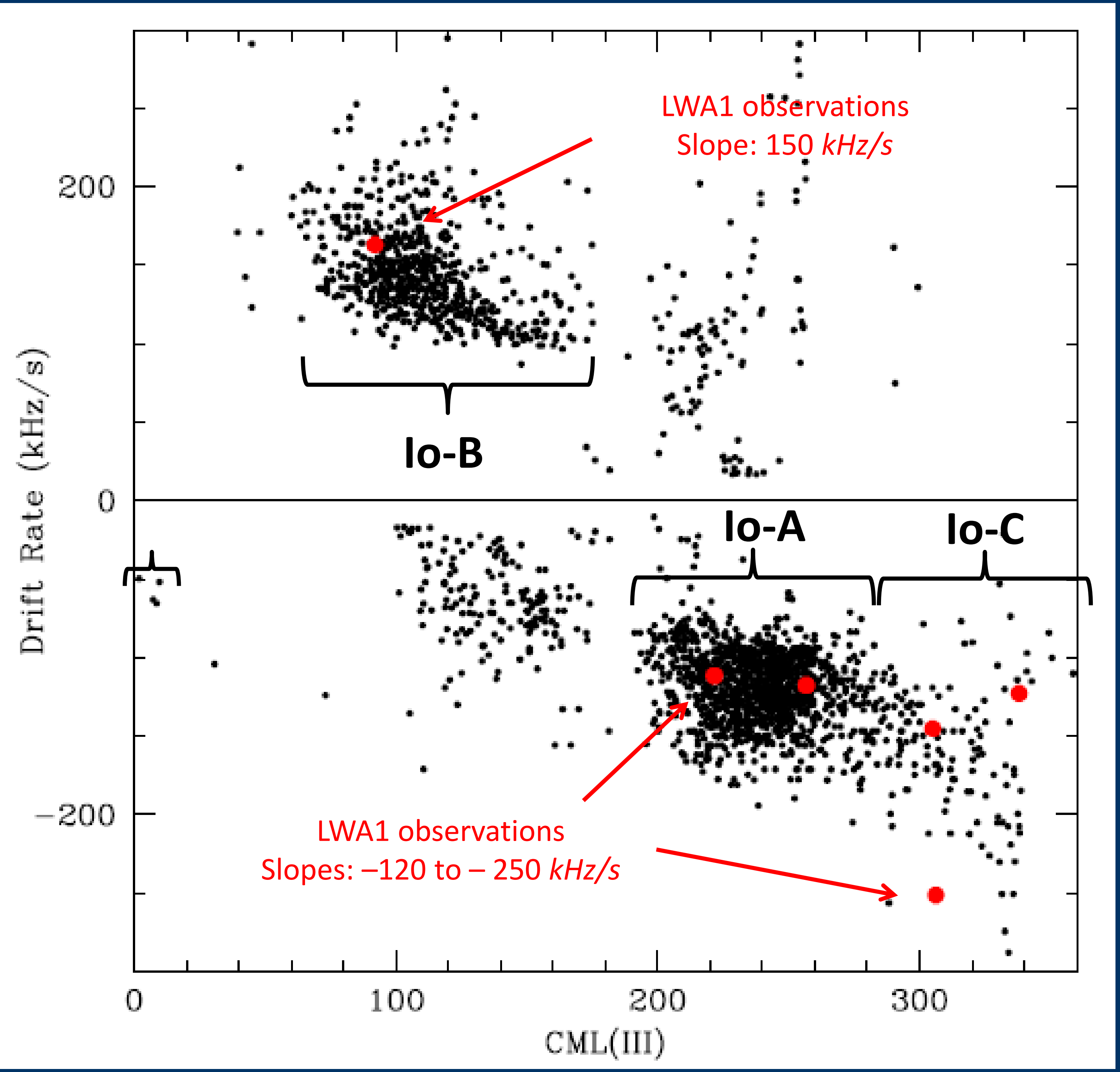


Positive slope modulation lanes from the Io-B burst of 27-Dec-2012. Resolution is 10 ms and 10 kHz.

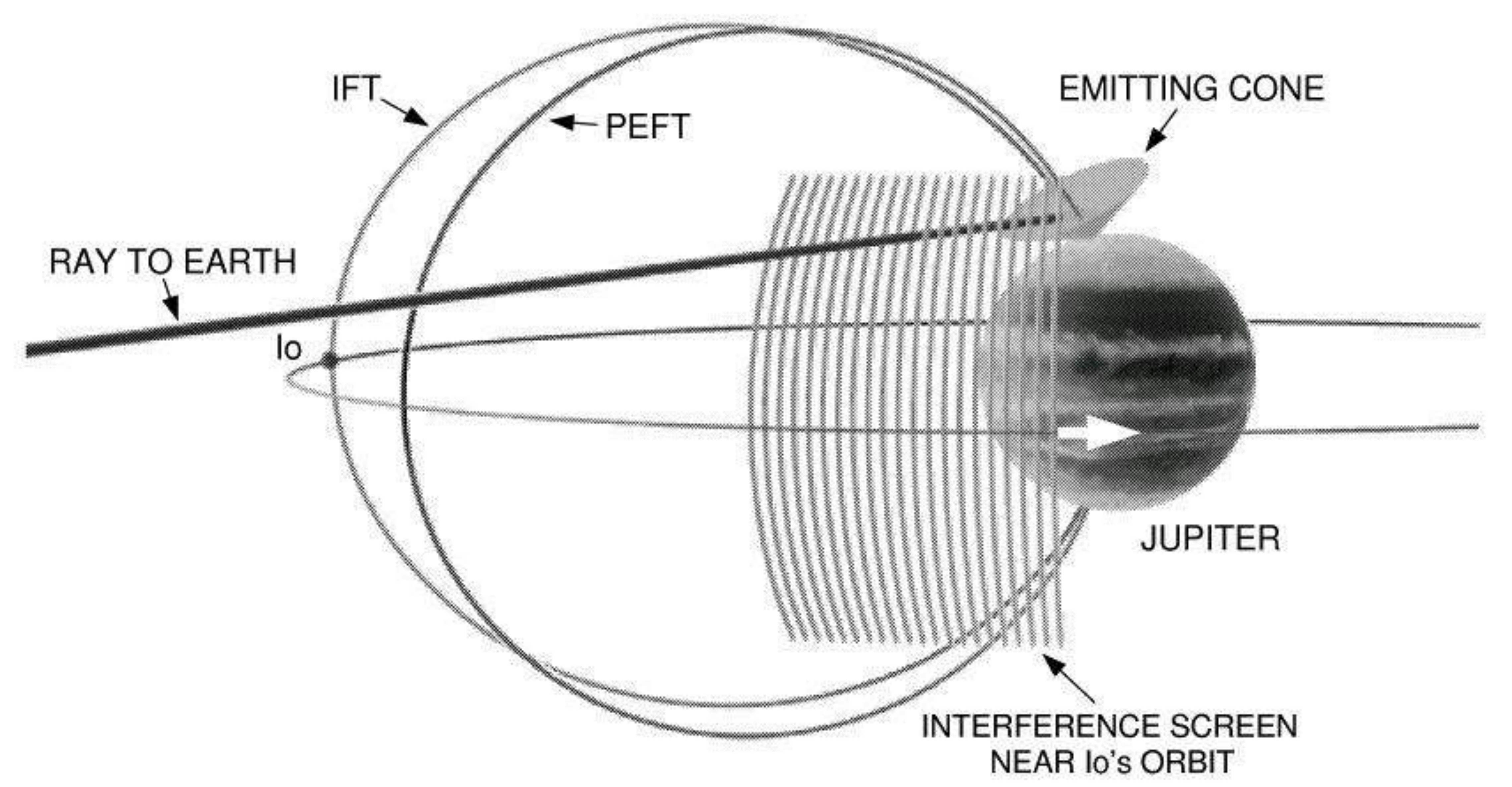
Io-B Modulation Lane Slopes

Modulation lane slope calculations are consistent with previous measurements

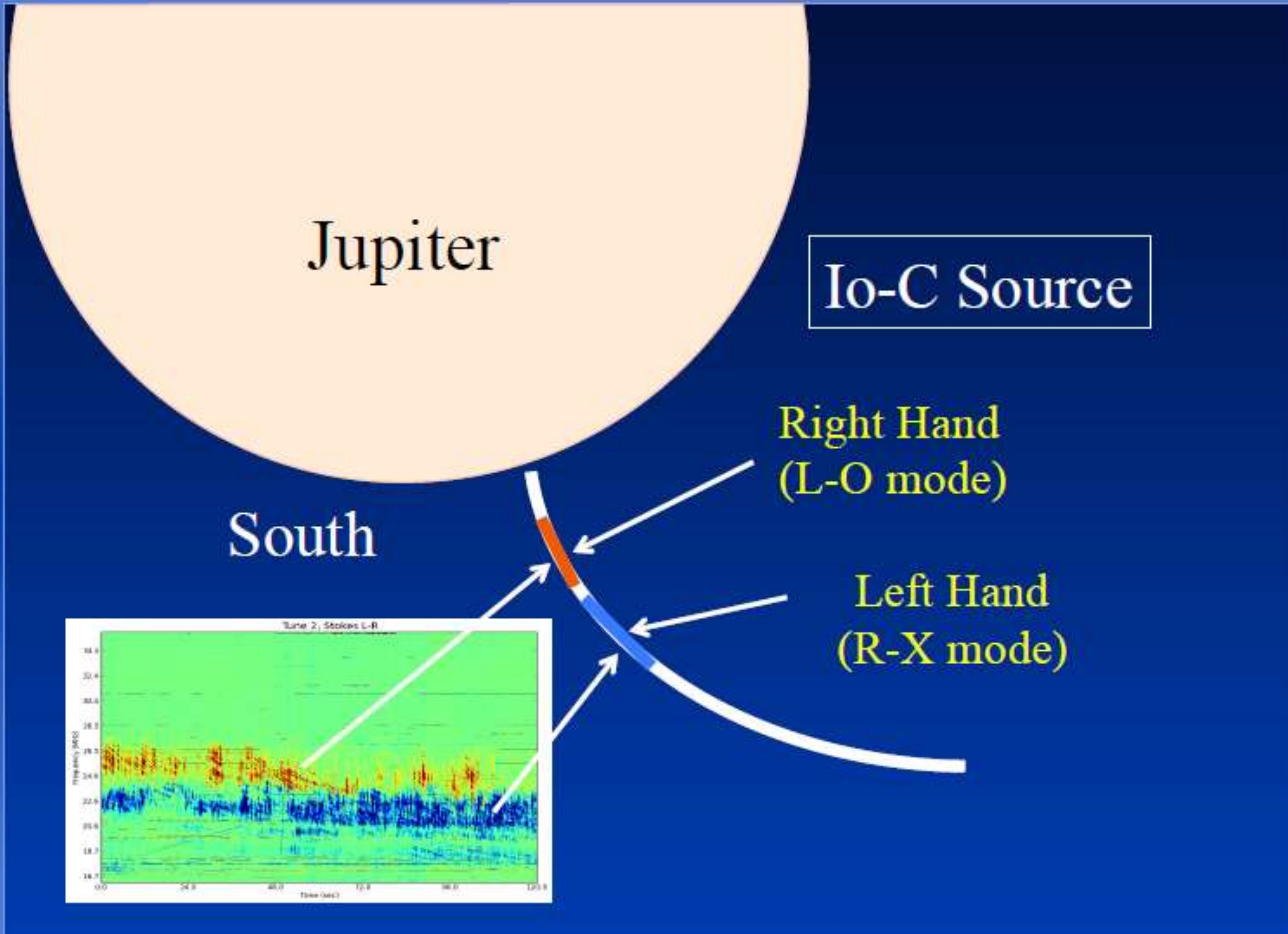
Previous data 21-23 MHz observations from 1966 – 1979 (Riihimaa, 1978, 1993)



Modulation Lanes



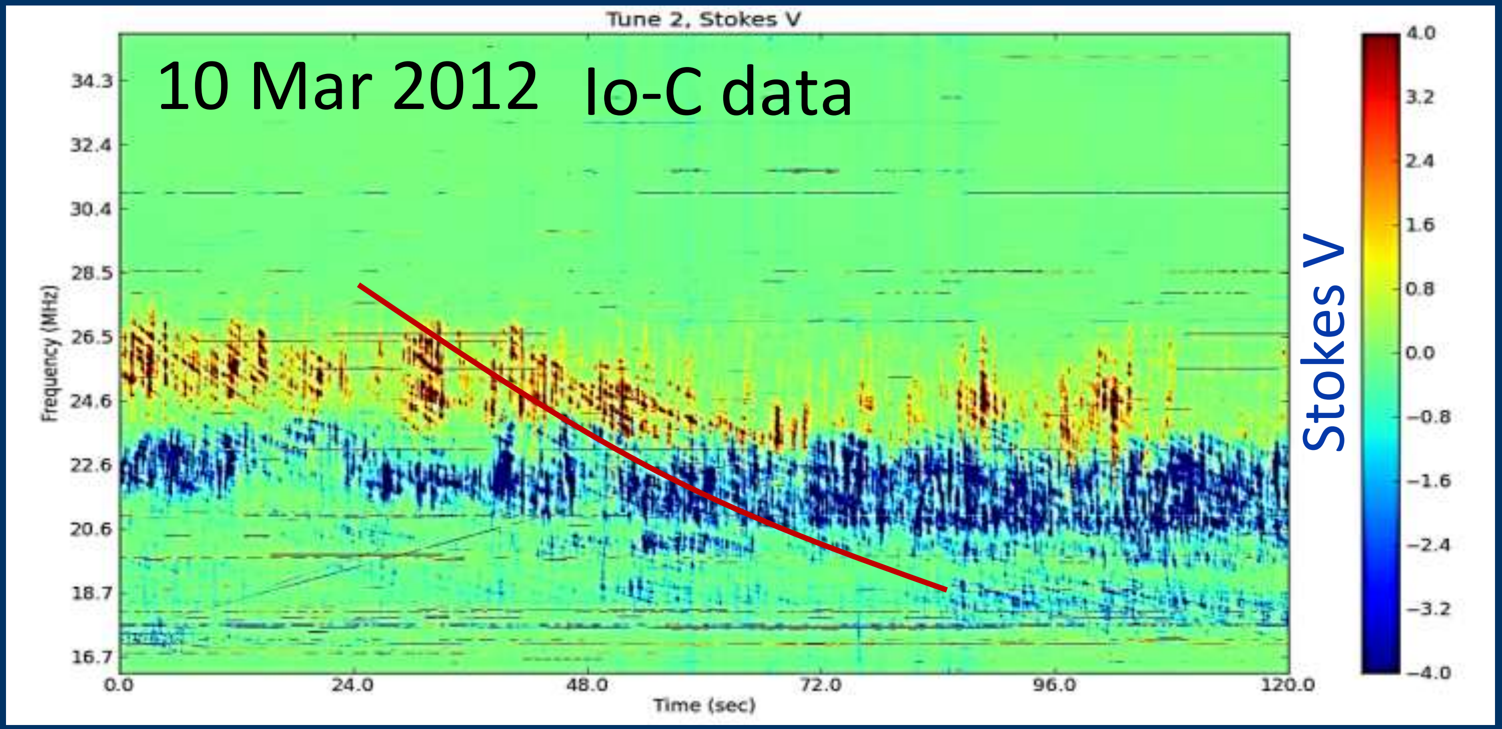
From Imai et al., 2013

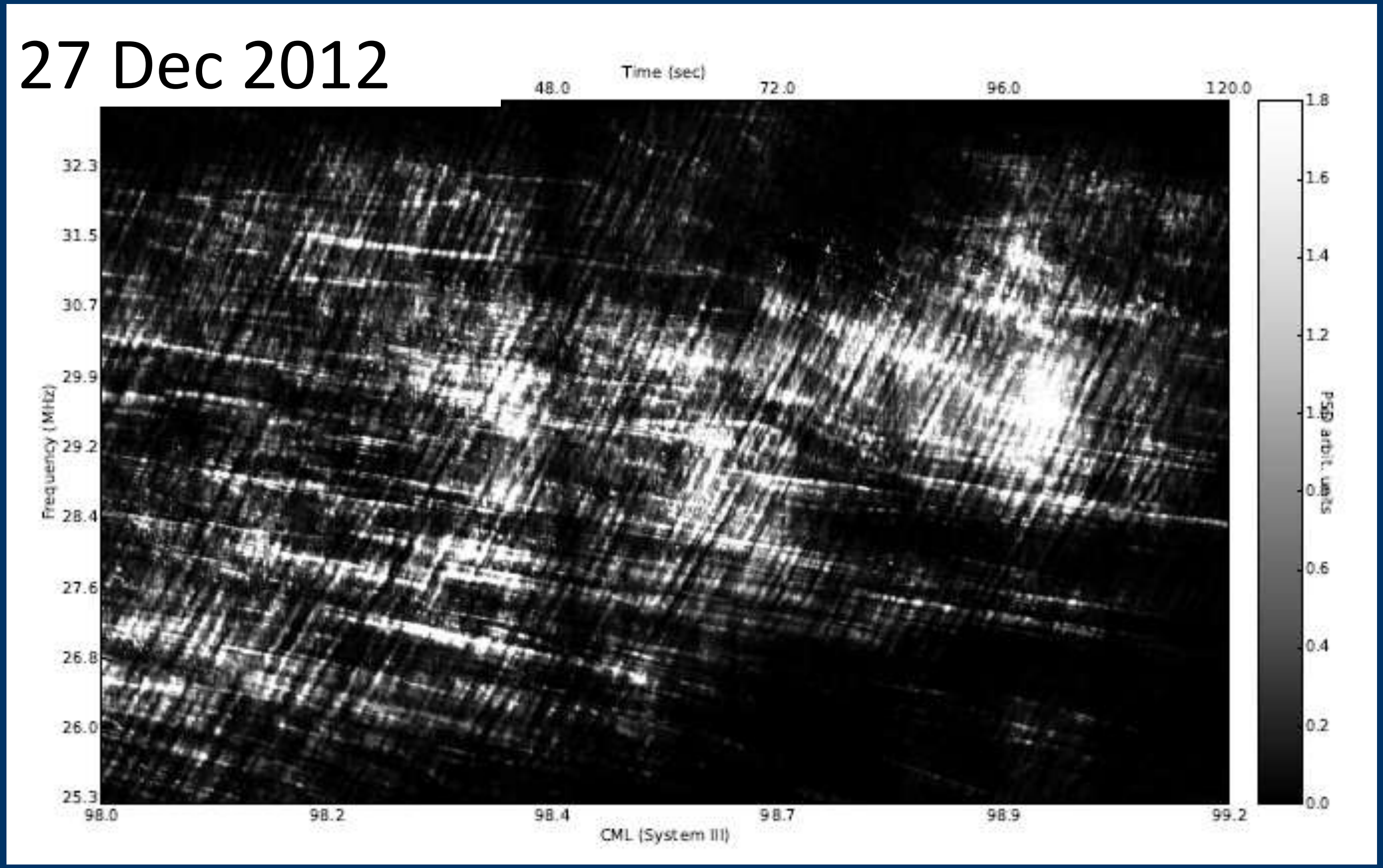


From Imai et al., 2013

Io-A/C Modulation Lanes

- Modeled as interference through the Io plasma torus (Imai et al., 1992, 1997)
- Modulation Lanes continuity argues for RH and LH emission from the SAME hemisphere
- Contradicts CMI emission theory – RX mode growth rates are much higher than LO mode
- Other mechanisms
  - Mode conversion?
  - Local Refraction?





Positive slope modulation lanes from the Io-B burst of 27-Dec-2012. Resolution is 10 ms and 10 kHz.

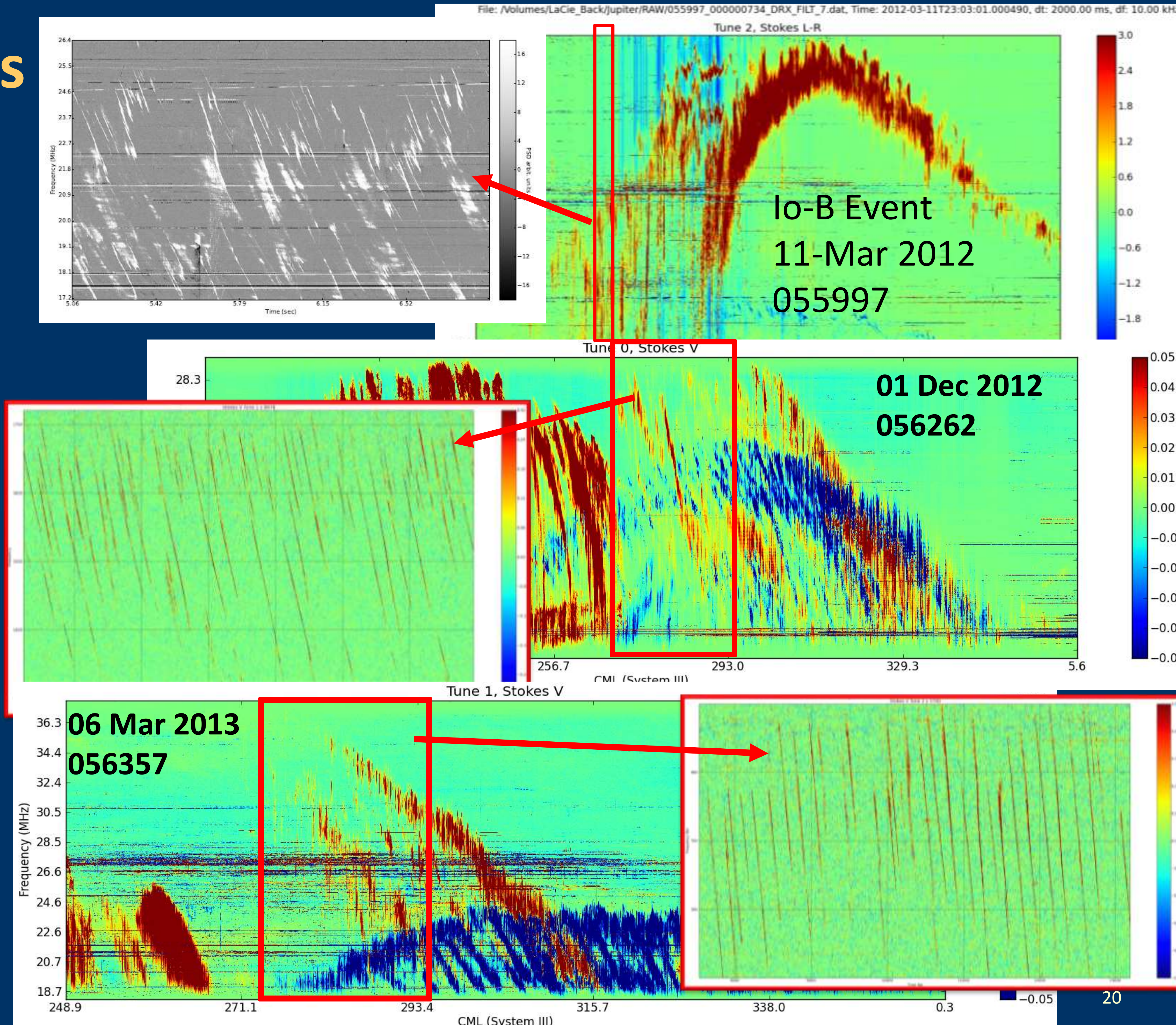
S-Bursts

<u>Drift Rates</u>

<u>Io-B</u>
–15 MHz/s
at 23 MHz

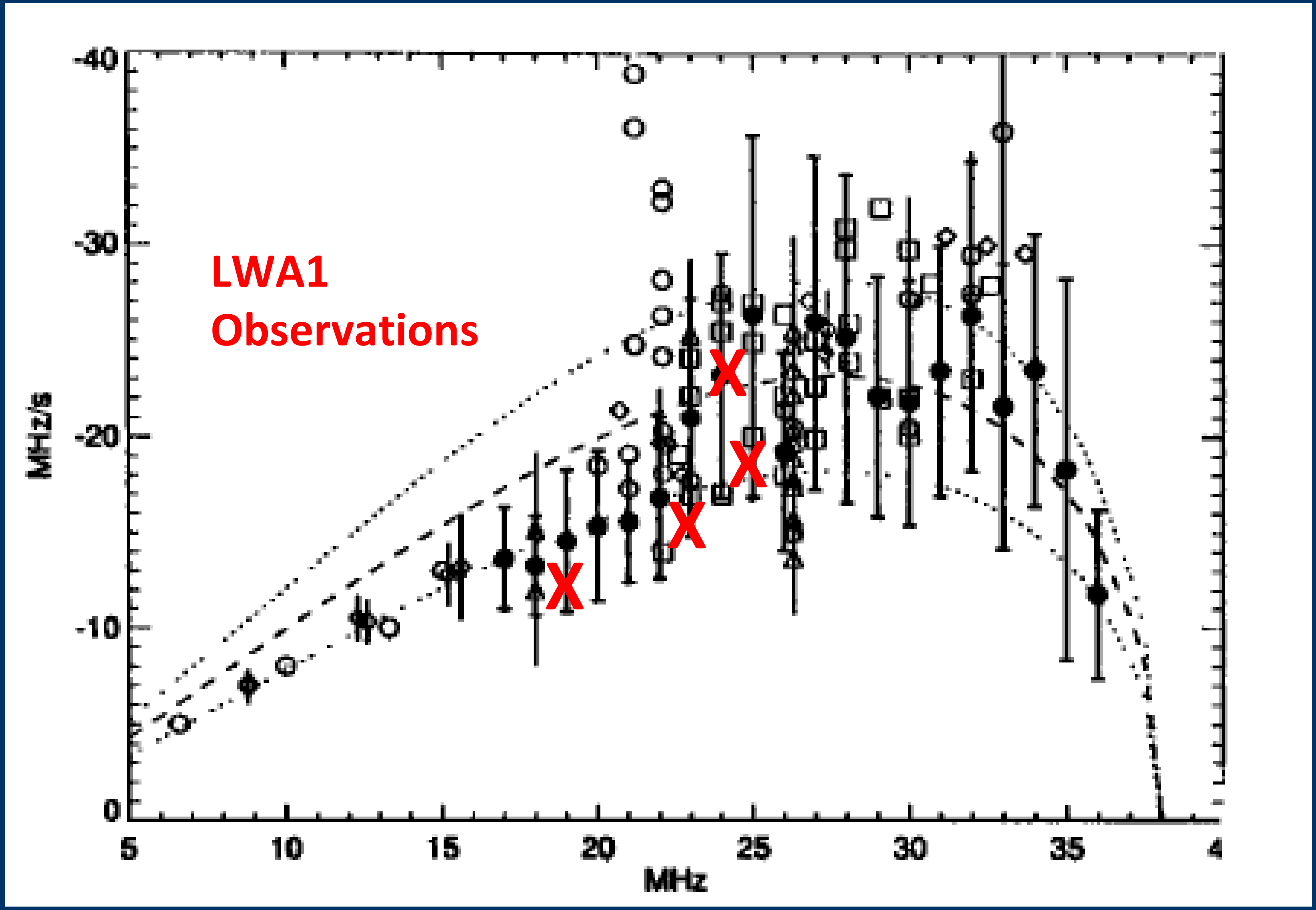
<u>Io-A/C</u>
–18 MHz/s
at 25 MHz

<u>Io-A</u>
–23 MHz/s
at 24 MHz



S-burst Drift Rates

S-burst Drift Rate vs Frequency



From Zarka et al., (1996)

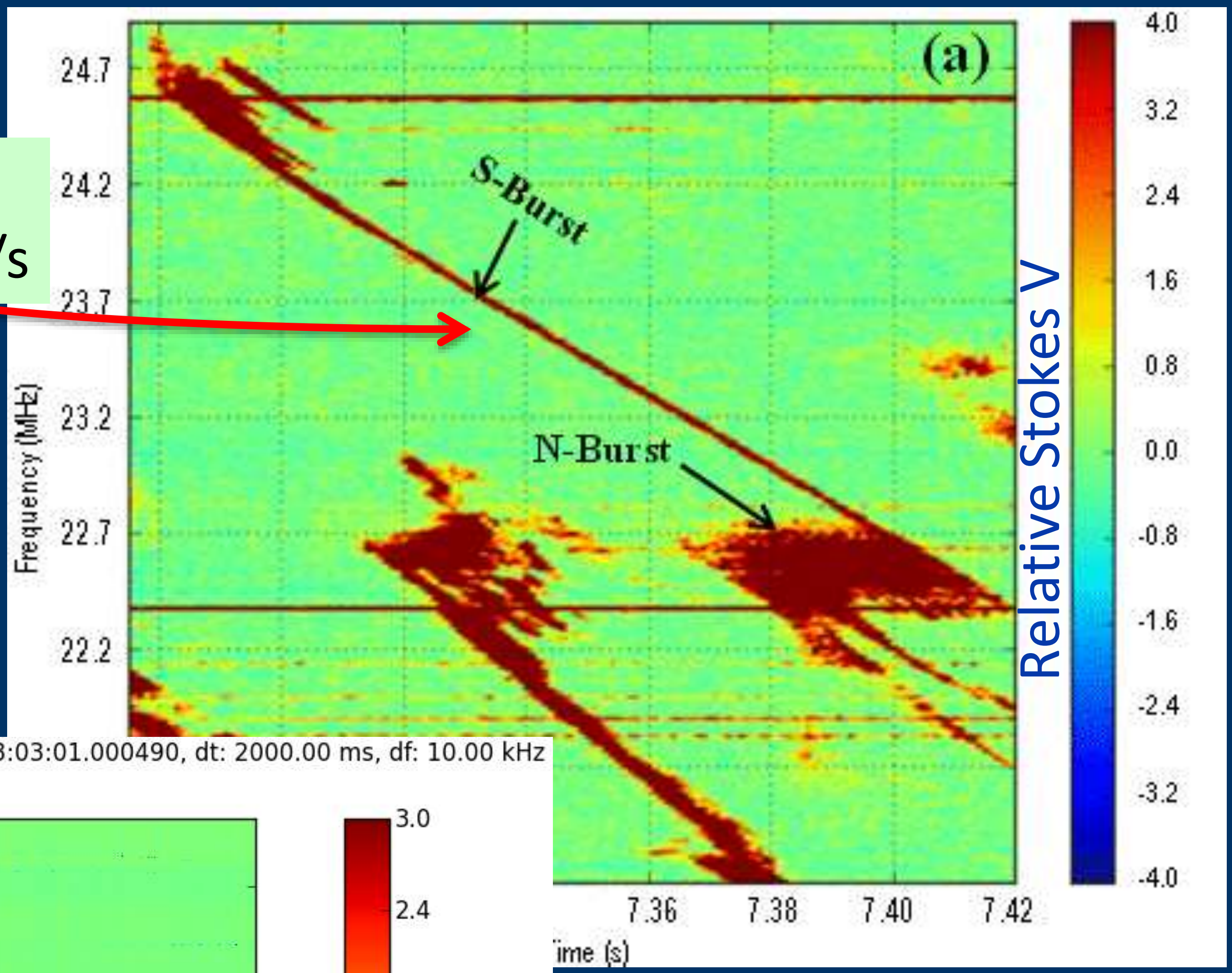
- Io related emission
- High-Intensity millisecond bursts
- CMI emission: ~5 keV electrons accelerated from Io to Jupiter – Mirrored near Jupiter resulting in a loss cone of amplified X-mode waves
- Adiabatic theory predicts the maximum drift rates (~30 MHz/s)

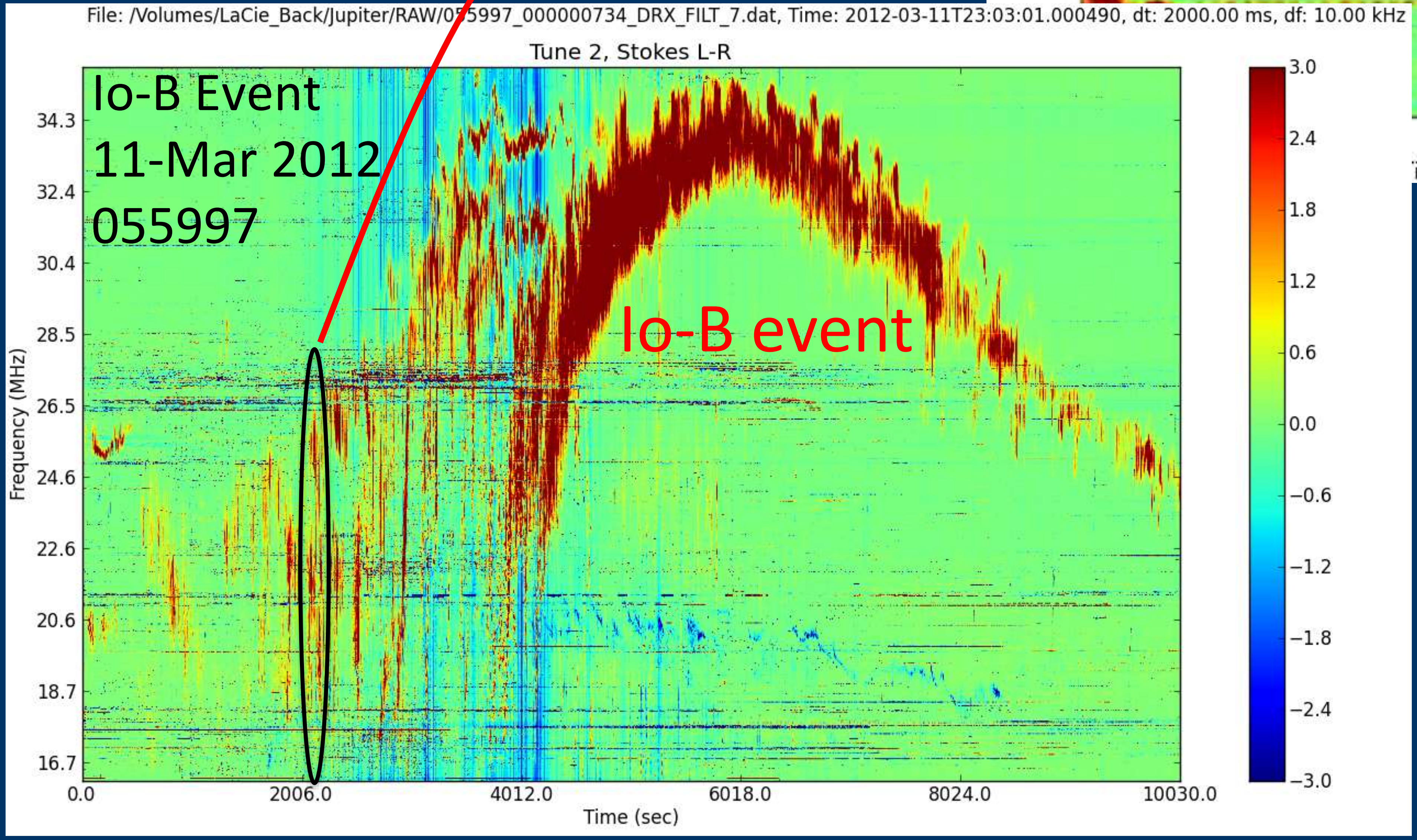
We can use LWA1 data to test this theory.
How do the drift rates correlate with the sources?

S-Bursts and N-events

- S-bursts and Narrow band (N) events show interactions (triggering & quenching)
- Argues for co-spatial sources

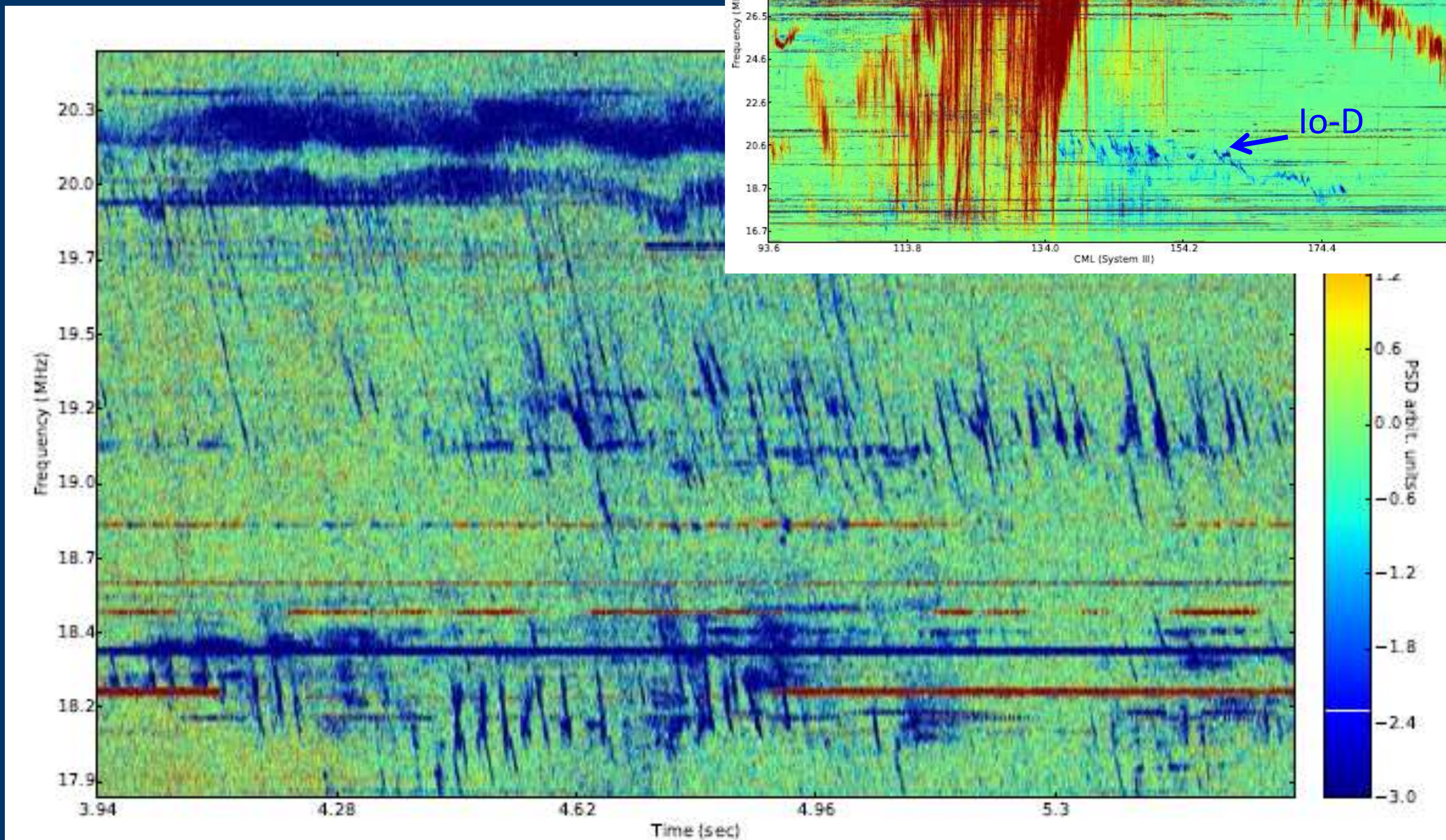
Δt ~100 ms
Δν ~ -15 MHz/s

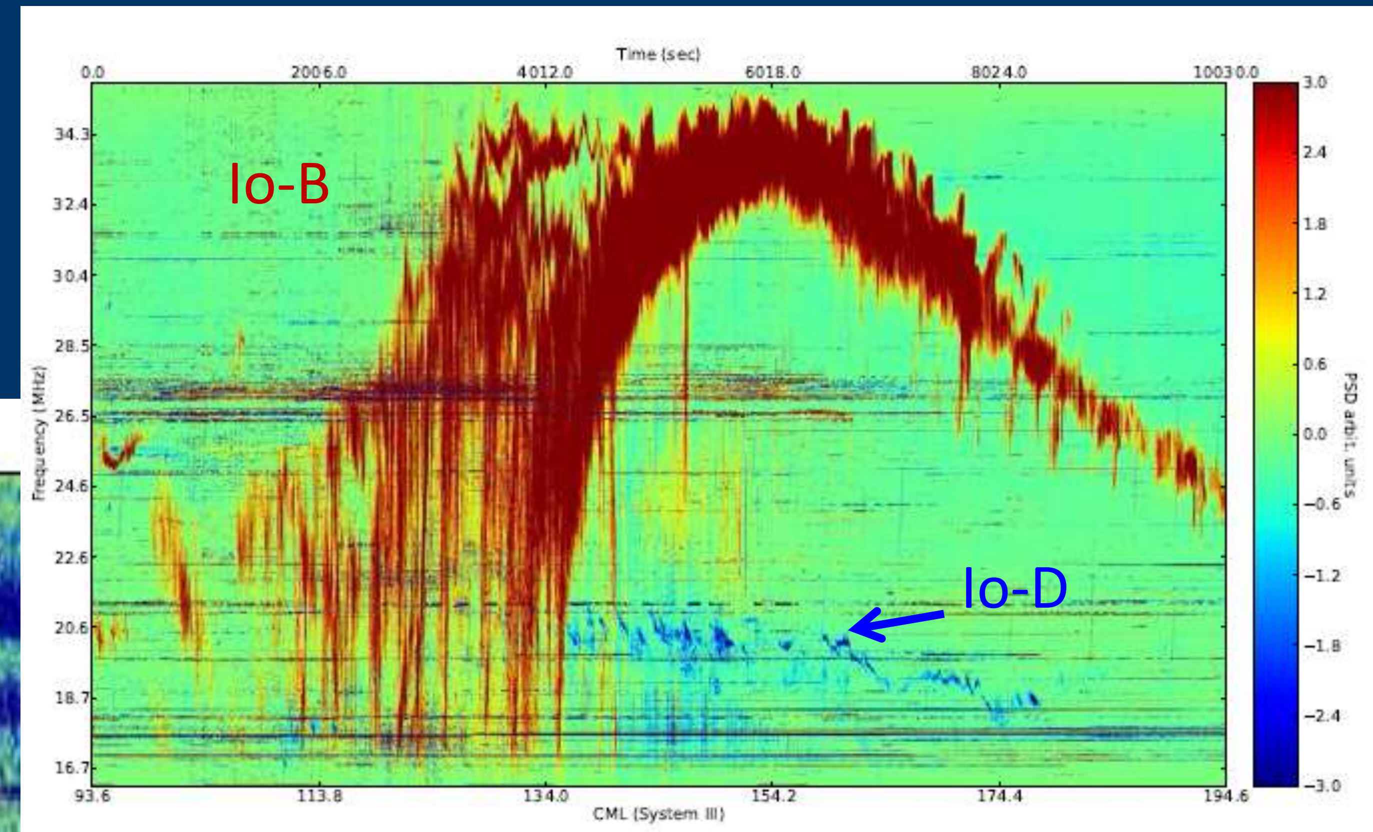




- Better resolution is showing new structure in the S, N, and S-N events
- New physics?

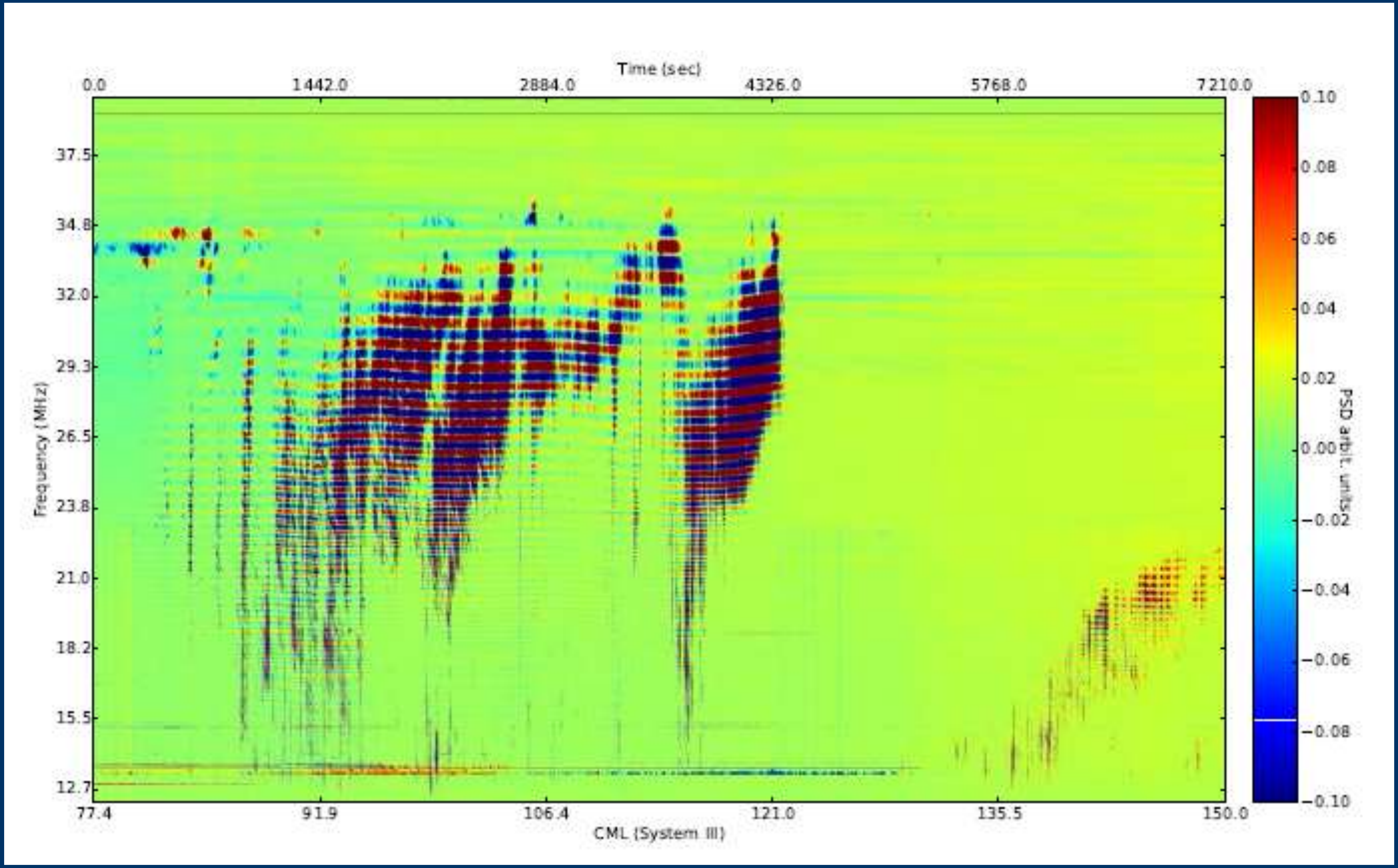
Rare Io-D S-bursts





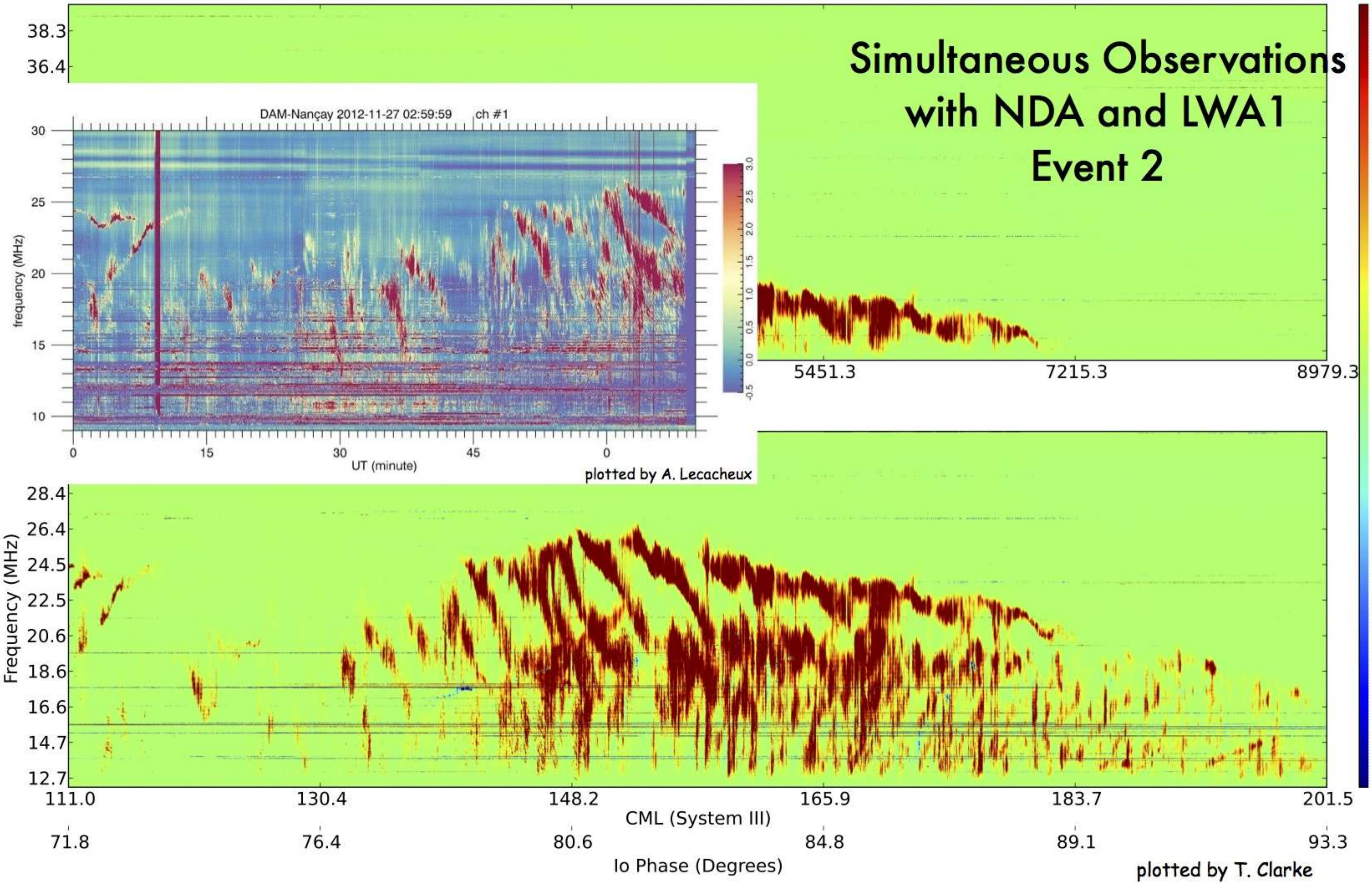
S-bursts for the Io-D event on 11-March-2012. Resolution is 0.25 ms and 10 kHz. Narrow-band emission as well as S-bursts are seen within the LHC Io-D emission.

Faraday Lanes

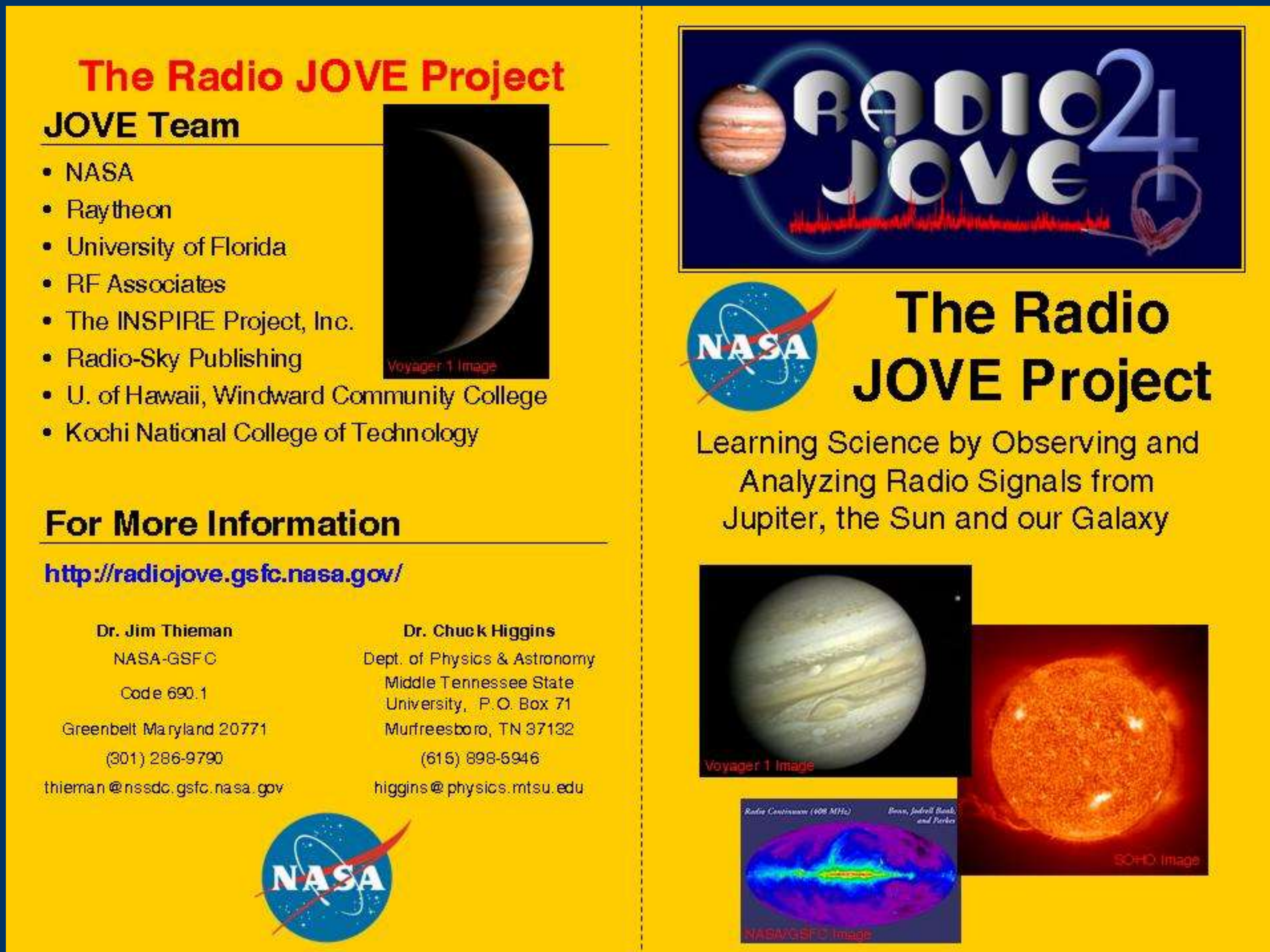


27-Dec-2012 Io-B event showing Faraday fringes in an X-Y spectrogram. The fringe separation decreases as the frequency decreases due to the λ^2 nature of Faraday rotation.

Simultaneous Observations with NDA and LWA1 Event 2



Education and Outreach



Summary of LWA1/Jupiter Studies

- First LWA Jupiter paper accepted October, 2014
- LWA1 is an excellent instrument for Jupiter decameter studies
  - Excellent spectral and temporal resolution
  - Shows fine structures and polarization
- Possible to learn some new physics at Jupiter
  - Modulation Lanes observations can be used to check CMI theory
  - S-burst drift rates at high frequencies
  - Narrow band (N) event characteristics (S-burst/N-event interactions)

- LH and RH emission can be used for Faraday rotation studies

Recent LWA1 Observations

Oct 2013 – Feb 2014

Recent LWA Coordinated Jupiter observing campaign with JAXA Hisaki (Exceed) mission, and HST, Gemini, Kitt Peak, Suzaku, Chandra, and XMM (thru Apr 2014)

Juno Mission, ~2015-2017

Coordinated observations?