

# Transients, fast and slow

*Kievney*  
**HOTEL**

ROOMS  
BY  
DAY

TRANSIENTS  
WELCOME

Dale A. Frail  
AD VLA and VLBA

**LOFAR**



**WSRT-Apertif**



**ASKAP**



**LWA**



**MeerKAT**





# Types of Radio Transients

## Slow = Incoherent

- Typically synchrotron emission
- Variable on timescales of seconds – years
- Brightness temperature limited to  $<10^{12}$  K
- Typically discovered in image data

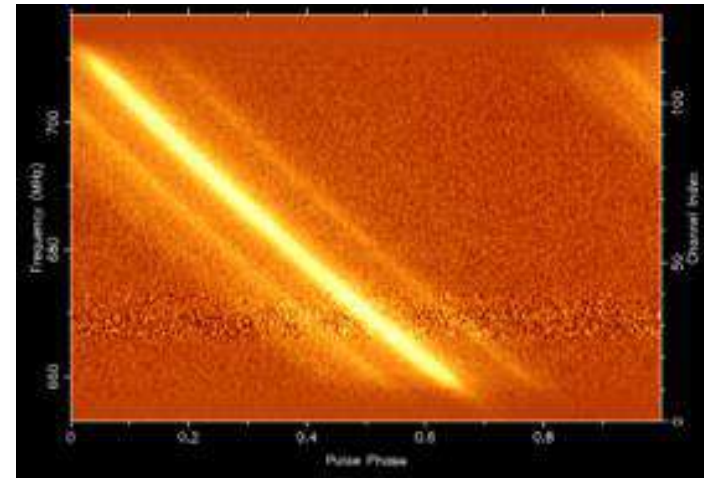


### Examples:

- AGN and Microquasar jets
- Supernovae & GRBs afterglows
- Black hole tidal disruption events (TDEs)
- Giant flares from magnetars

## Fast=Coherent

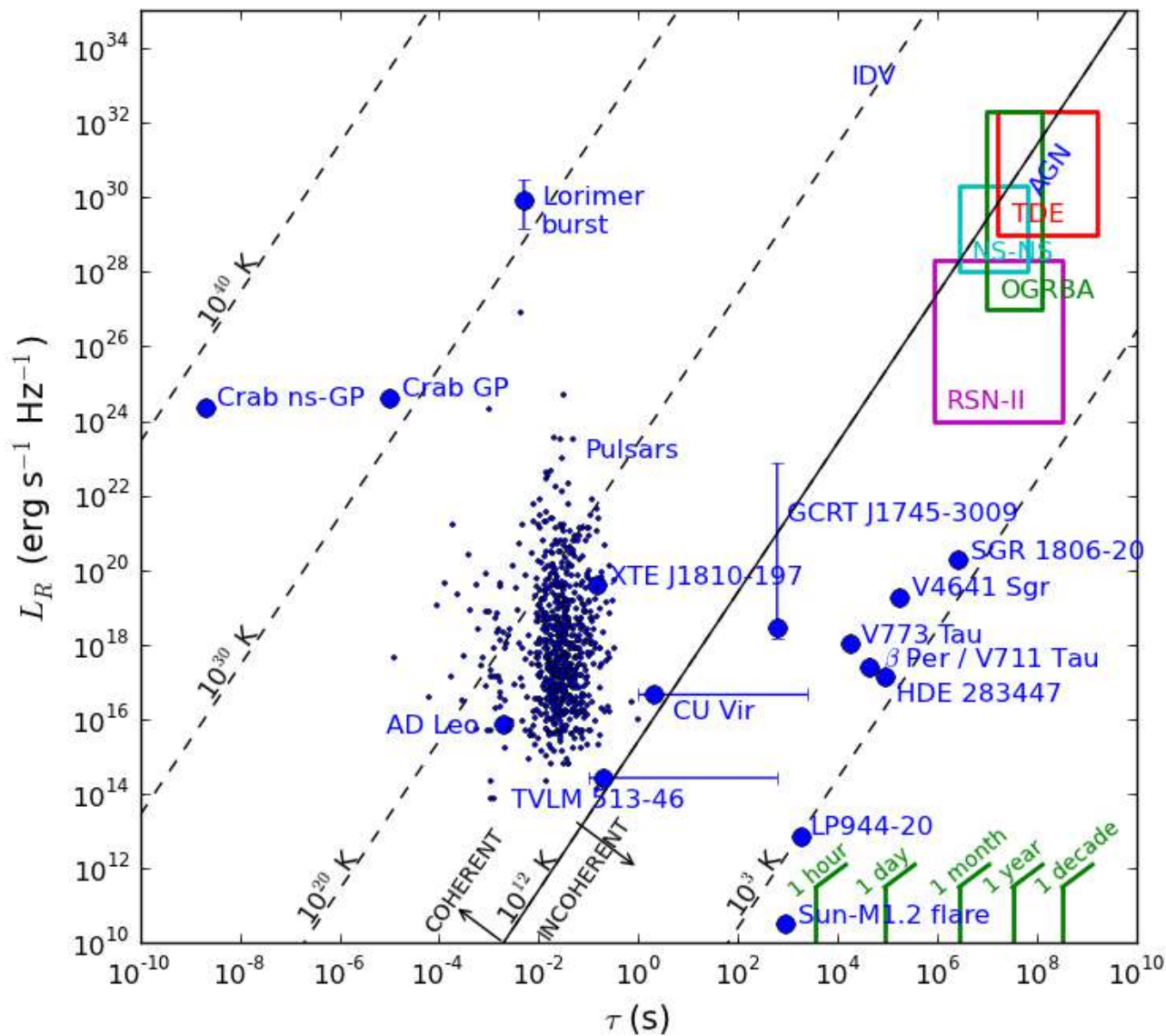
- Various flavors of coherent emission
- Variable on timescales of ns - minutes
- Brightness temperatures as high as  $>10^{38}$  K
- Typically discovered in time-series data



### Examples:

- Various classes of neutron stars
- Galactic Center Radio Transients
- Planets and Exoplanets
- Stellar bursts and pulsing brown dwarfs

# Radio Phase Space



# Be a Cartographer: Systematically survey the variable and transient radio sky



Credit: G. Bower

# Basic Questions About the Radio Sky

1. What do we know about the *quiescent* radio sky?
  - How do the populations vary with flux density and frequency?
2. What fraction of radio sources are *variable*?
  - On what flux level, at what frequency, and at what timescale?
3. What are the most common long duration *transients*?
  - “*Know your background*”. What are the “asteroids” of the radio sky?
  - i.e.  $m < 21$  mag asteroids are  $10^{-2}$  (in ecliptic) to  $10^{-4}$  of the persistent optical sky. A significant false-positive for other transient searches.

**Collaborators:** S. Kulkarni, G. Hallinan, K. Moody, S. Burke, A. Horesh, U. Nakar, E. Ofek, G. Bower, M. Kasliwal, B. Breslauer and more.





# The VLA and PTF Stripe-82 Project



**Real-Time  
Transient  
Detection Pipeline**

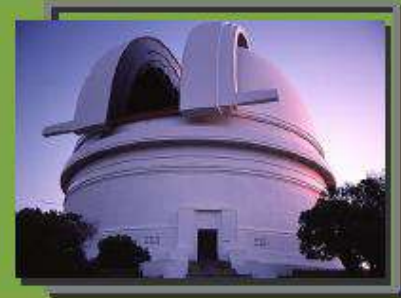
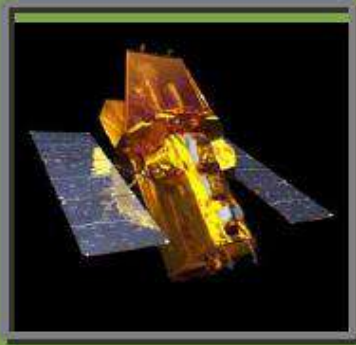
Each Epoch:  
2x7 hrs/night  
485 pointings/night  
250 GB/night  
Pipeline~5-7 hrs



**Transient Candidates**



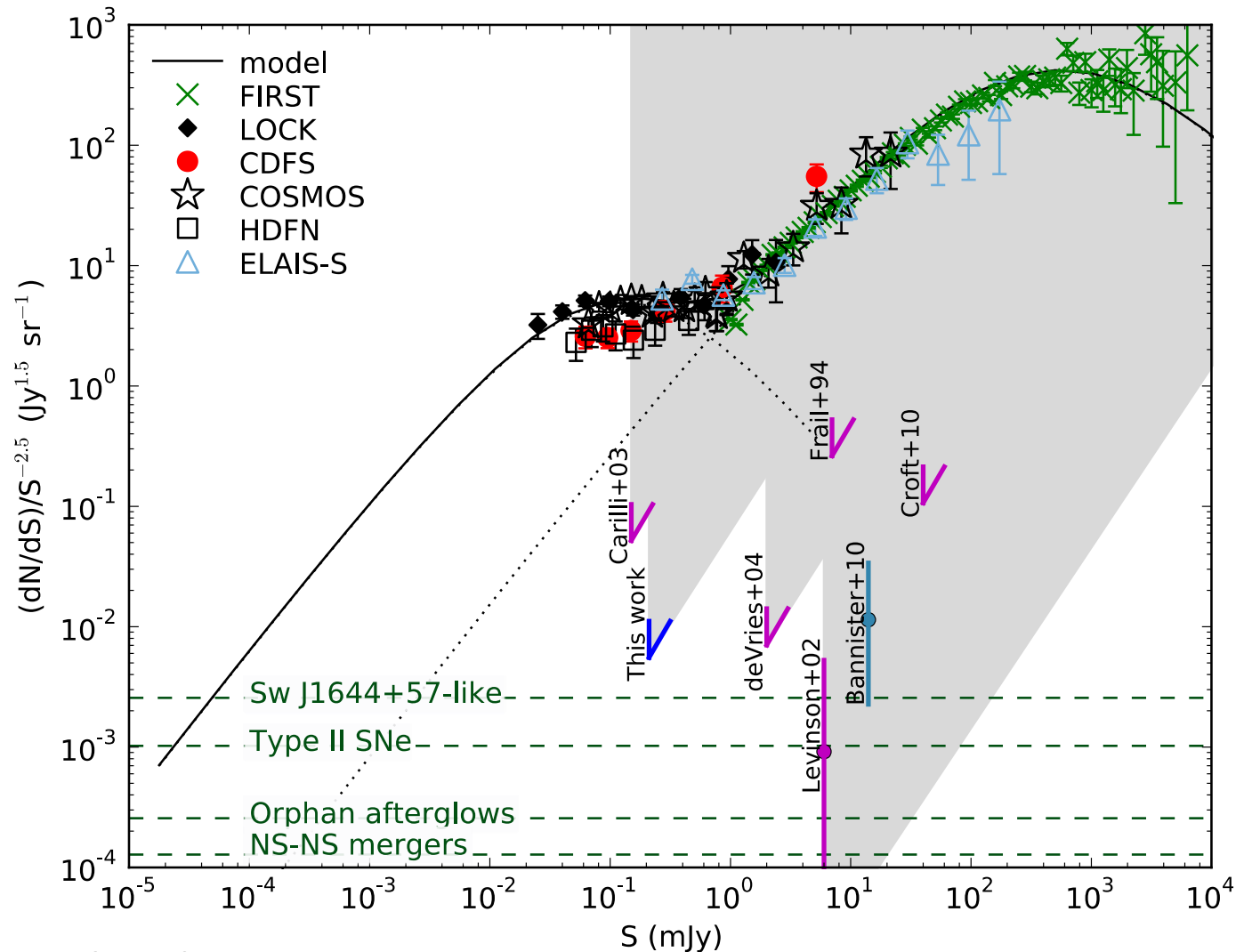
**Interesting Transients**



# A Revised View of the GHz Transient Sky

Transient  
radio sky is  
even quieter  
than originally  
thought

Implications  
for future  
survey design.



Mooley et al. (2012)

$$\text{FoM} = \text{rms}^{-1.5} * \text{Area} * N_{\text{epochs}}$$

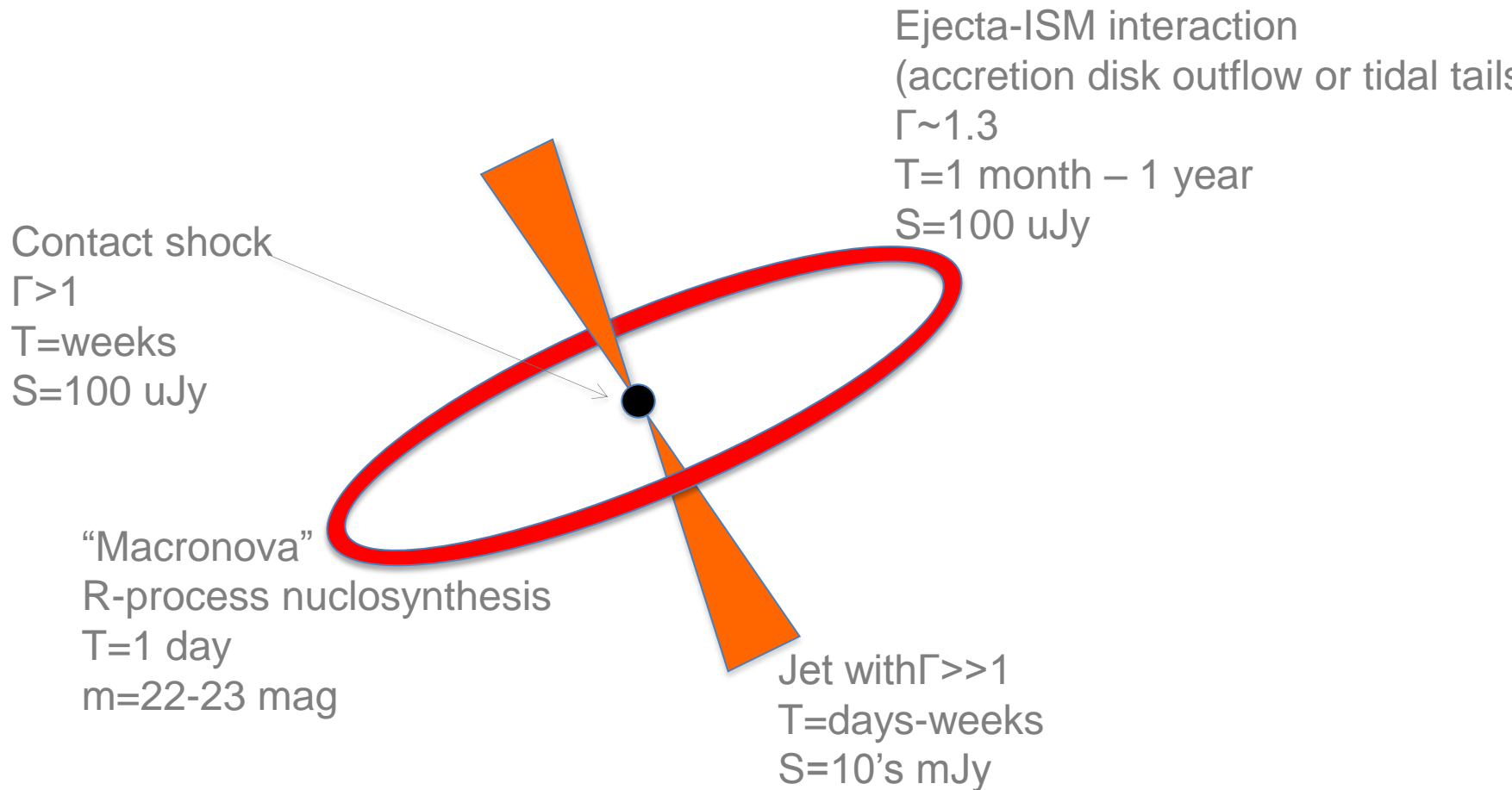


# Basic Questions About the Radio Sky

## Answers

- The quiescent radio sky is boring
  - It is sparsely populated ( $S > 1$  mJy) 90 sources deg<sup>2</sup>)
  - Isotropic source distribution on sky
    - $> 1$  mJy source populations are radio-loud AGN
    - $< 1$  mJy star-formation galaxies and radio-quiet AGN start to emerge
- The variable radio sky is boring
  - The fraction of strong variables at 1 GHz is small  $\ll 1\%$
  - AGNs appear to dominate the variable sky
- The (revised) transient radio sky is **really** boring
  - Transients are  $\leq 10^{-4}$  of the quiescent population

# Seeing is Believing: EM-GW Counterparts

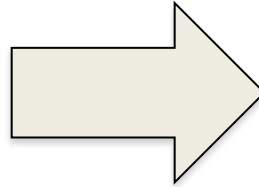
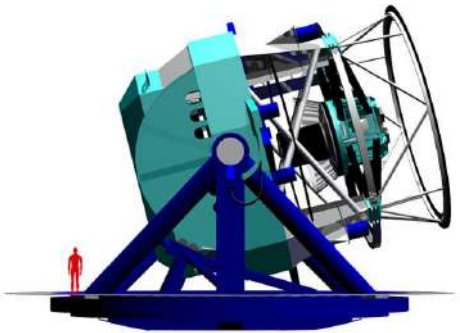


# Act Like A Buccaneer: Own the Follow-up





# Follow-up: A biased but rewarding approach



# Radio Transient Phase Space: Simplified

Extragalactic	Tidal disruption events (TDEs) Long duration GRBs Relativistic supernovae (SNe) Short duration GRBs Type II SNe Type I b/c SNe
Galactic	Novae and CVs Soft gamma-ray repeaters HMXBs and LMXBs GC transients Flare stars Brown Dwarfs


Short duration                      Long duration

# Fast Transients: A pragmatic definition

- Intense, short duration ( $\text{ct} < 1 \text{ s}$ ) activity from a compact object
- Pulse profile affected by plasma propagation effects, including dispersive smearing and interstellar scattering
- Fast transients can be either cataclysmic or repeatable
- Probe extremes of gravity, magnetism and/or states of matter
- Requires a non-thermal, *i.e.* coherent emission mechanism
  - There is no theory that can predict *a priori* what the specific intensity will be for a pulsed, coherent source

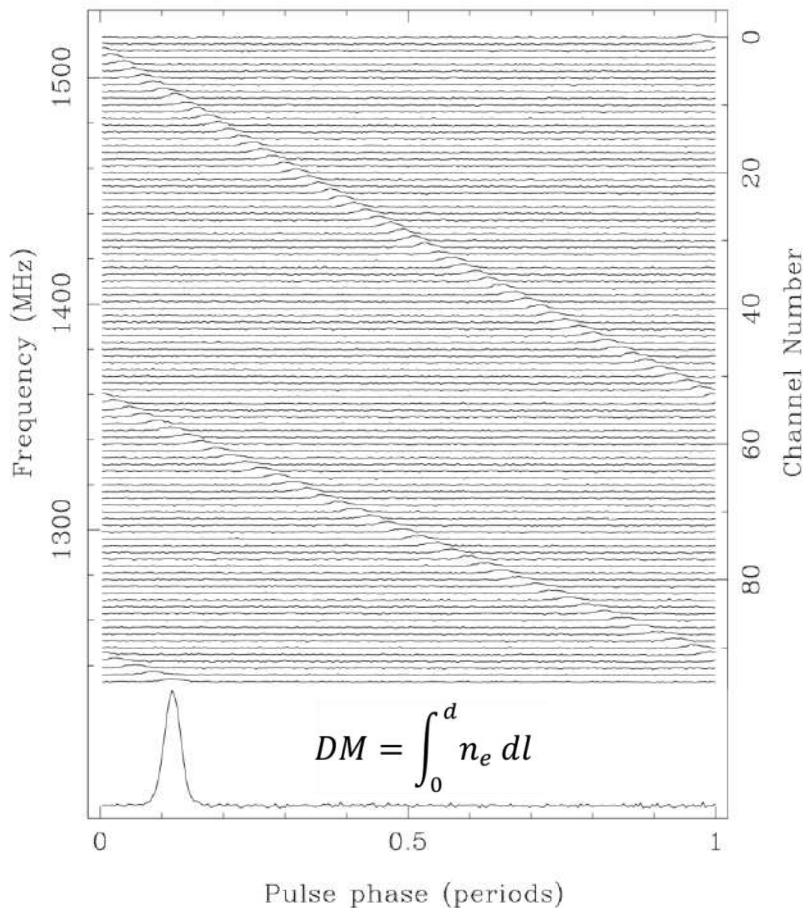


# Radio Transient Phase Space: Simplified

Extragalactic	 <p>Fast radio bursts? (Prompt GRBs?) (Evaporating BH's?)</p>	<p>Tidal disruption events (TDEs) Long duration GRBs Relativistic supernovae (SNe) Short duration GRBs Type II SNe Type I b/c SNe</p>
Galactic	<p>Crab giant pulses Normal and msec pulsars Nulling PSRs RRATs Rotating magnetars (extrasolar planets)</p>	<p>Novae and CVs Soft gamma-ray repeaters HMXBs and LMXBs GC transients Flare stars Brown Dwarfs</p>
	Short duration	Long duration

# Plasma Propagation I: Dispersion

Lorimer and Kramer (2005)

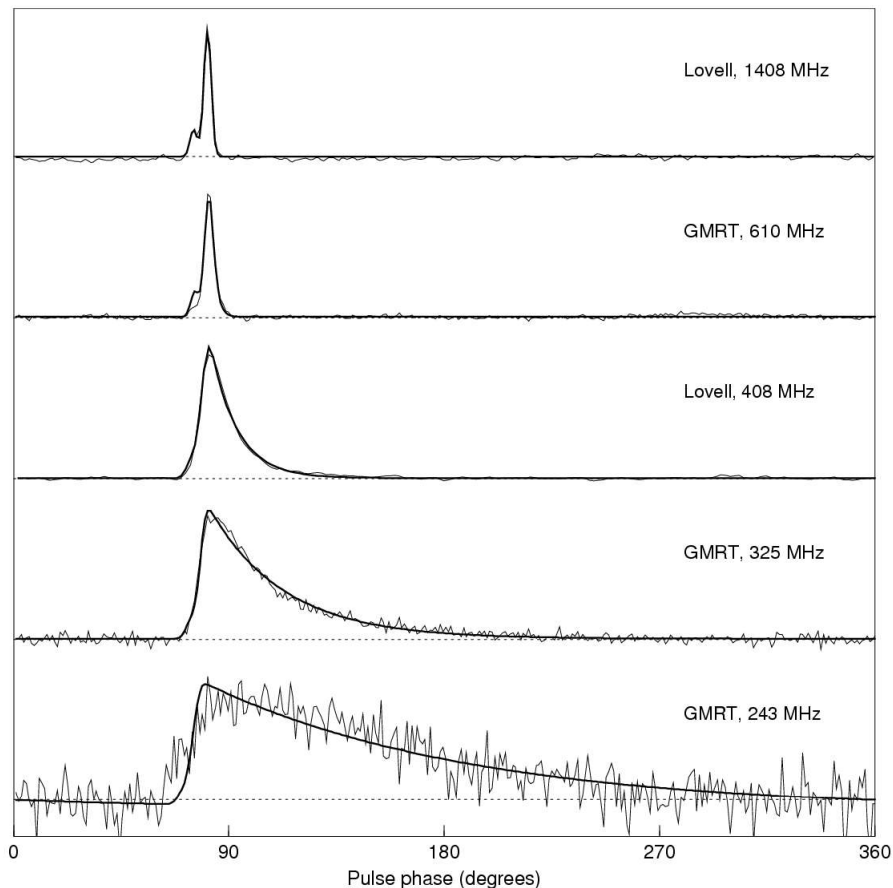


- Cold plasma dispersive delay, i.e. radio signals at lower frequencies arriving later than higher ones
- Without correction, pulse is temporally smeared
- DM (Galactic pole)=30 pc cm<sup>-3</sup> or electron column N<sub>e</sub>=10<sup>20</sup> cm<sup>-2</sup>
- *Negative*: Computational overhead. Must search for unknown DM in data reduction
- *Positive*: Excellent probe of ionized gas (i.e. IGM)



$$\tau_{DM} = 2.9 \text{ usec } DM^{-1} \text{ MHz}^{-1} \text{ at } 1.4 \text{ GHz}$$

# Plasma Propagation II: Scattering



- Multi-path scattering results in a broadening of pulsed signal
- Fluence is conserved
- A frequency “wall” below which you cannot see pulsations under some given period  $P > 5\tau_{\text{scat}}$
- Single pulses have an advantage over period pulses
- Deal with ISS through appropriate observing strategy.

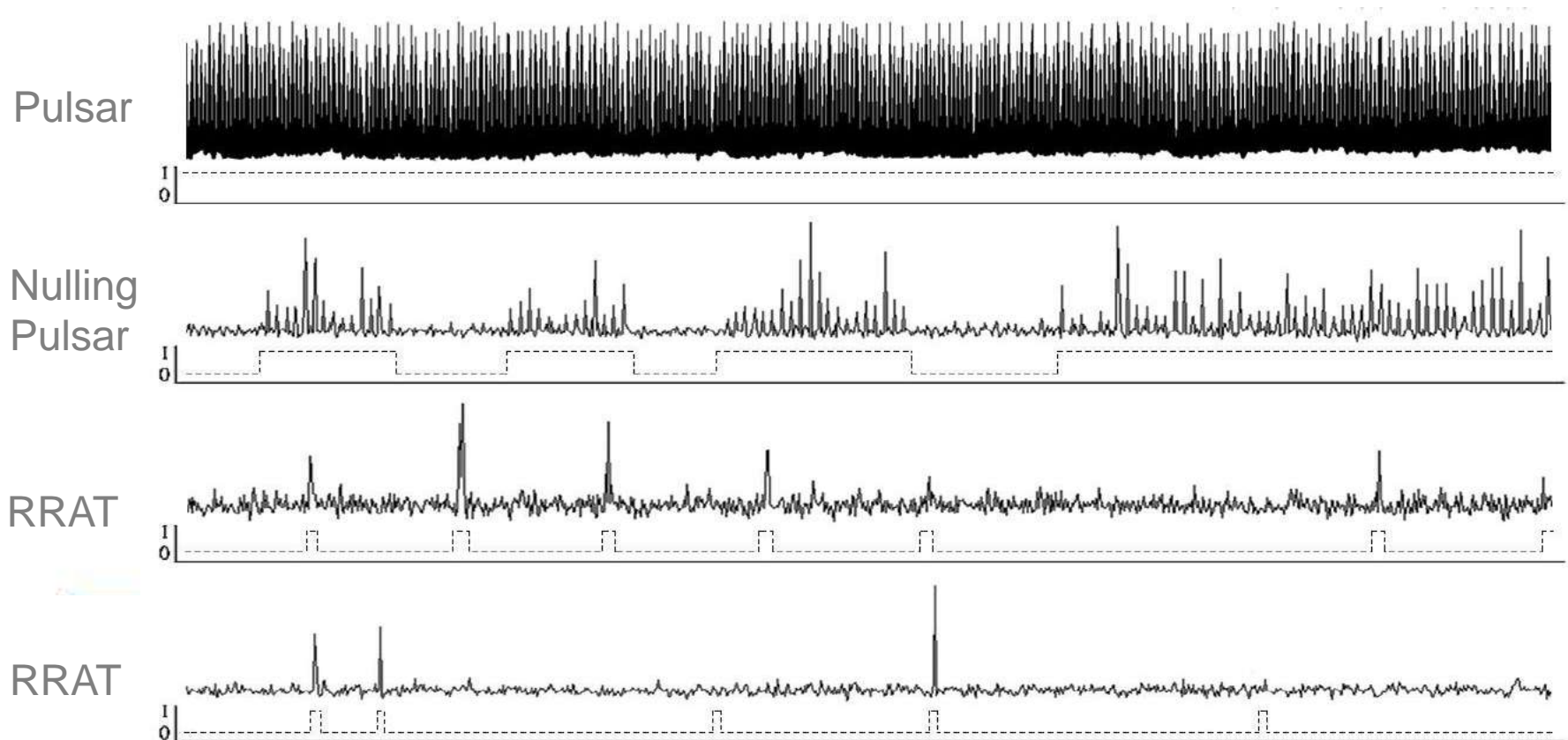
$$\tau_{ISS} \propto \nu^{-4.4}$$

Lorimer and Kramer (2005)



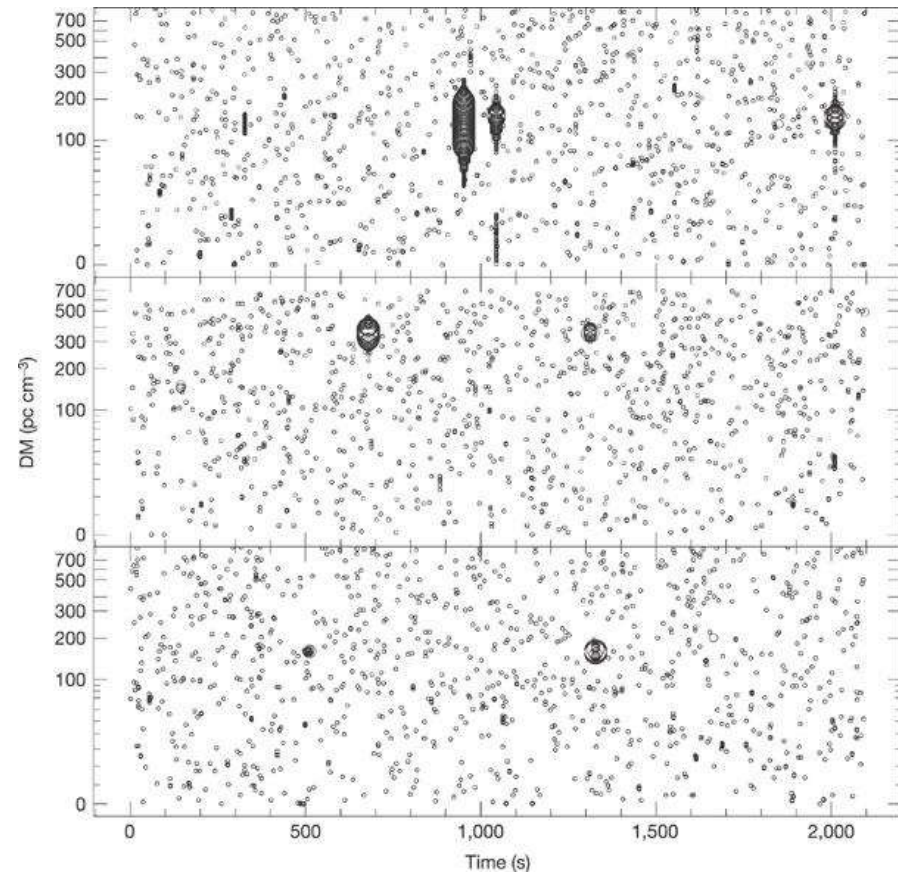
# Classes of fast transients: neutron stars

- Repeating, galactic sources with coherent emission processes
- Pulsars, nulling pulsars, magnetars, rotating radio transients (RRATs) and Crab giant pulses all originate from magnetized, rotating neutron stars



# Classes of fast transients: RRATs

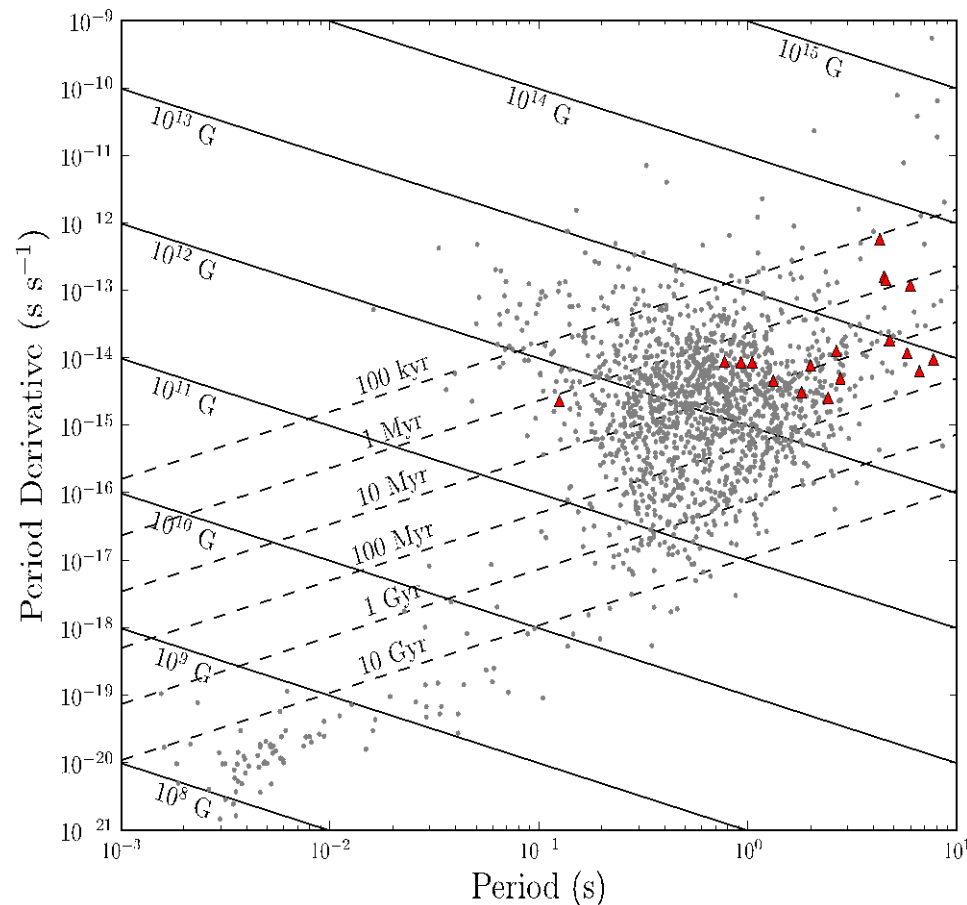
- Identified as single, dispersed pulses with durations 2-30 msec
- Repeat stochastically every few minutes to a ~hours at same DM
- Periods from 0.4 s to 7 s
- Concentrated in the galactic plane
- Some evidence that RRATs bridge an evolutionary gap between normal pulsars and magnetars in the P-Pdot diagram



McLaughlin et al. (2006)

# Classes of fast transients: RRATs

- Identified as single, dispersed pulses with durations 2-30 msec
- Repeat stochastically every few minutes to a ~hours at same DM
- Periods from 0.4 s to 7 s
- Concentrated in the galactic plane
- Some evidence that RRATs bridge an evolutionary gap between normal pulsars and magnetars in the P-Pdot diagram

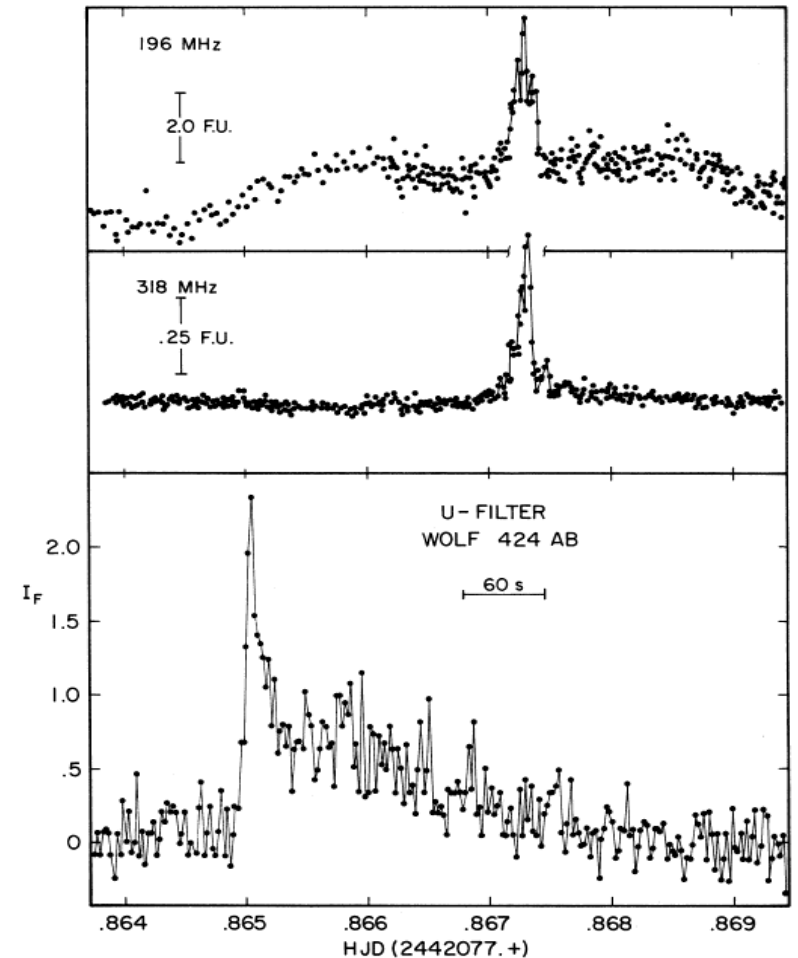
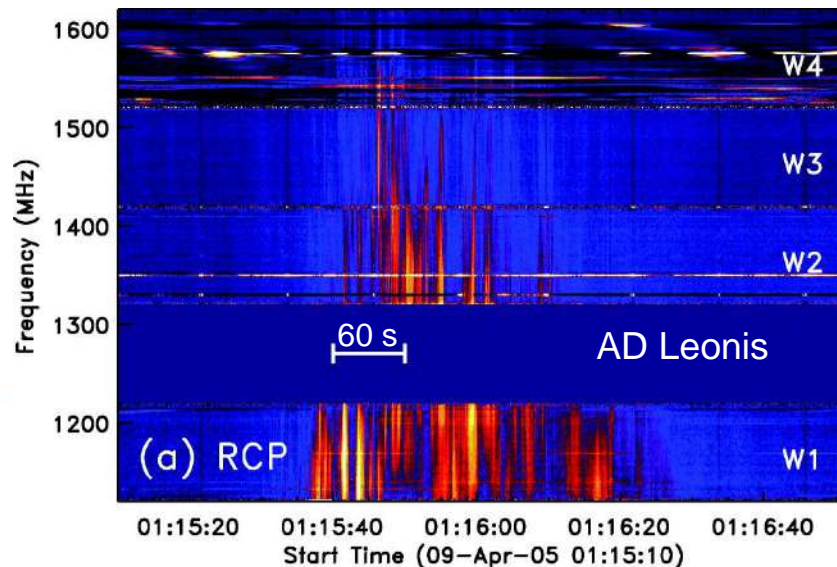


Karako-Argaman et al. astro-ph/1211.2183



# Classes of fast transients: Flare Stars

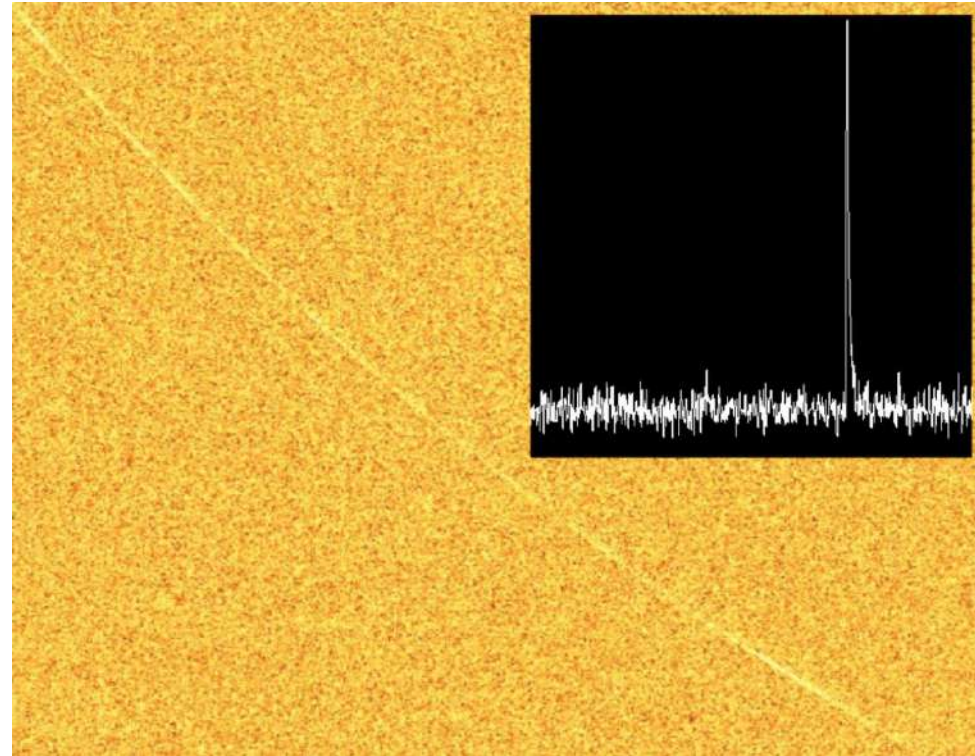
- The Sun, magnetically active stars and brown dwarfs all undergo dramatic flaring behavior
- Burst durations last typically 10s to 10's min
- Relatively rare or understudied
- Typically nearby,  $d < 30$  pc
- Strongly circularly polarized



Spangler & Moffett (1976)

# Fast Radio Bursts (FRBs aka Furbies)

- Single, intense millisecond bursts
- Parkes Observatory has now detected seven fast radio bursts. Arecibo has detected one
- Dispersion measure in excess of galactic values suggest extragalactic
  - Implied redshift  $z \sim 0.5$  to 1.5
- Implied rate is  $\sim 10,000/\text{day}$  all sky
- Next step is to verify and obtain an arcsecond localization
  - to enable host ID and distance measurement



Thornton et al (2013)

# Current VLA Capabilities for Time Domain

- Full-band frequency coverage tunable from 1 to 50 GHz
- Micro-Jy continuum sensitivity in snapshot observations
- Wide instantaneous bandwidth (2 to 8 GHz) allows for easy spectral index measurements
- Regular proposals as “Triggered Transients” and DDT proposals
- Dynamic scheduling of the array and coordinated scheduling with other Observatories (e.g. Chandra)
- A pipeline that produces calibrated visibility data
- A wide array of special modes, including pulsar modes, independent sub-arrays, phased array, and fast dumps

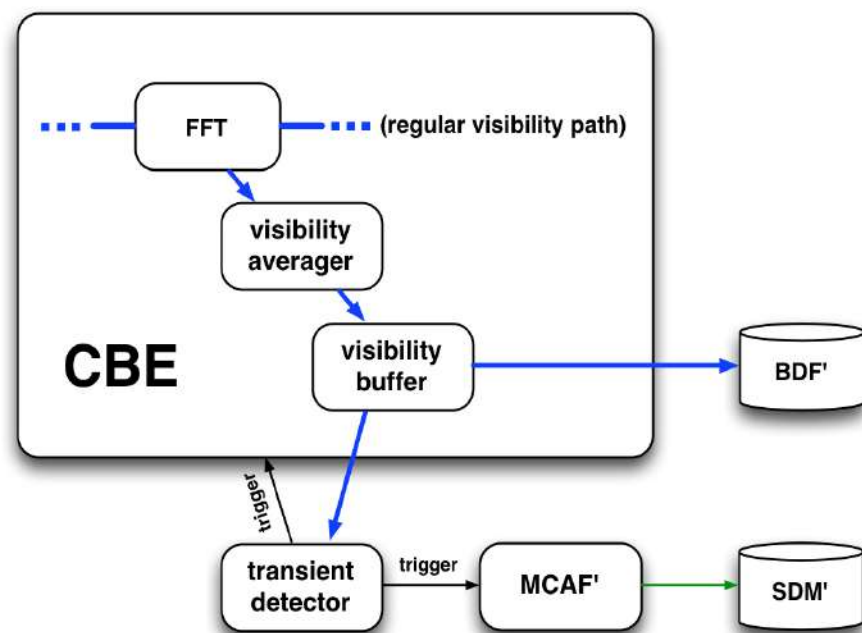
# Planned VLA Capabilities for Time Domain

- ✓ Fast dumps
- ✓ On the fly (OTF) imaging
  - Pulsar modes
  - Commensal observing
  - Automated rapid response to external triggers



# Fast Radio Bursts at the VLA

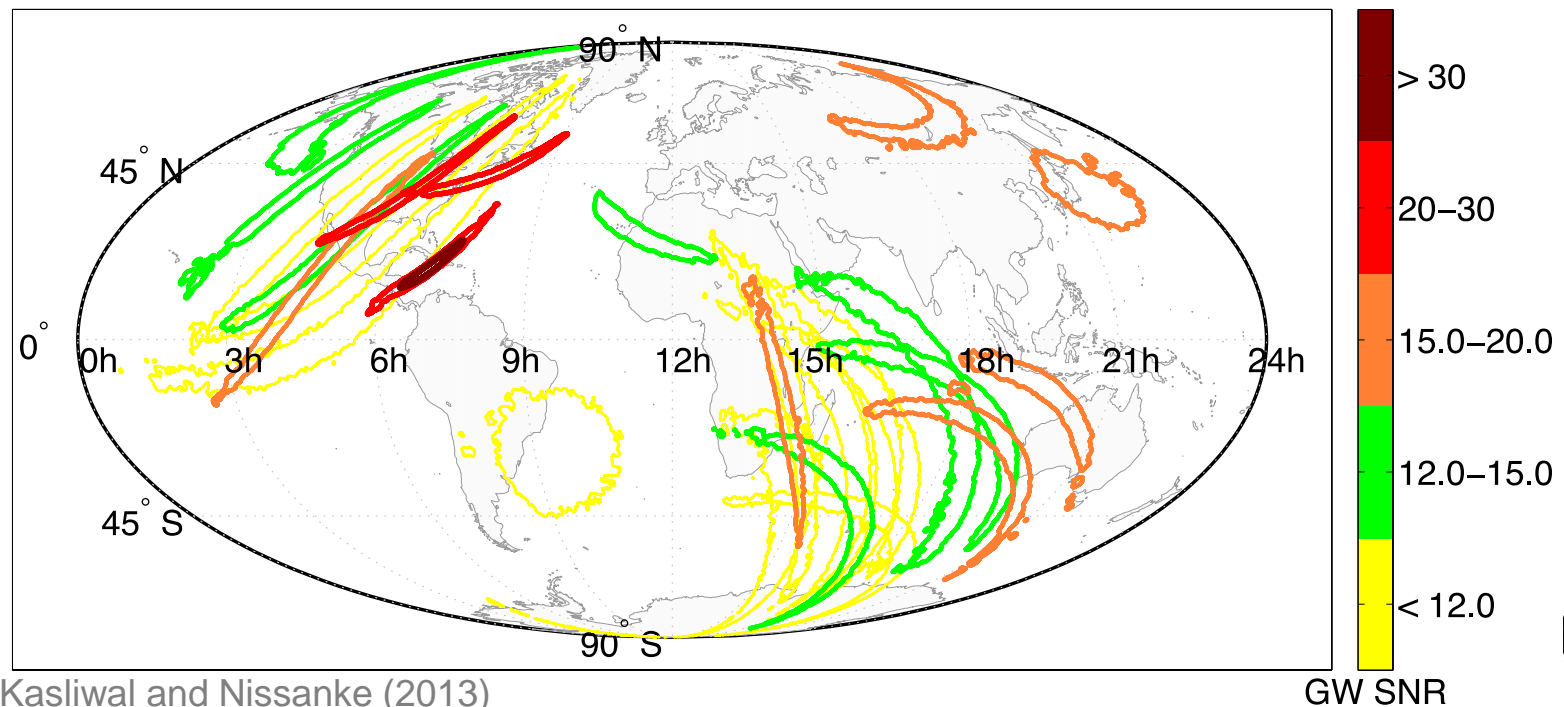
- VLA has high instantaneous sensitivity, wide FoV and arcsecond localization
- Approved DDT and Regular proposal (Law et al.) 300 hrs in fast-sampling mode
  - 1 Tb/hr data rate
  - 150 hrs already observed. Processing is complete.
- Funding proposal underway for a real-time commensal system with fast imaging, trigger and data buffer system



*All FRBs, all the time.*

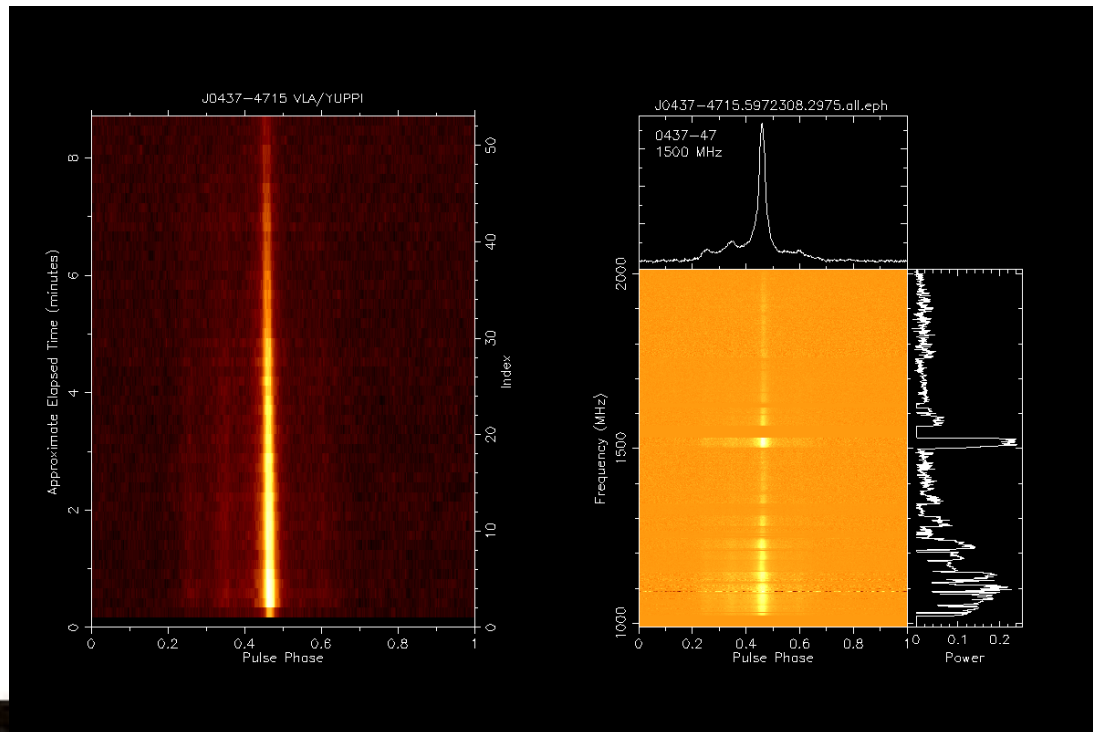
# On-the-fly (OTF) imaging and EM counterparts to gravitational waves

- Instantaneous sensitivity of VLA is very large, FoV is relatively small
- OTF: antennas continuously slewed while stepping phase centers
- Ideal for surveys (e.g. VLASS) and for irregularly shaped error boxes expected for EM counterpart searches of GW



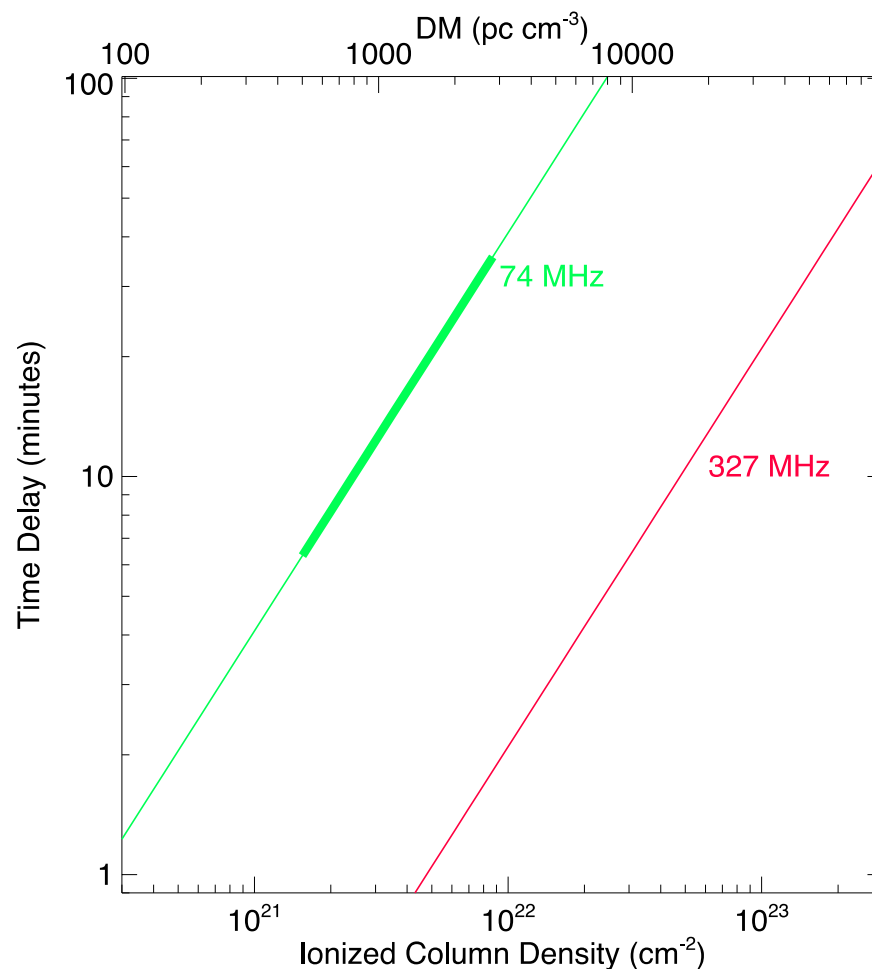
# Pulsar Modes

- Phased array VLA data processed in the WIDAR correlator or the correlator back end (CBE) computing nodes.
- Will allow searches (e.g. Galactic Center), pulsar timing for Nanograv and simultaneous pulsed/imaging experiments (PWN, GC)
- NM staff + Demorest, Lazio and Ransom



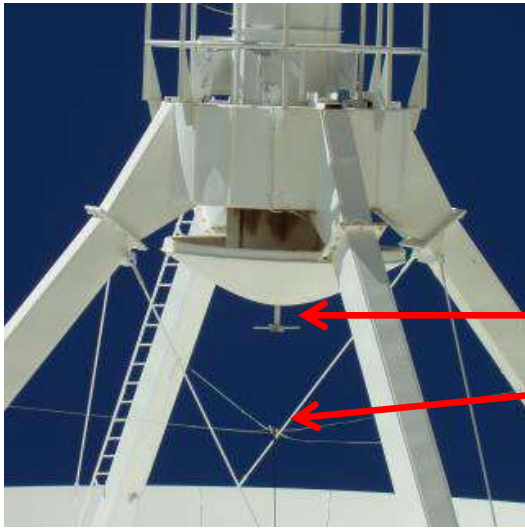
# Hot-wiring the VLA

- Autonomous response to external triggers via GCN socket or VOEvent alert
- VLA can slew to any part of sky in 4 min on average
- Already working on VLBA
- Software effort needed to bypass dynamic scheduler
- Limited science case
  - Prompt GRB emission
  - Flare stars
  - FRB “afterglows”





# Commensal Observing with LOBO

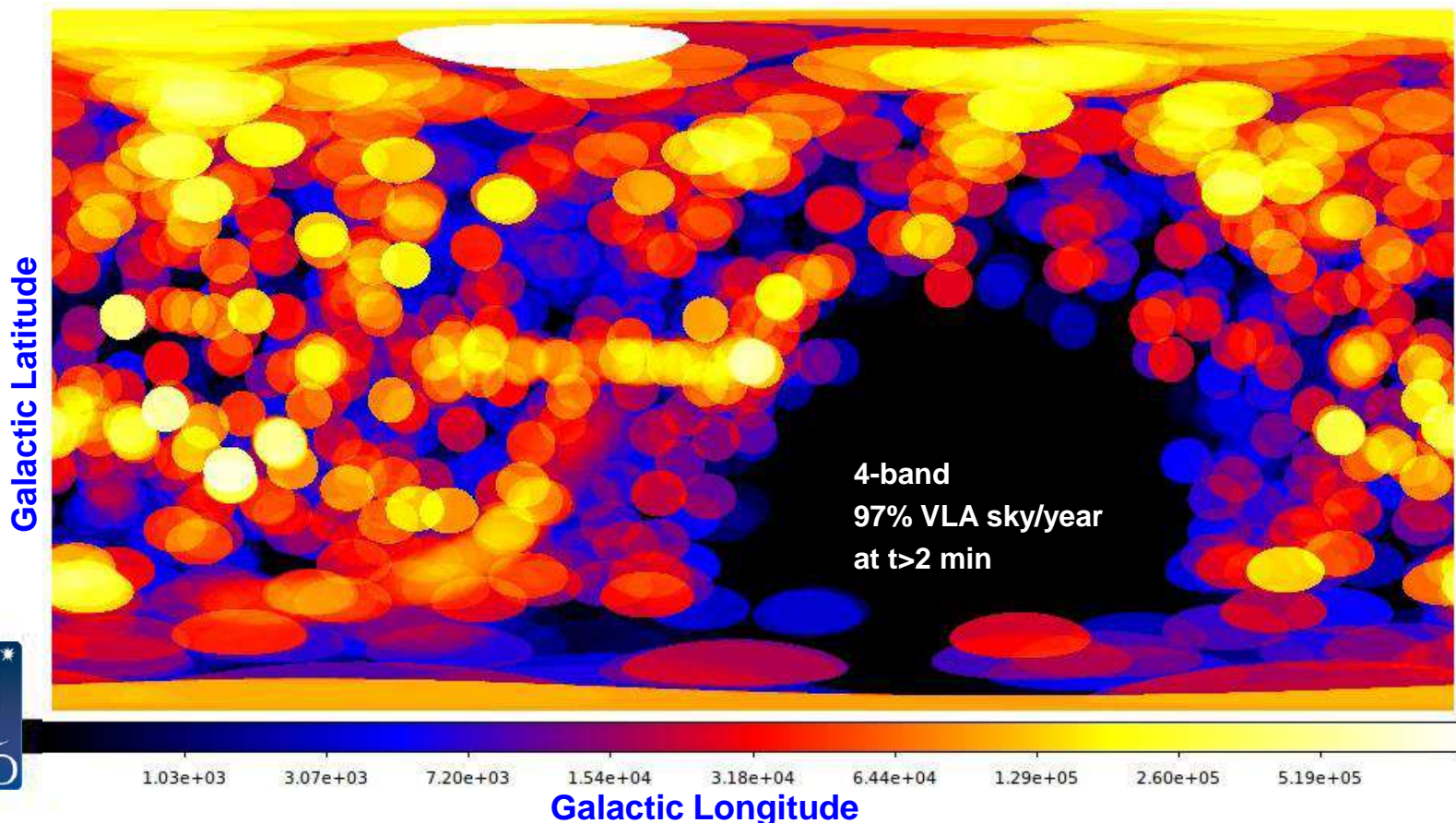


- A joint NRL-NRAO design concept
- Observe with the VHF systems at the prime focus in parallel with the Cassegrain system
  - P band 236-492 MHz
  - 4 band 54-86 MHz
- Capture full band and independently correlate
- A radio LSST A 24/7 synoptic, wide-field imager slaved to the Cassegrain science pointings



# The Low Band Observatory (LOBO)

- Main science drivers
  - Real-time, remote sensing of the ionosphere (NRL, DoD, NASA, etc.)
  - Radio transient detection (large FoV and ToS)
  - Range of low-frequency galactic and extra-galactic science



# V-LITE. A LOBO Prototype

- US Navy (NRL) funded a Kassim and Ray proposal for \$1.07M
- With design, development, etc. builds a 10-element prototype
- Design is P band only, 64 MHz BW, 8 bit
- Project complete October 2014.
- Expected to be ready for B config in 2015
- Transients
  - Galactic center transients (Hyman et al ) 20 events
  - Slow transients (Jaeger et al. 2011) 100 events in 5000 hrs
  - Fast transients (FRBs). 60 Lorimer-like events per year but requires a fast transient detection. Looking into a GPU-based system.

# Transients at the VLA

- Broad-band, solar flare science at msec time resolution
- Active flare stars and brown dwarf emission mechanisms
- Localizing Rotating Radio Transits (RRATs)
- Non-thermal emission from Galactic novae
- Jet formation in BH, NS and VWD binaries
- Full-band monitoring of G2 encounter of Sgr A\*. (Public data)
- Exposing the full diversity of supernova explosions (Ia, luminous Ib/c, BL Ic, fast Ib/c, IIn, IIL, IIP, IIb, etc)
- Discovery of new class of (relativistic) tidal disruption event (TDEs)
- Gamma-ray bursts (RS, SHB,  $z < 0.3$ ,  $z > 6$ , high E, etc.)
- Systematic exploration of the transient radio sky
- Confirming and localizing fast radio bursts