Transients, fast and slow

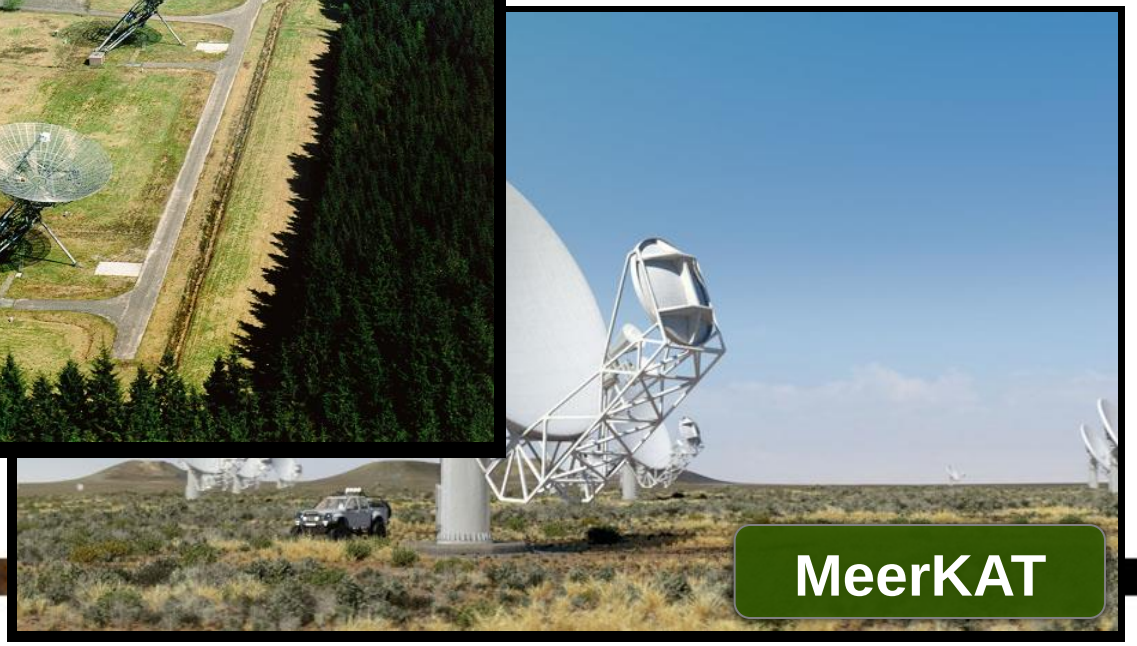
Dale A. Frail
AD VLA and VLBA


LOFAR


ASKAP


WSRT-Apertif

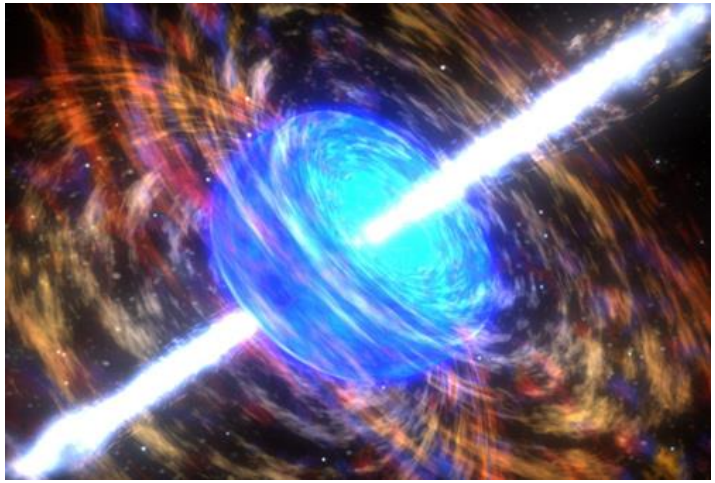

LWA


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

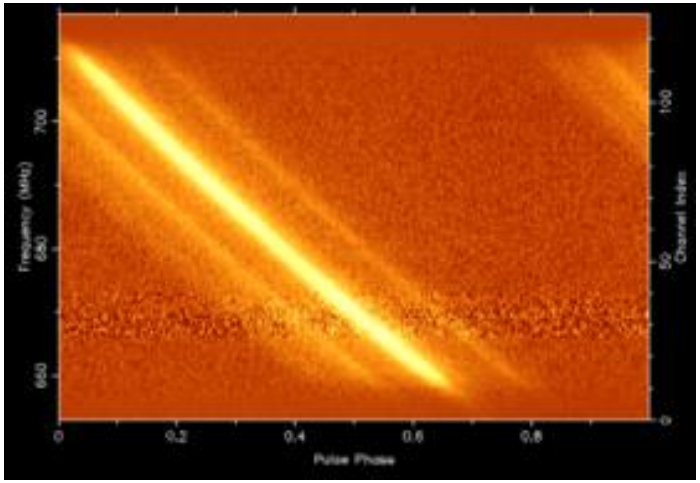


Examples:

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

Fast=Coherent

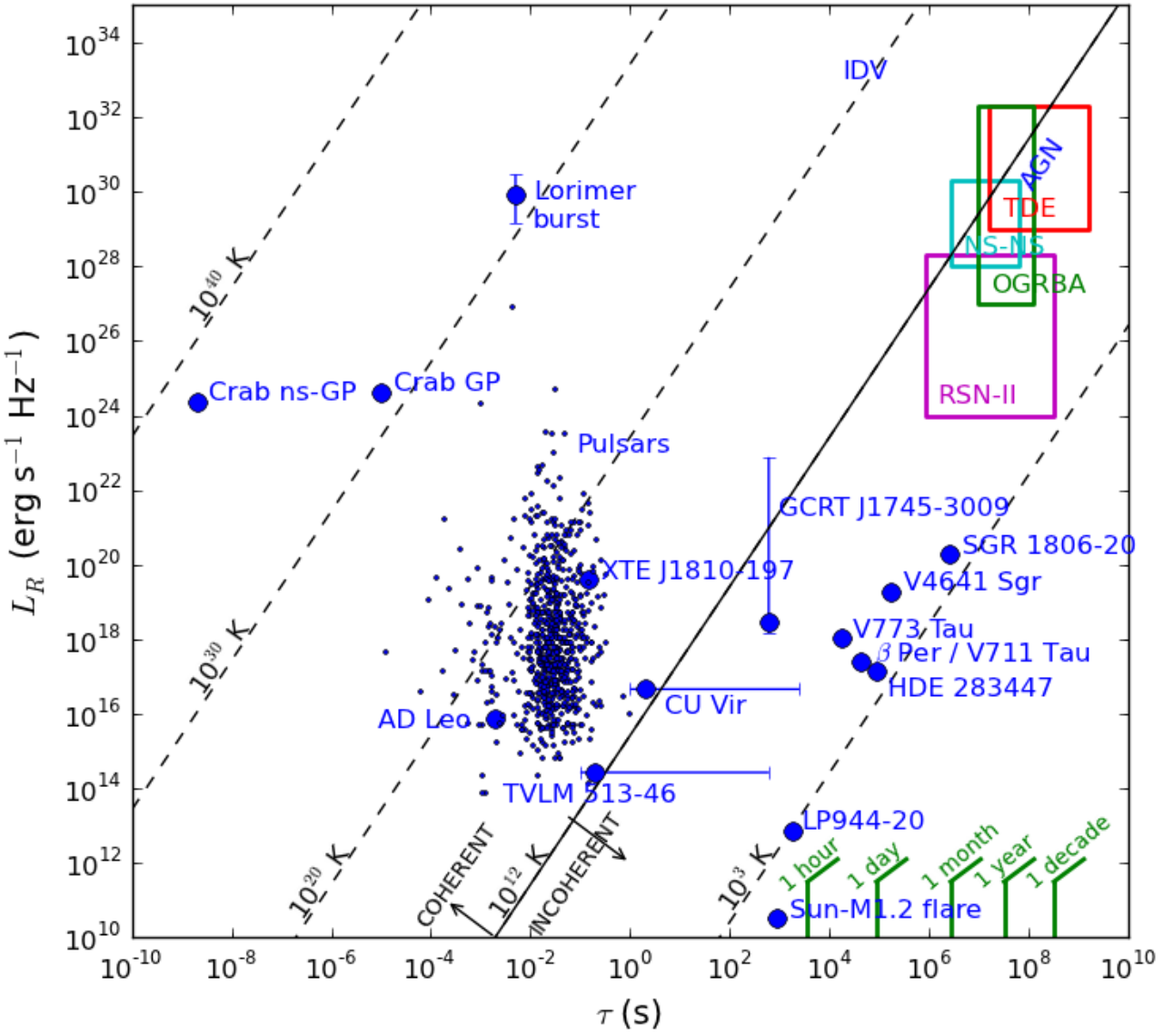
- Various flavors of coherent emission
- Variable on timescales of ns - minutes
- Brightness temperatures as high as $>10^{38}$ K
- Typically discovered in time-series data



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.

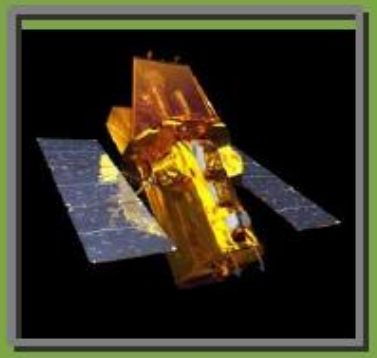
NRAO

The VLA and PTF Stripe-82 Project

Real-Time Transient Detection Pipeline

Transient Candidates

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

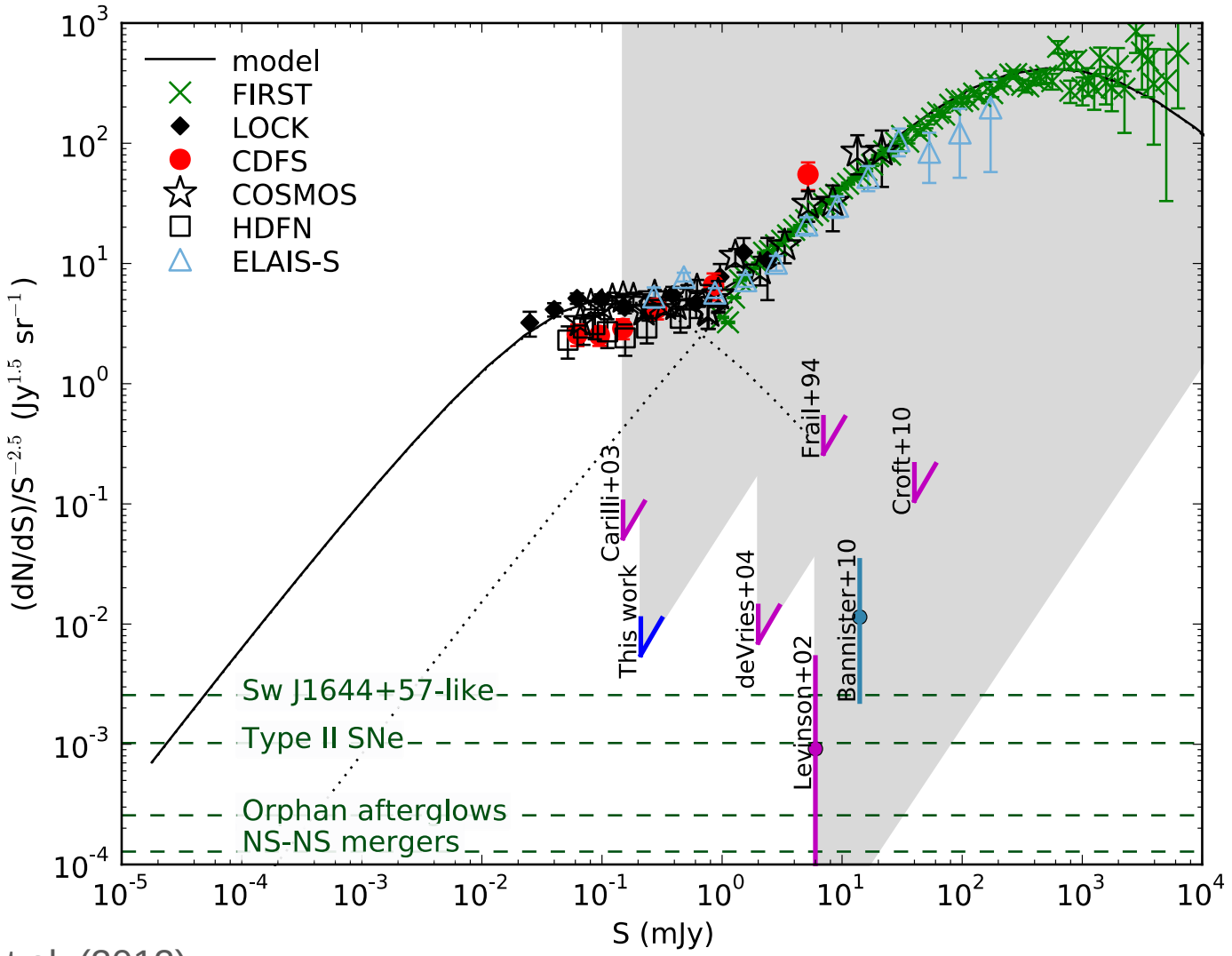


Interesting Transients

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^2)
  - Isotropic source distribution on sky
    - >1 mJy source populations are radio-loud AGN
    - <1 mJy star-formation galaxies and radio-quite AGN start to emerge
- The variable radio sky is boring
  - The fraction of strong variables at 1 GHz is small <<1%
  - AGNs appear to dominate the variable sky
- The (revised) transient radio sky is **really** boring
  - Transients are <=10^{-4} of the quiescent population

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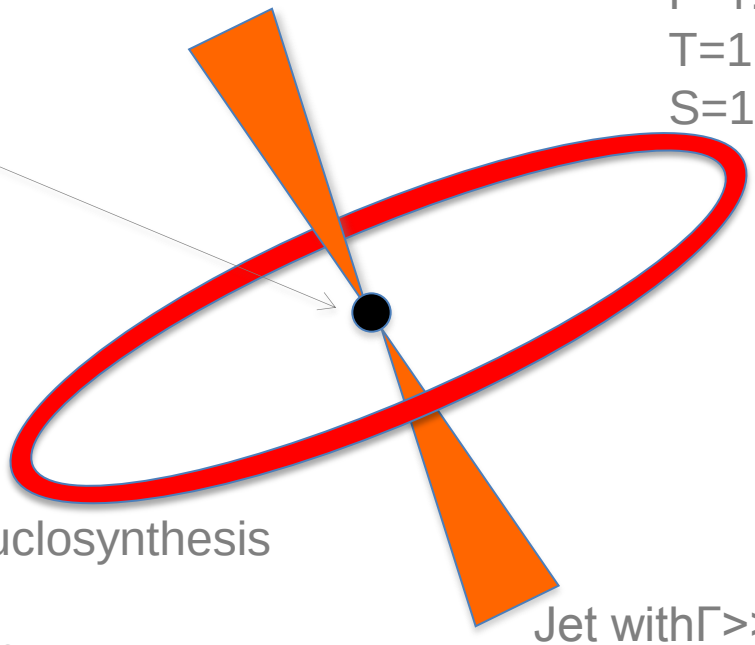
Seeing is Believing: EM-GW Counterparts

Ejecta-ISM interaction
(accretion disk outflow or tidal tails
Γ~1.3
T=1 month – 1 year
S=100 uJy

Contact shock
Γ>1
T=weeks
S=100 uJy

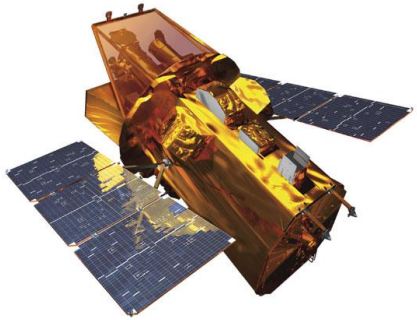


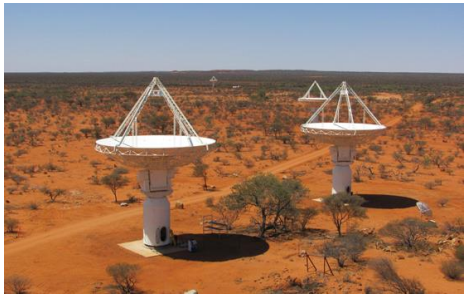
"Macronova"
R-process nuclosynthesis
T=1 day
m=22-23 mag

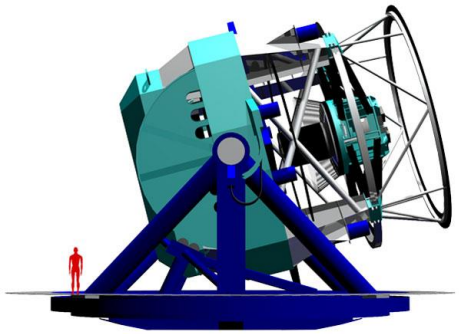
Jet withΓ>>1
T=days-weeks
S=10's mJy

Act Like A Buccaneer: Own the Follow-up

Follow-up: A biased but rewarding approach







Radio Transient Phase Space: Simplified

	Short duration	Long duration
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

Fast Transients: A pragmatic definition

- Intense, short duration (ct<1 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

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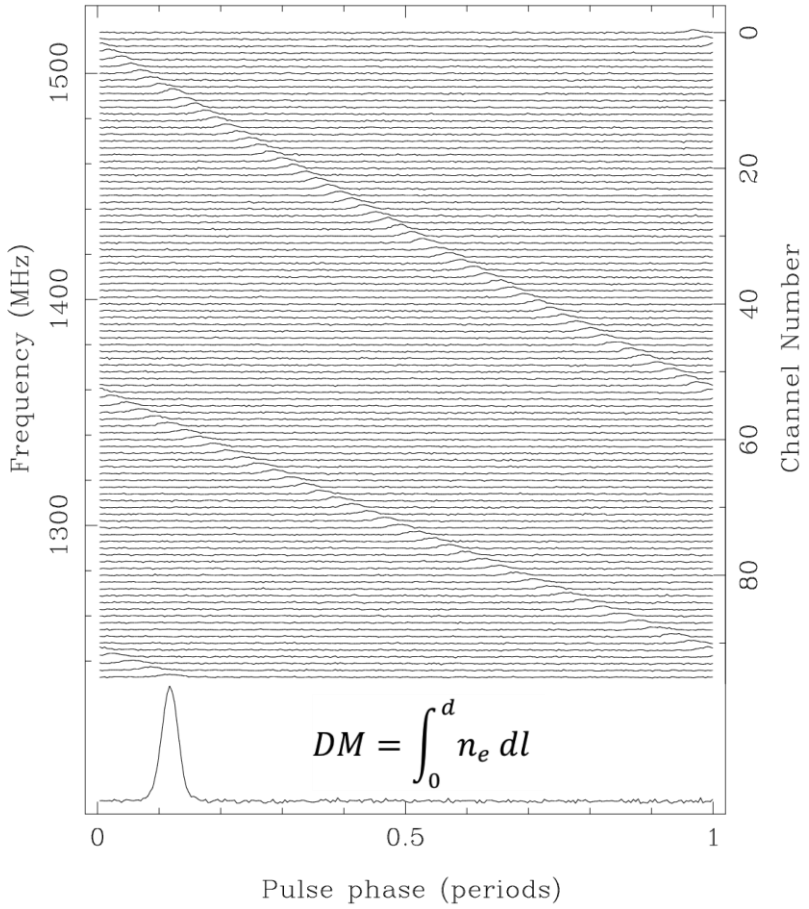
Radio Transient Phase Space: Simplified

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

Plasma Propagation I: Dispersion



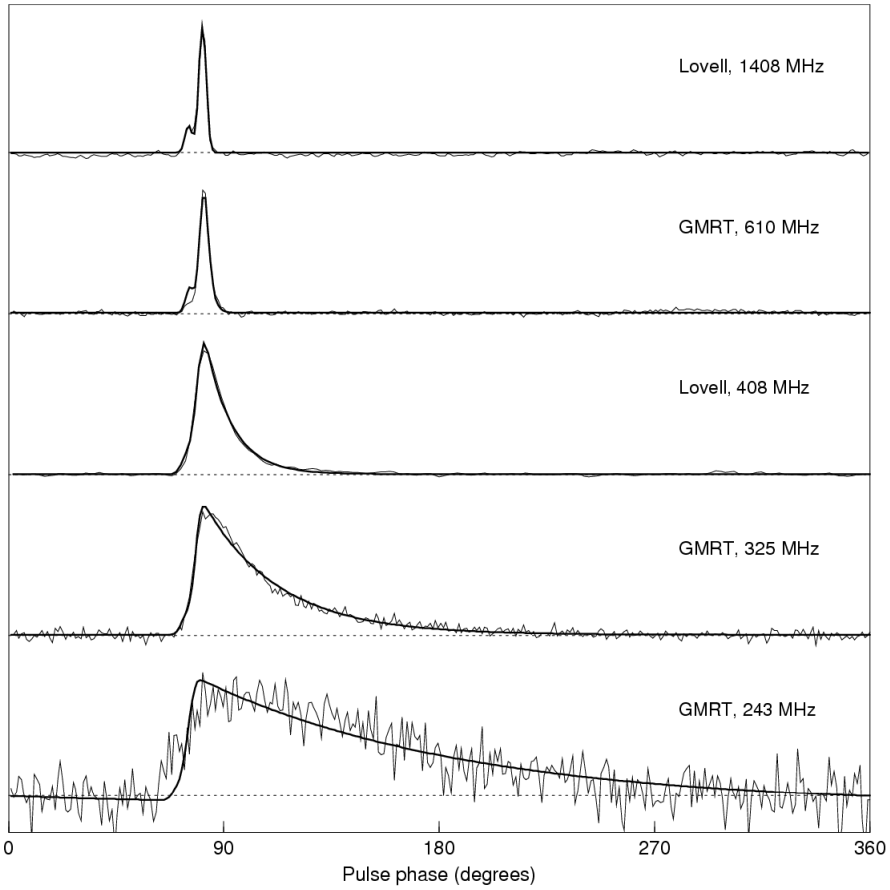
Lorimer and Kramer (2005)

- 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^{-3} or electron column $N_e=10^{20}$ cm^{-2}

- *Negative*: Computational overhead. Must search for unknown DM in data reduction
- *Positive*: Excellent probe of ionized gas (i.e. IGM)

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

Plasma Propagation II: Scattering



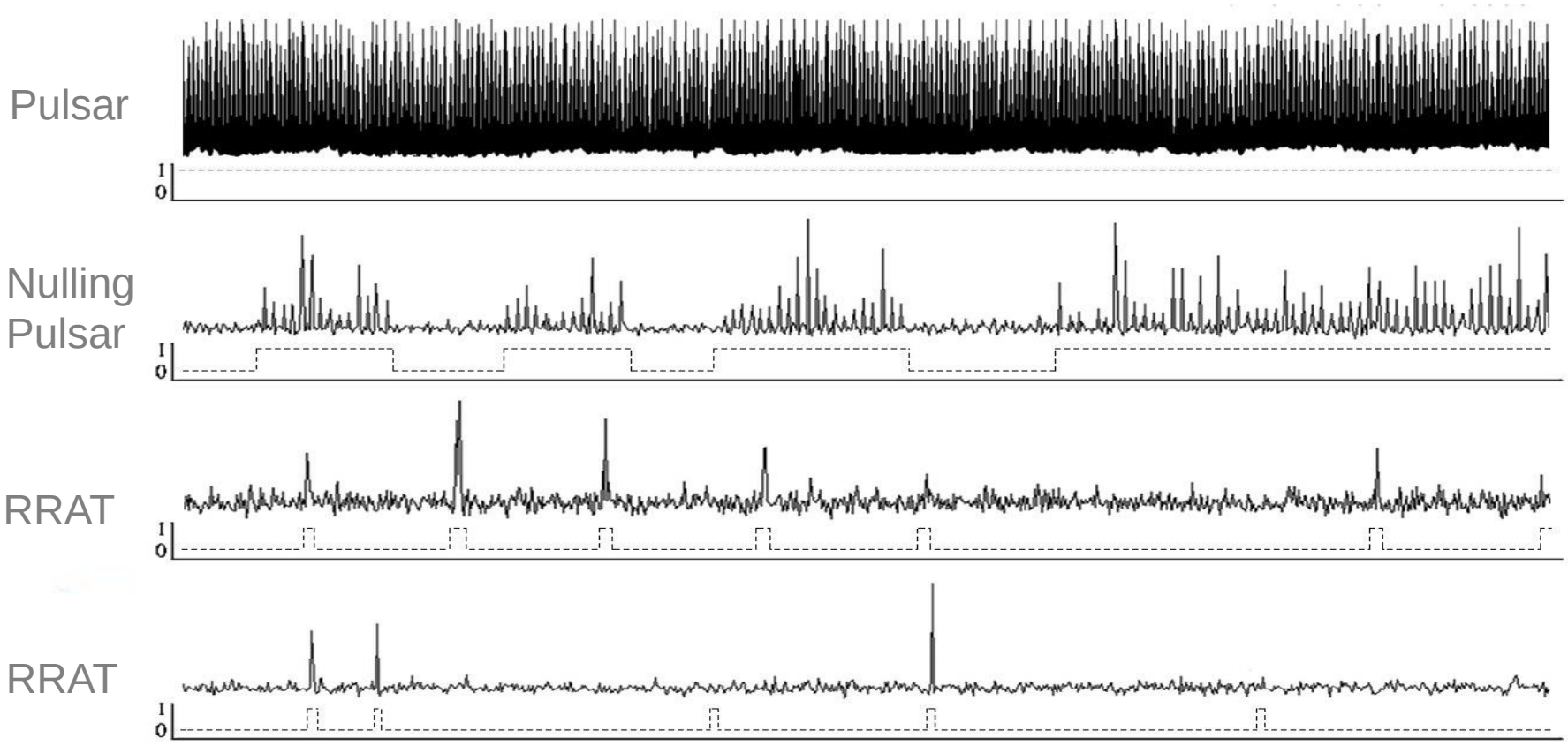
Lorimer and Kramer (2005)

- 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 $P > 5\tau_{scat}$
- Single pulses have an advantage over period pulses
- Deal with ISS through appropriate observing strategy.

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

Classes of fast transients: neutron stars

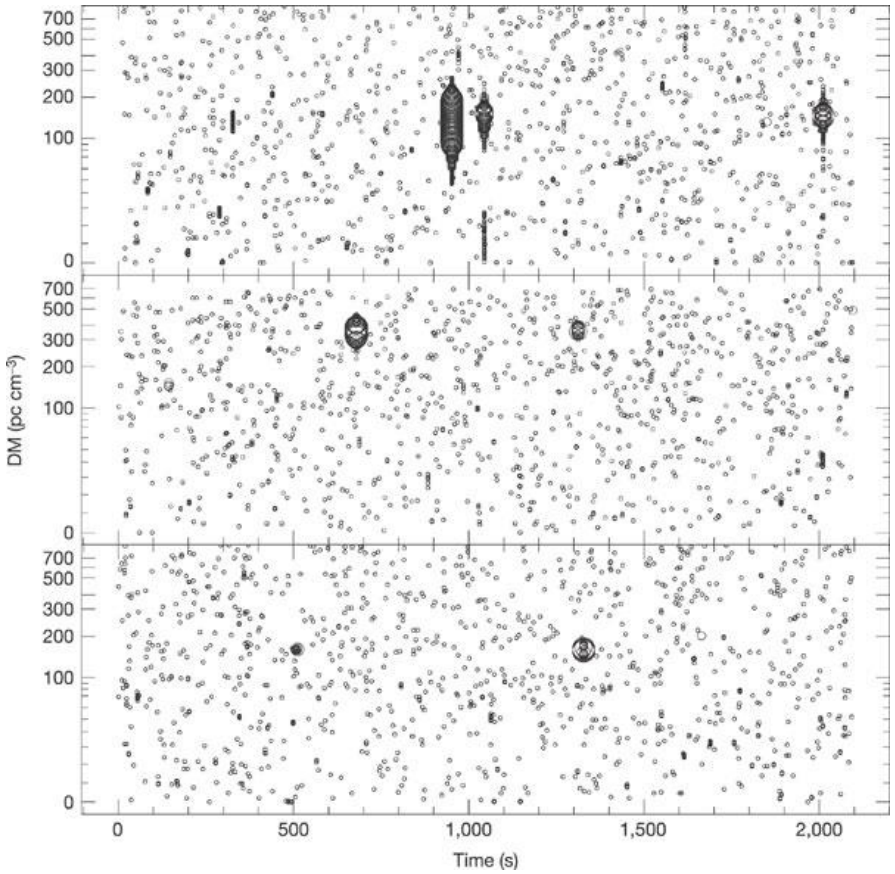
- Repeating, galactic sources with coherent emission processes
- Pulsars, nulling pulsars, magnetars, rotating radio transients (RRATs) and Crab giant pulses all originate from magnetized, rotating neutron stars



Burke-Spolar astro-ph/1212.1716

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)

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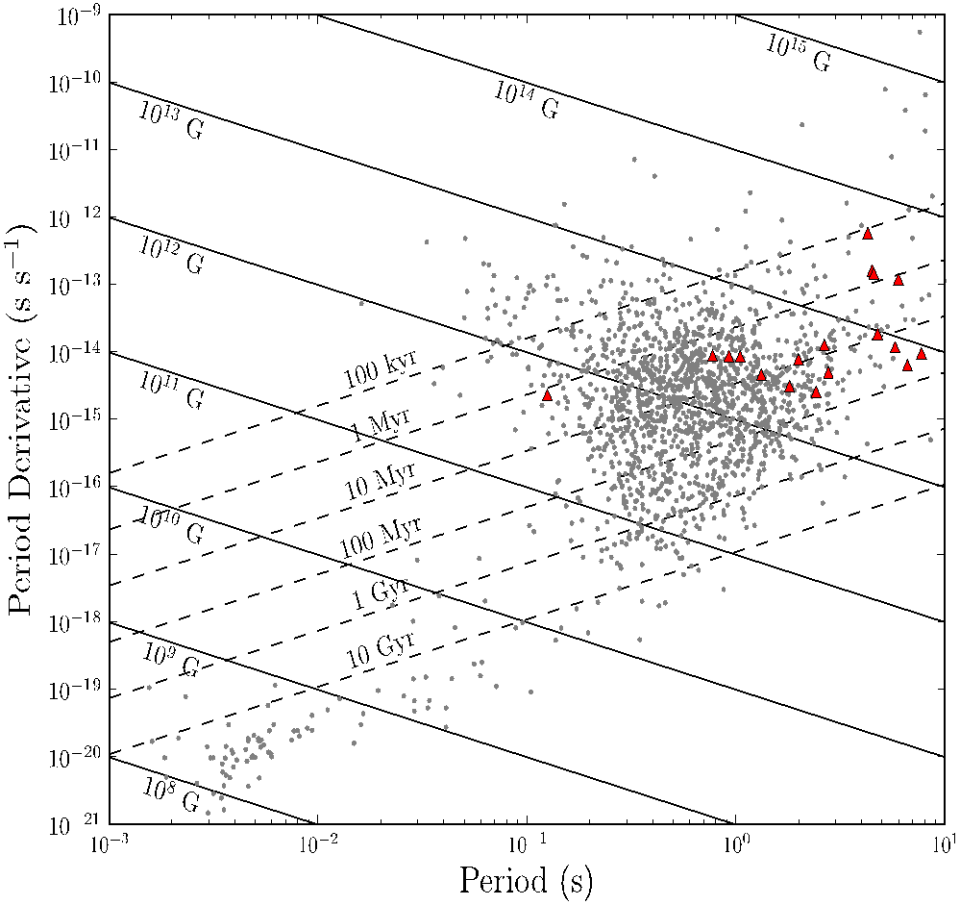
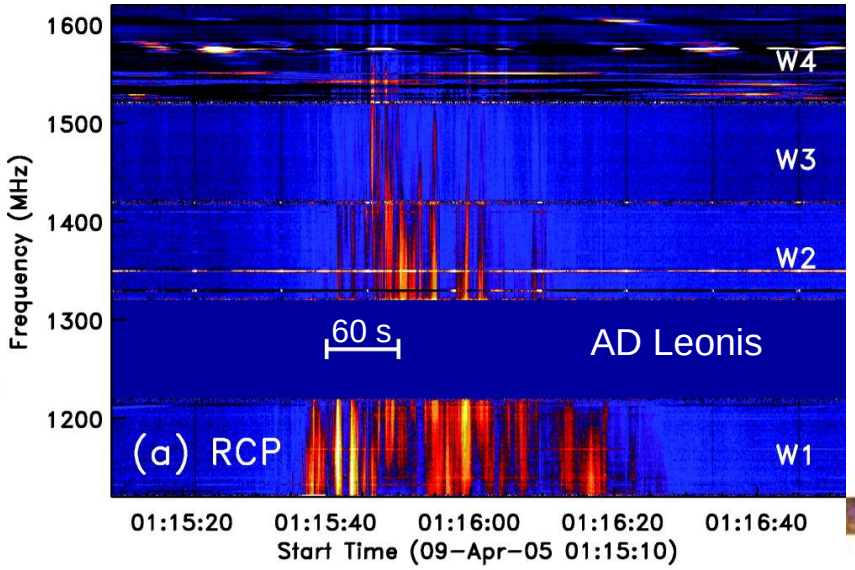


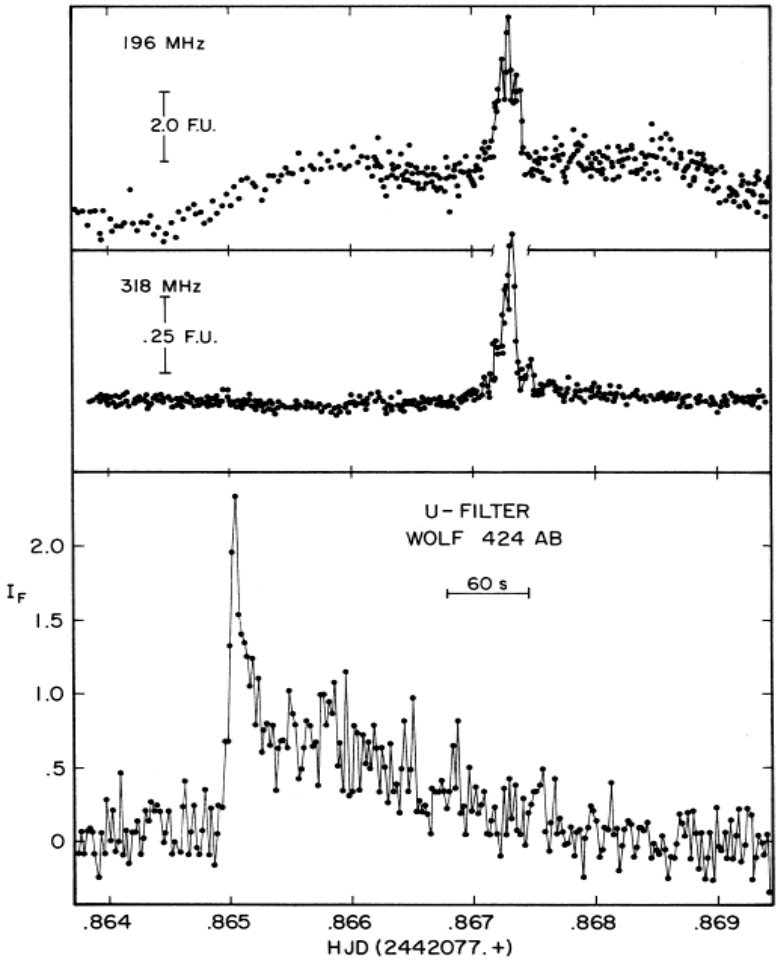
Karako-Argaman et al. astro-ph/1211.2183

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



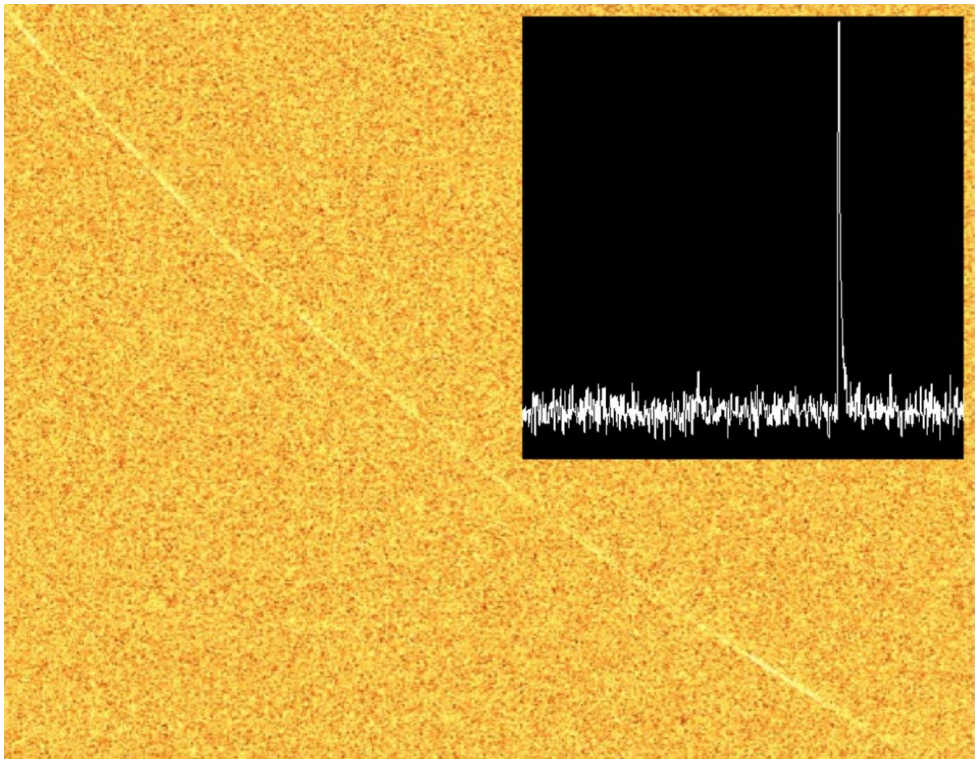
Osten and Bastian (2006)



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~0.5 to 1.5
- Implied rate is ~10,000/day all sky
- Next step is to verify and obtain an arcsecond localization
  - to enable host ID and distance measurement



Thornton et al (2013)

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Current VLA Capabilities for Time Domain

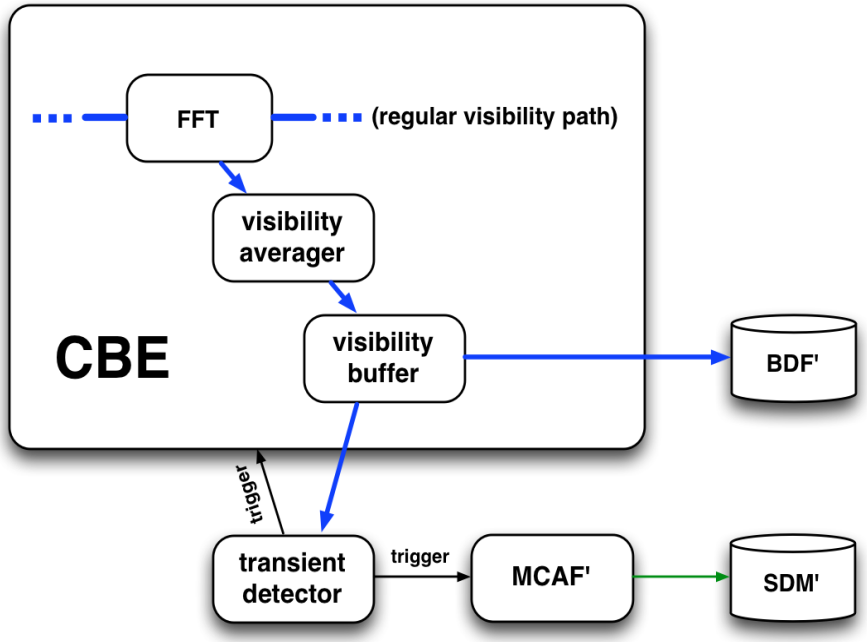
- Full-band frequency coverage tunable from 1 to 50 GHz
- Micro-Jy continuum sensitivity in snapshot observations
- Wide instantaneous bandwidth (2 to 8 GHz) allows for easy spectral index measurements
- Regular proposals as "Triggered Transients" and DDT proposals
- Dynamic scheduling of the array and 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

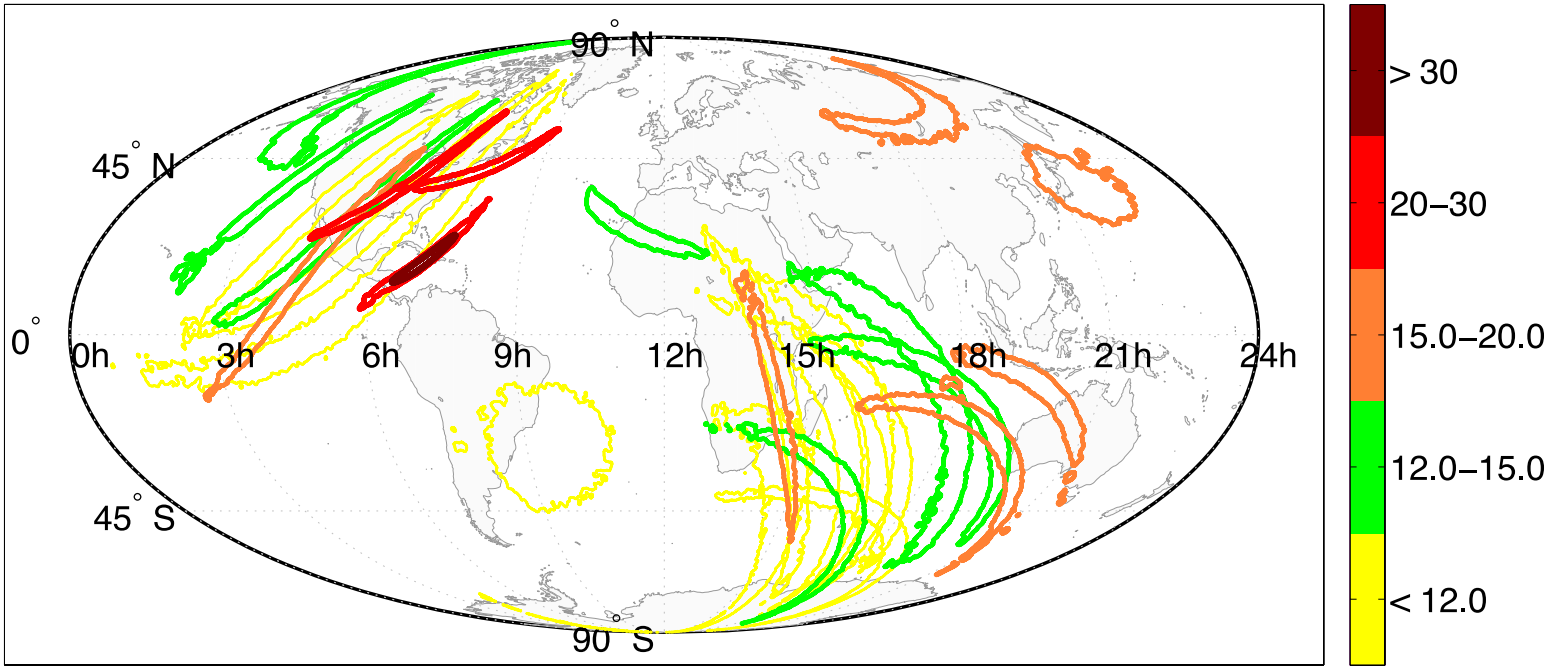
- VLA has high instantaneous sensitivity, wide FoV and arcsecond localization
- Approved DDT and Regular proposal (Law et al.) 300 hrs in fast-sampling mode
  - 1 Tb/hr data rate
  - 150 hrs already observed. Processing is complete.
- Funding proposal underway for a real-time commensal system with fast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



All FRBs, all the time.

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

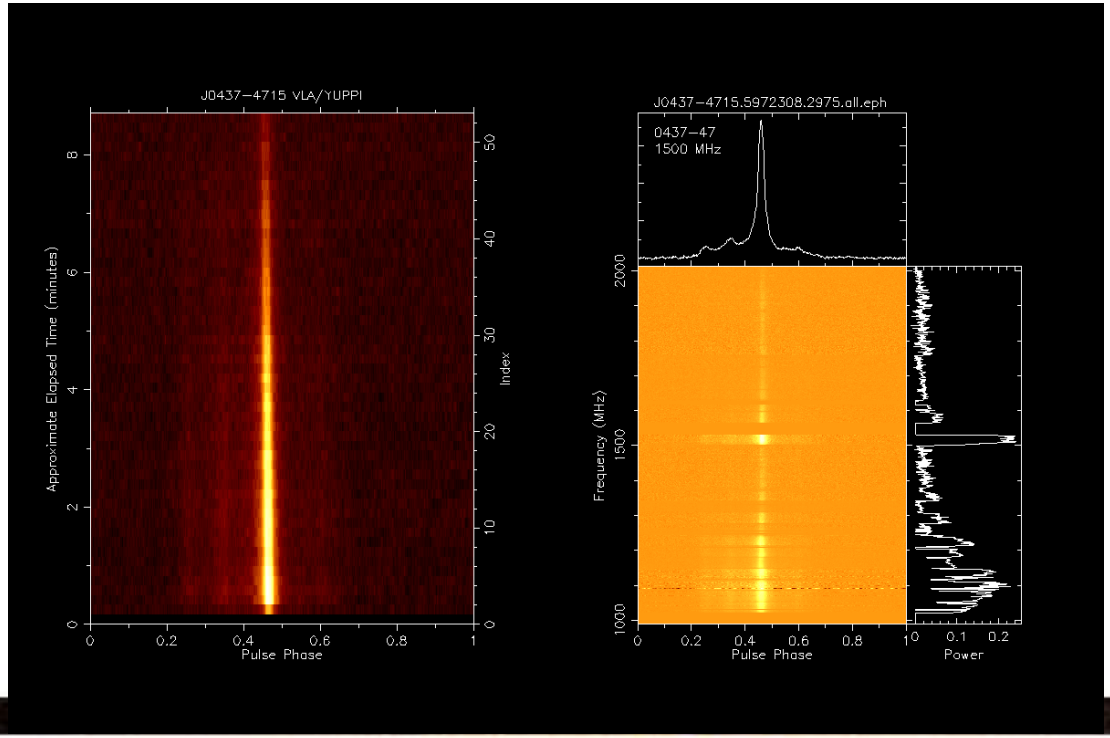
- Instantaneous sensitivity of VLA is very large, FoV is relatively small
- OTF: antennas continuously slewed while stepping phase centers
- Ideal for surveys (e.g. VLASS) and for irregularly shaped error boxes expected for EM counterpart searches of GW



Kasliwal and Nissanke (2013)

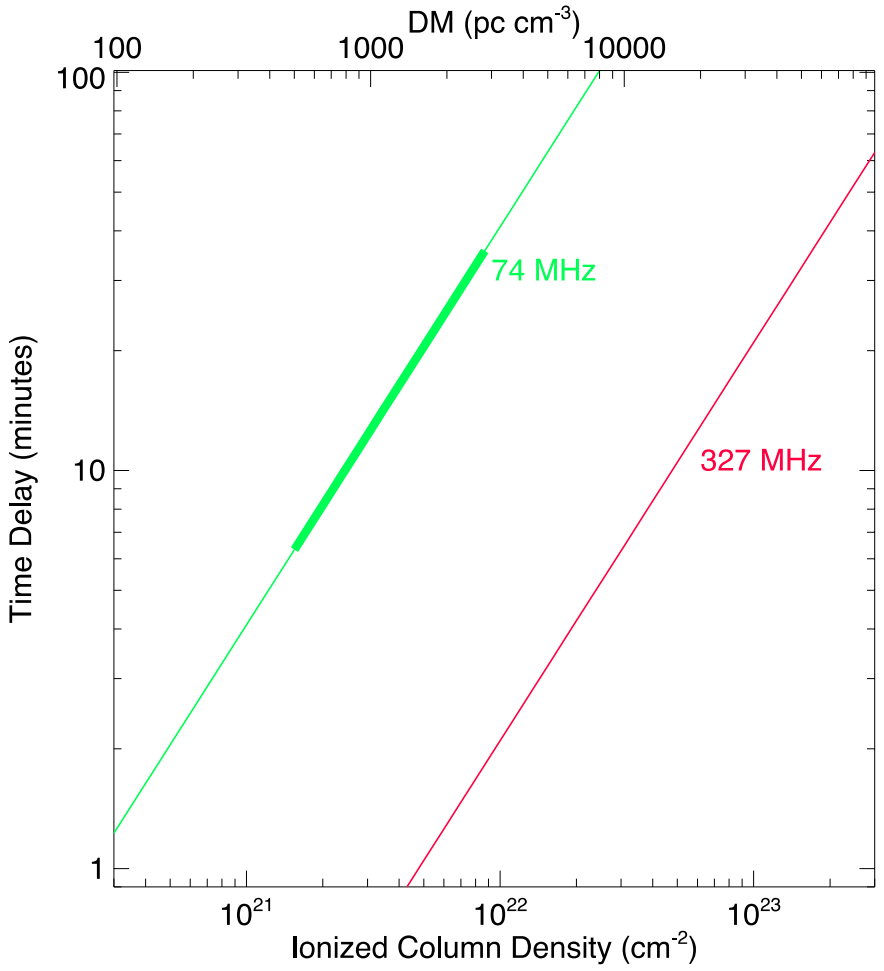
Pulsar Modes

- 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"

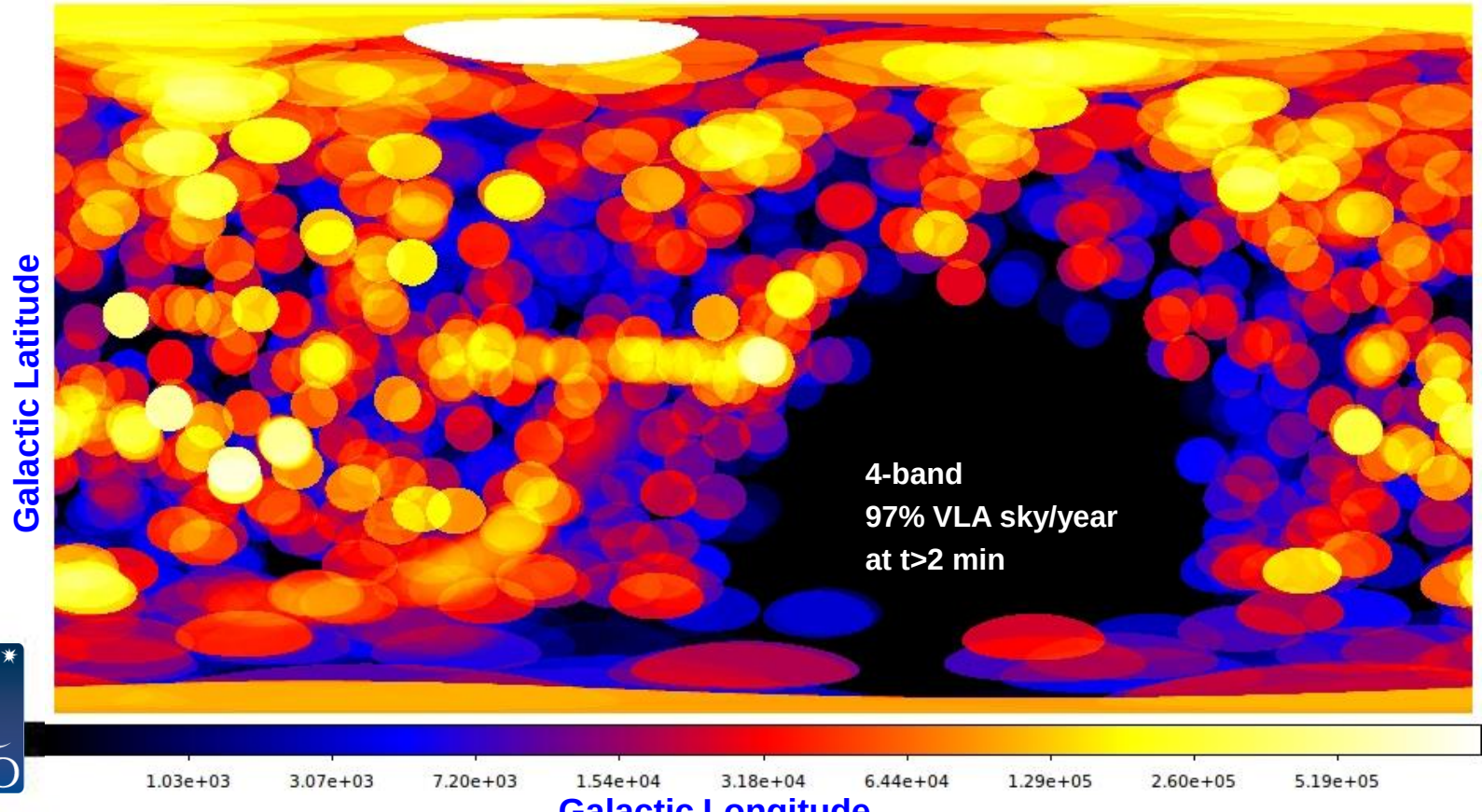


Commensal Observing with LOBO

- 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 WD 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