Pulsars at low radio frequencies

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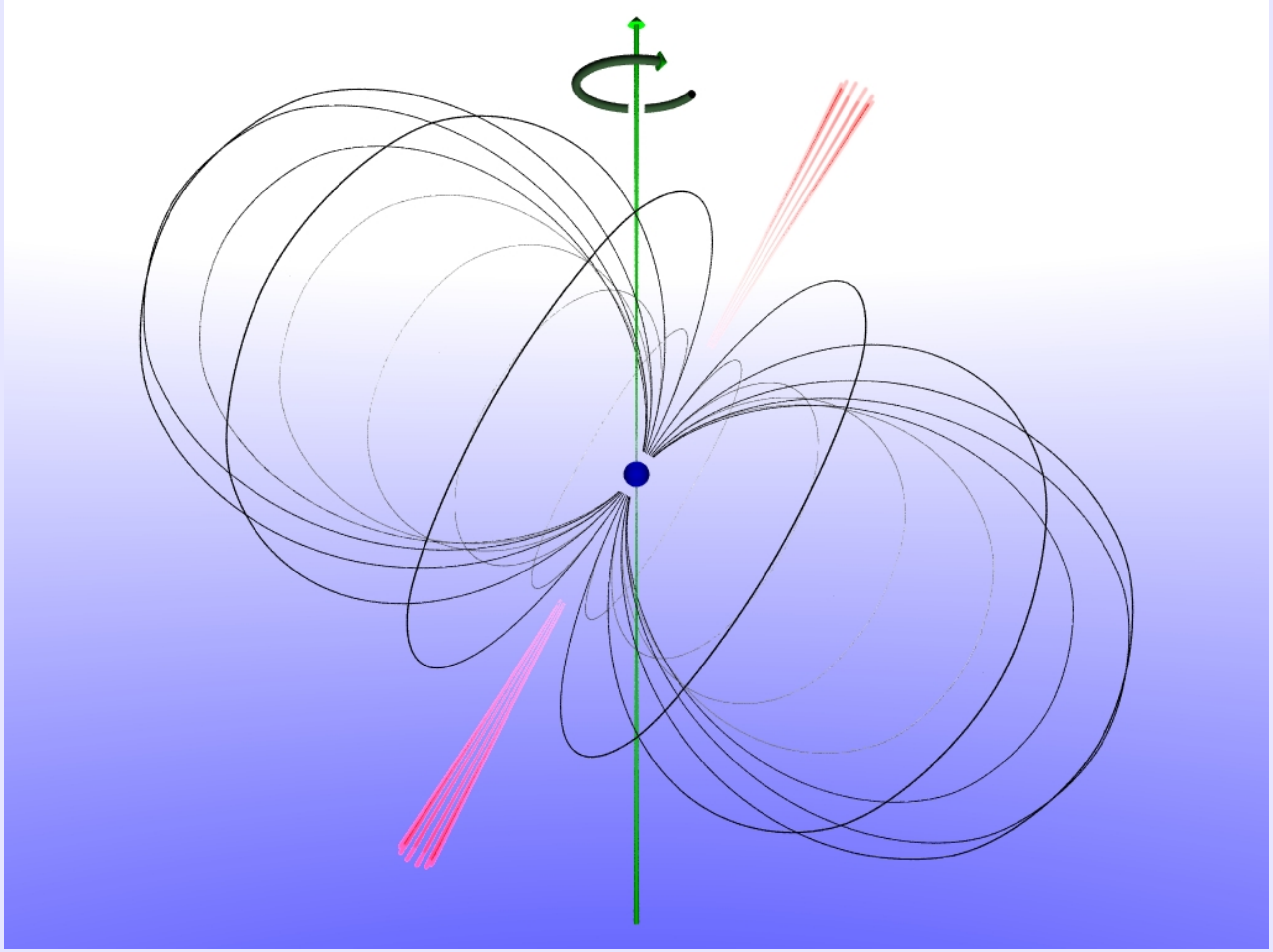
Science at Low Frequencies II Workshop, Dec 2015

Overview, caveats, etc

- Topic: Overview of pulsar science at low frequencies
- There is way too much to cover in one 20-min talk!
  - “Overview” == a couple things I think are interesting
- “Low” here will mainly mean ~sub-GHz
- Summary:
  - Pulsar signal overview – basic properties, propagation in the ISM
  - Brief mentions of various low-freq pulsar projects.
  - Application of low frequencies to high-precision pulsar timing and GW detection.
  - ISM scintillation studies.

Basic pulsar properties



Rapidly spinning, magnetized neutron star.

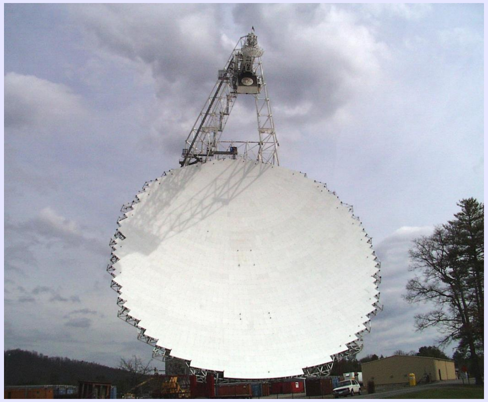
Spin periods ~few seconds to ~few ms.

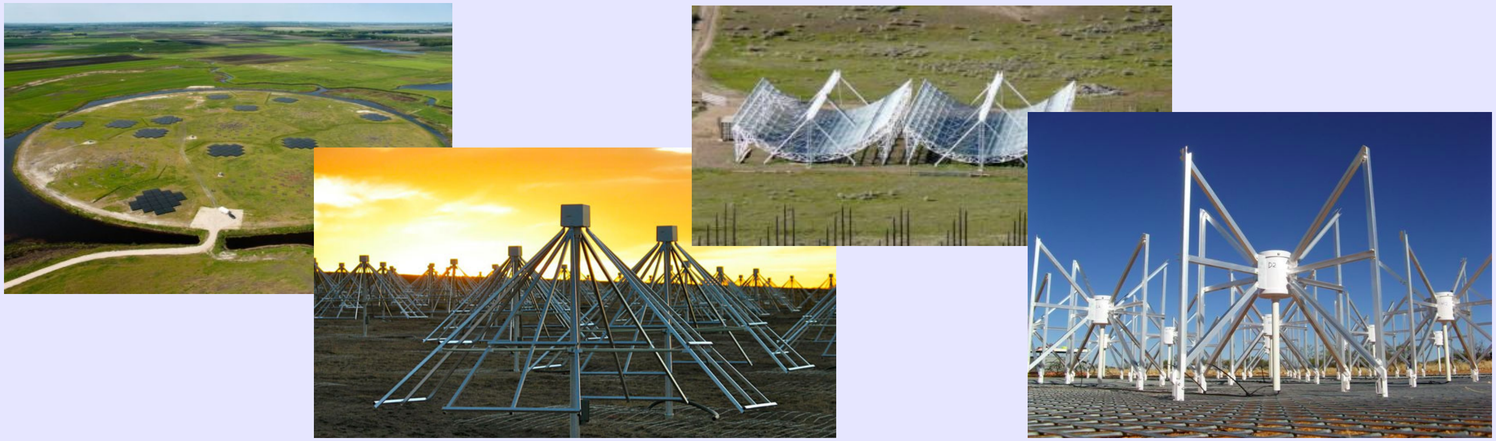
Emits beamed, broad-band, polarized radio signal from magnetosphere – exact details of this process still under active research!

Pulsar radio emission has steep spectral index; typical values range from ~ -1 to -3. Point source with natural pulsed “on – off” (no confusion) → ideal targets for low-freq telescopes.

Pulsar observations at low frequencies – history

Pulsars orginally discovered at ~80 MHz.
More recently field dominated by large single dishes at ~300 MHz – 3 GHz.





But now new era of low-freq telescopes is underway!

Interstellar medium propagation

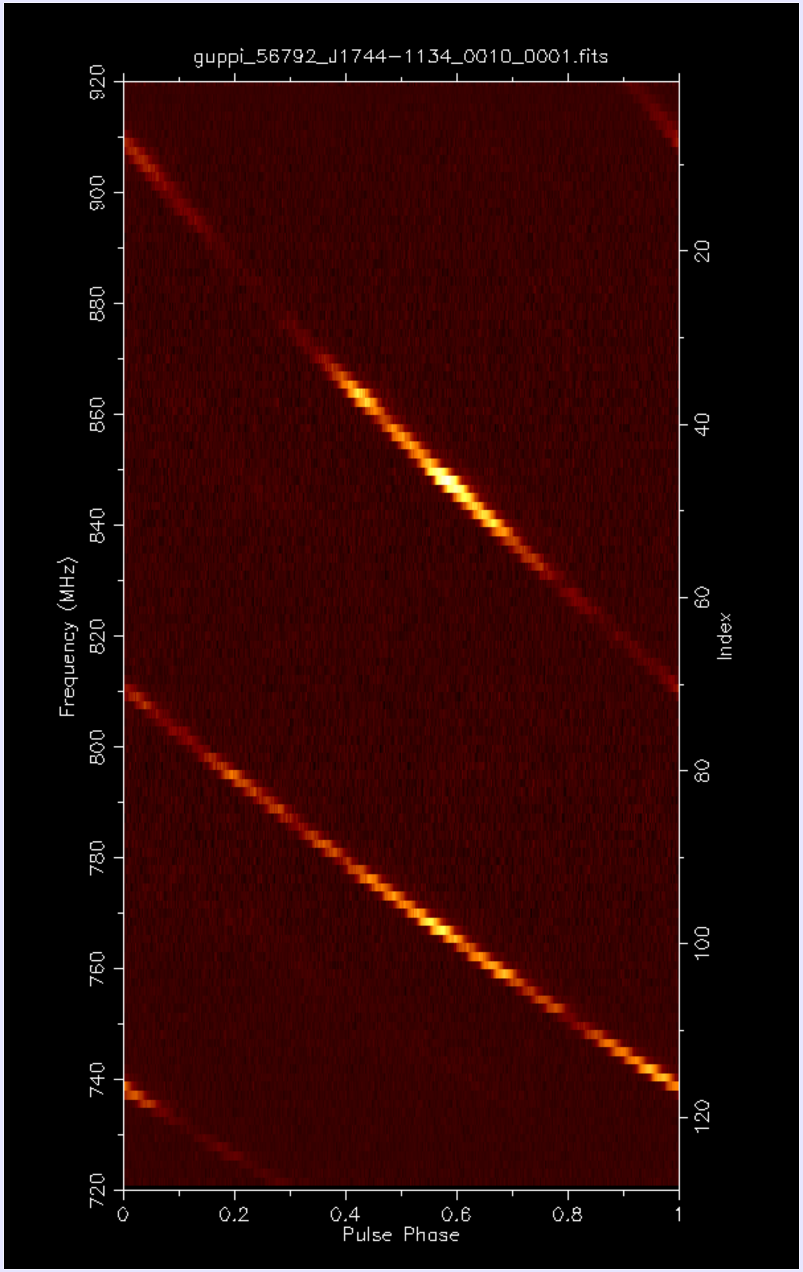
Radio waves propagating through ionized ISM get phase shift, inversely proportional to frequency:

$$\delta\phi \propto \nu^{-1} \int n_e(\mathbf{x})dx$$

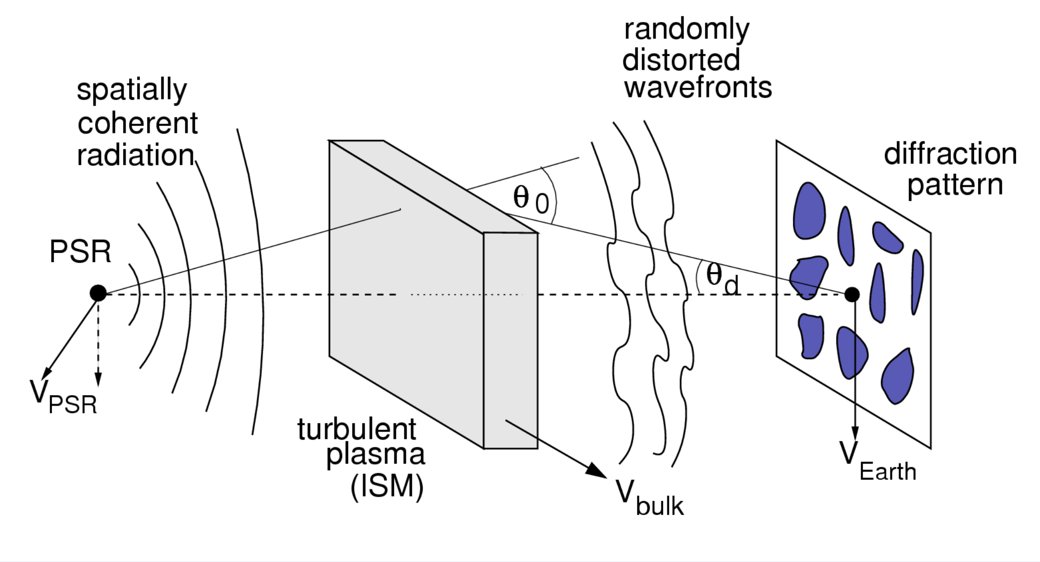
For pulsars most obvious consequence is dispersion delay vs freq. DM = dispersion measure is electron column density:

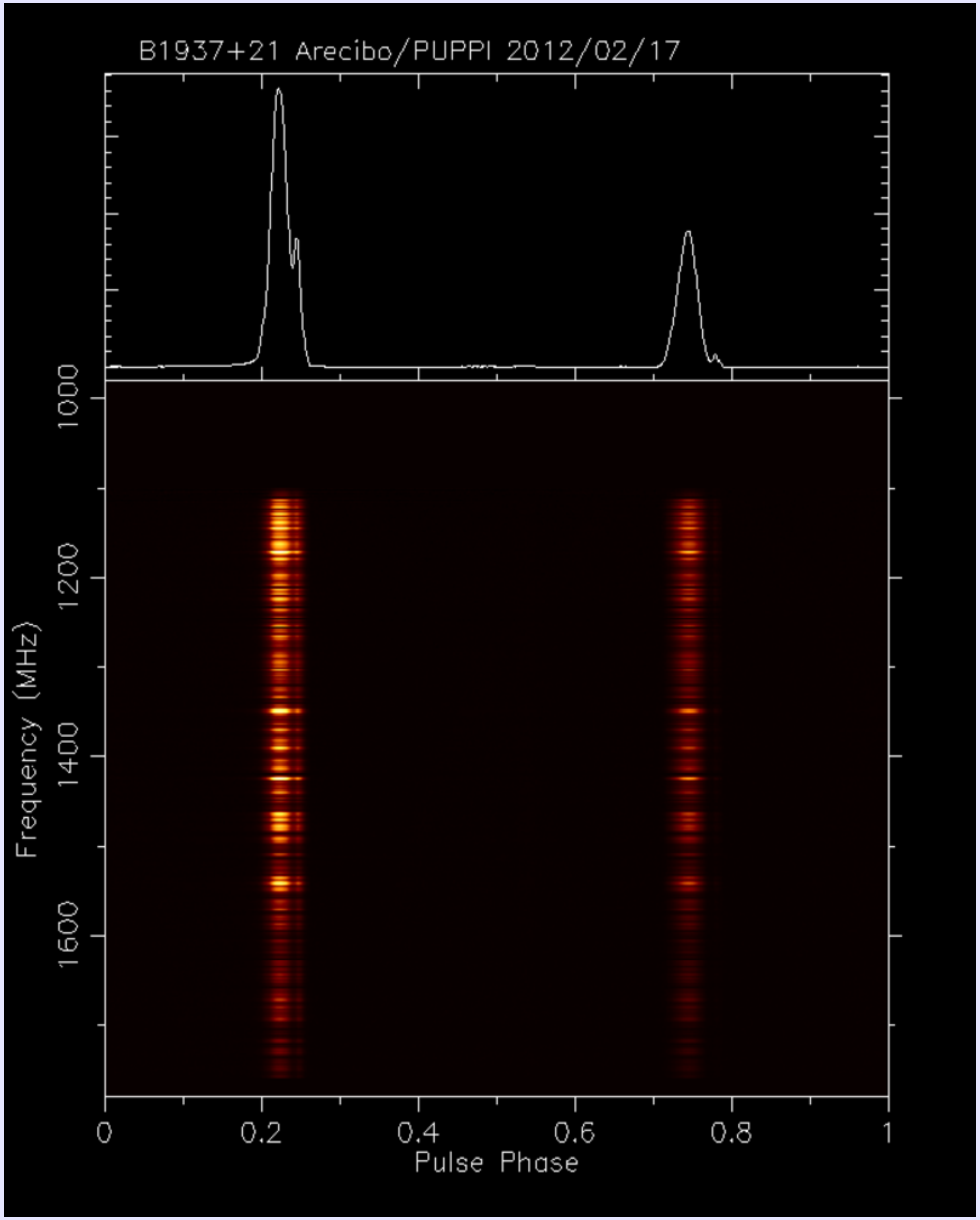
$$\tau = \frac{d\phi}{d\nu} \propto \nu^{-2}\mathrm{DM}$$

Because of inverse freq above, all ISM propagation effects become stronger at lower freqs!



Interstellar medium propagation



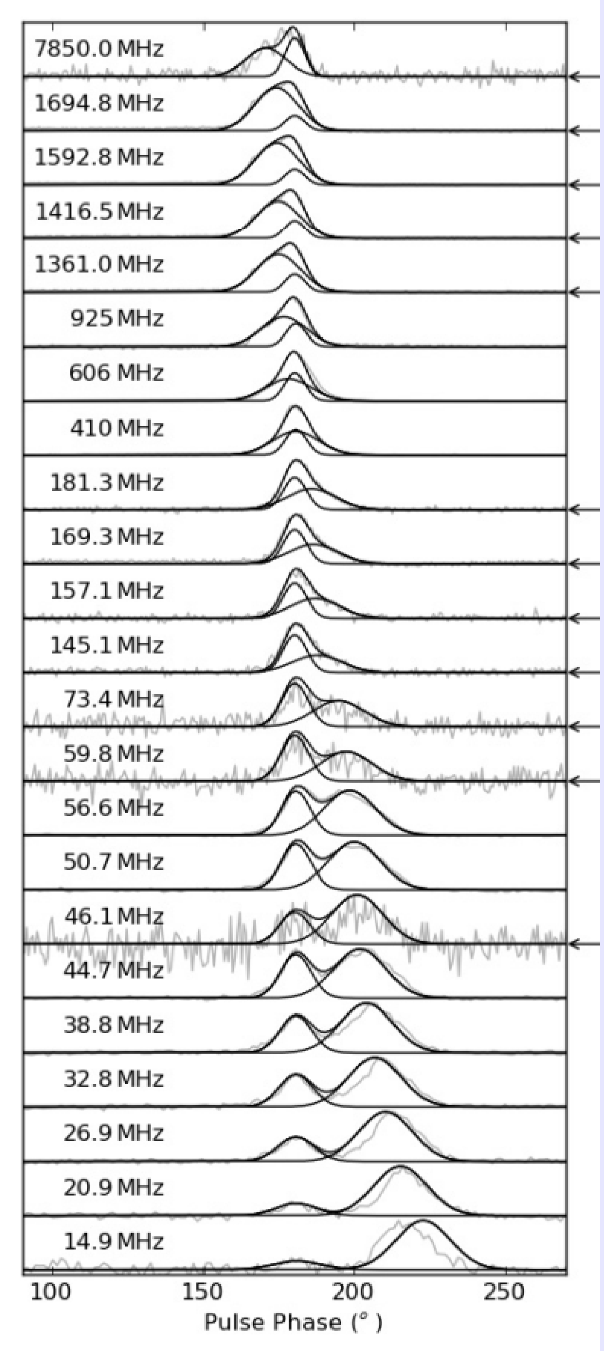


Propagation through inhomogeneous ISM produces multi-path effects (scattering) and results in characteristic interference patterns (scintillation) observed in pulsar data.

Extremely compact source size and pulsed signal makes pulsars ideal for studying these effects at low freqs.

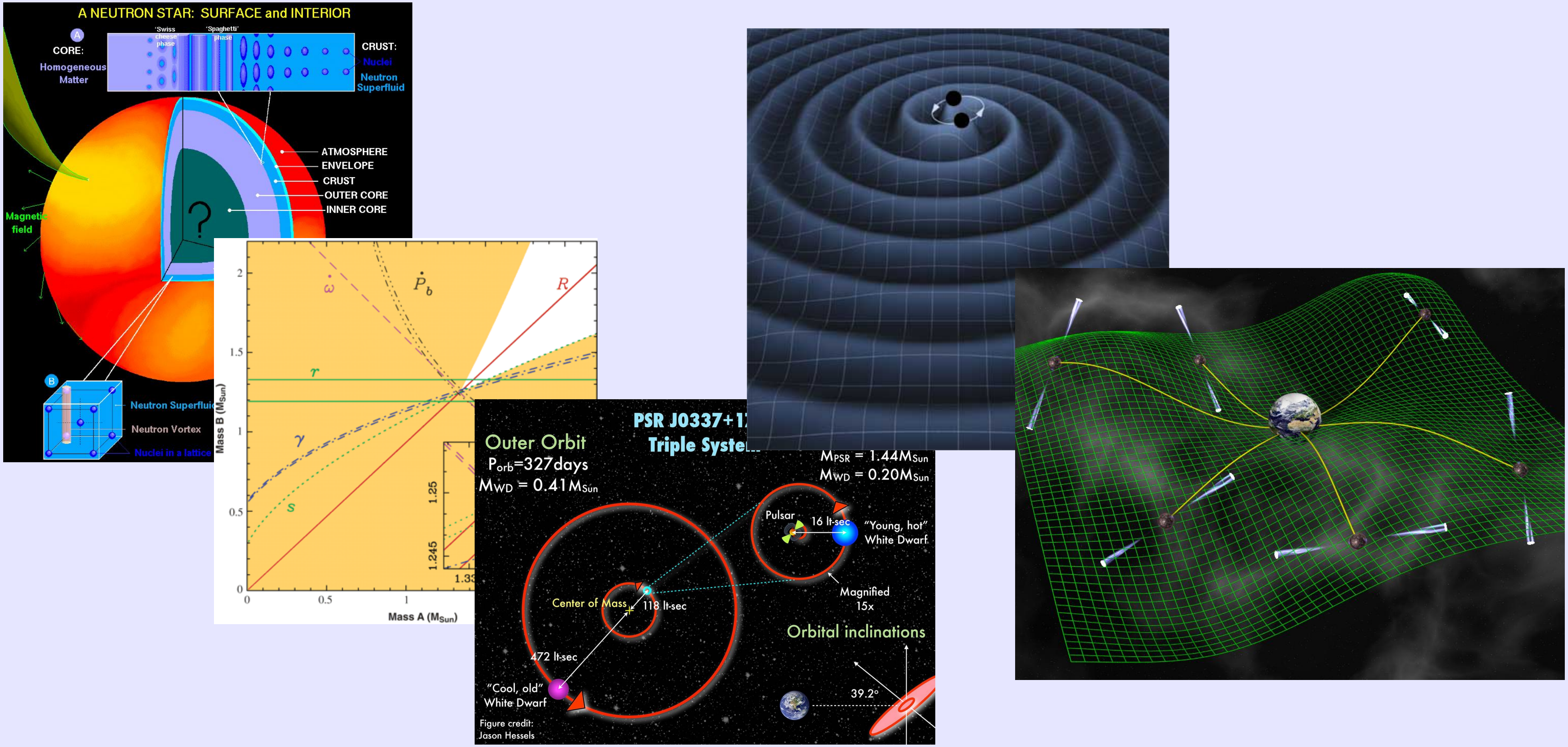
Various low-freq topics that deserve a mention!

- (...but that I won't be covering in more detail)
- Pulsar searching at low frequencies
  - Pros: Wider beams (=faster surveys); pulsars are brighter
  - Cons: Higher galactic Tsys; more dispersion/scattering.
  - Complementary to >1 GHz searches.
  - Many ongoing projects: LOFAR (next few talks), GBNCC (350 MHz), Arecibo drift scans (327 MHz), ...
- Pulsar spectra: Low-freq turnovers / "GPS" pulsars
  - Possibly due to absorption in pulsar local environment
- Mapping emission geometry
  - Low-freq observations enable huge fractional BW
- … and probably many other things!



(Hassall et al 2012)

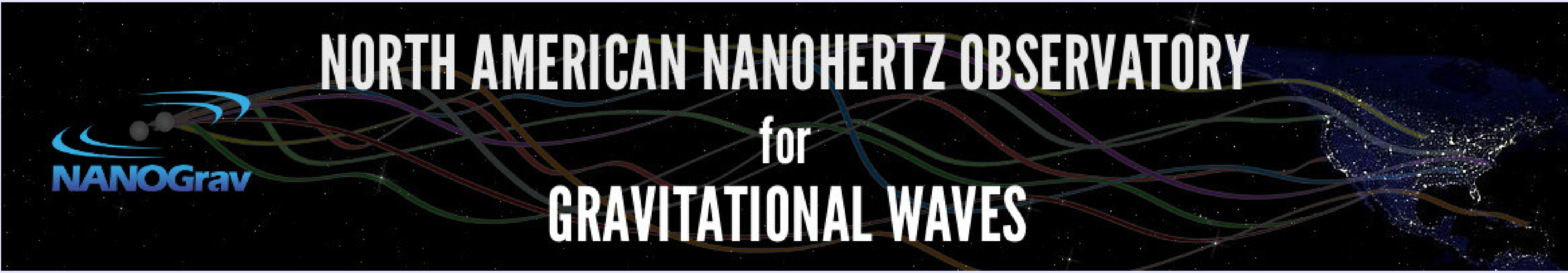
Pulsar timing science



Pulsar timing has many high-profile scientific applications, including: Tests of gravity and general relativity; NS masses and nuclear matter equation of state; potential direct detection of gravitational radiation.

Mostly done at >1 GHz, but also requires lower-freq data to cope with ISM.

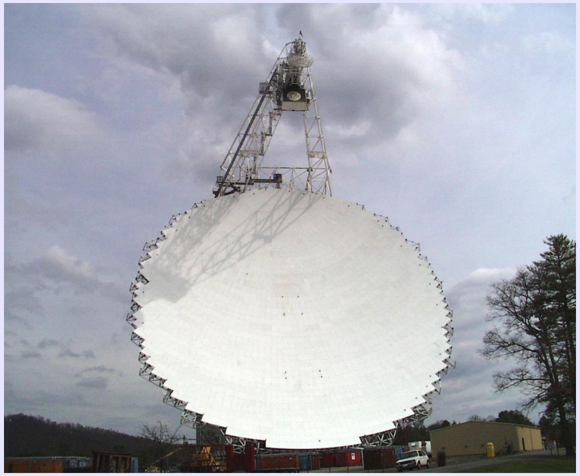
NANOGrav pulsar timing array project

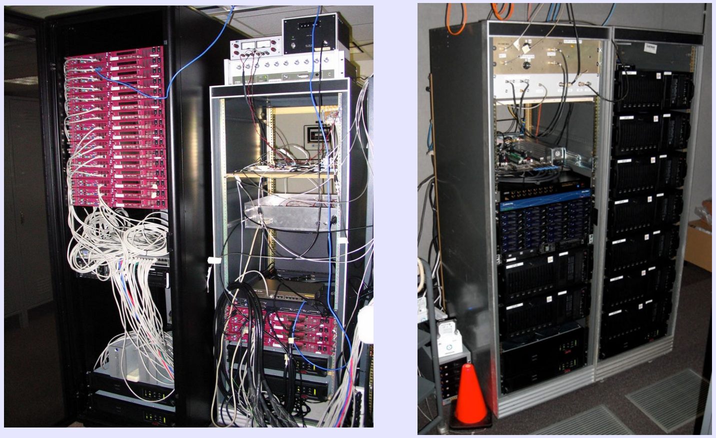


- One of several such projects worldwide (EPTA, PPTA).
- ~50 collaborators, mostly in US/Canada (see www.nanograv.org for more info).
- Goal is to detect nHz-freq GW via high precision timing of an array of millisecond pulsars.
  - GW from SMBH binaries induce correlated timing fluctuations in set of MSPs.
  - PTAs have most severe requirements of timing projects: For GW strain $h \sim dt/T \sim 10^{-15}$ need $dt \sim$ 10s of ns over many years. ISM “correction” crucial for this.

NANOGrav observations

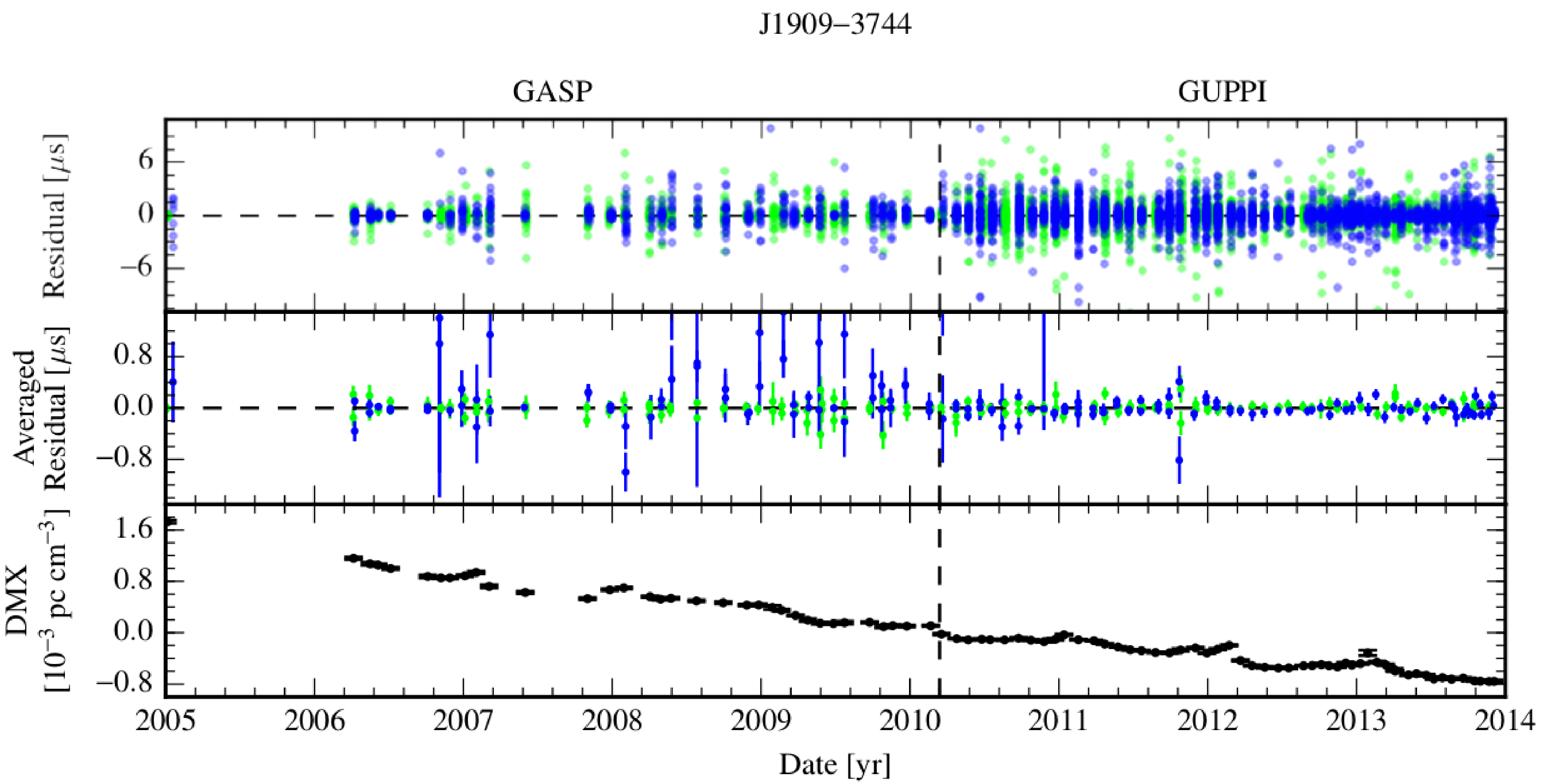
- Ongoing ~monthly observations of a set of MSPs
- Source list has grown from ~15 originally to 54
  - Arecibo used if possible, GBT otherwise.
- Paired dual-frequency sessions at 820 and 1400 MHz (GBT); two of 430, 1400, and 2000 MHz (Arecibo).
- Each pulsar observed for ~30 minutes per band per epoch.
- Backend upgrades 2010, 2012





NANOGrav 9-year data set

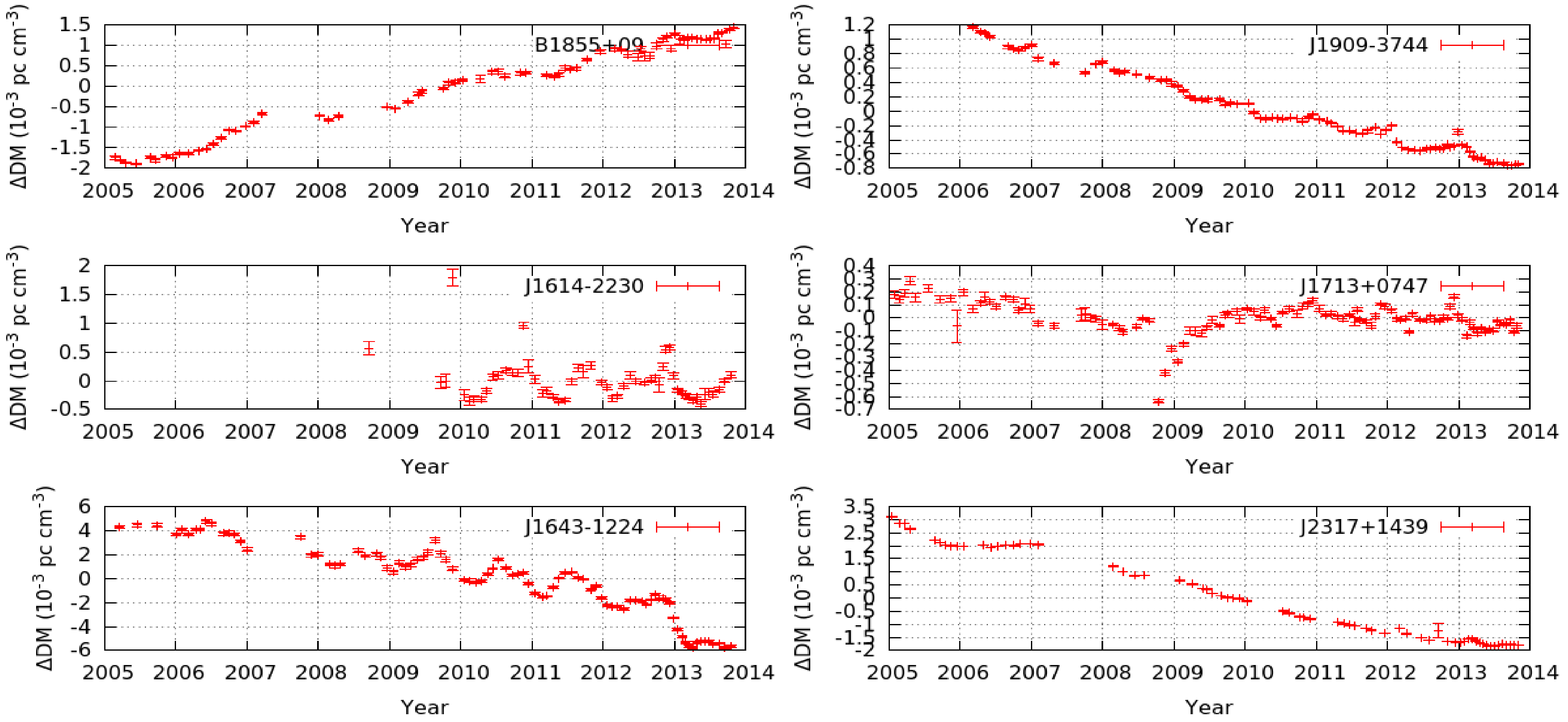
(Arzoumanian et al 2015)



37 pulsars total, ~2005 – 2013; best pulsar J1909—3744 : ~80 ns RMS timing residual.

Analysis includes time-varable dispersion measure (bottom panel).

Dispersion measure variation

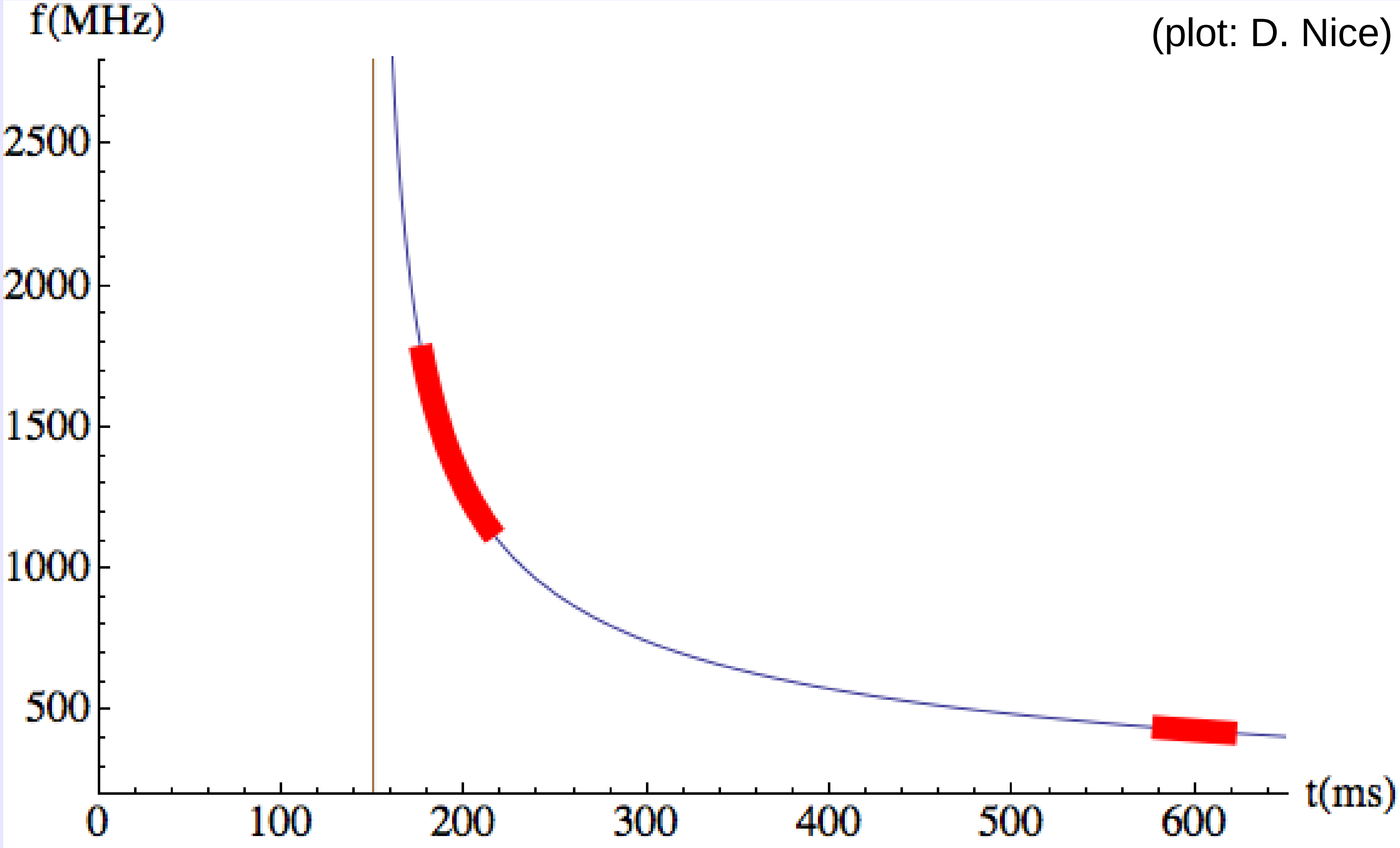


DM(t) occurs due to relative motions of pulsar, Earth, and ISM.

With modern instruments and sufficient timespan, DM(t) is now detectable for nearly all MSPs.

dDM of 10^{-3} pc/cm^{-3} ~ 1 us delay at L-band: big compared to GW!

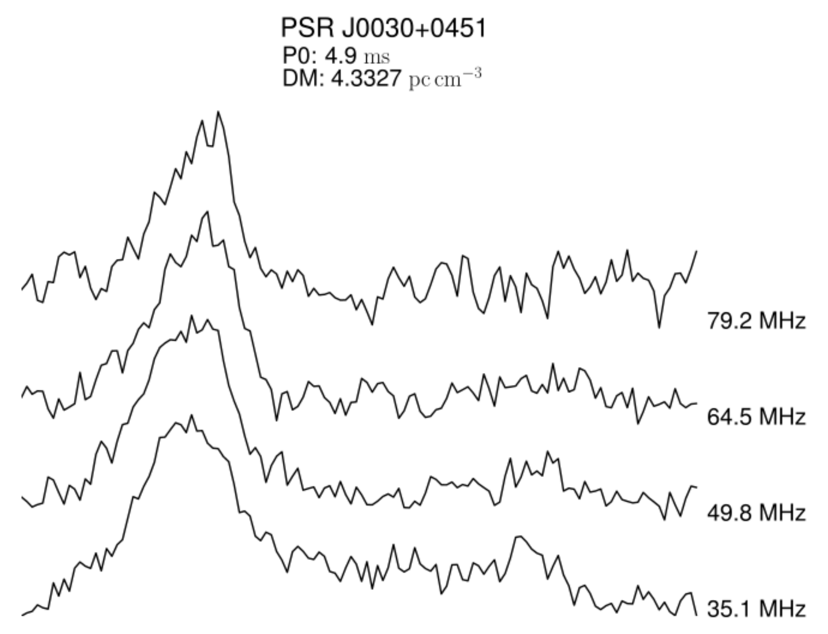
Pulsar timing and low frequencies



(plot: D. Nice)

Need to be able to separate chromatic dispersive delays from achromatic delays (like GW) → widely-separated frequencies. In general, lower freq → better "lever" for DM (detailed optimization depends on pulsar spectrum, telescope properties, etc).

MSP detection and DM(t) at low freq

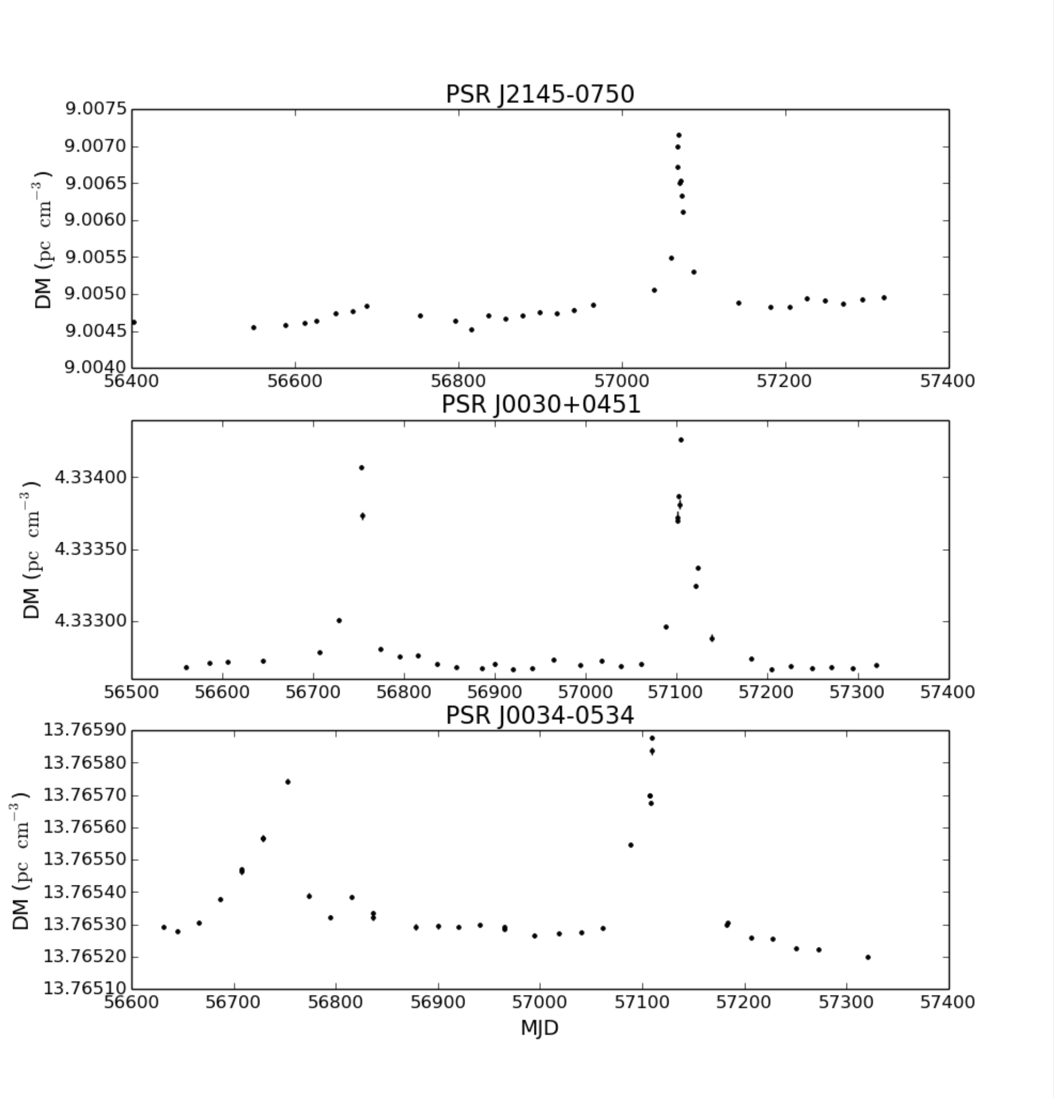


LWA detection of MSP J0030+0451.

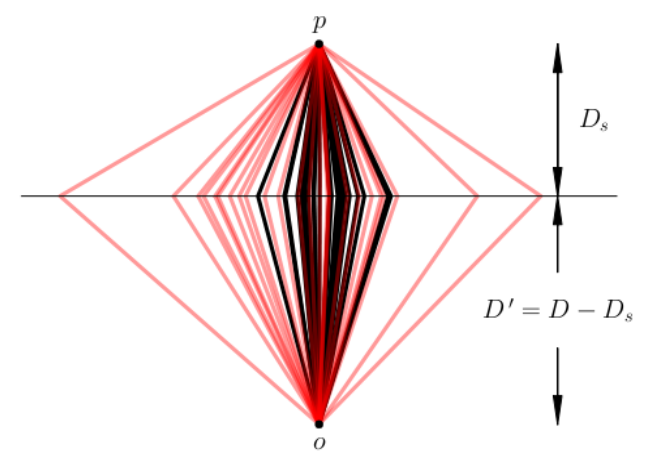
LWA DM(t) for three MSPs

Needs combination / comparison with contemporaneous higher-freq NANOGrav data.

(plots: K. Stovall)

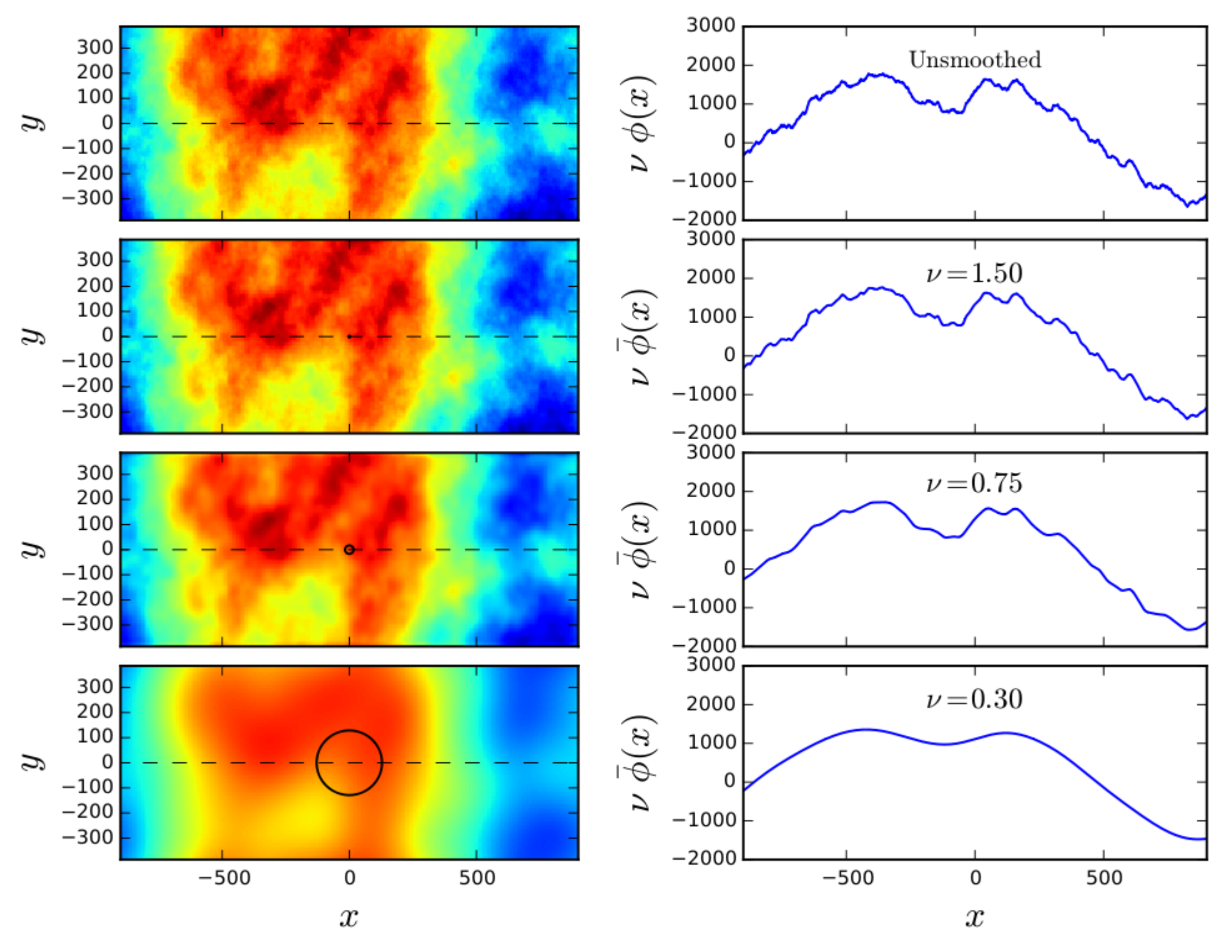


Frequency-dependent dispersion measure



Larger scattering angles at lower freqs means pulsar “sees” different patch of ISM at different frequency.

Acts to smooth out DM variations at low freqs.

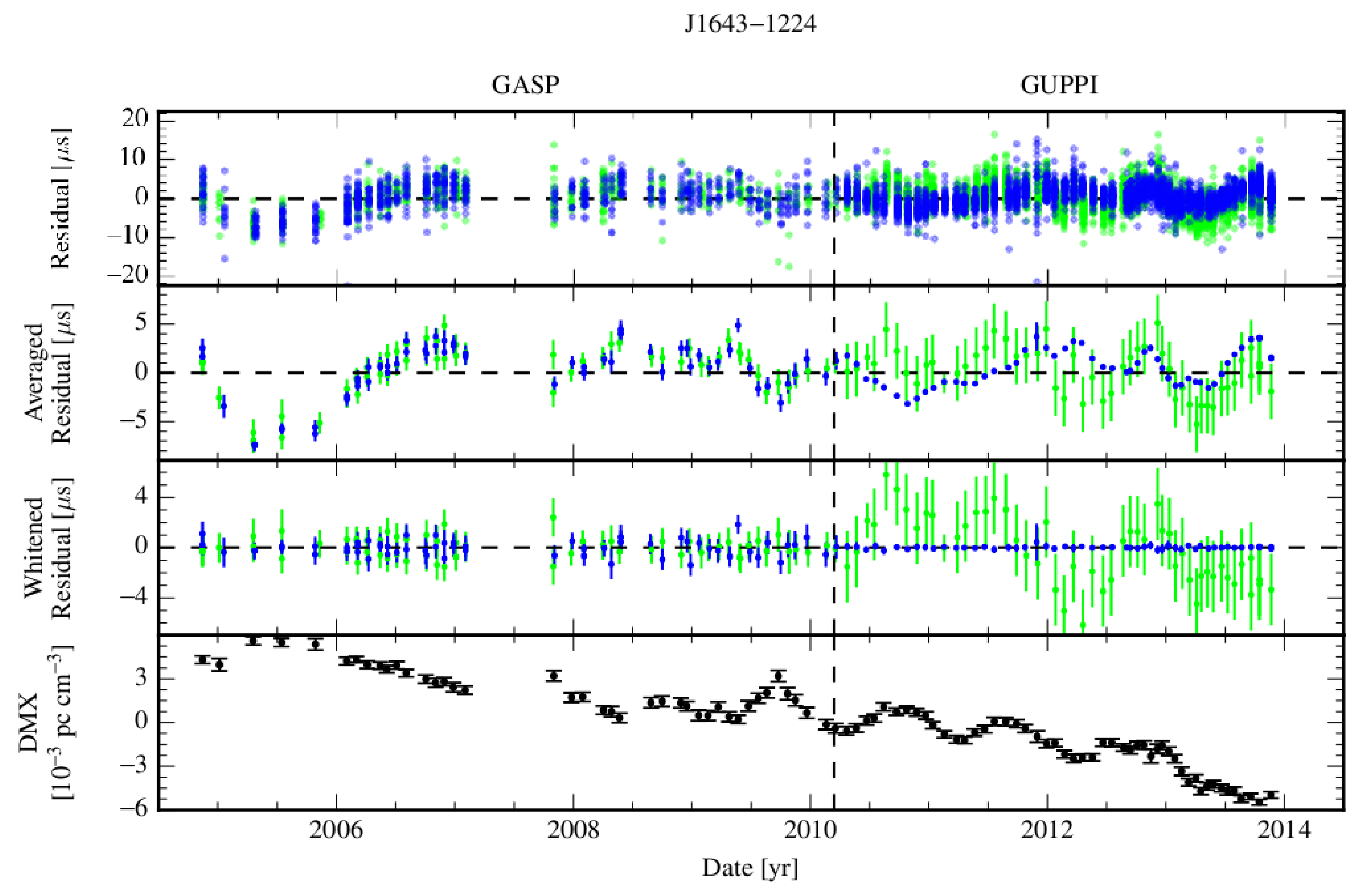


(Cordes et al 2015)

This effect may limit the range of frequency that can be used for DM estimation. However, smoothing or freq-dependent DM effect has yet to be clearly demonstrated with real data...

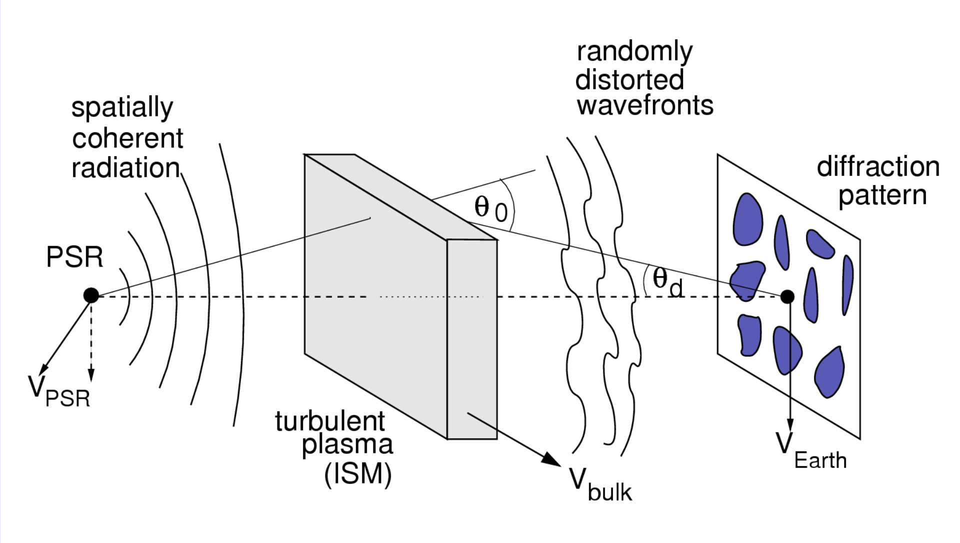
ISM effects in NANOGrav data

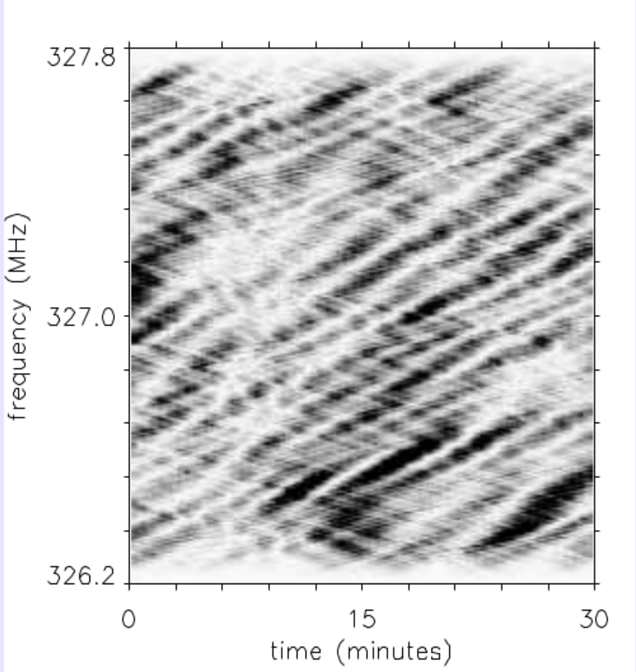
(Arzoumanian et al 2015)



PSR J1643-1224 one of ~5 in 9-year data set that shows timing residual structure not well modeled by “simple” DM(t) or achromatic red timing noise; additional lower-freq data could help explain these features.

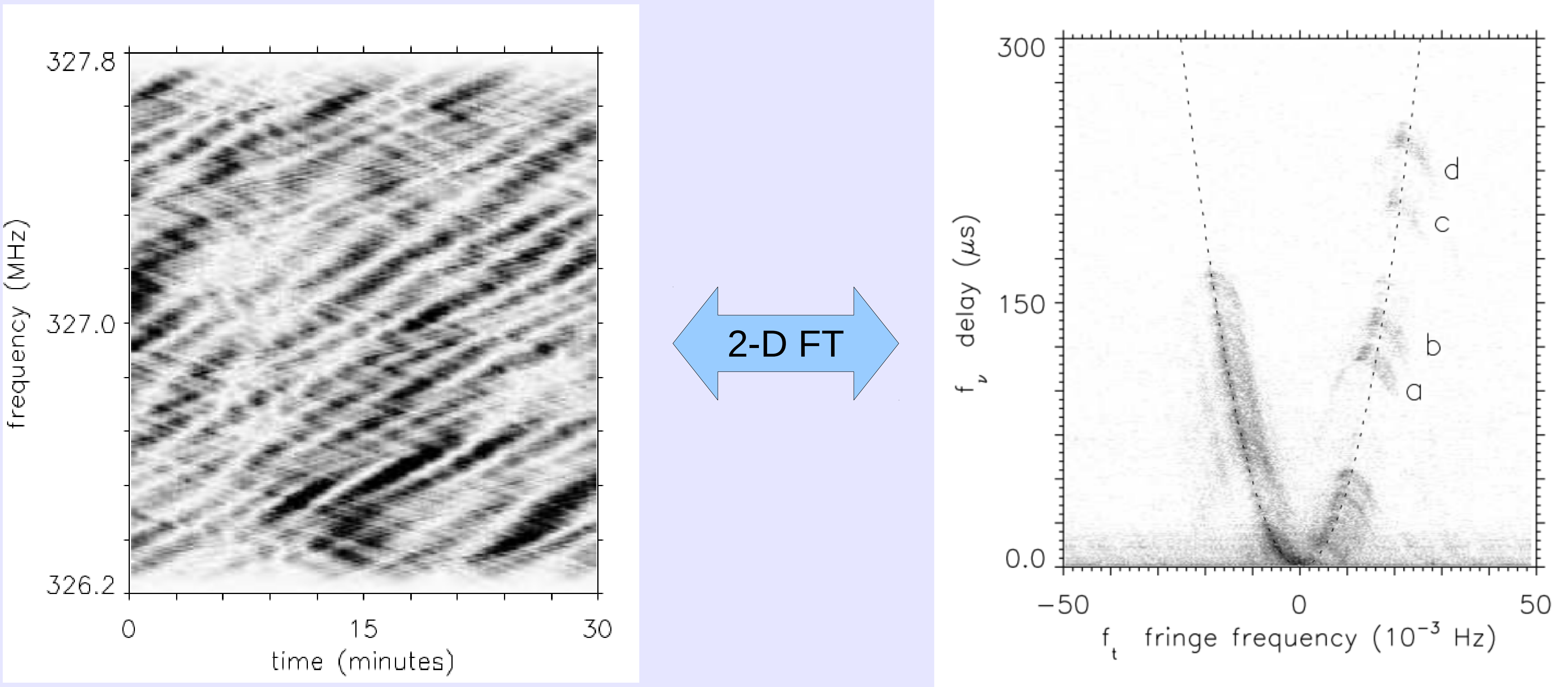
Scattering and dynamic spectra





- Much more information can be found in pulsar dynamic spectra (scintillation pattern vs time/freq).
    - Determination of scattering delays / timing corrections.
    - Detection of small-scale ISM structure.
    - Potential ISM-based resolution of pulsar emission.
- Techniques for this still in research/development!

Secondary spectra and scintillation arcs

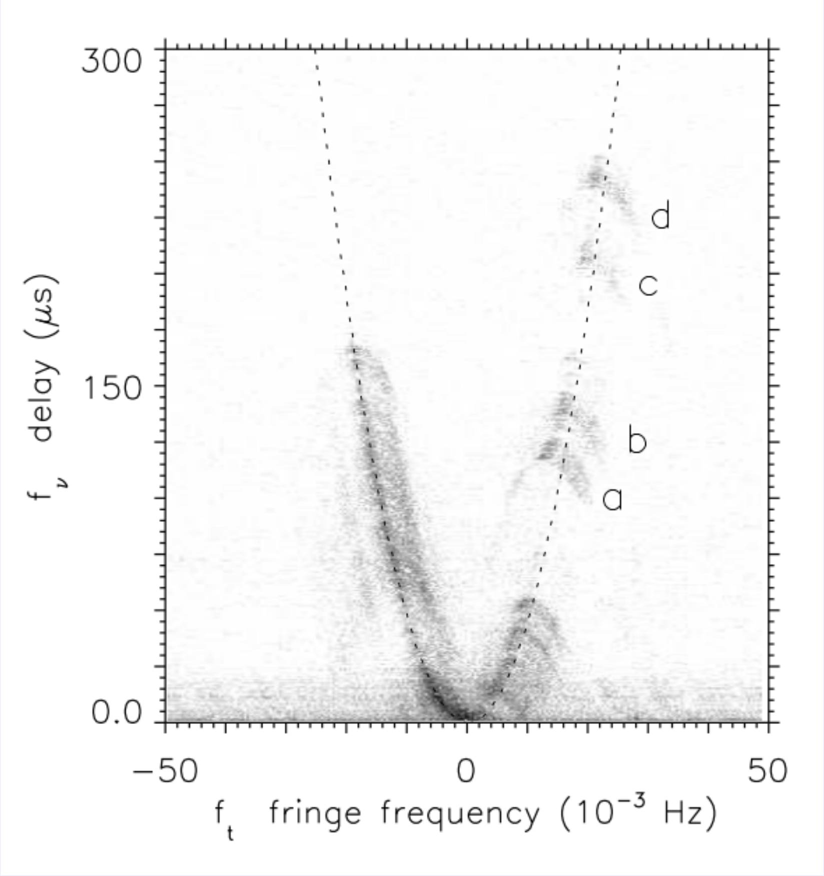


(Hill et al 2004; B0834+06, Arecibo)

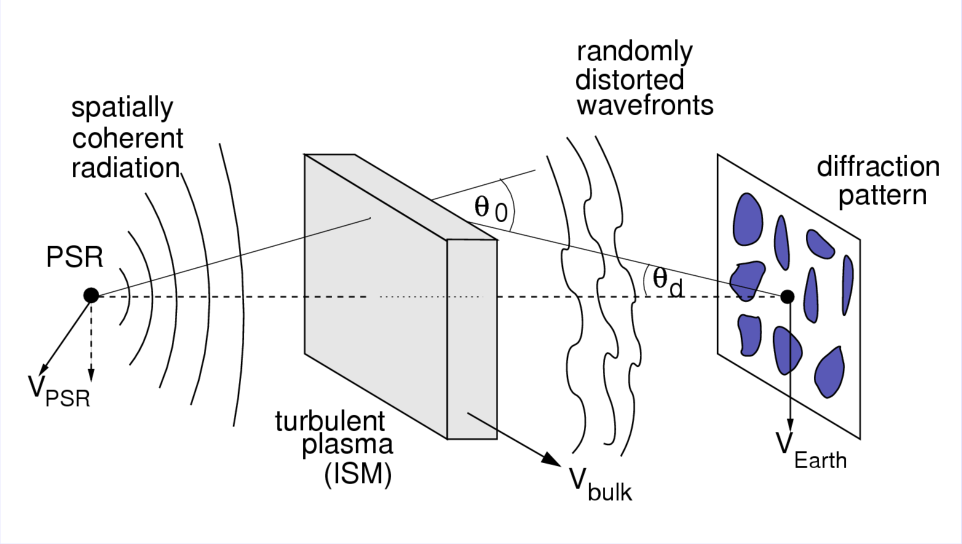
2-D Fourier transforms of dynamic spectra revealed characteristic parabolic structures; these seem to be fairly common, and have been observed in many pulsars (assuming sufficient sensitivity).

Secondary spectra and scintillation arcs

$$\tau = \theta^2 D_{\mathrm{eff}}/2c$$



$$f_{\mathrm{D}} = \mathbf{V}_{\mathrm{eff}} \cdot \boldsymbol{\theta}/\lambda.$$

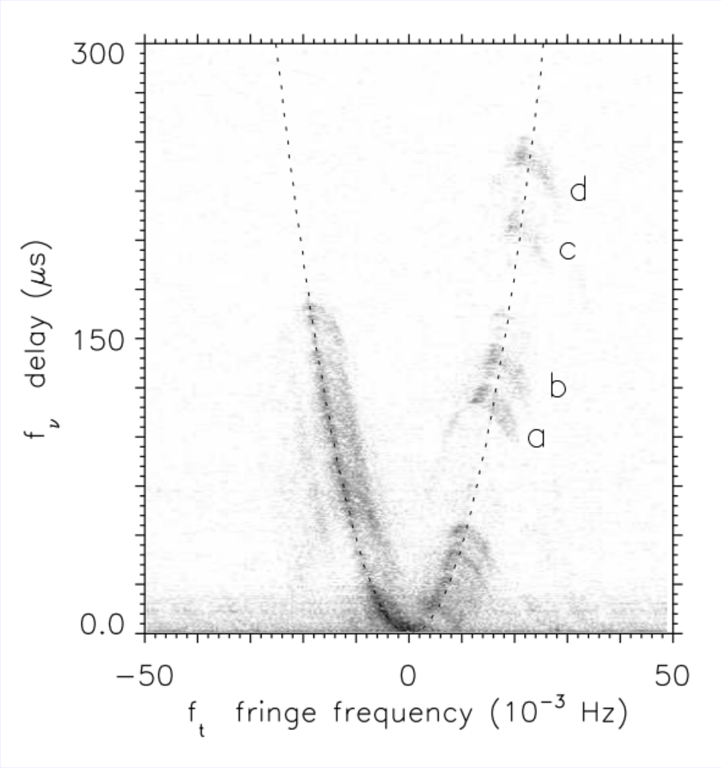


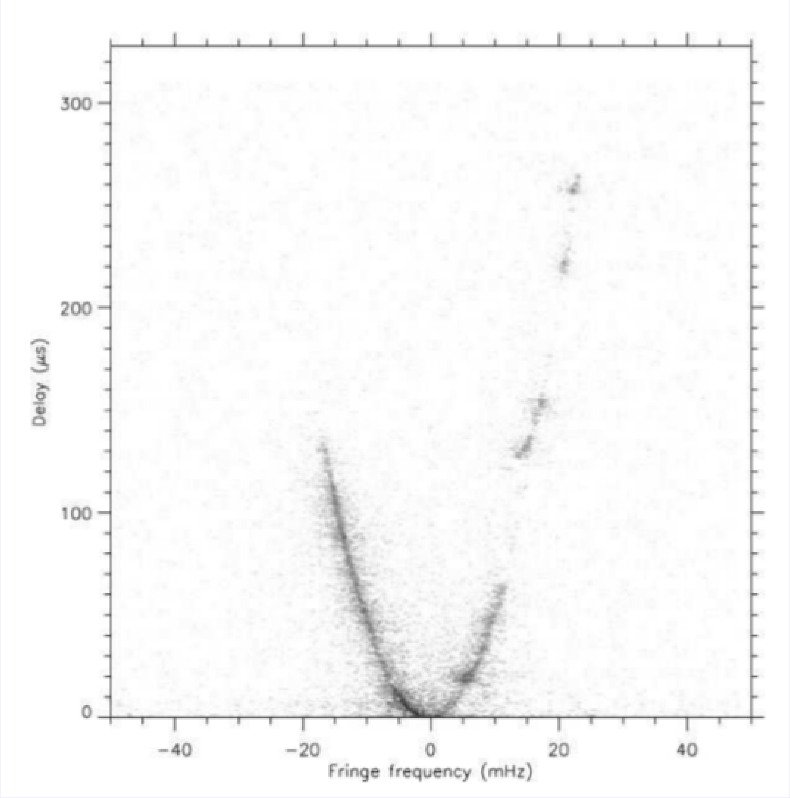
Parabolic shape can be understood by geometric arguments.

Requires highly anisotropic (~1-D) scattering, and/or discrete ~AU-sized scattering structures. Physical explanation still unclear.

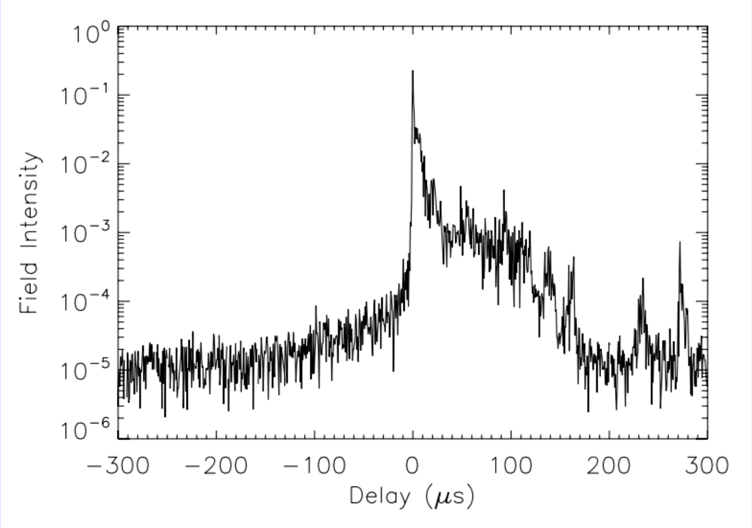
Possible connection to extreme scattering events.

Holography and SS deconvolution

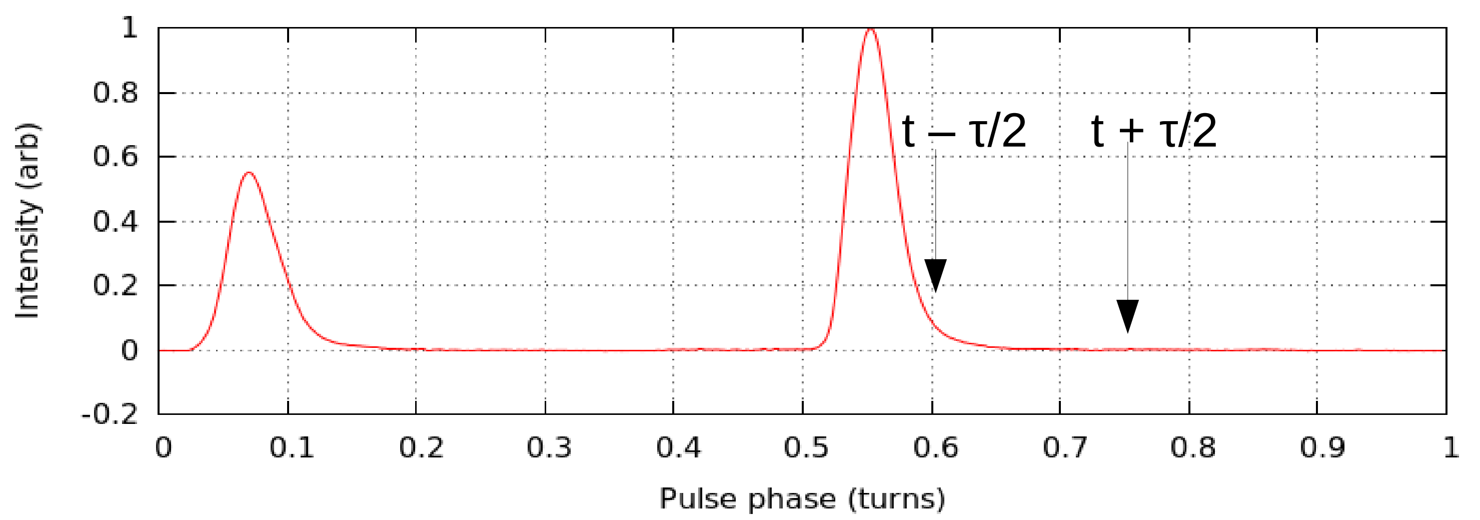




Walker et al (2008) show it is possible to deconvolve intensity-only dynamic spectrum (phase retrieval) and recover ISM impulse reponse.

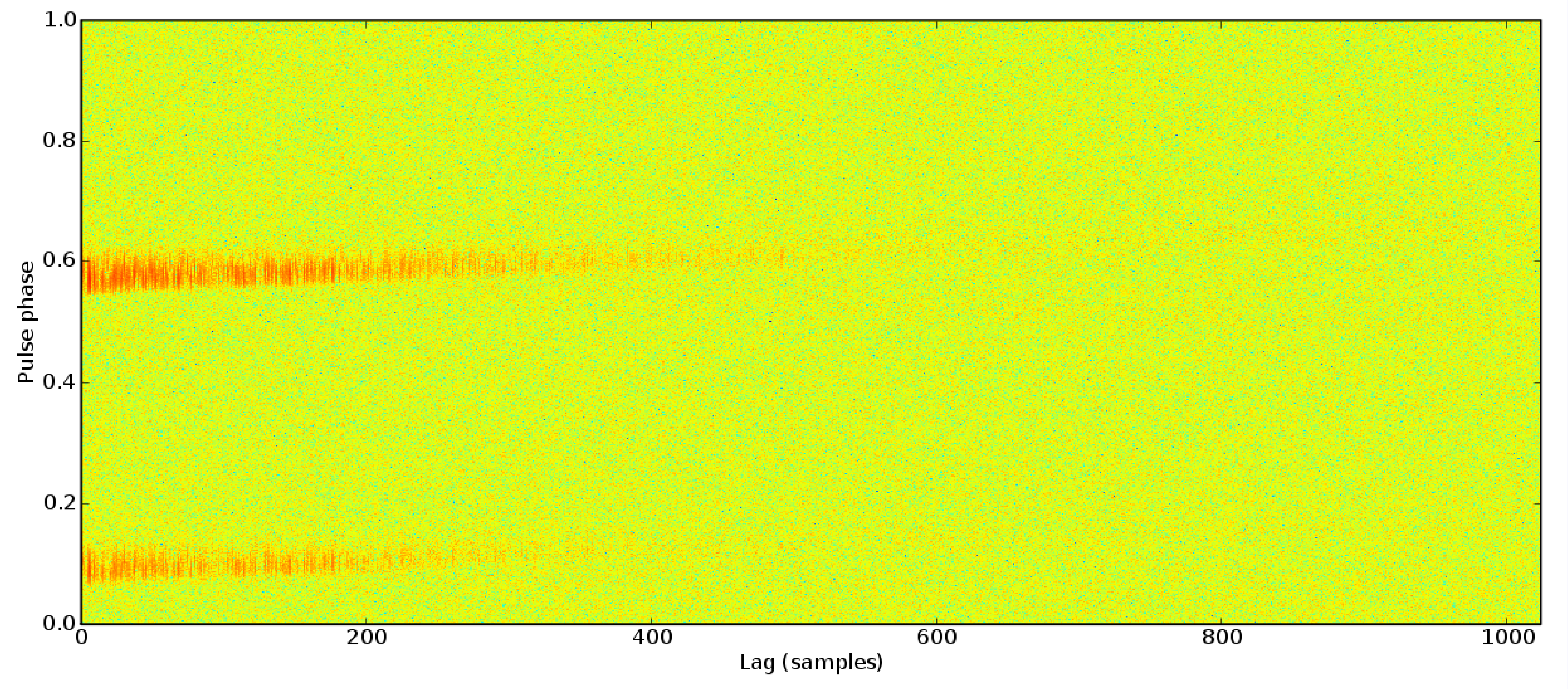


MSPs and cyclic spectra

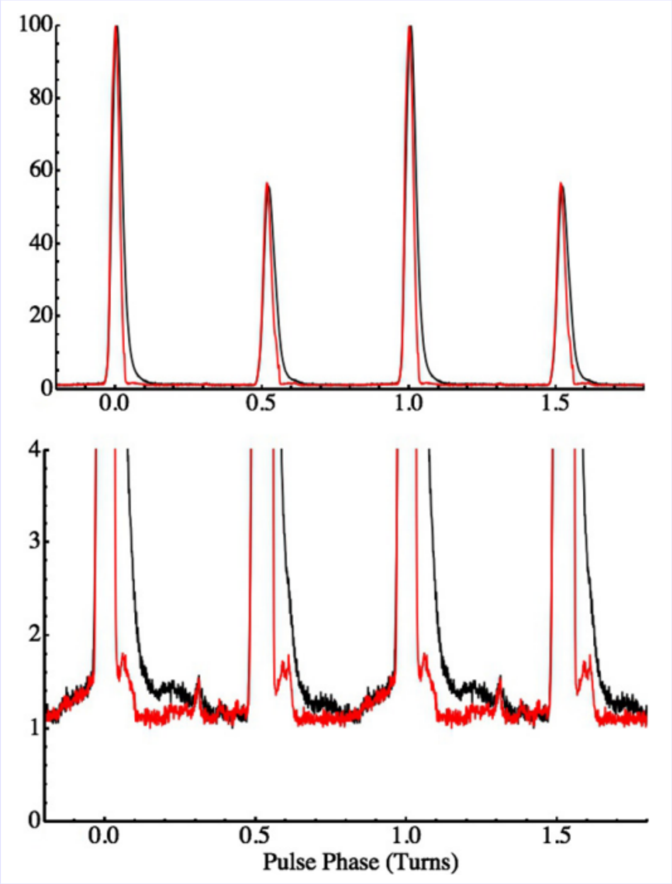


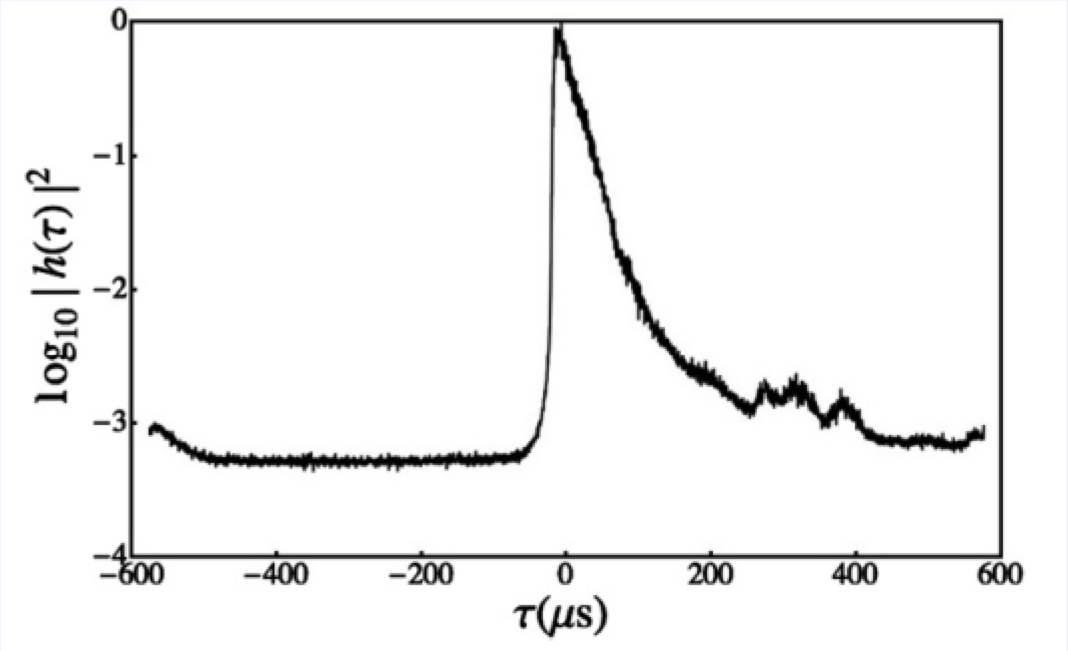
Pulse phase-resolved correlation; provides more info than standard pulsar filterbank (Demorest 2011).

Plots: B1937+21, Arecibo, 430 MHz



CS-based deconvolution

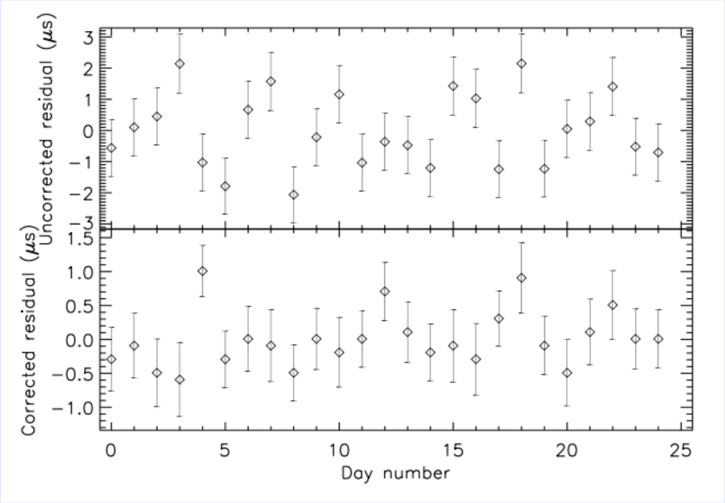




(Walker, Demorest, & van Straten 2013;
B1937+21, Arecibo, 430 MHz)

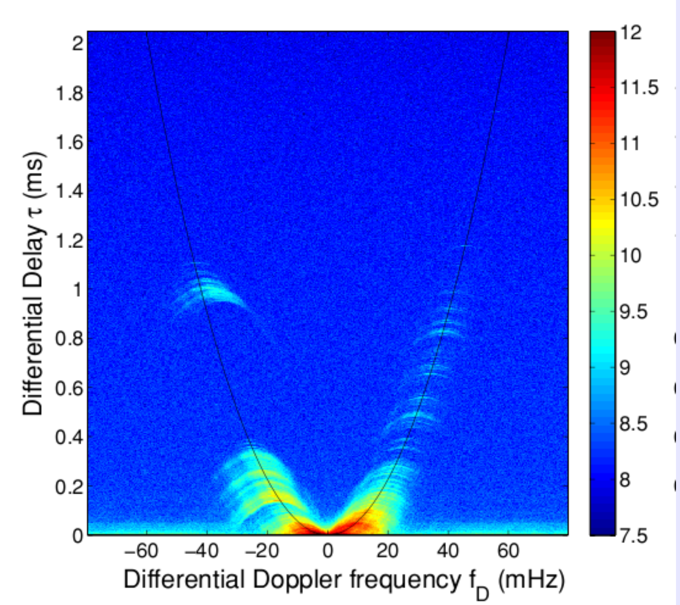
Cyclic spectrum info can also be used to deconvolve ISM impulse response from a single “snapshot” observation. This can be used to correct scattering delays in timing data.

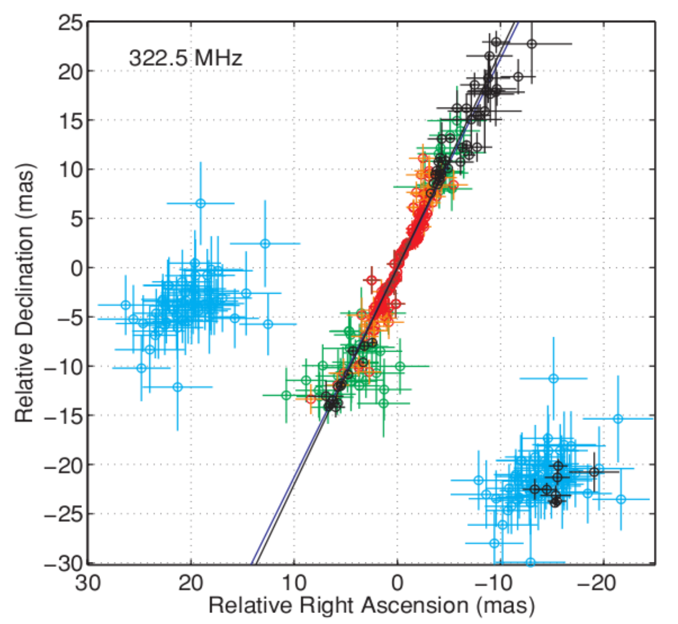
However, method requires bright pulsar and large telescope; may become more important in future (ie, SKA era)..

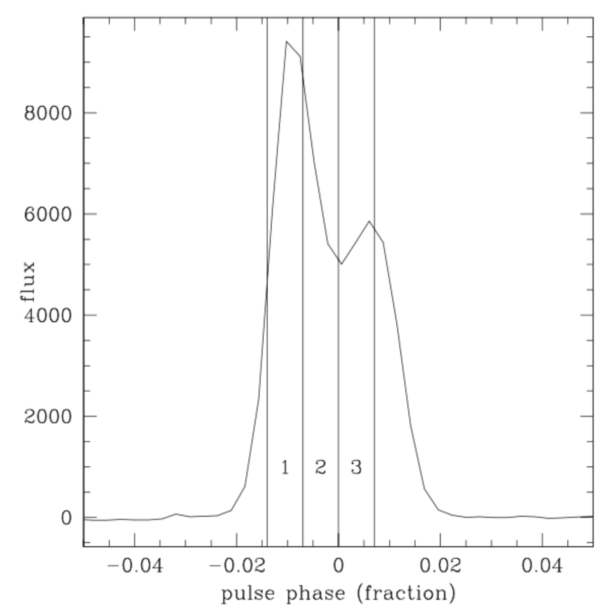


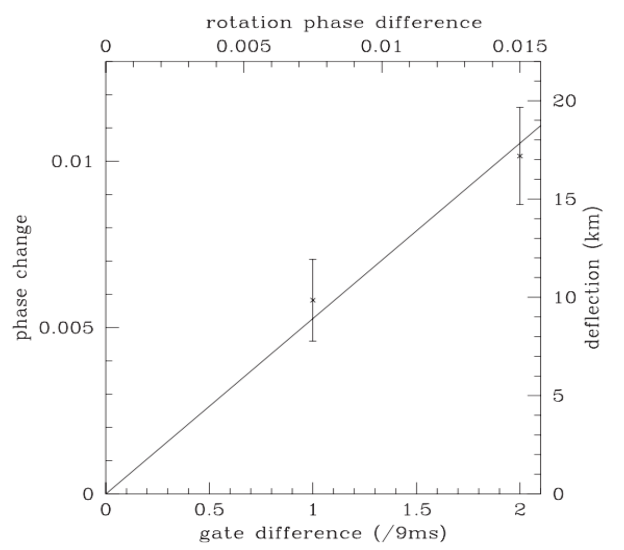
(Palliyaguru et al 2015;
simulated data)

Scintillation and VLBI







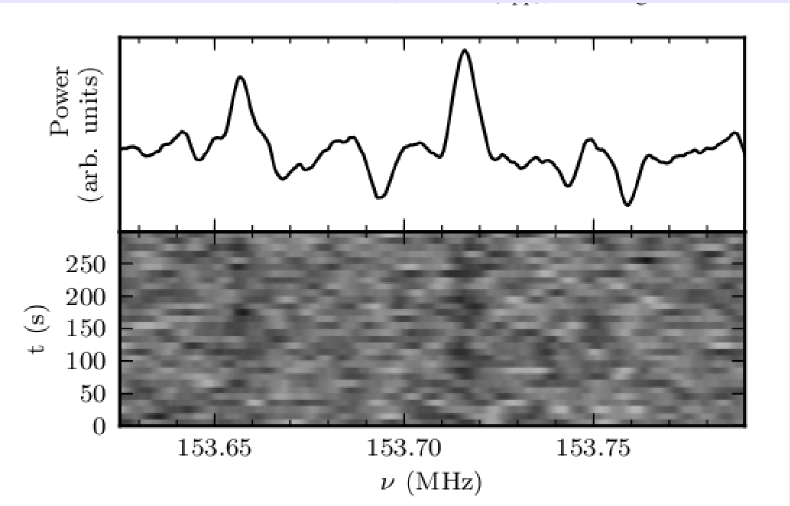


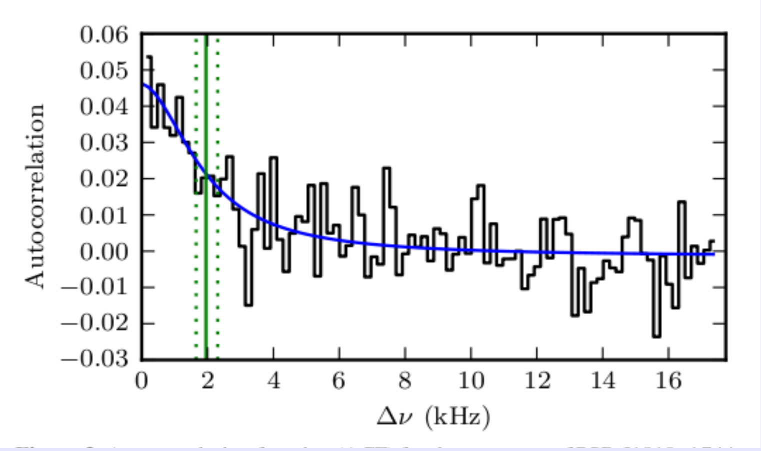
Brisken et al (2010; B0834+06 300 MHz VLBI; Arecibo, GBT, Jodrell, WSRT) VLBI imaging of individual scintillation components.

Pen et al. (2014) reprocess same data to (possibly) detect motion of emission region across pulse.

Scintillation – moving to lower frequencies

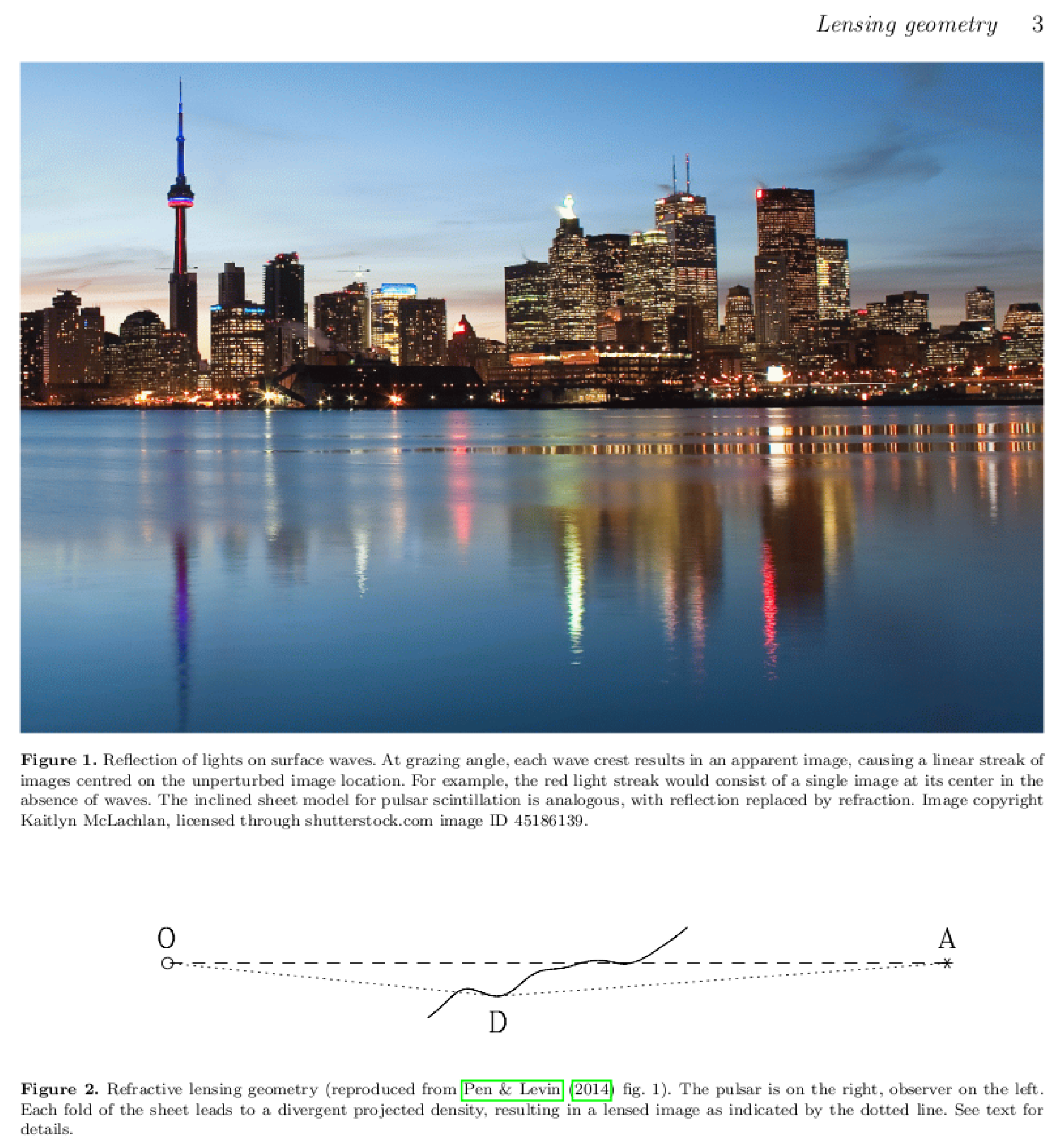
- Most work mentioned so far done in the ~300 – 400 MHz range. What about lower freqs?
- Recent use of cyclic spectra for LOFAR MSP scintillation detections (Archibald et al 2014)
- Thoughts on VLBI/scintillation below 300 MHz:
  - Scattered image size scales like $\sim f^{-2}$ while angular resolution goes as f^{-1}.
  - Larger illuminated patch on ISM, but may make imaging “messier”
  - Scintle size becomes tiny ($\sim f^{4}$)





Summary

- Pulsars are ideal sources to observe with low-freq telescopes!
- Low frequency data is required for high-precision timing projects to deal with ISM.
  - Best frequency range(s) still open question. Utility of <300 MHz for DM(t) uncertain; but will increase understanding of ISM behavior.
- Pulsar scintillation is a powerful (and still under-utilized) tool for probing the ISM and pulsar emission properties.
  - More low-frequency, high sensitivity VLBI needed.
- Thank you!



Lensing geometry 3

Figure 1. Reflection of lights on surface waves. At grazing angle, each wave crest results in an apparent image, causing a linear streak of images centred on the unperturbed image location. For example, the red light streak would consist of a single image at its center in the absence of waves. The inclined sheet model for pulsar scintillation is analogous, with reflection replaced by refraction. Image copyright Kaitlyn McLachlan, licensed through shutterstock.com image ID 45186139.

Figure 2. Refractive lensing geometry (reproduced from Pen & Levin (2014) fig. 1). The pulsar is on the right, observer on the left. Each fold of the sheet leads to a divergent projected density, resulting in a lensed image as indicated by the dotted line. See text for details.

(Liu et al 2015; Pen & Levin 2014)

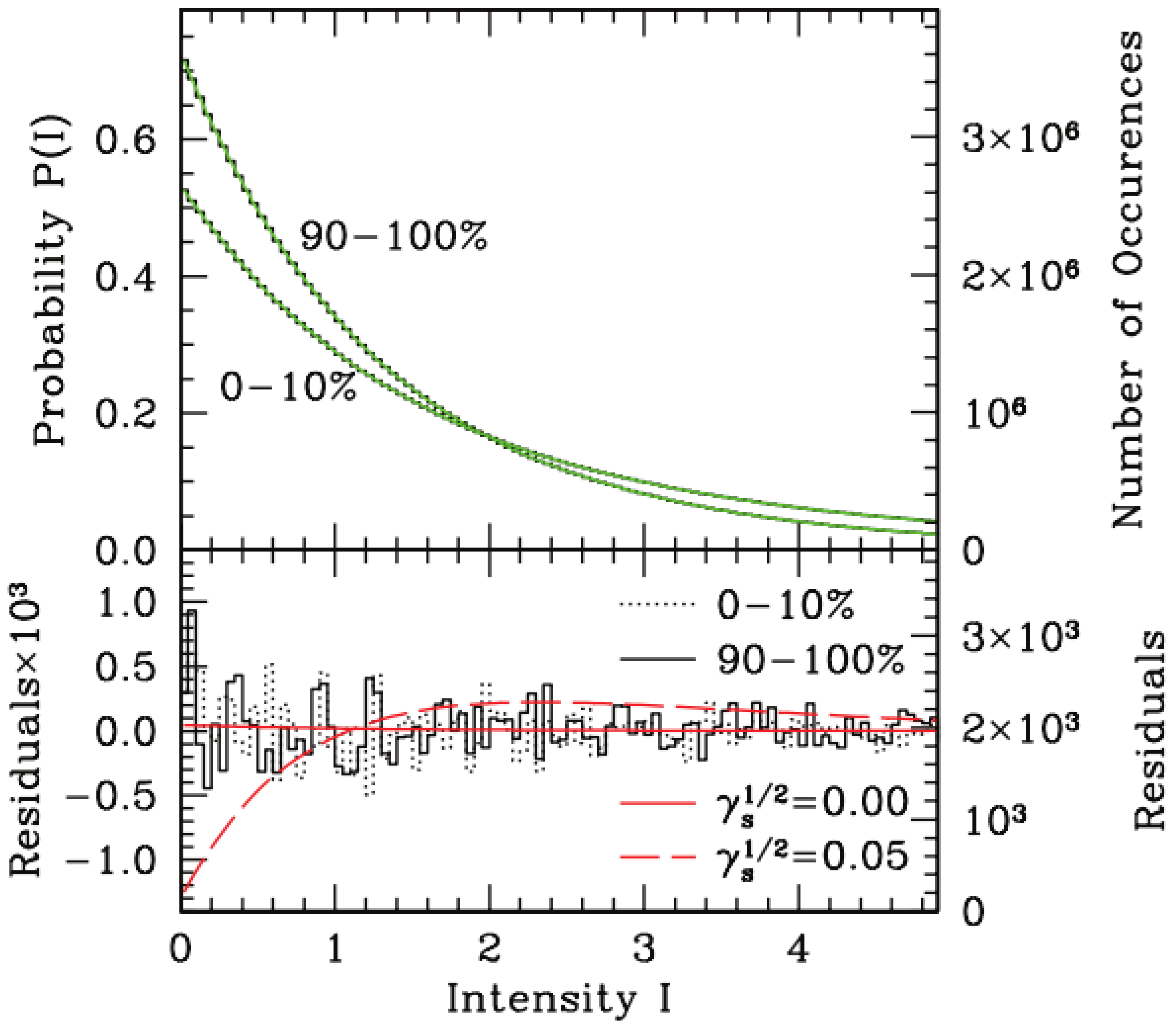
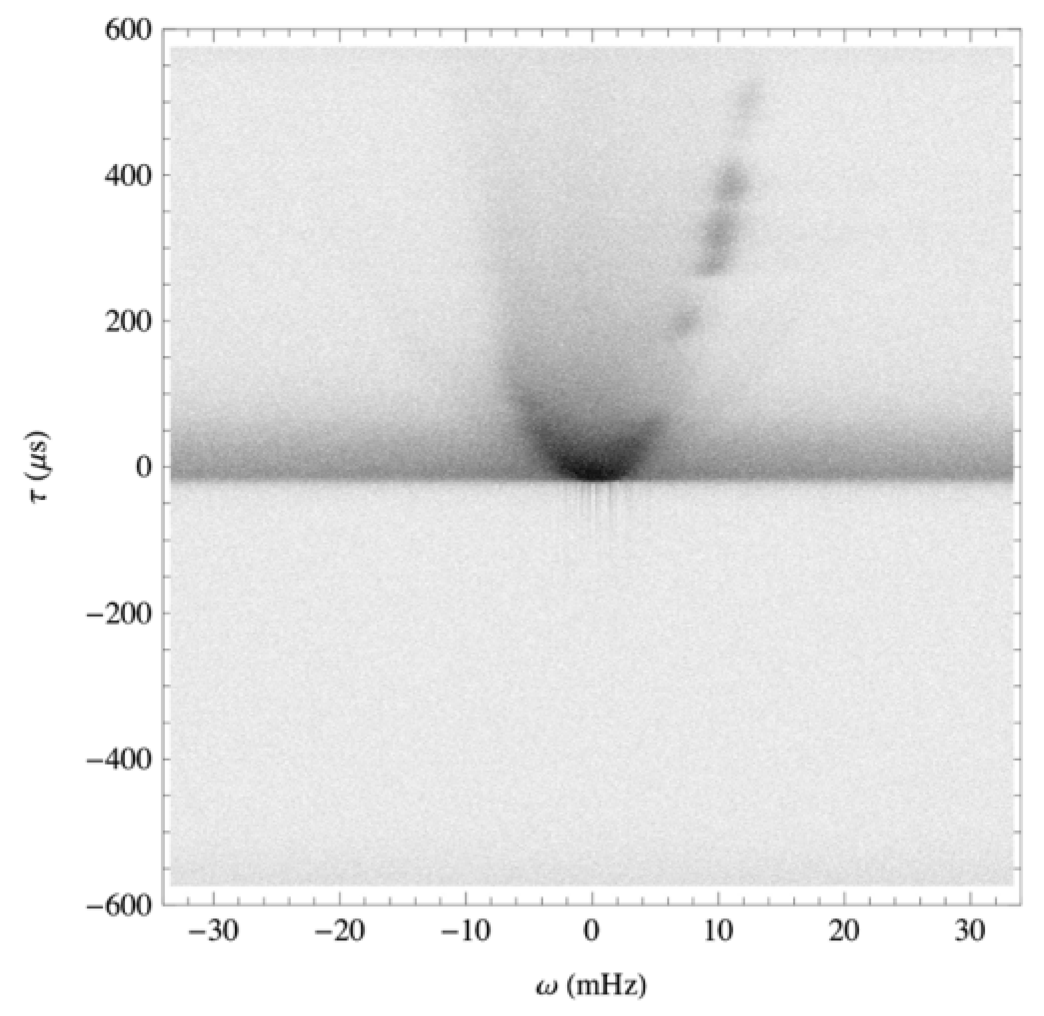


Figure 3. Observed and model PDFs of intensity for the subsets of pulses in the top and bottom deciles by pulse intensity. Theoretical residual curves are plotted for a point source (the slight variation is from finite histogram resolution) and for a source that extends over 5% of the magnified diffractive scale (i.e., $\sigma_c \approx 20$ km); the latter is clearly inconsistent with the observed statistics.

(Johnson et al 2012;
Vela, GBT, 800 MHz)



(Walker, Demorest, & van Straten 2013)