


Pulsars across wide bandwidths

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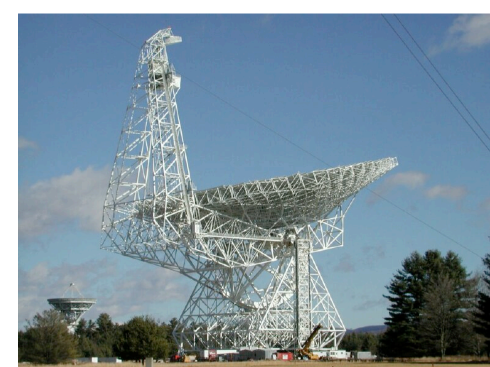
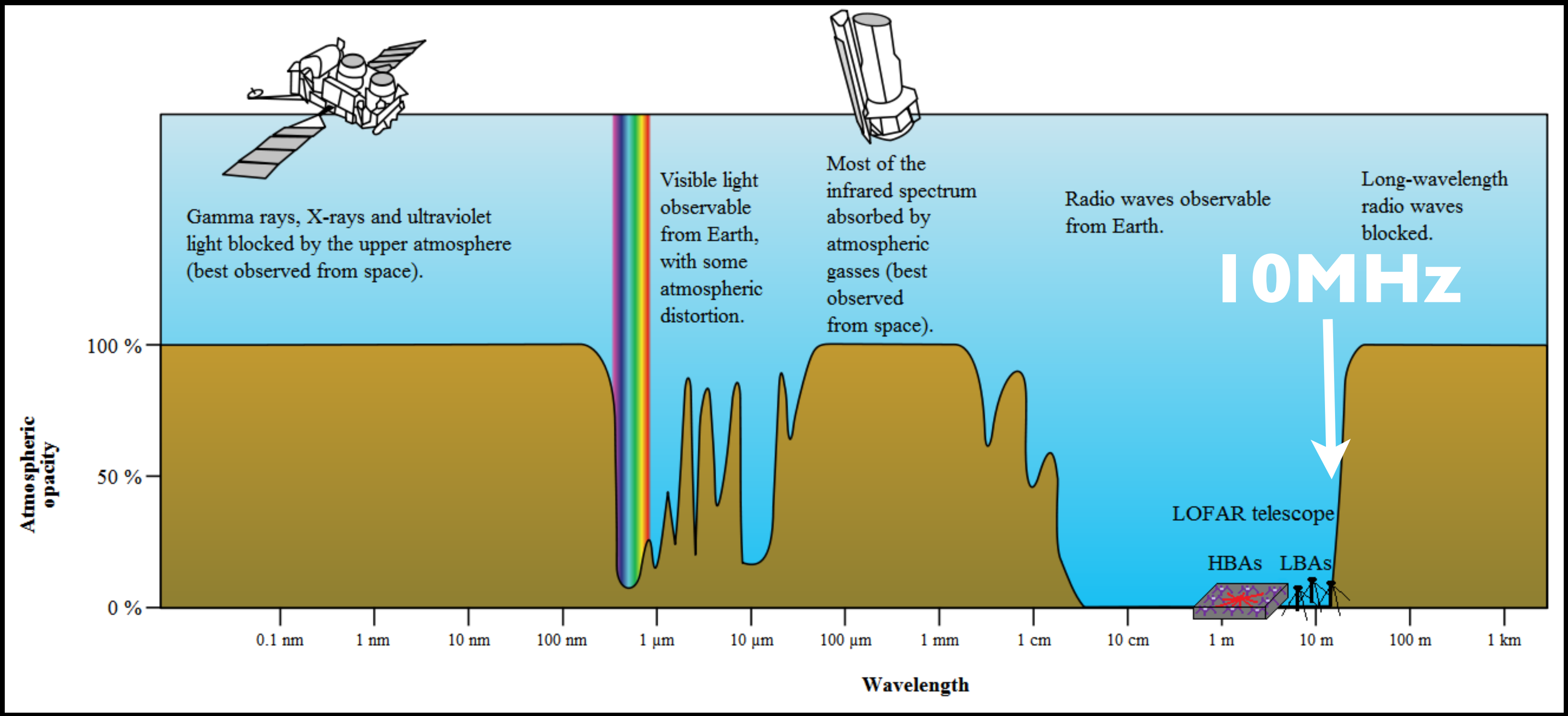
IPTA Student Week - Banff - 19/06/2014



At what frequencies do we observe, and why?

Frequency range for observing radio pulsars

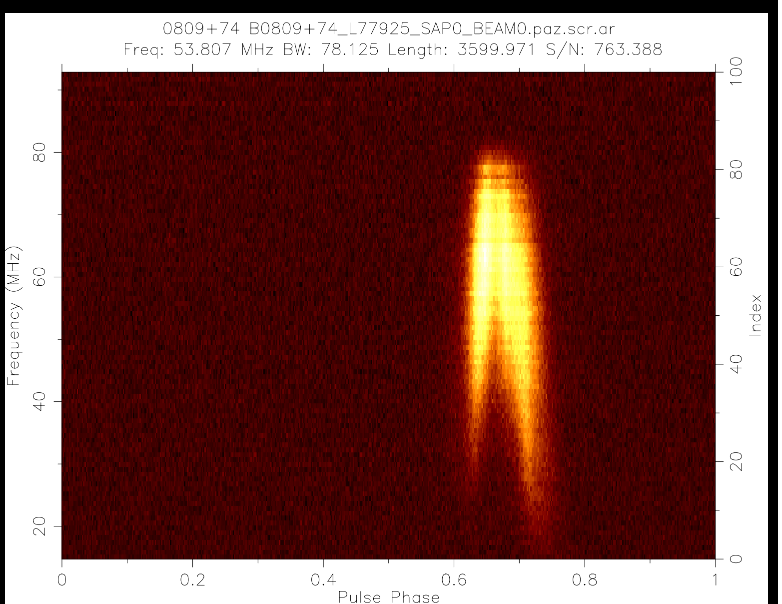


Can see radio pulsars (roughly!) from:

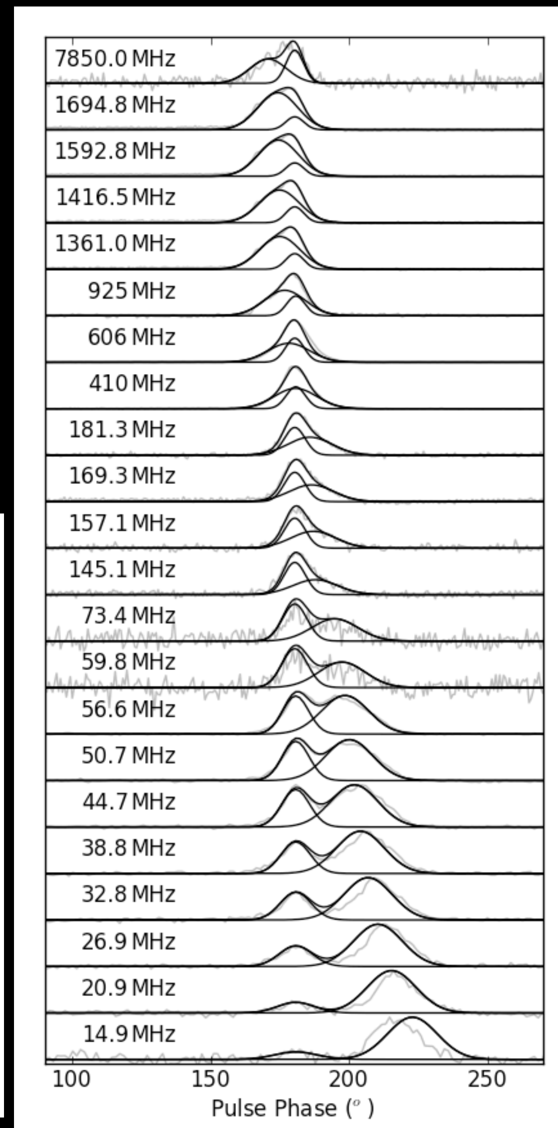
ν = **10 - 10,000MHz**

λ = **30m - 3cm**

Frequency range for observing radio pulsars



van Haarlem et al. 2013, *A&A*



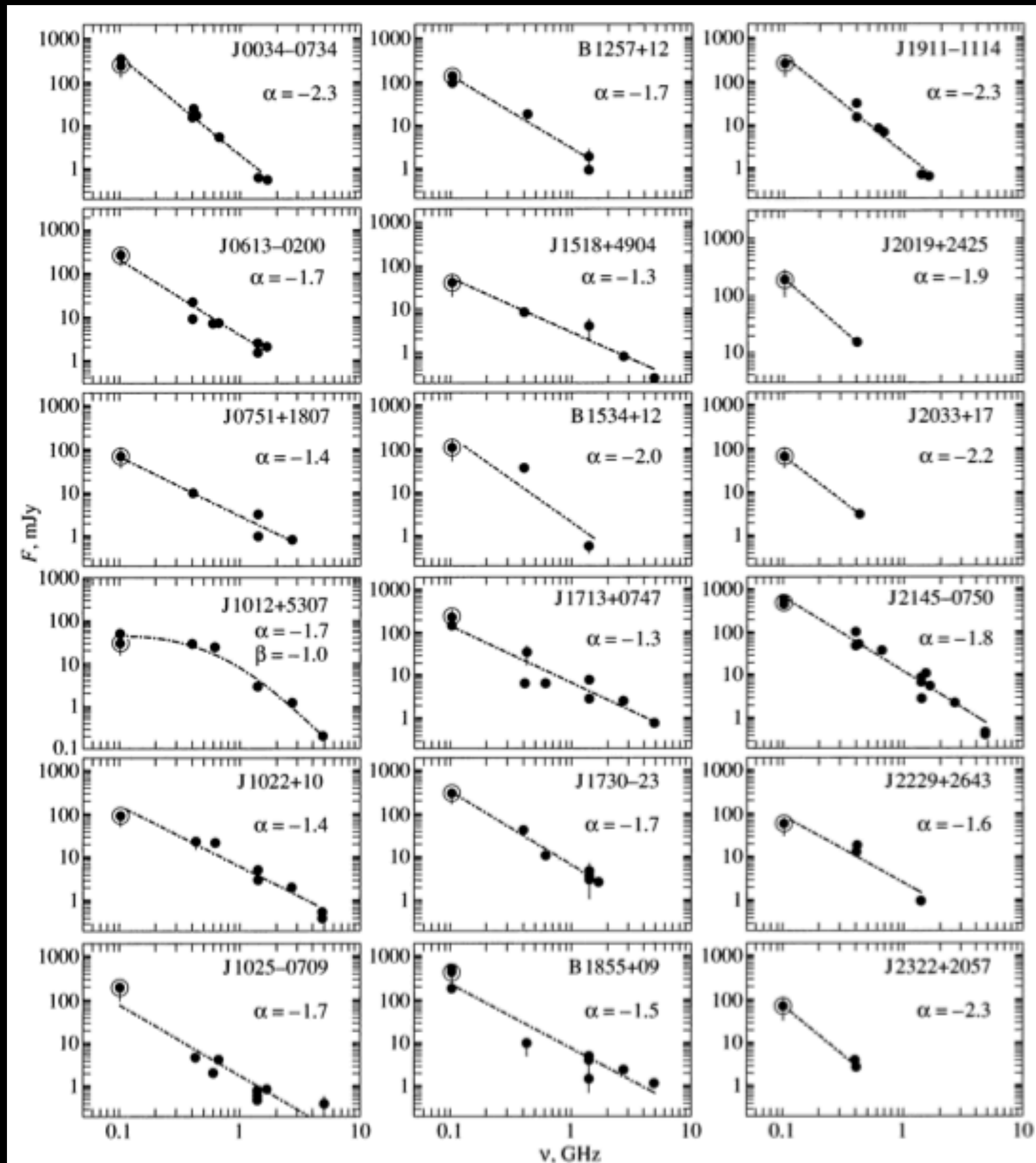
Hassall et al. 2012, A&A

8000MHz

9 octaves!

15MHz

ms-Pulsar Spectra



Kuz'min & Losovskii 2001

Pulsars typically have \`steep' power-law spectra:

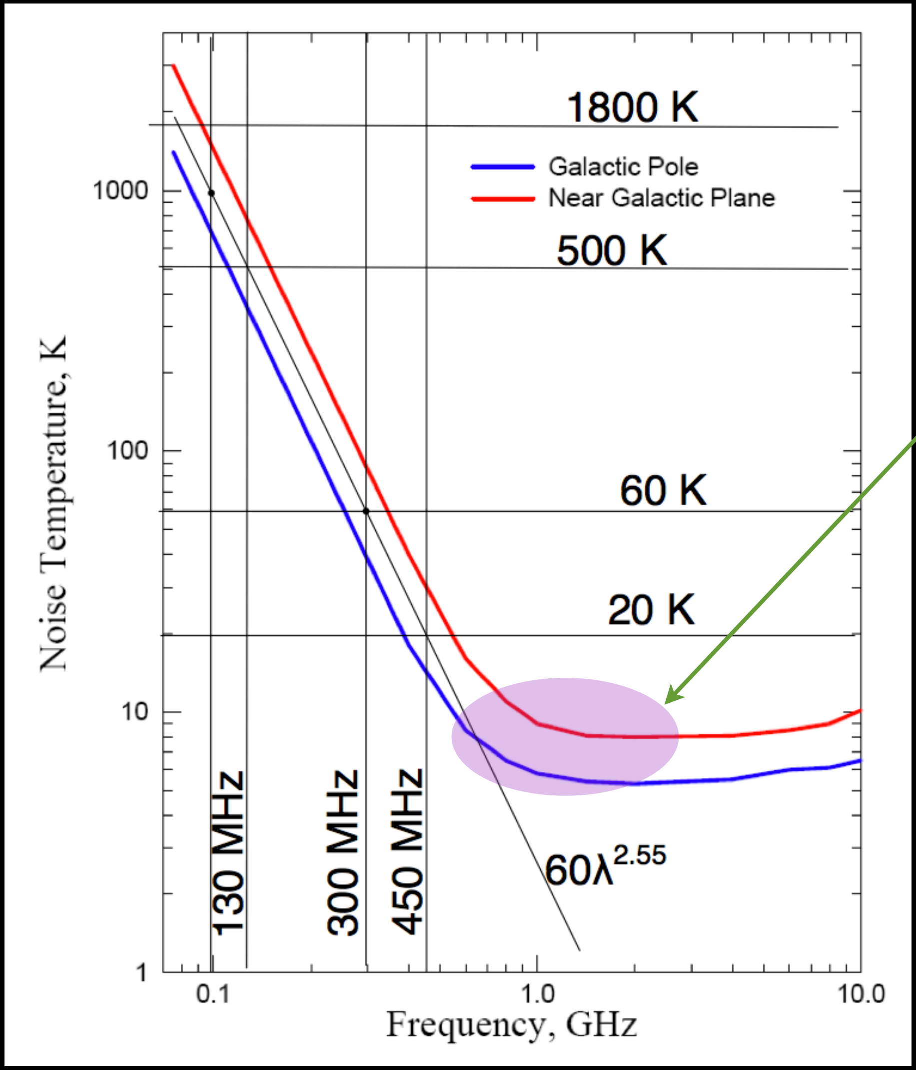
$$S \propto \nu^{-\alpha}$$

$$\alpha \sim 1 - 3$$

MSP spectra don't turn over?

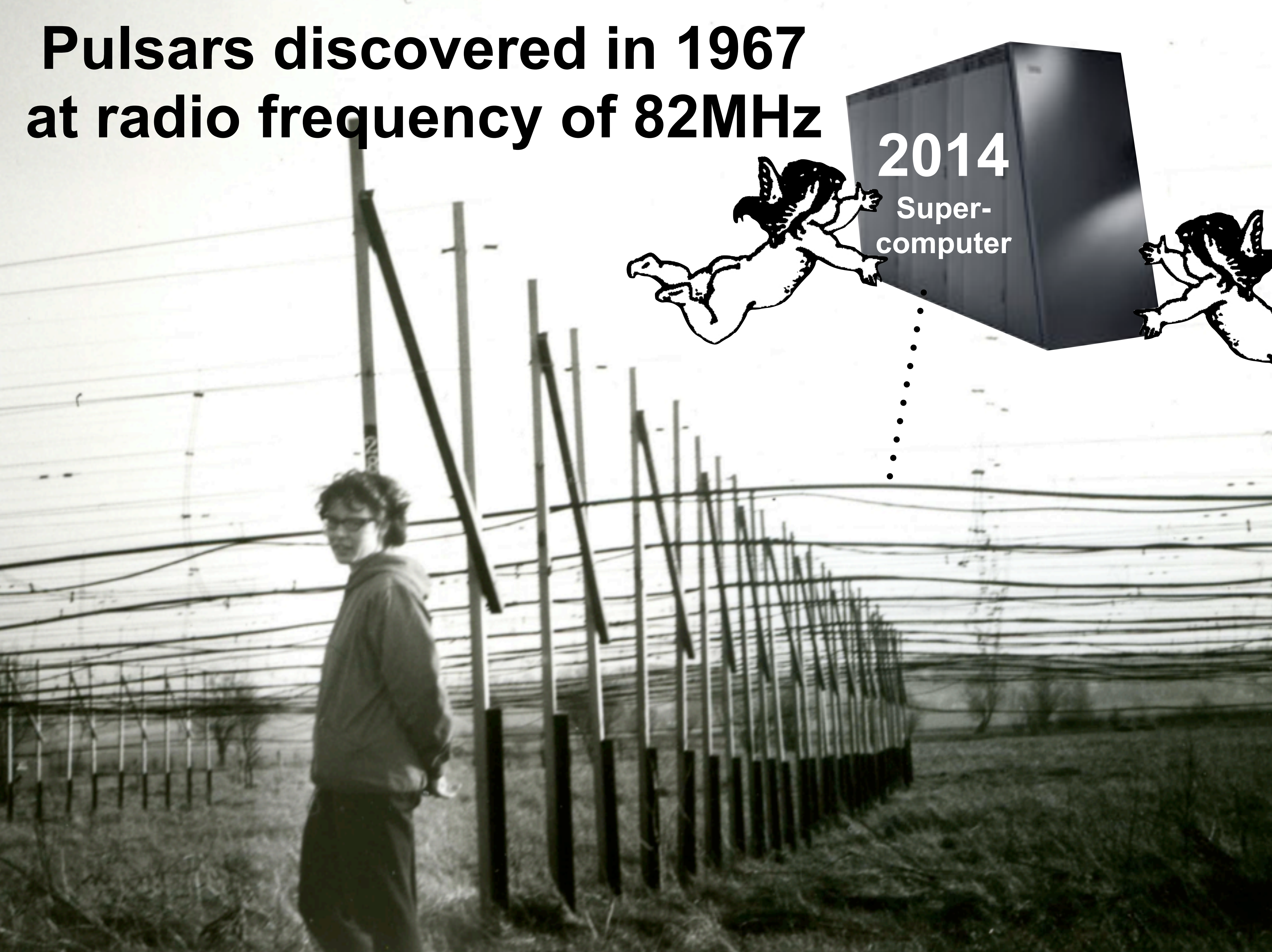
See Bates, Lorimer & Verbiest 2013, MNRAS, 431, 1352

Frequency range for observing radio pulsars



Dewdney

Good compromise better steep intrinsic spectrum and the sky temperature


Pulsars discovered in 1967
at radio frequency of 82MHz
2014
Super-
computer

Rebirth of Low-Frequency Radio Astronomy

LOFAR
LOw-Frequency ARray

LWA
Long-Wavelength Array

MWA
Murchison Widefield Array

Why Pulsars at < 300MHz

Emission mechanism

- Steep spectral indices
- Spectral turnover
- Profile evolution
- Different single-pulse properties

Interstellar medium

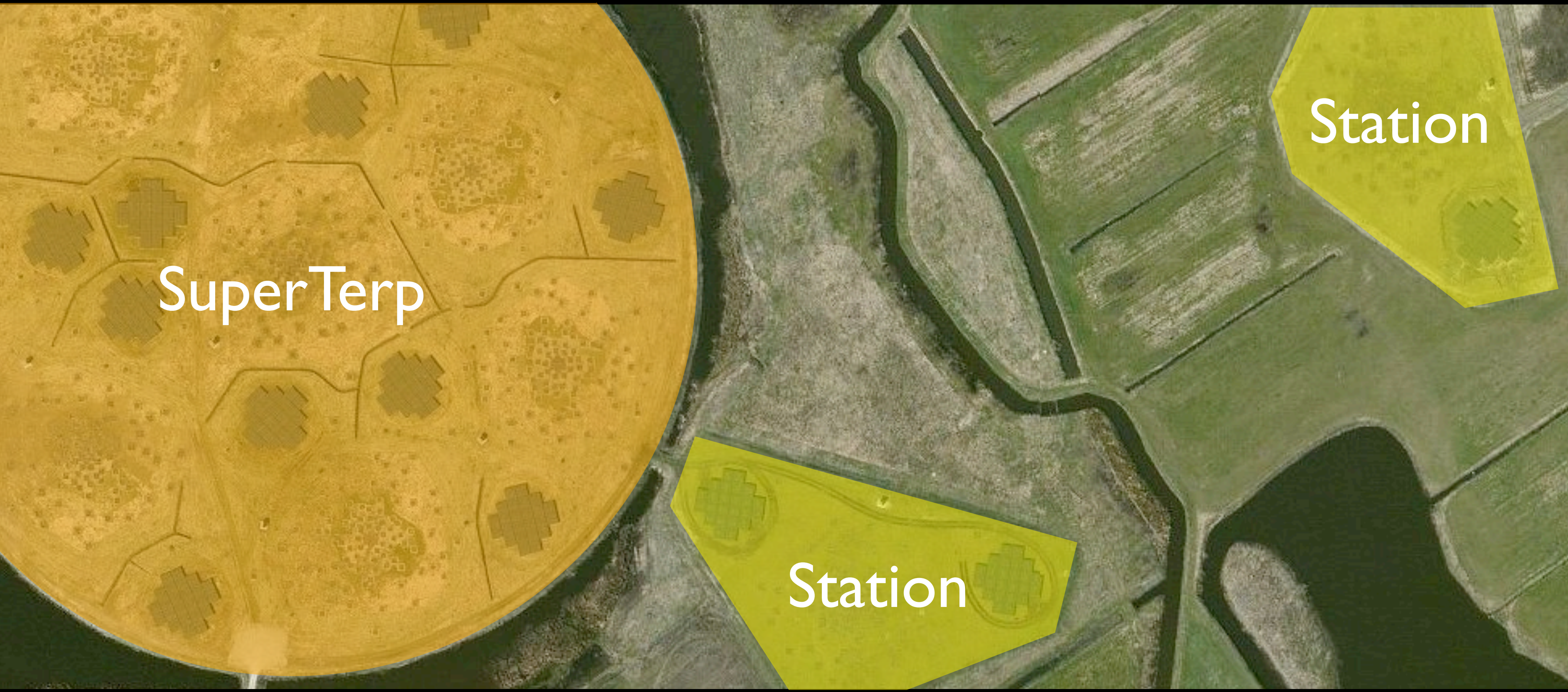
- Precision dispersion measure
- Scattering
- Precision rotation measures
- "Scintellometry"

Surveys

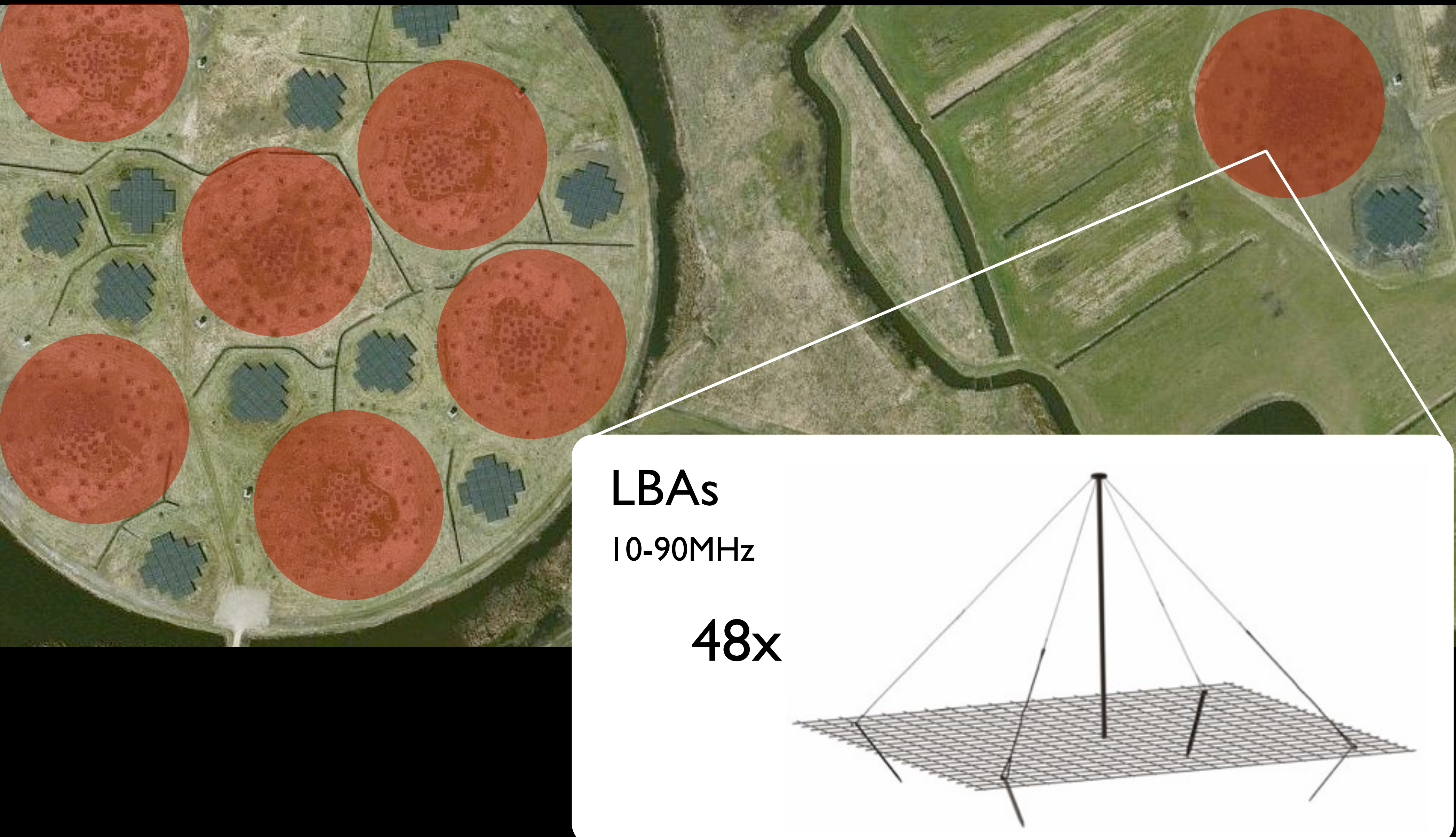
- Huge field-of-view
- Discriminate vs. RFI

LOFAR “Superterp”

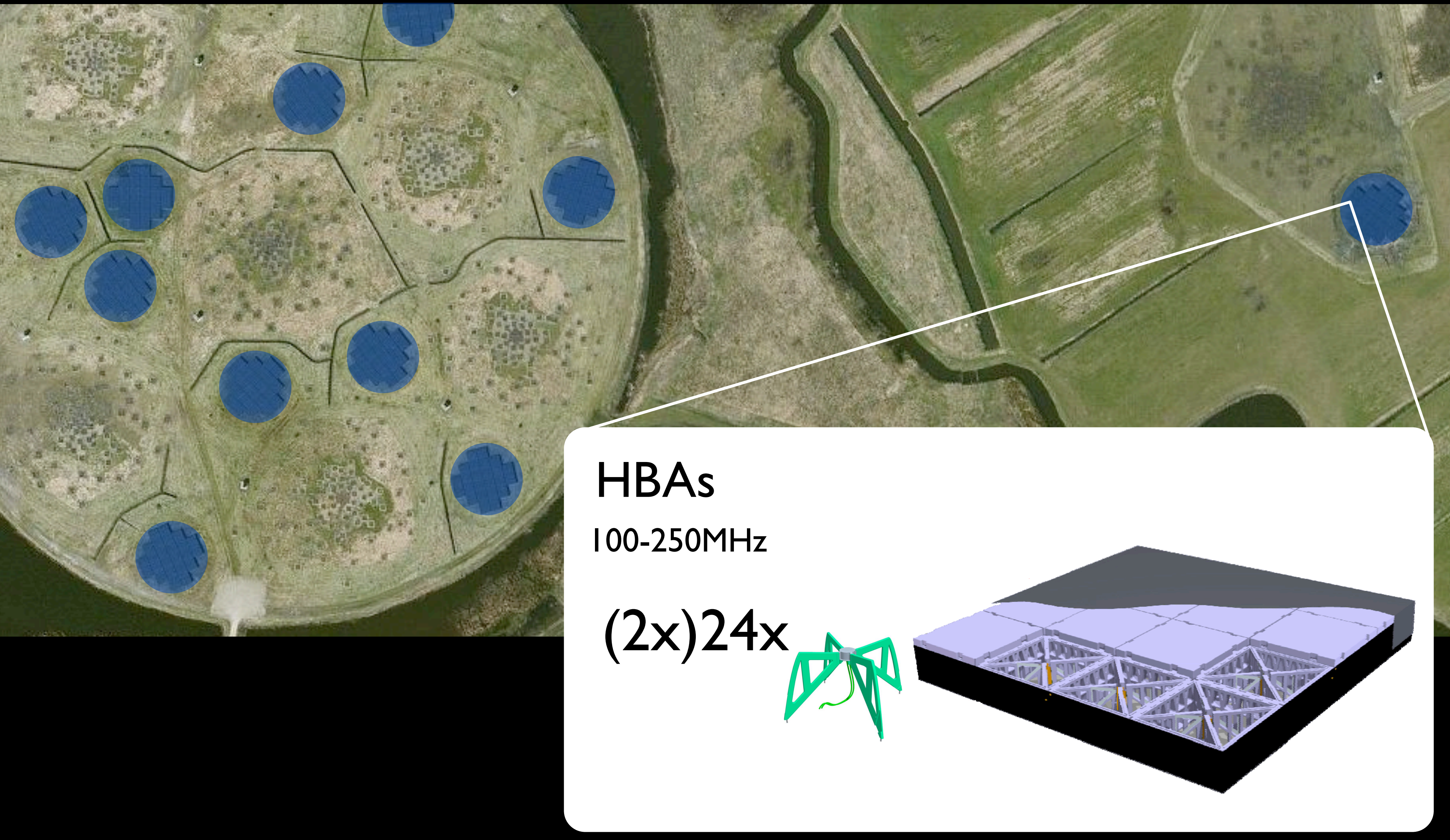
LOFAR



LOFAR



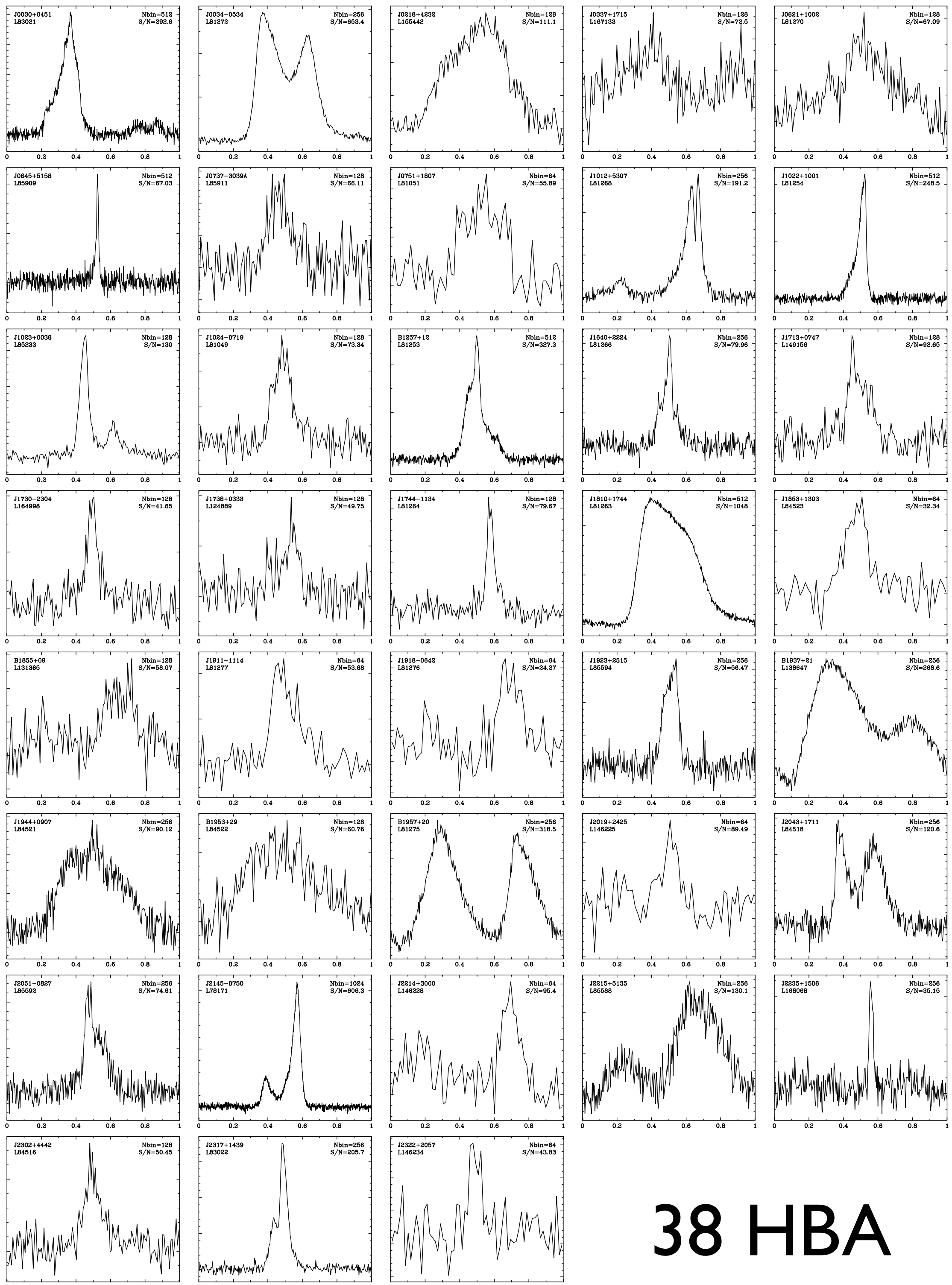
LOFAR



MSPs

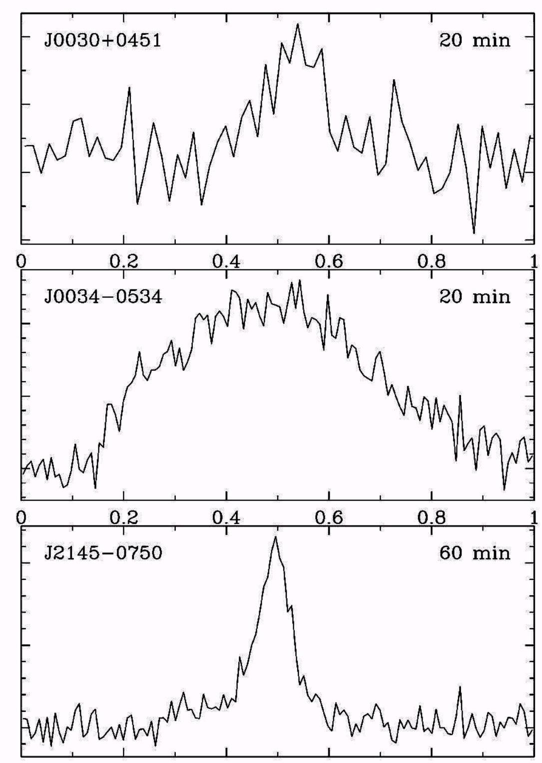
The premier low-frequency census

Kondratiev, Hessels et al. 2014, *almost submitted*



38 HBA

3 LBA



Why wide bandwidths?

World's Biggest Telescopes

NANOGrav


Arecibo


Green Bank

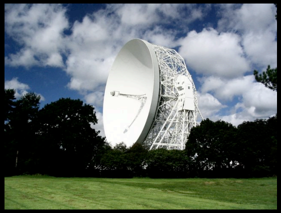
EPTA


Westerbork


Effelsberg


Nançay


Sardinia


Lovell

PPTA


Parkes

We're hitting the limit of what these can do!

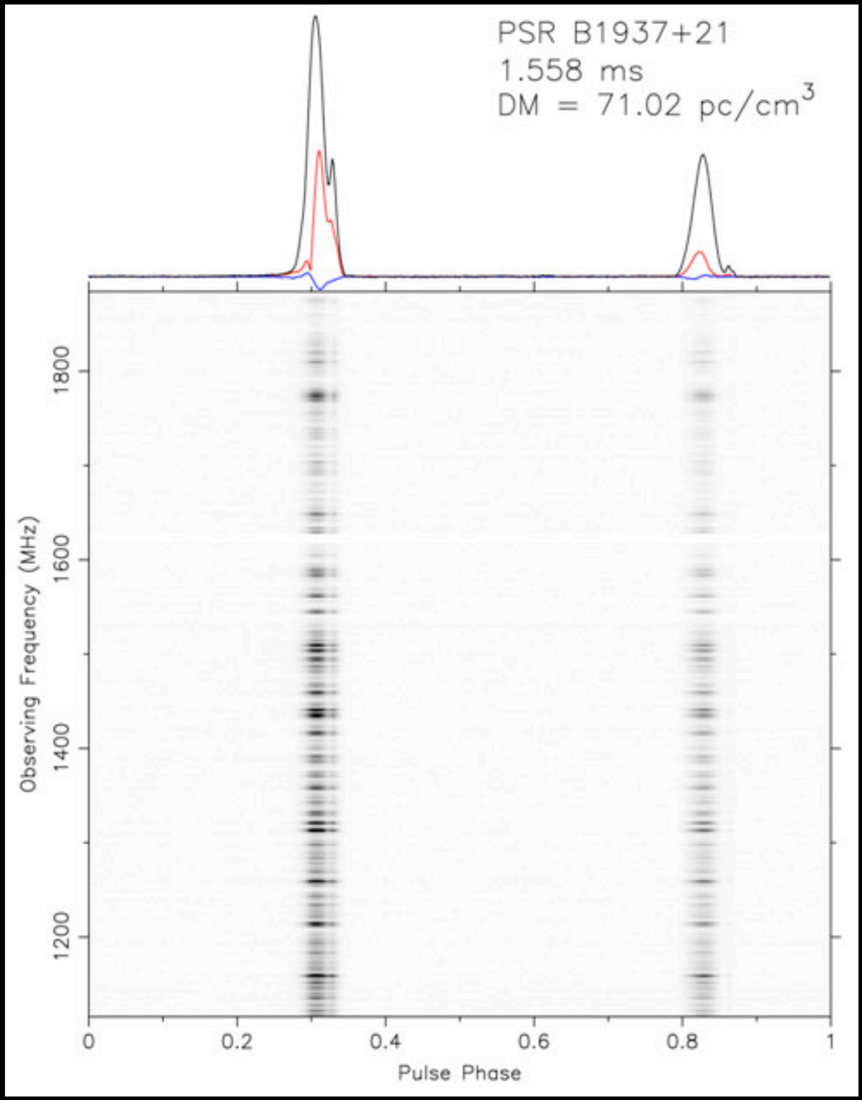
Sensitivity

$$\sigma_{\mathrm{TOA}} \sim \mathrm{width}/SNR$$

$$SNR \propto \sqrt{BW}$$

- Single-dish radio telescopes have basically reached their size limit (though don’t forget FAST).
- Recording more bandwidth increases sensitivity as sqrt(BW), and is a relatively cheap upgrade.
- Contamination from radio frequency interference (RFI) is an *increasing* challenge.
- Large data rates and wide-band, cooled receivers are also a challenge, but the technology is reaching maturity.

State-of-the-art backends



Ransom

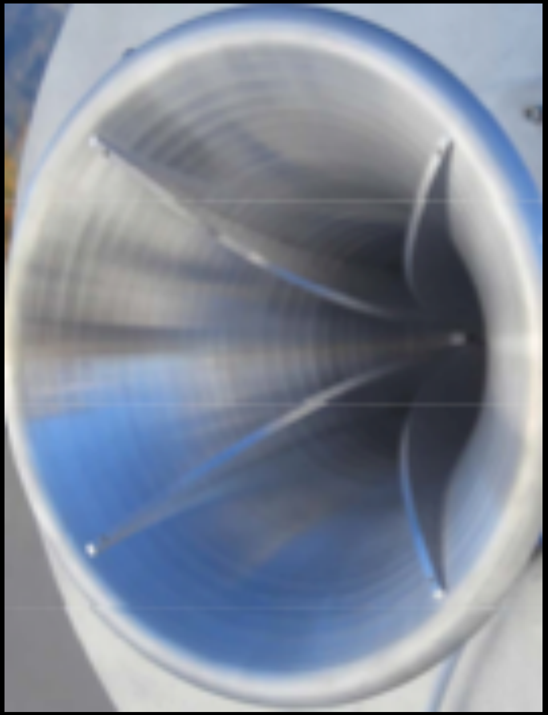
Green Bank Ultimate Pulsar Processor (GUPPI)

Routinely coherently dedisperse 100s of MHz

Wideband Receivers

(see also Lazio talk on Thu. June 26th)

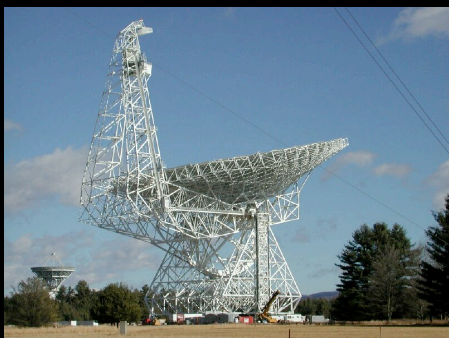
Ultra-Broad-Band receiver
ERC Grant to Paulo Freire
600MHz – 3GHz
coherent dedispersion using GPUs and ROACHes
Feed design: S. Weinreb(JPL)



Effelsberg UBB Receiver

Radio Pulsar Searches

Single Dishes


GBT


Parkes


Arecibo

Interferometers


GMRT


WSRT


LOFAR

SKA


SKA Mid

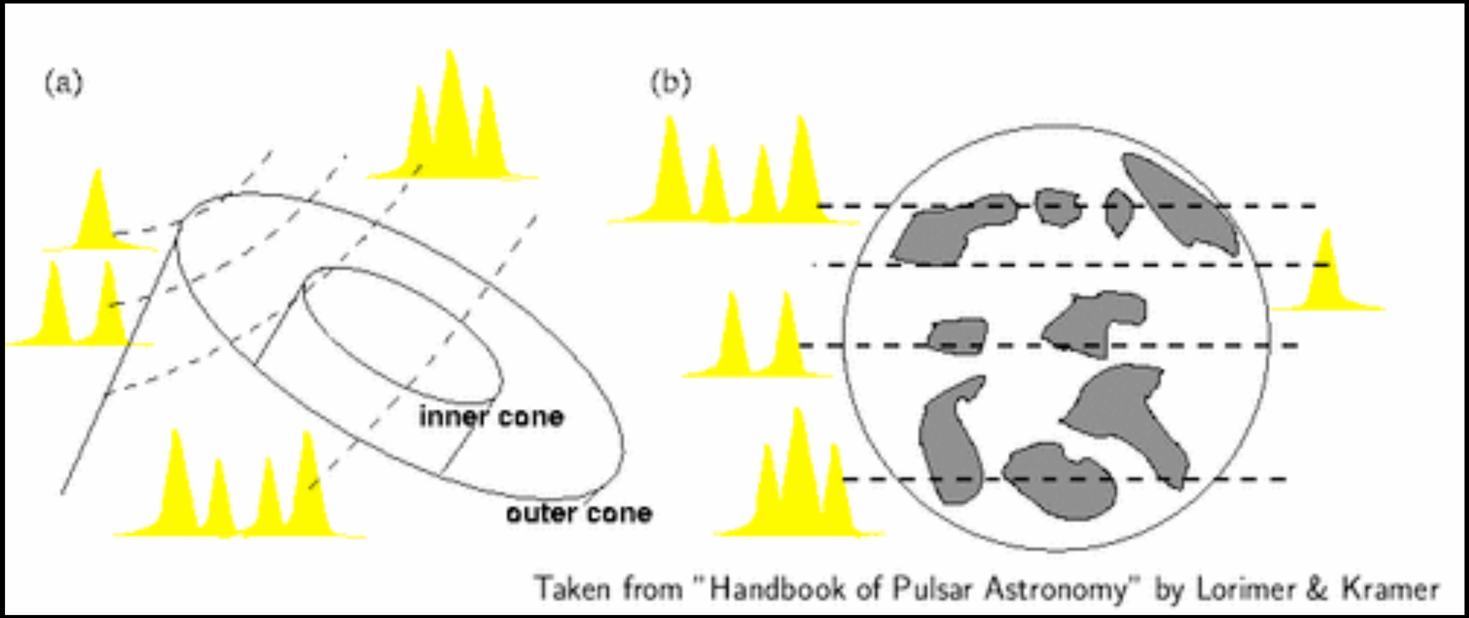

SKA Low

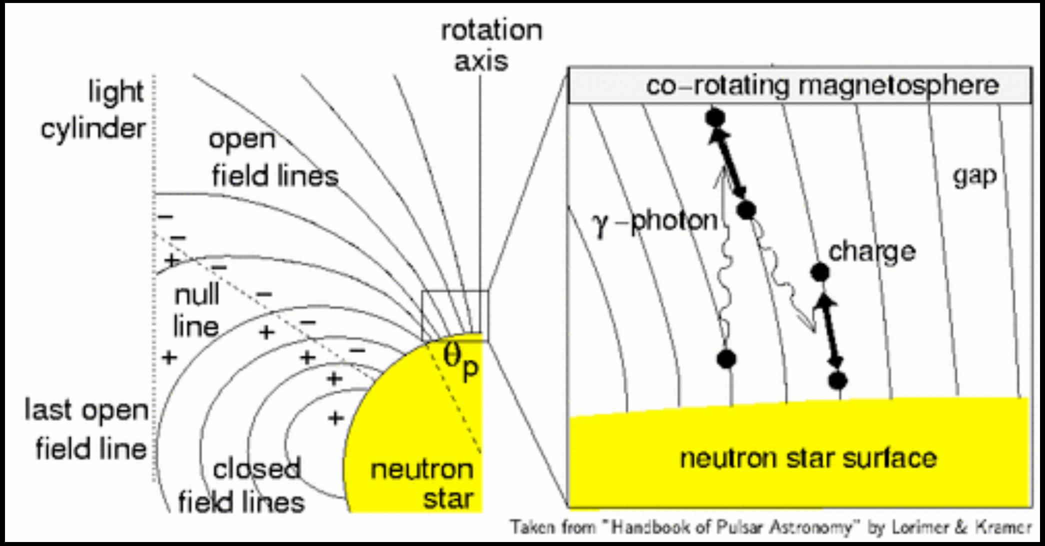

SKA Aperture Array

Science

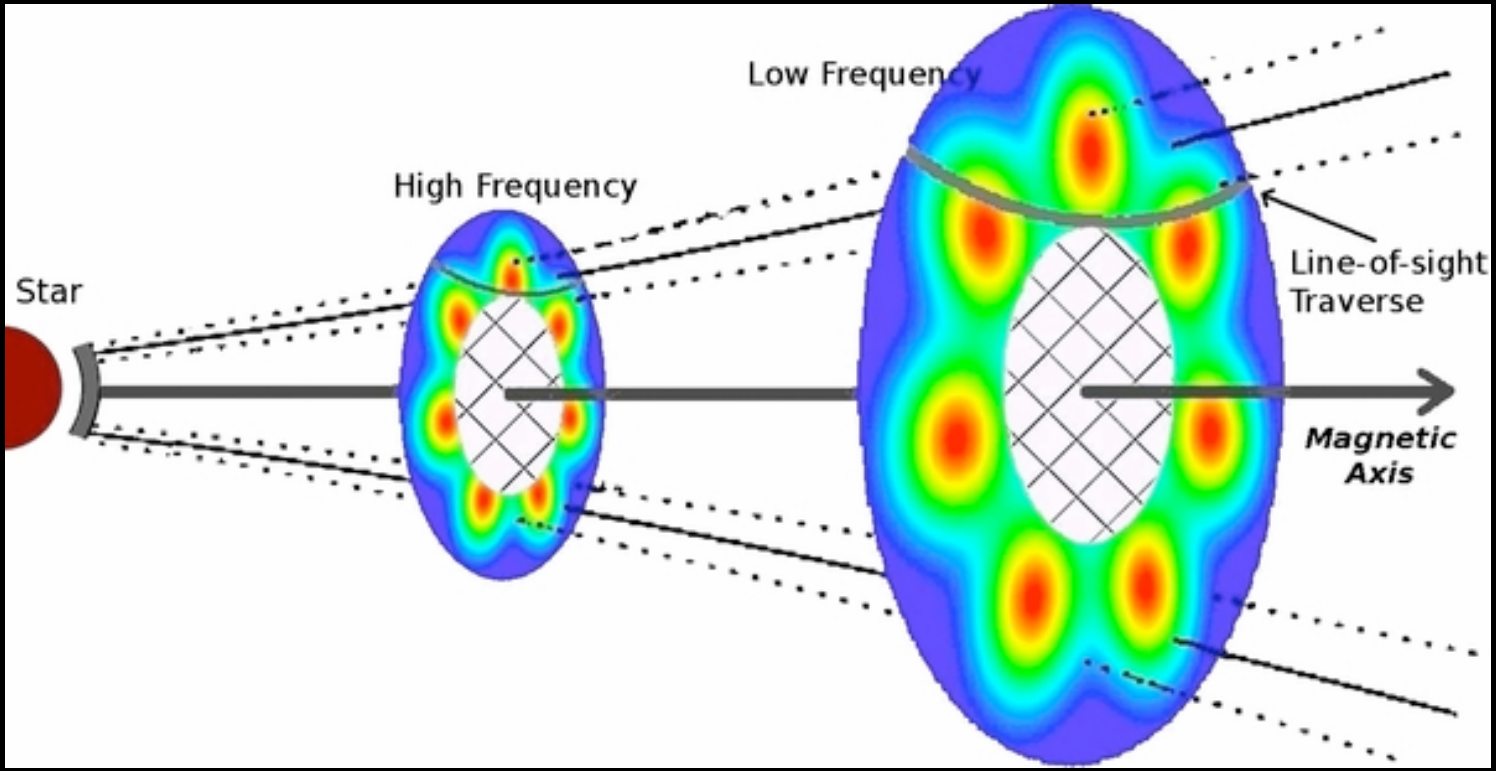
- Wide bandwidths aren't just about getting more sensitivity.
- Measure the pulsar's spectrum (fundamental to understanding the emission mechanism).
- Get a 3D picture of the emitting region.
- Precisely measure propagation effects and study the interstellar medium (more on that in a bit).

Pulsar Beam Shapes



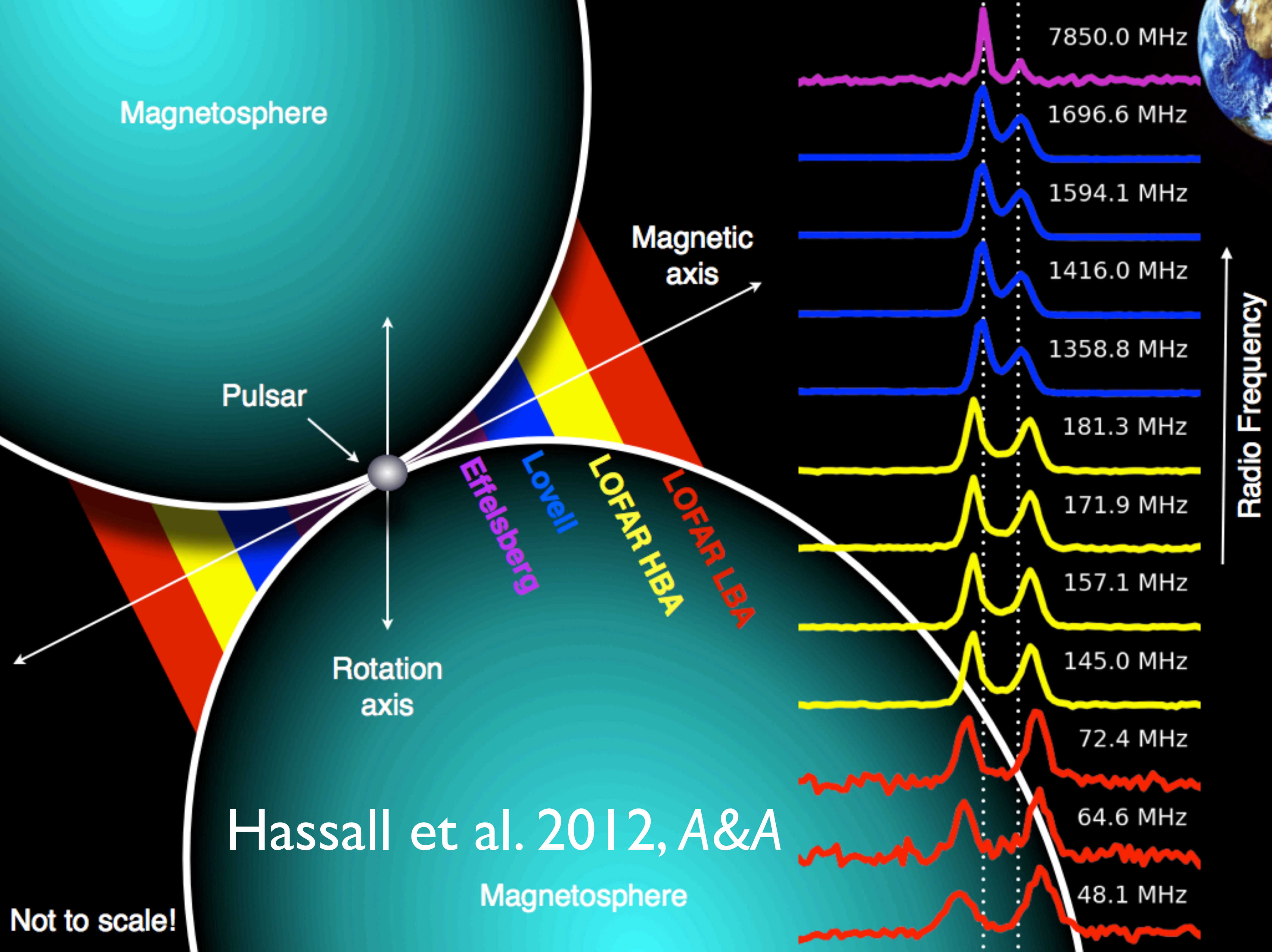


Pulsar Beam Shapes



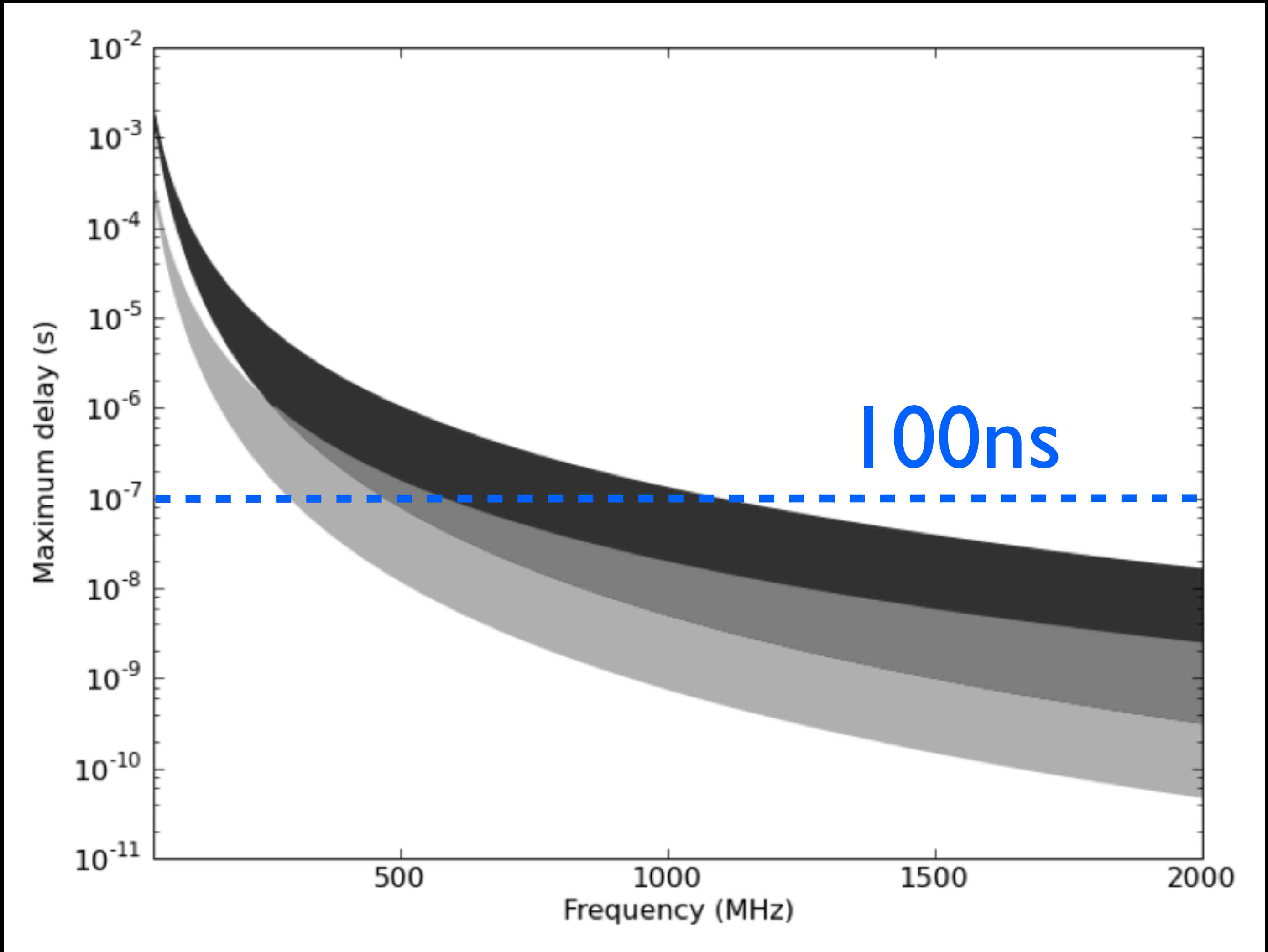
Maan

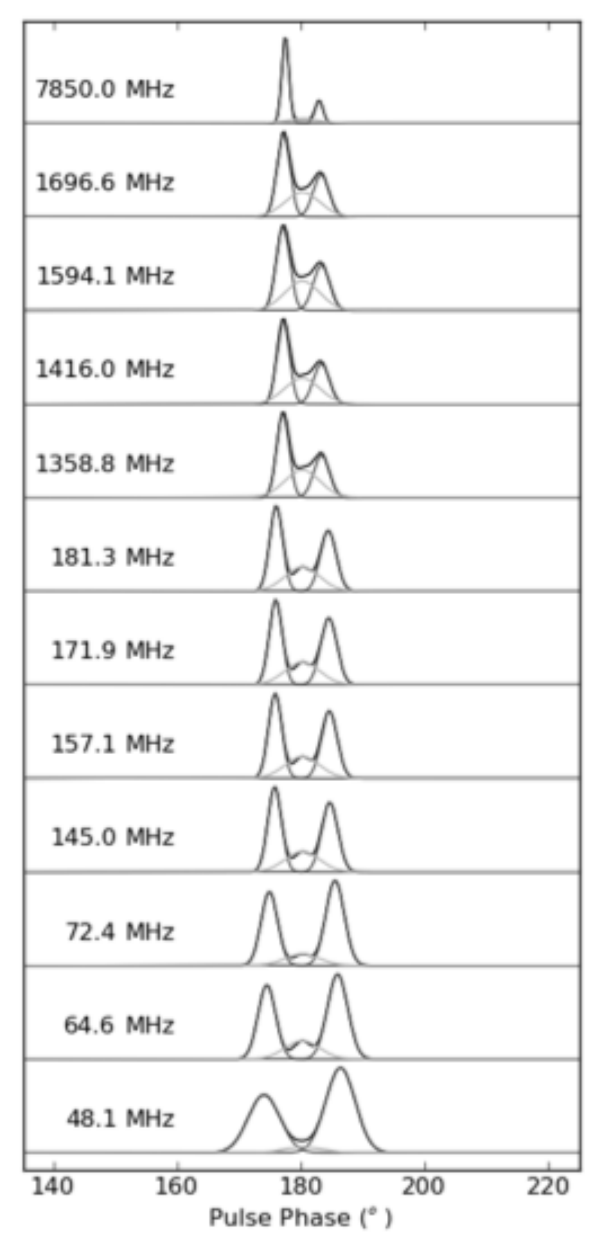
`Radius-to-frequency mapping': idea that lower-frequency emission comes from progressively higher altitudes above the magnetic polar caps.


Magnetosphere
Pulsar
Magnetic axis
Rotation axis
Effelsberg
Lovell
LOFAR HBA
LOFAR LBA
7850.0 MHz
1696.6 MHz
1594.1 MHz
1416.0 MHz
1358.8 MHz
181.3 MHz
171.9 MHz
157.1 MHz
145.0 MHz
72.4 MHz
64.6 MHz
48.1 MHz
Radio Frequency
Hassall et al. 2012, A&A
Magnetosphere
Not to scale!

Constraining the ISM

Dispersion law good to 1/100,000 (4 lines of sight)

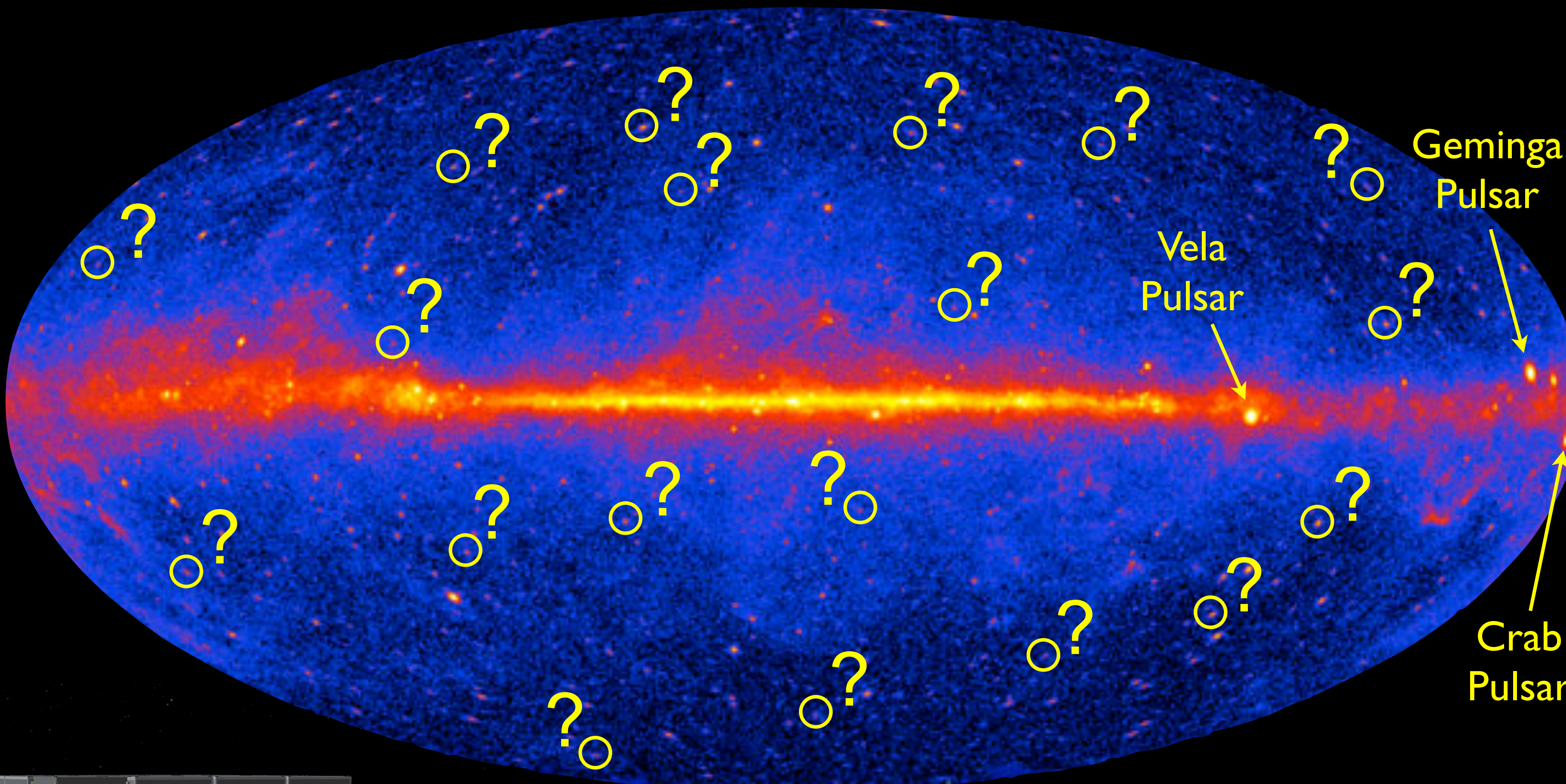


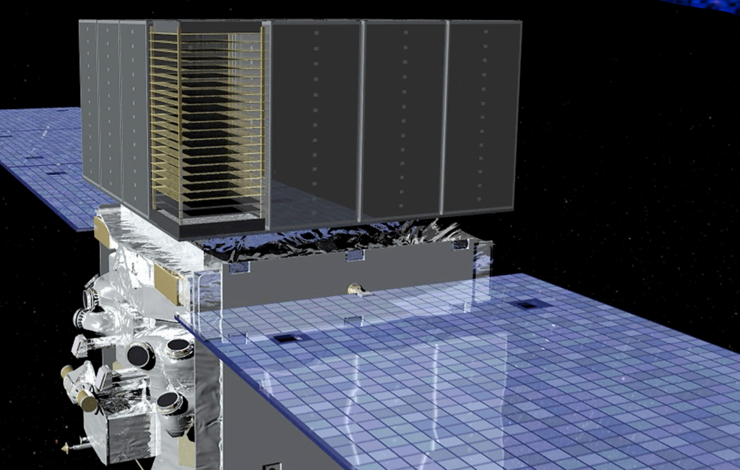


Hassall, Stappers, Hessels, Kramer et al. 2012

...and don't forget that pulsars can emit across the EM spectrum

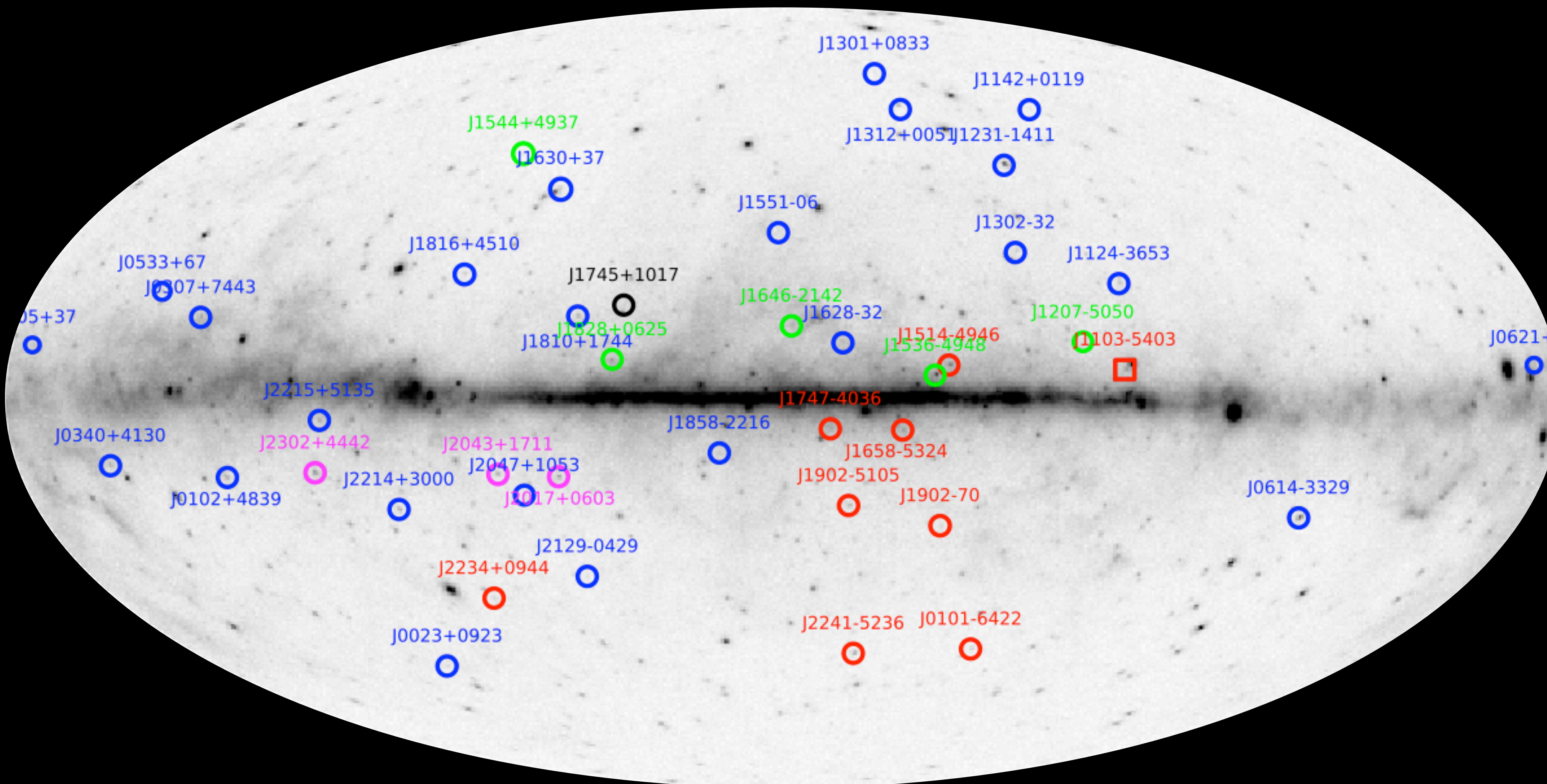
Fermi Gamma-ray Sky





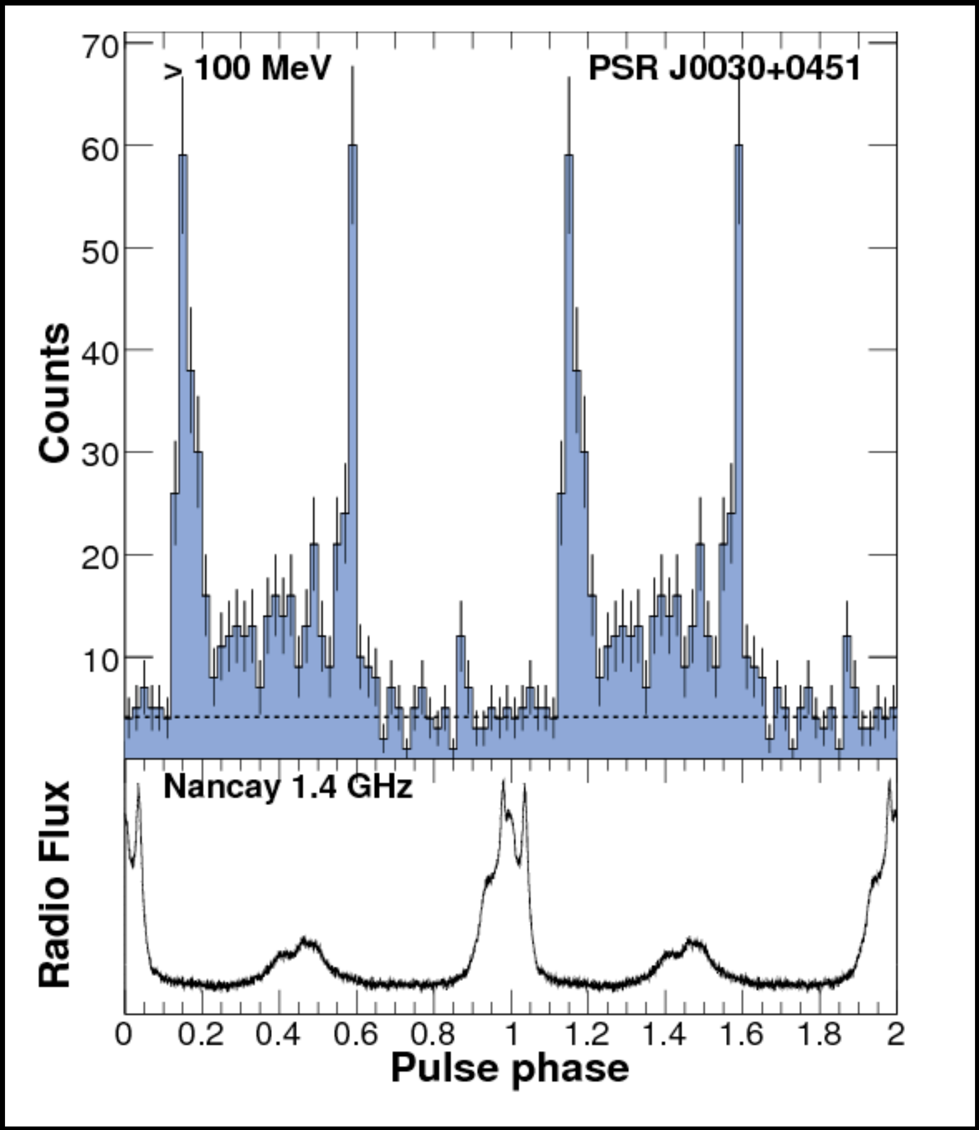
Fermi Gamma-Ray Space Telescope

Gamma-selected radio MSPs



See Ray et al. 2013

Gamma-selected radio MSPs



Fermi team

γ-ray pulse profile
~1400 000 000 000 000 000 MHz

Radio pulse profile
1400 MHz

What are the complications?

(besides RFI and data rate)

Propagation effects

(see ISM session on Wed. June 25th)

- The interstellar medium (ISM) between us and the pulsar is ionized, clumpy, and magnetized.
- Propagation through the ISM delays and distorts the pulses in a frequency-dependent way.
- Our line-of-sight through the ISM changes with time, and thus these effects are dynamic.

Propagation Effects

Observed signal

Signal as sent

Noise

$$I(t) = g_r g_d S(t) * h_{\rm DM}(t) * h_d(t) * h_{\rm Rx}(t) + N(t)$$

Refractive scintillation

Diffractive scintillation

Dispersion

Scattering

Faraday rotation

Propagation Effects

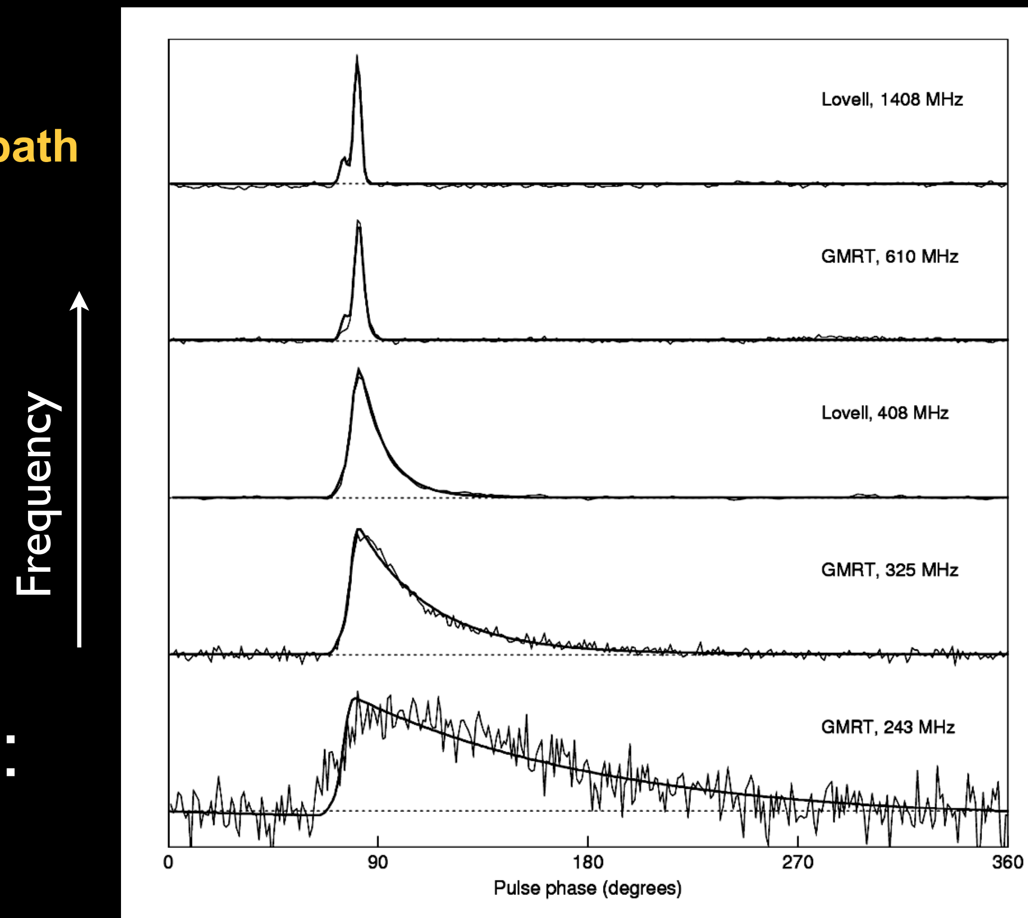
$$I(t) = g_r g_d S(t) * h_{\rm DM}(t) * h_d(t) * h_{\rm Rx}(t) + N(t)$$

Scattering: multi-path propagation

Dispersion: freq. dependent arrival time

Scintillation: const./dest. interference

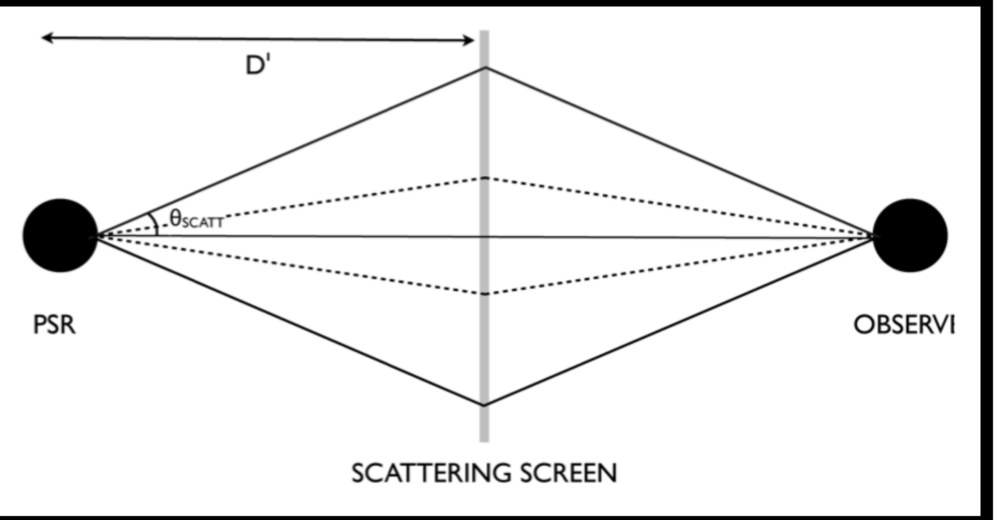
Faraday rotation: angle of linear polarization

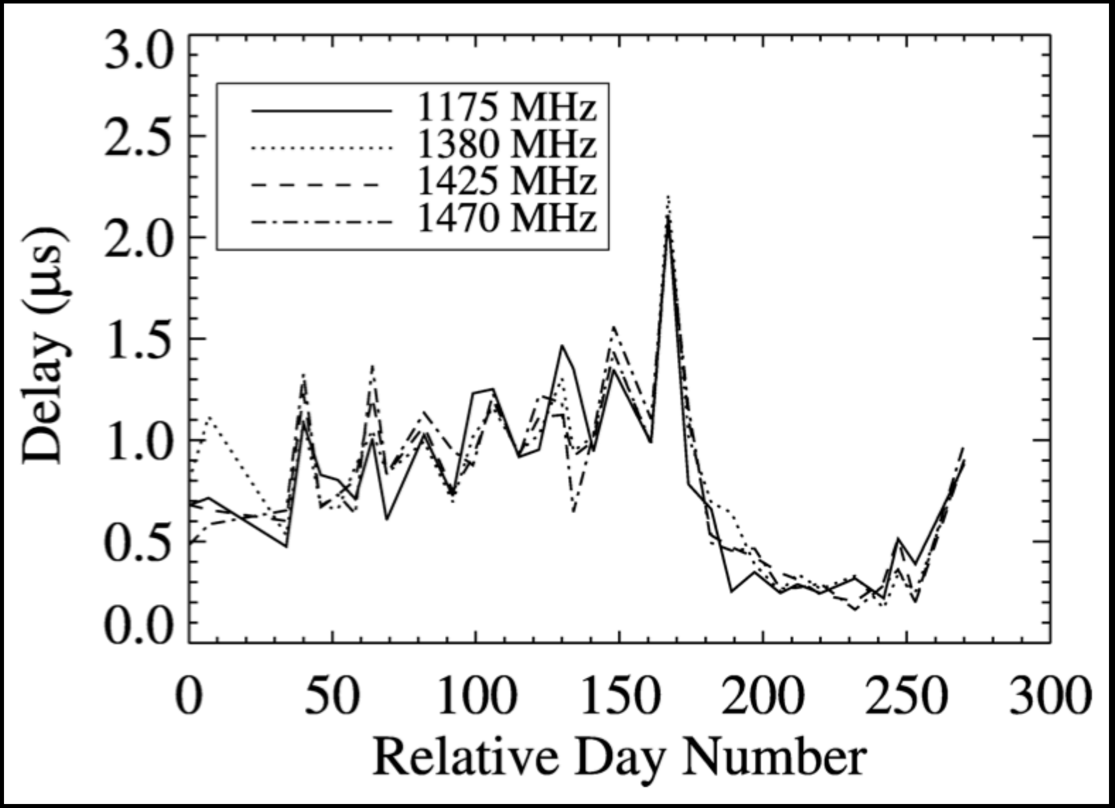


$$\tau \propto \nu^{-4}$$

See Levin, Palligayuru, etc. talks on Wed., June 25th

Variable scattering



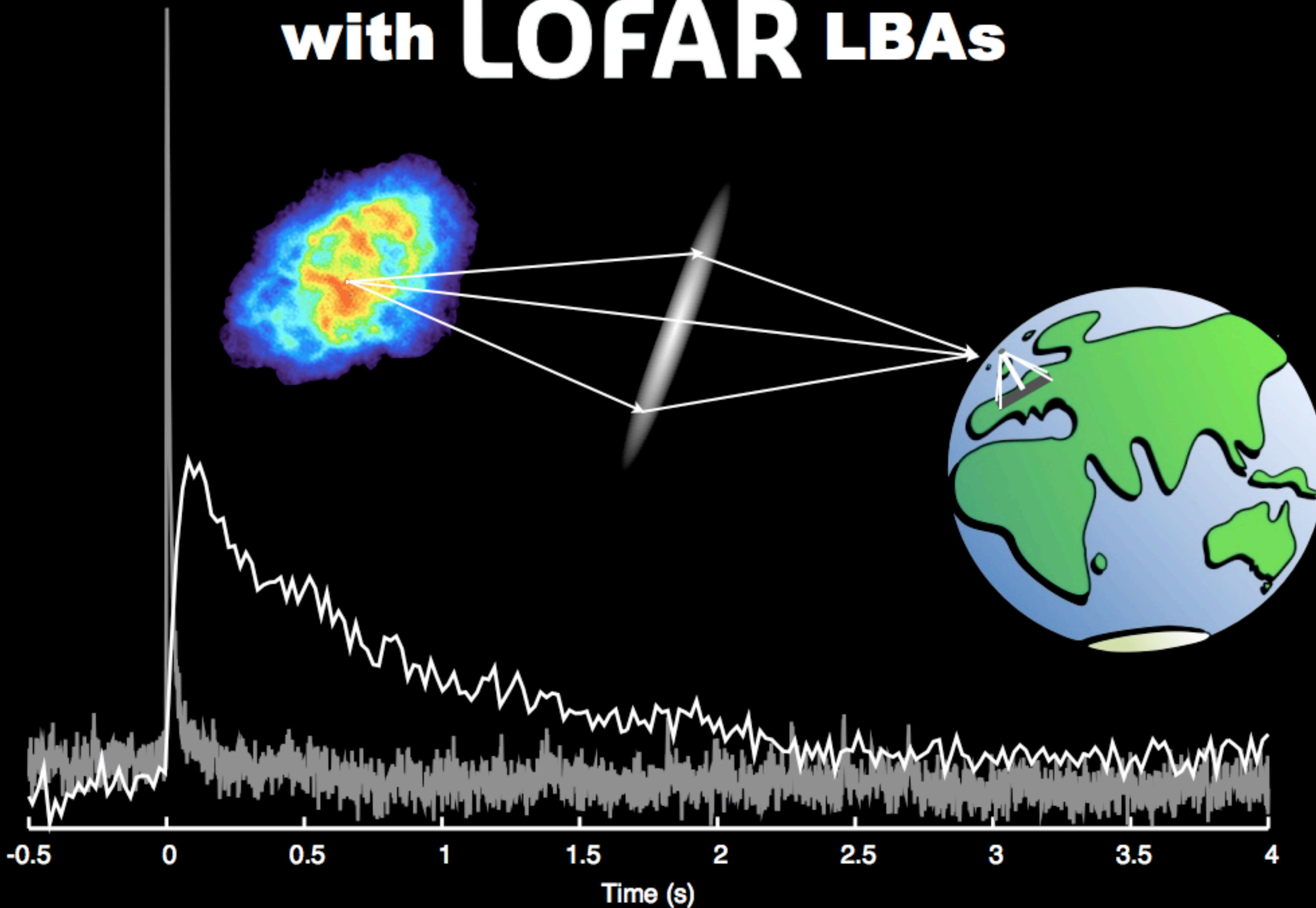


Hemberger & Stinebring 2008

How important is this for timing accuracy?

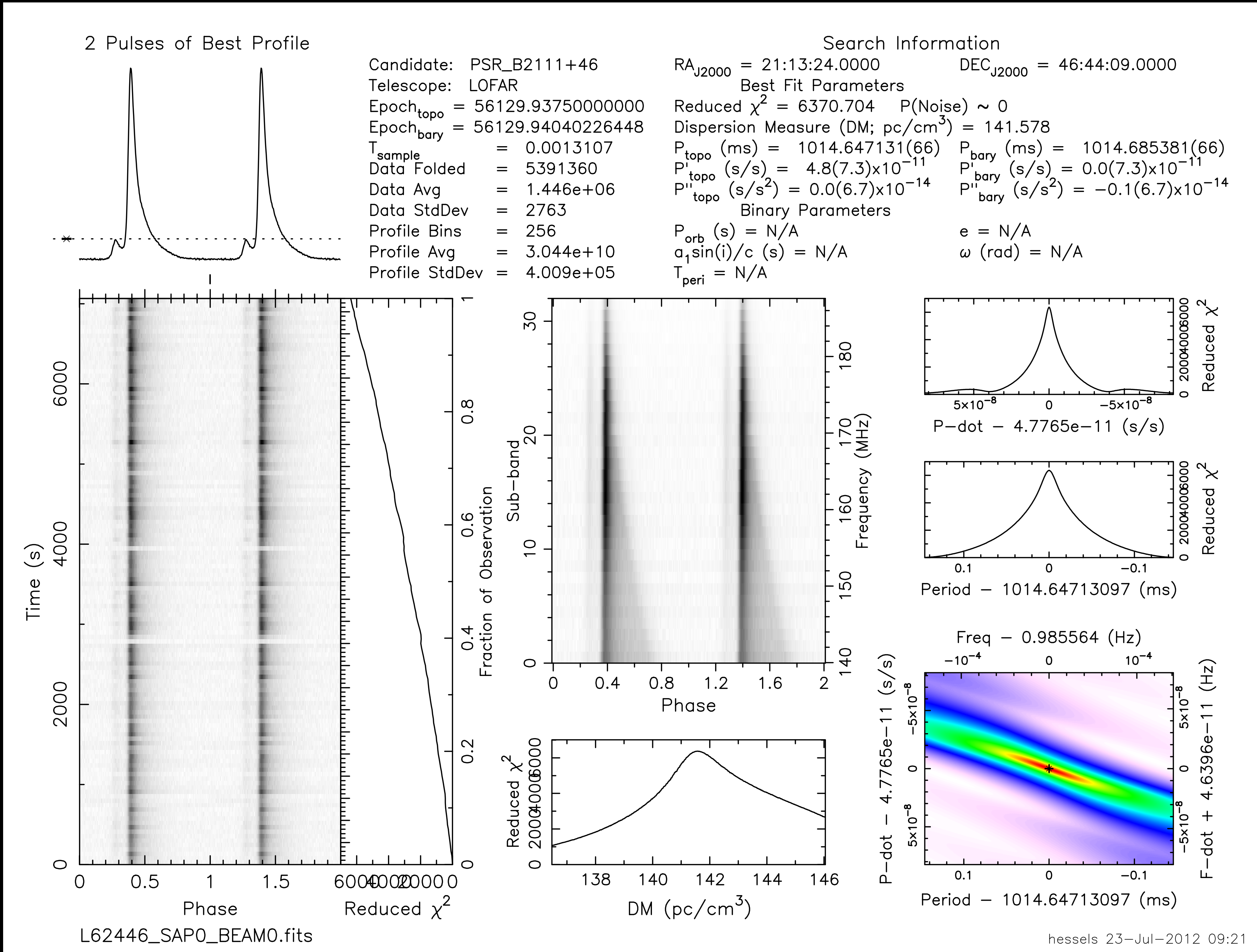
NB: at lower frequencies, we average over a larger cone of the ISM

Detection of Crab Giant Pulses with LOFAR LBAs



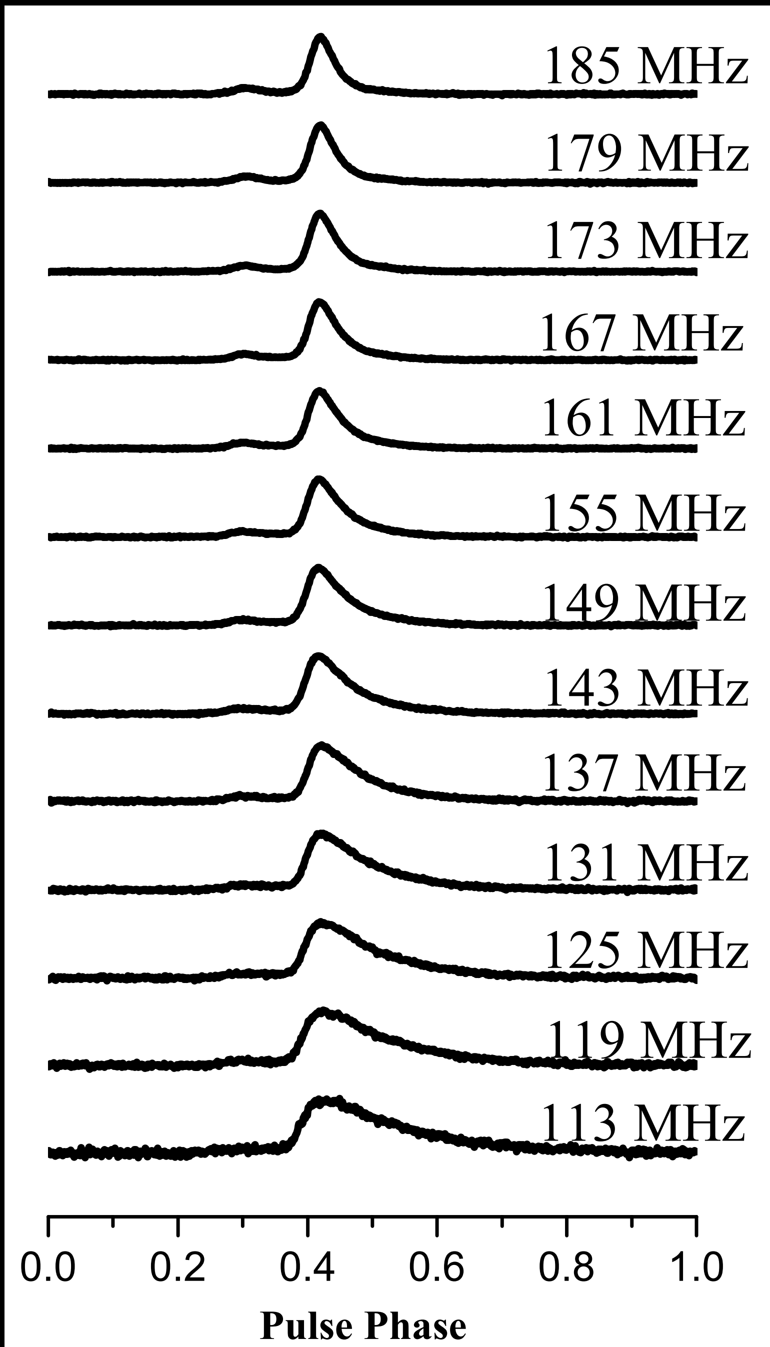
Hassall

Scattering

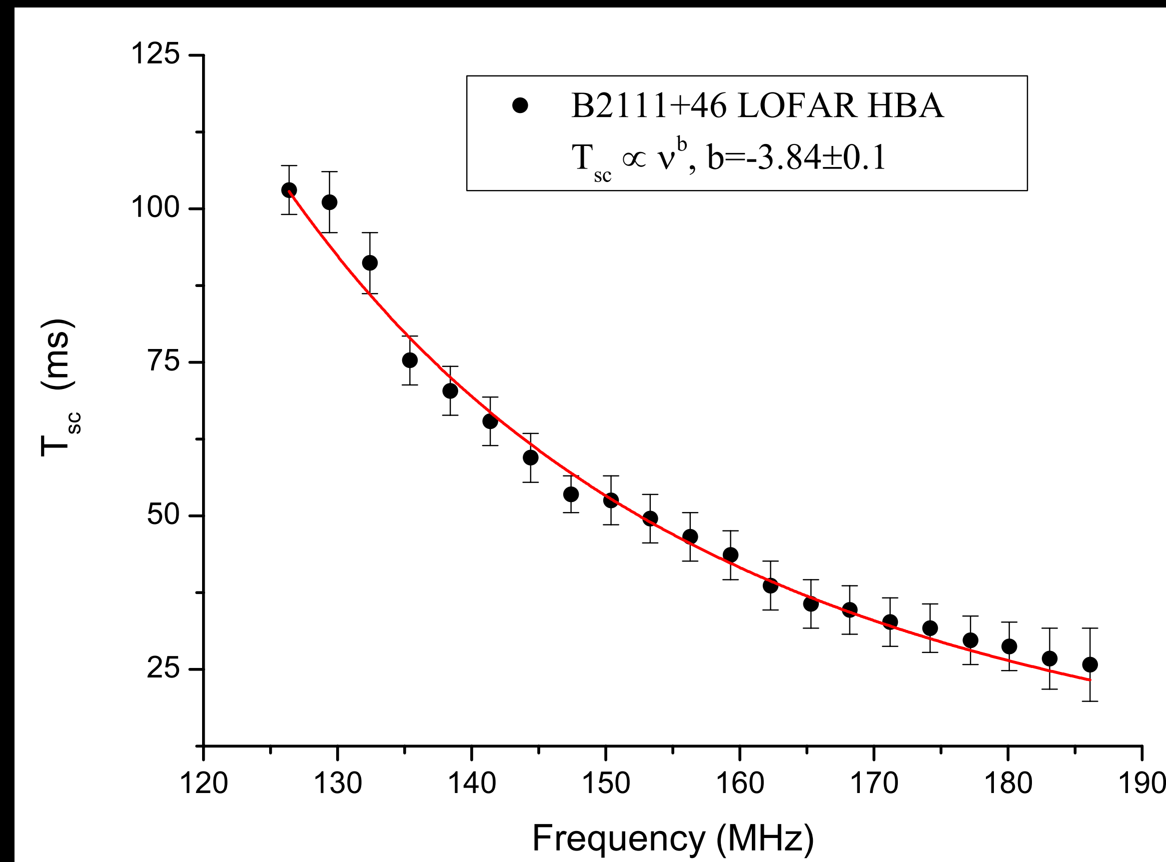


Hessels

Scattering



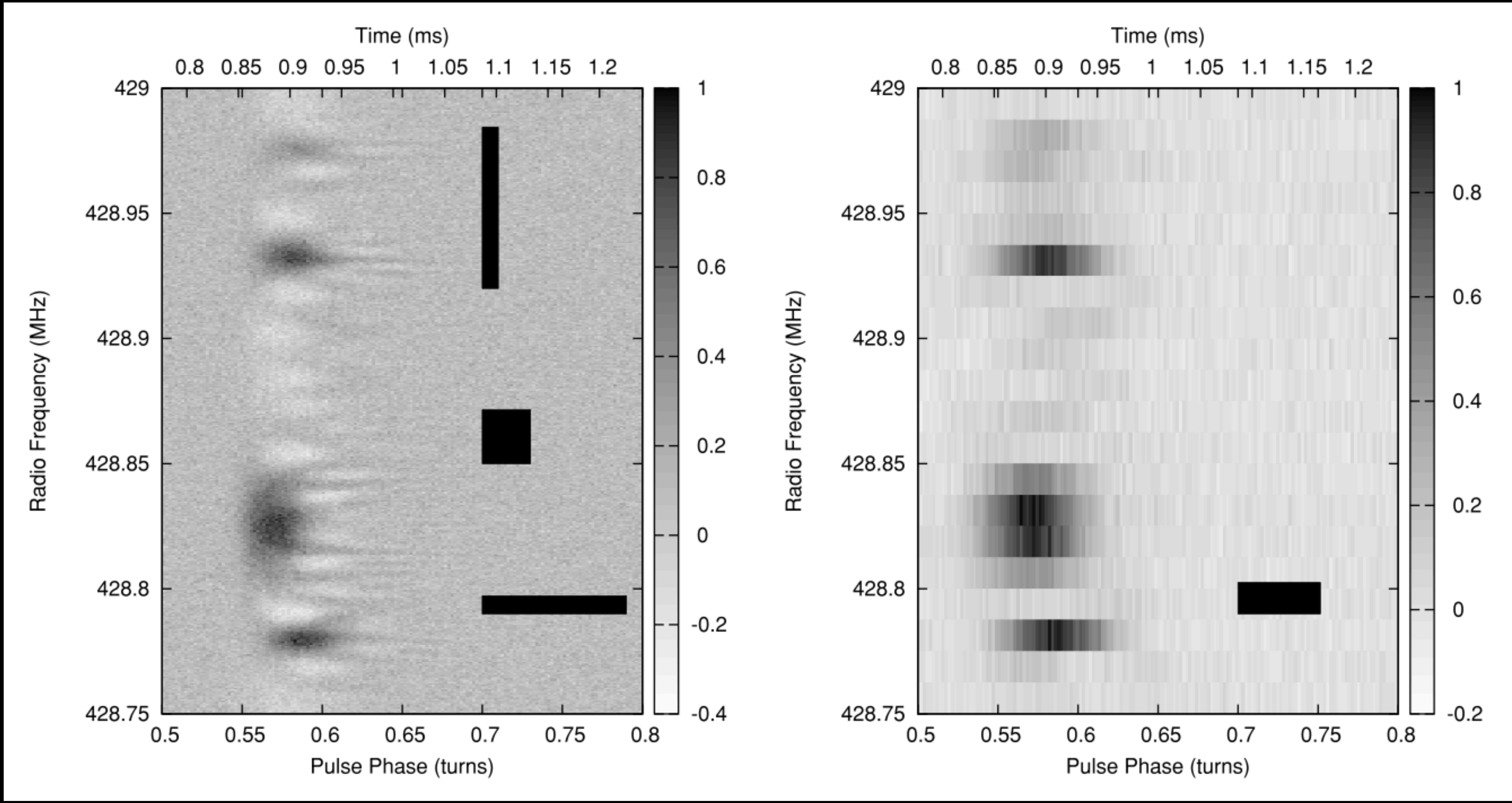
From a *single* LOFAR observation



Zagkouris et al. 2014, *in prep.*

Cyclic Spectroscopy

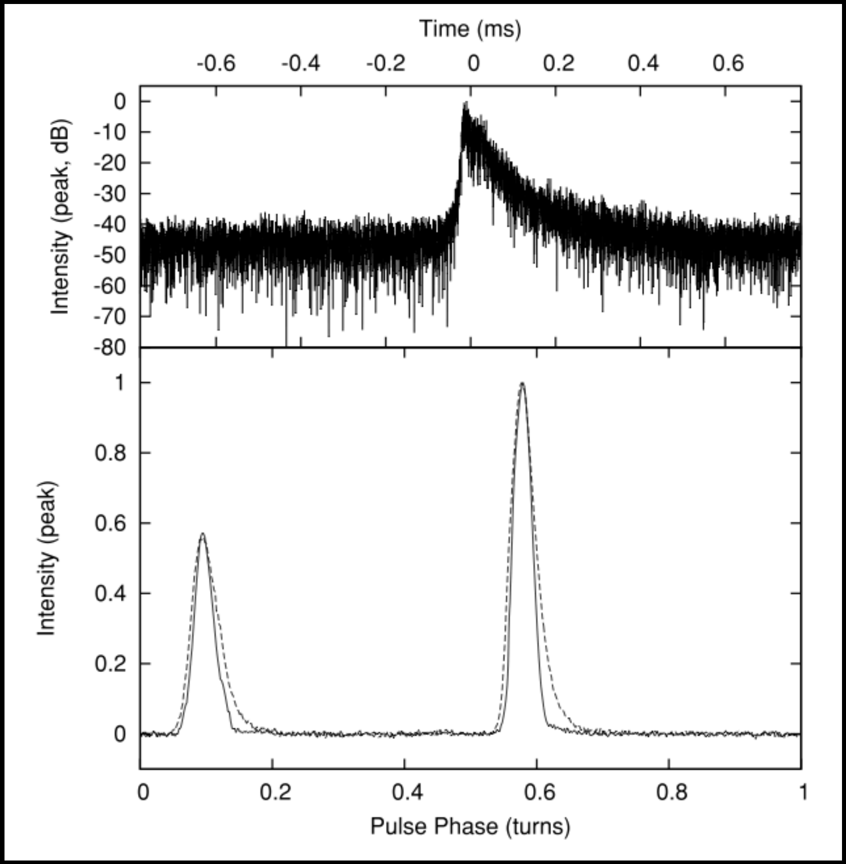
Periodic spectrum | Normal (filterbank) spectrum



See Demorest 2011, MNRAS, 416, 2821

`Beat' the Nyquist limit

Cyclic Spectroscopy



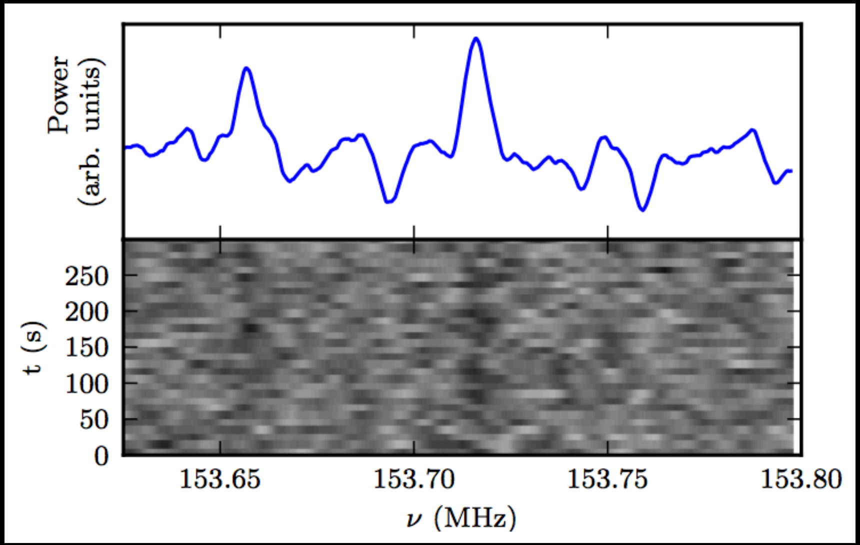
Absolute square impulse response

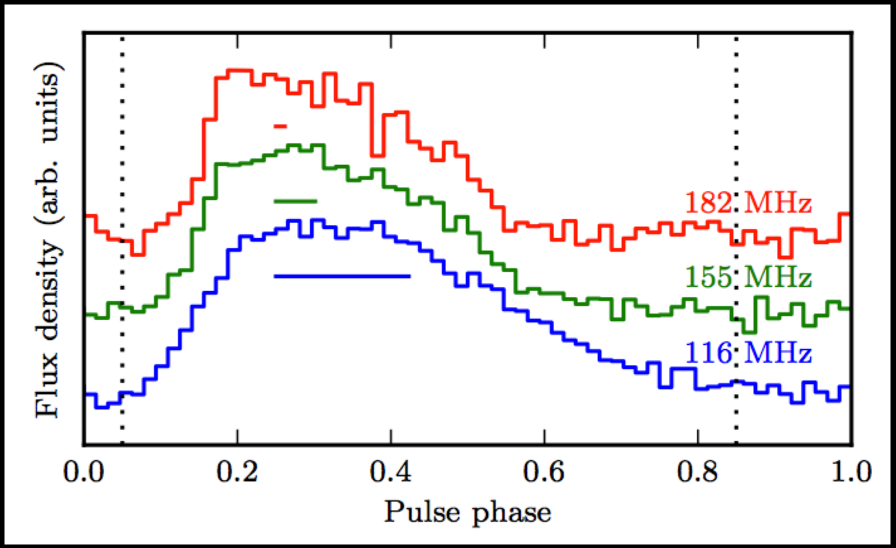
Scattered and de-scattered profile of PSR B1937+21

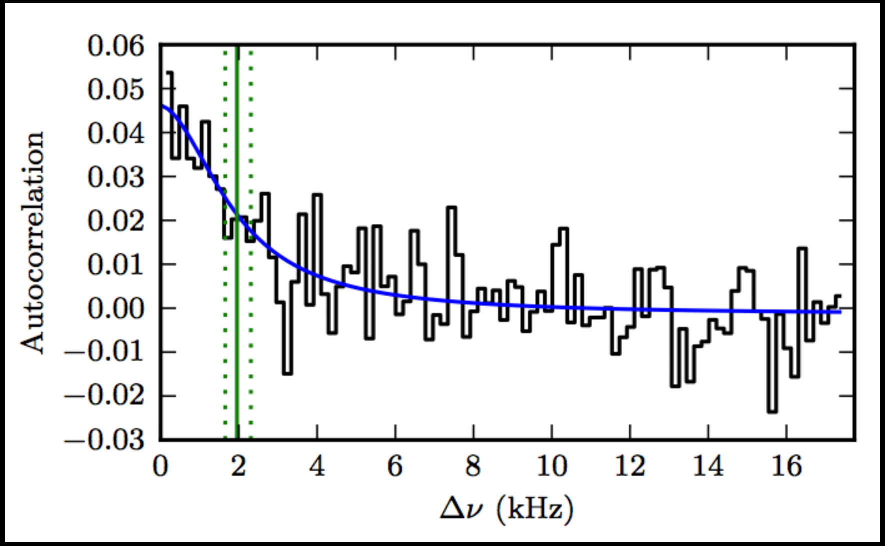
See Demorest 2011, MNRAS, 416, 2821

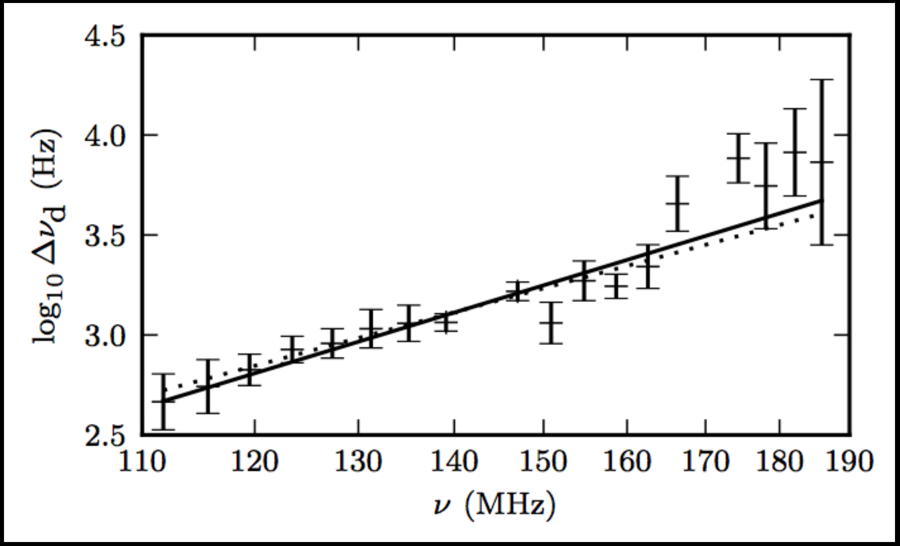
Determine impulse response of the ISM and de-scatter

Cyclic Spectroscopy









Archibald et al. 2014, *submitted*

Propagation Effects

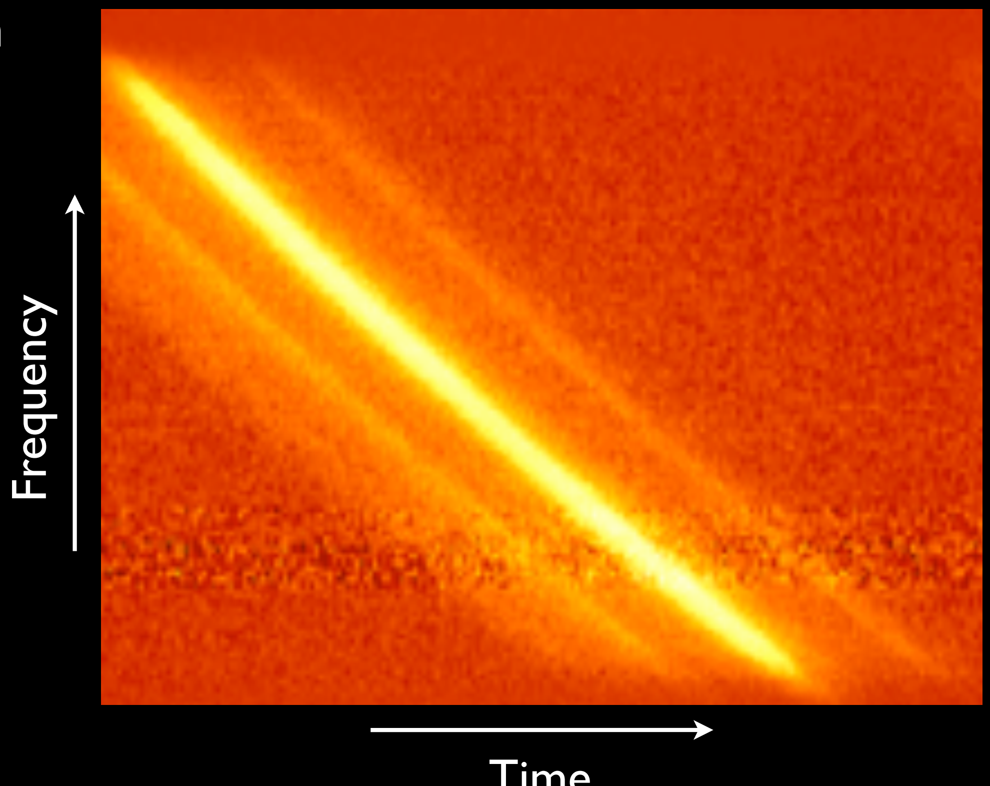
$$I(t) = g_r g_d S(t) * h_{\mathrm{DM}}(t) * h_d(t) * h_{\mathrm{Rx}}(t) + N(t)$$

Scattering: multi-path propagation

Dispersion: freq. dependent arrival time

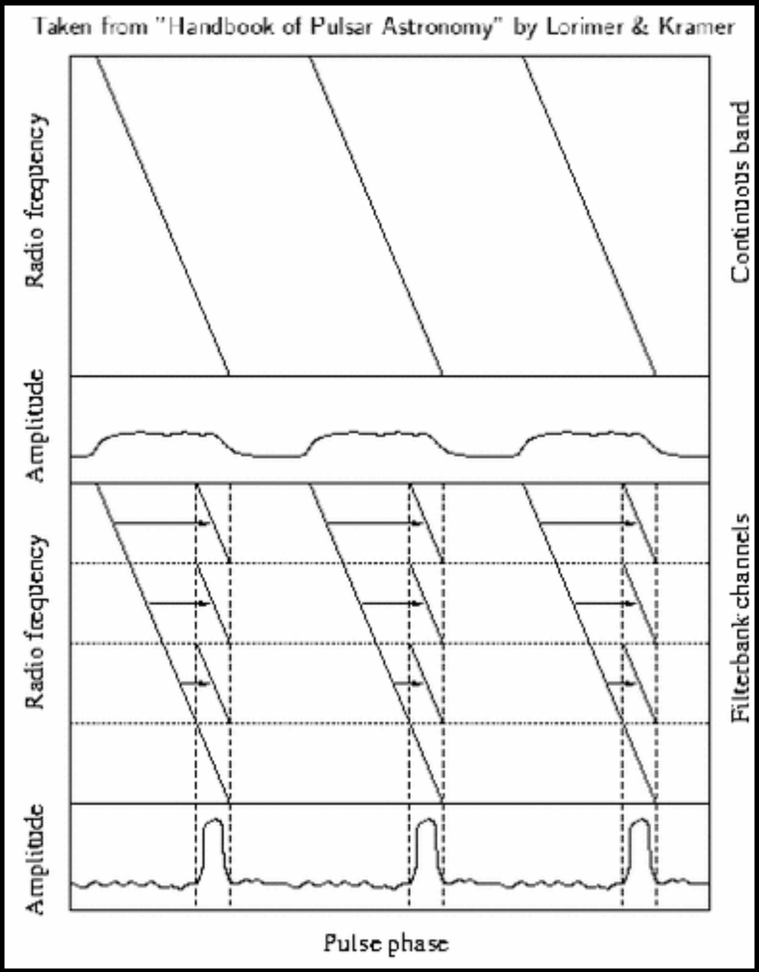
Scintillation: const./dest. interference

Faraday rotation: angle of linear polarization



$$\Delta t \propto \nu^{-2}$$

Coh./Incoh. Dedispersion

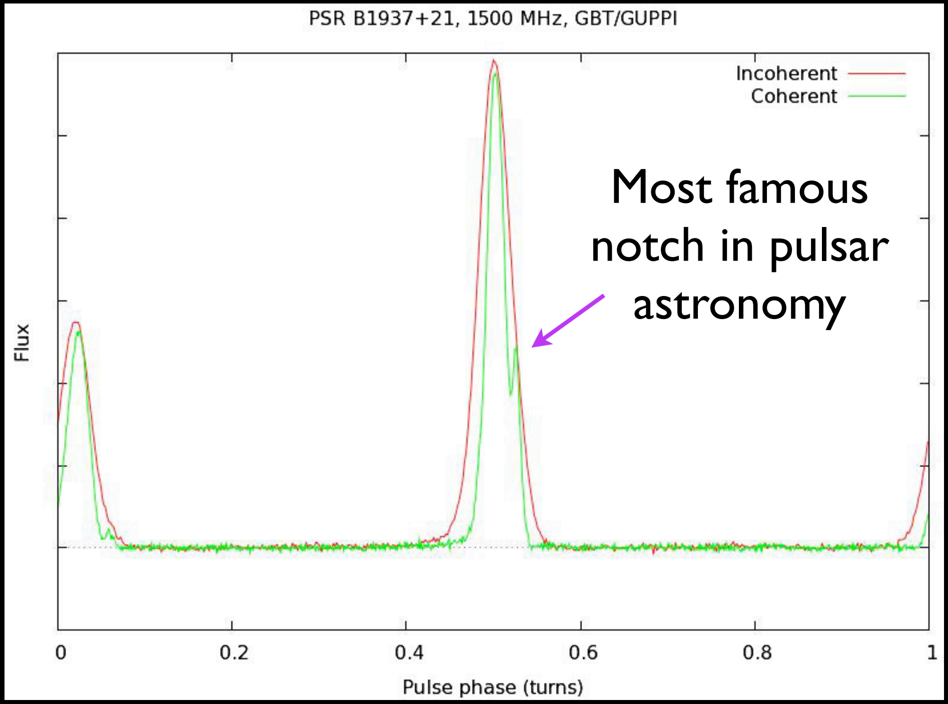


Lorimer & Kramer

- **Incoherent dedispersion**: use filterbank to divide the band into channels that can be delayed in time.
- **Coherent dedispersion**: apply inverse ISM-filter (chirp) to data before detection.

Coh./Incoh. Dedispersion

$$\sigma_{\rm TOA} \sim {\rm width}/SNR$$

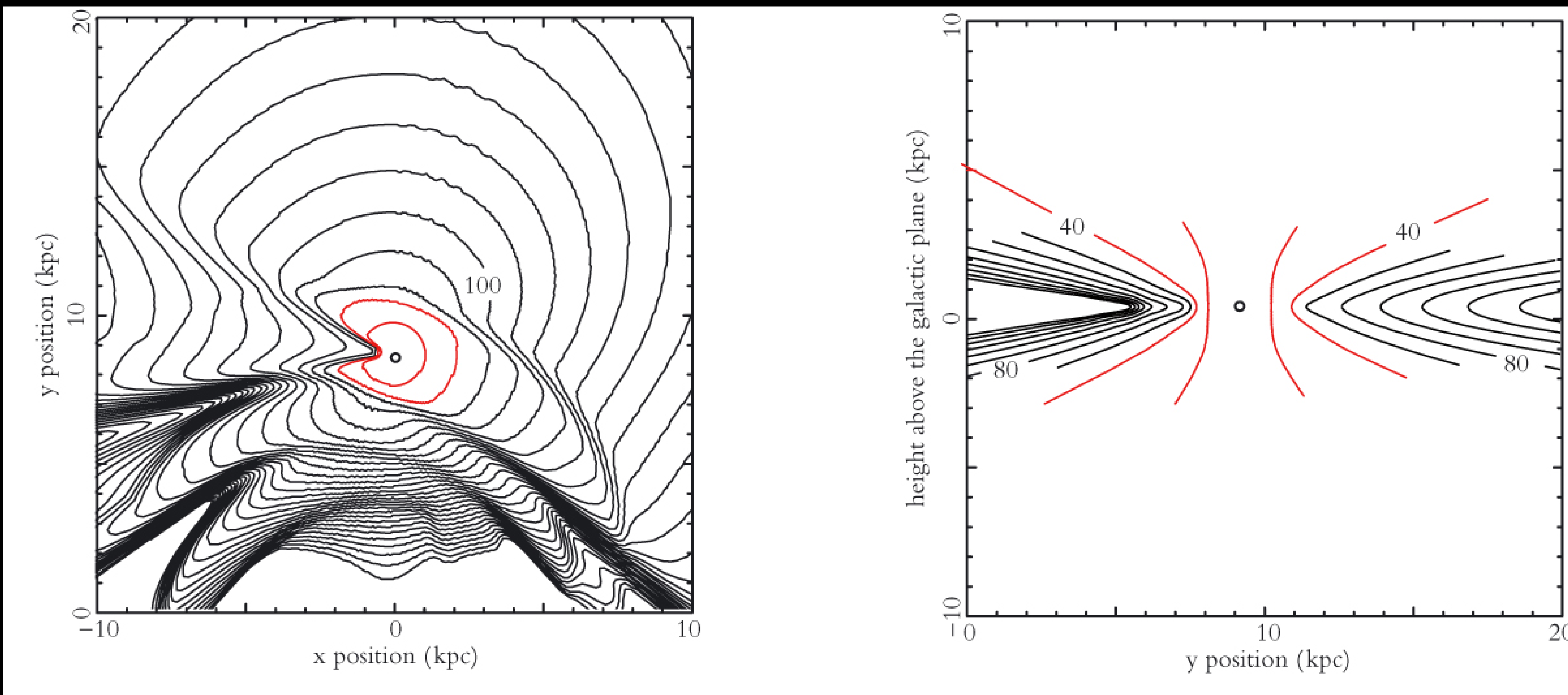


Demorest

Incoherent vs. coherent:

Advantages	Disadvantages
• simple, easy, good for searching	• remaining smearing, polarisation
• true pulse, best precision, polarisation	• small band, computationally expensive

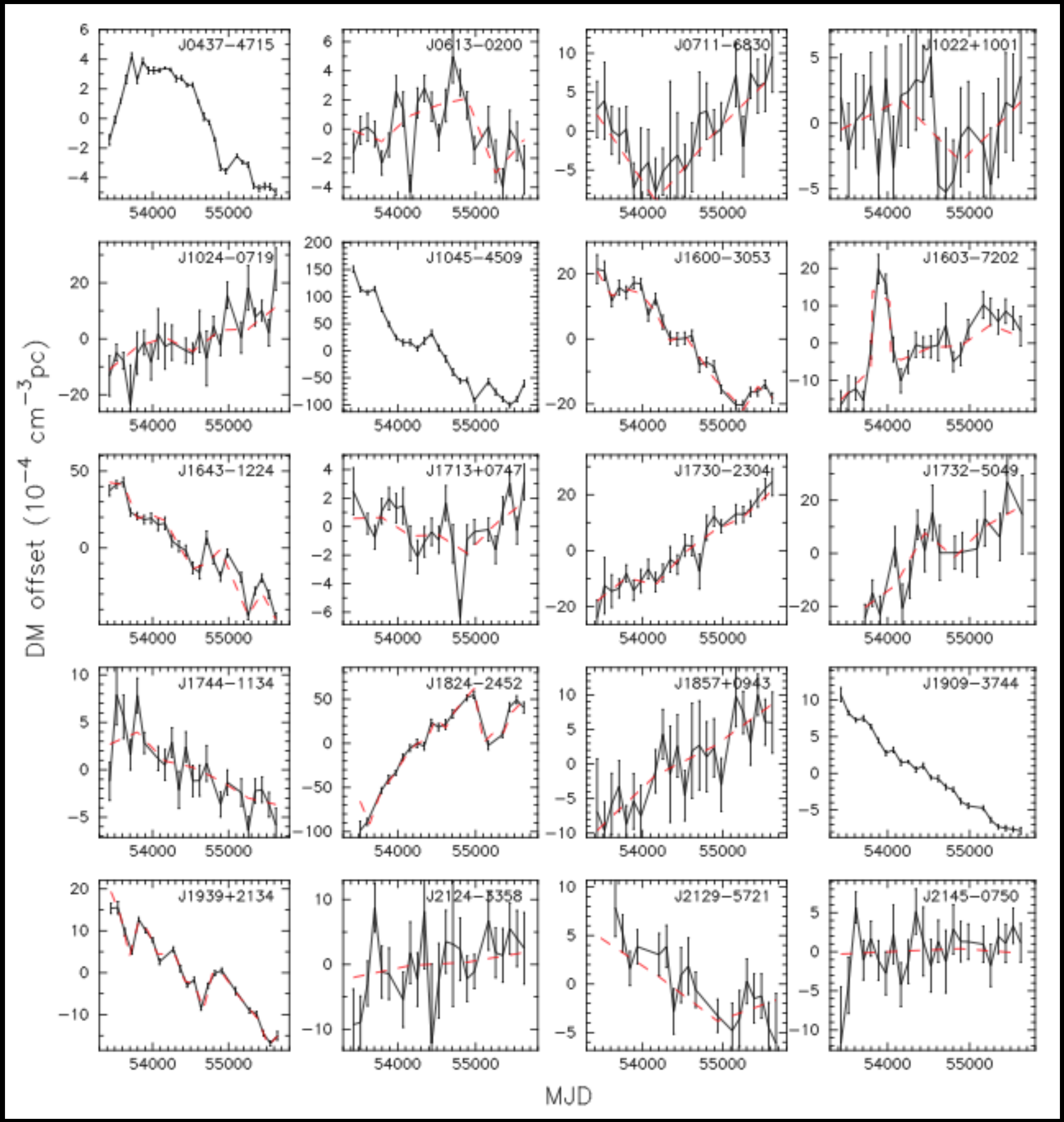
Galactic DM (NE2001)



van Leeuwen

See also Cordes & Lazio, arXiv:astro-ph/0207156

DM Variations

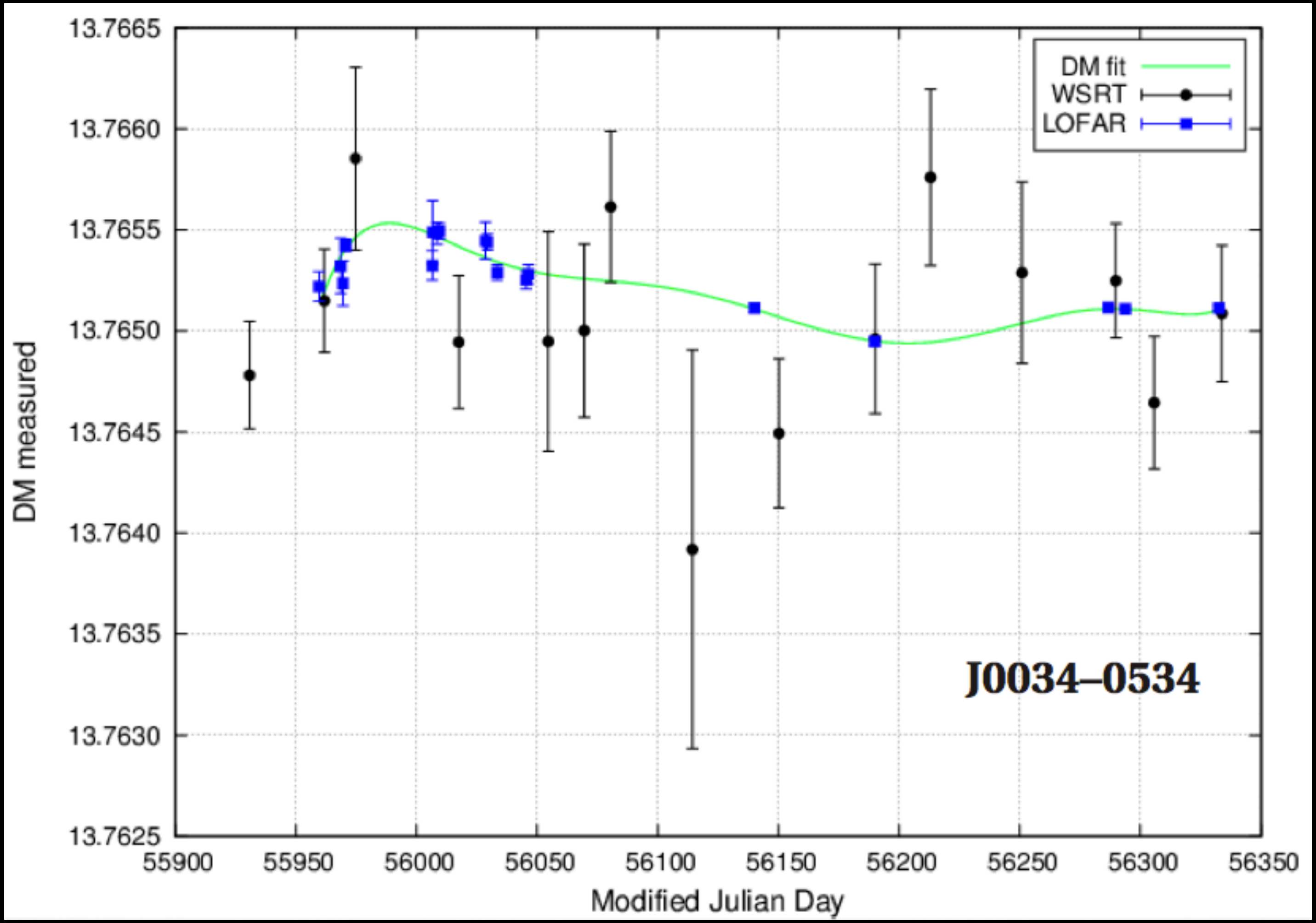


Keith et al. 2012

DM Variations

$$\Delta t \propto \nu^{-2}$$

Verbiest



WSRT @ 350MHz
LOFAR @140MHz

Propagation Effects

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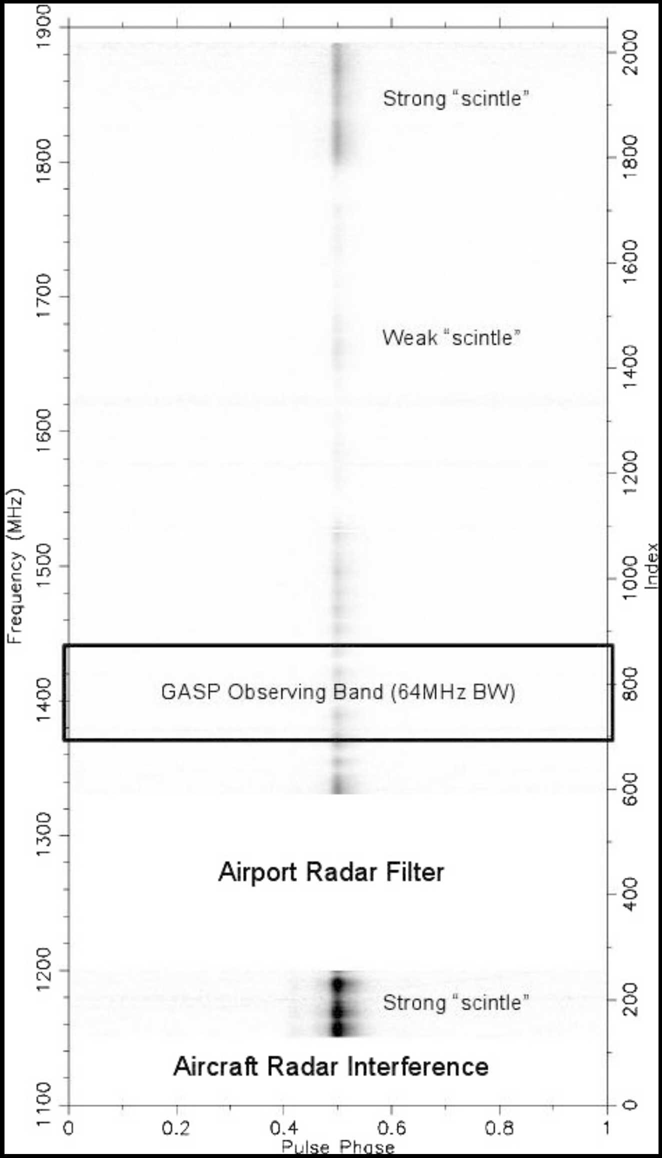
Scattering: multi-path propagation

Dispersion: freq. dependent arrival time

Scintillation: const./dest. interference

Faraday rotation: angle of linear polarization



PSR J1713+0747 with GUPPI

Ransom

Propagation Effects

$$I(t) = g_r g_d S(t) * h_{\rm DM}(t) * h_d(t) * h_{\rm Rx}(t) + N(t)$$

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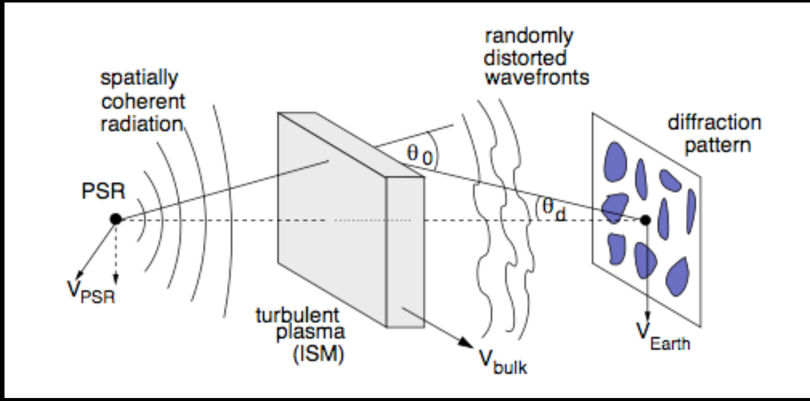
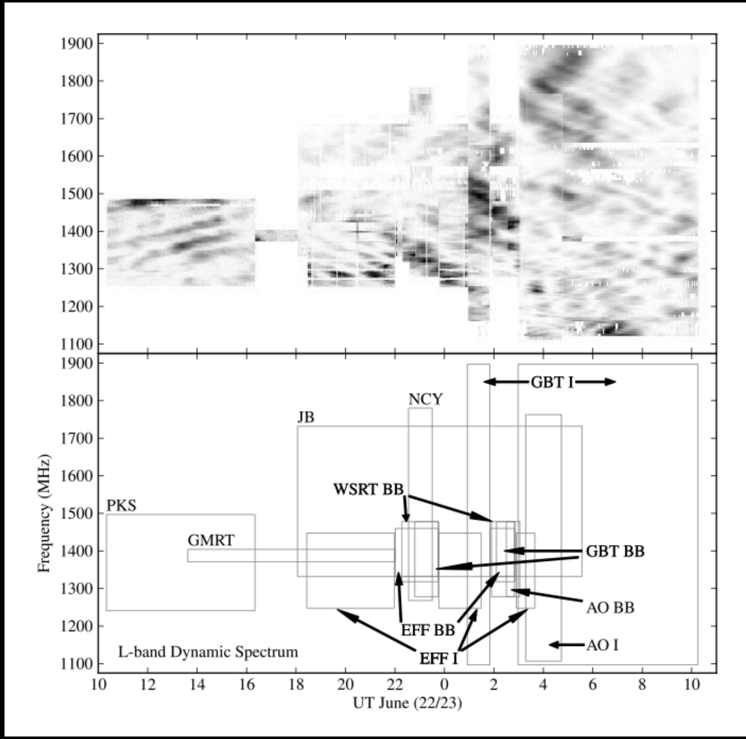


Kramer & Lorimer



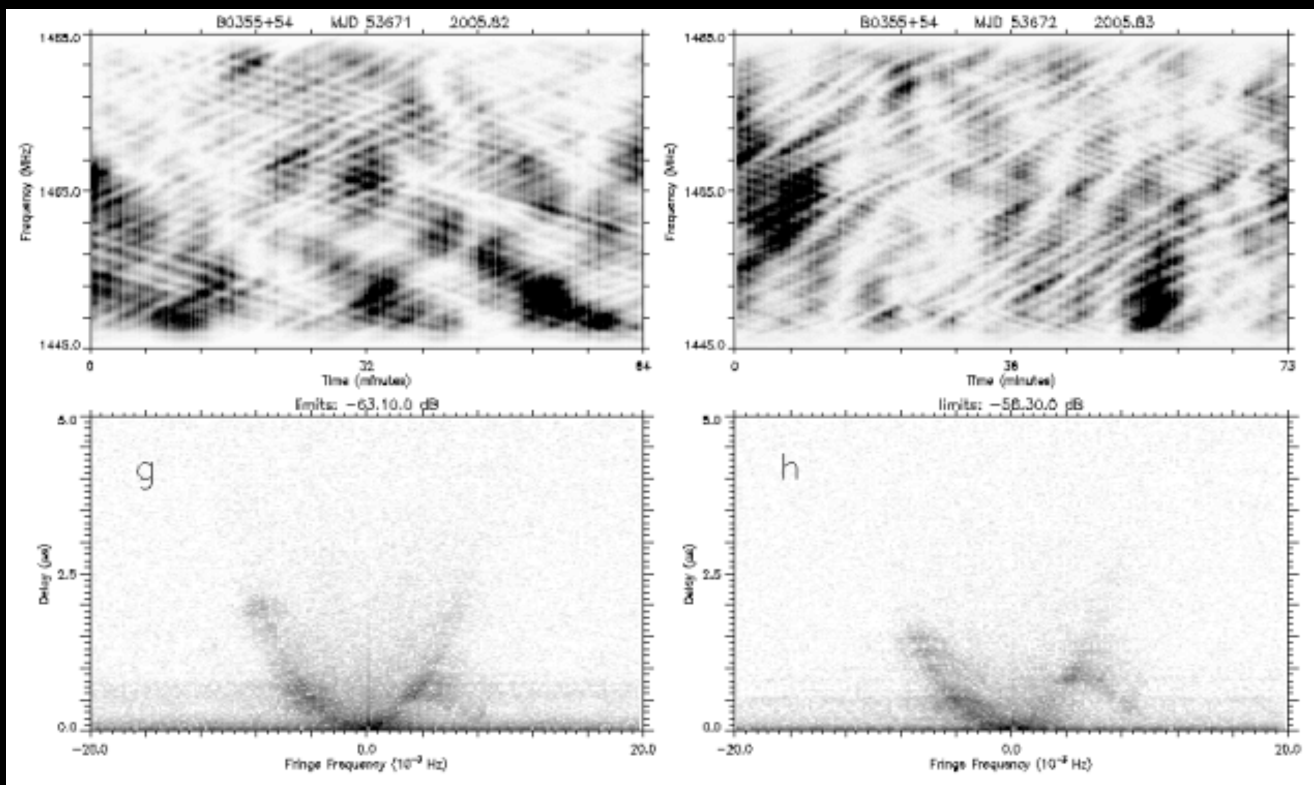
PSR J1713+0747

Scint. BW and scint. time become narrower and shorter, respectively, towards lower frequency.

Dolch, Lam et al.

Scintillation Arcs

Day 1 Day 2



Dynamic Spectrum

Secondary Spectrum

Stinebring

Propagation Effects

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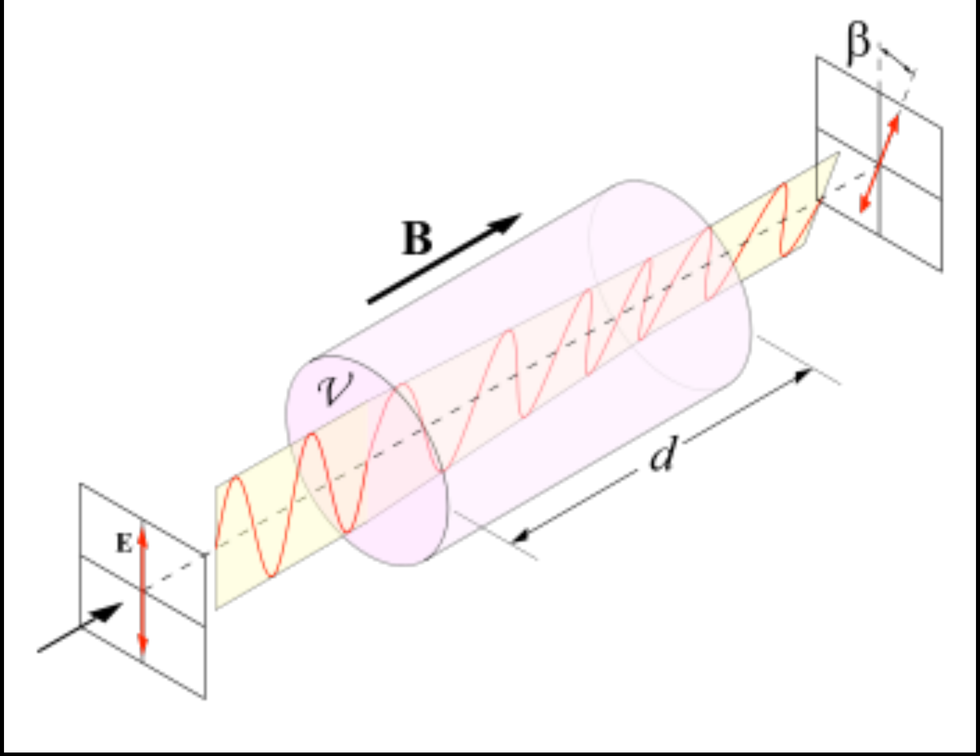
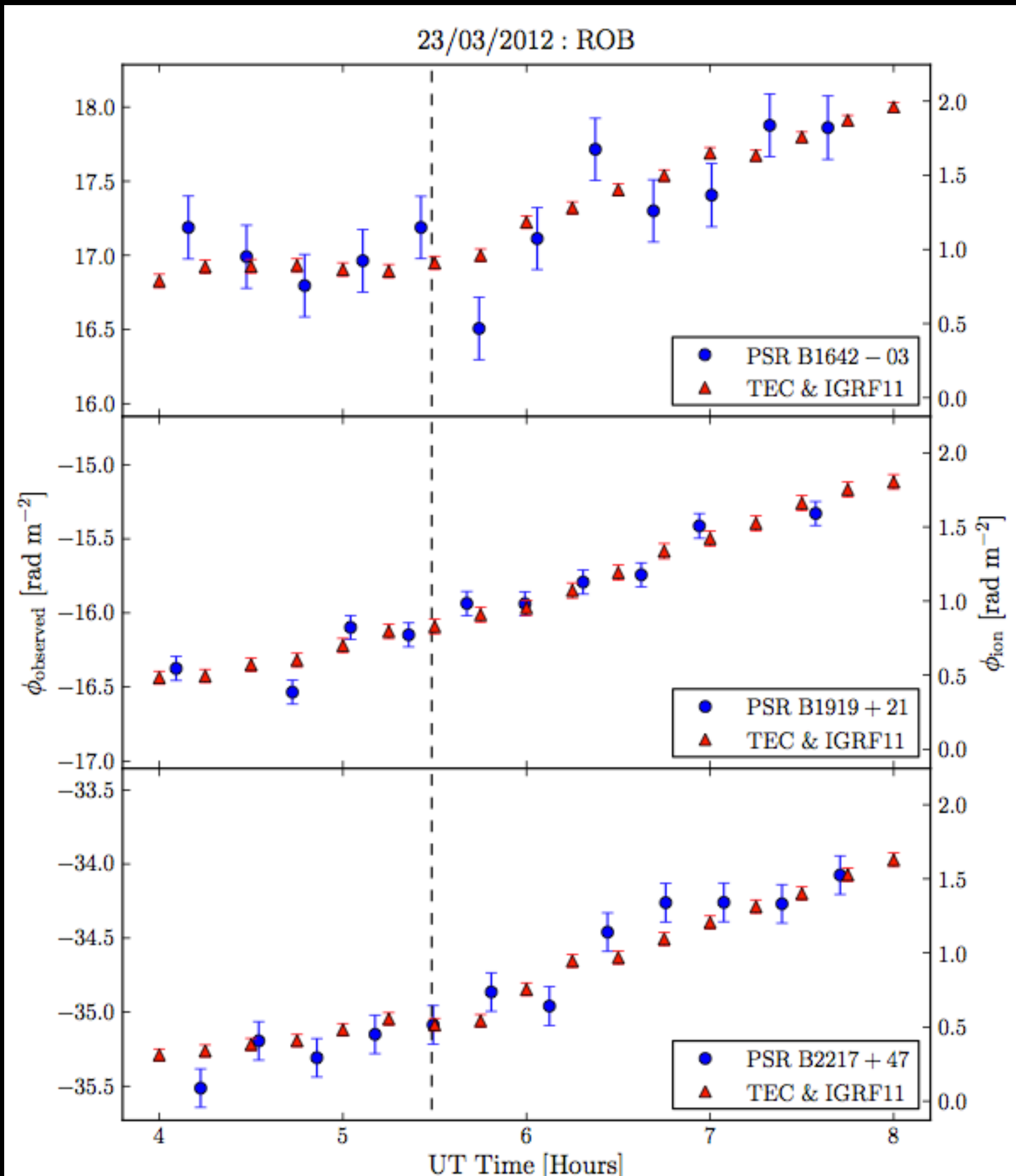
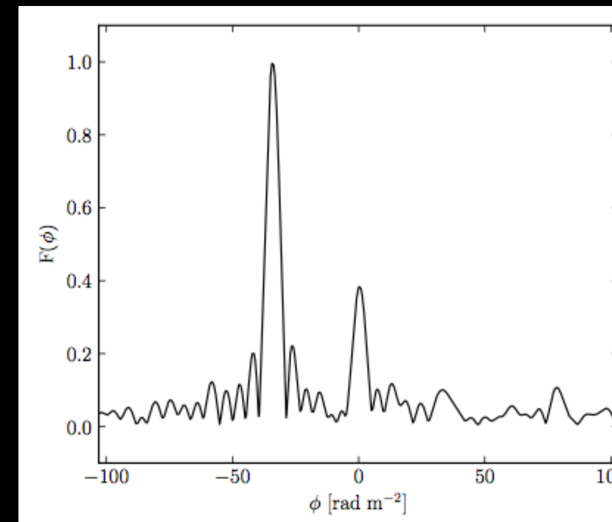


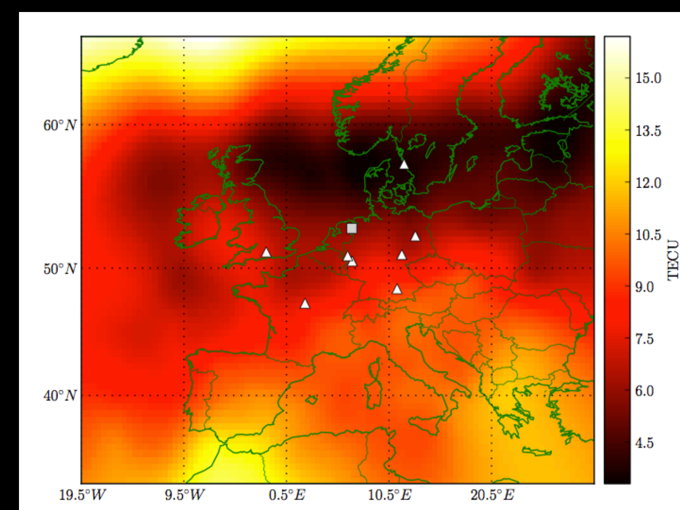
Calibrating Rotation Measure

Sotomayor-Beltran, Sobey, Hessels, de Bruyn et al. 2013





Sobey



ROB

TECU = 10^{16} electrons/m^2 = 3.2 x 10^{-7} pc/cc

Maximum expected DM_{ion} = ~7 x 10^{-6} pc/cc

Intrinsic Pulse Profile Evolution

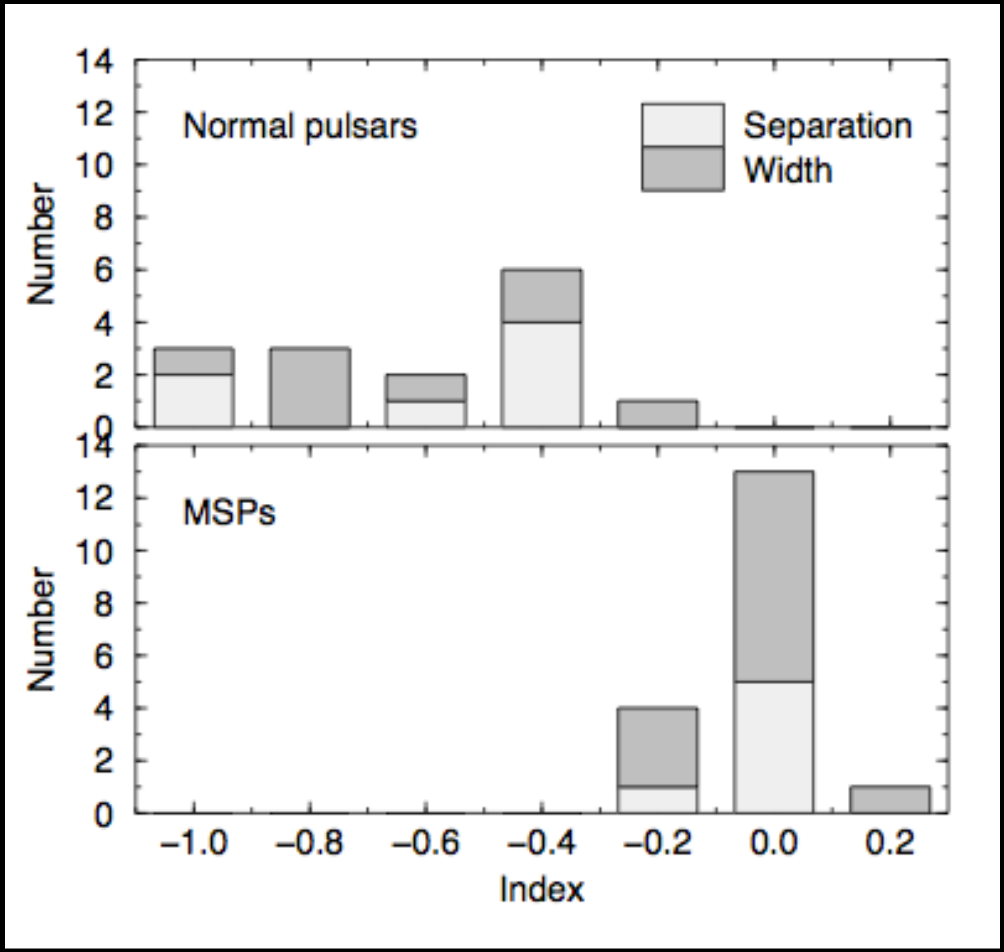
(see also Pennucci talk on Wed. June 25th)

- As shown earlier, the pulsar profile shape intrinsically varies with observing frequency.
- For pulsar timing we use a high SNR template to represent the profile shape, but how does that work for wide-BW observations?

MSP Profile Evolution

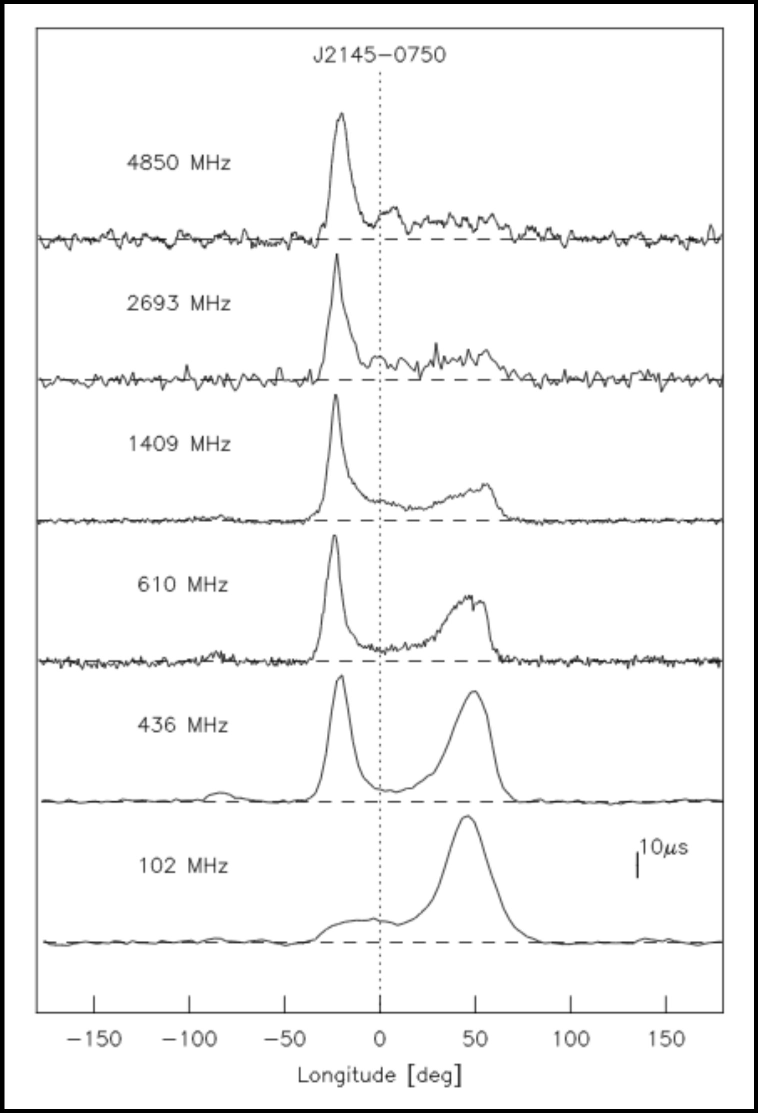
- Most MSPs don’t evolve as dramatically as slow pulsars, but there are definitely exceptions (e.g. J2145-0750, M28A, J2215+5135).
- Nonetheless, even very subtle profile evolution can impact timing at the sub-microsecond level.

MSP Profile Evolution



Kramer et al. 1999

MSP Profile Evolution



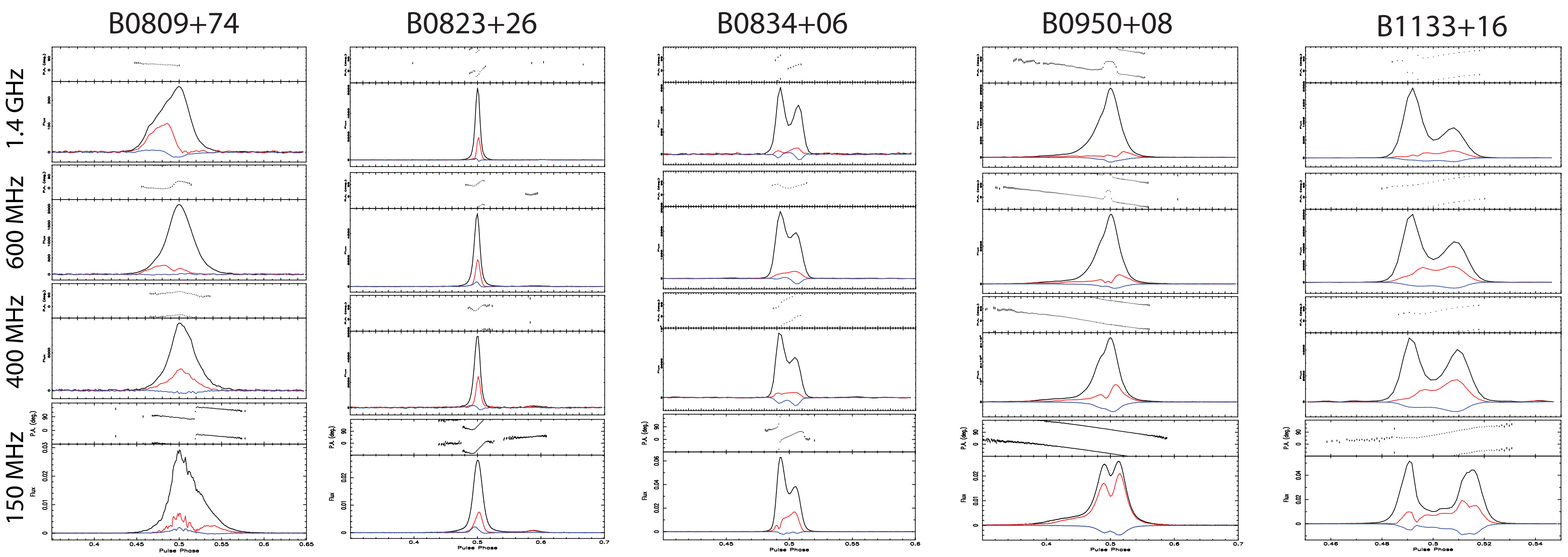
Kramer et al. 1999

Polarized Profile is Also Frequency Dependent

(see also Dai talk on Wed. June 25th)

- The linearly and circularly polarized components of the pulse profile also change with frequency.
- If not properly calibrated, this can also have subtle effects on the timing accuracy.

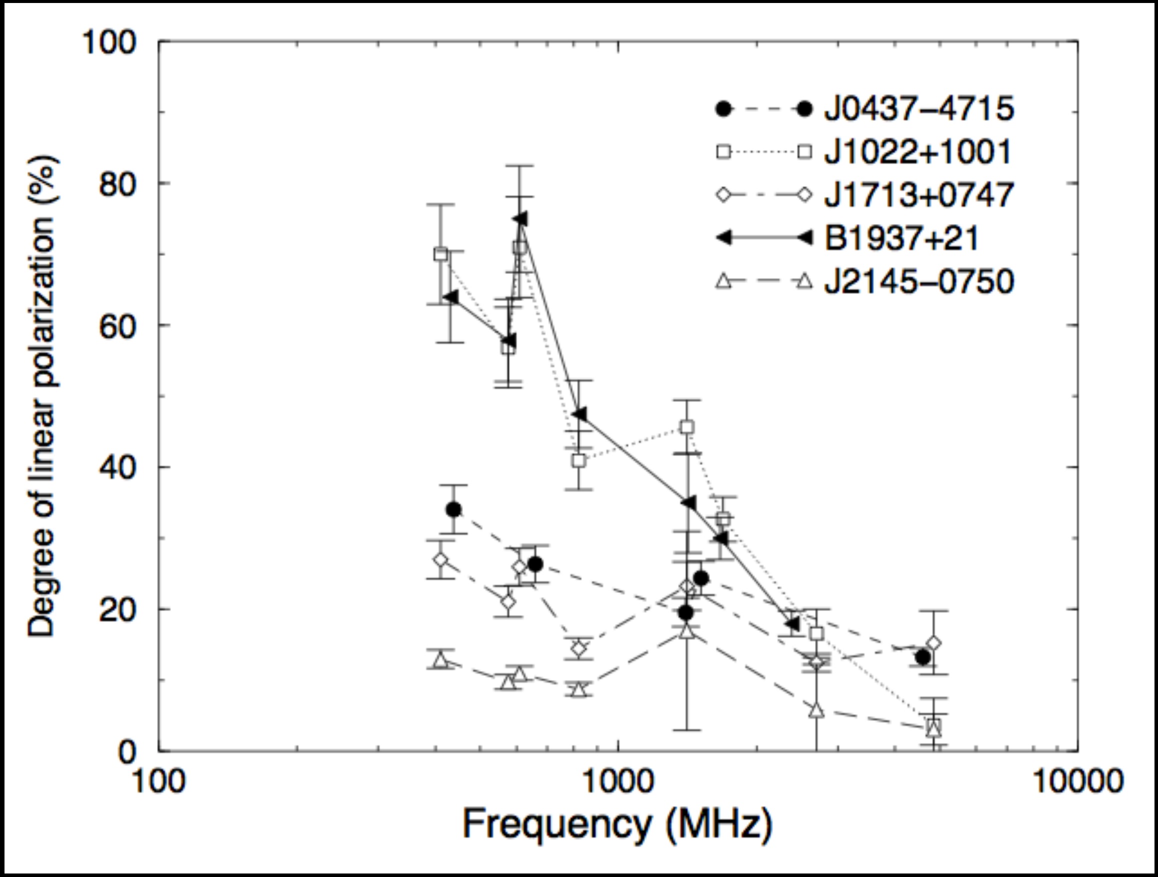
Polarimetric Profiles



Noutsos et al. in prep.

See also, e.g., van Straten 2006, ApJ, 642, 1004

Polarimetric Profiles



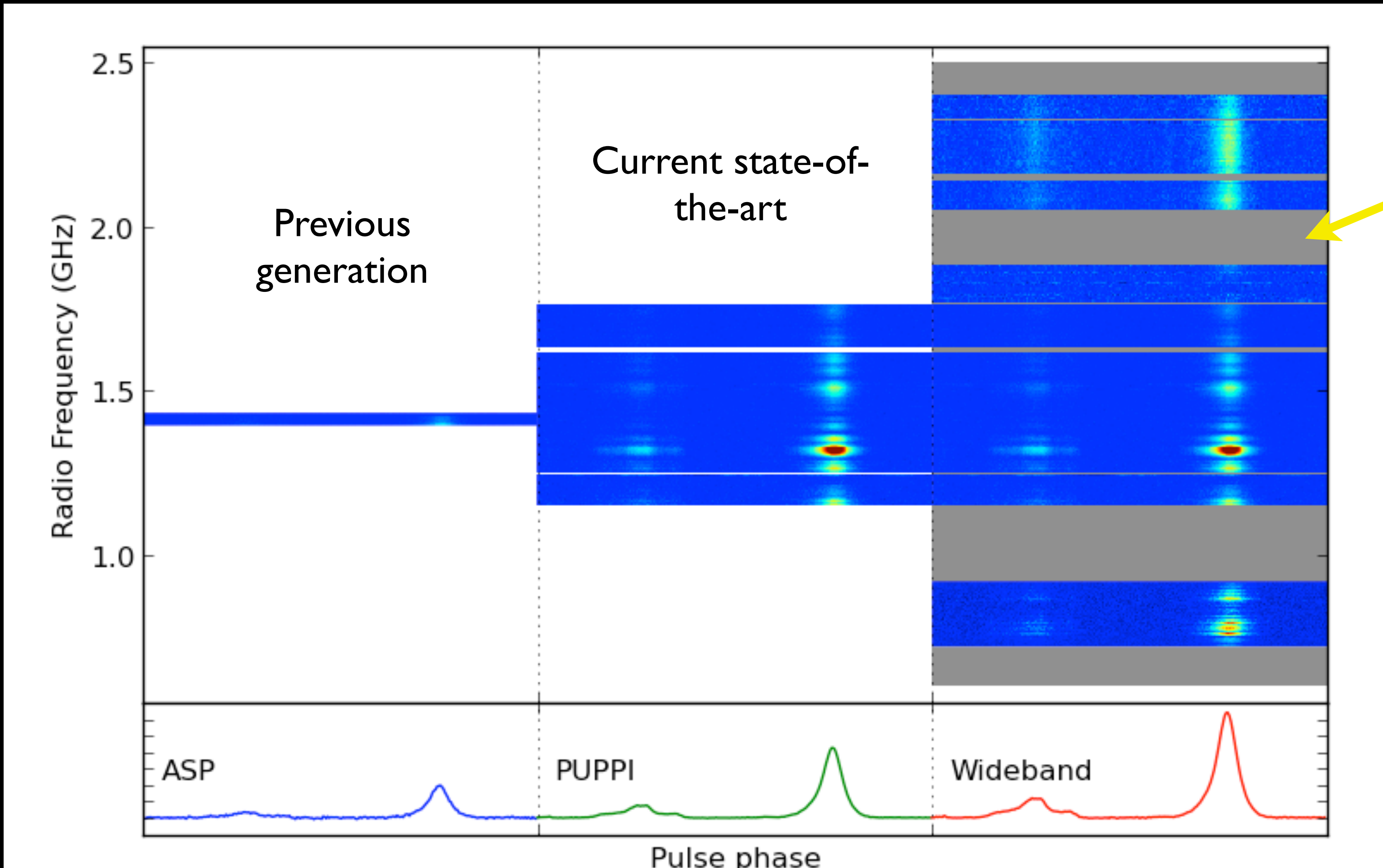
Kramer et al. 1999

See also, e.g., van Straten 2006, ApJ, 642, 1004

So wide-BWs introduce complications due to the variable ISM and intrinsic profile evolution

How do we deal with all this in order to maximize timing precision *and* accuracy?

Progression of timing BWs



Where we're headed

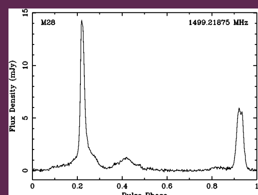
PSR J2214+3000

Demorest

2D Template Matching

Old

(Taylor 1992; Appendix A)



x-corr. ✻ 1D template = TOA

DFT'd

DFT'd

phase + MJD

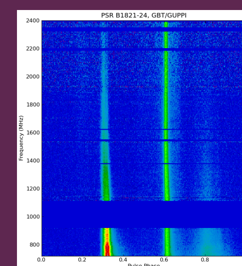
$$\chi^2(\phi, a) = \sum_k \frac{|d_k - a p_k e^{-2\pi i k \phi}|^2}{\sigma^2}$$

(1 param. fit)

scaling parameter "*a*" typically ignored

New

(Pennucci, Demorest, & Ransom 2014, submitted)



x-corr. ✻ 2D template = TOA & DM

1D-DFT'd

1D-DFT'd

"TOA per chan"

$$\chi^2(\phi, D, a_n) = \sum_{n,k} \frac{|d_{nk} - a_n p_{nk} e^{-2\pi i k \phi_n)}|^2}{\sigma_n^2}$$

$$\phi_n = \phi + D(\nu_n^{-2} - \nu_{ref}^{-2}) \qquad D = \frac{D_{const} \times \mathrm{DM}}{P}$$

TOA & DM

$$a_n|_{\chi^2_{min}} \sim d_{nl} \star p_{nl}$$

(2 param. fit)

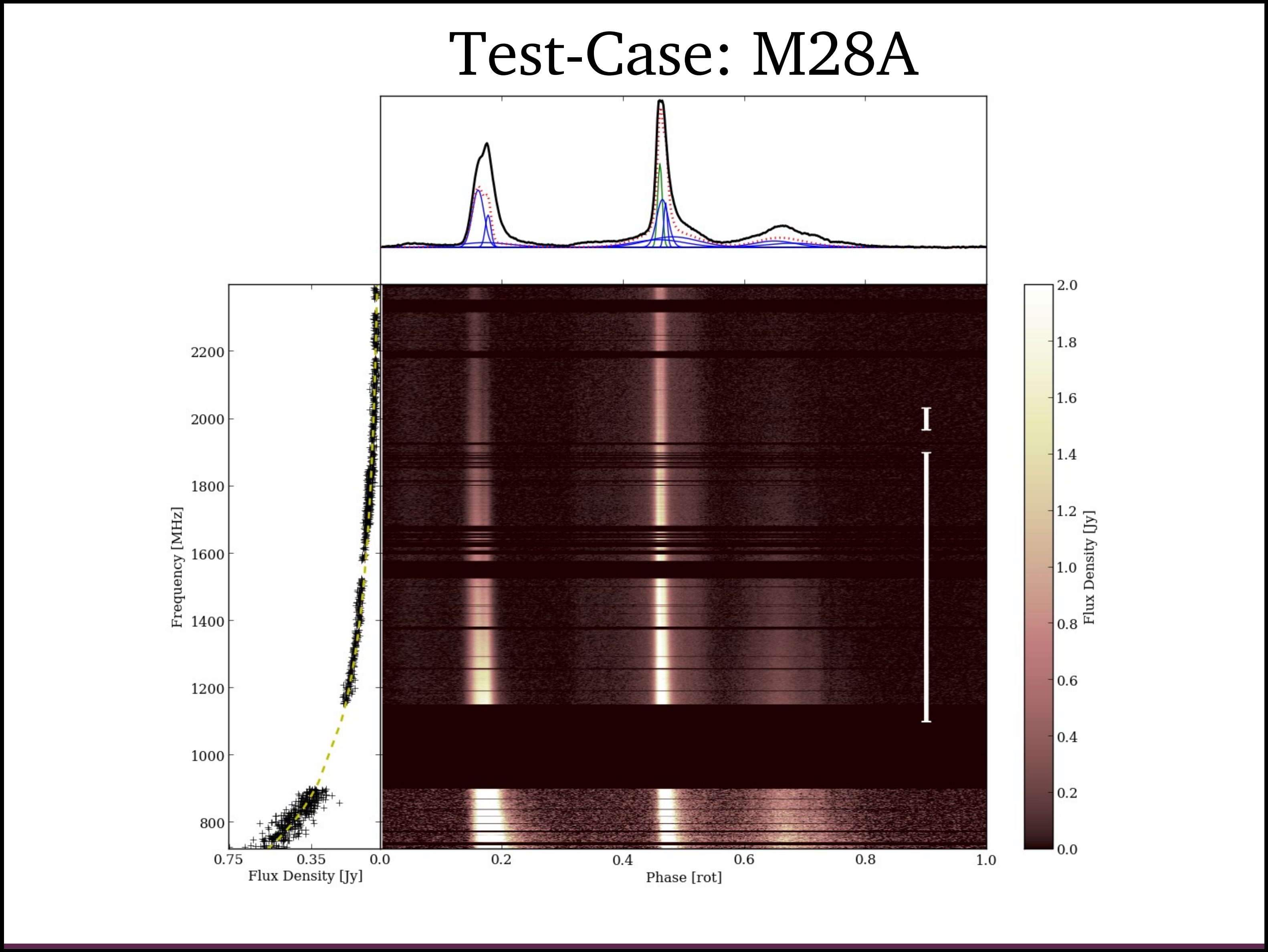
"a_n" scales ***are useful*** as weights for scintillation

Pennucci

See Pennucci talk on Wed., June 25th

See also work by Kuo Liu

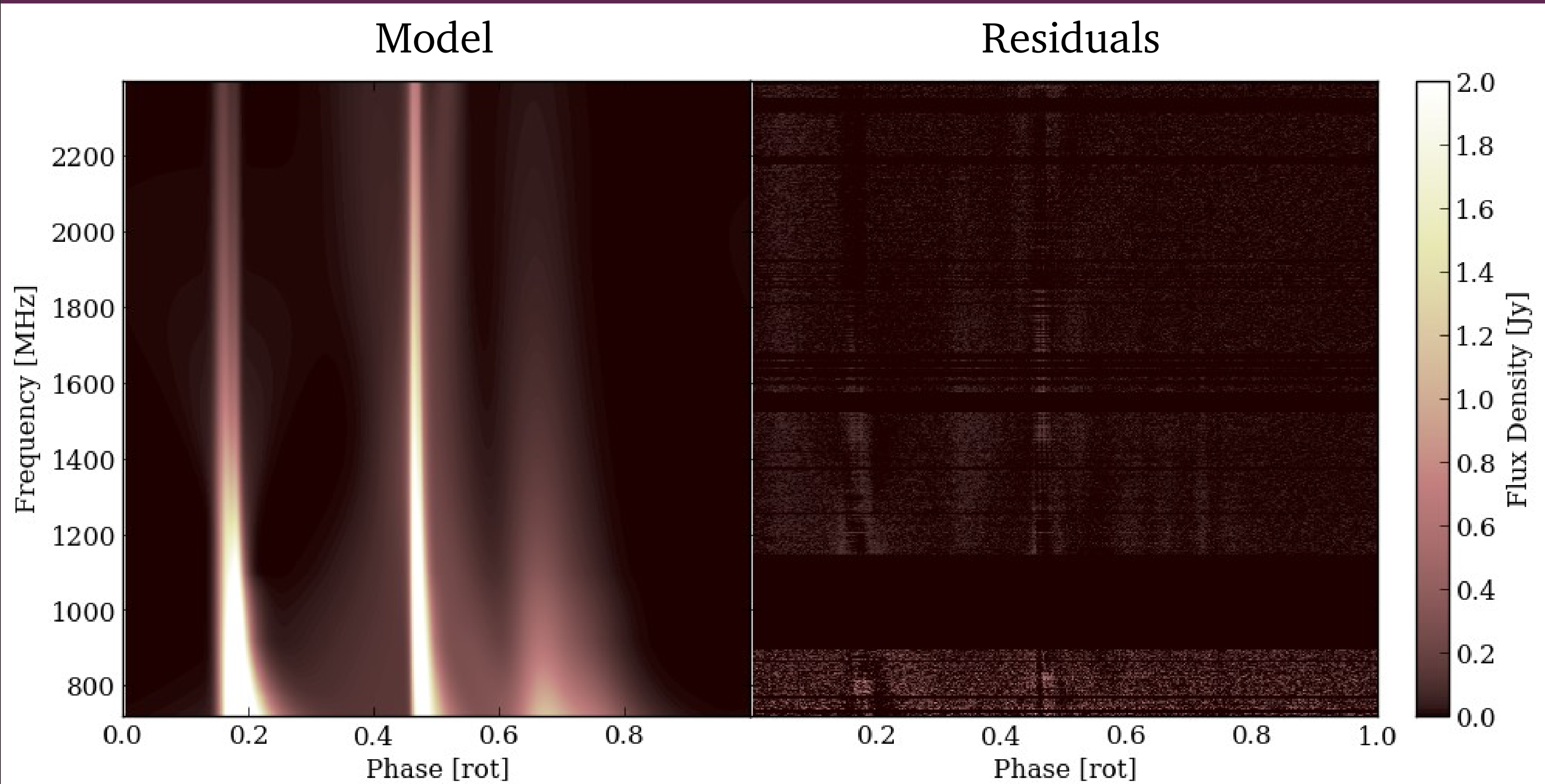
2D Template Matching



Pennucci

2D Template Matching

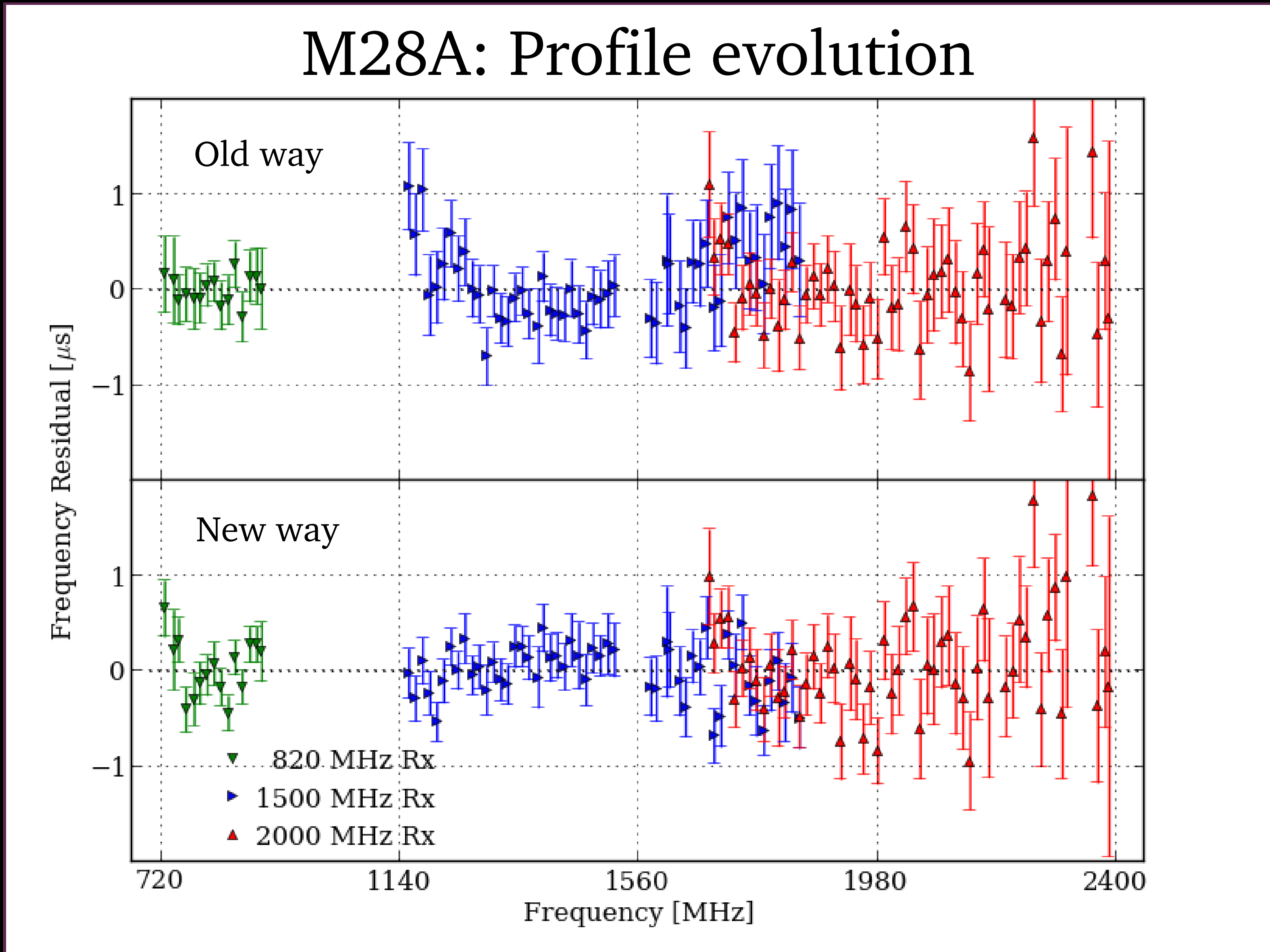
Gaussian component modeling



10 Gaussian components independently evolving with power-law dependencies

Pennucci

2D Template Matching



Pennucci

Summary

- Wide observing BWs offer higher sensitivity and stronger handle on the ISM.
- To take advantage of wide BWs for high-precision pulsar timing, we need to handle intrinsic/extrinsic profile evolution as well as the dynamic ISM.