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LOFAR

Ultra-Wideband Observations of Pulsars

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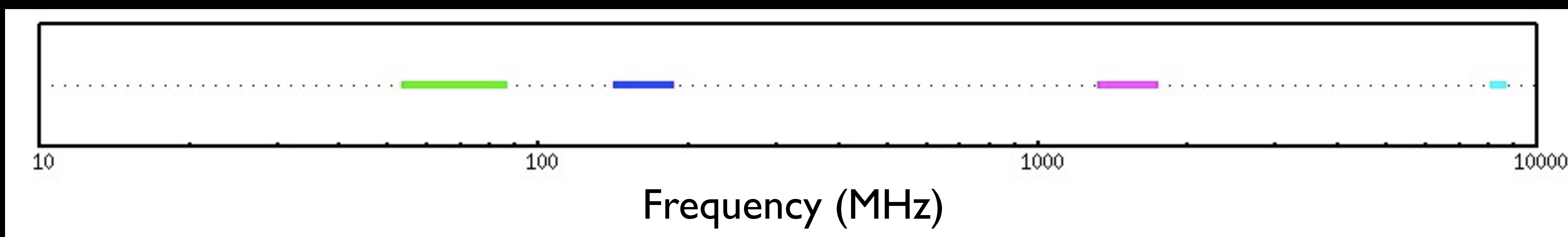
Observations

LOFAR LBA (DE601)	LOFAR HBA (CS302)	The Lovell Telescope	The Effelsberg Telescope
60MHz 36MHz bandwidth	163MHz 48MHz bandwidth	1524MHz 512MHz bandwidth	8350MHz 1000MHz bandwith



Using LOFAR to probe the ISM

- Dispersion
- Refractive index of the interstellar medium is frequency dependent
- Light travels slower at low frequencies
- Simple relationship to predict dispersive delay at a given frequency:

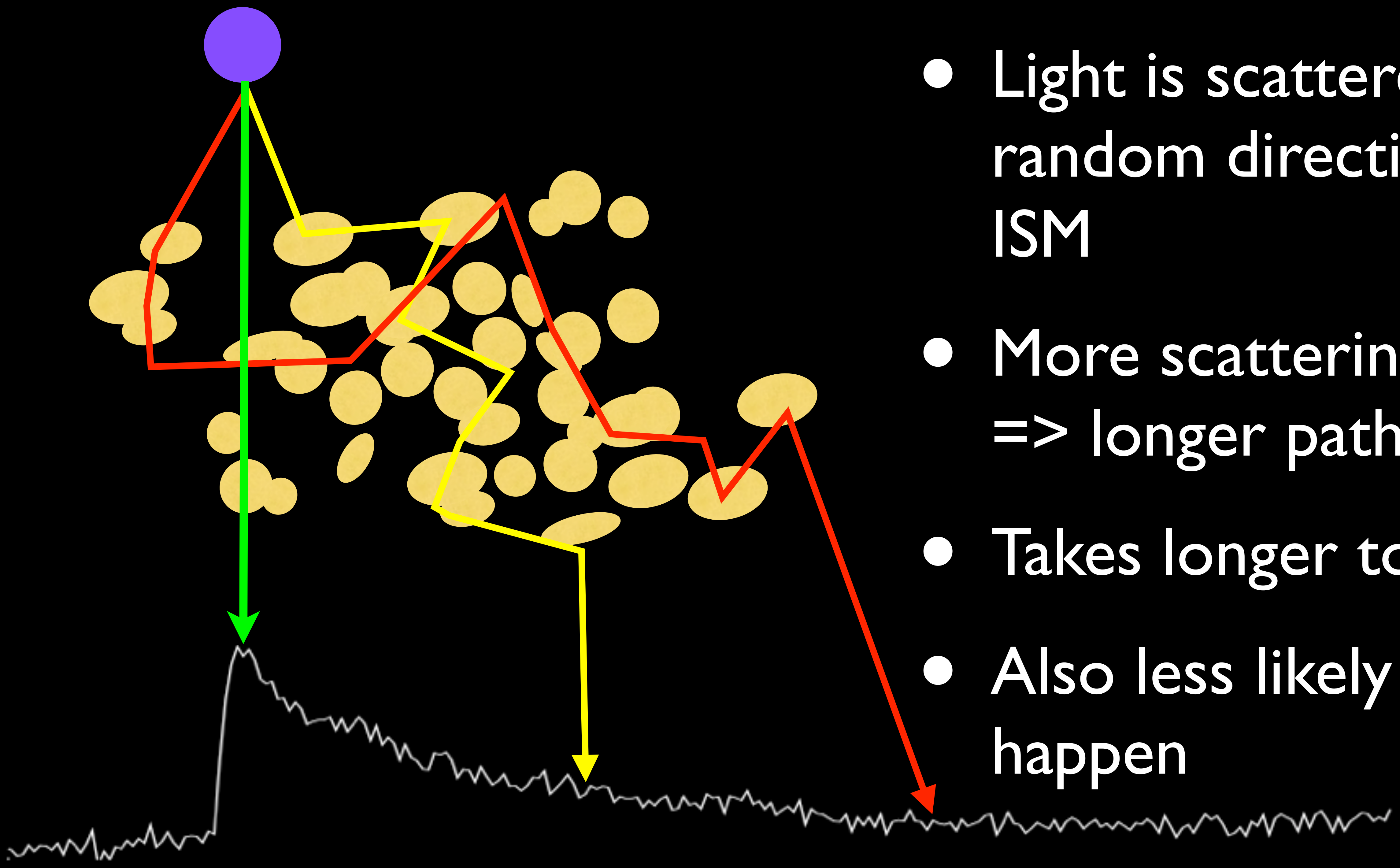
$$\Delta t_{\mathrm{DM}} = \frac{\mathrm{DM}}{2.41 \times 10^{-4} \nu_{MHz}^2}$$

- Drake et al 1968 showed that this holds to 1 part in 3000 at 40 MHz

Using LOFAR to probe the ISM

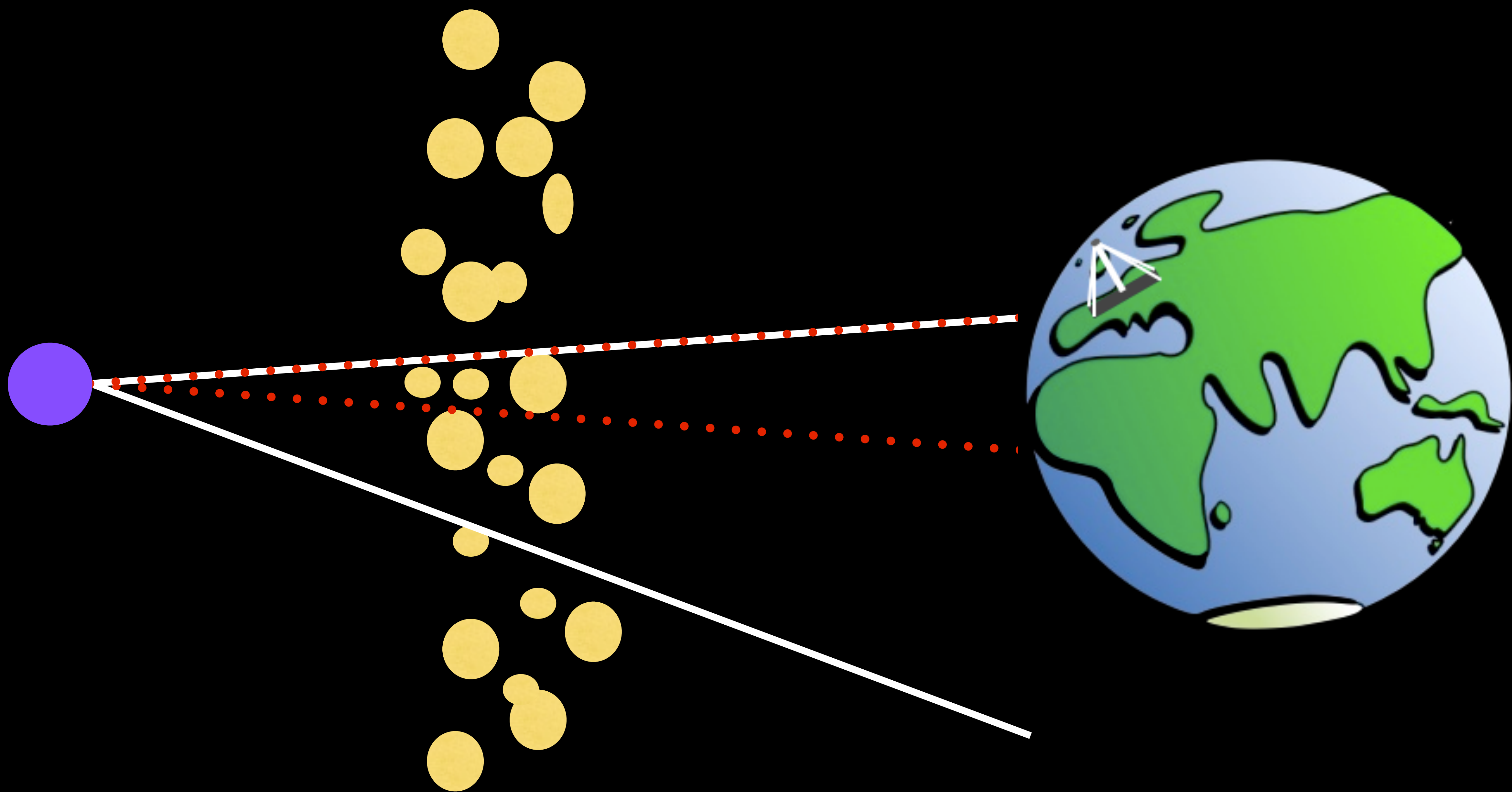
- Dispersion law scales as ν^{-2}
- But there are many other effects with steep frequency dependencies which are potentially detectable
(e.g. Cordes & Shannon 2010)
- LOFAR is the best instrument to detect delays like these

Scattering



- Light is scattered in random directions by ISM
- More scattering
  => longer path length
- Takes longer to arrive
- Also less likely to happen

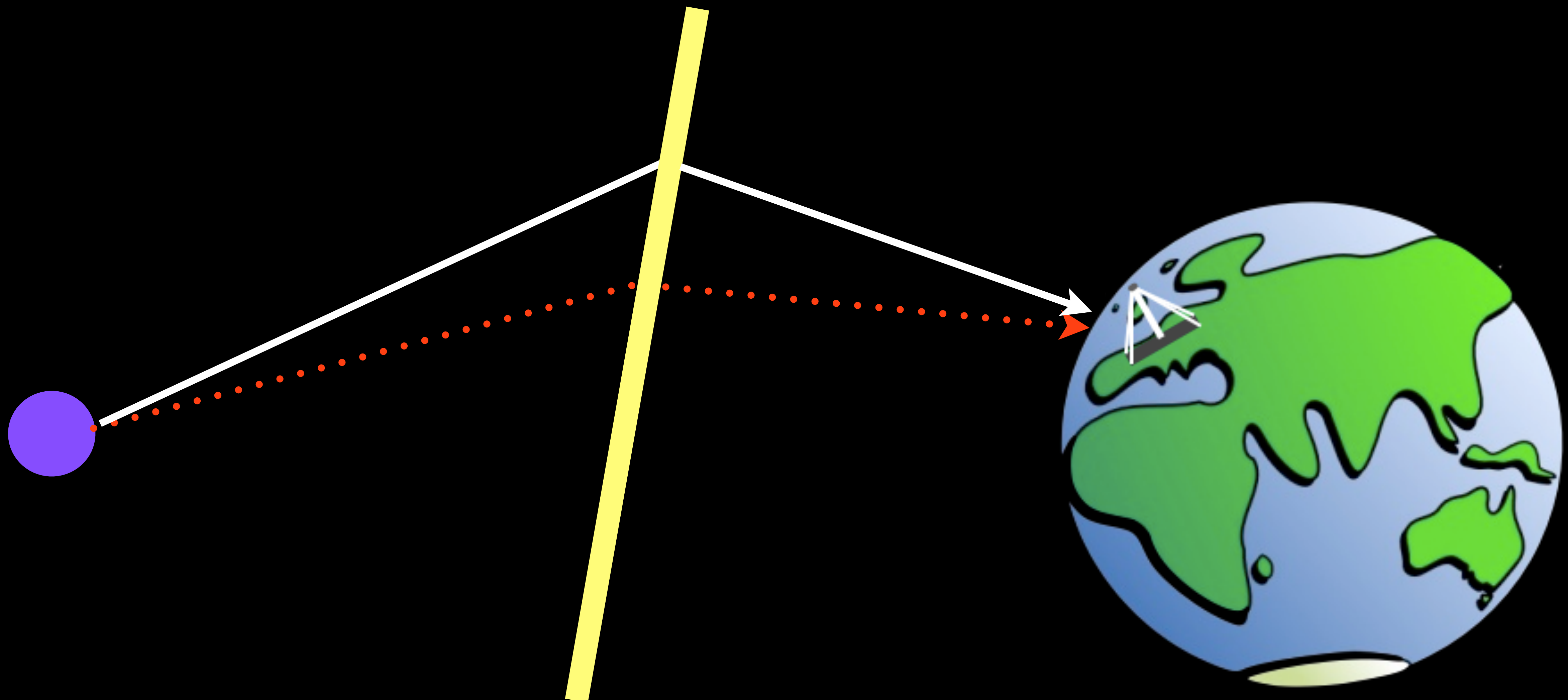
Multipath DM Averaging



$\Delta t_{MP} = 0.12\mu s\ D^{5/6}\ \nu^{-23/6}\ SM$

Cordes & Shannon 2010

Refraction



$$\Delta t_{ref} \sim 167\ D\ \nu^{-4} \left(\frac{dNe(x)}{dx} \right)^2$$

Foster & Cordes 1990

Extra DM Terms

- DM law is a Taylor series expansion
- Next term :

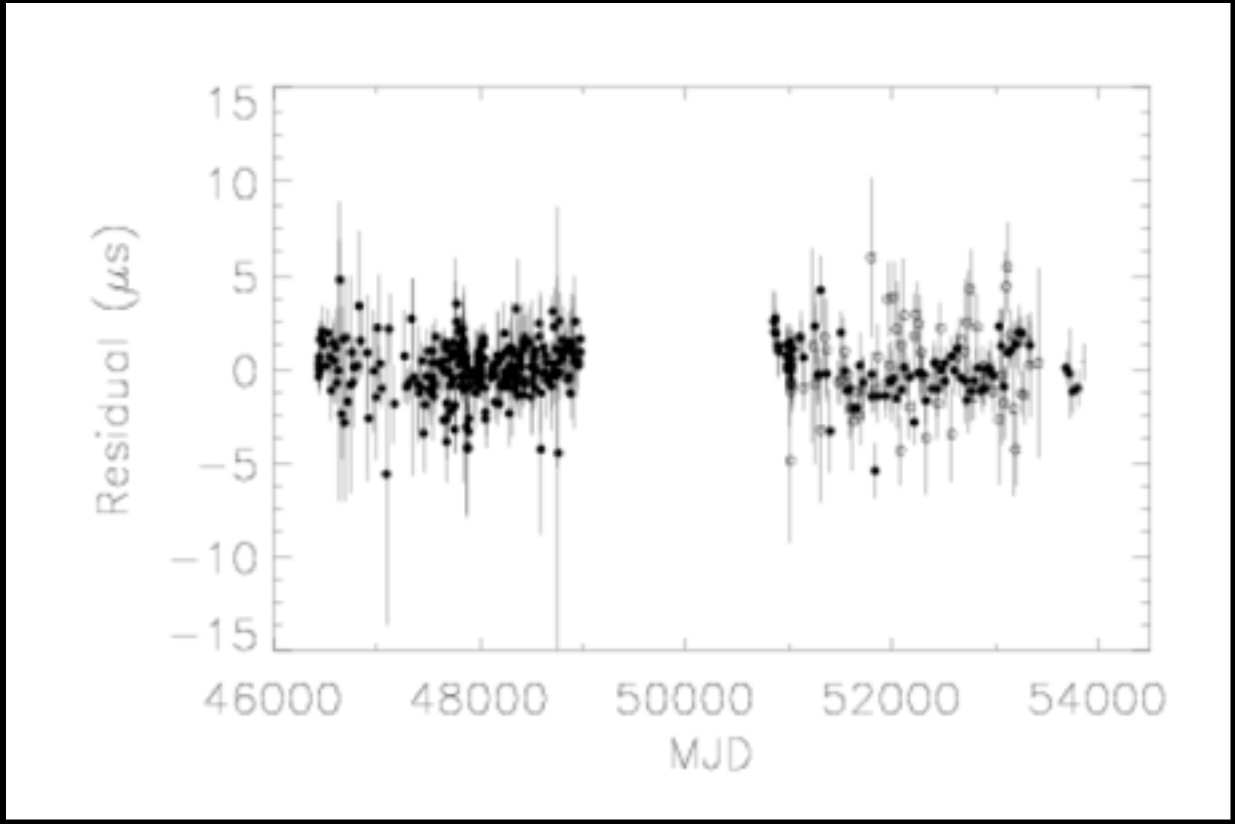
$$\Delta t_{2DM} = 0.25 \text{ EM } \nu^{-4}$$

- This can be used to determine the Emission Measure ($EM = \int n_e^2 dl$)
- A probe of the “clumpiness” of the ISM

Kuz’min Et Al 2007

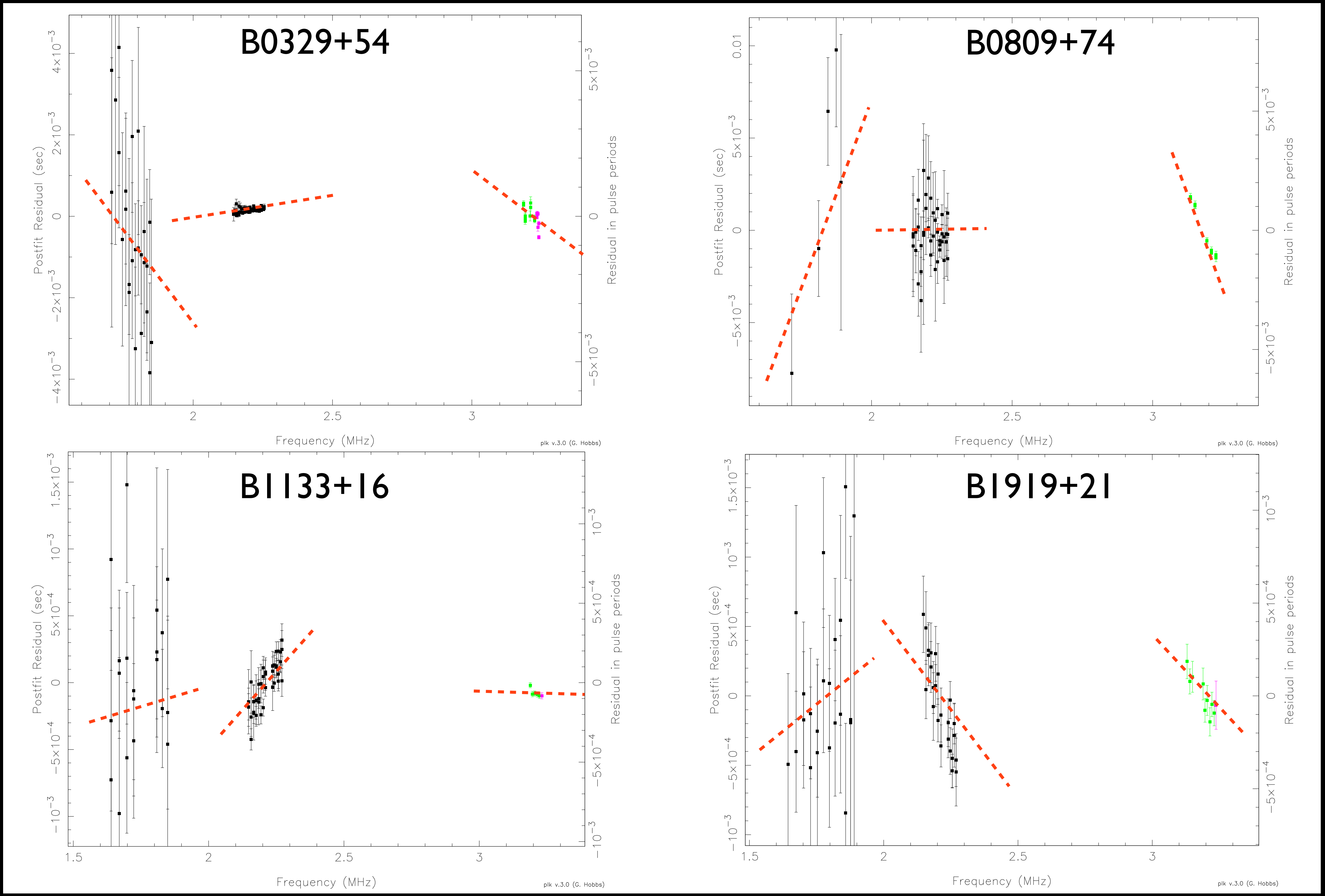
Aligning the Profiles

- De-disperse and fold data
- Cross correlation with a template
- Find peak of CCS and convert to TOA
- Subtract model
- Residuals

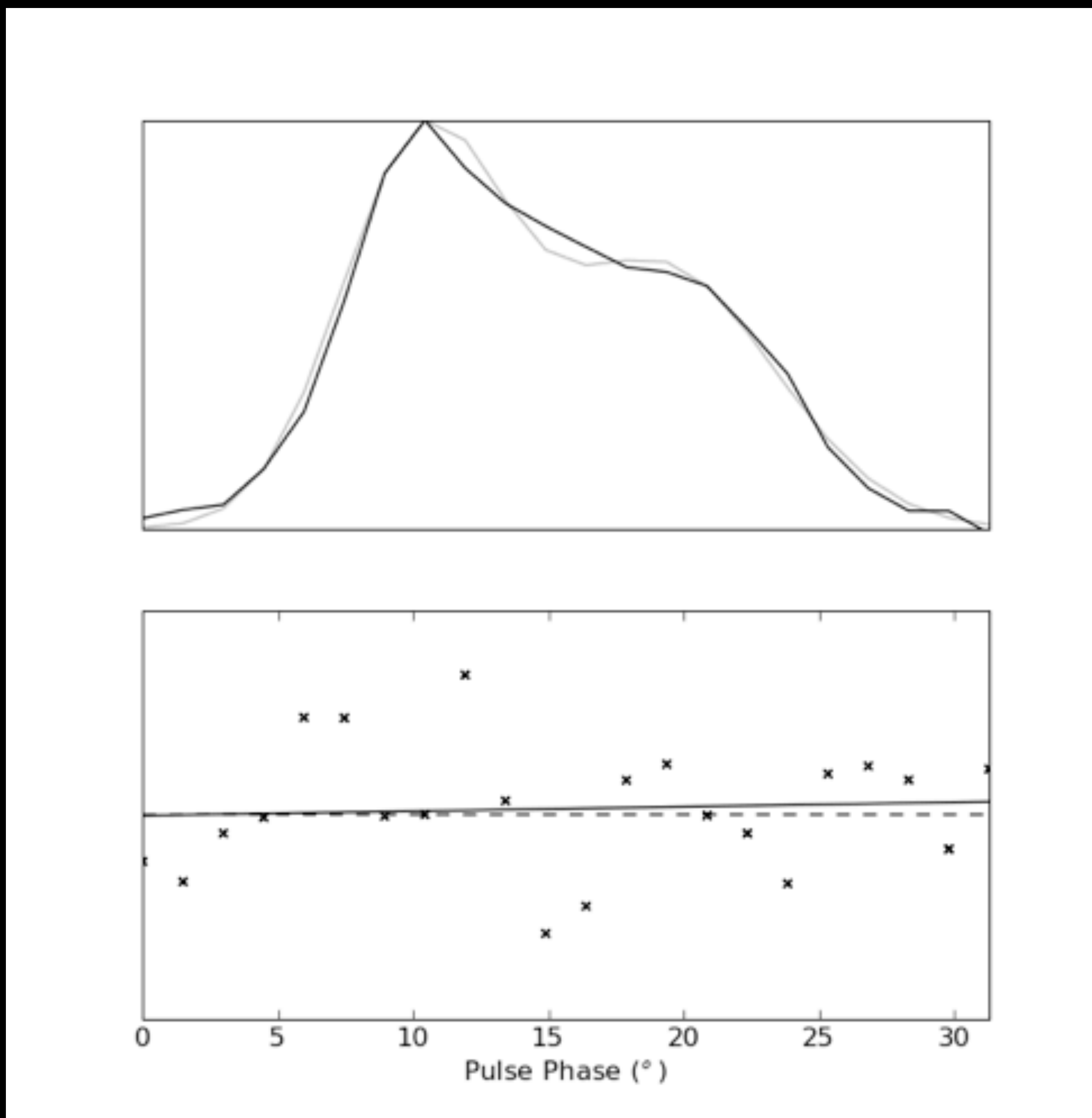


Lommen et al 2007

Aligning the Profiles

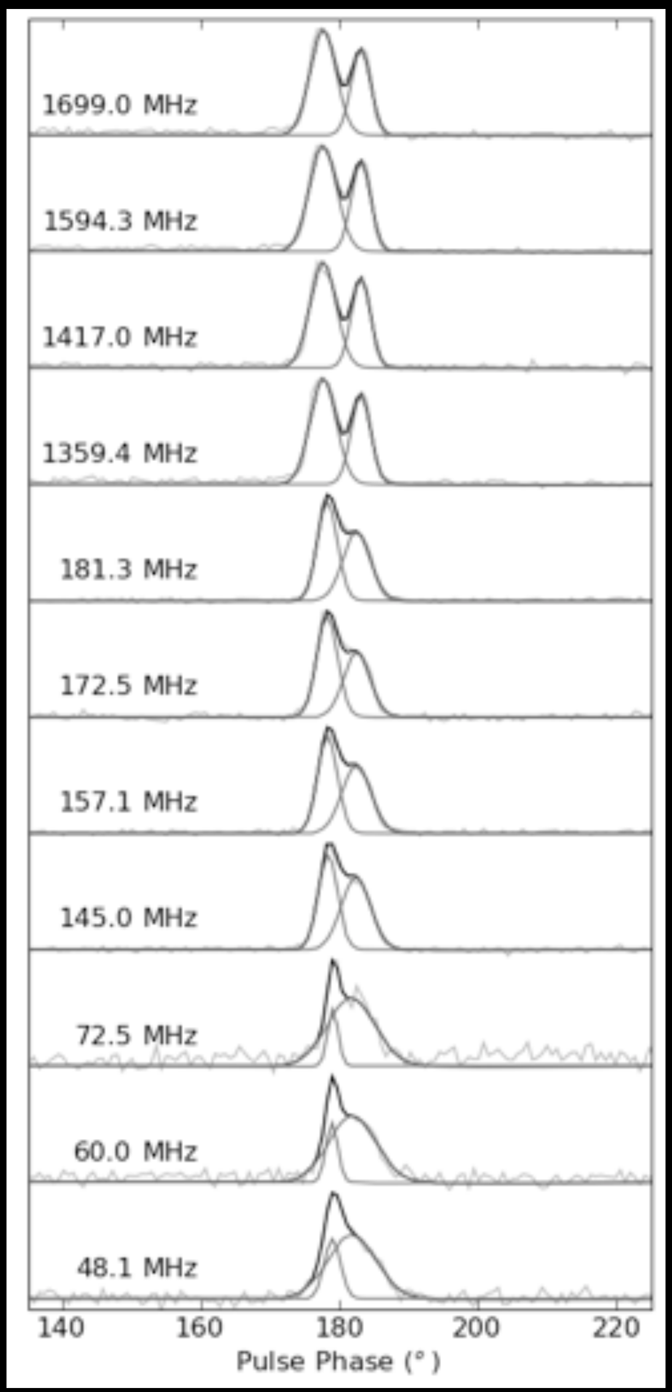


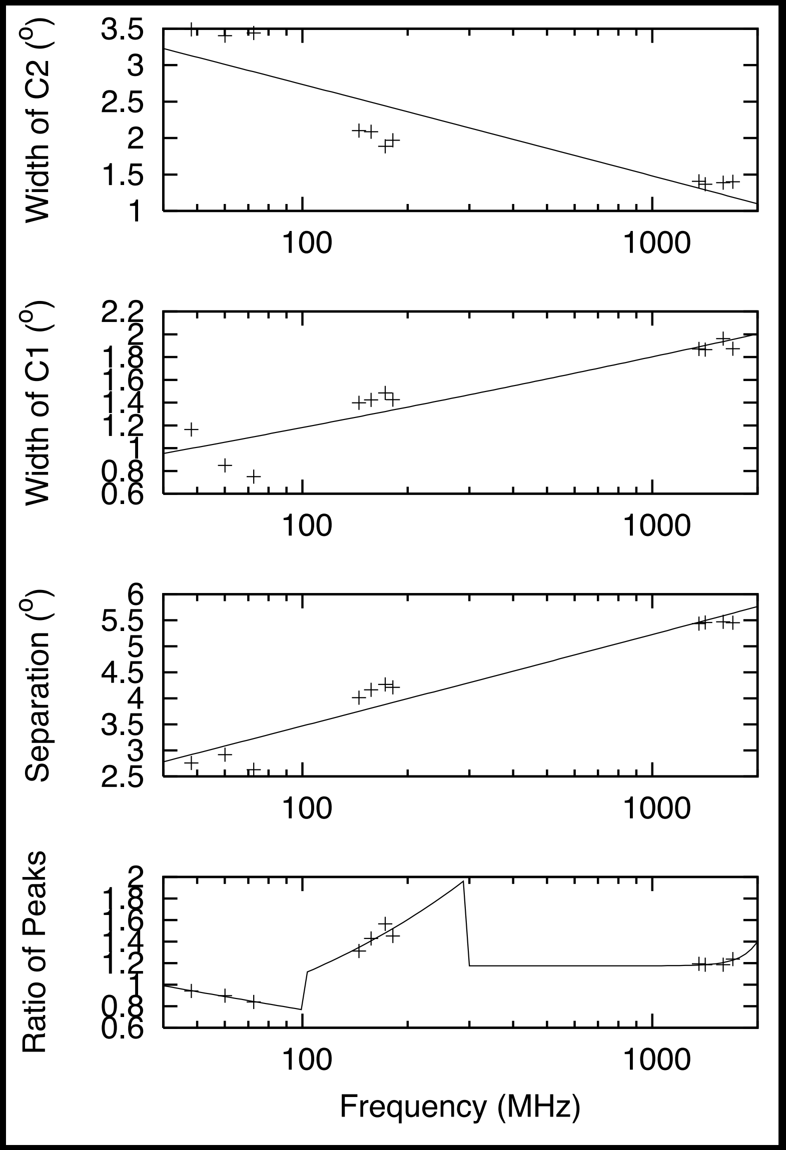
The Problem...



- Pulse profiles change with frequency
- Ahuja et al 2007 found that this can impose a gradient on the cross correlation phase spectrum
- The different shapes introduce systematic errors to our TOAs

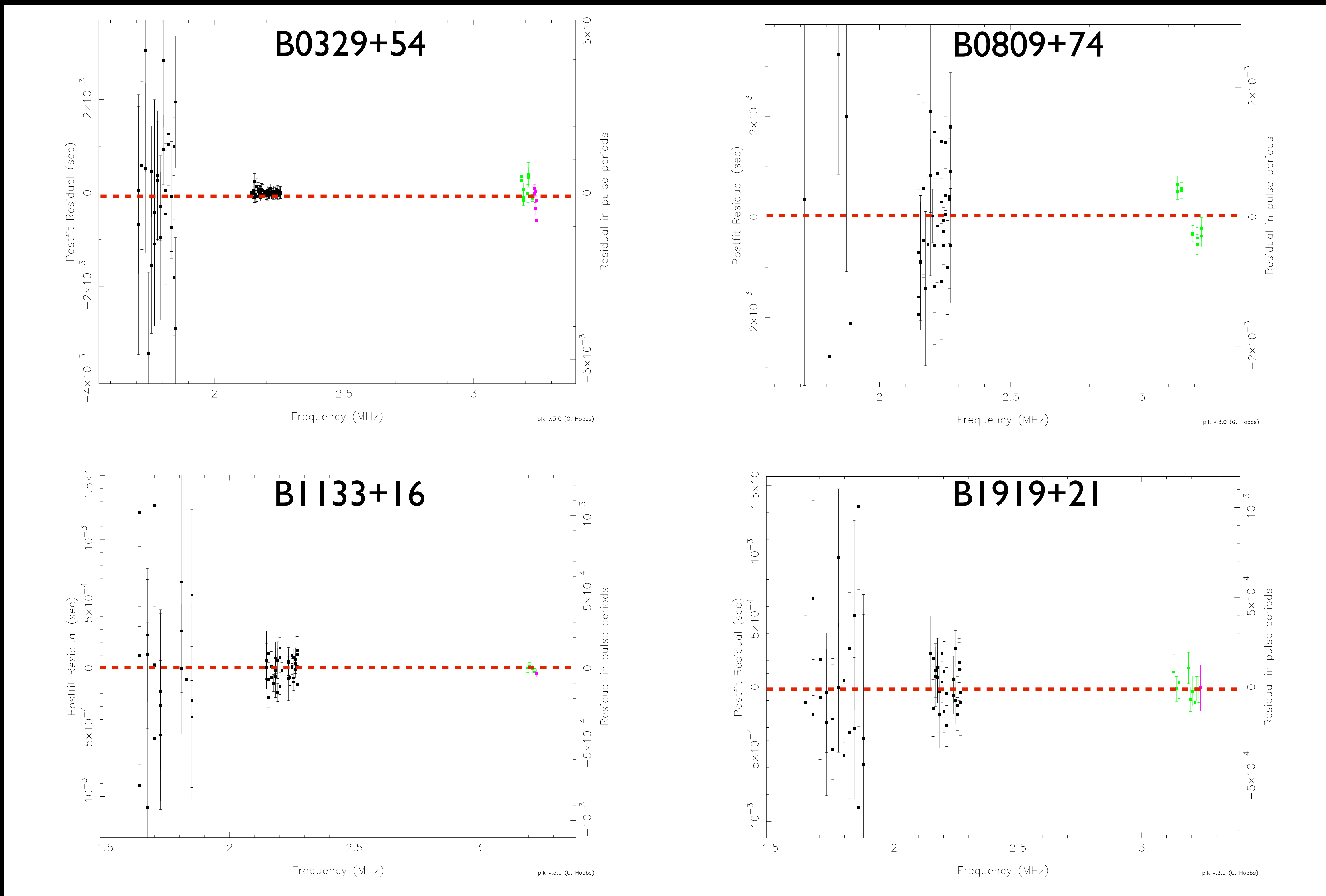
The Solution...





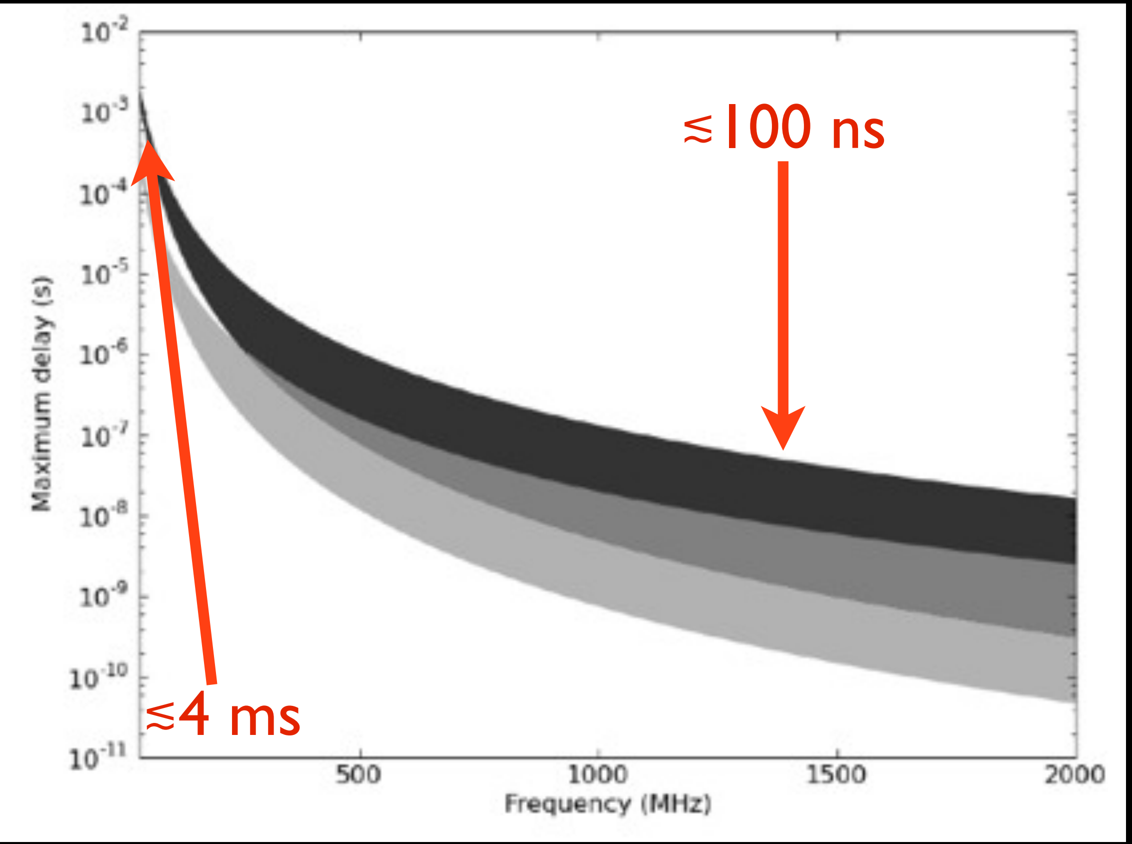
- Fit the profile at different frequencies with gaussians
- Determine how the profile evolves
- Use this to produce templates to time with

Aligned Profiles



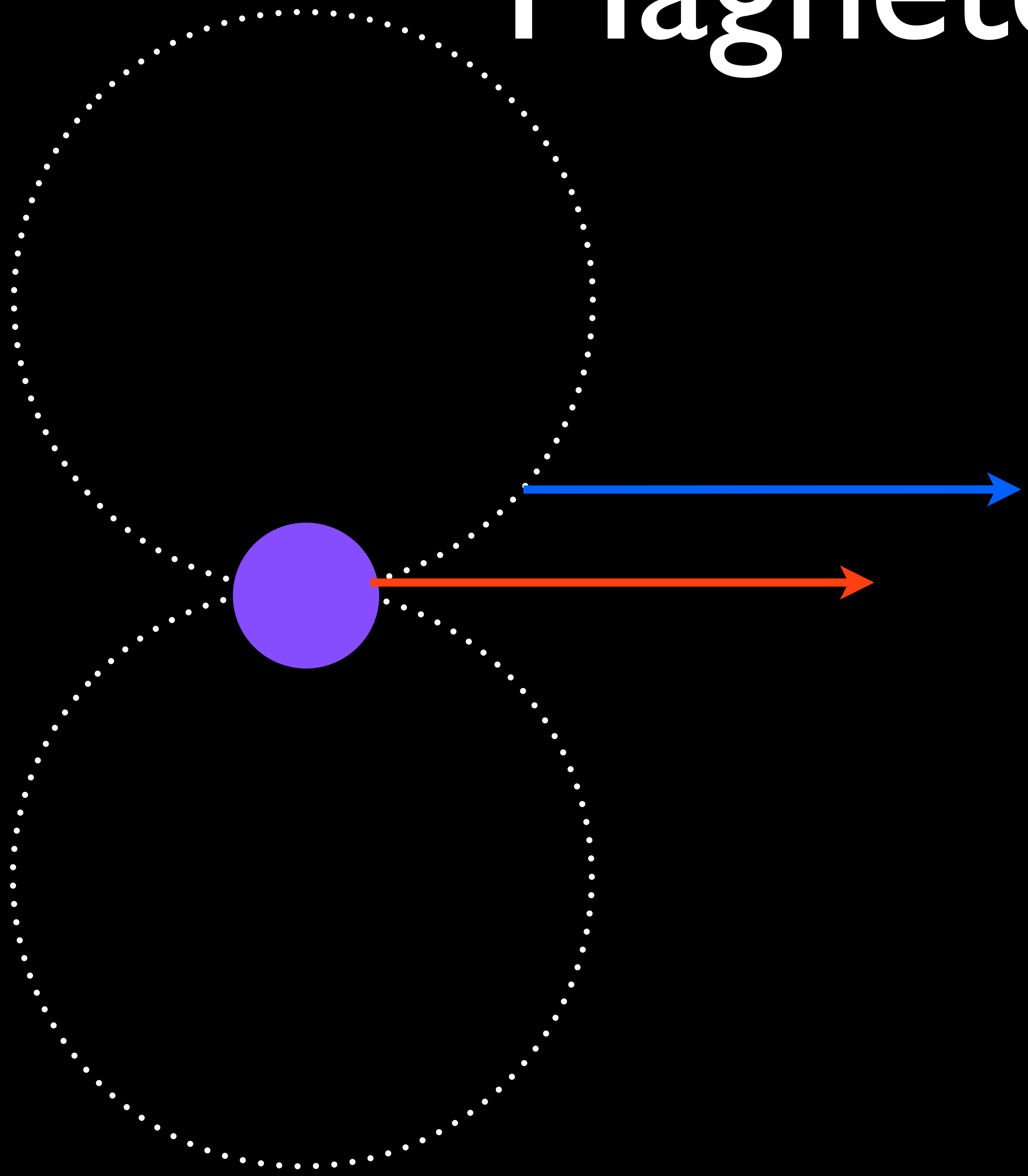
The Interstellar Medium

- We can set limits on the properties of the ISM
- It appears to be relatively smooth
- Extrapolating to higher ν shows that the ISM should not have a large effect on pulsar timing data (for these pulsars at least...)



	Delay (ms)	DM (pc cm^{-3})	SM (kpc m$^{-20/3}$)	$\frac{d}{dx}N_e(x)$ (pc cm^{-3} AU^{-1})	EM (pc cm^{-6})
B0329+54	1.95	26.764	< 0.25	$< 5.3 \times 10^{-5}$	< 42000
B0809+74	3.84	5.733	< 1.02	$< 1.2 \times 10^{-4}$	< 82000
B1133+16	1.05	4.845	< 0.32	$< 6.7 \times 10^{-5}$	< 22000
B1919+21	0.84	12.437	< 0.155	$< 4.4 \times 10^{-5}$	< 18000

The Pulsar Magnetosphere



Dipolar Magnetic Field

Emission traces last open field line

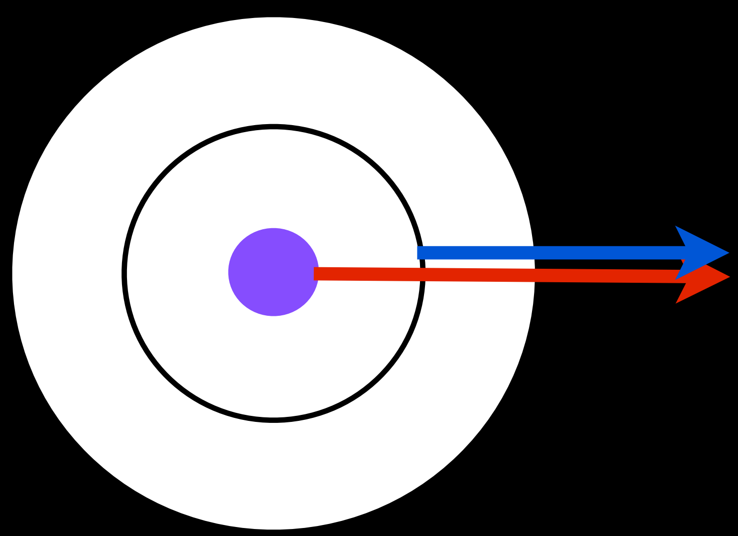
Radius-to-Frequency Mapping

High Frequency Emission comes from Lower in the magnetosphere than low frequency emission

Aberration and Retardation

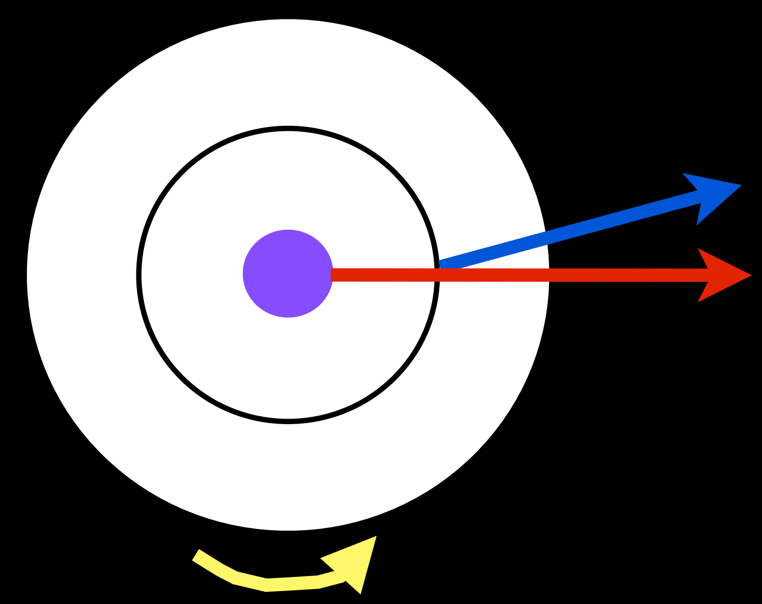
RFM ➔ High Frequency Emission comes from Lower in the magnetosphere than low frequency emission

Retardation



Path length difference

Aberration



Beam bent forward due to co-rotation

Cordes 1978, Phillips 1992

Aberration and Retardation

$$t_{AR} = \frac{\Delta r}{c}(1+\sin\alpha)$$

	Delay (ms)	α (^{o})	ΔR (km)
B0329+54	0.65	30.8	< 128
B0809+74	1.28	0.0^b	< 384
B1133+16	0.35	51.3	< 59
B1919+21	0.28	45.4	< 49

- Emission all comes from a surprisingly narrow range in the magnetosphere
- Within a few stellar radii of the neutron star surface

Conclusions

- Pulse profile evolution can cause (large) errors in TOAs
- Using a frequency dependent model can reduce these errors
- ISM should not cause too many problems at pulsar timing frequencies
- Non-detection of A/R effects shows that pulsar emission comes from a very narrow range of heights in the magnetosphere