Dispersion Measure Variability in NANOGrav data

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IPTA 2012, Kiama, NSW
25 June 2012

I. Overview of DM and dual-frequency measurements
(because I didn't give a student talk last week)

II. NANOGrav observations & a few pretty plots
(depending on your definition of "pretty")

III. Impact on fitting DM at every epoch on timing
(a *very* qualitative discussion)

IV. Wide-band timing analysis
(what happens next….)

V. A scary plot
(a reminder that DM variations are just one aspect of our ISM troubles)

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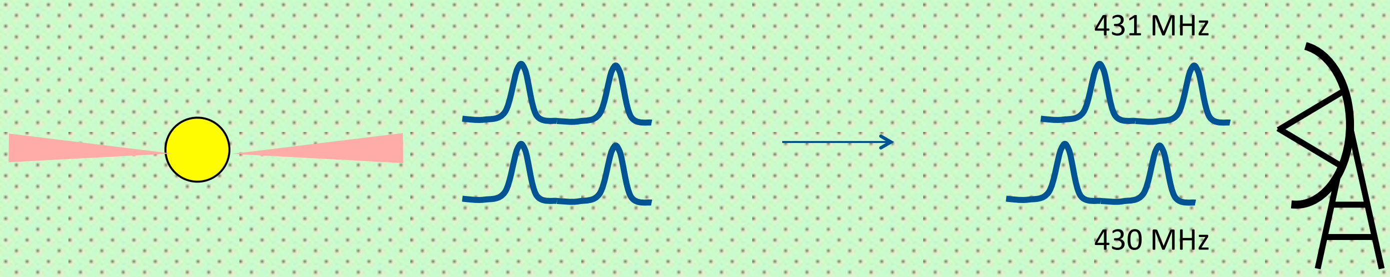
Interstellar Dispersion



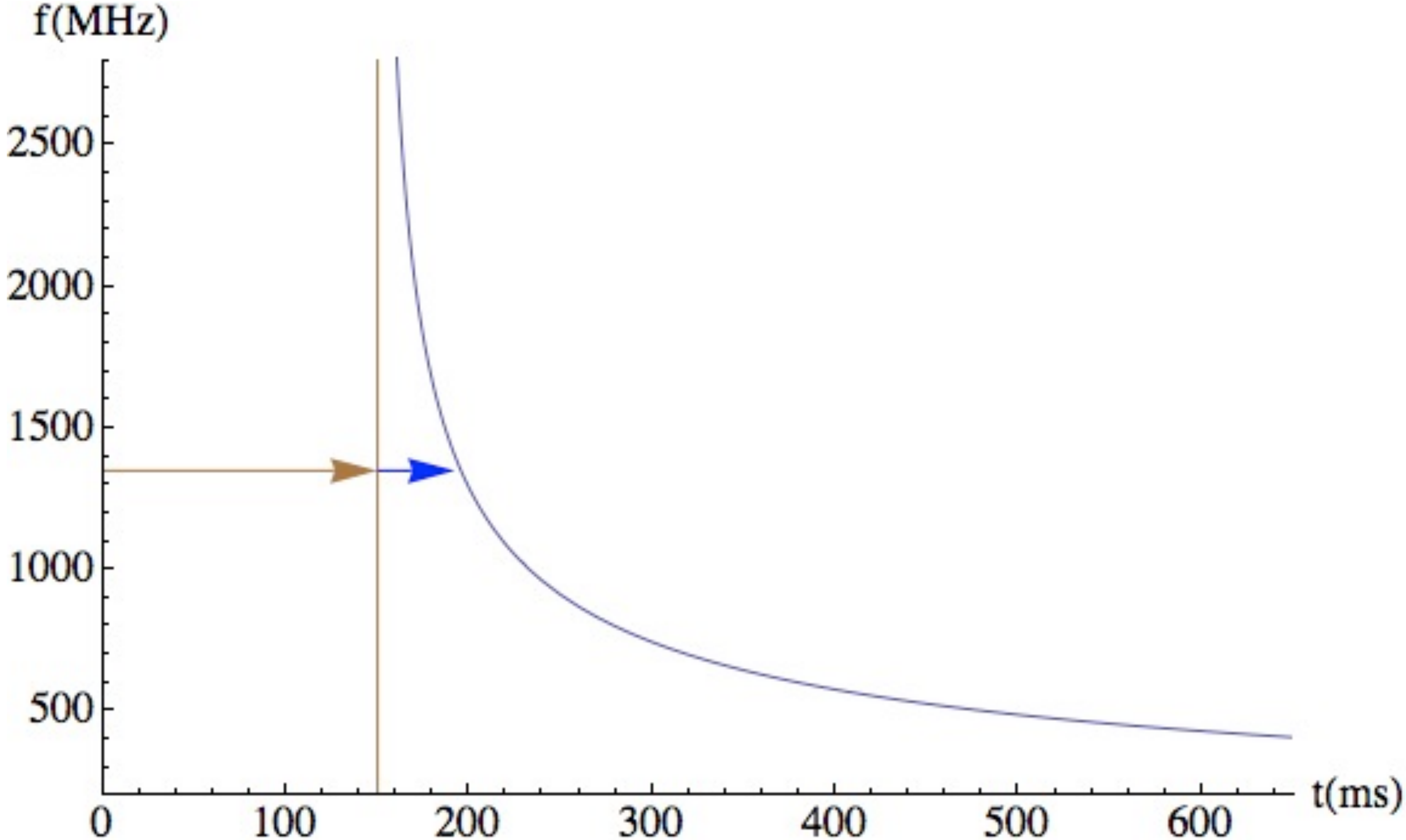
column density of electrons: $DM = \int n_e(l)\, dl$ usual units: pc cm^{-3}

excess delay (in seconds): $t_{delay}(sec) = t_f - t_\infty = DM / 2.41\times10^{-4} [f(MHz)]^2$

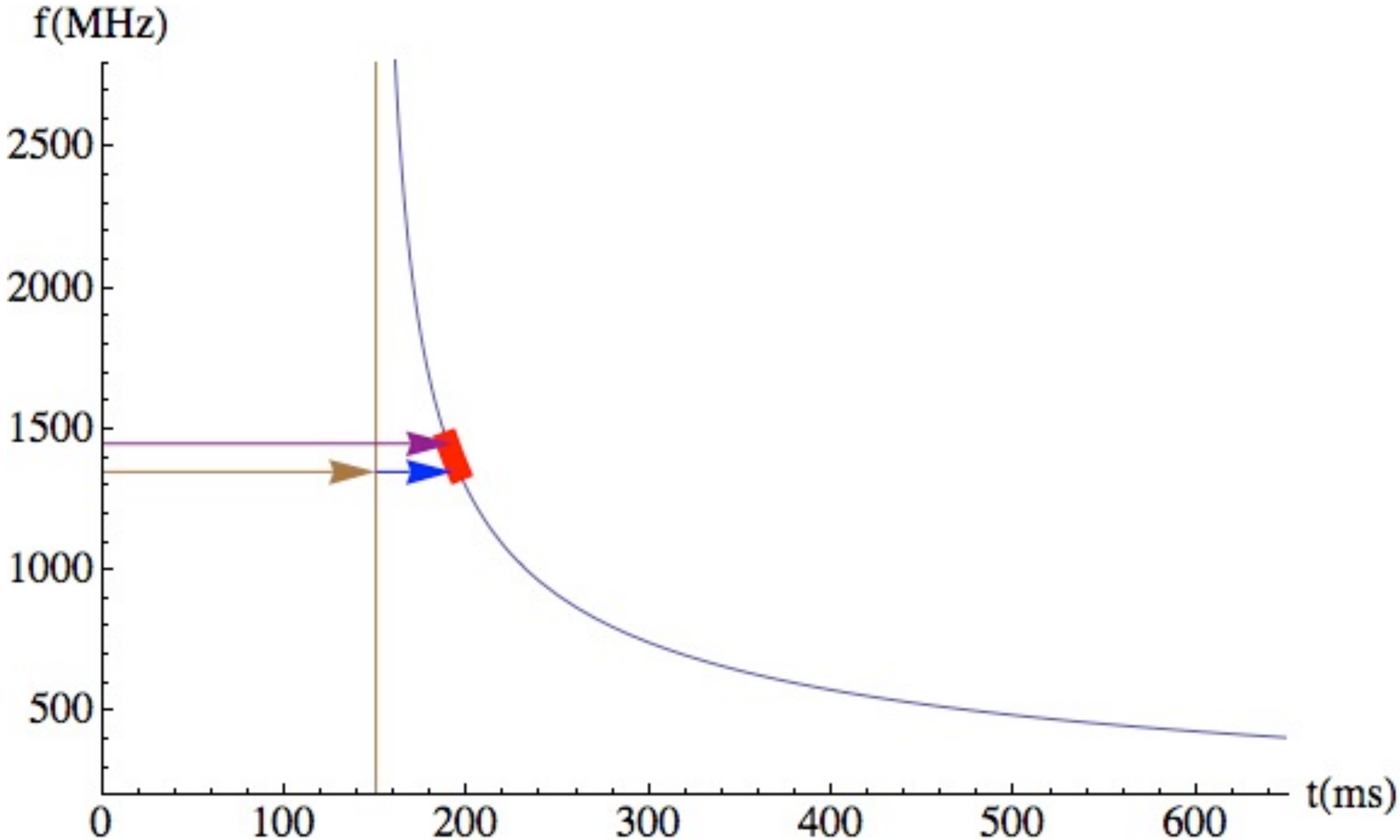
typical delay: t_{delay}=43 ms for a DM=20 pulsar at 1400 MHz.

a change in DM by 1 part in 10^4 changes the delay by 200 ns at 1400 MHz

$$t_f = t_\infty + \mathrm{DM} / 2.41\times10^{-4}\,[f(\mathrm{MHz})]^2$$



$$t_f = t_\infty + DM \, / \, 2.41{\times}10^{-4} \, [f(\mathrm{MHz})]^2$$



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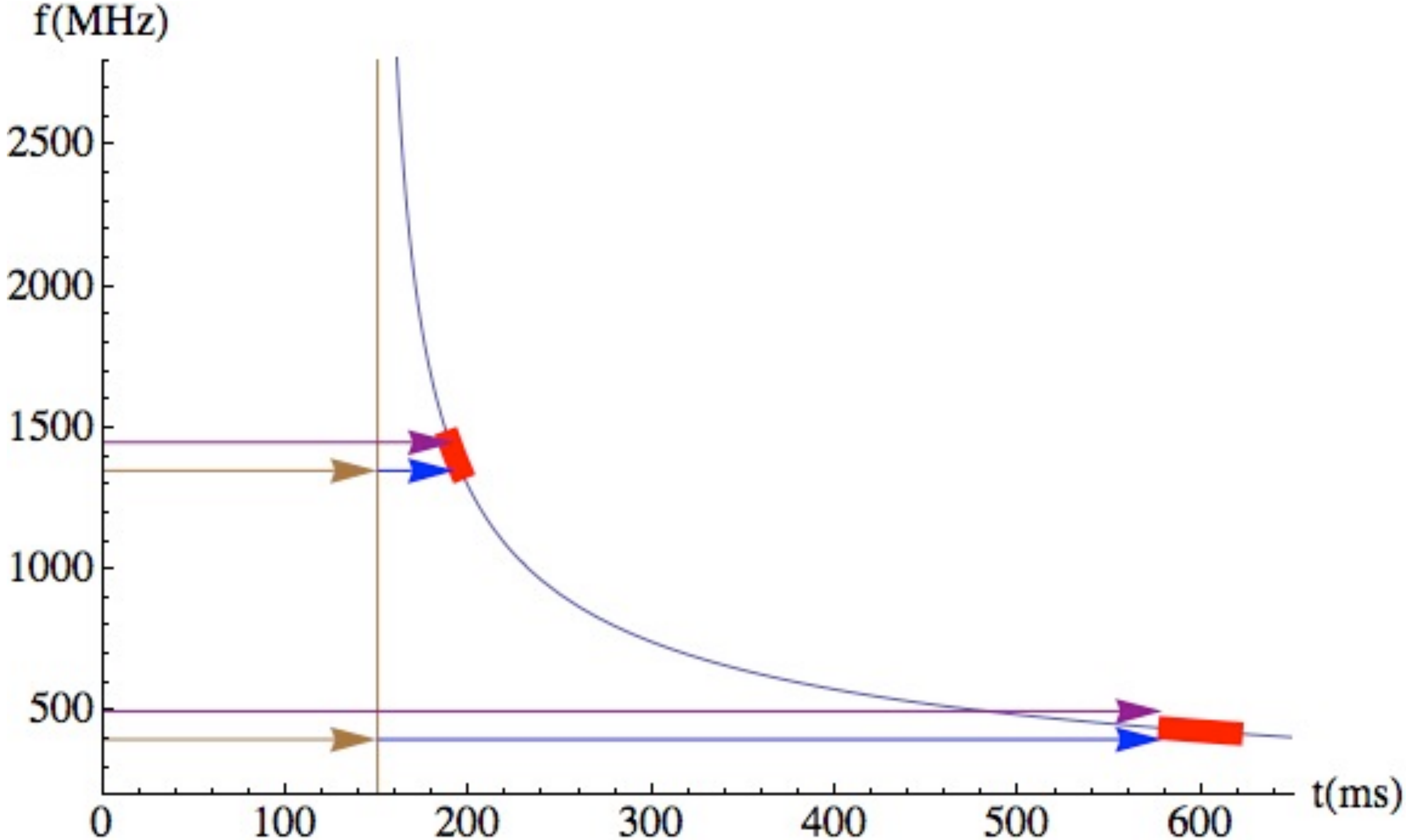

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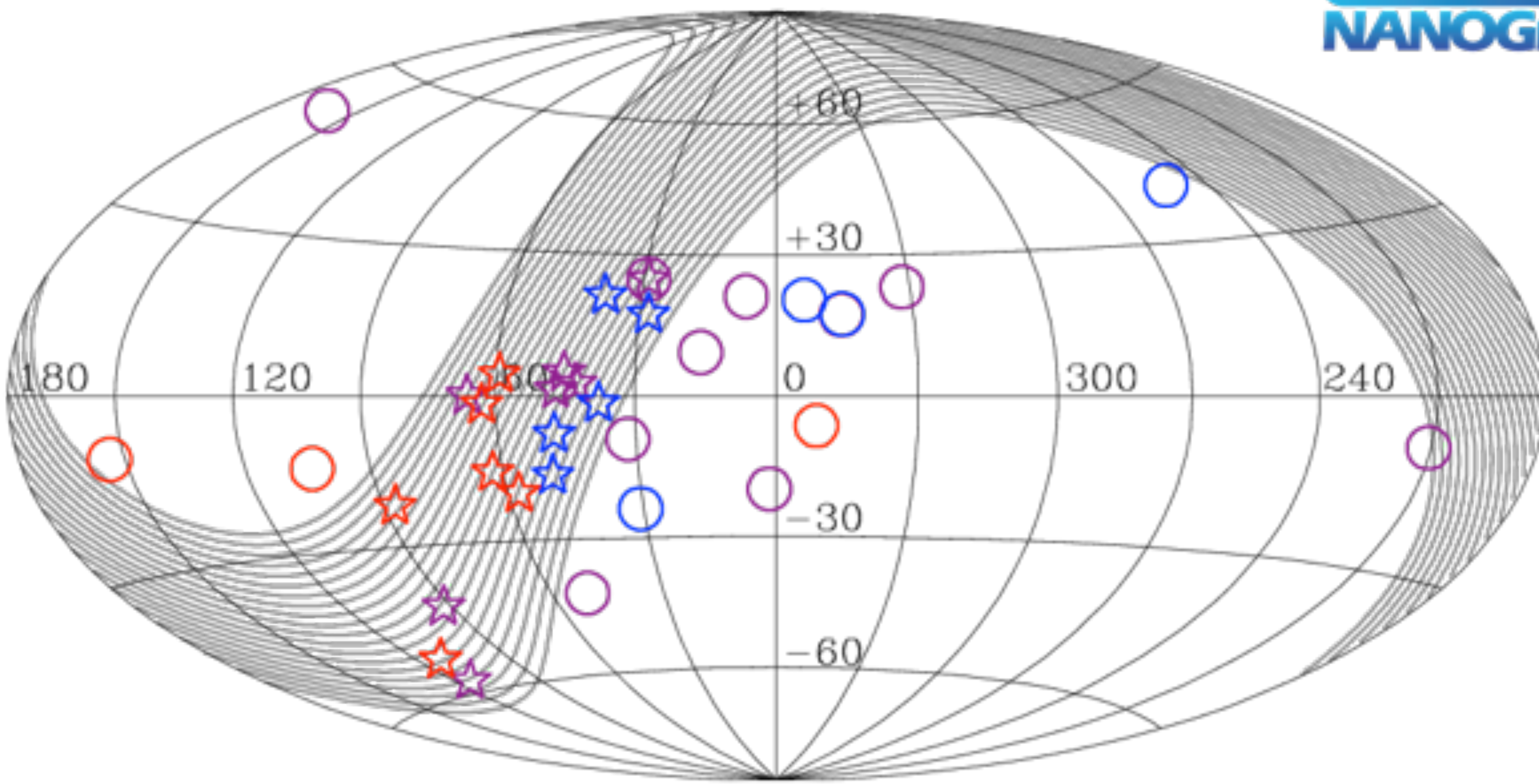
Pulsars We Observe



Under observation since 2005 using ASP/GASP — Arecibo (purple star), Green Bank (purple circle)

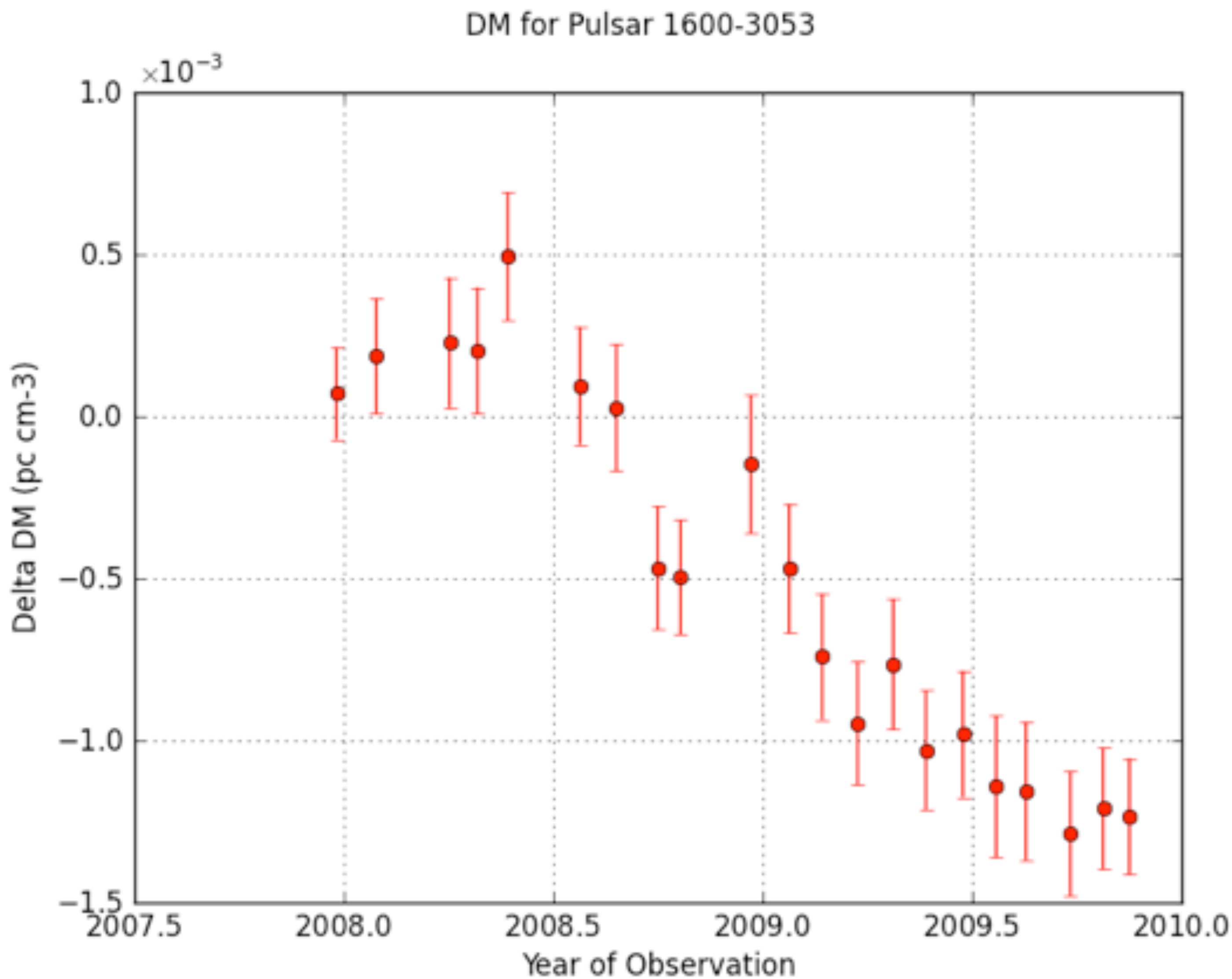
Millisecond pulsars added to NANOGrav campaigns starting in ~2009 — Arecibo (blue star), Green Bank (blue circle)

Millisecond pulsars added to NANOGrav campaigns starting in ~2011 — Arecibo (red star), Green Bank (red circle)

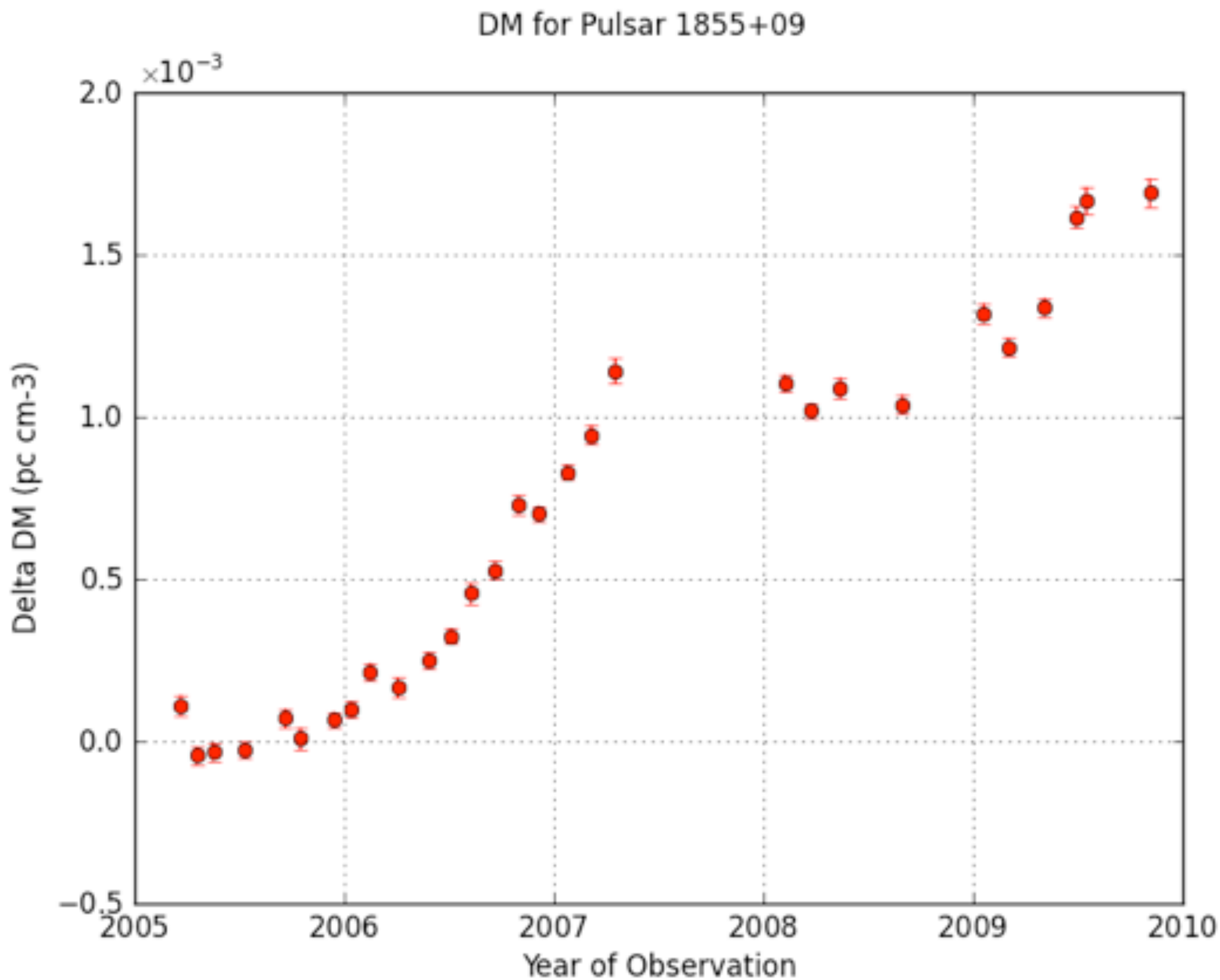
Demorest et al (2012) data set

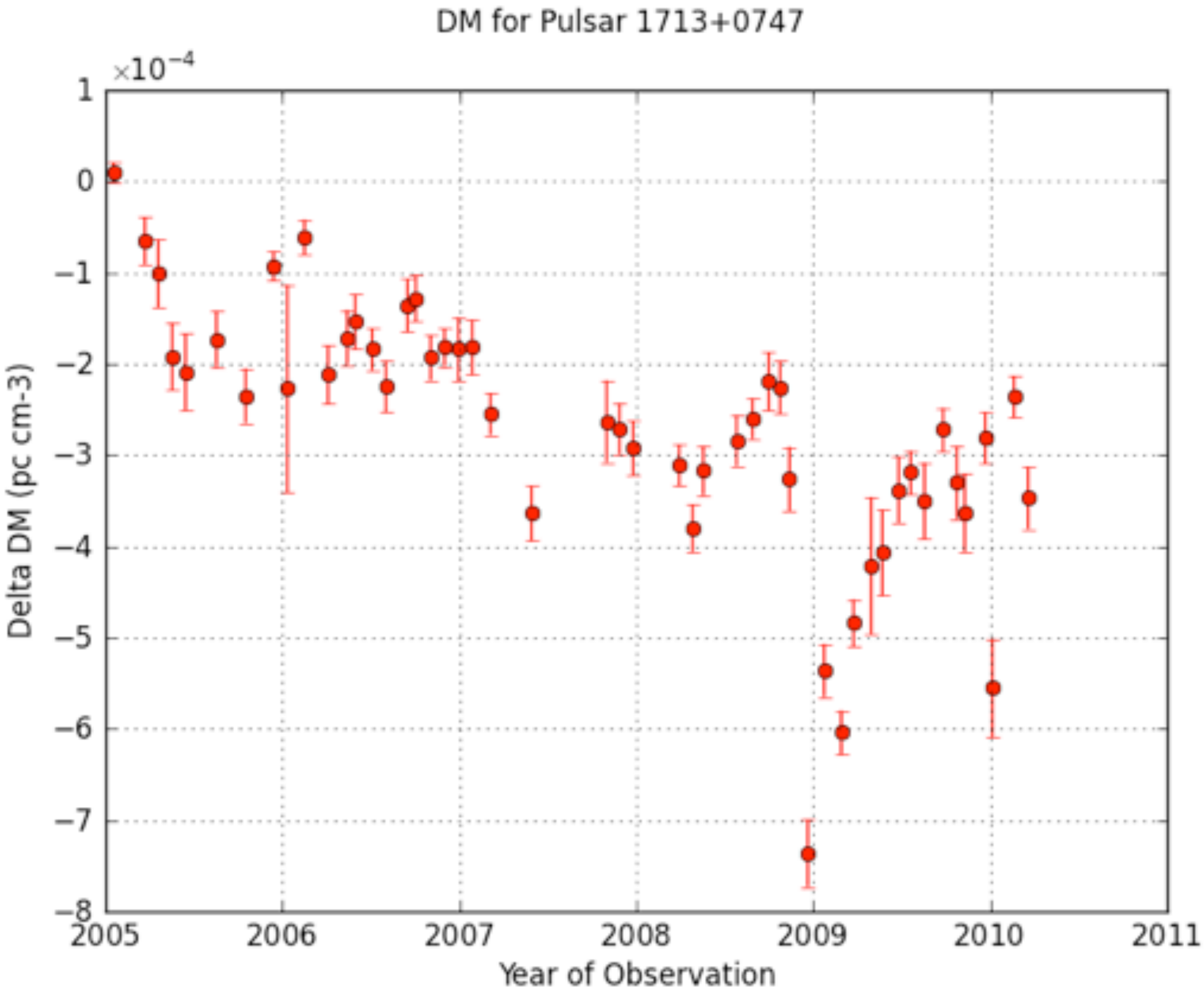
arXiv:1201.6641

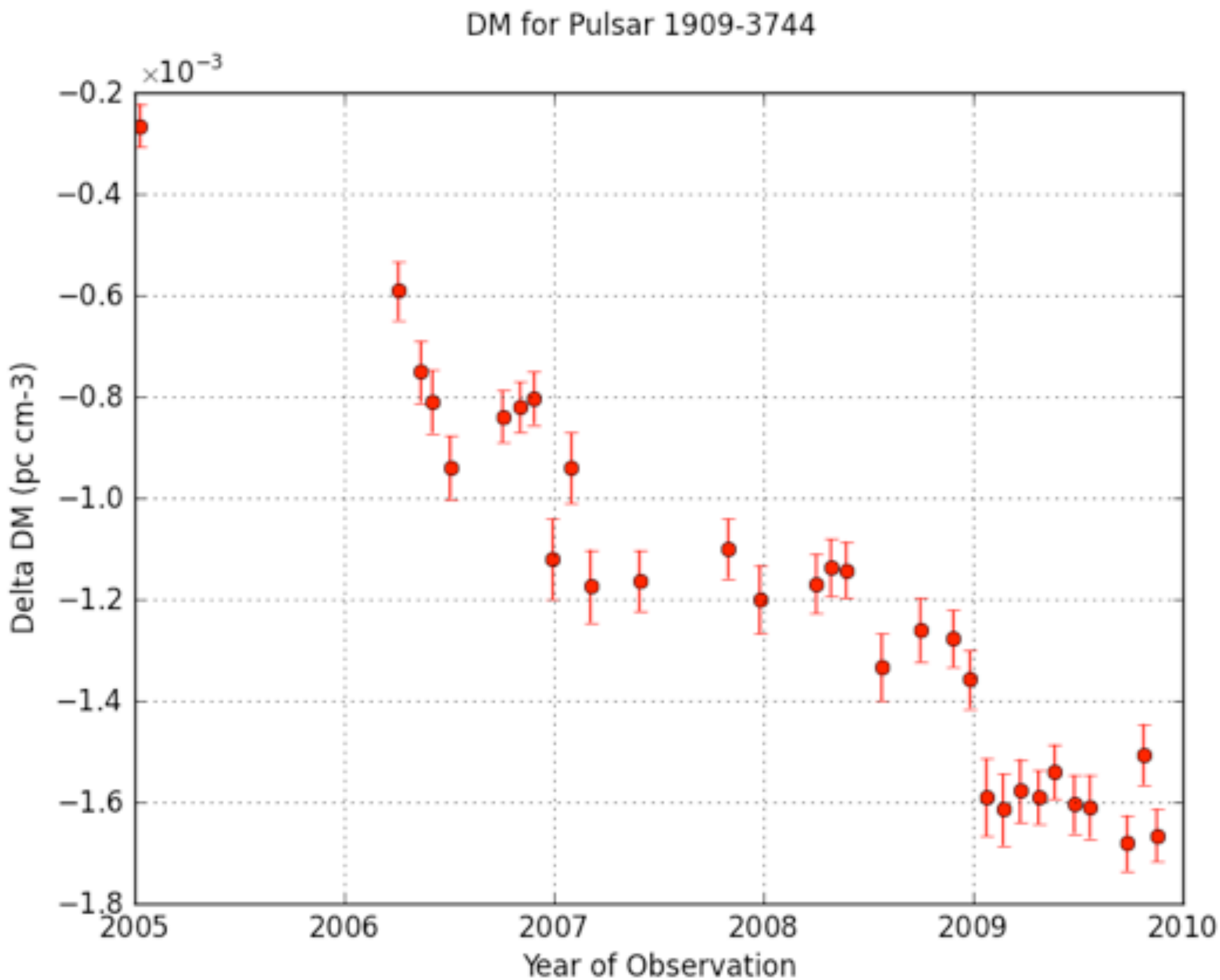
- 17 Pulsars (8 Arecibo, 10 GBT; 1 overlap)
- 5 years of observations, typically monthly (with some gaps)
- ASP (Arecibo) and GASP (Green Bank) backends
    - 64 MHz software coherent dedispersion, 4 MHz channels, full Stokes
- Dual frequency observations of all but three sources at every epoch
    - Green Bank
        - 800/1400 MHz
    - Arecibo: depends on pulsar spectrum, flux density, scintillation
        - 327/430 MHz
        - 430/1400 MHz
        - 1400/2350 MHz
- Timing analysis (tempo) fits for DM at every epoch in addition to fitting for all other usual parameters (spin, astrometry, binary).

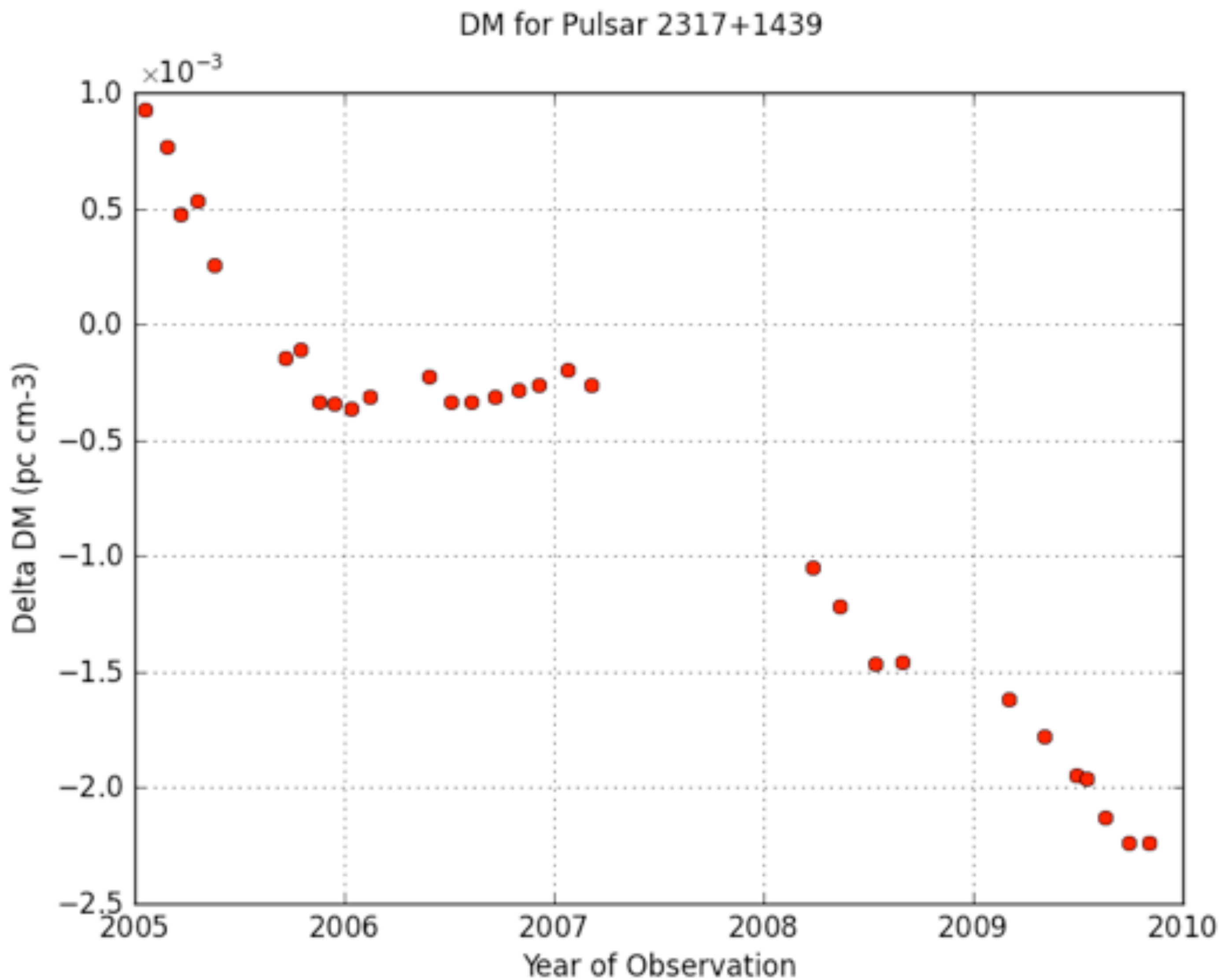


DM for Pulsar 1600-3053
×10^-3
Delta DM (pc cm-3)
Year of Observation
1.0
0.5
0.0
−0.5
−1.0
−1.5
2007.5
2008.0
2008.5
2009.0
2009.5
2010.0


DM for Pulsar 1855+09
×10^-3
2.0
1.5
1.0
0.5
0.0
−0.5
2005
2006
2007
2008
2009
2010
Year of Observation
Delta DM (pc cm-3)

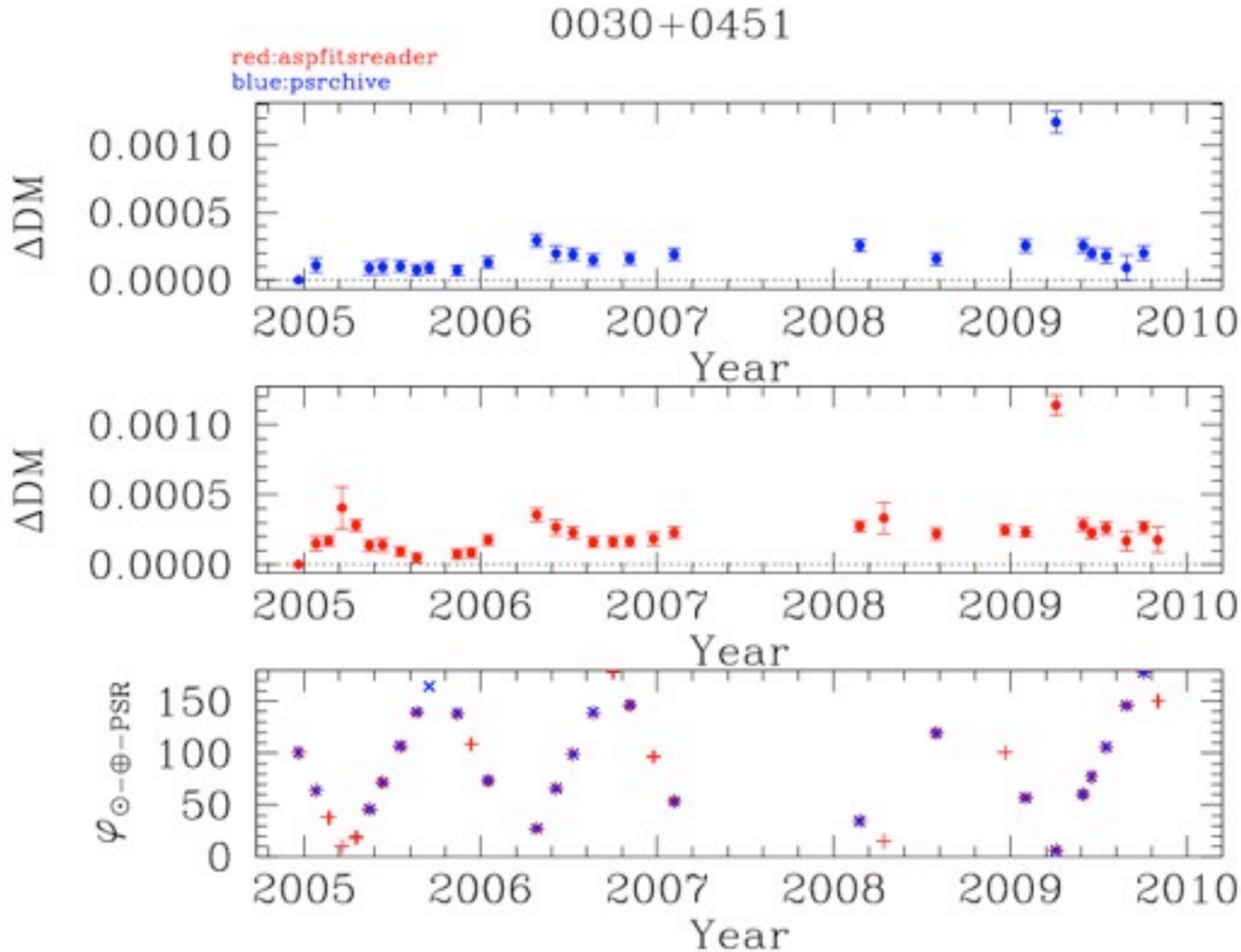

DM for Pulsar 1713+0747
×10−4
1
0
−1
−2
−3
−4
−5
−6
−7
−8
Delta DM (pc cm-3)
2005
2006
2007
2008
2009
2010
2011
Year of Observation

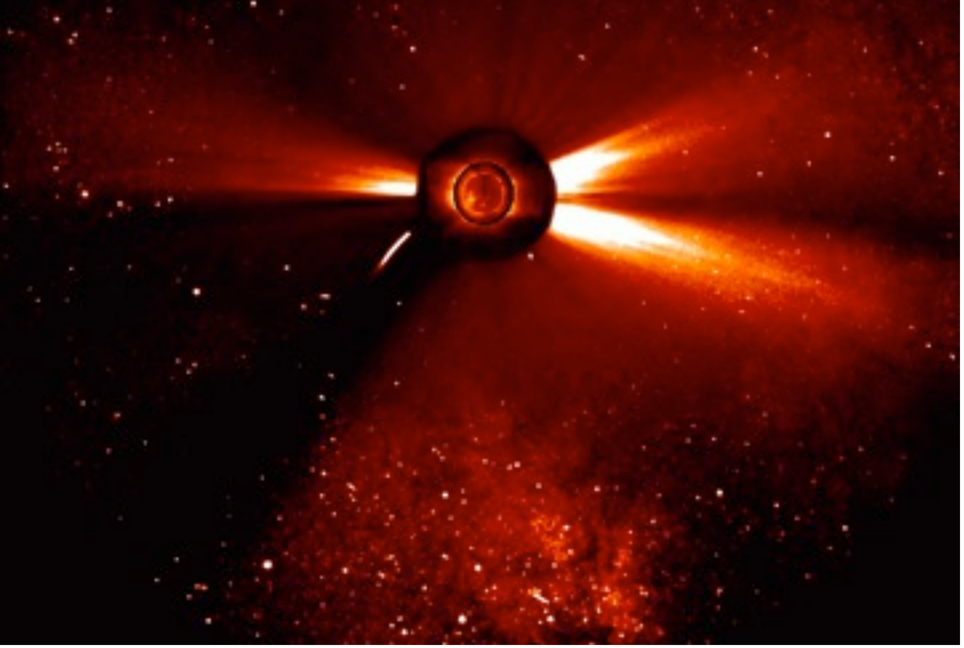

DM for Pulsar 1909-3744
×10^−3
Delta DM (pc cm-3)
Year of Observation
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
−1.4
−1.6
−1.8
2005
2006
2007
2008
2009
2010

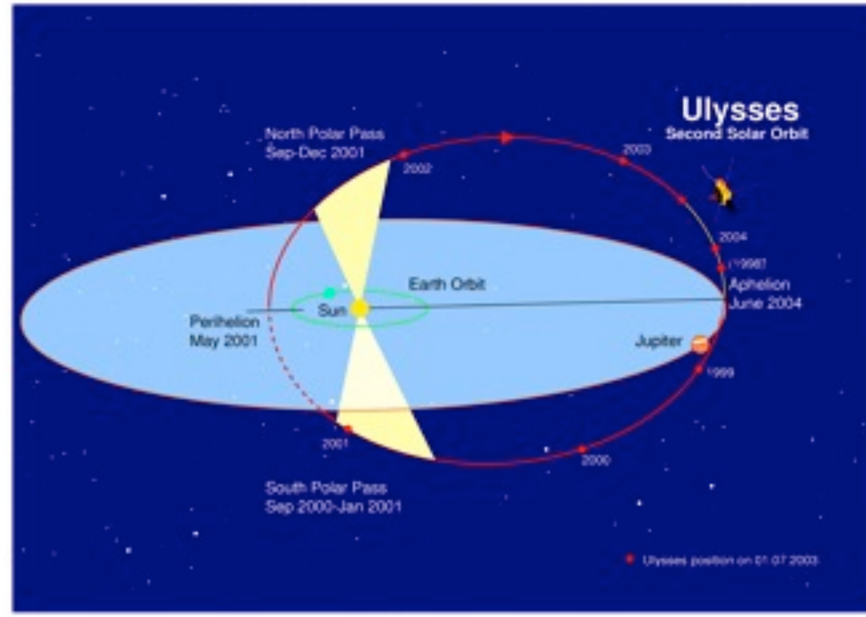


DM for Pulsar 2317+1439
×10−3
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
Delta DM (pc cm-3)
2005
2006
2007
2008
2009
2010
Year of Observation

Dispersion Measure Variation

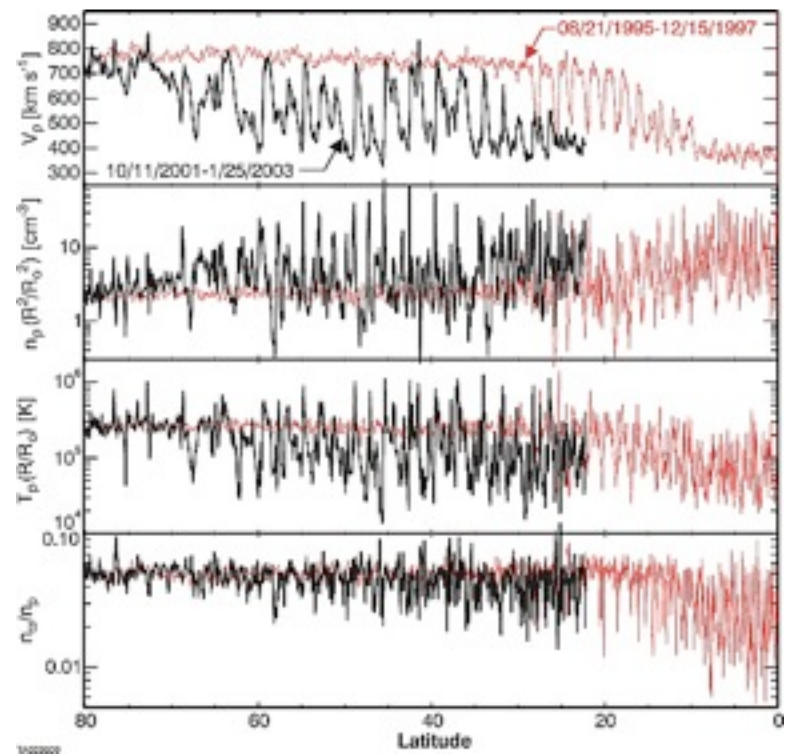




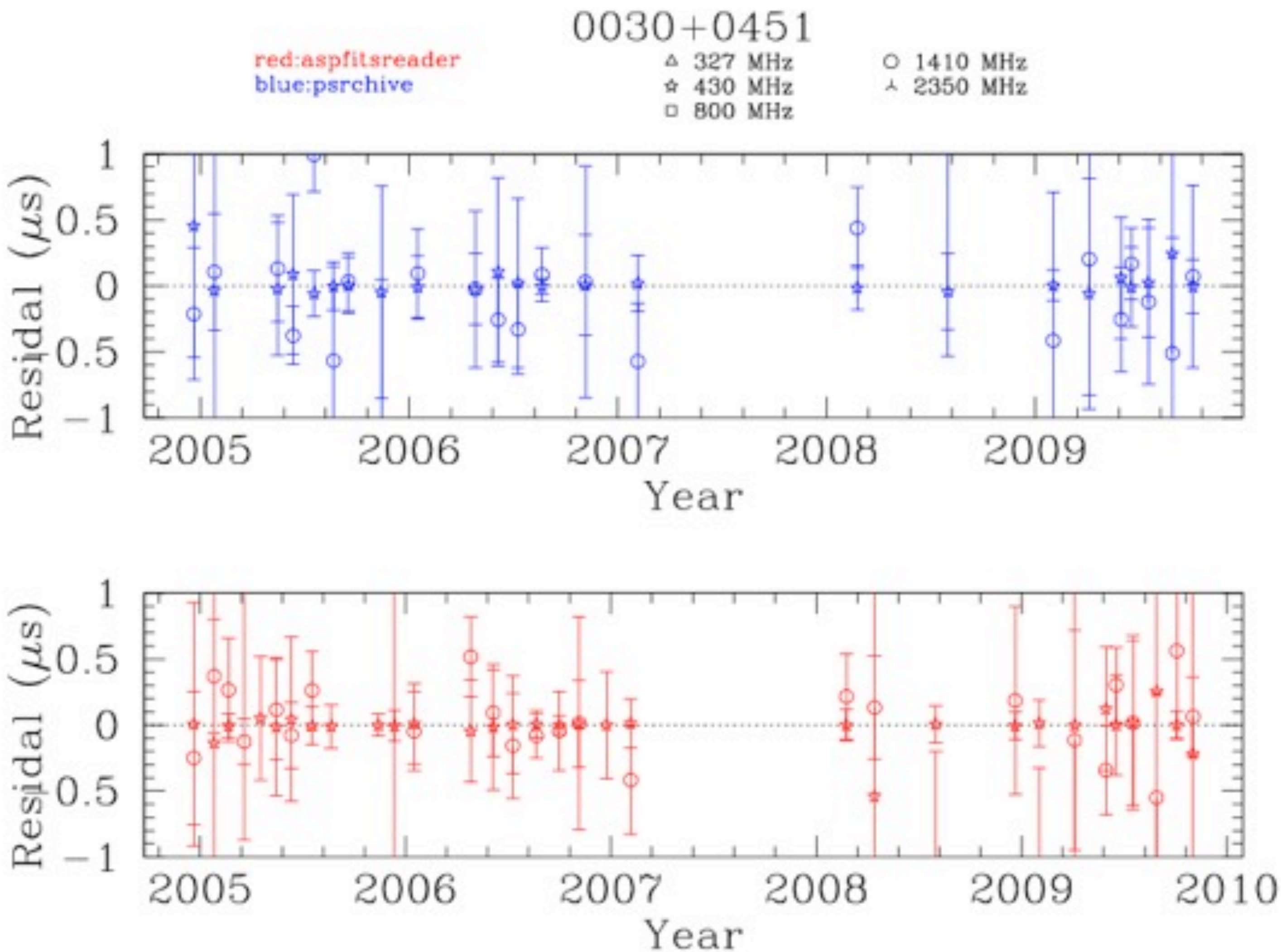


Variations in dispersion on small scales are *inevitable* due to the solar wind. Multi-frequency observations at each epoch are *crucial* to removing imprint of these variations from the data.

Twelve-Hour running average solar wind proton speed, density, temperature, and alpha-to-proton ratio over the equivalent portions of two orbits of Ulysses. From McComsas et al. 2003, Geophysical Research Letters, 30: 1517.



Solar Image: SOHO/NASA
Ulysses Orbit Figure: ESA



0030+0451
red:aspfitsreader
blue:psrchive
327 MHz
430 MHz
800 MHz
1410 MHz
2350 MHz
Residal (μs)
Year
2005
2006
2007
2008
2009
2010

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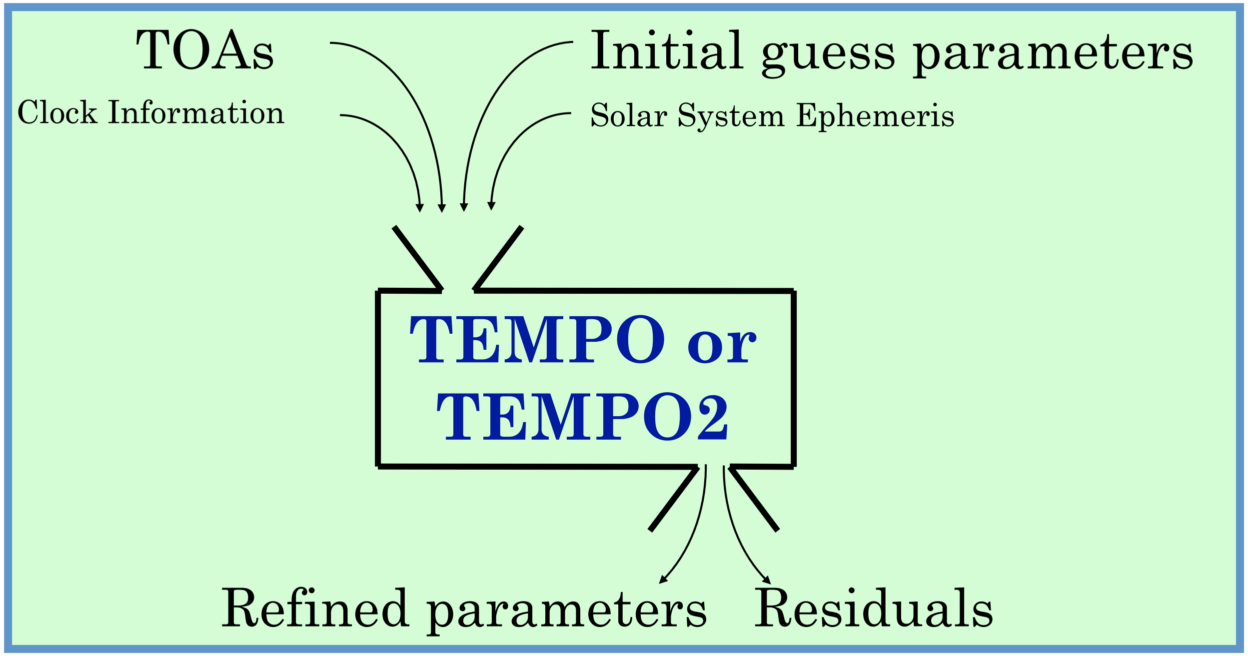
- We fit for DM at each epoch within tempo or tempo 2 ("DMX"). The fit is *simultaneous* with the fit for all other parameters.
- This approach is good *if* the timing model being used by tempo or tempo2 *completely describes* the data (i.e., post-fit residuals truly should be Gaussian).
- If the timing model is incomplete then tempo/tempo2 may mis-adjust DMX offsets in its effort to minimize the weighted residual. Un-modeled (non-white) signals in the residuals can be reduced by this.
- Because low-frequency points are usually weighted more heavily than high-frequency points, the daily post-fit-residuals for low-frequency points tend to be artificially low (see PSR J0030+0451 residuals on previous slide.) Better to use "common mode" residuals.



- Our approach of fitting DM independently at every epoch is absolutely necessary. At our desired level of measurement, DM(t) is not necessarily a smooth function; we must treat it as a "random variable" which must be measured at every epoch.

- As with any measurement, DM(t) can only be measured to finite precision. Uncertainty in DM(t) leads to effectively reduced precision of absolute (infinite frequency) TOAs within timing codes.

- At any given epoch, the inferred DM(t) and the inferred "average infinite frequency TOA" are covariant with each other. This magnifies the effect of uncertainty of DM(t) values.

- To date, we have taken the conservative approach of *not* attempting to take this additional noise into account when placing an upper limit on the GWB. Crudely speaking, the observed pulsar measurements might have:

  observed red noise = GWB signal + timing noise + DM-related-noise

  Hence:

  GWB signal = observed red noise - timing noise - DM-related-noise

  In other words, accounting for DM-covariance-noise might (in principle) allow for a reduced upper limit on the GWB signal. (But how to do this??)

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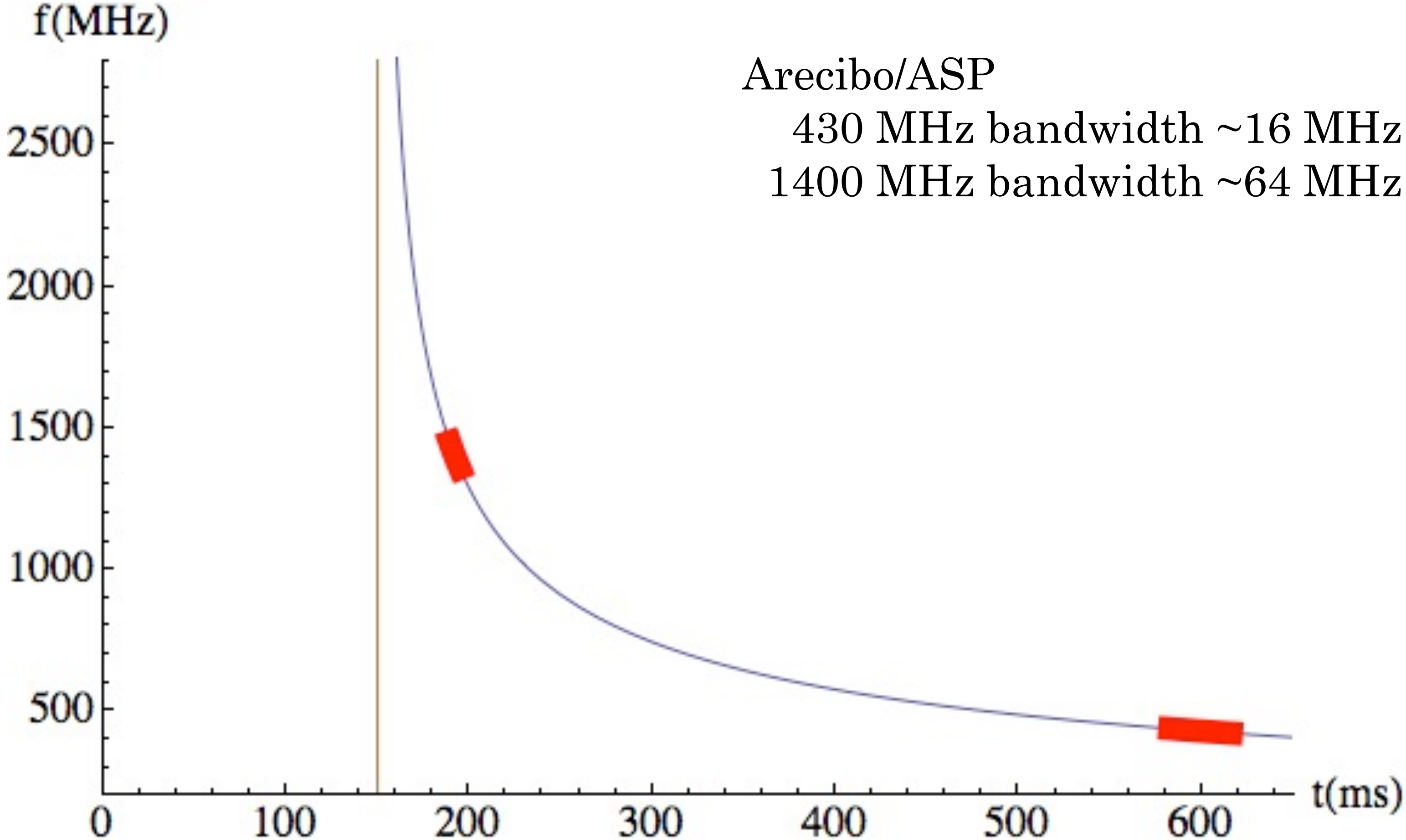
$$t_f = t_\infty + \mathrm{DM} \,/\, 2.41\times10^{-4}\,[f(\mathrm{MHz})]^2$$

Arecibo/ASP

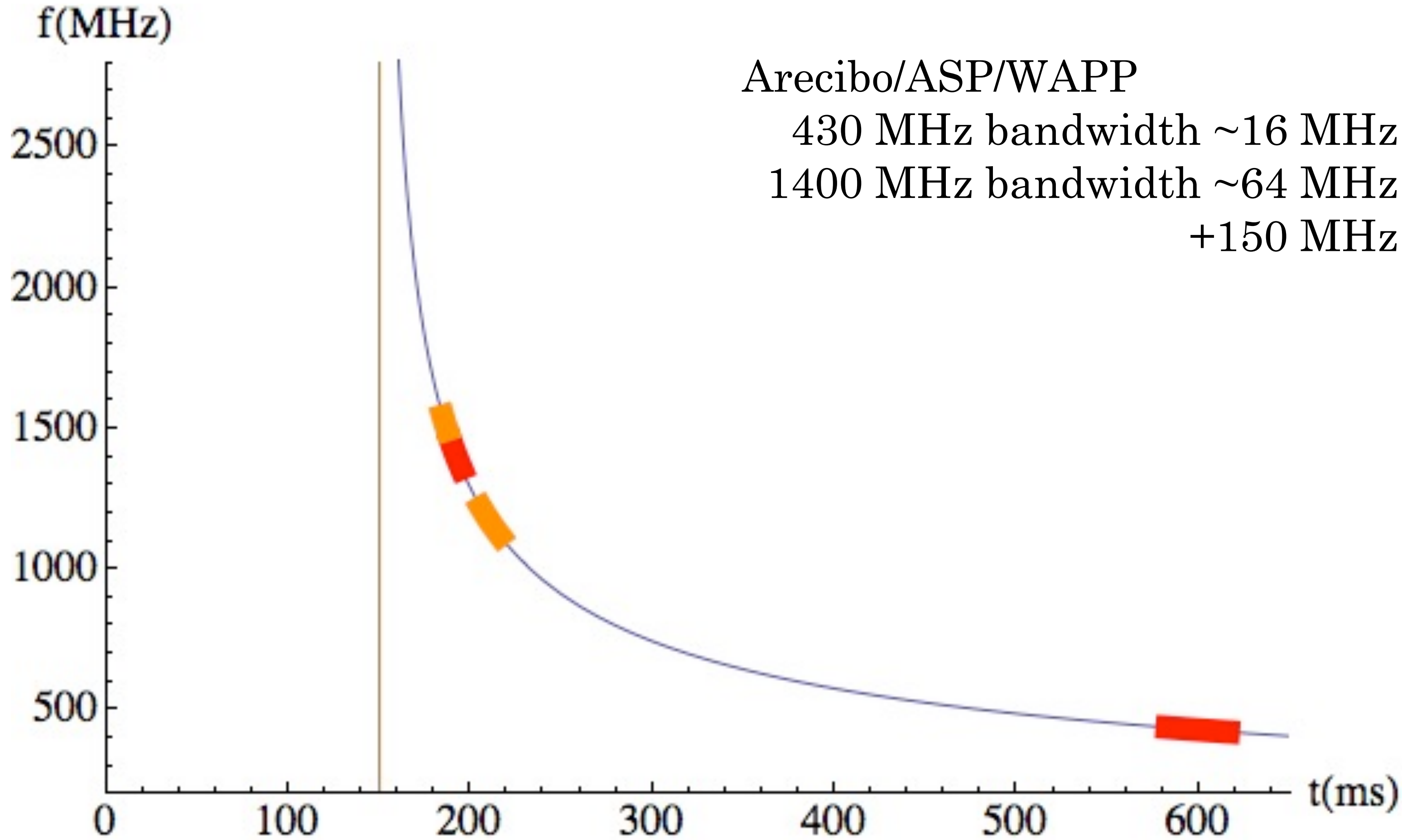
430 MHz bandwidth ~16 MHz

1400 MHz bandwidth ~64 MHz

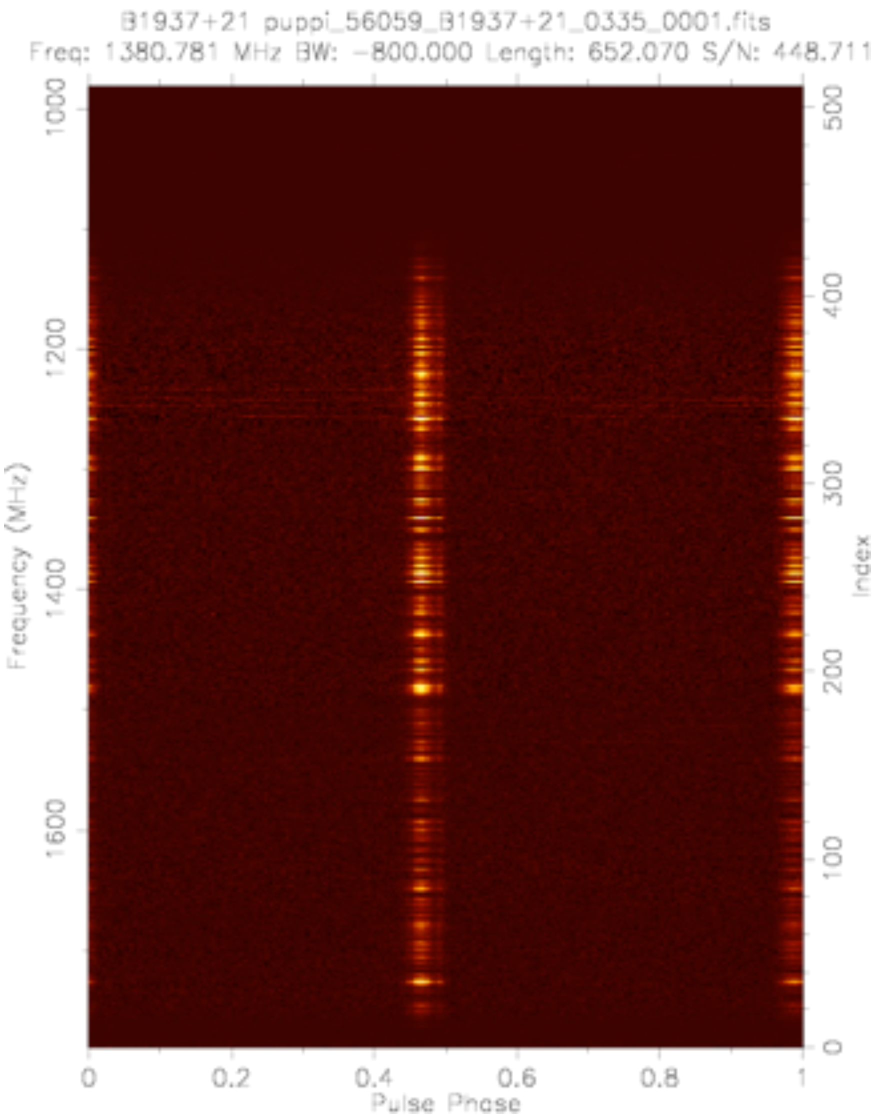


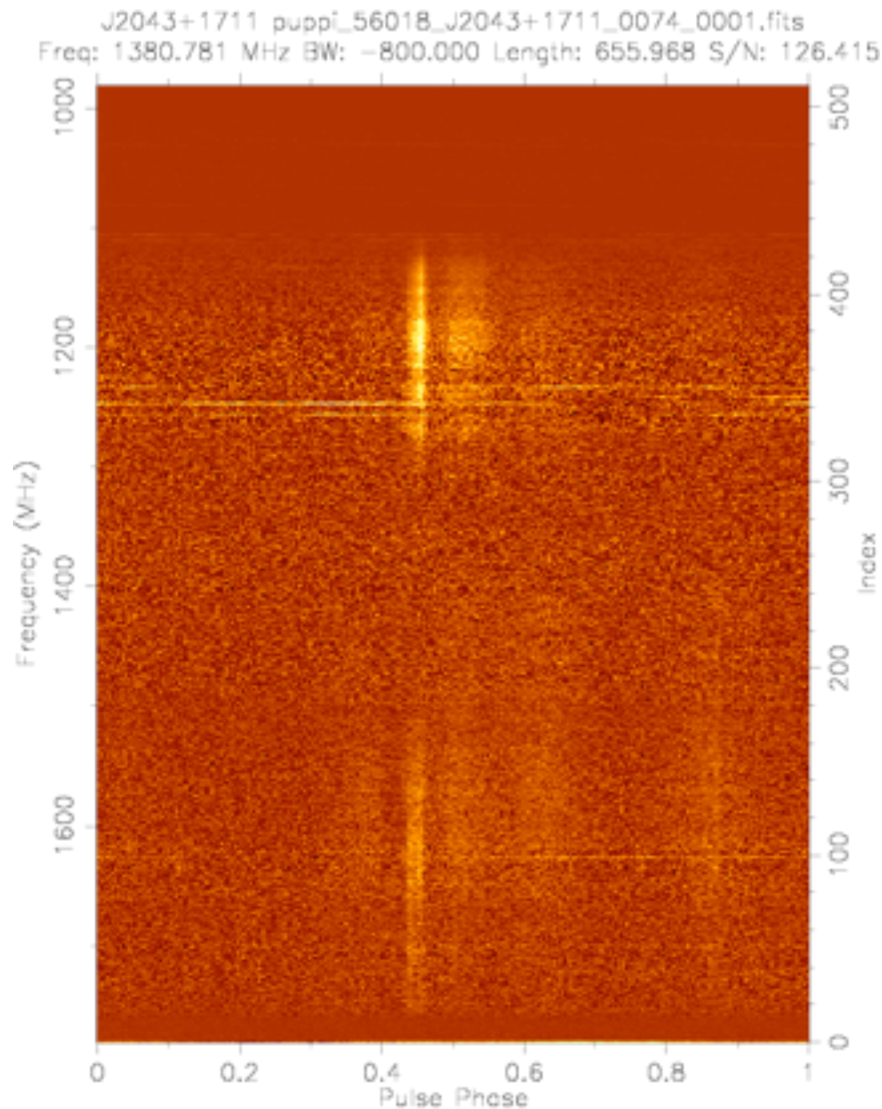
$$t_f = t_\infty + \mathrm{DM} / 2.41\times10^{-4}\,[f(\mathrm{MHz})]^2$$

Arecibo/ASP/WAPP
430 MHz bandwidth ~16 MHz
1400 MHz bandwidth ~64 MHz
+150 MHz



GUPPI (GBT), PUPPI (Arecibo)
coherent dedispersion 800 MHz bandwidth



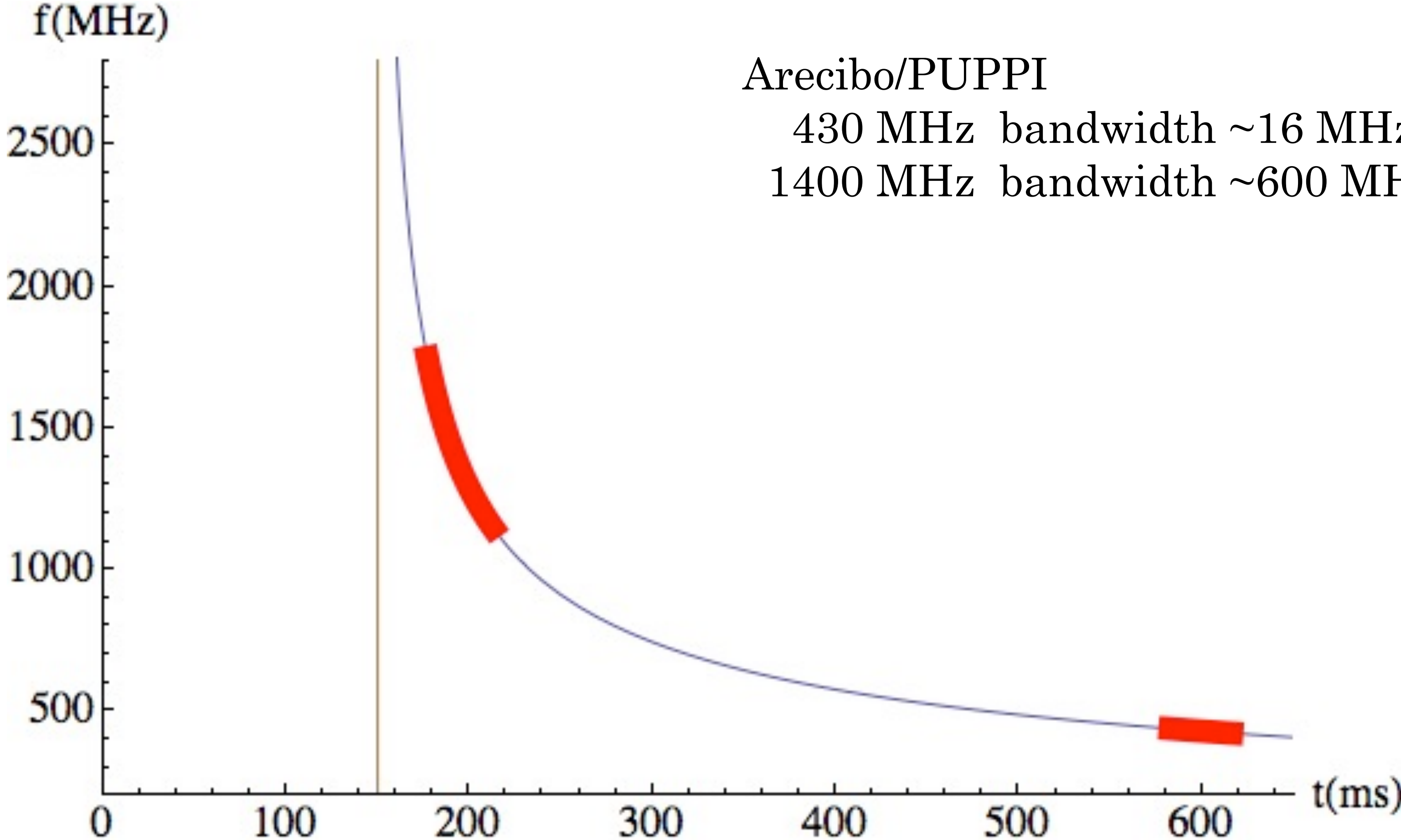


$$t_f = t_\infty + \mathrm{DM} \,/\, 2.41\times10^{-4}\,[f(\mathrm{MHz})]^2$$

Arecibo/PUPPI

430 MHz bandwidth ~16 MHz

1400 MHz bandwidth ~600 MHz

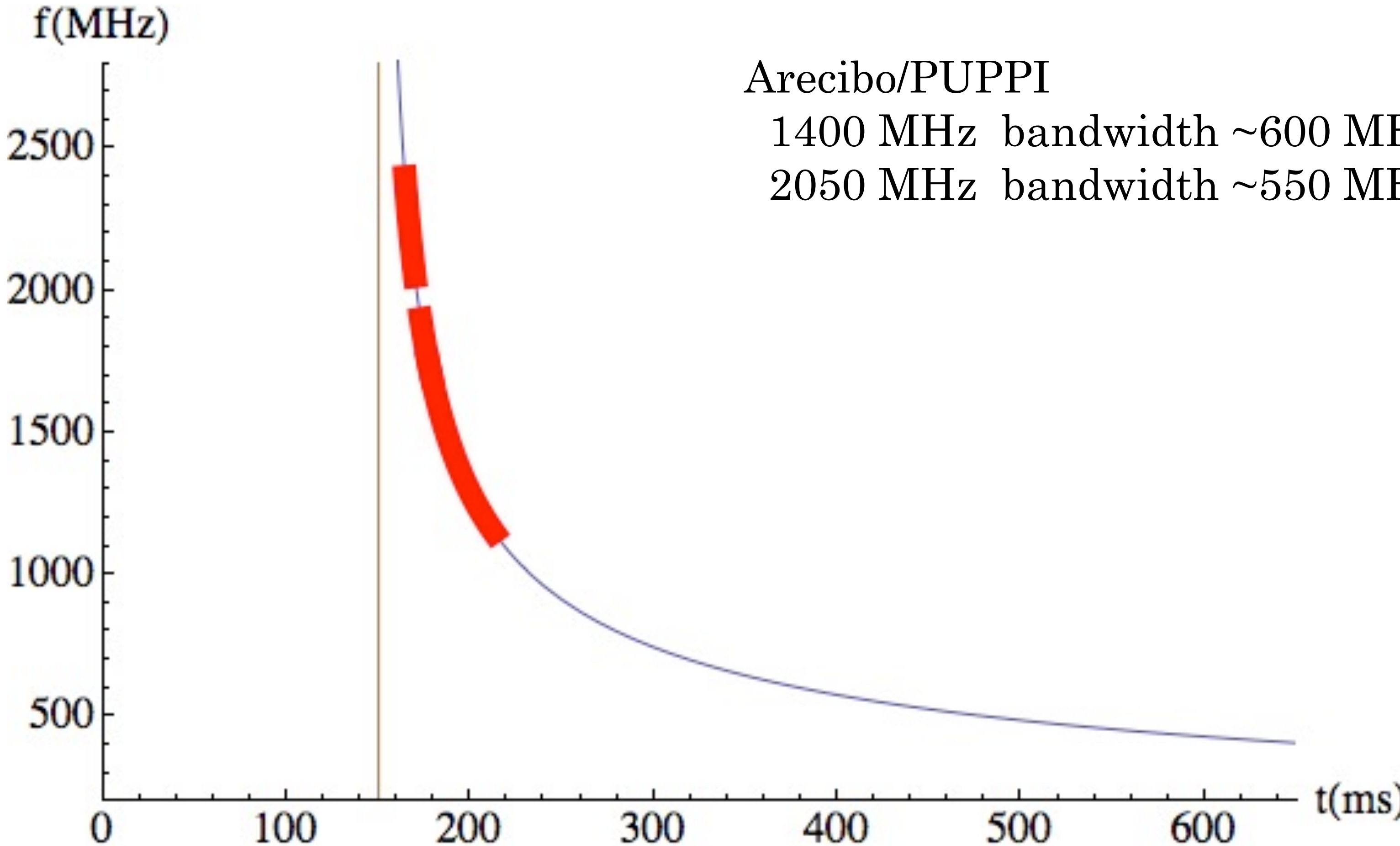


$$t_f = t_\infty + DM / 2.41\times10^{-4}\,[f(MHz)]^2$$

Arecibo/PUPPI

1400 MHz bandwidth ~600 MHz

2050 MHz bandwidth ~550 MHz



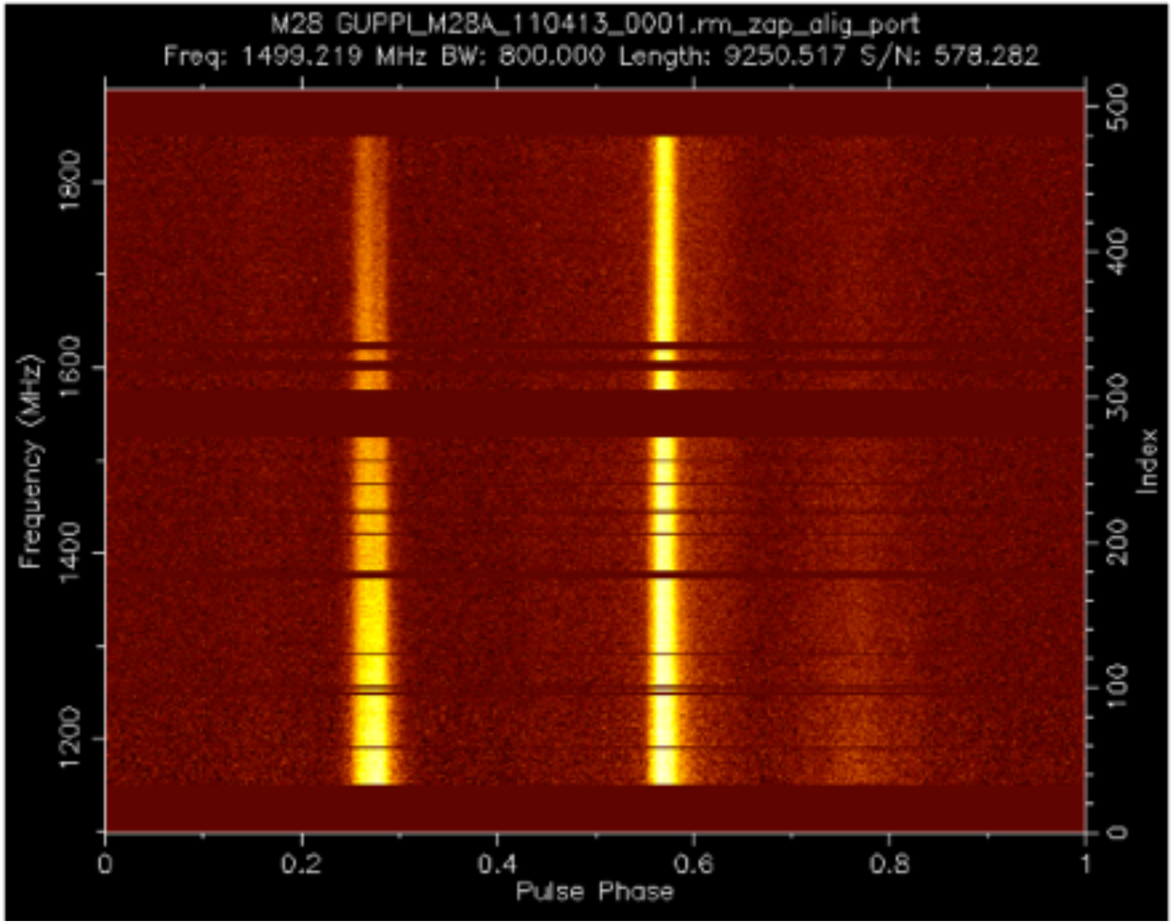


Figure: Tim Pennucci

In the works: Broadband timing code

- Profile variation over the band
  - A possible standard profile model: sum of Gaussian components with properties which vary over the band
- Cross correlate standard profile to data
  - Simultaneously fit for time shift *and DM shift*
  - Work in Fourier domain (similar to fftfit)

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DM variations are just one aspect of the corruption of pulsar signals by the ISM.

Hemberger & Stinebring 2008

(One of the scariest plots in the history of pulsar timing!)

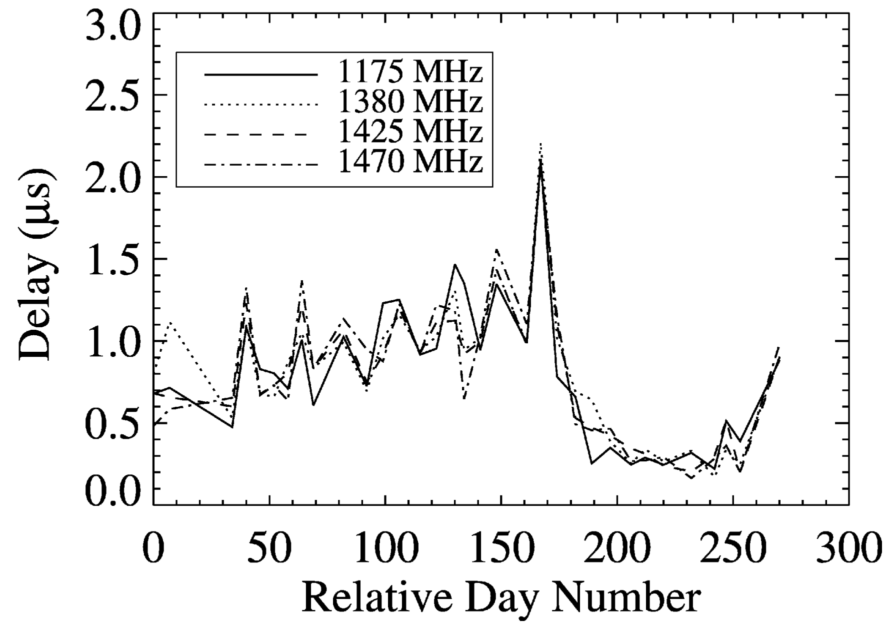

FIG. 2.—Scattering delay, τ_{ss}, as a function of time. The four frequencies were offset in average delay because of the frequency dependence of scattering. They have been aligned as shown here by performing a least-squares fit to a one-parameter function of the form $\tau_{ss} \propto \nu^{-\alpha}$. The best-fit value was $\alpha = 3.6 \pm 0.2$. The standard deviation for all the data is 100 ns. All delays have been referenced to 1380 MHz.

End of talk…

… beginning of discussion.

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