Nanohertz Gravitational Waves and Pulsar Timing

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Outline

Pulsar Timing and Gravitational Waves

NANOGrav GW/PTA Project

Improved Instrumentation for Pulsar Timing

Systematic Timing Effects / ISM

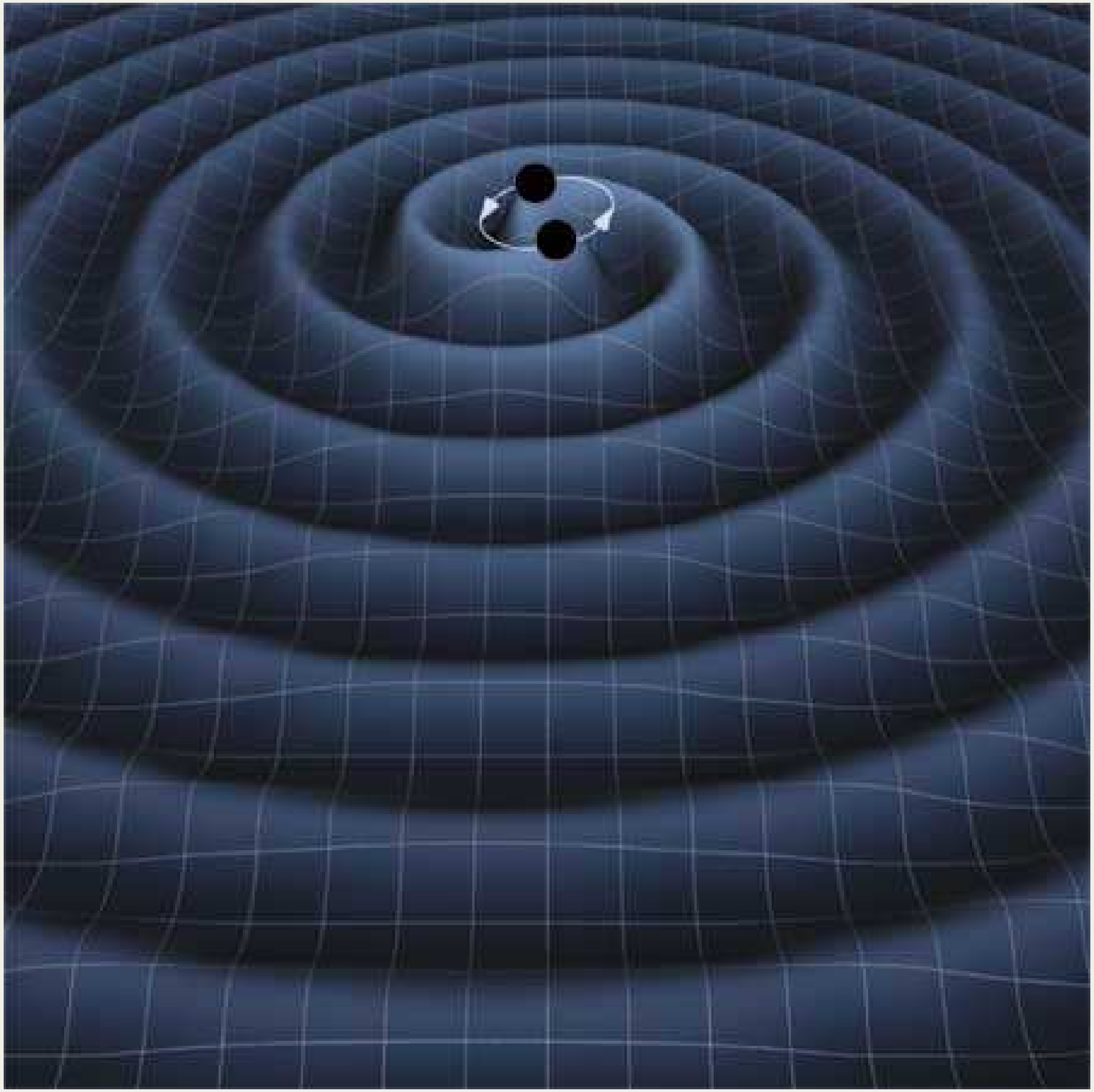
Advances in Pulsar Spectroscopy

Observational Results

Collaborators:

- GW: NANOGrav collaboration (`http://www.nanograv.org`)
- Instrumentation: S. Ransom, R. McCullough, J. Ford, J. Ray, R. Duplain, P. Brandt
- ISM: M. Walker, W. van Straten

Gravitational Waves



Gravitational Waves

Gravitational waves are . . .

- freely propagating ripples in the structure of spacetime.
- a prediction of General Relativity.
- generated by (almost) any moving mass/energy distribution.
- very weak (unless the source is very massive).
- as yet undetected! Detection would provide another confirmation of GR (fundamental physics), as well as information about the sources (astrophysics).

Indirect GW Evidence

4 *Weisberg & Taylor*

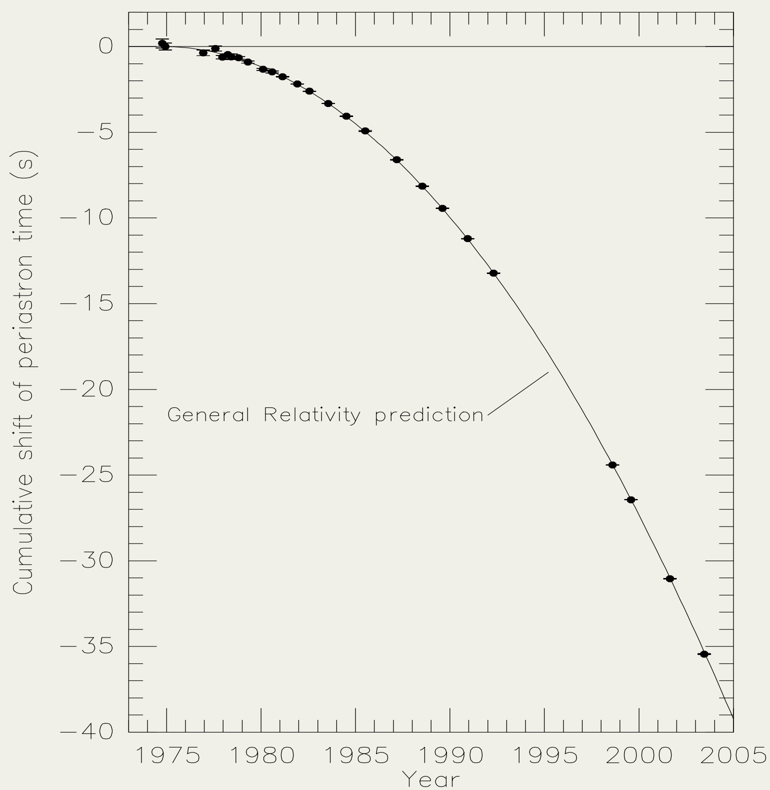


Figure 1. Orbital decay of PSR B1913+16. The data points indicate the observed change in the epoch of periastron with date while the parabola illustrates the theoretically expected change in epoch for a system emitting gravitational radiation, according to general relativity.

Orbital decay of PSR B1913+16 exactly matches expected GW emission.

Very strong evidence for GW existence, but not a *direct detection*.

Direct detection still not successful, although many are trying. . .

GW Detectors

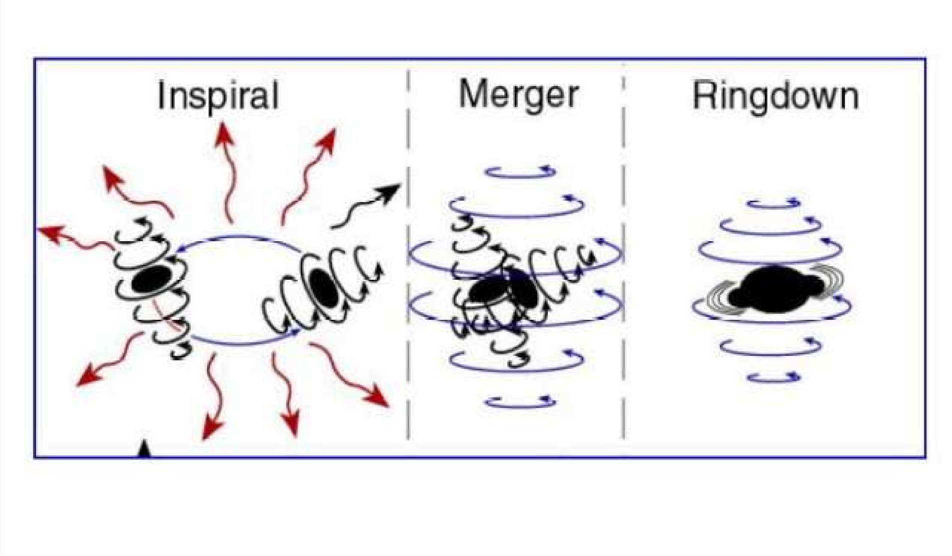
- LIGO = Laser Interferometer Gravitational Wave Observatory
  - $\nu_{GW} \sim$ kHz
  - Main targets are galactic sources (WD, NS, BH binaries)
  - Currently operating, major upgrade planned.

- LISA = Laser Interferometer Space Antenna
  - $\nu_{GW} \sim$ mHz
  - Both galactic and extragalactic (MBH) sources.
  - Still in planning stages.

- PTA = Pulsar Timing Array(s)
  - $\nu_{GW} \sim$ nHz
  - Extragalactic/cosmological sources (MBH, cosmic strings)
  - Several ongoing international efforts: NANOGrav (N. America), PPTA (Parkes), EPTA (Europe).

Stochastic MBH-MBH merger background

Following galaxy mergers . . .



At orbital freq Ω;
binary emits GW with amplitude $h \propto \Omega^{2/3}$;
evolution timescale $\tau_{GW} \propto \Omega^{-8/3}$.
Sum over many systems results in a stochastic spectrum with $h(\nu) \propto \nu^{-2/3}$. Overall amplitude less certain.

GW Spectrum

- Units:
  - Dimensionless strain tensor $h_{\mu\nu}(x,t)$.
  - Fractional closure energy density (per $\log\nu$): $\Omega_{GW}(\nu)$, dimensionless.
  - GW spectral power: $S_h(\nu)$, units h^2 Hz^{-1}.
  - Characteristic strain: $h_c(\nu) = \sqrt{\nu S_h(\nu)}$, dimensionless.
- Order-of-magnitude for pulsar timing $\delta t/T \sim h_c(T^{-1})$.

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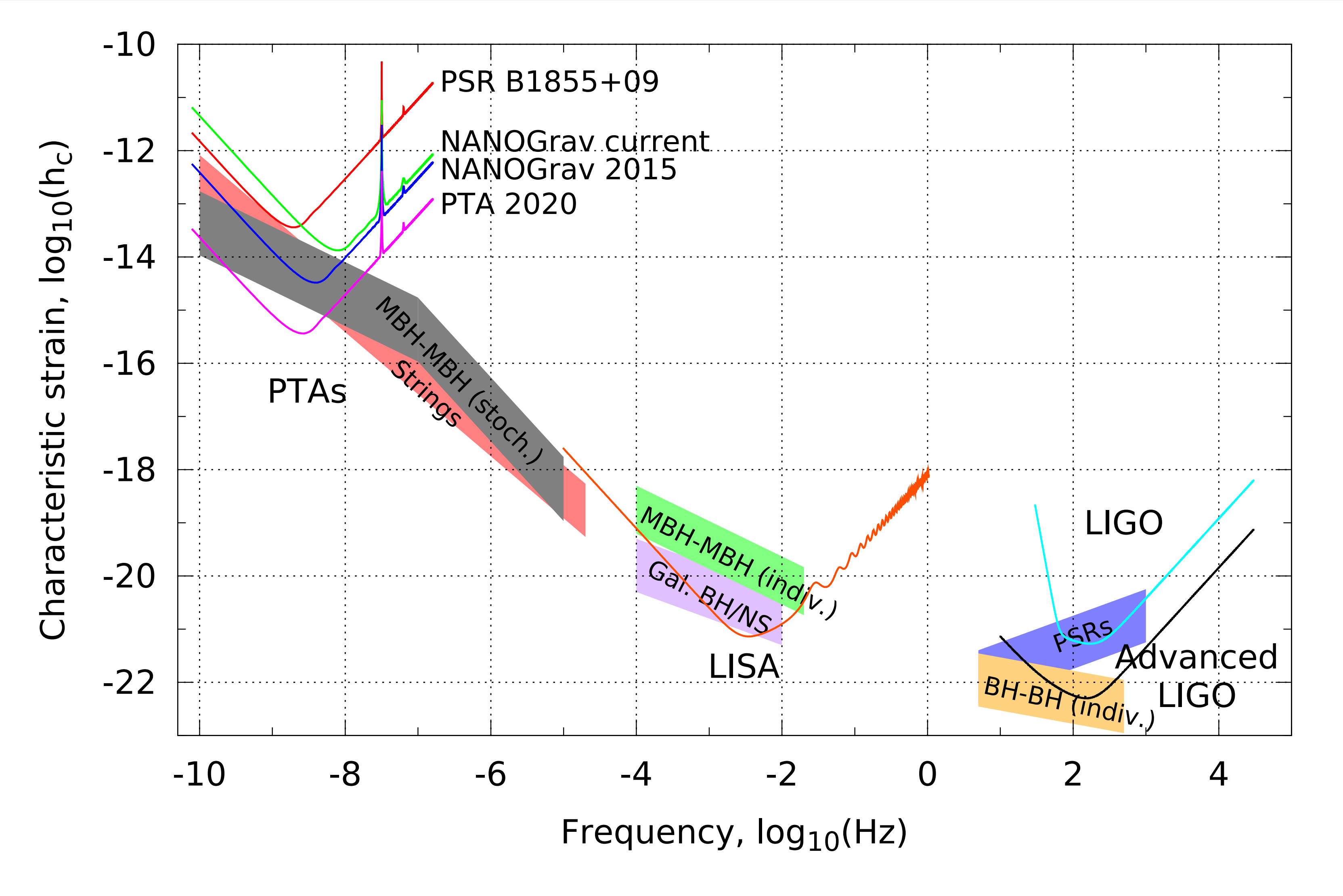
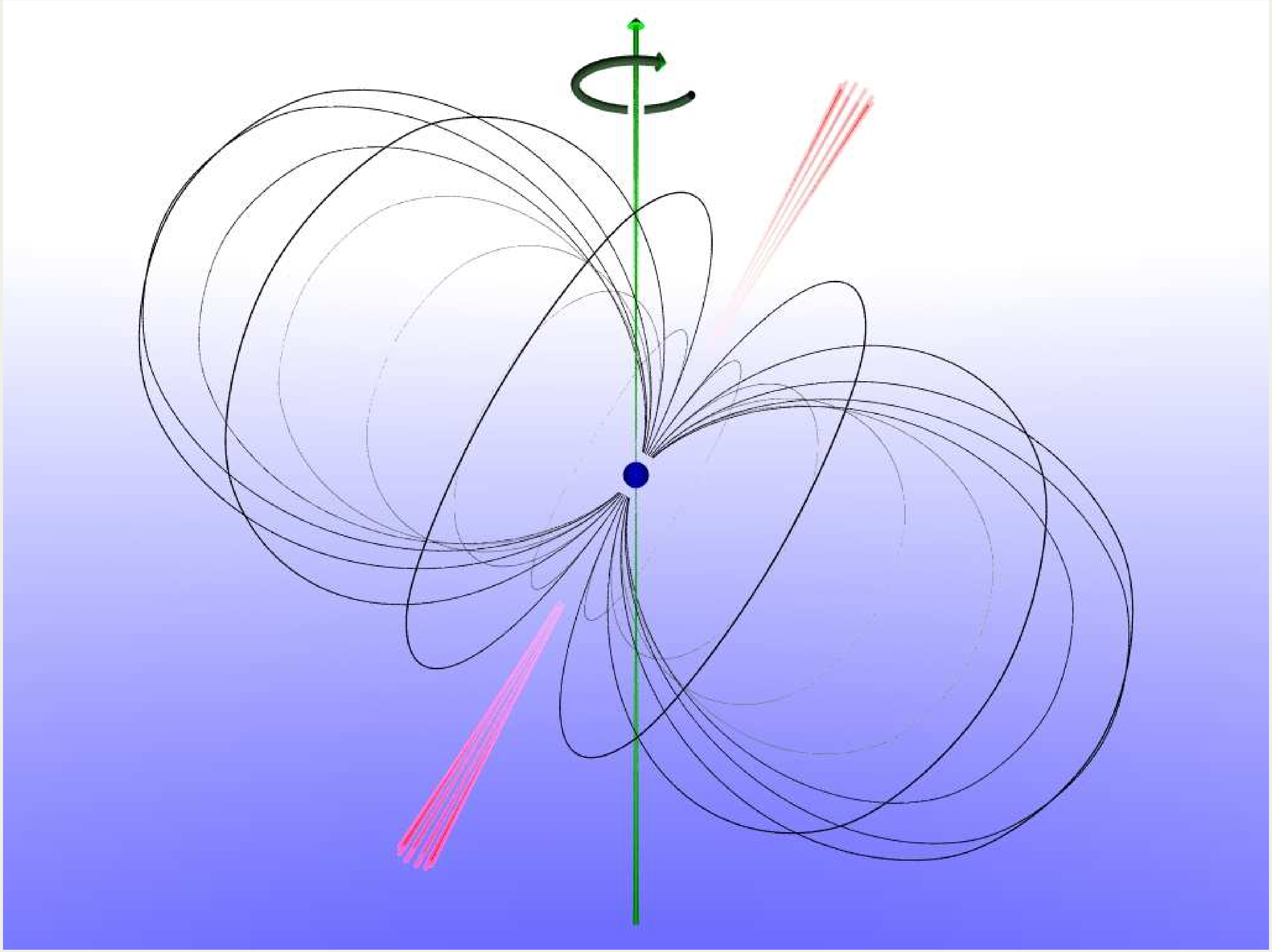
- Expected amplitude from stochastic MBH merger background $h_c(1\ \mathrm{y}^{-1}) \sim 10^{-16} - 10^{-15}$ (Jaffe & Backer 2003, Wyithe & Loeb 2003, Sesana et al. 2008).
- Other potential nHz sources are cosmic strings, single close/eccentric MBH systems, and “the unknown.”

GW Spectrum

Detector complementarity:



Pulsars as GW detectors



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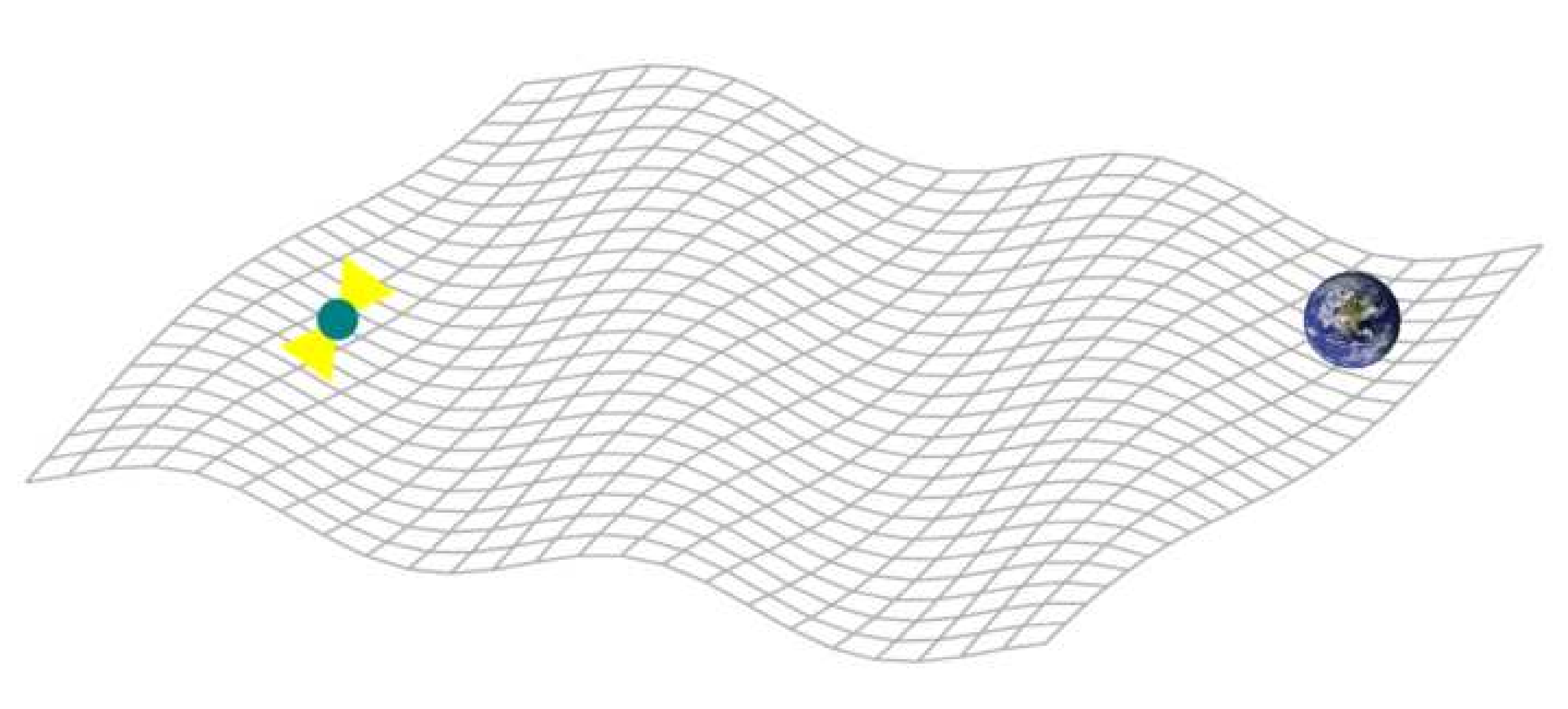


Radio pulses travelling through GW to Earth acquire additional delays.

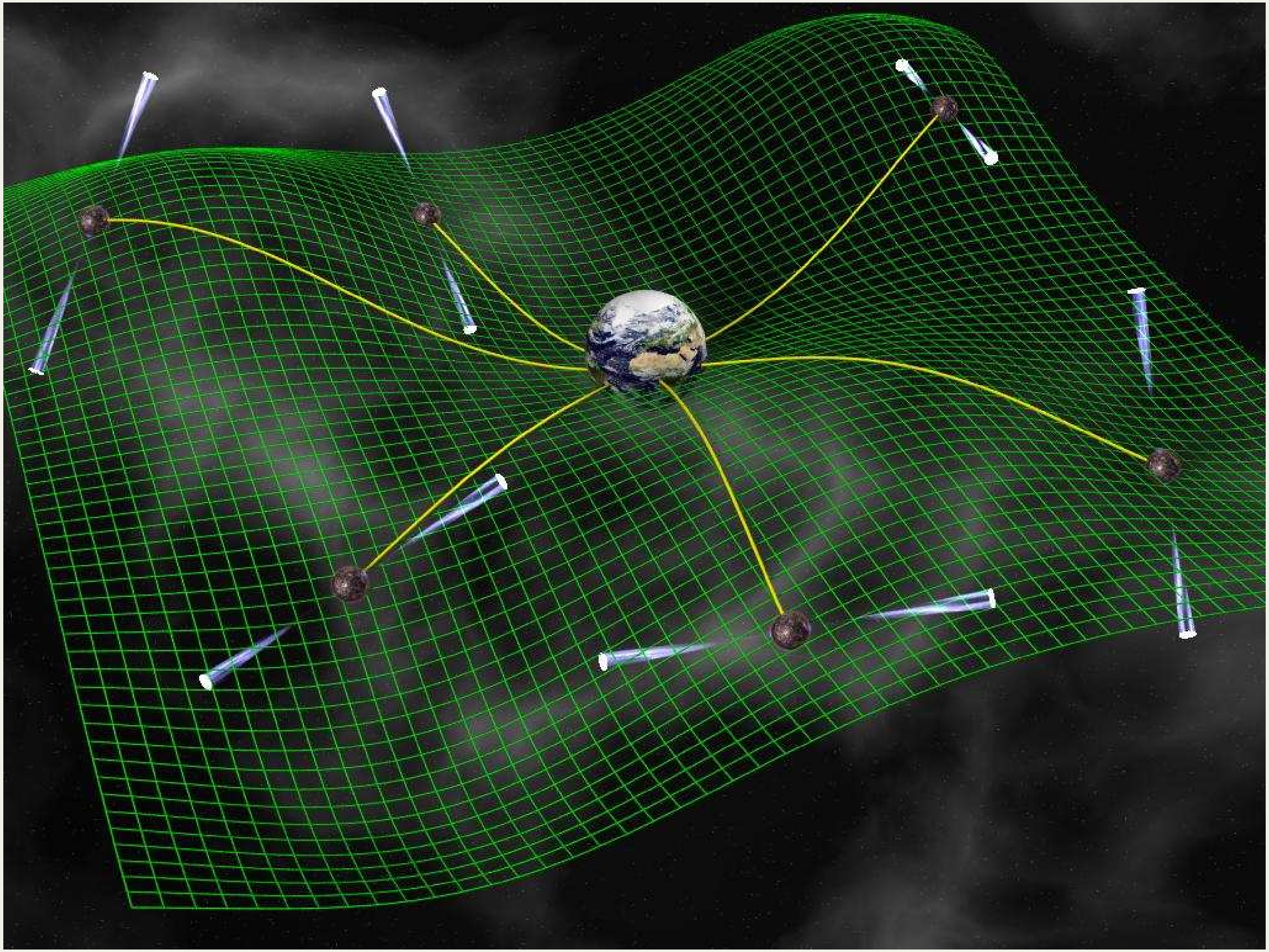
Effect on EM waves

- GW along an electromagnetic wave's path alters the travel time:

$$\Delta T = -\frac{1}{2} n_i n_j \int_0^d h_{ij}(x,t) dr$$

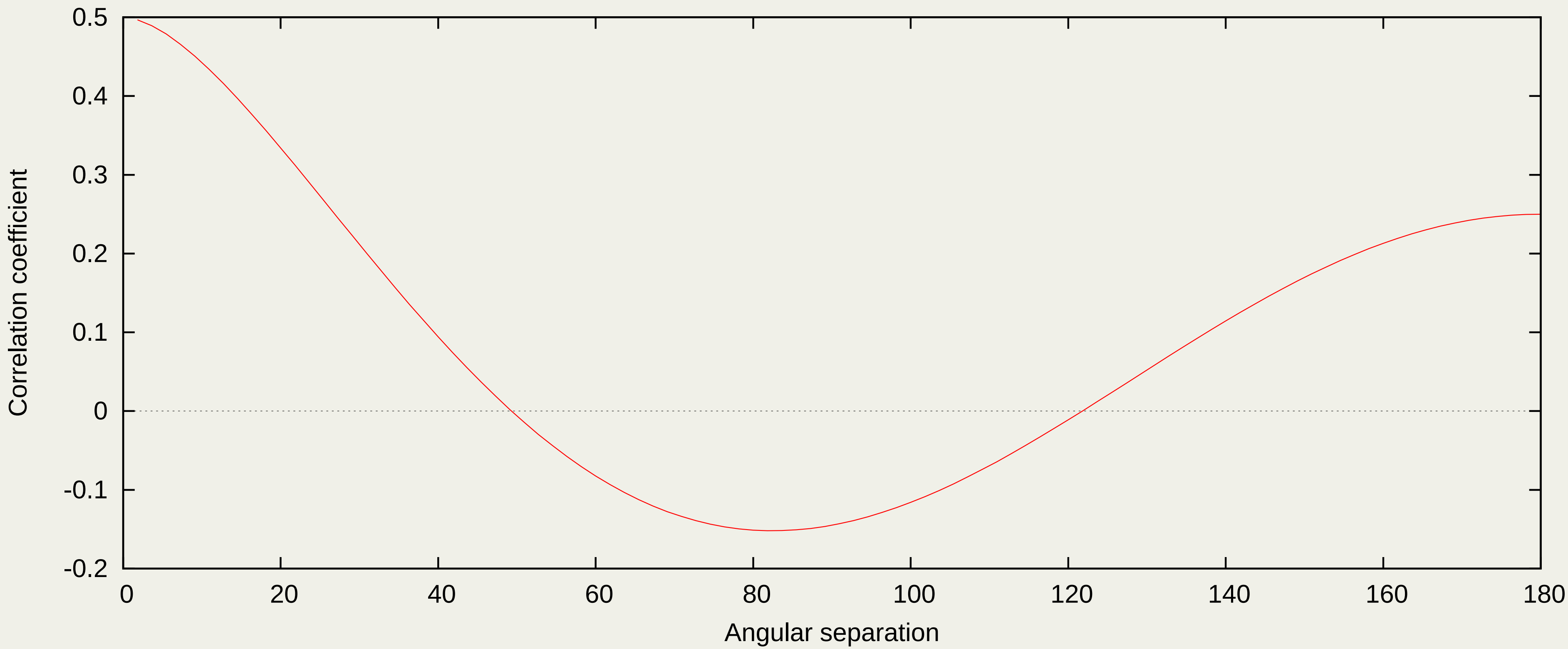
- ΔT varies with time, so we can potentially see its effect in measured radio pulse times of arrival.
- This is the principle behind all modern GW detectors. In the pulsar case, there are many GW wavelengths along the path.
- Very bright, stable pulsars (MSPs) are needed if this is to be successful: $h \sim 10^{-15} \sim 30 \text{ ns}/1 \text{ year}$.

Pulsar Timing Array



Pulsar Timing Array

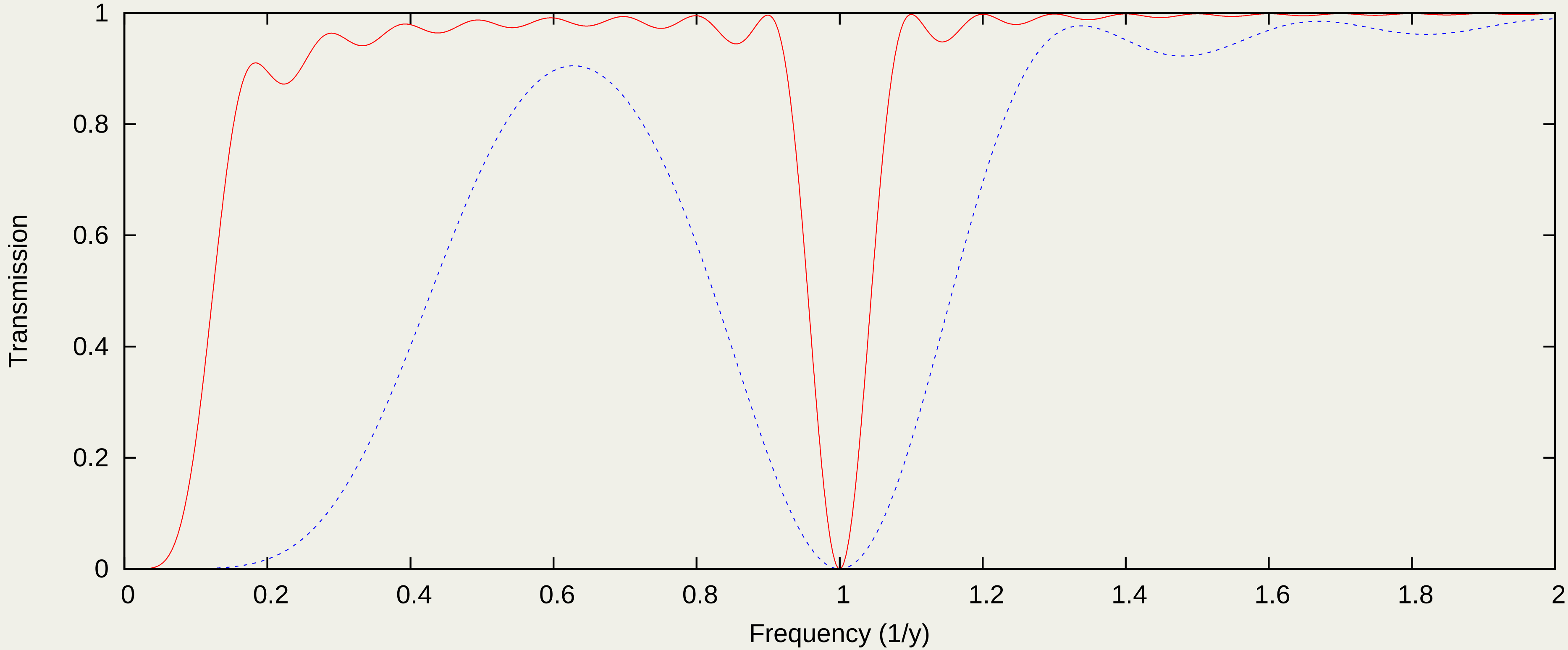
GW-induced timing fluctuations will be correlated between different pulsars (Hellings & Downs, 1982; isotropic GWB):



This method makes GW *detection* possible!
In this case, sensitivity $h_c \sim \delta t/(T\sqrt{N_{psr}})$.

Effect of the timing model

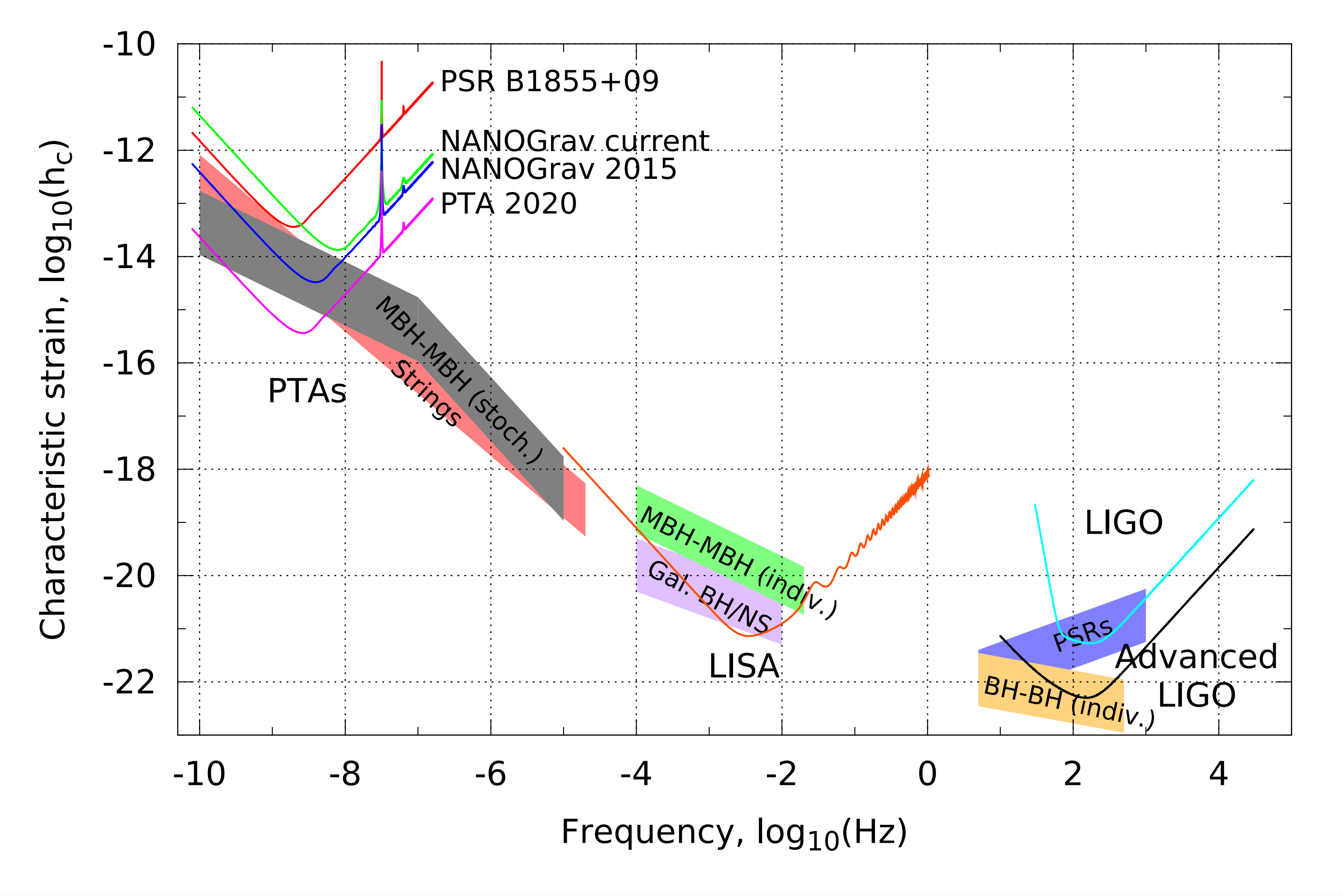
We don’t know pulsar spin period, spindown rate, etc *a priori*. Fitting for these removes GW power from the signal, and determines PTA sensitivity vs ν shape.



Fit residuals will include contribution from GW.

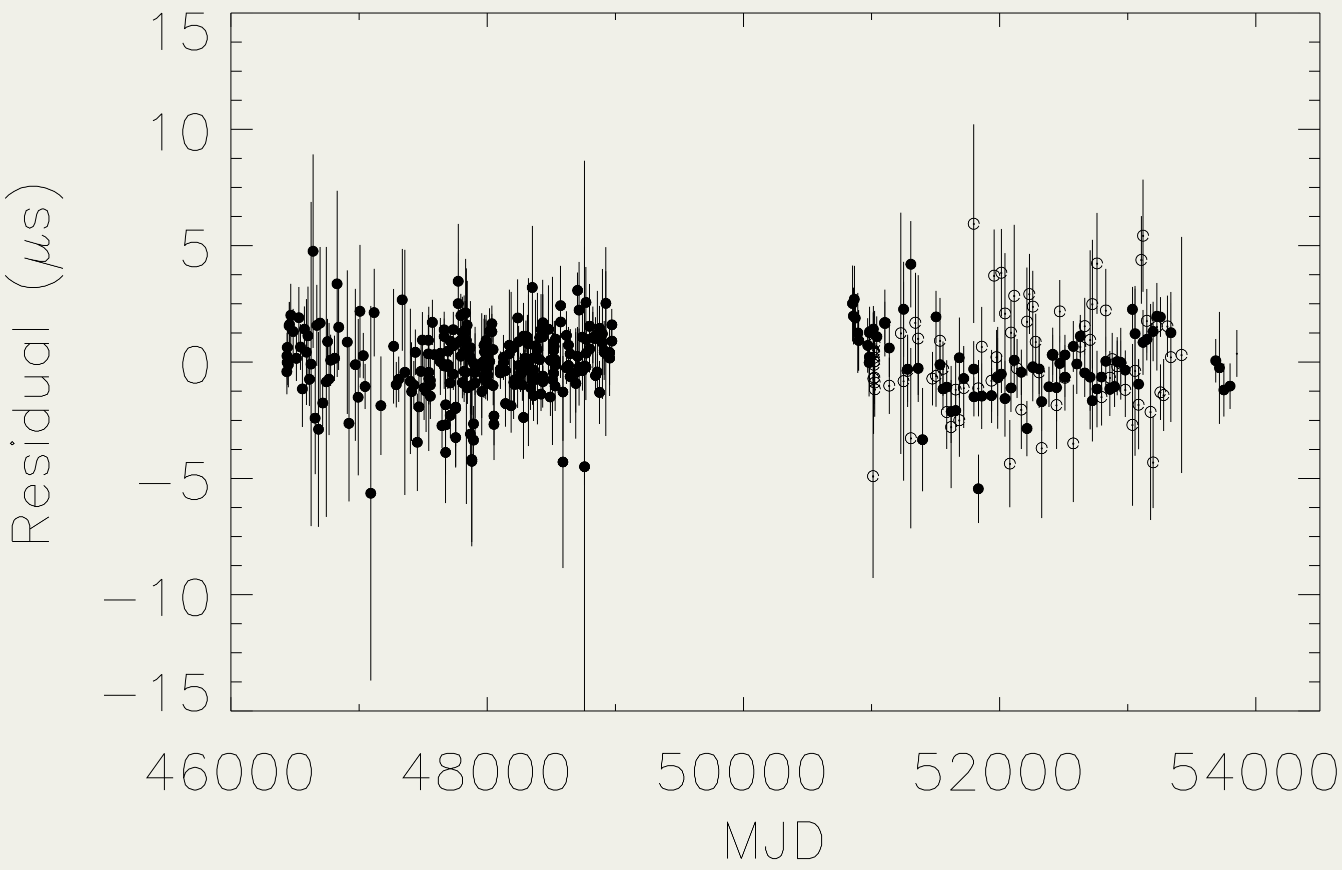
PTA Sensitivity

PTA sensitivity vs freq shape:



Single Pulsar Limits

Current best upper limits from timing PSR B1855+09 for 20 years (Kaspi et al. 1994, Lommen 2002, . . .): $h_c(1\ \mathrm{y}^{-1}) < 5 \times 10^{-15}$



NANOGrav

The North American Nanohertz Observatory for Gravitational Waves

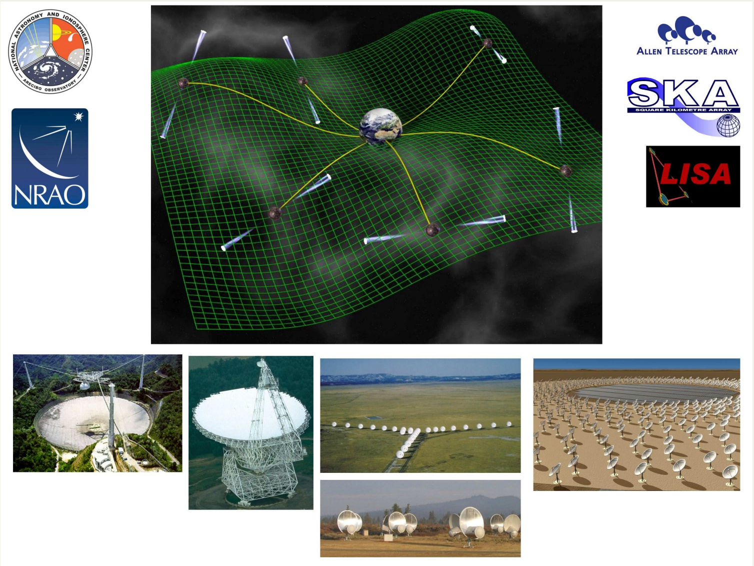
- Formally organized 2007
- 24 members, 14 institutions in US and Canada
- Main purpose: Increase visibility of PTA science. (Astro2010, conferences, NSF grants, . . .)

`http://www.nanograv.org`

Gravitational Wave Astronomy Using Pulsars: Massive Black Hole Mergers & the Early Universe

A White Paper for the Astronomy & Astrophysics Decadal Survey

NANOGrav:
The North American Nanohertz Observatory for Gravitational Waves



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Telescopes

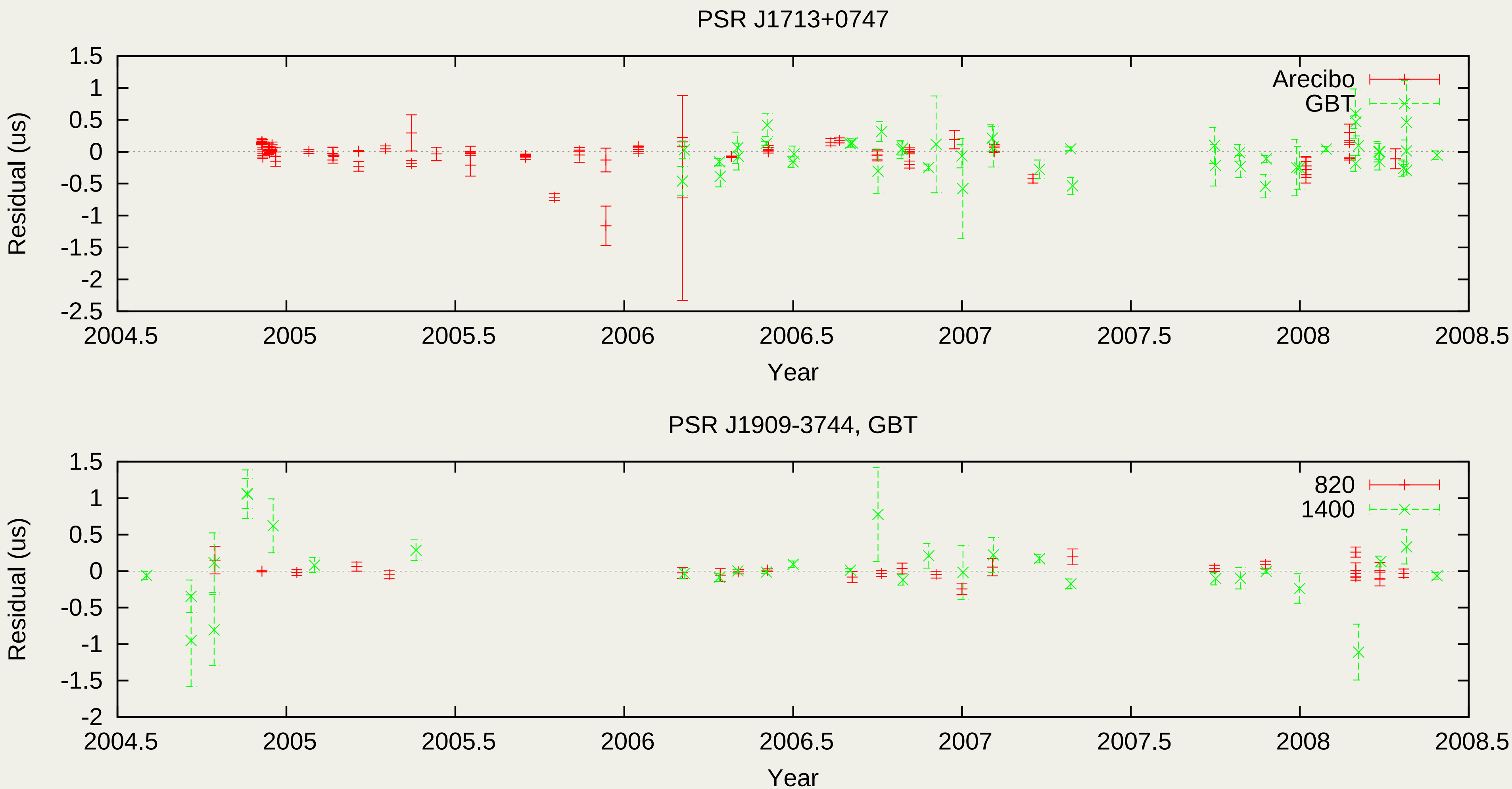
Telescopes

NANOGrav Observations

- Observe a set of 17 MSPs $\sim$monthly.
  - Sources chosen from bright northern MSPs.
  - 12 GBT, 7 Arecibo (2 overlap).
  - Most are binaries: Opportunity for non-GW science as well.
- Observations started in 2004-2005 using ASP backends.
- Typical observing frequencies of 820, 1400 MHz (GBT) and 430, 1400, 2300 MHz (Arecibo).
- $\sim$30 minutes per frequency per source.
- Timing residuals range from $\sim$100 ns to 1.5 μs.
  - GW results dominated by best $\sim$3 pulsars.

Timing Results

Best NANOGrav timing results have RMS ~ 100 ns:

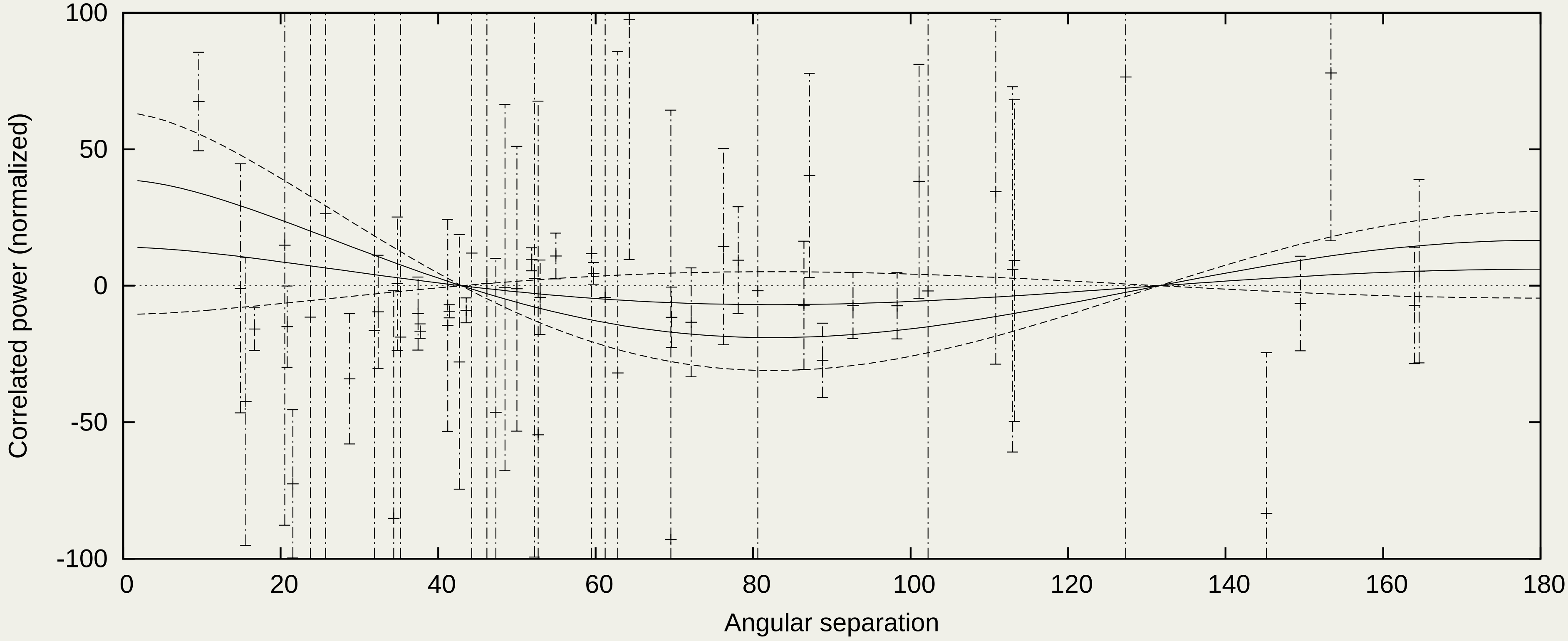


Order-of-magnitude GW sensitivity is $\sim \frac{\delta t}{T} N_{psr}^{-1/2}$.

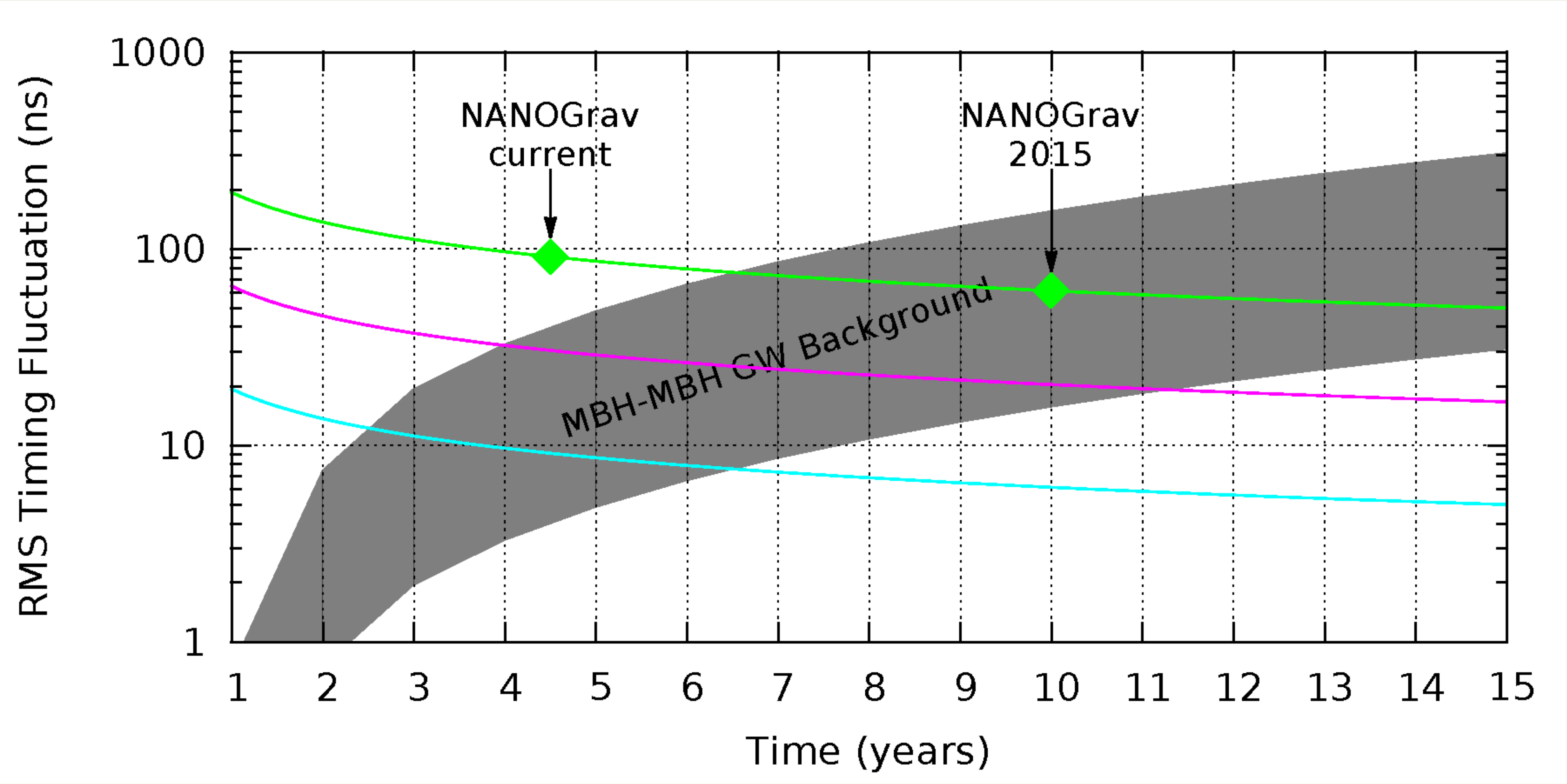
Timing Array Limits

Correlation analysis of first ∼4 years of NANOGrav data:

$h_c(1\ \mathrm{y}^{-1}) < 7 \times 10^{-15}$

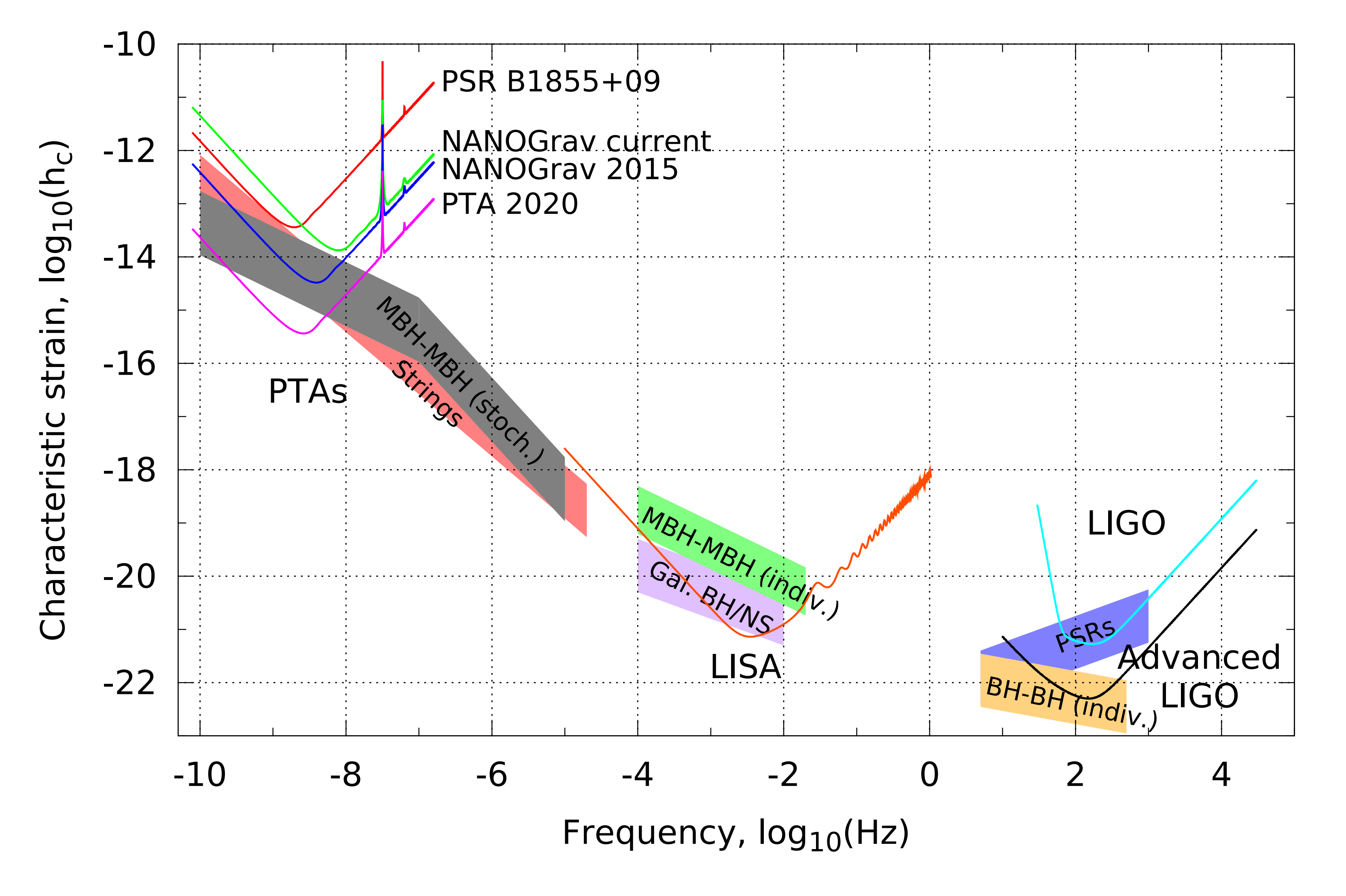


Improvement with time



GW Spectrum

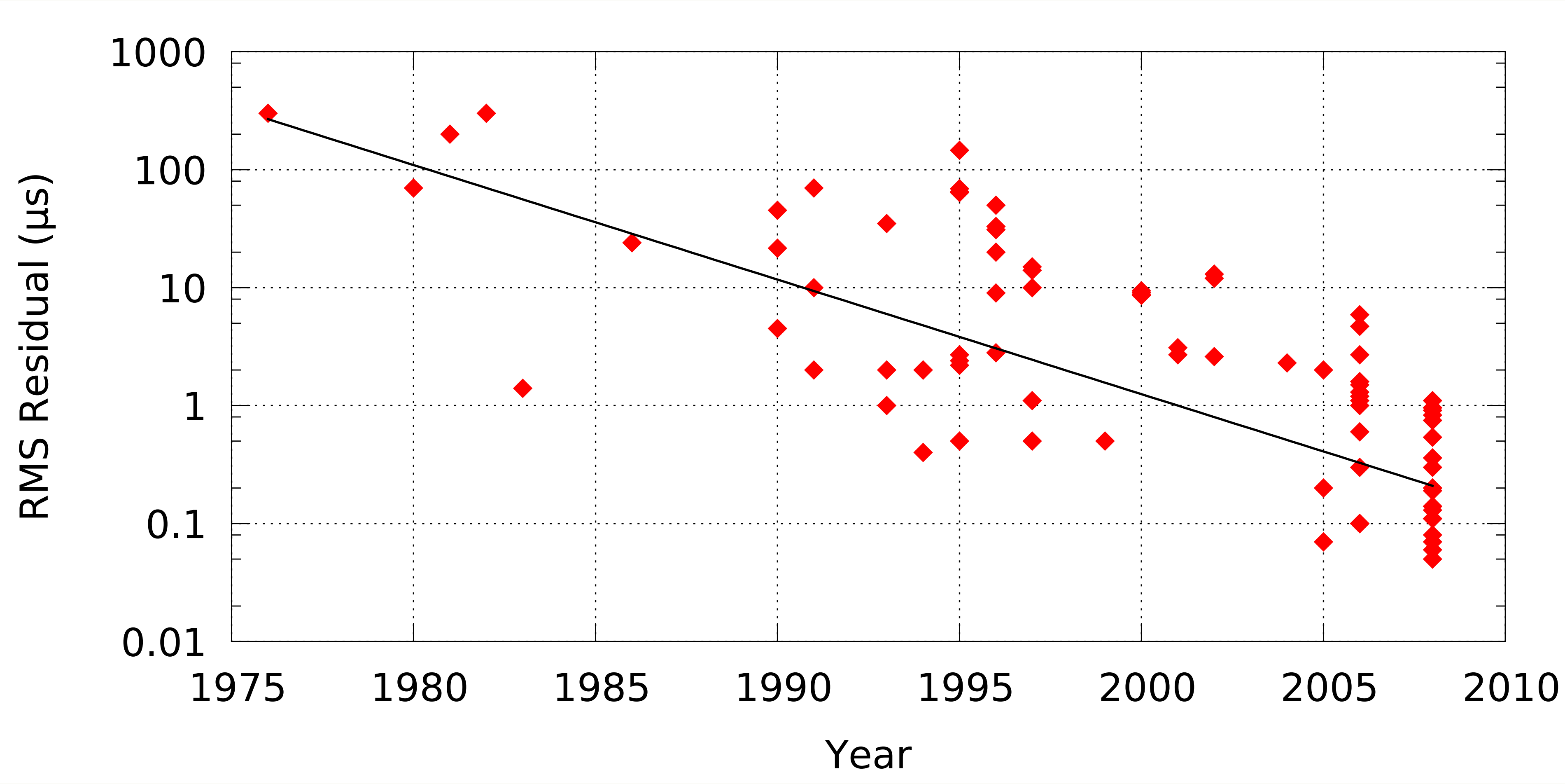
Improvement with time:



Timing Array Summary

- Current NANOGrav PTA limits are comparable to the 20-year single pulsar limit.
- Another $\sim$3–5 years reaches into plausible detection territory.
- Jenet et al. (2005) estimate that we need 20–40 pulsars at 100 ns for 5 years to ensure “robust” detection.
- More good-timing pulsars are needed.
  - Searching for new sources.
  - Increasing BW, G/T to improve currently known pulsars.
  - *Reduce systematic effects*, improve analysis algorithms.

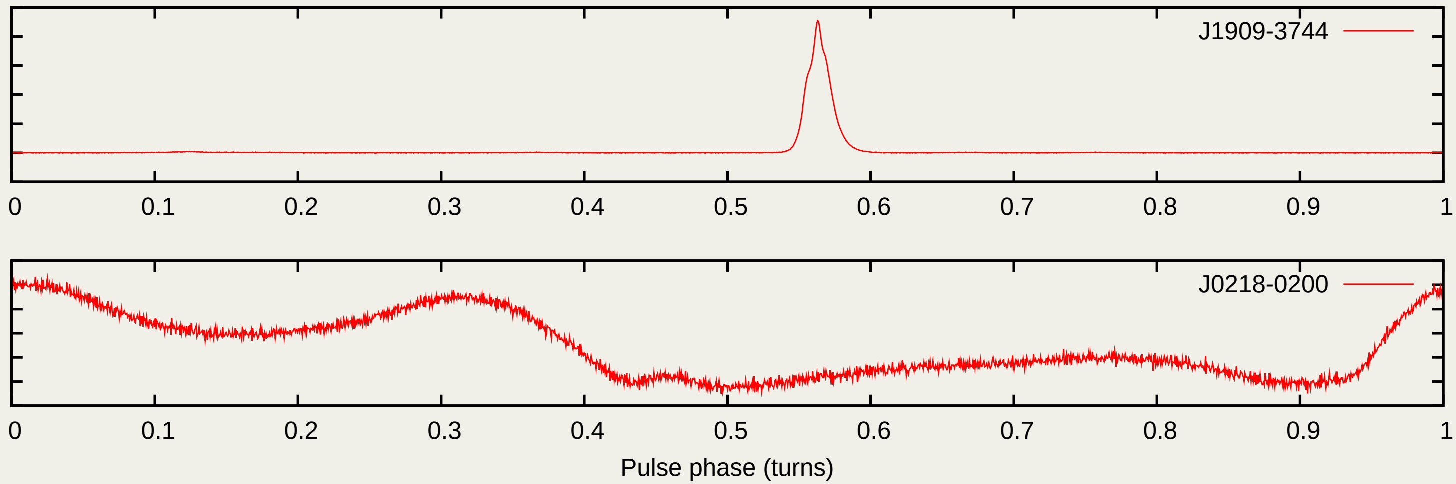
Pulsar Timing “Moore’s Law”



Improving Pulsar Timing

Increase S/N ratio:

- $\delta t \sim \frac{w}{\mathrm{SNR}} = w S_{psr} \frac{1}{\sqrt{Bt}} \frac{G}{T_{sys}}$



Reduce systematics:

- Calibration/polarimetry, RFI, ISM, . . .

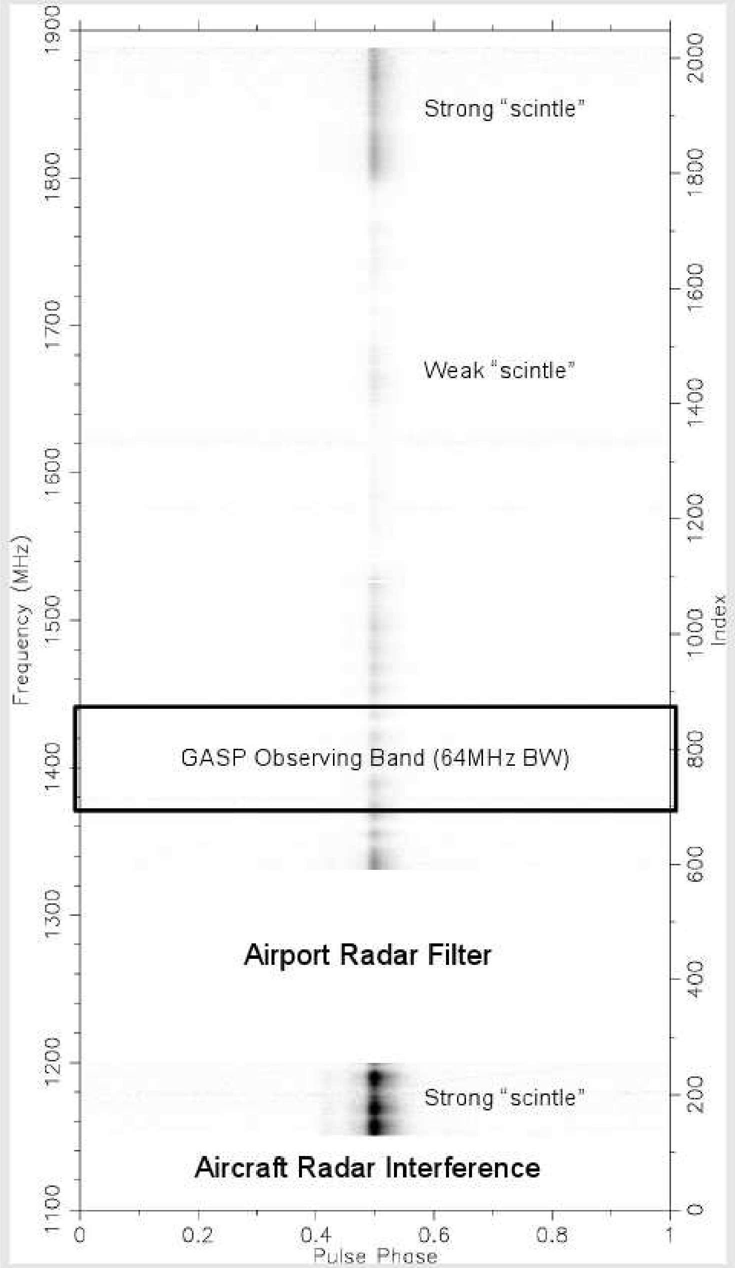
GUPPI

- ASP/GASP backends provide high-quality (8-bit, full-Stokes, coherent dedisp) data, but only $\sim$64 MHz total BW.
- GUPPI = the Green Bank Ultimate Pulsar Processing Instrument will handle up to 800 MHz.
  - Coherent dedispersion design uses flexible FPGA-based HW and GPU computing for processing.
  - *This is a non-trivial improvement over previous HW!*

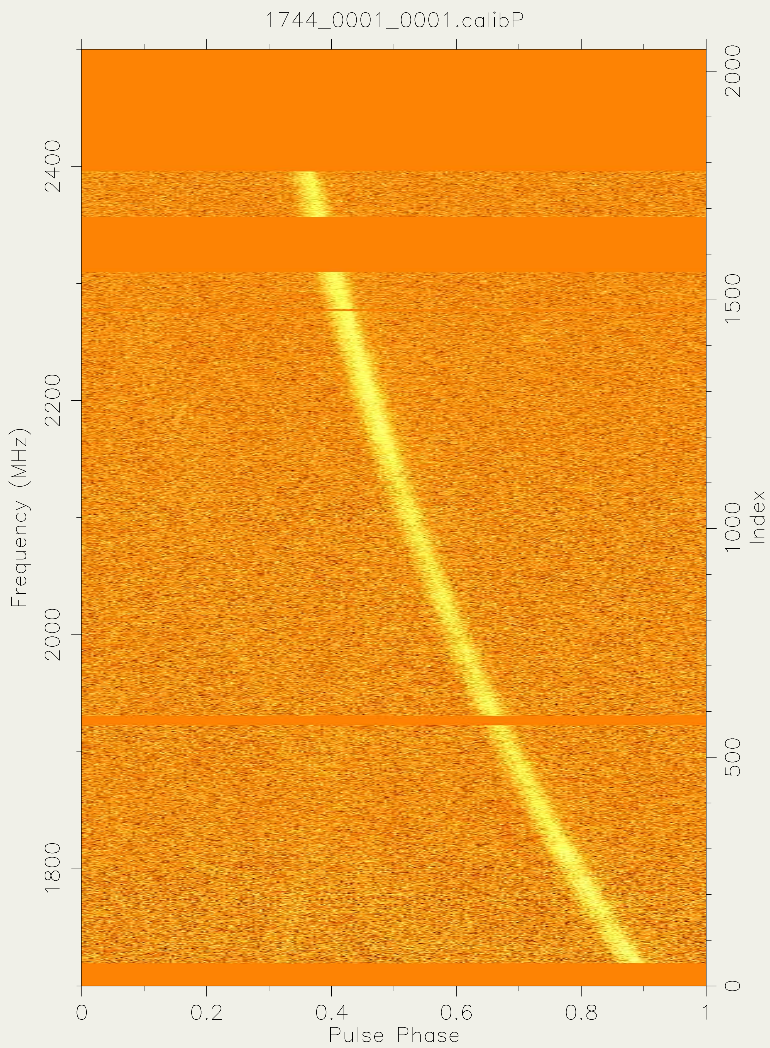
Bandwidth improvement

PSR J1713+0747, GBT/GUPPI:

Increased BW both improves S/N ratio as well as allows us to catch strong “scintles” more often.



Pulse Dispersion



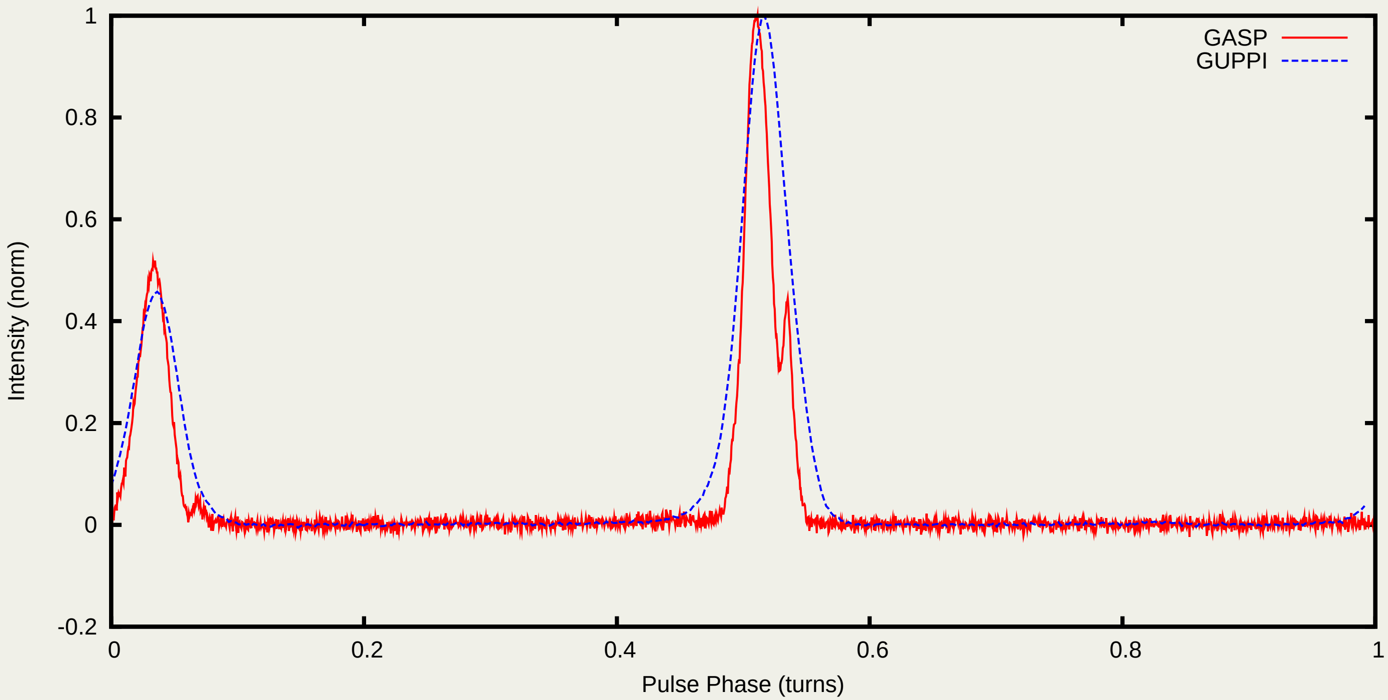
PSR J1744-1134, GBT/GUPPI

Higher frequency signal arrives earlier, due to plasma dispersion delay in the ISM.

Without correction (dedispersion), this leads to pulse smearing.

Coherent Dedispersion

Why is coherent dedispersion necessary?



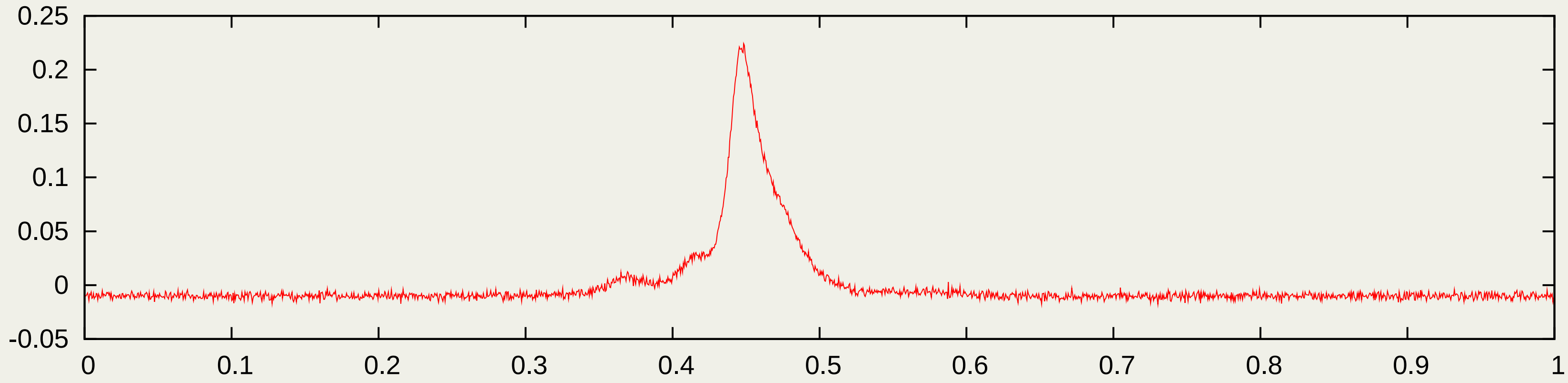
PSR B1937+21, GASP vs. (incoherent) GUPPI pulse profiles

GUPPI Status

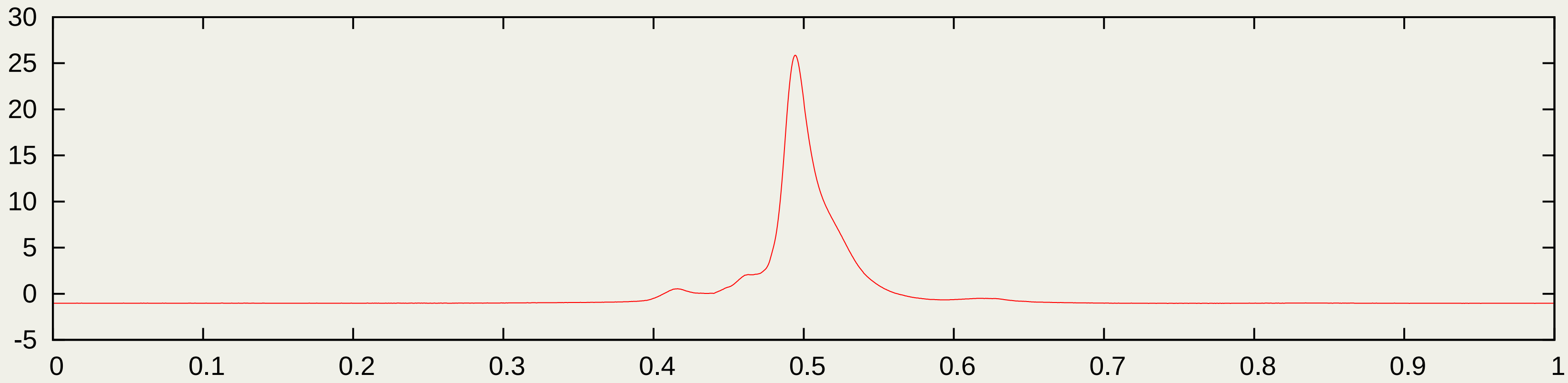
- “Phase I” incoherent/filterbank system currently in regular (near-daily) usage with GBT.
- “Phase II” coherent dedispersion system HW is ordered, will be tested this fall.

Systematic Timing Effects

We compute arrival times (TOAs) by matching data:



to a scaled, shifted “template”:



Any corruption in the measured profile shape can affect timing.

$100\ \mathrm{ns} \sim 10^{-5}$ turns.

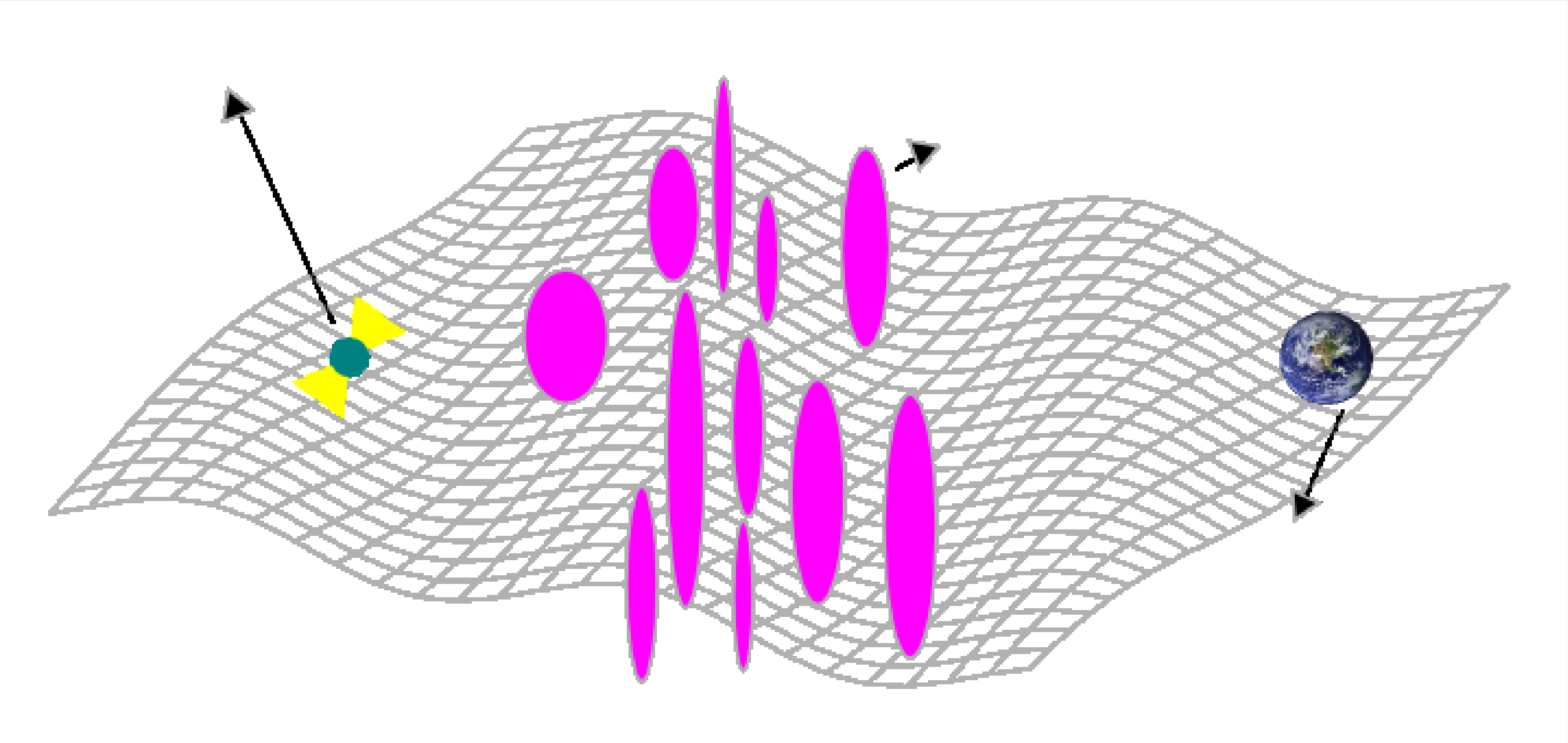
Systematic timing effects

- Local:
  - Polarimetry / calibration procedures
  - Radio-frequency interference
  - Instrumental effects

- ISM:
  - DM variation with time (and maybe frequency)
  - Scattering/scintillation
  - Refraction

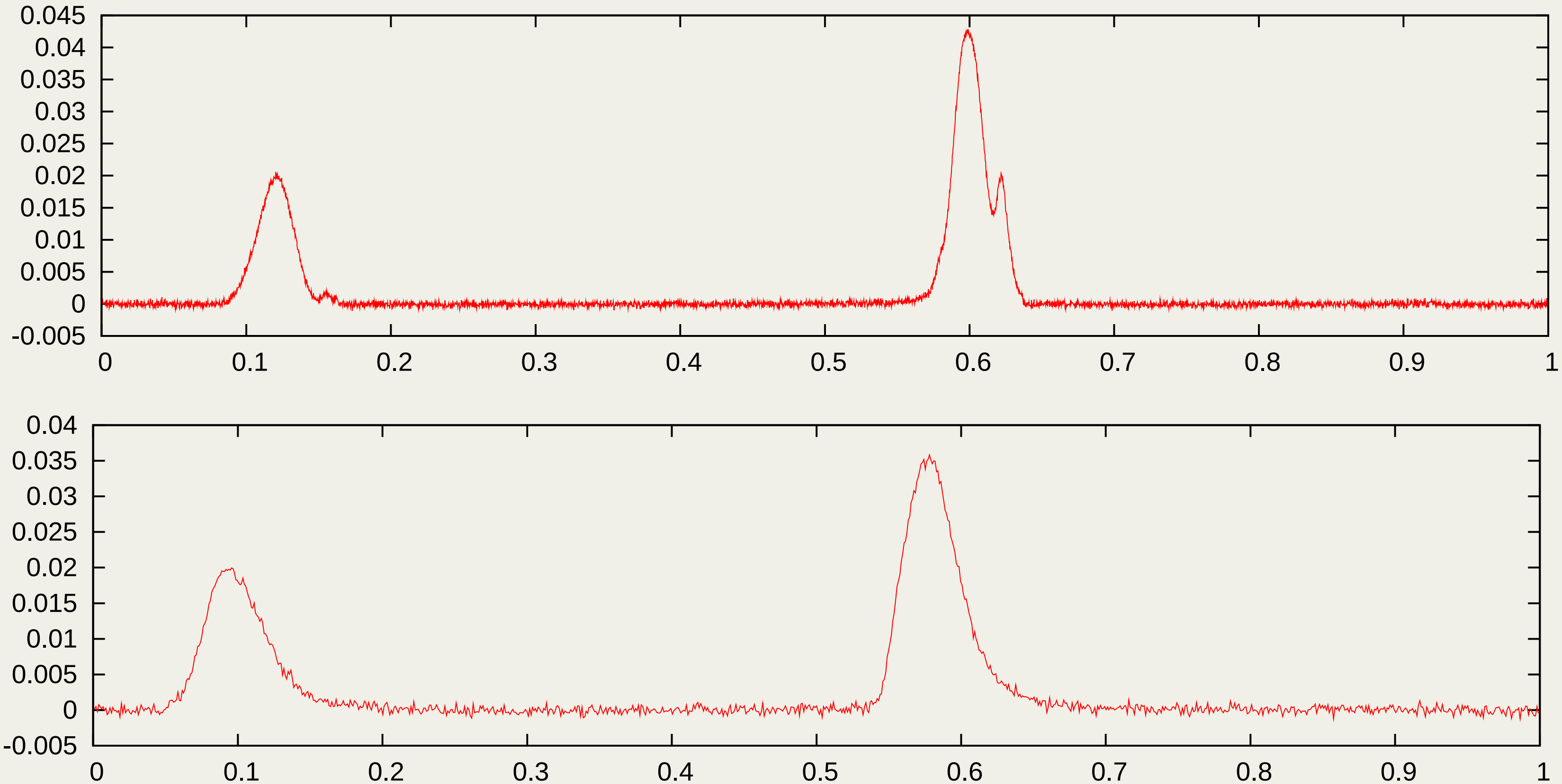
- Intrinsic:
  - Pulse-to-pulse “jitter”
  - “Timing noise”

ISM



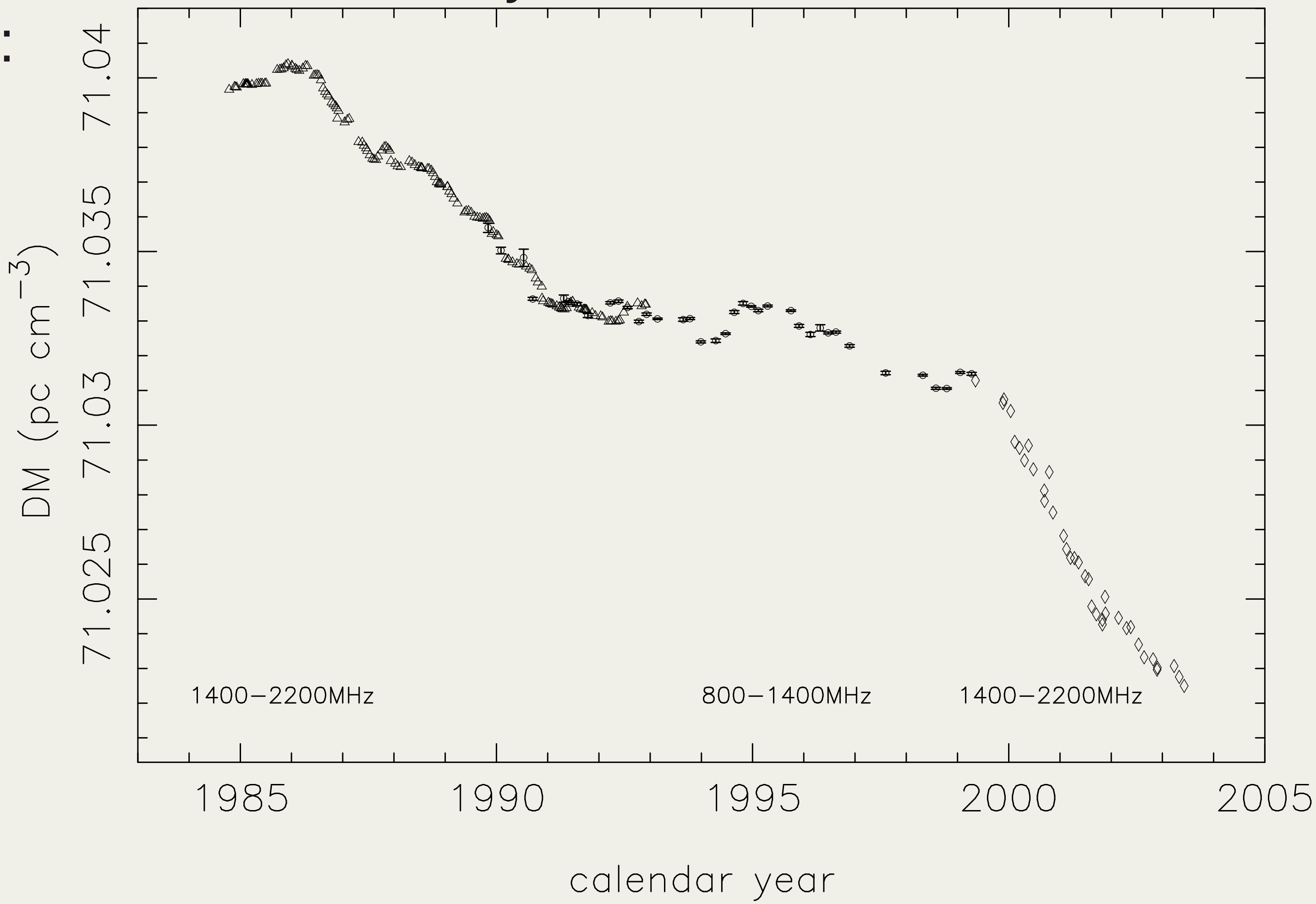
ISM effects

- Come from radio wave propagation through interstellar e^- plasma; strongly λ-dependent, based on plasma dispersion relation.
- Effects include $\mathrm{DM}(t)$, scattering/scintillation.
- One solution: Observe at higher RF, but psrs get weaker.



DM Variation

Total electron column density varies due to motions of Earth, PSR, and ISM:

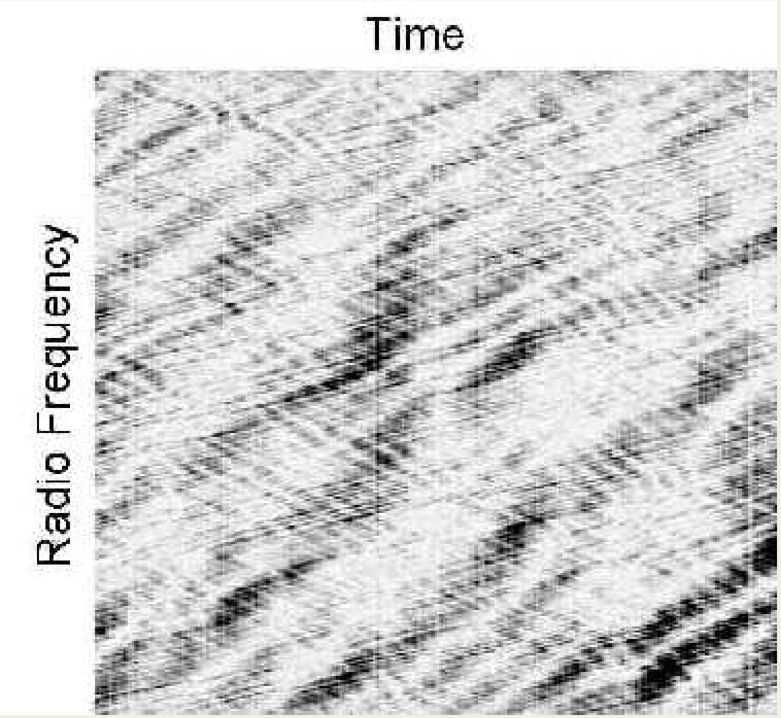


(PSR B1937+21; Ramachandran et al. 2006)

Can be measured/removed with multi-frequency timing measurements.

Scattering/Scintillation

Electron density variation transverse to the line-of-sight causes constructive/destructive interference:



(Walker et al. 2008)

Can be thought of as a (time-varying) “filter” with transfer function $H(\nu)$ or impulse response $h(t)$. This affects profile shapes!

Pulsar Spectroscopy

How to compute spectra from measured pulsar voltage signal $x(t)$:

Standard pulsar spectroscopy:

- Signal is divided into many radio frequency channels.
- In each channel, on-pulse and off-pulse flux are detected, integrated for some time and differenced (“gating”).
- Results in dynamic spectrum $S(t, \nu)$.

Limitations of this approach:

- Gate width and frequency resolution are coupled (via usual uncertainty principle).
- Discards all pulse shape information.
- Can only directly determine $|H(\nu)|^2$.

Pulsar Spectroscopy

In *cyclic spectroscopy*, we compute correlations as a function of pulse phase:

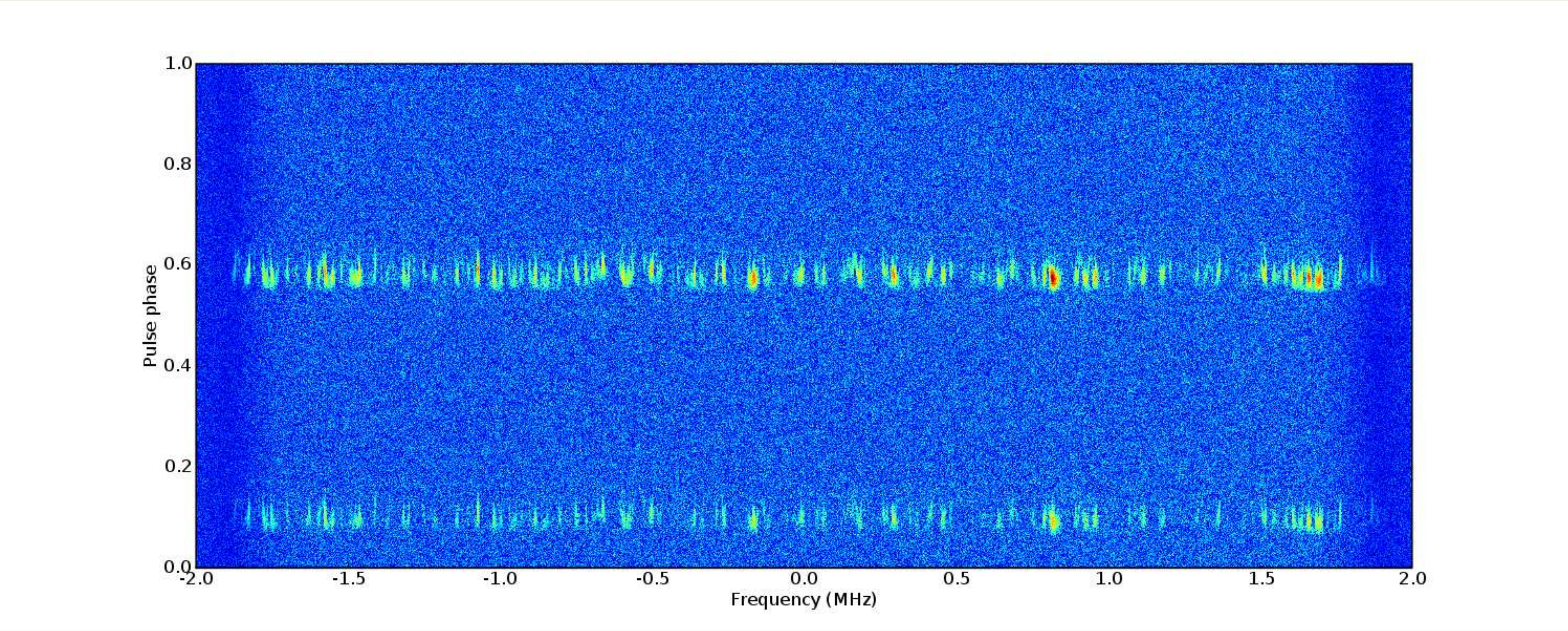
- Signal is delayed by many different lags τ.
- Each is cross-multiplied with original signal and averaged modulo the pulse period for some integration time ("folding").
- Results in periodic correlation $C(t, \tau, \phi) \rightarrow S(t, \nu, \phi)$.

Advantages of this approach:

- Number of lags (hence freq resolution) not constrained by pulse width or period.
- Makes full use of pulse shape information.
- Directly recovers $H(\nu)$ with phase!
- see reviews by Gardner (1991, 1992), Antoni (2007)

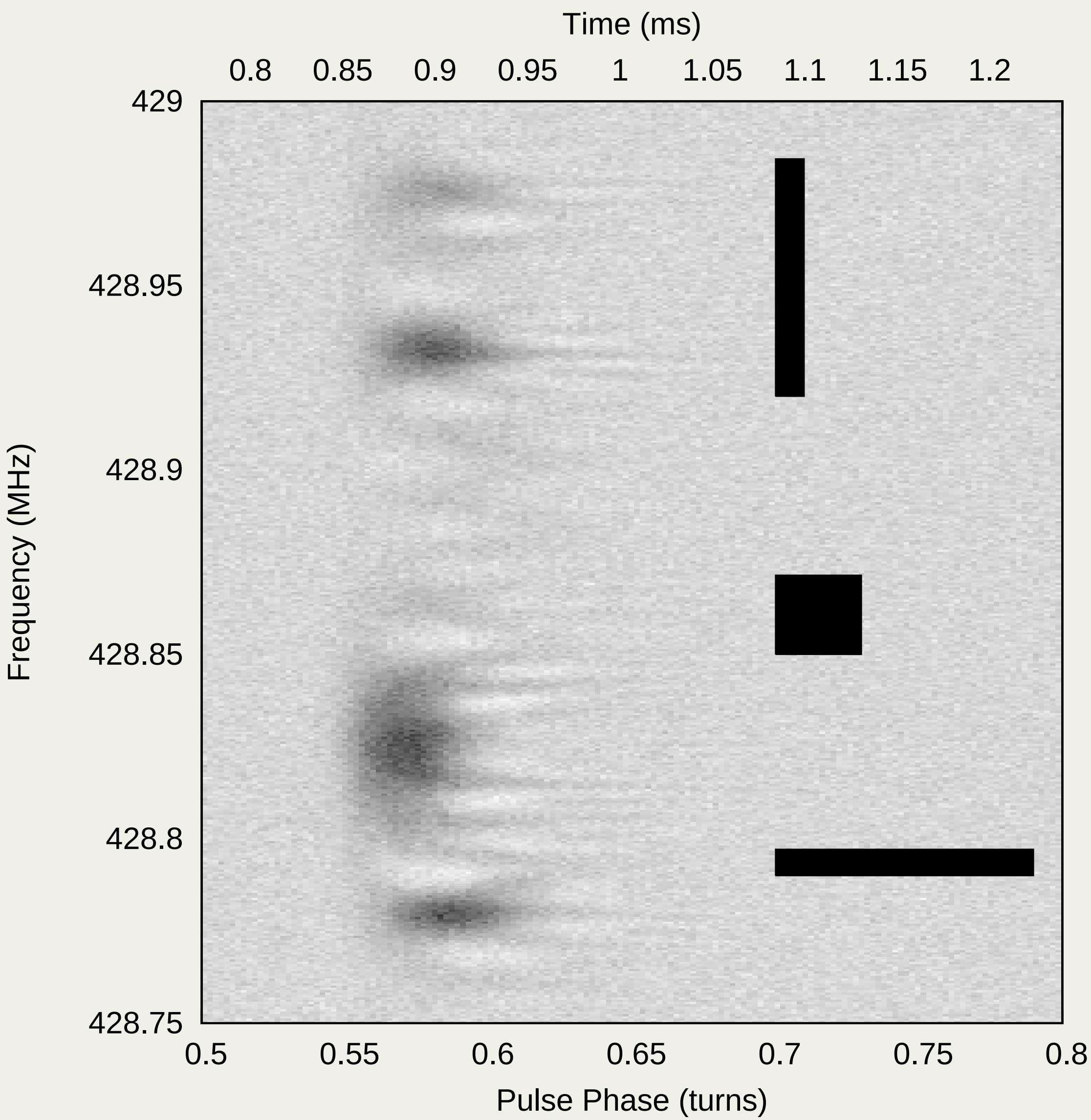
Cyclic Spectra

PSR B1937+21 at 430 MHz, Arecibo/ASP:



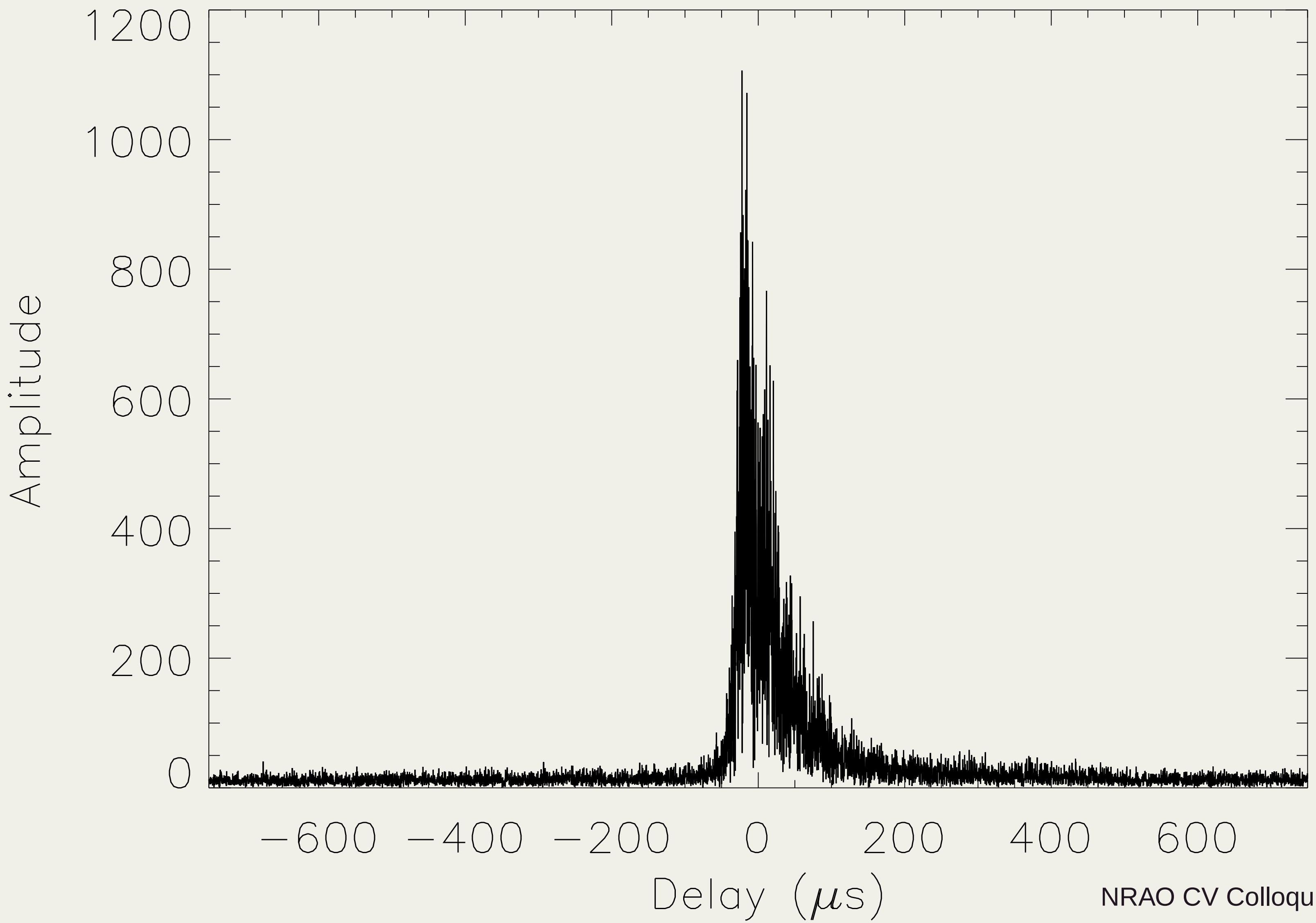
Cyclic Spectra

Same thing, zoomed in:



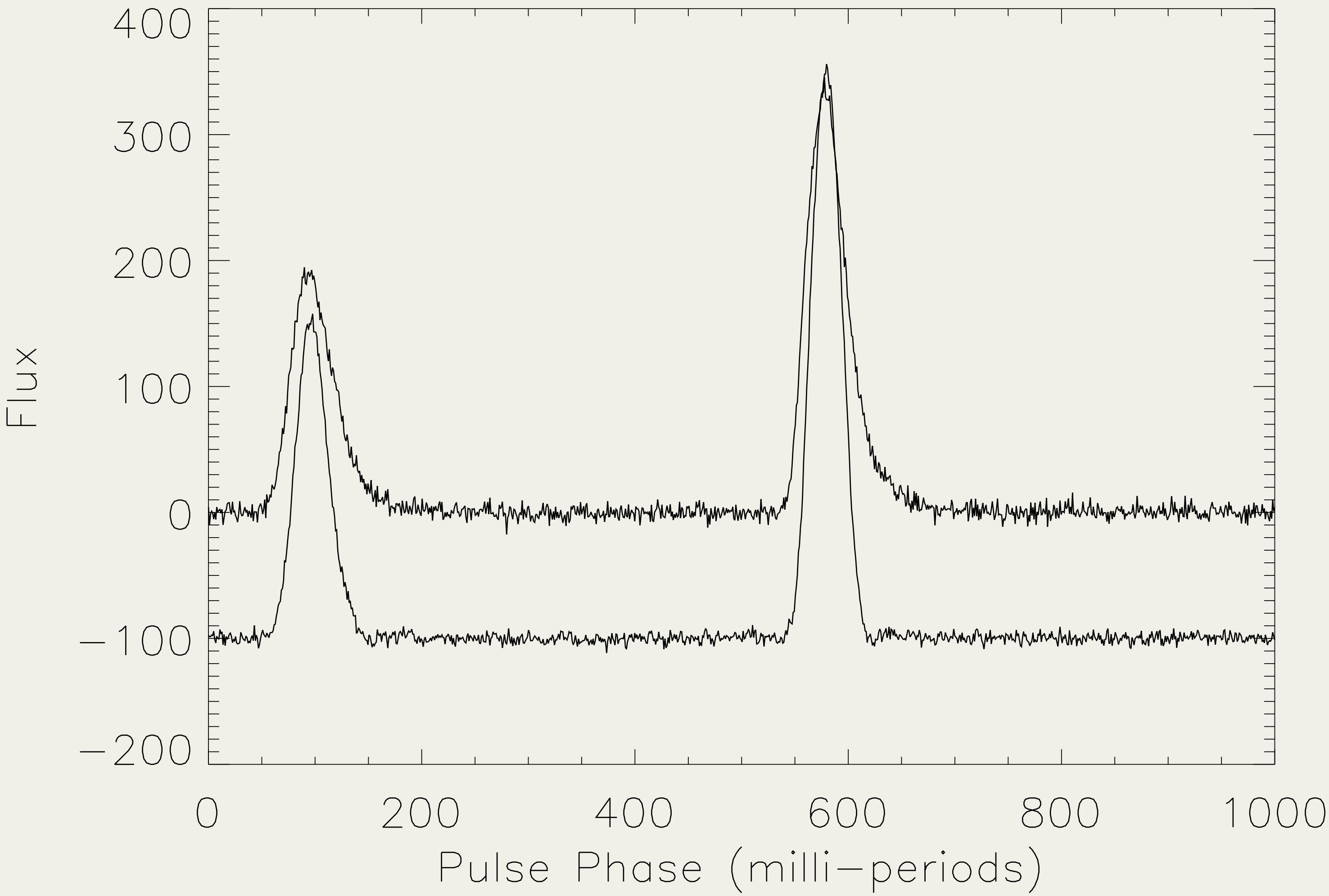
ISM De-scattering

"Snapshot" ISM impulse response $h(t)$ determined from data:



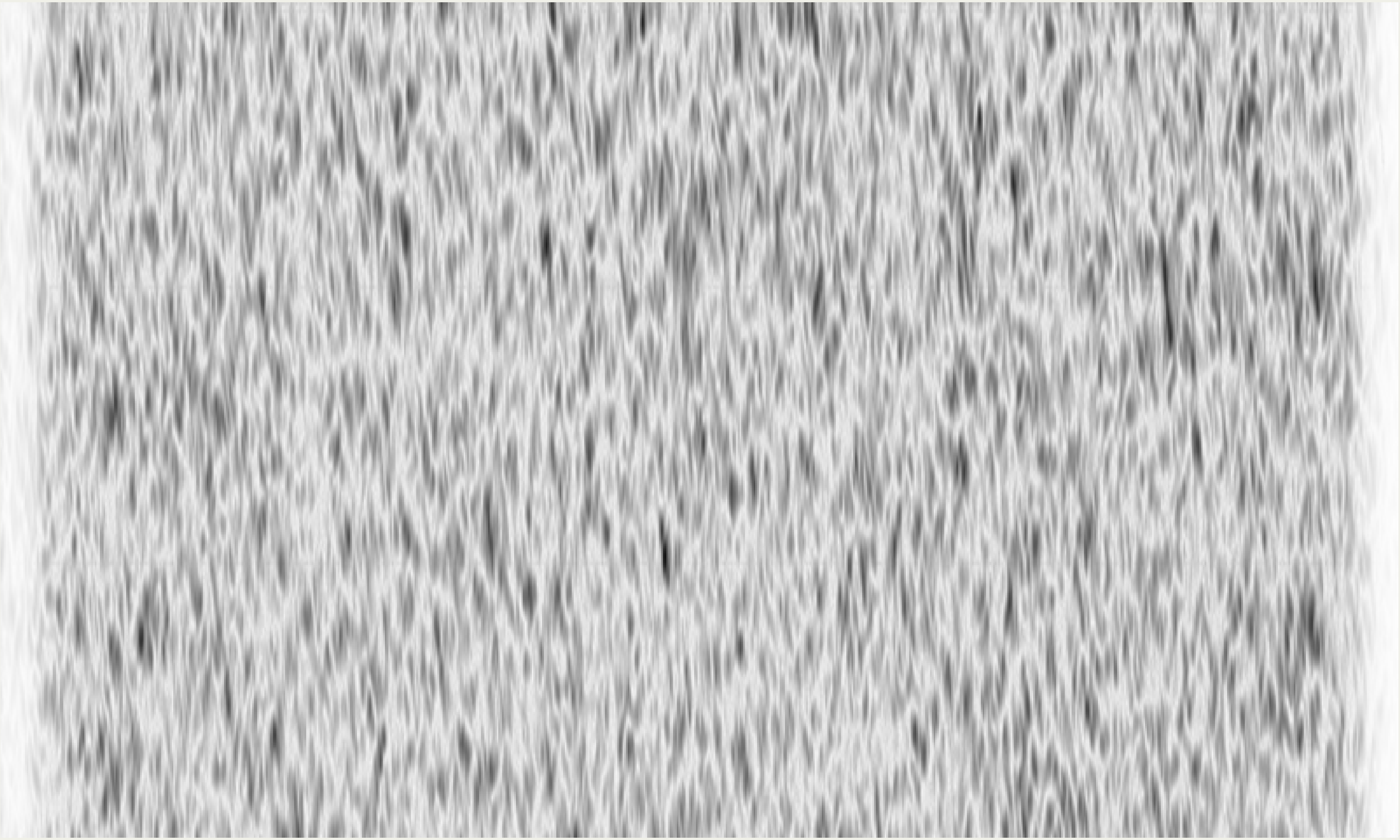
ISM De-scattering

Comparison of uncorrected and intrinsic pulse profiles:



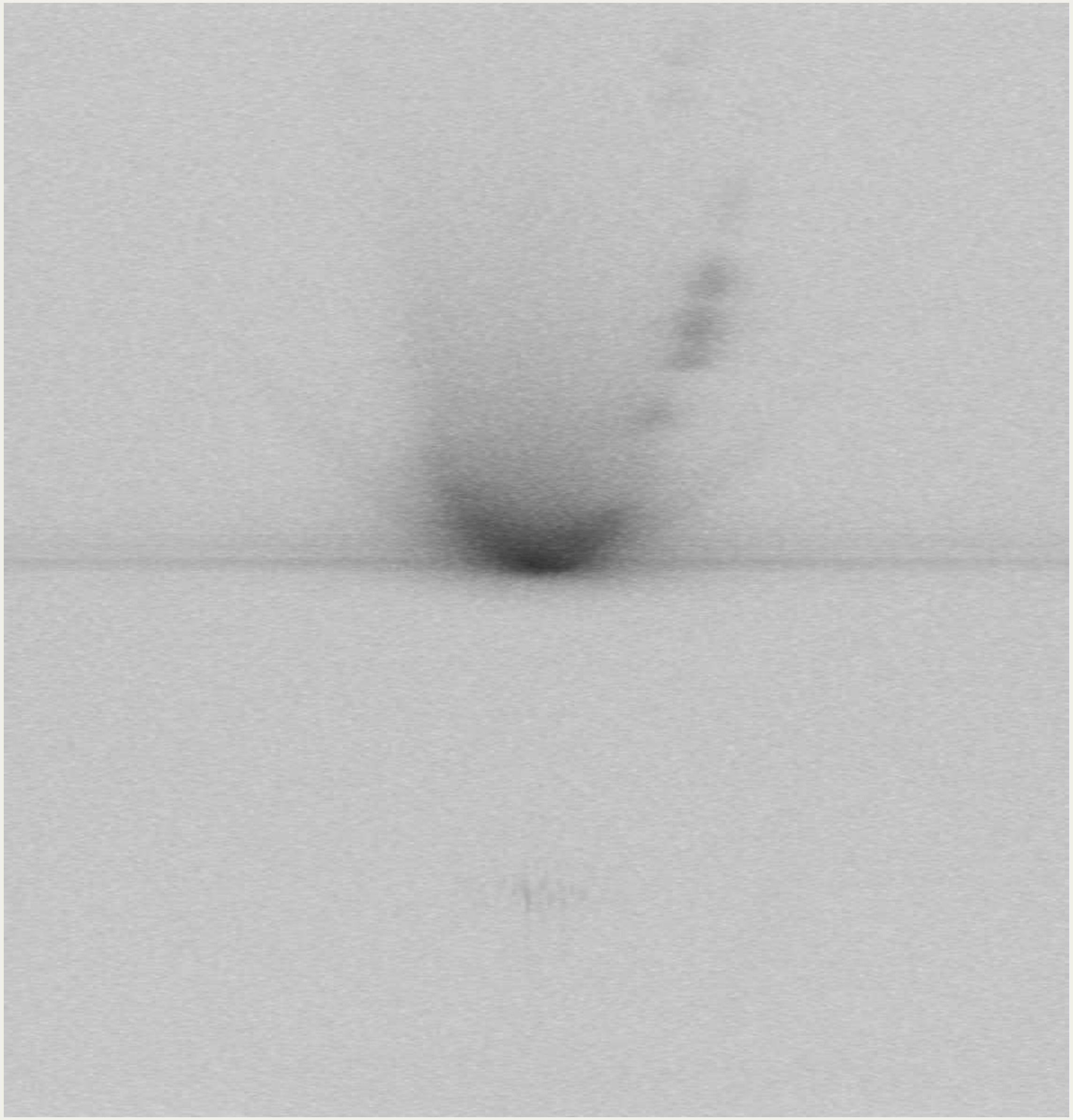
Dynamic Spectra

B1937+21, ν=430MHz, BW=4 MHz, $\Delta\nu$=0.64 kHz, T$\sim$1 hour



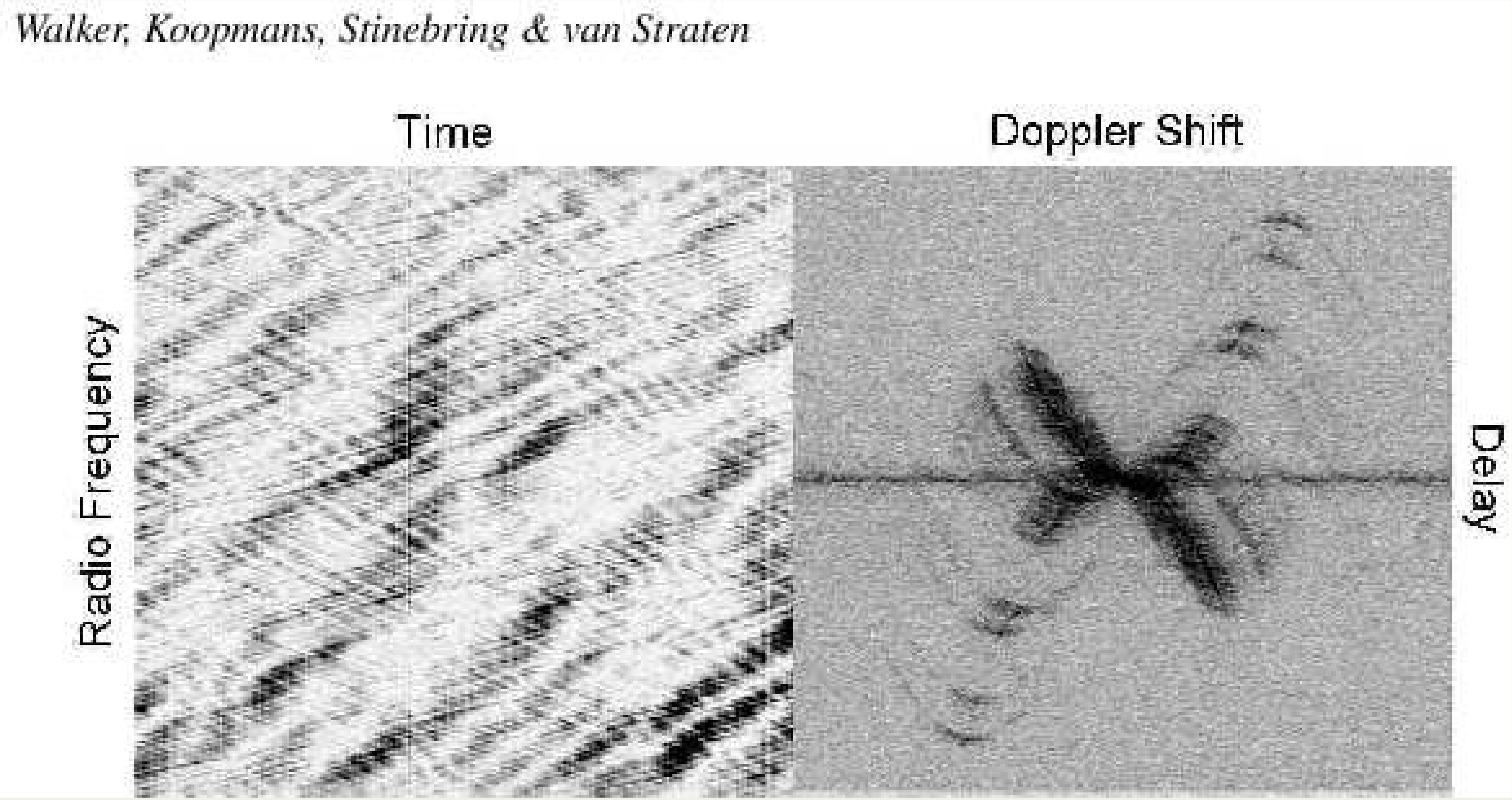
Secondary Spectra

2-D FT of dynamic spectrum, shows clear “arc” structure.



Secondary Spectra

Contrast with methods based on traditional dynamic spectra:



Future Directions

Future directions for ISM work:

- Get scattering-corrected TOAs, improve timing
- Investigate polarimetry aspects
- Explore more strongly scattered sources
- Work towards physical ISM images
- . . .