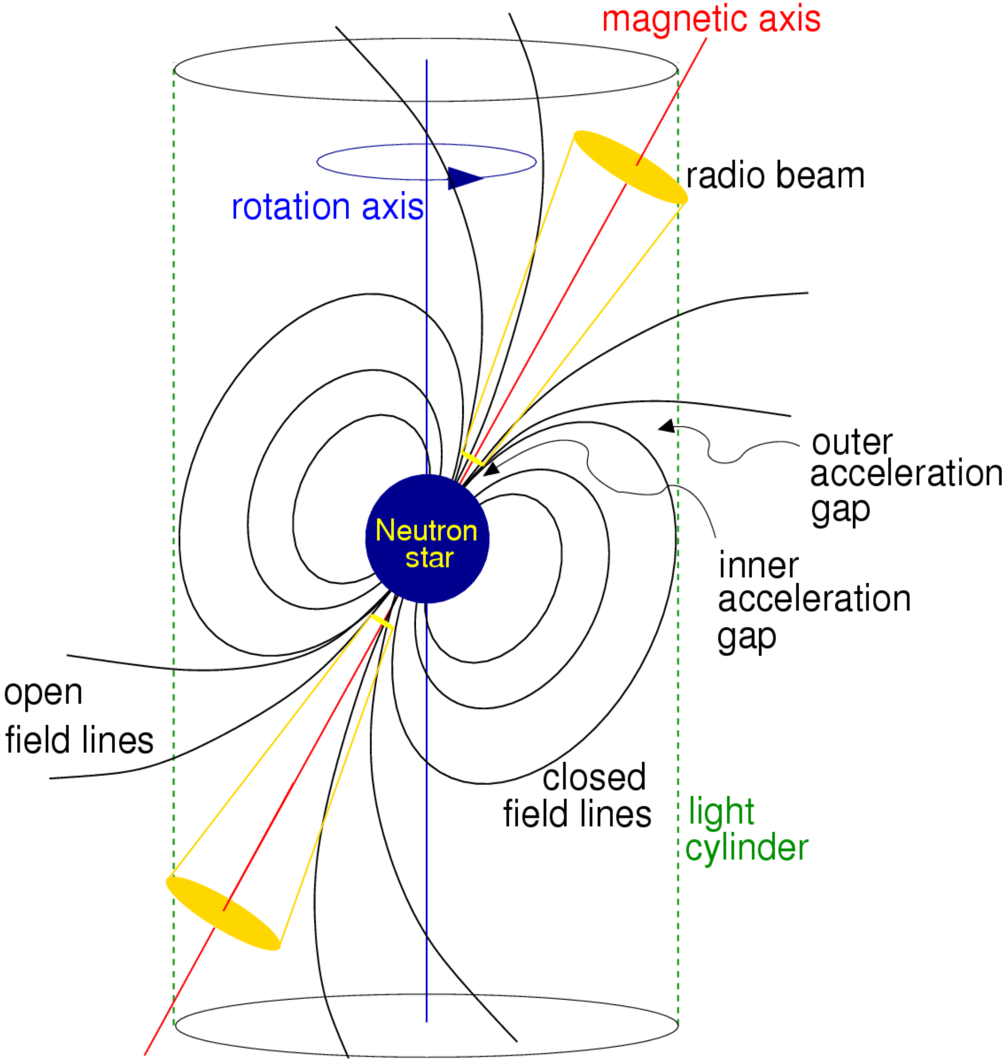
Pulsars

2019 GBO/AO Single Dish Workshop

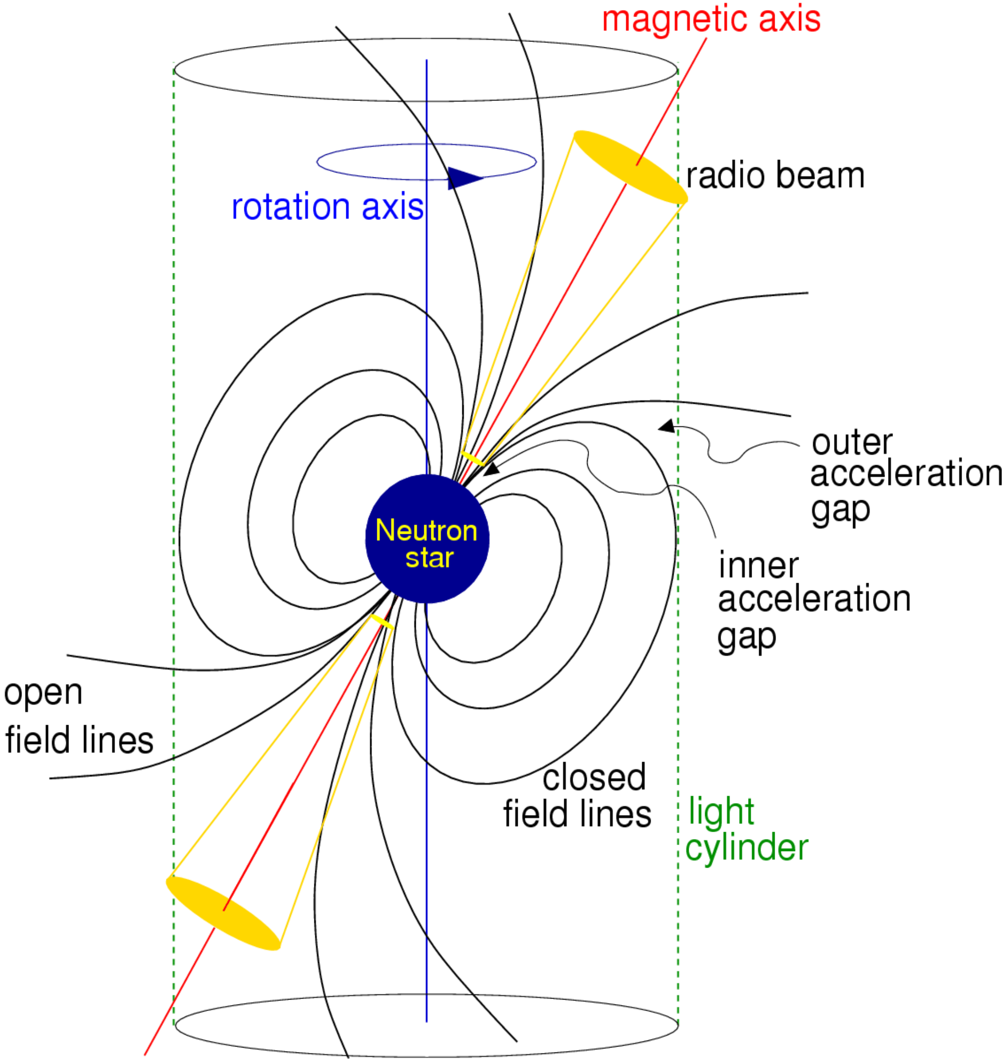
Ryan Lynch (GBO)

A Pulsar Model



- $M_p = 1.3 – 2.0\ M_{sun}$
- $R \sim 10$ km
- P_{rot} 1.4 ms – few sec
- $B_{surf} = 10^8 – 10^{14}$
- $L = 10^{30} – 10^{37}$ erg/s
  - Most energy lost via particle wind
- Age $10^3 – 10^9$ yr

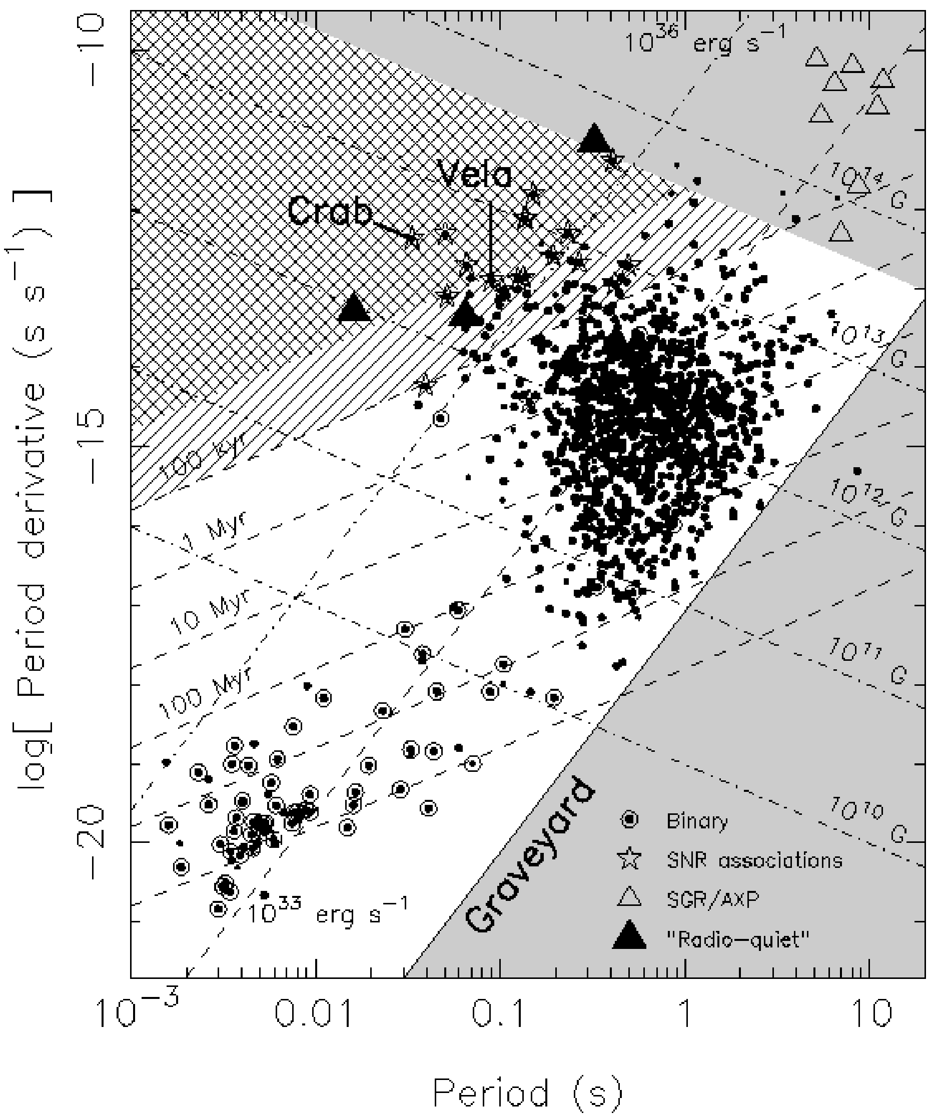
A Pulsar Model



- Point sources
  - No mapping
  - Sometimes imaged using VLBI for astrometry
- Broad-band continuum
  - Wide bandwidths
- Rapidly varying
  - High time resolution
- Highly polarized
  - Linear and circular
- Natural on/off sources
  - No position/frequency switching

Pulsar Population

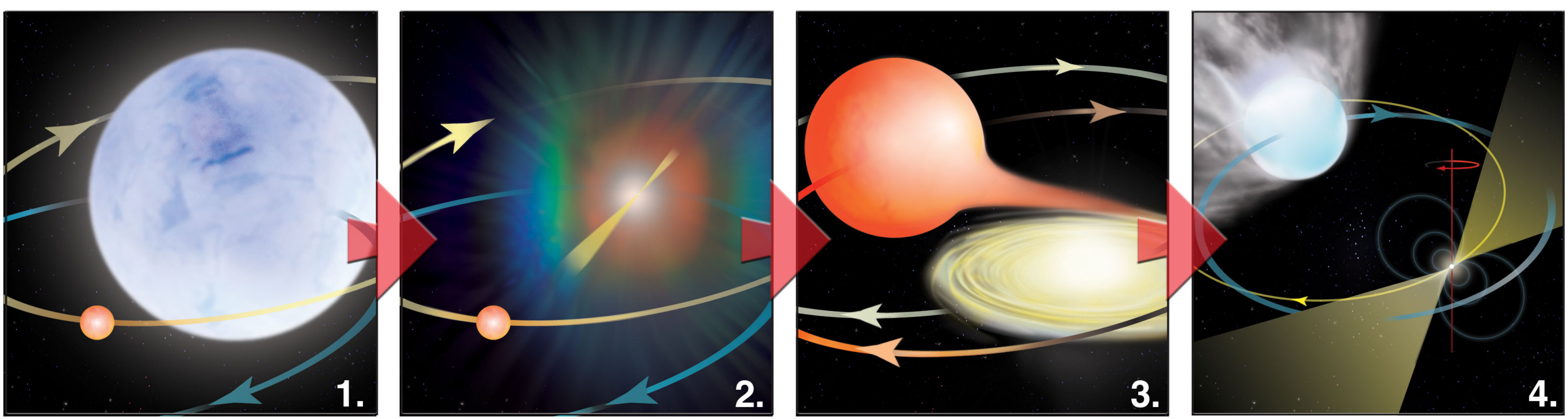
- ~2,400 pulsars known
  - ~10% are **millisecond pulsars**
  - ~100 transients (**RRATs**)
  - ~30 **magnetars** (4 radio)
- Pulsars are observed in radio, x-ray, γ-ray
  - Most discovered and studied in radio



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

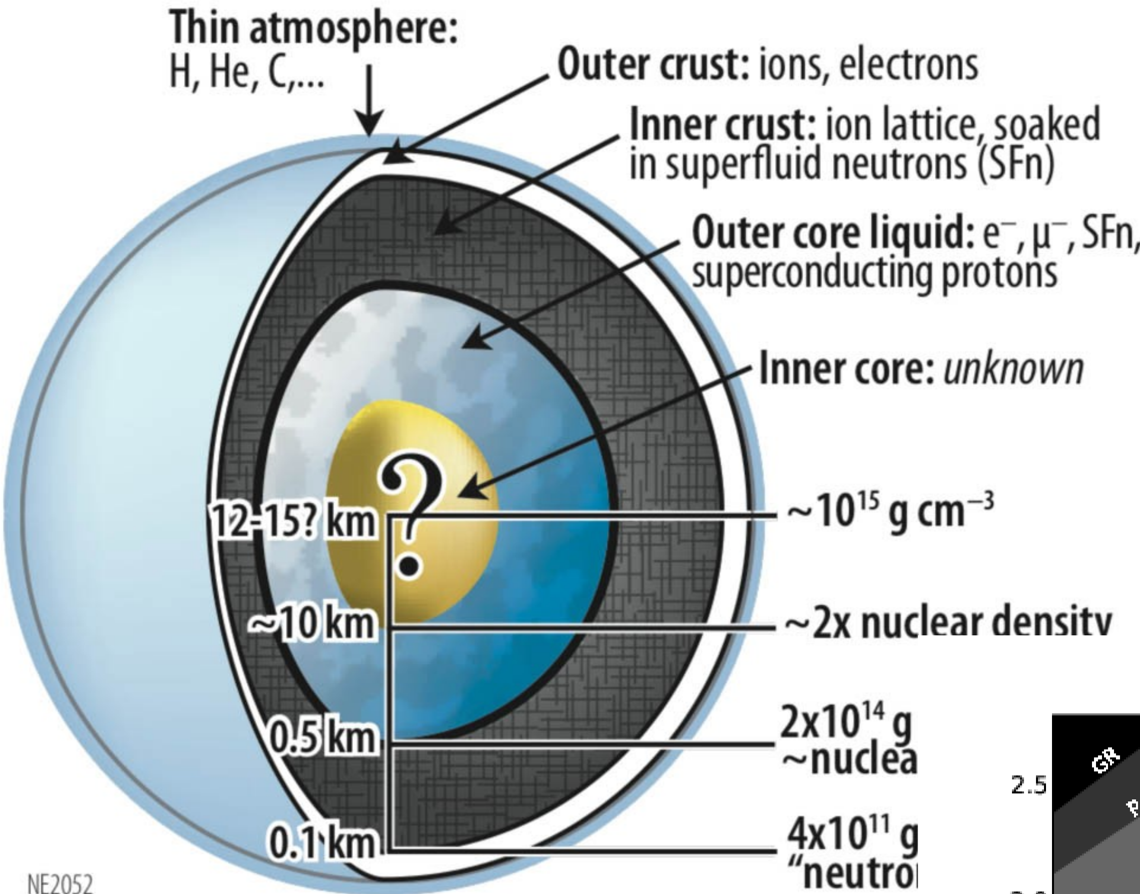
Millisecond Pulsars

- MSPs are often excellent physical tools
  - Often found in relativistic binaries
  - Most stable rotators → can be used as precise clocks
- **Recycled** by accreting matter and angular momentum from binary companion

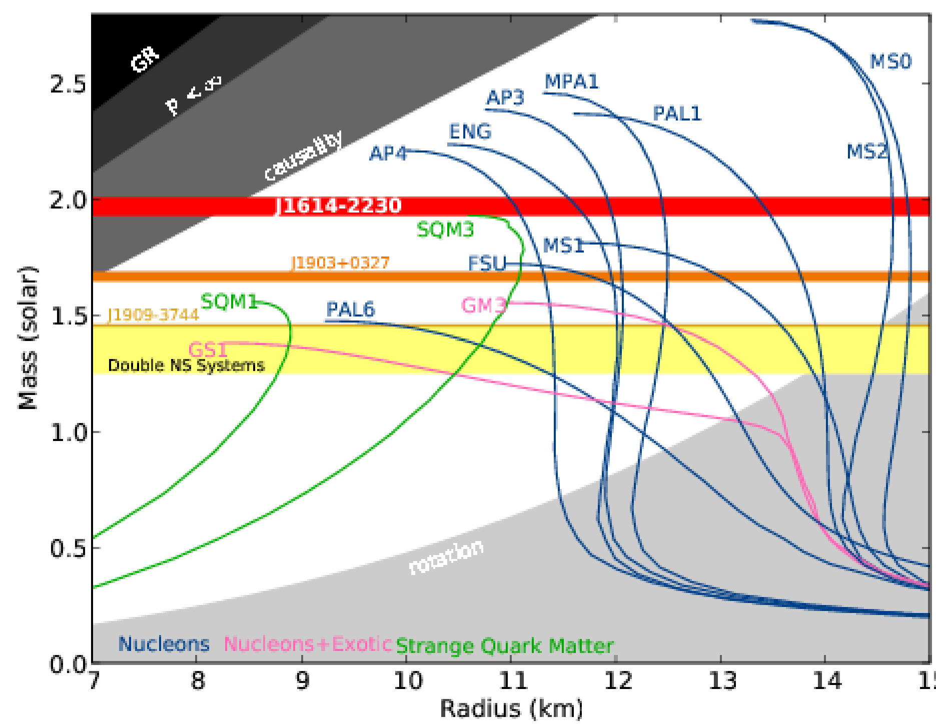


Structure and Equation of State

- Internal structure still uncertain
  - Equation of state of ultra-dense matter not known
- Basics…
  - Very thin atmosphere
  - Rigid outer crust
  - Superfluid neutron interior
- Different maximum masses predicted for different equations of state
  → pulsars can be used to do nuclear physics!



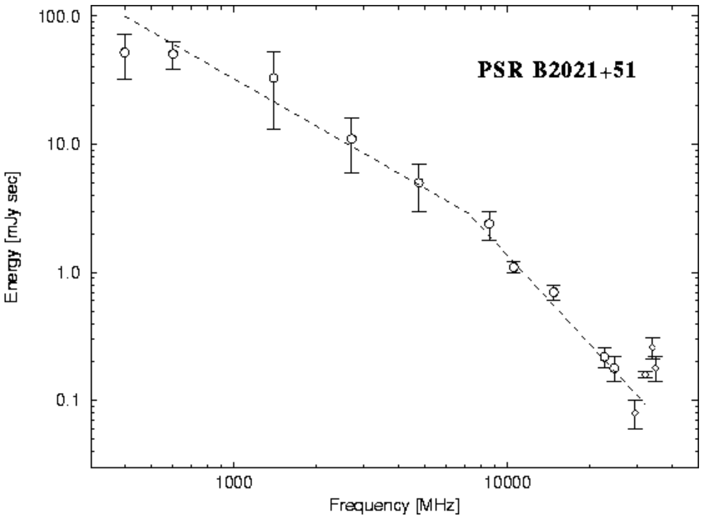
Thin atmosphere:
H, He, C,...
Outer crust: ions, electrons
Inner crust: ion lattice, soaked in superfluid neutrons (SFn)
Outer core liquid: e⁻, μ⁻, SFn, superconducting protons
Inner core: unknown
12-15? km
~10 km
0.5 km
0.1 km
~10^15 g cm^-3
~2x nuclear density
2x10^14 g
~nuclea
4x10^11 g
"neutro
NE2052



GR
P < ∞
causality
J1614-2230
J1903+0327
J1909-3744
Double NS Systems
rotation
MS0
MS2
MPA1
AP3
PAL1
ENG
AP4
SQM3
MS1
FSU
SQM1
PAL6
GM3
GS1
Nucleons
Nucleons+Exotic
Strange Quark Matter
Mass (solar)
Radius (km)

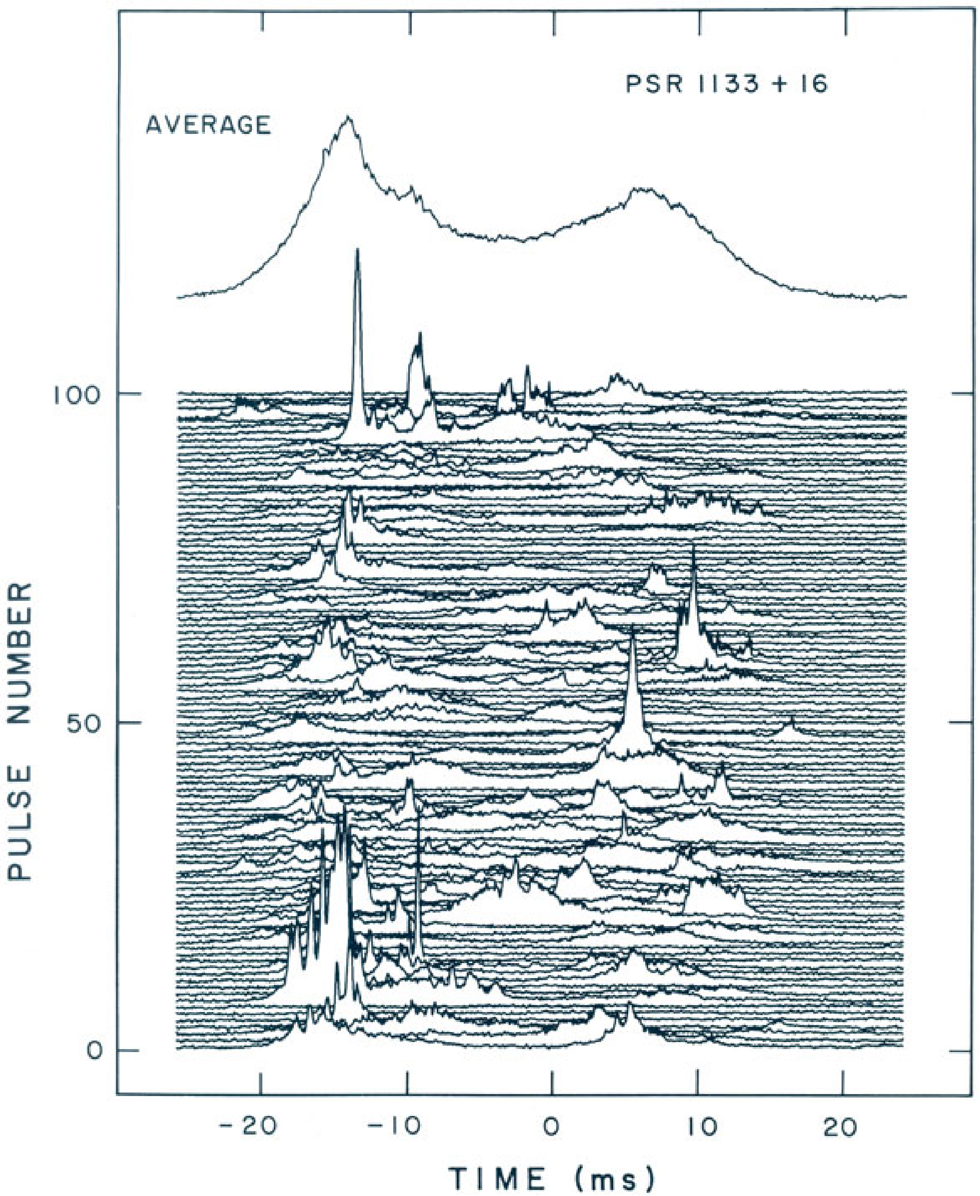
Pulsar Emission

- Emission still not well understood, despite 50 years of research
- Basic picture is…
  - Time varying magnetic field induces strong electric potential
  - Charged particles are pulled from NS surface
  - Accelerated along open magnetic field lines
  - Emit via curvature radiation (synchrotron-like process in extremely strong B-field)



Pulsar Emission

- Wide variety of pulse shapes are observed
  - Can be explained in terms of simple phenomenological models
- Individual pulse shapes vary
- **Average** profile observed to be *very* stable



Canonical Properties

- Pulsar rotation slows with time
  - In **rotation power pulsars** this is the primary source of energy
  - In magnetars magnetic field decay powers high-energy emission
- By *assuming* pulsars radiate like dipoles in a vaccuum certain properties can be inferred

$$B_s = \sqrt{\frac{3c^3 I}{8\pi^2 R^6 (\sin\alpha)^2} P\dot{P}} = 10^{12}\,\mathrm{G}\left(\frac{\dot{P}}{10^{-15}}\frac{P}{\mathrm{s}}\right)^{1.2}$$

$$\tau_c = \frac{P}{2\dot{P}} = 16\,\mathrm{Myr}\left(\frac{P}{\mathrm{s}}\right)\left(\frac{\dot{P}}{10^{-15}}\right)^{-1}$$

$$\dot{E} = 4\pi^2 I \dot{P} P^{-3} = 4\times 10^{35}\,\mathrm{erg/s}\left(\frac{\dot{P}}{10^{-15}}\right)\left(\frac{P}{\mathrm{s}}\right)^{-3}$$

Interstellar Dispersion

- The ISM is an ionized plasma with refractive index

$$\mu = \left[1 - \left(\frac{\nu_p}{\nu} \right)^2 \right]^{1/2}$$

  where ν_p~ few kHz << ν_{obs} for typical electron densities

- As a result, group velocity of radio waves $v_g(\nu) < c$
  - Lower frequencies travel more slowly than higher frequencies

Interstellar Dispersion

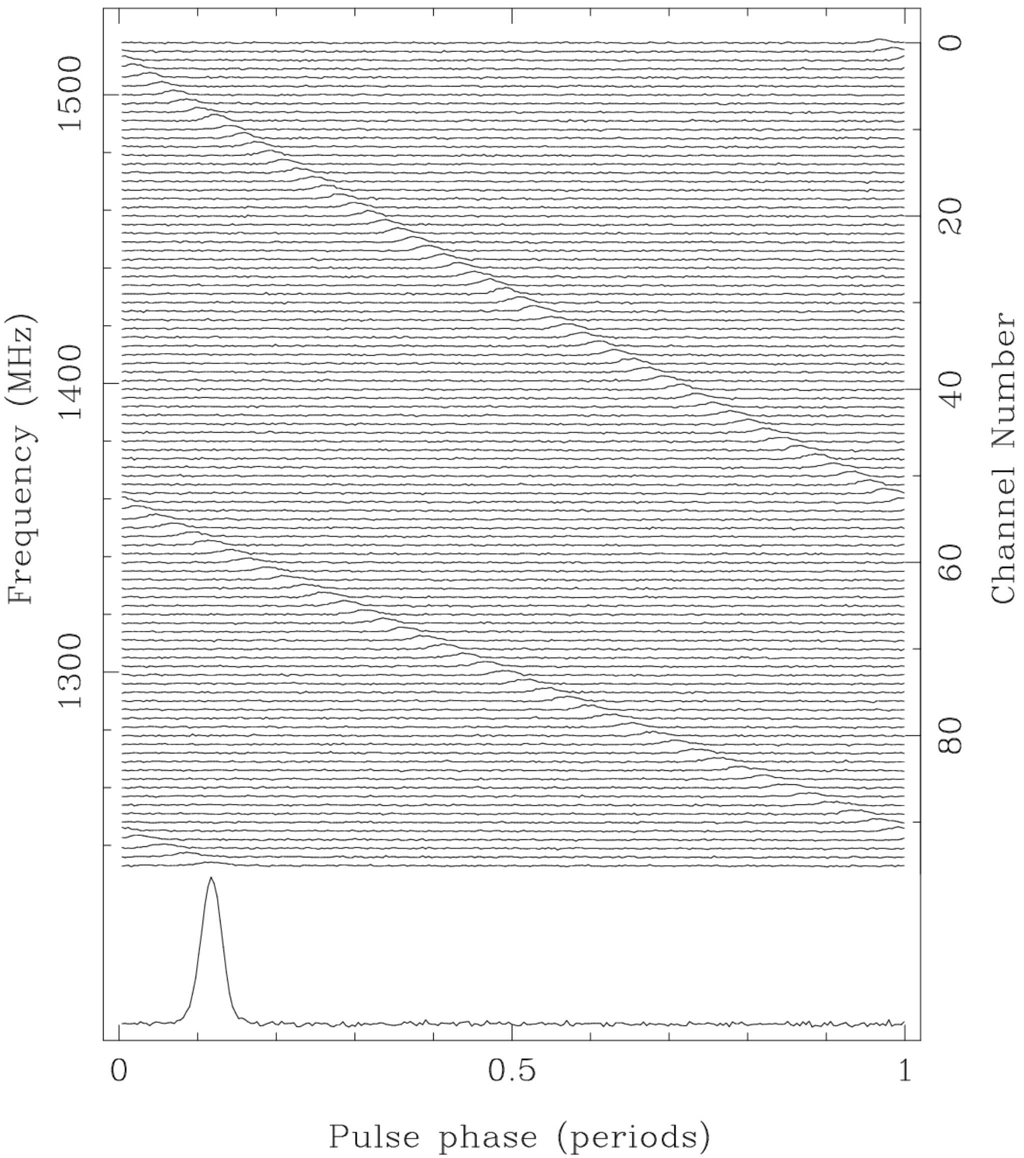
- This leads to a delay in arrival time for different frequencies of a broadband signal

$$\Delta t \approx 4 \times 10^3 \sec \left(\frac{DM}{\mathrm{pc\ cm}^{-3}} \right) \left[\left(\frac{\nu_{\mathrm{lo}}}{\mathrm{MHz}} \right)^{-2} - \left(\frac{\nu_{\mathrm{hi}}}{\mathrm{MHz}} \right)^{-2} \right]$$

where DM is the column density of electrons along a line of sight

$$\mathrm{DM} = \int n_e(s)\, ds$$

Interstellar Dispersion



- If we naively sum over frequency, pulses will be completely smeared out
- We must shift each frequency channel appropriately before summing

Figure credit: Handbook of Pulsar Astronomy Lorimer and Kramer

Interstellar Dispersion

- Intra-channel dispersion will still cause smearing

$$\Delta t_{\mathrm{DM}} = 8 \times 10^{3} \sec \left(\frac{\Delta \nu}{\nu^{3}} \right)$$

- Minimize by using many frequency channels (**incoherent de-dispersion**)
- Remove completely by operating on complex voltages (**coherent de-dispersion**)

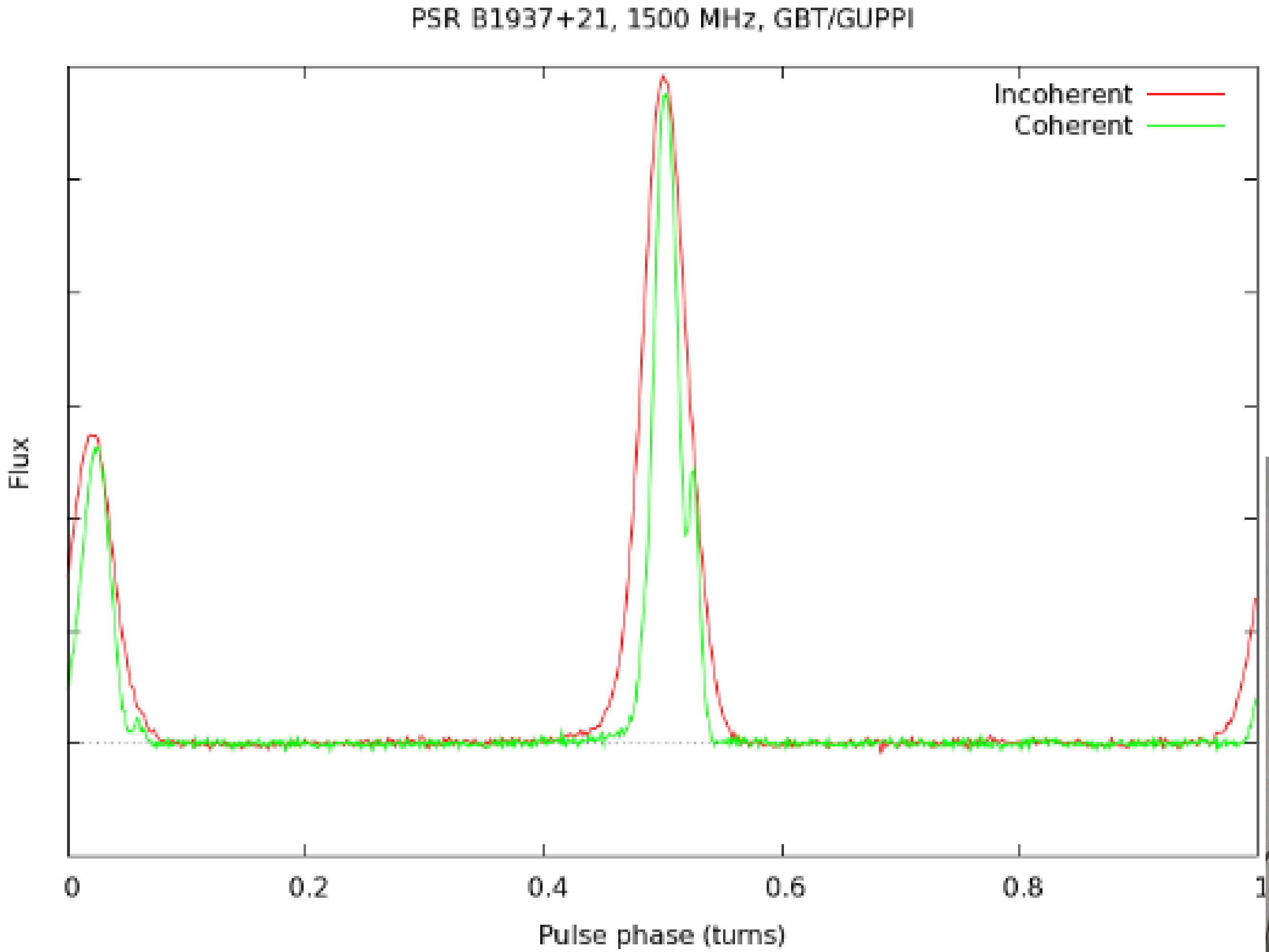
Coherent Dedispersion

- Observed voltage is a time domain *convolution* (frequency domain multiplication) of intrinsic voltage and **transfer function**

$$V(f) = \mathrm{FT}[v(t)]$$

$$V_o(f+\delta f) = V_i(f_0+f) \cdot H(f_0+f)$$

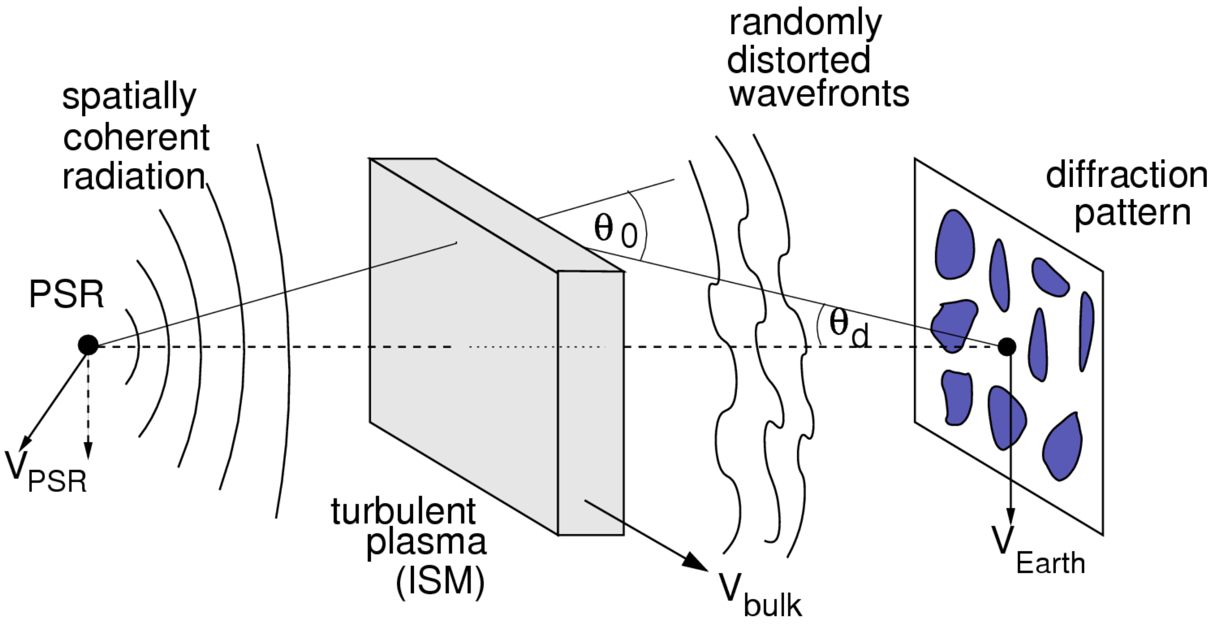
$$H(f+\delta f) = \exp\left[\frac{2\pi i}{(f_0+f)f_0^2} k\,\mathrm{DM} f^2\right]$$



Images courtesy of Paul
Demorest

Interstellar Scattering

- Imhomogenieties in the ISM lead to multi-path propagation



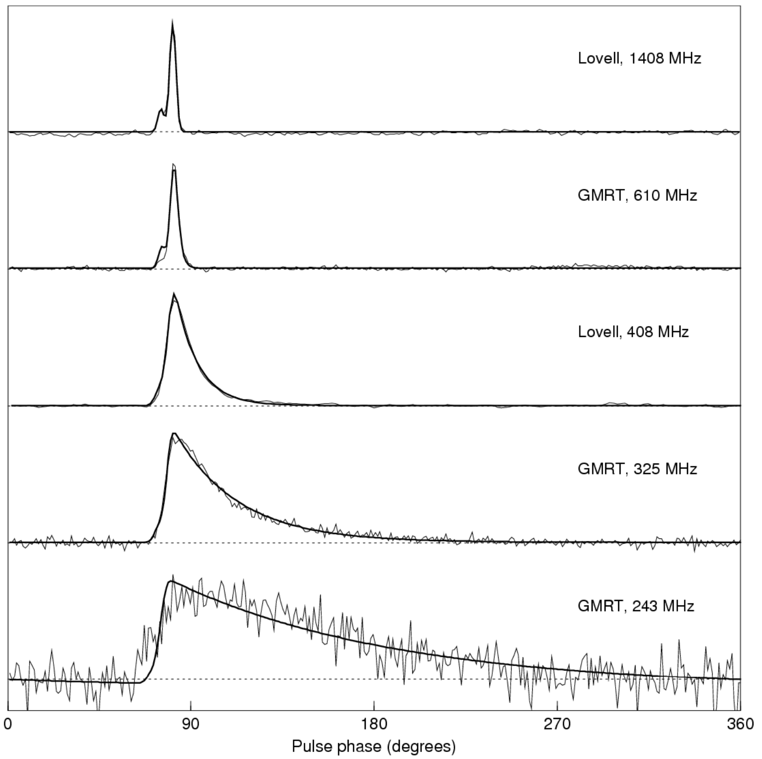


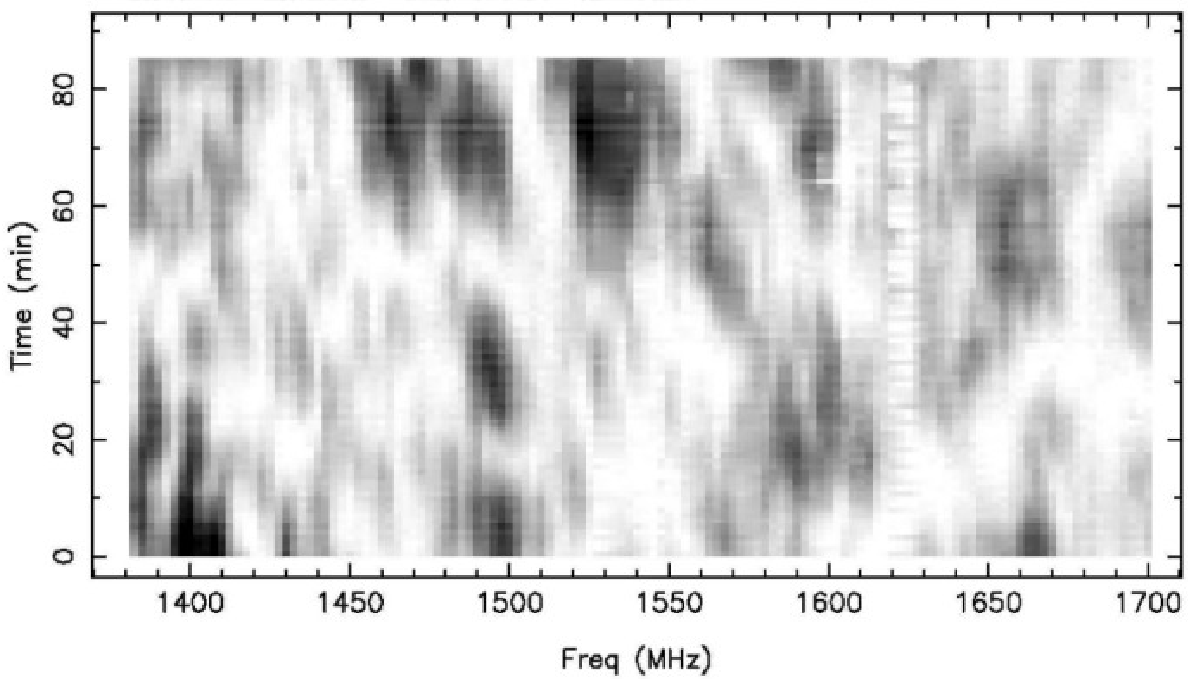
Figure credit: Handbook of Pulsar Astronomy Lorimer and Kramer

Interstellar Scattering

- Scattering is strongly dependent on frequency ($\sim \nu^{-4}$) and is not easy to mitigate
  - May be the limiting factor in searches of some regions, e.g. the Galactic center and certain globular clusters
- Mitigate by going to higher frequencies

Scintillation

- Multi-path propagation can lead to constructive and destructive interference
  – Modulates intensity of the pulsar in time **and** frequency on short and long time scales
- Equivalent to optical “twinkling”



Scintillation

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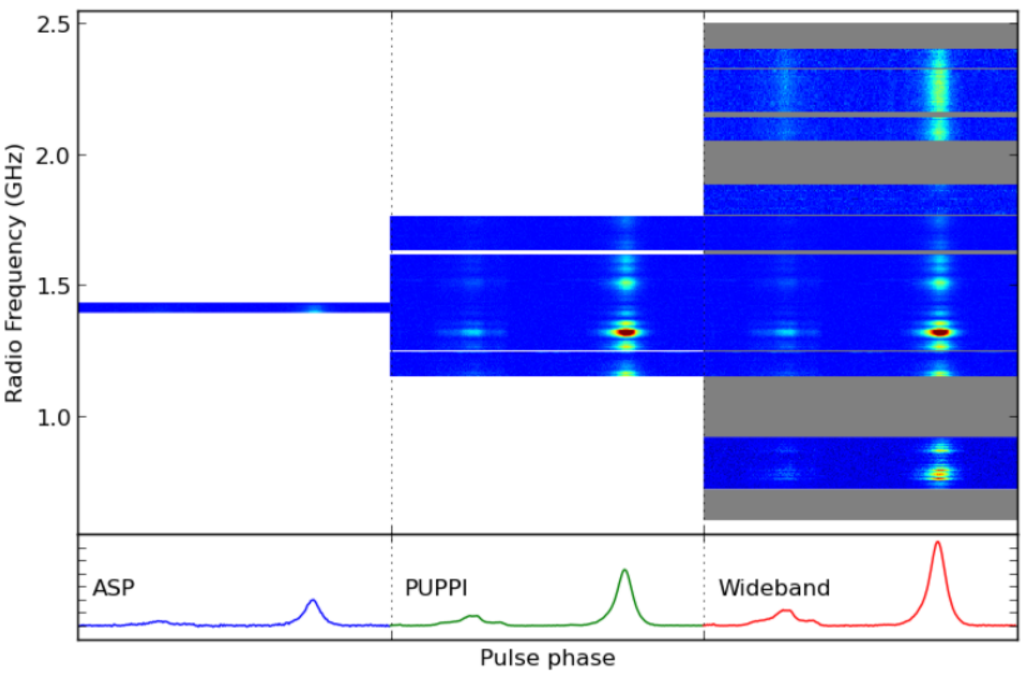
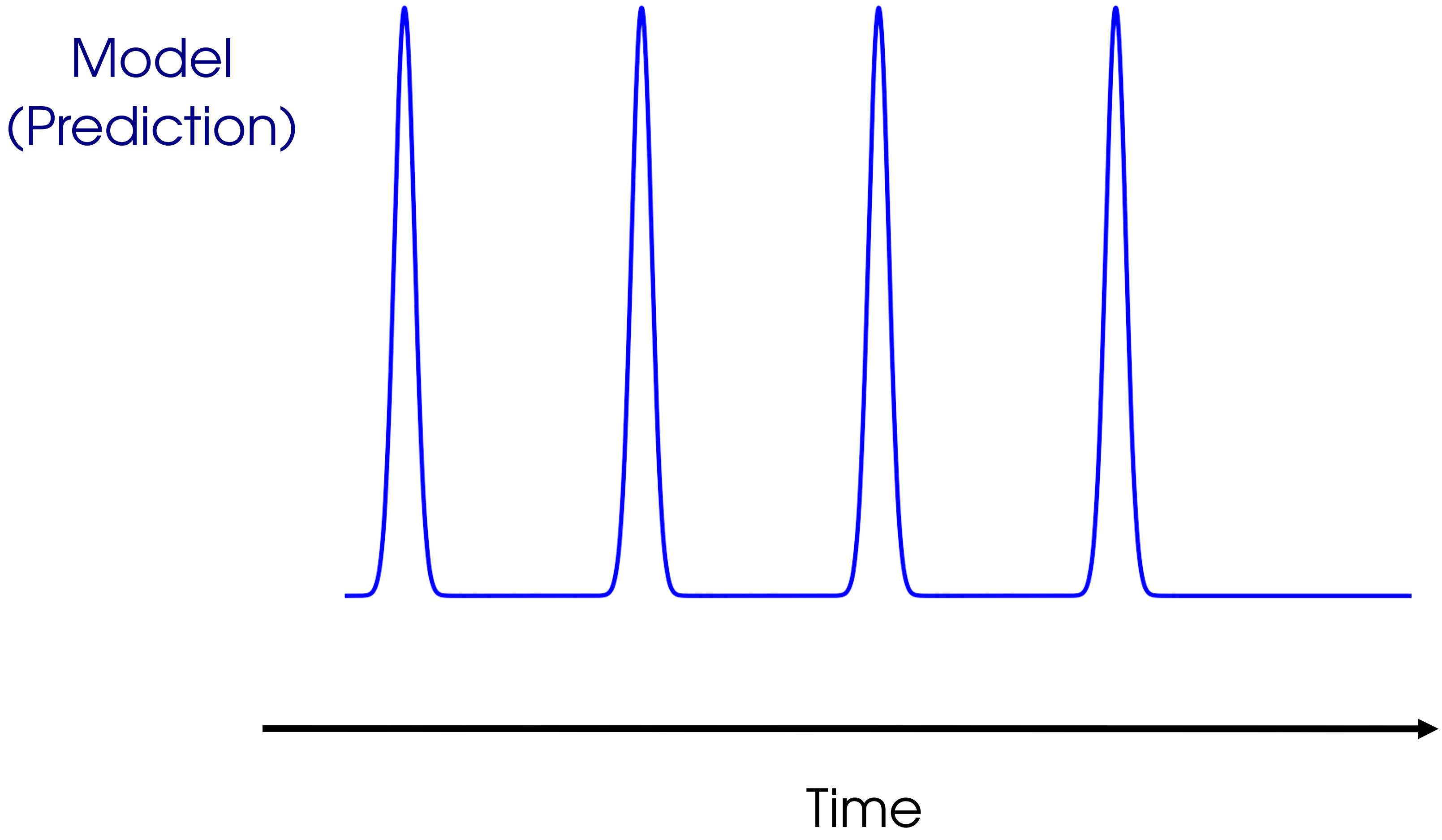


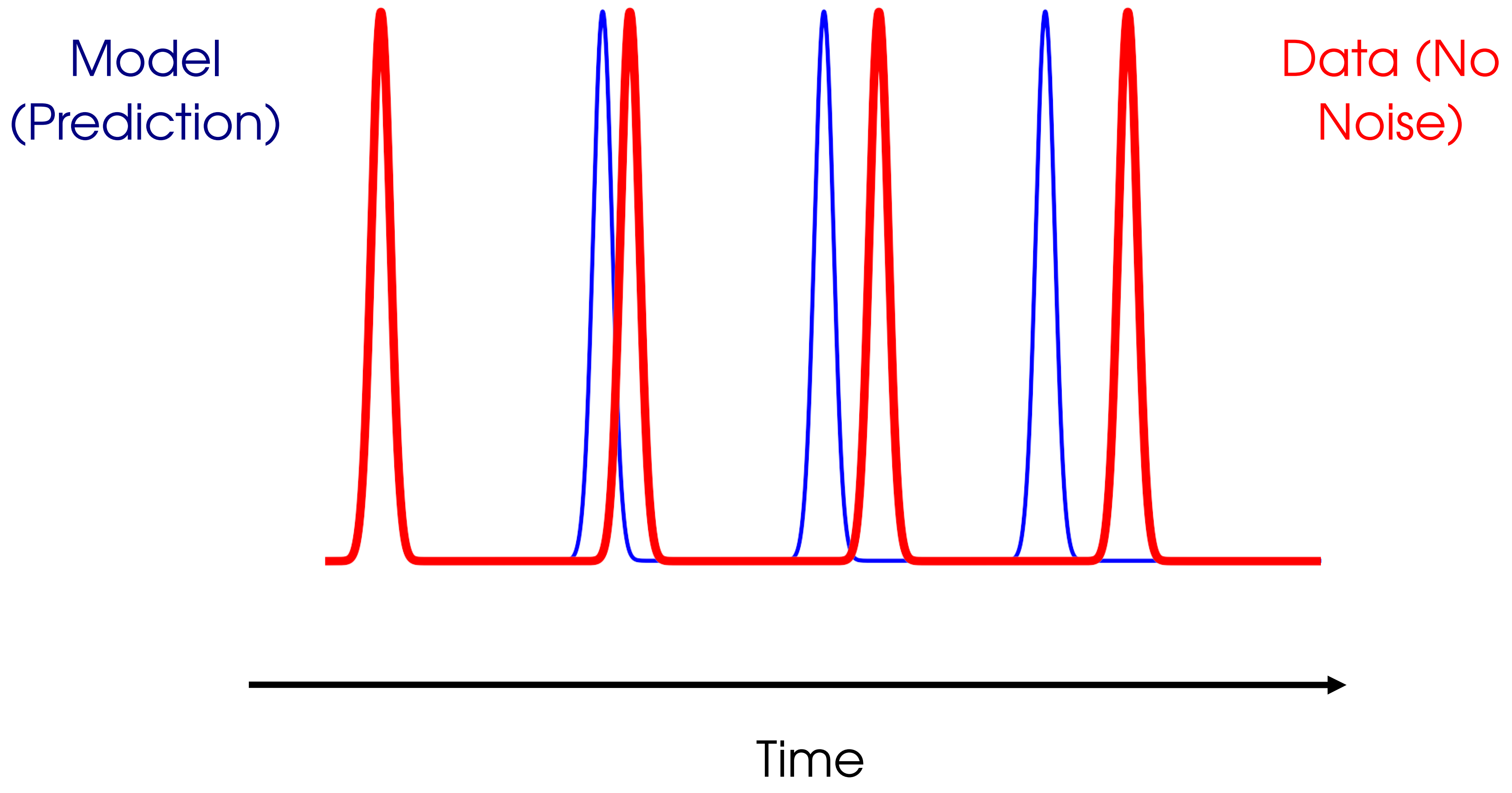
Observational Modes

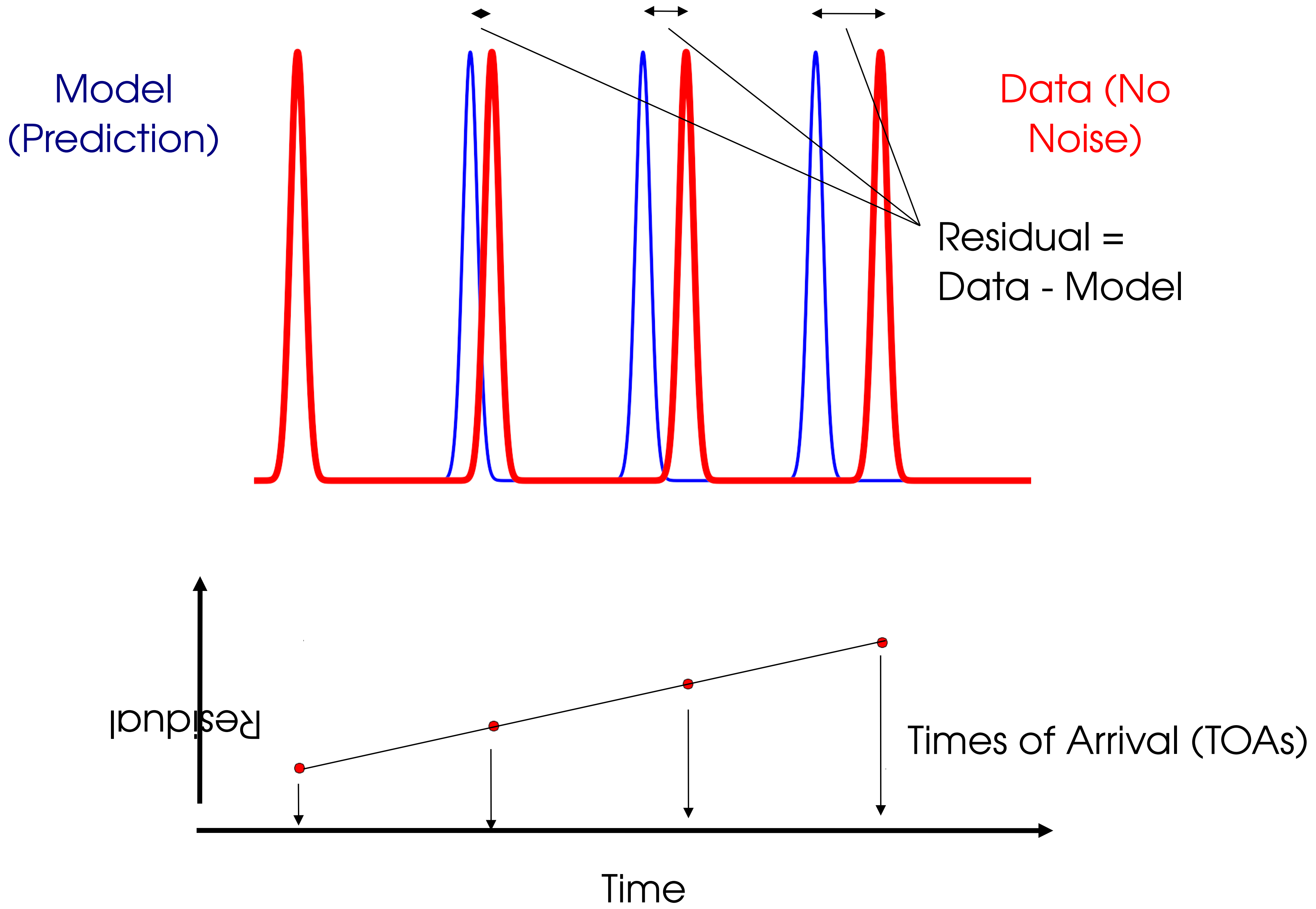
- Two primary observing modes
- “Search” modes → high time resolution spectra
  - Searching for new pulsars
  - Resolution of single pulses
  - Fast radio bursts
  - Simultaneous observations of multiple pulsars
- “Timing” modes → phase-folded spectra
  - Observations of known pulsars

Pulsar Timing (The Basics)

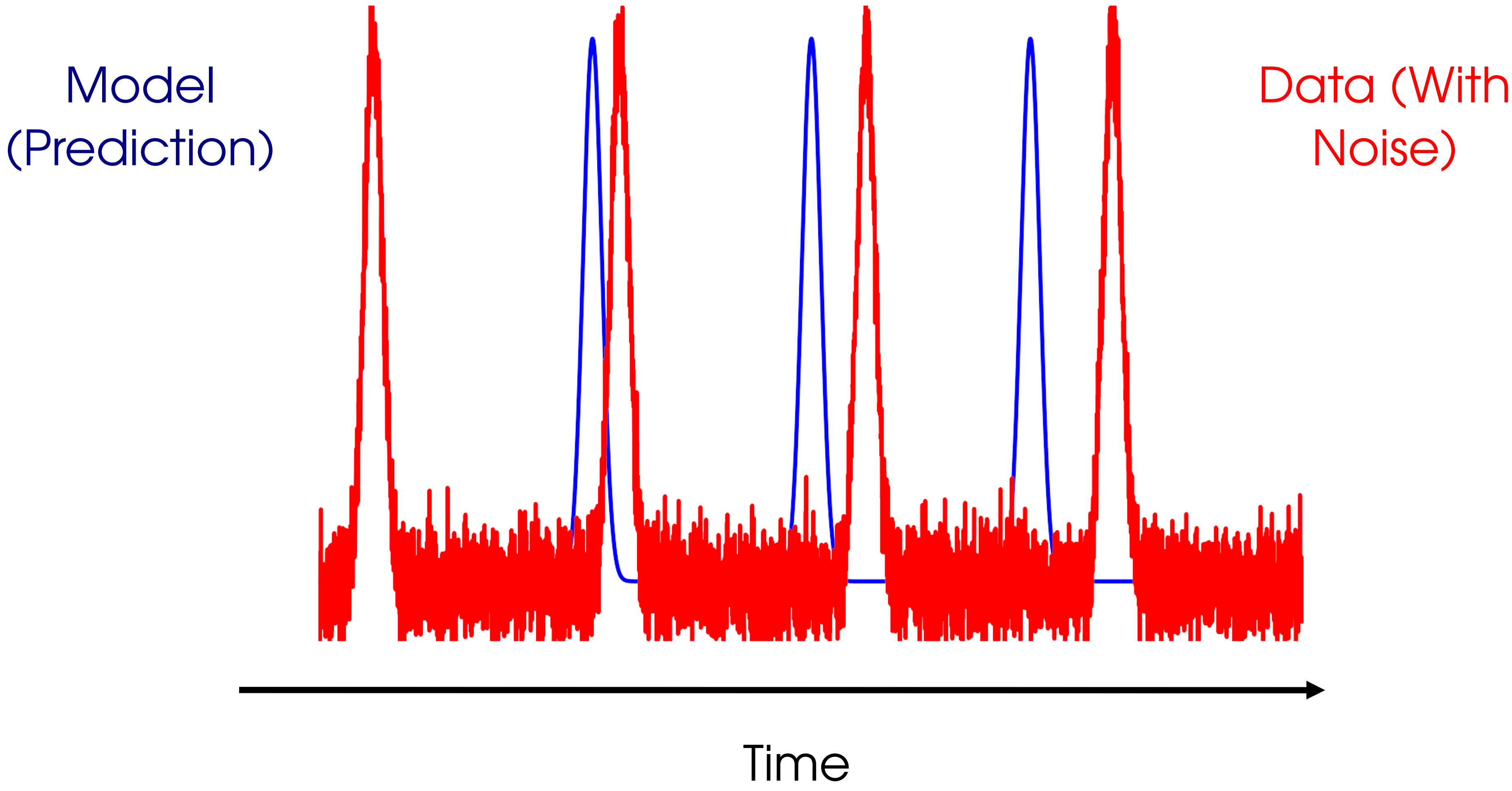
- **Timing** is one of the most powerful techniques for studying pulsars
- It takes advantage of the *clock-like* nature of pulsars
  - Deviations from the expected arrival time of a pulse contain useful information
- Let's go through timing schematically...

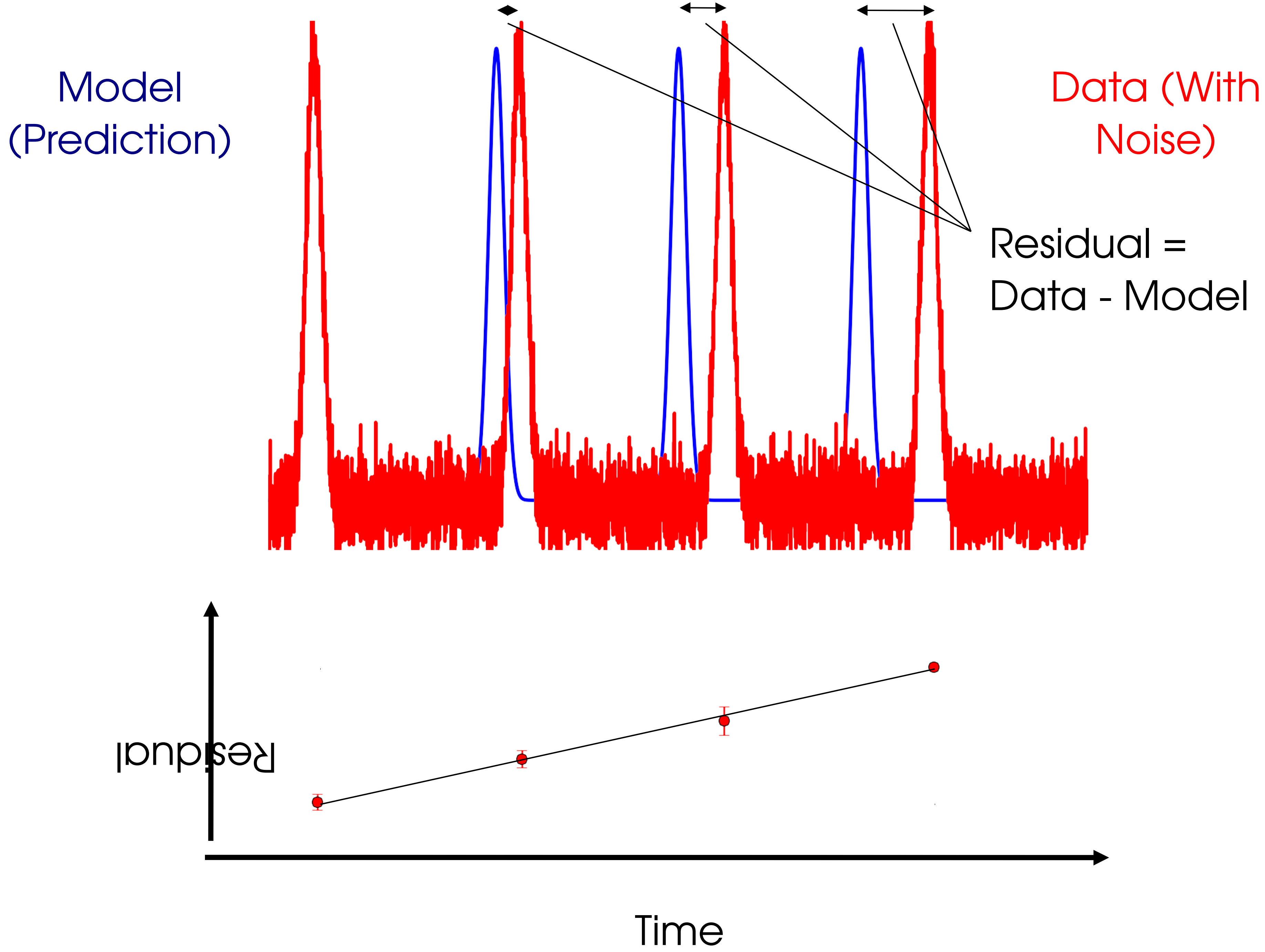

Model
(Prediction)
Time

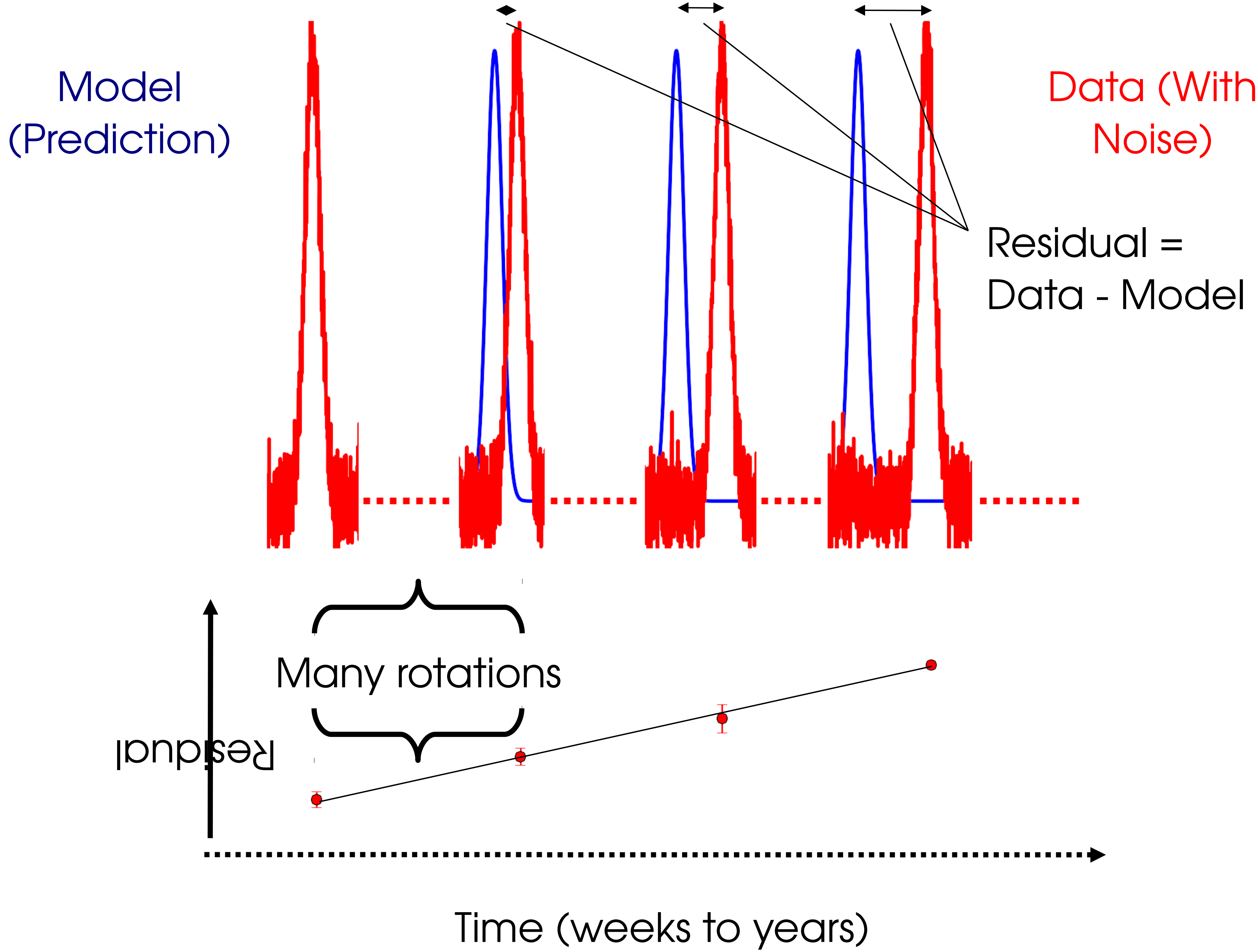

Model (Prediction)
Data (No Noise)
Time



Model (Prediction)
Data (No Noise)
Residual = Data - Model
Residual
Times of Arrival (TOAs)
Time


Model
(Prediction)
Data (With
Noise)
Time


Model
(Prediction)
Data (With
Noise)
Residual =
Data - Model
Residual
Time



Model
(Prediction)
Data (With
Noise)
Residual =
Data - Model
Many rotations
Residual
Time (weeks to years)

Timing Models

- Time of arrival (TOA) can be predicted from a model for pulsar rotation and other effects
  - Period, spin-down
  - Position, parallax, proper motion
  - Binary orbital parameters
  - The interstellar medium (ISM)
  - And more...
- Model is *coherent in rotational phase*
  - Every single rotation is accounted for
- Deviations from predicted arrival times used to update / improve model parameters

Timing Models

$$\phi(t) = \phi_0 + f\,(t - t_0) + ½\,\mathrm{d}f/\mathrm{dt}\,(t - t_0)^2 + \ldots$$

- Must be transformed to an inertial reference frame…

$$t_{\mathrm{SSB}} = t_{\mathrm{topo}} + t_{\mathrm{corr}} - k\,\mathrm{DM}/f^2 + \Delta_{\mathrm{R_S}} + \Delta_{\mathrm{S_S}} + \Delta_{\mathrm{E_S}} + \Delta_{\mathrm{R_B}} + \Delta_{\mathrm{S_B}} + \Delta_{\mathrm{E_B}}$$

- In order:
  - Topocentric (observatory) TOA
  - Clock corrections (Earth rotation, relativistic, etc.)
  - Dispersion delay
  - Roemer delay (geometric)
  - Shapiro delay (spacetime curvature)
  - Einstein delay (time dilation / gravitational redshift)
  - For Solar system and pulsar binary (if applicable)

Pulsar Timing

Disagreement between model and data

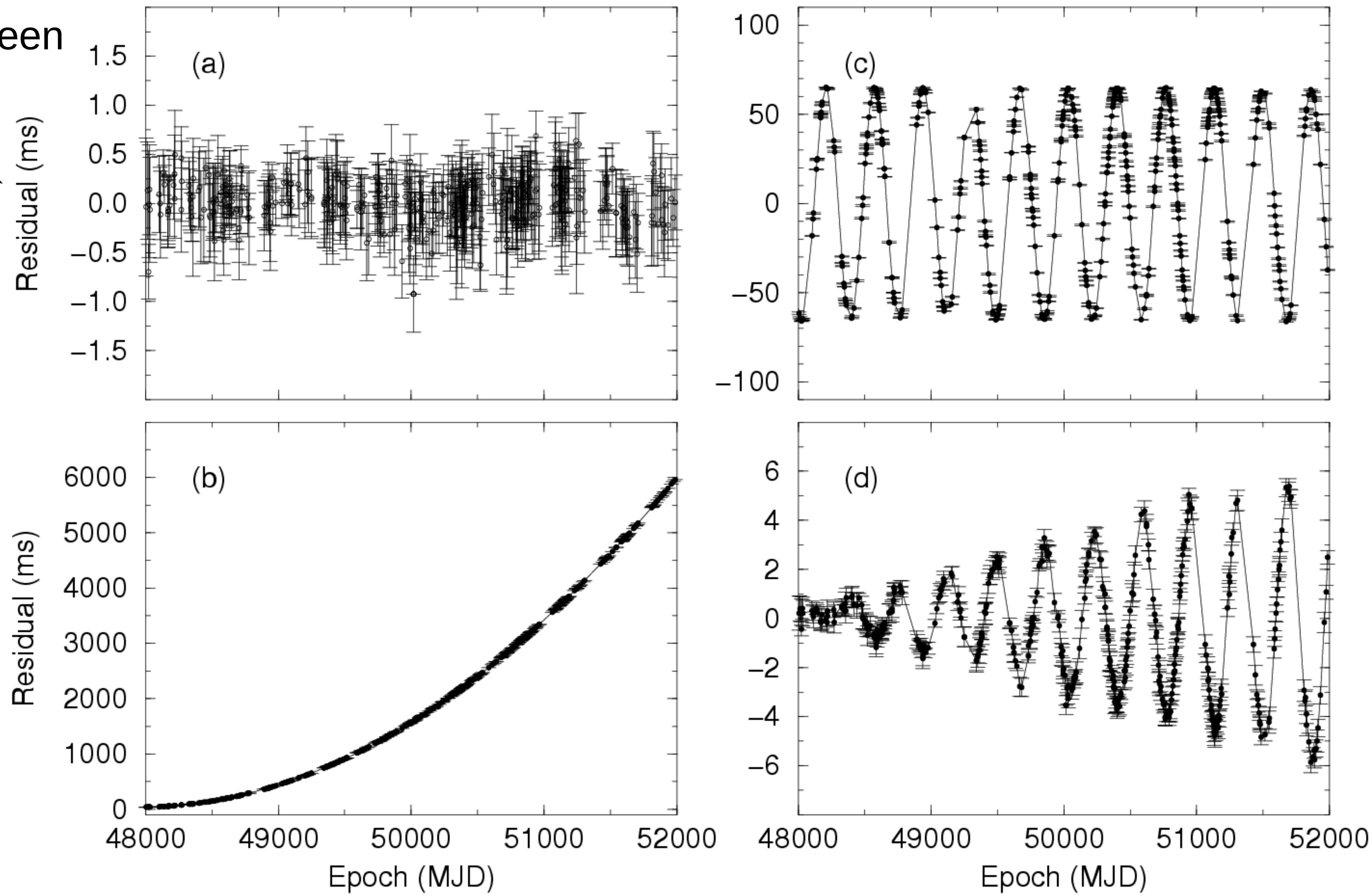


Figure credit: Handbook of Pulsar Astronomy Lorimer and Kramer

Pulsars as Clocks

$$f = \mathrm{d}\phi/\mathrm{d}t, \text{ at some reference } \mathrm{t}_0$$

$$\phi(t) = \phi_0 + f\,(t - t_0) + \tfrac{1}{2}\,\mathrm{d}f/\mathrm{dt}\,(t - t_0)^2 + \ldots$$

- Spin period can be measured to $\sim\delta/N_{rot}$
  - For MSPs observed over many years, $N_{rot}\sim10^9$
- At 2018-05-20 13:30 EDT the frequency of PSR J0437-4715 is/was

```
173.687945250858 ±
  0.000000000004 Hz
```

Timing Uncertainty

- Individual TOA error is roughly δ/(S/N)
  - Measured via Fourier domain cross correlation
  - Narrow profile features are good
- Often interested in long-term predictability
  - Want small scatter in **residuals**

$$\sigma^2_{\mathrm{rms}} = \sigma^2_{\mathrm{tm}} + \sigma^2_{\mathrm{jit}} + \sigma^2_{\mathrm{DISS}} + \sigma^2_{\mathrm{DM}} + \sigma^2_{\mathrm{DM}(\nu)} + \sigma^2_{\delta\tau} + \sigma^2_{\mathrm{pol}}$$

Radiometer noise

Scintillation

Freq-dependent DM

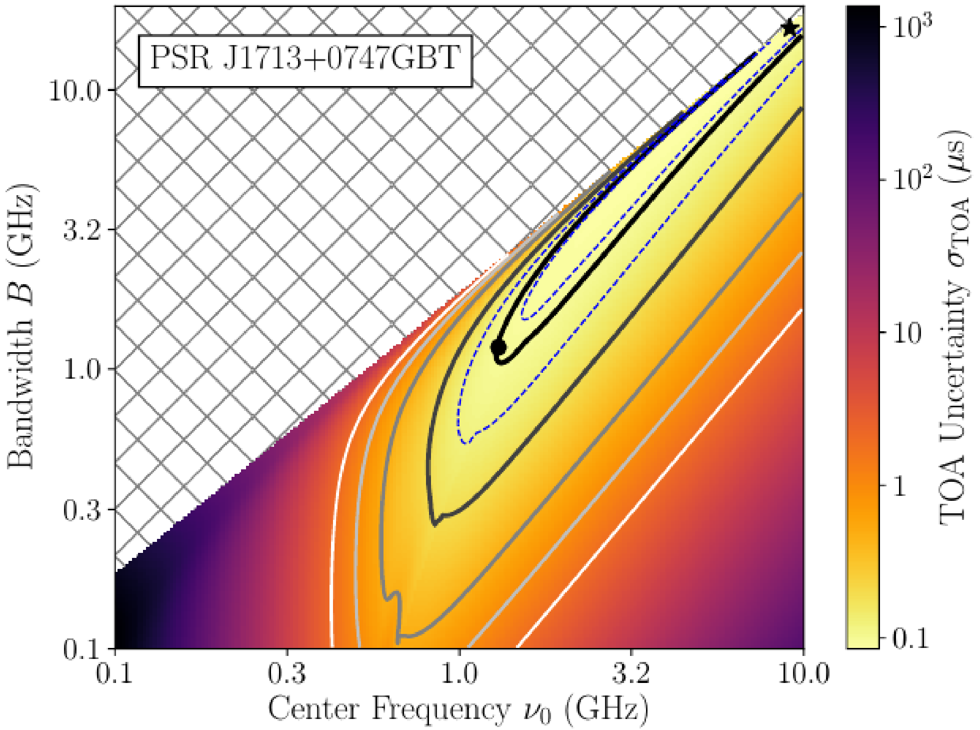
Pol. Calibration

Jitter

DM errors

Pulse broadening

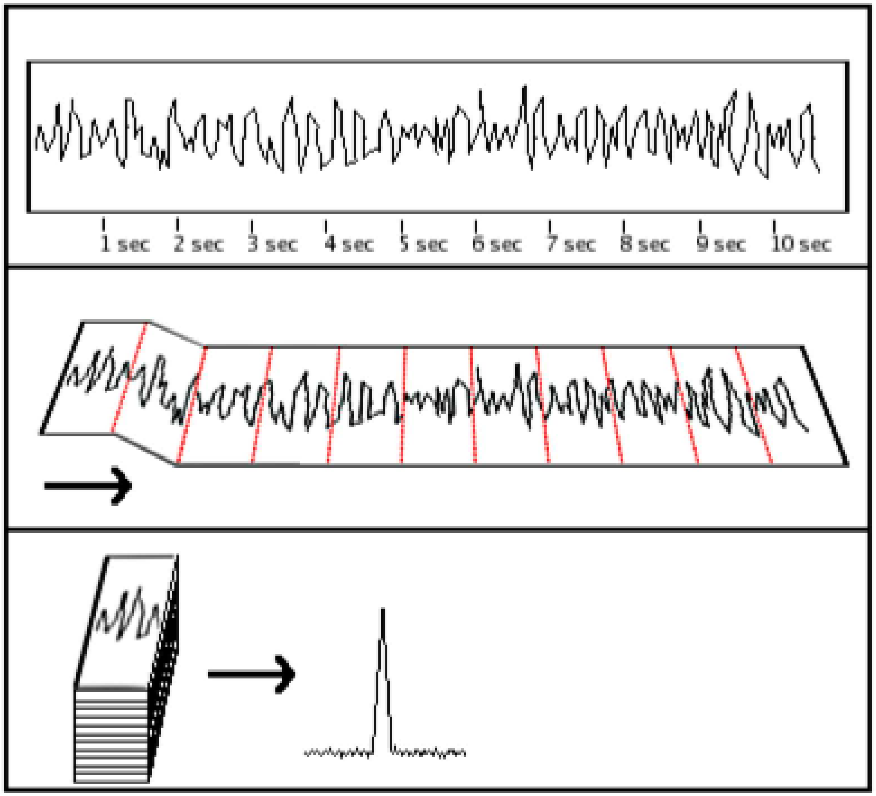
Optimal Frequencies for Pulsar Timing



Lam et al. (2018)

- Moving to higher frequencies, wider bandwidths can give substantial improvements in residual RMS
- Pulsar and telescope dependent!

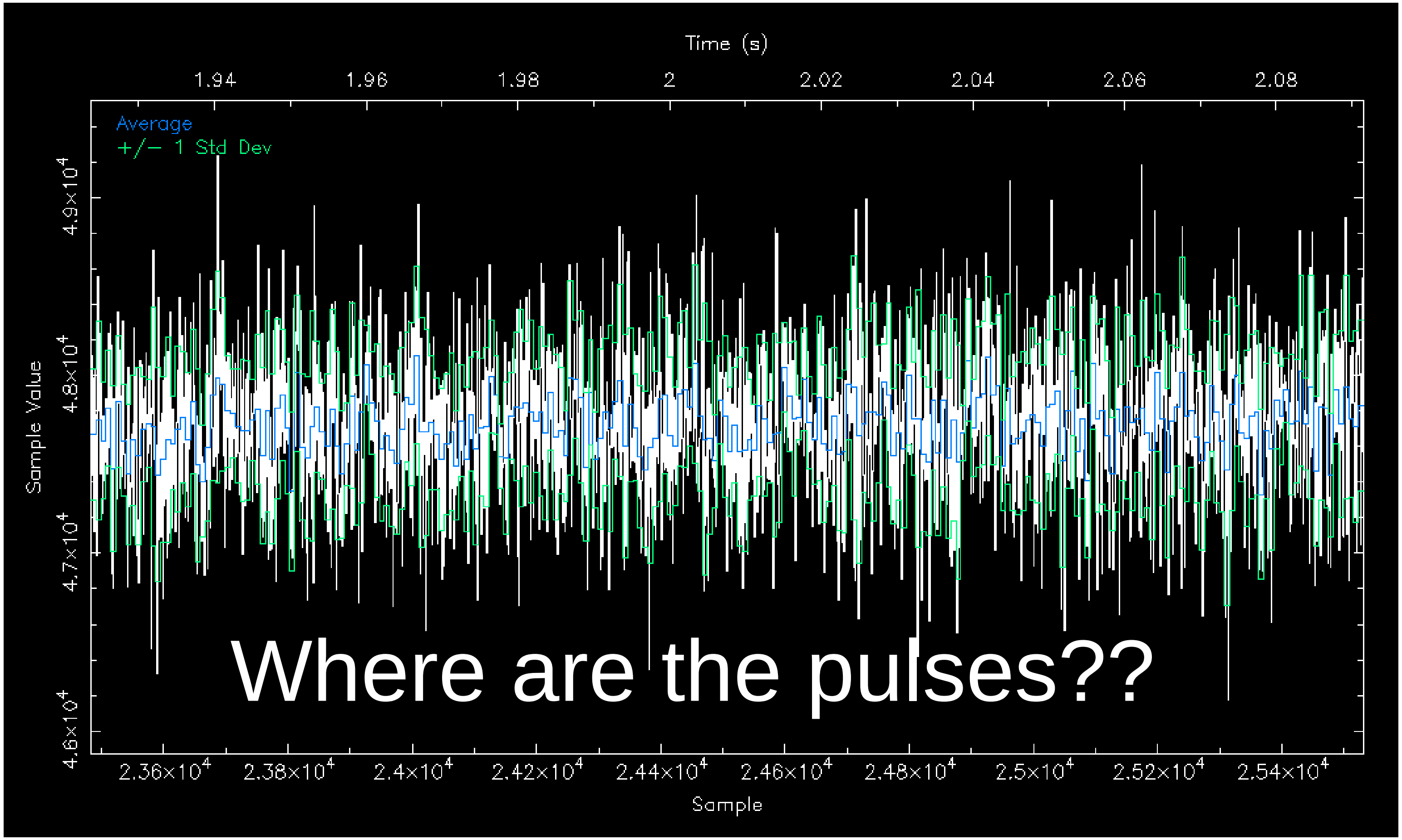
Folding



- With an accurate timing model, data can be phase folded in real-time
  - Reduces data rate, simplifies later processing

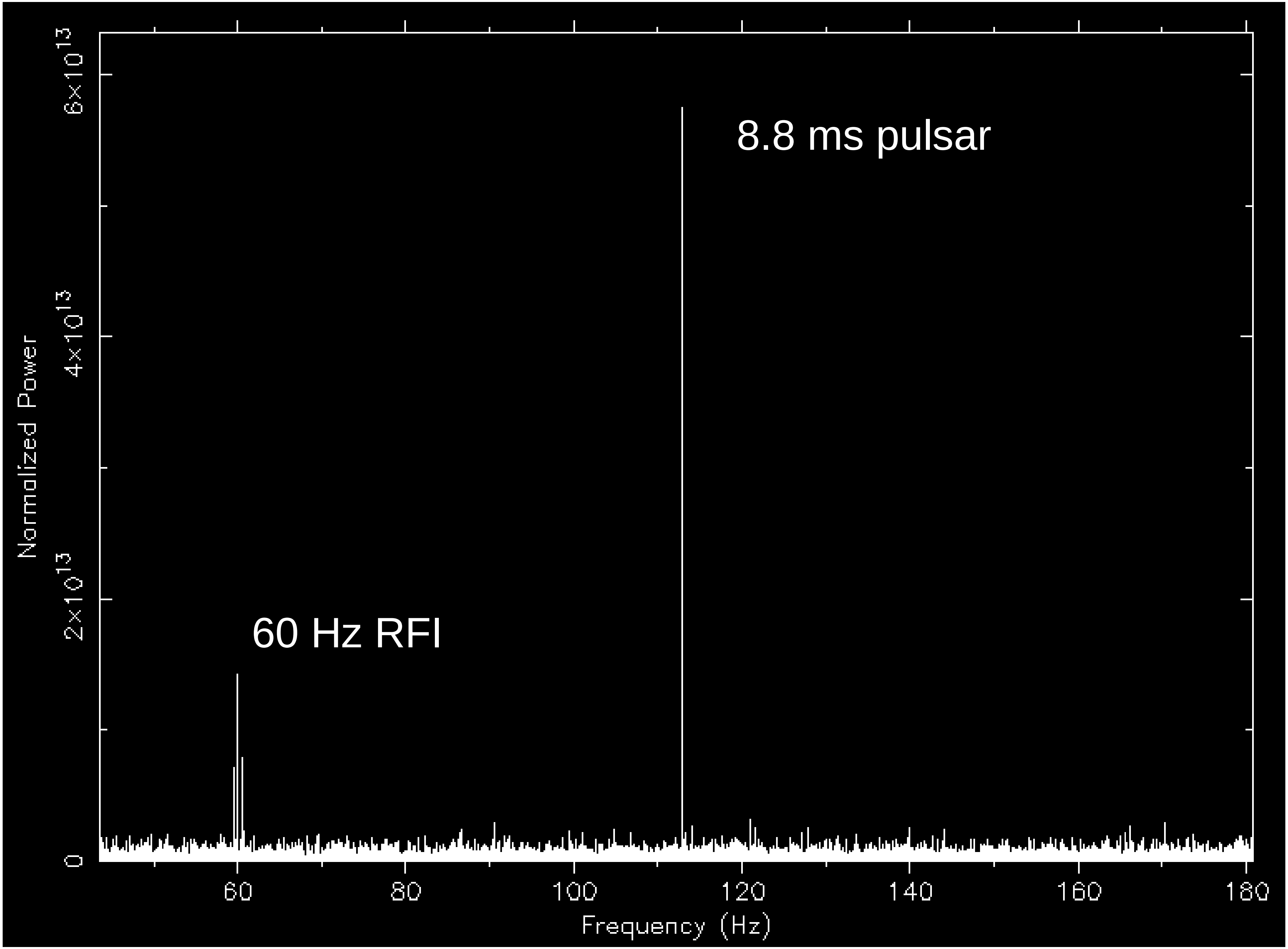
Searching for Pulsars

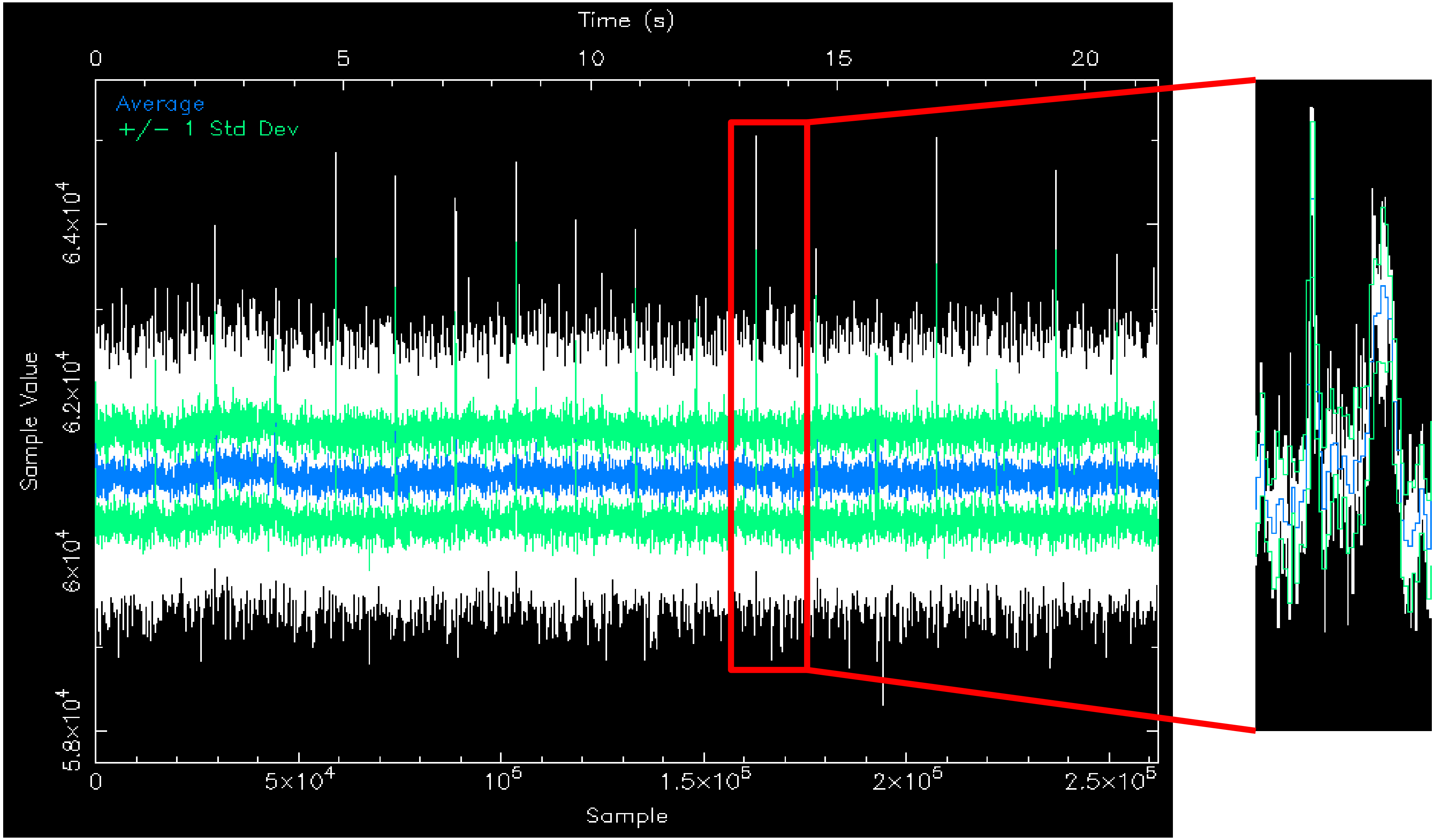
- After de-dispersion frequencies are typically summed to create a time series



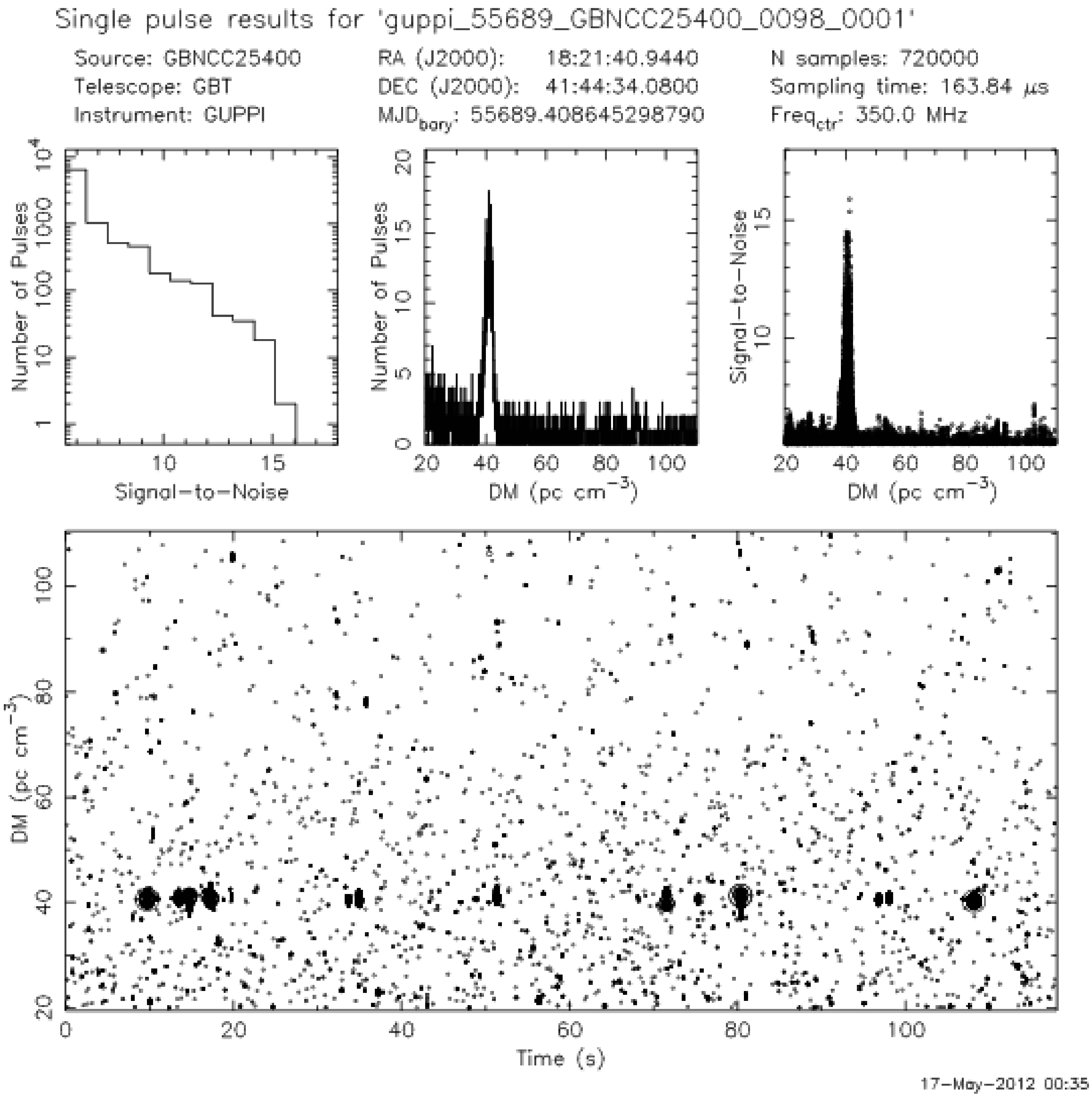
Searching for Pulsars

- In practice, single pulses are often below the noise floor
- Most pulsars are found via Fourier-domain searches
  - Care must be taken to account for Doppler shifting of pulse period due to binary acceleration
- Searches are often the most computational intensive part of a search


8.8 ms pulsar
60 Hz RFI
Normalized Power
0
2×10^13
4×10^13
6×10^13
60
80
100
120
140
160
180
Frequency (Hz)

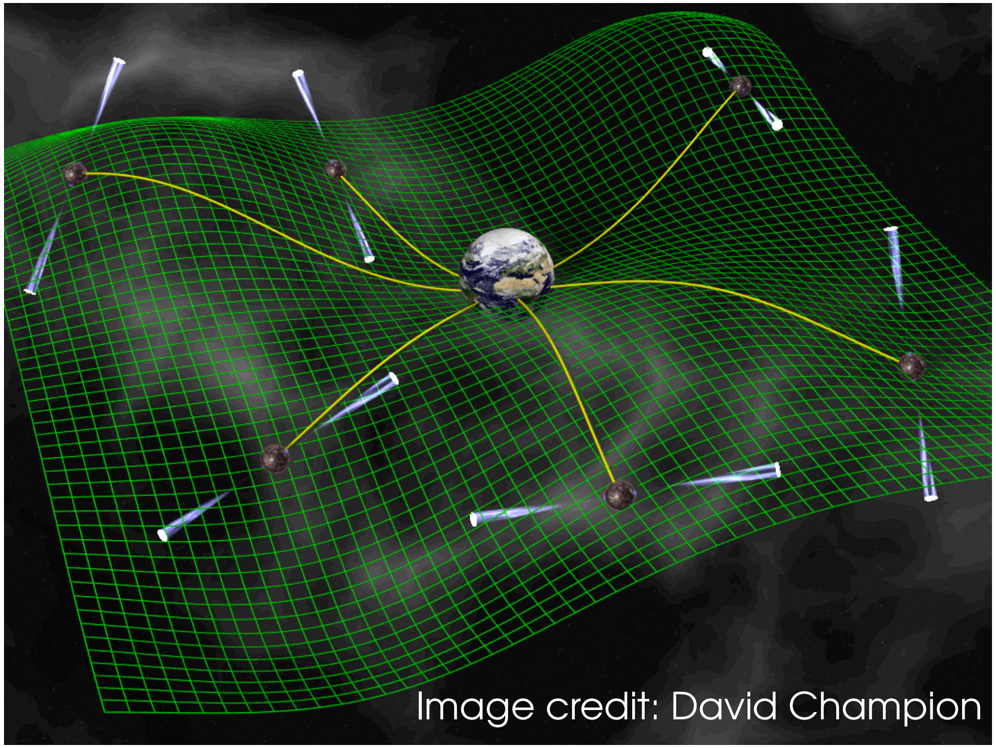


- Individual pulses are sometimes visible


Single pulse results for 'guppi_55689_GBNCC25400_0098_0001'
Source: GBNCC25400
Telescope: GBT
Instrument: GUPPI
RA (J2000): 18:21:40.9440
DEC (J2000): 41:44:34.0800
MJDbary: 55689.408645298790
N samples: 720000
Sampling time: 163.84 μs
Freqctr: 350.0 MHz
Number of Pulses
Signal-to-Noise
DM (pc cm−3)
Time (s)
17−May−2012 00:35

Millisecond Pulsar Timing Arrays

- GWs will cause a quadirpolar angular correlation signature
- Requirements: 10-100s ns residuals, full sky coverage, lots of pulsars, precise ISM measurements



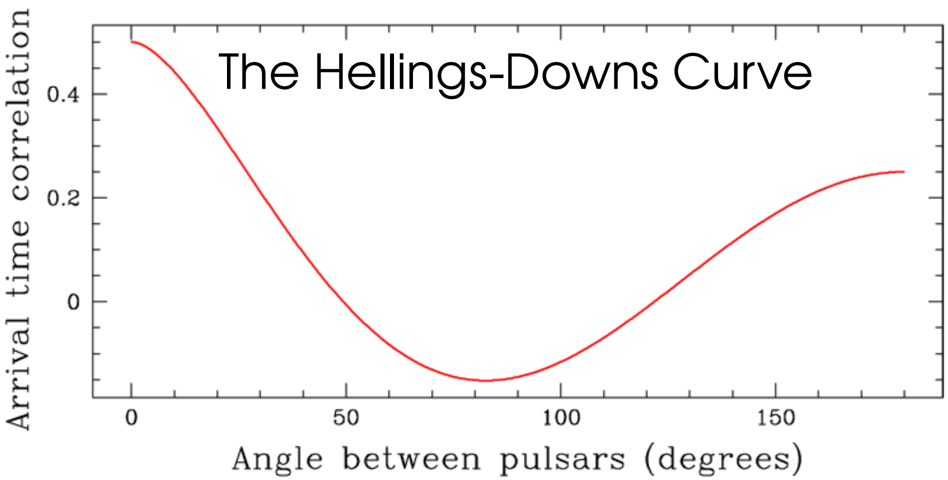
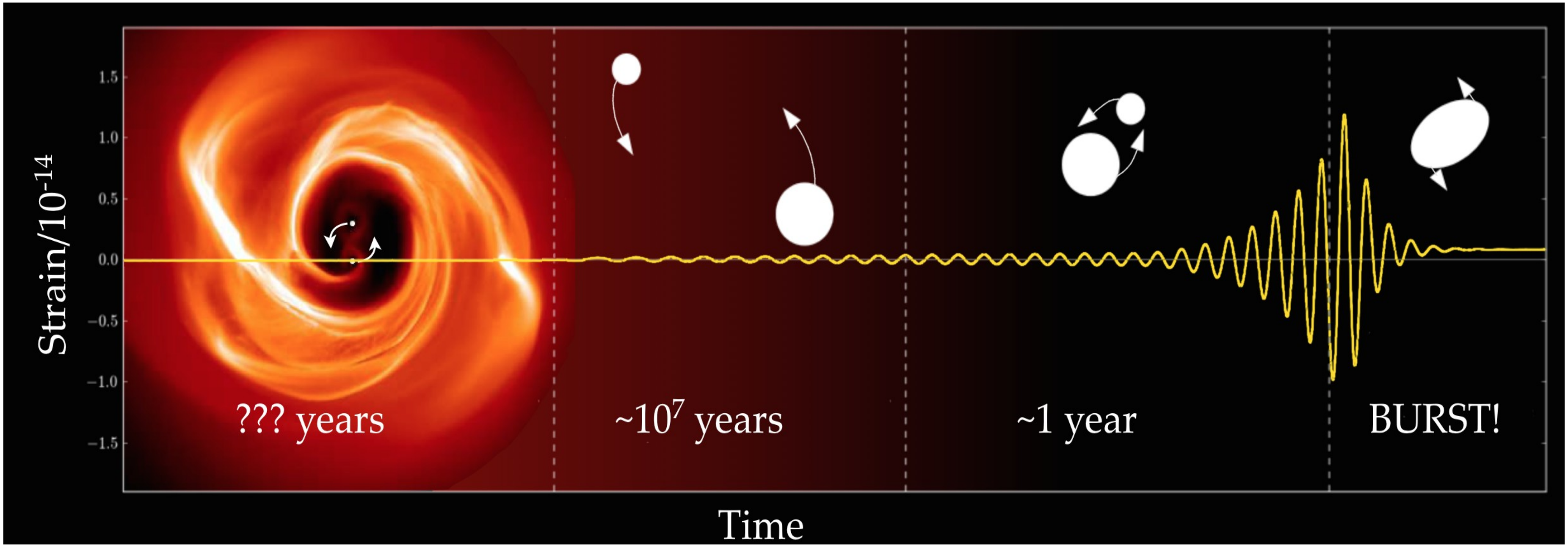


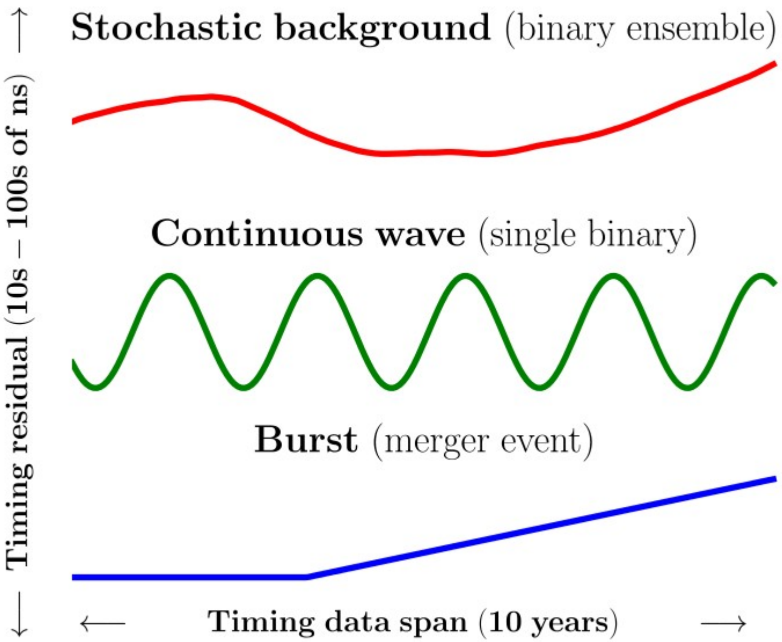
Image credit: NANOGrav

The nHz GW Universe



- Galaxies merge, so should their supermassive BHs
- Gravitational radiation will take over as dominant mechanism of energy loss
- Orbital periods of few years correspond to nHz GW frequency
  - This is the PTA band
- More exotic sources are also possible (e.g. cosmic strings)

Observational Signatures



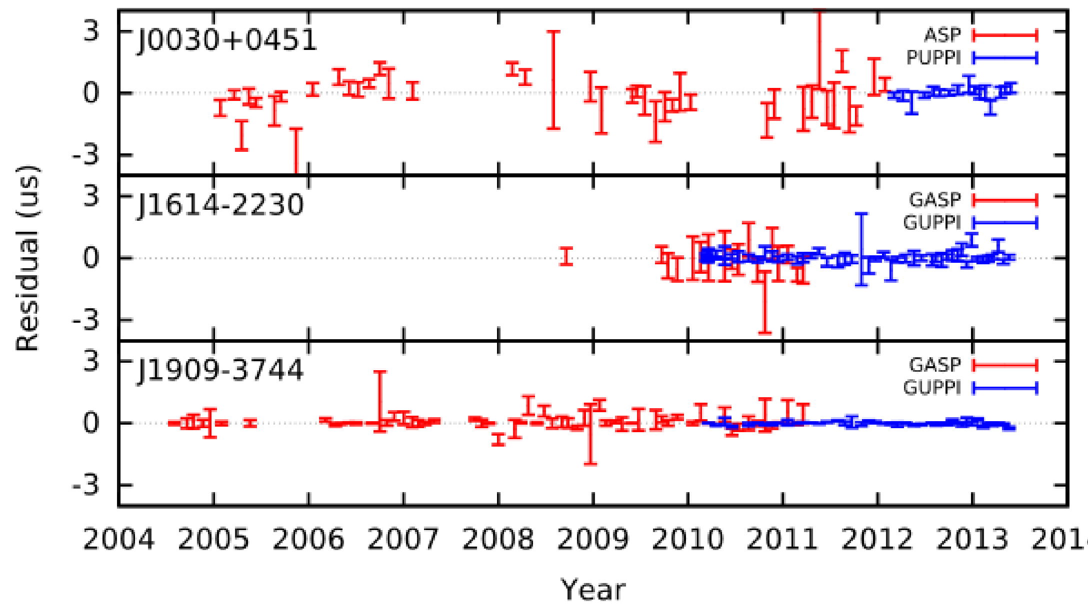
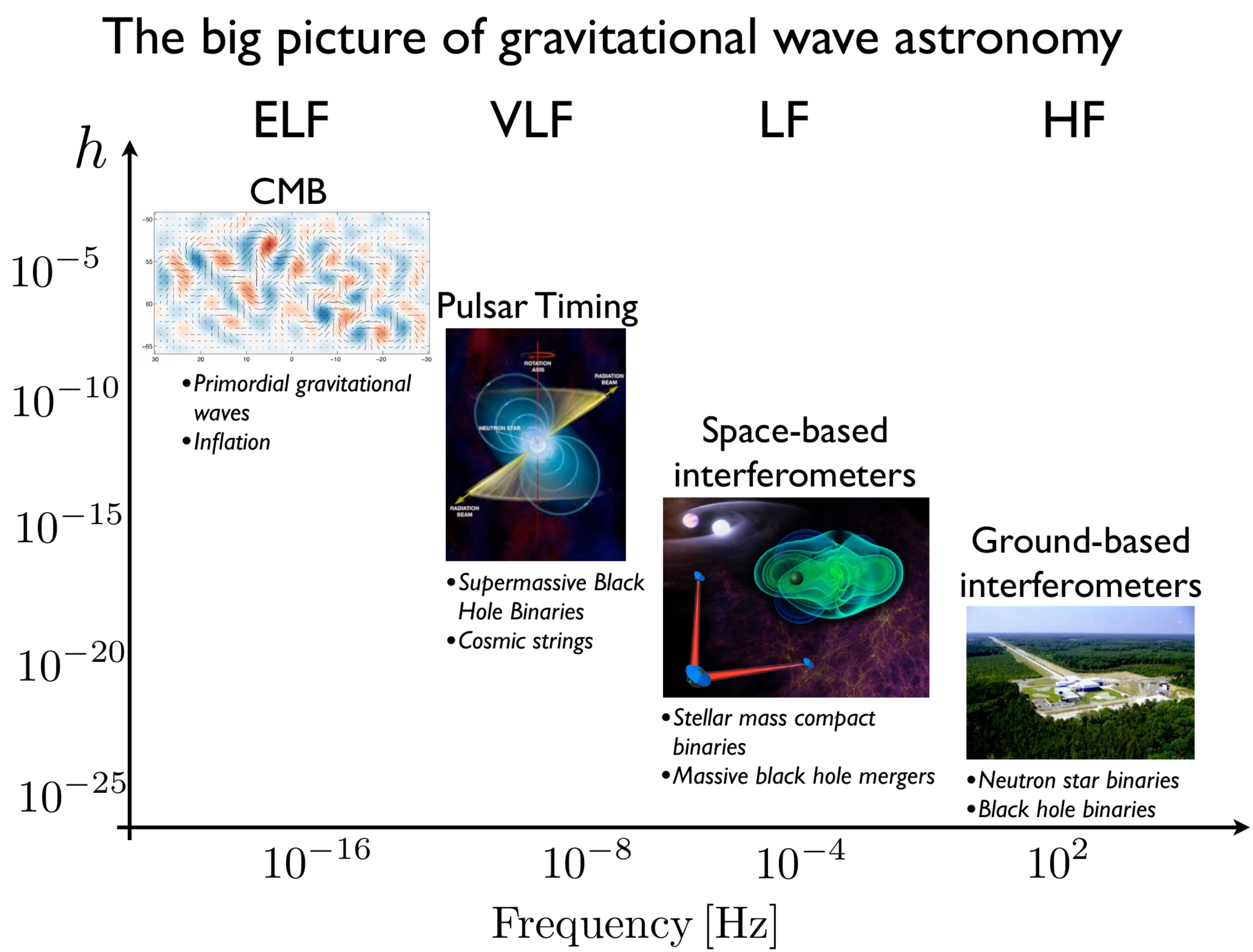


Image credits: NANOGrav

- Different source classes have different structure in residuals
- Sensitive to f_{GW} ~ nHz / $\lambda_{GW} \sim 10^{17}$ m

Complementary Gravitational Wave Detectors



NANOGrav

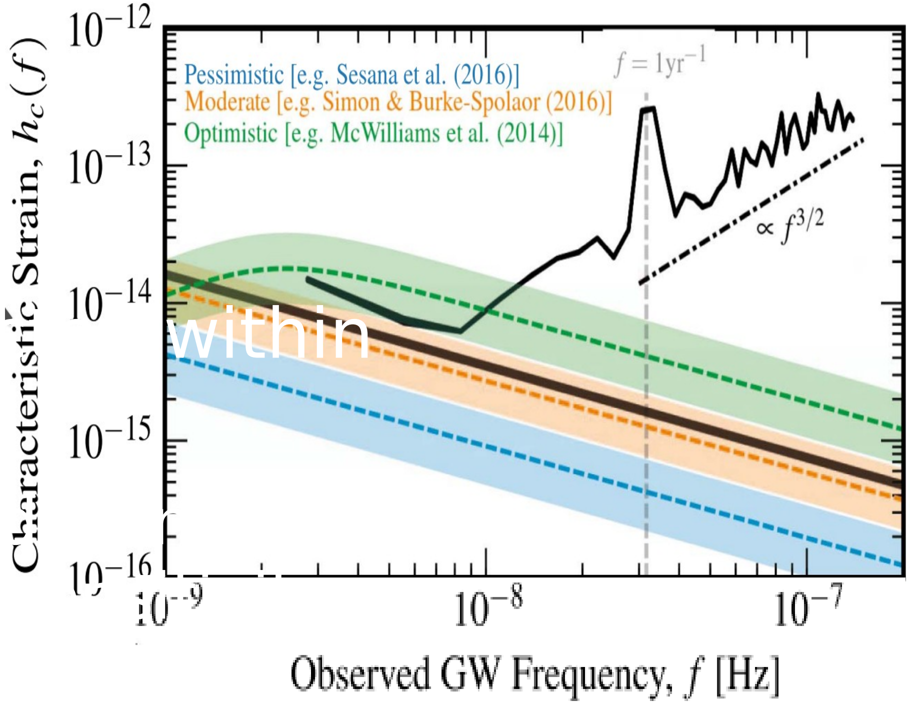
Physics Frontiers Center

NANOGrav

- North American PTA
  - Senior/affiliated researchers at over two dozen institutions (US, Canada, Europe)
- Funded by NSF Physics Frontier Center ($14.5M over 5 years)
  - Portion of funding supports GBT operations
- Currently time 45 pulsars at GBT and Arecibo
  - 500 (GBT) + 800 (AO) = 1300 hrs/year
  - Does not include pulsar searches!
  - **Each contributes 50% of overall GW sensitivity**
- International collaboration through IPTA

Sources of GWs – Stochastic Background

- Ensemble of binary BHs will give rise to a stochastic GW background
  - Amplitude depends upon merger rate, BH coupling to environment, eccentricity distribution
- Current limits are in an interesting range given astrophysical uncertainties



Arzoumanian et al. 2018, ApJ, 859, 22

Sources of GWs – Stochastic Background

- Ensemble of binary BHs will give rise to a stochastic GW background
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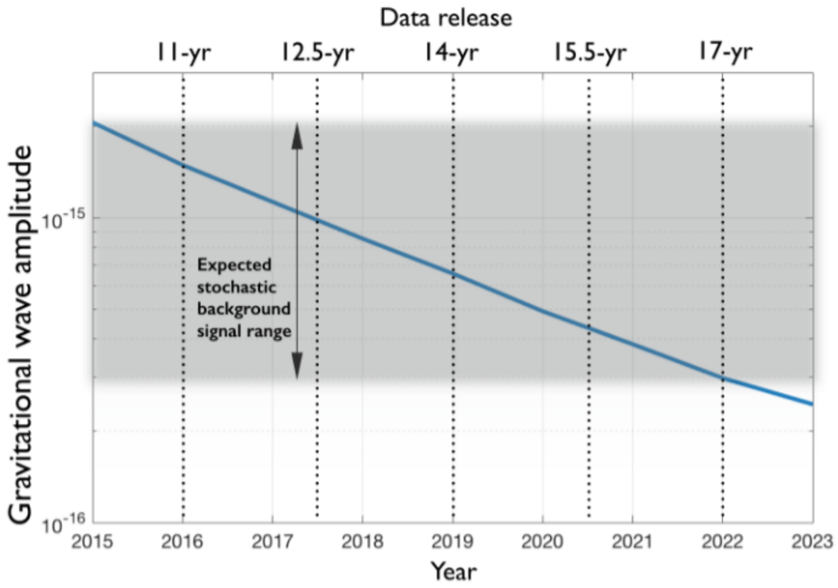
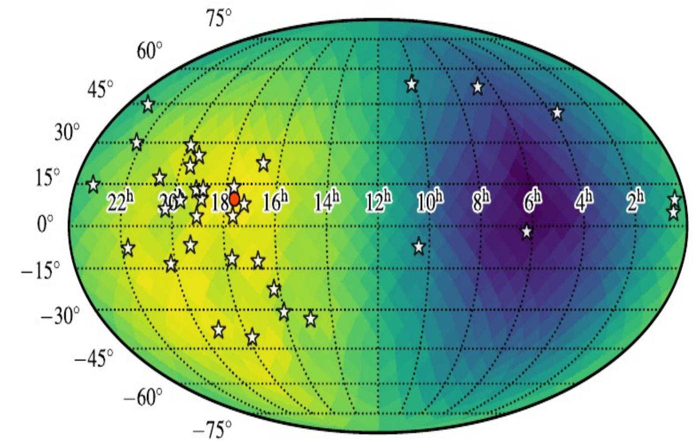
  Bottom line: detection expected early next decade

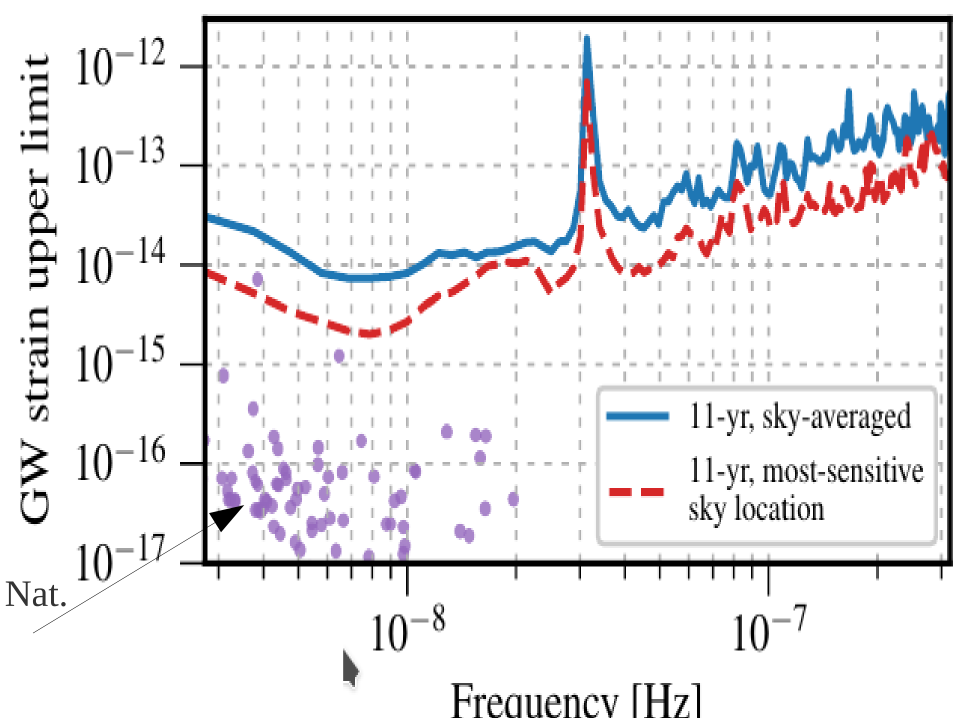


Sources of GWs – Individual Binaries

- Individual binaries will appear at ~constant GW frequency
- "PSF" depends strongly on sky-location of best-timed pulsars
  - Full-sky coverage and distribution of pulsars is essential!
- Detection of single sources will most likely come later this decade

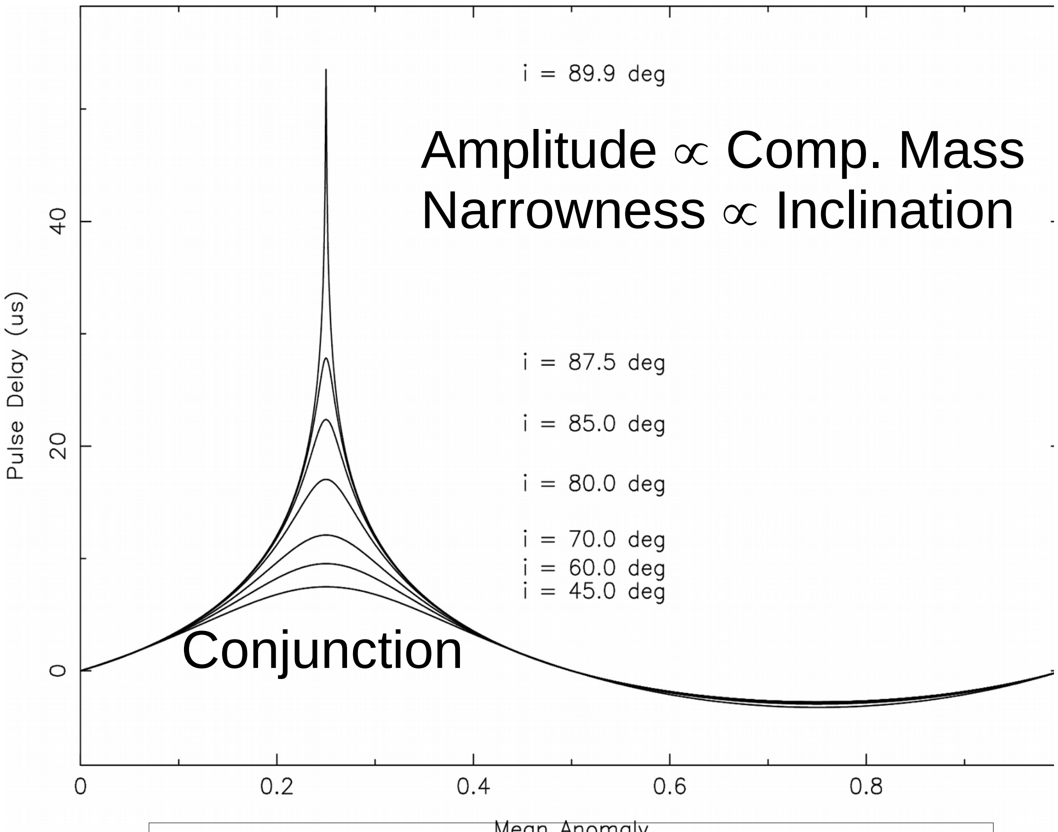


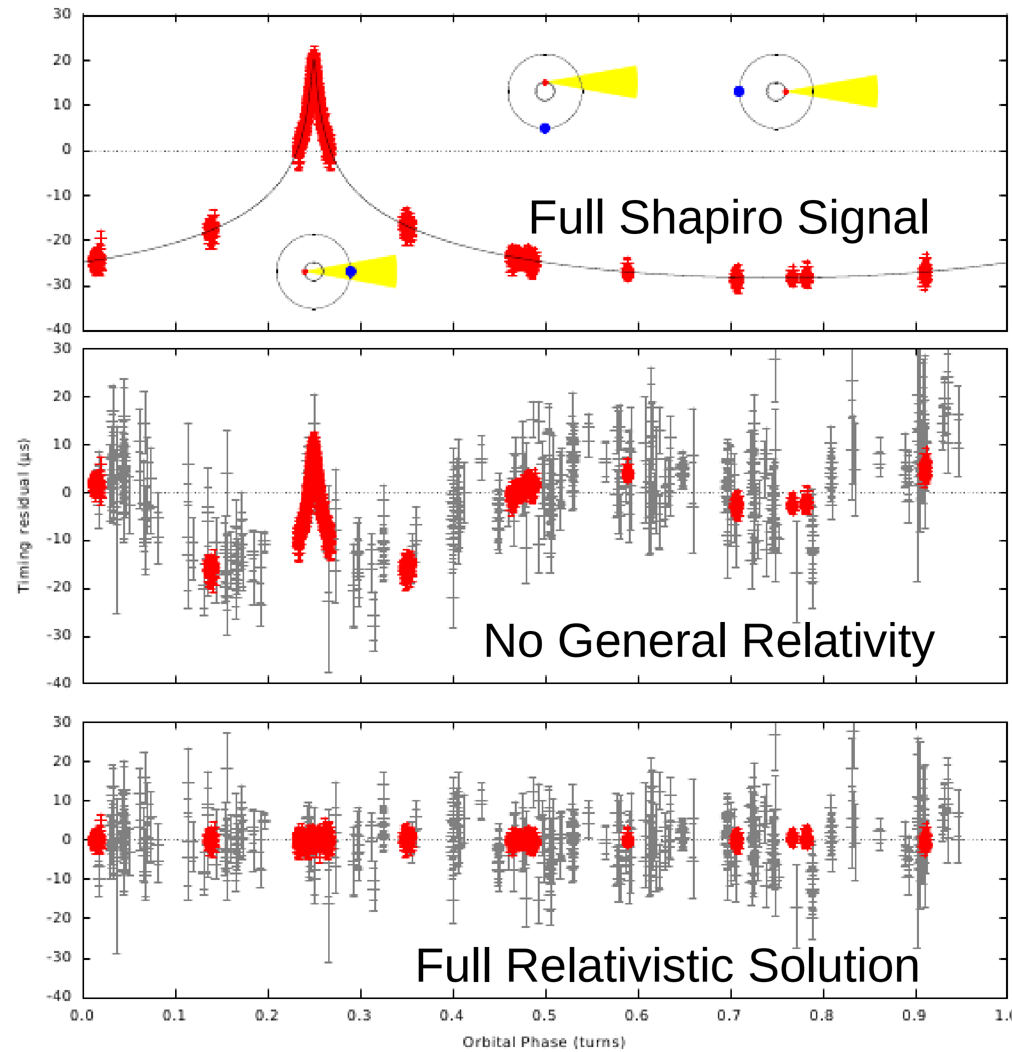
Arzoumanian et al. accepted by ApJ



Single sources from a snapshot population (Mingarelli et al. 2017, Nat. Astr., 1, 886)

Subatomic Physics





$M_{wd} = 0.500(6)\ M_\odot$

$M_{psr} = 1.97(4)\ M_\odot$!

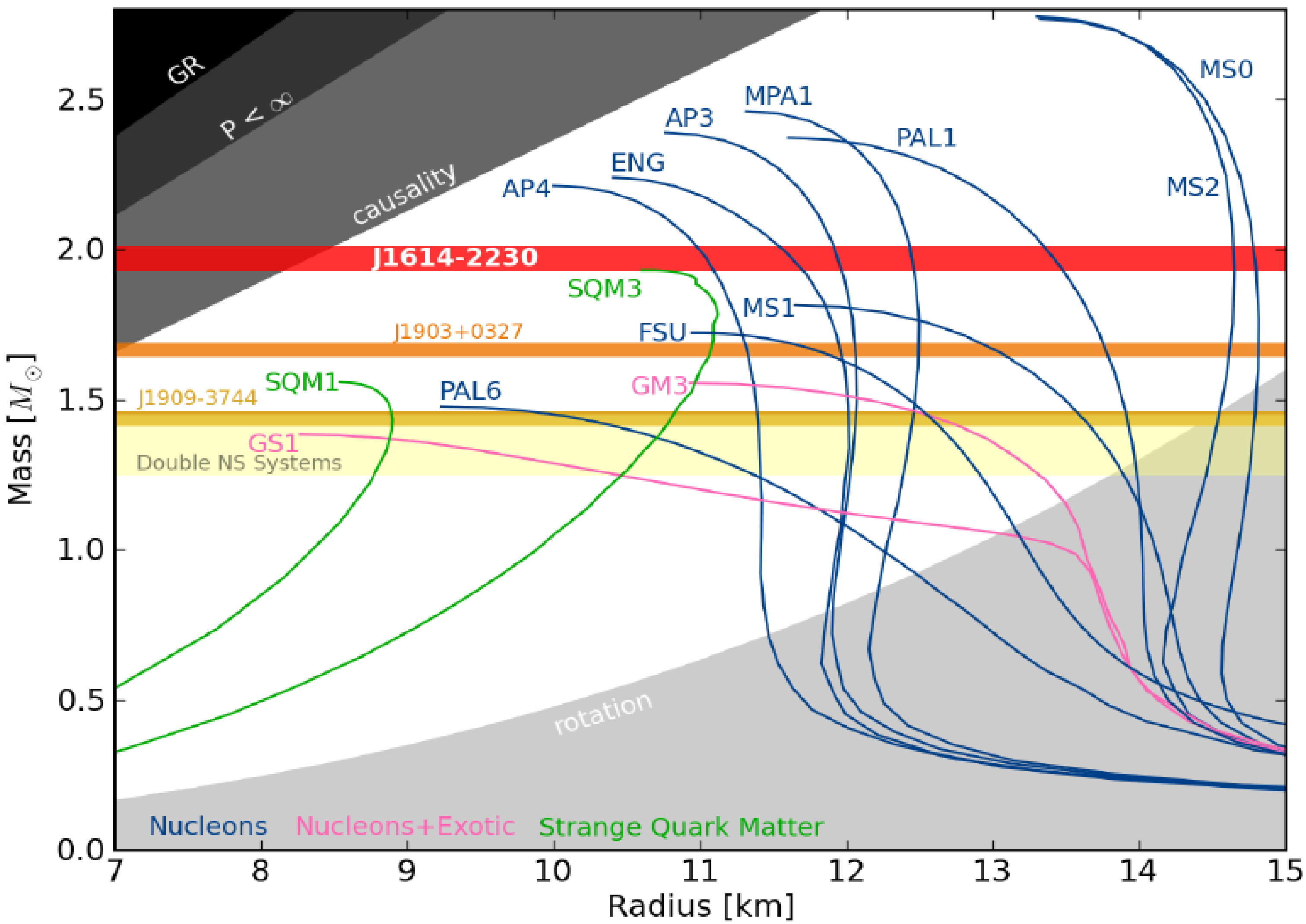
Inclination = 89.17(2) deg!

Demorest et al. 2010, Nature, 467, 1081D

Most highly cited GBT paper (1,550+)

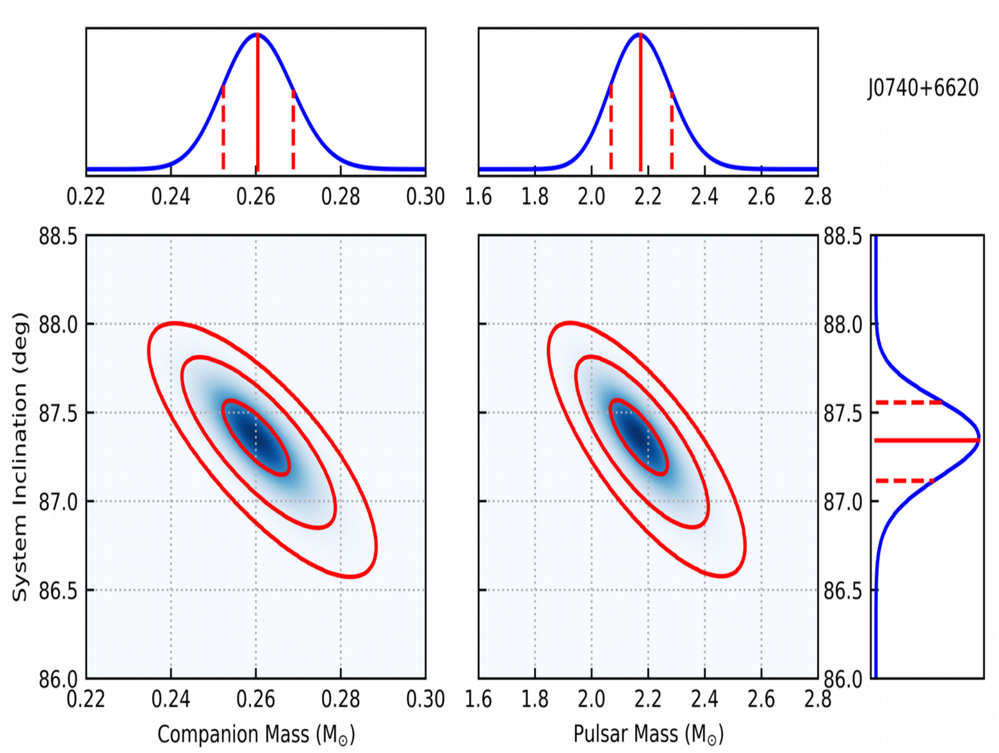
Subatomic Physics

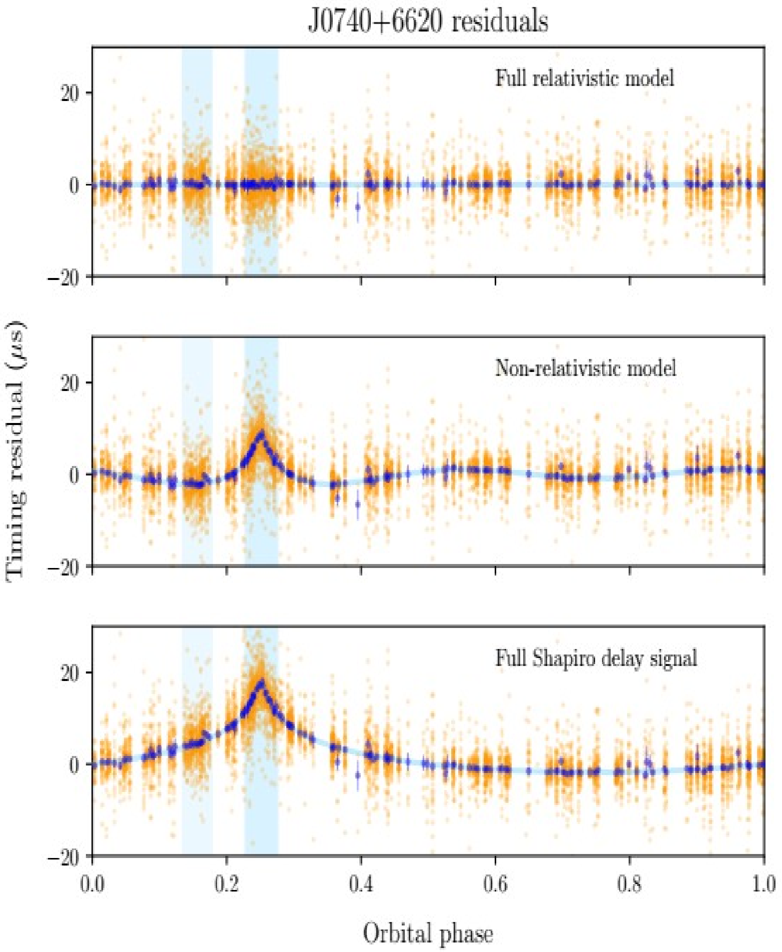
Rules out most or all EOSs
with exotic material in the cores



Latest Results

NANOGrav timing reveals another massive (> 2 M_{sun}) NS, pointing to “hard” EOS

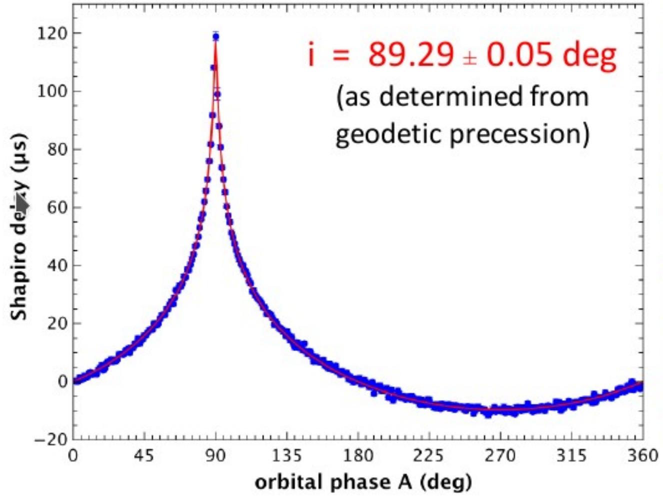


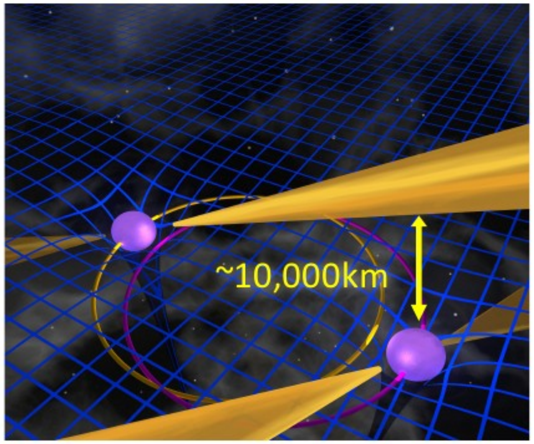


Cromartie et al., submitted to Nat. Astr.

Strong Field GR Tests

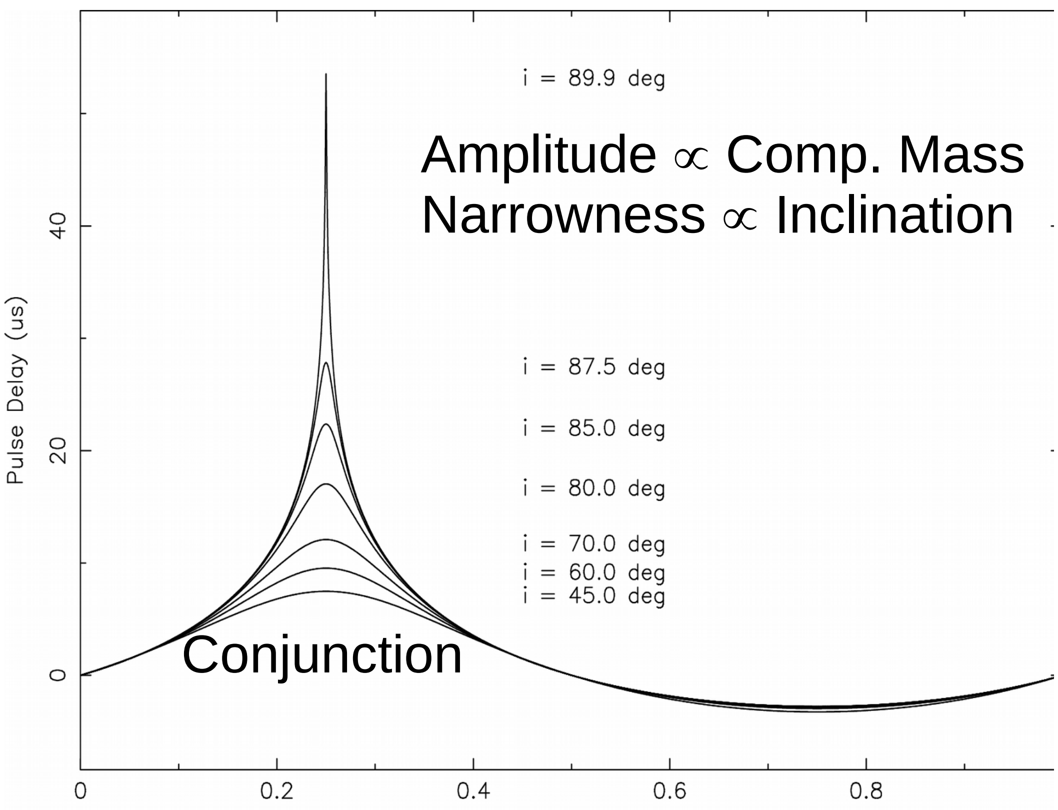
- Double Pulsar is the premier system for studying strong-field GR
  - Light from one pulsars passes within 10,000 km of the other
- Seeing 2nd order post-Newtonian effects

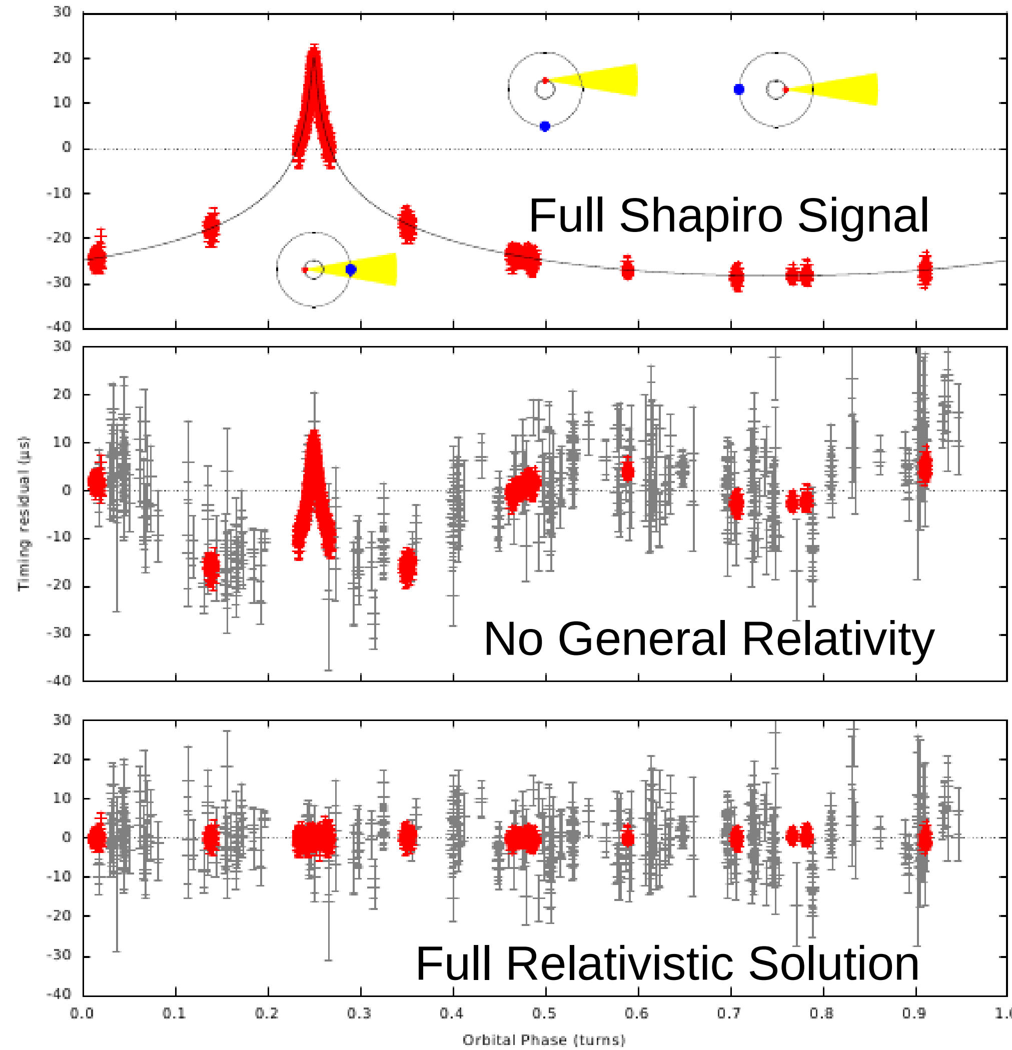




Courtesy of Michael Kramer

Subatomic Physics





$M_{wd} = 0.500(6)\ M_\odot$

$M_{psr} = 1.97(4)\ M_\odot$!

Inclination = 89.17(2) deg!

Demorest et al. 2010, Nature, 467, 1081D

Most highly cited GBT paper (1,550+)

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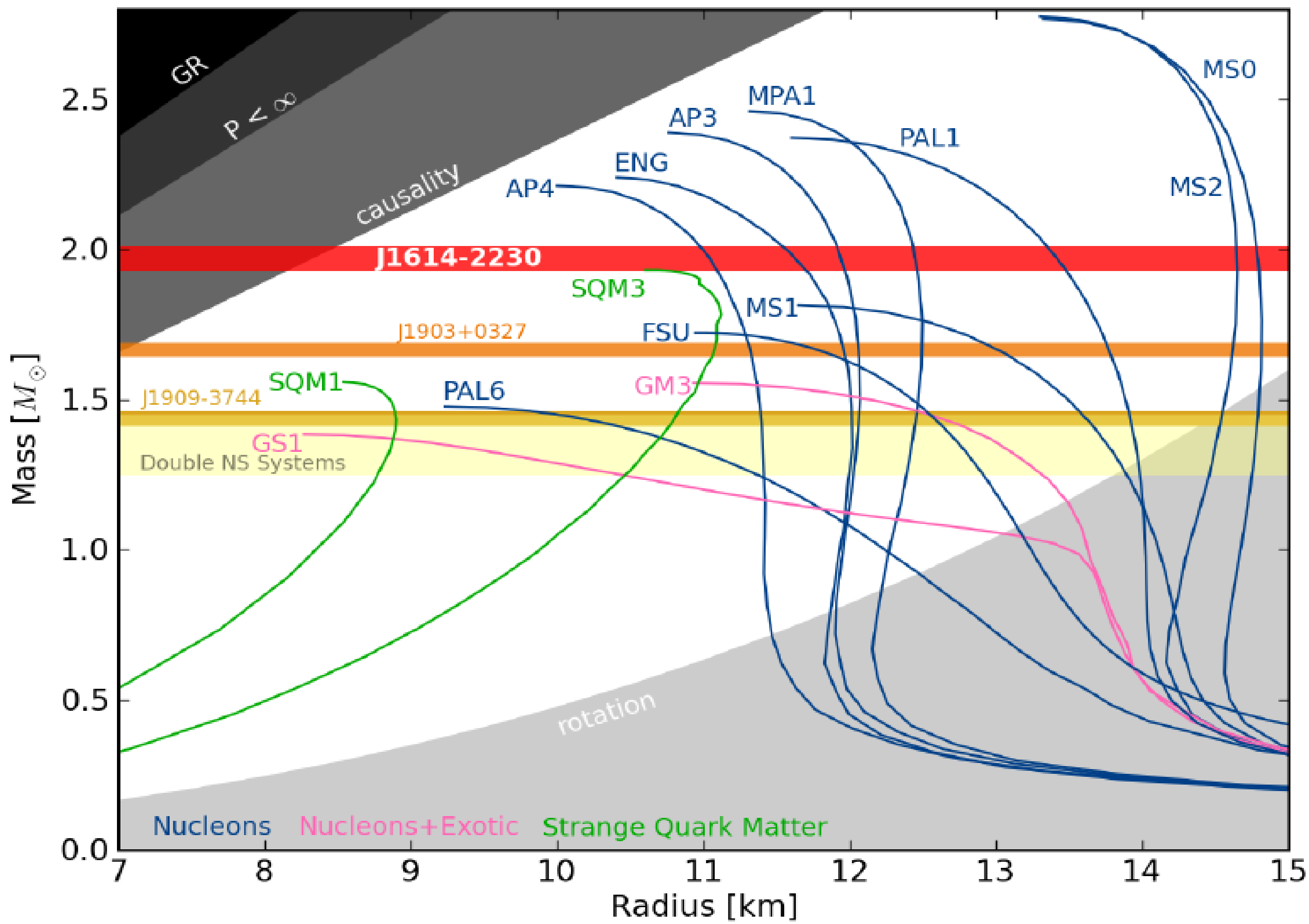
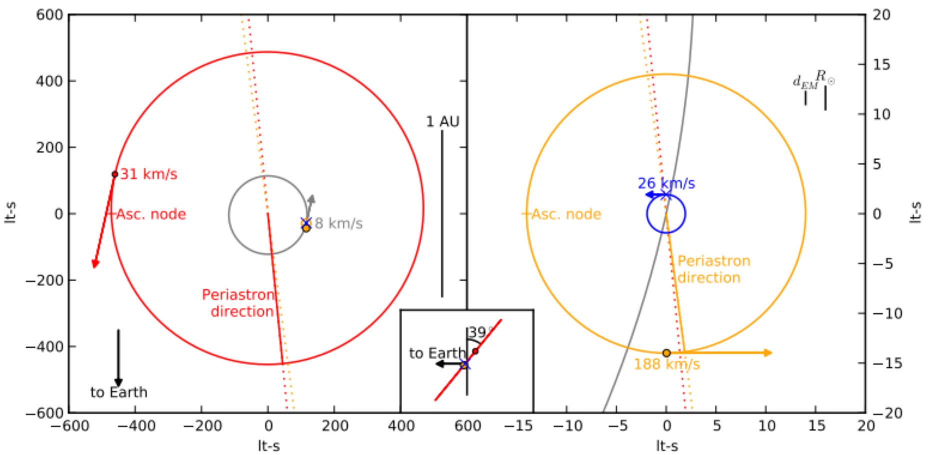


Testing the Strong Equivalence Principle

- PSR J0337+1717: First MSP in a stellar triple system
  - Discovered in GBT survey
- Three body dynamical effects cause secular changes in orbital parameters
  - Allow us to precisely solve for the **geometry and masses** of all stars and orbits



- All bodies fall at the same rate (?)
- MSP & inner WD falling in gravity of outer WD

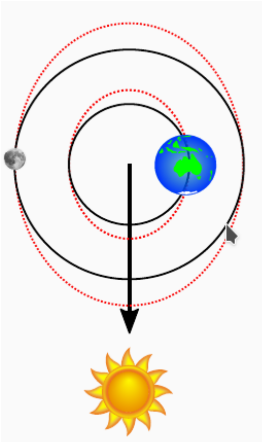
Image credit: Ransom et al. (2014, Nature, 505, 520)

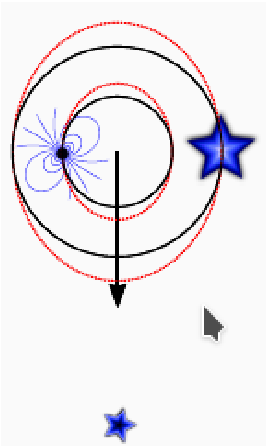
Testing the Strong Equivalence Principle

- Violations parameterized by differential acceleration

  Currently dominated by systematics

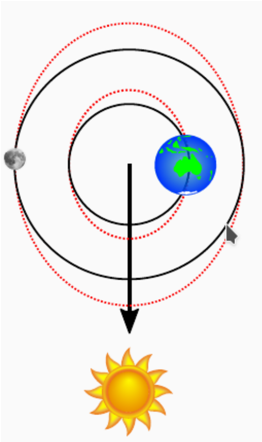
    Sensitive to Solar wind DM variations

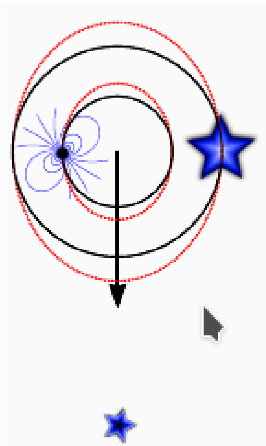


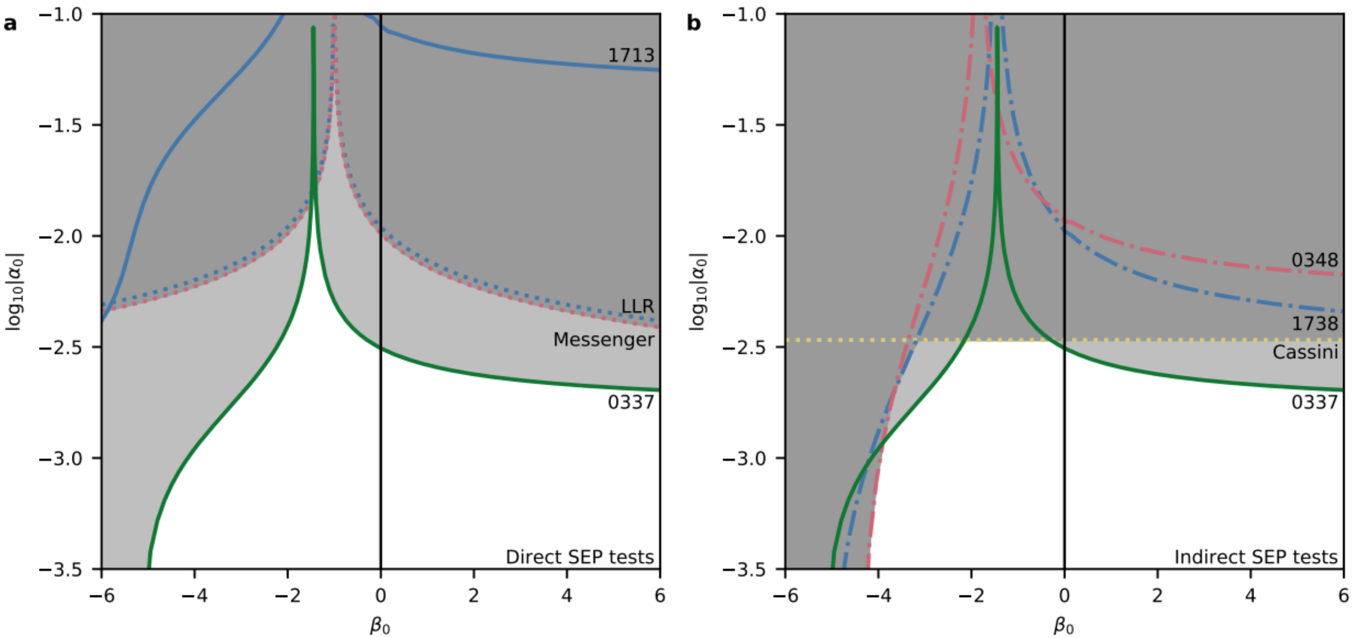


Testing the Strong Equivalence Principle

- Violations parameterized by differential acceleration
- Currently dominated by systematics
  - Sensitive to Solar wind DM variations
- Current best limit on differential acceleration $\Delta = 10^{-6}$
  - 100x improvement over Lunar ranging tests







Archibald et al. (2018)