An Introduction to Pulsar Timing Arrays

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INTERNATIONAL PULSAR TIMING ARRAY

IPTA

PPTA

NANOGrav

EPTA

Getting started...

- PTA stands for Pulsar Timing Array
- So we will talk about...
    - Pulsars: The basics you need to know
    - Timing: The general idea (more detail to follow)
    - Arrays: Using multiple pulsars to detect gravitational waves
- What we won't talk about...
    - Lots of details (you'll get plenty of this in the next 2 weeks)

Pulsars: The simple picture

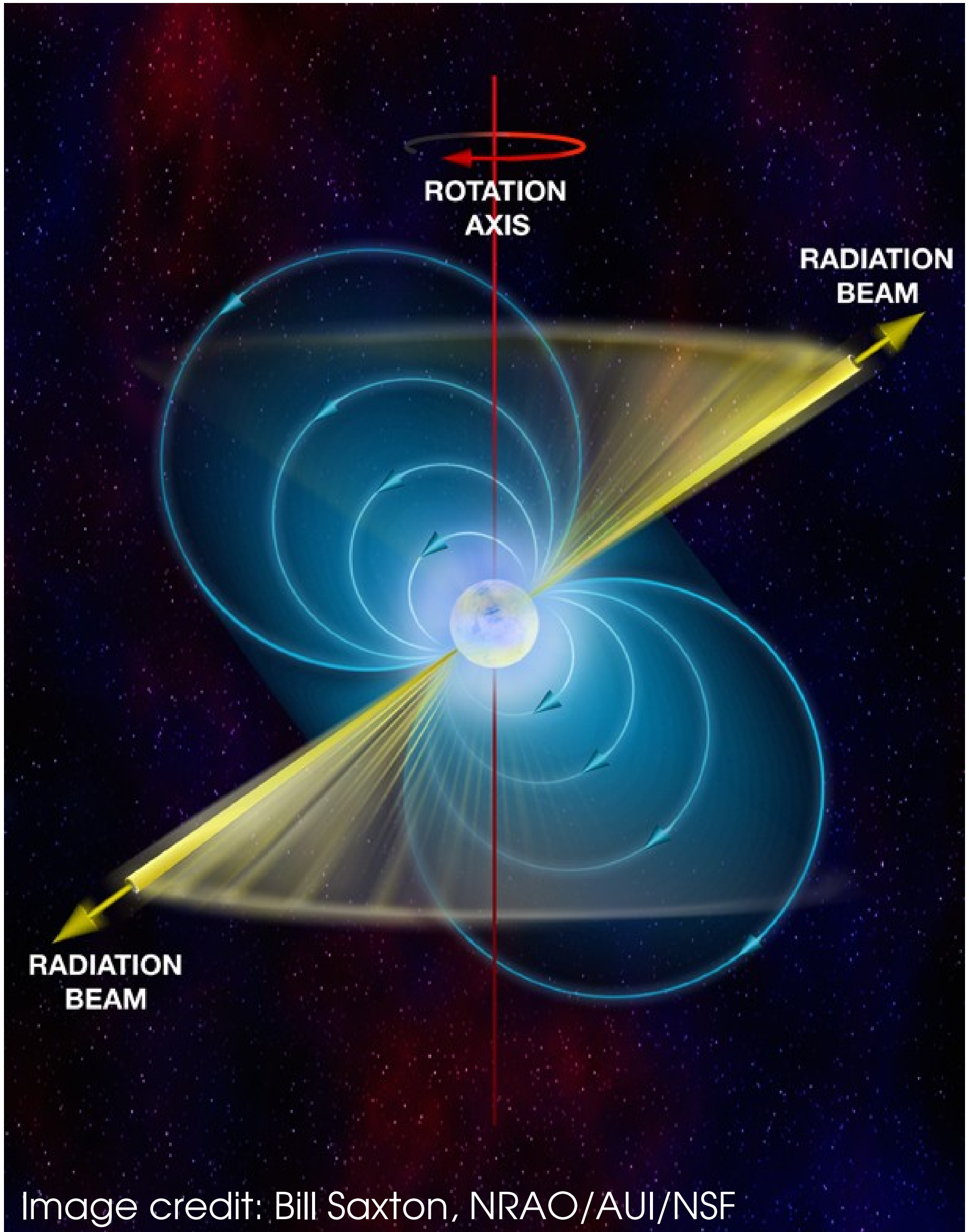


Image credit: Bill Saxton, NRAO/AUI/NSF

- Pulsars are like interstellar lighthouses
- Super strong magnetic fields (10^8 – 10^{15} Gauss)
- Rapid rotation (1 ms – 10 s
- Radio (and high energy) beams

Image credit: Michael Kramer

Pulsars are some of the most extreme objects in the Universe

500,000 Earth masses in a region the size of Manhattan

This is like squeezing the population of the Earth into a sugar cube

Like city-sized atomic nuclei with black-hole like gravity spinning as fast a blender

Magnetic fields billion to quadrillion times stronger than man-made magnets

Image credit: NASA / JPL-Caltech / R. Hurt (SSC)

Why do pulsars shine?

- Still an open area of research
- Basic picture is
  - Time varying *B* gives rise to huge *E*
  - Charged particles accelerated to relativistic *v* in magnetosphere
  - Gives rise to beamed radiation

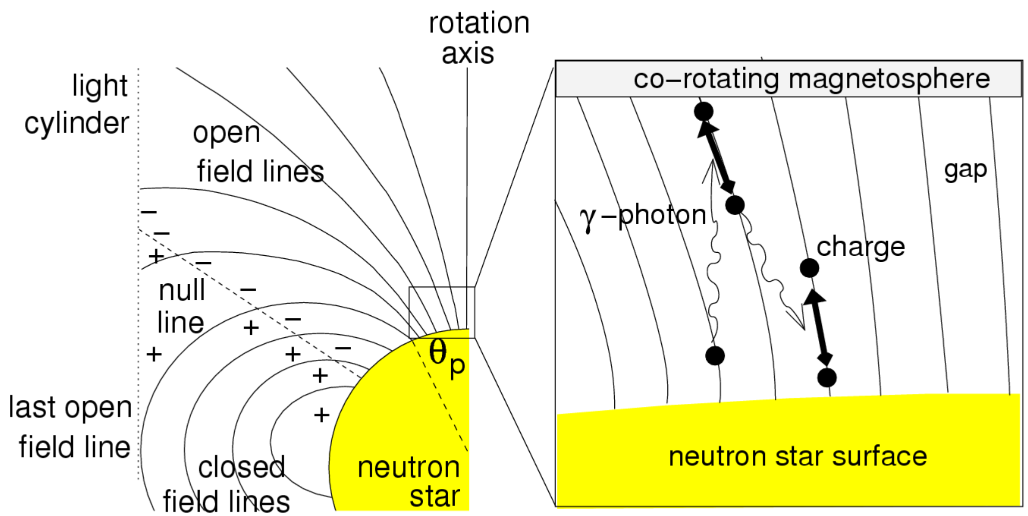
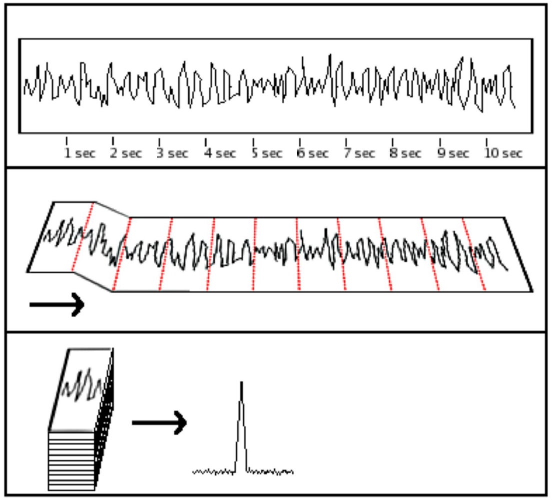


Image credit: Lorimer & Kramer, *HOPA*, 2005

Pulse stability

- Pulse shape/intensity can vary from rotation to rotation
- *But* a stable pulse profile emerges after summing over many rotations (~hundreds - thousands)



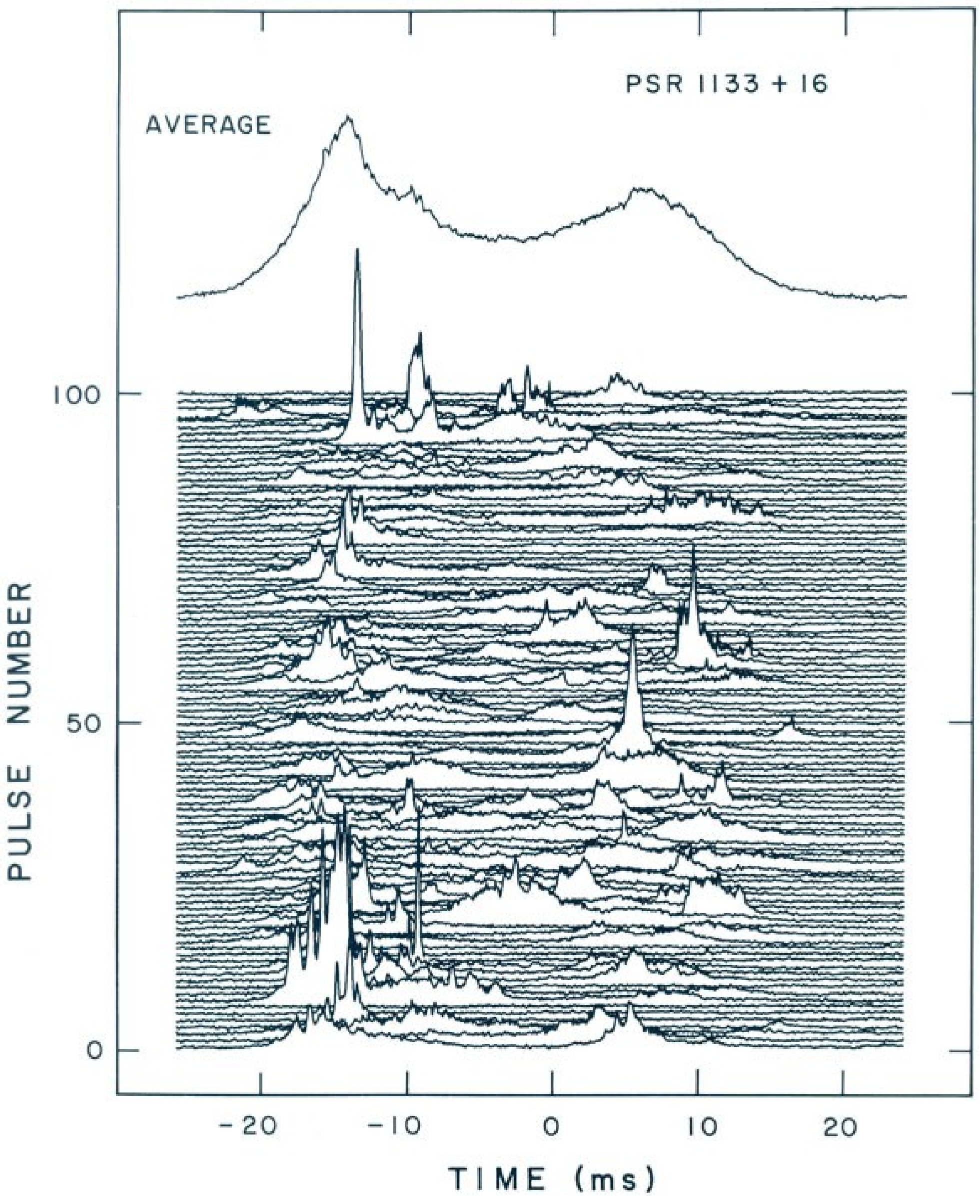


Image credit: Cordes, 1979, SSR, 24, 567

Observable and Derived Properties

- We measure the spin period (P) and its time derivative (spin-down, P-dot)
- From this, we can derive some model-dependent properties

$$B = 3.2 \times 10^{19} \text{ Gauss } \left(\frac{P \dot{P}}{\text{s}} \right)^{1/2}$$

$$\tau \equiv \frac{P}{2\dot{P}}$$

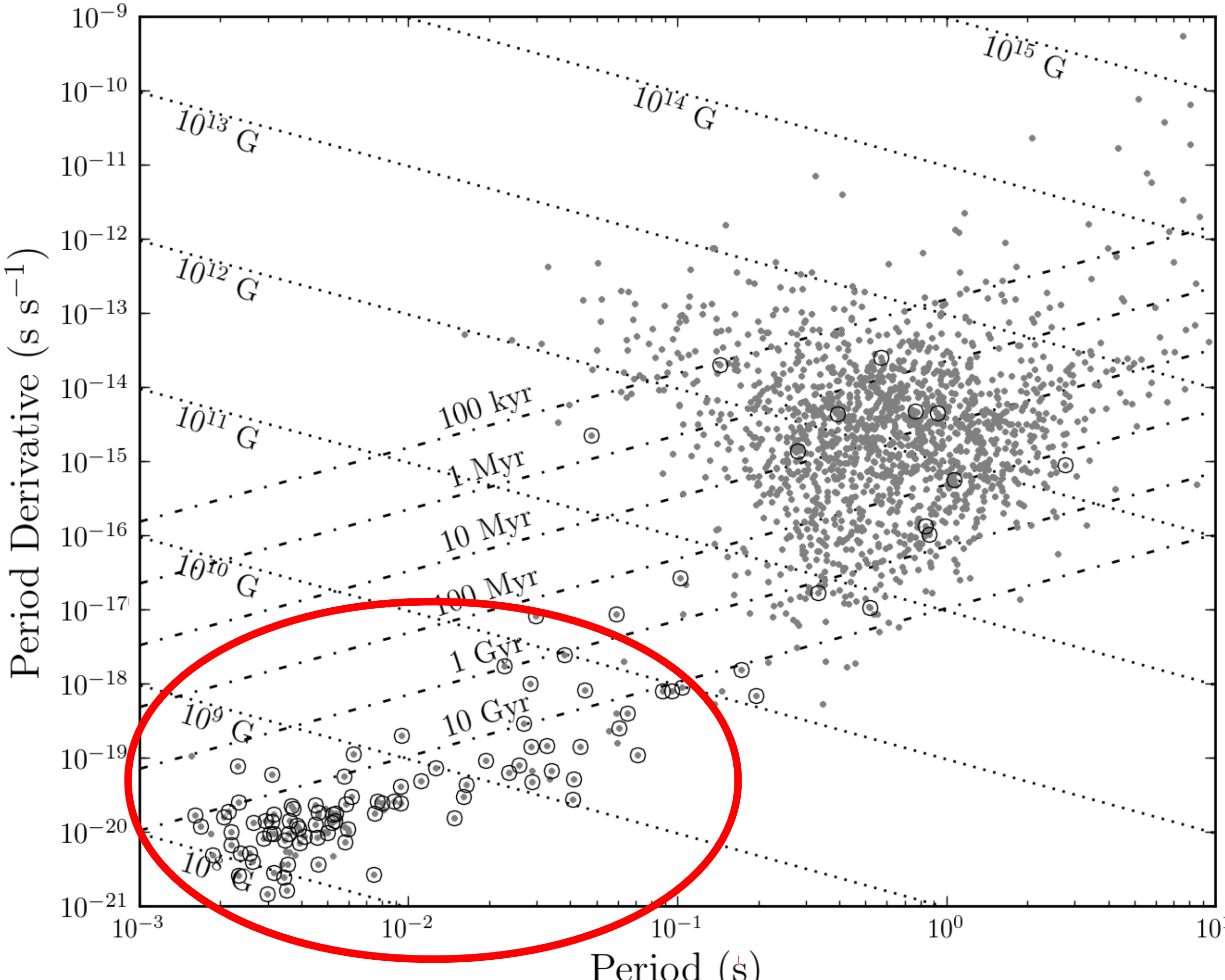
$$\dot{E} = -1.3 \times 10^{46} \text{ erg/s } \dot{P} \left(\frac{P}{\text{s}} \right)^{-3}$$

The Neutron Star Zoo

- The pulsar population is very diverse

- *P* and *P*-dot vary by orders of magnitude

- The fastest and most stable are the millisecond pulsars



Data from ATNF catalog

How to make an MSP

- Make a standard, long-period pulsar
- Once it dies, recycle it via accretion from a companion
- When accretion stops, we are left with a pulsar with very rapid and stable rotation

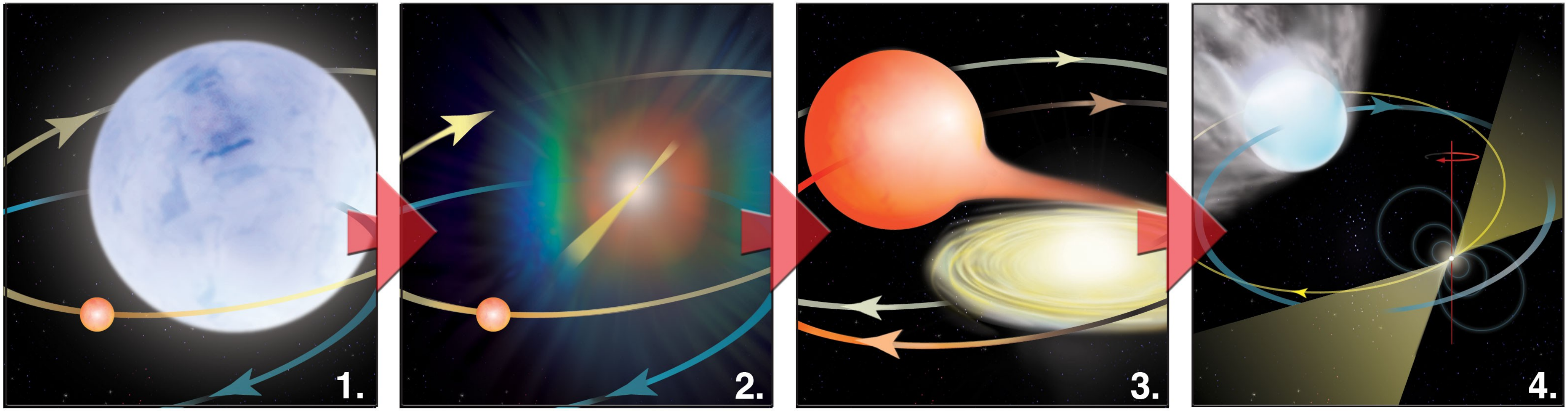
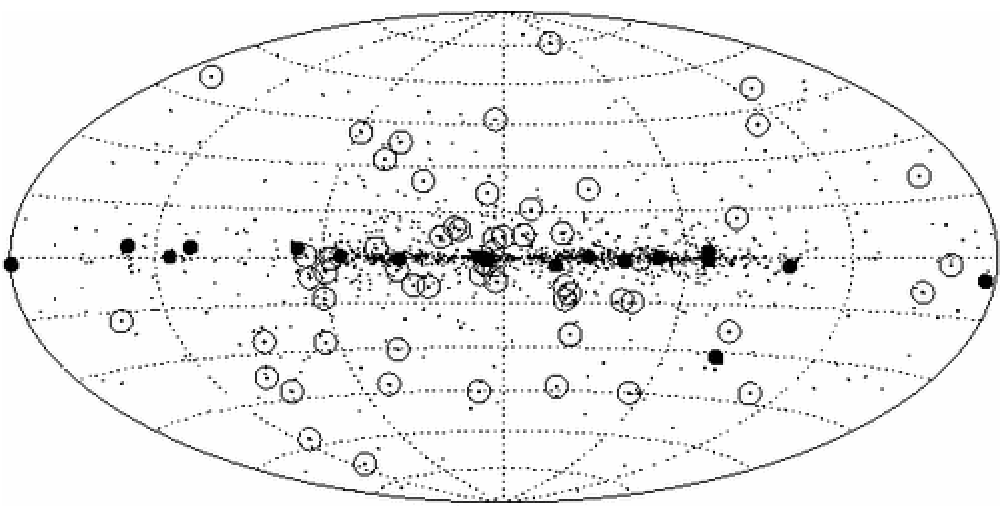


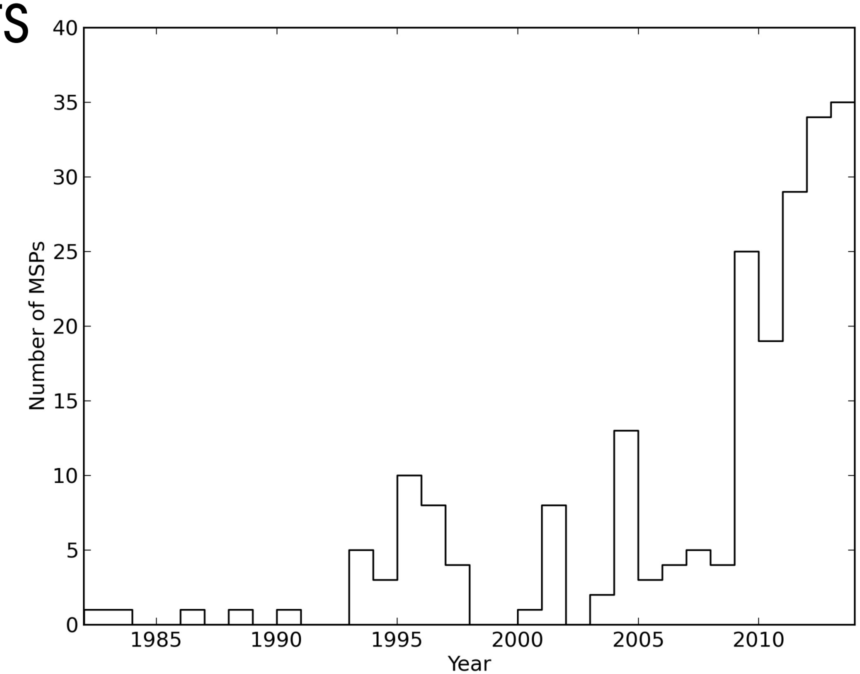
Image credit: Bill Saxton, NRAO/AUI/NSF

Finding pulsars

- We currently know of about 2,300 pulsars, ~200 of which are MSPs
- Finding new pulsars is a time and computationally intensive task
- Pulsar surveys are major projects at most large radio telescopes

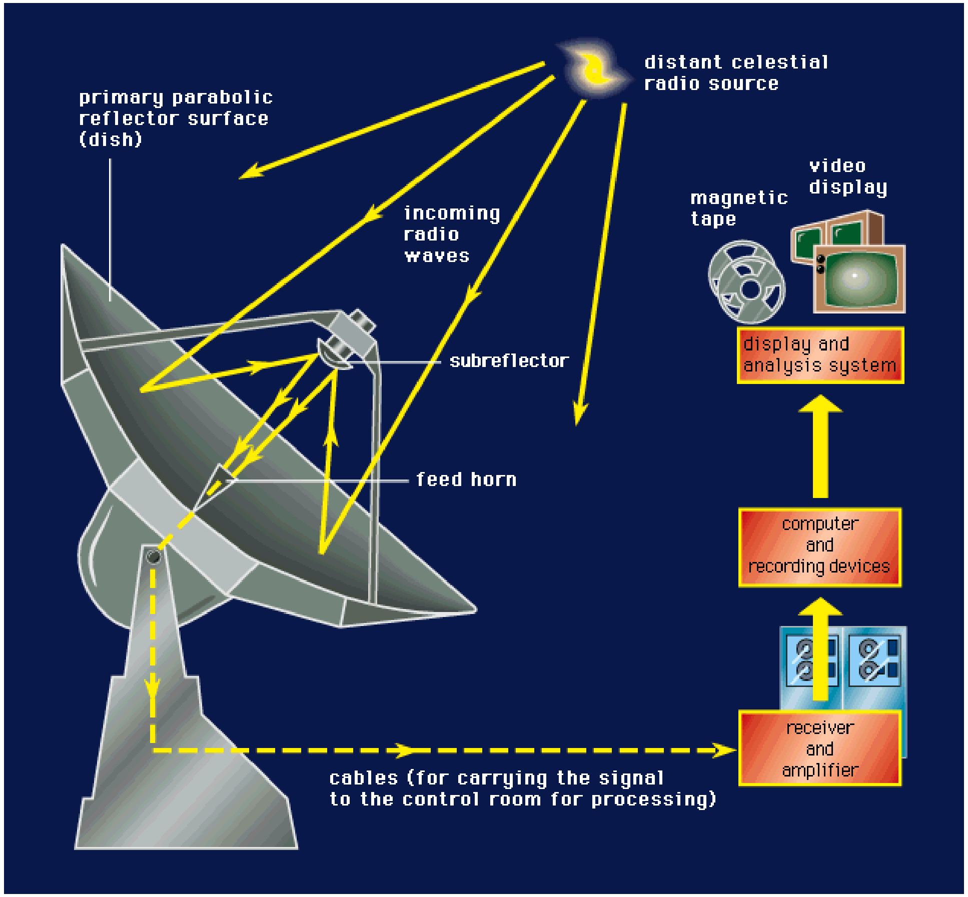


Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer



Data from Duncan Lorimer
http://astro.phys.wvu.edu/GalacticMSPs/GalacticMSPs.txt

Observing Pulsars

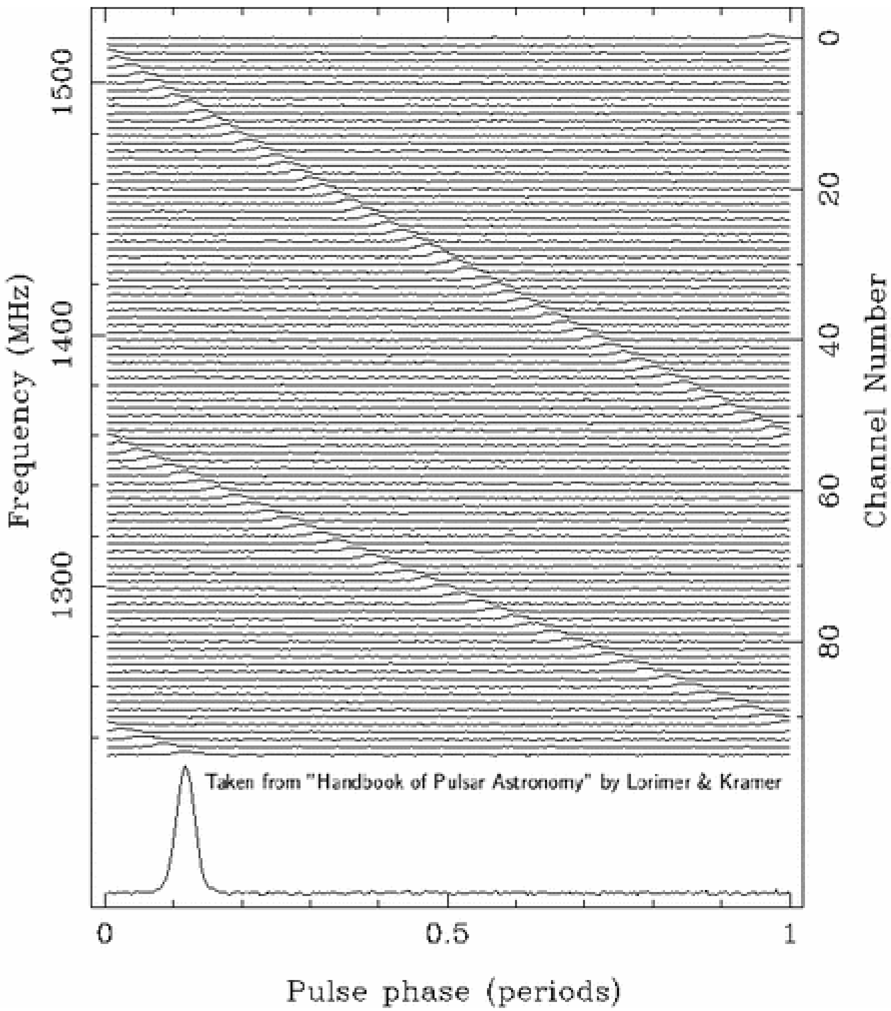


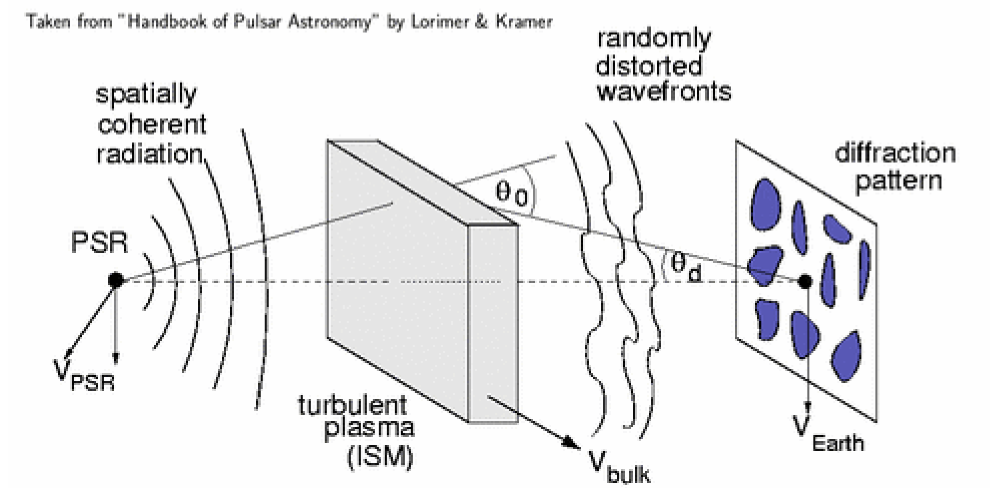
- Incoming radio waves are focused by optical system
- Receiver detects the electric field over a wide radio bandwidth
- Amplifiers, mixers, digitizers, and other components convert raw voltages into digital signals

Image credit: http://abyss.uoregon.edu/~js/images/radio_telescope.gif

Effects of the Interstellar Medium

- Two frequency-dependent effects: dispersion and scattering

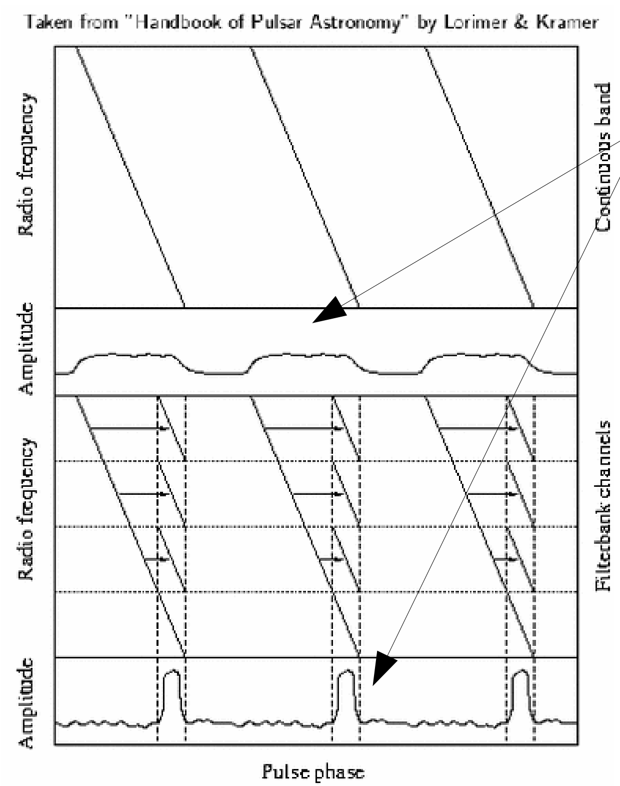




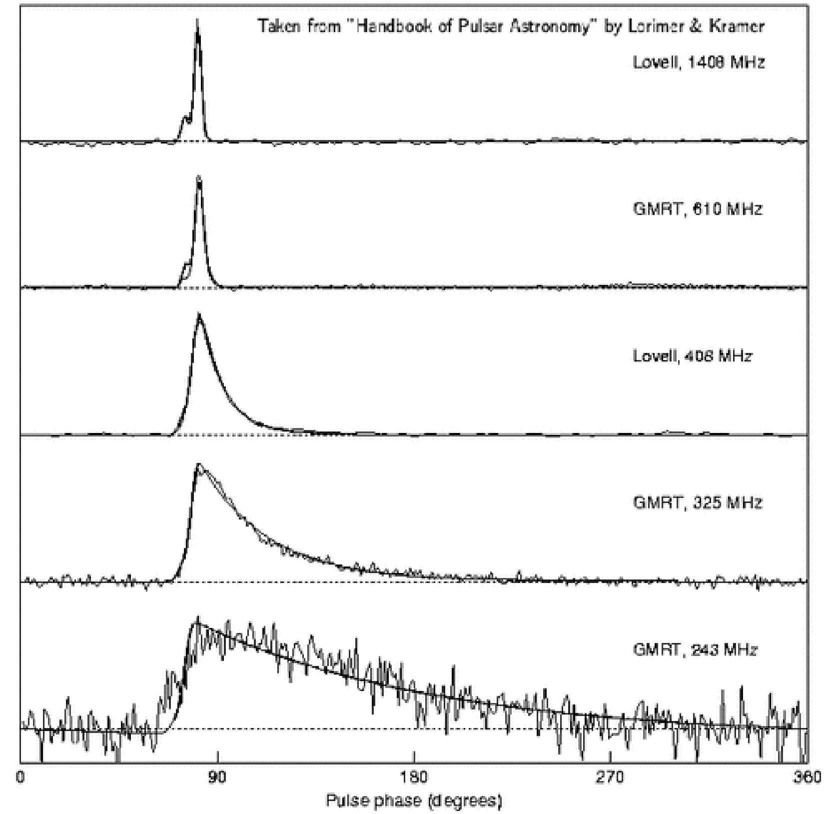
- Both smear out pulses and are worse at low frequencies
- They are also timing varying!

Overcoming ISM Effects

- Coherent de-dispersion can remove the effects of smearing
- Cyclic spectroscopy being used to mitigate scattering

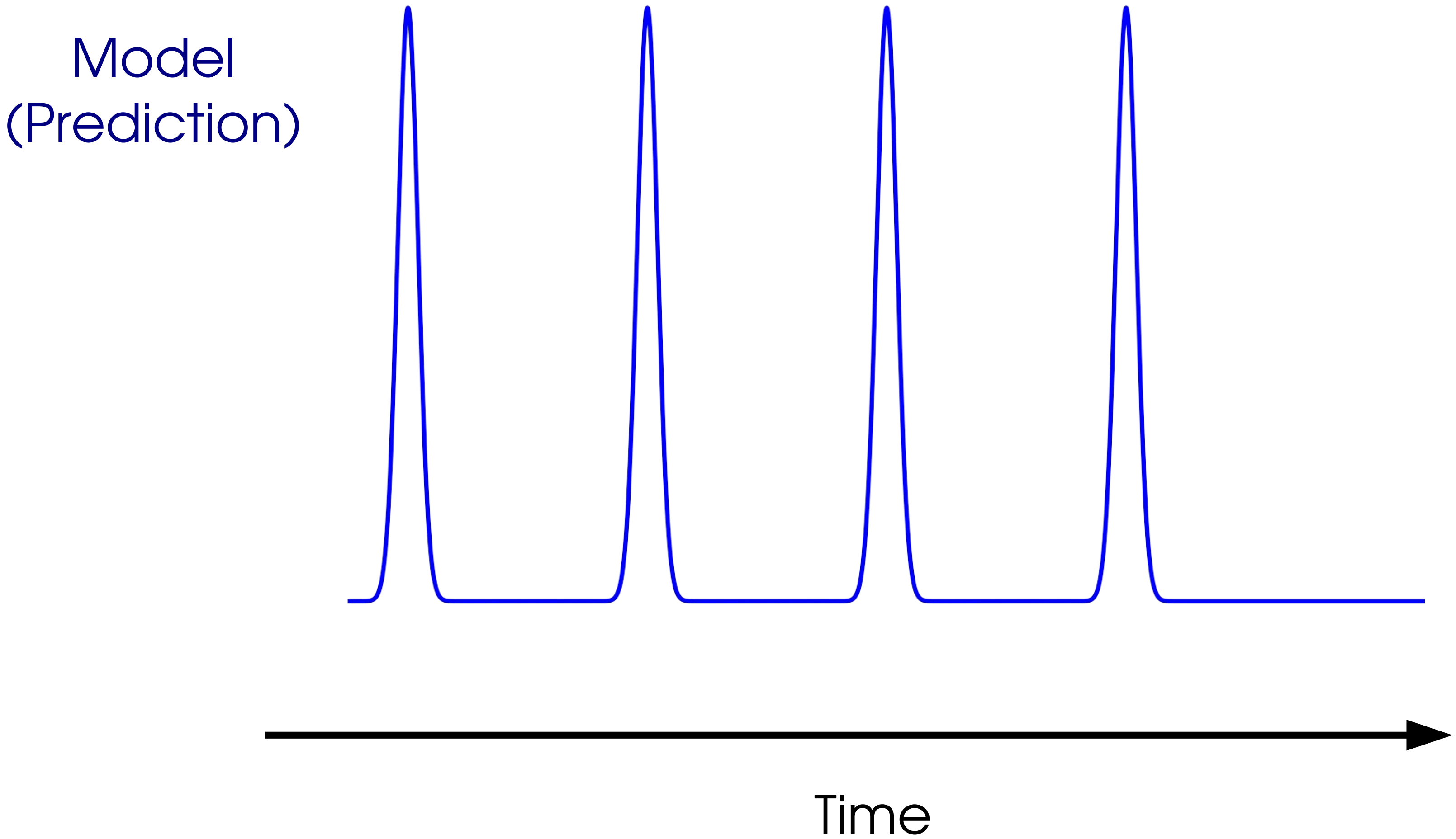


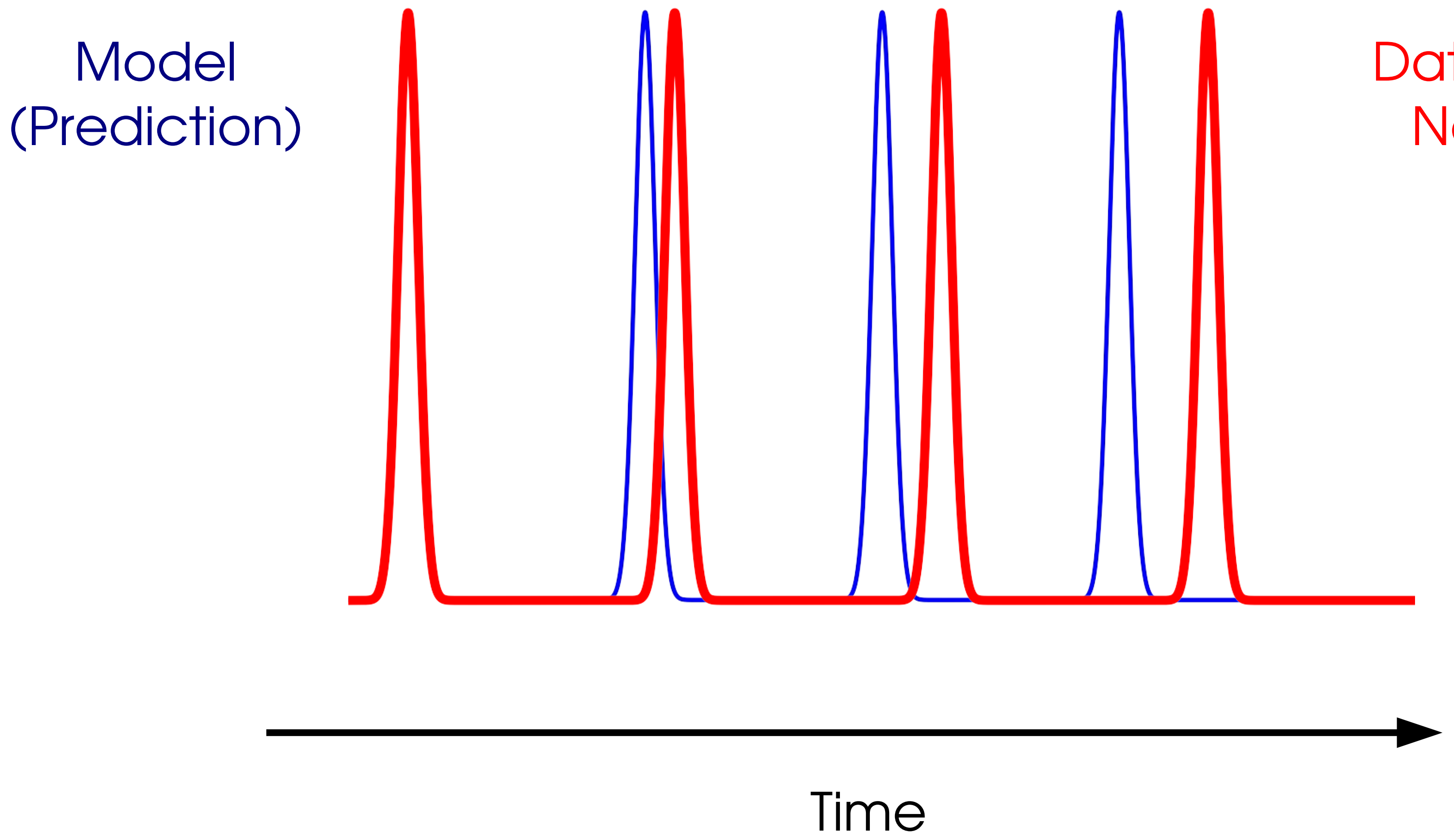
Not coherent de-dispersion

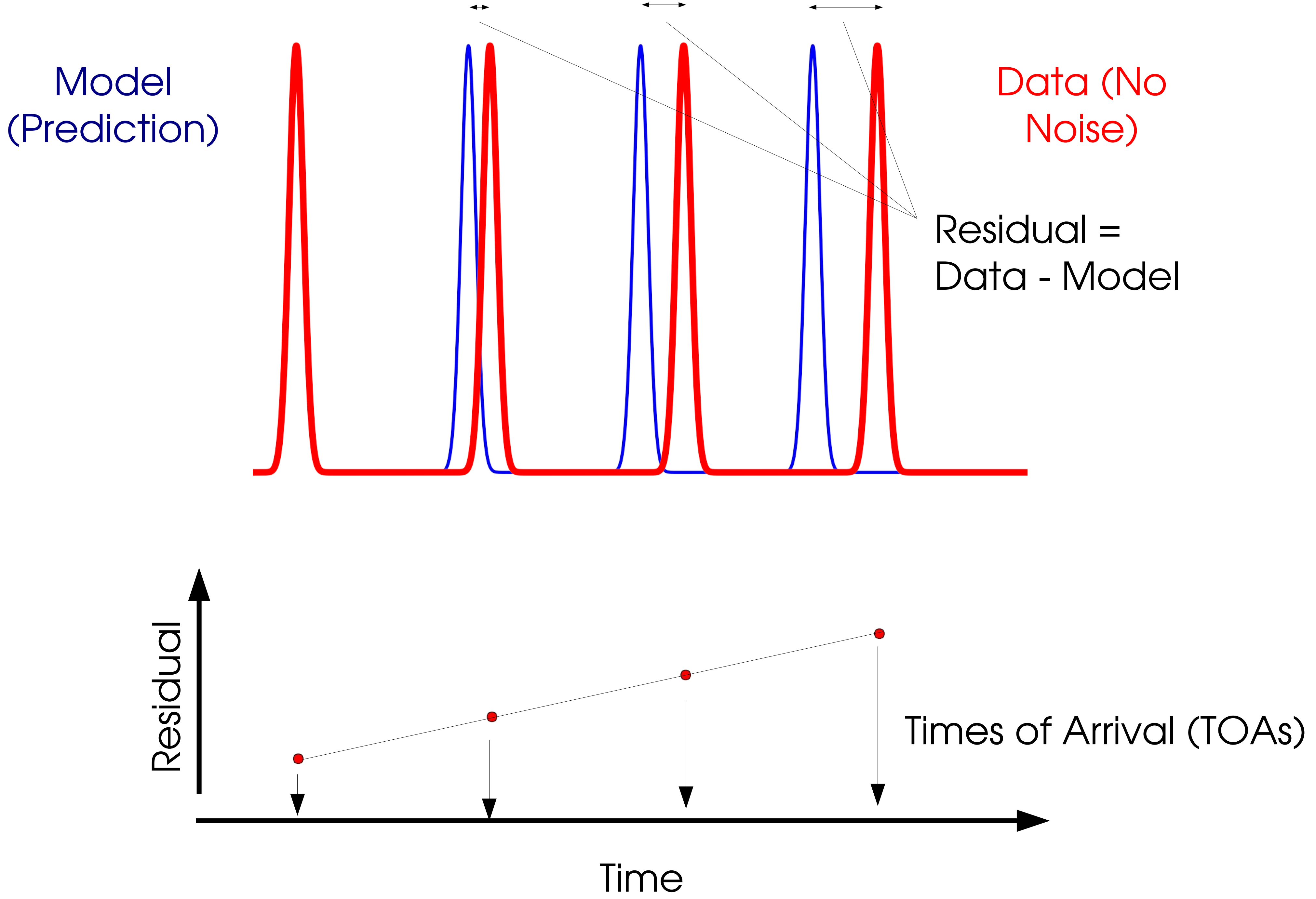


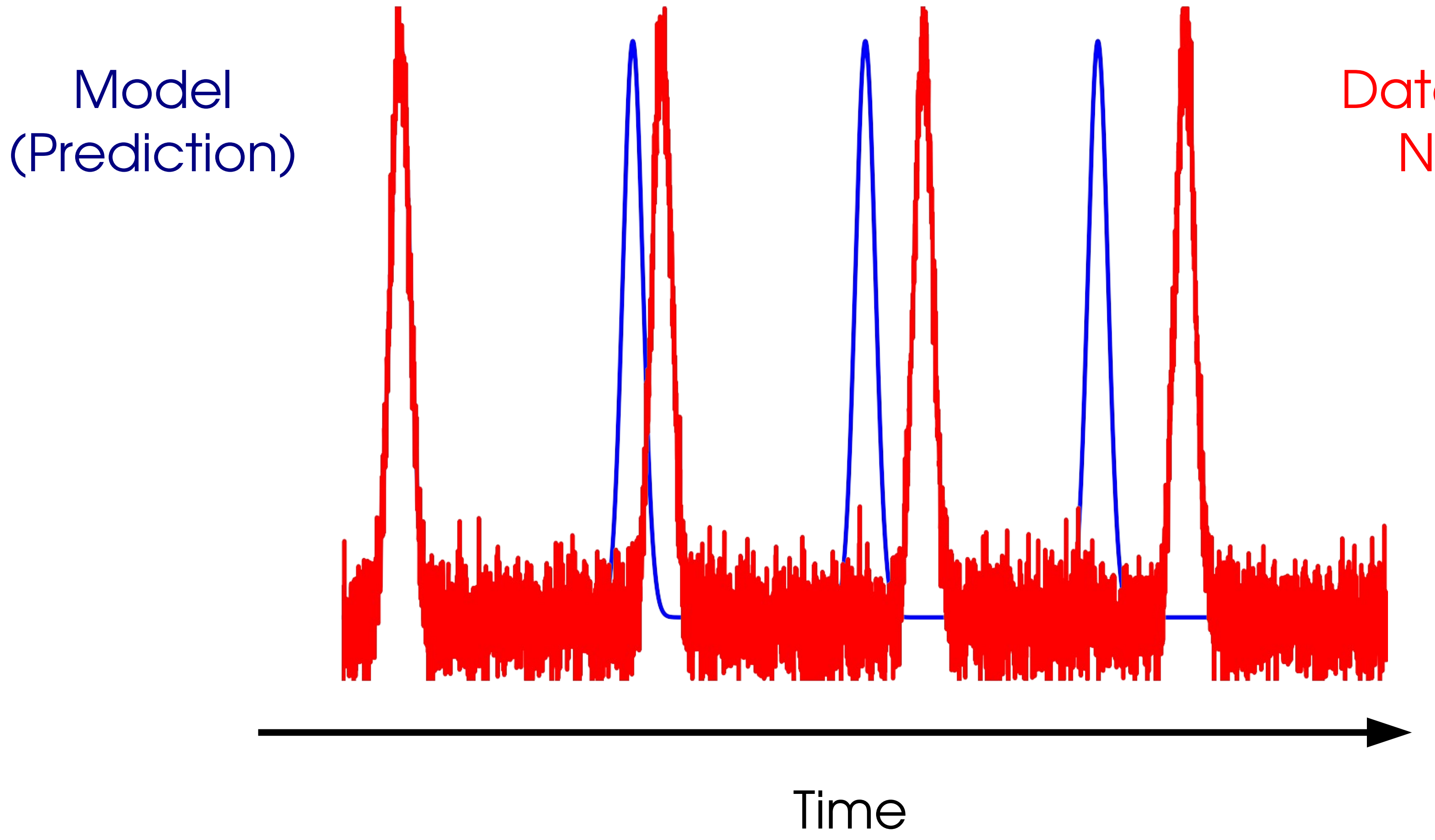
Pulsar Timing (The Basics)

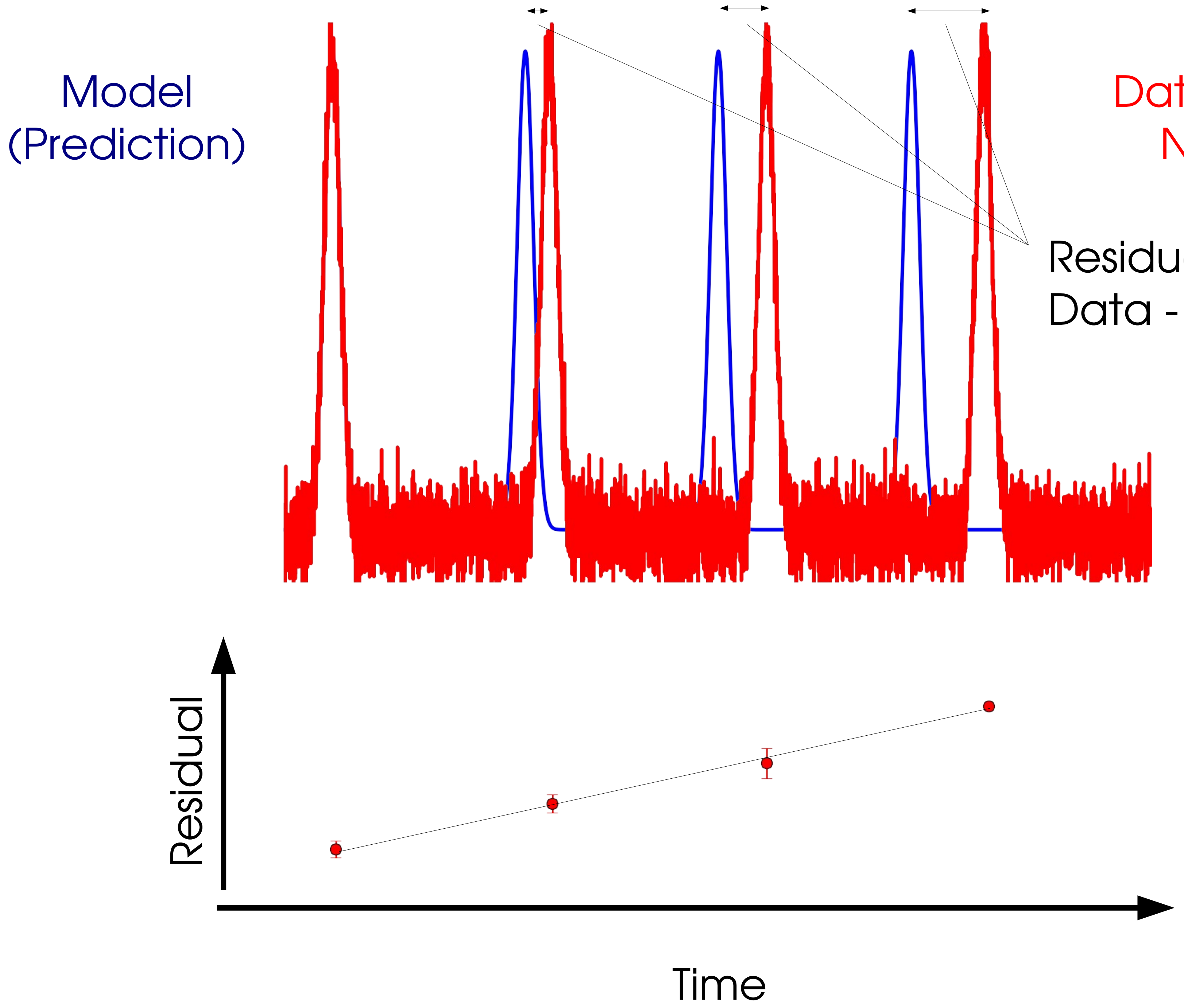
- Timing is one of the most powerful techniques for studying pulsars
- It takes advantage of the clock-like nature of pulsars
  - Deviations from the expected arrival time of a pulse contain useful information
- Let's go through timing schematically...

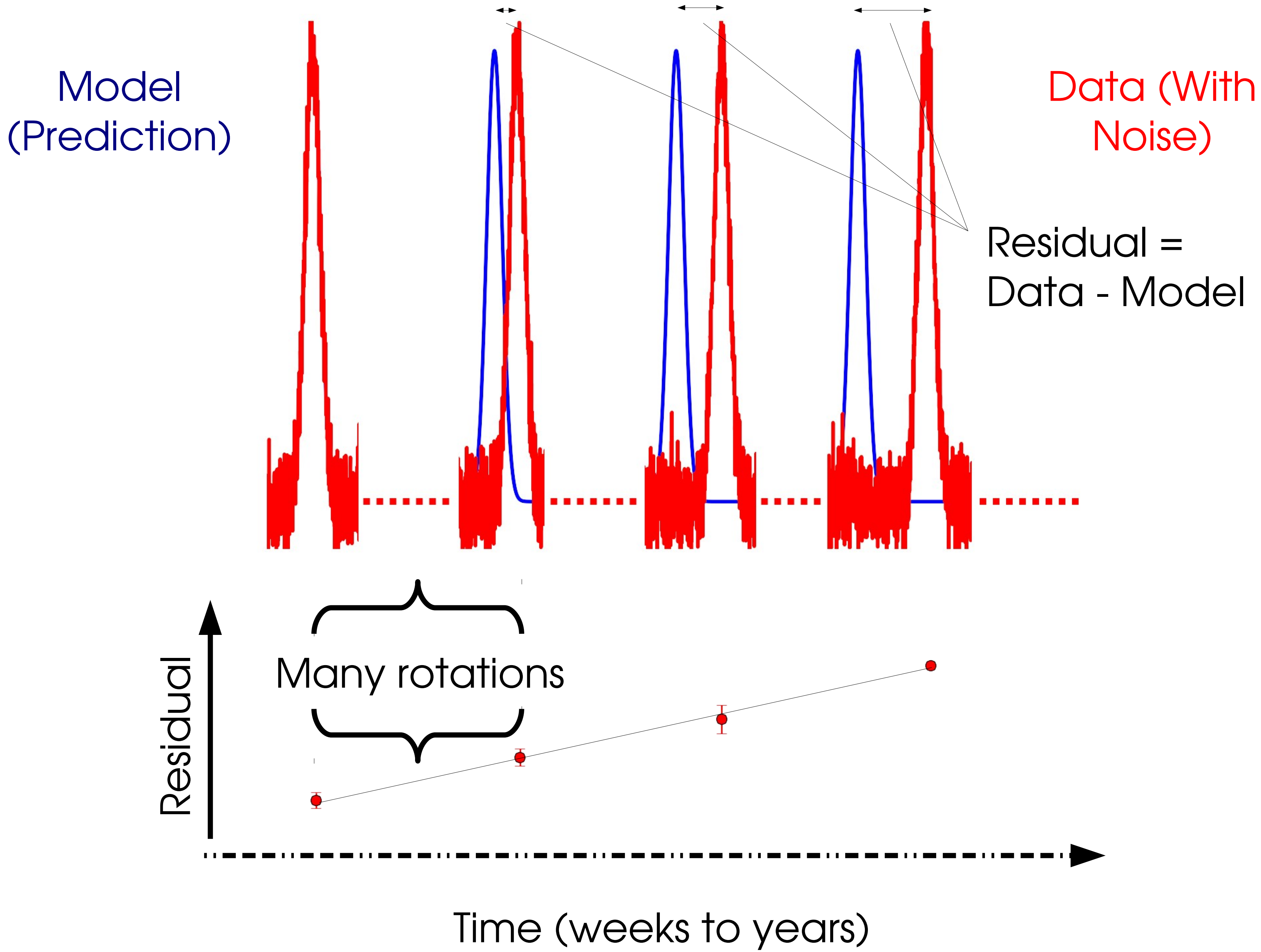

Model
(Prediction)
Time


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
Residual
Many rotations
Time (weeks to years)

Timing Models

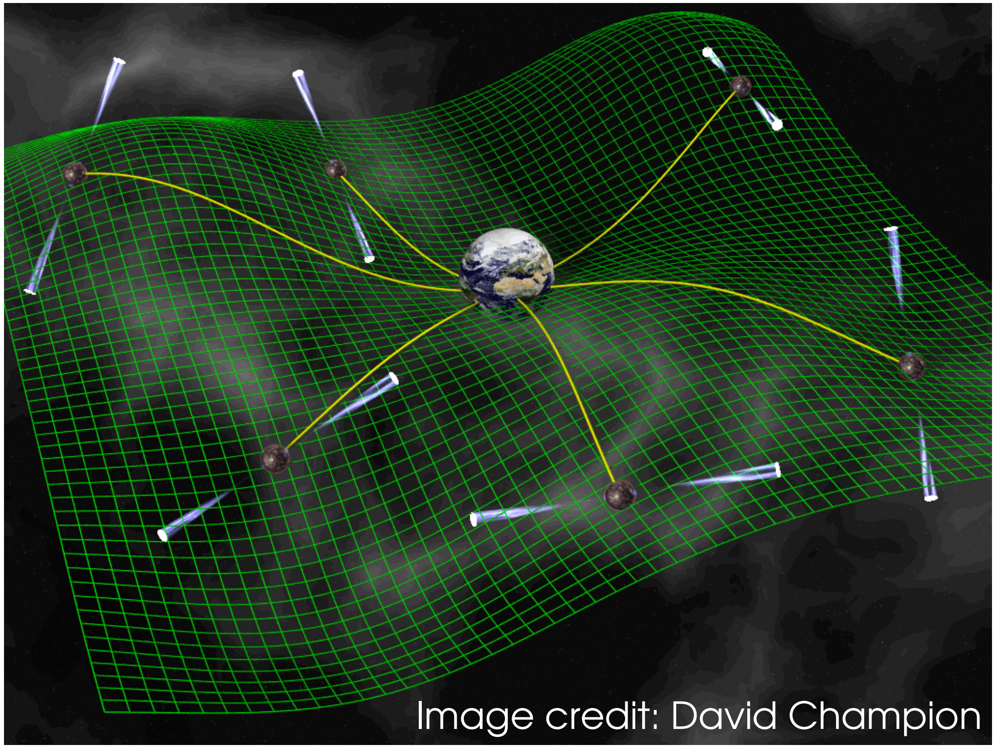
- Any phenomenon that changes the TOA of a pulse will lead to non-zero residuals
- If we can model this, we can measure/characterize the phenomenon
  - Period, spin-down
  - Position, parallax, proper motion
  - Binary orbital parameters
  - The interstellar medium (ISM)
  - And more...

Millisecond Pulsar Arrays

- Some things that affect TOAs are specific to an individual pulsar
  - Orbital motion, proper motion, changes in the ISM, etc.
- Some things that affect TOAs are correlated between pulsars
  - Changes in standard timescales
  - Gravitational influence of planets in the solar system
  - Gravitational waves

Millisecond Pulsar Arrays

- If we cross-correlate the residuals from many pulsars, we may be able to detect these effects
- To detect small changes in TOAs, we need very high precision data from very stable millisecond pulsars



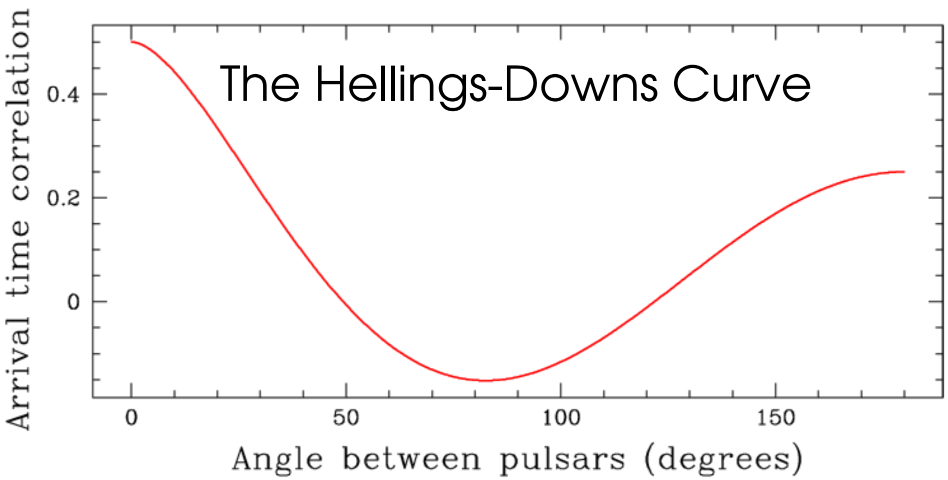


Image credit: NANOGrav

Pulsar Timing Arrays and Gravitational Waves

- Gravitational waves are small, time dependent perturbation in space-time
- These minute variations change the arrival time of pulses, but GWs are very weak
  - PTAs need timing precision of 10s – 100s of nanoseconds to directly detect GWs

Image credit: Wikipedia

Almost everything we have ever learned about the distant Universe throughout history has come from studying things that emit light

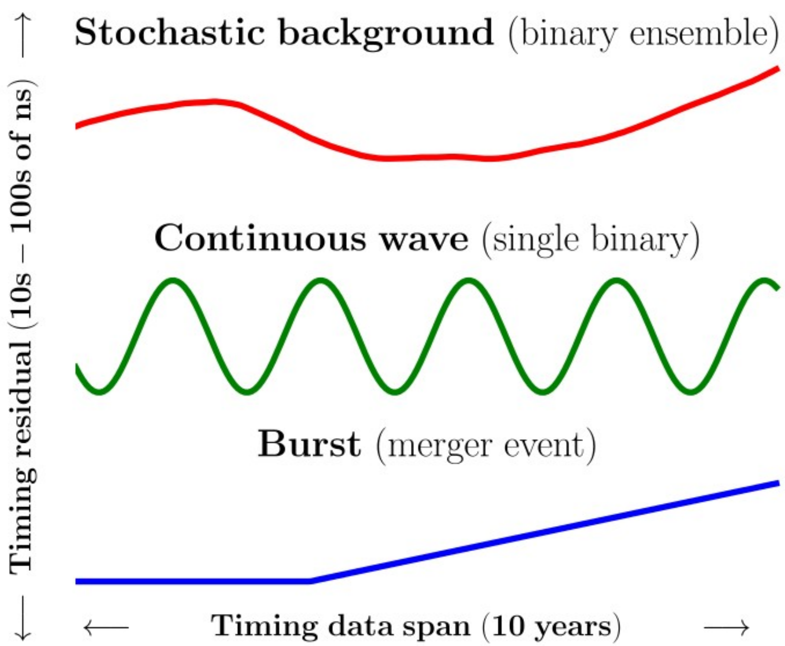
NASA, ESA, M. Livio and the Hubble 20th Anniversary Team (STScI)

Gravitational wave astronomy will give us an entirely new window on the Universe

We are guaranteed to learn amazing new things

NASA/Dana Berry, Sky Works Digital

Observational Signatures



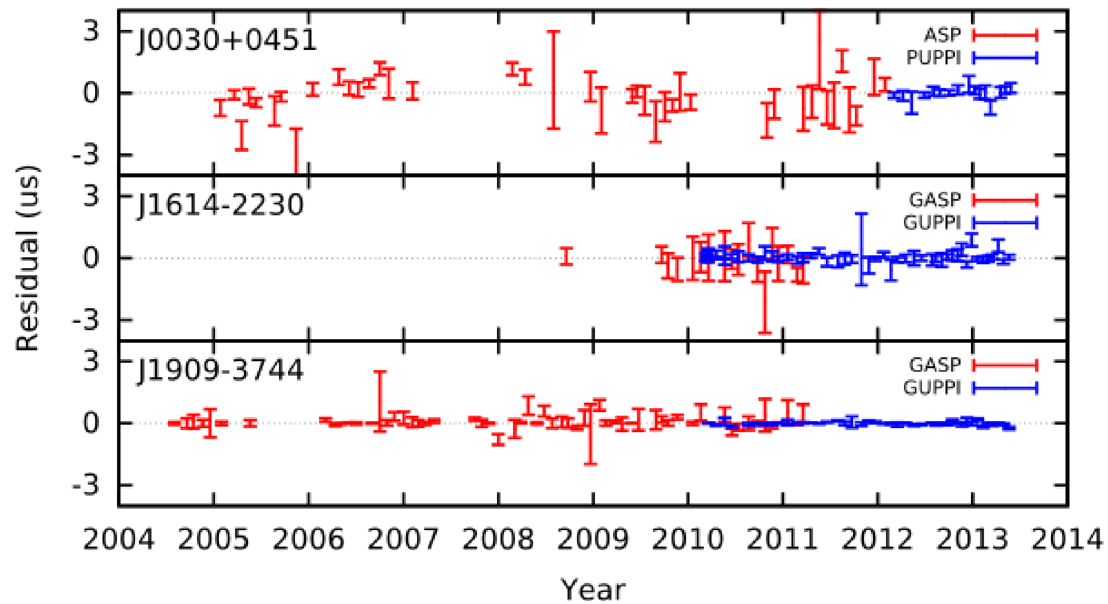


Image credits: NANOGrav

- Different source classes have different structure in residuals
- The IPTA is currently timing 50 MSPs, many with sub-μs RMS residuals

PTAs vs Double Neutron Stars

- PTAs != Hulse-Taylor and other double neutron star systems
- Both DO use pulsar timing
- DNSs are sensitive to GWs emitted by the binary
- PTAs are sensitive to cosmological sources

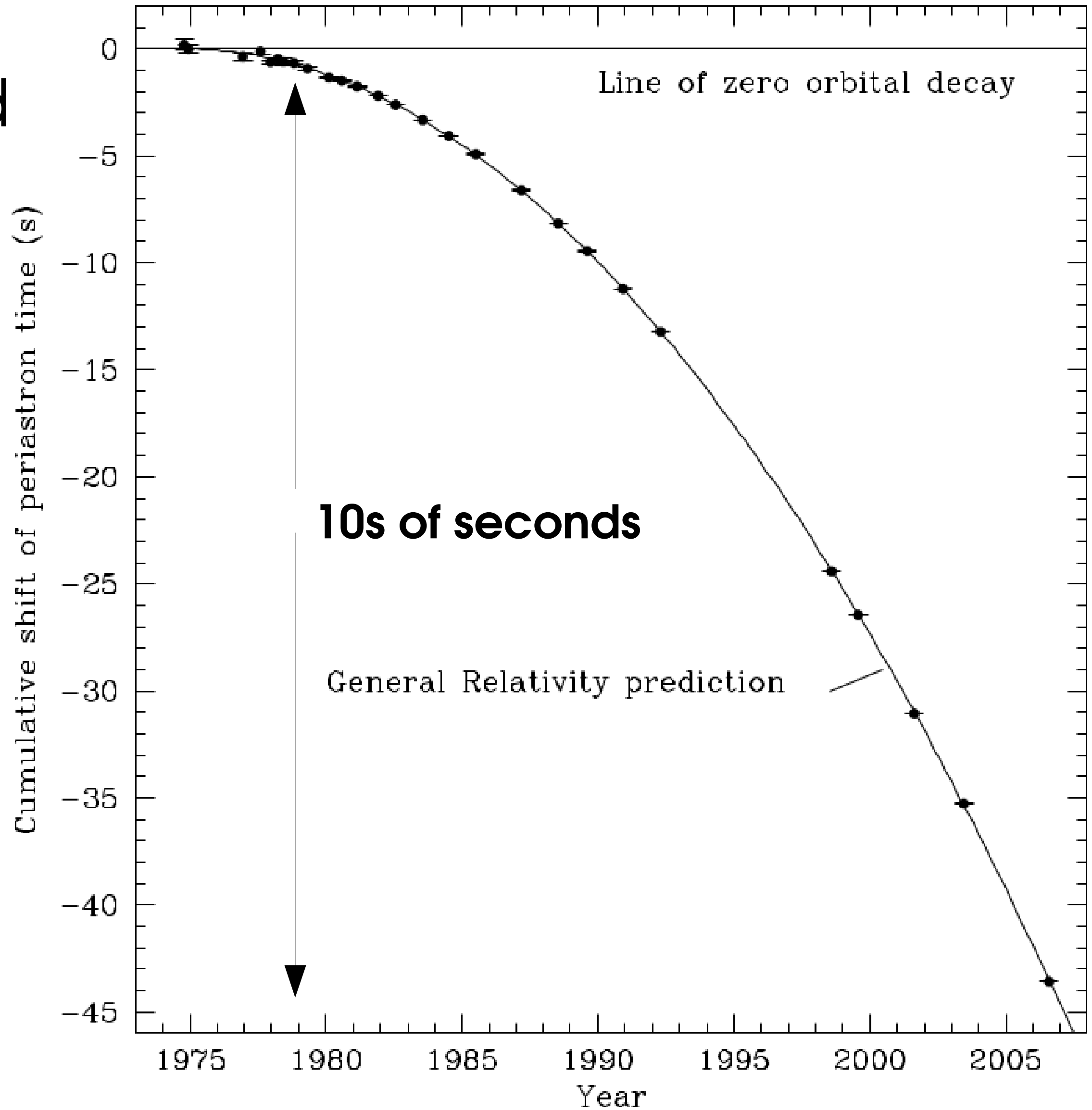


Image credit: Weisberg, Nice, & Taylor 2010, *ApJ*, 772, 1030

Sources of PTA GWs

- PTAs are most likely to detect GWs from merging supermassive binary black holes
  - It could be from an individual binary...
  - Or it could be a background consisting of the combined signals from binaries throughout the Universe (a stochastic background)...
  - Or it could be a burst signal from a merger event
- A more speculative source of GWs are cosmic strings
  - Predicted by certain theories

The big picture of gravitational wave astronomy

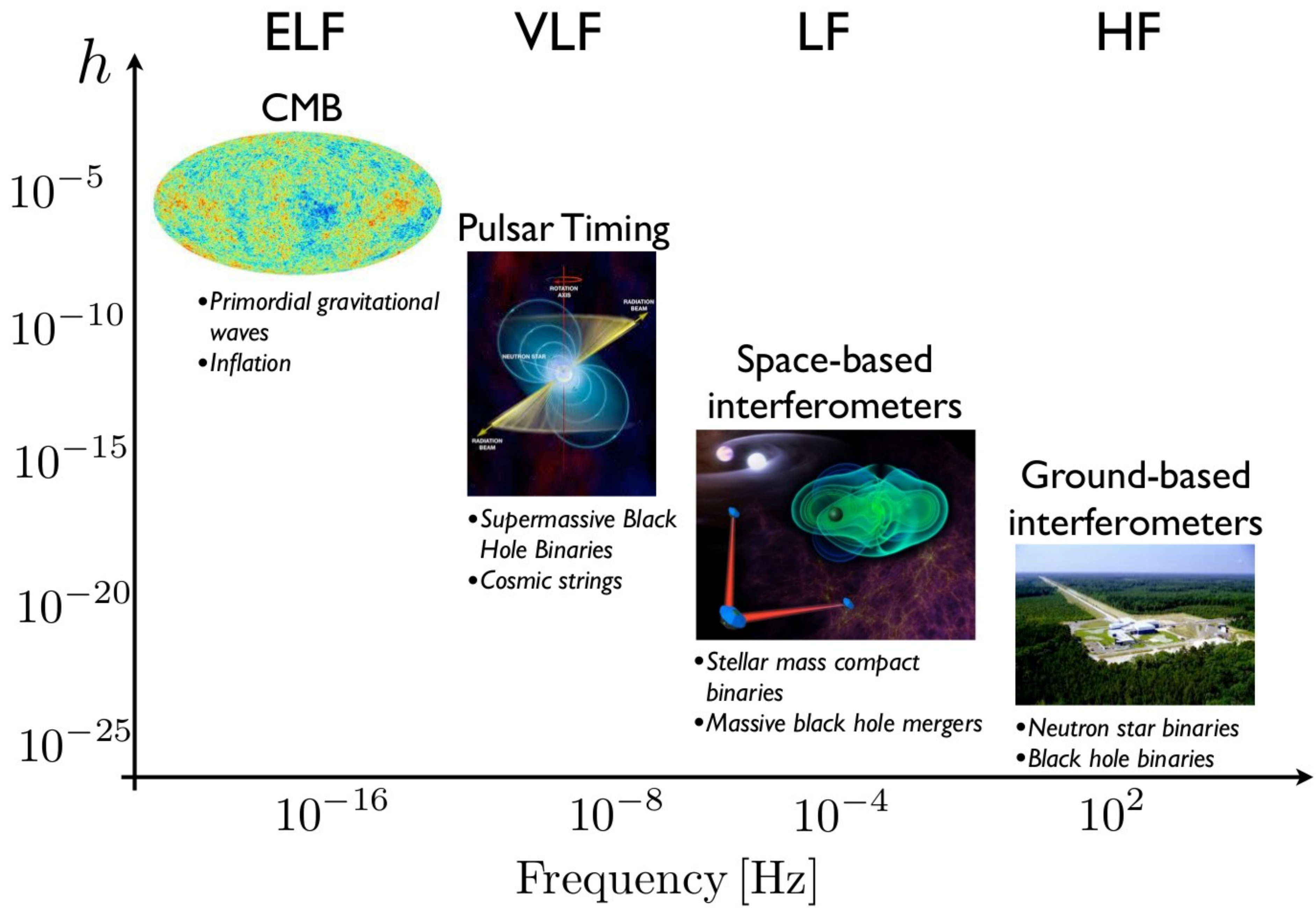
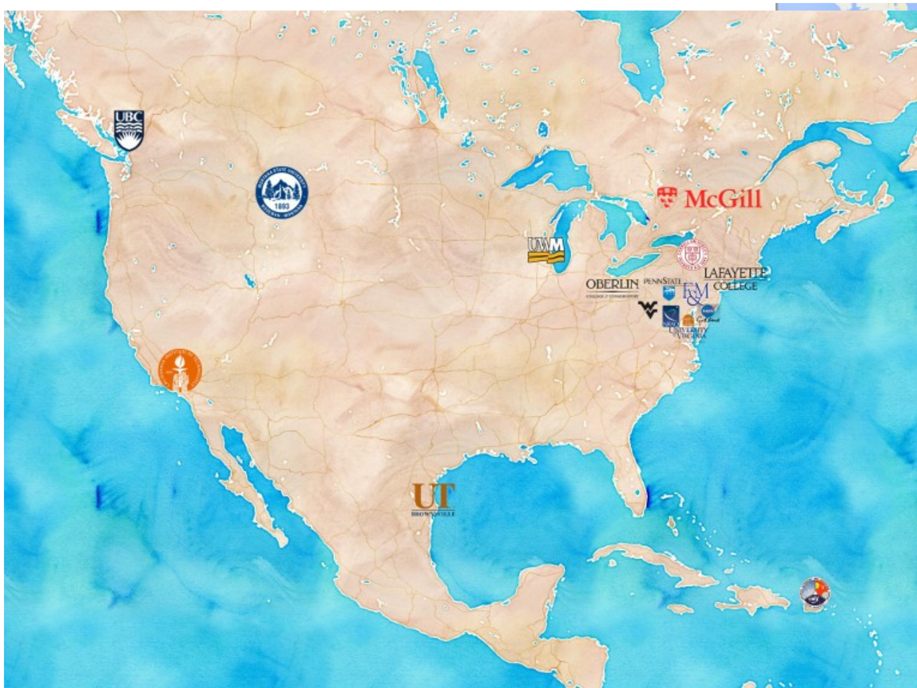
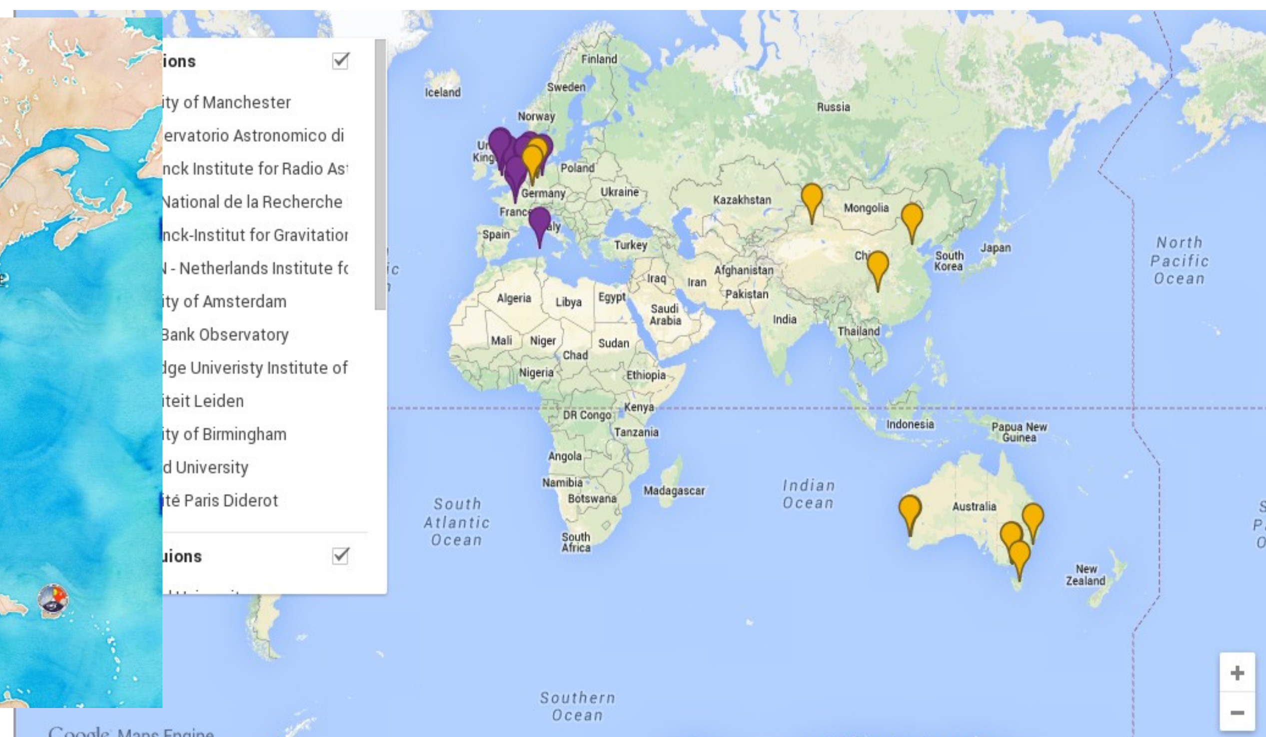


Image credit: NANOGrav

The IPTA

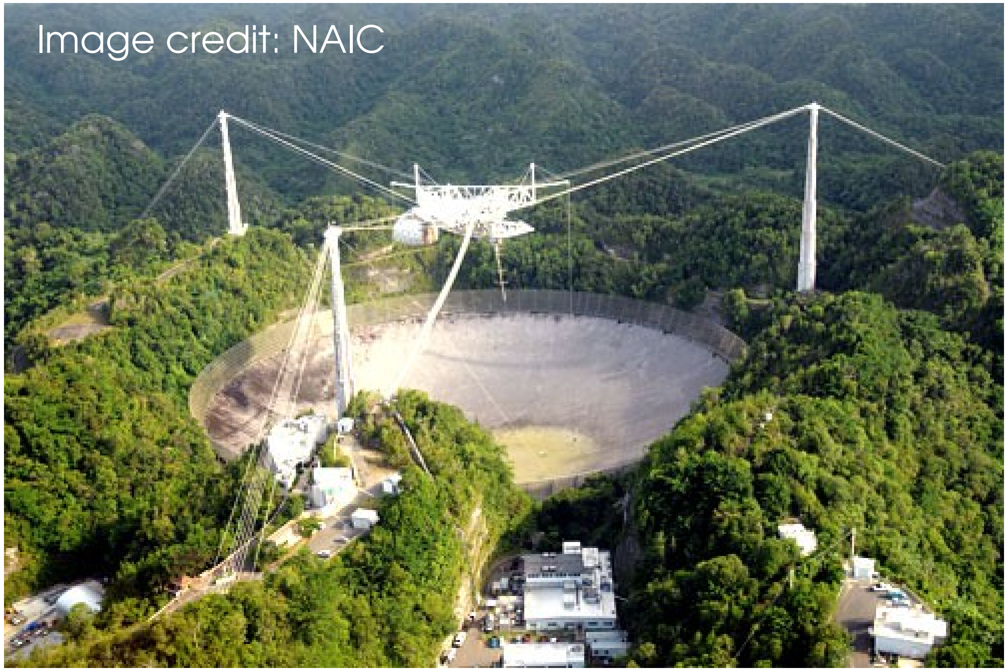
- NANOGrav – **N**orth **A**merican **N**anohertz **O**bservatory for **Grav**itational Waves
- EPTA – **E**uropean **P**ulsar **T**iming **A**rray
- PPTA – **P**arkes **P**ulsar **T**iming **A**rray
- IPTA – **I**nternational **PTA**





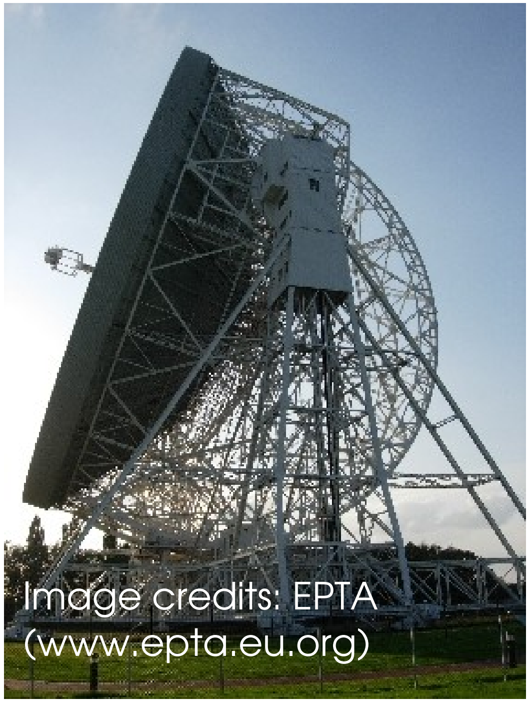
NANOGrav Radio Telescopes

- NANOGrav uses the Arecibo Observatory and Green Bank Telescopes
- Arecibo is the largest and most sensitive radio telescope in the world
- GBT is one of the largest fully-steerable dishes



EPTA Telescopes

- The EPTA uses 5 European telescopes
- The LEAP project seeks to tie these together into a phased array

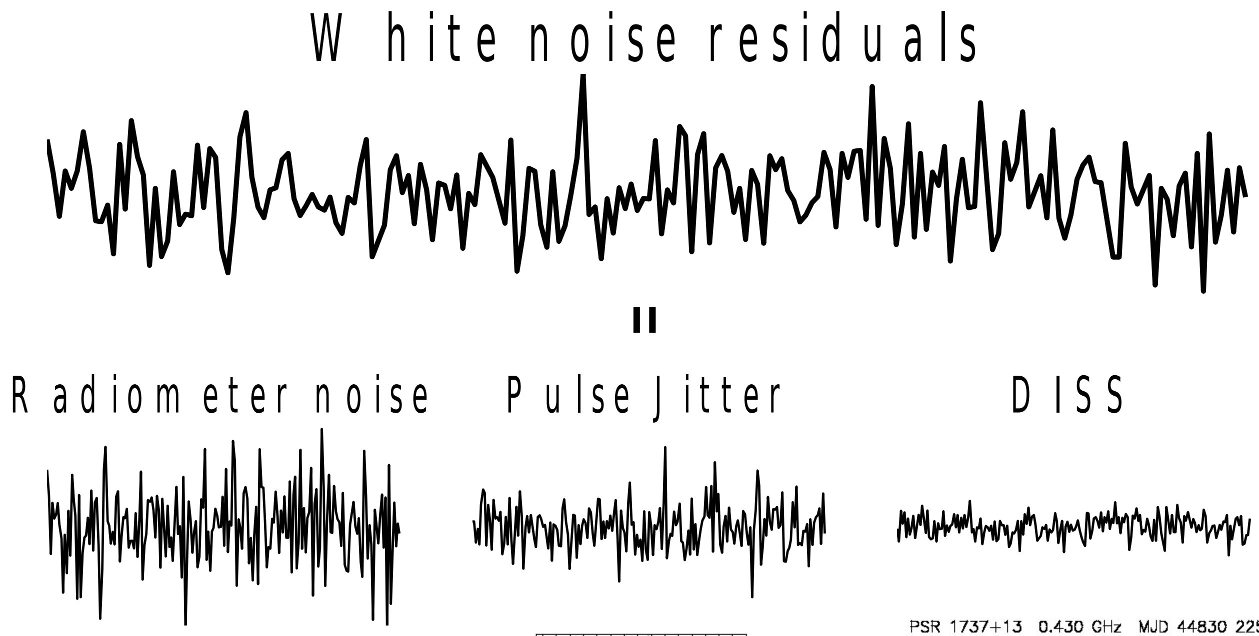


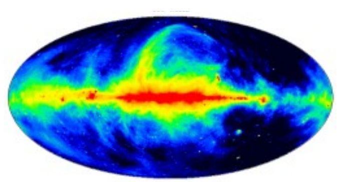
The Parkes Telescope and the PPTA

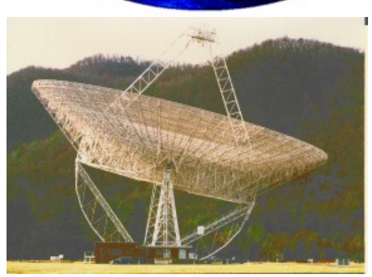
Image credit: ATNF/CSIRO

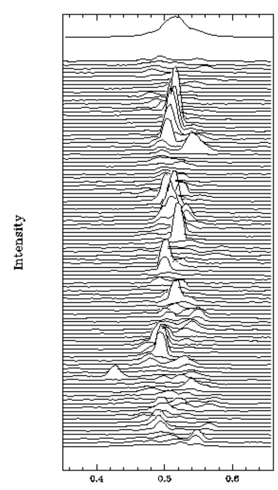
- The PPTA uses the 64-meter Parkes telescope
- An important southern hemisphere telescope that completes sky coverage of the IPTA

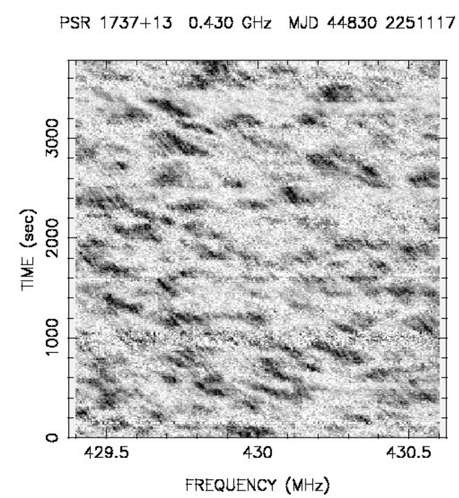
Challenges: Noise Sources









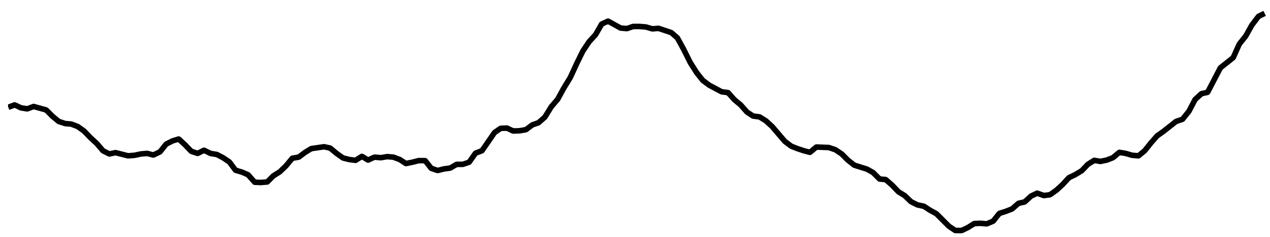


20 June 2013

Slide courtesy of Tim Dolch

Challenges: Noise Sources

Red noise residuals



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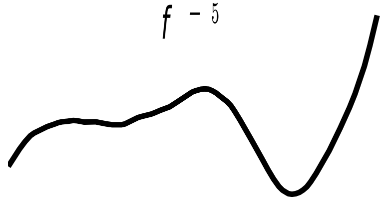
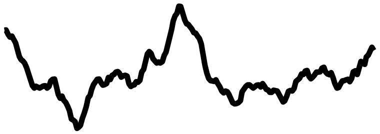
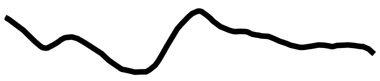
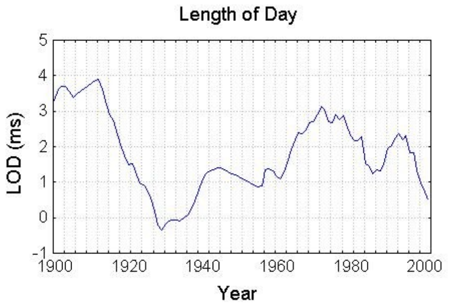
Spin noise + DM variations + GWs (stochastic)

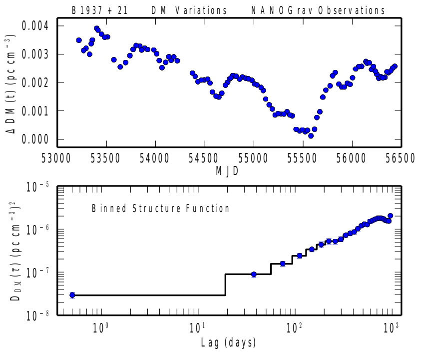
f^{-5} $f^{-8/3}$ $f^{-13/3}$

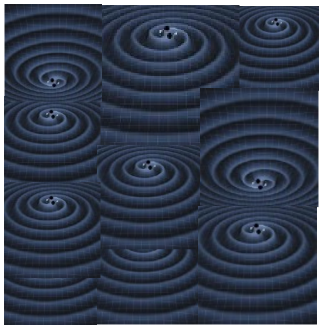












20 June 2013 IPTA Krabi

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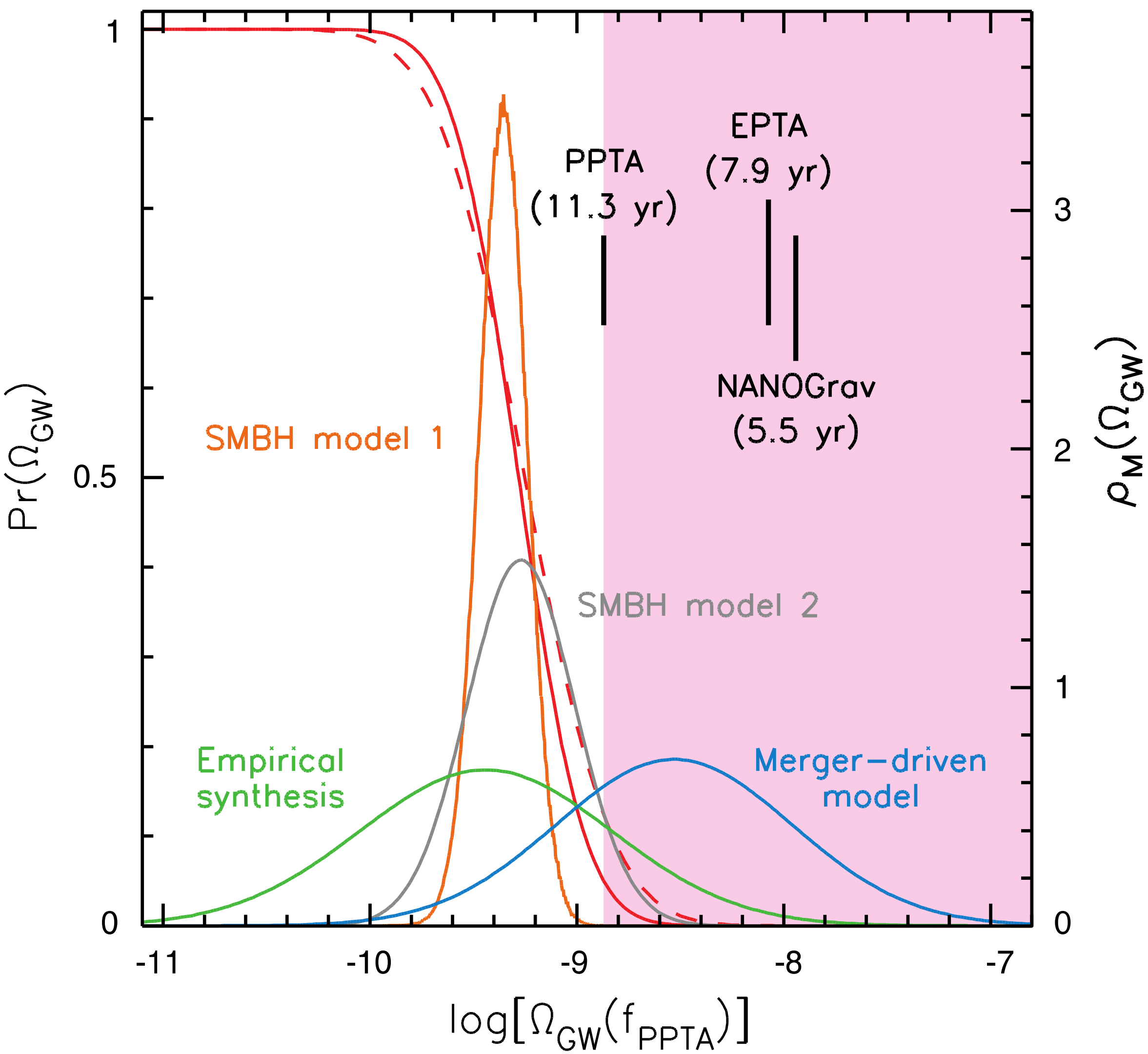
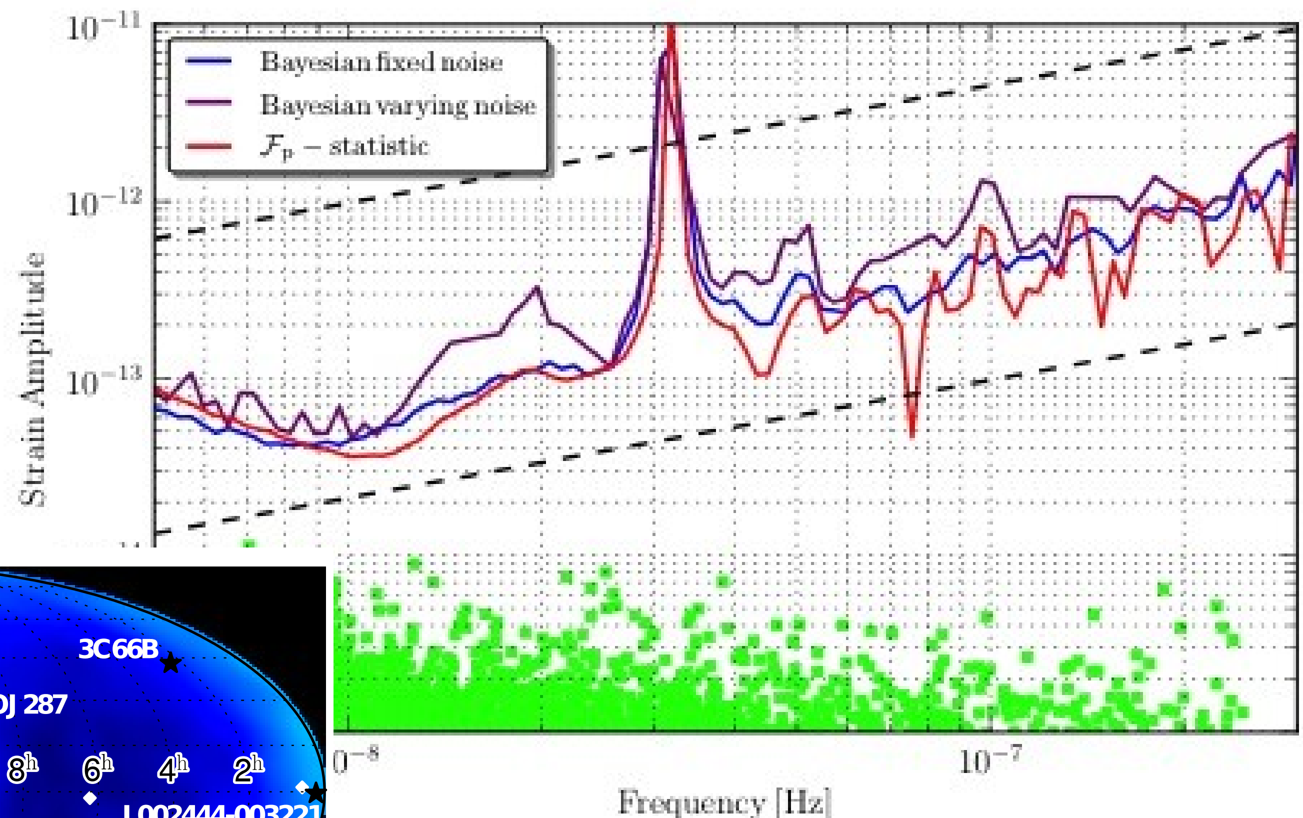
Current Limits: Stochastic Background

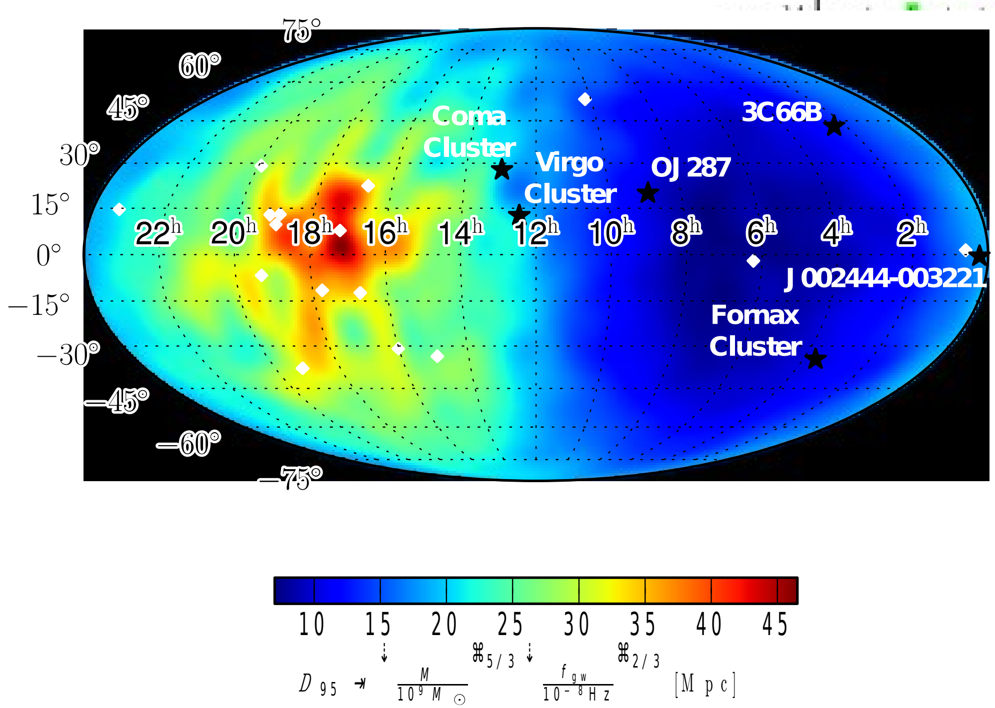


- PTAs are already putting useful constraints on SMBH merger models
- New data releases forthcoming from NANOGrav, EPTA, PPTA, and combined IPTA dataset

Image credit: Shannon et al., 2013, *Science*, 342, 334

Current Limits: Continuous Wave



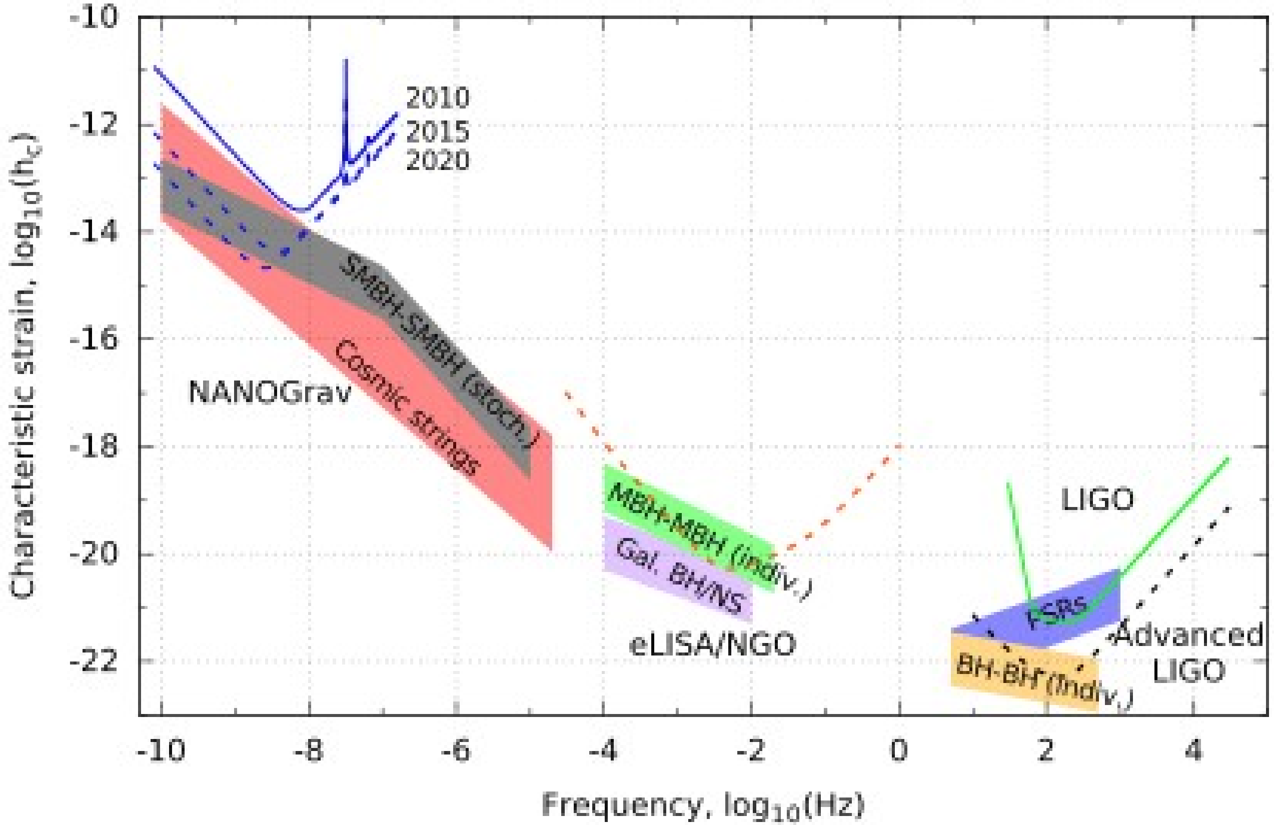


e credit: Arzoumanian et al., 2014, arxiv:1404.1267

When will we succeed

- Time to detection depends on
  - The Universe
  - Timing precision
  - Number of pulsars
  - And more

- We believe a detection will happen within the next 5 – 10 years



The Future: Instruments and Telescopes

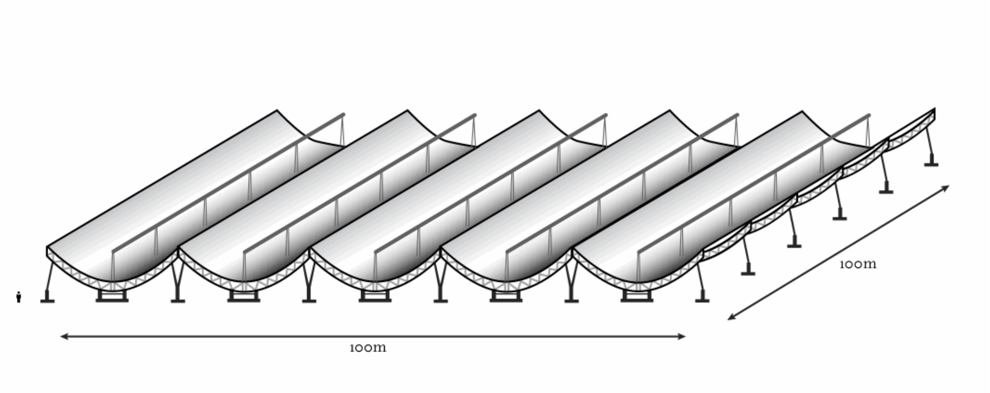


Image credit: chime.phas.ubc.ca

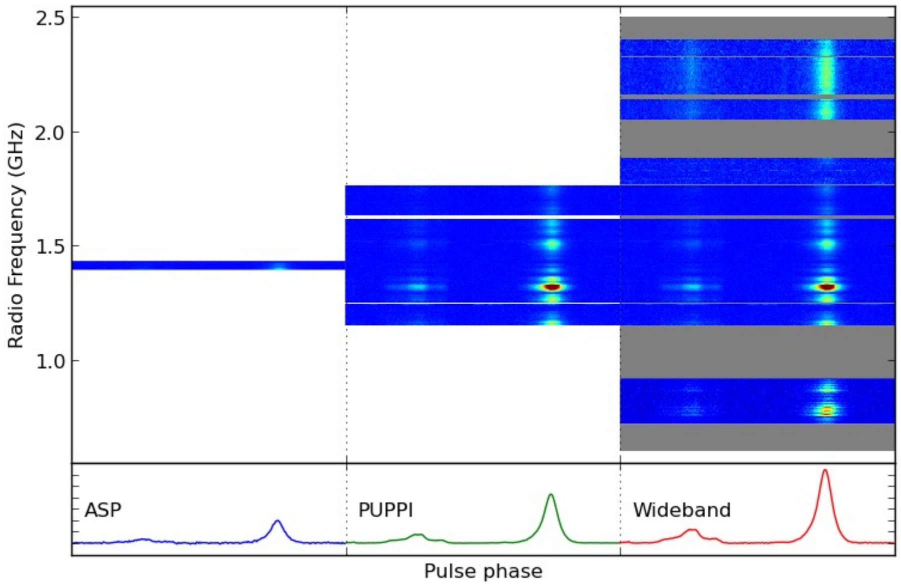


Image credit: NANOGrav

- CHIME is a Canadian cosmology experiment
  - Will include a pulsar backend allowing daily observations of northern IPTA MSPs
- Ultra-broad band receiver being commissioned at Effelsberg
  - Similar receiver is planned for the GBT
- **Important for mitigating ISM effects**

The Future: Instruments and Telescopes

Image credit: fast.boa.ac.cn

Image credit: SKA/Swinburne

- FAST is a 500-meter telescope that will illuminate 300 meters at a time
  - Like a more steerable Arecibo
- Eventually, the SKA will provide incredible sensitivity
- Better S/N -> better timing precision, more pulsars

Beyond Detection: PTA Astrophysics

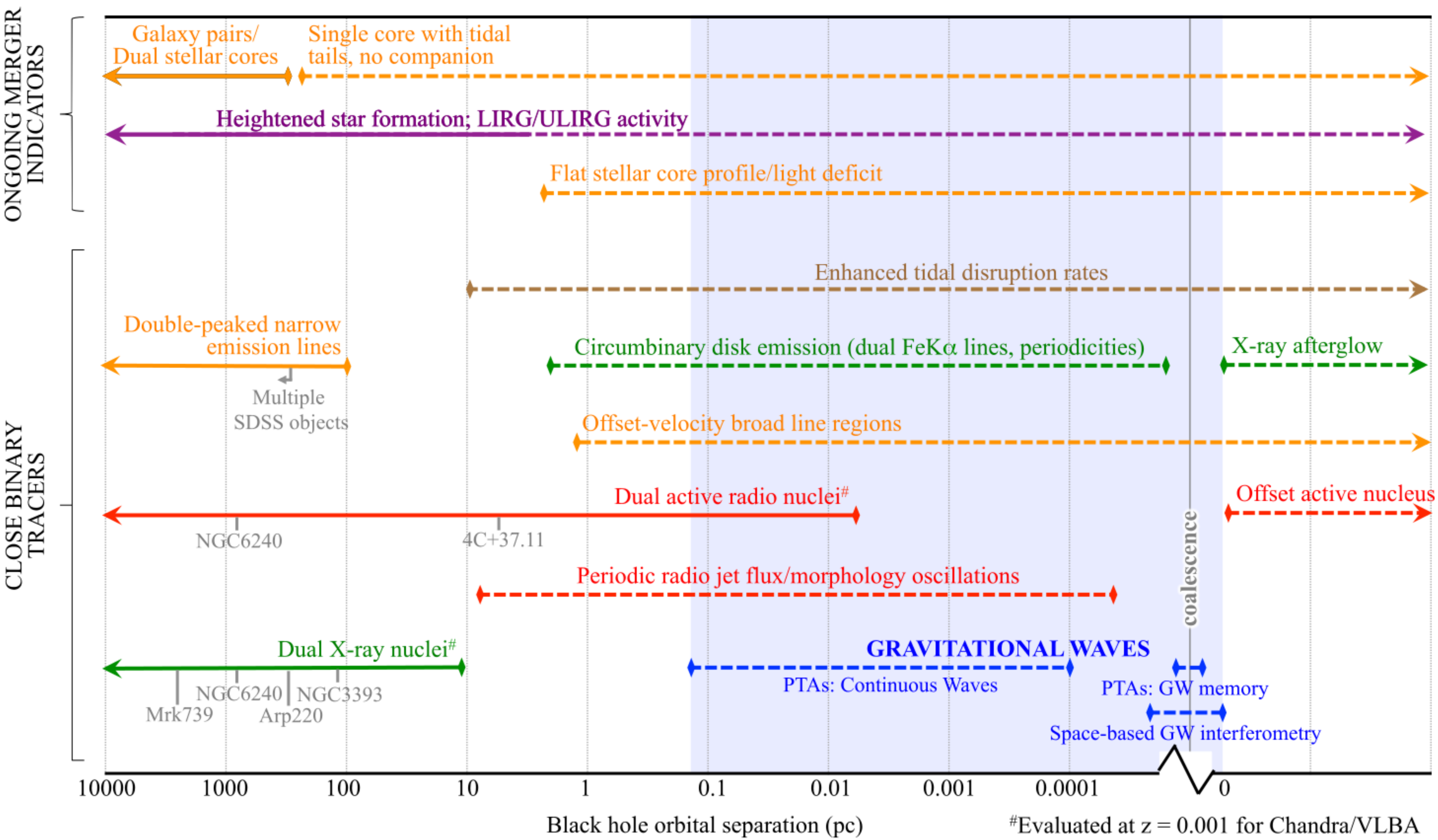


Image credit: NANOGrav

The Big Picture

- The IPTA is doing cutting edge, ground breaking, world class science (and you are a part of it)
- We are opening an entirely new frontier in astronomy
  - We will learn new and unexpected things
- The work is hard but exciting
  - Pushing new techniques, instruments, etc.
- Working together, this will be an exciting decade!