Pulsar Timing Arrays

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On behalf of NANOGrav and the International Pulsar Timing Array

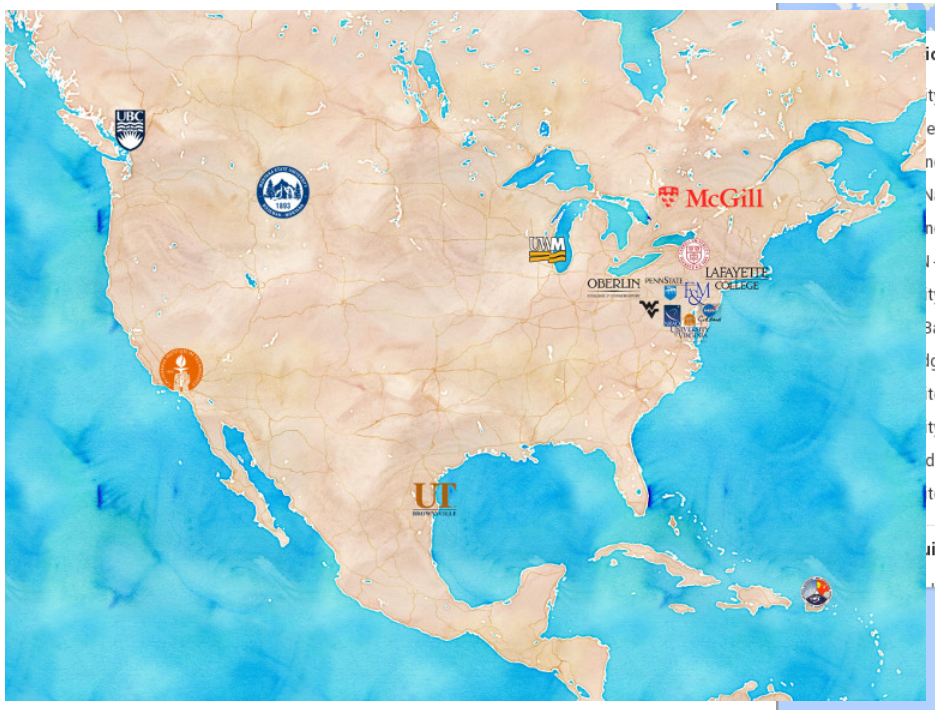
NSERC
CRSNG

What we'll talk about

- Review of basic pulsar properties
- Pulsar timing
- Using pulsars to detect gravitational waves
- Current limits
- Prospects for the future

NANOGrav and 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**



Pulsar “Lighthouse” Model

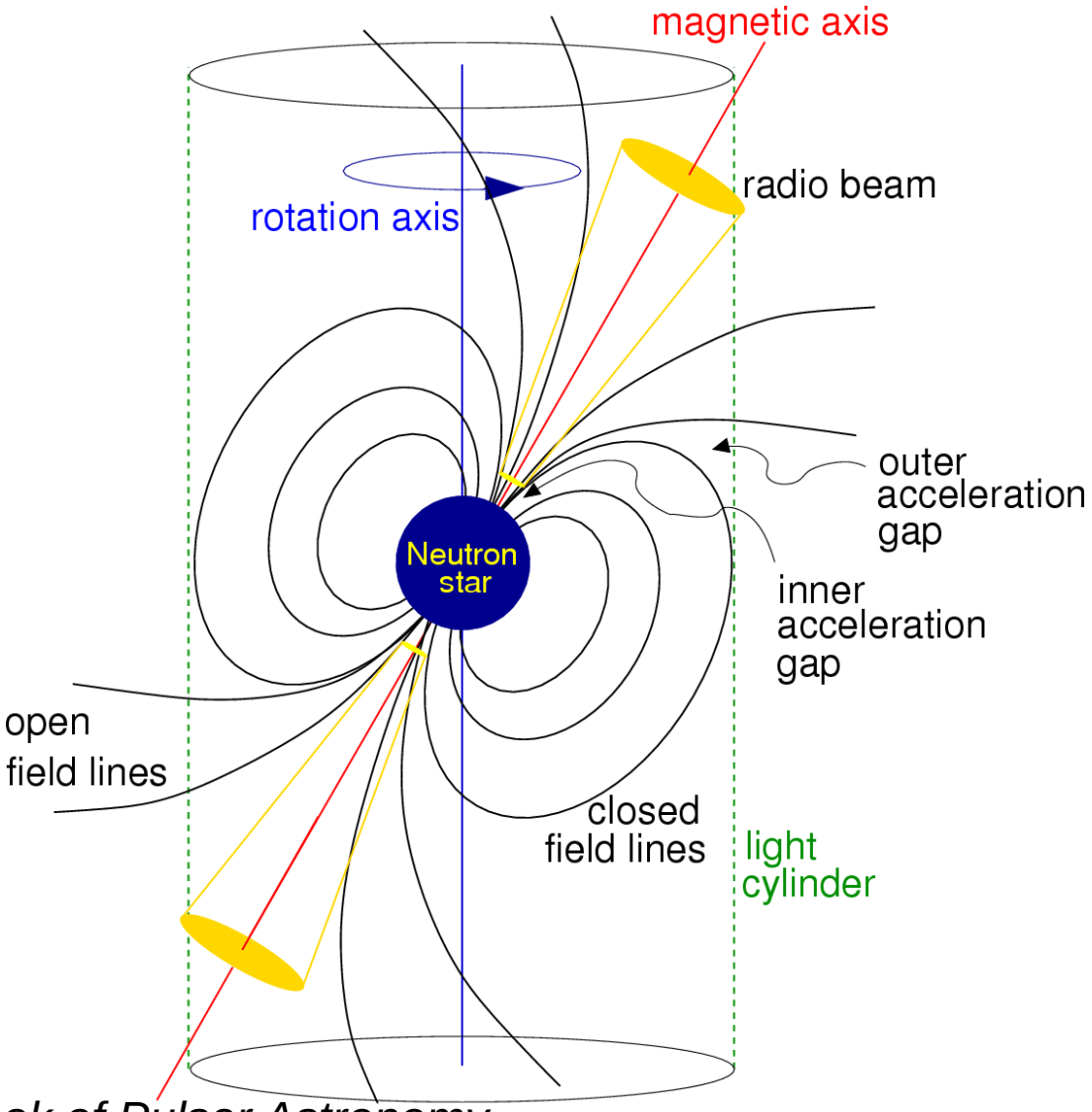
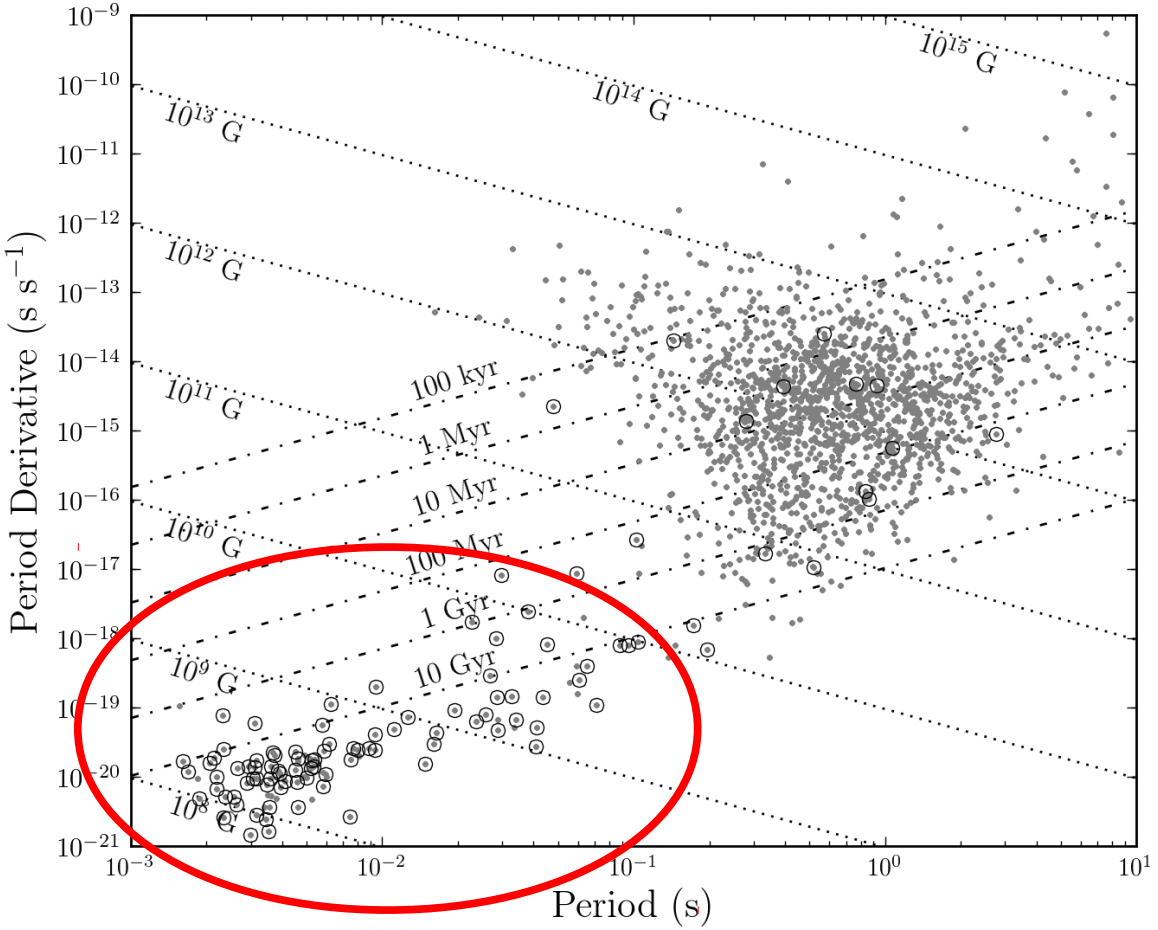


Image credit: *Handbook of Pulsar Astronomy*
(Lorimer and Kramer)

Millisecond pulsars



- Dead pulsars can be recycled by accreting mass from a binary companion
  - Spun up to millisecond periods
  - Magnetic field buried
  - Low spin-down and very stable rotation

Pulse stability

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

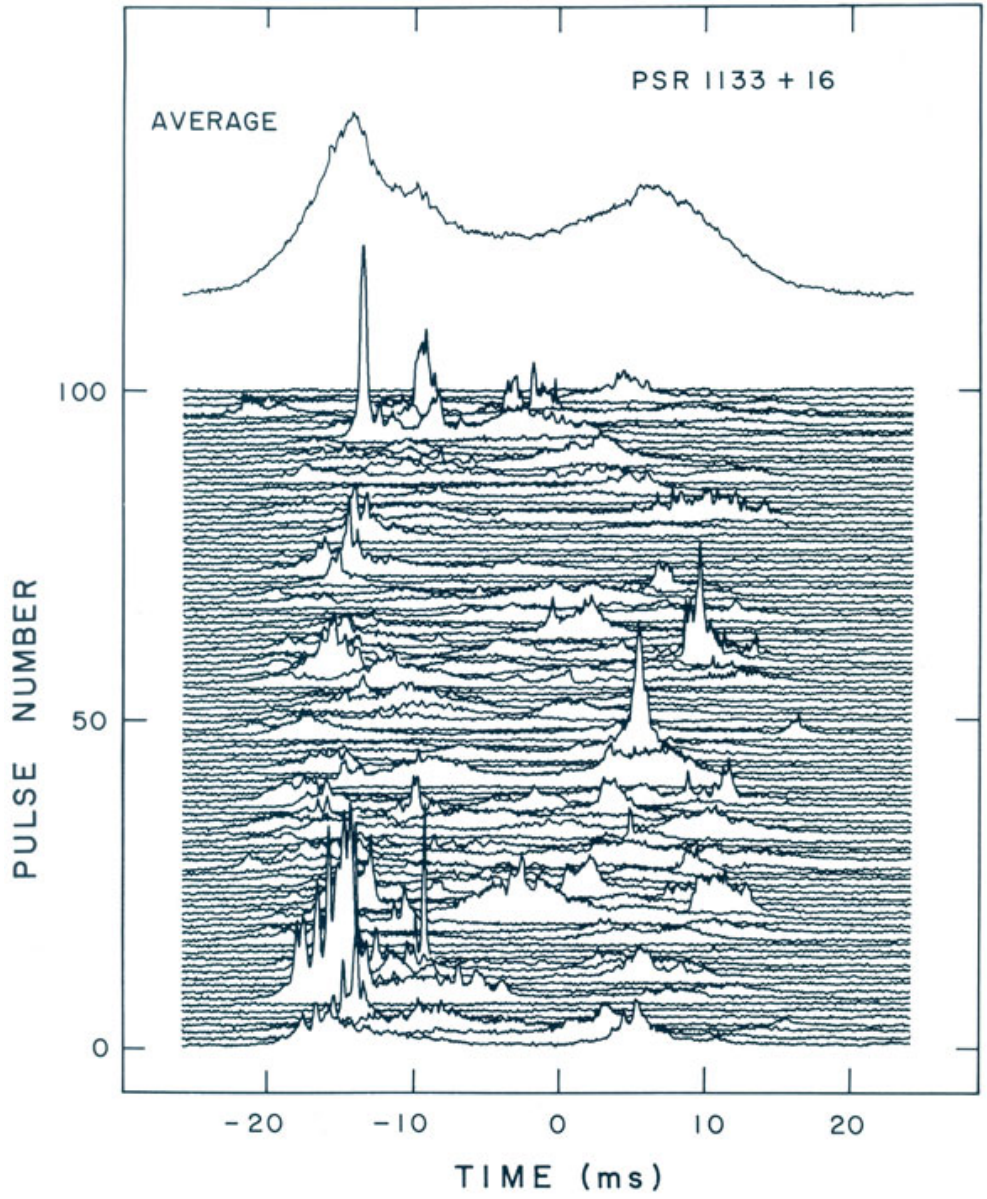
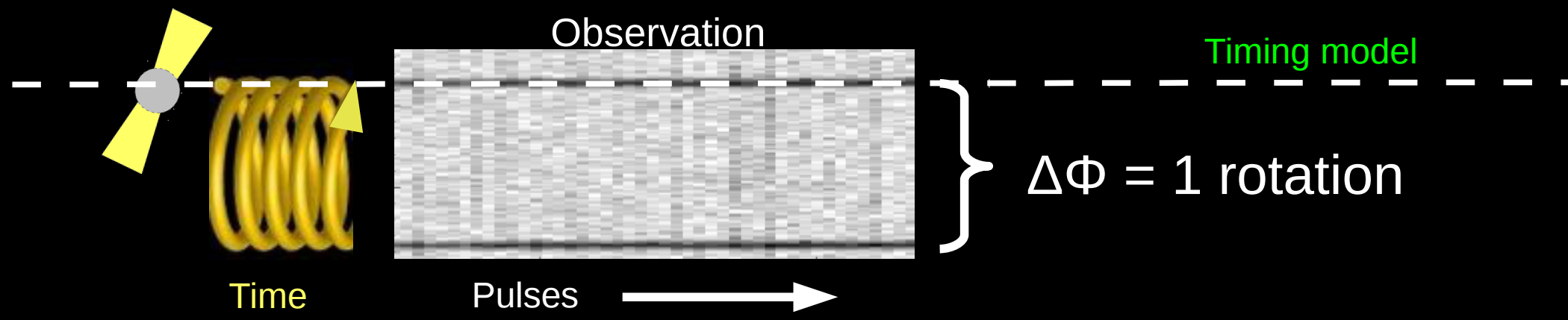


Image credit: Cordes, 1979, SSR, 24, 567

Pulsar Timing:

Unambiguously account for every rotation of a pulsar over years

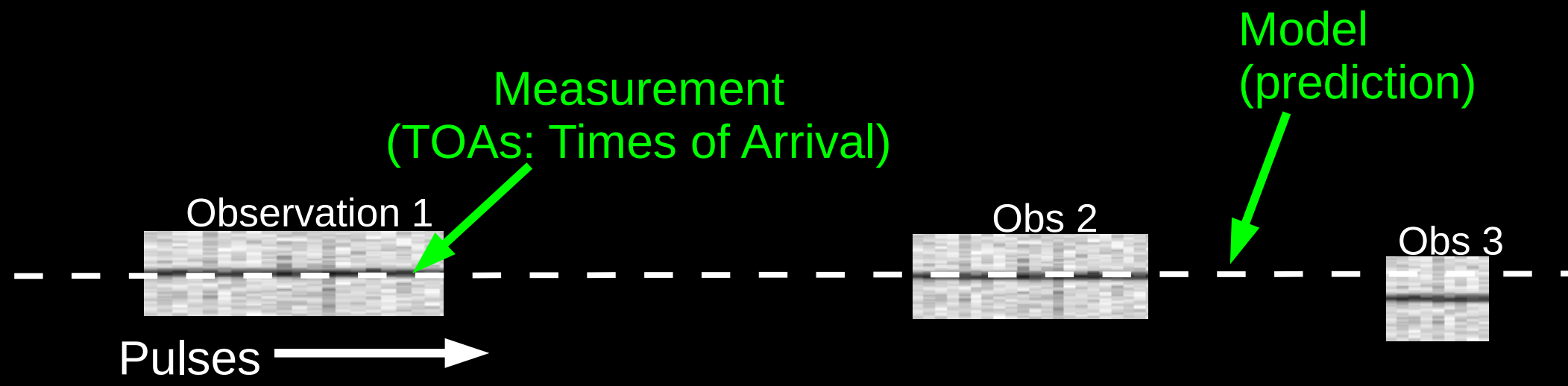


Slide courtesy of Scott Ransom

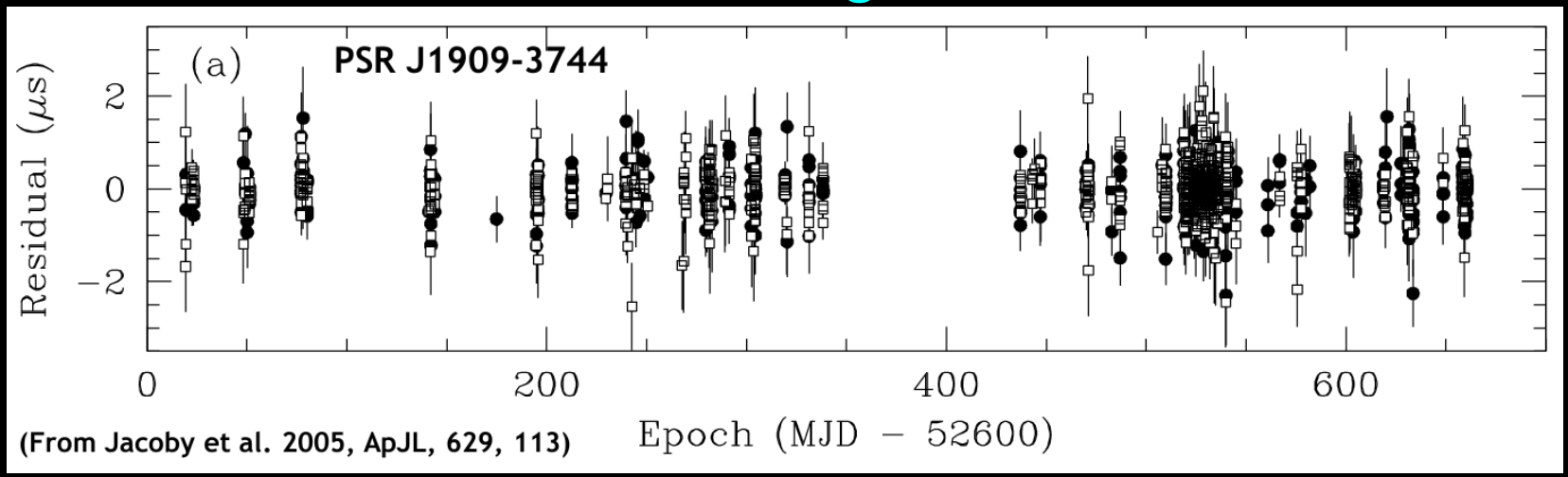
Pulsar Timing:

Slide courtesy of Scott Ransom

Unambiguously account for every rotation of a pulsar over years



Measurement – Timing Model = Residuals

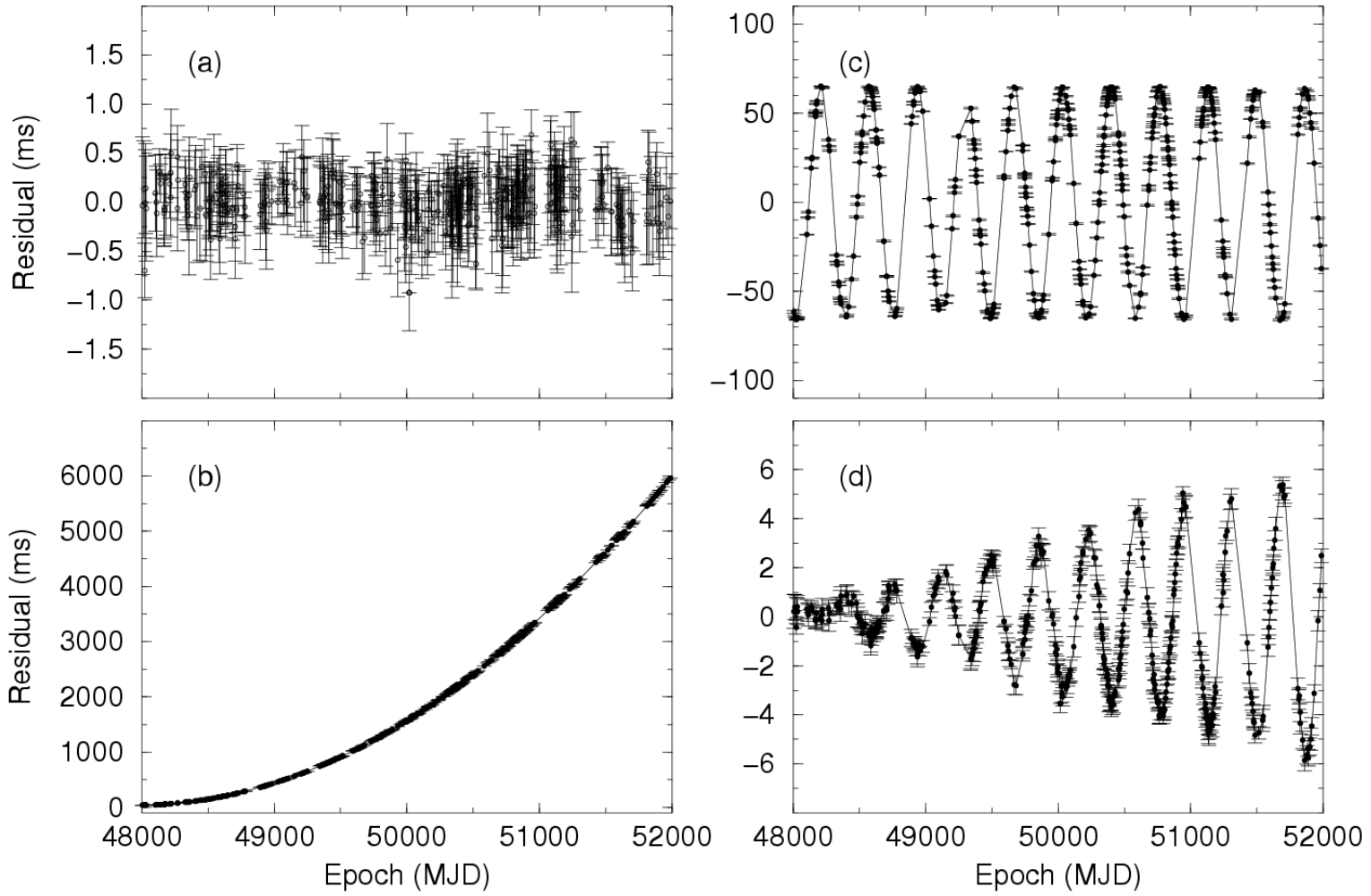


200ns RMS
over 2 yrs

Image credit: *Handbook of Pulsar Astronomy* (Lorimer and Kramer)

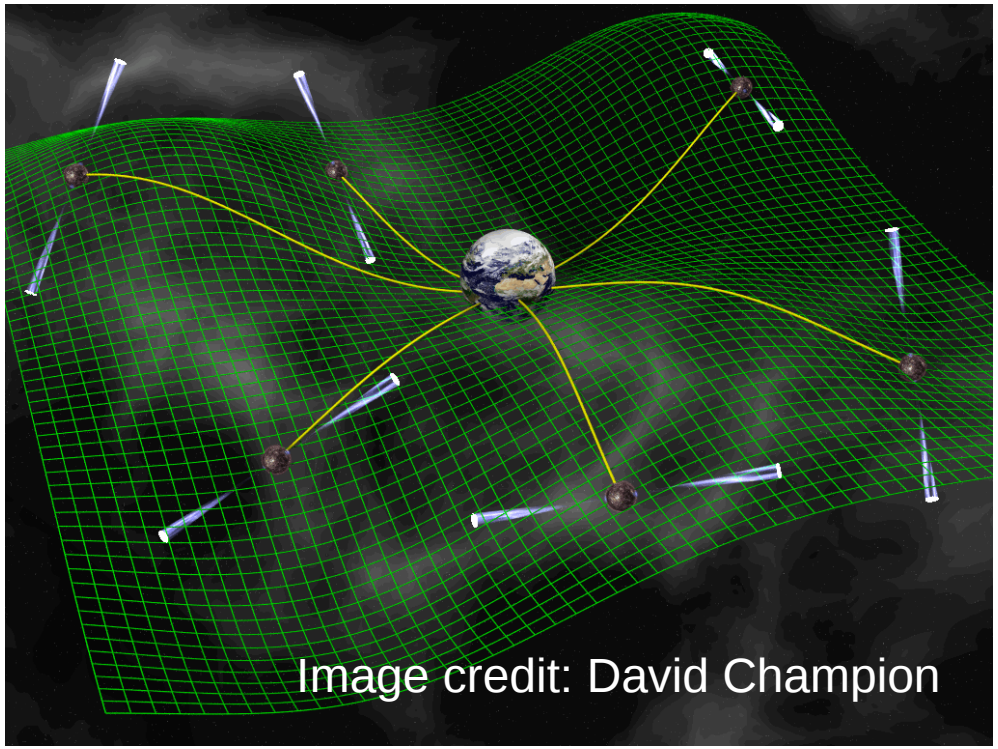
Pulsar Timing

- Deviations from white noise can be modeled -> science!

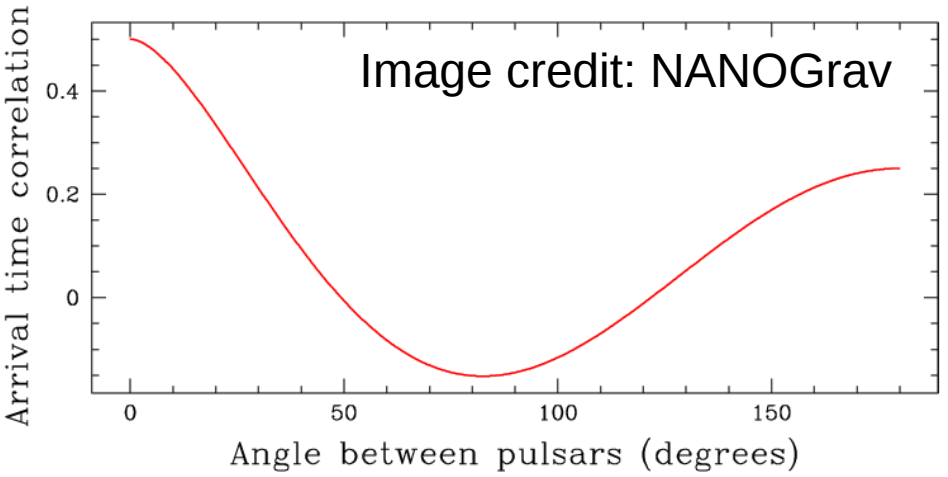


Pulsar Timing Arrays

- The influence of a GW at the Earth should be correlated between MSPs
- An array of MSPs timed to very high precision becomes a unique GW detector
  - Deviation in timing residuals ~10s – 100s of ns



- Note that PTAs are (currently) only sensitive to "Earth term"



- There are a number of large-area surveys underway to find new MSPs

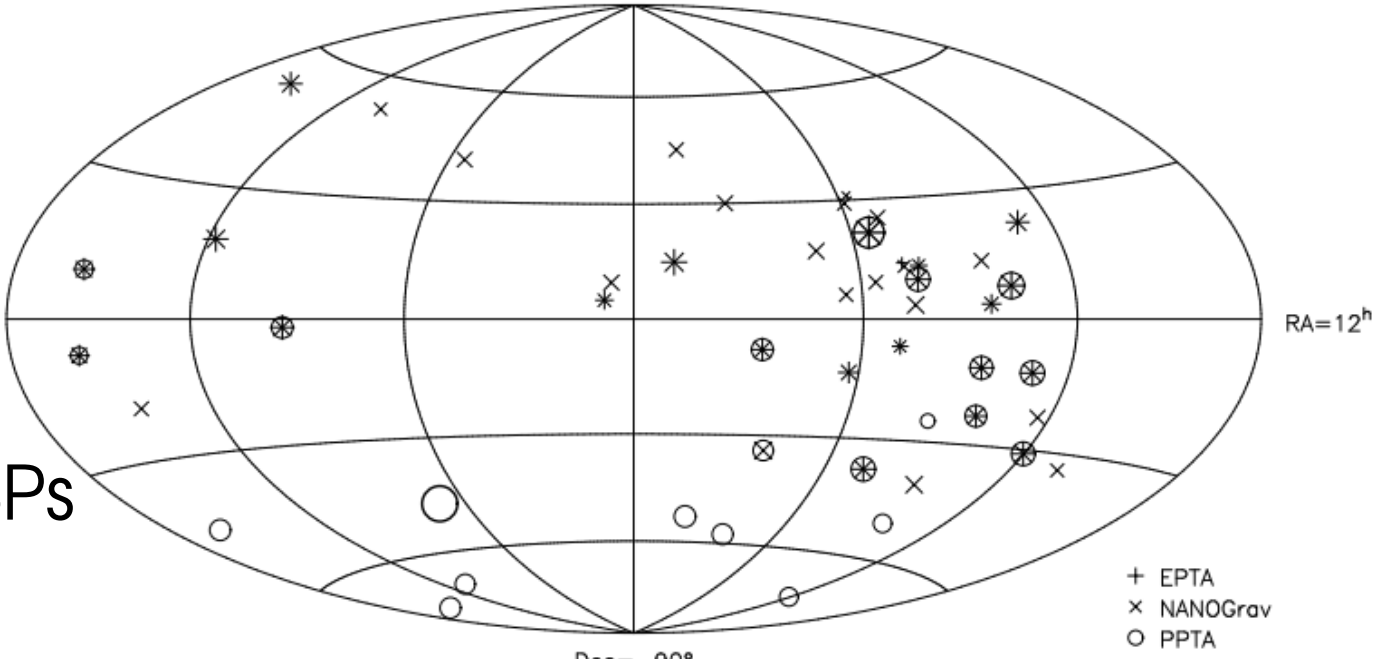
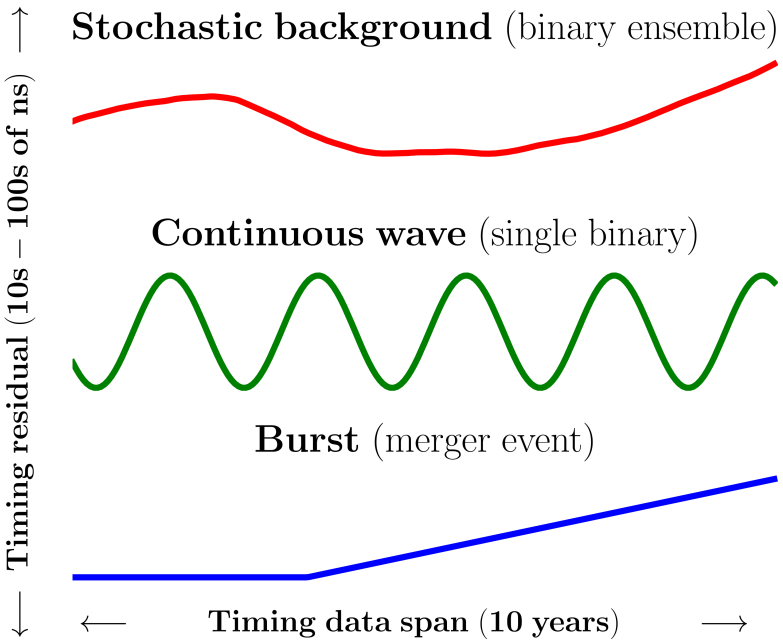


Image credit: Dick Manchester

Observational Signatures



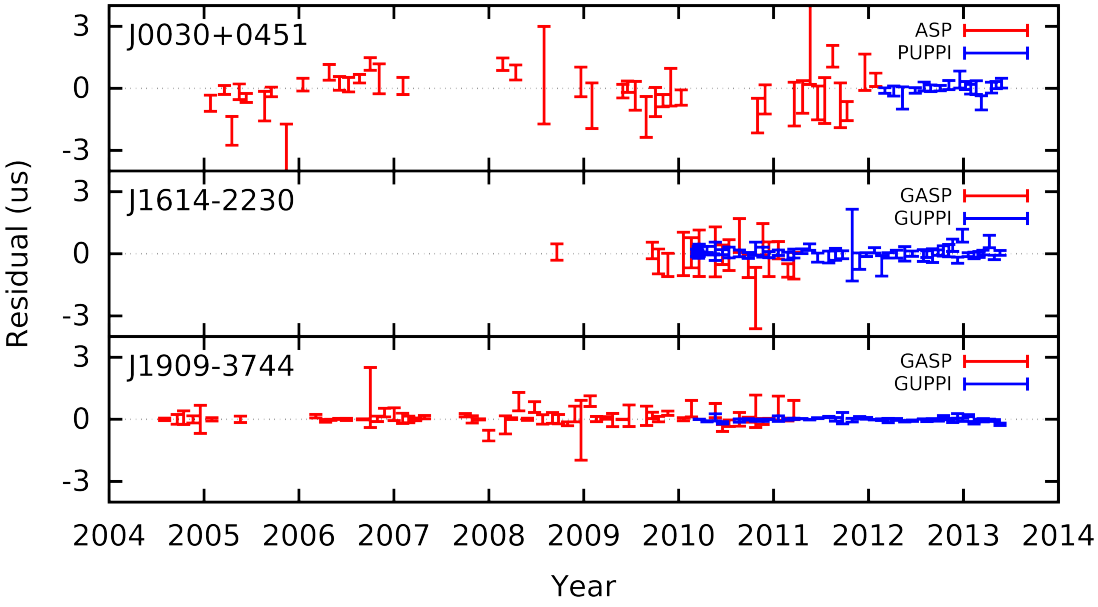


Image credit: NANOGrav

- 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 DNSs
- Both DO use pulsar timing
- DNSs are sensitive to GWs emitted by the binary
- PTAs are sensitive to cosmological sources

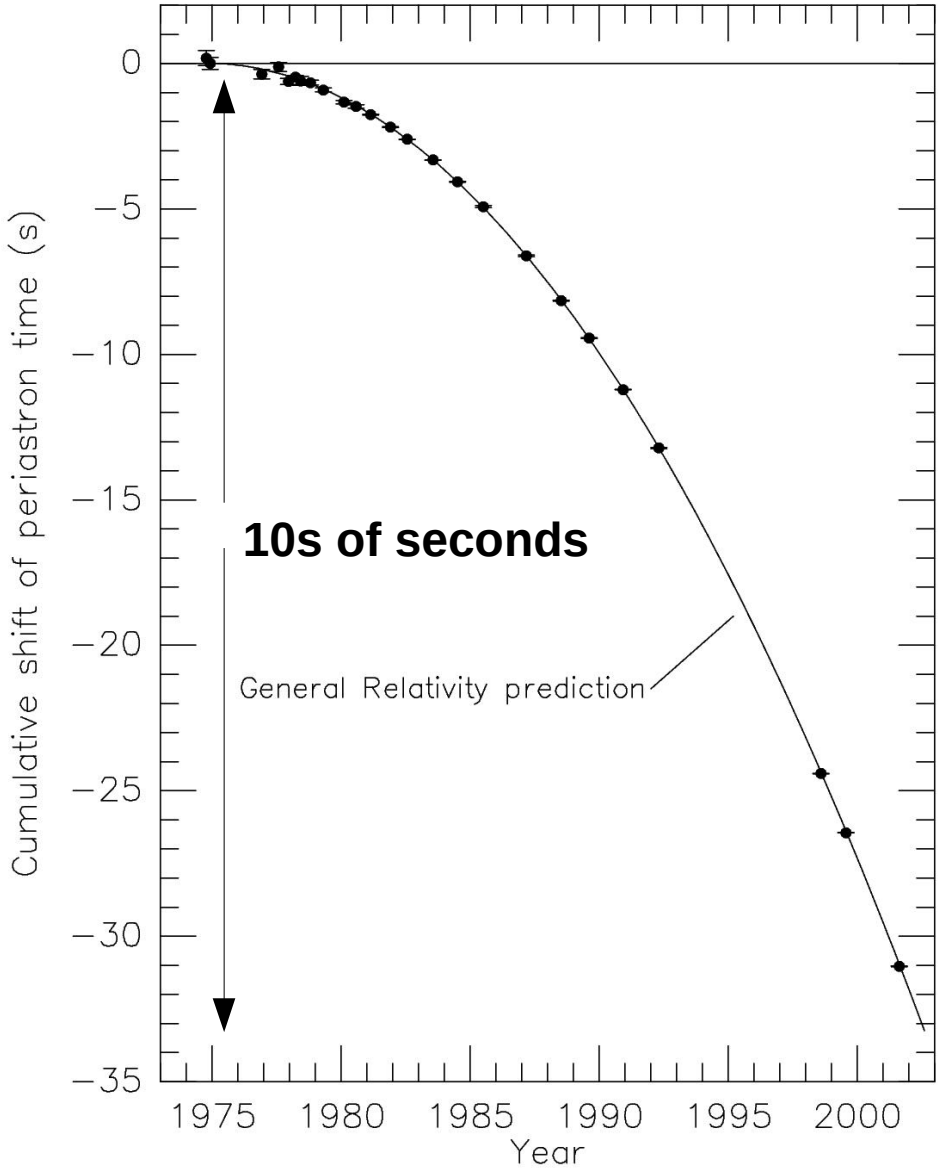


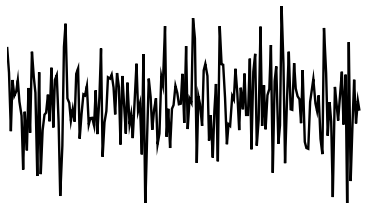
Image credit: Joel Weisberg

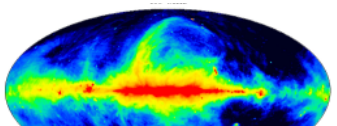
Challenges: Noise Sources

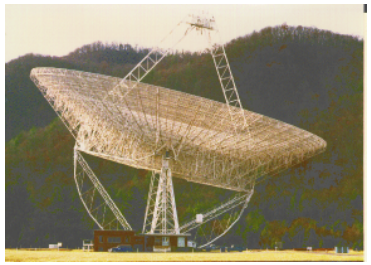
White noise residuals

=

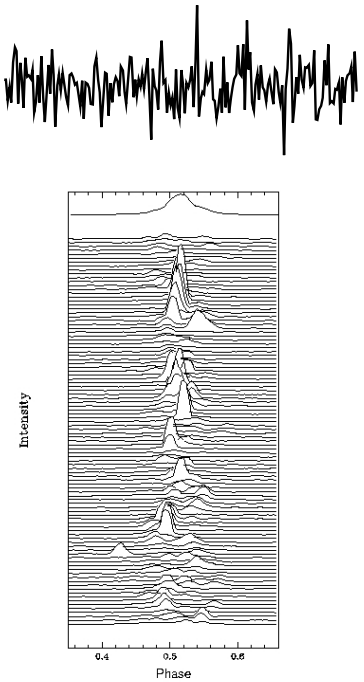
Radiometer noise



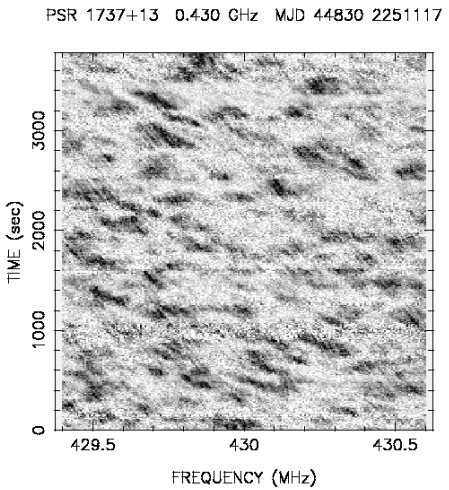




Pulse Jitter

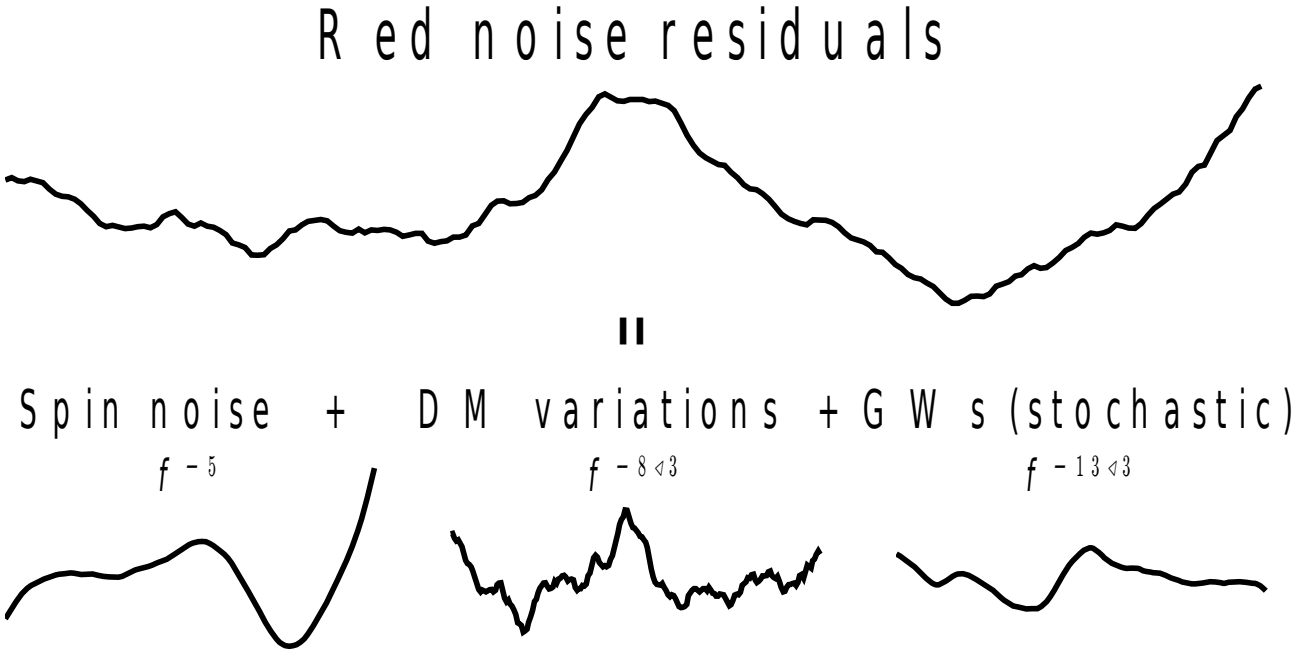


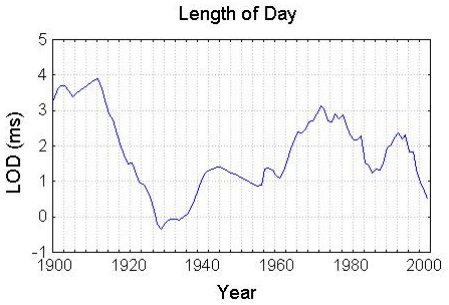
DISS

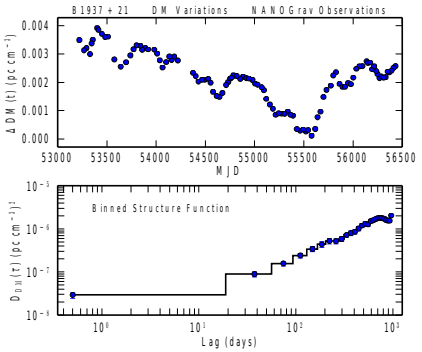


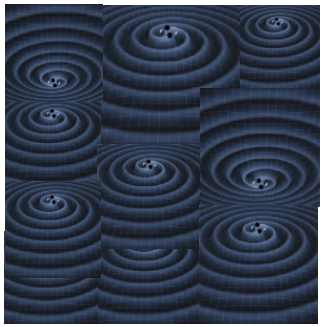
Slide courtesy of Tim Dolch

Challenges: Noise Sources









Slide courtesy of Tim Dolch

NANOGrav Radio Telescopes

- NANOGrav uses the Arecibo Observatory and Green Bank Telescopes
  - Leverage existing facilities and capabilities
- Telescopes are used in complimentary fashion and the loss of either telescope would be **extremely** detrimental


Image credit: NRAO/AUI


Image credit: NAIC

NANOGrav Radio Telescopes

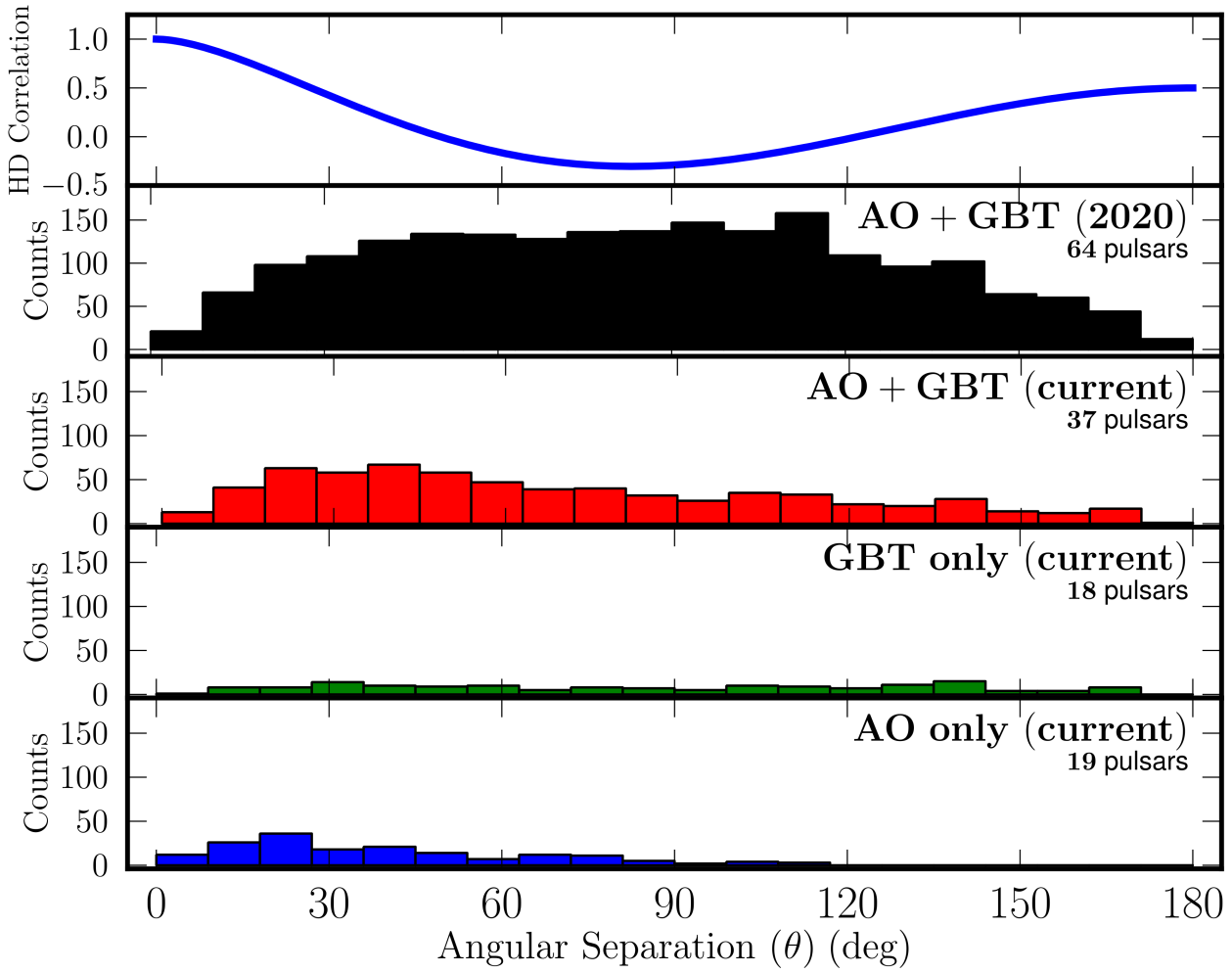
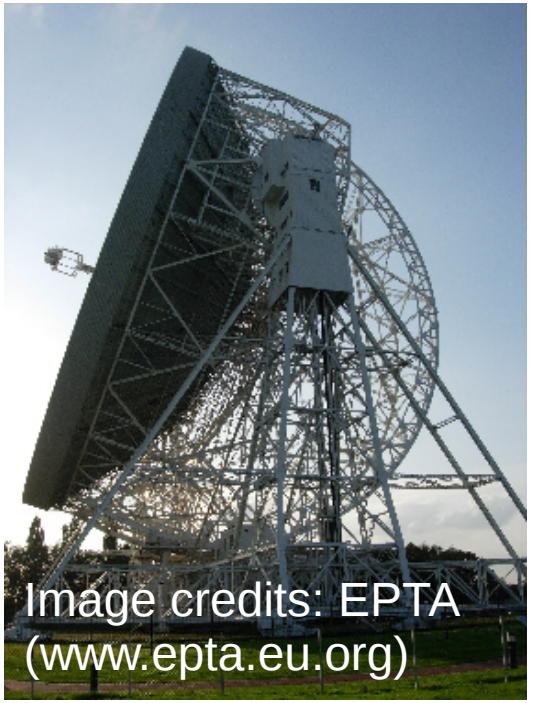


Image credit: NANOGrav

EPTA Telescopes

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

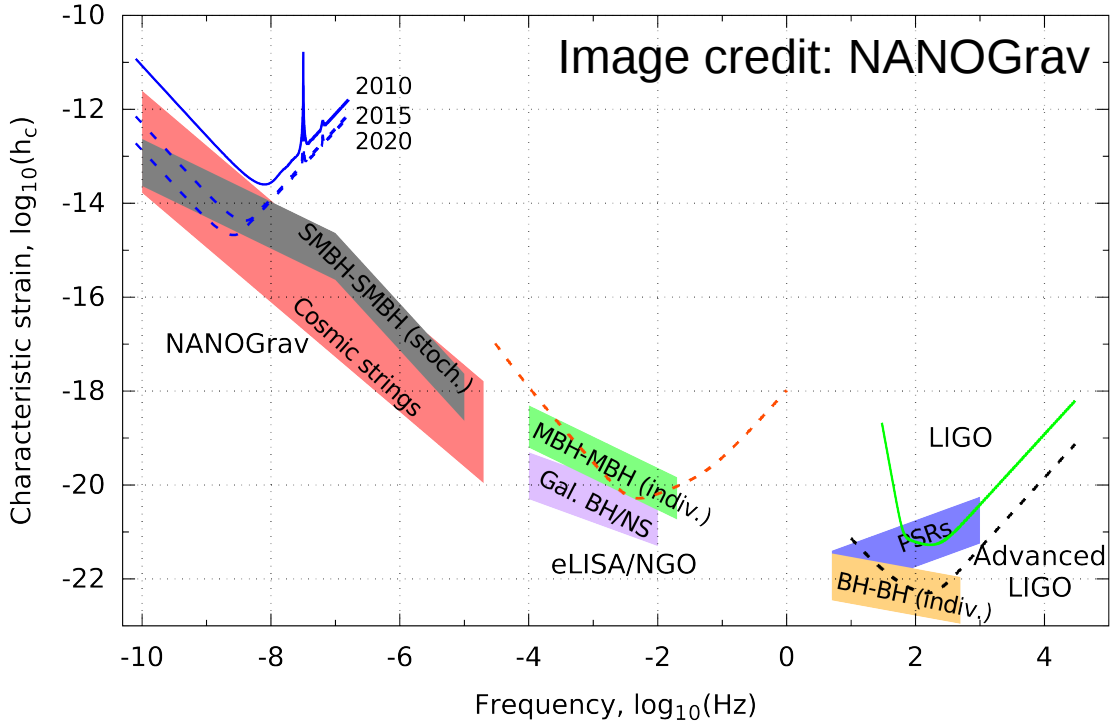


The Parkes Telescope and the PPTA

Image credit: ATNF/CSIRO

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

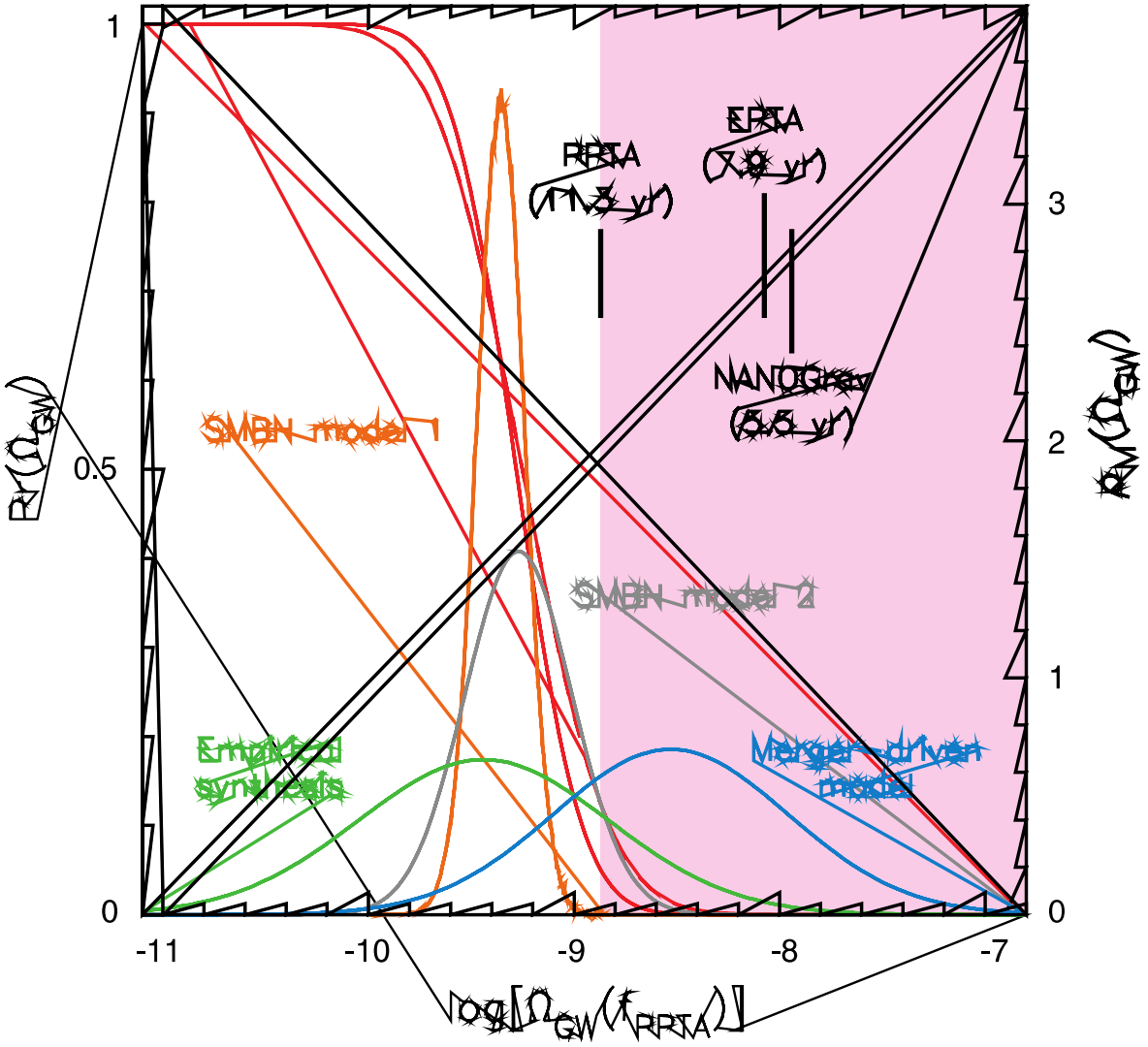
Complementary GW Detectors



- PTAs are sensitive to periods of ~weeks to years
  - Set by cadence (short) and span (long) of observations

Model	A	α	References
Supermassive black holes	$10^{-15} - 10^{-14}$	-2/3	Jaffe & Backer, 2003, ApJ, 583, 616 Wyithe & Loeb, 2003, ApJ, 590, 691 Enoki et al., 2004, ApJ, 615, 19 Sesana et al., 2008, MNRAS, 290, 192
Relic GWs	$10^{-20} - 10^{-15}$	-1 to -0.8	Grishchuk, 2005, PU, 48, 1235 Boyle & Buonanno, 2008,PRD,78,043531
Cosmic Strings	$10^{-16} - 10^{-14}$	-7/6	Maggiore, 2000, PR, 331, 283

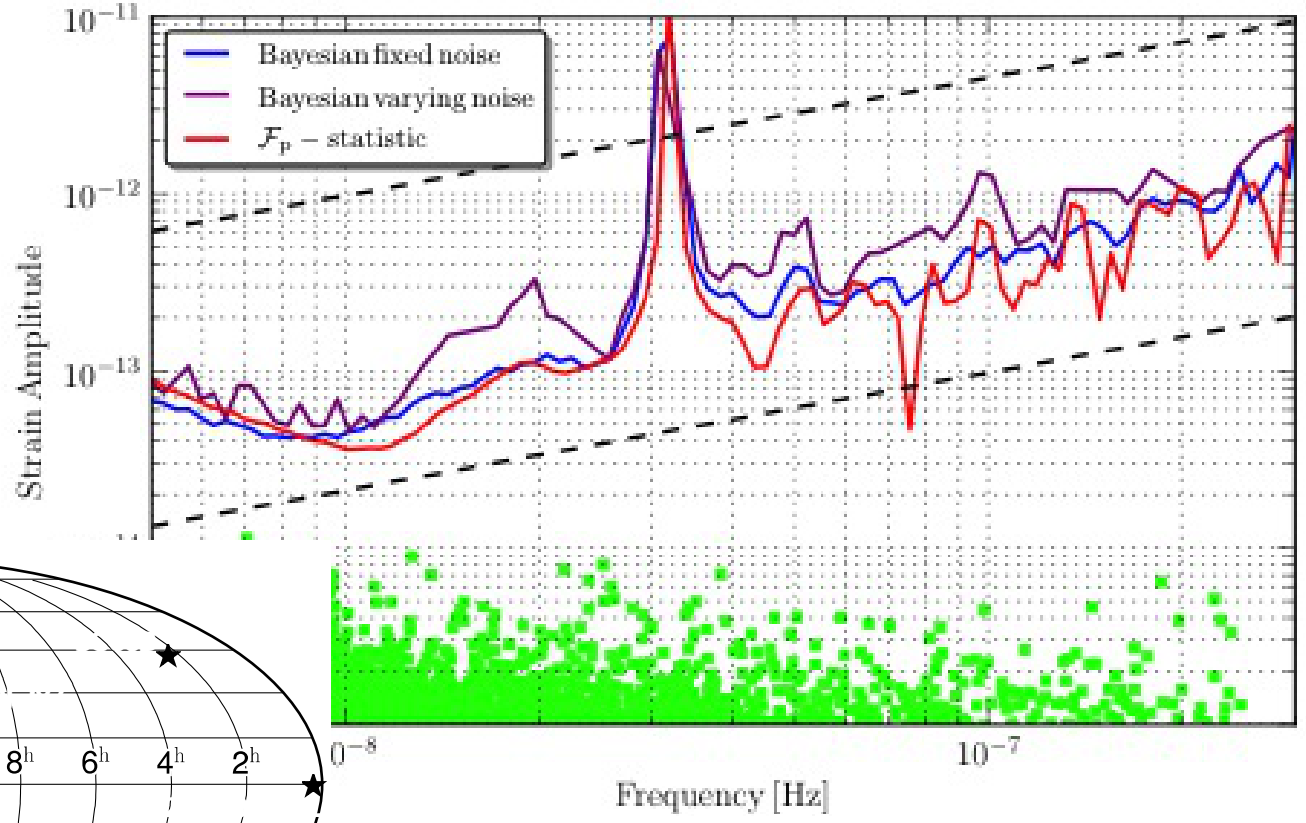
Current Limits: Stochastic Background

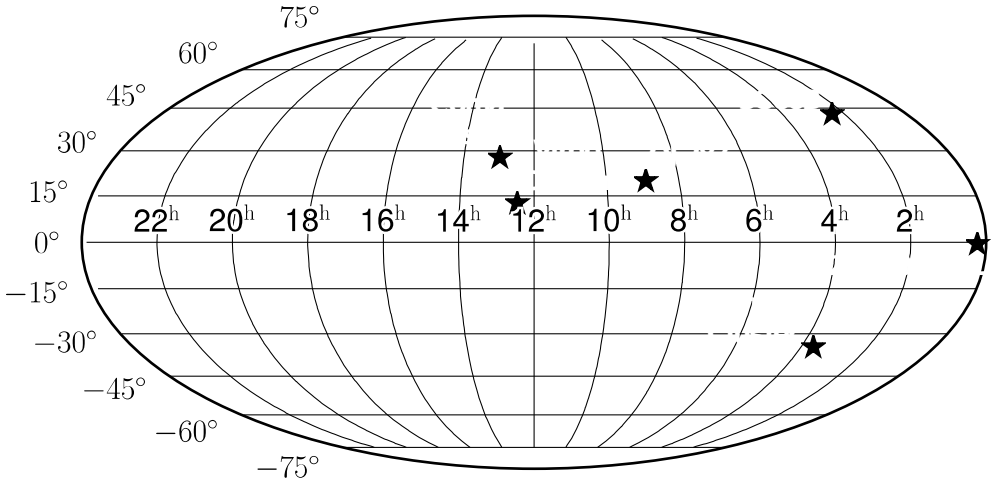


- PTAs are already putting useful constraints on SMBH merger models
- New data releases forthcoming from NANOGrav, EPTA, PPTA, and combined IPTA dataset

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

Current Limits: Continuous Wave





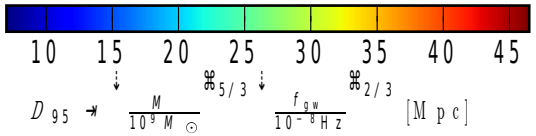


Image credit: Arzoumanian et al., 2014, arxiv:1404.1267

The Future: Instruments and Telescopes

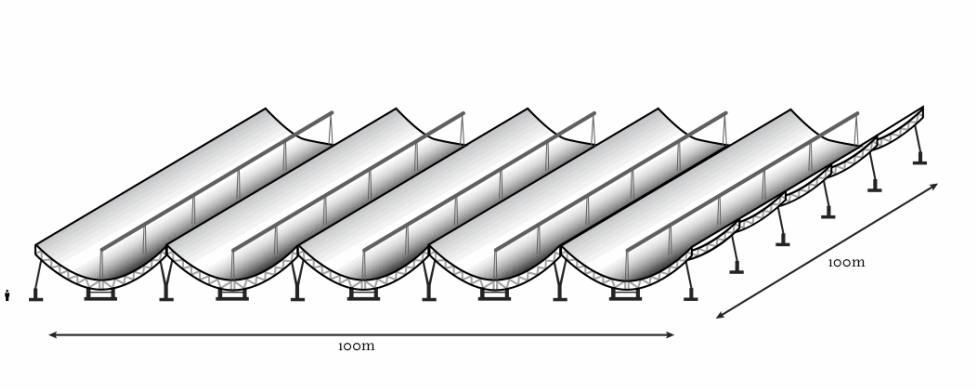


Image credit: chime.phas.ubc.ca

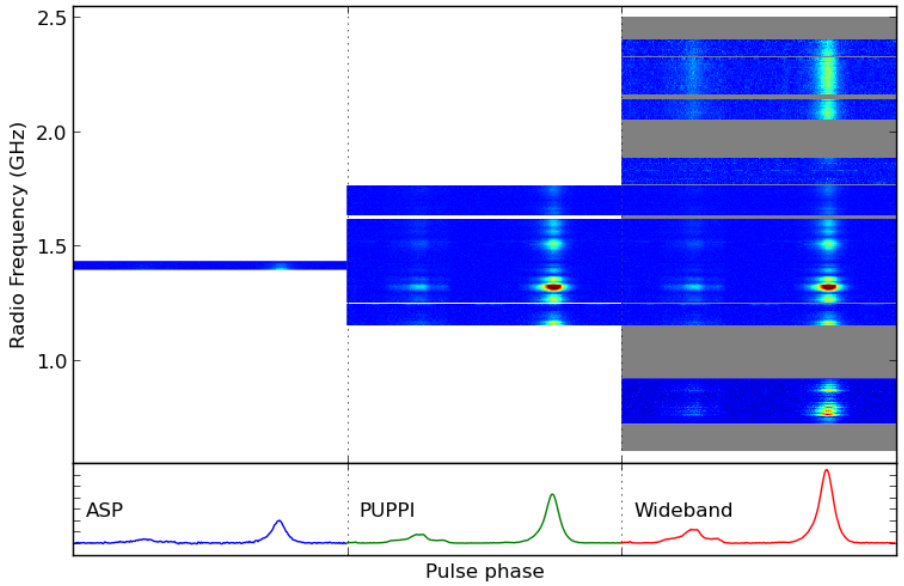


Image credit: NANOGrav

- CHIME is a Canadian BAO 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

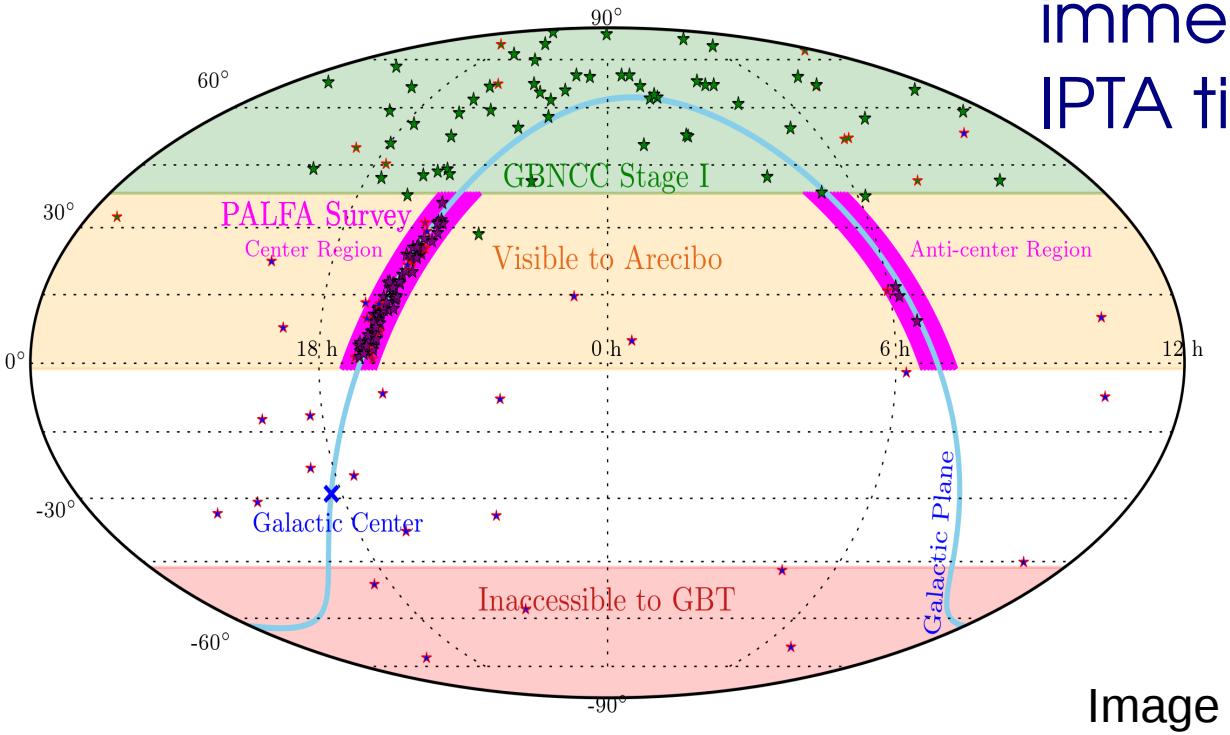
Image credit: fast.boa.ac.cn

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

The Future: New MSPs

- All PTAs are involved in large-area surveys
  - HTRU: Parkes
  - HTRU-North: Effelsberg
- PALFA (Arecibo) and GBNCC (GBT) most relevant for NANOGrav
- Data-sharing agreement allows new MSPs to be immediately included in IPTA timing



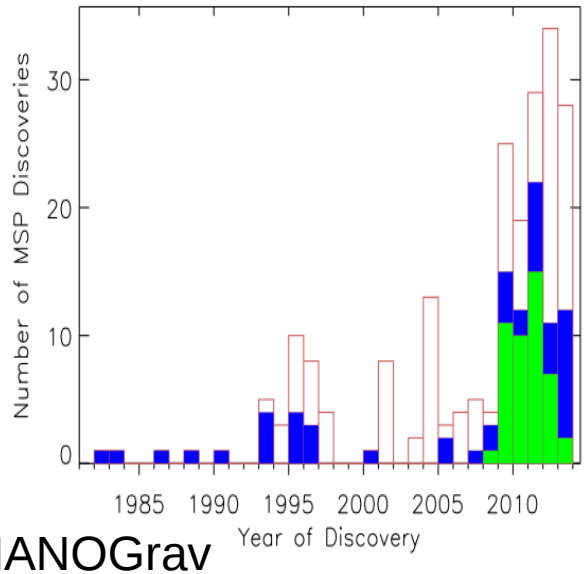
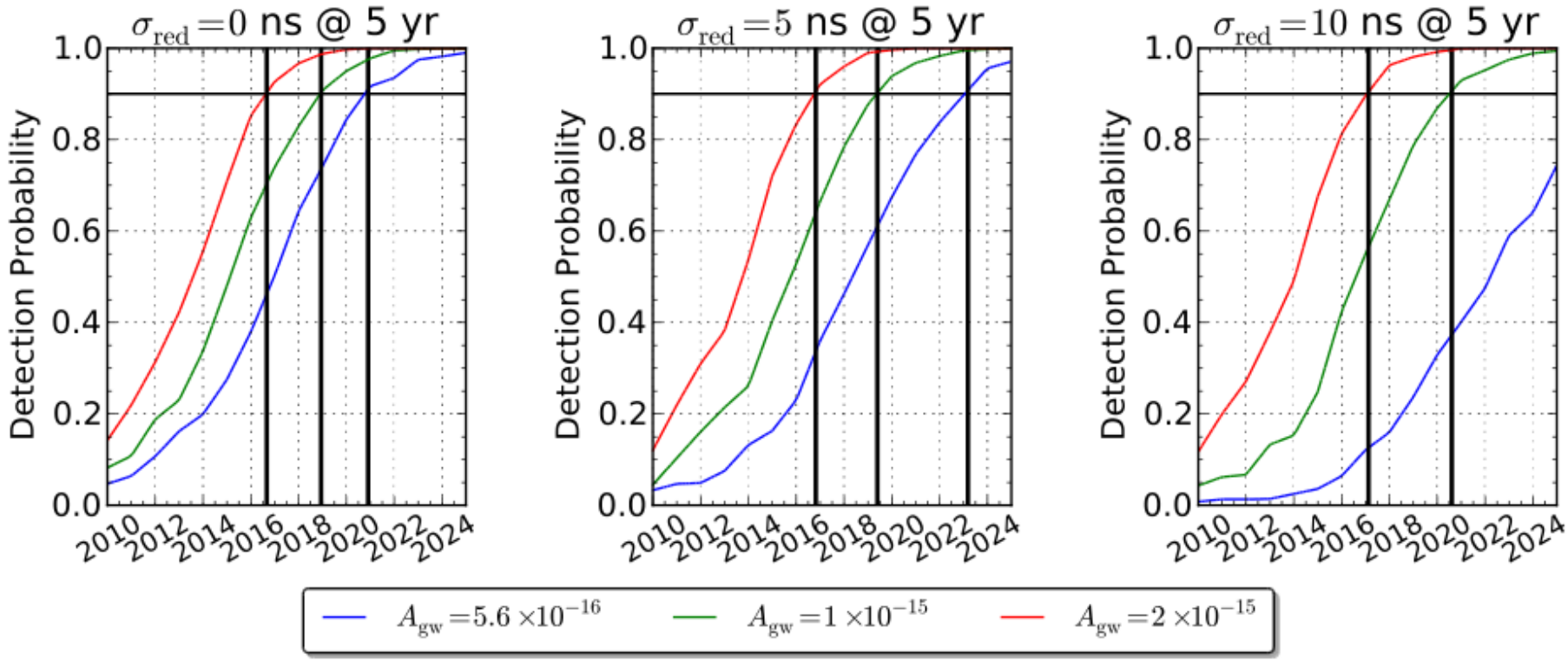


Image credit: NANOGrav

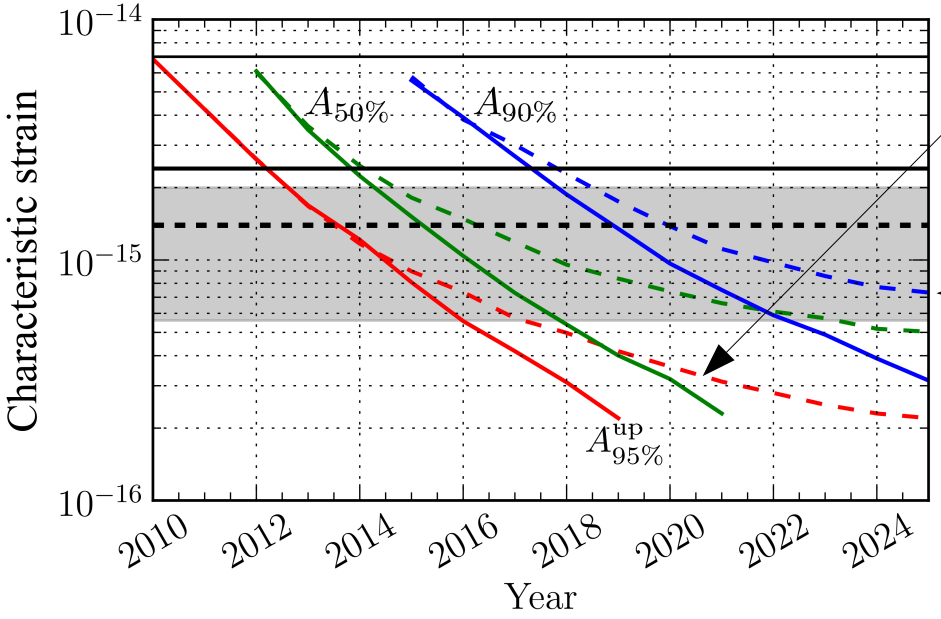
The Future: Detection



- Depends on pulsar properties (timing noise), number of sources, future of telescopes...
- A detection **within the current decade** seems very plausible

Image credit: NANOGrav

The Future: Detection

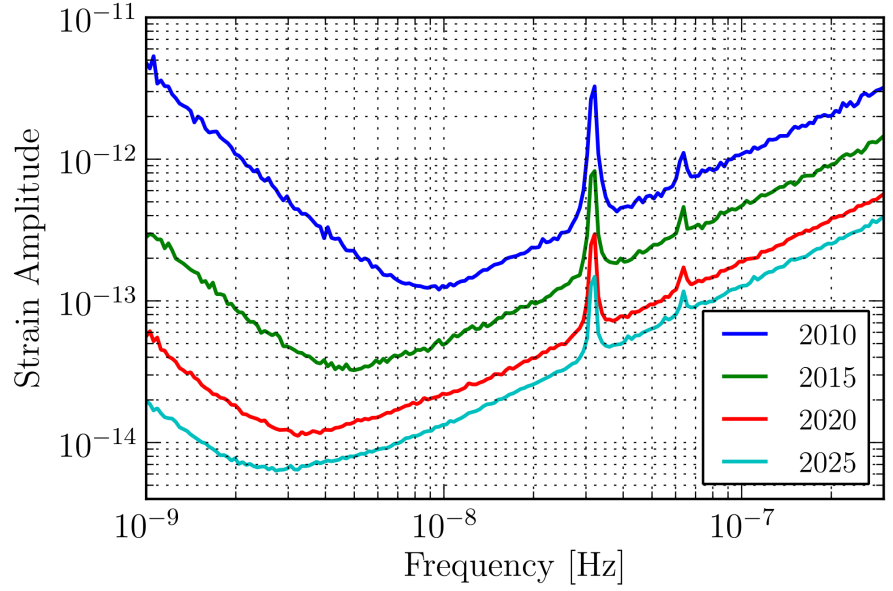


With red spin noise

Current background estimates

Expected phase space for BWM

Continuous waves



Bursts with memory

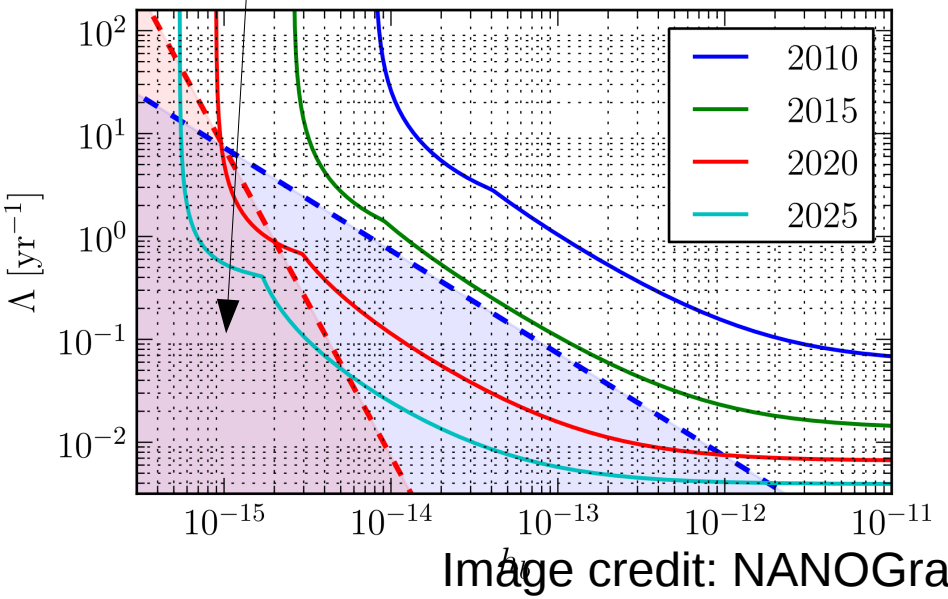


Image credit: NANOGrav

The Future: Astrophysics

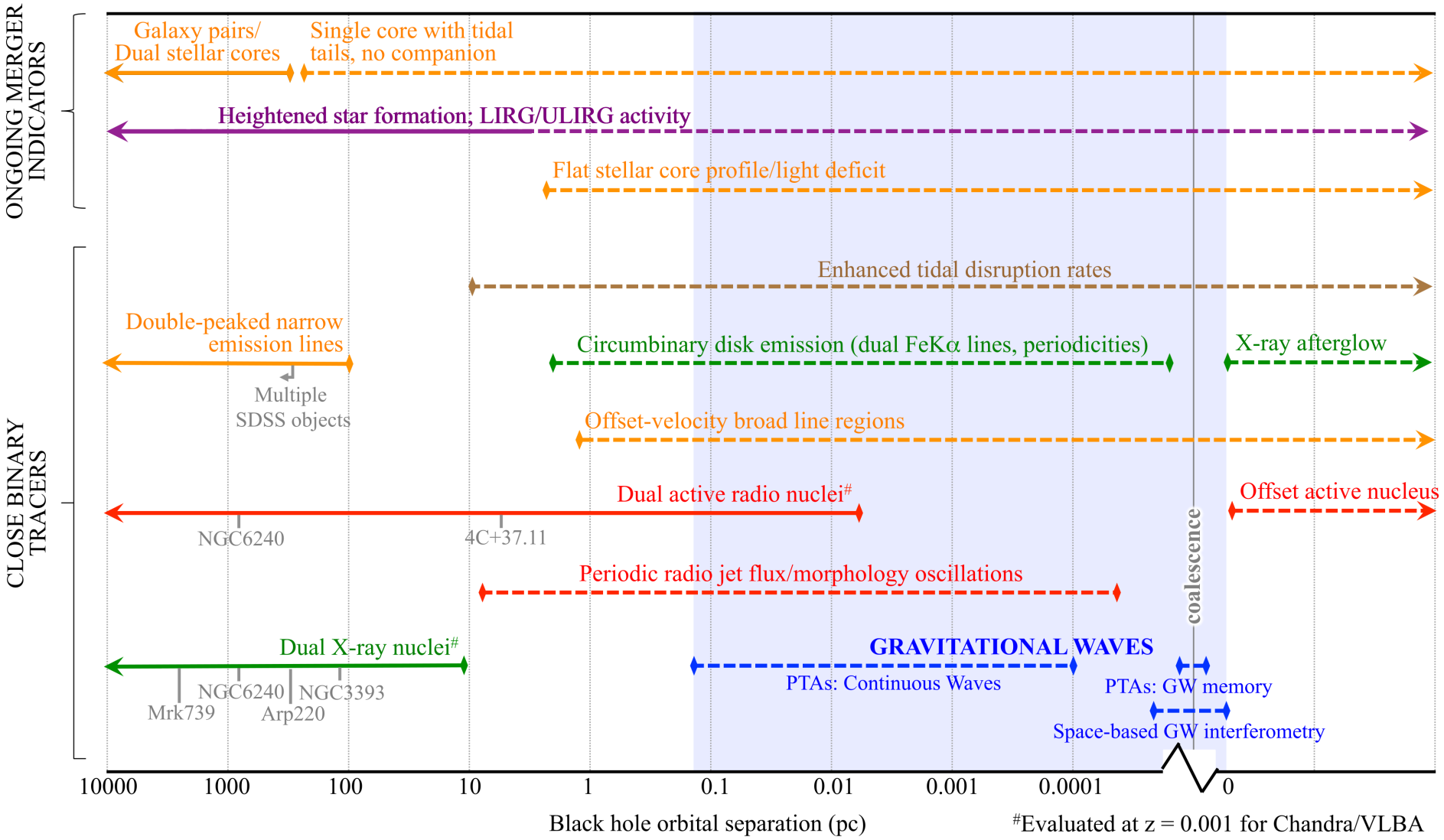
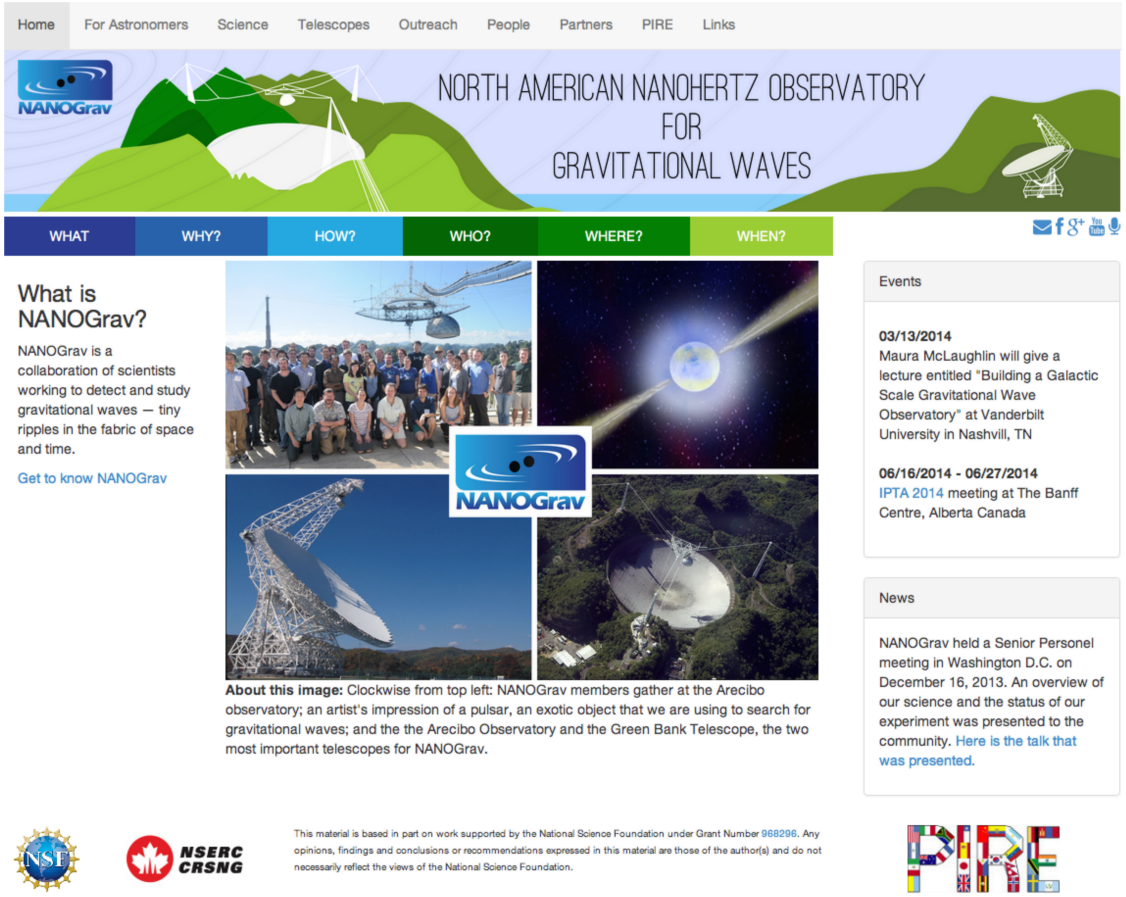


Image credit: NANOGrav

Learn more…



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- www.atnf.csiro.au/research/pulsar/ppta/
- NANOGrav, EPTA, IPTA also on Facebook
- New members/ collaborators welcome!

Thank you!