Pulsar Timing Arrays CHIME in on Gravitational Waves

Deborah Good (CHIME/Pulsar collaboration, NANOGrav)
June 24, 2019

Using Pulsars to detect gravitational waves

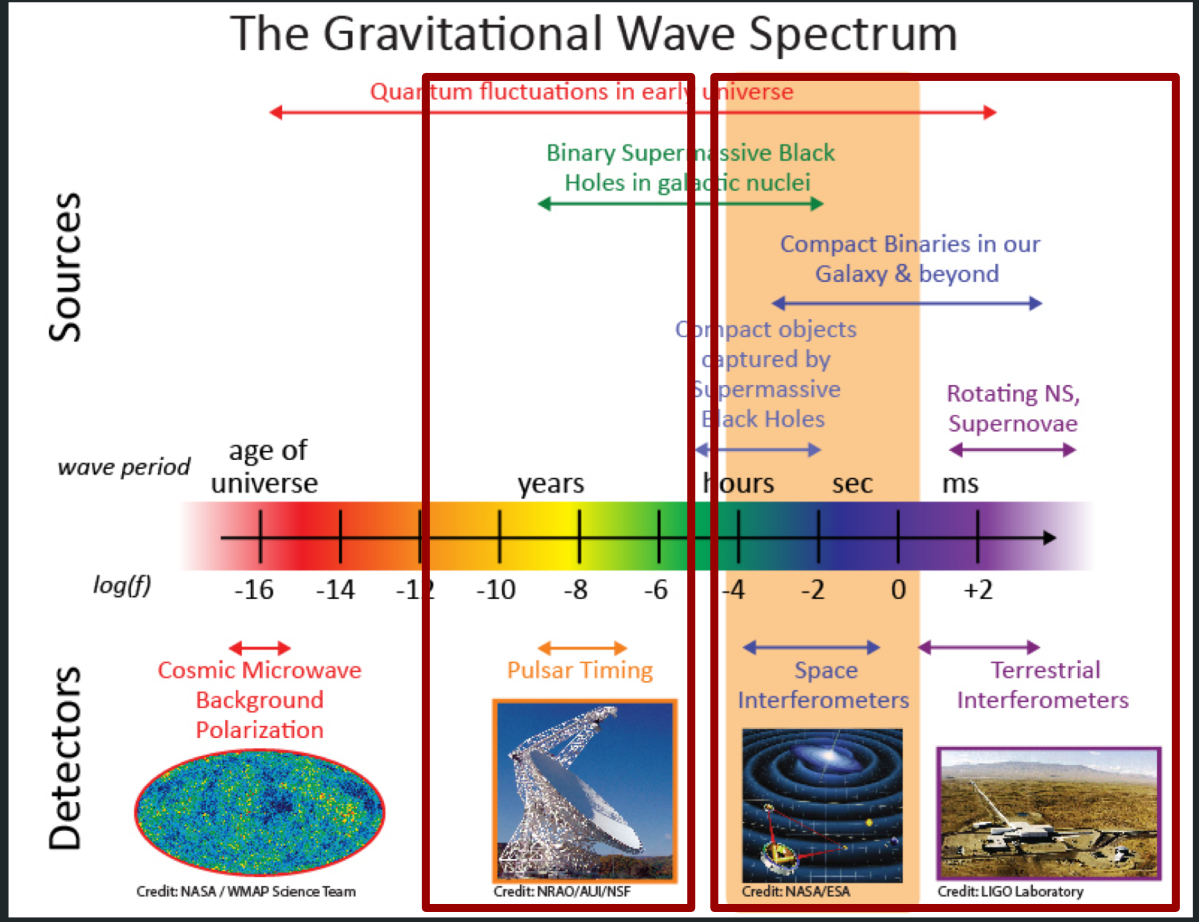


Image Credit: NASA

What (and who) is NANOGrav?

- NANOGrav is a collaboration of over 100 researchers from 40 institutions across North America.
- Our goal is to detect low-frequency gravitational waves resulting from the stochastic gravitational wave background or individual SMBH mergers (continuous wave signals), using precision pulsar timing measurements from an array of (currently) 56 pulsars.

Quick reminder: Pulsars

- Pulsars:
  - Rapidly rotating neutron stars
  - Large magnetic fields
- Pulsars & Gravity
  - Double pulsar system provided indirect proof of gravitational radiation
  - Pulsar binaries provide important tests of gravity.
- Millisecond pulsars:
  - “Recycled”
  - Extremely accurate clocks.

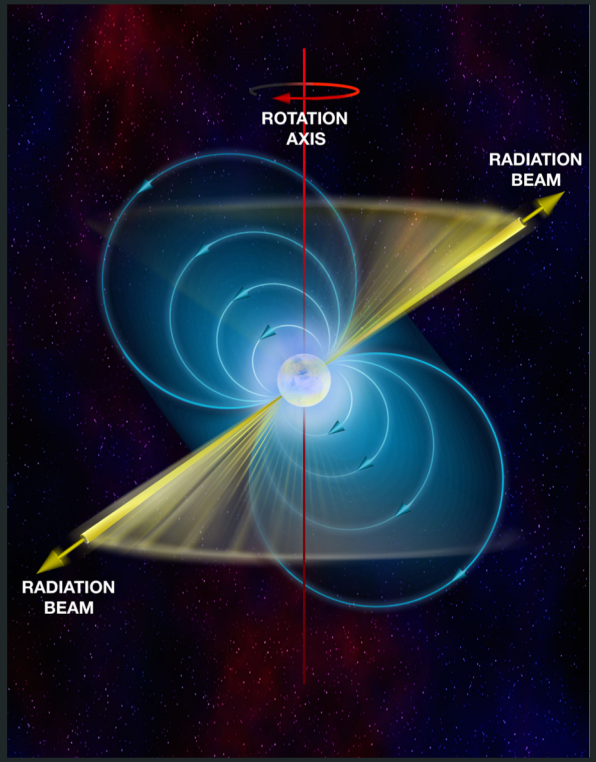


Image credit: NRAO

How do we see gravitational waves with pulsars?

A gravitational wave signal in pulsar-timing array data will create a correlated signature in the timing residuals for all pairs of pulsars, dependent only on the pulsar pair baseline.

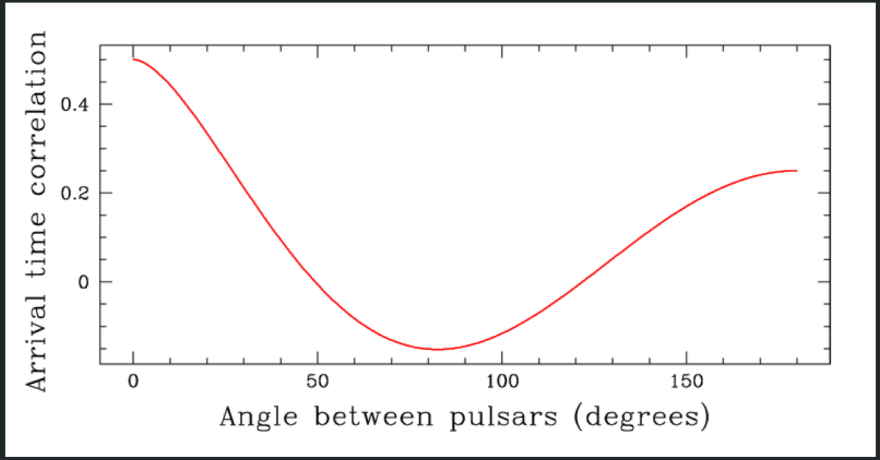
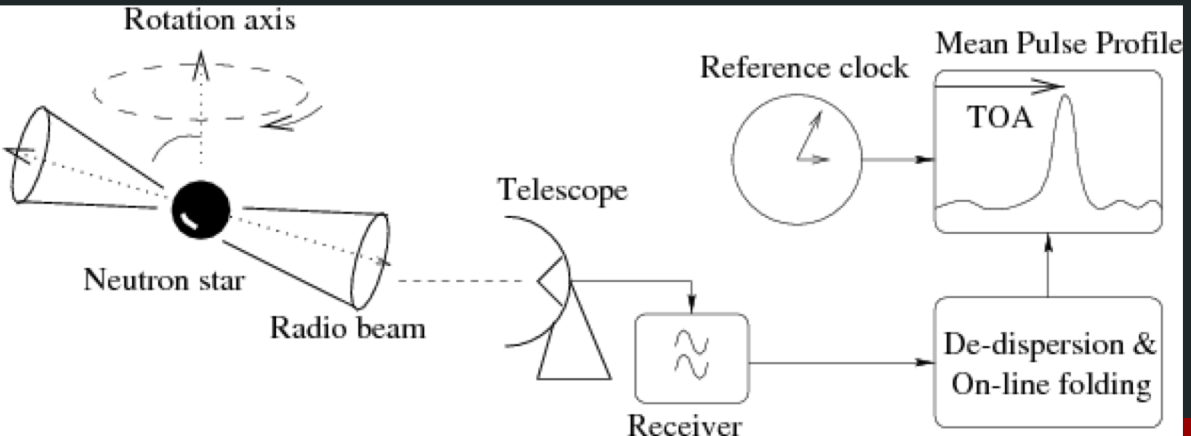


Image credit: NANOGrav Collaboration

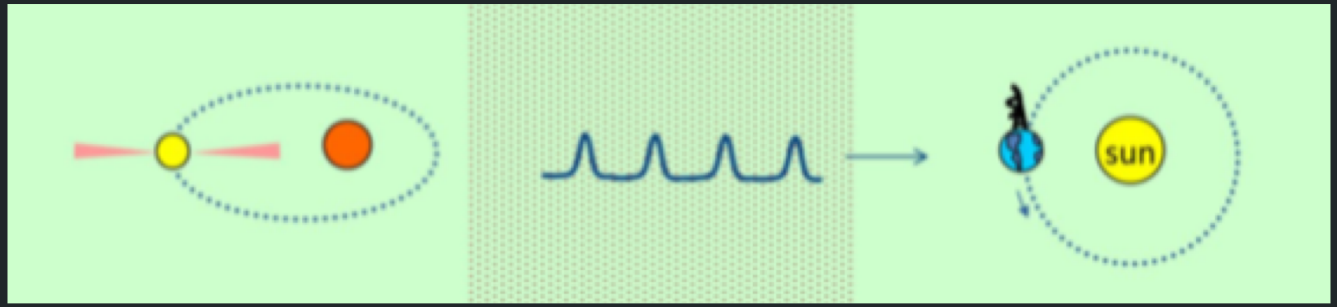
How do we time pulsars?

- Observe pulsars (we use mostly Arecibo Observatory & the Green Bank Telescope) regularly for a long period of time (14+ years for NANOGrav)
- Determine Times of Arrival (TOAs) for every observation
- Fit a timing solution to the total set of data.
- Focus in on residuals and model out as much structure as possible.



Lorimer & Kramer 2004

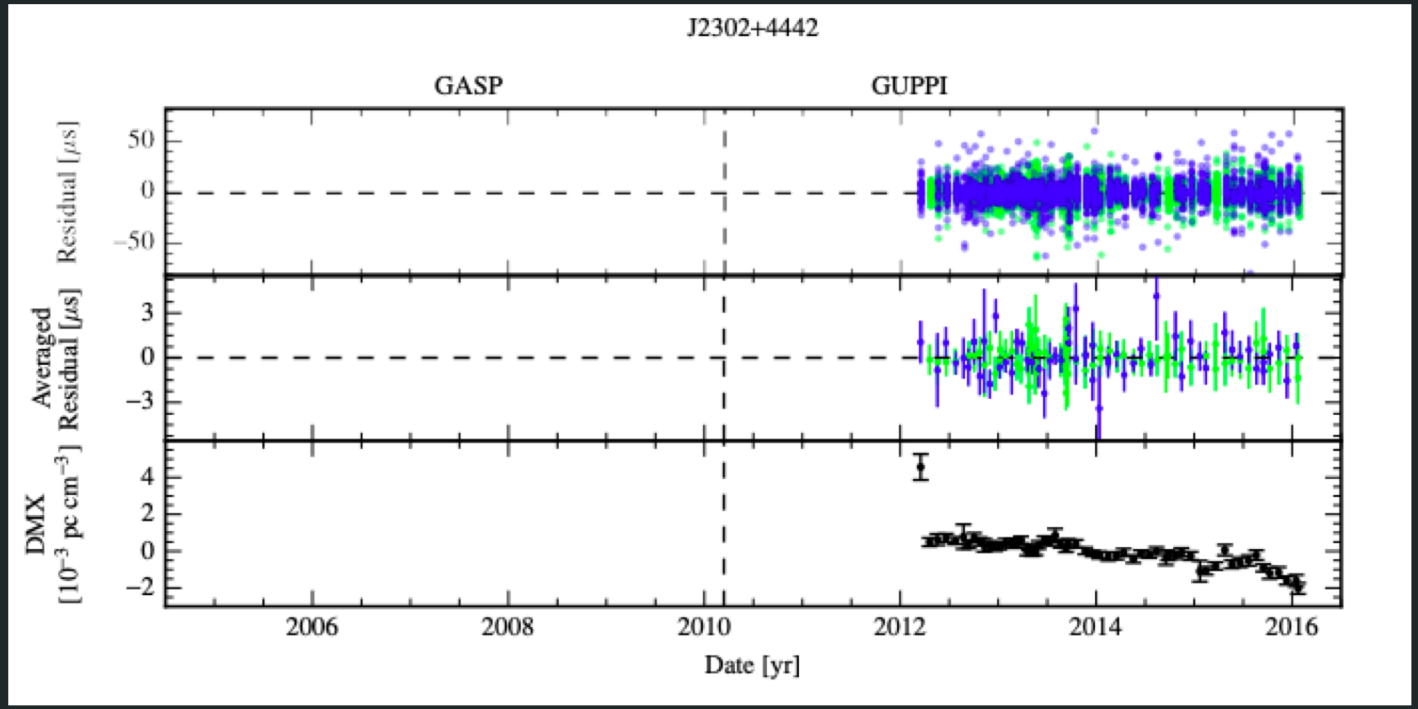
What do we see when we time pulsars?



Rotation Period Rotation Period Derivative Keplerian Orbital Elements Relativistic Orbital Elements Kinematic Perturbations of Orbital Elements	Dispersion Measure Dispersion Measure Variation	Position Proper Motion Parallax Solar Electron Density

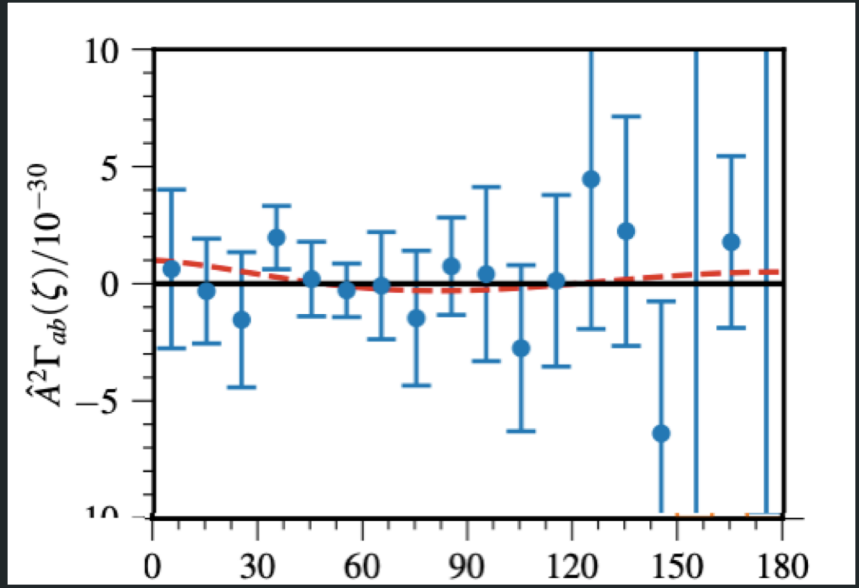
Slide from Jeff Hazboun (and David Nice)

What do we see when we time pulsars?



(Arzoumanian et. al. 2018)

NANOGrav Current Status
11 yr Spatial Correlations



(Arzoumanian et. al. 2018)

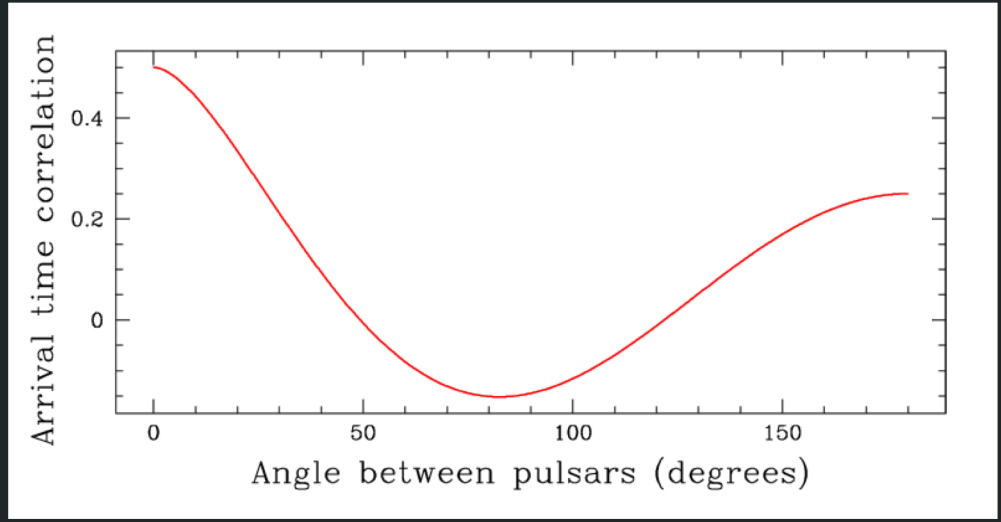
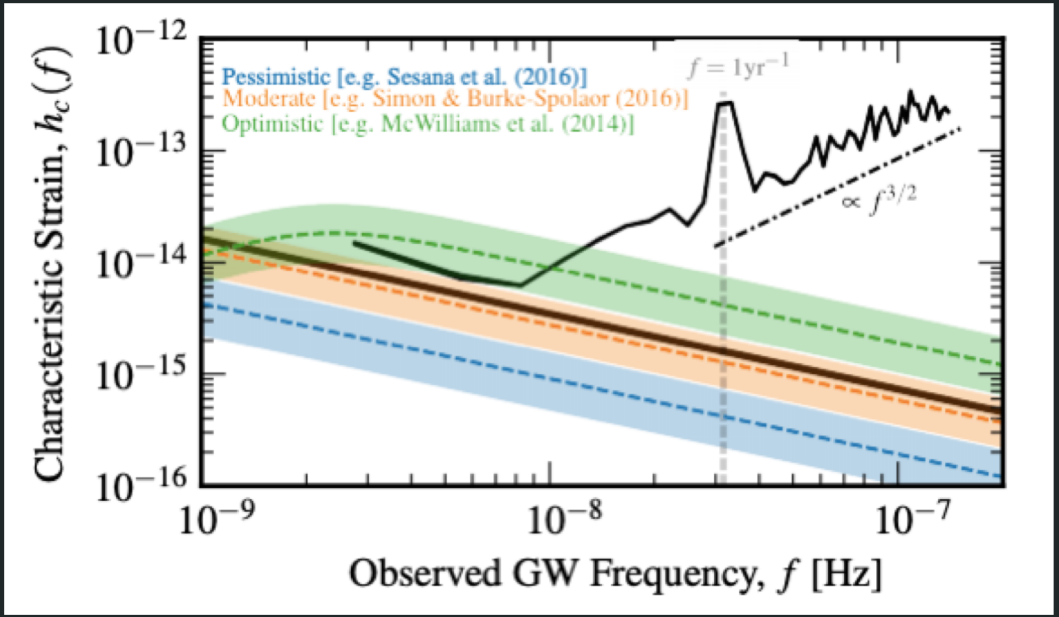


Image credit: NANOGrav Collaboration

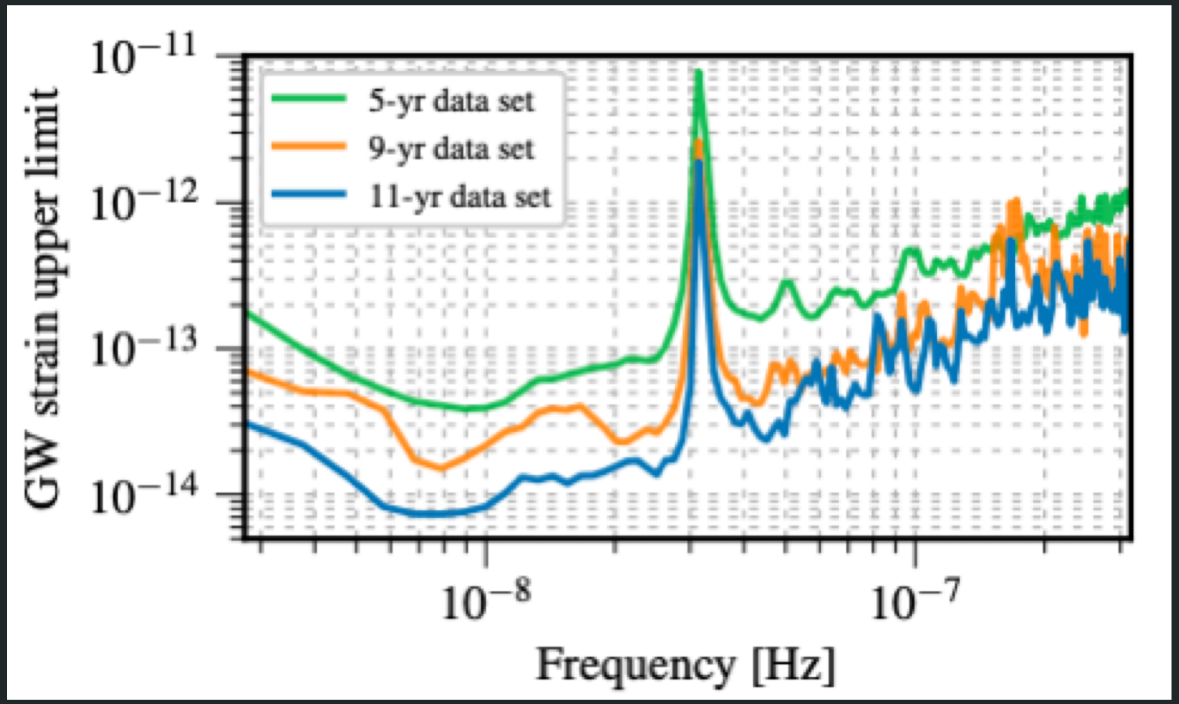
NANOGrav Current Status:
Upper Limit on Stochastic Gravitational Wave Background



(Arzoumanian et. al. 2018)

- Green, orange, and blue lines: predictions for the stochastic gravitational wave background.
- Black line: GWB-amplitude 95% upper limits for an uncorrelated common process
  - Solid: with γ = 13/3 power law
  - Dashed: with independently determined components.

NANOGrav Current Status:
Upper Limit on Continuous Wave Signals



(Aggarwal et. al. 2019)

Using CHIME for pulsar timing

Imagine you were designing a new instrument to improve the NANOGrav data set.

What data would you like to get from that instrument?

What isn’t well-covered by current NANOGrav data?

What other science could you explore at the same time?

Imagine you were designing a new instrument to improve the NANOGrav data set.

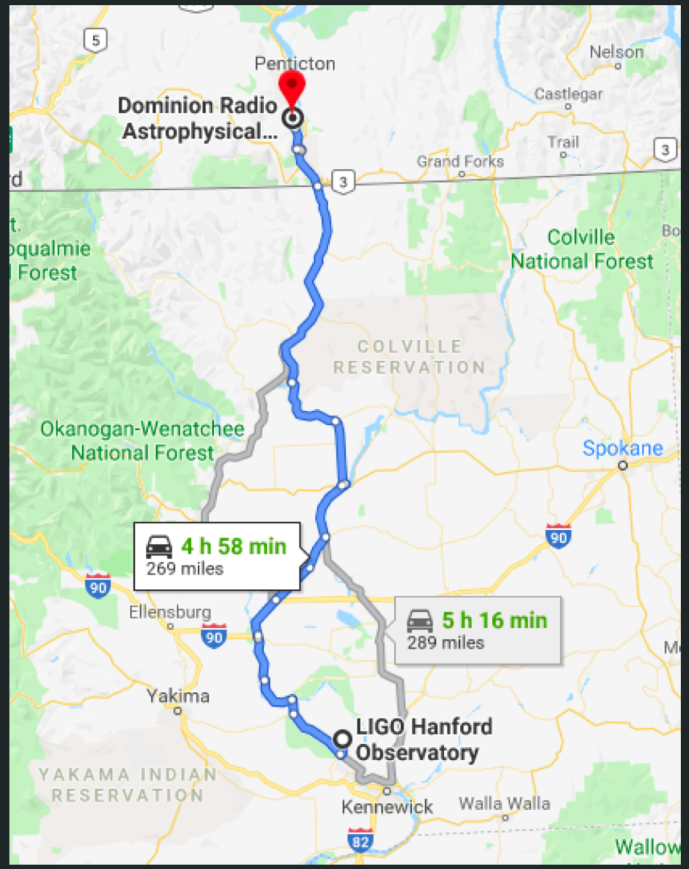
You would probably want...

- High cadence data with lots of TOAs
- At a frequency range where pulsar emission is bright
- But where you can learn new things you didn't know from other NANOGrav observations to improve that data
- While still being able to integrate new TOA measurements into the NANOGrav dataset.
- (And you might want to be able to do other science too!)

The Canadian Hydrogen Intensity Mapping Experiment (CHIME)

Originally designed to map redshifted neutral hydrogen to detect baryon acoustic oscillations and constrain dark energy, it now hosts several projects, including a pulsar timing project and a fast radio burst search.

CHIME is a radio transit telescope, with no moving parts, which observes 24/7.



What is CHIME?

Video Credit: Richard Shaw/CHIME Collaboration

Parameter	CHIME/FRB Value
Collecting Area	8000 m^2
Number of cylinders	4
Number of antennae	1024, each with 2 polarizations
Frequency Range	400-800 MHz
E-W FoV	2.5-1.3°
N-S FoV	~110°

How does CHIME meet NANOGrav's needs?

CHIME/Pulsar can:

- Observe (and time) every northern hemisphere NANOGrav pulsar every day
- Monitor for Dispersion Measure & scattering variations

Combined, this will result in up to factor of 2 timing improvement!

CHIME/Pulsar can observe NANOGrav pulsars daily

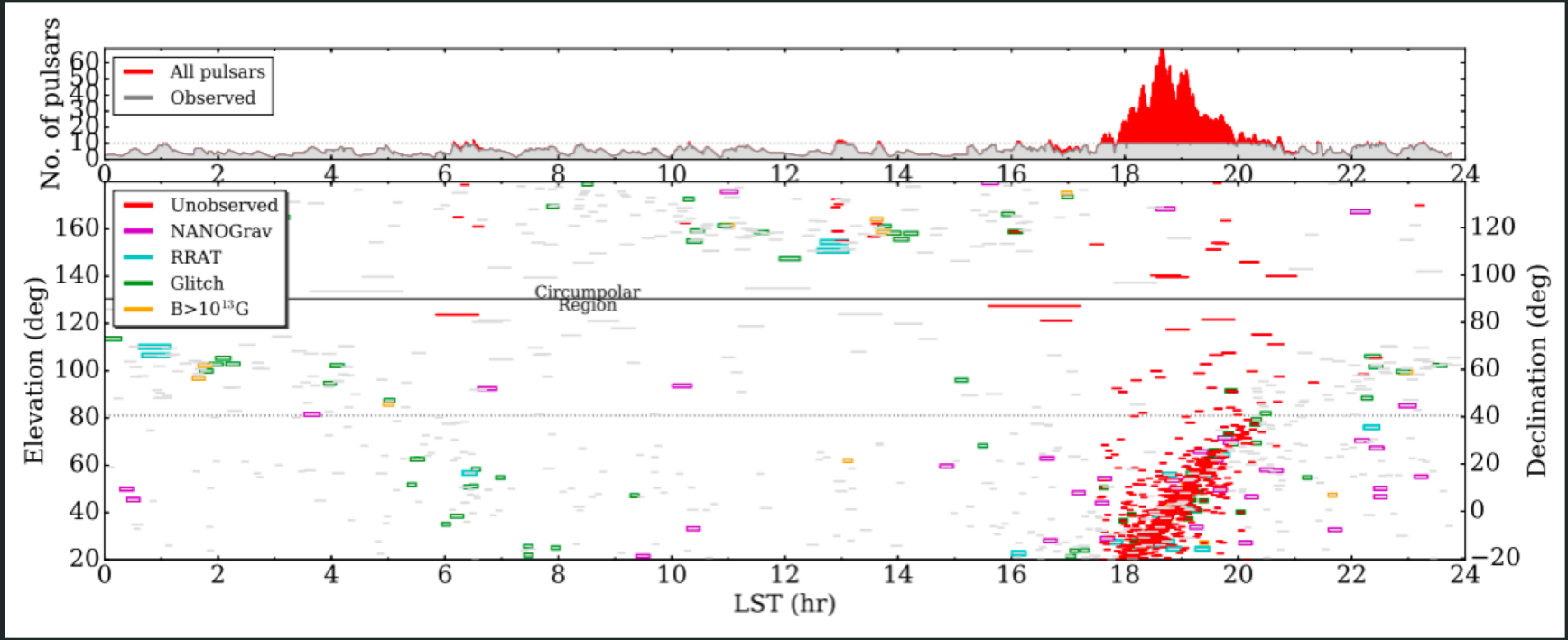


Image: Ng & CHIME/Pulsar Collaboration 2017

CHIME/Pulsar System Details

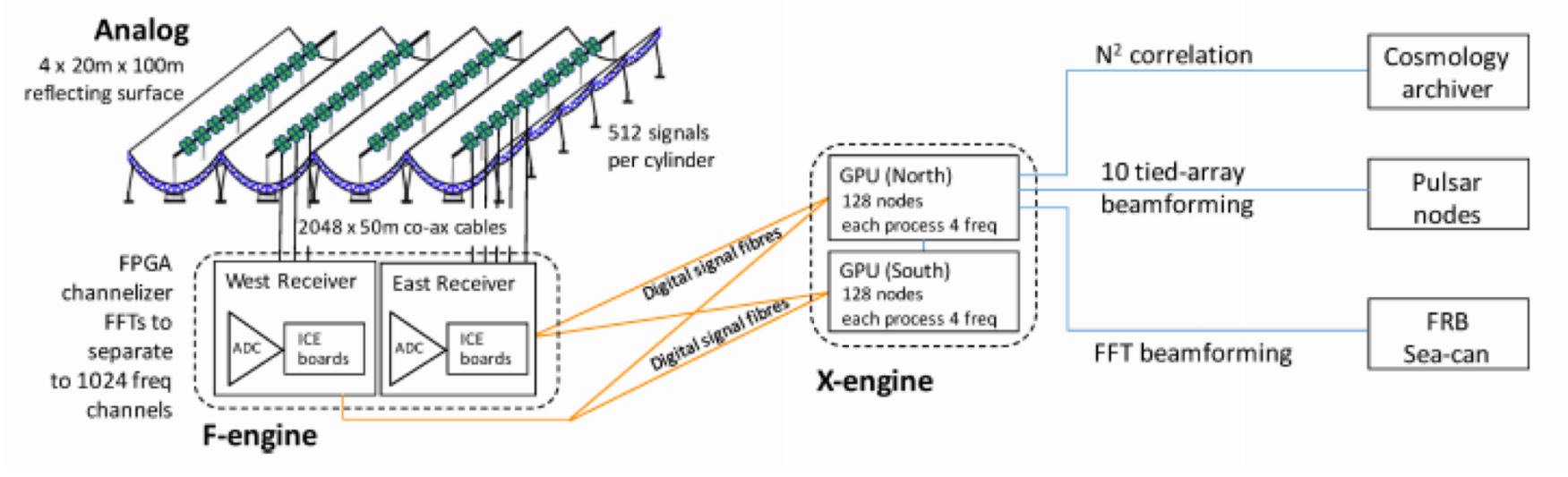


Image: Ng & CHIME/Pulsar Collaboration 2017

CHIME/Pulsar System Details

- In the X-Engine:
  - Form 10 tracking beams
- In 10 pulsar GPU nodes:
  - Data are scaled down, encoded into 4+4 complex numbers, and packetized in VDIF format.
  - Fold Mode: Data are coherently dedispersed with DSPSR
  - Filter-bank Mode: Data are processed using CHIME specific software capable of handling DM up to 2500 pc/cm^3.
- Scheduler & Monitoring
  - Automatic scheduler ensures pulsars are observed 24/7, prioritizing PTA pulsars.
  - Web monitoring tools to check on performance.

Parameter	CHIME Value
Number of Tracking Beams	10
Frequency Resolution	390 kHz
Spectral channels	1024
Output data bit depth	8 or 16 bits
Output polarization info	Full Stokes (fold mode) Total intensity (filter bank)
Pulsar data output rate	67 Mbps

CHIME/Pulsar System Performance

While we still have work to do, our observed signal to noise is increasingly lining up with our expected signal to noise.

Red points: Millisecond pulsars
Blue Points: Pulsars with declination <0 deg
Black Points: All other pulsars

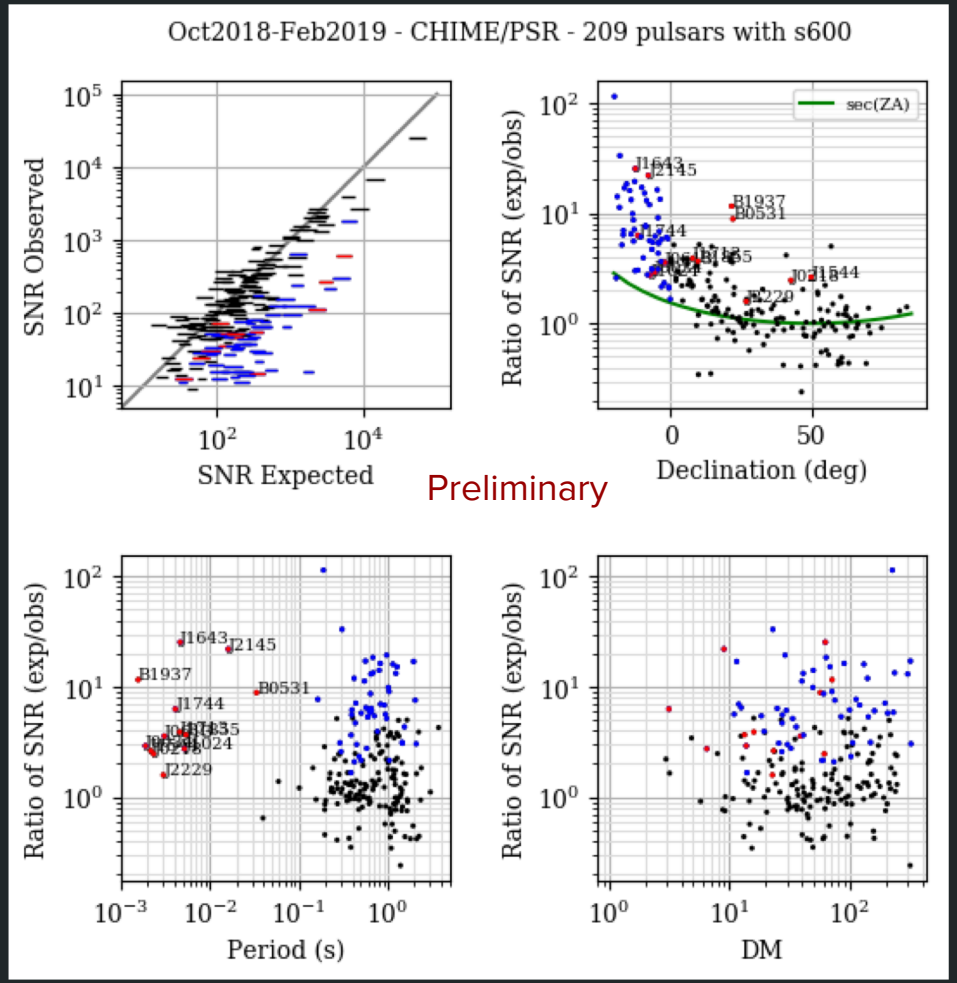
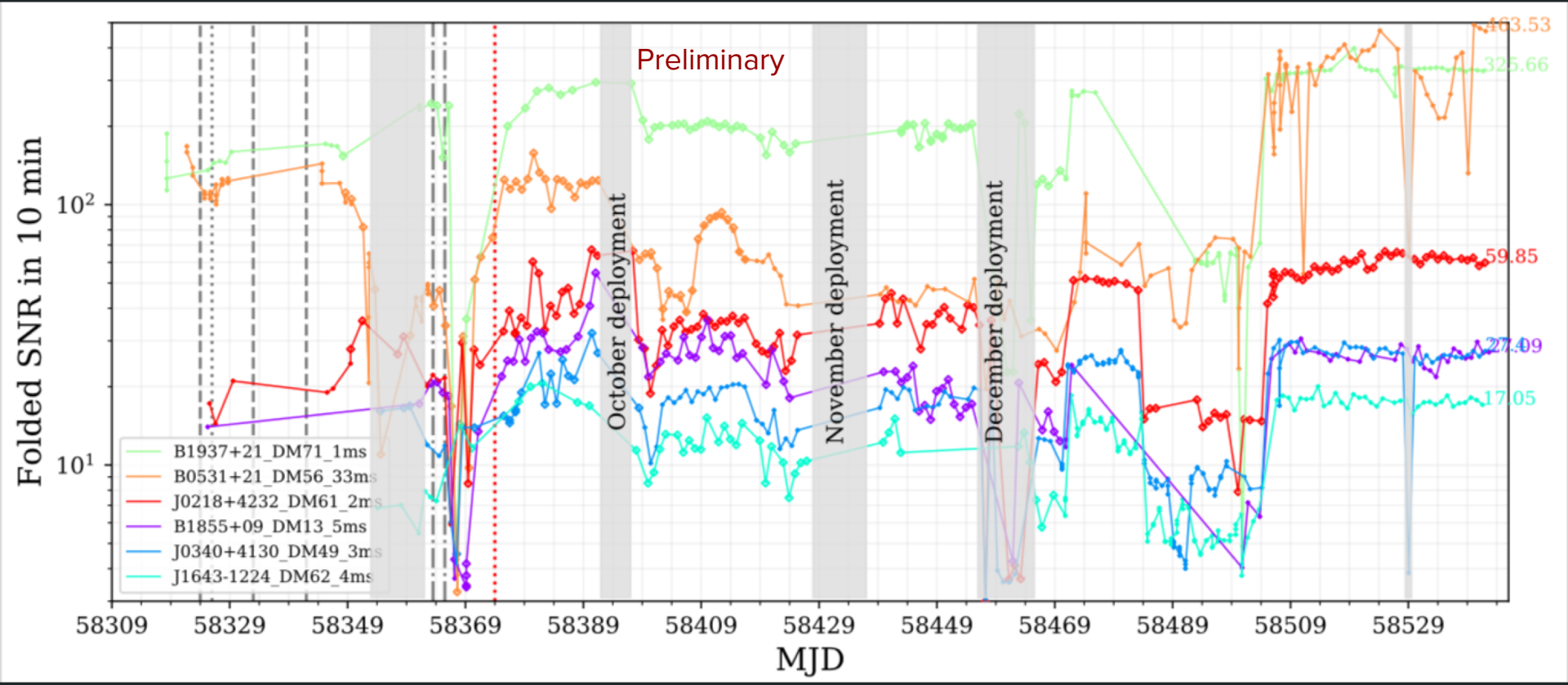


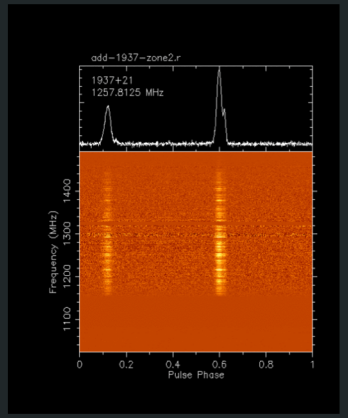
Image credit: Cherry Ng

CHIME/Pulsar System Performance

Image credit: Cherry Ng



Recent results:
Successful measurements of NANOGrav pulsars



Max Planck Institute for Radio Astronomy

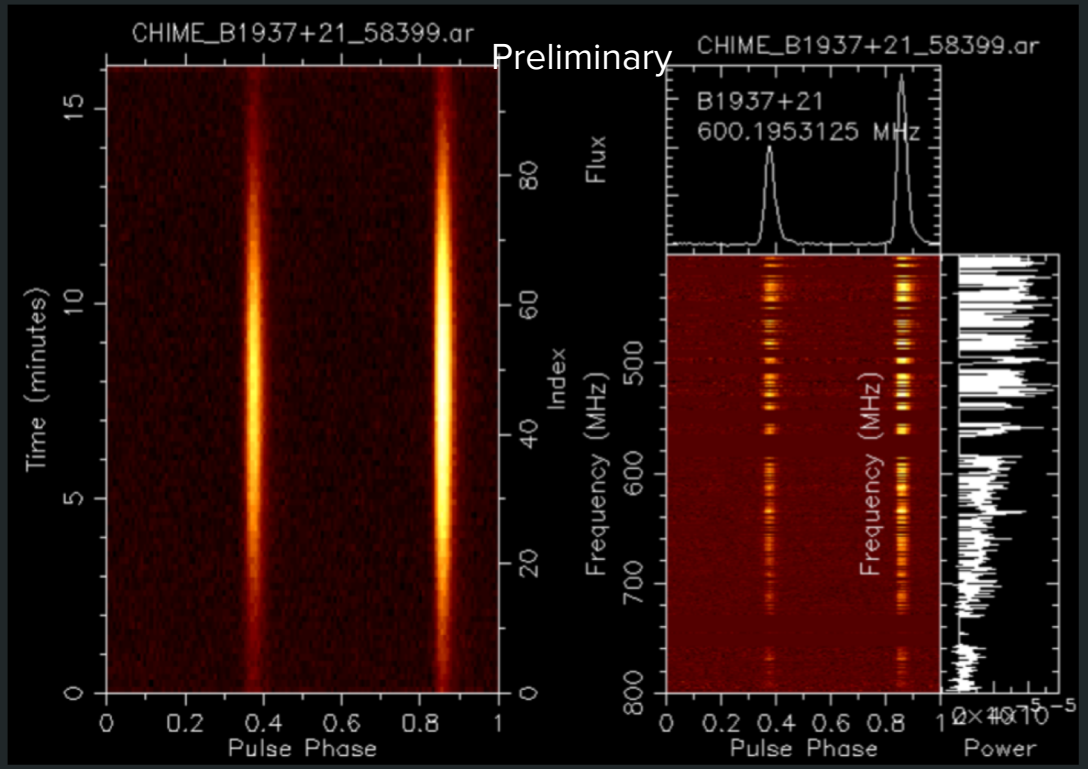
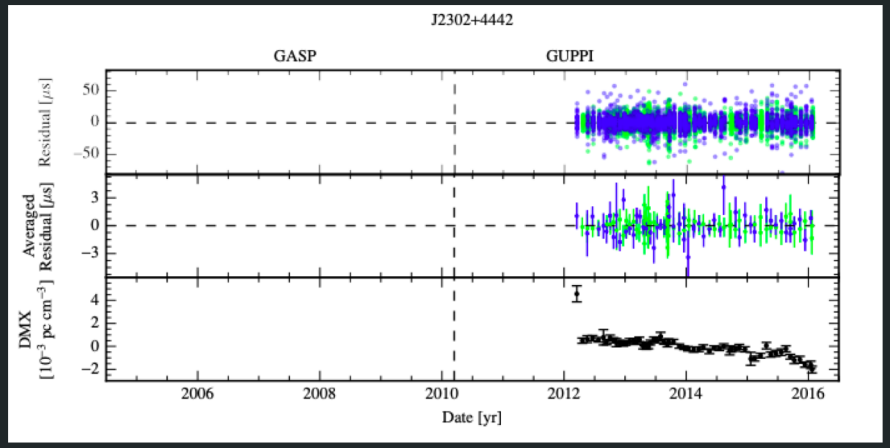


Image credit: Emmanuel Fonseca

Recent Results from CHIME: Early timing residuals

Left: NANOGrav 11 year release (Arzoumanian et. al. 2018).
Right: CHIME/Pulsar preliminary timing



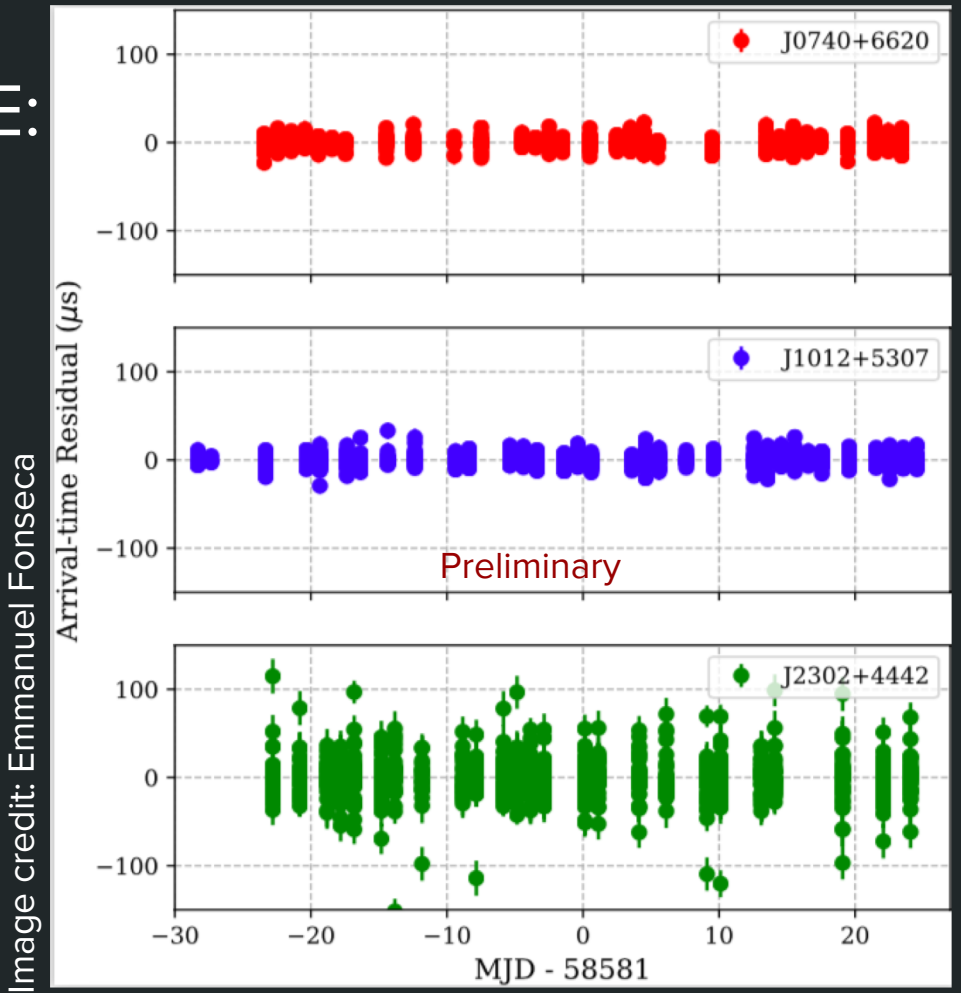
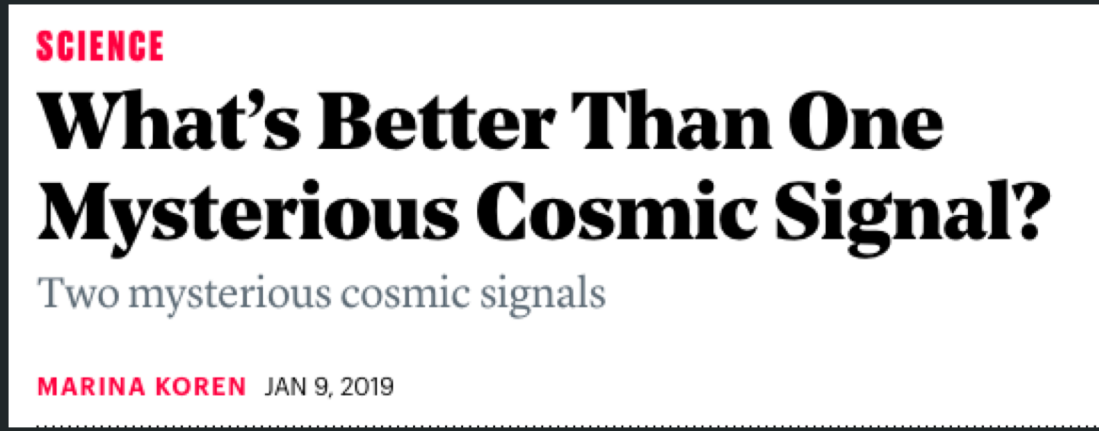


Image credit: Emmanuel Fonseca

Science with CHIME/Pulsar: beyond NANOGrav

- Discovering new (slow, not milli-second) pulsars
- Discovering new Rotating Radio Transients (RRATs)
- Monitoring known RRATs and pulsars with interesting time domain structure
  - Mode Changing
  - Nulling
- Monitoring ISM Weather
- Repeating FRB follow-up



SCIENCE

What's Better Than One Mysterious Cosmic Signal?

Two mysterious cosmic signals

MARINA KOREN JAN 9, 2019

Conclusions

- Searching for gravitational waves with pulsar timing provides a handle on a different portion of the gravitational wave spectrum than that studied by LIGO (or LISA).
- NANOGrav continues to set upper limits on the stochastic gravitational wave background, which are beginning to rule out models. 12.5 year dataset coming soon!
- CHIME/Pulsar is an exciting new instrument which will help improve our NANOGrav dataset by as much as a factor of 2.