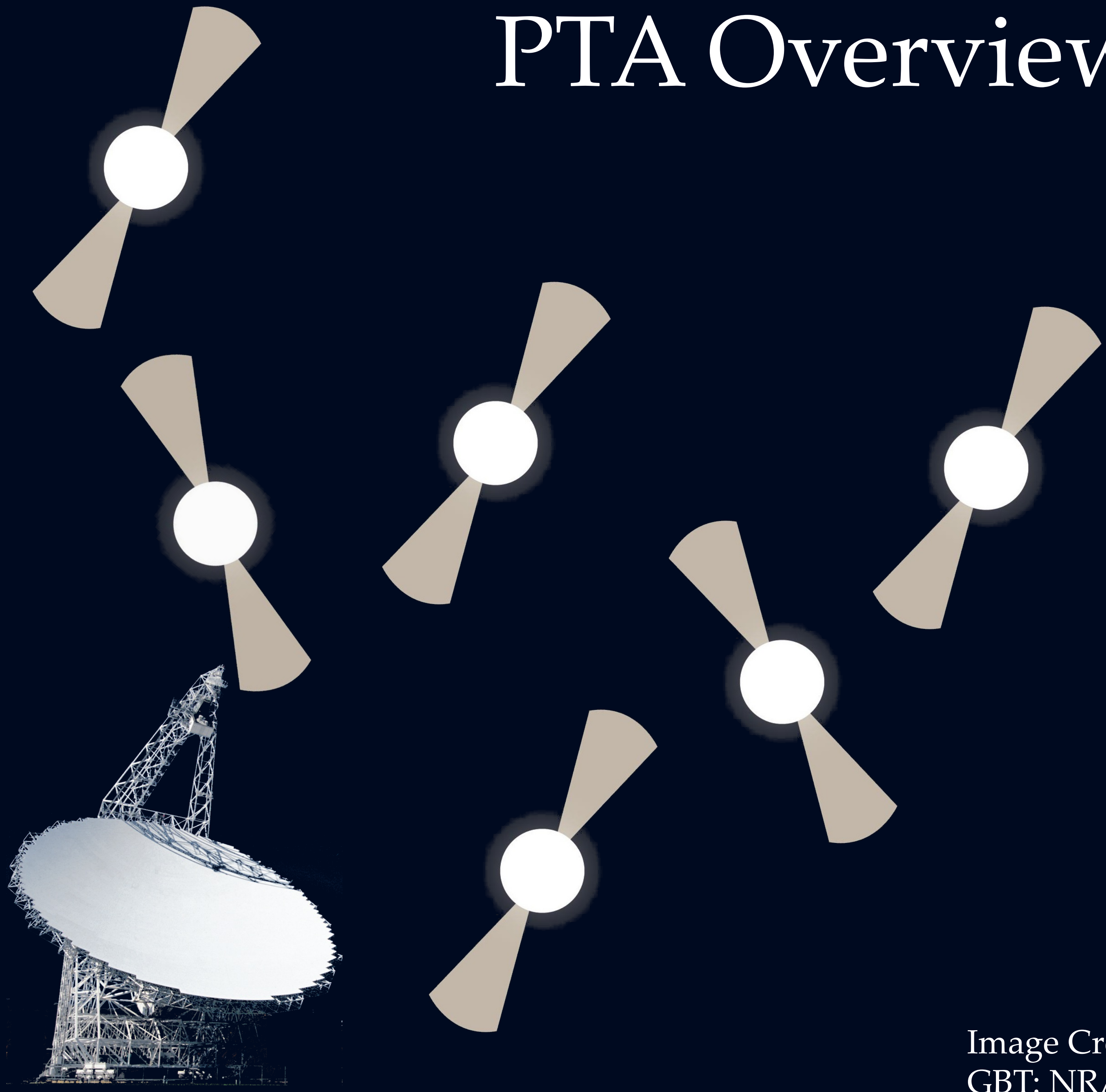
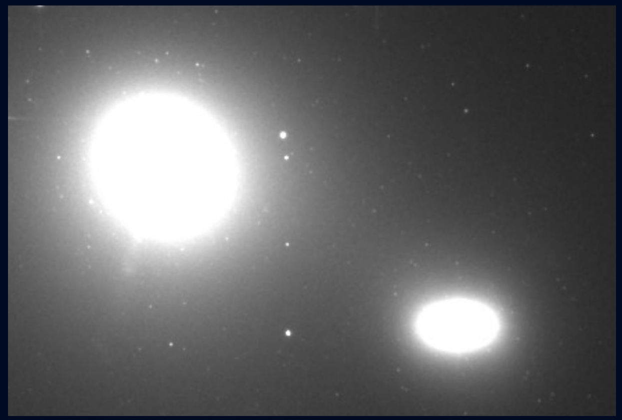
PTA Overview

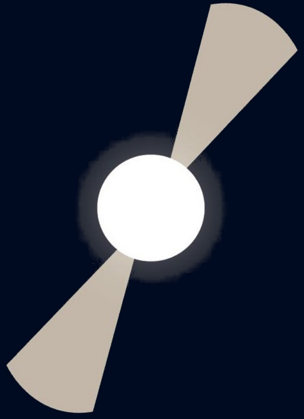


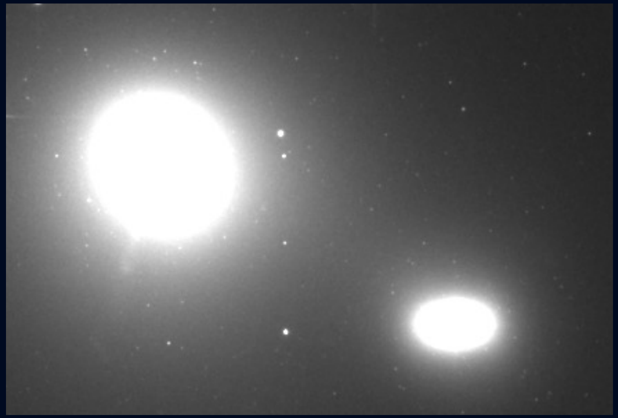


Deborah Good
GWANW

Image Credits:
GBT: NRAO, Pulsar schematic: NASA, 3C66B: Hubble Observation

Building a Galactic Scale Gravitational Wave Detector





Deborah Good
GWANW

Image Credits:
GBT: NRAO, Pulsar schematic: NASA, 3C66B: Hubble Observation

The full spectrum of gravitational waves

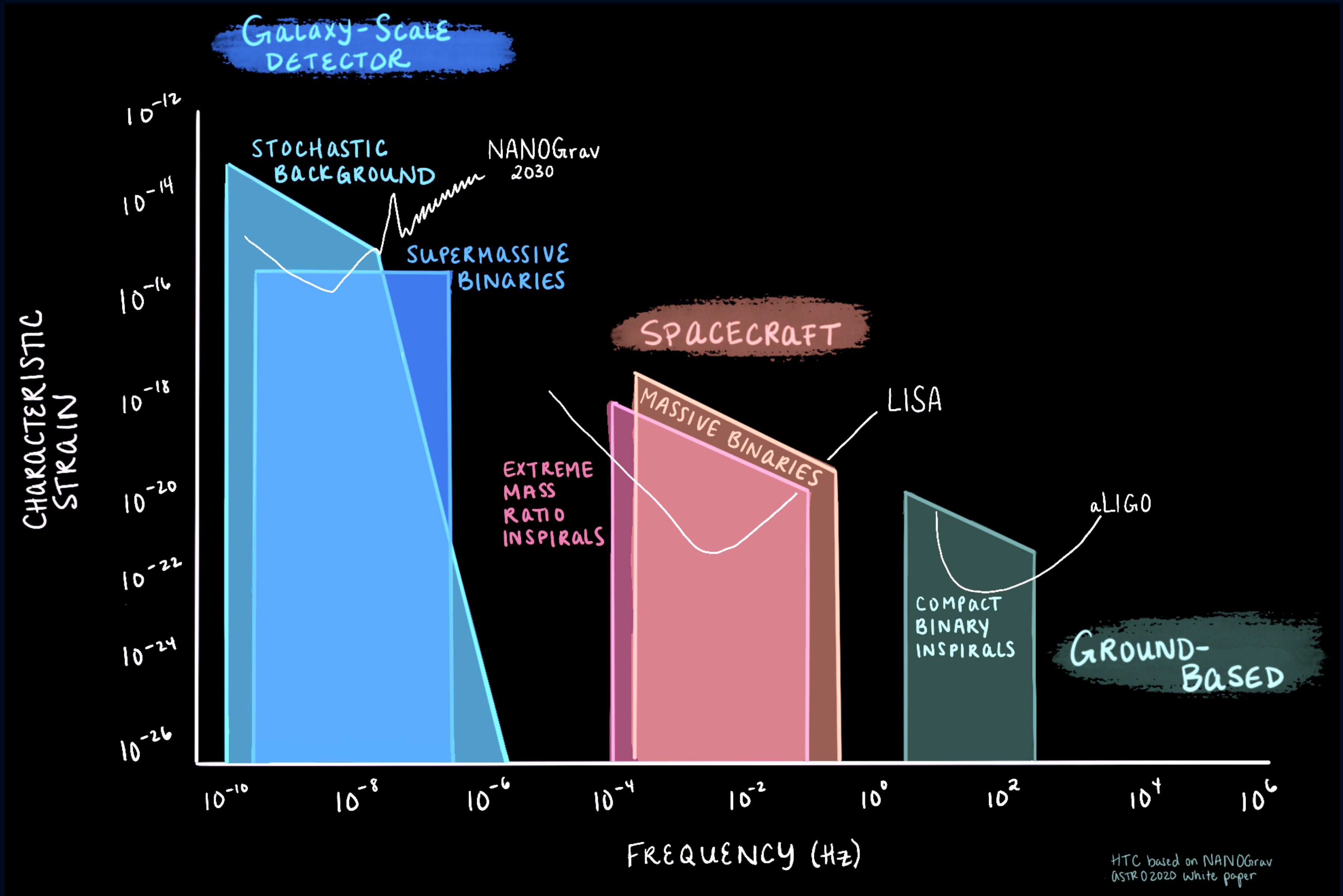


Image Credit: H. Thankful Cromartie

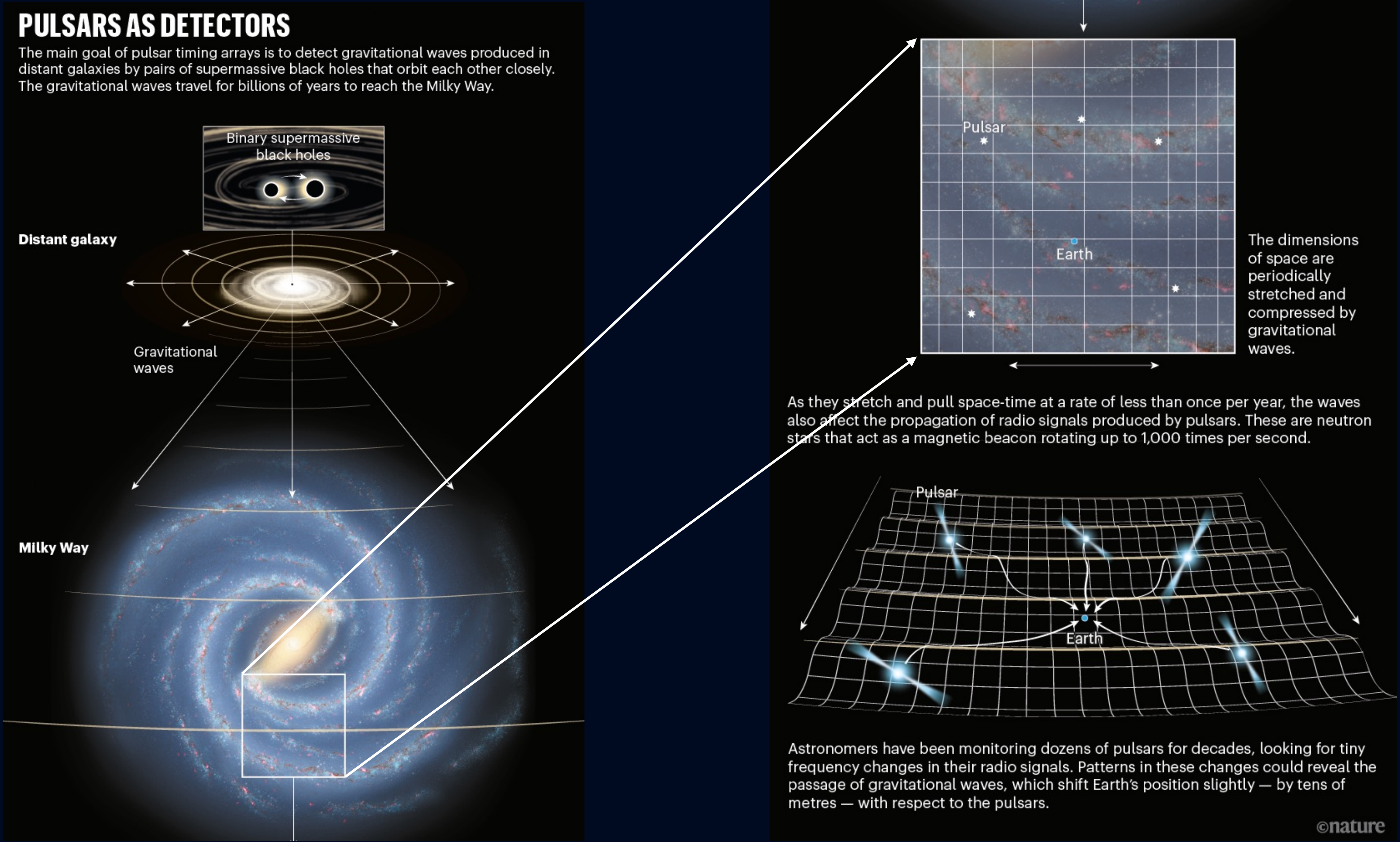


Image Credit: Nik Spencer/*Nature*; Milky way: NASA/JPL-Caltech/R. Hurt (SSC/Caltech)

Pulsars

The neutron star…aka the zombie star

Optical: NASA/HST/ASU/J. Hester et al.
X-Ray: NASA/CXC/ASU/J. Hester et al.

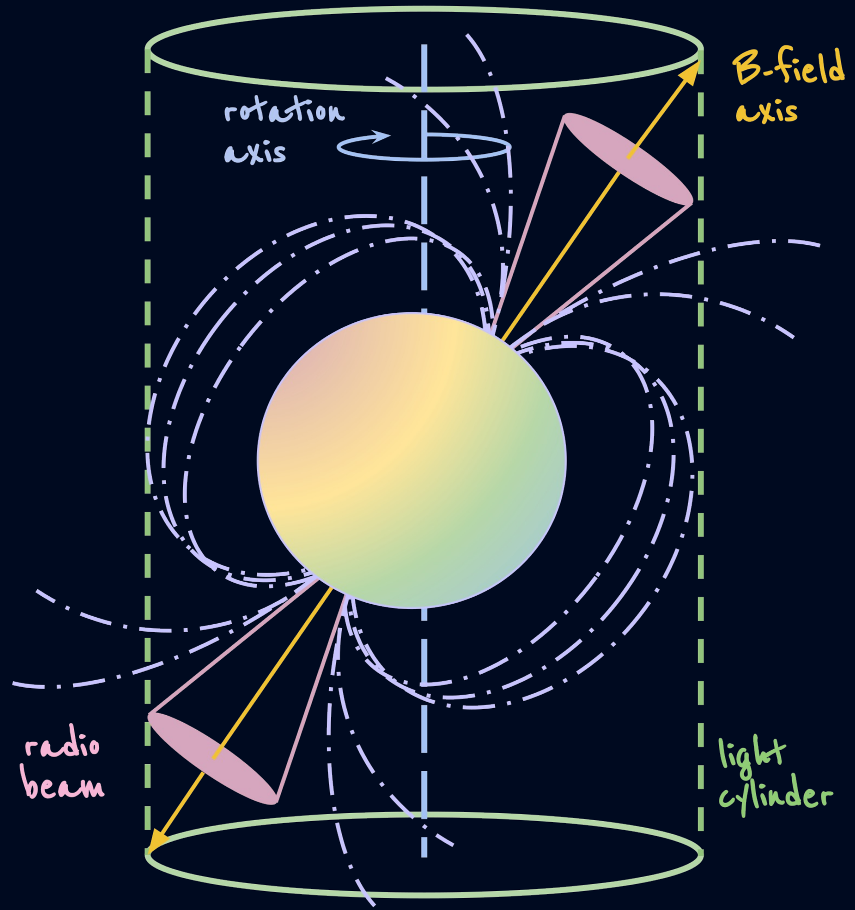
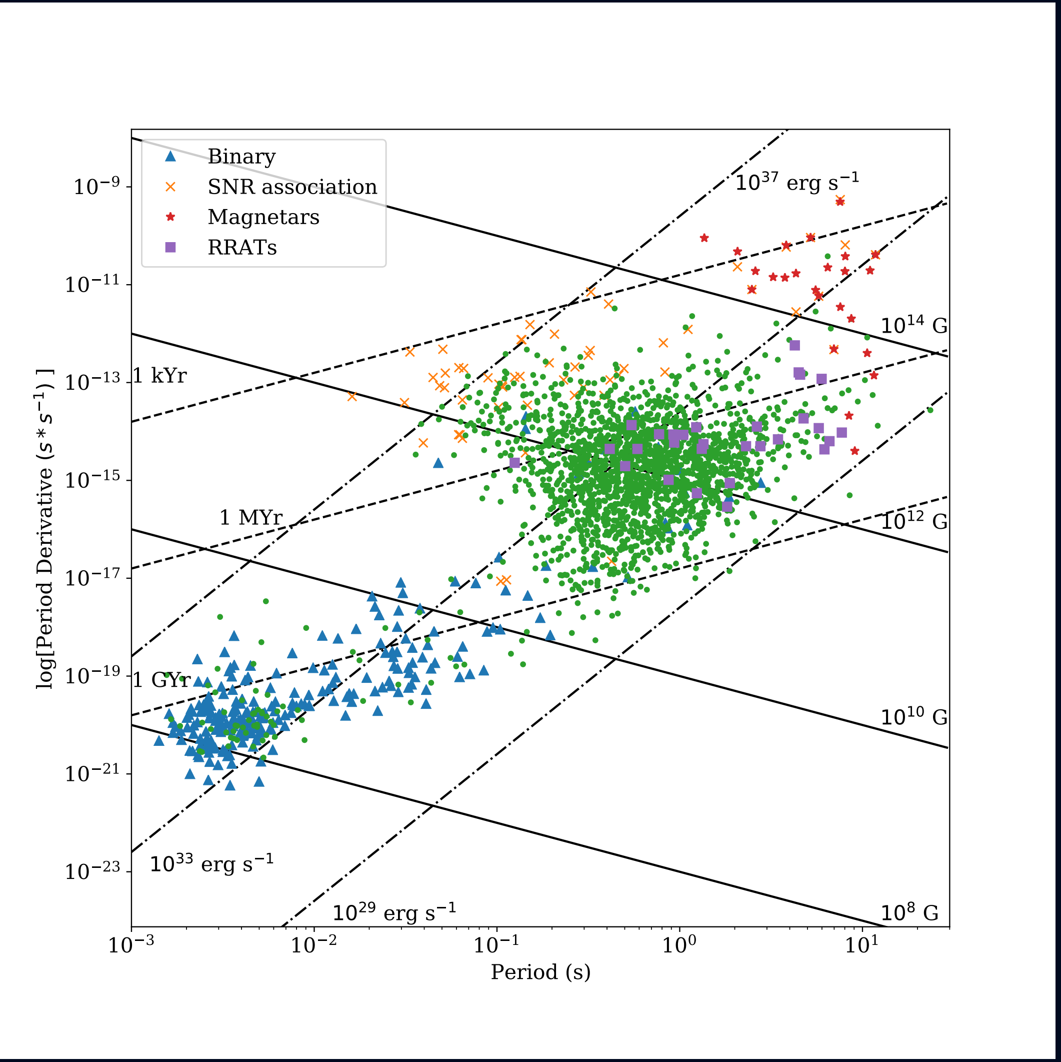


Image credit: H. Thankful Cromartie

The Pulsar: Key facts



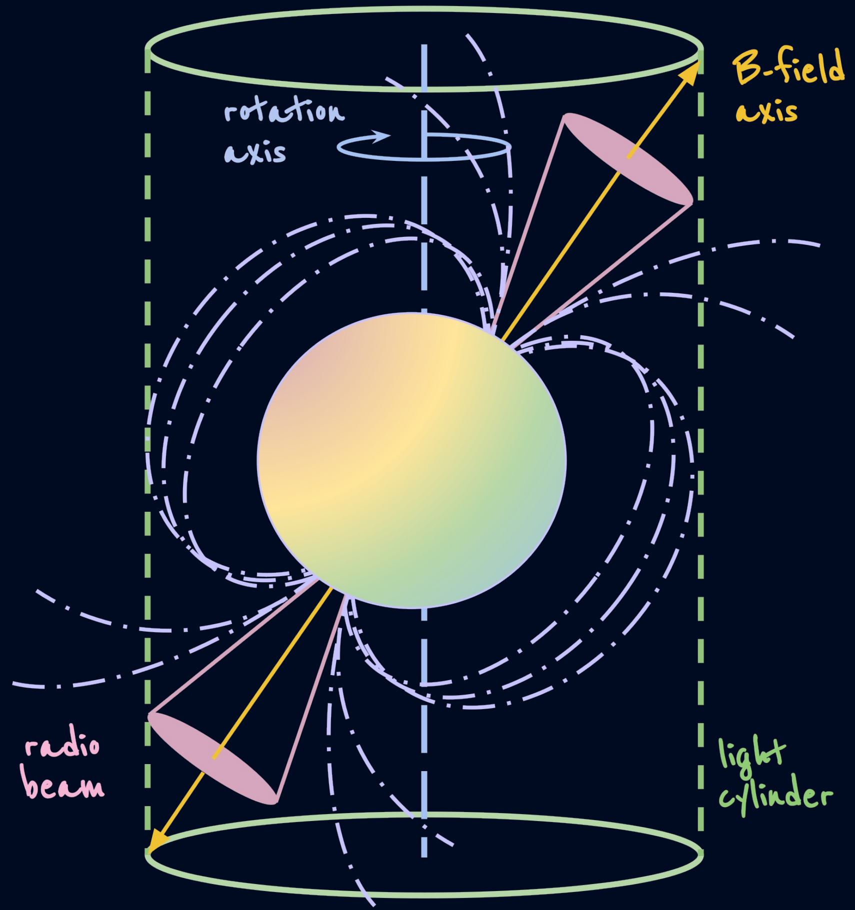


Image credit: H. Thankful Cromartie

Pulsar Timing

Pulsar Timing

What do we see when we observe a pulsar?

How do we observe pulsars?

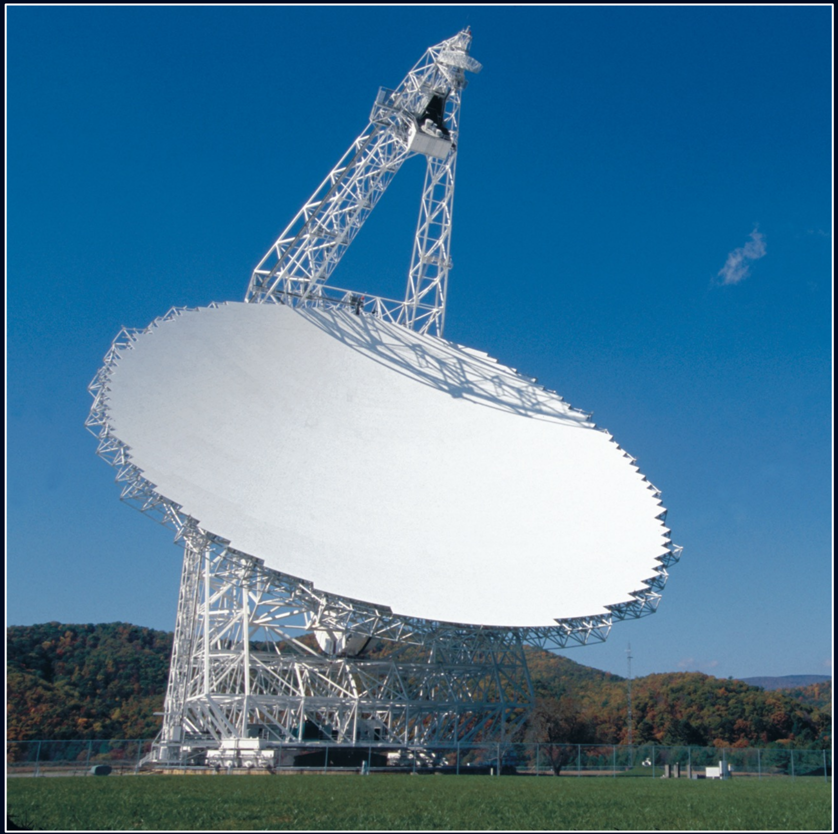
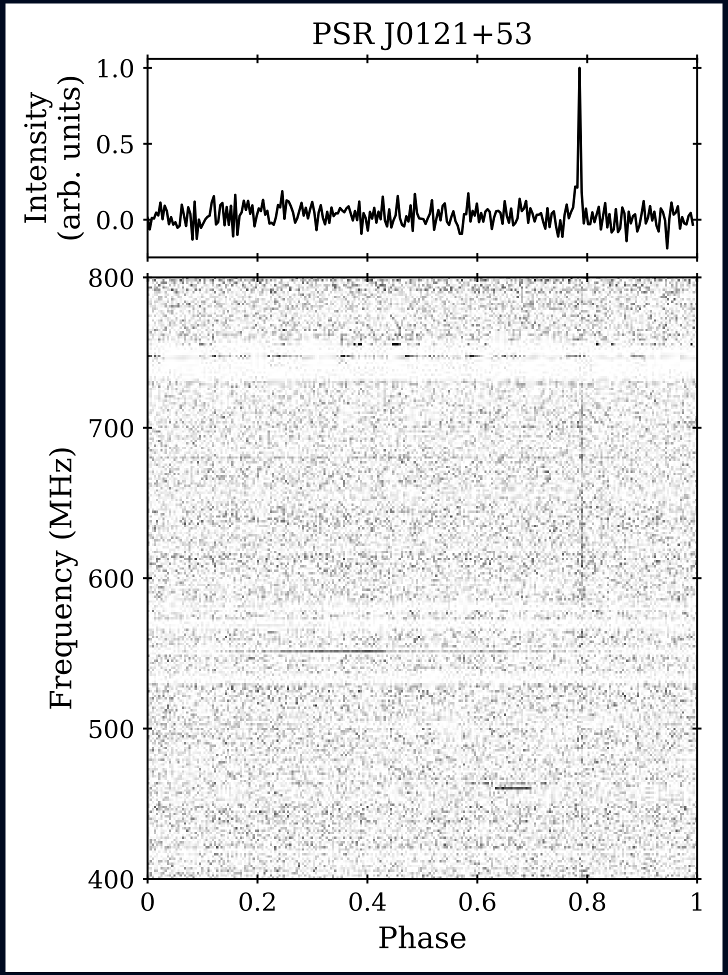


Photo credits:
NRAO, CHIME Collaboration, Arecibo Observatory/University of Central Florida, NRAO

What do we see when we observe a pulsar?

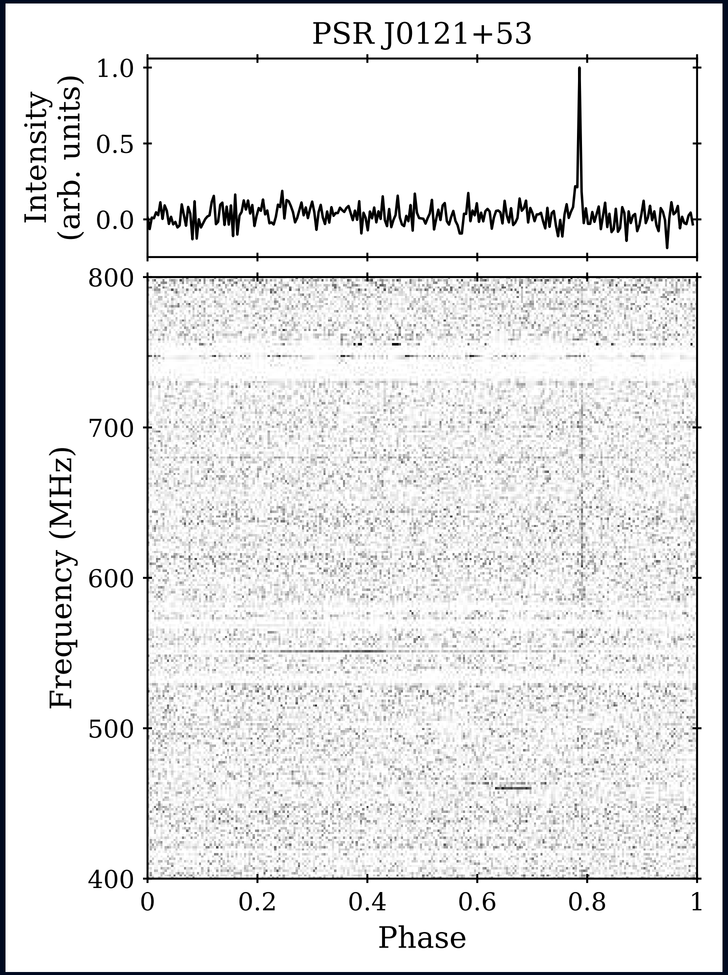
(Good et al. 2021)



1. Pulse profile
2. Time of arrival (when did we see the pulse?)

Single pulse profile, J0121+53 from Good et al. 2021.

What do we see when we observe a pulsar?



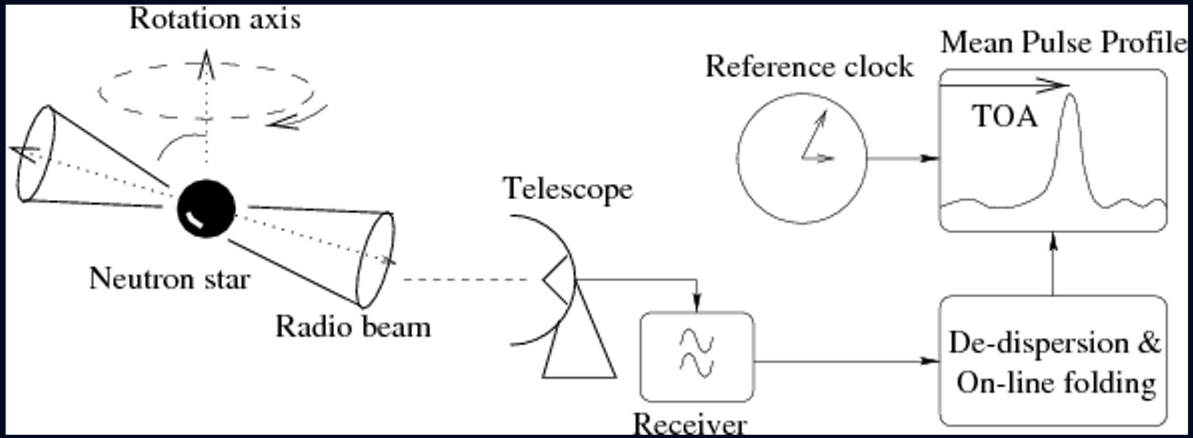
(Good et al. 2021)

But most pulsars are too dim for single pulse observations.

So we "fold" the data and find a single TOA for the observation duration.

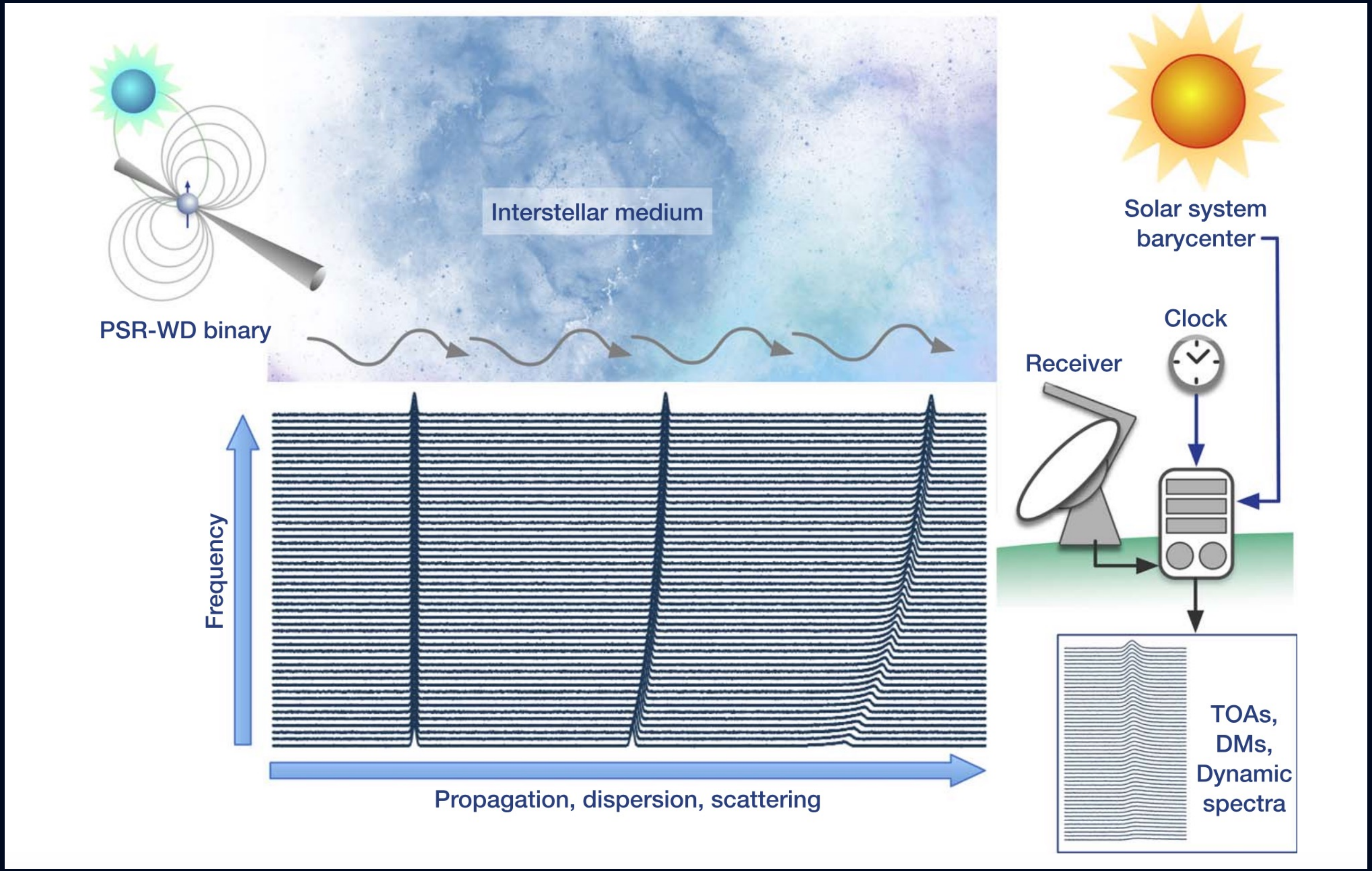
A (simplified) pulsar timing procedure

- Observe a pulsar for a long period of time.
- 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.



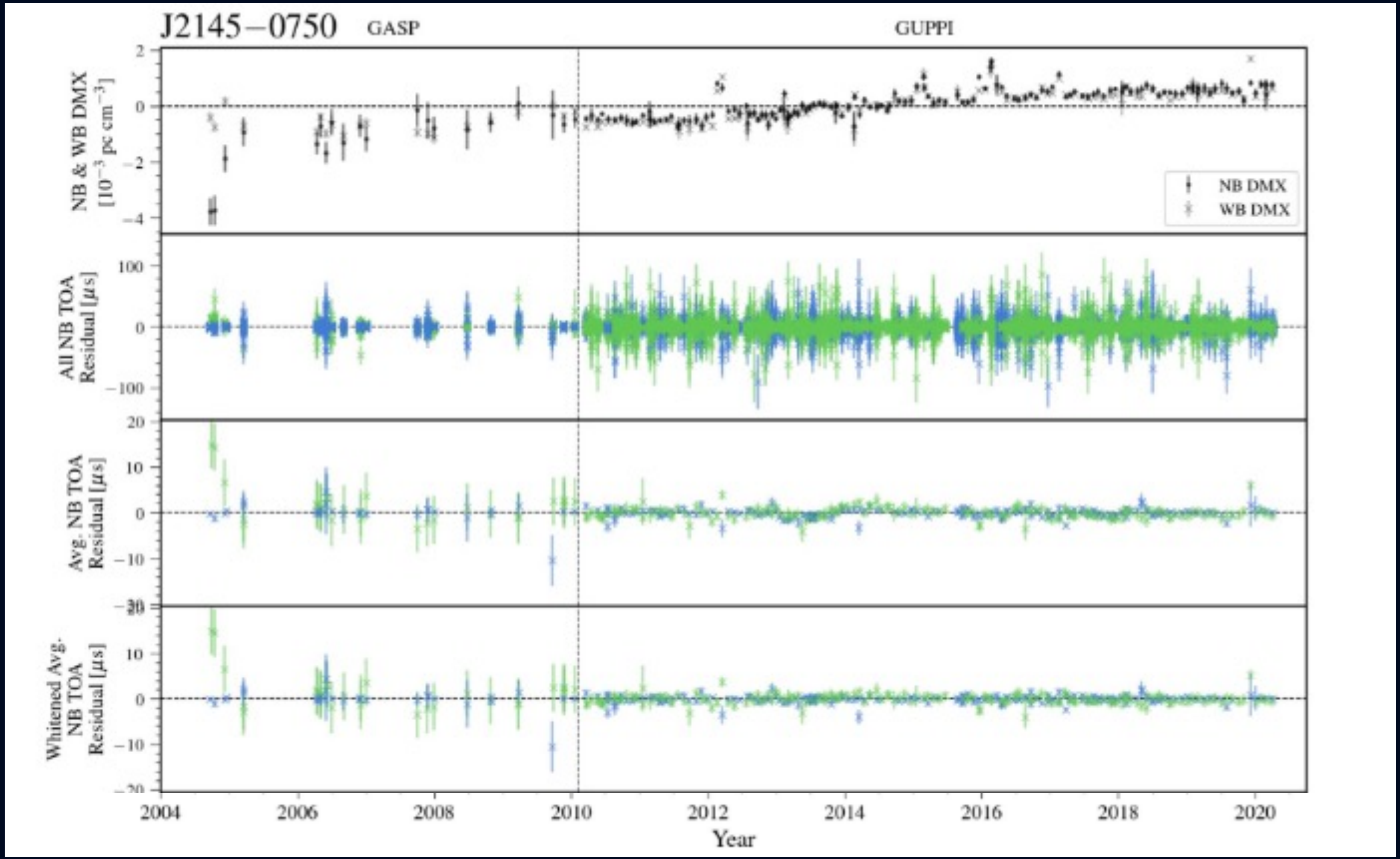
Lorimer & Kramer 2005

What do we see when we time pulsars?



- Spin Parameters
- Binary Parameters
- Astrometric Parameters
- ISM/dispersion model
- …Other

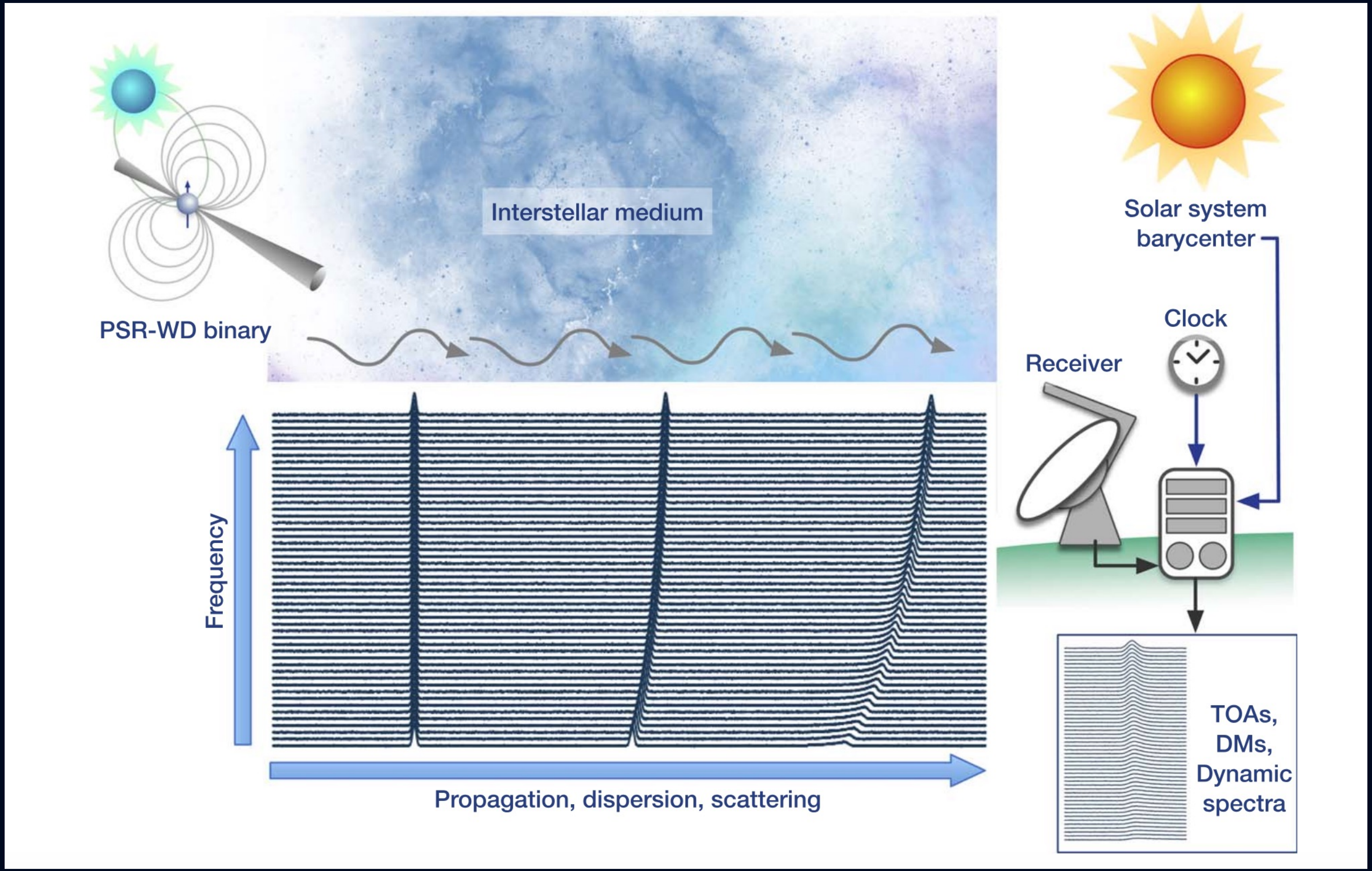
What do we see when we time pulsars?



(Agazie et al. including D. Good 2023)

The NANOGrav 15 yr Data Set: Observations and Timing of 68 Millisecond Pulsars

What do we see when we time pulsars?



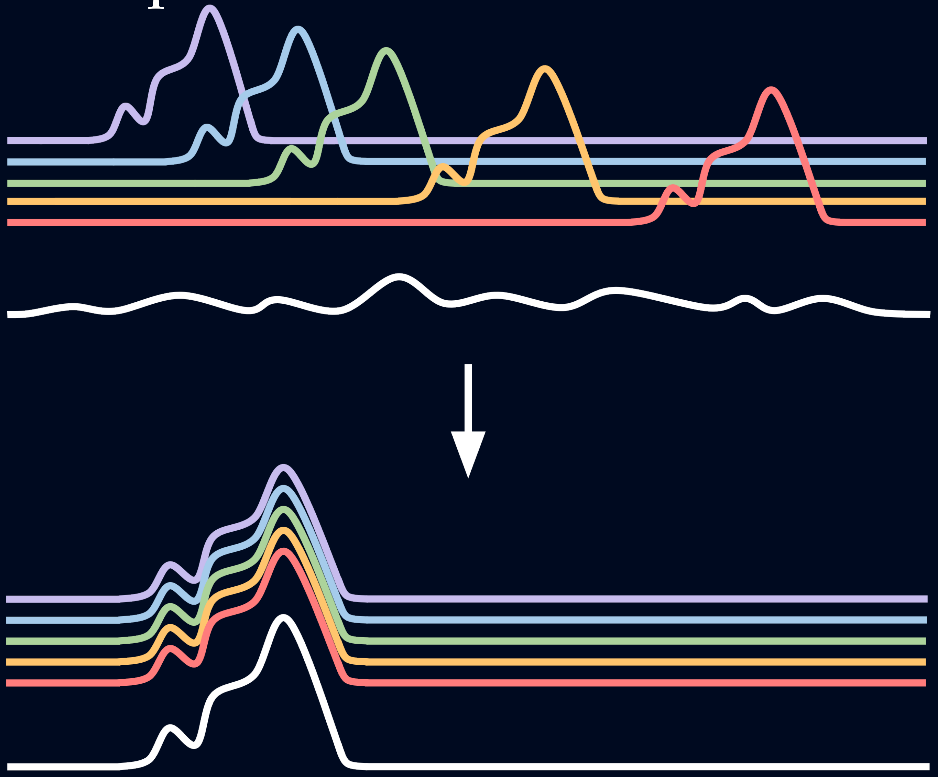
- Spin Parameters
- Binary Parameters
- Astrometric Parameters
- **ISM/dispersion model**
- **…Other**

Single Pulsar Noise Analysis

What per pulsar behavior is our timing model missing?

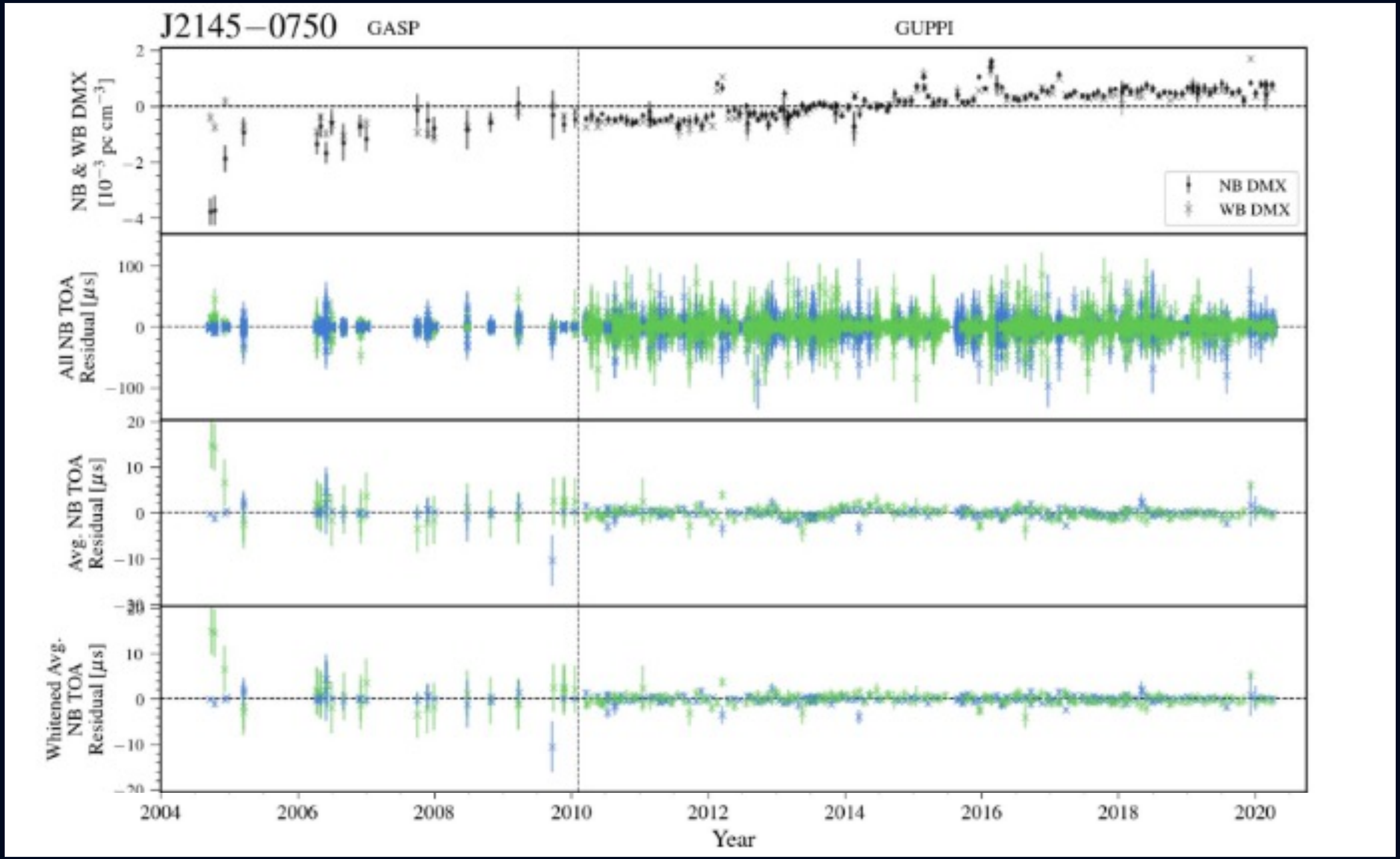
What per pulsar behavior is our timing model missing?

- Interstellar Medium Effects
  - Dispersion Measure
  - Dispersion Measure Variation



The NANOGrav 15 yr Data Set: Detector Characterization and Noise Budget, Agazie et al. 2023

DM variations



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What per pulsar behavior is our timing model missing?

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- "Pulsars are Like That" Effects
  - Jitter
  - Spin noise & glitches
  - Pulse profile shape changes
  - Binary orbit irregularities

The NANOGrav 15 yr Data Set: Detector Characterization and Noise Budget, Agazie et al. 2023

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- “Pulsars are Like That” Effects
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  - Spin noise & glitches
  - Pulse profile shape changes
  - Binary orbit irregularities
- Telescope Effects

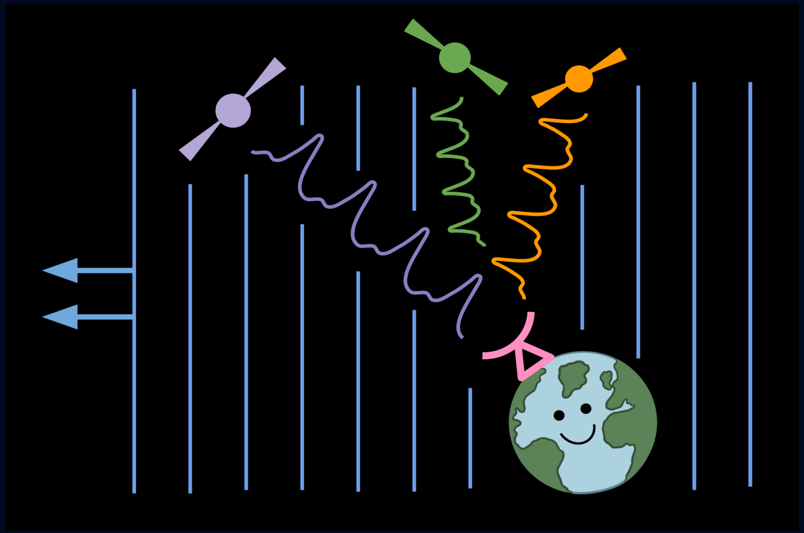
The NANOGrav 15 yr Data Set: Detector Characterization and Noise Budget, Agazie et al. 2023

Addressing Noise Processes

- Dispersion Measure Variations: DMX (or DMGP for IPTA)
- White noise parameters
  - EQUAD: Added in QUADrature to TOA uncertainty
  - EFAC: An additional FACtor in TOA uncertainty
  - ECORR: An additional component CORRelated within a single observation
- Single pulsar red noise (amplitude & spectral index)

How do we detect gravitational waves with pulsar timing arrays?

How do we search for gravitational waves with PTAs?



Credit: H. Thankful Cromartie

Observe a bunch of pulsars for a long time with excellent timing precision.

How many pulsars and how long a time?

$$p \propto N_{psrs}\sqrt{T_{obs}}$$

Look for gravitational wave signals in our timing residuals.

What will a gravitational wave signal look like in PTA data?

1. A common spectrum red noise process
2. With a spatial/angular correlation predicted by Hellings & Downs (1983).

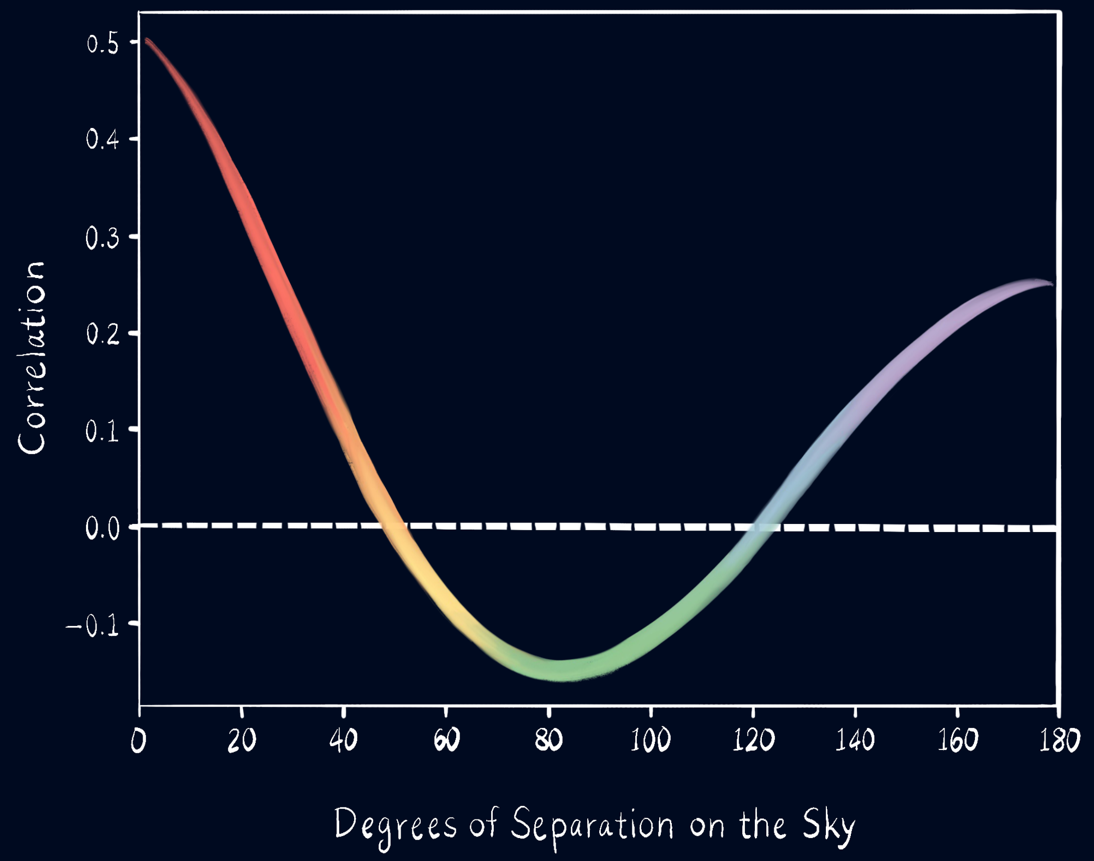
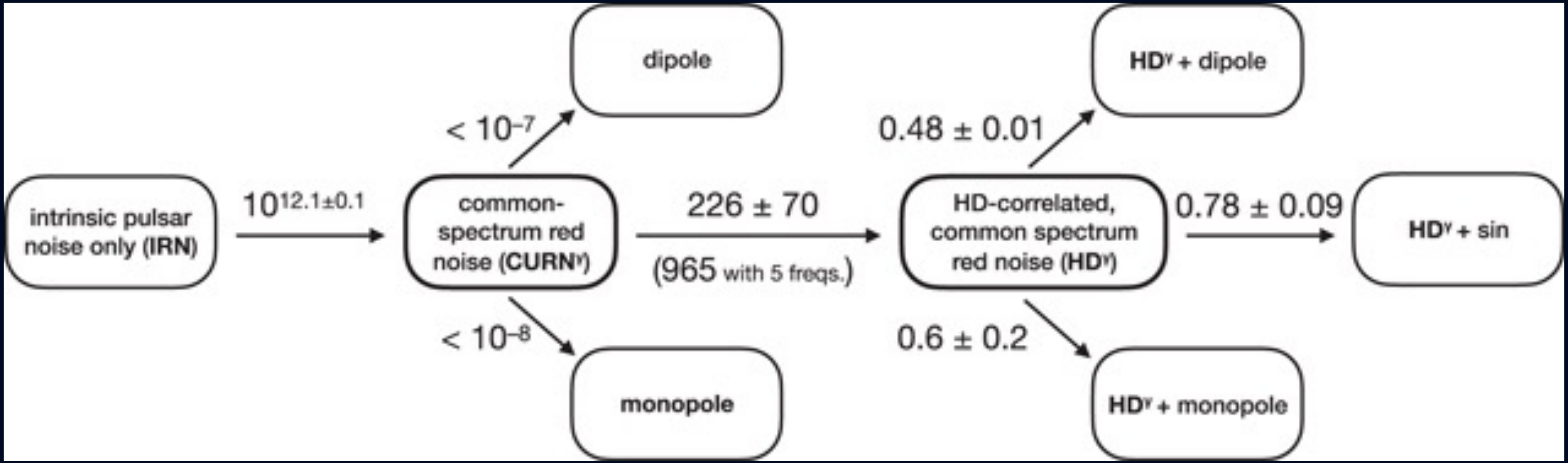
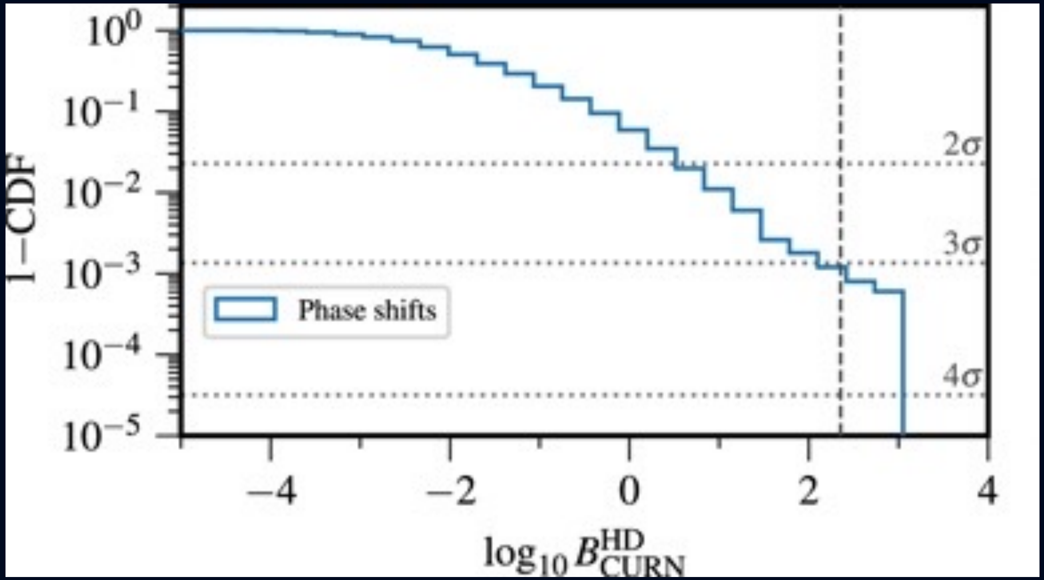


Image credit: H. Thankful Cromartie

Has NANOGrav seen gravitational waves?

Probably yeah





Top: Bayes factors for possible models.

Bottom: Interpreting these Bayes factors as "sigma"

Image credit: Agazie et al. 2023

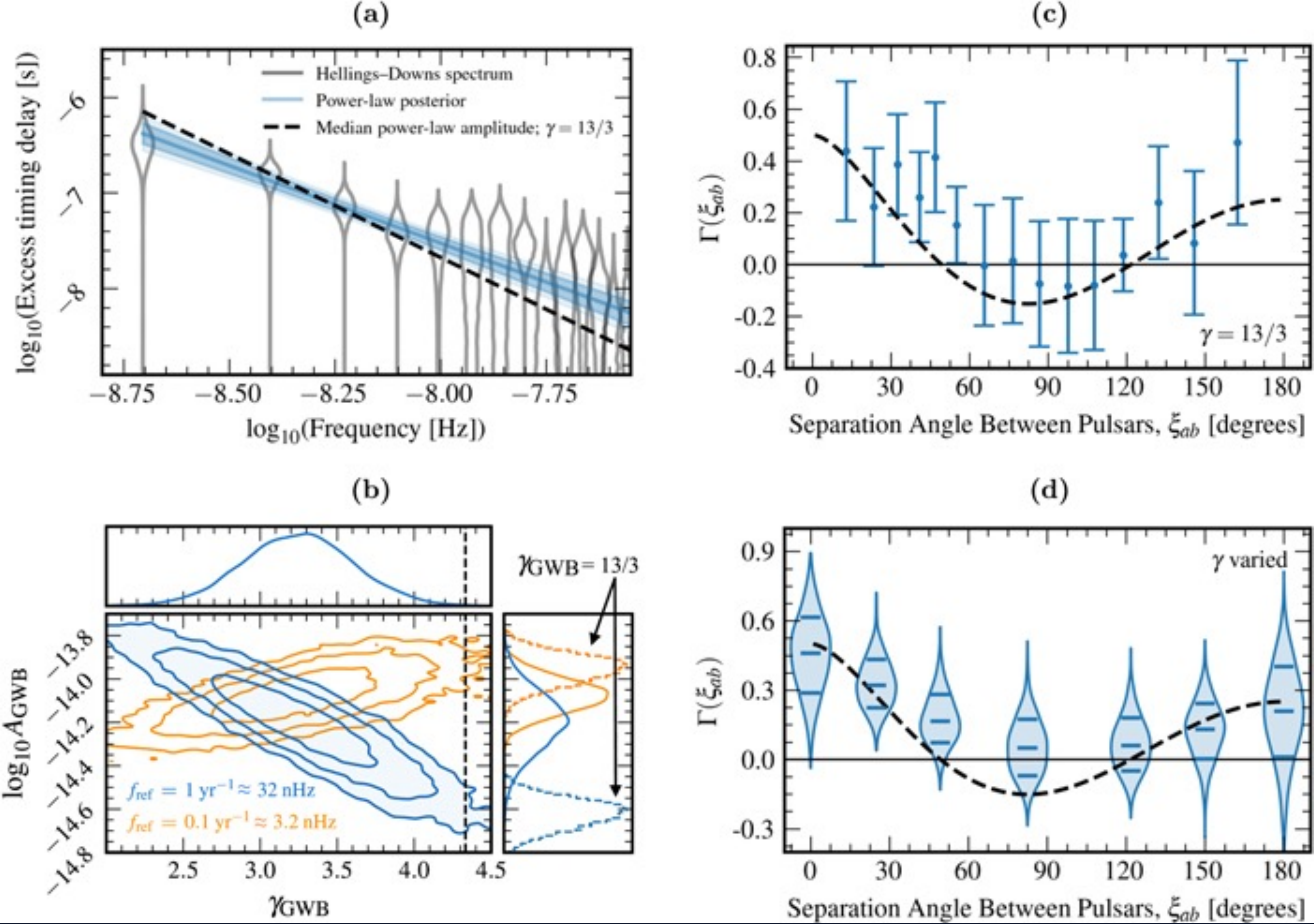
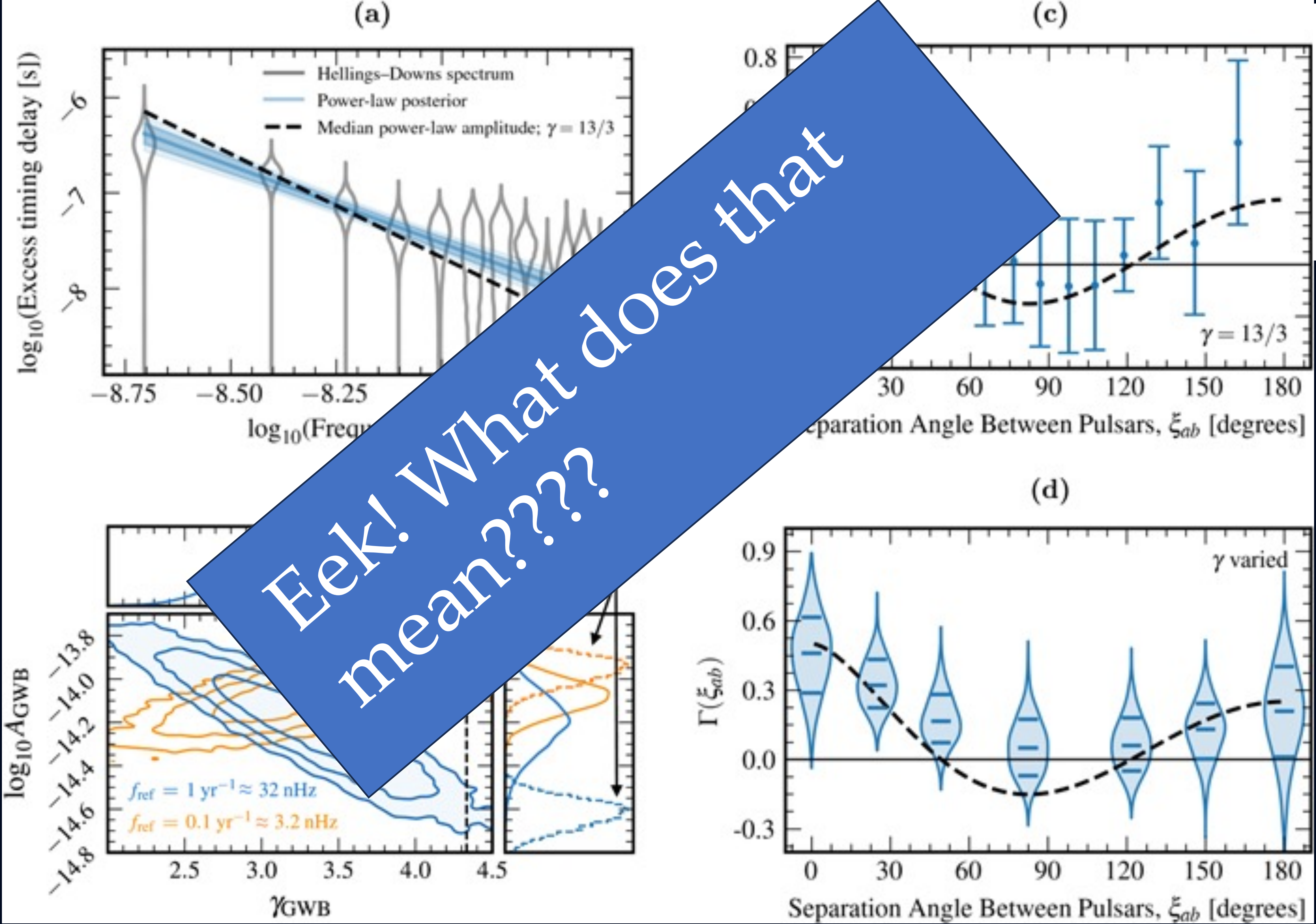


Image Credit: Agazie et al. 2023

The NANOGrav 15 yr Data Set: Evidence for a Gravitational-wave Background
Agazie et al. 2023

Image Credit: Agazie et al. 2023



The NANOGrav 15 yr Data Set: Evidence for a Gravitational-wave Background Agazie et al. 2023

Key Takeaways

- NANOGrav (and other PTAs) see "strong evidence for" a stochastic gravitational wave background
- Our "null hypothesis" model is that this is created by a cosmic history of supermassive binary black hole mergers.
- Our measured GW amplitude is a little high, which could mean…
  - Not just black holes
  - There's something we don't understand about black holes
  - Nothing – data fluke.

The NANOGrav 15-year Data Set: Constraints on Supermassive Black Hole Binaries from the Gravitational Wave Background

Additional Slides

The life cycle of a mid-size star

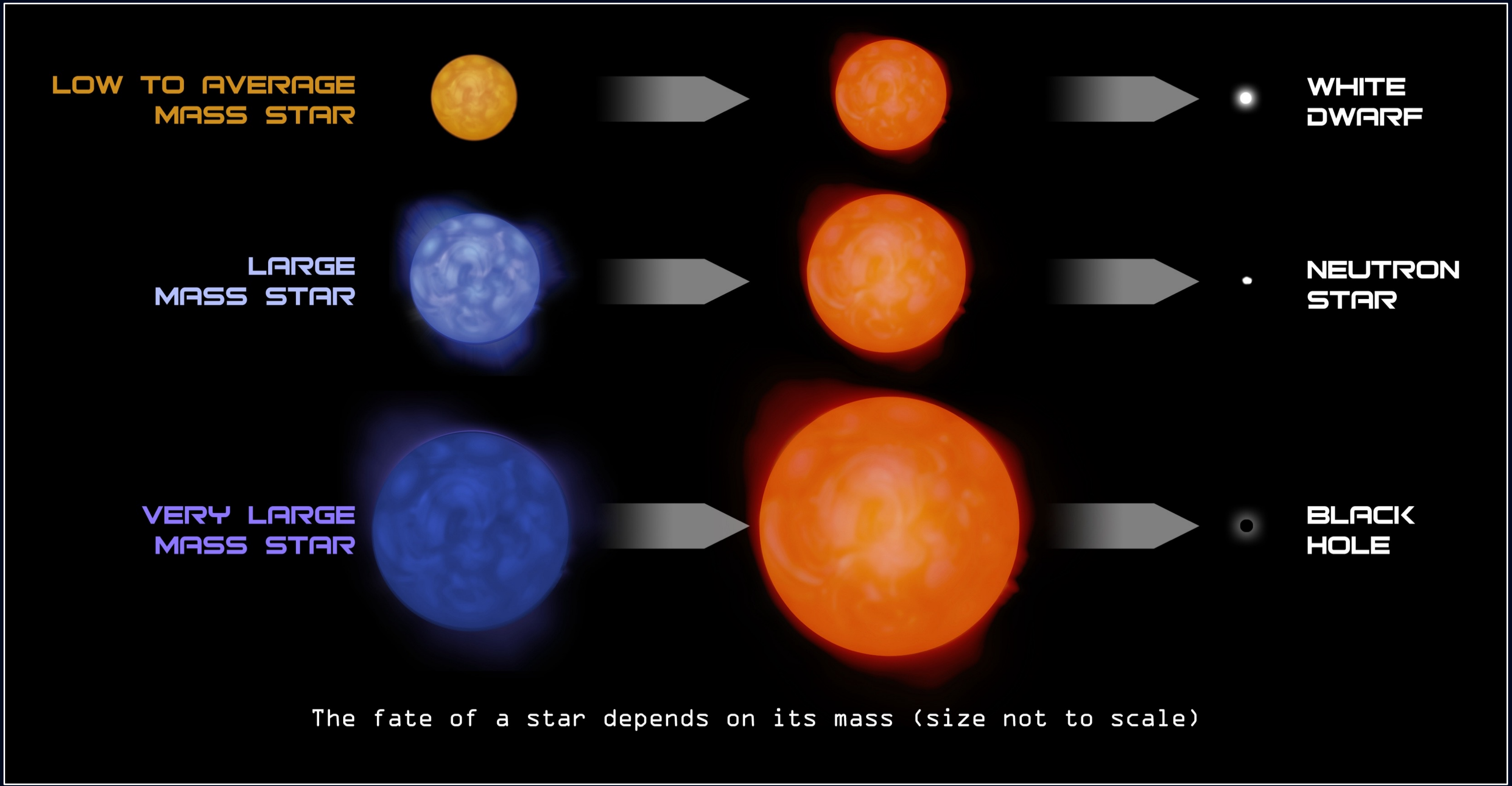
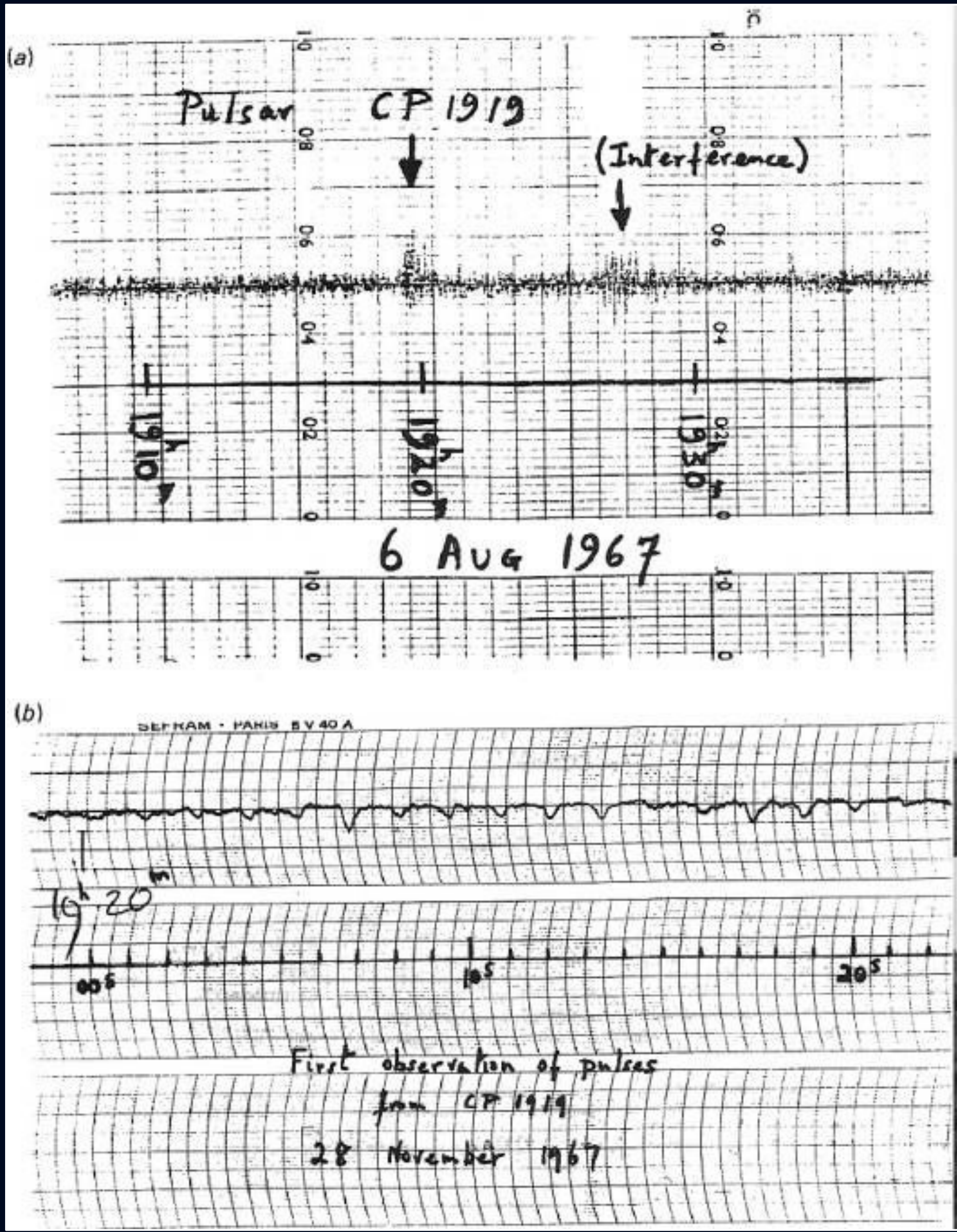


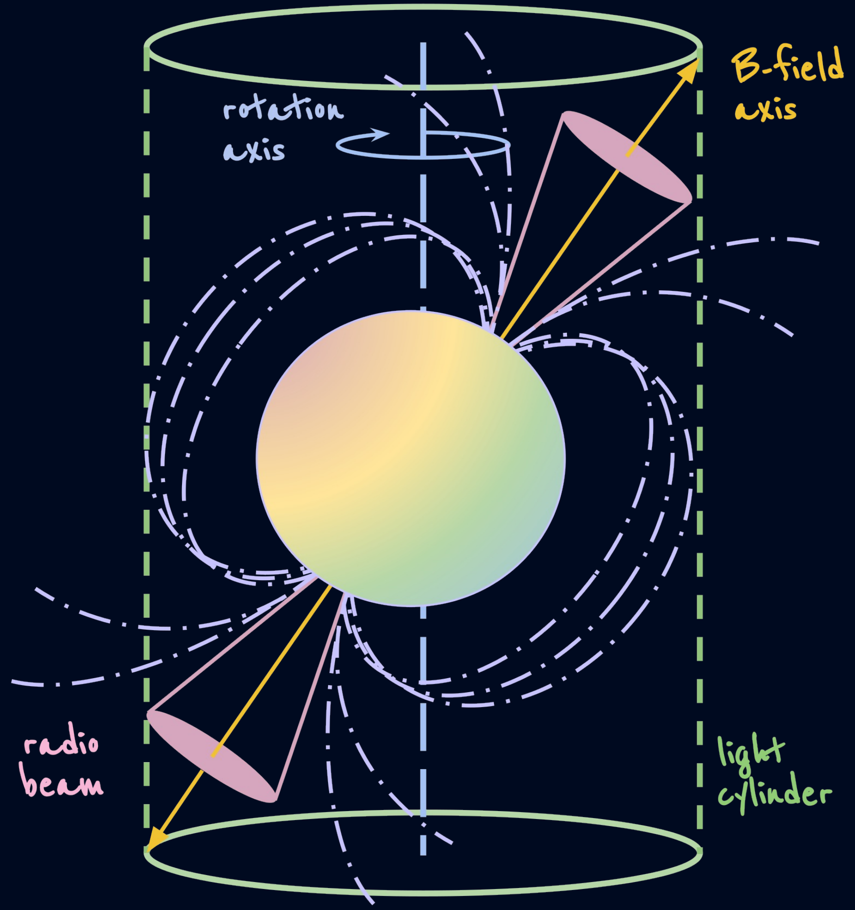
Image Credit: NASA


(a)
Pulsar CP 1919
(Interference)
19h 10m
19h 20m
19h 30m
6 AUG 1967
(b)
SEFRAM · PARIS 5 V 40 A
19h 20m
00s
10s
20s
First observation of pulses
from CP 1919
28 November 1967

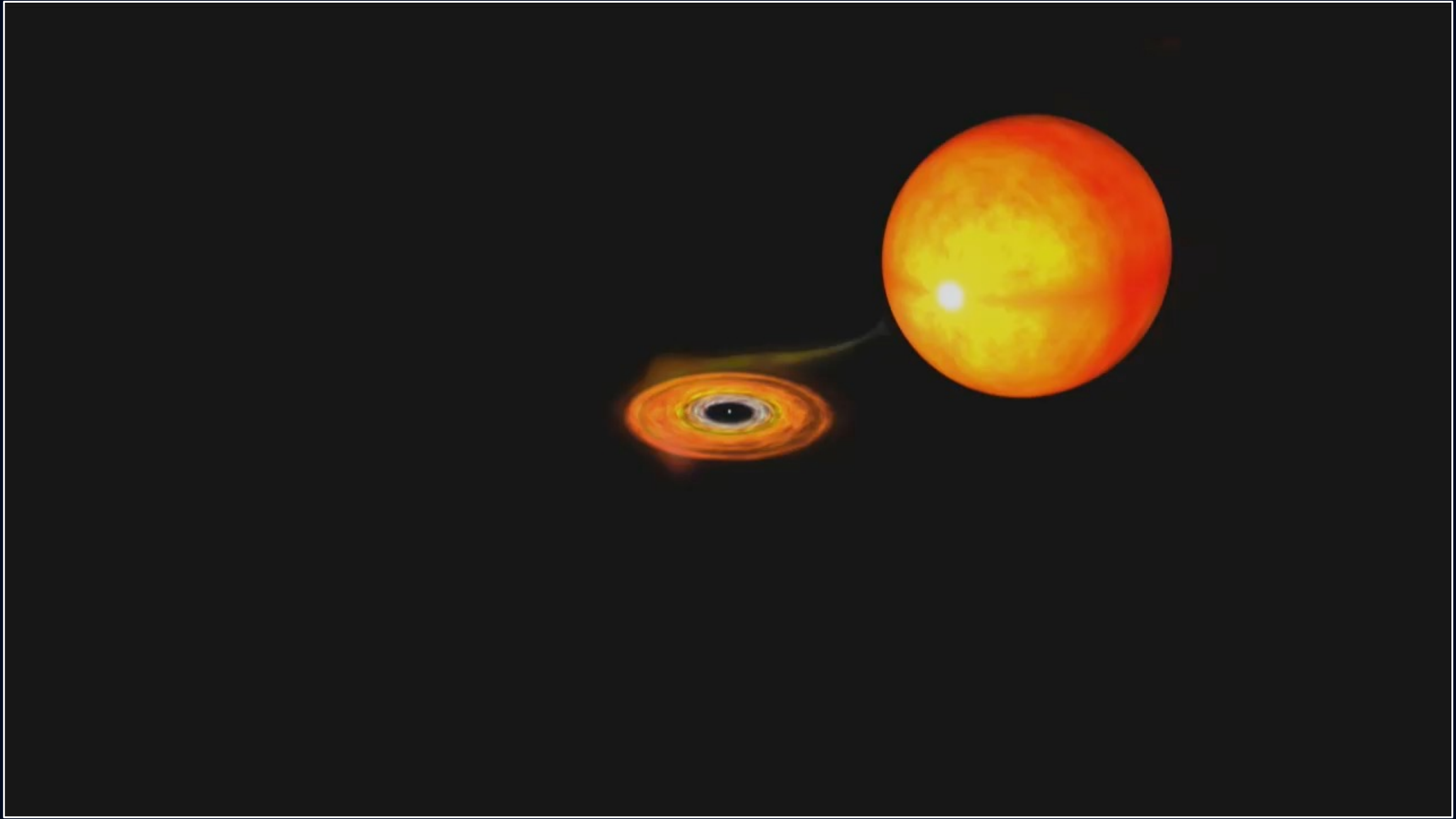
The Pulsar: Key facts

Mass	**1-2 solar masses**
Radius	~10-20 km
Magnetic Field	10^{12} -- 10^{14} G
Spin Period	~1.5 ms to ~1 minute

Image credit: H. Thankful Cromartie



The Millisecond Pulsar



Video credit: NASA

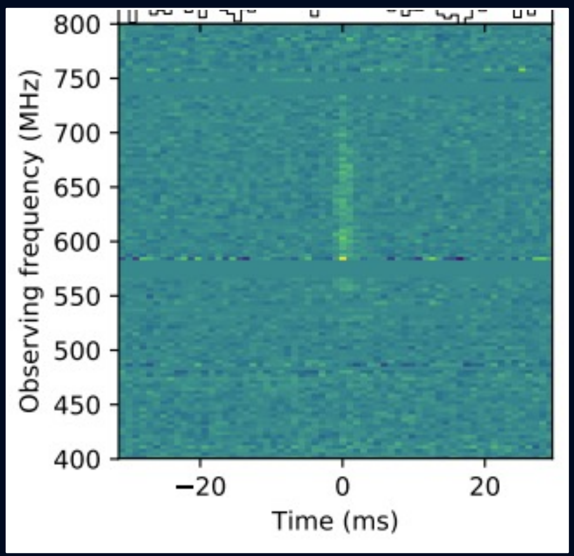
What is dispersion measure?

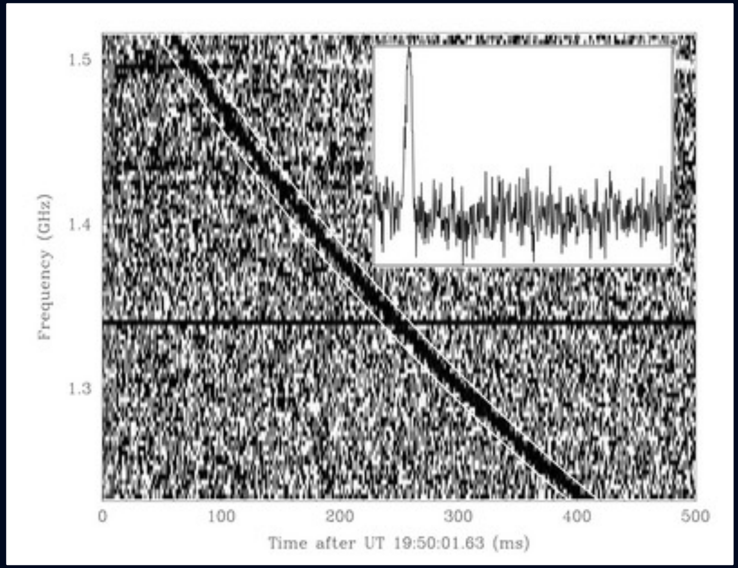
"The column density of electrons between the source and observer"

$$DM(t) = \int_0^D ds\, n_e\,(s\hat{n}(t), t)$$

The speed of light in the ISM is frequency dependent; different frequencies of light arrive at different times.

CHIME/FRB inc. D. Good





(Lorimer et al. 2007)

The Future

IPTA DR3

New instruments

Adding new telescopes

Imagine you were designing a new instrument to improve PTA data sets.

What data would you like to get from that instrument?

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

What other science could you explore at the same time?

Imagine you were designing a new instrument to improve PTA data sets.

You would probably want…

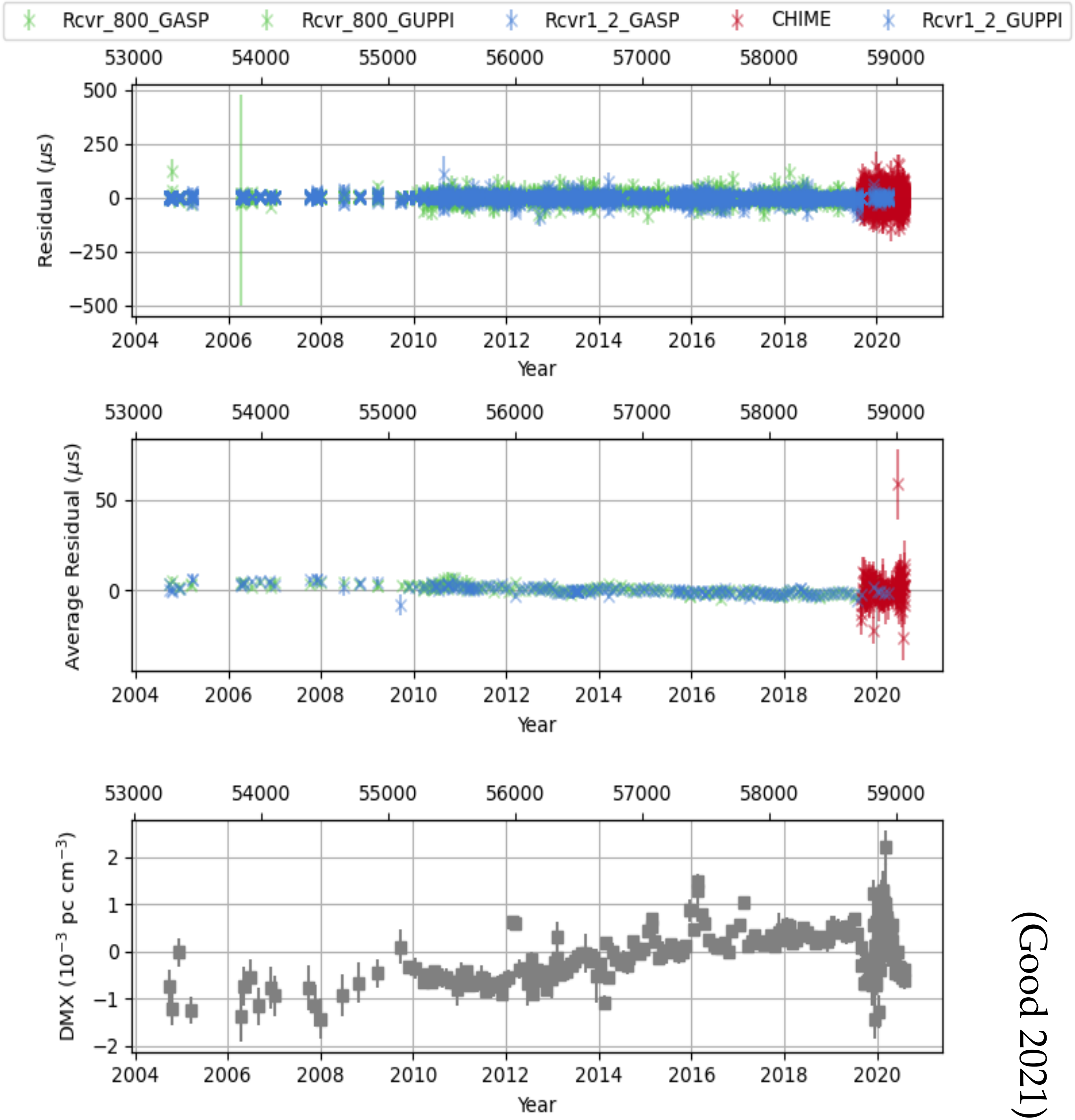
- High cadence data with lots of TOAs
- At a frequency range where pulsar emission is bright
- But where you can learn new things you didn’t know from other NANOGrav observations to improve that data
- While still being able to integrate new TOA measurements into the NANOGrav dataset.
- (And you might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

Meet CHIME

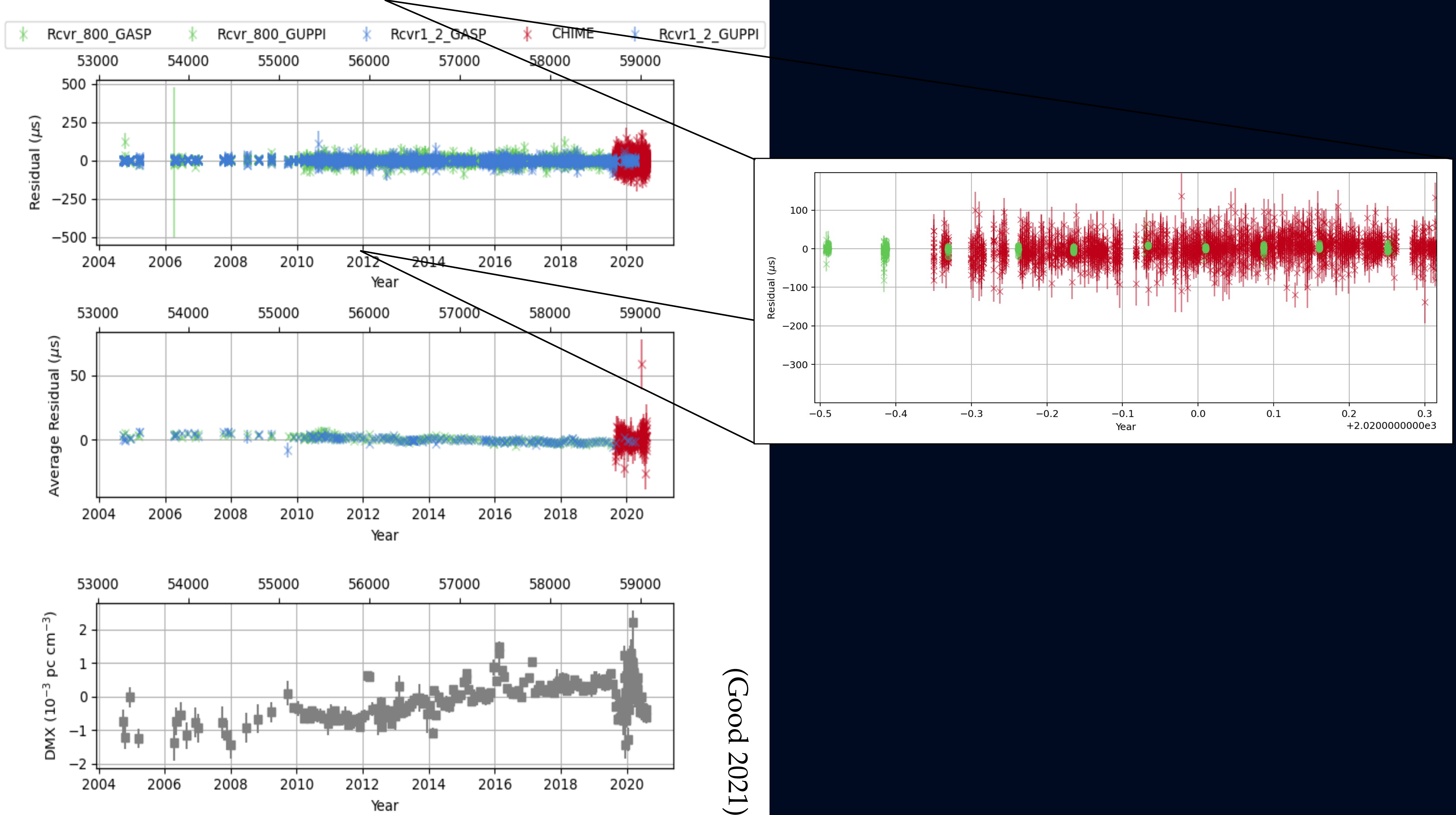
Image credit: CHIME Collaboration

Parameter	CHIME 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°
Pulsar tracking beams	10

A glimpse of NANOGrav’s future



(Good 2021)



Rcvr_800_GASP
Rcvr_800_GUPPI
Rcvr1_2_GASP
CHIME
Rcvr1_2_GUPPI
Residual (μs)
Average Residual (μs)
DMX (10^{-3} pc cm^{-3})
Year
+2.0200000000e3

(Good 2021)

The further future

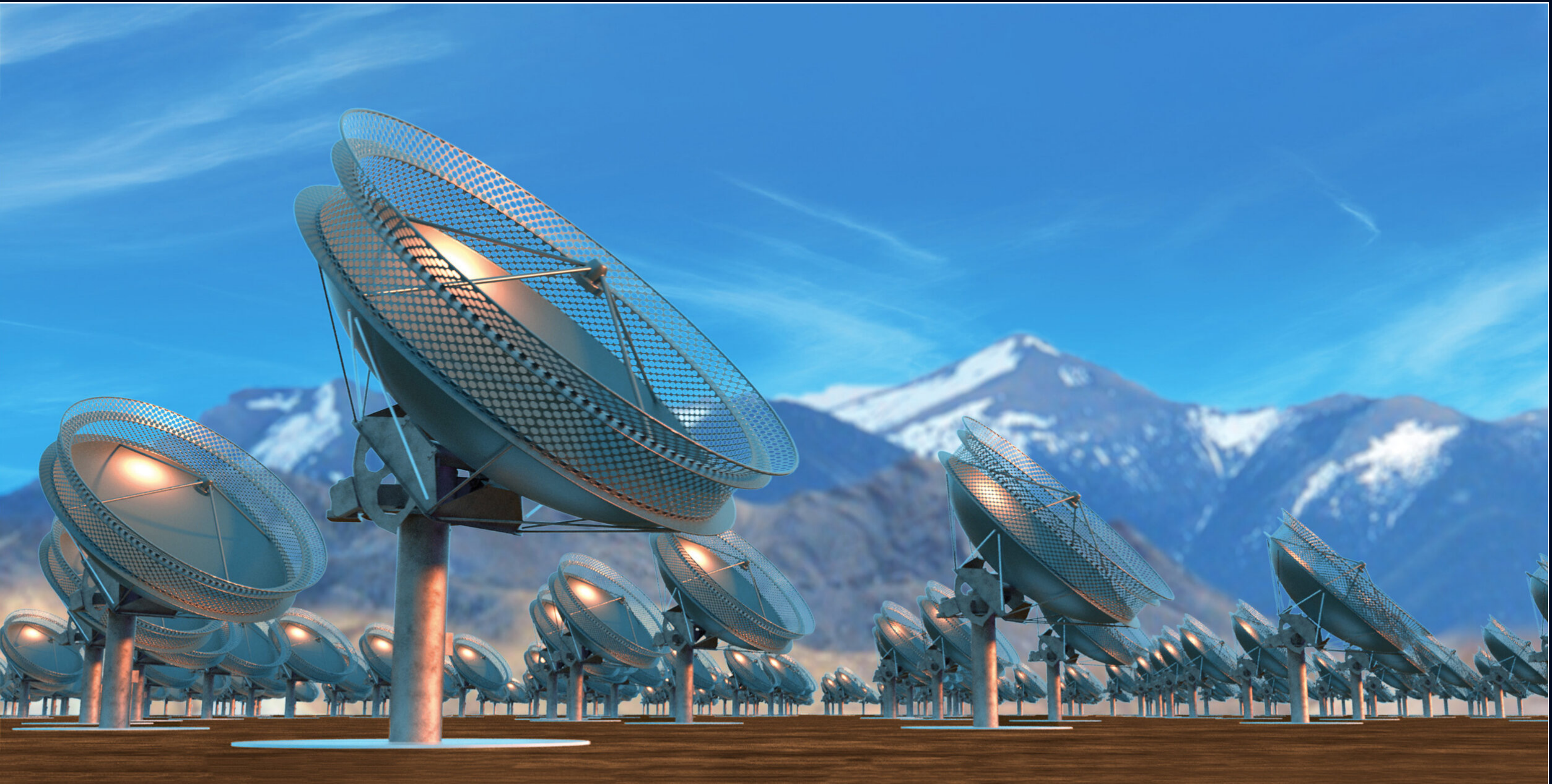


Image: C.Carter, DSA-2000

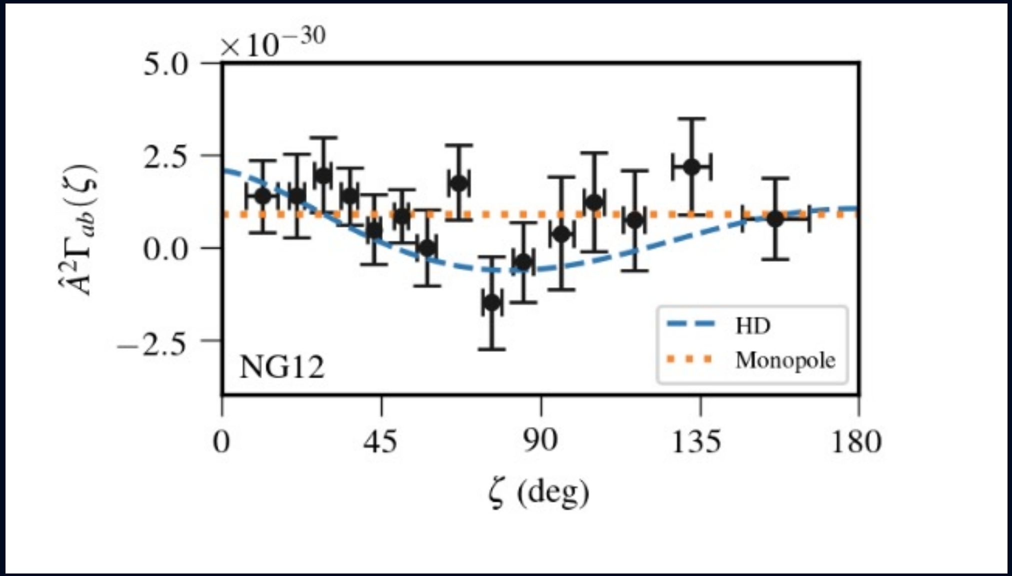
What sources does NANOGrav see?

- Primarily: the stochastic gravitational wave background.
  - An incoherent sum of many different gravitational wave sources to form a background.
  - Imagine the background noise at a party.
- Also: Continuous wave sources from SMBHB.
  - Imagine a specific conversation at a party.
- All of our sources are very low frequency, with very long periods where they're visible. (Years!)

How do we search for gravitational waves with PTAs?

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.

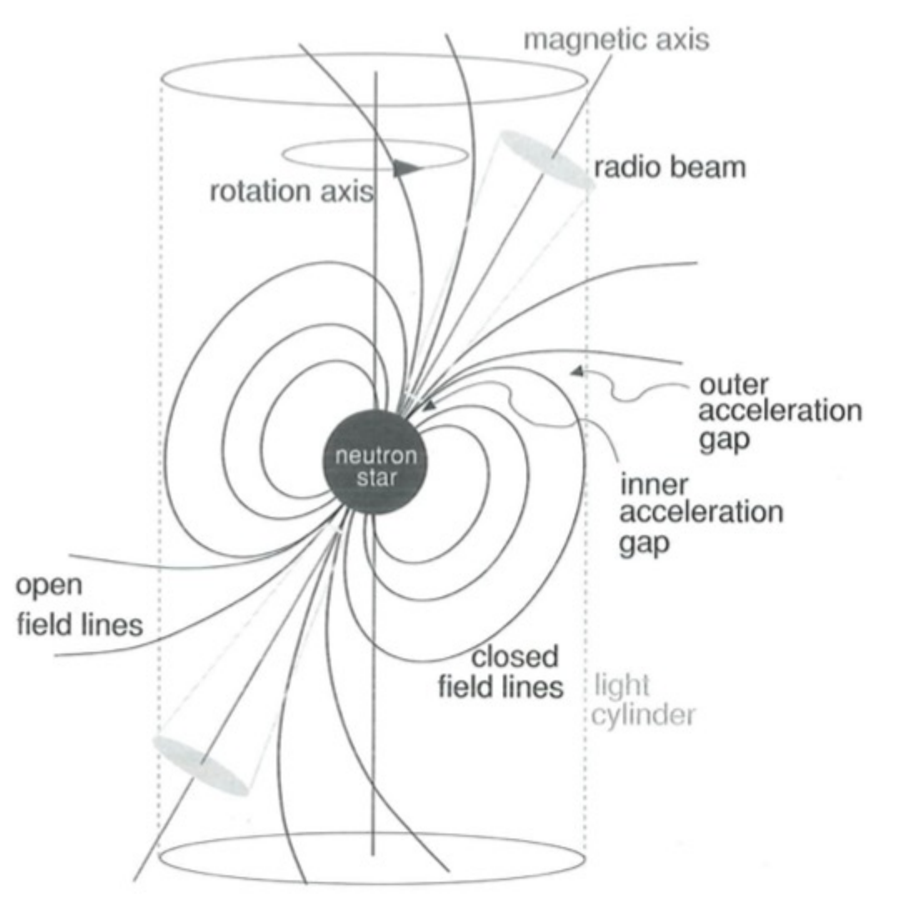
$$\alpha_{ij} = \frac{1-\cos(\zeta_{ij})}{2} \ln\left\{\frac{1-\cos(\zeta_{ij})}{2}\right\} - \frac{1}{6}\frac{1-\cos(\zeta_{ij})}{2} + 1/3$$



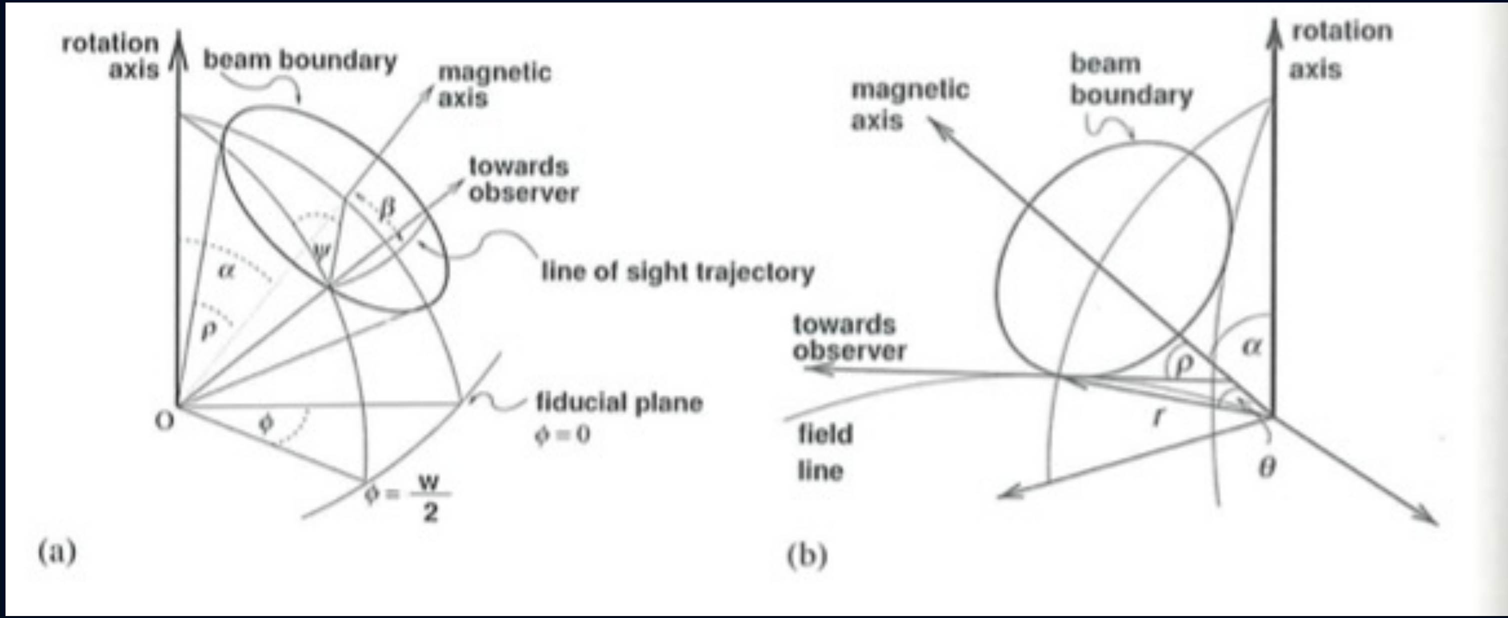
Arzoumanian et al. 2020

But to get there, we need really excellent pulsar timing solutions, for a whole bunch of pulsars.

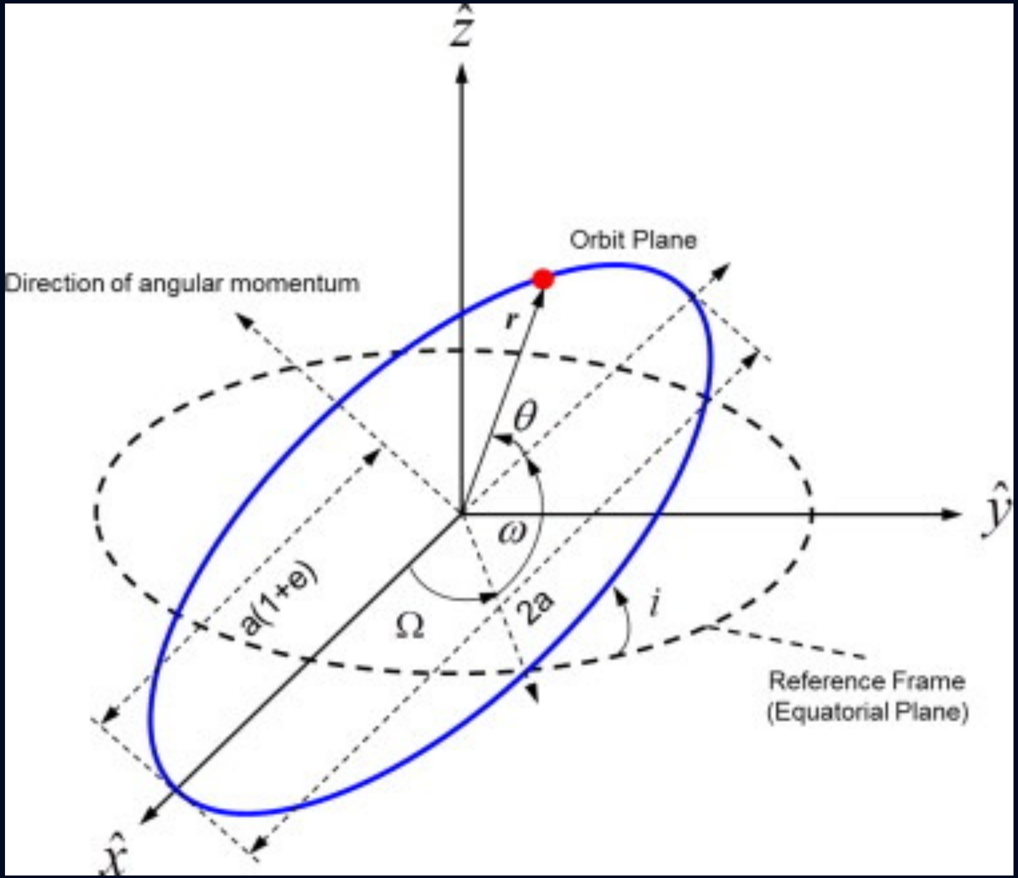
A model for pulsar geometry



Images: Lorimer & Kramer 2005



Binary systems



- All get: binary period (P_b), semi-major axis (x or a)
- Choose primarily based on eccentricity value:
  - ELL1: T_{asc}, ε_1, ε_2
  - ELL1+: T_{asc}, ε_1, ε_2 h3, h4
  - DD model: T_0, e, sin(i), γ, Ω
  - DDK model: : T_0, e, γ, Ω, KIN, KΩ (adds consideration of PM, PX)
- Also sometimes: m_2, time derivatives of assorted parameters.