Building the Strong Case for nHz Gravitational Waves with Pulsar Timing Arrays

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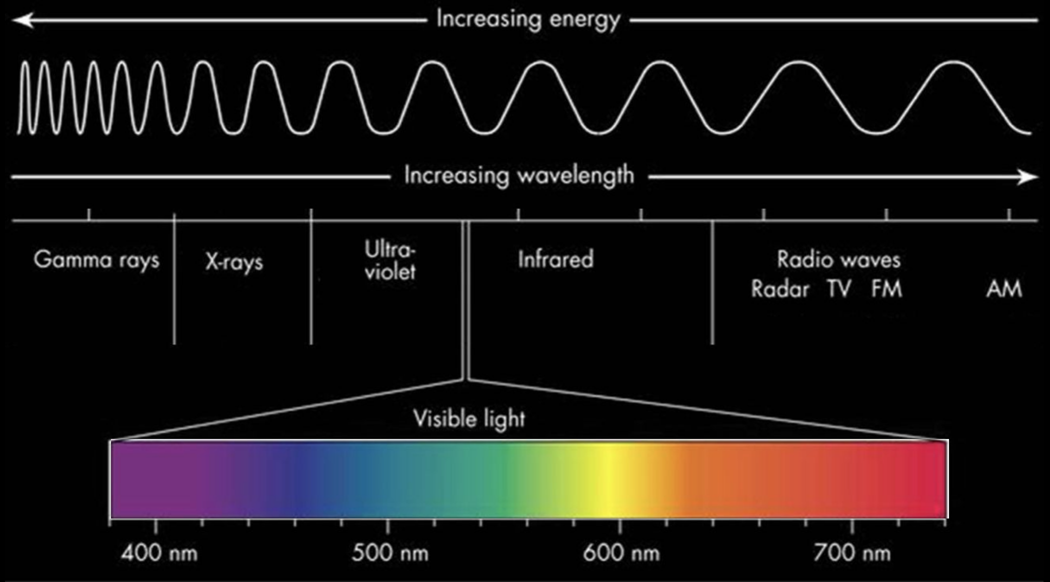
Chair, NANOGrav Timing Working Group

ICEPP Seminar | February 19, 2024

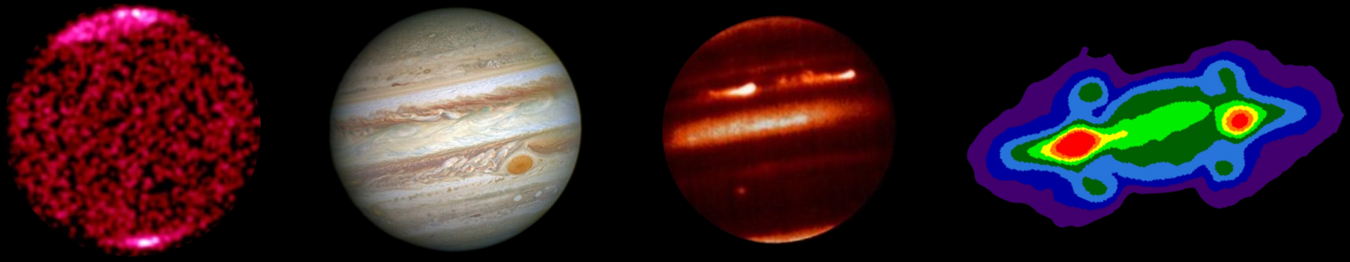
The Gravitational Wave Universe

“Traditional” Electromagnetic Astronomy

~10^{26} Hz



~10^{6} Hz

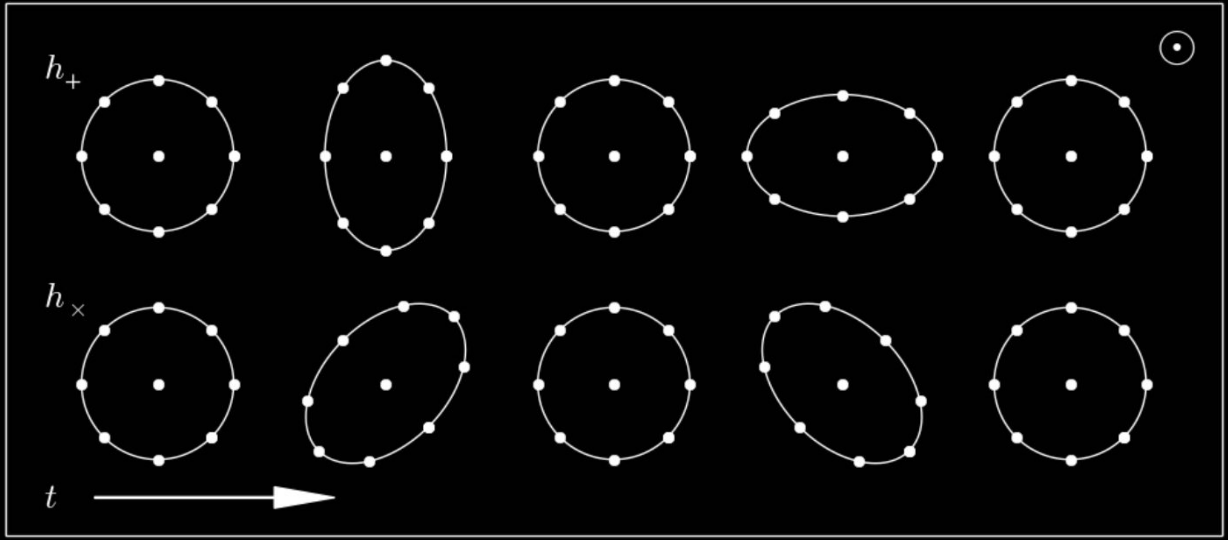


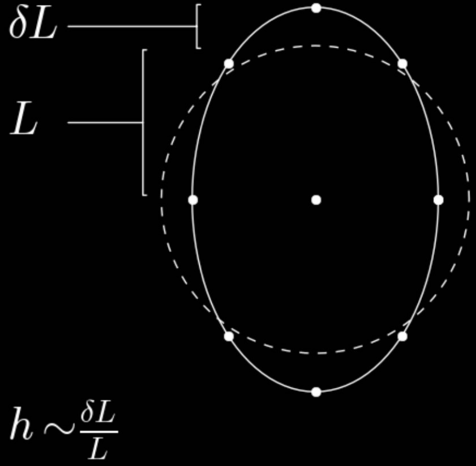
General Relativity: 1916

mass → curves space,
space → moves mass

Accelerating masses → gravitational waves moving at the speed of light

Spacetime is stretched and squeezed; *distances* change

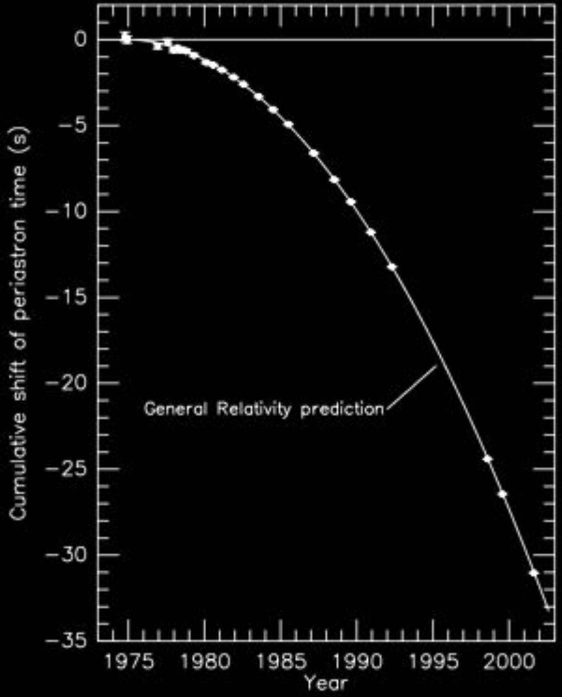




Light takes longer to traverse if spacetime is stretched

A telescope for gravitational waves

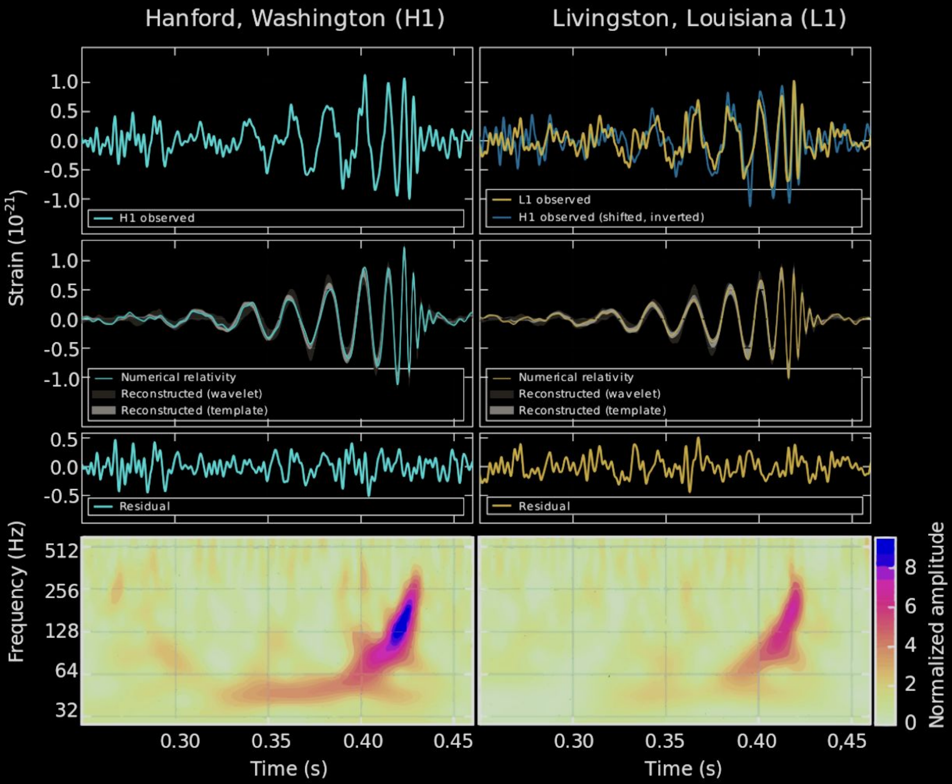
1960s: J. Weber's resonant mass detector

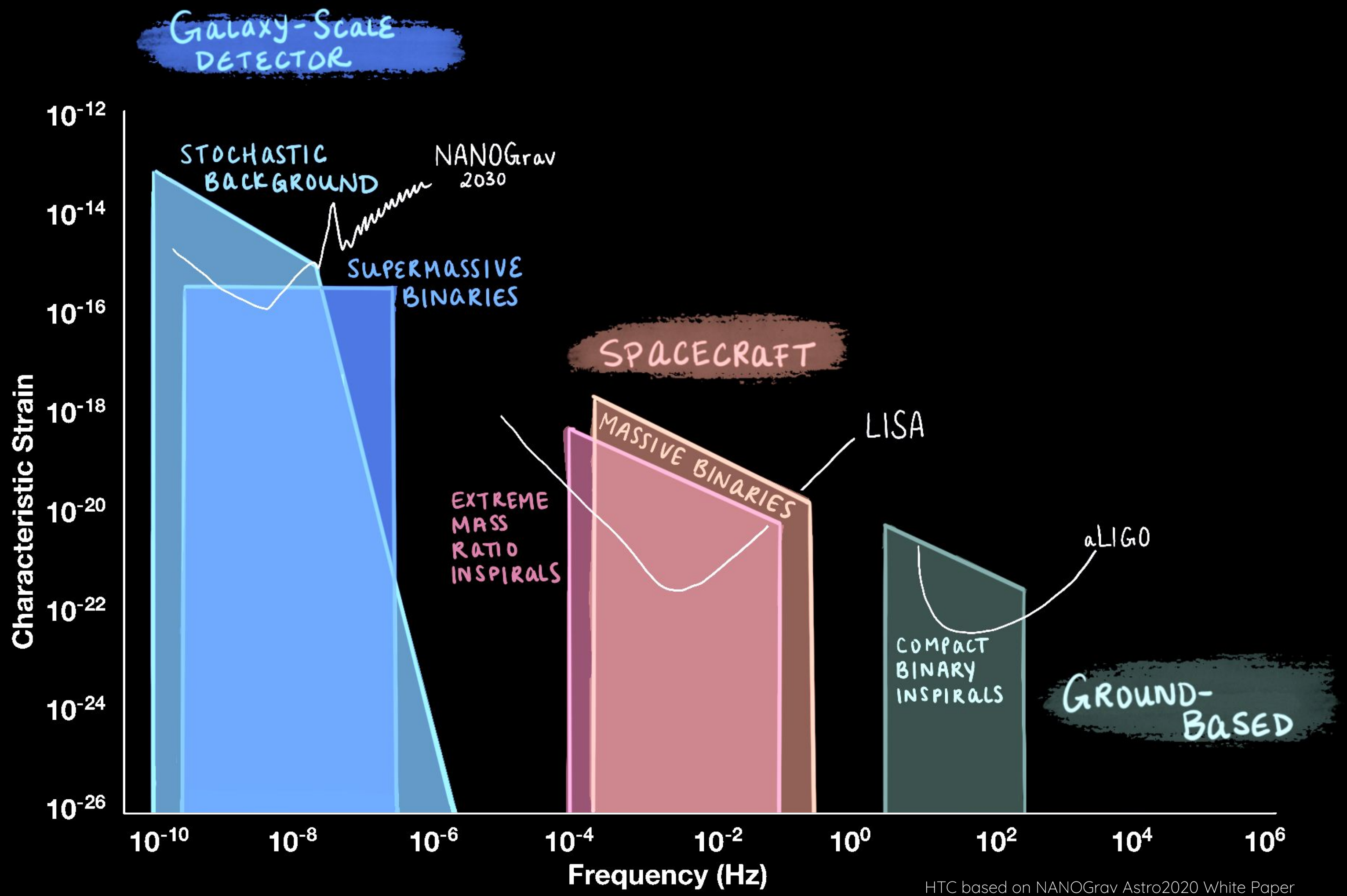


Indirect detection by Hulse & Taylor (PSR B1913+16 discovered 1974, Nobel Prize 1993)

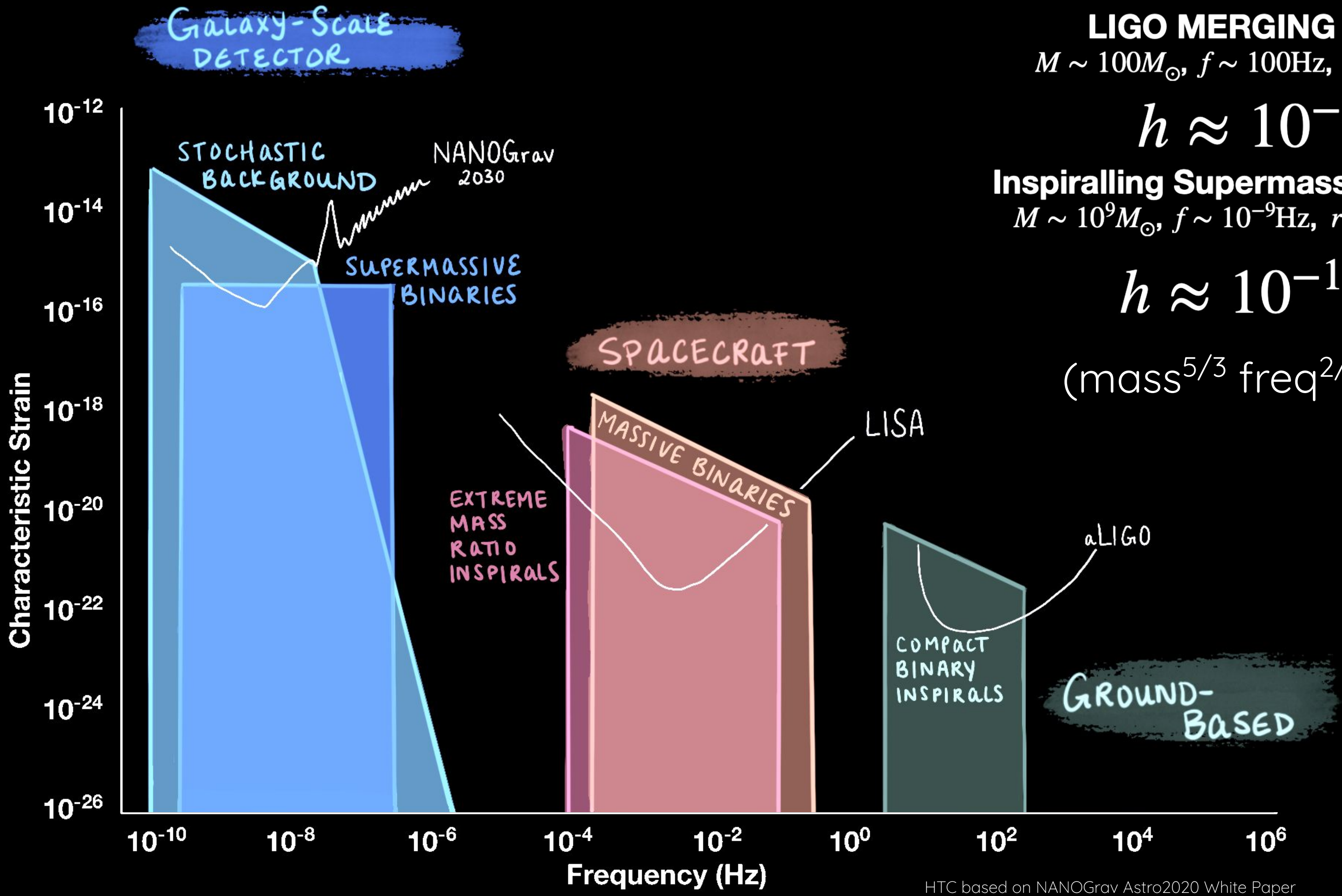
A telescope for gravitational waves

Caltech/LIGO





HTC based on NANOGrav Astro2020 White Paper



LIGO MERGING BBHs

$M \sim 100M_{\odot},\ f \sim 100\text{Hz},\ r \sim 400\text{Mpc}$

$$h \approx 10^{-21}$$

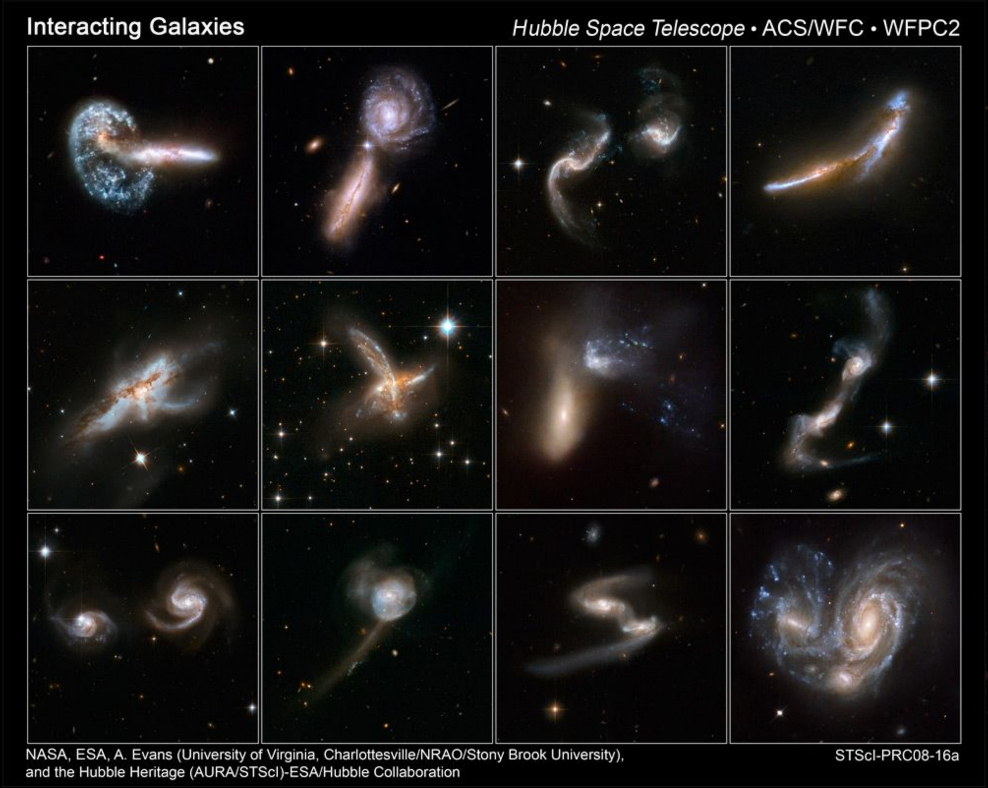
Inspiralling Supermassive BBHs

$M \sim 10^{9}M_{\odot},\ f \sim 10^{-9}\text{Hz},\ r \sim 400\text{Mpc}$

$$h \approx 10^{-17}$$

$(\text{mass}^{5/3}\ \text{freq}^{2/3})/d$

HTC based on NANOGrav Astro2020 White Paper

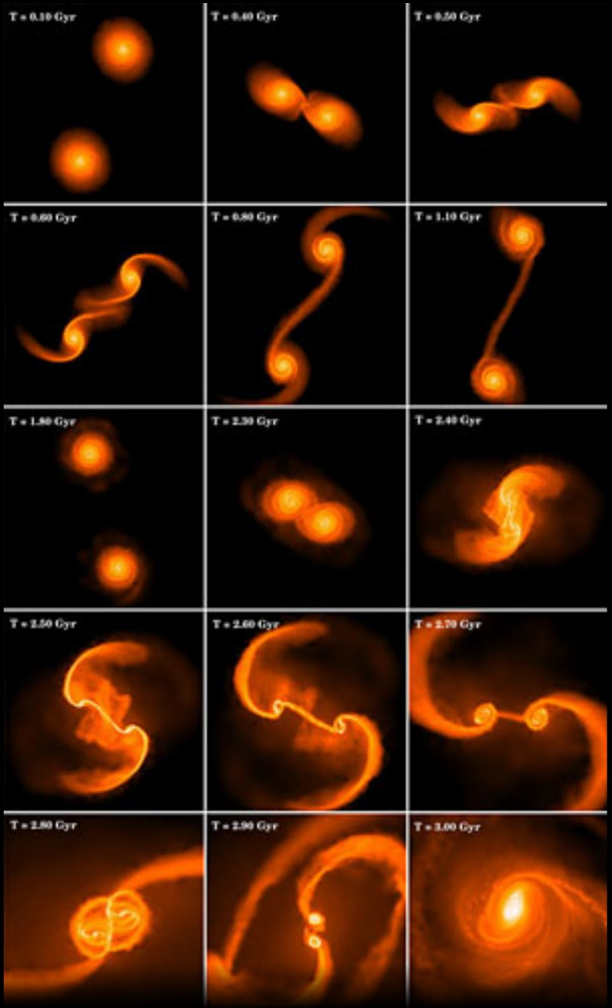


NASA, ESA, A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University), and the Hubble Heritage (AURA/STScI)-ESA/Hubble Collaboration

STScI-PRC08-16a

Distant, young galaxies → small and irregular

Old galaxies: large and structured → mergers



Phase 1: dynamical friction

- SMBHs feel drag from gas and stars during merger

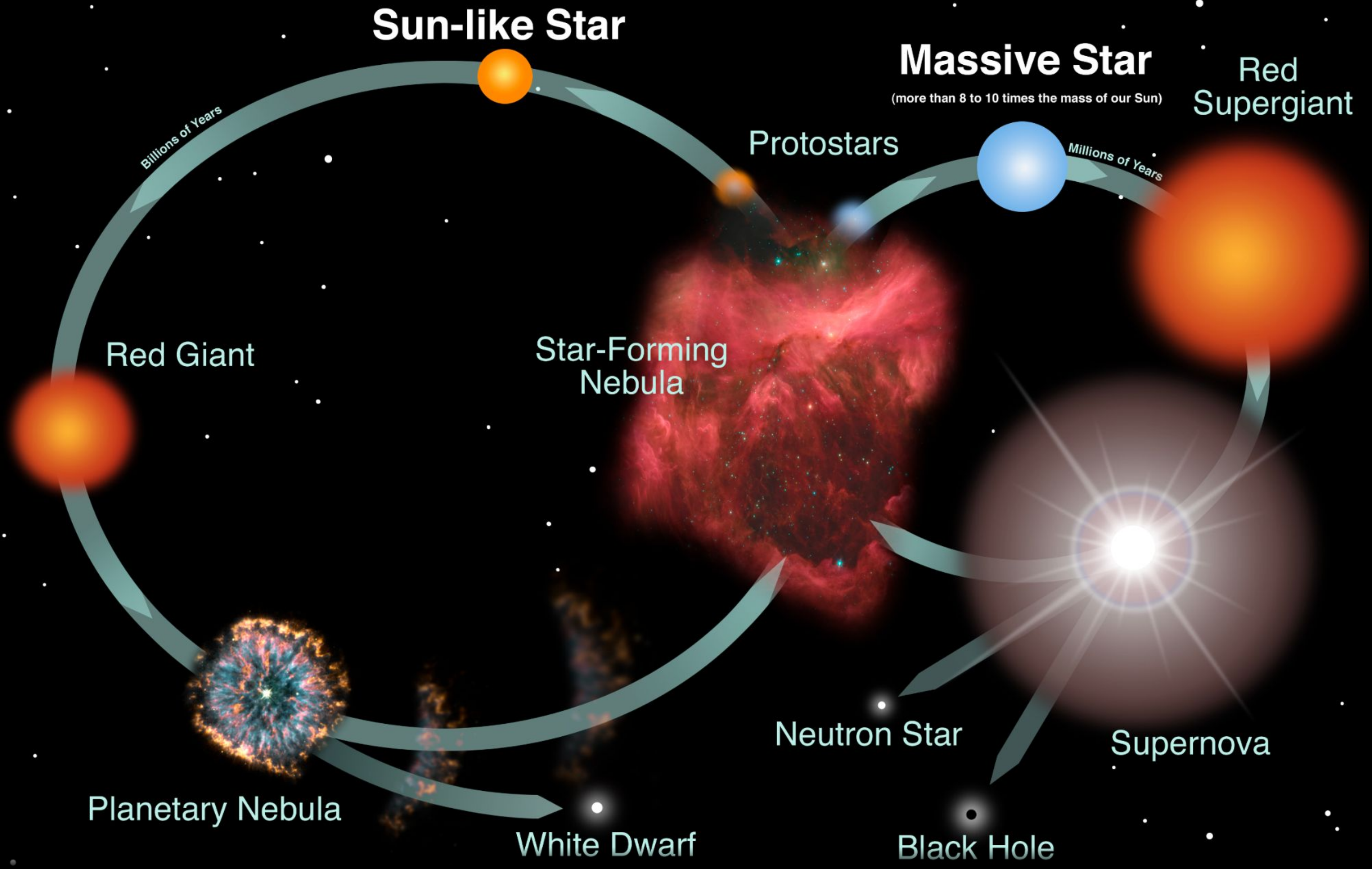
Phase 2: hardening / environmental coupling

- Accretion disk / three-body “slingshot” interactions remove energy?
- Final parsec problem if this can’t happen

Phase 3: gravitational radiation (very close)

- *This is what we see*

What Are the Pulsars in Pulsar Timing Arrays?



Sun-like Star

Billions of Years

Massive Star

(more than 8 to 10 times the mass of our Sun)

Red Supergiant

Protostars

Millions of Years

Red Giant

Star-Forming Nebula

Neutron Star

Supernova

Planetary Nebula

White Dwarf

Black Hole

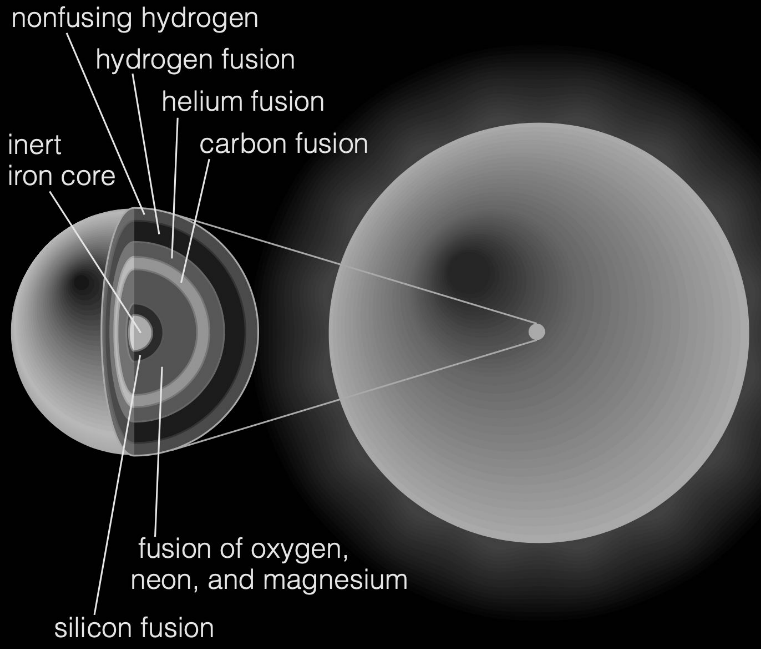
NASA and the Night Sky Network

The fate of stars depends on their mass:

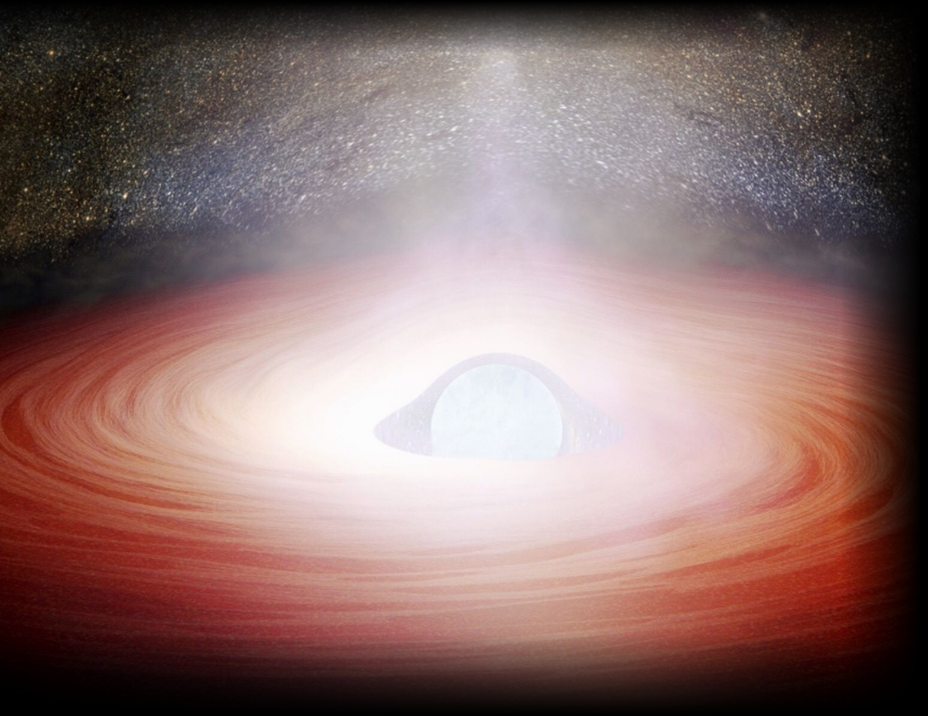
< 8 solar masses: white dwarfs
(1.4 solar masses)

> 8 solar masses: neutron stars
(up to ~3 solar masses)

> 10-30 solar masses: black holes
(> 3 solar masses)



High mass stars go through the process of fusing H → He → heavier elements → iron; core collapse when gravity wins



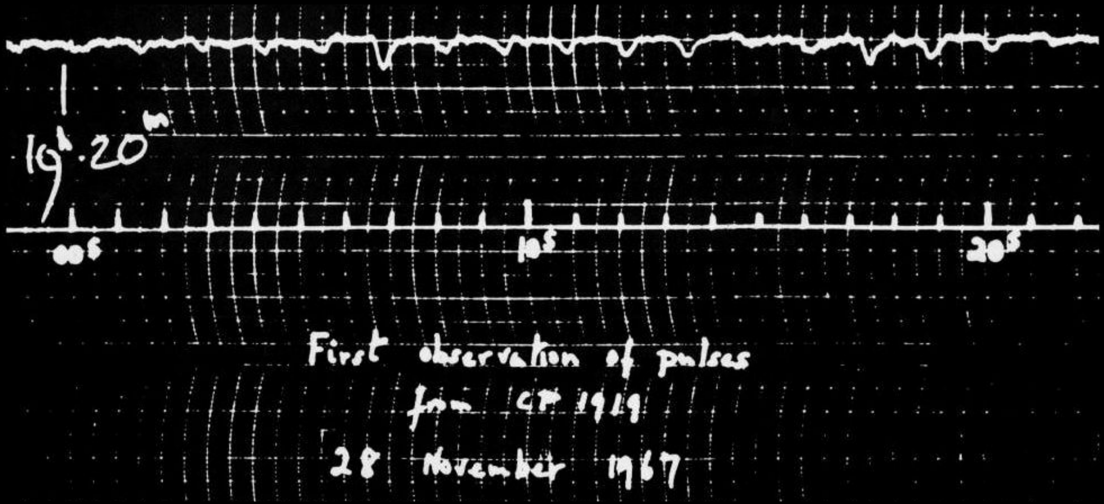
Massive stars can undergo supernovae and leave behind neutron stars:

- Compact object supported by neutron degeneracy pressure
- Density: a paperclip with a neutron star's density would weigh as much as Mount Everest
- Typical NS: 1.4 $M_\odot$, $r \approx 10$ km

Using a radio telescope in 1967, grad student Jocelyn Bell noticed very regular pulses of radio emission coming from a single part of the sky

Called “LGM” initially

Pulses from a spinning neutron star: **the first pulsar**

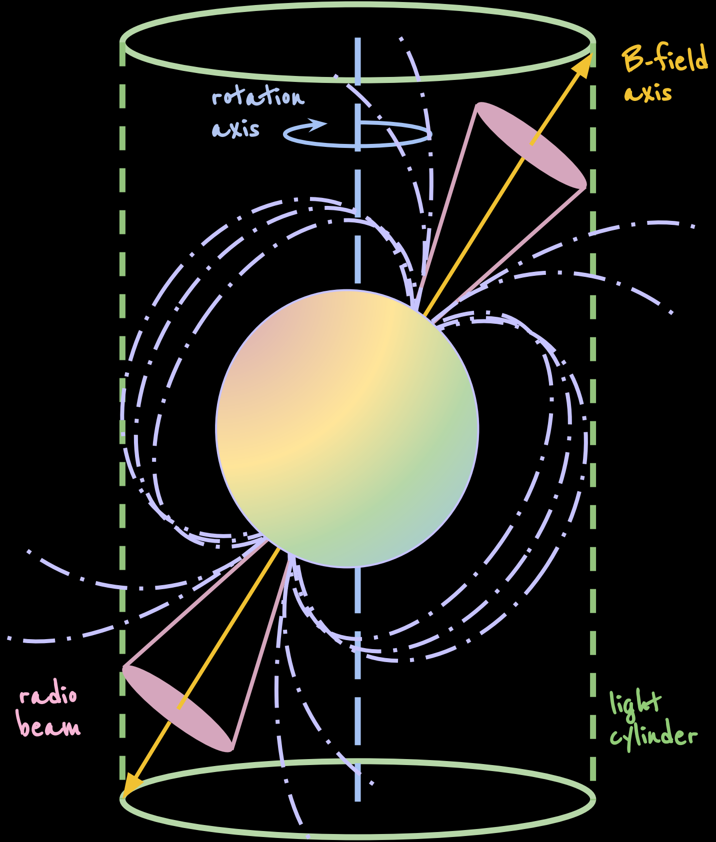


Pulsars

- Don't pulse (lighthouses)
- Centrifugal acceleration at the equator can't exceed gravitational acceleration:
    - Angular velocity $\Omega \equiv 2\pi/P$

$$\Omega^2 R < \frac{GM}{R^2} \xrightarrow{\hspace{3cm}} \rho > \frac{3\pi}{GP^2}$$

- Fastest < 1.4 ms → density > 10^{14} g cm^{-3} = atomic nuclei



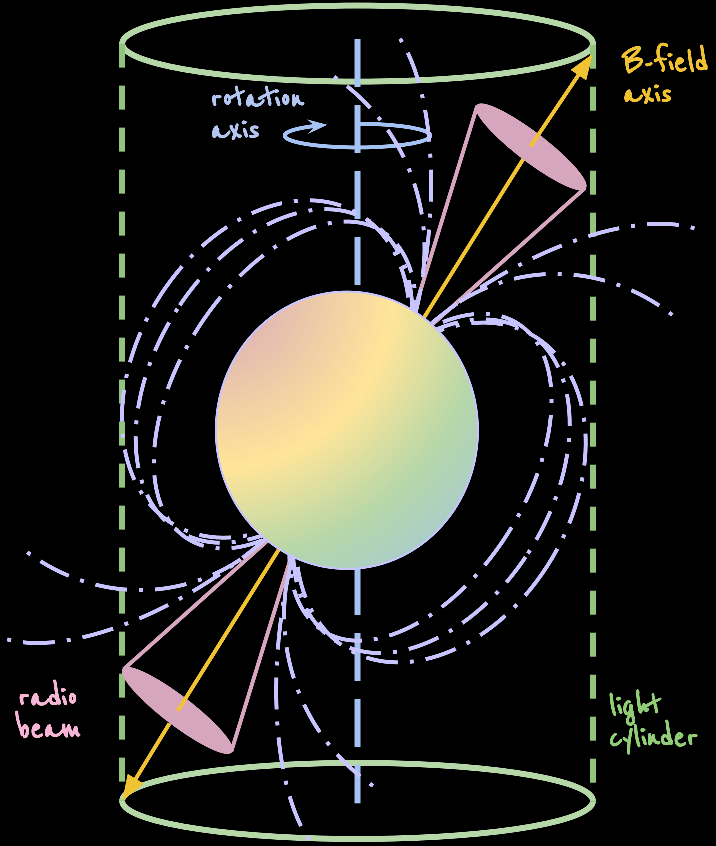
HTC based on Lorimer & Kramer

Pulsars

- Assuming dipole + measurement of spin-down, can calculate spin-down luminosity, B-field, characteristic age:

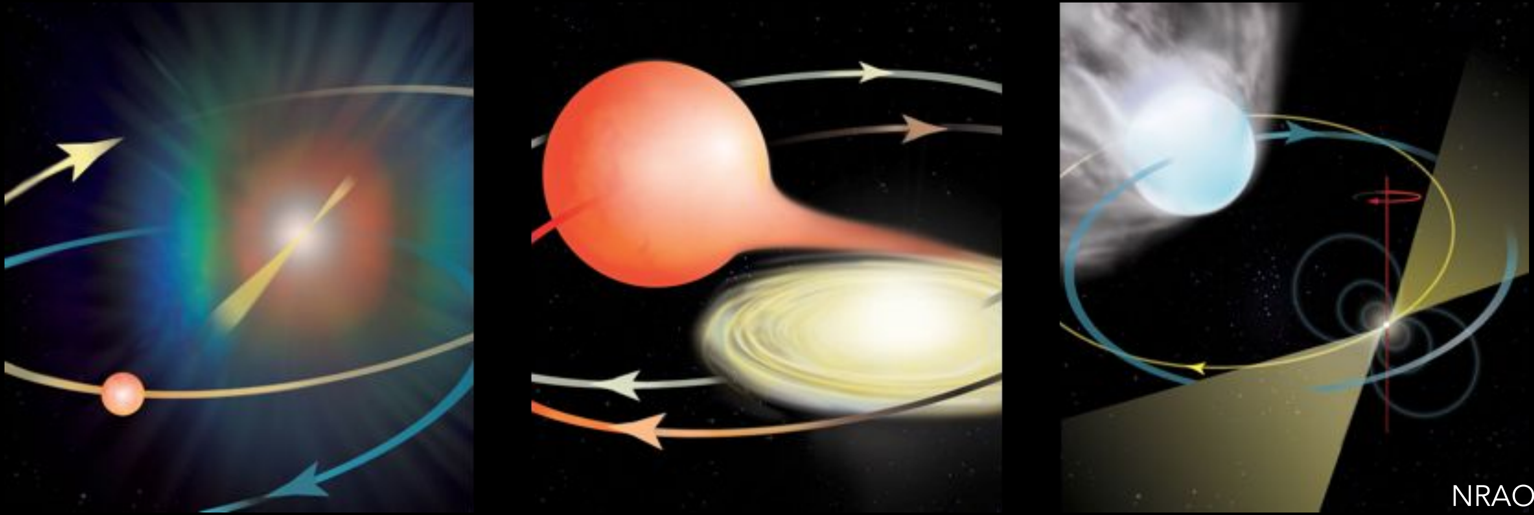
$$\tau \equiv \frac{P}{2\dot{P}}$$

- Most pulsars $10^5 <$ age $< 10^{10}$ yr (Galaxy)



HTC based on
Lorimer & Kramer

Millisecond Pulsars (MSPs): Faster than a Blender


NRAO

- Low B-fields ($<10^{11}$ G); plasma shielding during accretion
- Spun up by stellar companion (almost always binaries) → recycling
- Not eccentric, very stable rotators

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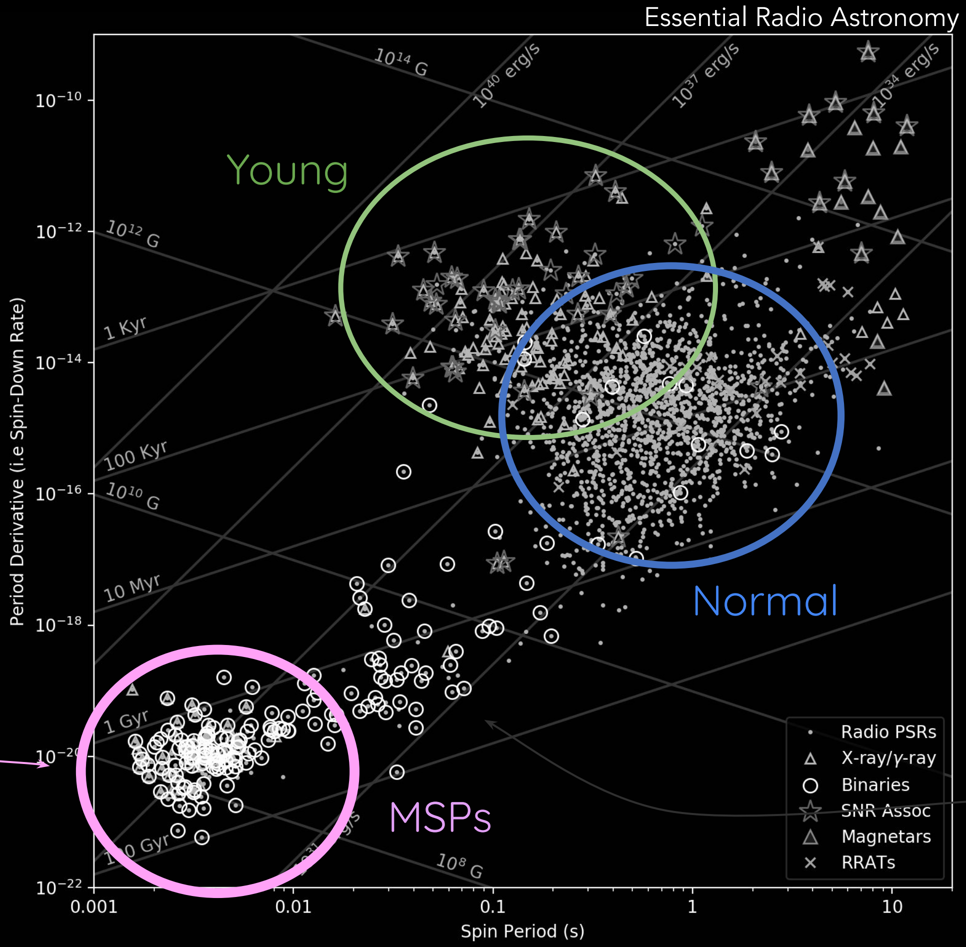
High B

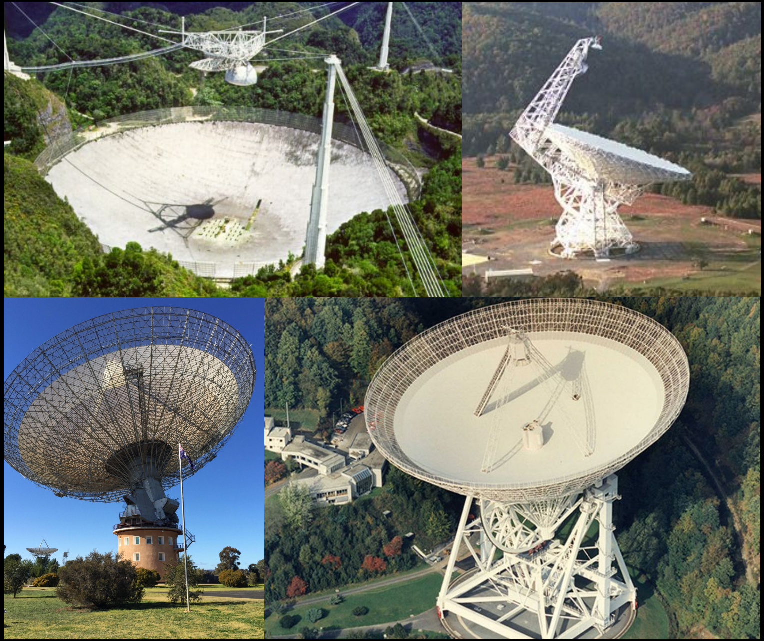
MSPs:
fully recycled,
low-e orbits,
stable, fast!



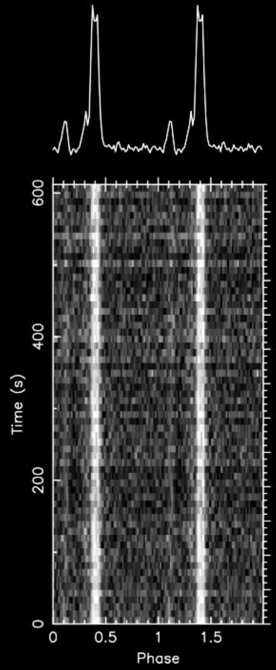
Low B

Double NS:
~17; mildly
recycled, high-e
orbits, good GR
tests

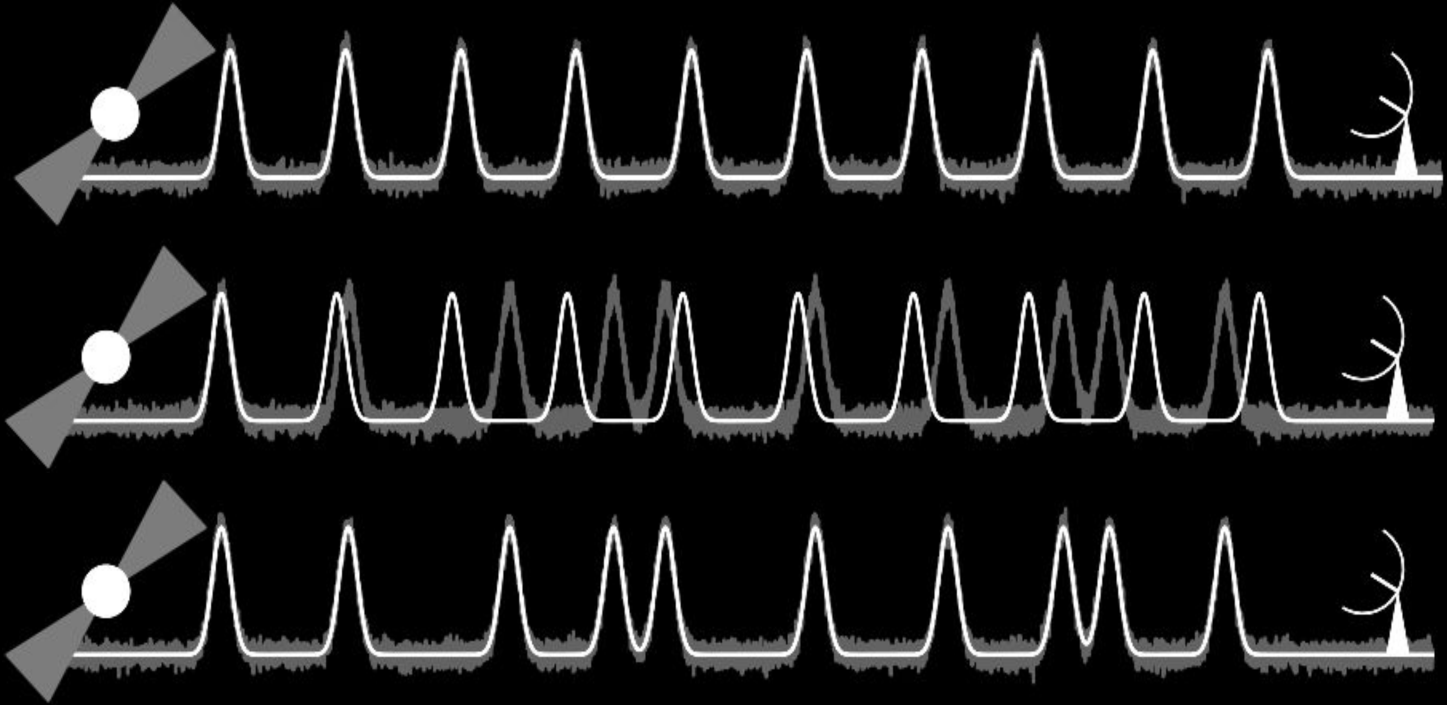
Observing MSPs



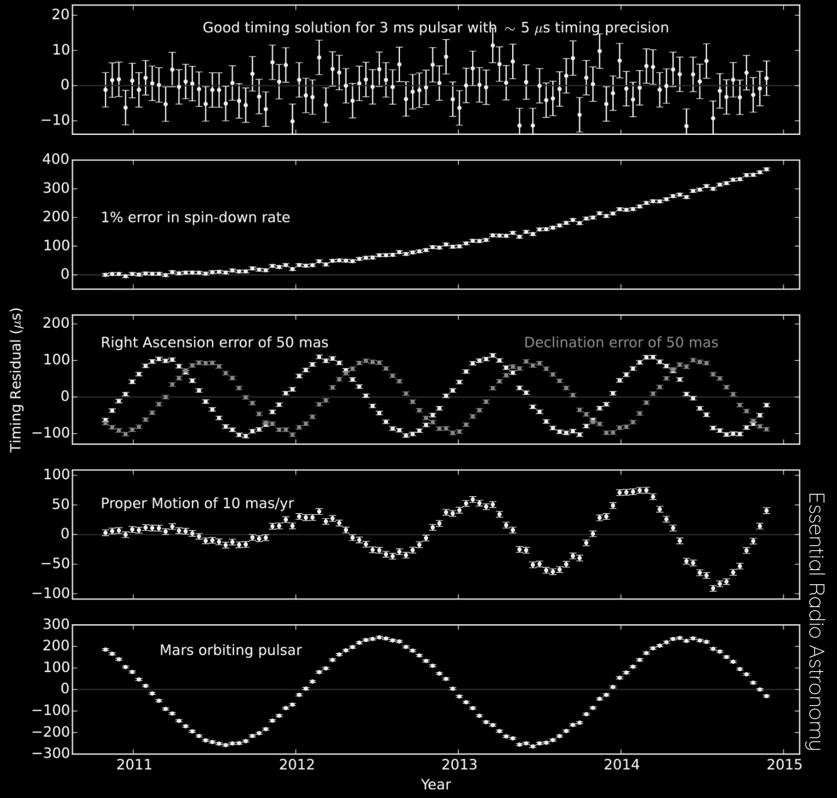
- Weak; need sensitivity
- Steep spectra → very low radio frequencies (< 1 GHz → ~few GHz)
  - High-frequencies, too (NICER, *Fermi*-LAT)
- Fold the data modulo the pulse period to bring out the signal



Pulsar Timing = Accounting for Every Pulse



Pulsar Timing = Accounting for Every Pulse



Difference between measured TOA and model = <u>timing residual</u>

<u>J1909-3744 on February 18, 2011 at 00:00:00 UTC:</u>

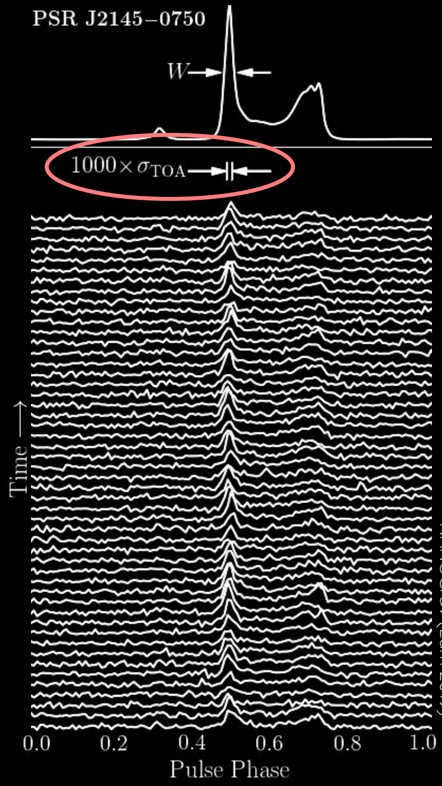
P = 2.947108024810317 ± 0.000000000000009 ms

The last digit changes by 1 every 71 seconds

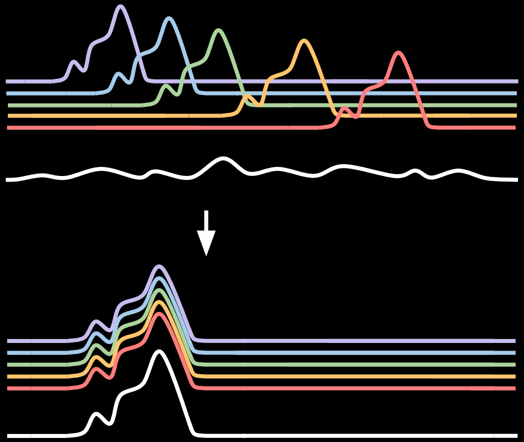
The sixth digit changes by 1 every 226 years

From February 18, 2011 at 00:00:00 UTC to October 22, 2022 at 00:30:00 UTC, the pulsar completed just over 125,007,769,167 rotations

Noise in MSPs



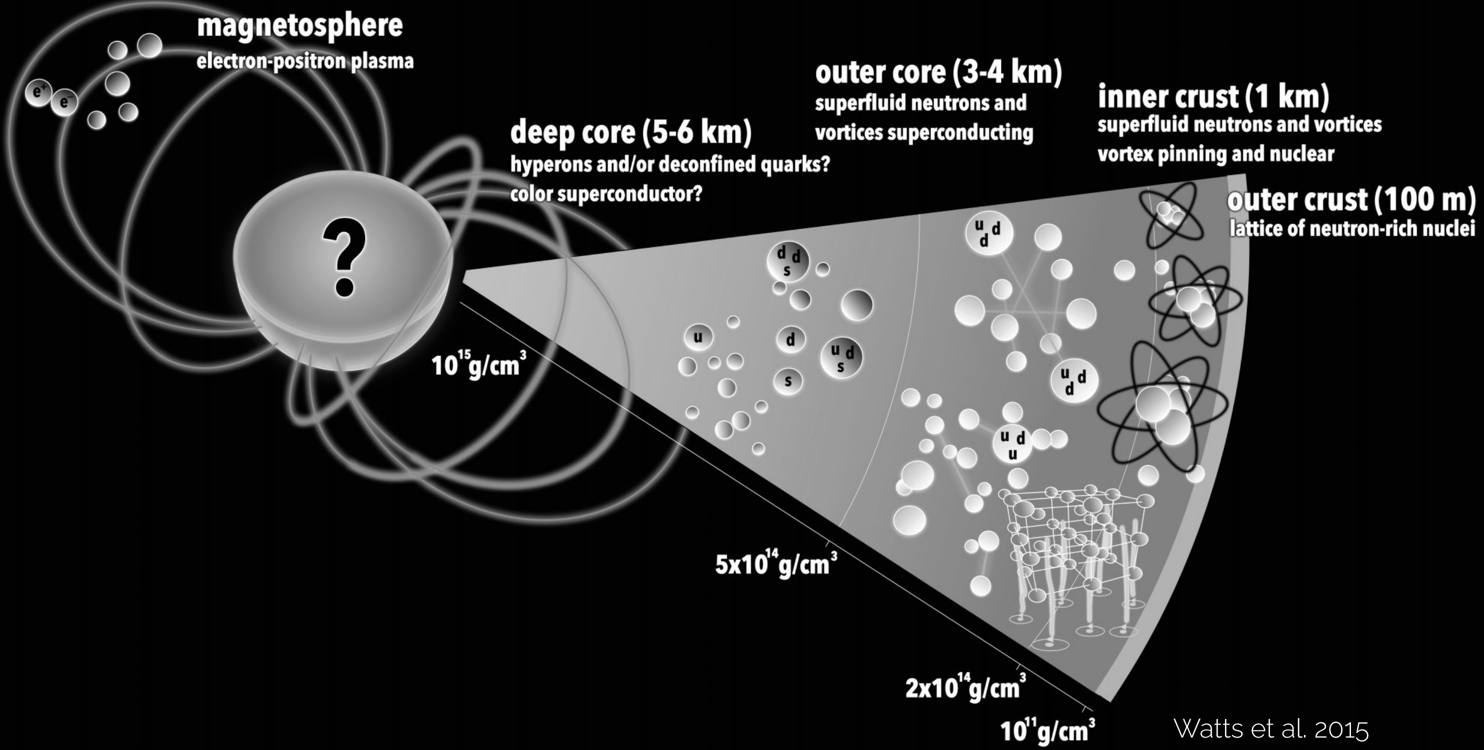
NANOGrav (Lam 2019)



- White noise (short timescales):
    - Radiometer noise
    - Pulse jitter (shape changes between pulses)
- Red noise (long periods):
    - Achromatic red noise = spin / timing noise
        - Due to irregularities in pulsar rotation
    - Chromatic red noise
        - DM variations ν^{-2}

MSP Timing Example:
The NS EOS

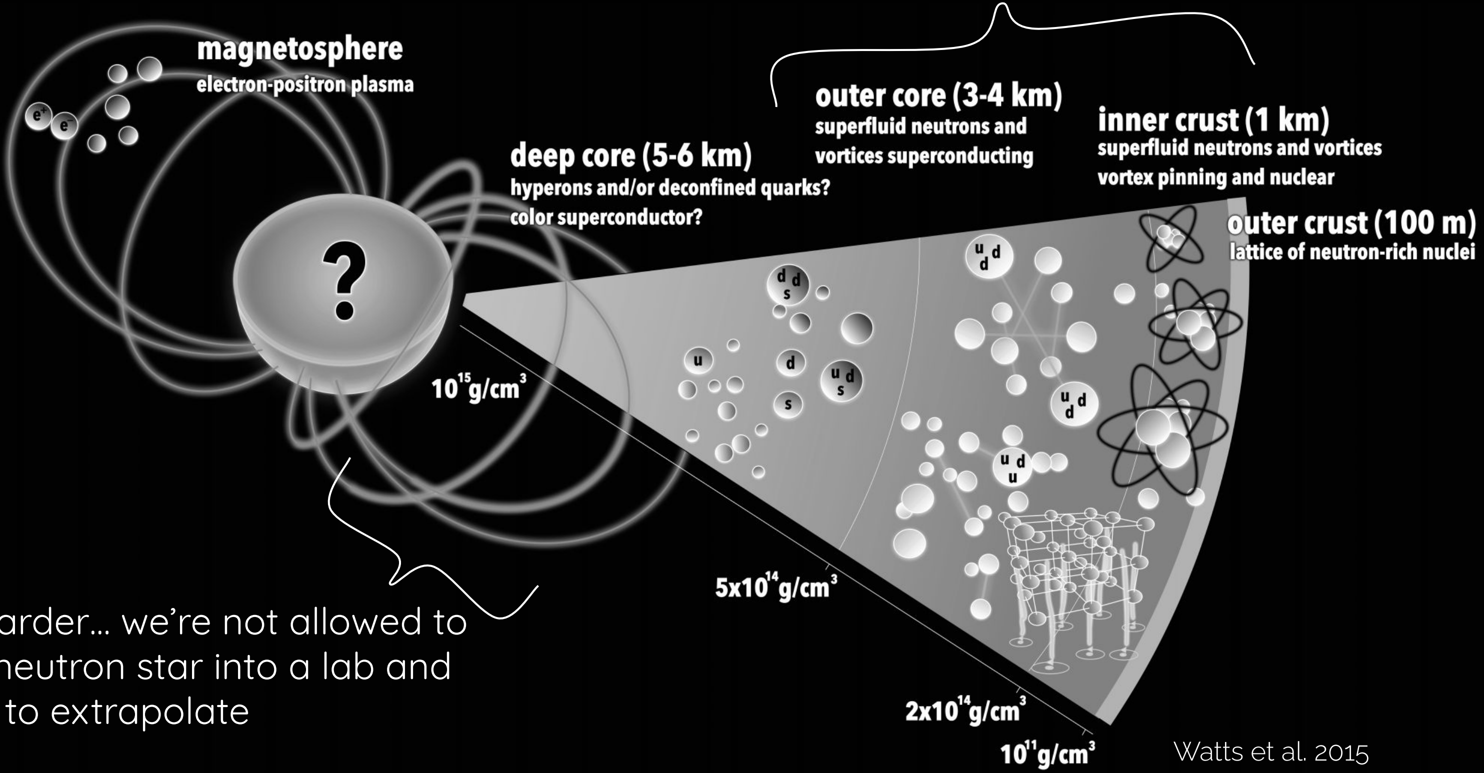
MSP Timing Example: the NS EOS



Watts et al. 2015

MSP Timing Example: the NS EOS

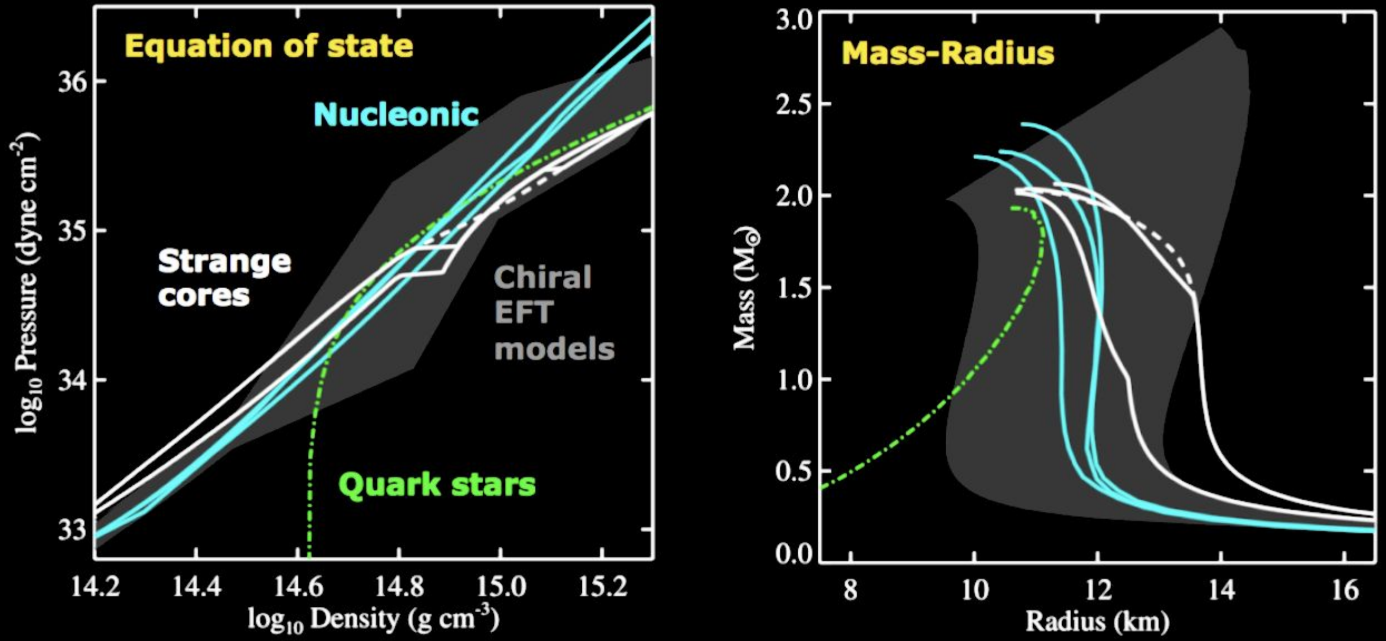
We're doing ok here with many-body calculations based on chiral EFT, lab experiments



This is harder… we're not allowed to bring a neutron star into a lab and it's hard to extrapolate

Watts et al. 2015

The Relativistic Shapiro Delay



Watts et al. 2015

The Relativistic Shapiro Delay

Five Keplerian parameters describe classical delay in binaries and can be measured:

- Projected semimajor axis: $x \equiv a \sin(i) / c$
- Longitude of periastron: ω
- Time of periastron passage: T_0
- Orbital period: P_b
- Orbital eccentricity: e

$$f(m_p, m_c) = \frac{4\pi^2}{G}\frac{(a \sin i)^3}{P_b^2} = \frac{(m_c \sin i)^3}{(m_p + m_c)^2}$$

The Relativistic Shapiro Delay

$$f(m_p, m_c) = \frac{4\pi^2}{G}\frac{(a\sin i)^3}{P_b^2} = \frac{(m_c \sin i)^3}{(m_p + m_c)^2}$$

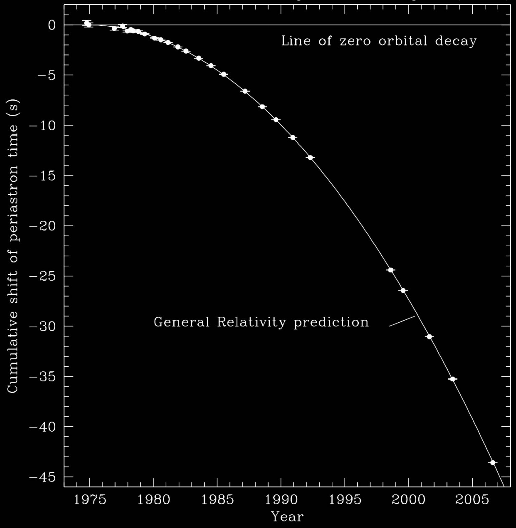
- Still don't have m_c, m_p, i → can't determine masses individually
- Break by measuring post-Keplerian parameters (only possible in a subset of systems):
    - Rate of periastron advance $\dot{\omega}$ and Einstein delay γ (eccentric)
    - Orbital period decay $\dot{P}_b$ (long timing baseline)
    - **Shapiro delay parameters *r*, *s***

The Relativistic Shapiro Delay

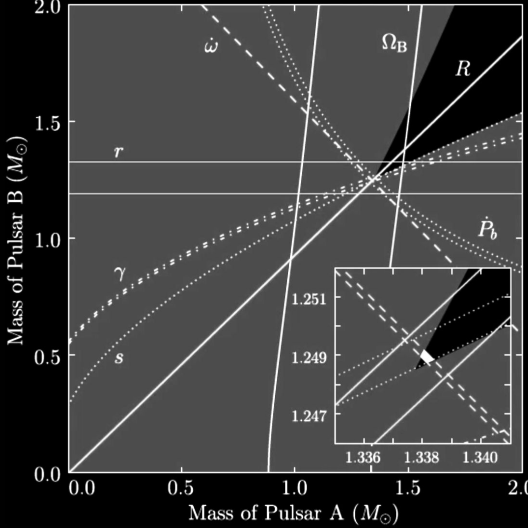
Notable PK measurements:

- B1913+16, the Hulse-Taylor DNS (1975):
  - Compact, eccentric (3 PK; GW energy loss)
- J0737-3039, the double pulsar (Burgay et al. 2003):
  - Most compact, highly inclined; seven measured parameters including M/R
  - Consistent independent of PK choice

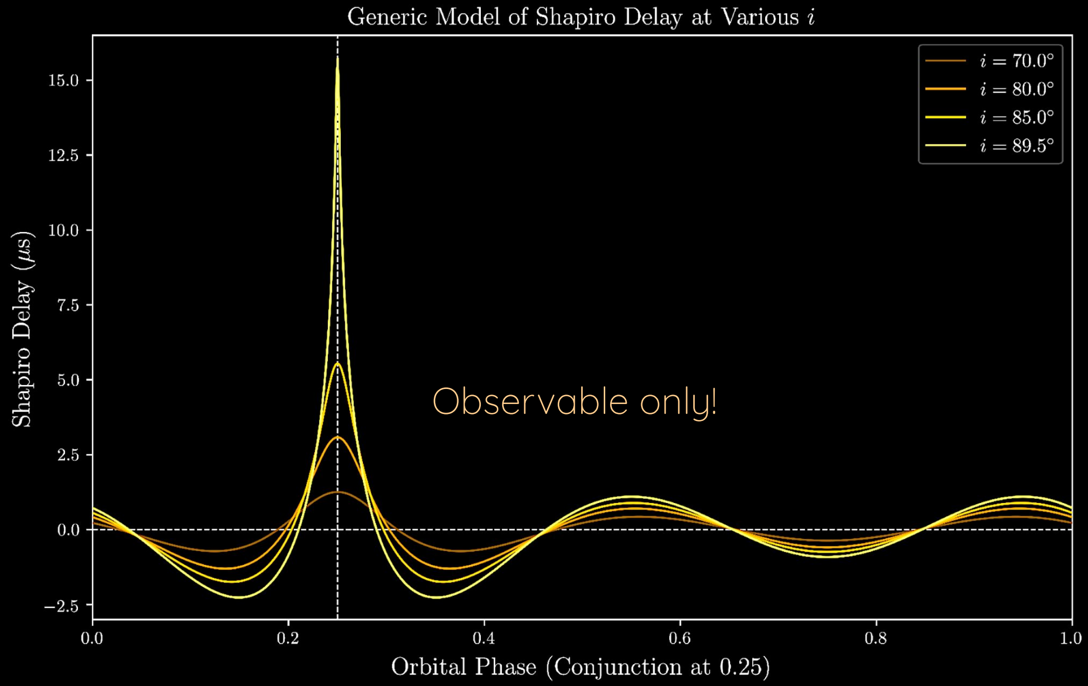
Weisberg, Nice & Taylor (2010)



Kramer et al. 2006 via R. Breton



The Relativistic Shapiro Delay

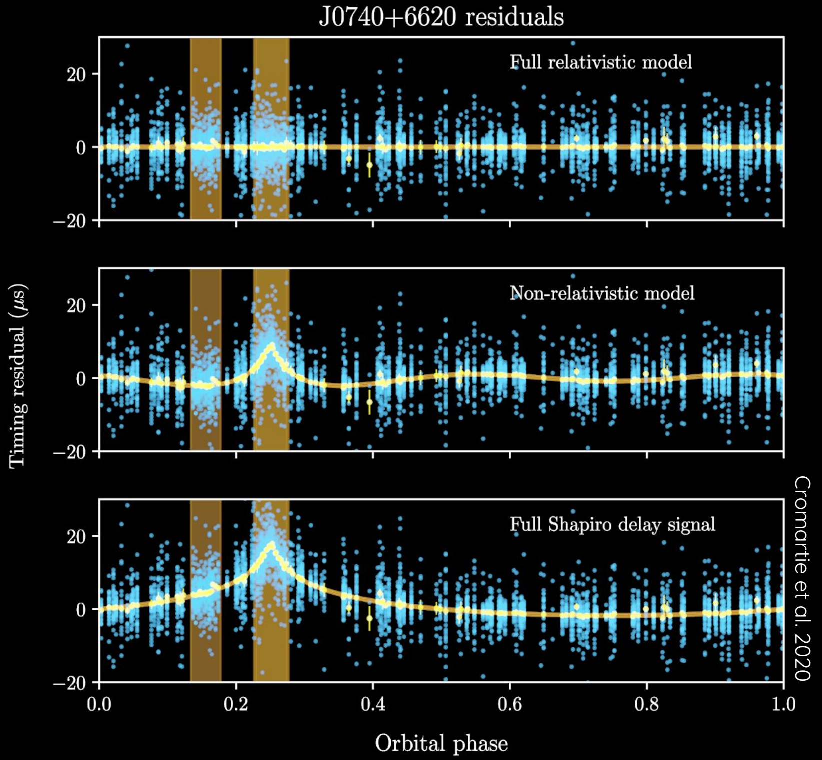


- Shapiro delay occurs at superior conjunction in edge-on binary systems
- “Range” and “shape” PK parameters are directly measurable:

$$r = T_\odot m_2$$

$$s = x \left(\frac{P_\mathrm{b}}{2\pi}\right)^{-2/3} T_\odot^{-1/3} M^{2/3} m_2^{-1}$$

The Relativistic Shapiro Delay for J0740+6620



Cromartie et al. 2020

Long-term **PTA timing** + phase-targeted campaigns:

- Demorest et al. 2010 (J1614-2230):
  - 1.97 ± 0.04 $M_\odot$, 1.928 ± 0.017 $M_\odot$ (Fonseca et al. 2016)
- First ~2 $M_\odot$ NS rules out softer EoS

Cromartie et al. 2020 / Fonseca et al. 2021:

- J0740+6620: m_p ~2.14 ± 0.09 $M_\odot$ (then the most massive NS; Cromartie et al. 2020)
- Higher mass ⟶ also in tension with “exotic” theories (quark matter, hyperons, meson condensates, etc.)

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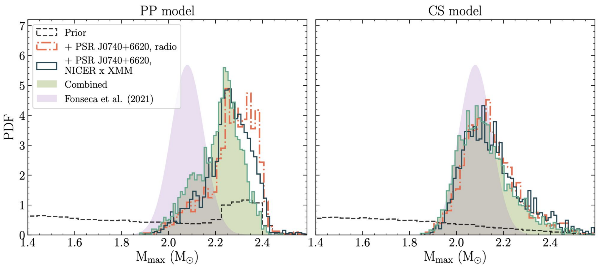
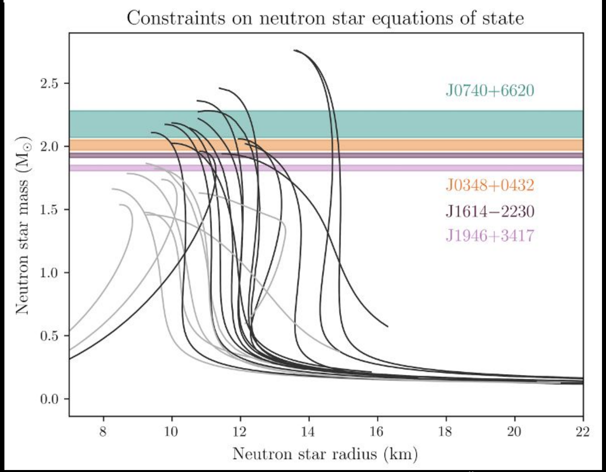
MSP Timing Example: Shapiro Delay



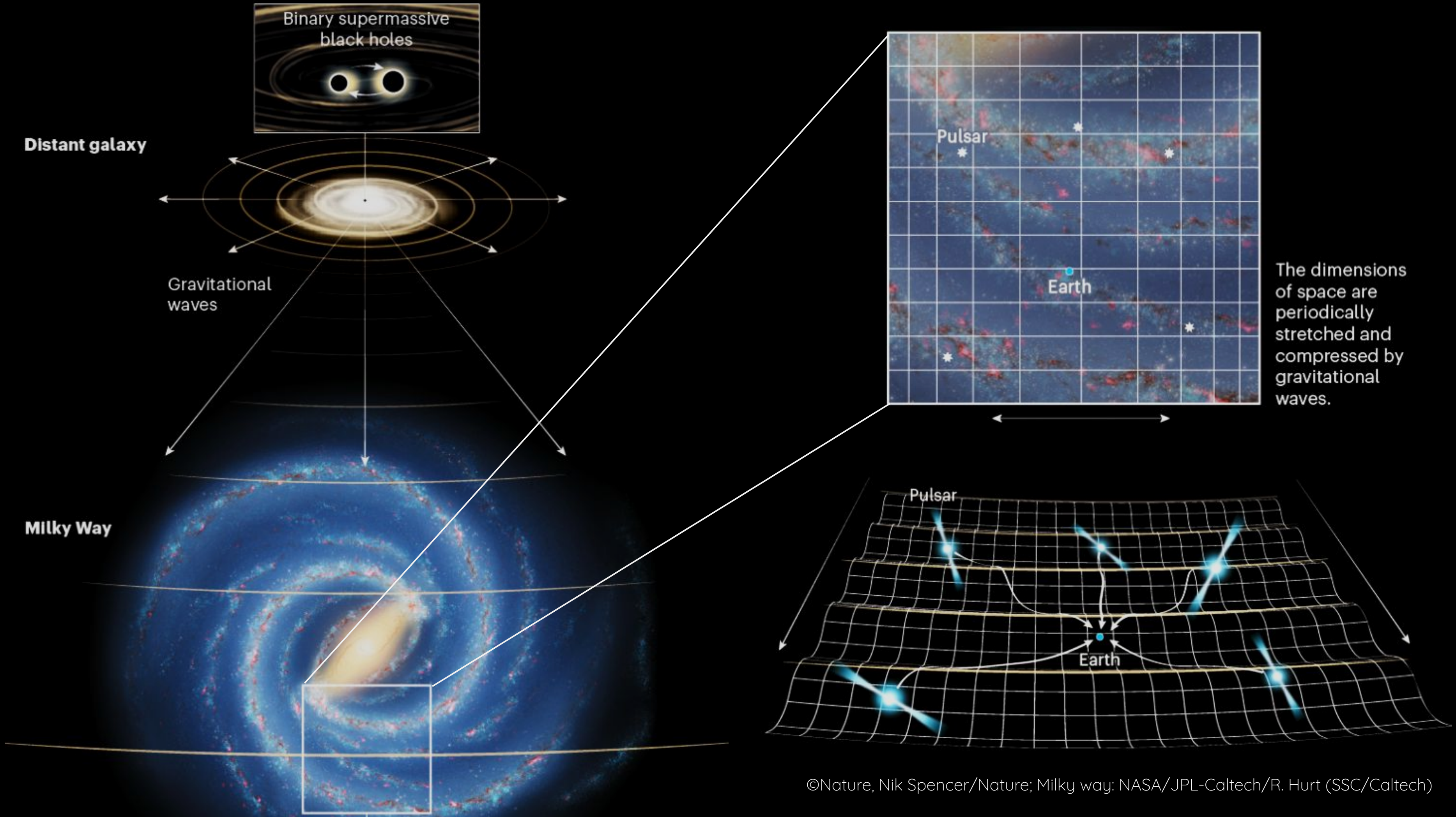


Fonseca & Cromartie based on Özel & Freire 2016

NICER + NANOGrav + XMM (0740):

- Riley et al. 2021:
  - R = 11.29 (+1.20, -0.81) km
- Miller et al. 2021:
  - R = 11.51 (+1.87, -1.13) km
- These analyses significantly constrain the EoS (Raaijmakers et al. 2021; PP model = piecewise polytropic based on 3 density transitions, CS = speed of sound)
- NICER provides constraints for NS pressure at ~2x saturation density

Pulsar Timing Arrays

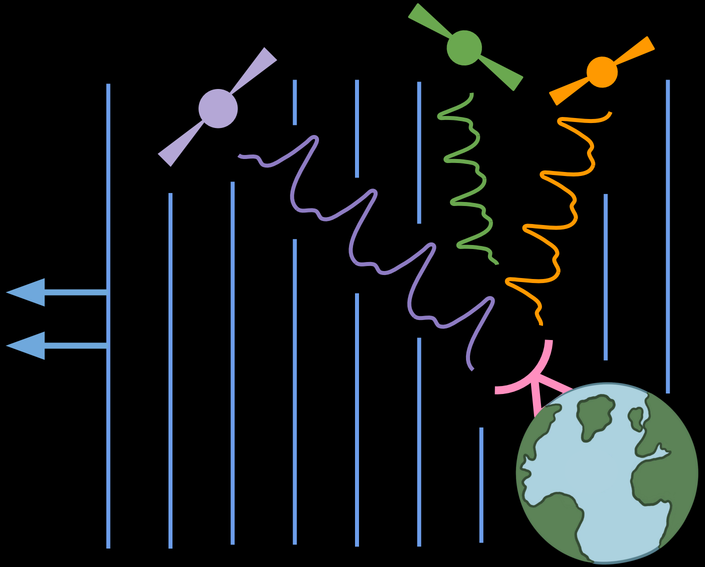


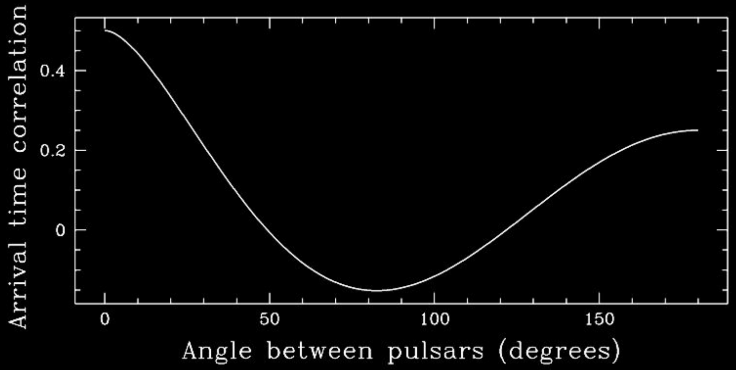
The dimensions of space are periodically stretched and compressed by gravitational waves.

©Nature, Nik Spencer/Nature; Milky way: NASA/JPL-Caltech/R. Hurt (SSC/Caltech)

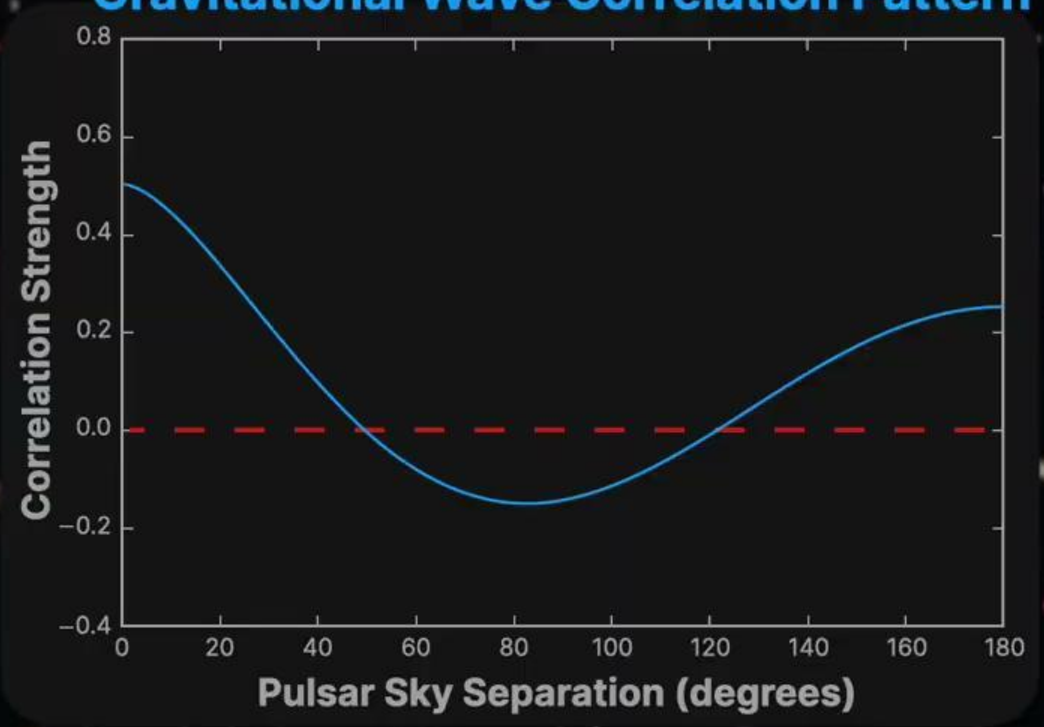
Pulsar Timing Arrays (PTAs)

- 1st goal: detect the stochastic background of nHz gravitational waves (GWs) from SMBBHs
- GWs cause perturbations in spacetime → pulsar “time of arrival” deviations
- Pulsar-Earth baseline pair response is described by the **Hellings and Downs curve**
- Later: continuous waves & exotic signals





Gravitational Wave Correlation Pattern



Interpreting GWB Results

GW strain:

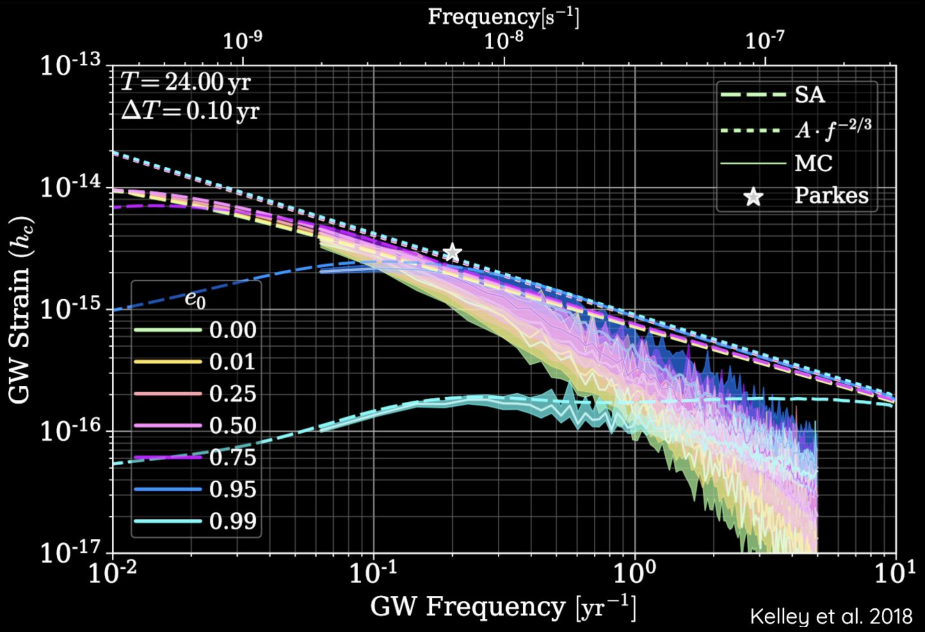
$$h_c(f) = A_{\mathrm{GWB}} \left(\frac{f}{f_{\mathrm{yr}}}\right)^{\alpha}$$

Circular, GW-only emission:
α = -2/3 (Phinney 2001) → γ = 13/3

Cross-power spectral density:

$$S_{ab}(f) = \Gamma_{ab} \frac{{A_{\mathrm{GWB}}}^2}{12\pi^2} \left(\frac{f}{f_{\mathrm{yr}}}\right)^{-\gamma} f_{\mathrm{yr}}^{-3}$$

Γ = overlap reduction function
quadrupolar: Hellings & Downs (1983)
dipolar / monopolar: SSE, clock errors

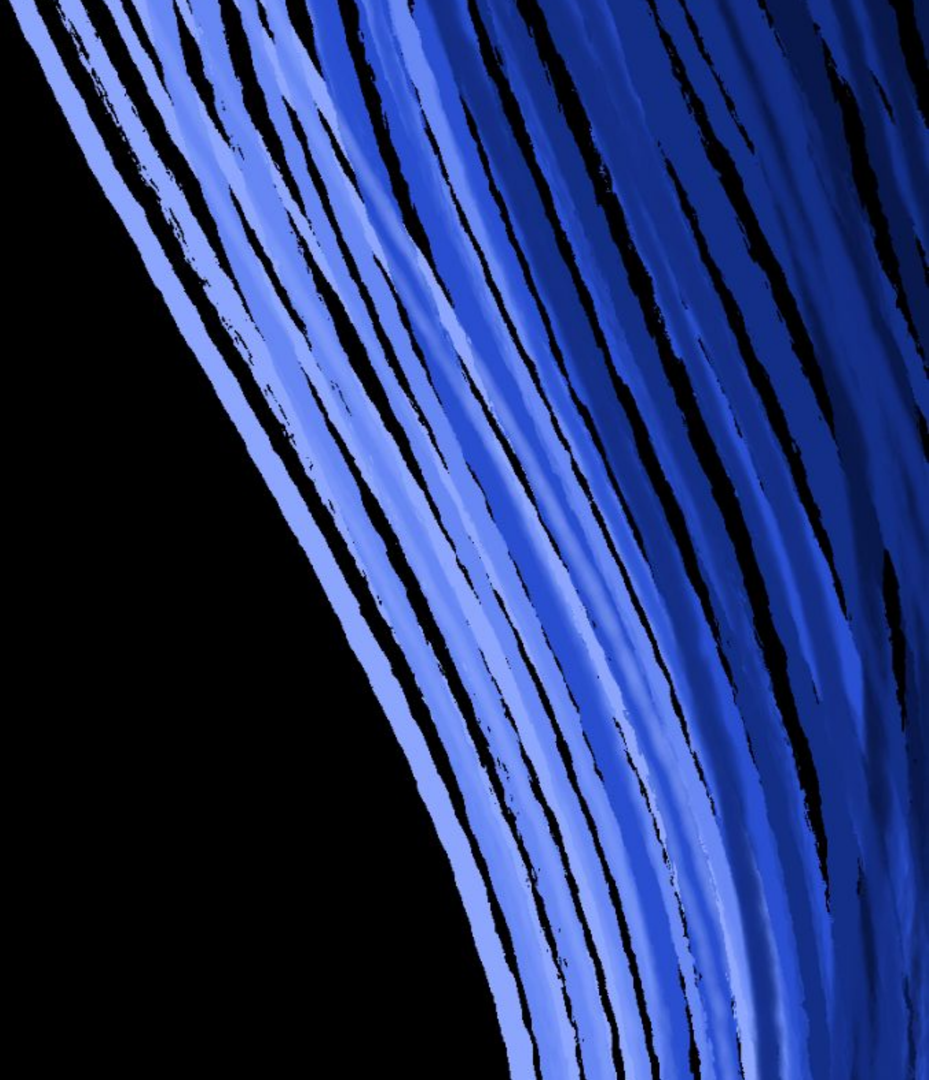


Kelley et al. 2018

Turnover in PL = astrophysics, characterize once HD correlations are detected

Amplitude → rates

Intermission with a video



NANOGrav & the IPTA

NANOGrav

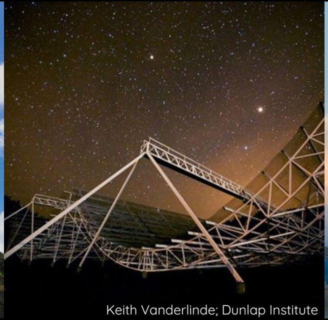
2021 Fall collaboration meeting

- North American Nanohertz Observatory for Gravitational Waves (est. 2007)
- NSF Physics Frontiers Center (PFC)
- >80 institutions, >180 scientists
- Green Bank Telescope (GBT), Very Large Array (VLA), Canadian Hydrogen Intensity Mapping Experiment (CHIME), Arecibo

NANOGrav
Physics Frontiers Center

GBO/AUI/NSF

Thankful Cromartie



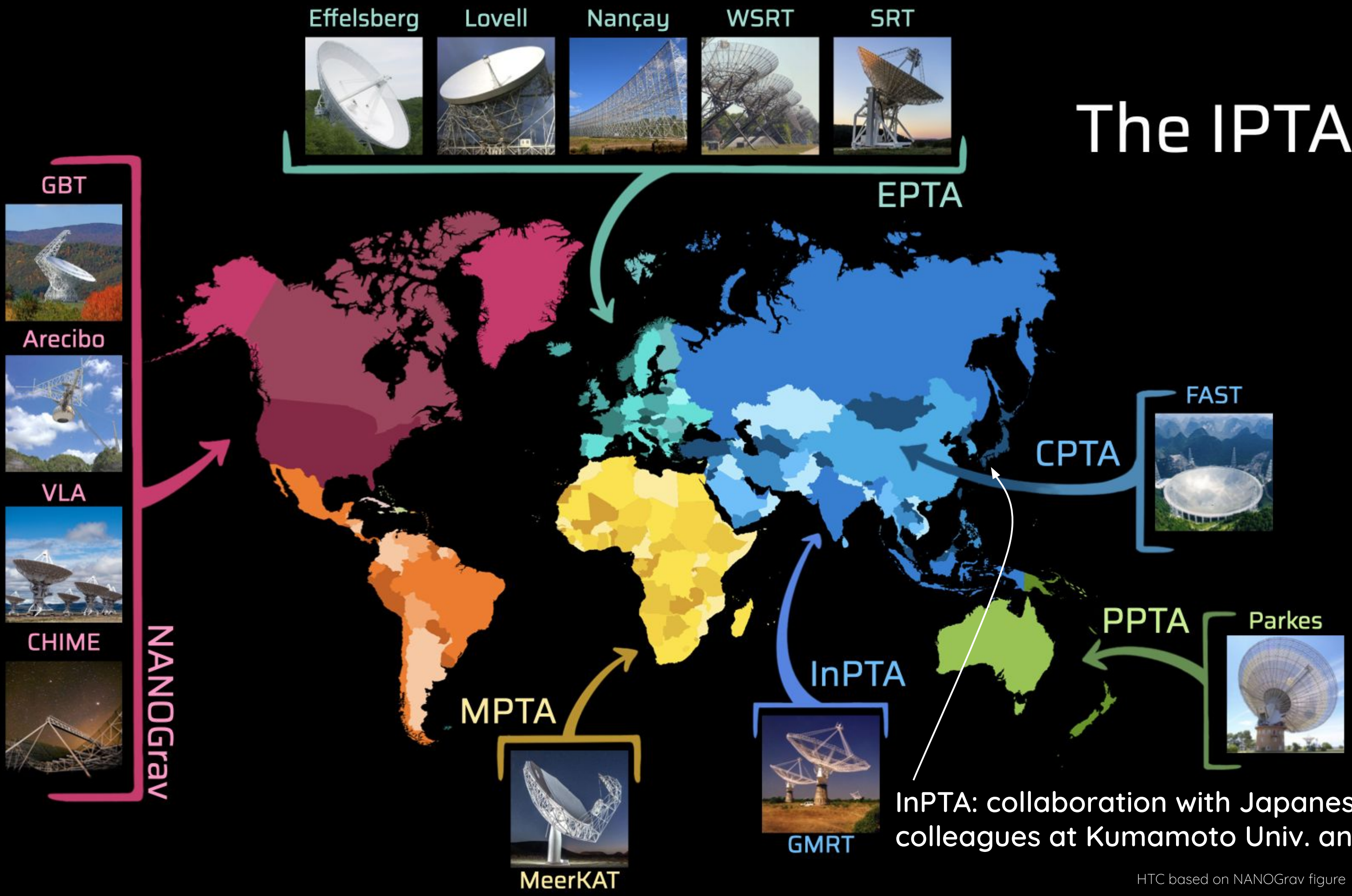
Keith Vanderlinde; Dunlap Institute

NRAO

The IPTA

HTC based on NANOGrav figure

The IPTA



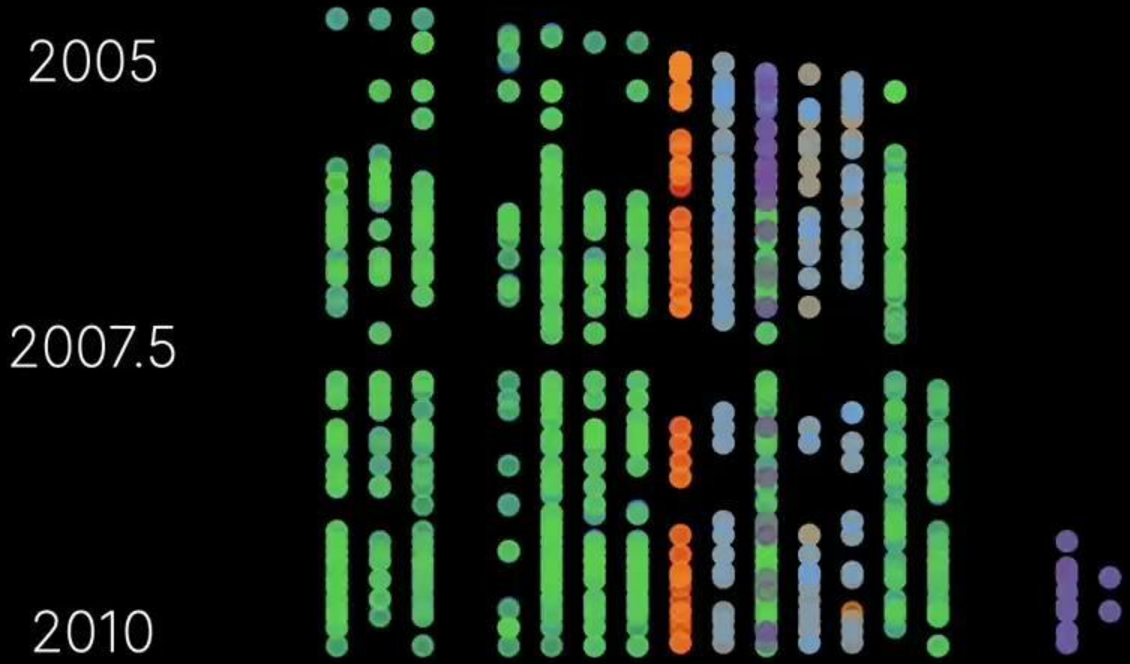
InPTA: collaboration with Japanese colleagues at Kumamoto Univ. and elsewhere

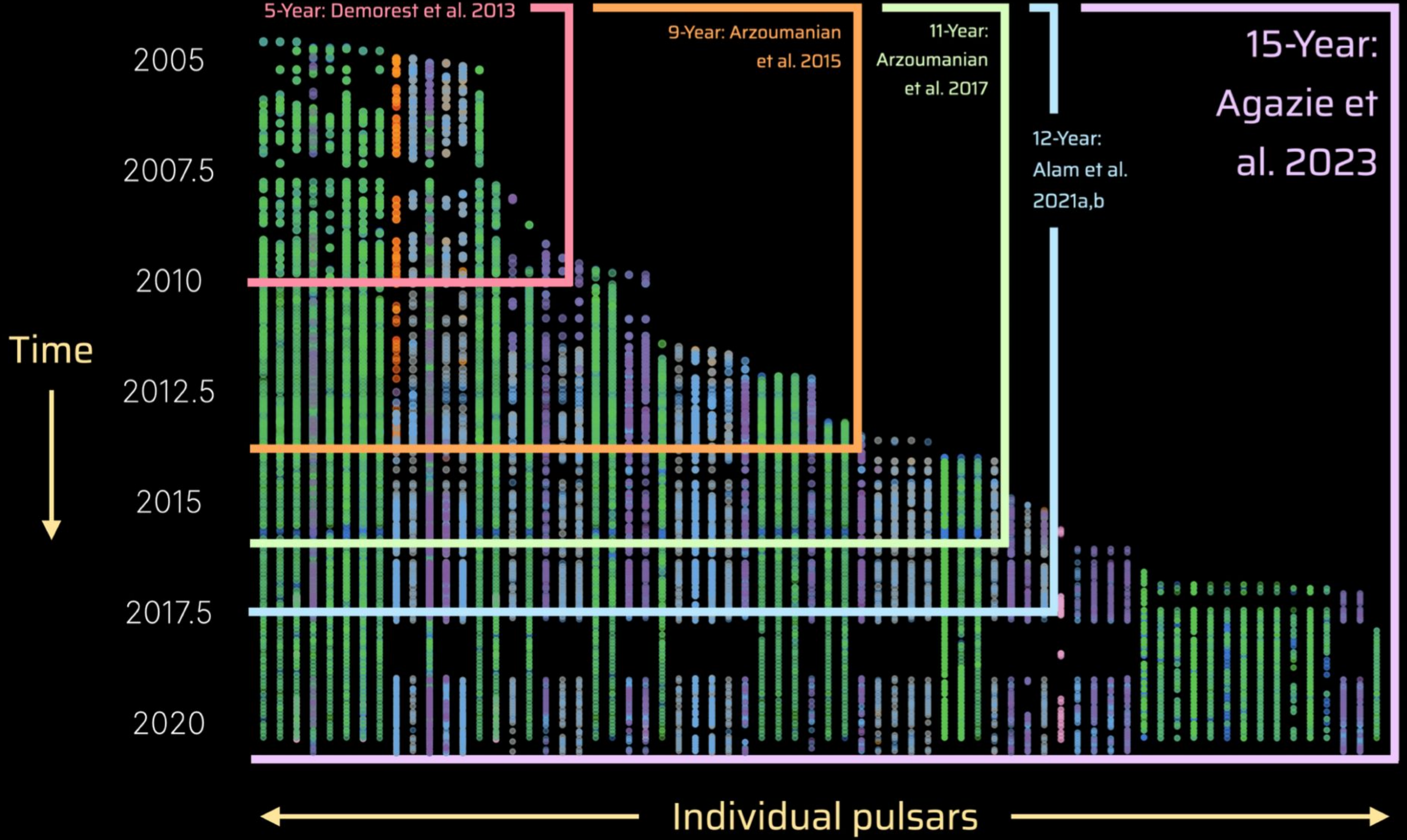
HTC based on NANOGrav figure

The (Current) NANOGrav Observing Program

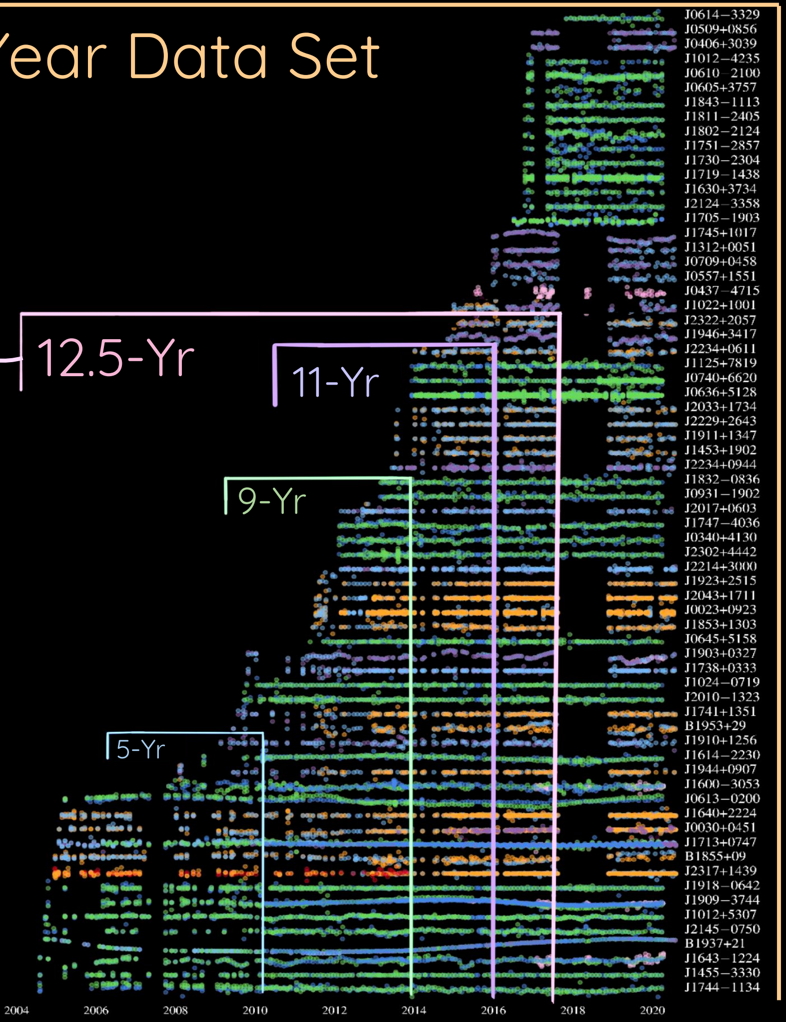
After the loss of Arecibo (half of our sensitivity), we restructured:

- **GBT monthly:** almost 80 pulsars (600 hr/yr; 18 dual-band, 53 L-only)
- **VLA monthly:** 15 pulsars at S-band (2-4 GHz, 120 hr/yr)
  - All but 1 overlap w/GBT source list
- **CHIME daily:** 53 pulsars at 400-800 MHz
  - All overlap w/GBT source list


2005
2007.5
2010


5-Year: Demorest et al. 2013
9-Year: Arzoumanian et al. 2015
11-Year: Arzoumanian et al. 2017
12-Year: Alam et al. 2021a,b
15-Year: Agazie et al. 2023
2005
2007.5
2010
2012.5
2015
2017.5
2020
Time
Individual pulsars

15-Year Data Set



47 MSPs, WB data set, common red noise process (Arzoumanian et al. 2020)

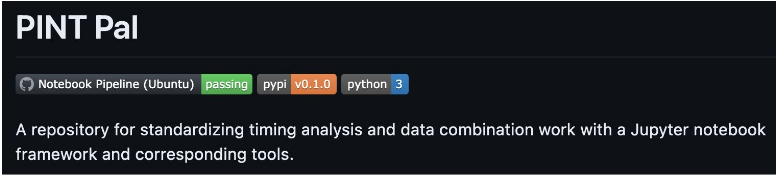
- 68 MSPs
- Narrowband and wideband
- Use of new timing software, pipeline
- ~16 years of data
- VLA data, J0437-4715
- End of Arecibo and GBT’s GUPPI backend

`PINT` & the `pint_pal` Pipeline

- `PINT` (“`PINT` is not `TEMPO3`”) – `github.com/nanograv/PINT`
- Luo et al. 2021

Why a pipeline?

- Many pulsars! $N_{\mathrm{PSR}} T^{1/2} \sigma^{-3/13}$
  - We want 200 MSPs; currently ~80
- New techniques, instruments, data combination: reliant on PINT and WB timing
- Transparency, accessibility to scientists (including students) and the public
- `github.com/nanograv/pint_pal`



PINT Pal

A repository for standardizing timing analysis and data combination work with a Jupyter notebook framework and corresponding tools.

Science Results

The NANOGrav 11 & 12.5-Year GWB

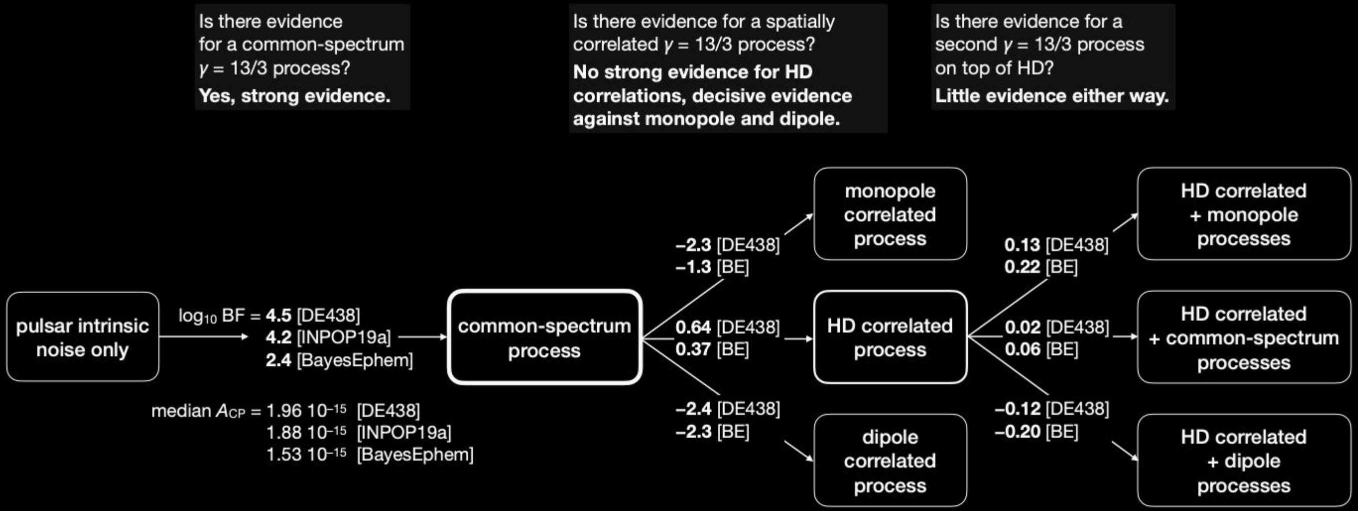
11-Year data set (Arzoumanian et al. 2018): A GWB upper limit: $< 1.45 \times 10^{-15}$ at a frequency of $f = 1\ \mathrm{yr}^{-1}$

- Vallisneri et al. 2020 (BayesEphem) to deal with Jupiter orbital elements; no longer an issue in our analyses (Juno!)
- Position of observatory wrt Solar System Barycenter ~few cm (<ns)
- This correction is important for timing delay measurements
- Corrected 11-year SSE ~ 1.94×10^{-15}
- Corrected for uniform prior on IRN amplitude ~ **2.4×10^{-15}**
- Astrophysics over-interpreted


NASA Juno

The NANOGrav 11 & 12.5-Year GWB

12.5-Year data set (Arzoumanian et al. 2020): First CURN (power law with common amplitude and spectral index across pulsars) detection, but no significant HD correlations (median amplitude **1.92×10^{-15}**)



Is there evidence for a common-spectrum $\gamma = 13/3$ process?
Yes, strong evidence.

Is there evidence for a spatially correlated $\gamma = 13/3$ process?
No strong evidence for HD correlations, decisive evidence against monopole and dipole.

Is there evidence for a second $\gamma = 13/3$ process on top of HD?
Little evidence either way.

pulsar intrinsic noise only

$\log_{10}$ BF = **4.5** [DE438]
4.2 [INPOP19a]
2.4 [BayesEphem]

median A_{CP} = $1.96\ 10^{-15}$ [DE438]
$1.88\ 10^{-15}$ [INPOP19a]
$1.53\ 10^{-15}$ [BayesEphem]

common-spectrum process

–2.3 [DE438]
–1.3 [BE]

monopole correlated process

0.64 [DE438]
0.37 [BE]

HD correlated process

–2.4 [DE438]
–2.3 [BE]

dipole correlated process

0.13 [DE438]
0.22 [BE]

HD correlated + monopole processes

0.02 [DE438]
0.06 [BE]

HD correlated + common-spectrum processes

–0.12 [DE438]
–0.20 [BE]

HD correlated + dipole processes

15-Year Results — June 2023

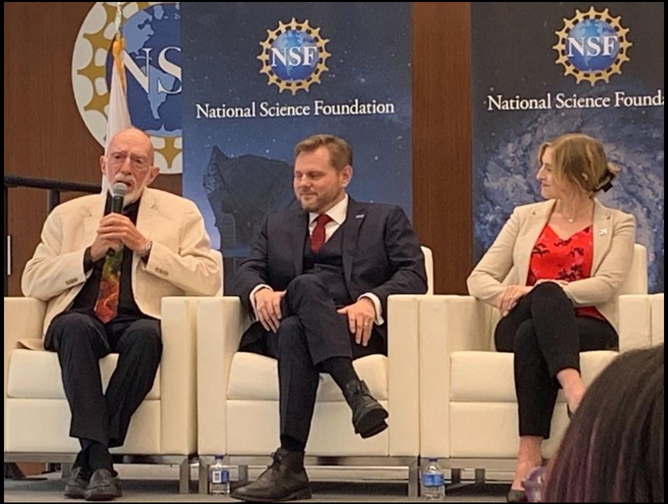
- NANOGrav and the IPTA simultaneously released their GWB search papers
- NANOGrav special issue in ApJL has many papers! Take a look :) See https://nanograv.org/15yr/Summary for summaries of the papers mentioned here
- We'll go over the data set, GWB search, astrophysics, and BSM conclusions

Scientists riding high on evidence of space-time waves

Teams concur on key element of Einstein's theory

BY JOEL ACHENBACH AND VICTORIA JAGGARD

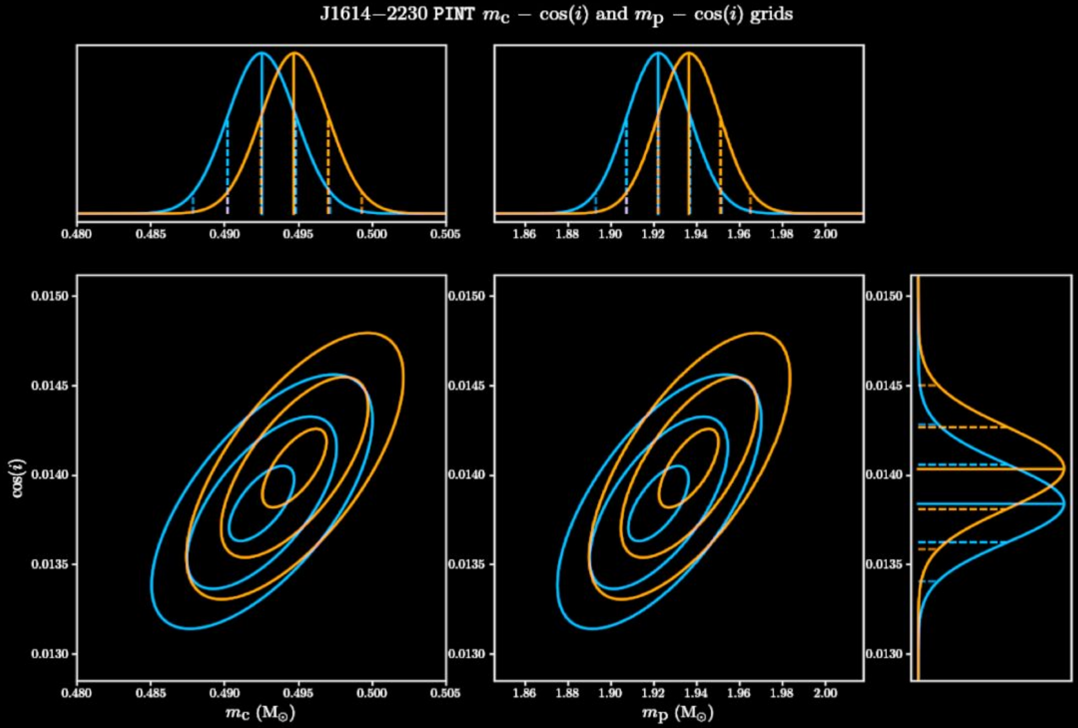
were unveiled late Wednesday. The discovery seems to affirm an astounding implication of Albert



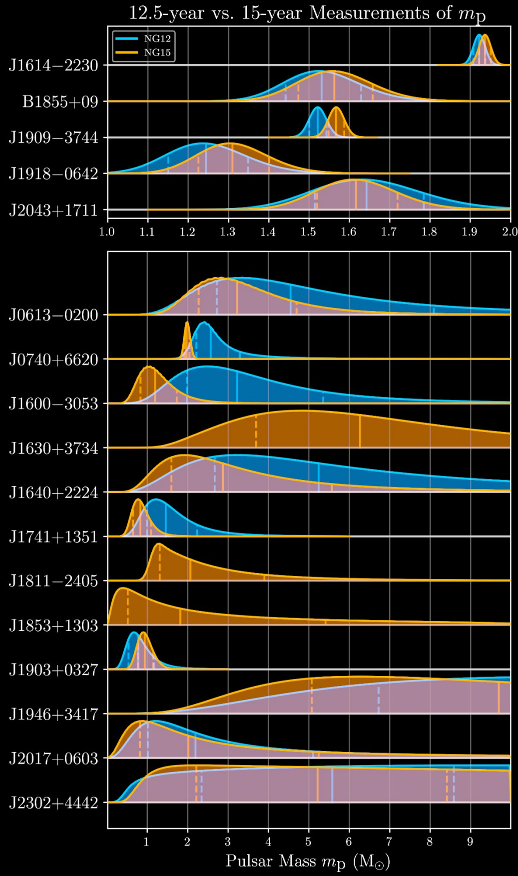
The NANOGrav 15yr Data Set: Observations and Timing of 68 Millisecond Pulsars

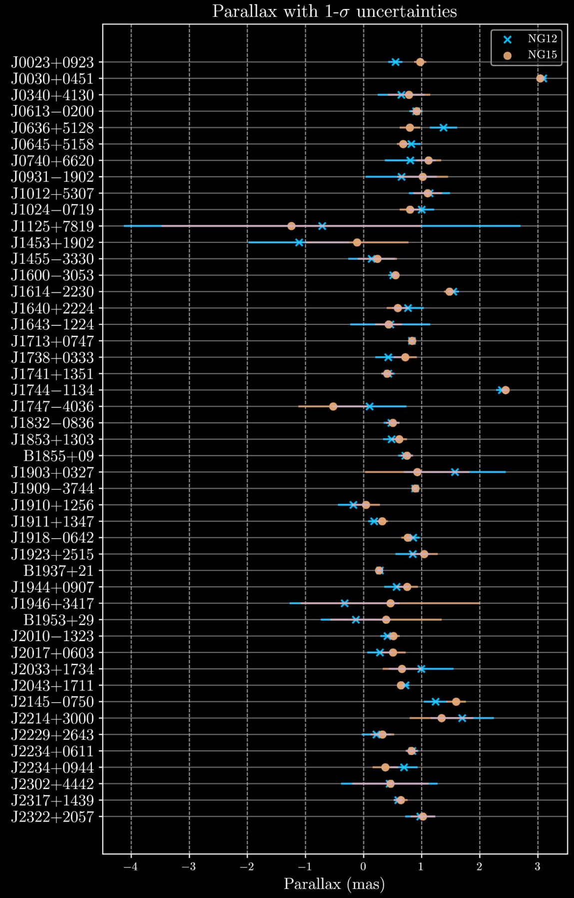
NB & WB data, synergistic science (e.g. NS masses):

- J0740+6620: slight decrease but NANOGrav m_p not state of the art
- J1614-2230: slight m_p increase, addition of RN?
- Possible high-mass sources including J1630+3734
- 5 borderline m_p measurements in new GBT campaign



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

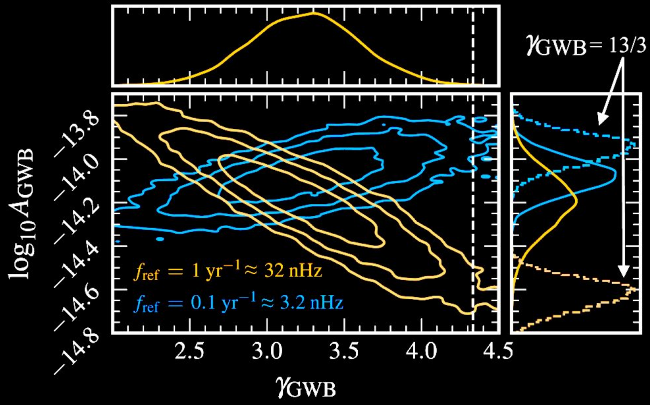

12.5-year vs. 15-year Measurements of m_{p}

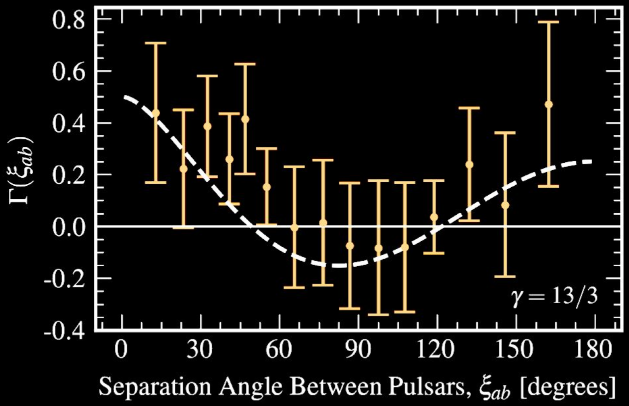

Parallax with 1-σ uncertainties

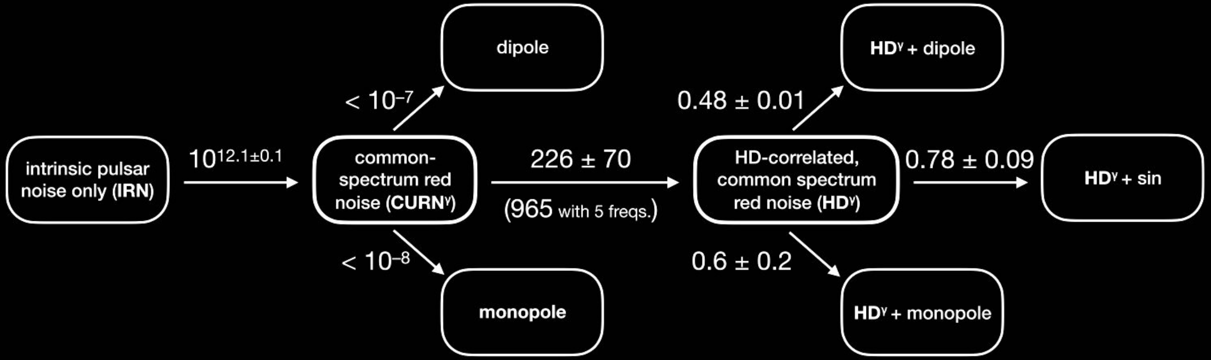
NANOGrav Physics Frontiers Center

U.S. NAVAL RESEARCH LABORATORY

The NANOGrav 15yr Data Set: ***Evidence for*** a Gravitational-Wave Background







intrinsic pulsar noise only (IRN) → $10^{12.1\pm0.1}$ → **common-spectrum red noise (CURN$^{\gamma}$)**

common-spectrum red noise (CURN$^{\gamma}$) → < 10^{-7} → **dipole**

common-spectrum red noise (CURN$^{\gamma}$) → < 10^{-8} → **monopole**

common-spectrum red noise (CURN$^{\gamma}$) → 226 ± 70 (965 with 5 freqs.) → **HD-correlated, common spectrum red noise (HD$^{\gamma}$)**

HD-correlated, common spectrum red noise (HD$^{\gamma}$) → 0.48 ± 0.01 → **HD$^{\gamma}$ + dipole**

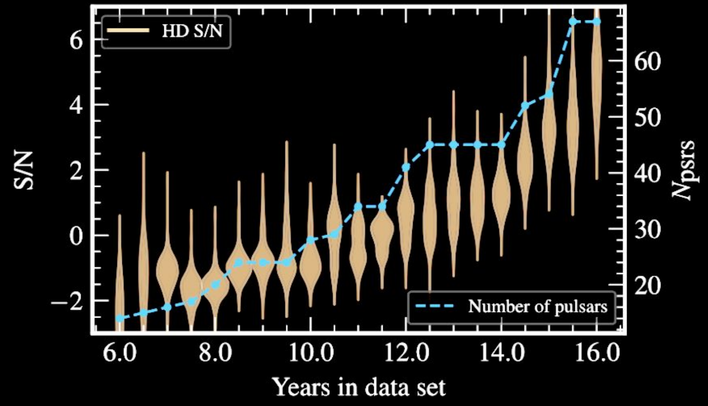
HD-correlated, common spectrum red noise (HD$^{\gamma}$) → 0.78 ± 0.09 → **HD$^{\gamma}$ + sin**

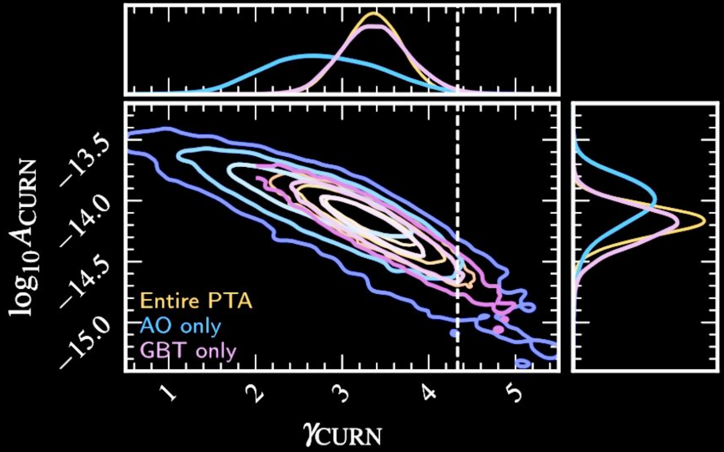
HD-correlated, common spectrum red noise (HD$^{\gamma}$) → 0.6 ± 0.2 → **HD$^{\gamma}$ + monopole**

The NANOGrav 15yr Data Set: ***Evidence for*** a Gravitational-Wave Background

- 67 pulsars in the 15 yr data set (>3 yr); total time span of 16.03 yr
- Common-spectrum stochastic signal gains greater significance (BF~10^{12})
- First compelling **evidence** of Hellings–Downs correlations, using both Bayesian and frequentist detection statistics
  - False-alarm probabilities of $p = 10^{-3}$ and $p = 5 \times 10^{-5}$ to 1.9×10^{-4} (**3-4σ**)
- HD significance increases up to 5 freq bins; essentially consistent with a power law

"How do you know you're not wrong?"





The NANOGrav 15yr Data Set: Bayesian Limits on Gravitational Waves from Individual Supermassive Black Hole Binaries

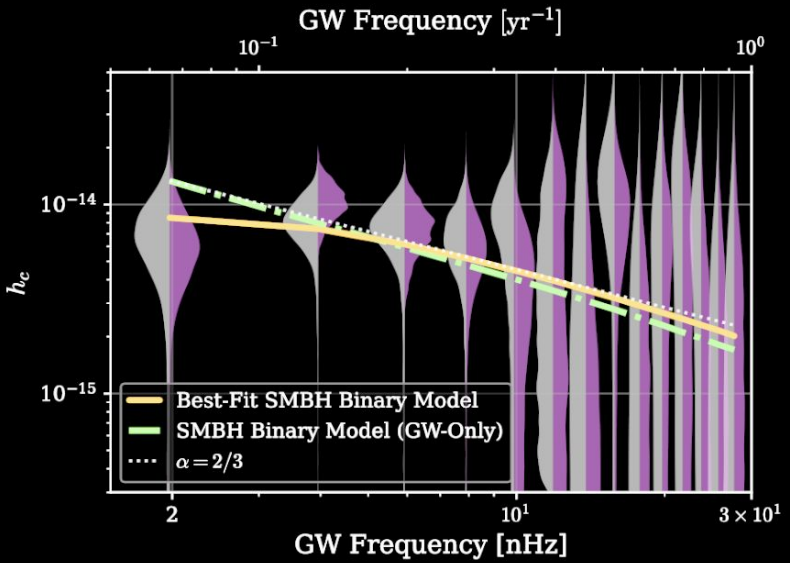
- No serious candidates, but able to put 95% upper limit on CW amplitude (8×10^{-15} at 6 nHz, the most sensitive frequency)

The NANOGrav 15yr Data Set: Search for Anisotropy in the Gravitational-Wave Background

- Do not find *strong* evidence of anisotropy on either large or small angular scales
- IPTA DR3, continued observing
- Evidence of anisotropy would support GWB from SMBBHs (many BSM = isotropic)

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

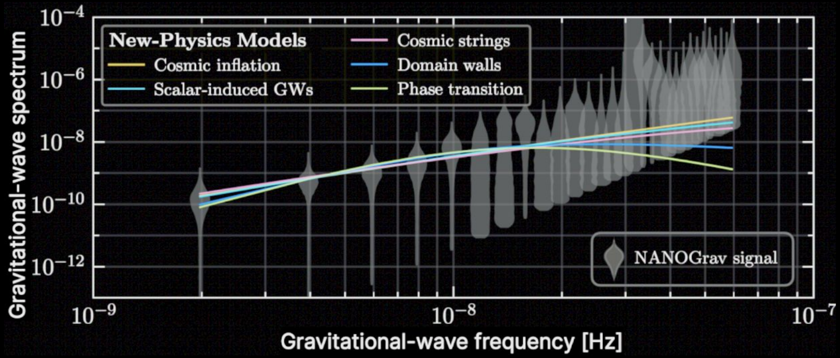
- 15-year results consistent with many models of SMBBH evolution, but still consistent with signal coming from SMBBHs - **cannot guarantee, though**
- Low-frequency part of spectrum hints that interactions with stars and gas of host might be necessary for evolution (spectral turnover at low freqs)
- GW amplitude higher than expected from most models — more frequent or more massive mergers
- Signal dominated by most massive, high-mass-ratio inspirals
- Typical redshifts z = 0.15 - 0.9
- Separations of 0.1 - 0.01 parsec



The NANOGrav 15yr Data Set: Search for Signals from New Physics

Open questions: matter-antimatter asymmetry, dark matter / dark energy, neutrino masses, etc.
PTAs might help! Many BSM theories predict GWs in the nHz band

- These GWs: analogous to the CMB but way before recombination = *very* early universe
- Afzal et al. 2023 covers: cosmic inflation, scalar-induced GWs, first-order phase transitions, cosmic strings, and domain walls
- NG BSM paper considers if the signal is due to a BSM theory or maybe due to a **combination** of SMBHs and BSM effects



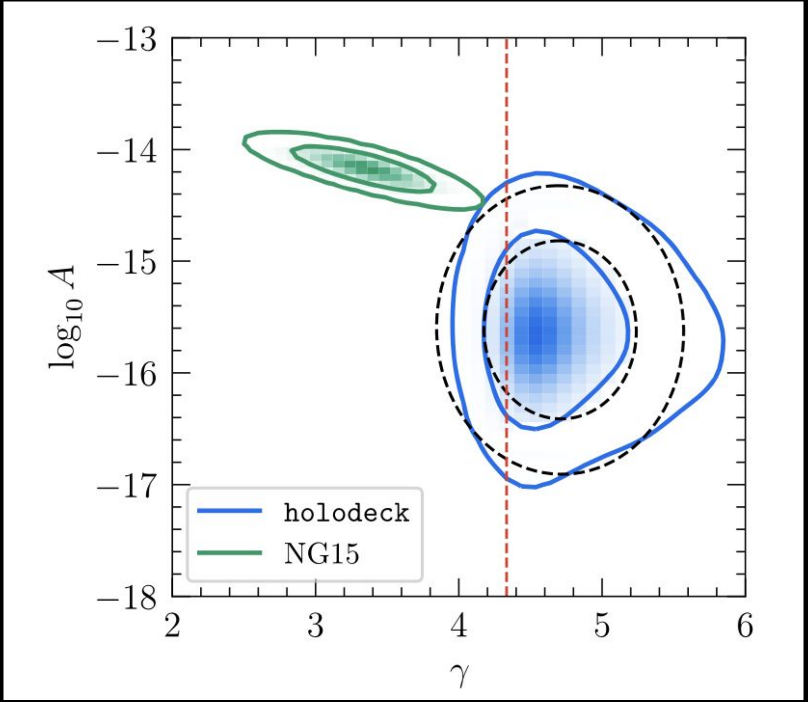
The NANOGrav 15yr Data Set: Search for Signals from New Physics

All models considered are consistent with the observed GWB, except stable cosmic strings from field theory (and deterministic models like fuzzy DM)

Many combined SMBH/BSM models also get good results, with BF ~10-100

One reason for high BF is that the actual GWB signal doesn't agree perfectly with the model used in the BSM paper!

> *"We stress that Bayes factors for additional models beyond the SMBHB interpretation are highly dependent on the range of priors with which these models are introduced. Thus, one should not assign too much meaning to the exact numerical values of the Bayes factors reported in this work."*



Their SMBH models use only circular binaries, GW-driven emission at <1pc; tension between holodeck and NG15

The NANOGrav 15yr Data Set: Search for Signals from New Physics

Inflation

Explains homogeneity of universe on cosmological scales, seeds for formation of structure

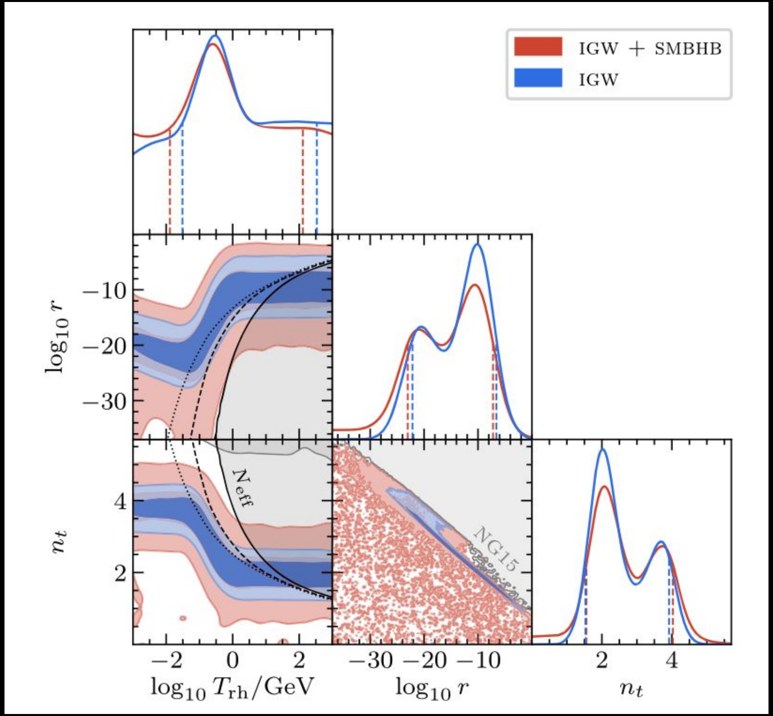
Inflation → amplifies tensor perturbations = stochastic GWs

Model-independent analysis (no microphysics); IGW is 4 params

IGW fits a bit better than SMBHB (BF~8.8) – IGW has more freedom!

Gray regions disfavored

Lots of interesting regions of parameter space; unclear if it's possible to explicitly pick out microscopic models



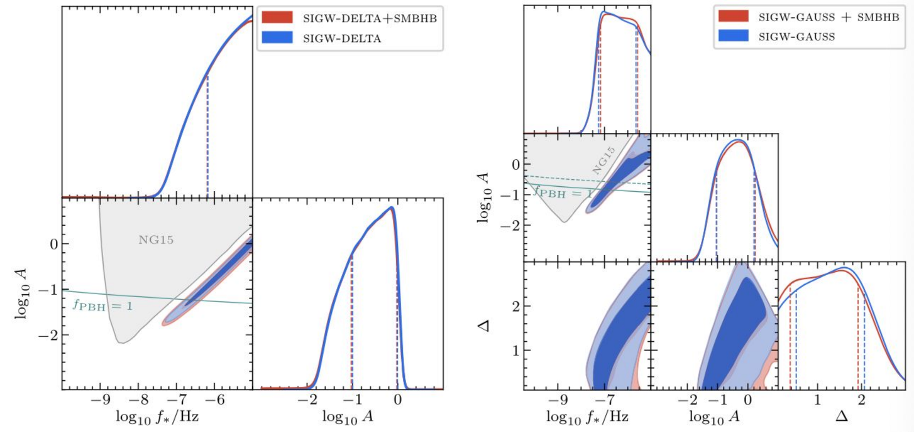
The NANOGrav 15yr Data Set: Search for Signals from New Physics

Scalar-induced GWs

Primordial scalar power spectrum measured by CMB observations; extrapolate to short scales, and you get very little (red-tilted power spectrum)

Different if you have different inflationary model: stage of inflation close to an inflection point in the scalar potential → amplifies scalar perturbations

Large first order scalar perturbations → second order tensor perturbations (coupled)



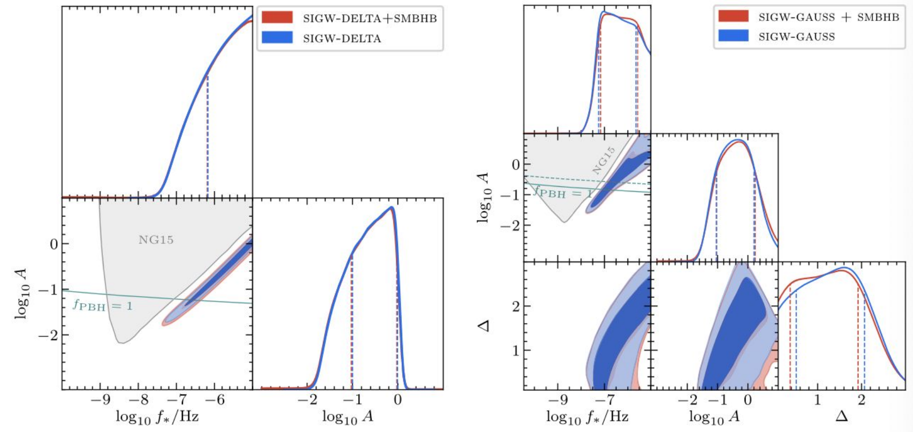
The NANOGrav 15yr Data Set: Search for Signals from New Physics

Scalar-induced GWs

SIGWs actually fit better than even IGWs (SIGW deviates from a power law and provides better fit across all of NG's GW freq sensitivity range)

Adding SMBHs also doesn't help here

Large region of space (above teal line) that overpredicts primordial black hole formation – lots of debate



The NANOGrav 15yr Data Set: Search for Signals from New Physics

Cosmological phase transitions

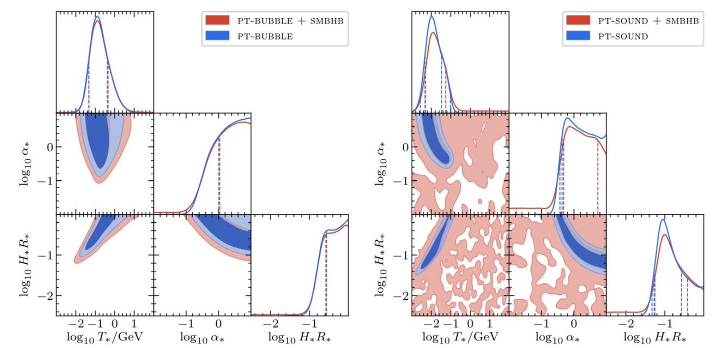
Phase transitions triggered by quantum or thermal fluctuations → scalar field tunnel through or fluctuate over the barrier, nucleates bubbles within which the scalar field is the true vacuum configuration

If big enough, bubbles expand in the surrounding plasma which is in the false/metastable vacuum

Expansion/collision of bubbles + sound waves generated in plasma make primordial GWB

Strong and slow phase transition preferred

Also better fit than SMBH data alone, *benefits* from SMBH though (for the sound model) - adds power to low freq in GW spectrum



The NANOGrav 15yr Data Set: Search for Signals from New Physics

Cosmic strings

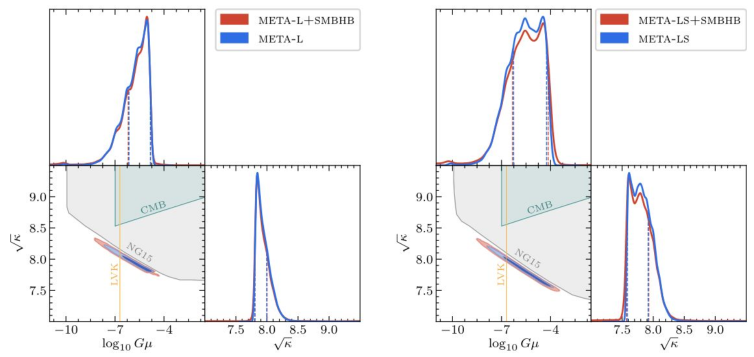
1D topological defects from early universe due to cosmological phase transition

Focus on strings from spontaneous breaking of a local U(1) symmetry which happens in lots of particle physics models; ordinary and metastable cosmic strings

After formation, cosmic strings enter scaling regime where energy in the network remains a constant fraction of the critical energy density: interconnect and form loops (with some tension and decay) that produce GWs

NG15 doesn't support stable strings; much of parameter space ruled out by NG15 , CMB, LVK

GW signal from *superstrings* not well understood and needs more work (but somewhat supported)



The NANOGrav 15yr Data Set: Search for Signals from New Physics

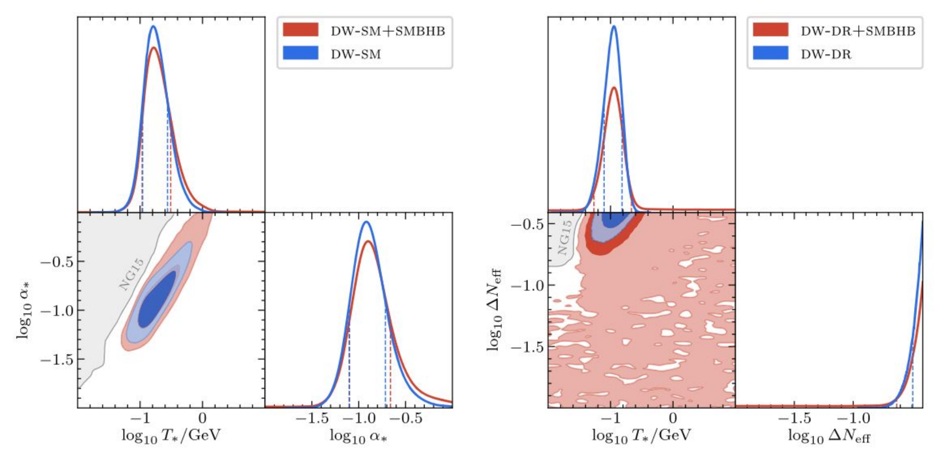
Domain walls

2D topological defects that form when a phase transition results in the spontaneous breaking of a discrete symmetry

Each Hubble volume contains O(1) domain walls. GWs from domain walls changing/shrinking

GWB dominated by emission right before decay of the domain wall network

Decay channels: dark radiation (BF~1.6) or SM particles (BF~15)



The NANOGrav 15yr Data Set: Search for Signals from New Physics

Deterministic signals from new physics: *no statistical support in NG15*

Ultra-light/fuzzy dark matter:

Freq of ULDM signal $\propto$ ULDM mass (NG sensitivity 10^{-23} eV < m < 10^{-20} eV); other astrophysics probes up to 10^{-19} eV

Two cool searches with scalar ULDM: periodic oscillations in fundamental constants (particle masses / couplings):

1. Pulsar spin fluctuations (particle mass fluctuations change moment of inertia of pulsar)
2. Reference clock shifts (observatory clocks are referenced to cesium atomic clocks)

DM substructures:

Structures seeded during inflation and imprinted onto DM density field

Population of PBHs could doppler shift apparent pulsar spin freq (pull of a passing PBH)

(GWB decreases sensitivity to PBH signal)

The NANOGrav 15yr Data Set: Search for Signals from New Physics

Conclusions:

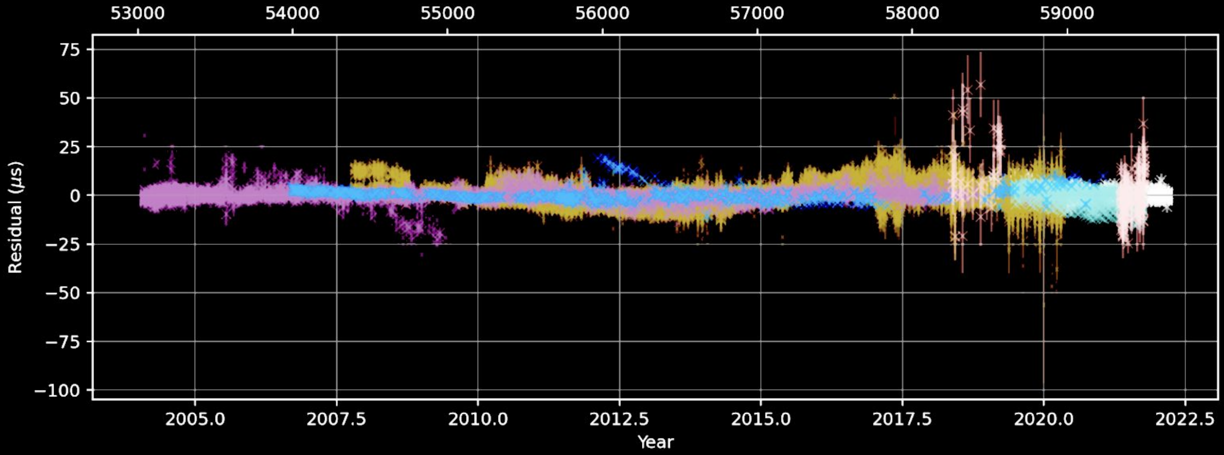
PTAs can constrain parameter space for many BSM theories

All but stable cosmic strings of FT origin can’t be ruled out, some fit “better” than SMBH

Caution against thinking it supports the GWB not being astrophysical. We have to keep observing and characterizing the GWB!

Results from our IPTA Colleagues

- PPTA: strong evidence for common red noise, some evidence for HD
- EPTA + InPTA: same, but stronger evidence for HD (depending on what data are included)
- CPTA: evidence for HD correlations but data span much shorter
- New results from MPTA coming soon
- DR3 ongoing!

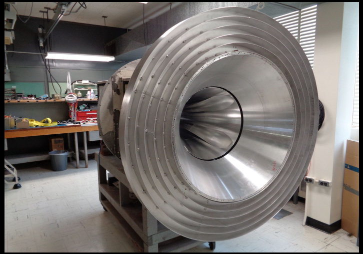


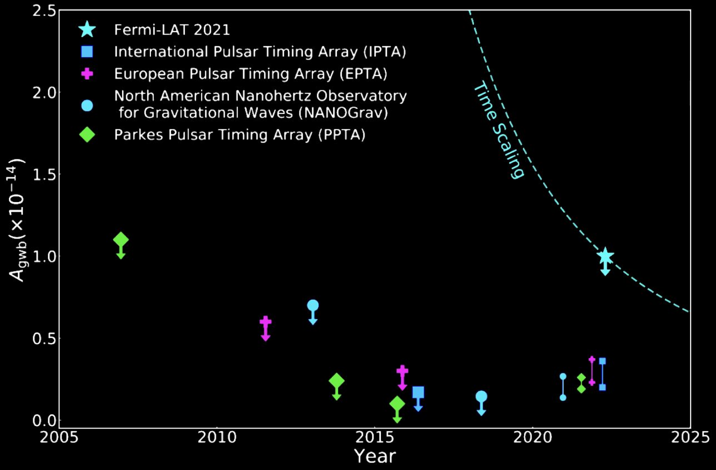
The Future

The 20-Year(?) Data Set & Beyond

- CHIME data integration
- **GBT UWB receiver**
- IPTA DR3
- Ongoing timing of new MSPs and evaluation for NANOGrav inclusion
- **A Gamma-ray Pulsar Timing Array!**
- New facilities…

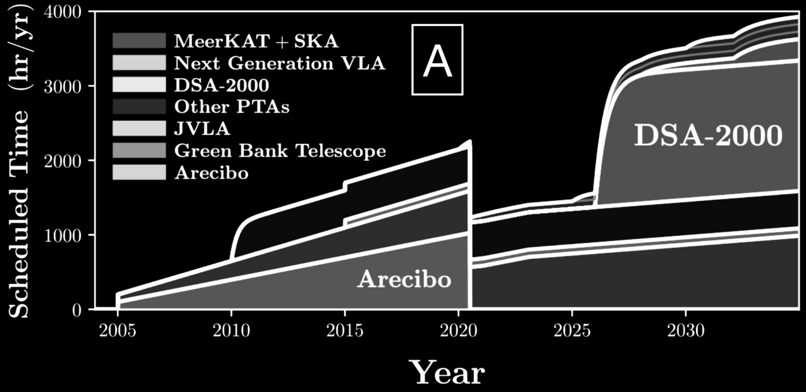
GBT UWB: 0.7 - 4 GHz





New Instruments & More


C. Carter



DSA-2000: 2000 x 5m

- Major projects:
  - NANOGrav: 25% of on-sky time; high and low-cadence: add MSPs immediately!
  - EM follow-up
  - Entire-sky survey (x16); 3.5-arcsec resolution (20x deeper than anything else) = 1 billion radio sources
- ngVLA, SKA, MeerKAT, and more!

Thank you

- NANOGrav has found strong evidence of spatial correlations that signal the presence of a gravitational wave background in its 15-year data set
    - A common red noise process was detected in the 12.5-year data set
- We can’t be sure it’s from SMBBH inspirals; more data will help us constrain the associated astrophysics and possible BSM theories
- Other PTAs are seeing the same trends and our results support each other
- As we observe more pulsars for a longer time span, we’ll be able to better constrain the spectral shape of the background

Email: thankful.cromartie@nanograv.org