Title: Observing sub-nanohertz gravitational waves with pulsar parameter drift

Speakers: William DeRocco

Series: Particle Physics

Date: January 31, 2023 - 1:00 PM

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Abstract: Gravitational waves with frequencies below 1 nHz are notoriously difficult to detect. With periods exceeding current experimental lifetimes, they induce slow drifts in observables rather than periodic correlations. Observables with well-known intrinsic contributions provide a means to probe this regime. In this talk, I will demonstrate the viability of using observed pulsar timing parameters to discover such ultralow frequency gravitational waves, presenting two complementary observables for which the systematic shift induced by ultralow-frequency gravitational waves can be extracted. I will then show the results of searches for both continuous and stochastic signals from supermassive black hole binaries using existing data for these observables, and demonstrate that this technique has the power to probe astrophysically-interesting strains.

Zoom Link: https://pitp.zoom.us/j/95734210379?pwd=Wnp1cHR2QW93bksxaGlCWEZVSjRsUT09

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Observing sub-nHz gravitational waves with pulsar parameter drift

William DeRocco

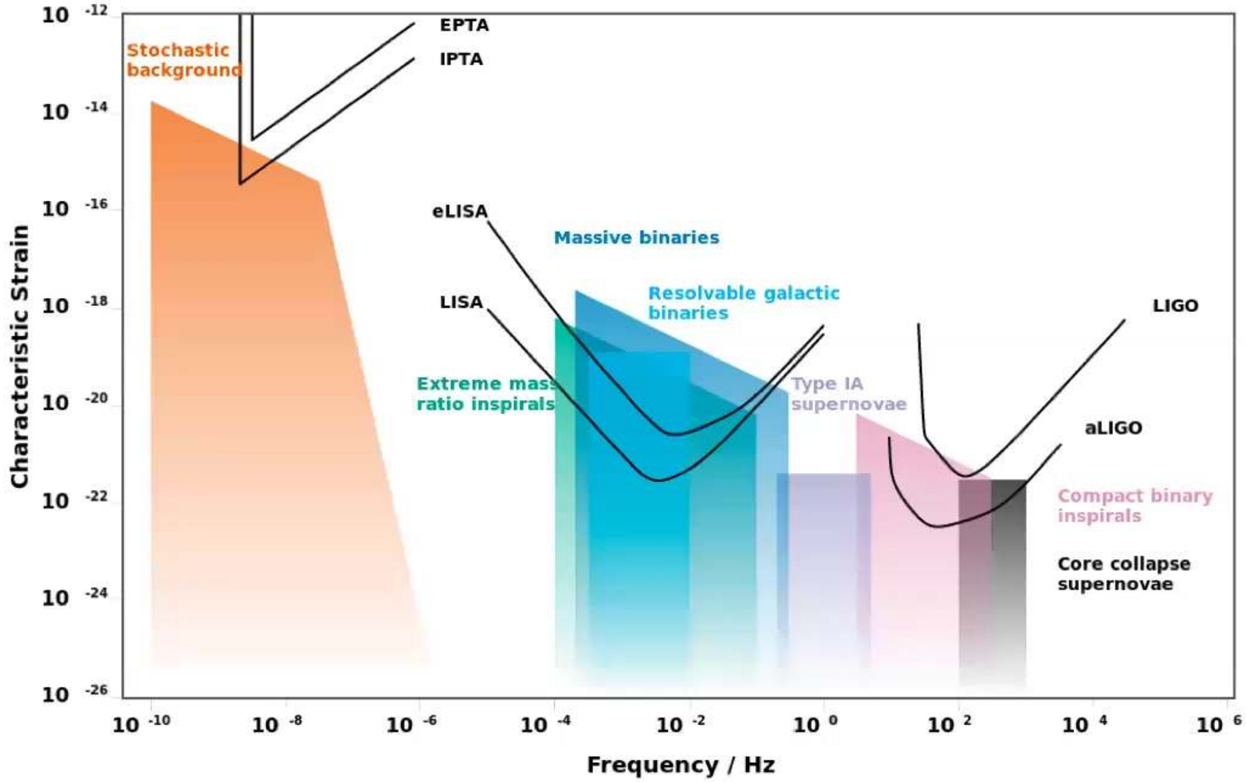
(with Jeff Dror)

University of California, Santa Cruz

Perimeter Theory Seminar

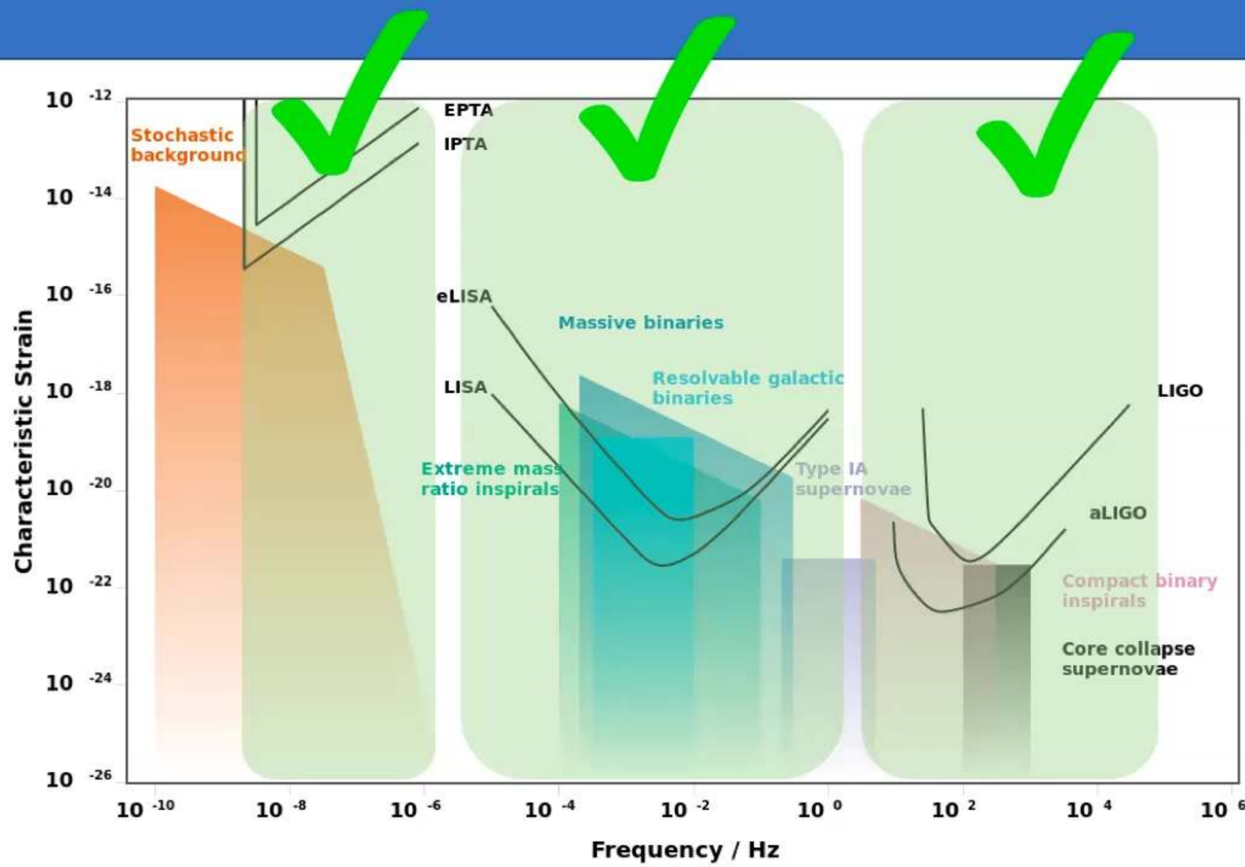
January 31st, 2023

Motivation



EPTA
IPTA
Stochastic background
eLISA
LISA
Massive binaries
Resolvable galactic binaries
Extreme mass ratio inspirals
Type IA supernovae
LIGO
aLIGO
Compact binary inspirals
Core collapse supernovae
Characteristic Strain
Frequency / Hz

Motivation



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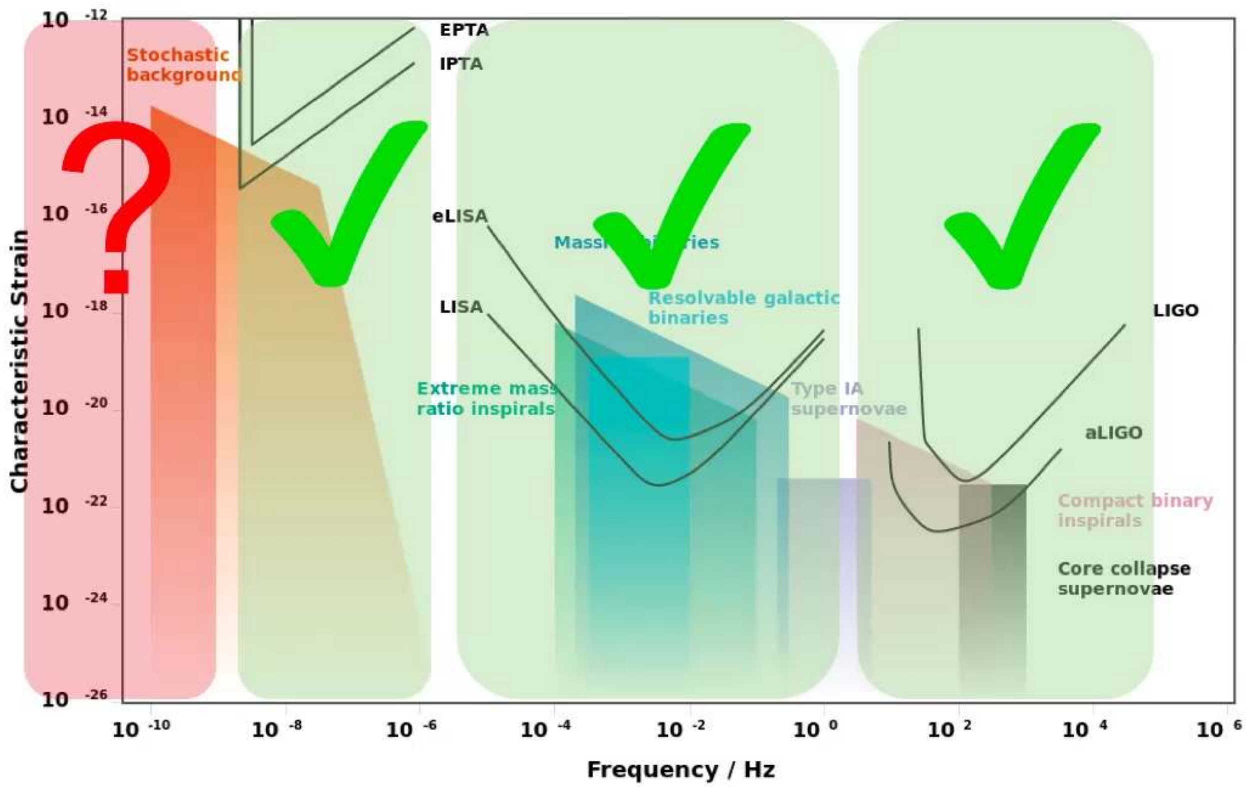

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?

Outline

- **Part I:** PTA analysis
- **Part II:** Extracting sub-period signal
- **Part III:** Results

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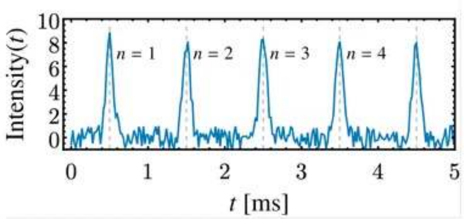
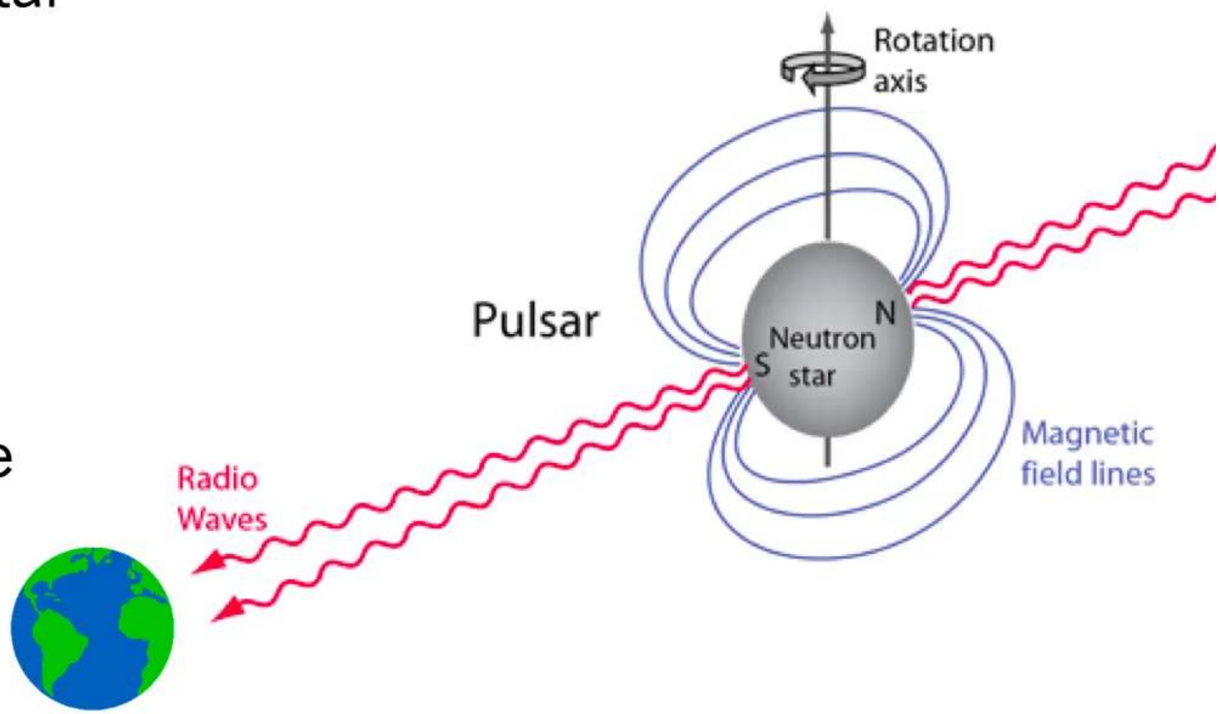
Pulsars

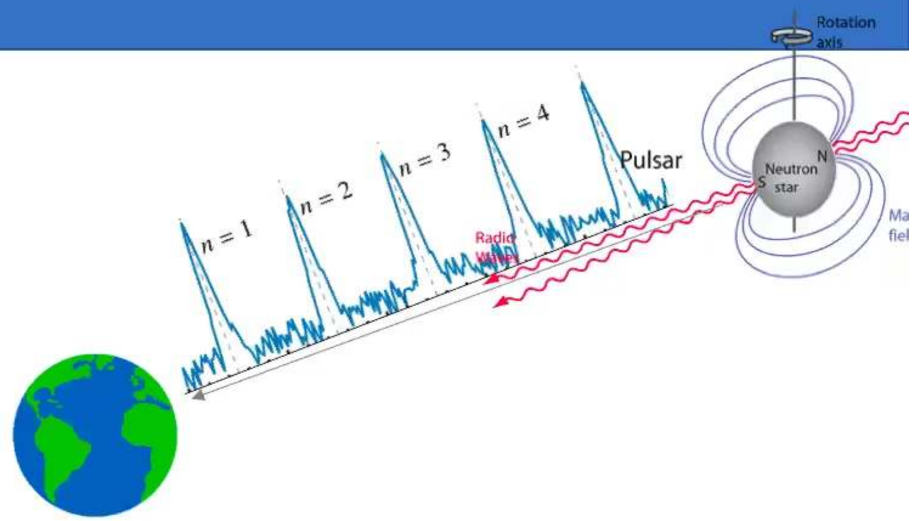
- Rapidly-rotating neutron star with directional beam of radiation
- Periods of ~ millisecond
- Pulse arrival = very precise clock





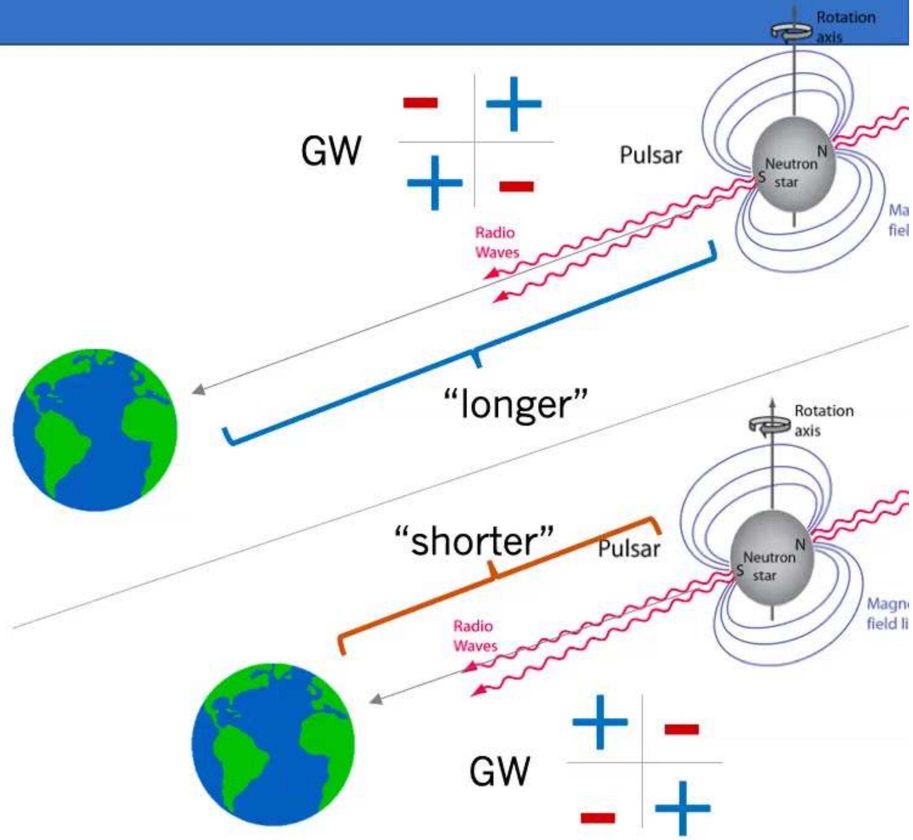
Pulsar timing

- Pulses **emitted** at fixed rate by pulsar



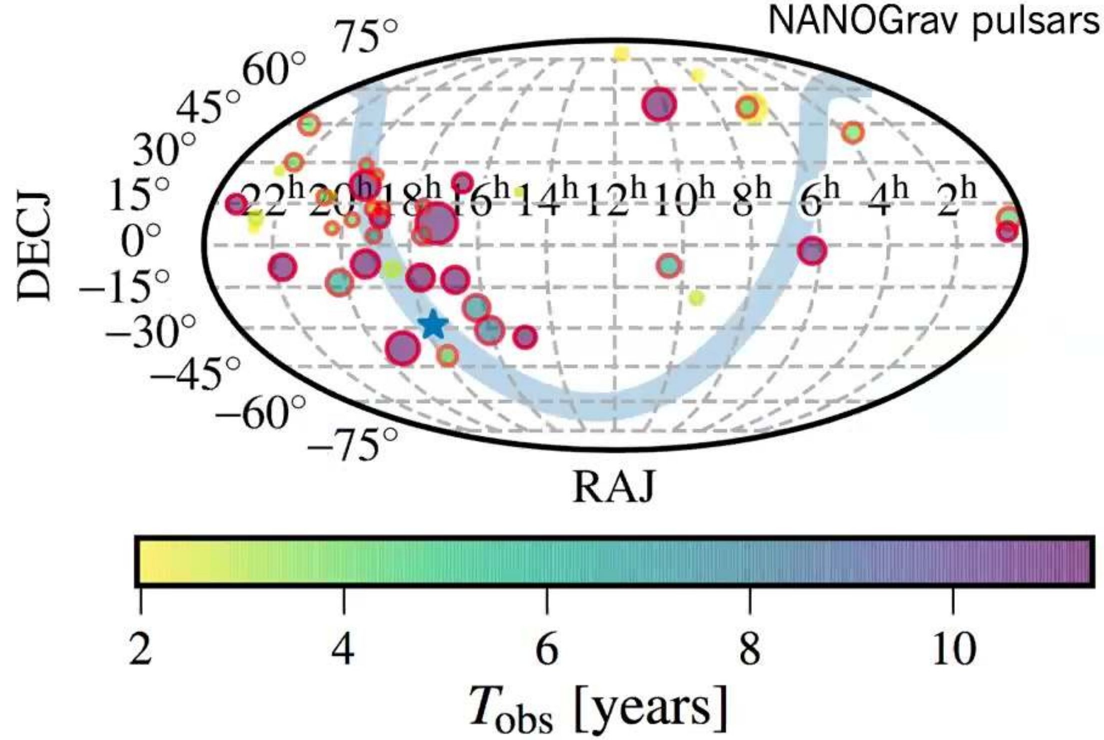
Pulsar timing

- Pulses **emitted** at fixed rate by pulsar
- GWs cause variation in light-travel time ⇒ variation in **arrival** times at Earth



Pulsar timing array

- GWs are quadrupolar
- Variations in arrival times are ***correlated across sky***
- Correlations help discriminate GWs from other sources of variation



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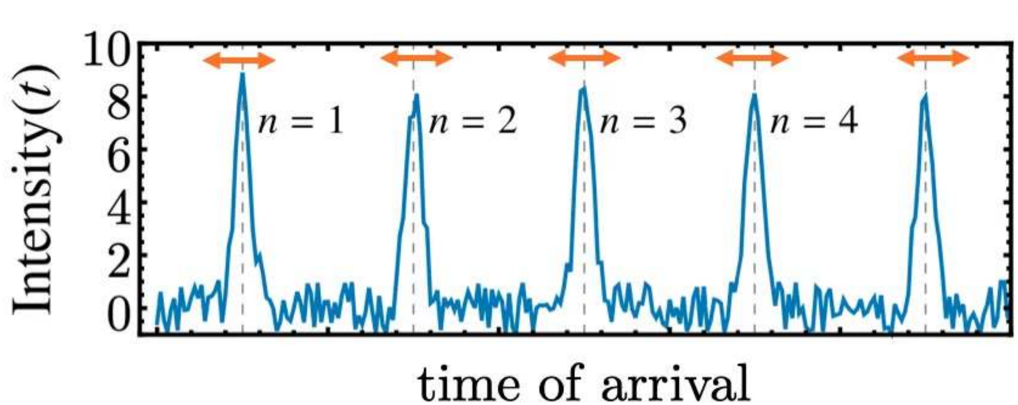
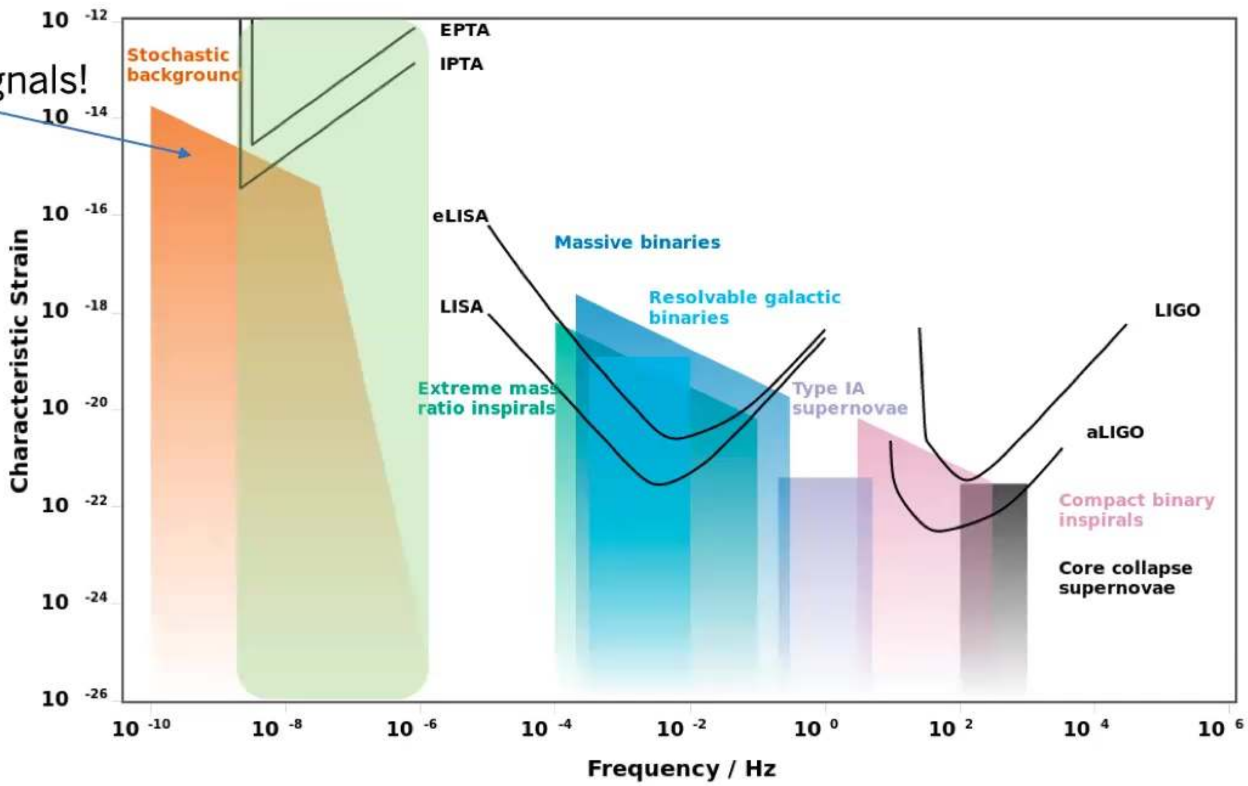


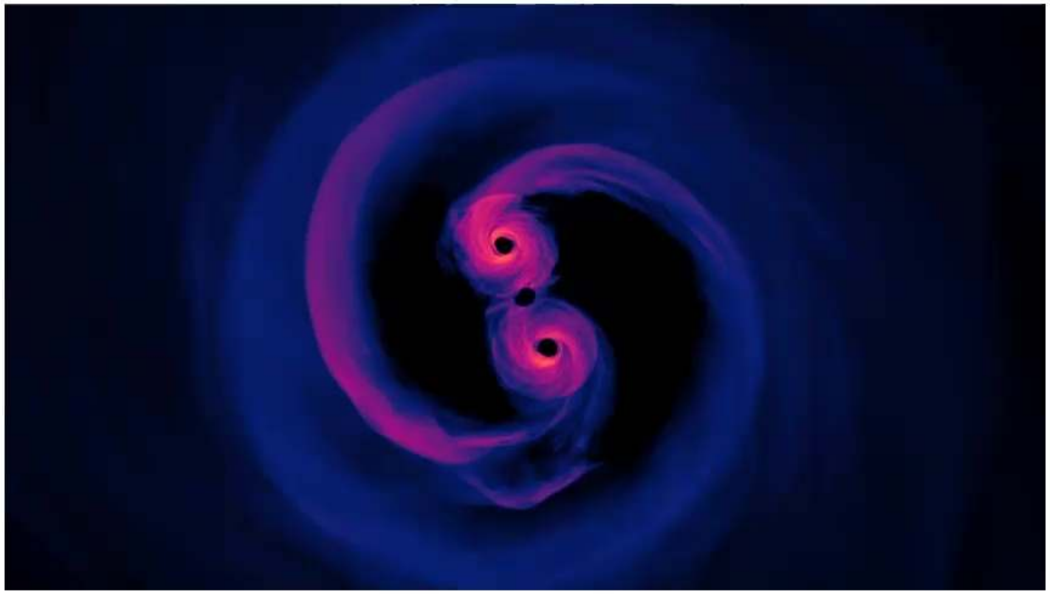
PTA band

astrophysical signals!

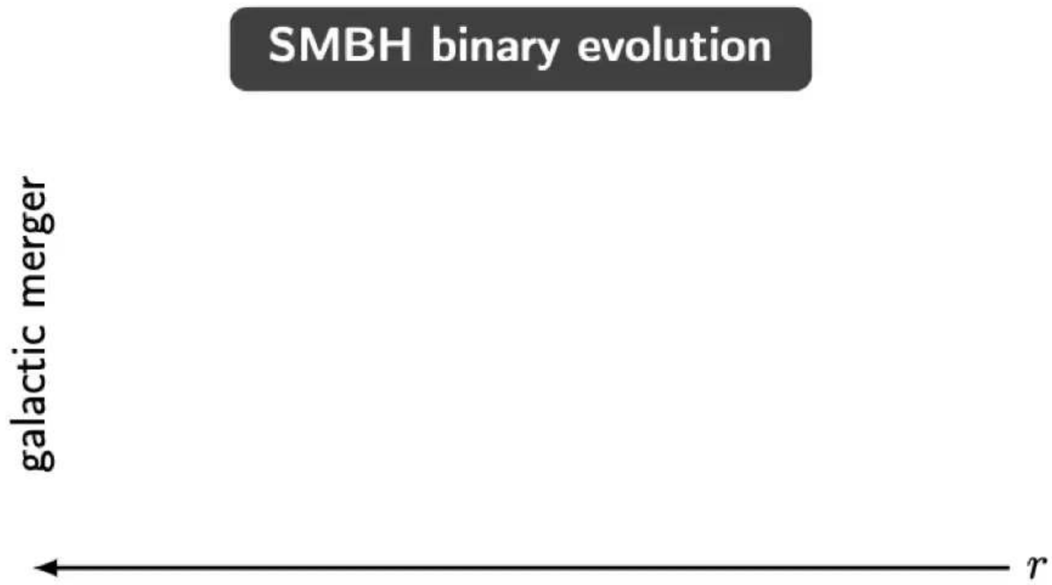


SMBH binaries

- $10^6 - 10^9\ M_\odot$ black holes in the center of galaxies
- Merging galaxies produce stochastic background of gravitational waves
- Expected discovery soon! (NANOGrav 2023 DR?)

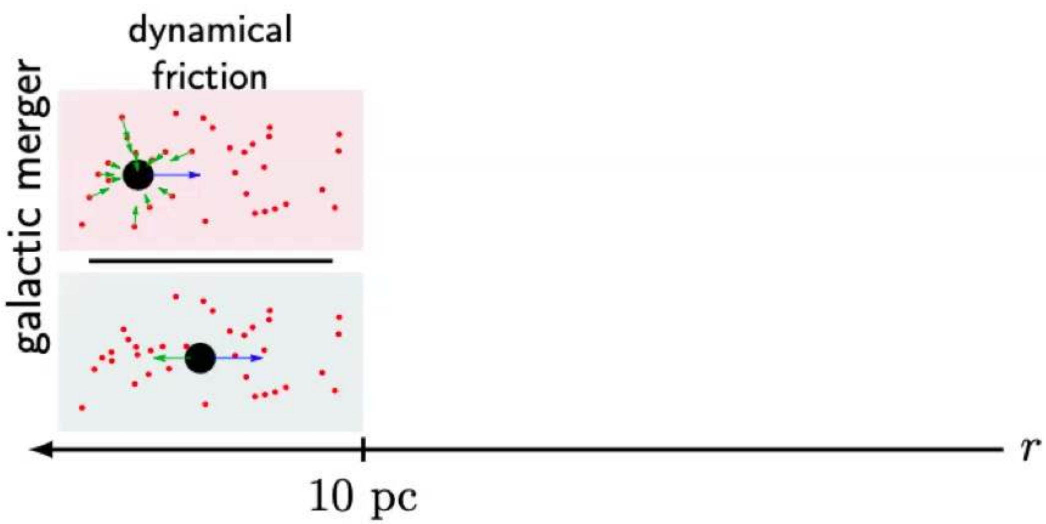


SMBH evolution



SMBH evolution

SMBH binary evolution



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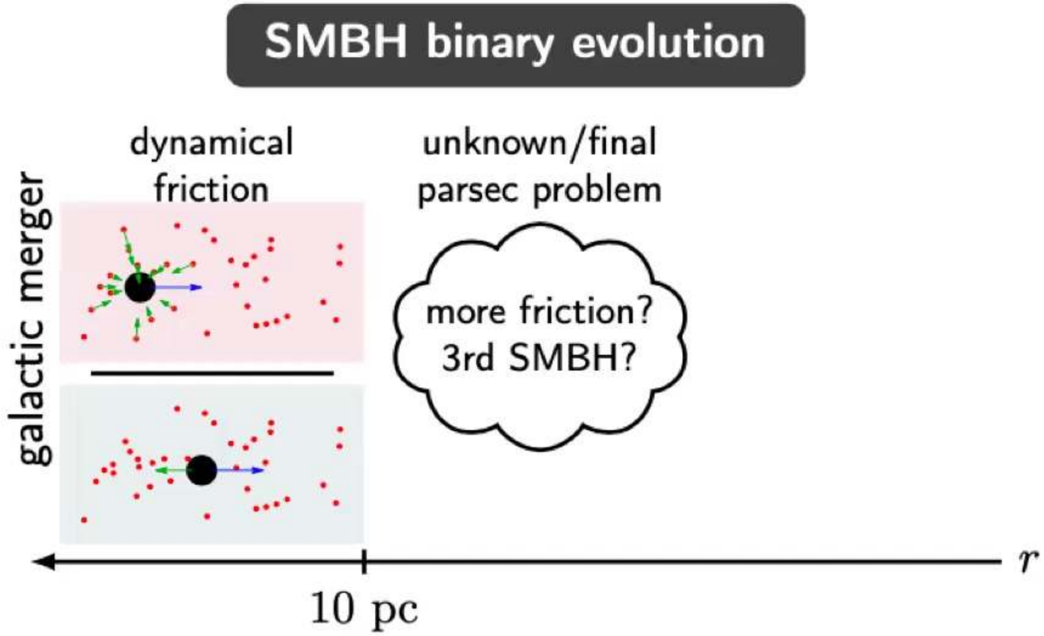

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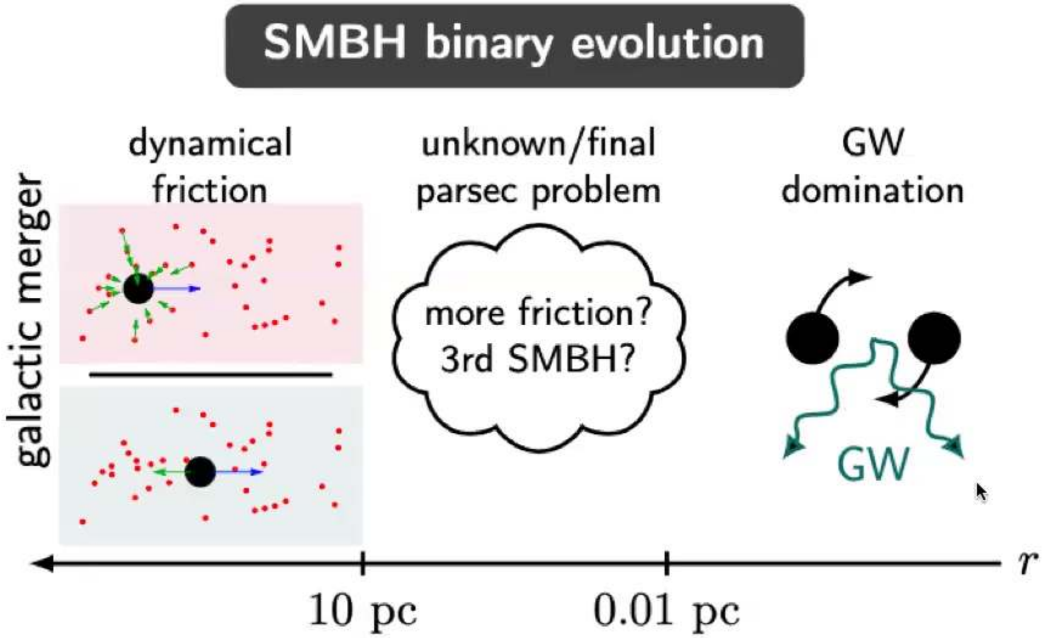

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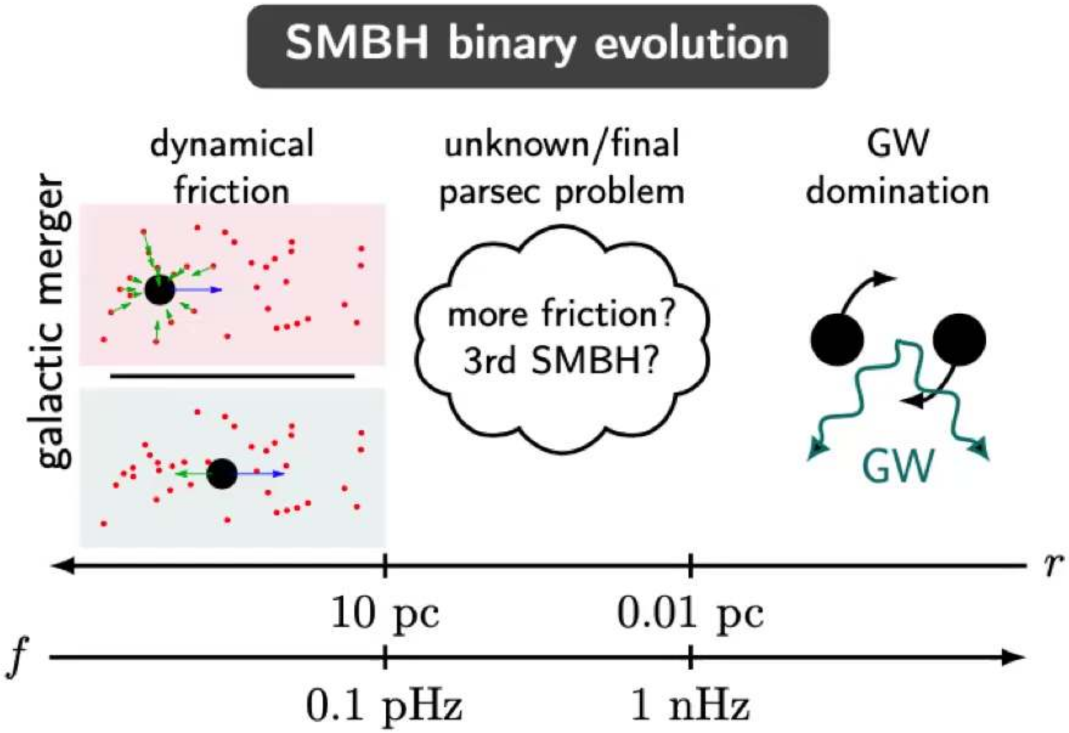

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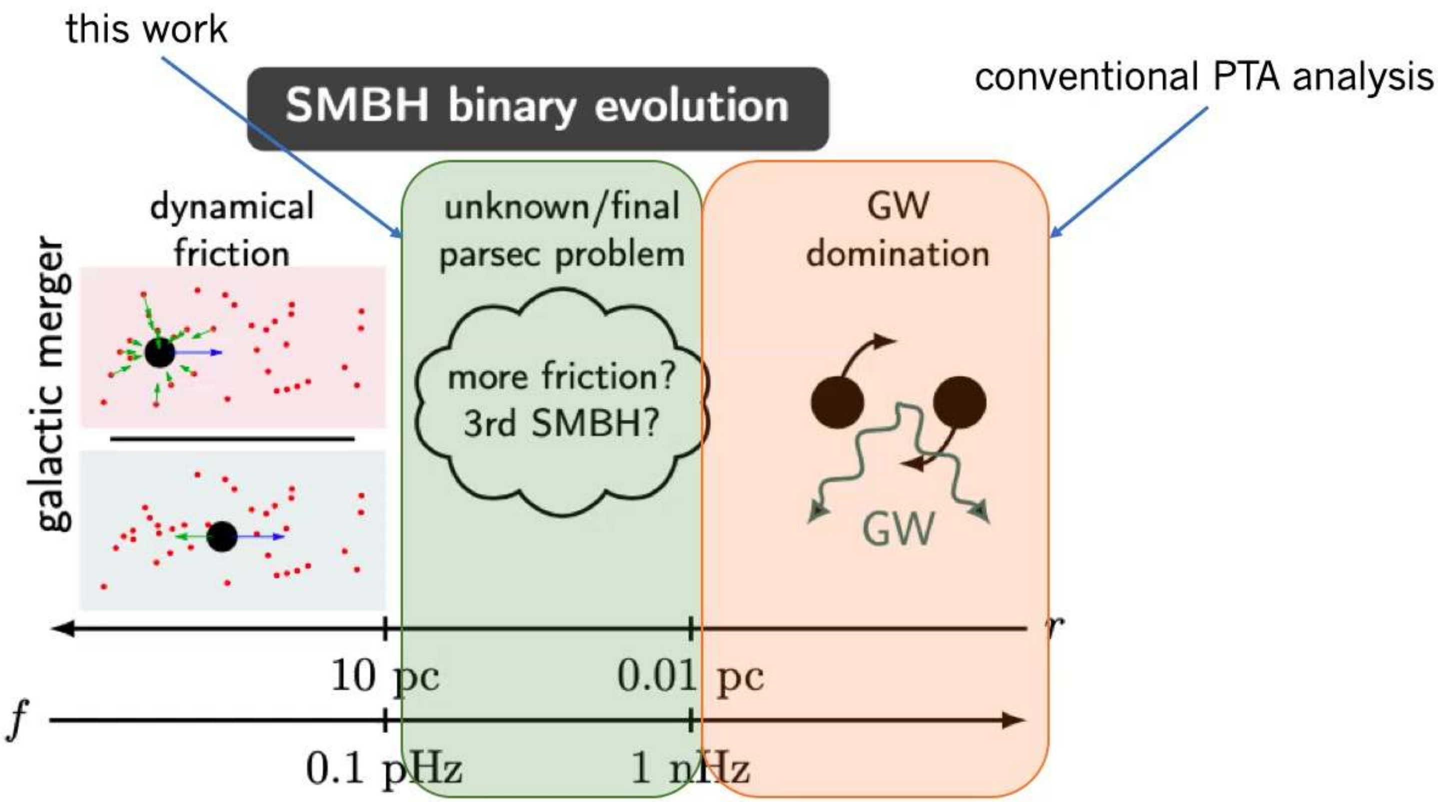

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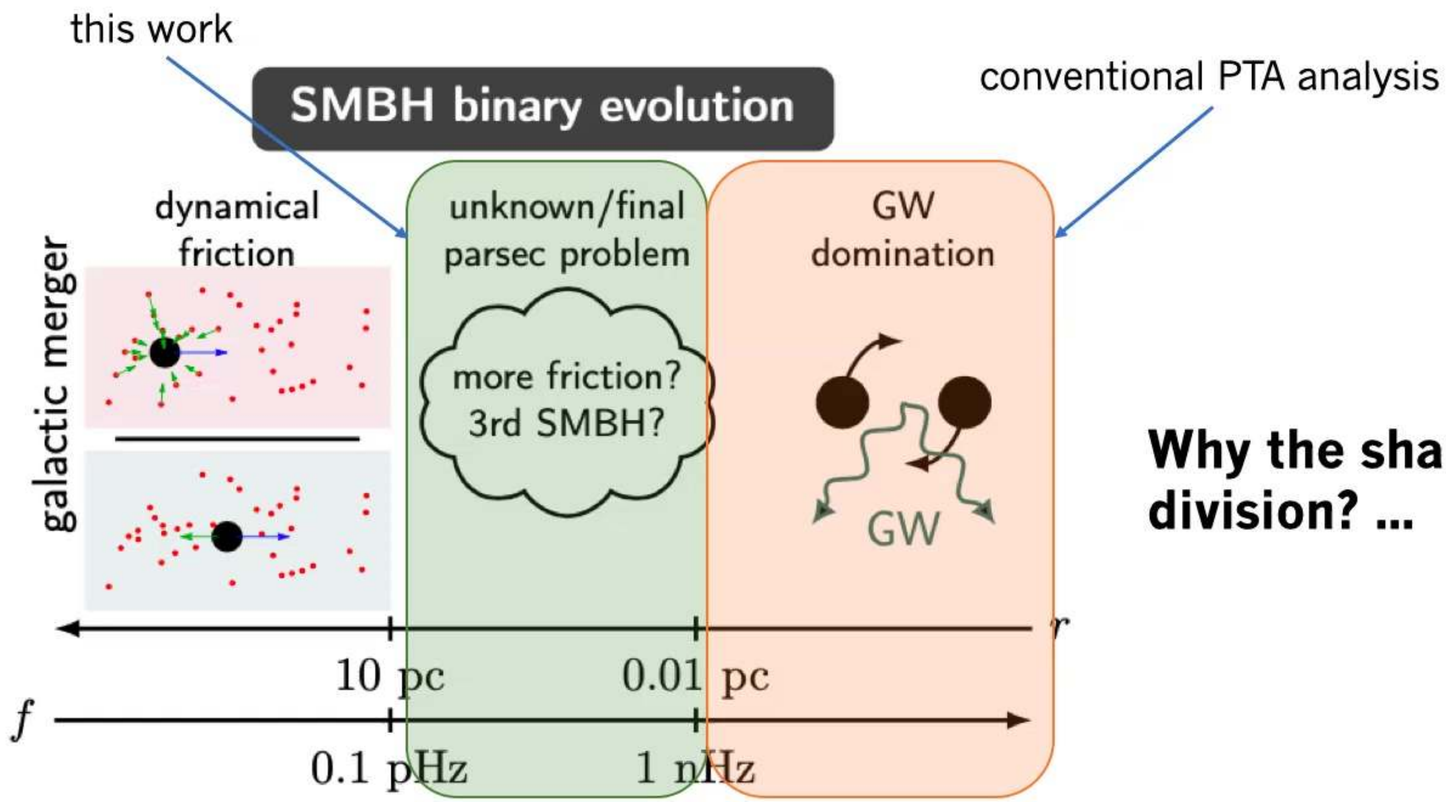
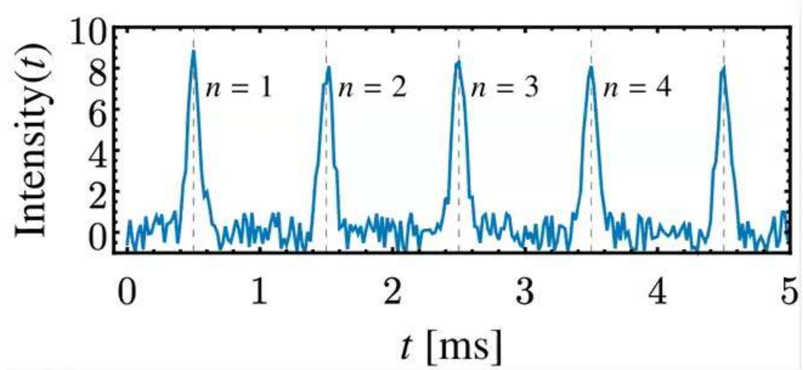


Why the sharp division? ...

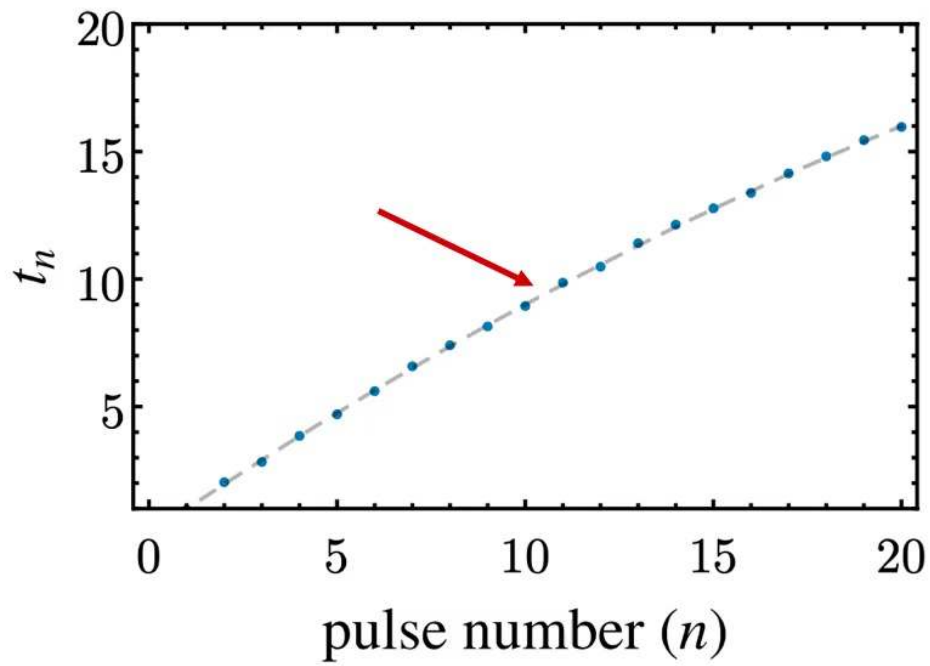
PTA Recipe

- **Step 1:** Pulses → **TOAs**



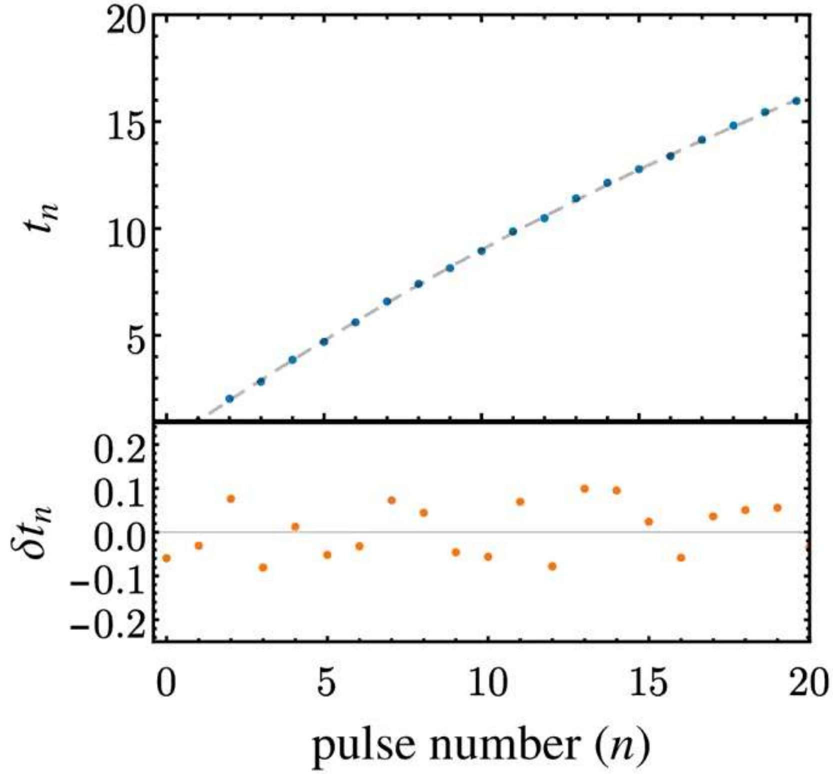
PTA Recipe

- **Step 1:** Pulses → **TOAs**
- **Step 2:** Fit **model** to TOAs
  - Model includes parameters such as $\dot{P}$, $\ddot{P}$, ...



PTA Recipe

- **Step 1:** Pulses → **TOAs**
- **Step 2:** Fit **model** to TOAs
- **Step 3:** Subtract model from TOAs to produce **residuals**



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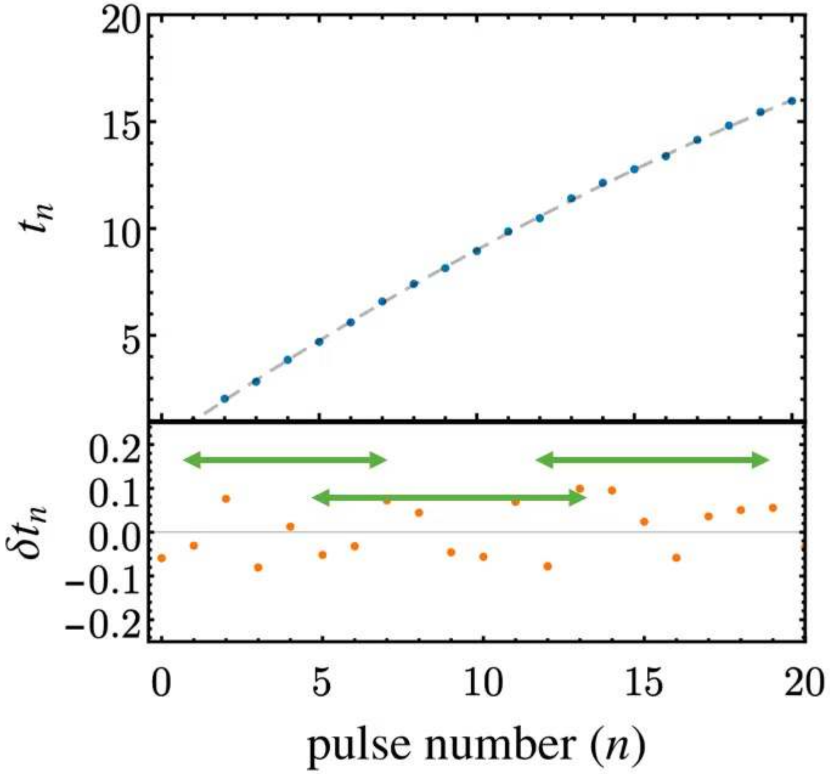
- **Step 4:** Test for **correlations** in residuals



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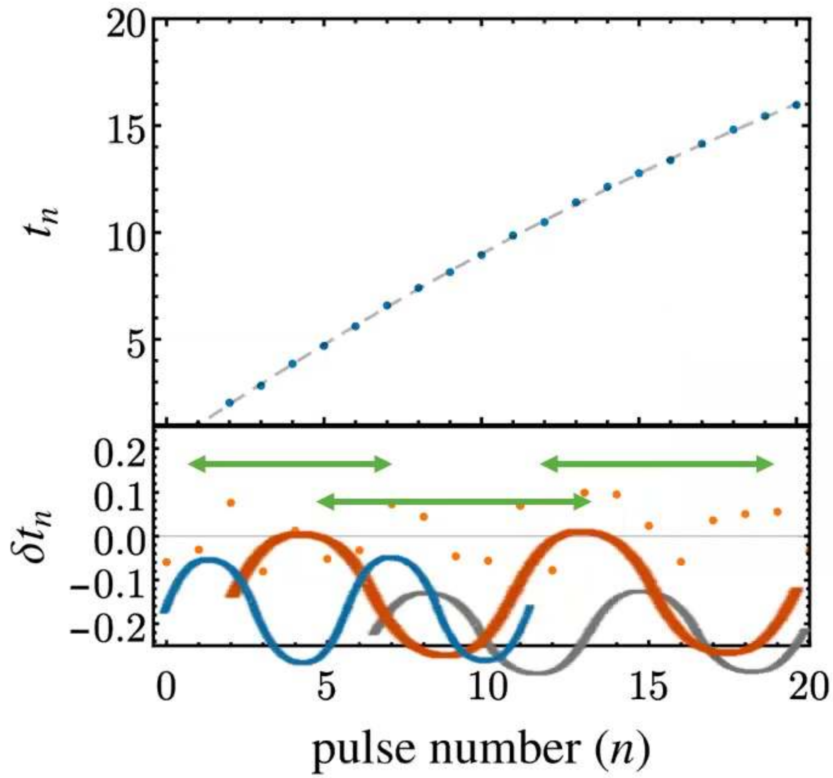
Correlations only observable for f > 1/T!



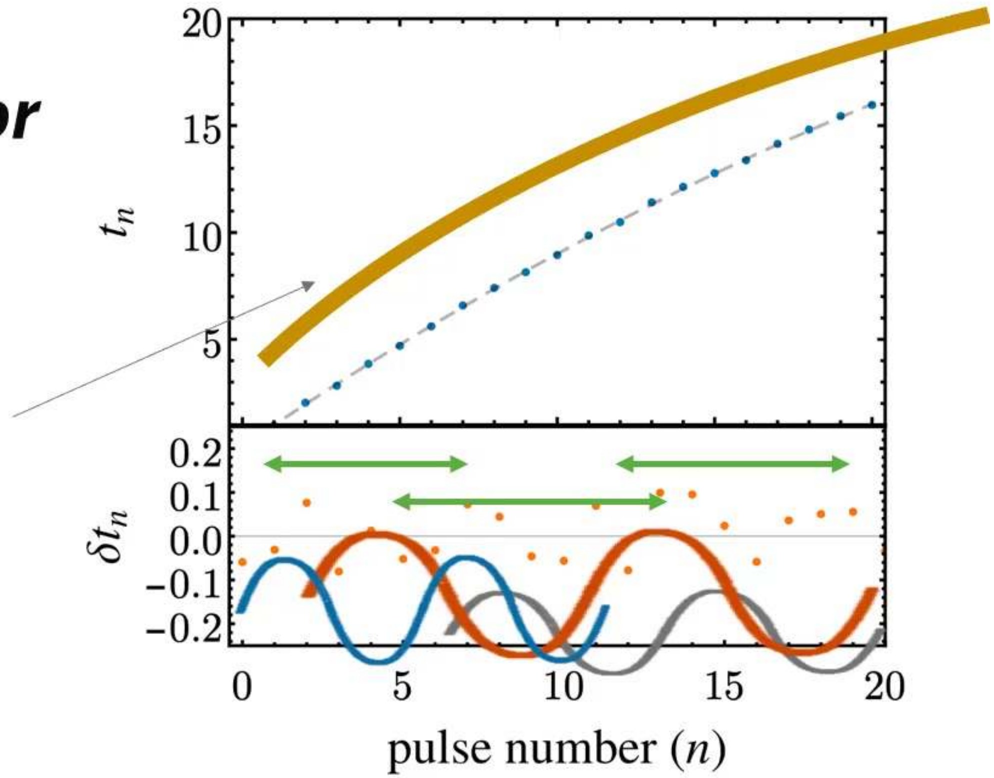
PTA Recipe

- **Step 1:** Pulses → **TOAs**
- **Step 2:** Fit **model** to TOAs
- **Step 3:** Subtract model from TOAs to produce **residuals**
- **Step 4:** Test for **correlations** in residuals
- **Step 5:** Nobel Prize(?)

PTA Recipe

Correlations only observable for f > 1/T!

- For f < 1/T, signal is "fit away"
- No sensitivity to ultralow-frequency gravitational waves



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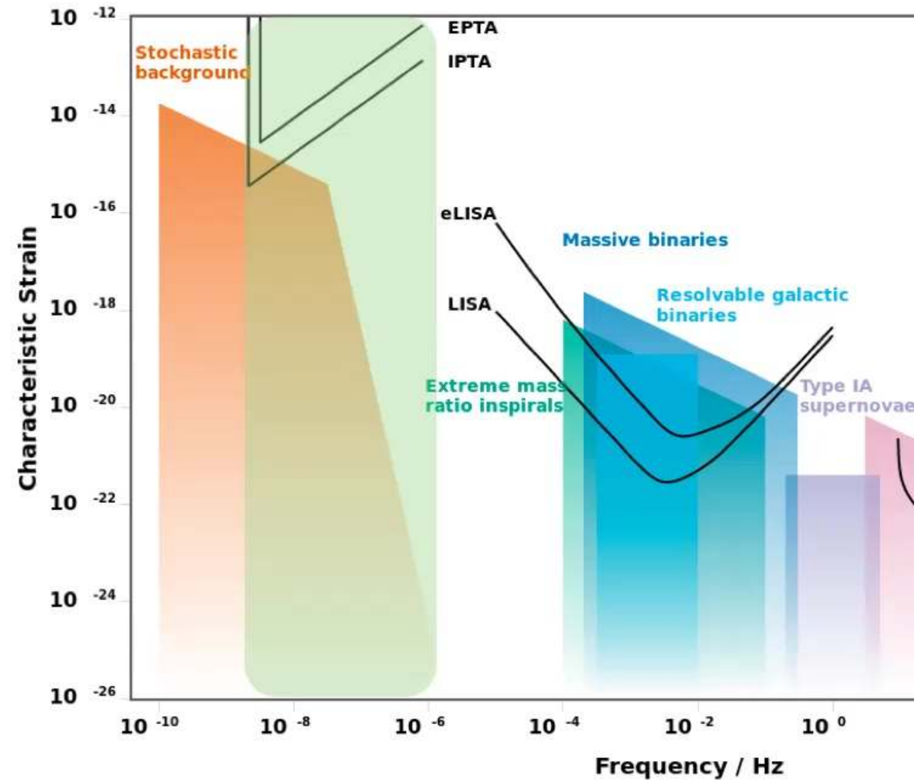
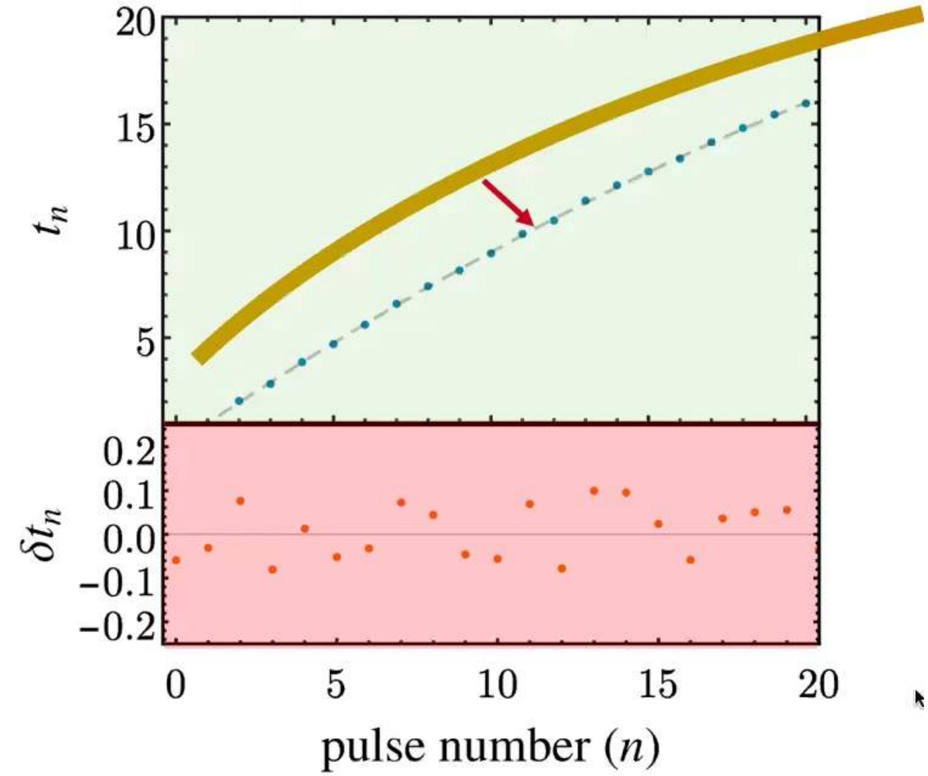


Fit parameters

Key Insight: "Fitting away" just means low-frequency information is stored in parameter fits!

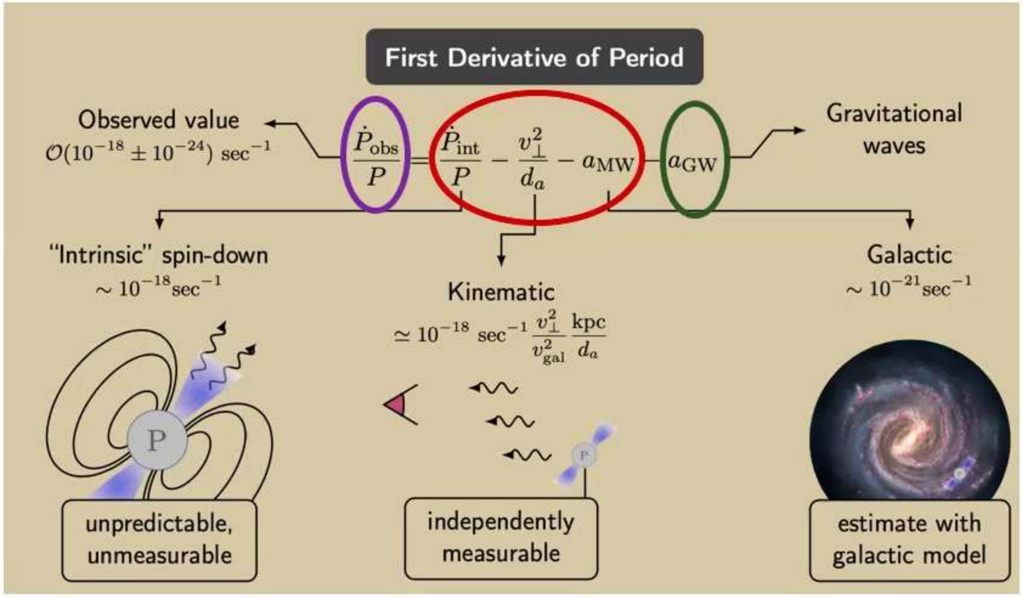


Fit parameters

Key Insight: "Fitting away" just means low-frequency information is stored in parameter fits!

- Example: $\dot{P}$
  - Contains information about GWs!
  - Also pulsar spin down, etc.

$$\dot{P}_{obs} = \dot{P}_{other} + \dot{P}_{GW}$$



Fit parameters

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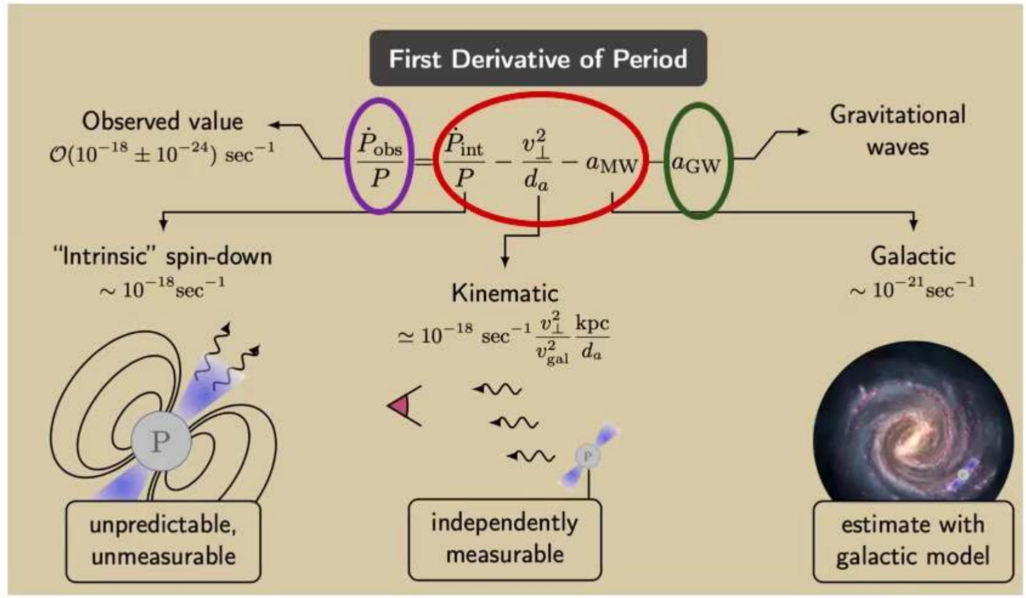
- Example: $\dot{P}$
  - Contains information about GWs!
  - Also pulsar spin down, etc.

$$\dot{P}_{obs} = \dot{P}_{other} + \dot{P}_{GW}$$

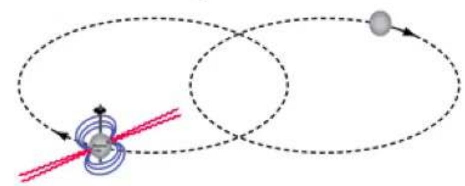
- Intrinsic contributions to $\dot{P}$ unpredictable ⇒ GW signal cannot be extracted

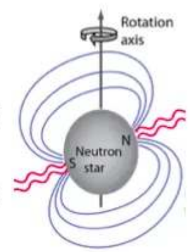


Sensitive parameters

- Non-GW contributions to some parameters are known and can be subtracted away!

- **Best parameters:**
  - $\dot{P}_b$: change in *binary* period
  - $\ddot{P}$: second derivative of *spin* period

$$\frac{d}{dt}\Big($$  $$\Big)$$

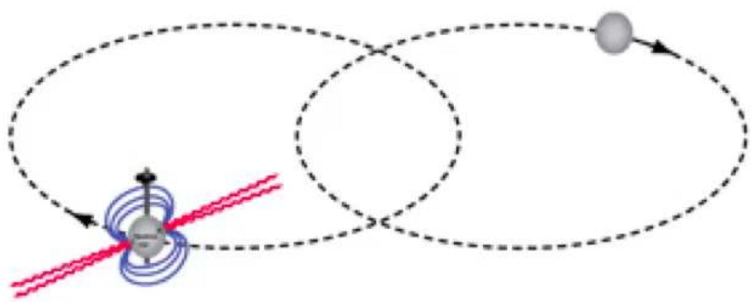
$$\frac{d^2}{dt^2}\Big($$  $$\Big)$$

Binary spin-down ($\dot{P}_b$)

$$\frac{\dot{P}_{b,\mathrm{obs}}}{P_b} = \frac{\dot{P}_{b,\mathrm{GR}}}{P_b} + \frac{\dot{P}_{b,\mathrm{Shk}}}{P_b} + a_{\mathrm{MW}} + a_{\mathrm{GW}}$$

- Change in *binary* period
- Induces apparent line-of-sight **acceleration**
- Three relevant non-GW contributions

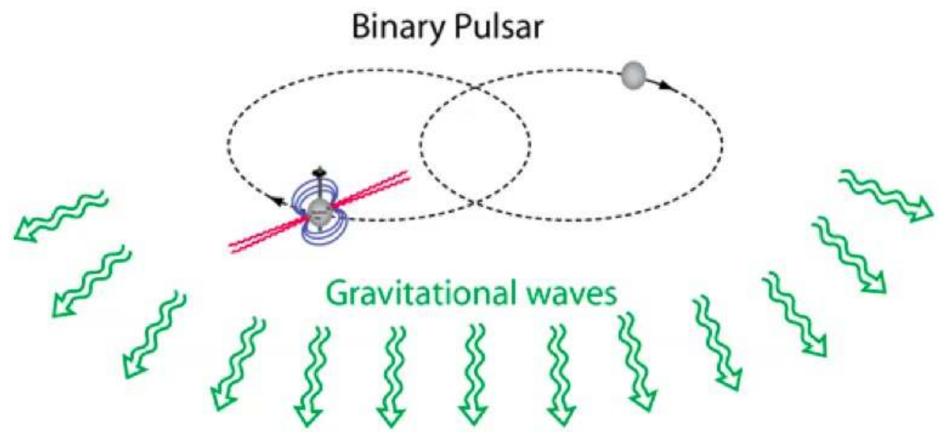
Binary Pulsar



Contribution #1: Gravitational radiation

$$\frac{\dot{P}_{b,\mathrm{obs}}}{P_b} = \frac{\dot{P}_{b,\mathrm{GR}}}{P_b} + \frac{\dot{P}_{b,\mathrm{Shk}}}{P_b} + a_{\mathrm{MW}} + a_{\mathrm{GW}}$$

- Binary systems emit gravitational radiation of their own
- This decreases energy, causing orbit to slow
- Mass + eccentricity are independently measured ⇒ contribution can be subtracted

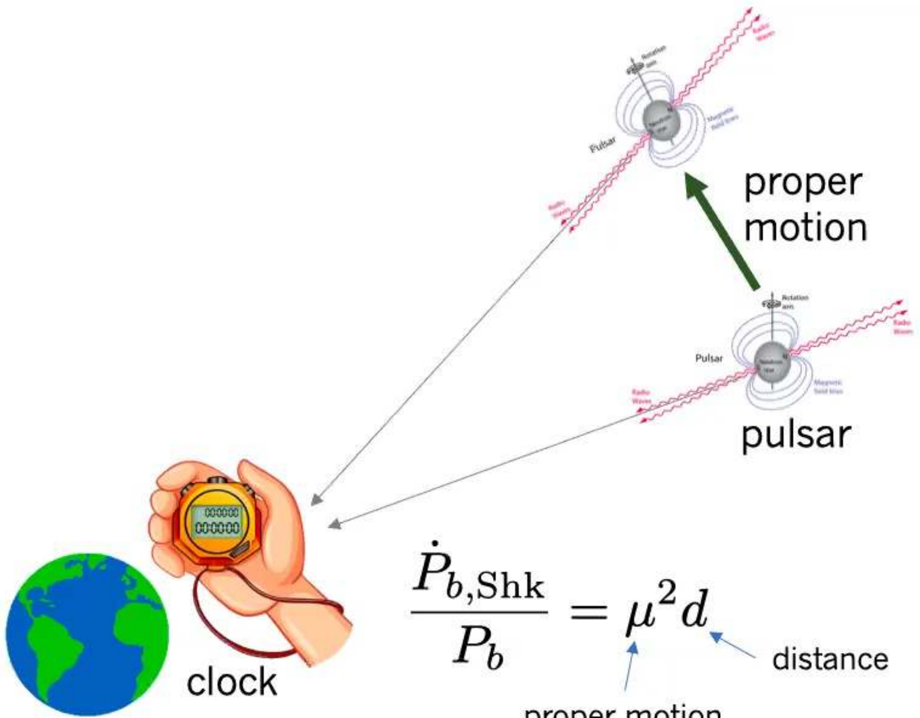


$$\dot{P}_b^{\mathrm{GR}} = -\frac{192\pi G^{5/3}}{5c^5}\left(\frac{P_b}{2\pi}\right)^{-5/3}(1-e^2)^{-7/2} \times \left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)\frac{m_p m_c}{(m_p+m_c)^{1/3}}$$

Contribution #2: Shklovskii Effect

$$\frac{\dot{P}_{b,\mathrm{obs}}}{P_b} = \frac{\dot{P}_{b,\mathrm{GR}}}{P_b} + \frac{\dot{P}_{b,\mathrm{Shk}}}{P_b} + a_{\mathrm{MW}} + a_{\mathrm{GW}}$$

- Proper motion on sky induces shift in residuals
- Distance + proper motion are independently measured ⇒ contribution can be subtracted



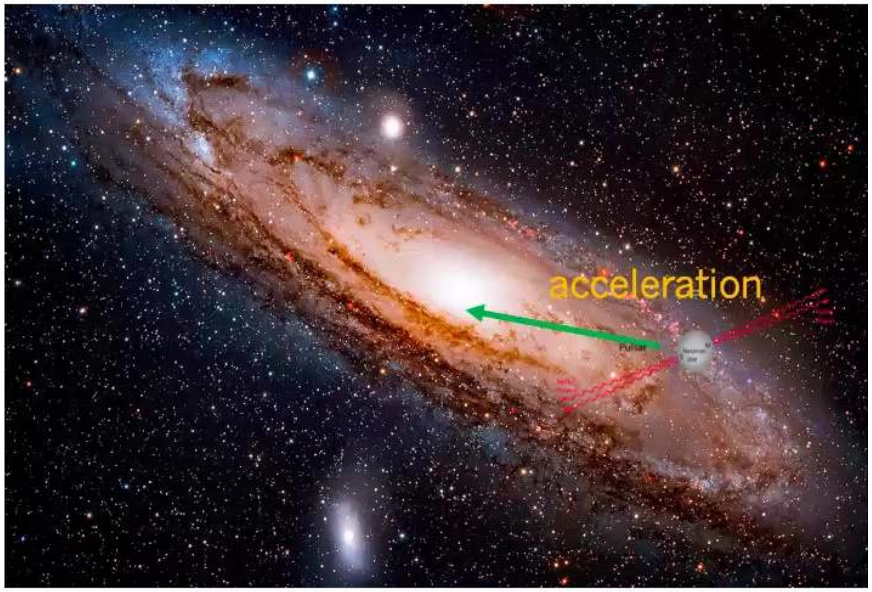
$$\frac{\dot{P}_{b,\mathrm{Shk}}}{P_b} = \mu^2 d$$

proper motion
distance

Contribution #2: Galactic acceleration

$$\frac{\dot{P}_{b,\mathrm{obs}}}{P_b} = \frac{\dot{P}_{b,\mathrm{GR}}}{P_b} + \frac{\dot{P}_{b,\mathrm{Shk}}}{P_b} + a_{\mathrm{MW}} + a_{\mathrm{GW}}$$

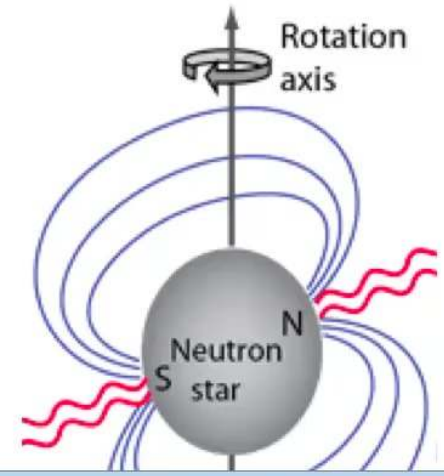
- Galactic potential tugs on pulsar
- Pulsar location independently measured ⇒ contribution can be subtracted
- Highly subdominant in most cases
  - *But that hasn't stopped people from trying... (Chakbrabarti et al. 2021)*



Second derivative of pulsar spin-down ($\ddot{P}$)

$$\frac{\ddot{P}_{\rm obs}}{P} = j_{\rm GW}$$

- Change in *pulsar* period
- Induces apparent line-of-sight **jerk**
- All non-GW contributions negligible →



Spin-down: 10^{-35} s^{-2}
Shklovskii: 10^{-32} s^{-2}
Galactic: 10^{-33} s^{-2}

Observational uncertainty: $>10^{-30}$ s^{-2}

Historical aside

Bertotti et al. point out the potential in same paper as they describe what would become the current PTA program

1983

EPTA project begins

1996

Kumamoto et al. use statistical distribution of $\dot{P}$

2019-2021

1982

First millisecond pulsar observed

1997-2004

Kopeikin notes that constraints could be set using the uncertainty on observed pulsar parameters

2022

First analysis to use sensitive pulsar parameters to reach astrophysically-interesting strains!

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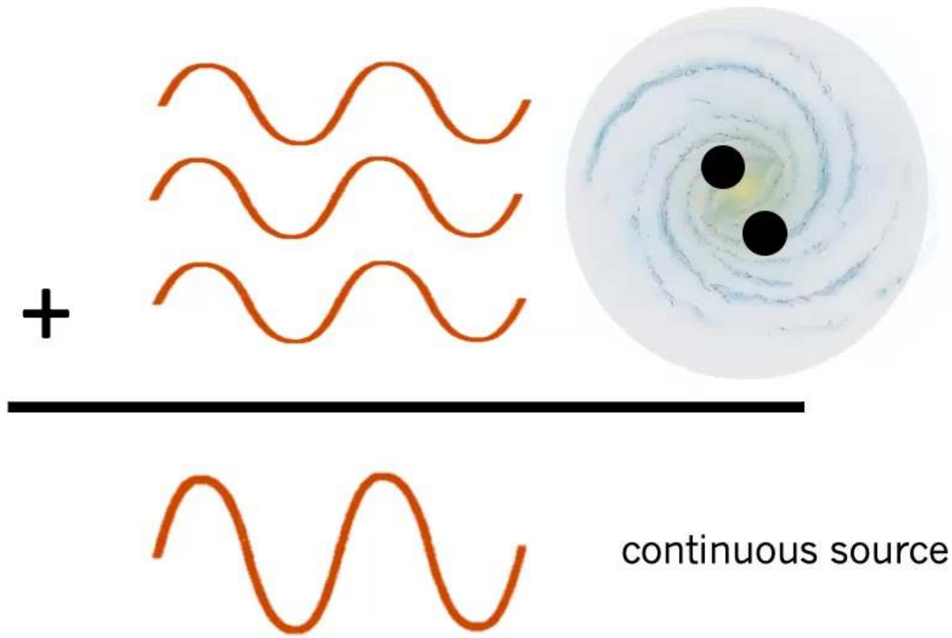
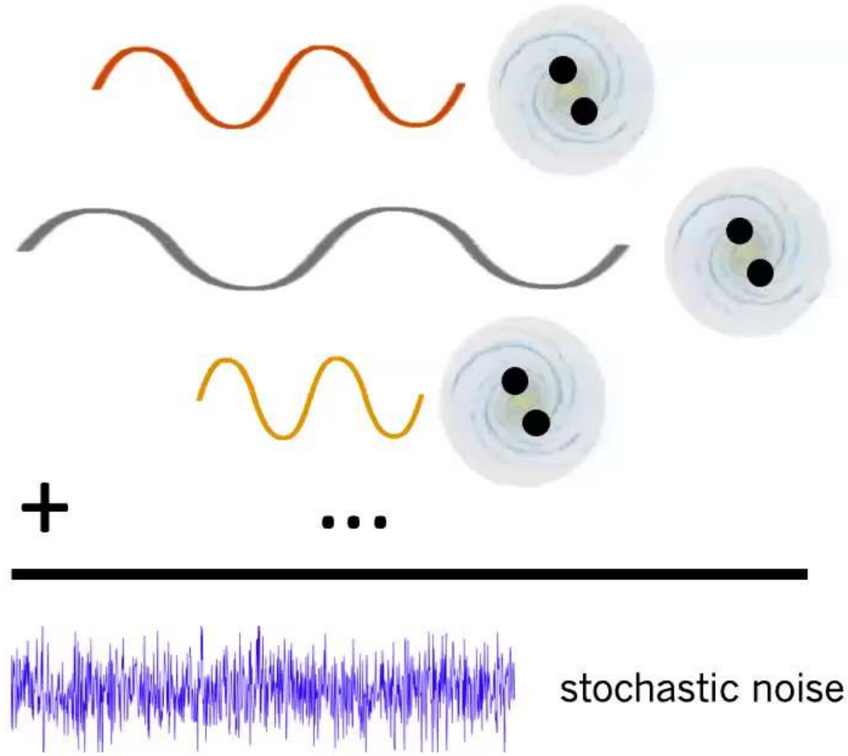
Continuous SMBH source

- Measured in terms of *strain* **h**
  - Relative change in path length
  - $h \sim v_{LOS}$
- Approximately sinusoidal at ultralow frequencies
- SMBH merger = single coherent source



Stochastic signal

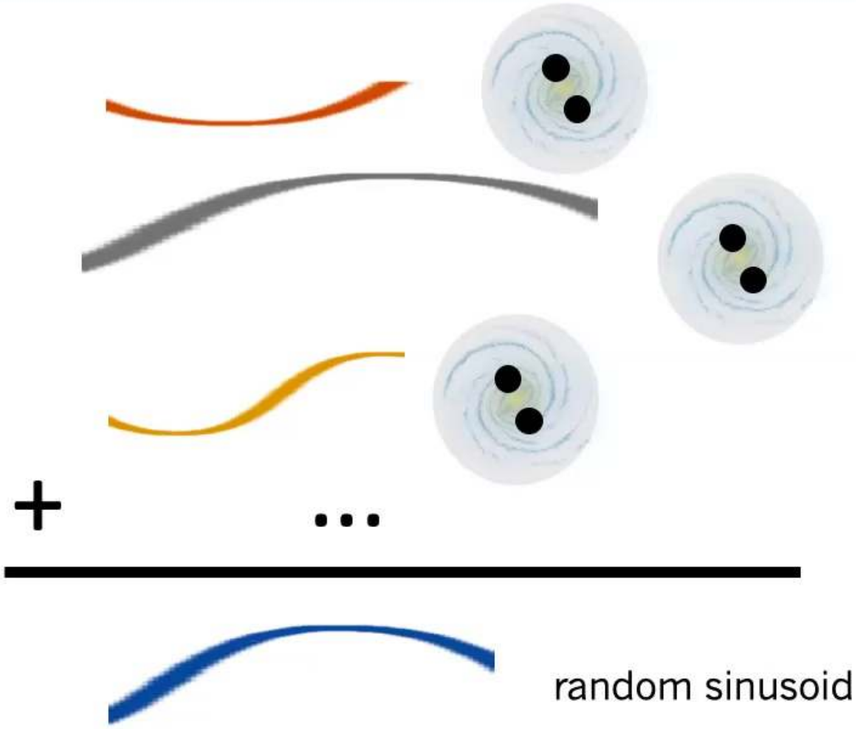
- **High frequencies (f > 1/T):** incoherent sum of sources ⇒ stochastic noise



Stochastic signal

- **High frequencies (f > 1/T):** incoherent sum of sources ⇒ stochastic noise

- **Ultralow frequencies (f < 1/T):** incoherent sum ⇒ sinusoid with random phase and amplitude

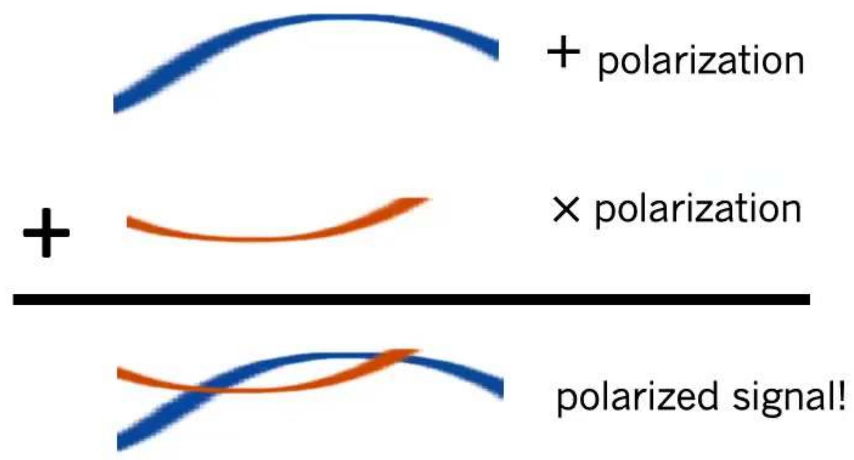


Stochastic signal

- **High frequencies (f > 1/T):** incoherent sum of sources ⇒ stochastic noise

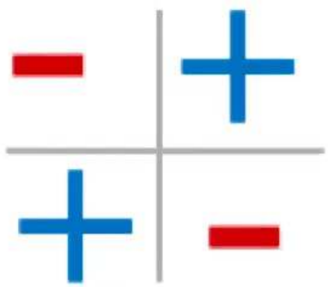
- **Ultralow frequencies (f < 1/T):** incoherent sum ⇒ sinusoid with random phase and amplitude

- Each polarization is separate random draw ⇒ **polarized** signal

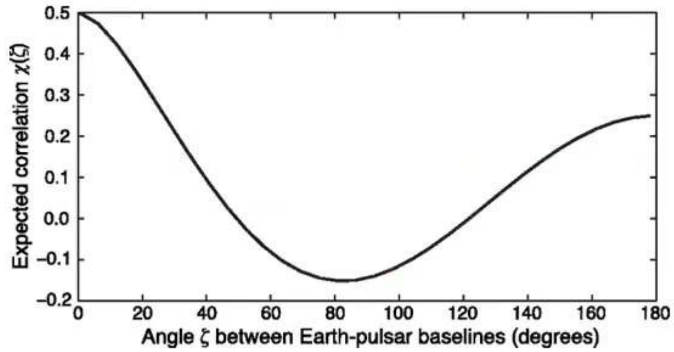


Angular correlations

- **Ultralow frequency (f < 1/T):**
  - Quadrupolar pattern function

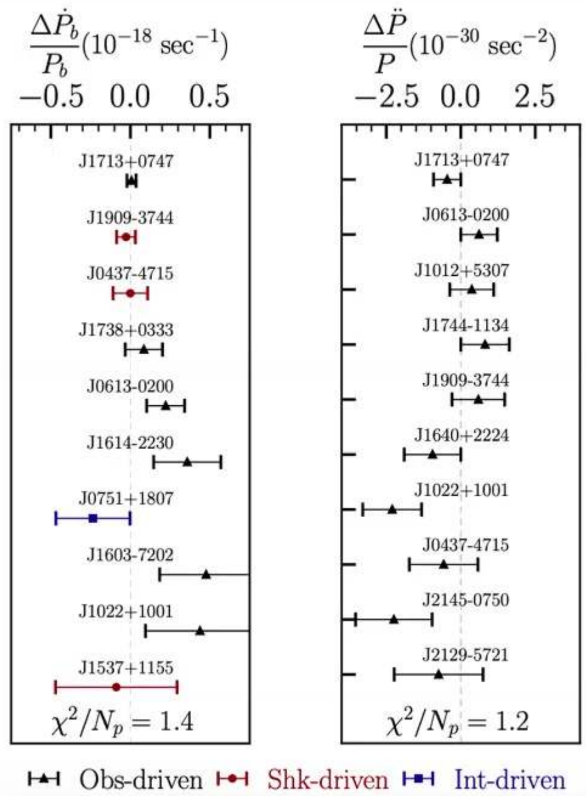


- **Higher frequency (f > 1/T):**
  - Hellings and Down curve



Data

- $\ddot{P}$: Liu et al. (2018)
  - jerk ~ **10^{-31} s^{-2}**
- $\dot{P}_b$: Chakrabarti et al. (2020)
  - acceleration ~ **10^{-19} s^{-1}**
- Pulsars are not in star clusters, no wide binaries, etc.



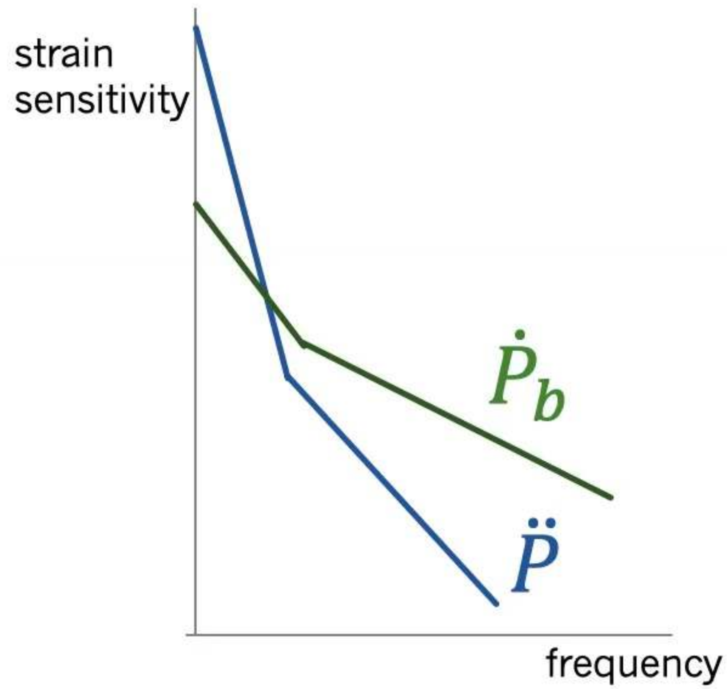
Scaling

- Line-of-sight velocity induced by GW:

  $\dot{x}_{LOS} \sim h_0 (\cos 2\pi f t_{em} - \cos 2\pi f t_{obs})$

- Wavelength < distance to pulsar:
  - **Acceleration**: $\dot{P}_b \propto a_{LOS} = \ddot{x}_{LOS} \sim \boldsymbol{h_0 f}$
  - **Jerk:** $\ddot{P} \propto j_{LOS} = \dddot{x}_{LOS} \sim \boldsymbol{h_0 f^2}$

- Wavelength > distance to pulsar:
  - Additional f from expansion of cosine
  - **Acceleration**: $\dot{P}_b \propto a_{LOS} = \ddot{x}_{LOS} \sim \boldsymbol{h_0 f^2}$
  - **Jerk:** $\ddot{P} \propto j_{LOS} = \dddot{x}_{LOS} \sim \boldsymbol{h_0 f^3}$



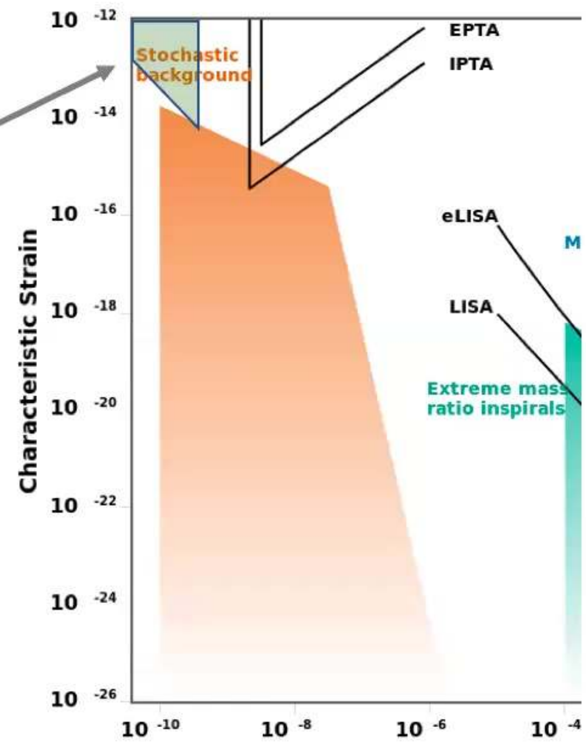
Back-of-the-envelope estimate

- Jerk ~ 10^{-31} s^{-2}

$$j_{LOS} \sim h_0(\pi f)^2 \Rightarrow h_0 \sim \mathbf{10^{-14}} \left(\frac{f}{\text{nHz}}\right)^2$$

- Acceleration ~ 10^{-19} s^{-1}

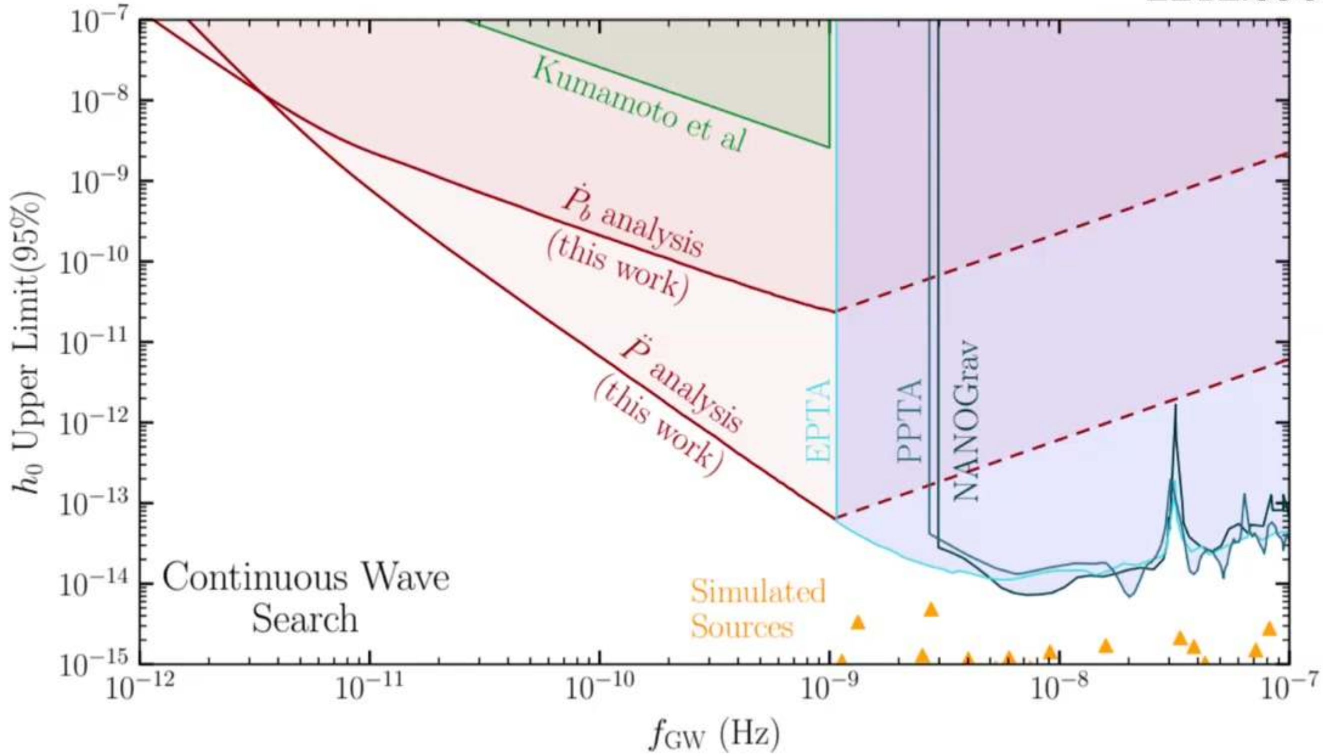
$$a_{LOS} \sim h_0(\pi f) \Rightarrow h_0 \sim \mathbf{10^{-11}} \left(\frac{f}{\text{nHz}}\right)$$



Results: continuous source

2212.09571

- Target: SMBH binaries
- Log-likelihood ratio test for averaged all-sky search



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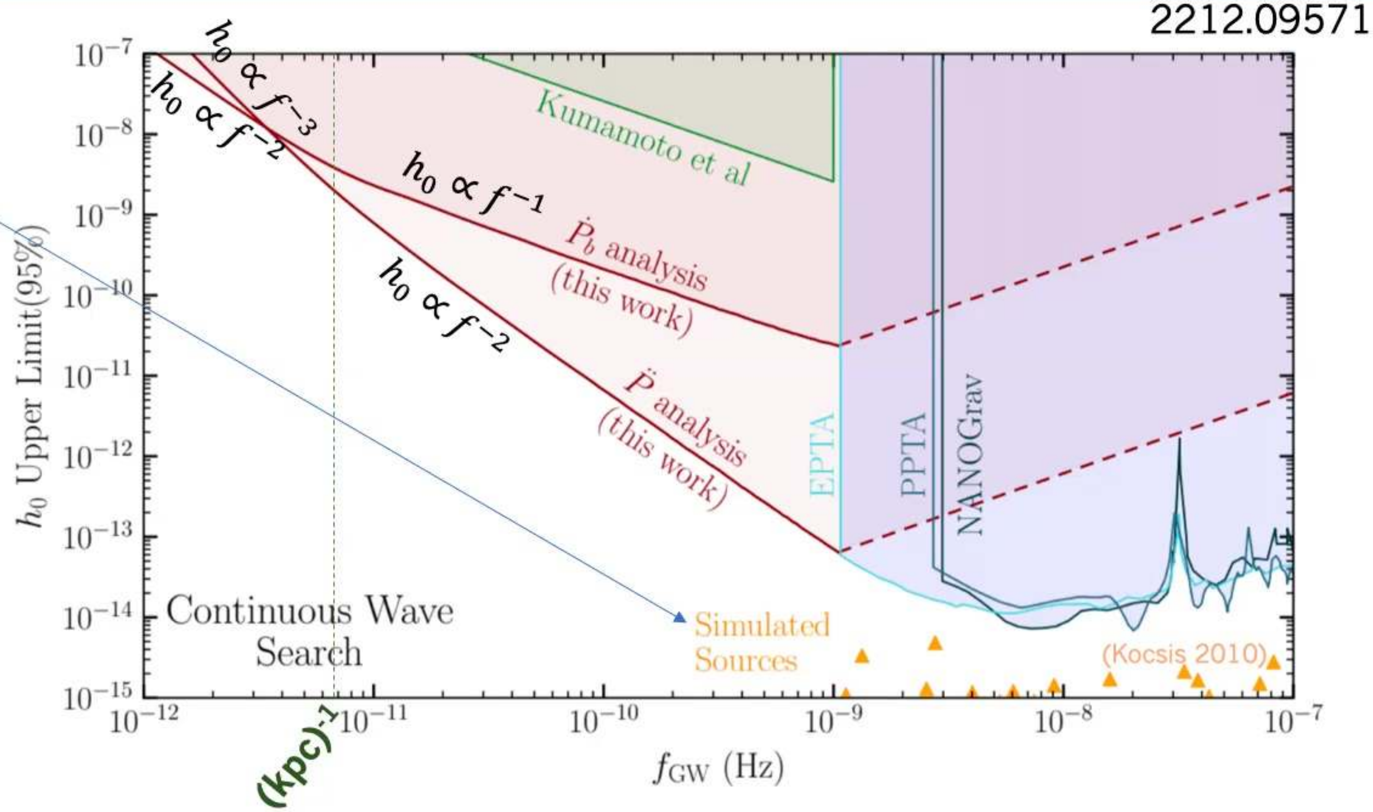
- Target: SMBH binaries
- Log-likelihood ratio test for averaged all-sky search
- Follows frequency scalings



More to come!

- Our data were exclusively EPTA and PPTA...
- Currently working with NANOGrav to implement this in their analysis pipeline!
- Observation of ultralow-frequency signal in next data release?

NANOGrav

Outline

- **Part I:** PTA analysis
  - **Takeaway I:** Standard PTA analysis "fits away" secular variation.
- **Part II:** Extracting sub-period signal
  - **Takeaway II:** Low-frequency behavior is stored in parameter estimates.
- **Part III:** Results
  - **Takeaway III:** Certain parameters offer sensitivity to gravitational waves at sub-nanohertz frequencies.


Thank you!