2212.XXXXX

Extending pulsar timing sensitivity below the nanohertz range

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(with Jeff Dror)

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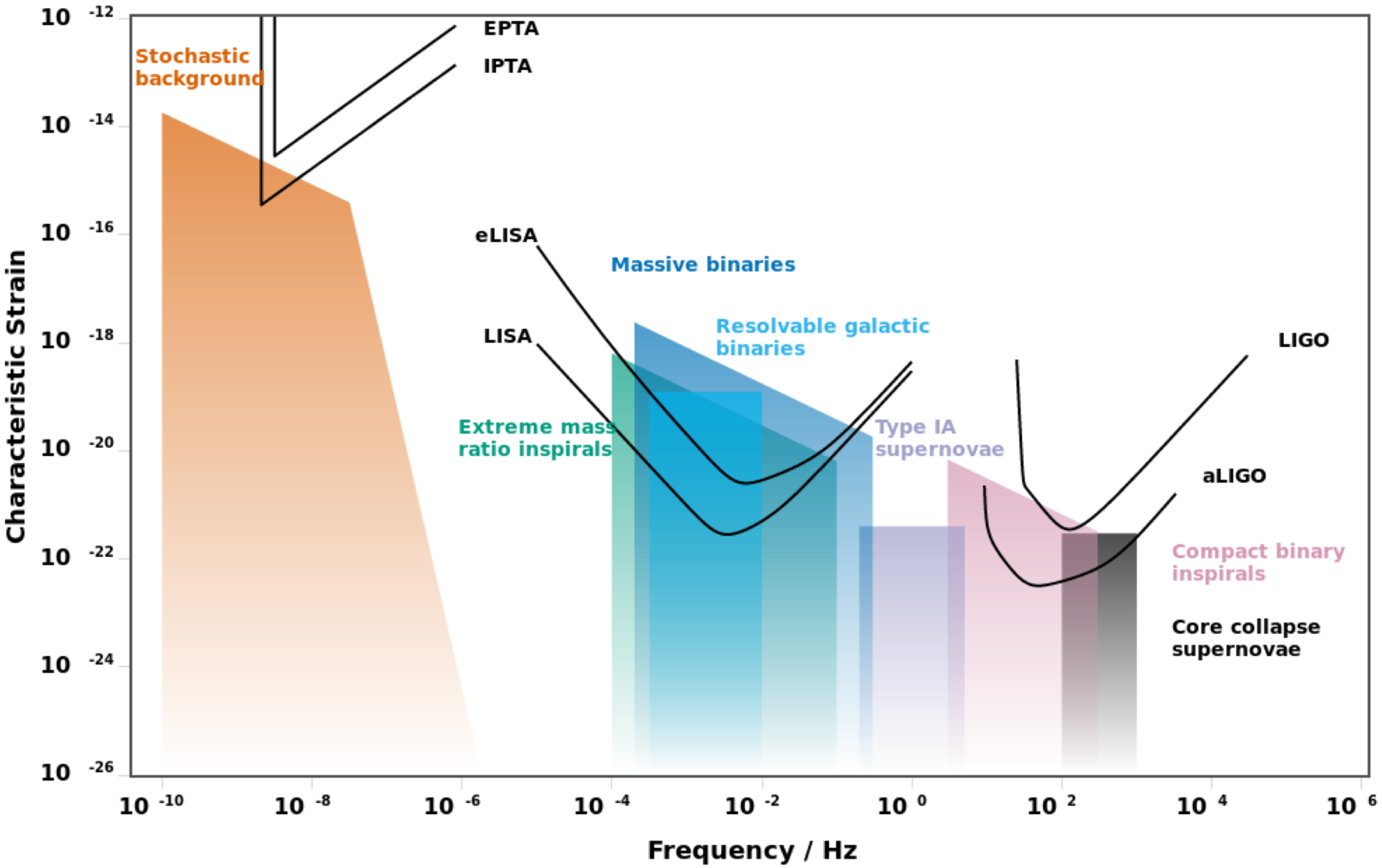
Motivation



Characteristic Strain
Frequency / Hz
10 -12
10 -14
10 -16
10 -18
10 -20
10 -22
10 -24
10 -26
10 -10
10 -8
10 -6
10 -4
10 -2
10 0
10 2
10 4
10 6
Stochastic background
EPTA
IPTA
eLISA
LISA
Massive binaries
Resolvable galactic binaries
Extreme mass ratio inspirals
Type IA supernovae
LIGO
aLIGO
Compact binary inspirals
Core collapse supernovae

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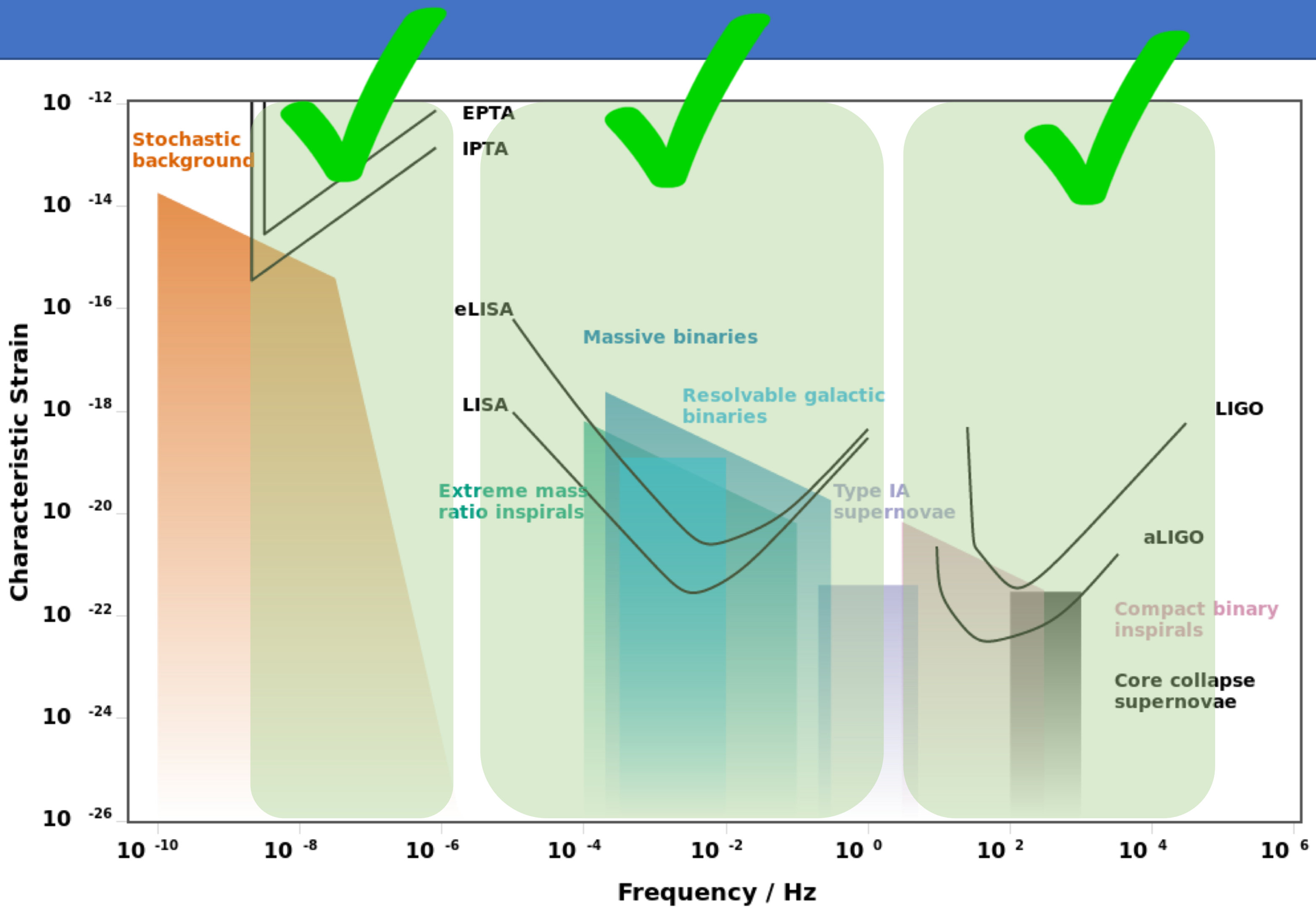

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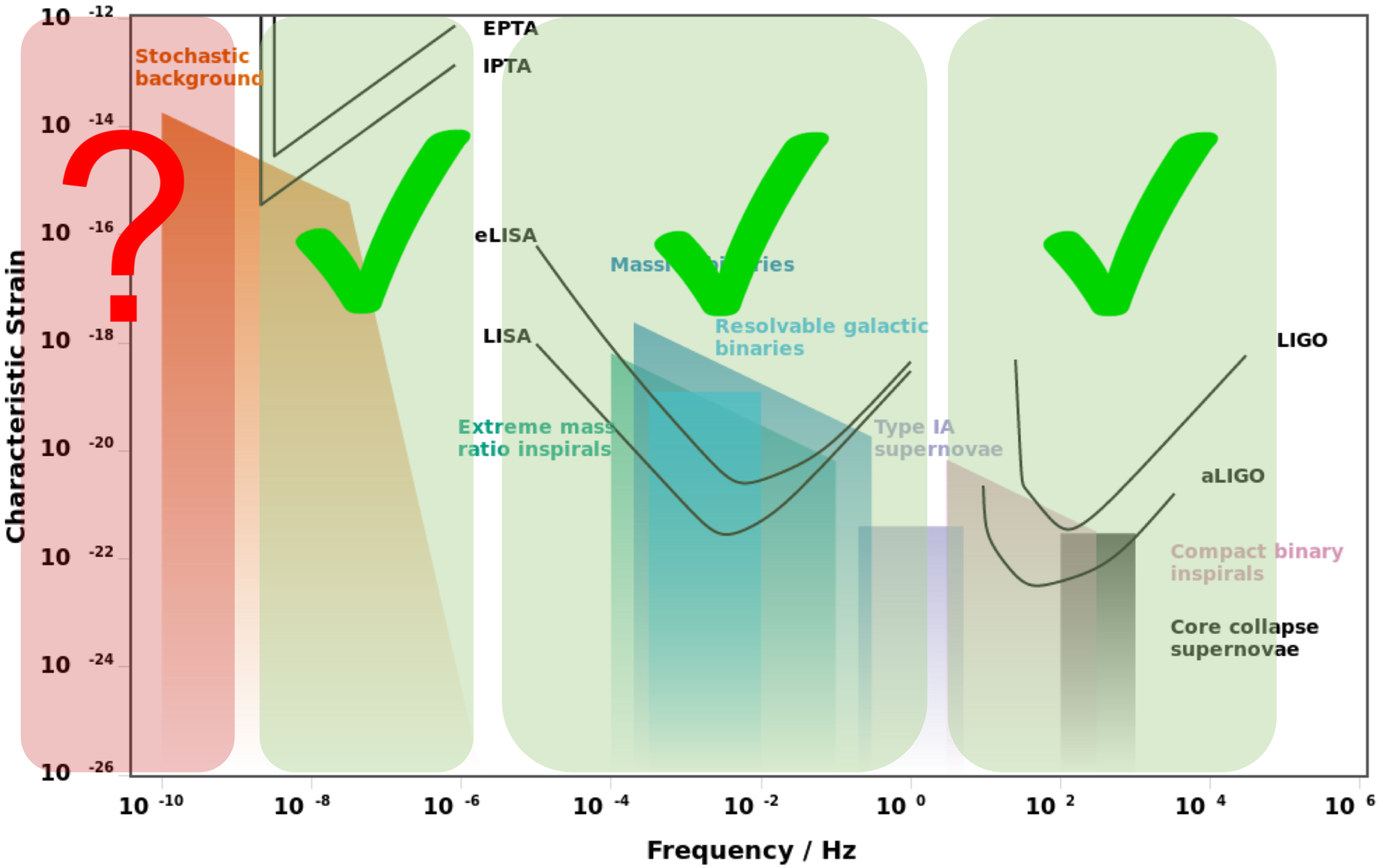

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Characteristic Strain
Frequency / Hz

Outline

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

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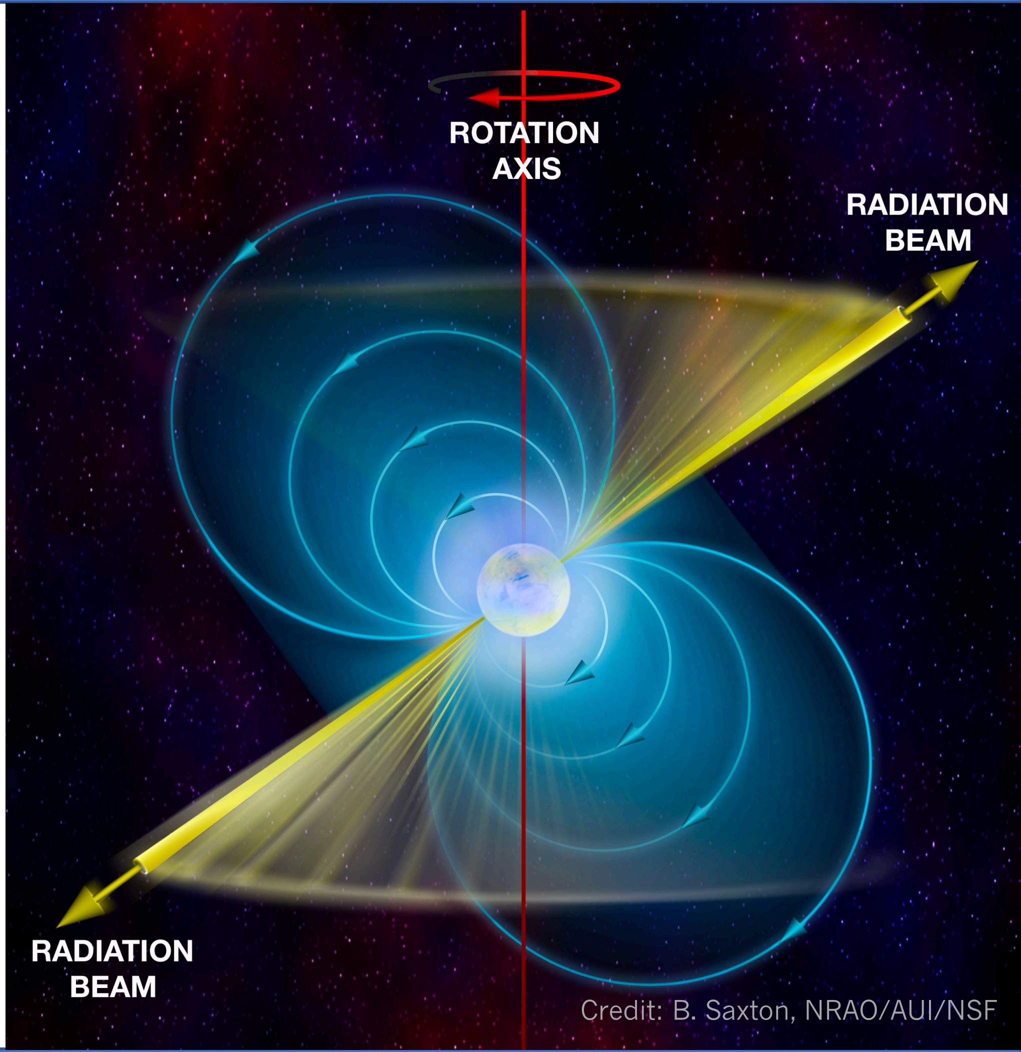
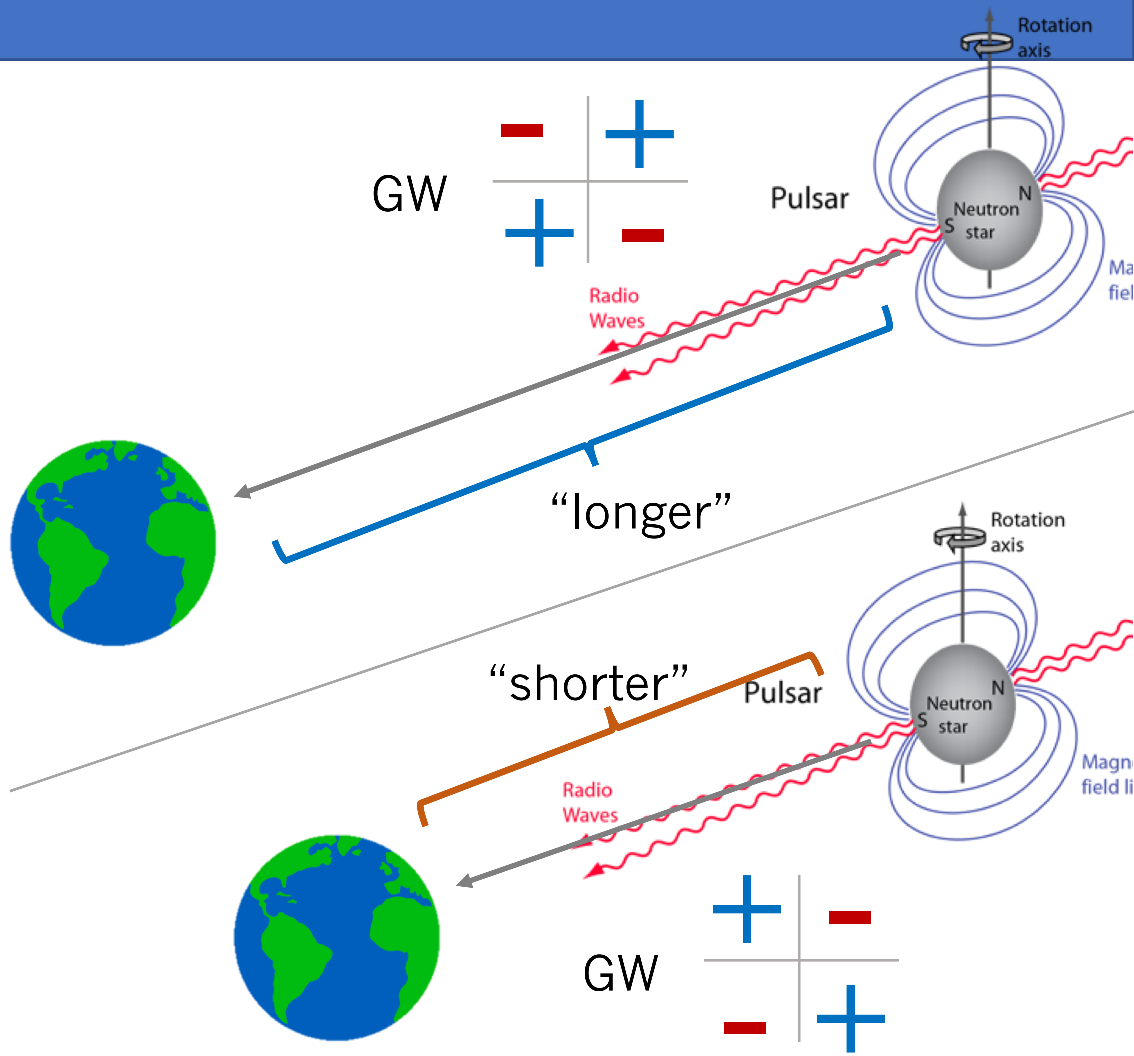
What is a pulsar?

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



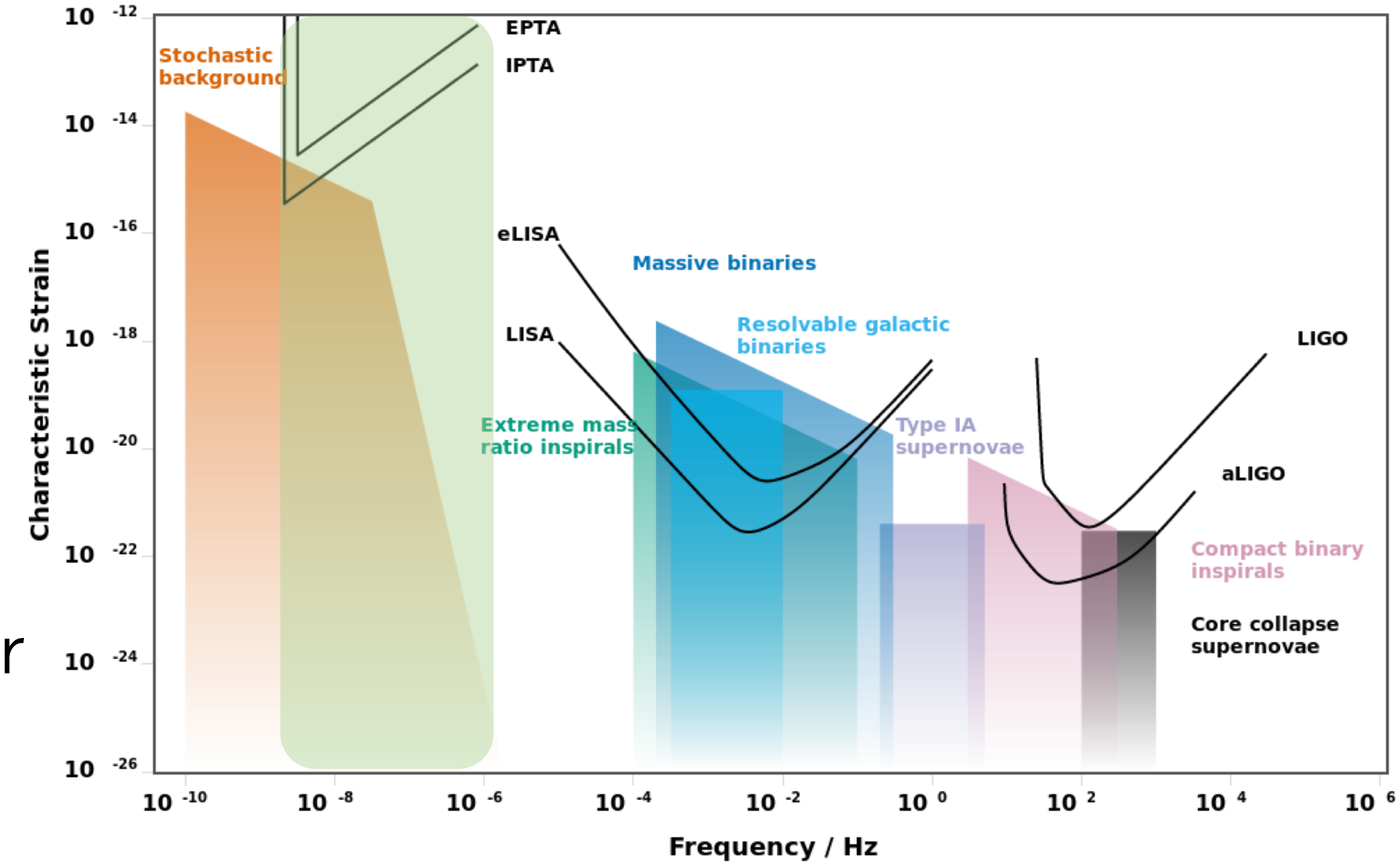
What is pulsar timing?

- Radiation points towards Earth briefly during each rotation ⇒ **pulse**
- Pulses **emitted** at fixed rate by pulsar
- GWs cause variation in light-travel time ⇒ variation in **arrival** times at Earth



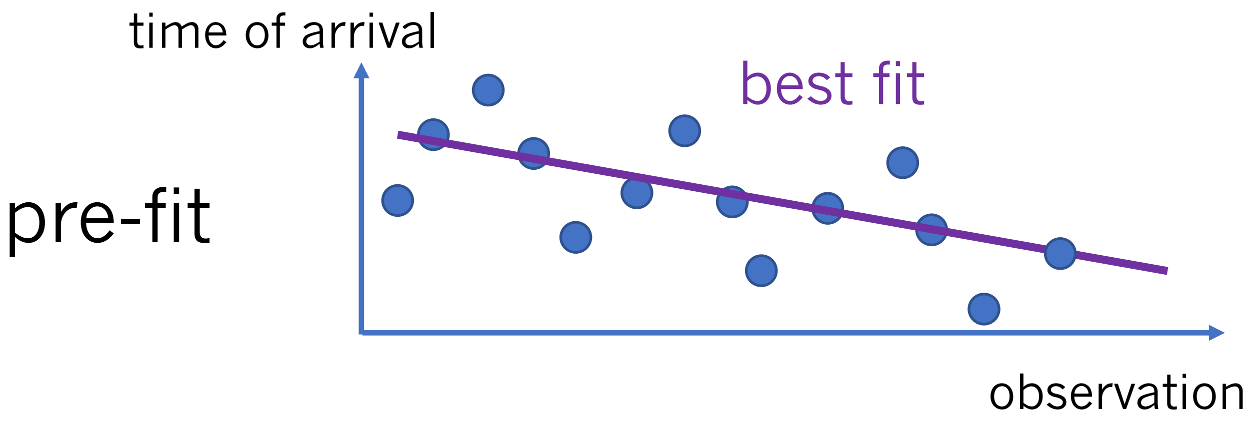
PTA band

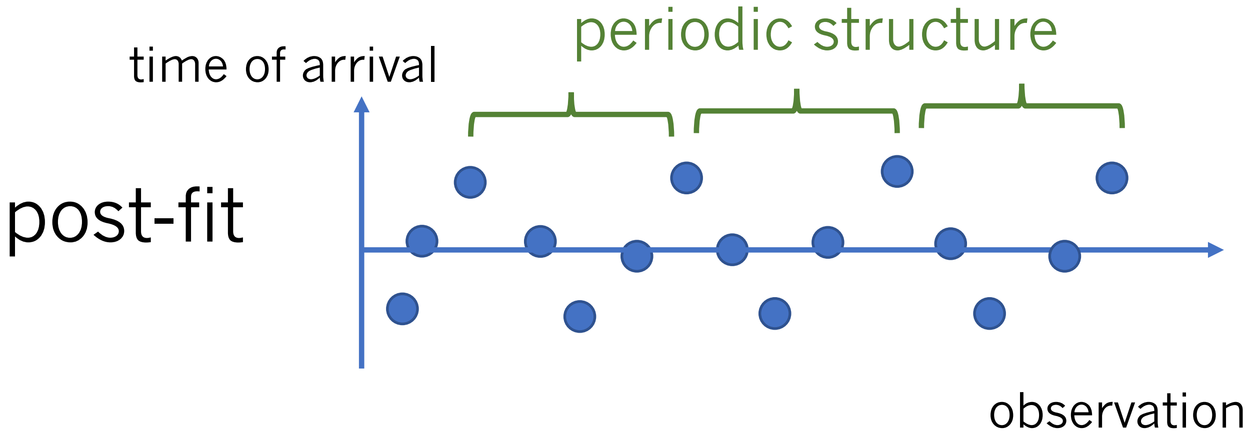
- Nanohertz frequencies
- *Targets:* supermassive black hole binaries, early universe phase transitions, …
- Sharp cutoff at ~ 30-year GW periods



PTA details

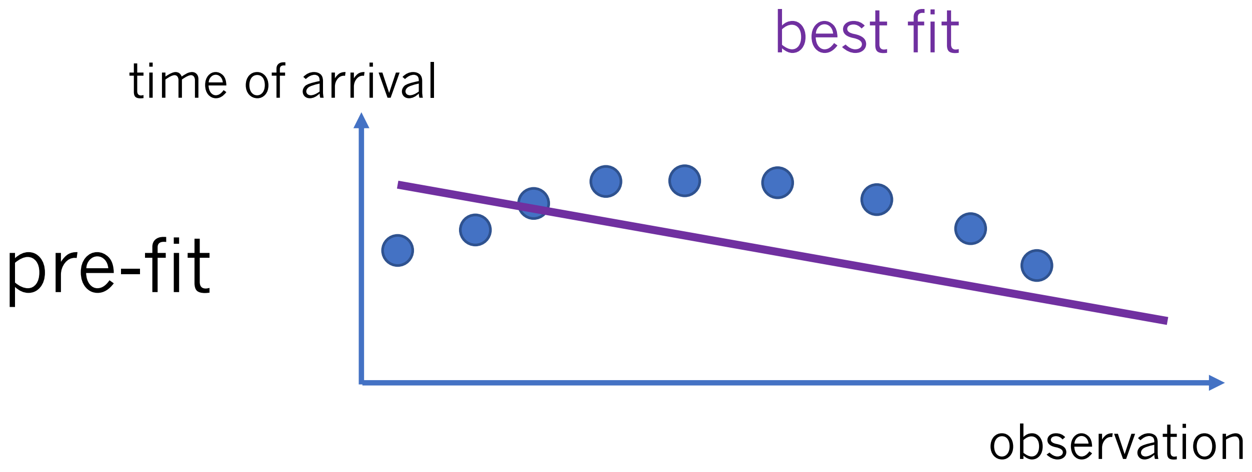
- Extract **residuals** by performing a **fit**
- Take Fourier Transform of residuals to pull out signal
- *Requires observation of full period!*
- 30 years = observation time of current PTAs

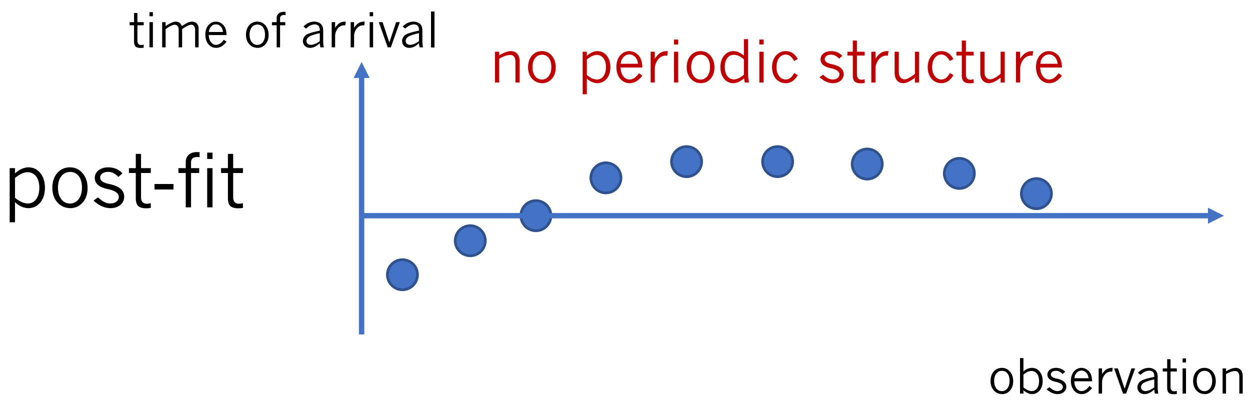




Sub-nHz gravitational waves

- Don't see full period
- Appear as "secular drift"
- Do not show up in Fourier Transform of residuals
- All the signal is lost during the fitting procedure…





Sub-nHz gravitational waves

- Don’t see full period
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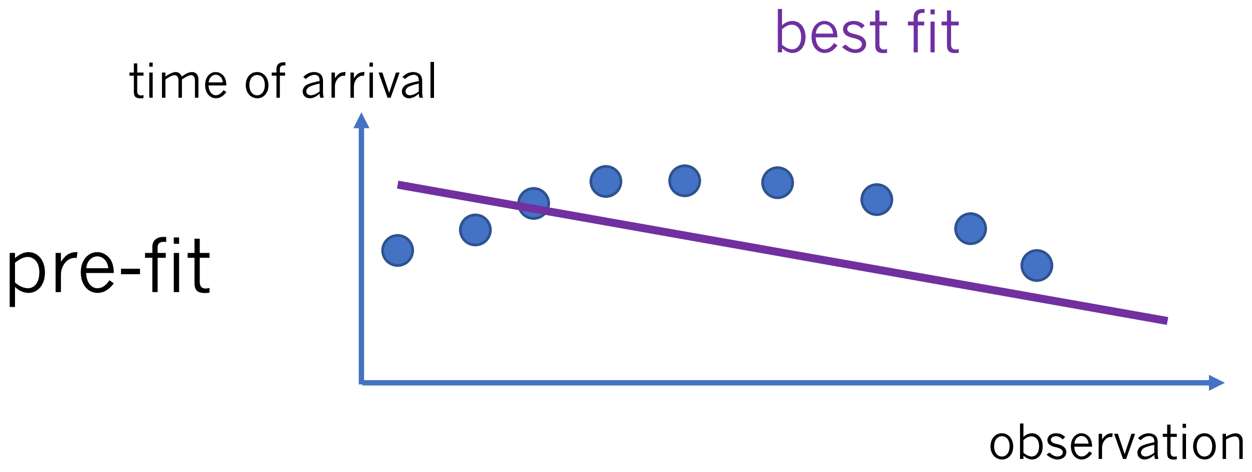

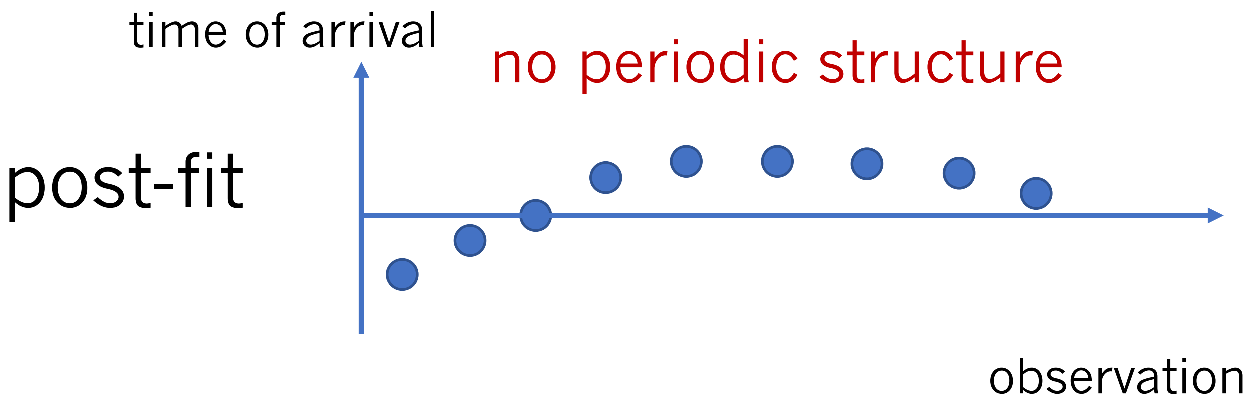

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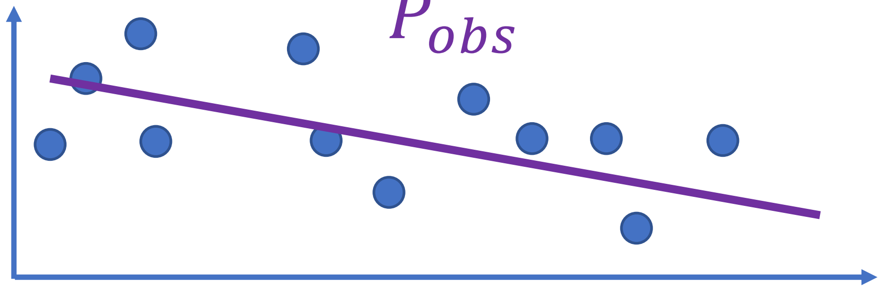
Fit parameters

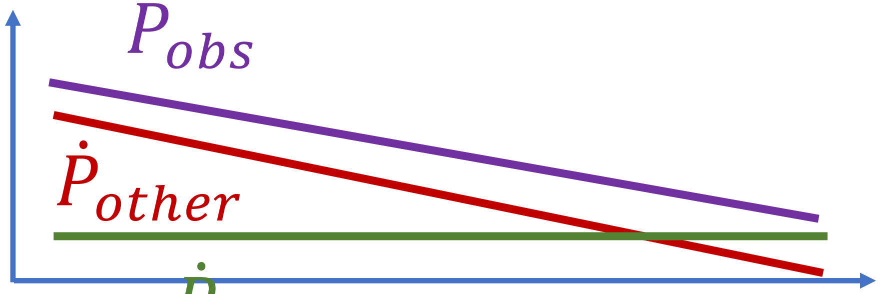
- "Fitting away" = low-frequency contributions stored in parameter fits!

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

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

- Intrinsic contributions to $\dot{P}$ unknown ⇒ GW signal obscured…





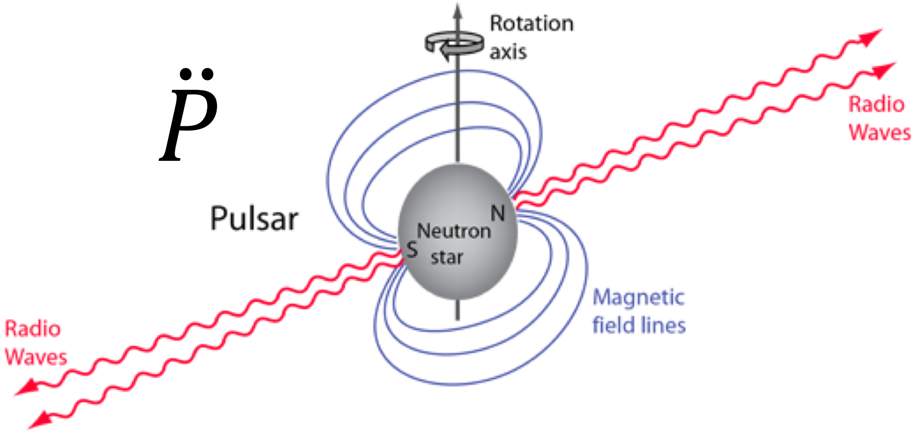
Credit: B. Saxton, NRAO/AUI/NSF

Sensitive parameters

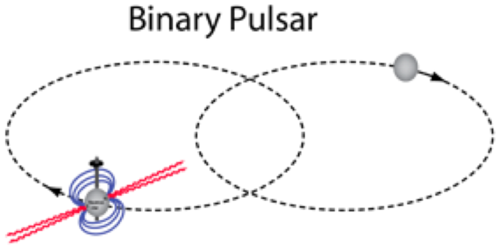
- Non-GW contributions to some parameters are known and can be subtracted away!

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

$\ddot{P}$



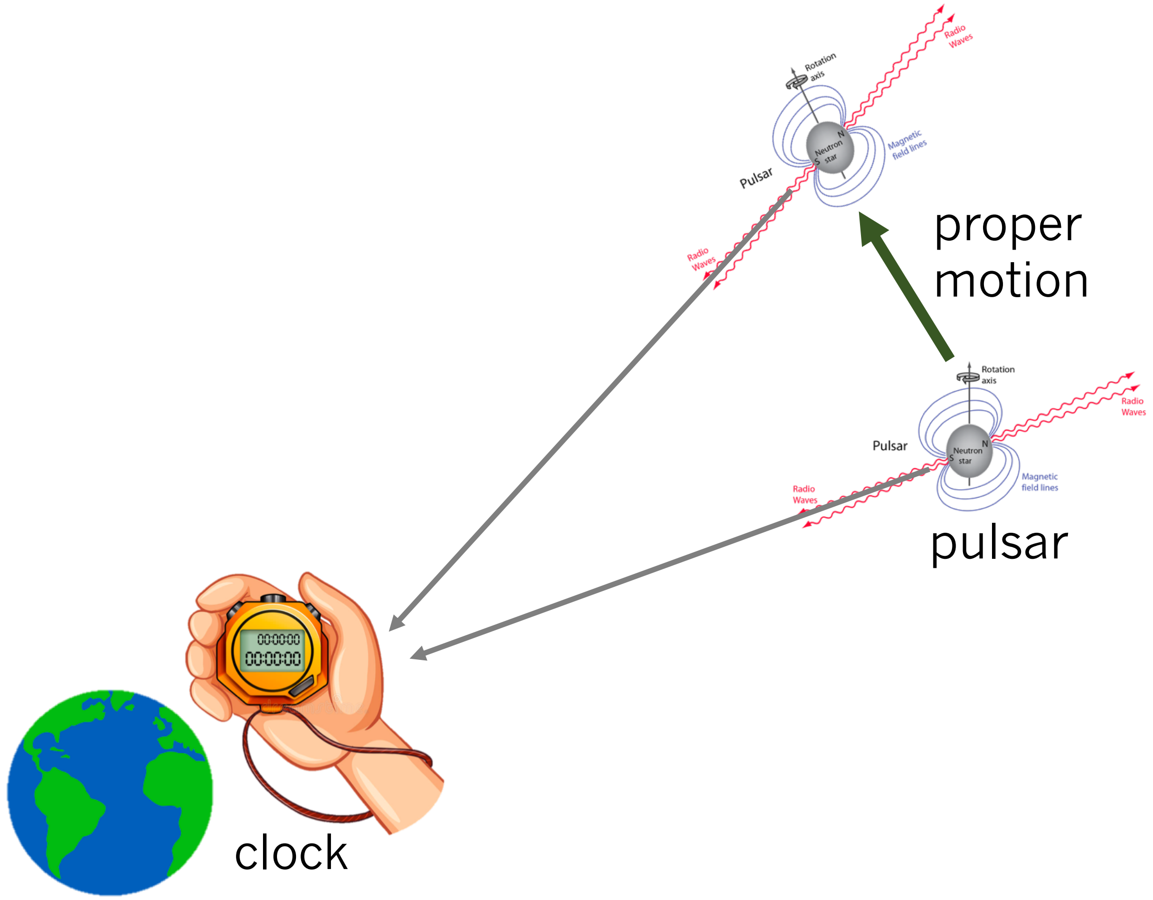
$\dot{P}_b$



http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/pulsrel.html

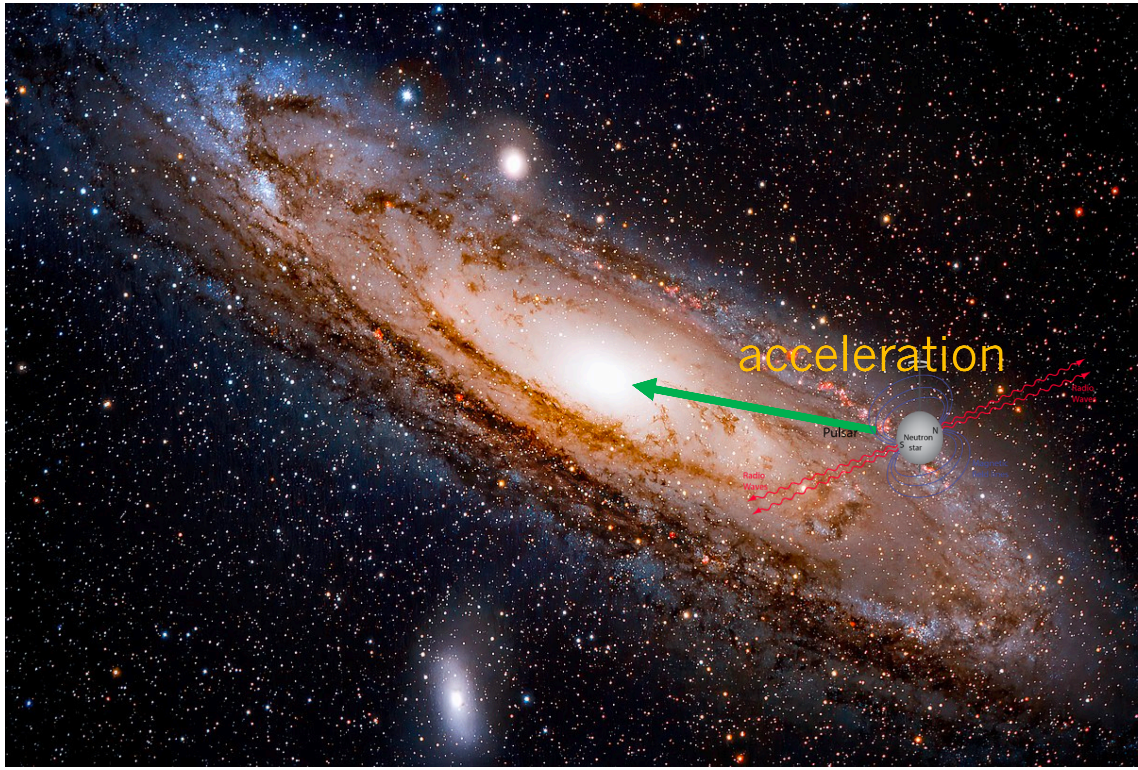
Contribution #1: Shklovskii Effect

- Proper motion on sky induces shift in residuals
- Distance + proper motion measurements = **predictable**!
- Dominant contribution for most pulsars



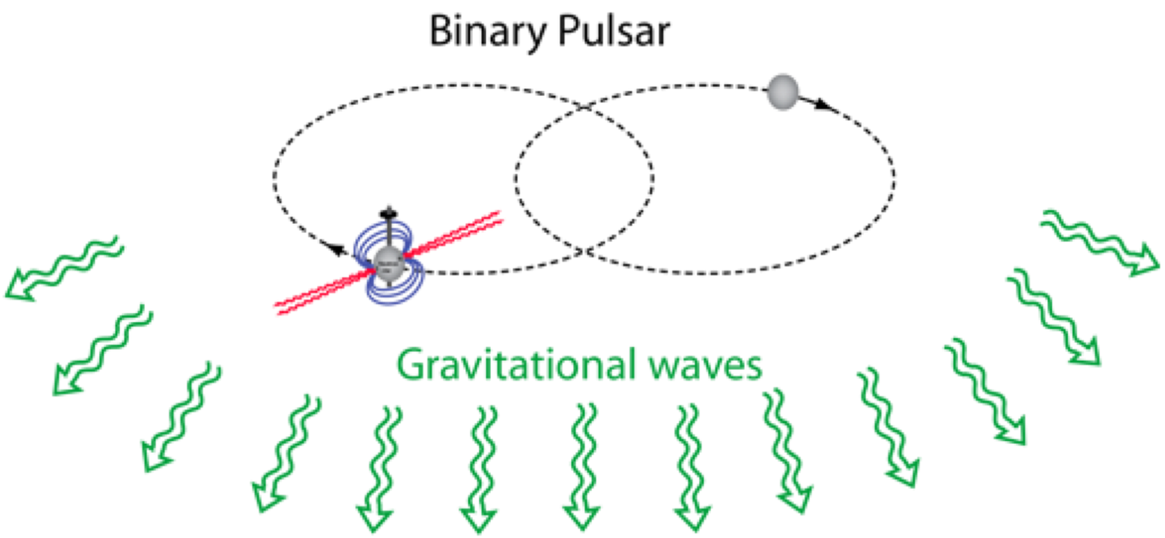
Contribution #2: Galactic acceleration

- Galactic potential tugs on pulsar
- Milky Way model + pulsar position measurements = **predictable**!
- Highly subdominant in most cases



Contribution #3: Gravitational radiation

- Binary systems emit gravitational radiation of their own
- This decreases energy, causing orbit to slow
- Mass + orbital parameter measurements = **predictable**!
- Subdominant in most settings



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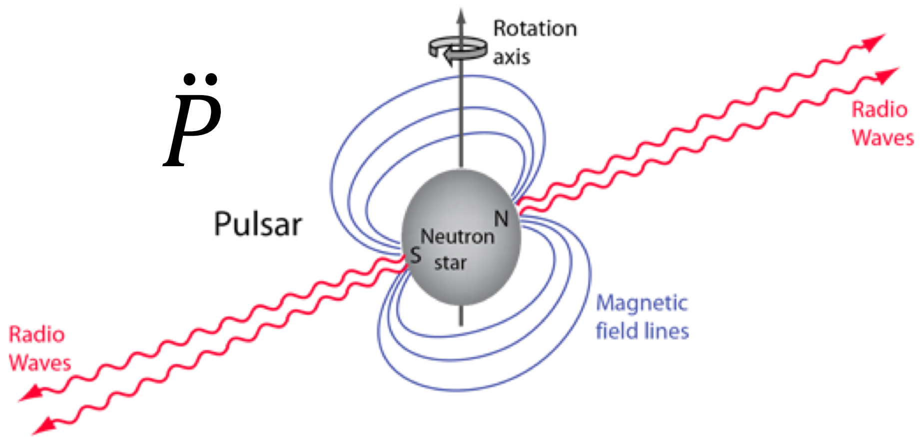
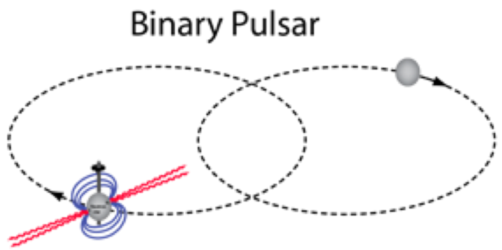
$$\dot{P}_{GW} = \dot{P}_{obs} - \dot{P}_{other}$$

$\ddot{P}$



$\dot{P}_b$



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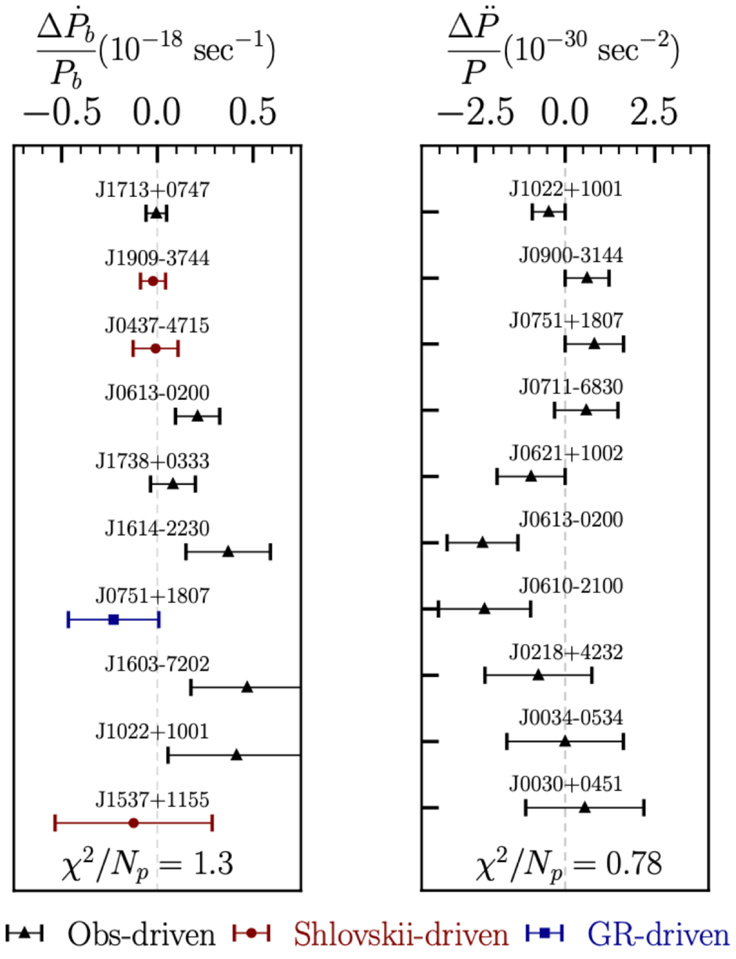
Data

- $\ddot{P}$: 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.



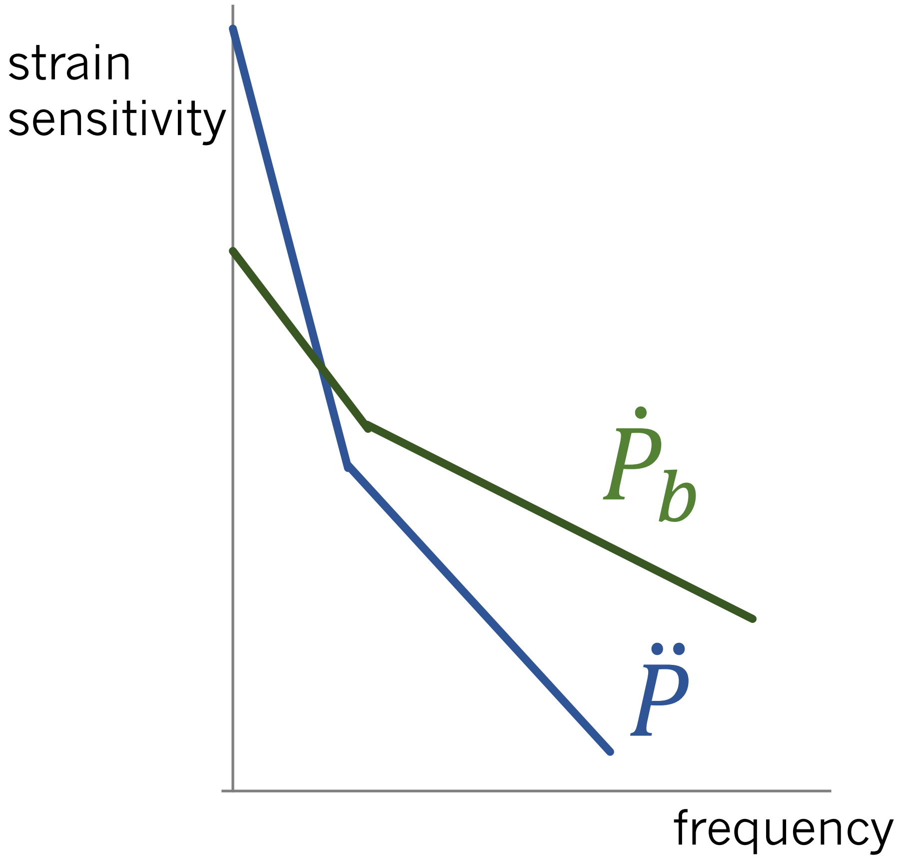
Scaling

- Line-of-sight velocity induced by GW:

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

- 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:** $\ddot{P} \propto j_{LOS} = \dddot{x}_{LOS} \sim \boldsymbol{h_0 f^3}$



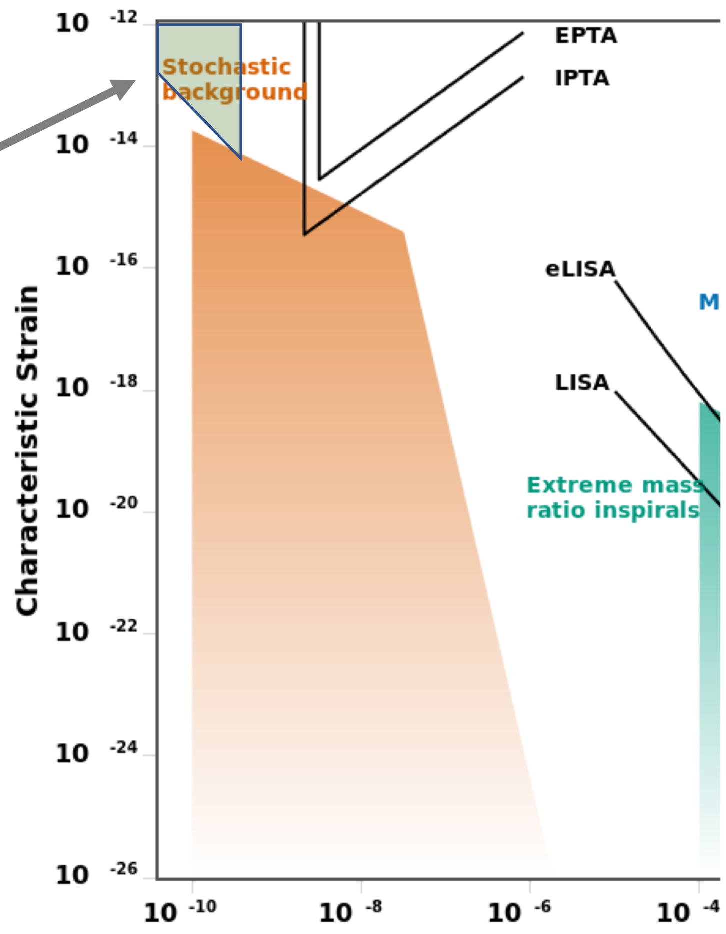
Back-of-the-envelope estimate

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

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

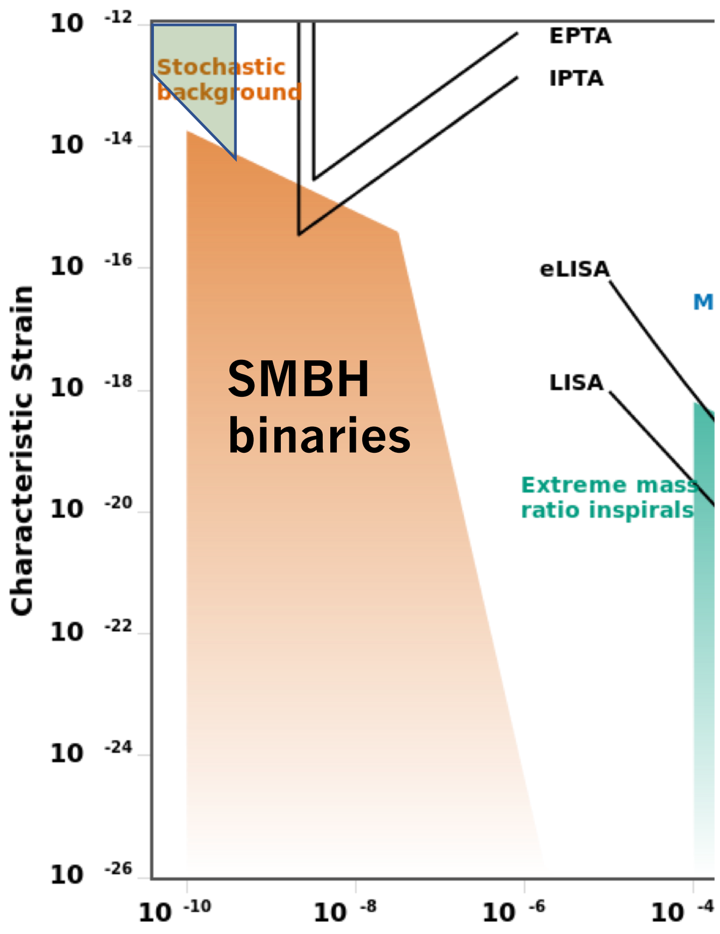
- Acceleration ~ 10^{-19} s^{-1}

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



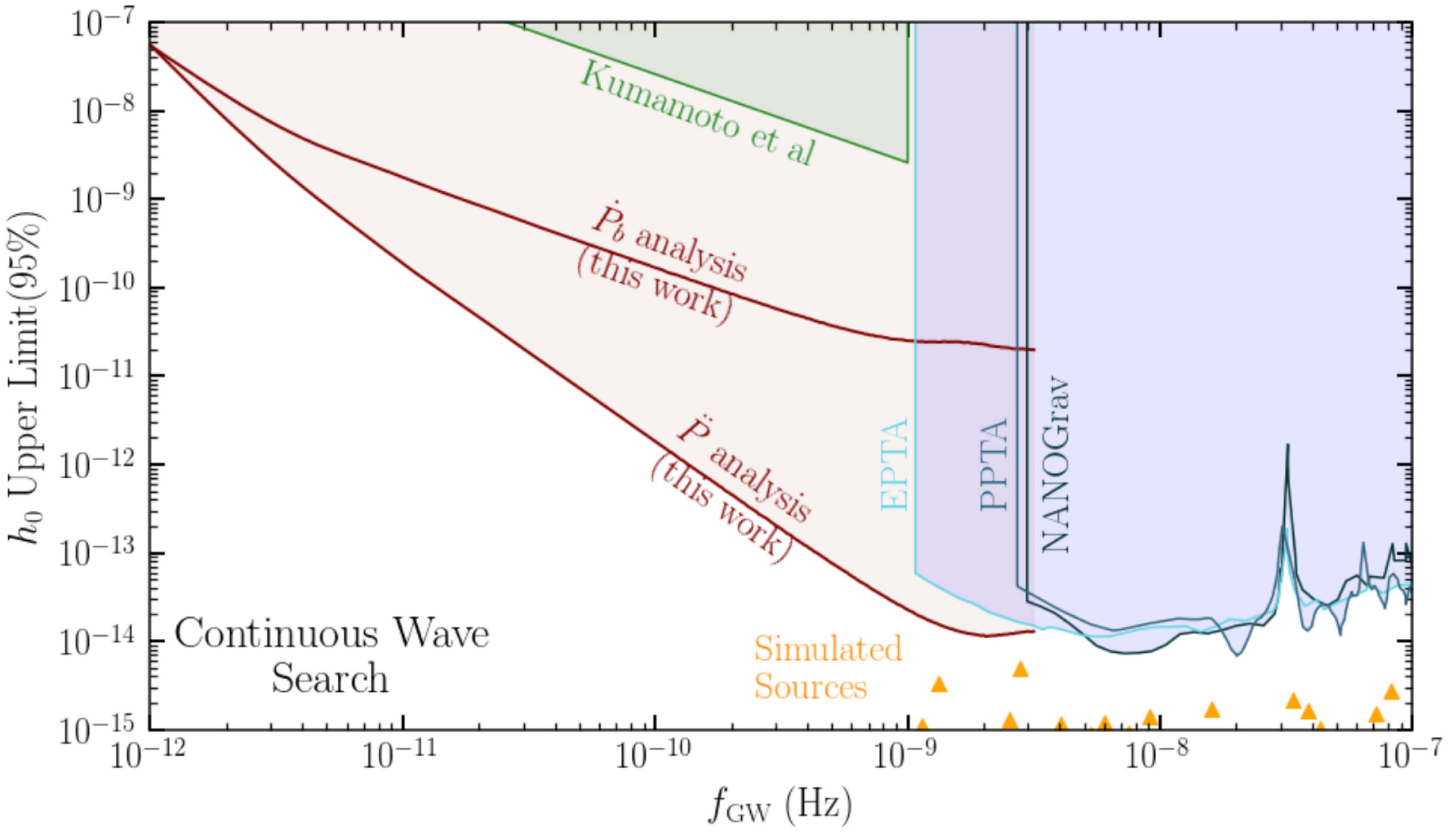
Supermassive Black Hole Binaries

- In-spiral of two SMBHs
- Predicted to follow power-law fall-off towards higher frequency
- Attractive target in ultra-low frequency band
- Expected to be observed imminently by conventional PTA analysis!



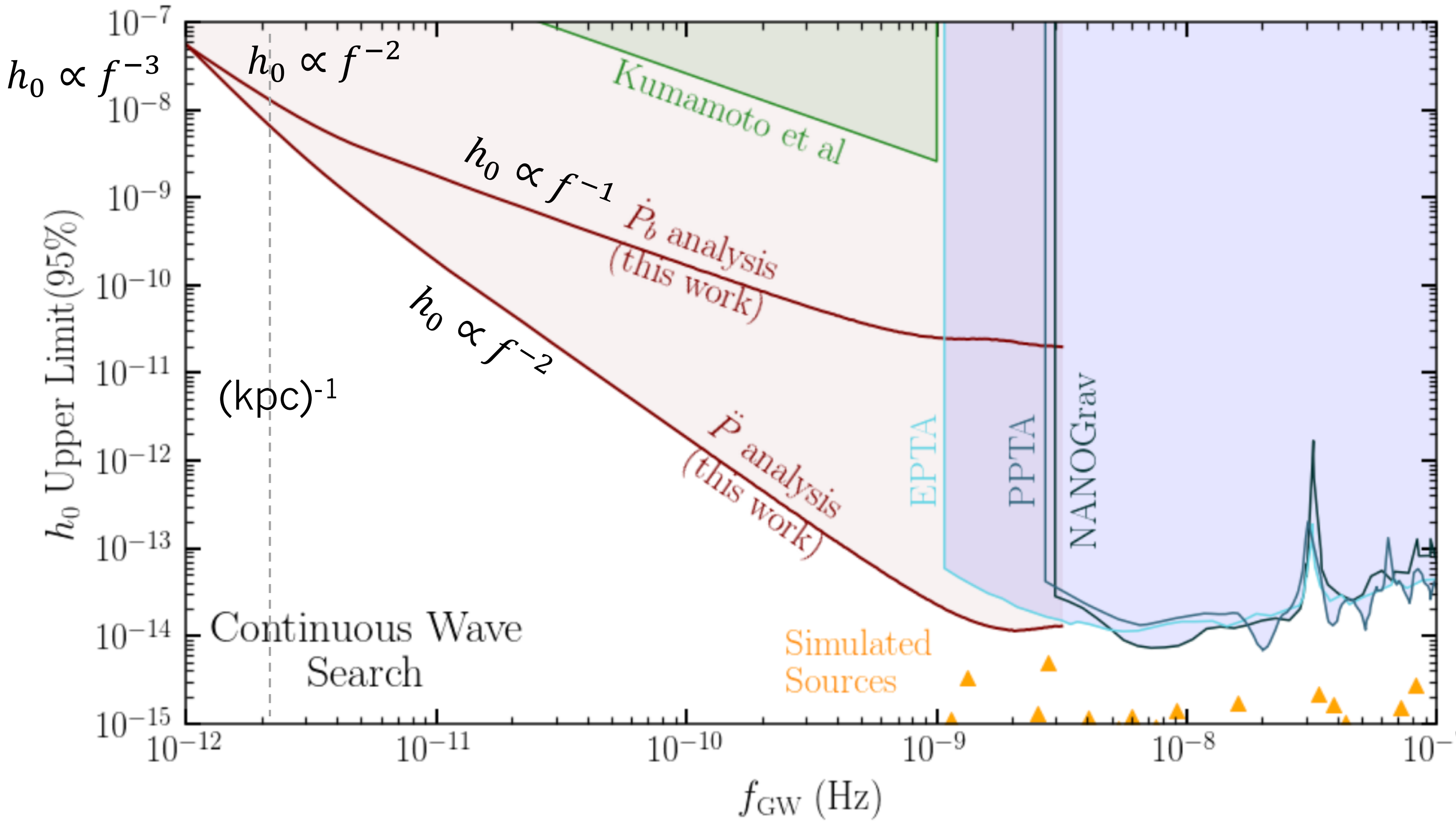
Results

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



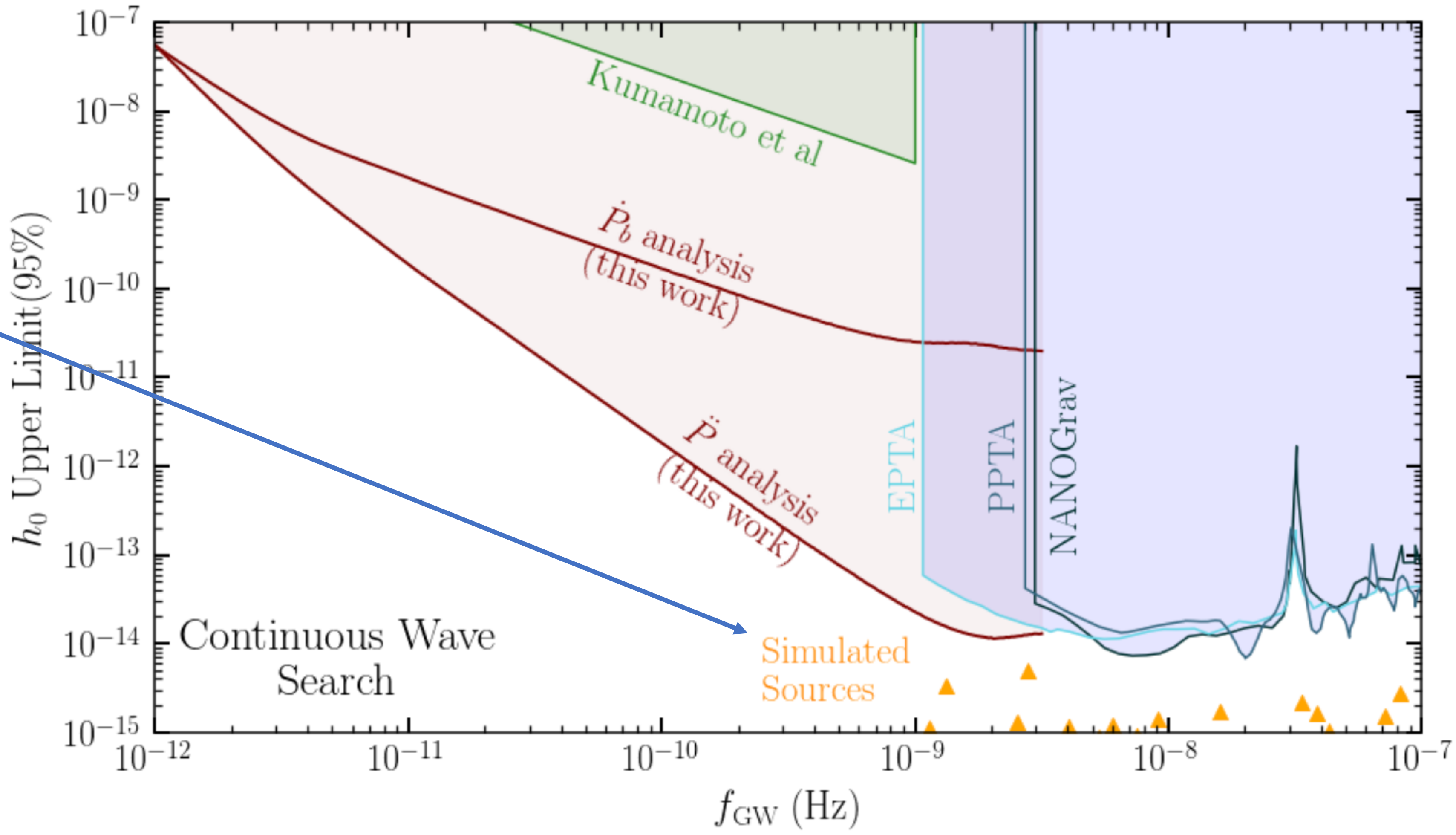
Results

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



Implications

- Decent chance of observing signal in the next decade!
- *Upcoming work:* **stochastic** GW background



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:** Cross-sky correlations in fit values offer sensitivity at sub-nanohertz frequencies.

Thank you!