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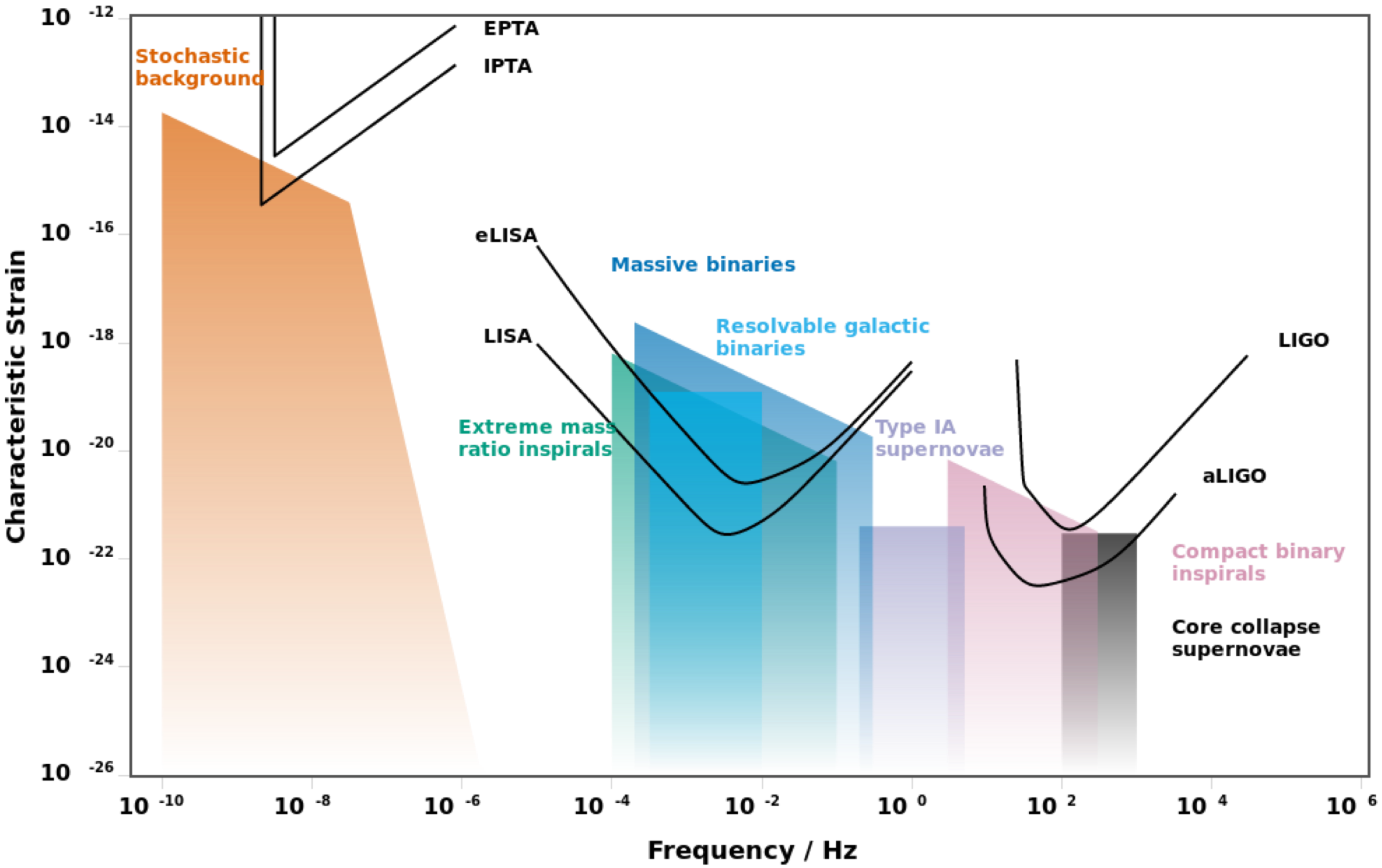
Searching for sub-nHz gravitational waves with pulsar parameter drift

William DeRocco
(with Jeff Dror)
University of California, Santa Cruz

Motivation



Characteristic Strain
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
Frequency / Hz
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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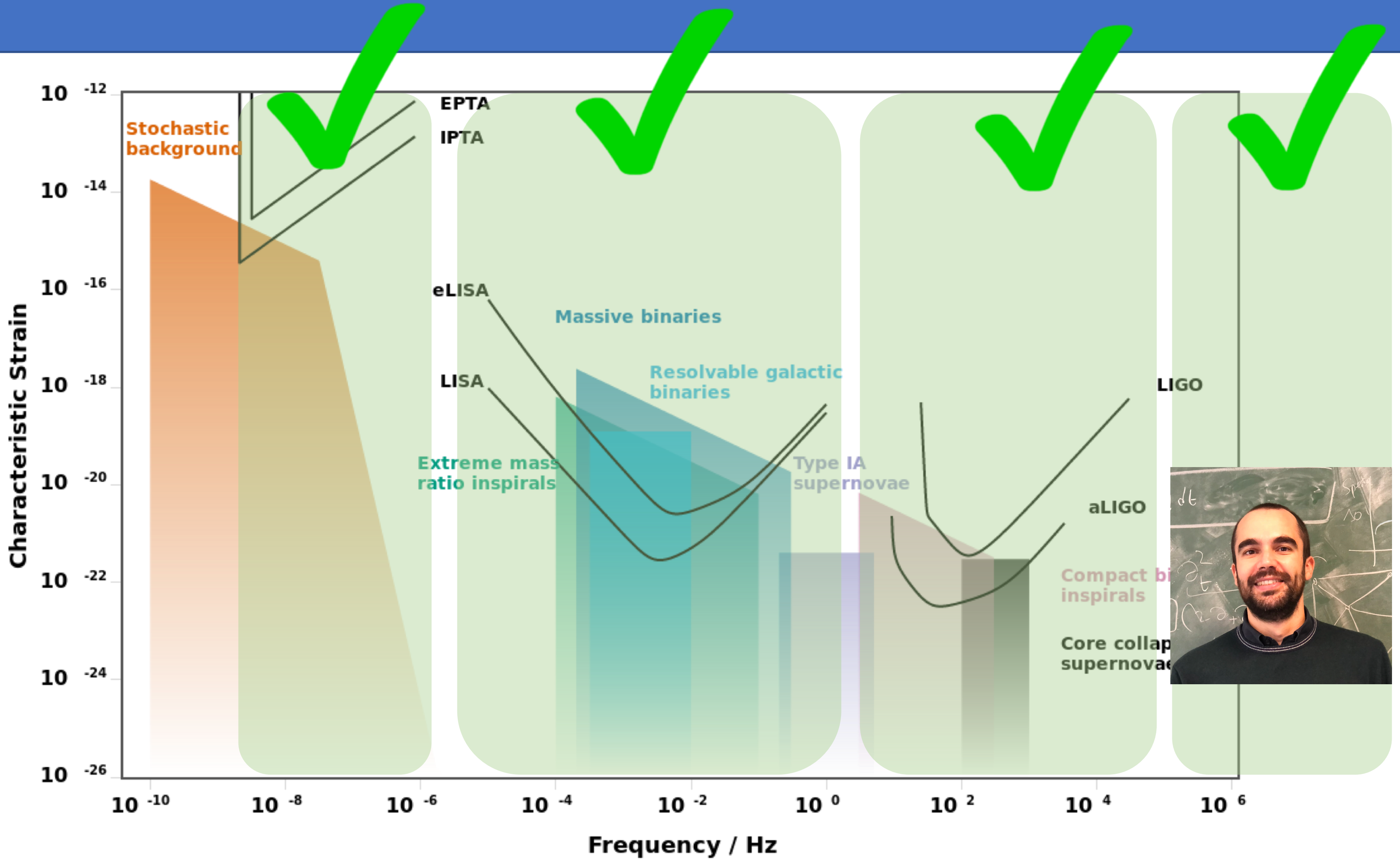

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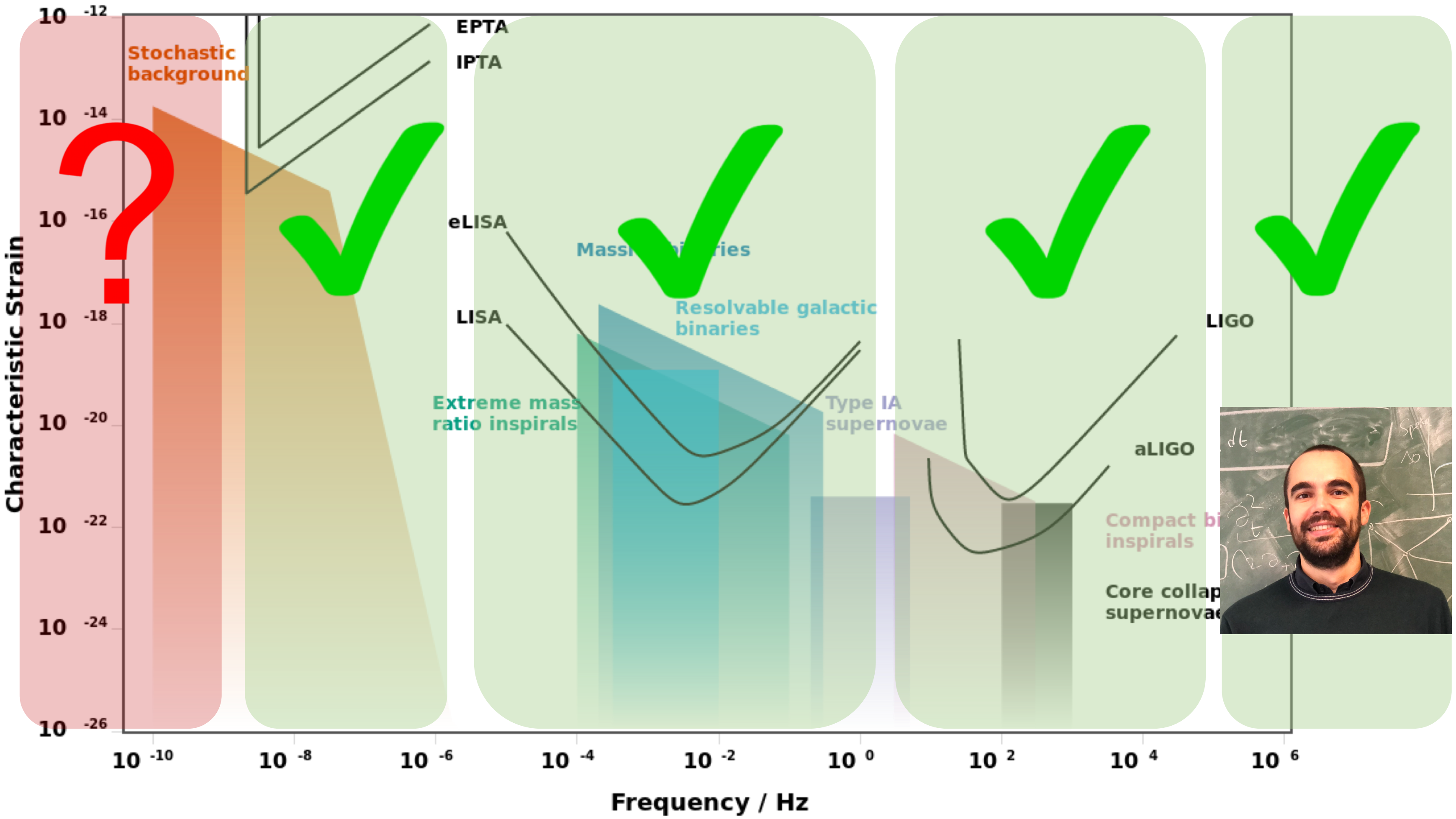

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Outline

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

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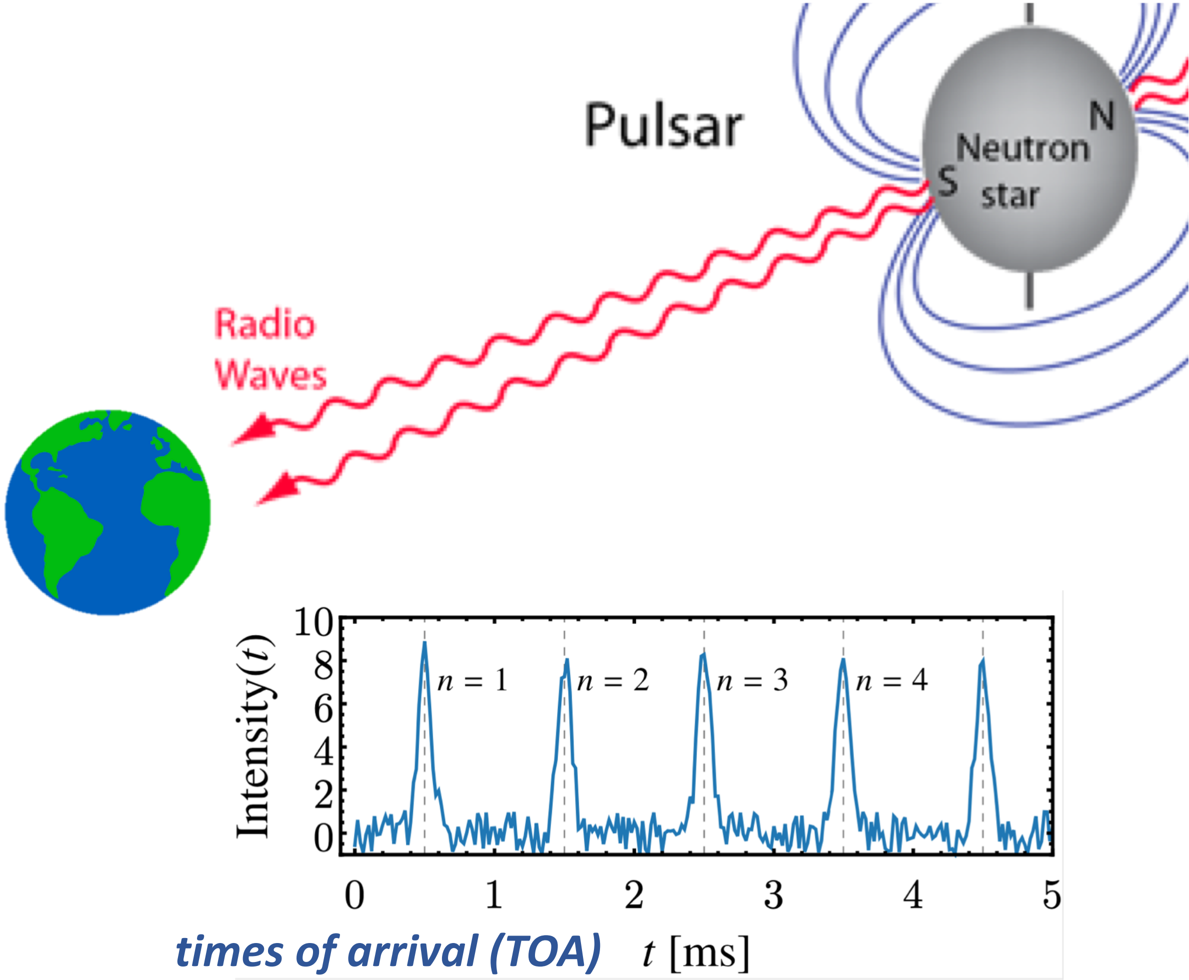
Pulsars

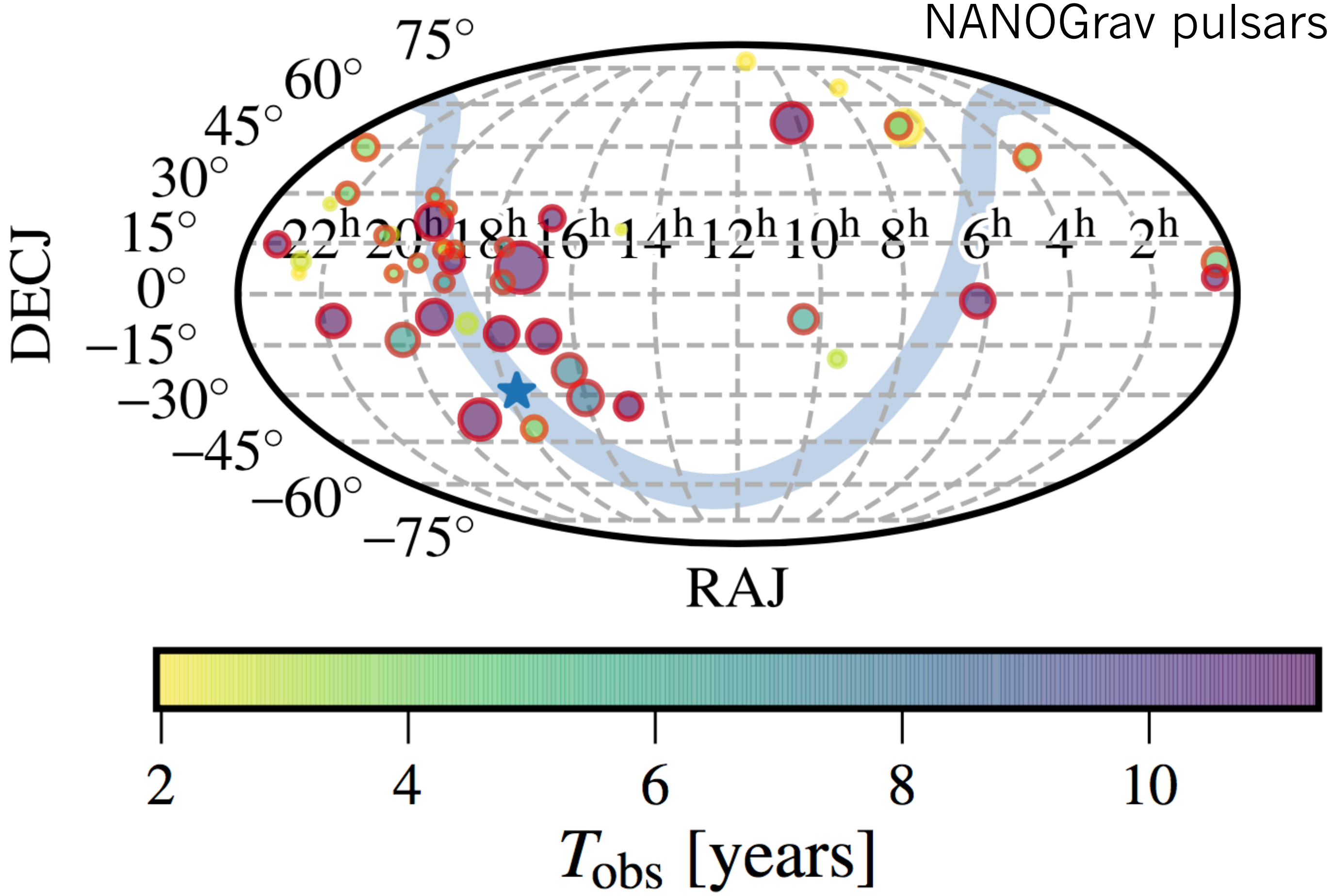
- Rapidly-rotating neutron star with directional beam of radiation
- Pulse arrival = very precise clock
  - Periods ~ 10^{-3} sec
  - Measured to ~ 10^{-7} sec
- Sensitive to variations in path length (GW signal)



Pulsar timing array

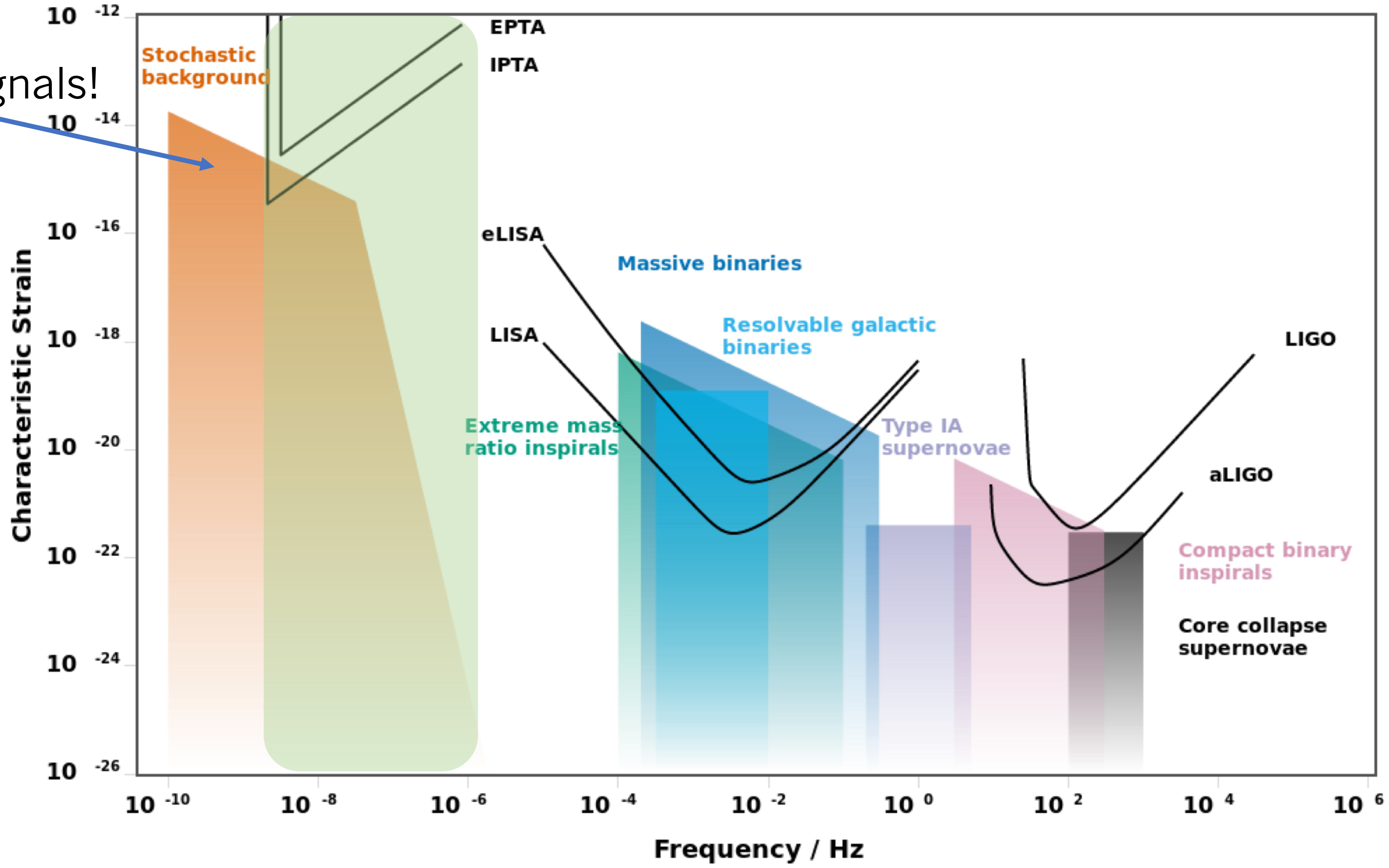
- GWs are quadrupolar
- Variations in arrival times are ***correlated across sky***
- Correlations help discriminate GWs from other sources of variation

NANOGrav pulsars



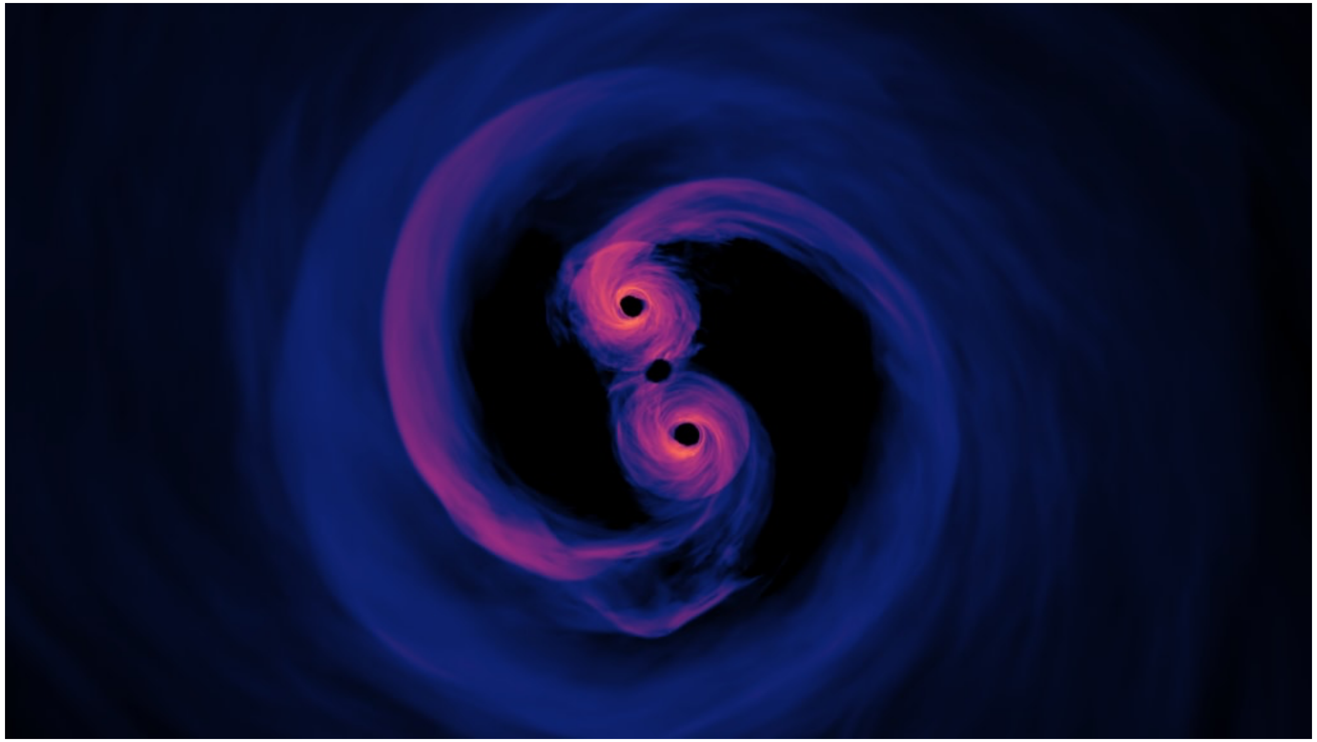
PTA band

astrophysical signals!

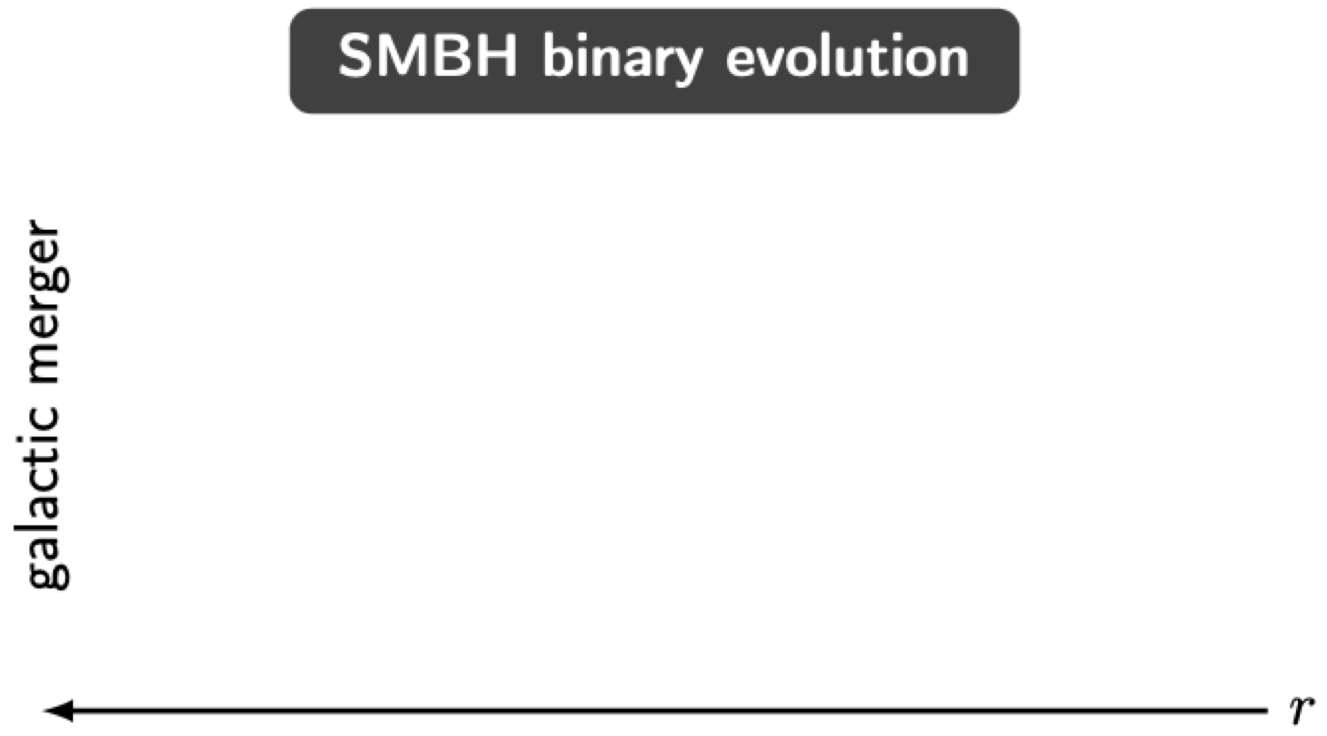


SMBH binaries

- 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



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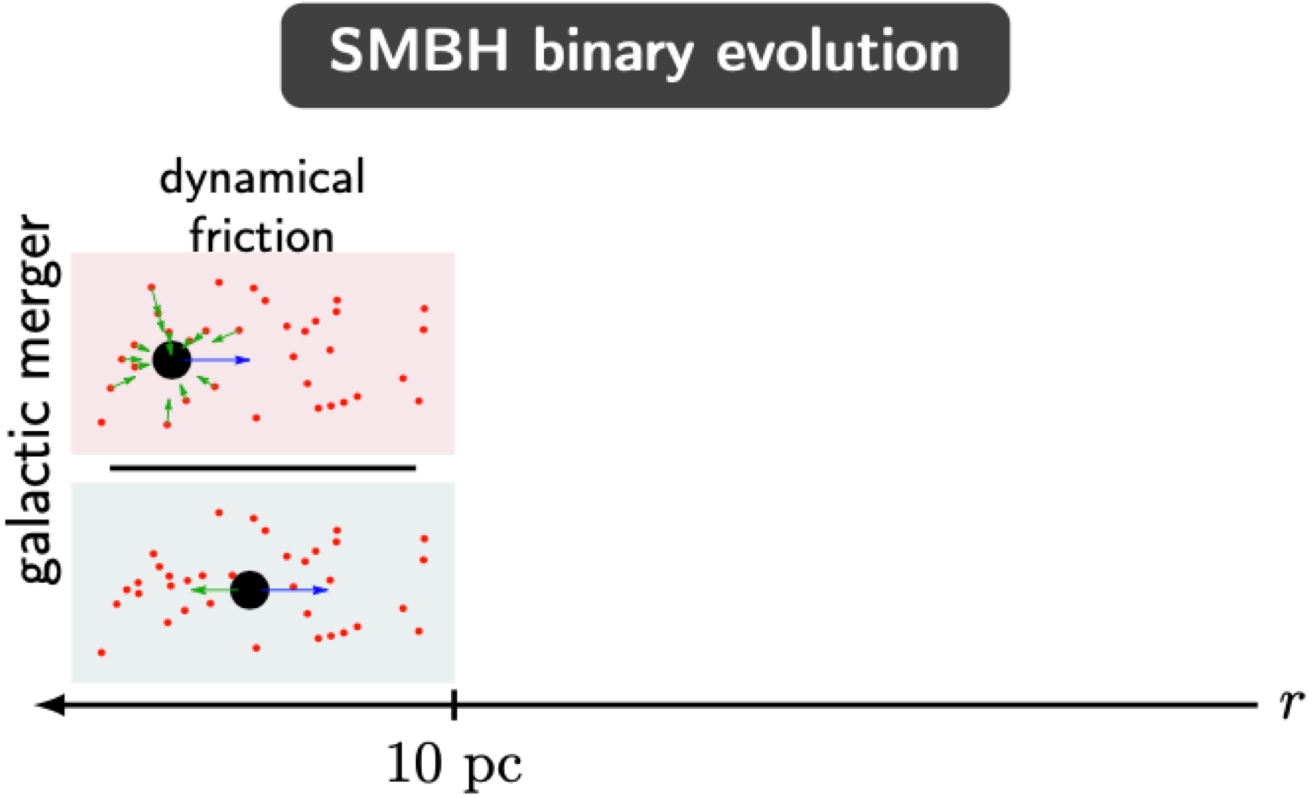

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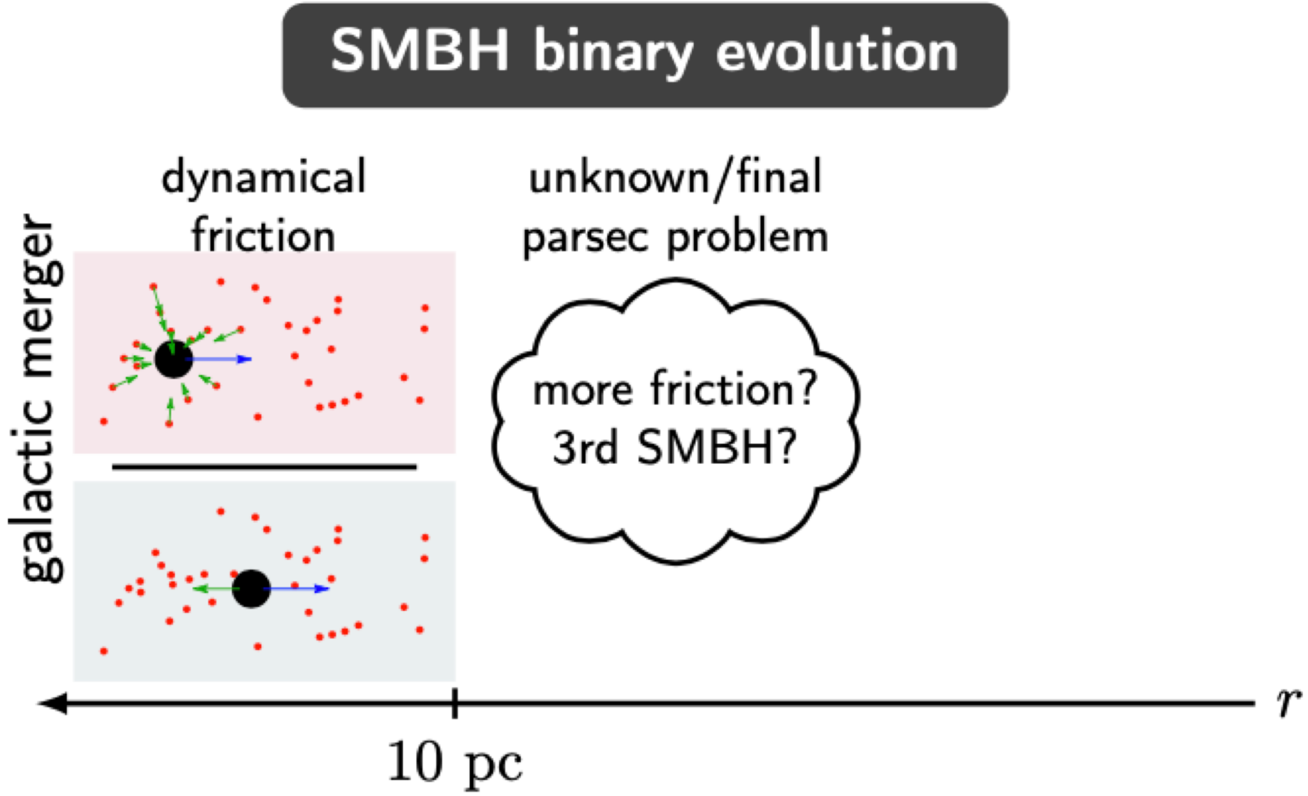

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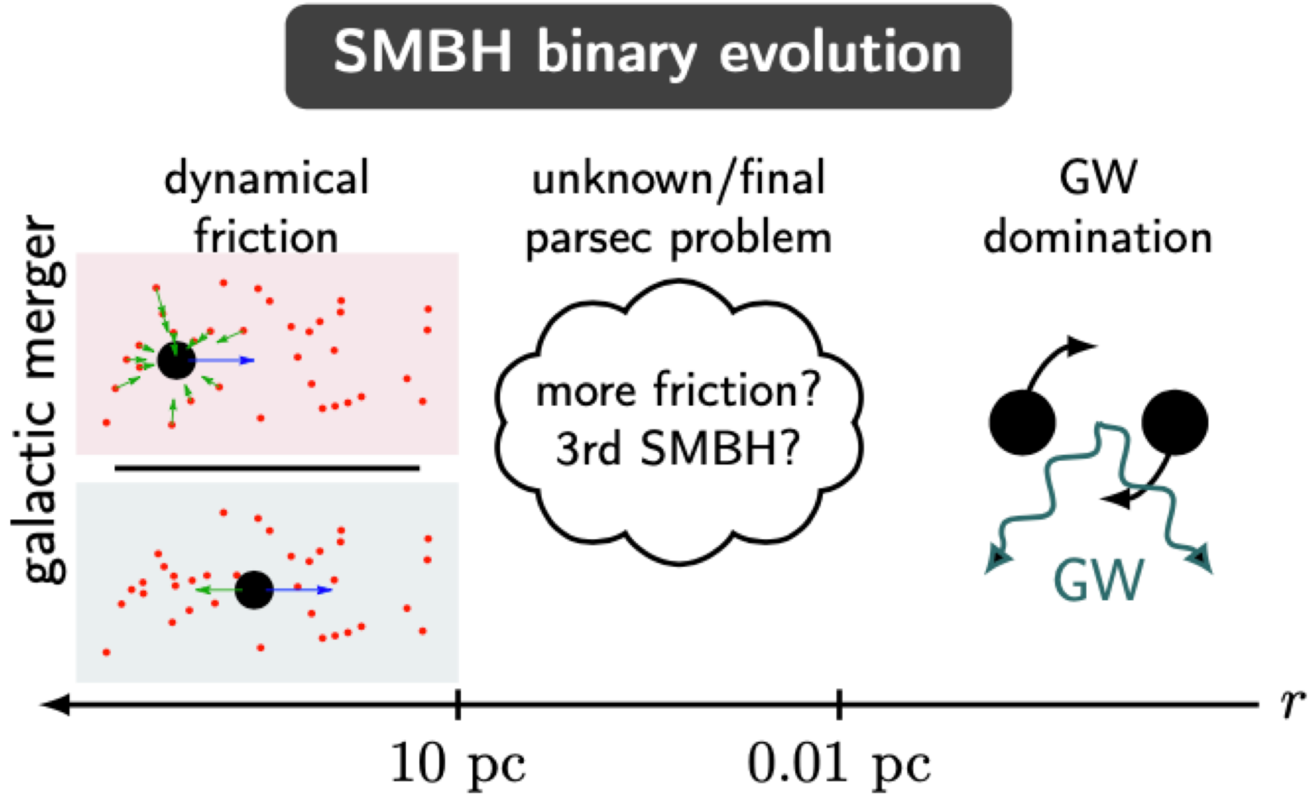

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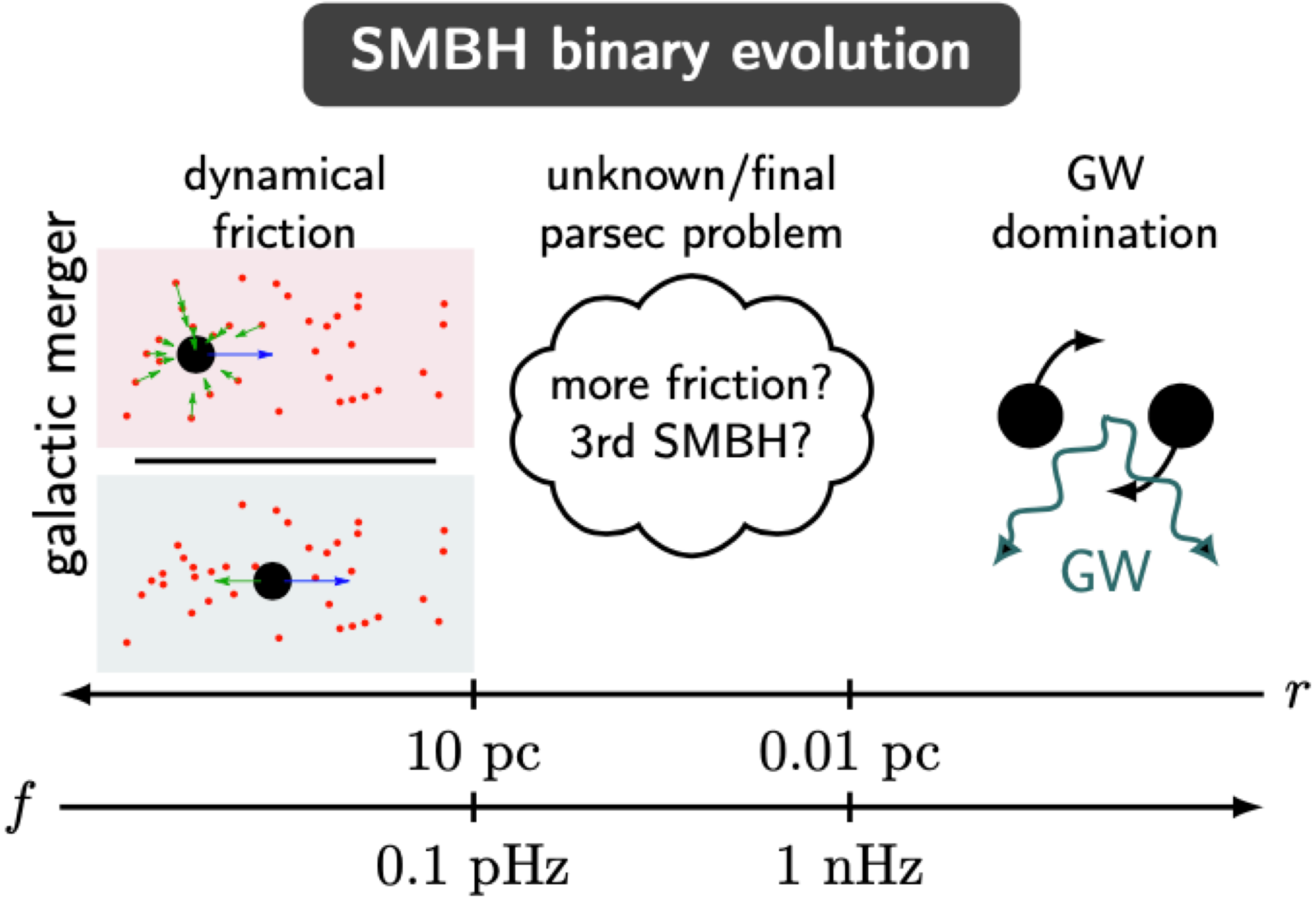

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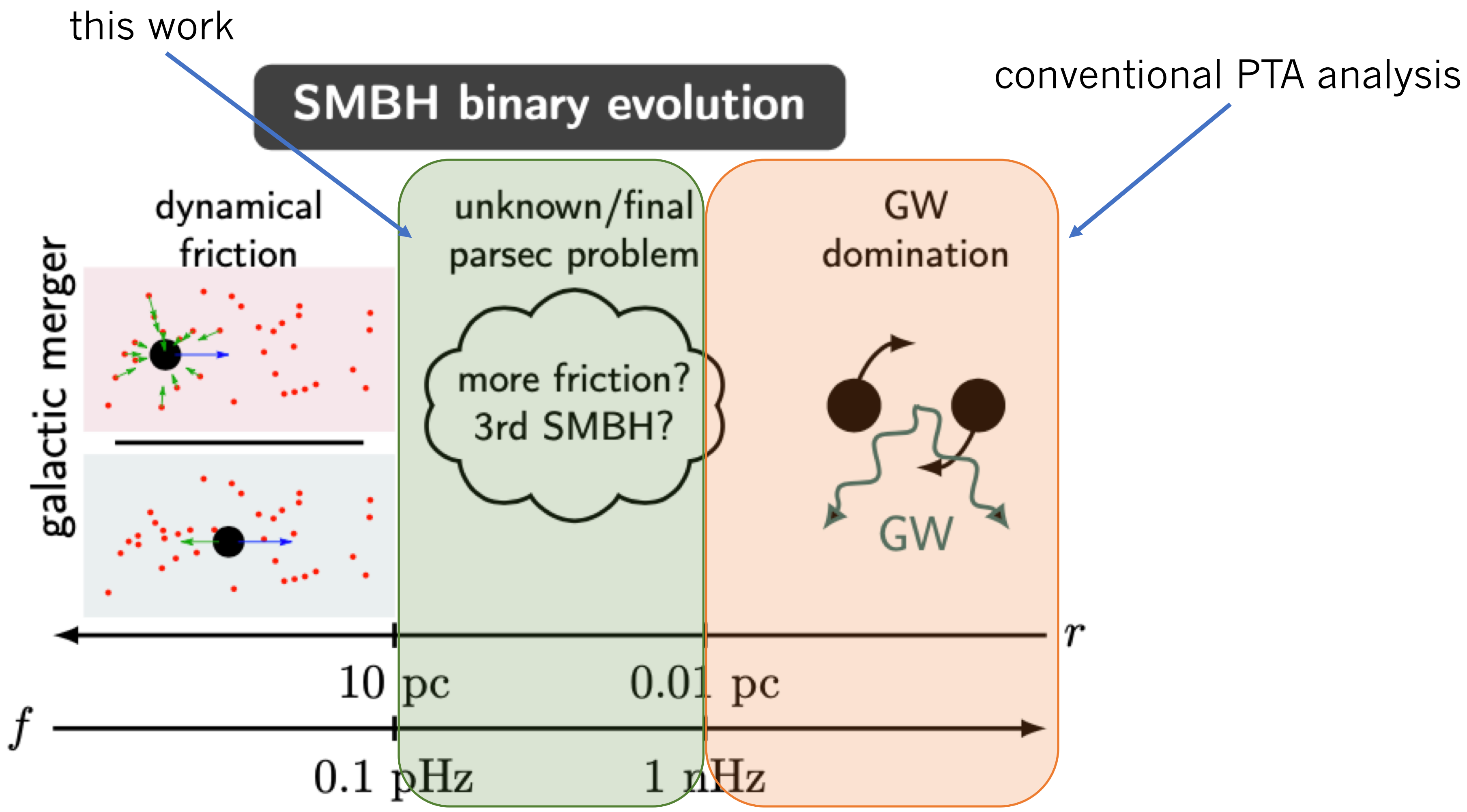
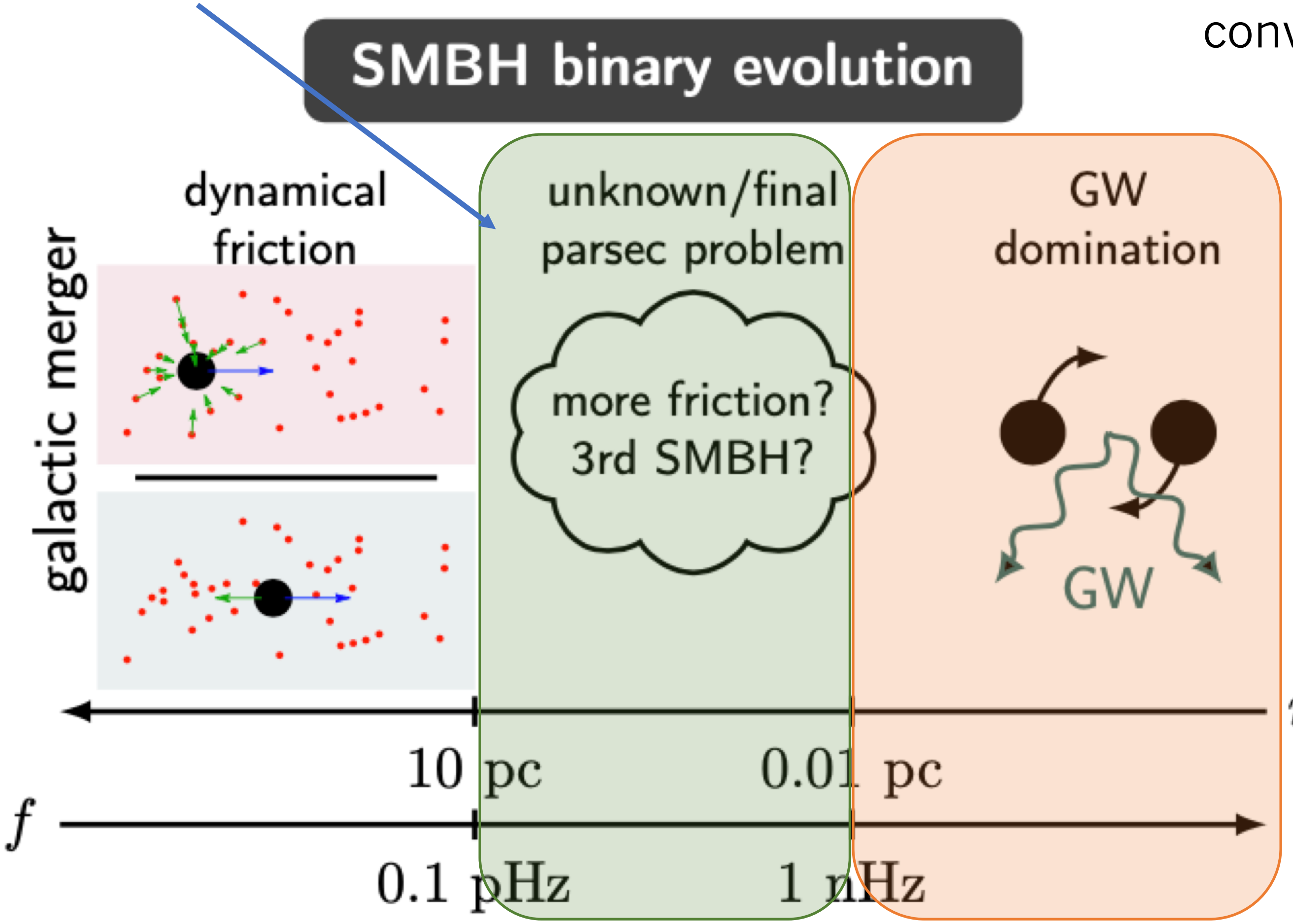


SMBH evolution

this work

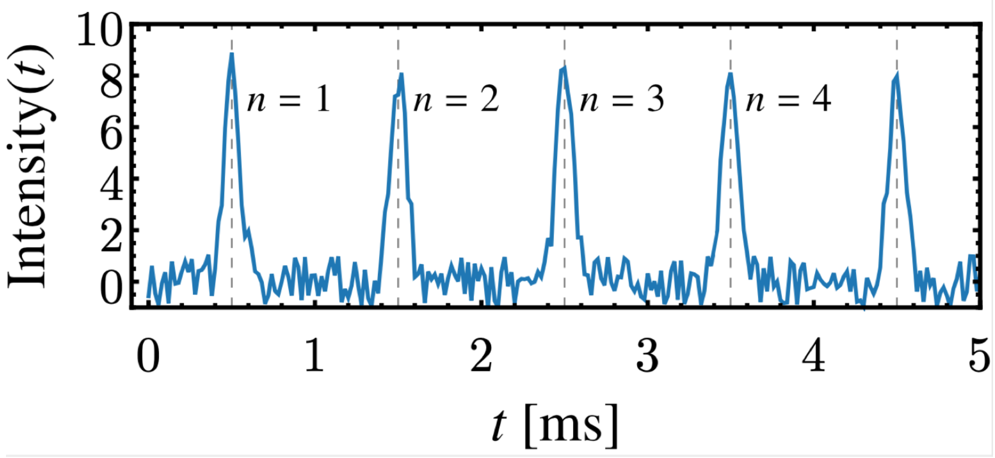
conventional PTA analysis



Why the sharp division? …

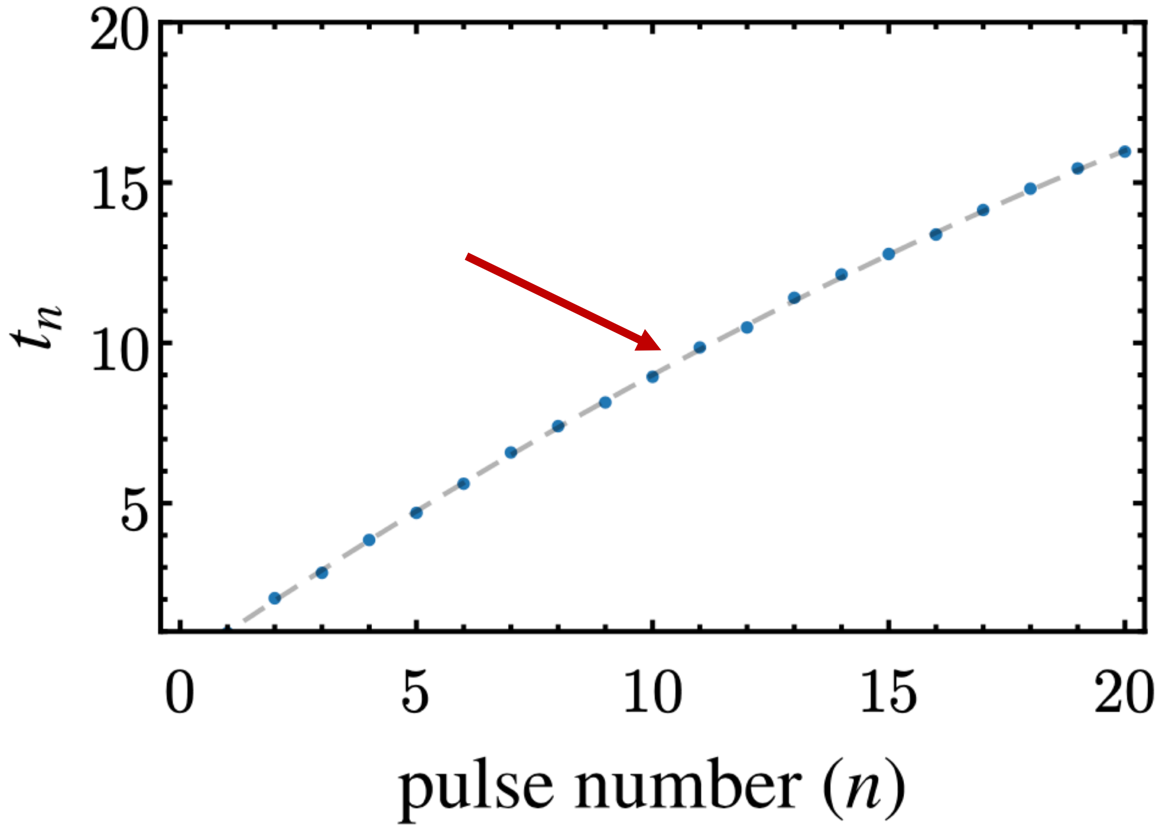
PTA Recipe

- **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**
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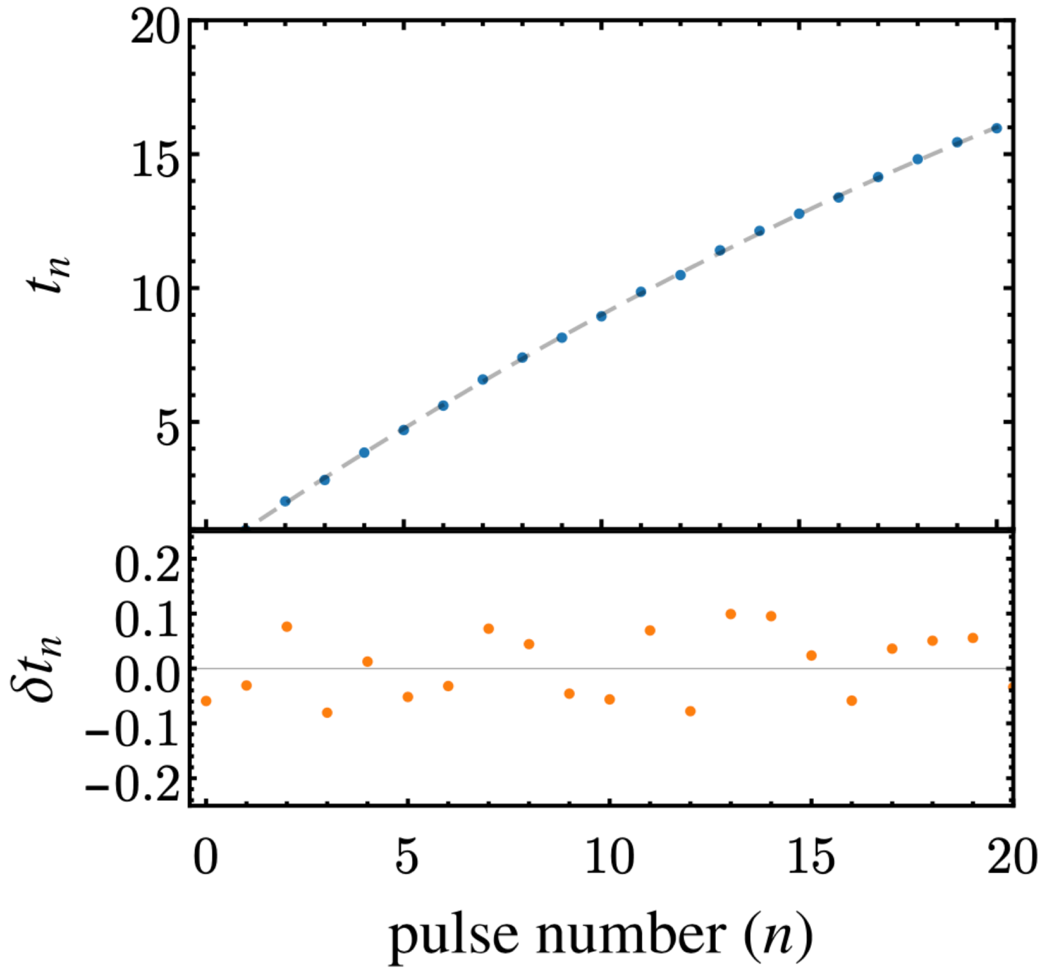
- **Step 3:** Subtract model from TOAs to produce **residuals**



PTA Recipe

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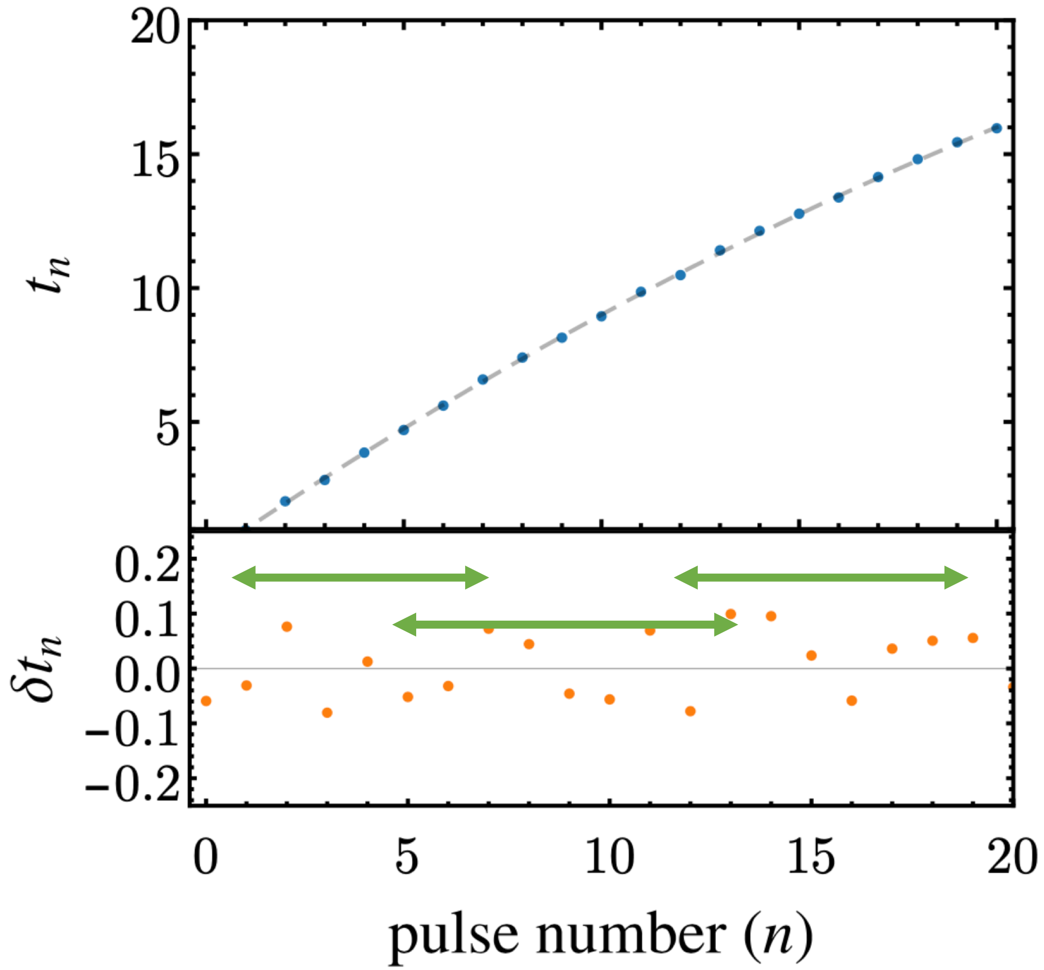

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- **Step 1:** Pulses → **TOAs**
- **Step 2:** Fit **model** to TOAs
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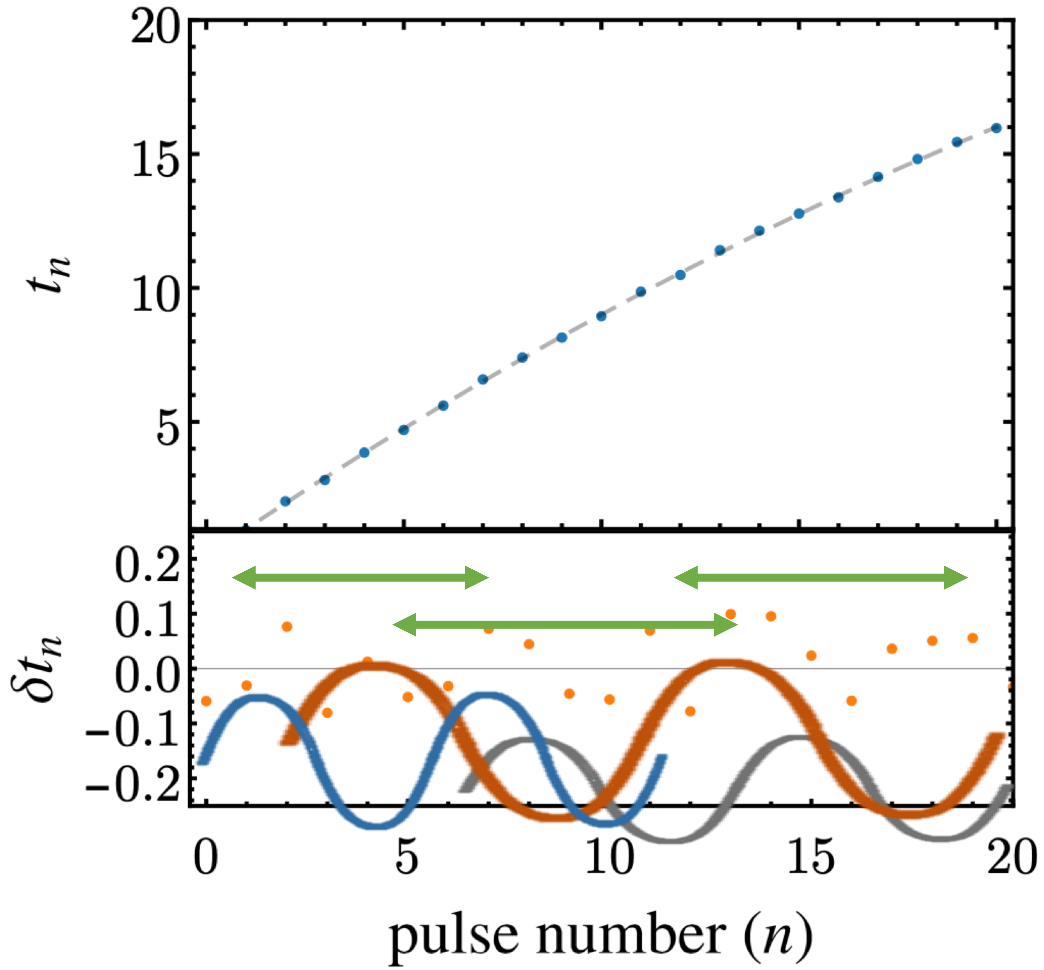
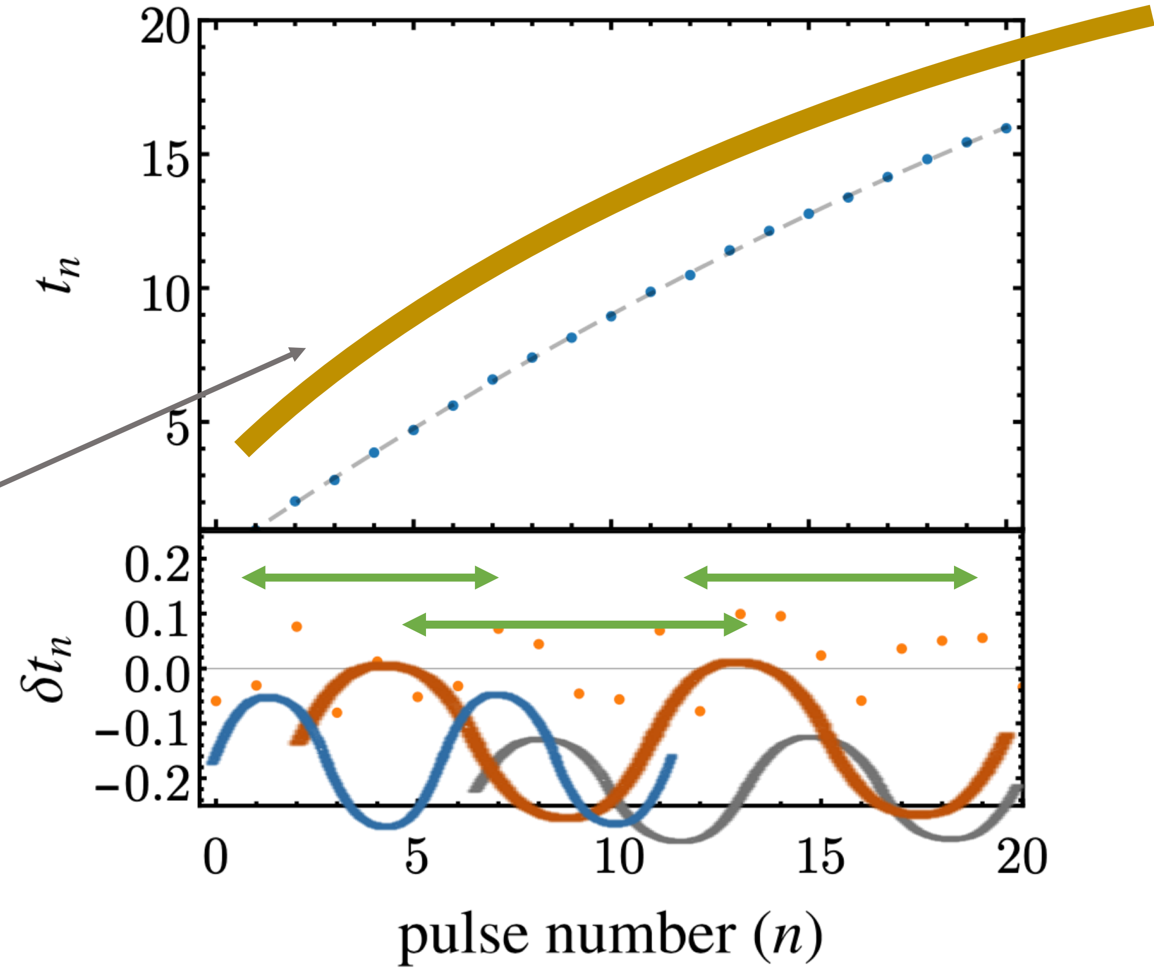
Correlations only observable for f > 1/T!



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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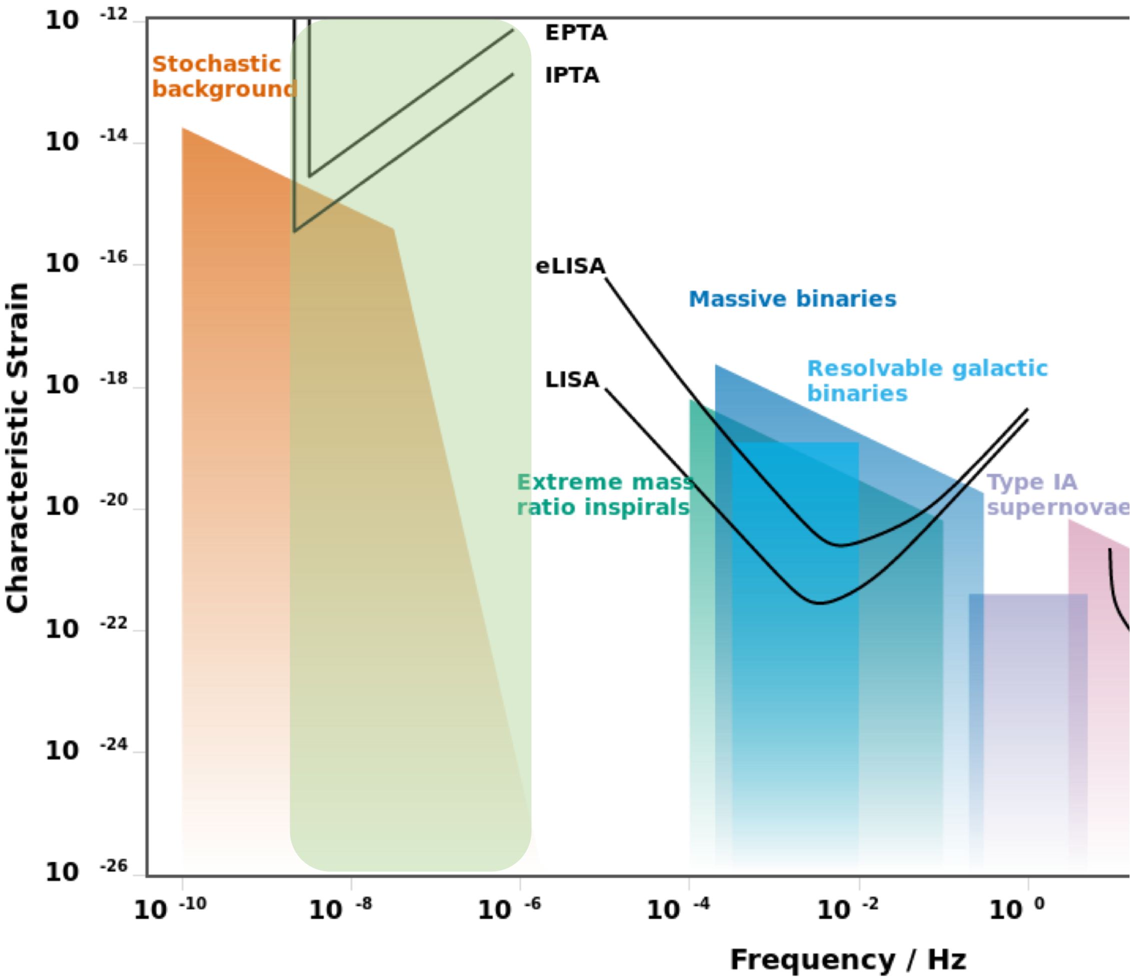

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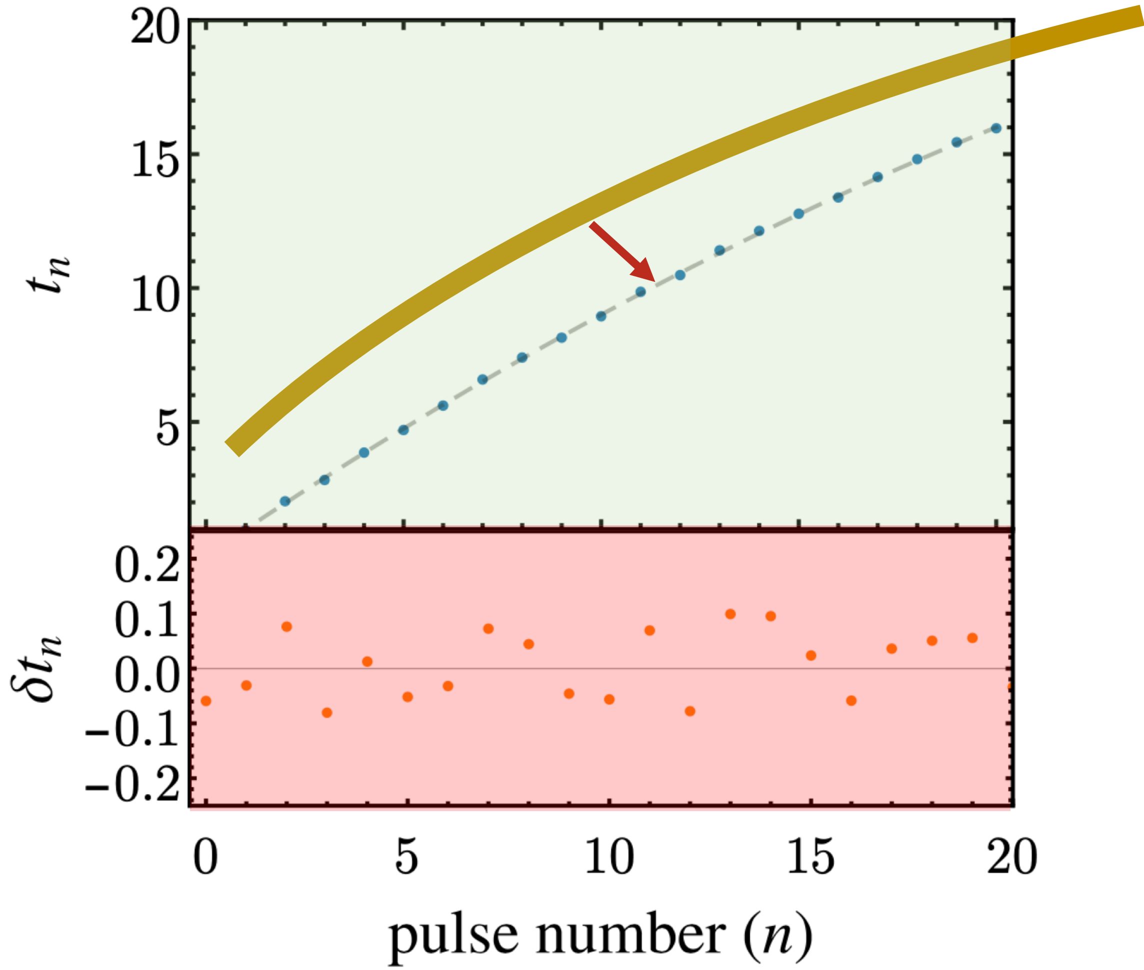
Fit parameters

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

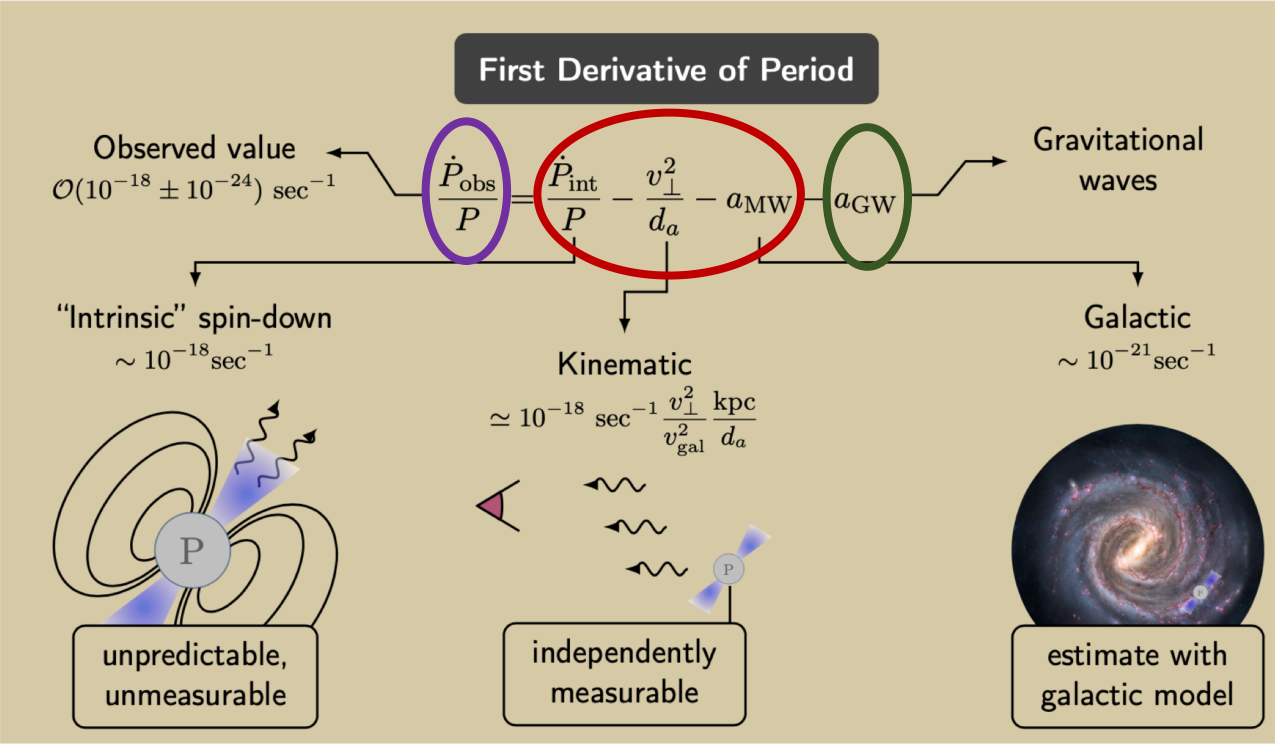


Fit parameters

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.

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



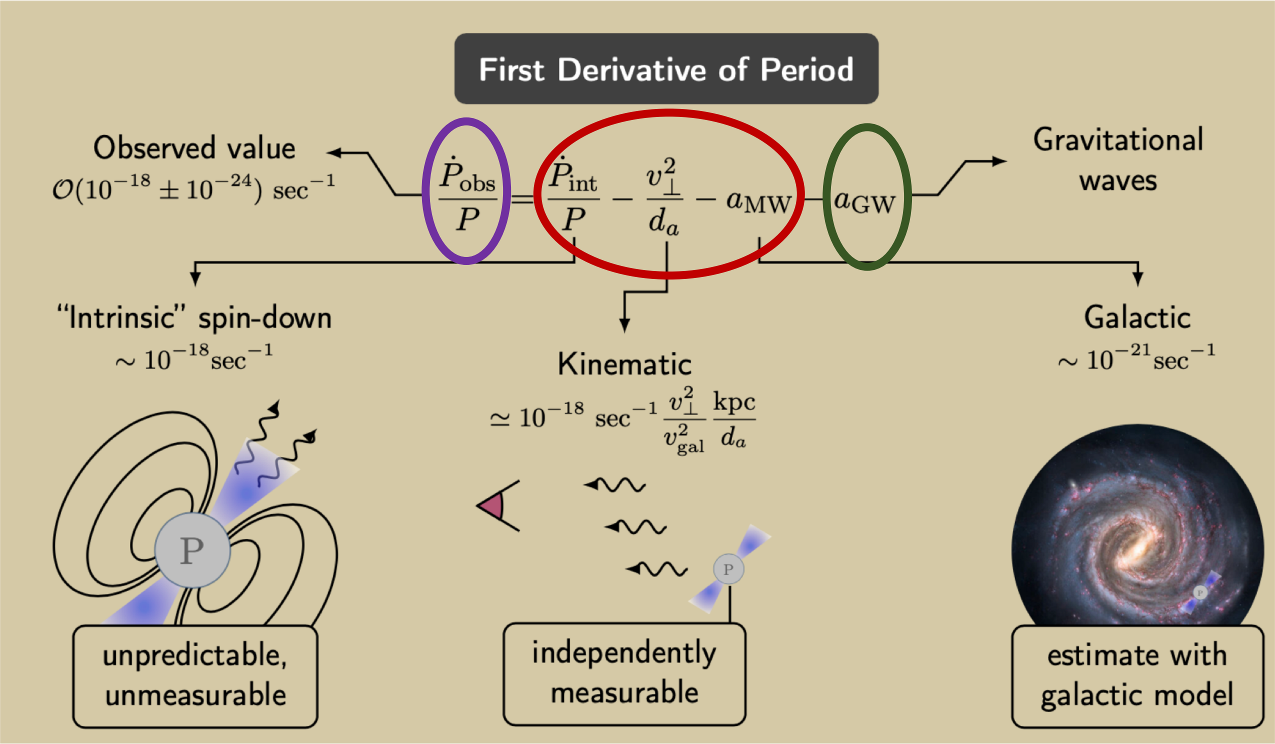
Fit parameters

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.

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

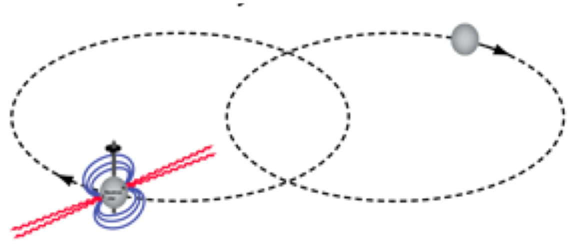
- Intrinsic contributions to $\dot{P}$ unpredictable ⇒ GW signal cannot be extracted

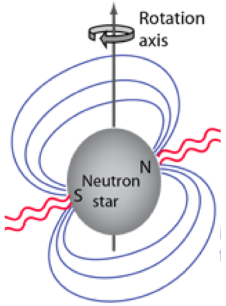


Sensitive parameters

- 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

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

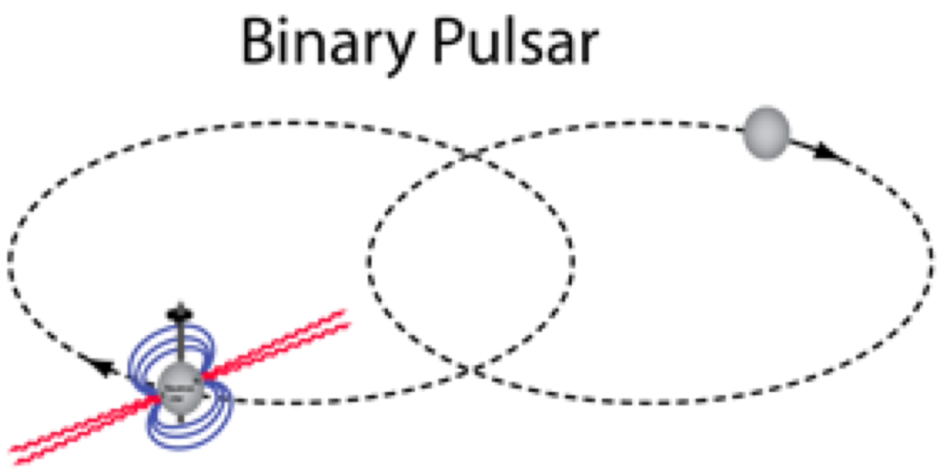
$\frac{d^2}{dt^2}\Big($ 

$\Big)$

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

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

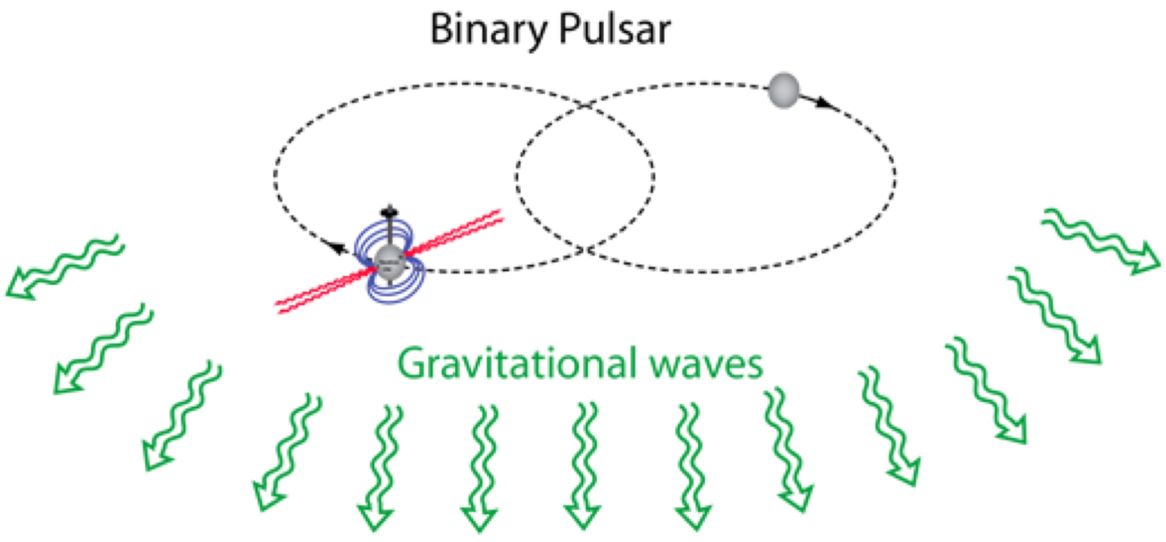
- Change in *binary* period
- Induces apparent line-of-sight **acceleration**
- Three relevant non-GW contributions



Contribution #1: Gravitational radiation

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

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



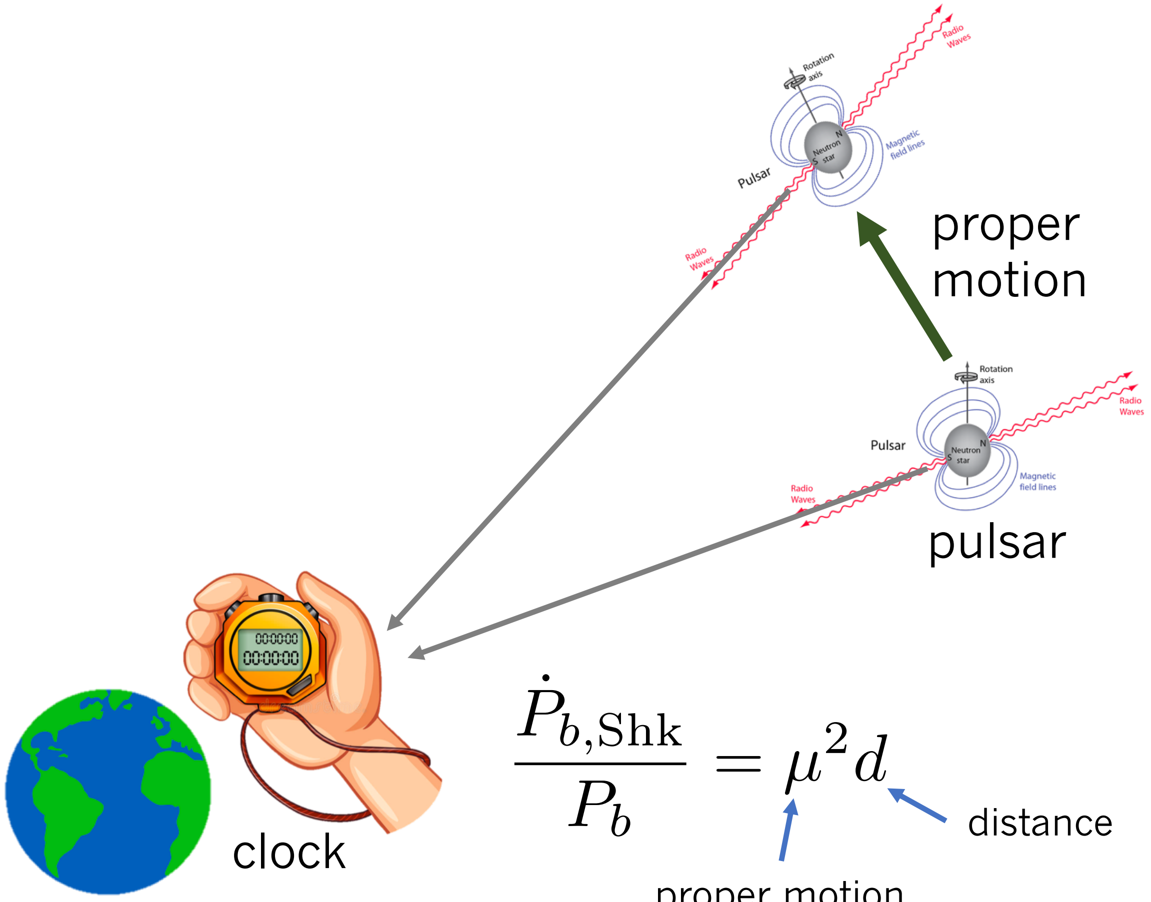
$$\dot{P}_b^{\mathrm{GR}} = -\frac{192\pi G^{5/3}}{5c^5}\left(\frac{P_b}{2\pi}\right)^{-5/3}(1-e^2)^{-7/2} \times \left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)\frac{m_p m_c}{(m_p+m_c)^{1/3}}$$

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



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

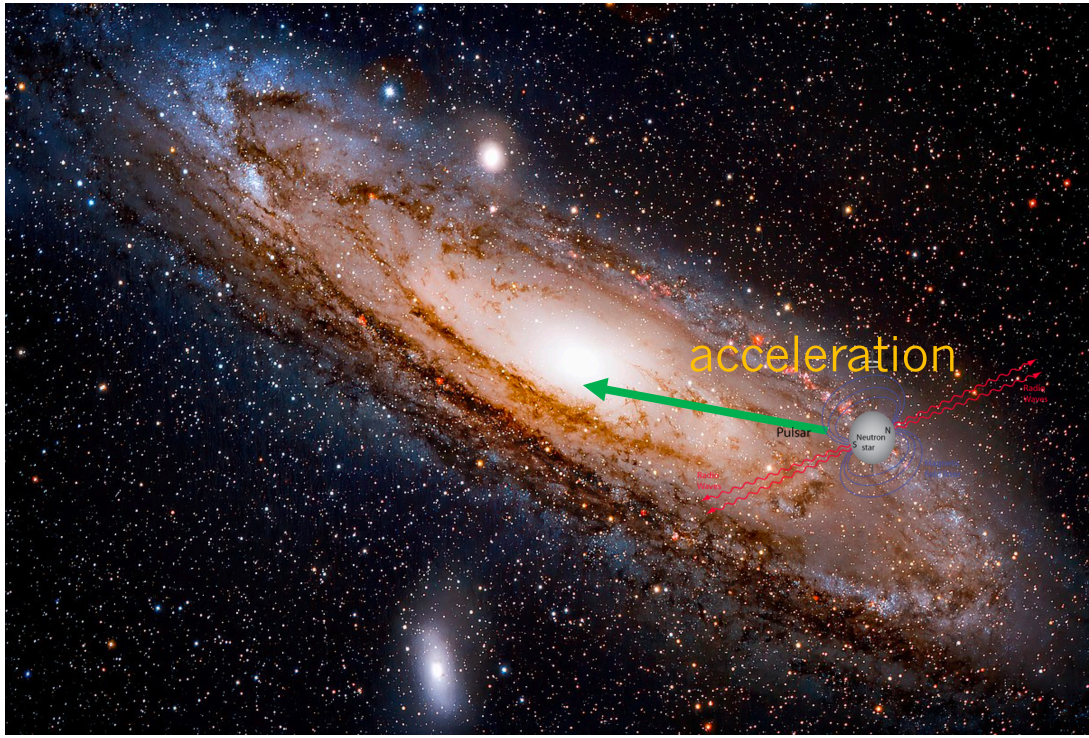
distance

proper motion

Contribution #2: Galactic acceleration

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

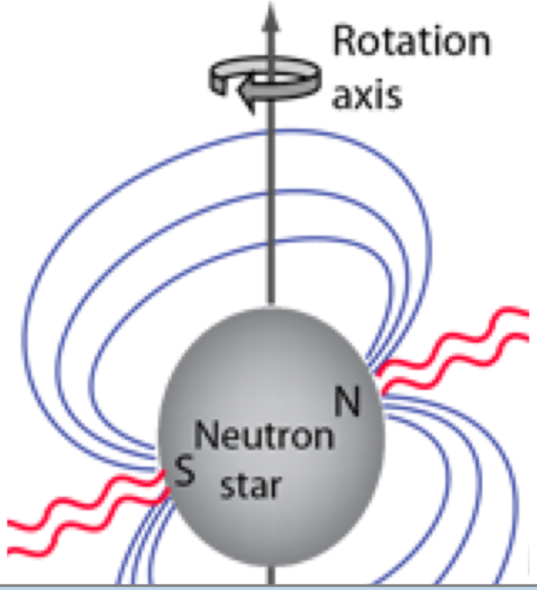
- Galactic potential tugs on pulsar
- Pulsar location independently measured ⇒ contribution can be subtracted
- Highly subdominant in most cases
  - *But that hasn't stopped people from trying... (Chakbrabarti et al. 2021)*



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

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

- Change in *<u>pulsar</u>* 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}

Outline

- **Part I:** PTA analysis
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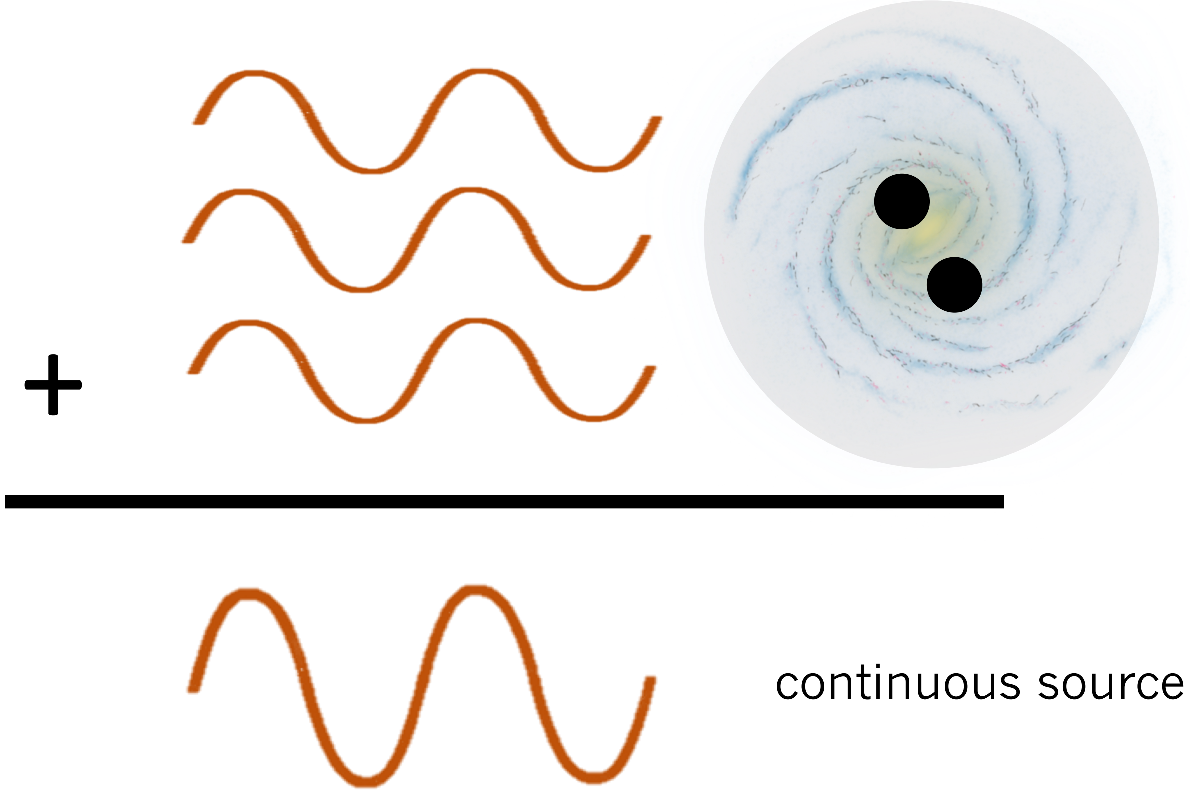
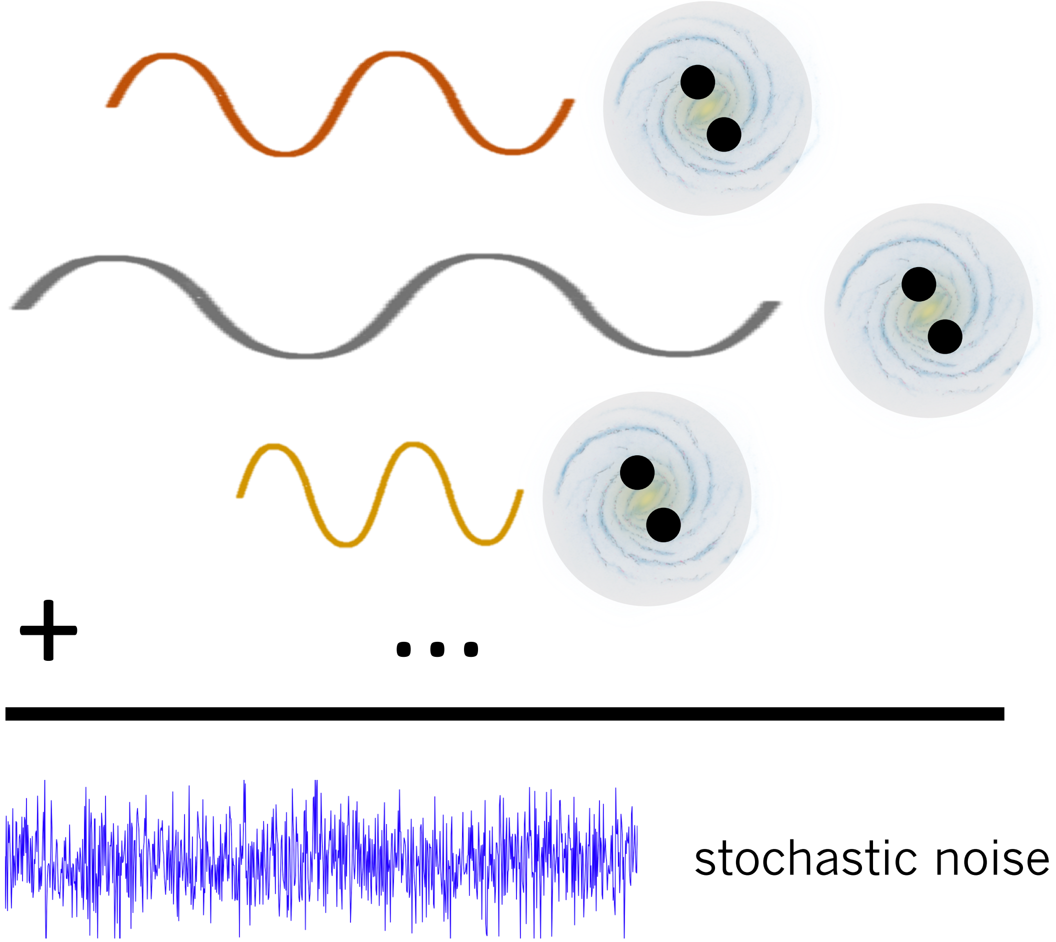
Continuous source

- 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



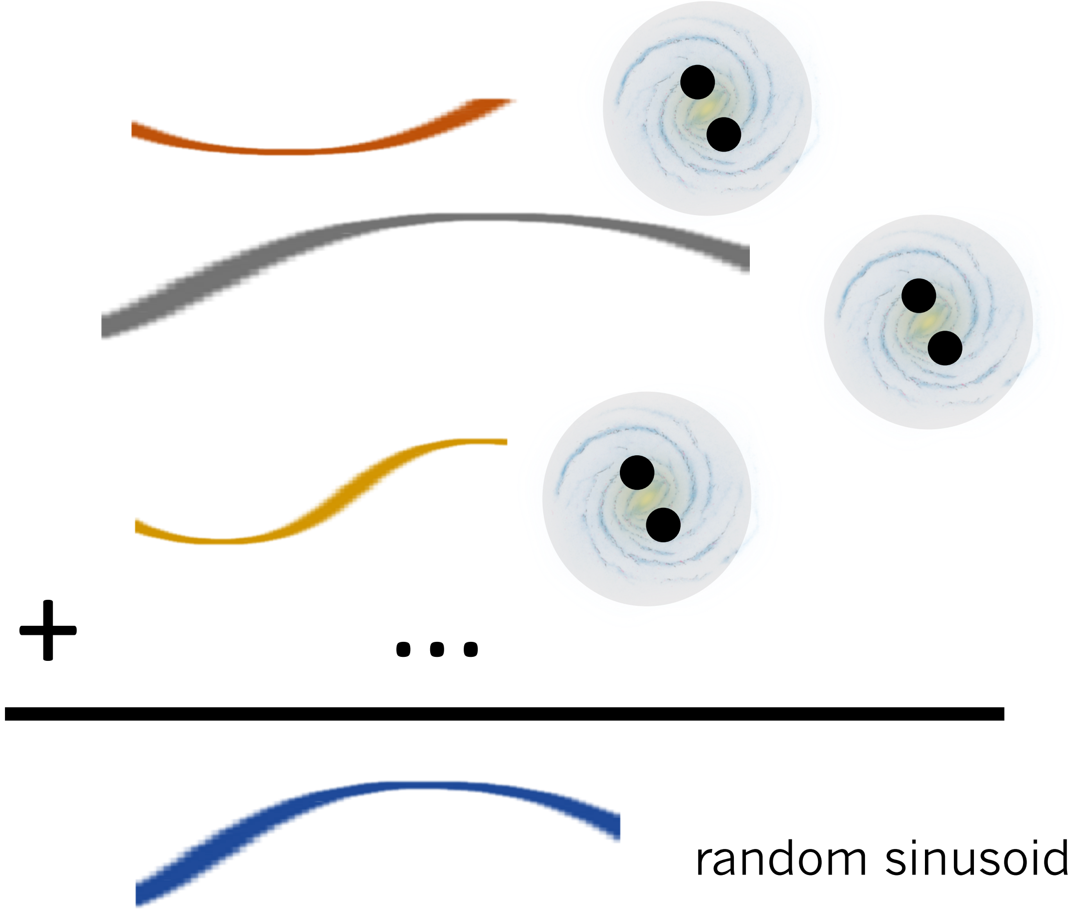
Stochastic signal

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



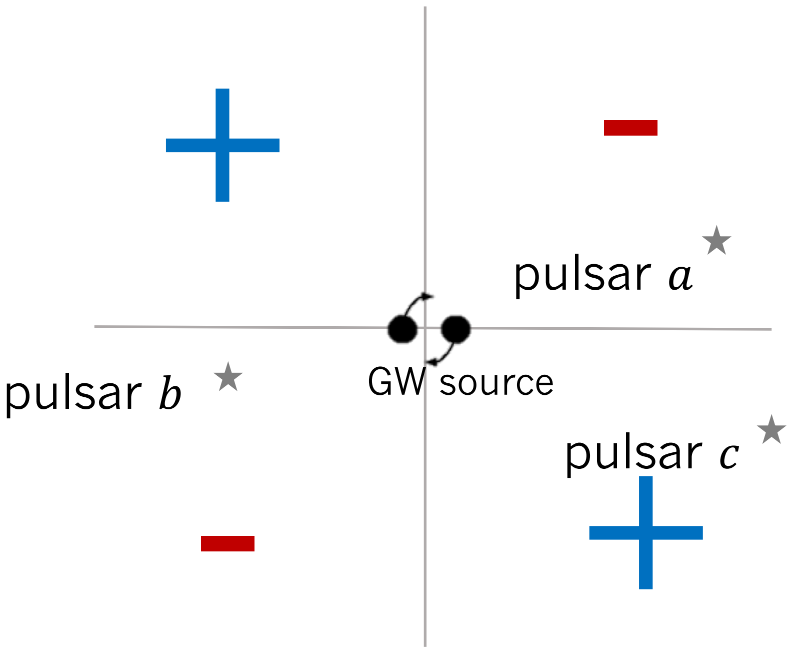
Stochastic signal

- **High frequencies (f > 1/T):** incoherent sum of sources ⇒ stochastic noise
- **Ultralow frequencies (f < 1/T):** incoherent sum ⇒ sinusoid with random phase and amplitude



Cross-sky correlation: continuous wave

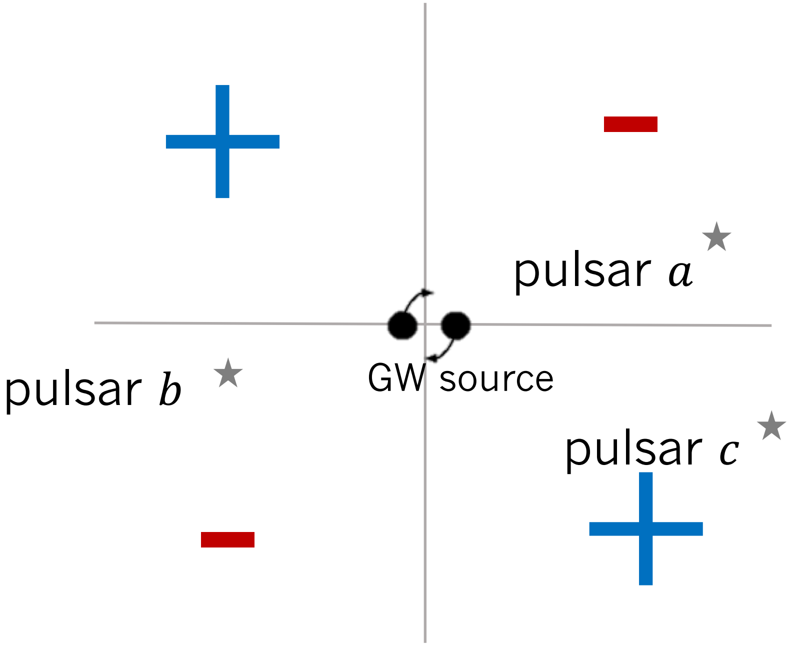
Continuous wave



Quadrupole pattern

Cross-sky correlation: stochastic signal

Continuous wave



Quadrupole pattern

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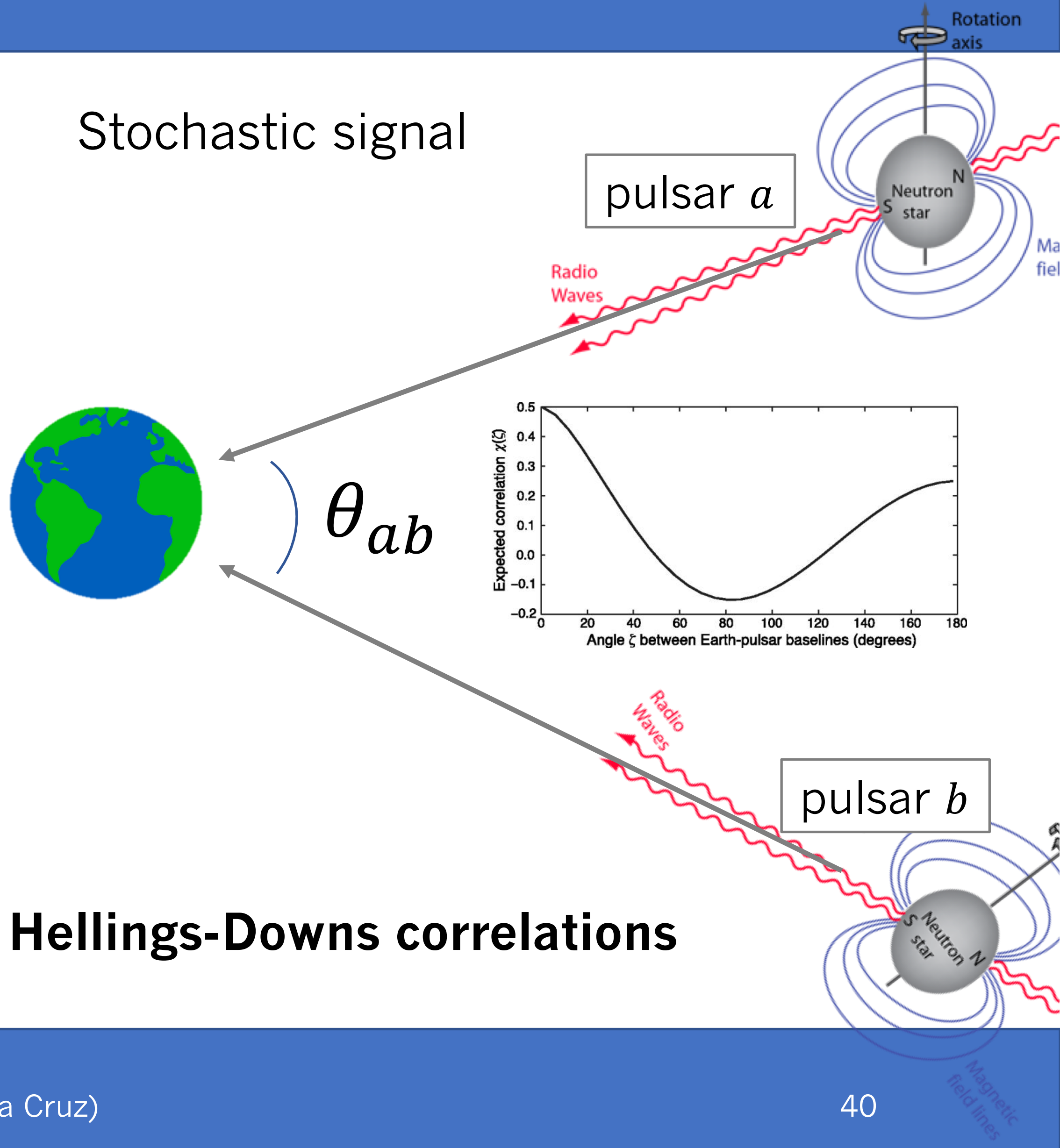
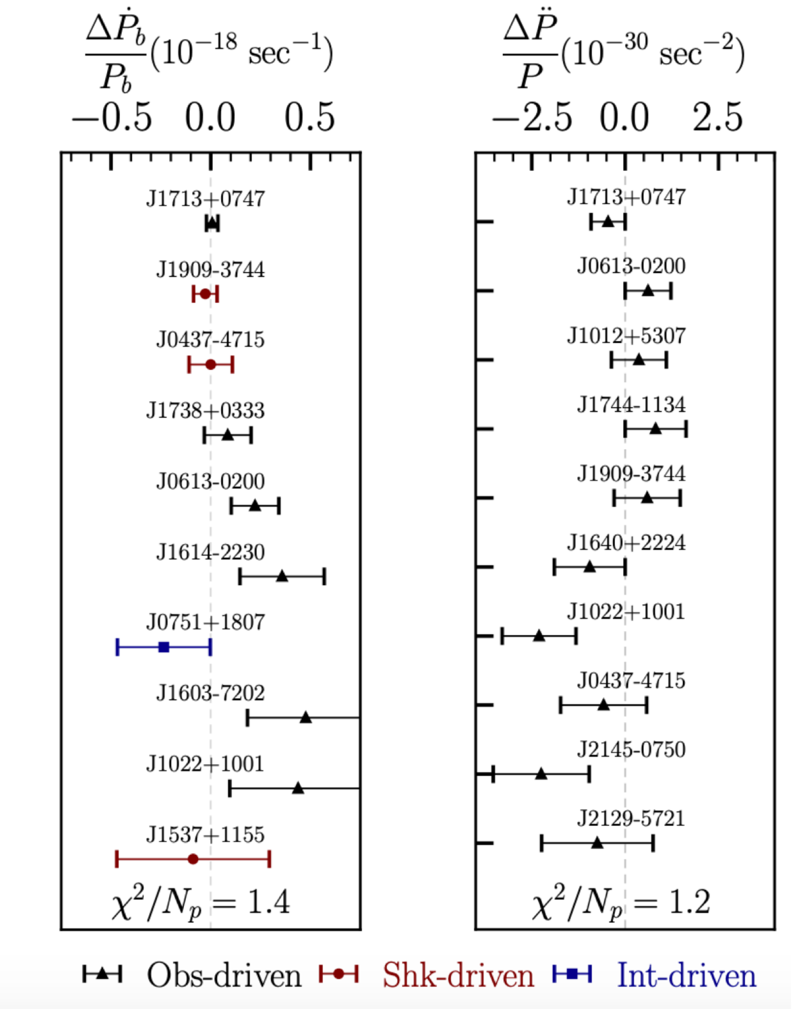


Hellings-Downs correlations

Data

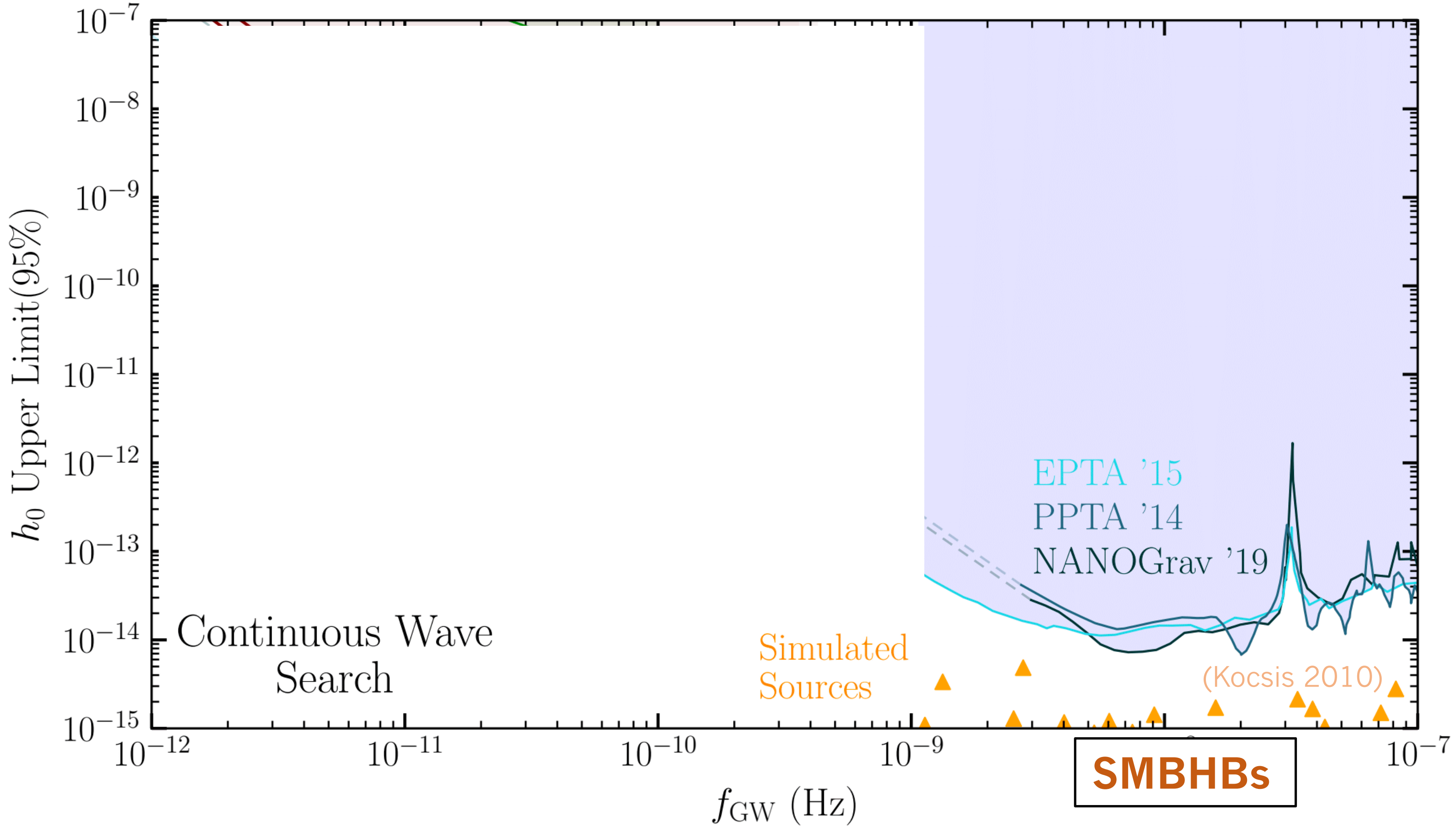
- $\ddot{P}$: Liu et al. (2018)
  - jerk ~ **10^{-31} s^{-2}**
- $\dot{P}_b$: Chakrabarti et al. (2020)
  - acceleration ~ **10^{-19} s^{-1}**
- Pulsars are well-modeled on individual basis (clean environments, dispersion measure, etc.)



Results: continuous source

- Target: SMBH binaries

2212.09571



Results: continuous source

- Target: SMBH binaries
- No statistical preference towards signal ($p > 0.2\ \forall f_{GW}$)

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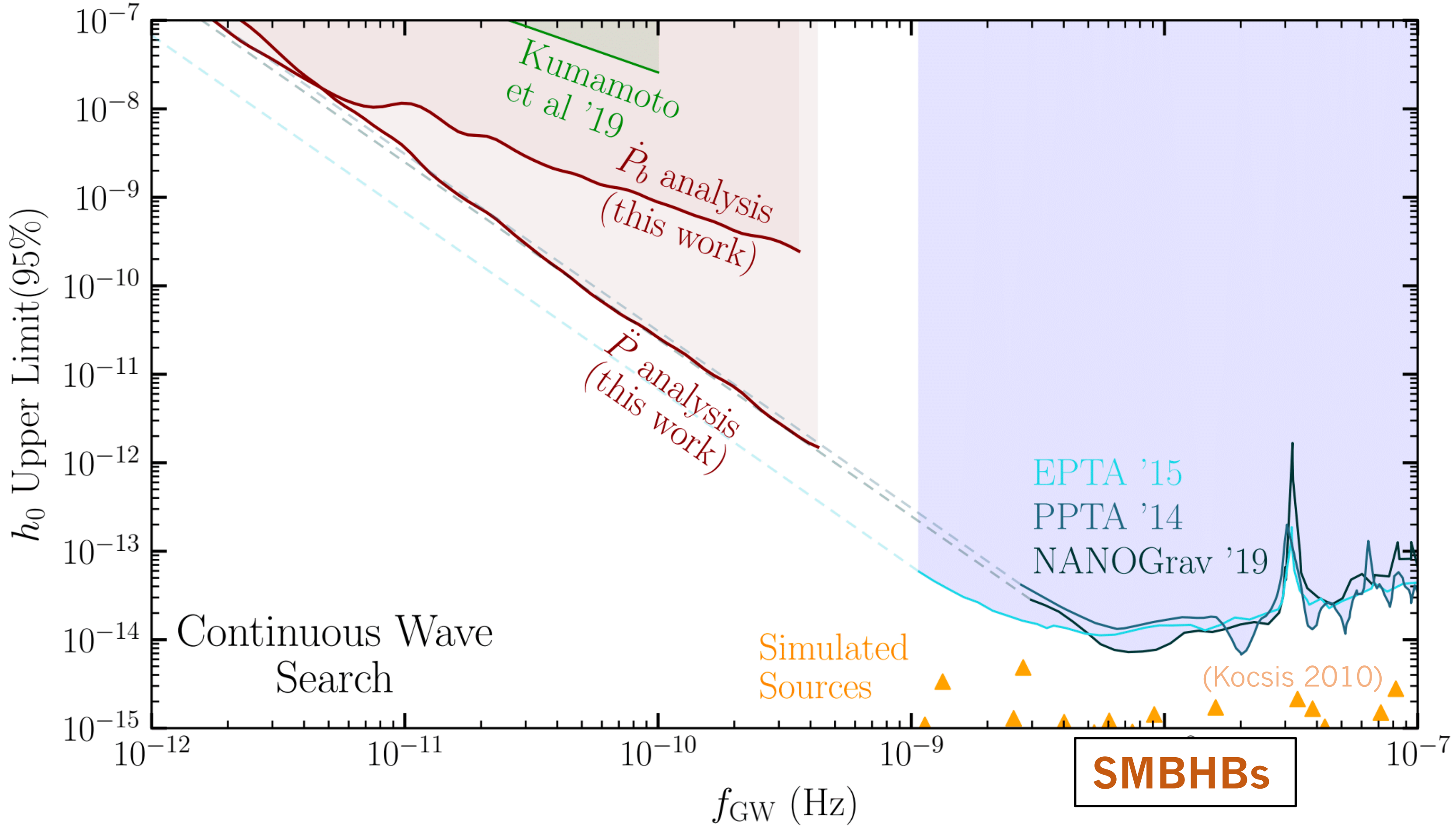
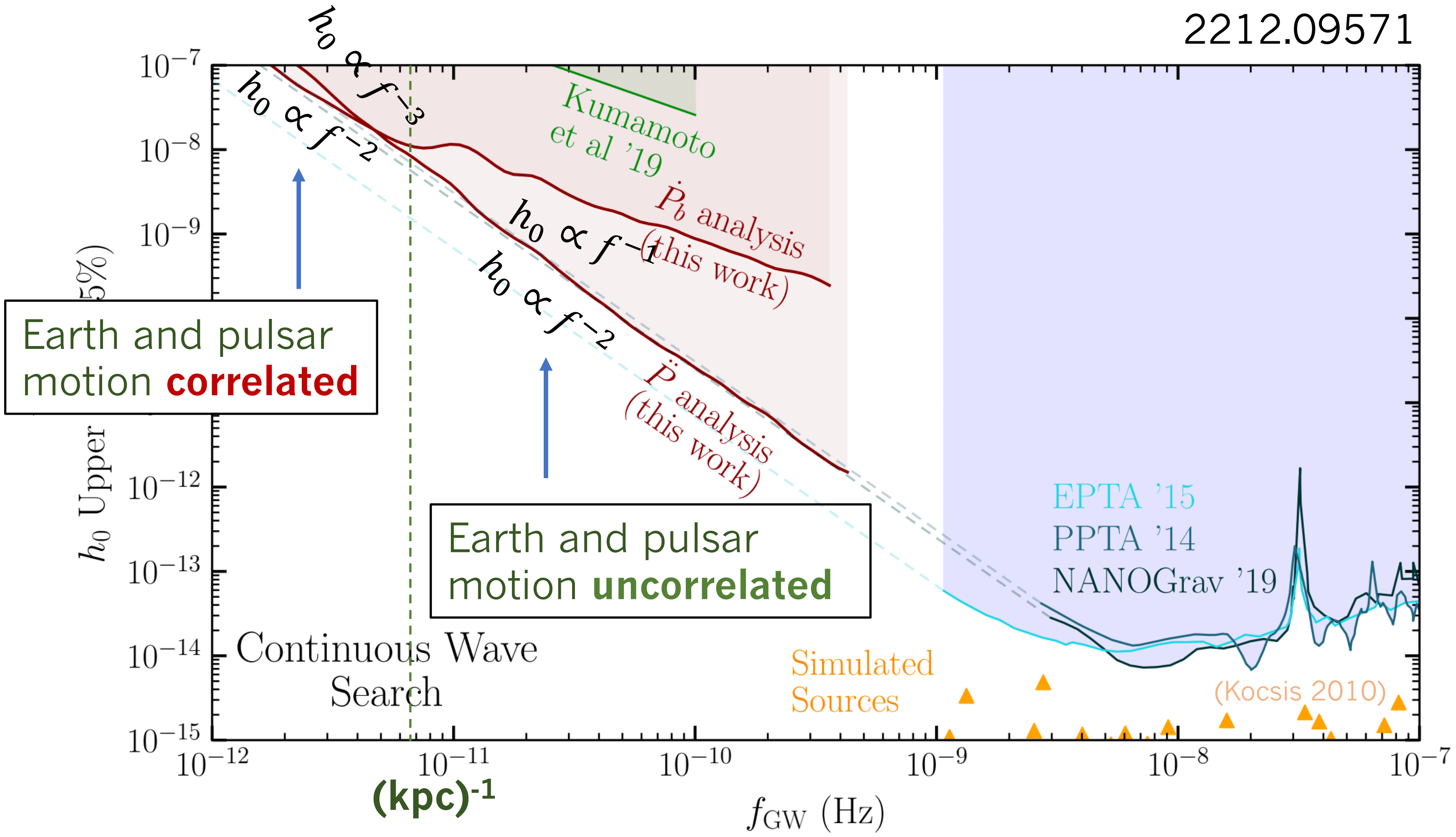


Results: continuous source

- Target: SMBH binaries
- No statistical preference towards signal ($p > 0.2\ \forall f_{GW}$)
- Follows analytic expectation for frequency scalings



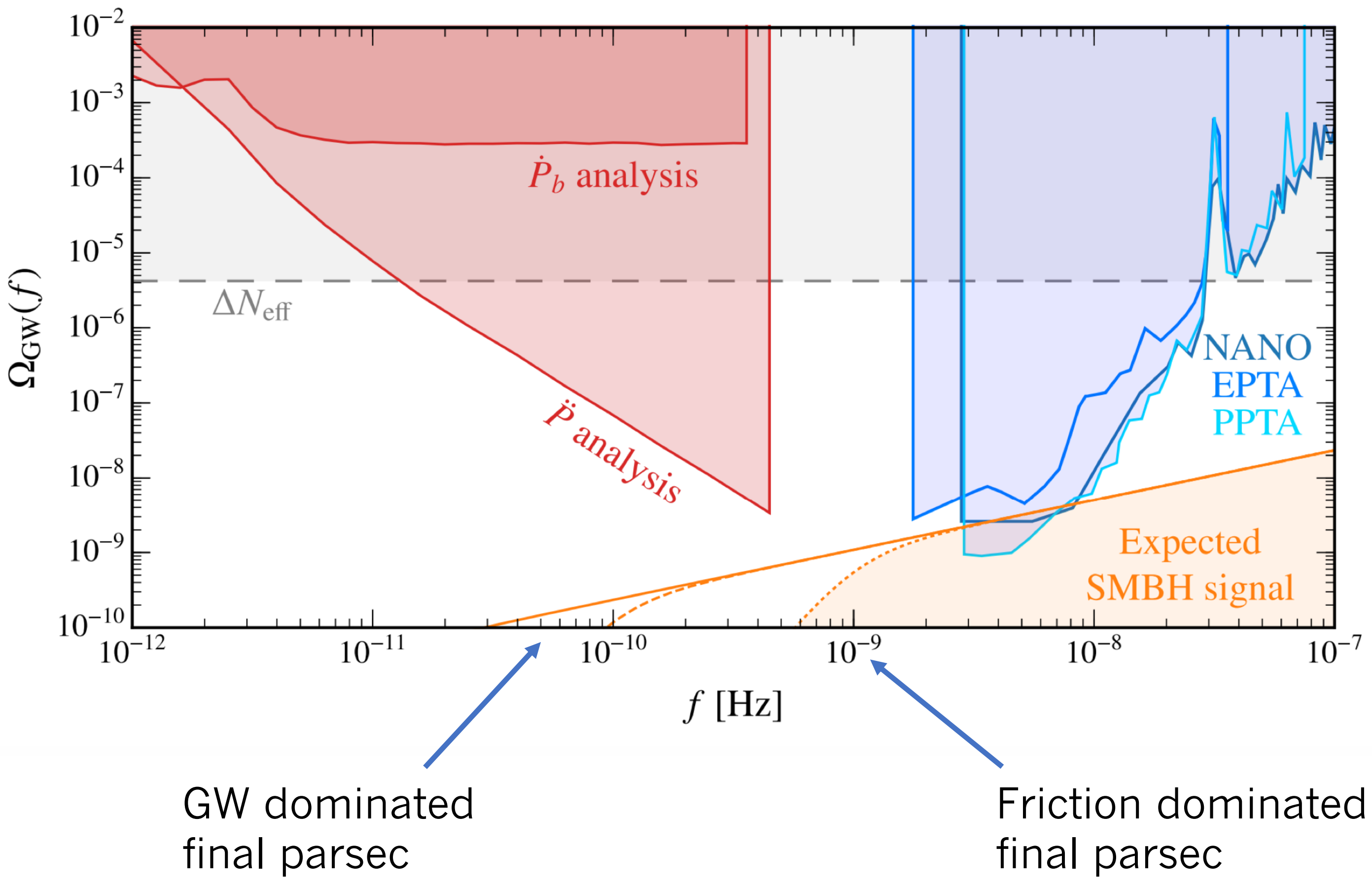
Results: stochastic source

2303.13042

- Plotted in terms of fractional energy density of the universe

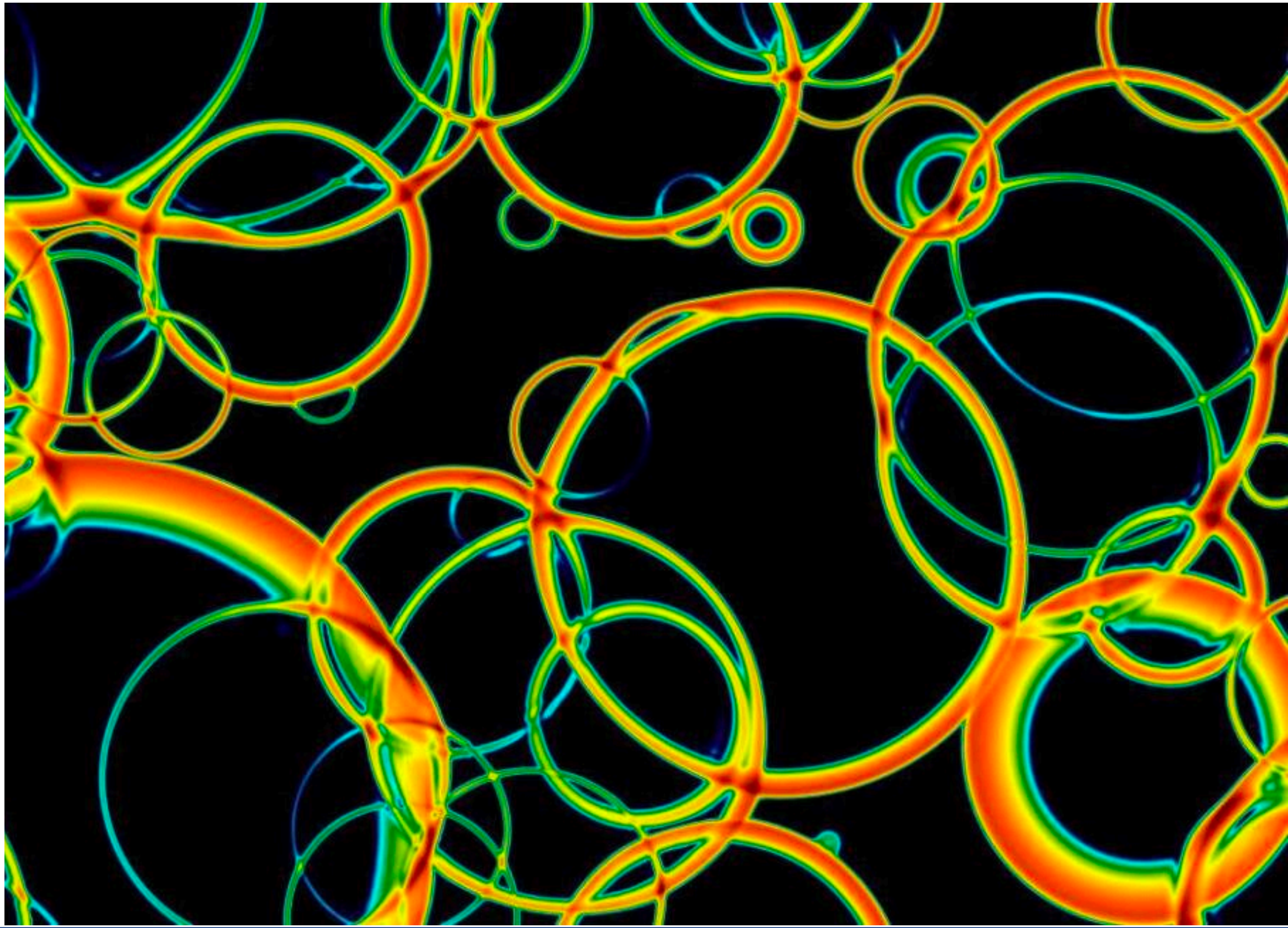
- Scaling: $h_0 \propto f^{-1} \Rightarrow \Omega \propto f^0$
  $h_0 \propto f^{-2} \Rightarrow \Omega \propto f^{-2}$

- Technique will be sensitive to final parsec problem!



BSM signals

- Turbulent QCD phase transition?
- Dark phase transitions?
- New symmetries?
- Tilted inflationary spectrum?



More to come!

- Our data were exclusively EPTA and PPTA…
- Currently working with NANOGrav on in-house analysis of their data
- 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!