

Searching for Intermediate Mass Black Holes using the MPTA

A proposal on how to do this :)

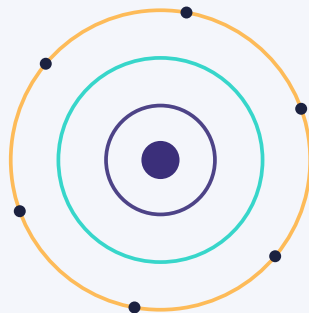
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Presentation overview

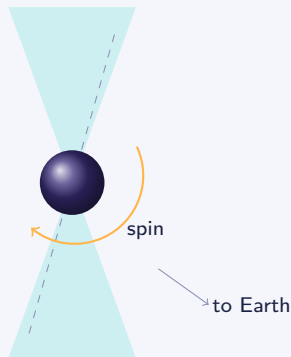
- 1 A quick intro to the MPTA and pulsar timing
- 2 Accelerometry with Pulsar Timing
- 3 So what's the idea
- 4 Results
- 5 Conclusion and future work



Introduction to pulsar timing

What is a millisecond pulsar?

- Pulsars are rapidly rotating, highly magnetised **neutron stars** that sweep beams of radio emission across our line of sight
- **Millisecond pulsars (MSPs)** have been spun up by accretion in binaries, giving rotation periods of only a few ms
- Their pulse arrival times are extraordinarily stable – rivalling the best atomic clocks over long timescales
- We **time** them: measure each pulse arrival, and compare to a precise model of the pulsar and the Solar System



Timing pulsars

Timing residual

$$\delta t_i = t_i^{\text{obs}} - t_i^{\text{model}}(\theta)$$

where θ includes spin, astrometric and binary parameters.

Deterministic effects

- Spin-down, position, proper motion
- Binary orbit
- Dispersion by the ionised ISM

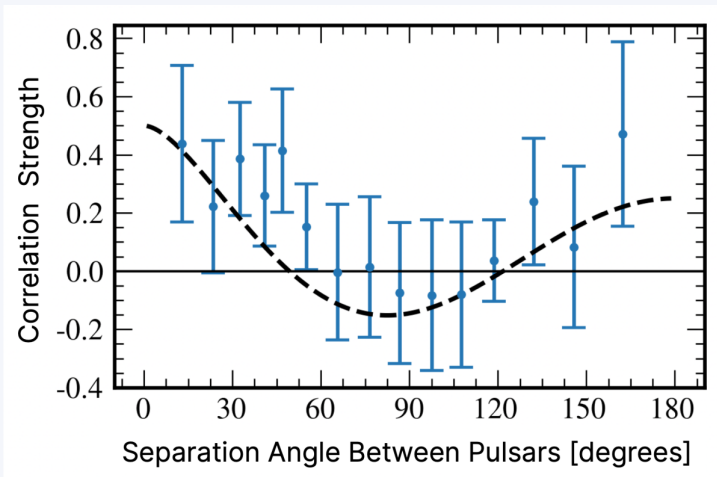
Stochastic effects

- White noise (radiometer, jitter)
- Red noise (spin irregularities, DM, scattering)
- Common signals: gravitational waves

Pulsar timing array



Detecting the Stochastic gravitational wave background



Accelerometry with Pulsar Timing

Accelerometry with Pulsar Timing

- 1 The observed orbital period of a binary pulsar will be Doppler shifted according to its line-of-sight velocity
- 2 The observed line-of-sight acceleration can be expressed as

$$a_{los}^{Obs} = \frac{\dot{P}_b^{Obs} c}{P_b} \quad (1)$$

- 3 $\dot{P}_b^{Obs}$ for a binary system not undergoing mass transfer can be decomposed as

$$\dot{P}_b^{Obs} = \dot{P}_b^{Shk} + \dot{P}_b^{GR} + \dot{P}_b^{Gal} \quad (2)$$

Accelerometry with Pulsar timing

- ① where

$$\dot{P}_b^{Shk} = \mu^2 d \frac{P_b}{c}$$

with μ being the total proper motion of the pulsar and d is the distance to the pulsar

- ② $\dot{P}_b^{GR}$ is given by

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

where e is the eccentricity of the binary orbit, m_p and m_c are the pulsar and companion masses respectively

Accelerometry with Pulsar Timing

- ① Lastly, $\dot{P}_b^{Gal}$ is given by

$$\dot{P}_b^{Gal} = \frac{P_b a_{Gal}}{c}$$

where a_{Gal} is the line of sight acceleration due to the Galaxy's gravitational potential

- ② Lastly, we can define the observed line of sight acceleration as

$$a_{los}^{Obs} = \frac{c \dot{P}_b^{Obs}}{P_b}$$

- ③ **NB!** From now on we will refer to the decomposition of the orbital drift $\dot{P}_b$ constructed using this decomposition as $\dot{P}_b^{Model}$

So what's the idea?

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- 1 In order to determine the contribution of the MilkyWay's gravitational potential to the orbital drift, we need to determine the line of sight acceleration due to this gravitational potential.
- 2 To do that, we need some model of this potential and then compute then compute the acceleration of the pulsar at its position in the galaxy
- 3 In literature, there is some mismatch in between the modeled line of sight acceleration obtained from $\dot{P}_b^{Model}$ and the observed line of sight accelerations.
- 4 This is commonly attributed to there being some problem with the modeled gravitational potentials

So what's the idea?

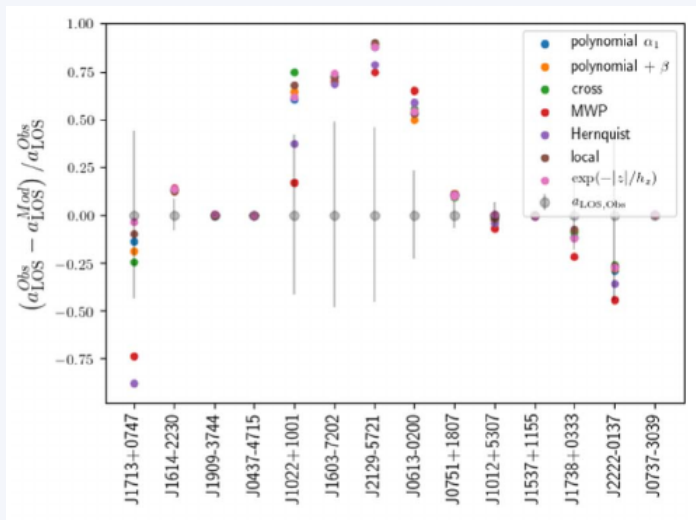


Figure: residuals of the line-of-sight acceleration for the individual pulsars by *Chakrabati et al*

So what's the idea? Let's look for an additional potential

- 1 In the studies, various gravitational potentials are proposed with varying effects on the residual with some pulsars having decent agreement between the modeled a_{los} and the observed a_{los}
- 2 We propose that this may be due to the inhomogeneity in the galaxy. We suggest that there may be an isolated black hole in the vicinity of the pulsar, that produces the difference between what is modeled and what is observed.
- 3 So let's look for a local potential

$$\dot{P}_b^{Obs} = \dot{P}_b^{Shk} + \dot{P}_b^{GR} + \dot{P}_b^{Gal} + \dot{P}_b^{BH}$$

**So what's the idea? Let's
look for an additional
potential**

So what's the idea? Let's look for an additional potential

- 1 We suggest that the residual is possibly caused by the potential of a nearby isolated black hole
- 2 We simply compute the a_{los} or $\dot{P}_b$ and then see if this can be produced by a suitably massive or nearby black hole

$$\dot{P}_b^{BH} = \frac{a_{BH} P_b}{c}$$

- 3 Given that we assume the BH is not directly in our line of sight (lack of lensing) it must be far away enough that the gravitational potential can be given by

$$U_{BH} = -\frac{GM_{BH}}{r} \quad (3)$$

Pulsar selection

Pulsar selection

To perform this calculation we look specifically for pulsars that satisfy the following conditions

- 1 The source had a measured P_b and $\dot{P}_b$
- 2 Had a measured parallax π and proper motion μ
- 3 Had measured orbital eccentricity e , pulsar mass m_p , companion mass m_c , or a binary period P_b greater than 5 days.
- 4 The source cannot be a redback, black widow, etc. or transferring mass with its companion, which can change the orbital period of the system.
- 5 The source cannot be in a globular cluster, as the internal accelerations of globular clusters are expected to overpower the Galactic acceleration signal.

Pulsar selection

- 1 We opted to look at pulsars in the MPTA given that they are not in globular clusters, nor have no mass transfer occurring.
- 2 Also we naively hoped that these pulsars would satisfy all the other conditions given how well these pulsars need to be modeled in order to be used for pulsar timing.
- 3 For this study we made use of the 4.5 year data release which is made available [here](#)
- 4 For pulsars where the companion mass is unknown, we made use of the approximation $\dot{P}_b^{GR} = 10^{-15}$ assuming $m_p = m_c = 1.4M_\odot$, and $e = 0$

Some caveats

A note on pulsars used

- ① The data made available are the Time of Arrivals (TOAs) and the timing models for each pulsar.
- ② To load the data we made use of the python package PINT, uses a TDB (Barycentric Dynamical Time) model while the timing models in the 4.5 year release use TCB (Barycentric Coordinate Time). These models needed to be transformed and then refitted to these timing models.
- ③ It seems that these files made use of a different clock and had to be refitted for a more up to date clock model

Gravitational potentials

- 1 For this work, we make use to two models: *Gala MilkyWay2022* and *galpy MWPotential2014*
- 2 *galpy's MWPotential2014* was fit to a large variety of data on the Milky Way and thus serves as both a simple and accurate model for the Milky Way's potential. Note that this potential assumes a circular velocity of 220 km/s at the solar radius at 8 kpc.
- 3 MWPotential2014 was initialized with a black hole with a mass of $4 \times 10^6 M_{\odot}$ at the center.
- 4 *Gala's MilkyWay2022* is a mass-model for the Milky Way consisting of a spherical nucleus and bulge, a 3-component sum of Miyamoto-Nagai disks to represent an exponential disk, and a spherical NFW dark matter halo.

Results

Results

- ➊ From the 83 pulsars in the MPTA, only 63 were in binary systems
- ➋ Of these 63, only 14 had an observed P_b , $\dot{P}_b$ and a measured parallax
- ➌ Of these 14, only 9 had periods greater than 5 days.

Results

Line-of-Sight Galactic accelerations using *galpy*'s MWPotential2014

PSR Name	RA(deg)	DEC(deg)	D(kpc)	μ (mas/yr)	P_b (days)	$\dot{P}_b$	$a_{Gal} \text{ m.s}^{-2}$
J0437-4715	69.31	-47.25	0.14	140.88	5.74	4.26×10^{-12}	-1.09×10^{-11}
J0613-0200	93.43	-2.01	1.17	10.49	1.19	3.70×10^{-14}	2.019×10^{-11}
J1017-7156	154.46	-71.94	1.029	10.247	6.511	4.15×10^{-13}	-6.179×10^{-12}
J1022+1001	155.741	10.031	1.22	23.209	7.805	1.35×10^{-12}	-2.80×10^{-11}
J1125-6014	171.48	-60.235	3.402	17.303	8.7526	6.69×10^{-13}	-1.03×10^{-12}
J1231-1411	187.79	-14.195	0.594	61.912	1.860	3.83×10^{-13}	-3.48×10^{-11}
J1600-3053	240.216	-30.89	5.57	6.4071	14.348	5.165×10^{-13}	-1.38×10^{-11}
J1603-7202	240.89	-72.042	8.58	7.75	6.31	2.81×10^{-13}	-3.46×10^{-11}
J1652-4838	253.15	-48.64	0.80	9.97	12.40	1.55×10^{-11}	2.11×10^{-11}
J1713+0747	258.45	7.79	1.32	6.34	67.83	9.10×10^{-15}	-9.51×10^{-12}
J1902-5105	285.511	-51.10	220.11	9.13	2.01	5.78×10^{-13}	1.77×10^{-10}
J1909-3744	287.44	-37.73	1.51	36.98	1.53	5.14×10^{-13}	1.24×10^{-11}
J2145-0750	326.46	-7.84	0.70	13.39	6.84	6.30×10^{-14}	-3.50×10^{-11}
J2222-0137	335.52	-1.62	0.31	45.30	2.45	3.28×10^{-13}	-2.48×10^{-11}

Results

Line-of-Sight Galactic accelerations using *Gala's* MilkyWay2022

PSR Name	RA(deg)	DEC(deg)	D(kpc)	μ (mas/yr)	P_b (days)	$\dot{P}_b$	$a_{Gal} \text{ m.s}^{-2}$
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J1902-5105	285.511	-51.10	220.11	9.13	2.01	5.78×10^{-13}	-1.92×-10
J1909-3744	287.44	-37.73	1.51	36.98	1.53	5.14×10^{-13}	5.58×10^{-12}
J2145-0750	326.46	-7.84	0.70	13.39	6.84	6.30×10^{-14}	-4.34×10^{-11}
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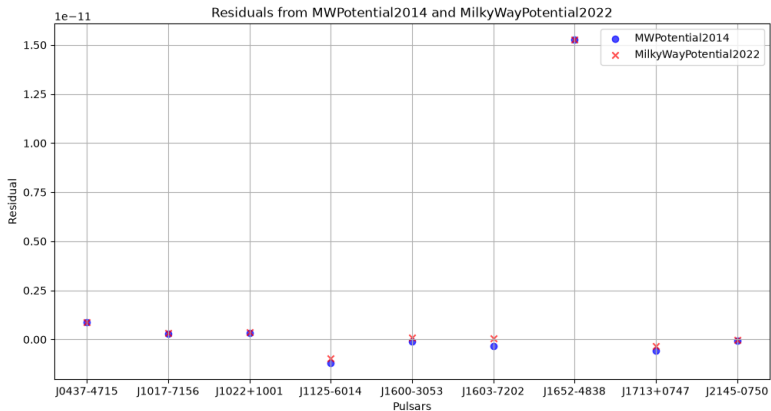


Figure: $\dot{P}_b^{Obs} - \dot{P}_b^{Model}$ for MWPotential2014 and MilkyWay2022

Conclusions and future work

- ① We have a large deviation in the residual for PSRJ1652-4838 indicating the possibility of a nearby gravitational potential.
- ② A comprehensive check on how errors are propagated through the analysis needs to be performed first before any strong conclusions can be formed.
- ③ A comparison with analysis of the noise embedded in the TOAs of candidate pulsars can be interesting. Agreement between the results would indicate a greater potential of the presence of isolated black holes nearby

References

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- ❷ Donlon, T., Chakrabarti, S., Widrow, L.M., Lam, M.T., Chang, P. and Quillen, A.C., 2024. Galactic structure from binary pulsar accelerations: Beyond smooth models. Physical Review D, 110(2), p.023026.
- ❸ Bovy, J., 2015. galpy: A python Library for Galactic Dynamics. The Astrophysical Journal Supplement Series, 216(2), p.29.
- ❹ Price-Whelan, A.M., 2017. Gala: A Python package for galactic dynamics. Journal of Open Source Software, 2(18), p.388.
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