北京大學
PEKING UNIVERSITY

Probing Dark Matters with Neutron Stars

Kavli Institute for Astronomy and Astrophysics

Speaker: Lijing Shao（邵立晶）

Overview

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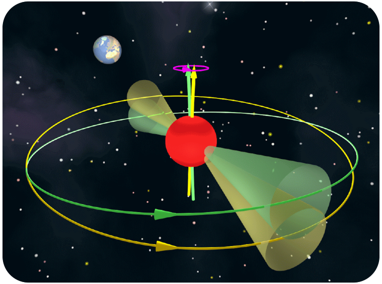
- **Accretion of dark matters** by neutron stars puts constraints on **dark matter – nucleon scattering cross-section**

1. Pulsars and Pulsar Timing

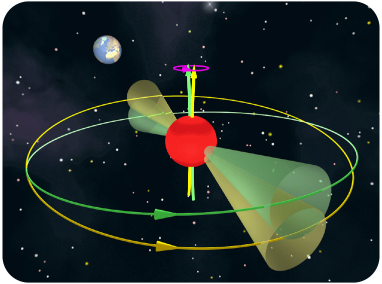
Pulsars

- Pulsars are rotating magnetized neutron stars



Pulsars

- Pulsars are rotating magnetized neutron stars
- Due to their large moment of inertia and small external torque, their rotation is extremely stable $\Rightarrow$ lighthouse



Pulsars are clocks

Pulsars are **precision** clocks

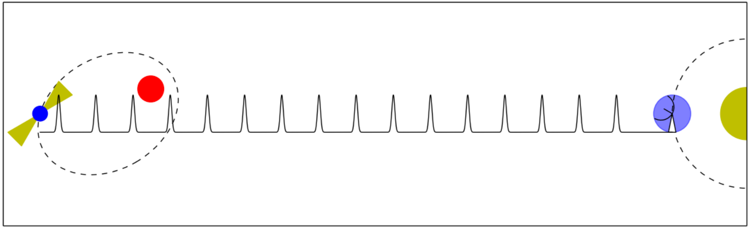
PSR J0737$-$3039A: $\nu = 44.054068641962 81(17)\,\mathrm{Hz}$

(16 significant digits!)

Kramer et al. 2021 [arXiv:2112.06795]

Pulsar Timing

- Large radio telescopes are used to record the times of arrival of pulses, which are affected by



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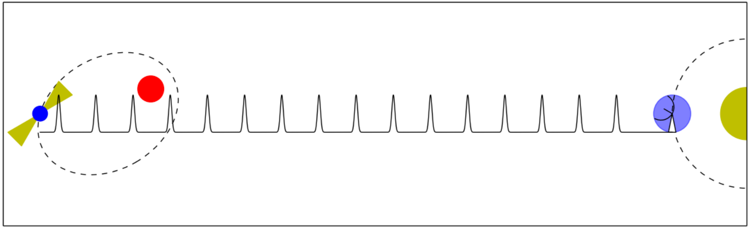
  - **Solar dynamics**: well understood from satellite observations



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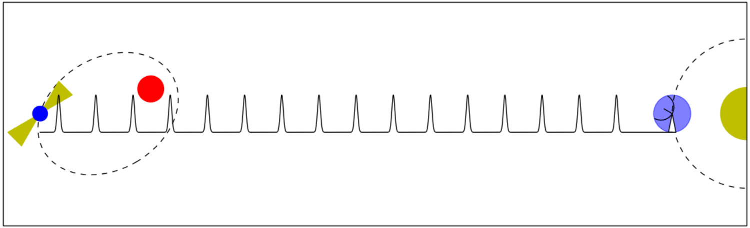
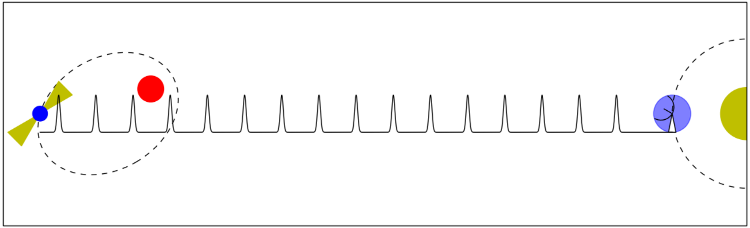


Pulsar Timing

- Large radio telescopes are used to record the times of arrival of pulses, which are affected by
  - **Solar dynamics**: well understood from satellite observations
  - **Binary motion**: gravitation and environments
  - **Interstellar medium**: well understood from plasma physics



Five-hundred-meter Aperture Spherical Telescope (FAST)

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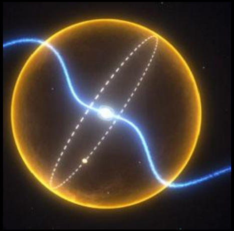
Perspective

Neutron stars as extreme laboratories for gravity tests

Lijing Shao [a,b,*,1], Kent Yagi [c,1]

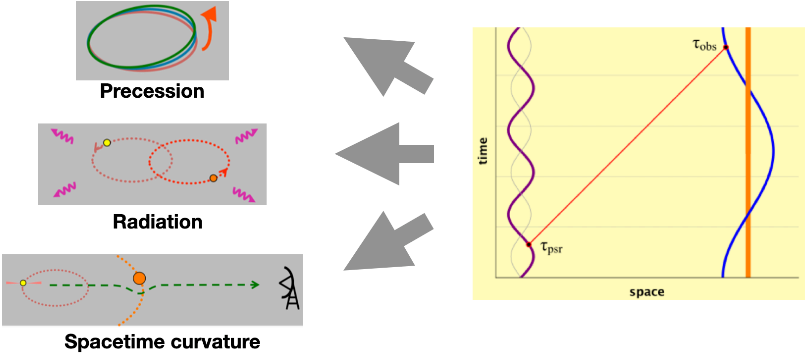
Pulsars are *truly* Extreme Laboratories

- strong gravity
- dense nuclear matters
- unique astrophysics
- ...



Binary Pulsars

- Binary pulsars are sensitive to effects beyond the Newtonian gravity



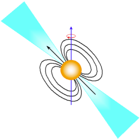
Sensitive to tiny changes in orbits

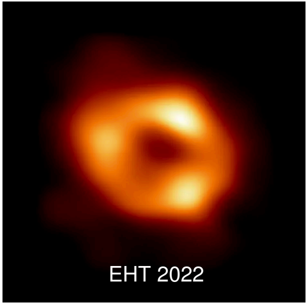
Binary pulsars are excellent testbeds of fundamental physics

2. Pulsar – Sagittarius A* Binaries

Pulsar – Sagittarius A* Binaries

- First, let's focus on the case where **Sagittarius A*** being the companion

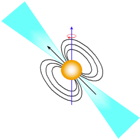


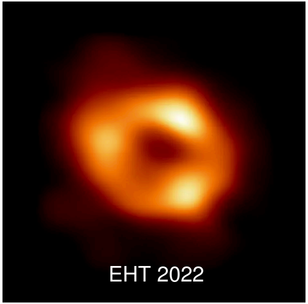


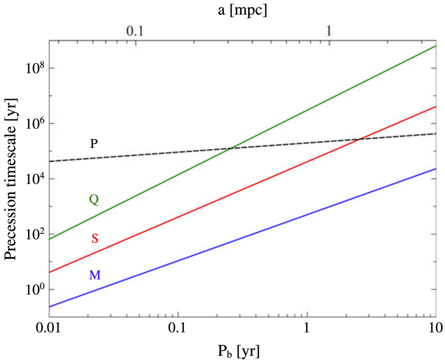
Wex & Kopeikin 1999 [arXiv:astro-ph/9811052]; Kramer et al. 2004 [arXiv:astro-ph/0409379]; Liu et al. 2012 [arXiv:1112.2151]

Pulsar – Sagittarius A* Binaries

- First, let's focus on the case where **Sagittarius A*** being the companion
- We need to find **close** pulsars



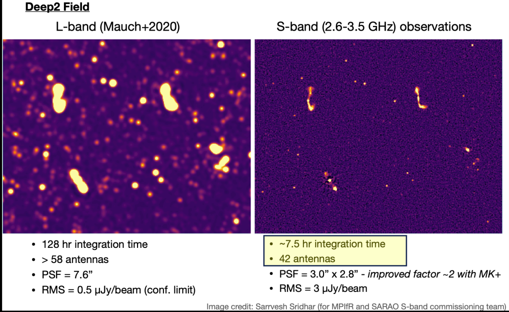




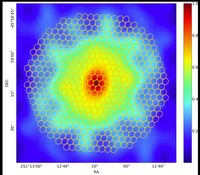
Wex & Kopeikin 1999 [arXiv:astro-ph/9811052]; Kramer et al. 2004 [arXiv:astro-ph/0409379]; Liu et al. 2012 [arXiv:1112.2151]

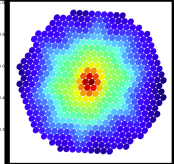
MPIfR systems for MeerKAT

- (64+2) x S-band receivers and digitisers
- Beamformer (~1,000 beams, dep on config.) for searching
- Second HPC cluster and software for pulsars & transients
- Storage space (~3.5 PB)
- 3000h of dedicated MPIfR time used for L-Band and S-Band survey of the Galactic plane
- Also: 200 hours survey of the Galactic Centre at S-Band
- S-band survey started - GC observations soon



Comparison of L-Band vs S-band: commissioning result





Chen et al. (2021)

36 GB/s or 127 TB/h or 3 PB/day.

slide credit: M. Kramer (MPIfR)

MPIfR S-Band on MeerKAT: commissioning results

slide credit: M. Kramer (MPIfR)

Galactic centre

- 1 hour observation, S2 (2187–3062 MHz), PSF = 3.1” x 2.5”, RMS = 70 μJy/beam

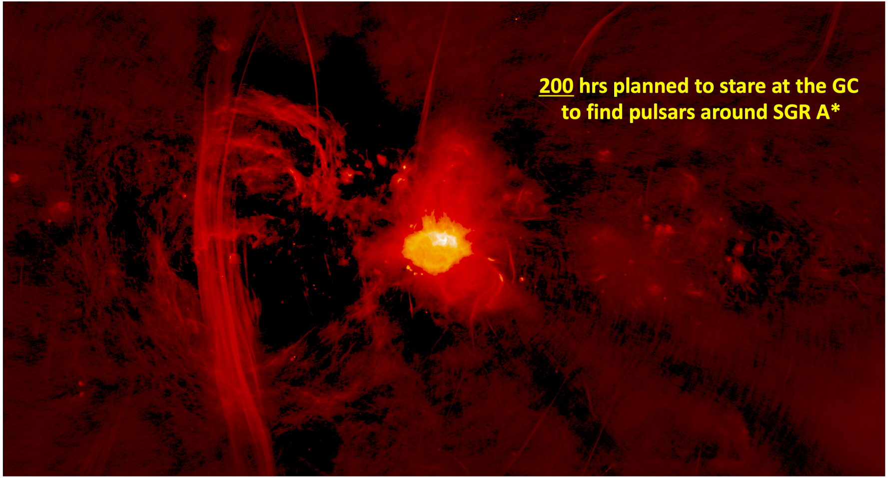


Image credit: Sarrvesh Sridhar (for MPIfR and SARAO S-band commissioning team)

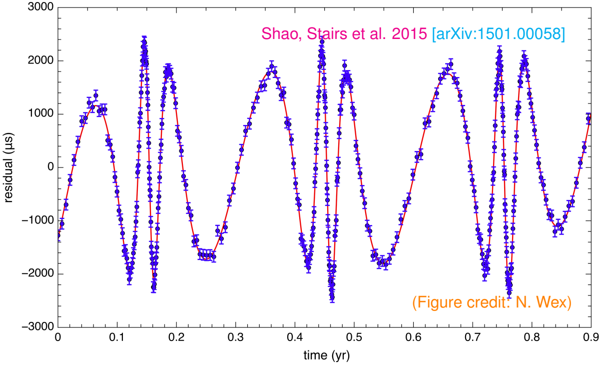
No-hair Theorem of Black Holes

- Mass M and spin $\boldsymbol{S}$ introduce HUGE timing residuals

Liu et al. 2012 [arXiv:1112.2151]

No-hair Theorem of Black Holes

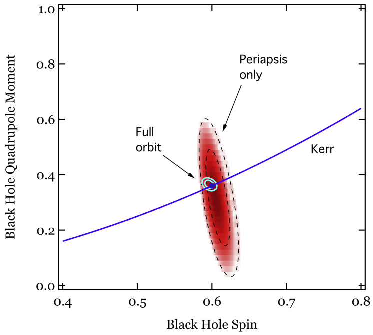
- Mass M and spin $\boldsymbol{S}$ introduce HUGE timing residuals
- Periodic timing residuals by the **quadrupole**



Liu et al. 2012 [arXiv:1112.2151]

Migrating Perturbations

- Only using **periastron passages** to reduce perturbations



Liu et al. 2012 [arXiv:1112.2151]; Psaltis et al. 2016 [arXiv:1510.00394]; Bower et al. 2018 [arXiv:1810.06623]

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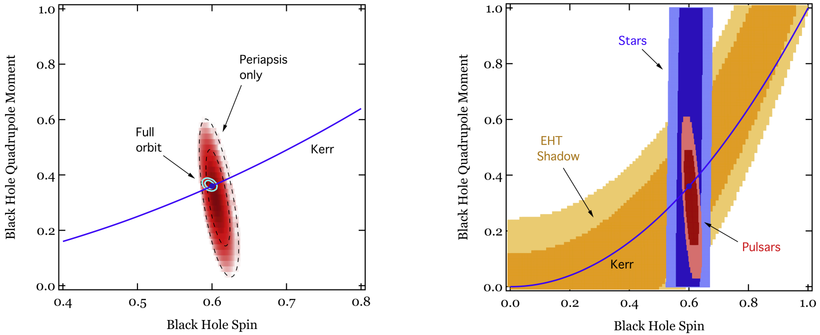

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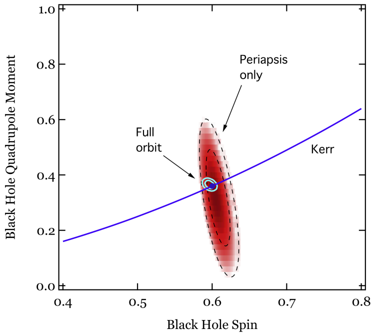
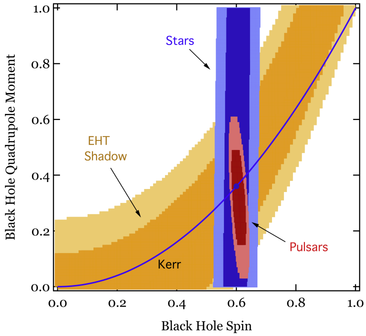
Migrating Perturbations

- Only using **periastron passages** to reduce perturbations
- **Incorporating perturbations to a numerical scheme?**

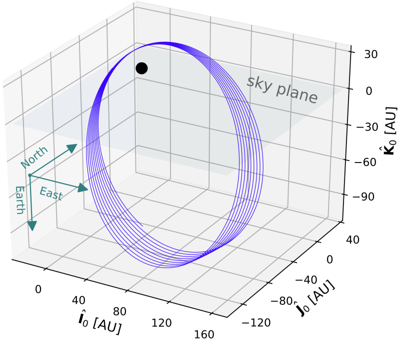




Liu et al. 2012 [arXiv:1112.2151]; Psaltis et al. 2016 [arXiv:1510.00394]; Bower et al. 2018 [arXiv:1810.06623]

Migrating Perturbations: a numerical scheme?

$$\ddot{\boldsymbol{r}} \equiv \frac{\mathrm{d}^2 \boldsymbol{r}}{\mathrm{d}t^2} = \ddot{\boldsymbol{r}}_{\mathrm{N}} + \ddot{\boldsymbol{r}}_{1\mathrm{PN}} + \ddot{\boldsymbol{r}}_{\mathrm{SO}} + \ddot{\boldsymbol{r}}_{\mathrm{Q}} + \ddot{\boldsymbol{r}}_{2\mathrm{PN}} + \ddot{\boldsymbol{r}}_{2.5\mathrm{PN}} + \cdots$$



Hu, Shao, Zhang 2023, PRD [arXiv:2312.01889]

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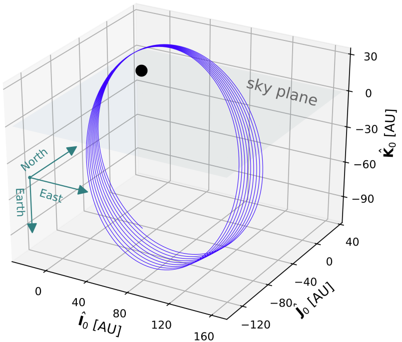

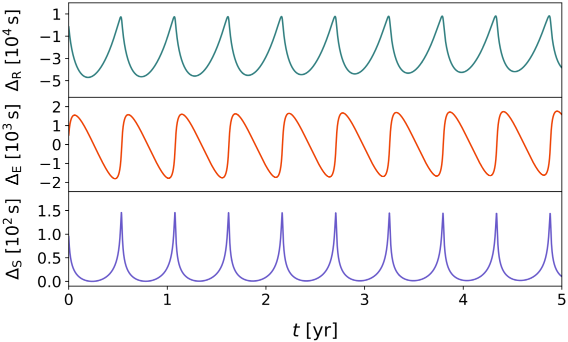

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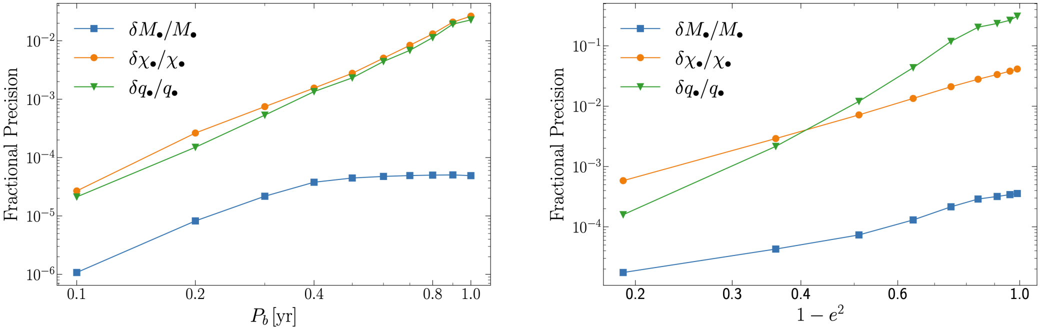


Our numerical scheme reproduces what was known in early studies

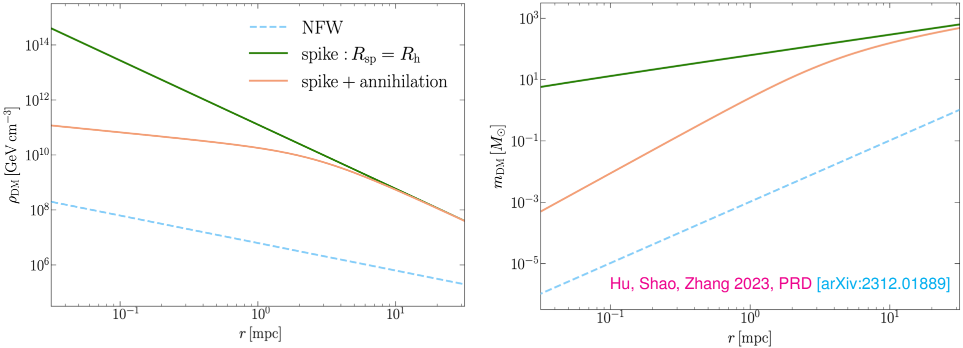
Hu, Shao, Zhang 2023, PRD [arXiv:2312.01889]

Migrating Perturbations: a numerical scheme?

- We want to incorporate a fly-by 10–10^3 $M_\odot$ black hole *Ongoing...*

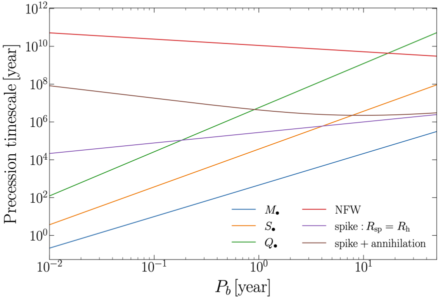
Migrating Perturbations: a numerical scheme?

- We want to incorporate a fly-by 10–$10^3\ M_\odot$ black hole *Ongoing...*
- A spherically distributed matter perturbation $\Leftarrow$ **Dark Matter Spike**



Gondolo & Silk 1999 [arXiv:astro-ph/9906391]; Sadeghian, Ferrer, Will 2013 [arXiv:1305.2619]; Fields, Shapiro, Shelton 2014 [arXiv:1406.4856]

Dark Matter Spike



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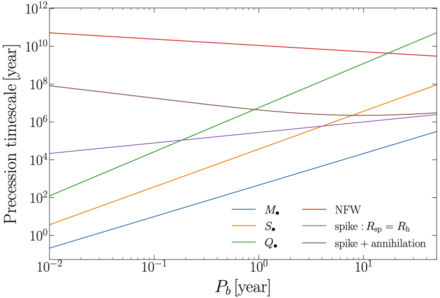

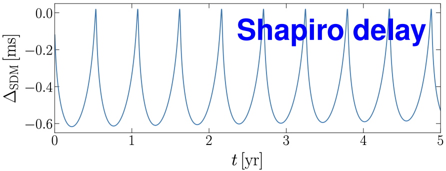

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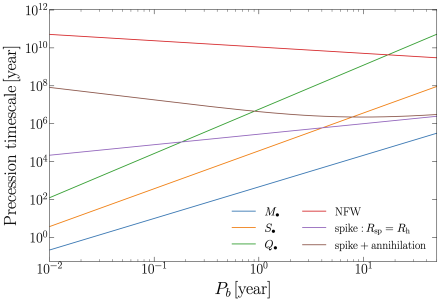

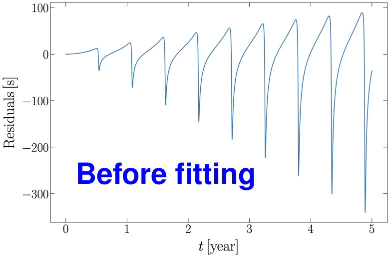

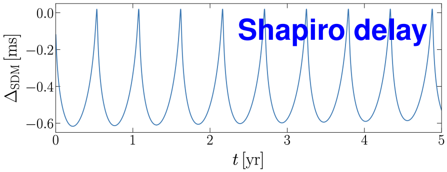

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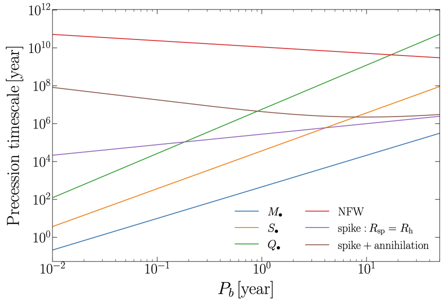

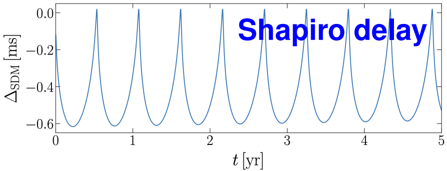

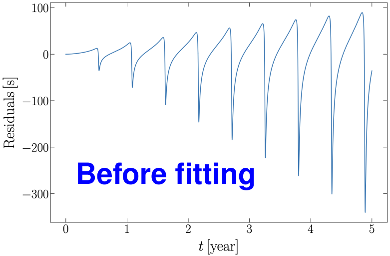

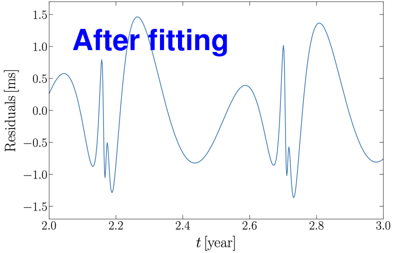

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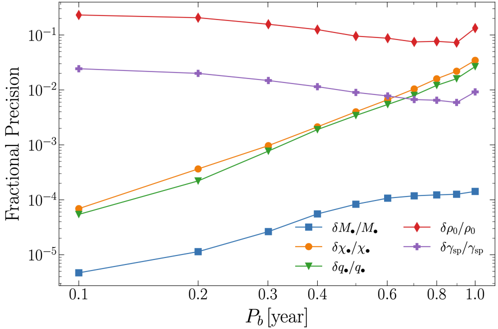
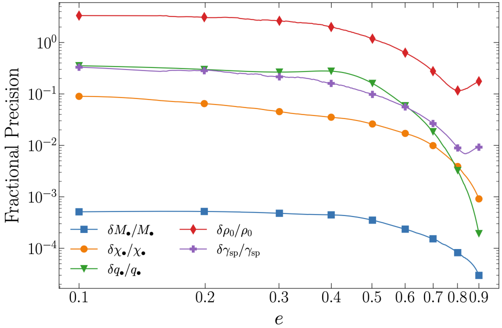
Dark Matter Spike

- We can constrain the **small-scale** dark matter profile index, $\gamma_{\rm sp} \sim 10^{-2}$





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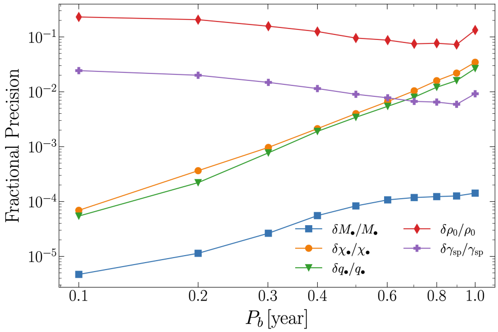
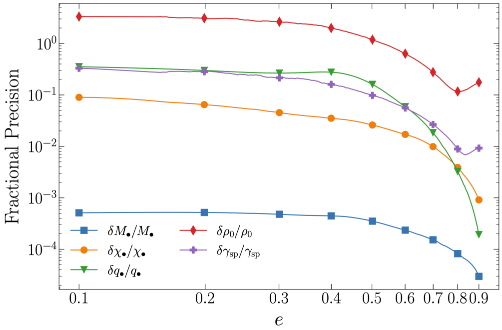
Dark Matter Spike

- We can constrain the **small-scale** dark matter profile index, $\gamma_{\rm sp} \sim 10^{-2}$
- It translates to **kpc-scale** constraints, comparable to maser observations *etc.*





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3. Fifth-force from Dark Matters

Detour: Tests of Strong Equivalence Principle

- For a **binary pulsar** in the Galactic potential (acceleration $\mathbf{a} \sim 2 \times 10^{-10}\,\mathrm{m\,s^{-2}}$), there is an extra acceleration from **SEP violation**

$$\mathbf{a}_{\Delta} = \left(\Delta_{\rm p} - \Delta_{\rm c}\right) \mathbf{a}$$

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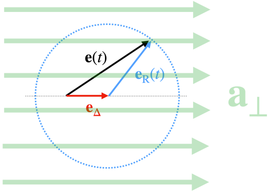
- At the 1 PN approximation, when the E.o.M.s are integrated, the evolution of the **eccentricity vector** is

$$\boldsymbol{e}(t) \equiv e\hat{\boldsymbol{a}} = \boldsymbol{e}_\mathrm{PN}(t) + \boldsymbol{e}_\Delta$$



Damour & Schäfer 1991; Zhu et al. 2019 [arXiv:1802.09206]; Shao 2023 [arXiv:2206.15187]

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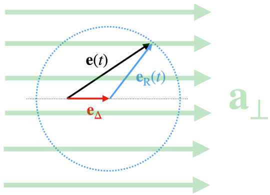
- The NS-WD binary PSR J1713+0747 gives $\Delta \lesssim 0.002$



Damour & Schäfer 1991; Zhu et al. 2019 [arXiv:1802.09206]; Shao 2023 [arXiv:2206.15187]

Strong Equivalence Principle and Dark Matter

- The "third" body in the Damour-Schäfer test is our Milky Way, which has a significant composition of **dark matters**

Damour & Schäfer 1991; Zhu et al. 2019 [arXiv:1802.09206]; Shao et al. 2018, PRL [arXiv:1805.08408]

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- We proposed a novel SEP-like test to constrain the **fifth force** from dark matter
  1. Large material difference in test-body pairs (NS vs WD)
  2. Significant gravitational binding energy

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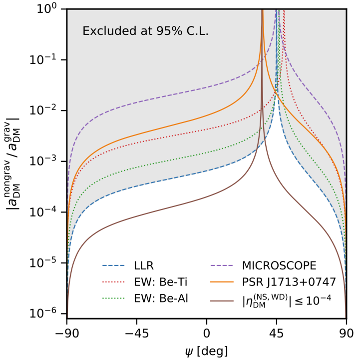
  1. Large material difference in test-body pairs (NS vs WD)
  2. Significant gravitational binding energy
- PSR J1713+0747 gives the best constraint
- If there is a long-range **fifth force**, it should be smaller than $1\% \times$ gravity

Damour & Schäfer 1991; Zhu et al. 2019 [arXiv:1802.09206]; Shao et al. 2018, PRL [arXiv:1805.08408]

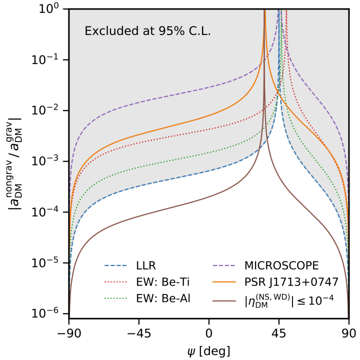
SEP and Dark Matter

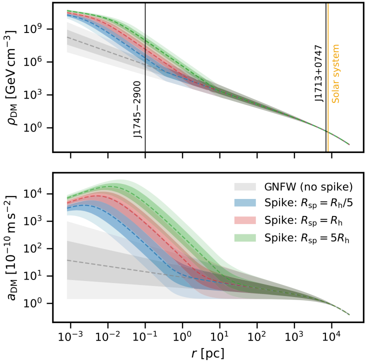


Shao et al. 2018, PRL [arXiv:1805.08408]

SEP and Dark Matter

- Because of the **dark matter spike**, **binary pulsars** within about 10 pc from the Galactic center will be extremely helpful in future





Shao et al. 2018, PRL [arXiv:1805.08408]

4. NSs’ Accretion of Dark Matters

Neutron Stars' Accretion of Dark Matters

- Depending on the **dark matter – nucleon scattering cross-section**, NSs are accreting dark matter particles after being born

Kouvaris & Tinyakov 2011 [arXiv:1012.2039]; McDermott et al. 2012 [arXiv:1103.5472]; Bramante et al. 2014 [arXiv:1405.1031]

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- If a neutron star that is not destroyed, we put constraints on the **dark matter – nucleon scattering cross-section**

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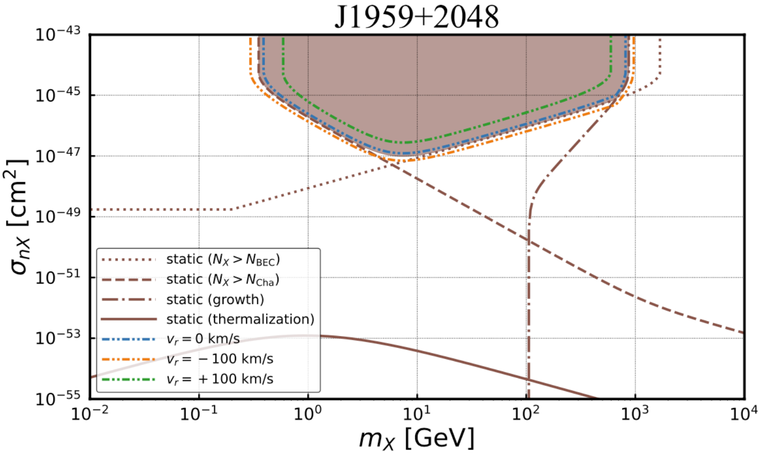
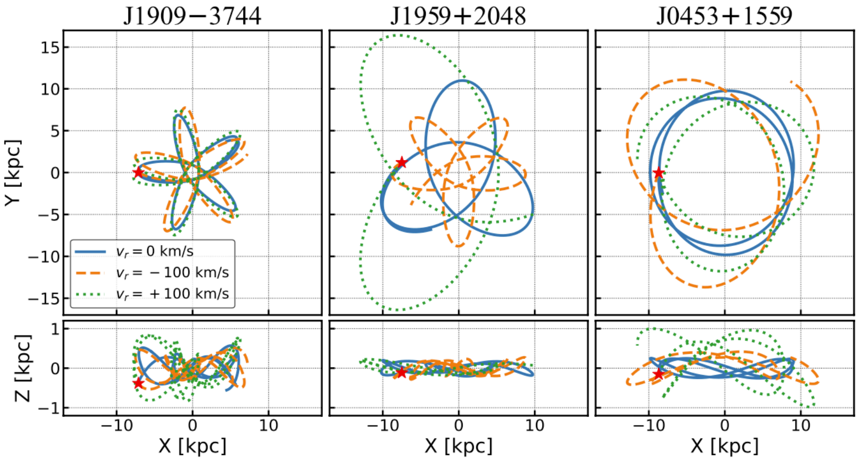
Example: Neutron Stars' Accretion of Dark Matters



Kouvaris & Tinyakov 2011 [arXiv:1012.2039]; McDermott et al. 2012 [arXiv:1103.5472]; Bramante et al. 2014 [arXiv:1405.1031]; Liang & Shao 2023 [arXiv:2303.05107]

Neutron Stars' Movements in the Milky Way



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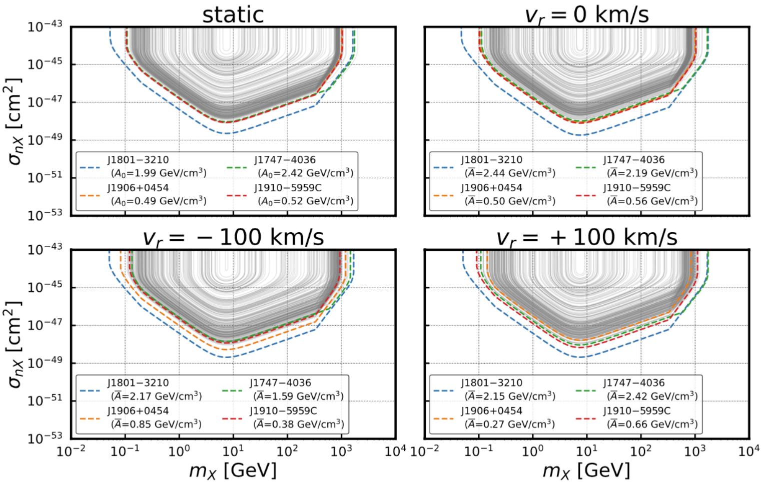

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- **Accretion of dark matters** by neutron stars puts constraints on **dark matter – nucleon scattering cross-section**

Thank you!