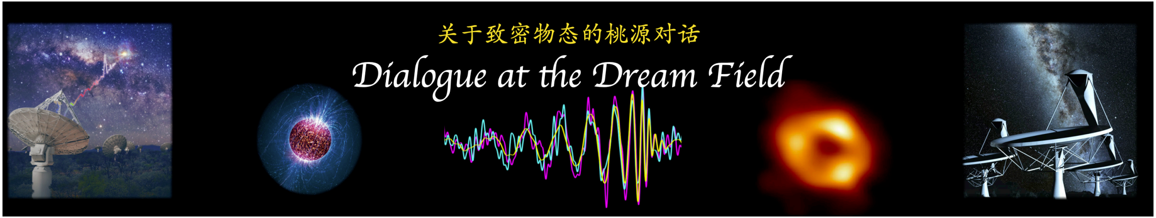


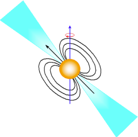
北京大学
PEKING UNIVERSITY

Fundamental Physics with Pulsars around Sgr A*

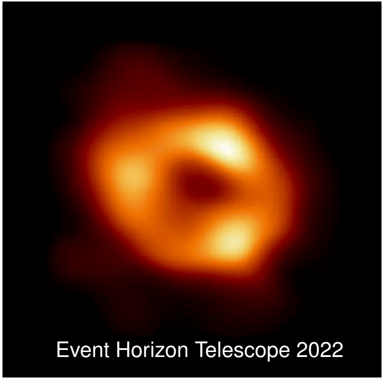
Kavli Institute for Astronomy and Astrophysics

Speaker: Lijing Shao（邵立晶）

Outline



1. **No-hair Theorem** of Black Holes
2. Small-scale **Dark Matter** Profiles
3. Sgr A* with **Vector Charge**
4. **Yukawa Gravity / Massive Graviton**
5. **Fifth Force** from Dark Matter



Event Horizon Telescope 2022

Collaborators: **Y. Dong** (PKU), **Z. Hu** (PKU), **M. Kramer** (MPIfR), **D. Liang** (PKU), **Z.-F. Mai** (PKU), **X. Miao** (NAOC), **Z. Wang** (PKU), **N. Wex** (MPIfR), **R. Xu** (Tsinghua), **F. Zhang** (GZU), **S.-Y. Zhou** (USTC)

No-hair Theorem of Black Holes

- **No-hair Theorem:** astrophysical black holes are fully characterized by just two numbers, mass M and spin S

Quadrupolar Moment

$$q = -\chi^2$$

where $q \equiv c^4 Q / G^2 M^3$ and $\chi \equiv cS / GM^2$

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

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Quadrupolar Moment

$$q = -\chi^2$$

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- By **independently** measuring M, S, and Q, one can test the **No-hair Theorem**
- **Pulsar Timing** provides a neat way in doing so!

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

No-hair Theorem of Black Holes

- In this talk, I focus on the case where **Sagittarius A*** being the black hole

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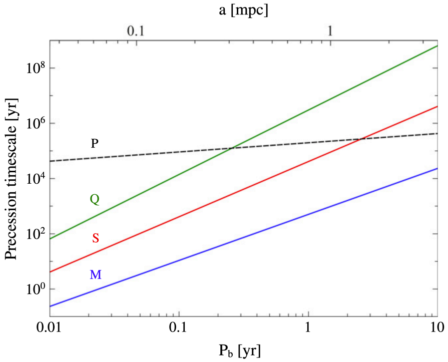
No-hair Theorem of Black Holes

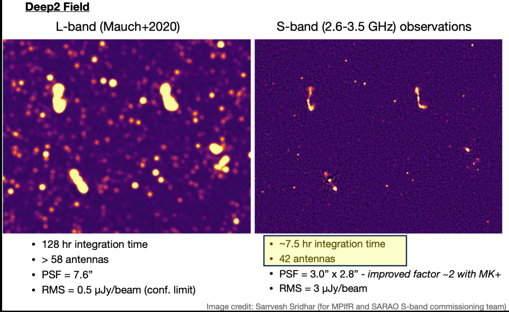
- In this talk, I focus on the case where **Sagittarius A*** being the black hole
- We need to find **close** pulsars



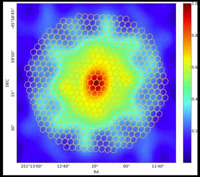
Wex & Kopeikin 1999 [arXiv:astro-ph/9811052]; Kramer et al. 2004 [arXiv:astro-ph/0409379]; Liu et al. 2012 [arXiv:1112.2151]

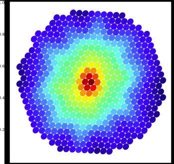
MPIfR systems for MeerKAT

– (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

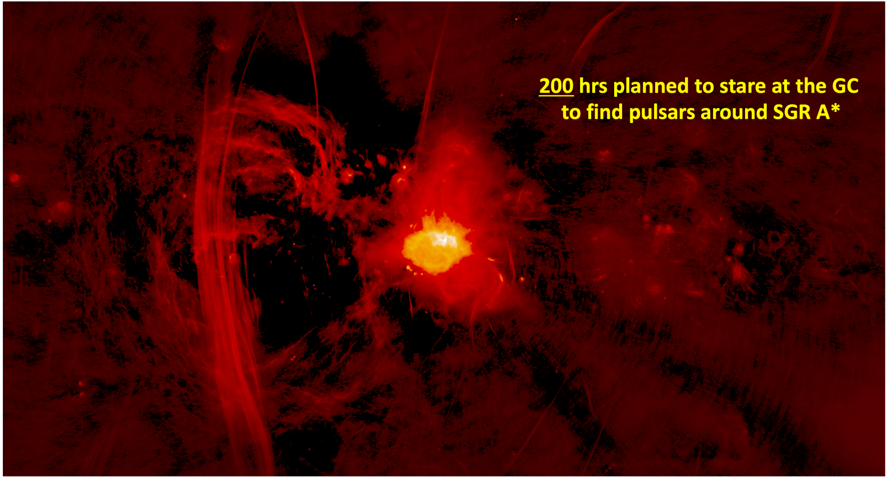


Image credit: Sarrvesh Sridhar (for MPIfR and SARAO S-band commissioning team)

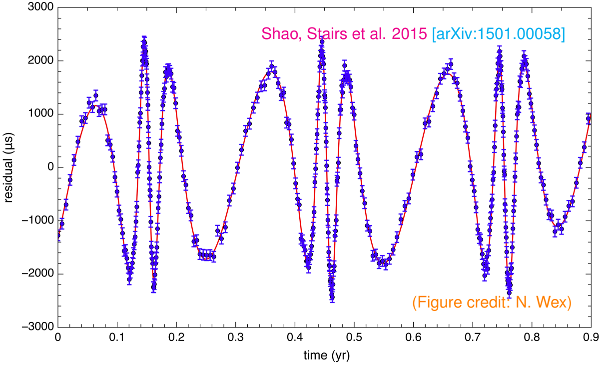
No-hair Theorem of Black Holes

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

Liu et al. 2012 [arXiv:1112.2151]

No-hair Theorem of Black Holes

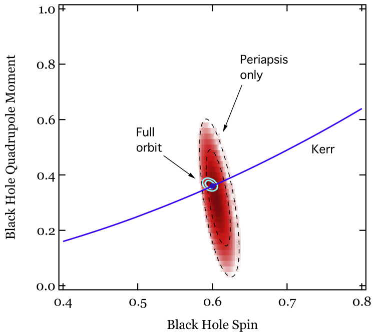
- Mass M and spin $\boldsymbol{S}$ introduce HUGE timing residuals
- Periodic timing residuals by the **quadupole**



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]

Migrating Perturbations

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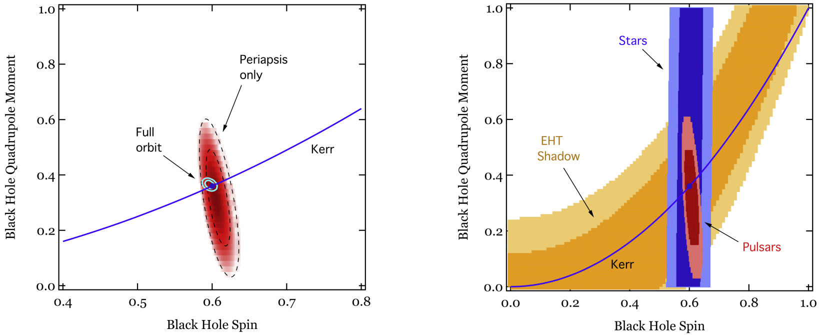

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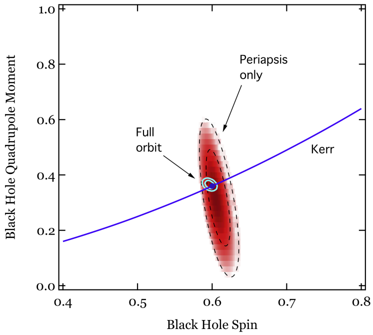
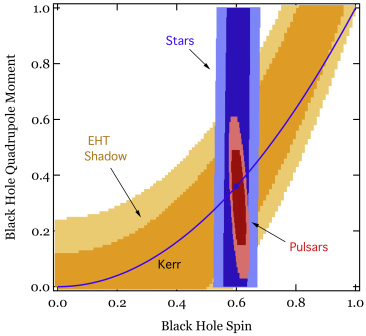
Migrating Perturbations

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

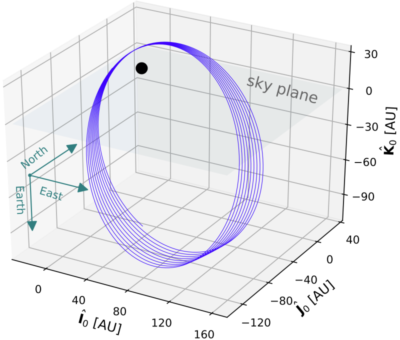




Liu et al. 2012 [arXiv:1112.2151]; Psaltis et al. 2016 [arXiv:1510.00394]; Bower et al. 2018 [arXiv:1810.06623]

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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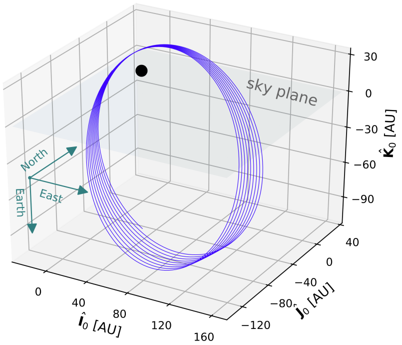

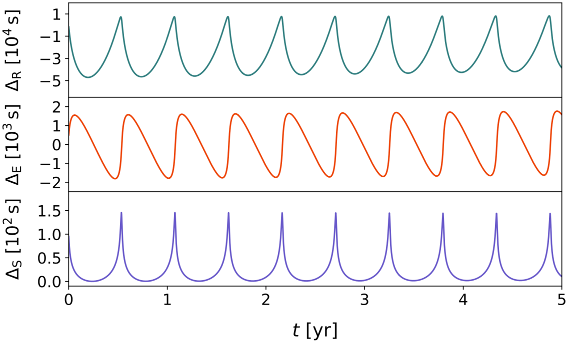

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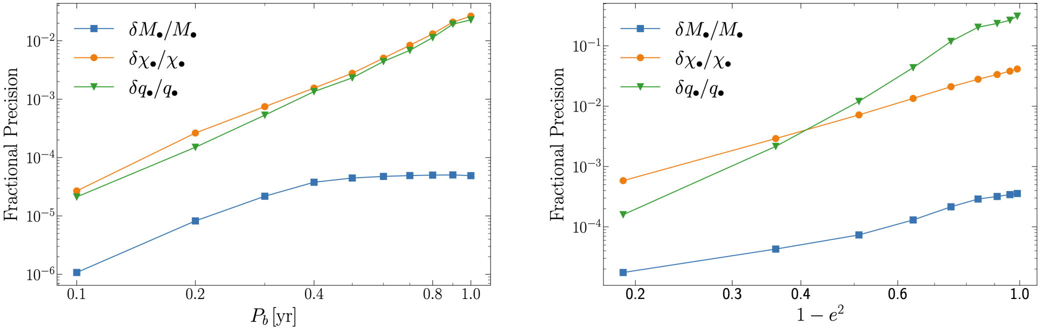
No-hair Theorem of Black Holes



Our numerical scheme reproduces what was known in early studies

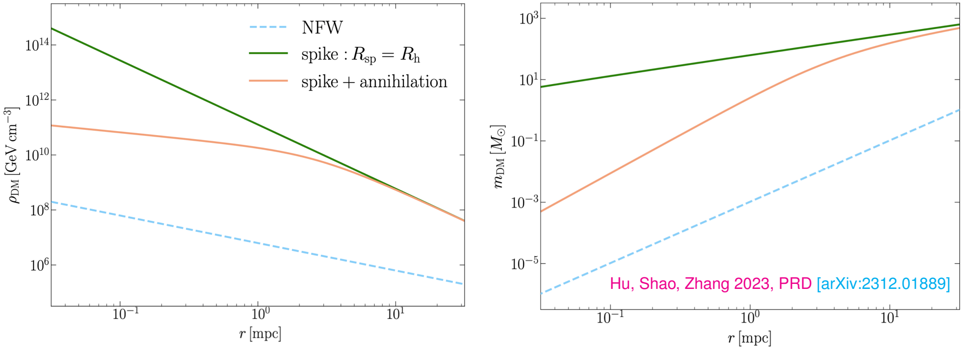
Hu, Shao, Zhang 2023, PRD [arXiv:2312.01889]

Migrating Perturbations: a numerical scheme?

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

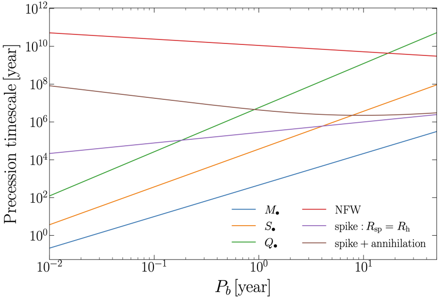
Migrating Perturbations: a numerical scheme?

- 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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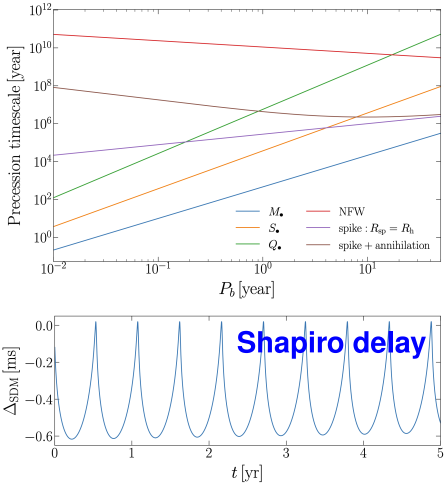

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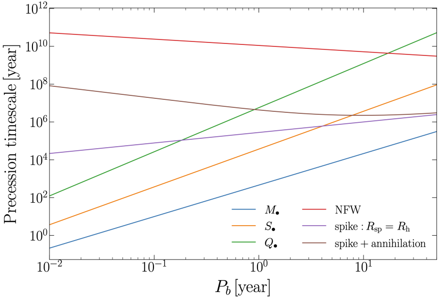

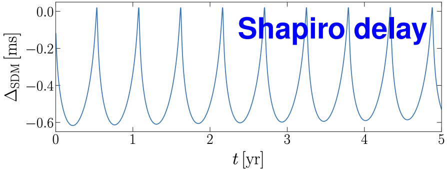

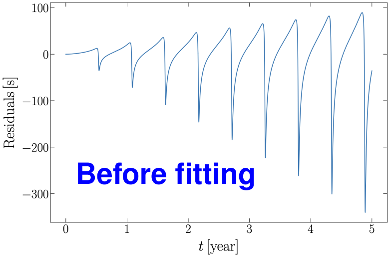

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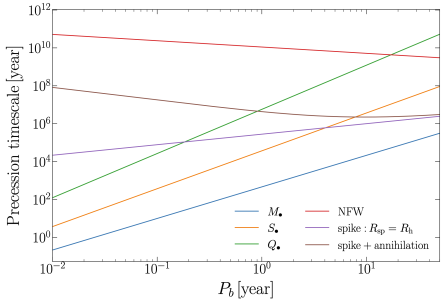

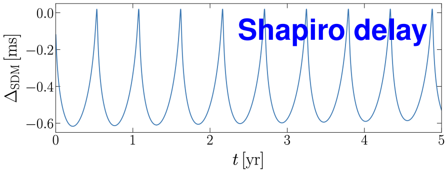

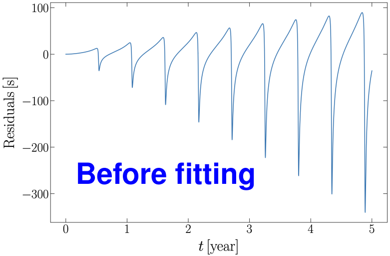

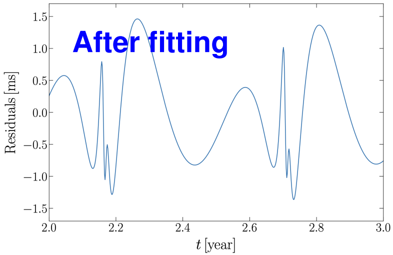

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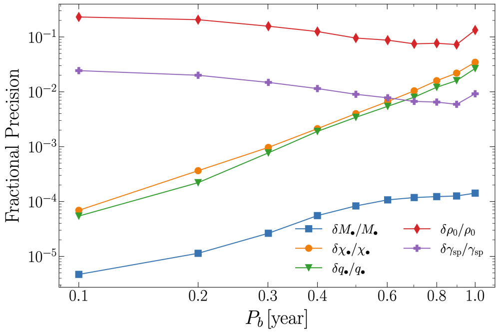
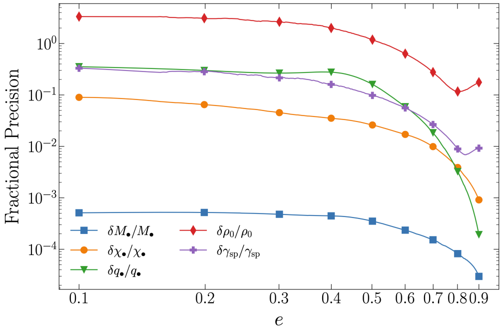
Dark Matter Spike

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

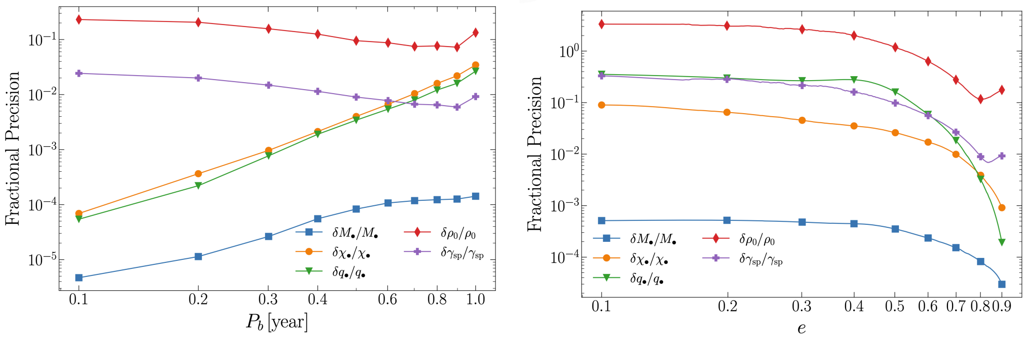




Hu, Shao, Zhang 2023, PRD [arXiv:2312.01889]

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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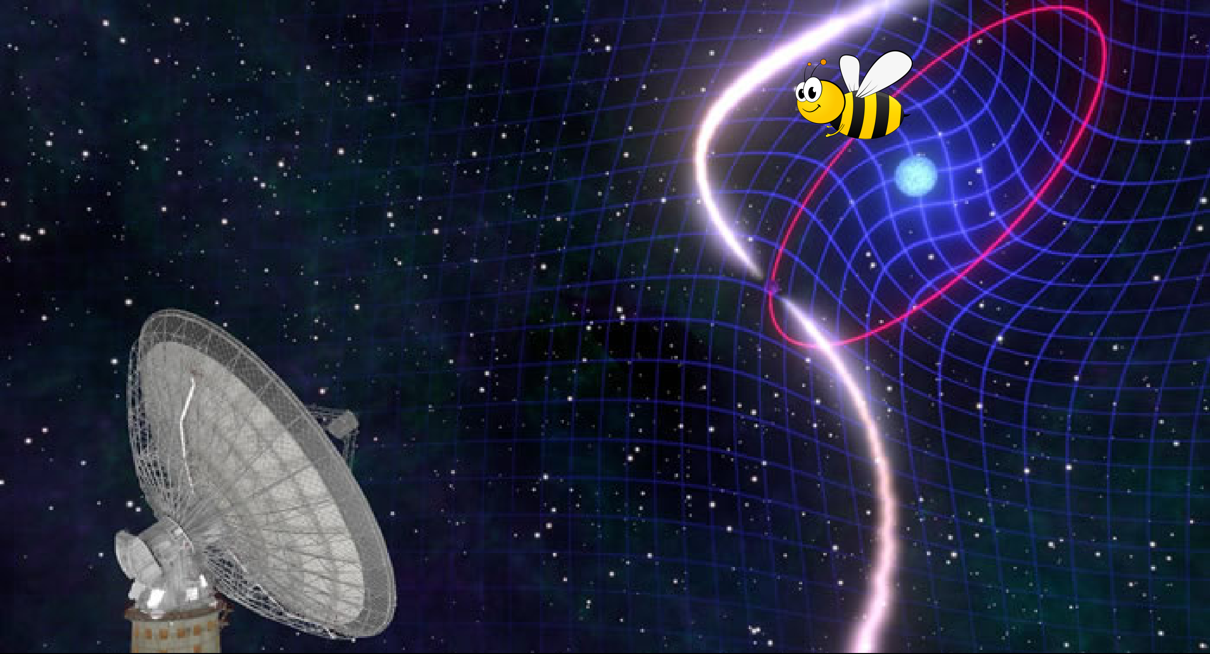


Bumblebee BHs

$$S = \int \sqrt{-g}\, \mathrm{d}^4x \left[\frac{1}{2\kappa}\left(R + \xi B^{\mu} B^{\nu} R_{\mu\nu}\right) - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} - V\left(B^{\mu}\right)\right] + S_{\mathrm{m}}$$

- **Ansatz**

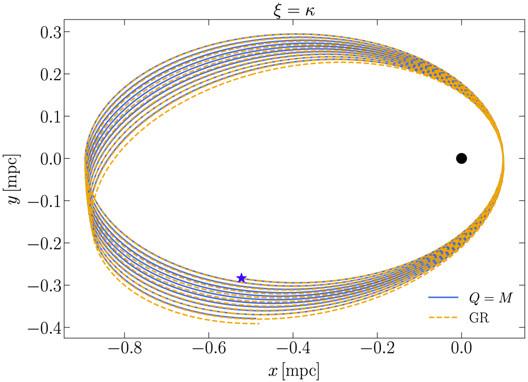
$$\mathrm{d}s^2 = -e^{2\nu}\mathrm{d}t^2 + e^{2\mu}\mathrm{d}r^2 + r^2\mathrm{d}\Omega^2$$

$$b_{\lambda} = \left(b_t, b_r, 0, 0\right)$$

where μ, ν, b_t, and b_r are functions of r

Xu, Liang, Shao 2023a, PRD [arXiv:2209.02209]; Xu, Liang, Shao 2023b, ApJ [arXiv:2302.05671]; Liang, Xu, Mai, Shao 2023, PRD [arXiv:2212.09346]
Liang, Xu, Shao 2022, PRD [arXiv:2207.14423]; Mai, Xu, Liang, Shao 2023, PRD [arXiv:2304.08030]; Mai, Xu, Liang, Shao 2024, PRD [arXiv:2401.07757]

Pulsars around Bumblebee Sgr A*



Orbital Precession for a $P_{\rm b} = 0.5\,{\rm yr}$ pulsar

Hu, Shao, Xu, Liang, Mai 2024, JCAP [arXiv:2312.02486]

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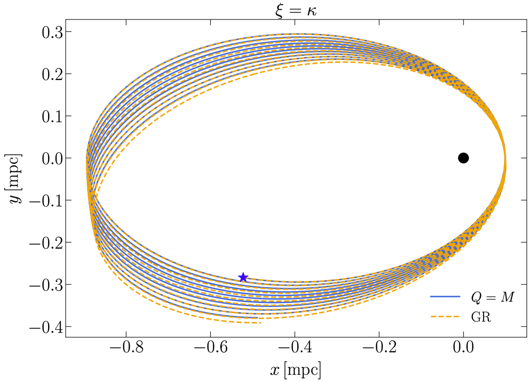

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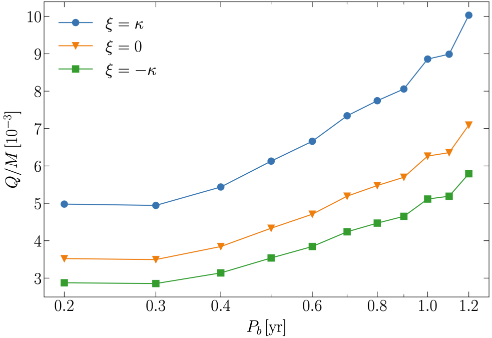
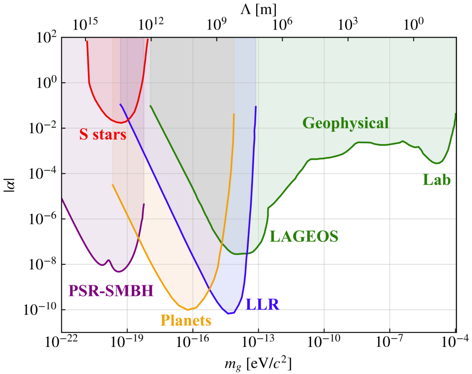


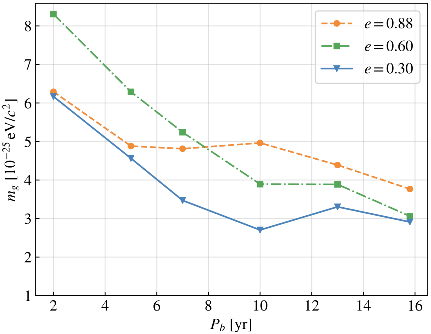
Bumblebee Charge for Sgr A*

Hu, Shao, Xu, Liang, Mai 2024, JCAP [arXiv:2312.02486]

Yukawa Gravity

$$\varphi(r) = -\frac{GM}{(1+\alpha)r}\left(1+\alpha e^{-\frac{r}{\Lambda}}\right)$$





Dong, Shao, Hu, Miao, Wang 2022, JCAP [arXiv:2210.16130]

Cubic Galileon / Massive Gravity

- **Cubic Galileon** with screening mechanics

$$S = \int \mathrm{d}^4 x \left[-\frac{1}{4} h^{\mu\nu} (\mathcal{E} h)_{\mu\nu} + \frac{h^{\mu\nu} T_{\mu\nu}}{2 M_{\mathrm{Pl}}} - \frac{3}{4} (\partial \pi_s)^2 \left(1 + \frac{1}{3\Lambda^3} \Box \pi_s \right) + \frac{\pi_s T}{2 M_{\mathrm{Pl}}} \right]$$

de Rham et al. 2013 [arXiv:1208.0580]; Shao, Wex, Zhou 2020, PRD [arXiv:2007.04531]

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- Extra **radiating channels** are introduced

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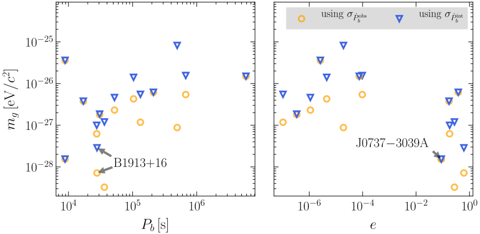


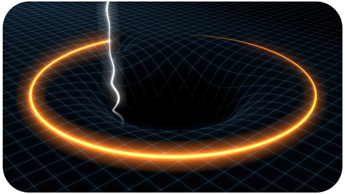
$$m_g \lesssim 2\times 10^{-28}\,\mathrm{eV}/c^2 \quad (95\%\ \text{C.L.})$$

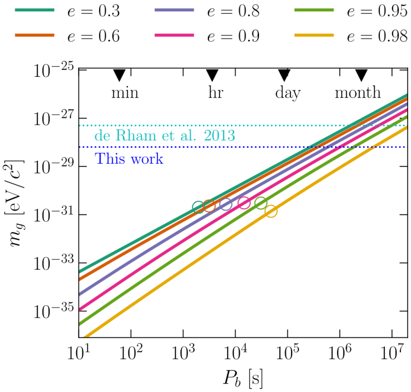
(collected in Particle Data Group)

de Rham et al. 2013 [arXiv:1208.0580]; Shao, Wex, Zhou 2020, PRD [arXiv:2007.04531]

Cubic Galileon / Massive Gravity

- We also investigated future pulsar-BH and pulsar-Sgr A* systems, in constraining the mass of graviton
  - MeerKAT, FAST, SKA, etc





Shao, Wex, Zhou 2020, PRD [arXiv:2007.04531]

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**

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

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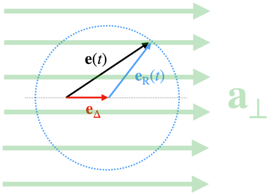
- At the 1 PN approximation, when the E.o.M.s are integrated, the evolution of the **eccentricity vector** is

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



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

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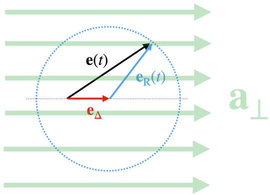
- At the 1 PN approximation, when the E.o.M.s are integrated, the evolution of the **eccentricity vector** is

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



- 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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- If there is a long-range **fifth force**, it should be smaller than $1\% \times$ gravity

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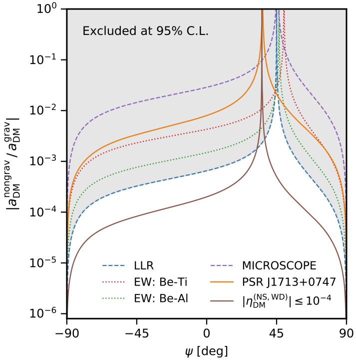
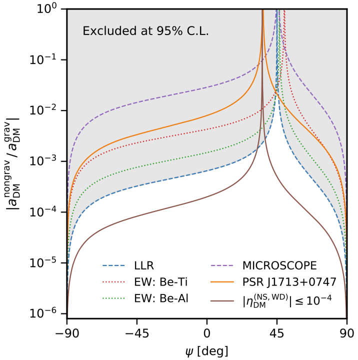
SEP and Dark Matter

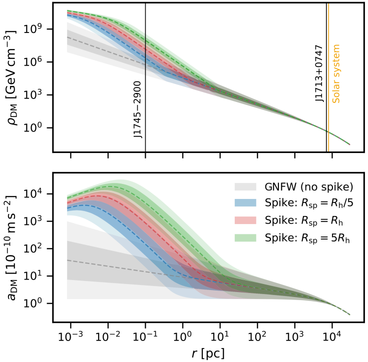


Shao et al. 2018, PRL [arXiv:1805.08408]

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





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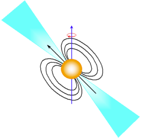
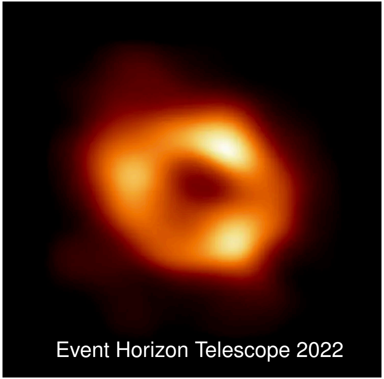
Summary



1. **No-hair Theorem** of Black Holes
2. Small-scale **Dark Matter** Profiles
3. Sgr A* with **Vector Charge**
4. **Yukawa Gravity / Massive Graviton**
5. **Fifth Force** from Dark Matter



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Thank you!