中国科学技术大学
交叉学科理论研究中心

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北京大學
PEKING UNIVERSITY

Testing Gravity Theories with Pulsars

Kavli Institute for Astronomy and Astrophysics

Speaker: Lijing Shao（邵立晶）

交叉学科理论研究中心

Kavli Institute for Astronomy and Astrophysics

- KIAA (2006-now) is jointly supported by **Peking University** and an endowment by **Kavli Foundation**
  1. Observational cosmology, galaxy formation and evolution
  2. Interstellar medium, star formation, and planets
  3. **Gravitational physics and high-energy phenomena**
  4. Computational astrophysics

Outline

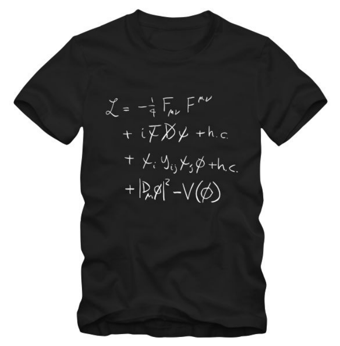
1. **Introduction to Gravity Tests**
2. **Binary Pulsar Timing**
3. **Strong Field Gravity**
4. **Massive Gravity**
5. **Fifth Force from Dark Matters**
6. **Summary**

1. Introduction to Gravity Tests

Modern Physics Landscape

Standard Model

quantum field theory

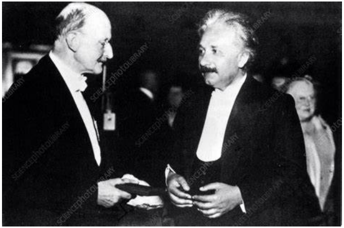


General Relativity

gravitation and spacetime

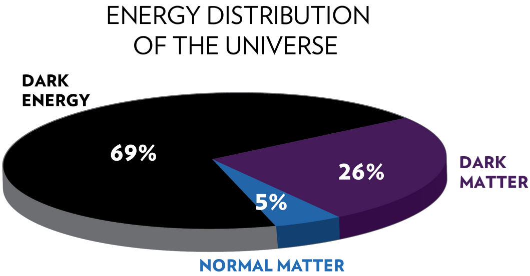
Absence of Quantum Gravity

- On one hand, we have **Quantum Field Theory** to describe the electromagnetic, strong, and weak interactions
- On the other hand, we have **General Relativity** to describe the gravity, as the dynamics of curved spacetime
- However, QFT and GR are **Not Compatible** with each other!



[Planck & Einstein]

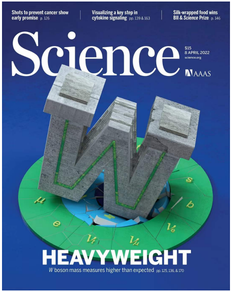
Pathways to New Physics?

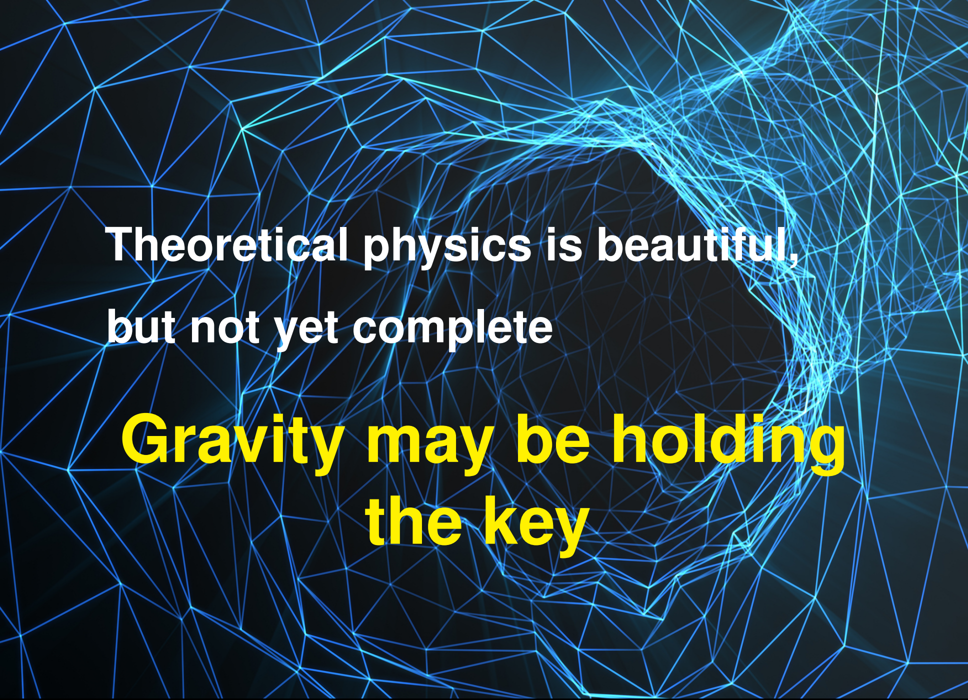


Dark energy? Dark matter?

Inflation? Heavy W boson?

Neutrino mass? ...





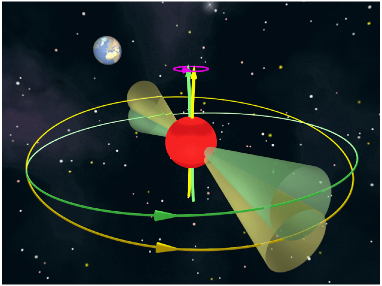
Theoretical physics is beautiful, but not yet complete

Gravity may be holding the key

2. Binary Pulsar Timing

Pulsars

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



Pulsars are clocks

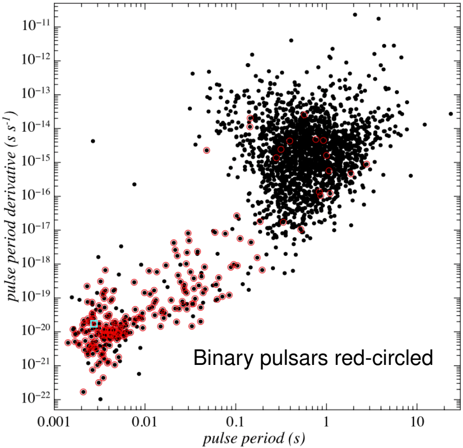
Pulsars are **precision** clocks

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

(16 significant digits!)

Kramer et al. 2021 [arXiv:2112.06795]

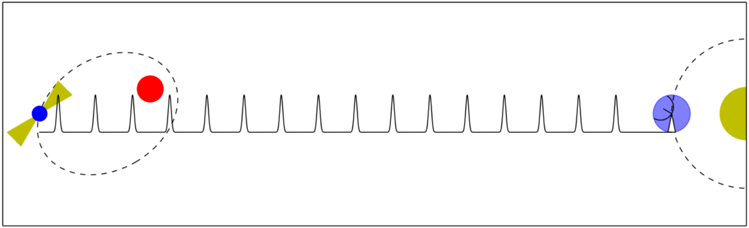
Pulsar Populations



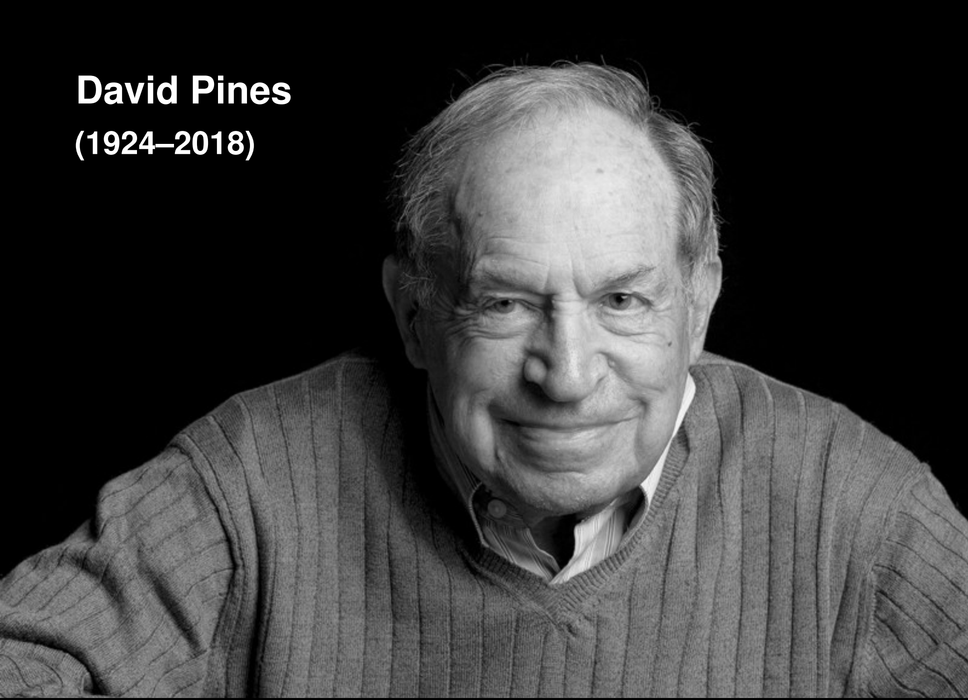
Manchester et al. 2005 [arXiv:astro-ph/0412641]; Wex & Kramer 2020

Pulsar Timing

- Large radio telescopes are used to record the times of arrival of pulses, which are affected by
  - Solar dynamics
  - Binary motion
  - Interstellar medium



Five-hundred-meter Aperture Spherical Telescope (FAST)



David Pines

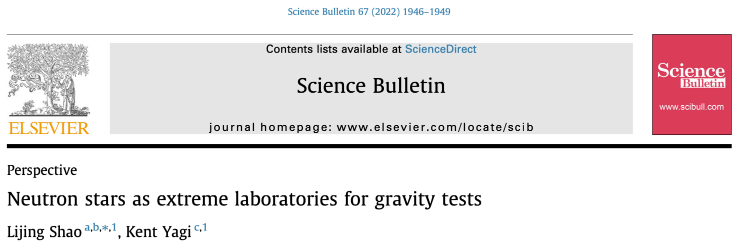
(1924–2018)

Pines Theorem: “NSs are *super*stars”

NSs’ *Super*properties

cf. Riccardo Ciolf’s PhD thesis

They are indeed ***super*dense** ($\bar{\rho} \gtrsim 2.8 \times 10^{14}\,\mathrm{g\,cm^{-3}}$), endowed with ***super*strong** gravity (in need of GR). They are ***super*fast** rotators ($\nu \sim 716\,\mathrm{Hz}$) and ***super*precise** timers (in need of $\gtrsim$ 10 digits), but also ***super*glitching** objects. NS matter is partially ***super*conducting** and/or ***super*fluid**. NSs possess ***super*strong** magnetic fields (up to $B \gtrsim 10^{15}$ G). In addition, NSs are ***super*rich** in the Physics involved (all four fundamental forces; Nuclear & Particle & Condensed Matter & Plasma & Magnetohydrodynamics & GR & Radio/Optical/X-ray/γ-ray & Neutrino & GW Physics etc.). ...and they are born in ***super*novae**!



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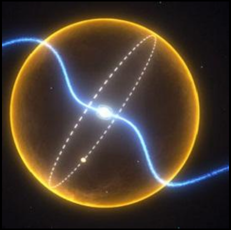
Perspective

Neutron stars as extreme laboratories for gravity tests

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

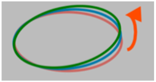
Pulsars are *truly* Extreme Laboratories

- **strong gravity**
- dense nuclear matters
- unique astrophysics
- …

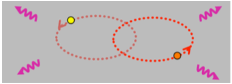


Binary Pulsars

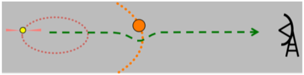
- Binary pulsars are sensitive to effects beyond the Newtonian gravity



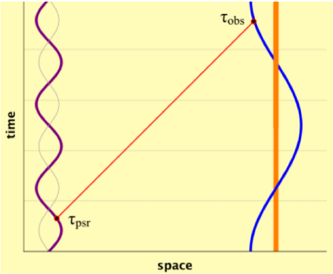
Precession



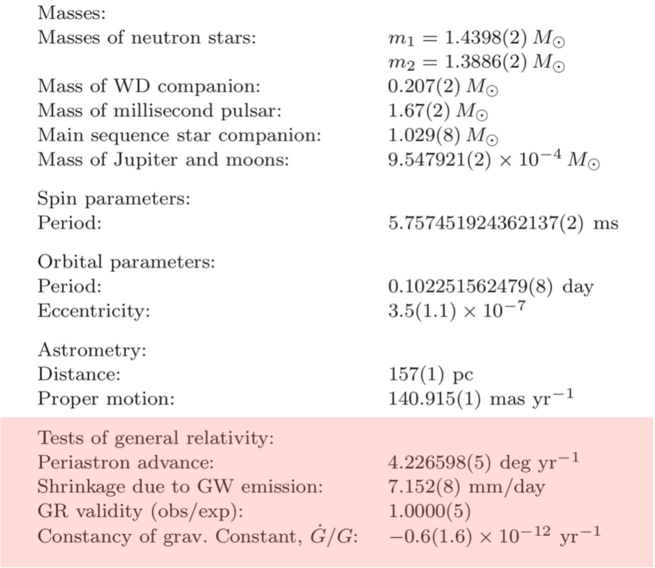
Radiation



Spacetime curvature



Precision Astrophysics (Kramer 2016)



Masses:	
Masses of neutron stars:	$m_1 = 1.4398(2)\,M_\odot$ $m_2 = 1.3886(2)\,M_\odot$
Mass of WD companion:	$0.207(2)\,M_\odot$
Mass of millisecond pulsar:	$1.67(2)\,M_\odot$
Main sequence star companion:	$1.029(8)\,M_\odot$
Mass of Jupiter and moons:	$9.547921(2) \times 10^{-4}\,M_\odot$
Spin parameters:	
Period:	5.757451924362137(2) ms
Orbital parameters:	
Period:	0.102251562479(8) day
Eccentricity:	$3.5(1.1) \times 10^{-7}$
Astrometry:	
Distance:	157(1) pc
Proper motion:	140.915(1) mas yr^{-1}
Tests of general relativity:	
Periastron advance:	4.226598(5) deg yr^{-1}
Shrinkage due to GW emission:	7.152(8) mm/day
GR validity (obs/exp):	1.0000(5)
Constancy of grav. Constant, $\dot{G}/G$:	$-0.6(1.6) \times 10^{-12}\ \text{yr}^{-1}$

Post-Keplerian Parameters

$$\dot{\omega} = 3\left(\frac{P_{\rm b}}{2\pi}\right)^{-5/3} (T_\odot M)^{2/3} \left(1-e^2\right)^{-1}$$

$$\gamma = e\left(\frac{P_{\rm b}}{2\pi}\right)^{1/3} T_\odot^{2/3} M^{-4/3} m_B \left(m_A + 2m_B\right)$$

$$\dot{P}_{\rm b} = -\frac{192\pi}{5}\left(\frac{P_{\rm b}}{2\pi}\right)^{-5/3}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)\left(1-e^2\right)^{-7/2} T_\odot^{5/3} m_A m_B M^{-1/3}$$

$$r = T_\odot m_B$$

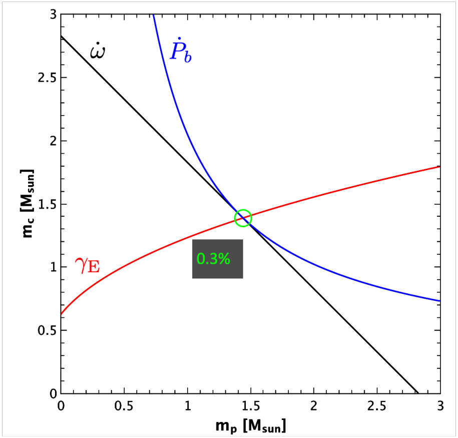
$$s = x\left(\frac{P_{\rm b}}{2\pi}\right)^{-2/3} T_\odot^{-1/3} M^{2/3} m_B^{-1}$$

$$\delta_{\rm r} = T_\odot^{2/3}\left(\frac{P_{\rm b}}{2\pi}\right)^{-2/3} M^{-4/3}\left(3m_A^2 + 6m_A m_B + 2m_B^2\right)$$

$$\delta_\theta = T_\odot^{2/3}\left(\frac{P_{\rm b}}{2\pi}\right)^{-2/3} M^{-4/3}\left(\frac{7}{2}m_A^2 + 6m_A m_B + 2m_B^2\right)$$

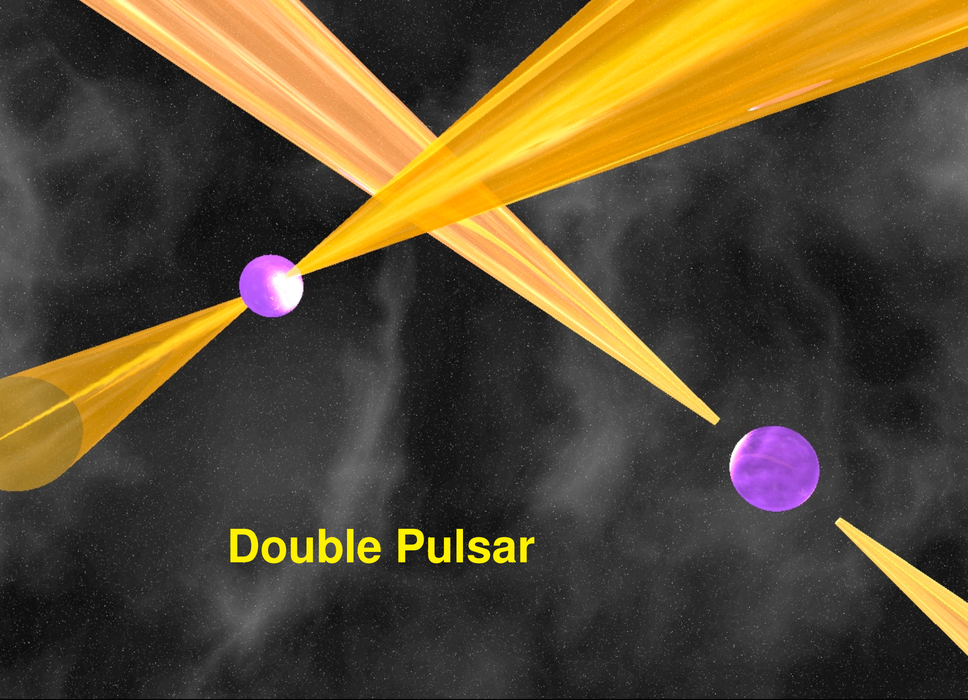
Damour & Deruelle 1985, 1986; Damour & Taylor 1992

The Hulse-Taylor Pulsar B1913+16



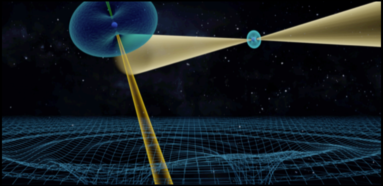
Nobel Prize in Physics 1993

Hulse & Taylor 1975; Weisberg & Huang 2016



Double Pulsar

The Double Pulsar J0737−3039A/B



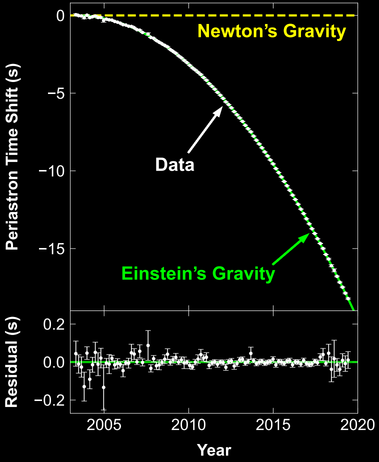
Physics

VIEWPOINT

General Relativity Withstands Double Pulsar's Scrutiny

Sixteen years of timing data from the double pulsar confirm the validity of Einstein's theory of general relativity to a new level.

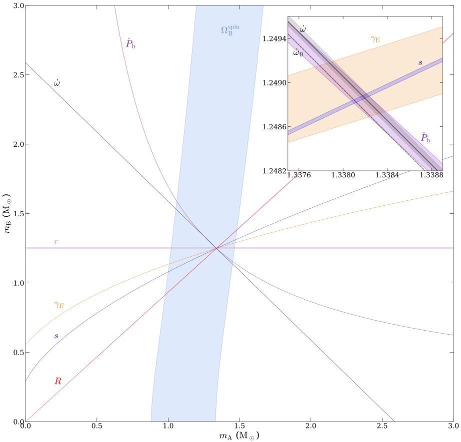
By Lijing Shao



In GR, observations of Double Pulsar agree within 0.01%

Kramer et al. 2021 [arXiv:2112.06795]

The Double Pulsar J0737−3039A/B



Double Pulsar passed a few tests of GR *simultaneously*

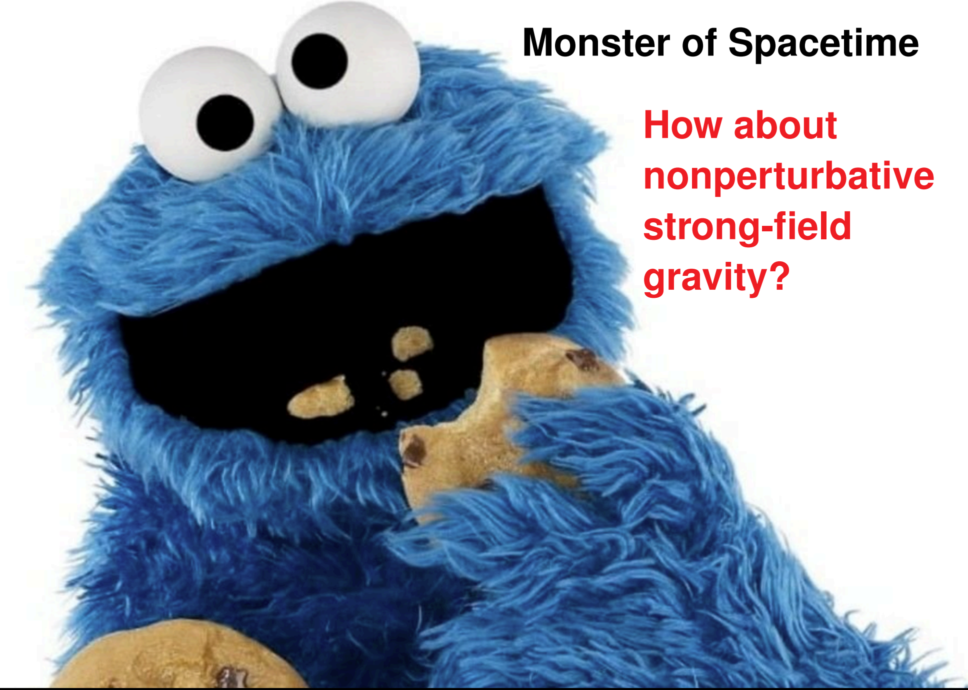
Breton et al. 2008 [arXiv:0807.2644]; Kramer et al., 2021 [arXiv:2112.06795]

Sensitive to tiny changes in orbits

Binary pulsars are excellent testbeds of gravity theories

3. Strong Field Gravity

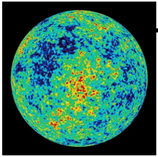
Precision clocks in curved spacetime

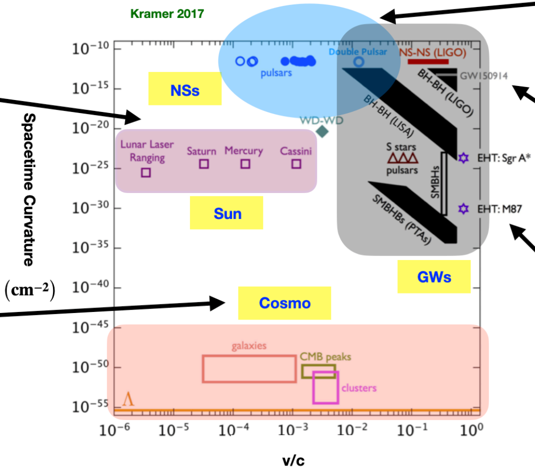


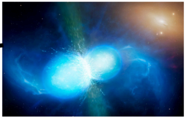
Monster of Spacetime

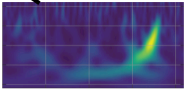
How about nonperturbative strong-field gravity?

Parameter Space in Gravity Tests









Scalar-Tensor Gravity

$$S = \frac{c^4}{16\pi G_*} \int \frac{\mathrm{d}^4 x}{c} \sqrt{-g_*} \left[R_* - 2 g_*^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi - V(\varphi) \right] + S_m \left[\psi_m ; A^2(\varphi) g^*_{\mu\nu} \right]$$

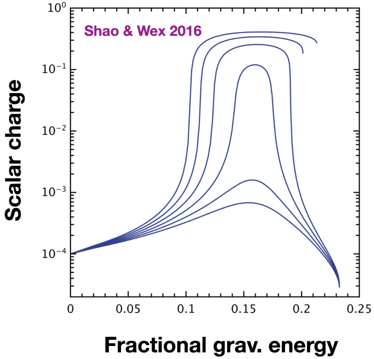
- **Example** A class of cosmologically well-motivated scalar-tensor theories $T(\varphi_0, \beta_0)$, that are solely described by two theory parameters: φ_0 & β_0

$$V(\varphi) = 0$$

$$A(\varphi) = \exp\left(\beta_0 \varphi^2 / 2\right)$$

Damour & Esposito-Farèse 1992; 1993; 1996 [arXiv:gr-qc/9602056]

Scalar-Tensor Gravity

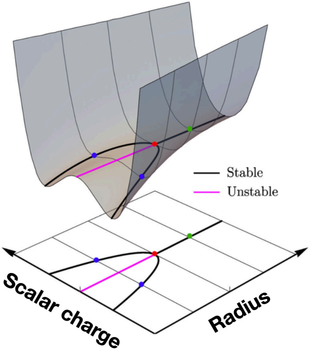


Nonperturbative **spontaneous scalarization**

could happen for isolated NSs

Damour & Esposito-Farèse 1992; 1993; 1996 [arXiv:gr-qc/9602056]

Scalar-Tensor Gravity



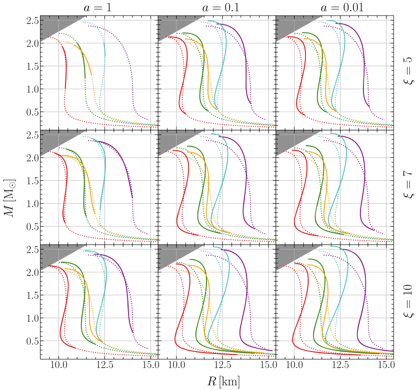
Strong-field behavior is analogous to **Landau's phase transition** after a critical point

Damour & Esposito-Farèse 1996 [arXiv:gr-qc/9602056]

Esposito-Farèse 2004 [arXiv:gr-qc/0409081]; Sennett et al. 2017 [arXiv:1708.08285]

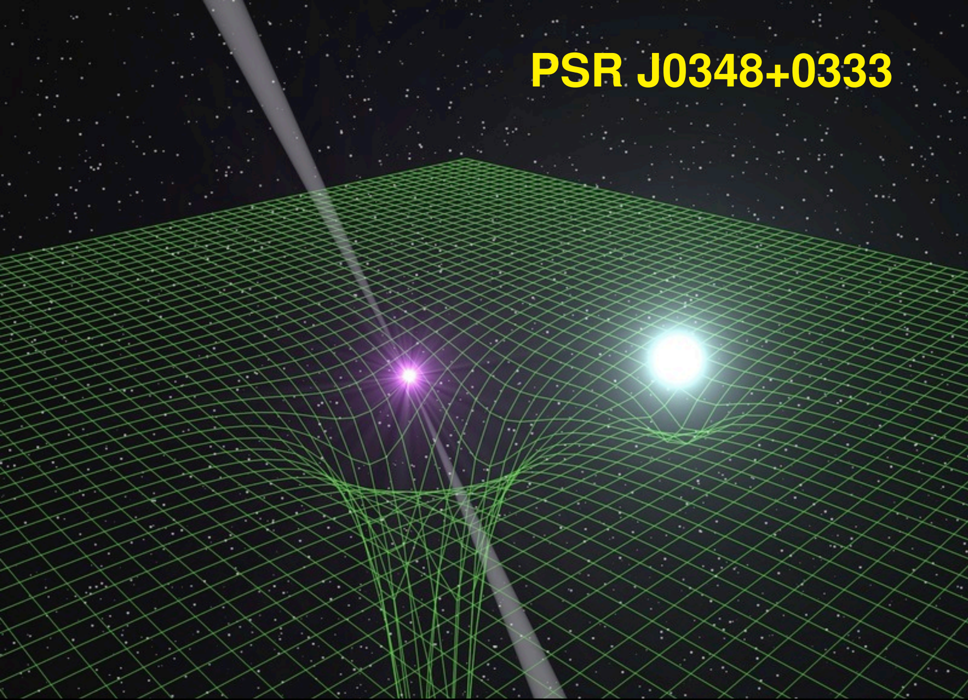
Massive Scalar-Tensor Gravity

- When a mass term is included, say $V(\varphi) \sim m^2\varphi^2$, a Yukawa-type suppression happens for the deviation



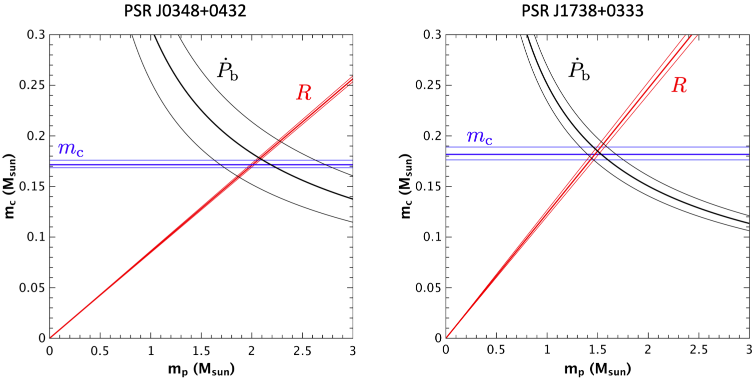
Ramazanoğlu & Pretorius 2016; Yazadjiev, Doneva, Popchev 2016; Xu, Gao, Shao 2020

Strong-field gravity can be VERY different from weak-field gravity



PSR J0348+0333

PSRs J0348+0432 and J1738+0333

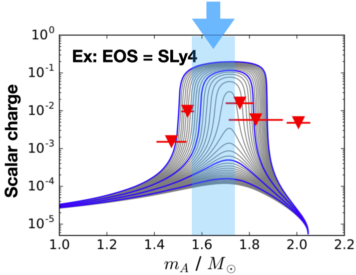


Due to their **asymmetry**, neutron-star white-dwarf systems provide stringent limits on dipole radiation $\dot{P}_b^{\rm dipole} \propto (\alpha_{\rm NS} - \alpha_0)^2$

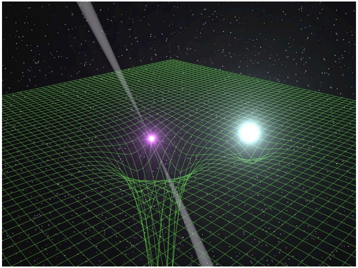
Freire et al. 2012 [arXiv:1205.1450]; Antoniadis et al. 2013 [arXiv:1304.6875]

Combination of Multiple NS-WD Binaries

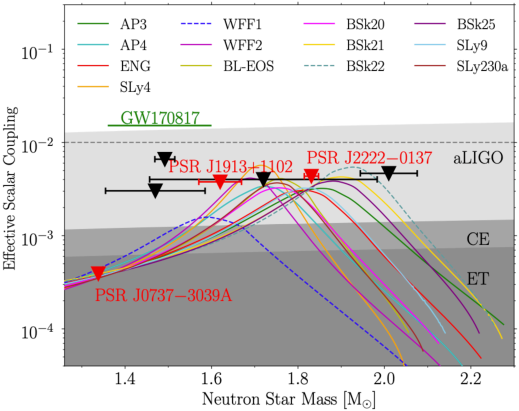
- Strong-field effects could happen at different NS masses for different EOSs Shibata et al. 2014 [arXiv:1310.0627]
- Combining NS-WDs put the best limits on a class of scalar tensor theories for different EOSs Shao et al. 2017 [arXiv:1704.07561]


"Scalarization window"

Ex: EOS = SLy4



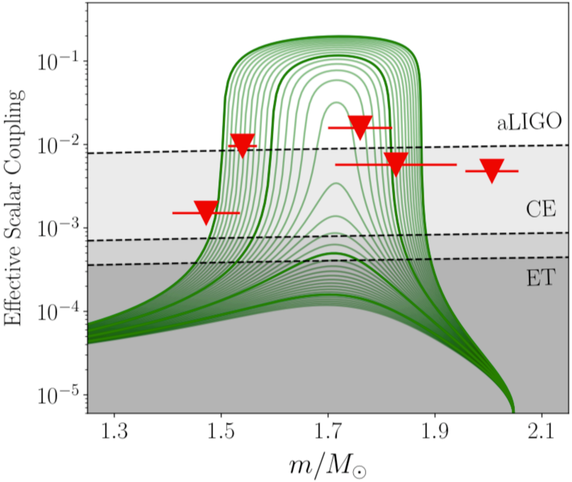
Combination of Multiple NS-WD Binaries



Scalarization window is closed for $T(\varphi_0, \beta_0)$ theories ($\lesssim 1\%$) with addition of new observations

Zhao et al. 2022 [arXiv:2201.03771]

Gravitational Waves



Will 1994; Damour & Esposito-Farèse 1998; Shao et al. 2017

4. Massive Gravity

Radiative tests are truly powerful

not only in dipole radiation

in other aspects as well

Linearized Fierz-Pauli Theory

- **Linearized gravity** with a massive graviton

$$S = \frac{1}{64\pi} \int \mathrm{d}^4 x \left[\partial_\lambda h_{\mu\nu} \partial^\lambda h^{\mu\nu} - 2\partial^\nu h_{\mu\nu} \partial_\lambda h^{\mu\lambda} + 2\partial^\nu h_{\mu\nu} \partial^\mu h \right.$$
$$\left. - \partial^\mu h \partial_\mu h - 32\pi h_{\mu\nu} T^{\mu\nu} + m_g^2 \left(h_{\mu\nu} h^{\mu\nu} - \frac{1}{2} h^2 \right) \right]$$

- The **unique** mass term for $h_{\mu\nu}$ when
  1. standard form for wave equation

$$\left(\Box - m_g^2\right) \bar{h}_{\mu\nu} + 16\pi T_{\mu\nu} = 0$$

  2. recovery of GR when $m_g \to 0$: no van Dam-Veltman-Zakharov discontinuity

Finn & Sutton 2002 [arXiv:gr-qc/0109049]

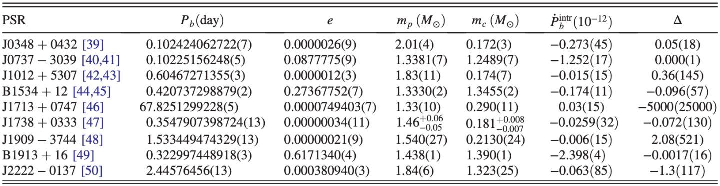
Linearized Fierz-Pauli Theory

- **Binary pulsars** can be used to constrain the graviton mass via bounding the gravitational backreaction

$$\Delta \equiv \frac{L_{\rm GW} - L_{\rm GW}^{\rm (GR)}}{L_{\rm GW}^{\rm (GR)}} \propto m_g^2 \left(\frac{c^2 P_b}{2\pi\hbar} \right)^2$$

- Bayesian analysis with a list of binary pulsars

(collected in Particle Data Group) Miao, Shao, Ma 2019 [arXiv:1905.12836]



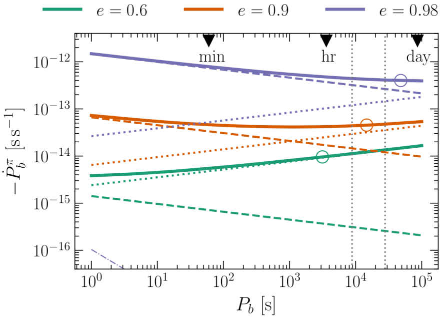
PSR	P_b(day)	e	$m_p\,(M_\odot)$	$m_c\,(M_\odot)$	$\dot{P}_b^{\rm intr}(10^{-12})$	Δ
J0348 + 0432 [39]	0.102424062722(7)	0.0000026(9)	2.01(4)	0.172(3)	−0.273(45)	0.05(18)
J0737 − 3039 [40,41]	0.10225156248(5)	0.0877775(9)	1.3381(7)	1.2489(7)	−1.252(17)	0.000(1)
J1012 + 5307 [42,43]	0.60467271355(3)	0.0000012(3)	1.83(11)	0.174(7)	−0.015(15)	0.36(145)
B1534 + 12 [44,45]	0.420737298879(2)	0.27367752(7)	1.3330(2)	1.3455(2)	−0.174(11)	−0.096(57)
J1713 + 0747 [46]	67.8251299228(5)	0.0000749403(7)	1.33(10)	0.290(11)	0.03(15)	−5000(25000)
J1738 + 0333 [47]	0.3547907398724(13)	0.00000034(11)	$1.46^{+0.06}_{-0.05}$	$0.181^{+0.008}_{-0.007}$	−0.0259(32)	−0.072(130)
J1909 − 3744 [48]	1.533449474329(13)	0.00000021(9)	1.540(27)	0.2130(24)	−0.006(15)	2.08(521)
B1913 + 16 [49]	0.322997448918(3)	0.6171340(4)	1.438(1)	1.390(1)	−2.398(4)	−0.0017(16)
J2222 − 0137 [50]	2.44576456(13)	0.000380940(3)	1.84(6)	1.323(25)	−0.063(85)	−1.3(117)

Cubic Galileon

- **Cubic Galileon** with screening mechanics [de Rham et al. 2013]

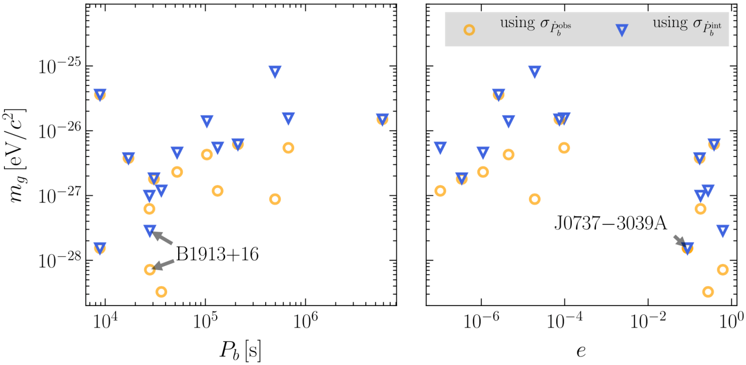
$$S = \int \mathrm{d}^4 x \left[-\frac{1}{4} h^{\mu\nu} (\mathcal{E} h)_{\mu\nu} + \frac{h^{\mu\nu} T_{\mu\nu}}{2M_{\rm Pl}} - \frac{3}{4} (\partial \pi_s)^2 \left(1 + \frac{1}{3\Lambda^3} \Box \pi_s \right) + \frac{\pi_s T}{2M_{\rm Pl}} \right]$$

- Extra radiating channels are introduced
  - monopole radiation
  - dipole radiation
  - quadrupole radiation



Shao, Wex, Zhou 2020 [arXiv:2007.04531]

Cubic Galileon



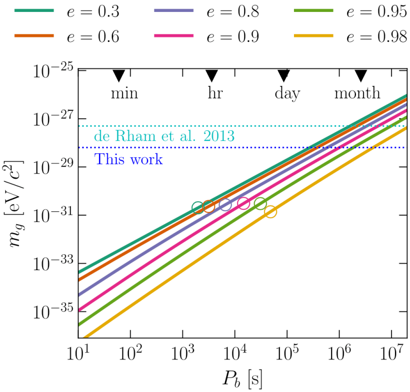
$$m_g \lesssim 2 \times 10^{-28}\,\mathrm{eV}/c^2 \quad \text{(95\% C.L.)}$$

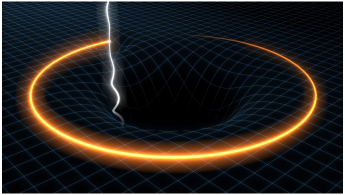
(collected in Particle Data Group)

Shao, Wex, Zhou 2020 [arXiv:2007.04531]

Cubic Galileon

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

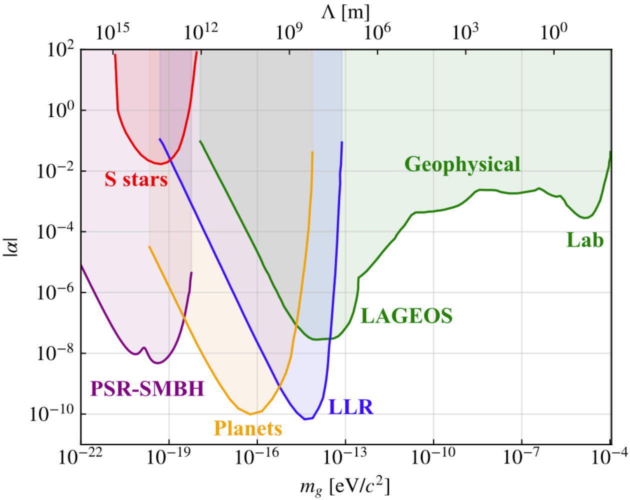




Shao, Wex, Zhou 2020 [arXiv:2007.04531]

Square Kilometre Array

Yukawa Gravity: Pulsars around Sgr A*



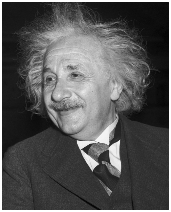
Dong, Shao, et al. 2022, JCAP [arXiv:2210.16130]

5. Fifth Force from Dark Matters

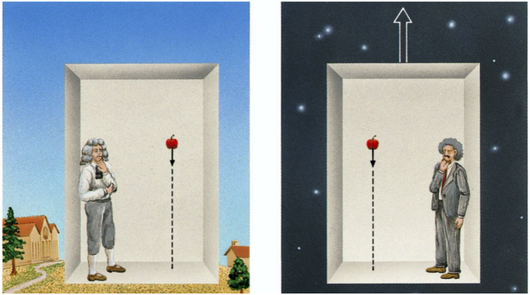
Conservative dynamics are also good friends

...in many aspects

Equivalence Principle

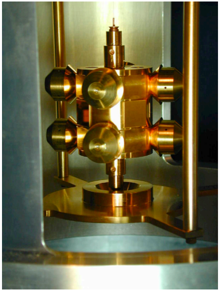


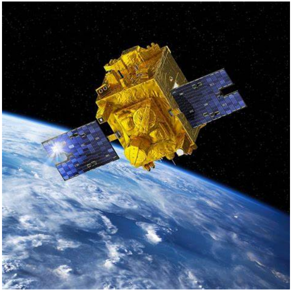
- Einstein's General Relativity (1915)
  1. Galilei's Relativity Principle
  2. Equivalence Principle **(EP)**
- **EP**: *Locally*, **gravity = accelerated system**



Tests of Equivalence Principle

- Galilei, Newton, Bessel, Potter
- Eötvös, Dicke, Braginsky, Adelberger $\sim 10^{-13}$
- Lunar laser ranging $\sim 10^{-13}$
- MICROSCOPE satellite $\sim 10^{-15}$





Strong Equivalence Principle

- How about "gravitational energy"? Nonlinearities?
- **Strong EP**: self-gravitating bodies also have $m_i = m_g$

$$\epsilon \sim \frac{GM}{Rc^2} \sim \begin{cases} 10^{-10}\,, & \text{Moon} \\ 10^{-9}\,, & \text{Earth} \\ 10^{-6}\,, & \text{Sun} \\ 0.2\,, & \text{Neutron Stars} \end{cases}$$

- GR is the only valid theory that perserves SEP

Will 2014; Adelberger et al. 2009; Shao & Wex 2016, SCPMA 59:699501

Damour-Schäfer Test

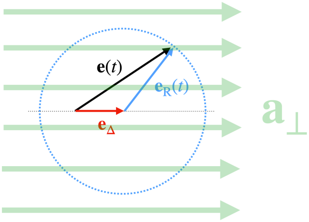
- For a binary pulsar in the Galactic potential (acceleration $\mathbf{a} \sim 2 \times 10^{-10}\,\mathrm{m\,s^{-2}}$), there is an extra acceleration from SEP violation

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

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

[Damour & Schäfer 1991, PRL 66:2549]

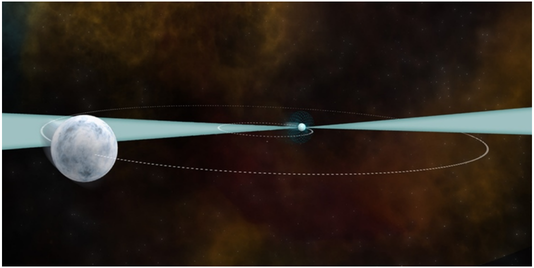
$$\boldsymbol{e}(t) \equiv e\hat{\boldsymbol{a}} = \boldsymbol{e}_\mathrm{PN}(t) + \boldsymbol{e}_\Delta$$



Shao 2023 [arXiv:2206.15187]

Damour-Schäfer Test

- Combined timing analysis on PSR J1713+0747 from NanoGRAV and EPTA [Zhu *et al*. 2019, MNRAS 482:3249]
  - $P_b = 67.8\,\mathrm{d}$, $e = 0.00007$
  - $m_p = 1.33\,M_\odot$ (neutron star), $m_c = 0.29\,M_\odot$ (white dwarf)
- Constraint on the **universality of free fall**: $\Delta \lesssim 0.002$



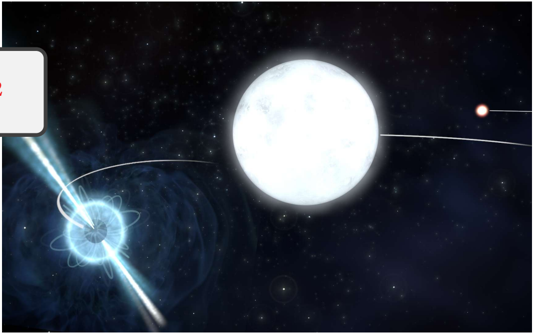
Triple Pulsar

- A millisecond pulsar in a stellar triple system

  [Ransom *et al*. 2014, Nature 505:520; Archibald *et al*. 2018, Nature 559:73]

  - $P_{b,I} = 1.6\,\mathrm{d}$, $e_I = 0.0007$; $P_{b,O} = 327\,\mathrm{d}$, $e_O = 0.04$
  - $m_p = 1.44\,M_\odot$ (neutron star), $m_{c,I} = 0.20\,M_\odot$ & $m_{c,O} = 0.41\,M_\odot$ (white dwarfs)

$$\boxed{a \sim 2 \times 10^{-3}\,\mathrm{m\,s^{-2}}}$$



Freire *et al*. 2012, CQG 29:184007

Shao 2016, PRD 93:084023

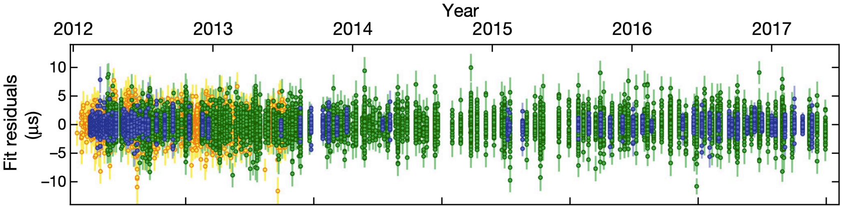
Triple Pulsar and the SEP

- The **universality of free fall** was constrained to

$$\Delta \begin{cases} \lesssim 2.6 \times 10^{-6}\,, \\ = (0.5 \pm 1.8) \times 10^{-6}\,, \end{cases}$$

[Archibald *et al.* 2018, Nature 559:73]

[Voisin *et al.* 2020, A&A 638:A24]

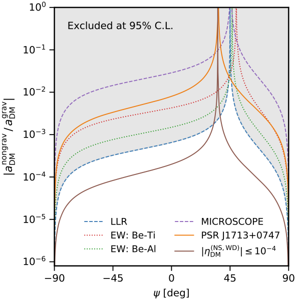


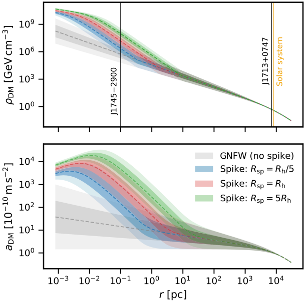
SEP and Dark Matter

- The “third” body in the Damour-Schäfer test is our Milky Way, which has a significant composition of **dark matters**
- We propose a novel SEP-like test to constrain the **fifth force** from dark matters Shao et al. 2018, PRL [arXiv:1805.08408]
  1. Large material difference in test-body pairs (NS vs WD)
  2. Significant gravitational binding energy
- Binary pulsar PSR J1713+0747 gives the best constraint, while the triple pulsar does not apply here
  - No dark matters involved in the triple pulsar system

SEP and Dark Matter

- If there is a long-range **fifth force**, it should be smaller than 1% × gravity ⇐ PSR J1713+0747 Shao et al. 2018 [arXiv:1805.08408]
- Because of the dark matter spike, binary pulsars within about 10 pc from the Galactic center will be extremely helpful in future

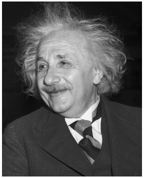




6. Summary

Summary

- Radio pulsars are **precision** clocks
  - Sensitive to tiny deviation from GR in dynamics
- Extremely useful in fundamental physics
  - spacetime symmetries
  - strong-field gravity theories
  - massive gravity
  - strong equivalence principle
  - dark matters
  - . . .
- **Einstein is *still* right**



Thank you!