北京大學
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New Graviton Mass Bound from Pulsars

Kavli Institute for Astronomy and Astrophysics

Speaker: Lijing Shao (邵立晶)

FPS9, Xiamen

References

X. Miao, L. Shao and B.-Q. Ma, Phys. Rev. D **99** (2019) 123015 [arXiv:1905.12836].

L. Shao, N. Wex and S.-Y. Zhou, Phys. Rev. D **102** (2020) 024069 [arXiv:2007.04531].

Absence of Quantum Gravity

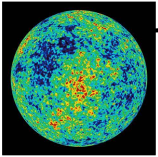
- On one hand, we have Quantum Field Theory to describe the electromagnetic, strong, and weak interactions
- On the other hand, we have General Relativity to describe the gravity, as the dynamics of curved spacetime
- However, QFT and GR are not compatible at their face values!

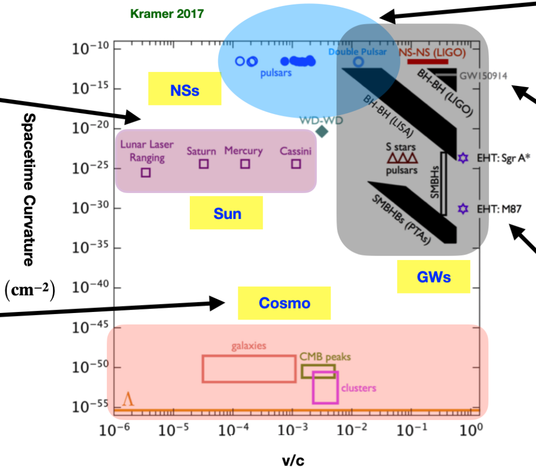
Theoretical physics is beautiful,

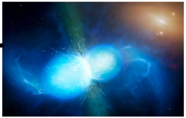
but not yet complete

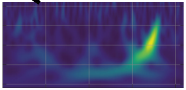
Gravity may be holding the key

Parameter Space in Gravity Tests









General Relativity

- In Einstein's general relativity, gravity is mediated by a spin-2 metric field $g_{\mu\nu}$

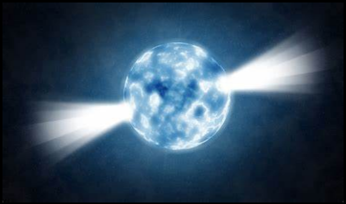
$$S = \frac{1}{16\pi} \int d^4x \sqrt{-g}\, R + S_m \left[\Psi_m; g_{\mu\nu}\right]$$

- Its linearized version reads,

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

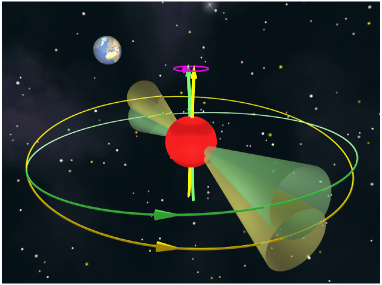
- In GR, gravitons are strictly **massless**

In this talk, I will use binary pulsar timing to test the masslessness of gravitons



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



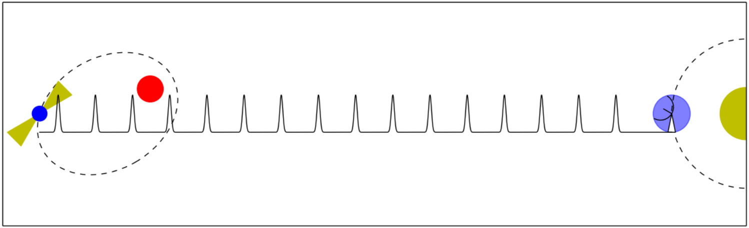
Pulsars are precision clocks

PSR J0437$-$4715: $f = 173.6879457375201(9)\,\mathrm{Hz}$

(IPTA 2nd Data Release 2019)

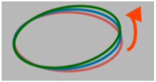
Pulsar Timing

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

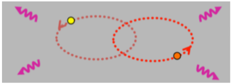


Binary Pulsars

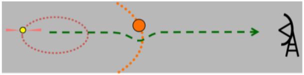
- Binary pulsars are sensitive to effects beyond the Newtonian gravity



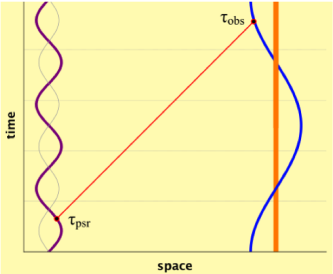
Precession



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, $\dot{G}/G$:	$-0.6(1.6) \times 10^{-12}\ \mathrm{yr}^{-1}$

Sensitive to tiny changes in orbits

Binary pulsars are excellent testbeds of gravity theories

Linearized Fierz-Pauli Theory

- **Linearized gravity** with a massive graviton [Finn & Sutton 2002]

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

- 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

Linearized Fierz-Pauli Theory

- **Binary pulsars** can be used to constrain the graviton mass via bounding the gravitational backreaction [Finn & Sutton 2002]

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

- Bayesian analysis with a list of binary pulsars [Miao, Shao, Ma 2019]

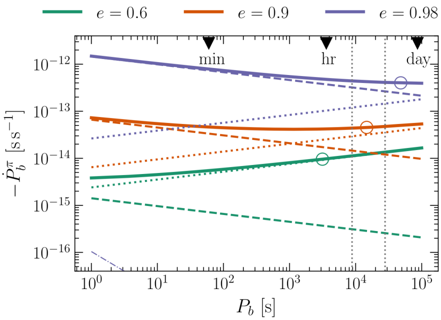
PSR	P_b(day)	e	$m_p\ (M_\odot)$	$m_c\ (M_\odot)$	$\dot{P}_b^{\rm intr}(10^{-12})$	Δ
J0348 + 0432 [39]	0.102424062722(7)	0.0000026(9)	2.01(4)	0.172(3)	−0.273(45)	0.05(18)
J0737 − 3039 [40,41]	0.10225156248(5)	0.0877775(9)	1.3381(7)	1.2489(7)	−1.252(17)	0.000(1)
J1012 + 5307 [42,43]	0.60467271355(3)	0.0000012(3)	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]

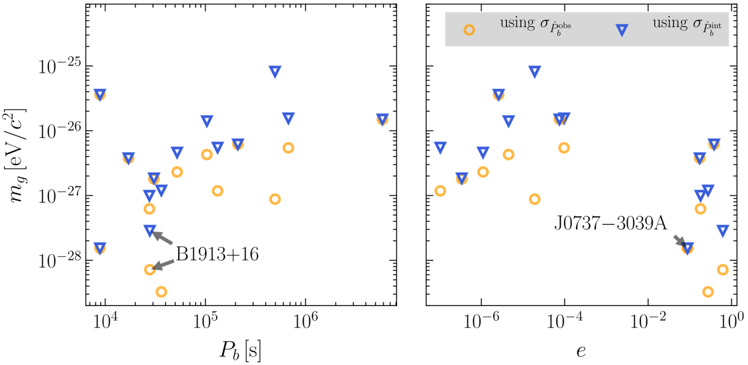
$$S = \int d^4x \left[-\frac{1}{4} h^{\mu\nu} (\mathcal{E} h)_{\mu\nu} + \frac{h^{\mu\nu} T_{\mu\nu}}{2M_{\rm Pl}} - \frac{3}{4} (\partial \pi_s)^2 \left(1 + \frac{1}{3\Lambda^3} \Box \pi_s \right) + \frac{\pi_s T}{2M_{\rm Pl}} \right]$$

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



Shao, Wex, Zhou 2020, PRD102:024069

Cubic Galileon

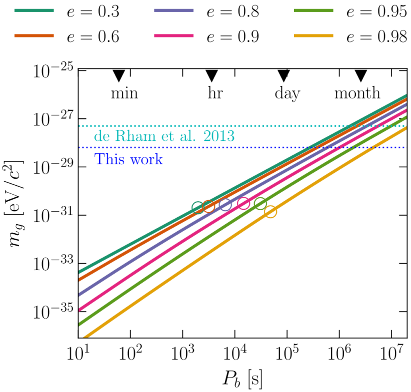


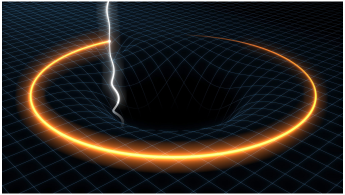
$$m_g \lesssim 2 \times 10^{-28}\, \mathrm{eV}/c^2 \quad (95\%\ \mathrm{C.L.})$$

Shao, Wex, Zhou 2020, PRD102:024069

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

Summary

- **Einstein is still right**
  - $m_g \to 0$
- Radiative **strong-field** gravity tests
- Complementary to
  - Solar System (Yukawa potential)
  - Gravitational Waves
- FAST, SKA telescopes

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Albert Einstein (1915)


THANK YOU