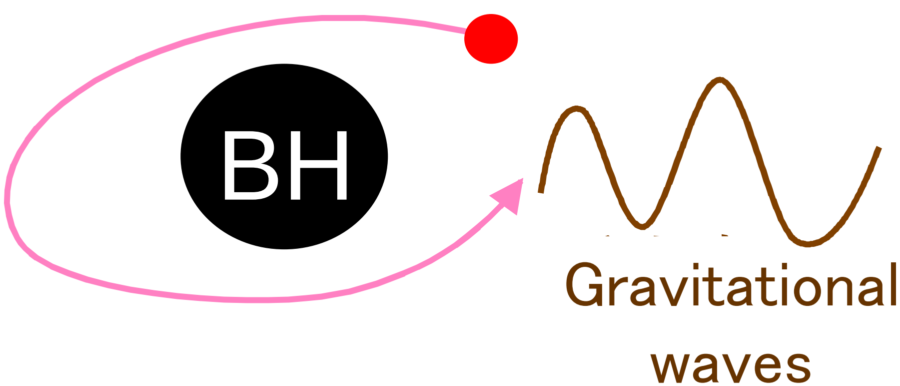
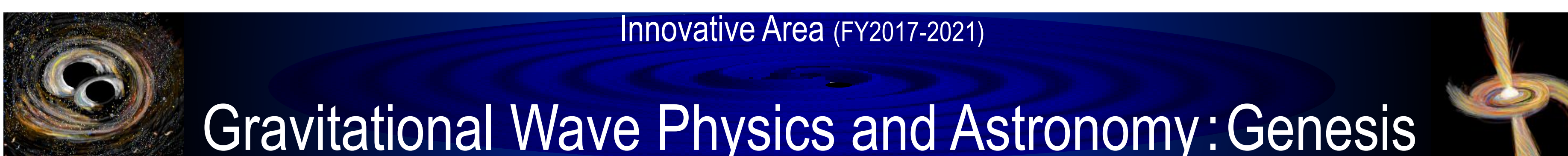
パルサー精密観測による重力理論検証

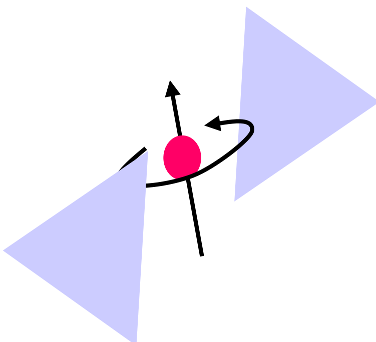


Takahiro Tanaka
(Dept. of Phys./YITP
Kyoto university)

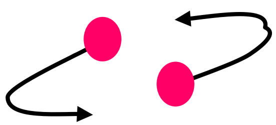


Indirect evidence of GW emission

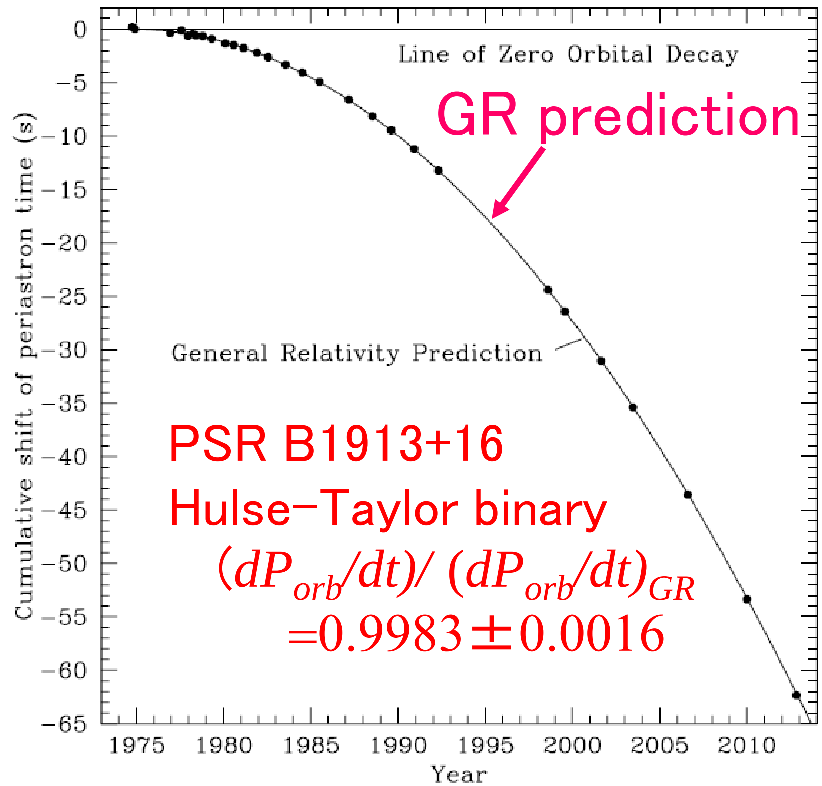
Pulsar is an ideal clock



Binary pulsar can be used to test GR



Periastron time shift due to GW emission



(J.M. Weisberg and Y. Huang arXiv:1606.0274)

Hulse and Taylor were awarded Nobel prize in 1993

- GW emission was confirmed but its propagation was not.
- It is still uncertain if the GW propagation is as expected.

>2500 pulsars are known in the Galaxy
About 10% of pulsars are binaries, which are mostly recycled.
Precise mass measurement for ∼35 neutron stars

As for already known pulsars:
SKA1-MID
will improve the timing precision by an order of magnitude
SKA2
will improve it by up to two orders of mangitude

As for discovery:
Higher sensitivity makes the acceleration search more effective.
SKA1
will find 1800 millisecond pulsars
SKA2
will find even more and may have pulsar-BH binaries

Keplerian parameters:

$$P_b\,(\text{period}),\, e\,(\text{eccetricity}),$$

$$x_{PSR} = a_{PSR}\sin i \;\; (\text{projected semi - major axis}),$$

$$T_0(\text{periastron time})$$

Constraint on mass: $\dfrac{(M_c \sin i)^3}{M_{tot}^2} = \dfrac{4\pi^2}{T_{Sun}} \dfrac{x_{PSR}^3}{P_b^2}$

If the companion is visible: $\dfrac{M_{PSR}}{M_c} = \dfrac{x_c}{x_{PSR}}$

Post-Keplerian parameters:

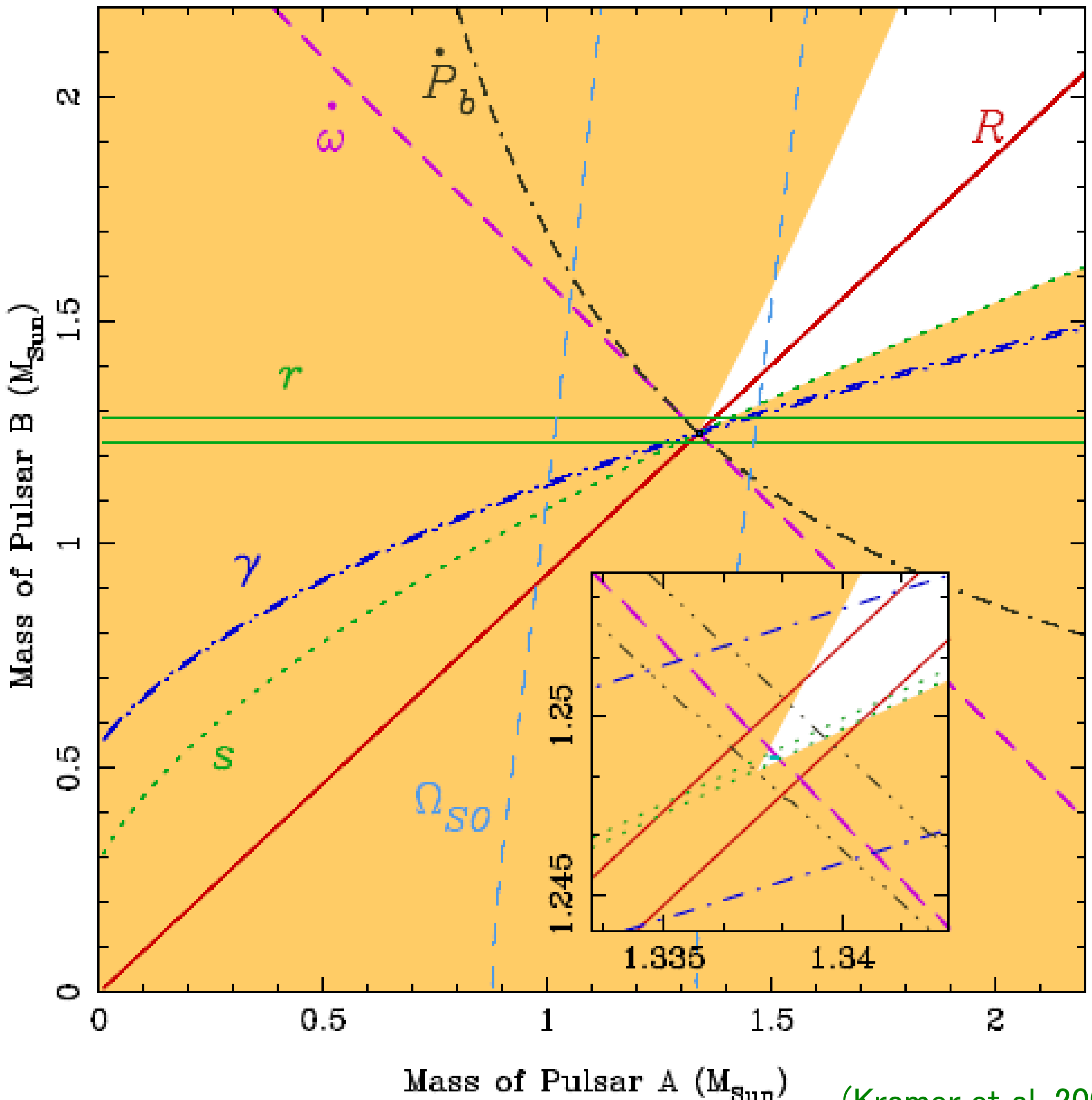
$\dot{\omega}$: perihelion advance

γ : Einstein delay (gratibational redshift + α for ccentric orbits)

$\dot{P}_b$: orbital period decay

r(range), s(shape) : Shapiro time decay(significant for edge on case)

Mass-mass diagram of PSR J0737-3039A/B



(Kramer et al. 2006)

Double pulsar

$P_b = 2\text{h } 27\text{m}$

$i = 89\text{deg}$

Ω_{SO} : spin precession

Masses are fixed by the Keplerian parameters
⇒ 5 independent tests of GR using post-Keplerian parameters

Masses of Double Neutron Star Systems and Non-recycled pulsars

System	$M_{\rm T}$ ($M_\odot$)	$M_{\rm PSR}$ ($M_\odot$)	$M_{\rm c}$ ($M_\odot$)	Mass const.
Systems with well-measured component masses				
J0453+1559	2.734(4)	1.559(5)	1.174(4)	$\dot\omega, h_3$
J0737−3039	2.58708(16)	1.3381(7)	1.2489(7) y	$\dot\omega, q$
B1534+12	2.678463(8)	1.3330(4)	1.3455(4)	$\dot\omega, \gamma$
J1756−2251	2.56999(6)	1.341(7)	1.230(7)	$\dot\omega, \gamma$
J1906+0746	2.6134(3)	1.291(11) y	1.322(11) ?	$\dot\omega, \gamma$
B1913+16	2.828378(7)	1.4398(2)	1.3886(2)	$\dot\omega, \gamma$
B2127+11C g	2.71279(13)	1.358(10)	1.354(10)	$\dot\omega, \gamma$
Systems with total binary mass measurement only				
J1518+4904	2.7183(7)	<1.768	>0.950	$\dot\omega$
J1811−1736	2.57(10)	<1.64	>0.93	$\dot\omega$
J1829+2456	2.59(2)	< 1.34	>1.26	$\dot\omega$
J1930−1852	2.59(4)	< 1.32	>1.30	$\dot\omega$
Non-recycled pulsars with massive WD companions				
J1141−6545	2.2892(3)	1.27(1) y	1.01(1)	$\dot\omega, \gamma$
B2303+46	2.64(5)	1.24-1.44 y	1.4-1.2	$\dot\omega, M_{\rm WD}$

(arXiv:1603.02698)

Masses of Milisecond Pulsars

System	M_T ($M_\odot$)	M_{PSR} ($M_\odot$)	M_c ($M_\odot$)	Mass const.
		MSPs with WD companions and low-eccentricity		
J0348+0432		2.01(4)	0.172(3)	q, M_{WD}
J0437−4715		1.44(7)	0.224(7)	r, s
J0621+1002	2.32(8)	$1.53^{+0.10}_{-0.20}$	$0.76^{+0.28}_{-0.07}$	$\dot{\omega}, s$
J0751+1807		1.72(7)	0.13(2)	$s, \dot{P}_b$
J1012+5307		1.83(11)	0.16(2)	q, M_{WD}
J1614−2230		1.928(17)	0.500(6)	r, s
J1713+0747		1.31(11)	0.286(12)	r, s
J1738+0333		$1.47^{+0.07}_{-0.06}$	$0.181^{+0.007}_{-0.005}$	q, M_{WD}
J1802−2124		1.24(11)	0.78(4)	r, s
J1807−2500B	2.57190(73)	1.3655(21)	1.2064(20)(?)	$\dot{\omega}, h_3$
B1855+09		1.58^{+10}_{-13}	$0.267^{+0.010}_{-0.014}$	r, s
J1909−3744		1.47(3)	0.2067(19)	r, s
J2222−0137		1.20(14)	1.05(6)	r, s
		MSPs with eccentric orbits and triples		
J0337+1715		1.4378(13)	0.19751(15) 0.4101(3)	i, q
J1903+0327	2.697(29)	1.667(21)	1.029(8)	$\dot{\omega}, h_3$
J1946+3417	2.097(28)	1.832(28)	0.2659(30)	$\dot{\omega}, h_3$
J2234+0611	1.668(6)	1.393(13)	0.276(9)	$\dot{\omega}, h_3$
		MSPs in globular clusters		
J0024−7204H	1.61(4)	< 1.52	> 0.164	$\dot{\omega}$
J0514−4002A	2.453(14)	< 1.50	> 0.96	$\dot{\omega}$
B1516+02B	2.29(17)	< 2.52	> 0.13	$\dot{\omega}$
J1748−2021B	2.92(20)	< 3.24	> 0.11	$\dot{\omega}$
J1748−2446I	2.17(2)	< 1.96	> 0.24	$\dot{\omega}$
J1748−2446J	2.20(4)	< 1.96	> 0.38	$\dot{\omega}$
J1750−37A	1.97(15)	< 1.65	> 0.53	$\dot{\omega}$
B1802−07	1.62(7)	< 1.7	> 0.23	$\dot{\omega}$
J1824−2452C	1.616(7)	< 1.35	> 0.26	$\dot{\omega}$
J1910-5958A		1.3(2)	0.180(18)	q, M_{WD}

Famous 2solar mass NS found by Antoniadis et al. discovered in 2007. Radio observation aided by precise spectroscopy of the WD companion

Radio observation aided by precise spectroscopy of the WD companion

Triple system: Outer WD orbital period is < 1year.

(arXiv:1603.02698)

Motivation for modified gravity

1) Incompleteness of General relativity

GR is non-renormalizabile

Singularity formation after gravitational collapse

2) Dark energy problem

3) To test General relativity

GR has been repeatedly tested since its first proposal.

The precision of the test is getting higher and higher.

⇒ Do we need to understand what kind of modification is theoretically possible before experimental test?

Yes, especially in the era of gravitational wave observation!

Comparison with constraints from GW observations

$$\boxed{h(f) \approx A f^{-7/6} e^{i\Psi(f)}}$$ GW waveform for Quasi-circular orbits

$$\Rightarrow \quad \Psi(f) \to \left(\Psi_{GW}(f) + \sum_i \beta_i u^{b_i} \right)$$

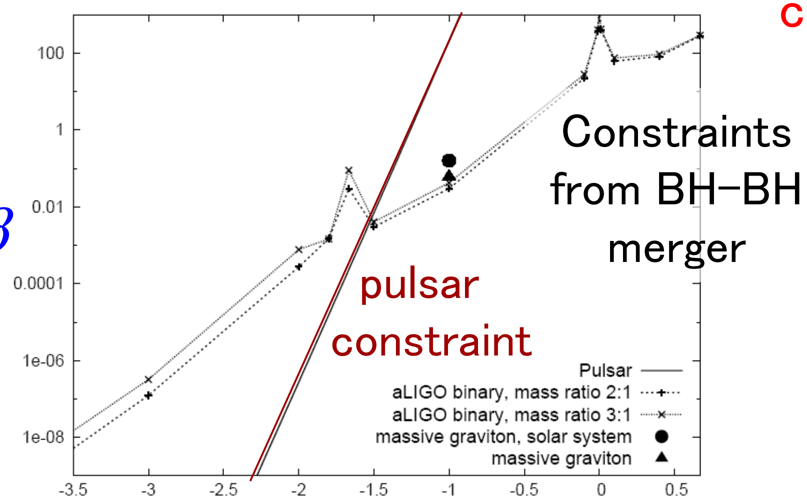
Theory	a	α	b	β
Brans-Dicke [9, 10, 14–16]	–	0	-7/3	β
Parity-Violation [22, 34–37]	1	α	0	–
Variable $G(t)$ [38]	-8/3	α	-13/3	β
Massive Graviton [8–14]	–	0	-1	β
Quadratic Curvature [23, 44]	–	0	-1/3	β
Extra Dimensions [45]	–	0	-13/3	β
Dynamical Chern-Simons [46]	+3	α	+4/3	β

(Yunes & Pretorius (2009))

Better constraint than pulsar timing for $b_i > -5/3$.

corresponding to Newtonian order

β



b

$12M_\odot$BH–$6M_\odot$BH and $18M_\odot$BH–$6M_\odot$BH mergers

(Cornish, Sampson, Yunes, Pretorius. (2011))

Typical modification of GR

often discussed in the context of test by GWs

Scalar–tensor gravity

$$S=\frac{1}{16\pi}\int d^4x\sqrt{-g}\left(\phi R-\omega_{BD}\phi^{-1}\phi_{,\alpha}\phi^{,\alpha}\right)-\sum_a\int d\tau_a m_a(\phi)$$

$$G=\frac{4+2\omega_{BD}}{\phi(3+2\omega_{BD})}$$

scalar charge of self–gravitating body a:

$$\boxed{s_a=-\left[\partial(\ln m_a)/\partial(\ln G)\right]_0}$$

G–dependence of the gravitational binding energy

$$\frac{df}{dt}=\frac{96\pi^{8/3}}{5}\mathcal{M}^{5/3}f^{11/3}\left[Sv^{-2}+1-\left(\frac{743}{336}+\frac{11}{4}\eta\right)v^2+(4\pi-\beta)v^3+\cdots\right]$$

Dipole radiation＝－1 PN frequency dependence

$$v=(\pi M f)^{1/3}$$

$$\boxed{S=\frac{5(s_1-s_2)^2}{48\omega_{BD}}}$$

For binaries composed of similar NSs, $(s_1-s_2)^2\ll 1$

Spontaneous scalarization

$$S=\frac{1}{16\pi}\int d^4x\sqrt{-g}\left(\phi R-\frac{\omega_{BD}(\phi)}{\phi}\phi_{,\alpha}\phi^{,\alpha}\right)$$

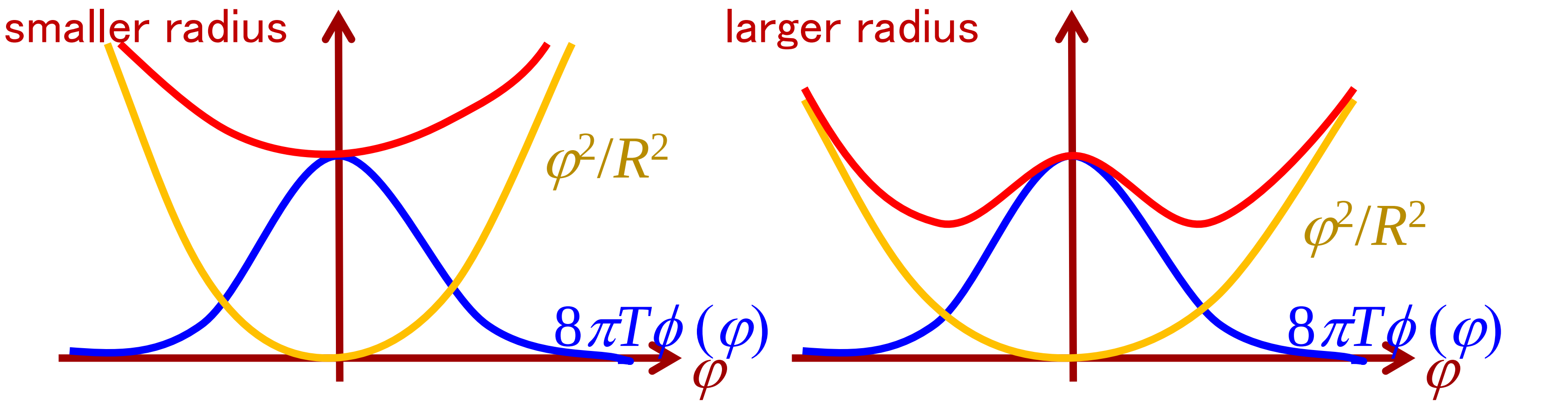
More general model

$$=\frac{1}{16\pi}\int d^4x\sqrt{-g}\left(\phi(\varphi)R-\frac{1}{2}\varphi_{,\alpha}\varphi^{,\alpha}\right)$$

φ is canonically normalized

EOM $\Rightarrow$ $0\approx\Delta\varphi+8\pi\phi'(\varphi)T\approx\partial_\phi(\text{potential})$

Effective potential for a star with radius R.



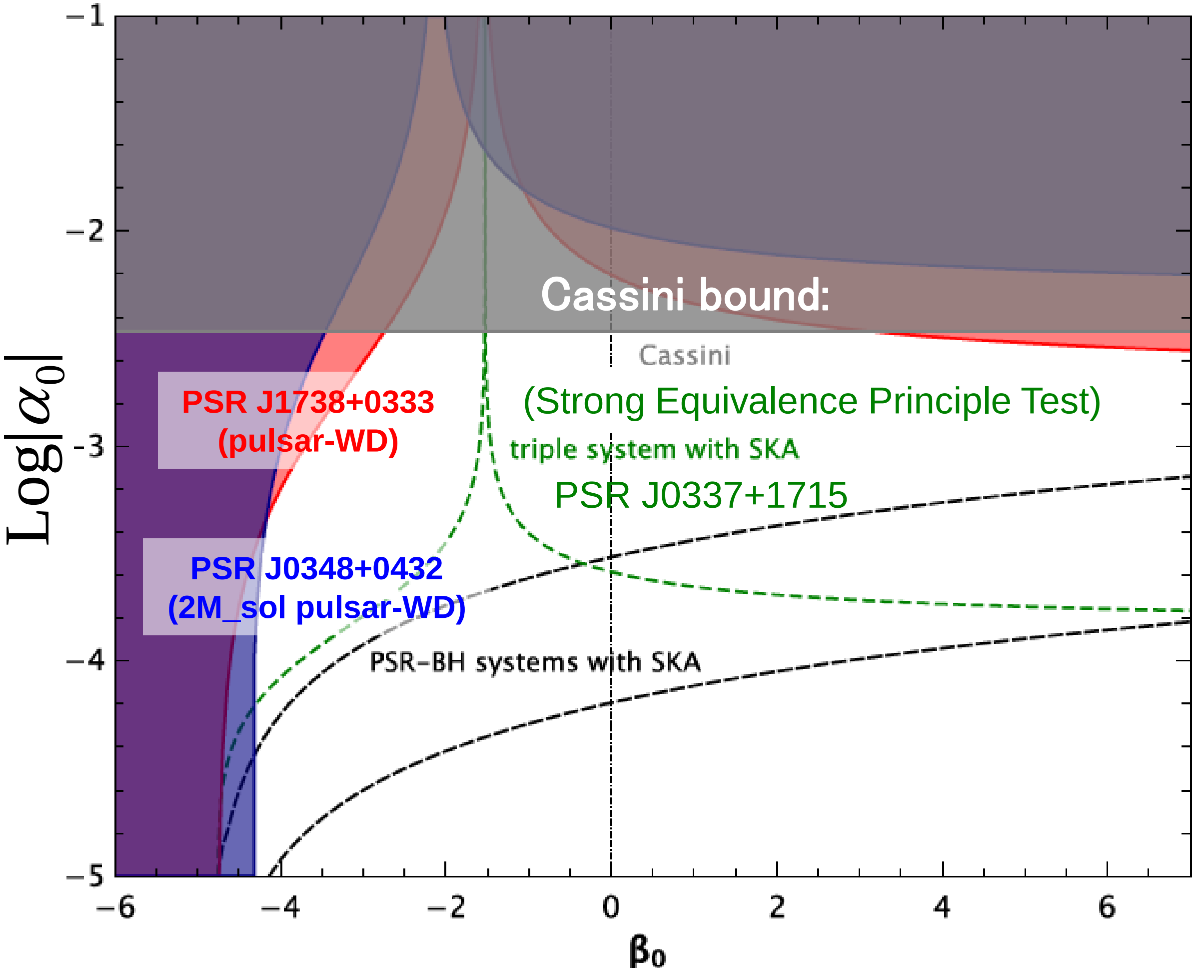
As two NS get closer, "spontaneous scalarization" may happen.
Sudden change of structure and starting scalar wave emission.

Most of parameter region will be excluded by the discovery of many pulsars.

After conformal transformation, the action can be recast into the following form:

$$\tilde{I} = (16\pi G)^{-1} \int [\tilde{R} - 2\tilde{g}^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - V(\varphi)](-\tilde{g})^{1/2} d^4x + I_{\rm m}(\psi_{\rm m}, A^2(\varphi)\tilde{g}_{\mu\nu}),$$

$$\ln A(\varphi) = \alpha_0(\varphi - \varphi_0) + \frac{1}{2}\beta_0(\varphi - \varphi_0)^2 + \cdots$$



$$\alpha_0^2 = \frac{1}{2\omega_{\rm BD} + 3}$$

Constraint from future GW observations:

(Yagi & TT, arXiv:0908.3283)

LISA– $1.4M_\odot$NS+$1000M_\odot$BH:

at 40Mpc

corresponding to $SNR = \sqrt{200}$

$\log|\alpha_0| > -2$

DECIGO–$1.4M_\odot$NS+$10M_\odot$BH:

collecting 10^4events

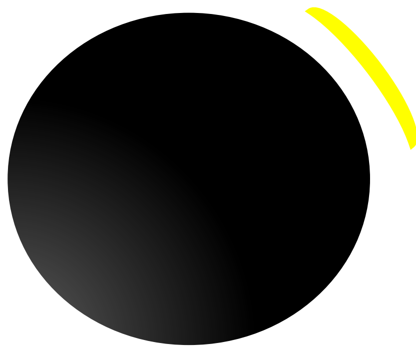
at cosmological distances

$\log|\alpha_0| > -4.1$

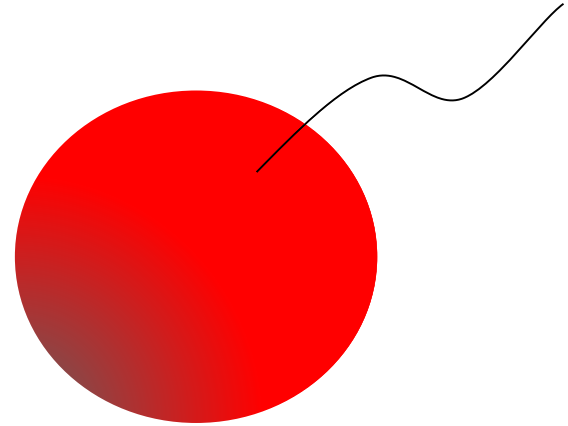
(Berti et al., arXiv:1501.07274)

Ordinary scalar–tensor theory

BH no hair



Turu–turu



NS can have a scalar hair

Einstein dilaton Gauss–Bonnet, Chern–Simons gravity

$$S \supset \frac{\alpha}{G_N}\underbrace{\int d^4x\sqrt{-g}\,\theta\begin{pmatrix} R_{GB} \\ {}^{*}R\,R \end{pmatrix}}_{\theta\,\times\,\text{(higher curvature)}} - \frac{1}{2G_N}\int d^4x\sqrt{-g}\left[(\partial\theta)^2 + 2V(\theta)\right]$$

$$R_{GB} = R^2 - 4R_{\mu\nu}R^{\mu\nu} + R^{\alpha\beta}{}_{\mu\nu}R^{\mu\nu}{}_{\alpha\beta} \qquad {}^{*}R\,R = \varepsilon^{\alpha\beta}{}_{\sigma\chi}R^{\sigma\chi}{}_{\mu\nu}R^{\mu\nu}{}_{\alpha\beta}$$

- For constant θ, these higher curvature terms are topological invariant. Hence, no effect on EOM.
- Higher derivative becomes effective only in strong field.

Hairy BH – bold NS

- NS in EDGB and CS do not have scalar monopole charge.

$$\Box\theta \approx "R^2" \Rightarrow Q = \int d^3x "R^2" = \frac{1}{T}\int \underline{d^4x "R^2"}$$

topological invariant, which vanishes on topologically trivial spacetime.

- By contrast, BH solutions in EDGB and CS have scalar monopole and dipole, respectively.

EDGB: monopole charge $\Rightarrow$ dipole radiation (−1PN order)

CS: dipole charge $\Rightarrow$ 2PN order corrections

(Yagi, Stein, Yunes, Tanaka (2012))

Observational bounds

- EDGB

Cassini $\alpha_{EDGB}^{1/2} < 1.3 \times 10^{12}\,\mathrm{cm}$ (Amendola, Charmousis, Davis (2007))

Low mass X-ray binary, A0620-00

$$\alpha_{EDGB}^{1/2} < 1.9 \times 10^{5}\,\mathrm{cm}$$

(Yagi, arXiv:1204.4524)

Future Ground-based GW observation

SNR=20, 6Msol＋12Msol

$$\alpha_{EDGB}^{1/2} < 4 \times 10^{5}\,\mathrm{cm}$$

(Yagi, Stein, Yunes, TT, arXiv:1110.5950)
(See also Yagi, Stein, Yunes, arXiv:1510.02152)

- CS

Gravity Probe B, LAGEOS (Ali-Haimound, Chen (2011))

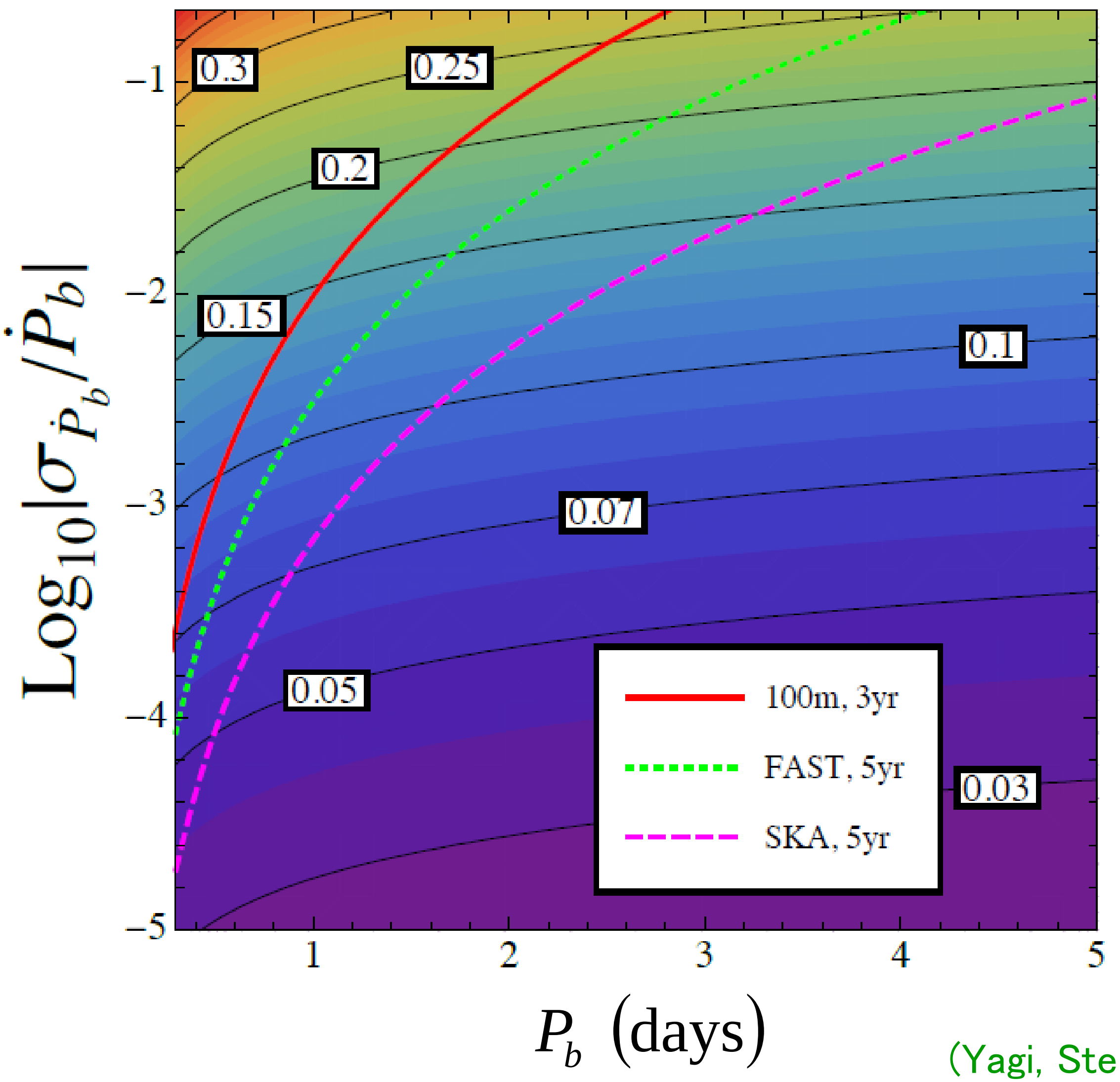
$$\alpha_{CS}^{1/2} < 10^{13}\,\mathrm{cm}$$

Ground GW observation with favorable spin alignment:
100Mpc, $a \sim 0.8M$

$$\alpha_{CS}^{1/2} < 10^{6-7}\,\mathrm{cm}$$

(Yagi, Yunes, TT, arXiv:1208.5102)

Future bounds on EDGB from BH-pulsar system



$\alpha_{EDGB}^{1/2}$ in the unit of km

Once a BH-pulsar system is found, how precisely one can measure the orbital decay rate determines the strength of the constraint on α_{BDGB}.

(Yagi, Stein, Yunes, arXiv:1510.02152)

Constraint on the modification of gravity by GW150914

Theoretical Mechanism	GR Pillar	PN	$\|\beta\|$ GW150914	Example Theory Constraints: Repr. Parameters	GW150914	Current Bounds
Scalar Field Activation	SEP	-1	$\mathbf{1.6\times10^{-4}}$	$\sqrt{\|\alpha_{\rm EdGB}\|}$ [km]	—	10^7 [39], 2 [40–42]
	SEP, No BH Hair	-1	$\mathbf{1.6\times10^{-4}}$	$\|\dot{\phi}\|$ [1/sec]	—	10^{-6} [43]
	SEP, Parity Invariance	$+2$	$\mathbf{1.3\times10^{1}}$	$\sqrt{\|\alpha_{\rm CS}\|}$ [km]	—	10^8 [44, 45]
Vector Field Activation	SEP, Lorentz Invariance	0	$\mathbf{7.2\times10^{-3}}$	(c_+, c_-)	$\mathbf{(0.9, 2.1)}$	$(0.03, 0.003)$ [46, 47]
Extra Dimension Mass Leakage	4D spacetime	-4	$\mathbf{9.1\times10^{-9}}$	ℓ [μm]	$\mathbf{5.4\times10^{10}}$	10–10^3 [48–52]
Time-Varying G	SEP	-4	$\mathbf{9.1\times10^{-9}}$	$\|\dot{G}\|$ [10^{-12}/yr]	$\mathbf{5.4\times10^{18}}$	0.1–1 [53–57]
Massive graviton	massless graviton	$+1$	$\mathbf{1.3\times10^{-1}}$	m_g [eV]	$\mathbf{1.2\times10^{-22}}$ [12]	10^{-29}–10^{-18} [58–62]
Modified Dispersion Relation	$v_g = c$	$+5.5$	$\mathbf{2.3\times10^{2}}$	$\mathbb{A} > 0$ [1/eV]	$\mathbf{1.6\times10^{-7}}$	—
(*Modified Special Relativity*)		$+5.5$	$\mathbf{2.3\times10^{2}}$	$\mathbb{A} < 0$ [1/eV]	$\mathbf{1.6\times10^{-7}}$	2.7×10^{-36} [63]
Modified Dispersion Relation	$v_g = c$	$+7$	$\mathbf{8.7\times10^{2}}$	$\mathbb{A} > 0$ [1/eV^2]	$\mathbf{9.3\times10^{4}}$	—
(*Extra Dimensions*)		$+7$	$\mathbf{8.7\times10^{2}}$	$\mathbb{A} < 0$ [1/eV^2]	$\mathbf{9.3\times10^{4}}$	4.6×10^{-56} [63]
Modified Dispersion Relation (*Lorentz Violation*)	SEP, Lorentz Invariance	—	—	c_+	$\mathbf{0.7}$ [64]	$(0.03, 0.003)$ [46, 47]

$$\tilde{h}_i(f) = A_i(f) e^{i\Phi_i(f)} \,. \qquad \delta\Phi_{\rm I,ppE}(f) = \beta\,(\pi\mathcal{M}f)^{b/3}$$

(arXiv:1603.08955)

Constraints on the Gauss–Bonnet and Chern–Simons gravity do not apply since the constrained parameter region is outside the weak coupling regime.

Lorentz violation

Einstein Æther

$$S=\frac{1}{16\pi}\int d^4x\sqrt{-g}\left(R-M^{\alpha\beta}{}_{\mu\nu}\nabla_\alpha U^\mu\nabla_\beta U^\nu\right)$$

U is not coupled to matter field directly.

$$M^{\alpha\beta}{}_{\mu\nu}=c_1 g^{\alpha\beta}g_{\mu\nu}+c_2\delta^\alpha_\mu\delta^\beta_\nu+c_3\delta^\alpha_\nu\delta^\beta_\mu+c_4U^\alpha U^\beta g_{\mu\nu}$$

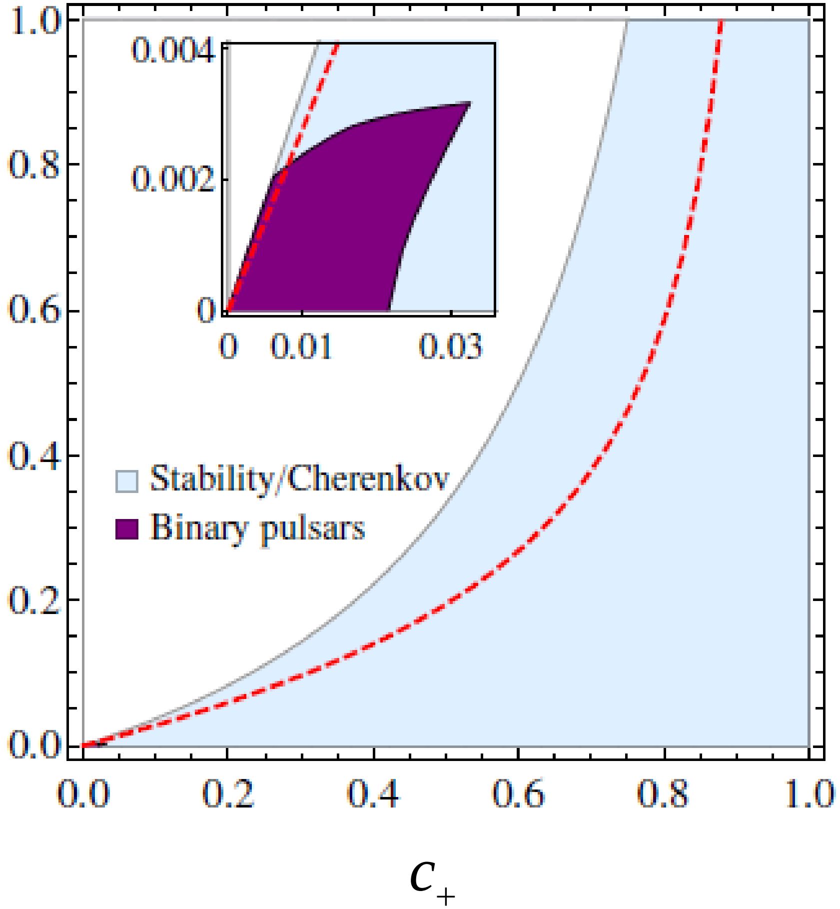
with $U^\alpha U_\alpha=-1$

- At the lowest order in the weak field approximation, there is no correction to the metric if $U^\alpha // u^\alpha$ ($\equiv$ the four velocity of the star).
- The Lorentz violating effects should be suppressed.

⇨ two constraints among the four coefficients $c_1 \sim c_4$

Compact self-gravitating bodies can have significant scalar charge due to the strong gravity effect.

⇨ Dipole radiation.



PSR J1141-6545
PSR J0348+0432
PSR J0737-3039
PSRJ1738-0333

$$c_\pm = c_1 \pm c_3$$

(Yagi et al. arXiv:1311.7144)

Constraints from the GW propagation speed:

$\delta c_{GW} = c_+/2$

$\delta c_{GW} < 9.7 \times 10^{-16}$ SN @10kpc $\Delta t_{\rm int}$=10msec

$\delta c_{GW} < 4.9 \times 10^{-16}$ SGRB @200Mpc $\Delta t_{\rm int}$=10sec

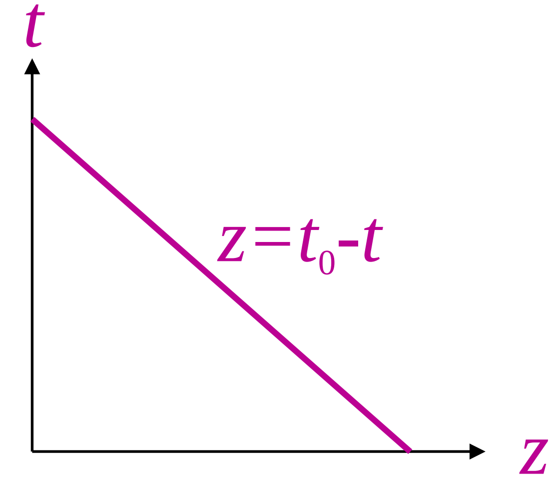
(Nishizawa et al. arXiv:1406.5544)

Detecting GWs by Pulsar Timing Array

- It is convenient to consider in $h_{0\mu}$=0 gauge,

  in which spatial coordinates of observers remain constant.

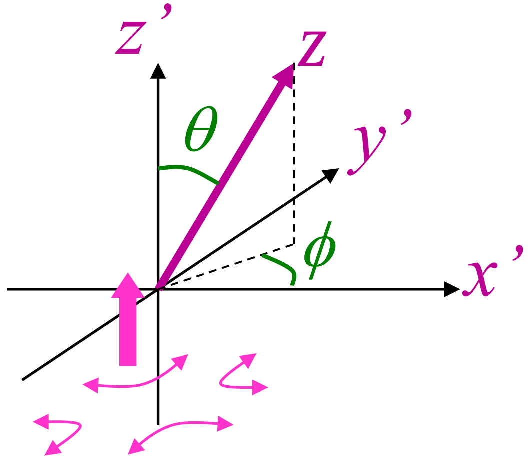
$$ds^2 = -\left[\left(\frac{dt}{dz}\right)^2 - \left(1 + h_{zz}\right)\right]dz^2 = 0$$



$$\delta t = \frac{1}{2}\int \underbrace{h_{zz}\left(t, z = t_0 - t\right)}_{\int d^3k\, h_{zz}(\boldsymbol{k}) e^{-ikt + i\boldsymbol{kx}}} dt$$

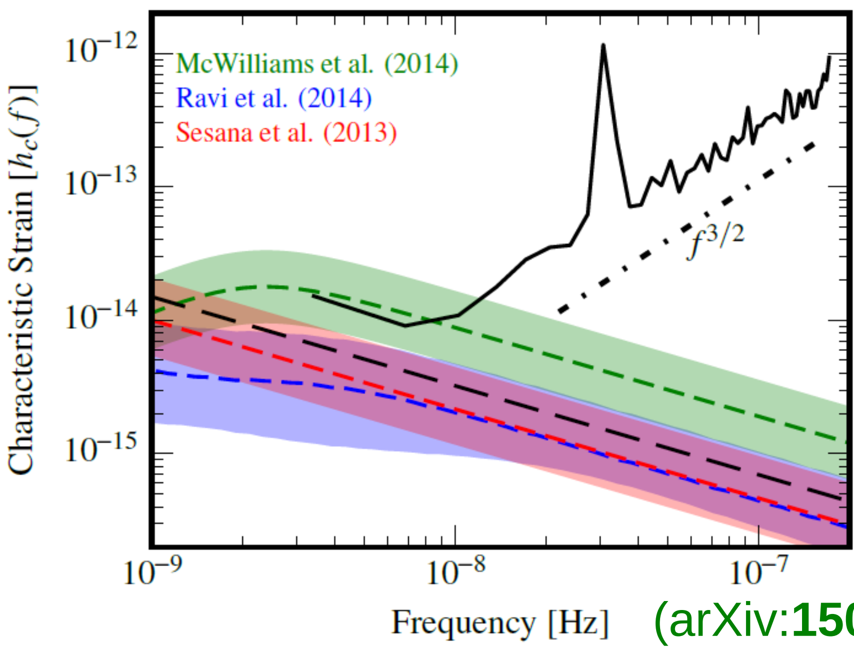
$$\frac{\delta f}{f} = \delta t = \frac{1}{2}\frac{k}{k + k_z}\left[h_{zz}(\mathrm{emit}) - h_{zz}(\mathrm{receieve})\right]$$

$$= \frac{1}{2}\frac{\sin^2\theta\cos 2\phi}{1 + \cos\theta} h_{zz}(\mathrm{receive})\left[1 - e^{ik\Delta t(1 + \cos\theta)}\right]$$



$$\frac{\delta f_i}{f} = \frac{1}{2} \underbrace{\frac{\sin^2\theta_i \cos 2\phi_i}{1+\cos\theta_i}}_{\text{characteristic pattern}} h_{zz}(\text{receive})\left[1 - e^{ik\Delta t_i(1+\cos\theta_i)}\right]$$

- h on the emitter side does not contribute to $\langle \delta f_i \delta f_j \rangle$ for $i \neq j$, but h on receiver side does.
- If the number of pulsars to monitor becomes N times larger, the number of pairs becomes N^2 times larger and the timing error is reduced by $1/N$.



(arXiv:**1508.03024**)

- Supermassive BH mergers are the promising source.
- The current bound on the GW amplitude is already very close to predictions.
- Other GW sources:
  - Cosmic strings
  - Secondary cosmological BG

Summary

- Pulsars have been playing an important role in testing gravity.
- GW test is complimentary.
  - For low energy modifications like scalar–tensor theories pulsar constraint tends to be more stringent,
  - while GW can test GR in the strong gravity regime.
- Improvement of the pulsar constraints in coming years is quite promising.

Generic references

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