Probing Extreme Gravity through Gravitational-wave Observations

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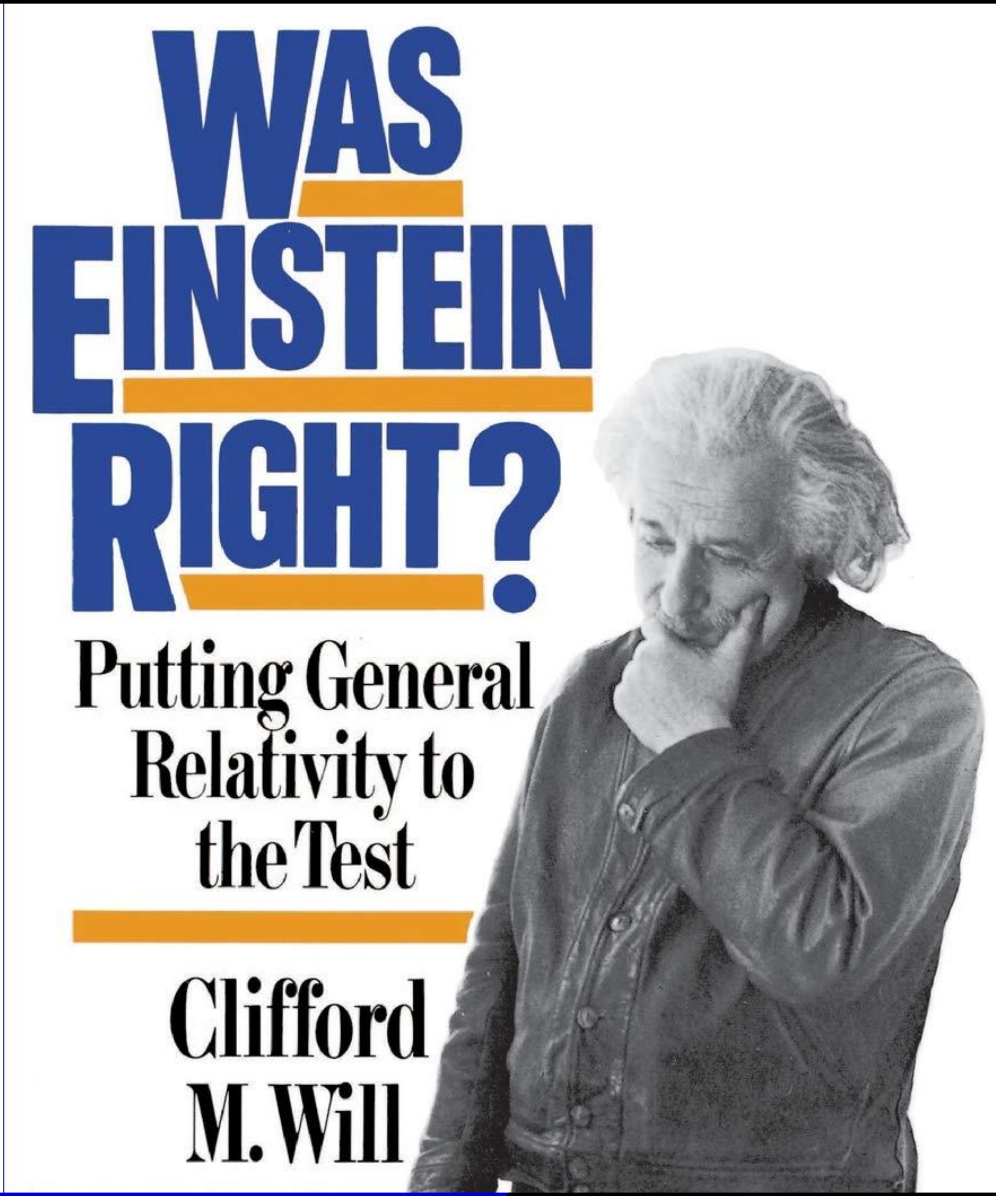
University of Virginia

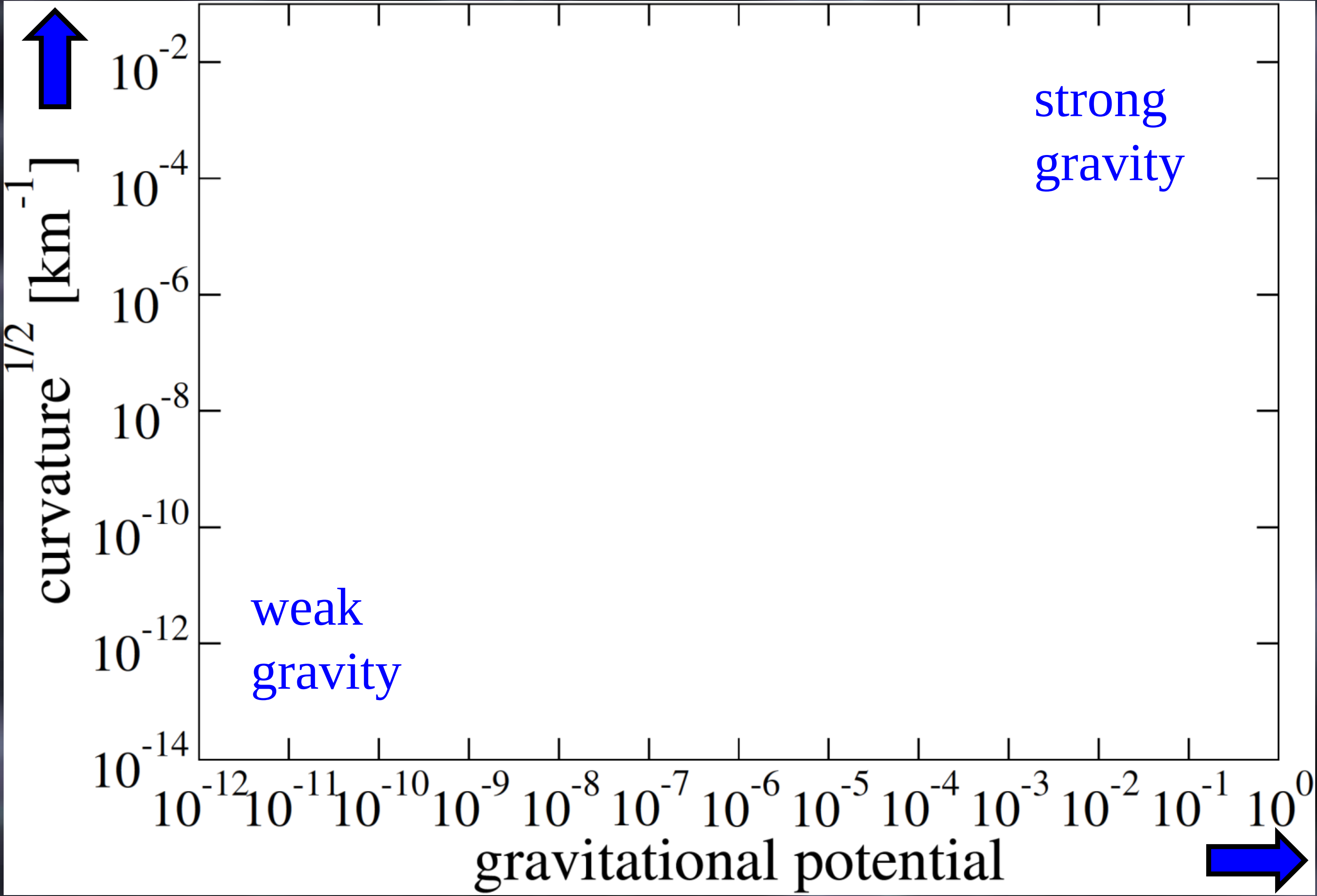
TeVPA, Sydney
Dec. 5th 2019

Goal


WAS
EINSTEIN
RIGHT?
Putting General
Relativity to
the Test
Clifford
M. Will

Weak-field Tests? Strong-field Tests?

strong

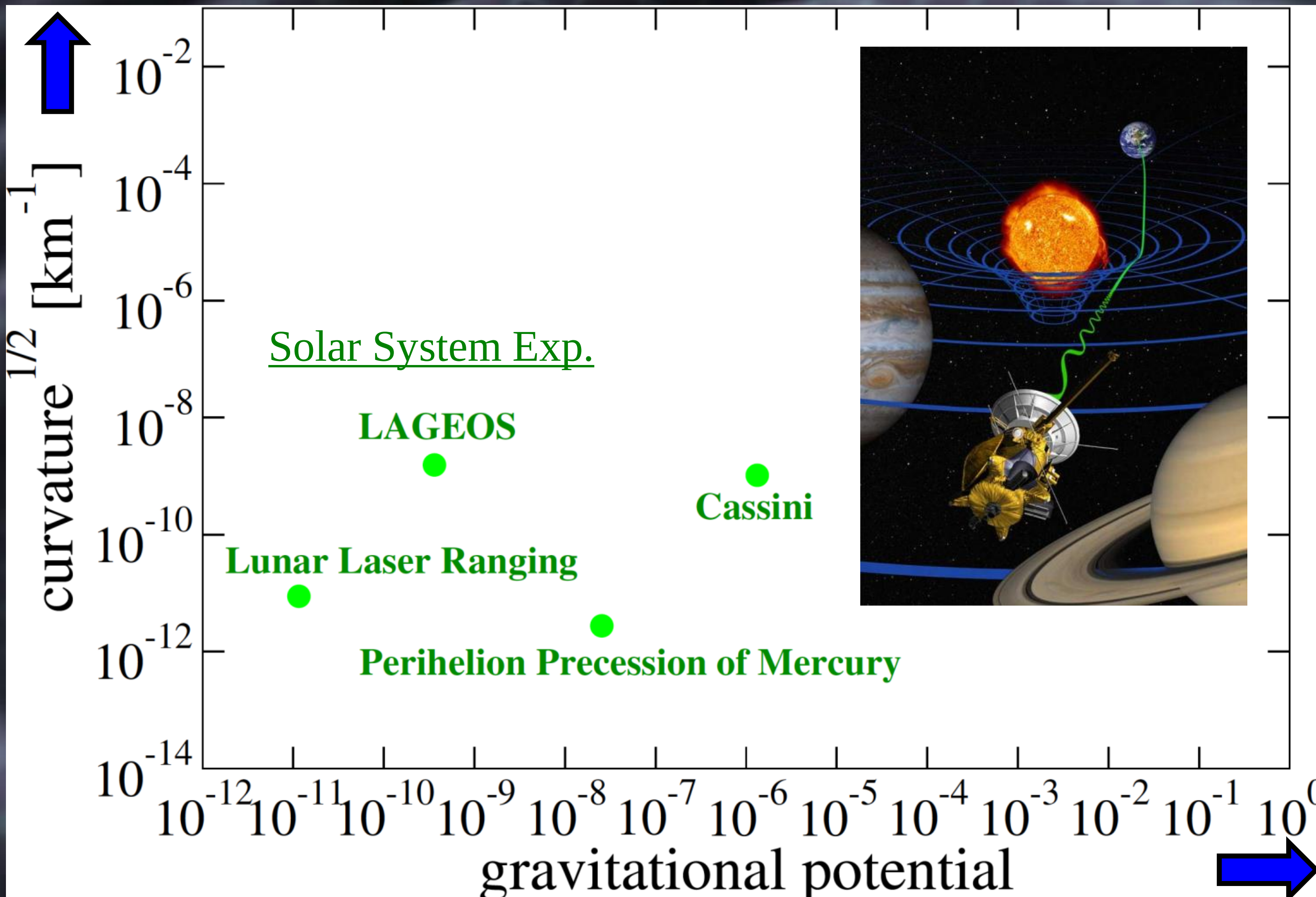


[Yunes, KY & Pretorius PRD (2016)]

large

Weak-field Tests? Strong-field Tests?

strong



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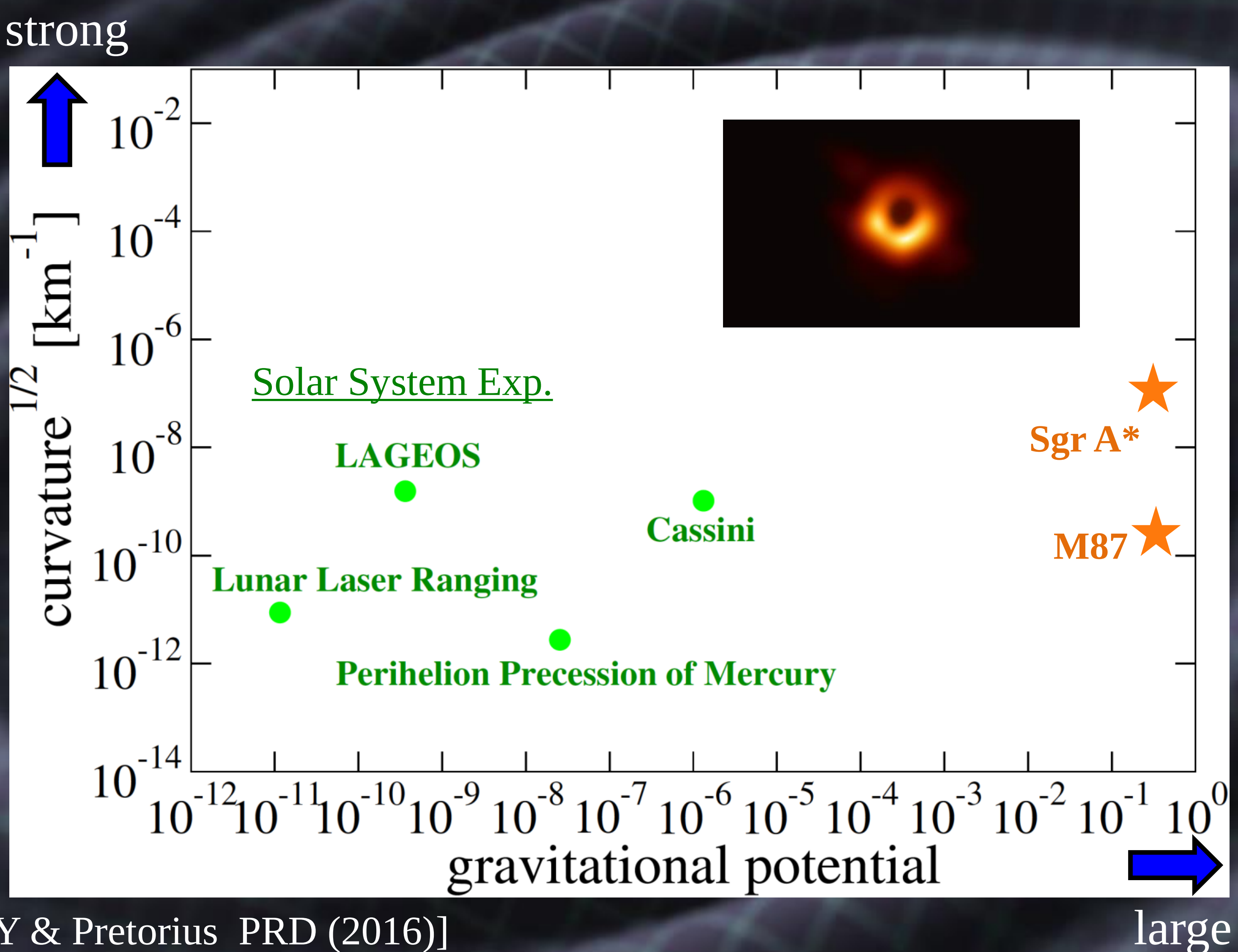

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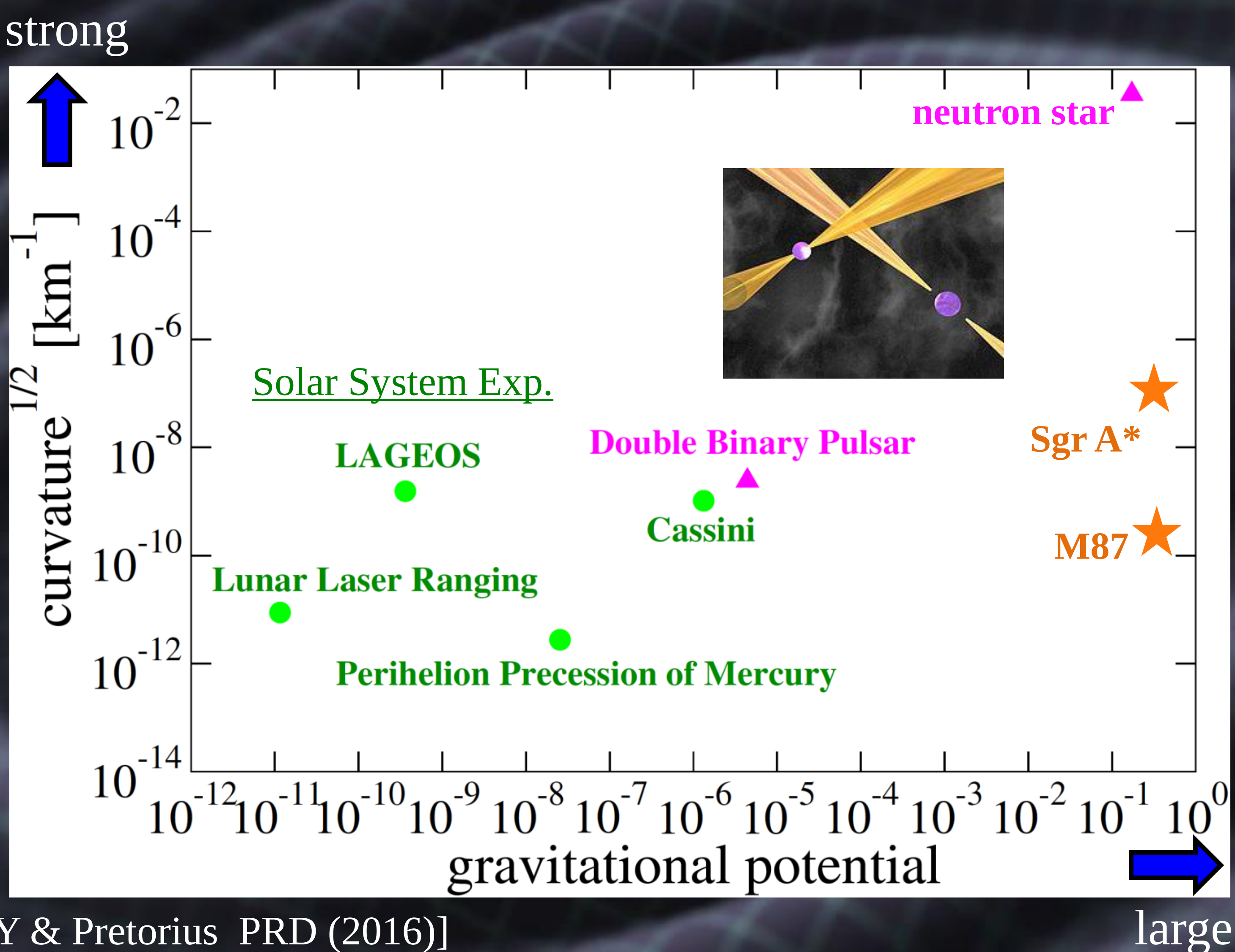
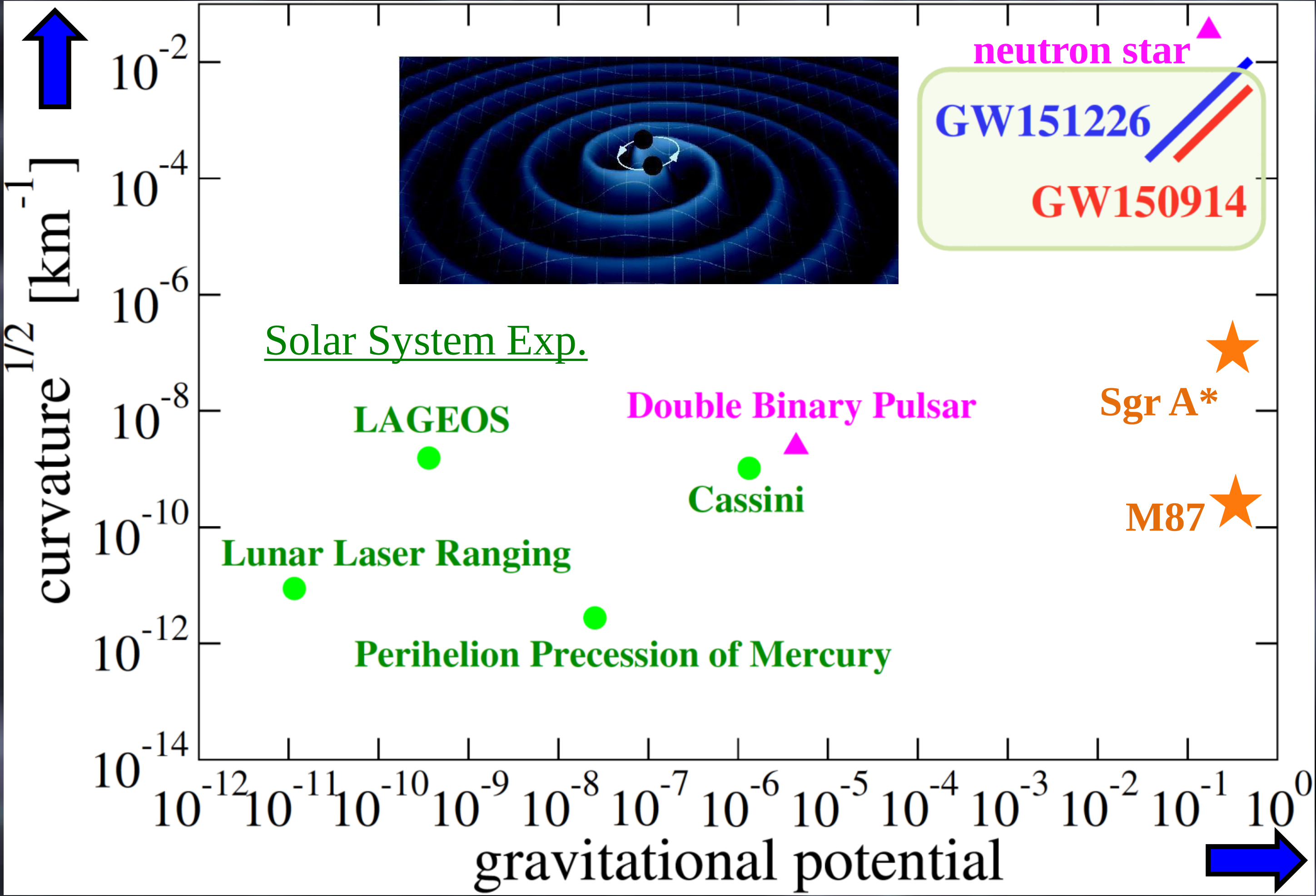


[Yunes, KY & Pretorius PRD (2016)]

Weak-field Tests? Strong-field Tests?

Strong & Dynamical Gravity

strong



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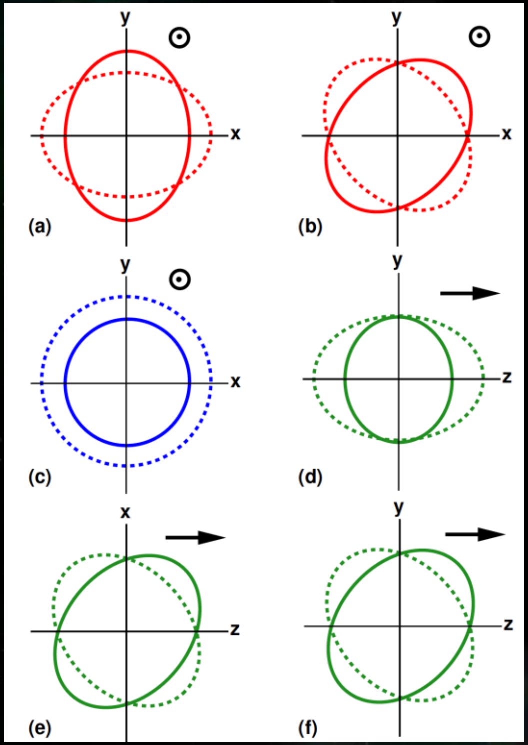
[Yunes, KY & Pretorius PRD (2016)]

Tests of GR with GWs (based on LVC's work)

[PRL 116, 221101 (2016); PRX 6, 041015 (2016); PRL 118, 221101 (2017);
PRL 119, 141101 (2017); ApJL 848, L13 (2017); arXiv:1811.00364; arXiv:1903.04467; …]

✓ residual signal-to-noise ratio (SNR) from best-fit template
GR prediction for GW150914 verified within 4% error

✓ Non-GR polarization



[Will (2014)]

GW170817

Bayesian Model Selection:

$$(\text{tensor only}) \text{ vs } (\text{scalar only}) = 10^{21} : 1$$

$$(\text{tensor only}) \text{ vs } (\text{vector only}) = 10^{23} : 1$$

Tests of GR with GWs (based on LVC's work)

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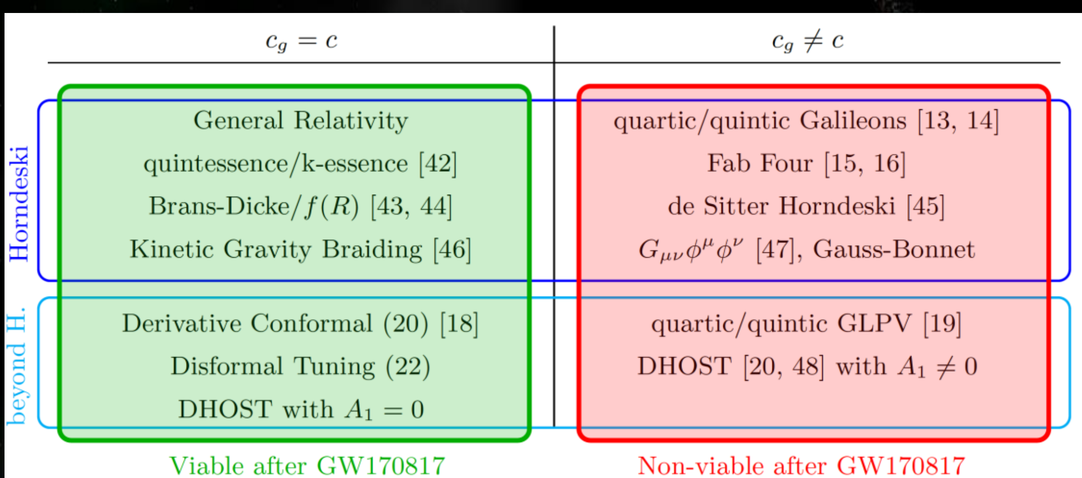
  dispersion relation of gravitons

<u>scalar-tensor theories after GW170817</u>



[Ezquiaga & Zumalacarregui (2017)]

<u>graviton mass bounds</u>

Event	m_g [10^{-23} eV/c^2]
GW150914	10
GW151012	17
GW151226	29
GW170104	9.4
GW170608	30
GW170729	7.6
GW170809	9.6
GW170814	8.8
GW170818	7.4
GW170823	6.4
Combined	5.0

[LVC arXiv:1903.04467]

Tests of GR with GWs (based on LVC's work)

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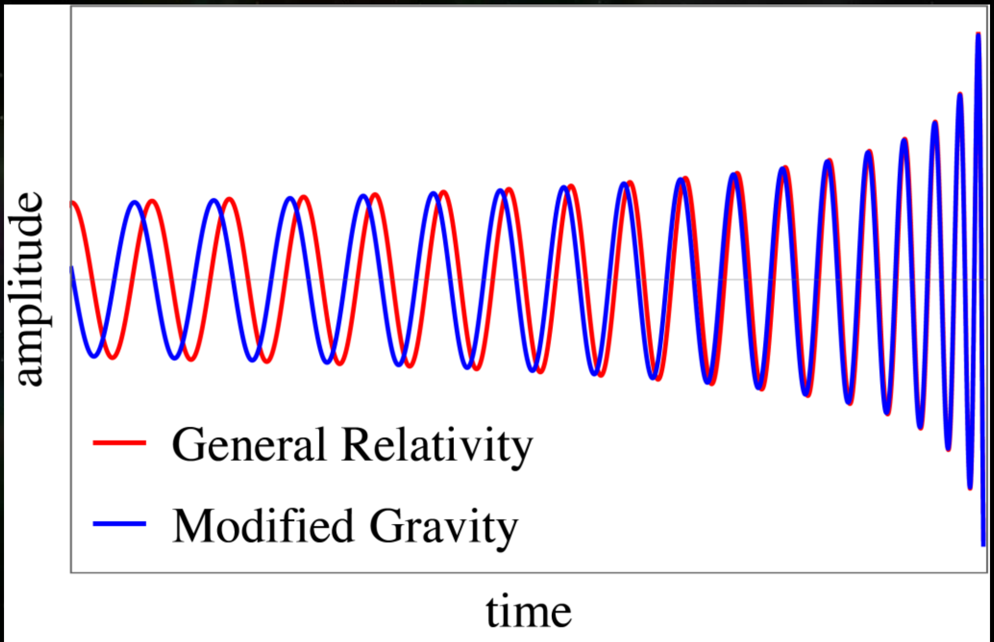
- ✓ Parameterized deviation from GR

parameterized post-Einsteinian (ppE) Formalism

[Yunes & Pretorius (2009)]
[LVC, PRL 116, 221101 (2016)]



waveform phase:

$$\Psi^{(\mathrm{insp})} = \Psi^{(\mathrm{insp})}_{\mathrm{GR}} + \beta\,(v/c)^{2n-5}$$

ppE parameter

relative velocity

*n*th post-Newton (PN) correction

PN approximation:

$$v/c \ll 1$$

PPE Dictionary

Theories	PPE Phase Parameters: Magnitude (β)	Exponent $(2n-5)$
Scalar-Tensor [95, 96]	$-\frac{5}{7168}\eta^{2/5}(\alpha_1-\alpha_2)^2$	-7
Einstein-dilaton Gauss-Bonnet	$-\frac{5}{7168}\zeta_{\rm EdGB}\frac{\left(m_1^2\tilde{s}_2^{\rm EdGB}-m_2^2\tilde{s}_1^{\rm EdGB}\right)^2}{m^4\eta^{18/5}}$	-7
dynamical Chern-Simons	$\frac{1549225}{11812864}\eta^{-14/5}\zeta_{\rm dCS}\left[-2\delta_m\chi_a\chi_s+\left(1-\frac{16068\eta}{61969}\right)\chi_a^2+\left(1-\frac{231808\eta}{61969}\right)\chi_s^2\right]$	-1
Einstein-Æther [99]	$-\frac{5}{3584}\eta^{2/5}\frac{(s_1^{\rm EA}-s_2^{\rm EA})^2}{[(1-s_1^{\rm EA})(1-s_2^{\rm EA})]^{4/3}}\left[\frac{(c_{14}-2)w_0^3-w_1^3}{c_{14}w_0^3w_1^3}\right]$	-7
Khronometric [99]	$-\frac{5}{3584}\eta^{2/5}\frac{(s_1^{\rm kh}-s_2^{\rm kh})^2}{[(1-s_1^{\rm kh})(1-s_2^{\rm kh})]^{4/3}}\sqrt{\bar{\alpha}_{\rm kh}}\left[\frac{(\bar{\beta}_{\rm kh}-1)(2+\bar{\beta}_{\rm kh}+3\bar{\lambda}_{\rm kh})}{(\bar{\alpha}_{\rm kh}-2)(\bar{\beta}_{\rm kh}+\bar{\lambda}_{\rm kh})}\right]^{3/2}$	-7
Noncommutative [100]	$-\frac{75}{256}\eta^{-4/5}(2\eta-1)\Lambda^2$	-1
Varying-G [92]	$-\frac{\mathbf{25}}{\mathbf{851968}}\eta_0^{3/5}\dot{\mathbf{G}}_{\mathbf{C,0}}\left[\mathbf{11m_0}+\mathbf{3}(\mathbf{s_{1,0}}+\mathbf{s_{2,0}}-\delta_{\dot{G}})\mathbf{m_0}-\mathbf{41}(\mathbf{m_{1,0}s_{1,0}}+\mathbf{m_{2,0}s_{2,0}})\right]$	$\mathbf{-13}$

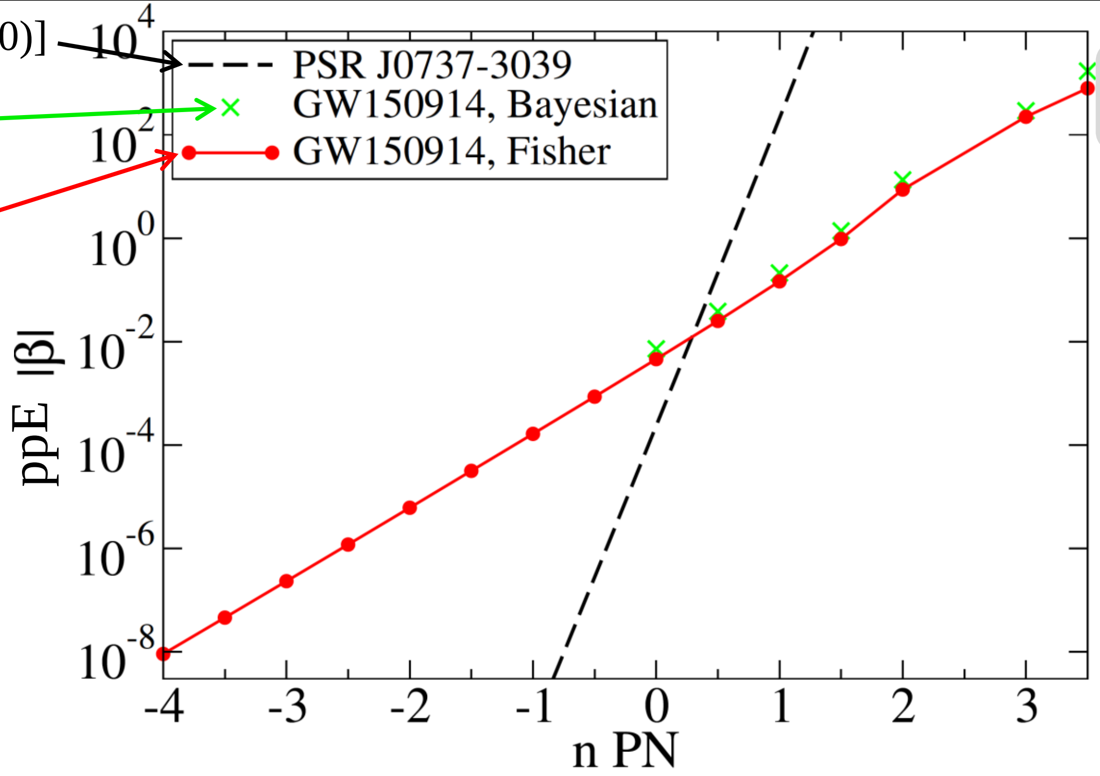
[Tahura & KY (2018)]

Constraining GR Fundamental Pillars

[Yunes & Hughes (2010)]

[LIGO-Virgo Collaboration (2016)]

[Yunes, KY & Pretorius (2016)]



$$\delta\Psi = \beta\, v^{2n-5}$$

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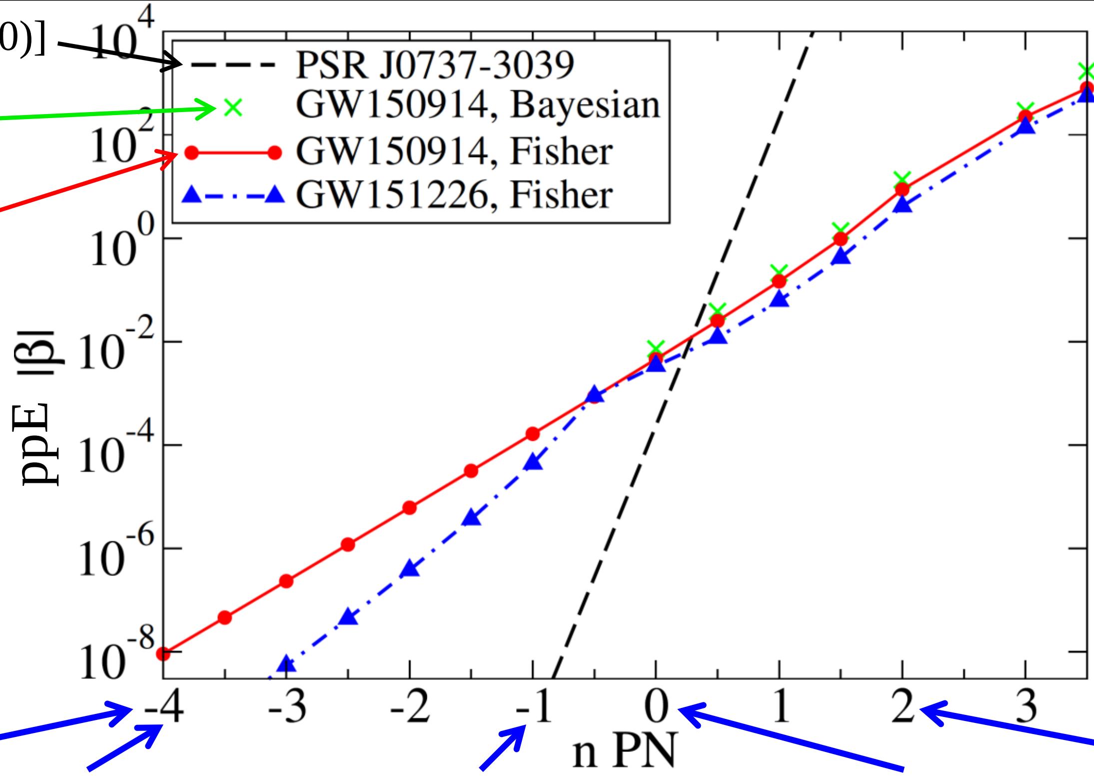


$$\delta\Psi = \beta\, v^{2n-5}$$

extra dimension	time varying G	scalar monopole activation	vector field activation	scalar dipole activation
⬇	⬇	⬇	⬇	⬇
4D	equivalence principle	equivalence principle	Lorentz invariance	parity invariance

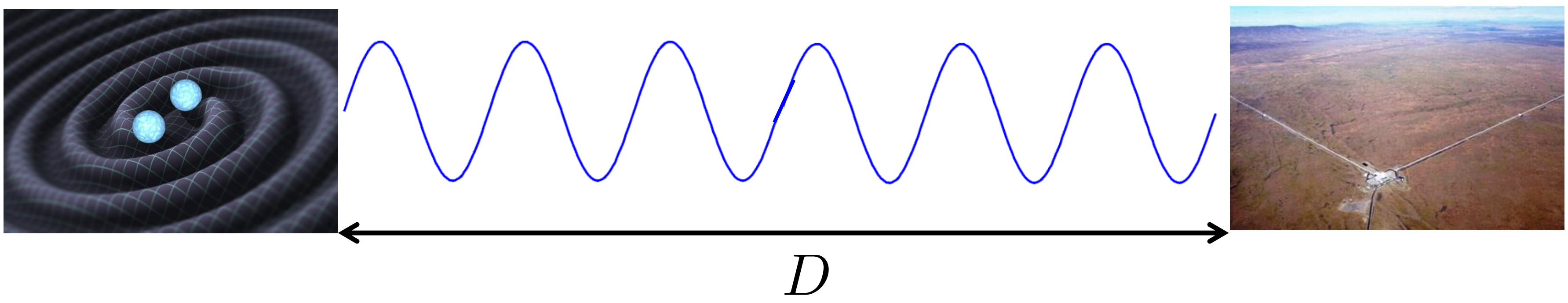
PPE for Modified GW Propagation

$c = 1$

[Will PRD57 2061 (1998), Mirshekari et al. PRD85 024041 (2012)]

-graviton dispersion relation

$$E^2 = p^2 + A\,p^{\gamma} \;\Rightarrow\; v_g^2 \approx 1 + (\gamma - 1)\,A\,E^{\gamma - 2}$$



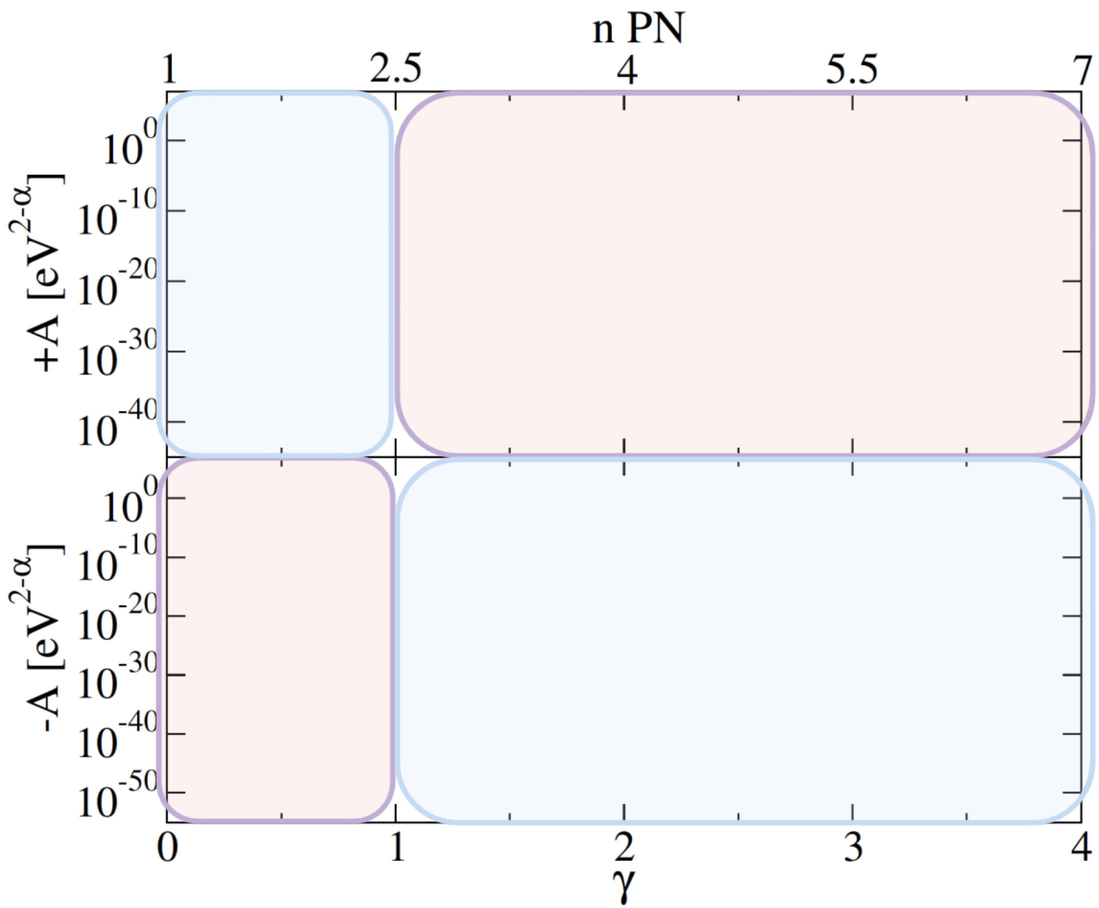
$$\Psi \sim 2\pi f \frac{D}{v_g} \;\Rightarrow\;$$

$$\Psi = \Psi_{\rm GR} + \beta (v/c)^{2n-5}$$

$$\beta \sim A\,D\,M^{1-\gamma} \qquad n = (3\gamma + 2)/2$$

Constraints on GW Propagation

$$E^2 = p^2 + A\, p^\gamma$$



superluminal

subluminal

$$v_g^2 \approx 1 + (\gamma - 1)\, A\, E^{\gamma - 2}$$

Constraints on GW Propagation

[Kiyota & Yamamoto (2015)]

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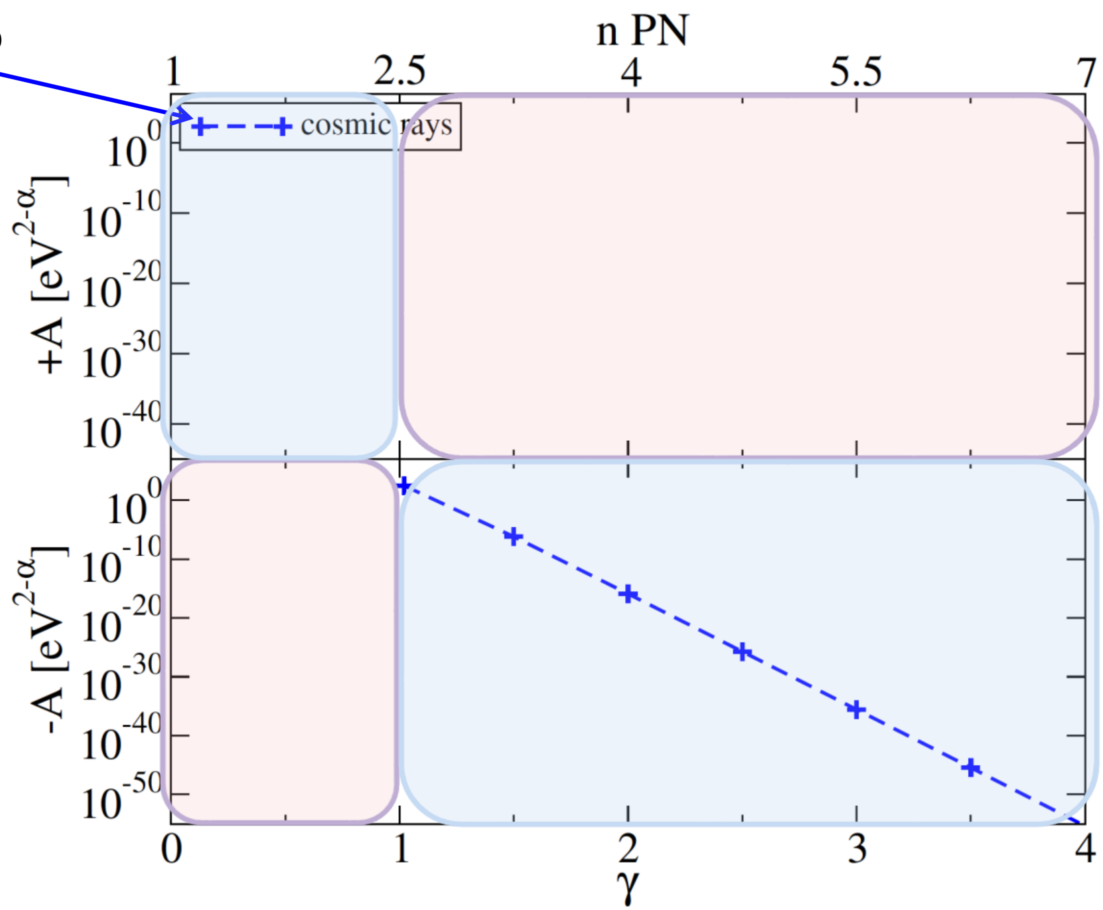

superluminal

subluminal

Constraints on GW Propagation

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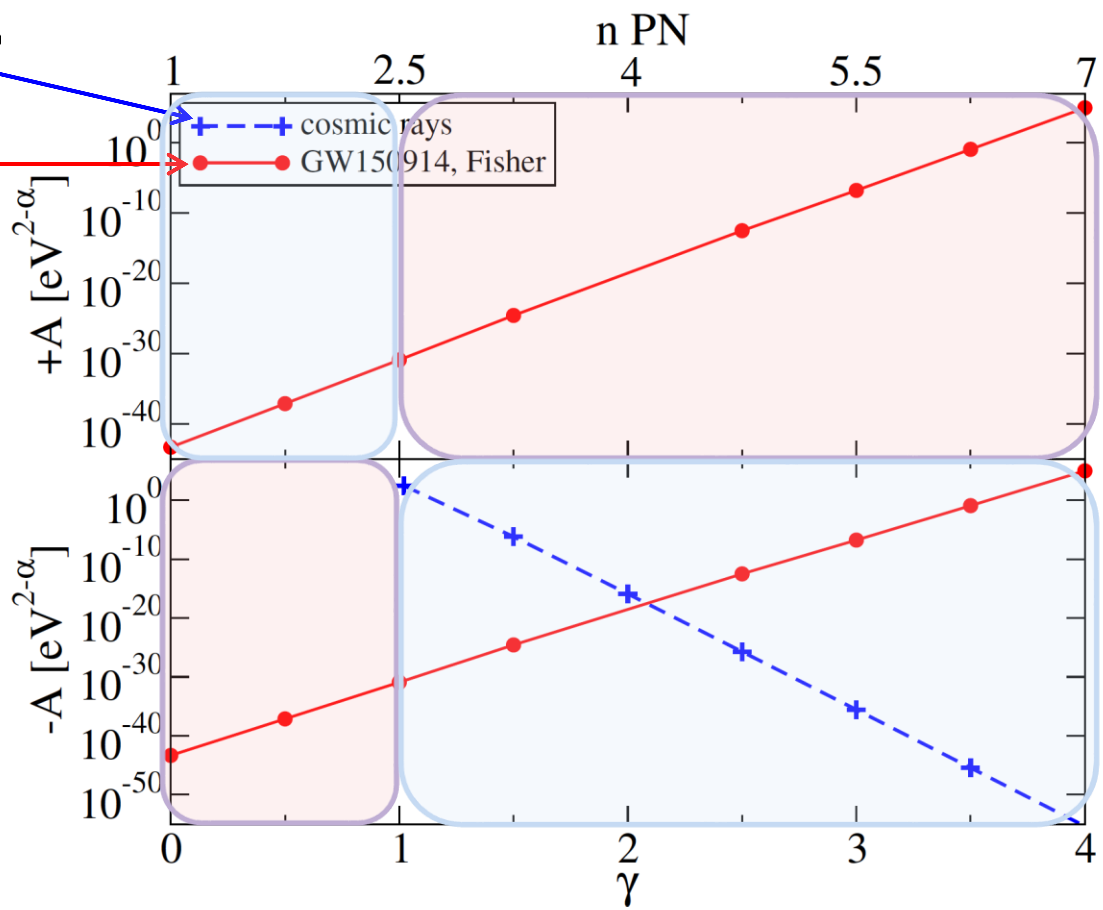

superluminal

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Constraints on GW Propagation

$$E^2 = p^2 + A\,p^\gamma$$

[Kiyota & Yamamoto (2015)]

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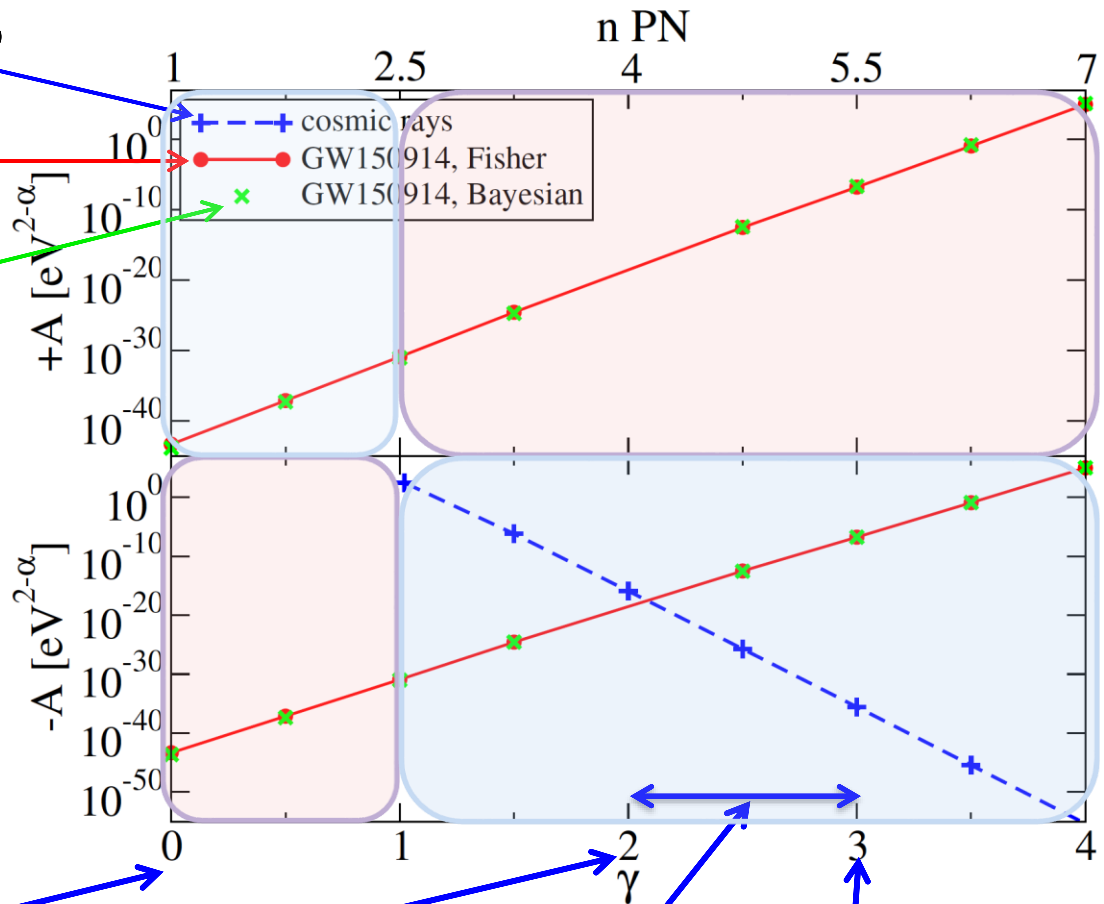

superluminal

subluminal

-massive gravity

-Lorentz violation

-multifractional spacetime

-Lorentz violation
-mod. special relativity

-Lorentz violation
-extra dimension

Tests of GR with GWs (based on LVC's work)

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- ✓ Consistency test of GR Kerr with inspiral and post-inspiral

IMR Consistency Test of GR with GW150914

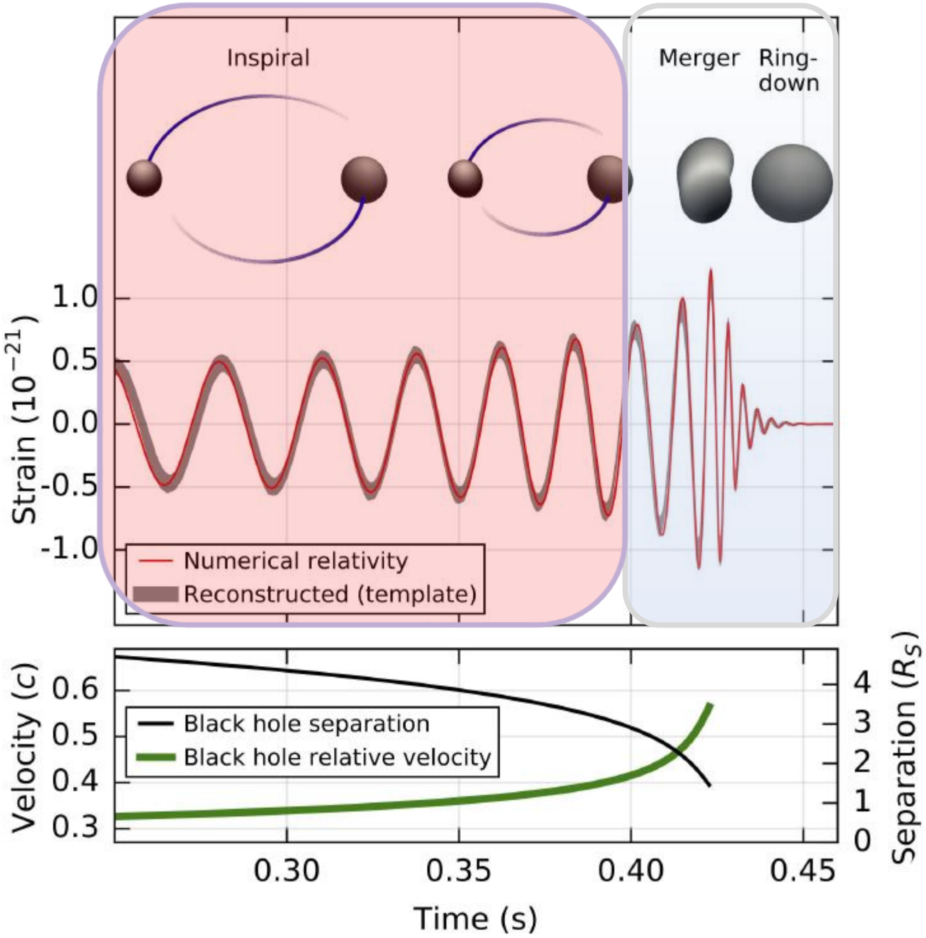
initial masses & spins

$$(m_1, m_2, \chi_1, \chi_2)$$

final mass & spin

$$(M_f, \chi_f)$$

numerical relativity
assuming GR

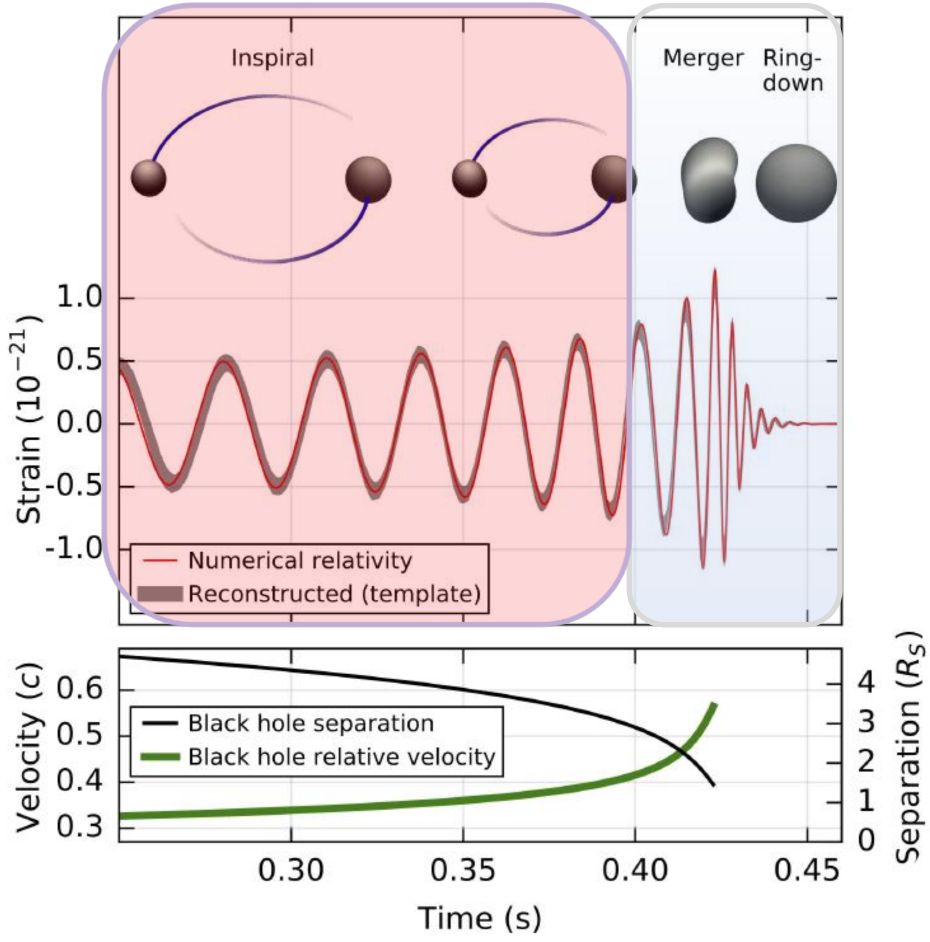


IMR Consistency Test of GR with GW150914

initial masses & spins

$$(m_1, m_2, \chi_1, \chi_2) \Rightarrow (M_f, \chi_f)$$

final mass & spin



numerical relativity
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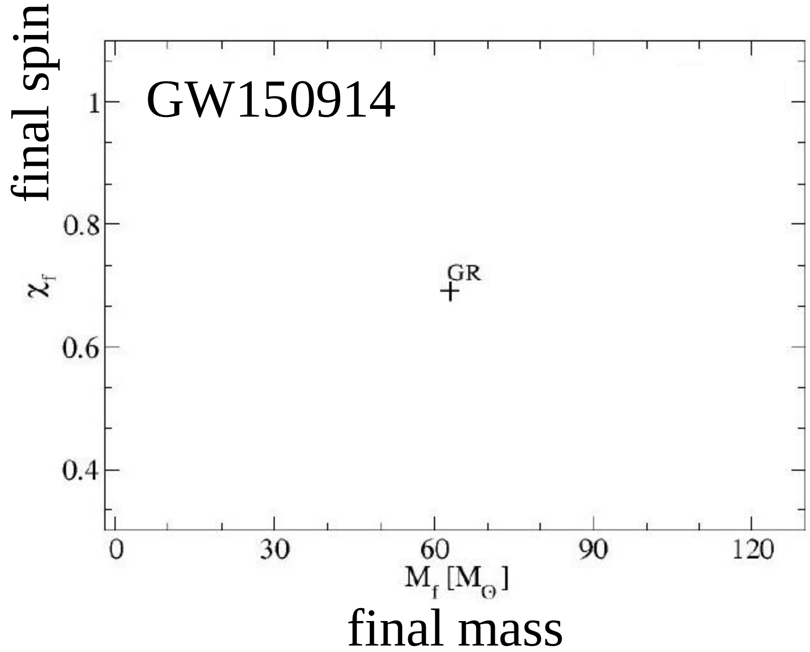

Fisher analysis

[credit: Zack Carson]

IMR Consistency Test of GR with GW150914

initial masses & spins $(m_1, m_2, \chi_1, \chi_2)$ → final mass & spin (M_f, χ_f)

numerical relativity
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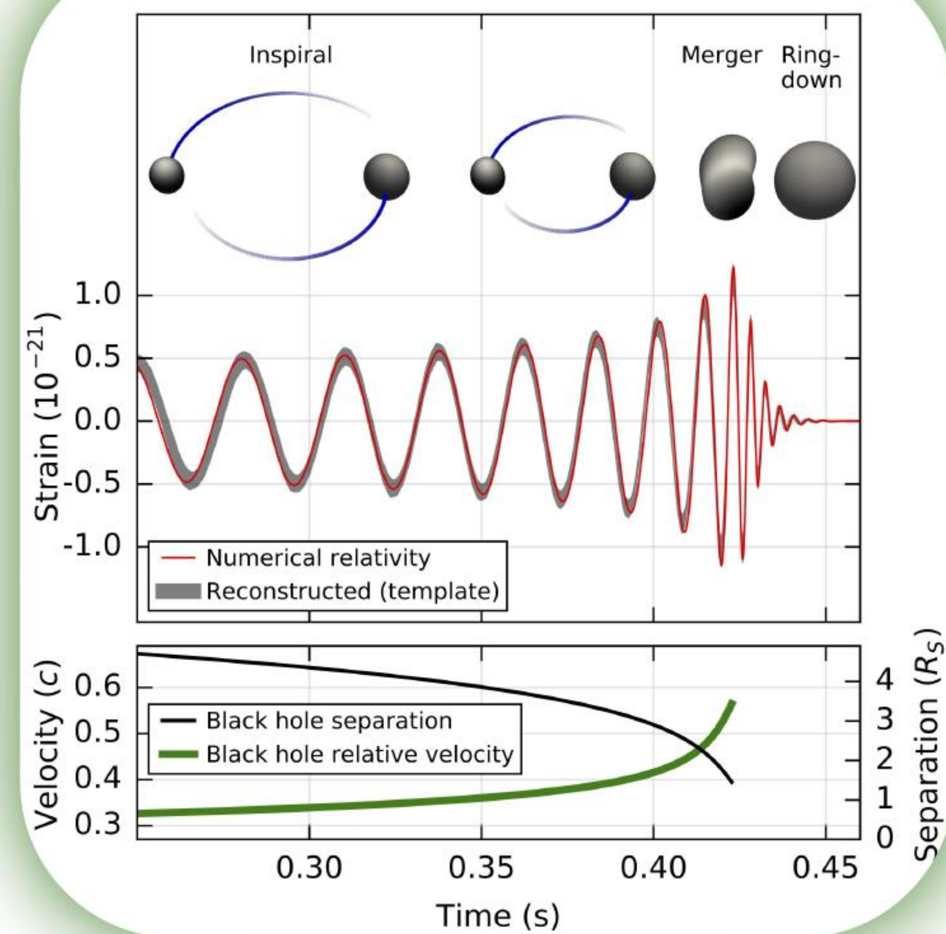

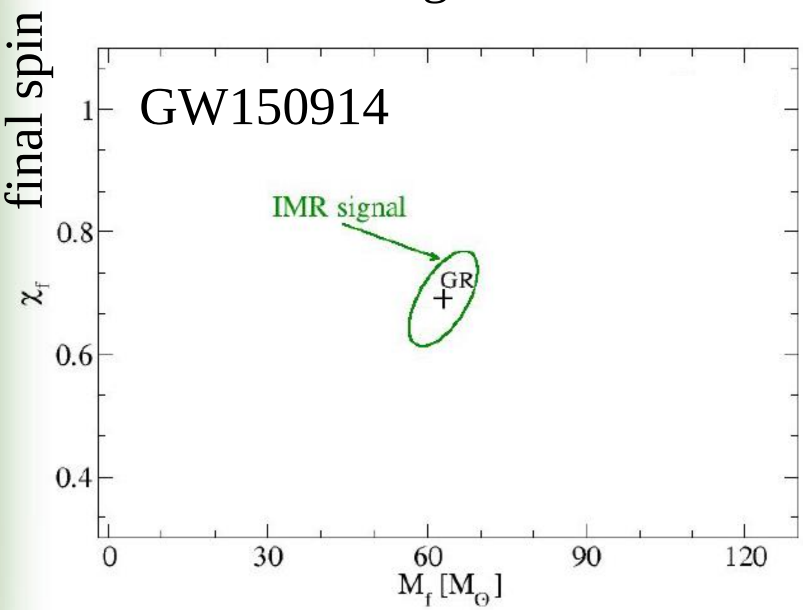

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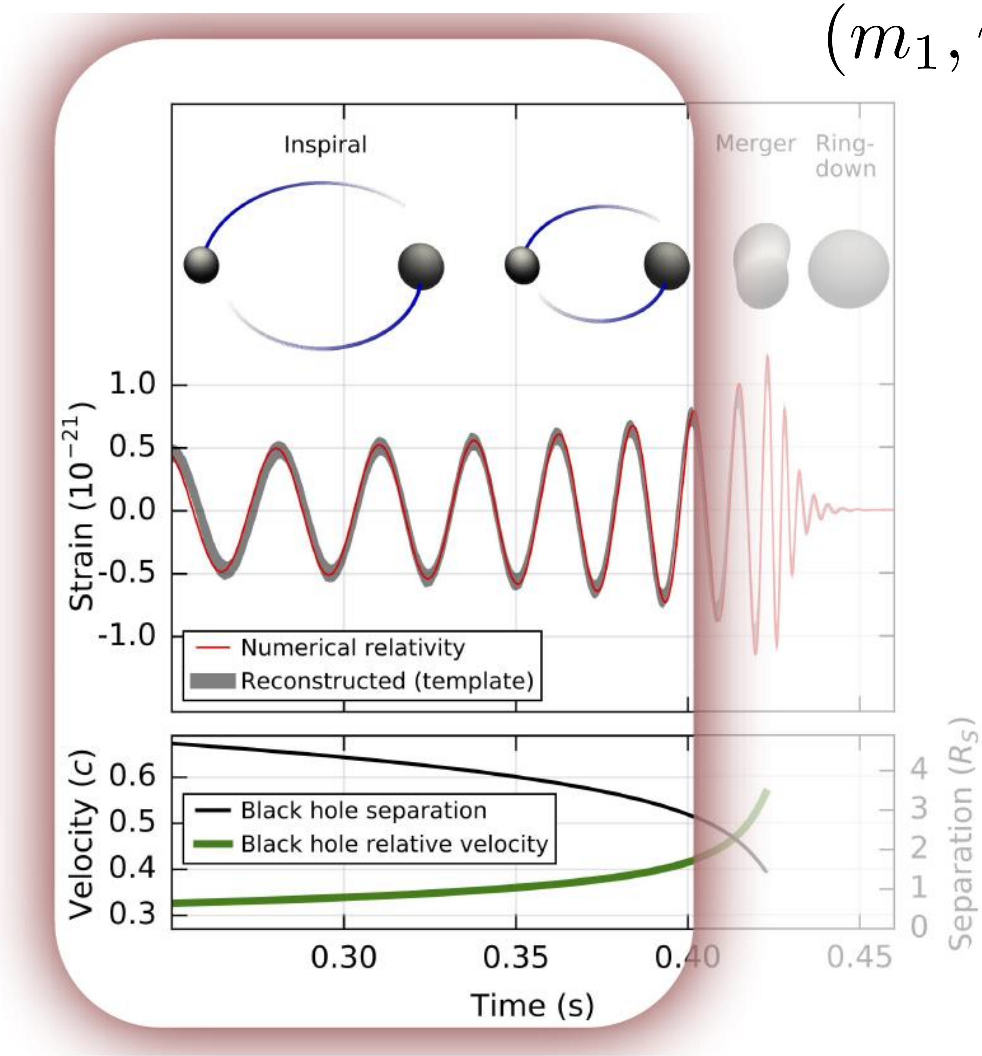

numerical relativity
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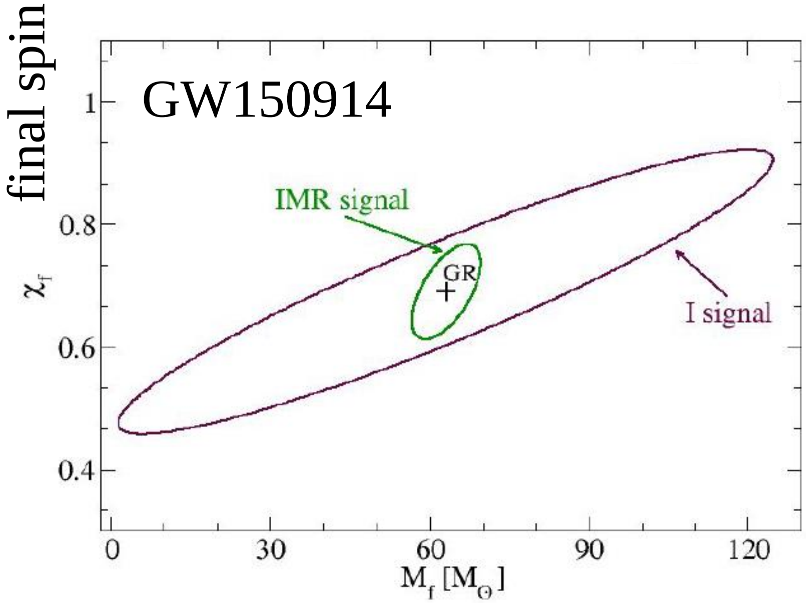

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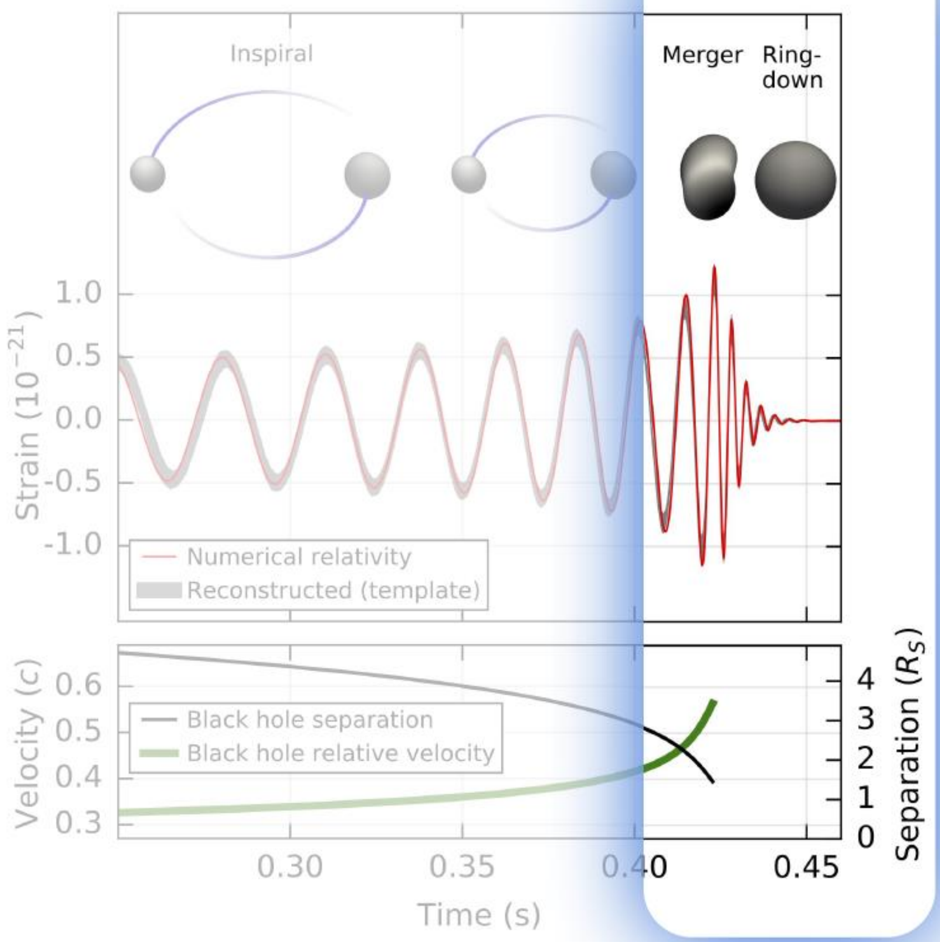

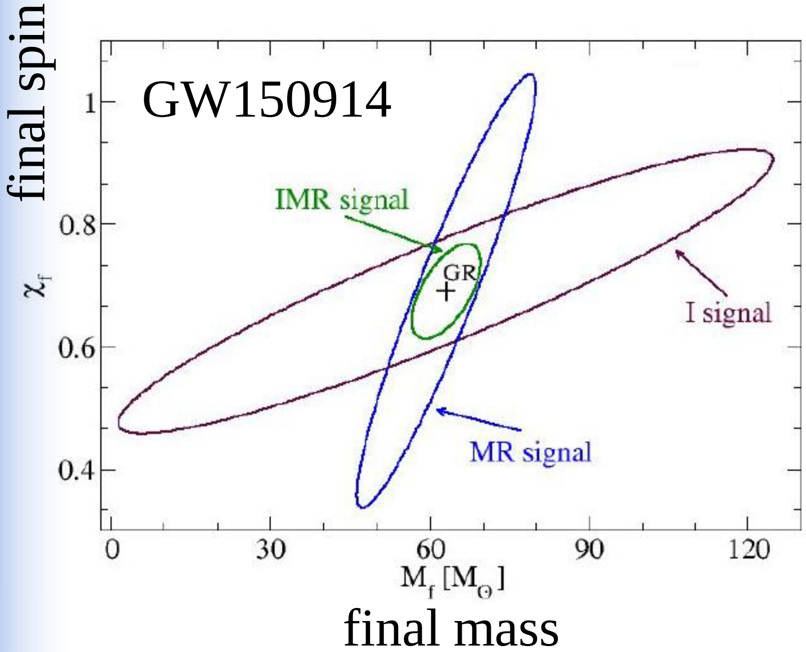

Fisher analysis

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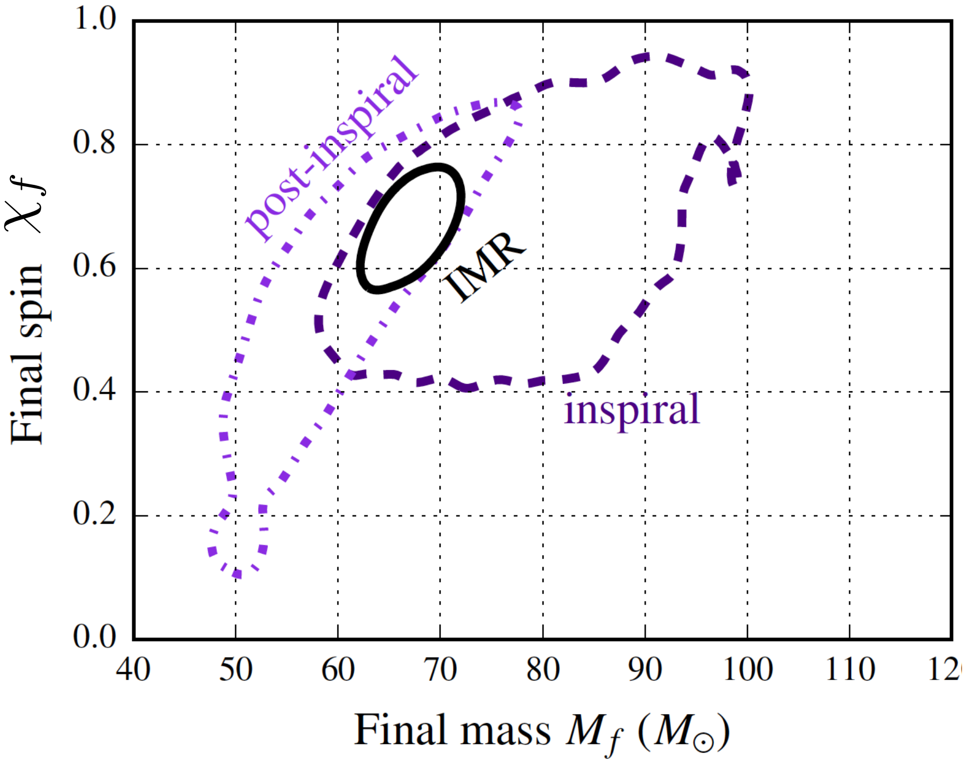
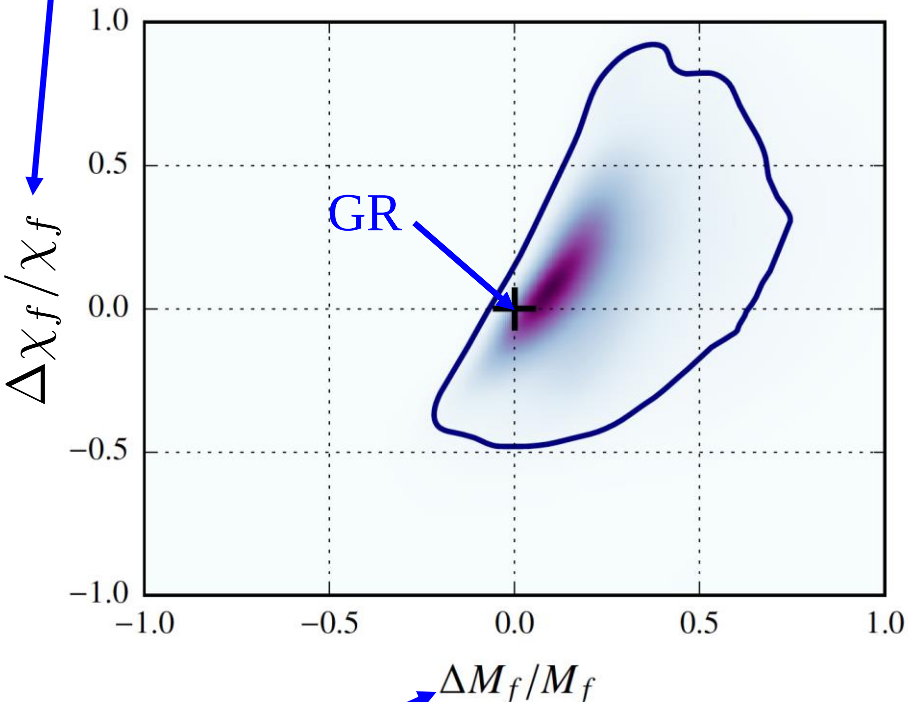
IMR Consistency Test of GR with GW150914

[LVC, PRL 116, 221101 (2016)]

Bayesian, actual data

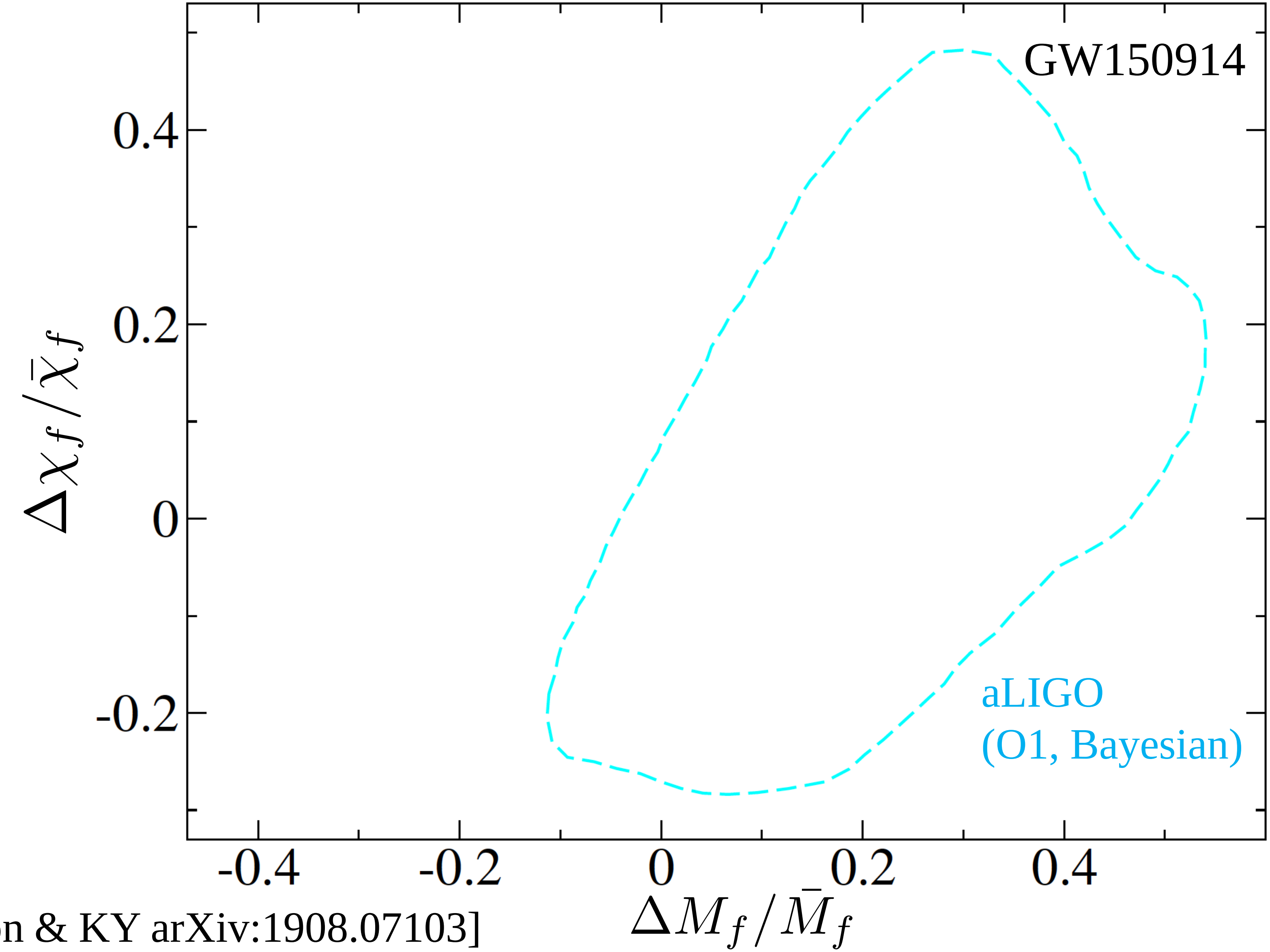
$$\Delta\chi_f = \chi_f^{\mathrm{I}} - \chi_f^{\mathrm{MR}}$$





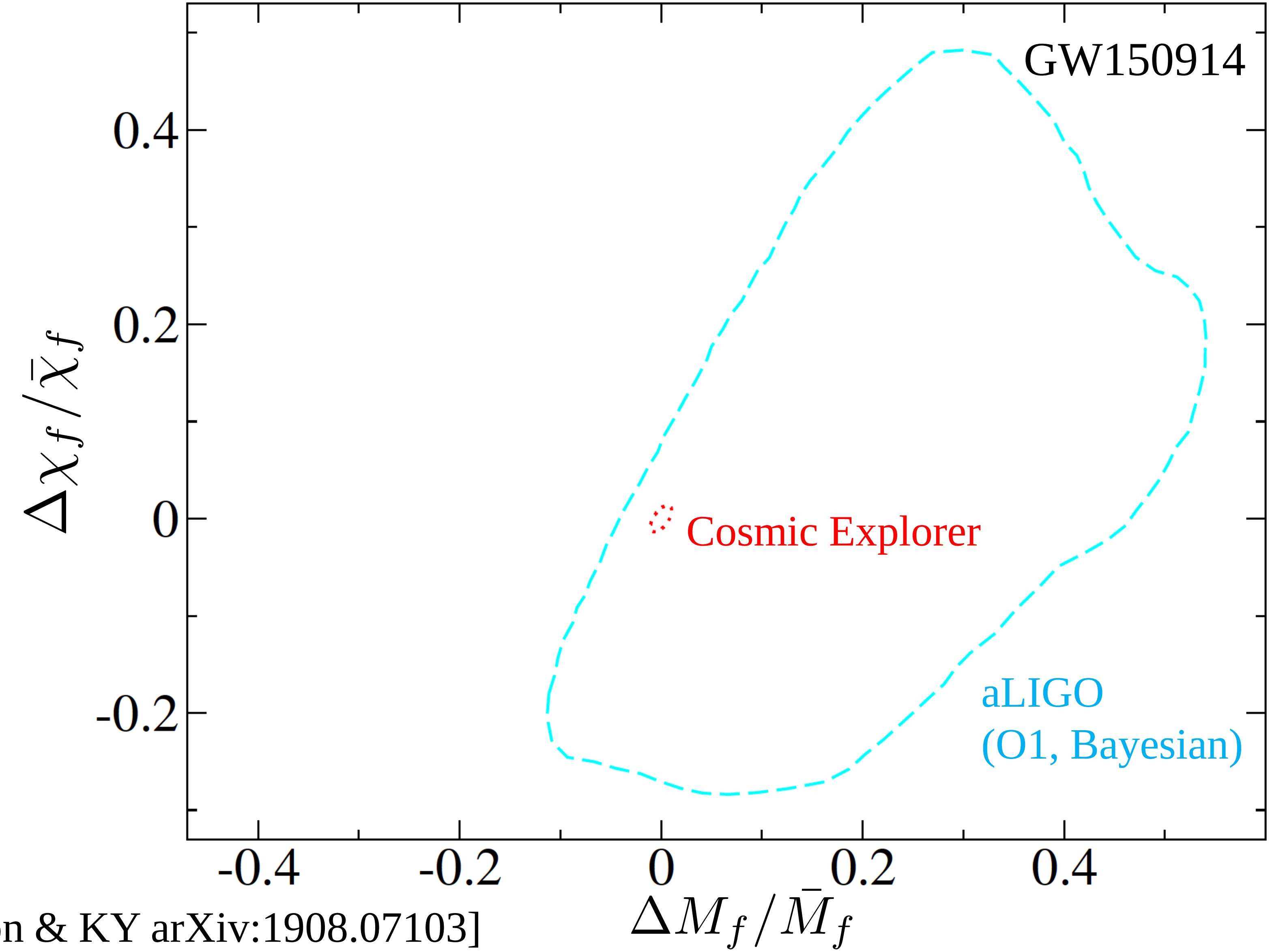
$$\Delta M_f = M_f^{\mathrm{I}} - M_f^{\mathrm{MR}}$$

Future Improvement on IMR Consistency Tests



[Carson & KY arXiv:1908.07103]

Future Improvement on IMR Consistency Tests



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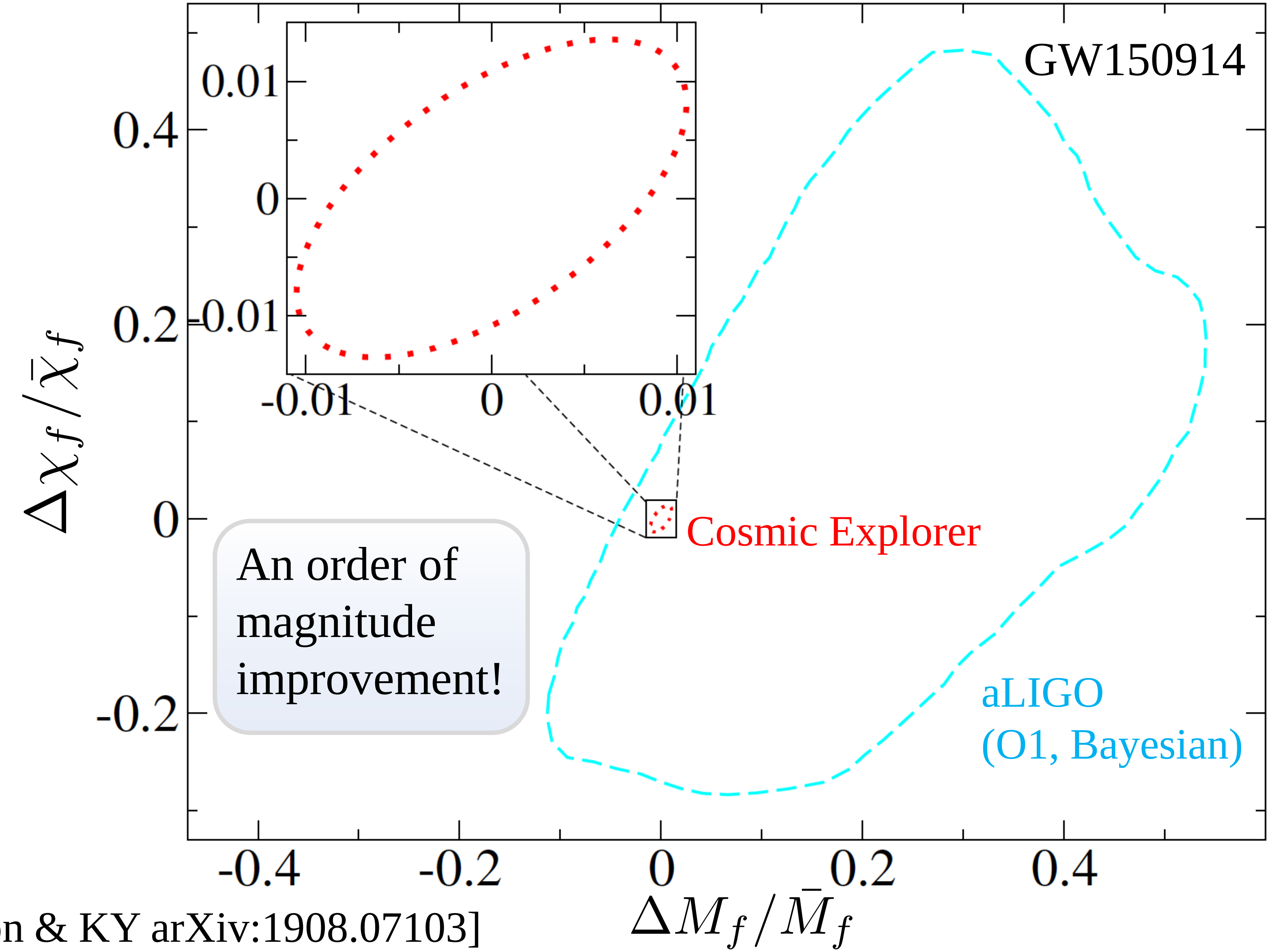


An order of magnitude improvement!

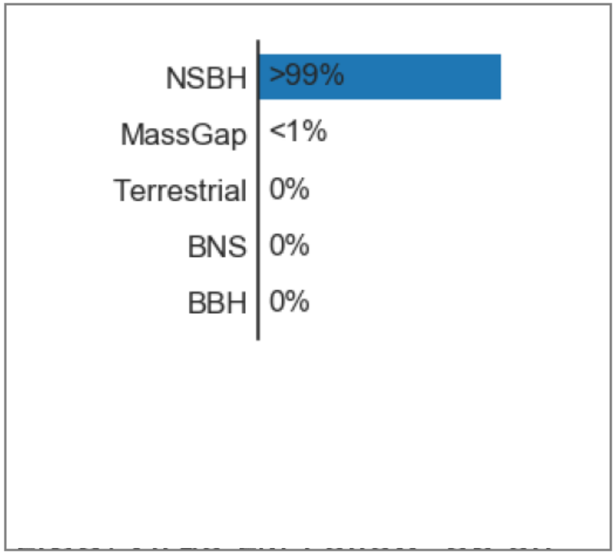
[Carson & KY arXiv:1908.07103]

Black Hole / Neutron Star

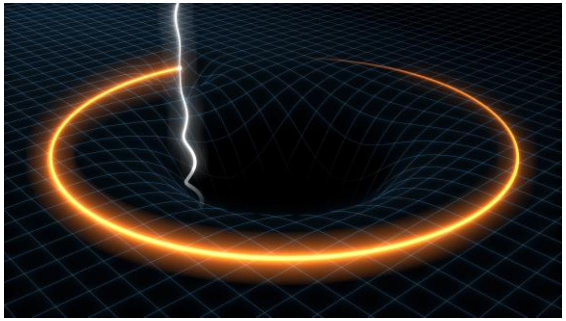
Black Hole / Neutron Star

NS/BH

S190814



$$D_L = 267 \pm 52 \text{ Mpc}$$



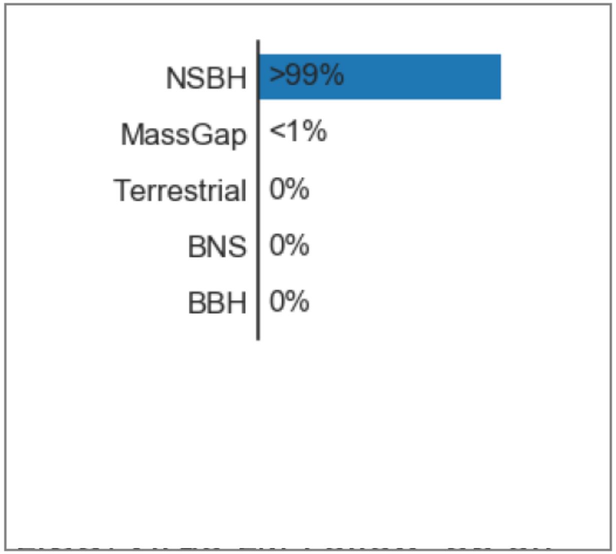
Einstein-dilaton Gauss-Bonnet (EdGB) gravity

$$\mathcal{L} \sim R + \alpha e^{\phi} R_{\rm GB}^2$$

Black Hole / Neutron Star

NS/BH

S190814



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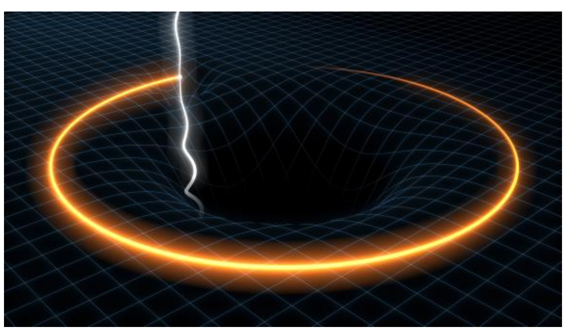
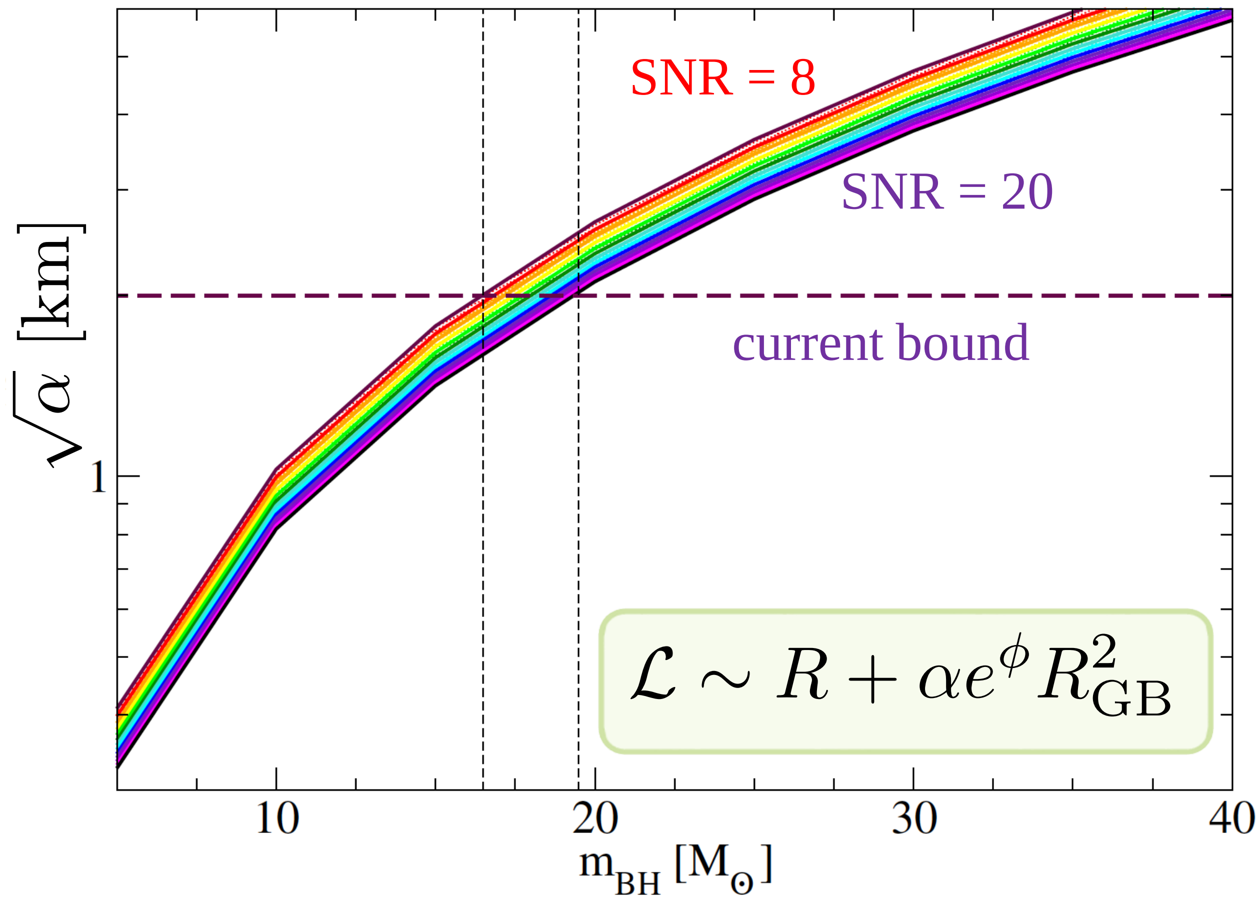


Einstein-dilaton Gauss-Bonnet (EdGB) gravity



[Carson, Seymour & KY arXiv:1907.03897]

Black Hole / Neutron Star

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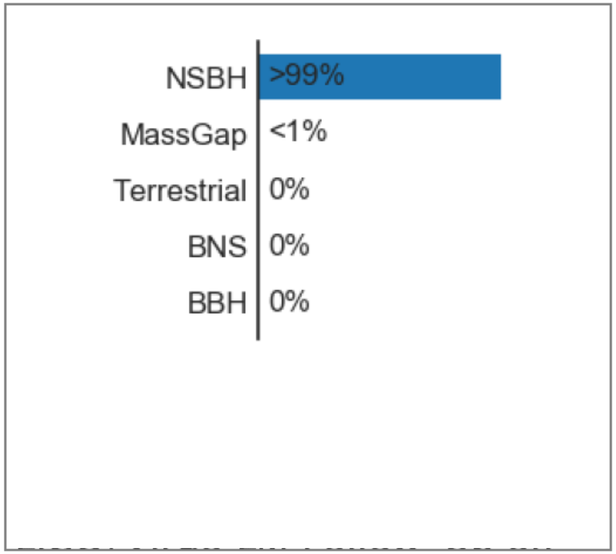

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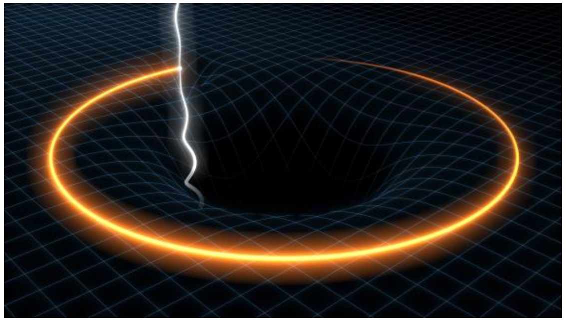
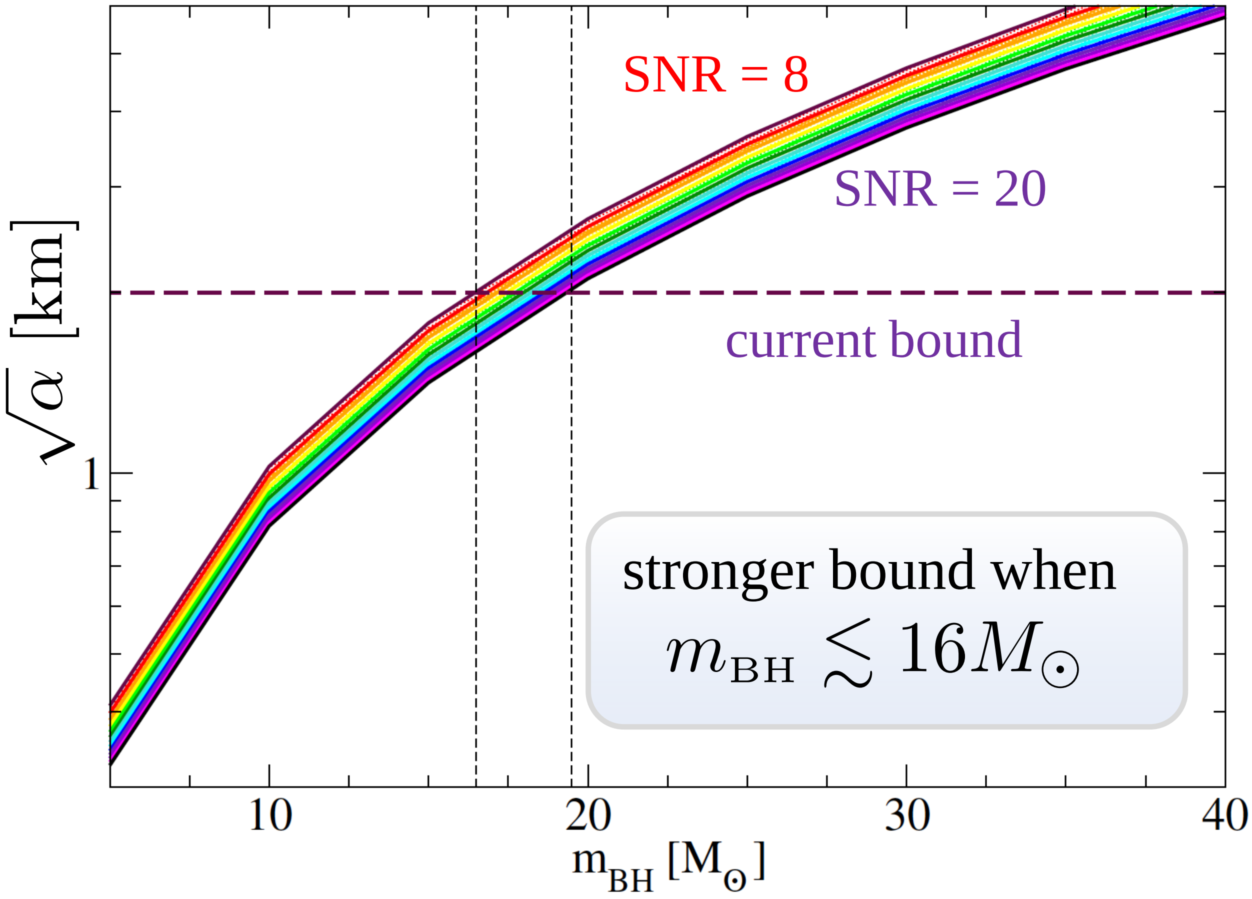


Einstein-dilaton Gauss-Bonnet (EdGB) gravity



stronger bound when $m_{\rm BH} \lesssim 16 M_\odot$

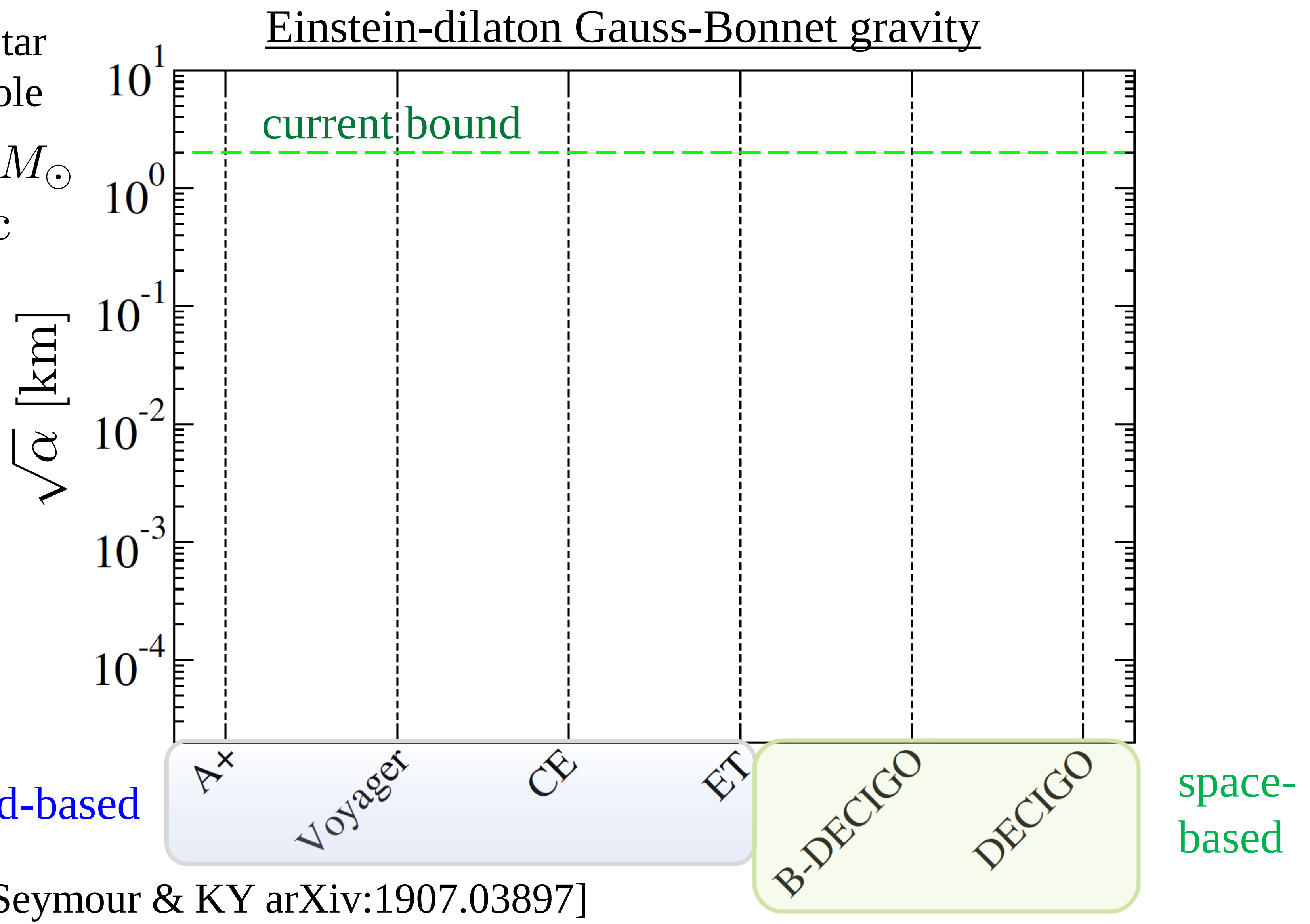
[Carson, Seymour & KY arXiv:1907.03897]

Black Hole / Neutron Star (Future Prospect)

neutron star / black hole

$(1.4, 10) M_\odot$

1Gpc



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neutron star / black hole

$(1.4, 10) M_\odot$

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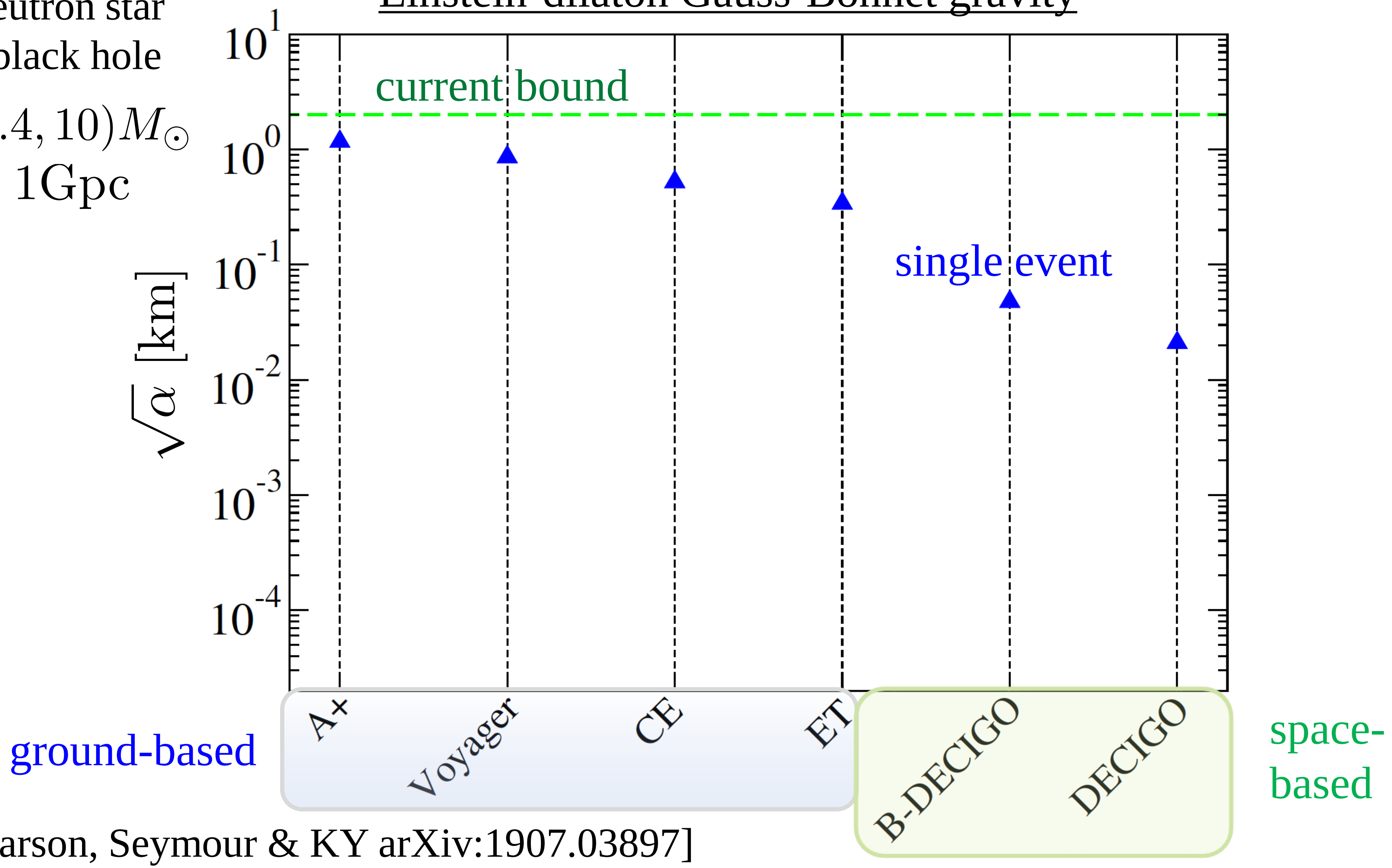

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Black Hole / Neutron Star (Future Prospect)

neutron star / black hole

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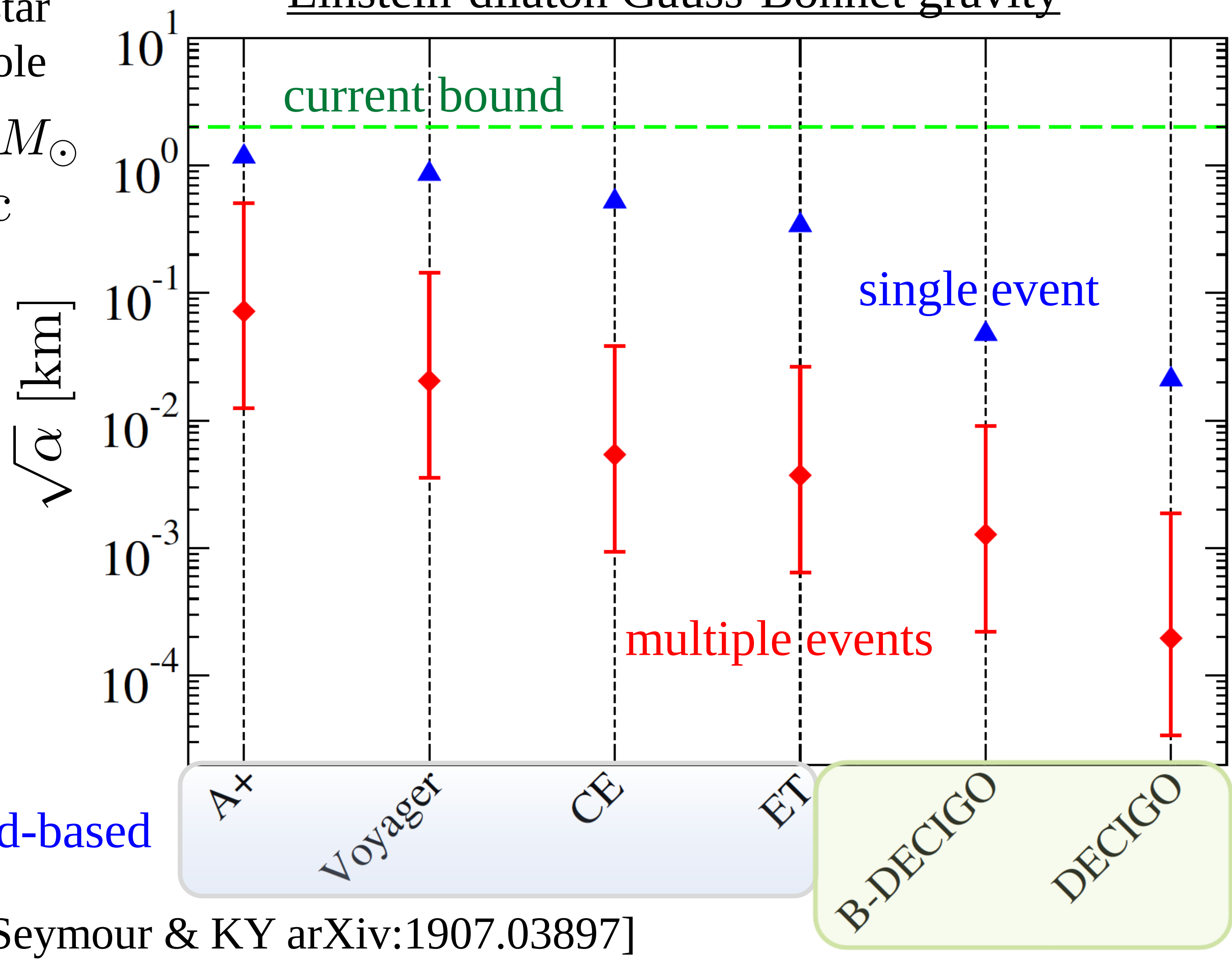


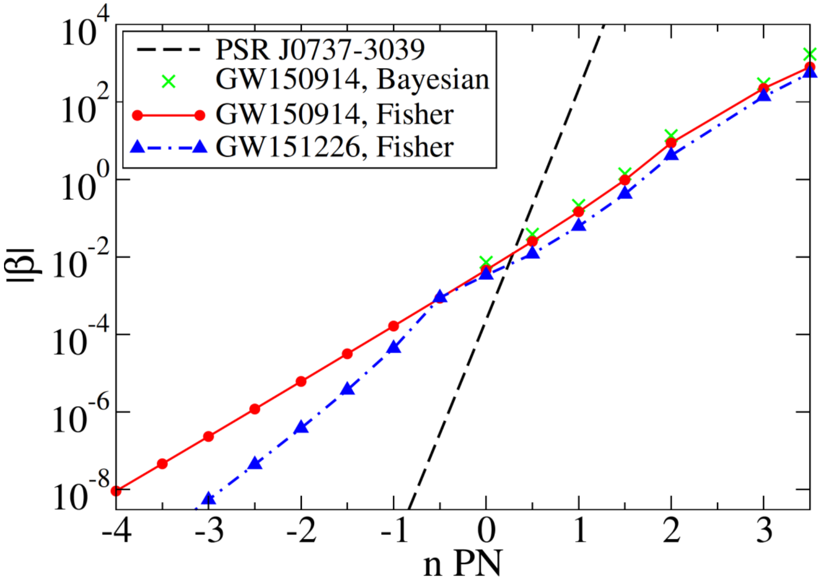
ground-based

space-based

[Carson, Seymour & KY arXiv:1907.03897]

Conclusions

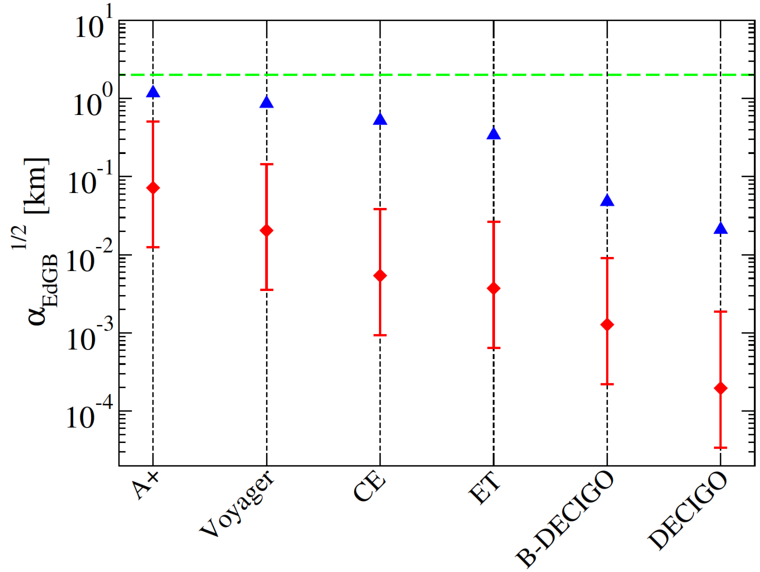
Takeaway



✓ various tests of GR with GWs being carried out

✓ no evidence for beyond-GR effects so far

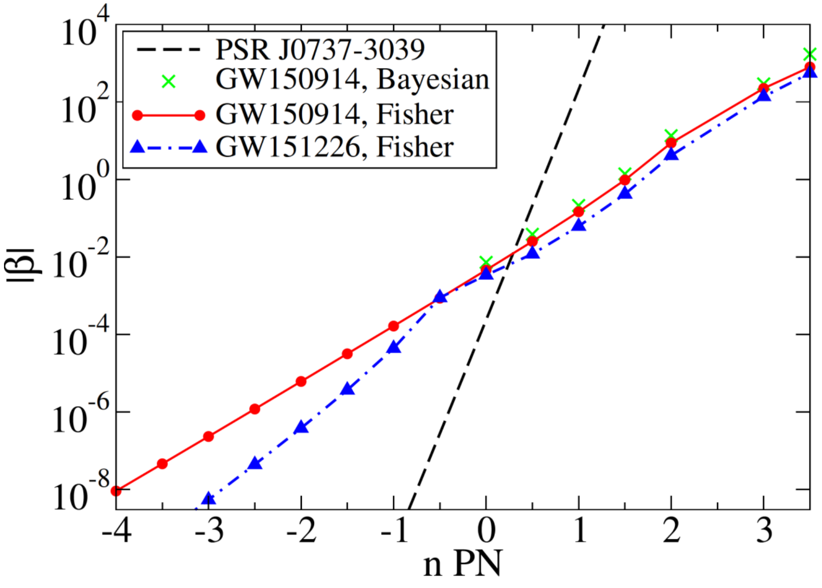
✓ model-independent analyses include parameterized tests & inspiral-merger-ringdown consistency tests



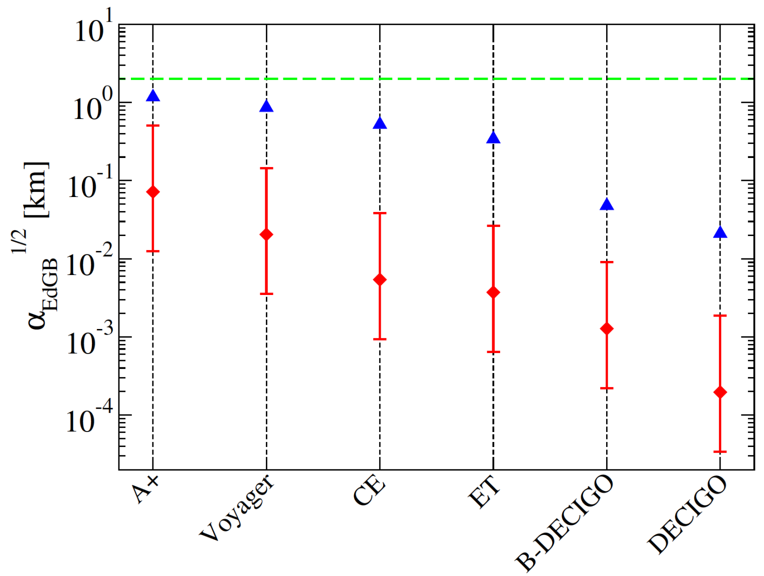
✓ can be applied to specific theories such as string-inspired ones

✓ black hole / neutron star binaries will improve the bounds significantly

Takeaway



- ✓ various tests of GR with GWs being carried out
- ✓ no evidence for beyond-GR effects so far
- ✓ model-independent analyses include parameterized tests & inspiral-merger-ringdown consistency tests

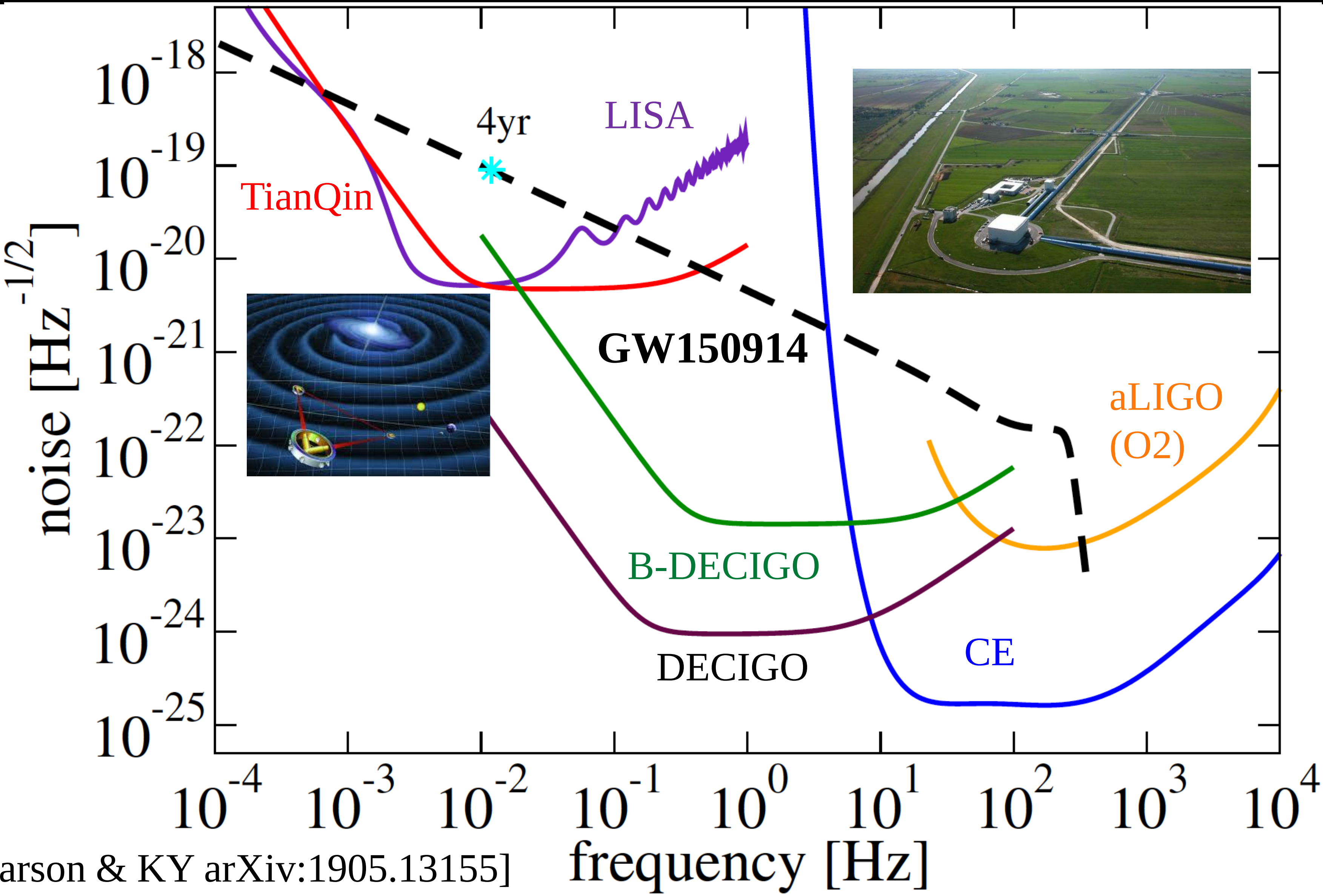


- ✓ can be applied to specific theories such as string-inspired ones
- ✓ black hole / neutron star binaries will improve the bounds significantly

Thank You!

Back Up

Future Detectors



[Carson & KY arXiv:1905.13155]

Theoretical Constraints

[Yunes, KY & Pretorius PRD (2016)]

Example Theories (Theoretical Parameters)	GR Pillar	Example Theory Constraints		
		GW150914	**GW151226**	Others
Einstein-dilaton Gauss-Bonnet ($\sqrt{\lvert\alpha_{\rm EdGB}\rvert}$ [km])	Equiv. Princ.	—	4.7	10^7, 2
scalar-tensor ($\lvert\dot{\phi}\rvert$ [1/sec])	Equiv. Princ.	—	—	10^{-6}
dynamical Chern-Simons ($\sqrt{\lvert\alpha_{\rm dCS}\rvert}$ [km])	Parity Inv.	—	—	10^8
Einstein-Æther (c_+, c_-)	Lorentz Inv.	$(\mathbf{0.9}, \mathbf{2.1})$	$(\mathbf{0.8}, \mathbf{1.1})$	$(0.03, 0.003)$
RS-II Braneworld (ℓ [μm])	4D	$\mathbf{5.4 \times 10^{10}}$	$\mathbf{2.0 \times 10^{9}}$	10–10^3
time-varying G ($\lvert\dot{G}\rvert/G$ [10^{-12}/yr])	Equiv. Princ.	$\mathbf{5.4 \times 10^{18}}$	$\mathbf{1.7 \times 10^{17}}$	0.1–1
Massive Gravity (m_g [eV])	$m_g = 0$	10^{-22}	10^{-22}	10^{-29}–10^{-18}
Modified Special Rel. ($\eta_{\rm dsrt}/L_{\rm Pl} > 0$)	Lorentz Inv.	$\mathbf{1.3 \times 10^{22}}$	$\mathbf{3.8 \times 10^{22}}$	—
Modified Special Rel. ($\eta_{\rm dsrt}/L_{\rm Pl} < 0$)				2.1×10^{-7}

graviton dispersion relation: $E^2 = (p\ c)^2 + A\ (p\ c)^\alpha$

[Mirshekari, Yunes & Will (2011)]