Theoretical Physics Implications of the Binary Black-Hole Merger GW150914

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Yunes, Yagi & Pretorius arXiv: 1603.08955

Direct GW Detection, at last!

SNR $= 24$
$D_L = 410\text{Mpc}$
$z = 0.09$

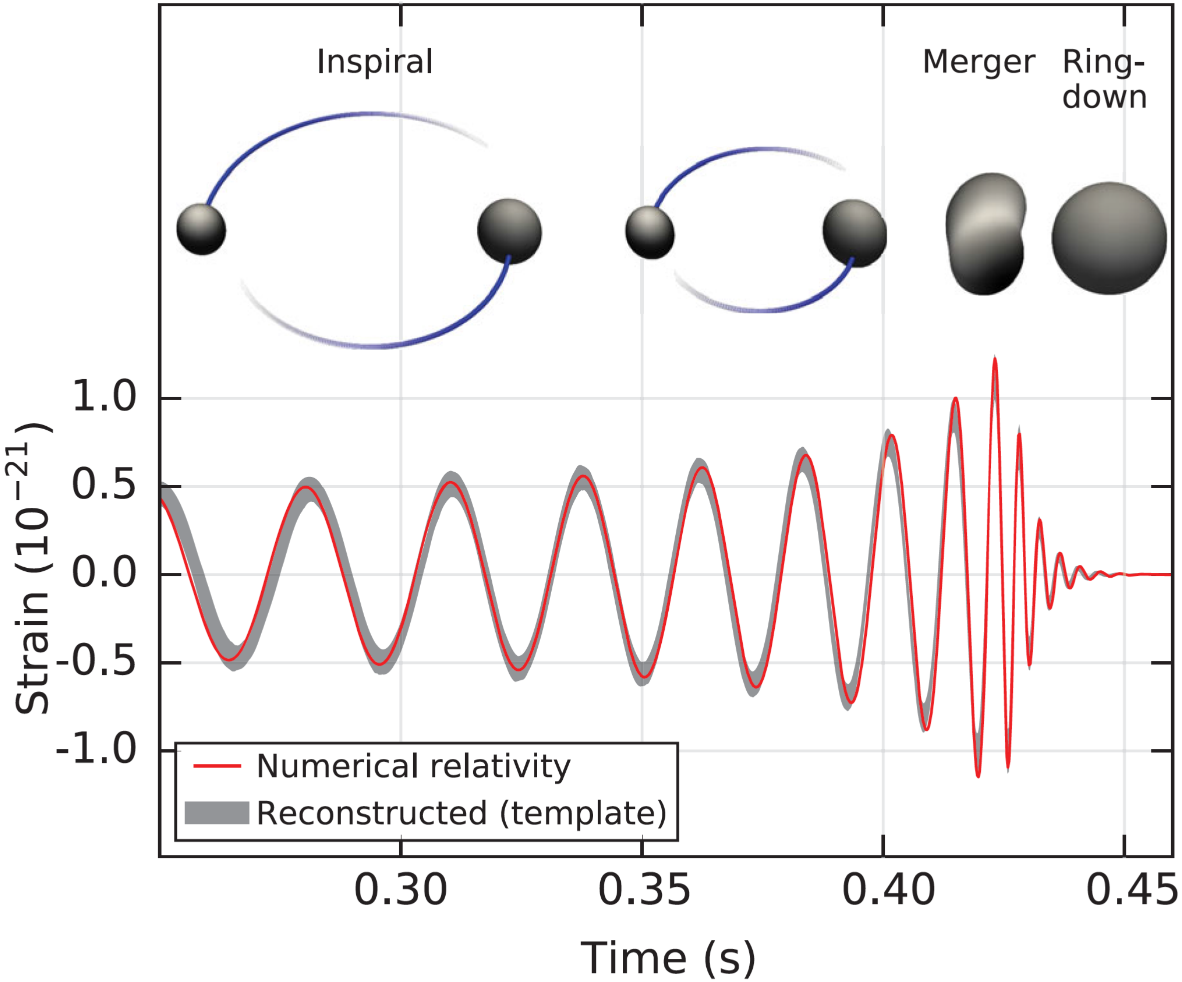
pre-merger

$m_1 = 36 M_\odot$
$m_2 = 29 M_\odot$
$\chi_1 \lesssim 0.7$
$\chi_2 \lesssim 0.9$

post-merger

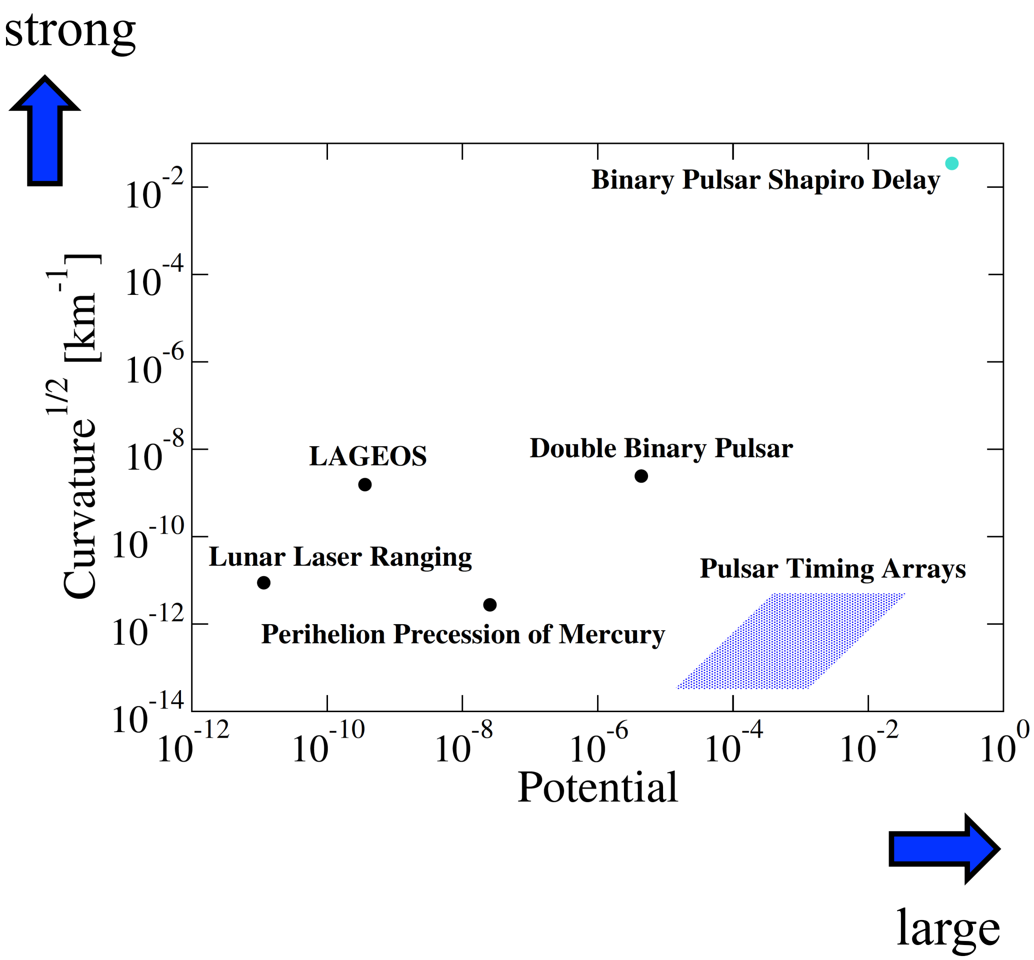
$M_f = 65 M_\odot$
$\chi_f = 0.67$

GW150914



[GW150914 Detection Paper]

Strong/Dynamical Nature of GW150914



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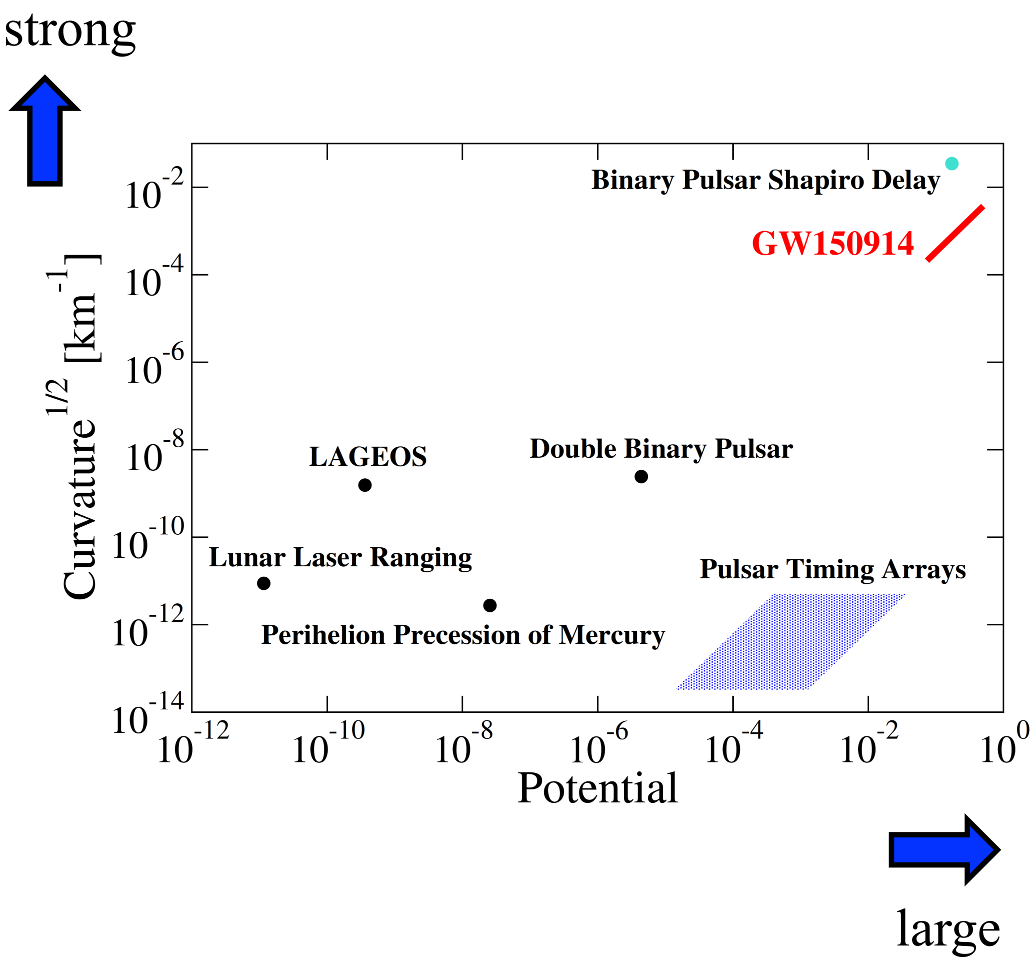

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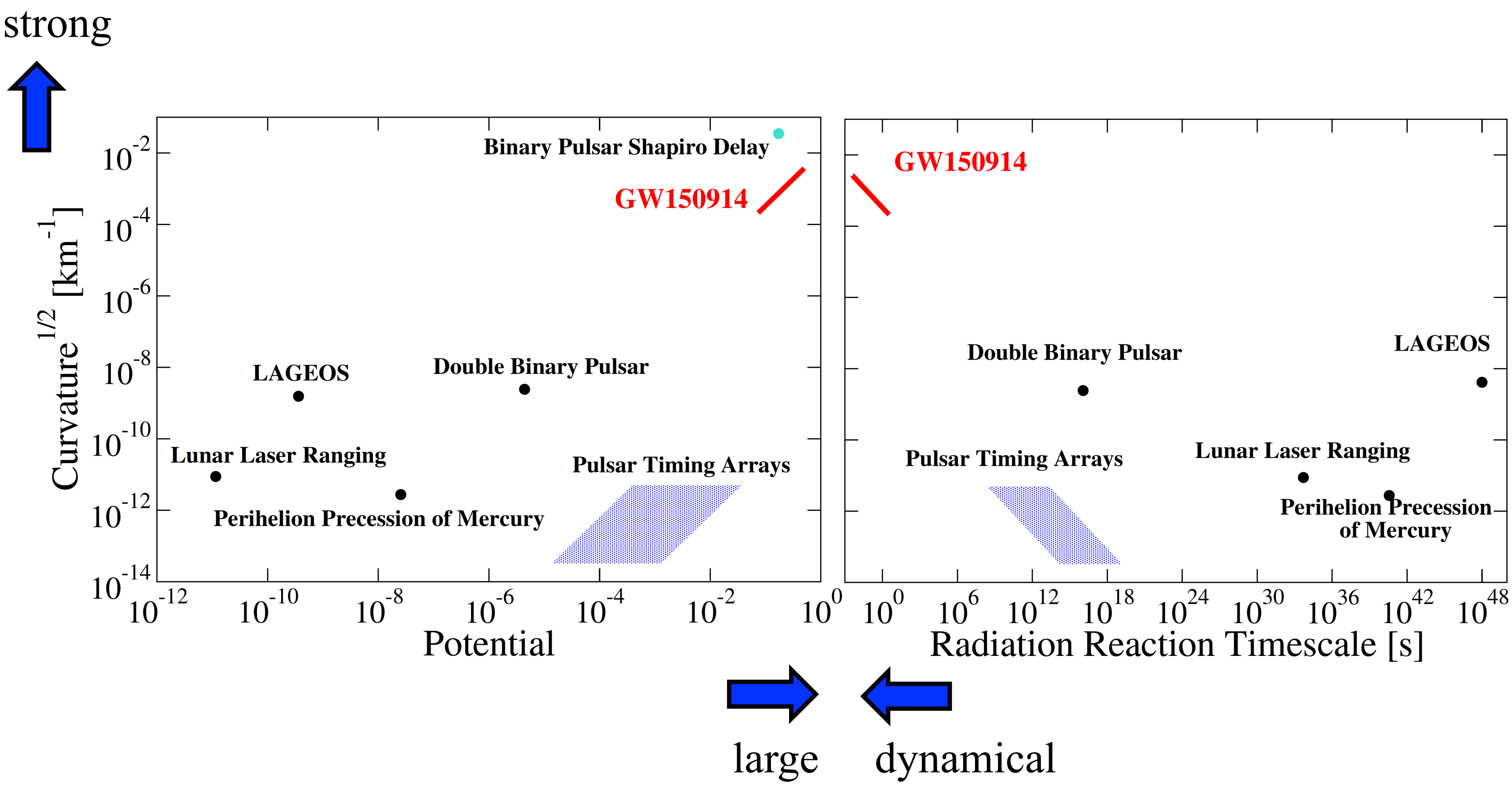

Testing GR with GW150914

[GW150914 Testing GR Paper]

Residual from GR template < 4%

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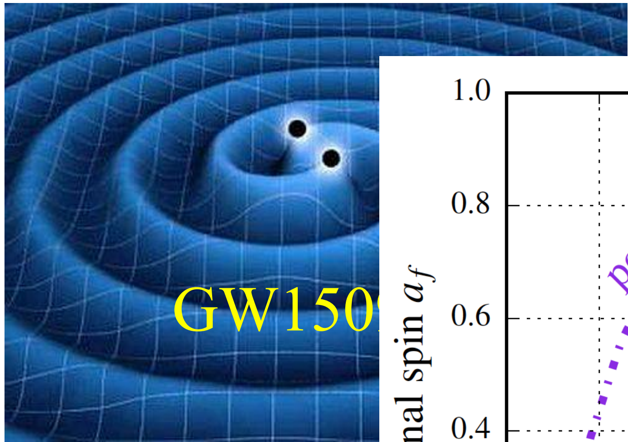
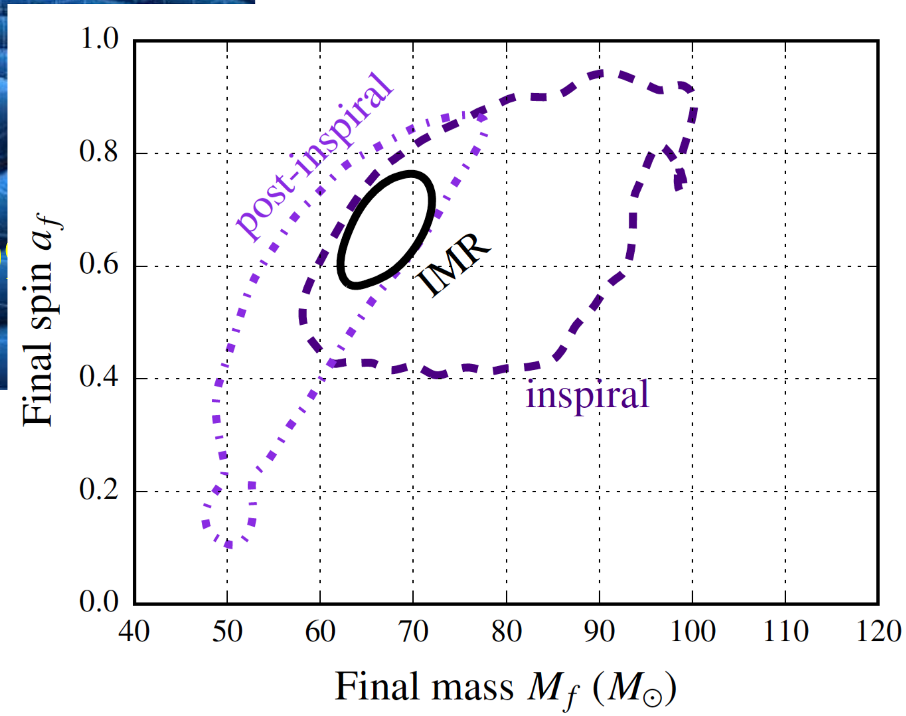
GR consistency in the final mass & spin





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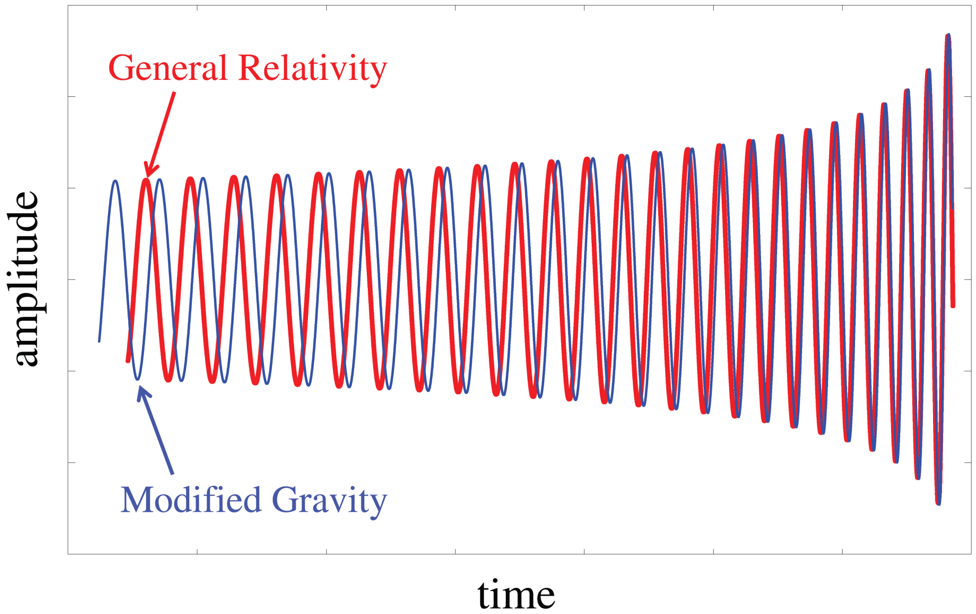
GR consistency in the final mass & spin

Constraining parameterized deviations from GR in the waveform

parameterized post-Einsteinian (ppE) Formalism

[Yunes & Pretorius (2009)]



Gravitational Waveform Phase (Inspiral)

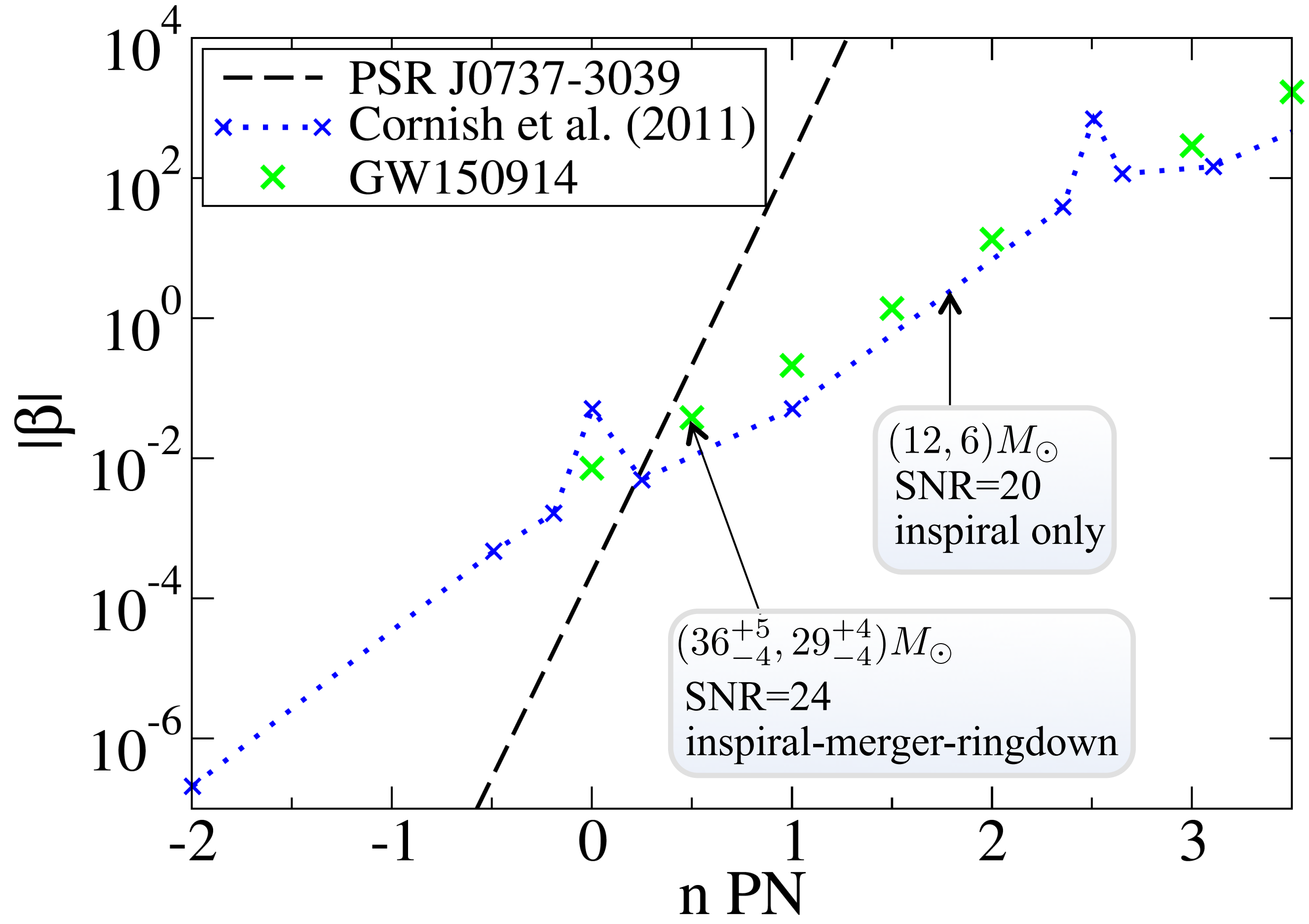
chirp mass: $\mathcal{M} = \left(\frac{m_1^3 m_2^3}{m_1 + m_2} \right)^{3/5}$

$$\Psi^{(\mathrm{insp})} = \Psi_{\mathrm{GR}}^{(\mathrm{insp})} + \beta (\pi \mathcal{M} f)^{(2n-5)/3}$$

n post-Newtonian (PN) correction relative to GR

$$v^2 \sim (\pi \mathcal{M} f)^{2/3} \ll 1$$

ppE parameter constraints from GW150914



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Constraining the graviton mass

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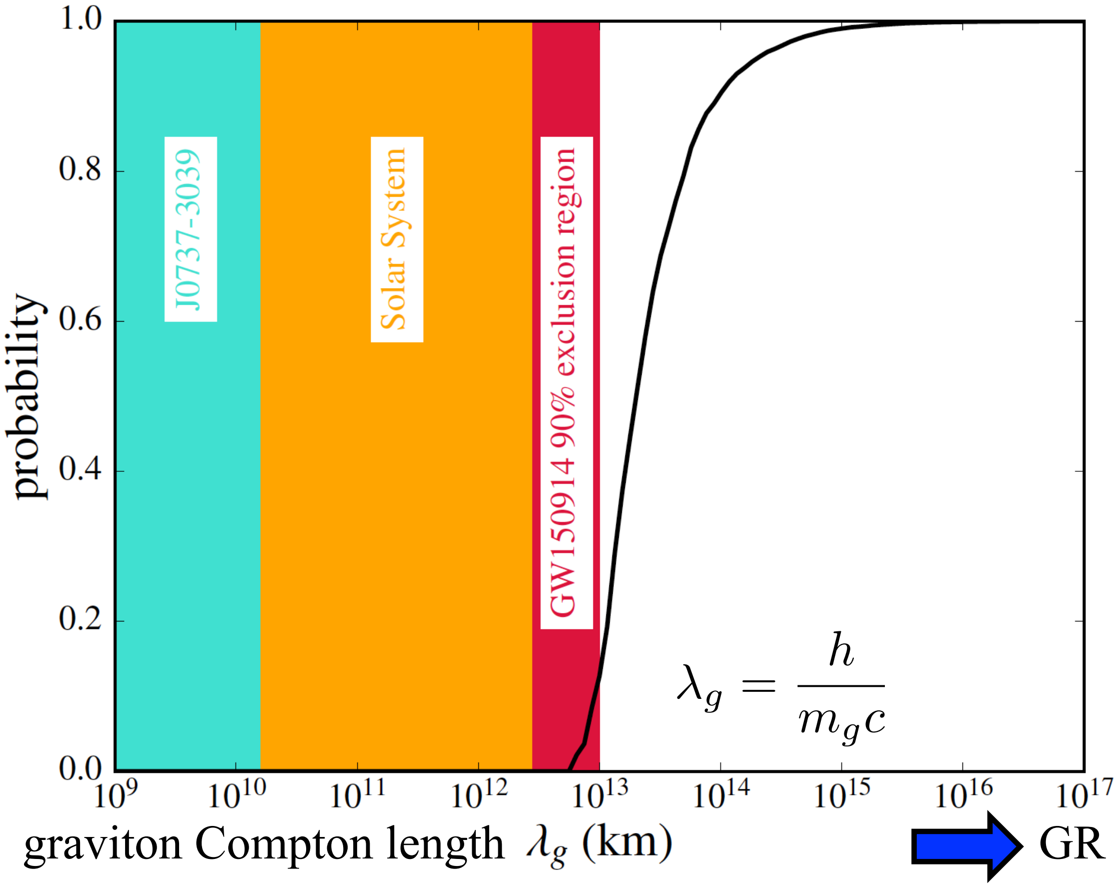


Constraining parameterized deviations from GR in the waveform

Constraining the graviton mass

What else can GW150914 tell us…?

-Was the remnant really a Kerr BH?

-Generic properties of the remnant?

-What do constraints on β mean physically?

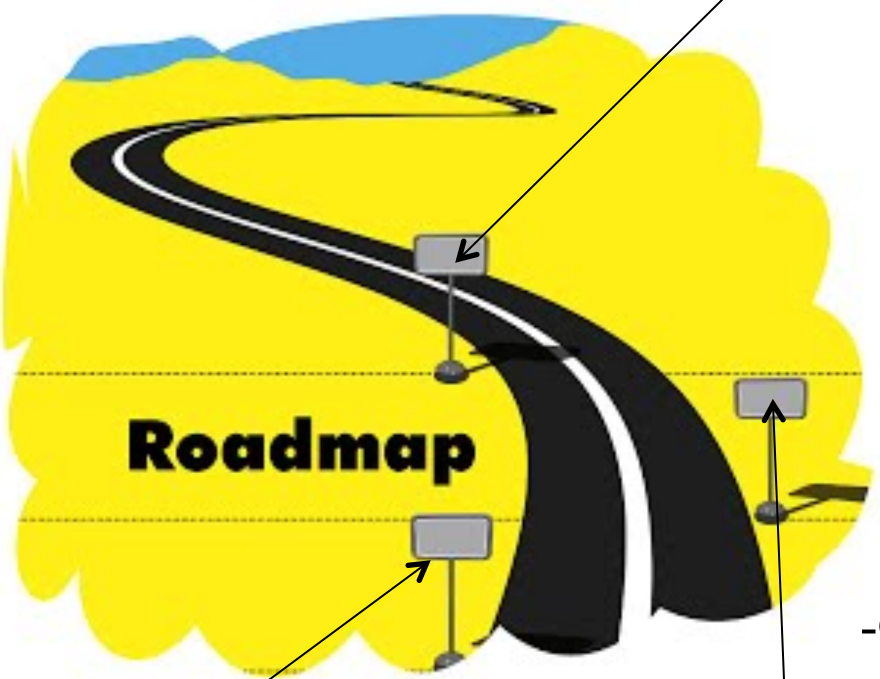
-Generic bounds on graviton propagation?

Roadmap

(III) Probing Exotic Compact Objects

-Was the remnant really a Kerr BH?

-Generic properties of the remnant?



-What do constraints on β mean physically?

(I) Constraining Generation Mechanisms

-Generic bound on graviton propagation?

(II) Constraining Propagation Mechanisms

Constraints on Generation Mechanisms

Fisher Analysis

-constraints on ppE parameters including negative PN orders

assumptions:

-Gaussian probability distribution

-large SNR [valid to $\mathcal{O}\left(\mathrm{SNR}^{-1}\right)$]

parameters:

$$\theta^i = (\mathcal{M}, \eta, D_L, ..., \beta)$$

η: $\frac{m_1 m_2}{(m_1+m_2)^2}$

measurement accuracy:

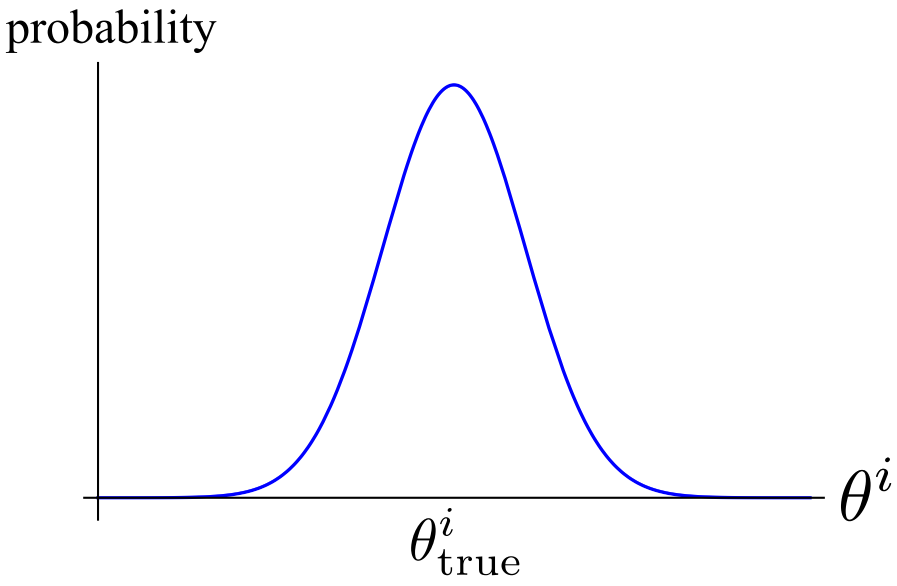
$$\Delta\theta^i = \sqrt{(\Gamma^{-1})_{ii}}$$

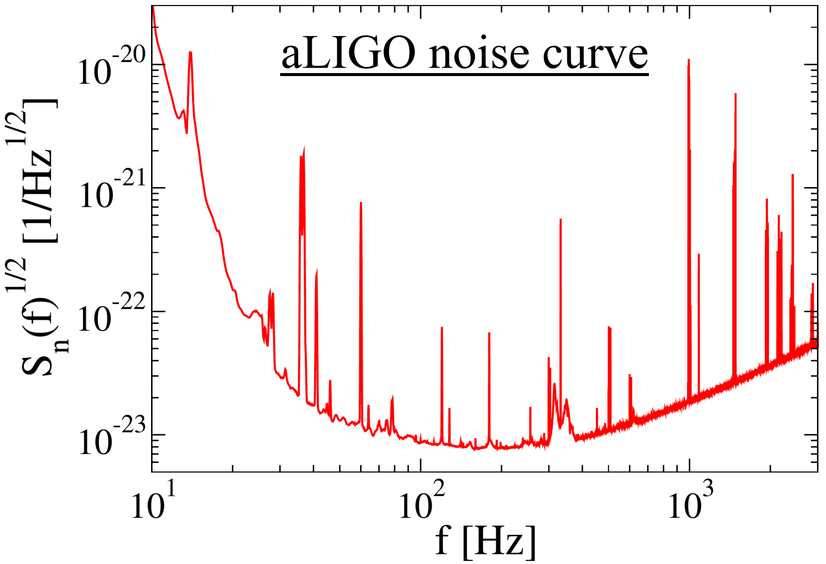
Fisher matrix

$$\Gamma_{ij} \equiv \left(\frac{\partial h}{\partial \theta^i} \middle| \frac{\partial h}{\partial \theta^j}\right)$$

inner product

$$(A|B) \equiv 4\Re \int_0^\infty \frac{\tilde{A}^*(f)\tilde{B}(f)}{S_n(f)} df$$

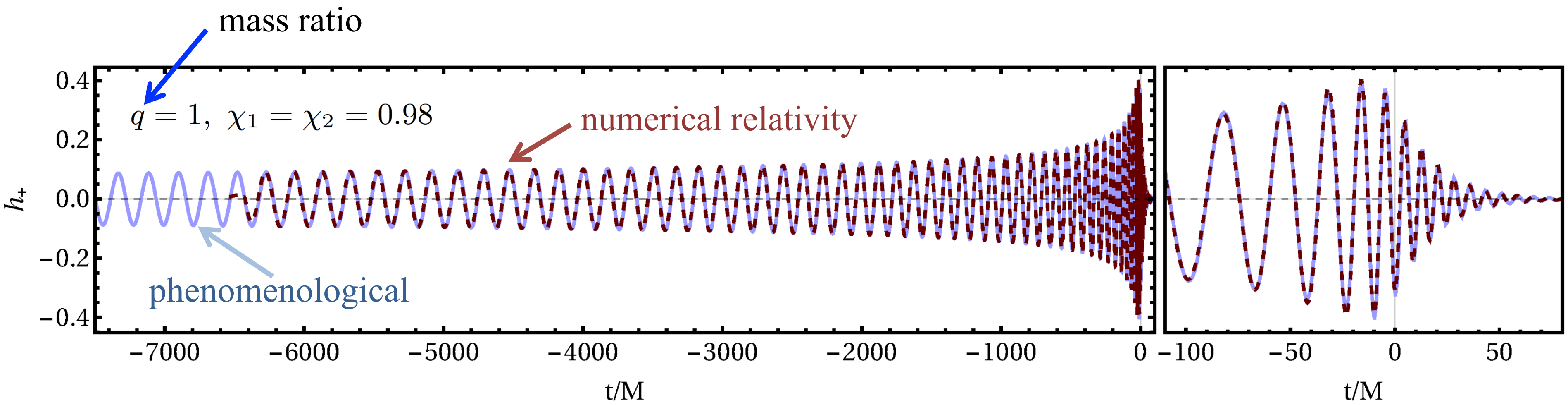




Phenomenological Waveform

[Khan et al (2016)]

-non-precessing inspiral-merger-ringdown phenomenological waveform in terms of $(m_1, m_2, \chi_1, \chi_2)$ in GR



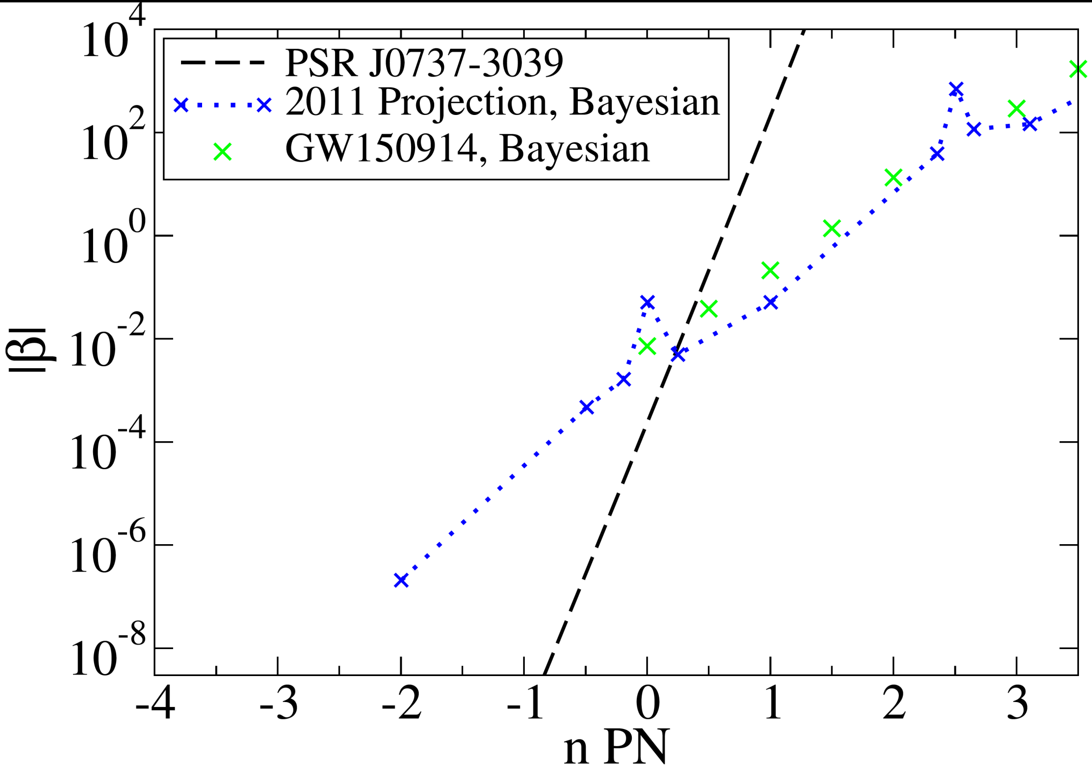
-adding ppE parameter correction only to the inspiral phase (due to lack of BH binary merger simulations in non-GR theories)

$$\Psi^{(\mathrm{insp})} = \Psi^{(\mathrm{insp})}_{\mathrm{GR}} + \beta(\pi \mathcal{M} f)^{(2n-5)/3}$$

-Injection: GR waveform consistent with GW150914

-Template: ppE modified waveform

Constraining GR Fundamental Pillars



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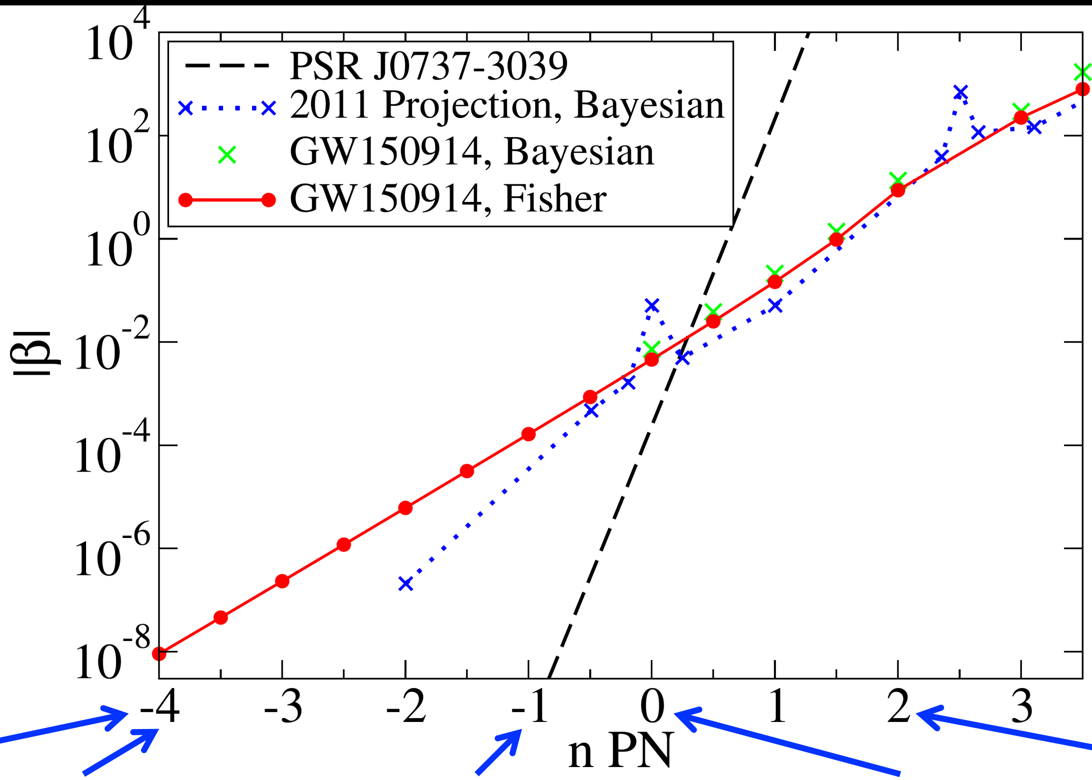


- extra dimension → 4D
- time varying G → strong equivalence principle (SEP)
- scalar monopole activation → SEP
- vector field activation → Lorentz invariance
- scalar dipole activation → parity invariance

GW150914 vs Current Bounds

GR Pillar	PN	$\lvert\beta\rvert$ GW150914	Example Theory Constraints: Repr. Parameters	GW150914	Current Bounds
SEP	-1	$\mathbf{1.6 \times 10^{-4}}$	$\sqrt{\lvert\alpha_{\rm EdGB}\rvert}$ [km]	—	10^7 [39], 2 [40–42]
SEP, No BH Hair	-1	$\mathbf{1.6 \times 10^{-4}}$	$\lvert\dot{\phi}\rvert$ [1/sec]	—	10^{-6} [43]
SEP, Parity Invariance	$+2$	$\mathbf{1.3 \times 10^{1}}$	$\sqrt{\lvert\alpha_{\rm CS}\rvert}$ [km]	—	10^8 [44, 45]
SEP, Lorentz Invariance	0	$\mathbf{7.2 \times 10^{-3}}$	(c_+, c_-)	$(\mathbf{0.9}, \mathbf{2.1})$	$(0.03, 0.003)$ [46, 47]
4D spacetime	-4	$\mathbf{9.1 \times 10^{-9}}$	ℓ [μm]	$\mathbf{5.4 \times 10^{10}}$	10–10^3 [48–52]
SEP	-4	$\mathbf{9.1 \times 10^{-9}}$	$\lvert\dot{G}\rvert$ [10^{-12}/yr]	$\mathbf{5.4 \times 10^{18}}$	0.1–1 [53–57]

Einstein-dilaton Gauss-Bonnet (EdGB)
Scalar-Tensor
dynamical Chern-Simons (CS)

→ no meaningful constraints (beyond small-coupling approximation)

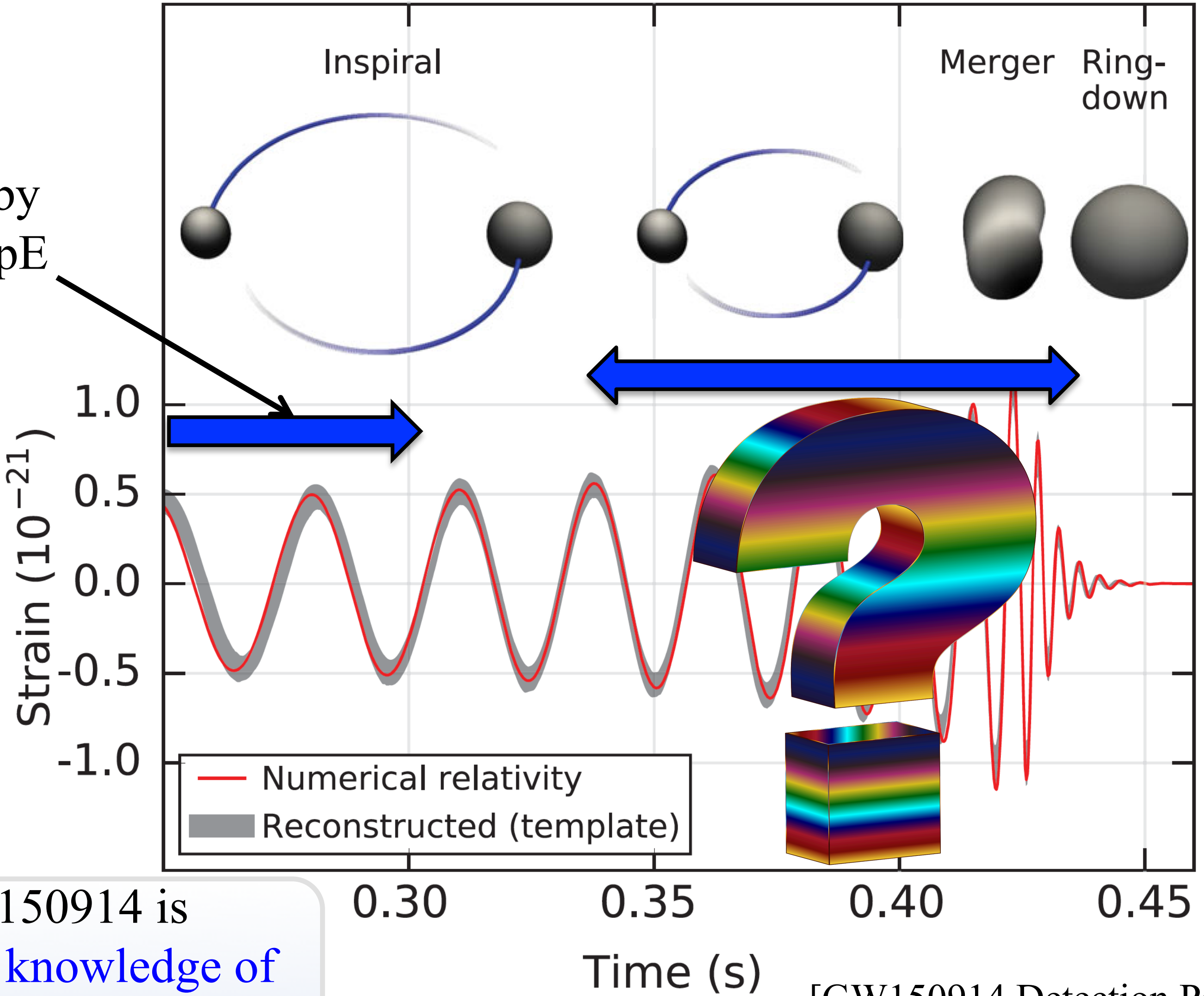
Einstein-AEther
Extra Dimension
Time-varying G

→ -weaker than current bounds

-first constraint in the extreme gravity regime

Why GW bounds so weak…?

captured by
inspiral ppE



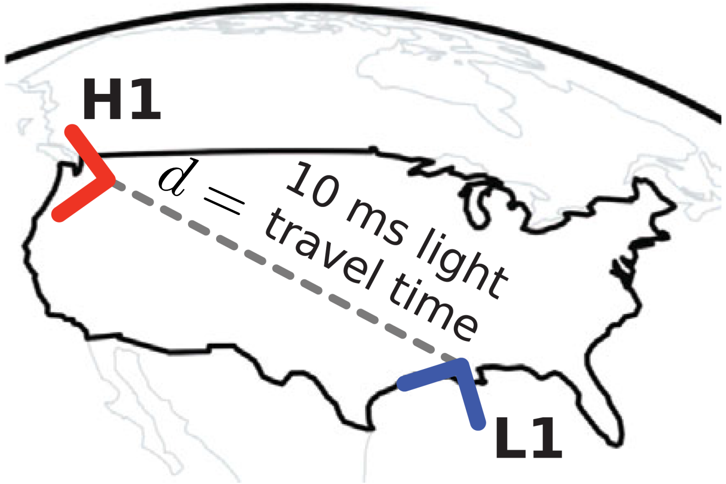
[GW150914 Detection Paper]

True potential of GW150914 is limited by the lack of knowledge of the merger phase in non-GR theories.

Constraints on Propagation Mechanisms

GW150914 Constraint on GW propagation speed

Constraining the propagation speed of the graviton v_g via the arrival time delay between Hanford and Livingston. [Blas et al. (2016)]



[GW150914 Detection Paper]

Observed time delay:

$$\Delta t = 6.9^{+0.5}_{-0.4} \text{ ms}$$

Upper bound:

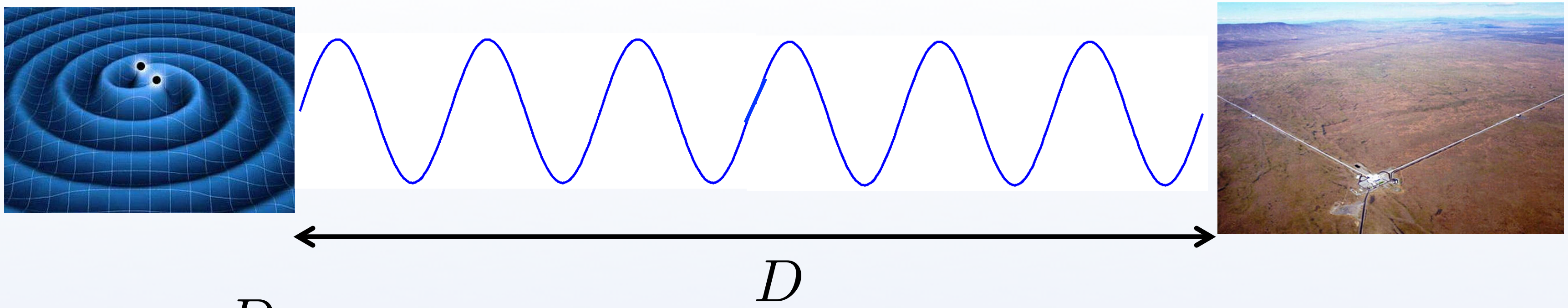
$$v_g \Delta t \leq d \quad \Rightarrow \quad v_g \leq 1.7$$

GW Propagation and ppE parameter

-graviton dispersion relation $E^2 = p^2 + Ap^\alpha$ [Mirshekari et al. (2011)]

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

-ppE parameter



$$\Psi \sim 2\pi f \frac{D}{v_g} \Rightarrow \Psi - \Psi_{\rm GR} \sim A D \mathcal{M}^{1-\alpha} (\pi \mathcal{M} f)^{\alpha - 1}$$

-propagation vs generation in massive gravity

$$\frac{\Psi^{(\rm prop, 1PN)}}{\Psi^{(\rm gen, -3PN)}} \sim 10^{18} \left(\frac{\mathcal{M}}{28 M_\odot}\right)^{5/3} \left(\frac{D}{410 \rm Mpc}\right) \left(\frac{f}{100 \rm Hz}\right)^{8/3}$$

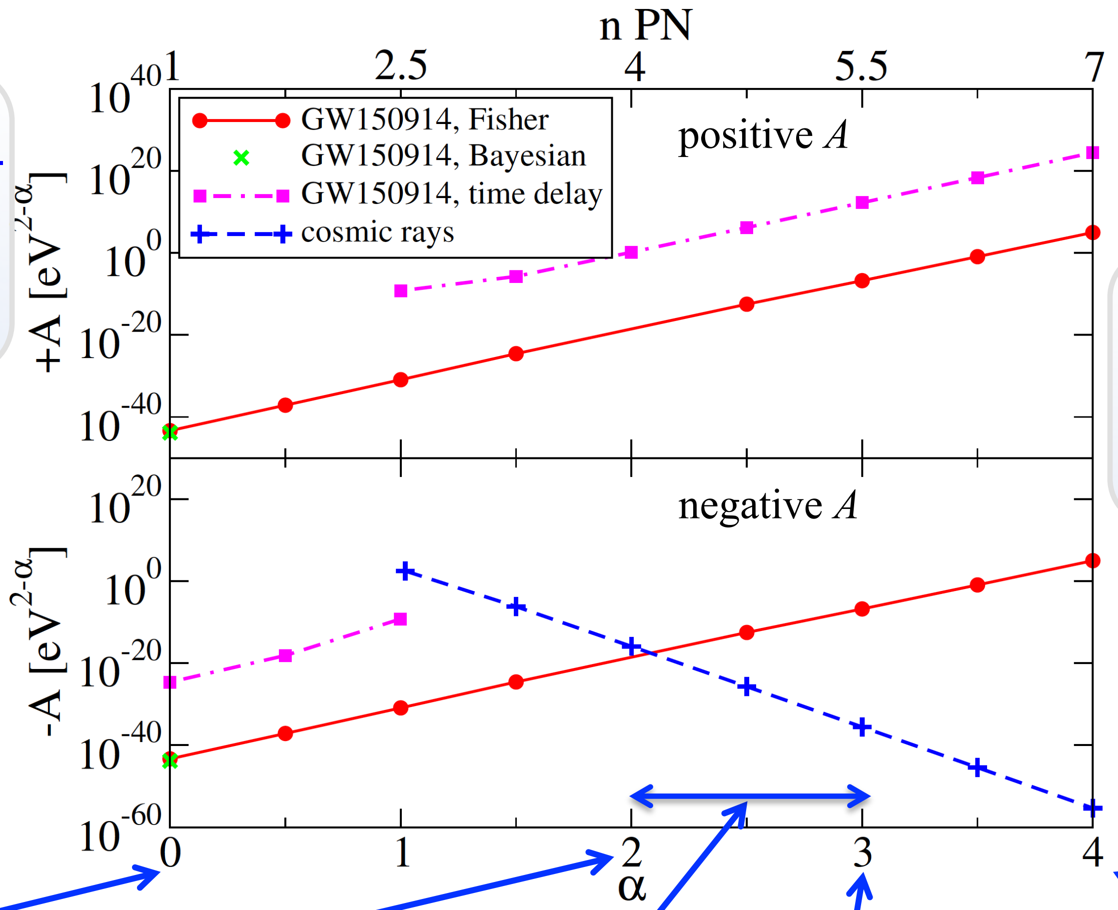
Propagation dominates generation due to accumulation over distance.

Bounds on the Propagation Mechanisms

$$E^2 = p^2 + Ap^\alpha$$

-ppE modification in inspiral-merger-ringdown

-Fisher analysis



-strong constraints from GW150914

-complementary to cosmic ray bounds

-massive gravity

-Lorentz violation

-multifractional spacetime

-Lorentz violation
-mod. special relativity

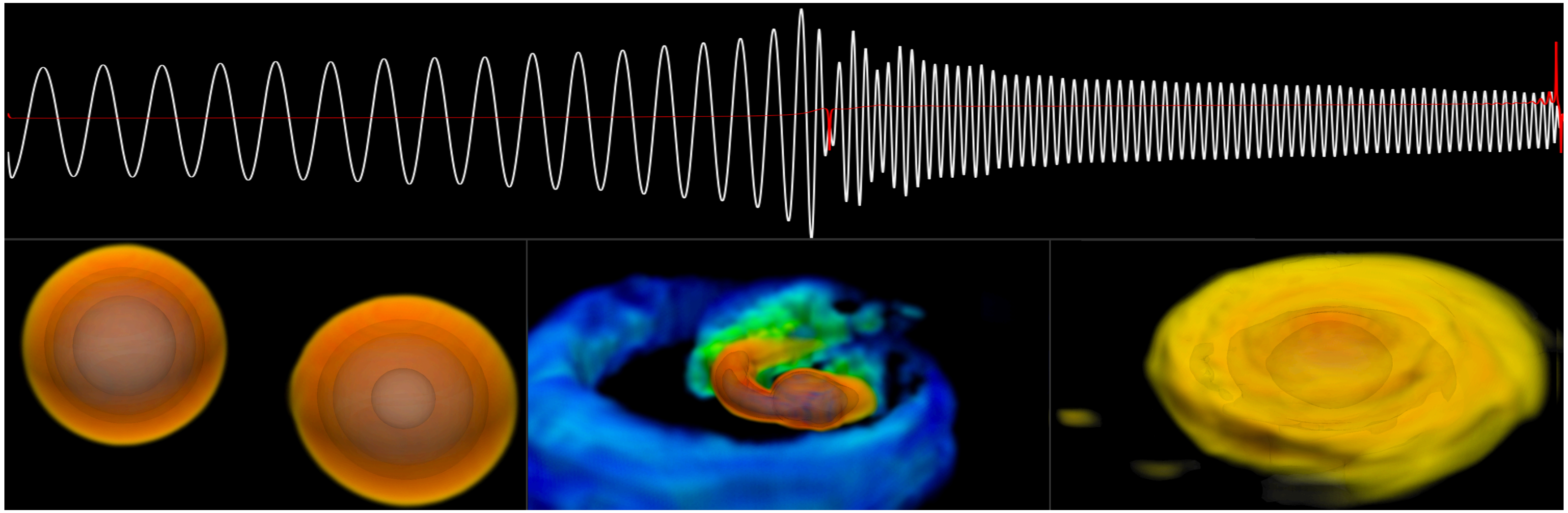
-Lorentz violation
-extra dimension

Probing Exotic Compact Objects

Effective Viscosity of the Remnant

What are effective hydrodynamic properties (in particular viscosities) of the GW150914 remnant?

c.f.) NS/NS merger



http://www.fis.unipr.it/~sebastiano.bernuzzi/images/BNSWave2.png

-longer-lived ringdown

-smaller viscosities than BHs

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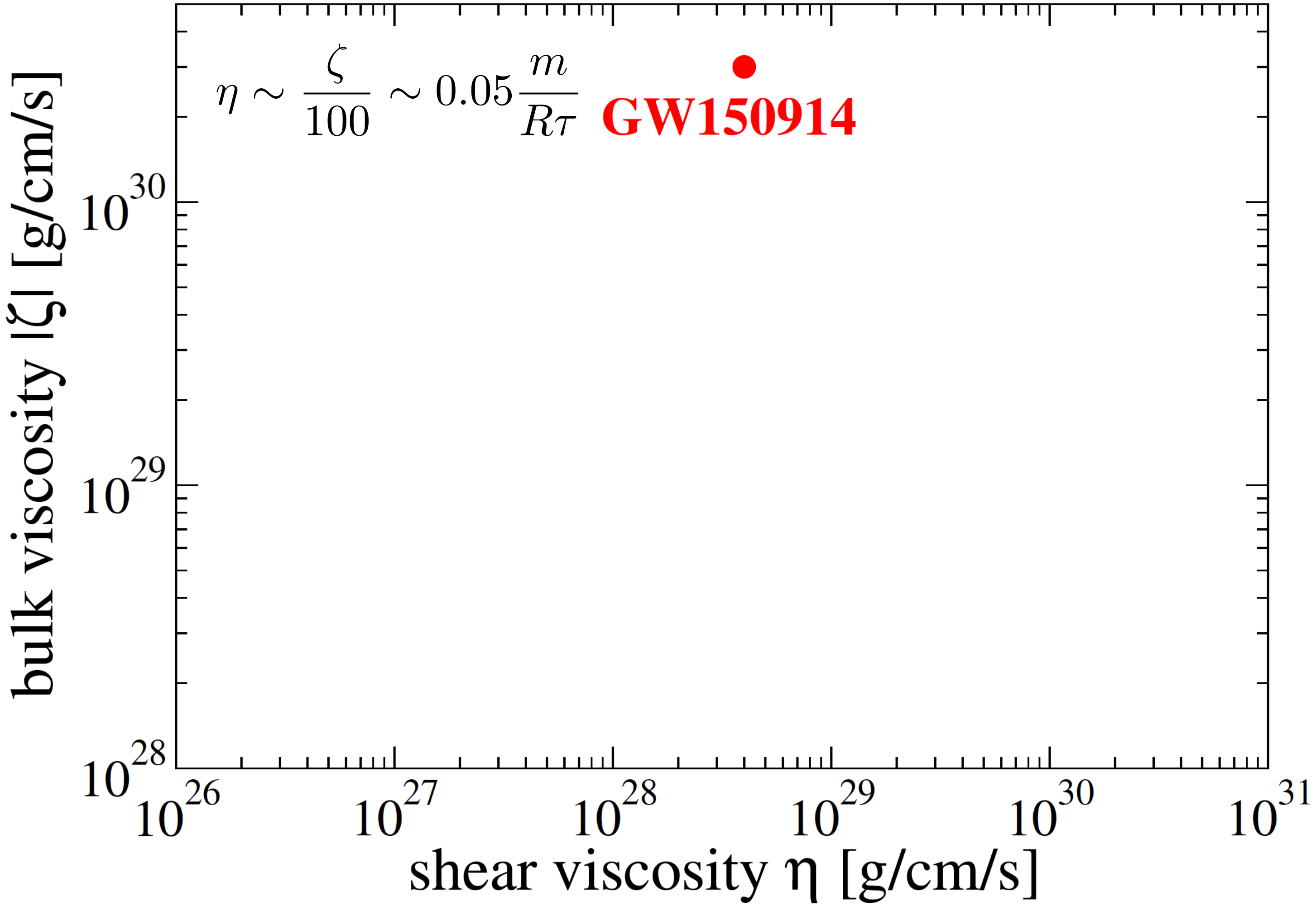

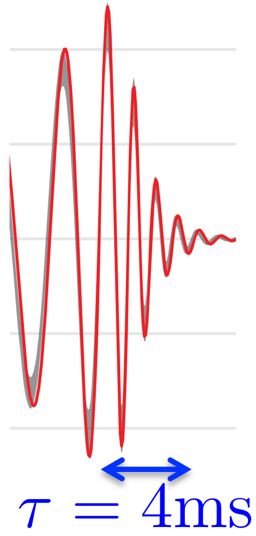

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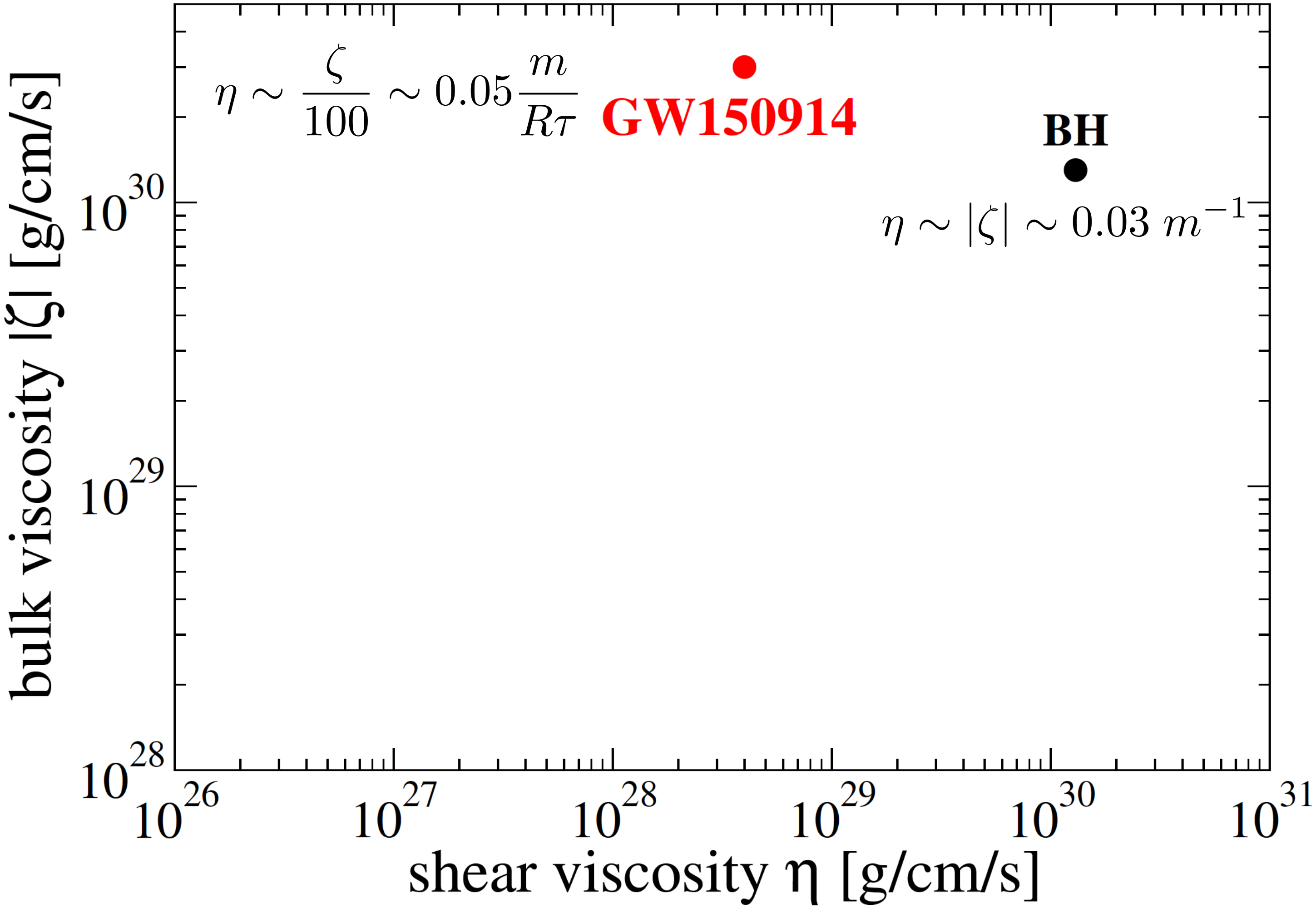

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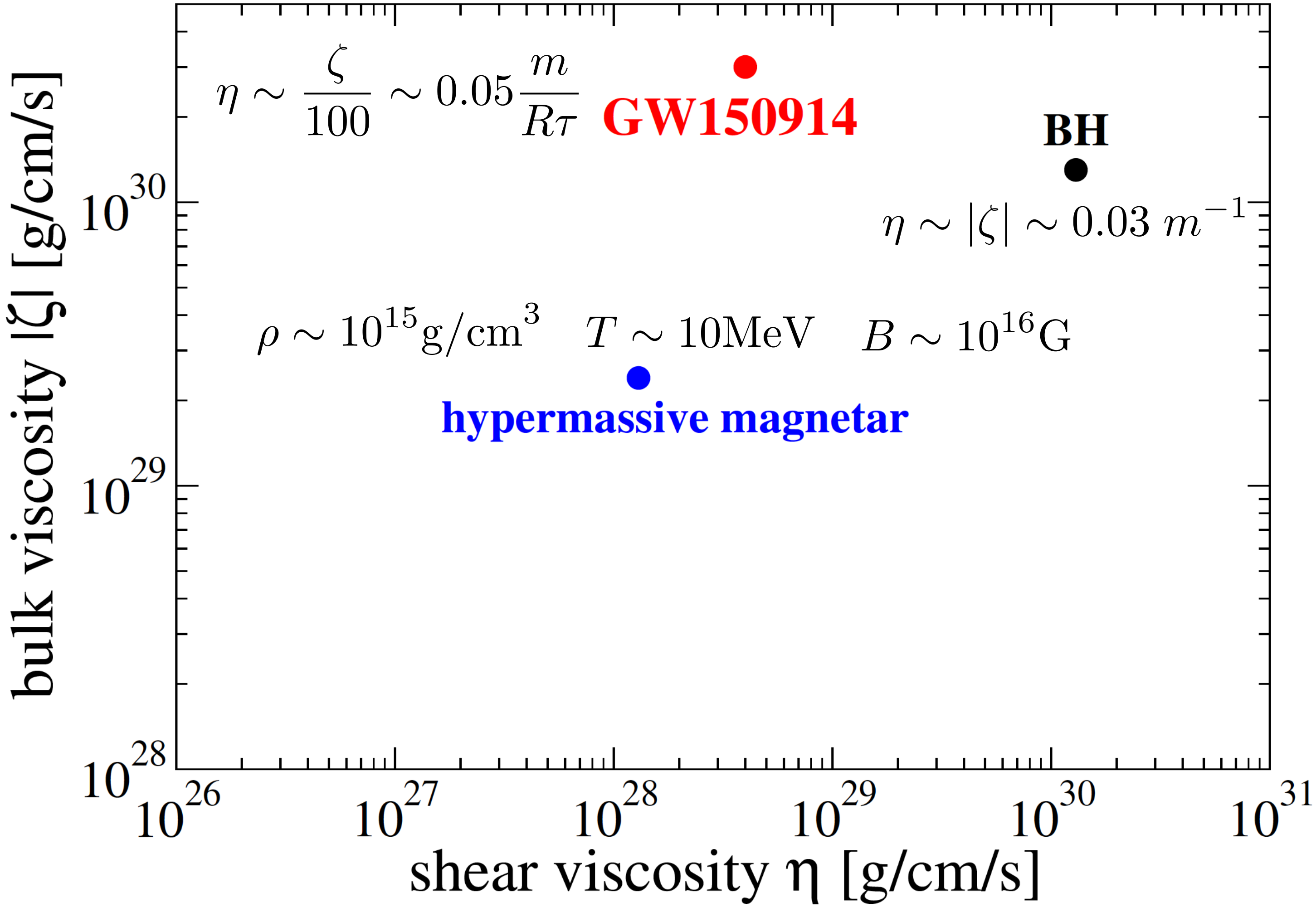

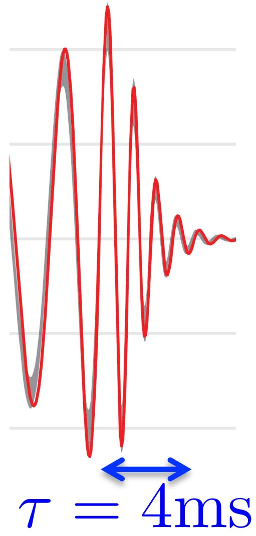

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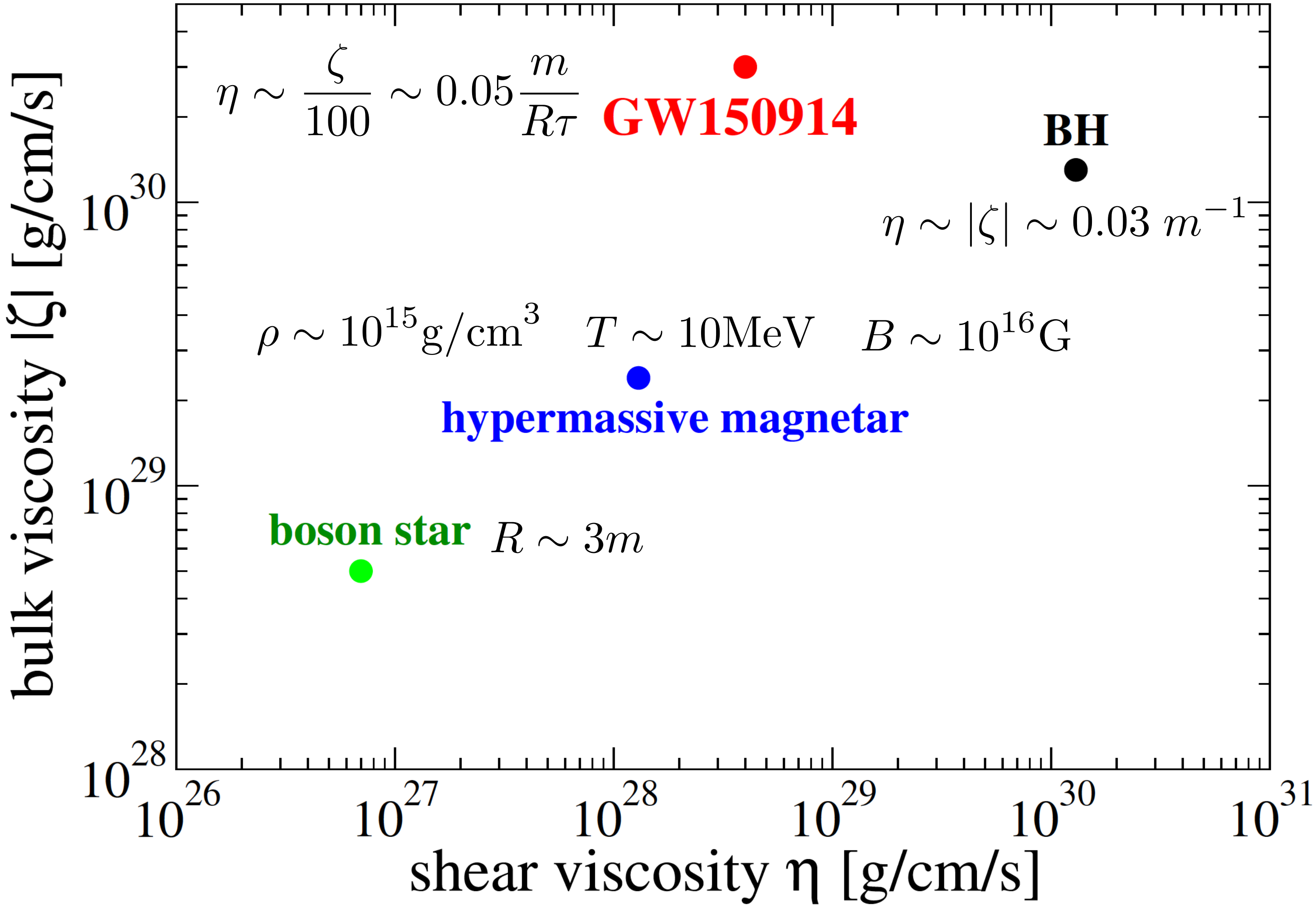
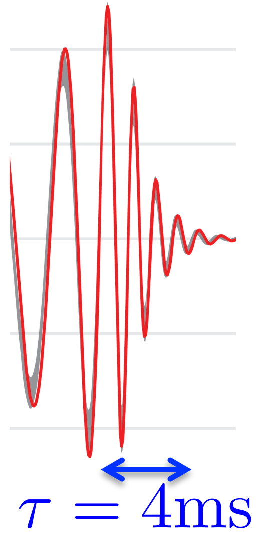


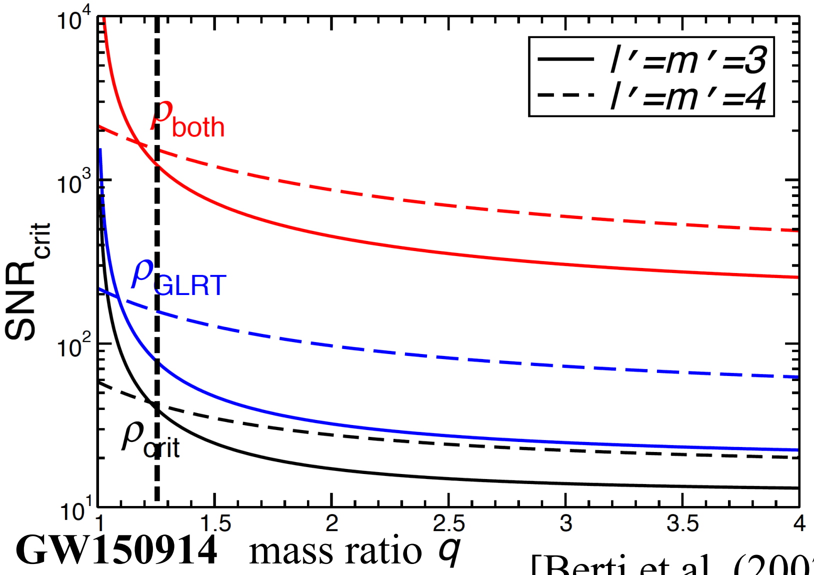


Additional Oscillation Modes

-BHs

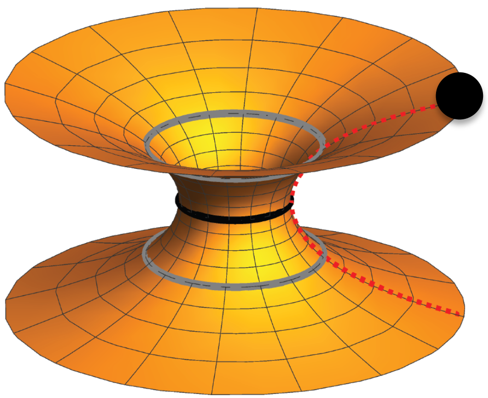
For GW150914, the dominant sub-leading mode is $\ell = m = 3$

Need ringdown SNR of ~80 to detect this additional mode



[Berti et al. (2007)]

-wormholes



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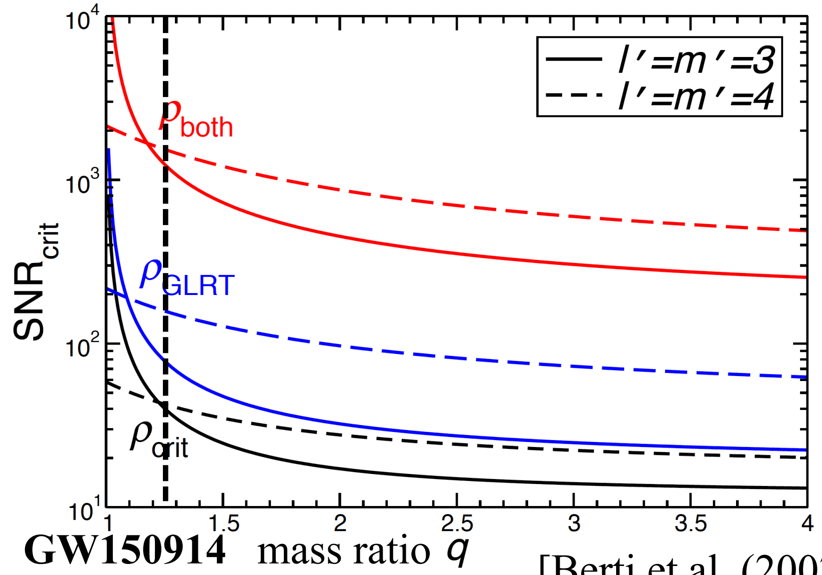
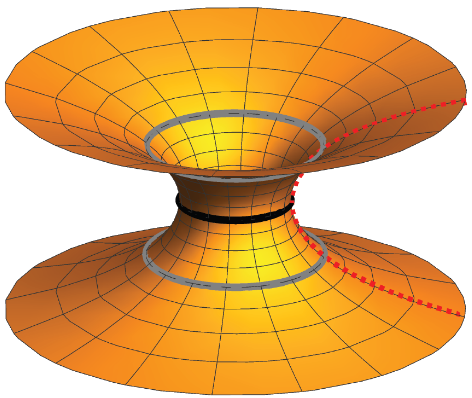
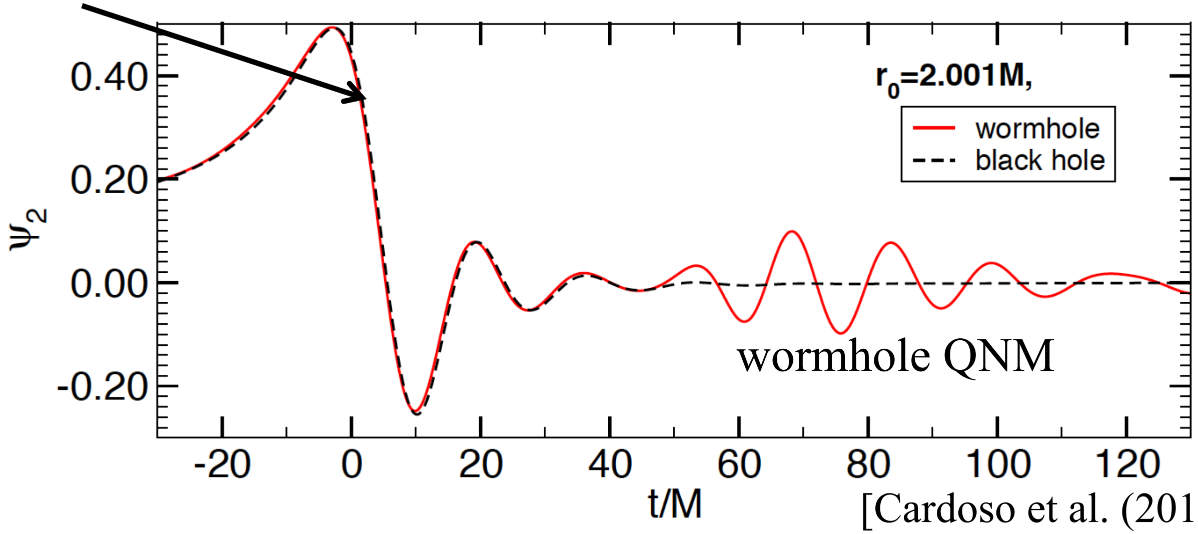


[Berti et al. (2007)]

-wormholes

primary oscillation similar to BH quasi-normal mode (QNM)

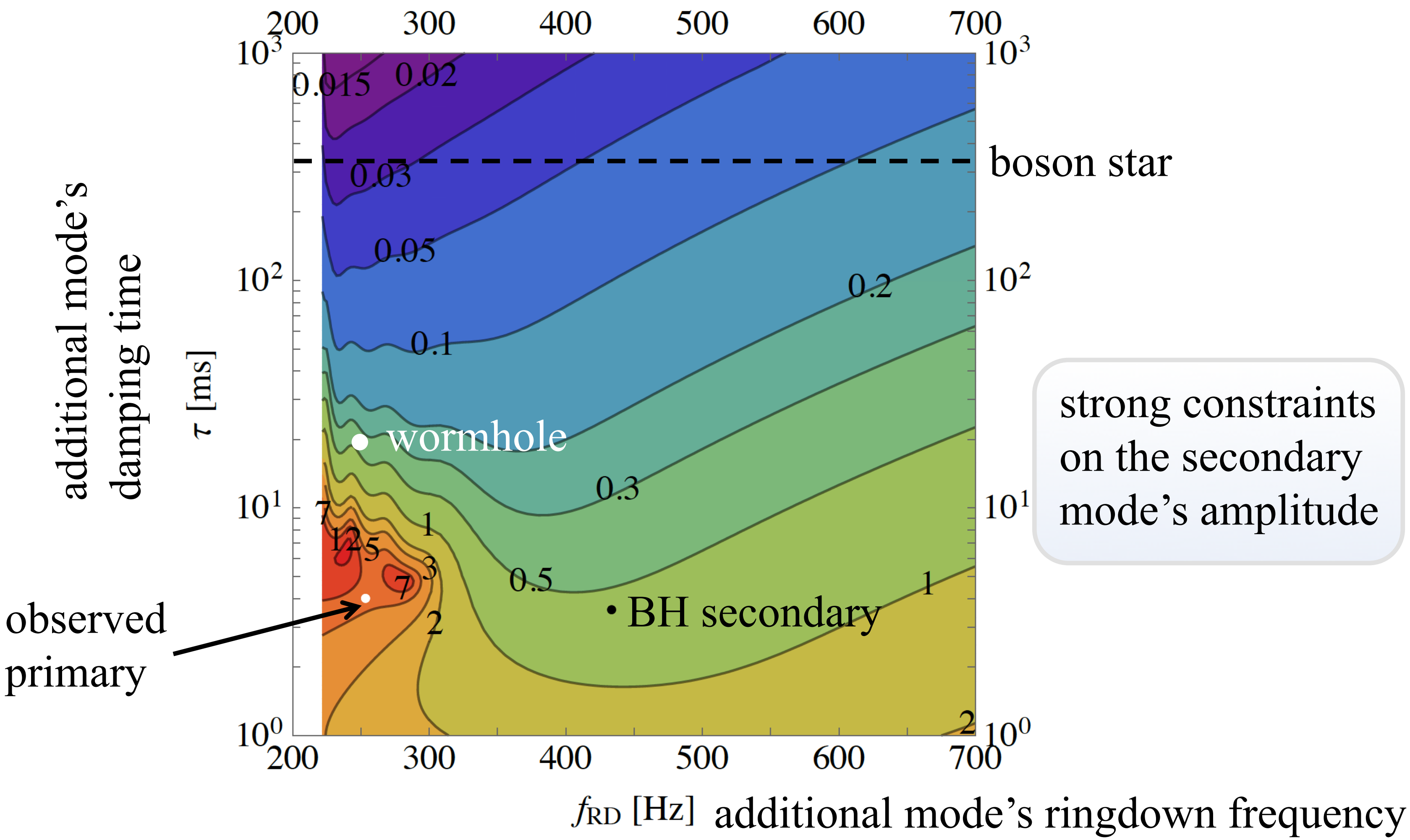




[Cardoso et al. (2016)]

Bounds on Additional Oscillation Modes

-bounds on the additional oscillation mode amplitude relative to the observed primary one



strong constraints on the secondary mode's amplitude

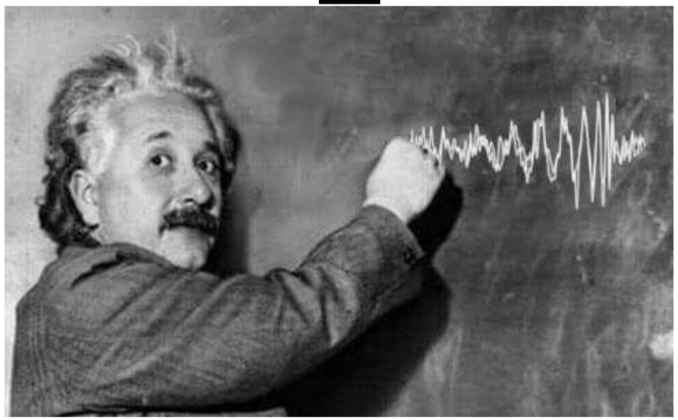
Conclusions

Takeaway

generation mechanisms:
-weak bound
-first extreme gravity constraint

Bounds will further improve due to

-better sensitivity
 (larger SNR)
-different masses
-stacking different sources



THANK YOU!!

https://igoligo.wordpress.com/2016/02/12/einstein-was-right/

propagation mechanisms:
-strong bound
-complementary to cosmic rays

exotic compact objects:
-large effective viscosity
-small additional oscillation amplitude