Title: What does the Advanced LIGO detection say about gravity?

Date: Jun 15, 2016 03:00 PM

URL: http://pirsa.org/16060016

Abstract: The gravitational-wave observation GW150914 by Advanced LIGO provides the first opportunity to learn about theoretical physics mechanisms that may be present in the extreme gravity environment of coalescing binary black holes. The LIGO collaboration verified that this observation is consistent with Einstein's theory of General Relativity, constraining the presence of parametric anomalies in the signal. In this talk, I will discuss the plethora of additional inferences about gravity that can be drawn from the absence of such anomalies in the LIGO observation. I will focus and classify these inferences into those that inform us about the generation of gravitational waves (e.g. the activation of scalar fields, black hole graviton leakage into extra dimensions, the variability of Newton's constant, the breakage of Lorentz invariance and parity invariance), and the propagation of gravitational waves (e.g. the speed of gravity and the existence of large extra dimensions). I will conclude with a discussion of how these inferences may inform us about the models of modified gravity in cosmology.

What does the Advanced LIGO detection say about theoretical physics in extreme gravity ?

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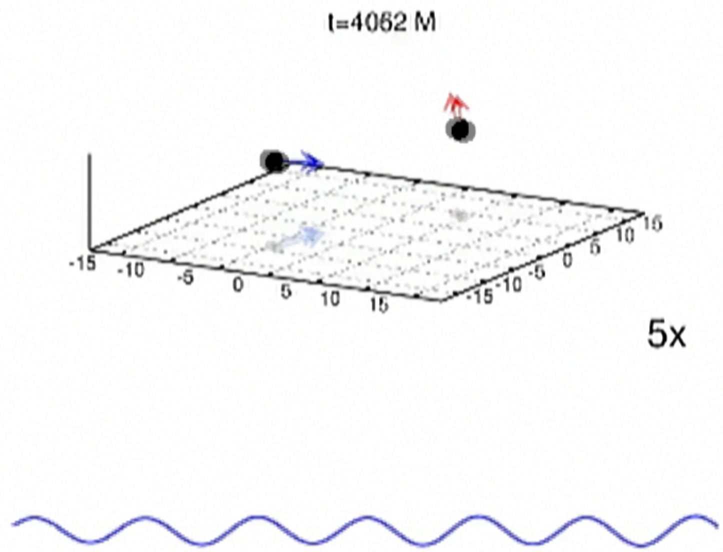
Cosmological Frontiers in Fundamental Physics 2016
Perimeter Institute, June 15th, 2016

Yunes, Yagi & Pretorius, arXiv: 1603.08955

What is eXtreme Gravity?

Definition: where gravity is
(a) strong
(b) non-linear
(c) dynamical

[RIT Group, Drasco]



Production of GWs: Accelerating masses (t-variation in multipoles)

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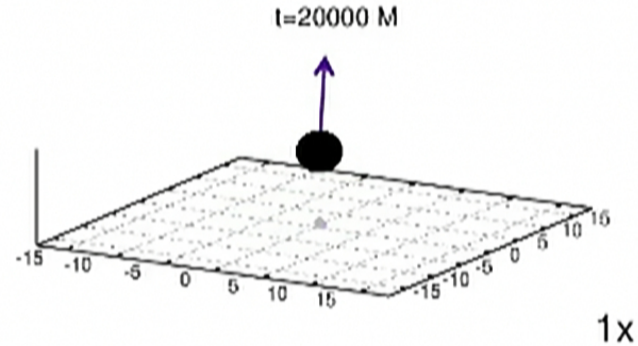
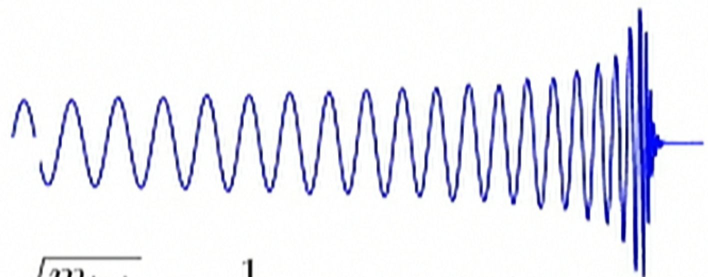


Production of GWs: Accelerating masses (t-variation in multipoles)

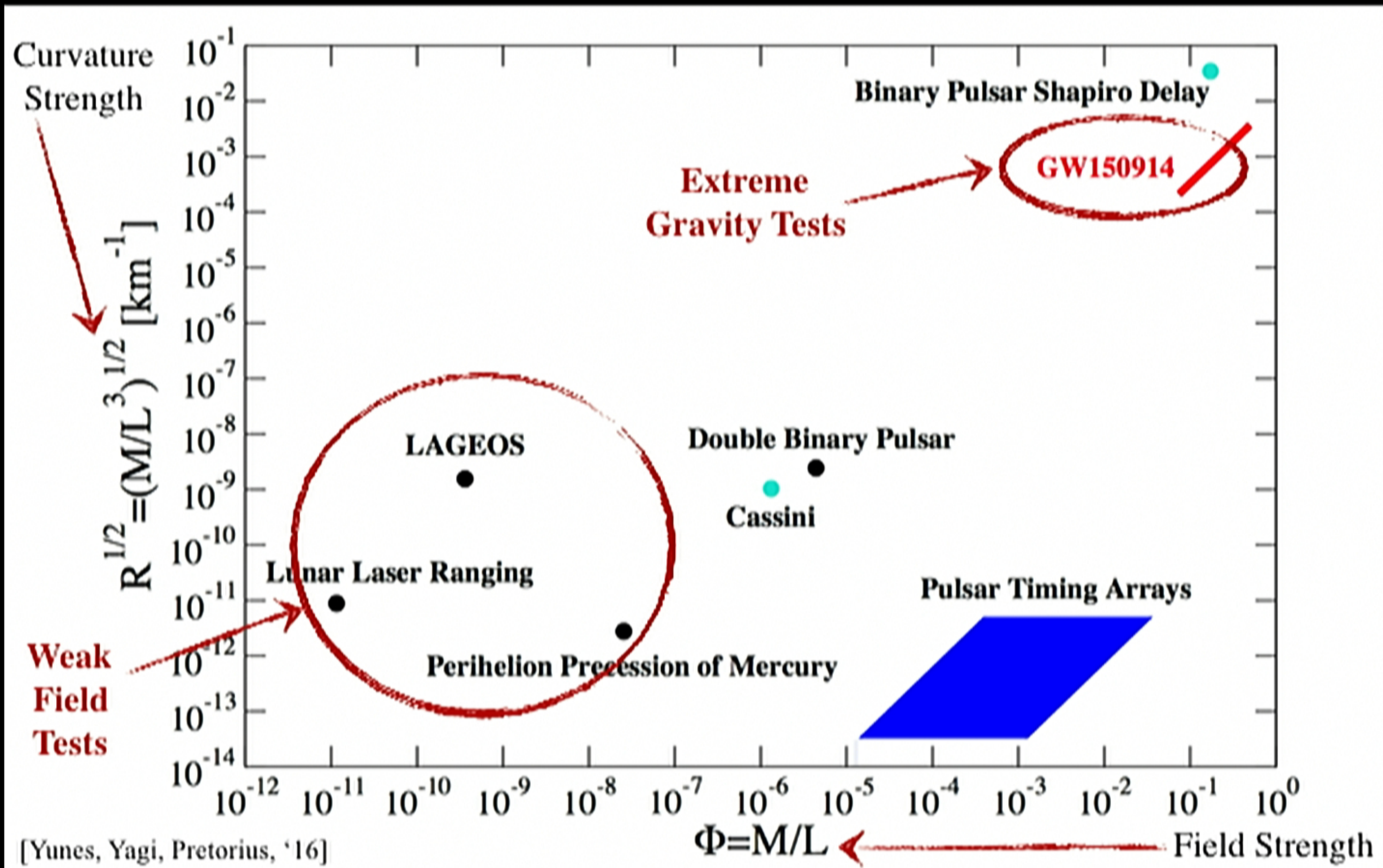
Propagation of GWs: Light speed, weakly interacting, 1/R decay.



GW Spectrum: Kepler 3rd Law: $2\pi f = \sqrt{\frac{m_{\rm tot}}{r_{12}^3}} \sim \frac{1}{m_{\rm tot}}, \; E_{\rm rad} \sim 3\% \, m_{\rm tot}$

Eg: A Binary BH merger, $E_{\rm rad} \sim 3 \times 10^{54} \, {\rm erg} \left(\frac{\epsilon}{3\%}\right) \left(\frac{M}{65 M_\odot}\right) \sim 1000 E_{\rm SN}$

Probing Extreme Gravity with GW150904



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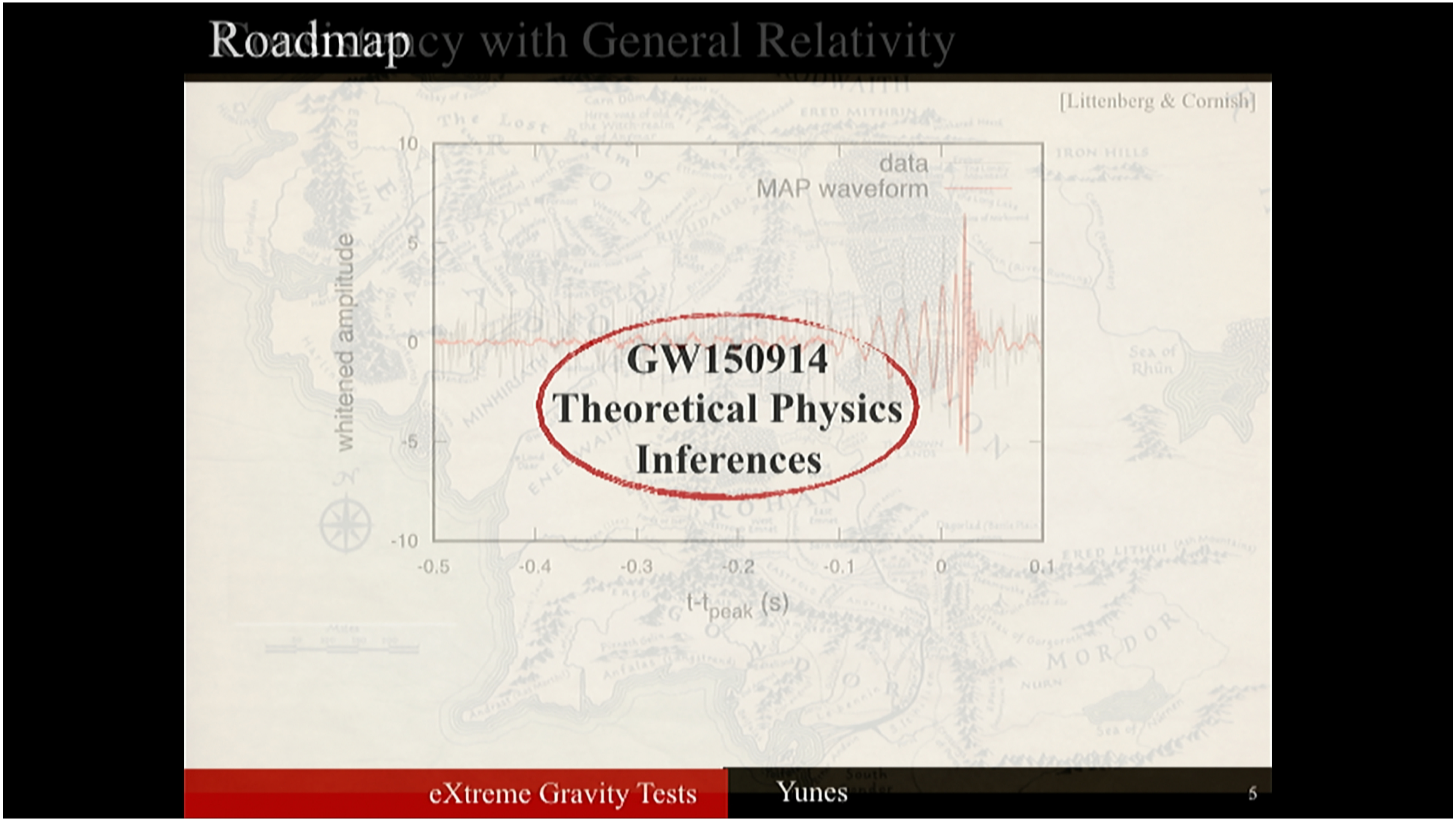
Roadmap

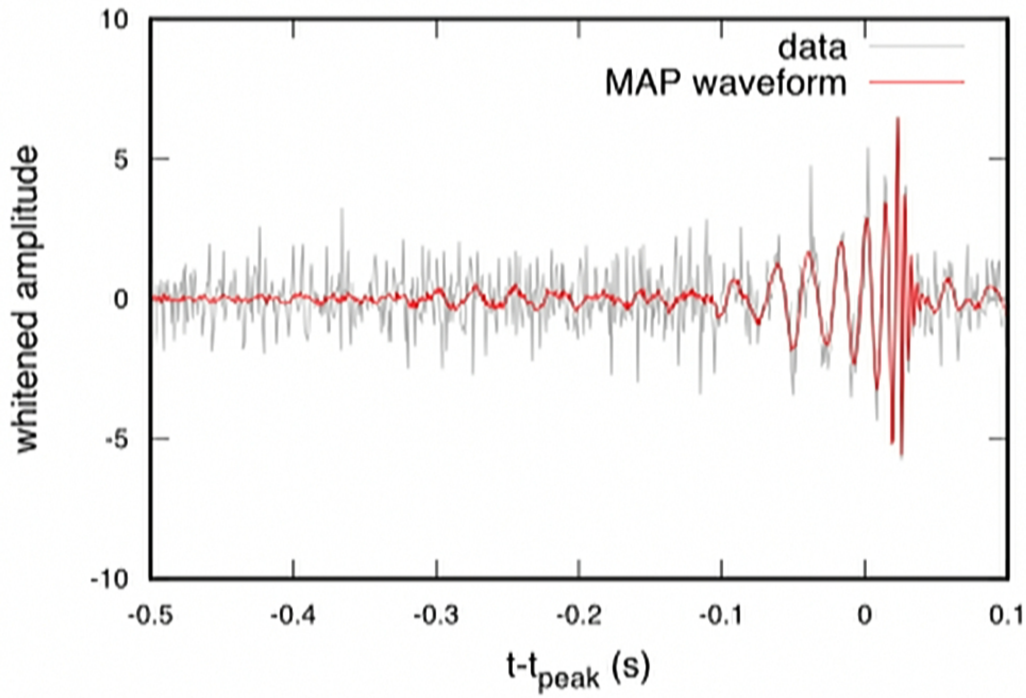
GW150914
Theoretical Physics
Inferences

Cosmology and
Extreme Gravity


Roadmap
Consistency with General Relativity
[Littenberg & Cornish]
data
MAP waveform
whitened amplitude
t-t$_{peak}$ (s)
10
5
0
-5
-10
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
GW150914
Theoretical Physics
Inferences
eXtreme Gravity Tests
Yunes
5

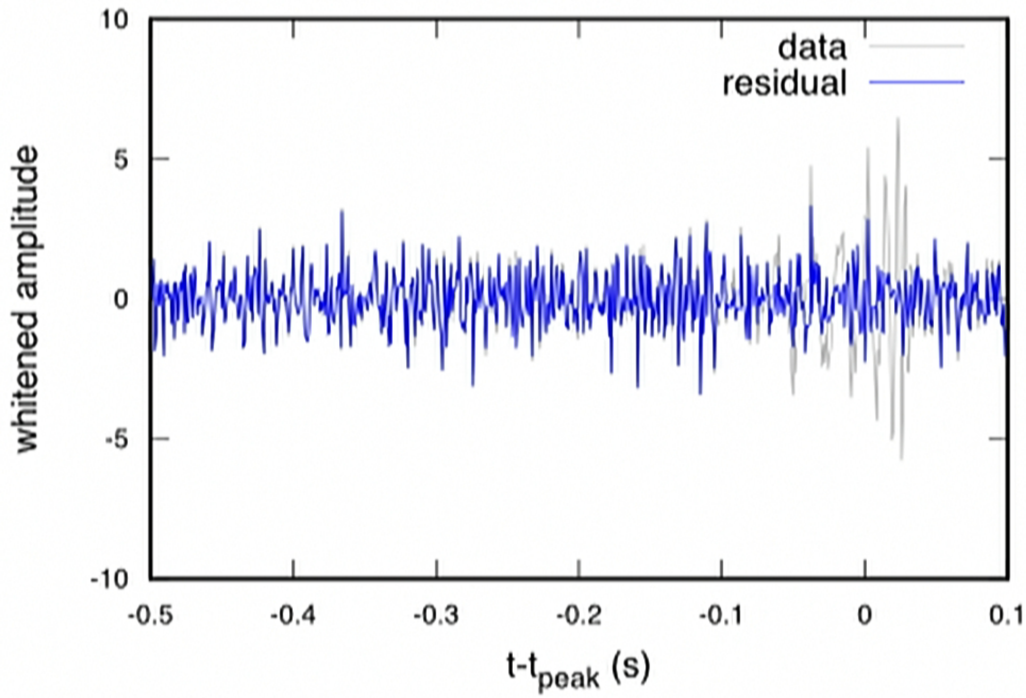
Consistency with General Relativity

[Littenberg & Cornish]



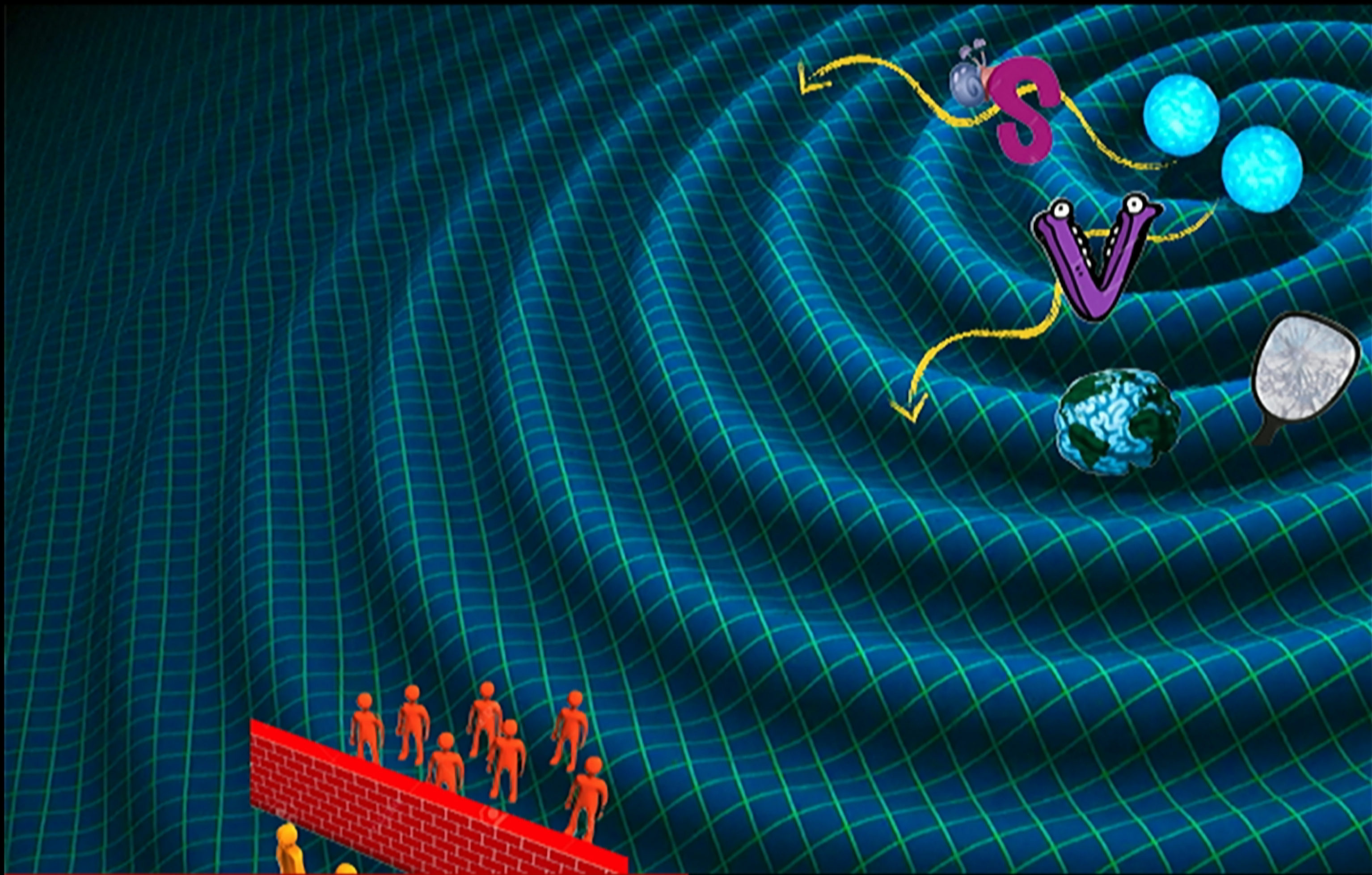
Consistency with General Relativity

[Littenberg & Cornish]



SNR of Residual (data - best fit) is consistent with noise

Is that it?



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Classify Inferences to Discover What to Ask

Gravitational Wave Generation

Scalar/Vector Field Activation

Gravitational Parity Violation

Gravitational Lorentz Violation

Extra-Dimensional Leakage

Time-Variation of G

⋮

Spacetime Dimensionality

Parity Violation

Lorentz Violation

SEP Violation

Test Fundamental Pillars of GR

Gravitational Wave Propagation

Modified Dispersion Relations

Modified Kinematics

Gravitational Lorentz Violation

Cosmological Screening

Time-Variation of G

⋮

Speed of Gravity

Mass of Graviton

Lorentz Violation

SEP Violation

A Unified Framework to Test General Relativity

The parameterized post-Einsteinian Framework

[Yunes & Pretorius, PRD 2009]

$$\tilde{h}(f) = \tilde{h}_{GR}(f)\,(1 + \alpha f^{a})\, e^{i\beta f^{b}}$$

Theoretical Effect	Theoretical Mechanism	Theories	ppE b	Order	Mapping
Scalar Dipolar Radiation	Scalar Monopole Field Activation	EdGB [131, 133, 140, 141]	-7	-1PN	$\beta_{\rm EdGB}$ [131]
	BH Hair Growth	Scalar-Tensor Theories [50, 142]	-7	-1PN	$\beta_{\rm ST}$ [50, 142]
Anomalous Acceleration	Extra Dimension Mass Leakage	RS-II Braneworld [143, 144]	-13	-4PN	$\beta_{\rm ED}$ [132]
	Time-Variation of G	Phenomenological [128, 145]	-13	-4PN	$\beta_{\dot{G}}$ [128]
Scalar Quadrupolar Radiation Scalar Dipole Force Quadrupole Moment Deformation	Scalar Dipole Field Activation due to Gravitational Parity Violation	dCS [131, 146]	-1	$+2$PN	$\beta_{\rm dCS}$ [137]
Scalar/Vector Dipolar Radiation Modified Quadrupolar Radiation	Vector Field Activation due to Lorentz Violation	EA [102, 103], khronometric [104, 105]	-7 -5	-1PN 0PN	$\beta_{\text{Æ}}^{(-1)}$ [106] $\beta_{\text{Æ}}^{(0)}$ [106]
Modified Dispersion Relation	GW Propagation/Kinematics	Massive Gravity [147–150] Double Special Relativity [151–154] Extra Dim. [155], Horava-Lifshitz [156–158] multifractional spacetime [159–161]	-3 $+6$ $+9$ 3–6	$+1$PN $+5.5$PN $+7$PN 4–5.5PN	$\beta_{\rm MDR}$ [136, 147]

[MSU: Cornish et al PRD 84 ('11), Sampson et al PRD 87 ('13), Sampson, et al PRD 88 ('13), Sampson et al PRD 89 ('14), Nikhef: Del Pozzo et al PRD 83 ('11), Li et al PRD 85 ('12), Agathos et al PRD 89 ('14), Del Pozzo et al CQG ('14).]

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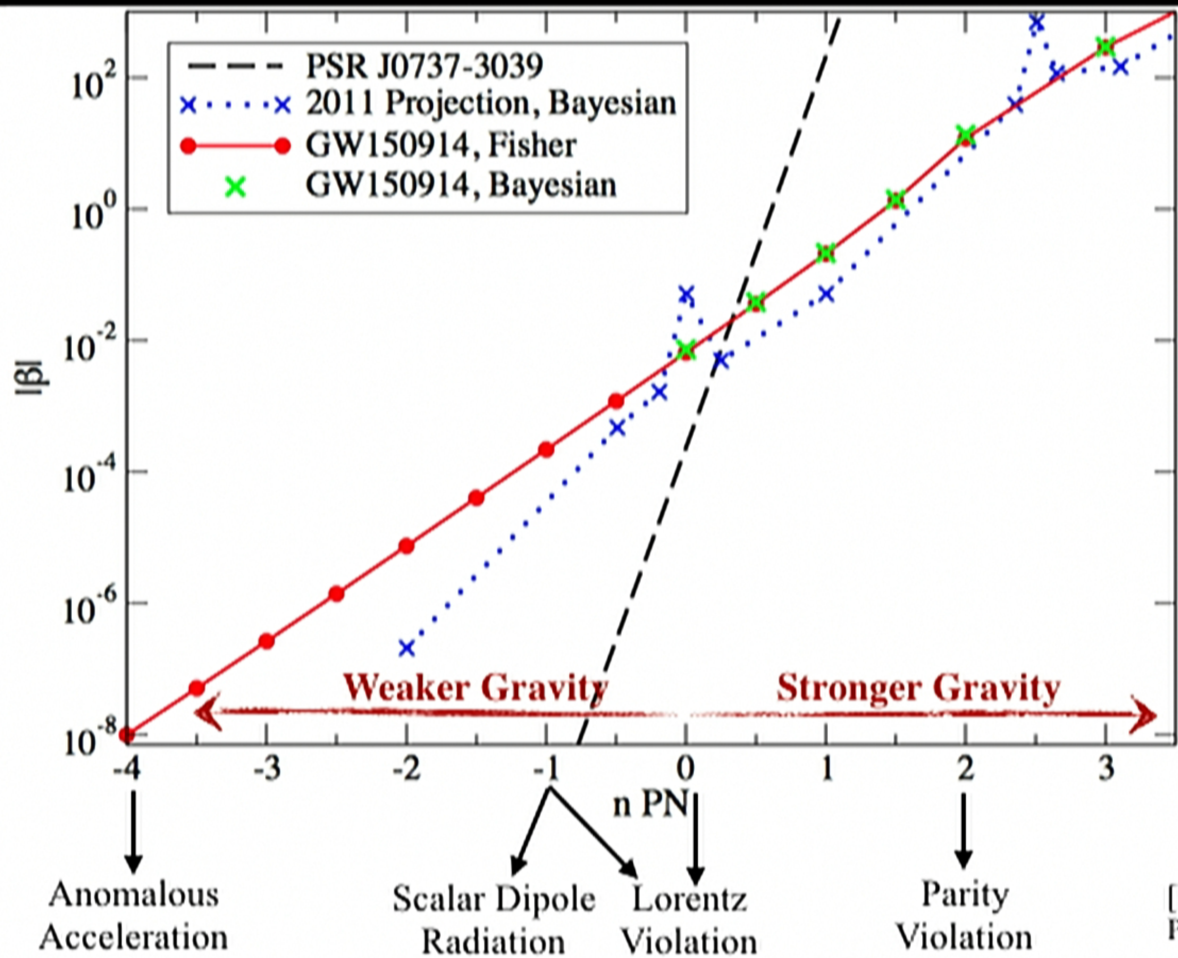
ppE Constraints on Wave Generation



[Yunes, Yagi, Pretorius, '16]

Constraints on Particular Modified Theories

$$\Psi_{\rm GW} = \Psi_{\rm GR} + \beta_{\rm EdGB} \left(\pi \mathcal{M} f\right)^{-7/3}$$

$$\beta_{\rm EdGB} \sim \zeta_{\rm EdGB} \left(m_1^2 s_2^2 - m_2^2 s_1^2\right) \qquad s_A = \frac{2}{\chi_A^2}\left(\sqrt{1-\chi_A^2} - 1 + \chi_A^2\right)$$

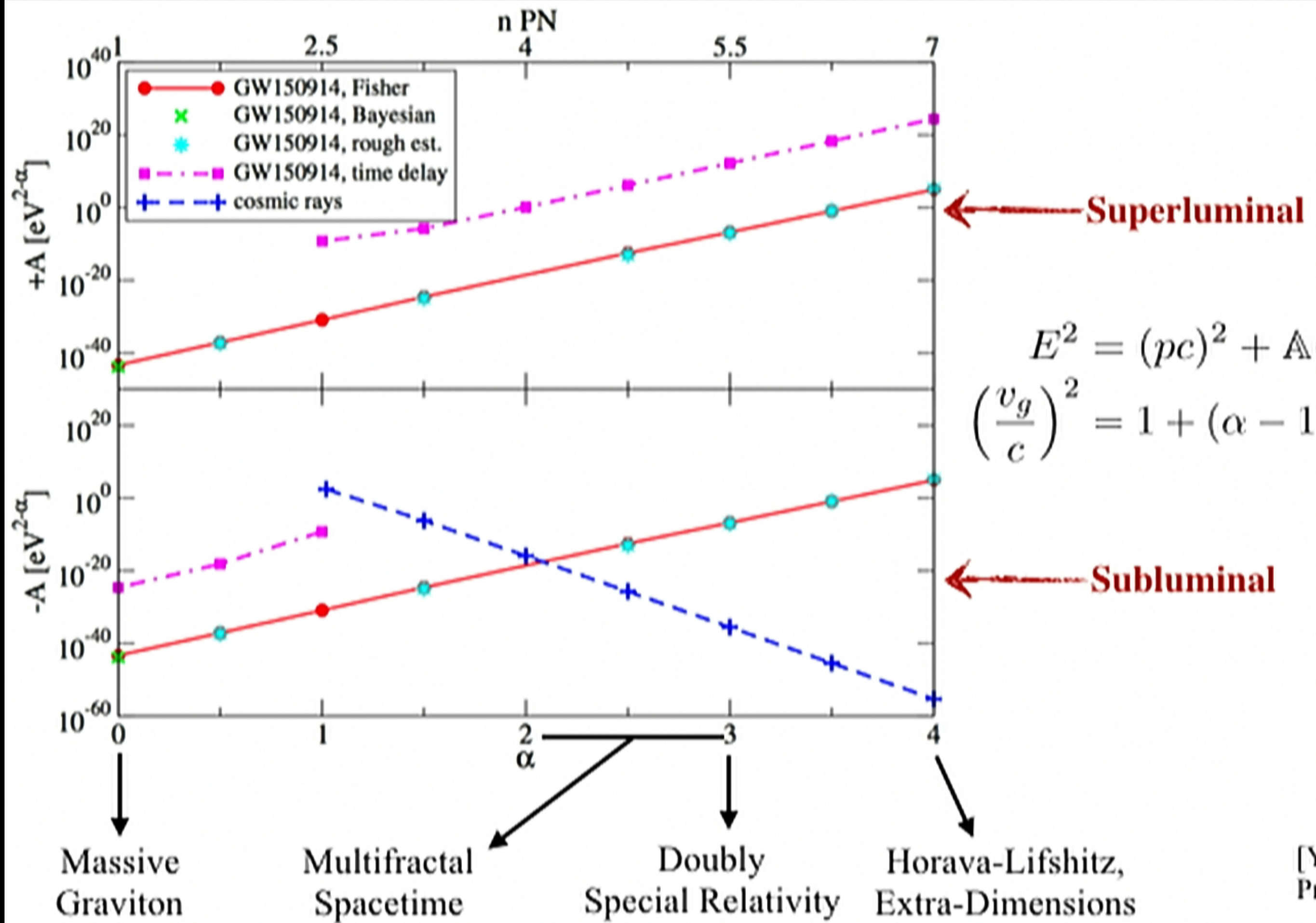
There are values of the spin for which the effect vanishes!

Actual GW150914 Constraints on GR Pillar Violations in Wave Generation

Theoretical Mechanism	GR Pillar	PN	$\lvert\beta\rvert$	Example Theory Constraints		
			GW150914	Repr. Parameters	GW150914	Current Bounds
	SEP	-1	1.6×10^{-4}	$\sqrt{\lvert\alpha_{\rm EdGB}\rvert}$ [km]	—	10^7 [46], 2 [47–49]
Scalar Field Activation	SEP, No BH Hair	-1	1.6×10^{-4}	$\lvert\dot{\phi}\rvert$ [1/sec]	—	10^{-6} [50]
	SEP, Parity Invariance	$+2$	1.3×10^{1}	$\sqrt{\lvert\alpha_{\rm CS}\rvert}$ [km]	—	10^8 [51, 52]
Vector Field Activation	SEP, Lorentz Invariance	0	7.2×10^{-3}	(c_+, c_-)	$(0.9, 2.1)$	$(0.03, 0.003)$ [53, 54]
Extra Dimension Mass Leakage	4D spacetime	-4	9.1×10^{-9}	ℓ [μm]	5.4×10^{10}	10–10^3 [55–59]
Time-Varying G	SEP	-4	9.1×10^{-9}	$\lvert\dot{G}\rvert$ [10^{-12}/yr]	5.4×10^{18}	0.1–1 [60–64]

[Yunes, Yagi, Pretorius, '16]

ppE Constraints on Wave Propagation

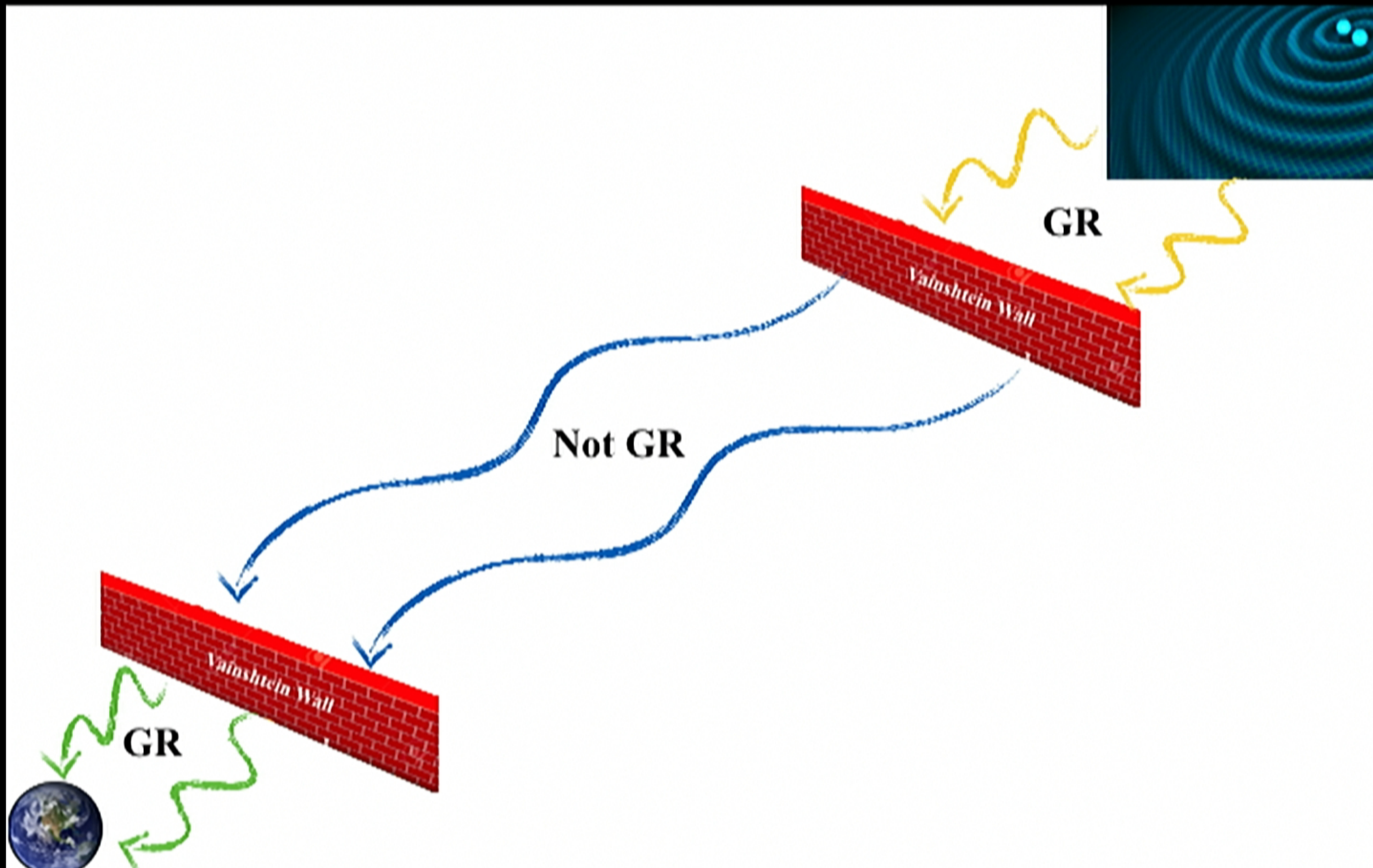


$$E^2 = (pc)^2 + \mathbb{A}(pc)^\alpha$$

$$\left(\frac{v_g}{c}\right)^2 = 1 + (\alpha - 1)\,\mathbb{A}E^{\alpha-2}$$

[Yunes, Yagi, Pretorius, '16]

Extreme Gravity Informing Cosmology



Cosmology Informing Extreme Gravity

Consider Scalar-Tensor Theories of the form

$$S_E = \int d^4x \frac{\sqrt{-g_*}}{2\kappa} \left[R_* - 2 g_*^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi\right] + S_{E,mat}[\chi, e^{\beta\varphi^2} g^*_{\mu\nu}]$$

- S_E → Einstein Frame
- $2 g_*^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi$ → Massless Scalar
- $e^{\beta\varphi^2} g^*_{\mu\nu}$ → violates WEP

whose field equations are

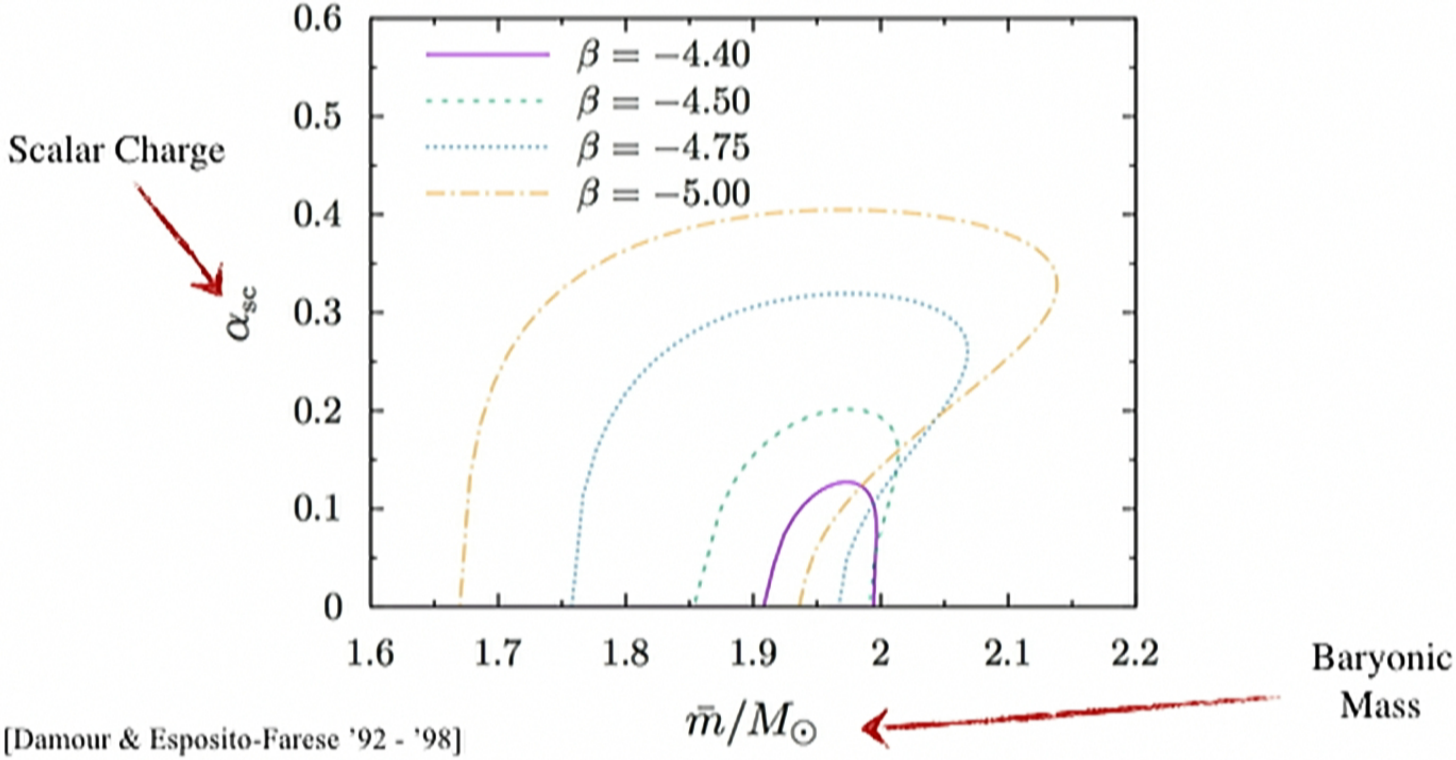
$$\Box_* \varphi = -\left(\frac{\kappa}{2}\beta\right) \varphi \, T_*^{\rm mat}$$

$$G^*_{\mu\nu} = \kappa \, T^{*,\rm tot}_{\mu\nu}$$

[Damour & Esposito-Farese '92 - '98]

Spontaneous Scalarization

$$\Box_* \varphi = -\left(\frac{\kappa}{2}\beta\right) \varphi\, T_*^{\rm mat} \longrightarrow \varphi_{\rm ext} = \varphi_\infty - \alpha_{\rm sc}\frac{m_*}{r_*}$$



[Damour & Esposito-Farese '92 - '98]

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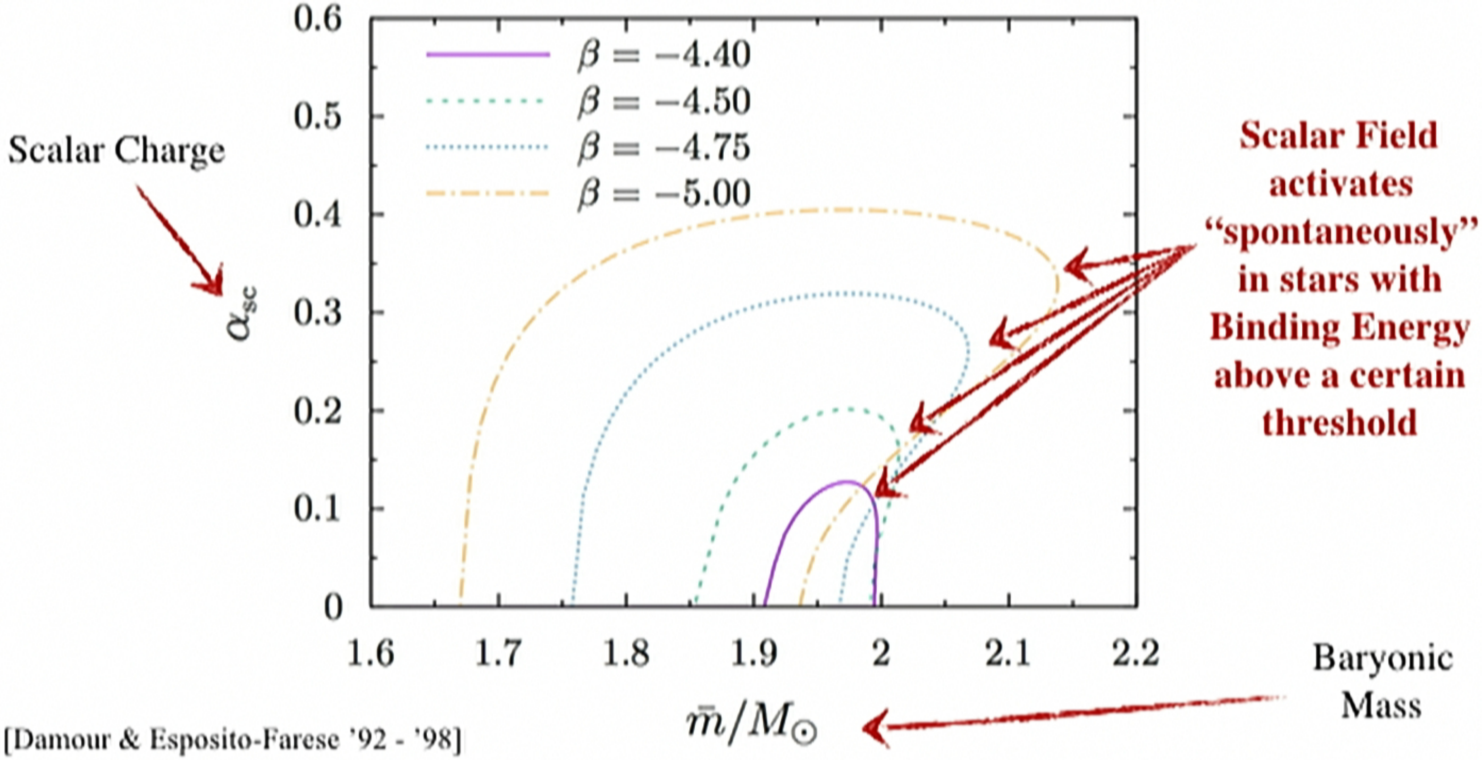

[Damour & Esposito-Farese '92 - '98]

Cosmological Evolution and Solar System Bounds

Does this theory pass Solar System Constraints?

$$\gamma_{\rm ppN} - 1 = -\left(\frac{2\beta^2\varphi^2}{1+\beta^2\varphi^2}\right)_{\rm today} < 2.3\times 10^{-5}$$

Cassini Tracking

What is the value of the field today (after cosmological evolution)?

$$\frac{2}{3-\varphi'^2}\varphi'' + (1-\omega_{\rm eos})\varphi' = (1-3\omega_{\rm eos})\beta\varphi \longrightarrow \text{HO with } V_\varphi \sim \beta\varphi^2$$

Option 1: $\beta > 0 \longrightarrow V_\varphi > 0$ (convex) $\longrightarrow \varphi_{\rm today} \sim 0$ and $\gamma_{\rm ppN} - 1 \ll 1$

Option 2: $\beta < 0 \longrightarrow V_\varphi > 0$ (concave) $\longrightarrow \varphi_{\rm today} \gg 1$ and $\gamma_{\rm ppN} - 1 \sim -2$

Cosmological Evolution allows massless Scalar-Tensor theories to pass Solar System constraints if they disallow spontaneous scalarization

[Damour & Nordvedt '93, Sampson et al '14, Anderson, Yunes, Barausse '16]

Outlook

GW150914's consistency with GR places constraints on modified gravitational wave propagation → **New bounds on multifractional spacetimes, extra dimensions, modified special relativity**

GW tests of extreme gravity will necessarily become much stronger

(more detections, higher SNR, more physical effects, other binaries e.g. NSNS, electromagnetic counterparts, etc.)

More interplay between cosmological frontiers and extreme gravity

(theories that modify extreme gravity already ruled out cosmologically?)

(cosmological modified theories already ruled out with GWs?)