Probing Modified Gravity with Gravitational Waves

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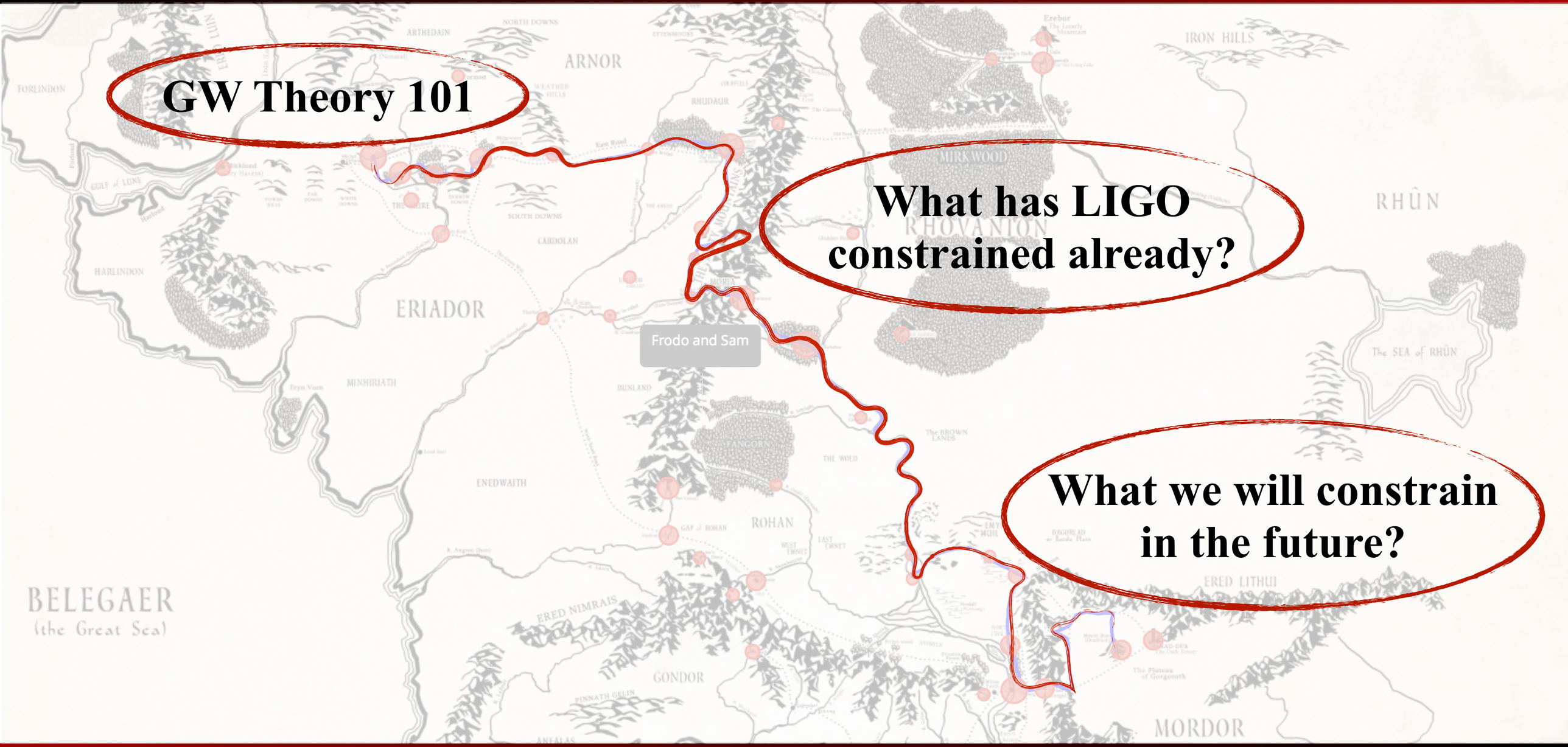
Accelerating Universe in the Dark Workshop
Yukawa Institute for Theoretical Physics
March 5th, 2019

Roadmap


GW Theory 101
What has LIGO constrained already?
What we will constrain in the future?
Frodo and Sam
ARNOR
IRON HILLS
RHÛN
ERIADOR
ROHAN
GONDOR
MORDOR
BELEGAER
(the Great Sea)
The SEA of RHÛN
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HARLINDON
FORLINDON
ERED LITHUI
ERED NIMRAIS

What do interferometers measure?

Parameter Estimation 101

Modelling 1. Create template "filters"

Data Analysis 2. Cross-correlate filters & data

3. Find filter that maximizes the likelihood function.

Fourier transform of data

template param that characterize system

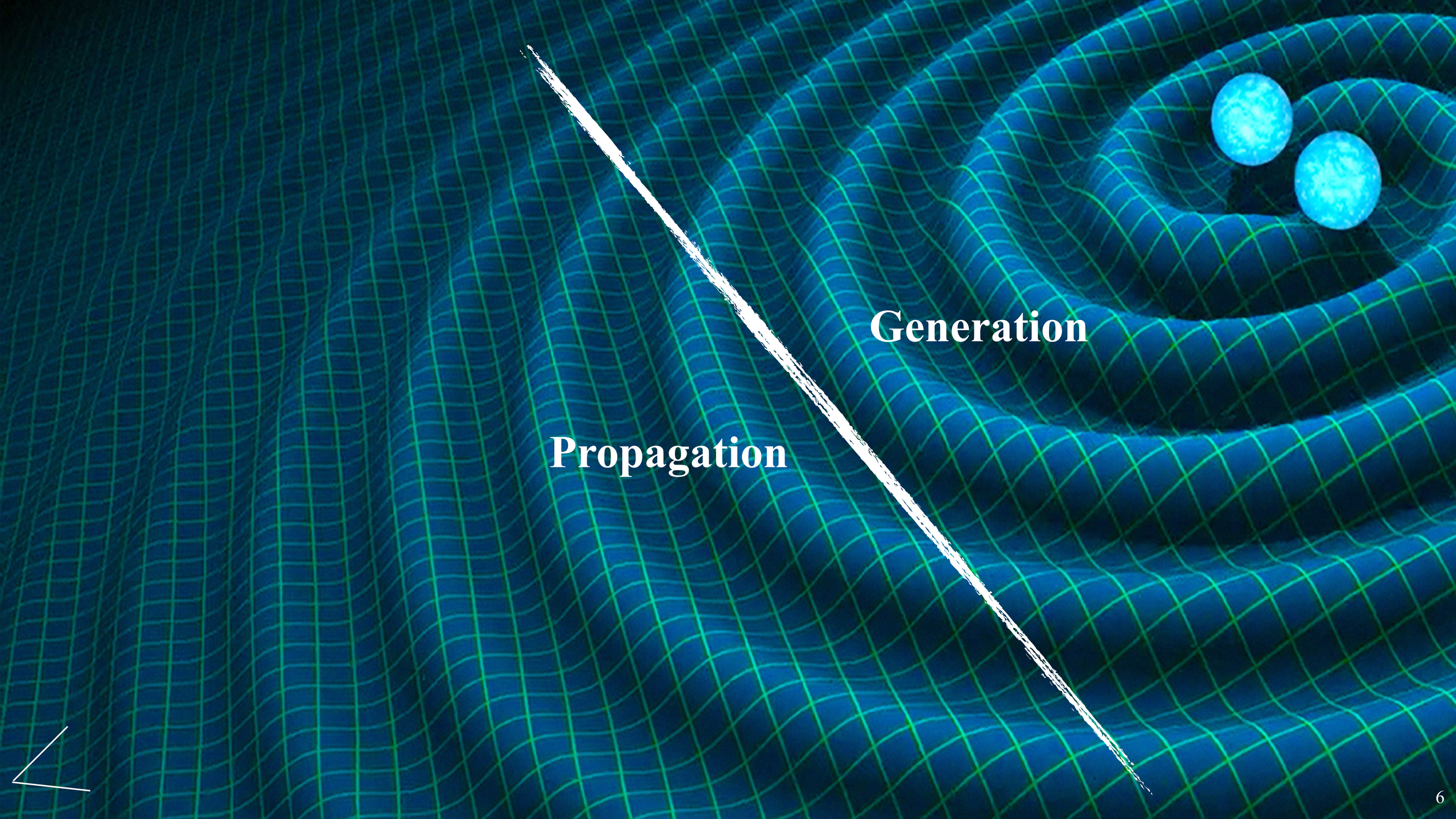
Likelihood function

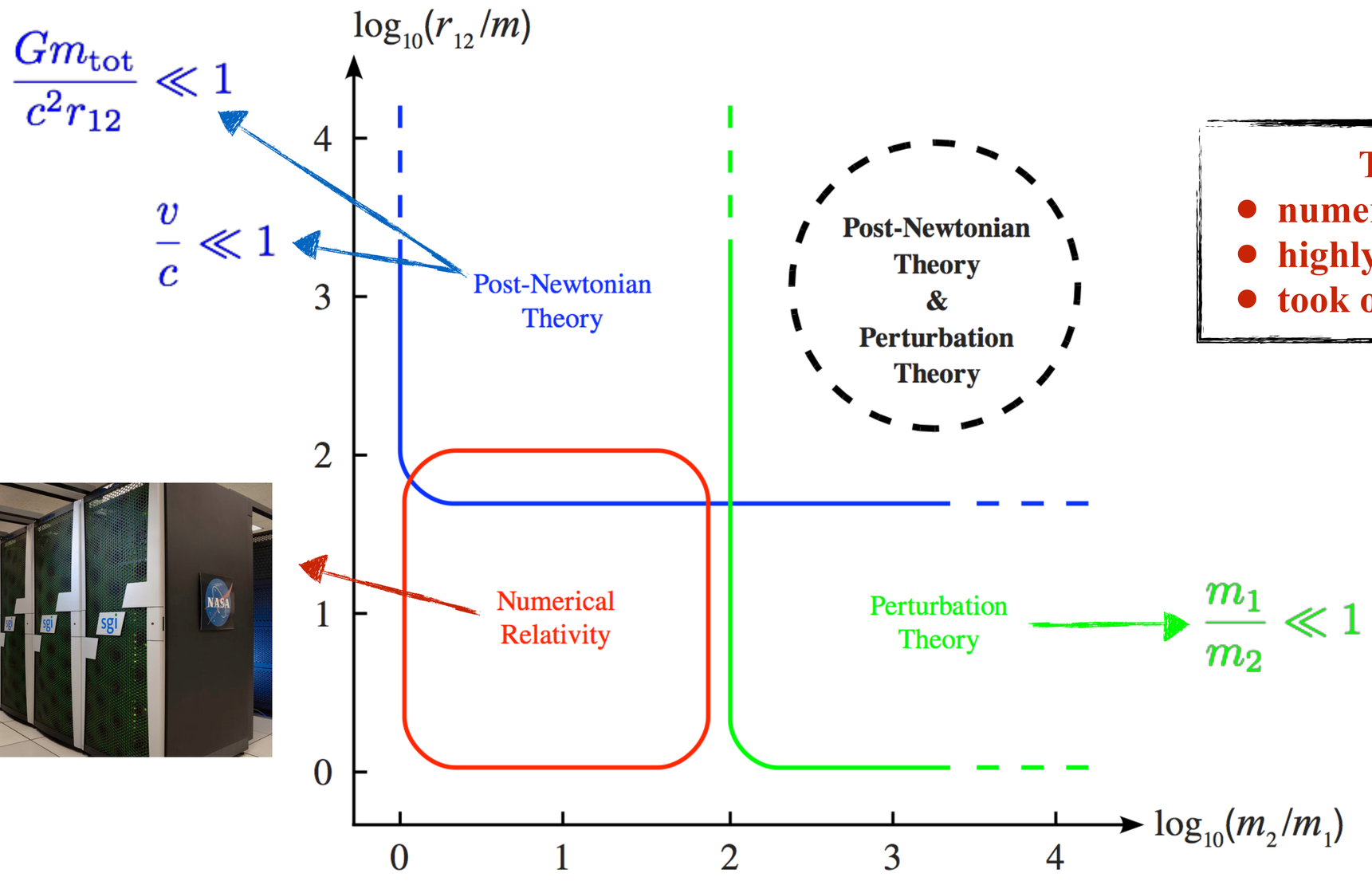
$$\mathcal{L} = e^{-\frac{1}{2}(s-h|s-h)} \sim C_0(\rho^2)\, e^{4\Re \int \frac{\tilde{s}^*(f)\ \tilde{h}(f,\lambda^\mu)}{S_n(f)} df}$$

inner product

detector noise (spectral noise density)

template (projection of GW metric perturbation)


Generation
Propagation



The GW models are

- **numerical and analytic**
- **highly accurate**
- **took over 50 years to develop**

[see e.g. Blanchet, Liv. Rev. in Rel.]

Inspiral with post-Newtonian theory in General Relativity

I. Construct the Hamiltonian (conservative). $E_b = -\frac{\mu m}{r}\left[1 + 1\text{PN} + \ldots + 3\text{PN} + \mathcal{O}\left(\frac{1}{c^8}\right)\right]$

II. Construct the RR force (dissipative). $\dot{E}_b = -\frac{32}{5}\eta^2\left(\frac{v}{c}\right)^{10}\left[1 + 1\text{PN} + 1.5\text{PN} + \ldots + 3.5\text{PN} + \mathcal{O}\left(\frac{1}{c^8}\right)\right]$

III. Determine propagating dof and its EOM $h_{ij} = \frac{1}{\text{D}_\text{L}}\ddot{I}_{ij}\left[1 + \ldots + \mathcal{O}\left(\frac{1}{c^8}\right)\right]$

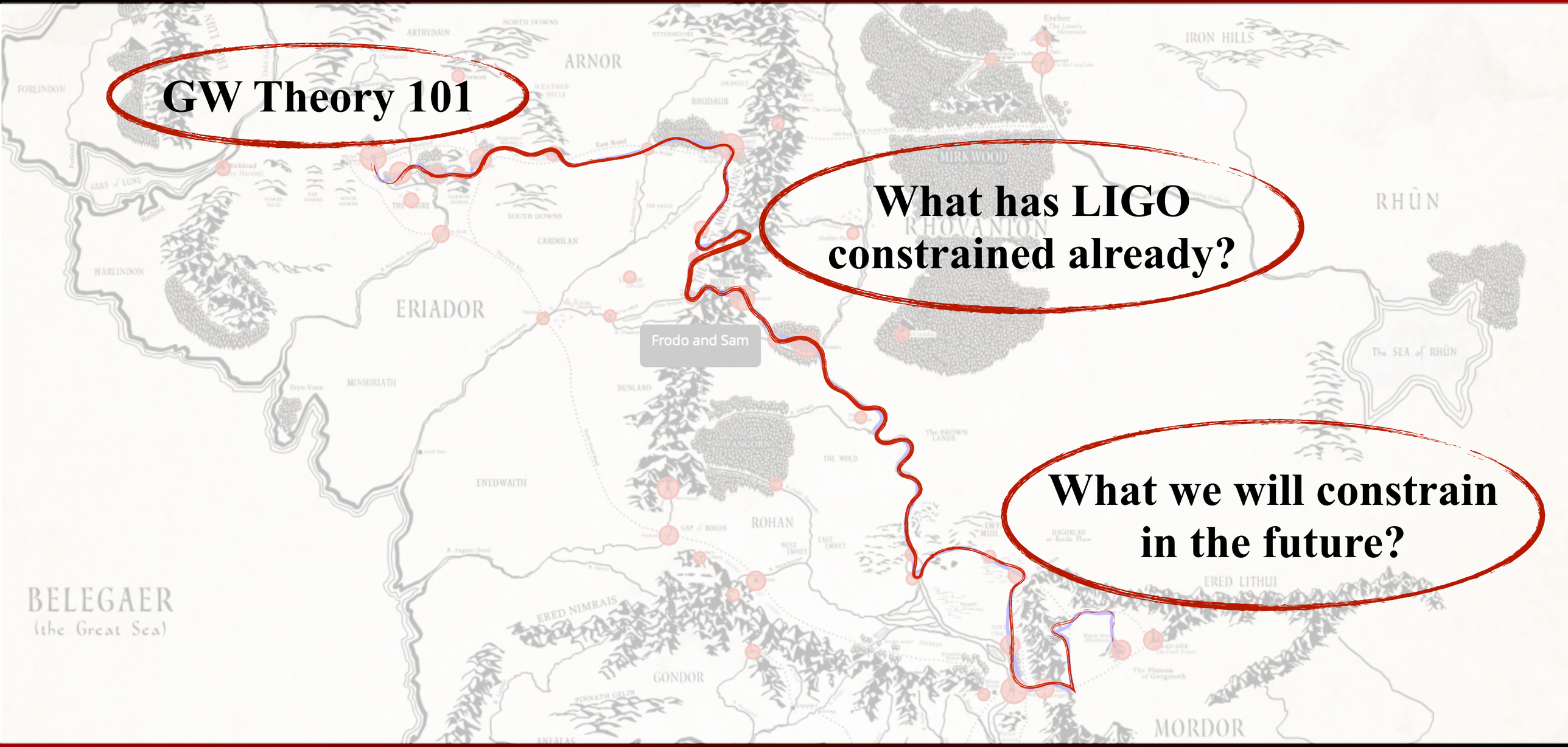
IV. Construct the propagator & the dispersion relation $E_g = p_g \to \omega = k$

$$\boxed{h_\times(t) \sim \frac{\eta M}{D_L}\cos\iota\,(M\omega)^{2/3}\cos 2\Phi + \ldots}$$

gravitational wave | symmetric mass ratio | distance to the source | inclination angle | total mass | orbital freq. | orbital phase

[see e.g. Blanchet, Liv. Rev. in Rel.]

Roadmap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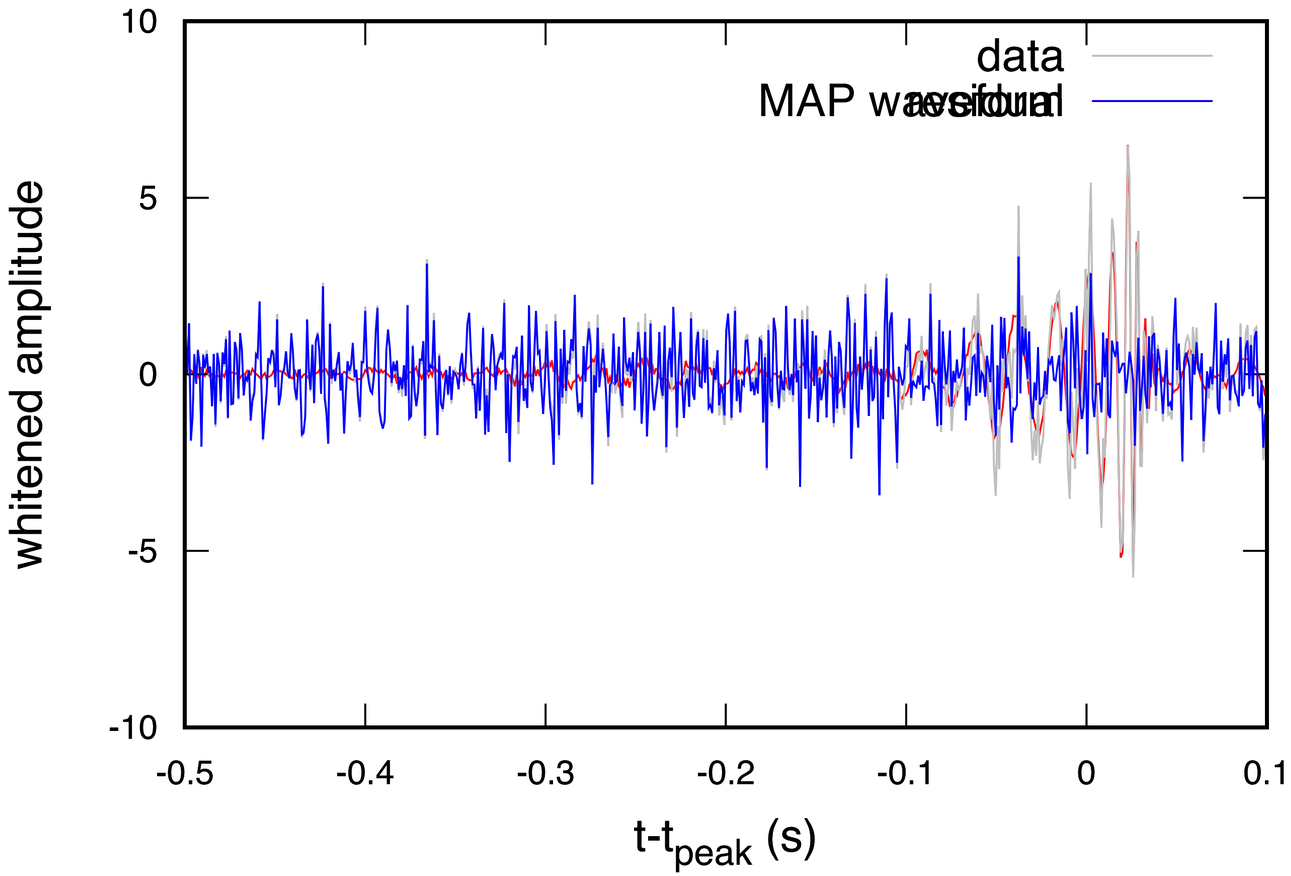
What tests has LIGO carried out?

Residual tests and other consistency checks (e.g. jackknife type tests)

Parameterized post-Einsteinian tests

Speed of gravity

Residual tests



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

[LIGO]

Parameterized post-Einsteinian test

The parameterized post-Einsteinian Framework

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

[Yunes & Pretorius, PRD 80 ('09)]

But where does this come from?

Properties of General Relativity

Principle of Equivalence | massless spin-2 field | Lorentz Invariance | Parity Invariance | Diffeomorphism Invariance | Dispersionless Propagation | ...

E.g. $$S = \int \sqrt{-g} \quad \kappa R$$

Test properties of General Relativity by constructing theories that violate its pillars

Dynamical Chern-Simons | Scalar-tensor theories | Horava gravity

Einstein-dilaton-Gauss-Bonnet | Einstein-AEther theory | Massive gravity

...

[Yunes & Pretorius, PRD 80 ('09)]
[Endlich, Gorbenko, Huang, Senatore, JHEP 09 ('17)]
[Yunes & Siemens, Liv. Rev. in Rel ('13)]

Parameterized post-Einsteinian test

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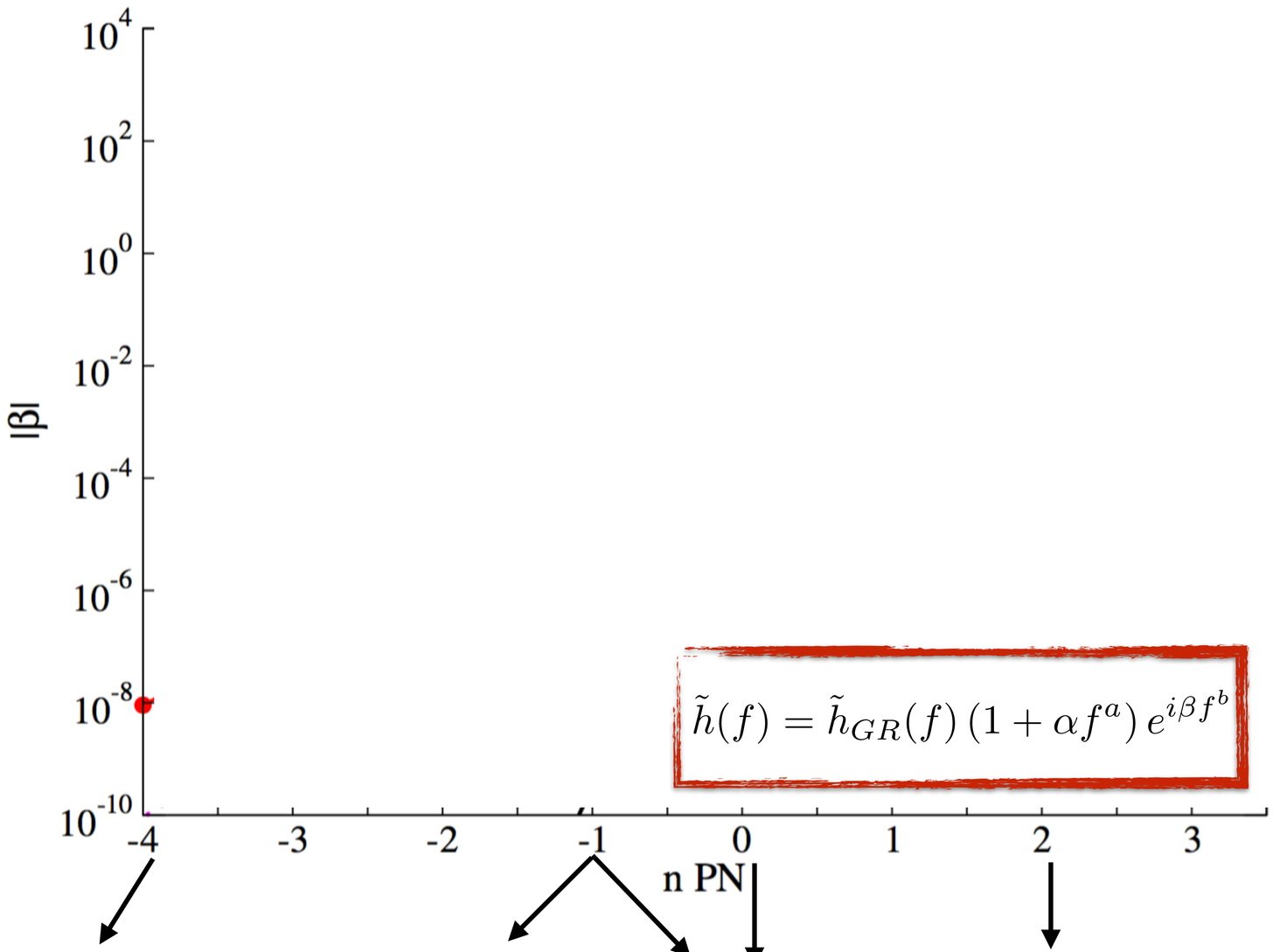
[Yunes & Pretorius, PRD 80 ('09)]

Theoretical Effect	Theoretical Mechanism	Theories	ppE b	Order	Mapping
Scalar Dipolar Radiation	Scalar Monopole Field Activation	EdGB [140, 142, 149, 150]	-7	-1PN	$\beta_{\rm EdGB}$ [140]
	BH Hair Growth	Scalar-Tensor Theories [59, 151]	-7	-1PN	$\beta_{\rm ST}$ [59, 151]
Anomalous Acceleration	Extra Dimension Mass Leakage	RS-II Braneworld [152, 153]	-13	-4PN	$\beta_{\rm ED}$ [141]
	Time-Variation of G	Phenomenological [137, 154]	-13	-4PN	$\beta_{\dot{G}}$ [137]
Scalar Quadrupolar Radiation Scalar Dipole Force Quadrupole Moment Deformation	Scalar Dipole Field Activation due to Gravitational Parity Violation	dCS [140, 155]	-1	$+2$PN	$\beta_{\rm dCS}$ [146]
Scalar/Vector Dipolar Radiation Modified Quadrupolar Radiation	Vector Field Activation due to Lorentz Violation	EA [109, 110], Khronometric [111, 112]	-7 -5	-1PN 0PN	$\beta_{Æ}^{(-1)}$ [113] $\beta_{Æ}^{(0)}$ [113]
Modified Dispersion Relation	GW Propagation/Kinematics	Massive Gravity [156–159]	-3	$+1$PN	$\beta_{\rm MDR}$ [145, 156]
		Double Special Relativity [160–163]	$+6$	$+5.5$PN	
		Extra Dim. [164], Horava-Lifshitz [165–167],	$+9$	$+7$PN	
		gravitational SME ($d = 4$) [179]	$+3$	$+4$PN	
		gravitational SME ($d = 5$) [179]	$+6$	$+5.5$PN	
		gravitational SME ($d = 6$) [179]	$+9$	$+7$PN	
		Multifractional Spacetime [168–170]	3–6	4–5.5PN	

[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).]

Current ppE constraints



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

Anomalous Acceleration

Scalar Dipole Radiation

Lorentz Violation

Parity Violation

[Yunes, Yagi, Pretorius, PRD 94 '(16), Editor's suggestion]

Current Constraints on Modified Gravity

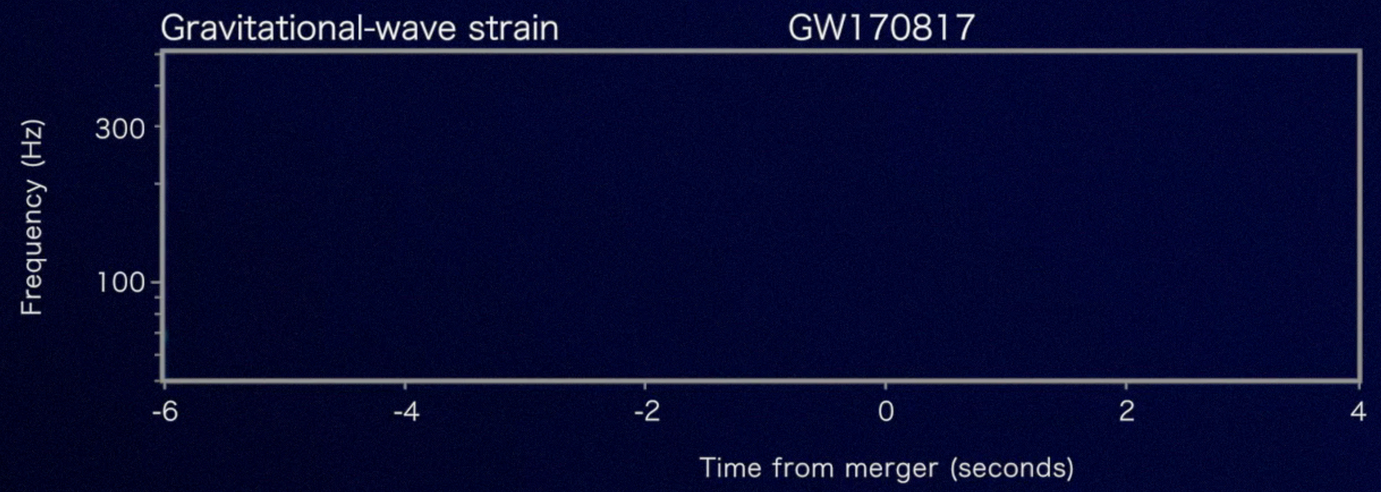
Theoretical Mechanism	GR Pillar	PN	$\lvert\beta\rvert$		Example Theory Constraints			
			GW150914	**GW151226**	Repr. Parameters	**GW150914**	**GW151226**	Current Bounds
Scalar Field Activation	SEP	-1	$\mathbf{1.6 \times 10^{-4}}$	$\mathbf{4.4 \times 10^{-5}}$	$\sqrt{\lvert\alpha_{\rm EdGB}\rvert}$ [km]	—	—	10^7 [56], 2 [57–59]
					$\lvert\dot{\phi}\rvert$ [1/sec]	—	—	10^{-6} [60]
Scalar Field Activation	SEP, PI	$+2$	$\mathbf{1.3 \times 10^{1}}$	$\mathbf{4.1}$	$\sqrt{\lvert\alpha_{\rm dCS}\rvert}$ [km]	—	—	10^8 [61, 62]
Vector Field Activation	SEP, LI	0	$\mathbf{7.2 \times 10^{-3}}$	$\mathbf{3.4 \times 10^{-3}}$	(c_+, c_-)	$(\mathbf{0.9}, \mathbf{2.1})$	$(\mathbf{0.8}, \mathbf{1.1})$	$(0.03, 0.003)$ [63, 64]
					$(\beta_{\rm KG}, \lambda_{\rm KG})$	$(\mathbf{0.42}, -)$	$(\mathbf{0.40}, -)$	$(0.005, 0.1)$ [63, 64]
Extra Dimensions	4D	-4	$\mathbf{9.1 \times 10^{-9}}$	$\mathbf{9.1 \times 10^{-11}}$	ℓ [μm]	$\mathbf{5.4 \times 10^{10}}$	$\mathbf{2.0 \times 10^{9}}$	10–10^3 [65–69]
Time-Varying G	SEP	-4	$\mathbf{9.1 \times 10^{-9}}$	$\mathbf{9.1 \times 10^{-11}}$	$\lvert\dot{G}\rvert$ [10^{-12}/yr]	$\mathbf{5.4 \times 10^{18}}$	$\mathbf{1.7 \times 10^{17}}$	0.1–1 [70–74]
Massive graviton	$m_g = 0$	$+1$	$\mathbf{1.3 \times 10^{-1}}$	$\mathbf{8.9 \times 10^{-2}}$	m_g [eV]	$\mathbf{10^{-22}}$ [19]	$\mathbf{10^{-22}}$ [5]	10^{-29}–10^{-18} [75–79]
Mod. Disp. Rel. (*Multifractional*)	LI	$+4.75$	$\mathbf{1.1 \times 10^{2}}$	$\mathbf{2.6 \times 10^{2}}$	E_*^{-1} [eV^{-1}] (time)	$\mathbf{5.8 \times 10^{-27}}$	$\mathbf{3.3 \times 10^{-26}}$	—
					E_*^{-1} [eV^{-1}] (space)	$\mathbf{1.0 \times 10^{-26}}$	$\mathbf{5.7 \times 10^{-26}}$	3.9×10^{-53} [80]
Mod. Disp. Rel. (*Modified Special Rel.*)	LI	$+5.5$	$\mathbf{1.4 \times 10^{2}}$	$\mathbf{4.3 \times 10^{2}}$	$\eta_{\rm dsrt}/L_{\rm Pl} > 0$	$\mathbf{1.3 \times 10^{22}}$	$\mathbf{3.8 \times 10^{22}}$	—
					$\eta_{\rm dsrt}/L_{\rm Pl} < 0$			2.1×10^{-7} [80]
Mod. Disp. Rel. (*Extra Dim.*)	4D	$+7$	$\mathbf{5.3 \times 10^{2}}$	$\mathbf{2.4 \times 10^{3}}$	$\alpha_{\rm edt}/L_{\rm Pl}^2 > 0$	$\mathbf{5.5 \times 10^{62}}$	$\mathbf{2.5 \times 10^{63}}$	2.7×10^2 [80]
					$\alpha_{\rm edt}/L_{\rm Pl}^2 < 0$			—
Mod. Disp. Rel. (*Standard Model Ext.*)	LI	$+4$	—	—	$\mathring{k}^{(4)}_{(I)} > 0$	—	—	6.1×10^{-17} [80, 81]
					$\mathring{k}^{(4)}_{(I)} < 0$	$\mathbf{0.64}$	$\mathbf{19}$	—
		$+5.5$	$\mathbf{1.4 \times 10^{2}}$	$\mathbf{4.3 \times 10^{2}}$	$\mathring{k}^{(5)}_{(V)} > 0$ [cm]	$\mathbf{1.7 \times 10^{-12}}$ [82]	$\mathbf{3.1 \times 10^{-11}}$	1.7×10^{-40} [80, 81]
					$\mathring{k}^{(5)}_{(V)} < 0$ [cm]			—
		$+7$	$\mathbf{5.3 \times 10^{2}}$	$\mathbf{2.4 \times 10^{3}}$	$\mathring{k}^{(6)}_{(I)} > 0$ [cm^2]	$\mathbf{7.2 \times 10^{-4}}$	$\mathbf{3.3 \times 10^{-3}}$	3.5×10^{-64} [80, 81]
					$\mathring{k}^{(6)}_{(I)} < 0$ [cm^2]			—
Mod. Disp. Rel. (*Hořava-Lifshitz*)	LI	$+7$	$\mathbf{5.3 \times 10^{2}}$	$\mathbf{2.4 \times 10^{3}}$	$\kappa_{\rm hl}^4 \mu_{\rm hl}^2$ [1/eV^2]	$\mathbf{1.5 \times 10^{6}}$	$\mathbf{6.9 \times 10^{6}}$	—
Mod. Disp. Rel. (*Lorentz Violation*)	LI	$+4$	—	—	c_+	$\mathbf{0.7}$ [83]	$\mathbf{0.998}$	0.03 [63, 64]

[Yunes, Yagi, Pretorius, PRD 94 ’(16), Editor’s suggestion]

Speed of Gravity Test

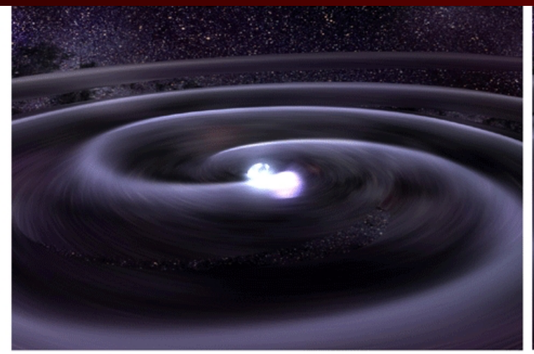
Fermi

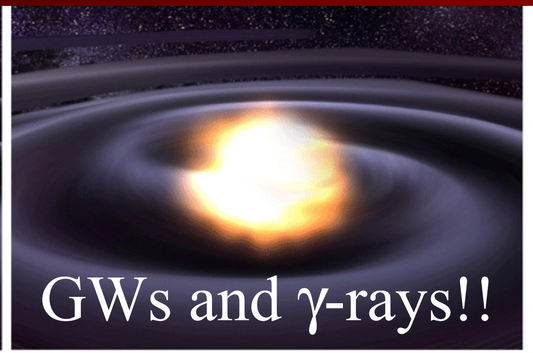
LIGO



Speed of Gravity Test

[Nishizawa & Nakamura, PRD 90 ('14)]
[LIGO ApJ L 848 ('17)]





GW detection gives you distance D (~26Mpc) and thus, an arrival time $T_g = D/v_g$

Short GRB + galaxy identification (w/LIGO+Virgo) gives you distance D, so $T_\gamma = D/c + \tau_{\rm int}$

If $\tau_{\rm int} = 0$ → GW travelled faster than γ to arrive 1.7 s before γ → $\Delta t_{\rm obs} = \frac{D}{c} - \frac{D}{v_g}$ → $\frac{v_g}{c} \sim 1 + \frac{c\,\Delta t_{\rm obs}}{D}$

If $\tau_{\rm int} = 10$ secs → GW travelled slower than γ to allow γ to catch up to a 1.7 sec delay → $\Delta t_{\rm obs} = \frac{D}{v_g} - \frac{D}{c} + \tau_{\rm int}$ → $\frac{v_g}{c} \sim 1 - \frac{c\,(\tau_{\rm int} - \Delta t_{\rm obs})}{D}$

$$-3 \times 10^{-15} < \frac{v_g}{c} - 1 < 7 \times 10^{-16}$$

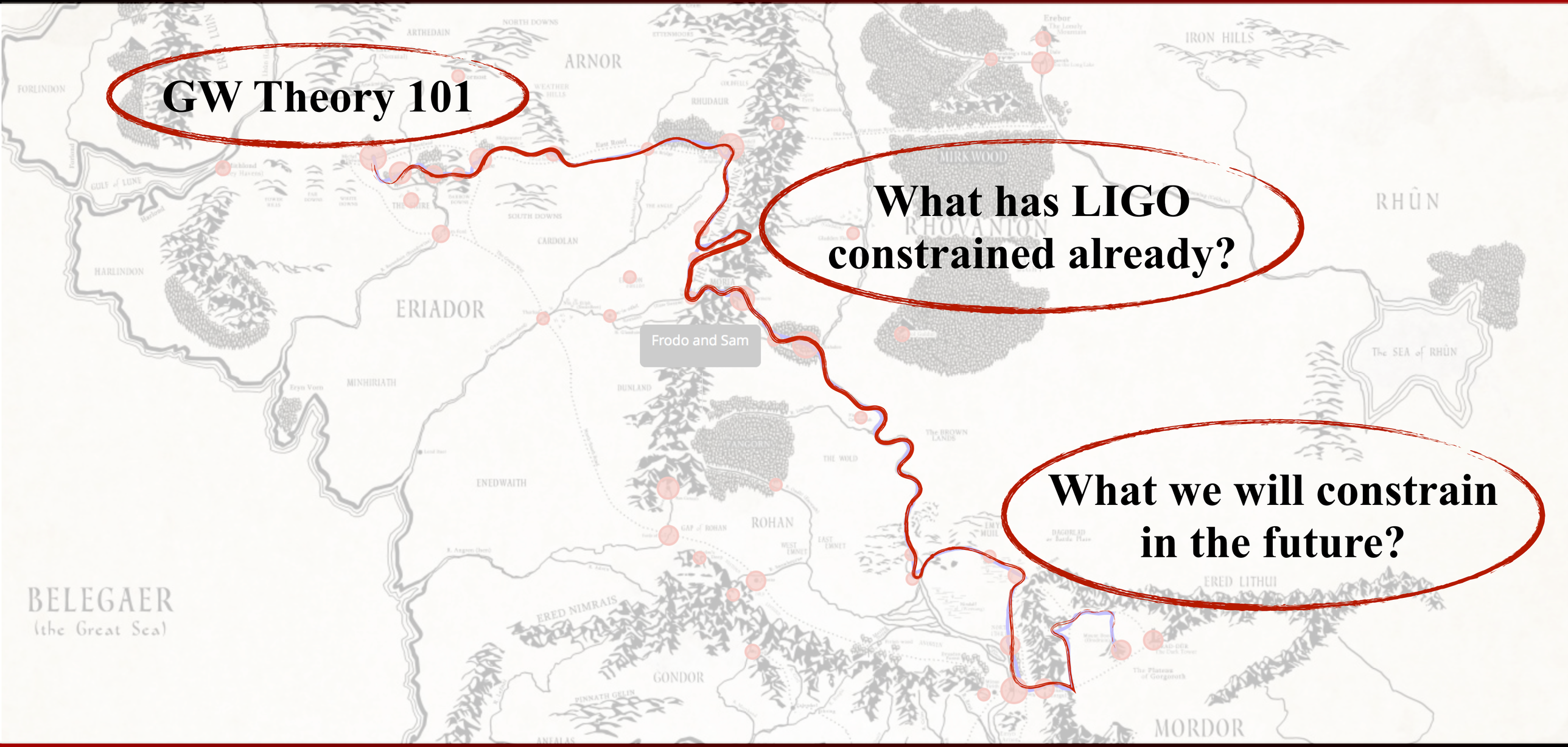
$$\ddot{h}_{ij} + (3+\alpha_M)H\dot{h}_{ij} + (1+\alpha_T)k^2 h_{ij} = 0\,,$$
$$i\phi + (3+\alpha_M)iH\phi + \phi^{\angle} - (1+\alpha_T)k_i k^i = 0,$$

"Dead" Theories: Quartic/ Quintic Galileon, Fab Four, quadratic/cubic DHOST, etc.

Caveats: [de Rham & Melville PRL 121 ('18)] + [Alexander & Yunes, PRD 97 ('28)]

[Ezquiaga & Zumalacarregui PRL 119 ('17)]
[Baker, Bellini, Ferreira, Lagos, Noller, Sawicki, PRL 119 ('17)]

Roadmap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A Fantastical Timeline

2020 | 2024 | 2028 | 2032 | 2036

aLIGO
aVirgo
KAGRA

A+

LIGO-India

Voyager

Cosmic Explorer

Einstein Telescope

LISA, DECIGO

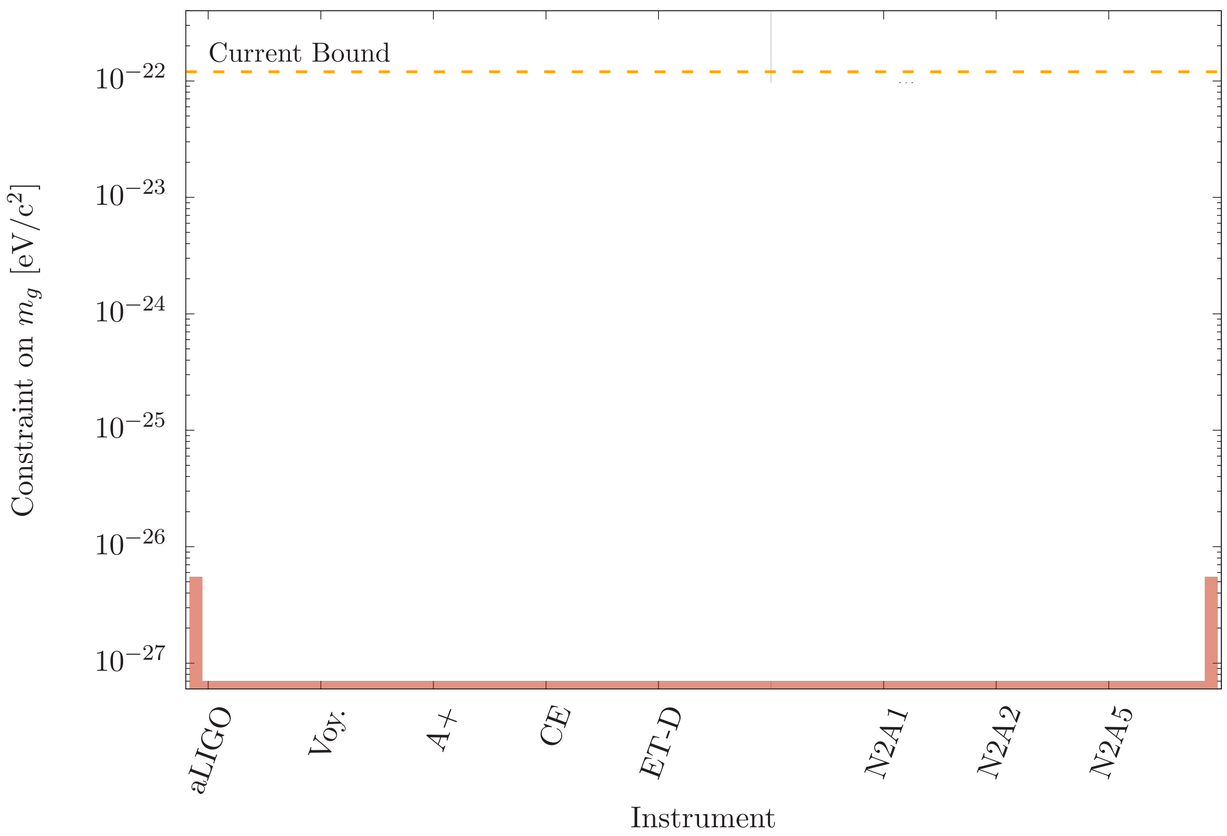
improved quantum noise
improved thermal coating
increased range to 140% wrt aLIGO

silicon mirrors and suspensions
low temperature (120K)
increased range to 200% wrt aLIGO

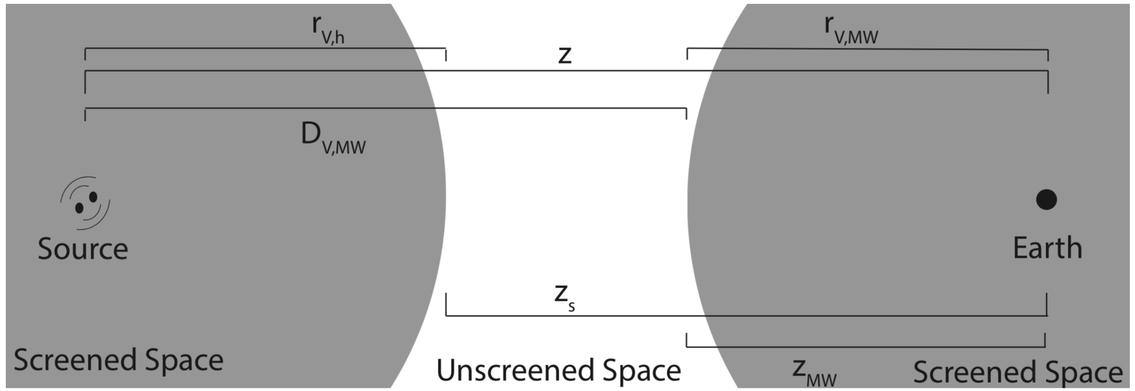
Moderate Improvements of Constraints

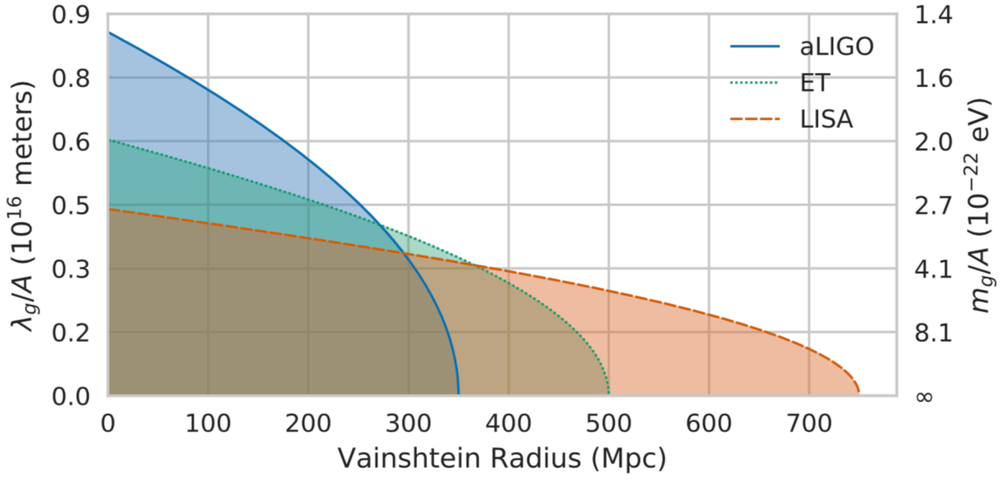
New Tests

Future Constraints on Graviton Mass and Screening



[Chamberlain & Yunes, PRD 96 ('17)]





[Perkins & Yunes CQG 36 ('19)]

Future Constraints on Dark Photons

Self-Interacting Asymmetric Dark Matter coupled to a Light Massive Dark Photon

[Kopp, Laha, Opferkuch, Shepherd, JHEP 11 ('18)]
[Petraki, Pearce, Kusenko, JCAP 1407 ('14)]

$$\mathcal{L}_{\rm DS} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_v^2 V_\mu V^\mu + \bar{\chi}\left(i\gamma^\mu D_\mu - m_\chi\right)\chi,$$

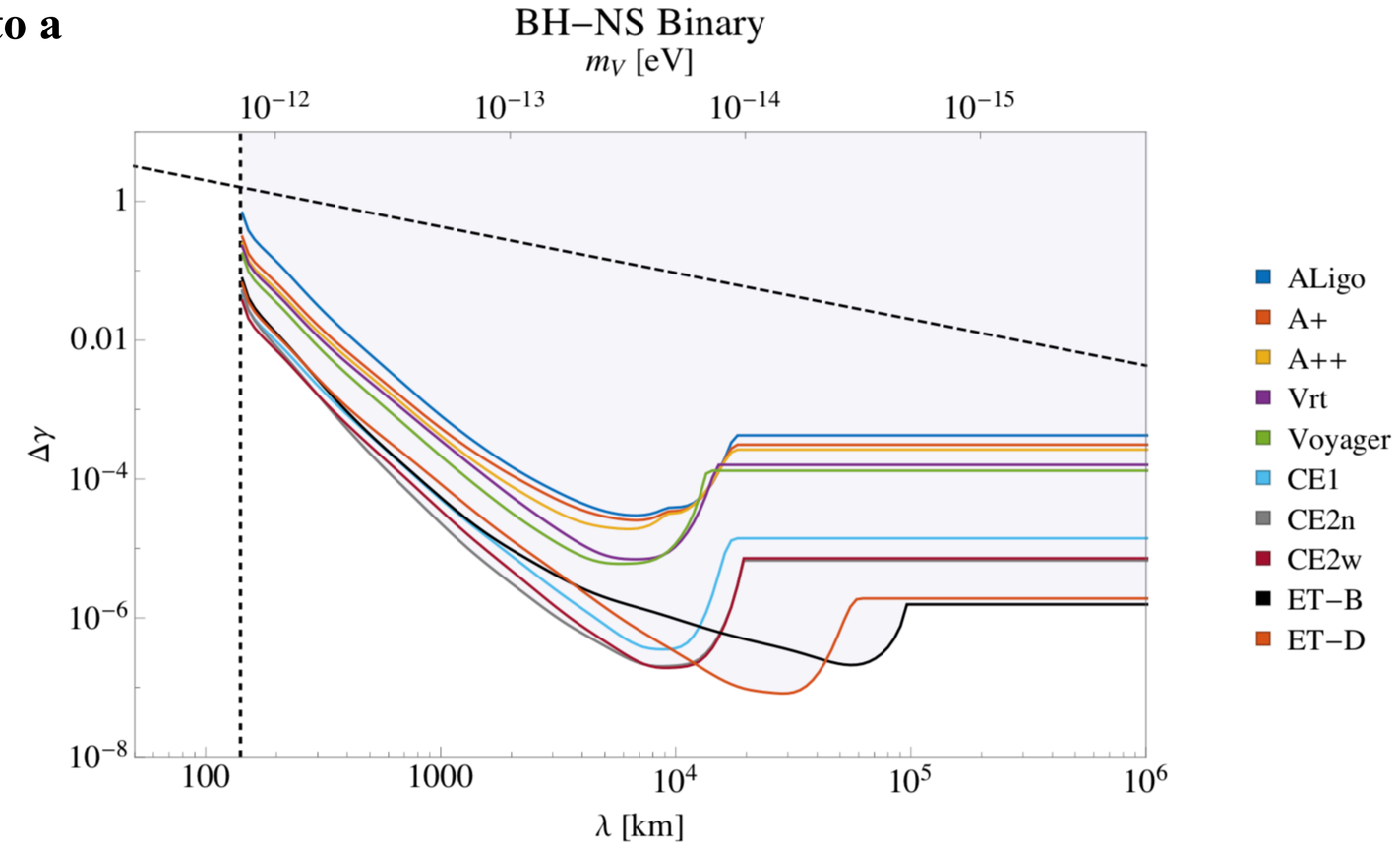
Modifications to the Conservative Sector:

$$V_{\rm Yuk}(r) = \alpha\frac{m^2\eta}{r}e^{-r/\lambda} \qquad \alpha = \frac{q_1 q_2}{m_1 m_2} = \tilde{q}_1\,\tilde{q}_2$$

Modifications to the Dissipative Sector:

$$P_{\rm dark} = \frac{2}{3}\gamma\eta^2 m^2\omega^4 r^2\left(1 + \frac{1}{2(\lambda\omega)^2}\right)\left(1 - \frac{1}{\lambda\omega}\right)^{\frac{1}{2}}$$

$$\gamma \equiv (\tilde{q}_1 - \tilde{q}_2)^2$$



[Alexander, McDonough, Sim, Yunes, CQG 35 ('18)]

Future Constraints on Echoes from ECOs

Exotic Compact Objects (ECOs or "NICOs")

Two paths to constraints:
echoes or tidal deformability

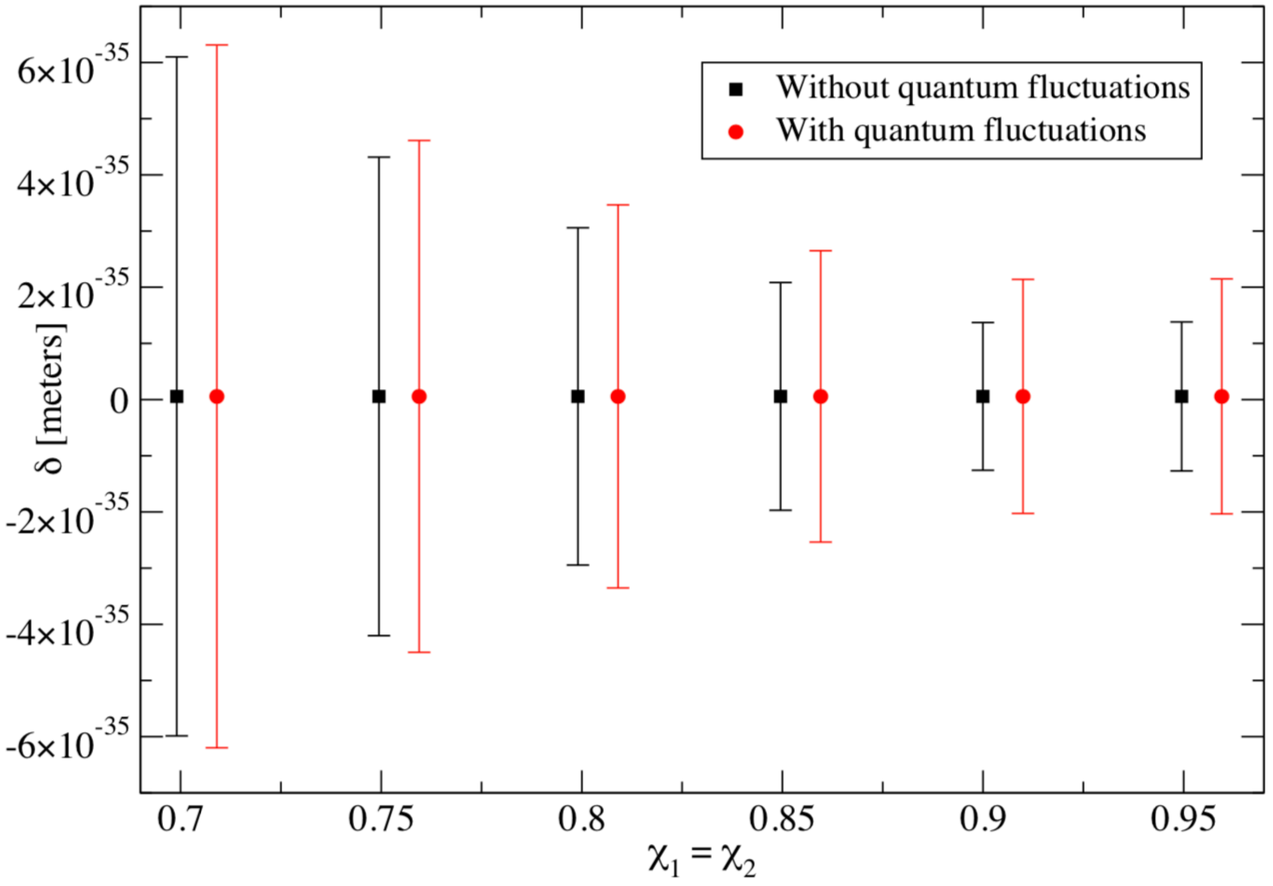
ECOs have tidal deformability λ that scales as $2M\text{-}R_s = 2M\, e^{-1/\lambda}$

[Cardoso, et al, PRD '95 (2017)]

GW measurement of tidal deformability can distinguish BH from ECO

Can a non-zero GW measurement of a small enough λ measure the surface of the object to Planckian precision?

[Maselli, et al, PRL 120 (2018), Cardoso and Pani, Nature Astronomy (2017)]



[Adazzi, Marciano &Yunes, PRL '(19), Editor's Suggestion]

ECO Caveats: No exact solutions, unstable to collapse, magnitude of stress at surface, etc.

Conclusions

Gravitational Waves Are Already Telling Us About Theoretical Physics
(consistency tests, ppE tests, speed of gravity)

Future Gravitational Waves Constraints Will Be Stronger And Constrain New Modified Gravity Ideas
(graviton mass & screening, dark photons, but also dipole emission, Lorentz violation, higher curvature action, no-hair theorem, time-varying Planck mass, etc.)

Things I had to leave out: *Constraints on light scalar fields due to superradiance, no-hair and ringdown tests,* and emri tests/chaos, I-Love-Q tests, etc.

Modified Theories Must Pass A New High Bar
(They must be consistent with GW observations, existance and stability of NSs and spinning BHs)

Thank You