Theoretical Physics Implications of Gravitational Wave Detections

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eXtreme Gravity Institute
Montana State University

New Frontiers in Gravitational-Wave Astrophysics
June 21st, 2017

eXtreme Gravity Institute

Now accepting Applications for our Physics PhD Program!!

eXtreme Matter meets eXtreme Gravity

hyperspace@gu
Editor: Luciano Rezzolla

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More info: external link
Contact: ncornish[AT]montana.edu
Date: 2017-08-17 - 2017-08-19
Location: Bozeman, Montana, USA

eXtreme Matter meets eXtreme Gravity Workshop, Bozeman, Montana, USA

XGI Workshop First Announcement:

"eXtreme Matter meets eXtreme Gravity"
August 17-19, Bozeman Montana

The eXtreme Gravity Institute at Montana State University will hold a workshop to discuss methods for constraining the properties of Neutron Stars and the dense-matter equation of state. Like previous XGI workshops, the format will emphasize discussion and exchange of ideas over formal presentations. Each session will be organized around a science question, with a moderator and two discussion leaders. Topics to be covered include gravitational-wave observations of Neutron Star – Neutron Star and Neutron Star – Black Hole binaries, X-ray observations by the NICER mission (set to launch very soon), theoretical calculations of the dense-matter equation of state, and numerical simulations of NS-NS and NS-BH mergers.

The meeting is being held immediately prior to the HEAD meeting in Sun Valley, and participants may choose to drive between the meetings, or simply head a little south of Bozeman to view the total eclipse on the 21st of August. Bozeman is a beautiful mountain town a one-hour drive from the North entrance of Yellowstone National Park. The surrounding area offers great opportunities for hiking, fishing, white water rafting, and mountain biking.

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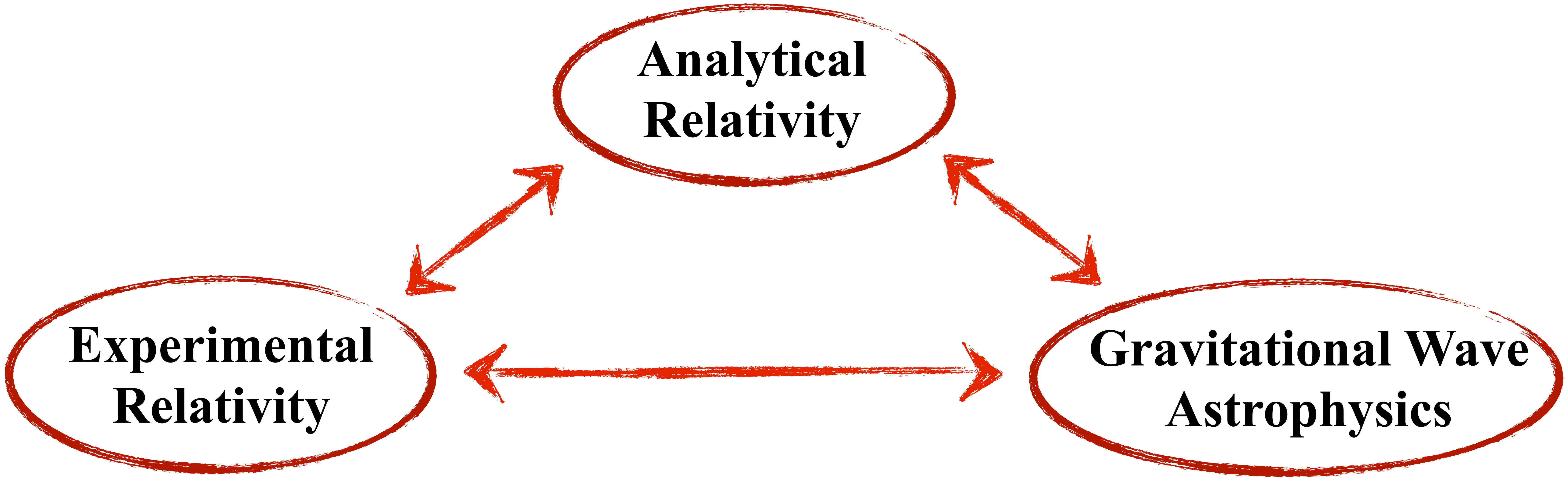
CONFERENCES
- ICRANet-Minsk workshop on high energy astrophysics, Minsk, Belarus
- Fifth Galileo-Xu Guangqi Meeting, Chengdu, China
- 15th Italian-Korean Symposium on Relativistic Astrophysics, Seoul, Korea
- Geometric Foundations of Gravity in Tartu, Estonia
- 3rd Karl Schwarzschild Meeting – Gravity and the Gauge/Gravity Correspondence, Frankfurt, Germany

JOBS
- Assistant Lecturer in Gravitational Wave Astrophysics at Monash University, Australia
- Professor/Reader in Gravitational Wave Science at Portsmouth, UK

What do I do and what will this talk be about?

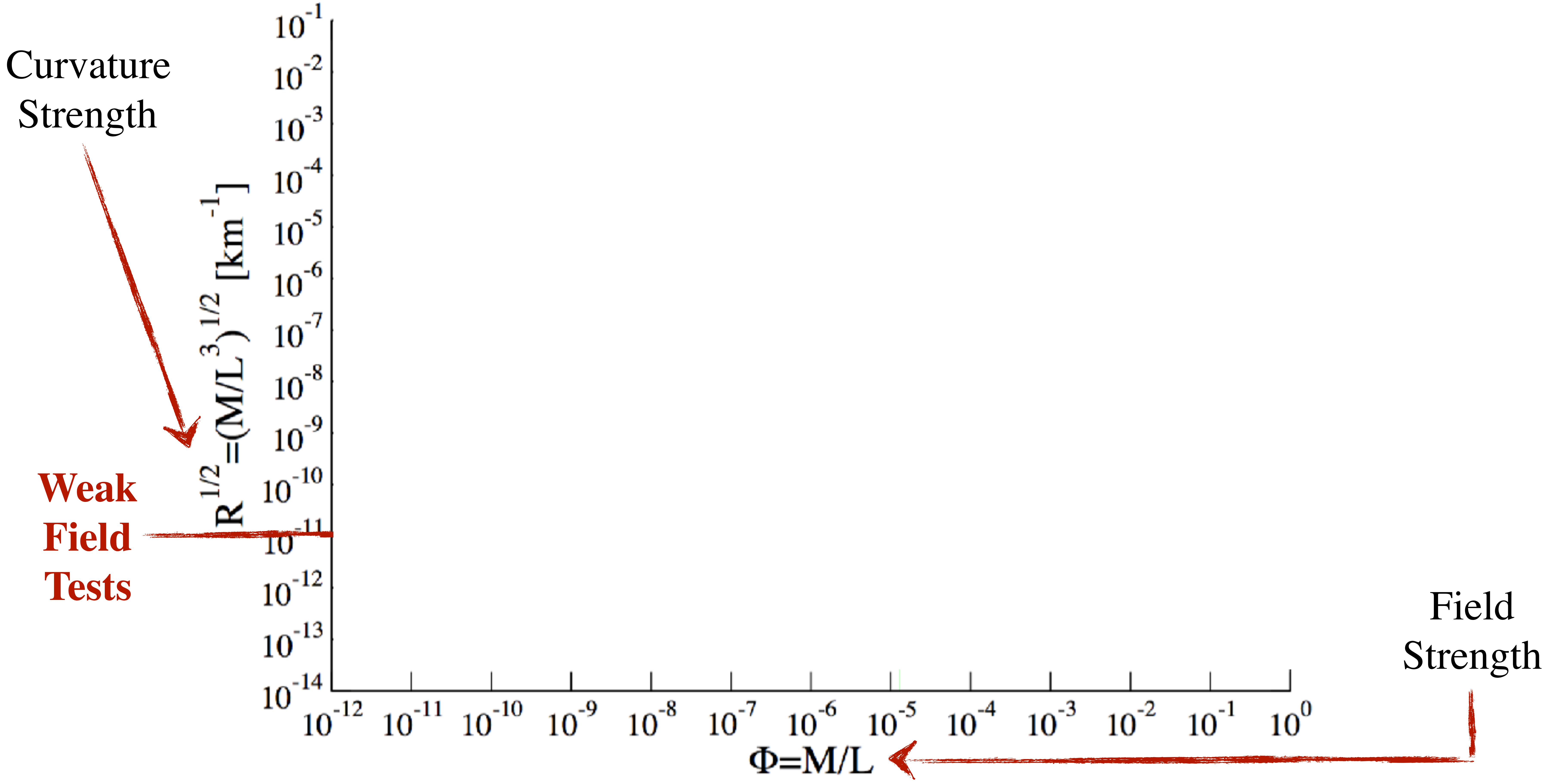


What can we learn about physics & gravity from precision gravitational wave observations?

Roadmap


Extreme Gravity
ppE Theory
Constraints &
Limitations
Frodo and Sam
ARNOR
IRON HILLS
MIRKWOOD
RHOVANION
RHÛN
The SEA of RHÛN
ERIADOR
FORLINDON
HARLINDON
MINHIRIATH
ENEDWAITH
DUNLAND
ROHAN
GONDOR
ERED NIMRAIS
MORDOR
BELEGAER
(the Great Sea)

What Physics Regime do GWs Probe?



GWs probe e$\mathcal{X}$treme Gravity

[Will, Liv. Rev., 2005, Psaltis, Liv. Rev., 2008, Baker, et al, Siemens & Yunes, Liv. Rev. 2013, Yunes, et al PRD 2016]

What is interesting to constrain?

Agnostic Approach

Effective Field Theory

Broken Symmetries

Generic Anomalies

Advantages:

Generic properties of gravity

PT calculations are "doable"

Disadvantages:

Hard to put it on a computer

Regime of validity of EFT

LIGO needs to work with theorists to decide what to search for

Religious Approach

Pick a theory and stick to it!

Eg. scalar-tensor theories, EA theory, EdGB gravity, Bigravity

Advantages:

You have the complete action

You can put it on a computer

Disadvantages:

Non-generic approach

Hard to make theory pass all tests

Main Difficulty of the Religious Approach: Catch-22

Case Study: Scalar-Tensor Theories

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

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

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

Induce Strong Field Corrections

weak field, inside star with $K^2 \sim |\beta\, T_{\rm mat}| \sim |-\beta\, \rho|$

$$\nabla_r^2\varphi = -K^2\varphi\, \mathrm{sign}\,(-\beta\rho)$$

$\varphi'(0)=0$ & φ is C^1 @ sfc R & $\beta < 0$

$$\varphi = \frac{\varphi_\infty}{\cos(KR)}\frac{\sin(Kr)}{Kr}$$

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

Pass Solar System Constraints

weak field analysis $\quad \varphi = \varphi_\infty + \alpha_{\rm sc}\dfrac{m}{r}$

$$\gamma_{\rm ppN} - 1 = -\frac{2\beta^2\varphi_\infty^2}{1+\beta^2\varphi_\infty^2}$$

(Shapiro time-delay)

Easy to pass test if you set $\quad \varphi_\infty^2 \leq \mathcal{O}(10^{-5})$

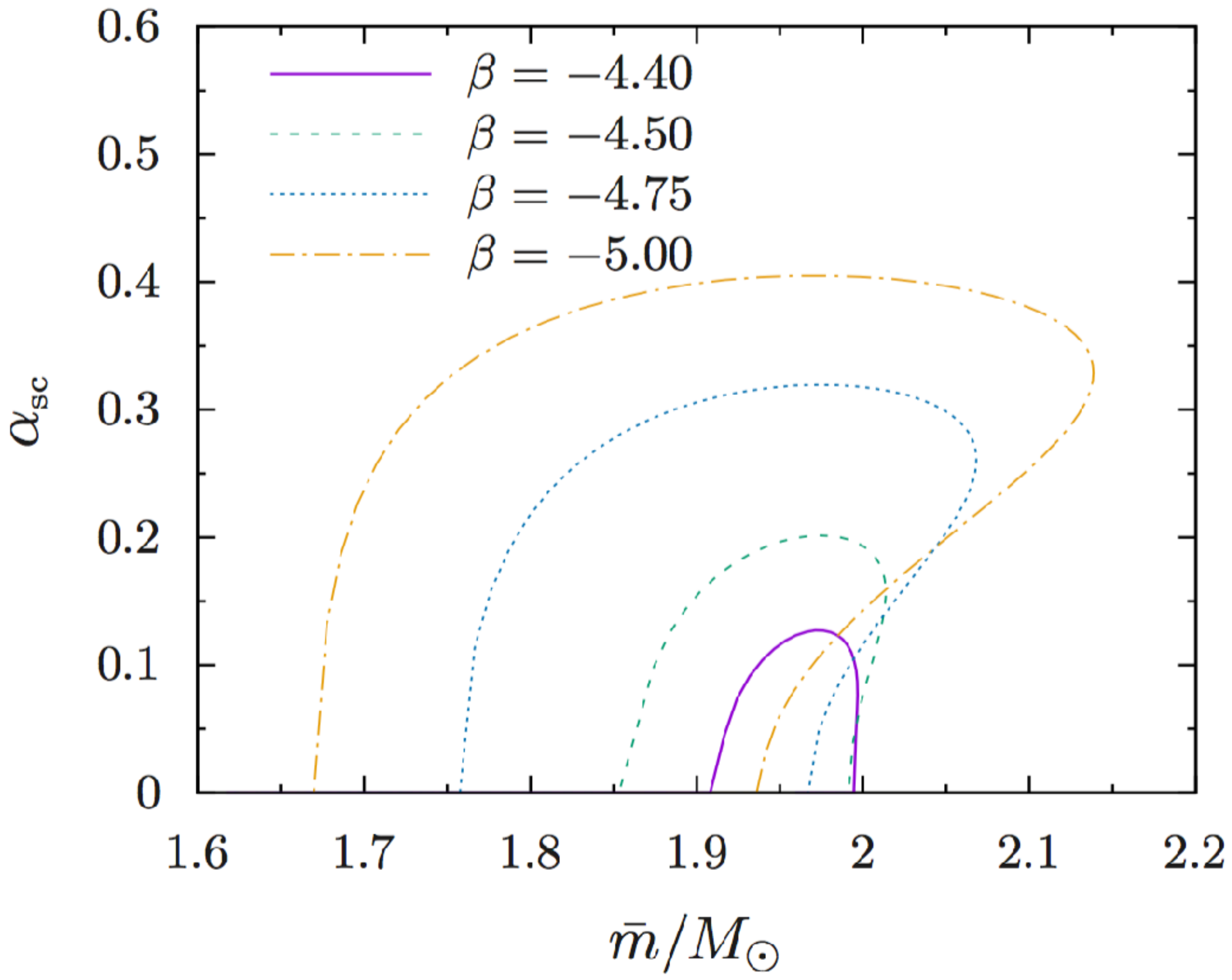
Inducing Strong Field Corrections

Matching the interior and exterior solutions at the surface

$$\varphi_{\rm inside} = \frac{\varphi_\infty}{\cos(KR)} \frac{\sin(Kr)}{Kr}$$

related to

$$\varphi_{\rm outside} = \varphi_\infty + \alpha_{\rm sc} \frac{m}{r}$$



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

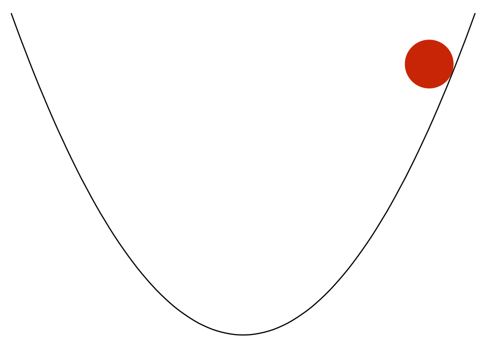
Cosmological Evolution and a Catch-22

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

But what is $\varphi_{\rm today}$ after cosmological evolution?

$$\Box_* \varphi = -\left(\frac{\kappa}{2}\beta\right) \varphi\, T_*^{\rm mat} \longrightarrow \frac{2}{3-\varphi'^2}\varphi'' + (1-\omega_{\rm eos})\varphi' = (1-3\omega_{\rm eos})\beta\varphi \longrightarrow \text{HO with } V_\varphi \sim \beta\varphi^2$$

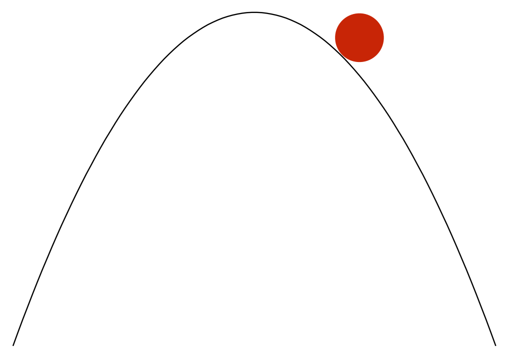
Option 1: $\beta > 0 \longrightarrow V_\varphi > 0$



$\longrightarrow \varphi_{\rm today} \sim 0$ and $\gamma_{\rm ppN} - 1 \ll 1$

[Damour & Nordvedt '93]

Option 2: $\beta < 0 \longrightarrow V_\varphi < 0$



$\longrightarrow |\varphi_{\rm today}| \gg 1$ and $\gamma_{\rm ppN} - 1 \sim -2$

[Sampson et al '14, Anderson, Yunes, Barausse '16]

Cosmological Evolution allows massless Scalar-Tensor theories to pass Solar System constraints if β<0 spontaneous scalarization is disallowed

Roadmap

Extreme Gravity
ppE Theory
Constraints &
Limitations
Frodo and Sam
ARNOR
ERIADOR
RHOVANION
MIRKWOOD
IRON HILLS
RHÛN
The SEA of RHÛN
BELEGAER
(the Great Sea)
ROHAN
GONDOR
MORDOR
ENEDWAITH
MINHIRIATH
HARLINDON
FORLINDON
DUNLAND
CARDOLAN
RHUDAUR
ARTHEDAIN
NORTH DOWNS
SOUTH DOWNS
ERED NIMRAIS
THE WOLD


Generation
Propagation

How is the GW observable modified? Generation Example

Case Study: Dipole Radiation

Conservation laws disallow dipole radiation in GR, but not in mod gravity

$$\dot{E}_b = -\mathcal{L} = -\left(\mathcal{L}_{\rm GW} + \mathcal{L}_\theta\right)$$

Dipole radiation removes energy more effectively than quadrupole radiation

$$\mathcal{L}_{\rm GW} \sim \left\langle \dddot{I}_{ij} \dddot{I}^{ij} \right\rangle \sim \left(\frac{v}{c}\right)^{10} \qquad \mathcal{L}_\theta \sim \left\langle \ddot{D}_i \ddot{D}^i \right\rangle \sim \left(\frac{v}{c}\right)^{8}$$

Dipole radiation forces binary to inspiral faster and GWs to chirp faster

GW Phase is sensitive to rate of inspiral

$$\Psi_{\rm GW} = \dot{f} T_g^2 = \left(\frac{dE}{df}\right)^{-1} \left(\frac{dE}{dt}\right) T_g^2 \quad \sim \left(\pi M f\right)^{-5/3} + \beta_\theta \left(\pi M f\right)^{-7/3}$$

Propagation Effect Enhancement Conjecture

Case Study: Massive Graviton

$$\delta\Psi_{\rm prop} = \pi^2 \frac{D_L \mathcal{M}}{\lambda_g^2} (\pi \mathcal{M} f)^{-1}$$

$$\delta\Psi_{\rm gen} = \frac{3}{128} \pi^2 \frac{\mathcal{M}^2}{\lambda_g^2} (\pi \mathcal{M} f)^{-11/3}$$

$$\frac{\delta\Psi_{\rm prop}}{\delta\Psi_{\rm gen}} \sim 10^{18} \left(\frac{\mathcal{M}}{28 M_\odot}\right)^{5/3} \left(\frac{D_L}{380 {\rm Mpc}}\right) \left(\frac{f}{100 {\rm Hz}}\right)^{8/3}$$

Modifications in GW propagation dominate over modifications in GW generation irrespective of PN order

[Yunes, Yagi, Pretorius, PRD '16]

Parameterized post-Einsteinian Framework

I. Parametrically deform the Hamiltonian.

II. Parametrically deform the RR force.

$$\boxed{\begin{gathered} A = A_{GR} + \delta A \\ \delta A_{H,RR} = \bar{\alpha}_{H,RR} v^{\bar{a}_{H,RR}} \end{gathered}}$$

III. Deform waveform generation.

$$\boxed{h = F_+ h_+ + F_\times h_\times + F_s h_s + \ldots}$$

IV. Parametrically deform g propagation.

$$\boxed{E_g^2 = p_g^2 c^4 + \tilde{\alpha} p_g^{\tilde{\alpha}}}$$

Result: To leading PN order and leading GR deformation, *inspiral* waveform is

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

Yunes & Pretorius, PRD 2009
Mirshekari, Yunes & Will, PRD 2012
Chatziioannou, Yunes & Cornish, PRD 2012

Mapping ppE to Theories

[Yunes & Pretorius, PRD 2009]

The parameterized post-Einsteinian Framework

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

Theoretical Effect	Theoretical Mechanism	Theories	ppE b	Order	Mapping
Scalar Dipolar Radiation	Scalar Monopole Field Activation	EdGB [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	$\beta_{\rm Æ}^{(-1)}$ [113] $\beta_{\rm Æ}^{(0)}$ [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).]

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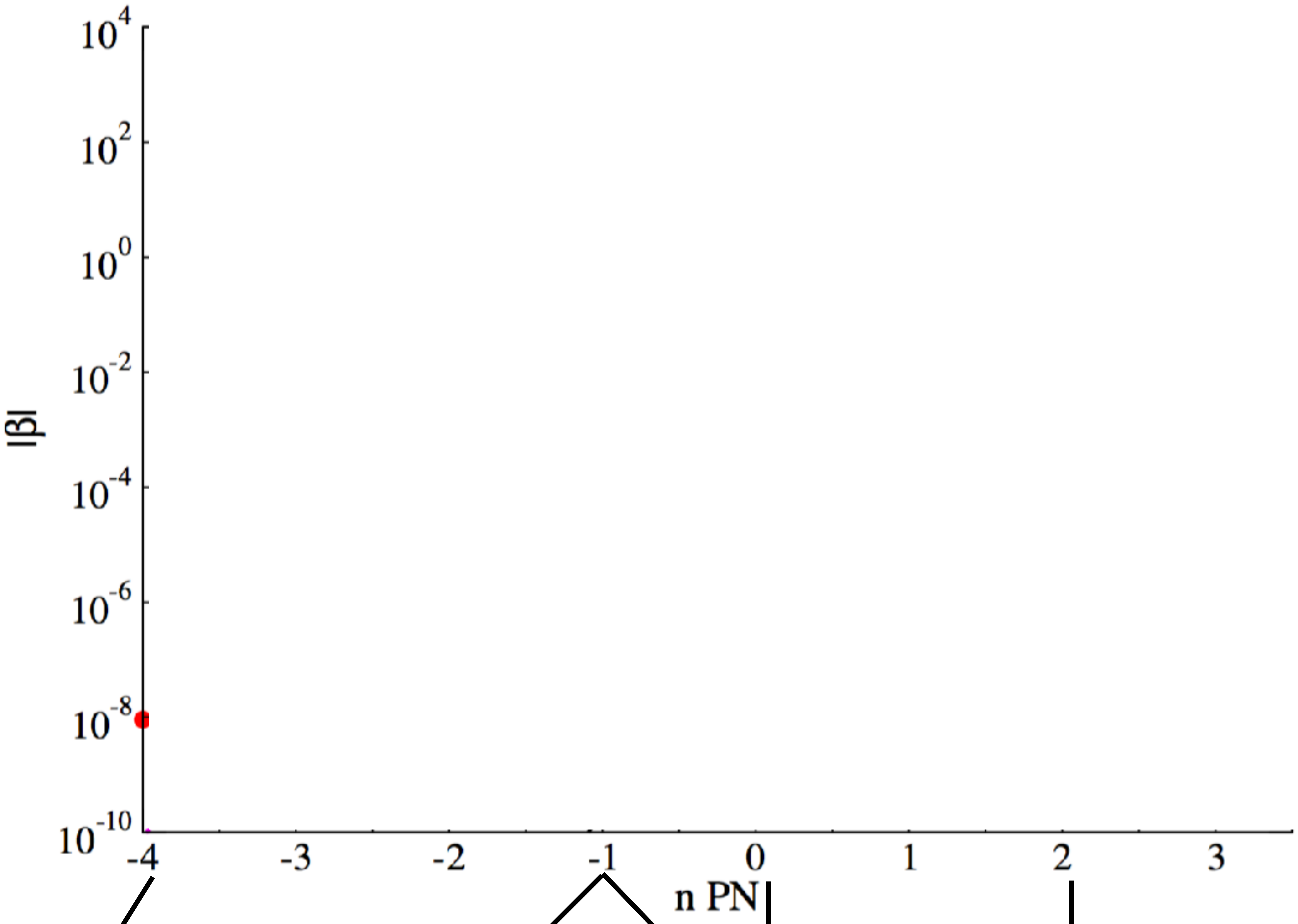
DUNLAND
ROHAN
GONDOR
MORDOR
ERED NIMRAIS
BELEGAER
(the Great Sea)

GW Constraints on Modified Generation



Anomalous Acceleration

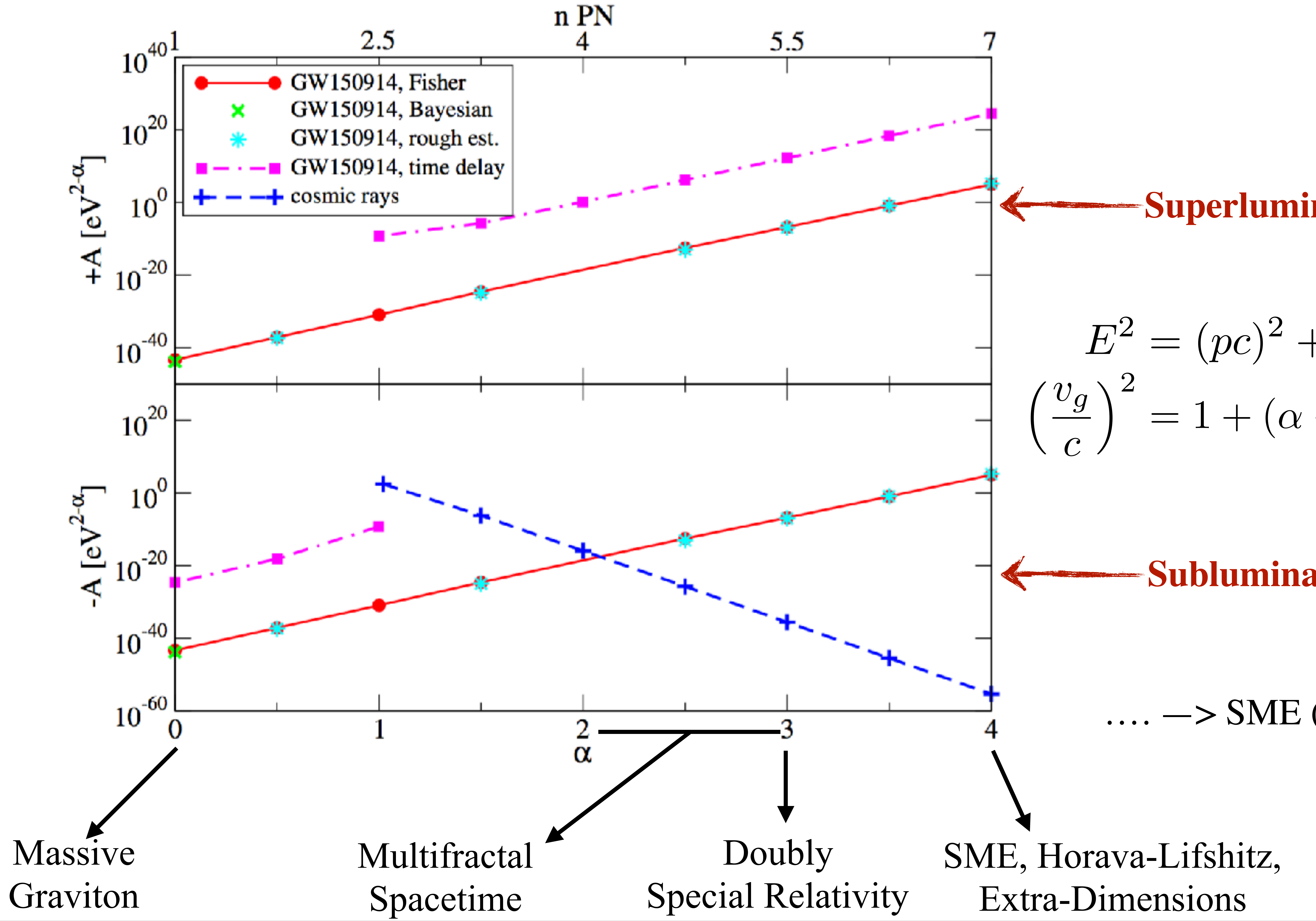
Scalar Dipole Radiation

Lorentz Violation

Parity Violation

[Yunes, Yagi, Pretorius, PRD '16]

GW Constraints on Modified Propagation



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

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

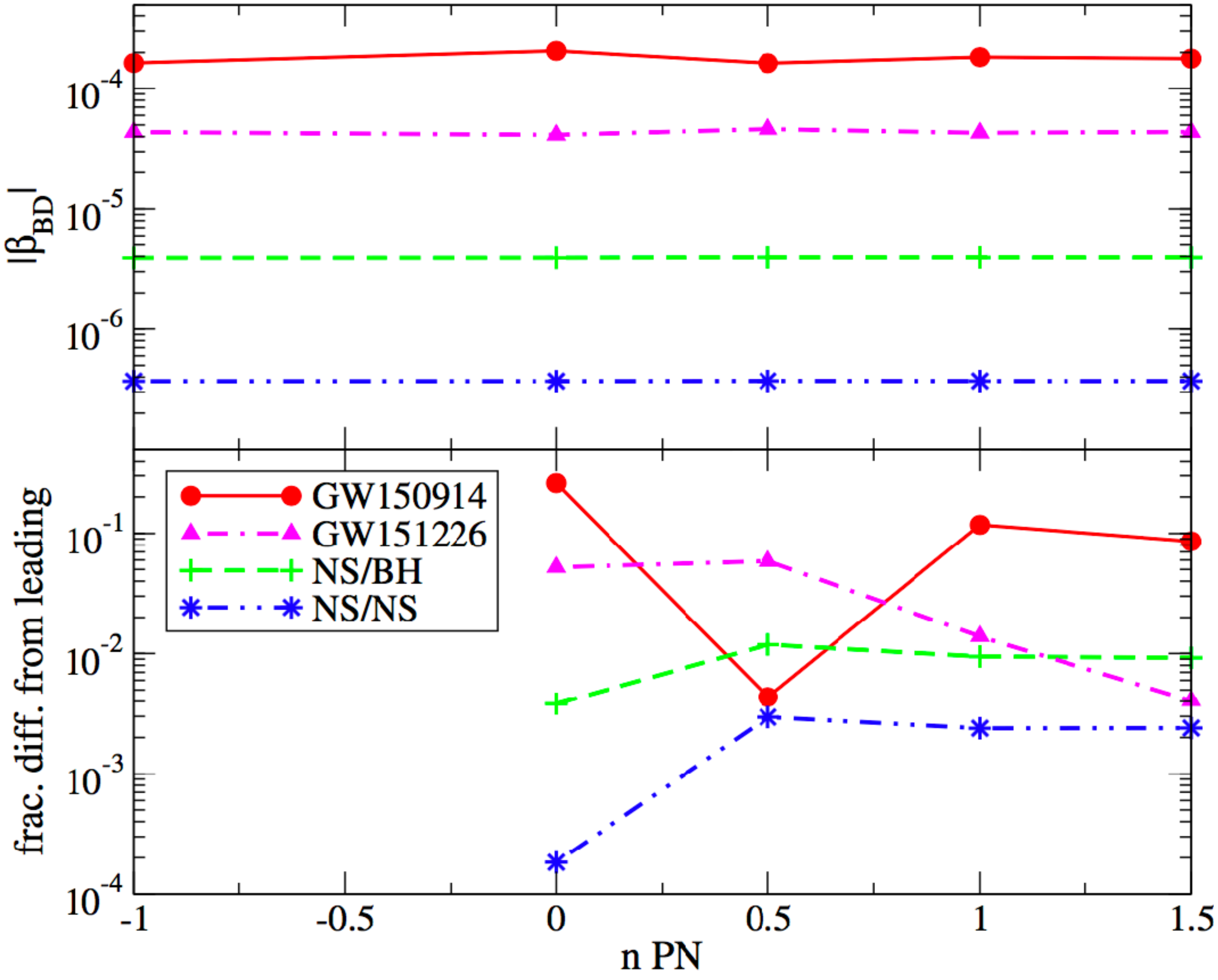
…. —> SME (5.5PN, 7PN)

[Yunes, Yagi, Pretorius, PRD '16]

Limitations: What about the higher PN order terms?

Case Study: Scalar-Tensor (Brans Dicke) theory

$$\Phi_{\rm I}^{\rm BD}(f) = \Phi_{\rm I}^{\rm GR}(f) + \beta_{\rm BD}\left(\pi\mathcal{M}f\right)^{b_{\rm BD}} \left[1 + \sum_{i=2}^{5}\delta\phi_i^{\rm BD}(\eta)\left(\pi\mathcal{M}f\right)^{i/3}\right]$$



Caveat: Constraints are "conservative." Limited by ignorance of merger (see talk by Leo Stein)

[Yunes, Yagi, Pretorius, PRD '16]

Limitations: What about parameter degeneracies?

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

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

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

Actual GW150914 Constraints on GR Pillar Violations in Wave Generation

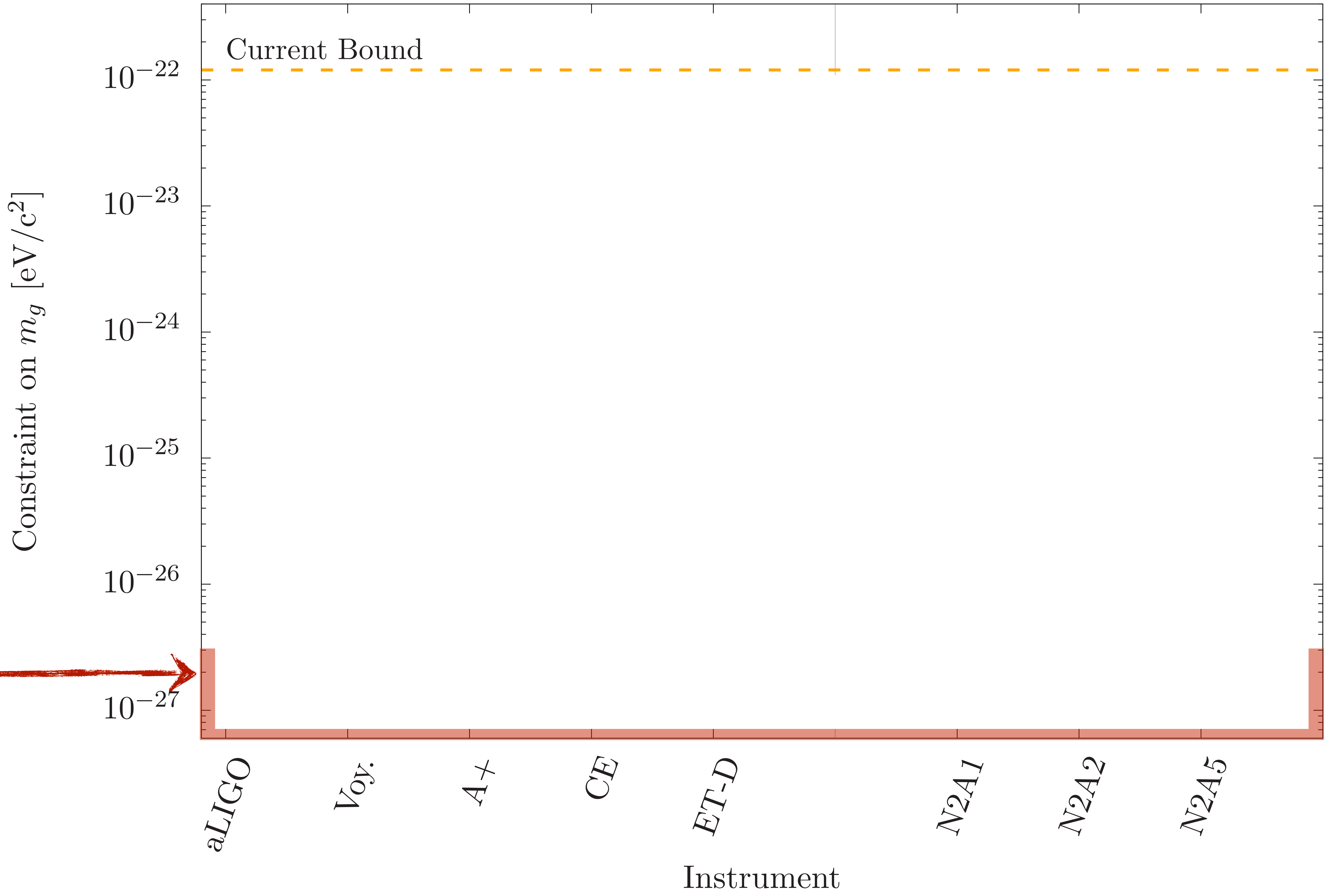
Theoretical Mechanism	GR Pillar	PN	$\lvert\beta\rvert$ **GW150914**	Example Theory Constraints: Repr. Parameters	Example Theory Constraints: **GW150914**	Example Theory Constraints: Current Bounds
Scalar Field Activation	SEP	-1	$\mathbf{1.6 \times 10^{-4}}$	$\sqrt{\lvert\alpha_{\rm EdGB}\rvert}$ [km]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

[Yunes, Yagi, Pretorius, PRD '16]

Case Study:
Massive Graviton

(see talk by Enrico Barausse)

10^5 times better than current bounds!!



[Chamberlain & Yunes, 2017]

$$\beta = \pi^2 \frac{D\, \mathcal{M}_z}{1+z} m_g^2$$

But this is not all!!

Horizon Tests
(Vitor's Talk)

Goal: Verify existence of marginally trapped surface

Example: Boson Stars, Gravastars, Wormholes

Features: Echoes?

Comments:

Dynamics? Cut and paste…

Stability?

From gravitational collapse?

Merger Tests
(Leo's Talk)

Goal: Verify GR in the merger phase

Example: scalar-tensor theories, dynamical Chern-Simons gravity

Features: dipole burst

Comments:

Well-posedness or EFT

Ensure validity of EFT

Numerical Relativity

Equivalence Principle Tests
(Enrico's Talk)

Goal: Verify SEP in extreme gravity

Example: scalar-tensor, Einstein-AEther, dynamical Chern-Simons, Horndeski, etc.

Features: dipole radiation

Comments:

Best with multi-wavelength

Agnostic or Religious?

Ringdown tests

Take Home Message

Model-Independent Framework To Search For Anomalies In The Data Allows For Constraints On Deviations
(parameterized post-Einsteinian and Bayesian model selection)

Gravitational Waves Are Already Telling Us About Theoretical Physics
(Lorentz violation, graviton mass, dipole emission, higher curvature action, screening mechanisms, no-hair theorem)

Modified Theories Must Pass A New High Bar
(They must be consistent with LIGO's observations of BHs and GWs)

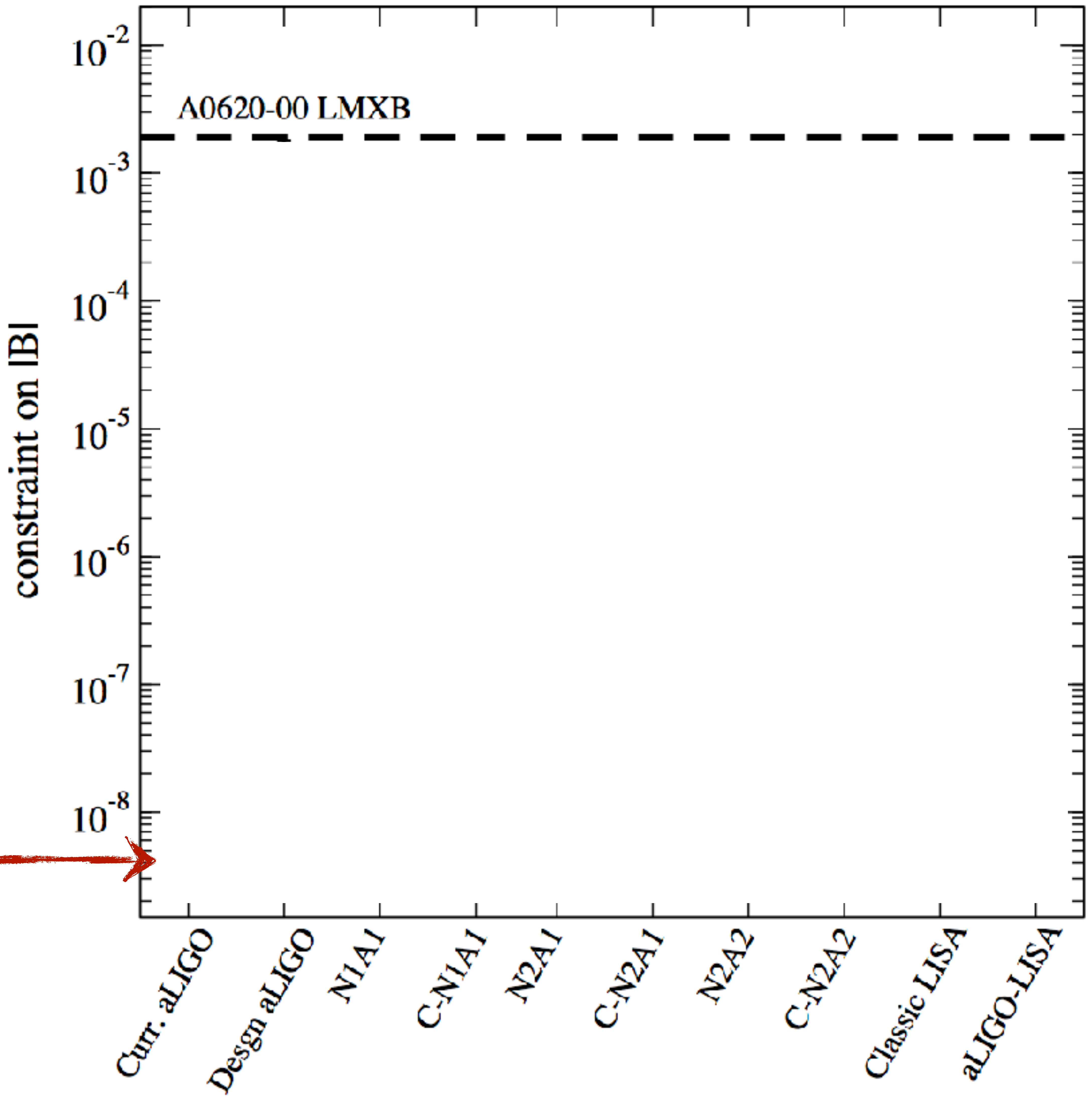
If it bleeds,
we can kill it!

Thank You

Future Constraints with Multi-Wavelength Observations

Case Study:
Dipole Radiation

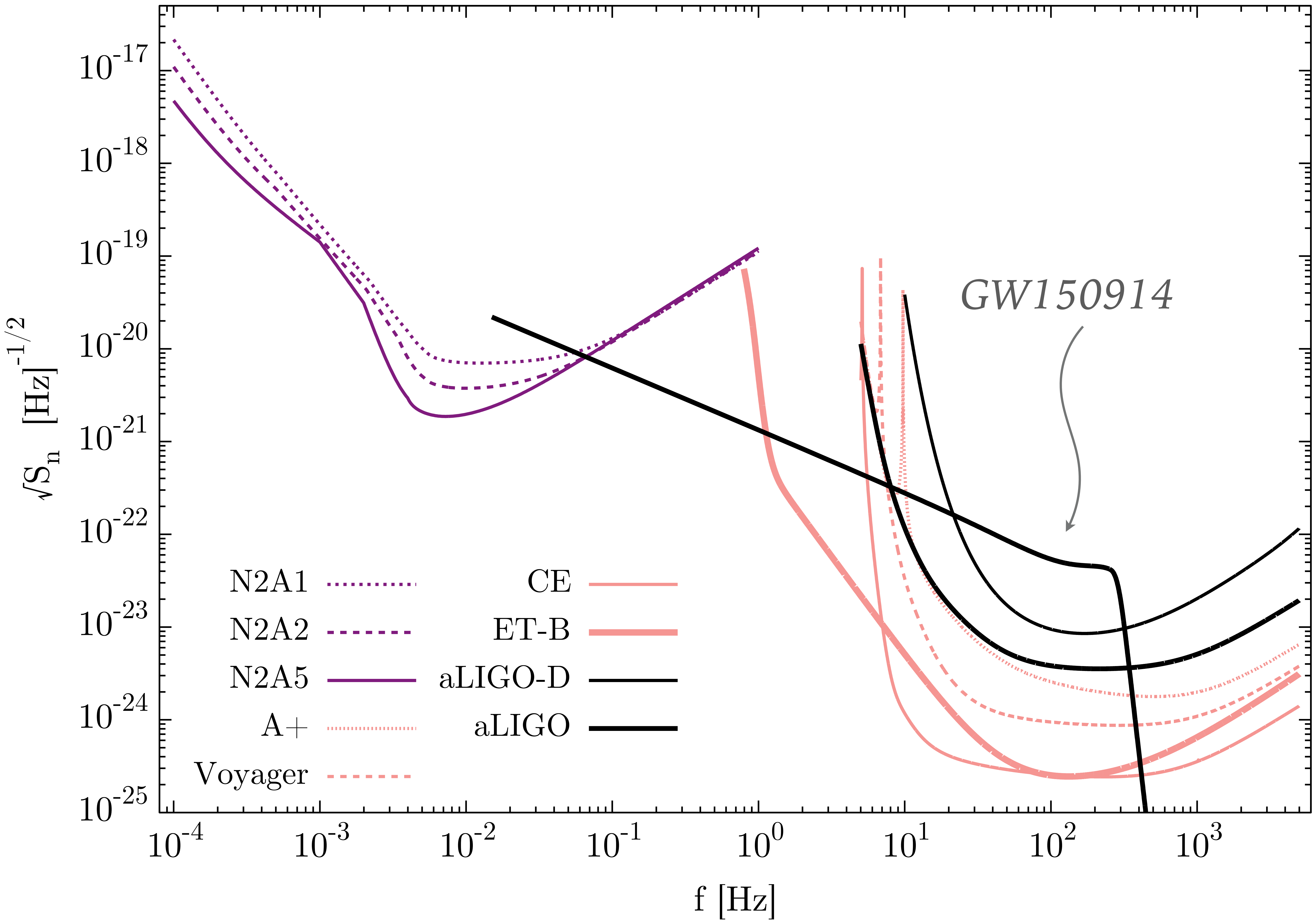
$$\beta = -\frac{3}{224}\eta^{2/5} B$$



10^6 times better than current bounds!!

[Barausse, Yunes, Chamberlain, PRL '16]

Spectral Noises of Future Instruments

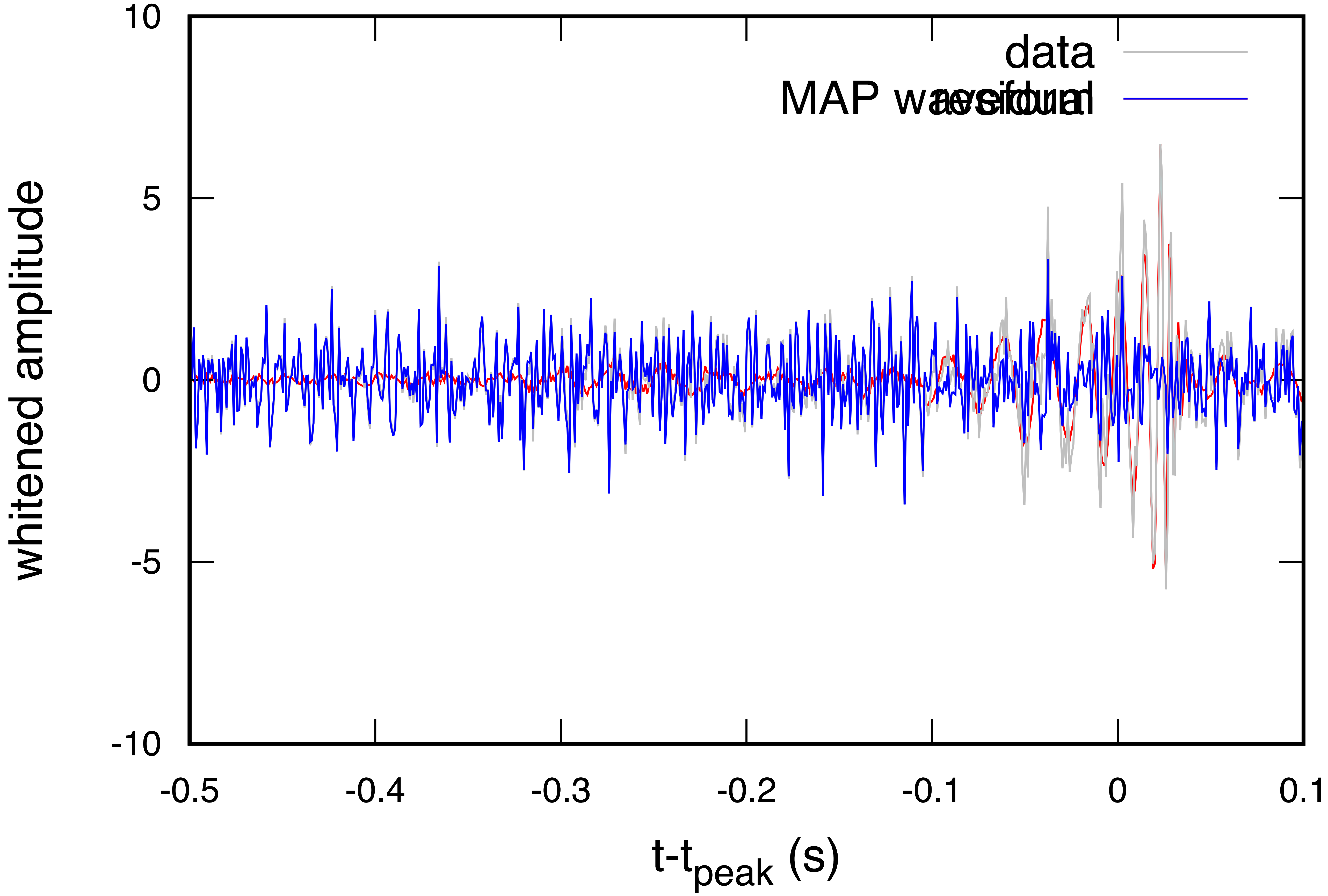


Theory Implications of GW Observations

Theoretical Mechanism	GR Pillar	PN	$\vert\beta\vert$ GW150914	$\vert\beta\vert$ GW151226	Repr. Parameters	Example Theory Constraints GW150914	GW151226	Current Bounds
Scalar Field Activation	SEP	-1	1.6×10^{-4}	4.4×10^{-5}	$\sqrt{\vert\alpha_{\rm EdGB}\vert}$ [km] $\vert\dot{\phi}\vert$ [1/sec]	— —	— —	10^7 [56], 2 [57–59] 10^{-6} [60]
Scalar Field Activation	SEP, PI	$+2$	1.3×10^{1}	4.1	$\sqrt{\vert\alpha_{\rm dCS}\vert}$ [km]	—	—	10^8 [61, 62]
Vector Field Activation	SEP, LI	0	7.2×10^{-3}	3.4×10^{-3}	(c_+, c_-) $(\beta_{\rm KG}, \lambda_{\rm KG})$	$(0.9, 2.1)$ $(0.42, -)$	$(0.8, 1.1)$ $(0.40, -)$	$(0.03, 0.003)$ [63, 64] $(0.005, 0.1)$ [63, 64]
Extra Dimensions	4D	-4	9.1×10^{-9}	9.1×10^{-11}	ℓ [μm]	5.4×10^{10}	2.0×10^{9}	10–10^3 [65–69]
Time-Varying G	SEP	-4	9.1×10^{-9}	9.1×10^{-11}	$\vert\dot{G}\vert$ [10^{-12}/yr]	5.4×10^{18}	1.7×10^{17}	0.1–1 [70–74]

[Yunes, Yagi, Pretorius, PRD ‘16]

Consistency with General Relativity

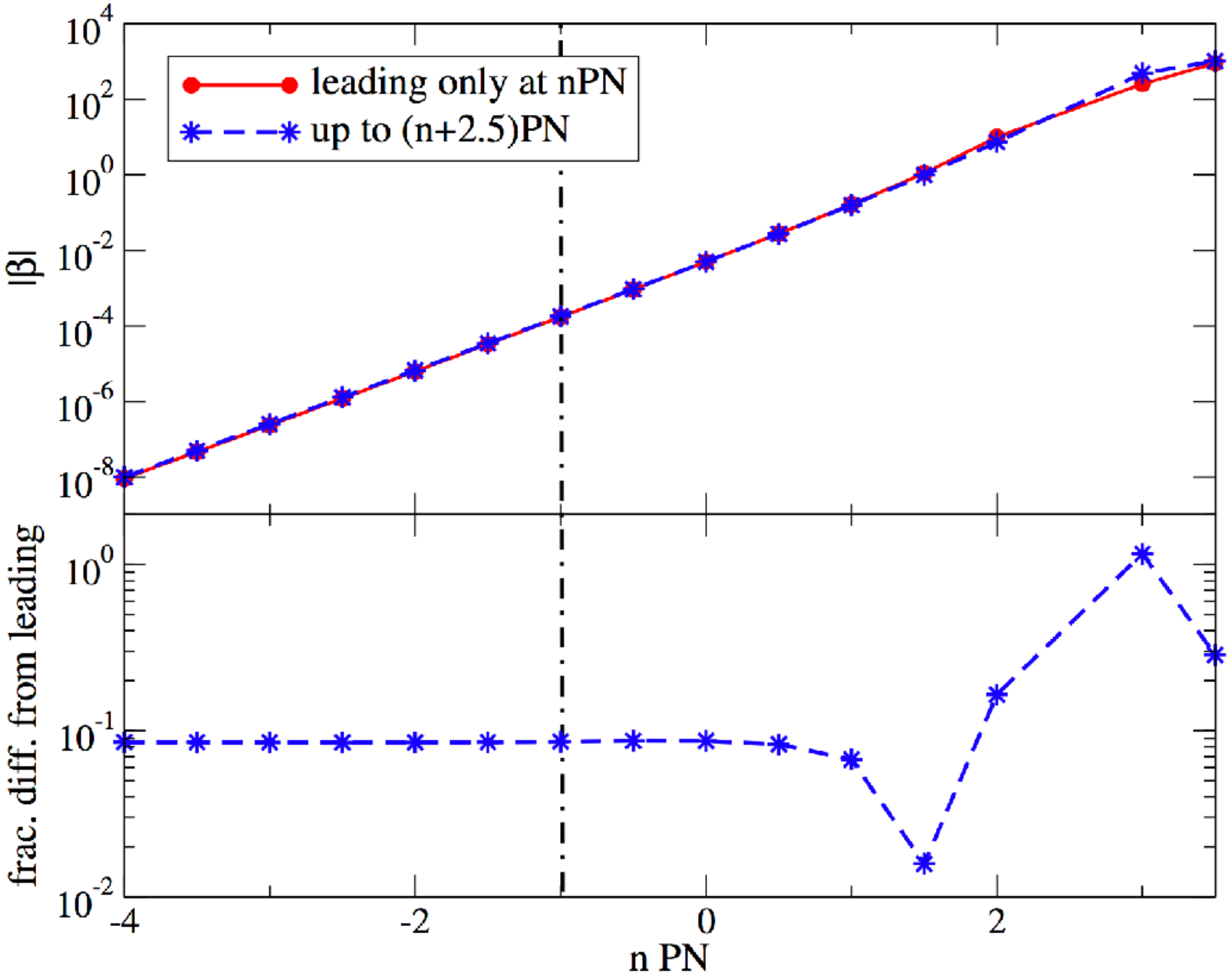


SNR of Residual (data - best fit) is consistent with noise

[LIGO PRL 116 (2016)]

More on Robustness of Constraints

Constraint on ppE amplitude as a function of PN order at which the modification first enters (assuming BD functional structure)



Constraints are always robust, provided the modifications to the GW generation enter below 2.5PN order (ie. provided there is enough "information" in the inspiral part of the waveform)

Future ppE Constraints on GR

space-based **ground-based**

[Chamberlain & Yunes, to appear soon]

Classification of Inferences

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

⋮

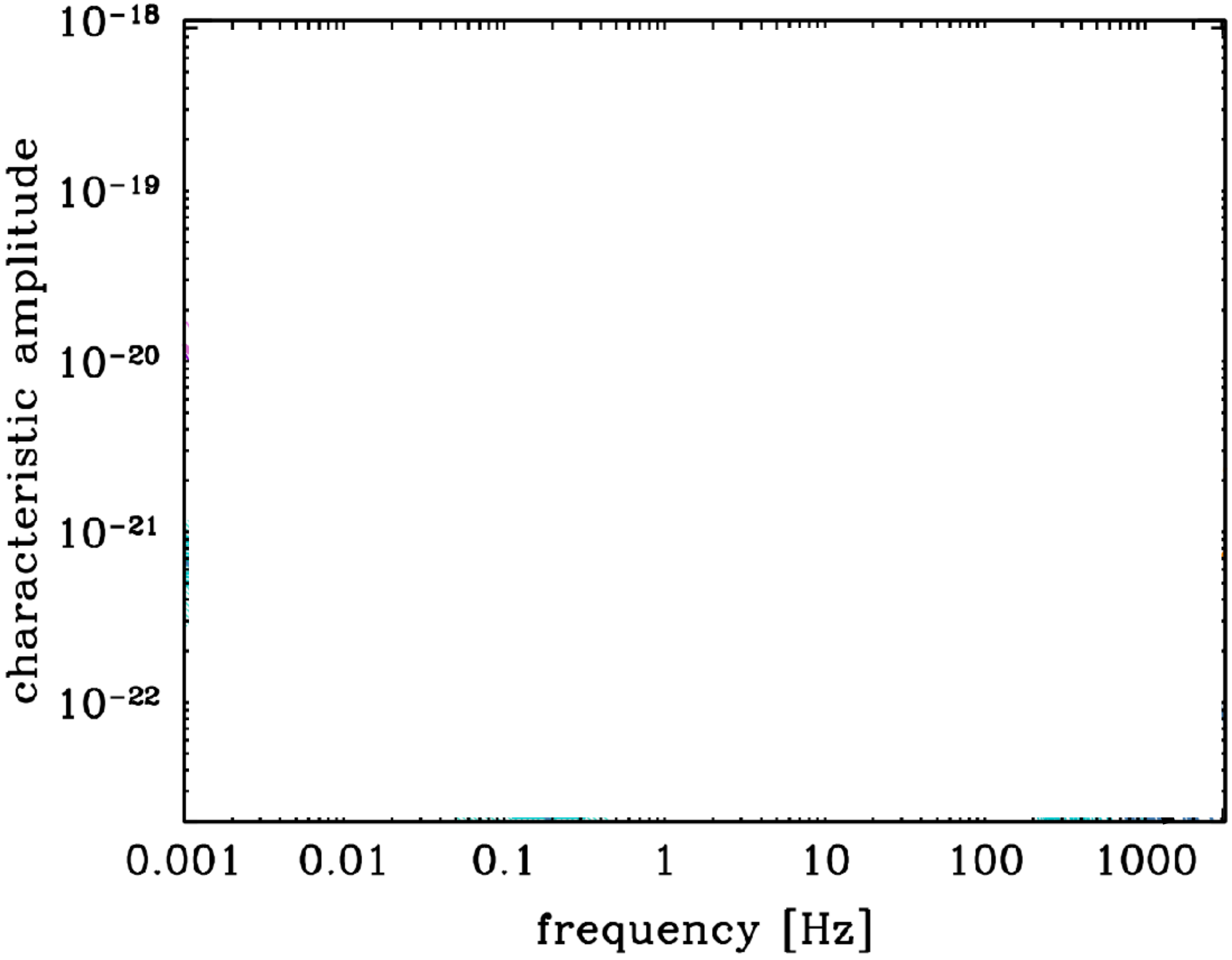
Speed of Gravity

Mass of Graviton

Lorentz Violation

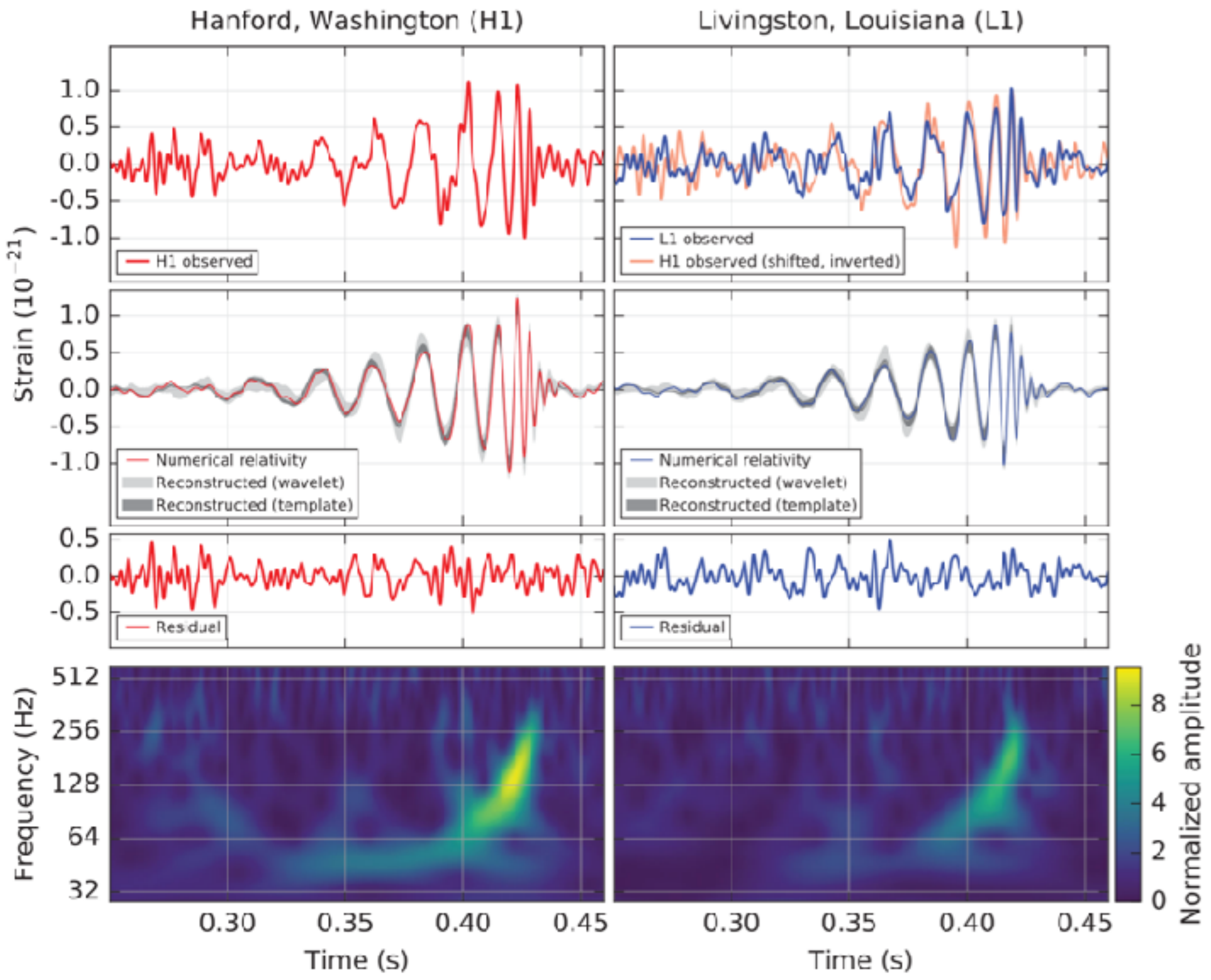
SEP Violation

Multi-Band Observations



[Amaro-Seoane & Santamaria Ap.J. ’10, Sesana, PRL ’16]

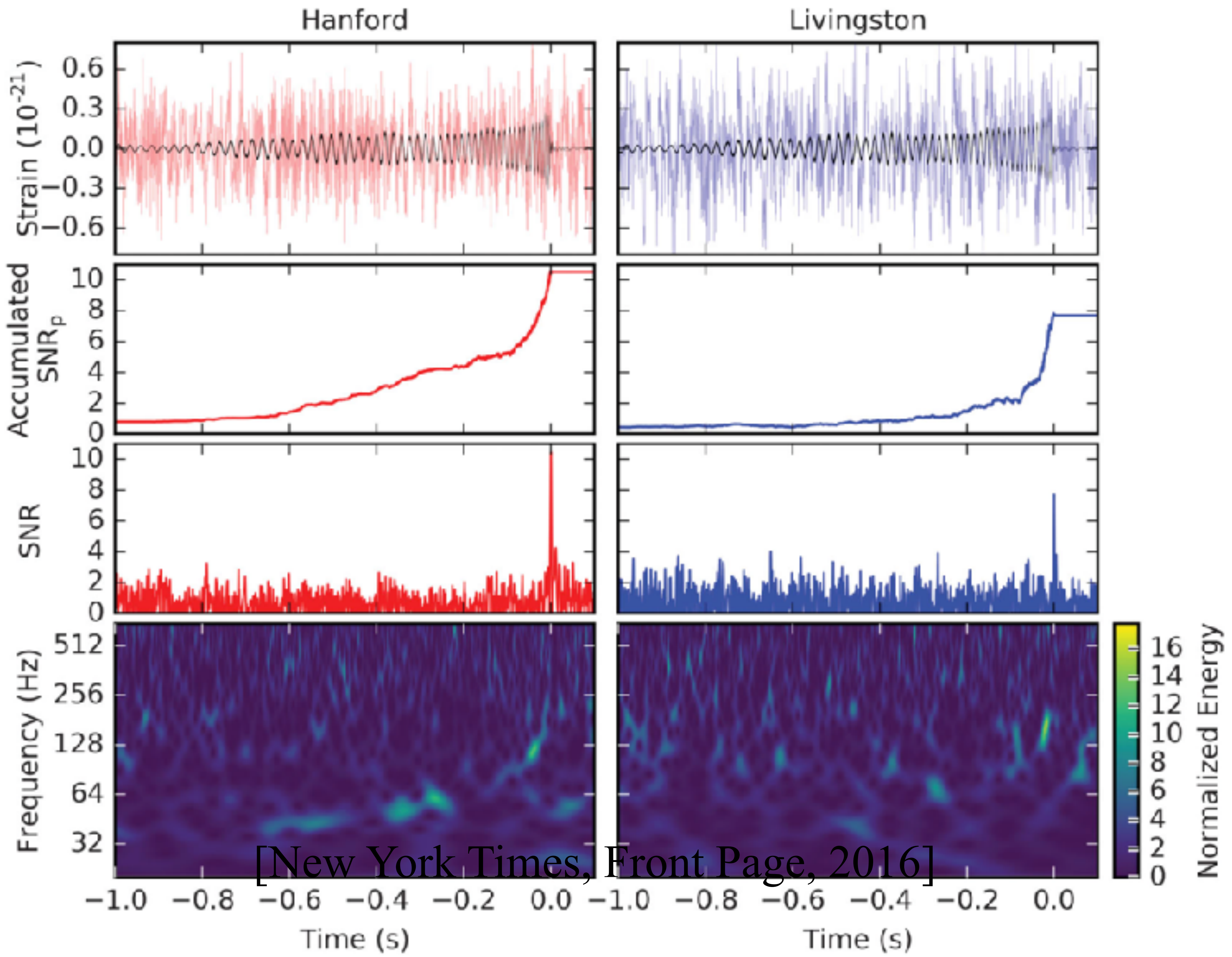
LIGO’s First Direct Detection of Gravitational Waves



GW150914

[LIGO, PRL, ’16]

GW151226



[New York Times, Front Page, 2016]

Properties of GW150914

$$m_1 = 35.7^{+5.4}_{-3.8} M_\odot$$

$$m_2 = 29.1^{+3.8}_{-4.4} M_\odot$$

$$|\vec{S}_1|/m_1^2 = 0.31^{+0.48}_{-0.28}$$

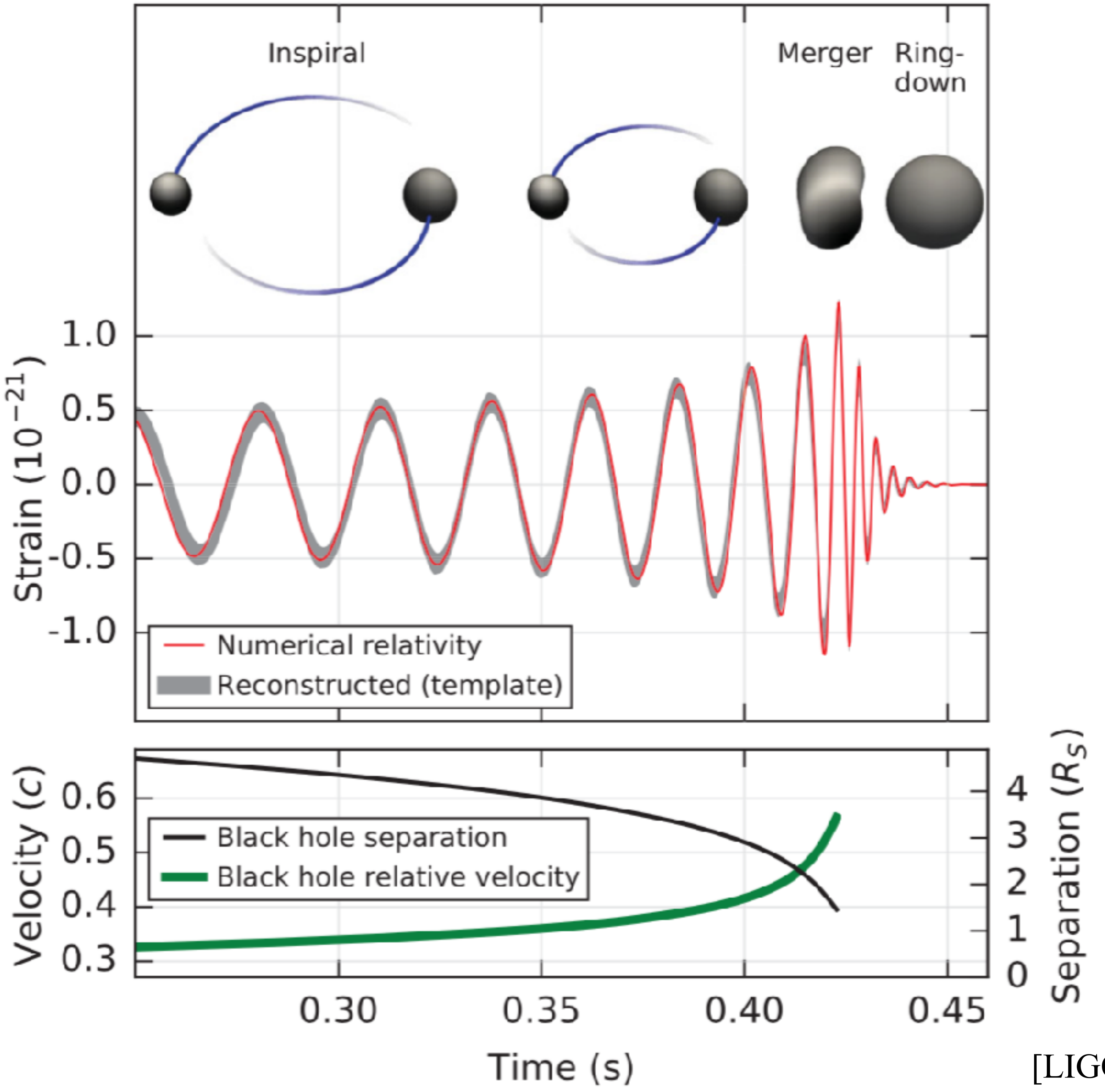
$$|\vec{S}_2|/m_2^2 = 0.46^{+0.48}_{-0.42}$$

$$m_f = 61.8^{+4.2}_{-3.5} M_\odot$$

$$|\vec{S}_f|/m_f^2 = 0.67^{+0.05}_{-0.07}$$

$$D_L = 410^{+160}_{-180}\ \mathrm{Mpc}$$

$$z = 0.088^{+0.031}_{-0.038}$$



[LIGO, PRL 116 (2016)]

Dipole Energy Flux

dipole
strength

$$\dot{E}_{\rm GW} \sim \left(\frac{m}{r_{12}}\right)^5 + B\left(\frac{m}{r_{12}}\right)^4$$

Quadrupole +
Octopole + …

Dipole
scaling

Effect of Dipole Flux

Faster Inspiral, Faster Merger

$$\frac{df_{\rm GW}}{dt} = \left(\frac{df_{\rm GW}}{dE_{\rm b}}\right)\left(\frac{dE_{\rm b}}{dt}\right) = -\left(\frac{df_{\rm GW}}{dE_{\rm b}}\right)\dot{E}_{\rm GW} = -\left(\frac{df_{\rm GW}}{dE_b}\right)\left[\left(\frac{m}{r_{12}}\right)^5 + B\left(\frac{m}{r_{12}}\right)^4\right]$$

Faster Inspiral, Faster Gravitational Wave Chirp

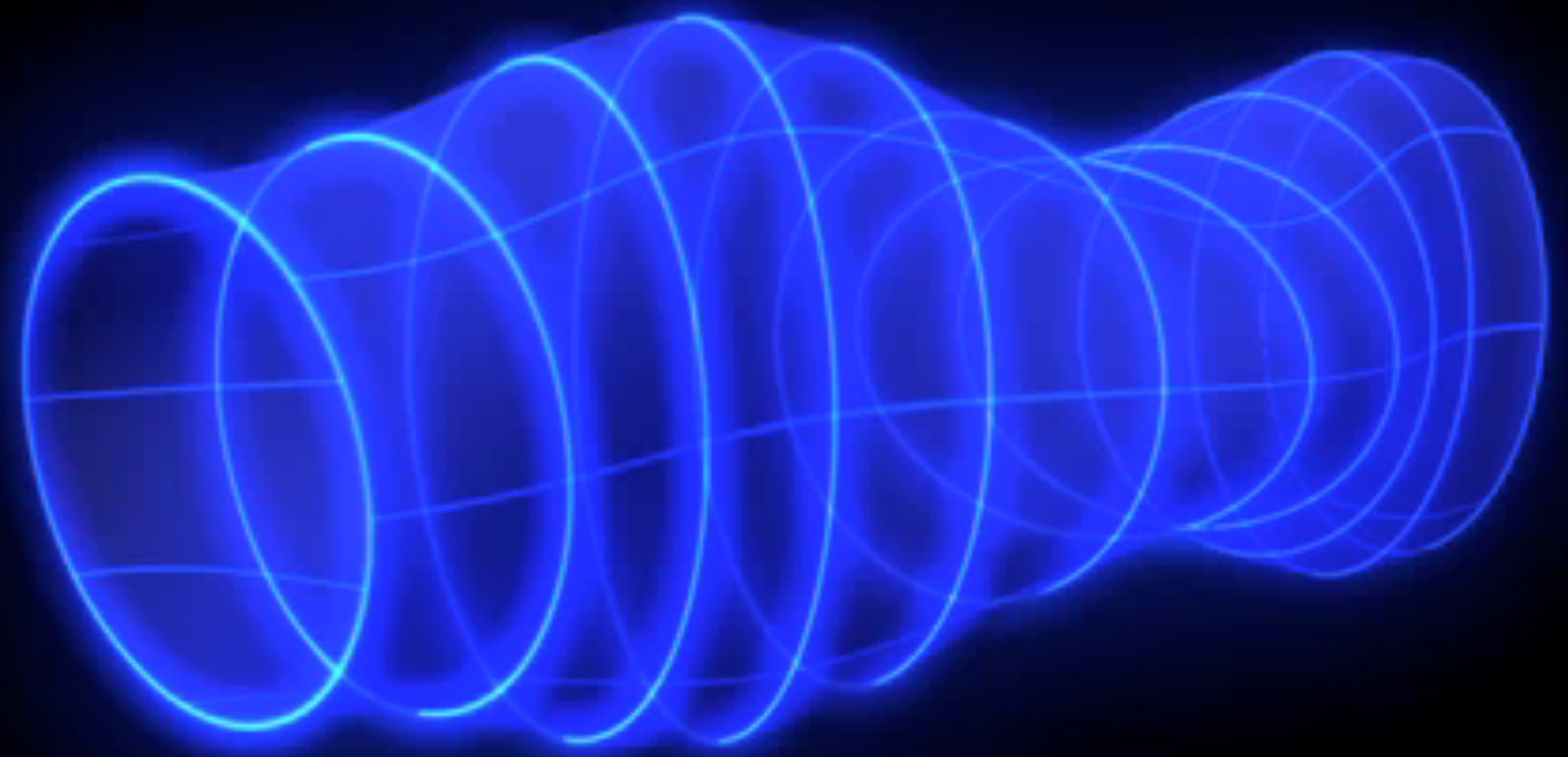
$$\Psi_{\rm GW} \propto \int^t\!\!\int^{t'} \left(\frac{df_{\rm GW}}{dt''}\right) dt''dt' = \Psi_{\rm GW,GR} + \beta(B)\left(\pi\mathcal{M}f_{\rm GW}\right)^{-7/3}$$

Quadrupole +
Octopole + …

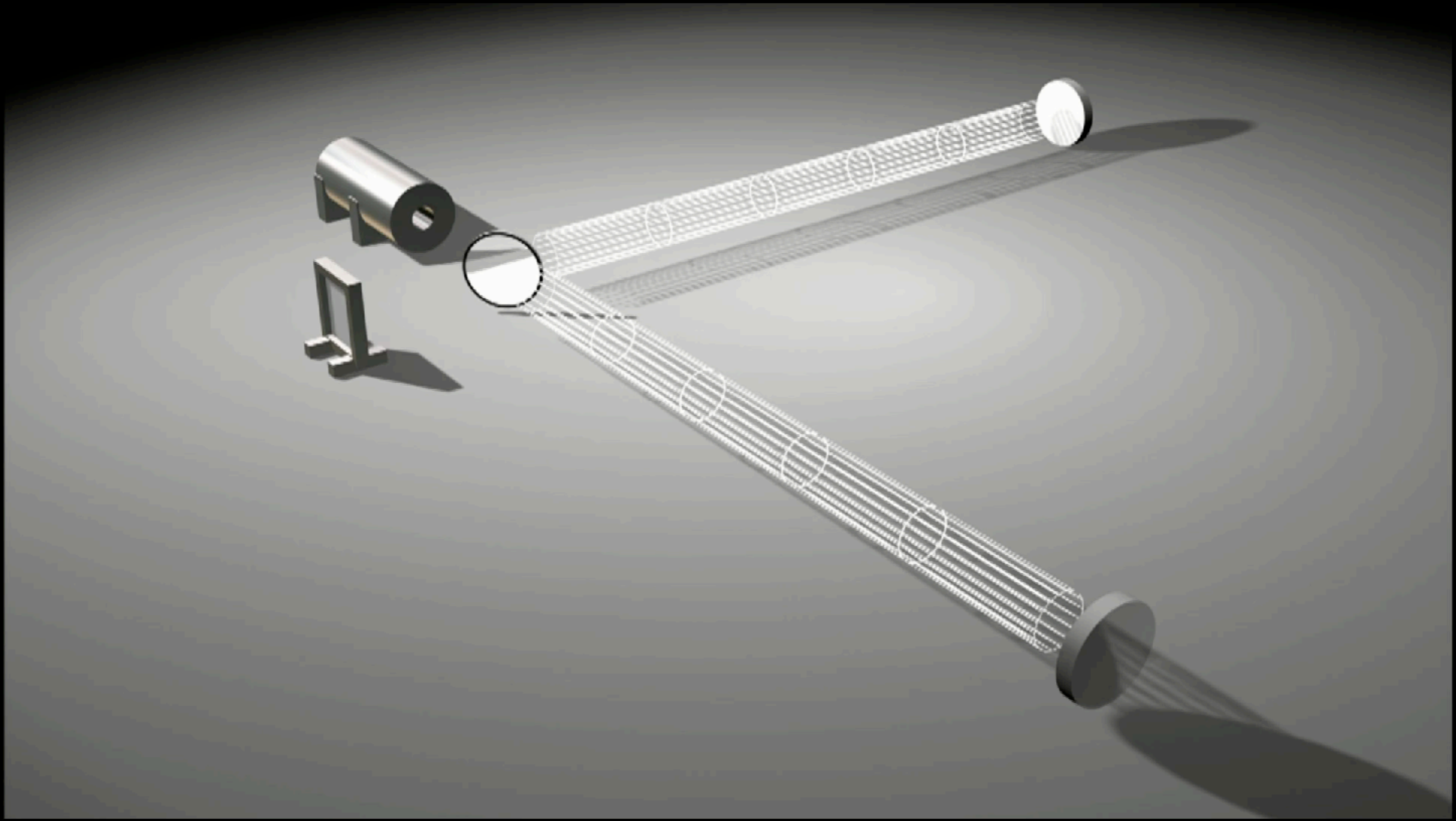
Dipole
GW Term

The eXtreme Gravity Spectrum

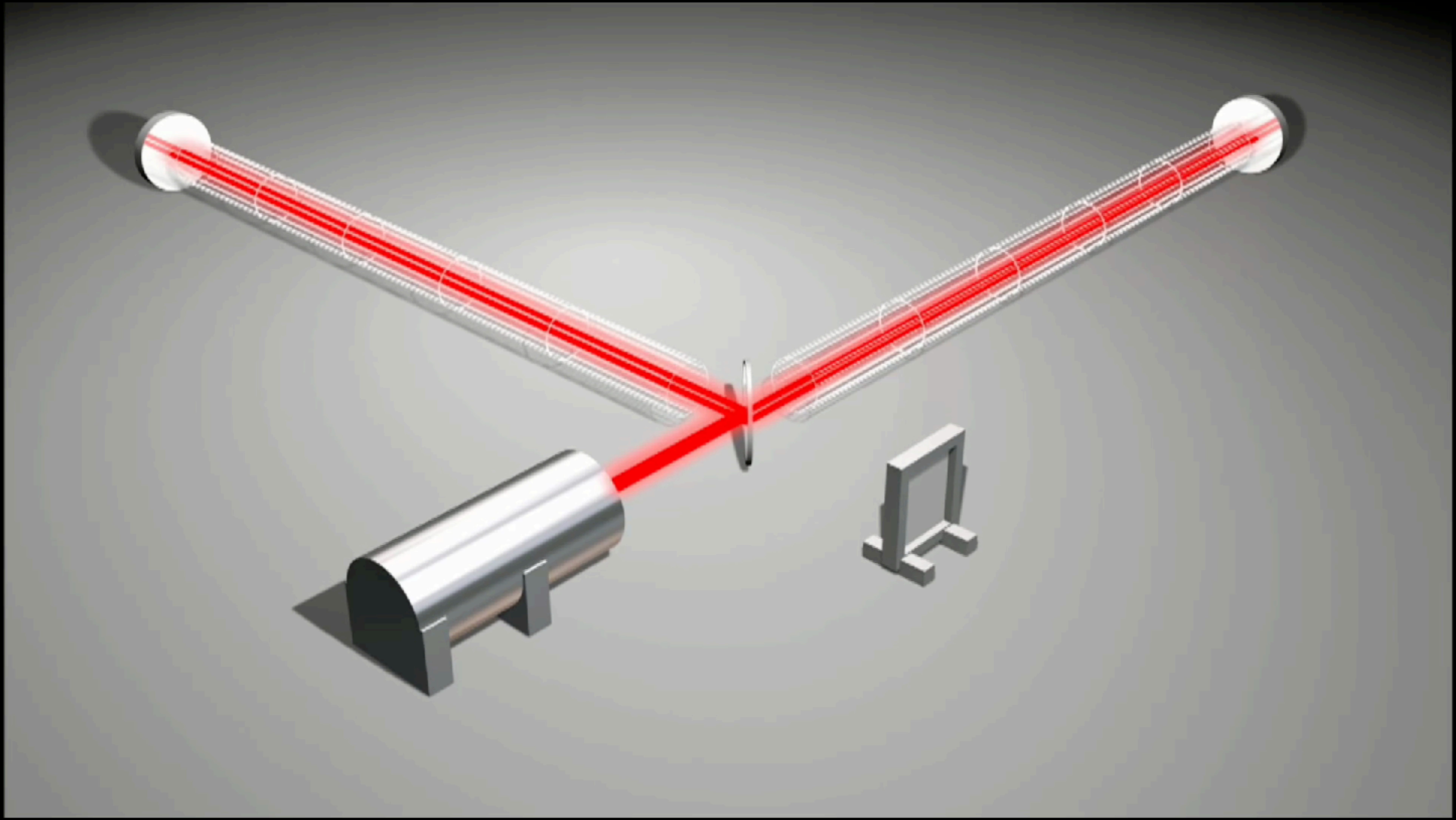
How do we detect gravitational waves?



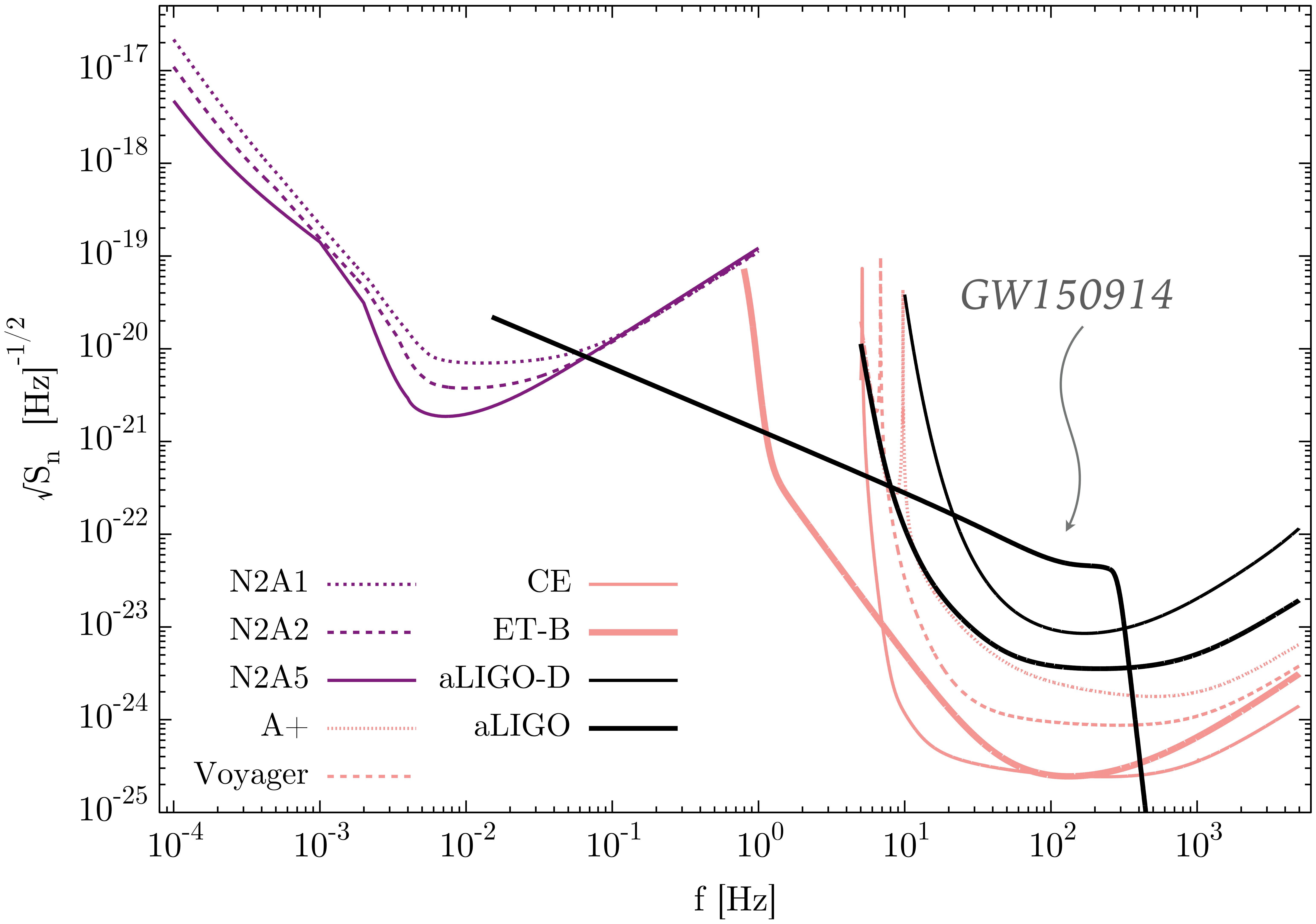
How do we detect gravitational waves?



How do we detect gravitational waves?



Spectral Noises of Future Instruments

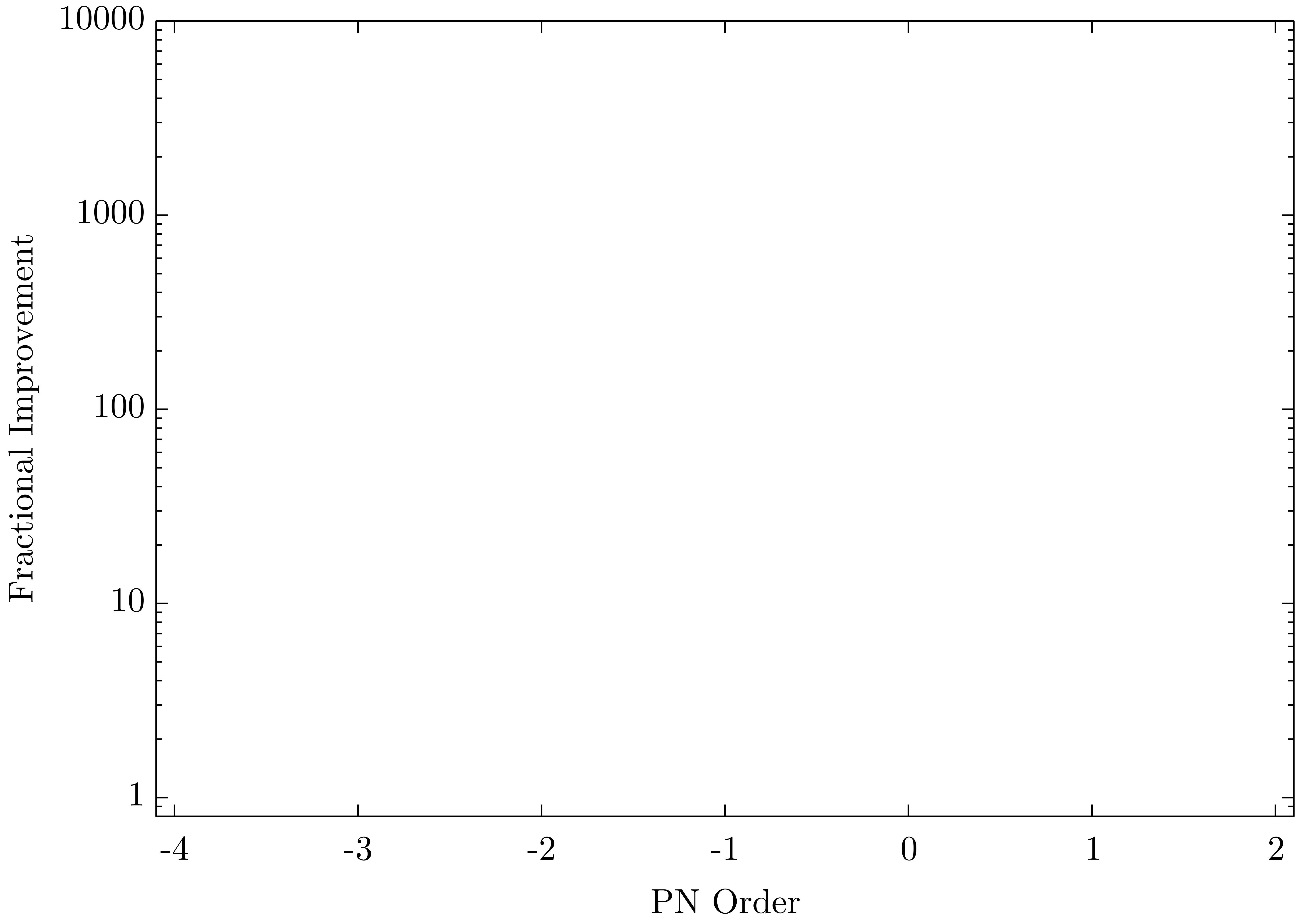


In life you have to make choices, so we made some…

Name	$m_1[M_\odot]$	$m_2[M_\odot]$	(χ_1, χ_2)	D_L	z	ρ -range
GW150914	35.1	29.5	(0.31, 0.39)	400 Mpc	~ 0.09	6 – 12
EMRI	10^5	10	(0.8, 0.4)	1 Gpc	~ 0.2	60 – 235
IMRI	10^5	10^3	(0.7, 0.9)	5 Gpc	~ 0.8	166 – 659
IMBH	5×10^3	4×10^3	(0.7, 0.9)	16 Gpc	~ 2	58 – 227
SMBH	5×10^6	4×10^6	(0.7, 0.9)	48 Gpc	~ 5	372 – 1110

Name	$m_1[M_\odot]$	$m_2[M_\odot]$	(χ_1, χ_2)	D_L	ρ_{aLIGO}	ρ_{A+}	$\rho_{Voyager}$	ρ_{ET-B}	ρ_{CE}
NSNS	2	1.4	(0.01, 0.02)	100 Mpc	23.23	33.65	109.55	332.98	541.14
ℓBHNS	5	1.4	(0.2, 0.02)	150 Mpc	22	31	103	312	511
ℓBHBH	8	5	(0.2, 0.3)	250 Mpc	28	40	132	398	656
BHBH	25	20	(0.3, 0.4)	800 Mpc	26	38	123	372	615
GW150914	35.1	29.5	(0.31, 0.39)	400 Mpc	66	95	310	951	1556

Fractional Improvement of ppE Constraints



[Chamberlain & Yunes, to appear soon]

What are we really learning with GWs?

Violations of the Strong Equivalence Principle

Lorentz Violations in Gravity

Gravitational Parity Violation

What matters the most is the *mapping* between ppE constraints and theoretical physics inferences

Graviton Mass and Propagation Effects

.
.
.

(leaving out a lot of stuff here, e.g. no-hair tests with ringdown)

Future Constraints on Violations of SEP

Extractable Physics:

Non-Schw BHs (yes-hair theorem in EdGB)

NSs have scalar charge (scalar-tensor)

Compact Object binaries inspiral faster due to dipole radiation

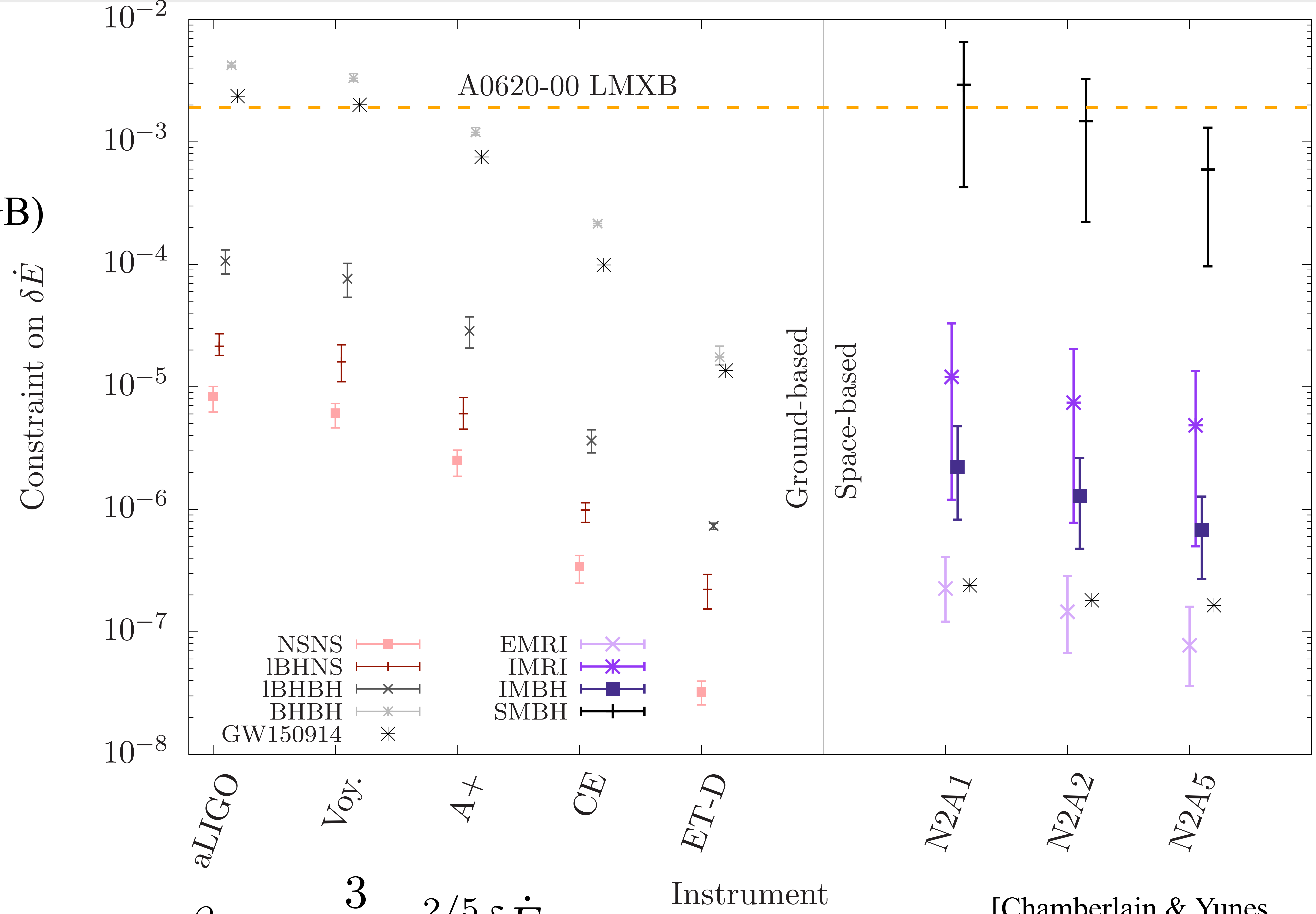
Maximize Extraction:

Low-mass BH or NS (long-inspiral) GWs

Binary with tiny mass ratio

Open Questions:

Merger?
Hybrid IMR waveforms?



$$\beta = -\frac{3}{224}\eta^{2/5}\delta\dot{E}$$

[Chamberlain & Yunes, to appear soon]

Future Constraints on Gravitational Lorentz Violation

Extractable Physics:

Non-Spinning BH is not Schwarzschild

NSs have sensitivity-dependent GR deviatio

Compact Object binaries inspiral faster due to dipole radiation

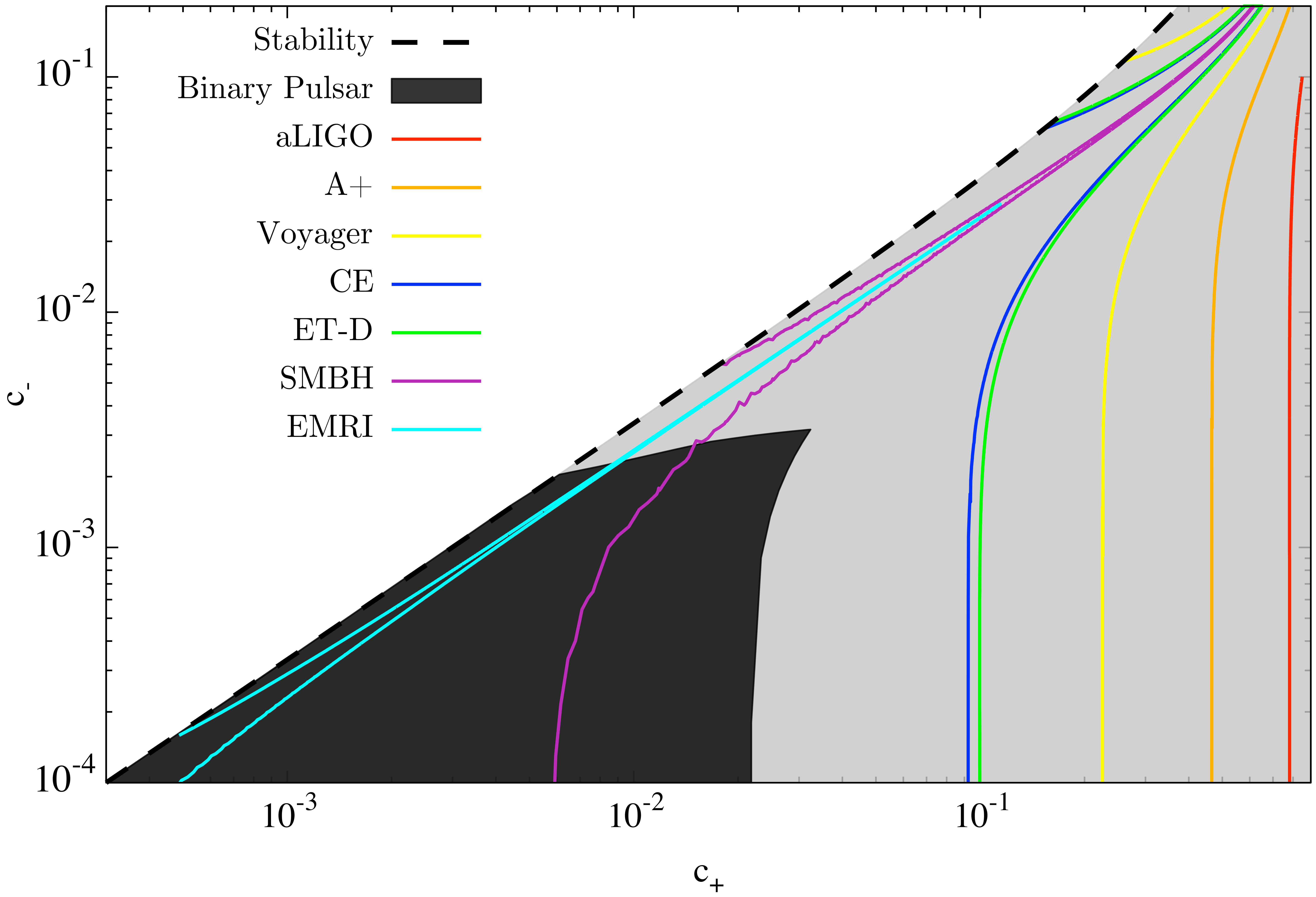
Maximize Extraction:

SMBHs or EMRIs do best

Open Questions:

BH sensitivities and Inspiral BH waveforms

Merger? Hybrid IMR waveforms?



$$\beta = \frac{3}{128}\text{nasty}(c_+, c_-)$$

[Chamberlain & Yunes, to appear soon]

Future Constraints on the Variation of Newton's G

Maximize Extraction:

Binary system at widest separation possible (lowest frequency)

Binary with largest chirp mass

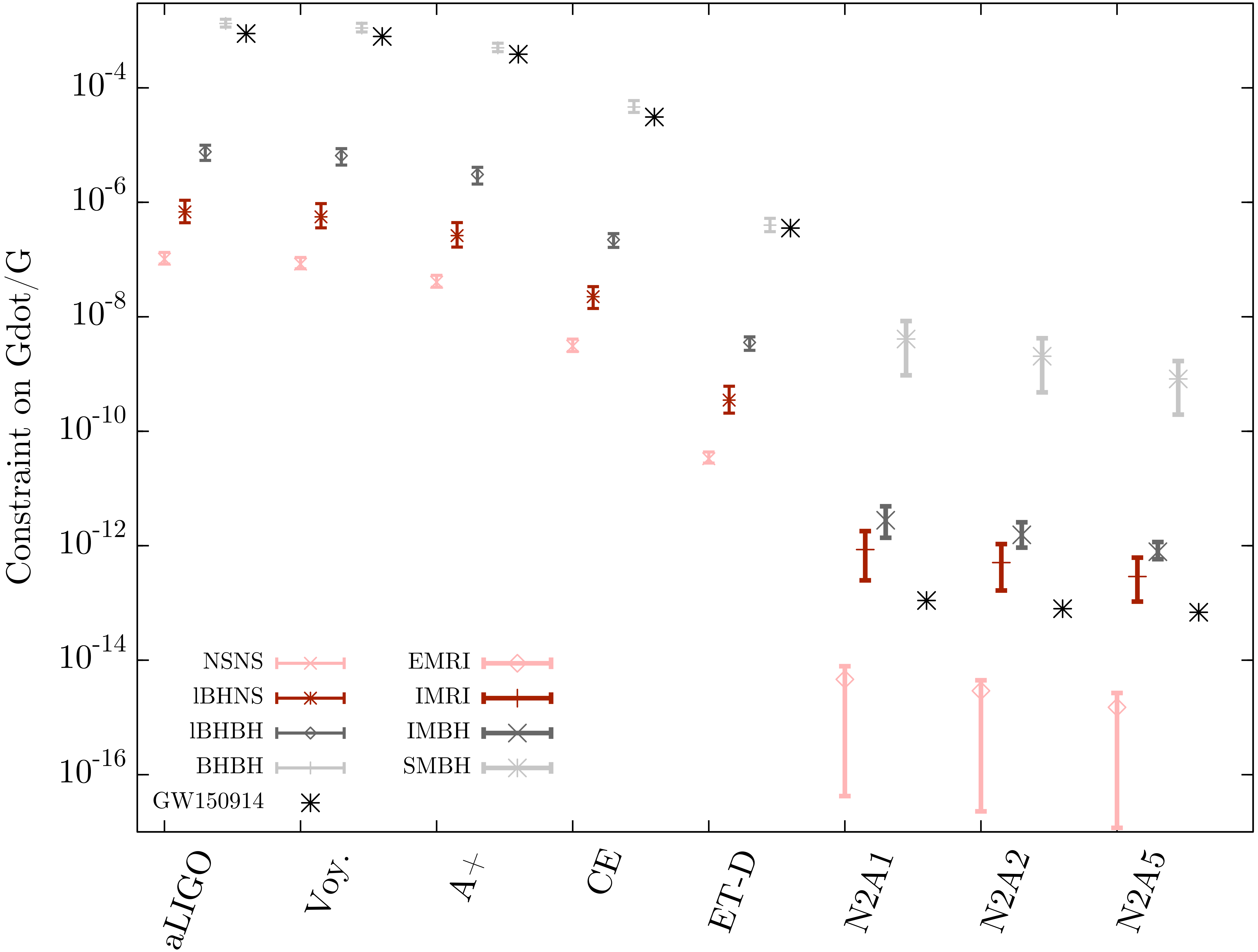
Open Questions:

Generation of GWs?

Merger? Hybrid IMR waveforms?

$$\beta = -\frac{25}{65526}\frac{\dot{G}}{G}\mathcal{M}_z$$

[Chamberlain & Yunes, to appear soon]



And now what?

Why?	How?
Duty	More Consistency ?
Curiosity	Better ppE ?
Religion	Compelling Alternative?

Nico's Crystal Ball

5 years *Observations*: 25/year

Detectors: aLIGO —> A+, AVirgo, Kagra

Theory: in GR: IMR of precessing inspirals and (maybe) eccentric

in not GR: mergers and 1 PN in a few theories (e.g. EdGB)

10 years *Observations*: 100/year

Detectors: A+ —> Voyager, AVirgo, Kagra, Indian LIGO

Theory: in GR: single model for spin-precessing, eccentric, with NR calibration

in not GR: mergers in more theories with spin precession

15 years *Observations*: rate limited

Detectors: Voyager —> CE, aVirgo, aKagra, Indian LIGO, LISA

Theory: in GR: EMRIs (with second-order self-force)

in not GR: EMRIs in modified gravity?

Some Open Problems

Theory

New & Interesting Physical Mechanisms?

Cosmological Modified Theories?

Spin Precession in Modified Gravity?

Mergers in Modified Gravity?

EMRIs and resonances in Modified Gravity?

"New" sources of GWs? (eg. eccentric)

Experiment

Efficient data analysis w/spin precession?

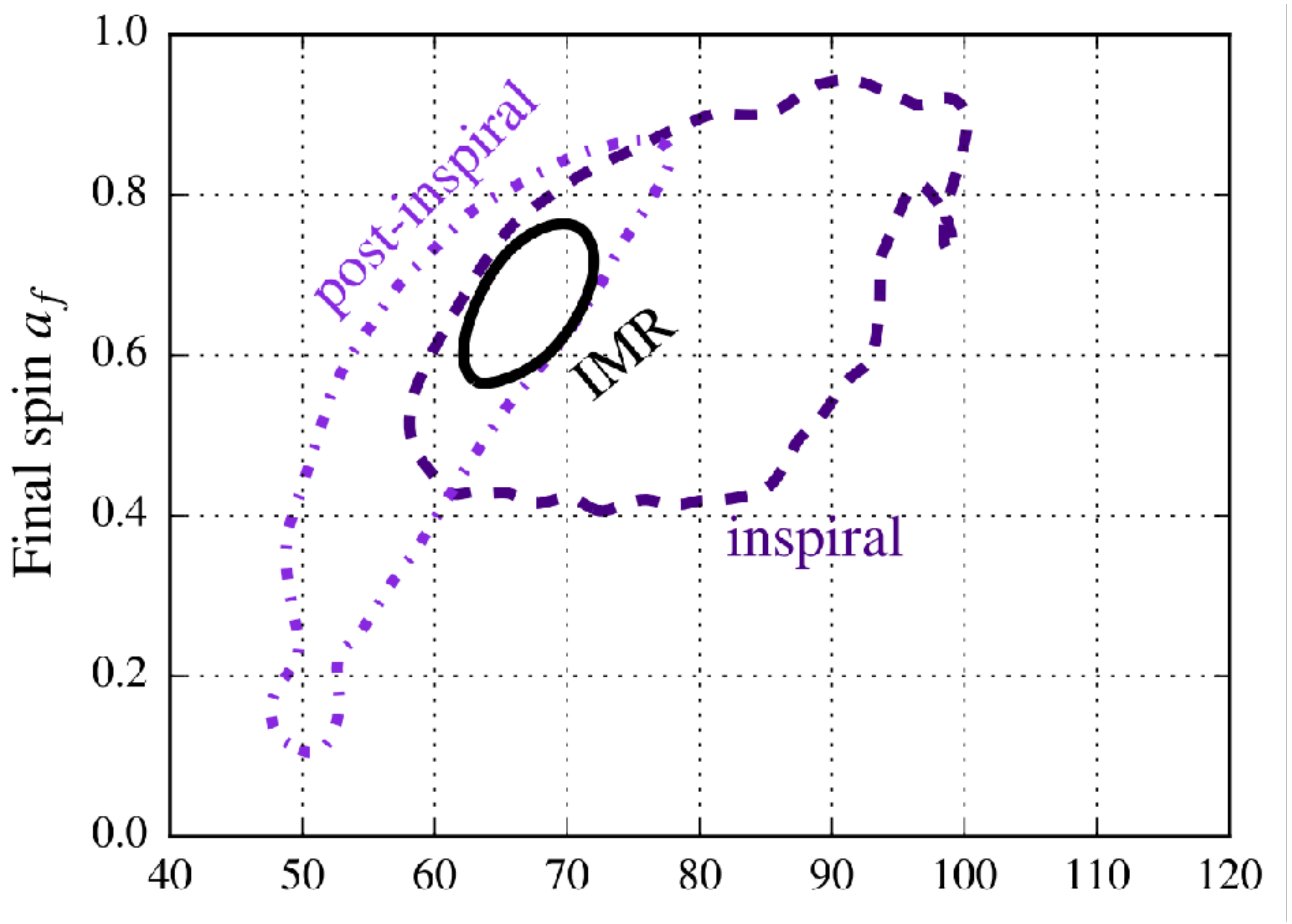
Reduced Order Methods for Mod. Grav. ?

Improved instruments vs new instruments?

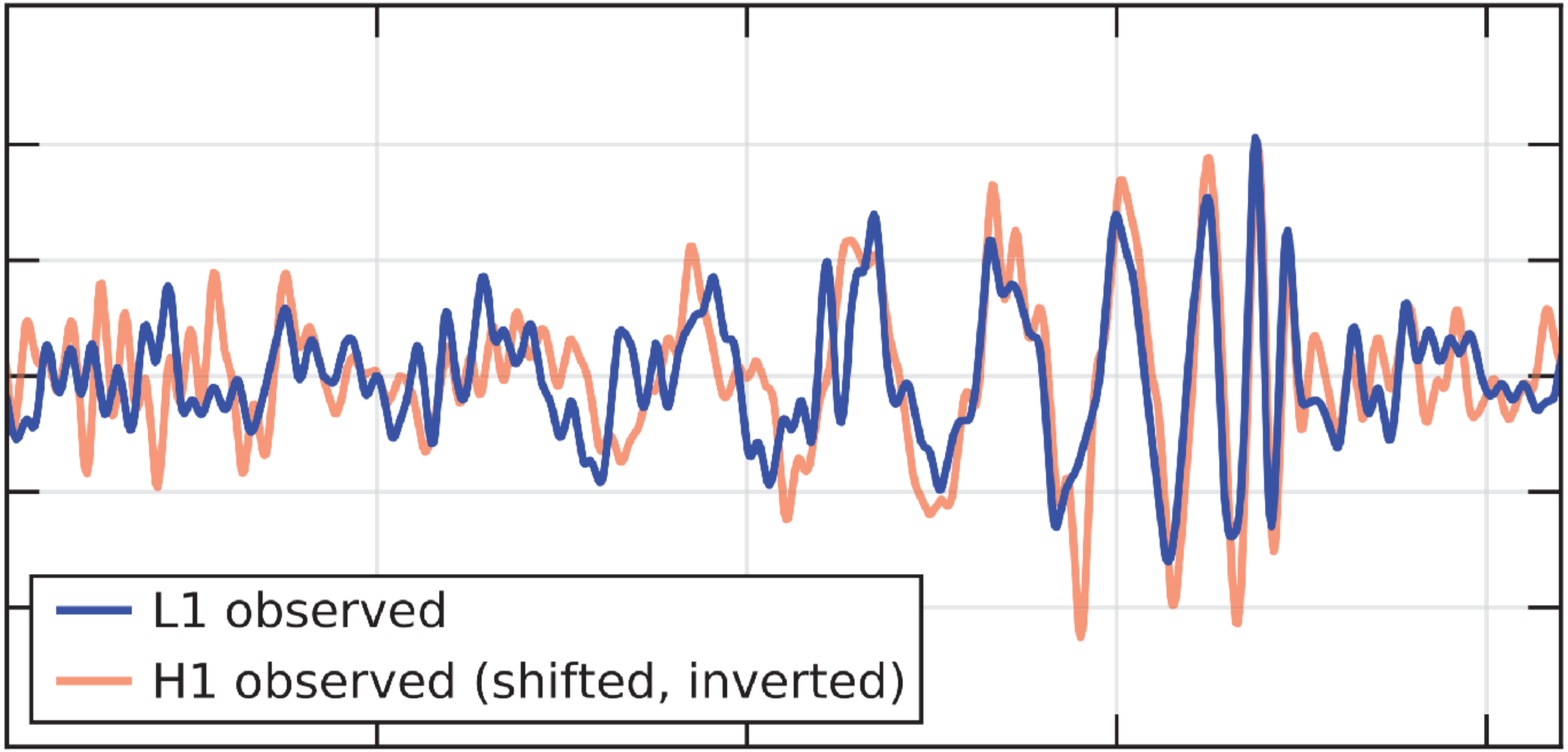
Combining EM information ?

Ringdown tests? Stacking?

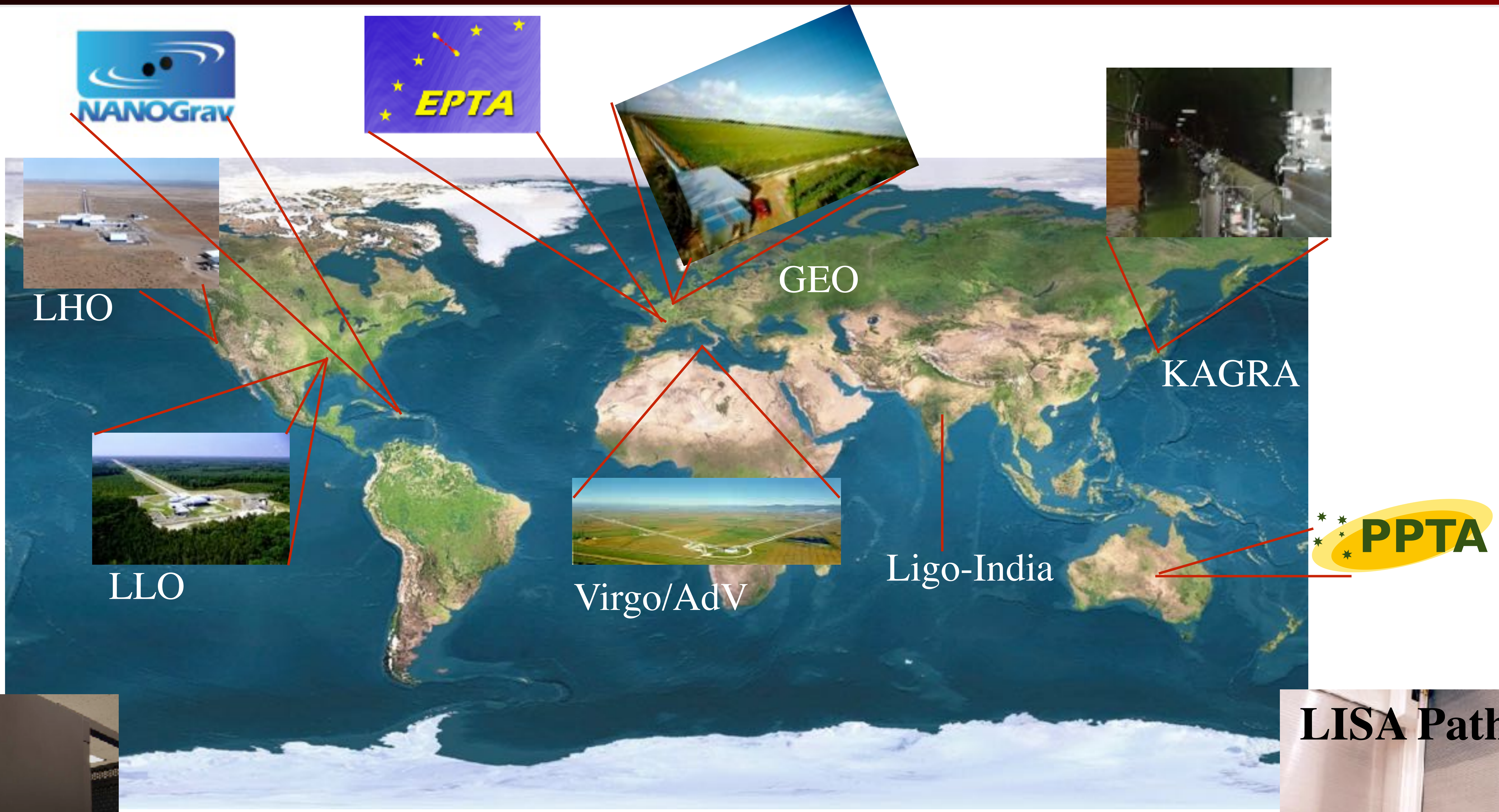
(Sort of) Jack-knife Consistency

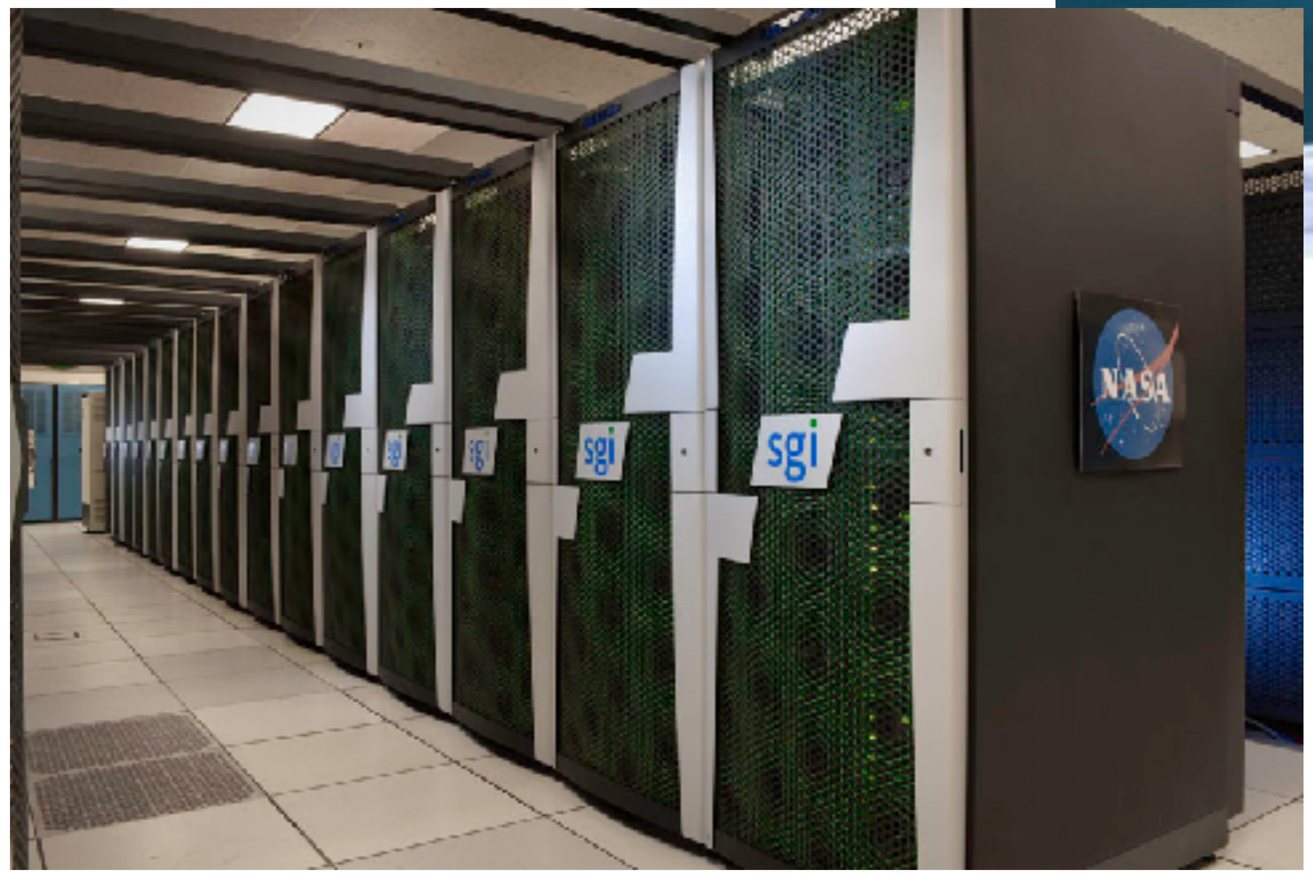


Why is this important now?



Why is this even more important in the near future?

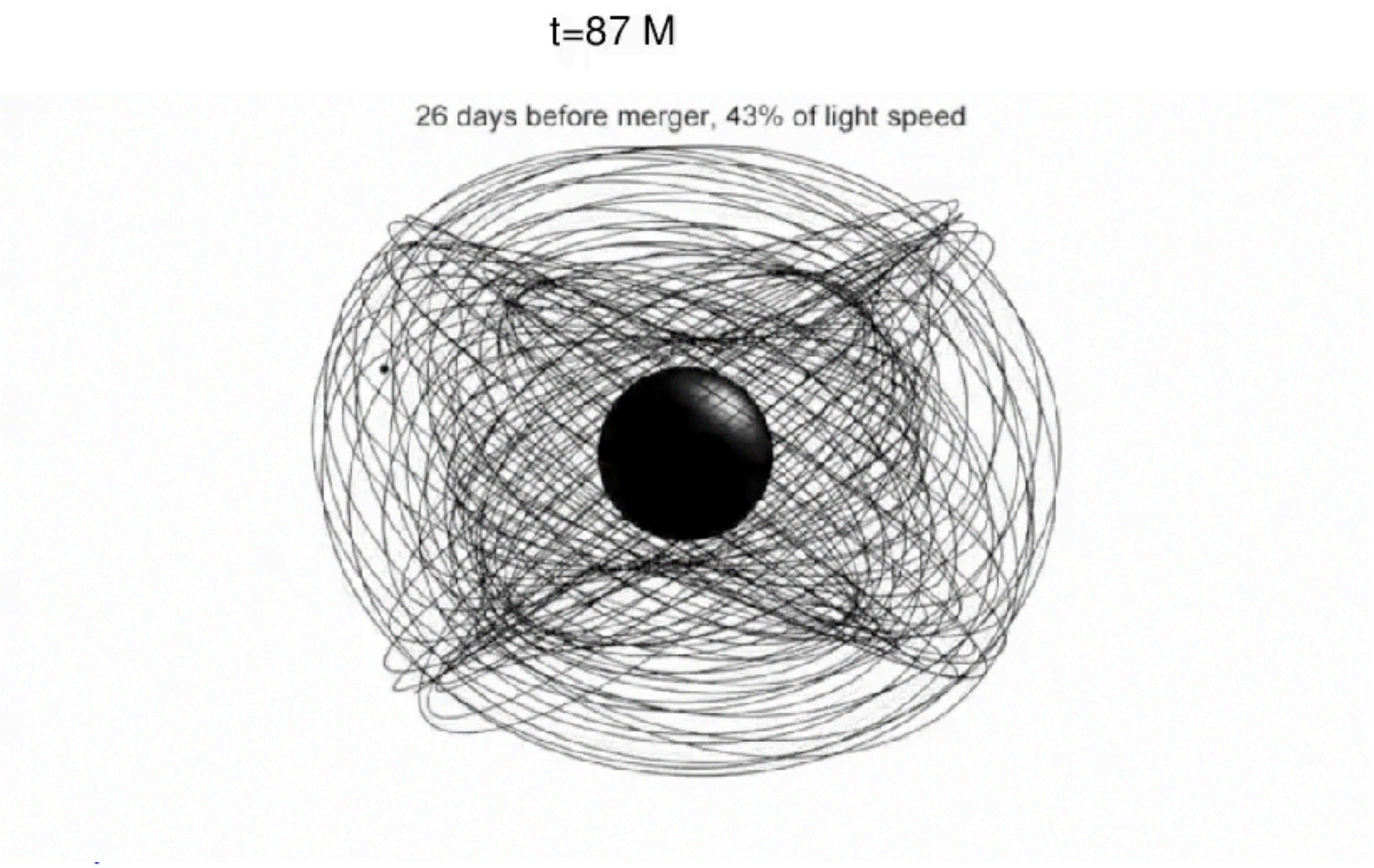




What is eXtreme Gravity & Gravitational Waves?

eXtreme Gravity: where gravity is
(a) very strong,
(b) non-linear
(c) dynamical

[RIT Group]



Gravitational Waves (GWs): Wave-like perturbation of the grav. field.

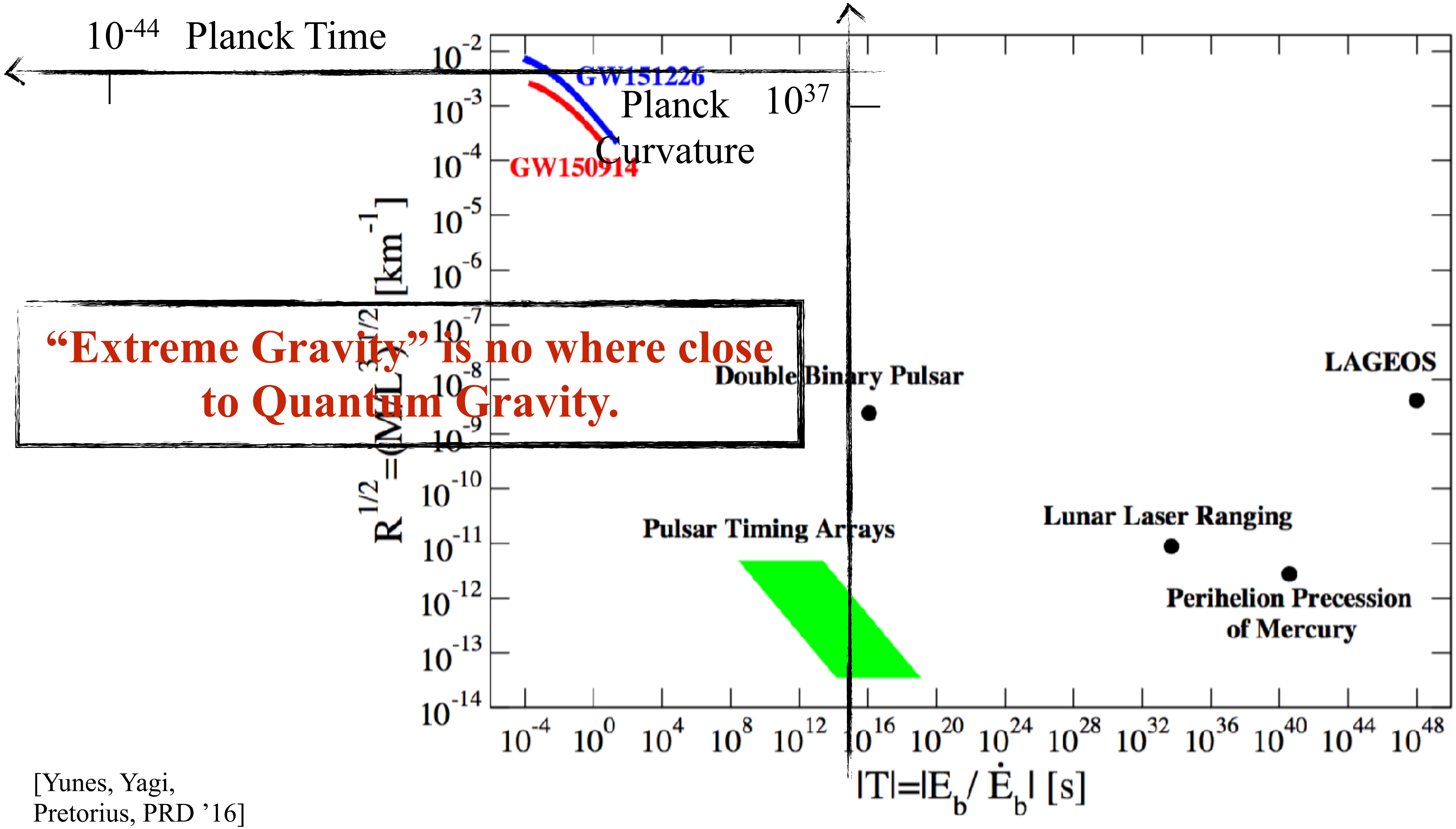
Generation of GWs: Accelerating masses (t-variation in multipoles)

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

GW Spectrum: Kepler 3rd Law: $\frac{f}{2\pi} = \sqrt{\frac{m_{\rm tot}}{r_{12}^3}} \sim \frac{1}{m_{\rm tot}}$, $E_{\rm rad} \sim \%\, m_{\rm tot}$ in about 10^{79} gravitons

Example: Binary BH merger, $E_{\rm rad} \sim 10^{46}\, J \left(\frac{\epsilon}{1\%}\right) \left(\frac{M}{10 M_\odot}\right) \sim 10^2 E_{\rm SN}$

Extreme Gravity versus Strong Gravity



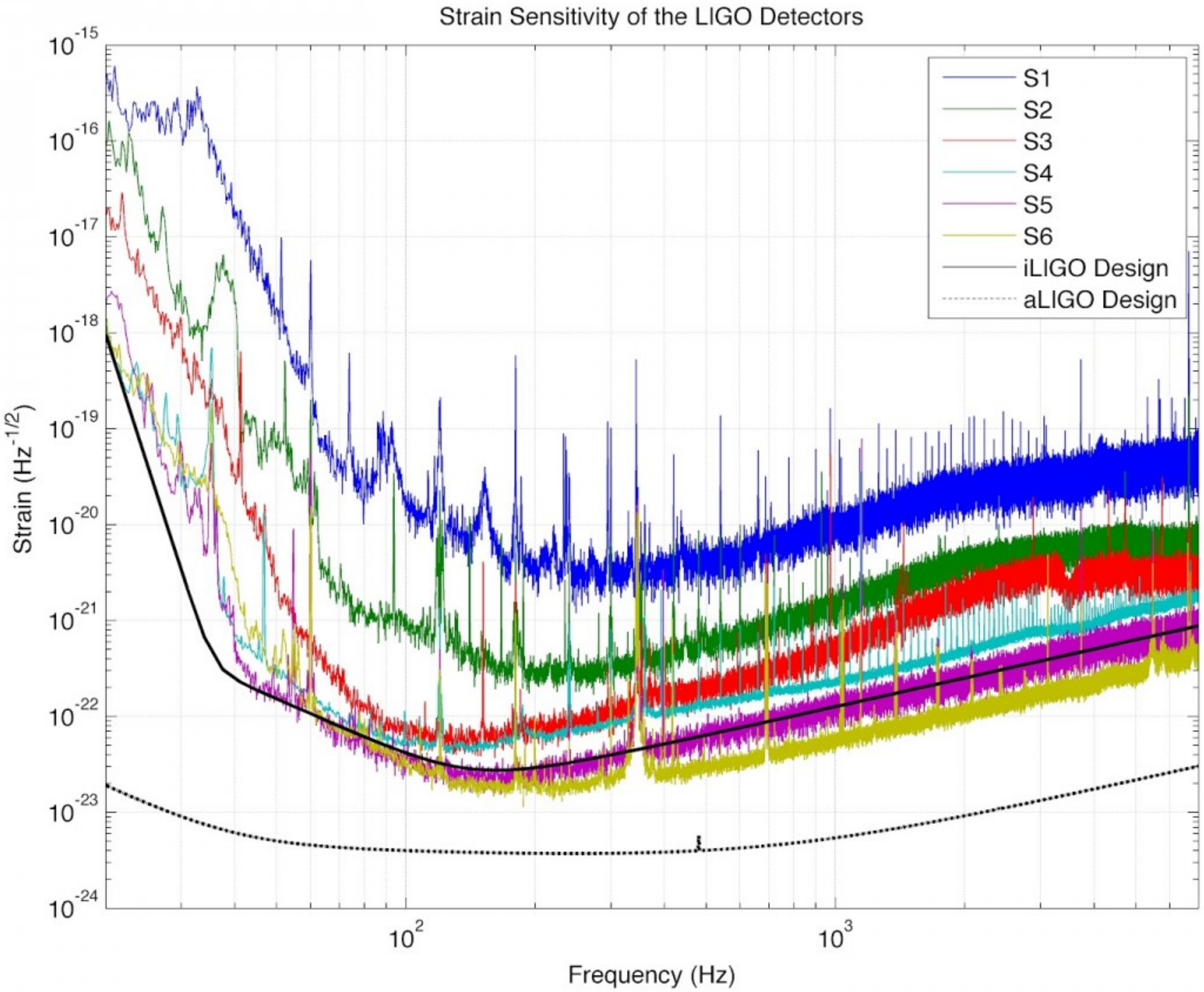
"Extreme Gravity" is no where close to Quantum Gravity.

[Yunes, Yagi, Pretorius, PRD '16]

How do we extract signals from the noise?

Modellin

Data Analysis



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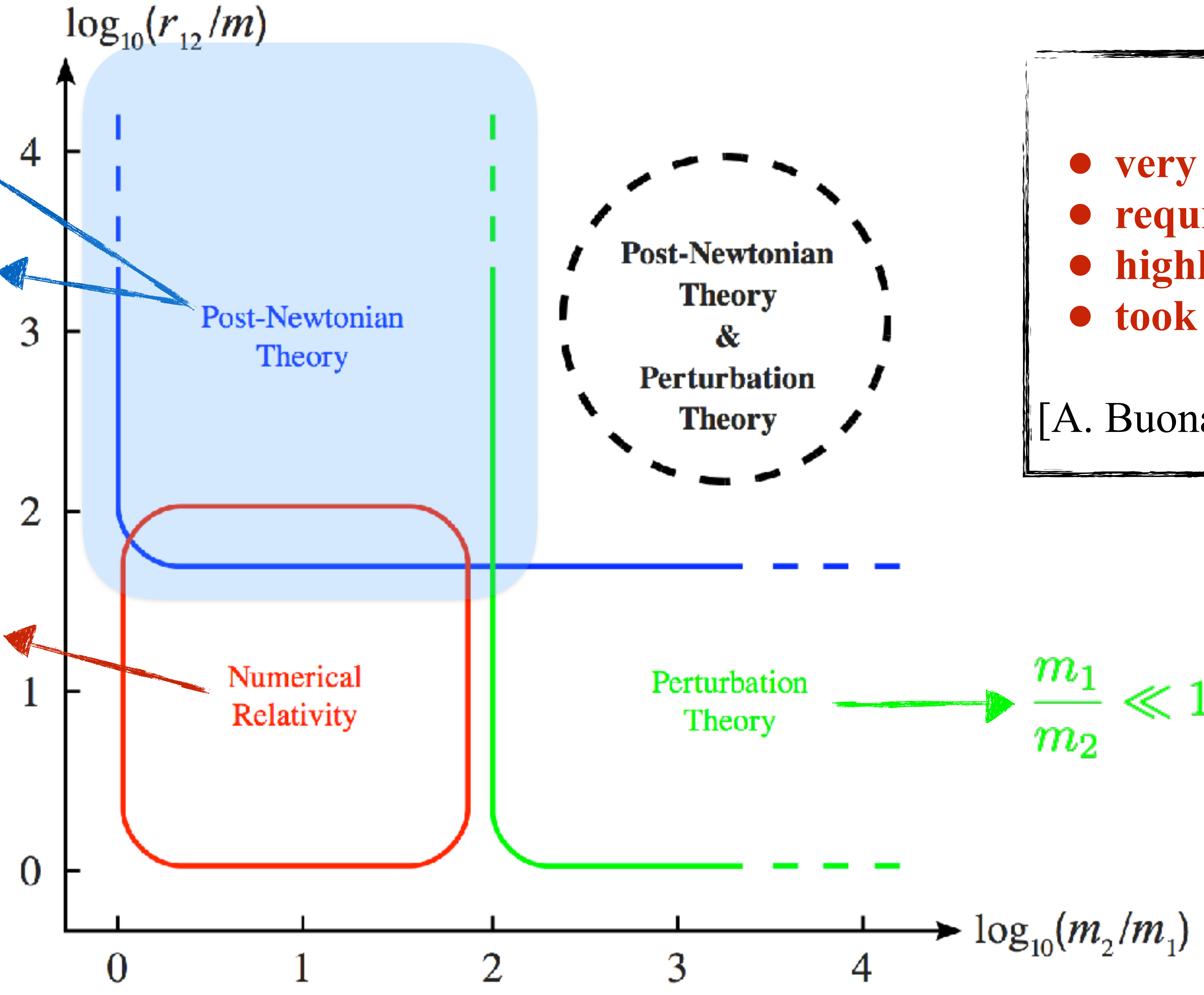
How do we build GW models?

$$\frac{G m_{\rm tot}}{c^2 r_{12}} \ll 1$$

$$\frac{v}{c} \ll 1$$



$$\frac{m_1}{m_2} \ll 1$$

The GW models are

- **very complicated,**
- **require numerics and analytics**
- **highly accurate**
- **took over 50 years to develop**

[A. Buonanno's talk]

[Blanchet, LRR]

What can we learn from GWs? Propagation Example

Case Study: Massive Graviton

Special Relativity tells us that for a propagating massive particle

$$\frac{v_g^2}{c^2} = 1 - \frac{m_g^2 c^4}{h^2 f^2} = 1 - \frac{c^2}{\lambda_g^2 f^2}$$

GWs emitted close to merger travel faster than those emitted in the early inspiral.

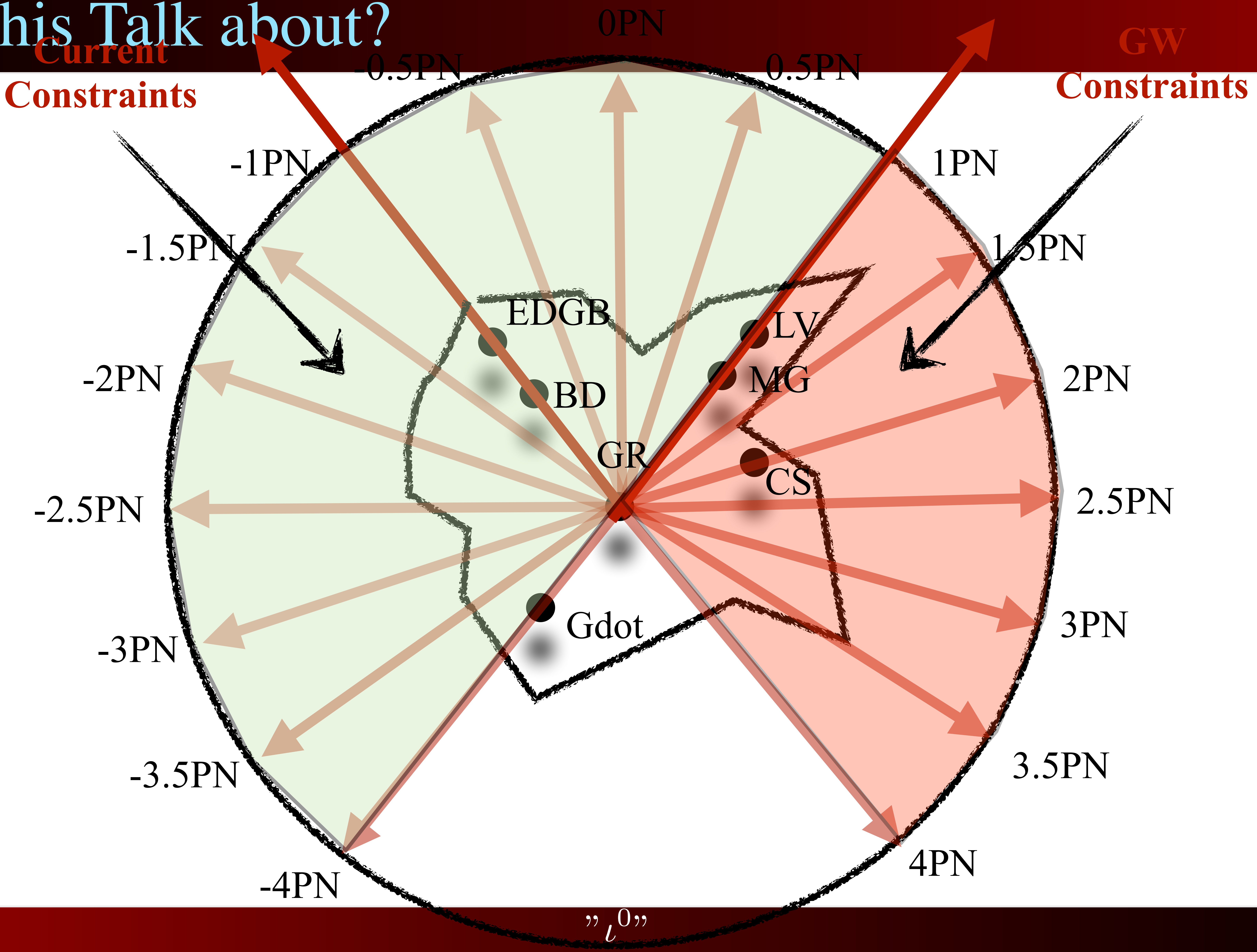
GW Phase is sensitive to the GW frequency x GW travel time

$$\Psi_{\rm GW} = f T_g = f \frac{D}{v_g} \sim \frac{f D}{c} + \frac{c D}{2\lambda_g^2 f}$$

Massive graviton effect accumulates with distance travelled.

[Will, PRD 1998, Will & Yunes, CQG 2004, Berti, Buonanno & Will, CQG 2005 Mirshekari, Yunes & Will, PRD 2012]

What is this Talk about?



How are GW Probes of e$\mathcal{X}$treme Gravity Different?

1. e$\mathcal{X}$treme Gravity:

Sources: **Compact Object Coalescence,** SN, deformed NSs, etc.

Processes: Generation & Propagation of metric perturbation

2. Clean:

Absorption is negligible, lensing unimportant at low z, accretion disk and B fields unimportant during inspiral.

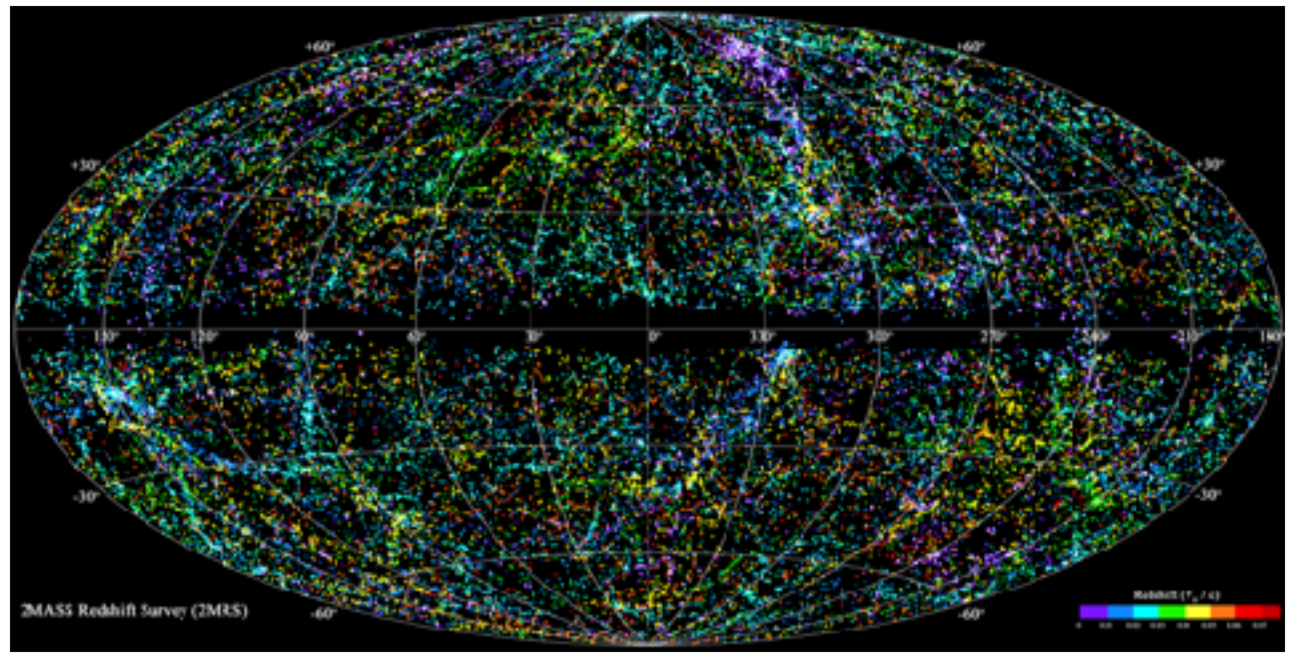
[Yunes, et al PRL ('11), Kocsis, et al PRD 84 ('11), Barausse, et al PRD 89 ('14)]

3. Localized:

Point sources in spacetime

Constraint Maps

[Yunes & Pretorius, PRD 81 ('10)]



Model for the GW Observable during Inspiral (PN)

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

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

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

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

Blanchet's Living Reviews