What Theoretical Physics can we learn from LISA Gravitational Wave Observations ?

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Montana State University

LISA Telecon
May, 2017

eXtreme Matter meets eXtreme Gravity

hyperspace@gu

Editor: Luciano Rezzolla

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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

Plan of Attack

What are we testing?

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

Constrain Deviations of GR Pillars

Gravitational Wave Propagation

Modified Dispersion Relations

Modified Kinematics

Gravitational Lorentz Violation

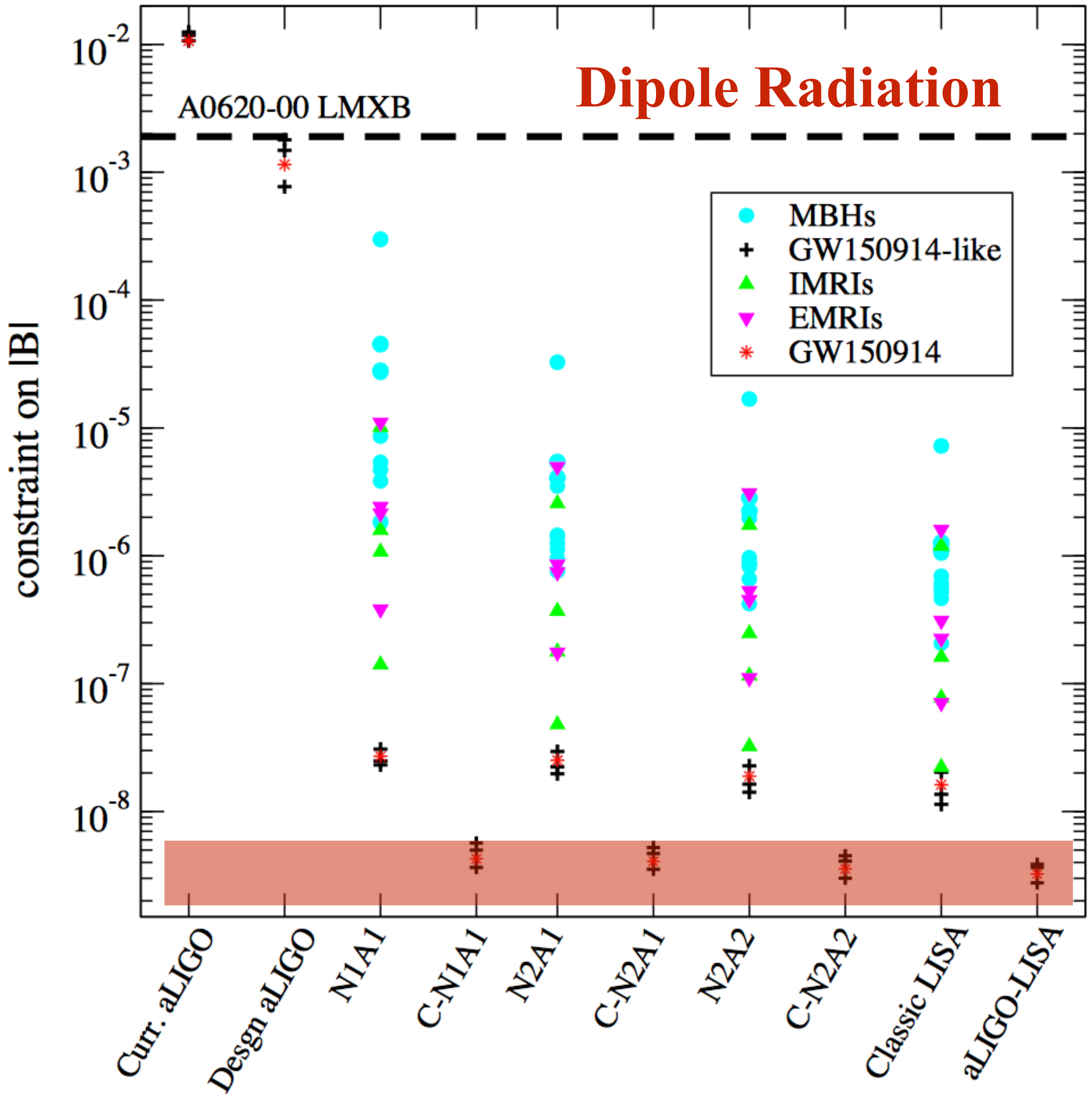
Cosmological Screening

Time-Variation of G

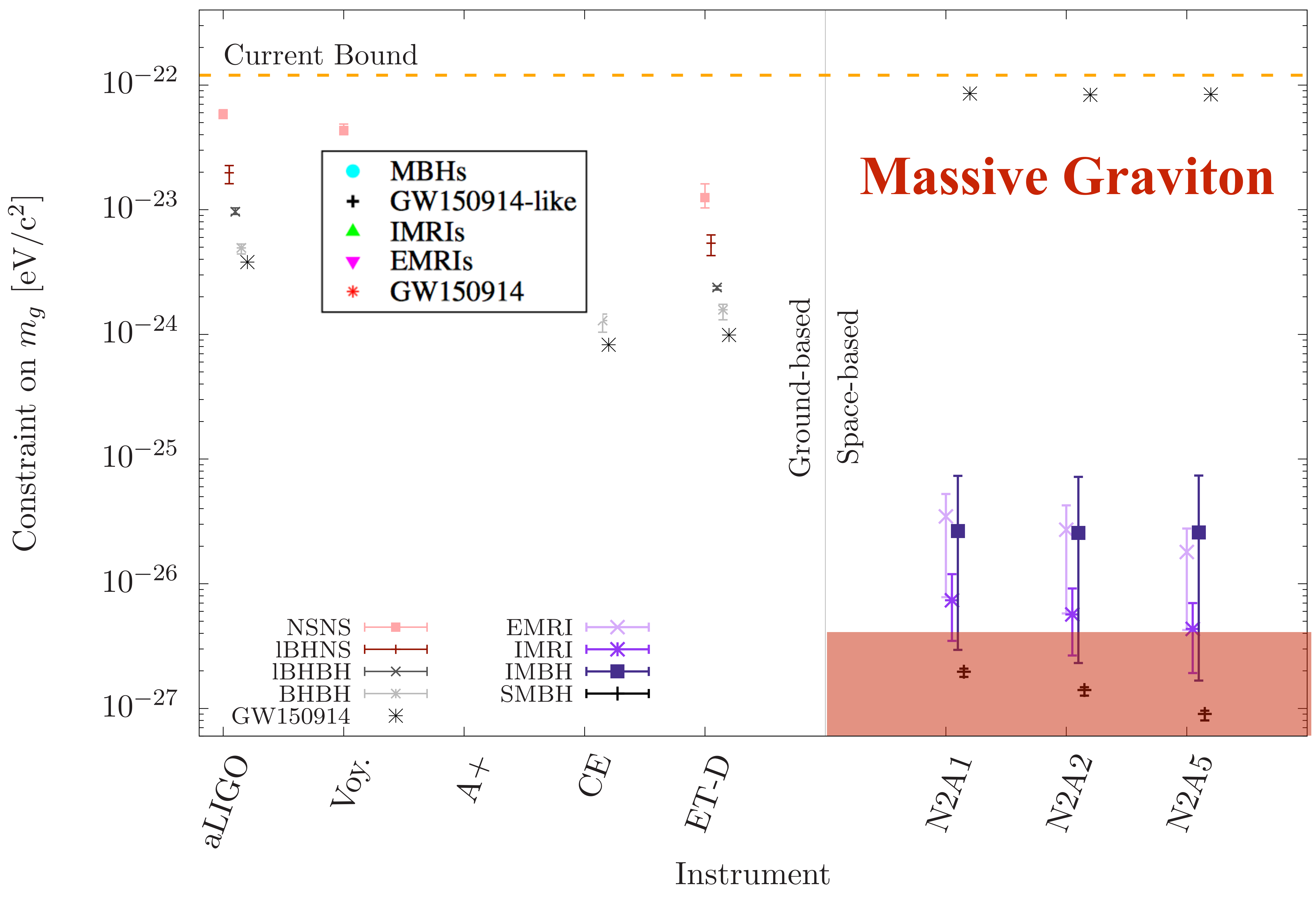
⋮

- Speed of Gravity
- Mass of Graviton
- Lorentz Violation
- SEP Violation

What well will we do?



[Barausse, Yunes, Chamberlain, PRL '16]



[Chamberlain & Yunes, submitted]

What are the open problems?

Theory

Modified Gravity

New & Interesting Physical Mechanisms?

Cosmological Modified Theories?

GR Modeling

Spin Precession in Modified Gravity?

Mergers in Modified Gravity?

EMRIs and resonances in Modified Gravity?

Data Analysis

Efficient data analysis w/high D parameter space?
Reduced order methods for Modified gravity?

Pipelines for combined GW+EM studies of modified gravity

Pipelines for stacking tests of gravity ?
(including e.g. coherent stacking and ringdown tests)

Community

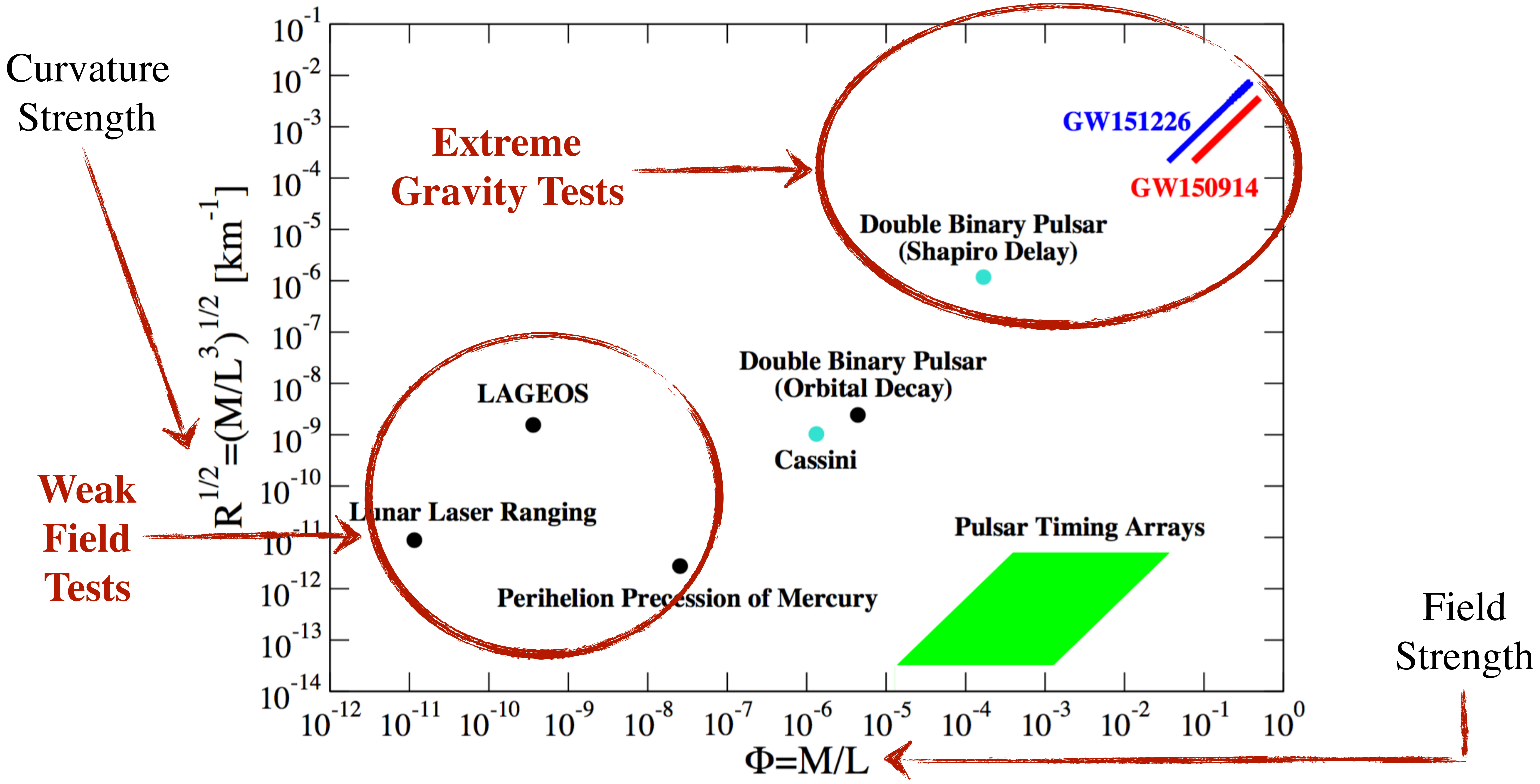
Collaborative structure for theorists and data analysts?
Just releasing analysis “code” will not work

Support for **both** data analysis development and theory development is needed.

Back Up Slides

Intro Stuff

What Physics Regime do GWs Probe?



GWs probe eXtreme Gravity

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

The Parameterized post-Einsteinian Framework

[Yunes & Pretorius, PRD 2009]

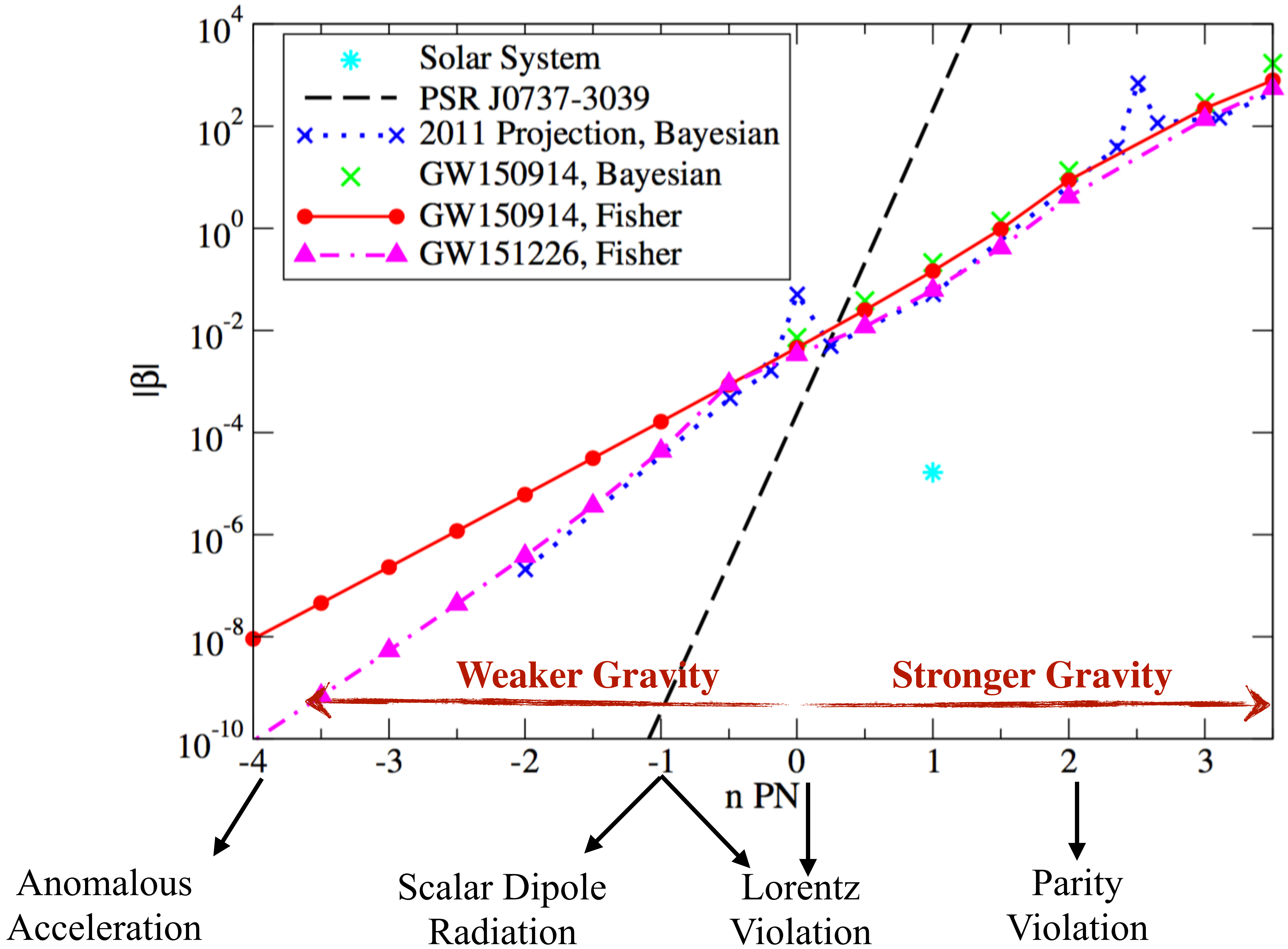
$$\tilde{h}(f) = \tilde{h}_{GR}(f)\,(1+\alpha f^{a})\,e^{i\beta f^{b}}$$

Theoretical Effect	Theoretical Mechanism	Theories	ppE b	Order	Mapping
Scalar Dipolar Radiation	Scalar Monopole Field Activation	EdGB [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).]

Current Ligo Bounds

GR Consistency Implies Constraints on Modified



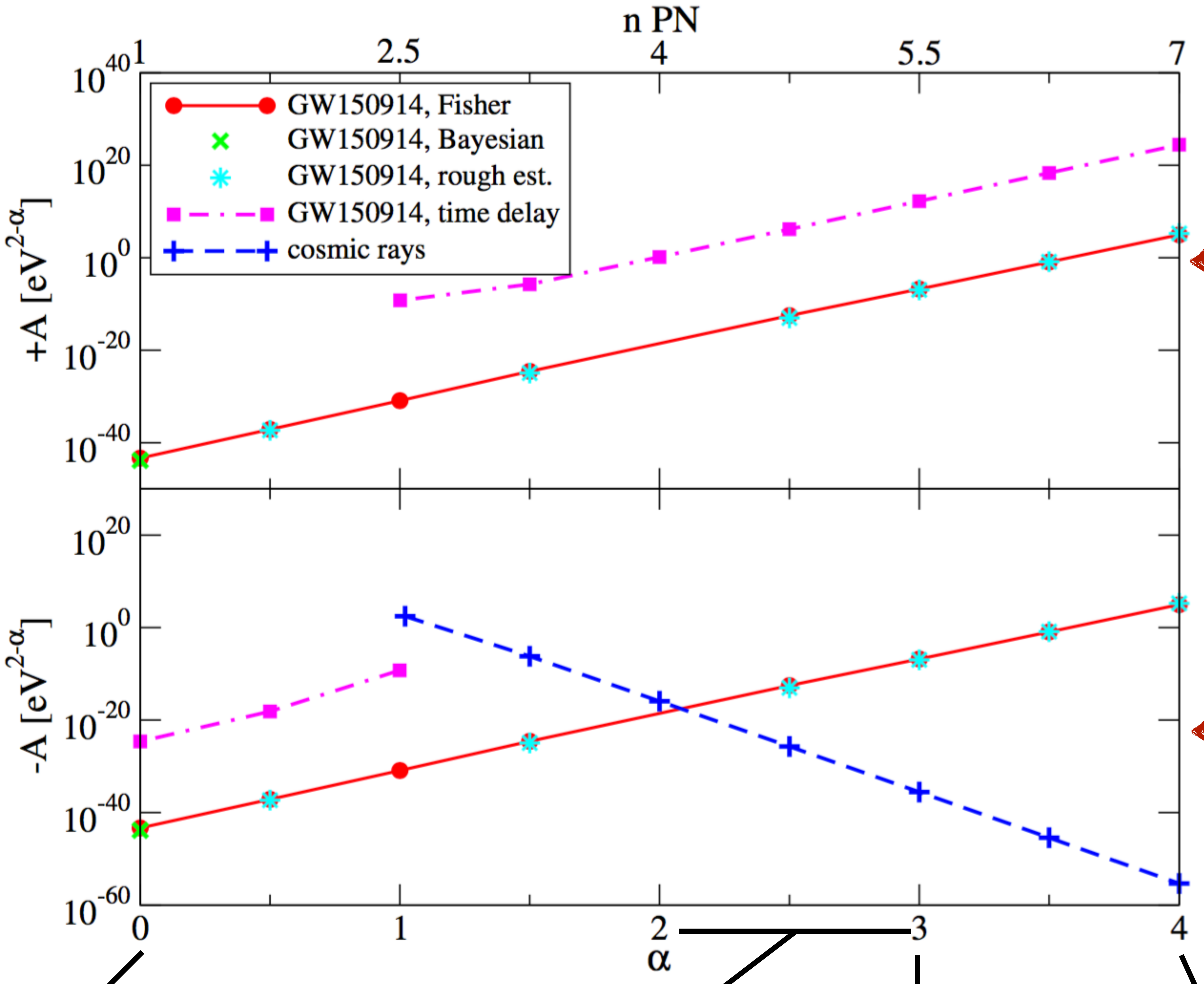
[Yunes, Yagi, Pretorius, PRD '16]

Theory Implications of Published GW Observations

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

[Yunes, Yagi, Pretorius, PRD '16]

GR Consistency Implies Constraints on Modified



Superluminal

Subluminal

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

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

…. —> SME (5.5PN, 7PN)

Massive Graviton

Multifractal Spacetime

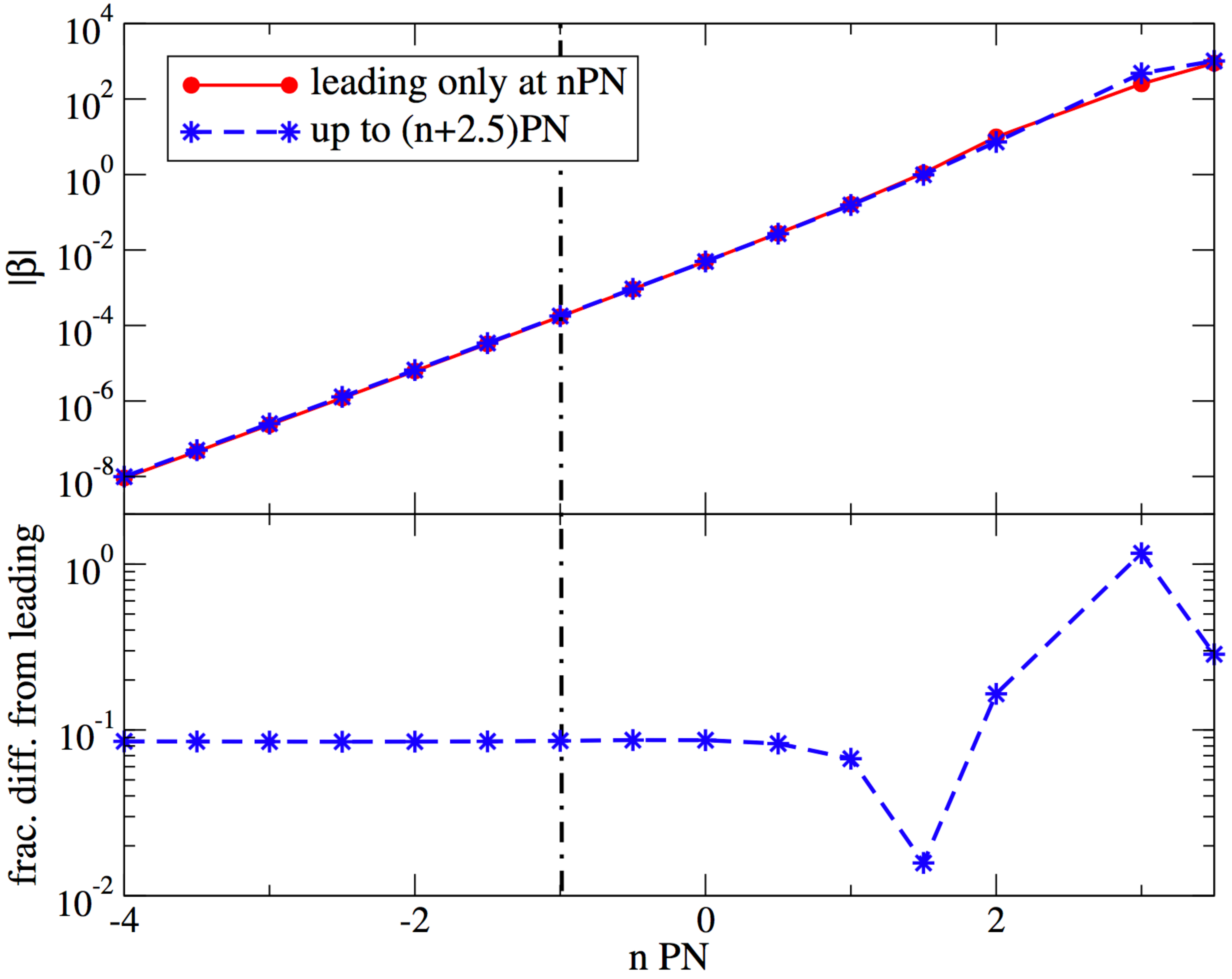
Doubly Special Relativity

SME, Horava-Lifshitz, Extra-Dimensions

[Yunes, Yagi, Pretorius, PRD ‘16]

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)



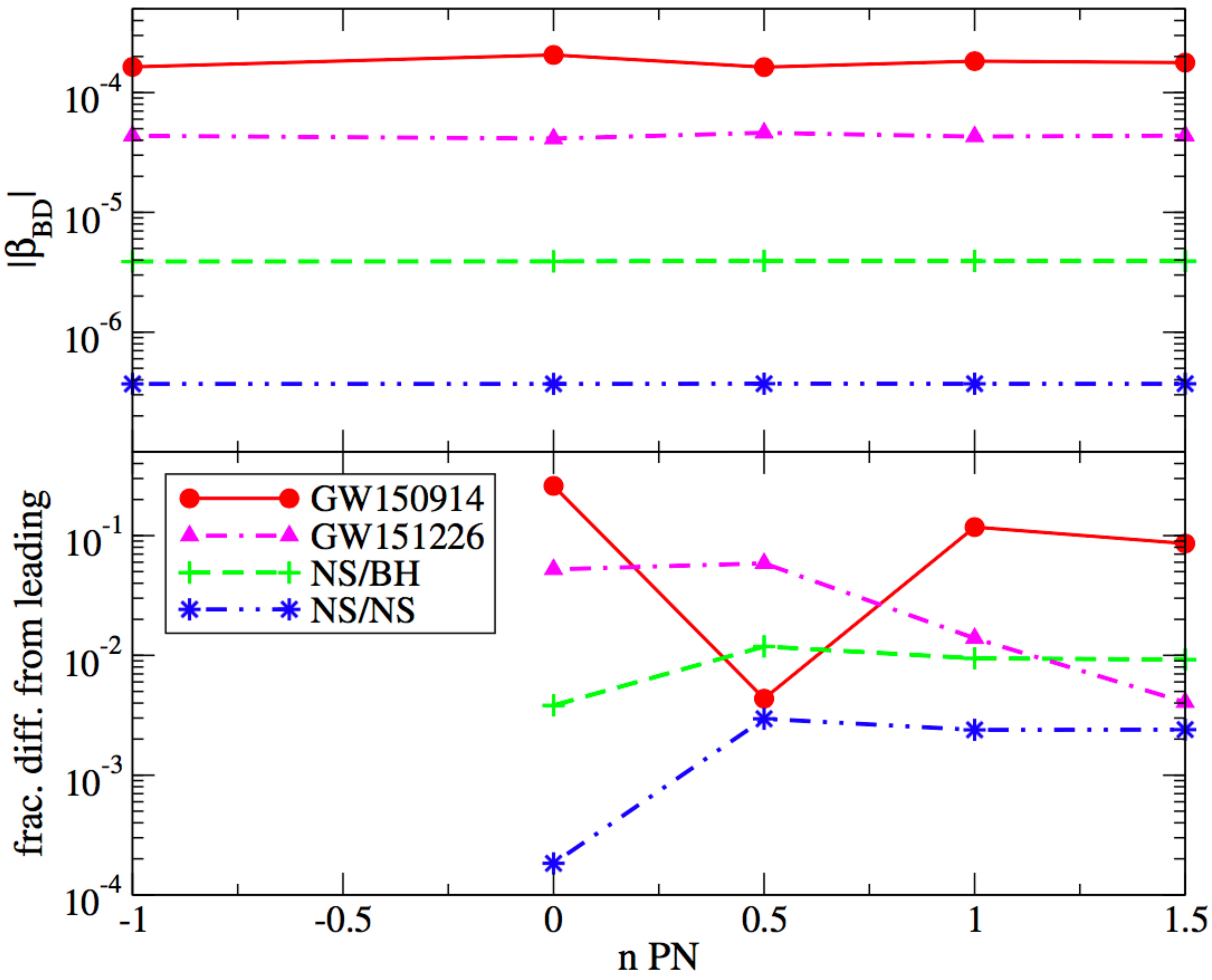
Constraints are always robust, provided the modifications to the GW generation enter below 2.5PN order (ie. provided there is enough "information" in the inspiral part of the waveform)

But what about the higher PN order terms?

Case Study: Scalar-Tensor (Brans Dicke) theory

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

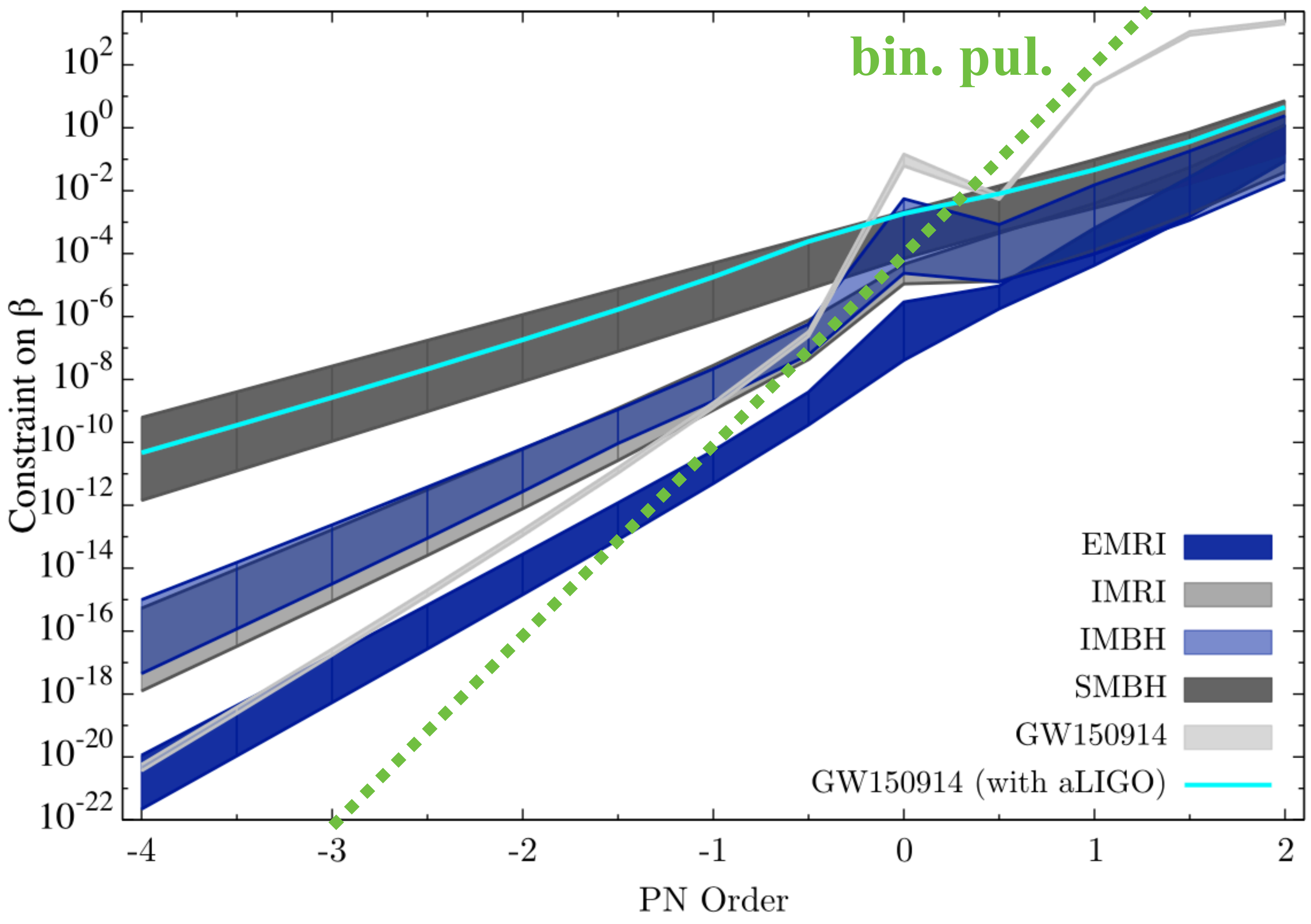
Caveat: These constraints are "conservative." We could do better if we knew how the merger was modified and we included this in the analysis.



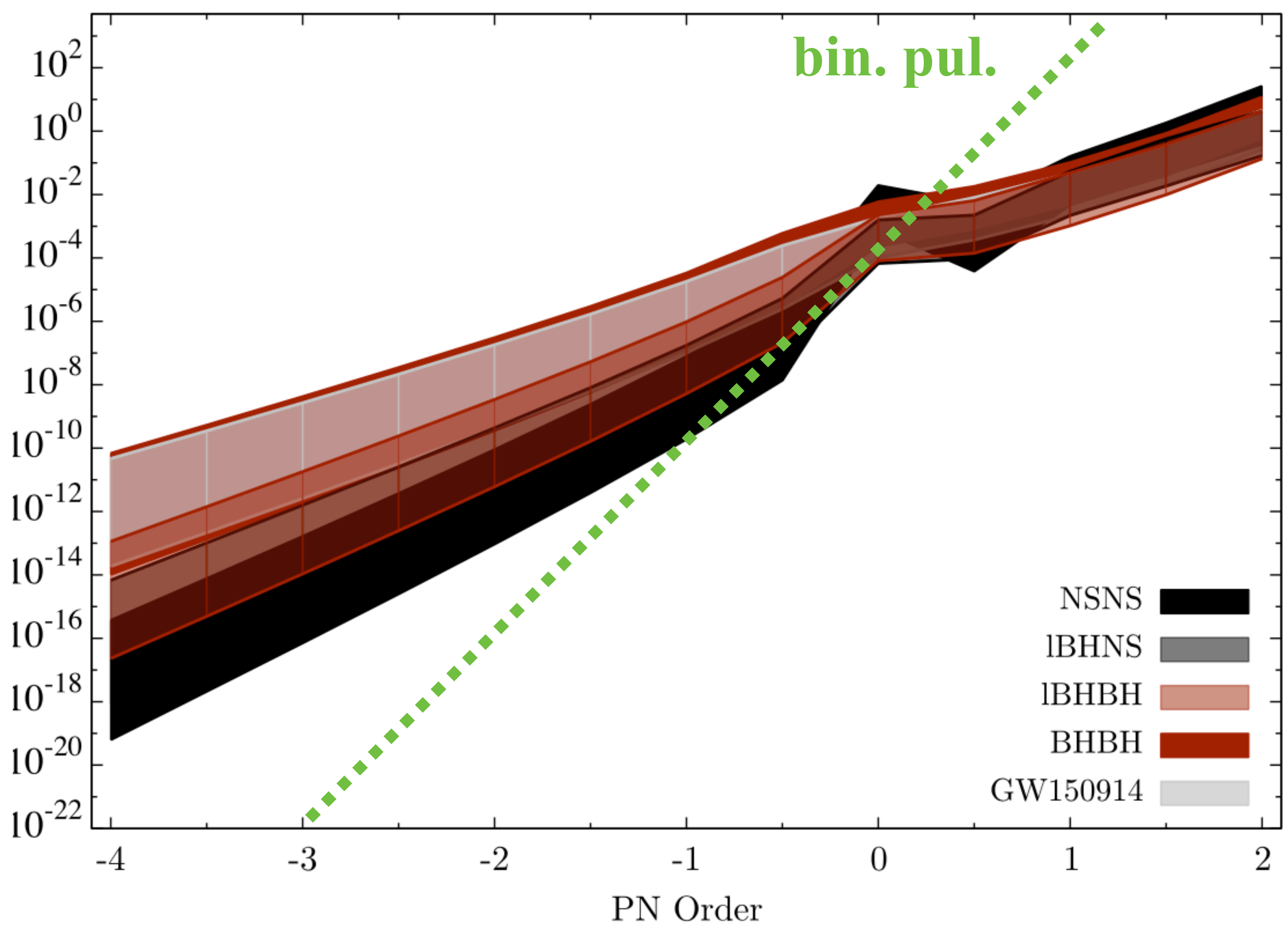
Some Future Bounds (Including With Lisa)

Future ppE Constraints on GR

space-based



ground-based



[Chamberlain & Yunes, to appear soon]

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

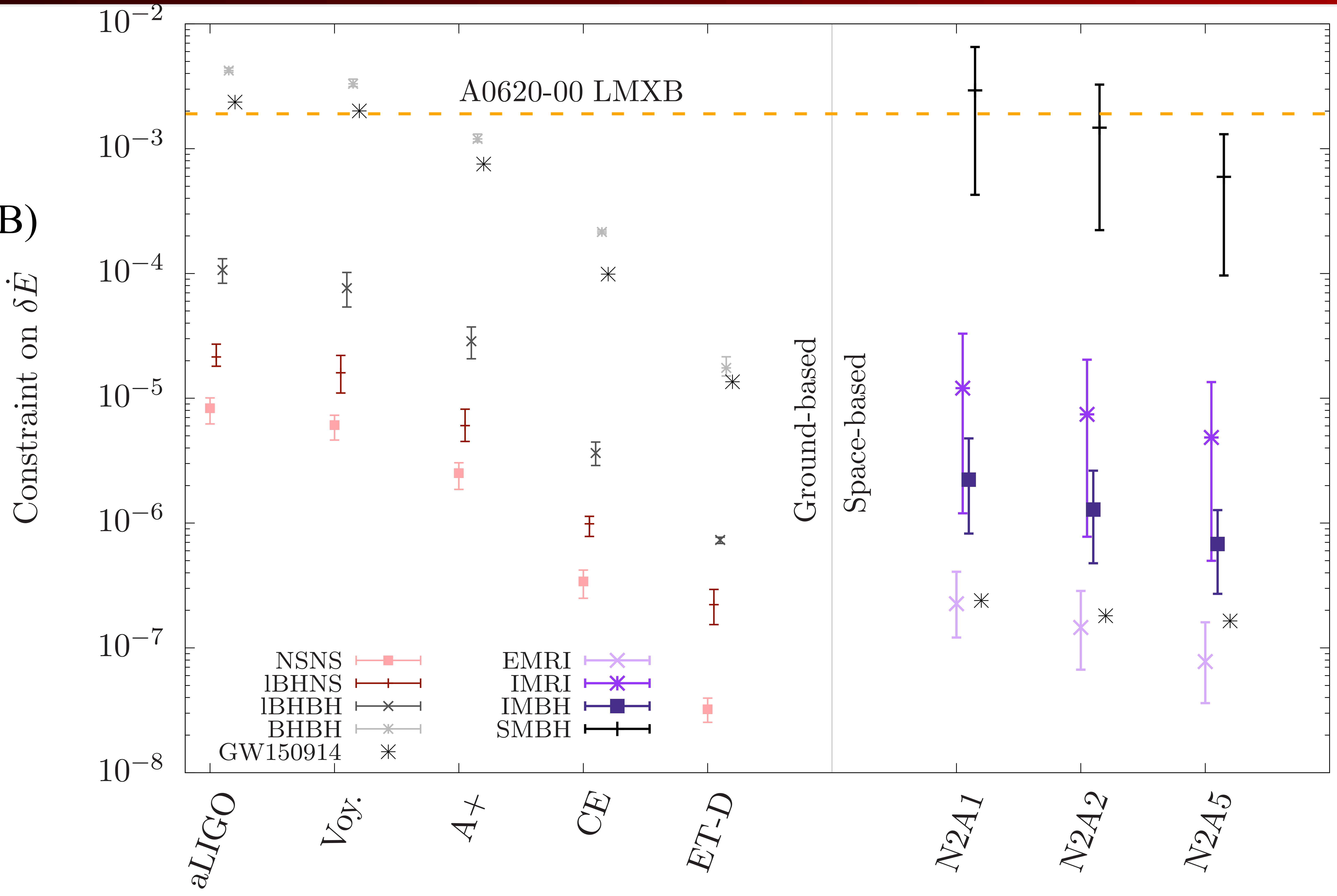
Maximize Extraction:

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

Extractable Physics:

Non-Spinning BH is not Schwarzschild

NSs have sensitivity-dependent GR deviatio

Compact Object binaries inspiral faster due to dipole radiation

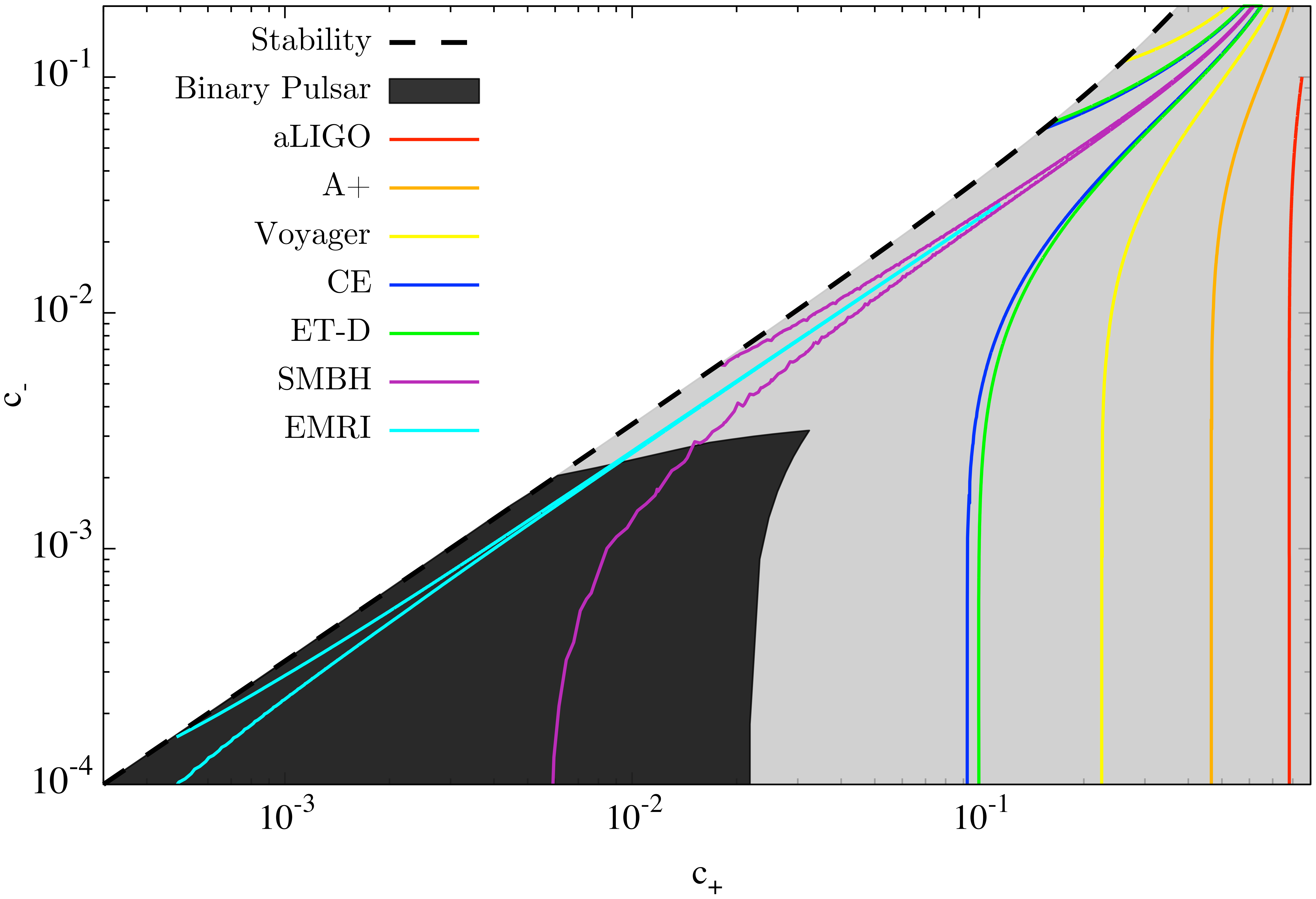
Maximize Extraction:

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]