Future Tests of General Relativity with Gravitational Waves

Nicolas Yunes
eXtreme Gravity Institute
Montana State University

StronG BaD Workshop
March 2nd, 2017

Barausse, Yunes, Chamberlain, arXiv 1603.04075, PRL (2016)
Yunes, Yagi, Pretorius, arXiv 1608.06187, PRD (2016)
Chamberlain and Yunes, to be submitted (very soon!)

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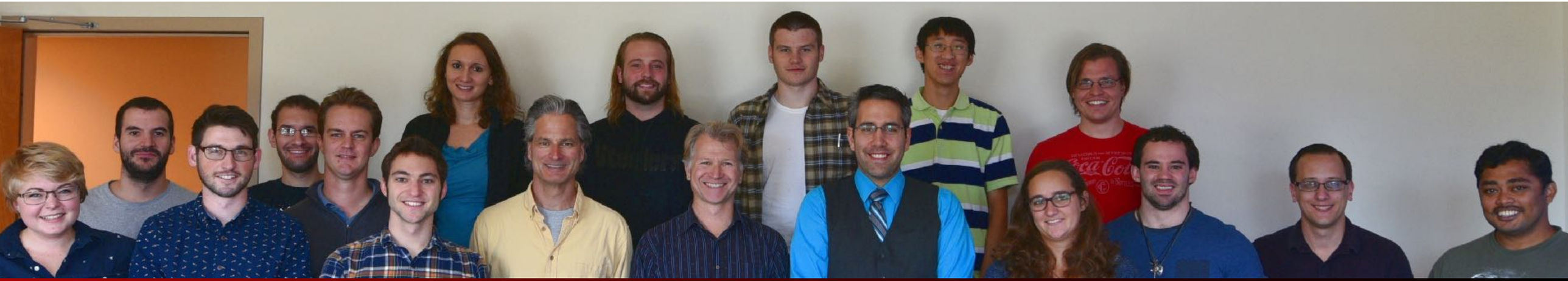

eXtreme Matter meets eXtreme Gravity

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

Previous Next

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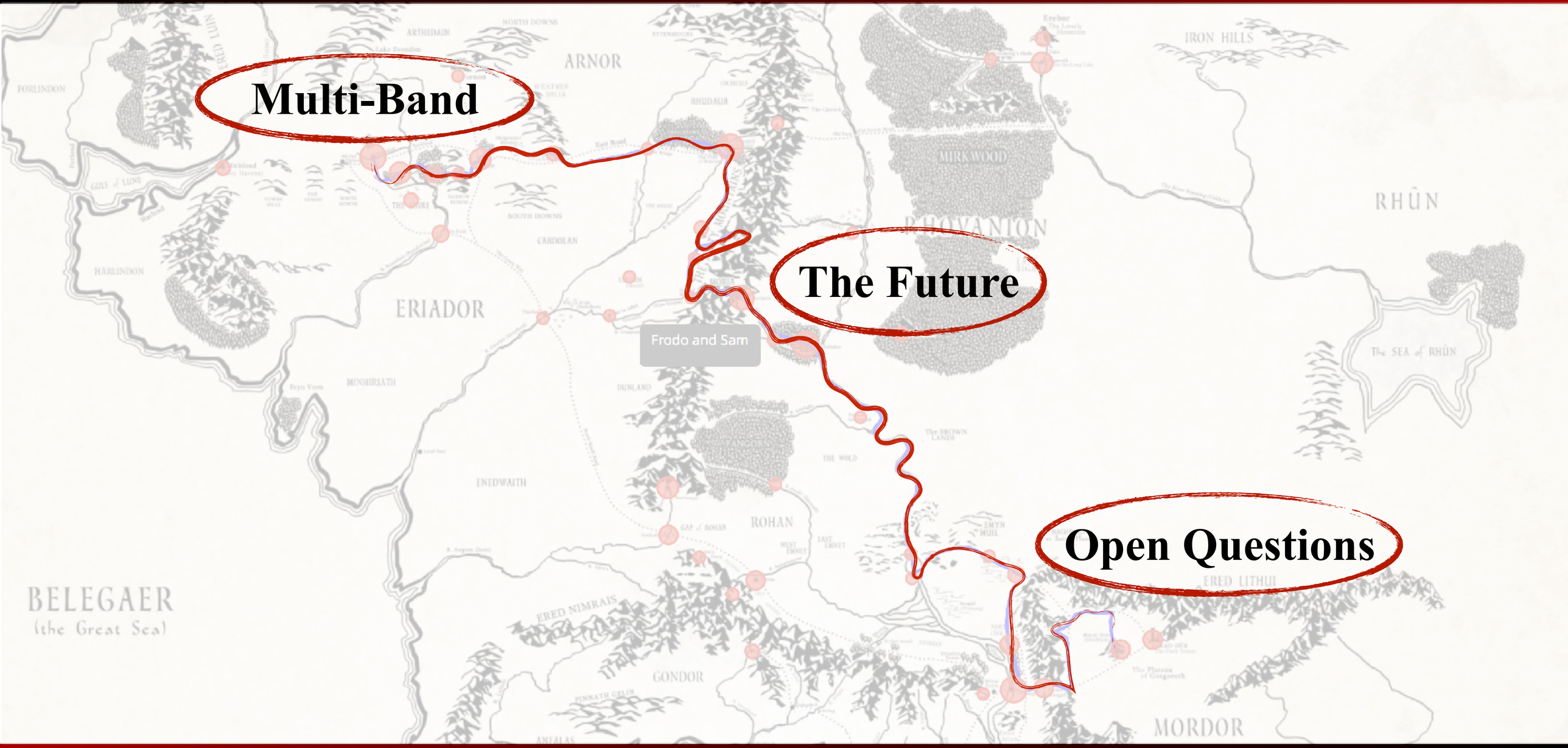
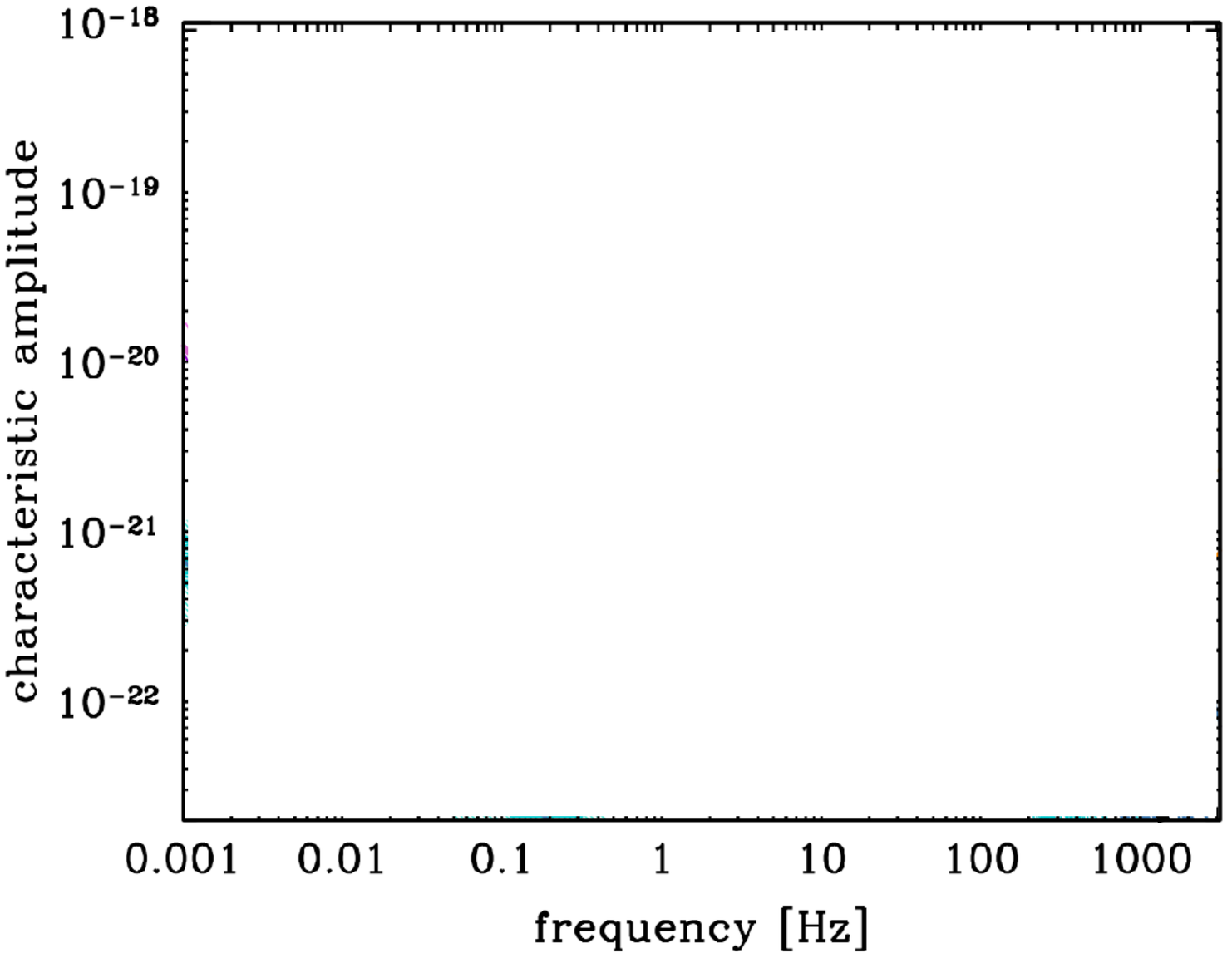
CONFERENCES
- ICRANet-Minsk workshop on high energy astrophysics, Minsk, Belarus
- Fifth Galileo-Xu Guangqi Meeting, Chengdu, China
- 15th Italian-Korean Symposium on Relativistic Astrophysics, Seoul, Korea
- Geometric Foundations of Gravity in Tartu, Estonia
- 3rd Karl Schwarzschild Meeting – Gravity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

Roadmap

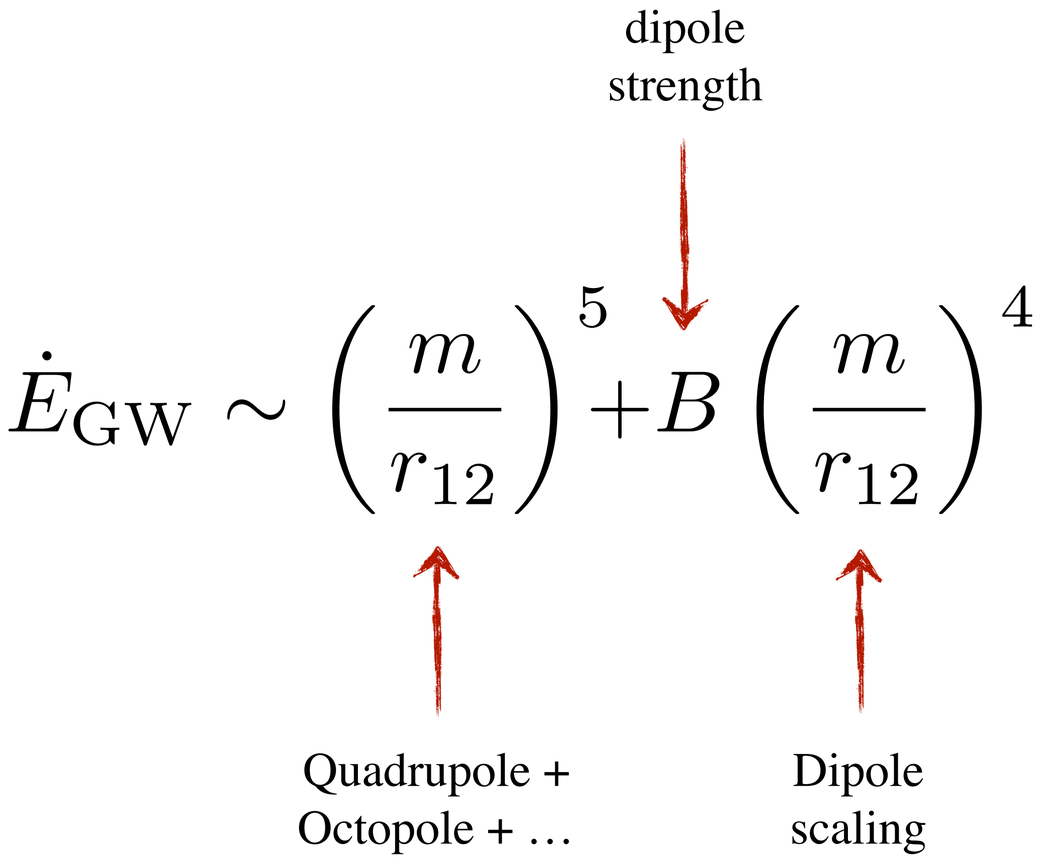

Multi-Band
The Future
Open Questions
Frodo and Sam
ARNOR
ERIADOR
ROHAN
GONDOR
MORDOR
RHÛN
IRON HILLS
MIRKWOOD
RHOVANION
BELEGAER
(the Great Sea)

Multi-Band Observations



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

Dipole Energy Flux



Effect of Dipole Flux

Faster Inspiral, Faster Merger

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

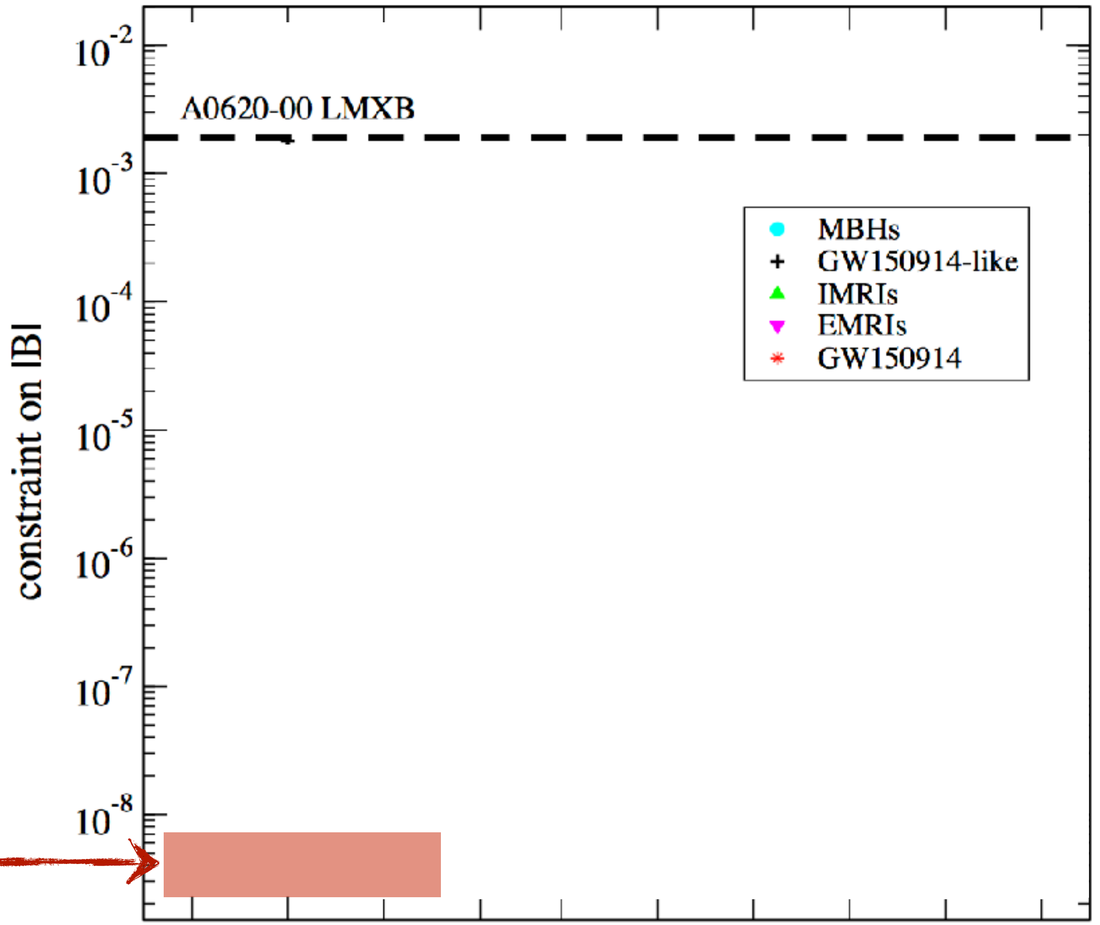
Faster Inspiral, Faster Gravitational Wave Chirp

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

Quadrupole + Octopole + …

Dipole GW Term

Projected Constraints on Dipole Radiation

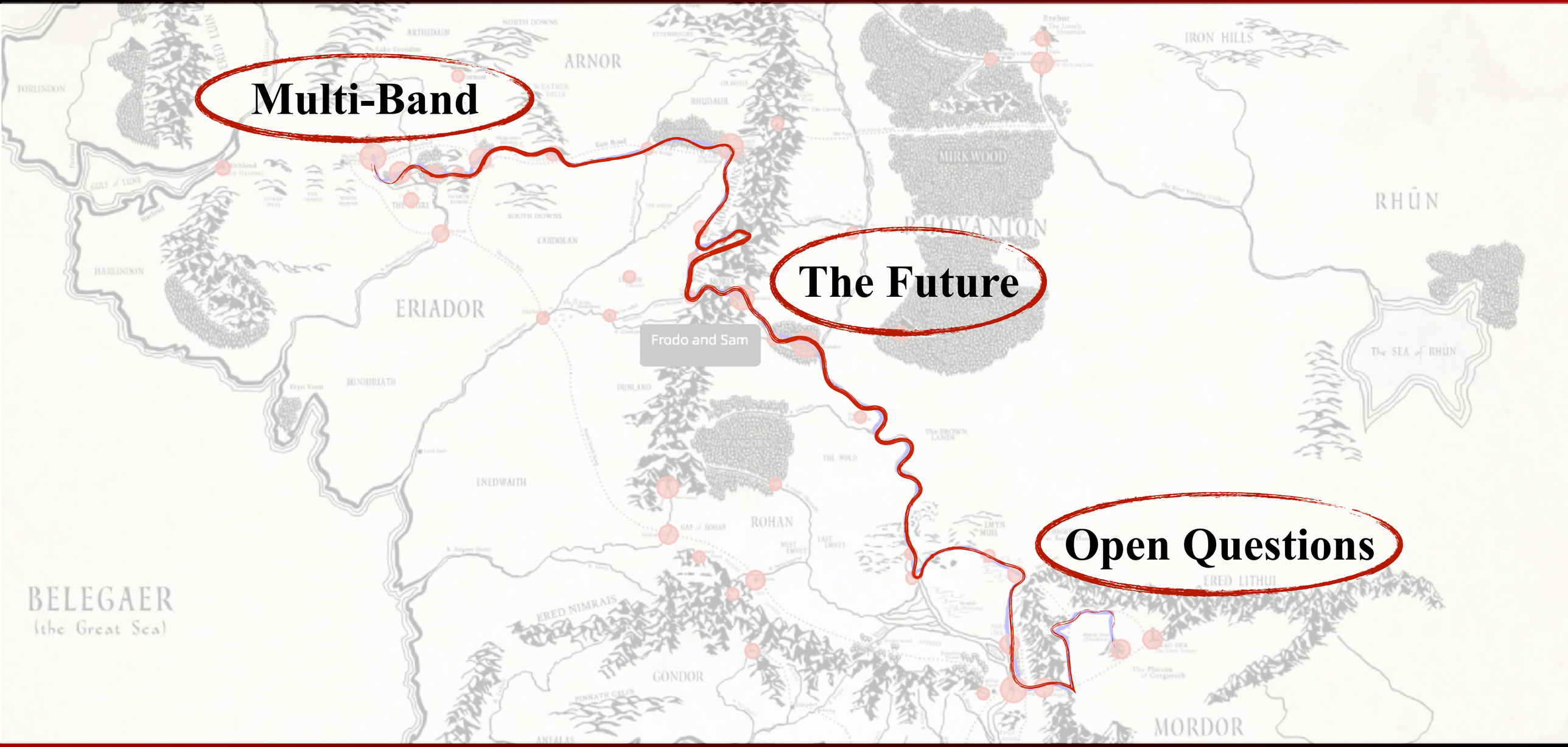


$$\beta = -\frac{3}{224}\eta^{2/5}B$$

10^6 times better than current bounds!!

[Barausse, Yunes, Chamberlain, PRL '16]

Roadmap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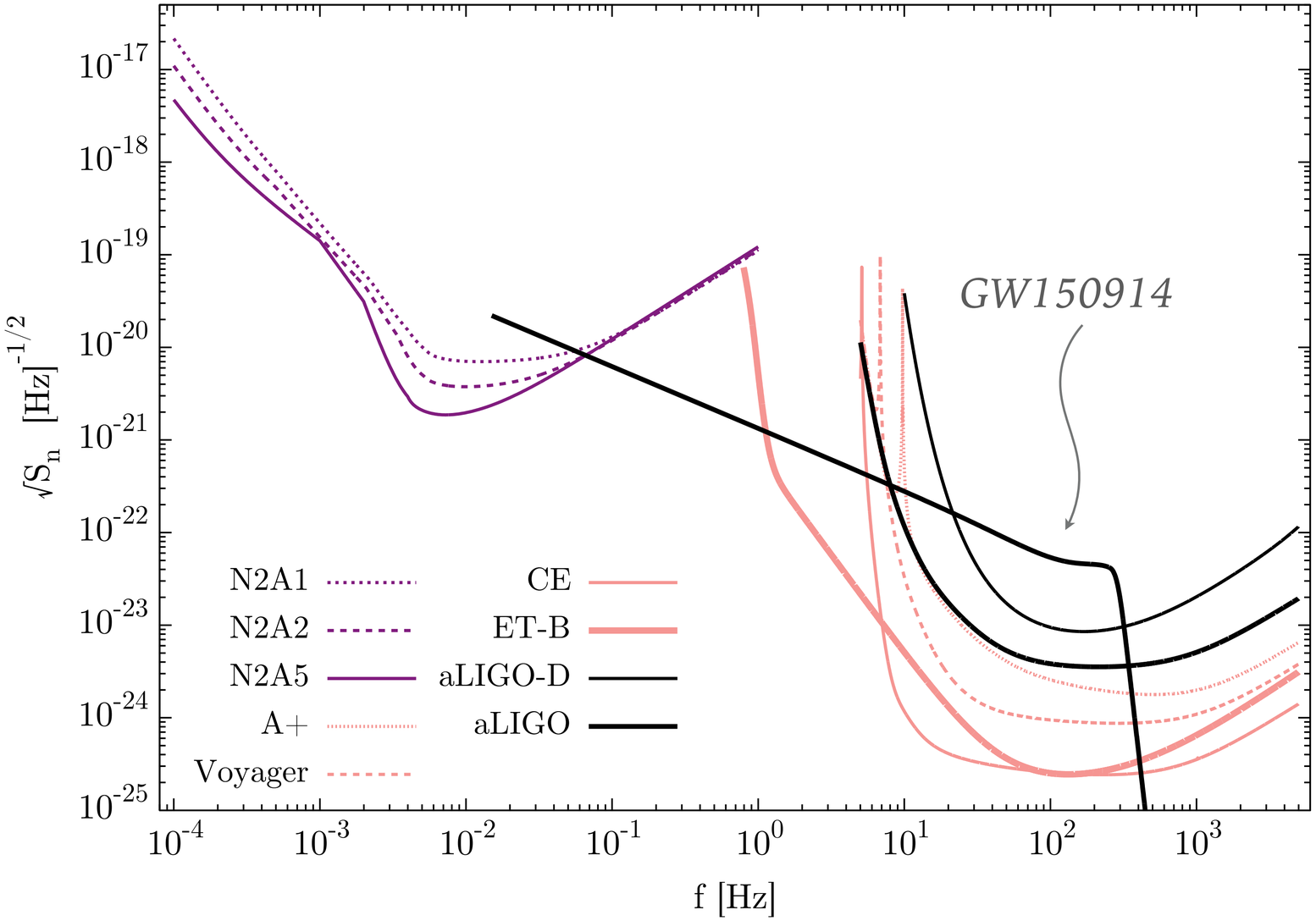
Estúpidamente Preliminary

Greek for “somewhat”

Spectral Noises of Future Instruments



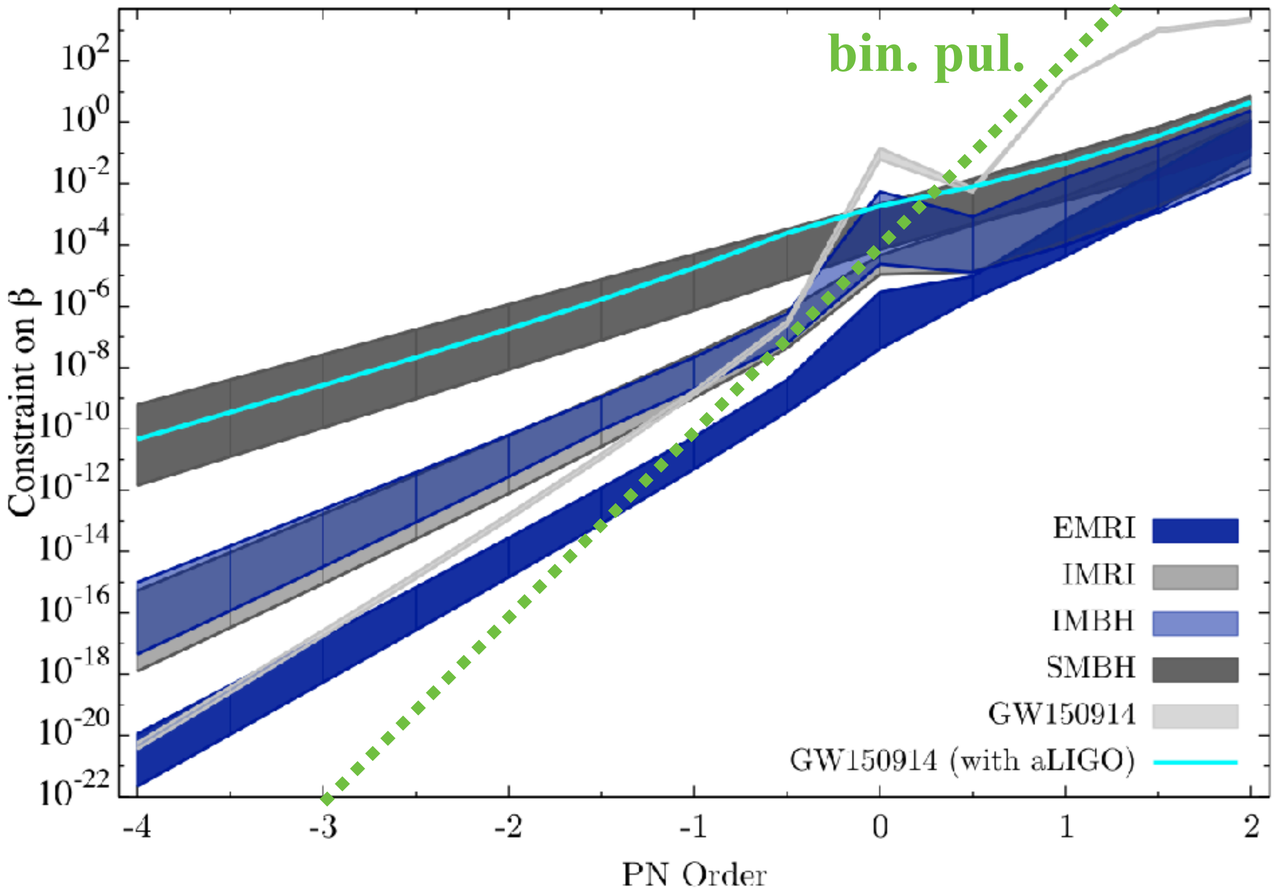
In life you have to make choices, so we made some…

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	$372 - 1110$

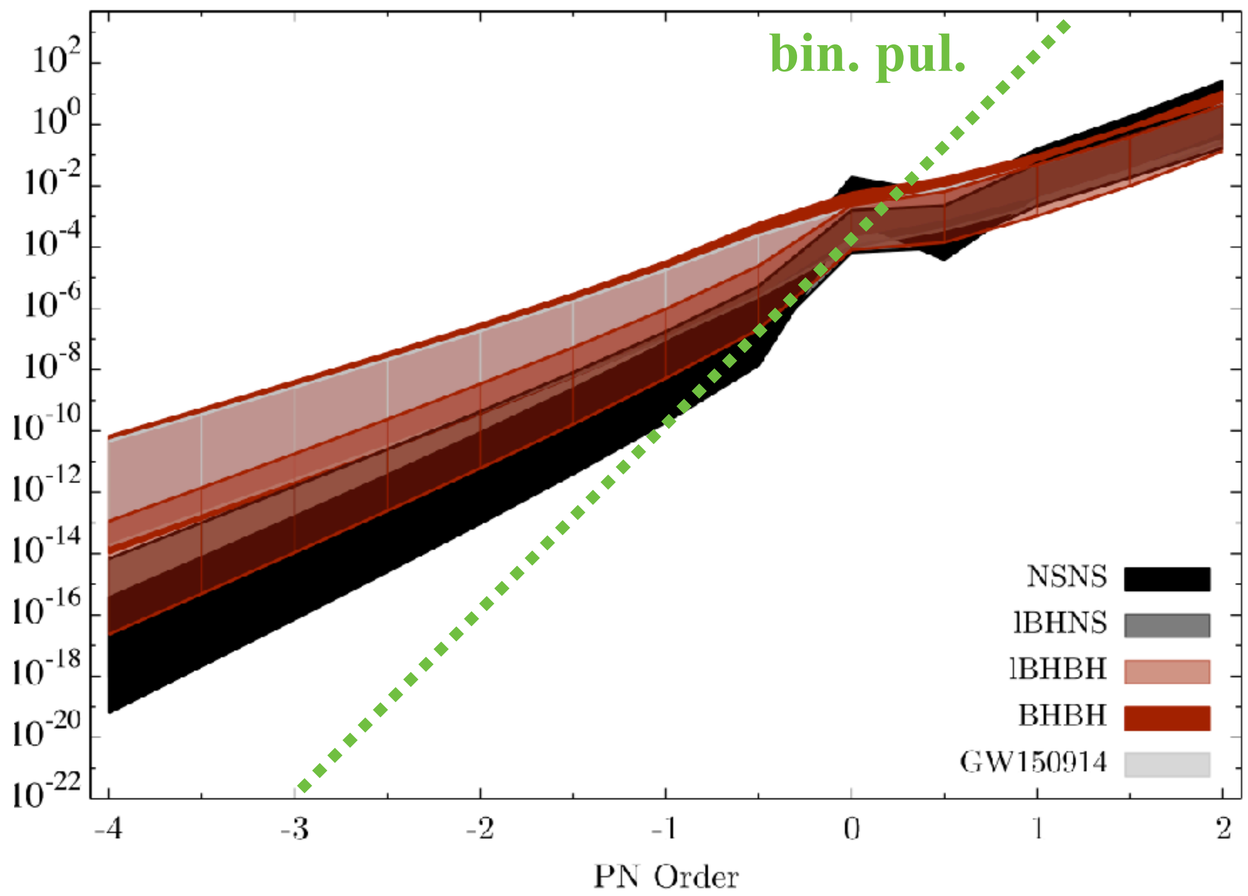
Name	$m_1[M_\odot]$	$m_2[M_\odot]$	(χ_1, χ_2)	D_L	ρ_{aLIGO}	ρ_{A+}	$\rho_{Voyager}$	ρ_{ET-B}	ρ_{CE}
NSNS	2	1.4	(0.01, 0.02)	100 Mpc	23.23	33.65	109.55	332.98	541.14
ℓBHNS	5	1.4	(0.2, 0.02)	150 Mpc	22	31	103	312	511
ℓBHBH	8	5	(0.2, 0.3)	250 Mpc	28	40	132	398	656
BHBH	25	20	(0.3, 0.4)	800 Mpc	26	38	123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

Future ppE Constraints on GR

space-based

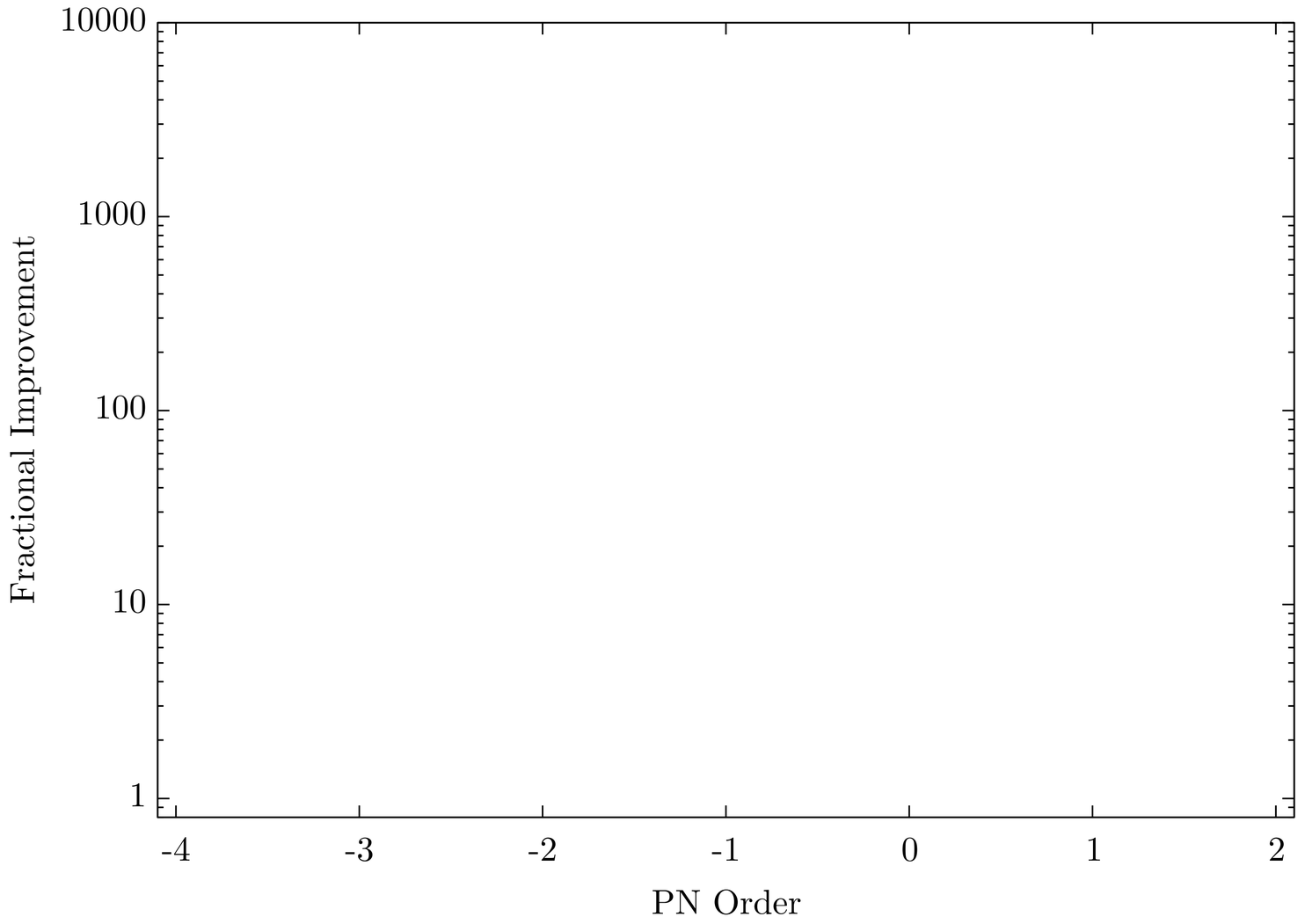


ground-based



[Chamberlain & Yunes, to appear soon]

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

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

Future Constraints on the Graviton Mass

Maximize Extraction:

Binary systems that are as far away as possible (SMBHs)

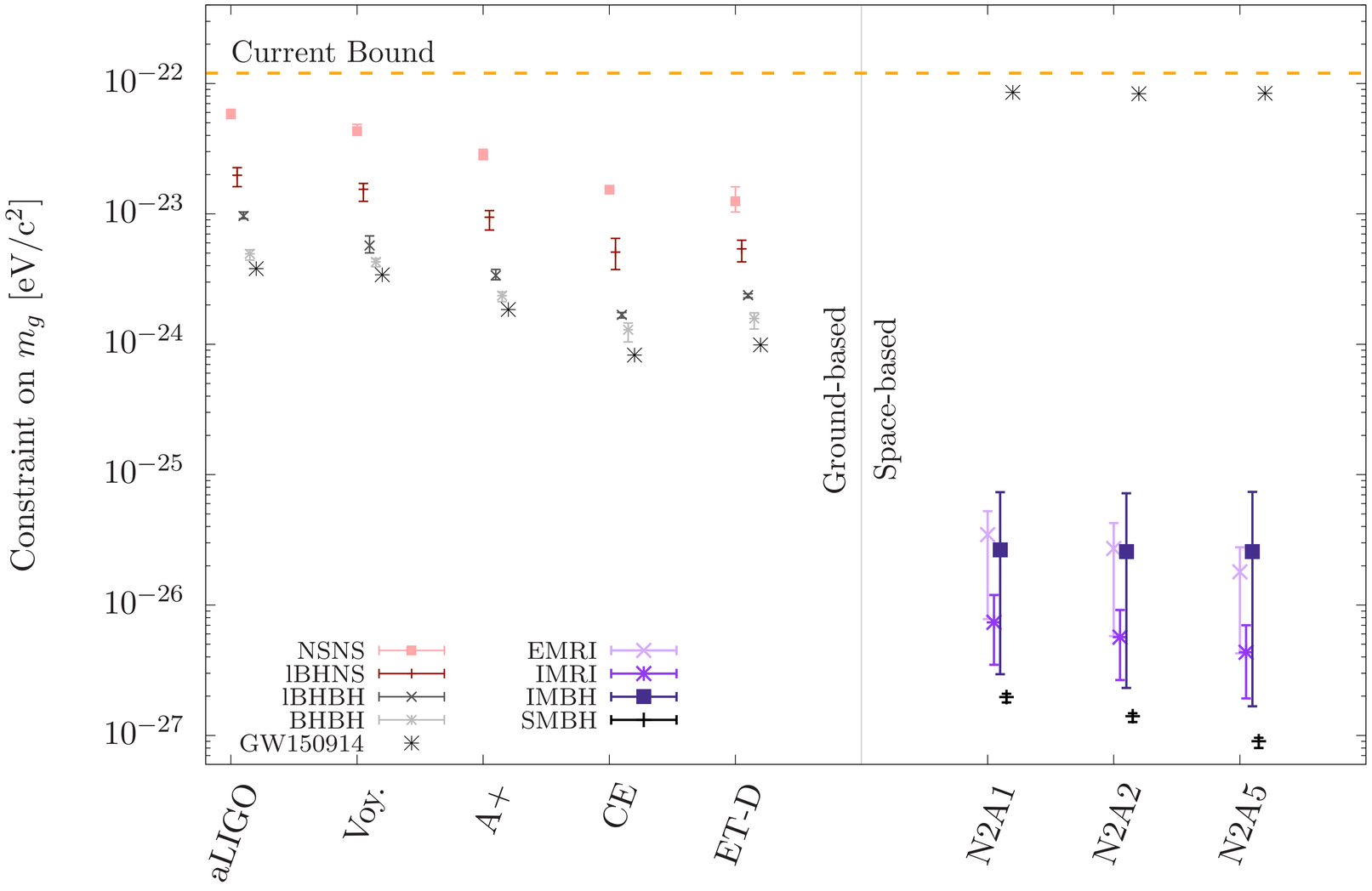
Binary with largest chirp mass

Open Questions:

Generation of GWs?

Merger? Hybrid IMR waveforms?

What is the Goal?



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

[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

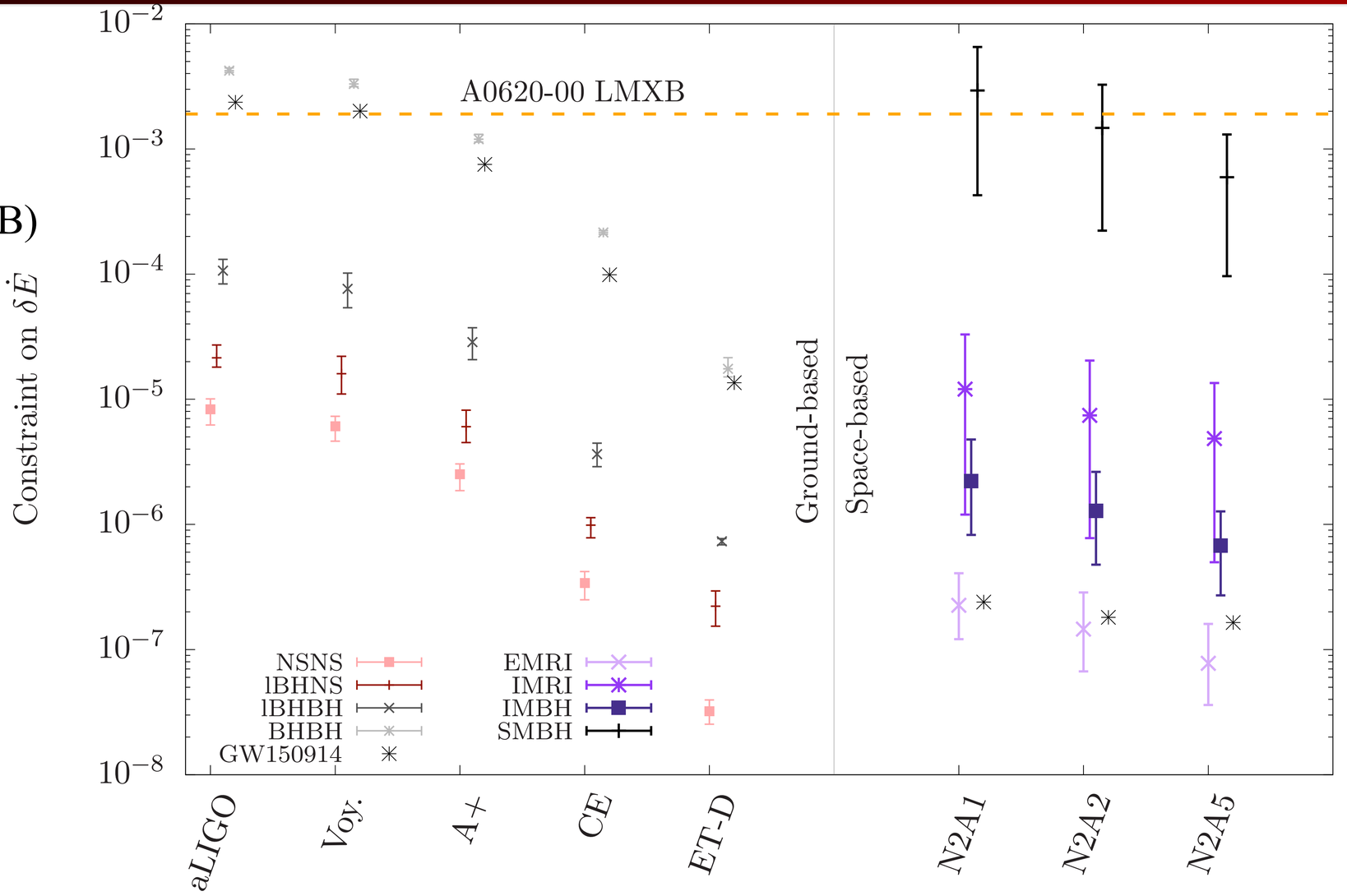
Maximize Extraction:

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 Violation

Extractable Physics:

Non-Spinning BH is not Schwarzschild

NSs have sensitivity-dependent GR deviations

Compact Object binaries inspiral faster (dipole

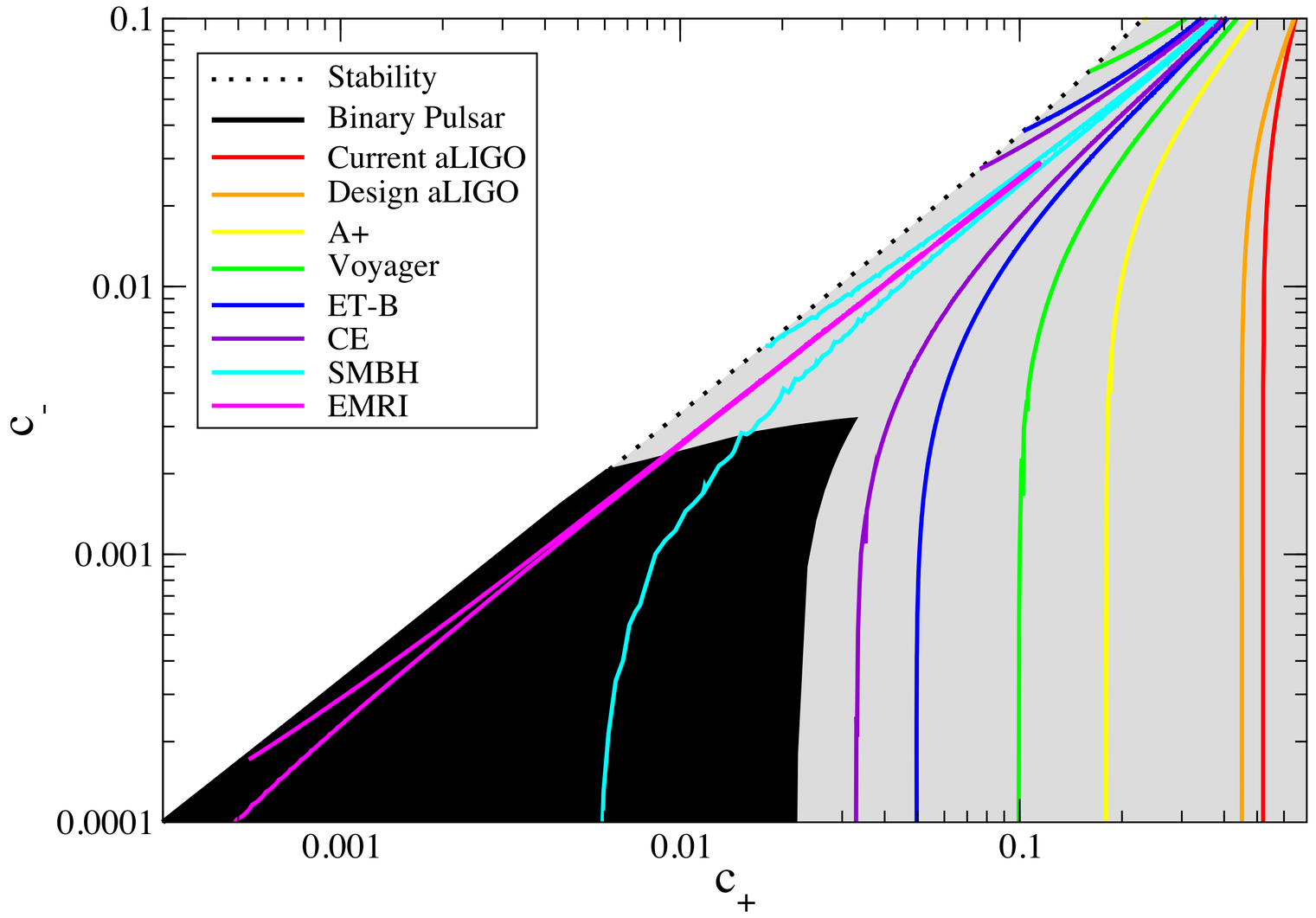
Maximize Extraction:

SMBHs or EMRIs do best

Open Questions:

BH sensitivities and Inspiral BH waveforms?

Merger? Hybrid IMR waveforms?



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

[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

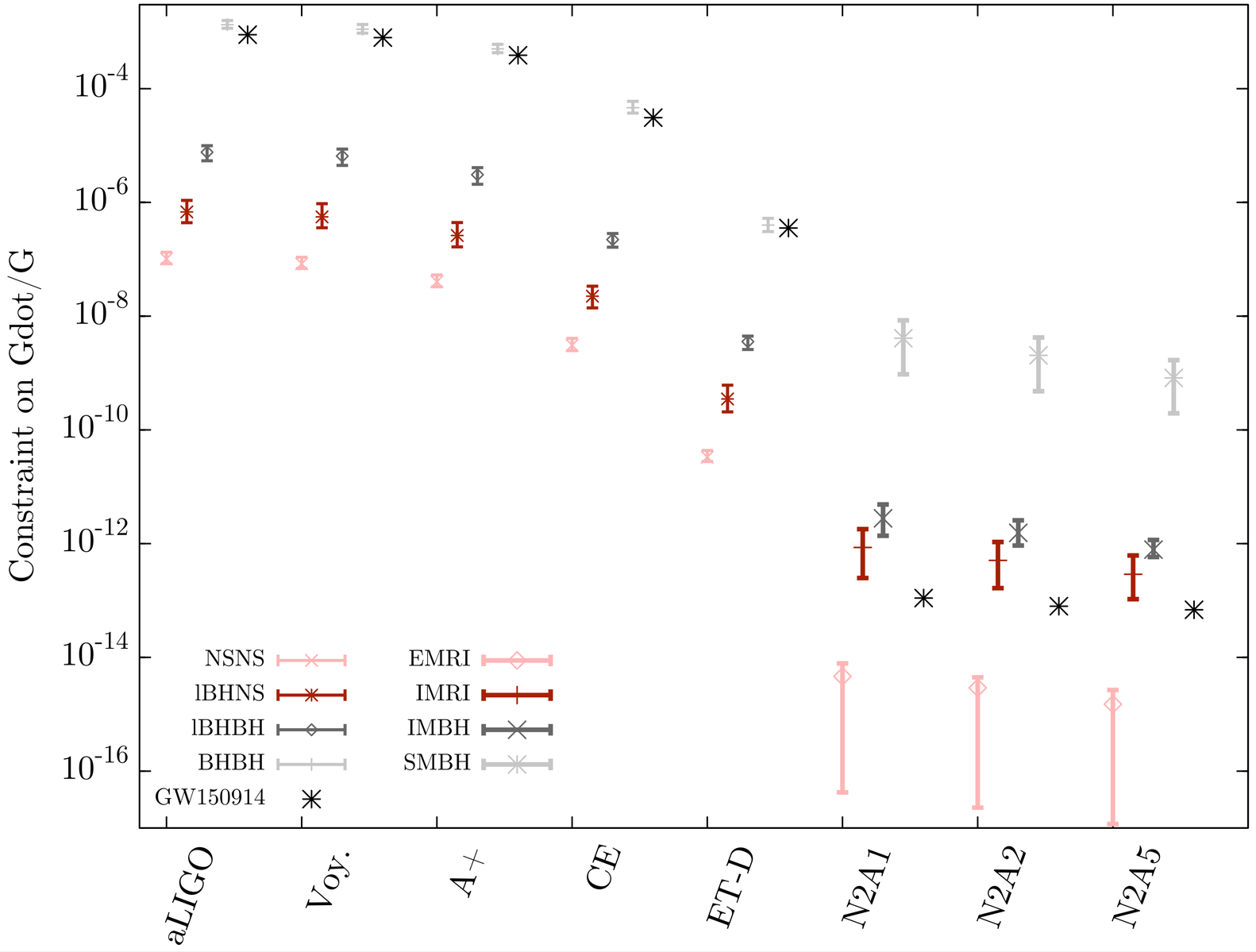
Open Questions:

Generation of GWs?

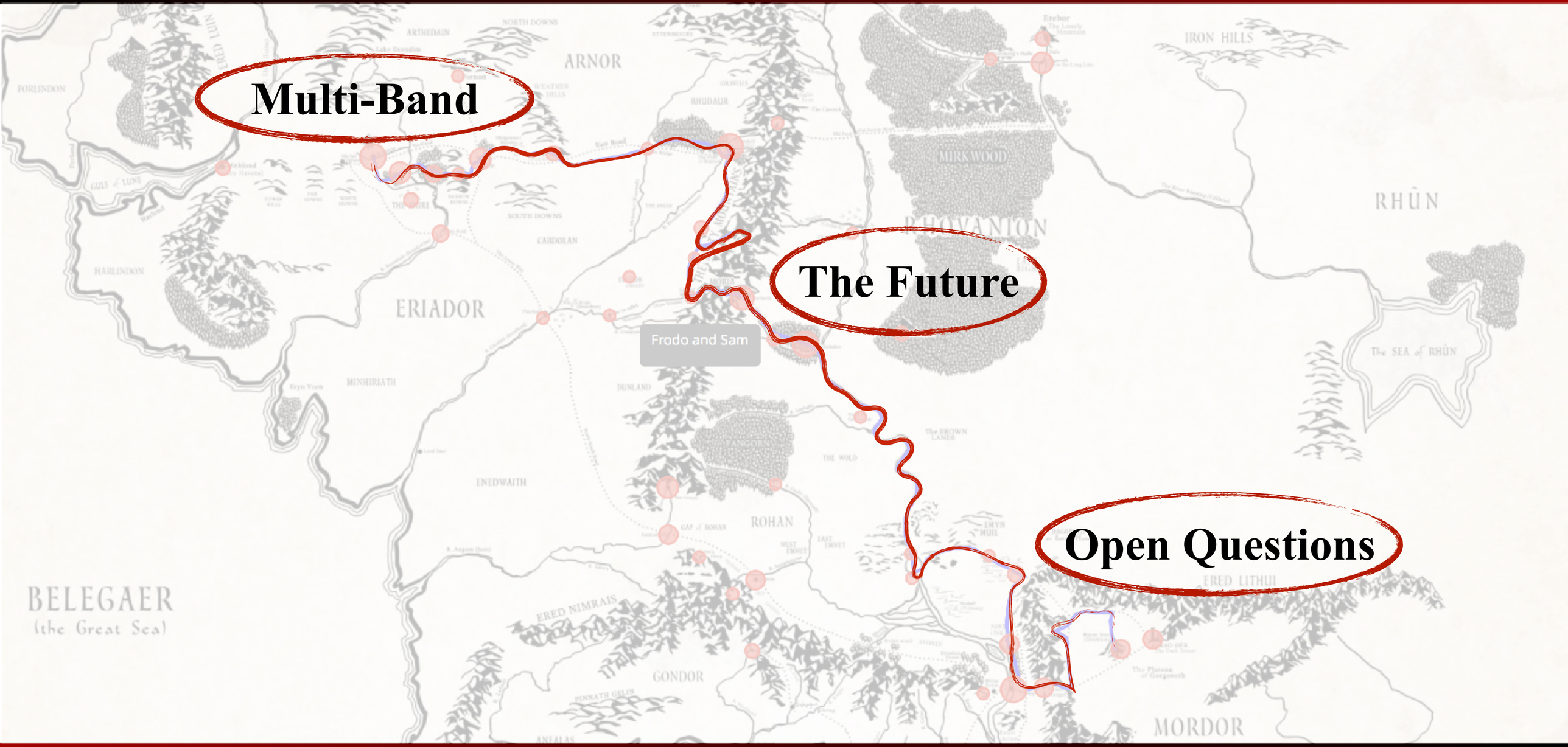
Merger? Hybrid IMR waveforms?

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

[Chamberlain & Yunes, to appear soon]



Roadmap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(the Great Sea)

And now what?

Why?

Duty

Curiosity

Religion

How?

More Consistency ?

Better ppE ?

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?

Thank You

Future Constraints on Gravitational Parity Violation

Extractable Physics:

Left/Right polarized waves propagate differently

Spinning BH is not Kerr (yes-hair theorem)

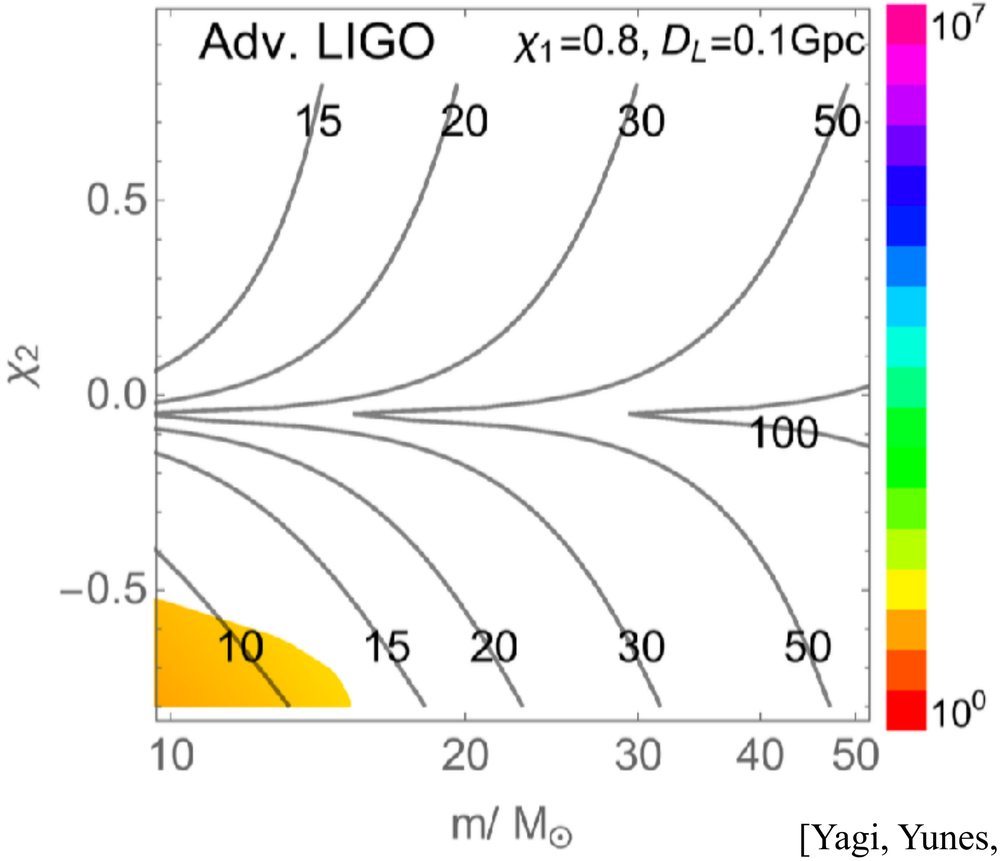
Spinning BH binaries inspiral faster (magnetic dipole)

$$\beta_{\rm dCS} = \frac{1549225}{11812864}\frac{\zeta_{\rm dCS}}{\eta^{14/5}}\left[\left(1-\frac{231808}{61969}\eta\right)\chi_s^2 + \left(1-\frac{16068}{61969}\eta\right)\chi_a^2 - 2\delta_m\chi_s\chi_a\right],$$

Maximize Extraction:

Low-mass (long-inspiral)
high spin (precession)
BH binaries

Open Questions: Merger? Hybrid IMR waveforms?



[Yagi, Yunes, Tanaka, PRL '13]

Parametrized post-Einsteinian Framework

The parameterized post-Einsteinian Framework

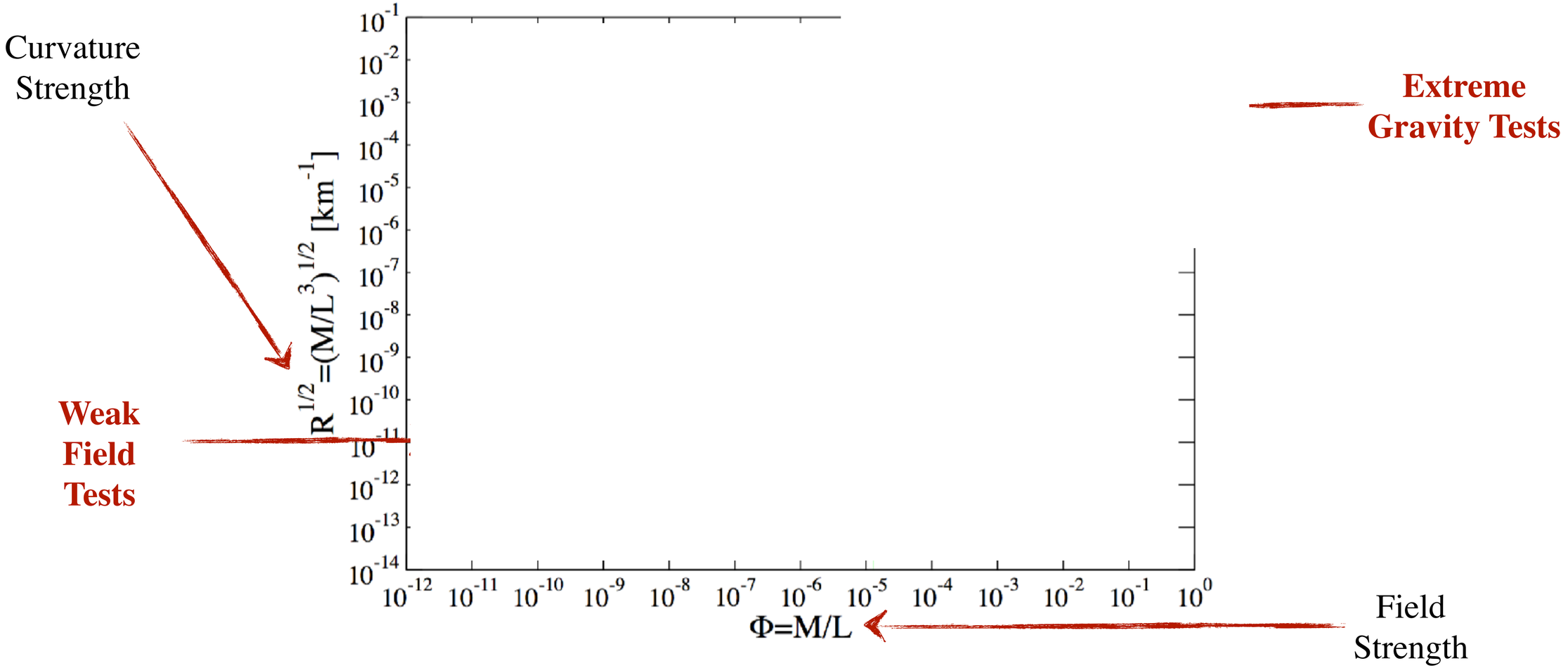
$$\tilde{h}(f) = \tilde{h}_{GR}(f)\,(1+\alpha f^{a})\,e^{i\beta f^{b}}$$

[Yunes & Pretorius, PRD 2009]

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	Vector Field Activation due to Lorentz Violation	EA [109, 110], Khronometric [111, 112]	-7	-1PN	$\beta^{(-1)}_{\text{Æ}}$ [113]
Modified Quadrupolar Radiation			-5	0PN	$\beta^{(0)}_{\text{Æ}}$ [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).]

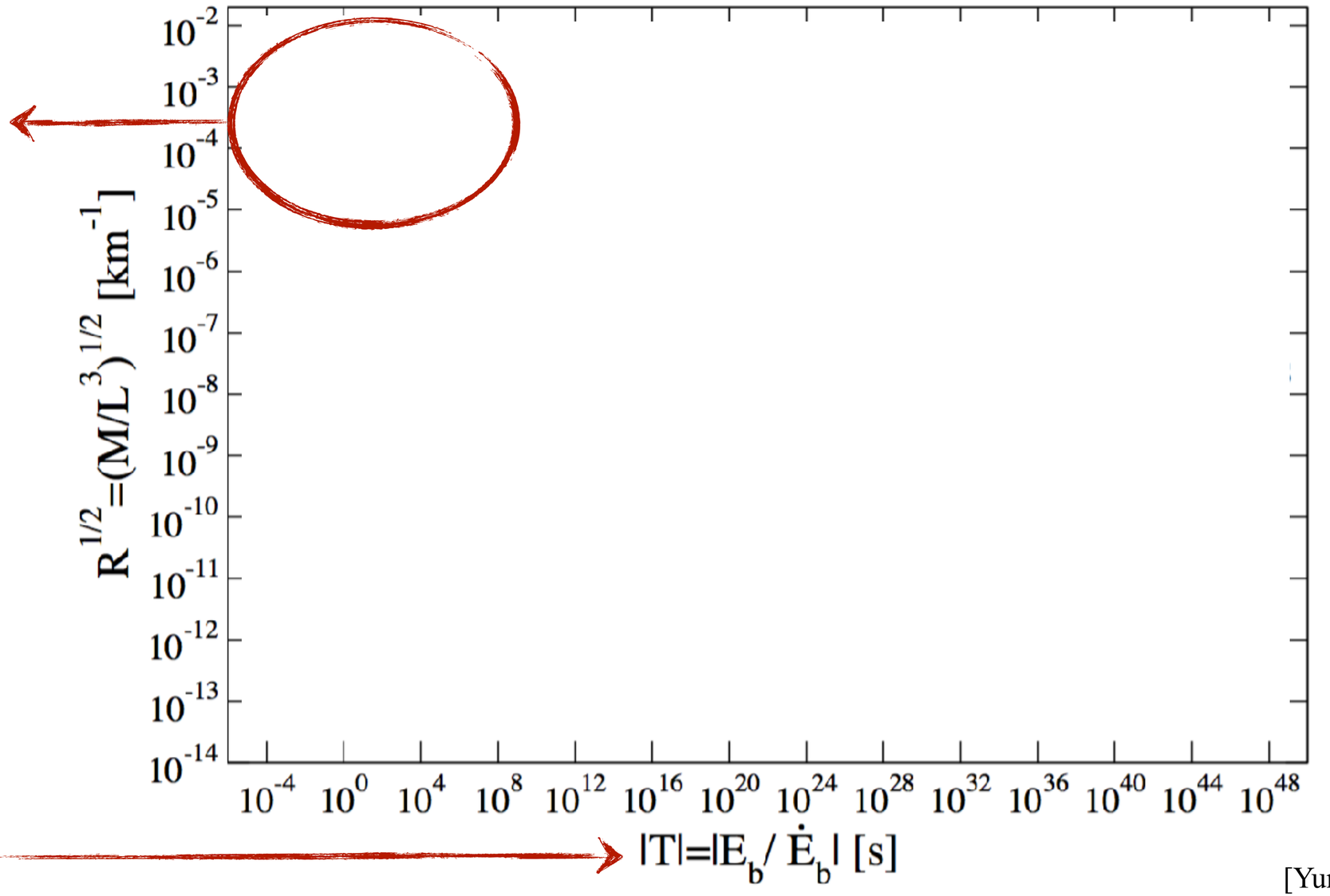
Strong Gravity versus Extreme Gravity



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

Extreme Gravity versus Strong Gravity

Extreme Gravity Tests

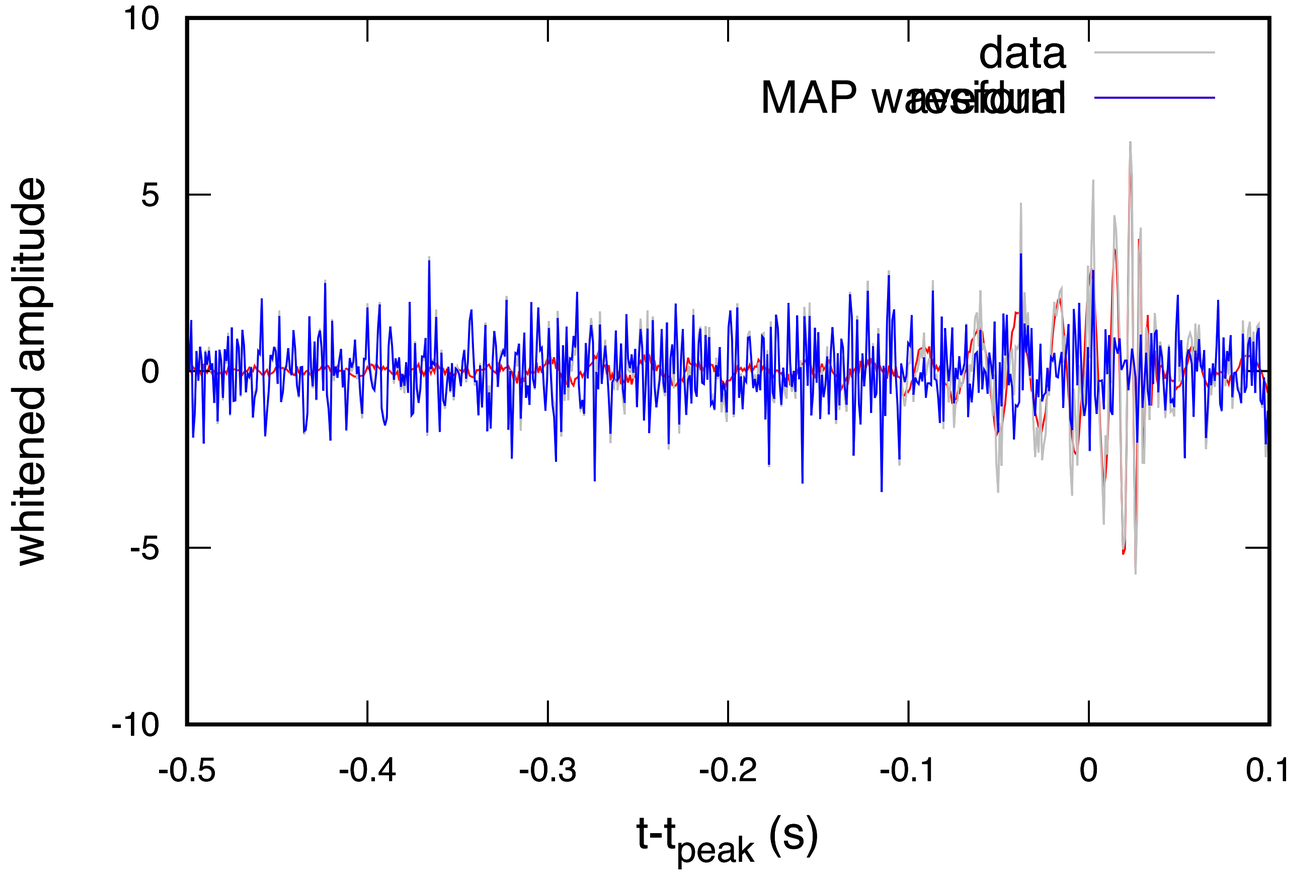


Dynamical Timescale

[Yunes, Yagi, Pretorius, PRD '16]

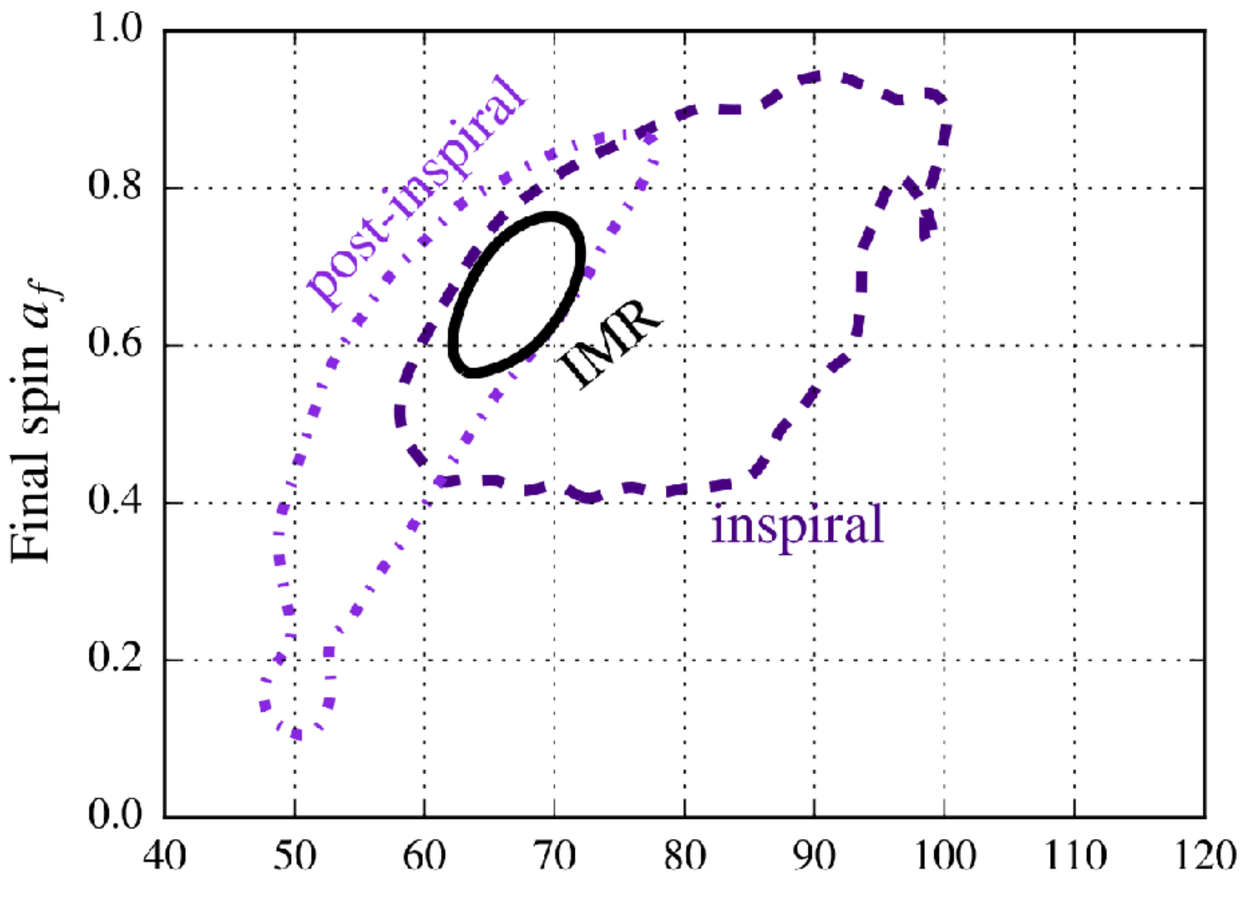
Residual Consistency

[Littenberg & Cornish]



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

(Sort of) Jack-knife Consistency



Classifying Deviations

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

⋮

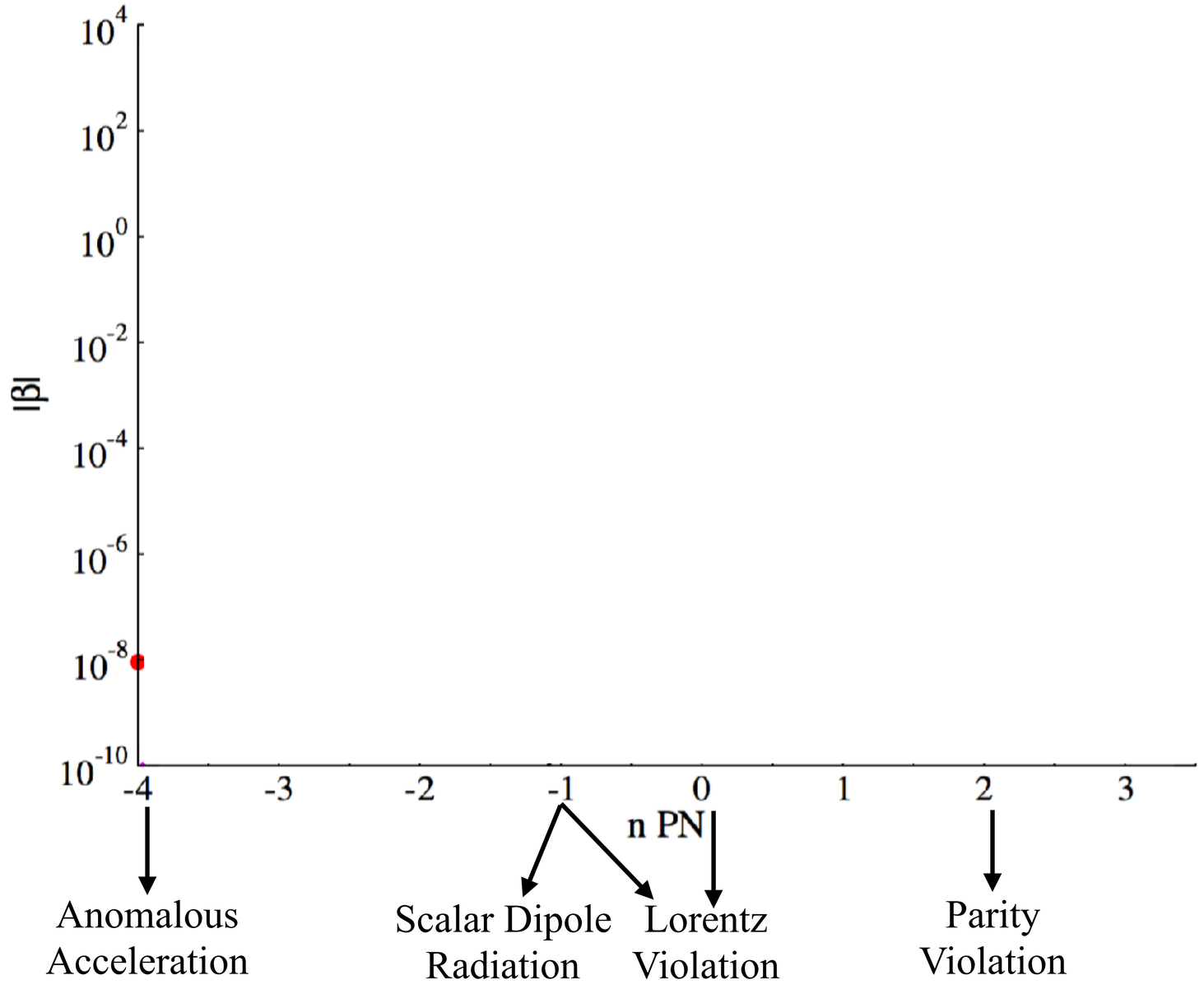
Speed of Gravity

Mass of Graviton

Lorentz Violation

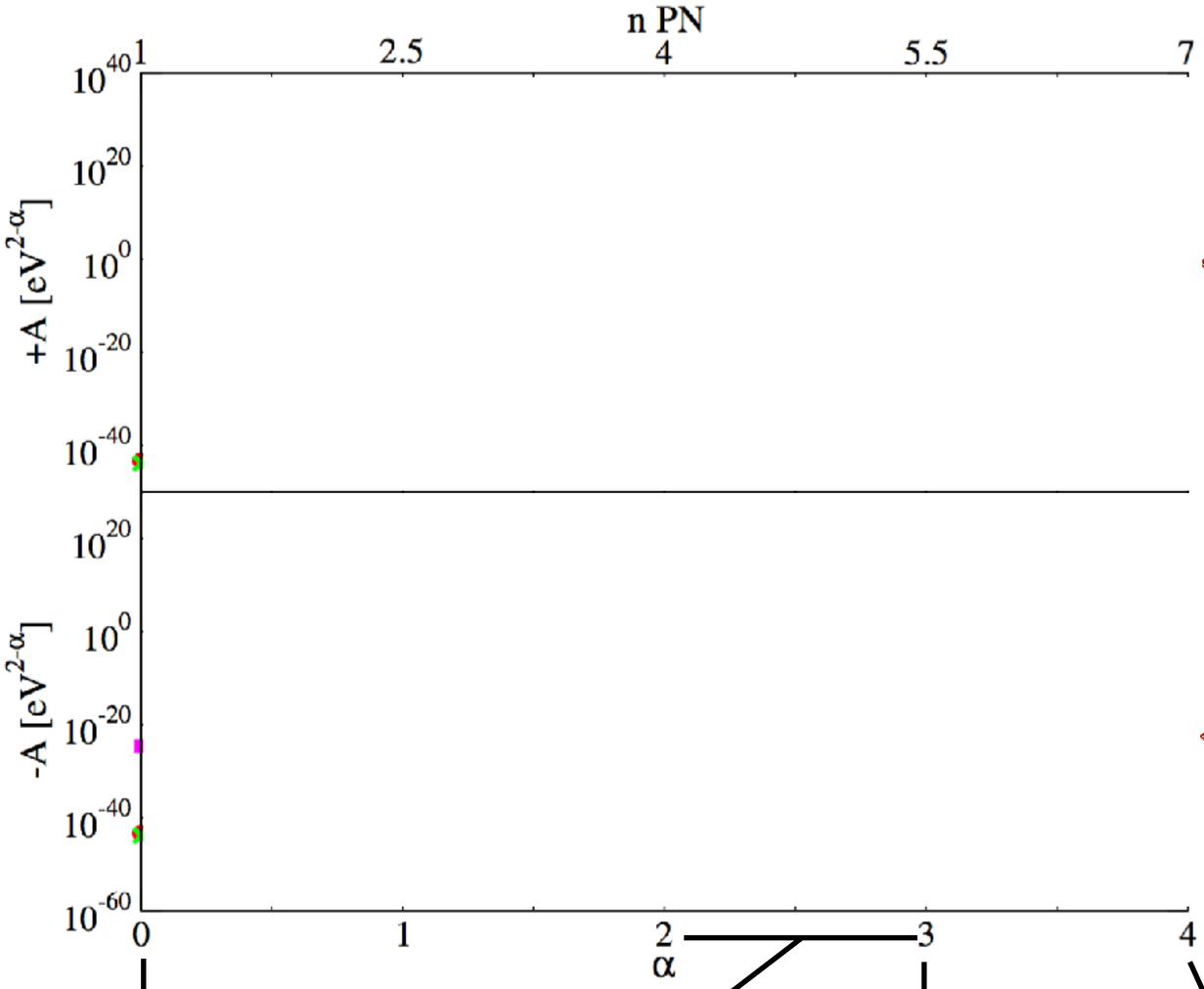
SEP Violation

O1 Constraints on GW Generation Effects



[Yunes, Yagi, Pretorius, PRD '16]

O1 Constraints on Propagation Effects



Superluminal

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

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

Subluminal

…. —> SME (5.5PN, 7PN)

Massive Graviton

Multifractal Spacetime

Doubly Special Relativity

SME, Horava-Lifshitz, Extra-Dimensions

[Yunes, Yagi, Pretorius, PRD ‘16]

Theoretical Physics Implications

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_-)	$\mathbf{(0.9, 2.1)}$	$\mathbf{(0.8, 1.1)}$	$(0.03, 0.003)$ [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]

[Yunes, Yagi, Pretorius, PRD '16]