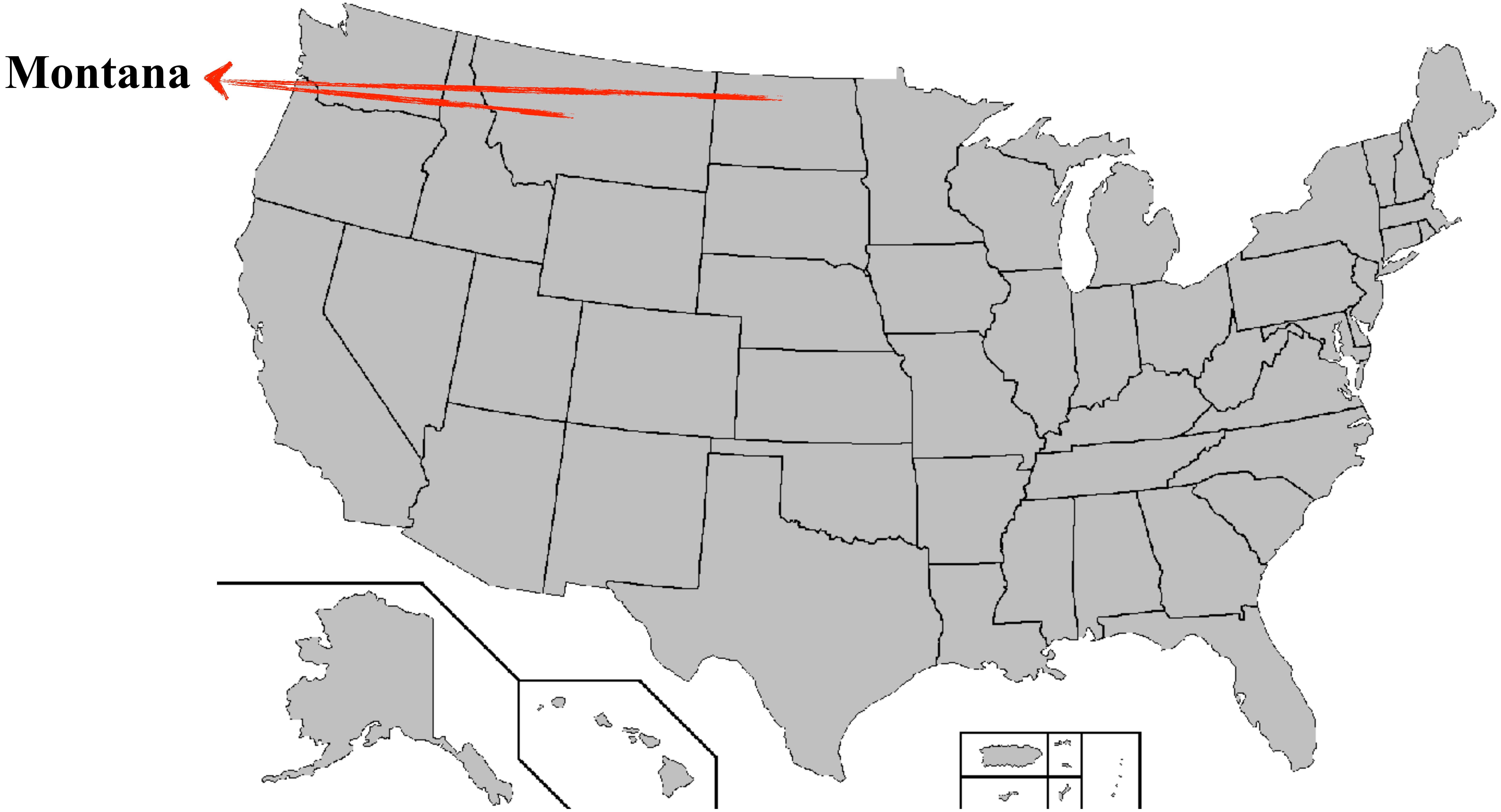
Theoretical Physics Implications of the Advanced LIGO Gravitational Wave Observations

Nicolas Yunes
eXtreme Gravity Institute
Montana State University

MiTP Workshop
March 23rd 2017

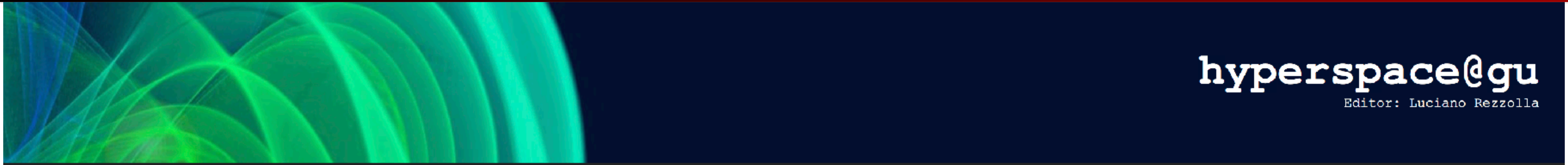
What is Montana?



eXtreme Gravity Institute

Now accepting Applications for our Physics PhD Program!!

eXtreme Matter meets eXtreme Gravity



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:

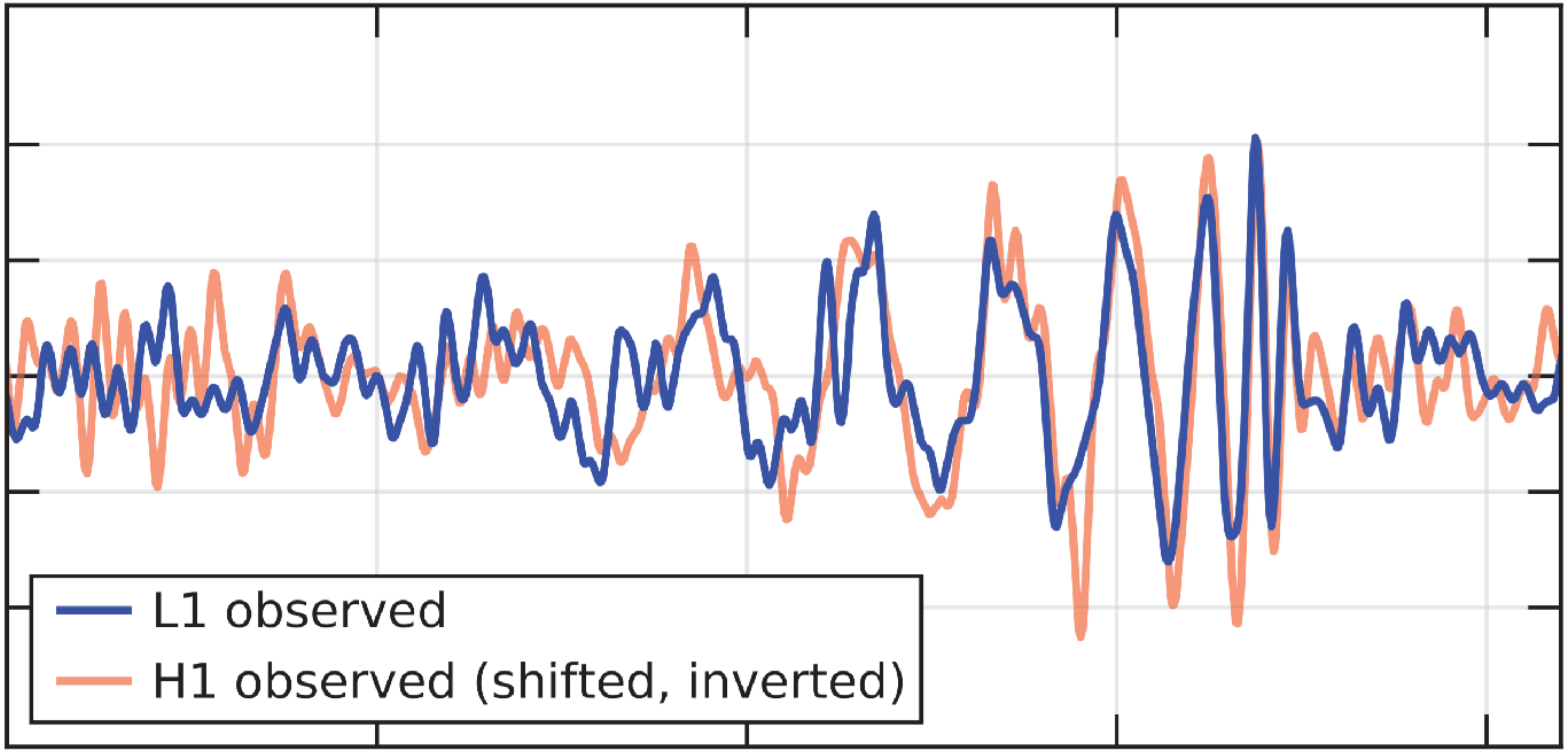
"eXtreme Matter meets eXtreme Gravity"
August 17-19, Bozeman Montana

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.

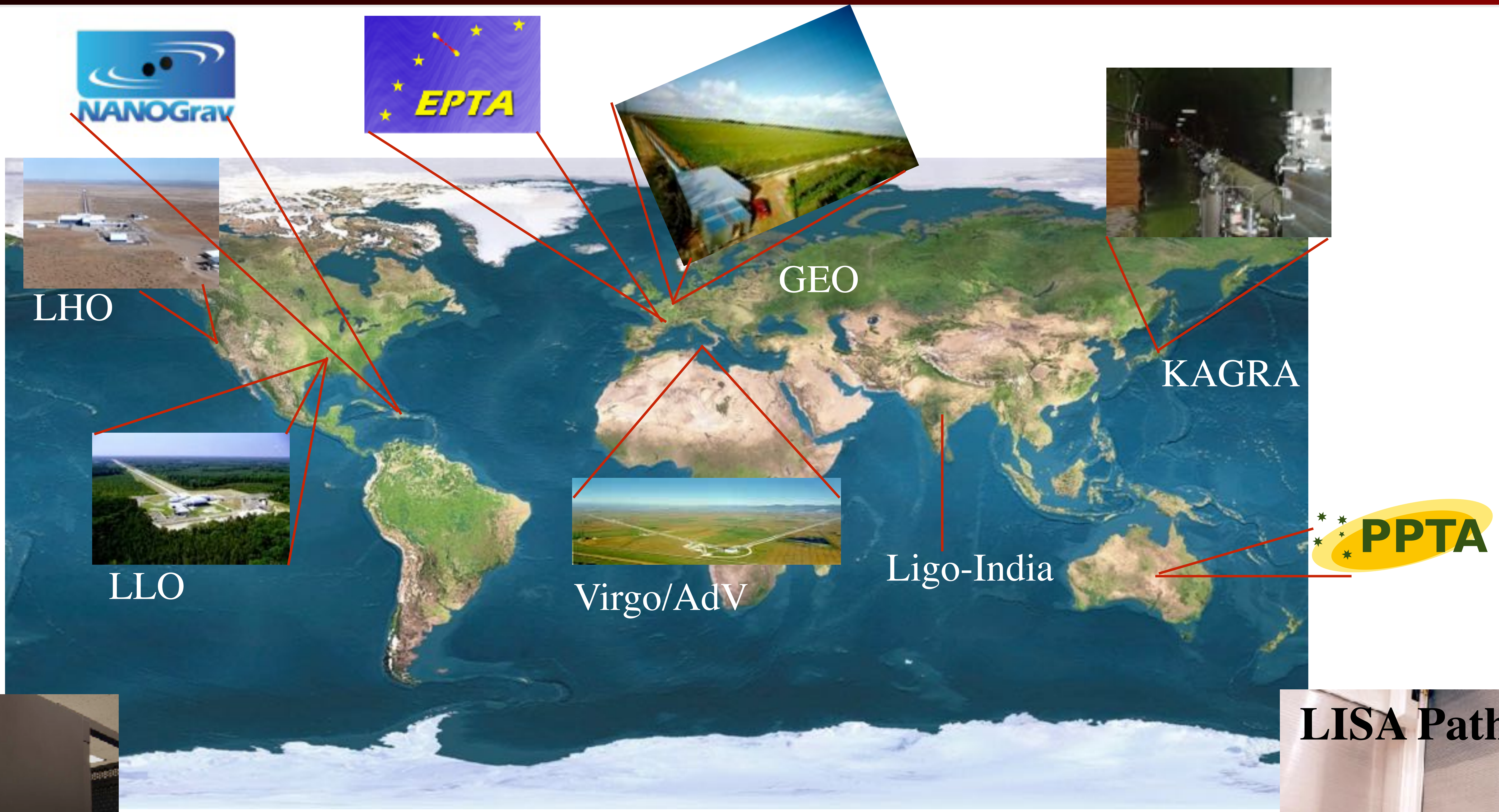
The meeting is being held immediately prior to the HEAD meeting in Sun Valley, and participants may choose to drive between the meetings, or simply head a little south of Bozeman to view the total eclipse on the 21st of August. Bozeman is a beautiful mountain town a one-hour drive from the North entrance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

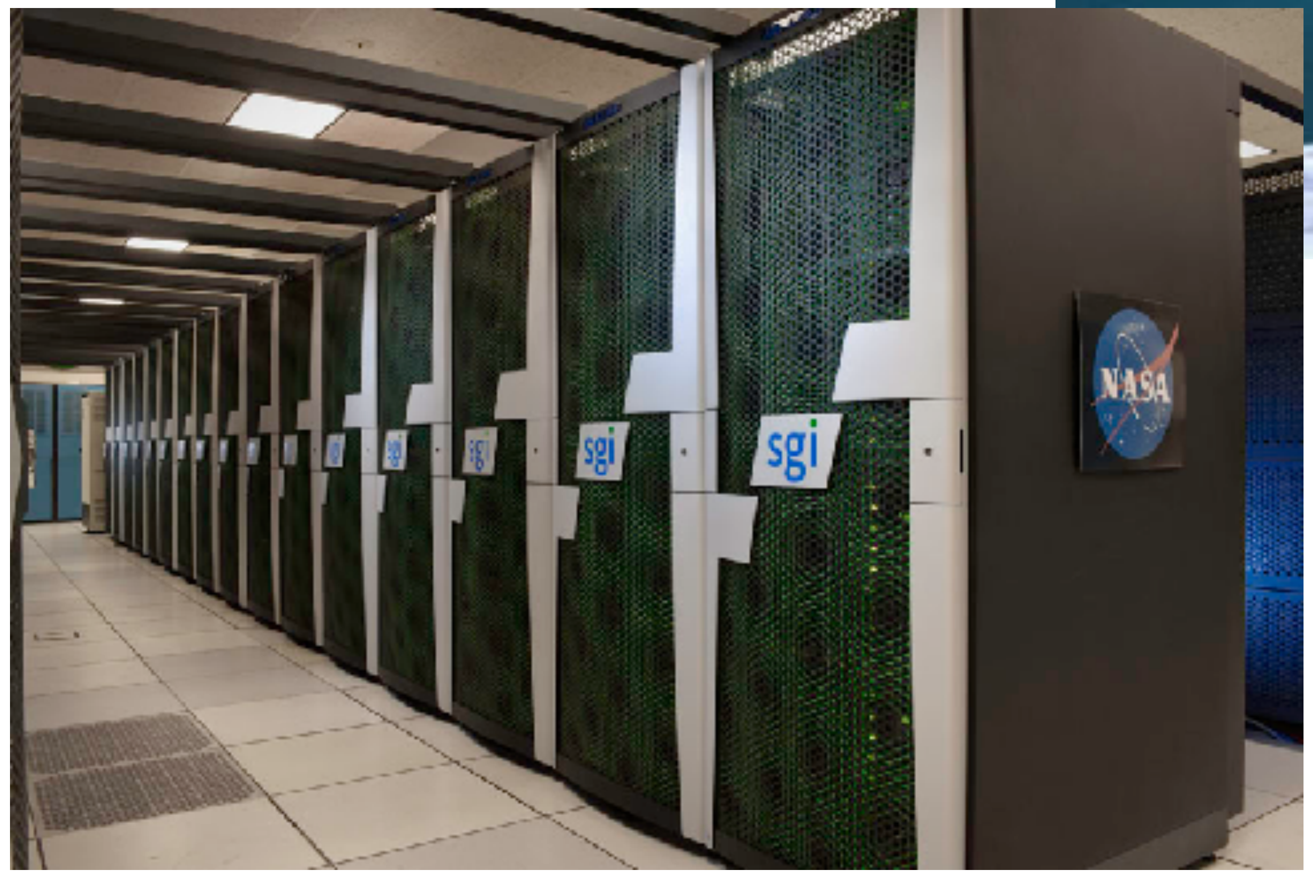
Share this:

Why is this important now?



Why is this even more important in the near future?






LISA Pathfinder Success!

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



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

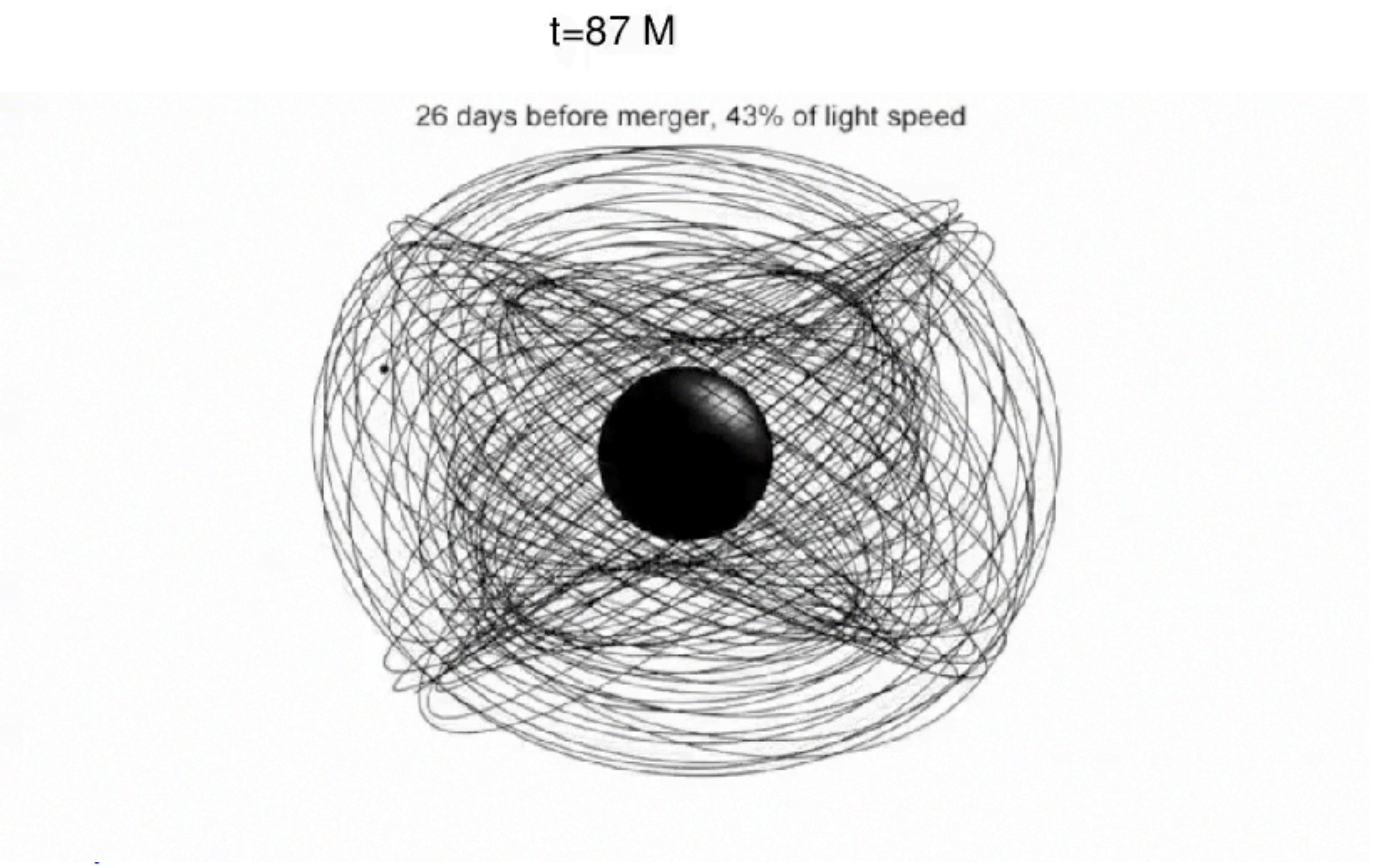
Roadmap

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

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

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.

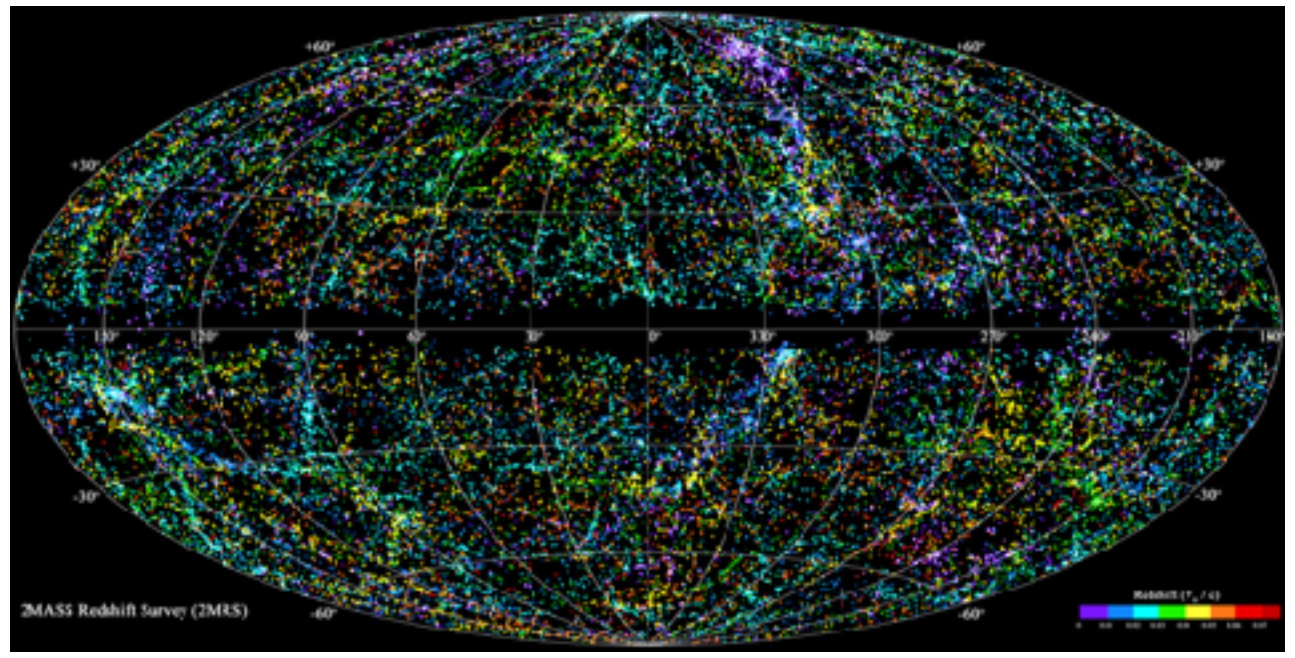
[Yunes, et al PRL ('11), Kocsis, et al PRD 84 ('11), Barausse, et al PRD 89 ('14)]

3. Localized:

Point sources in spacetime

Constraint Maps

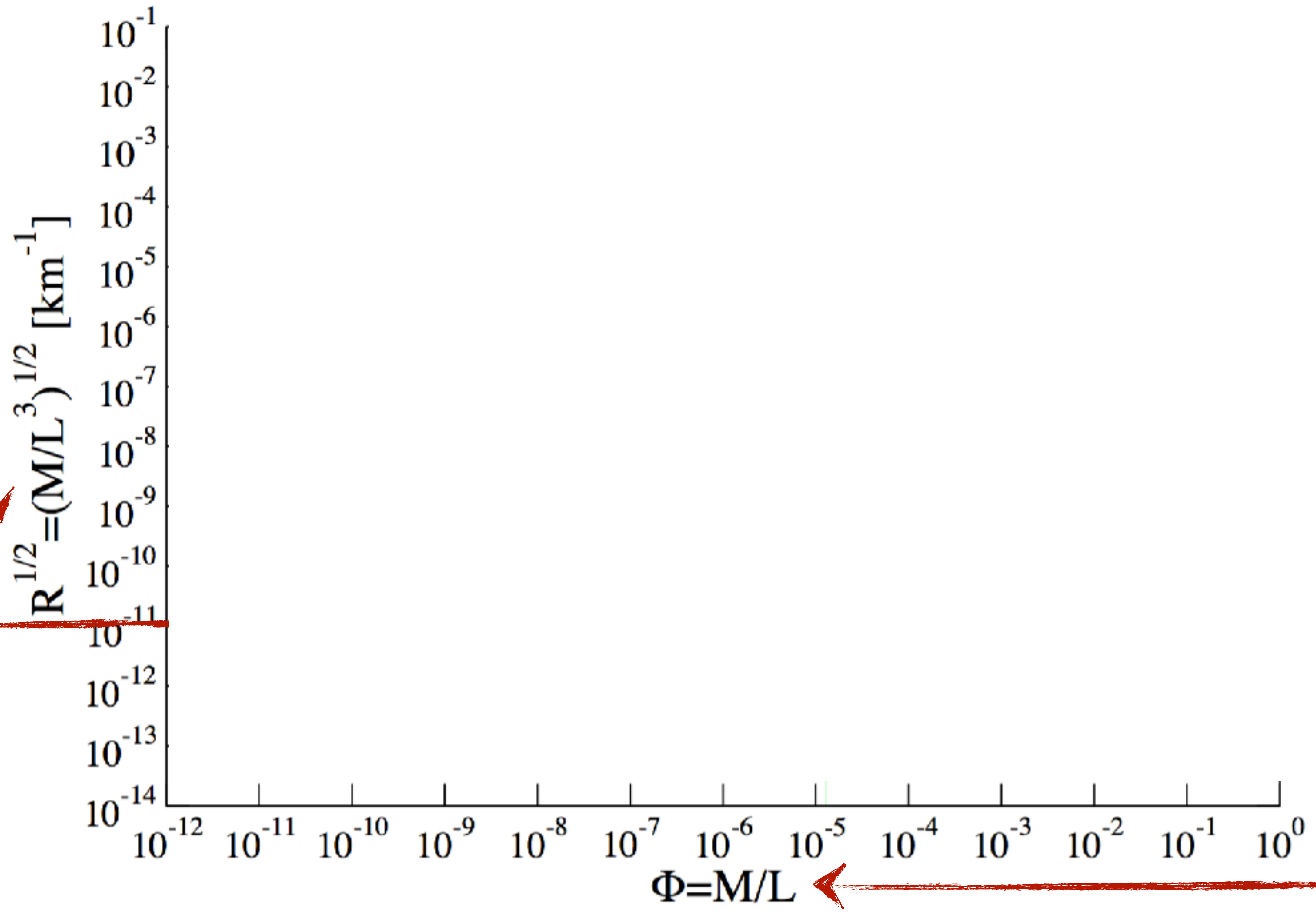
[Yunes & Pretorius, PRD 81 ('10)]



What Physics Regime do GWs Probe?

Curvature
Strength

Weak
Field
Tests

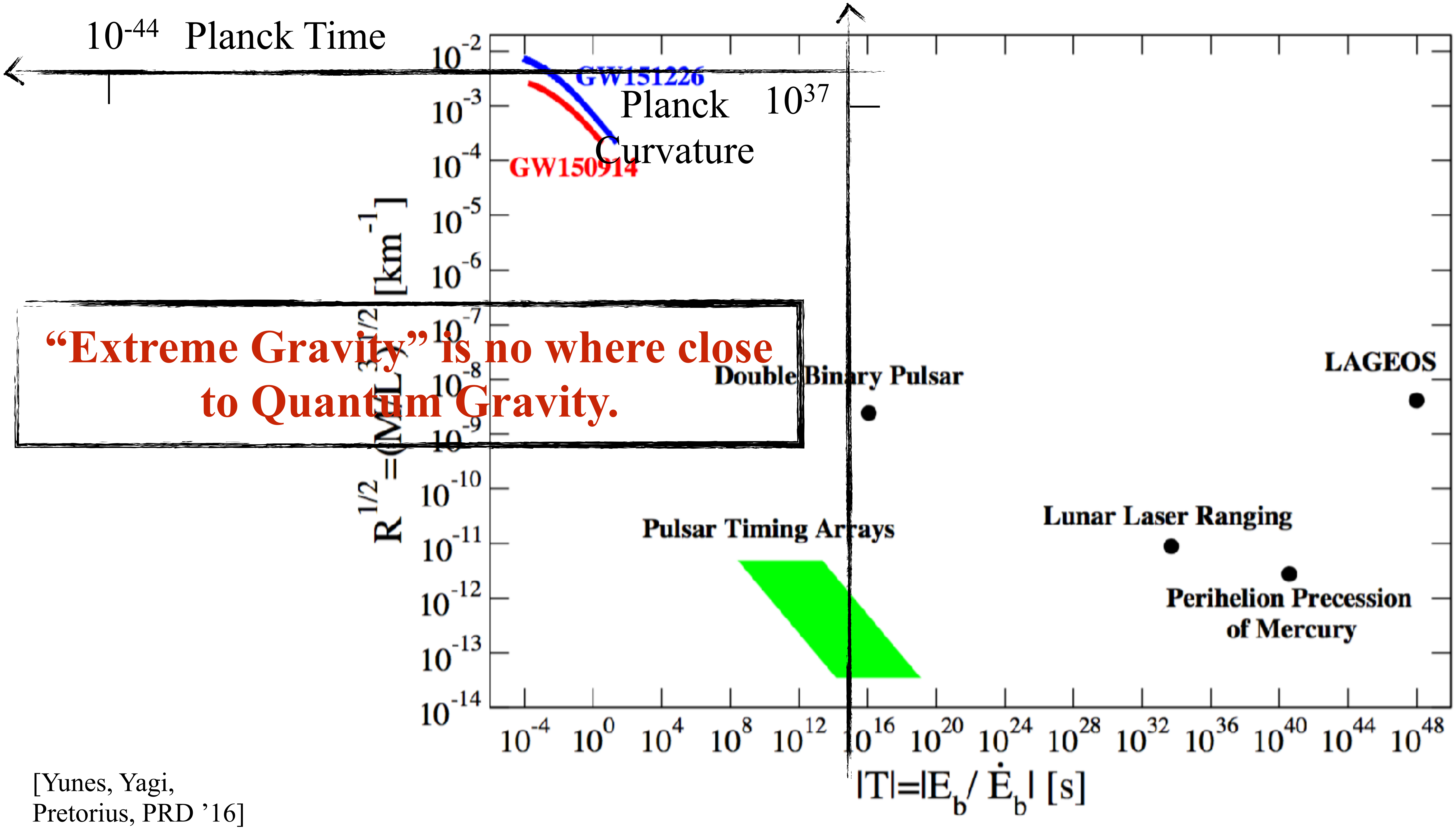


Field
Strength

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]

Extreme Gravity versus Strong Gravity



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

[Yunes, Yagi, Pretorius, PRD '16]

What is interesting to constrain?

Agnostic Approach

Effective Field Theory

Broken Symmetries

Generic Anomalies

Advantages:

Generic properties of gravity

PT Analytic calculations are “doable”

Disadvantages:

Hard to put it on a computer

Regime of validity of EFT

Theorists need to speak up and argue for 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 $K^2 \sim |\beta\, T_{\rm mat}| \sim |-\beta\,\rho|$

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

$\varphi'(0)=0$ & 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 $\varphi = \varphi_\infty + \alpha_{\rm sc}\dfrac{m}{r}$

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

(Shapiro time-delay)

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

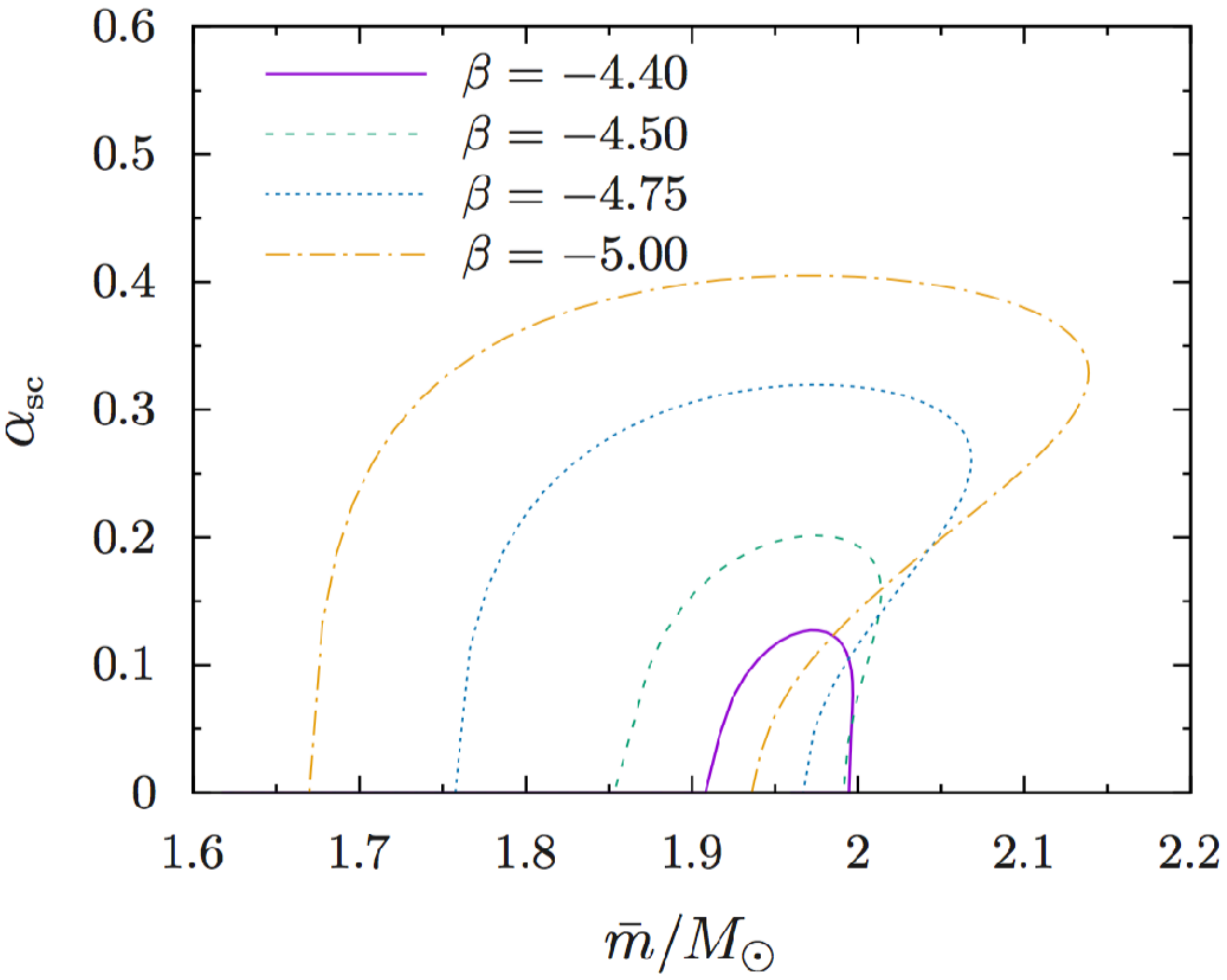
Inducing Strong Field Corrections

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]

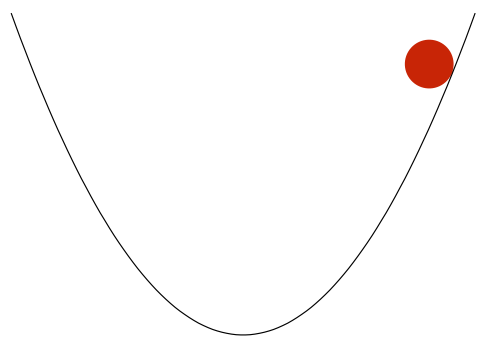
Cosmological Evolution and a Catch-22

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

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

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

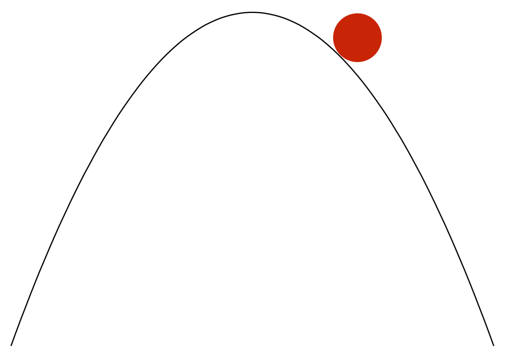
<u>Option 1</u>: $\beta > 0 \longrightarrow V_\varphi > 0$



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

[Damour & Nordvedt '93]

<u>Option 2</u>: $\beta < 0 \longrightarrow V_\varphi < 0$



$\longrightarrow |\varphi_{\rm today}| \gg 1$ 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

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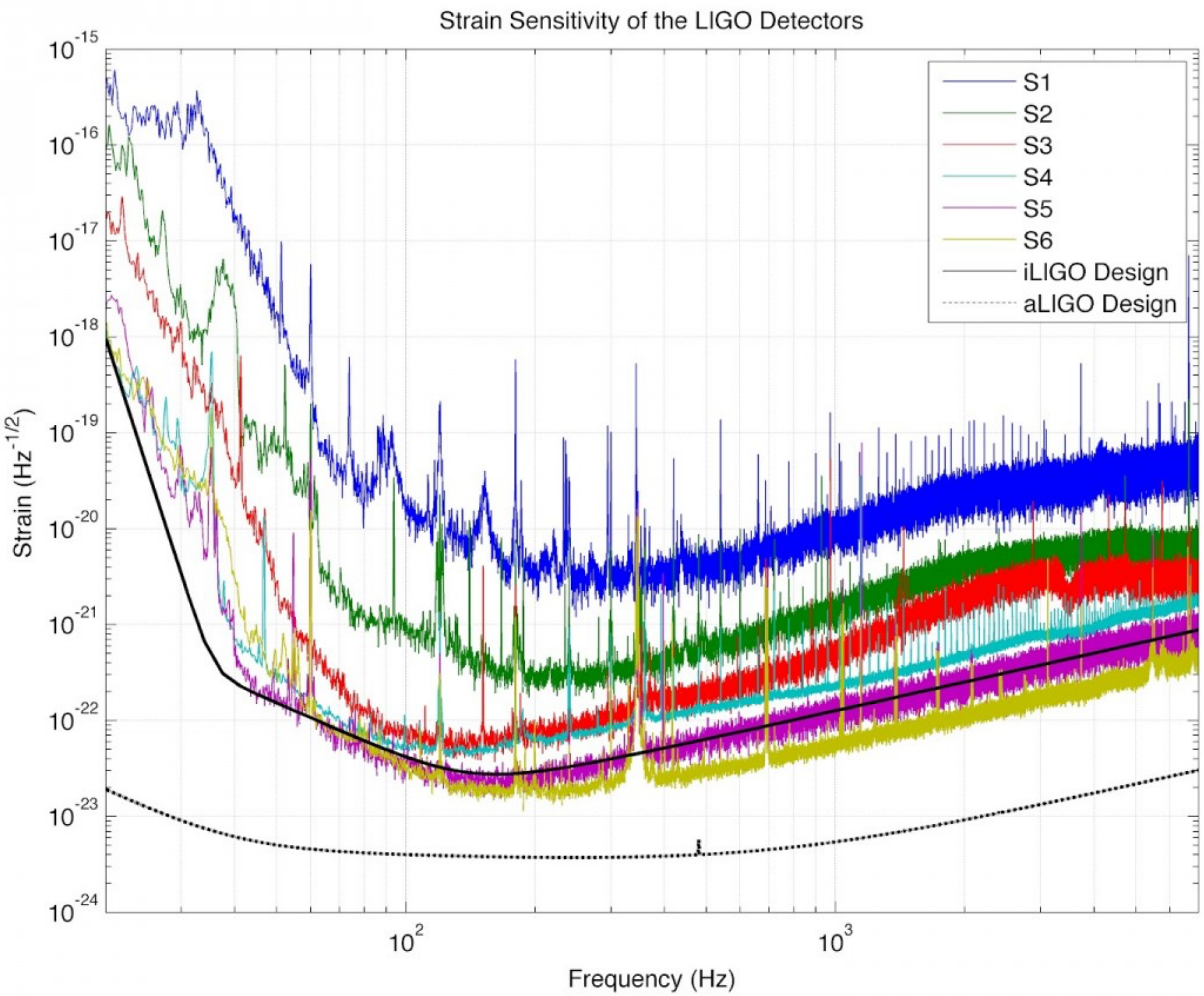
RHUDAUR
CARDOLAN
SOUTH DOWNS
FORLINDON
HARLINDON
ERIADOR
MINHIRIATH
ENEDWAITH
DUNLAND
MIRKWOOD
RHOVANION
IRON HILLS
RHÛN
The SEA of RHÛN
ROHAN
ERED NIMRAIS
GONDOR
MORDOR
BELEGAER
(the Great Sea)

How do we extract signals from the noise?

Modellin

Data Analysis



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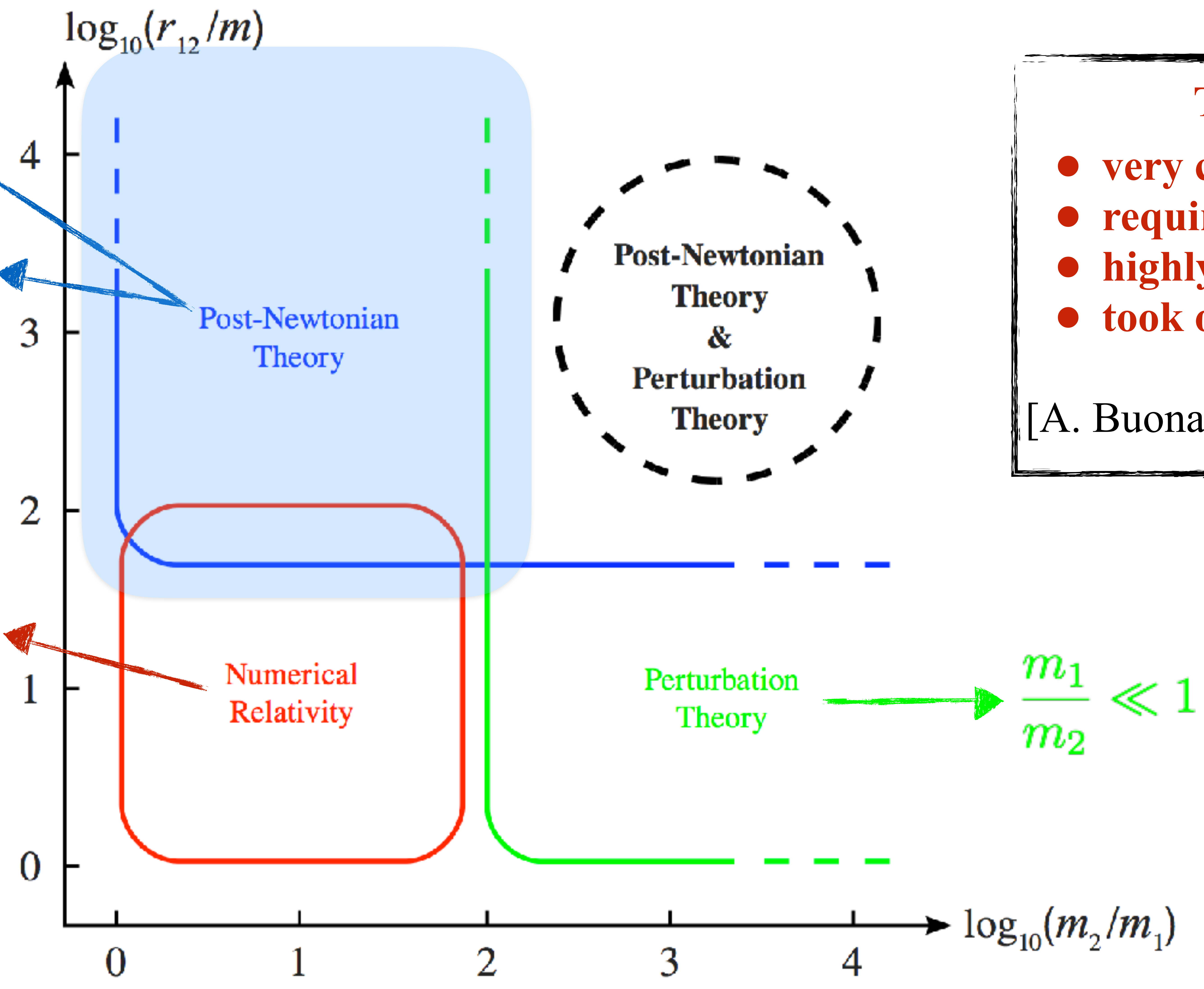
How do we build GW models?

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

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



The GW models are

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

[A. Buonanno's talk]

[Blanchet, LRR]


Generation
Propagation

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 $E_g = p_g \to \omega = k$

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

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

Blanchet's Living Reviews

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

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

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]

Propagation Effect Enhancement Conjecture

Generic Argument

Correction in GW prop. proportional to D_L $\quad \delta\Psi_{\rm prop} =$

Correction in GW gen. proportional to total mass $\quad \delta\Psi_{\rm gen} =$

Ratio is then $$\frac{\delta\Psi_{\rm prop}}{\delta\Psi_{\rm gen}} = \left(\frac{D_L}{\mathcal{M}}\right)^a (\pi\mathcal{M}f)^{(b-d)/3}$$

Case Study: Massive Graviton

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

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

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

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

Parameterized post-Einsteinian Framework

I. Parametrically deform the Hamiltonian.

II. Parametrically deform the RR force.

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

III. Deform waveform generation.

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

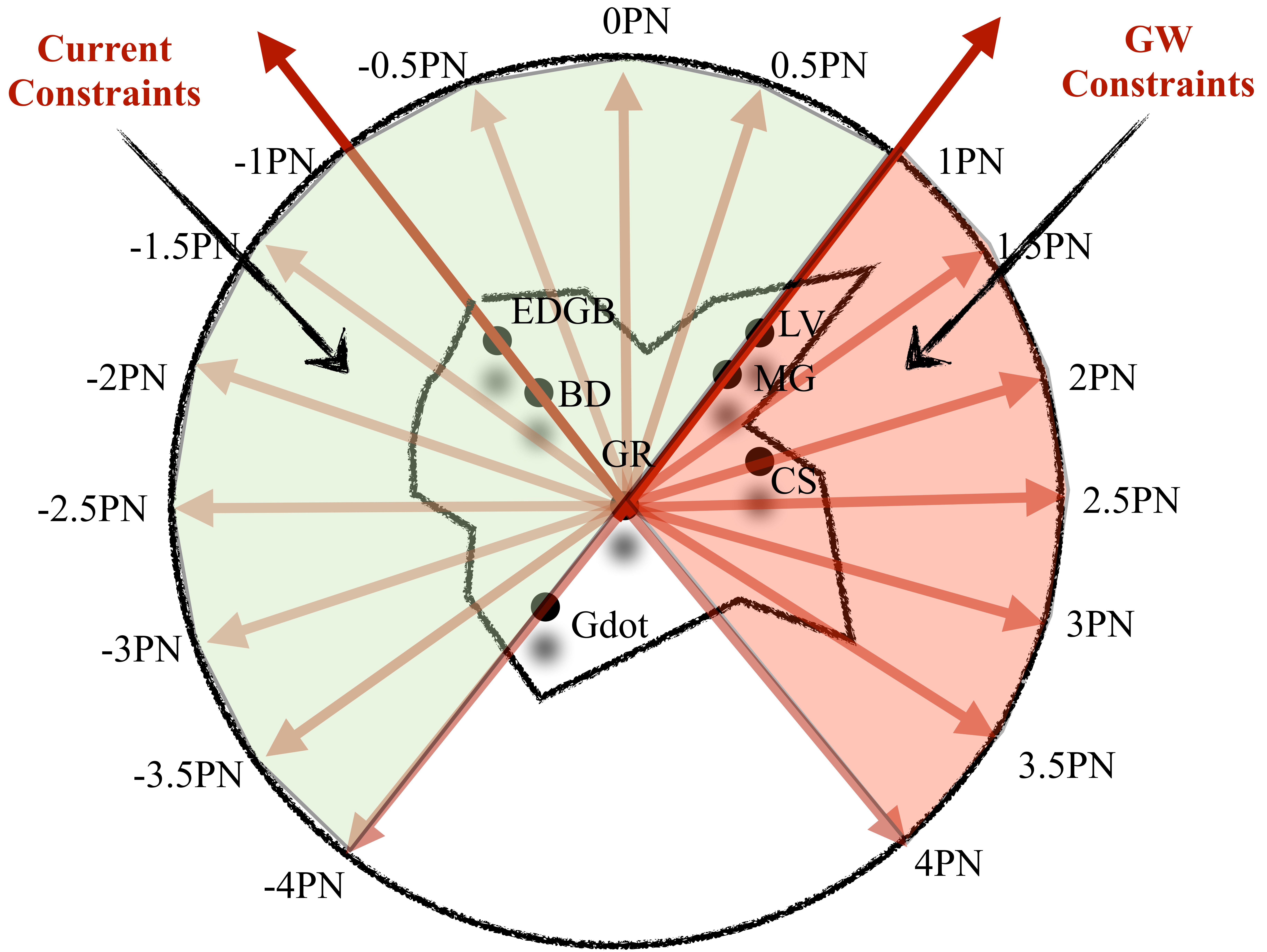
IV. Parametrically deform g propagation.

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

Result: To leading PN order and leading GR deformation

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

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


Current Constraints
GW Constraints
0PN
-0.5PN
0.5PN
-1PN
1PN
-1.5PN
1.5PN
-2PN
2PN
-2.5PN
2.5PN
-3PN
3PN
-3.5PN
3.5PN
-4PN
4PN
EDGB
BD
LV
MG
GR
CS
Gdot

Test Principles, not 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	$\beta_{\AE}^{(-1)}$ [113] $\beta_{\AE}^{(0)}$ [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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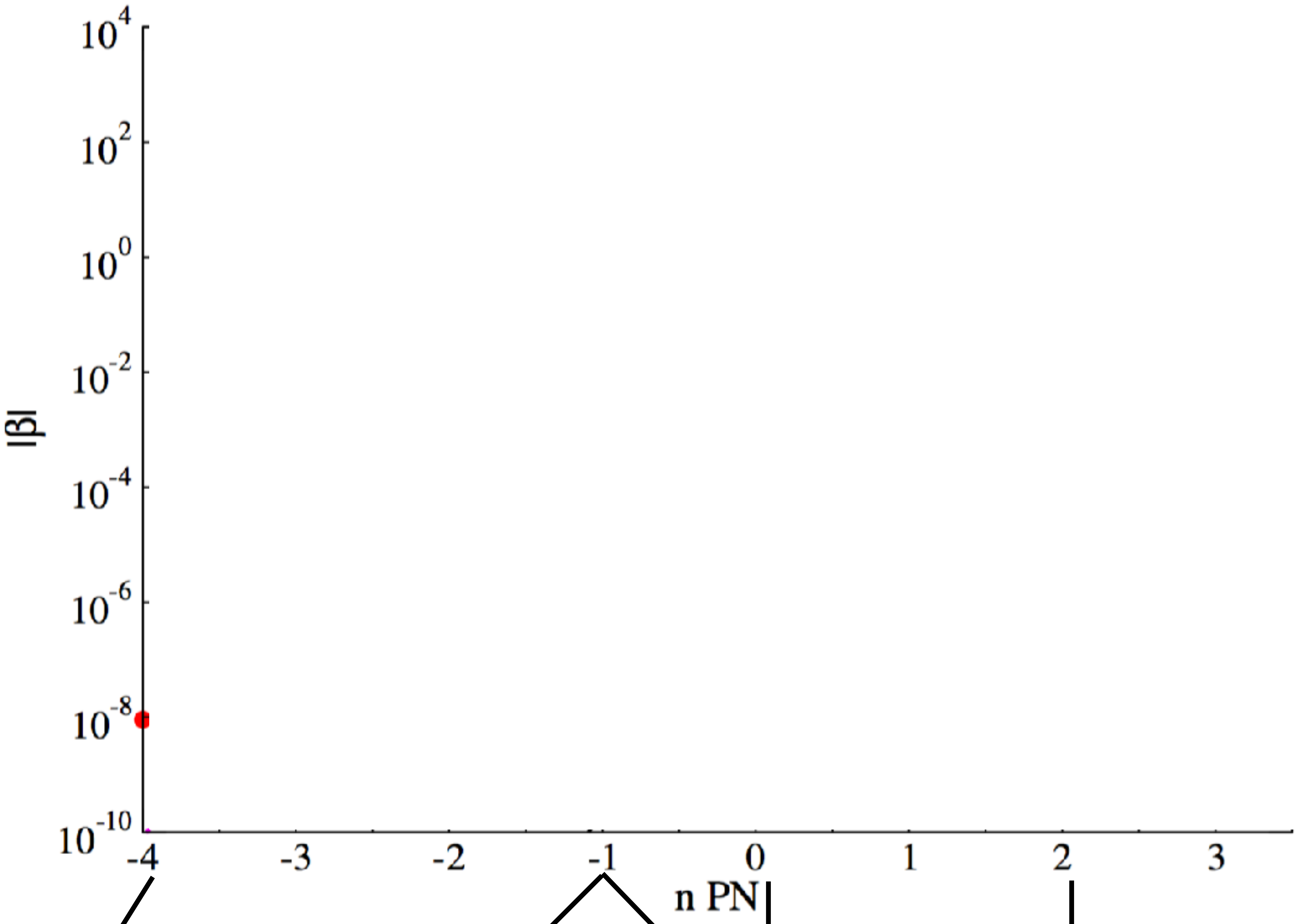
BELEGAER
(the Great Sea)

GW Constraints on Modified Generation



Anomalous Acceleration

Scalar Dipole Radiation

Lorentz Violation

Parity Violation

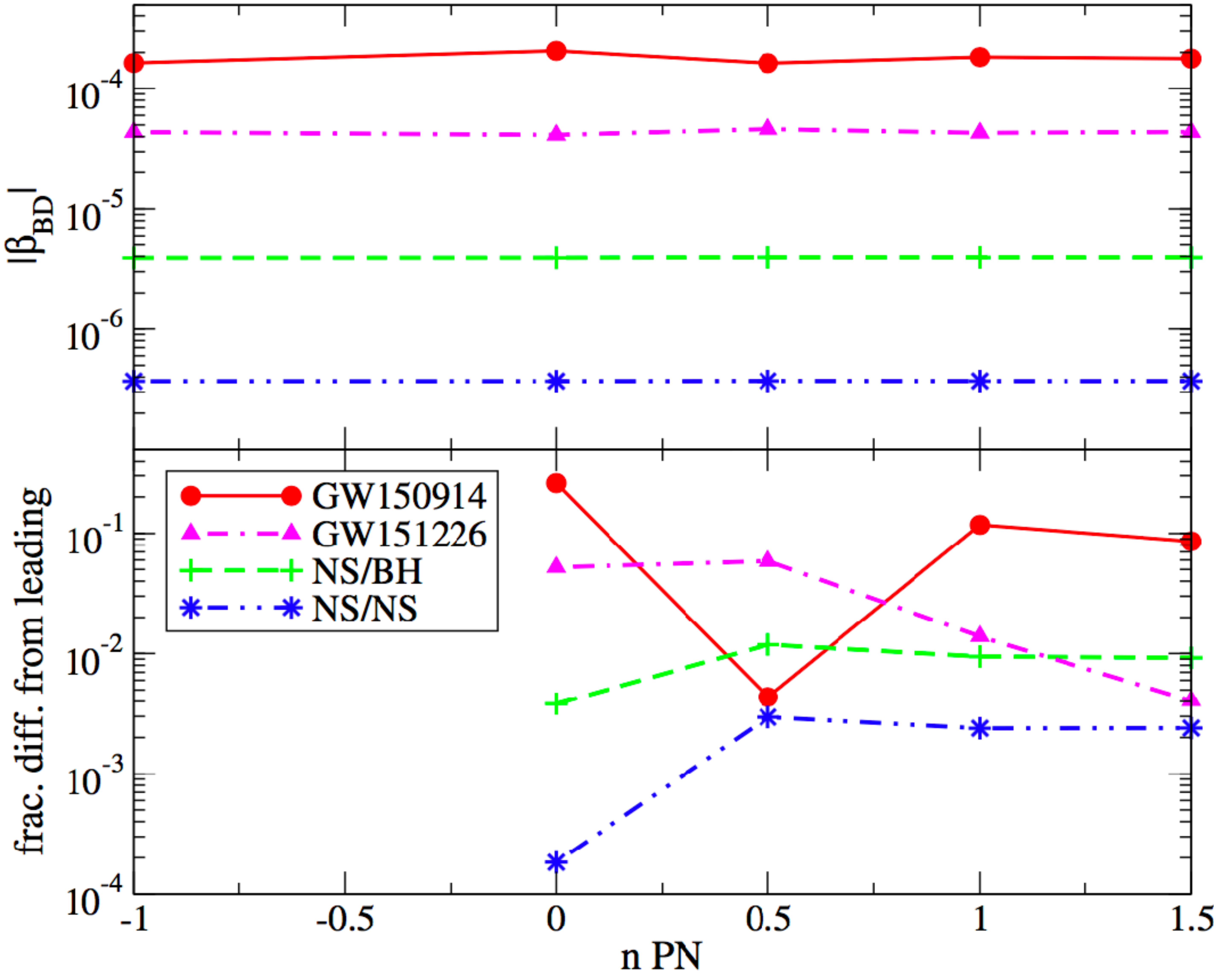
[Yunes, Yagi, Pretorius, PRD '16]

But what about the higher PN order terms?

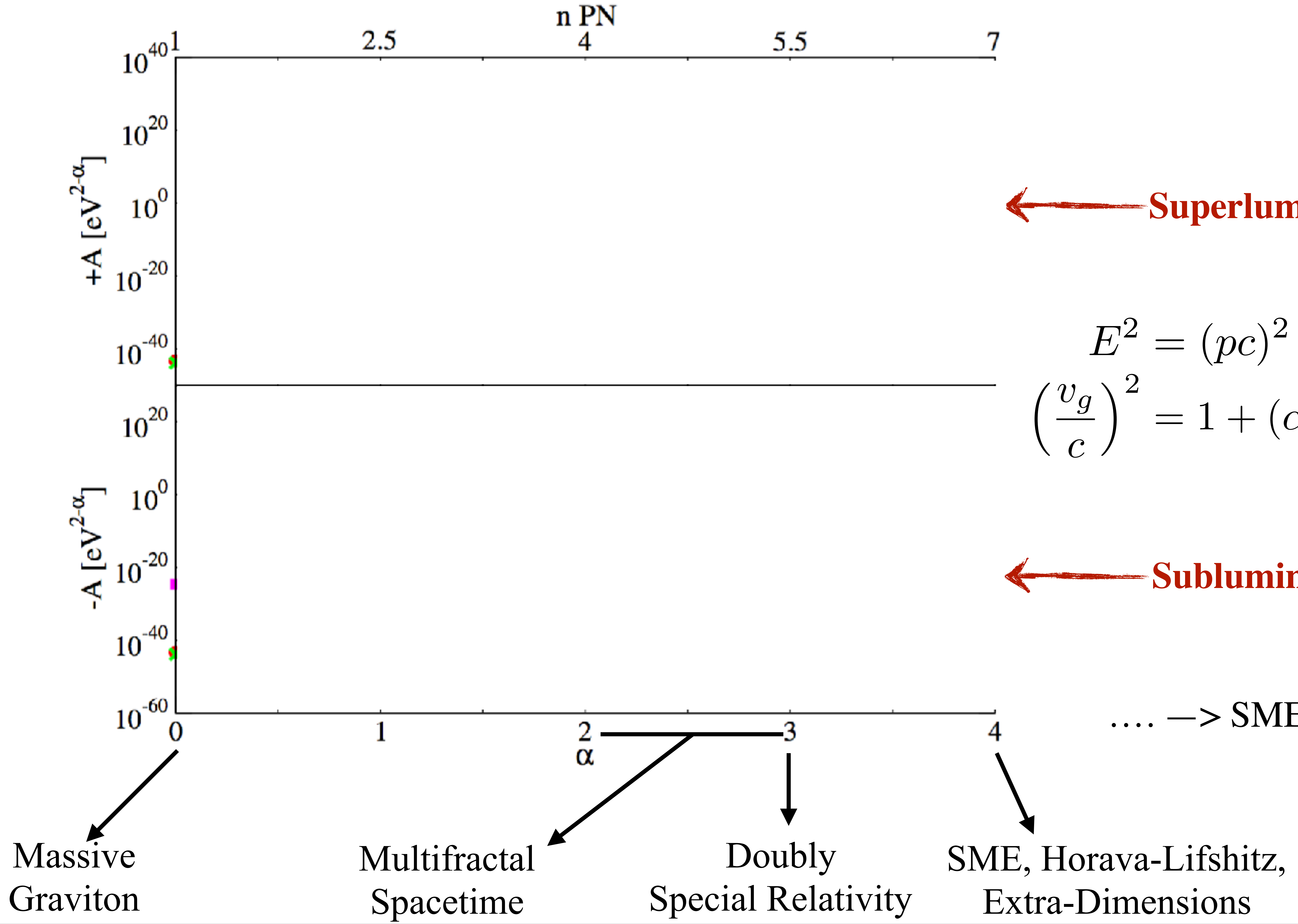
Case Study: Scalar-Tensor (Brans Dicke) theory

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

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



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]

Theory Implications of GW Observations

Theoretical Mechanism	GR Pillar	PN	$\lvert\beta\rvert$		Example Theory Constraints			
			GW150914	GW151226	Repr. Parameters	GW150914	GW151226	Current Bounds
Scalar Field Activation	SEP	-1	1.6×10^{-4}	4.4×10^{-5}	$\sqrt{\lvert\alpha_{\rm EdGB}\rvert}$ [km] $\lvert\dot{\phi}\rvert$ [1/sec]	— —	— —	10^{7} [56], 2 [57–59] 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_-) $(\beta_{\rm KG}, \lambda_{\rm KG})$	$(0.9, 2.1)$ $(0.42, -)$	$(0.8, 1.1)$ $(0.40, -)$	$(0.03, 0.003)$ [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}	$\lvert\dot{G}\rvert$ [10^{-12}/yr]	5.4×10^{18}	1.7×10^{17}	0.1–1 [70–74]

[Yunes, Yagi, Pretorius, PRD '16]

The Problem of Degeneracies

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

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

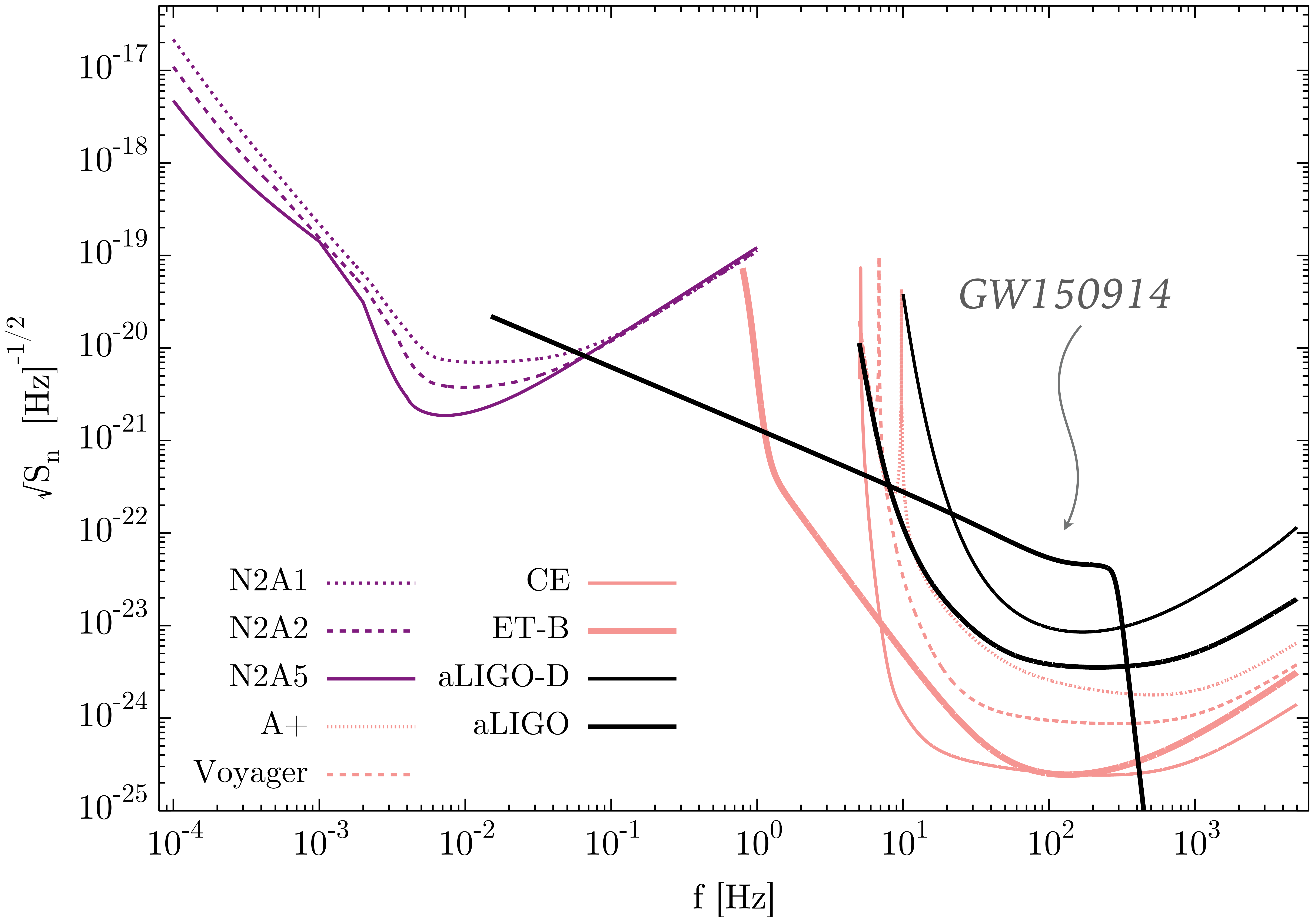
There are values of the spin for which the effect vanishes!

Actual GW150914 Constraints on GR Pillar Violations in Wave Generation

Theoretical Mechanism	GR Pillar	PN	$\lvert\beta\rvert$ GW150914	Example Theory Constraints: Repr. Parameters	GW150914	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]

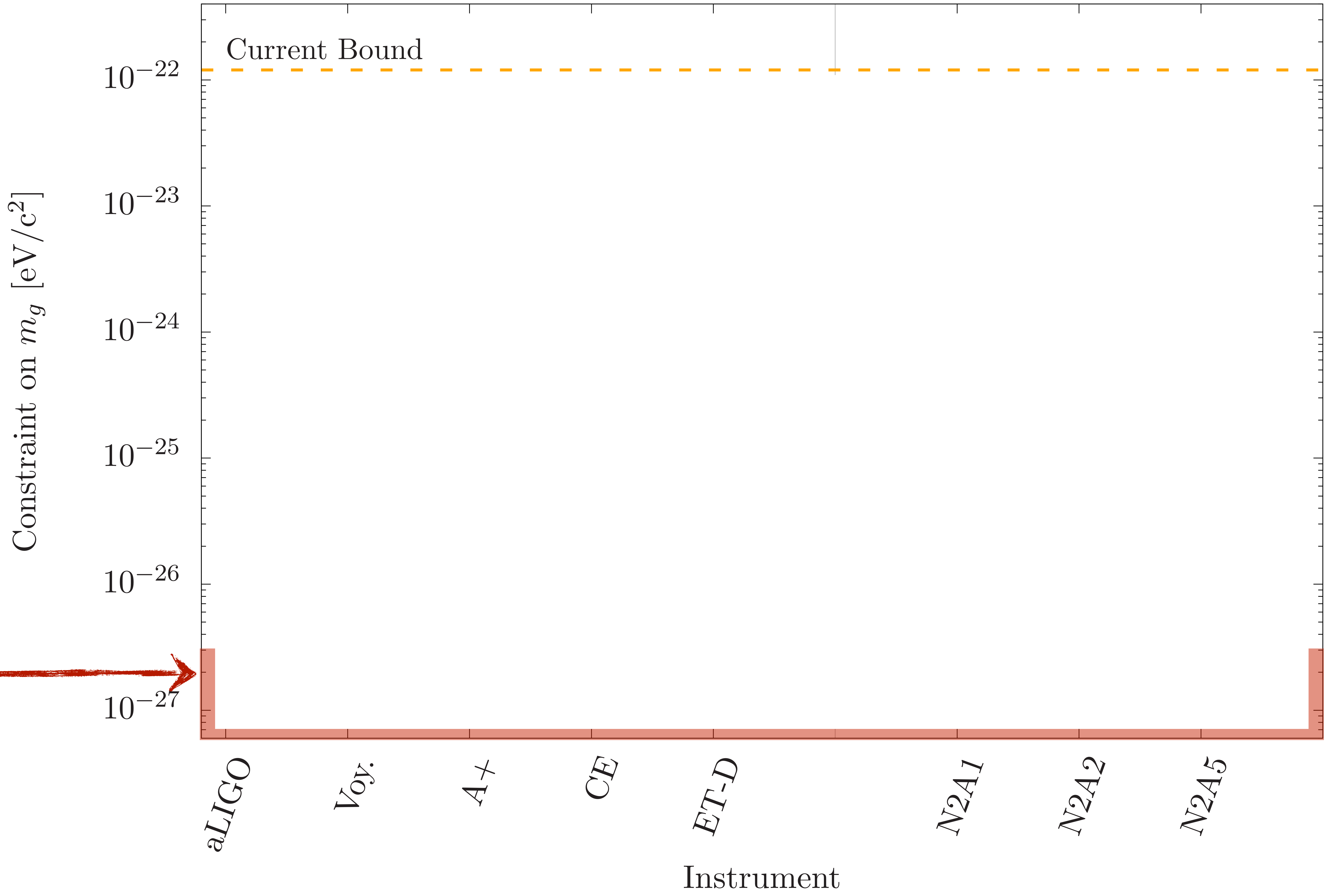
[Yunes, Yagi, Pretorius, '16]

Spectral Noises of Future Instruments



Future Constraints with Single Instruments

Case Study:
Massive Graviton



10^5 times better than current bounds!!

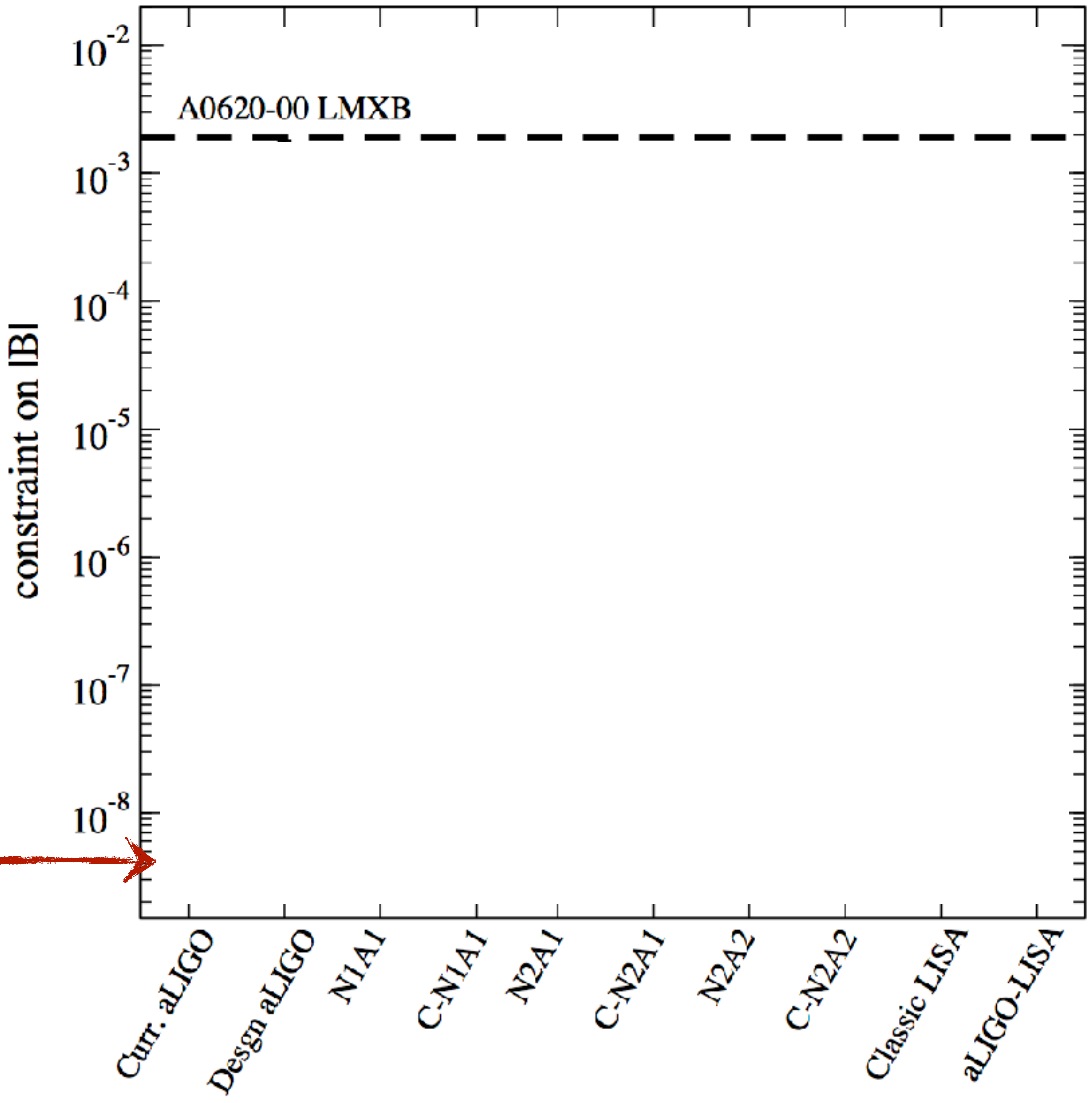
$$\beta = \pi^2 \frac{D \, \mathcal{M}_z}{1+z} m_g^2$$

[Chamberlain & Yunes, to appear soon]

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]

Conclusions

Gravitational Wave Tests Are Special Probes of Physics
(extreme gravity, clean, localized, constraint maps)

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