強重力場からの重力波による様々な重力理論の検証

Probing Various Gravitational Theories with Strong-field Gravitational-wave Observations

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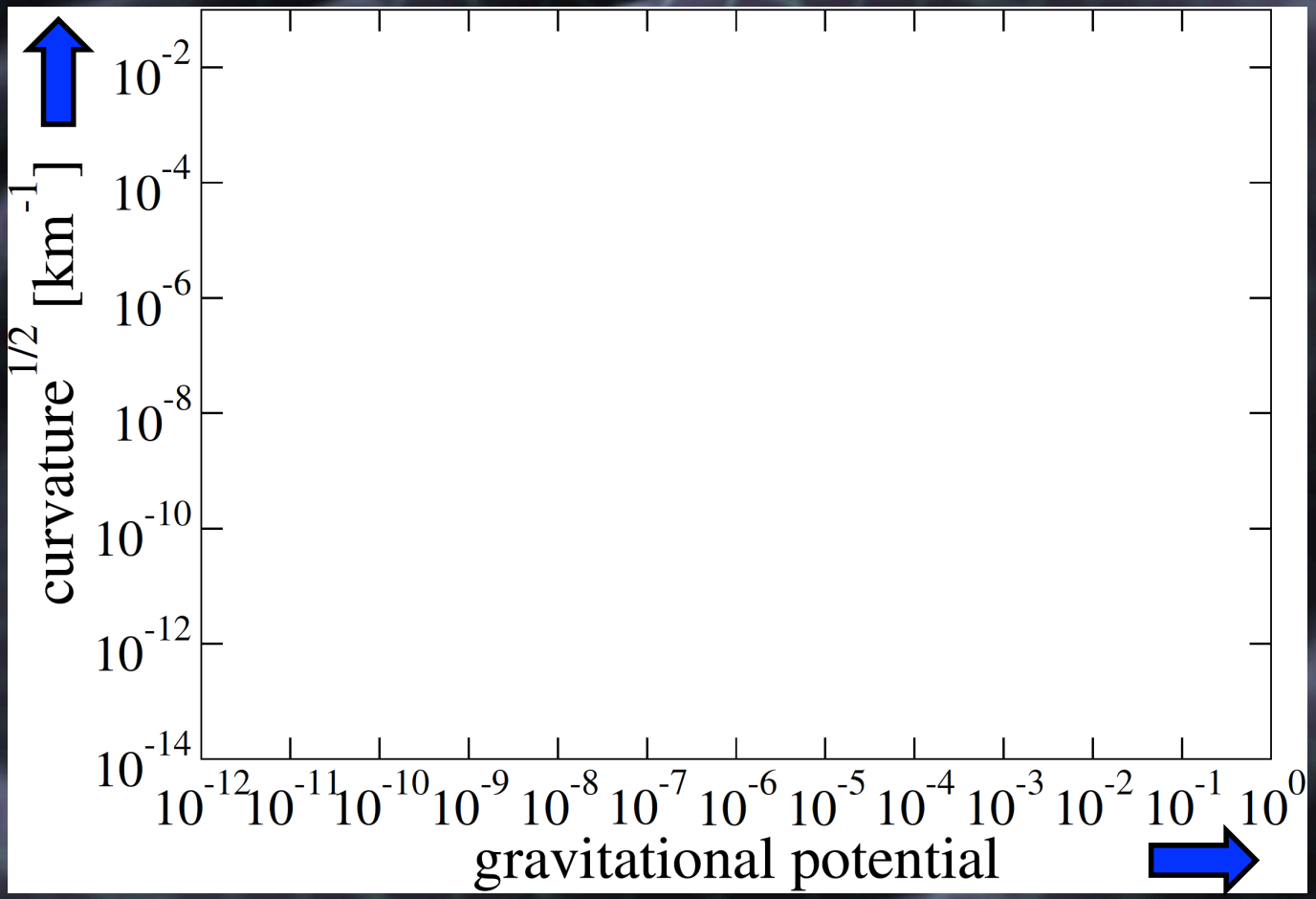
JPS Meeting

Miyazaki U.　Sept. 23rd 2016

N. Yunes (Montana State U.), F. Pretorius (Princeton U.)

arXiv: 1603.08955 (to appear in PRD)

Strong/Dynamical Nature of GW Sources



[Yunes, KY & Pretorius arXiv:1603.08955]

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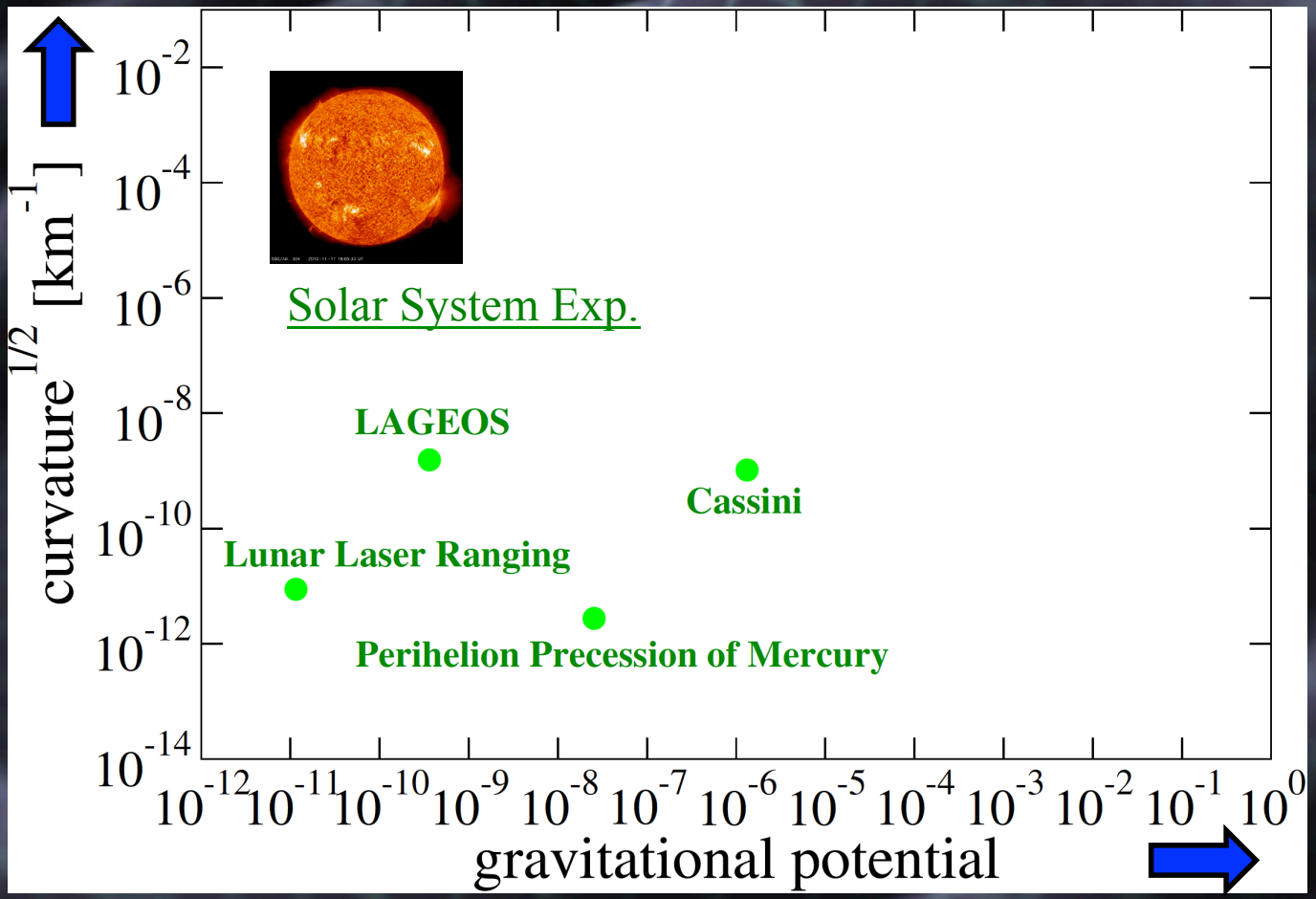

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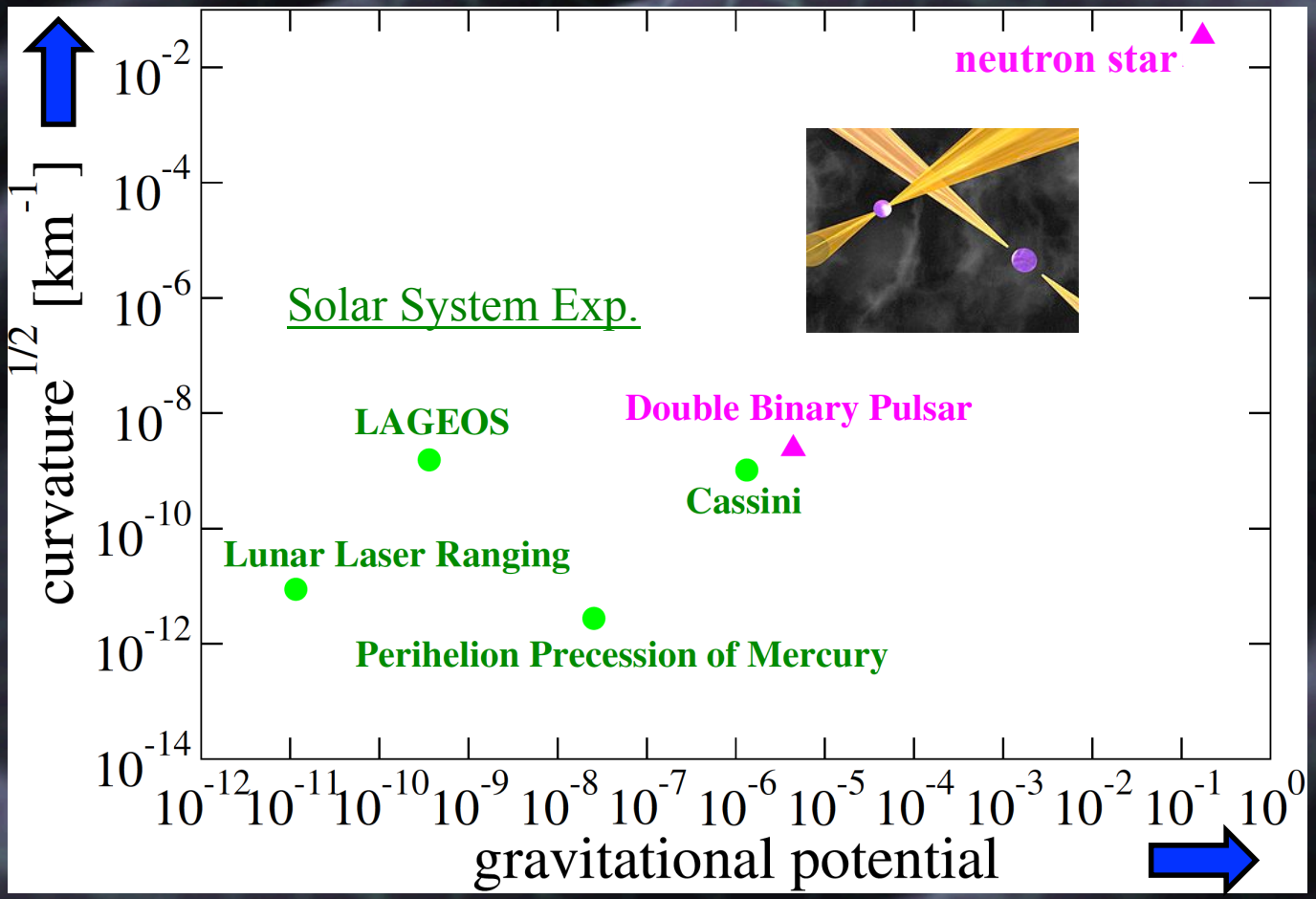

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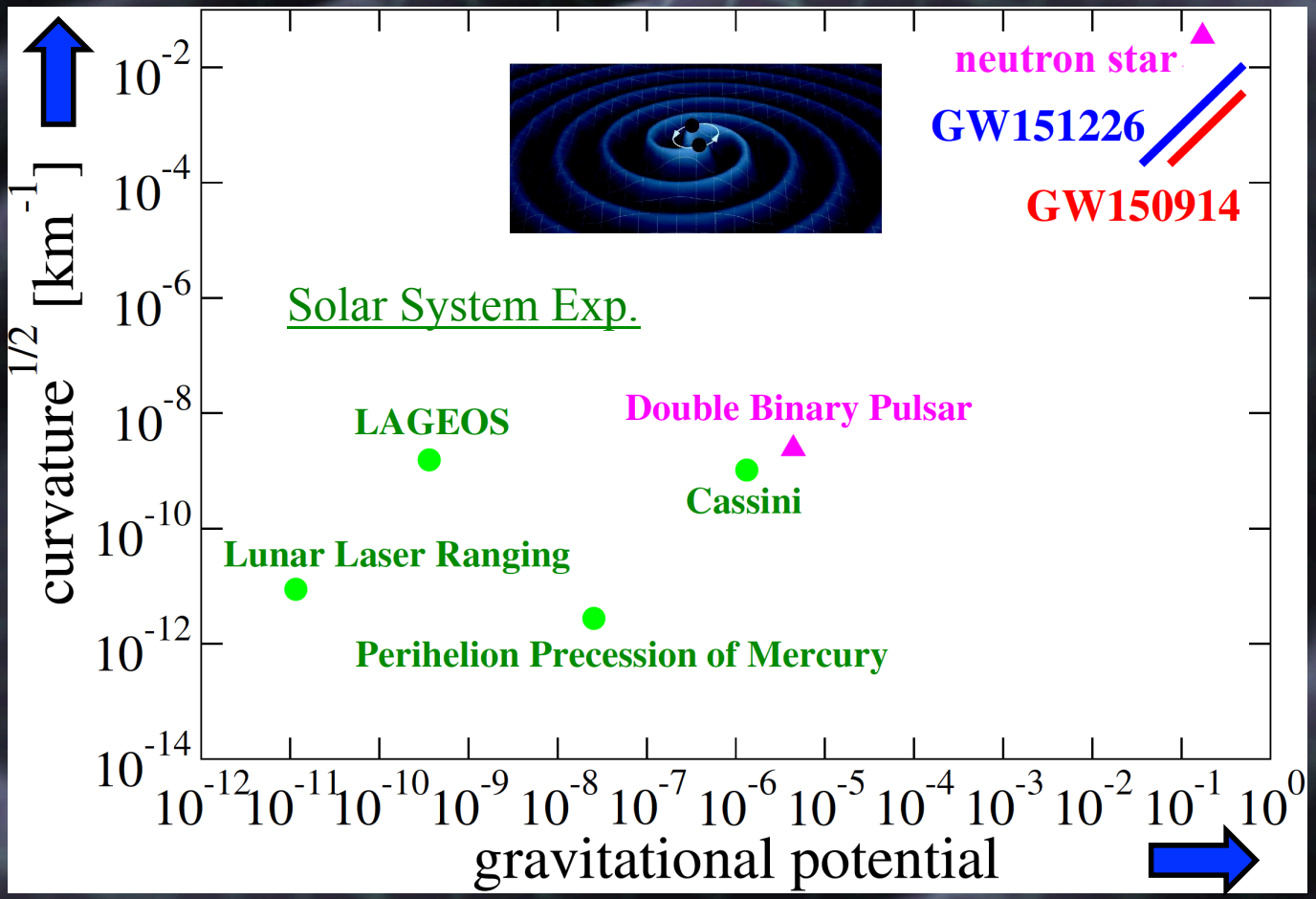

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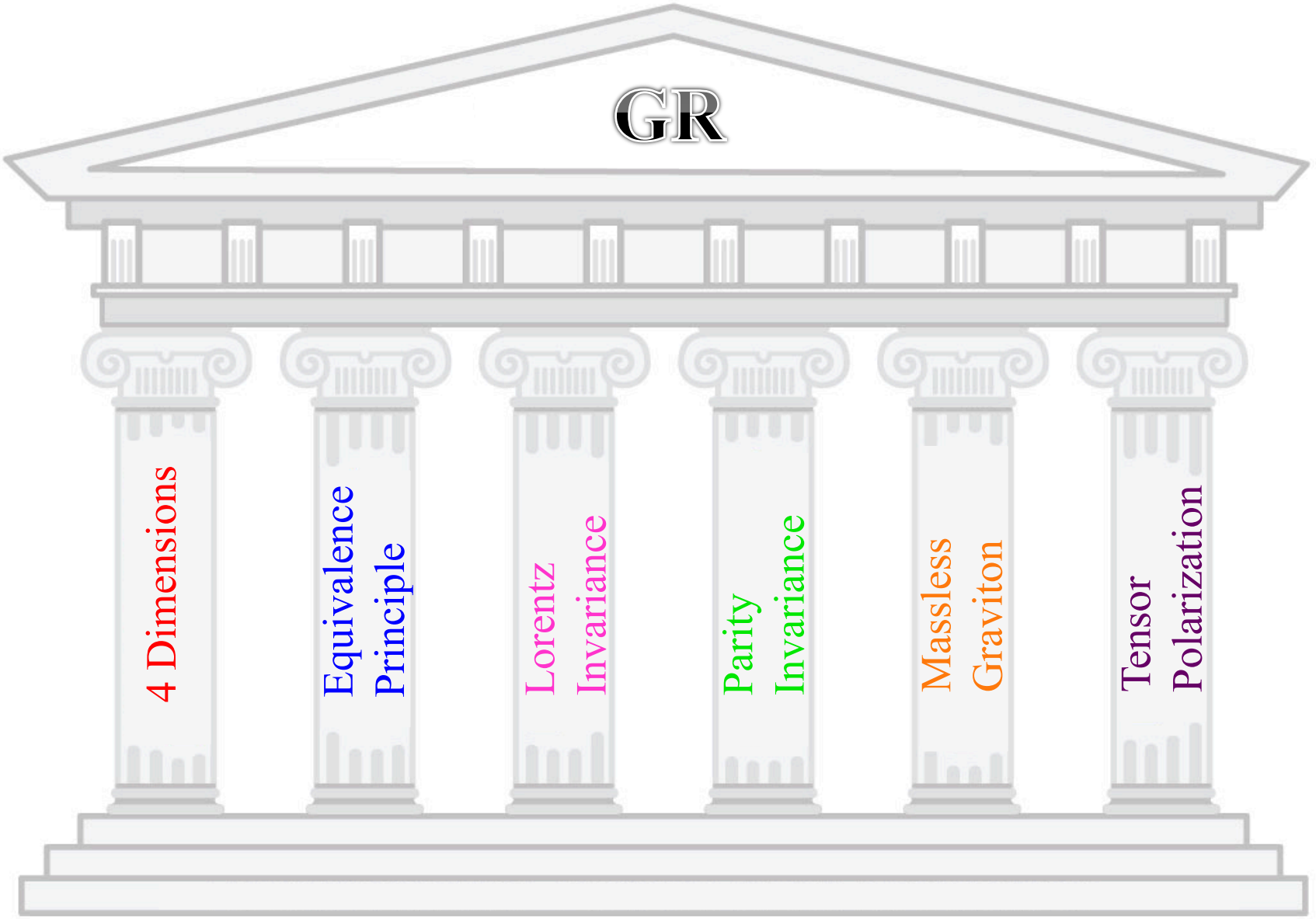
Fundamental Pillars in General Relativity (GR)



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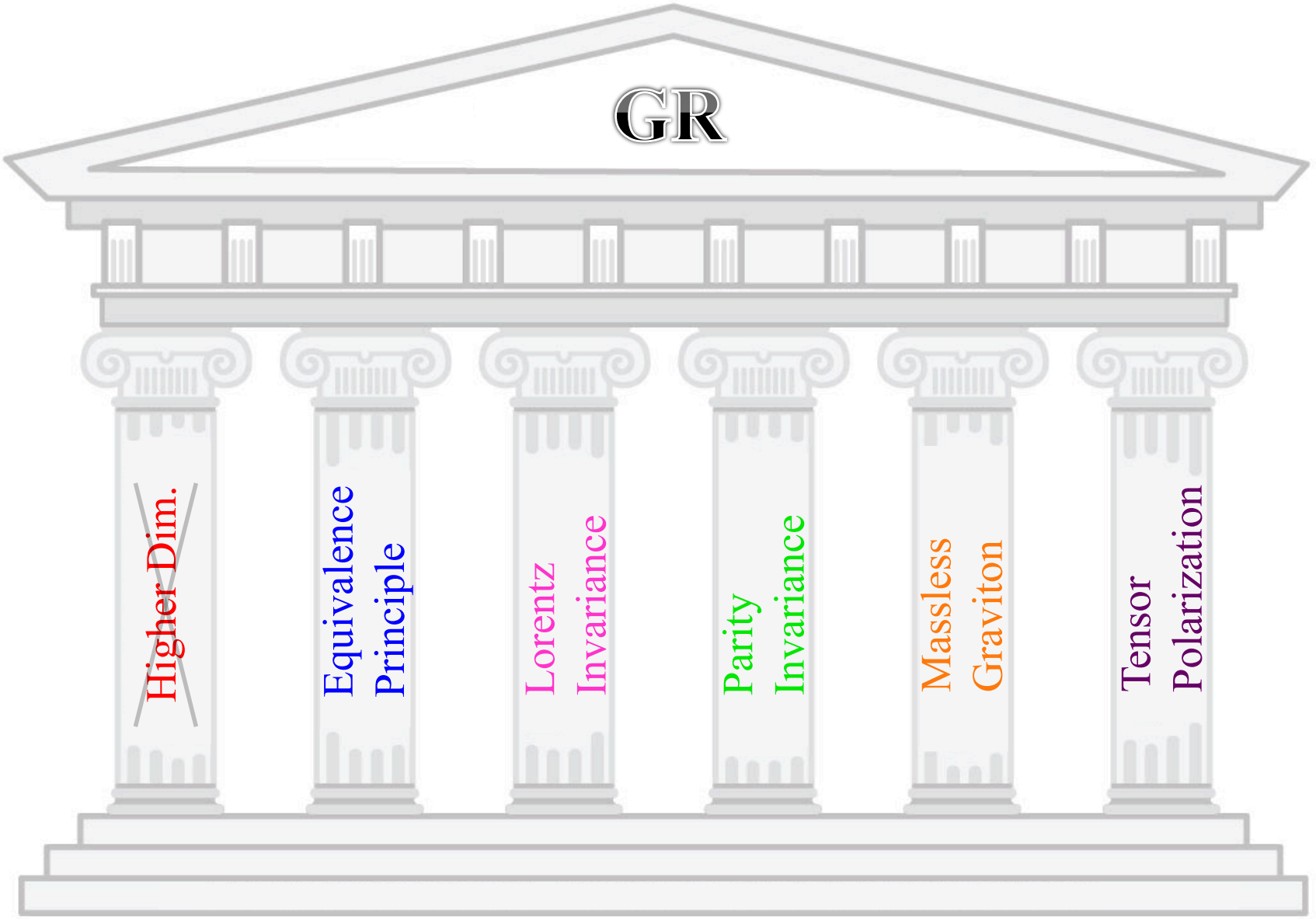

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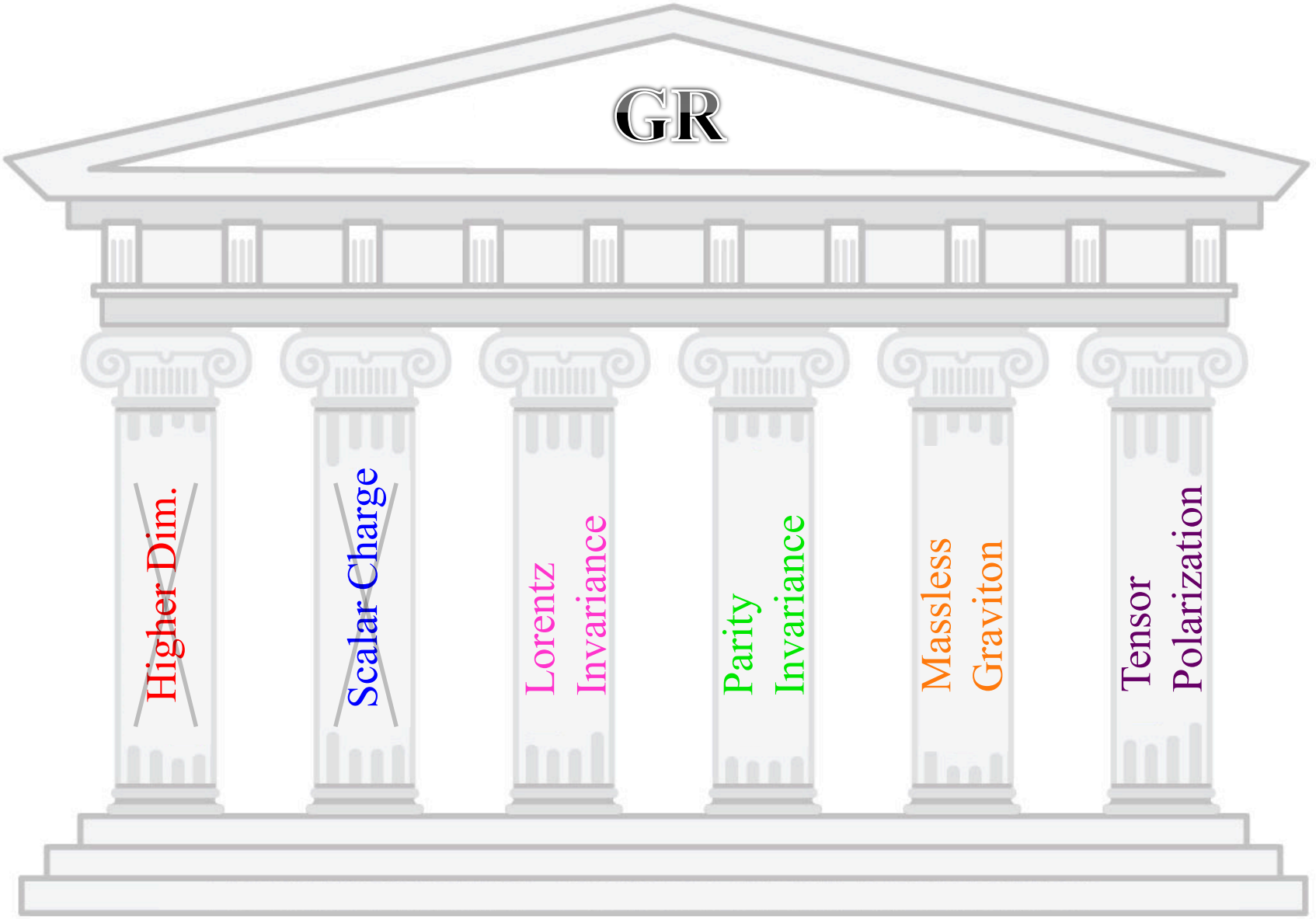

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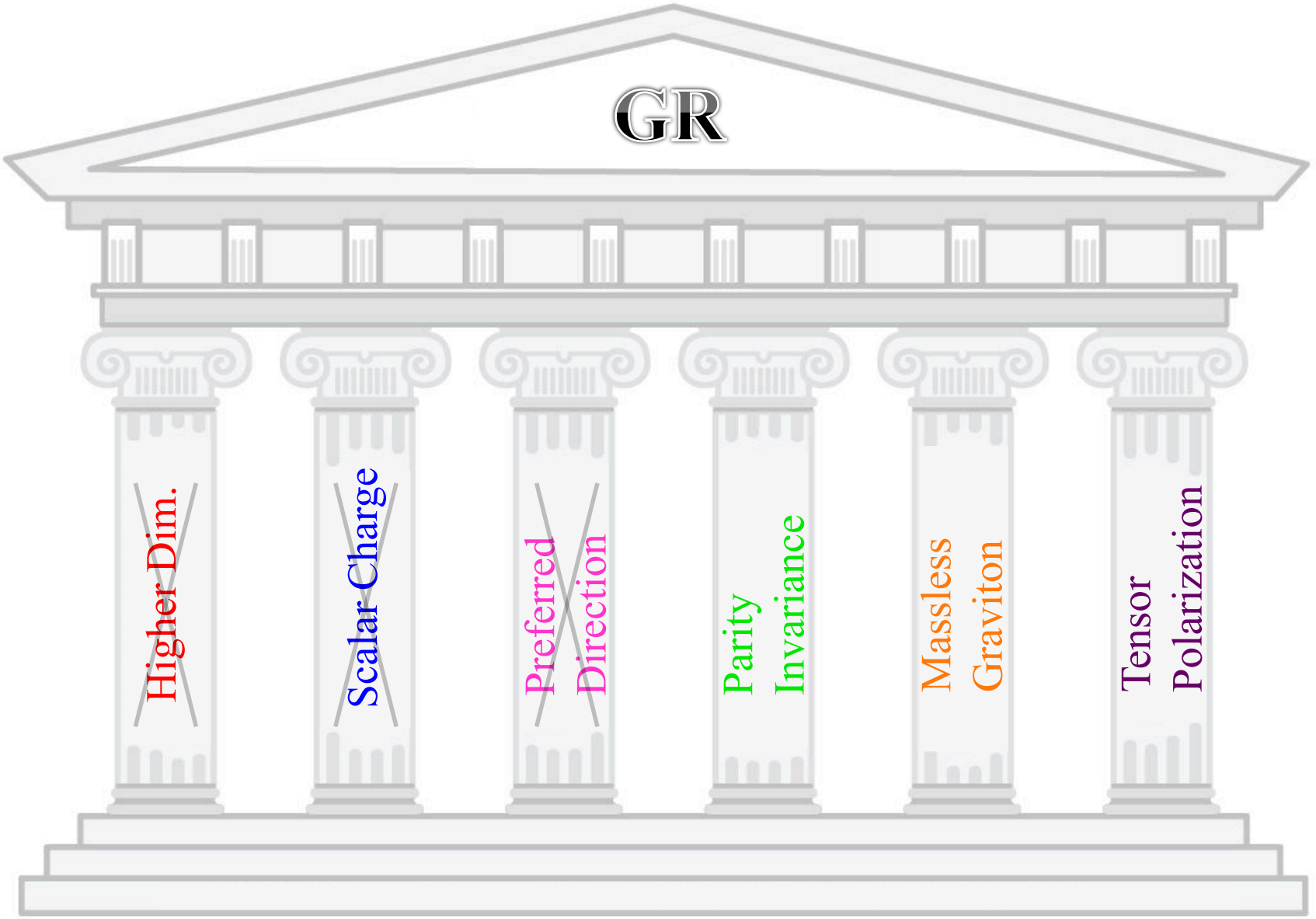

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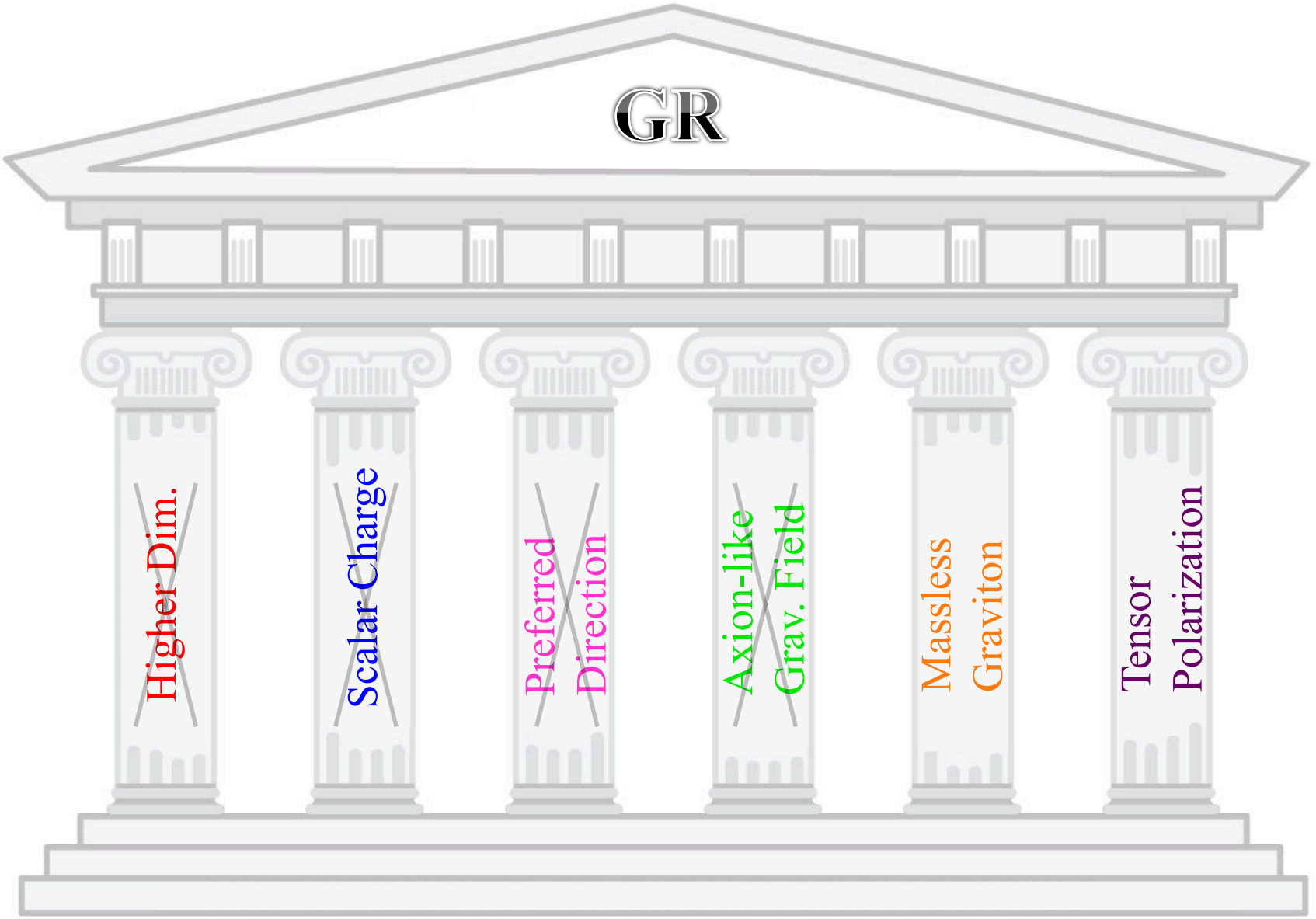

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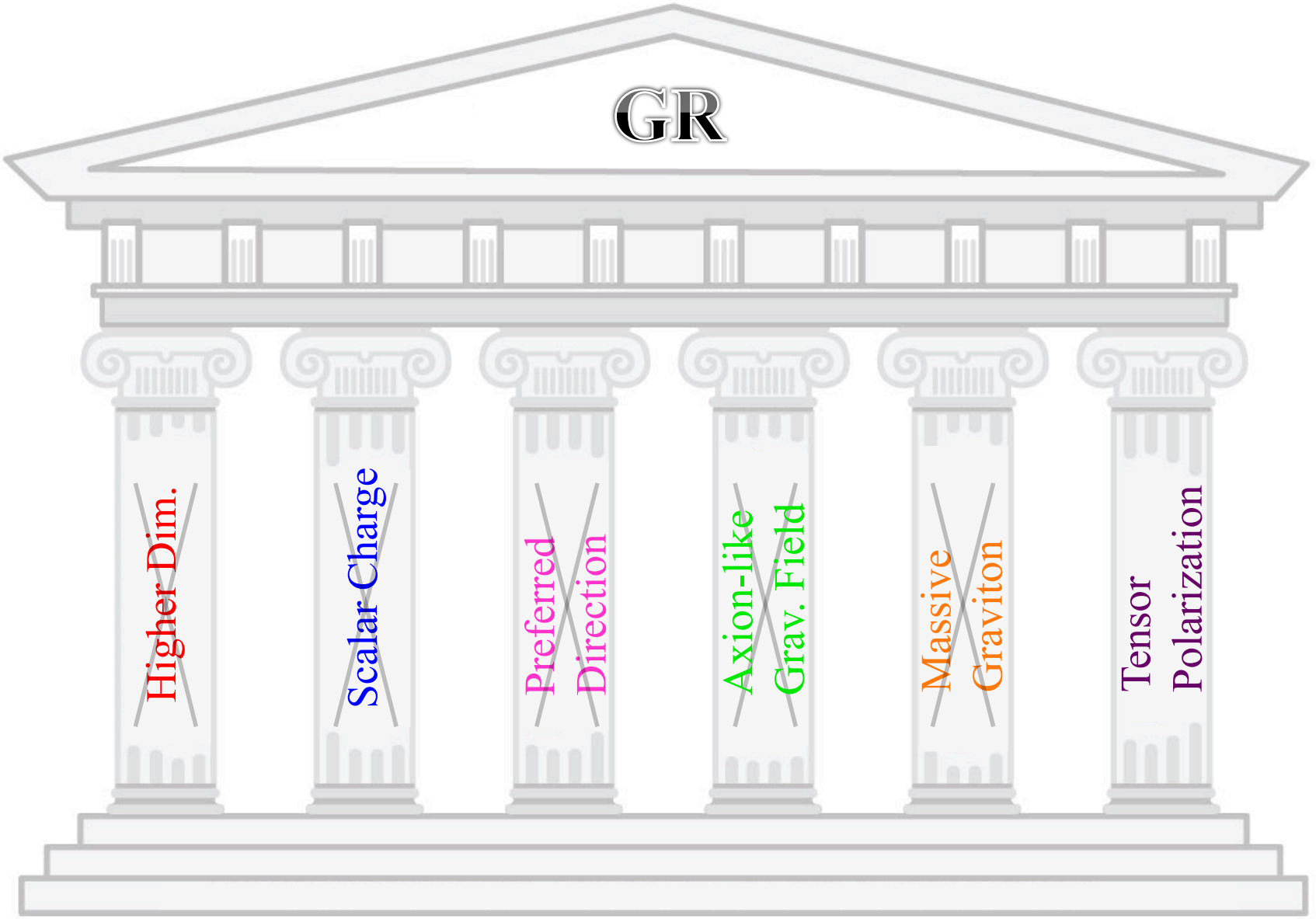

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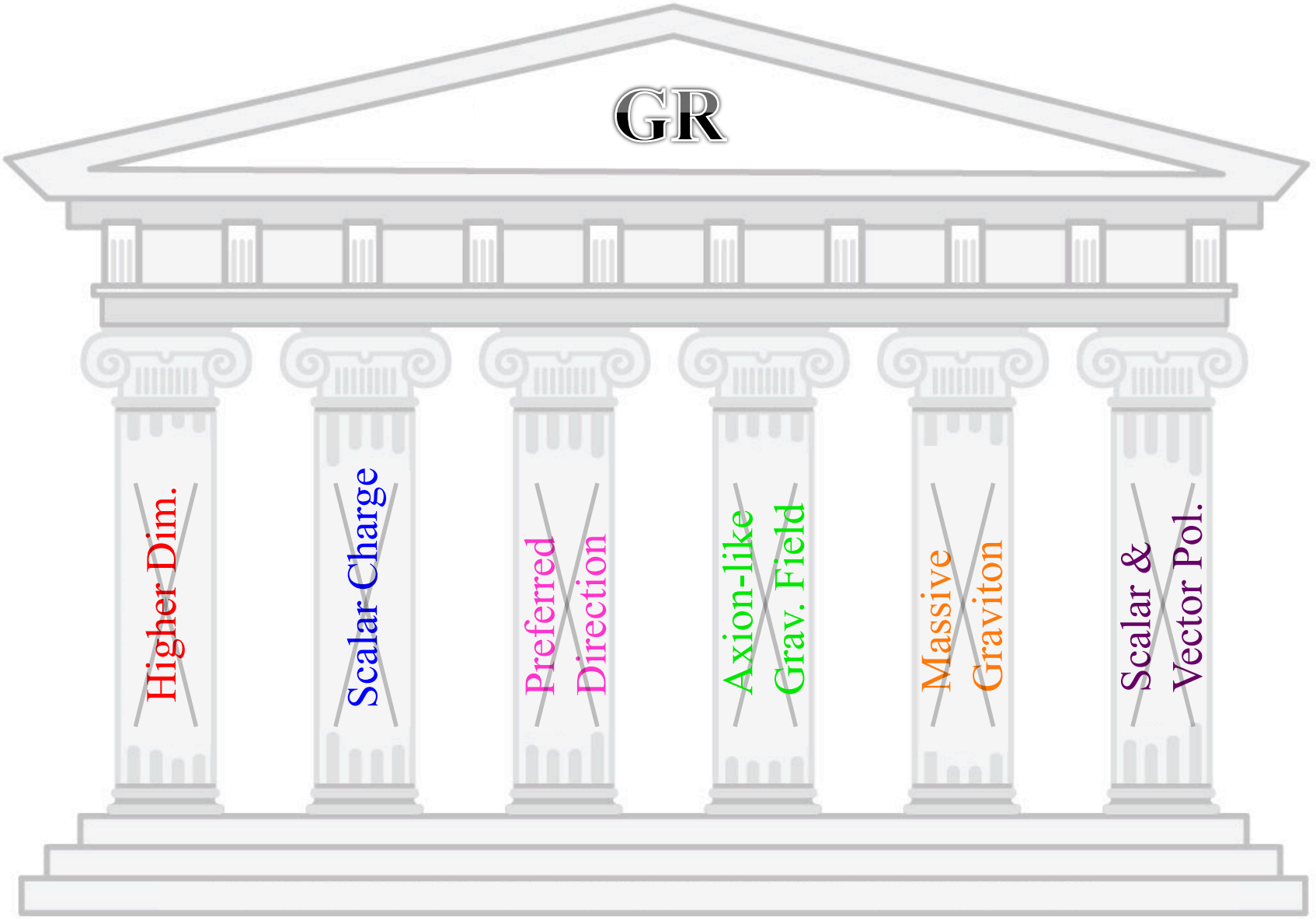


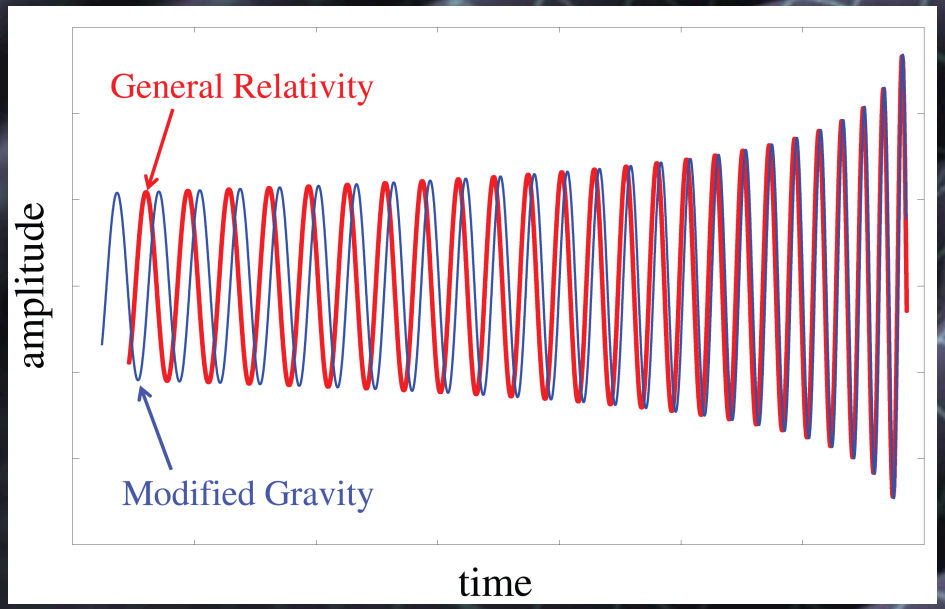
parameterized post-Einsteinian (ppE) Formalism

$c = G = 1$

[Yunes & Pretorius (2009)]

ppE parameter

gravitational waveform phase: $\Psi(f) = \Psi_{\rm GR}(f) + \beta\, v^{2n-5}$



n-th post-Newtonian (PN) correction relative to GR

Time-varying G theories

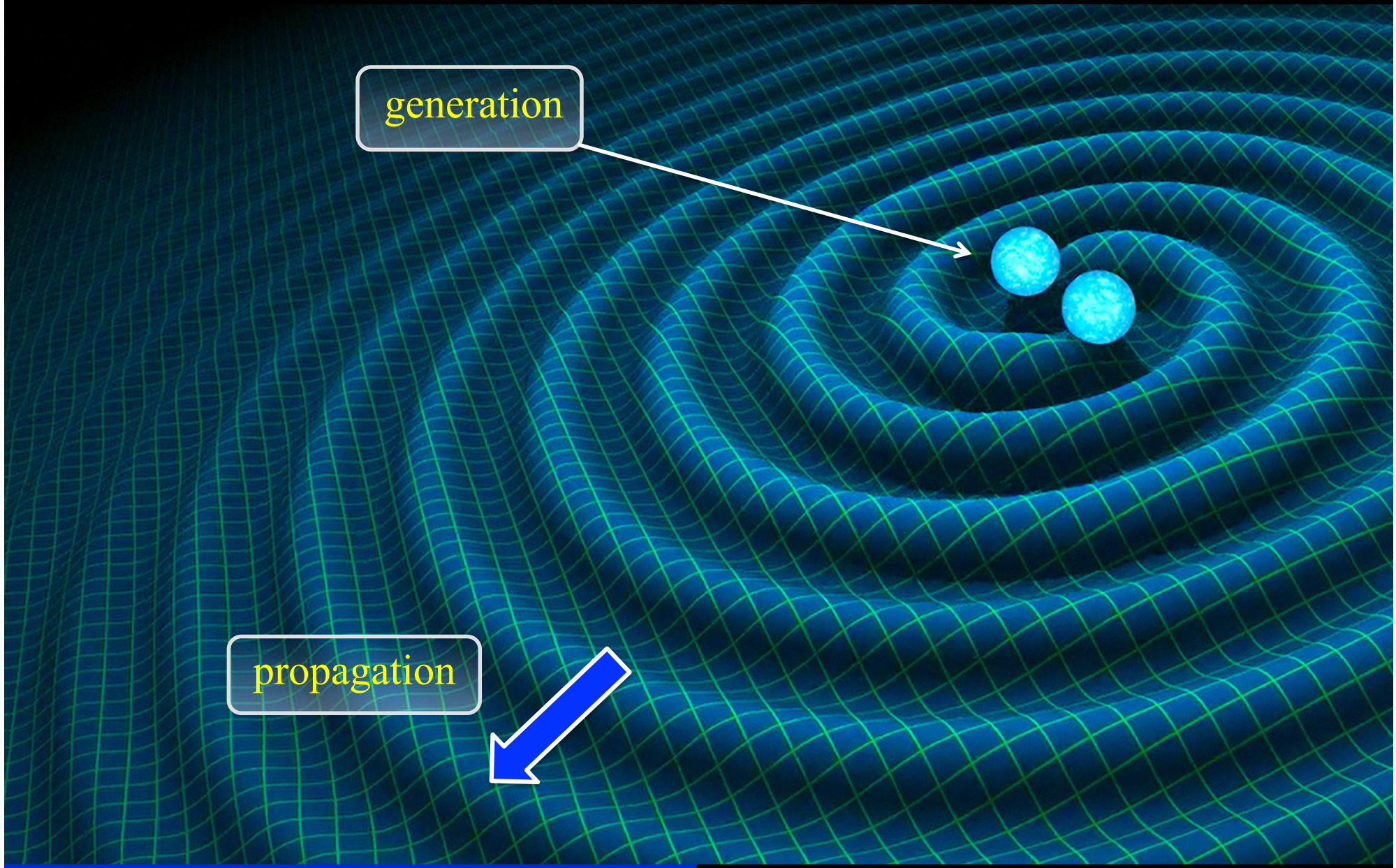
$\beta_{\dot G} \sim \dot G\, M_{\rm tot}$

Fisher Analysis

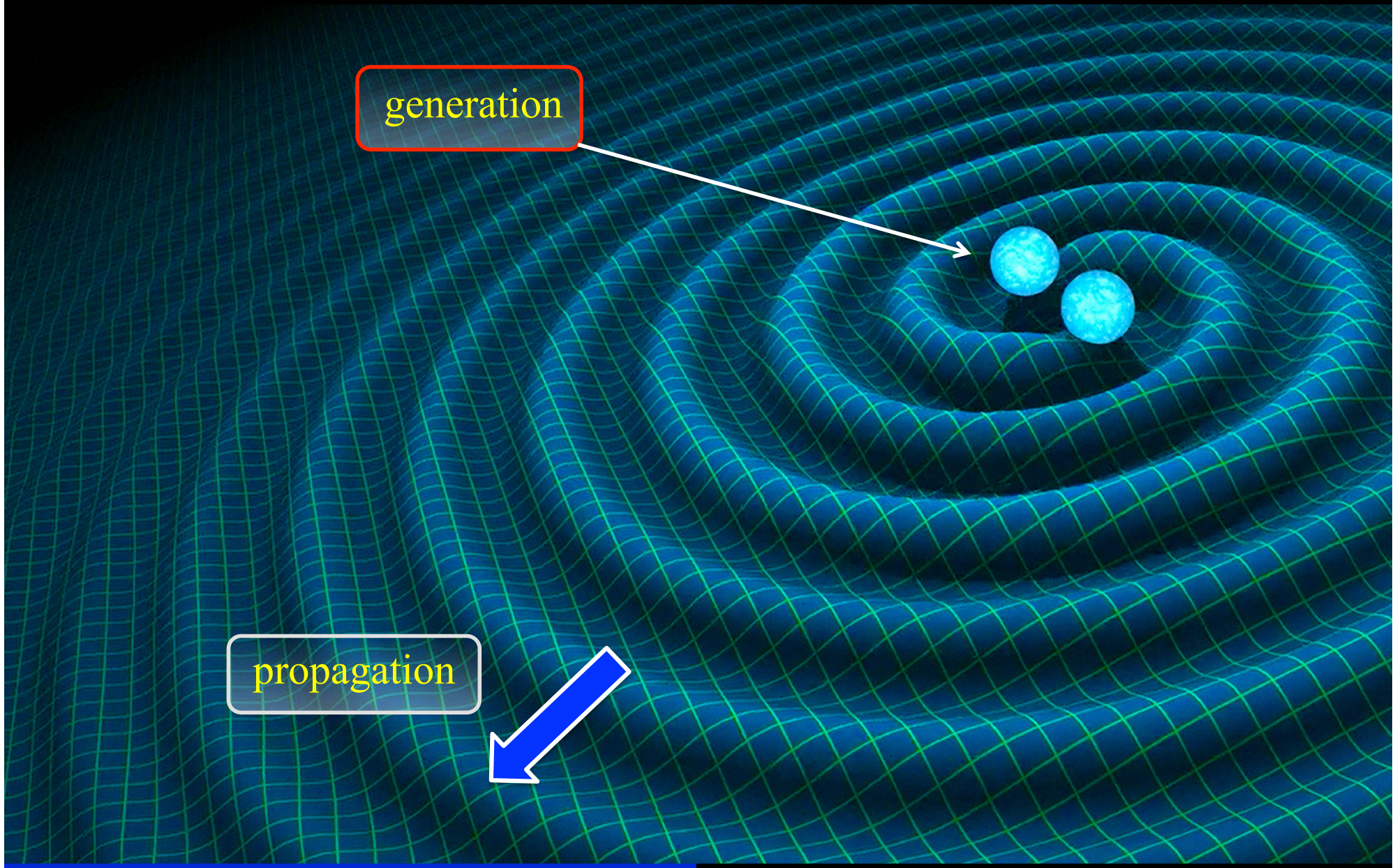
signal: GR waveform consistent with GW150914 & GW151226

template: ppE modified waveform

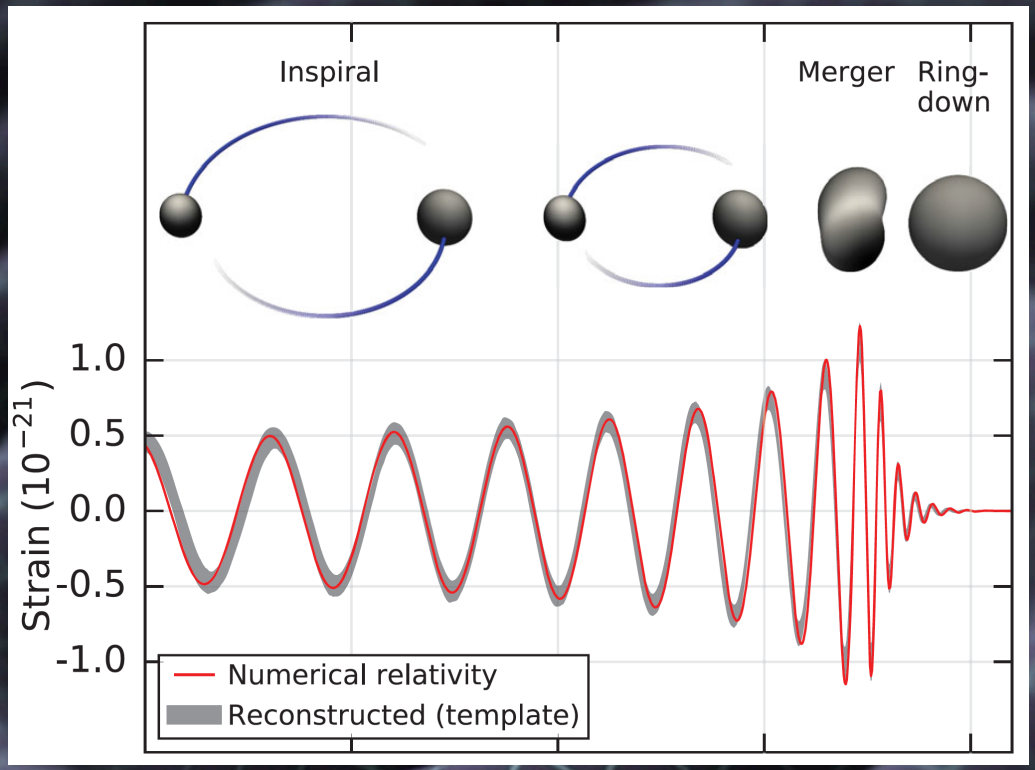
Different Types of Modifications



Outline



ppE Phase for Modified GW Generation



[Abbott et al. PRL 116 061102 (2016)]

non-GR correction in inspiral only

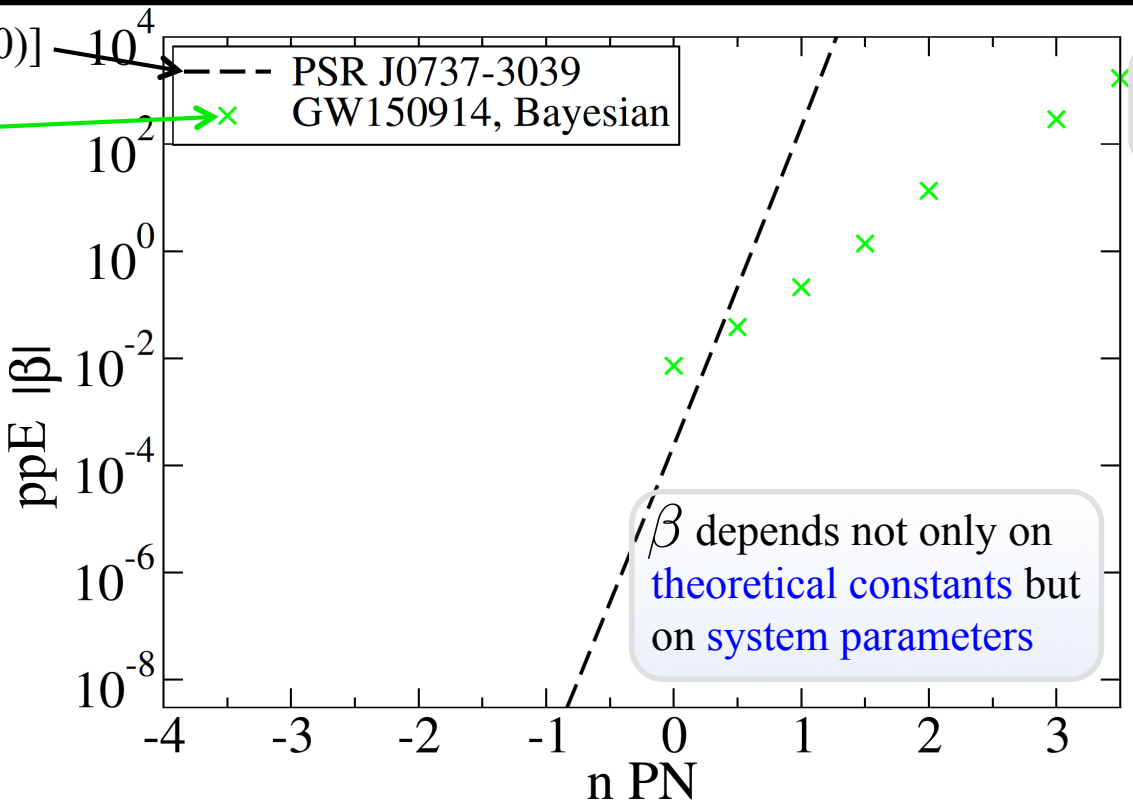
$$\Psi^{(\mathrm{insp})} = \Psi^{(\mathrm{insp})}_{\mathrm{GR}} + \beta\, v^{2n-5}$$
$$\Psi^{(\mathrm{merg,ring})} = \Psi^{(\mathrm{merg,ring})}_{\mathrm{GR}}$$

(due to the lack of BH binary merger simulations in non-GR theories)

Constraining GR Fundamental Pillars

[Yunes & Hughes (2010)]

[LIGO-Virgo Collaboration (2016)]



β depends not only on theoretical constants but on system parameters

$$\delta\Psi = \beta\, v^{2n-5}$$

Be careful when comparing these bounds!!

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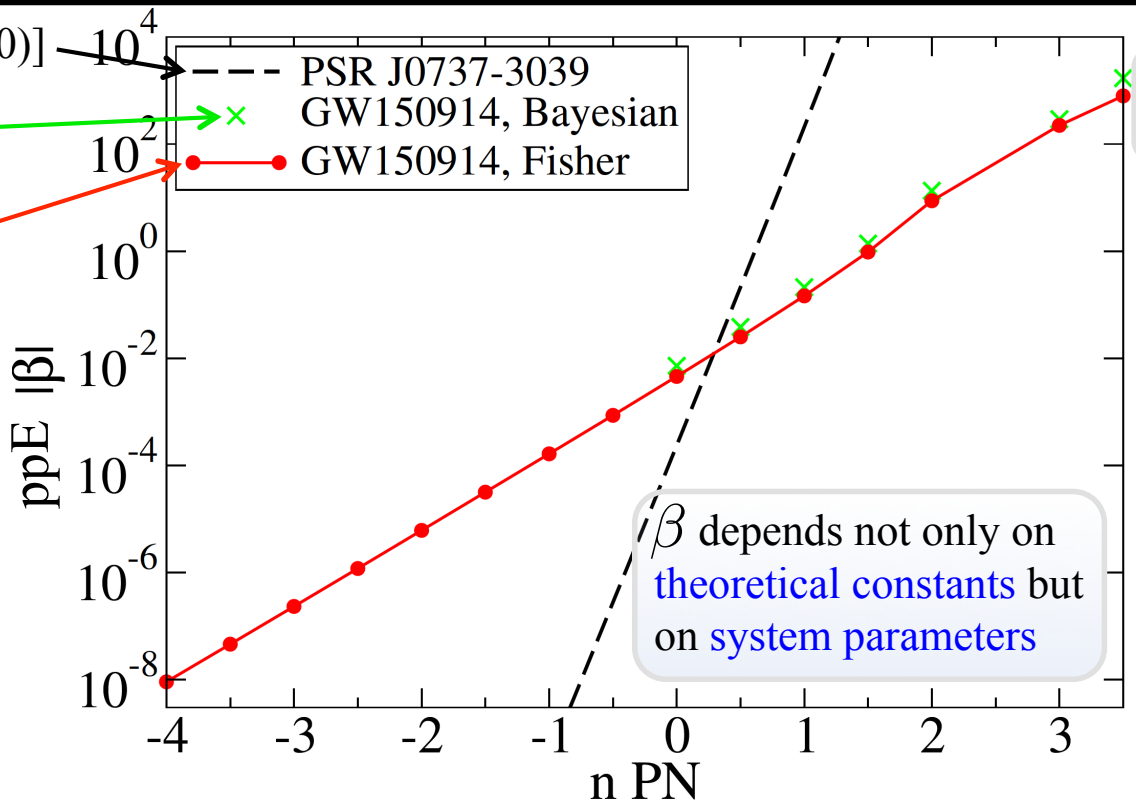

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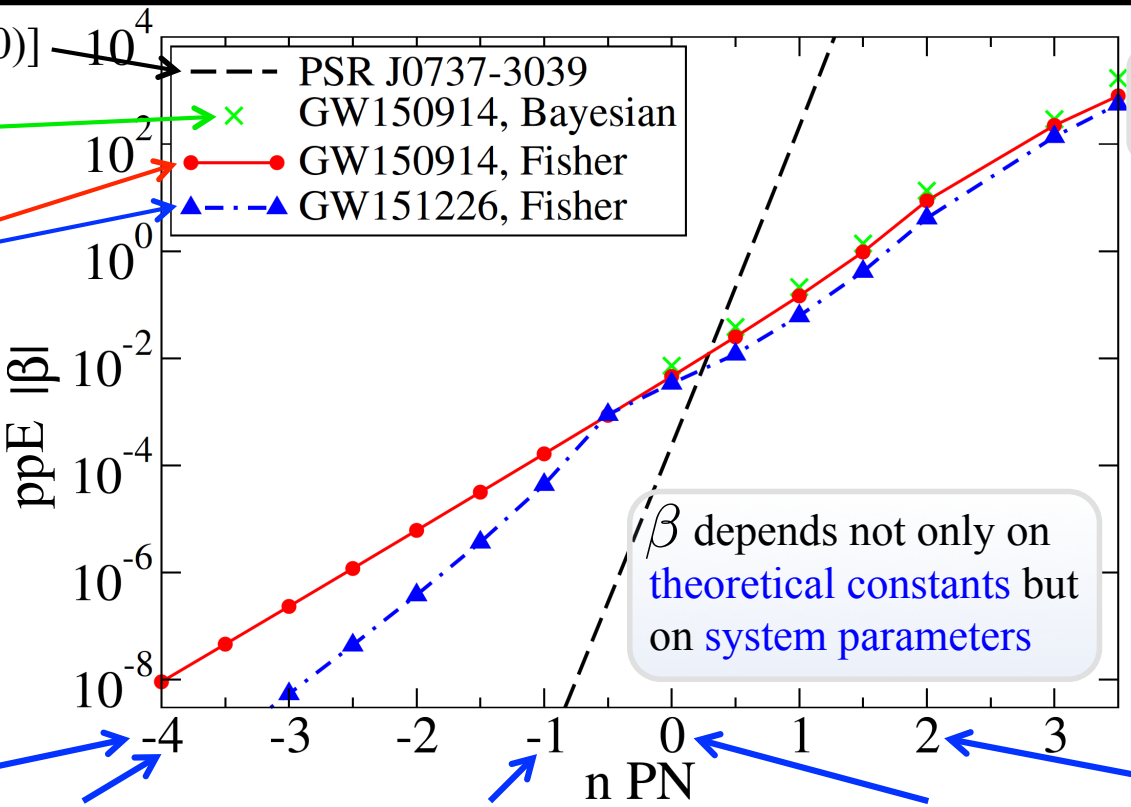

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extra dimension	time varying G	scalar monopole activation	vector field activation	scalar dipole activation
4D	equivalence principle	equivalence principle	Lorentz invariance	parity invariance

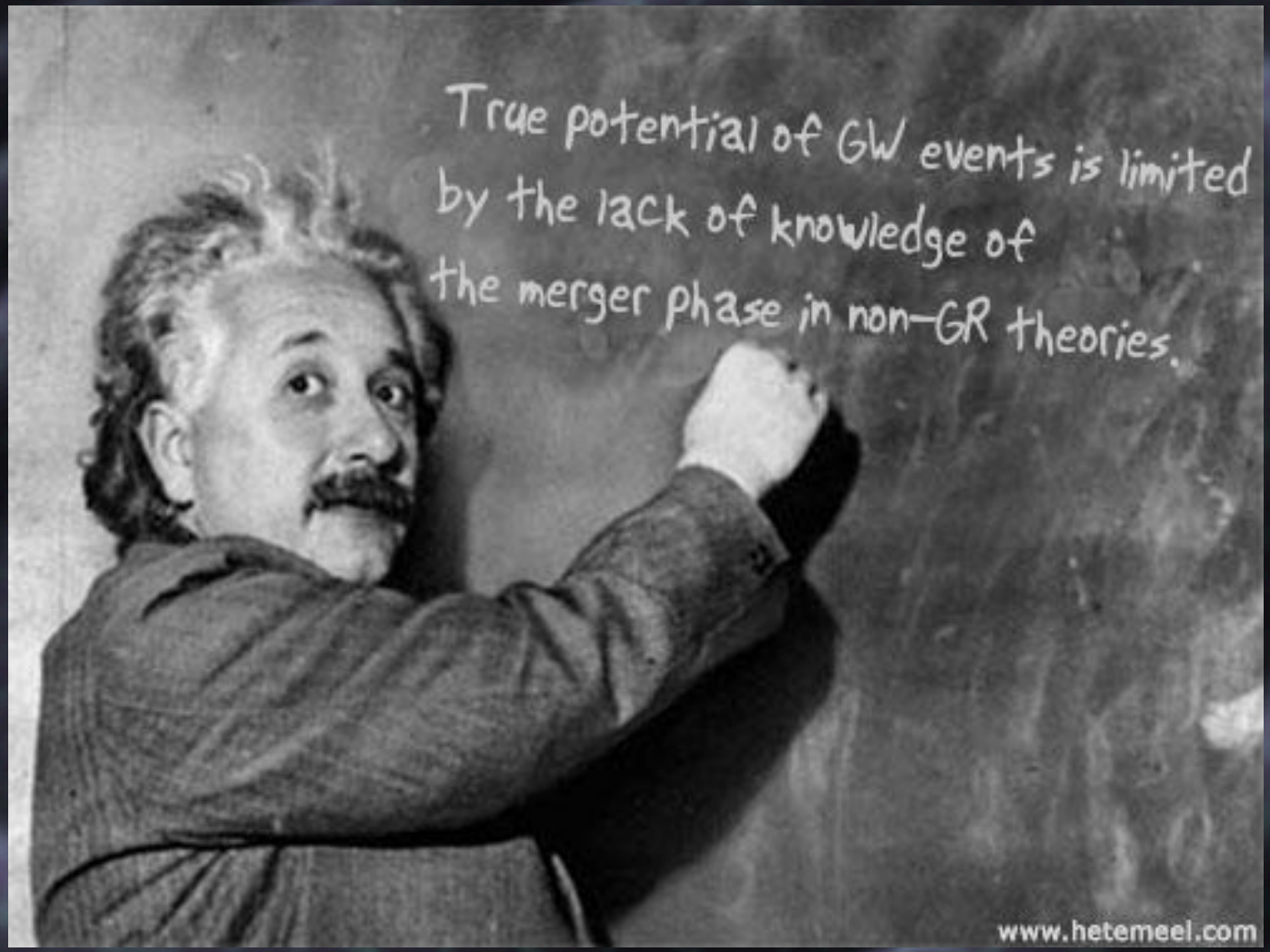
Mapping to Theoretical Constraints

no meaningful constraints
(beyond small-coupling approximation)

Example Theories (Theoretical Parameters)	GR Pillar	PN	Example Theory Constraints		
			GW150914	**GW151226**	Current
Einstein-dilaton Gauss-Bonnet ($\sqrt{\lvert\alpha_{\rm EdGB}\rvert}$ [km])	Equiv. Princ.	-1	—	—	10^7, 2
scalar-tensor ($\lvert\dot{\phi}\rvert$ [1/sec])	Equiv. Princ.	-1	—	—	10^{-6}
dynamical Chern-Simons ($\sqrt{\lvert\alpha_{\rm dCS}\rvert}$ [km])	Parity Inv.	$+2$	—	—	10^8
Einstein-Æther (c_+, c_-)	Lorentz Inv.	0	$(\mathbf{0.9}, \mathbf{2.1})$	$(\mathbf{0.8}, \mathbf{1.1})$	$(0.03, 0.003)$
RS-II Braneworld (ℓ [μm])	4D	-4	$\mathbf{5.4 \times 10^{10}}$	$\mathbf{2.0 \times 10^{9}}$	10–10^3
time-varying G ($\lvert\dot{G}\rvert/G$ [10^{-12}/yr])	Equiv. Princ.	-4	$\mathbf{5.4 \times 10^{18}}$	$\mathbf{1.7 \times 10^{17}}$	0.1–1

weaker than current bounds
first constraint in the strong/dynamical gravity regime

Important Message



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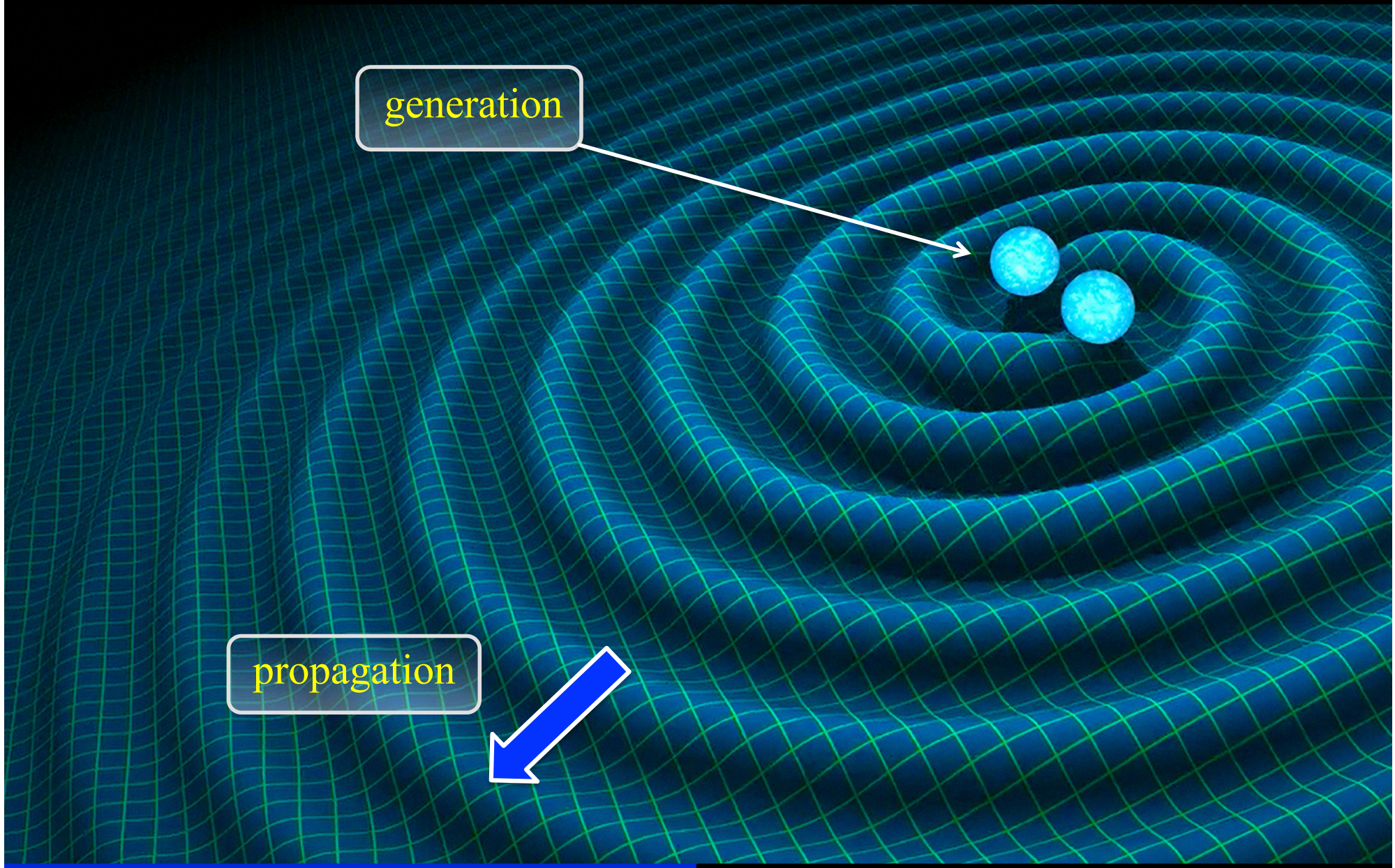

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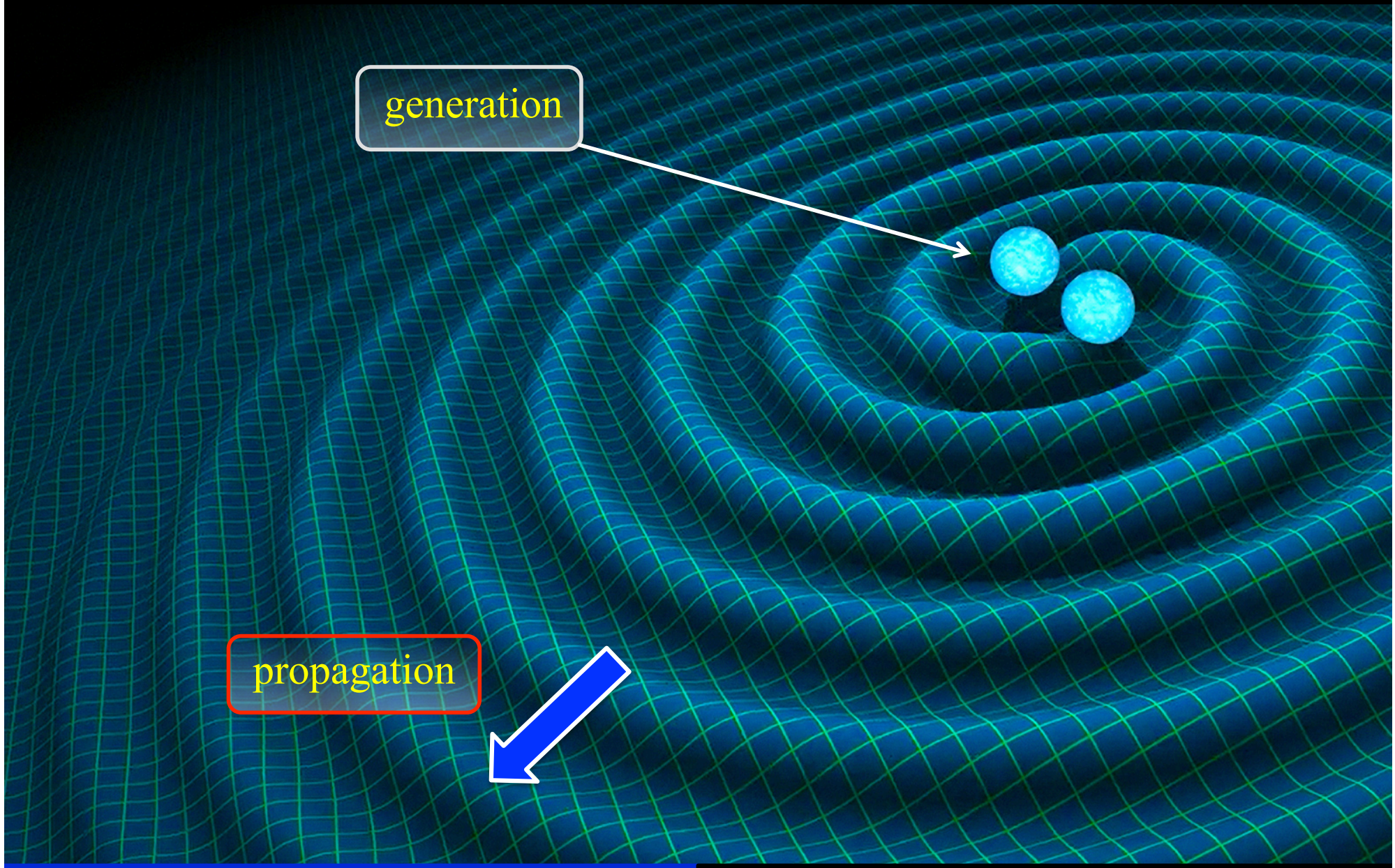


Modified GW Propagation

graviton dispersion relation

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

$$\Psi - \Psi_{\rm GR} \sim A\,D\,f^{\alpha-1}$$

D

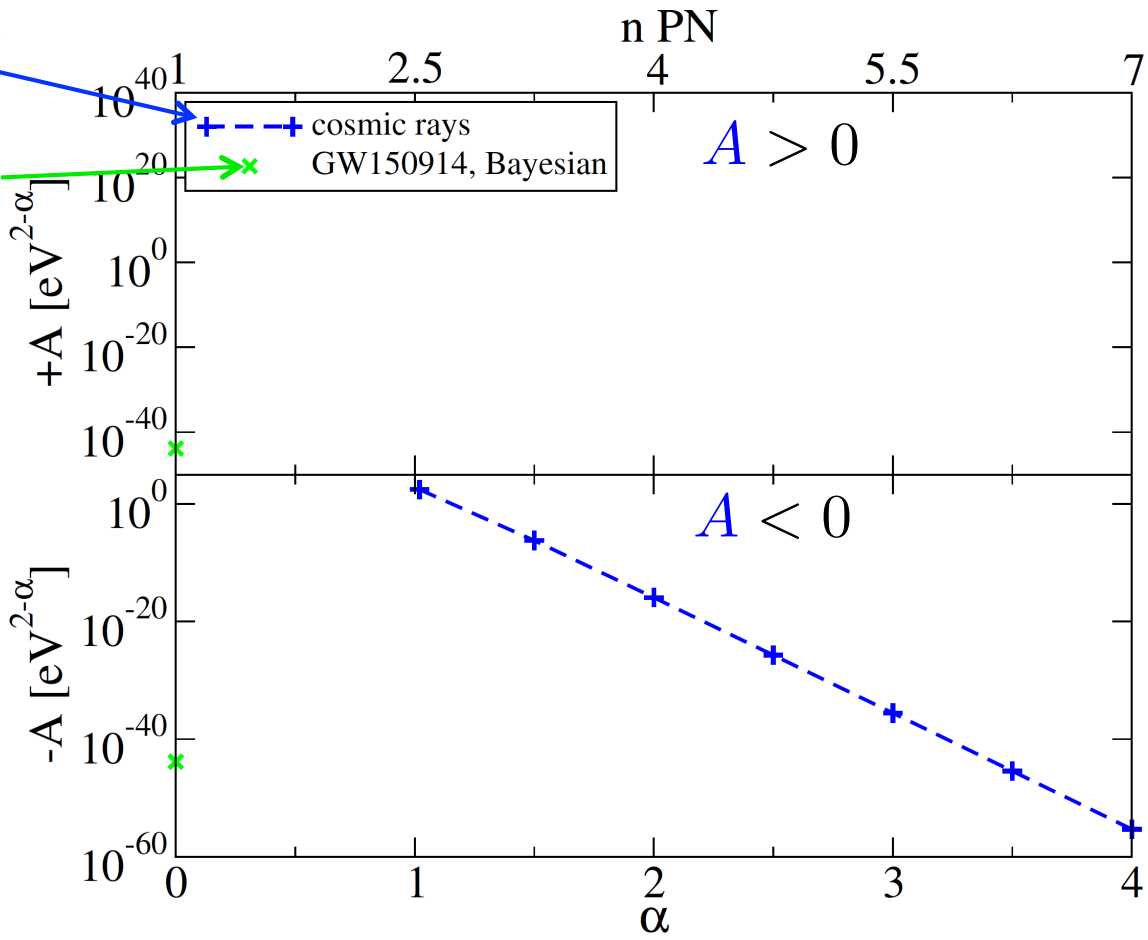
This correction is added to full inspiral-merger-ringdown GR phase.

Bounds on the Propagation Mechanisms

[Kiyota & Yamamoto (2015]

[LIGO-Virgo Collaboration (2016)]

$E^2 = (p\,c)^2 + A\,(p\,c)^\alpha$



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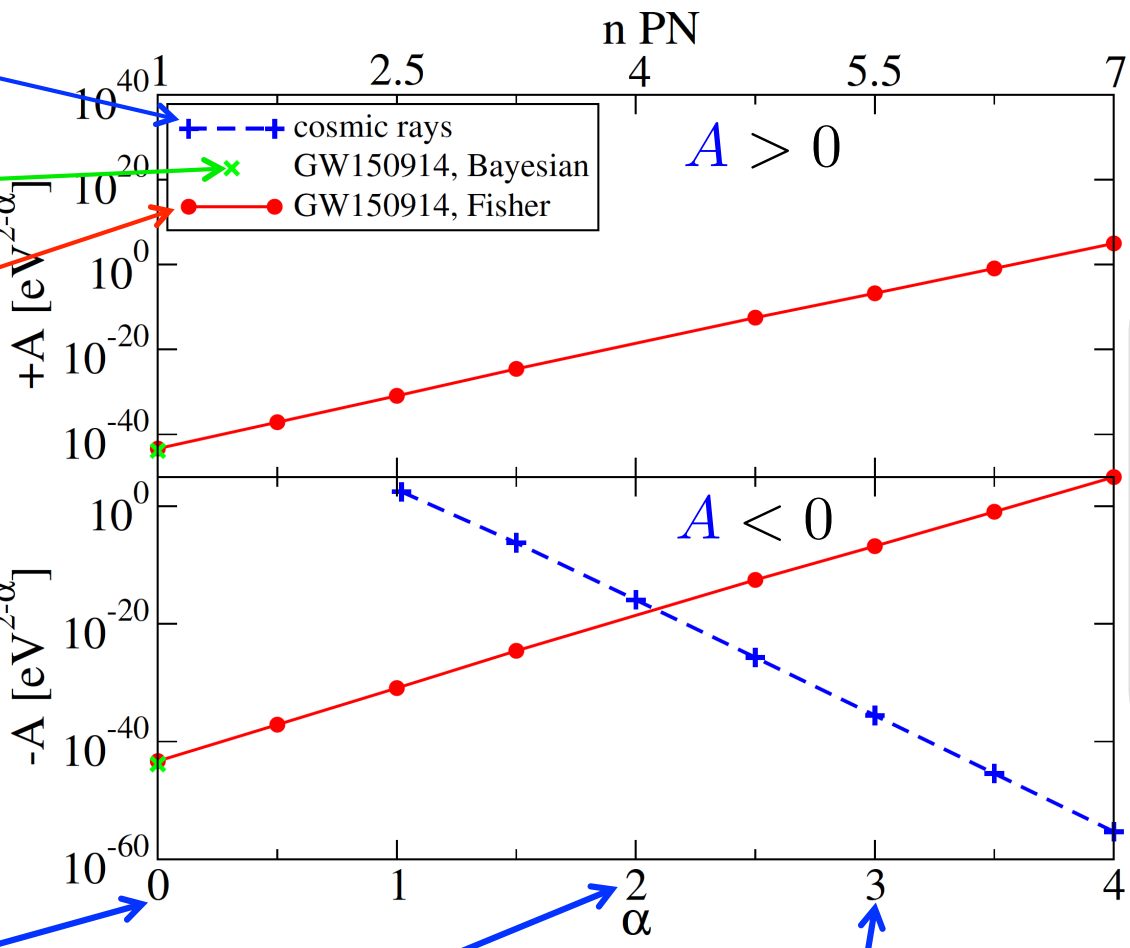


-GW151226 bound similar to GW150914

-strong constraints from GWs

-complementary to cosmic ray bounds

-massive gravity

-Lorentz violation

-Lorentz violation
-mod. special relativity

-Lorentz violation
-extra dimension

Mapping to Theoretical Constraints

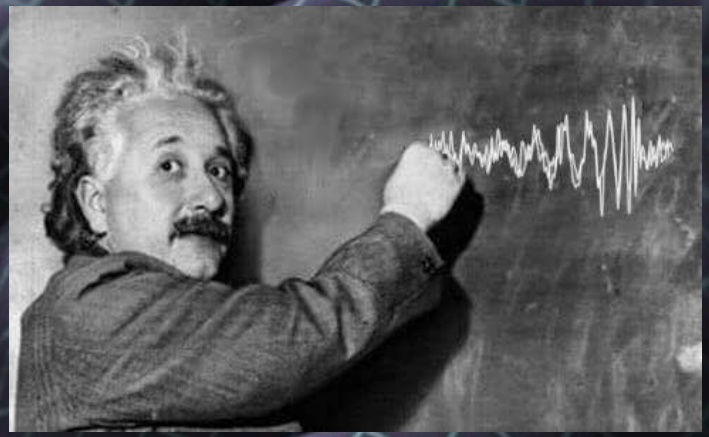
Example Theories	Repr. Parameters	GR Pillar	PN	Example Theory Constraints		
				GW150914	**GW151226**	Current
Massive graviton	m_g [eV]	$m_g = 0$	+1	$\mathbf{10^{-22}}$	$\mathbf{10^{-22}}$	10^{-29}–10^{-18}
Multifractional	E_*^{-1} [eV^{-1}] (time)	Lor. Inv.	+4.75	$\mathbf{5.8 \times 10^{-27}}$	$\mathbf{3.3 \times 10^{-26}}$	—
	E_*^{-1} [eV^{-1}] (space)			$\mathbf{1.0 \times 10^{-26}}$	$\mathbf{5.7 \times 10^{-26}}$	3.9×10^{-53}
Modified Special Rel.	$\eta_{\rm dsrt}/L_{\rm Pl} > 0$	Lor. Inv.	+5.5	$\mathbf{1.3 \times 10^{22}}$	$\mathbf{3.8 \times 10^{22}}$	—
	$\eta_{\rm dsrt}/L_{\rm Pl} < 0$					2.1×10^{-7}
Standard Model Ext.	$\mathring{k}^{(4)}_{(I)} > 0$	Lor. Inv.	+4	—	—	6.1×10^{-17}
	$\mathring{k}^{(4)}_{(I)} < 0$			**0.64**	**19**	—
	$\mathring{k}^{(5)}_{(V)} > 0$ [cm]		+5.5	$\mathbf{1.7 \times 10^{-12}}$	$\mathbf{3.1 \times 10^{-11}}$	1.7×10^{-40}
	$\mathring{k}^{(5)}_{(V)} < 0$ [cm]					—
	$\mathring{k}^{(6)}_{(I)} > 0$ [cm^2]		+7	$\mathbf{7.2 \times 10^{-4}}$	$\mathbf{3.3 \times 10^{-3}}$	3.5×10^{-64}
	$\mathring{k}^{(6)}_{(I)} < 0$ [cm^2]					—
Hořava-Lifshitz	$\kappa_{\rm hl}^4 \mu_{\rm hl}^2$ [1/eV^2]	Lor. Inv.	+7	$\mathbf{1.5 \times 10^{6}}$	$\mathbf{6.9 \times 10^{6}}$	—
Einstein-Æther	c_+	Lor. Inv.	+4	**0.7**	**0.998**	0.03
khronometric	β					0.005

Conclusions

Takeaway

generation mechanisms:
-weak bound
-first strong/dyn. gravity constraint

propagation mechanisms:
-strong bound
-complementary to cosmic rays



https://igoligo.wordpress.com/2016/02/12/einstein-was-right/

Thank You

-Merger simulations in non-GR theories
-Stacking multiple signals
-Electromagnetic counterpart

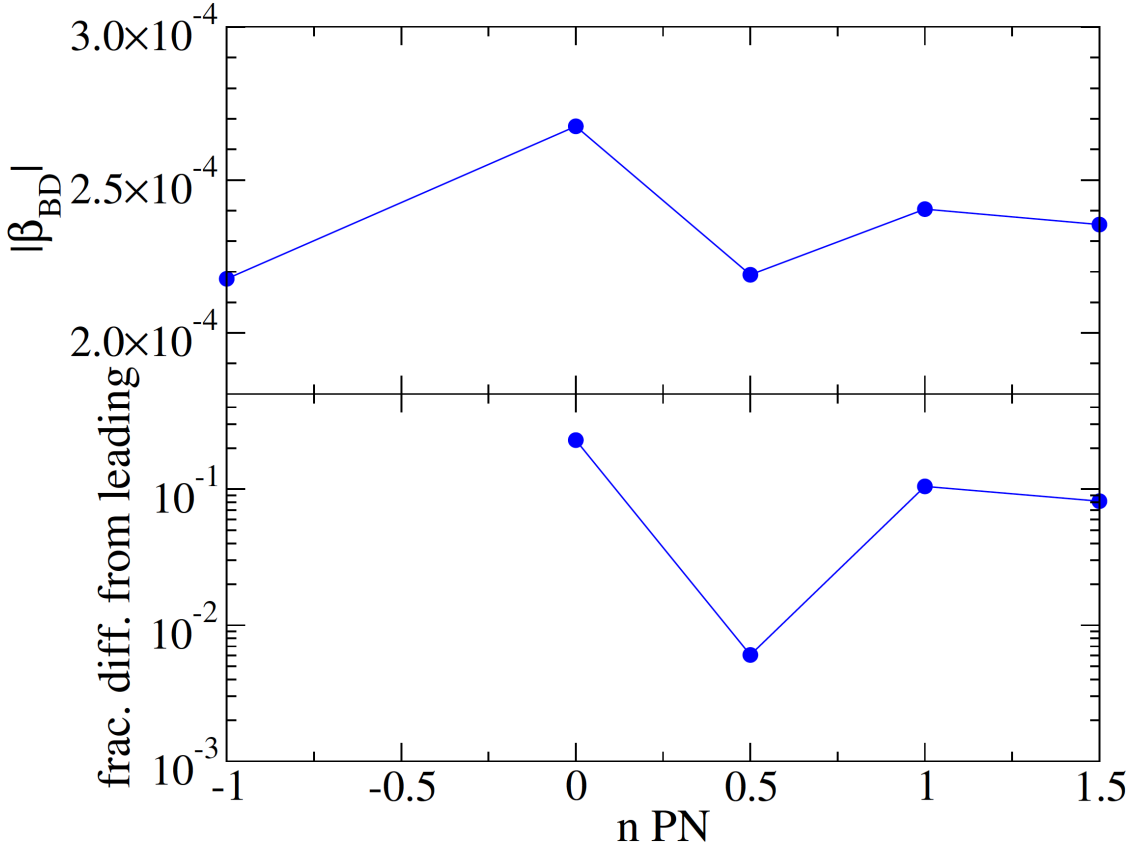
Back Up

Effect of Higher PN Corrections

Brans-Dicke (BD) theory as an example

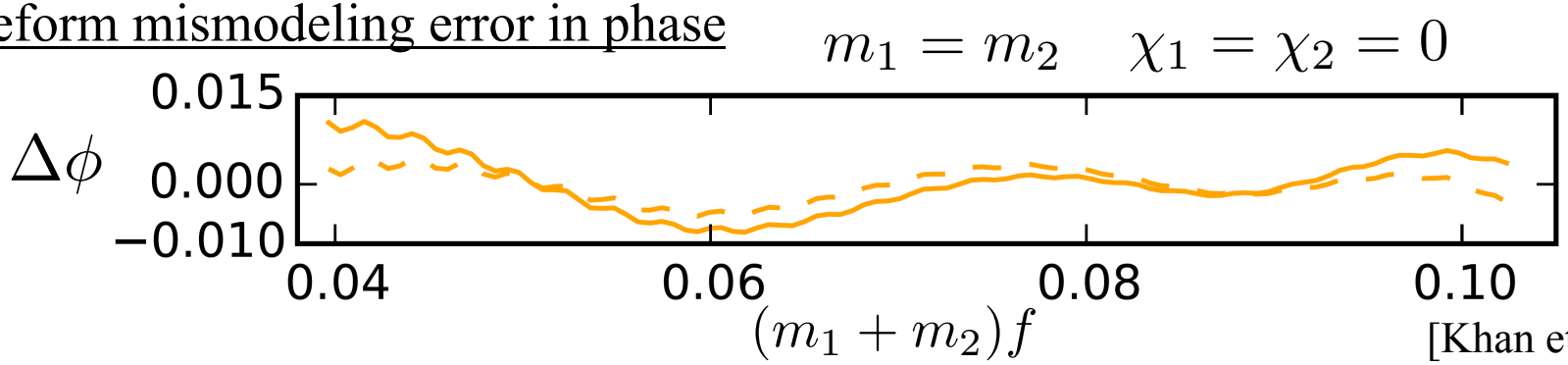
$$\Psi_{\rm BD}(f) = \Psi_{\rm GR}(f) + \beta_{\rm BD}\,(\pi\mathcal{M}f)^{-7/3}\left[1+\sum_{k=2}^{5}\delta\psi_k^{\rm BD}(\eta)\,(\pi\mathcal{M}f)^{k/3}\right]$$

Higher PN corrections know for small mass ratio limit

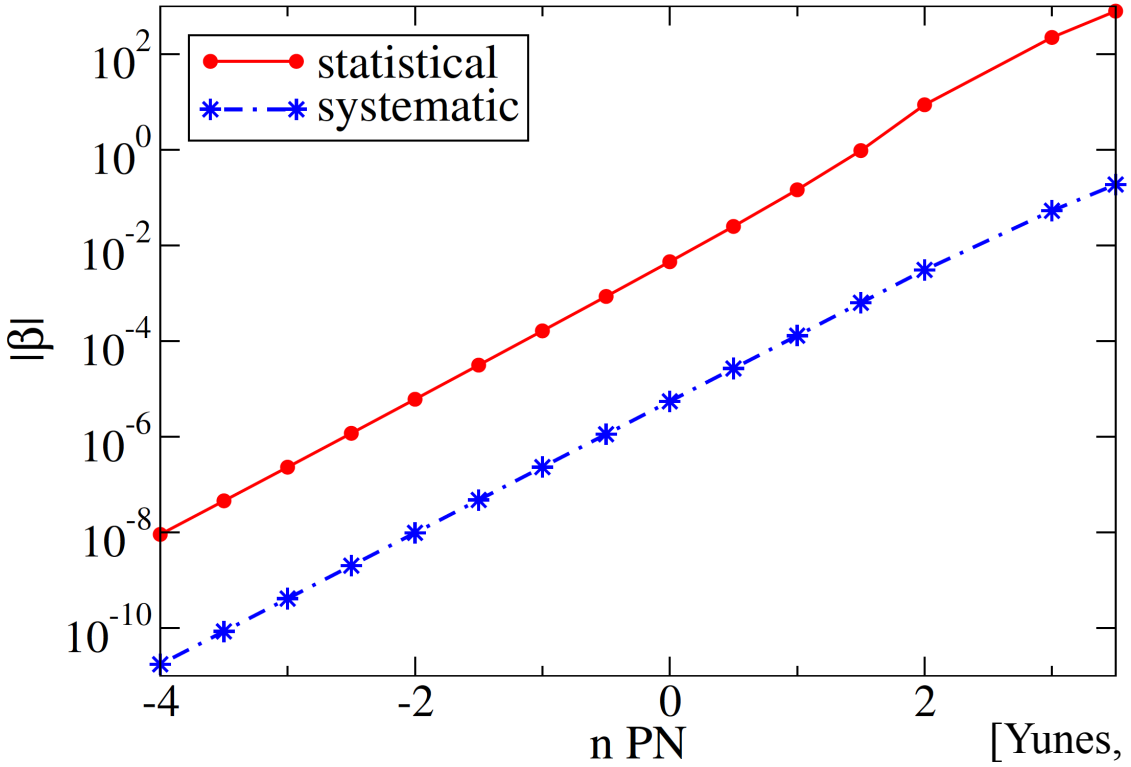


Mismodeling Template Systematics

Waveform mismodeling error in phase



[Khan et al. (2015)]



[Yunes, KY & Pretorius (2016)]

Mismodeling systematics much smaller than statistical errors

Strong Equivalence Principle

[Will, Living Review (2006)]

1. The trajectories of freely-falling test bodies, including self-gravitating ones, are independent of their internal structure and composition.

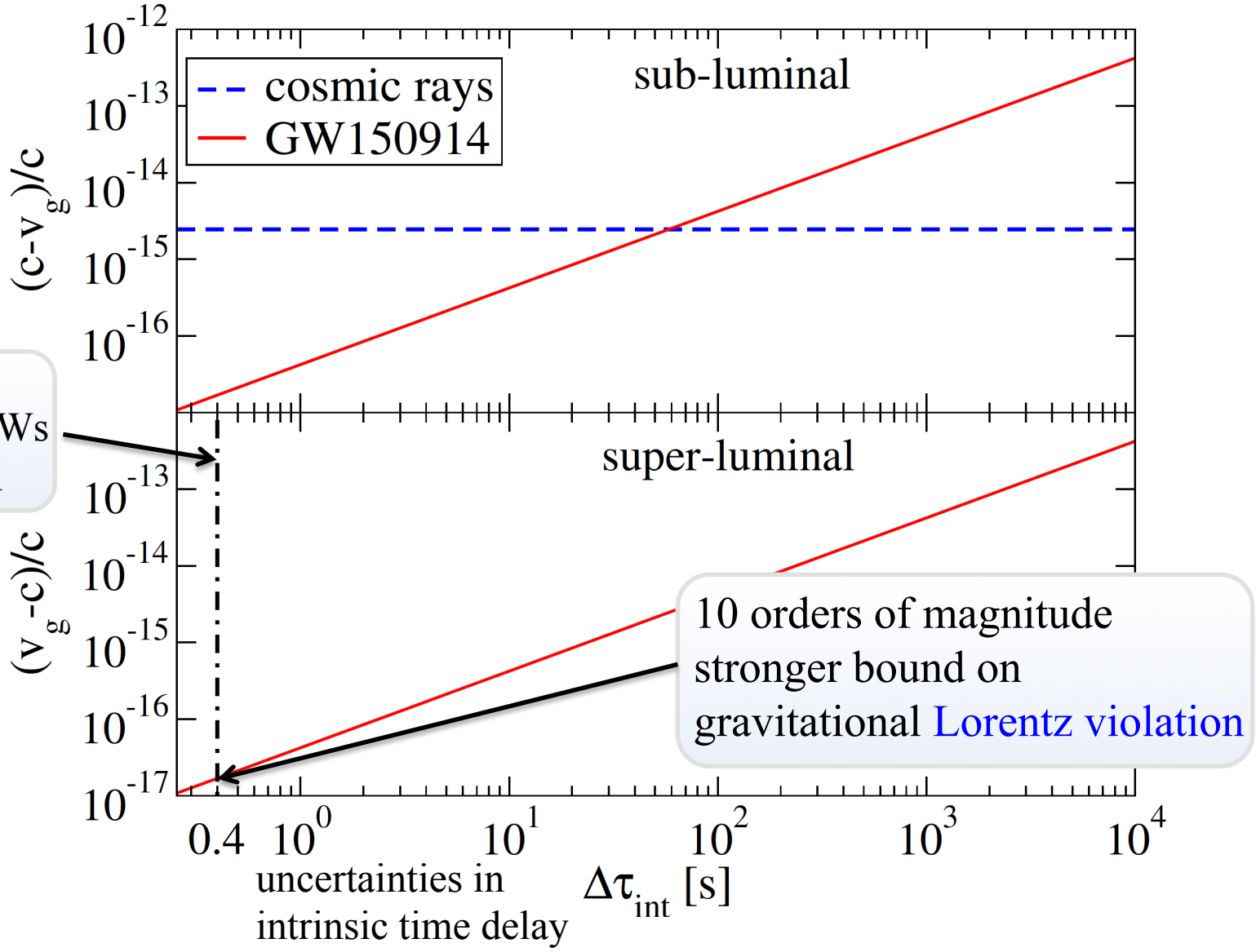
2. Results of any local experiment, including gravitational ones, are independent of when and where they are performed (local position invariance), and of the velocity of the experimental apparatus (local Lorentz invariance).

Constraining GW Propagation with EM Counterparts

$$\left|\frac{v_g - c}{c}\right| < \frac{c\Delta\tau_{\rm int}}{D}$$

[Nishizawa & Nakamura (2014)]

- Fermi GBM
- super-luminal GWs
- prompt emission



10 orders of magnitude stronger bound on gravitational Lorentz violation