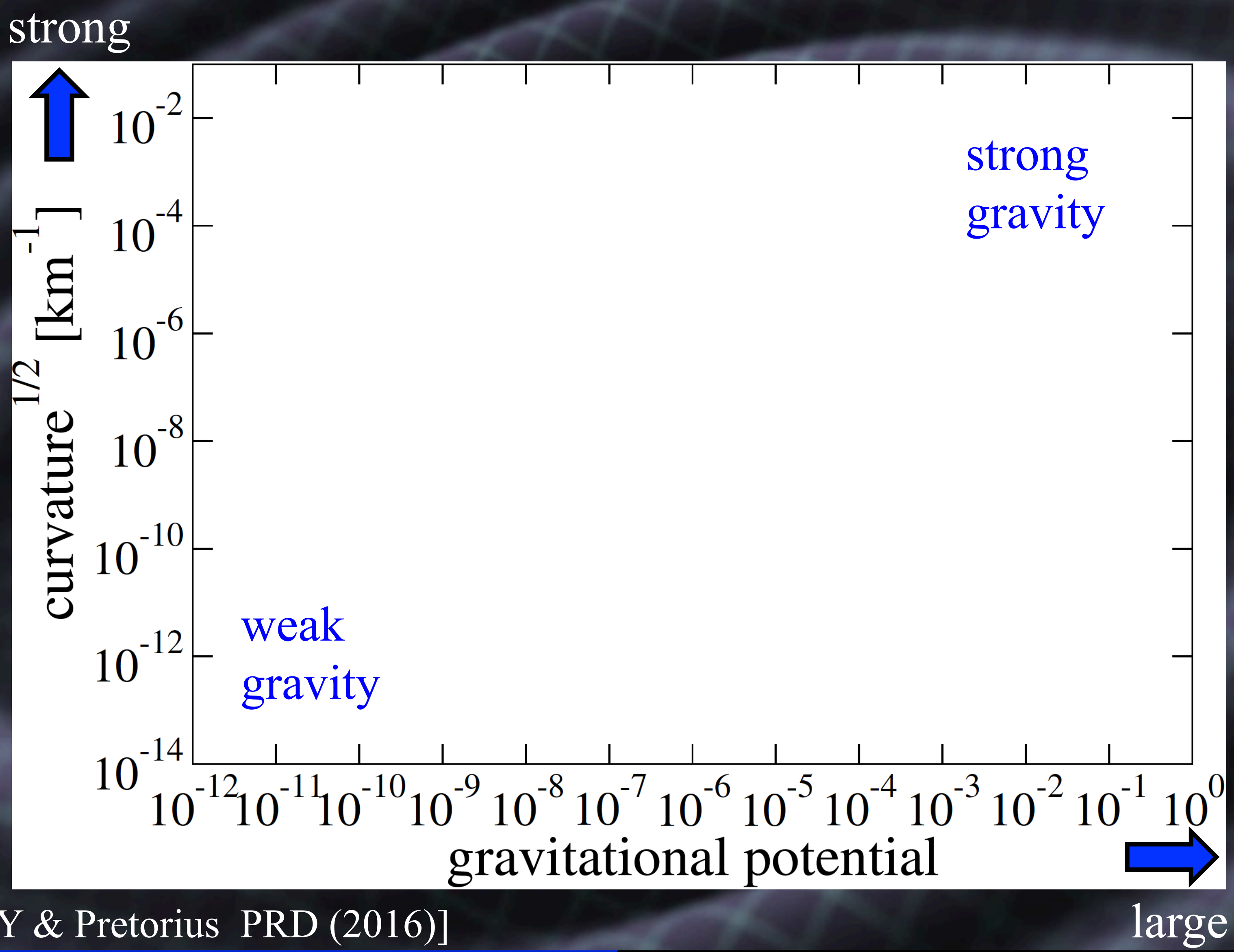
Current Status on Probing Gravity with Binary Black Hole Coalescences

Kent Yagi
Princeton University

StronG BaD Workshop
Oxford, Mississippi, March 1st 2017

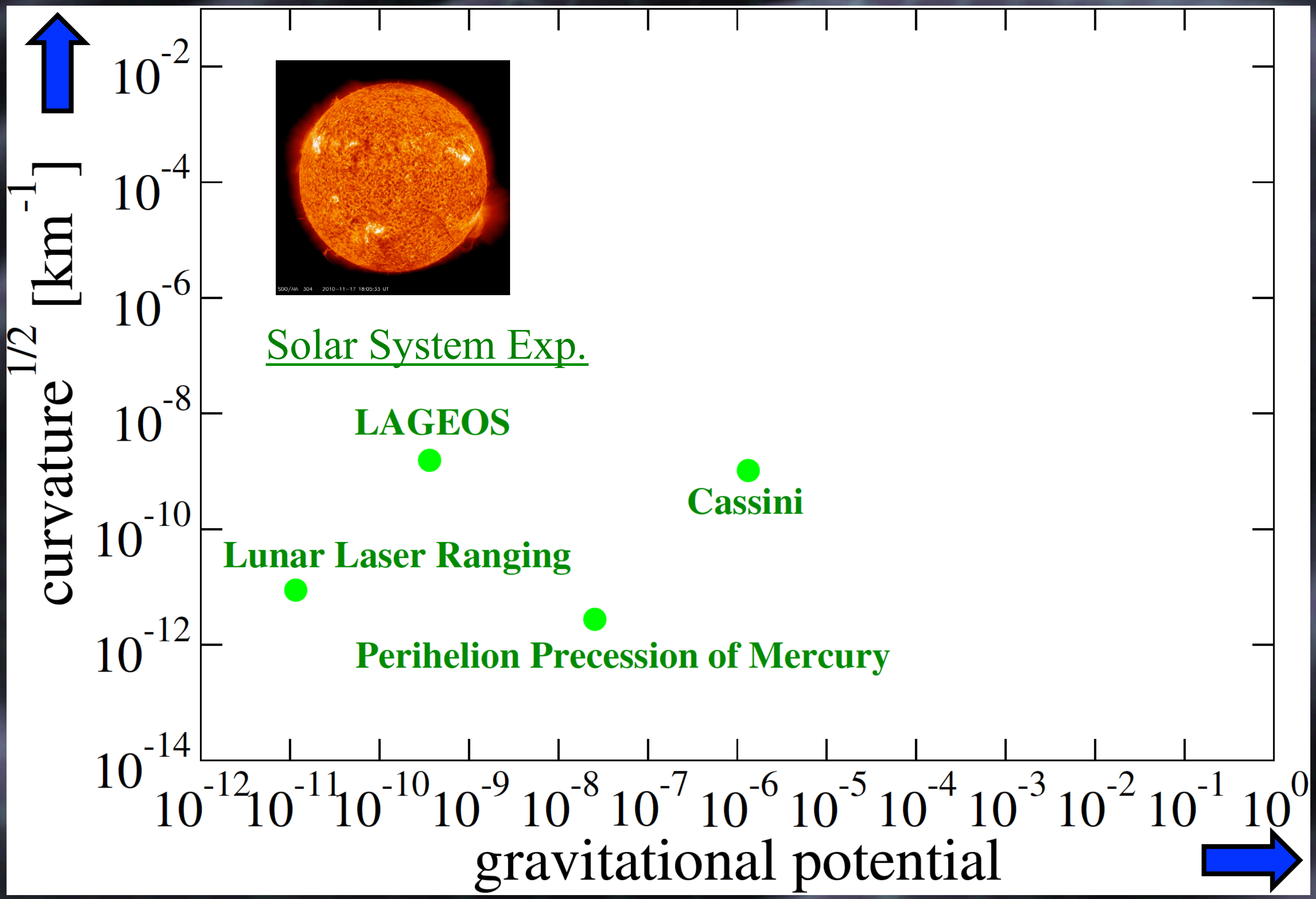
Strong/Dynamical Nature of GW Sources



[Yunes, KY & Pretorius PRD (2016)]

Strong/Dynamical Nature of GW Sources

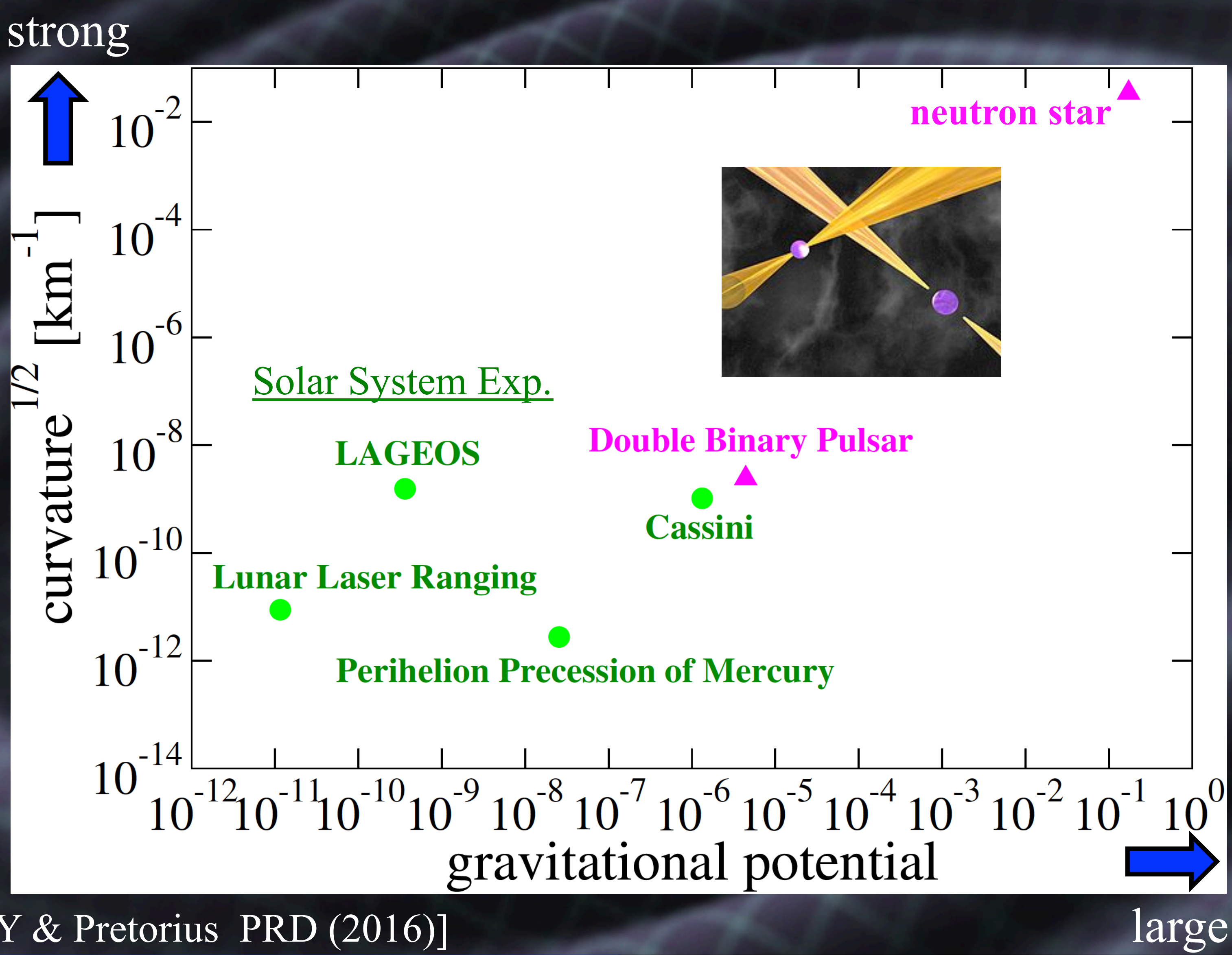
strong



[Yunes, KY & Pretorius PRD (2016)]

large

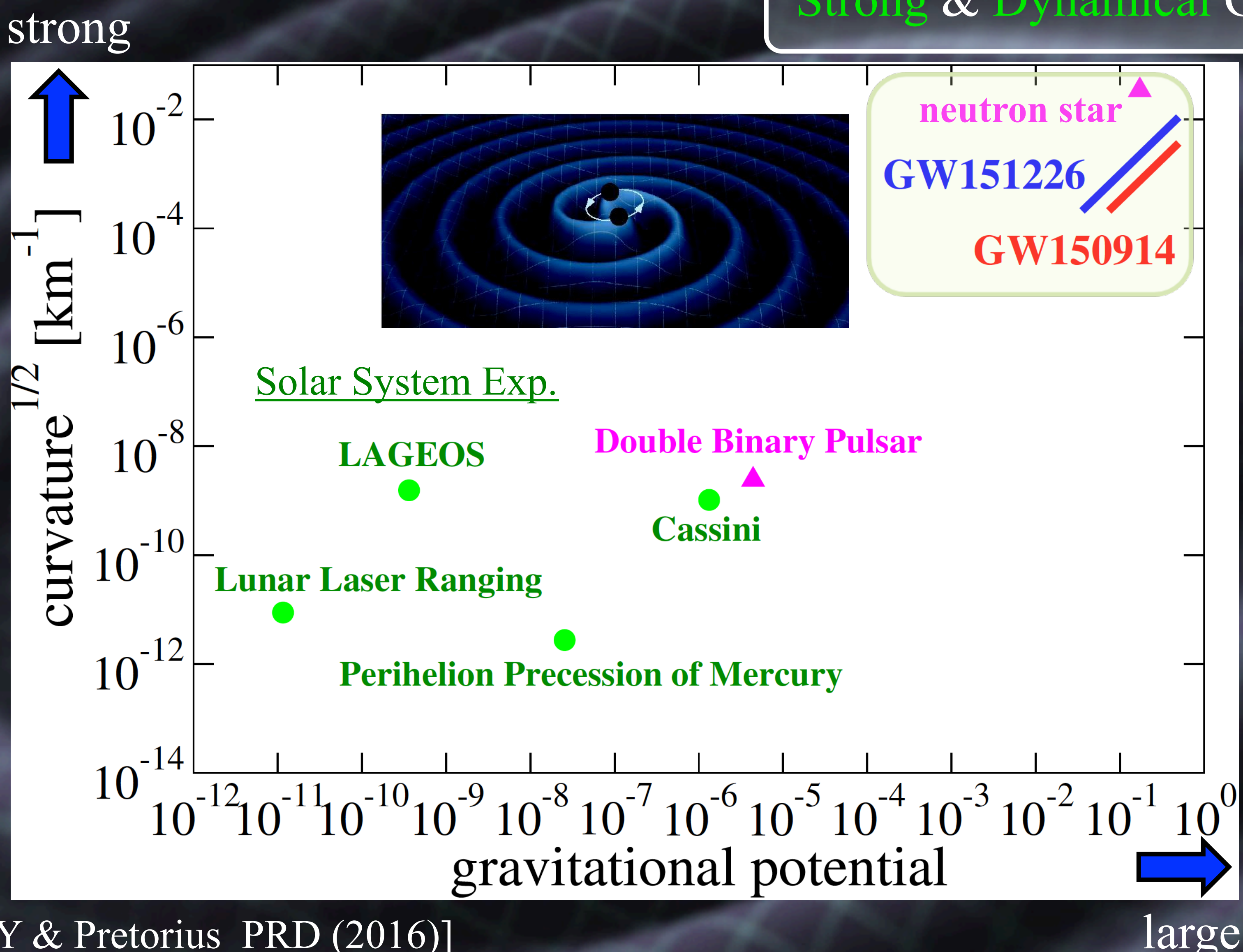
Strong/Dynamical Nature of GW Sources



[Yunes, KY & Pretorius PRD (2016)]

Strong/Dynamical Nature of GW Sources

Strong & Dynamical Gravity



[Yunes, KY & Pretorius PRD (2016)]

Outline

Current Status

Open Problems

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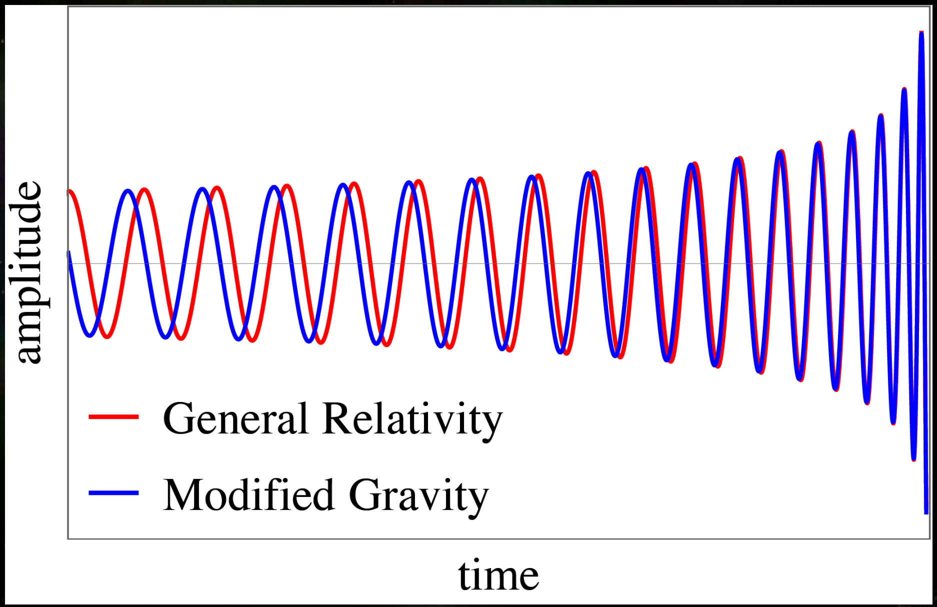
parameterized post-Einsteinian (ppE) Formalism

[Yunes & Pretorius (2009)]



Fisher Analysis

signal: GR waveform consistent with GW150914 & GW151226

template: ppE modified waveform

waveform phase:

relative velocity

ppE parameter

*n*th post-Newton (PN) correction

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

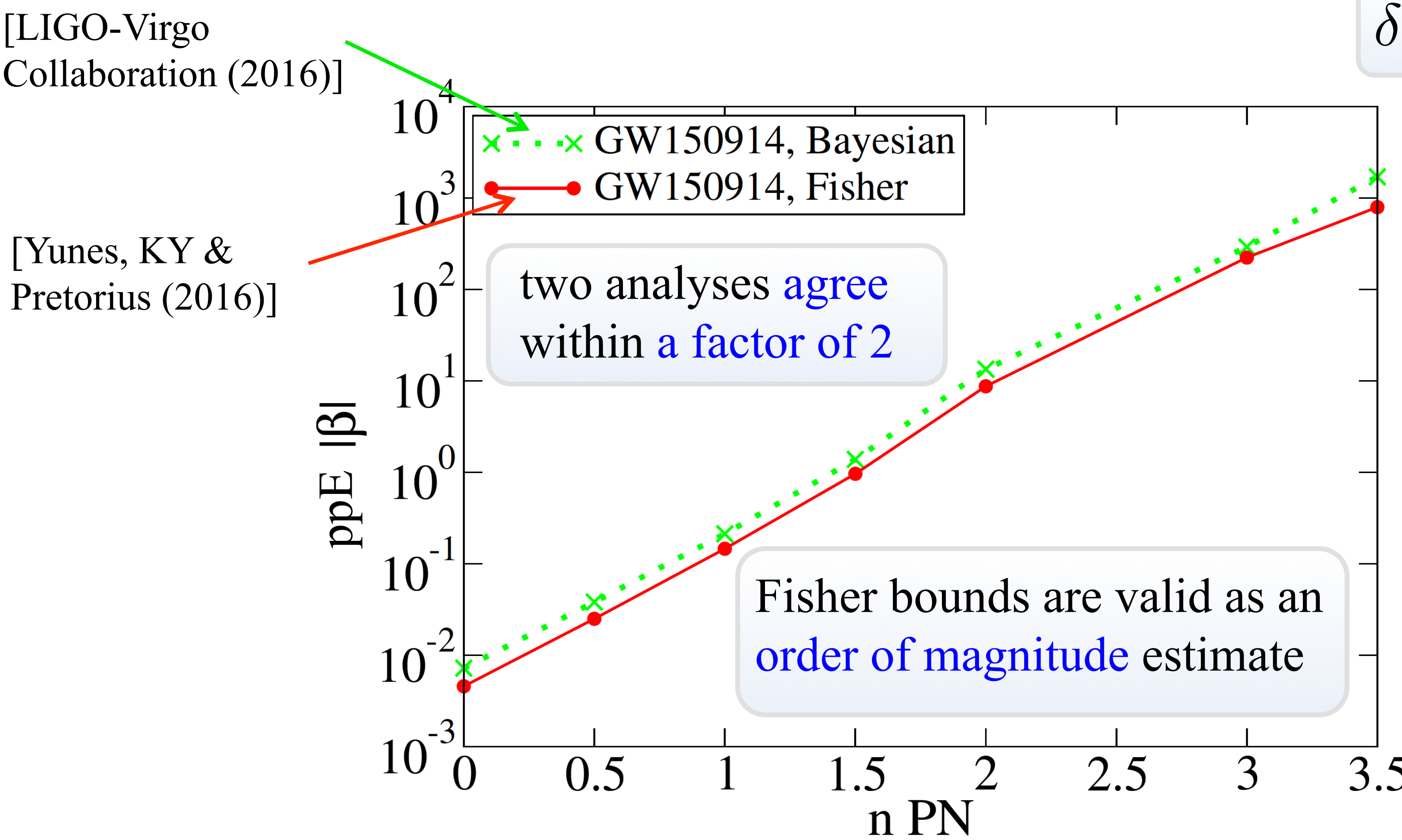
PN approximation:

$$v/c \ll 1$$

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

Validity of Fisher Analysis

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

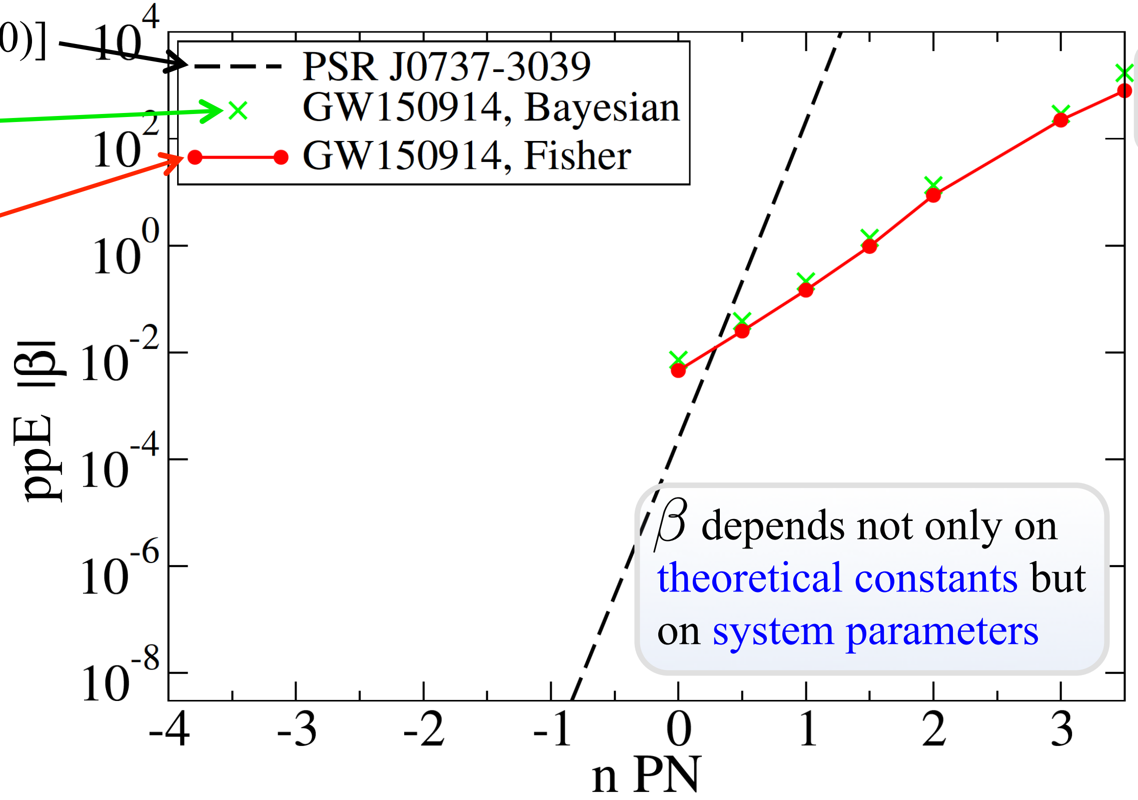


Constraining GR Fundamental Pillars

[Yunes & Hughes (2010)]

[LIGO-Virgo Collaboration (2016)]

[Yunes, KY & Pretorius (2016)]

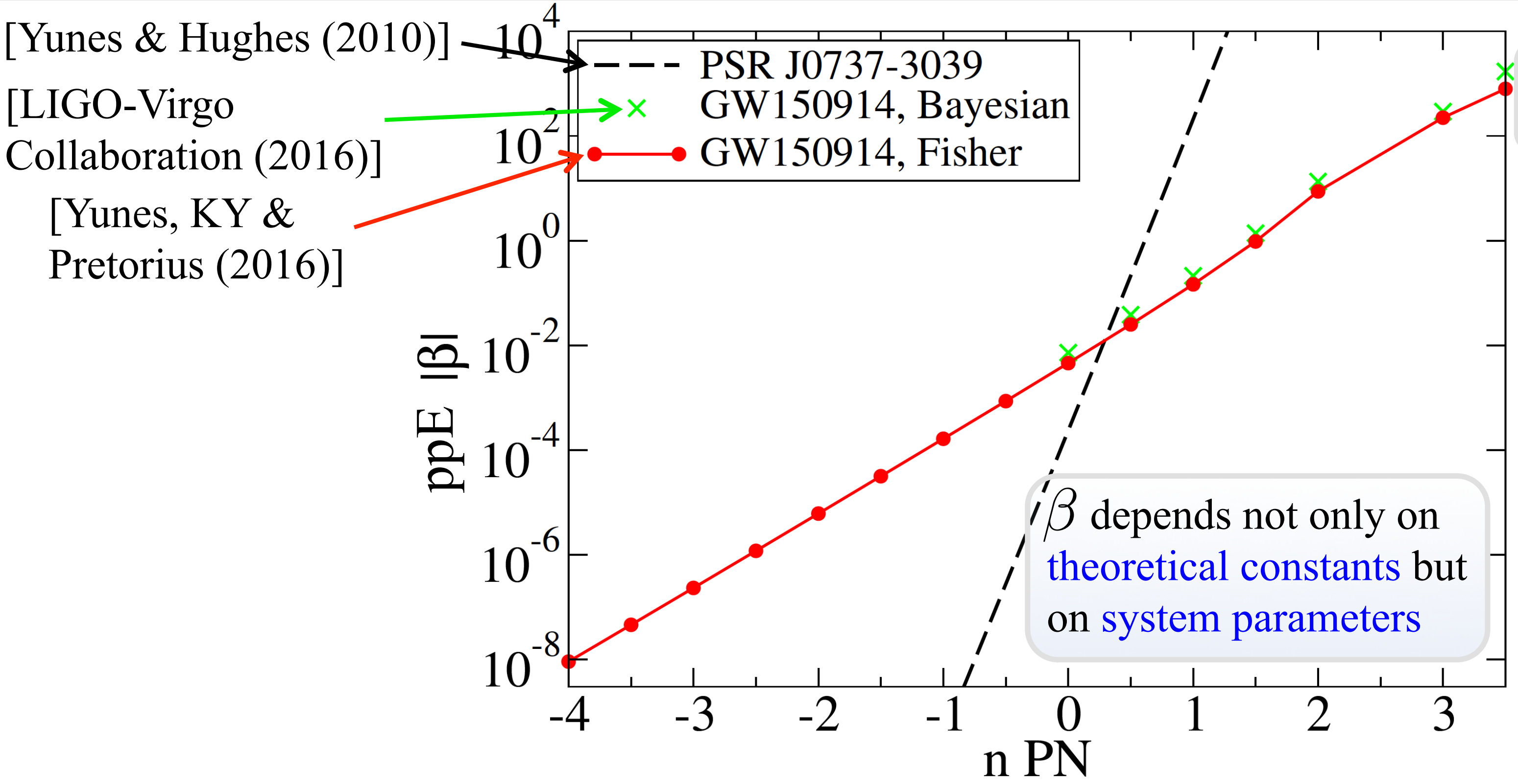


β depends not only on theoretical constants but on system parameters

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

Be careful when comparing these bounds!!

Constraining GR Fundamental Pillars



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Constraining GR Fundamental Pillars

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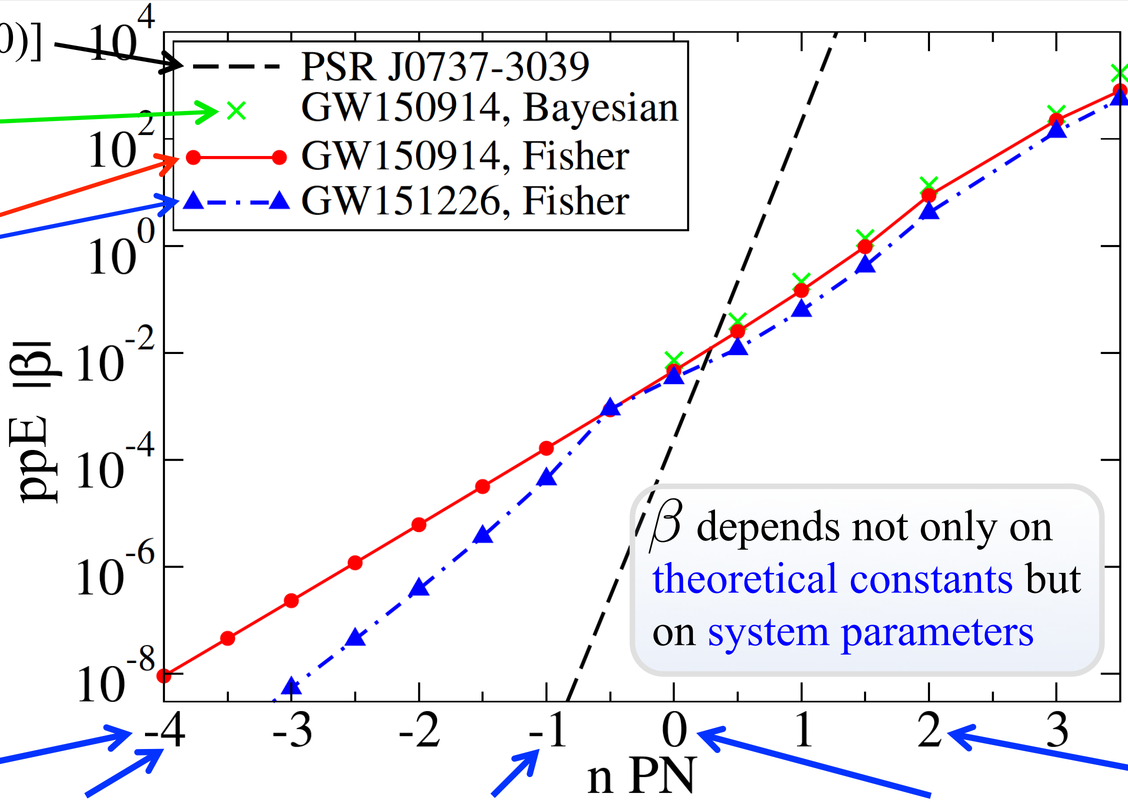


$$\delta\Psi = \beta\, v^{2n-5}$$

Be careful when comparing these bounds!!

β depends not only on theoretical constants but on system parameters

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

Is PN Approximation Valid…?

What does it mean to include only the leading PN correction?

PN approximation:
$v/c \ll 1$

$$\Psi_{\rm non-GR} = \Psi_{\rm GR} + \delta\Psi^{(\rm lead)} + \delta\Psi^{(\rm rest)}$$

PN bound is valid as long as there is no fine-tuned cancellation

	leading PN bound validity	
$\lvert\delta\Psi^{(\rm lead)}\rvert \gg \lvert\delta\Psi^{(\rm rest)}\rvert$	✓	accurate
$\lvert\delta\Psi^{(\rm lead)}\rvert \ll \lvert\delta\Psi^{(\rm rest)}\rvert$	✓	conservative
$\delta\Psi^{(\rm lead)} \sim +\delta\Psi^{(\rm rest)}$	✓	order of magnitude
$\delta\Psi^{(\rm lead)} \sim -\delta\Psi^{(\rm rest)}$	✗	too strong

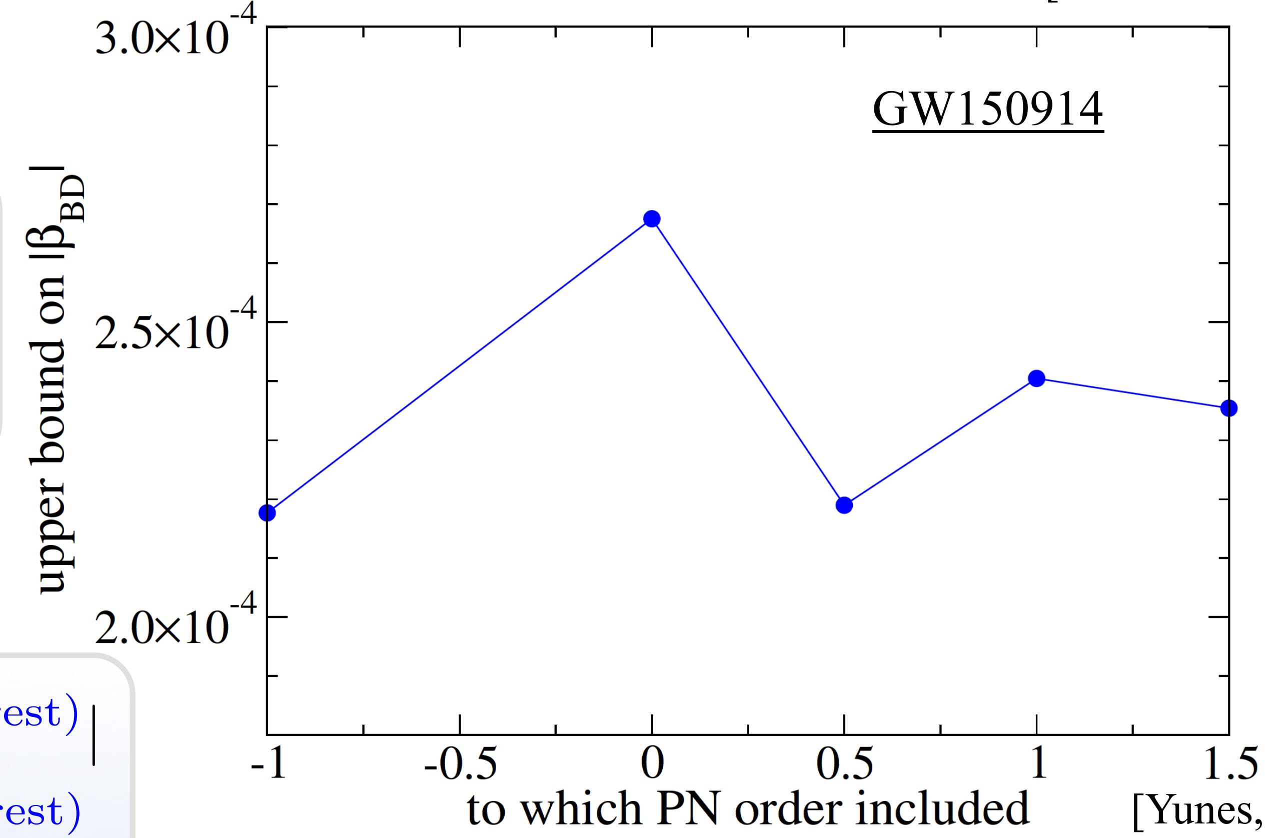
Example

Brans-Dicke theory

-1PN   symmetric mass ratio   0 ~ 1.5PN

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

[Yunes et al. (2012)]



[Yunes, KY & Pretorius (2016)]

Higher PN terms affect the leading PN bound only by ~10%.

$$|\delta\Psi^{\rm (lead)}| \gg |\delta\Psi^{\rm (rest)}|$$

$$\delta\Psi^{\rm (lead)} \sim +\delta\Psi^{\rm (rest)}$$

Mapping to Theoretical Constraints

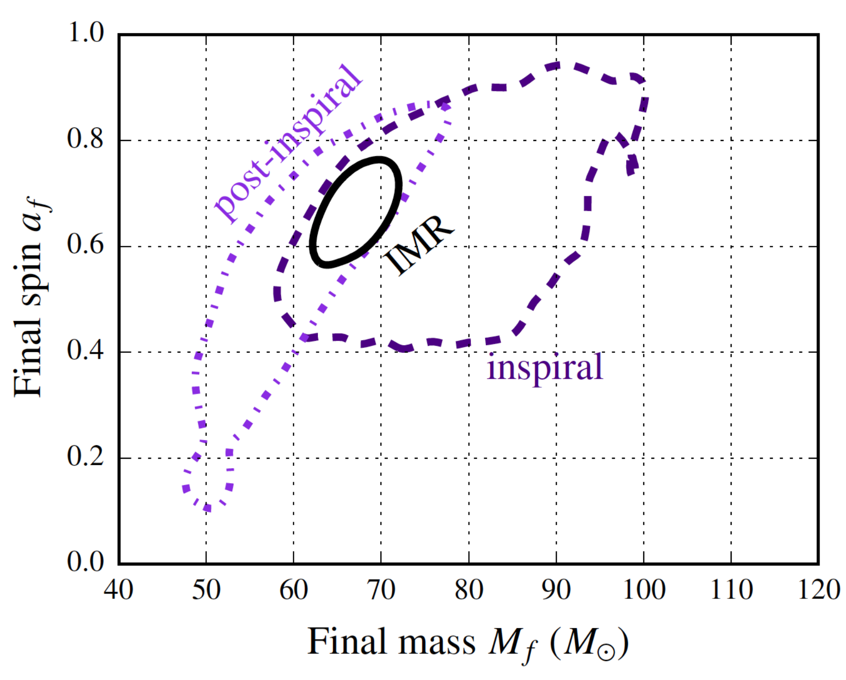
no meaningful constraints
(beyond small-coupling approximation)

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

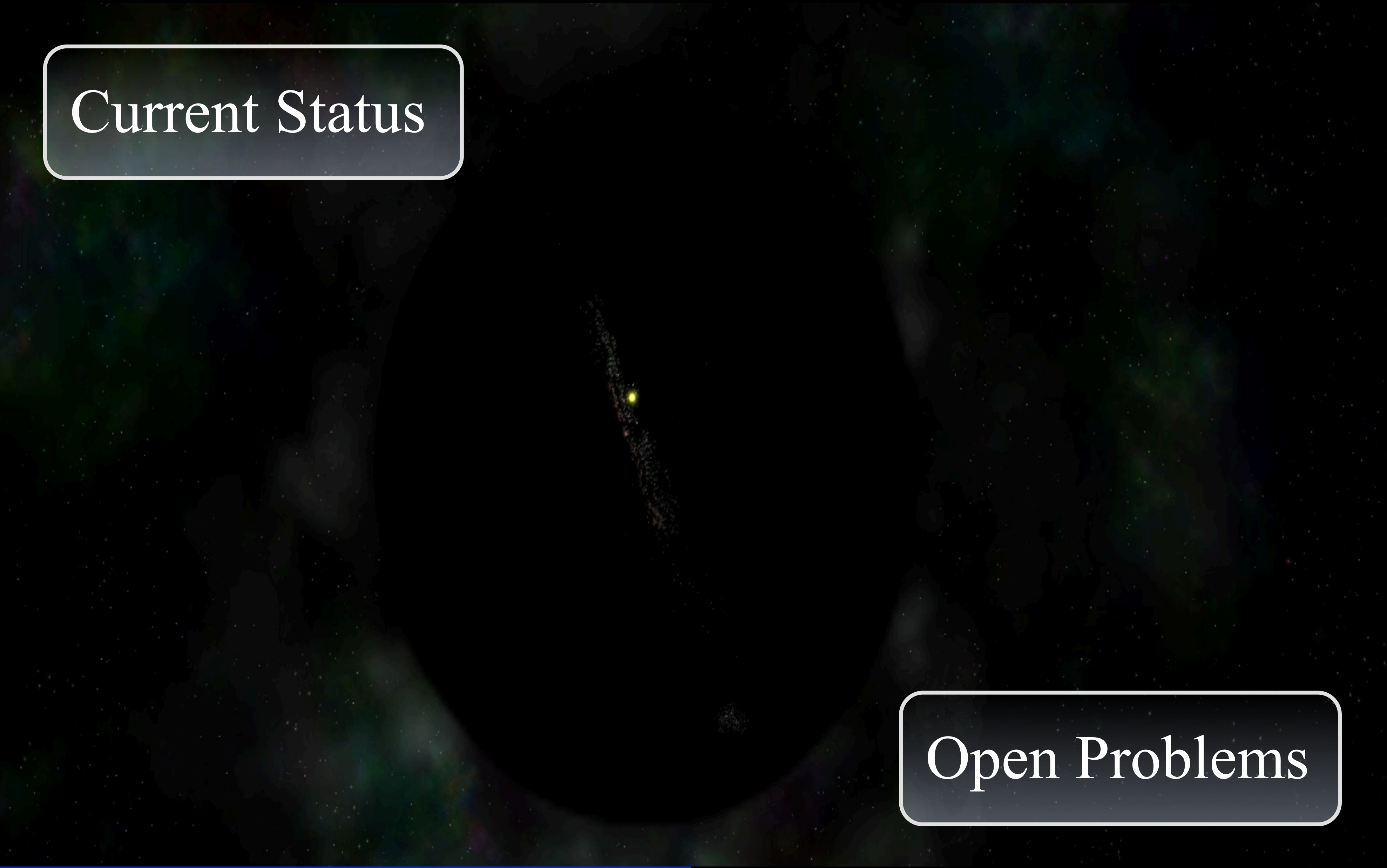
Other Tests of GR done by LVC

- residual SNR from best-fit template
  GR prediction for GW150914 verified to at least 4%
- Constraint on the graviton mass
- Consistency test of GR Kerr with inspiral and post-inspiral



[LVC PRL 116 221101 (2016)]

Outline



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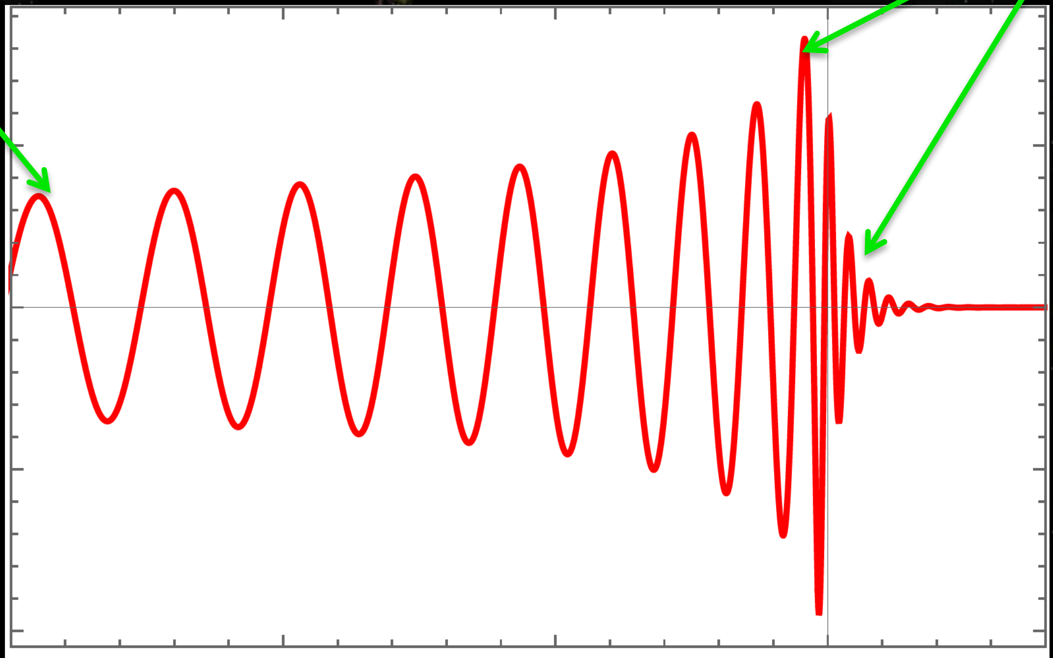
Open Problems

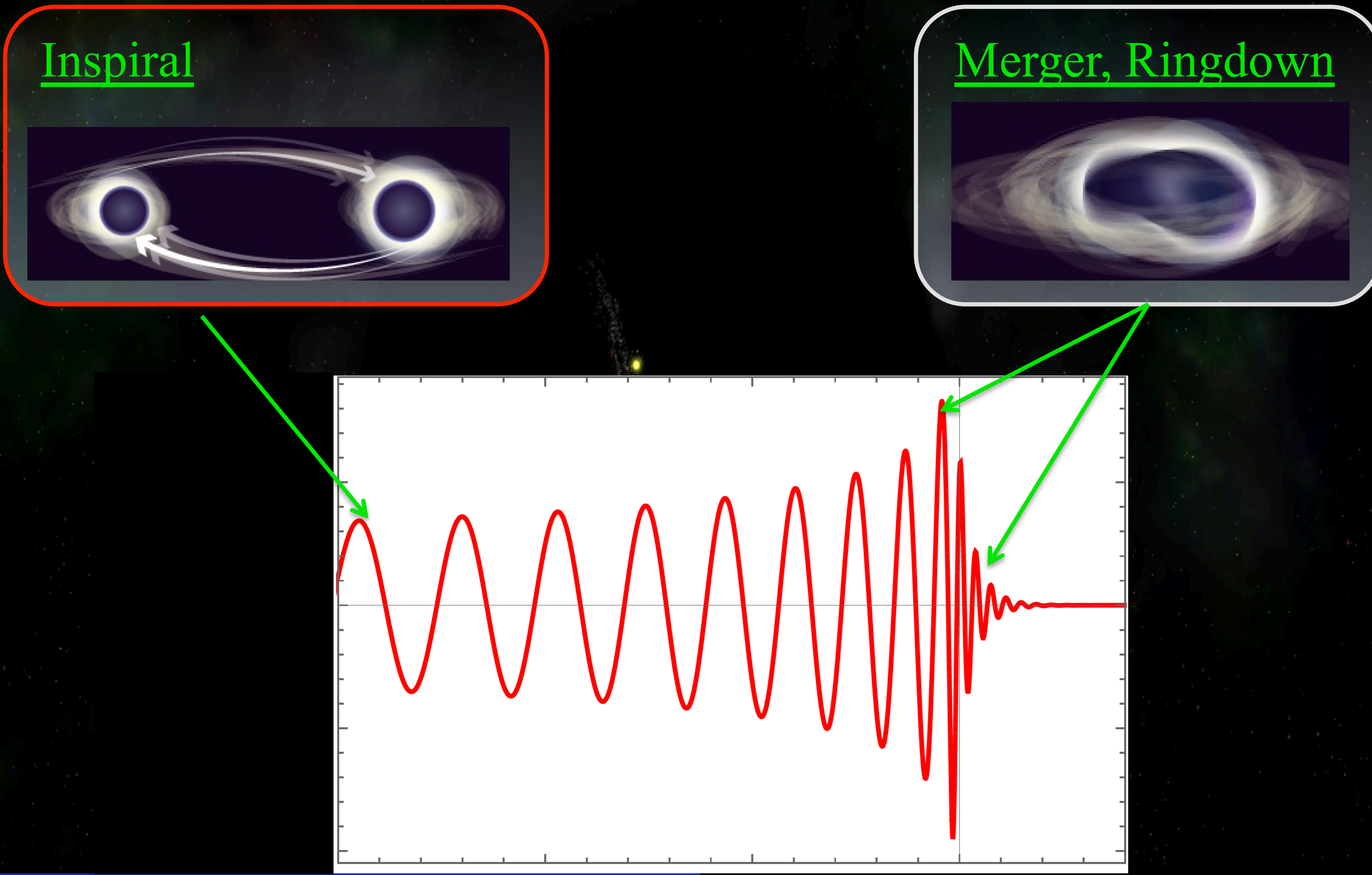
Gravitational Waveform Template

Inspiral

Merger, Ringdown



Gravitational Waveform Template



Higher PN terms for Stronger Constraints

binary parameters consistent with no scalar dipole radiation
(equal scalar charges for 2 BHs)

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0PN correction (modified quadrupolar radiation) might be larger than -1PN

Spin Precession is also Important!

parity-violating theory
BH spin is crucial

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spin-aligned PN waveform [KY et al. (2012)]
precessing waveform is missing

BH Sensitivities…

BH sensitivities (scalar or "vector" charges) unknown

c.f.) NS sensitivities [KY et al. PRL, PRD (2014)]

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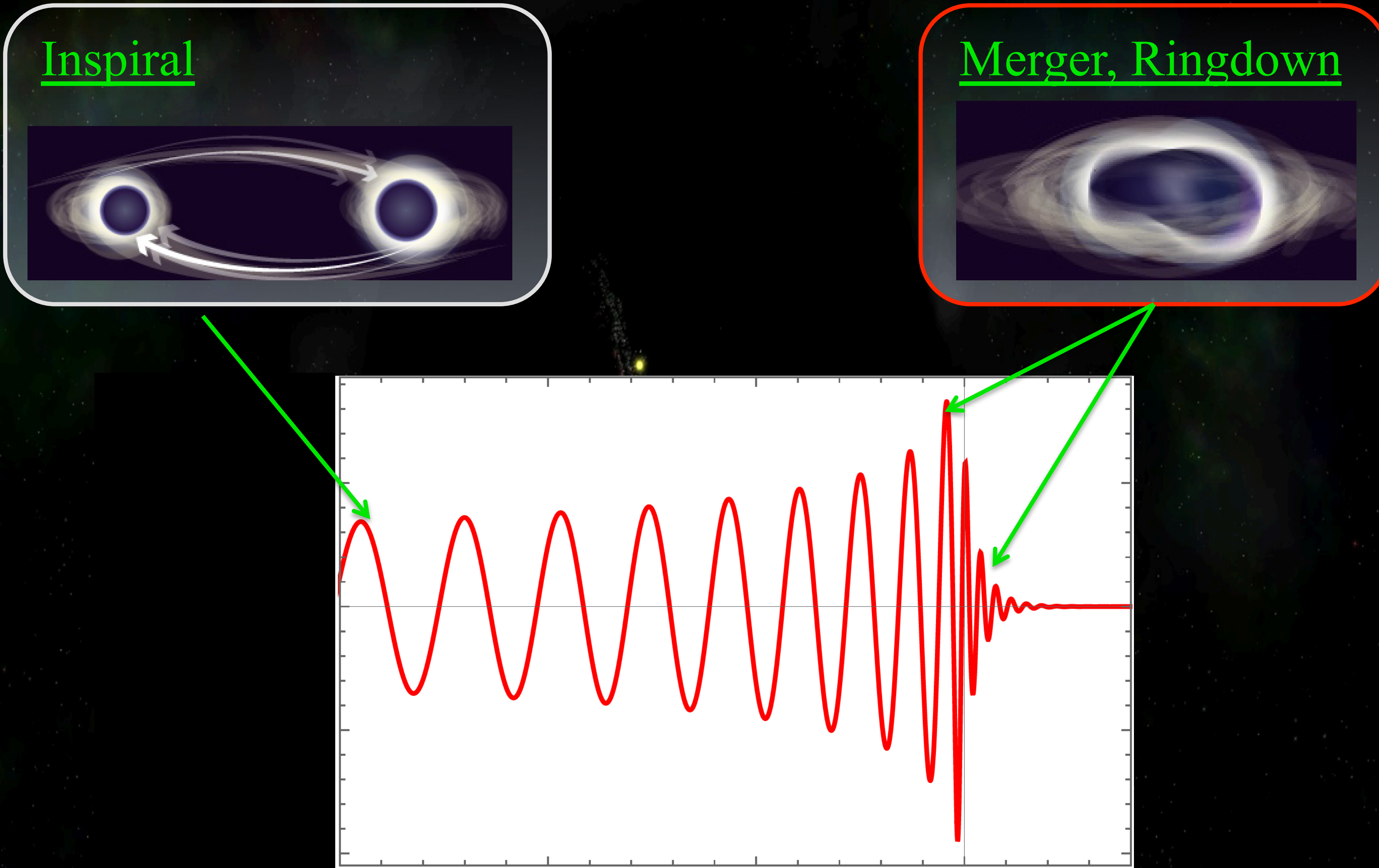
-1PN correction currently unknown
may be important for future detections

Gravitational Waveform Template



Open Problems (Merger, Ringdown)

- parameterized non-GR waveform
- binary BH coalescence simulations in non-GR theories
  - ✓ Scalar-tensor theories [Healy et al. (2012), Berti et al. (2013)]
  - ✓ dynamical Chern-Simons [Stein, Berti, Chen… (in progress)]
- well-posedness

  effective field theory approach (small coupling approximation)
- Effective-one-Body calculation in non-GR theories

Open Problems (Merger, Ringdown)

- Is ringdown always damped sinusoid?
  Same parameterization as in GR?
- Is analytic waveform useful?
  Should the waveform be obtained numerically?

IMRPhenomD Merger-Ringdown Amplitude

γ_2, γ_3 : fitting coefficients

damping time

$$A_{\rm merg,ring} \propto f^{-7/6} \frac{\gamma_3/\tau}{4\pi^2 (f-f_0)^2 + (\gamma_3/\tau)^2} e^{-\gamma_2 (f-f_0)\tau}$$

ringdown frequency

different from simple Lorentzian

Summary

List of Open Problems

Inspiral

- Higher PN terms
- precessing waveform
- BH sensitivities

Merger, Ringdown

- parameterized non-GR waveform
- binary BH coalescence simulations in non-GR theories
- well-posedness
- Effective-one-Body calculation in non-GR theories
- Can GR ringdown waveform be used for non-GR theories?

Other Open Issues

- Probing negative PN corrections with the actual data
- Other fundamental pillars in GR?
  Other theories?
  Screening?
- Amplitude corrections?
- Stochastic GW background
  [Maselli et al. (2016)]
  Large astrophysical systematics?
- Large eccentricity (burst search) [Loutrel Yunes & Pretorius (2014)]
- Probing gravity with future detectors (Nico)

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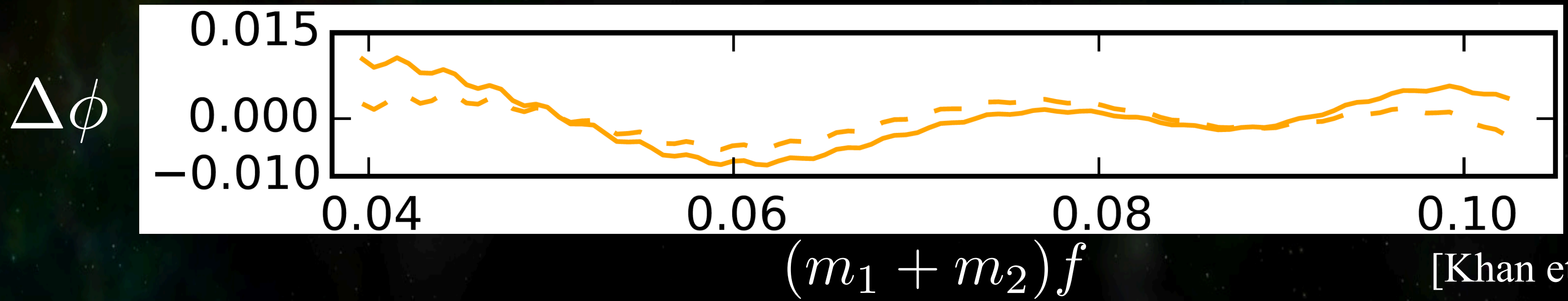
Thank You

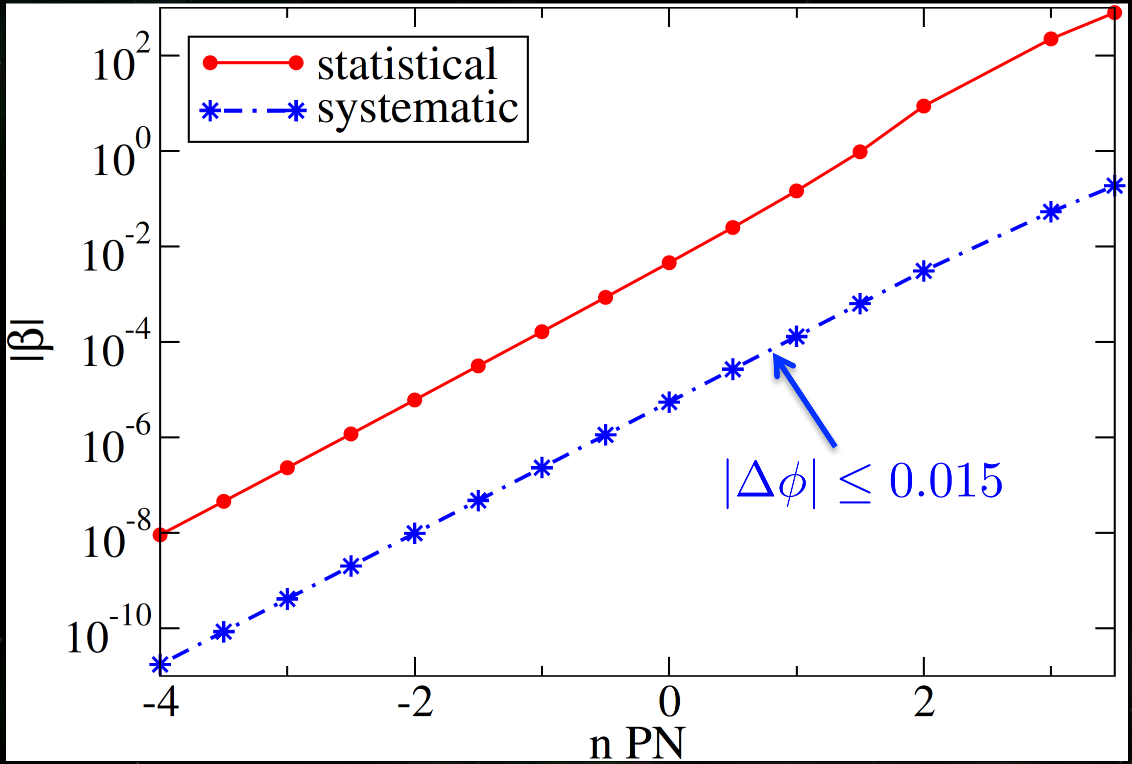
Back Up

Systematics due to Mismodeling Templates

Waveform mismodeling error in phase $m_1 = m_2$ $\chi_1 = \chi_2 = 0$



[Khan et al. (2015)]



mismodeling systematics much smaller than statistical errors

[Yunes, KY & Pretorius (2016)]

Well-posedness

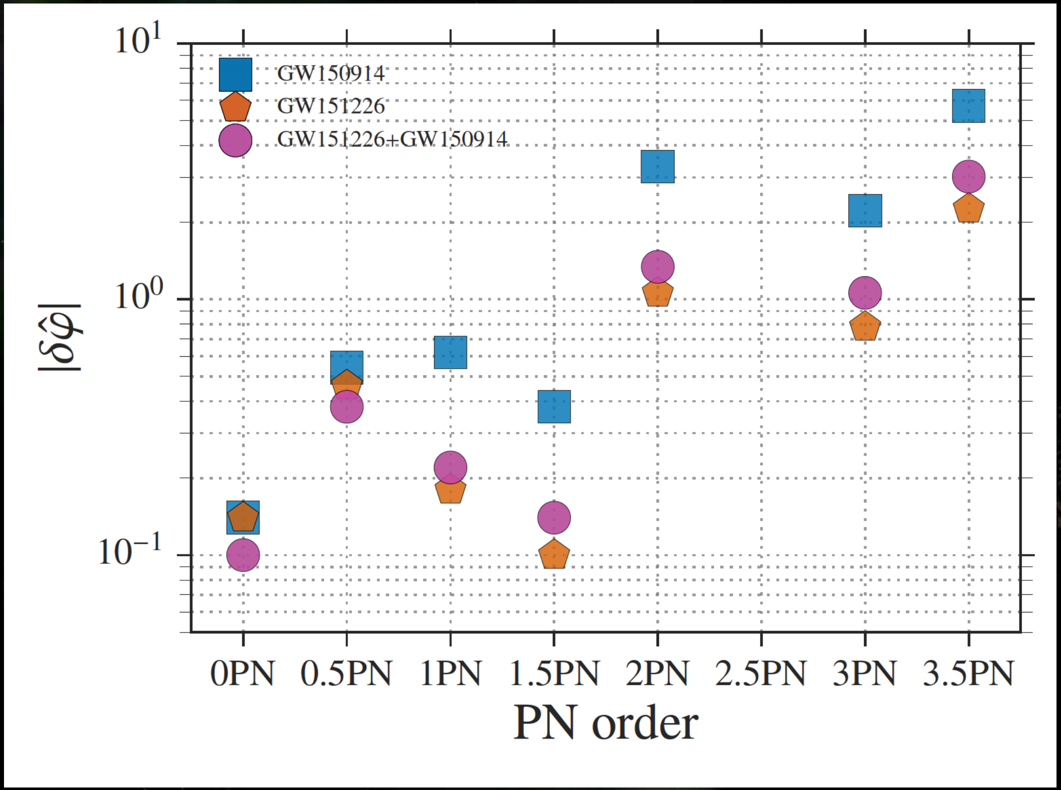
Theory	Field content	Strong EP	Massless graviton	Lorentz symmetry	Linear $T_{\mu\nu}$	Weak EP	Well- posed?	Weak-field constraints
Extra scalar field								
Scalar–tensor	S	×	✓	✓	✓	✓	✓[34]	[35–37]
Multiscalar	S	×	✓	✓	✓	✓	✓[38]	[39]
Metric $f(R)$	S	×	✓	✓	✓	✓	✓[40, 41]	[42]
Quadratic gravity								
Gauss–Bonnet	S	×	✓	✓	✓	✓	✓?	[43]
Chern–Simons	P	×	✓	✓	✓	✓	×✓? [44]	[45]
Generic	S/P	×	✓	✓	✓	✓	?	
Horndeski	S	×	✓	✓	✓	✓	✓?	
Lorentz-violating								
Æ-gravity	SV	×	✓	×	✓	✓	✓?	[46–49]
Khronometric/ Hořava–Lifshitz	S	×	✓	×	✓	✓	✓?	[48–51]
n-DBI	S	×	✓	×	✓	✓	?	none ([52])
Massive gravity								
dRGT/Bimetric	SVT	×	×	✓	✓	✓	?	[17]
Galileon	S	×	✓	✓	✓	✓	✓?	[17, 53]
Nondynamical fields								
Palatini $f(R)$	—	✓	✓	✓	×	✓	✓	none
Eddington–Born–Infeld	—	✓	✓	✓	×	✓	?	none
Others, not covered here								
TeVeS	SVT	×	✓	✓	✓	✓	?	[37]
$f(R)\mathcal{L}_m$	?	×	✓	✓	✓	×	?	
$f(T)$	?	×	✓	×	✓	✓	?	[54]

Note. See text for details of the entries. Key to abbreviations: S: scalar; P: pseudoscalar; V: vector; T: tensor; ?: unknown; ✓?: not explored in detail or not rigorously proven, but there exist arguments to expect ✓. The occurrence of ×✓? means that there exist arguments in favor of well-posedness within the EFT formulation, and against well-posedness for the full theory. Weak-field constraints (as opposed to strong-field constraints, which are the main topic of this review) refer to Solar System and binary pulsar tests. Entries below "Others, not covered here" are not covered in this review.

[Berti et al. (2015)]

Combined Bounds

$$\Psi = \Psi_{\rm GR}\left(1 + \delta\hat{\varphi}\, v^{n/2}\right)$$



[LVC, PRX6 (2016)]

How can we map combined constraints on model-independent non-GR parameters to physical parameters?

Einstein-dilaton Gauss-Bonnet Gravity

$$\beta_{-1\mathrm{PN}} \sim \frac{\alpha^2}{m_{\mathrm{tot}}^4} \frac{\left[m_2^2 s_1(\chi_1) - m_1^2 s_2(\chi_2)\right]^2}{m_{\mathrm{tot}}^4}$$

(dimensionless) scalar charge

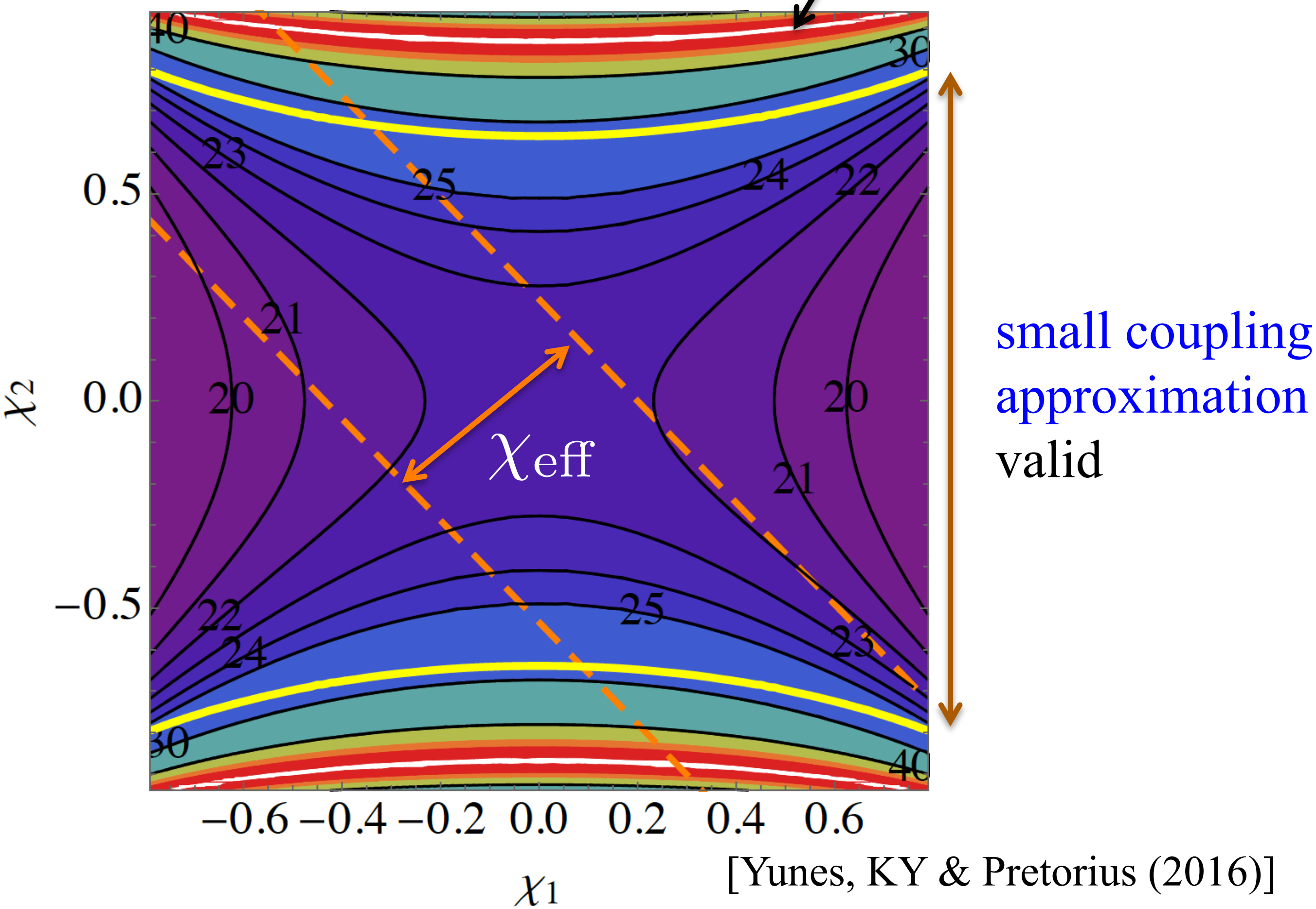
(dimensionless) spin

current bound

$$\sqrt{\alpha} \lesssim 1\mathrm{km}$$

0PN correction (modified quadrupolar radiation) might be larger than -1PN

GW150914 bound on $\sqrt{\alpha}$ [km]



[Yunes, KY & Pretorius (2016)]