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The implications of GW detections for GR extensions

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"Quest for the Origin of Particles and the Universe"

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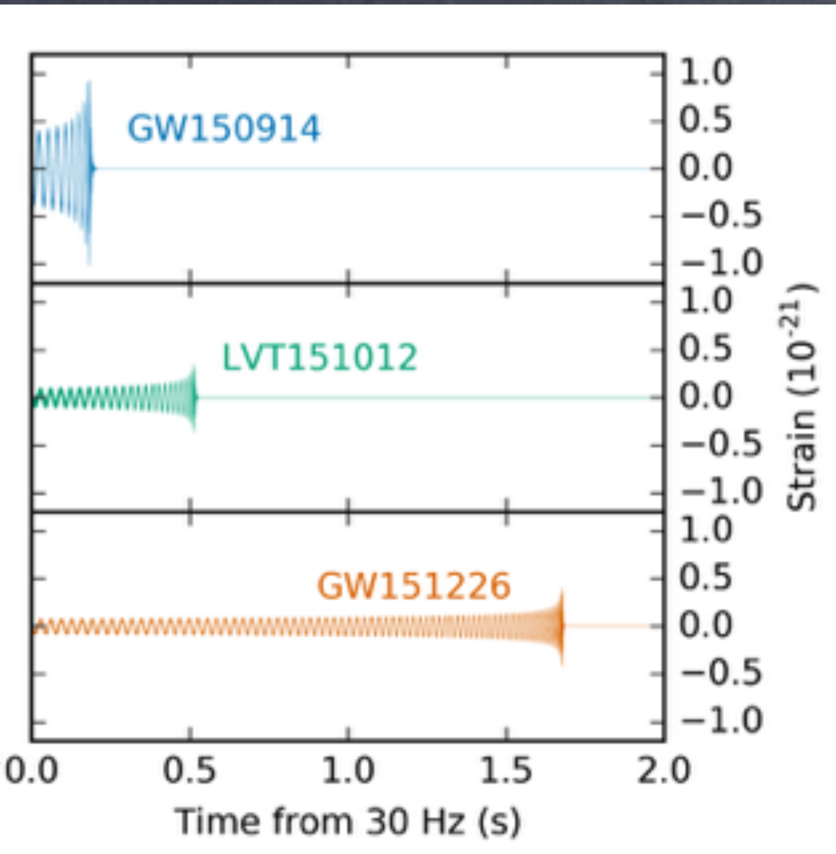
“2.9” GW detections



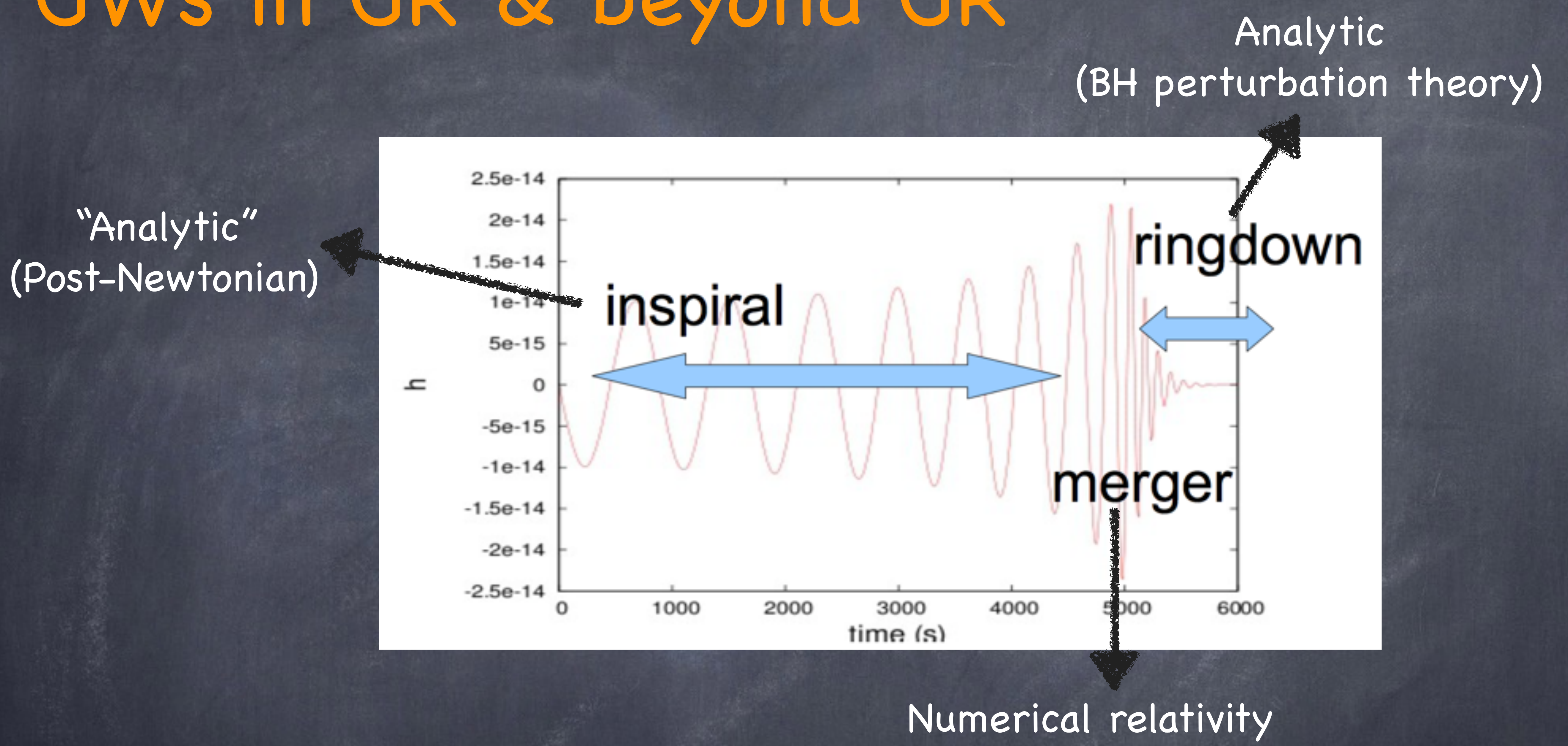
Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate FAR/yr^{-1}	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\sigma$	$> 5.3\sigma$	1.7σ
Primary mass $m_1^{\rm source}/M_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\rm source}/M_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathcal{M}^{\rm source}/M_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\rm source}/M_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin $\chi_{\rm eff}$	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_{\rm f}^{\rm source}/M_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin $a_{\rm f}$	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\rm rad}/(M_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\rm peak}/({\rm erg\,s^{-1}})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance D_L/Mpc	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/{\rm deg}^2$	230	850	1600

Why important?

- First direct detection of GWs (indirect evidence from binary pulsars)
- High BH masses imply formation in weak-wind/low-metallicity environment
- Opens up era of multi-band EM+GW astronomy
- Test GR for the first time in strong-field ($U_{\rm Newton}$~c^2) and highly relativistic (v~c) regime

This talk: why we expect GWs to be different in theories that extend GR, and what is the physics behind these differences

GWs in GR & beyond GR



- Focus on inspiral (where we can make predictions in modified gravity theories)
- Some general consideration on merger (if time allows)
- No ringdown tests (anyway possible only with third generation/space-based detector, cf Berti, Sesana, EB, Cardoso, Belczynski 2016)
- No propagation effects (weak constraints on GR alternatives unless EM counterpart)

Beyond GR: how?

Lovelock's theorem

In a 4-dimensional spacetime, the only divergence-free symmetric rank-2 tensor constructed only from the metric $g_{\mu\nu}$ and its derivatives up to second differential order, and preserving diffeomorphism invariance, is the Einstein tensor plus a cosmological term, i.e. $G_{\mu\nu} + \Lambda\, g_{\mu\nu}$

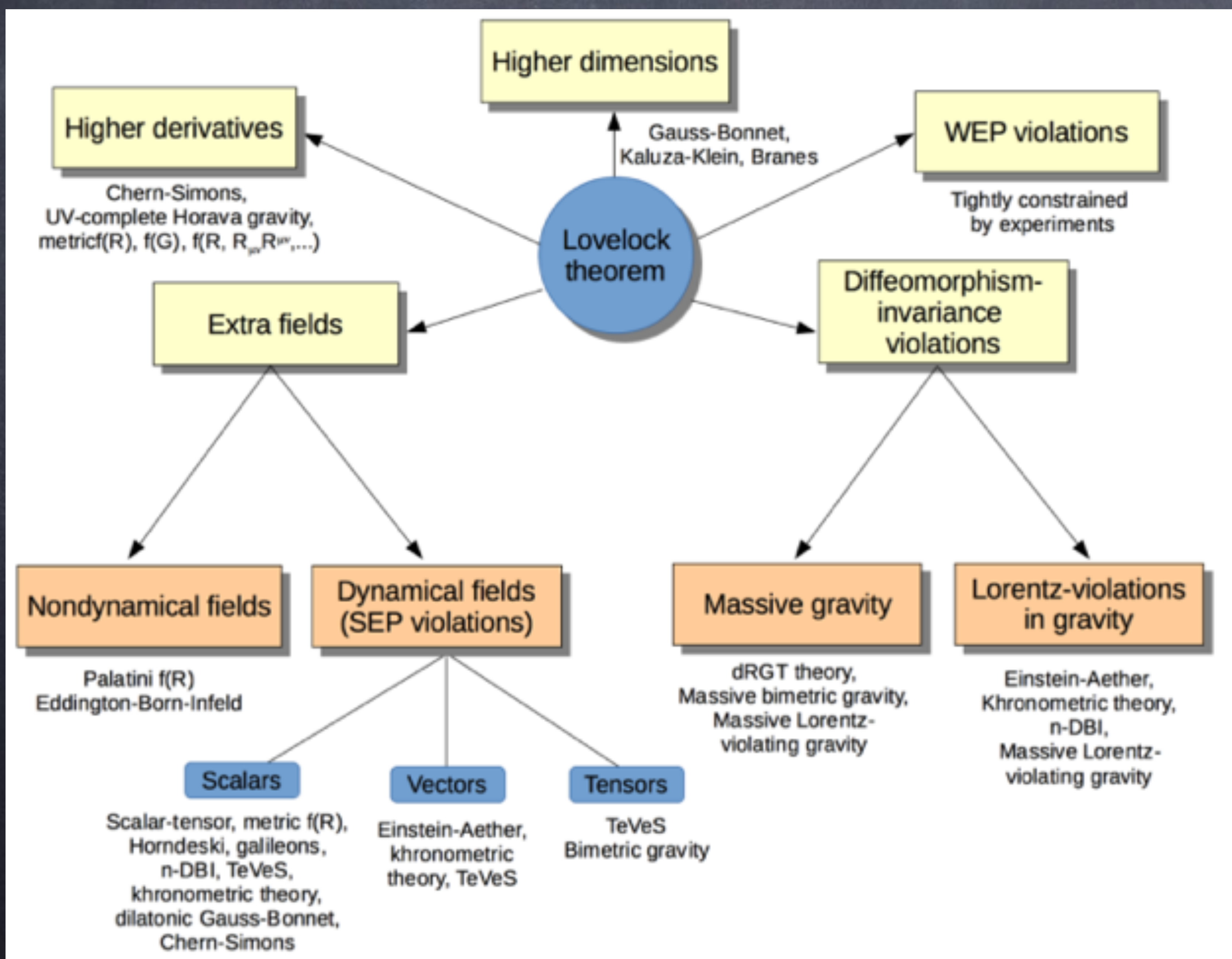


Figure adapted from Berti, EB et al 2015

Generic way to modify GR is to add extra fields!

How to couple extra fields?

- Satisfy weak equivalence principle (i.e. universality of free fall for bodies with weak self-gravity) by avoiding coupling extra fields to matter (i.e. no fifth forces at tree level)

$$S_m(\psi_{matter}, g_{\mu\nu})$$

- But extra fields usually couple non-minimally to metric, so gravity mediates effective interaction between matter and new field in strong gravity regimes (Nordtvedt effect)
- Equivalence principle violated for strongly gravitating bodies

Strong EP violations

For strongly gravitating bodies, gravitational binding energy gives large contribution to total mass, but binding energy depends on extra fields! Examples:

- Brans-Dicke, scalar-tensor theories: $S = \int d^4x \frac{\sqrt{-g}}{2\kappa} \left[\varphi R - \frac{\omega(\varphi)}{\varphi} \partial_\mu \varphi \partial^\mu \varphi \right]$

  $G_{eff} \propto G_N/\varphi$, but φ in which star is immersed depends on cosmology, presence of other star

- Lorentz-violating gravity (Einstein-aether, Horava): preferred frame exists for gravitational physics → gravitational mass of strongly gravitating bodies depends on velocity wrt preferred frame

If gravitational mass depends on fields, deviations from GR motion already at geodesics level

$$S_m = \Sigma_n \int m_n(\varphi) ds \qquad u_n^\mu \nabla_\mu (m_n u^\nu) \sim \mathcal{O}(s_n) \qquad s_n \equiv \frac{\partial m_n}{\partial \varphi}$$

sensitivities or charges or hairs,
i.e. response to change in field boundary conditions

Strong EP violations and GW emission

- Whenever strong equivalence principle is violated, monopolar and dipolar radiation may be produced

- In electromagnetism, no monopolar radiation because electric charge conservation is implied by Maxwell eqs

- In GR, no monopolar or dipolar radiation because energy and linear momentum conservation is implied by Einstein eqs

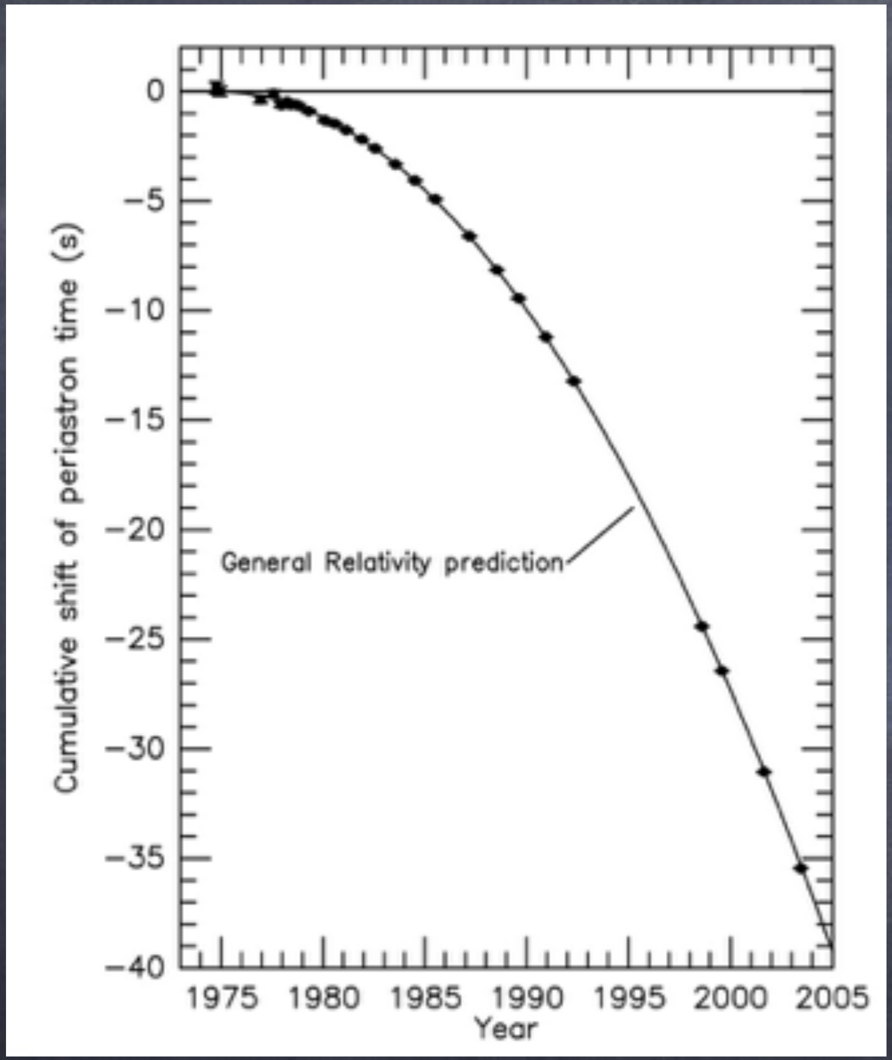
e.g. $M_1 \sim \int \rho x^i d^3x \quad h \sim \frac{G}{c^3}\dot{M}_1 \sim \frac{G}{c^3}\frac{P}{r}$ not a wave!

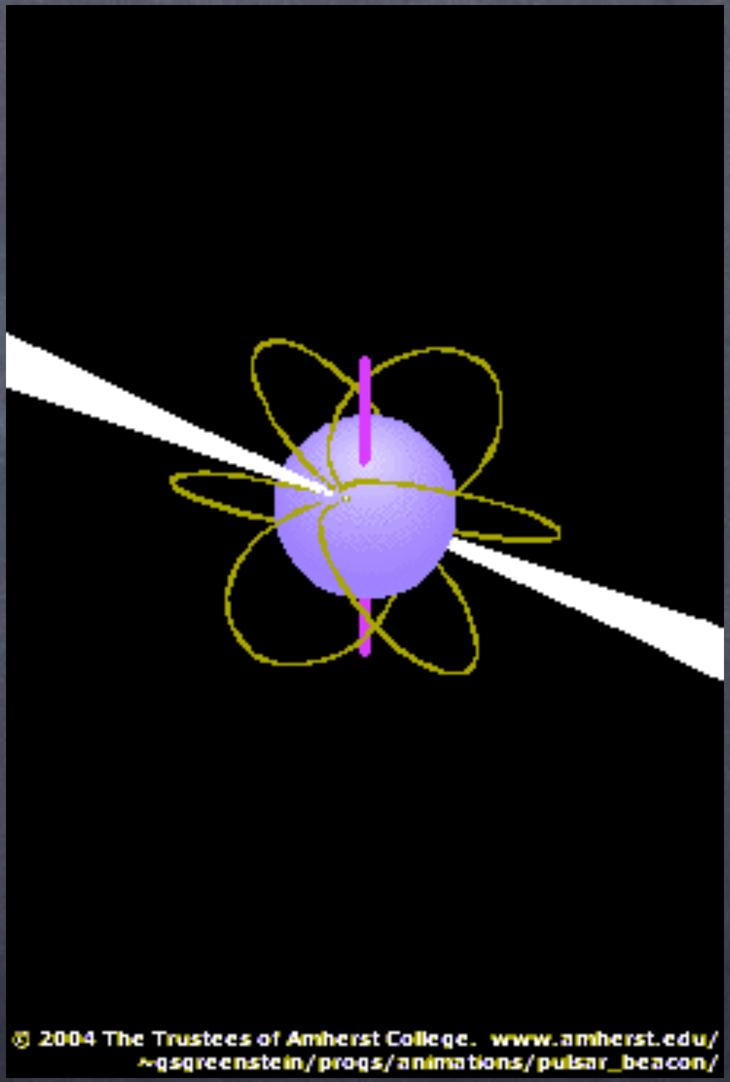
- In GR extensions, effective coupling matter-extra fields in strong gravity regimes → energy and momentum transfer between bodies and extra field, monopolar and dipolar GW emission, modified quadrupole formula

$$h \sim \frac{G}{c^3}\dot{M}_1 \sim \frac{G}{c^3}\frac{d}{dt}(m_1(\varphi)x_1 + m_2(\varphi)x_2) \sim \frac{G}{c^3}\mathcal{O}(s_1 - s_2)$$

Dipolar emission dominant for quasi-circular systems;
1.5 PN effect vs 2.5 PN in GR! But effect depends on nature of bodies

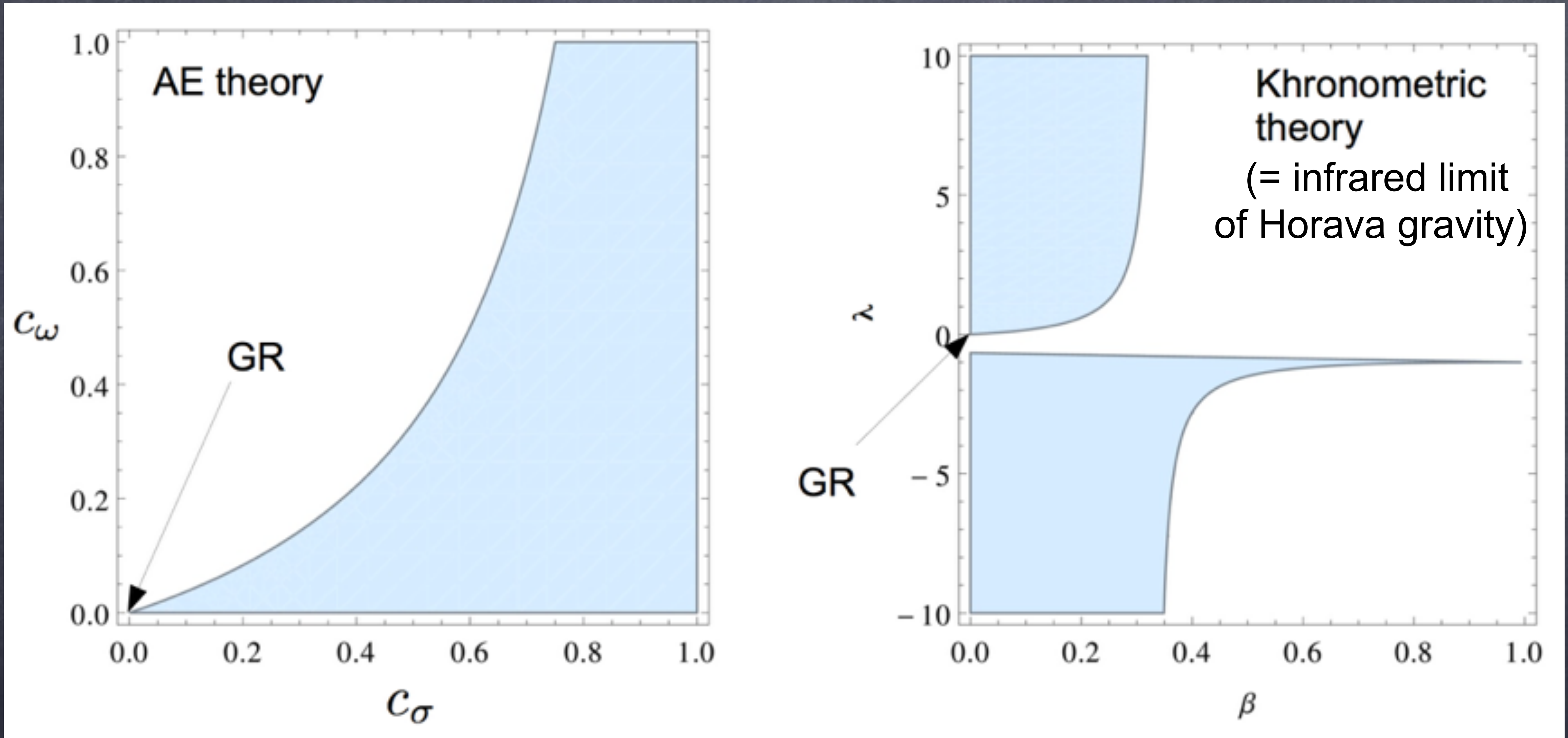
(Absence of) dipolar emission in binary pulsars





(Absence of) dipolar emission in binary pulsars

An example: Lorentz-violating gravity



No ghosts+no gradient instabilities+solar system tests +absence of Cherenkov gravitational radiation (to agree with cosmic rays)

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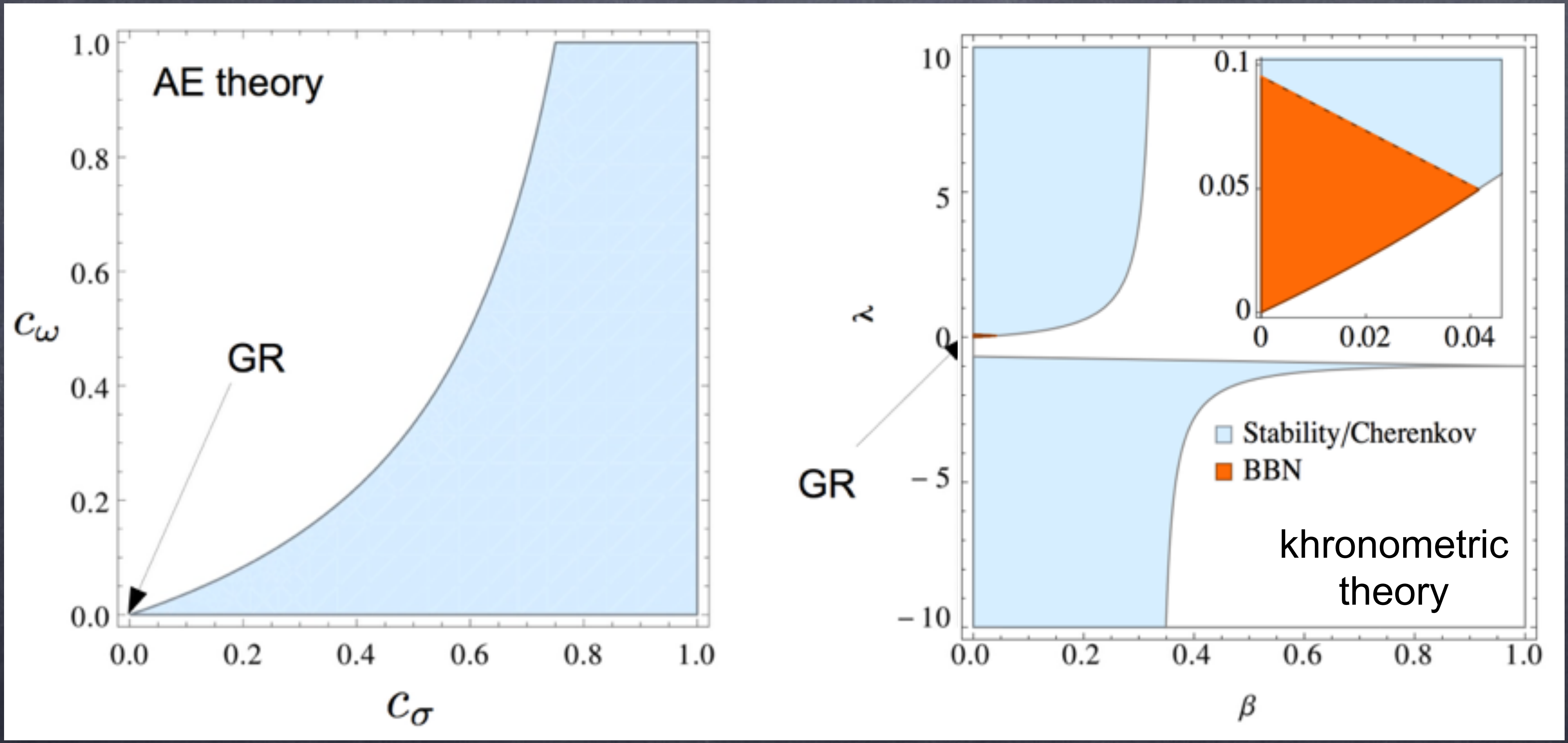

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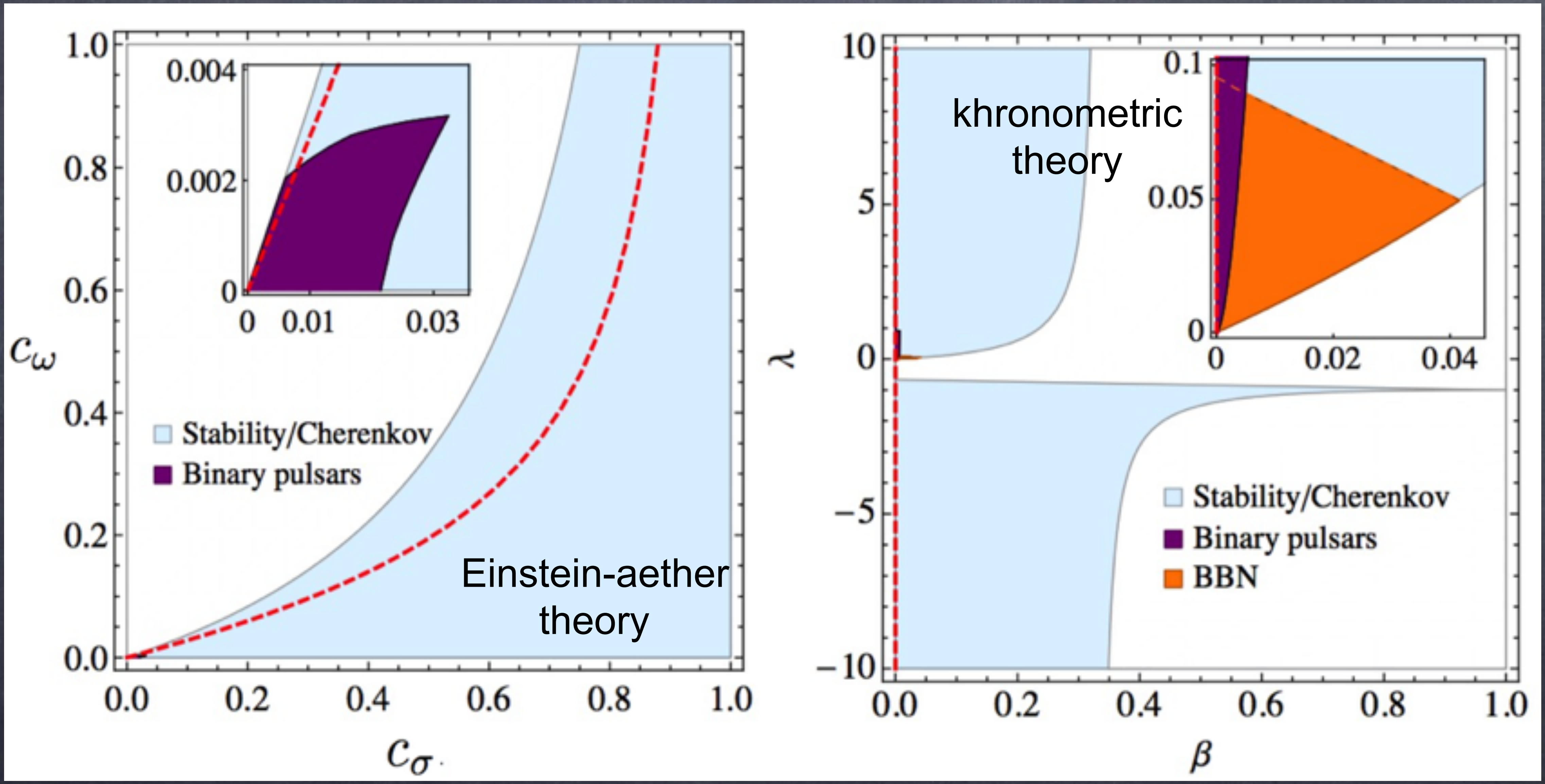
Yagi, Blas, EB & Yunes 2014



No ghosts+no gradient instabilities+solar system tests +absence of Cherenkov gravitational radiation (to agree with cosmic rays)+cosmology+pulsars

(Absence of) dipolar emission in binary pulsars

- Damour-Esposito-Farese scalar-tensor theory

$$S = \int d^4x \frac{\sqrt{-g}}{2\kappa} \left[\varphi R - \frac{\omega(\varphi)}{\varphi} \partial_\mu \varphi \partial^\mu \varphi \right] + S_m(\psi_{matter}, g_{\mu\nu})$$

- Generalizes Fierz-Jordan-Brans-Dicke by introducing linear coupling β between scalar and curvature, besides constant coupling α:

$$\Box\varphi \sim \alpha R + \beta \varphi R$$

- Strongly non linear effects inside NS ("spontaneous scalarization")

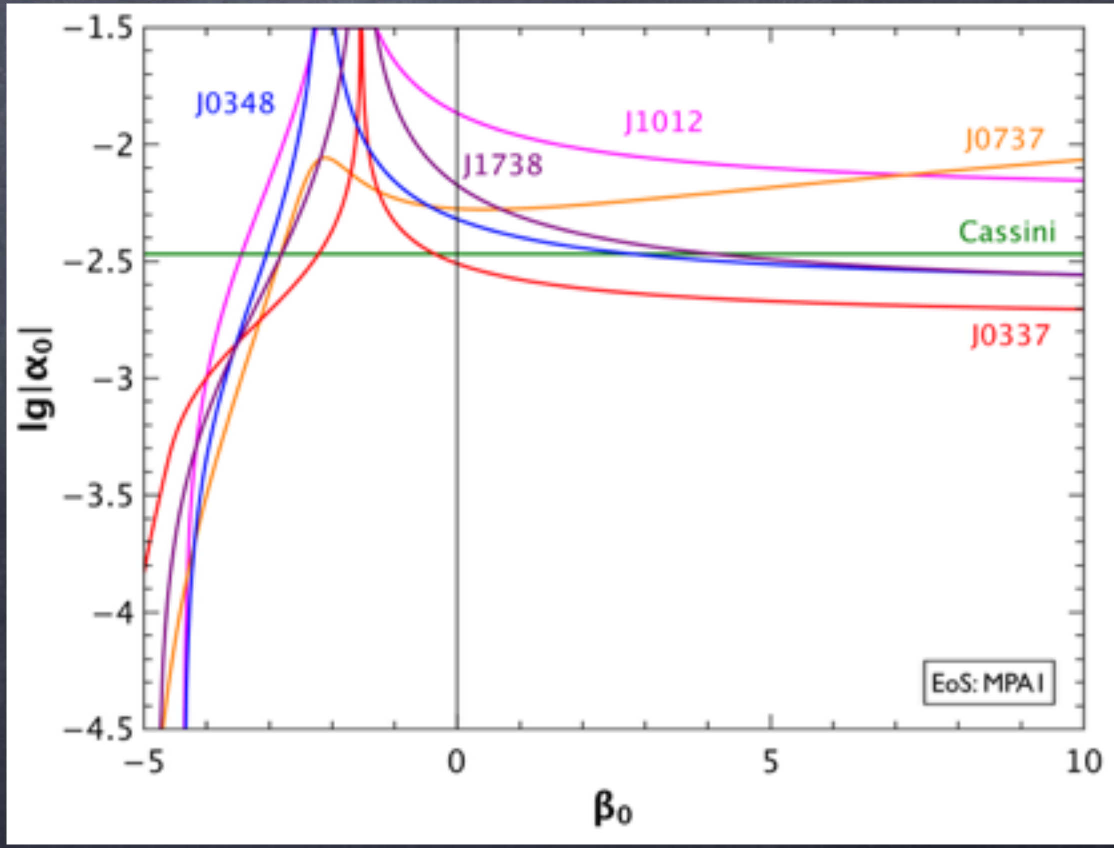


Figure credits: Wex, private comm.

Dipolar emission in BH binaries?

- Not present in Fierz-Jordan-Brans-Dicke-like theories (e.g. Damour-Esposito-Farese theory) because R=0 in vacuum

$$\Box\varphi \sim \alpha R + \beta\varphi R$$

Loophole: non-trivial (cosmological) boundary conditions

- But other curvature invariants do not vanish in vacuum, e.g. Kretschmann, Gauss-Bonnet, Pontryagin

$$S = \int d^4x\sqrt{-g}\left[R + \frac{1}{2}(\nabla\varphi)^2 + f_0(\varphi)R + f_1(\varphi)R^2 + f_2(\varphi)K + f_3(\varphi)^*RR + f_4(\varphi)\mathcal{G}\right]$$

$$^*RR \equiv {}^*R^{\alpha\beta\gamma\delta}R_{\alpha\beta\gamma\delta}, \qquad K \equiv R^{\alpha\beta\gamma\delta}R_{\alpha\beta\gamma\delta}$$

$$\mathcal{G} \equiv R^2 - 4R^{\alpha\beta}R_{\alpha\beta} + R^{\alpha\beta\gamma\delta}R_{\alpha\beta\gamma\delta}$$

$$\Box\varphi = f_0'(\varphi)R + f_1'(\varphi)R^2 + f_2'(\varphi)K + f_3'(\varphi)^*RR + f_4'(\varphi)\mathcal{G} \neq 0$$

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Caveats

$$S = \int d^4x\sqrt{-g}\left[R + \frac{1}{2}(\nabla\varphi)^2 + f_0(\varphi)R + f_1(\varphi)R^2 + f_2(\varphi)K + f_3(\varphi)^*RR + f_4(\varphi)\mathcal{G}\right]$$

$$\Box\varphi = f_0'(\varphi)R + f_1'(\varphi)R^2 + f_2'(\varphi)K + f_3'(\varphi)^*RR + f_4'(\varphi)\mathcal{G} \neq 0$$

f_1 = const: f(R) gravity = FJBD like theory with a potential
$f_1 \neq$ const: higher-order field equations, Ostrogradsky ghost

Ostrogradsky ghost

f_3 = const: same dynamics as GR (Pontryagin density is 4D topological invariant)
$f_3 \neq$ const: dynamical Chern-Simons, Ostrogradsky ghost

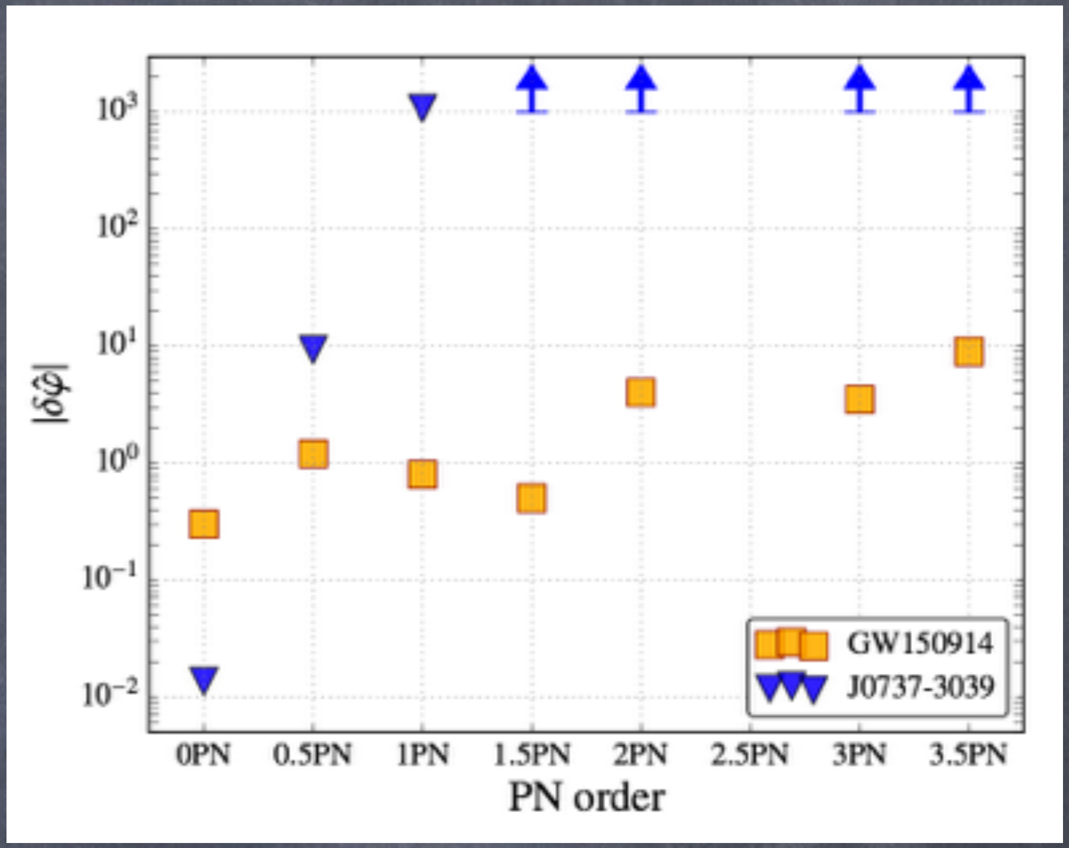
f_4 = const: same dynamics as GR (Gauss-Bonnet term is 4D topological invariant)
$f_4 \neq$ const: dilatonic Gauss-Bonnet gravity, 2nd-order field eqs, no Ostrogradsky ghost)

In shift-symmetric dilatonic Gauss-Bonnet [$f_4(\varphi) = \varphi$], sensitivities (and thus dipole emission) are zero for NS but NOT for BHs (EB & Yagi 2015, Yagi, Stein & Yunes 2015)

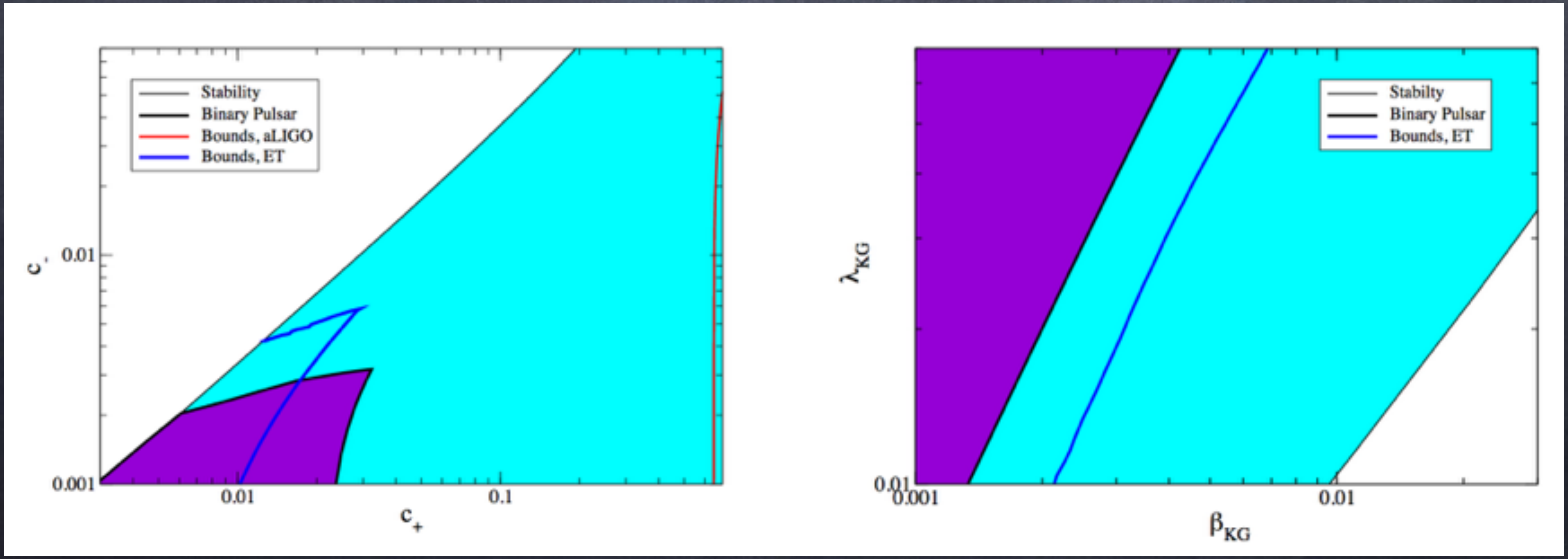
More general theories (with extra vector or tensor dof's) predict dipole emission also (though not exclusively) in BH binaries

Constraints on dipolar emission from direct detections

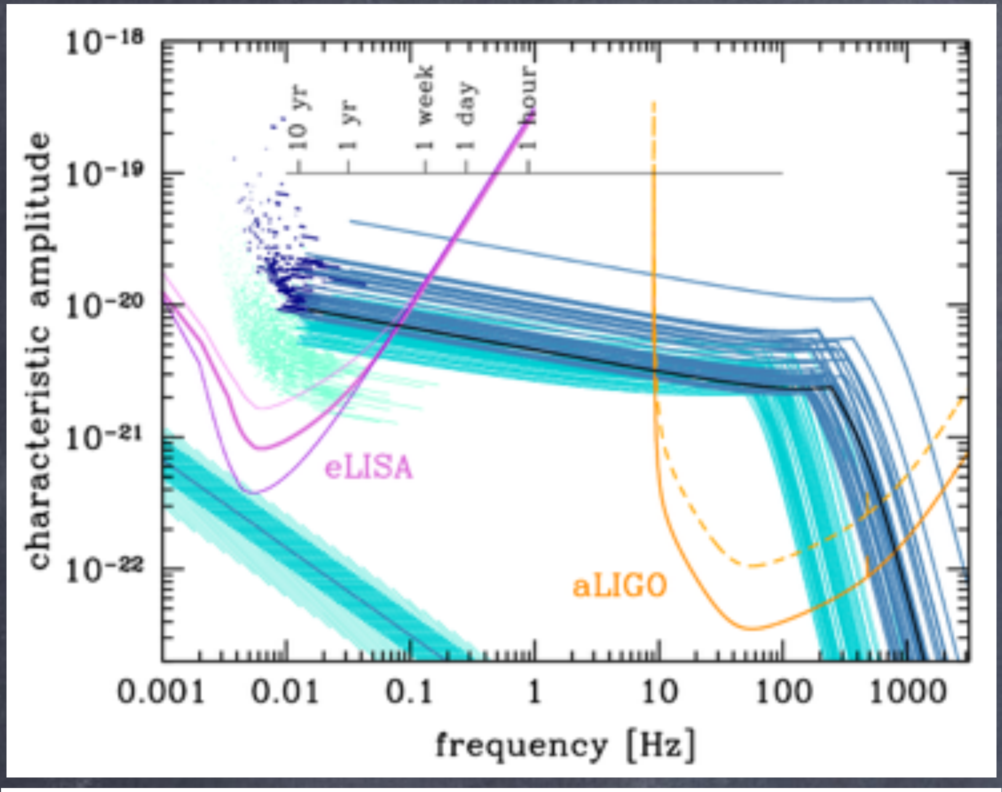
Weak bounds from advanced detectors



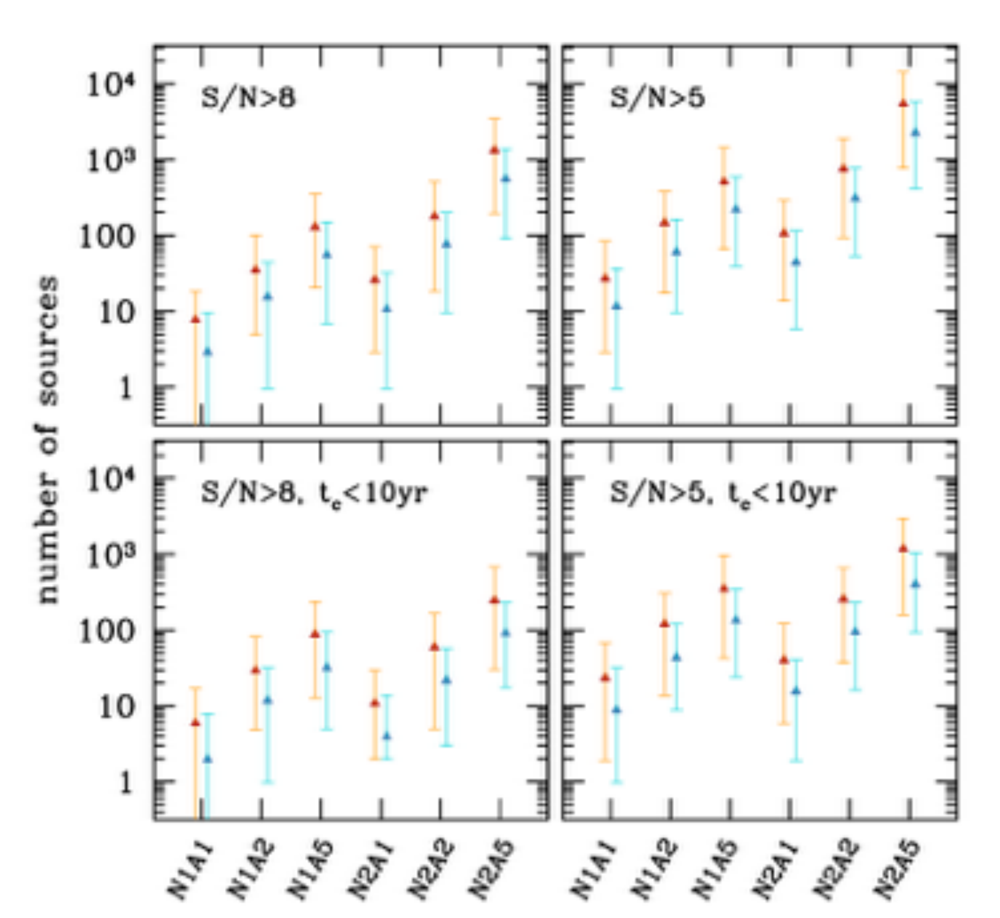
Better for 3rd-gen detectors, e.g. Lorentz violating gravity (Hansen, Yunes, Yagi 2015)

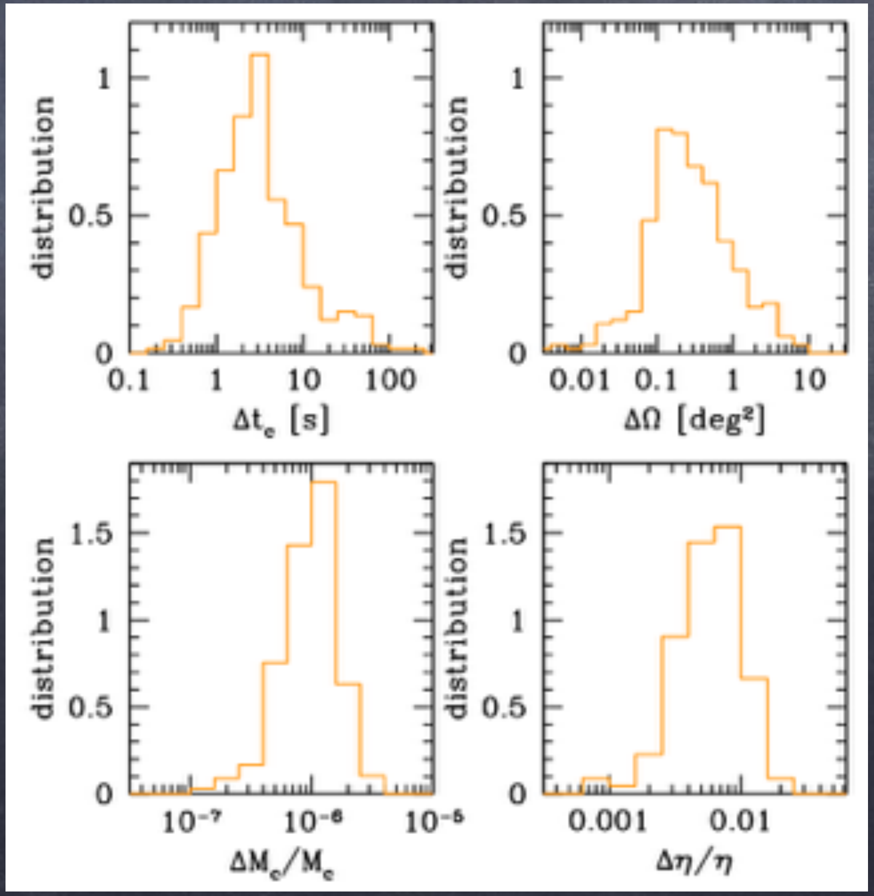


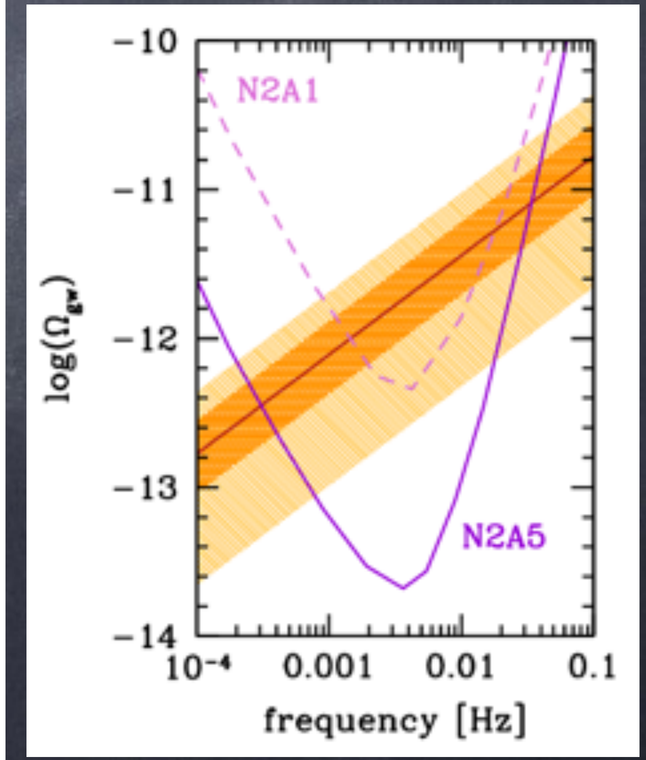
Multi-band observations of GW150914-like/ intermediate-mass binary BHs



- Also visible by eLISA if 6 links and 5 year mission! (Sesana 2016, Amaro-Seoane & Santamaria 2009)
- High-frequency noise is crucial!
- Astrophysical stochastic background may screen primordial ones





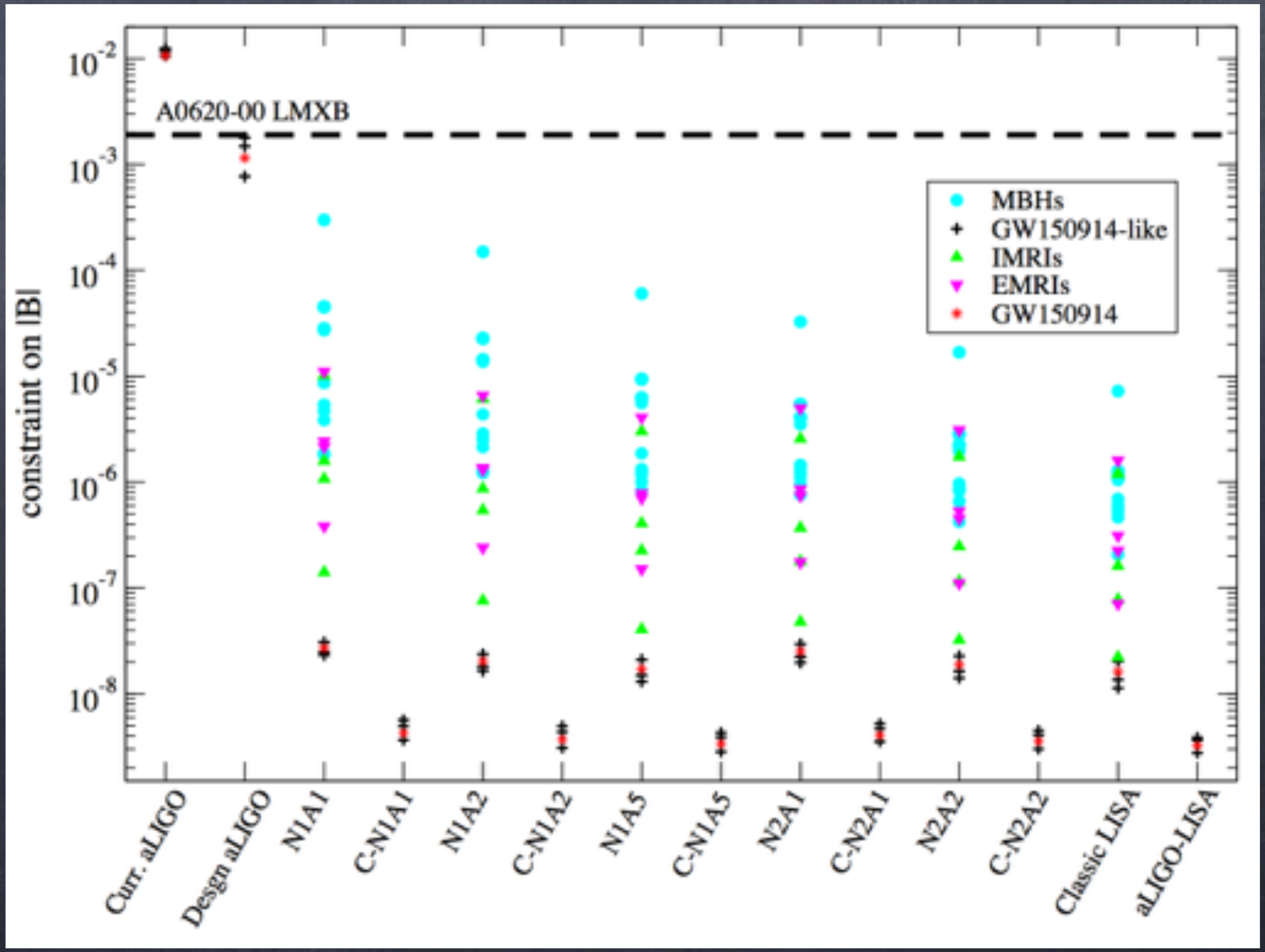


Figures from Sesana 2016

Tests of BH-BH dipole emission

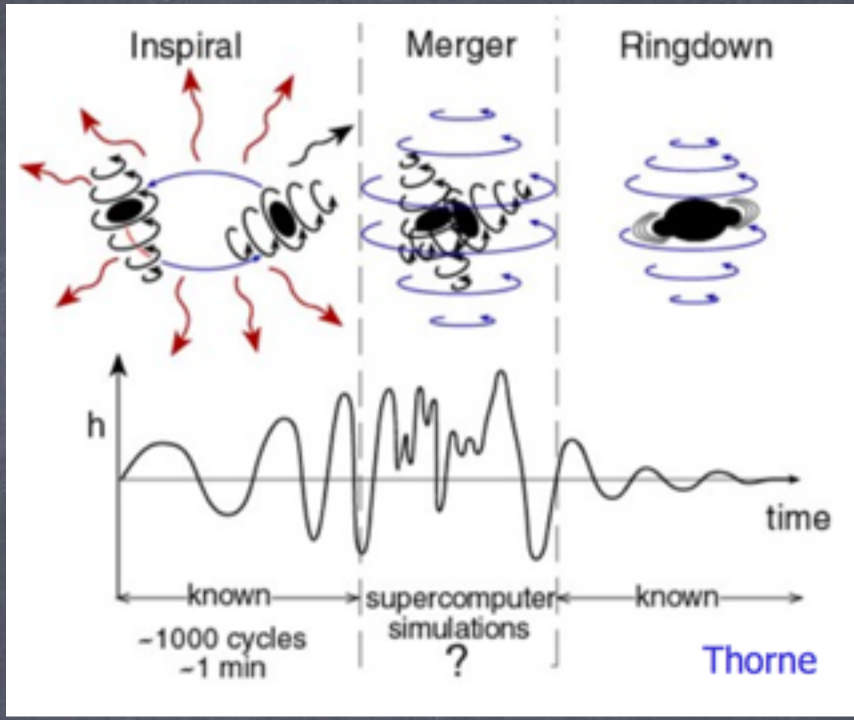
$$\dot{E}_{GW} = \dot{E}_{GR}\left[1 + B\left(\frac{v}{c}\right)^{-2}\right] \qquad B \propto (s_1 - s_2)^2$$

- Pulsar constrain $|B| \lesssim 2 \times 10^{-9}$, GW150914-like systems + eLISA will constrain same dipole term in BH-BH systems to comparable accuracy



From EB, Yunes & Chamberlain 2016

How about merger?



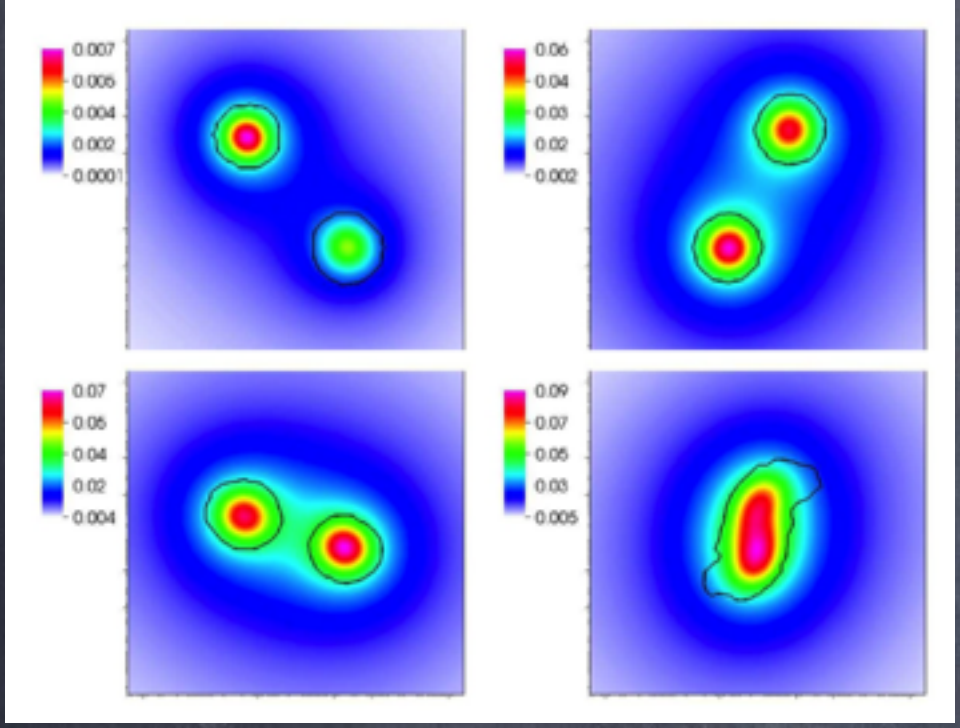
Possible surprises/
highly non-linear dynamics?

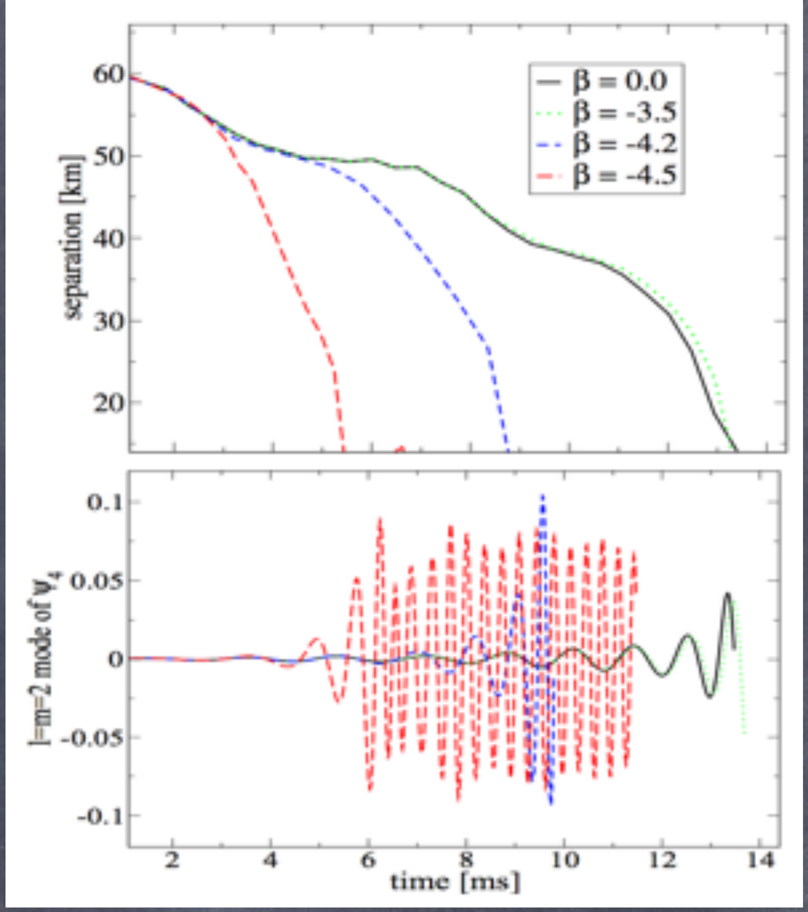
Need numerical-relativity simulations: prerequisite is that Cauchy problem be well-posed (e.g. that eqs be strongly hyperbolic, i.e. wave eqs)

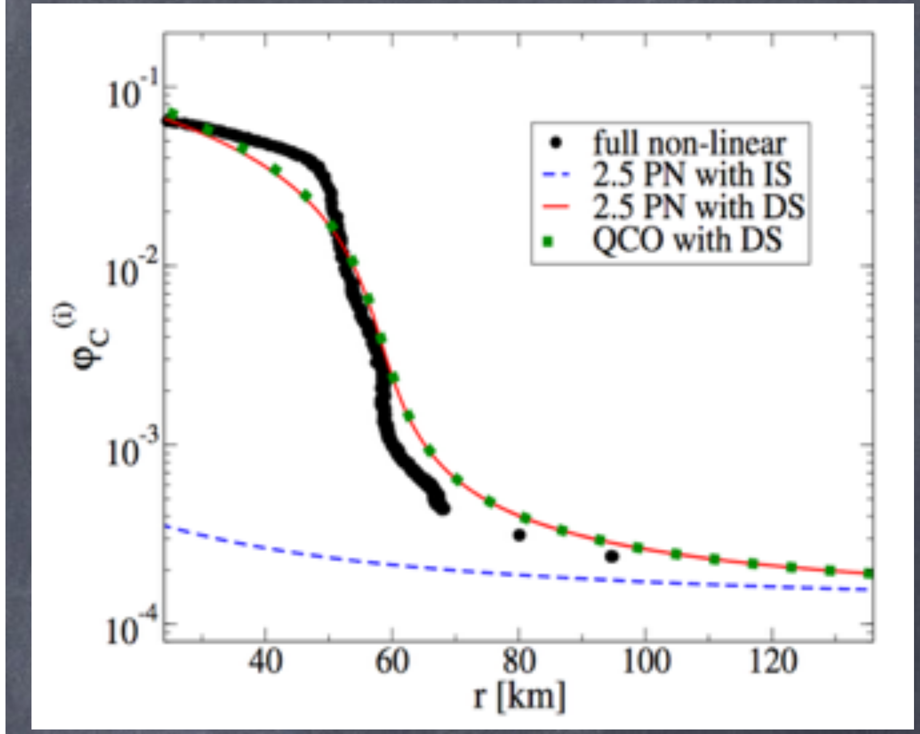
- True for FJBD-like scalar-tensor theories (i.e. with NO galileon terms), but GR dynamics in vacuum (modulo boundary/initial conditions, mass term)
- True in flat-space & spherical symmetry for Lorentz-violating gravity and galileons; dynamics differs from GR both in vacuum and matter, but no general formulation/simulations
- Cauchy problem easier to formulate if theory interpreted as EFT (eg Chern-Simons)

Smoking-gun scalar effects?

- Earlier plunge than in GR for LIGO NS-NS sources, in DEF scalar-tensor theories







EB, Palenzuela, Ponce & Lehner 2013, 2014;
also Shibata, Taniguchi, Okawa & Buonanno 2014, 2015; Sennett & Buonanno 2016

- Detectable with custom-made templates but also by ppE or "cut" waveforms (Sampson et al 2015)

- Caused by induced scalarization of one (spontaneously scalarized) star on the other, or by dynamical scalarization of an initially non-scalarized binary

Spontaneous/dynamical scalarization as "phase transitions"

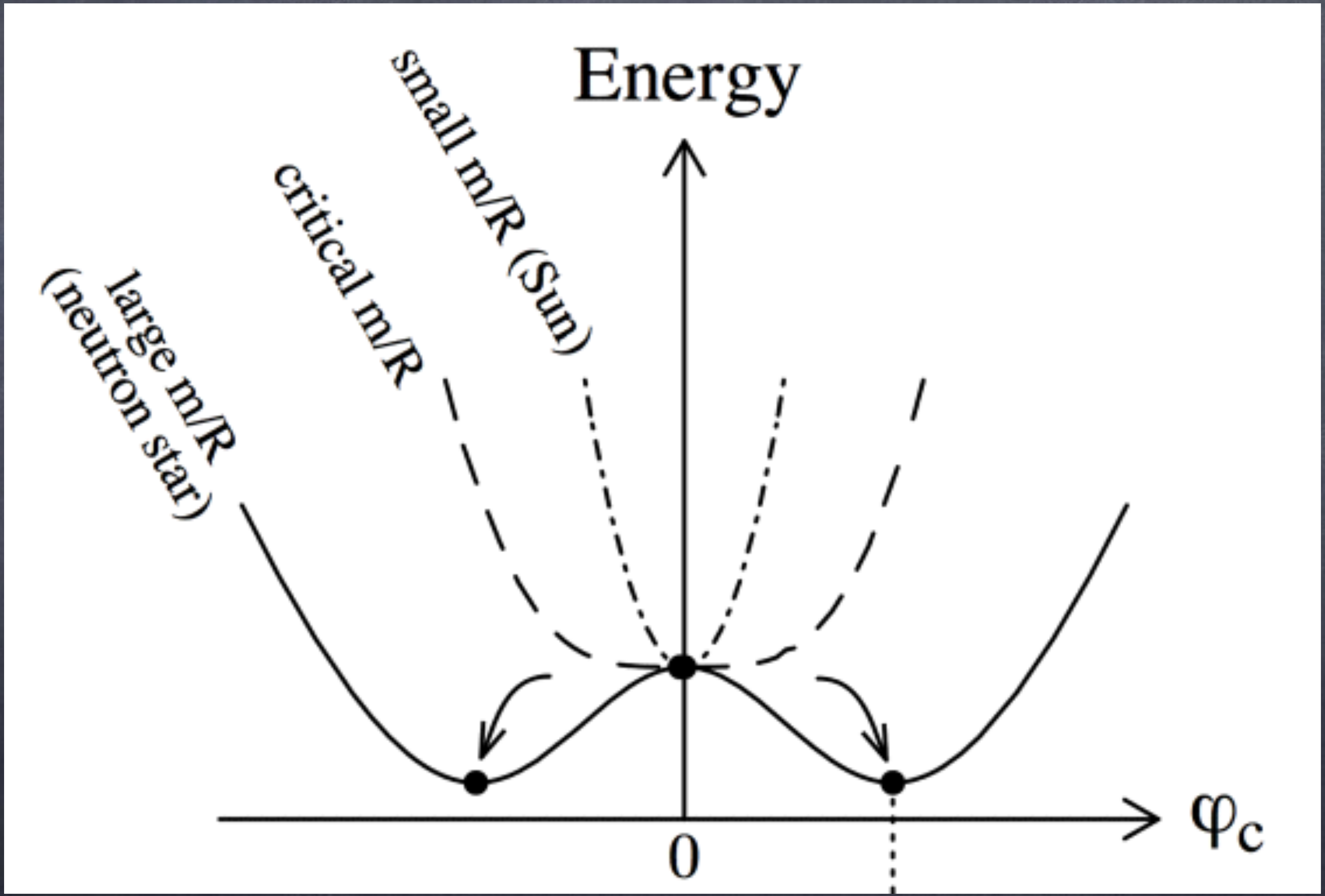
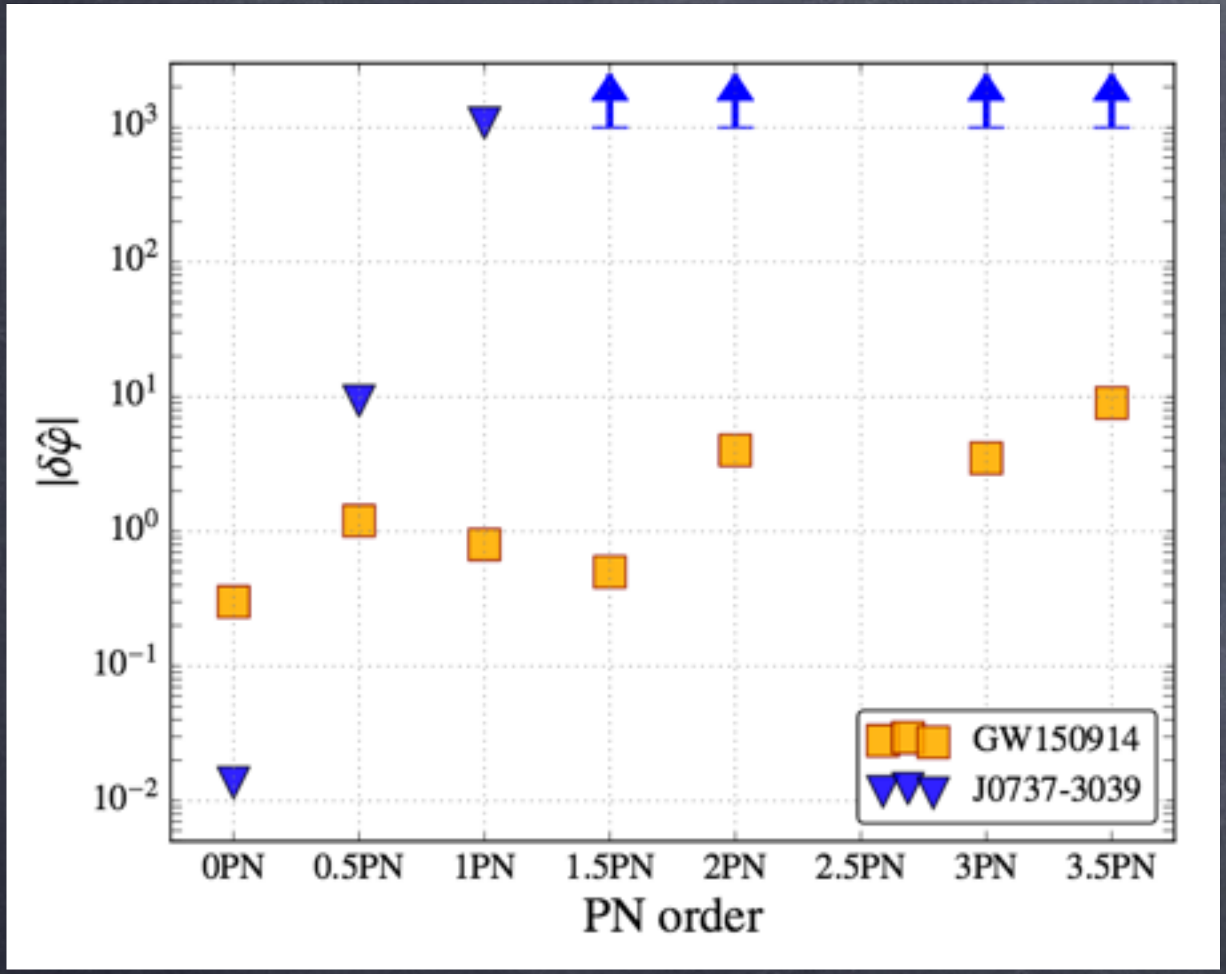


Figure from Esposito-Farese, gr-qc/0402007

Can we learn something from BH-BH GW detections without NR simulations?



- Dynamics is perturbative in v/c (as also shown by binary pulsars and solar-system tests!)
- In (some) theories with screening, the PN expansion becomes NON-perturbative

Galileon/Horndeski screening

- Generalized Galileon action is most generic with 2nd order eqs
- Galleons also arise in massive gravity

$$\mathcal{L}_\phi = \frac{\sqrt{-g}}{16\pi G}\Big\{K(\phi,X) - G_3(\phi,X)\Box\phi + G_4(\phi,X)R + \partial_X G_4(\phi,X)\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2\right]$$
$$+G_5(\phi,X)G_{\mu\nu}\nabla^\mu\nabla^\nu\phi - \frac{1}{6}\partial_X G_5(\phi,X)\left[(\Box\phi)^3 - 3(\Box\phi)(\nabla_\mu\nabla_\nu\phi)^2 + 2(\nabla_\mu\nabla_\nu\phi)^3\right]\Big\}$$

$$X \equiv -\nabla_\mu\phi\nabla^\mu\phi/2 \quad (\nabla_\mu\nabla_\nu\phi)^2 \equiv \nabla_\mu\nabla^\nu\phi\nabla_\nu\nabla^\mu\phi \quad (\nabla_\mu\nabla_\nu\phi)^3 \equiv \nabla_\mu\nabla^\rho\phi\nabla_\rho\nabla^\nu\phi\nabla_\nu\nabla^\mu\phi$$

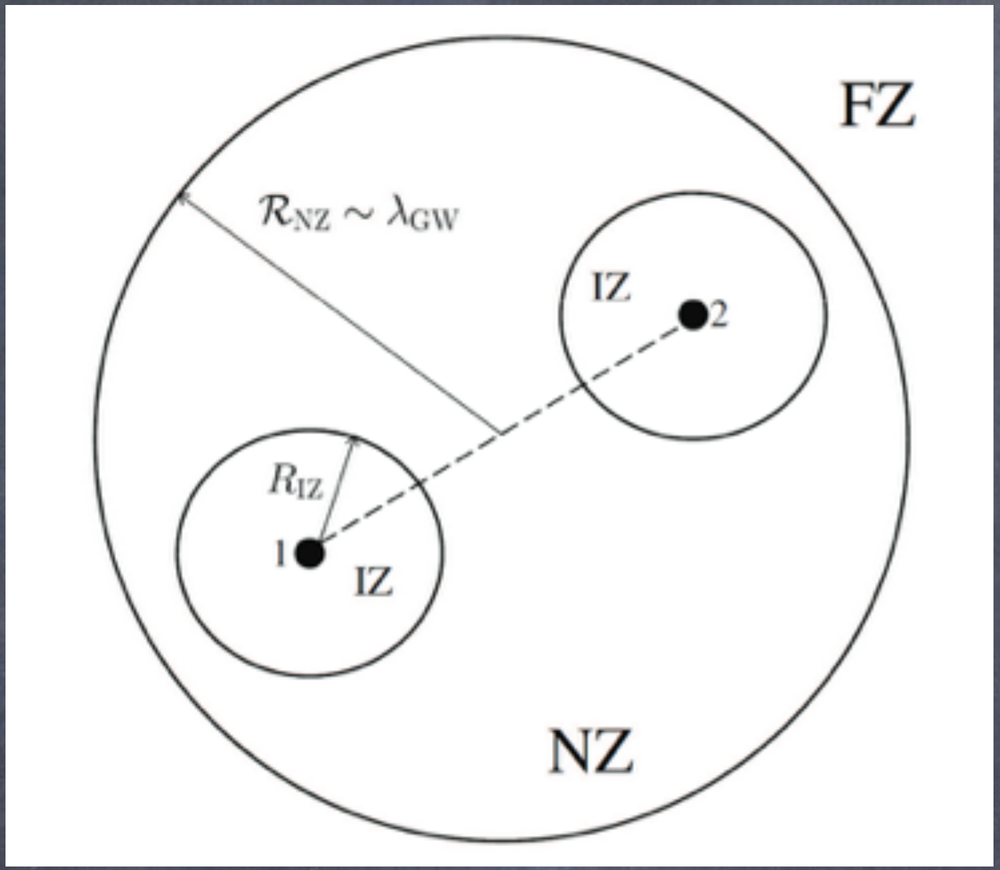
- Non-linear field eqs allow "Vainshtein mechanism"

$$\Box\phi + \partial_X G_3[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2 - R_{\mu\nu}\nabla^\mu\phi\nabla^\nu\phi] + \ldots = \ldots$$

$$\frac{d\phi}{dr} \propto \frac{r^3}{r_V^3}\left[\sqrt{1+\frac{r_V^3}{r^3}} - 1\right]\frac{GM(r)}{r^2}$$

Scalar effects only arise for r>> r_V (Vainshtein radius)

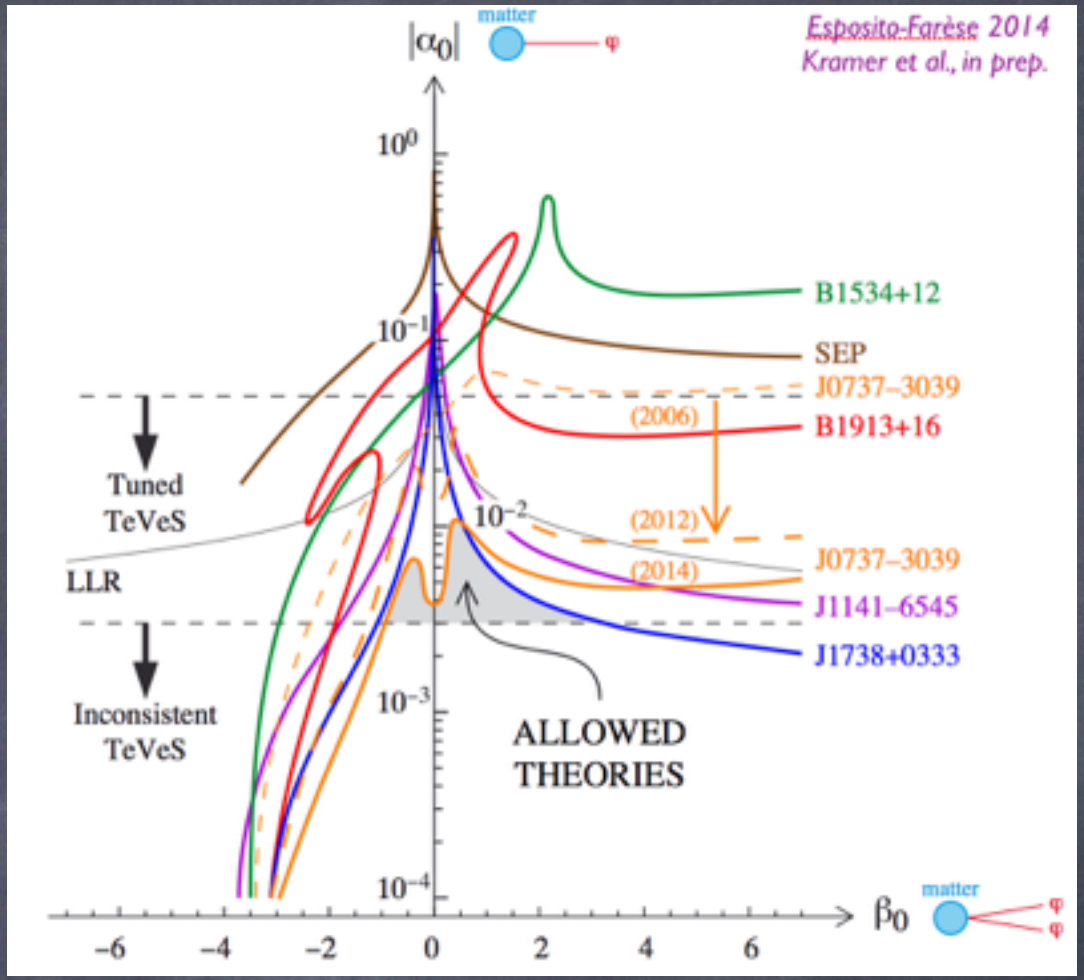
Non-perturbative PN expansion in Horndeski with Vainshtein mechanism



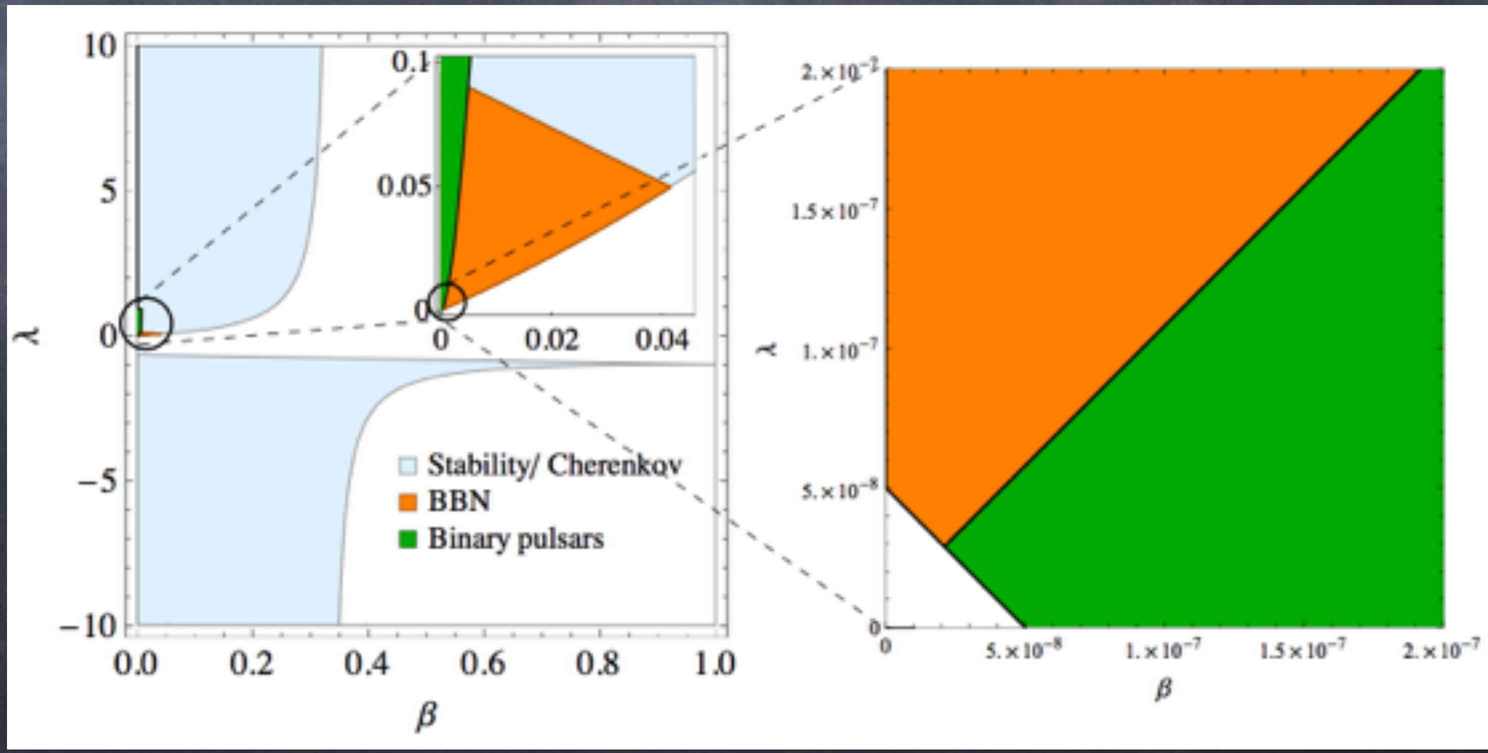
- Vainshtein radius r_V is effective size of point pass
- If $r_V \gtrsim \lambda$, we have a problem! (de Rham, Matas & Tolley 2012, Chu & Trodden 2013, EB & Yagi 2015)
- WKB analysis predicts all multipole moments radiate with same strength in binary systems (de Rham, Matas & Tolley 2012)

An example: acceleration-based screening à la MOND

- Similar to Lorentz-violating gravity, e.g. TeVeS, generalized Einstein-Aether theories: dipole radiation in BH and NS binaries



- Intrinsically non-linear dynamics: strong coupling when trying to recover GR at high accelerations



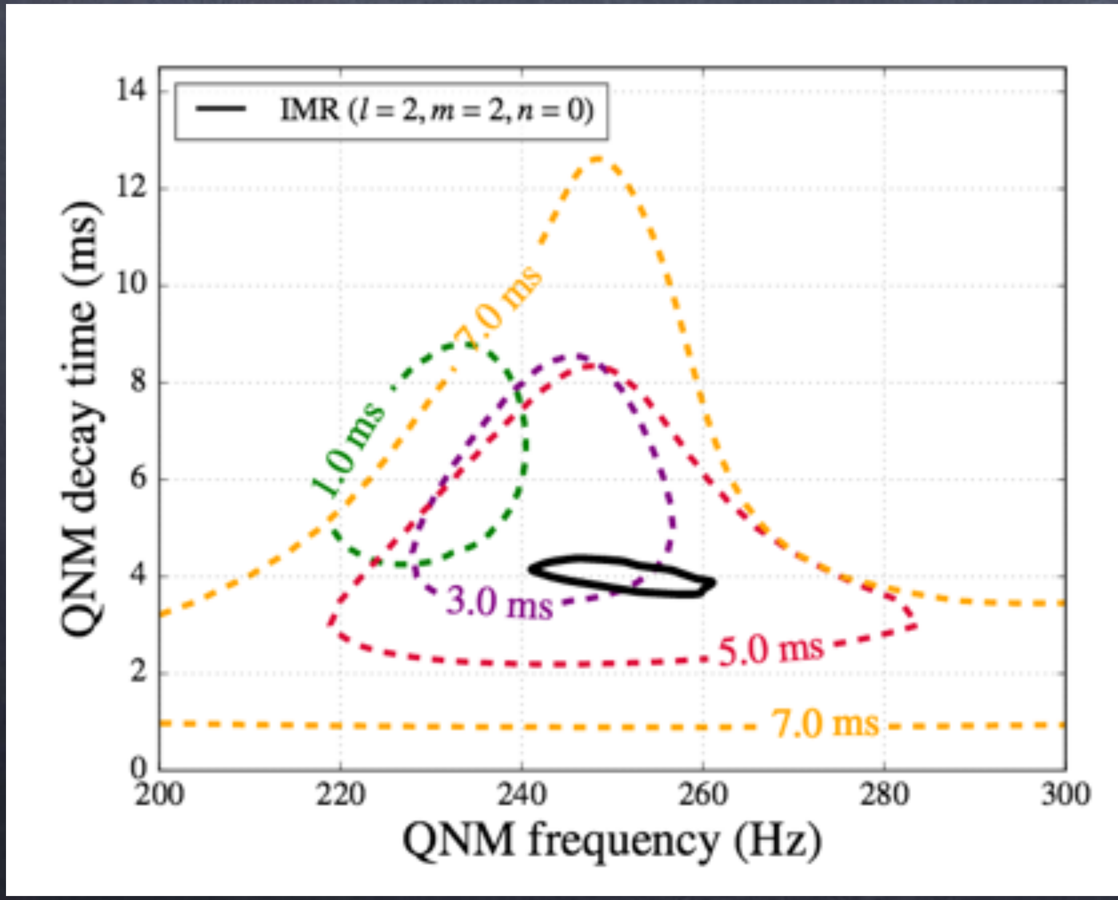
Bonetti & EB 2015

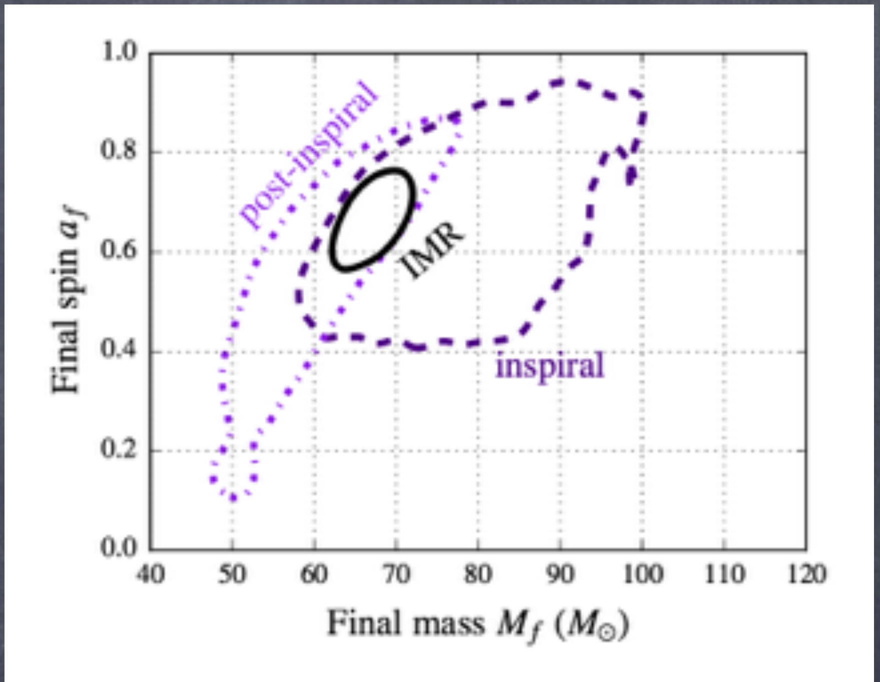
(Future) ringdown tests

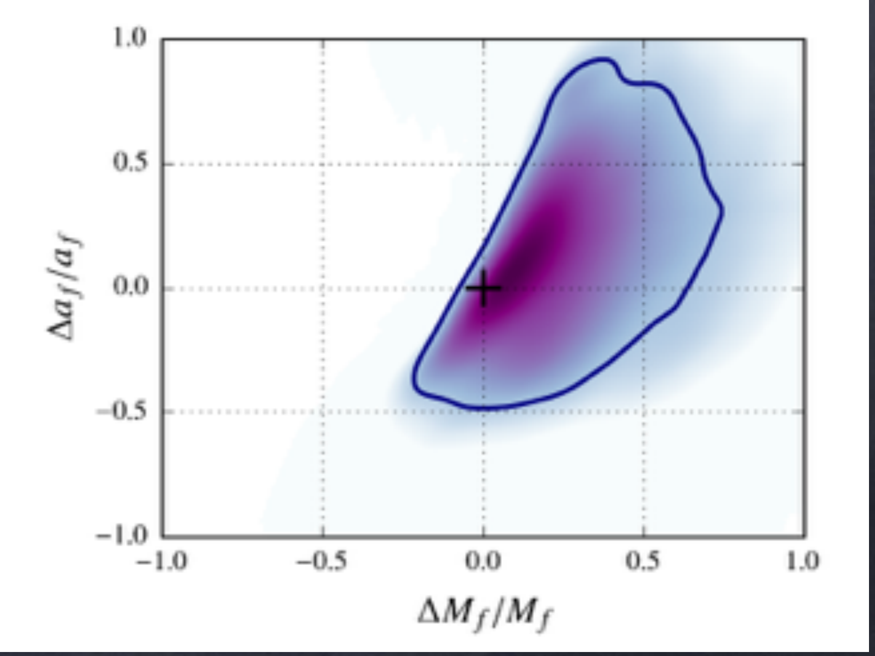
Tests of the no-hair theorem:

$$\omega_{\ell m} = \omega_{\ell m}^{GR}(M,J)(1+\delta\omega_{\ell m}) \qquad \tau_{\ell m} = \tau_{\ell m}^{GR}(M,J)(1+\delta\tau_{\ell m})$$

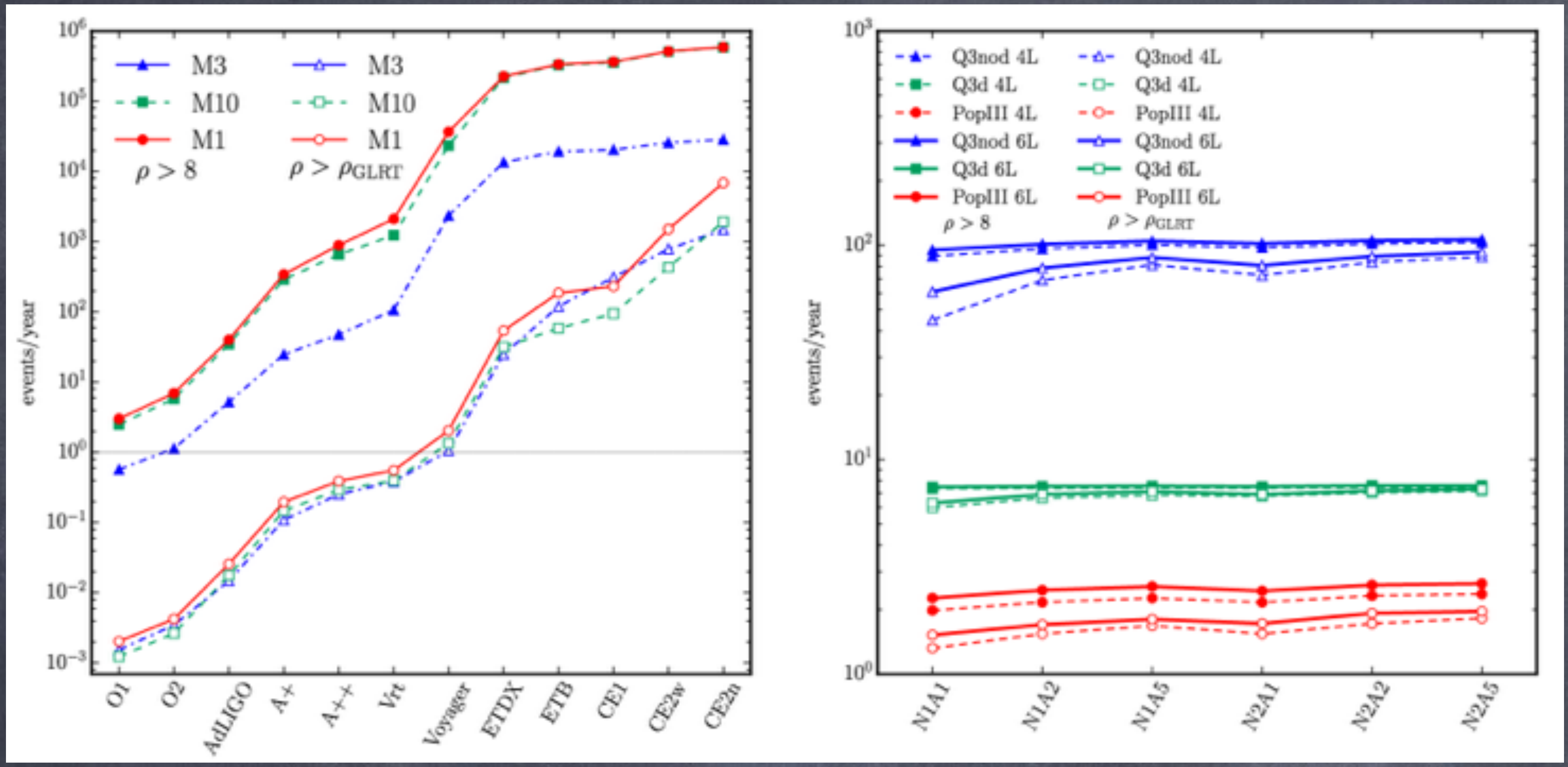
Difficult with advanced detectors because little SNR in ringdown



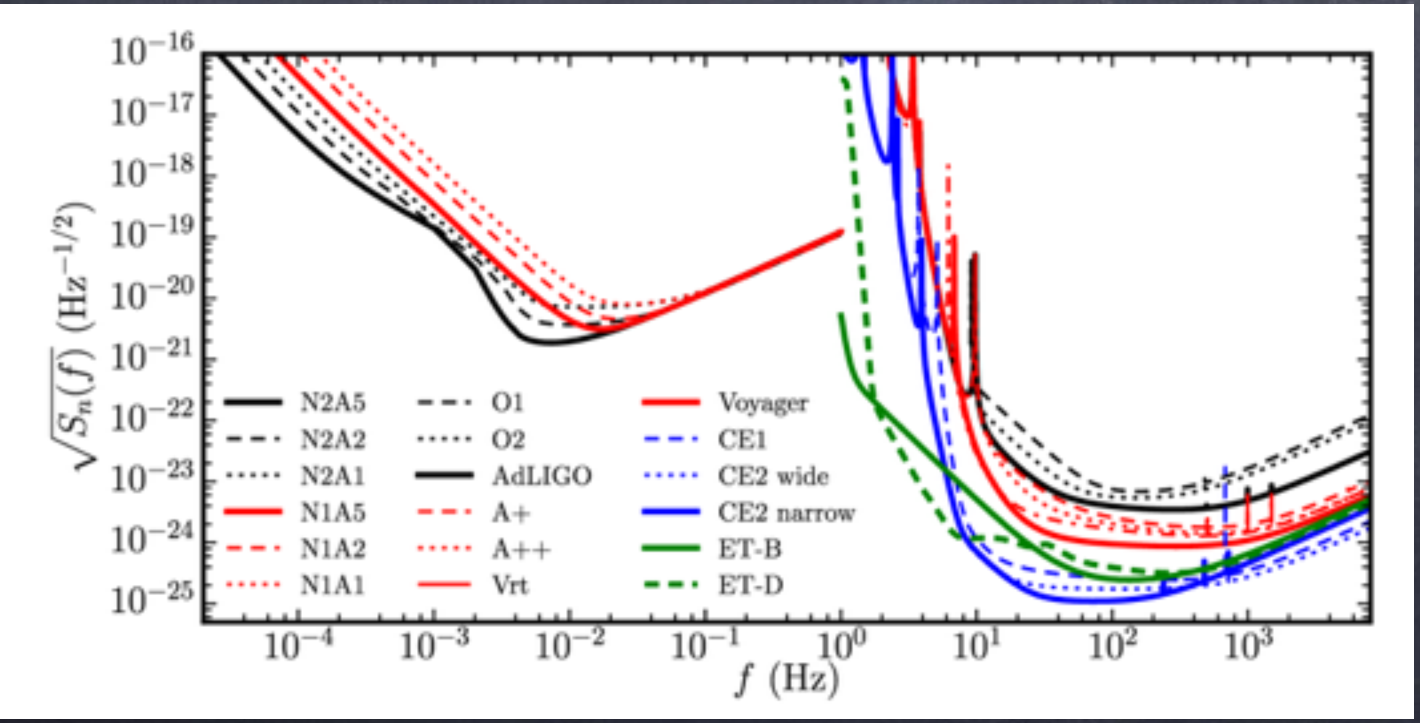




Tests of no-hair theorem by BH ringdown



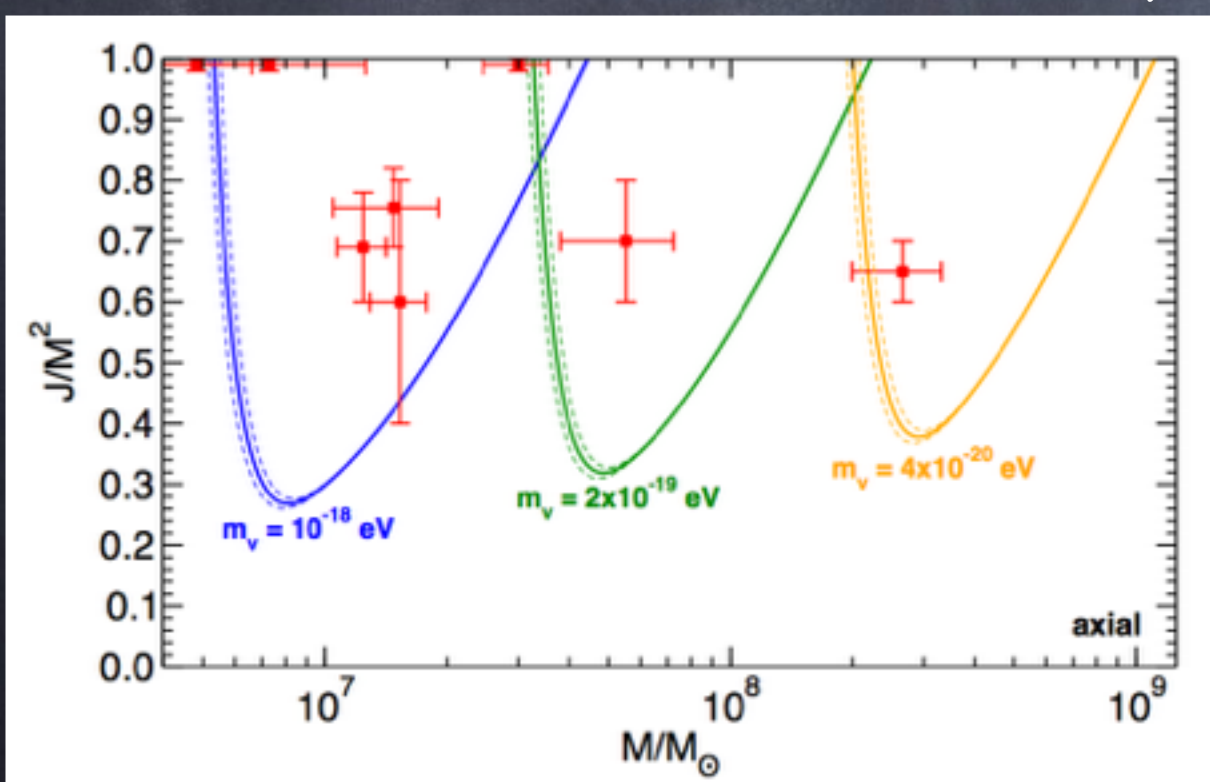
$$\rho_{\rm GLRT} \equiv \min(\rho^{2,3}_{\rm GLRT}, \rho^{2,4}_{\rm GLRT})$$



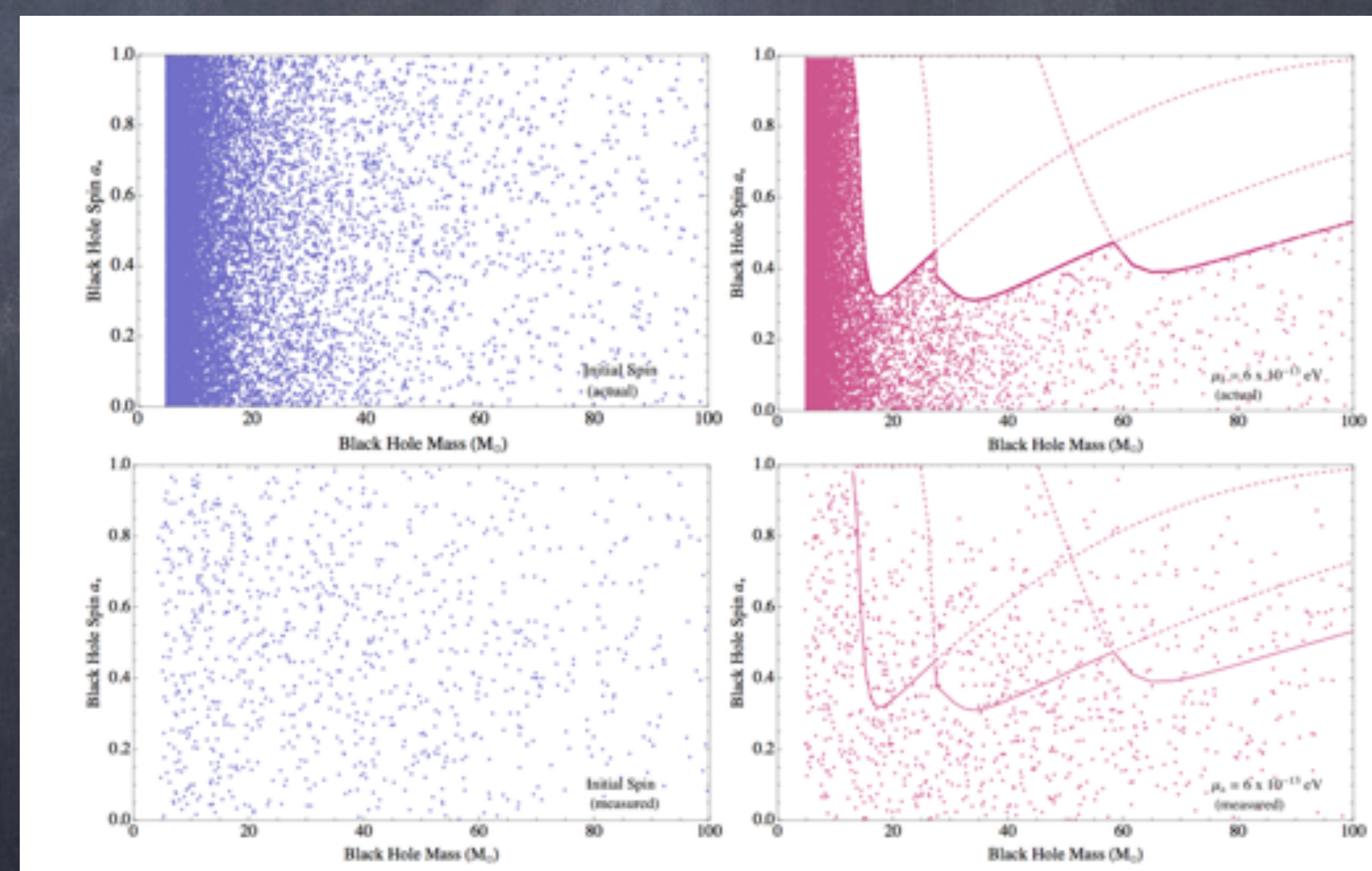
Berti, Sesana, EB,
Cardoso, Belczynski, PRL in press, 2016

Constraints on massive fields around spinning BHs

- Spinning BH + massive fields with Compton wavelength comparable to event horizon radius are unstable under superradiance (Cardoso, Pani, Berti, Brito, Arvanitaki, etc)
- Scenario explored for Proca field, axion-like particles, massive graviton, etc
- Instability endpoint unclear, but might be BH with scalar hair (Cardoso, Pani, Brito, Witek, Herdeiro, etc)
- Caveat: instability must be faster than system's timescale (e.g. Salpeter time, orbital time, formation time, etc)



Pani et al 2012



Arvanitaki et al 2016

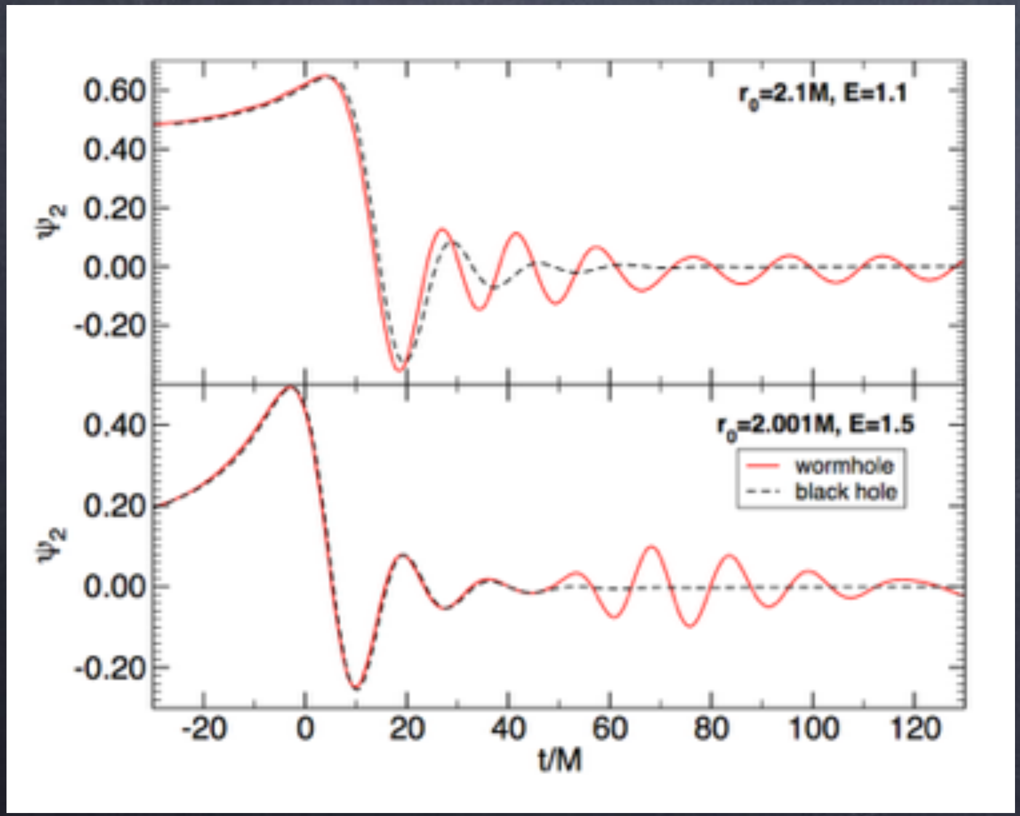
Ringdown's sensitivity to near-horizon physics

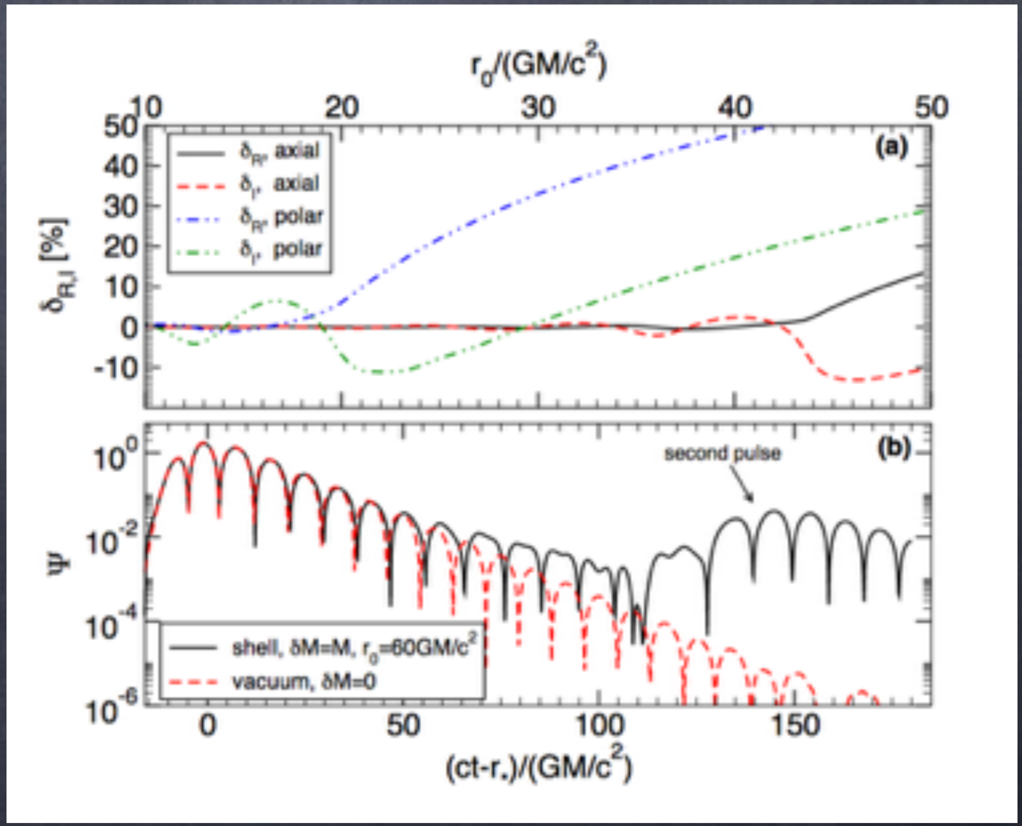
- Deviations away from Kerr geometry near horizon (e.g. firewalls, gravastars, wormholes, etc) can produce significant changes in QNM spectrum

- Deviations take $\Delta t \sim \log[r_0/(2M)-1]$ to show up in time-domain signal because QNMs generated at the circular null orbit (Damour & Solodukhin 2007, EB, Cardoso & Pani 2014, Cardoso, Franzin & Pani 2016) and coordinate time diverges on horizon

- Need "matter" with high viscosity to explain absence of hydrodynamic modes; possible with NS matter+large B, but not with boson stars (Yunes, Yagi & Pretorius 2016);

Schwarzschild BH of mass M+thin shell of 0.01 M at r_0





Cardoso, Franzin & Pani 2016

EB, Cardoso & Pani 2014

r_0 =60 M, shell of mass M, Gaussian wavepacket initially at ISCO

Conclusions

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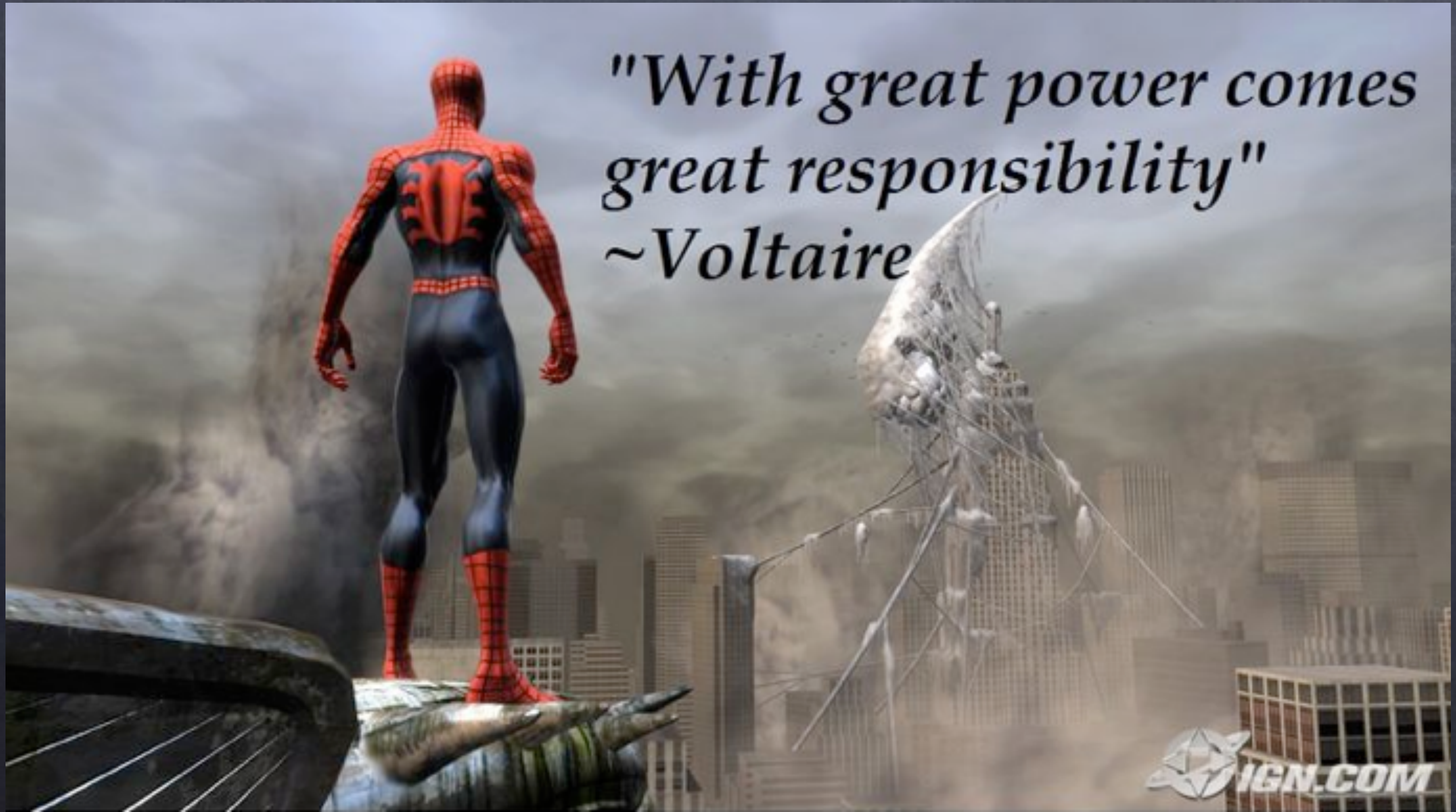
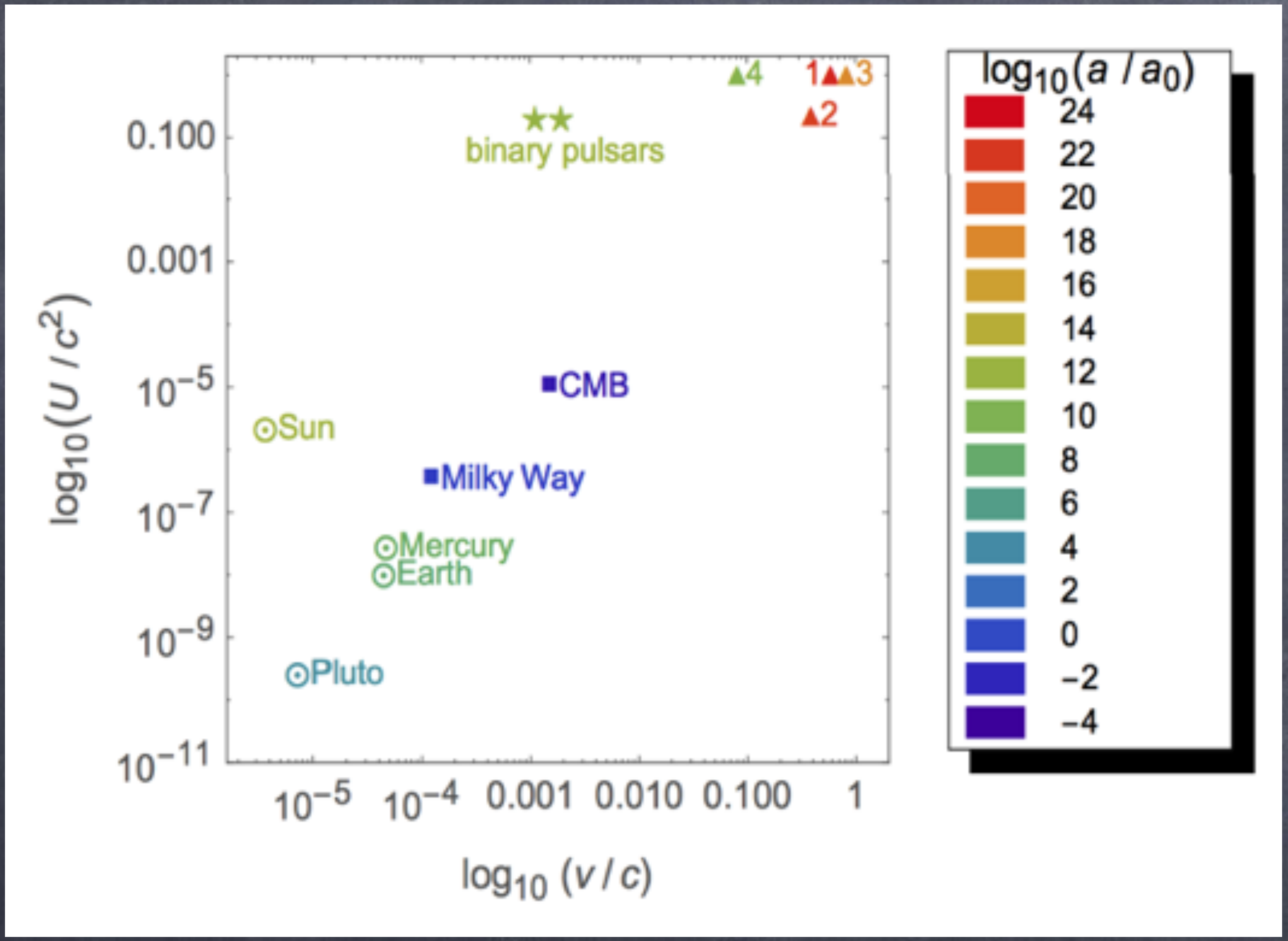


Thank you!

ありがとうございました!

Beyond GR: why?



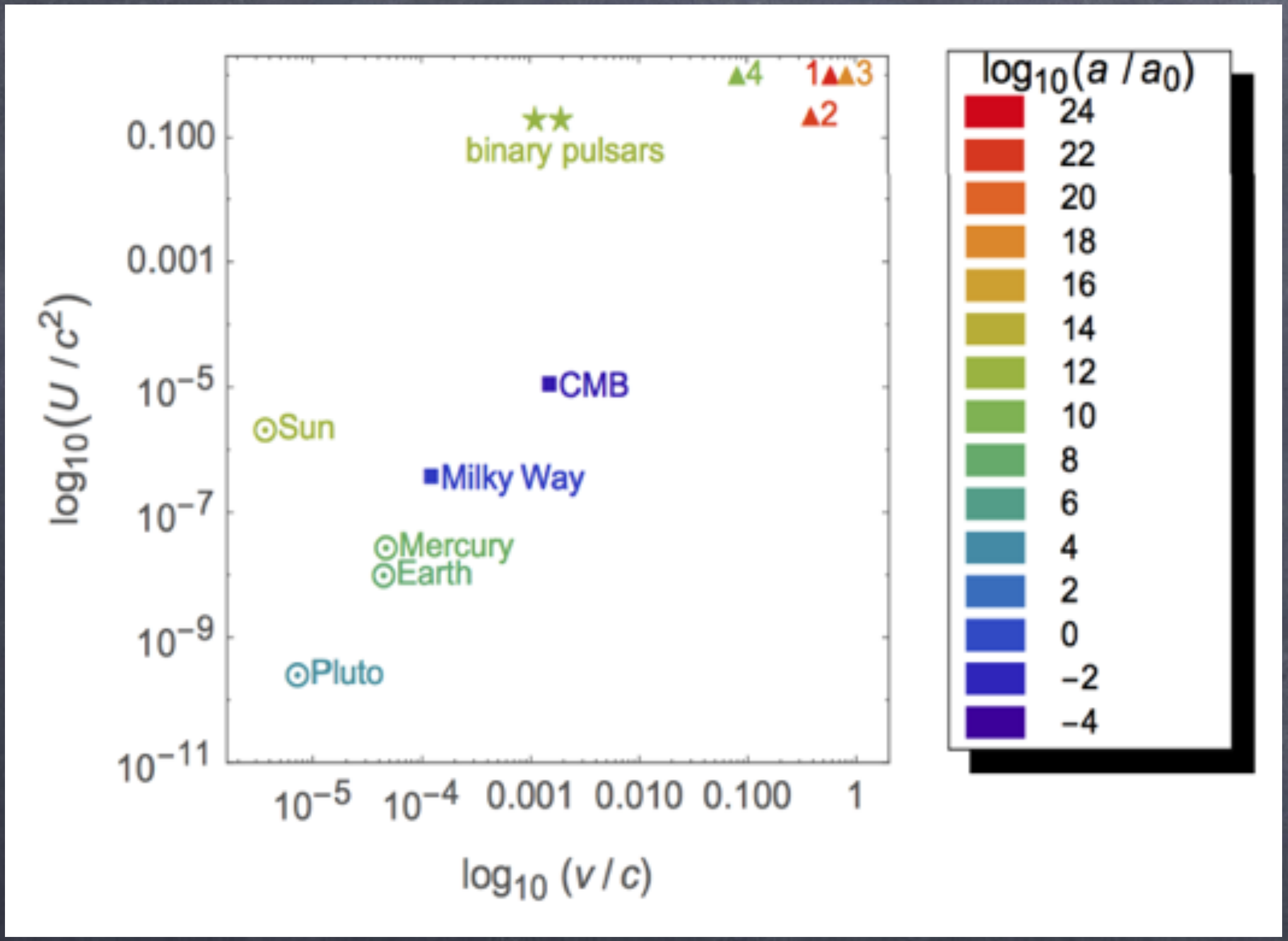
1=BH-BH systems with aLIGO/aVirgo/KAGRA

2=NS-NS systems with aLIGO/aVirgo/KAGRA,

3=BH-BH with eLISA,

4=BH- BH with PTAs

Beyond GR: why?



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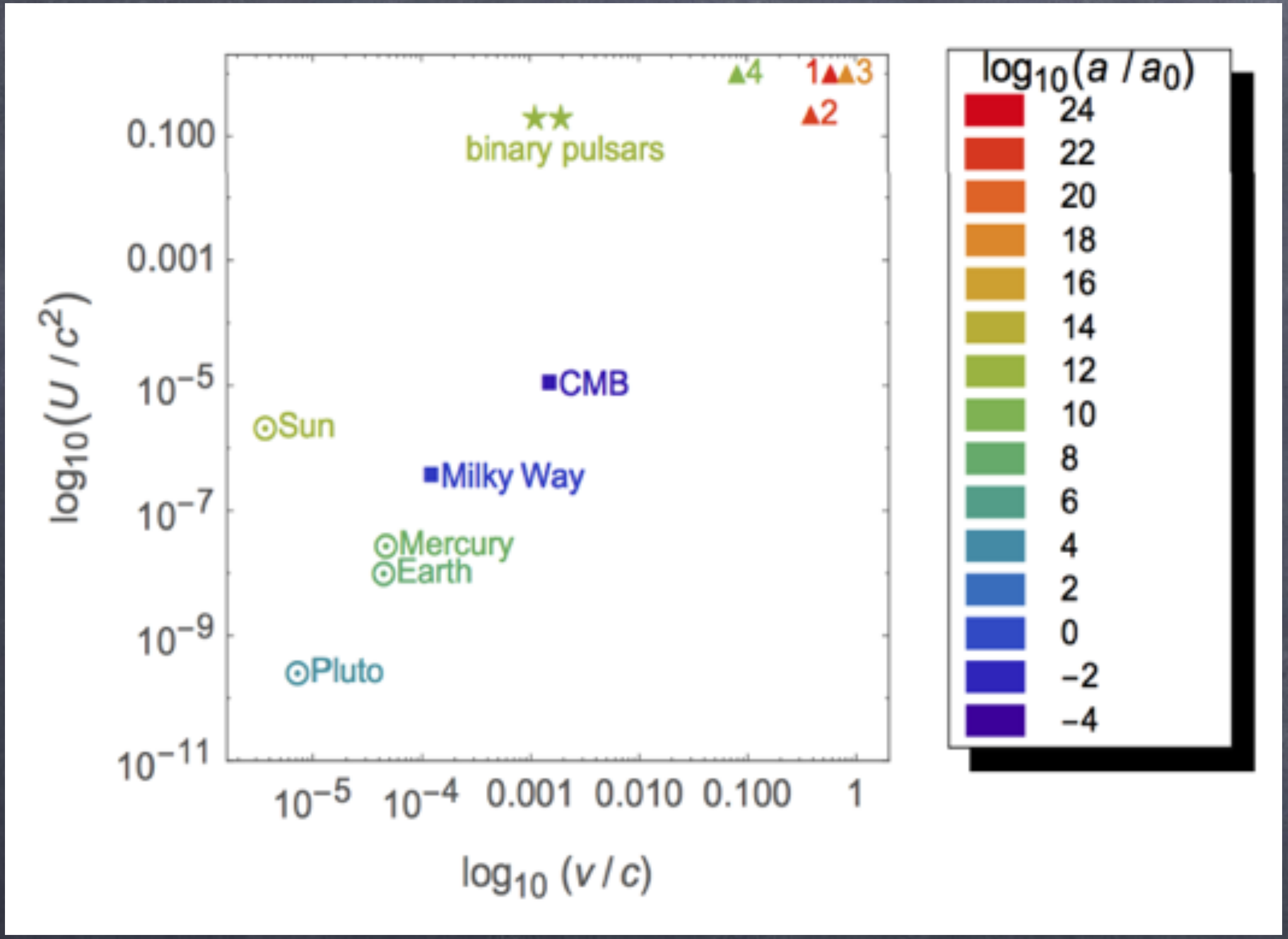

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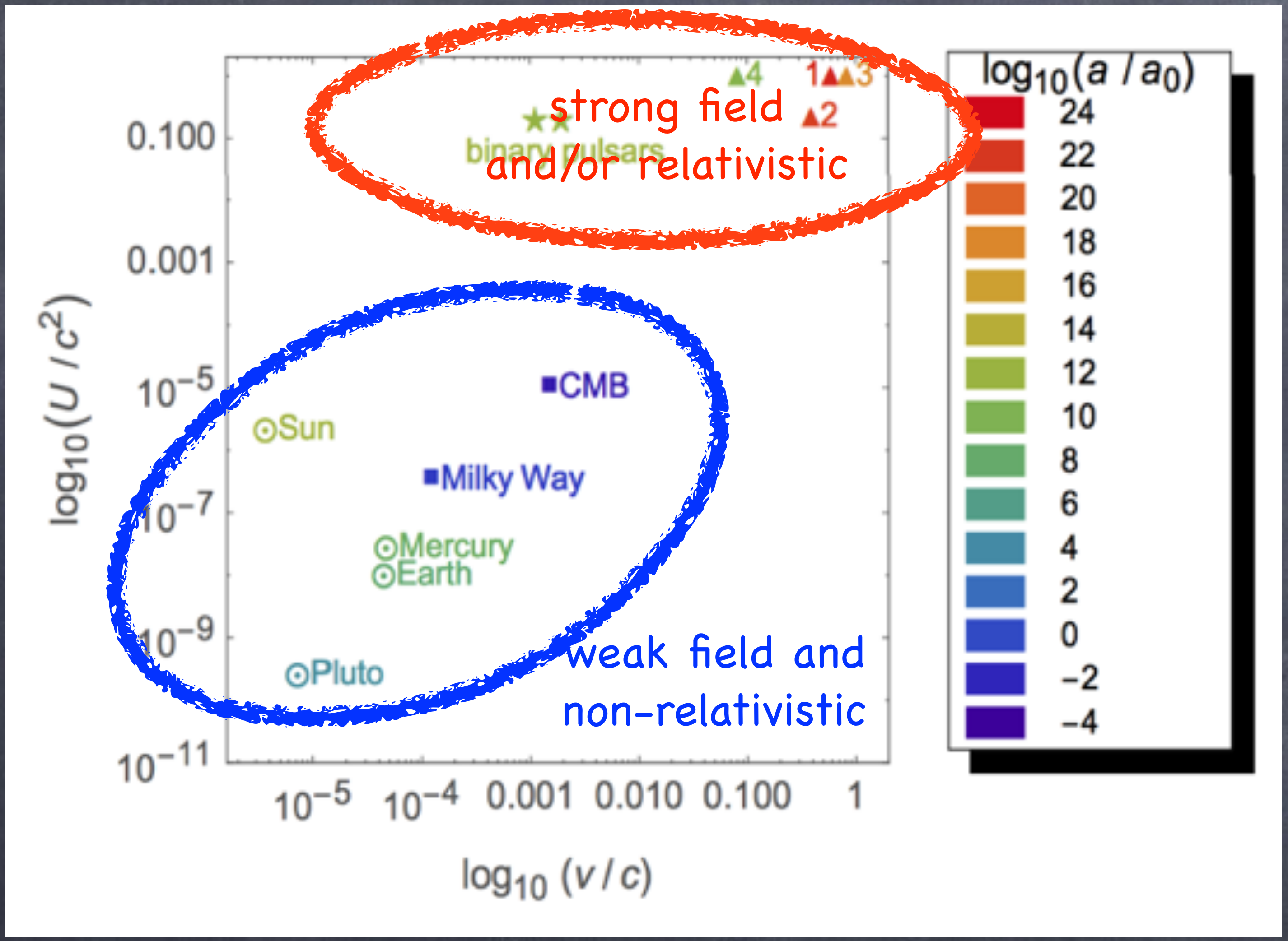

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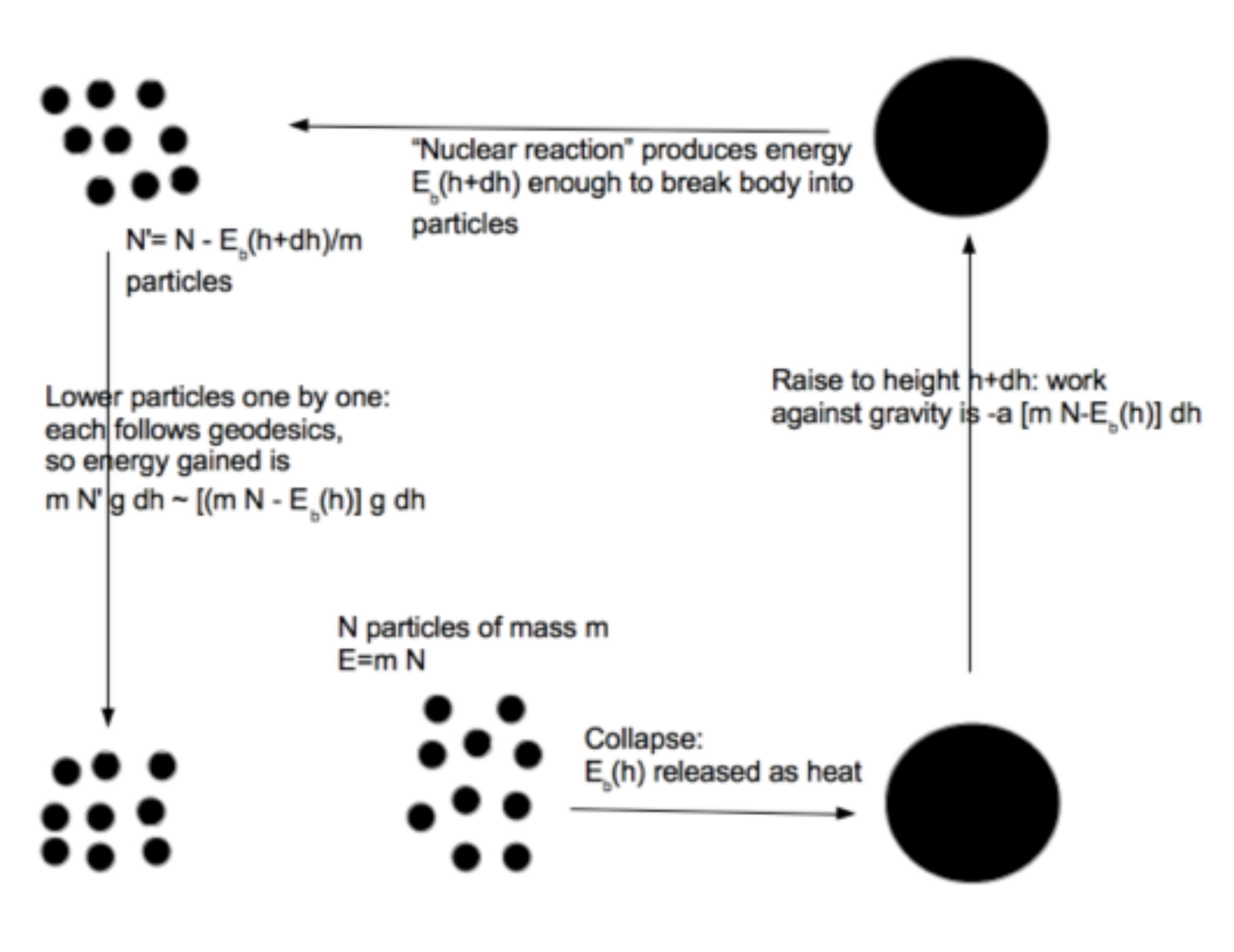
Strong-equivalence principle violations by thought experiments (Dicke 1969)



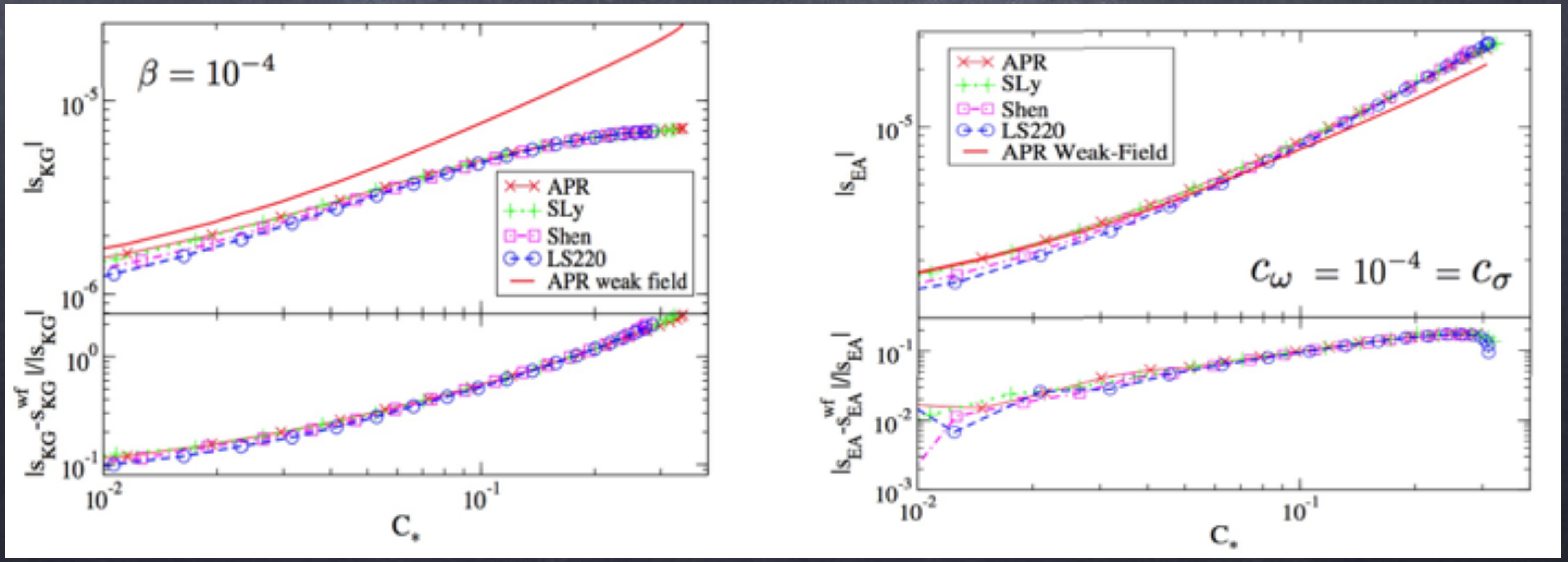
Energy balance gives $(-g+a)(Nn - E_b) = -\dfrac{dE_b}{dh} = -\dfrac{dE_b}{dU}\dfrac{dU}{dh} = -\dfrac{dE_b}{dU}g$

$\Longrightarrow$ $m_{in}a = m_{grav}g \qquad m_{in} = Nm - E_b, \quad m_{grav} = m_{in} - \dfrac{dE_b}{dU}$

Tests of dipolar emission with GWs

- Difficulty is to calculate sensitivities $s \equiv \left.\frac{\partial m}{\partial \varphi}\right|_{\Sigma, M_b}$
- Since they are response to field boundary conditions, need to calculate compact-object solution for different boundary conditions
- Calculation needs to be done exactly (no extrapolation of weak field approximation) and (for NS) for different EOS's

Example: NS sensitivities in Lorentz violating gravity (Yagi, Blas, EB and Yunes et al 2014)



Dipolar emission in BH binaries?

- Ostrogradsky instabilities not enough to rule dynamical Chern-Simons out from EFT standpoint (Yagi, Stein & Yunes 2015)

  If dCS interpreted as EFT, deviations from GR in GW emission in BH-BH appear at high PN orders (3PN in fluxes, 2PN in waveforms, if spinning BH-BH, NS-NS; 5PN in waveforms/fluxes for non-spinning BH-BH, 6PN for non-spinning NS-NS), cf Yagi, Yunes & Tanaka 2012

- In dilatonic Gauss-Bonnet, dipolar -1PN term in fluxes & waveforms, for both NS-NS and BH-BH

  In shift-symmetric dilatonic Gauss-Bonnet [$f_4(\varphi) = \varphi$], sensitivities (and thus dipole emission) are zero for NS but NOT for BHs (EB & Yagi 2015, Yagi, Stein & Yunes 2015)

- Dipolar BH-BH fluxes expected also in theories with vector fields (Horava gravity, Einstein-aether, TeVeS, etc) or tensor fields (bi-metric massive gravity)

Other inspiral effects: mass changes

- Emparan-Fabbri-Kaloper-Tanaka conjecture:

  In braneworld models, Hawking evaporation may be enhanced due to large number of horizon degrees of freedom (cf AdS-CFT), and evaporation may be interpreted classically from 5D viewpoint

  $$\dot{M} = -2.8 \times 10^{-7} \left(\frac{1M_\odot}{M}\right)^2 \left(\frac{\ell}{10\mu\mathrm{m}}\right)^2 M_\odot \mathrm{yr}^{-1} \qquad \tau = 5.93 \times 10^5 \left(\frac{14\mu\mathrm{m}}{\ell}\right)^2 \left(\frac{M}{M_\odot}\right)^3 \mathrm{yr}$$

  Caveat: brane-localized BH solutions computed numerically and do not seem to support conjecture

- Accretion of Dark Energy with $w < -1$ ("phantom energy"; allows for CTC's, wormholes, big rip...)

- Phenomenological time variation of G

-4 PN effects

Summary: inspiral effects

Tables from Yunes, Yagi & Pretorius 2016

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 [39], 2 [40–42]
	SEP, No BH Hair	-1	$\mathbf{1.6 \times 10^{-4}}$	$\lvert\dot\phi\rvert$ [1/sec]	—	10^{-6} [43]
	SEP, Parity Invariance	$+2$	$\mathbf{1.3 \times 10^{1}}$	$\sqrt{\lvert\alpha_{\rm CS}\rvert}$ [km]	—	10^8 [44, 45]
Vector Field Activation	SEP, Lorentz Invariance	0	$\mathbf{7.2 \times 10^{-3}}$	(c_+, c_-)	$\mathbf{(0.9, 2.1)}$	$(0.03, 0.003)$ [46, 47]
Extra Dimension Mass Leakage	4D spacetime	-4	$\mathbf{9.1 \times 10^{-9}}$	ℓ [μm]	$\mathbf{5.4 \times 10^{10}}$	10–10^3 [48–52]
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 [53–57]

Theoretical Effect	Theoretical Mechanism	Theories	ppE b	Order	Mapping
Scalar Dipolar Radiation	Scalar Monopole Field Activation	EdGB [110, 112, 120, 121]	-7	-1PN	$\beta_{\rm EdGB}$ [110]
	BH Hair Growth	Scalar-Tensor Theories [43, 122]	-7	-1PN	$\beta_{\rm ST}$ [43, 122]
Anomalous Acceleration	Extra Dimension Mass Leakage	RS-II Braneworld [123, 124]	-13	-4PN	$\beta_{\rm ED}$ [111]
	Time-Variation of G	Phenomenological [107, 125]	-13	-4PN	$\beta_{\dot G}$ [107]
Scalar Quadrupolar Radiation Scalar Dipole Force Quadrupole Moment Deformation	Scalar Dipole Field Activation due to Gravitational Parity Violation	dCS [110, 126]	-1	$+2$PN	$\beta_{\rm dCS}$ [116]
Scalar/Vector Dipolar Radiation Modified Quadrupolar Radiation	Vector Field Activation due to Lorentz Violation	EA [89, 90], khronometric [91, 92]	-7 -5	-1PN 0PN	$\beta_{\rm EA}^{(-1)}$ [93] $\beta_{\rm EA}^{(0)}$ [93]

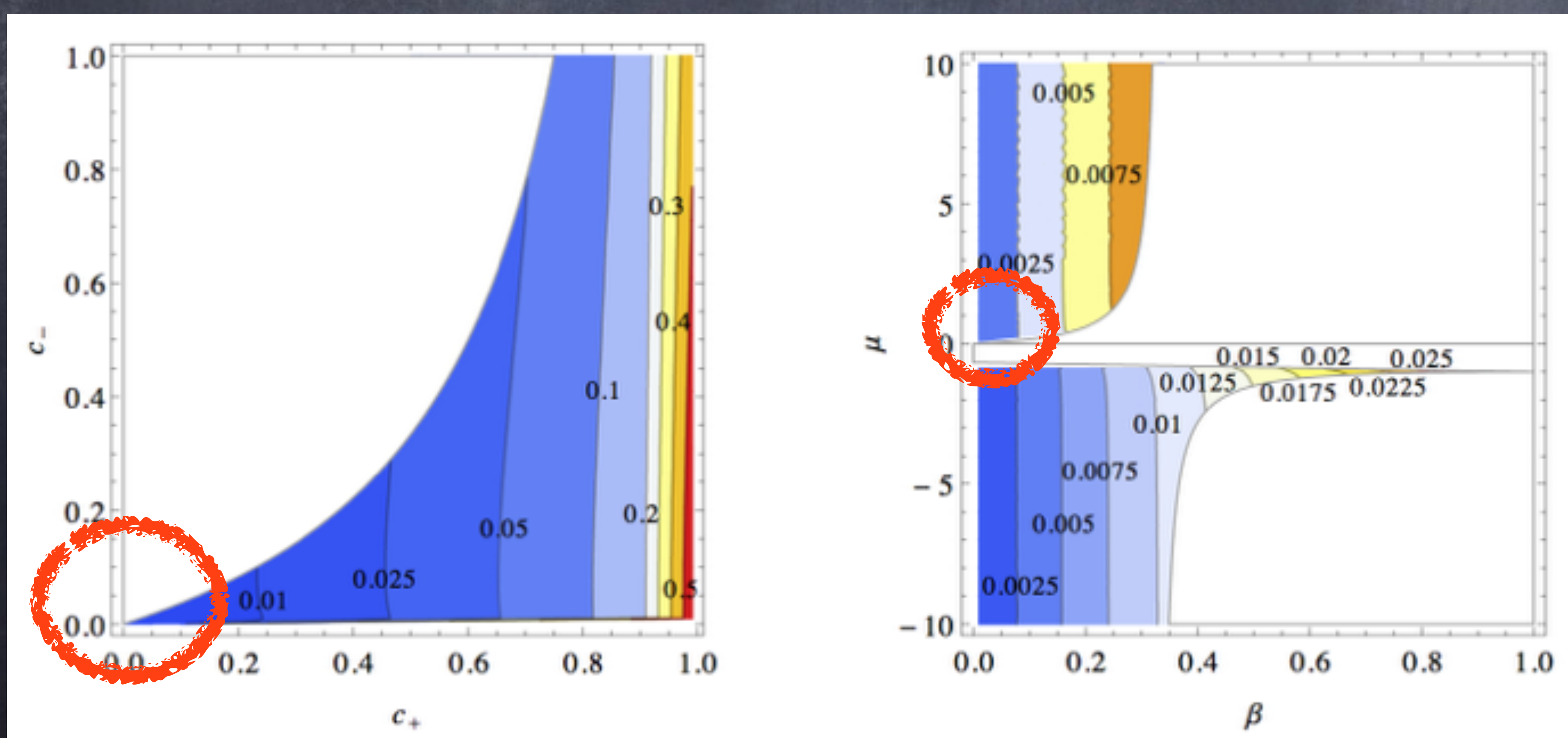
- Inspired effects mappable to parametric formalisms (ppE, TIGER,...):

$$h_{ppE}(f) = h_{GR}(f)(1+\alpha u^a)e^{i\beta u^b} \qquad u = (\pi \mathcal{M} f)^{1/3}$$

- Caveat: ppE parameters may depend on sources (e.g. sensitivities different in NSs and BHs), so stacking may not be physically meaningful!

BH QNM calculations in modified theories

- Calculation often non-trivial because formulation in terms of wave eqs needed (if elliptic sector present, need to worry about boundary conditions, etc)
- Excitation amplitudes can only be calculated by full numerical-relativity simulation
- Extra fields lead to different GW polarizations, each may have its own horizon
- Linked to question of (linear) stability, c.f. e.g. massive fields in Kerr
- In eikonal limit, QNM frequencies and decay times linked to orbital frequencies and instability timescales of circular null geodesics, i.e. "QNM produced at the light ring"

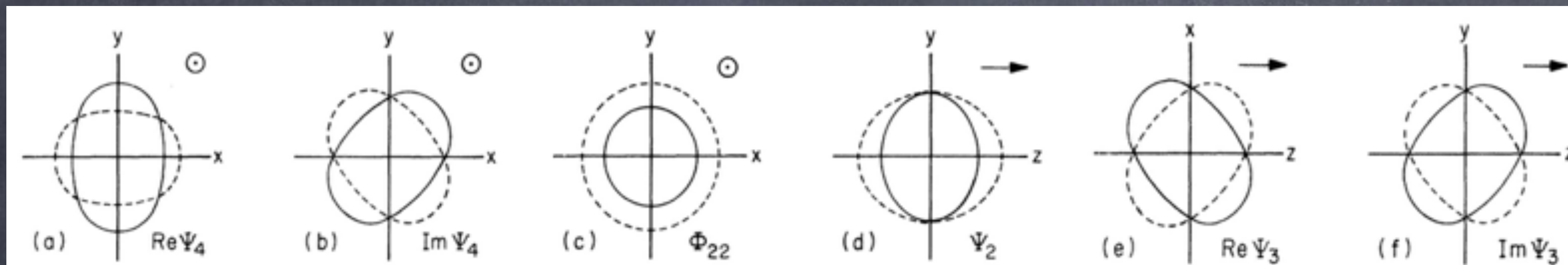


Eikonal limit fractional deviations from GR in LV gravity

EB, Jacobson & Sotiriou 2011

Propagation effects

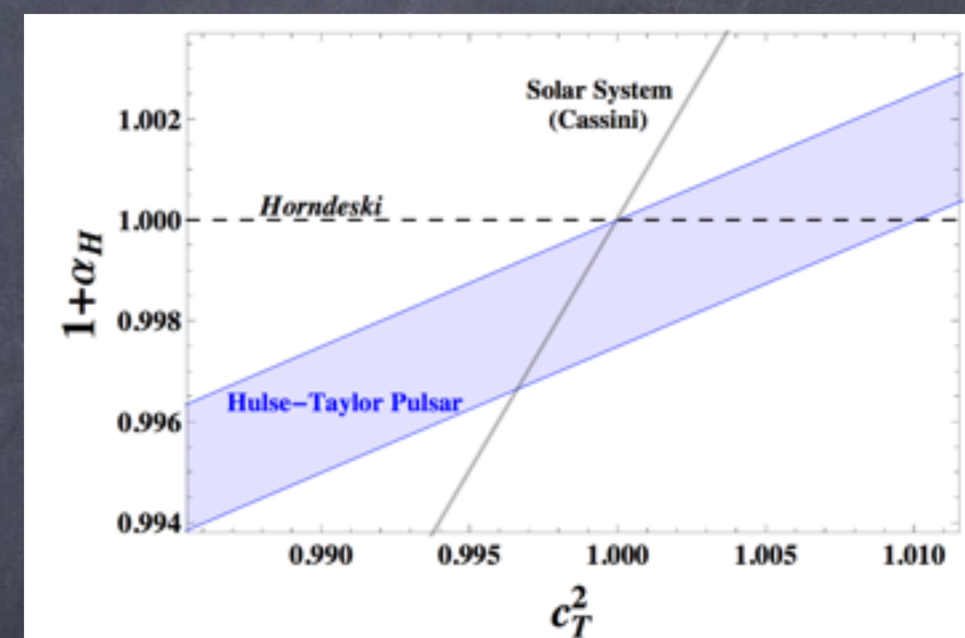
- Direct searches for extra polarizations beyond quadrupole (need a network)



$$\Psi_2(u) \quad (s=0), \quad \Phi_{22}(u) \quad (s=0) \quad \Psi_3(u) \quad (s=\pm 1), \quad \Psi_4(u) \quad (s=\pm 2)$$

- Modified propagation velocity:

- e.g. LV gravity, Horndeski, etc
- Must be superluminal to avoid Cherenkov
- Strong constraints from binary pulsars
- Weak GW constraints from time of arrival at different detectors (Blas et al 2016)
- Strong bounds if EM counterpart



e.g. Horndeski/beyond-Horndeski theories (Jimenez, Piazza, Velten 2015)

α_H and c_T are theory's parameters ($\alpha_H = 0$ in Horndeski)

Propagation effects

Modified dispersion relations $E^2 = (pc)^2 + \mathbb{A}\,(pc)^\alpha$

- Generically predicted by quantum-gravity theories
- Pros: effects accumulate over distance, mappable to ppE phase term

$$\beta = \frac{\pi^{2-\alpha}}{(1-\alpha)}\frac{D_\alpha}{\lambda_{\mathbb{A}}^{2-\alpha}}\frac{\mathcal{M}^{1-\alpha}}{(1+z)^{1-\alpha}}\,, \qquad b = 3\alpha - 3\,. \qquad \lambda_{\mathbb{A}} \equiv h\,\mathbb{A}^{1/(\alpha-2)}$$

- Cons: GWs have low energies compares to cosmic rays/Planck scale

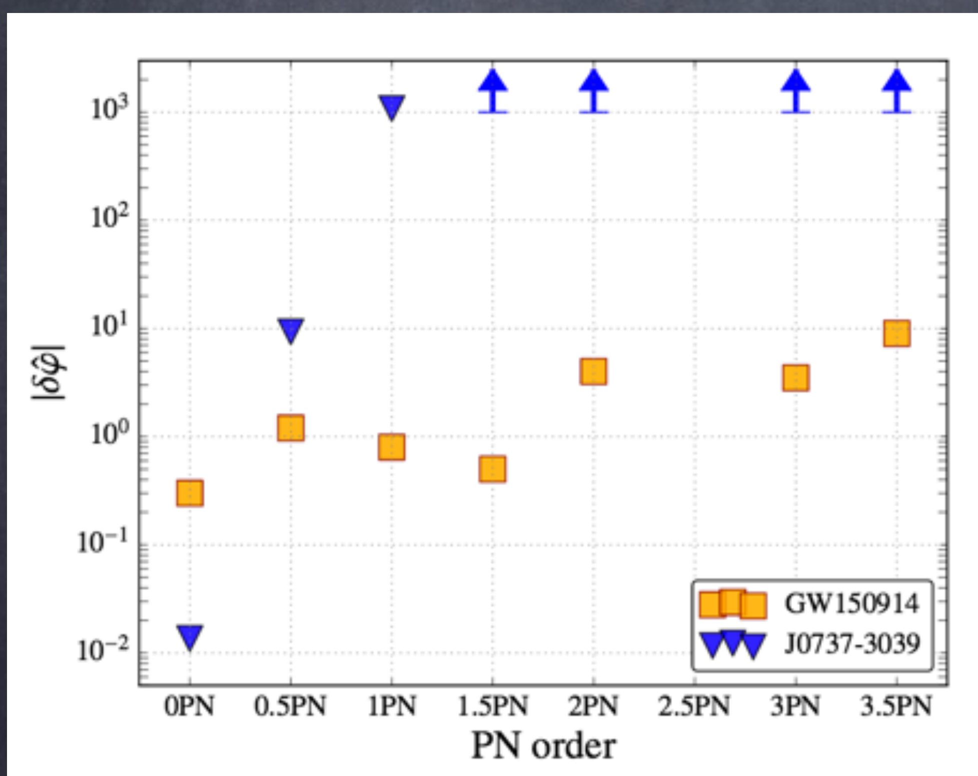
Tables from Yunes, Yagi & Pretorius 2016

Theoretical Effect	Theoretical Mechanism	Theories	ppE b	Order	Mapping
Modified Dispersion Relation	GW Propagation/Kinematics	Massive Gravity [127–130]	-3	$+1$PN	$\beta_{\rm MDR}$ [115, 127]
		Double Special Relativity [131–134]	$+6$	$+5.5$PN	
		Extra Dim. [135], Horava-Lifshitz [136–138]	$+9$	$+7$PN	

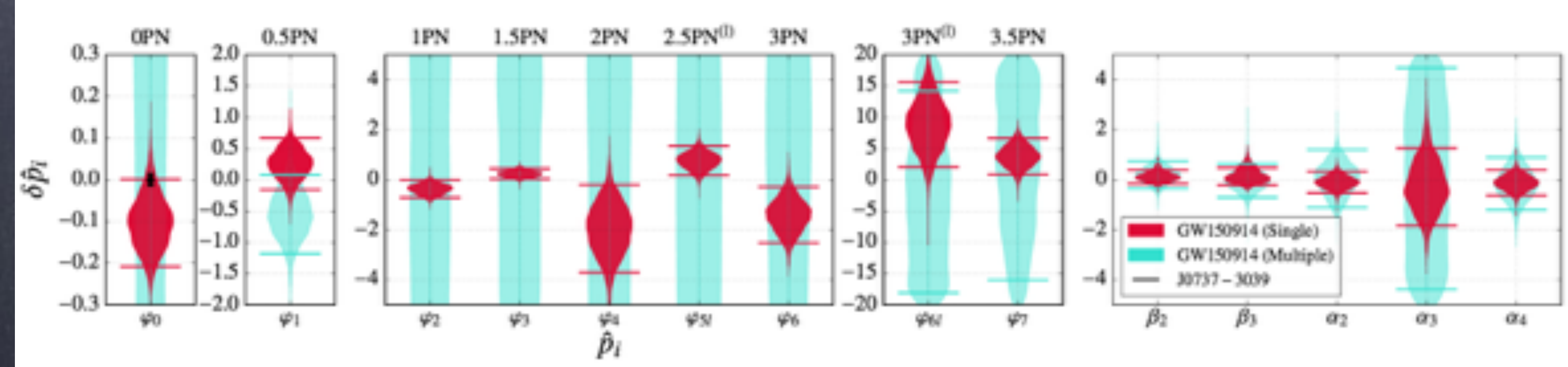
Theoretical Mechanism	GR Pillar	PN	$\lvert\beta\rvert$ GW150914	Example Theory Constraints: Repr. Parameters	GW150914	Current Bounds
Massive graviton	massless graviton	$+1$	$\mathbf{1.3 \times 10^{-1}}$	m_g [eV]	$\mathbf{1.2 \times 10^{-22}}$ [12]	10^{-29}–10^{-18} [58–62]
Modified Dispersion Relation (*Modified Special Relativity*)	$v_g = c$	$+5.5$	$\mathbf{2.3 \times 10^{2}}$	$\mathbb{A} > 0$ [1/eV]	$\mathbf{1.6 \times 10^{-7}}$	—
		$+5.5$	$\mathbf{2.3 \times 10^{2}}$	$\mathbb{A} < 0$ [1/eV]	$\mathbf{1.6 \times 10^{-7}}$	2.7×10^{-36} [63]
Modified Dispersion Relation (*Extra Dimensions*)	$v_g = c$	$+7$	$\mathbf{8.7 \times 10^{2}}$	$\mathbb{A} > 0$ [1/eV^2]	$\mathbf{9.3 \times 10^{4}}$	—
		$+7$	$\mathbf{8.7 \times 10^{2}}$	$\mathbb{A} < 0$ [1/eV^2]	$\mathbf{9.3 \times 10^{4}}$	4.6×10^{-56} [63]
Modified Dispersion Relation (*Lorentz Violation*)	SEP, Lorentz Invariance	—	—	c_+	$\mathbf{0.7}$ [64]	$(0.03, 0.003)$ [46, 47]

Actual tests with GW150914

- Constraints on deviations from GR's PN parameters

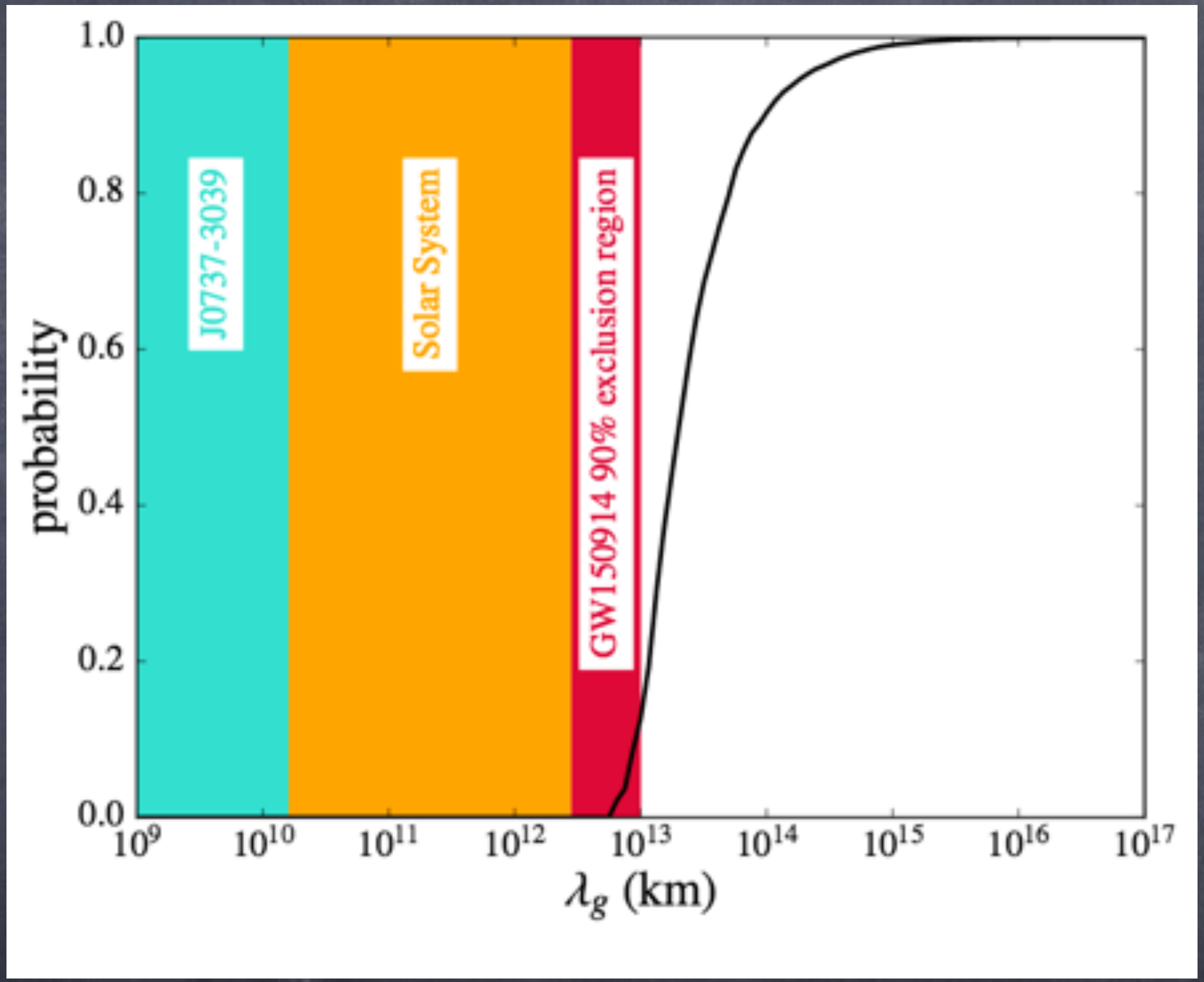


waveform regime	parameter	f−dependence	median single	median multiple	GR quantile single	GR quantile multiple	$\log_{10} B^{GR}_{model}$ single	$\log_{10} B^{GR}_{model}$ multiple
early-inspiral regime	$\delta\hat{\varphi}_0$	$f^{-5/3}$	$-0.1^{+0.1}_{-0.1}$	$1.3^{+3.0}_{-3.2}$	0.94	0.30	1.9 ± 0.2	3.7 ± 0.6
	$\delta\hat{\varphi}_1$	$f^{-4/3}$	$0.3^{+0.4}_{-0.4}$	$-0.5^{+0.6}_{-0.6}$	0.16	0.93	1.6 ± 0.2	
	$\delta\hat{\varphi}_2$	f^{-1}	$-0.4^{+0.3}_{-0.4}$	$-1.6^{+18.8}_{-16.6}$	0.96	0.56	1.2 ± 0.2	
	$\delta\hat{\varphi}_3$	$f^{-2/3}$	$0.2^{+0.2}_{-0.2}$	$2.0^{+13.4}_{-13.9}$	0.02	0.42	1.2 ± 0.2	
	$\delta\hat{\varphi}_4$	$f^{-1/3}$	$-1.9^{+1.6}_{-1.7}$	$-1.9^{+19.3}_{-16.4}$	0.98	0.56	0.3 ± 0.2	
	$\delta\hat{\varphi}_{5l}$	$\log(f)$	$0.8^{+0.5}_{-0.6}$	$-1.4^{+18.6}_{-16.9}$	0.01	0.55	0.7 ± 0.4	
	$\delta\hat{\varphi}_6$	$f^{1/3}$	$-1.4^{+1.1}_{-1.1}$	$1.2^{+16.8}_{-18.9}$	0.99	0.47	0.4 ± 0.2	
	$\delta\hat{\varphi}_{6l}$	$f^{1/3}\log(f)$	$8.9^{+6.8}_{-6.8}$	$-1.9^{+19.1}_{-16.1}$	0.02	0.57	-0.3 ± 0.2	
	$\delta\hat{\varphi}_7$	$f^{2/3}$	$3.8^{+2.9}_{-2.9}$	$3.2^{+15.1}_{-19.2}$	0.02	0.41	-0.0 ± 0.2	
intermediate regime	$\delta\hat{\beta}_2$	$\log f$	$0.1^{+0.4}_{-0.3}$	$0.2^{+0.6}_{-0.5}$	0.24	0.28	1.4 ± 0.2	2.3 ± 0.2
	$\delta\hat{\beta}_3$	f^{-3}	$0.1^{+0.6}_{-0.3}$	$-0.0^{+0.8}_{-0.7}$	0.31	0.56	1.2 ± 0.4	
merger-ringdown regime	$\delta\hat{\alpha}_2$	f^{-1}	$-0.1^{+0.4}_{-0.4}$	$0.0^{+1.0}_{-1.2}$	0.68	0.50	1.2 ± 0.2	2.1 ± 0.4
	$\delta\hat{\alpha}_3$	$f^{3/4}$	$-0.3^{+1.9}_{-1.5}$	$0.0^{+4.4}_{-4.4}$	0.60	0.51	0.7 ± 0.2	
	$\delta\hat{\alpha}_4$	$\tan^{-1}(af + b)$	$-0.1^{+0.5}_{-0.5}$	$-0.1^{+1.1}_{-1.0}$	0.68	0.62	1.1 ± 0.2	



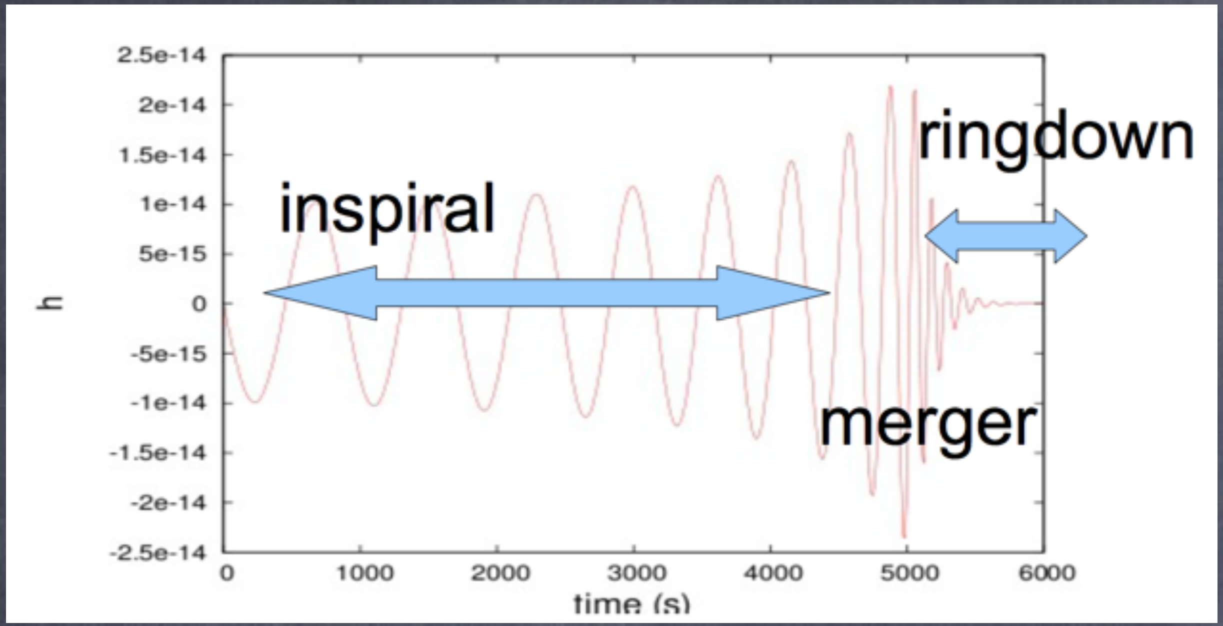
Actual tests with GW150914

- Bounds on graviton's mass



- No constraints on extra polarizations

GR tests with direct detections



Parametric inspiral-based tests (ppE, TIGER,...):

$$h_{ppE}(f) = h_{GR}(f)(1 + \alpha u^a)e^{i\beta u^b} \qquad u = (\pi \mathcal{M} f)^{1/3}$$

- probe similar physics to binary pulsars (e.g. -1PN terms constrained by pulsars in NS-NS systems)...
- .. but since sensitivities depend on source, -1PN term may be present in BH-BH system or in NS-NS systems if NS mass > 1.4 Msun
- Caveat: stacking may not be physically meaningful!

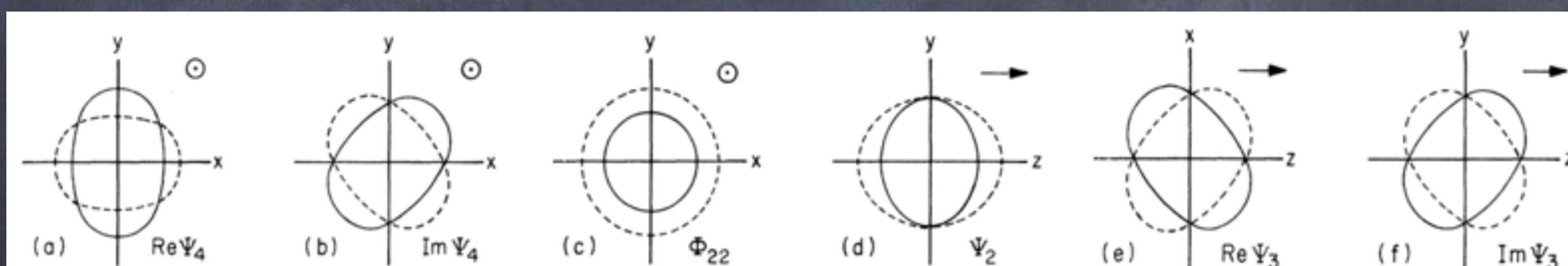
GR tests with direct detections

- Parametric ringdown tests, i.e. tests of the no-hair theorem:

$$\omega_{\ell m} = \omega_{\ell m}^{GR}(M,J)(1+\delta\omega_{\ell m}) \qquad \tau_{\ell m} = \tau_{\ell m}^{GR}(M,J)(1+\delta\tau_{\ell m})$$

Difficult with advanced detectors because little SNR in ringdown

- Direct searches for extra polarizations beyond quadrupole



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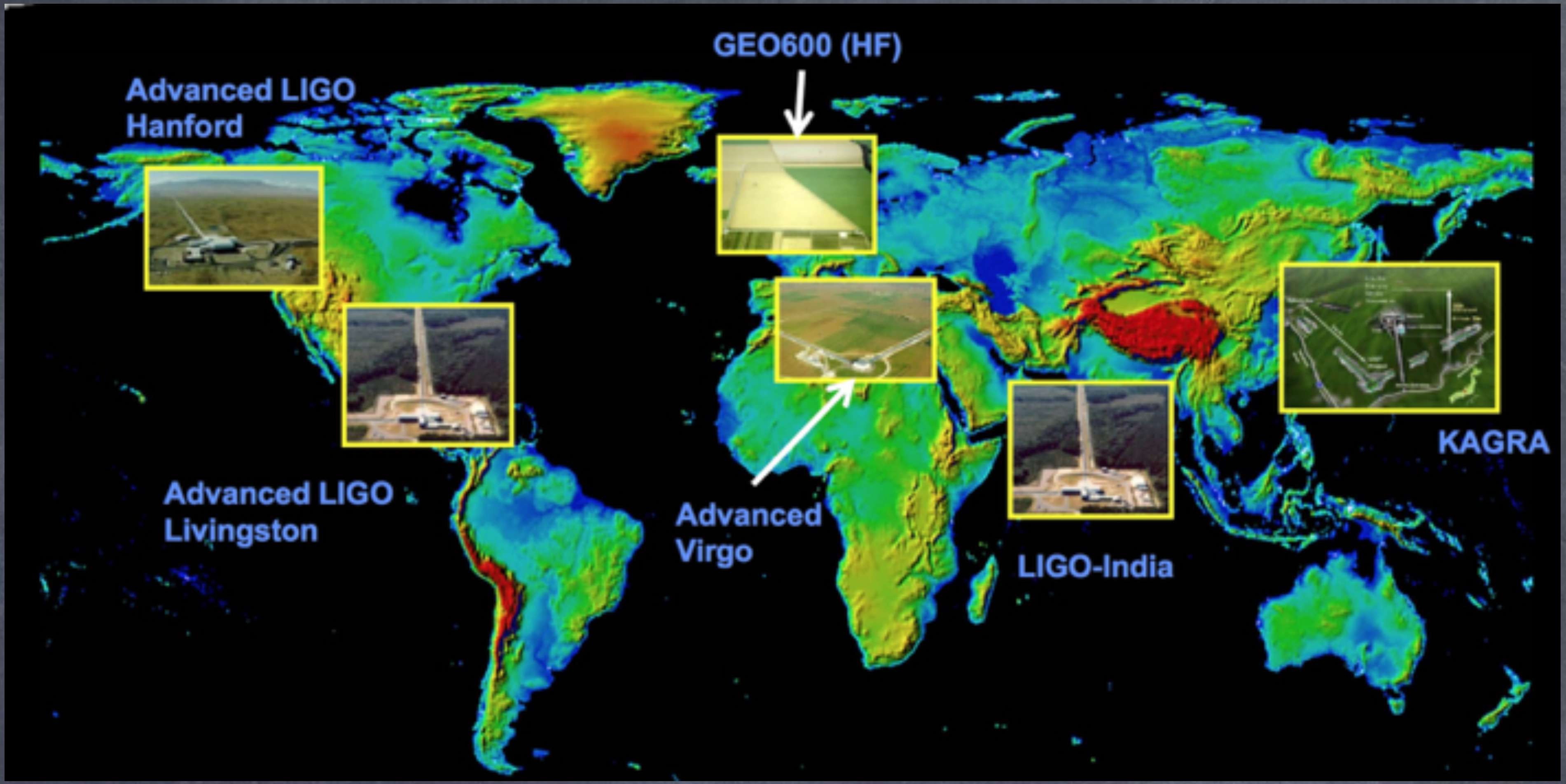
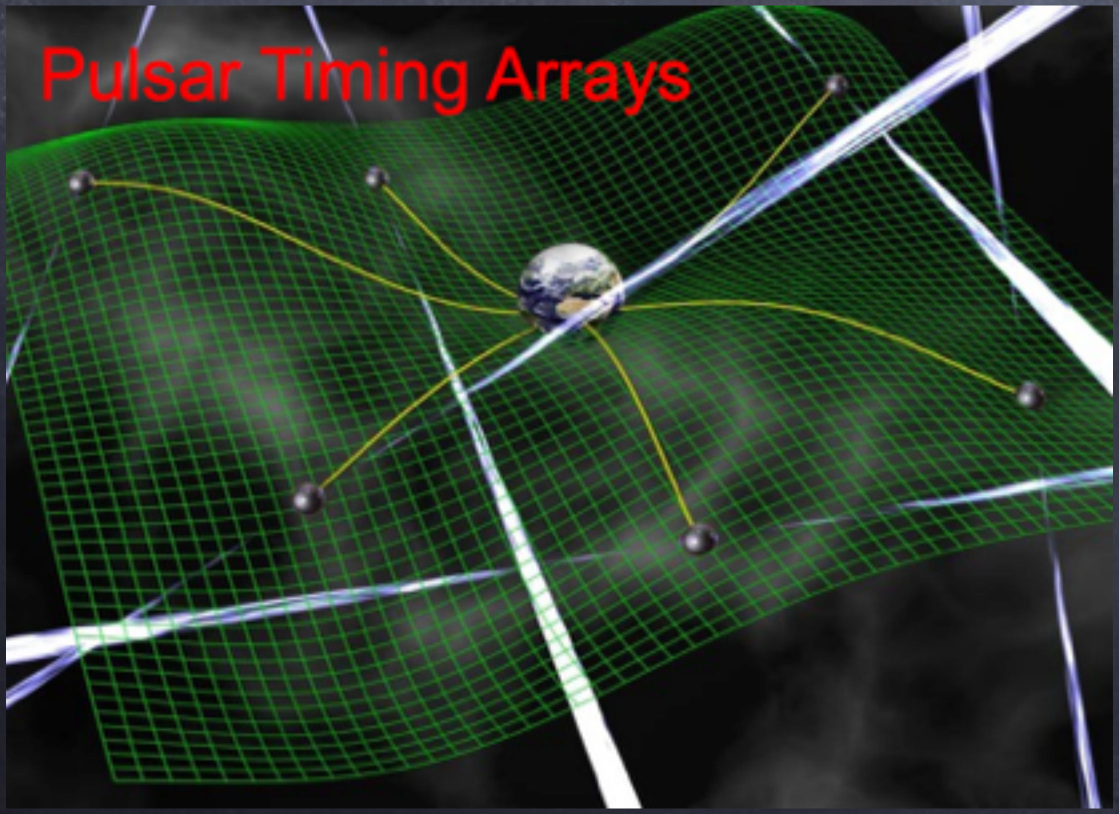
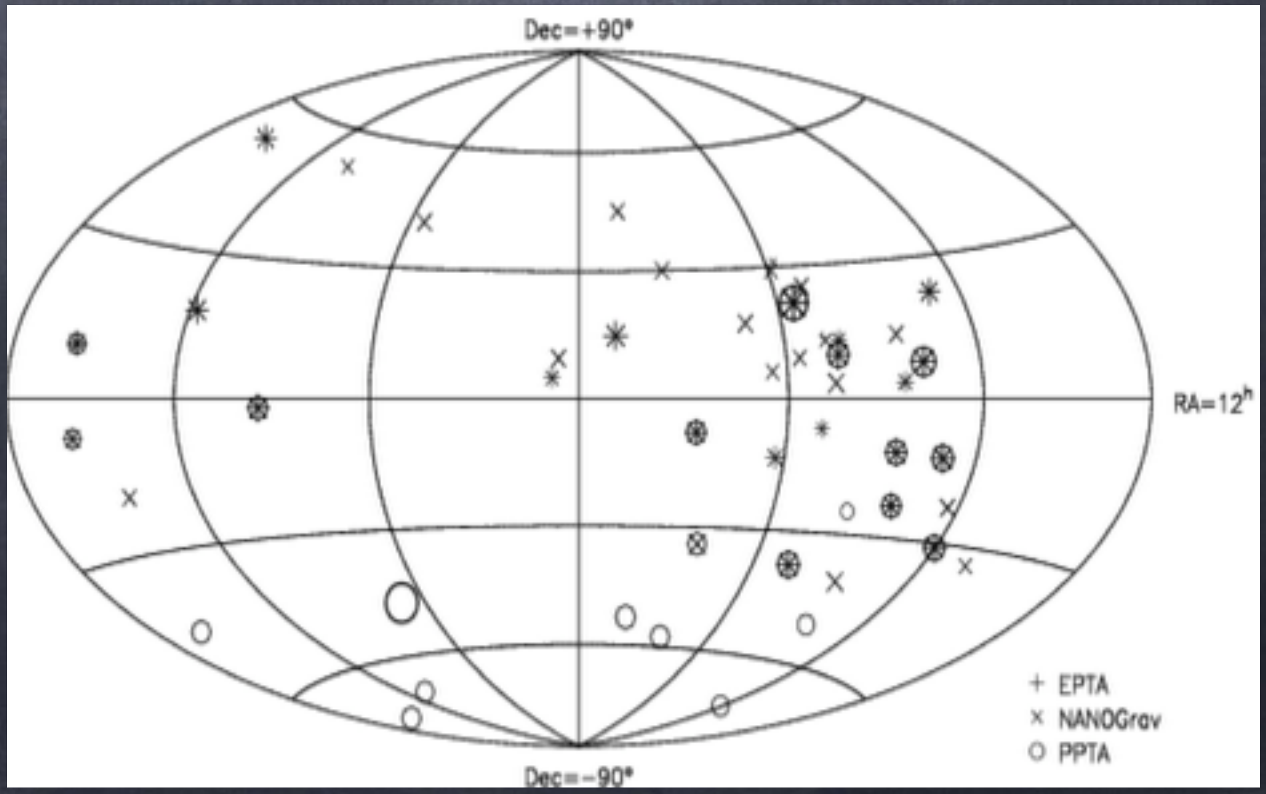
Need a detector network / many-pulsar timing array

- Propagation effects (bounds on graviton mass, graviton oscillations in biometric gravity)

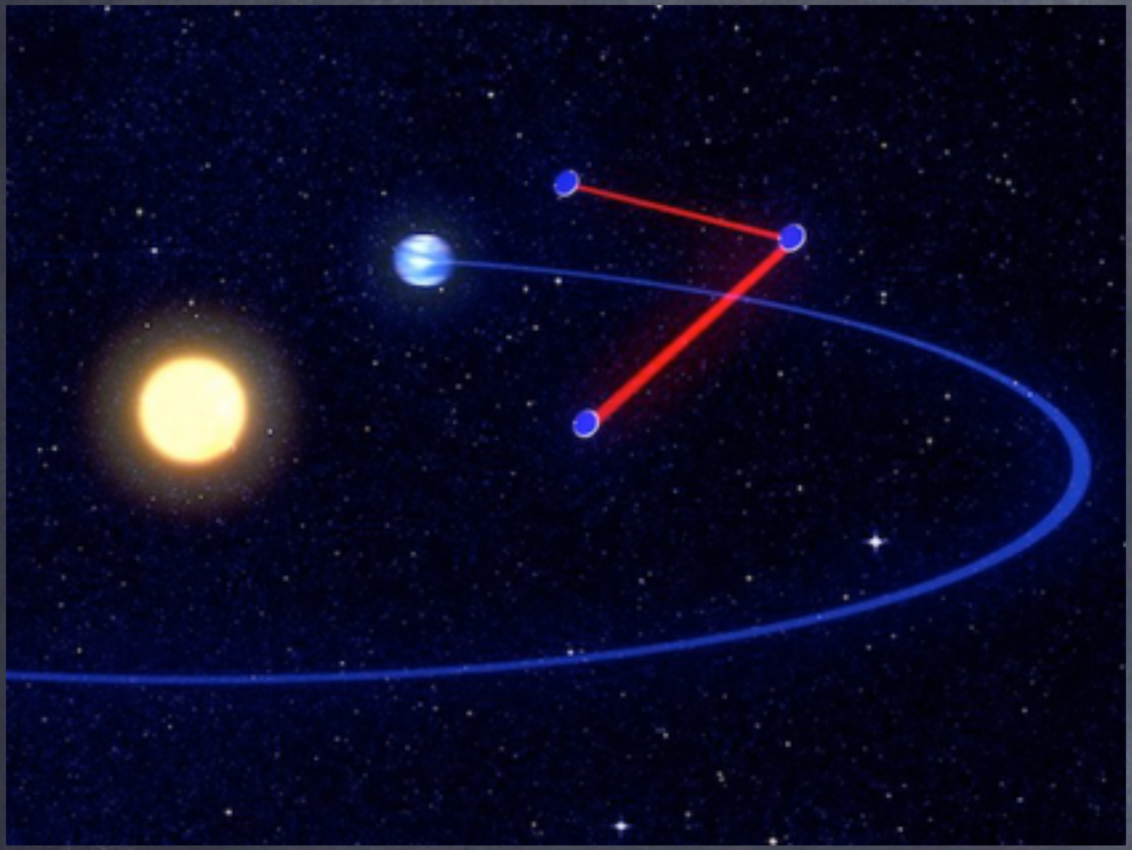
GW detectors



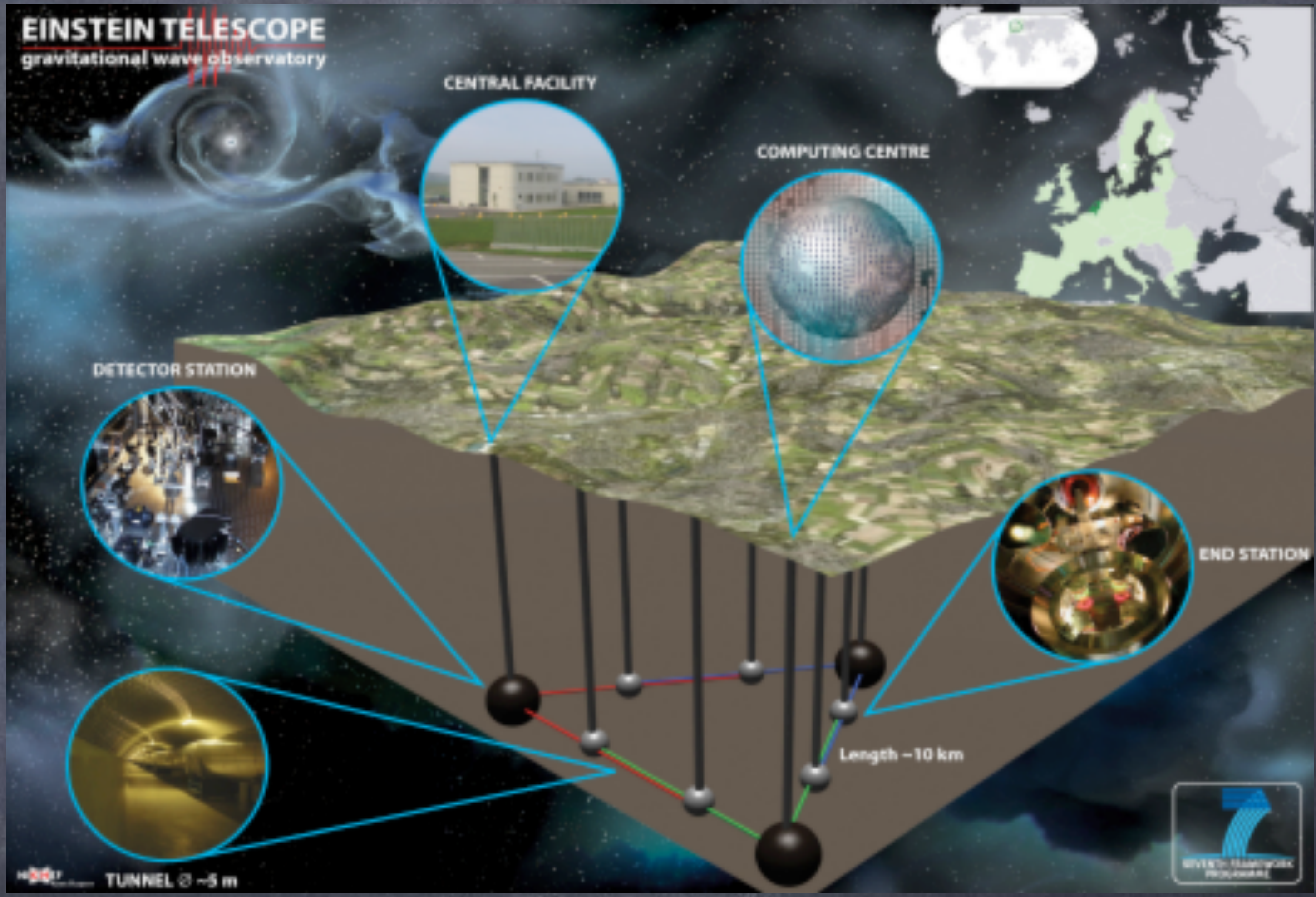




Next-generation detectors

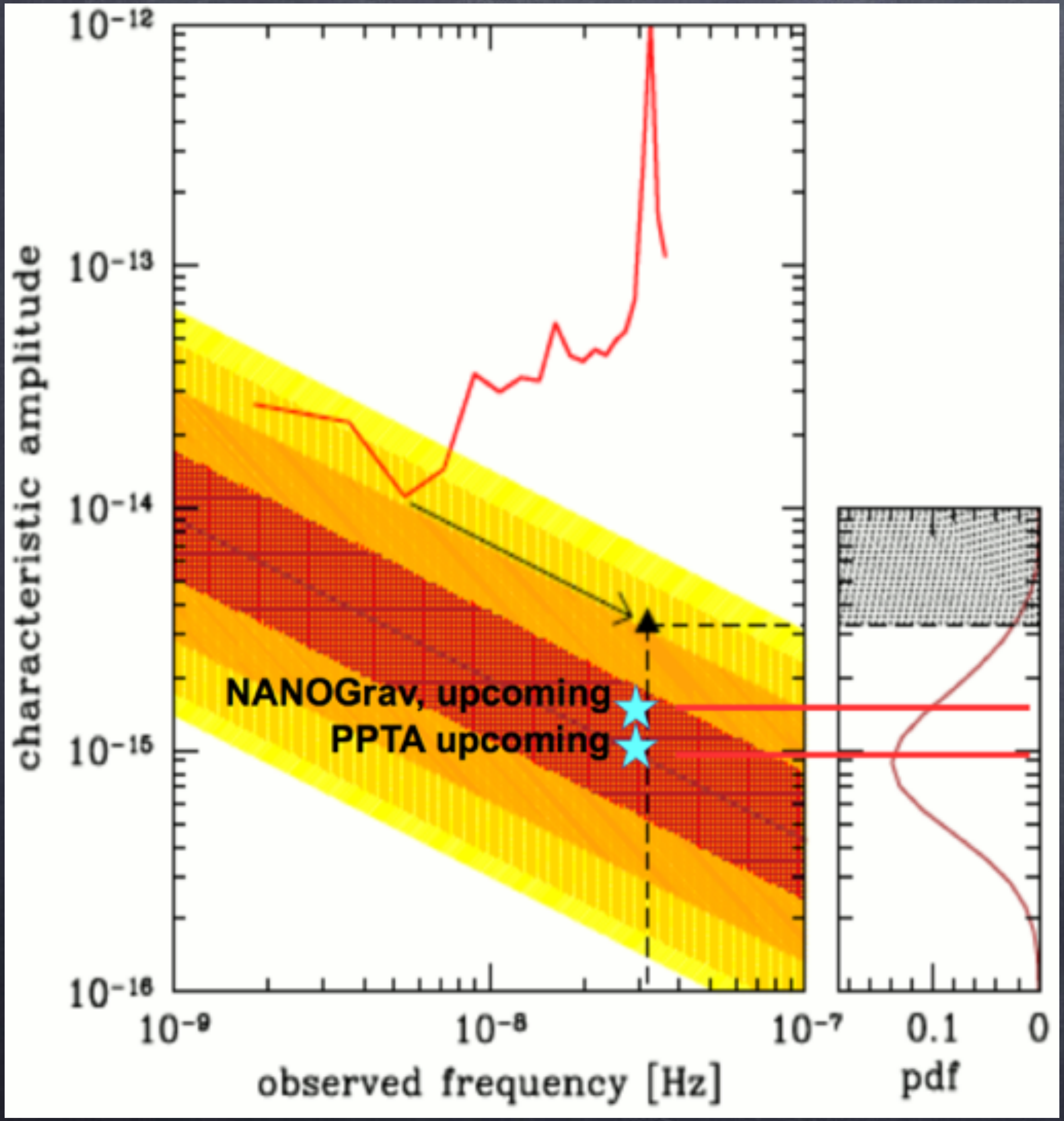


eLISA: selected as ESA's L3 mission (Pathfinder mission underway; launch 2028-2034)



ET: design study funded; 2020s?

Current PTA limits



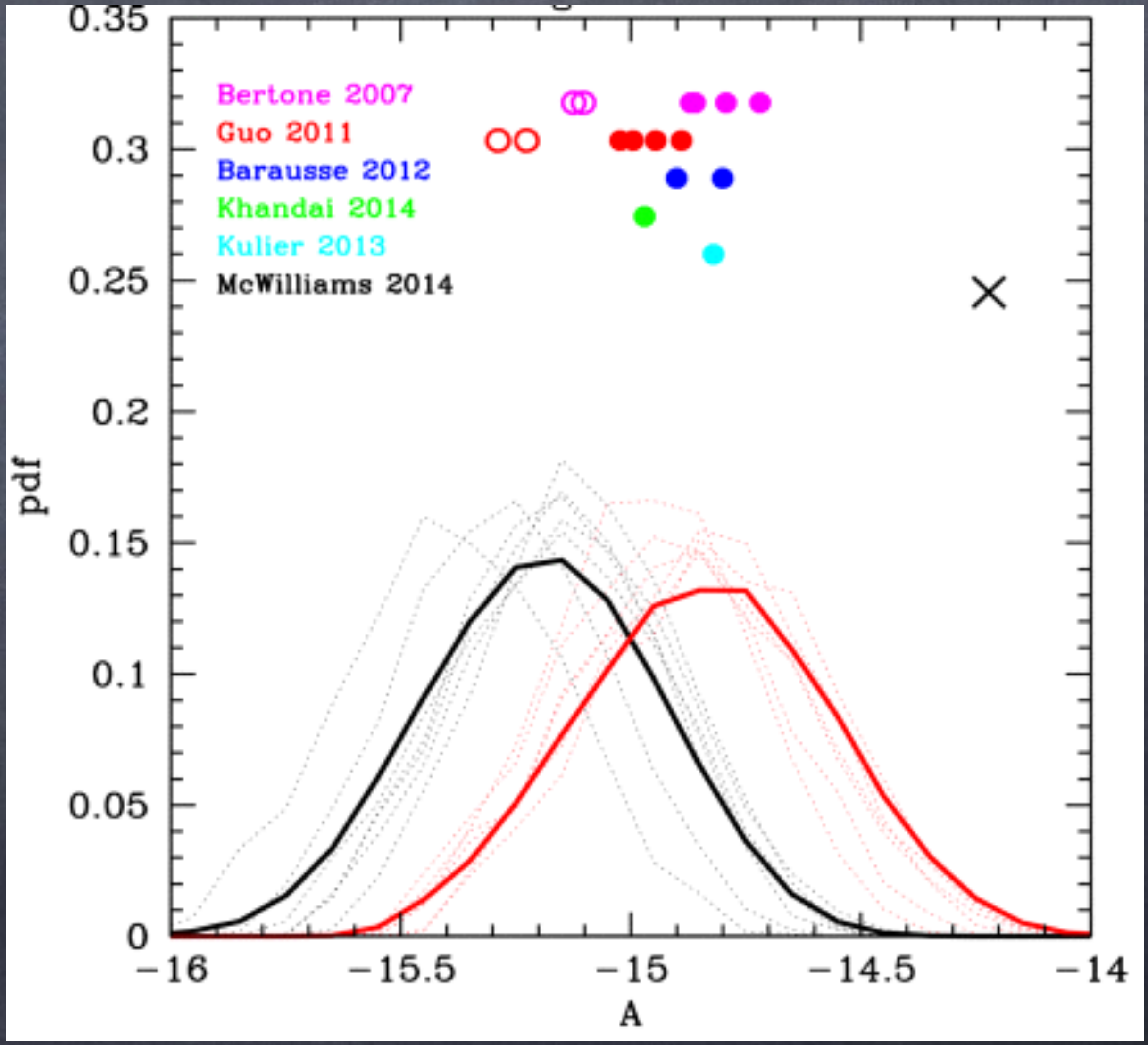
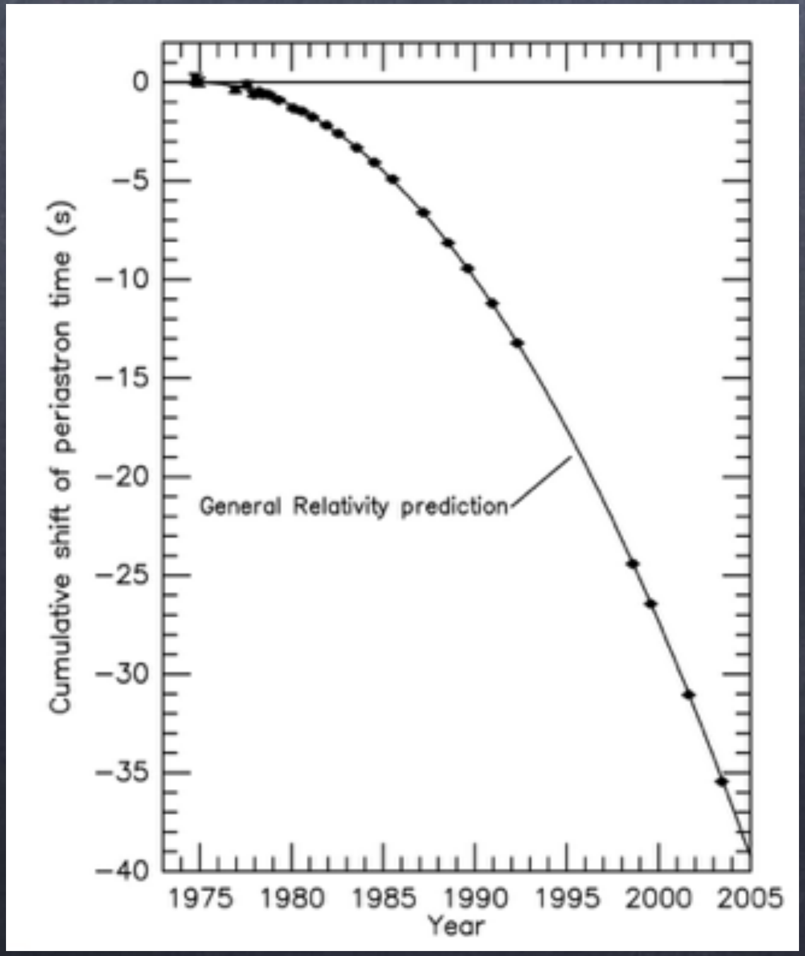
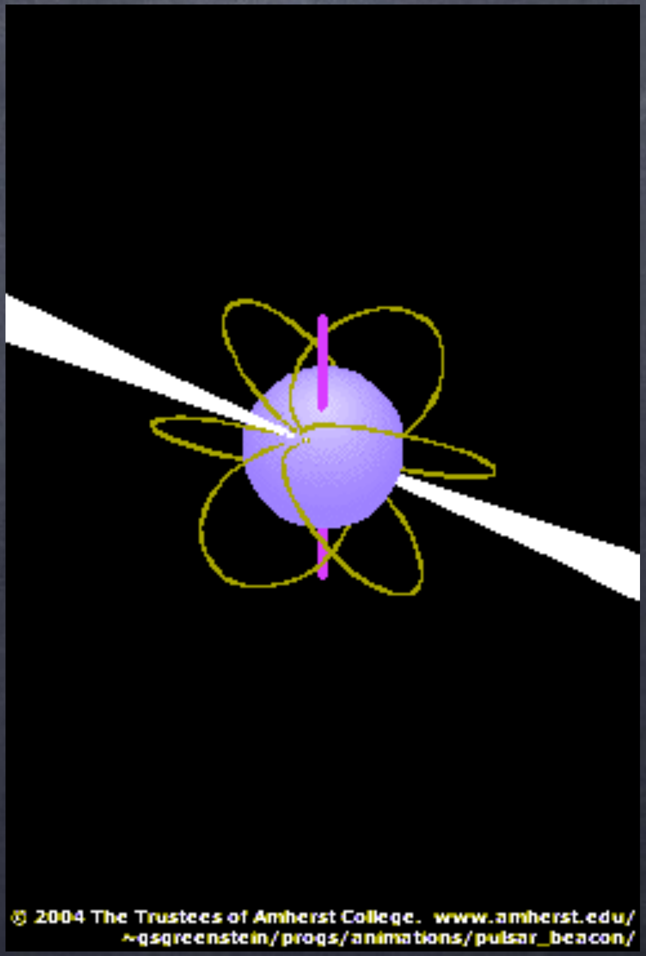


Figure courtesy of A. Sesana

Binary pulsars

- Binary system of stars on circular orbits has time changing mass quadrupole → GW emission
- GWs carry energy and angular momentum away from system, binding energy gets more and more negative and binary shrinks
- Indirect detection by binary pulsar systems (e.g. Hulse-Taylor pulsar)





Compact-object binaries are main GW sources

- Adv LIGO/Virgo: stellar-mass range, i.e. NS-NS up to $z \sim 0.1$, NS-BH, BH-BH up to $z \sim 0.5 - 1$
- ET: stellar and intermediate mass range, i.e. NS-NS, BH-NS, NS-NS at $z < 5$, IMBH-IMBH, BH-IMBH, NS-IMBH at $z < 10 - 15$
- PTA: supermassive range, i.e. SMBH-SMBH at $z < 1$
- eLISA: supermassive range, i.e. SMBH-SMBH at $z < 10 - 15$; IMBH-SMBH at $z < 5$, BH-SMBH, NS-SMBH at $z < 1$