Enrico Barausse
(Institut d’Astrophysique de Paris/CNRS, France)

The implications of GW detections for GR extensions

Journée Ondes Gravitationnelles

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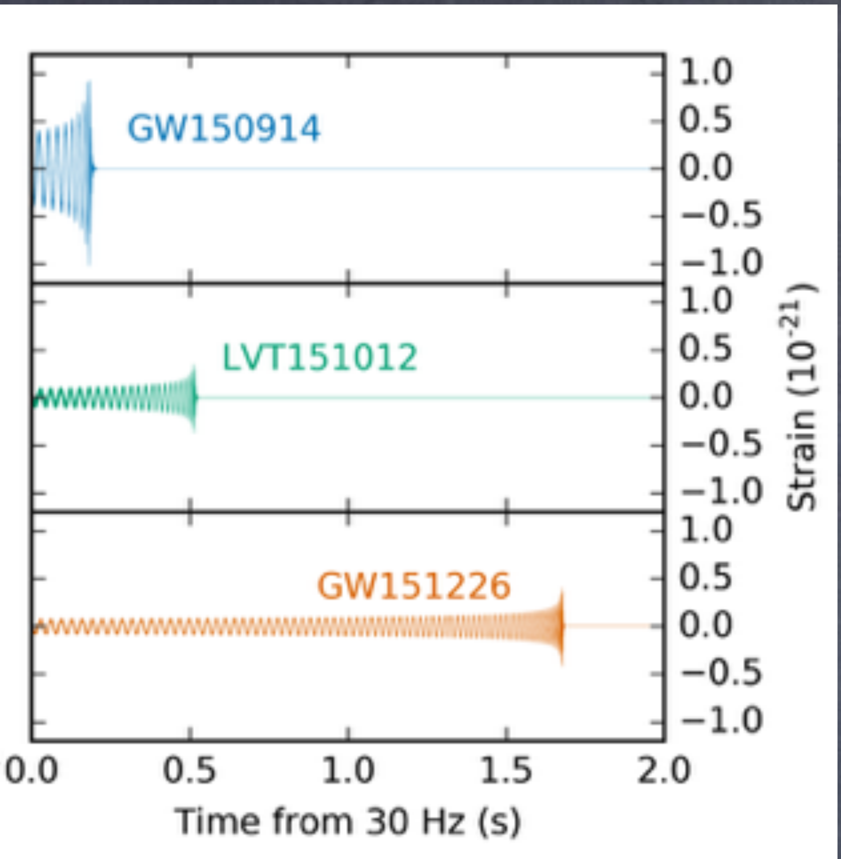
H2020-MSCA-RISE-2015 StronGrHEP-690904

“2.9” GW detections



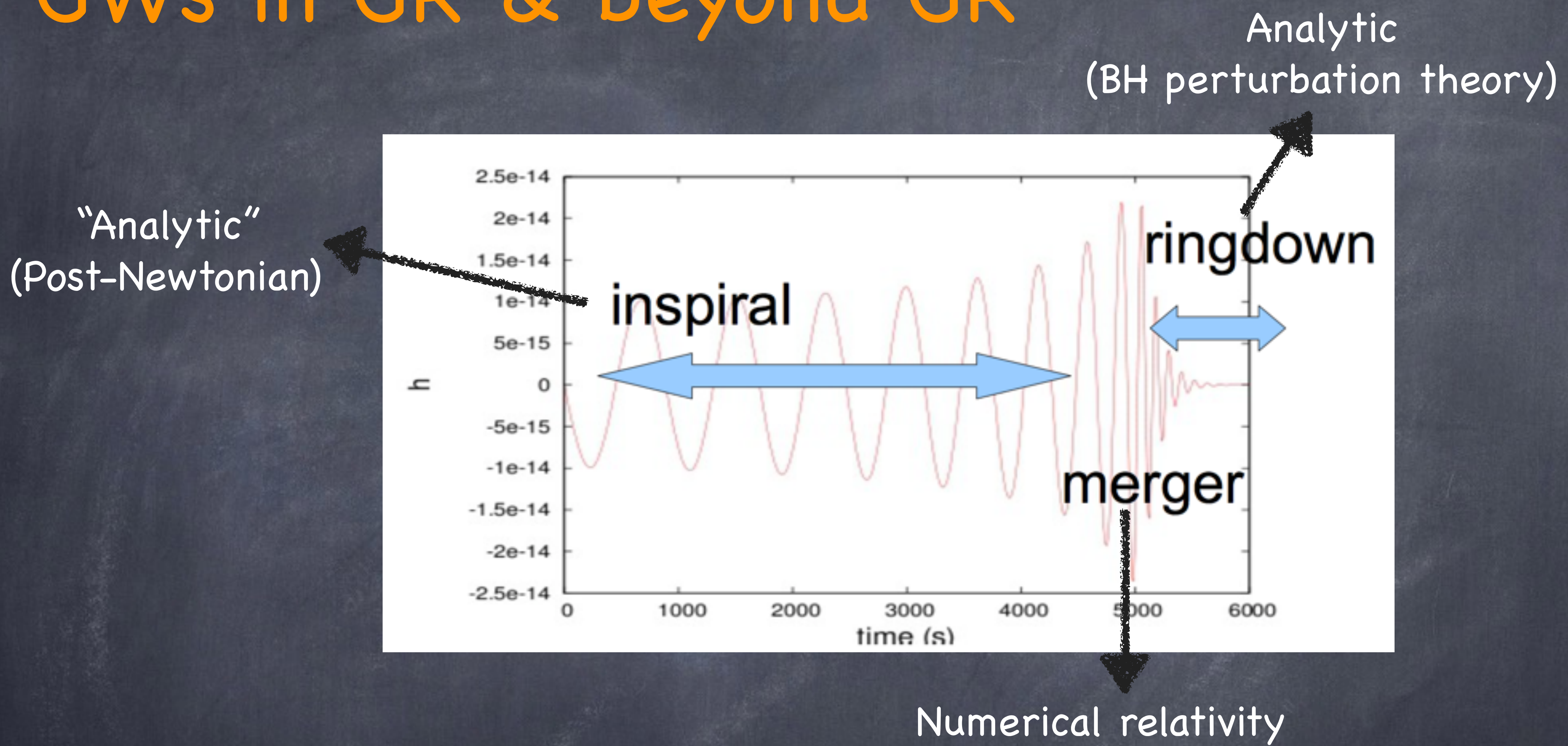
Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate FAR/yr^{-1}	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\sigma$	$> 5.3\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathcal{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_{\mathrm{f}}^{\mathrm{source}}/\mathrm{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin a_{f}	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s^{-1}})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$	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 $\Delta\Omega/\mathrm{deg}^2$	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 ($U_{\mathrm{Newton}} \sim c^2$) and highly relativistic ($v \sim c$) 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. $G_{\mu\nu} + \Lambda g_{\mu\nu}$

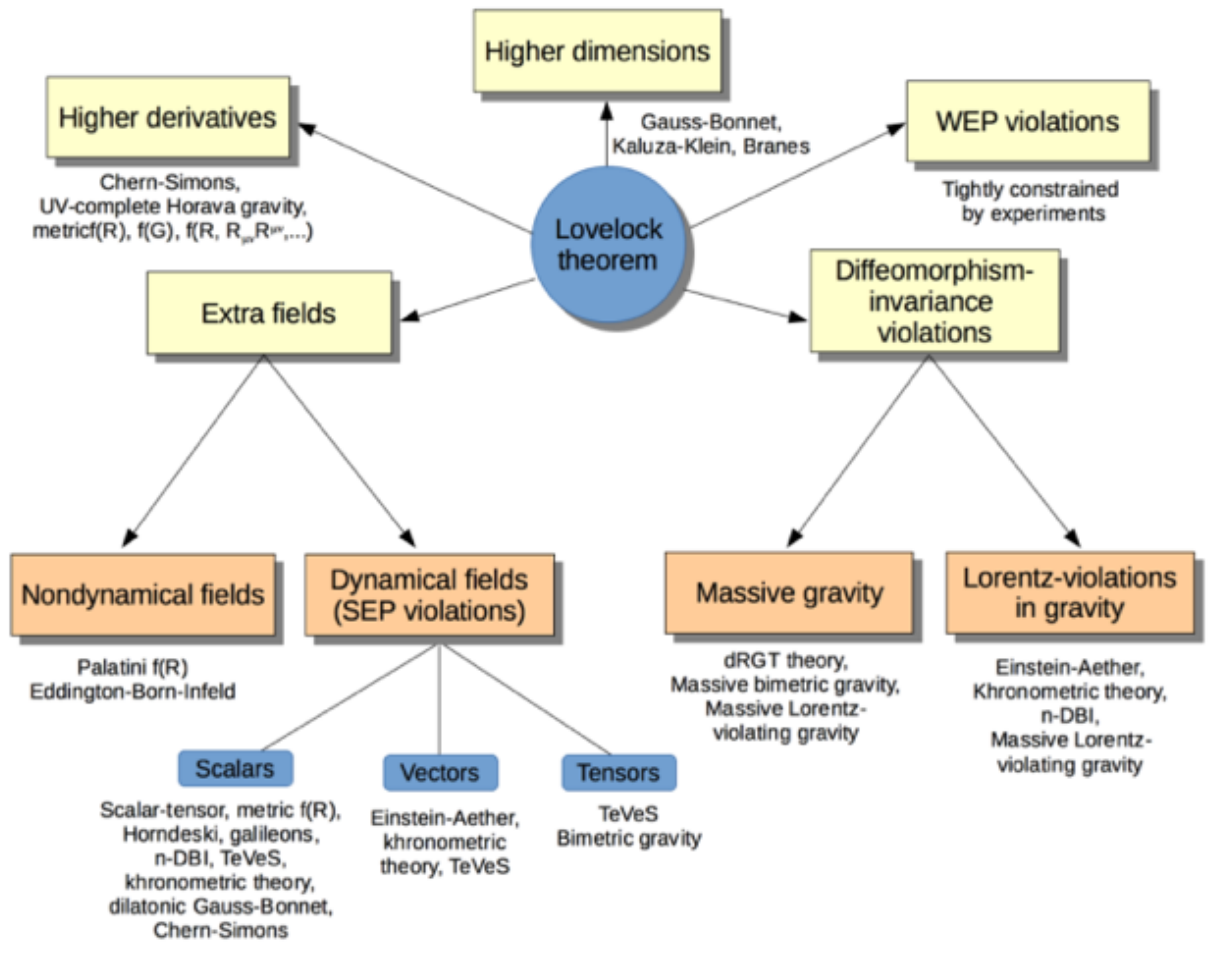


Figure adapted from Berti, EB et al 2015

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 $\Rightarrow$ 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

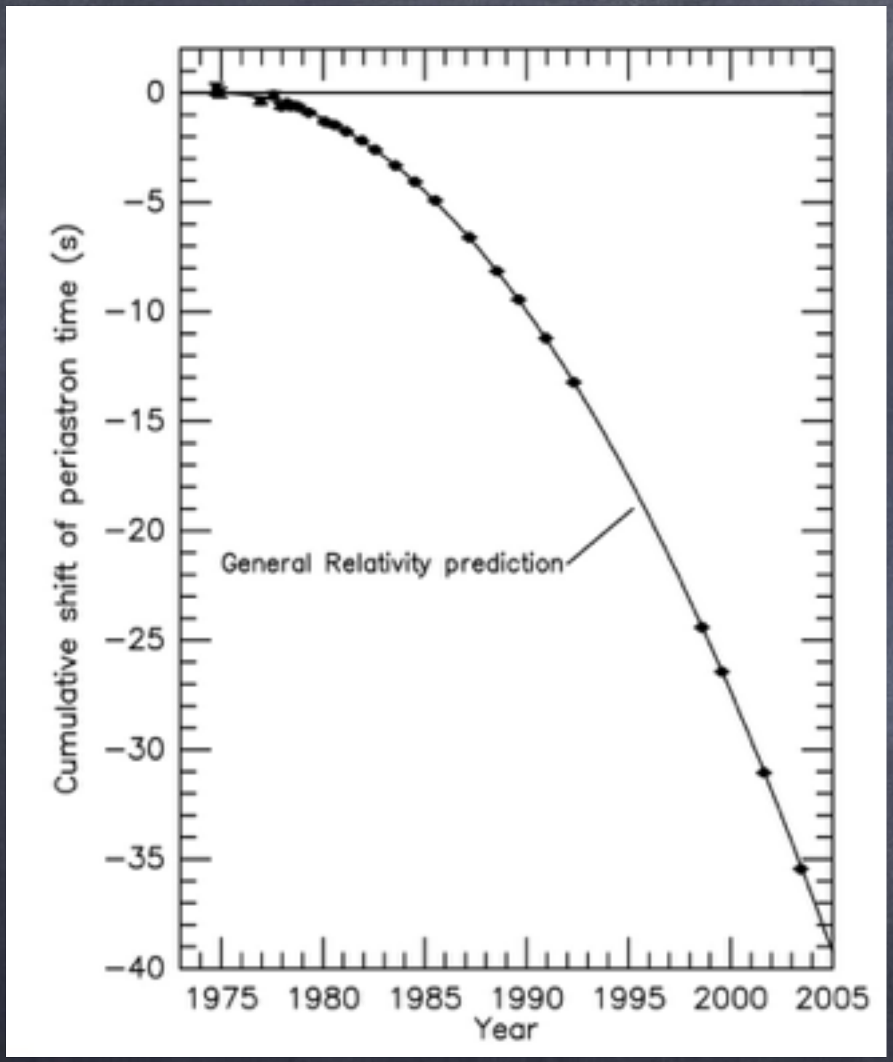
e.g. $M_1 \sim \int \rho x^i d^3x \quad h \sim \frac{G}{c^3}\dot{M}_1 \sim \frac{G}{c^3}\frac{P}{r}$ not a wave!

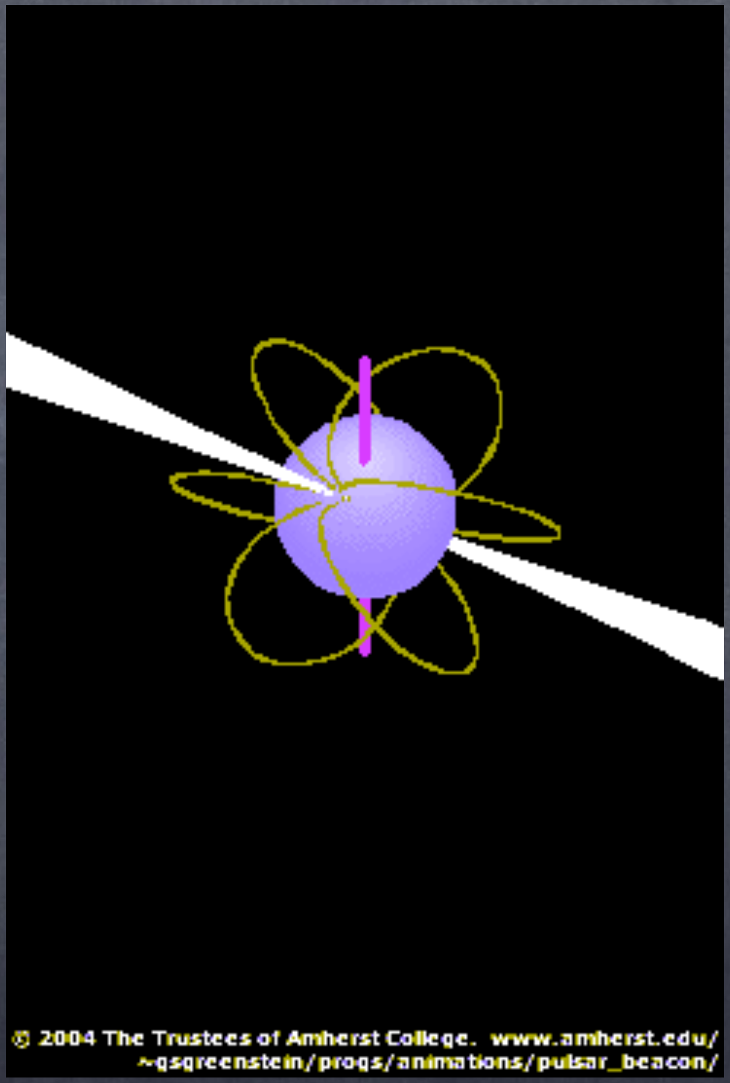
- In GR extensions, effective coupling matter-extra fields in strong gravity regimes $\Rightarrow$ energy and momentum transfer between bodies and extra field, monopolar and dipolar GW emission, modified quadrupole formula

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

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

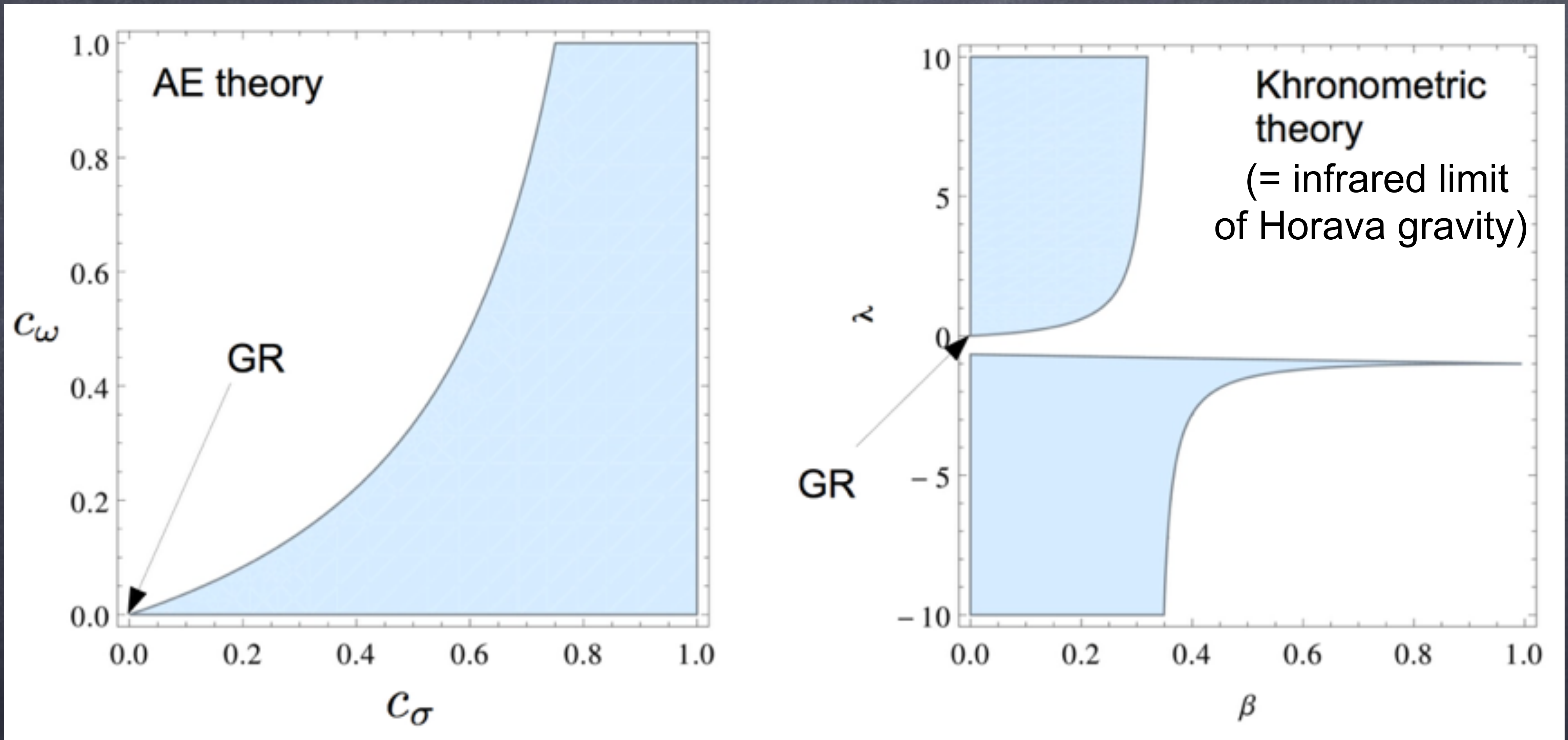
(Absence of) dipolar emission in binary pulsars





(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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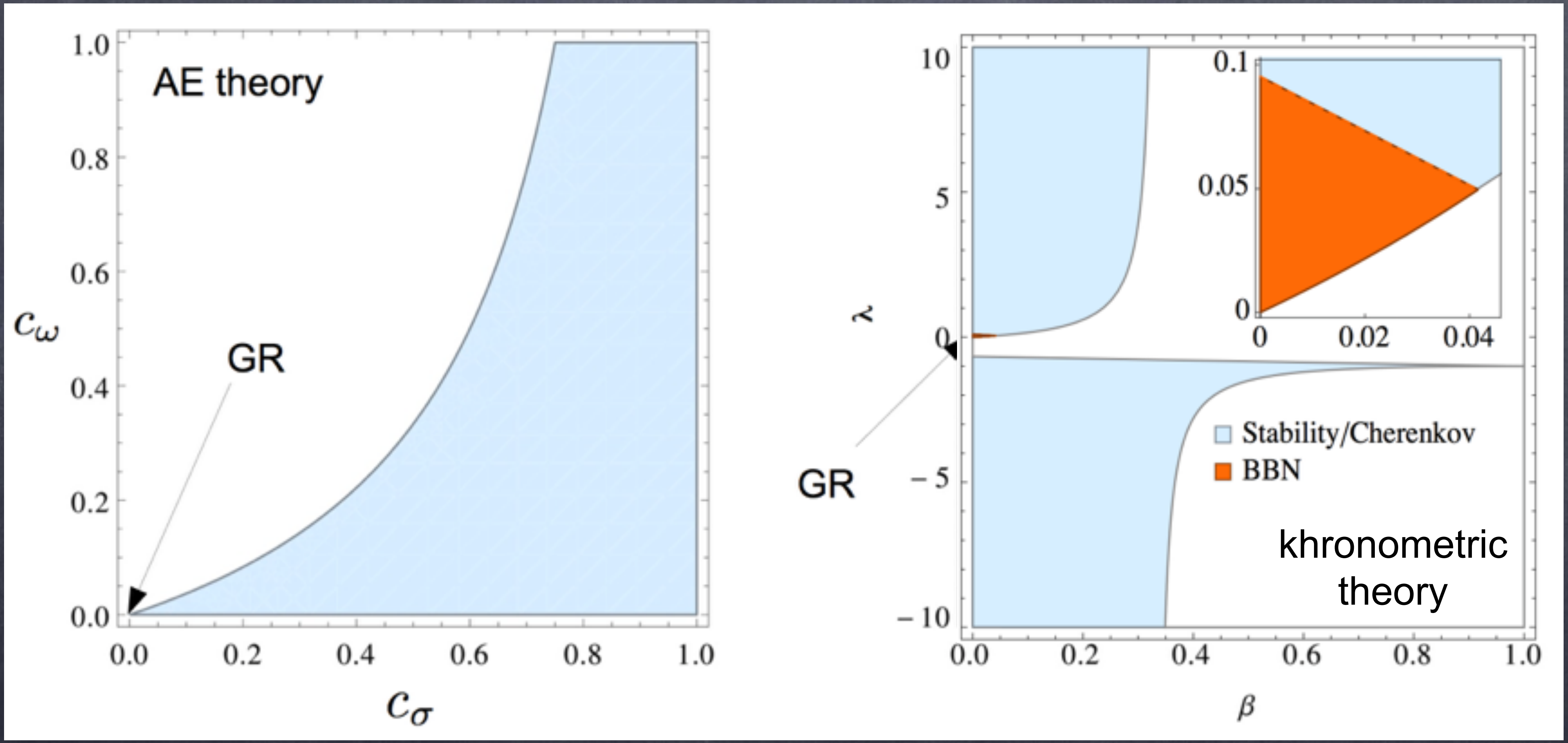

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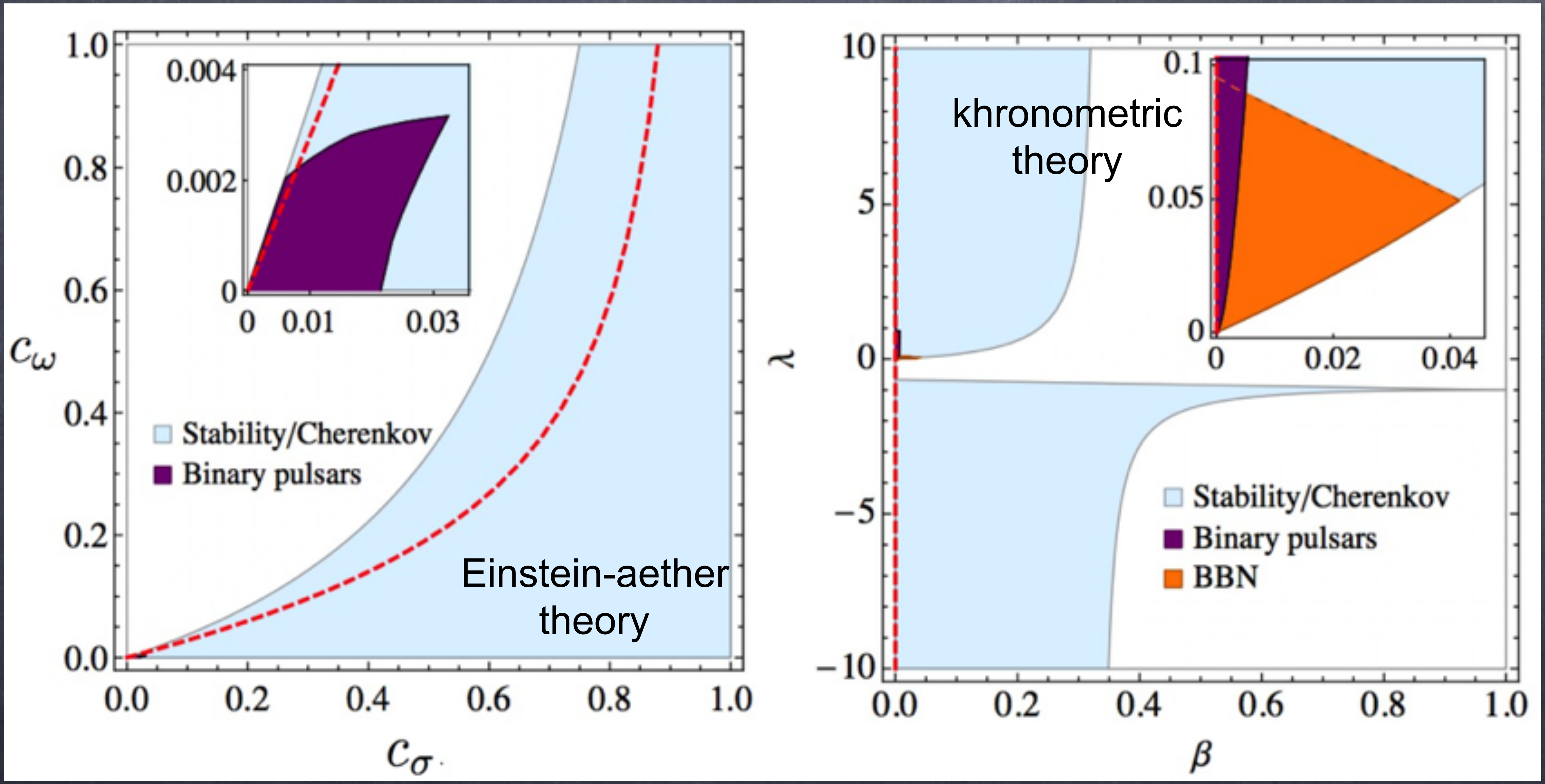
Yagi, Blas, EB & Yunes 2014



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")

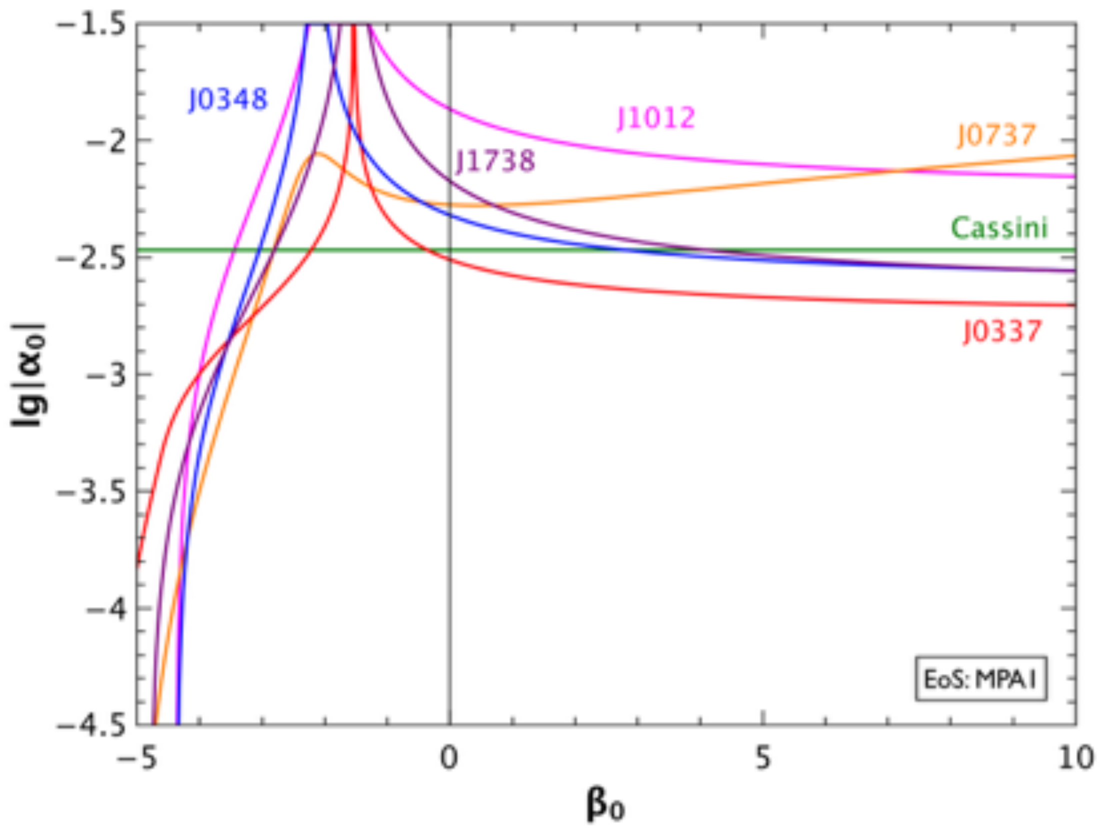


Figure credits: Wex, private comm.

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 ≠ const: higher-order field equations, Ostrogradsky ghost

Ostrogradsky ghost

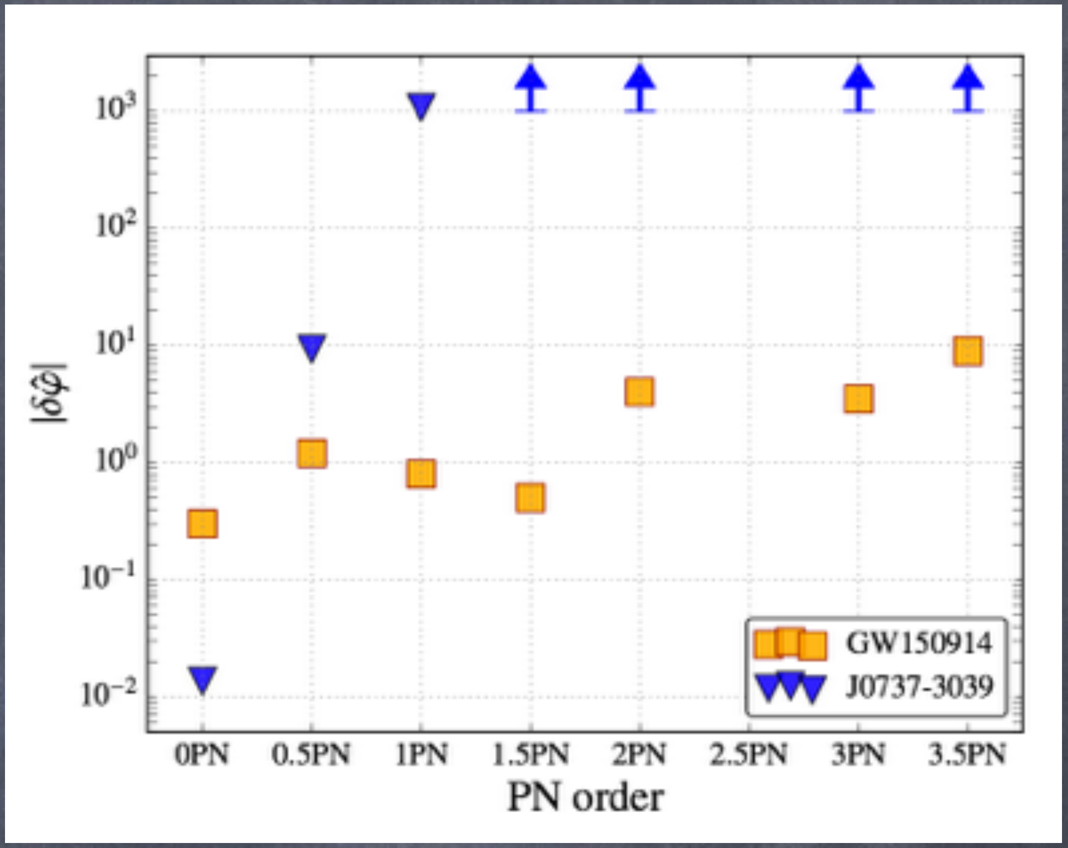
f_3 = const: same dynamics as GR (Pontryagin density is 4D topological invariant)
f_3 ≠ const: dynamical Chern-Simons, Ostrogradsky ghost

f_4 = const: same dynamics as GR (Gauss-Bonnet term is 4D topological invariant)
f_4 ≠ 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)

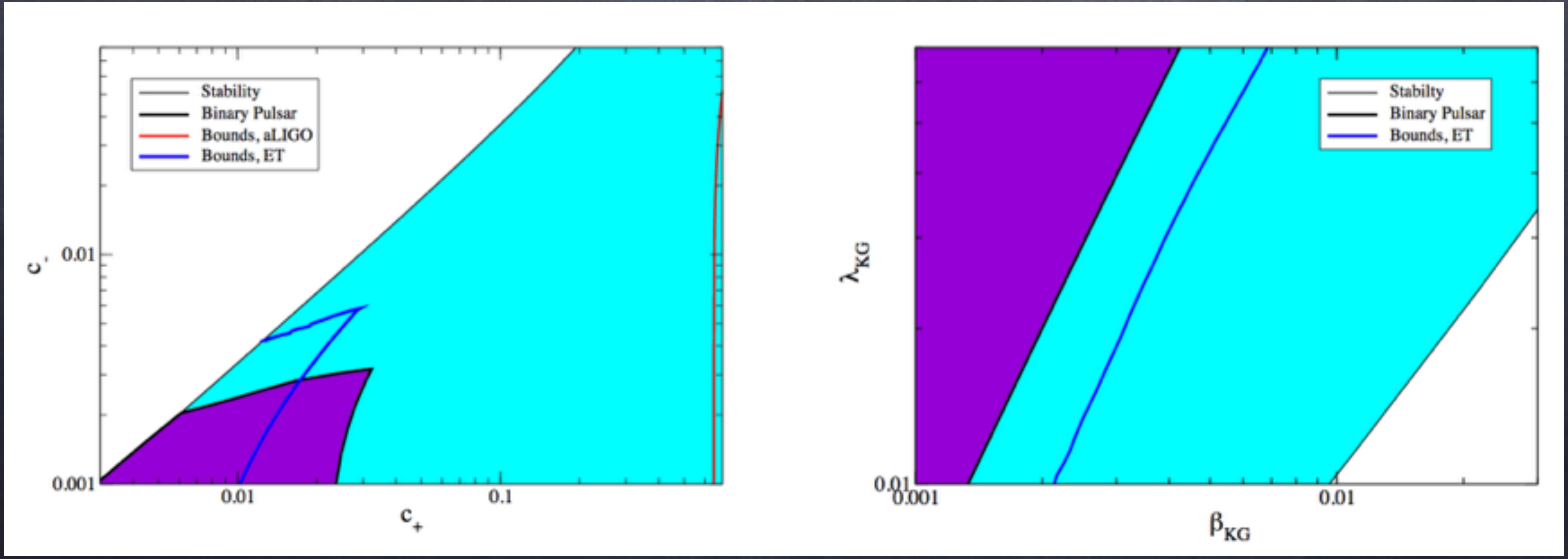
More general theories (with extra vector or tensor dof's) predict dipole emission also (though not exclusively) in BH binaries

Constraints on dipolar emission from direct detections

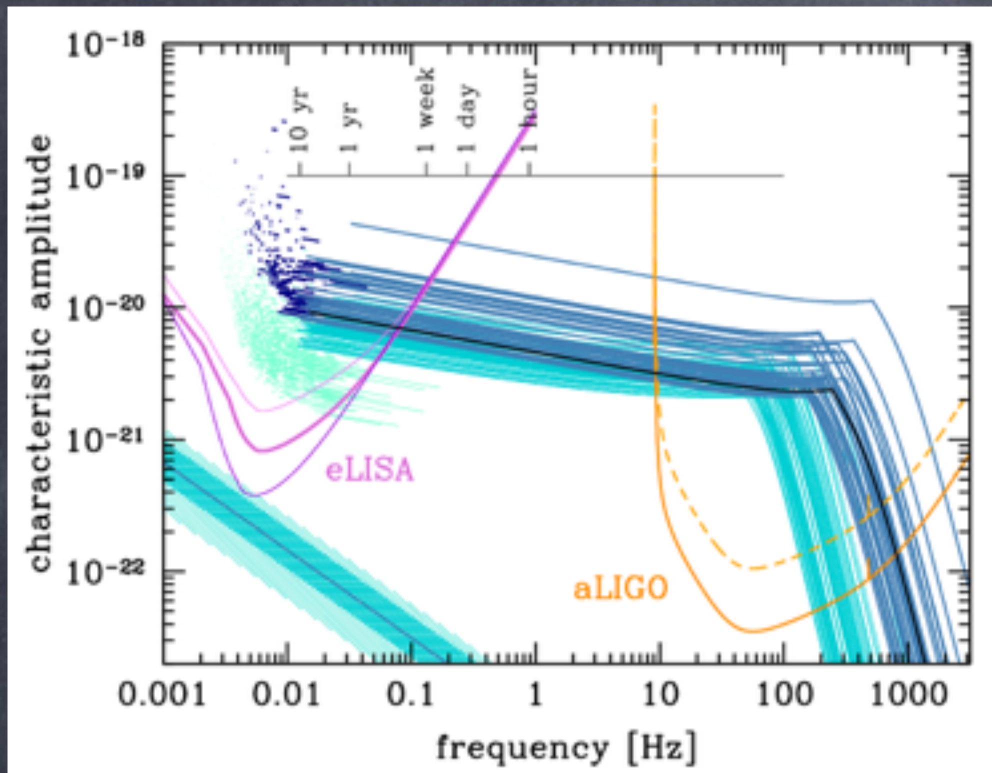


Weak bounds from advanced detectors

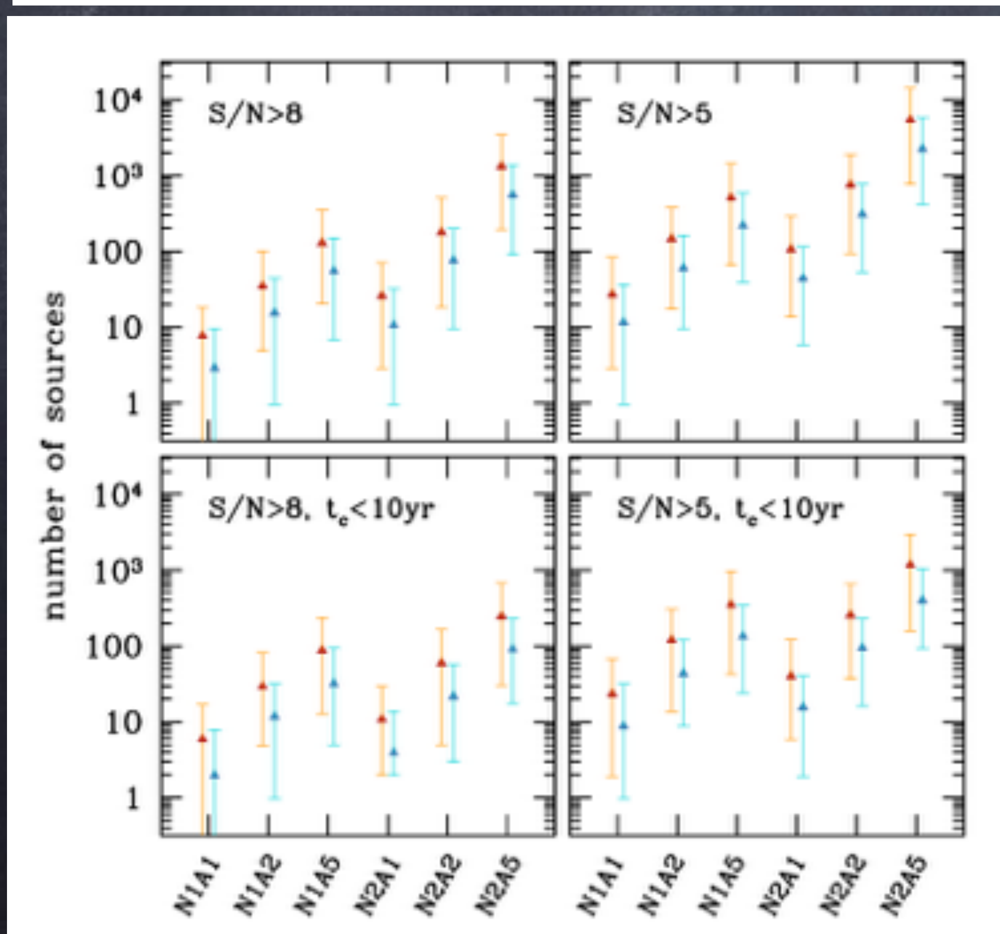
Better for 3rd-gen detectors, e.g. Lorentz violating gravity (Hansen, Yunes, Yagi 2015)

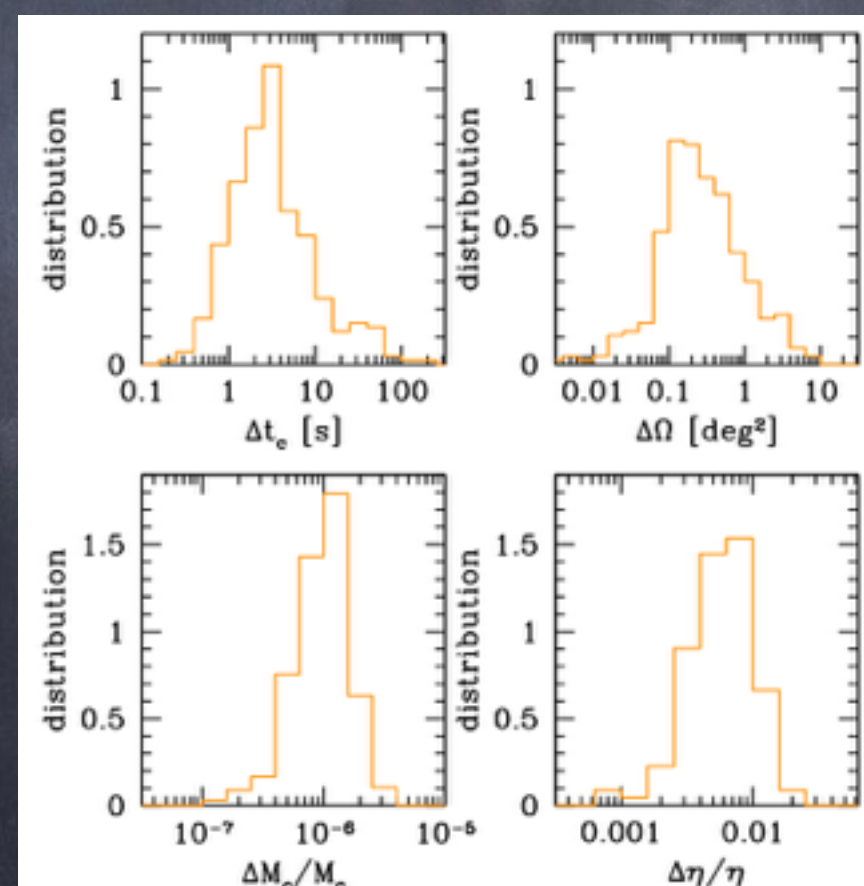


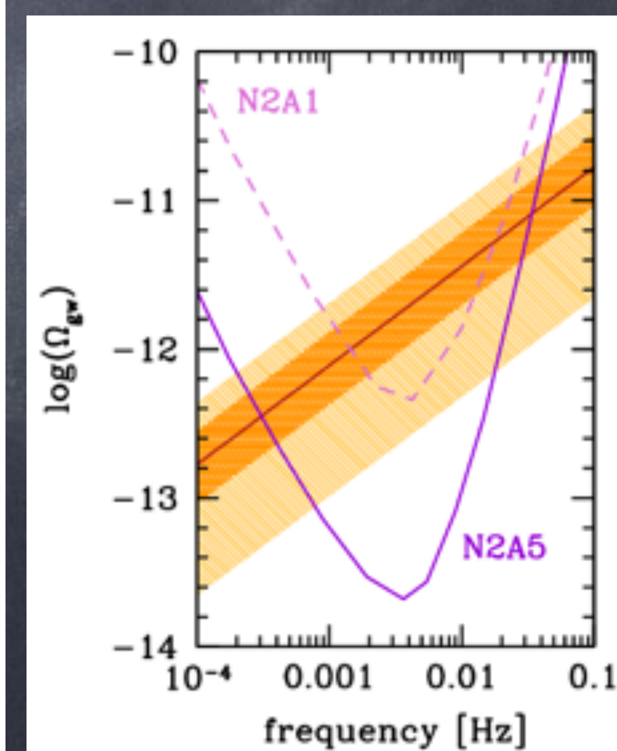
Multi-band observations of GW150914-like/ intermediate-mass binary BHs



- 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





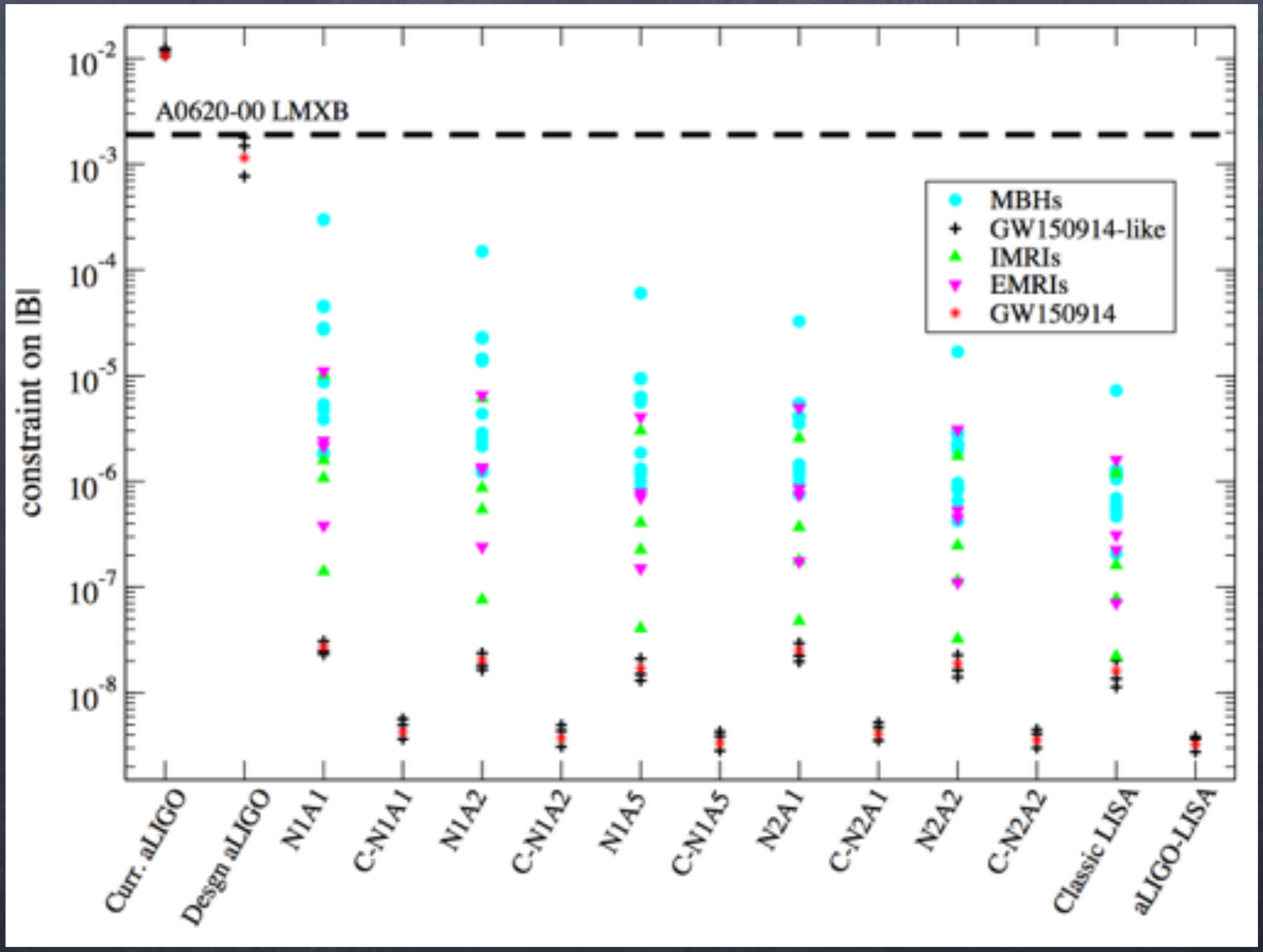


Figures from Sesana 2016

Tests of BH-BH dipole emission

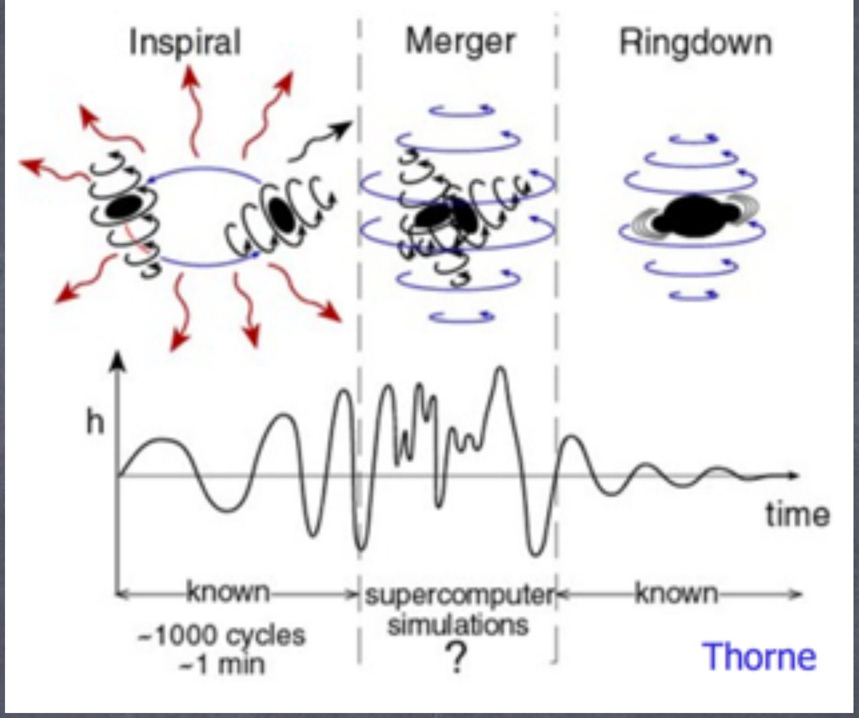
$$\dot{E}_{GW} = \dot{E}_{GR}\left[1 + B\left(\frac{v}{c}\right)^{-2}\right] \qquad B \propto (s_1 - s_2)^2$$

- 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?



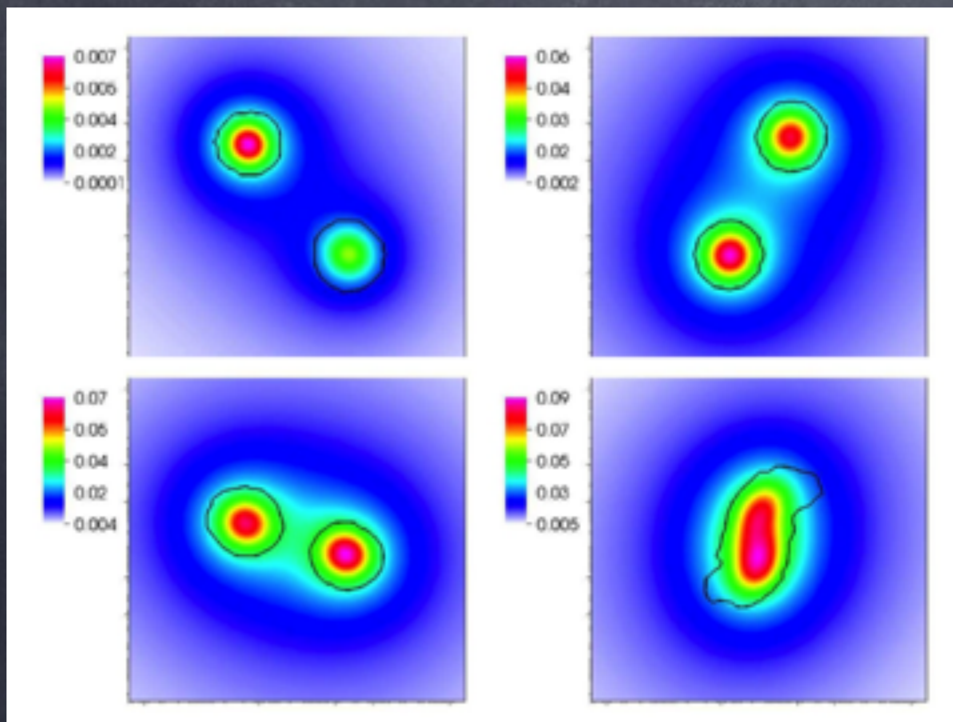
Possible surprises/
highly non-linear dynamics?

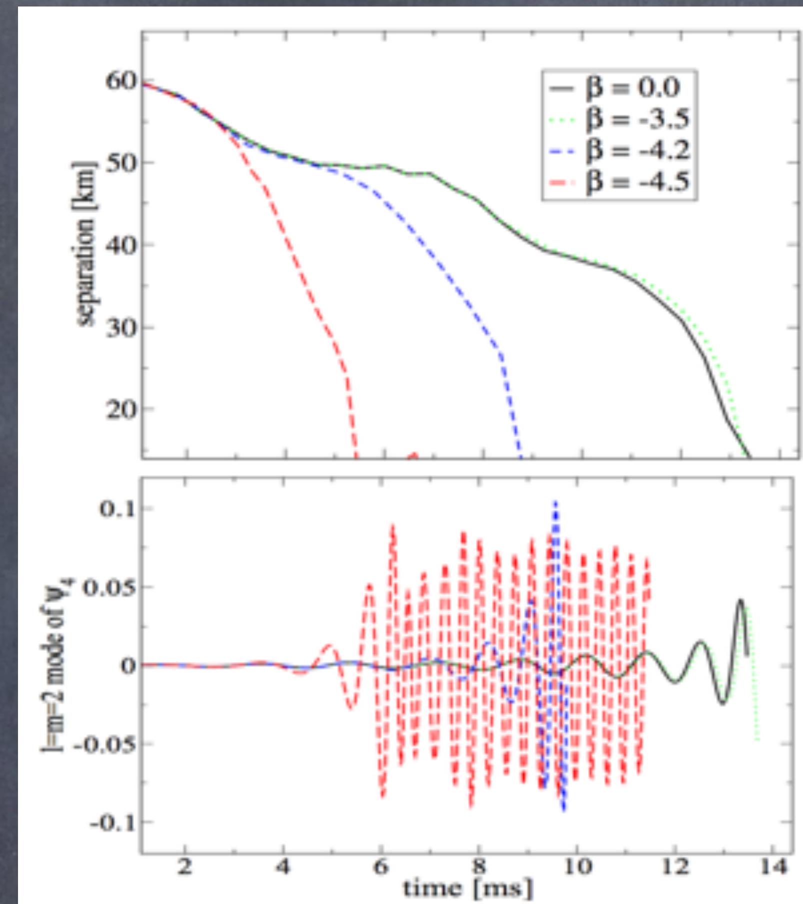
Need numerical-relativity simulations: prerequisite is that Cauchy problem be well-posed (e.g. that eqs be strongly hyperbolic, i.e. wave eqs)

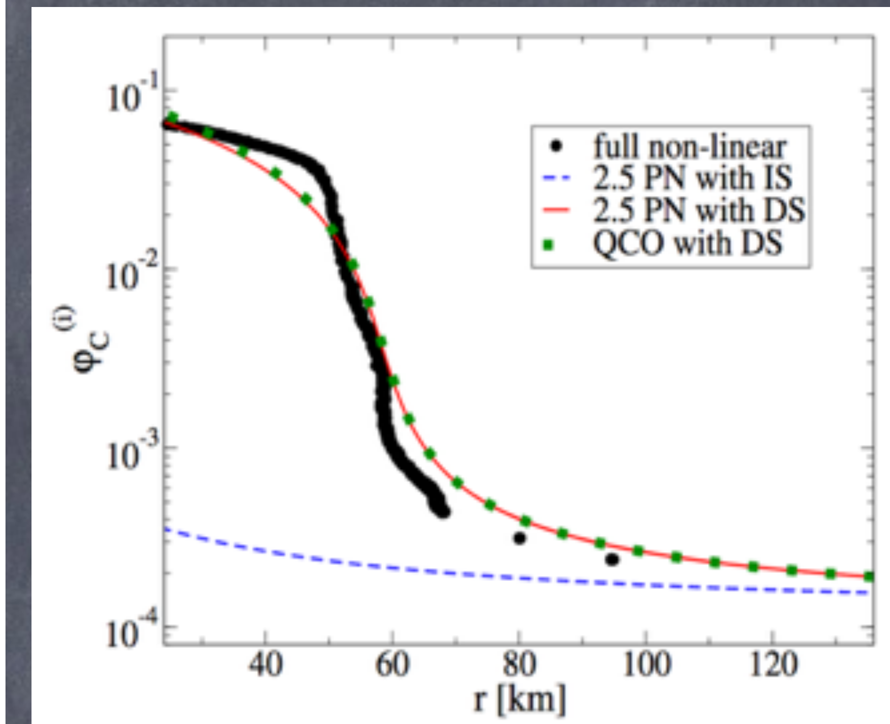
- True for FJBD-like scalar-tensor theories (i.e. with NO galileon terms), but GR dynamics in vacuum (modulo boundary/initial conditions, mass term)
- True in flat-space & spherical symmetry for Lorentz-violating gravity and galileons; dynamics differs from GR both in vacuum and matter, but no general 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"

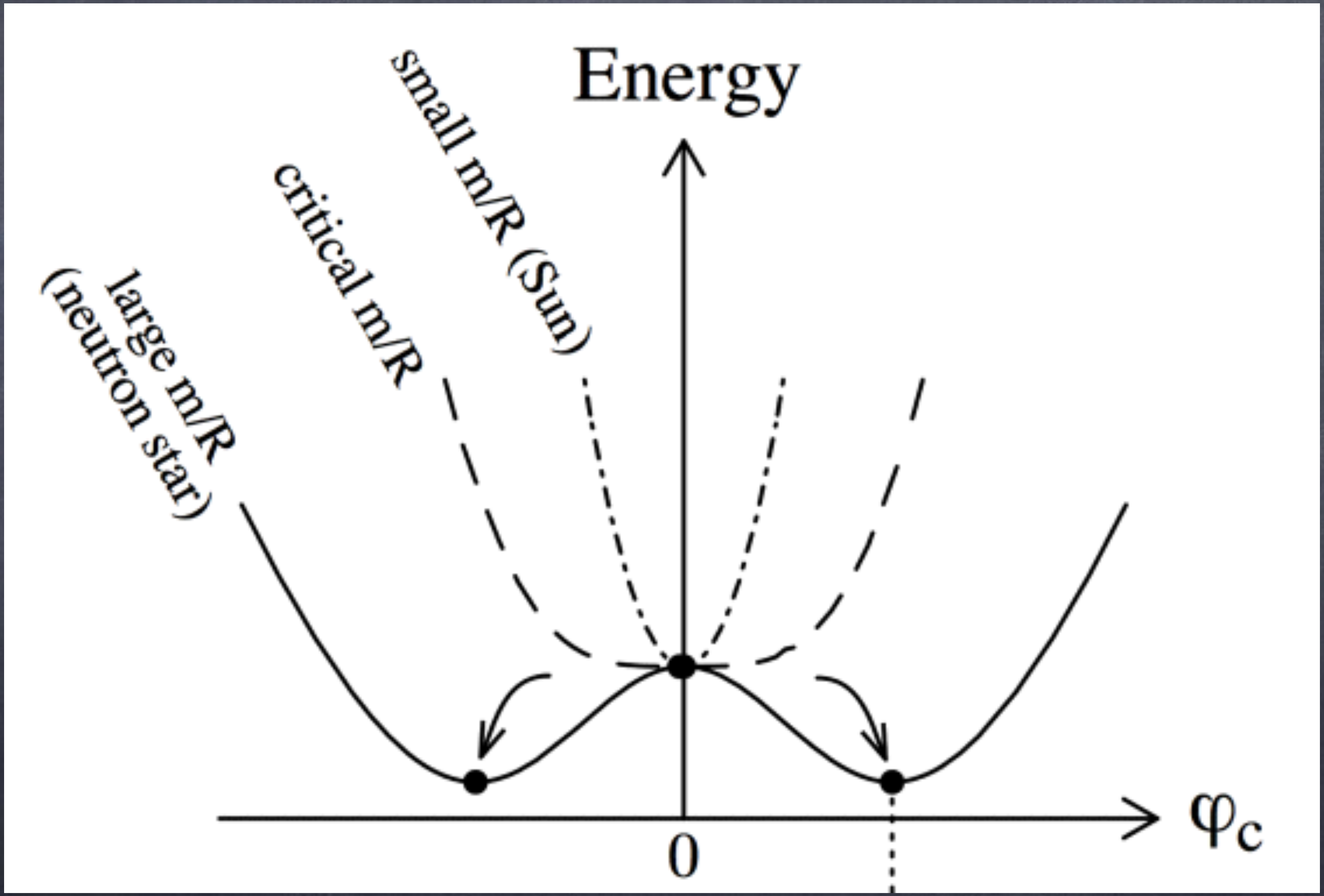
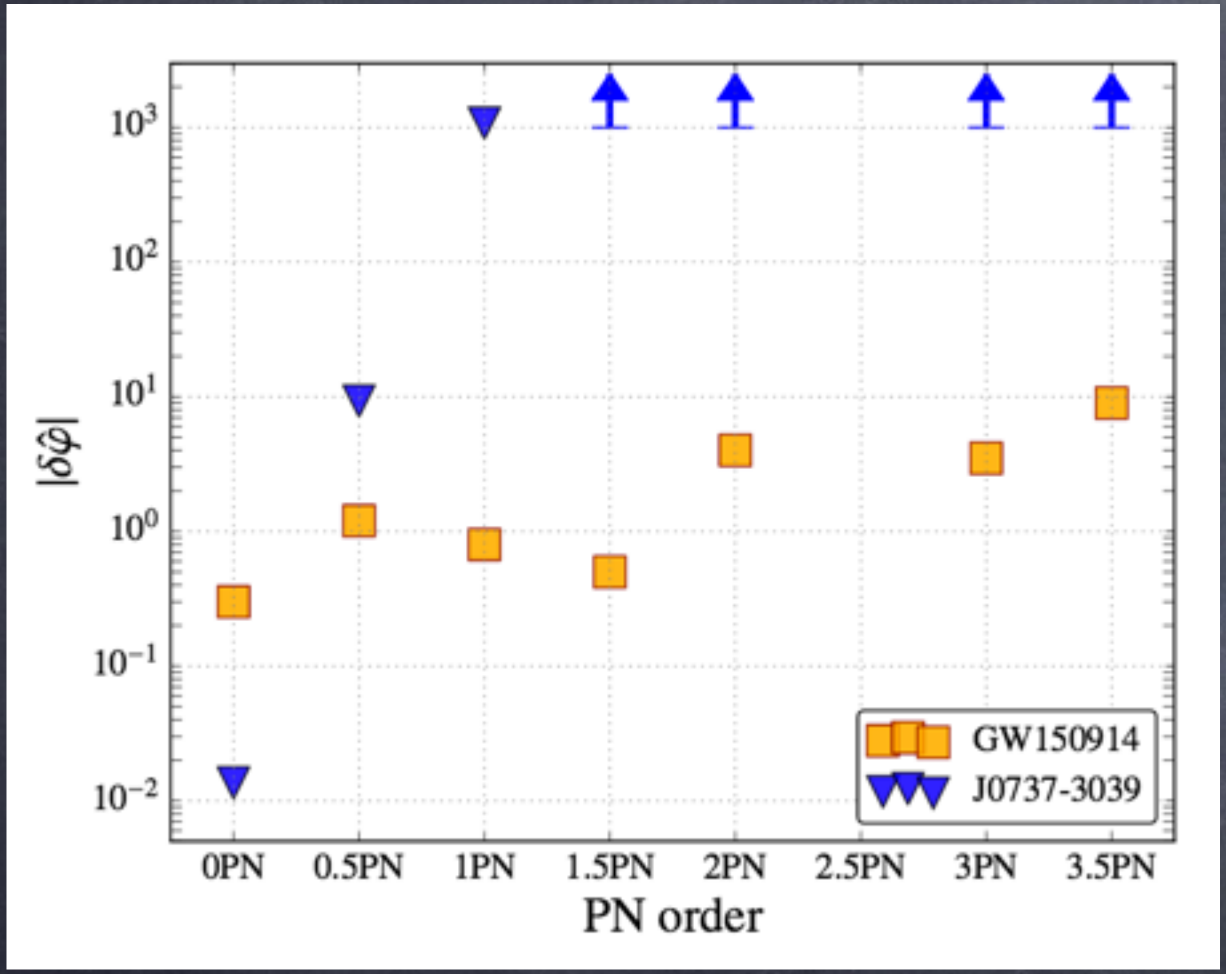


Figure from Esposito-Farese, gr-qc/0402007

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

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

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

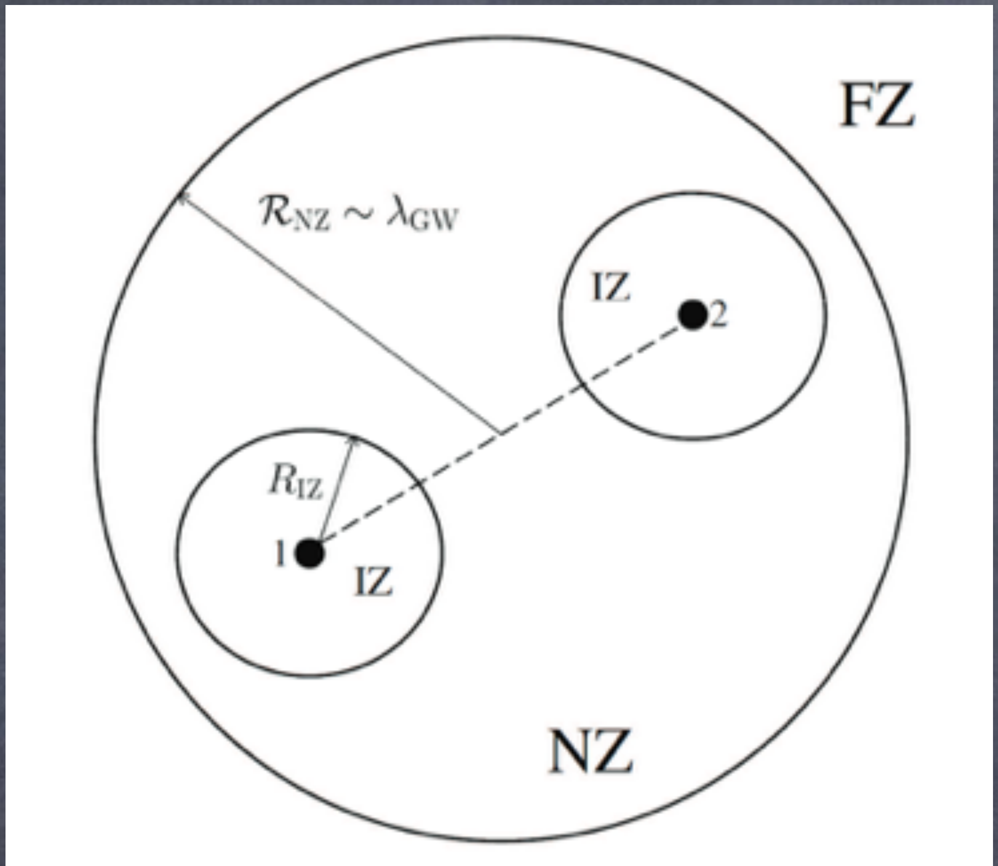
- Non-linear field eqs allow “Vainshtein mechanism”

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

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

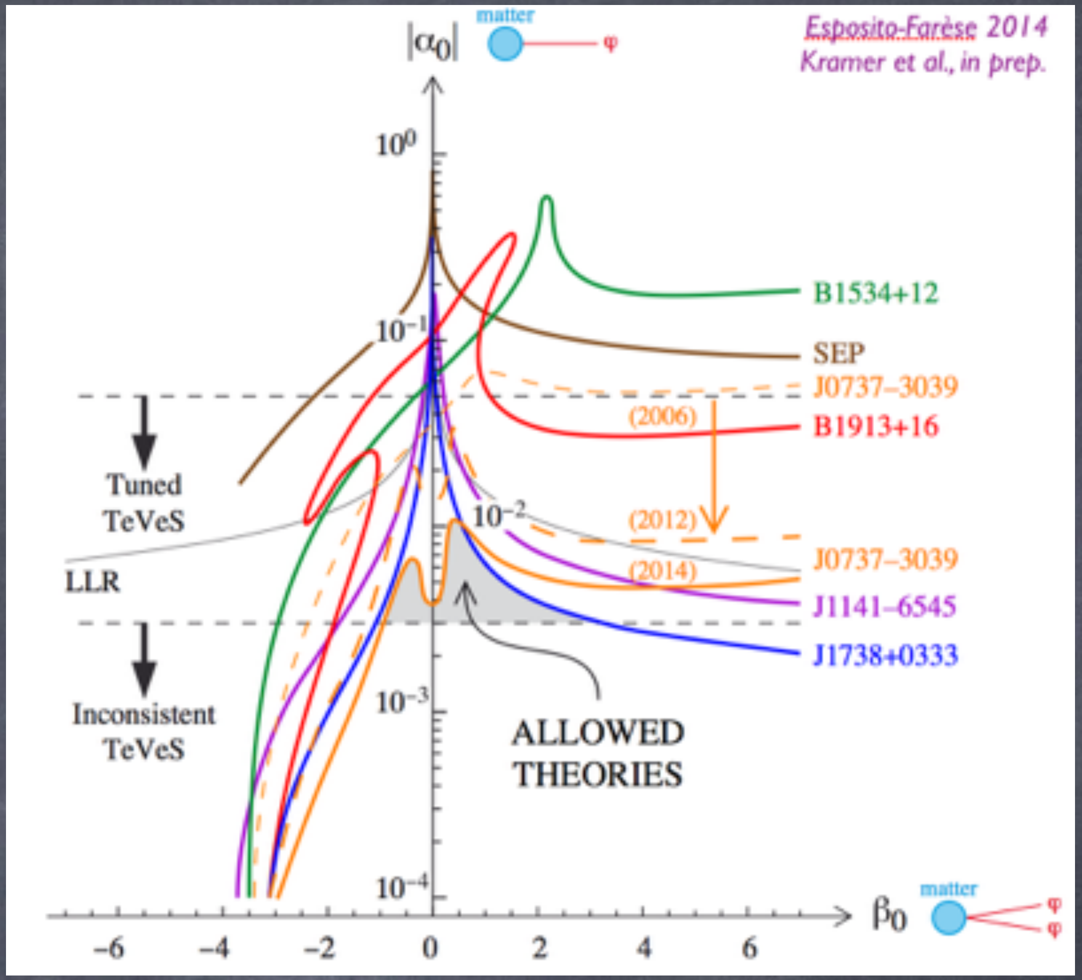
Scalar effects only arise for r>> r_V (Vainshtein radius)

Non-perturbative PN expansion in Horndeski with Vainshtein mechanism



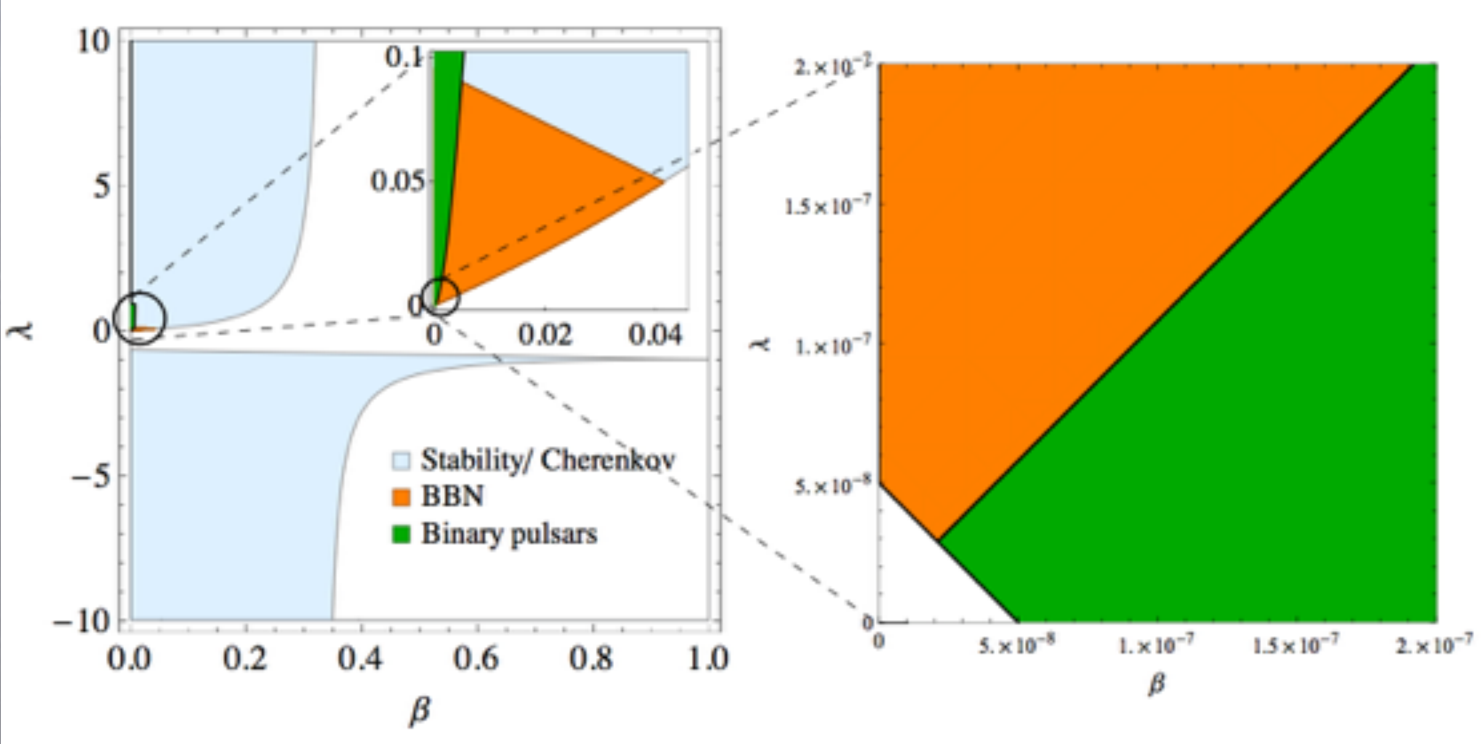
- Vainshtein radius r_V is effective size of point pass
- If $r_V \gtrsim \lambda$, we have a problem! (de Rham, Matas & Tolley 2012, Chu & Trodden 2013, EB & Yagi 2015)
- WKB analysis predicts all multipole moments radiate with same strength in binary systems (de Rham, Matas & Tolley 2012)

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



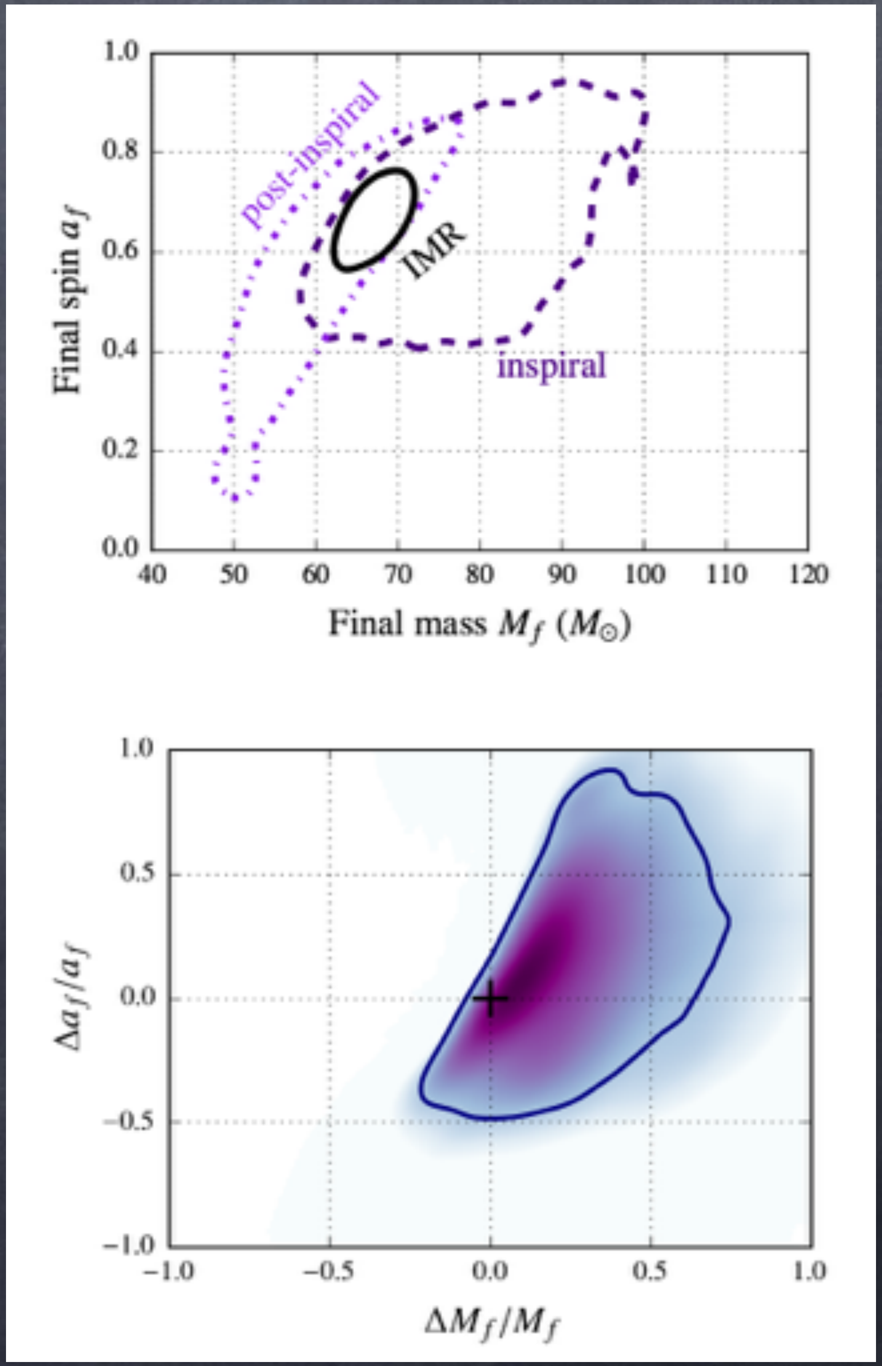
Bonetti & EB 2015

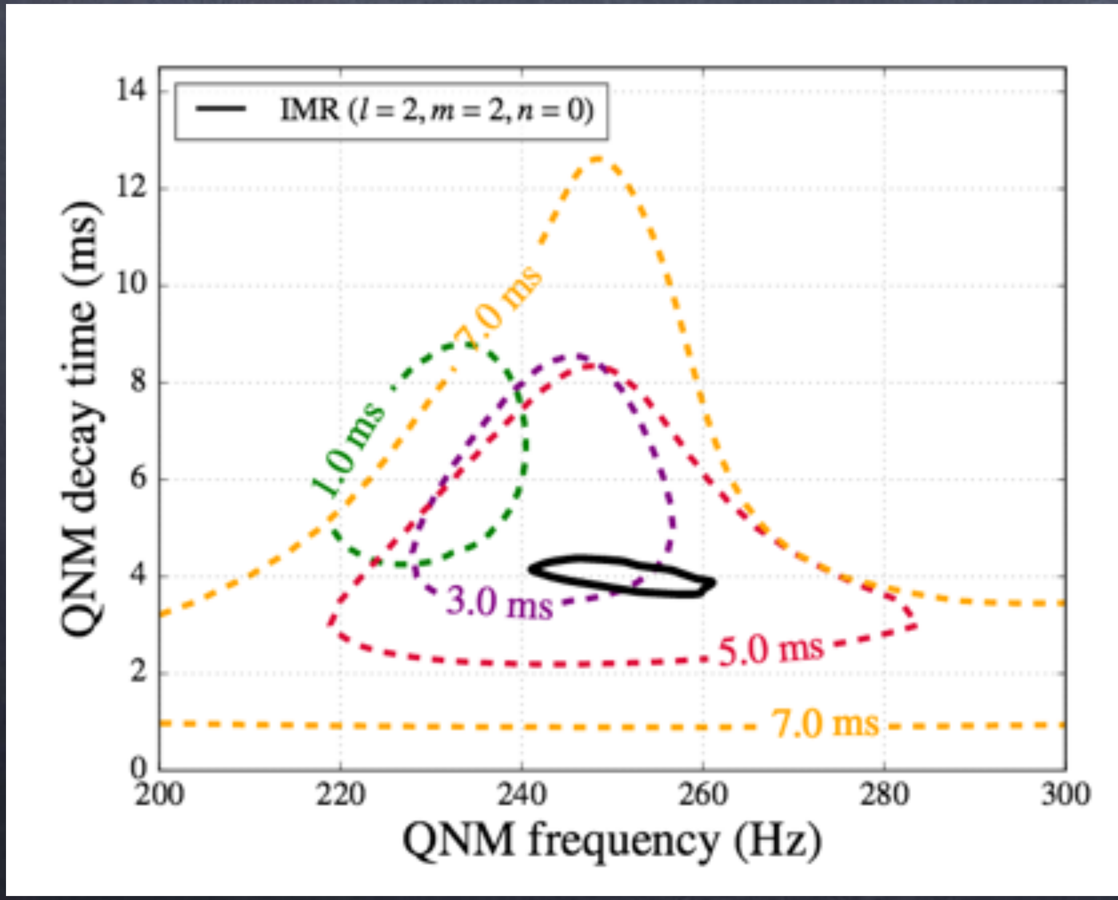
(Future) ringdown tests

Tests of the no-hair theorem:

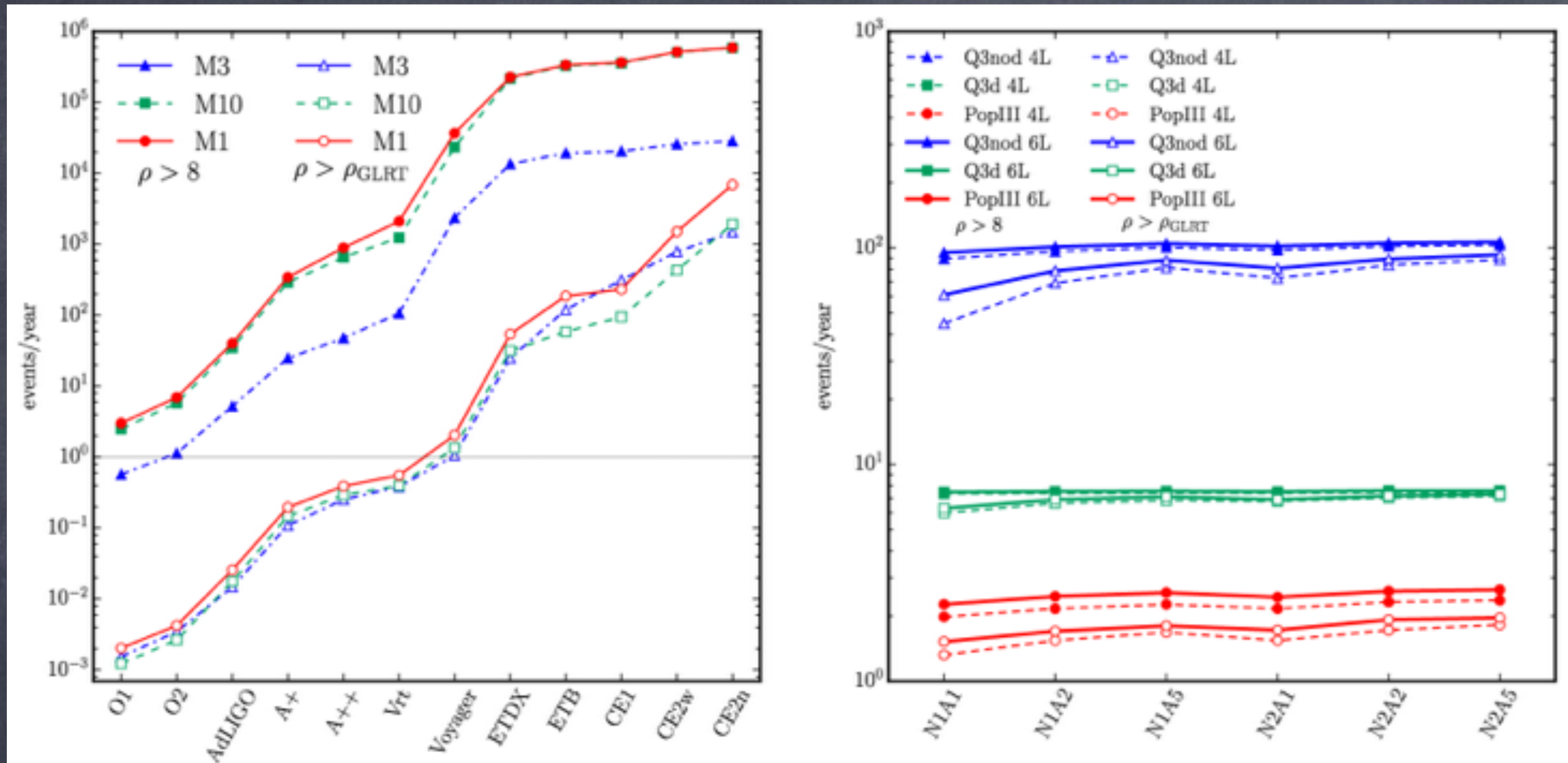
$$\omega_{\ell m} = \omega_{\ell m}^{GR}(M, J)(1 + \delta\omega_{\ell m}) \qquad \tau_{\ell m} = \tau_{\ell m}^{GR}(M, J)(1 + \delta\tau_{\ell m})$$

Difficult with advanced detectors because little SNR in ringdown

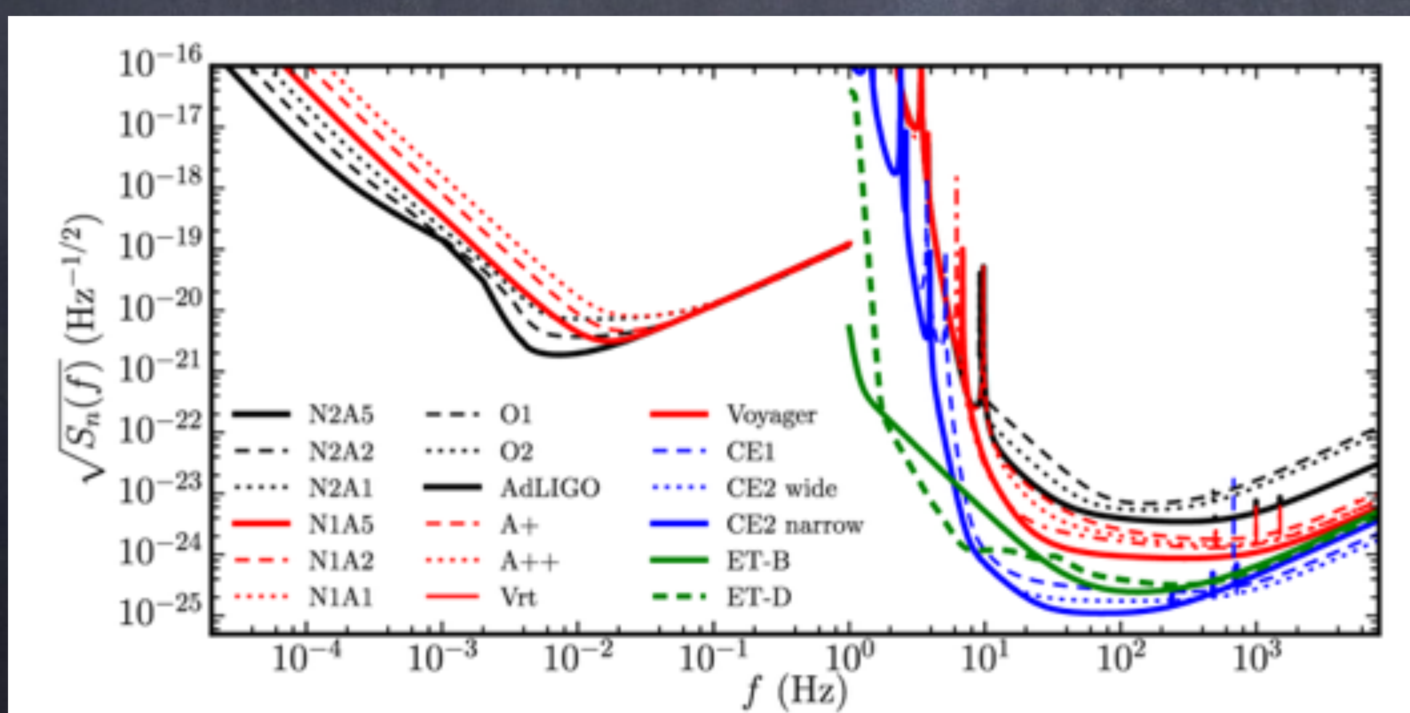




Tests of no-hair theorem by BH ringdown



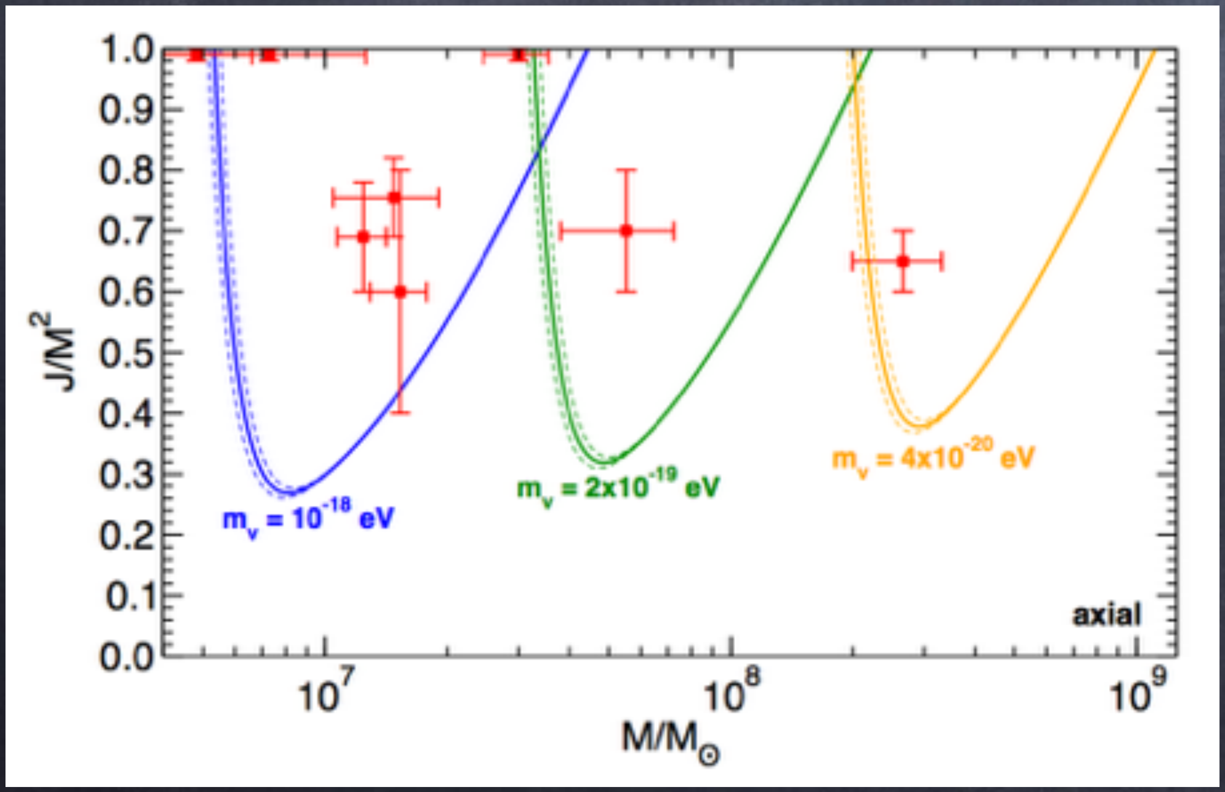
$$\rho_{\rm GLRT} \equiv \min(\rho^{2,3}_{\rm GLRT}, \rho^{2,4}_{\rm GLRT})$$



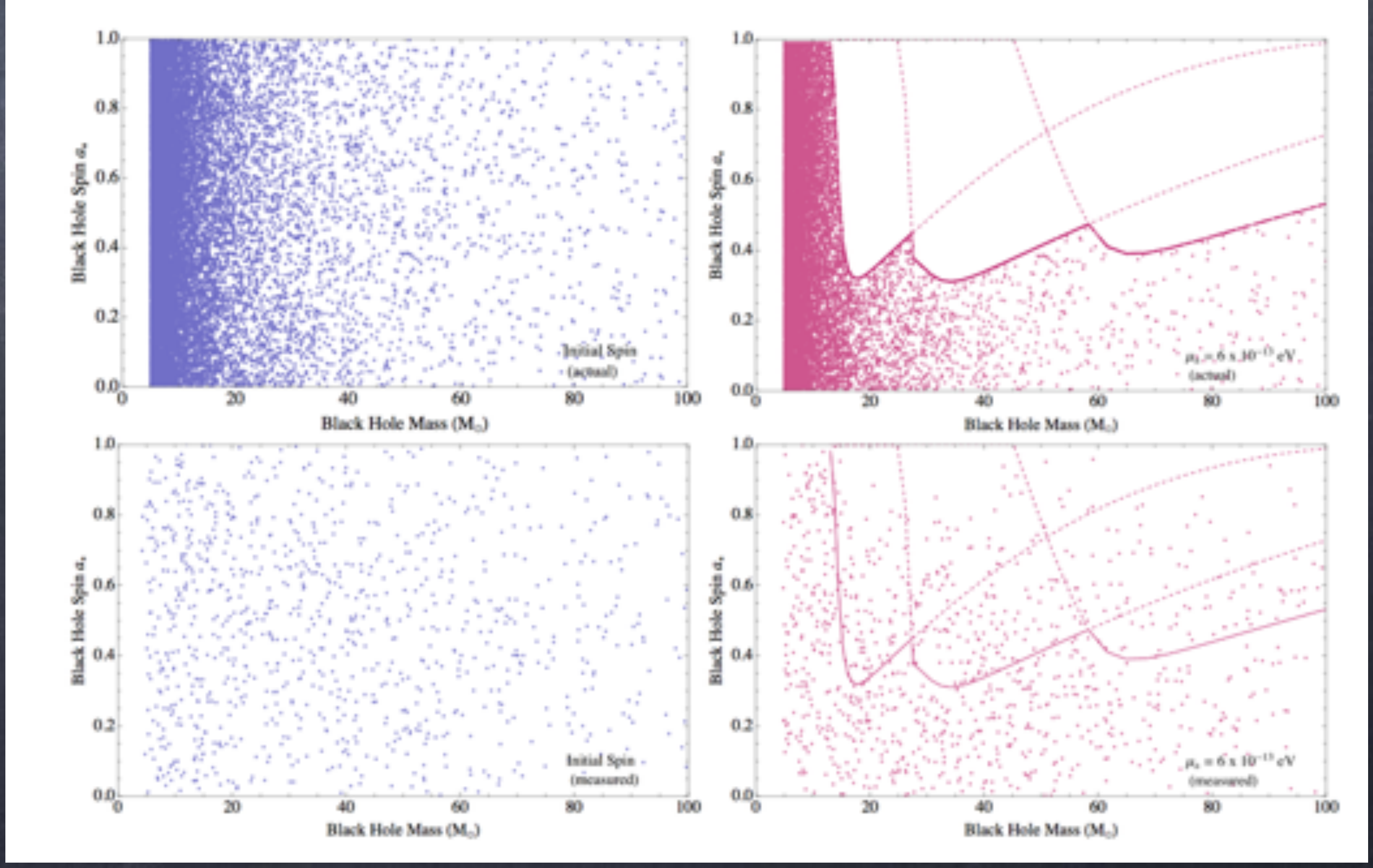
Berti, Sesana, EB,
Cardoso, Belczynski, PRL in press, 2016

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

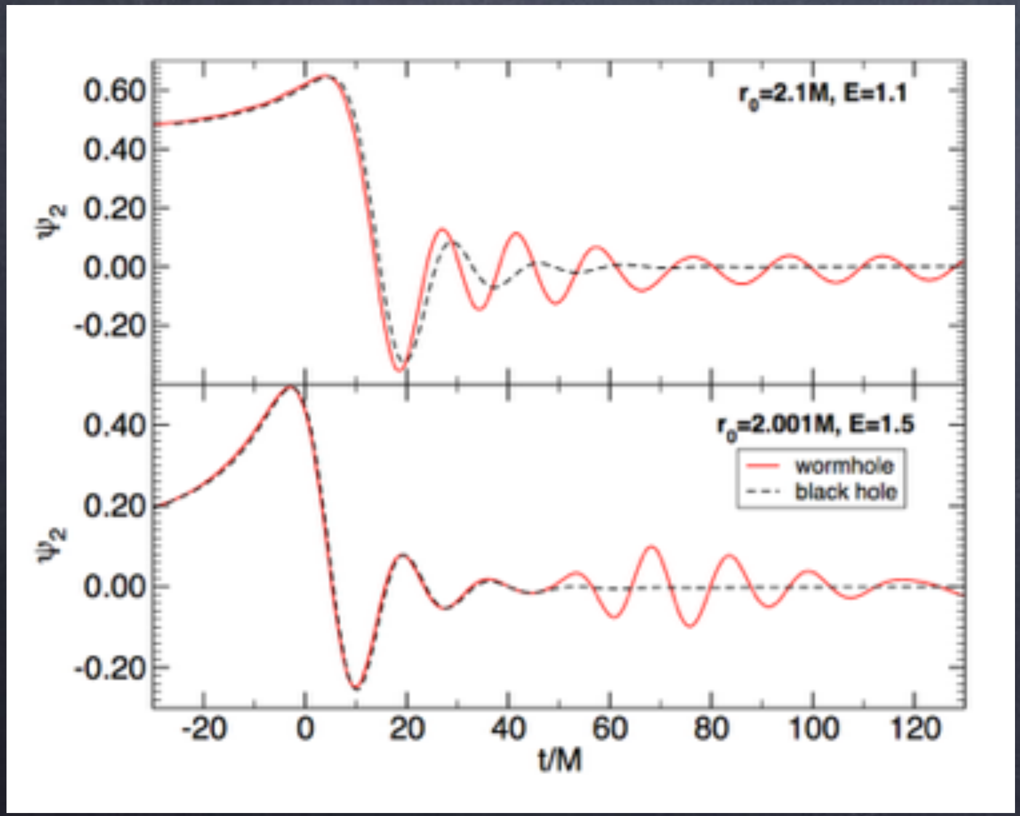


Arvanitaki et al 2016

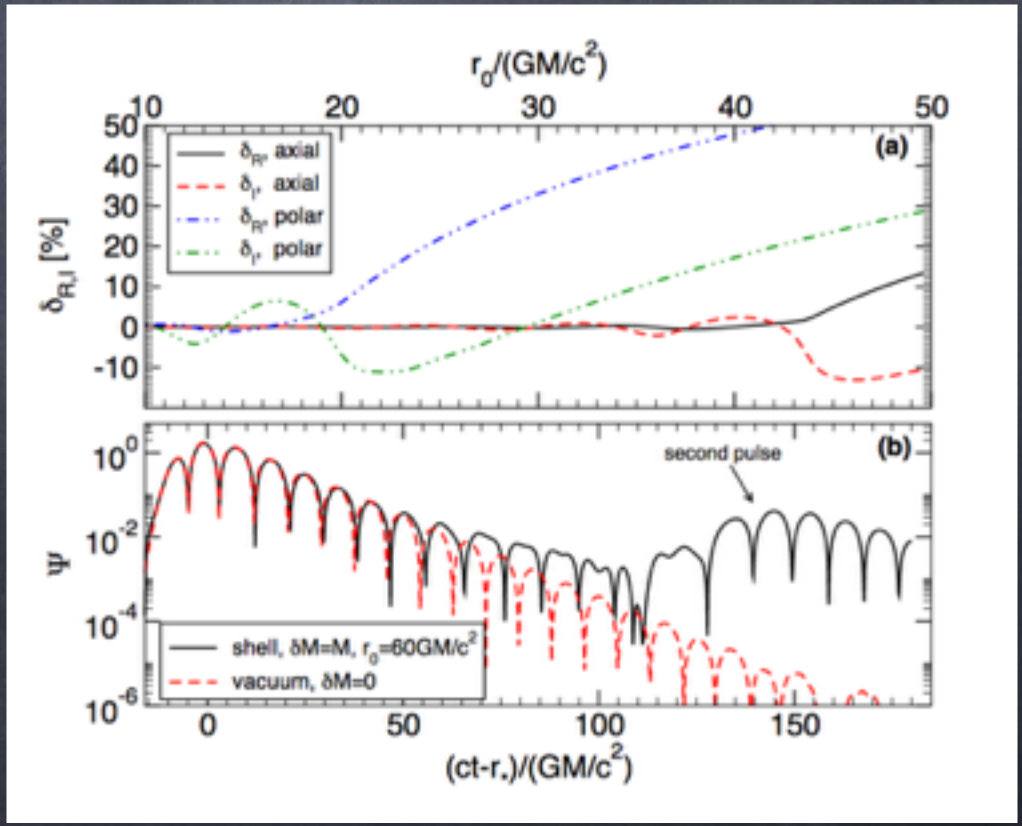
Ringdown's sensitivity to near-horizon physics

- 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

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