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Gravitational waves beyond GR

New Frontiers in Gravitational-Wave Astrophysics
Rome, June 19-22, 2017

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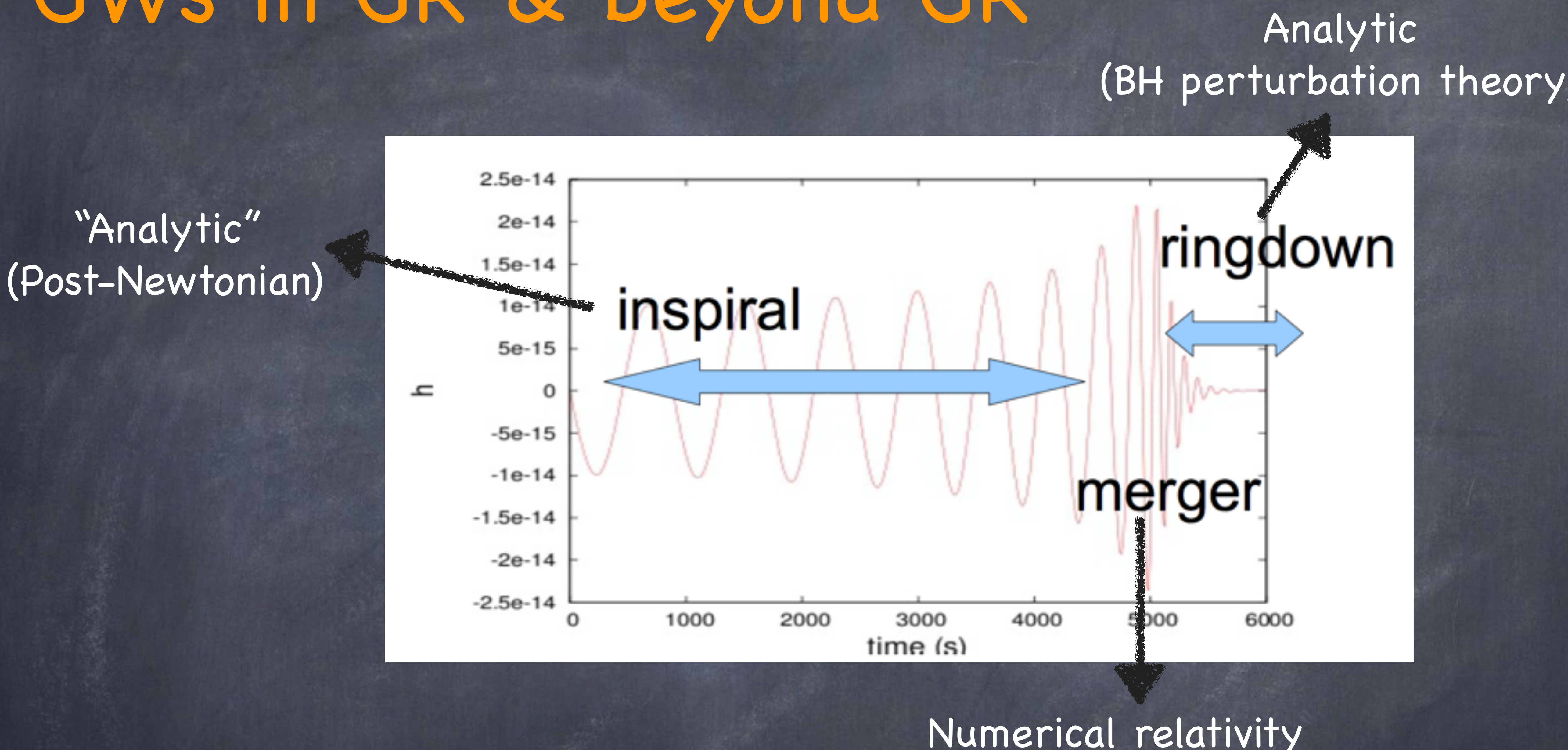
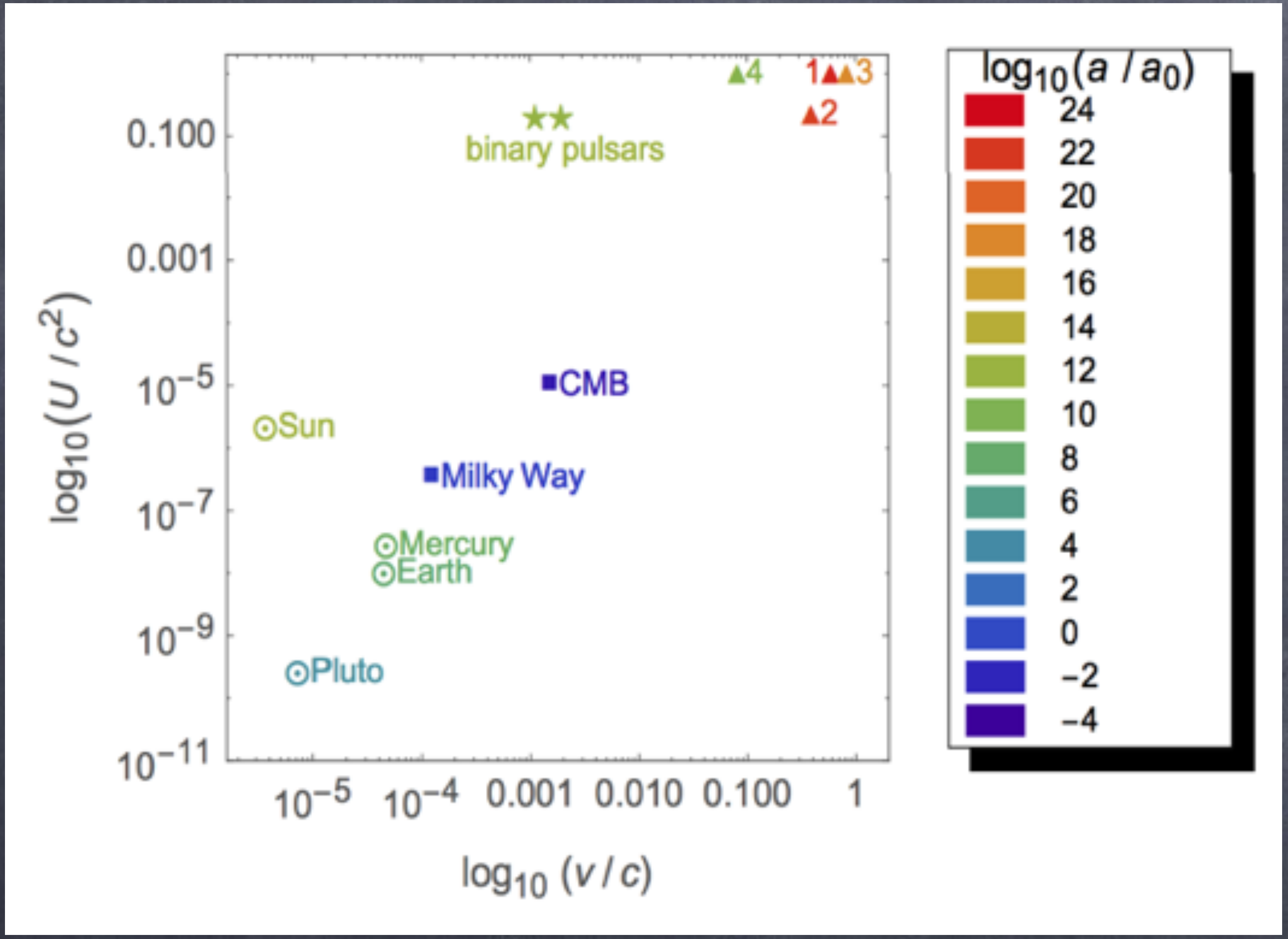
Collaborators:
E. Berti, V. Cardoso, P. Pani, N. Yunes, K. Yagi, K. Chamberlain, R. Brito, D. Blas, S. Ghosh, I. Dvorkin, A. Sesana, M. Bonetti, C. Palenzuela, L. Lehner, T. Sotiriou ...

GWs in GR & beyond GR



- Focus on inspiral (where we can make predictions in modified gravity theories)
- Some general considerations on merger (if time allows), c.f. Leo Stein's talk
- A bit on ringdown tests (anyway possible only with third generation/space-based detector, cf Berti, Sesana, EB, Cardoso, Belczynski 2016); see also Vitor Cardoso's talk
- No propagation effects (c.f. Nico Yunes' talk)

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

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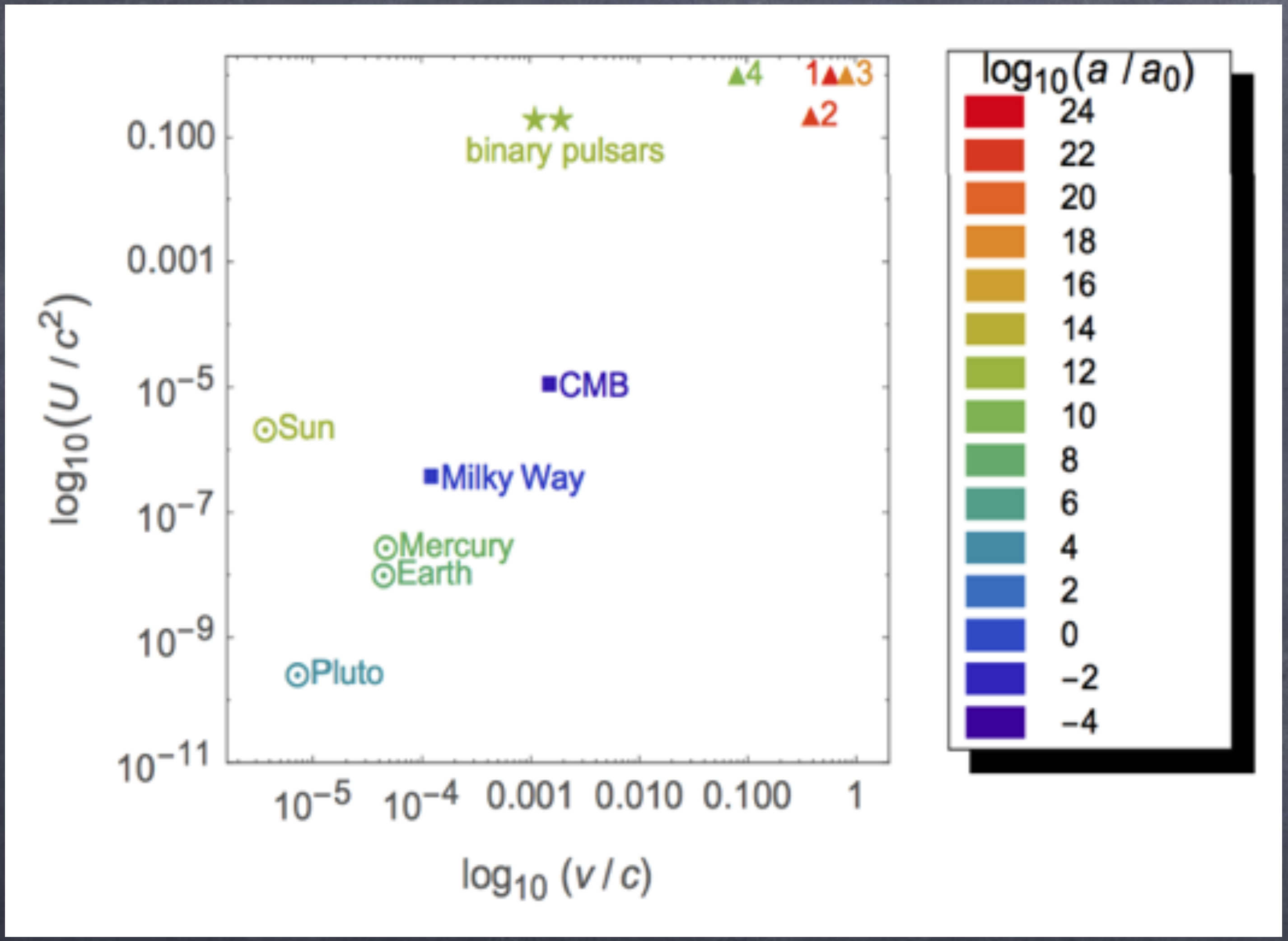

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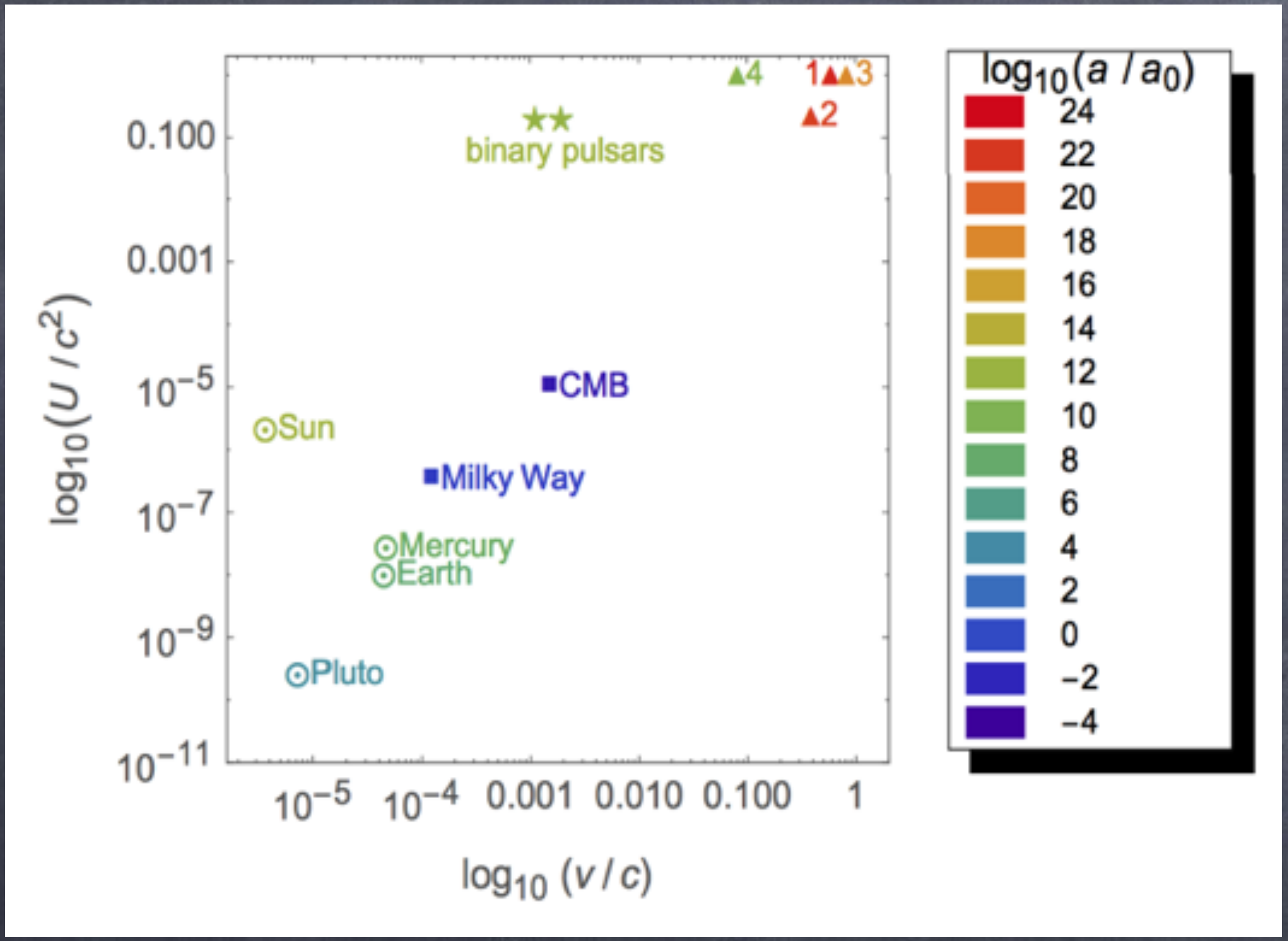

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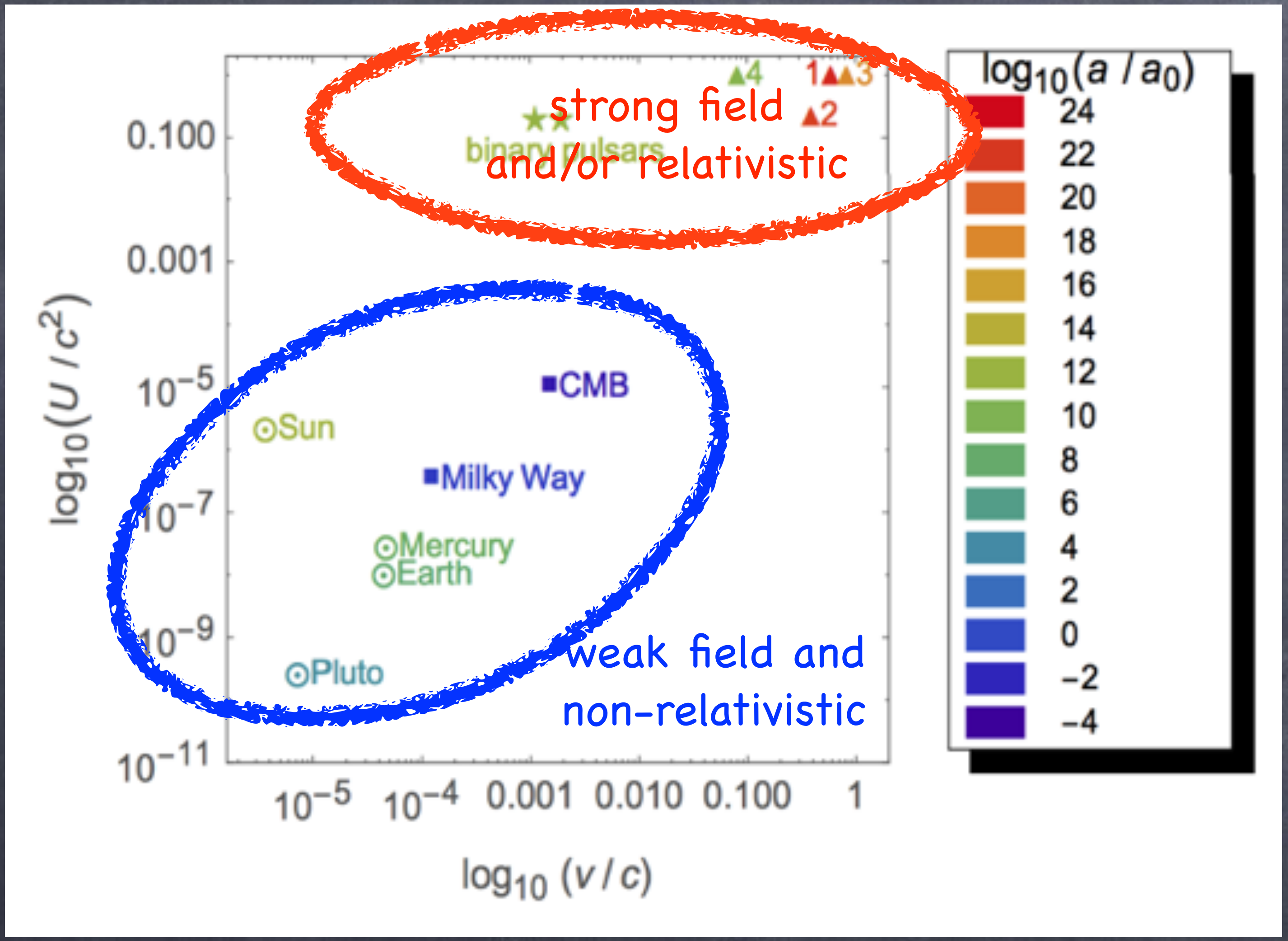
Beyond GR: why?



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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. $G_{\mu\nu} + \Lambda g_{\mu\nu}$

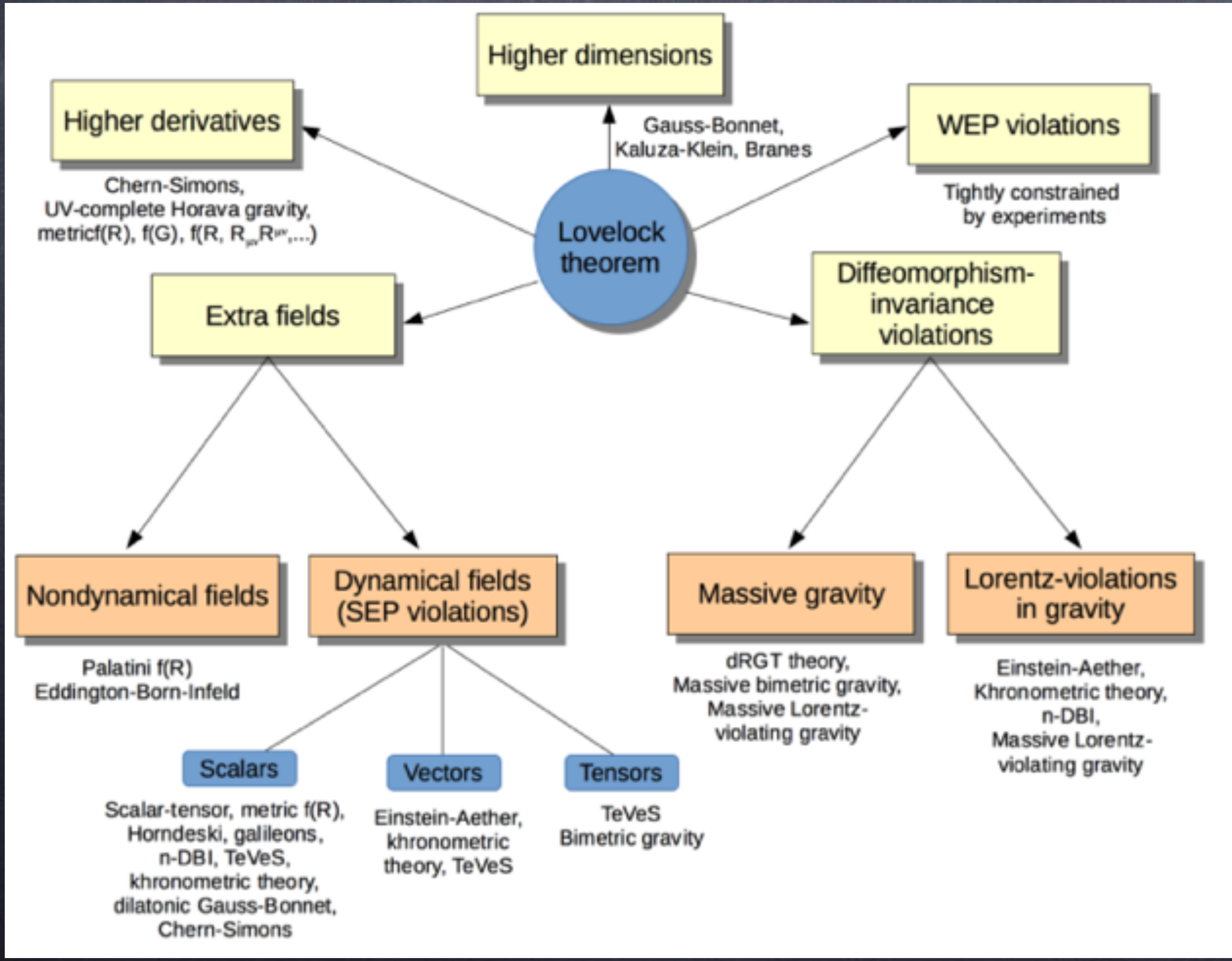


Figure adapted from Berti, EB et al 2015

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. $$M_1 \sim \int \rho x^i d^3x \qquad h \sim \frac{G}{c^3}\dot{M}_1 \sim \frac{G}{c^3}\frac{P}{r}$$ 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

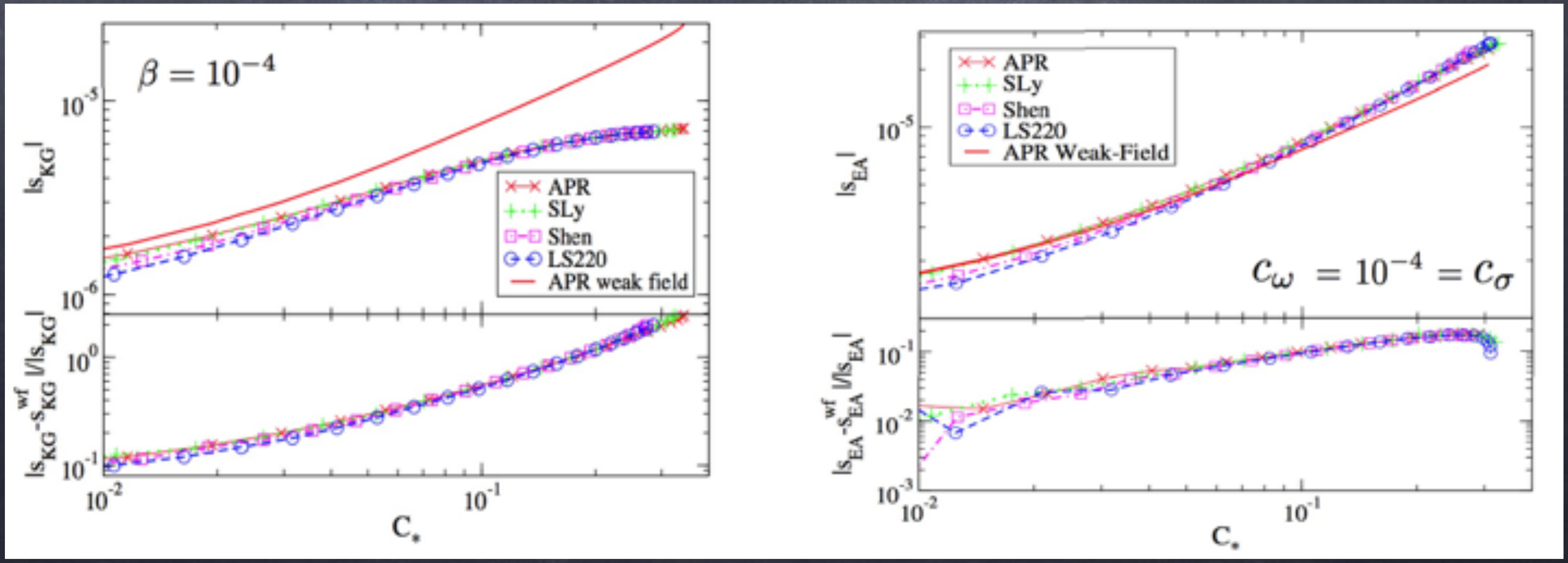
Tests of dipolar emission with GWs

- Difficulty is to calculate sensitivities $s \equiv \left.\dfrac{\partial m}{\partial \varphi}\right|_{\Sigma, M_b}$

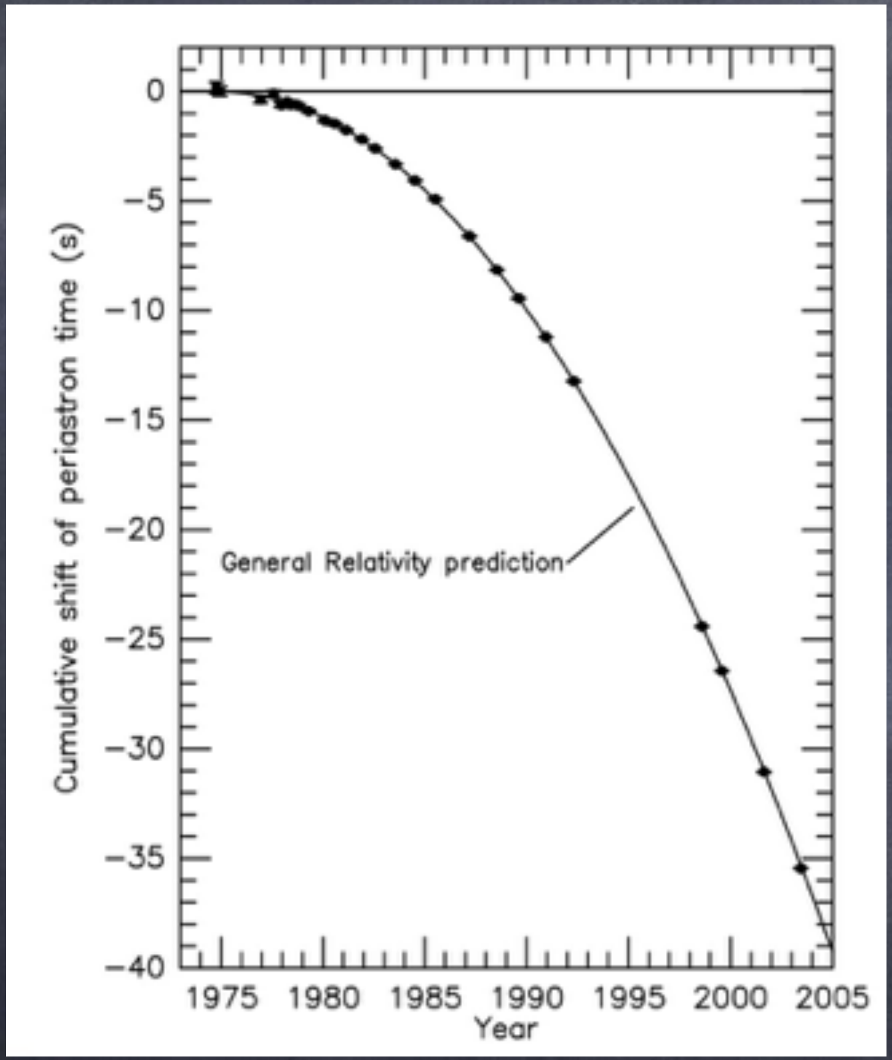
- Since they are response to field boundary conditions, need to calculate compact-object solution for different boundary conditions

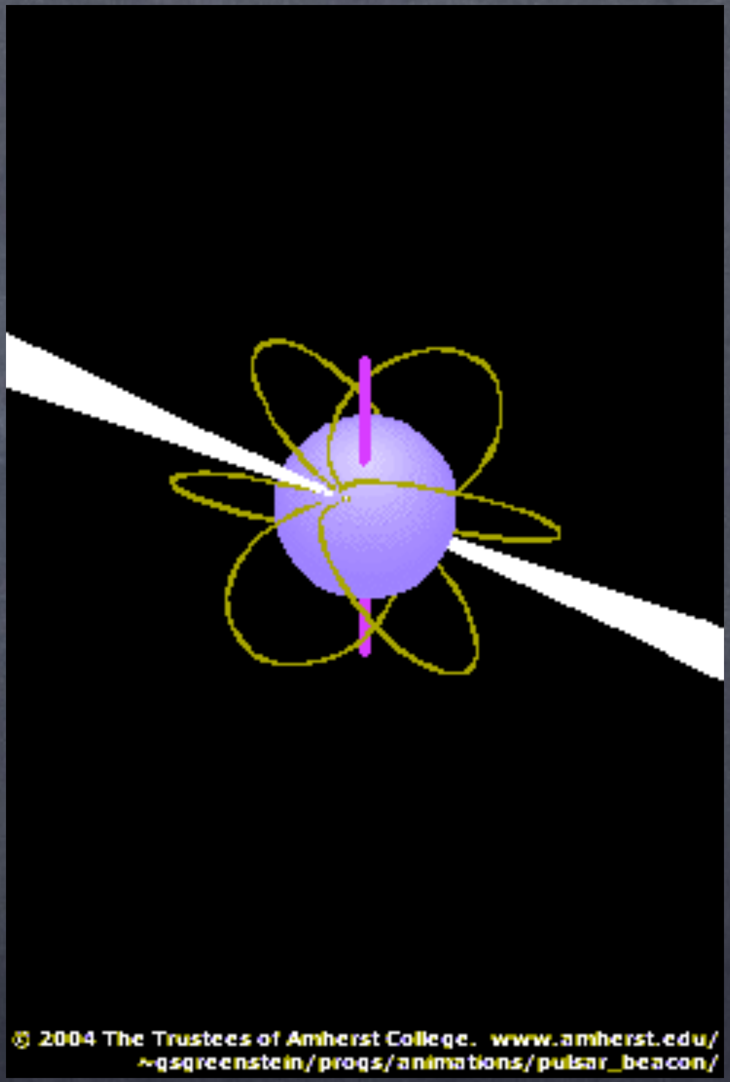
- Calculation needs to be done exactly (no extrapolation of weak field approximation) and (for NS) for different EOS's

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



(Absence of) dipolar emission in binary pulsars





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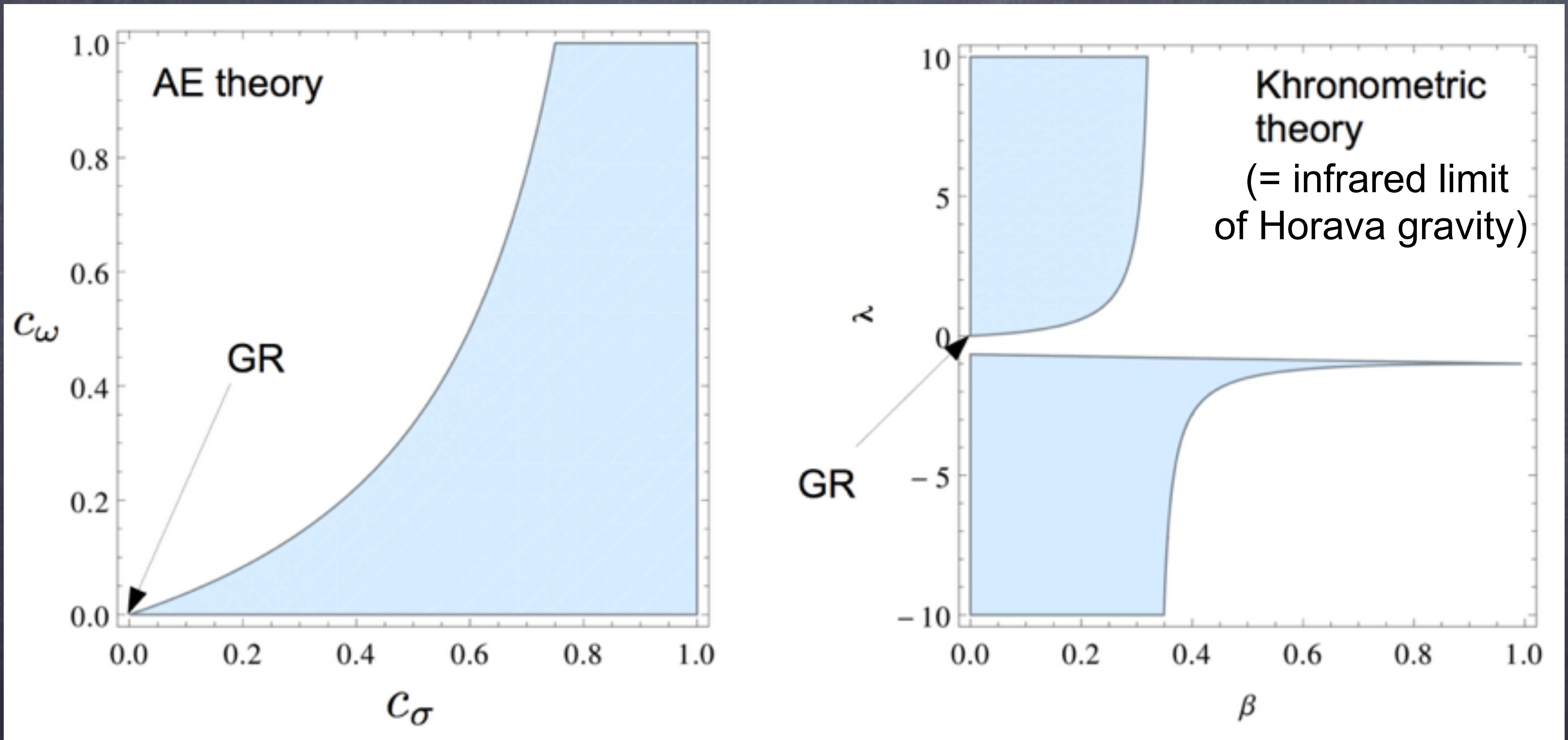
An example: Lorentz-violating gravity



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

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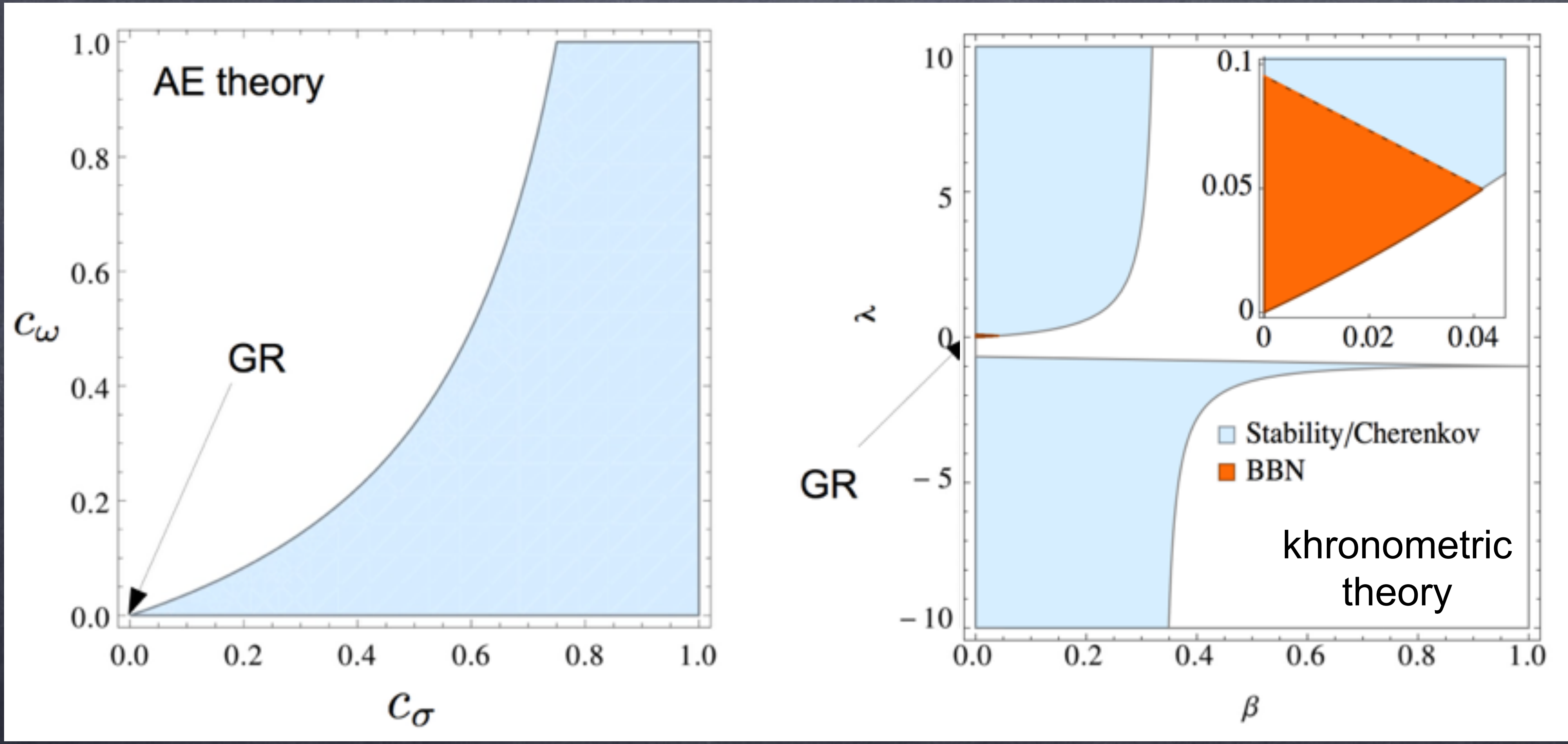

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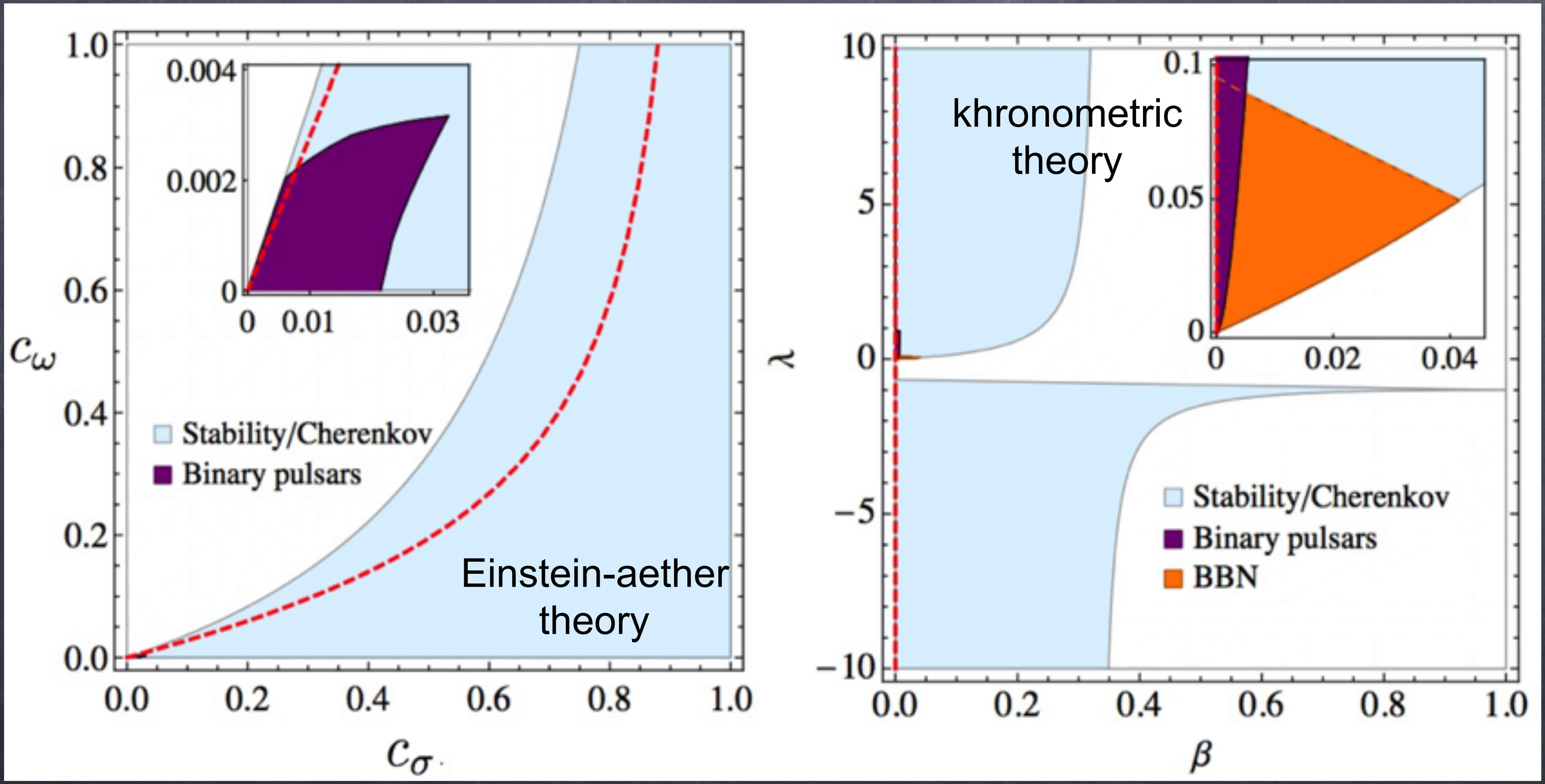
An example: Lorentz-violating gravity

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")

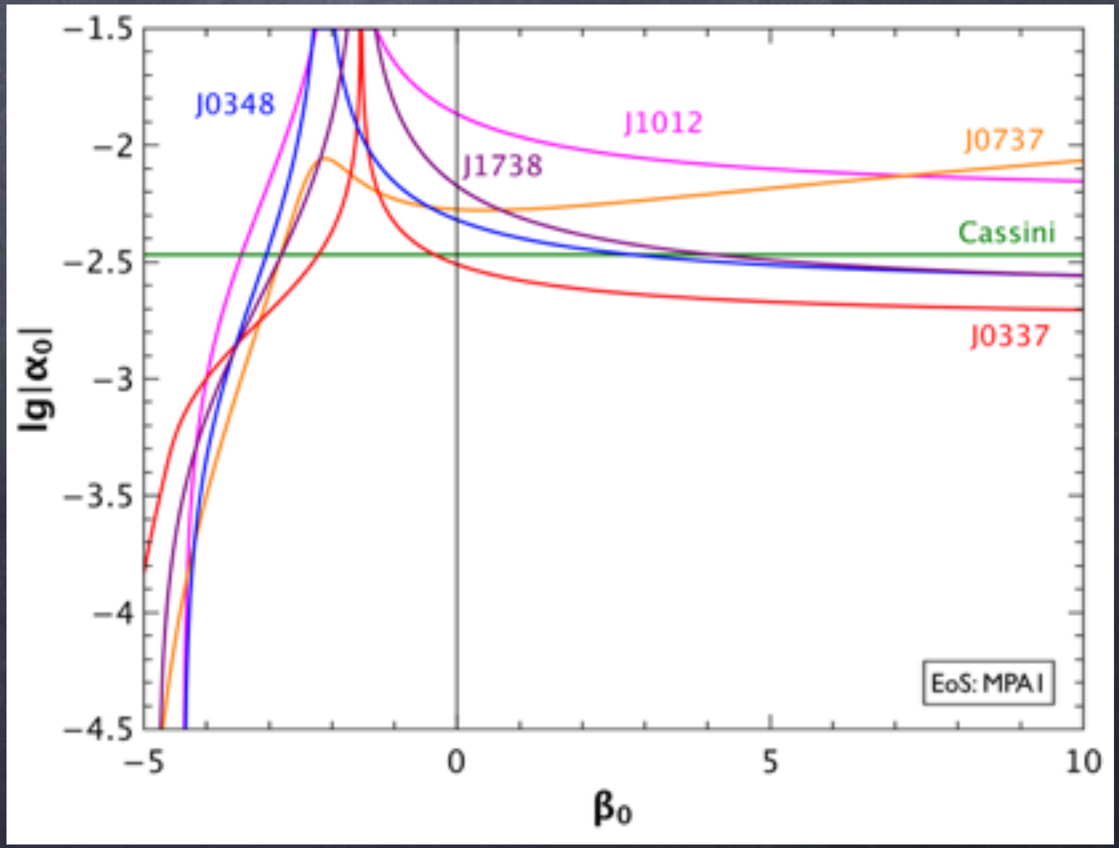


Figure credits: Wex, private comm.

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

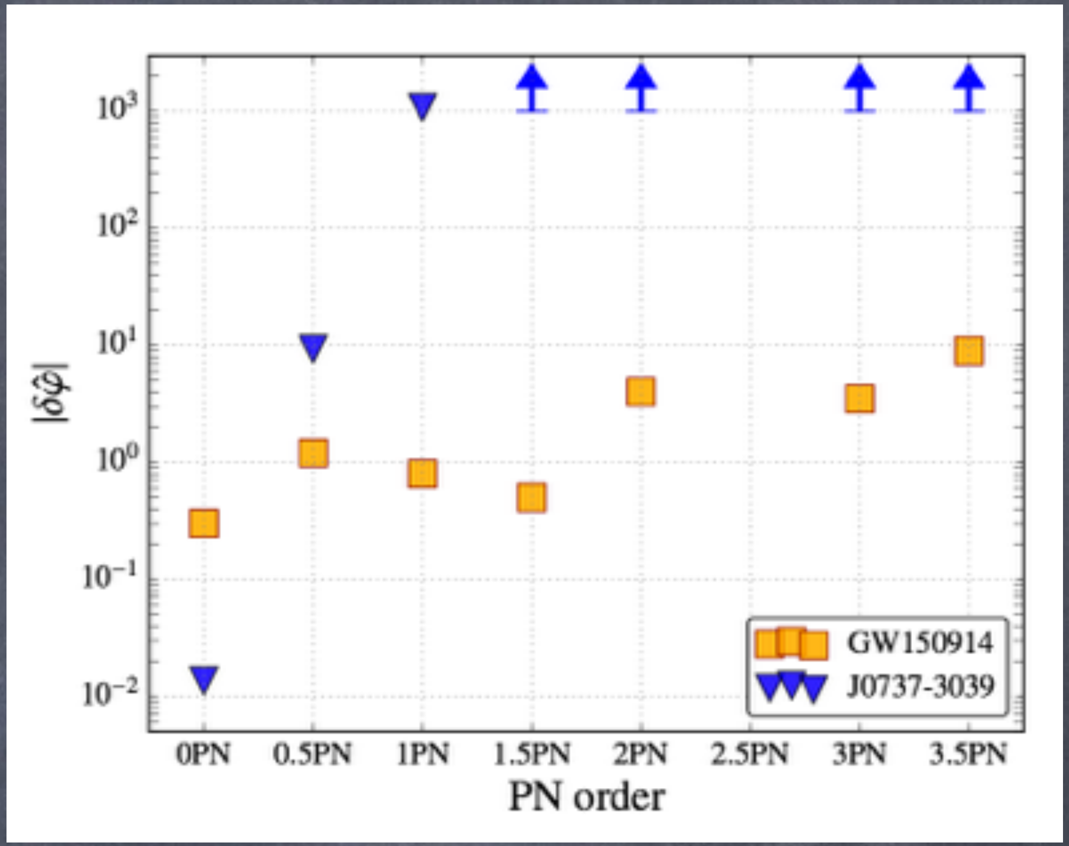
f_4 = const: same dynamics as GR (Gauss-Bonnet term is 4D topological invariant)
f_4 ≠ const: dilatonic Gauss-Bonnet gravity, 2nd-order field eqs, no Ostrogradsky ghost)

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 et al 2015)

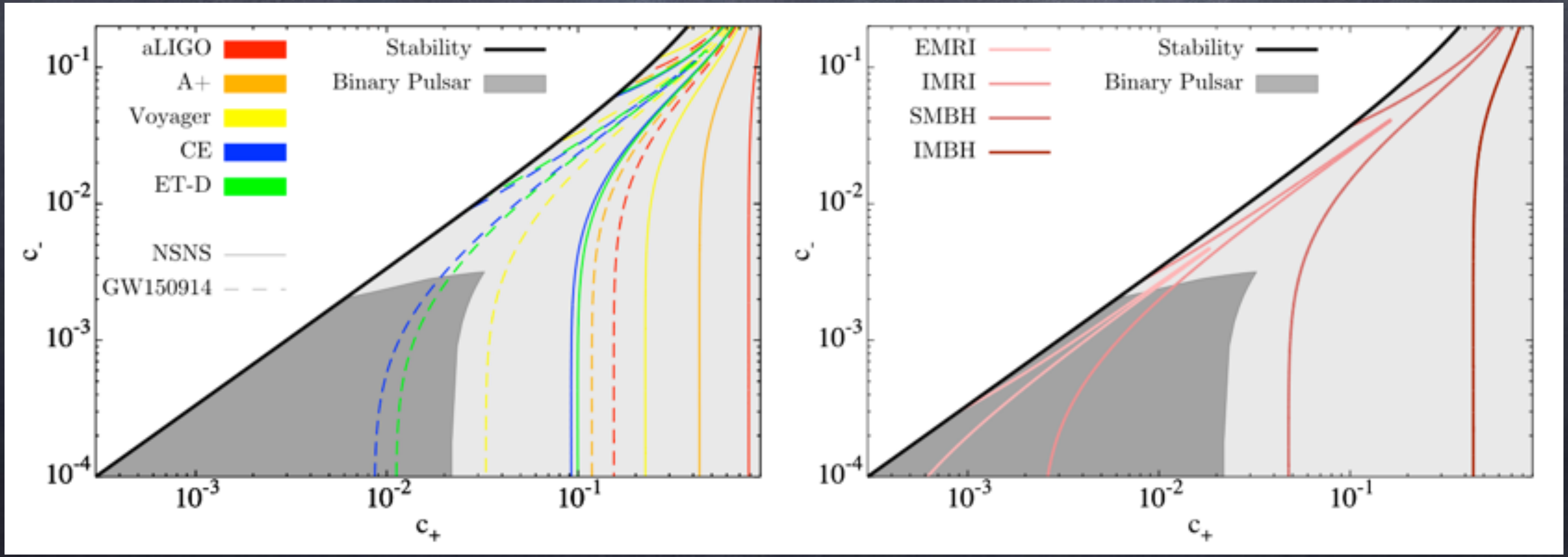
More general theories (with extra vector or tensor dof's) predict dipole emission also (though not exclusively) in BH binaries

Constraints on dipolar emission from direct detections

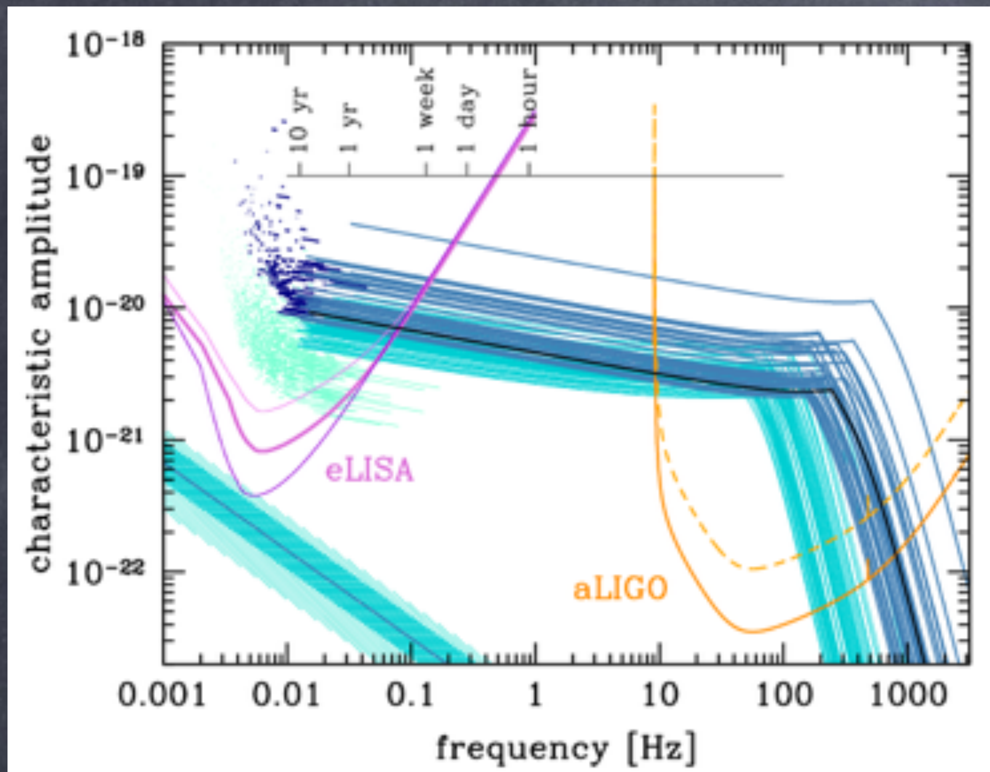
Weak bounds from advanced detectors



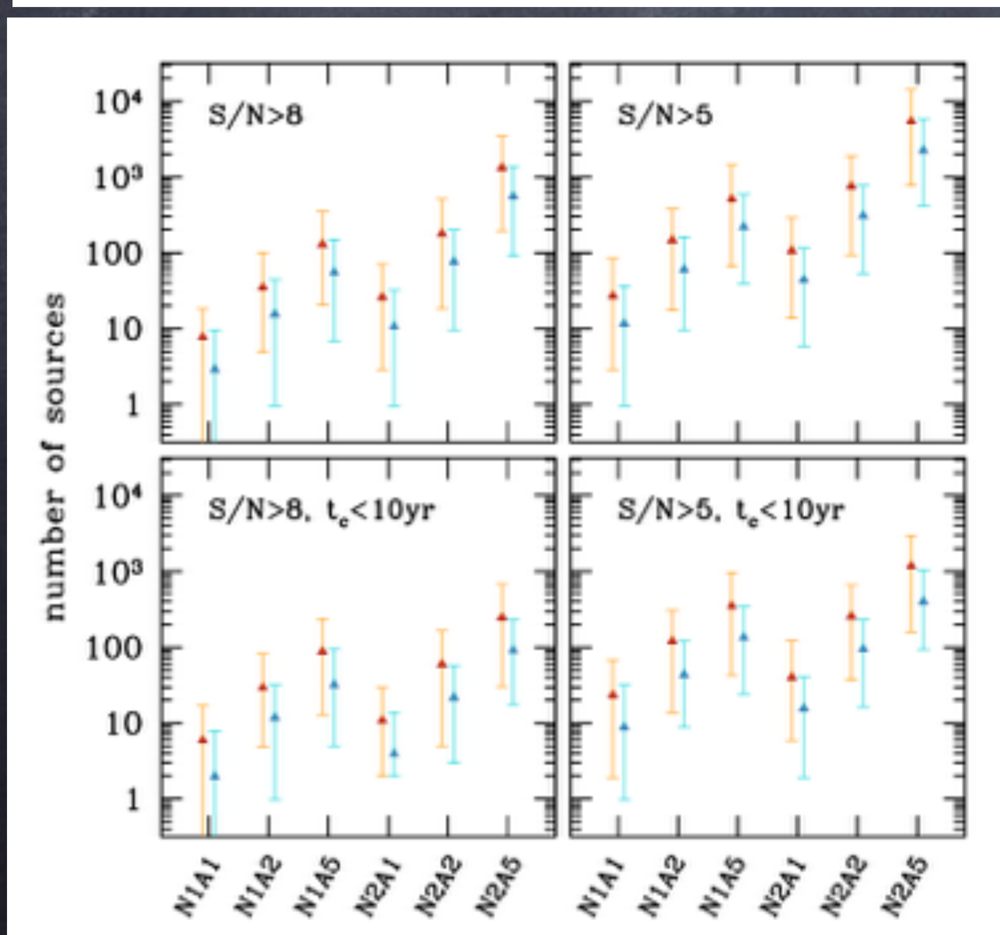
Better for 3rd-gen detectors, e.g. Lorentz violating gravity (Hansen, Yunes, Yagi 2015; Yunes & Chamberlain 2017)

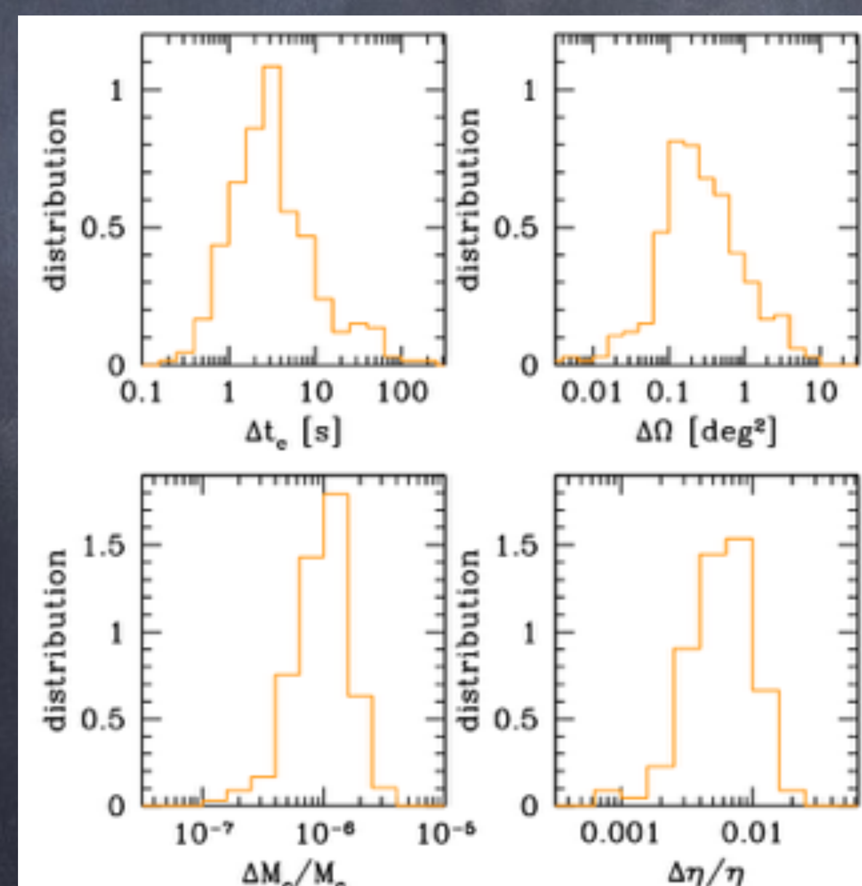


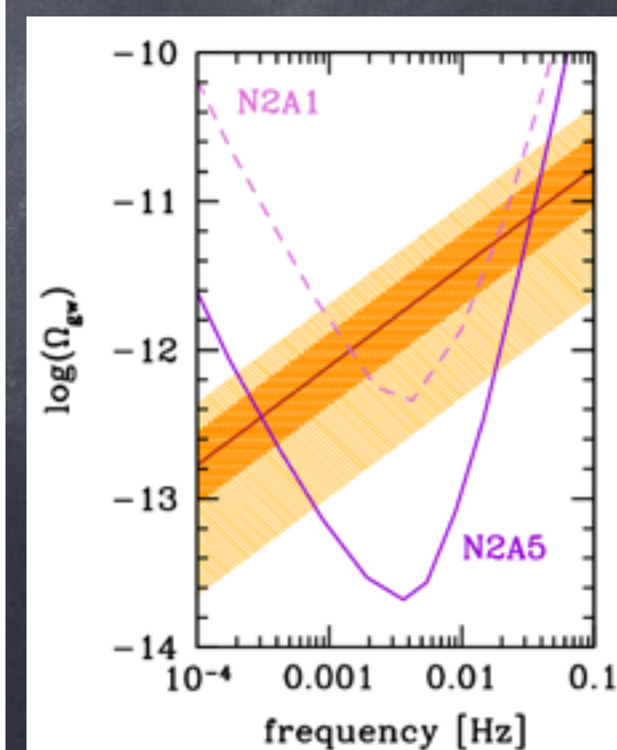
Multi-band observations of GW150914-like/ intermediate-mass binary BHs (cf A. Sesana's talk)



- 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





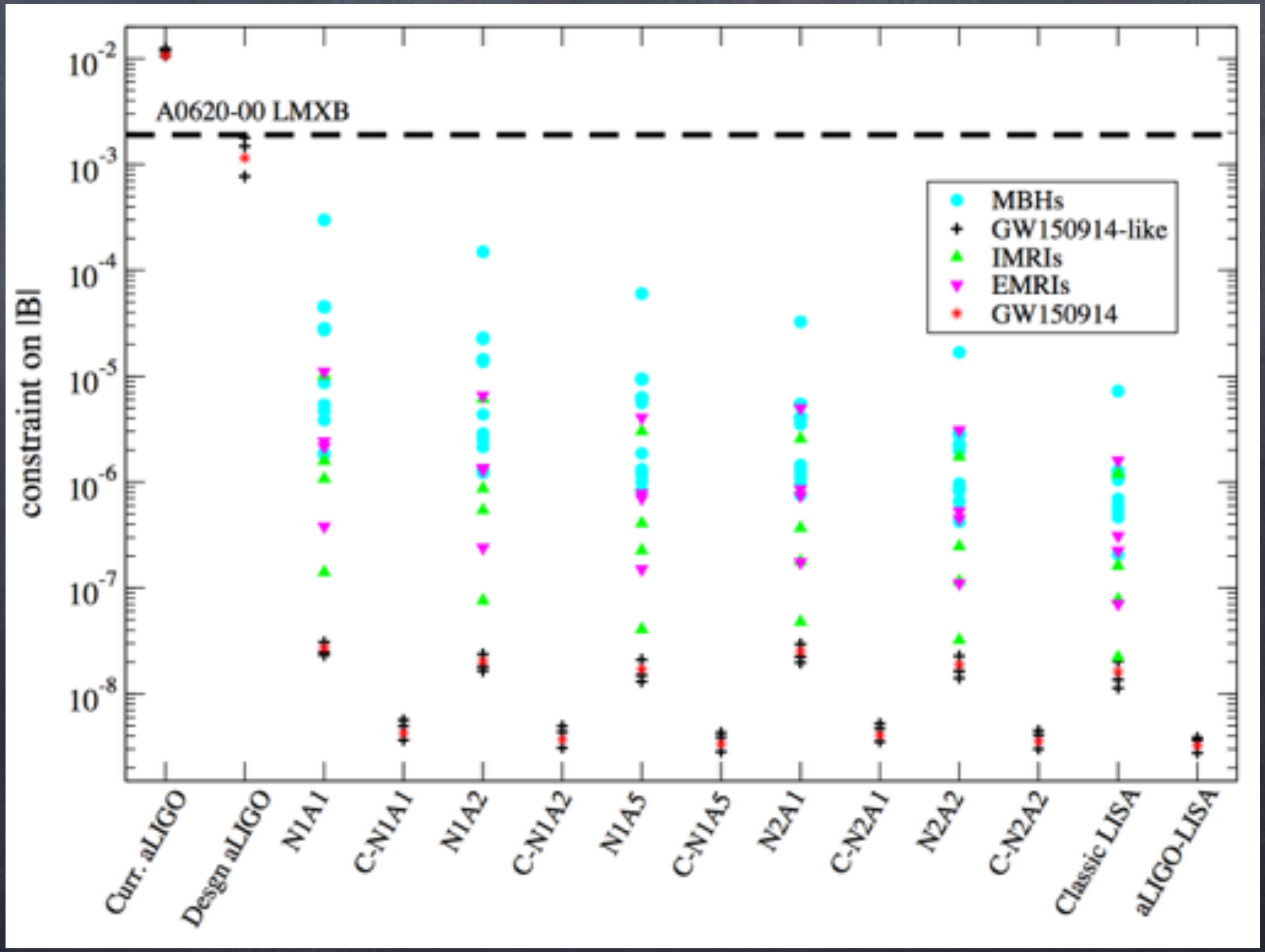


Figures from Sesana 2016

Tests of BH-BH dipole emission

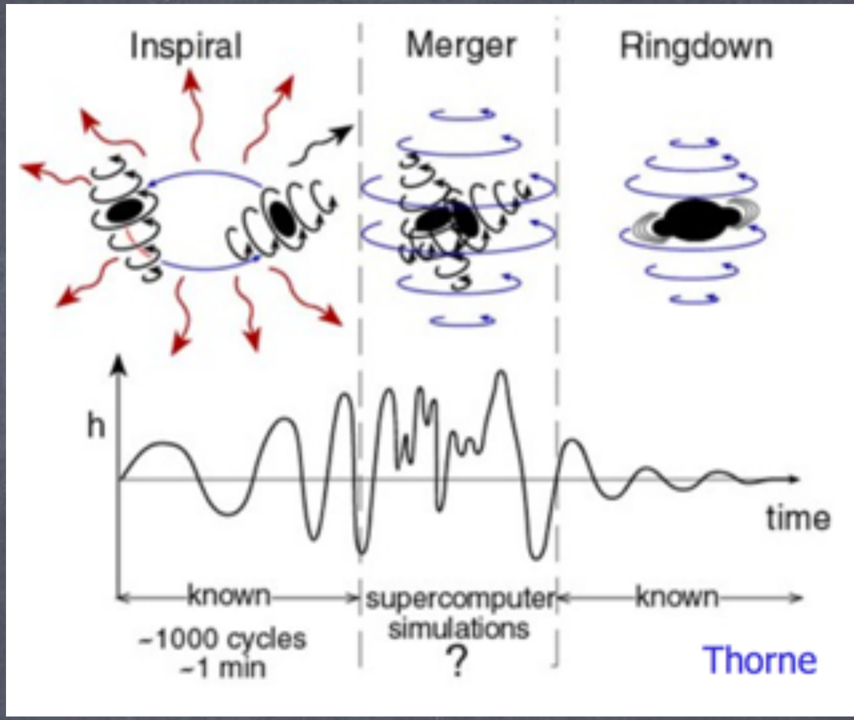
$$\dot{E}_{GW} = \dot{E}_{GR}\left[1 + B\left(\frac{v}{c}\right)^{-2}\right] \qquad B \propto (s_1 - s_2)^2$$

- 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?



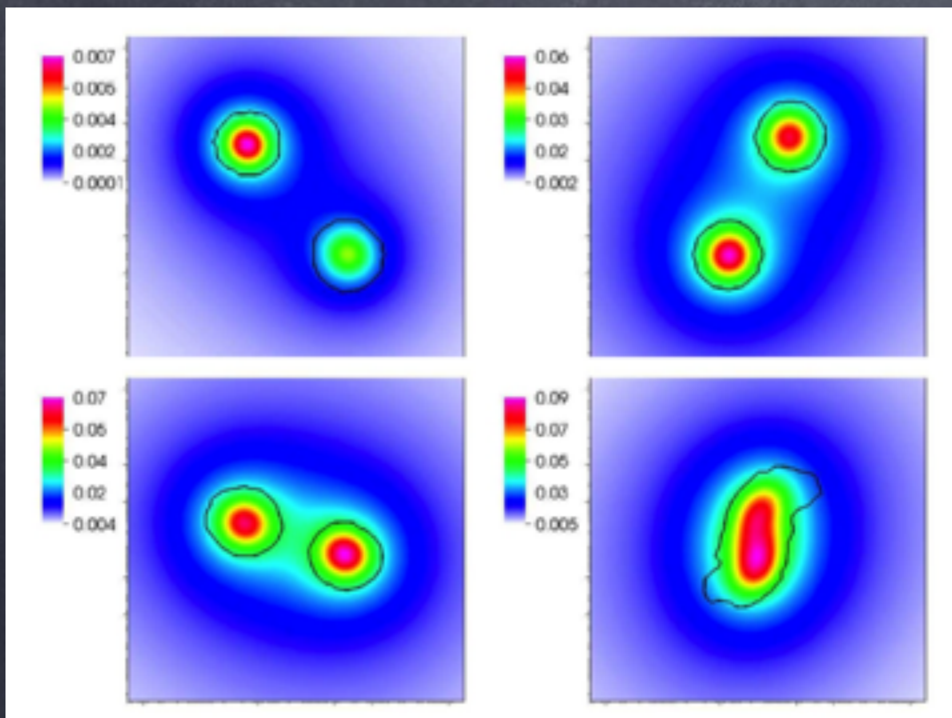
Possible surprises/
highly non-linear dynamics?

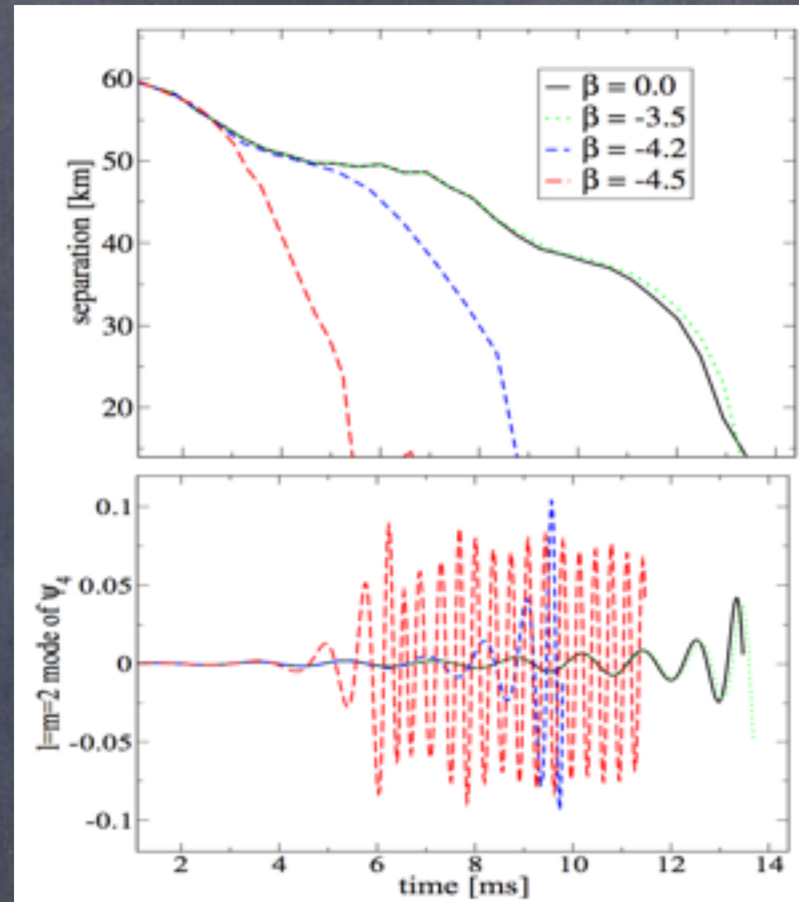
Need numerical-relativity simulations: prerequisite is that Cauchy problem be well-posed (e.g. that eqs be strongly hyperbolic, i.e. wave eqs)

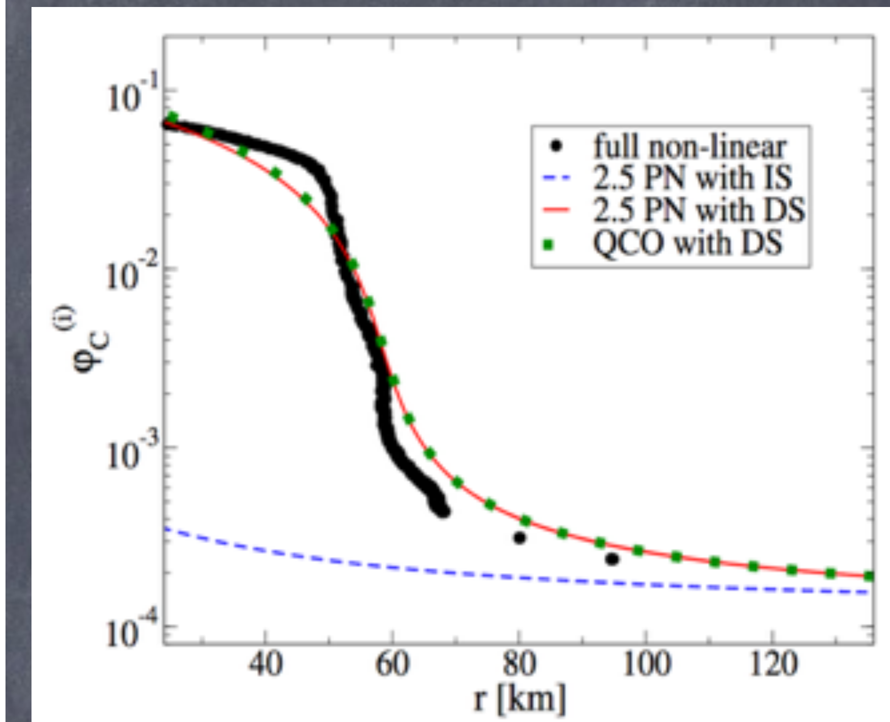
- True for FJBD-like scalar-tensor theories (i.e. with NO galileon terms), but GR dynamics in vacuum (modulo boundary/initial conditions, mass term)
- True in flat-space & spherical symmetry for Lorentz-violating gravity and galileons; dynamics differs from GR both in vacuum and matter, but no general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

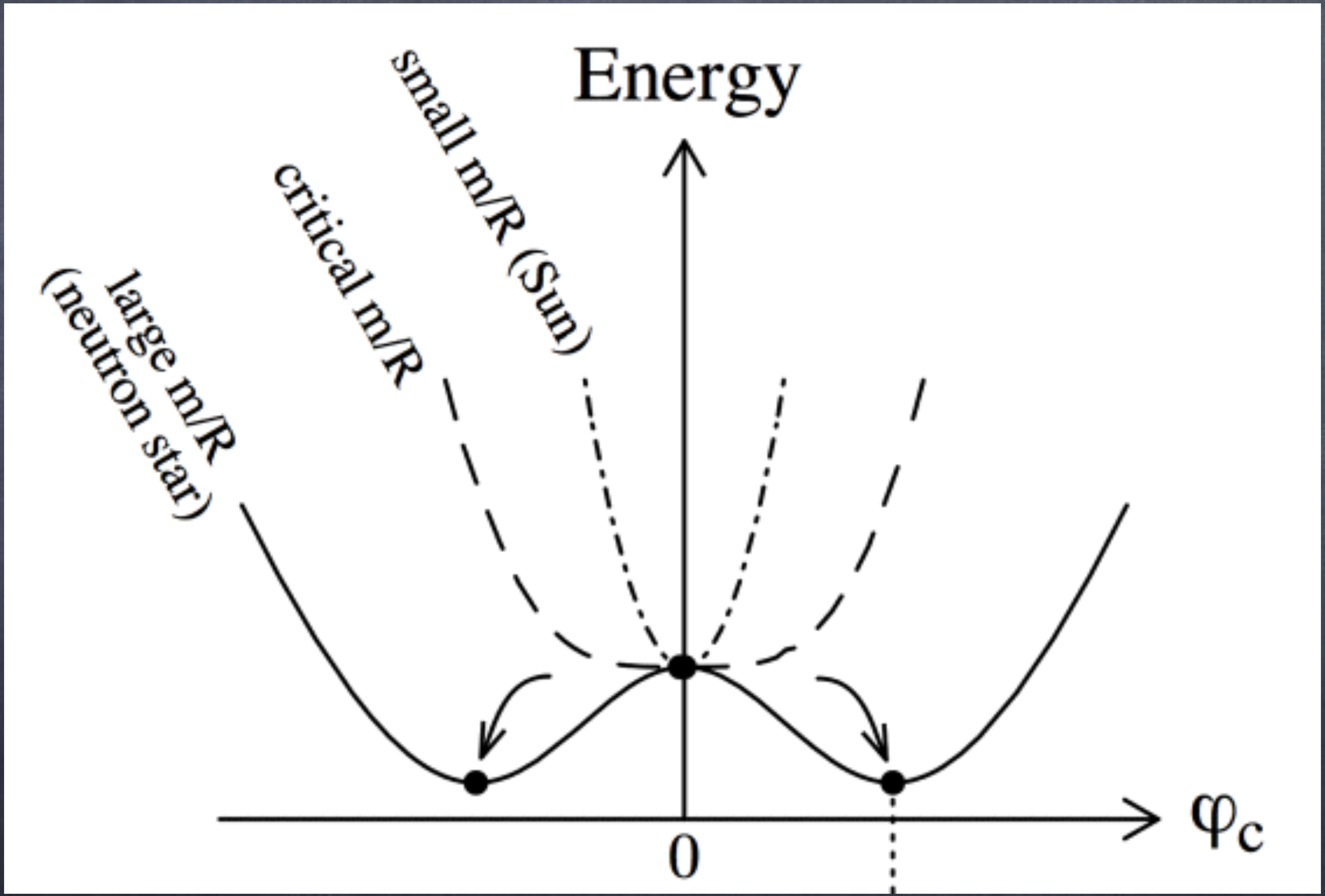
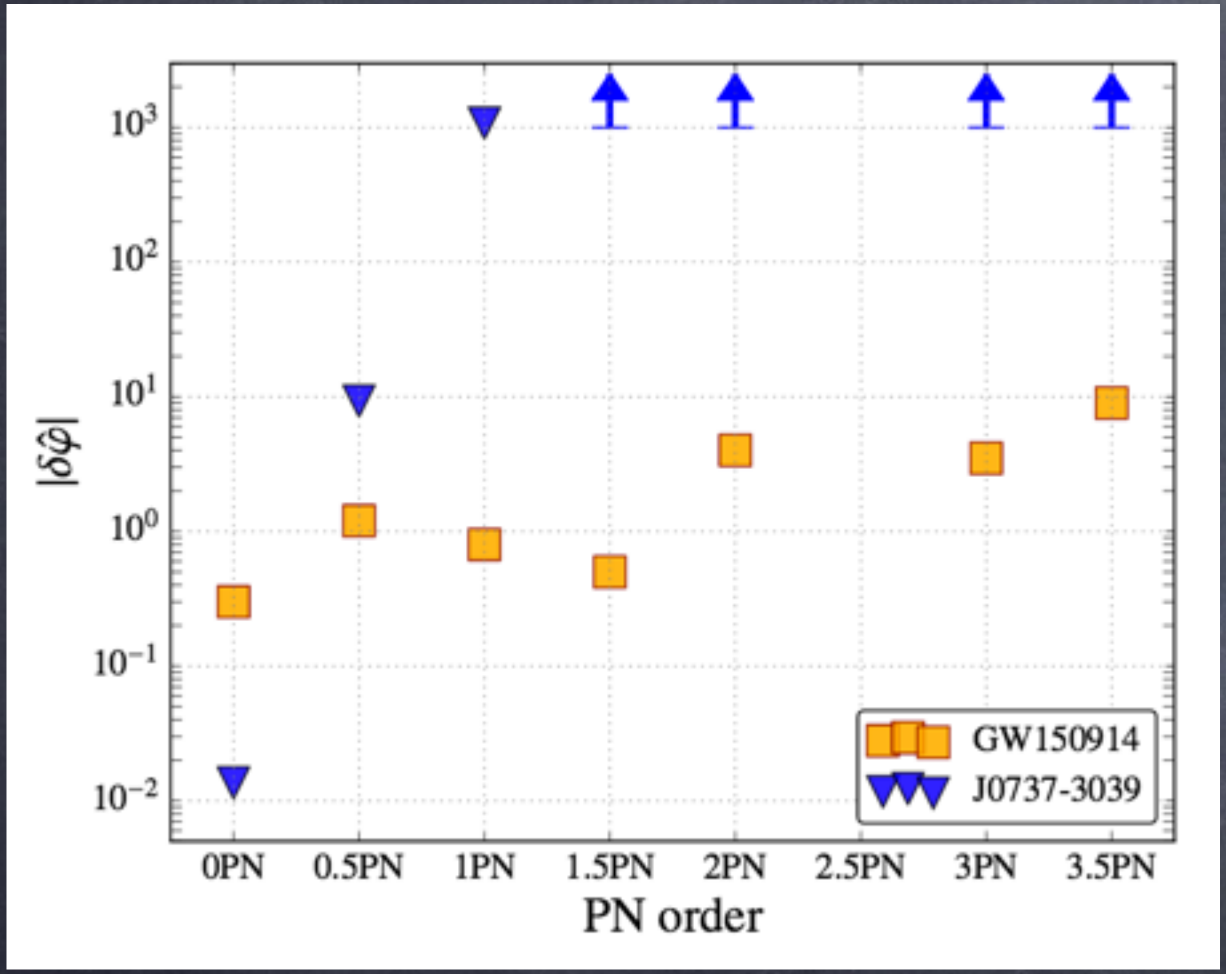


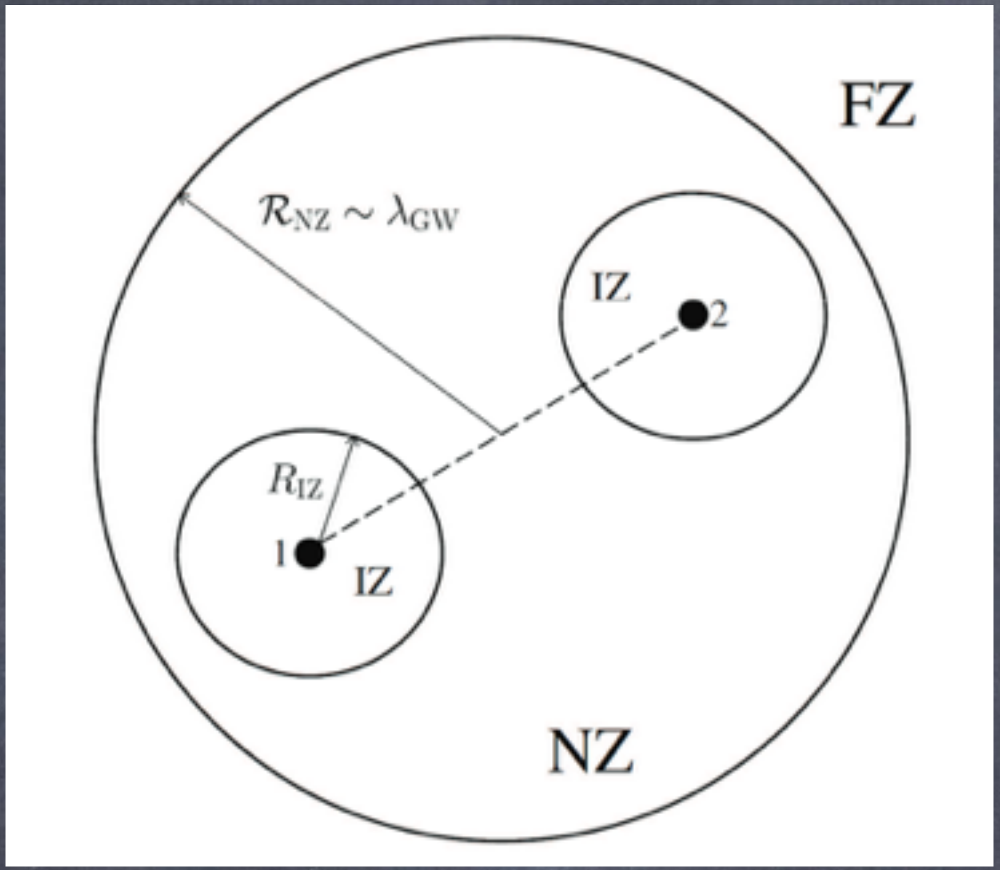
Figure from Esposito-Farese, gr-qc/0402007

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

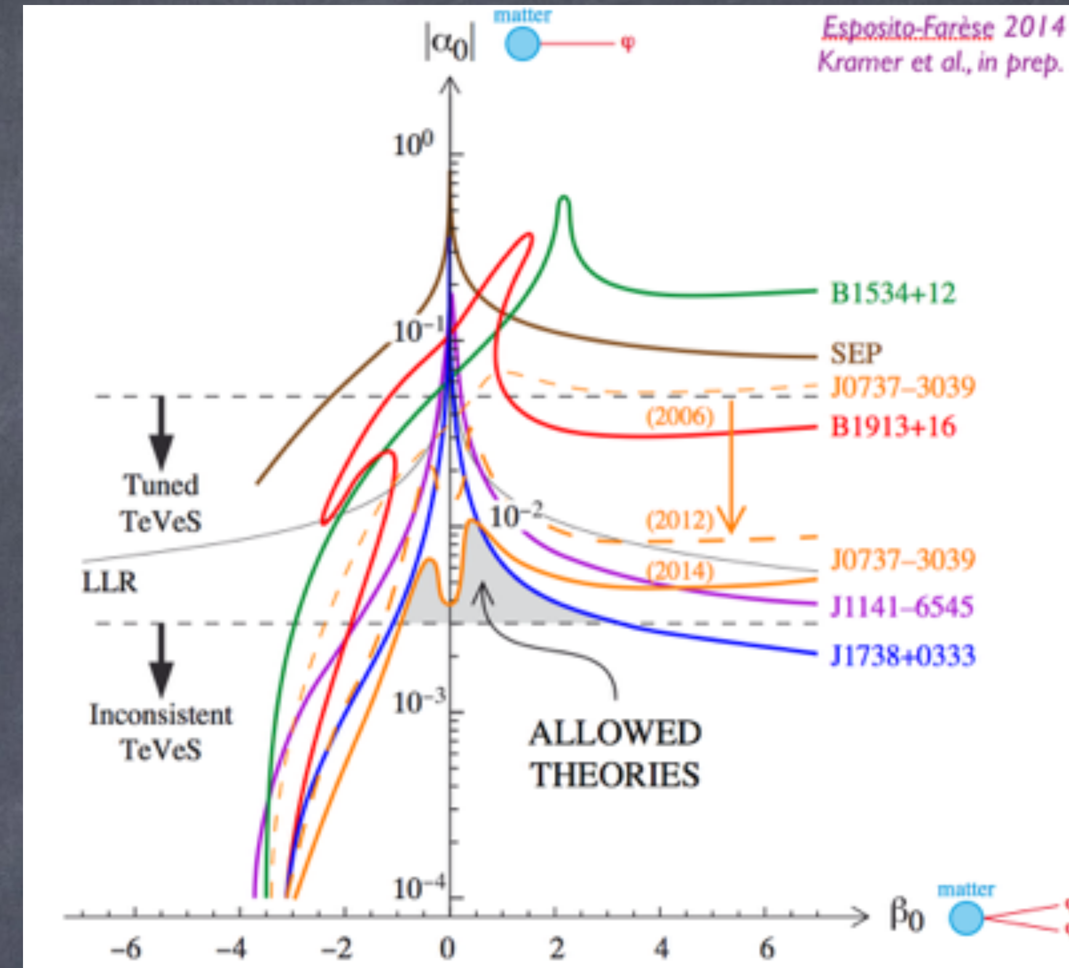
Non-perturbative PN expansion in Horndeski with Vainshtein mechanism



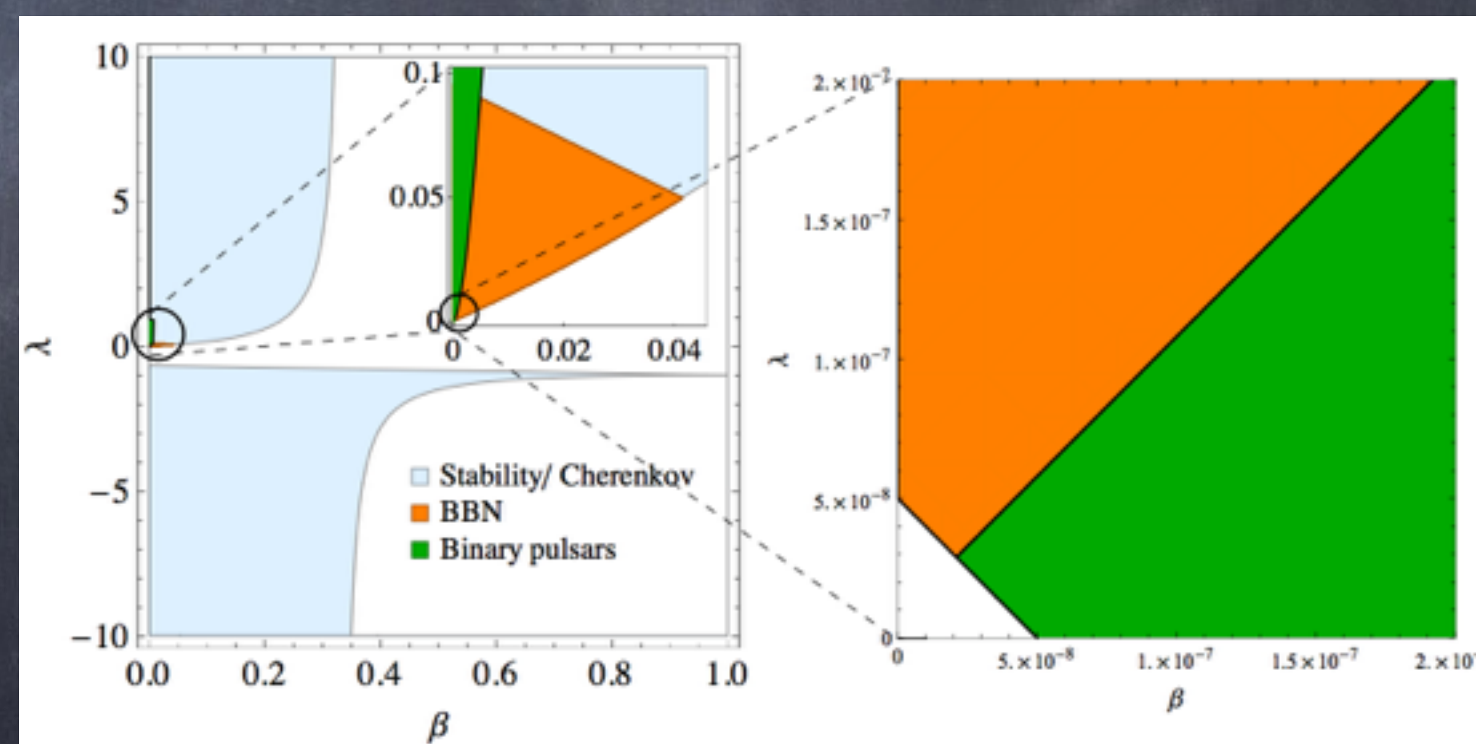
- Vainshtein radius r_V is effective size of point pass
- If $r_V \gtrsim \lambda$, we have a problem! (de Rham, Matas & Tolley 2012, Chu & Trodden 2013, EB & Yagi 2015)
- WKB analysis predicts all multipole moments radiate with same strength in binary systems (de Rham, Matas & Tolley 2012)

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



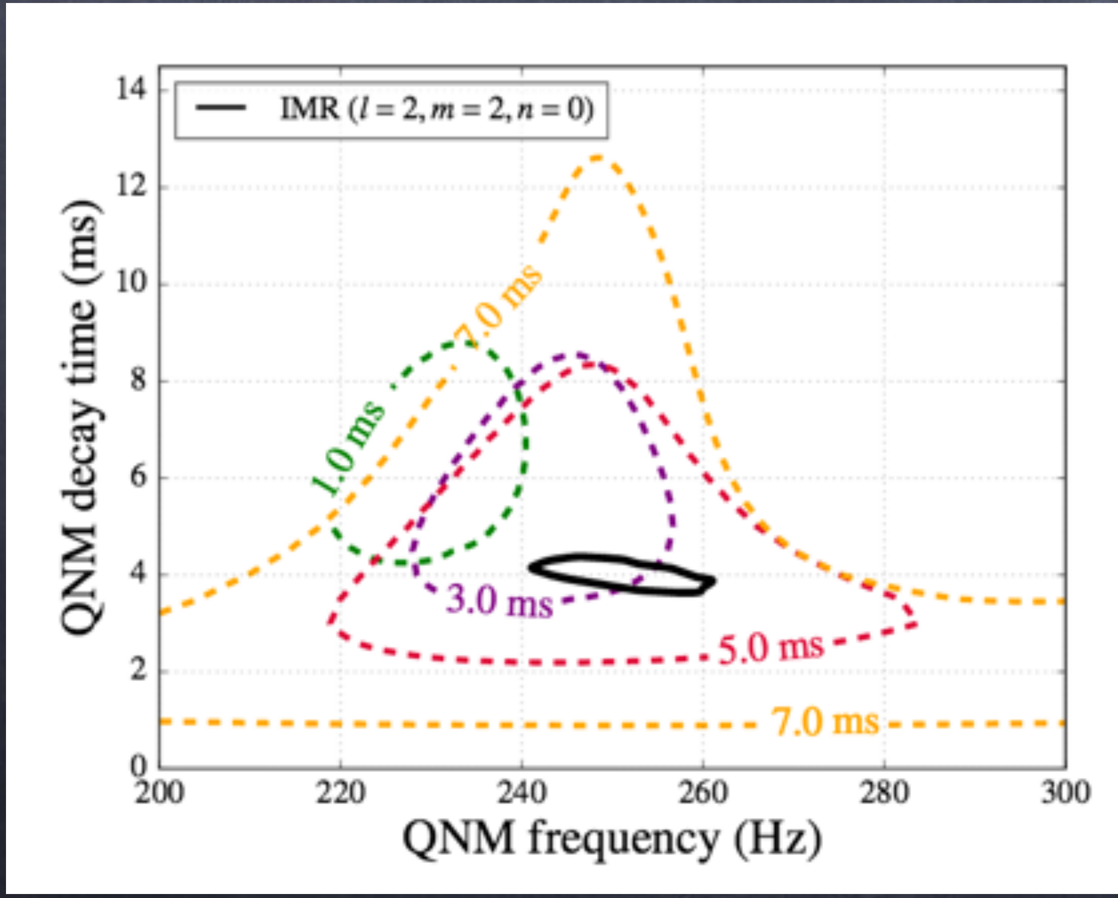
Bonetti & EB 2015

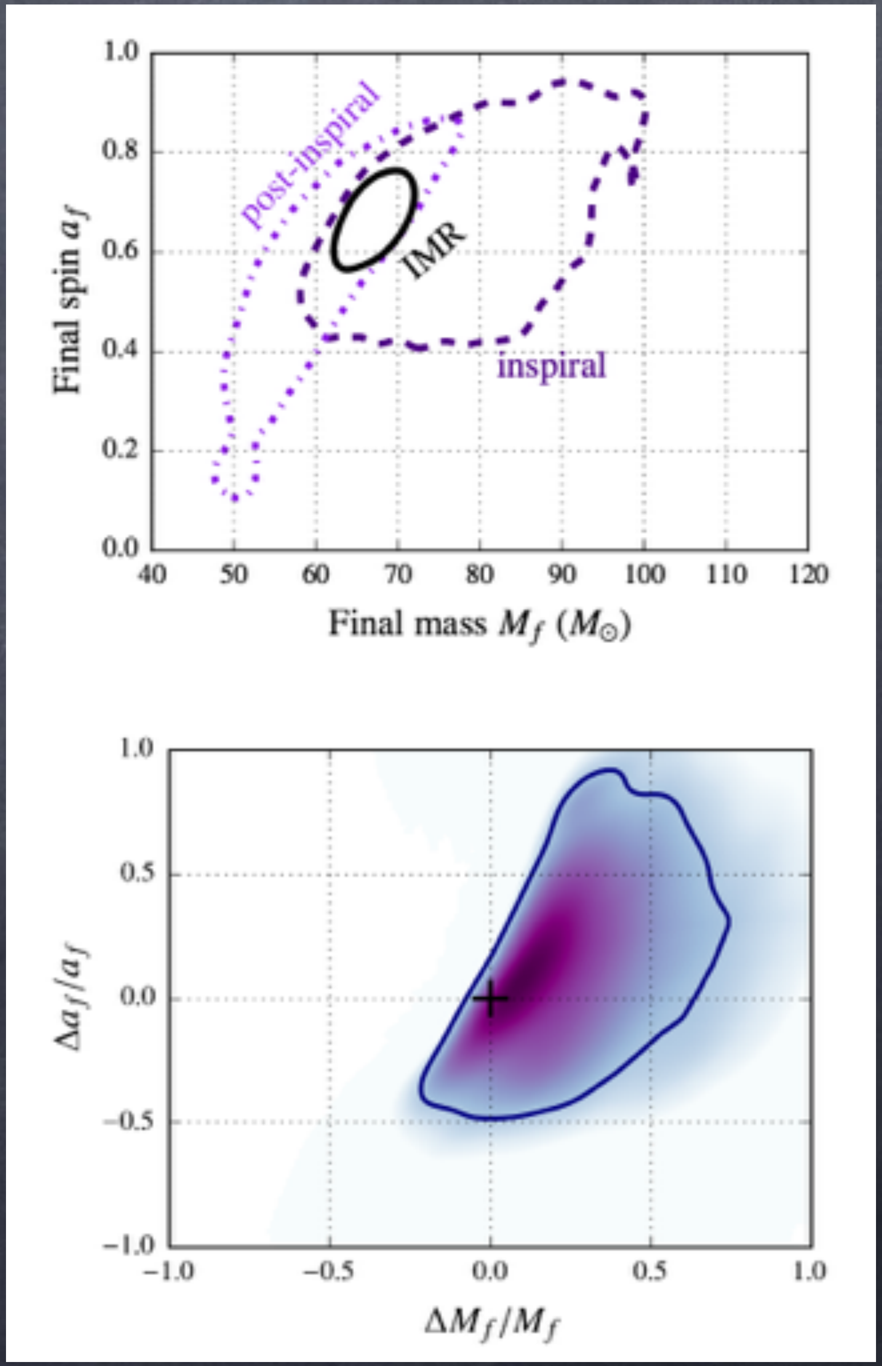
(Future) ringdown tests

Tests of the no-hair theorem:

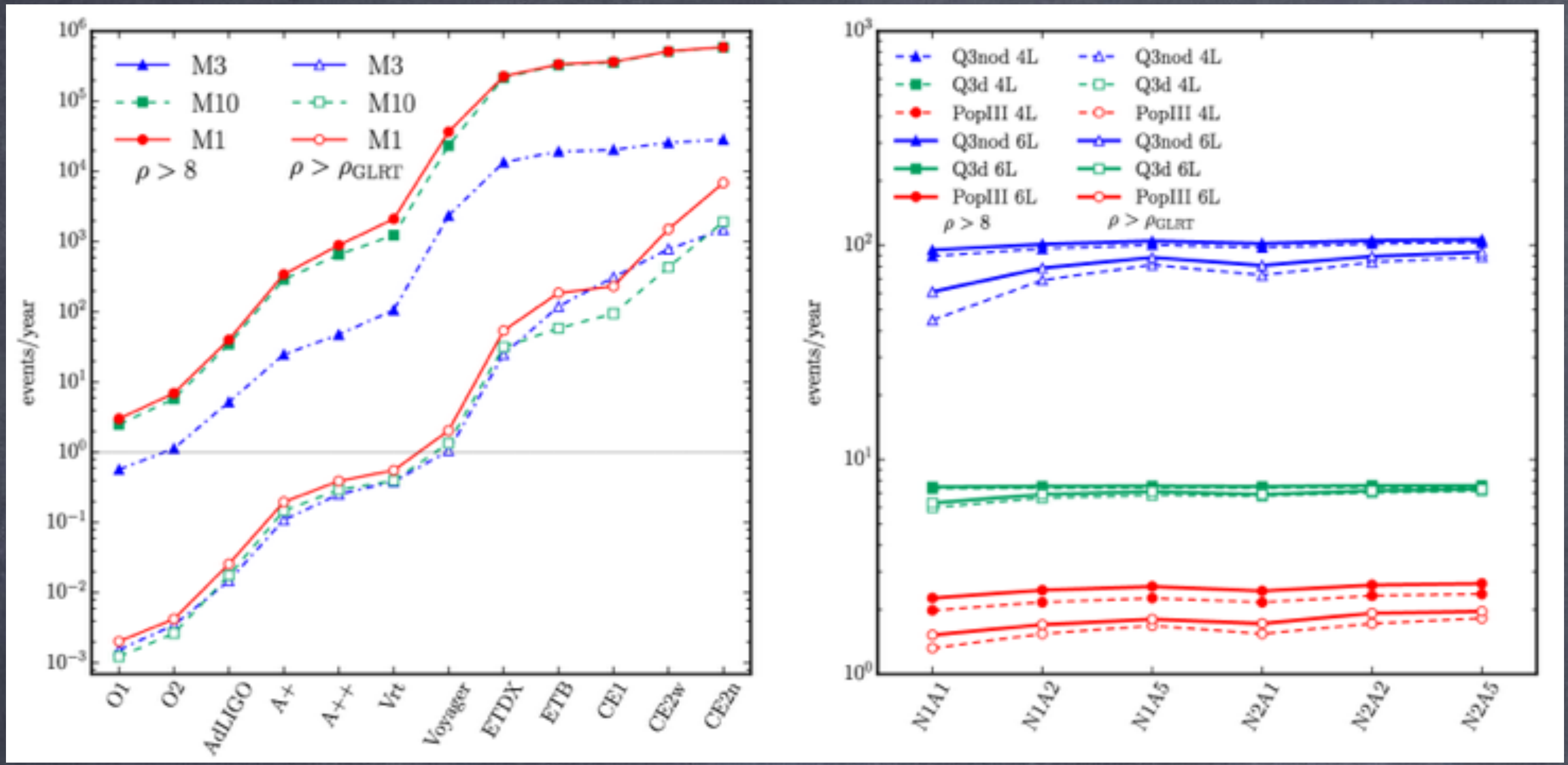
$$\omega_{\ell m} = \omega_{\ell m}^{GR}(M, J)(1 + \delta\omega_{\ell m}) \qquad \tau_{\ell m} = \tau_{\ell m}^{GR}(M, J)(1 + \delta\tau_{\ell m})$$

Difficult with advanced detectors because little SNR in ringdown

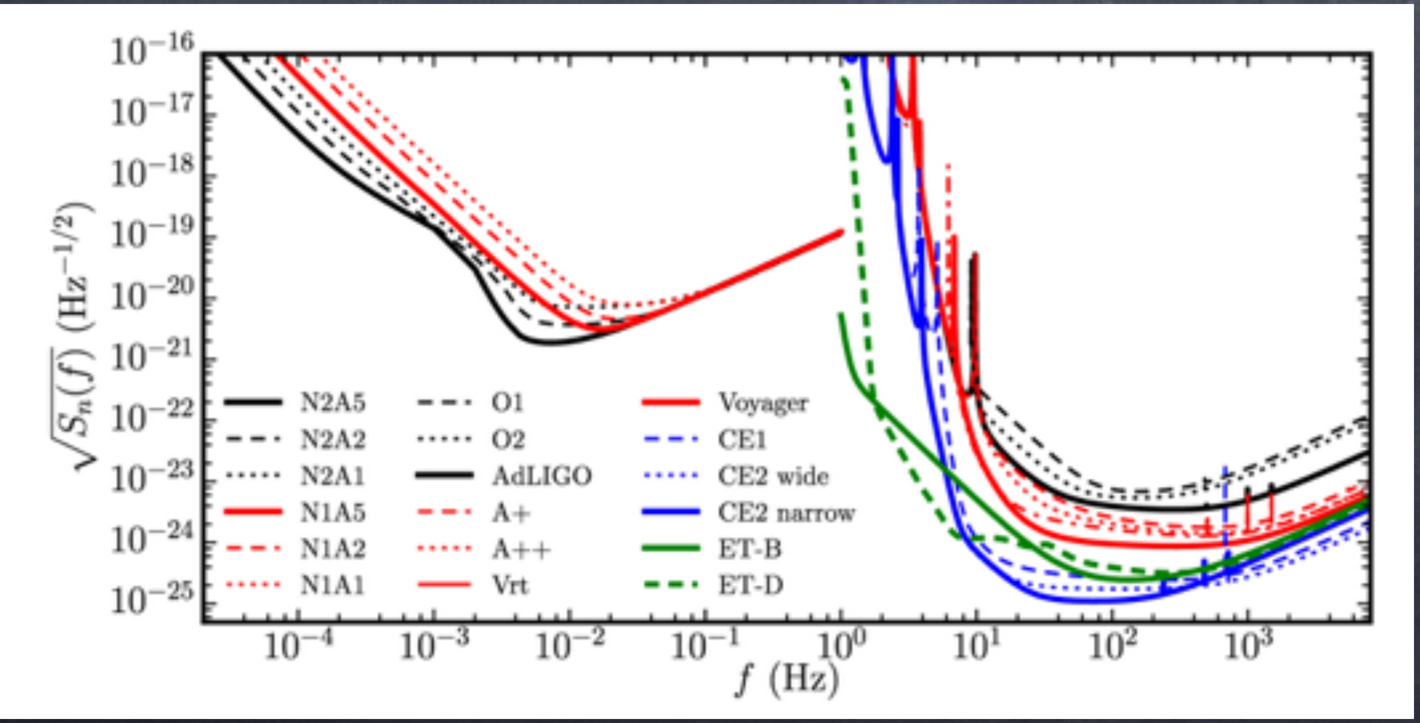




Tests of no-hair theorem by BH ringdown



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



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

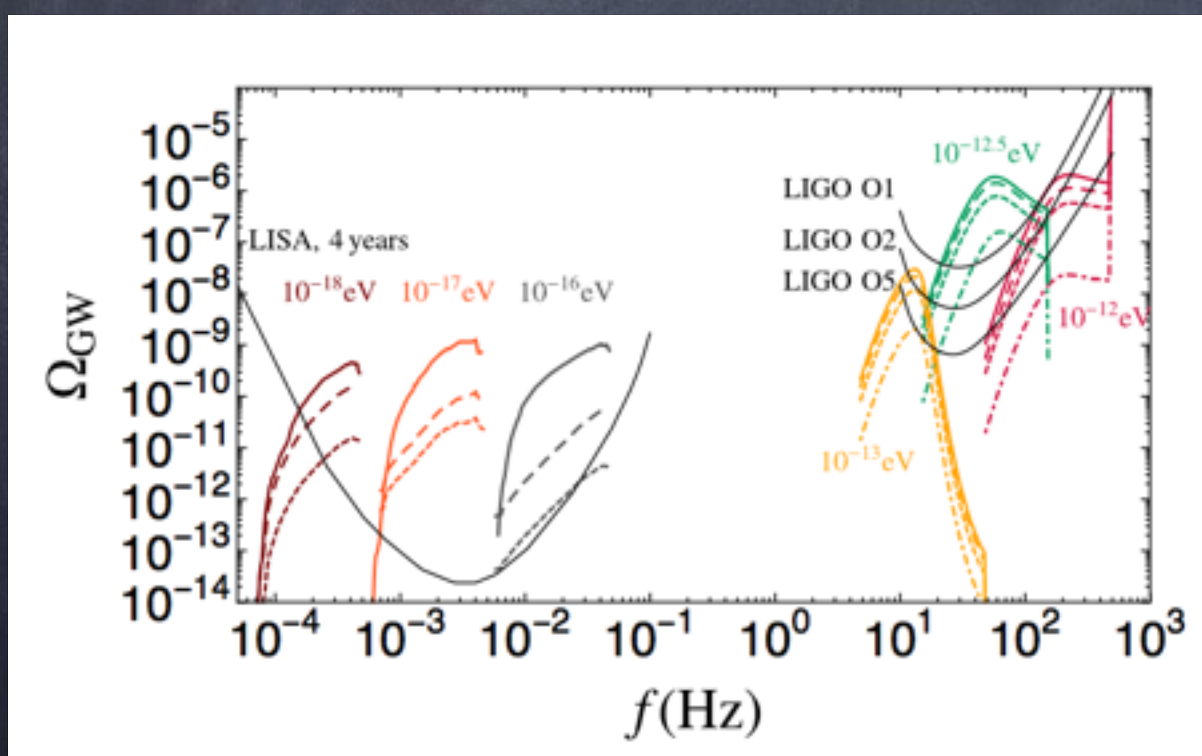
Constraints on massive fields around spinning BHs

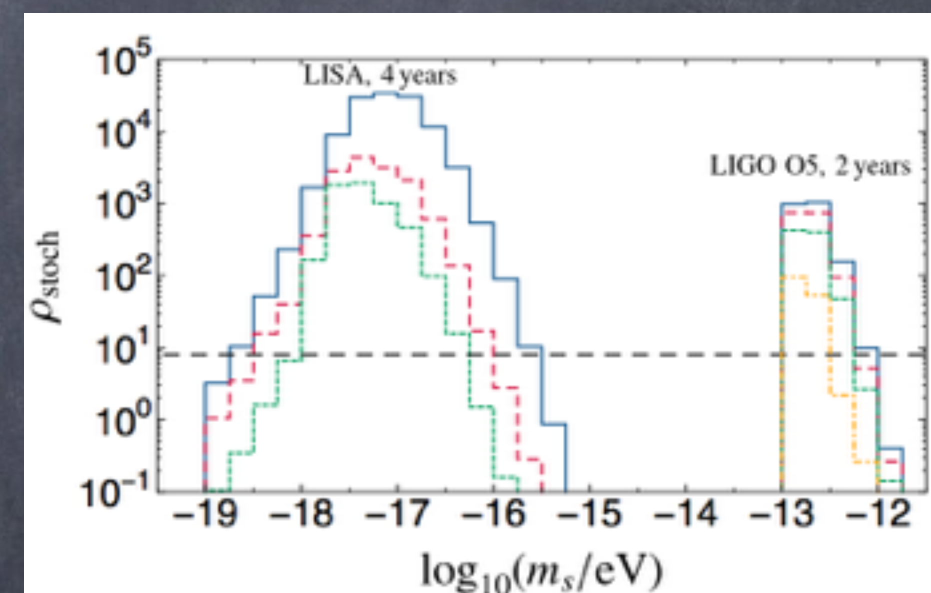
- Isolated spinning BH + massive fields (e.g. light axion-like particles) with Compton wavelength comparable to event horizon radius are unstable under superradiance

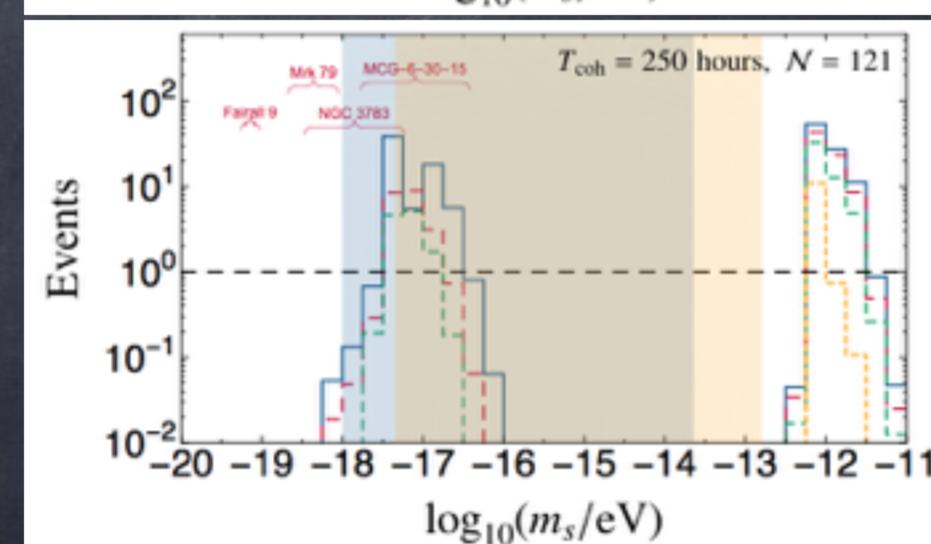
- Mass and (mostly) angular momentum are transferred from BH to scalar condensate surrounding BH on instability timescale; condensate then emits almost monochromatic waves on timescale

$$\tau_{\rm inst} \sim 0.07\,\chi^{-1}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^{9}\,{\rm yr}\,,\quad \tau_{\rm GW} \sim 6\times10^{4}\,\chi^{-1}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^{15}\,{\rm yr}\,.$$

- Observable by LIGO/LISA as background and resolved sources







Brito, Ghosh, EB, Berti, Cardoso, Dvorkin, Klein & Pani in prep.

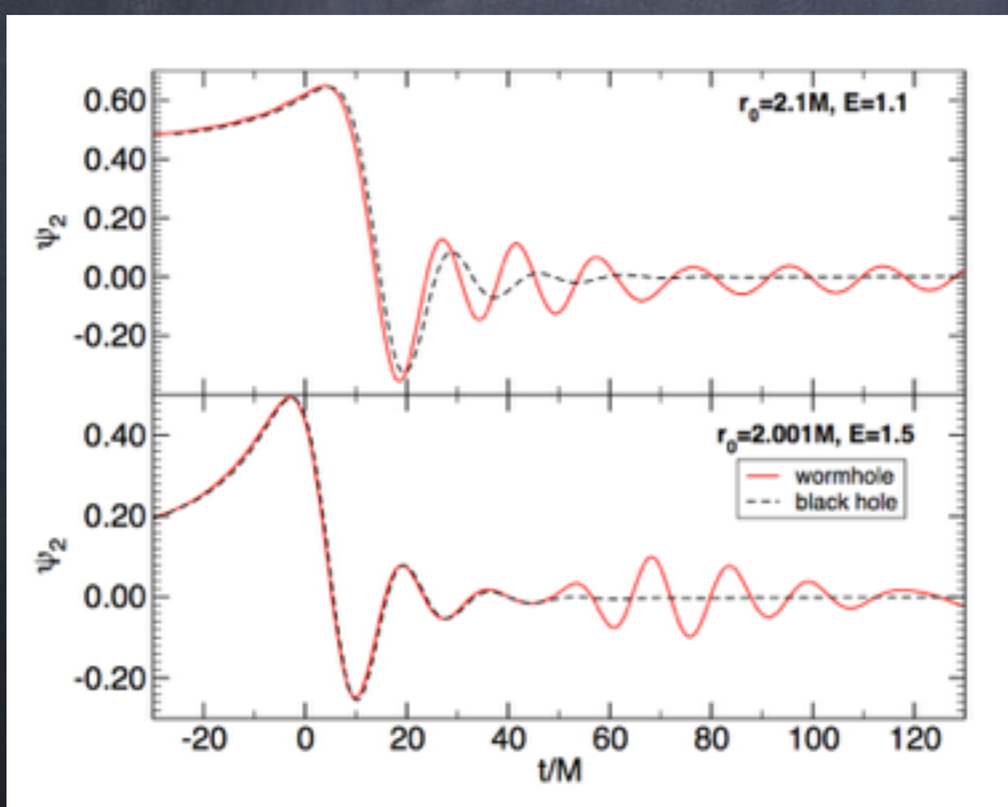
Ringdown's sensitivity to near-horizon physics

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

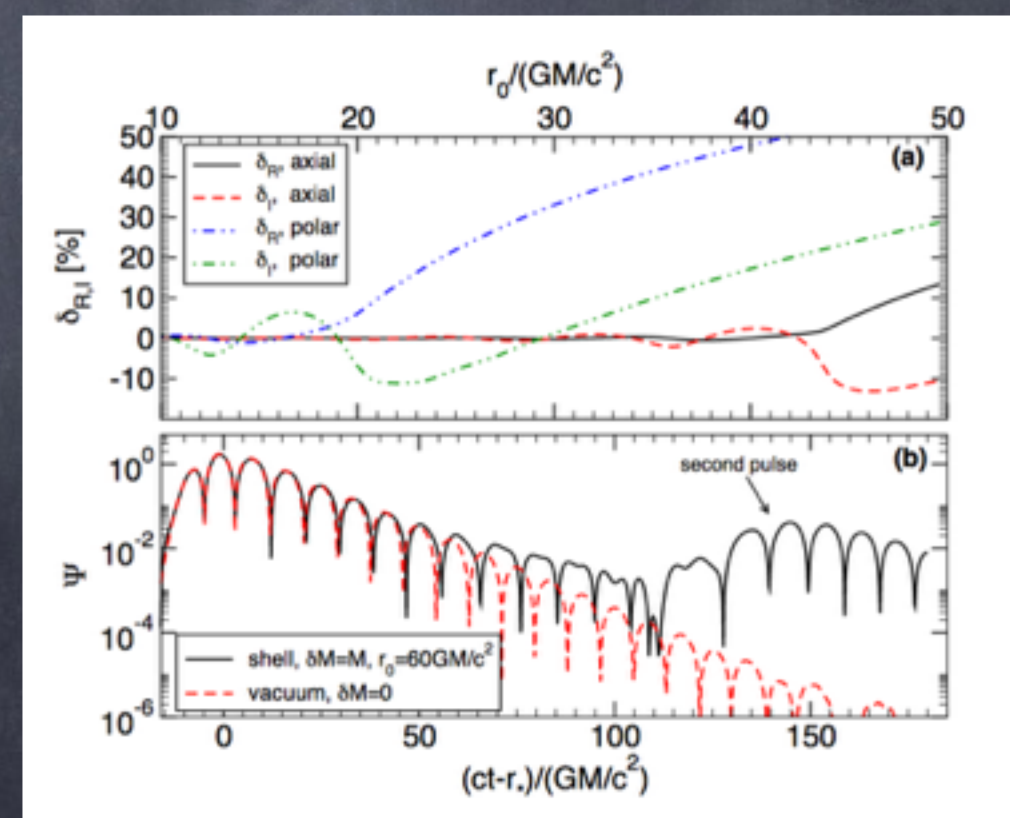
- Deviations take $\Delta t \sim \log[r_0/(2M)-1]$ to show up in time-domain signal because QNMs generated at the circular null orbit (Damour & Solodukhin 2007, EB, Cardoso & Pani 2014, Cardoso, Franzin & Pani 2016) and coordinate time diverges on horizon

- 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

- GR extensions already tightly constrained by binary pulsars/ solar system
- Direct GW detections push tests to more extreme regimes (strong gravitational fields, relativistic velocities) and different objects
- Perturbative effects are small and may require more detections
- Non-perturbative "smoking-gun" effects may be present, probably first detectable by parametrized tests if present

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