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# Theoretical implications of gravitational-wave observations

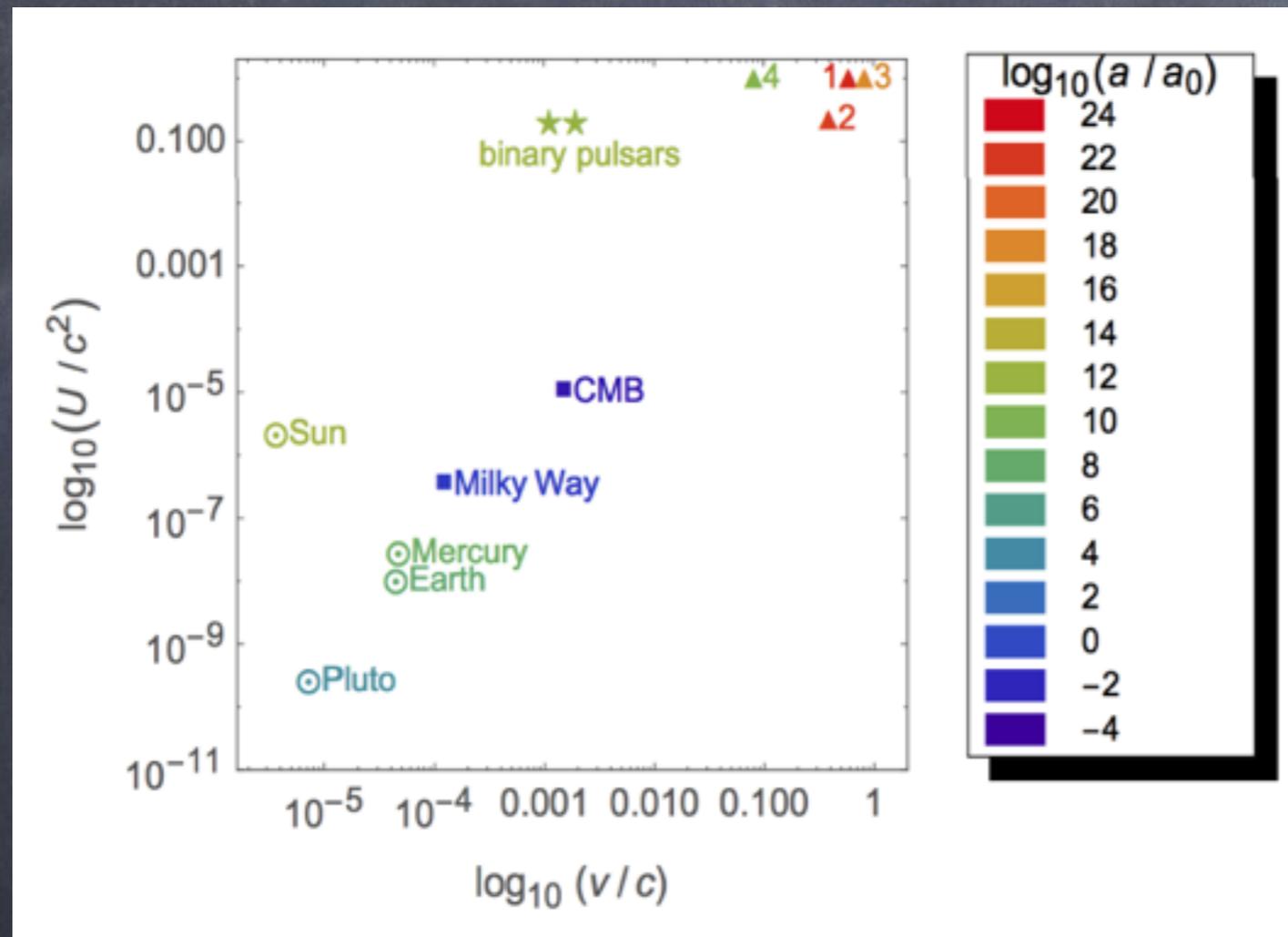The first observation of a binary black hole merger:
Status and future prospects

AEI Hannover, May 23-26, 2016

# Outline

- Why and how to extend GR

- Tests of GR extensions by GWs

- Modified GW generation: inspiral, merger, ringdown

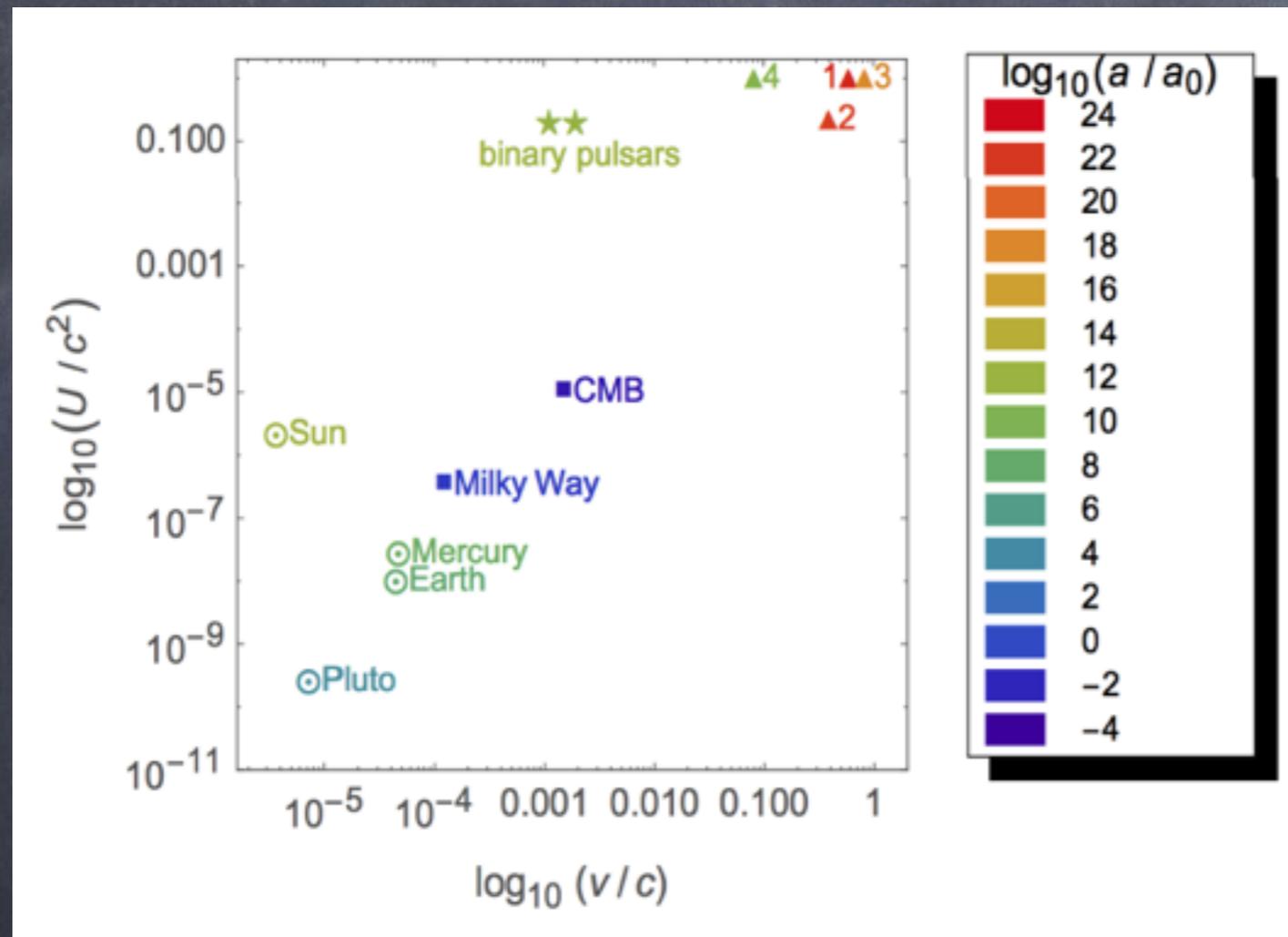- Modified GW propagation/polarization

# 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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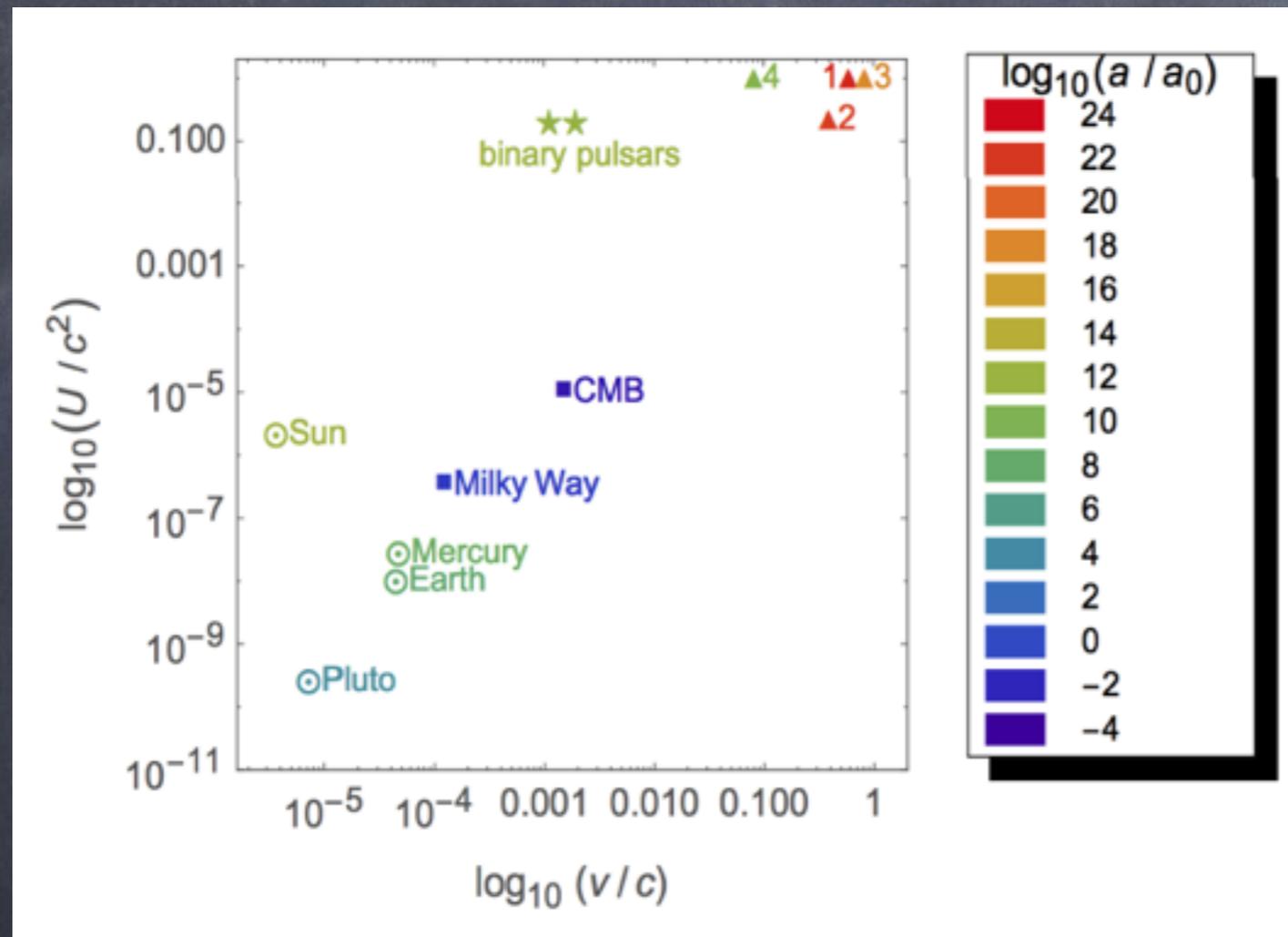1=BH–BH systems with aLIGO/aVirgo/KAGRA

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**Evidence for Dark Sector from systems with $a < 10^{-10}$ m/s$^2$ $\sim c/H_0$ : need screening!**

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# Beyond GR: why?



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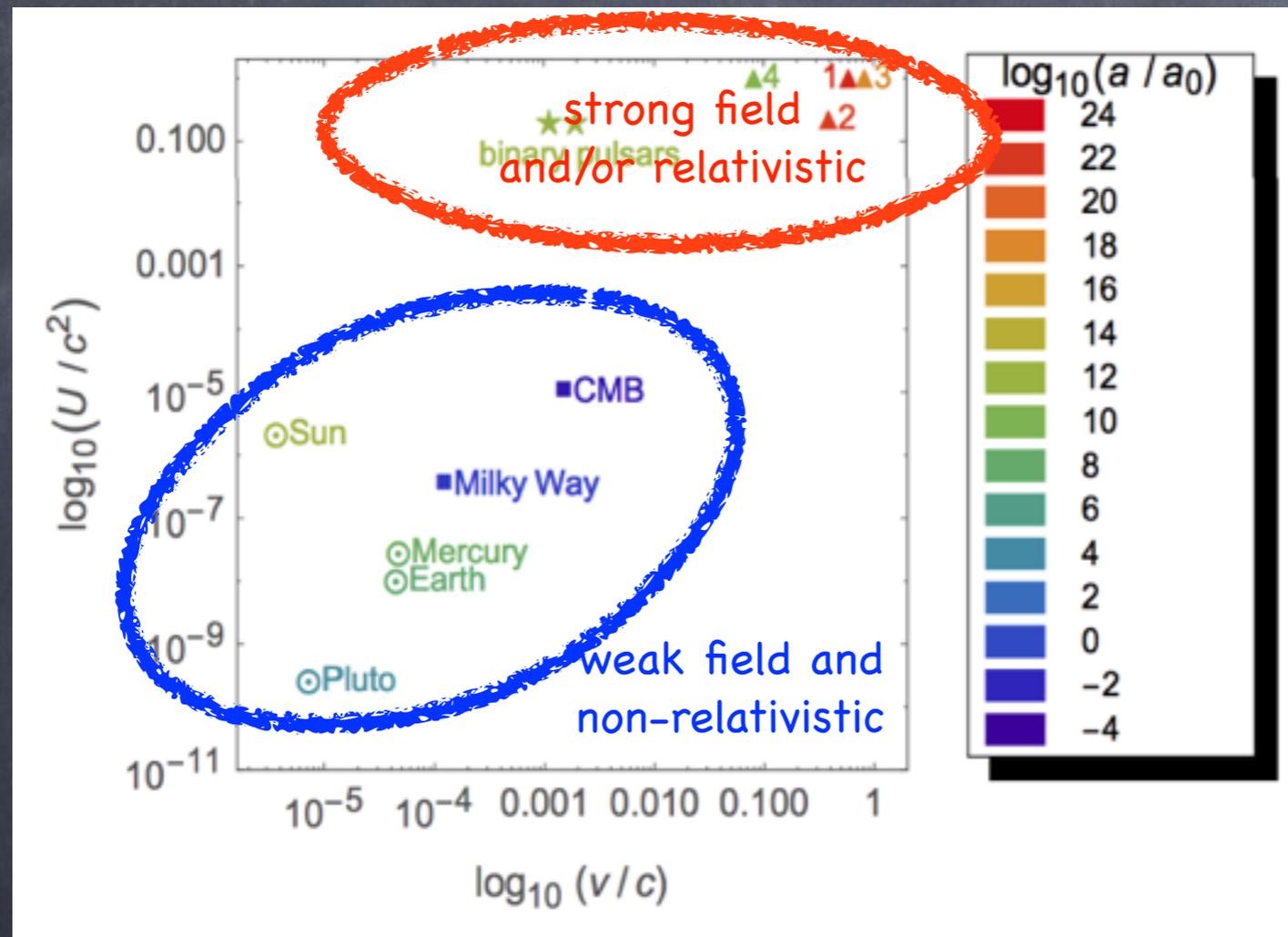
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- Evidence for Dark Sector from systems with $a < 10^{-10}$ m/s$^2$ $\sim c/H_0$ : need screening!

- **GR never tested in highly relativistic AND strong-field regime**

# 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. $G_{\mu\nu} + \Lambda\, g_{\mu\nu}$*
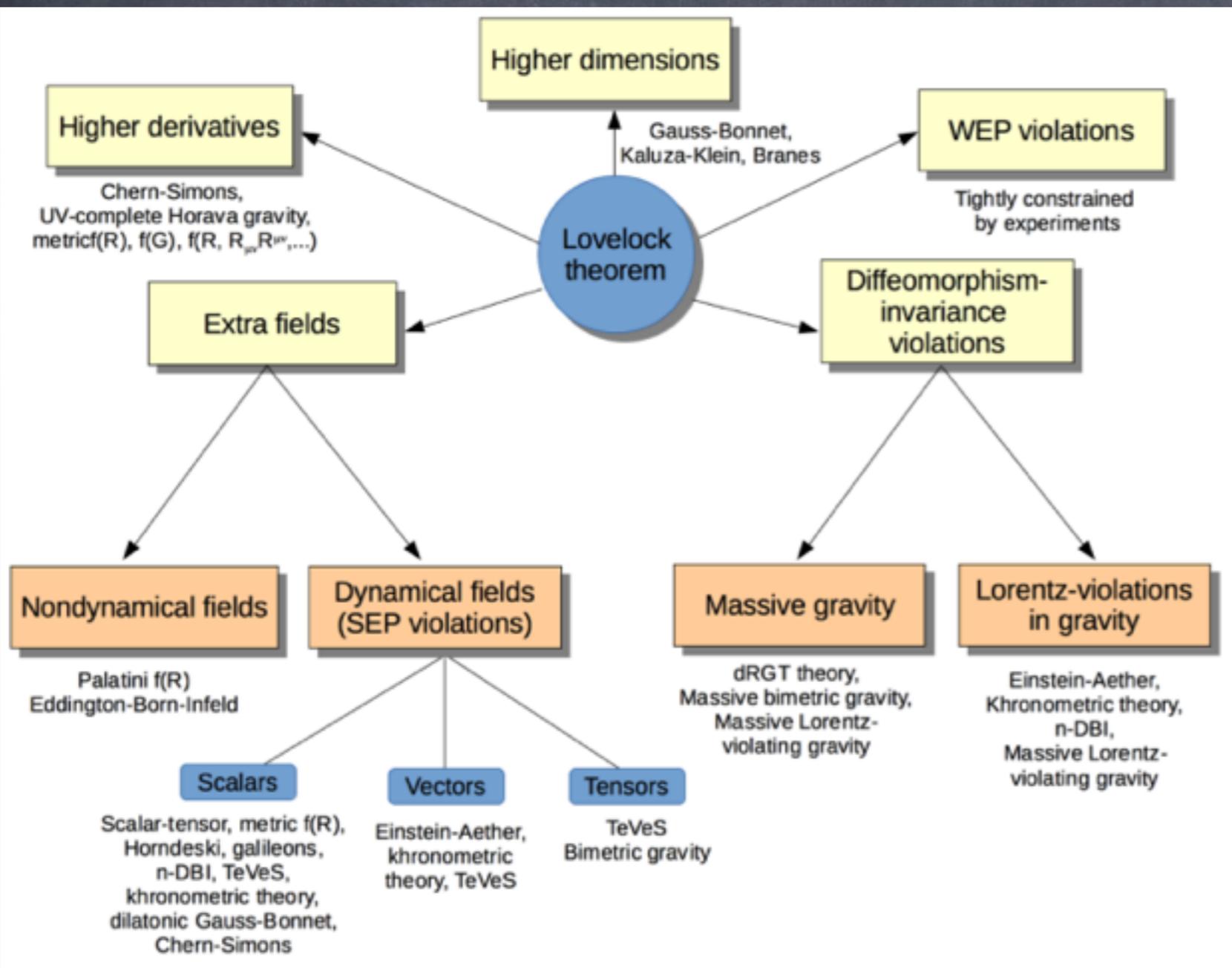


Figure adapted from Berti, EB et al 2015

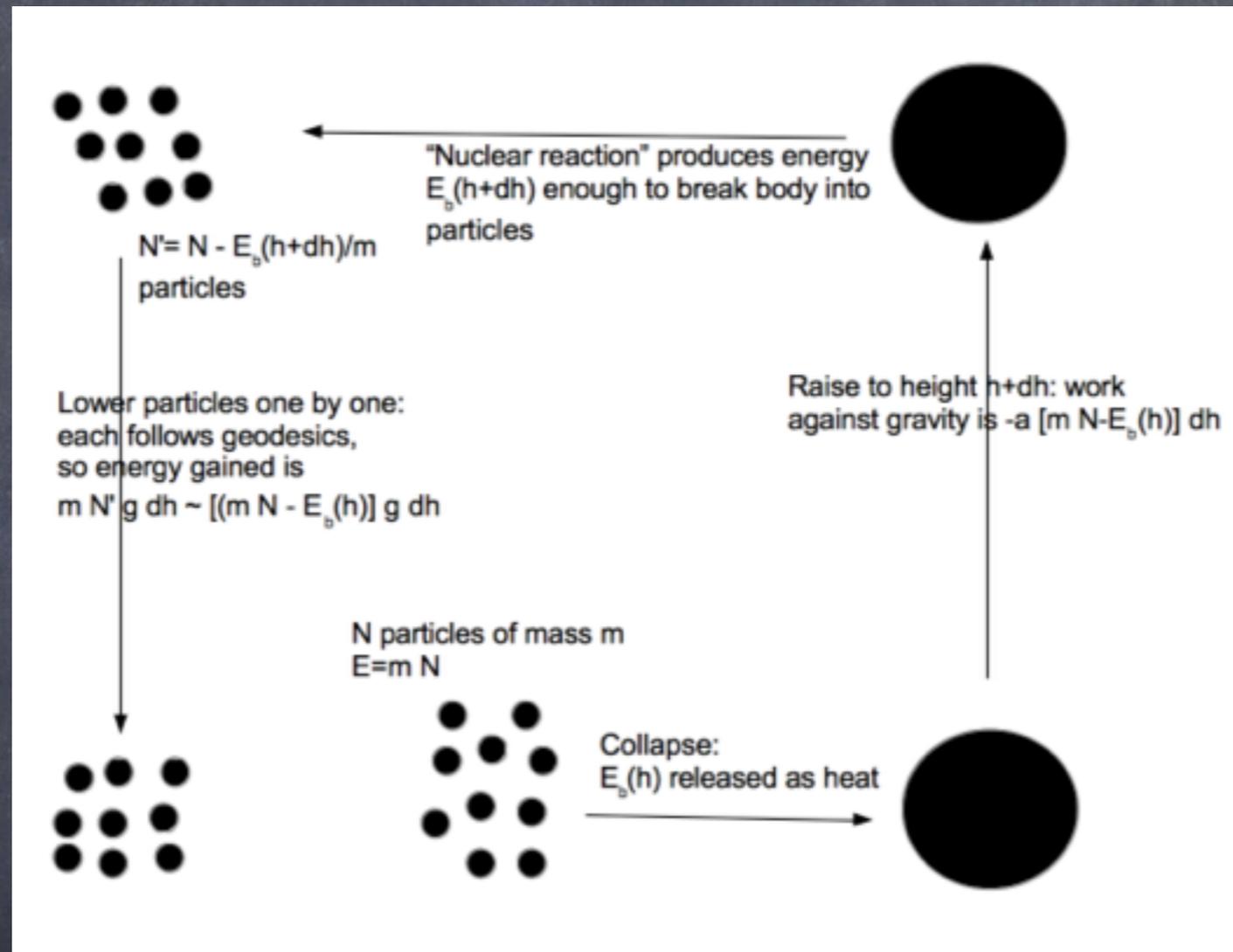Generic way to modify GR is to add extra fields!

# 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

$$S_m(\psi, g_{\mu\nu})$$

- 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

- For strongly gravitating bodies, gravitational binding energy gives large contribution to total mass, but binding energy depends on extra fields!
$m_{inertial}/m_{gravitational}$ depends on local field value and may be $\neq 1$

# Strong–equivalence principle violations by thought experiments (Dicke 1969)



"Nuclear reaction" produces energy $E_b(h+dh)$ enough to break body into particles

$N' = N - E_b(h+dh)/m$ particles

Lower particles one by one: each follows geodesics, so energy gained is $m\,N'\,g\,dh \sim [(m\,N - E_b(h)]\,g\,dh$

Raise to height $h+dh$: work against gravity is $-a\,[m\,N-E_b(h)]\,dh$

$N$ particles of mass $m$
$E = m\,N$

Collapse: $E_b(h)$ released as heat

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

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

# A few 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 $\varphi$ in which star is immersed depends on cosmology, presence of other star $\Longrightarrow$
  $m_{inertial}/m_{gravitational}$ changes with time

- Lorentz-violating gravity (Einstein-aether, Horava): preferred frame exists for gravitational physics $\Longrightarrow$
  gravitational mass of strongly gravitating bodies depends on velocity wrt preferred frame $\Longrightarrow$ $m_{inertial} \neq m_{gravitational}$ for compact objects because v changes with time

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

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

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

# Strong-equivalence principle violations in 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. $\quad M_1 \sim \int \rho x^i d^3 x \quad h \sim \dfrac{G}{c^3} \dot{M}_1 \sim \dfrac{G}{c^3}\dfrac{P}{r}$ <span style="color:red">not a wave!</span>

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

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

<span style="color:red">Dipolar emission dominant for quasi-circular systems;
1.5 PN effect vs 2.5 PN in GR! But effect depends on nature of bodies</span>

# Tests of dipolar emission with GWs

- Difficulty is to calculate sensitivities   $s_{Q_A} = \frac{1}{M}\frac{\partial M}{\partial Q_A}\Big|_{N,\Sigma}$

- 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)
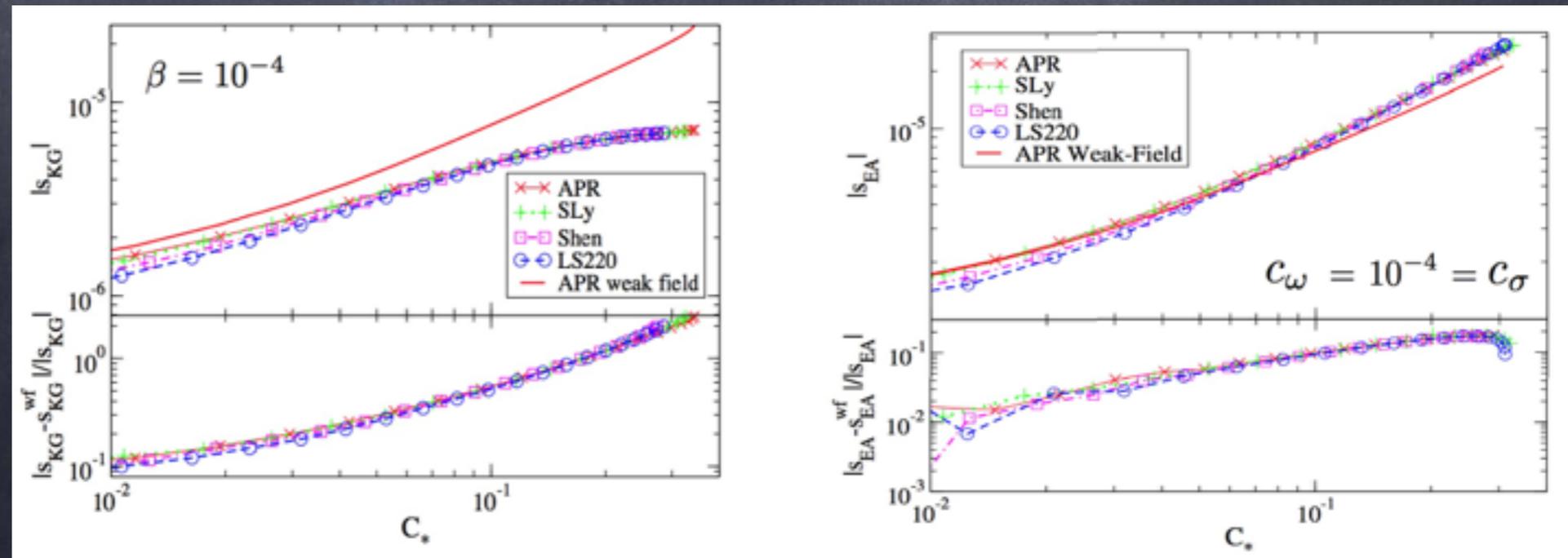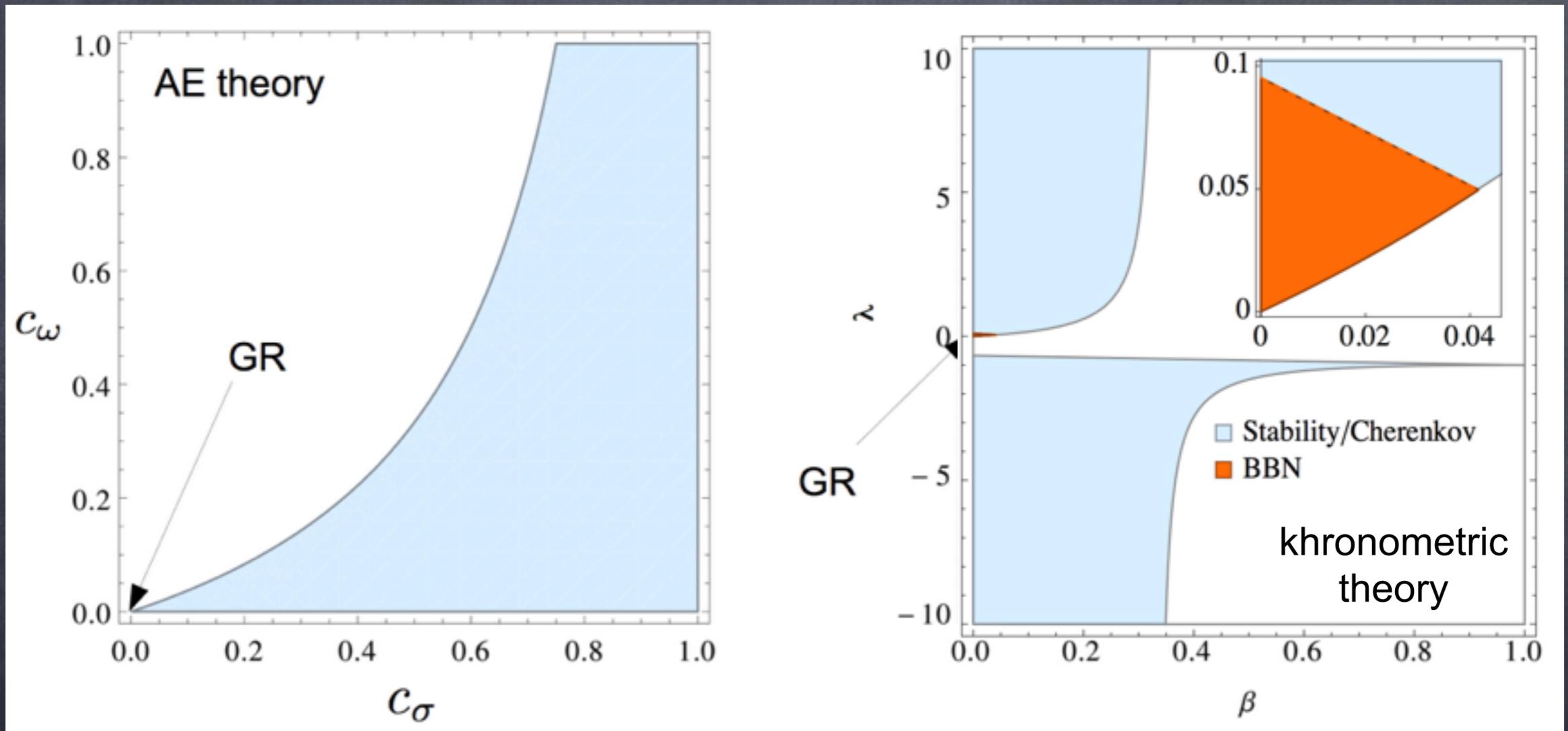
# Dipolar emission in binary pulsars
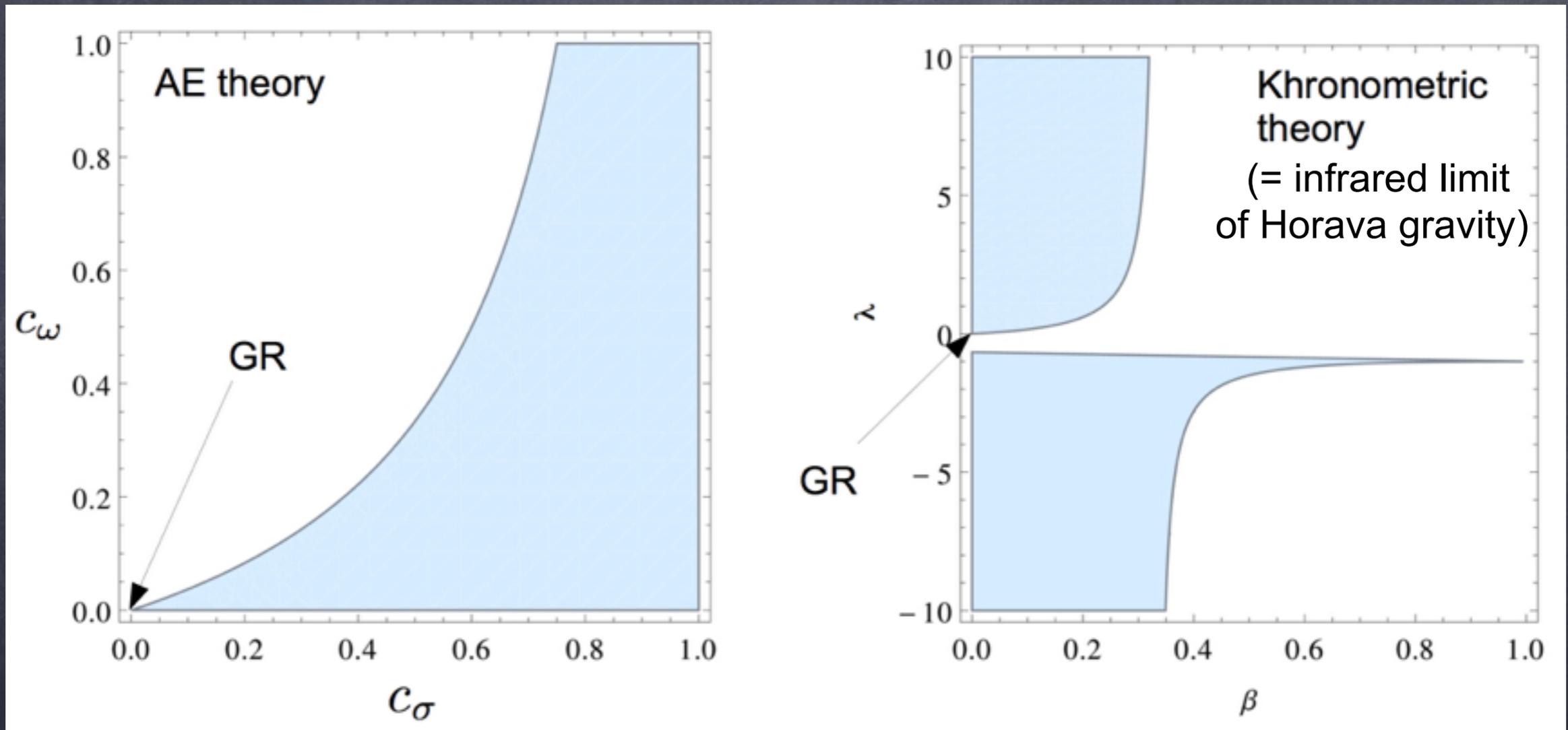
An example: Lorentz-violating gravity



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

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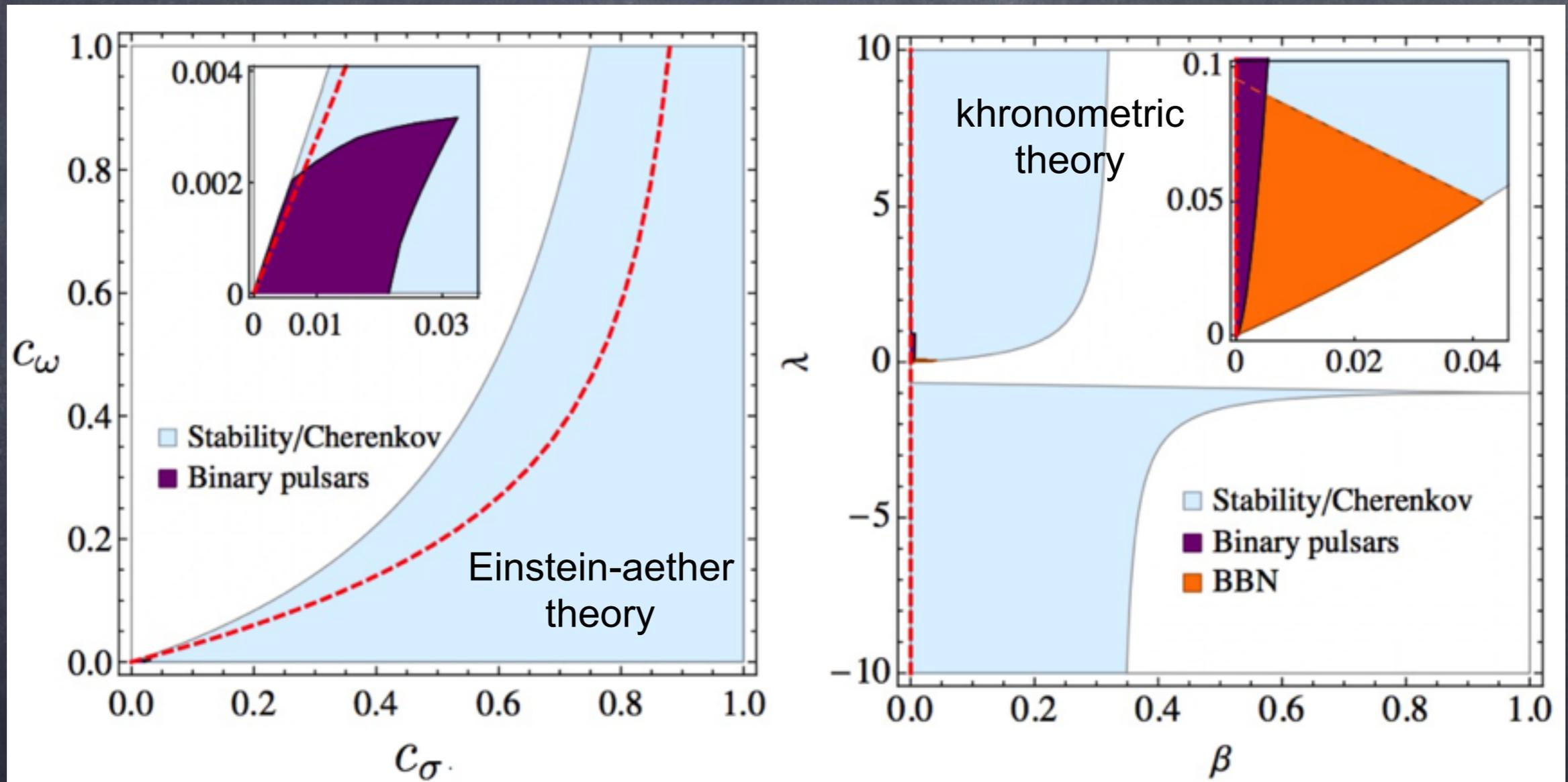
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# Dipolar emission in binary pulsars

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

# Dipolar emission in binary pulsars

- Damour-Esposito-Farese scalar-tensor theory

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

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

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

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

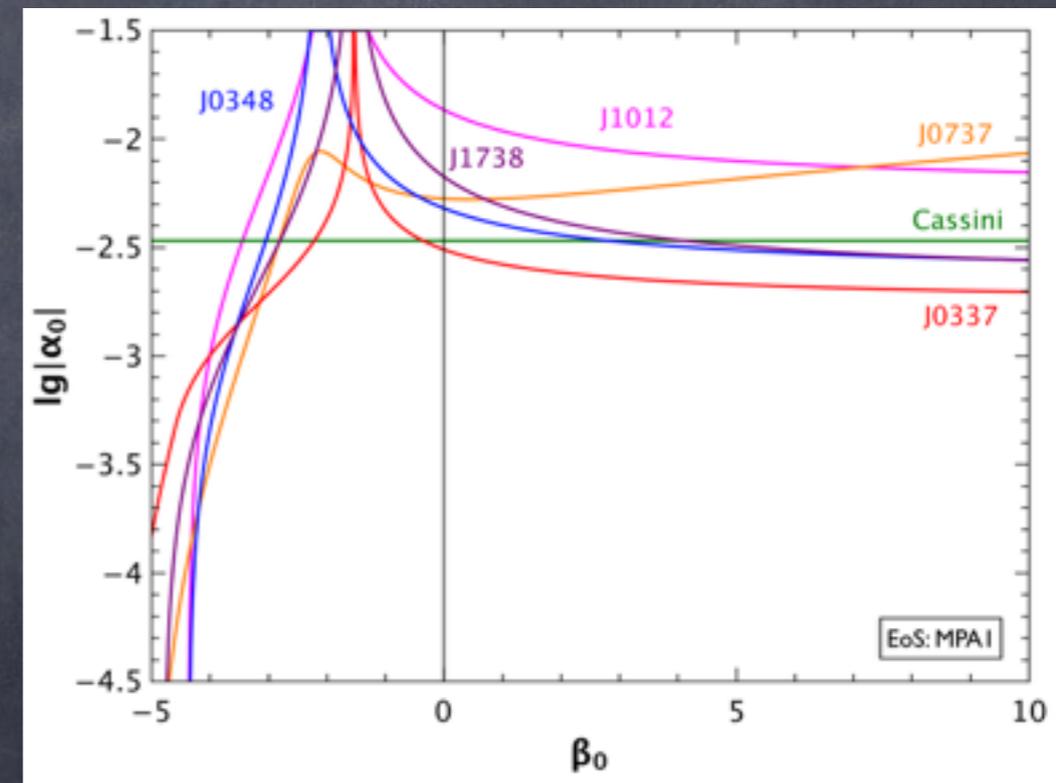- "Good cosmology" (assuming DM and DE) requires β ≥ 0 or mass term



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

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

Loophole: non-trivial (cosmological) boundary conditions

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

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

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

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

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

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# Caveats

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

$f_1$ = 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)

# 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) [Ramos & EB in prep.]
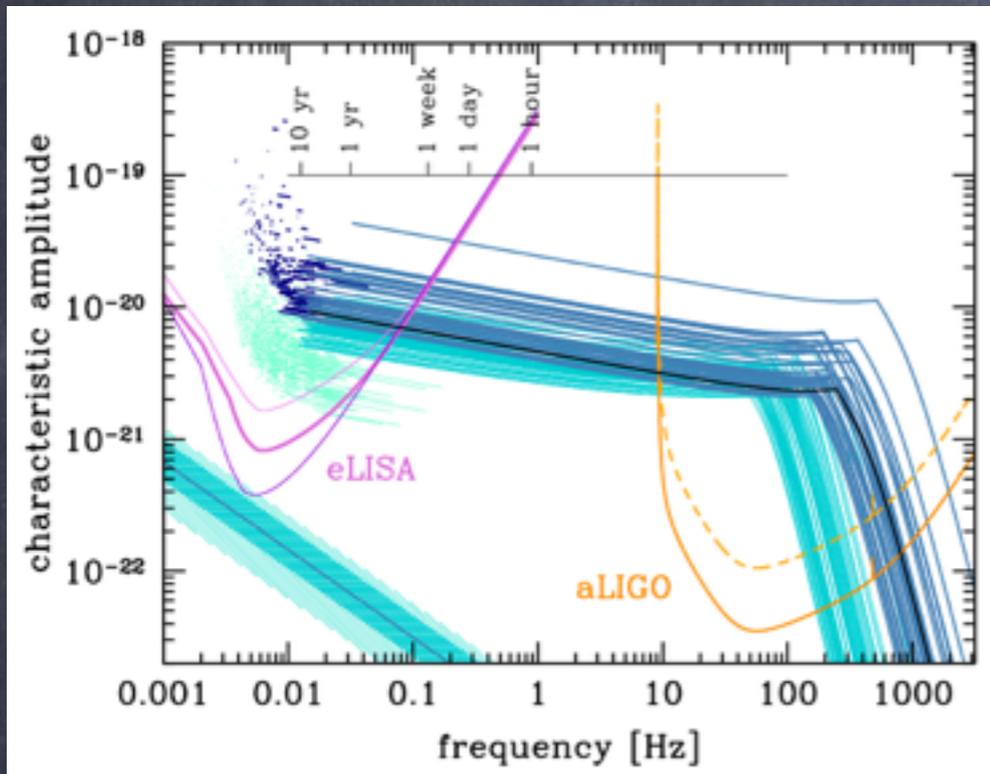
# Constraints on dipolar emission from direct detections

Weak bounds from advanced detectors

Better for 3rd-gen detectors,
e.g. Lorentz violating gravity
(Hansen, Yunes, Yagi 2015)
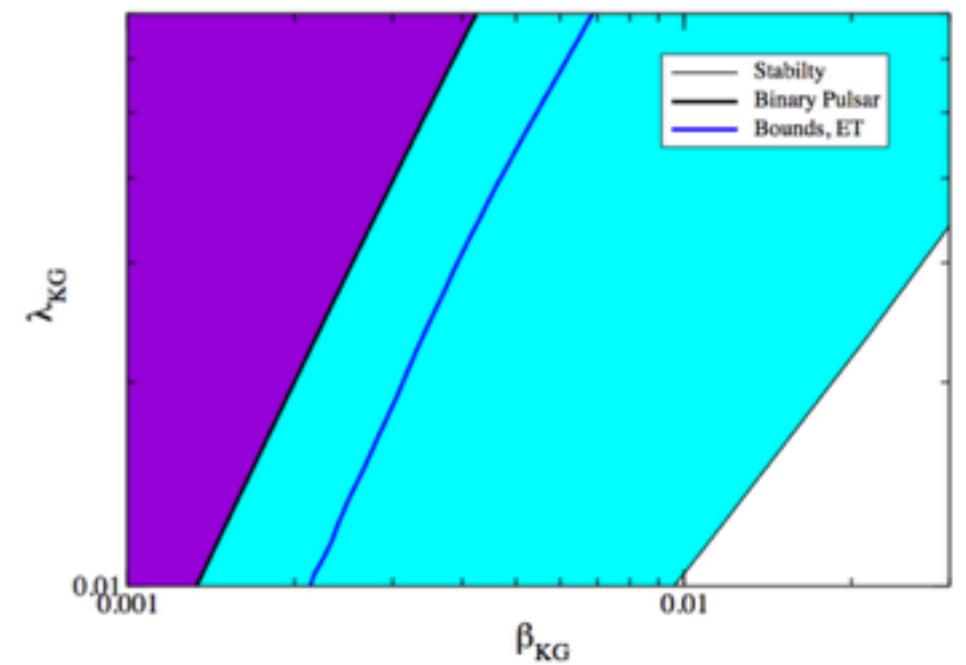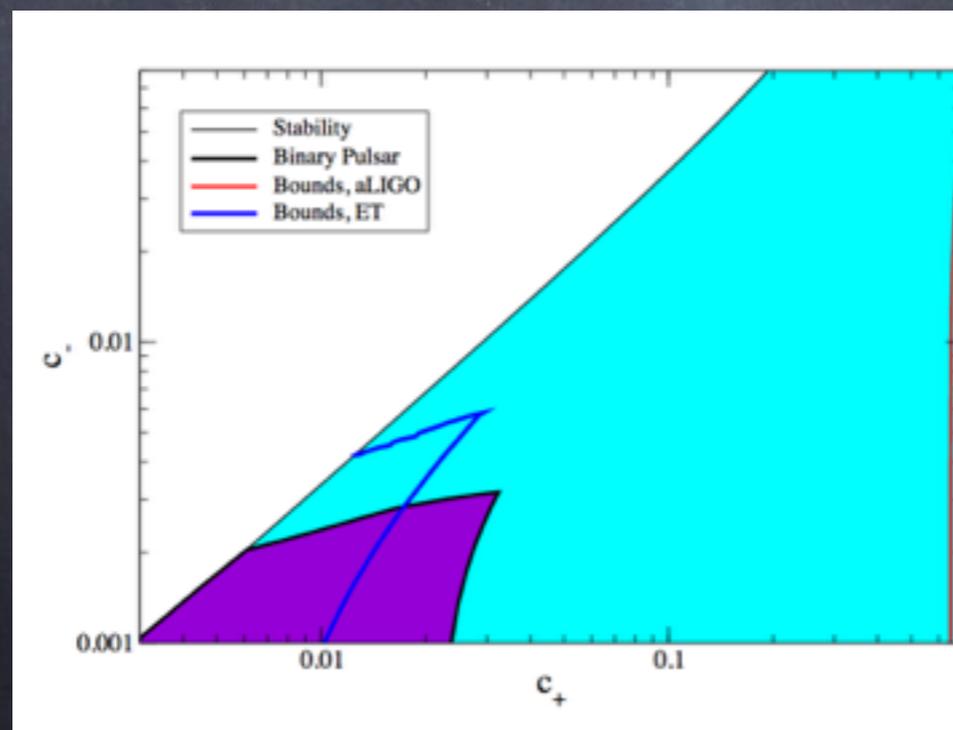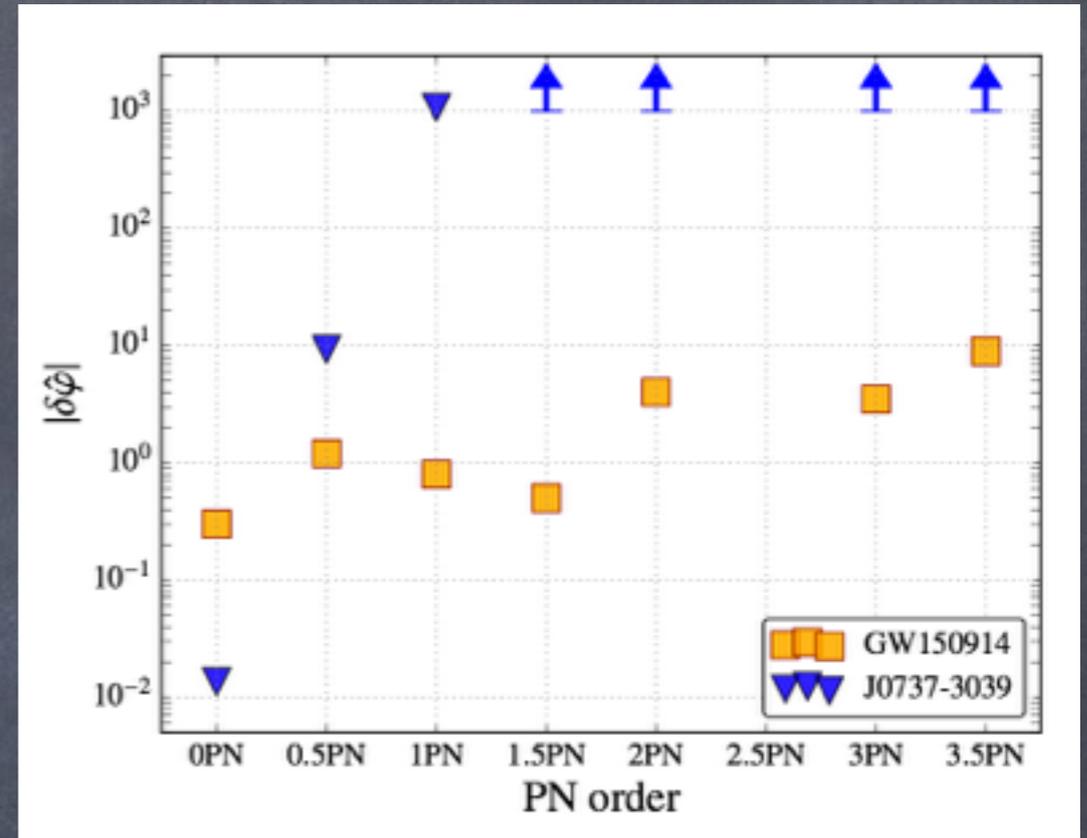
# Multi-band observations of GW150914-like/ intermediate-mass binary BHs



- Also visible by eLISA if 6 links and 5 year mission! (Sesana 2016, Amaro-Seoane & Santamaria 2009)

- High-frequency noise is crucial!

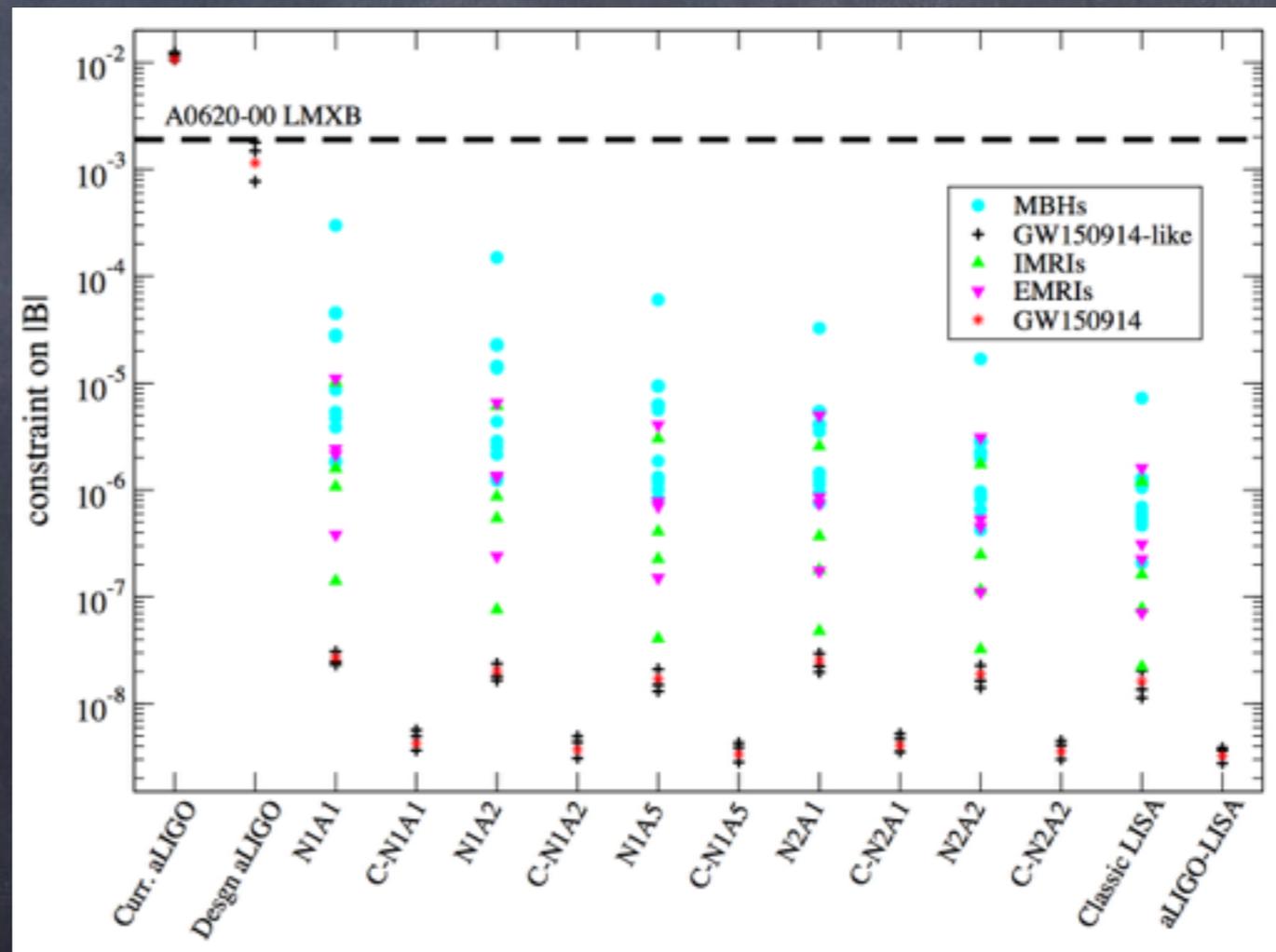- Astrophysical stochastic background may screen primordial ones
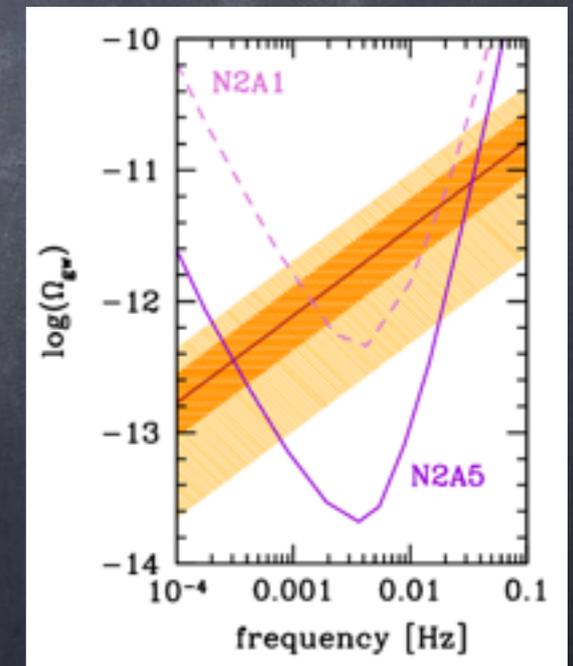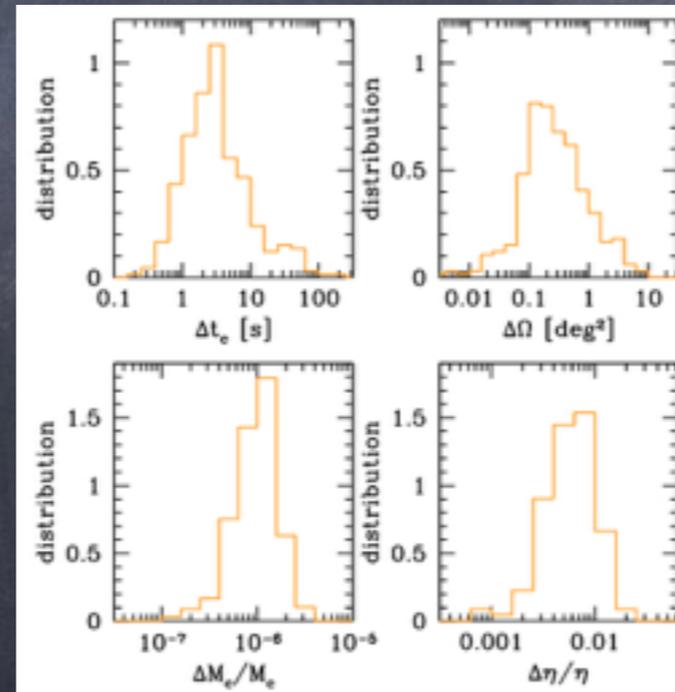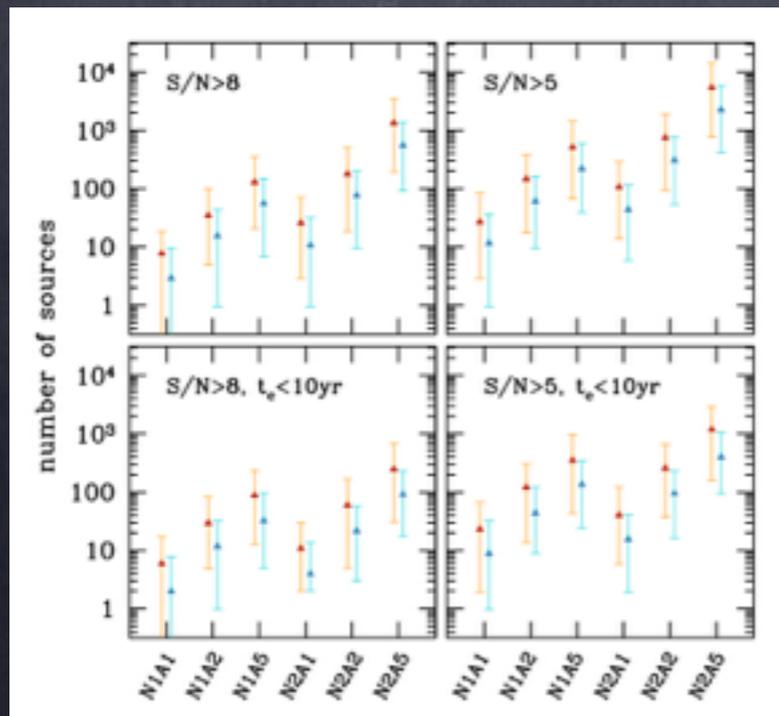






Figures from Sesana 2016

# 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

# 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

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

  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

| Theoretical Mechanism | GR Pillar | PN | $\|\beta\|$ GW150914 | Example Theory Constraints | | |
|---|---|---|---|---|---|---|
| | | | | Repr. Parameters | GW150914 | Current Bounds |
| Scalar Field Activation | SEP | $-1$ | $1.6 \times 10^{-4}$ | $\sqrt{\|\alpha_{\rm EdGB}\|}$ [km] | — | $10^7$ [39], 2 [40–42] |
| | SEP, No BH Hair | $-1$ | $1.6 \times 10^{-4}$ | $\|\dot{\phi}\|$ [1/sec] | — | $10^{-6}$ [43] |
| | SEP, Parity Invariance | $+2$ | $1.3 \times 10^{1}$ | $\sqrt{\|\alpha_{\rm CS}\|}$ [km] | — | $10^8$ [44, 45] |
| Vector Field Activation | SEP, Lorentz Invariance | $0$ | $7.2 \times 10^{-3}$ | $(c_+, c_-)$ | $(0.9, 2.1)$ | $(0.03, 0.003)$ [46, 47] |
| Extra Dimension Mass Leakage | 4D spacetime | $-4$ | $9.1 \times 10^{-9}$ | $\ell$ [$\mu$m] | $5.4 \times 10^{10}$ | $10$–$10^3$ [48–52] |
| Time-Varying $G$ | SEP | $-4$ | $9.1 \times 10^{-9}$ | $\|\dot{G}\|$ [$10^{-12}$/yr] | $5.4 \times 10^{18}$ | $0.1$–$1$ [53–57] |

| Theoretical Effect | Theoretical Mechanism | Theories | ppE $b$ | Order | Mapping |
|---|---|---|---|---|---|
| Scalar Dipolar Radiation | Scalar Monopole Field Activation | EdGB [110, 112, 120, 121] | $-7$ | $-1$PN | $\beta_{\rm EdGB}$ [110] |
| | BH Hair Growth | Scalar-Tensor Theories [43, 122] | $-7$ | $-1$PN | $\beta_{\rm ST}$ [43, 122] |
| Anomalous Acceleration | Extra Dimension Mass Leakage | RS-II Braneworld [123, 124] | $-13$ | $-4$PN | $\beta_{\rm ED}$ [111] |
| | Time-Variation of $G$ | Phenomenological [107, 125] | $-13$ | $-4$PN | $\beta_{\dot{G}}$ [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] | $-7$ $-5$ | $-1$PN 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!

# How about merger?

Possible surprises/
highly non-linear dynamics?
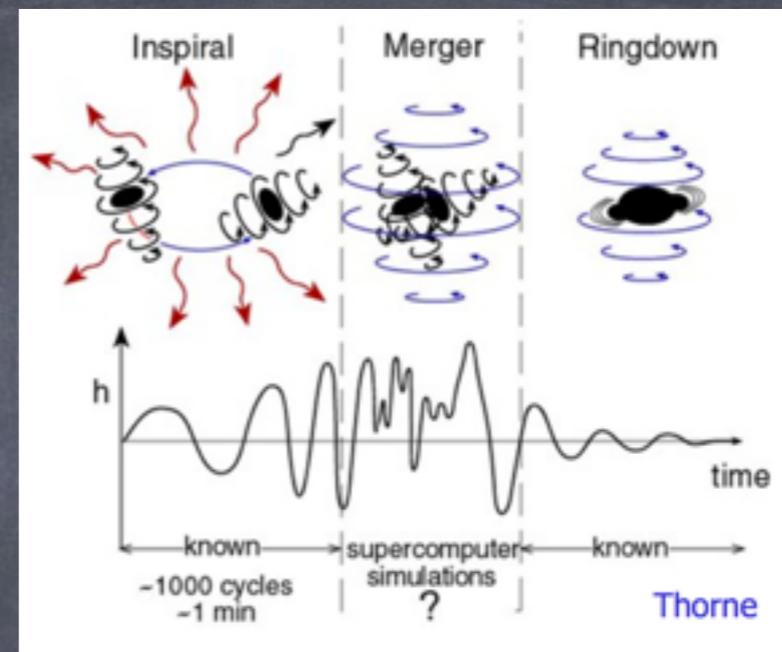


Approach 1: Like pornography...
"When you see it, you know it"! (Supreme Court Justice Potter Stewart, 1964)

Approach 2: Simulate!
Prerequisite for numerical-relativity simulations is that Cauchy problem well-posed (e.g. if eqs are 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
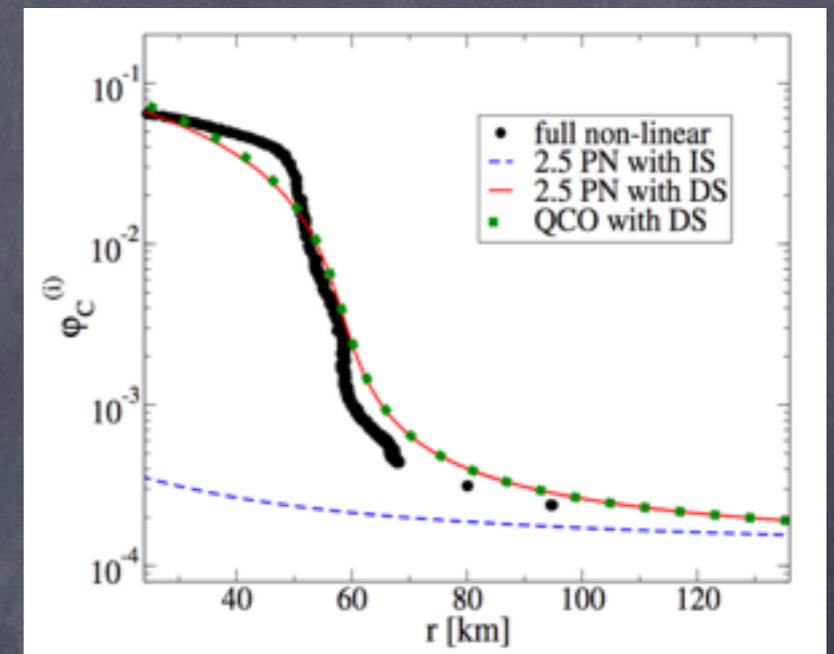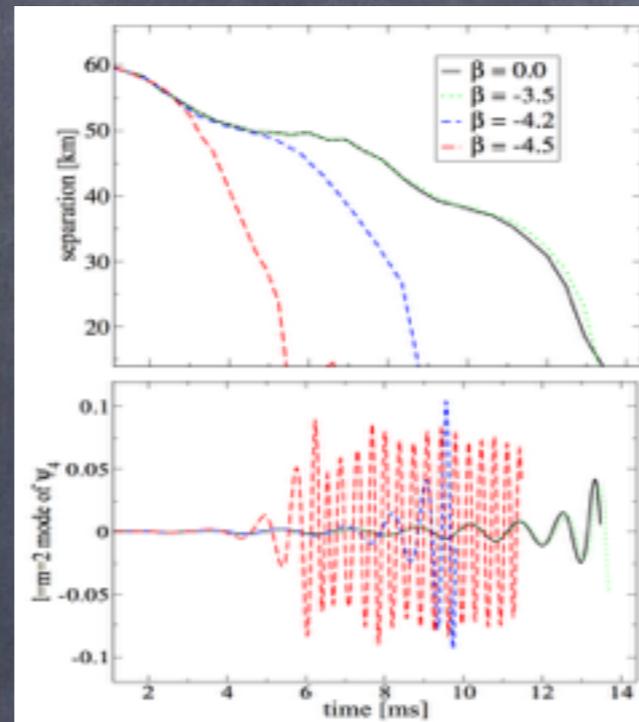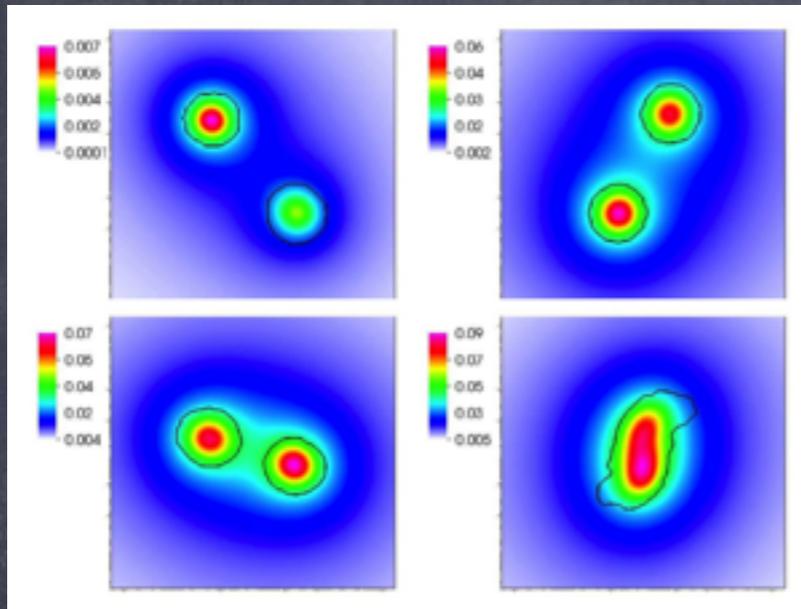


EB, Palenzuela, Ponce & Lehner 2013, 2014;
also Shibata, Taniguchi, Okawa & Buonanno 2014, 2015; Sennett & Buonanno 2016

- 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

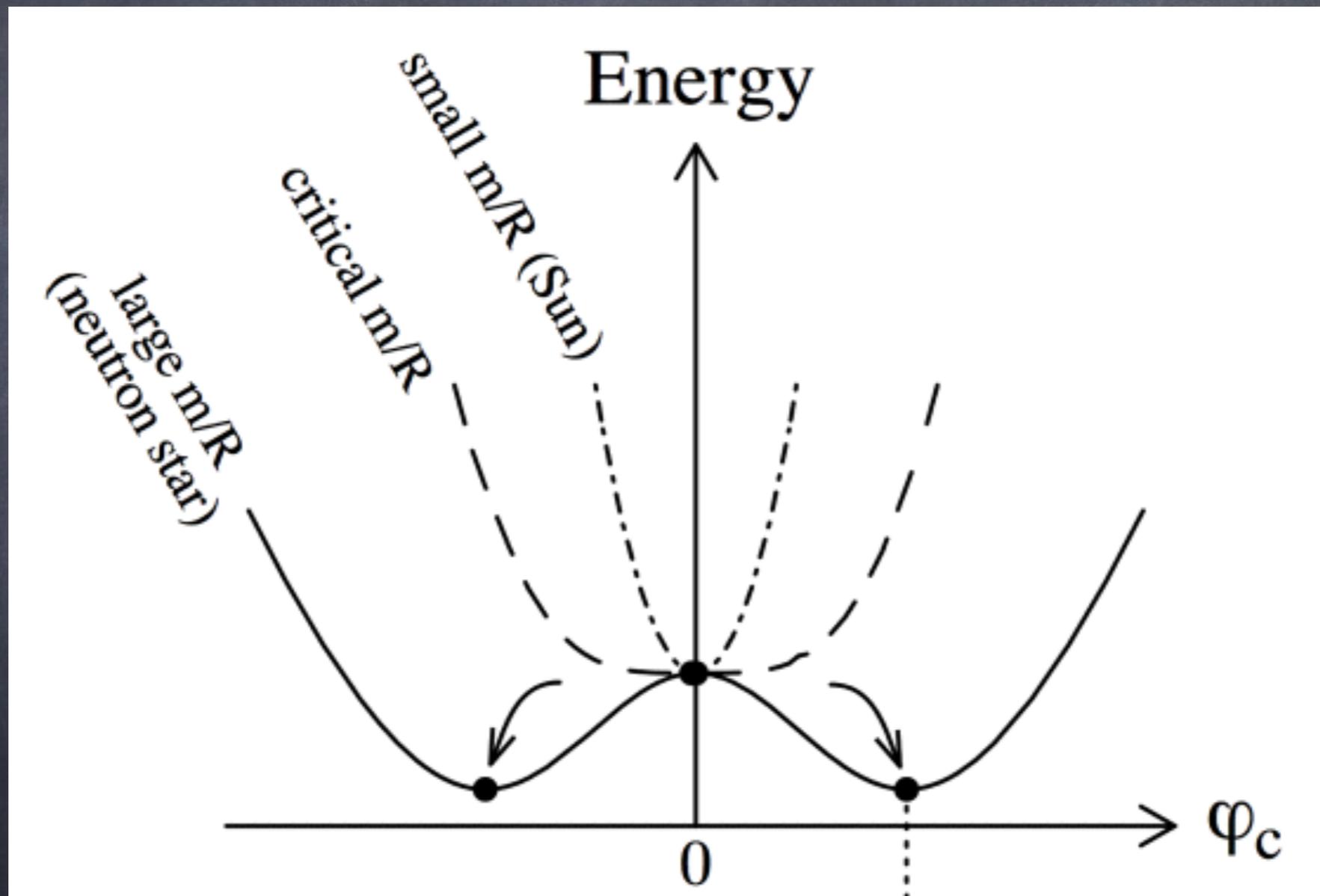# Spontaneous/dynamical scalarization as "phase transitions"



Figure from Esposito-Farese, gr-qc/0402007

# 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)
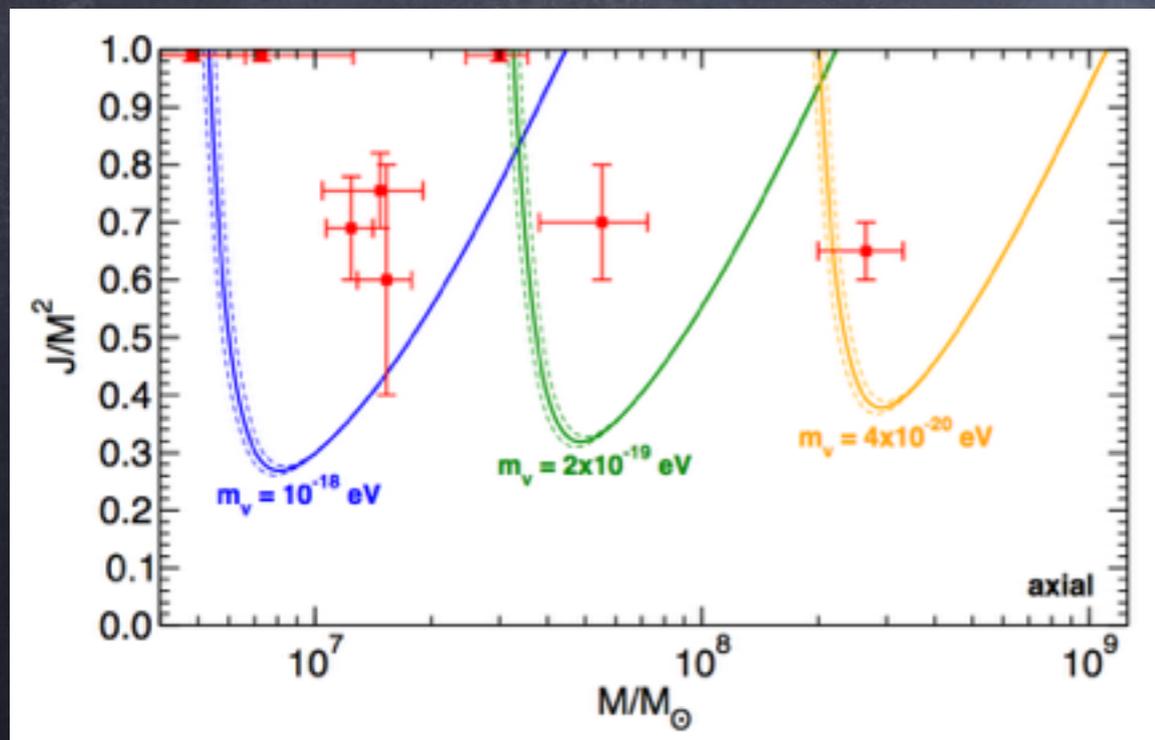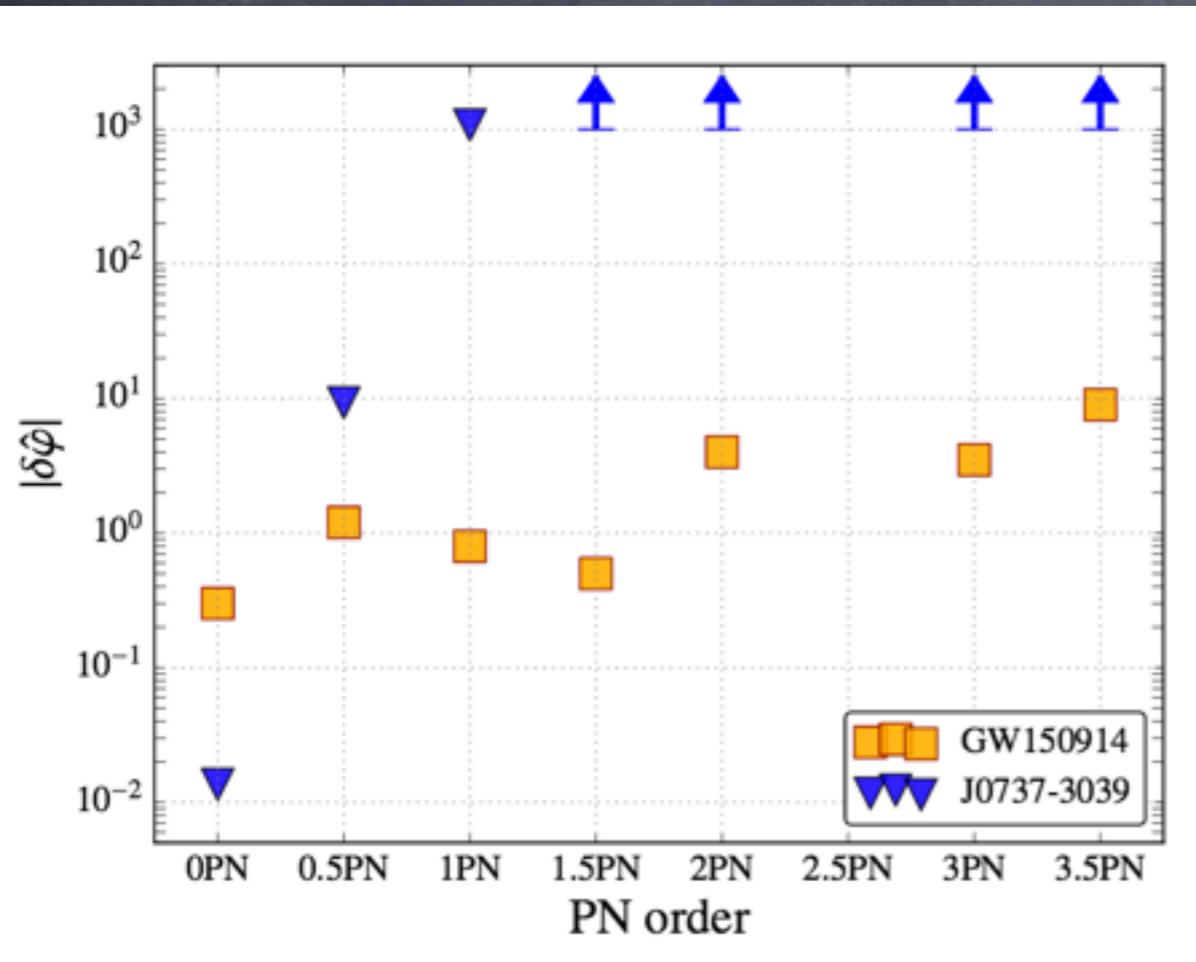


Pani et al 2012
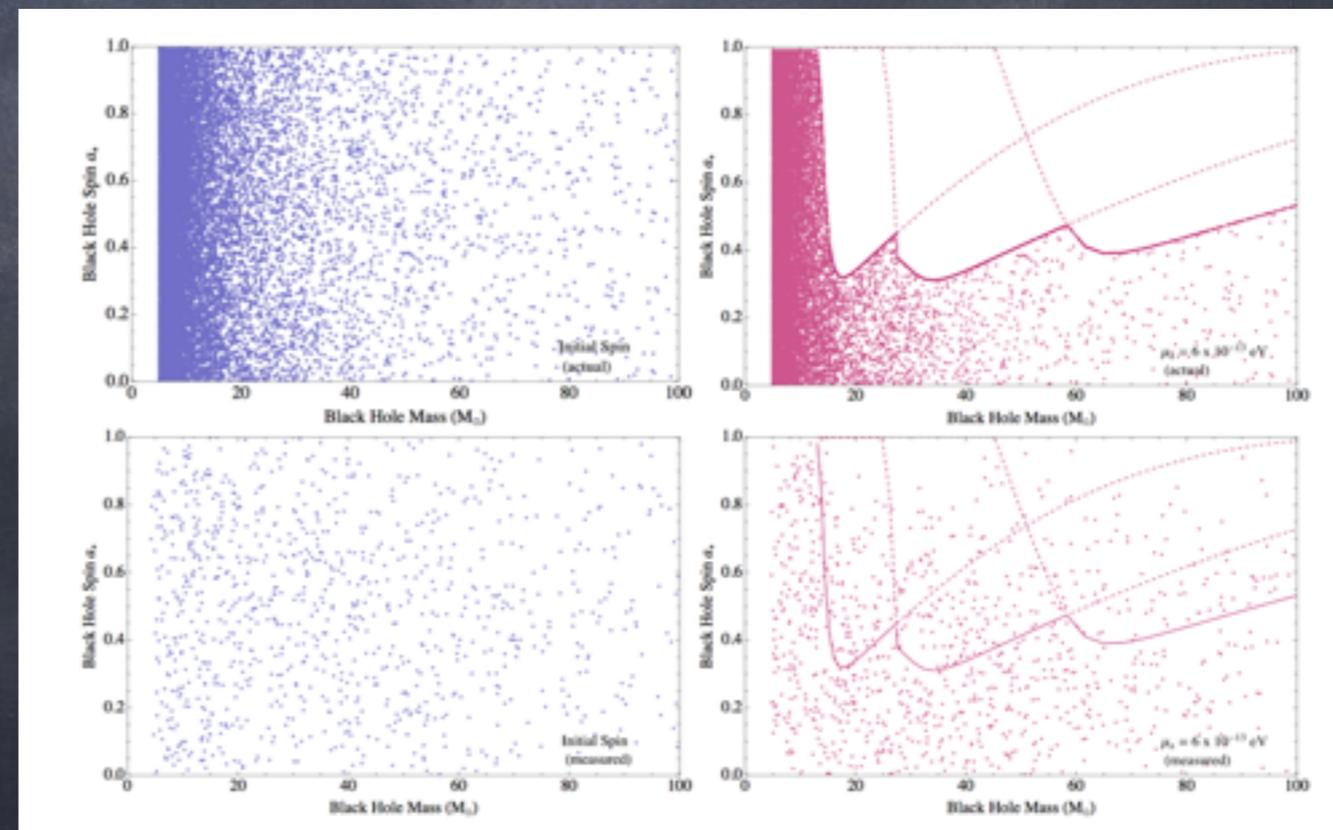
Arvanitaki et al 2016

# Can we learn something from GW150914's 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

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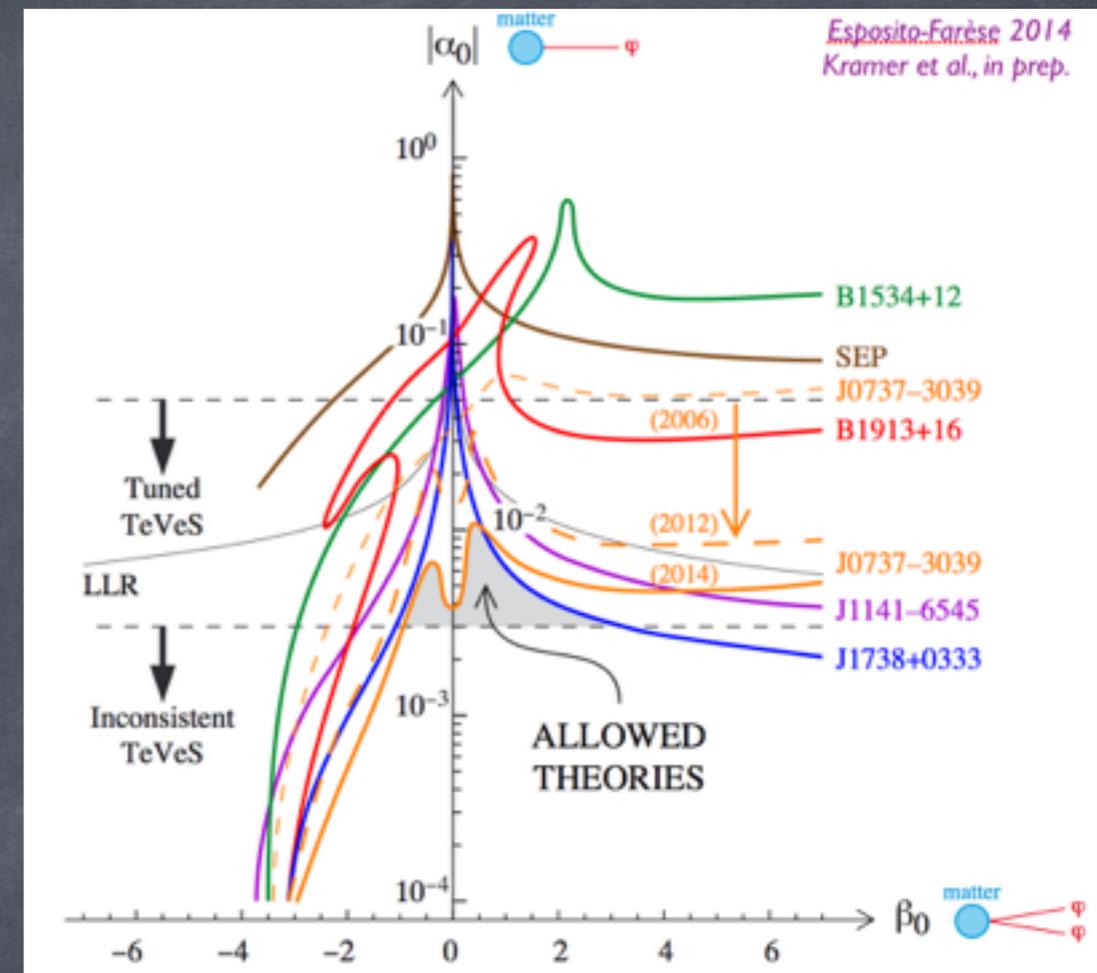
- Intrinsically non-linear dynamics: strong coupling when trying to recover GR at high accelerations

Bonetti & EB 2015
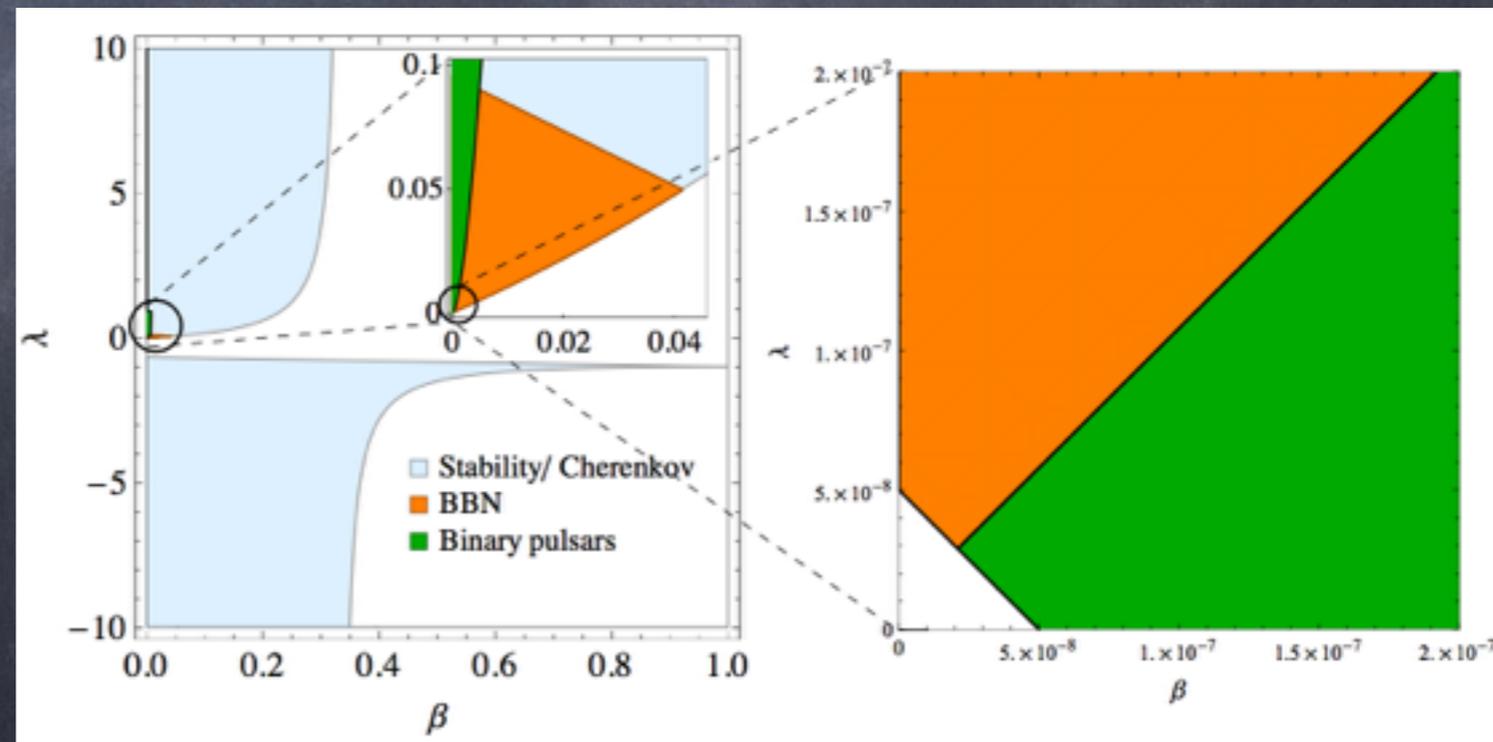
# Galileon/Horndeski screening

- Generalized Galileon action is most generic with 2nd order eqs

- Galleons also arise in massive gravity

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

$$\left. + G_5(\phi,X)G_{\mu\nu}\nabla^\mu\nabla^\nu\phi - \frac{1}{6}\partial_X G_5(\phi,X)\left[(\Box\phi)^3 - 3(\Box\phi)(\nabla_\mu\nabla_\nu\phi)^2 + 2(\nabla_\mu\nabla_\nu\phi)^3\right]\right\}$$

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

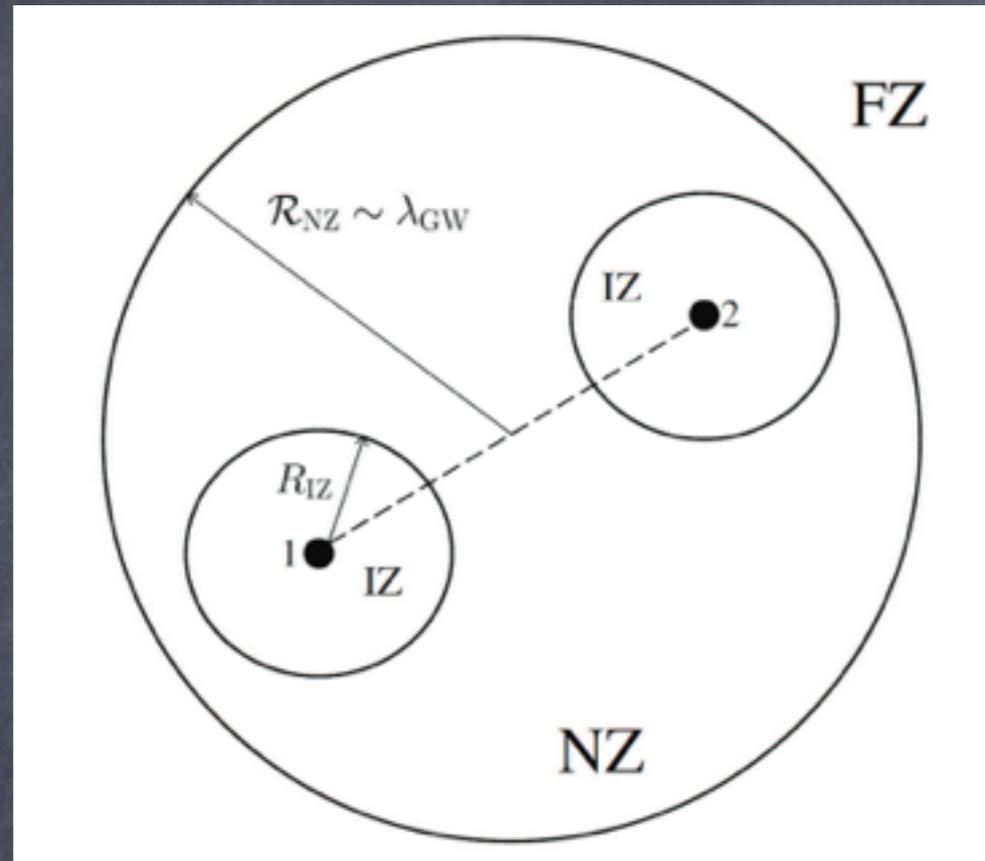- Non-linear field eqs allow "Vainshtein mechanism"

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

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

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)
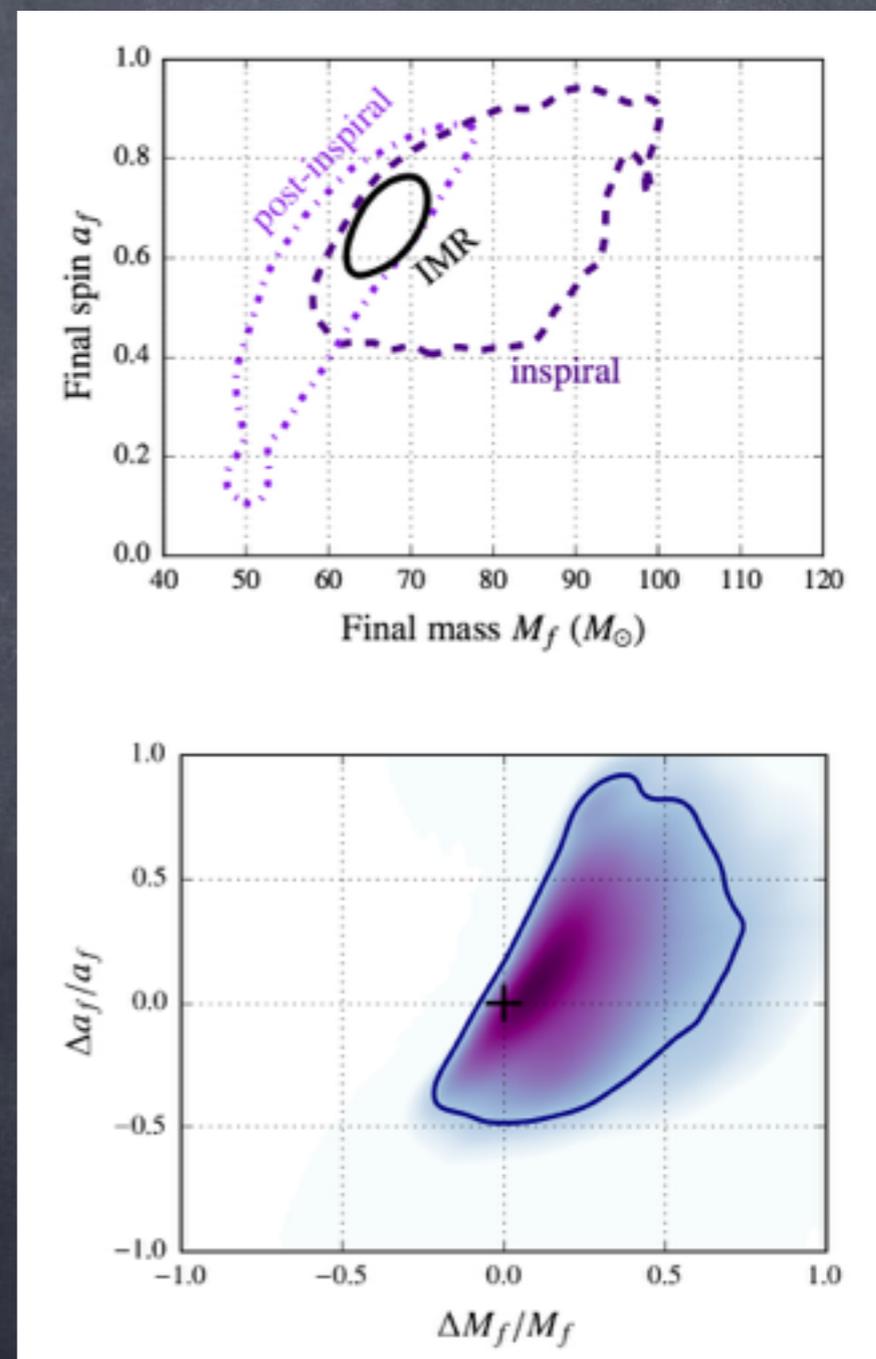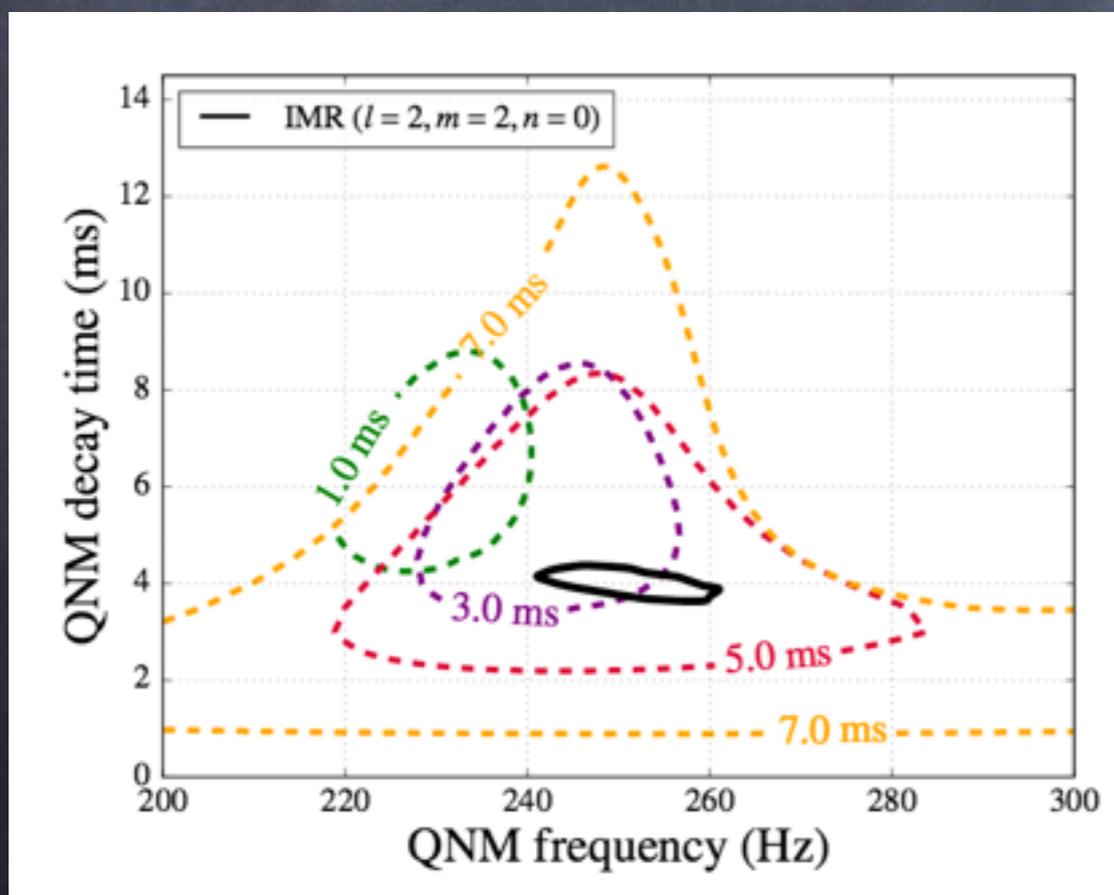
# (Future) ringdown tests

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

# 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"
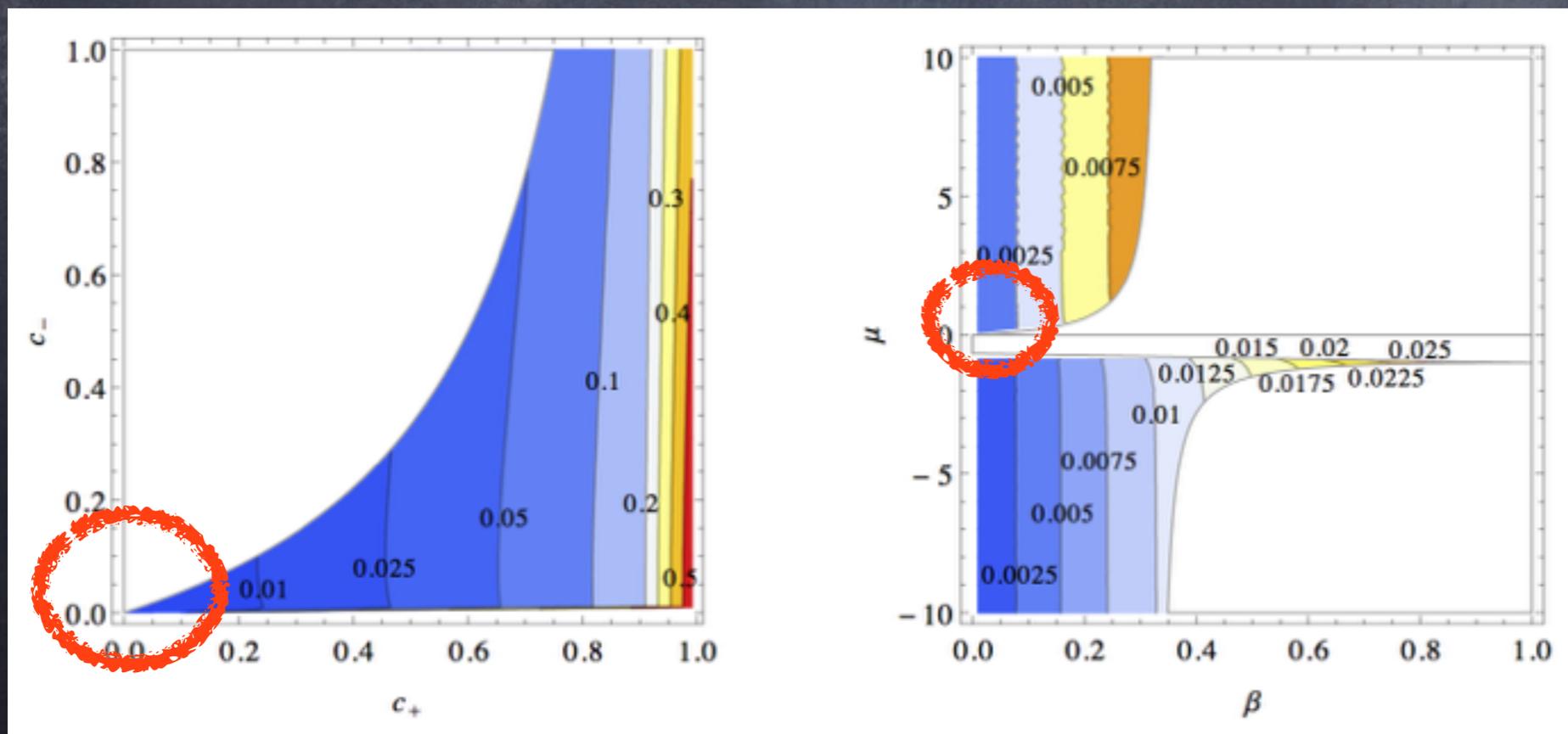


Eikonal limit fractional deviations from GR in LV gravity

EB, Jacobson & Sotiriou 2011

# 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 $r_0$
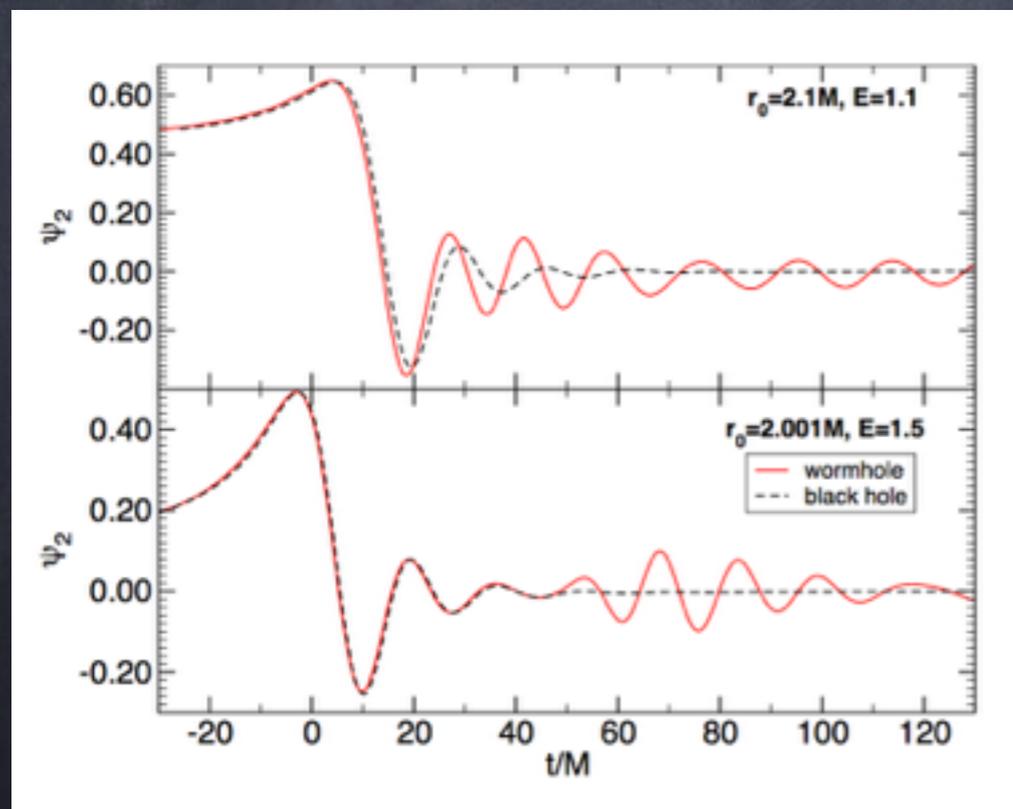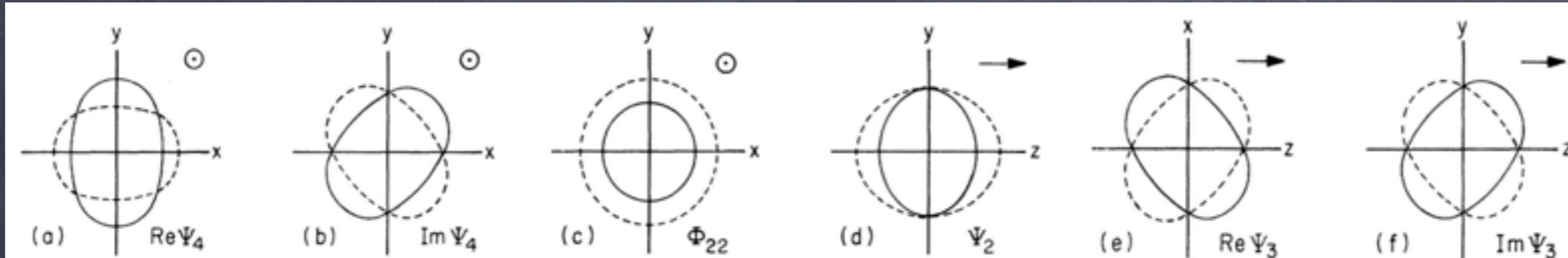


Cardoso, Franzin & Pani 2016
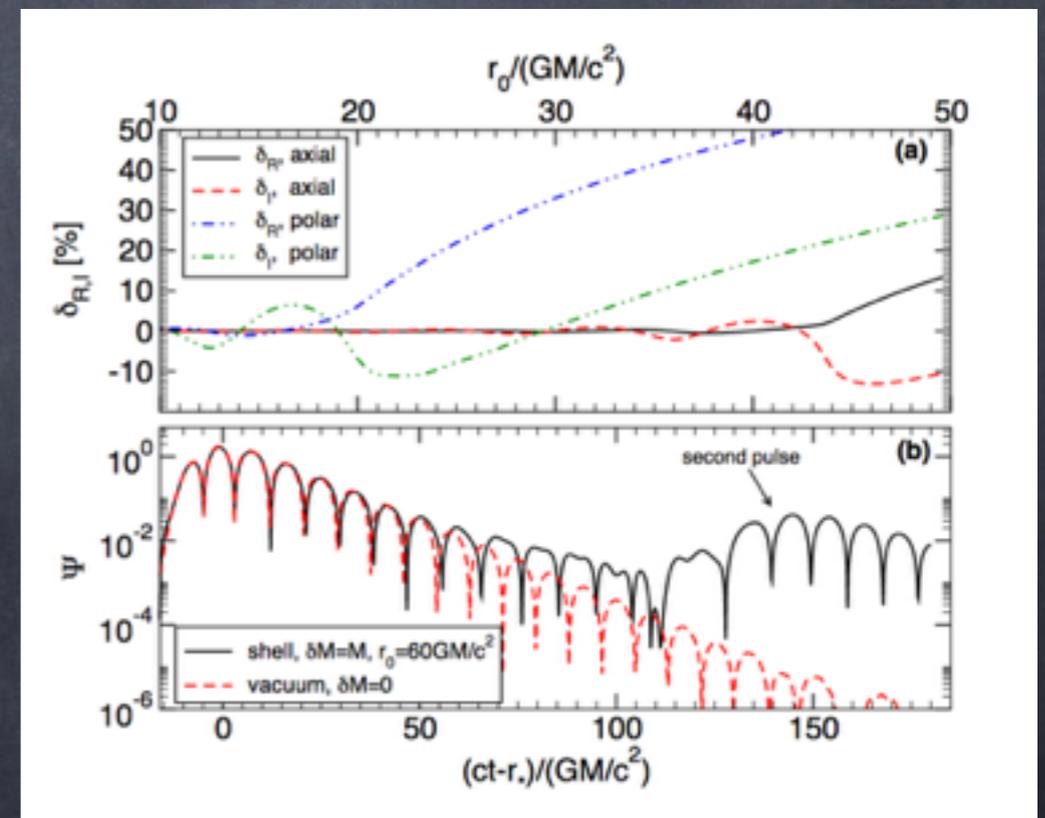
EB, Cardoso & Pani 2014

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

# 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
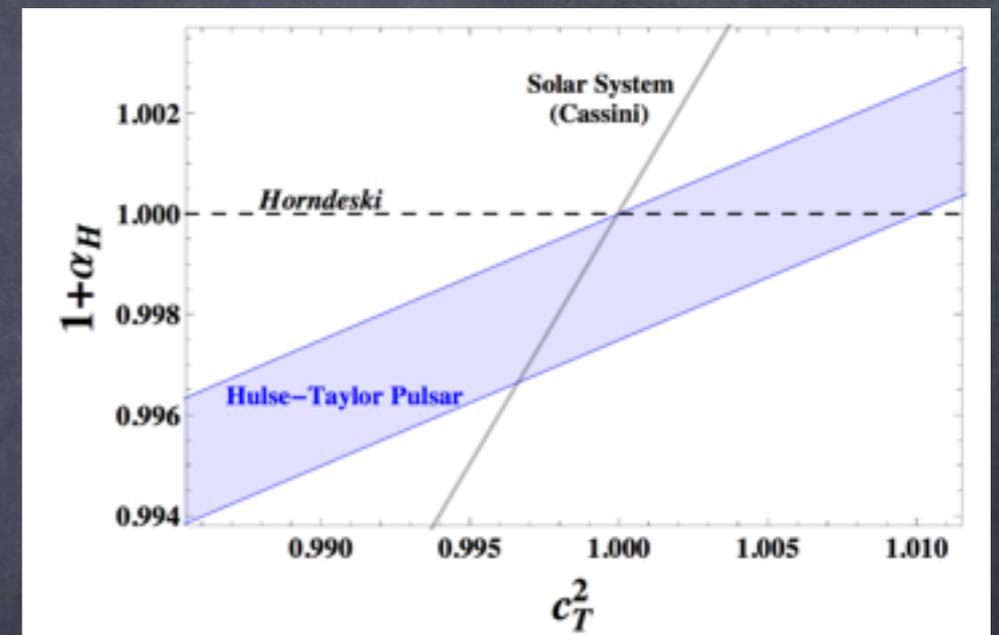


e.g. Horndeski/beyond-Horndeski theories (Jimenez, Piazza, Velten 2015)

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

# Propagation effects

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

- Generically predicted by quantum-gravity theories

- Pros: effects accumulate over distance, mappable to ppE phase term

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

- 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] | $-3$ | +1PN | |
| | | Double Special Relativity [131–134] | $+6$ | +5.5PN | $\beta_{\mathrm{MDR}}$ [115, 127] |
| | | Extra Dim. [135], Horava-Lifshitz [136–138] | $+9$ | +7PN | |

| Theoretical Mechanism | GR Pillar | PN | $\|\beta\|$ GW150914 | Repr. Parameters | Example Theory Constraints GW150914 | Example Theory Constraints Current Bounds |
|---|---|---|---|---|---|---|
| Massive graviton | massless graviton | $+1$ | $1.3\times10^{-1}$ | $m_g$ [eV] | $1.2\times10^{-22}$ [12] | $10^{-29}$–$10^{-18}$ [58–62] |
| Modified Dispersion Relation (*Modified Special Relativity*) | $v_g = c$ | $+5.5$ | $2.3\times10^{2}$ | $\mathbb{A} > 0$ [1/eV] | $1.6\times10^{-7}$ | — |
| | | $+5.5$ | $2.3\times10^{2}$ | $\mathbb{A} < 0$ [1/eV] | $1.6\times10^{-7}$ | $2.7\times10^{-36}$ [63] |
| Modified Dispersion Relation (*Extra Dimensions*) | $v_g = c$ | $+7$ | $8.7\times10^{2}$ | $\mathbb{A} > 0$ [1/eV$^2$] | $9.3\times10^{4}$ | — |
| | | $+7$ | $8.7\times10^{2}$ | $\mathbb{A} < 0$ [1/eV$^2$] | $9.3\times10^{4}$ | $4.6\times10^{-56}$ [63] |
| Modified Dispersion Relation (*Lorentz Violation*) | SEP, Lorentz Invariance | — | — | $c_+$ | $0.7$ [64] | $(0.03, 0.003)$ [46, 47] |

# Conclusions

- GR extensions already tightly constrained by binary pulsars/ solar system

- Direct GW detections push tests to more extreme regimes/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

# Conclusions

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Thank you!