Black holes beyond GR

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Talk outline

- How to go beyond GR?
- BH charges beyond GR:

  - perturbative vs non-perturbative generation
  - violations of the strong equivalence principle
  - implications for GW (inspiral, ringdown) and EM (eg EHT)

- Near horizon deviations from GR (superradiance, “firewalls”, universal horizons/Lorentz violations)
- Non-stationary dynamics

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

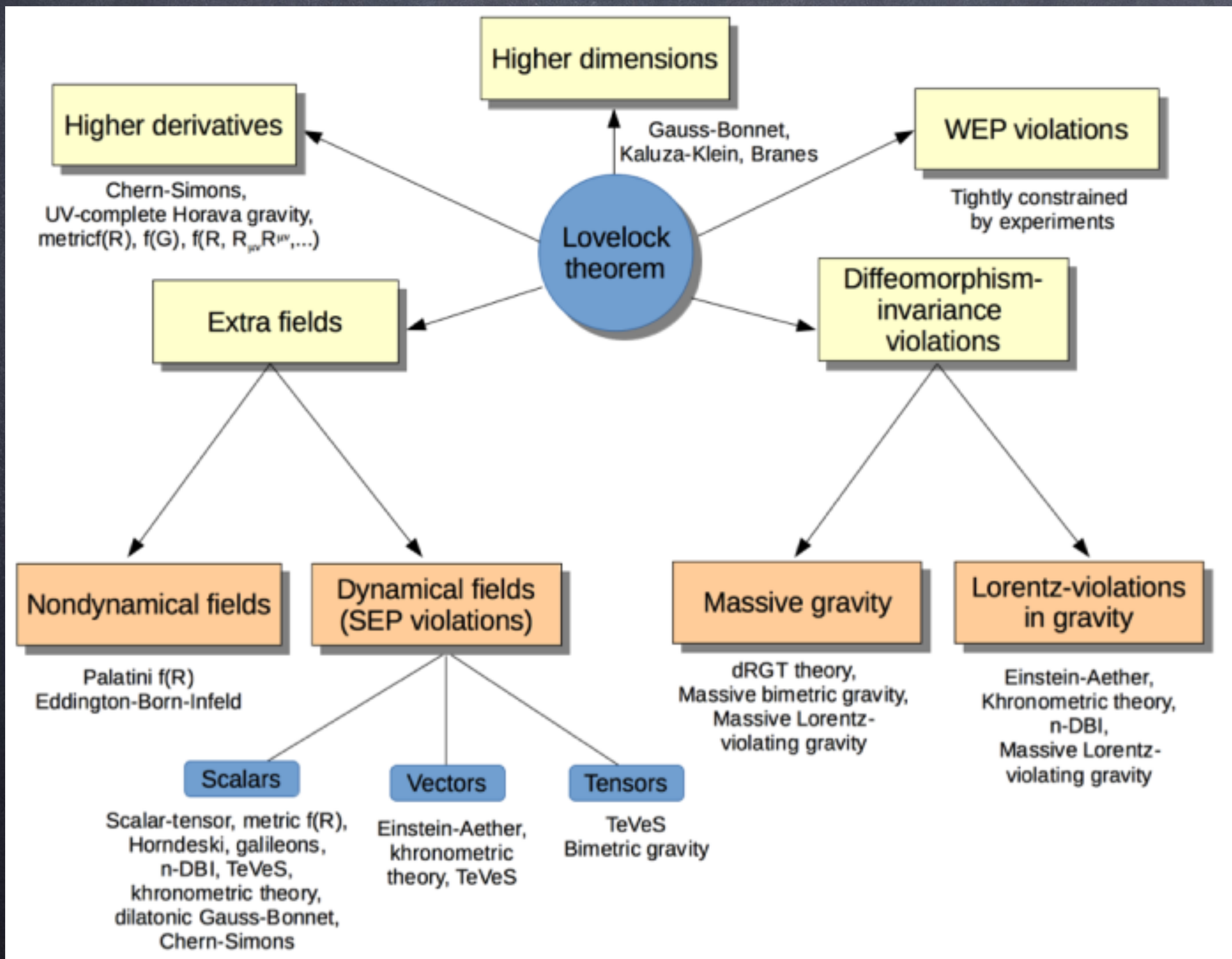


Figure adapted from Berti, EB et al 2015

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, monopole and dipole GW emission, modified quadrupole formula

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

Dipole emission dominant for quasi-circular systems;
1.5 PN vs 2.5 PN in GR (= -1 PN)! But effect depends on nature of bodies

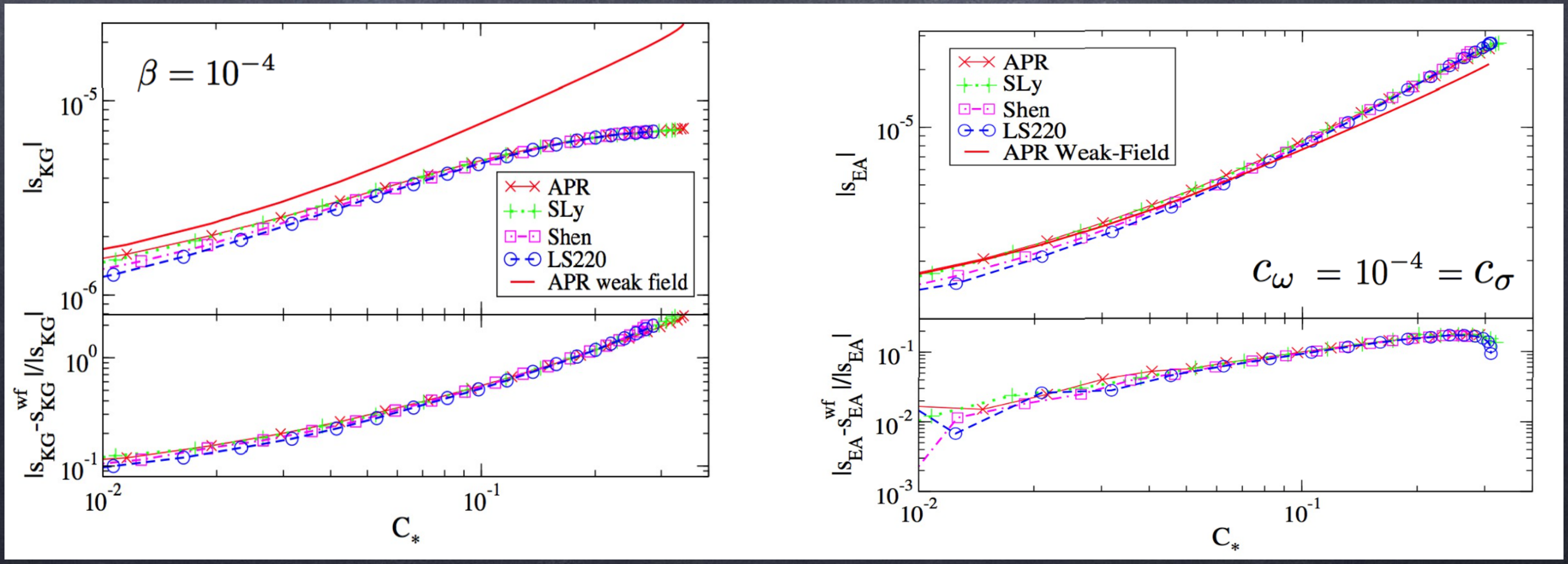
Tests of dipolar emission with GWs

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

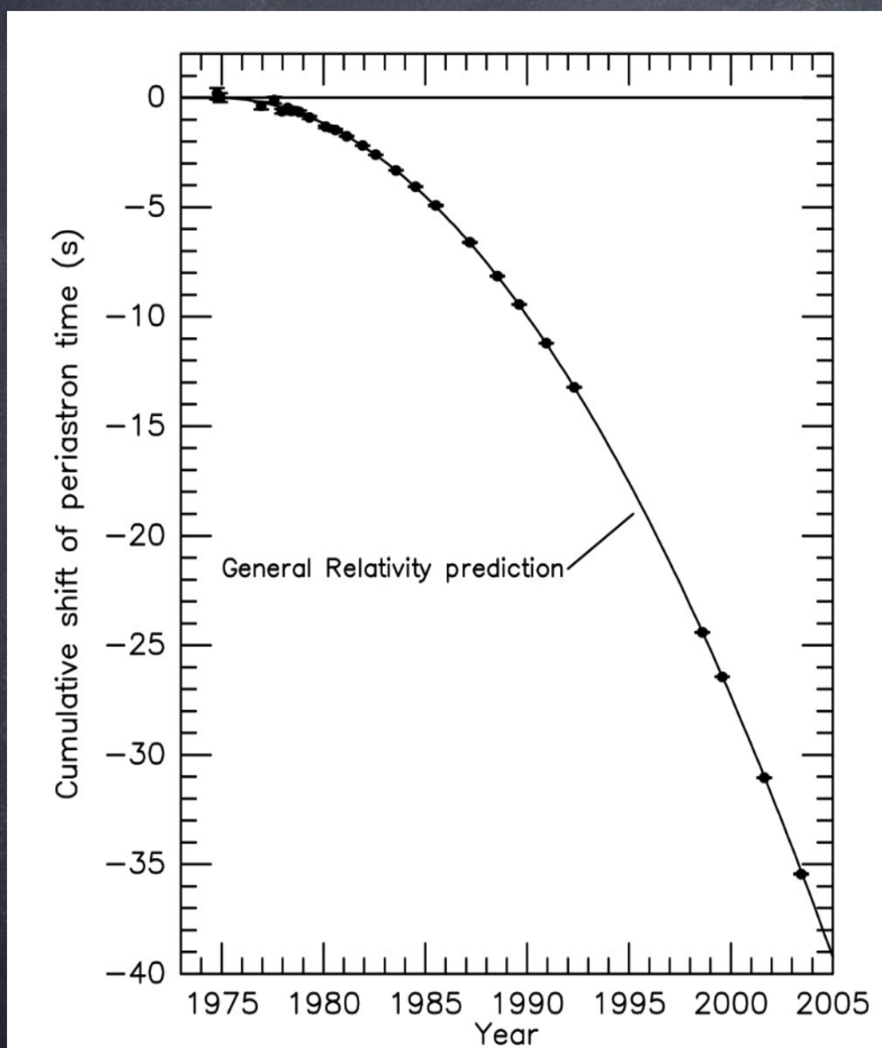
- Since they are response to field boundary conditions, need to calculate compact-object solution for different boundary conditions

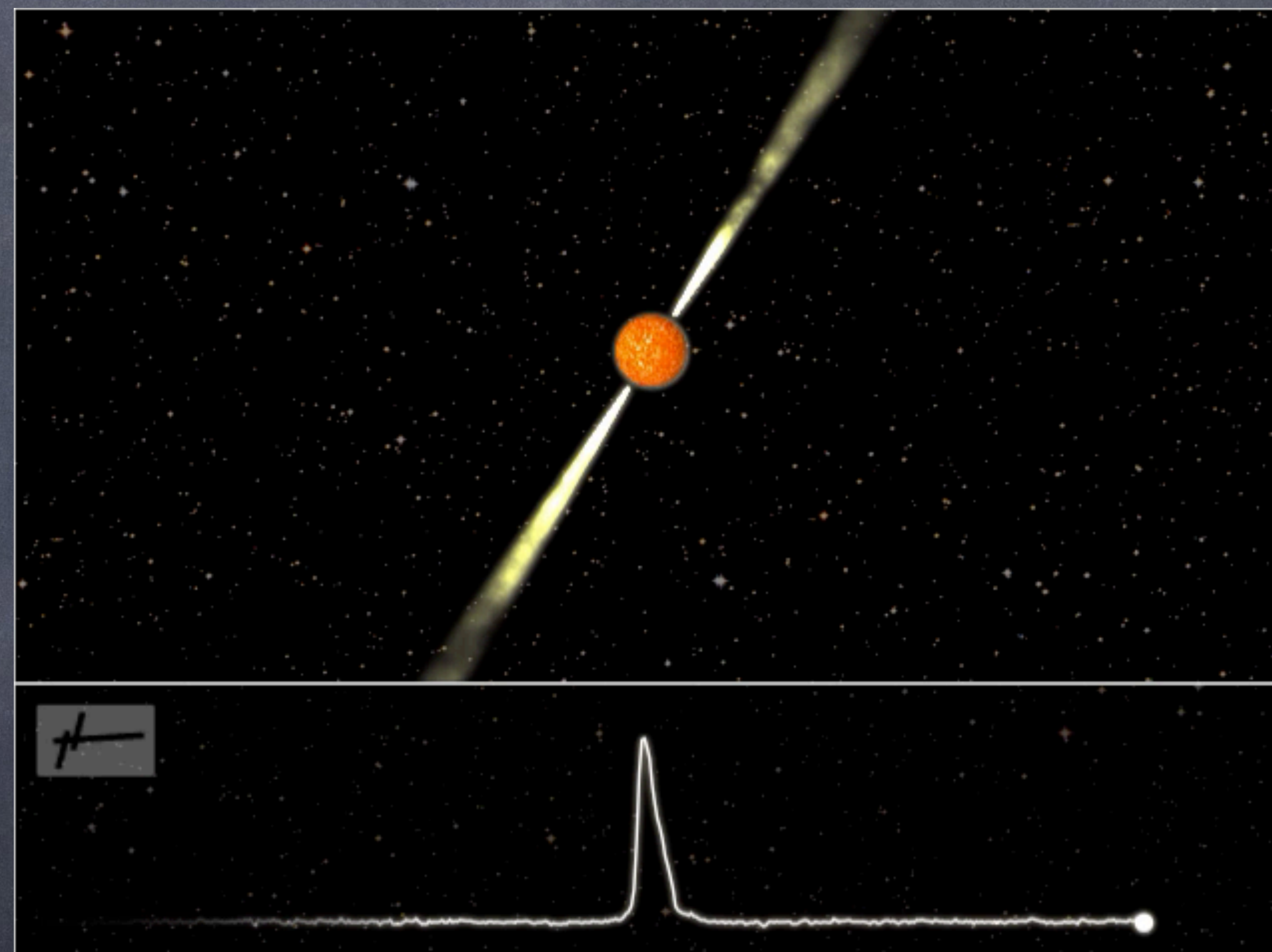
- Calculation needs to be done exactly (no extrapolation of weak field approximation) and (for NS) for different EOS's

Example: NS sensitivities in Lorentz violating gravity (Yagi, Blas, EB and Yunes et al 2014, Ramos & EB 2018; EB 2019)



(Absence of) dipole emission in binary pulsars

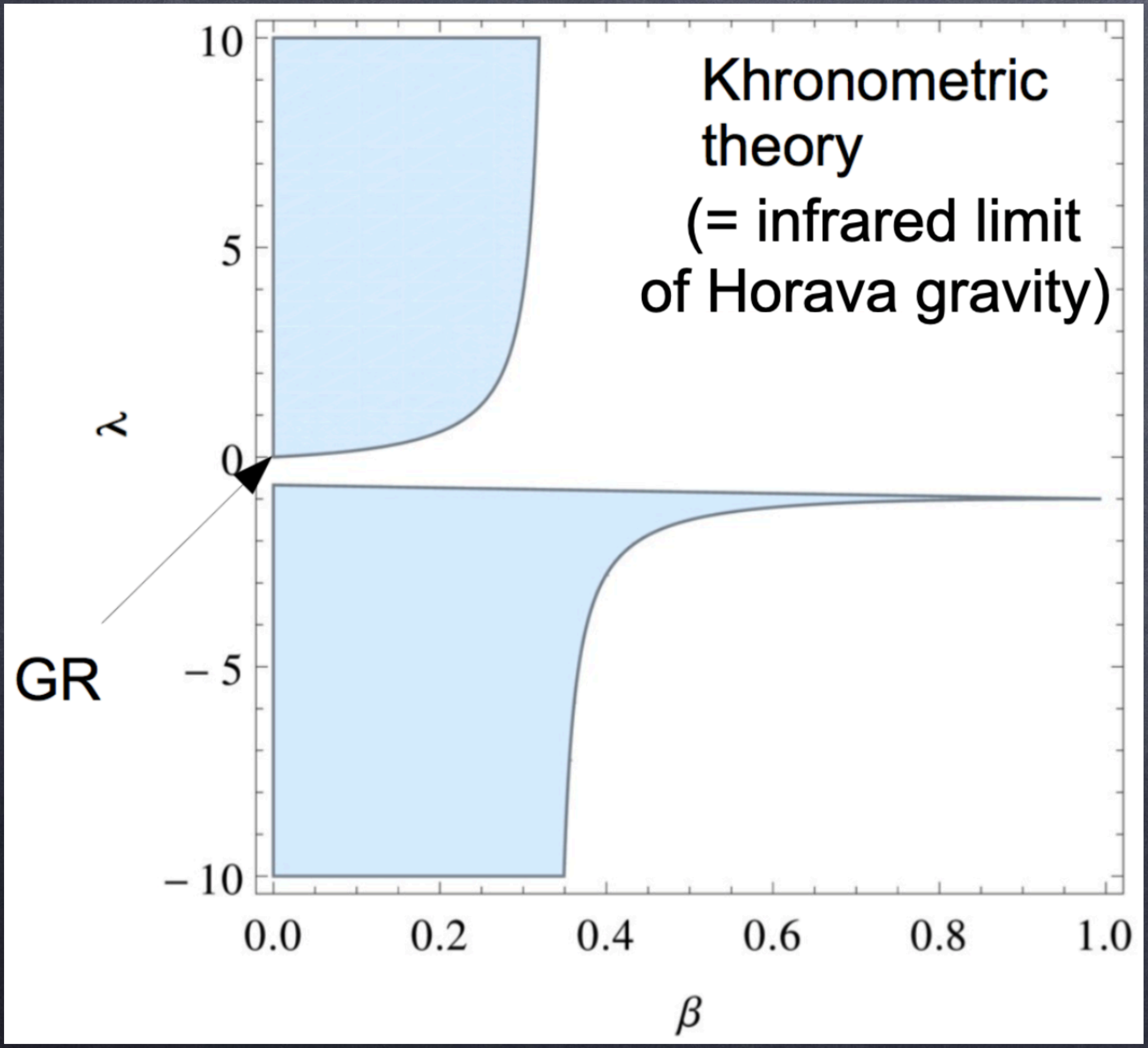




Credits: Joeri van Leeuwen

(Absence of) dipole emission in binary pulsars

An example: Lorentz-violating gravity



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

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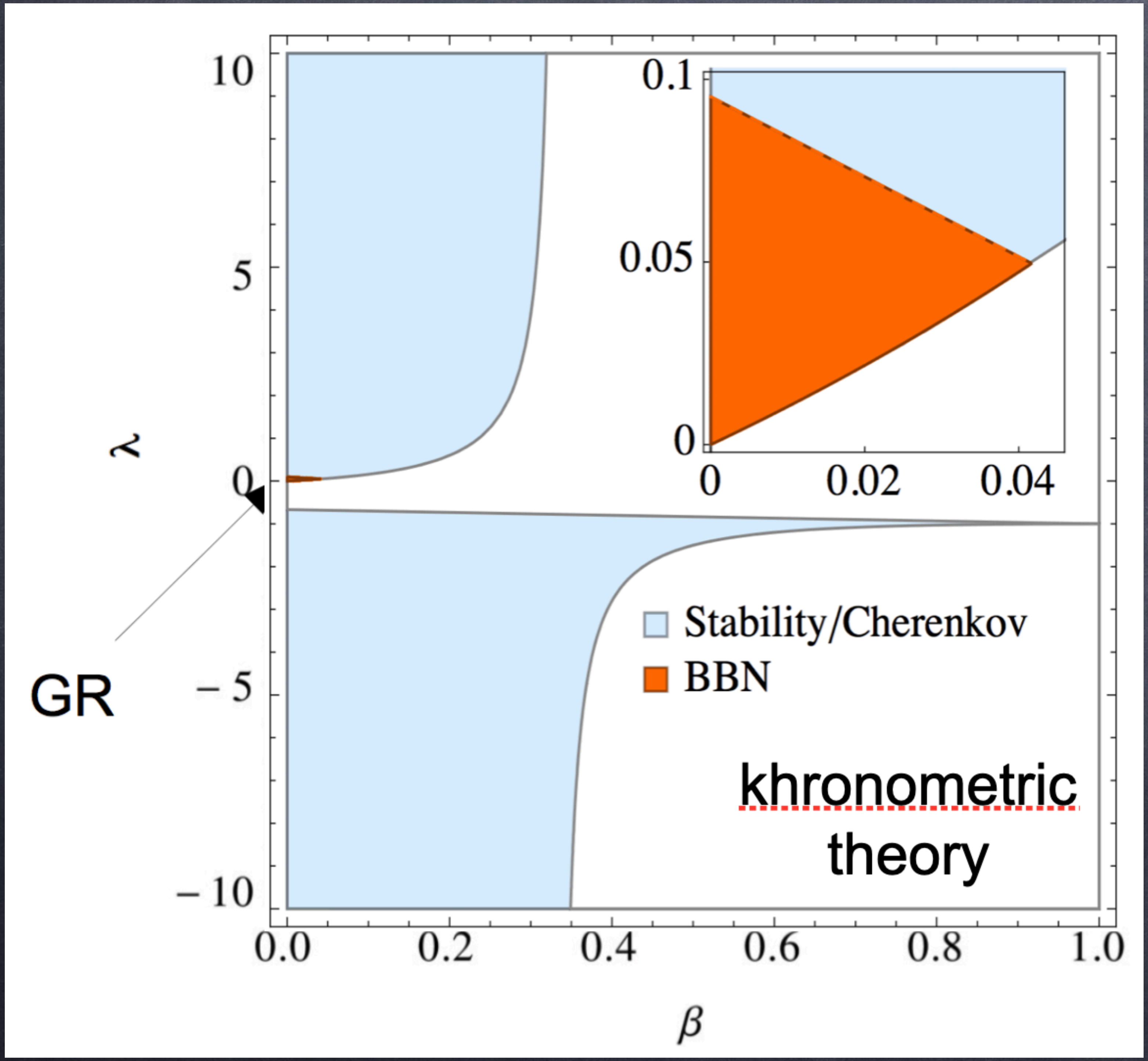

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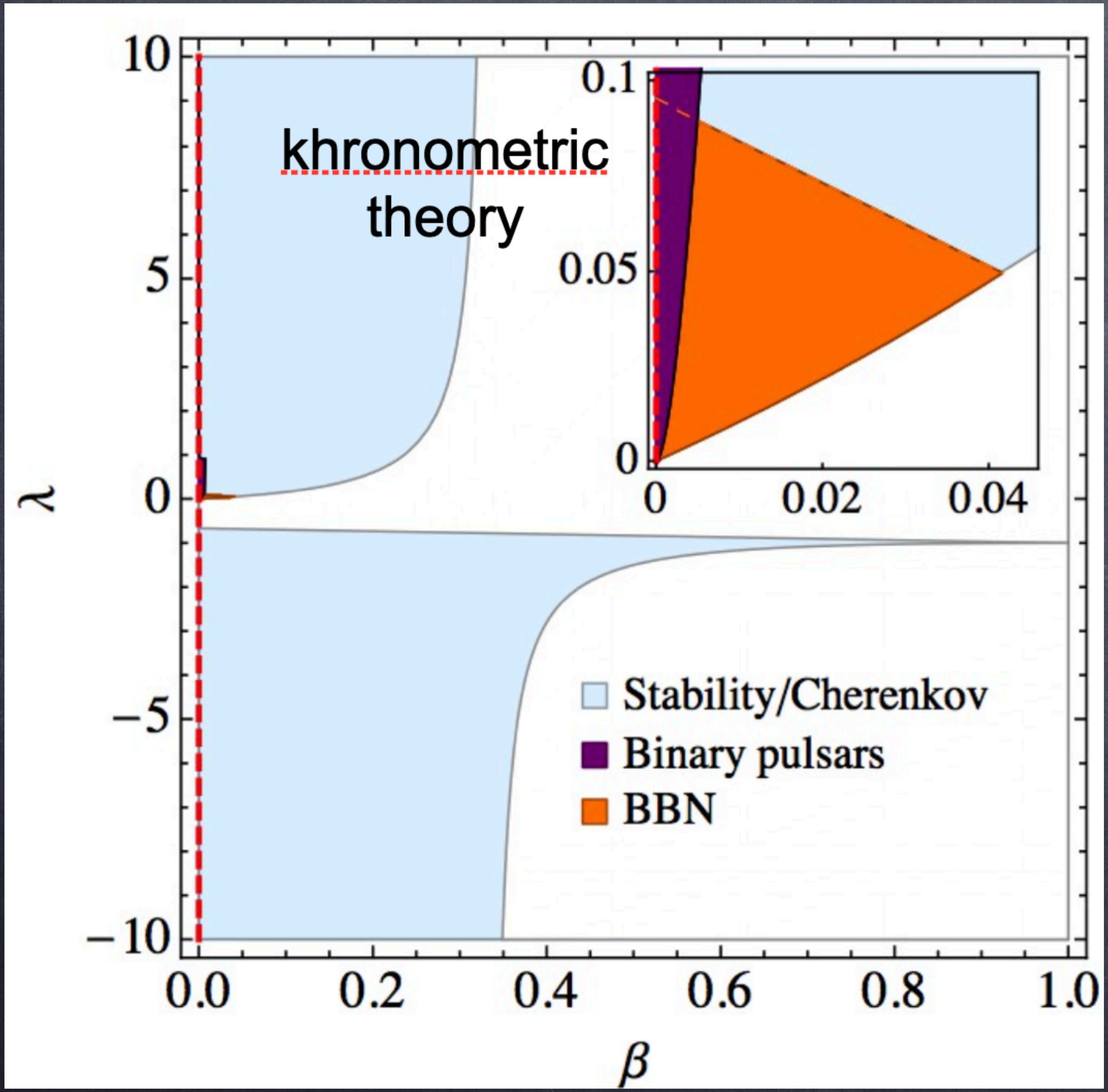

No ghosts+no gradient instabilities+solar system tests+absence of vacuum Cherenkov (to agree with cosmic rays)+BBN+pulsars +GW170817

Yagi, Blas, EB & Yunes 2014
Ramos & EB 2018, EB 2019

(Absence of) dipole 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") for $\beta < 0$

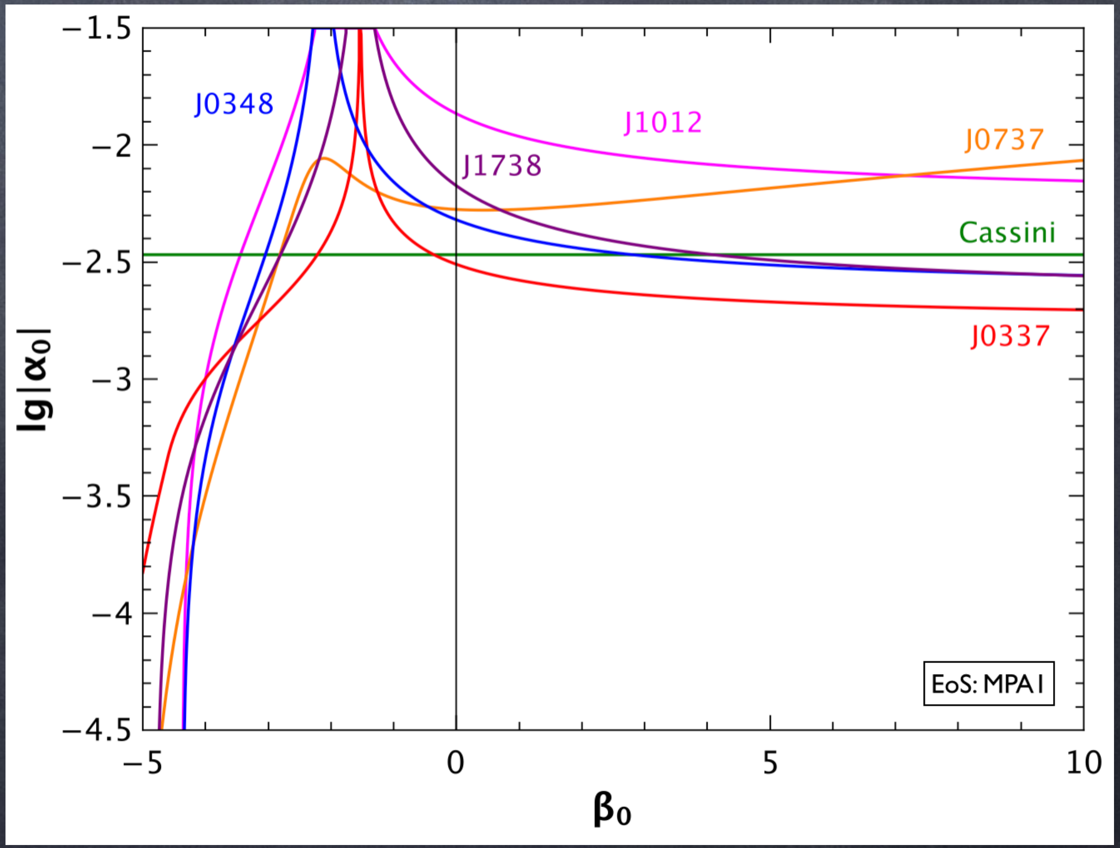

Fig. credits: N. Wex, private comm.

Spontaneous scalarization as phase transition/tachyonic instability

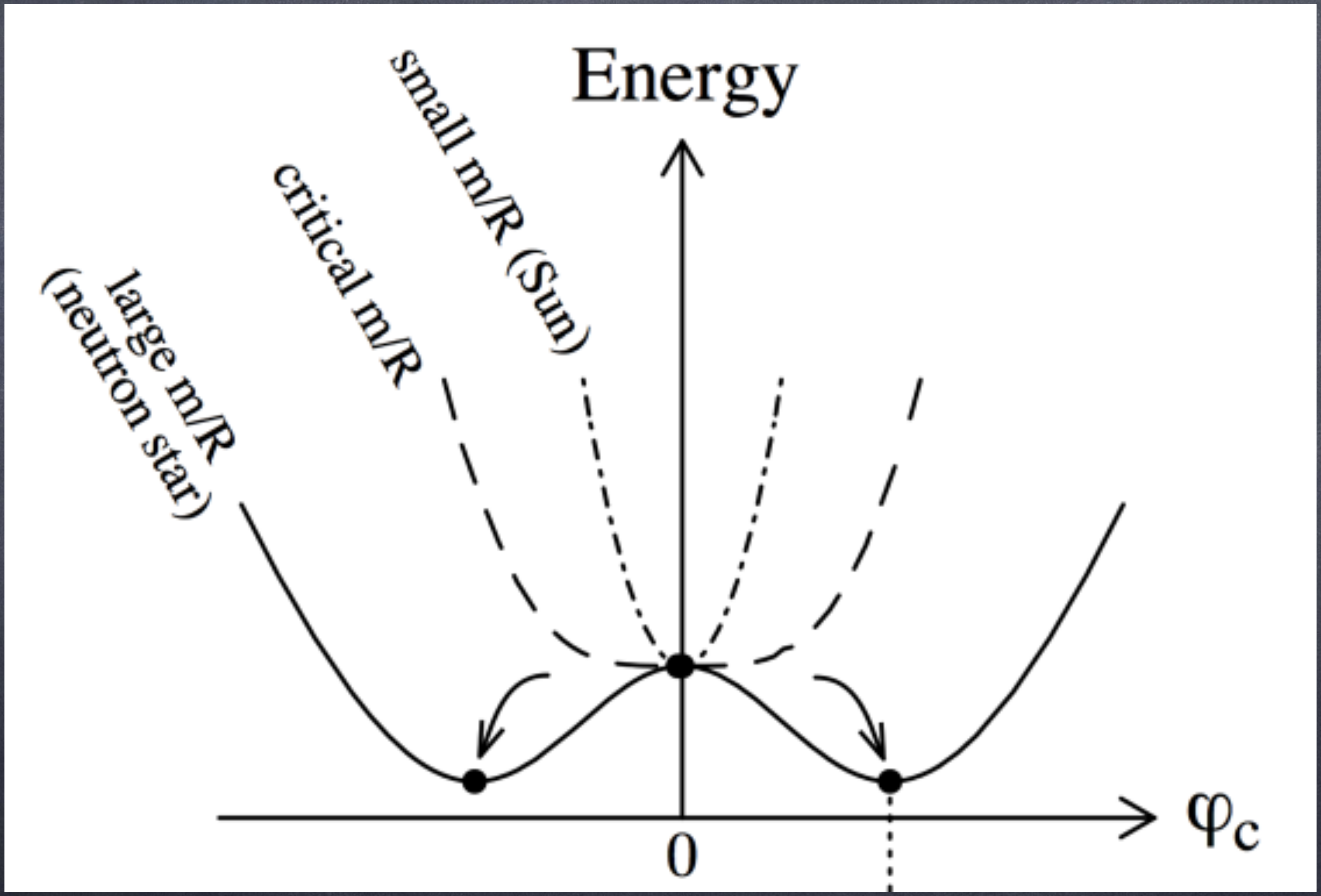

Figure from Esposito-Farese, gr-qc/0402007

Dipole 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 et al 2015)

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

Spontaneous BH scalarization

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

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

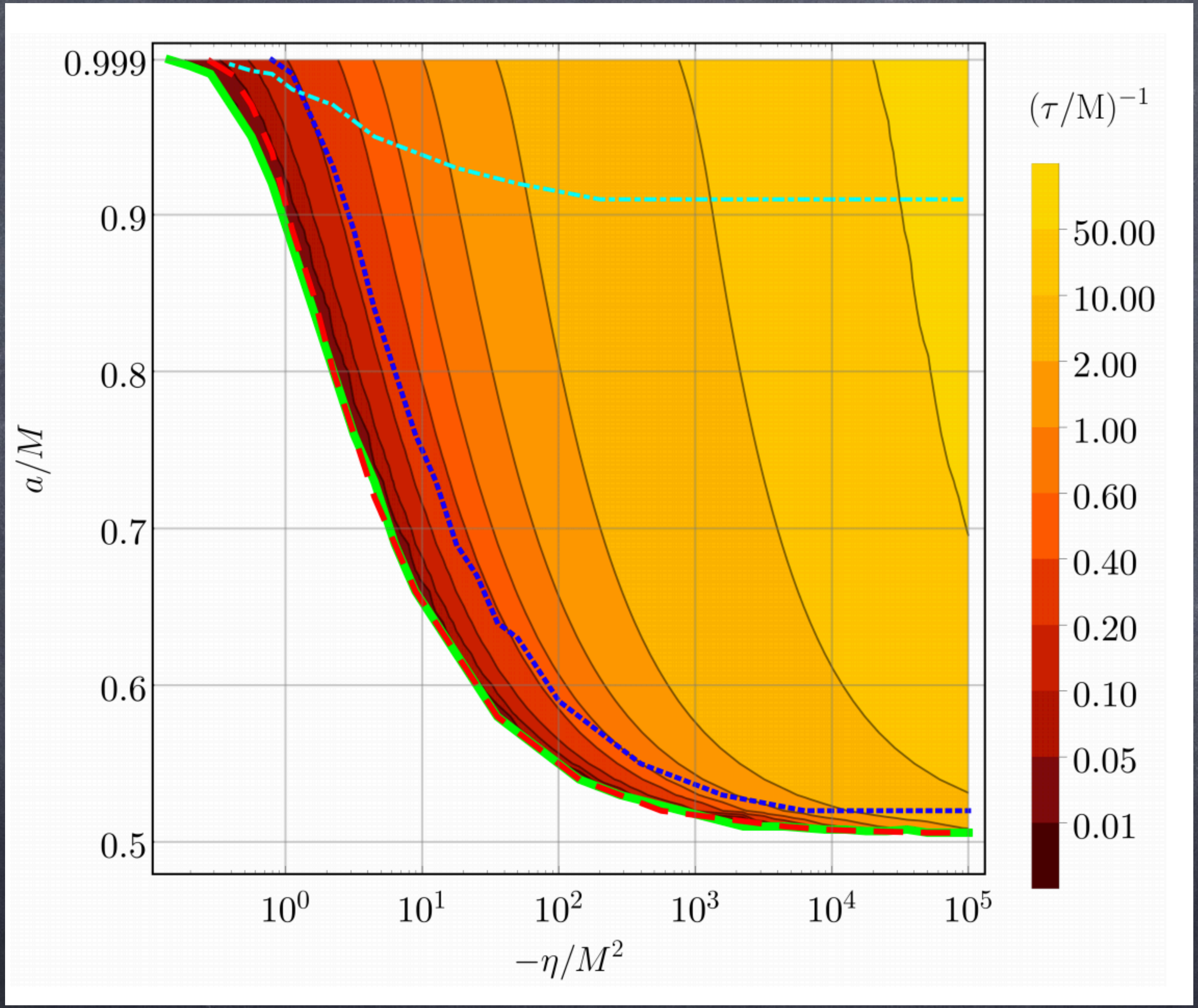
- If f_2, f_3 or f_4 are quadratic in φ ($\sim\eta\,\varphi^2/2$), effective mass term $m^2\varphi^2/2$ with m^2 given by $-\eta K$, $-\eta\, {}^*RR$ or $-\eta\, G$

- If $\varphi = 0$, action and BH solutions match GR (Schwarzschild, Kerr)

- According to sign of K,*RR or G , mass term can become tachyonic: eg in Schwarzschild $G = 48\, M^2/r^6$ so $\eta>0$ gives instability. Endpoint is scalarized BH (Silva+2018, Doneva & Yazadjiev 2018, Herdeiro+2018, etc) with scalar charge

- Even for $\eta<0$, tachyonic instability can occur at high spins: G changes sign when going from Schwarzschild to Kerr (Dima, EB, Franchini & Sotiriou 2020)

Spontaneous BH scalarization triggered by spin



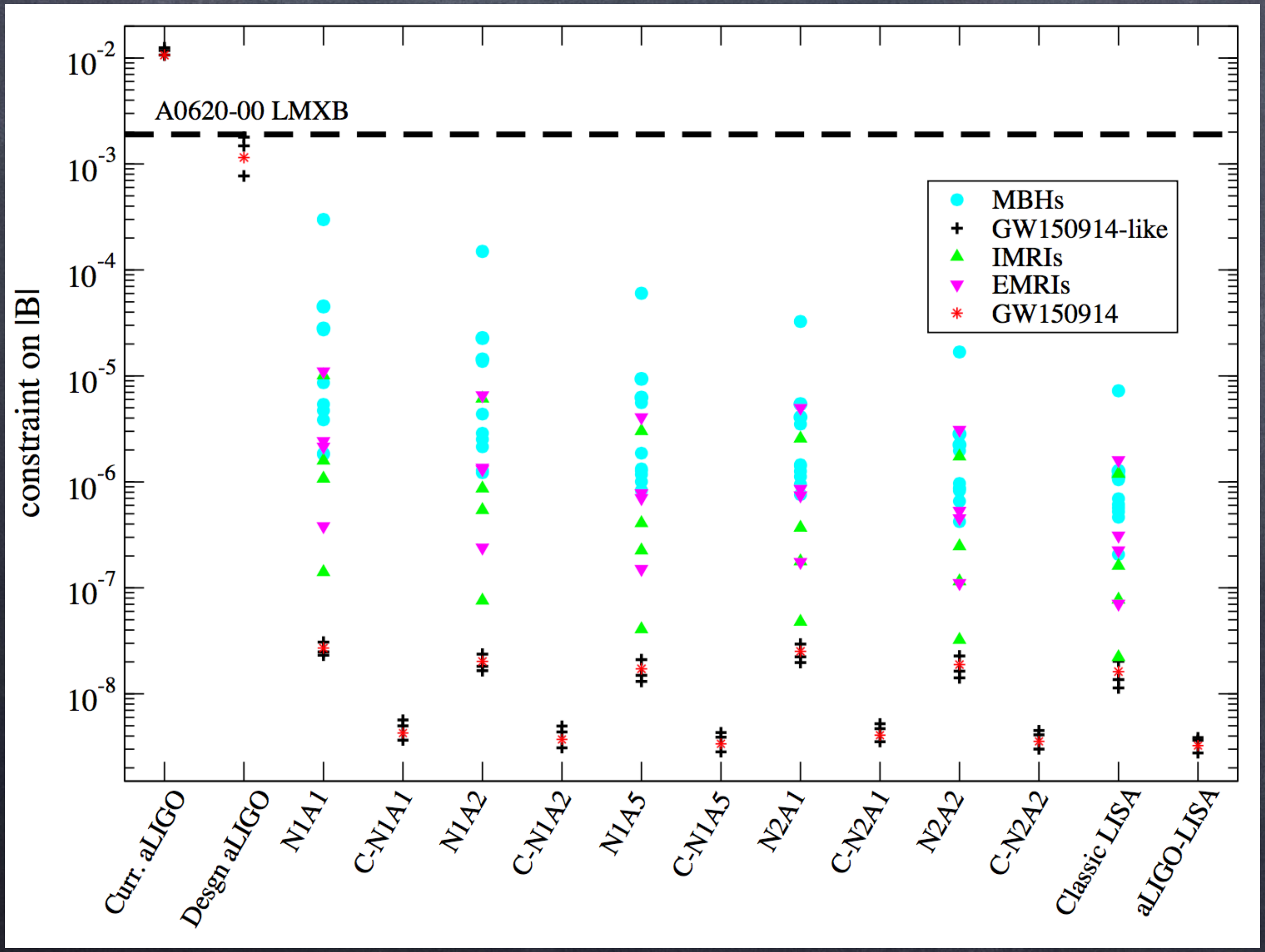
$$\mathcal{G} = \frac{48M^2}{(r^2+\chi^2)^6}\left(r^6 - 15r^4\chi^2 + 15r^2\chi^4 - \chi^6\right) \qquad \chi = a\cos\theta$$

Dima, EB, Franchini & Sotiriou 2020

Tests of BH-BH dipole emission

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

Pulsars constrain |B| ≲ 2 x 10^{-9}, GW150914-like systems + LISA will constrain same dipole term in BH-BH systems to comparable accuracy



EB, Yunes & Chamberlain 2016

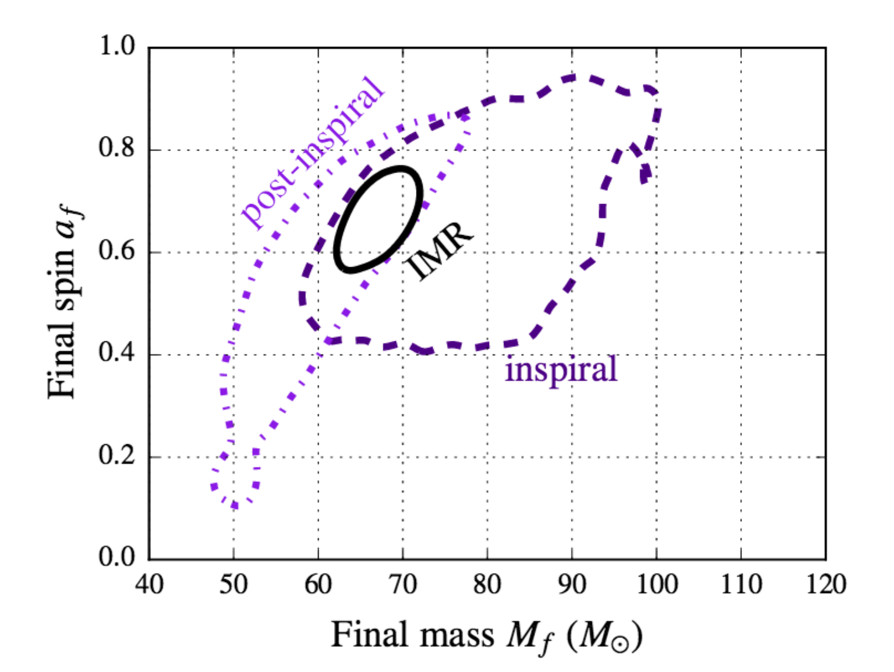
Toubiana, Marsat, Babak, EB & Baker 2020

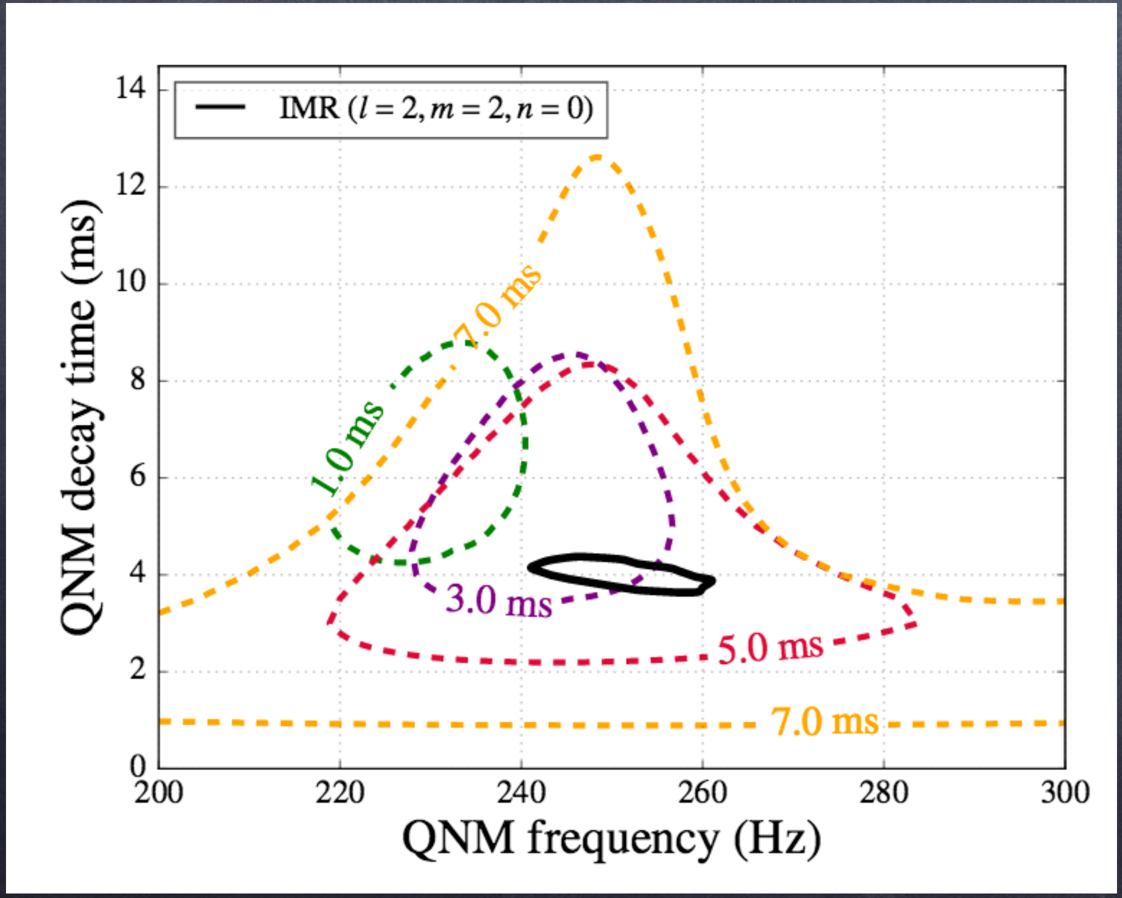
Ringdown tests

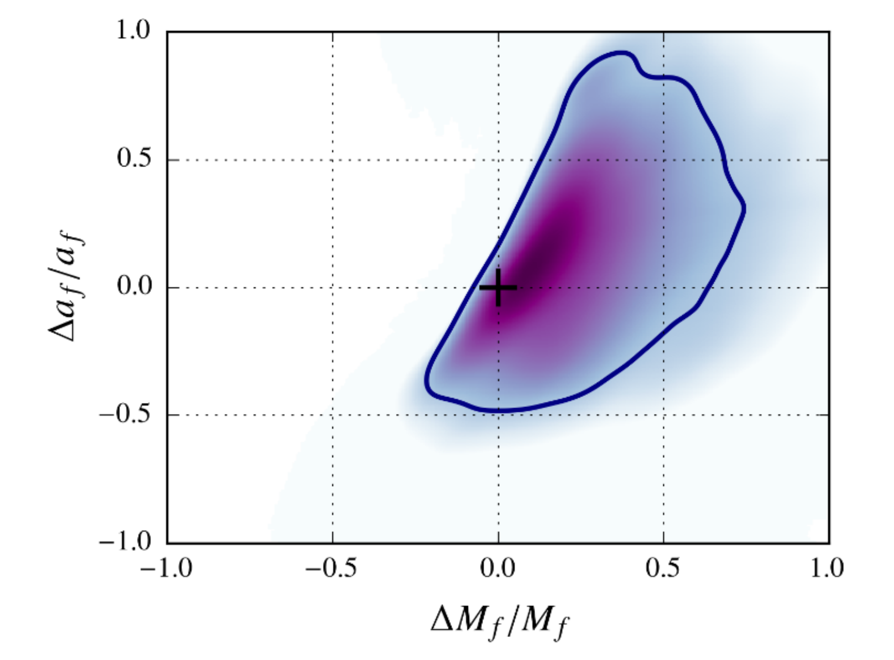
Tests of the no-hair theorem:

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

Difficult with advanced detectors because little SNR in ringdown (Berti+EB+16) but higher overtones may help (Giesler+19)





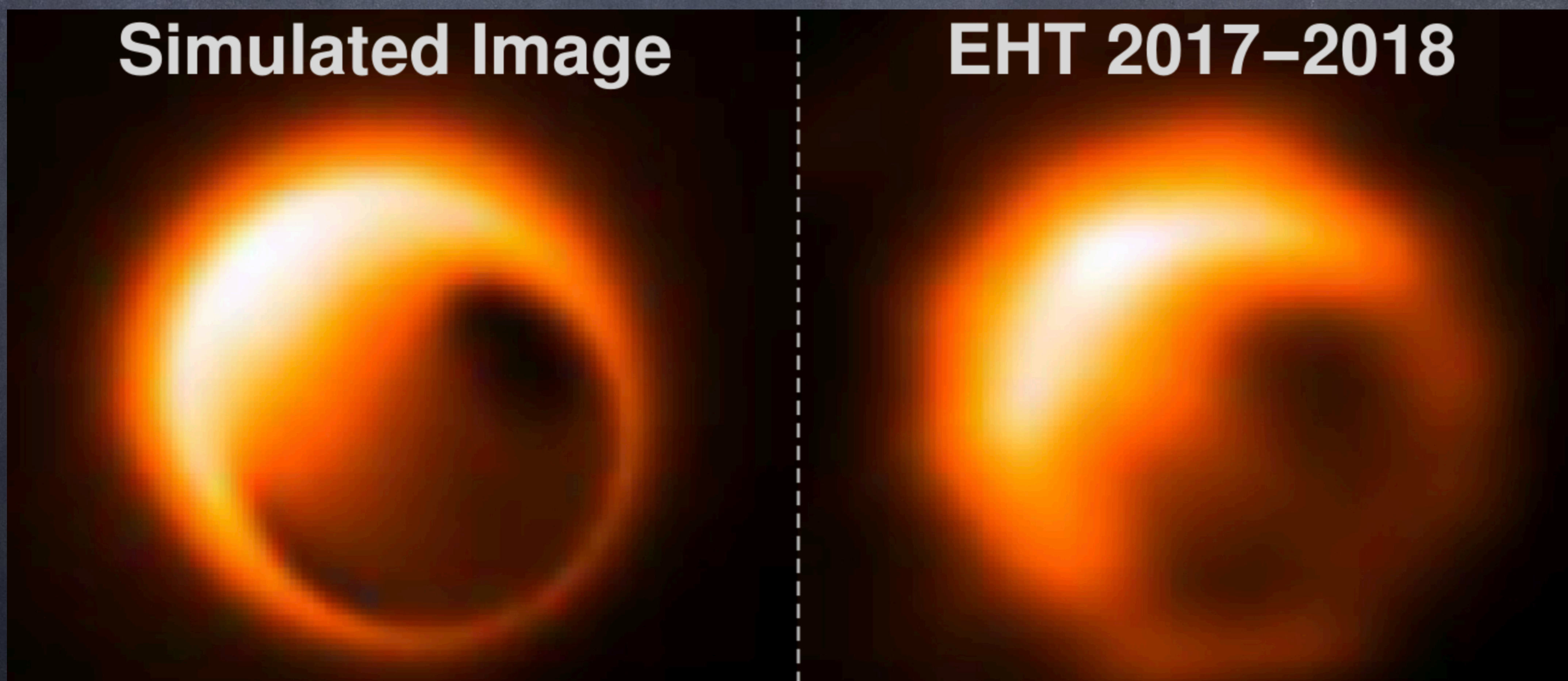


BH shadows and QNMs

- QNMs connected to prograde circular photon orbit frequency ω and Lyapunov coefficient λ (i.e. curvature of geodesics effective potential) in geometric optics limit!

$$\omega_{ln}^{m=l} \approx l\omega_{+} - i\lambda_{+}(n+1/2)$$

- Same physics as EHT observations of M87*



Imaging a Black Hole. At left is a model image for Sgr A* using a semi-analytic accretion flow (Broderick et al. 2011). Light is gravitationally lensed by the black hole to form a distinctive "ring" encircling the black hole's "shadow" (Falcke et al. 2000). The ring diameter is ~5 Schwarzschild radii . The image is bright on the approaching side of the accretion disk and faint on the receding side because of Doppler effects. At right, a sample image shows expected EHT performance in 2017-2018 (Fish, Johnson, et al. 2014).

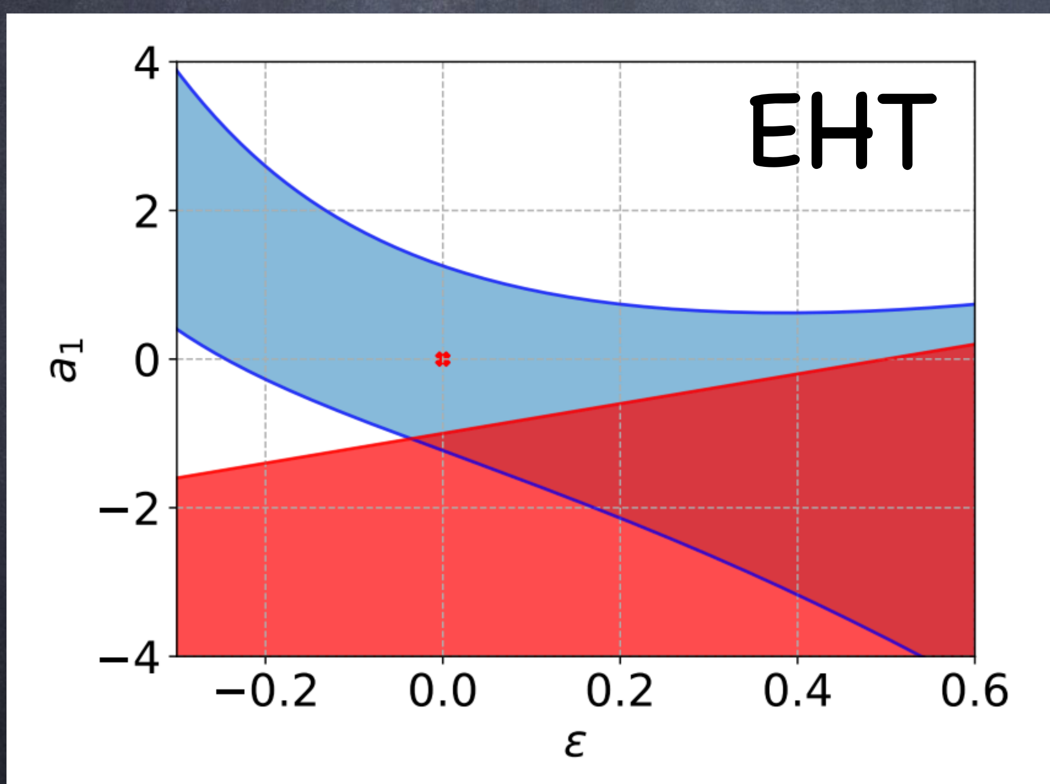
BH shadows and QNMs

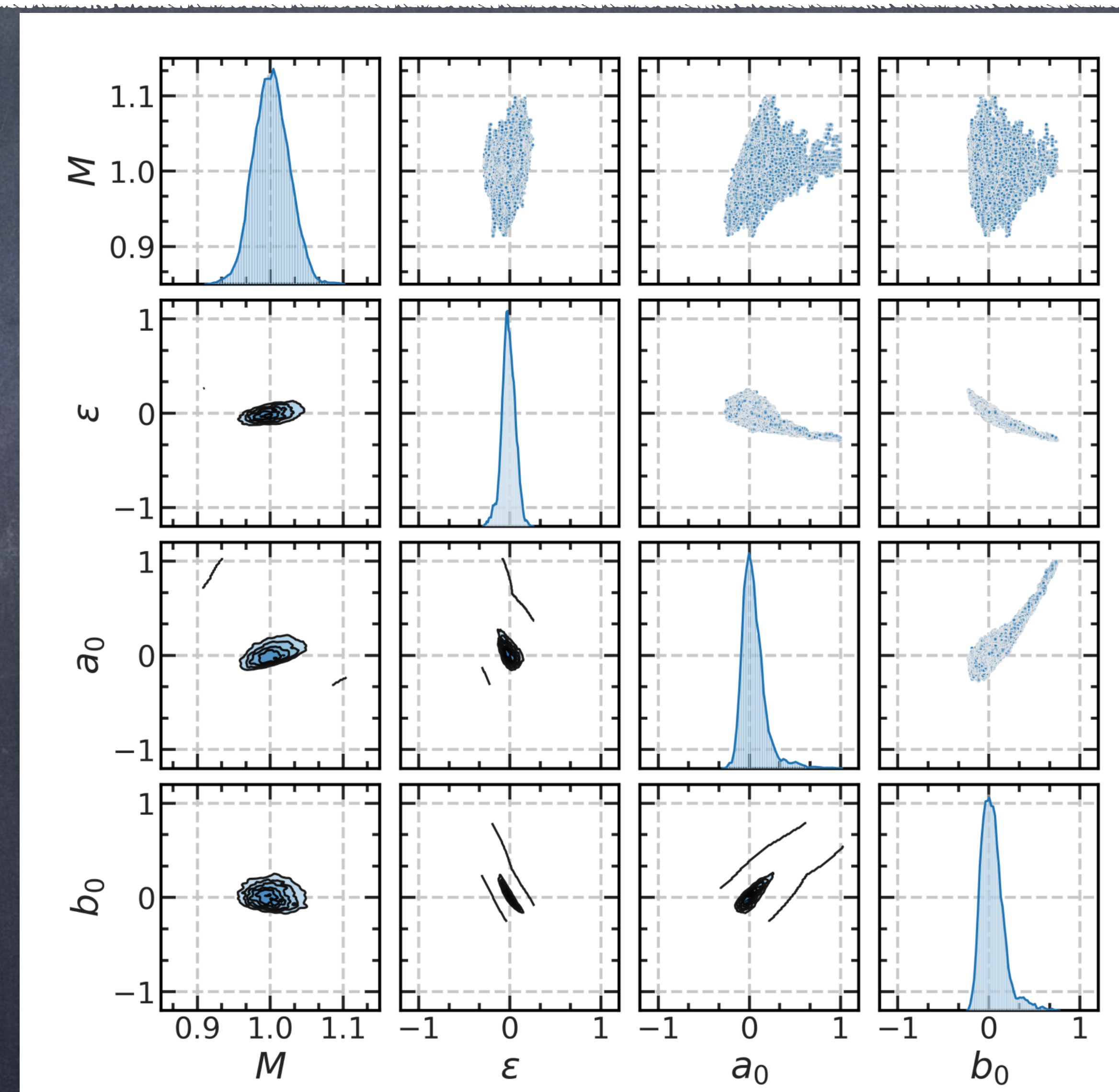
Shadow of M87* and QNMs can constrain on parametrized BHs (eg Rezzolla-Zhidenko)

$$\mathrm{d}s^2 = -N^2(r)\mathrm{d}t^2 + \frac{B^2(r)}{N^2(r)}\mathrm{d}r^2 + r^2\mathrm{d}\Omega^2, \qquad x \equiv 1 - \frac{r_0}{r} \qquad N^2 = xA(x) \qquad \varepsilon = -\left(1 - \frac{2M}{r_0}\right),$$

$$A(x) = 1 - \varepsilon(1-x) + (a_0 - \varepsilon)(1-x)^2 + \tilde{A}(x)(1-x)^3 \qquad \tilde{A}(x) = \frac{a_1}{1 + \frac{a_2 x}{1 + \frac{a_3 x}{1 + \dots}}}, \qquad a_0 = \frac{(\beta - \gamma)(1+\varepsilon)^2}{2},$$

$$B(x) = 1 + b_0(1-x) + \tilde{B}(x)(1-x)^2, \qquad \tilde{B}(x) = \frac{b_1}{1 + \frac{b_2 x}{1 + \frac{b_3 x}{1 + \dots}}}. \qquad b_0 = \frac{(\gamma - 1)(1+\varepsilon)}{2},$$



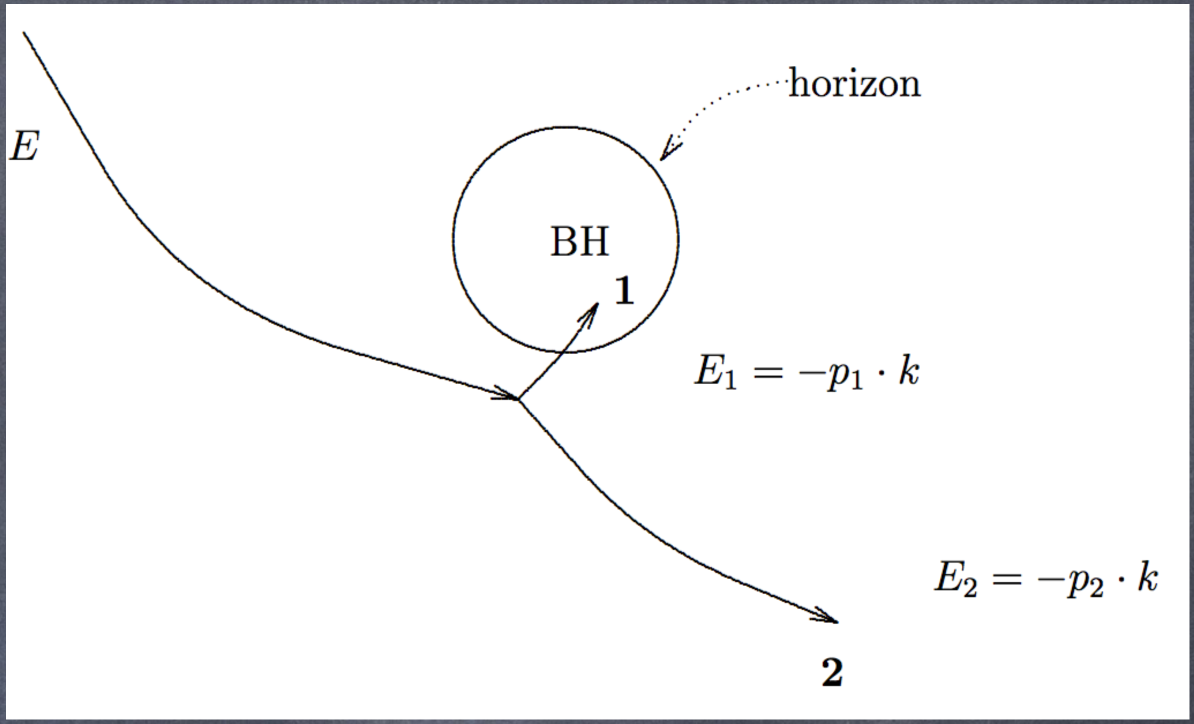


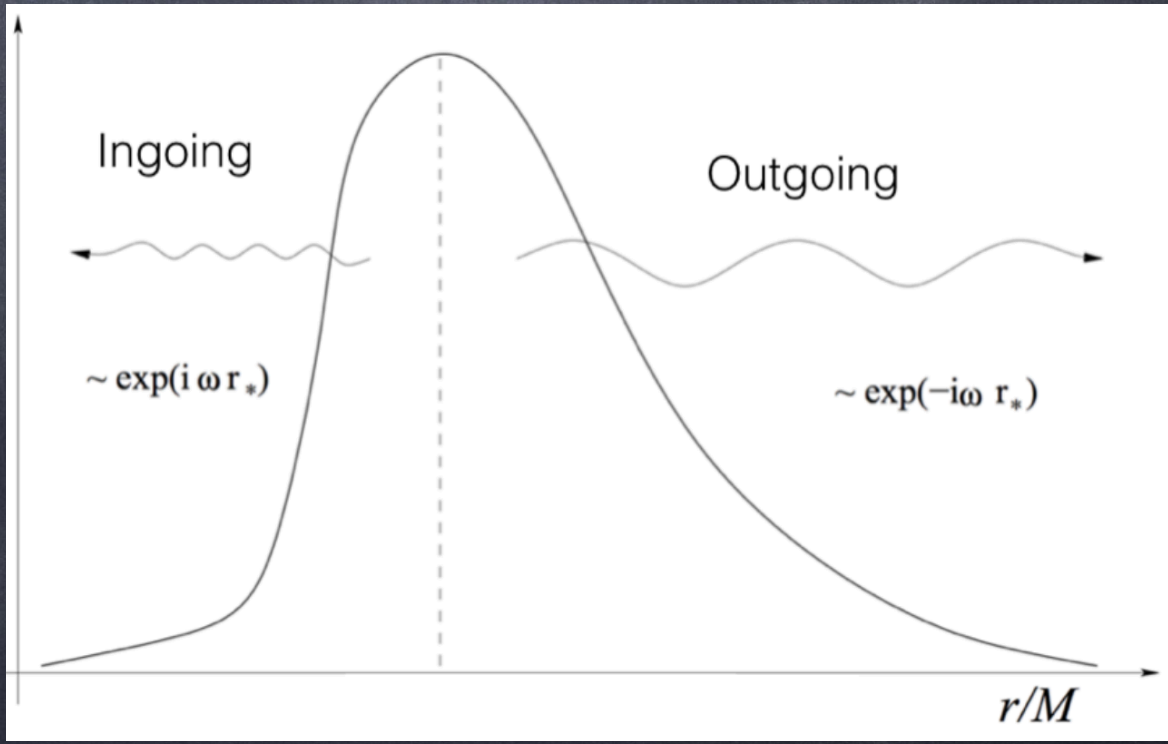
EB+Voelkel 2020

(l,n)=(2,0), (2,1), (3,0), (3,1) modes with 1% error

BH-boson condensates

- Formation linked to superradiant instabilities/Penrose process (amplification of scattered waves with $\omega < m\,\Omega$)
- BH with high enough spin and "mirror" are superradiance unstable (BH bomb; Zeldovich 71, Press & Teukolsky 72, Cardoso et al 04)
- In ergoregion, negative energy modes can be produced but are confined (only positive energy modes can travel to infinity)
- By energy conservation, more and more negative energy modes can be produced, which may cause instability according to boundary conditions (at horizon and spatial infinity)





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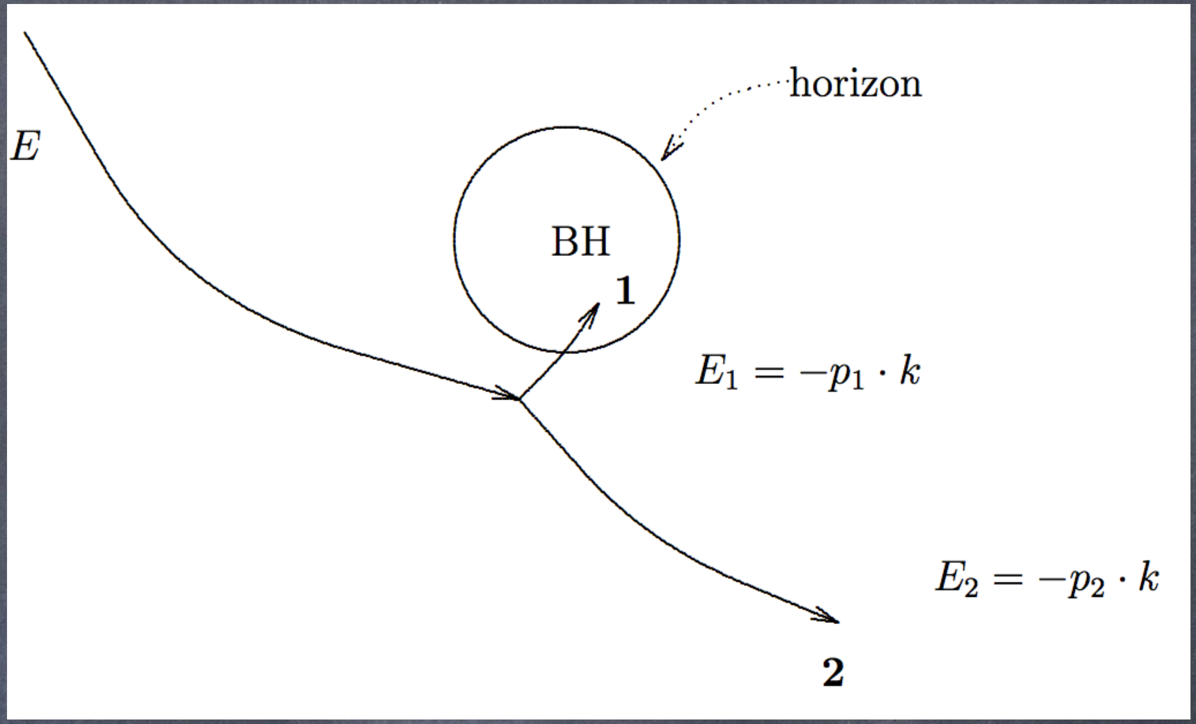
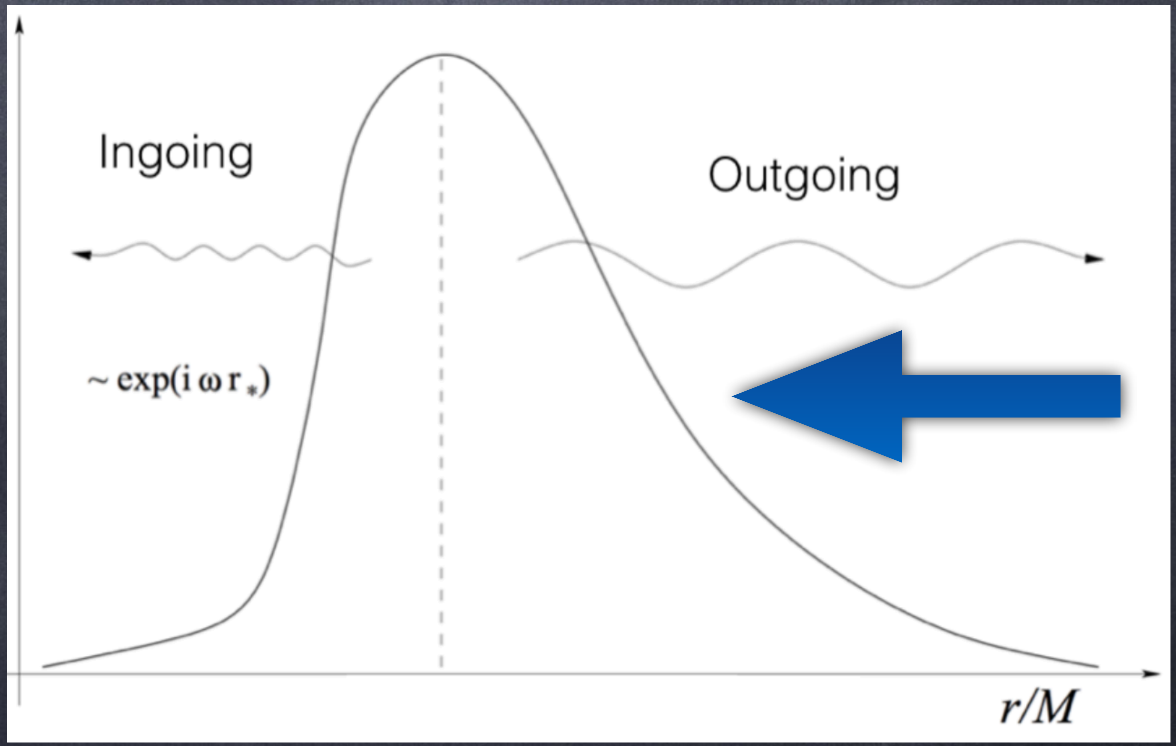
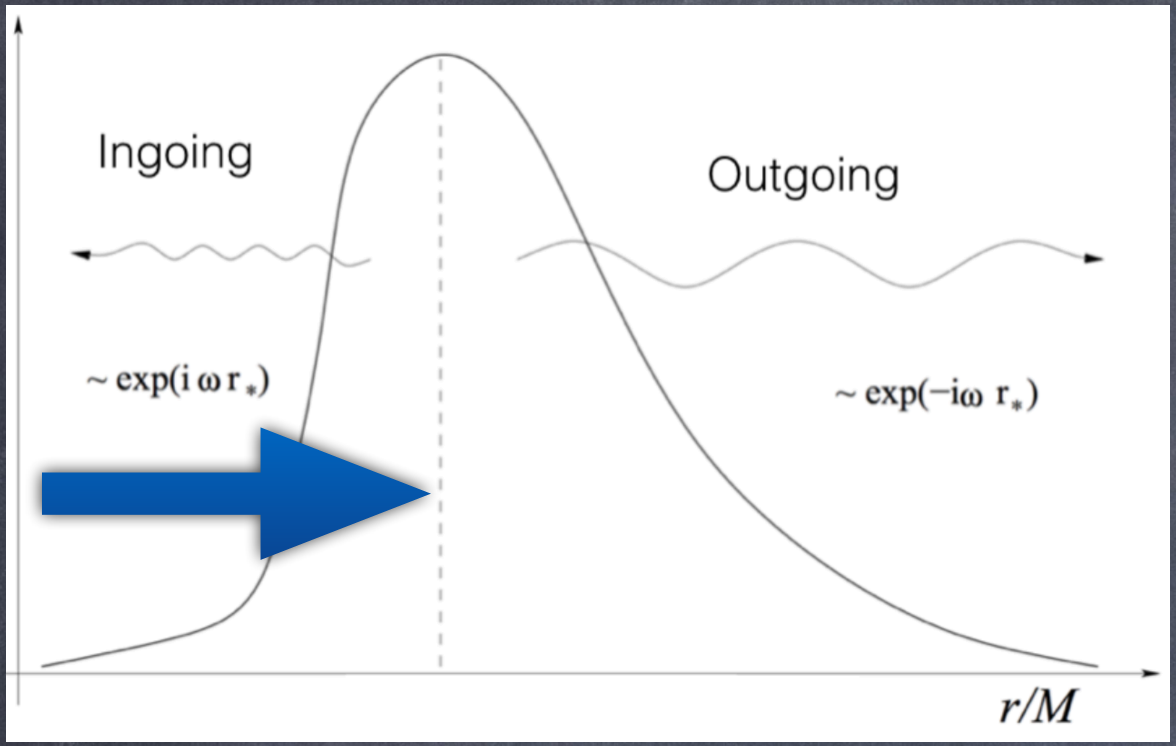
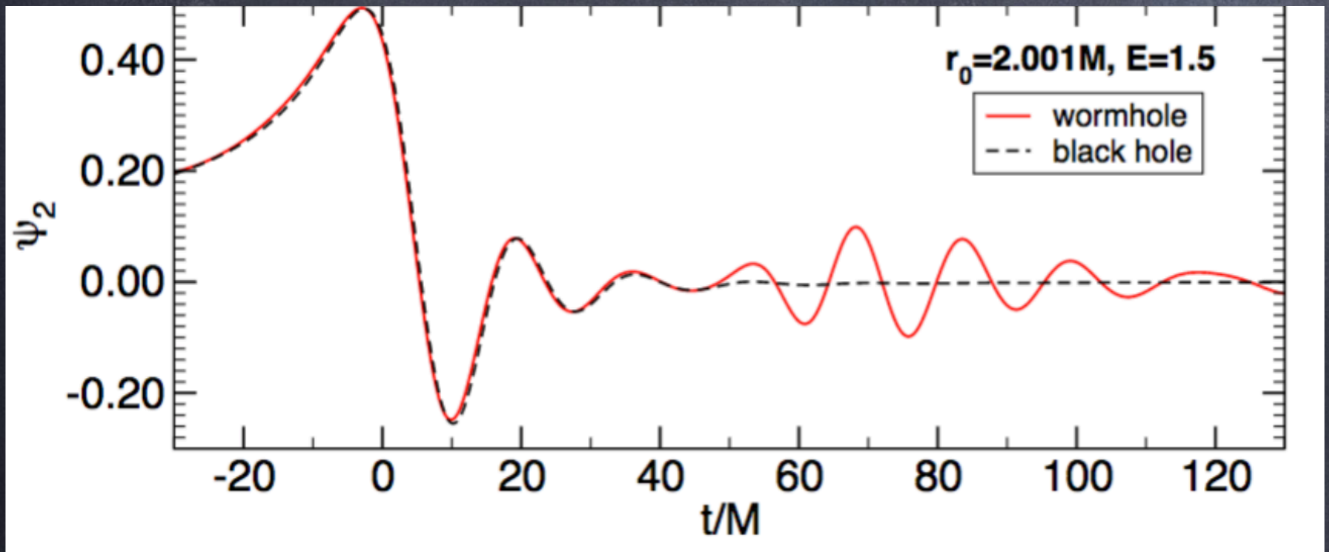




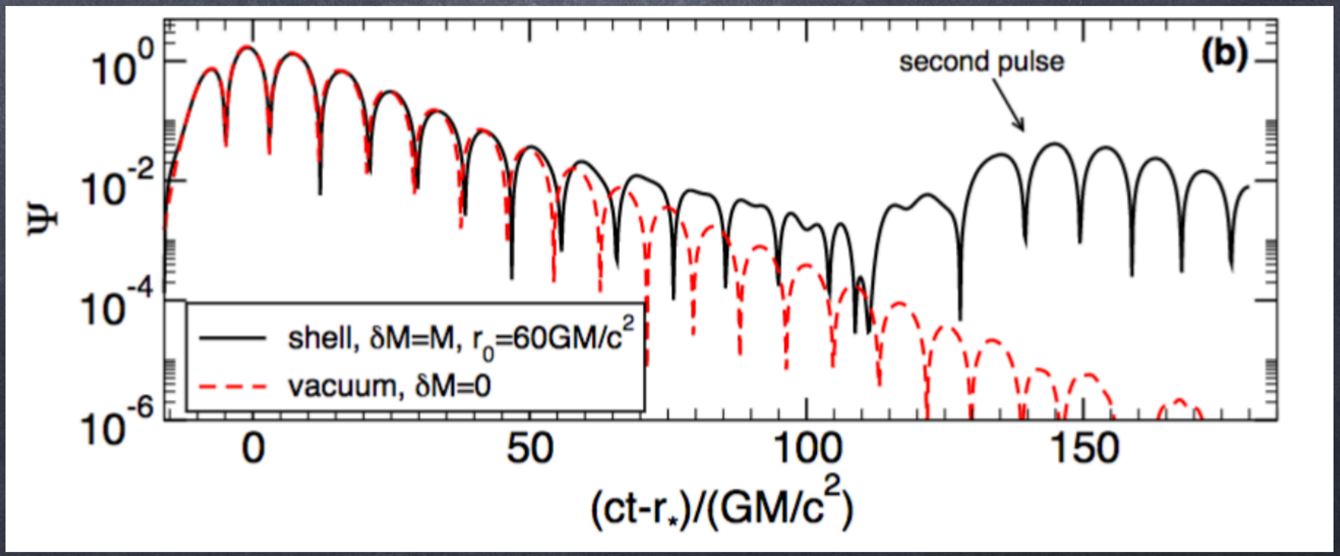
Superrandiance from near horizon physics



- Deviations away from Kerr geometry near horizon (e.g. firewalls, gravastars, wormholes, Lorentz violations, etc) can produce significant changes in QNM spectrum
- Delays $\Delta t \sim \log[r_0/(2M) - 1]$



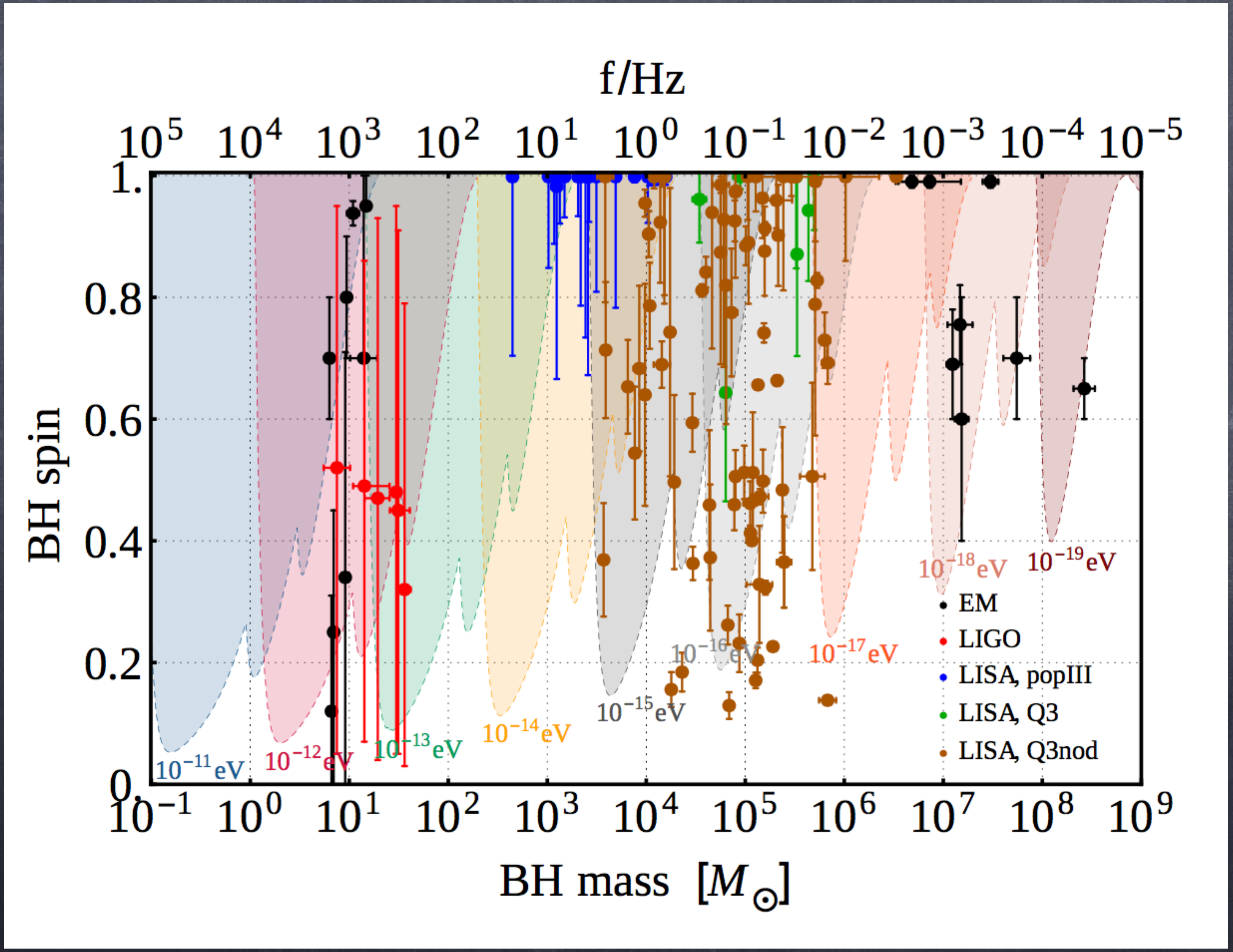
Cardoso, Franzin & Pani 2016



EB, Cardoso & Pani 2014

BH-boson condensates

Same instability of spinning BH + massive boson (mass acts as "mirror" and allows for bound states), but NOT for fermions. Cf Damour, Deruelle & Ruffini 76



Brito+EB+17

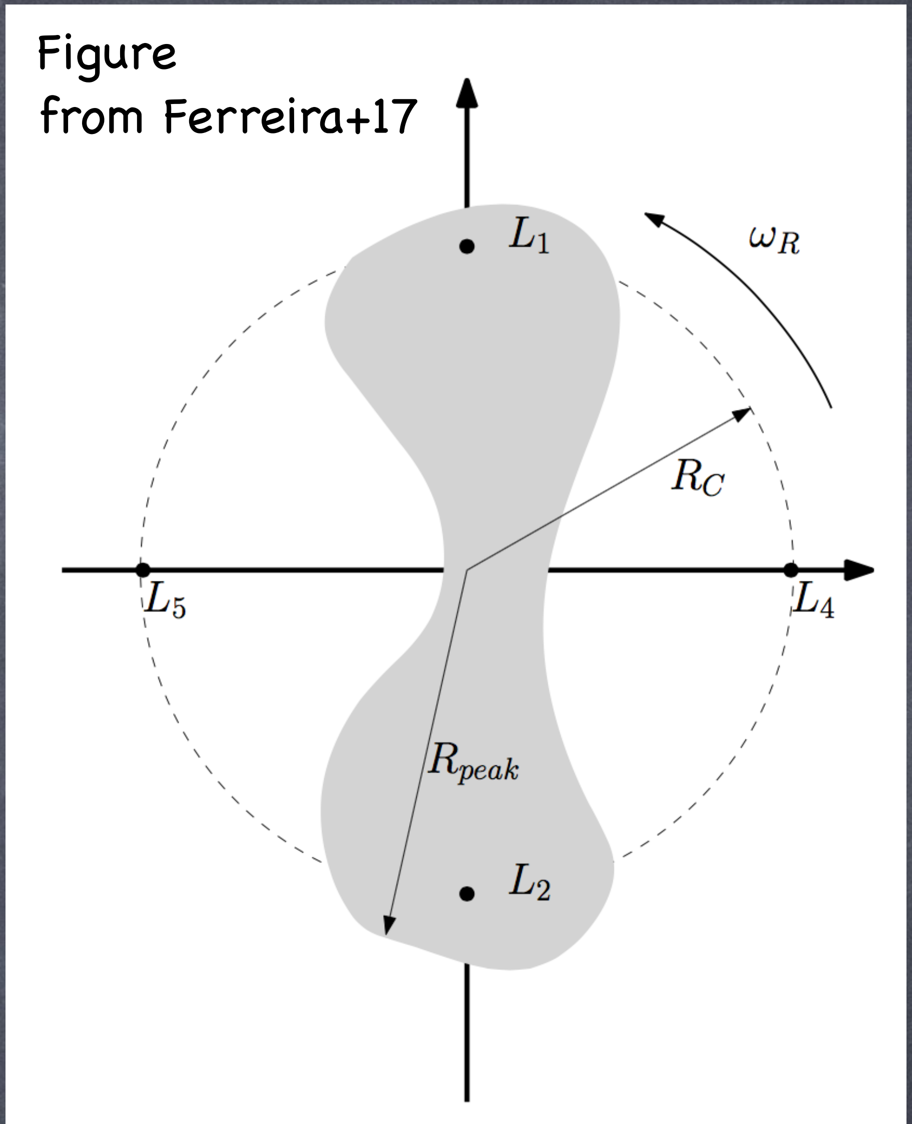
Instability end point

- BH sheds excess spin (and to a lesser degree mass) into a mostly dipolar rotating boson cloud ...

$$m_s \equiv \mu\hbar,$$

$$\omega_R \sim \mu - \frac{M^2\mu^3}{8}$$

$$\Phi = A_0 g(r)\cos(m_\phi\phi - \omega_R t)\sin\theta\,,$$



- ... till instability saturates

$$\mu \sim m\Omega_{\rm H}$$

$$\tau_{\rm inst} \sim 0.07\,\chi^{-1}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^9 \,{\rm yr}\,,$$

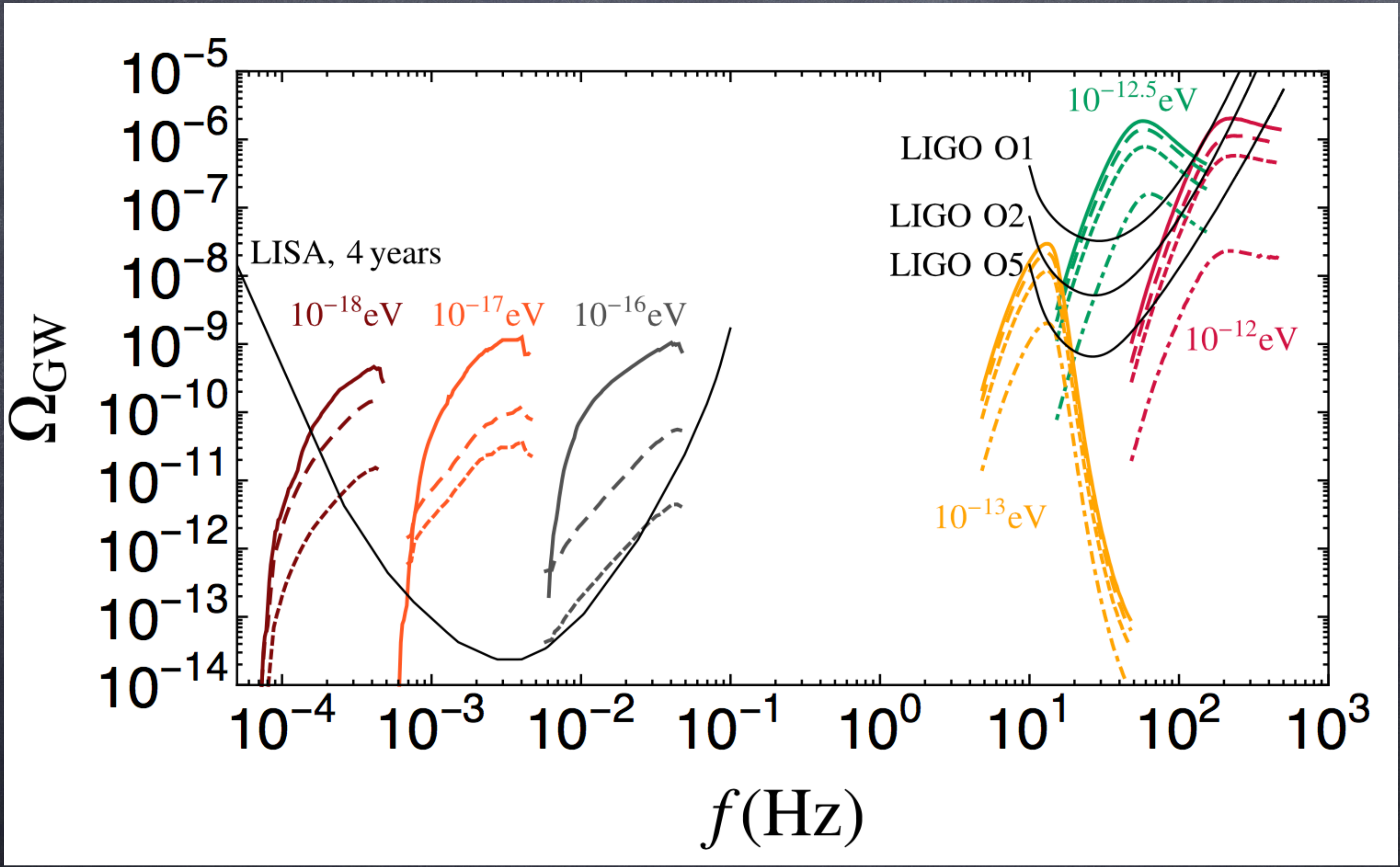
(for Mμ<<1 and χ<<1; max instability for Mμ=0.42)

- Emission of almost monochromatic GWs

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

$$\omega \sim \mu$$

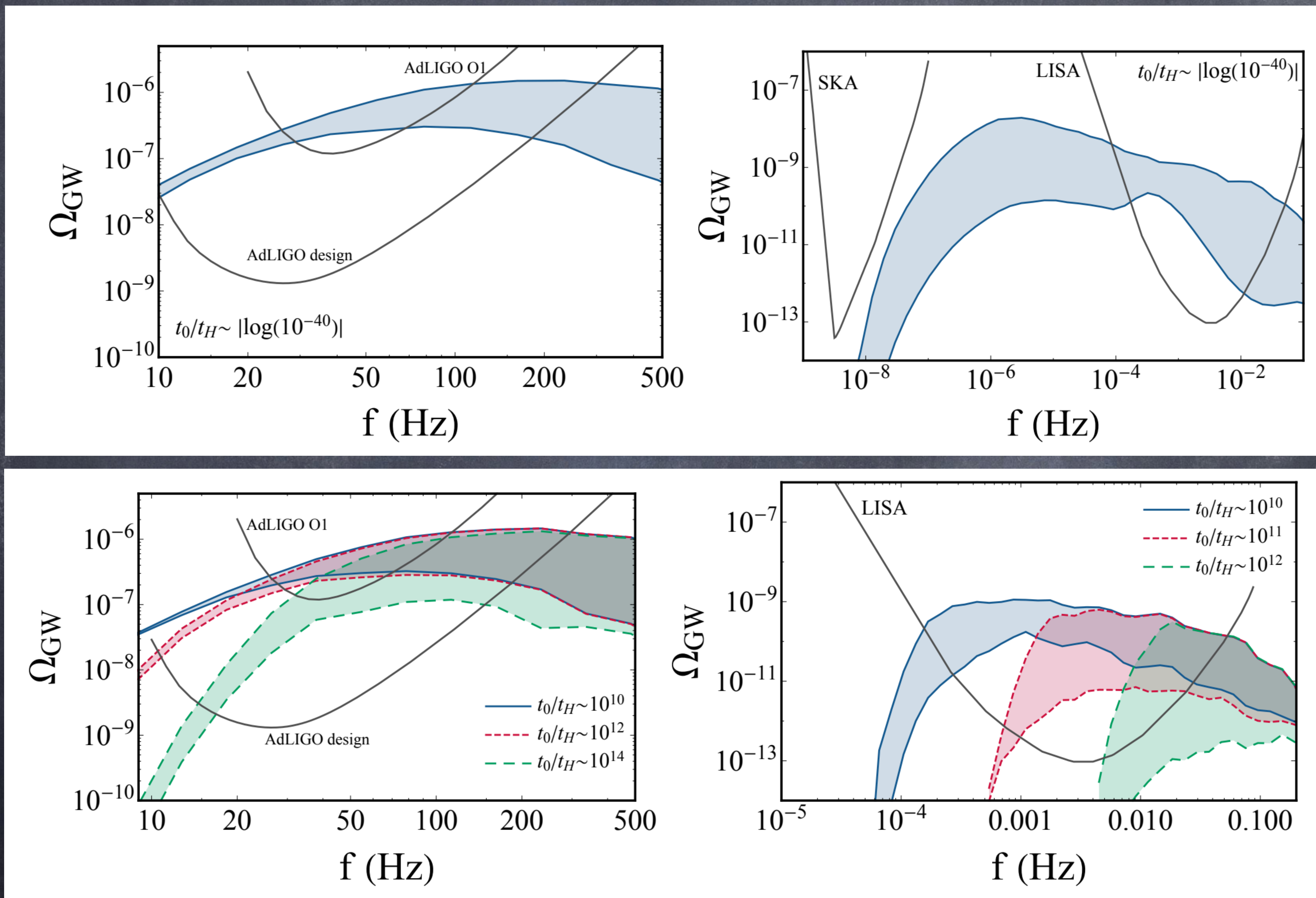
Background from isolated BHs



Brito+EB+17

Bounds on BH mimickers

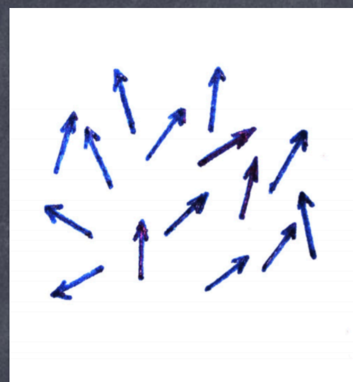
BH mimickers with no horizon are unstable to superradiance



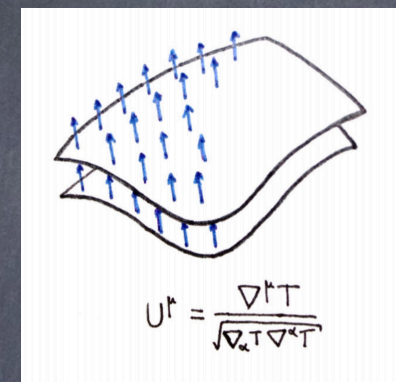
EB, Brito, Cardoso, Dvorkin, Pani 2018

Lorentz violations and horizons

- Lorentz violations = "asymmetry" between space & time (preferred time direction)



= Einstein-aether theory



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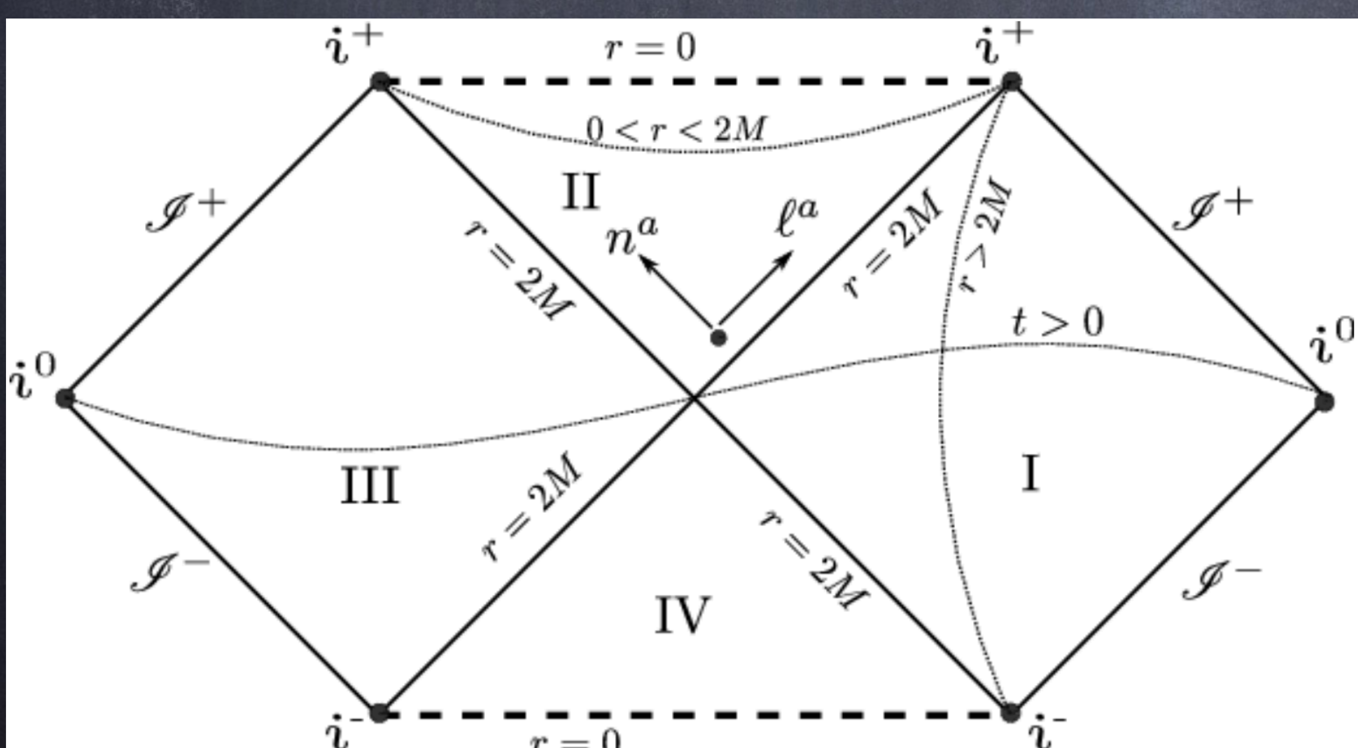


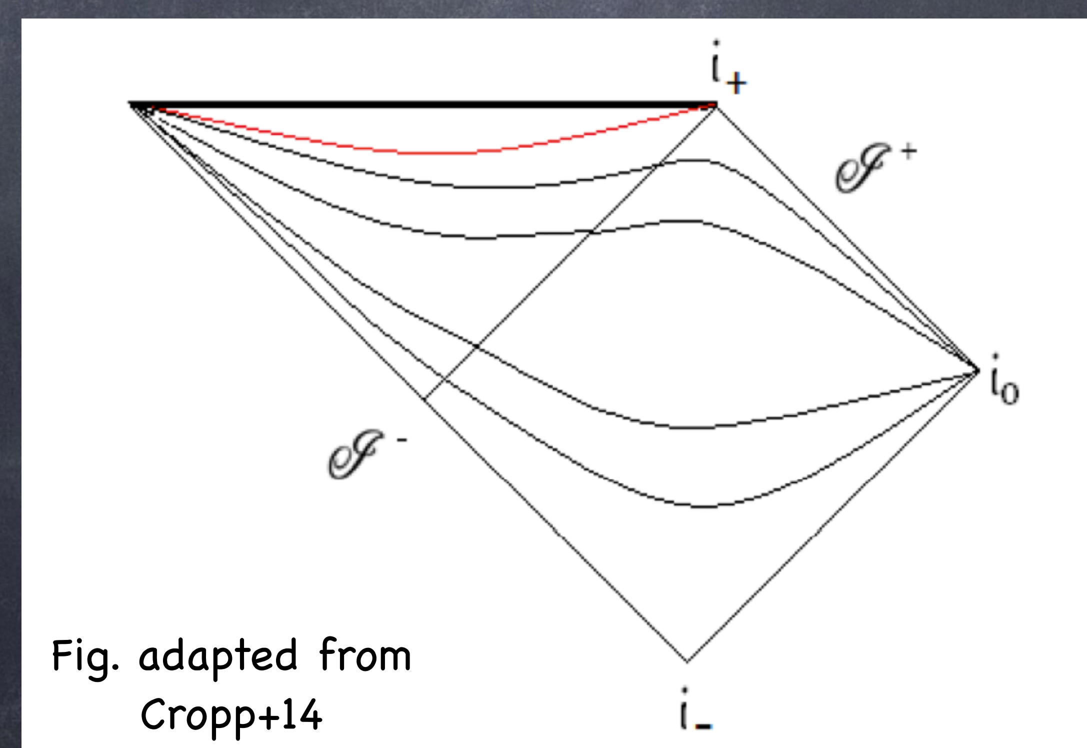
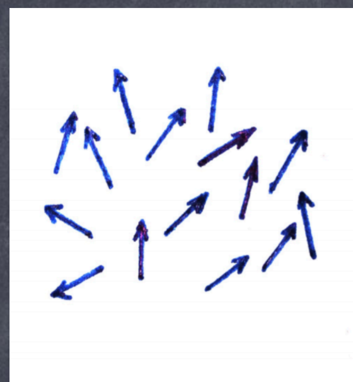


Fig. adapted from Cropp+14

Lorentz violations and horizons

- Lorentz violations = "asymmetry" between space & time (preferred time direction)



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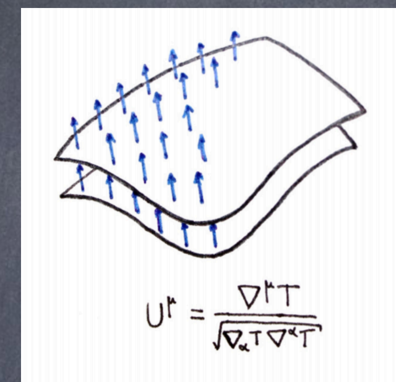

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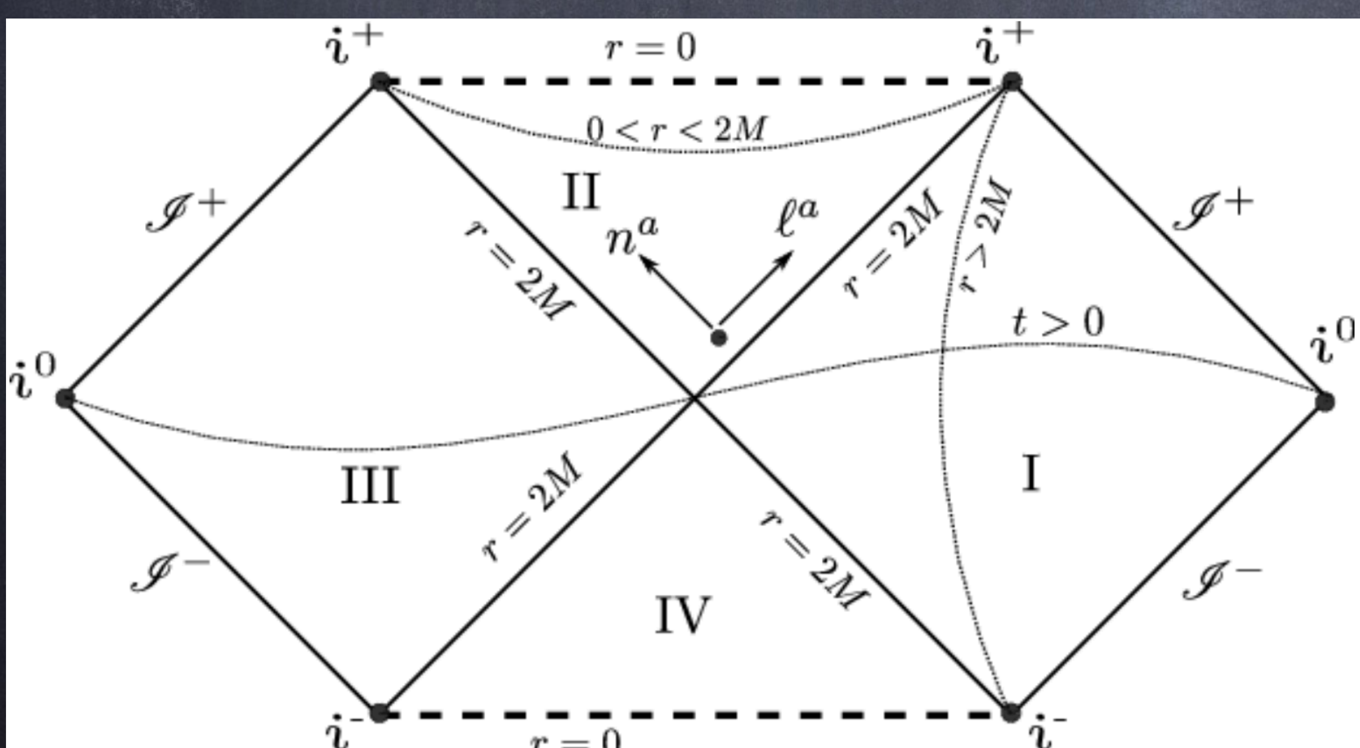

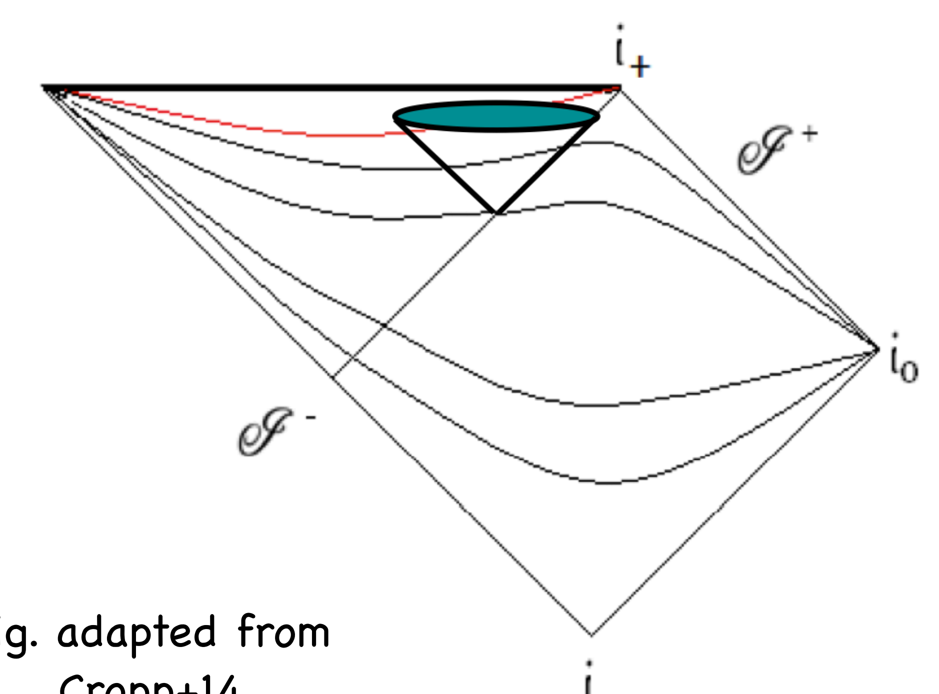

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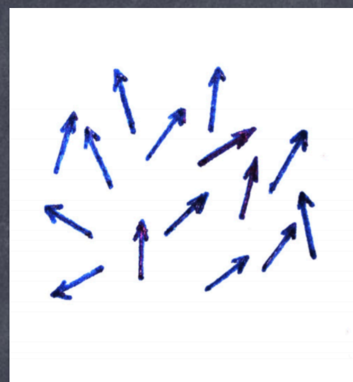

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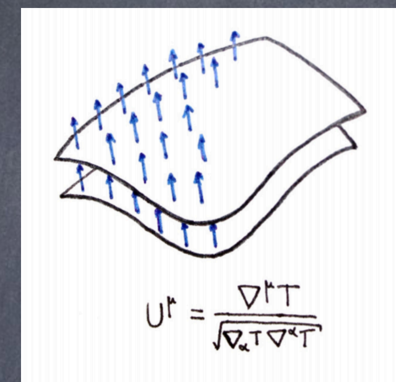

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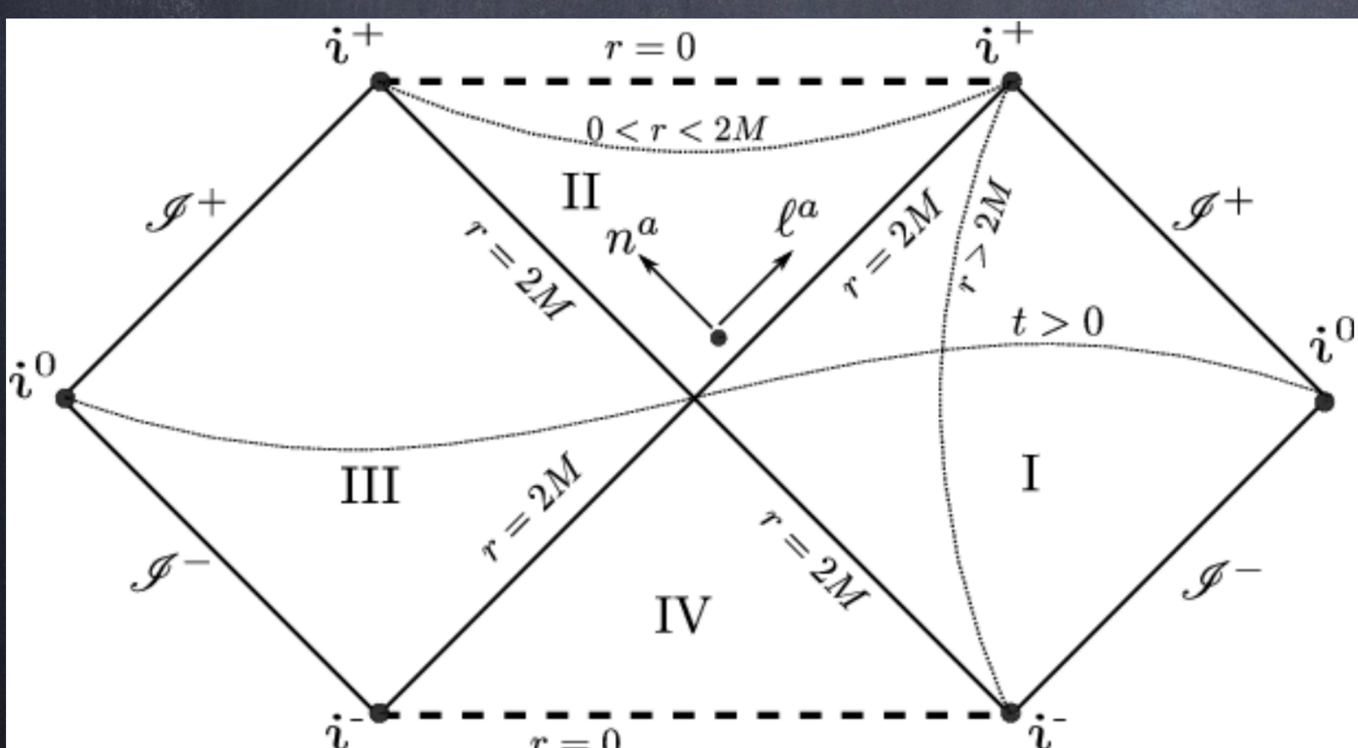

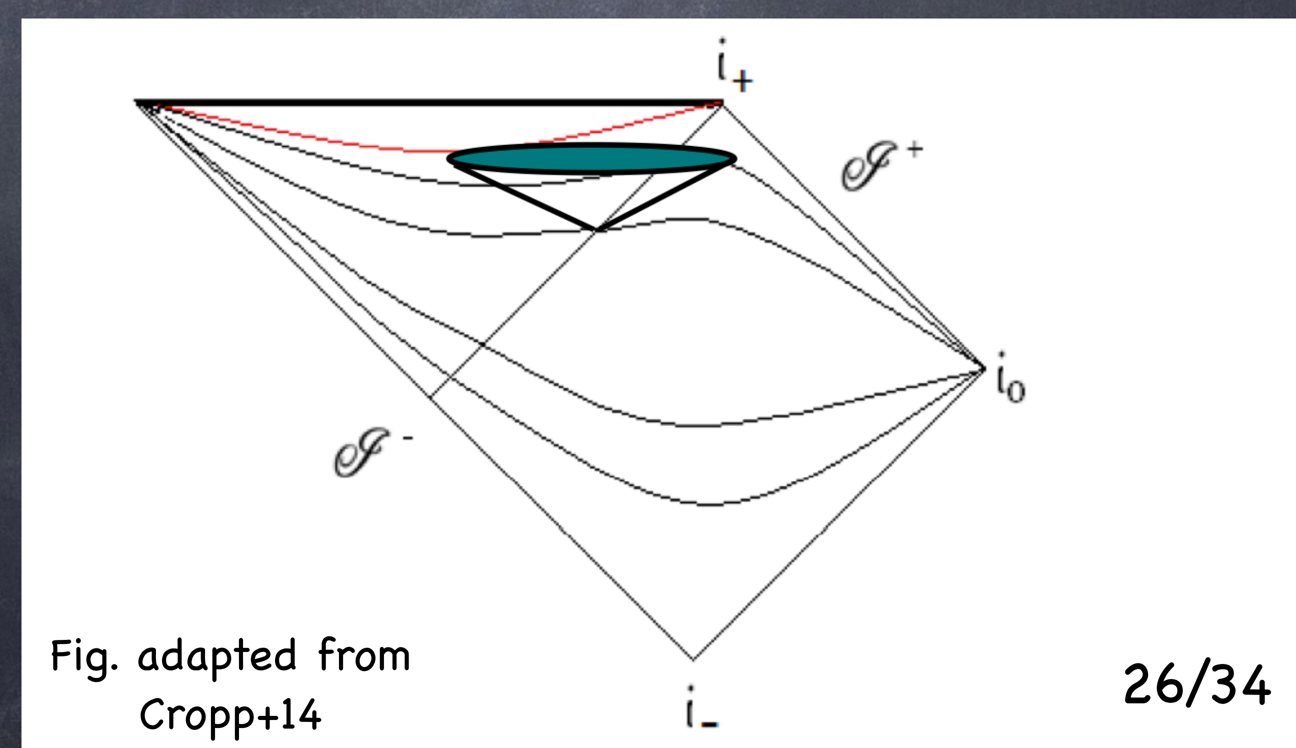

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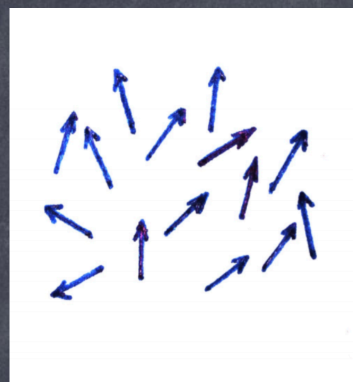

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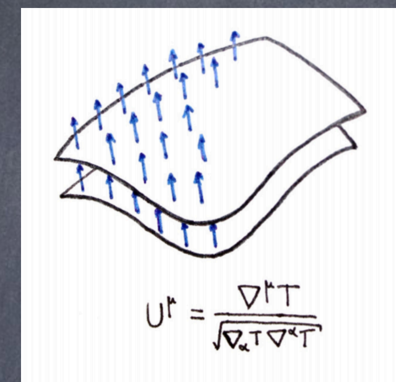

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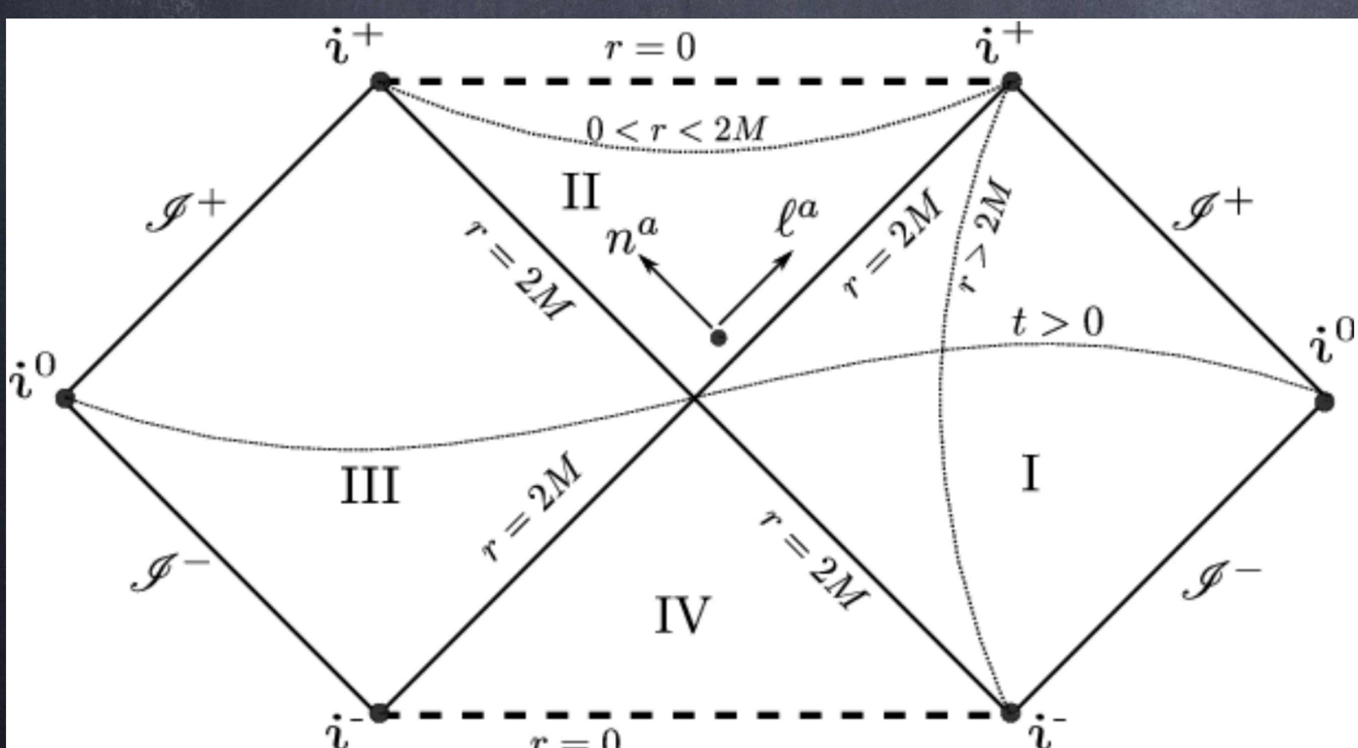

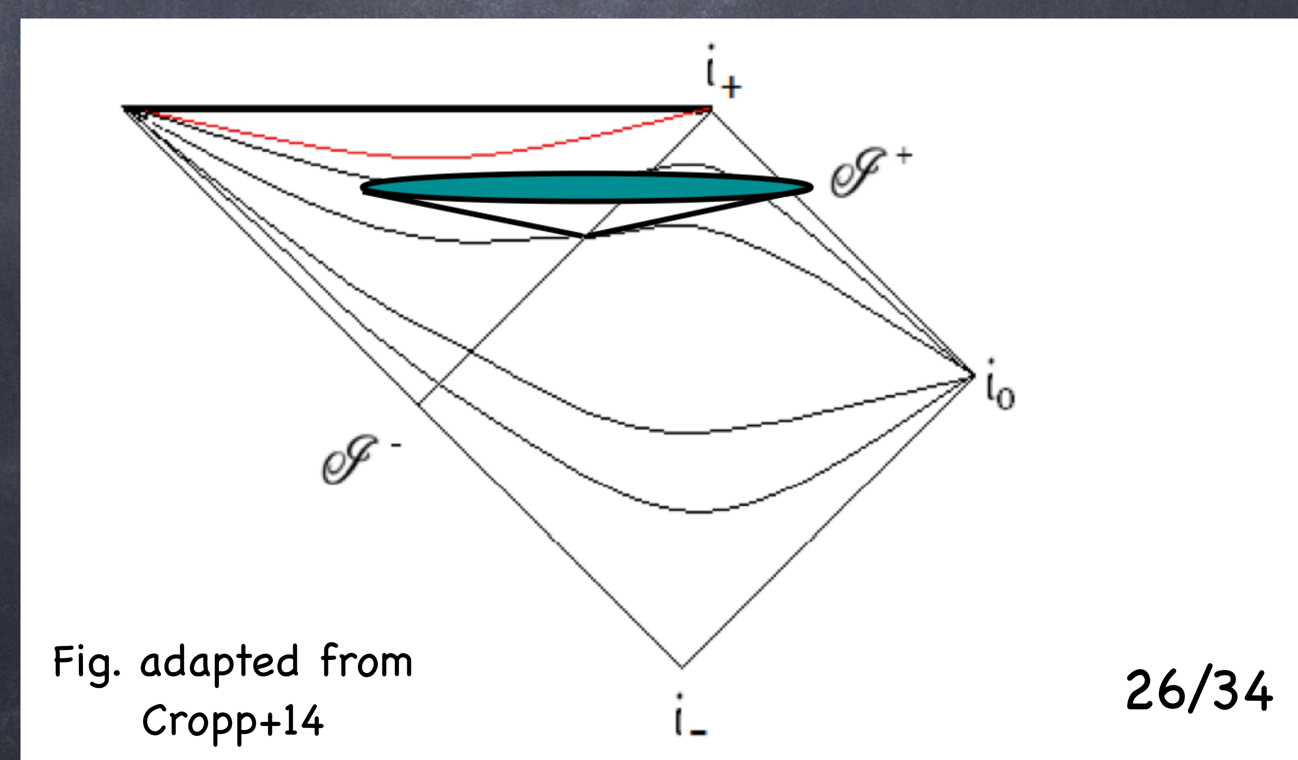

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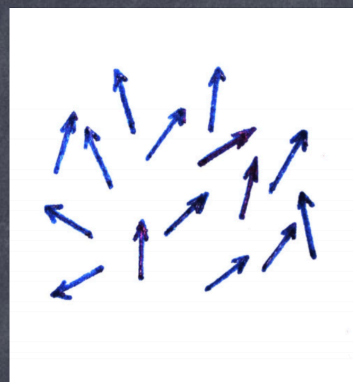

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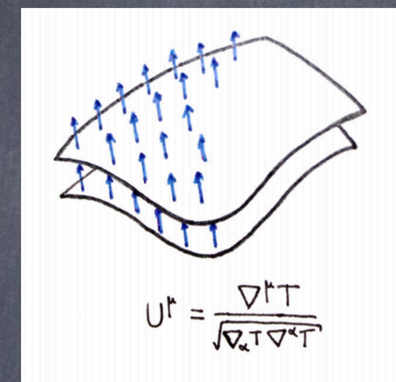

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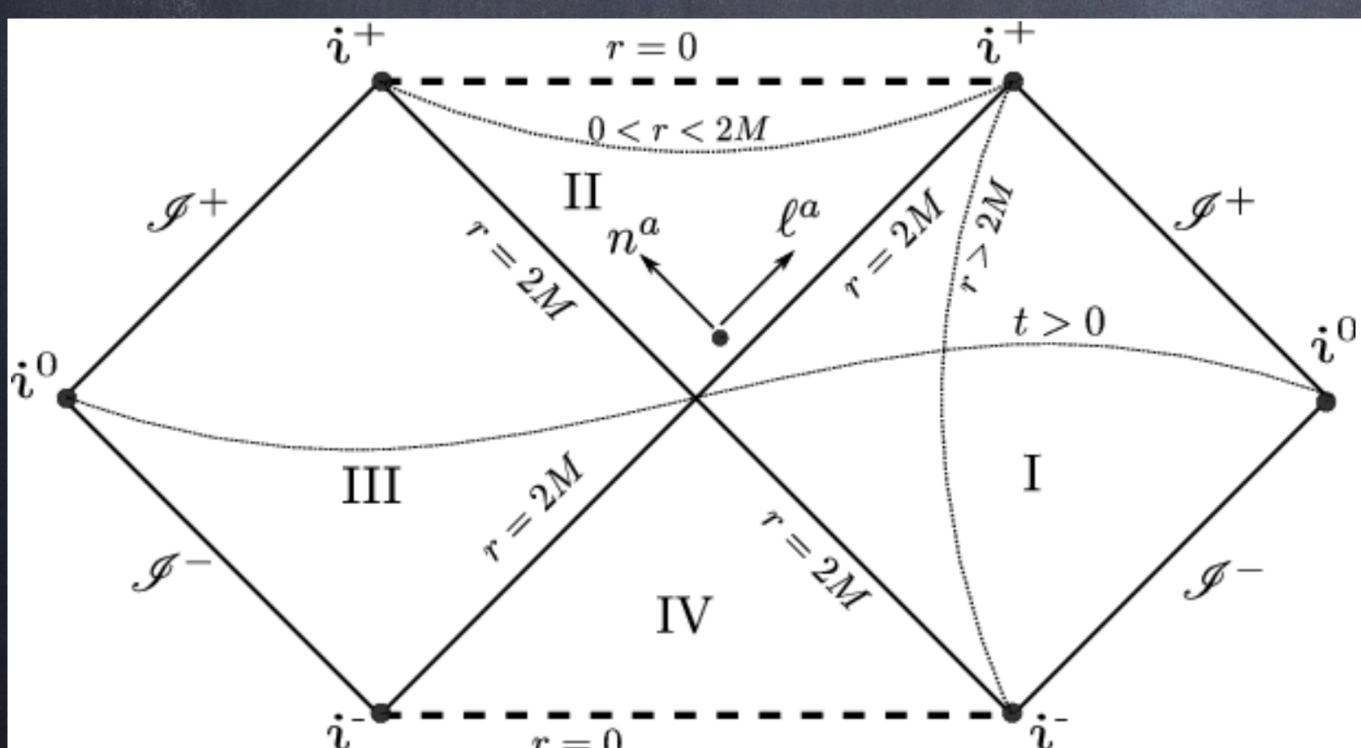

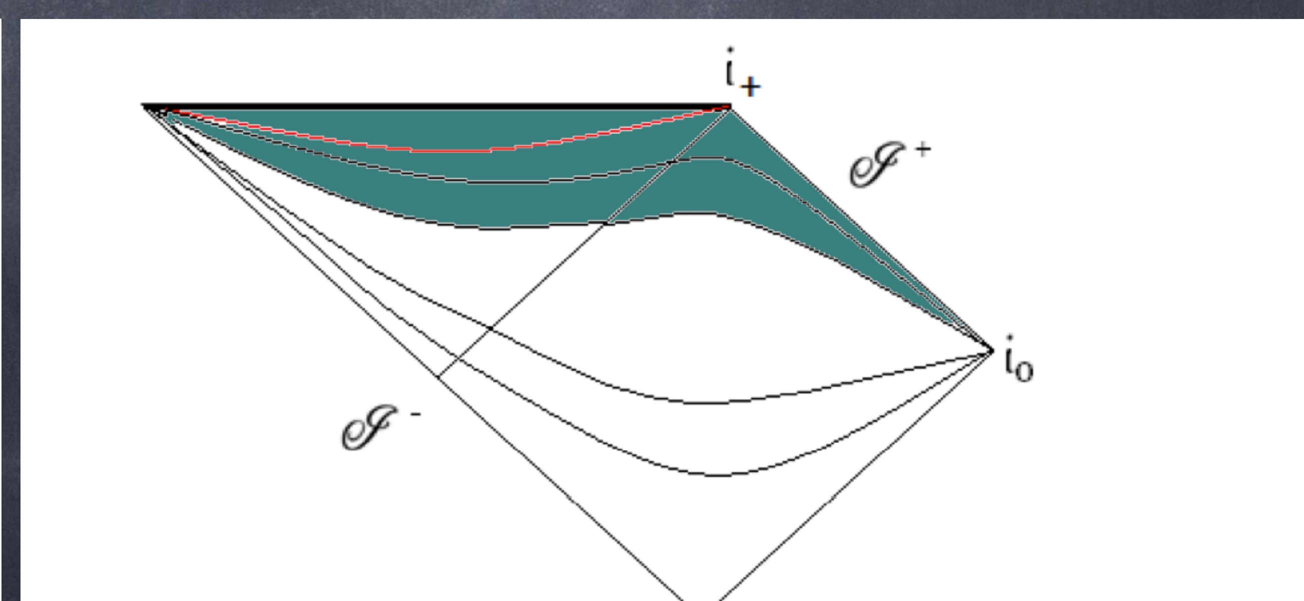

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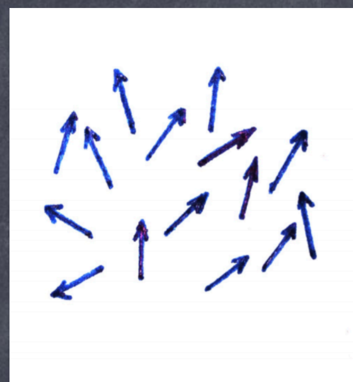

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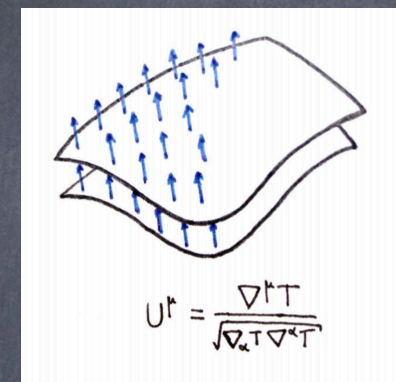

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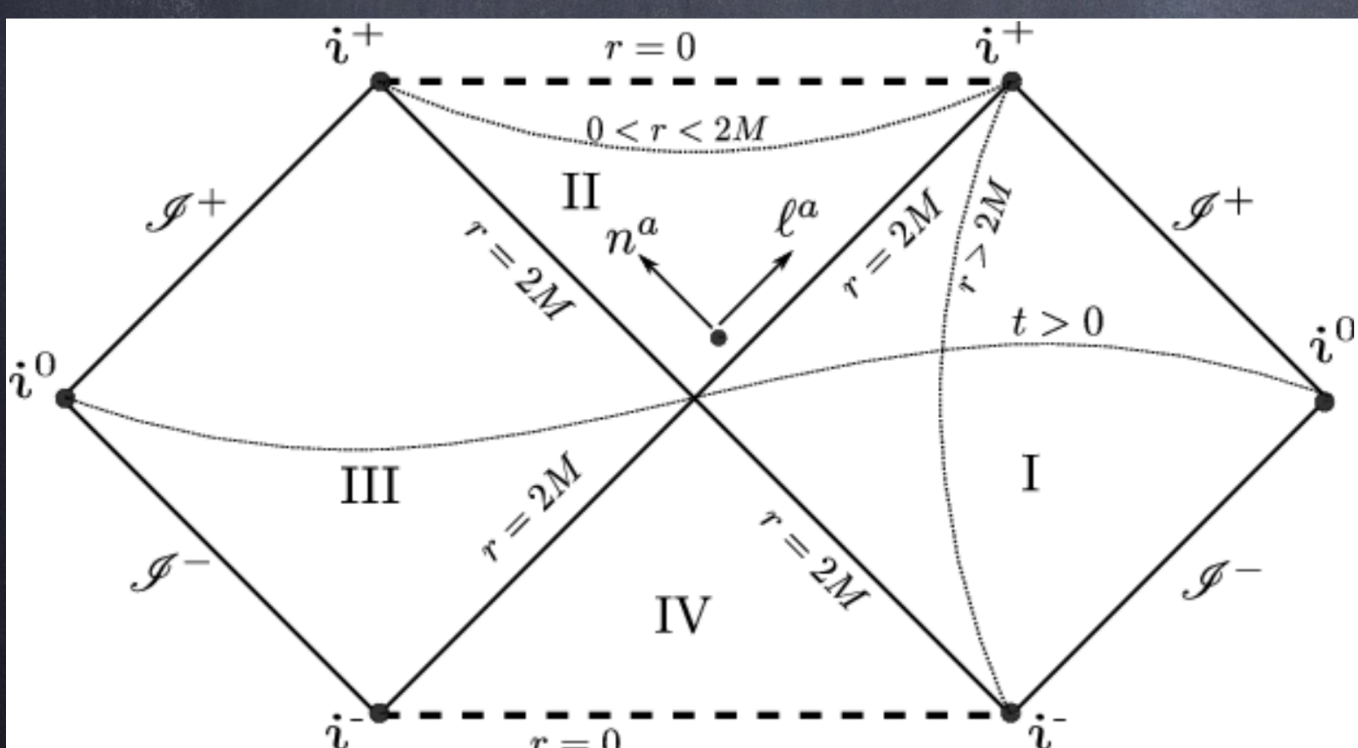

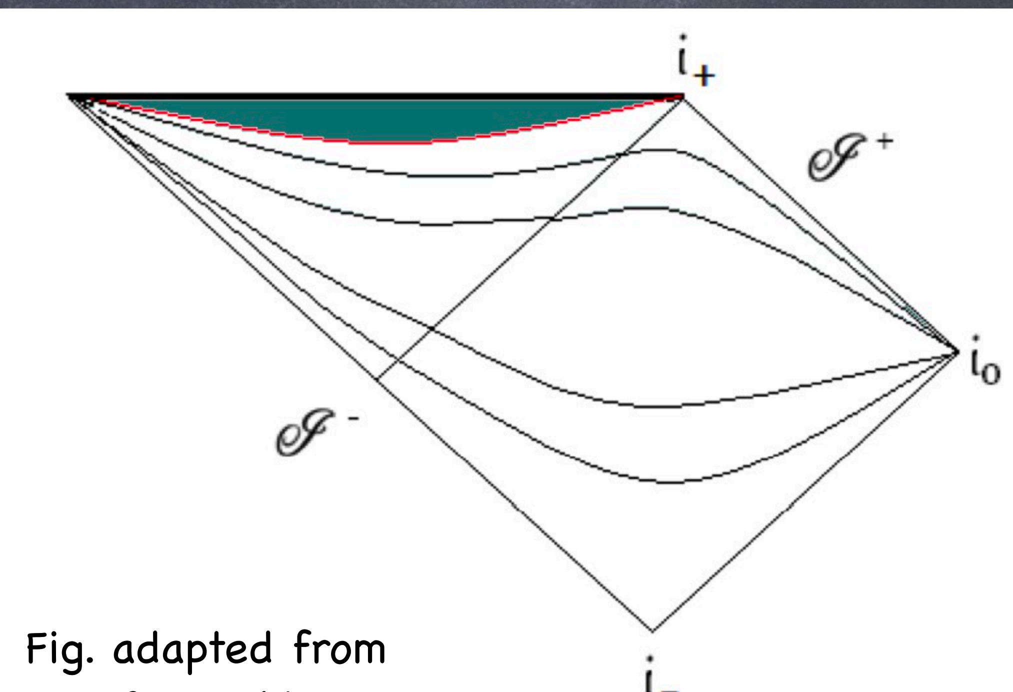

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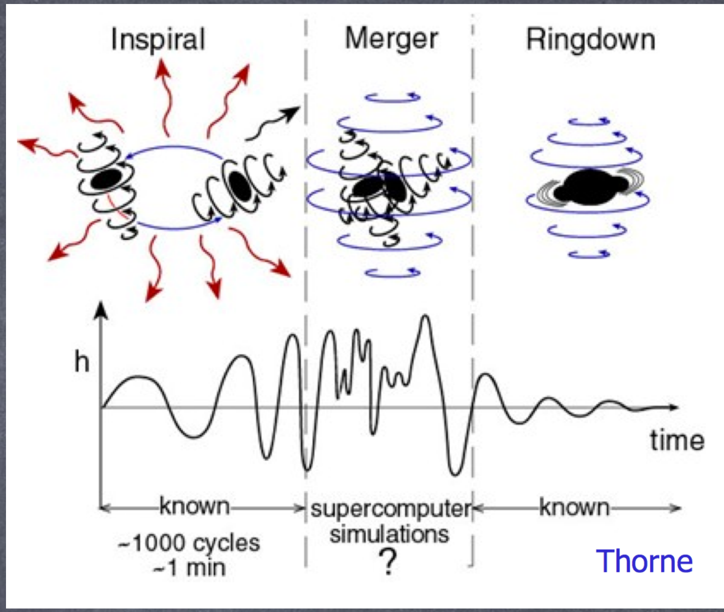
How about BH mergers?



Possible surprises/
highly non-linear dynamics?

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

True only for a handful of theories:

- FJBD-like/DEF scalar-tensor theories, but GR dynamics in vacuum (modulo boundary/initial conditions, mass term)
- True for Lorentz-violating gravity (Sarbach, EB, Preciado-Lopez 2019), but no simulations yet (tetrad-based formulation is complicated)
- Cubic Galileons/K-essence/Einstein dilaton-Gauss-Bonnet are locally but not globally well-posed (Bernard, Luna & Lehner 2019, Ripley & Pretorius 2019, Figueras & Franca 2020)
- Cauchy problem easier to formulate if theory interpreted as EFT (eg Chern-Simons, cf Okounkova+2020, Allwright & Lehner 2018), but non-linear dynamics may be lost

General scalar-tensor theories

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

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

- Horndeski class; can be generalized to DHOST
- Model for Dark-Energy like phenomenology: screening mechanism (Vainstein, K-mouflage, etc), self-accelerating solutions

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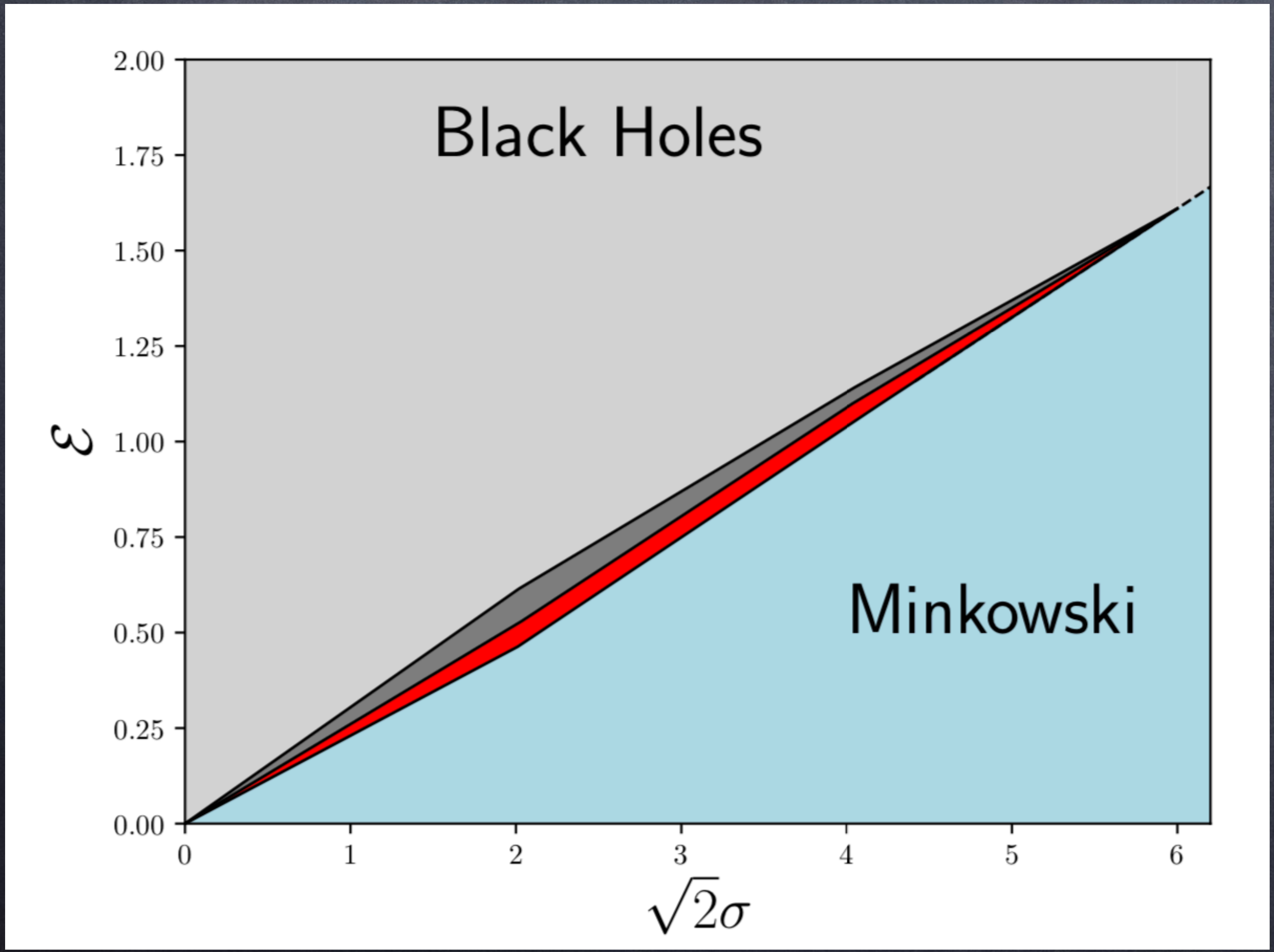
- Horndeski class; can be generalized to DHOST
- Model for Dark-Energy like phenomenology: screening mechanism (Vainstein, K-mouflage, etc), self-accelerating solutions
- Constraints from GW170817 and from decay of propagating GWs into scalar (Creminelli+2020) imply that only theories with sizeable cosmological effects are k-essence models, with a possible conformal coupling with matter.

K-essence screening (AKA K-mouflage, kinetic screening)

$$S = \int d^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R + K(X)\right] \qquad K(X) = -\frac{1}{2}X + \frac{\beta}{4\Lambda^4}X^2 - \frac{\gamma}{8\Lambda^8}X^3$$

$$X \equiv \nabla_\mu\phi\nabla^\mu\phi \qquad \Lambda \sim (H_0 M_{\rm Pl})^{1/2} \sim 5\times 10^{-3}\ {\rm eV} \qquad \alpha,\beta,\gamma \sim \mathcal{O}(1)$$



Cauchy problem is well-posed for most initial data in vacuum and 1+1 dimension

Bezares, Crisostomi, Palenzuela & EB, to appear tomorrow

K-essence vacuum evolutions

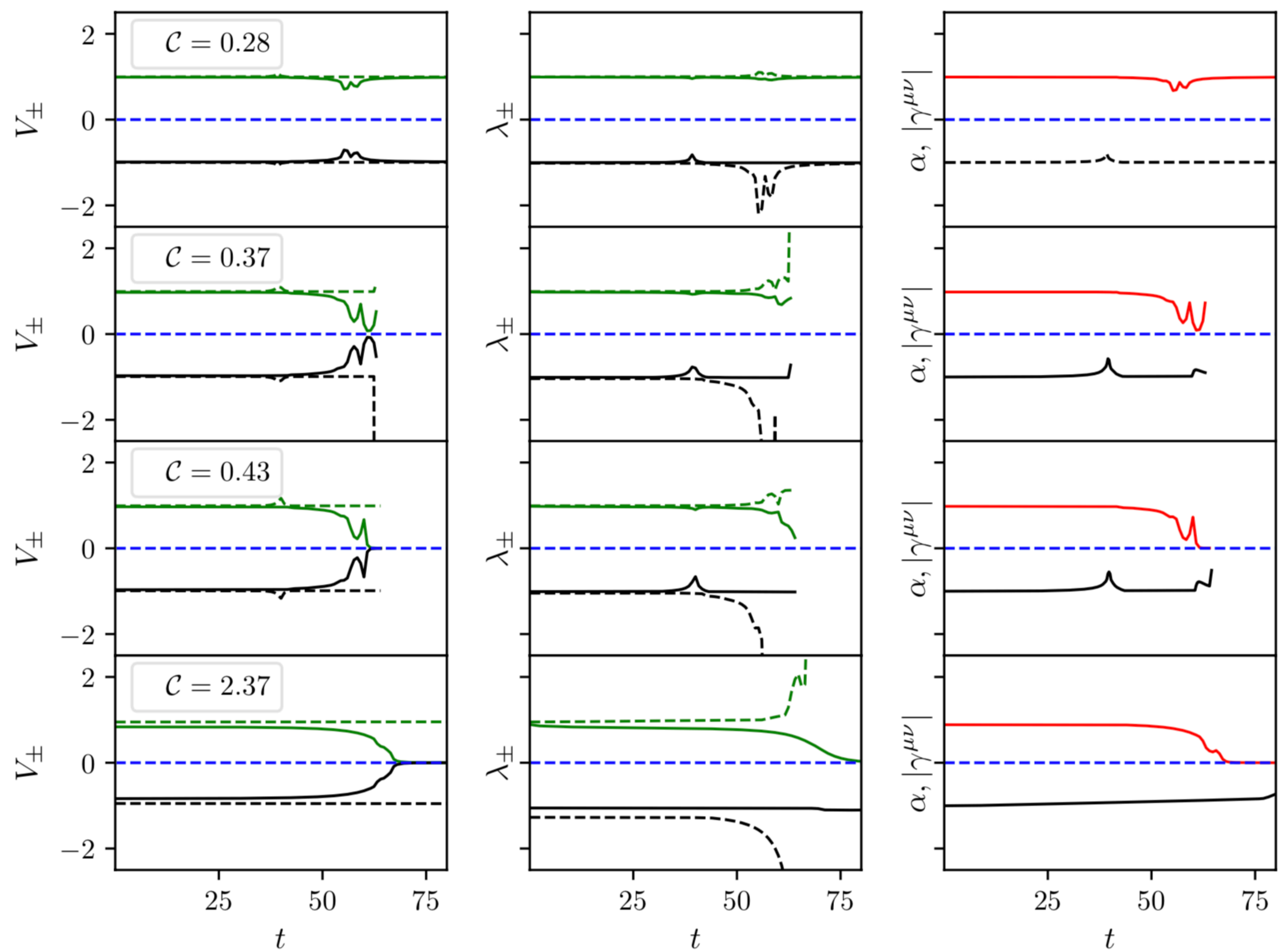


FIG. 2. *Dynamics of the pulse.* Each row corresponds to a different compactness $\mathcal{C}$ of the initial scalar field pulse (from top to bottom, 0.28, 0.37, 0.43 and 2.37). *First and second columns*: the green dashed line represents $\max(V_+)$ and $\max(\lambda_+)$; the green solid line is $\min(V_+)$ and $\min(\lambda_+)$; the black solid line is $\max(V_-)$ and $\max(\lambda_-)$; and the black dashed line is $\min(V_-)$ and $\min(\lambda_-)$. *Third column:* the solid red line is $\min(\alpha)$ (which is useful to track black hole formation), while the solid black line is $\max \det(\gamma^{\mu\nu})$ [which is always non-zero, c.f. Eq. (29)].

Bezares, Crisostomi, Palenzuela & EB, to appear tomorrow

$$\gamma^{\mu\nu}\nabla_\mu\nabla_\nu\phi = 0$$

$V_{+/-}$ are eigenvalues of principal part, $\lambda_{+/-}$ of effective metric γ

K-essence vacuum evolutions

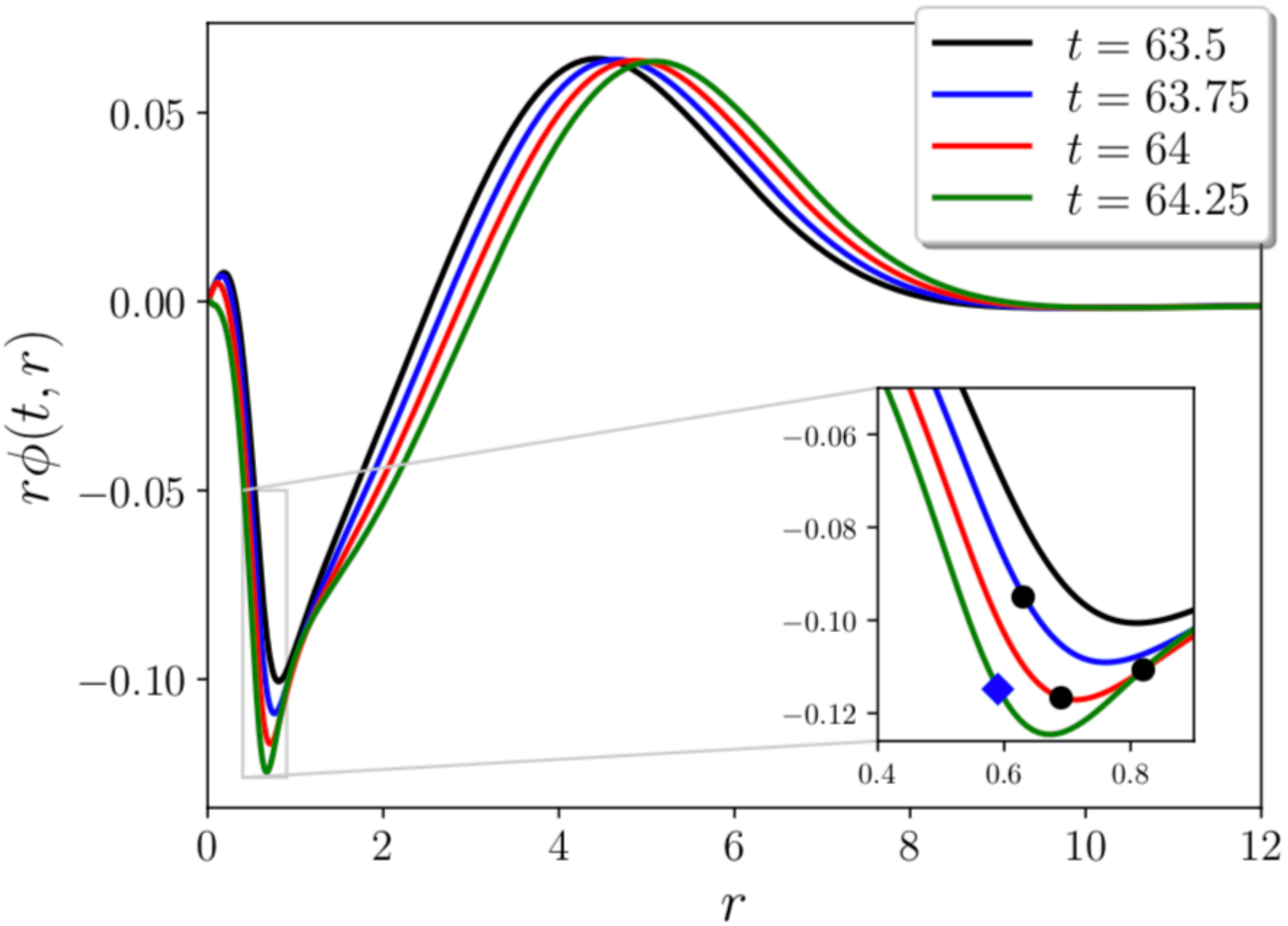
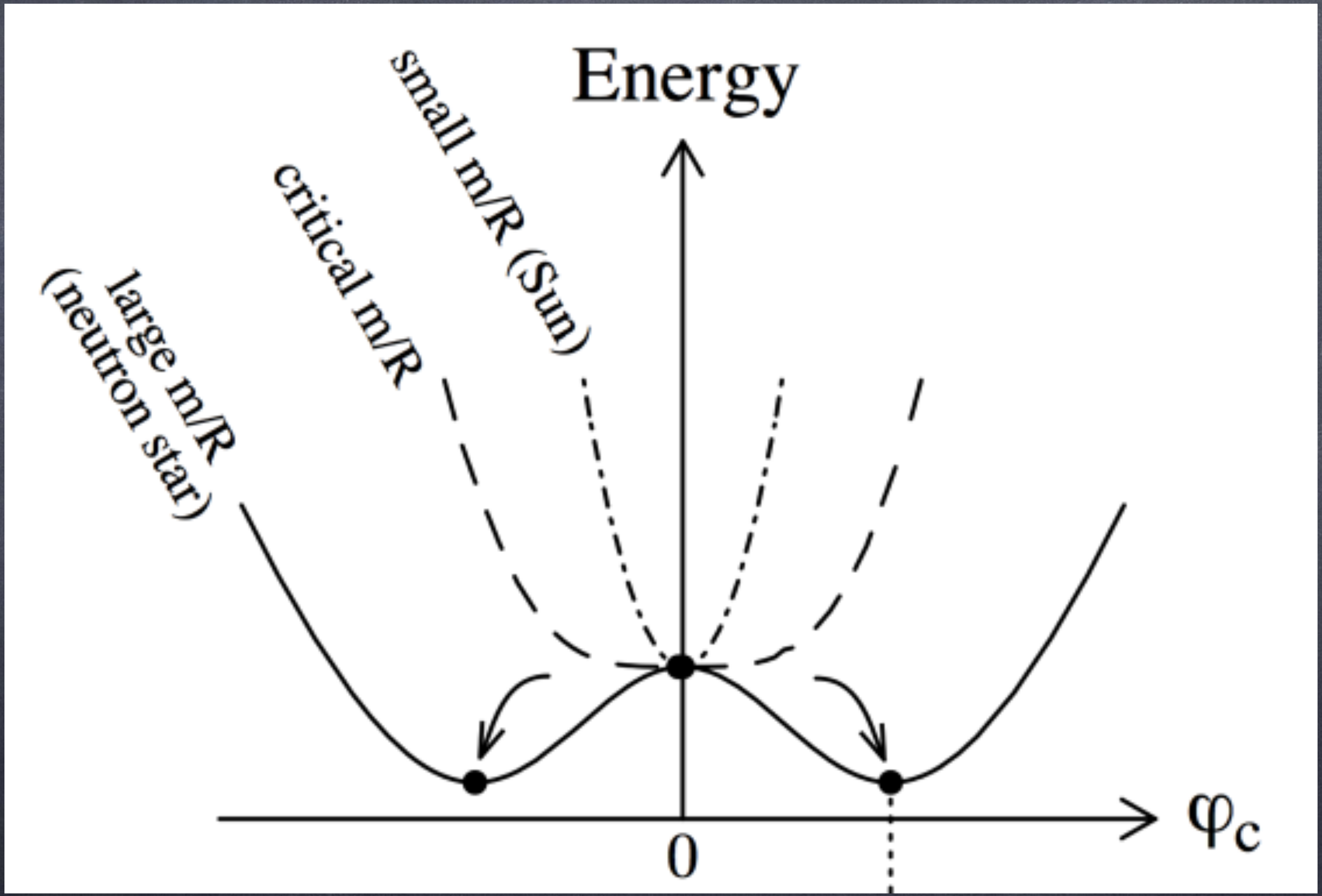


FIG. 3. *Evolution of the scalar field for* $\mathcal{C} = 0.43$. Time snapshots of the radial profile of the scalar field $\phi(t,r)$ (multiplied by r) near the collapse to a black hole. The black dots denote the position of the apparent black hole horizon, while the blue diamond point marks the position of the (apparent) sound horizon, which appears shortly after.

Bezares, Crisostomi, Palenzuela & EB, to appear tomorrow

Spontaneous/dynamical scalarization as "phase transitions"



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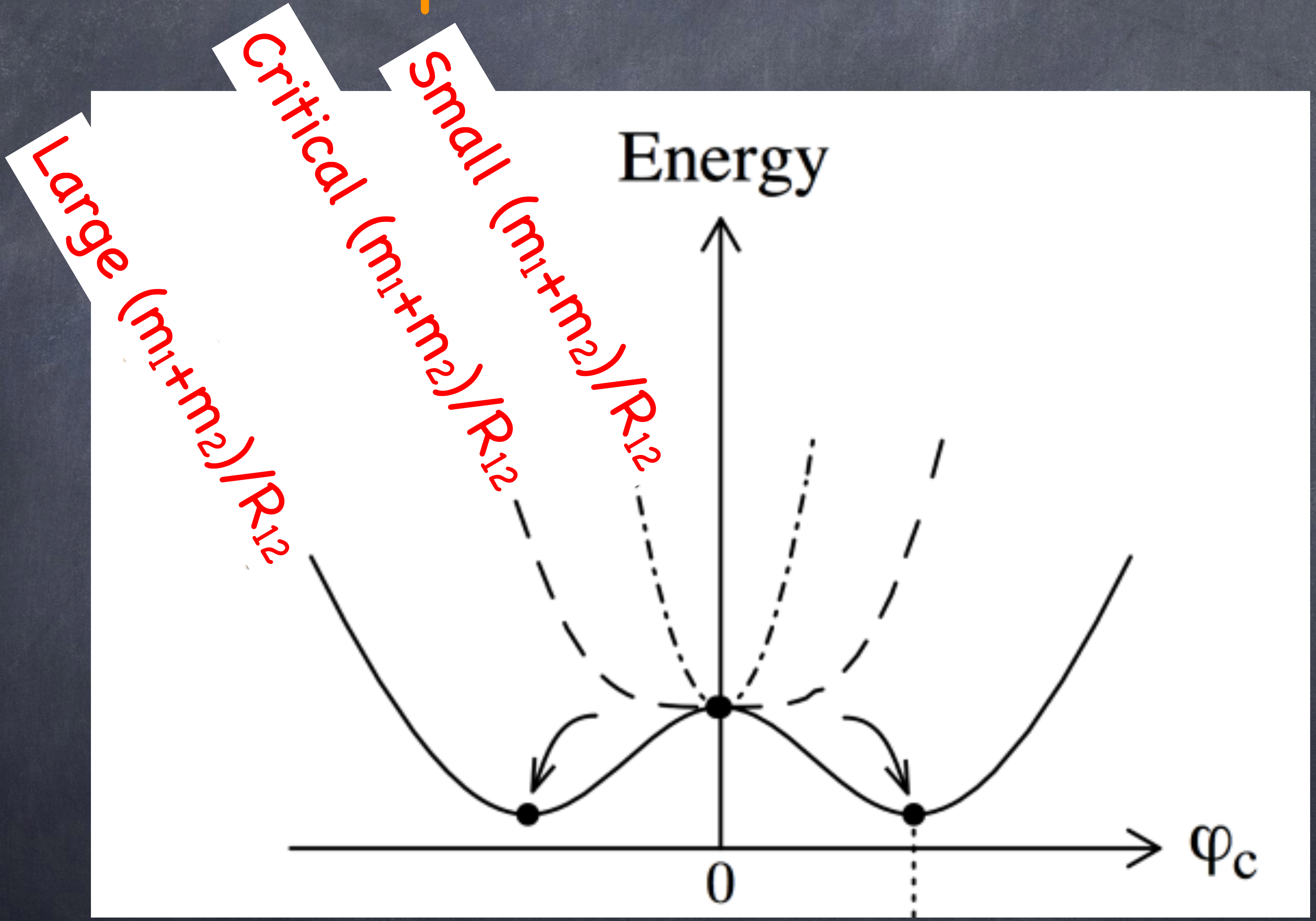
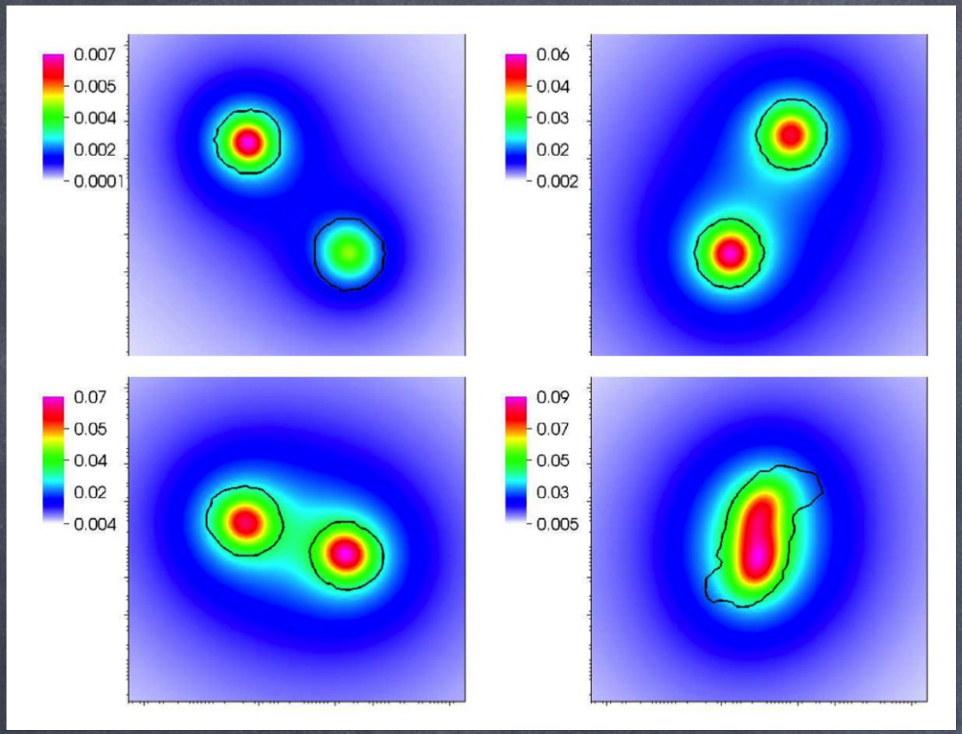
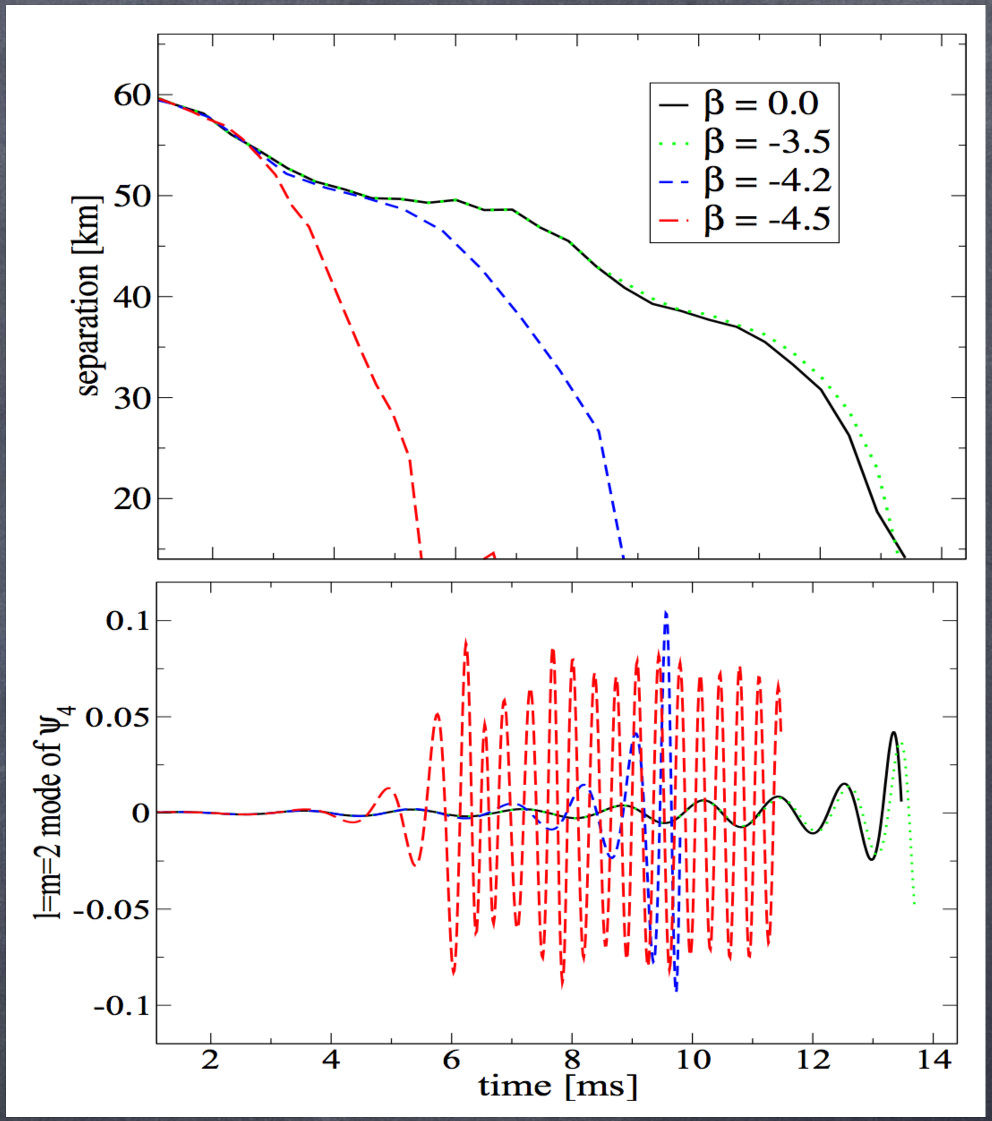


Smoking-gun scalar effects?

- 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

Conclusions

- BH charges beyond GR be produced perturbatively & non-perturbatively, like for neutron stars (BH/NS scalarization)
- BH charges lead to violations of the strong equivalence principle, to modified binary inspiral/ringdown
- Implications for GW and EM experiments (EHT, X-rays)
- Parametrized approached possible for both GW generation and BH geometry
- Strong deviations from GR possible also near horizon (superradiance, "firewalls", Lorentz violations) and potentially in mergers