Testing fields beyond GR and the Standard Model

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Why bother?

Pillars of modern physics:

General Relativity + Standard Model of Particle Physics

???

GR is not renormalizable

Dark Matter

Dark Energy

But also test the robustness of the assumptions behind the currently accepted paradigms.

GR "uniqueness" theorems

The Four-Dimensionality of Space and the Einstein Tensor

David Lovelock
Department of Applied Mathematics, University of Waterloo, Waterloo, Ontario, Canada
(Received 10 January 1972)

All tensors of contravariant valency two, which are divergence free on one index and which are concomitants of the metric tensor, together with its first two derivatives, are constructed in the four-dimensional case. The Einstein and metric tensors are the only possibilities.

D. Lovelock, Journal of Mathematical Physics 13, 874 (1972)

PHYSICAL REVIEW VOLUME 138, NUMBER 4B 24 MAY 1965

Photons and Gravitons in Perturbation Theory: Derivation of Maxwell's and Einstein's Equations*

STEVEN WEINBERG†
Department of Physics, University of California, Berkeley, California
(Received 7 January 1965)

We shall find within this perturbative dynamical framework that *Maxwell's theory and Einstein's theory are essentially the unique Lorentz-invariant theories of massless particles with spin $j=1$ and $j=2$.* By "essentially" we mean only that the conserved current $\mathcal{J}^\mu$ and $\mathcal{J}^{\mu\nu}$ to which the photon and graviton are coupled need

Modifying GR

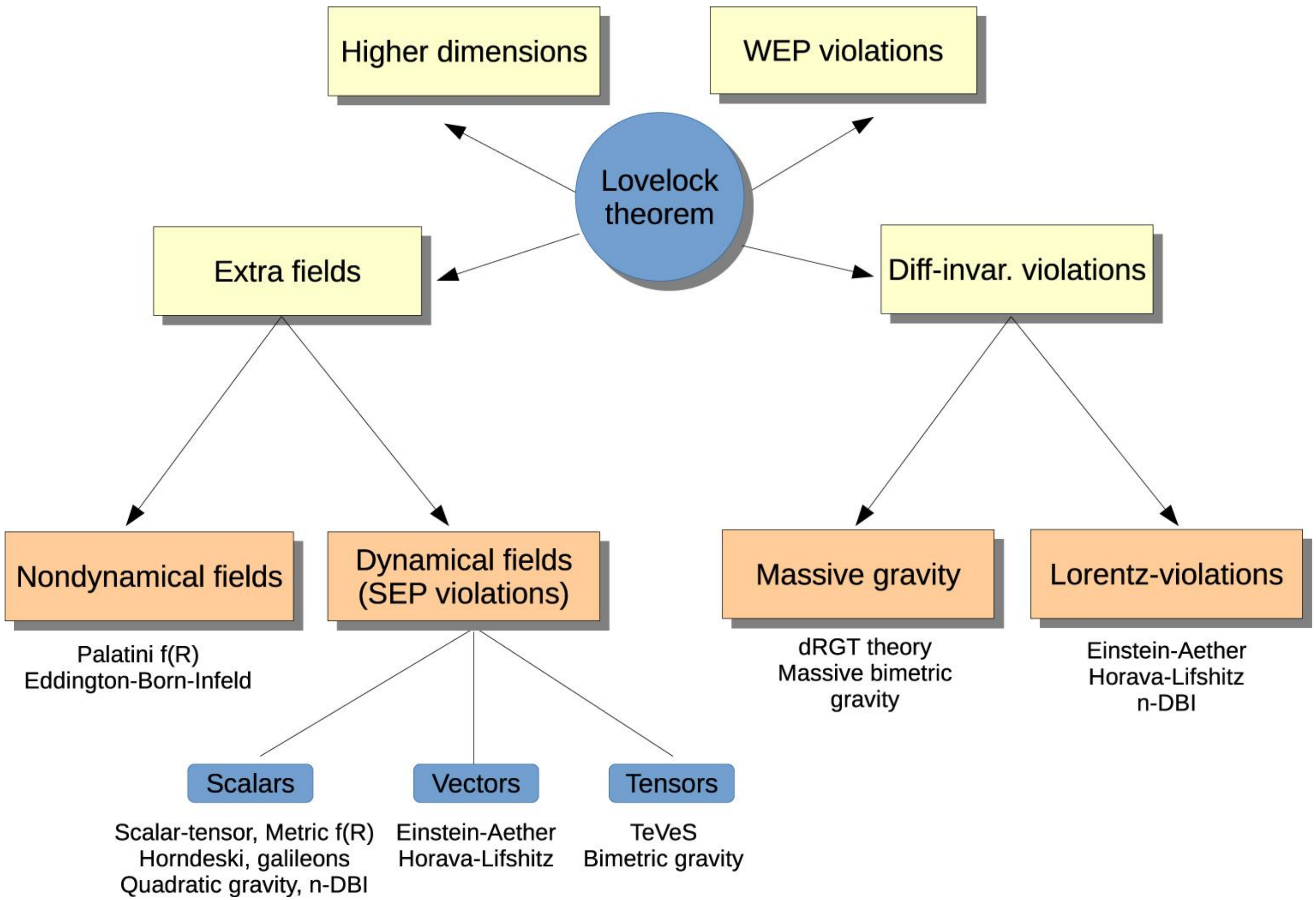
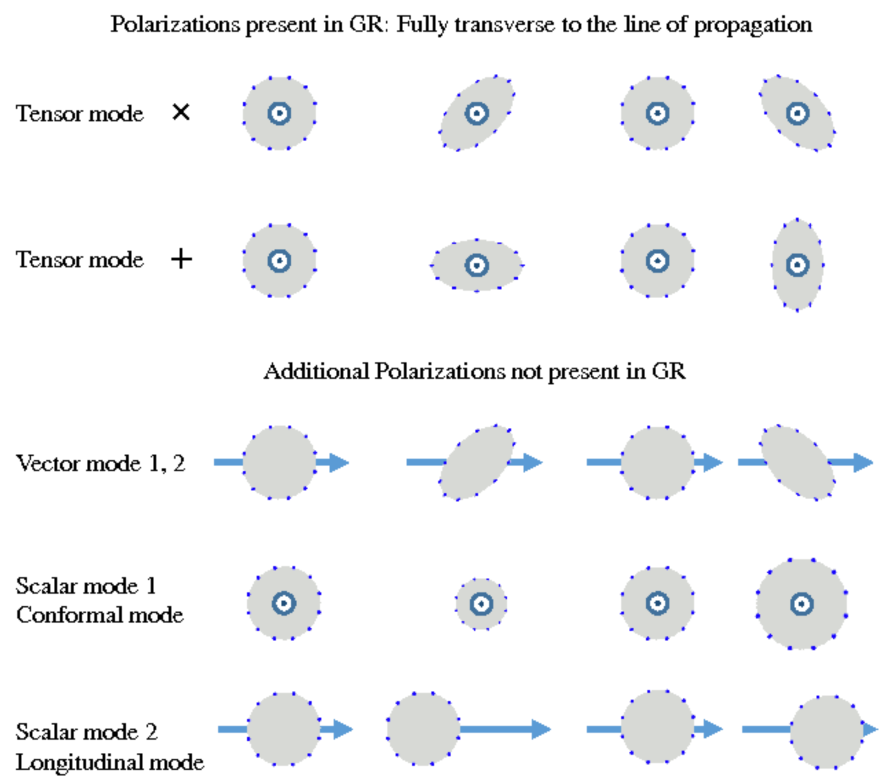


Figure from: Emanuele Berti et al 2015 Class. Quantum Grav. 32 243001

Consequences for GW physics

C. Will, Living Rev. Relativity (2014); N. Yunes & X. Siemens Living Rev. Relativity (2013); Gair *et al*, Living Rev. Relativity (2013); SEE ALSO BARAUSSE'S TALK

- Additional polarizations (up to 6 independent polarizations for a metric theory);
- Additional channels for energy loss, e.g. monopolar or dipolar radiation;
- Modified graviton dispersion relation (propagation speed ≠ c and frequency dependent speed; Lorentz violations);
- But also possibly different BH ringdown, BH hair, and other interesting phenomena (superradiant instabilities).



From: C. Rham, Living Rev. Relativity 17, (2014)

Going beyond GR: the example of black holes in theories with massive spin-2 fields (bimetric theories)

RB, Cardoso & Pani, Phys.Rev. D88 (2013) 023514
RB, Cardoso & Pani, Phys.Rev. D87 (2013) 124024
RB, Cardoso & Pani, Phys.Rev. D87 (2013) 064006
Babichev, RB & Pani, Phys. Rev. D93 (2016) 044041
Babichev & RB, Class. Quant. Grav. 32 (2015) 154001

Massive spin-2 fields

- Massive spin-2 fields are predicted by alternative theories of gravity called massive (bi)gravity. (de Rham, Gabadadze & Tolley '10, '11; Hassan & Rosen '12)

$$S = M_P^2 \int d^4x\sqrt{-g}\left[R[g] - m^2 V(\mathbf{g}^{-1}\mathbf{f})\right] + \kappa M_P^2 \int d^4x\sqrt{-f}\,\mathcal{R}[f]$$

- If $g_{\mu\nu}^{(0)} = C^2 f_{\mu\nu}^{(0)}$, then $V(\mathbf{g}^{-1}\mathbf{f}) \propto \Lambda \implies$ black-hole solutions are the same of General Relativity with a cosmological constant Λ in vacuum. Consider small perturbations around these solutions:

$$g_{\mu\nu} = g_{\mu\nu}^{(0)} + h_{\mu\nu}^{(g)}\,, \qquad f_{\mu\nu} = f_{\mu\nu}^{(0)} + h_{\mu\nu}^{(f)}$$

$$\begin{cases} \Box h_{\mu\nu}^{-} + 2R^{\alpha\ \ \beta}_{\ \mu\ \ \nu} h_{\alpha\beta}^{-} - \mu^2 h_{\mu\nu}^{-} = 0\,, \\ \mu^2 \nabla^\mu h_{\mu\nu}^{-} = 0\,, \\ \left(\mu^2 - 2\Lambda/3\right) h^{-} = 0 \end{cases}$$

Massive spin-2 field with mass μ

where $h_{\mu\nu}^{-} = h_{\mu\nu}^{(g)} - h_{\mu\nu}^{(f)}$.

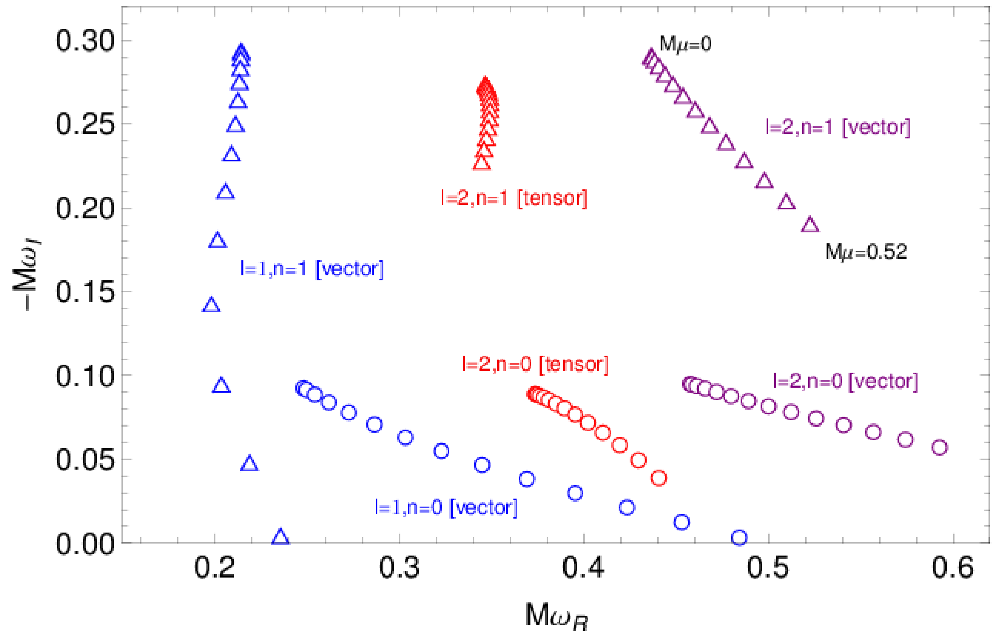
+ massless spin-2

Black hole ringdown (in Schwarzschild)

Brito, Cardoso & Pani, '13

$$h_{\mu\nu}(t,r,\theta,\phi) = \sum_{l,m} \int_{-\infty}^{+\infty} \delta X_{lm}^{(i)}(r) \mathcal{Y}_{\mu\nu}^{lm\,(i)}(\theta) e^{im\phi} e^{-i\omega t} d\omega$$

$$\omega = \omega_R + i\omega_I$$



Mode excitation?
Even if monopolar and dipolar modes might not be excited, quadrupolar mode still different from GR, making GW-based tests relevant.
SEE ALSO CARDOSO'S AND BARAUSSE'S TALK

Asymptotically flat hairy black holes

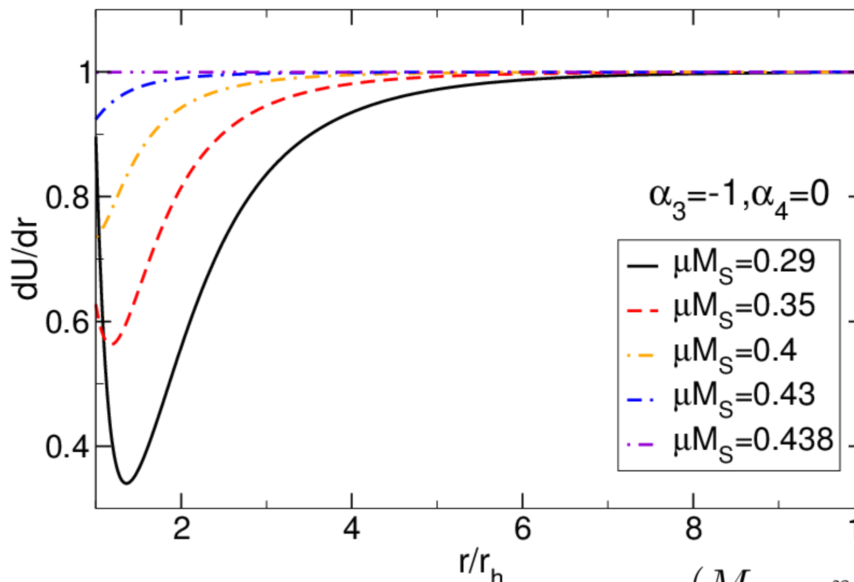
Babichev & Fabbri, ’13; Brito, Cardoso & Pani, ‘13

- Schwarzschild geometry is unstable against massive spin-2 perturbations for $\mu M \lesssim 0.43$.(Babichev & Fabbri, ’13; Brito, Cardoso & Pani, ‘13)

- Instability indicates the onset of non-Schwarzschild solutions (“hairy BHs”) which can be found numerically in the framework of massive bigravity. (Brito, Cardoso & Pani, ’13)

$$
\begin{aligned}
g_{\mu\nu}dx^\mu dx^\nu &= -F^2\,dt^2 + B^{-2}\,dr^2 + r^2 d\Omega^2 \\
f_{\mu\nu}dx^\mu dx^\nu &= -p^2\,dt^2 + \left(U'/Y\right)^2\,dr^2 + U^2 d\Omega^2
\end{aligned}
$$

Specific example of a theory that admits different black-hole solutions than GR. GW and electromagnetic based tests may test the no-hair theorem. SEE ALSO CARDOSO’S TALK



$(M_S = r_h/2)$

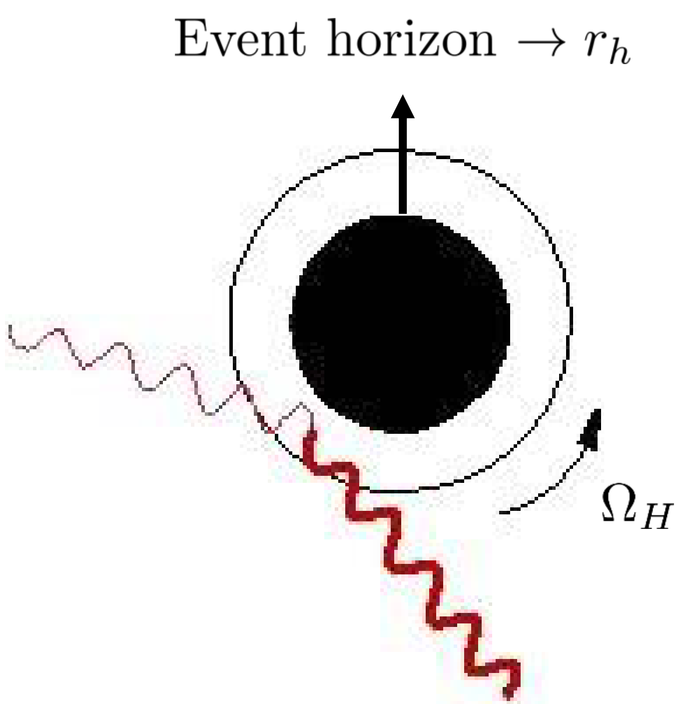
Superradiant instabilities & black holes as particle detectors

RB, Cardoso & Pani, Phys.Rev. D88 (2013) 023514
RB, Cardoso & Pani, Phys.Rev. D89 (2014) 104045
RB, Cardoso & Pani, Class. Quant. Grav. 32 (2015) no.13, 134001
RB, Cardoso & Pani, “Superradiance”, Lect.Notes Phys. 906 (2015), Springer-Verlag

SEE ALSO DUBOVSKY’S TALK

Rotating BHs: Superradiance

Zel'dovich, '71; Misner '72; Press and Teukolsky ,'72-74



$$\Phi(t, r, \theta, \phi) = \Psi(r) e^{-i\omega t + im\phi} P_l(\cos\theta)$$

$$\frac{\omega}{m} < \Omega_H$$

$$\Omega_H = \frac{J}{2 r_h M^2}$$

$J \rightarrow$ angular momentum

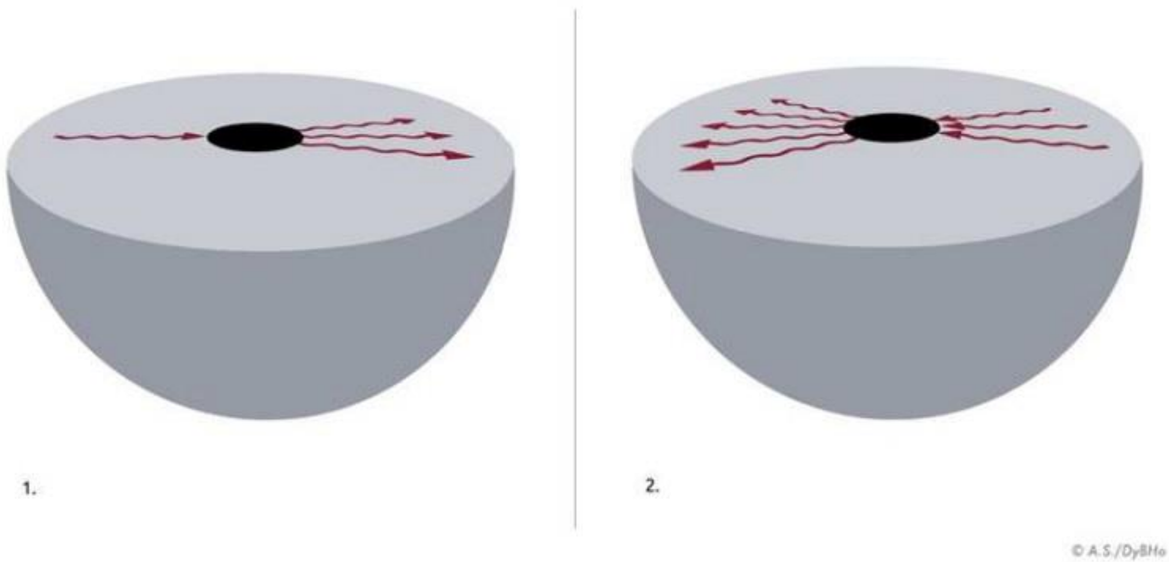
Amplified scattering of **bosonic** waves ⇒ Extraction of energy and angular momentum from the BH

Brito, Cardoso & Pani, "Superradiance", '15

Superradiant instability

Press & Teukolsky, '72; Cardoso, Dias, Lemos & Yoshida '04

Confinement + Superradiance $\longrightarrow$ Superradiant instability



Kerr surrounded by a perfectly reflecting mirror is unstable against bosonic radiation (includes gravitational radiation) with frequency:

$$\omega < m\Omega_H$$

Massive bosonic fields around Kerr

Detweiler , PRD22 (1980) 2323, Pani *et al*, PRD86 (2012) 104017, Witek *et al*, PRD87 (2013) 043513, Brito, Cardoso & Pani, PRD88 (2013) 023514

- s=0,

$$\Box\Phi - \mu_S^2\Phi = 0$$

- s=1,

$$\begin{cases} \Box A_\nu - \mu_V^2 A_\nu = 0\,, \\ \mu_V^2 \nabla^\mu A_\mu = 0\,. \end{cases}$$

- s=2,

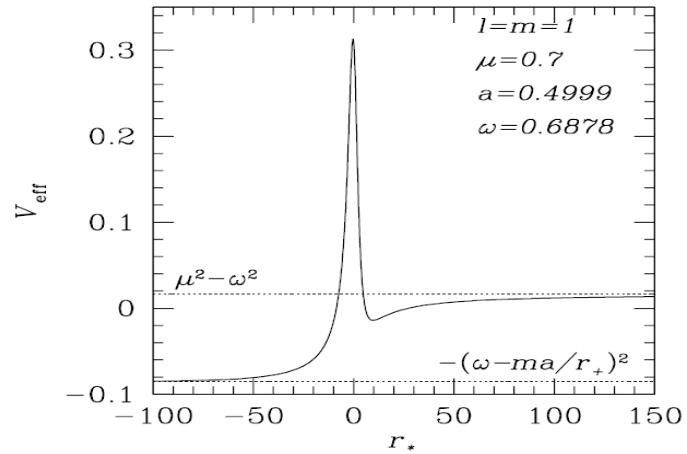
$$\begin{cases} \Box h_{\mu\nu} + 2R_{\alpha\mu\beta\nu}h^{\alpha\beta} - \mu_T^2 h_{\mu\nu} = 0\,, \\ \mu_T^2 \nabla^\mu h_{\mu\nu} = 0\,, \\ \mu_T^2 h = 0\,. \end{cases}$$

$$X_{\mu_1\ldots}(t,r,\vartheta,\varphi) = X^{(i)}_{lm}(r)\mathcal{Y}^{lm\,(i)}_{\mu_1\ldots}(\vartheta)e^{im\varphi}e^{-i\omega t}$$

$$\frac{d^2X}{dr_*^2} + (\omega^2 - V_{\rm eff})X = 0$$

$$\omega = \omega_R + i\omega_I$$

$$\boxed{\begin{array}{ccc} \omega_R & \sim & \mu \\ \omega_I & \propto & (m\Omega_H - \omega_R)\,(M\mu)^\alpha \end{array}}$$



From: Cardoso & Yoshida, JHEP 0507 (2005) 009

Massive bosonic fields around Kerr are unstable when $\omega_R < m\Omega_H$.

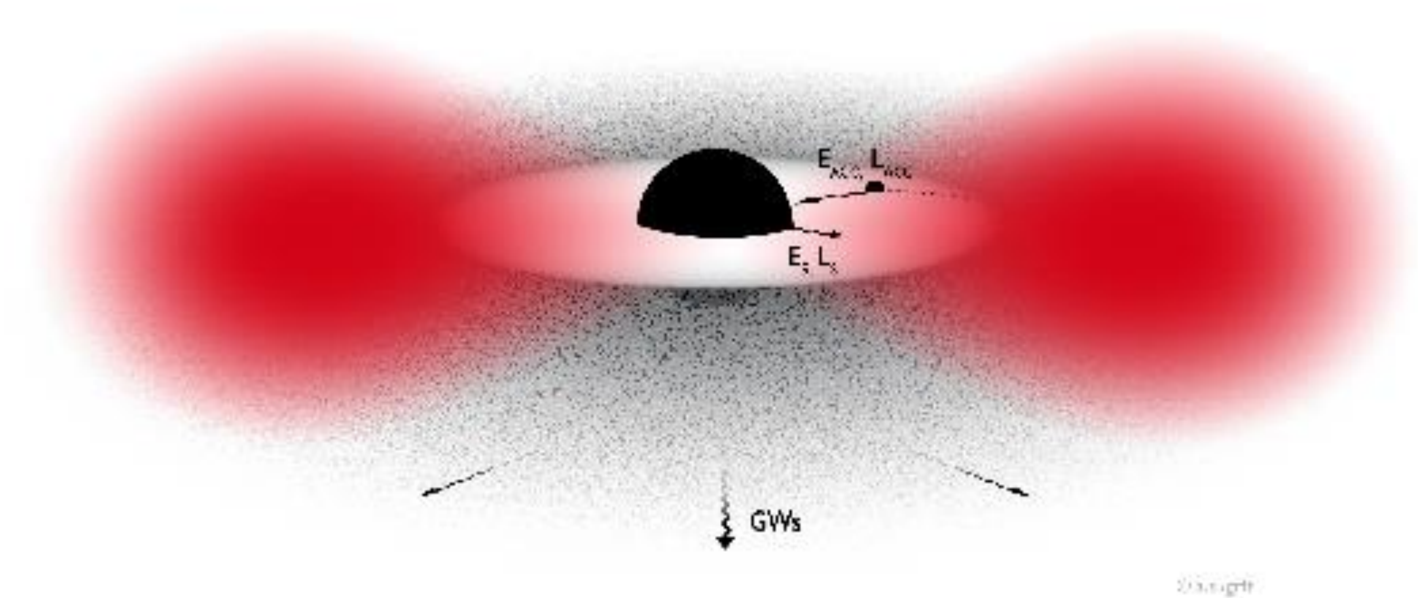
Relevant when $r_h/\lambda_c \lesssim 1$.

$$a \sim M\,,\ \mu_S \sim 0.42M^{-1} \sim 5.6\times10^{-17}\left(\frac{10^6 M_\odot}{M}\right)\text{eV}\,,\ \tau \sim 6.7\times10^6 M \sim \left(\frac{M}{10^6 M_\odot}\right)\text{yr}$$

Evolution of the superradiant instability

- End-state is still theoretically unknown, but we know that black hole slowly loses spin and mass due to the instability until reaching saturation $\omega_R = m\Omega_H$.

- Formation of bosonic condensates around BHs (or hairy black holes for complex scalar and vector fields Herdeiro & Radu '14; Herdeiro, Radu & Runarsson '16).



Continuous gravitational-wave sources

- "Gravitational wave lighthouses"– long-lived gravitational signals. Arvanitaki & Dubovsky , '11; SEE DUBOVSKY'S TALK

$$\Phi \sim \cos(\omega_R t) e^{\omega_I t}, \qquad T^{\mu\nu}_{\rm scalar} = -\frac{1}{4} g^{\mu\nu} \left(\Phi_{,\alpha}\Phi^{,\alpha} + \mu_S^2 \Phi^2\right) + \frac{1}{2}\Phi^{\mu}\Phi^{,\nu} \sim \Re(e^{2i\omega_R t})$$

- If only the fundamental mode for l=m=1 is populated, $f_{\rm GW} \sim 5\,{\rm mHz}\left(\frac{m_B c^2}{10^{-17}{\rm eV}}\right)$,

$$h \sim 8 \times 10^{-20} \left(\frac{a}{0.9}\right) \left(\frac{r_h/\lambda_c}{0.4}\right)^7 \left(\frac{M_{BH}}{10^6 M_\odot}\right) \left(\frac{1{\rm Mpc}}{d}\right)$$

$$t_{\rm GW} \sim 10^5 \left(\frac{0.9}{a}\right) \left(\frac{0.4}{r_h/\lambda_c}\right)^{15} \left(\frac{M_{BH}}{10^6 M_\odot}\right) \text{years}$$

- Periodic GW signal could be observable by LIGO and by eLISA (number of events highly dependent of the field mass). Arvanitaki, Baryakhtar & Huang '15; Barausse, Berti, RB, Cardoso, Ghosh & Pani, *work in progress*; SEE DUBOVSKY'S TALK

Gaps in the M vs J plane

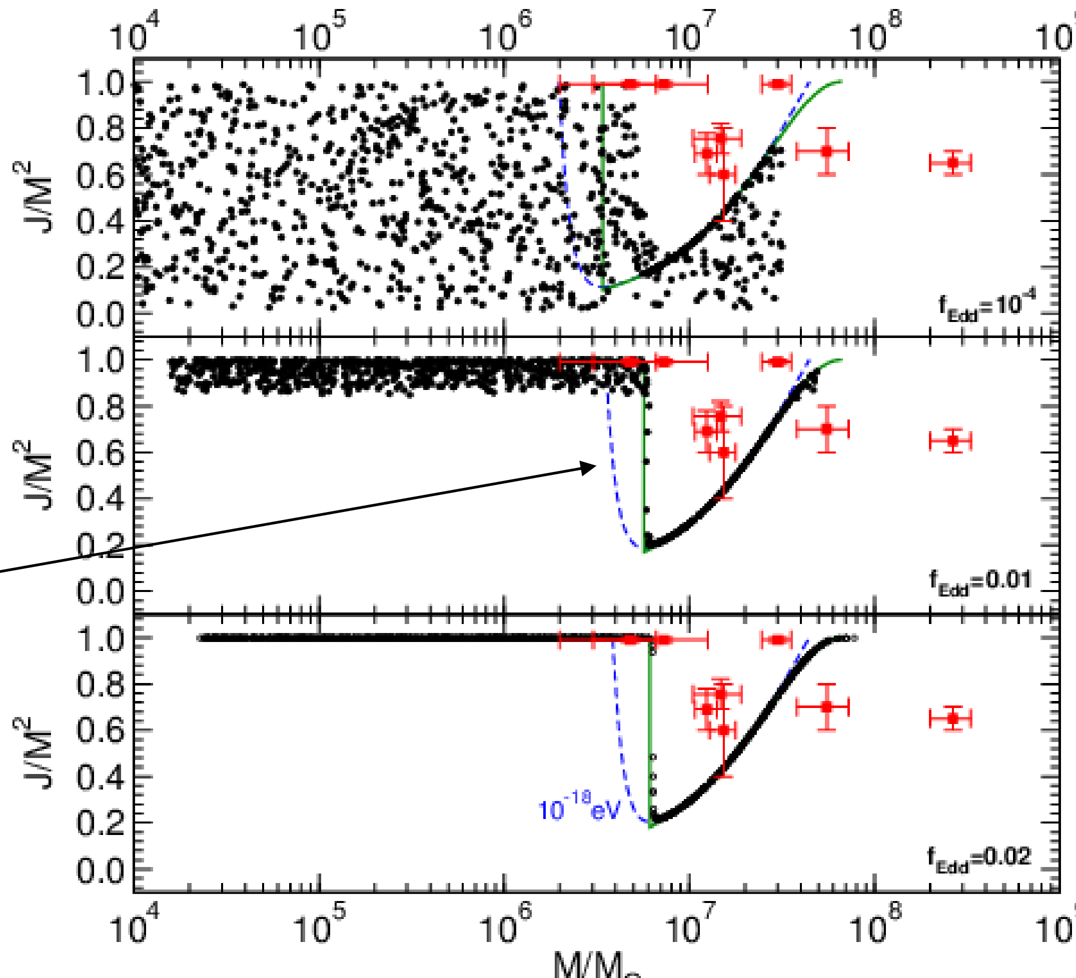
Arvanitaki & Dubovsky , '11; Brito, Cardoso, Pani, '14; SEE DUBOVSKY'S TALK

- Adiabatic evolution of the instability is a very good approximation for SMBHs.
- Instability timescale should be shorter than typical spin up effects, e.g. accretion of gas:

$$\tau_{\text{instability}} \approx \tau_{\text{accretion}}$$

$$\tau_{\text{accretion}} \sim 4.5 \times 10^7 \text{yr}/f_{\text{Edd}}$$

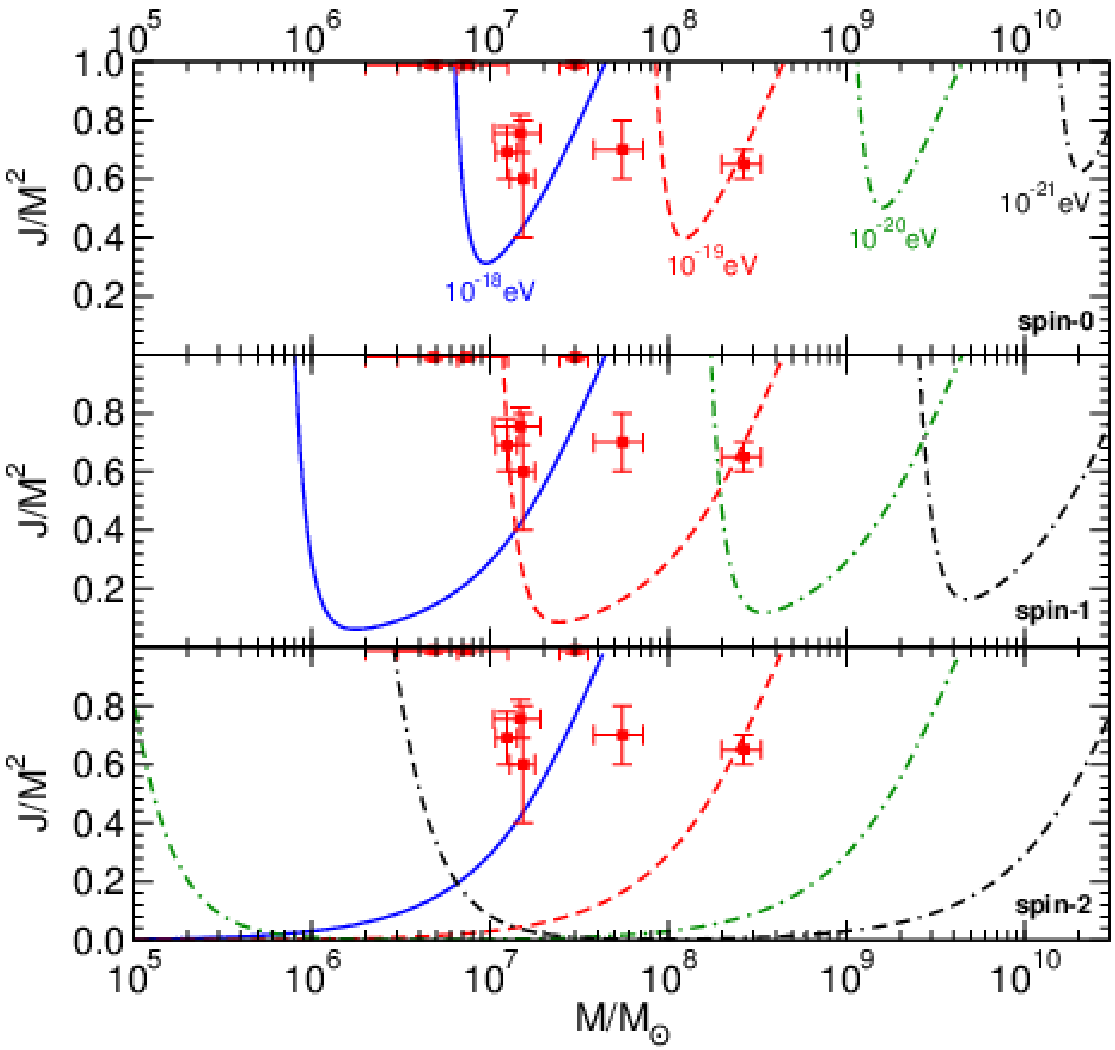
- Observations of several BHs, with **precise** measurement of mass and spin, could give indications of new physics.



Random distributions of the initial BH mass between $\log_{10} M_0 \in [4, 7.5]$ and $J_0/M_0^2 \in [0.001, 0.99]$ extracted at $t = t_F$, where t_F is distributed on a Gaussian centered at $\bar{t}_F \sim 2 \times 10^9$yr with width $\sigma = 0.1\bar{t}_F$.

Bounds on light bosons

Arvanitaki & Dubovsky Phys.Rev. D83 (2011) 044026 , Pani *et al*, Phys.Rev.Lett. 109 (2012) 131102, Phys.Rev. D86 (2012) 104017, Brito, Cardoso & Pani, Phys.Rev. D88 (2013) 023514



Conclusions

- Extra classical fields, either in the form of minimally coupled fields or under curvature couplings have a very rich and unexplored phenomenology.

- GW-based tests will become an important tool to study the geometry near black-hole spacetimes and to constrain modified theories of gravity.

- Superradiant instabilities can provide strong constraints on ultra-light bosons, turning black holes into effective particle detectors.

- Bosonic condensates around BHs can act as GW lighthouses, so if we listen carefully, we may find the first hints for new fundamental particles through GWs.

Thank you

Backup Slides

Radial Instability of SdS

Babichev & Fabbri, '13; Brito, Cardoso & Pani, '13

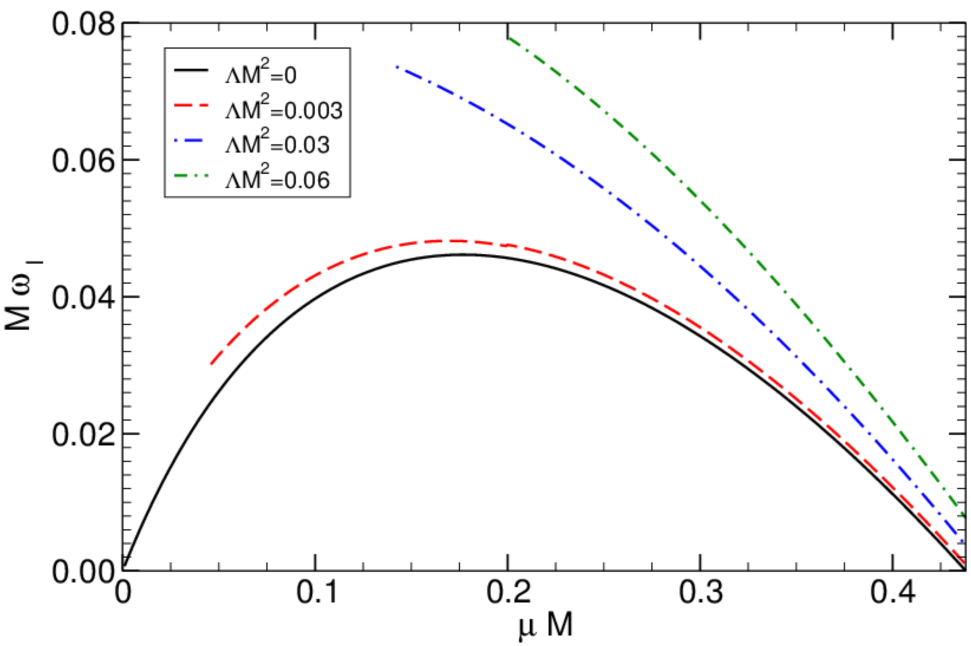
Massive spin-2 field equations in Schwarzschild equivalent to gravitational perturbations of a black string (Babichev & Fabbri, '13) : black strings are unstable against the Gregory-Laflamme instability. (Gregory & Laflamme, '93)

- Radial perturbations of Schwarzschild-de Sitter (SdS):

$$h \sim e^{\omega_I t}$$

- Schwarzschild(-de Sitter) BHs are **unstable** against massive spin-2 field radial perturbations!

$M \to$ black-hole mass



Asymptotically flat:

$$0 < \mu M \lesssim 0.43$$

Asymptotically de Sitter:

$$\mu^2 = 2\Lambda/3 \implies \text{stable}$$

$$\mu^2 < 2\Lambda/3 \implies \text{ghost in de Sitter}$$

Higuchi '87

Evolution of the instability

Brito, Cardoso, Pani, arXiv:1411.0686, 2014

- **Accretion:**

$$\dot{M}_{\rm ACC} \equiv f_{\rm Edd}\dot{M}_{\rm Edd}$$

$$\dot{J}_{\rm ACC} \equiv \frac{L_{\rm ISCO}(M,J)}{E_{\rm ISCO}(M,J)}\dot{M}_{\rm ACC}$$

- **GW emission:**

$$\dot{E}_{\rm GW} = \frac{484+9\pi^2}{23040}\left(\frac{M_S^2}{M^2}\right)(M\mu)^{14}$$

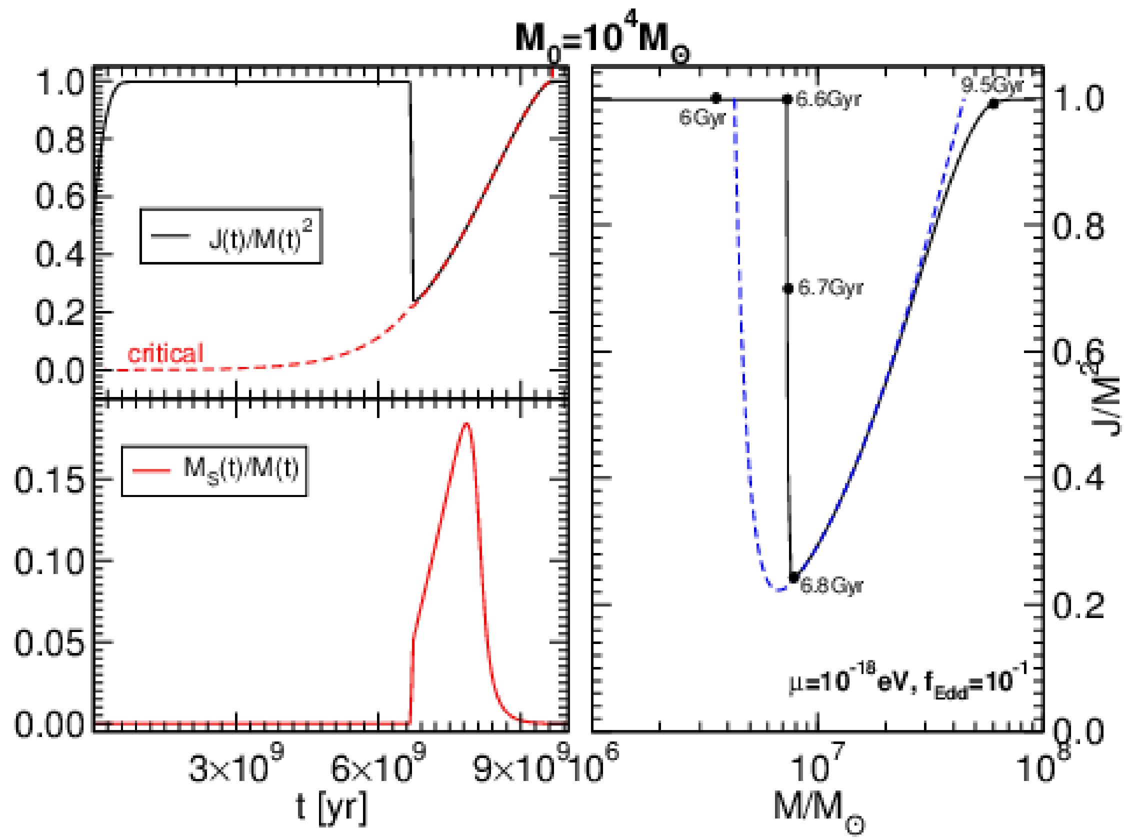
$$\dot{J}_{\rm GW} = \frac{1}{\mu}\dot{E}_{\rm GW}$$

- **Scalar energy flux:**

$$\dot{E}_S = 2M_S\omega_I$$

$$M\omega_I = \frac{1}{48}(a/M - 2\mu r_+)(M\mu)^9$$

$$\begin{aligned} \dot{M}_S &= \dot{E}_S - \dot{E}_{\rm GW} \\ \dot{J}_S &= \frac{1}{\mu}\dot{E}_S - \dot{J}_{\rm GW} \end{aligned} \qquad \begin{aligned} \dot{M} &= -\dot{E}_S + \dot{M}_{\rm ACC} \\ \dot{J} &= -\frac{1}{\mu}\dot{E}_S + \dot{J}_{\rm ACC} \end{aligned}$$



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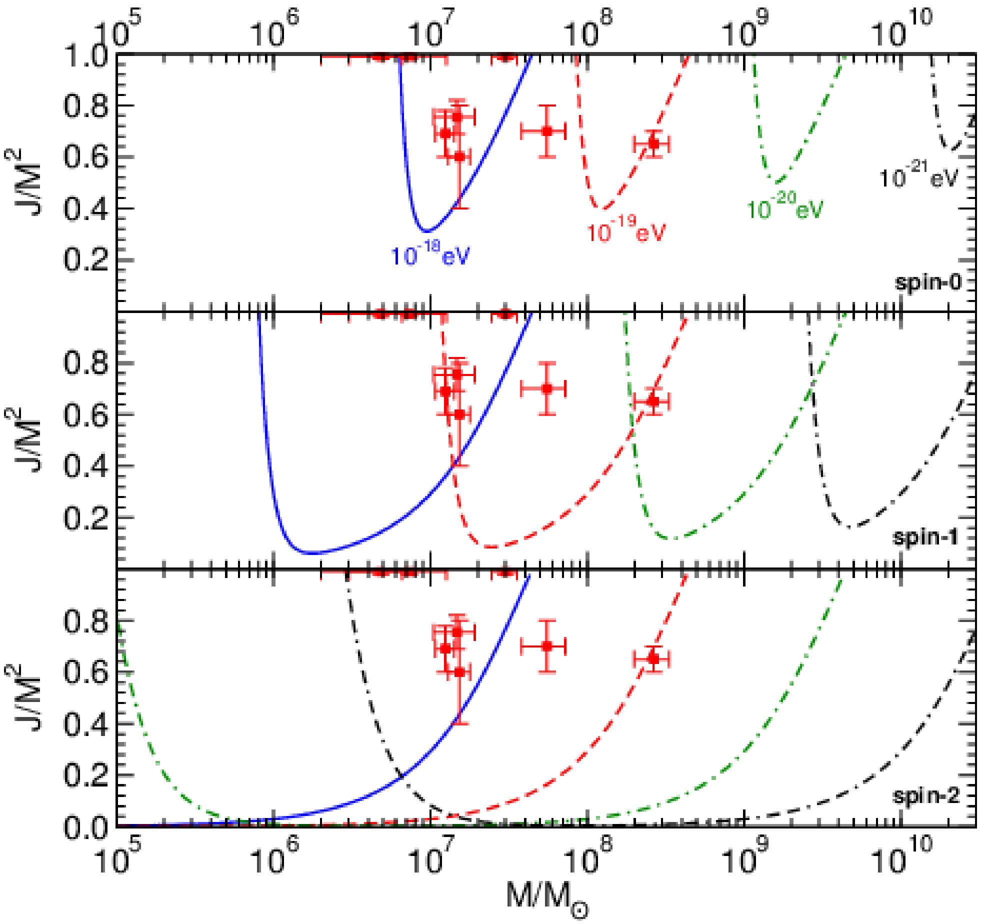

$$M_\odot \lesssim M \lesssim 10^9 M_\odot \quad \Longrightarrow \quad \begin{array}{lcl} m_S \lesssim 5\times 10^{-20}\text{eV} & \cup & m_S \gtrsim 10^{-11}\text{eV} \\ m_V \lesssim 5\times 10^{-21}\text{eV} & \cup & m_V \gtrsim 10^{-11}\text{eV} \\ m_T \lesssim 5\times 10^{-23}\text{eV} & \cup & m_T \gtrsim 10^{-11}\text{eV} \end{array}$$