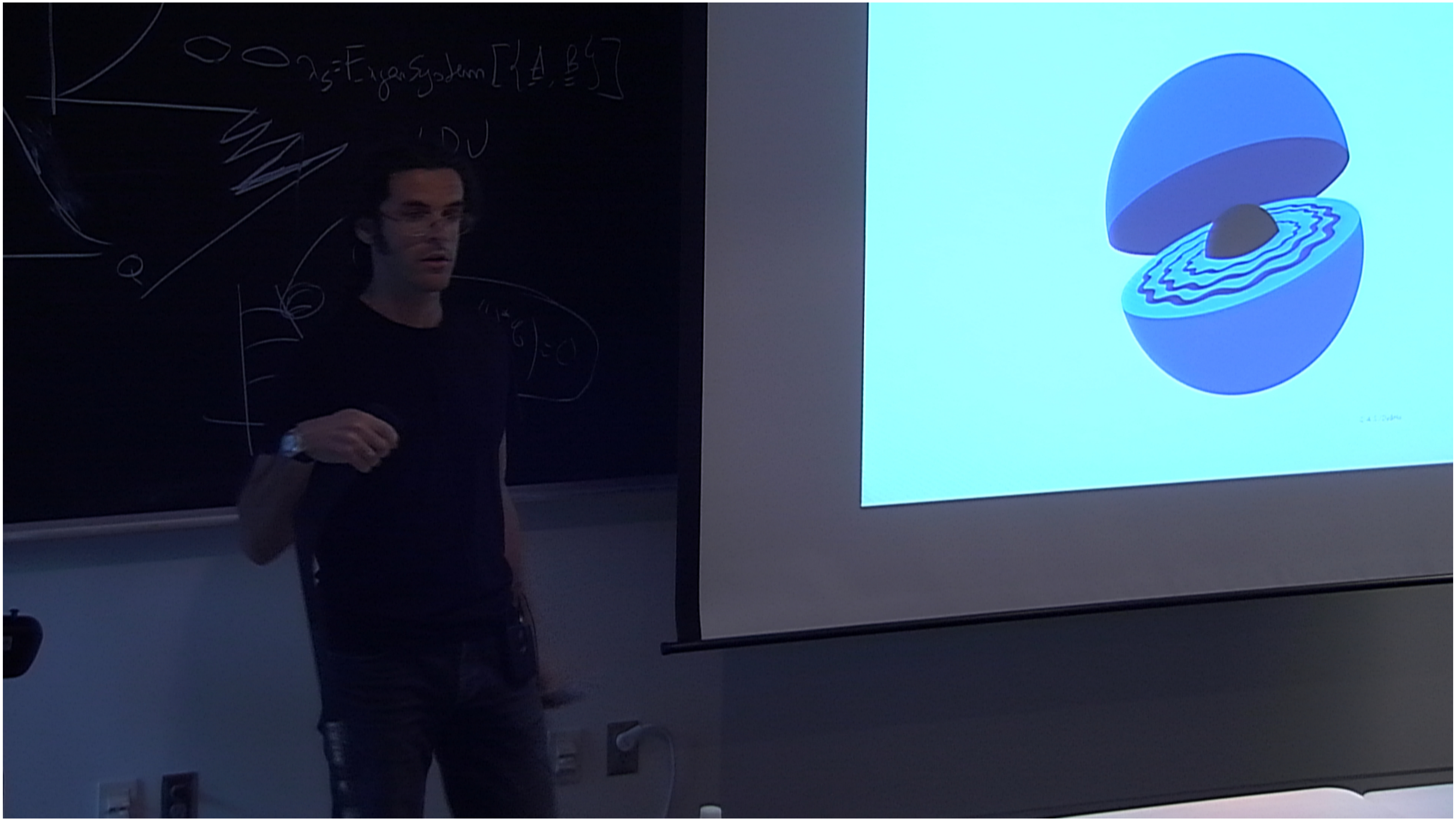
Title: Black Hole Bombs

Date: Jun 06, 2012 10:30 AM

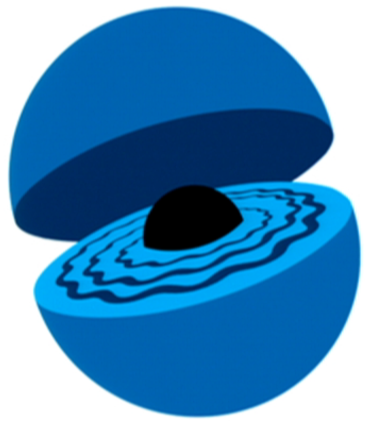
URL: http://pirsa.org/12060012

Abstract: Superradiance in black hole physics is responsible for a chief number of interesting and spectacular effects. Here I will discuss some attempts at understanding the behavior of massive bosonic fields around rotating black holes, with focus on superradiance.


λs=EigenSystem[{A,B}]

Black hole bombs

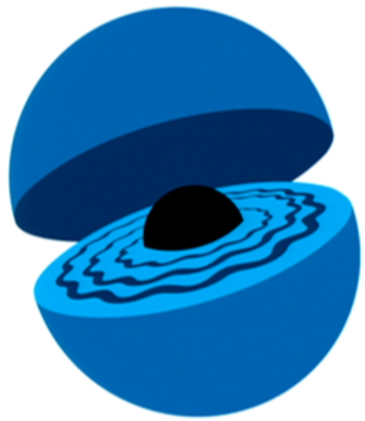
Vítor Cardoso • June 06, 2012 • Perimeter Institute



More info at http://blackholes.ist.utl.pt | erc supports this project

Black hole bombs

Vítor Cardoso • June 06, 2012 • Perimeter Institute

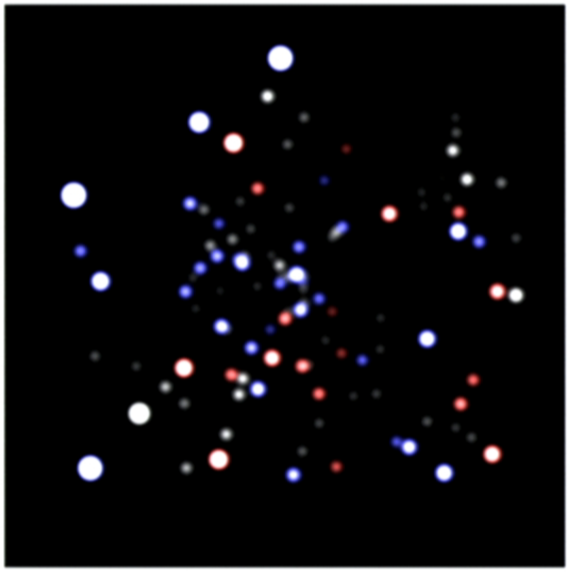


More info at http://blackholes.ist.utl.pt | erc supports this project

Berti, **Brito**, Gualtieri, Ishibashi, **Pani**, Sperhake, **Witek**, Yunes

* * *

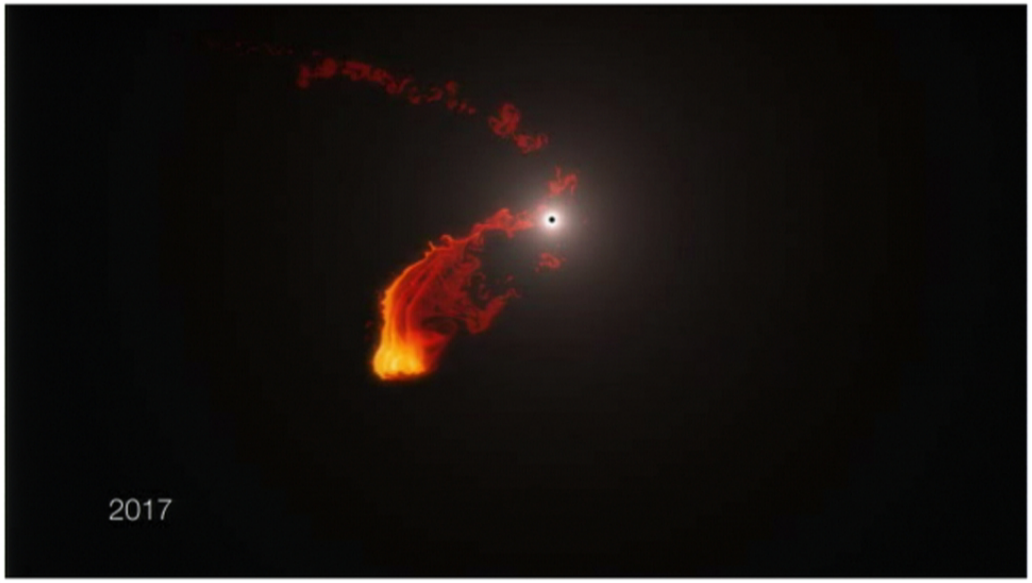
Cardoso et al, Phys. Rev. Lett. 107:241101 (2011)
Yunes et al, Phys. Rev. D 81:084052 (2011)
Pani et al, Phys. Rev. Lett., submitted (2012)
Witek et al, in preparation (2012?)



Credit: ESO/MPE (2010)

Credit: ESO/MPE/M.Schartmann (2011)

Gillessen et al, Nature 481, 51 (2012)



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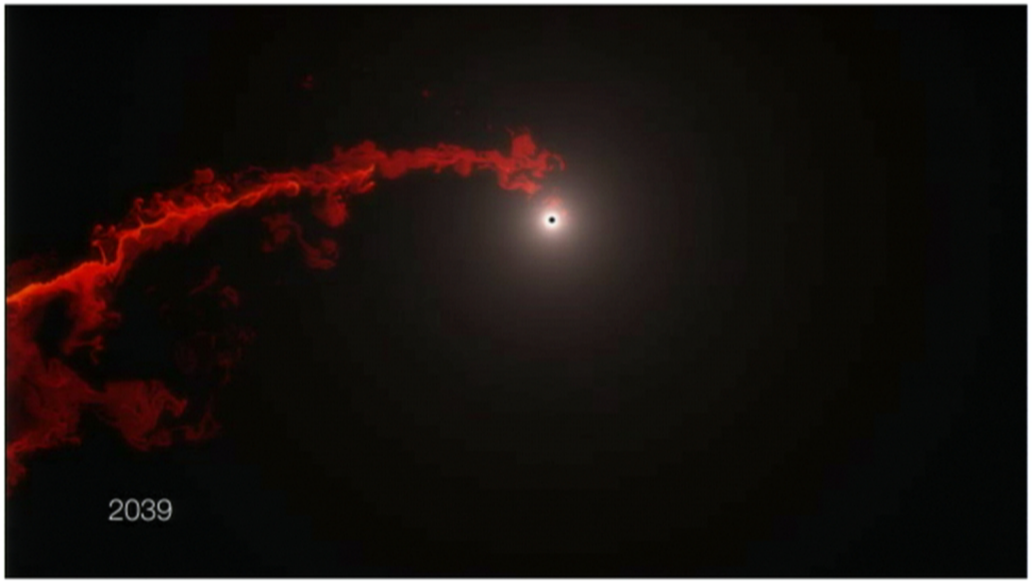
Gillessen et al, Nature 481, 51 (2012)



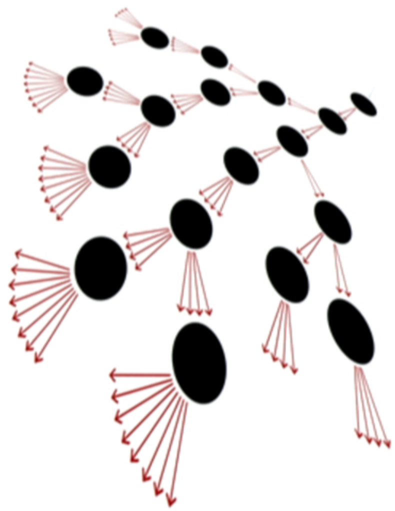
Credit: ESO/MPE/M.Schartmann (2011)

Gillessen et al, Nature 481, 51 (2012)

AGN	a	$W_{K\alpha}$	q_1	Fe/solar	ξ	log M	$L_{\rm bol}/L_{\rm Edd}$	Host	WA
MCG–6-30-15[a]	≥ 0.98	305^{+20}_{-20}	$4.4^{+0.5}_{-0.8}$	$1.9^{+1.4}_{-0.5}$	68^{+31}_{-31}	$6.65^{+0.17}_{-0.17}$	$0.40^{+0.13}_{-0.13}$	E/S0	yes
Fairall 9[b]	$0.65^{+0.05}_{-0.05}$	130^{+10}_{-10}	$5.0^{+0.0}_{-0.1}$	$0.8^{+0.2}_{-0.1}$	$3.7^{+0.1}_{-0.1}$	$8.41^{+0.11}_{-0.11}$	$0.05^{+0.01}_{-0.01}$	Sc	no
SWIFT J2127.4+5654[c]	$0.6^{+0.2}_{-0.2}$	220^{+50}_{-50}	$5.3^{+1.7}_{-1.4}$	$1.5^{+0.3}_{-0.3}$	40^{+70}_{-35}	$7.18^{+0.07}_{-0.07}$	$0.18^{+0.03}_{-0.03}$	—	yes
1H0707–495[d]	≥ 0.98	1775^{+511}_{-594}	$6.6^{+1.9}_{-1.9}$	≥ 7	50^{+40}_{-40}	$6.70^{+0.40}_{-0.40}$	$\sim 1.0_{-0.6}$	—	no
Mrk 79[e]	$0.7^{+0.1}_{-0.1}$	$377^{+}47_{-34}$	$3.3^{+0.2}_{-0.1}$	1.2∗	177^{+6}_{-6}	$7.72^{+0.14}_{-0.14}$	$0.05^{+0.01}_{-0.01}$	SBb	yes
Mrk 335[f]	$0.70^{+0.12}_{-0.01}$	146^{+39}_{-39}	$6.6^{+2.0}_{-1.0}$	$1.0^{+0.1}_{-0.1}$	207^{+5}_{-5}	$7.15^{+0.13}_{-0.13}$	$0.25^{+0.07}_{-0.07}$	S0a	no
NGC 7469[f]	$0.69^{+0.09}_{-0.09}$	91^{+9}_{-8}	≥ 3.0	≤ 0.4	≤ 24	$7.09^{+0.06}_{-0.06}$	$1.12^{+0.13}_{-0.13}$	SAB(rs)a	no
NGC 3783[g]	≥ 0.98	263^{+23}_{-23}	$5.2^{+0.7}_{-0.8}$	$3.7^{+0.9}_{-0.9}$	≤ 8	$7.47^{+0.08}_{-0.08}$	$0.06^{+0.01}_{-0.01}$	SB(r)ab	yes

Brenneman et al, ApJ736, 103 (2011)

Fission through BH superradiance?



$$\sigma \sim r_+^{D-2} < 0$$

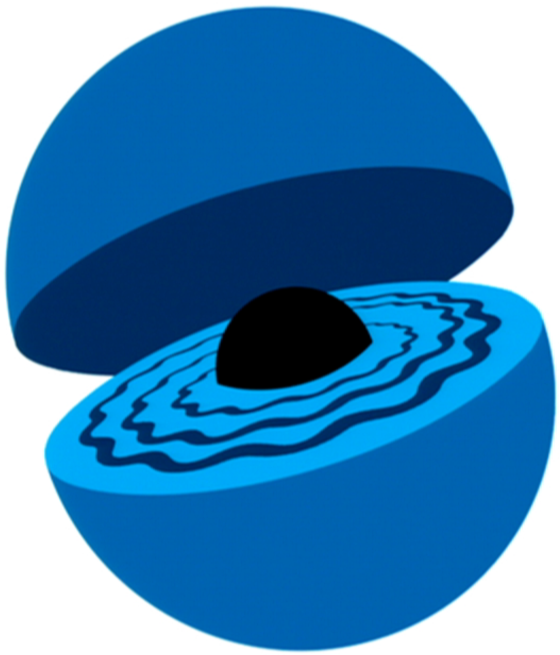
$$\ell_{\text{free path}} \sim \frac{1}{\sigma n}$$

$$\ell_{\text{free path}} \leq R \rightsquigarrow \frac{NM}{R^{D-3}} \gtrsim N^{\frac{1}{D-2}}$$

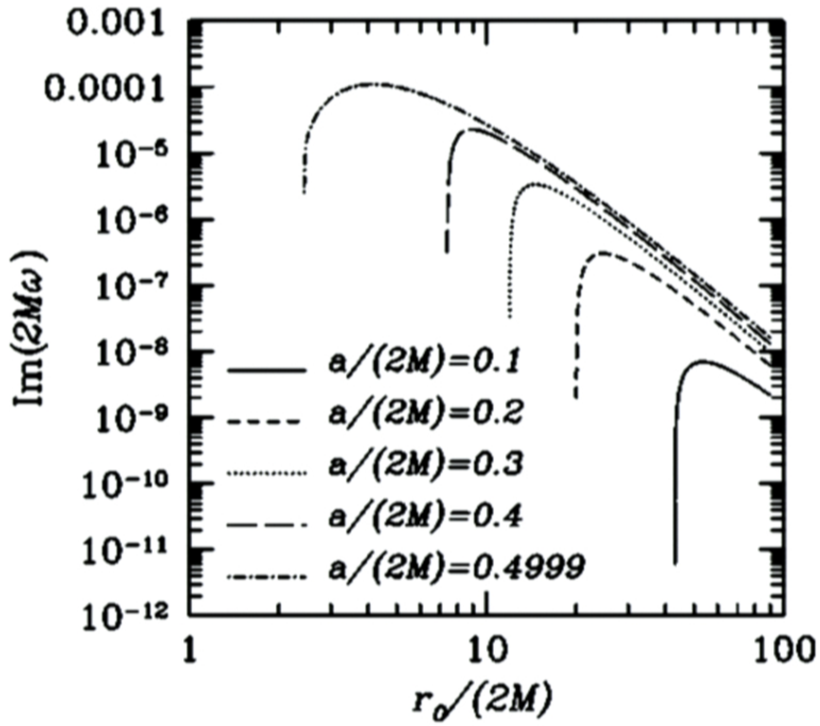
No fission for D>3

Black hole bombs

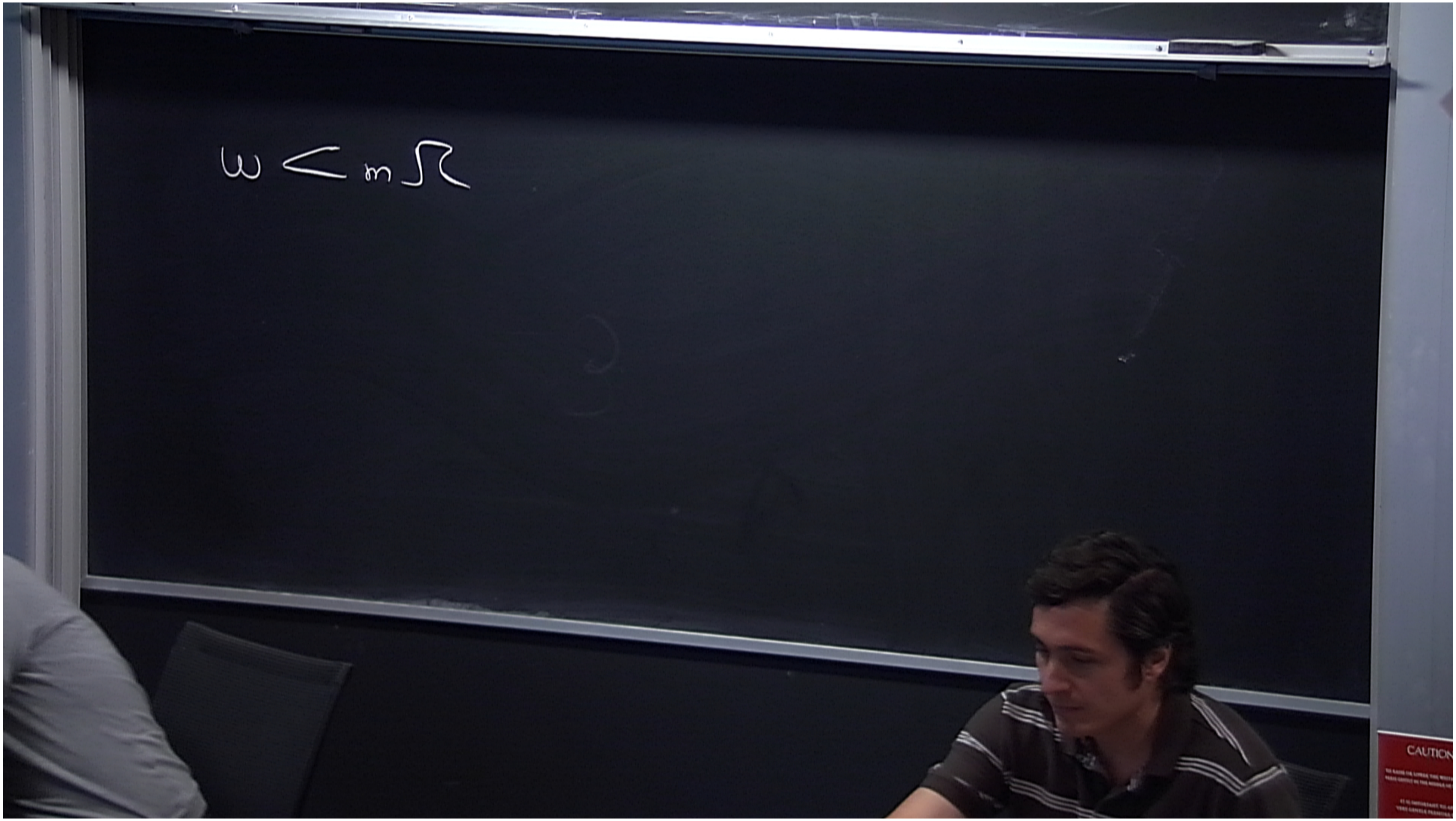
Zel'dovich '71; Press and Teukolsky '72; Cardoso et al '04



Scalar fields



Cardoso, Dias, Lemos & Yoshida '04


ω < mΩ

Nature may provide its own mirrors:

AdS boundaries **("covariant box")** *Cardoso & Dias '04; Jorge & Oscar's talk*

Massive scalars *Detweiler '80; Cardoso & Yoshida '05; Dolan '07*

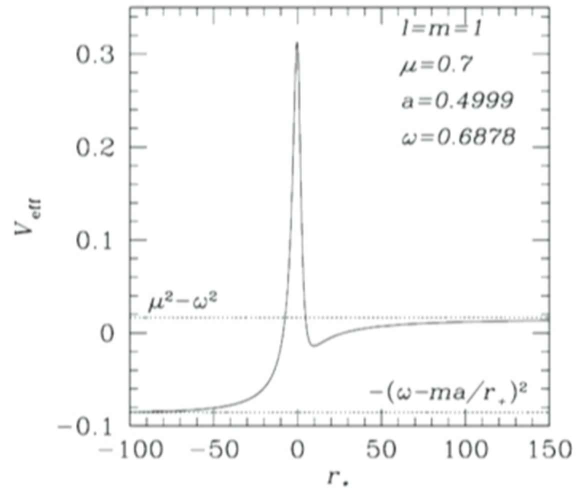
Interesting as effective description

Proxy for more complex interactions

Arise as interesting extensions of GR

(Brans-Dicke or generic scalar-tensor theories; quadratic f(R))

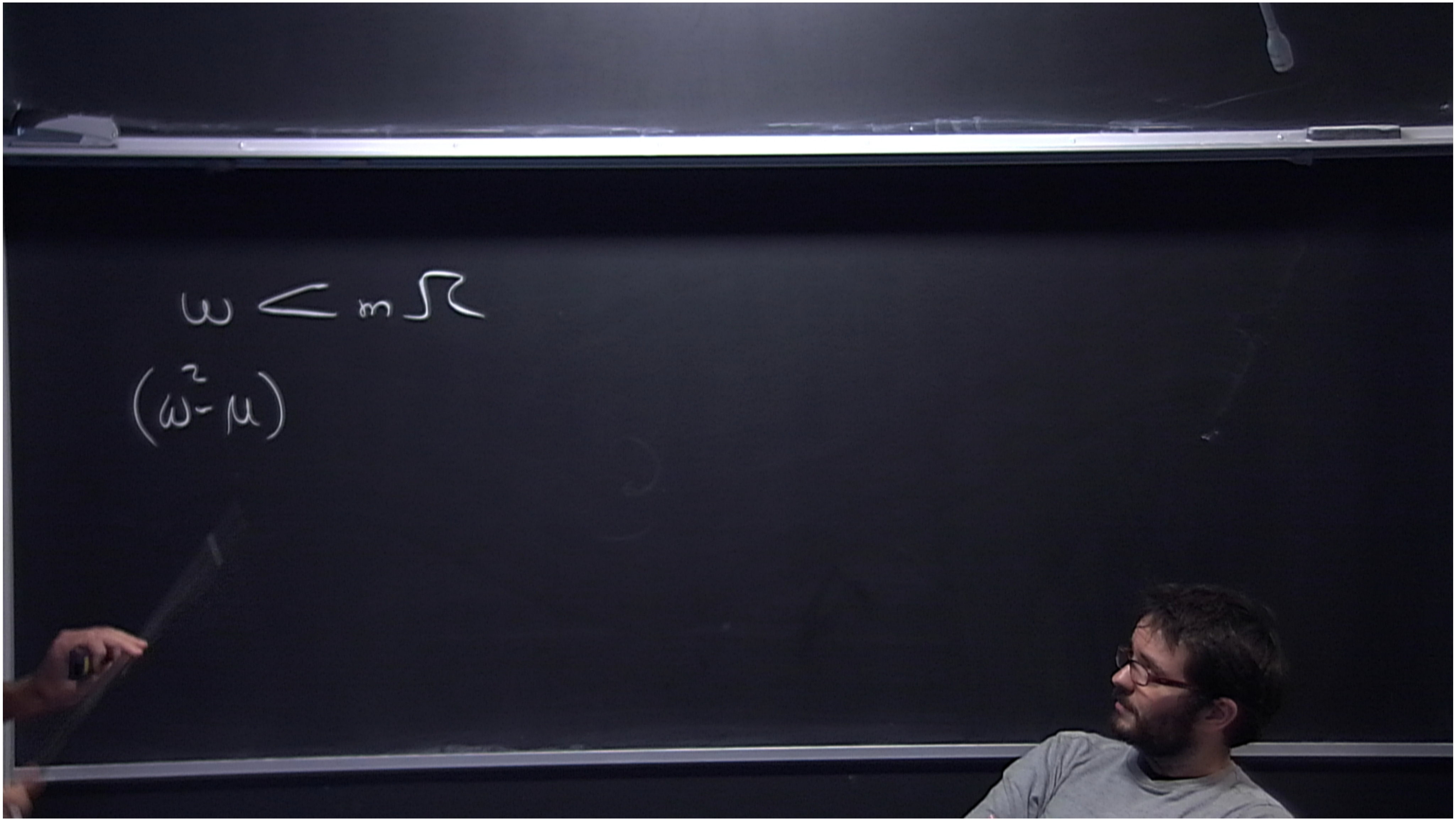
Axiverse scenarios (moduli and coupling constants in string theory, Peccei-Quinn mechanism in QCD, etc) *Arvanitaki et al '10*

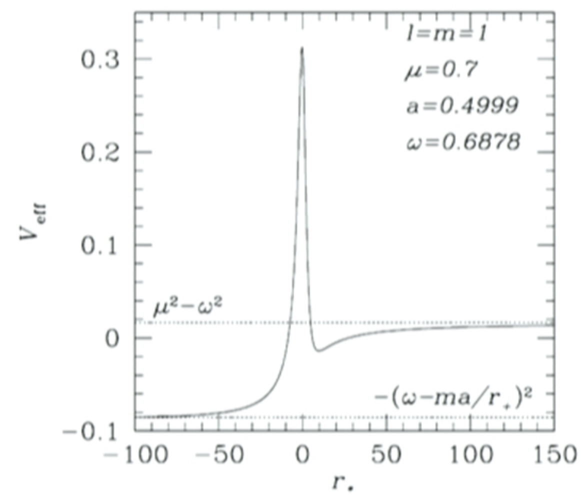


$$\omega_{\rm res}^2 = \mu_s^2 - \mu_s^2 \left(\frac{\mu_s M}{l+1+n}\right)^2 \qquad \omega_I = \mu_s \frac{(\mu_s M)^8}{24} \left(a/M - 2\mu_s r_+\right)$$

Massive scalar fields around Kerr are unstable

Damour et al '76; Detweiler '80; Cardoso & Yoshida '05; Dolan '07


ω < mΩ
(ω² - μ)



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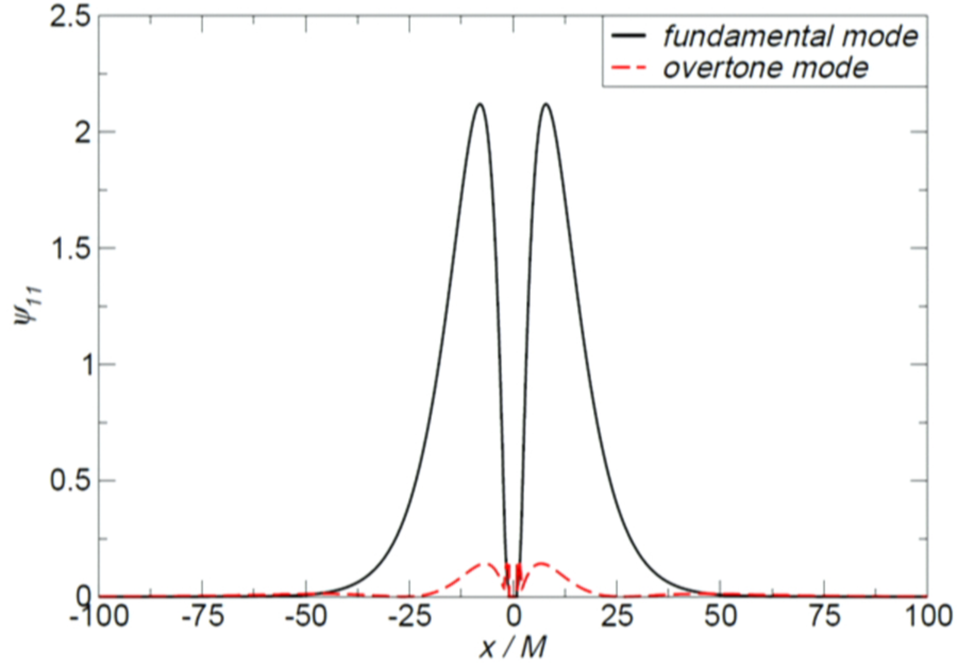
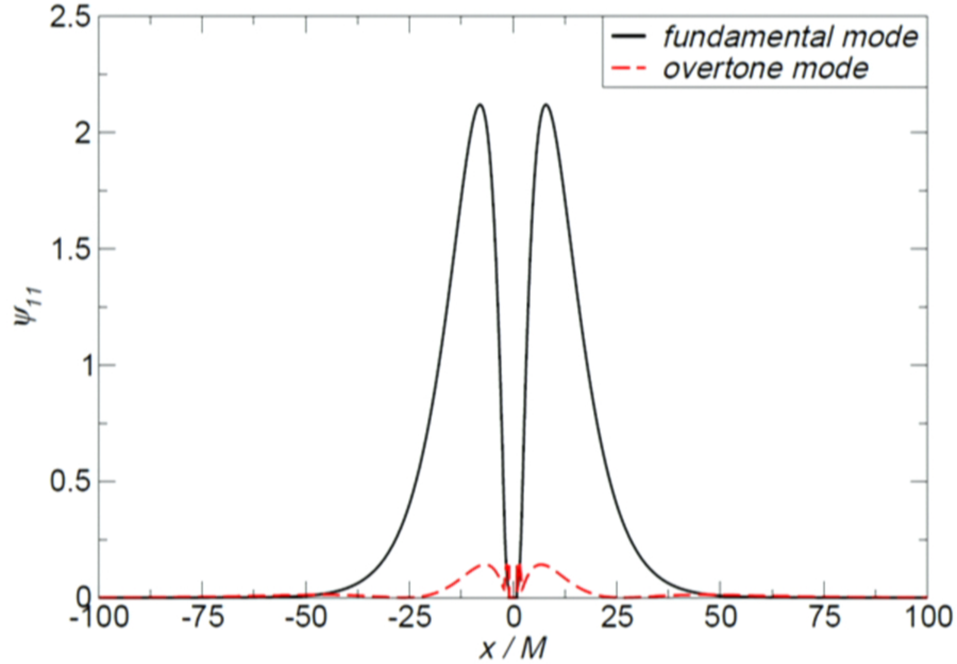
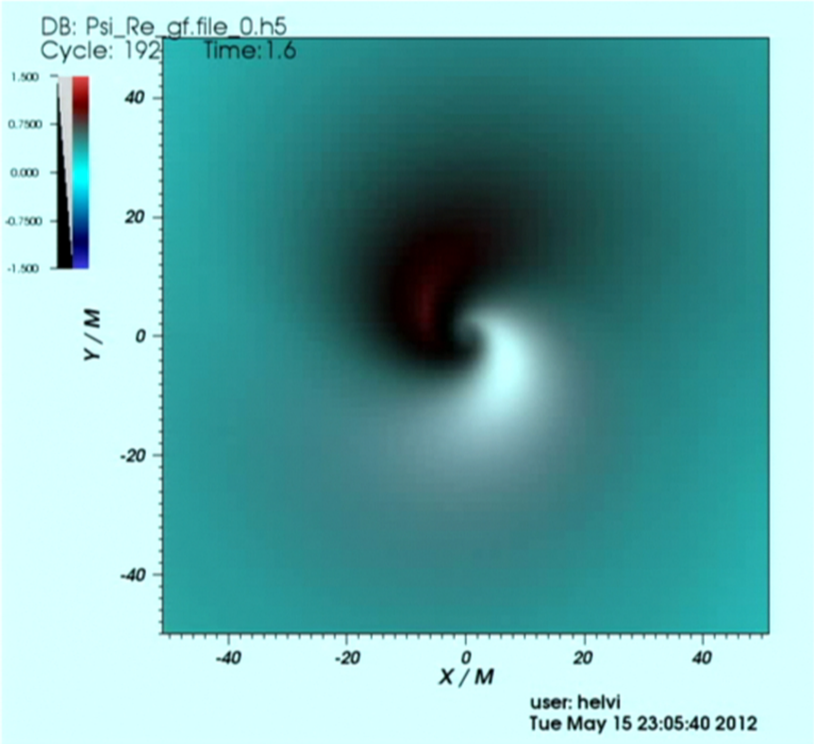


Witek et al, in preparation



Witek et al, in preparation



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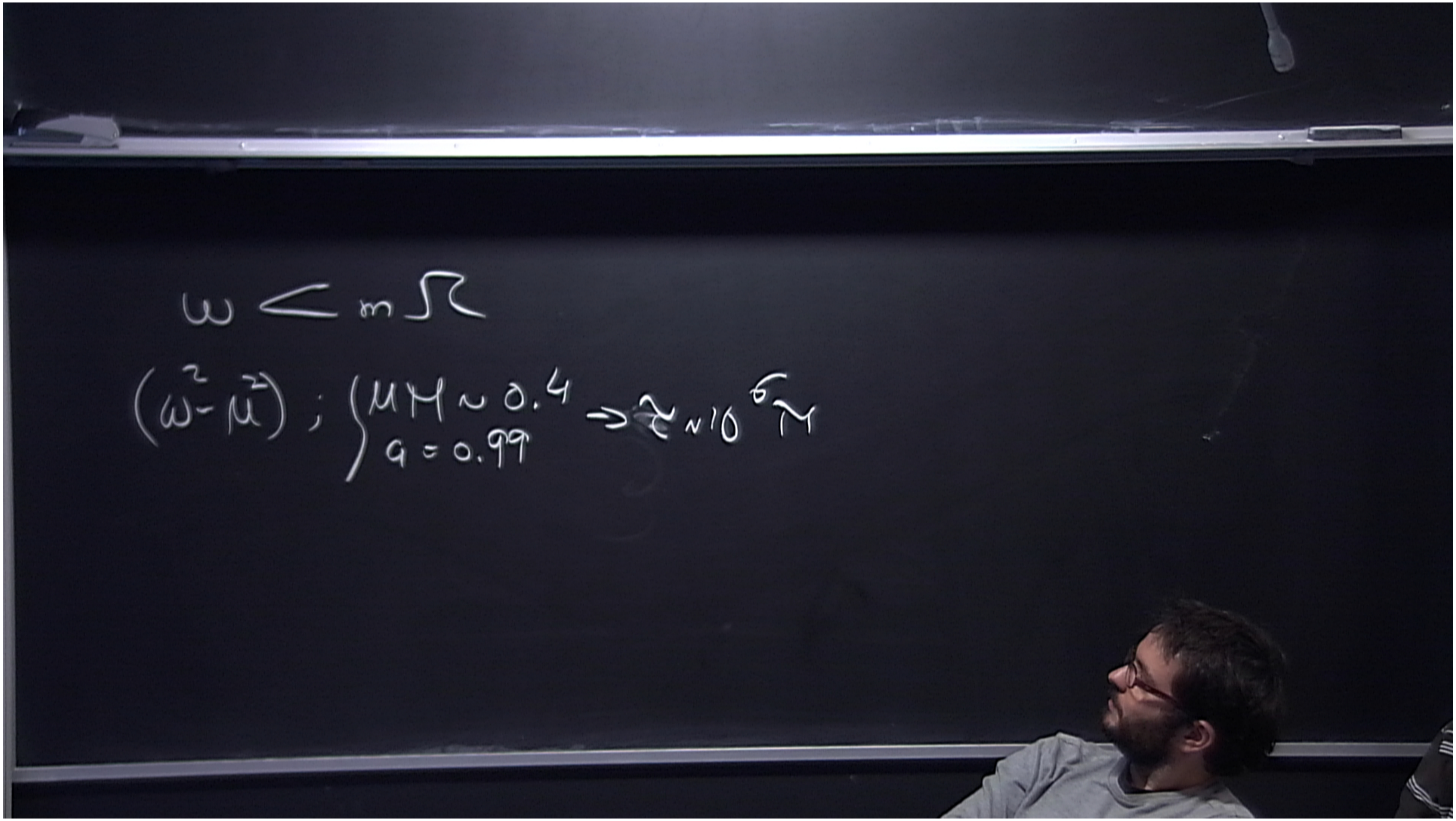
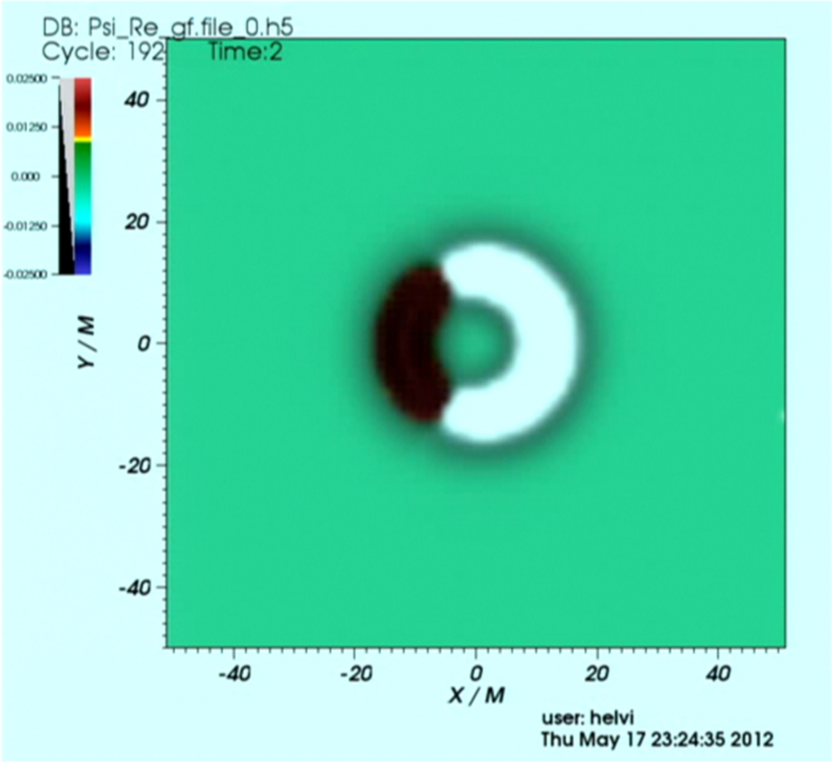

ω < mΩ
(ω² - μ²) ; μM ~ 0.4
a = 0.99 → τ ~ 10⁶ M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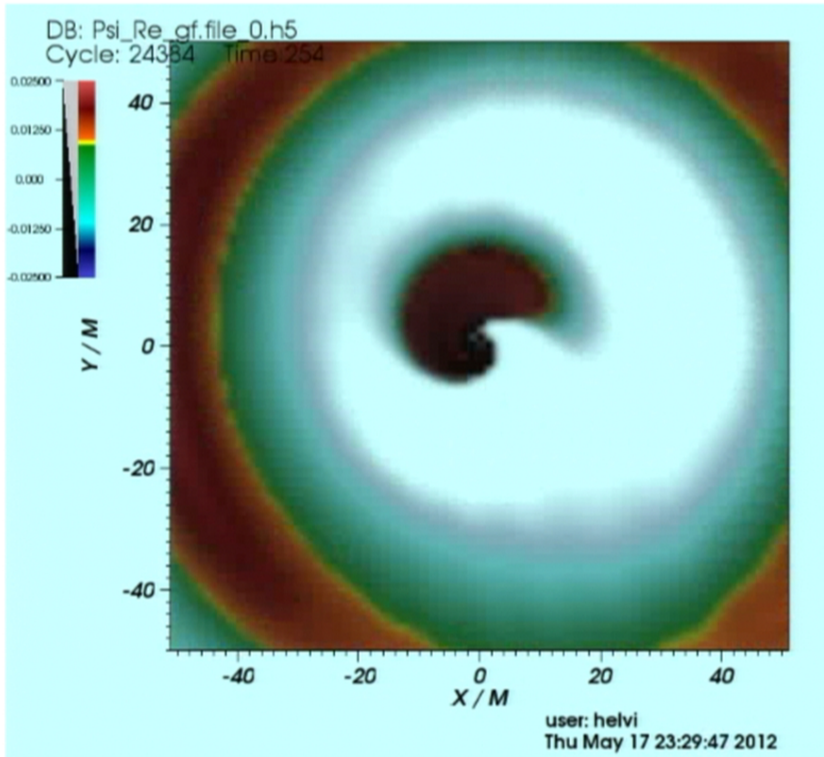
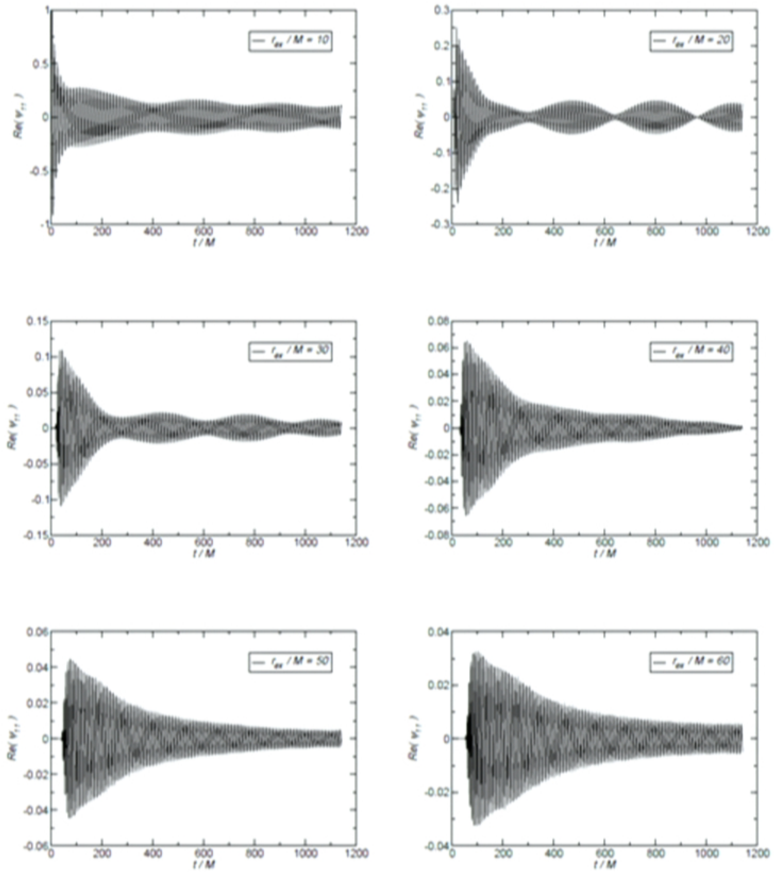
Cycle: 192 Time:2
0.02500
0.01250
0.000
-0.01250
-0.02500
Y / M
40
20
0
-20
-40
-40 -20 0 20 40
X / M
user: helvi
Thu May 17 23:24:35 2012


DB: Psi_Re_gf.file_0.h5
Cycle: 24384 Time:254
0.02500
0.01250
0.000
-0.01250
-0.02500
Y / M
X / M
user: helvi
Thu May 17 23:29:47 2012

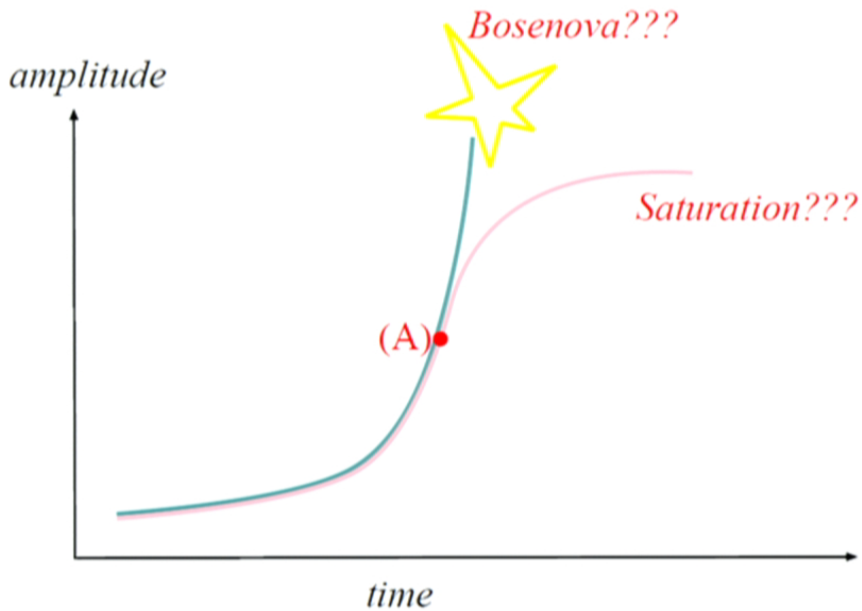
Beatings



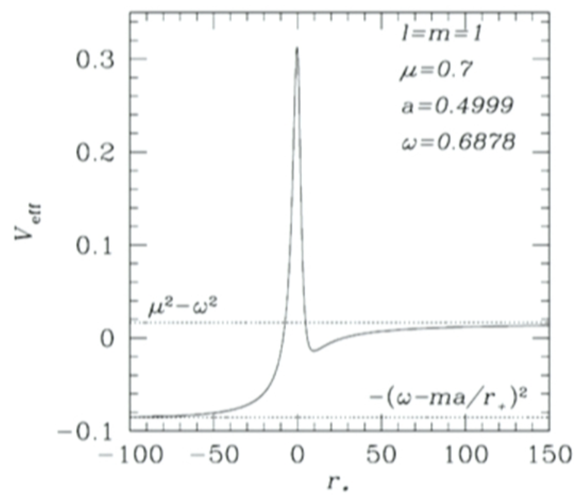
$$\omega_{\rm res}^2 = \mu_s^2 - \mu_s^2 \left(\frac{\mu_s M}{l+1+n} \right)^2$$

Does this explain previous results, claiming smaller timescales?

Bosenova collapse of axion cloud



Yoshino and Kodama '12



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Massive scalar fields around Kerr are unstable

Damour et al '76; Detweiler '80; Cardoso & Yoshida '05; Dolan '07

Other fields

For rotating black holes, separability of massless fields is a miracle

* * *

Important: most objects spin! Non-separable problems

- Massive vectors (Proca fields) on a Kerr background
- Gravito-EM perturbations of KN BHs
- Rotating objects in alternative theories
- Rotating stars (r-mode, etc)
- Myers-Perry BHs with generic spin, other rotating solutions
- Stability, greybody factors, quasinormal modes?

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Proca fields

$$\nabla_\sigma F^{\sigma\nu} - \mu^2 A^\nu = 0$$
$$\implies \nabla_\sigma A^\sigma = 0 \implies \Box A^\nu - \mu^2 A^\nu = 0$$

- Massive hidden U(1) fields are quite generic features of extensions of GR

  Goodsel et al '09; Jaekel et al '09; Goldhaber &Nieto '08

- Current bound on photon mass $\mu < 10^{-18}$eV [PDG]
- (Apparently) non-separable in Kerr background perturbations
- Massless EM in Kerr-(A)dS are separable

$$\nabla_\sigma F^{\sigma\nu} = 0 \implies \Box A^\nu - \nabla^\nu(\nabla_\sigma A^\sigma) + \Lambda A^\nu = 0$$

- However, gauge freedom gives 2 dofs for massless. Proca implies Lorenz condition. No more freedom, 3dofs.

Perturbations of slowly rotating objects: first order

- Slowly rotating background

$$ds_0^2 = -F(r)dt^2 + B(r)^{-1}dr^2 + r^2 d^2\Omega - 2\varpi(r)\sin^2\vartheta d\varphi dt$$

- Expand any equation in spherical harmonics

$$\delta X_{\mu_1\ldots}(t,r,\vartheta,\varphi) = \delta X_{\ell m}^{(i)}(r)\mathcal{Y}_{\mu_1\ldots}^{\ell m\,(i)} e^{-\mathrm{i}\,\omega t}$$

- For any metric, any theory: at first order, system of radial ODEs

$$\mathcal{A}_{\ell m} + \tilde{a}m\bar{\mathcal{A}}_{\ell m} + \tilde{a}(\mathcal{Q}_{\ell m}\tilde{\mathcal{P}}_{\ell-1m} + \mathcal{Q}_{\ell+1m}\tilde{\mathcal{P}}_{\ell+1m}) = 0$$
$$\mathcal{P}_{\ell m} + \tilde{a}m\bar{\mathcal{P}}_{\ell m} + \tilde{a}(\mathcal{Q}_{\ell m}\tilde{\mathcal{A}}_{\ell-1m} + \mathcal{Q}_{\ell+1m}\tilde{\mathcal{A}}_{\ell+1m}) = 0$$

- Zeeman splitting, Laporte-like selection rule and propensity rule:

$$\mathcal{Q}_{\ell m} = \sqrt{\frac{(\ell-m)(\ell+m)}{(2\ell-1)(2\ell+1)}}$$

Kojima '93; Pani et al, to appear

Perturbations of slowly rotating objects: higher order

(Pani et al, in progress)

Change in horizon location, ergosphere appears, etc

$$0 = \mathcal{A}_l \qquad \text{0th order}$$

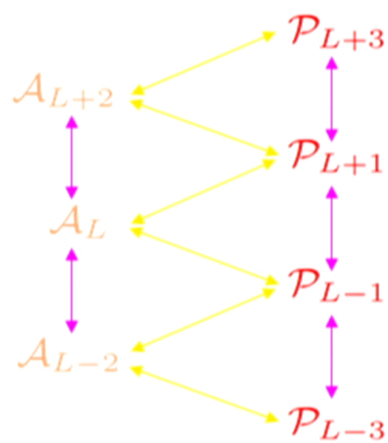
$$+\tilde{a}m\bar{\mathcal{A}}_l + \tilde{a}(\mathcal{Q}_l\tilde{\mathcal{P}}_{\ell-1} + \mathcal{Q}_{\ell+1}\tilde{\mathcal{P}}_{\ell+1}) \qquad \text{1st order}$$

$$+\tilde{a}^2\left(\hat{\mathcal{A}}_{\ell m} + \mathcal{Q}_{l-1}\mathcal{Q}_l\breve{\mathcal{A}}_{\ell-2} + \mathcal{Q}_{\ell+2}\mathcal{Q}_{\ell+1}\breve{\mathcal{A}}_{\ell+2}\right) \qquad \text{2nd order}$$

$$0 = \mathcal{P}_l$$

$$+\tilde{a}m\bar{\mathcal{P}}_l + \tilde{a}(\mathcal{Q}_l\tilde{\mathcal{A}}_{\ell-1} + \mathcal{Q}_{\ell+1}\tilde{\mathcal{A}}_{\ell+1})$$

$$+\tilde{a}^2\left(\hat{\mathcal{P}}_{\ell m} + \mathcal{Q}_{l-1}\mathcal{Q}_l\breve{\mathcal{P}}_{\ell-2} + \mathcal{Q}_{\ell+2}\mathcal{Q}_{\ell+1}\breve{\mathcal{P}}_{\ell+2}\right)$$



Proca fields

$$\delta A_\mu(t,r,\vartheta,\varphi) = \sum_{l,m} \begin{bmatrix} 0 \\ 0 \\ u_{(4)}^{\ell m}(t,r) S_a^{\ell m} \end{bmatrix} + \sum_{l,m} \begin{bmatrix} u_{(1)}^{\ell m}(t,r) Y^{\ell m} \\ u_{(2)}^{\ell m}(t,r) Y^{\ell m} \\ u_{(3)}^{\ell m}(t,r) Y_a^{\ell m} \end{bmatrix}$$

$$\begin{aligned} Y_a^{\ell m} &= \left(\partial_\vartheta Y^{\ell m}, \partial_\varphi Y^{\ell m}\right) \\ S_a^{\ell m} &= \left(\frac{1}{\sin\vartheta}\partial_\varphi Y^{\ell m}, -\sin\vartheta \partial_\vartheta Y^{\ell m}\right) \end{aligned}$$

$$\hat{\mathcal{D}}_2 u_{(4)}^\ell - \frac{4\tilde{a}M^2 m\omega}{r^3} u_{(4)}^\ell = \frac{6\tilde{a}M^2}{r^4}\left[(\ell+1)\mathcal{Q}_{\ell m}\left(F u_{(1)}^{\ell-1} - \mathrm{i}\, r\omega u_{(2)}^{\ell-1} - F r {u'}_{(1)}^{\ell-1}\right) + \ell \mathcal{Q}_{\ell+1 m}\left(\mathrm{i}\, r\omega u_{(2)}^{\ell+1} - F u_{(1)}^{\ell+1} + F r {u'}_{(1)}^{\ell+1}\right)\right],$$

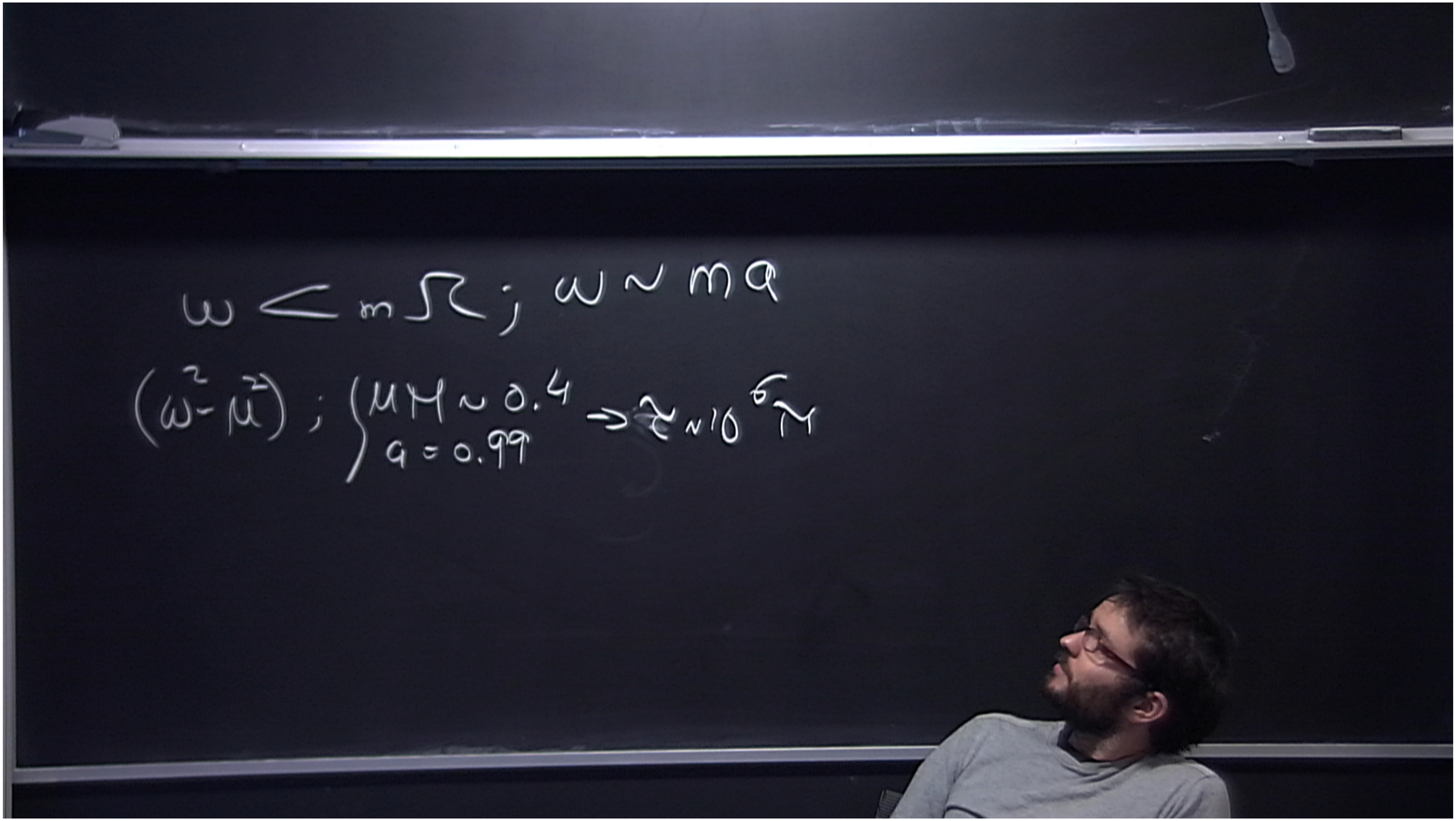
$$\mathrm{i}\, r\omega u_{(1)}^\ell + F\left(u_{(2)}^\ell - u_{(3)}^\ell + r {u'}_{(2)}^\ell\right) - \frac{2\tilde{a}M^2 m}{r^2}\left(\mathrm{i}\, u_{(1)}^\ell + \frac{r\omega}{\Lambda} u_{(3)}^\ell\right) = \frac{2\mathrm{i}\,\tilde{a}M^2\omega}{r\Lambda}\left[(\ell+1)\mathcal{Q}_{\ell m} u_{(4)}^{\ell-1} - \ell \mathcal{Q}_{\ell+1 m} u_{(4)}^{\ell+1}\right],$$

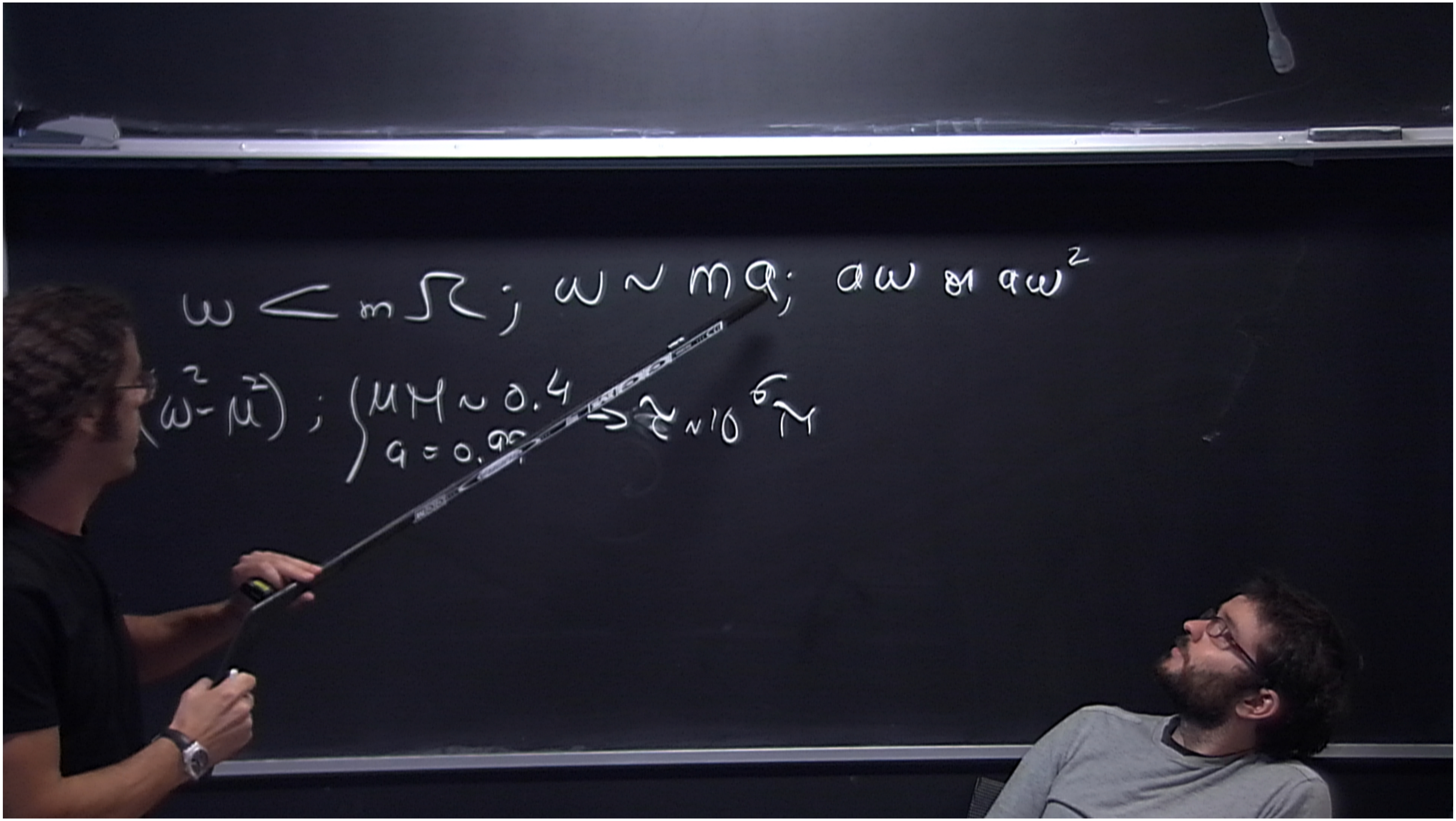
$$\hat{\mathcal{D}}_2 u_{(3)}^\ell + \frac{2F\ell(\ell+1)}{r^2} u_{(2)}^\ell + \frac{2\tilde{a}M^2 m}{r^4}\left[r\omega(3u_{(2)}^\ell - 2u_{(3)}^\ell) + 3\mathrm{i}\, F\left(u_{(1)}^\ell - r {u'}_{(1)}^\ell\right)\right] = 0,$$

$$\hat{\mathcal{D}}_2 u_{(2)}^\ell - \frac{2F}{r^2}\left(1 - \frac{3M}{r}\right)\left[u_{(2)}^\ell - u_{(3)}^\ell\right] - \frac{2\tilde{a}M^2 m}{\ell(\ell+1)r^4}\left[\ell(\ell+1)(2r\omega u_{(2)}^\ell - 3\mathrm{i}\, F u_{(1)}^\ell) - 3r\omega F u_{(3)}^\ell\right]$$

$$= -\frac{6\mathrm{i}\,\tilde{a}M^2 F\omega}{\ell(\ell+1)r^3}\left[(\ell+1)\mathcal{Q}_{\ell m} u_{(4)}^{\ell-1} - \ell \mathcal{Q}_{\ell+1 m} u_{(4)}^{\ell+1}\right]$$

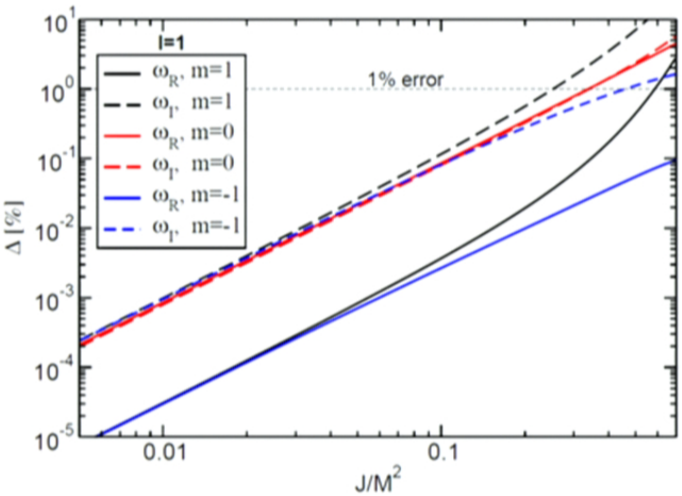
$$\hat{\mathcal{D}}_2 = d^2/dr_*^2 + \omega^2 - F\left[\ell(\ell+1)/r^2 + \mu^2\right]$$


ω < mΩ ; ω ~ ma
(ω² - μ²) ; μM ~ 0.4
a = 0.99 → τ ~ 10⁶ M

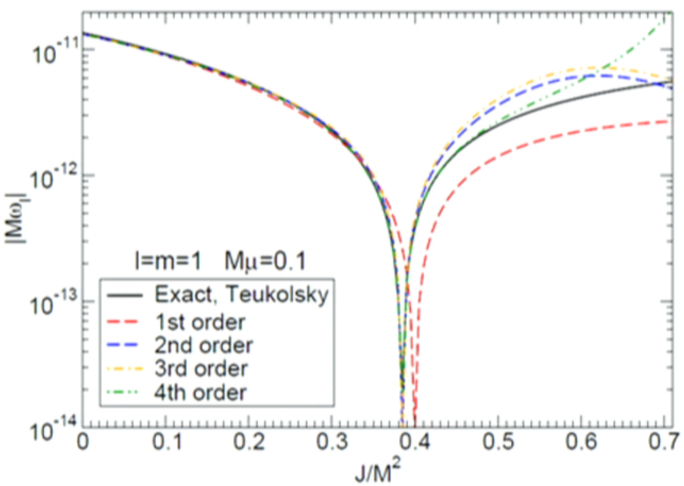

ω < mΩ ; ω ~ ma ; aω or aω²
(ω² − μ²) ; μM ~ 0.4
a = 0.99 → τ ~ 10⁶ M

Integration of ODEs: Direct integration, continued fraction, “Breit-Wigner”

Check: massless (vector) perturbations



Check II: massive scalars



Pani et al, to appear

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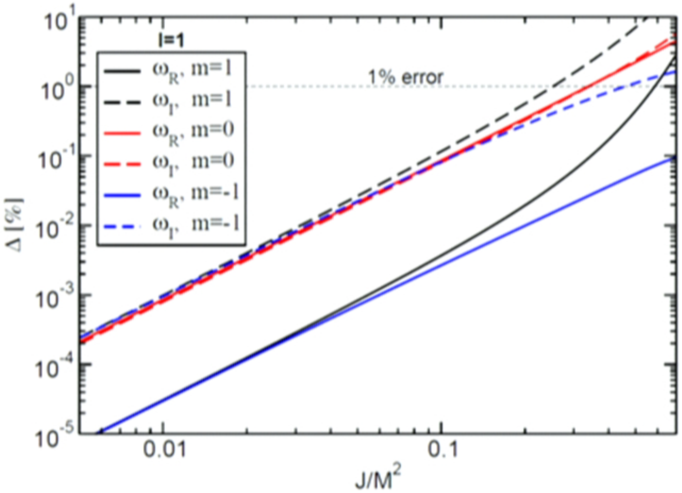

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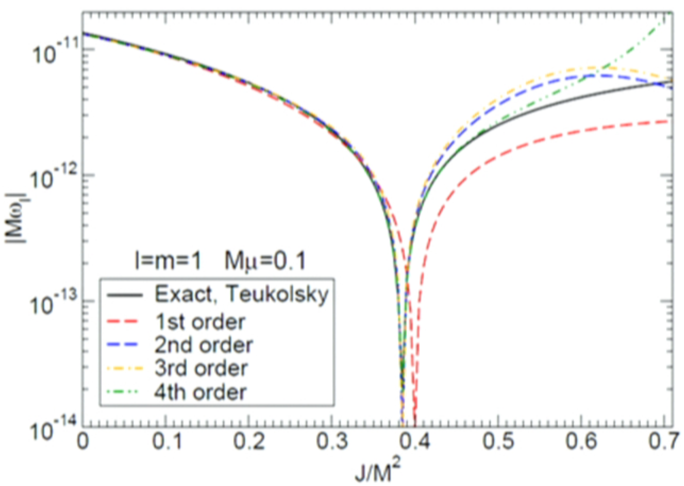

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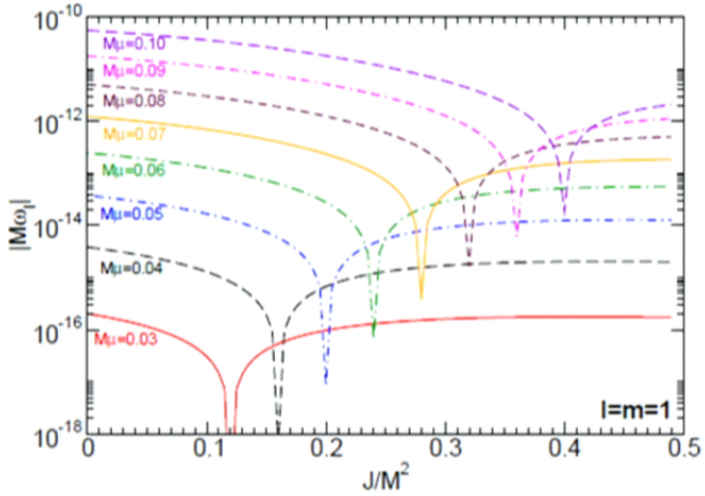
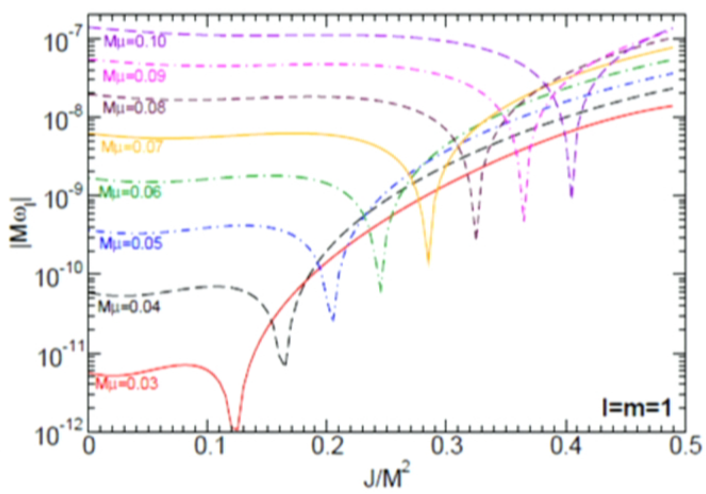


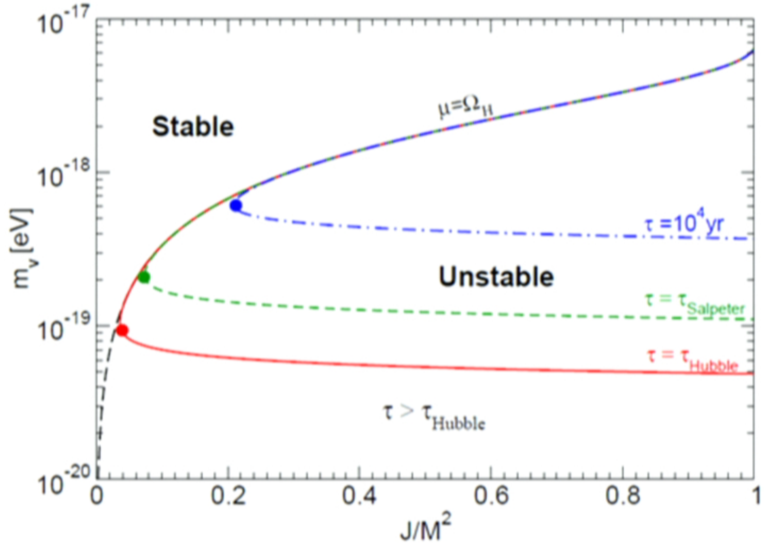


$$\tau_{\rm vector} = \omega_I^{-1} \sim \frac{M(M\mu)^{-7}}{\gamma_{-11}(\tilde{a} - 2\mu r_+)}$$

See also Rosa and Dolan '11

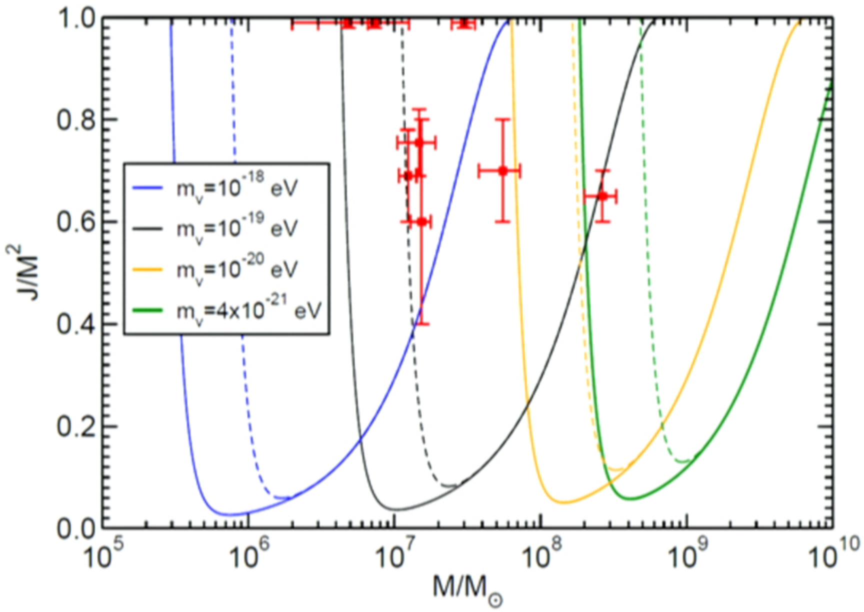
Pani et al, to appear

Proca instability



For a 10 million solar mass BH

Proca instability

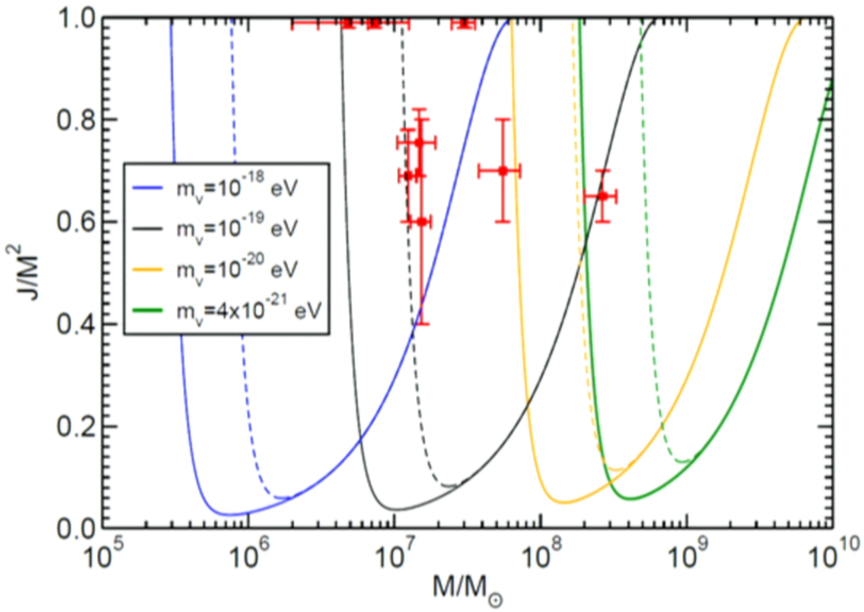


Depend very mildly on the fit coefficient and on the threshold

*

$\tau_{\text{Salpeter}} \rightarrow$ timescale for accretion at the Eddington limit

Proca instability



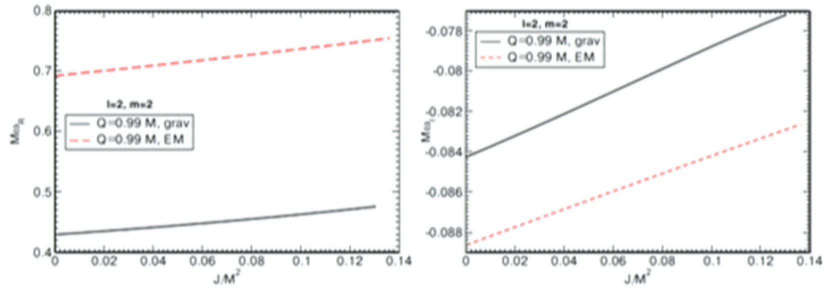
Depend very mildly on the fit coefficient and on the threshold

*

$\tau_{\text{Salpeter}} \rightarrow$ timescale for accretion at the Eddington limit

Superradiance leads to interesting phenomena and can be instrumental to constrain or prove existence of massive scalars coupled to matter... Still a lot to do at the perturbative level.

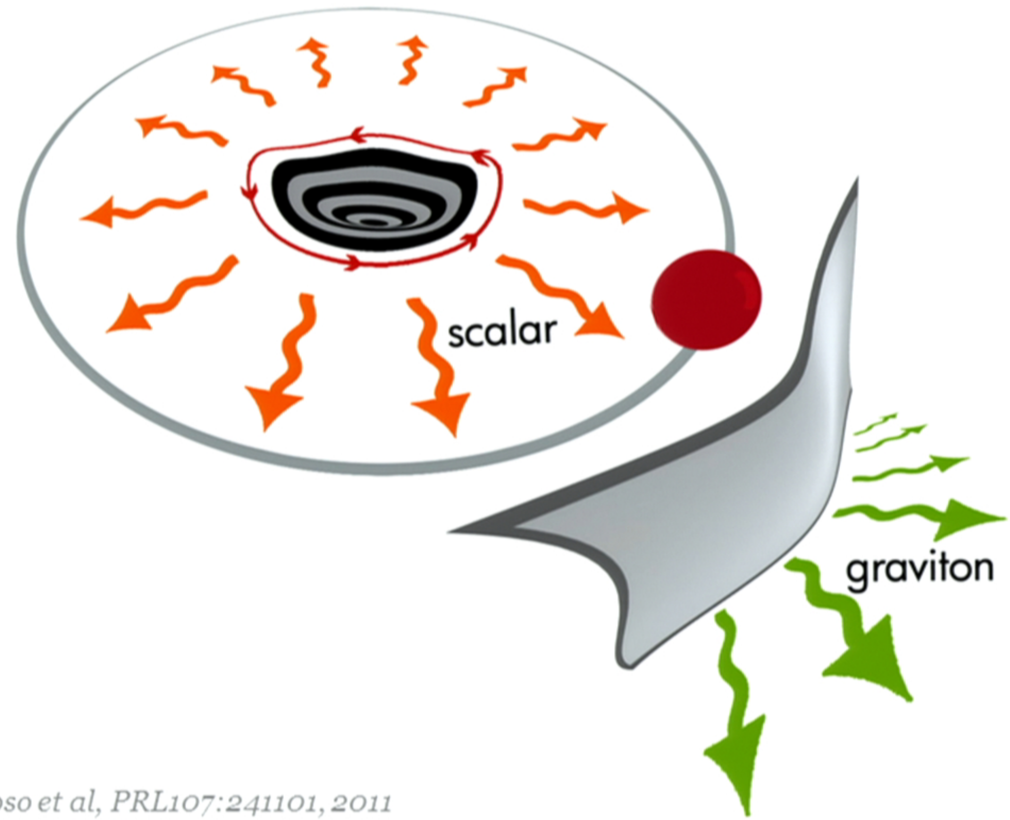
- 3rd order and higher in rotation, under way
- Gravito-EM perturbations of Kerr-Newman, under way



- Higher dimensions: bar-modes, greybody factors, singly spinning?
- Alternative theories?
- Time-evolutions: purify the initial state, or wait!

- Astrophysics: coupling to matter, can it deffuse the instability?

Floating orbits

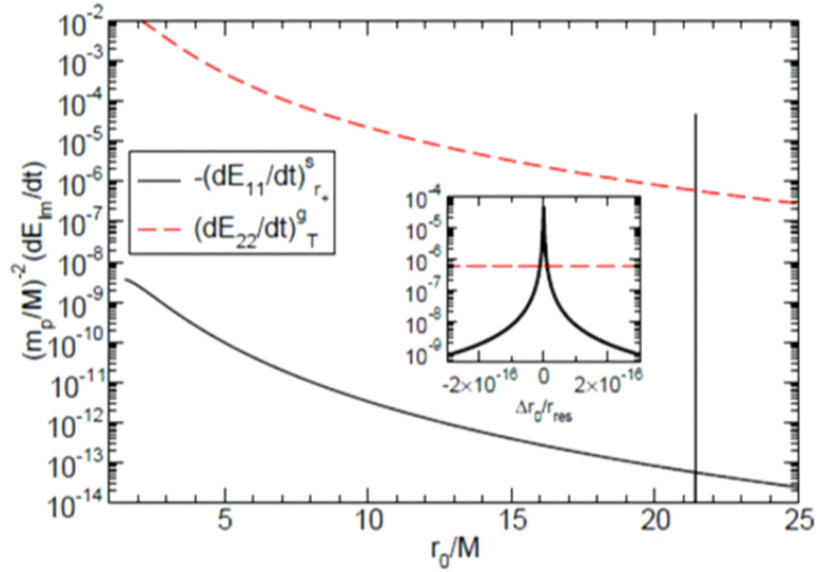


Cardoso et al, PRL107:241101, 2011

Yunes et al PRD81, 084052, 2012

$$\left[\Box - \mu_s^2\right]\varphi = \alpha\mathcal{T}$$

$$\dot{E}_{r_+}^{s,\mathrm{peak}} \sim -\frac{3\alpha^2\sqrt{\frac{r_0}{M}}\,m_p^2 M}{16\pi r_+\left(M^2-a^2\right)\left(\frac{a}{2r_+}-\left(\frac{M}{r_0}\right)^{3/2}\right)\mathcal{F}}$$



Rotational energy: tidal acceleration

Earth-moon: 0.002s/cent

4cm/yr

$$\mu = \frac{\kappa}{2} m_p \left(\frac{R}{r_0}\right)^3$$

$$\phi = (\Omega_H - \Omega)\tau$$

$$\dot{E}_{\rm orbital} = 3G\kappa m_p^2 \frac{R^5}{r_0^6} \Omega(\Omega_H - \Omega)\tau$$

Tidal acceleration is in general impossible for BHs!

$$\dot{E}_{\rm H} \sim \frac{G^7}{c^{13}} \frac{M^6 m_p^2}{r_0^6} \Omega(\Omega - \Omega_H)$$

$$\dot{E}_{\infty} \sim \frac{32}{5} \frac{G^4}{c^5} \frac{M^3 m_p^2}{r_0^5}$$

$$\frac{\dot{E}_{\rm H}}{\dot{E}_{\infty}} = \left(\frac{GM}{c^2 r_0}\right)^3 \frac{r_0 \Omega}{c} \left(\frac{r_0\Omega - r_0\Omega_H}{c}\right) \sim (v/c)^8$$

Press & Teukolsky, Nature (1973)

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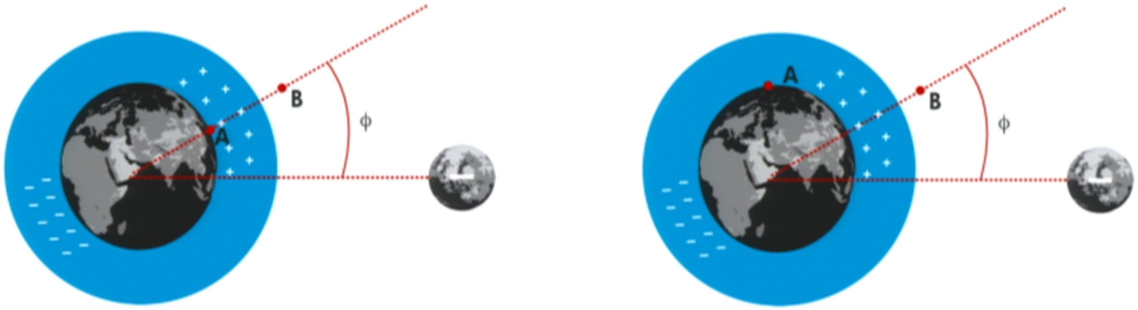


$$\sigma_{\rm pol} = 3\epsilon_0 \left(\frac{\epsilon_r - 1}{2\epsilon_r + 1}\right) E_0 \cos\theta$$

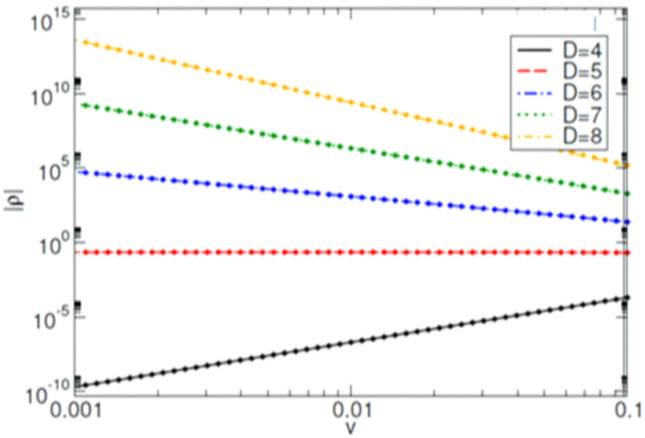
$$p \quad = 4\pi\epsilon_0 \left(\frac{\epsilon_r - 1}{2\epsilon_r + 1}\right) R^3 E_0$$

$$\dot{E}_{\rm orbital} = \left(\frac{\epsilon_r - 1}{2\epsilon_r + 1}\right) \frac{q_p^2 R^3 \tau}{r_0^4} \Omega(\Omega_H - \Omega)$$

Tidal acceleration in higher dimensions

$$\frac{\dot{E}_{\rm H}}{\dot{E}_{\infty}} \sim (v/c)^{\frac{-(D-5)(D+1)}{D-3}} \qquad s=2$$

$$\frac{\dot{E}_{\rm H}}{\dot{E}_{\infty}} \sim (v/c)^{\frac{-(D-5)(D-1)}{D-3}} \qquad s=0$$



D>5 particles do not merge, tidal effects are too large?

Circular orbits are unstable, on much smaller timescale...what happens?!

Brito, Cardoso & Pani '12

Tidal acceleration is equivalent to superradiance in BH physics

In absence of other dissipative effects leads to floating

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... still a lot to do:

- Equal-mass case, what happens to floating?
- Eccentricity OK, what about other sources of noise? Higher multipoles?
- Spinning companion, is floating enhanced? Does is still require massive fields?
- Tidal acceleration requires dissipation (EH). Can it occur for spinning objects without horizon? In principle no, but Blandford-Zjanek seems to, or does it? (see Ruiz et al, arXiv:1203.4125)
- Higher dimensional spacetime: tidal dissipation is dominant mechanism. Consequence for mergers?