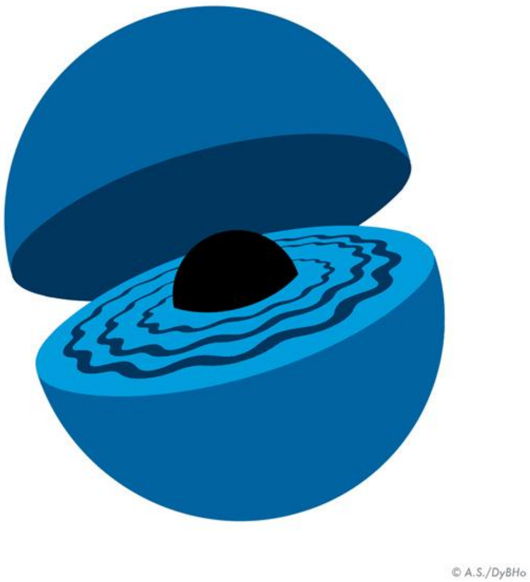
Black hole bombs

Vítor Cardoso • June 06, 2012 • Perimeter Institute



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

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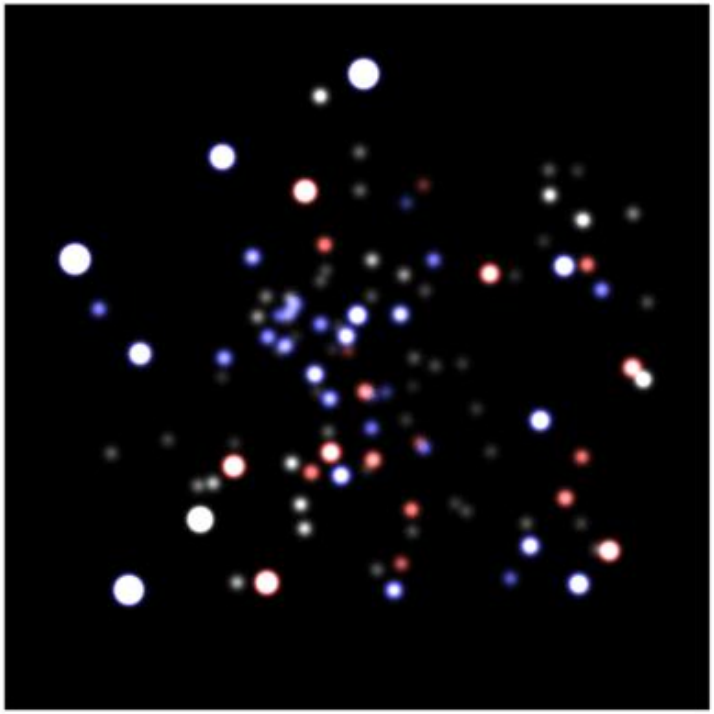
Cardoso et al, Phys. Rev. Lett. 107:241101 (2011)
Yunes et al, Phys. Rev. D 81:084052 (2011)
Pani et al, Phys. Rev. Lett., submitted (2012)
Witek et al, in preparation (2012?)



Credit: ESO/MPE (2010)

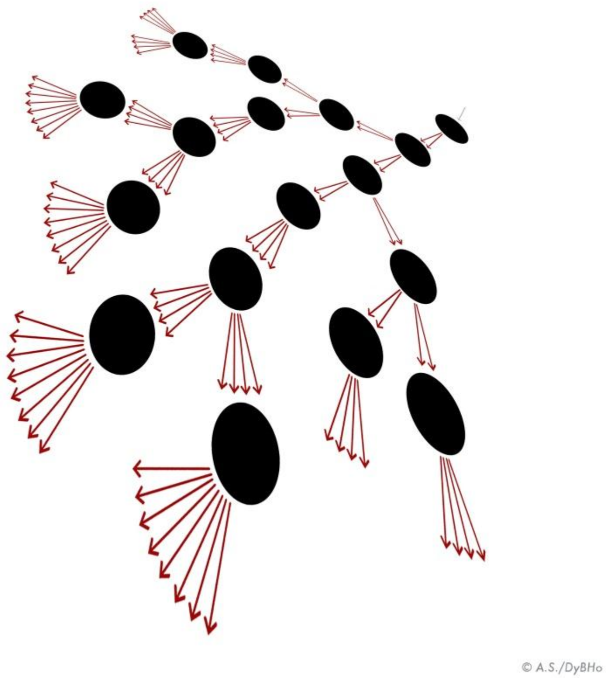
Credit: ESO/MPE/M.Schartmann (2011)

Gillessen et al, Nature 481, 51 (2012)

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?



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

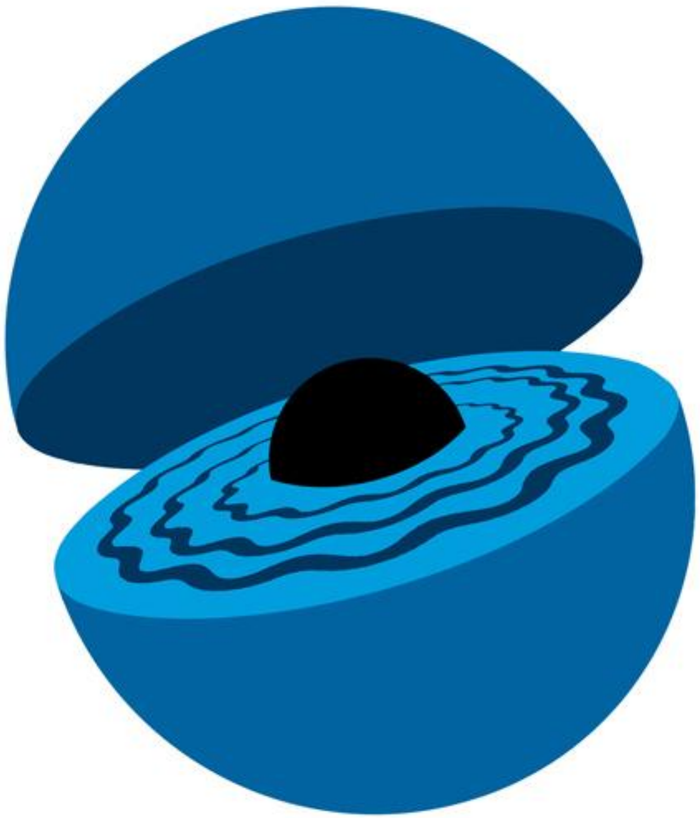
$$\ell_{\text{free path}} \sim \frac{1}{\sigma n}$$

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

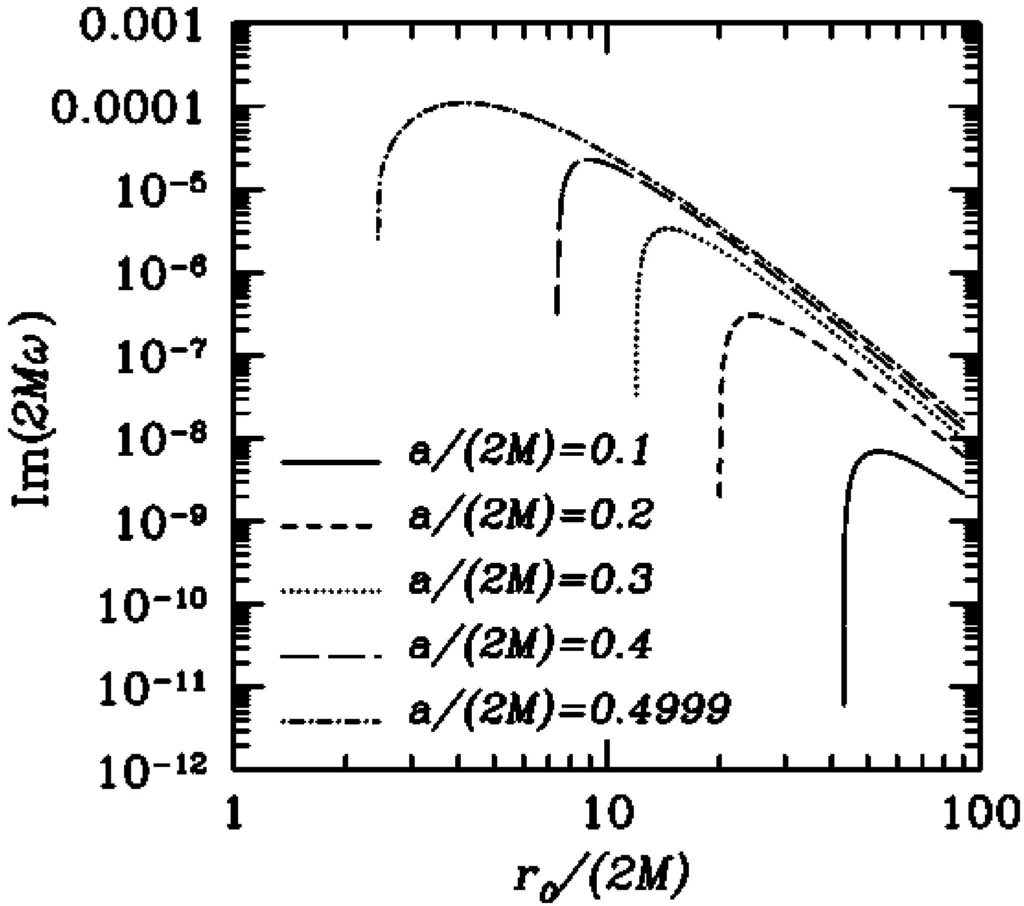
No fission for D>3

Black hole bombs

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



Scalar fields



Cardoso, Dias, Lemos & Yoshida '04

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

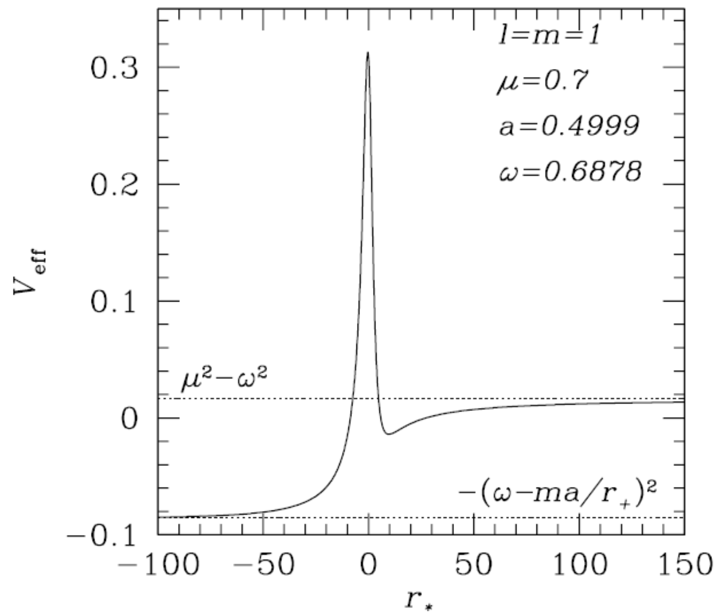
Proxy for more complex interactions

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,

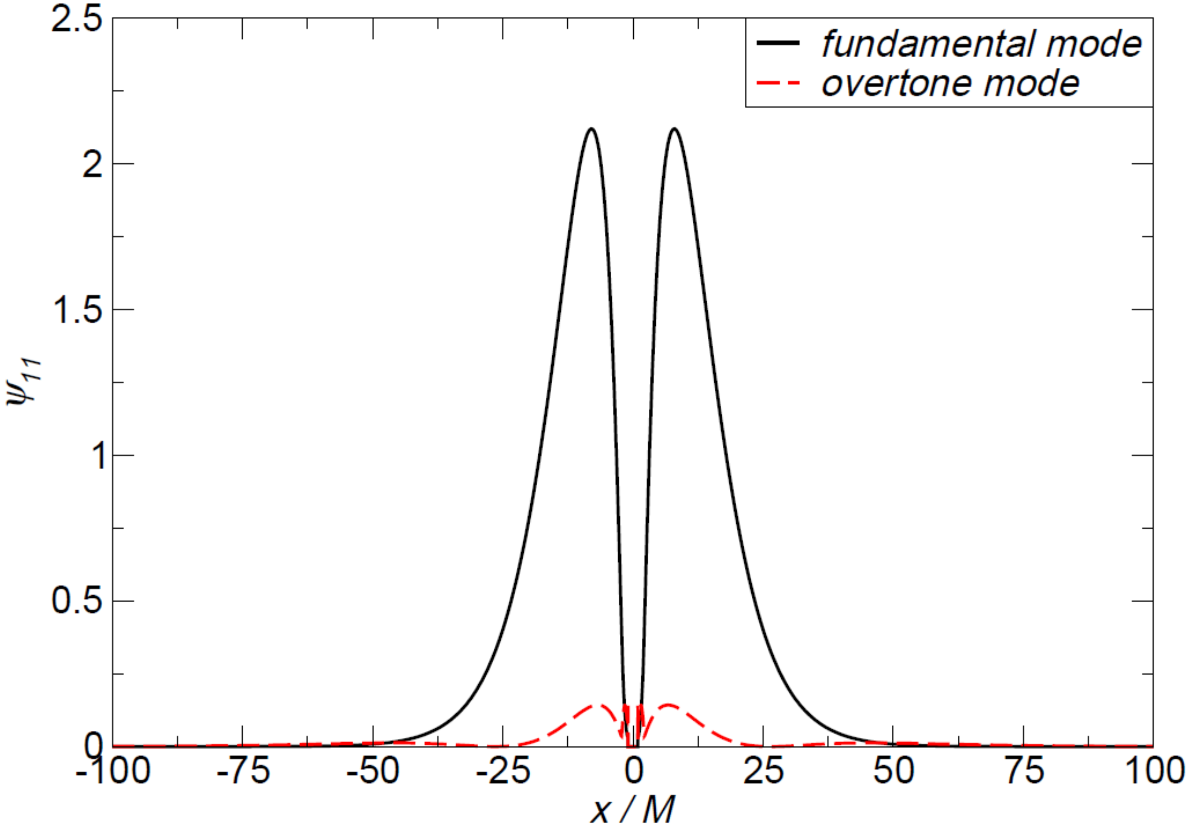
Peccei-Quinn mechanism in QCD, etc) *Arvanitaki et al '10*



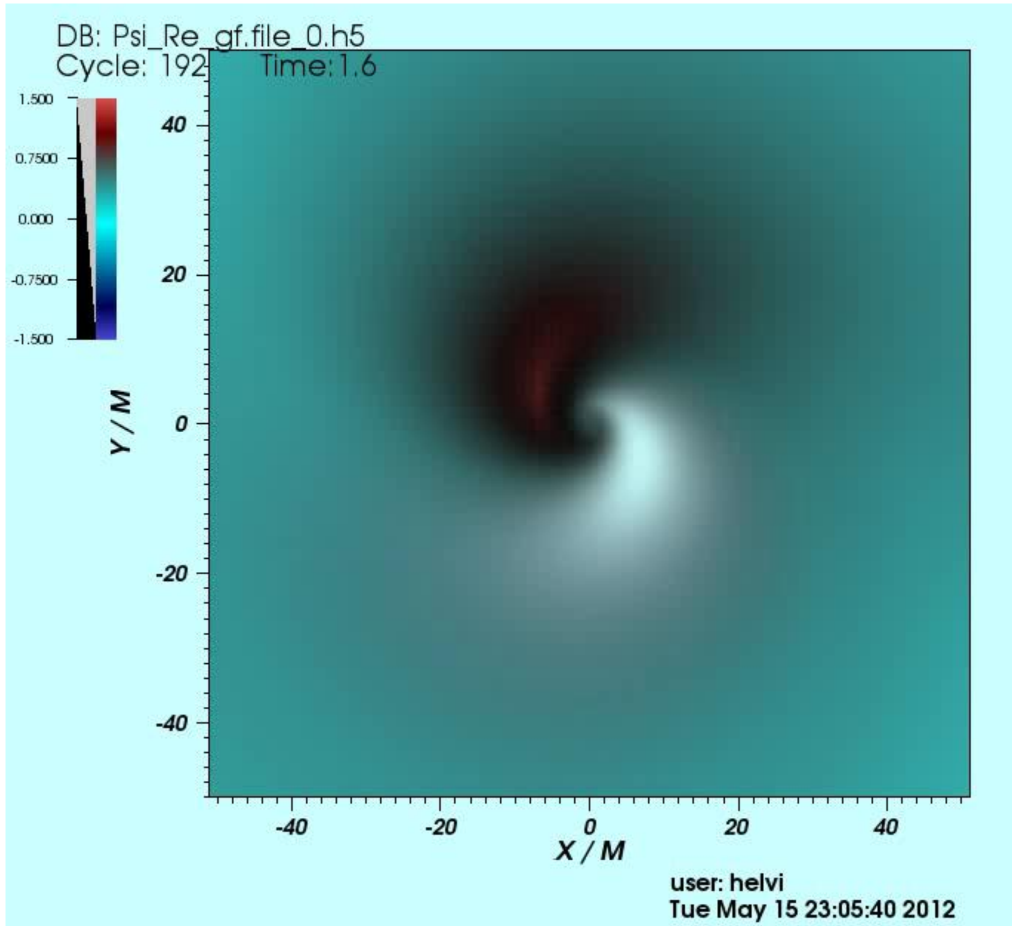
$$\omega_{\rm res}^2 = \mu_s^2 - \mu_s^2 \left(\frac{\mu_s M}{l+1+n} \right)^2 \qquad \omega_I = \mu_s \frac{(\mu_s M)^8}{24} \left(a/M - 2\mu_s r_+\right)$$

Massive scalar fields around Kerr are unstable

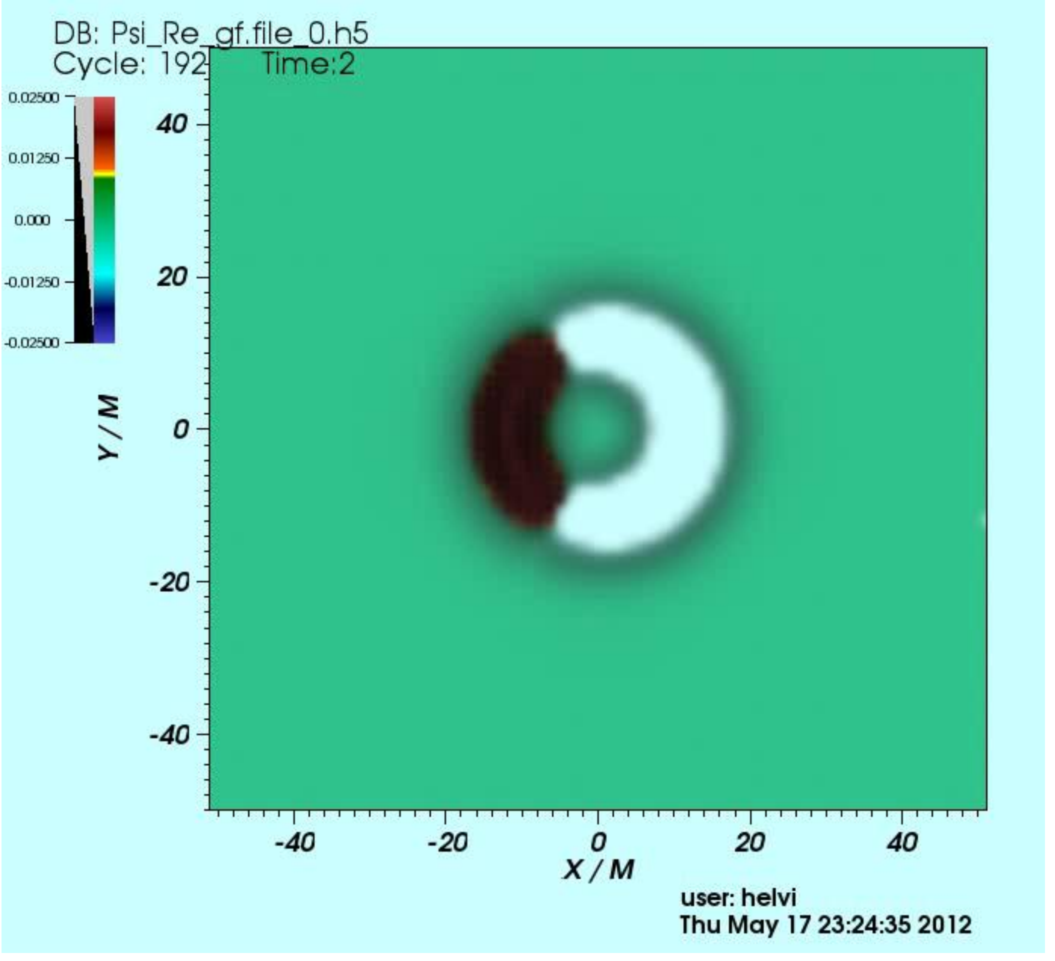
Damour et al ‘76; Detweiler ’80; Cardoso & Yoshida ’05; Dolan ‘07



Witek et al, in preparation

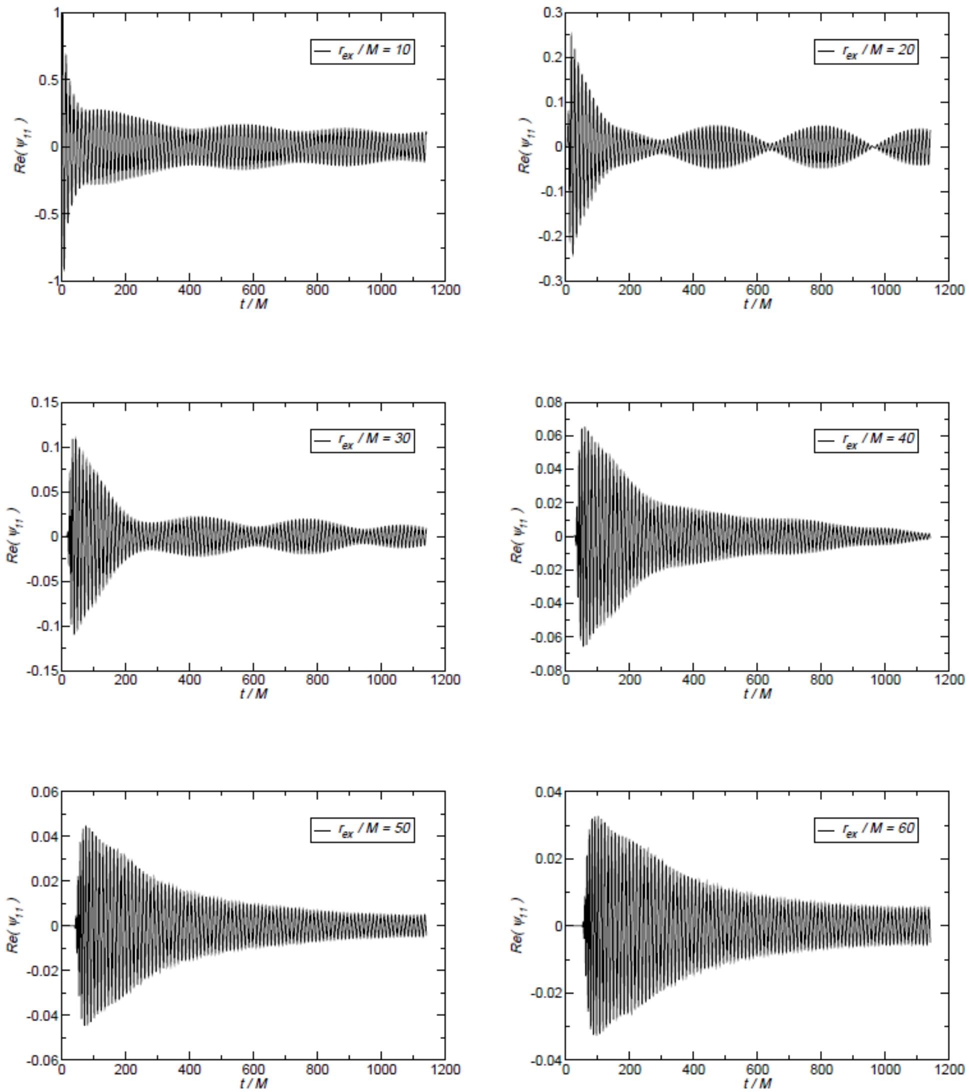


Witek et al, in preparation



DB: Psi_Re_gf.file_0.h5
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

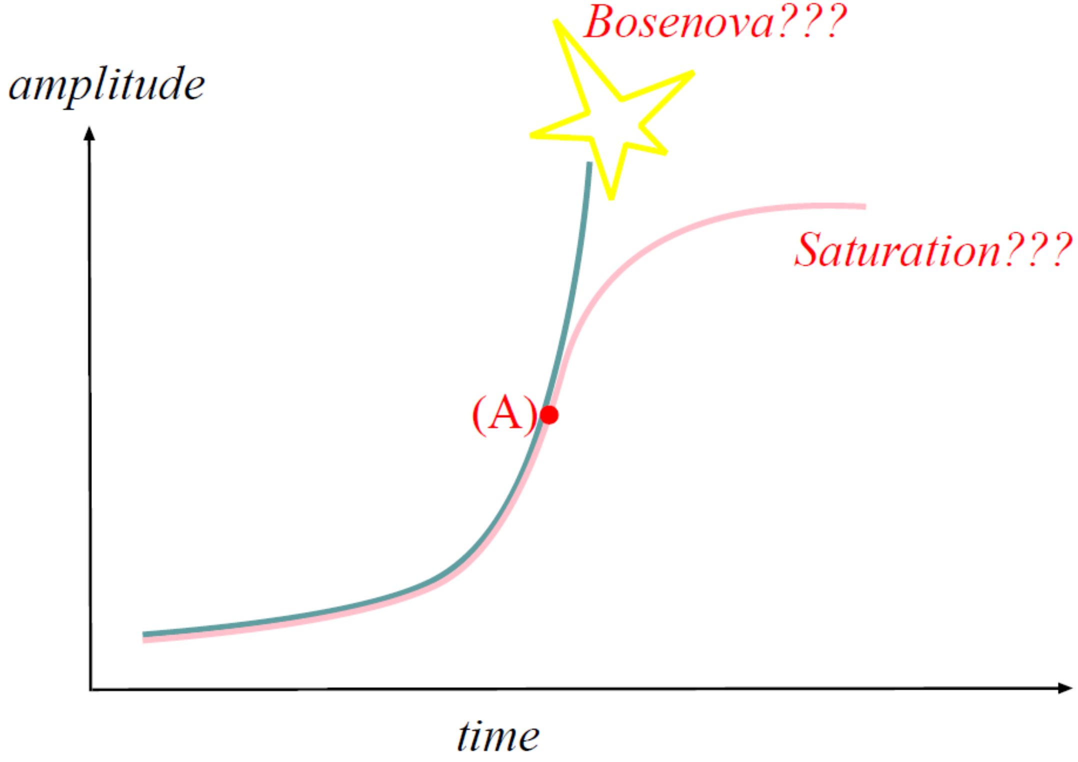
Beatings



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

Does this explain previous results, claiming smaller timescales?

Bosenova collapse of axion cloud



Yoshino and Kodama '12

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?

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

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

- Expand any equation in spherical harmonics

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

- 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

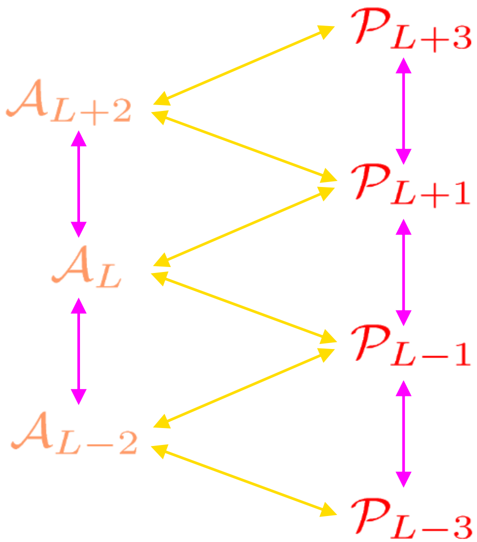
$$0 = \mathcal{A}_l$$
$$+\tilde{a}m\bar{\mathcal{A}}_l + \tilde{a}(\mathcal{Q}_l\tilde{\mathcal{P}}_{\ell-1} + \mathcal{Q}_{\ell+1}\tilde{\mathcal{P}}_{\ell+1})$$
$$+\tilde{a}^2\left(\hat{\mathcal{A}}_{\ell m} + \mathcal{Q}_{l-1}\mathcal{Q}_l\breve{\mathcal{A}}_{\ell-2} + \mathcal{Q}_{\ell+2}\mathcal{Q}_{\ell+1}\breve{\mathcal{A}}_{\ell+2}\right)$$

0th order

1st order

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

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

$$Y^{\ell m}_a = \left(\partial_\vartheta Y^{\ell m}, \partial_\varphi Y^{\ell m}\right)$$
$$S^{\ell m}_a = \left(\frac{1}{\sin\vartheta}\partial_\varphi Y^{\ell m}, -\sin\vartheta\partial_\vartheta Y^{\ell m}\right)$$

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

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

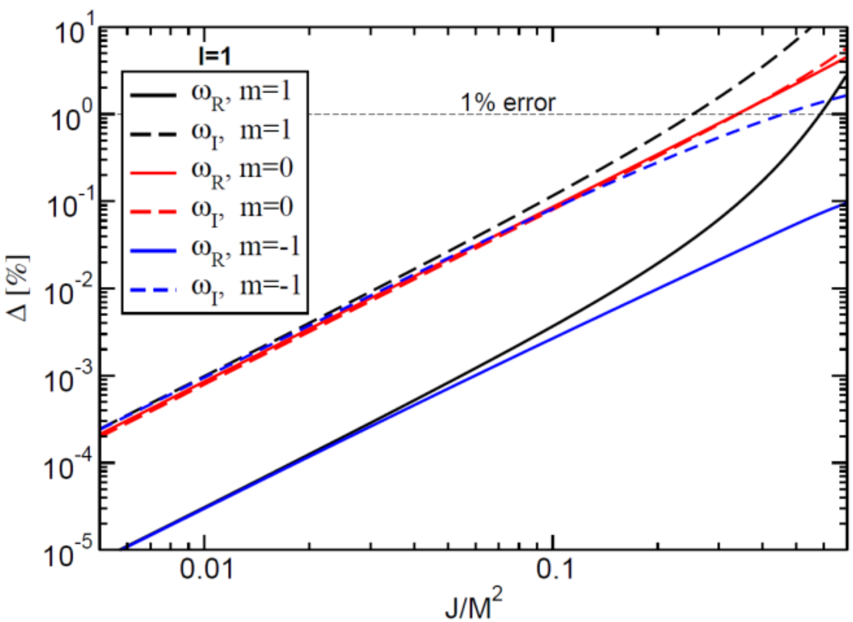
$$\hat{\mathcal{D}}_2 u^\ell_{(3)} + \frac{2F\ell(\ell+1)}{r^2}u^\ell_{(2)} + \frac{2\tilde{a}M^2 m}{r^4}\left[r\omega(3u^\ell_{(2)} - 2u^\ell_{(3)}) + 3\mathrm{i}\,F\left(u^\ell_{(1)} - ru'^\ell_{(1)}\right)\right] = 0,$$

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

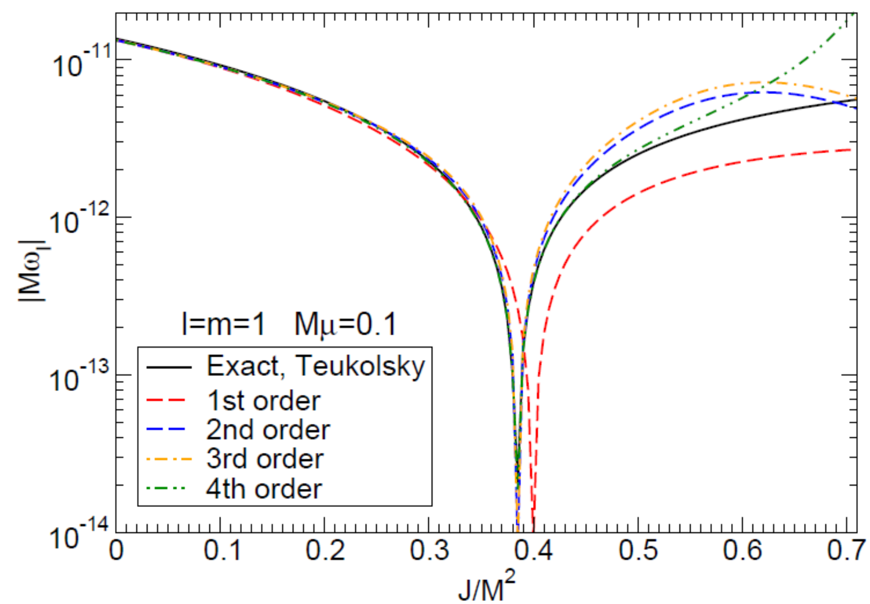
$$\hat{\mathcal{D}}_2 = d^2/dr_*^2 + \omega^2 - F\left[\ell(\ell+1)/r^2 + \mu^2\right]$$

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

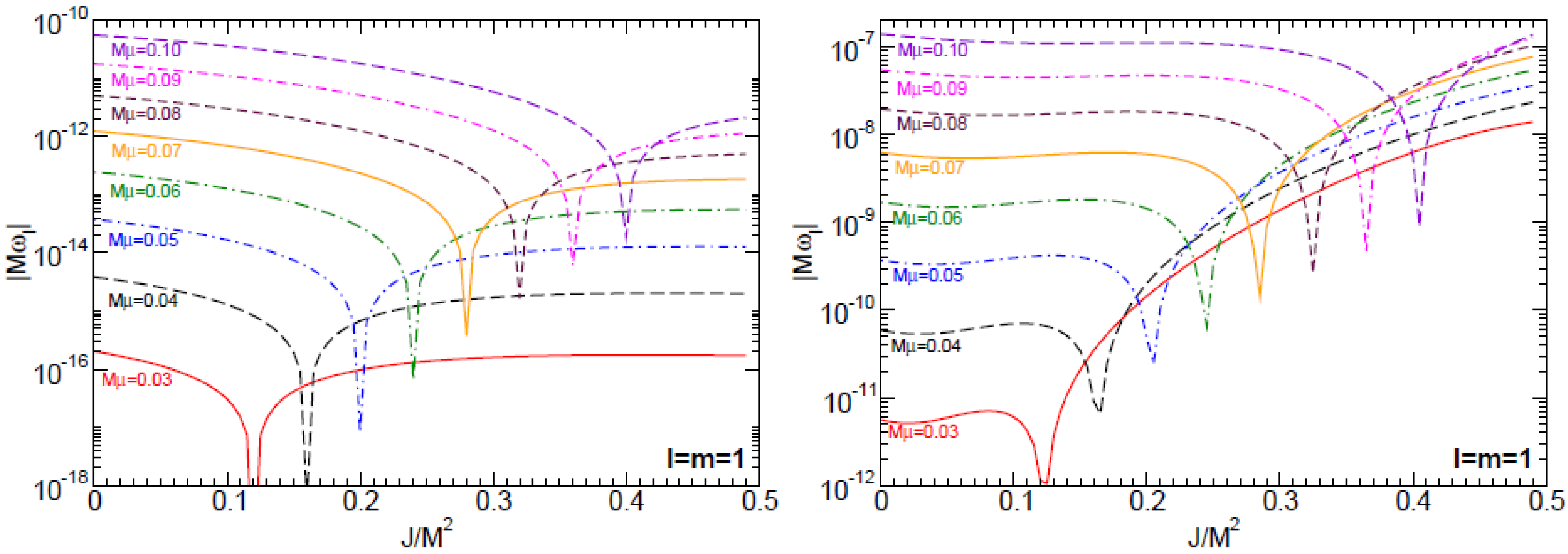
Check: massless (vector) perturbations



Check II: massive scalars



Pani et al, to appear

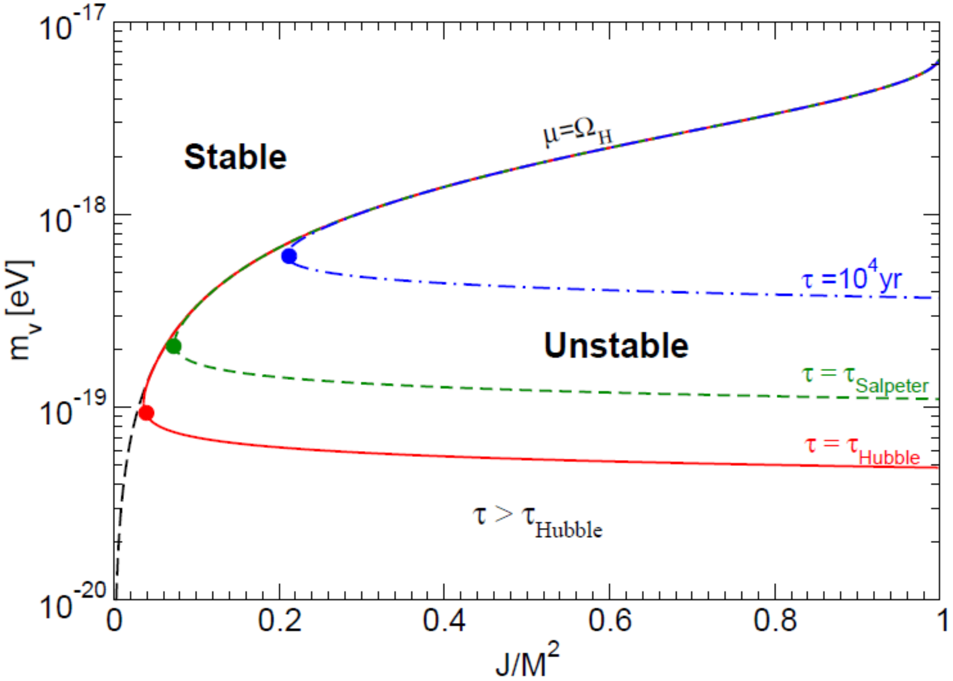


$$\tau_{\text{vector}} = \omega_I^{-1} \sim \frac{M(M\mu)^{-7}}{\gamma_{-11}(\tilde{a} - 2\mu r_+)}$$

See also Rosa and Dolan '11

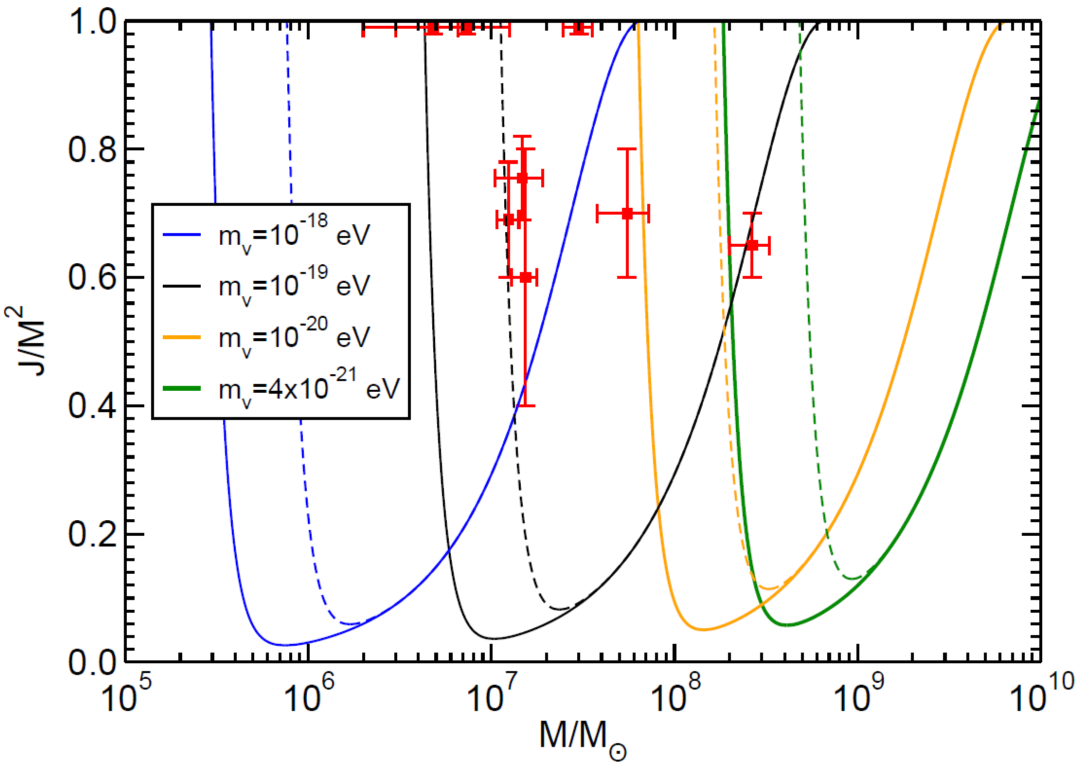
Pani et al, to appear

Proca instability



For a 10 million solar mass BH

Proca instability



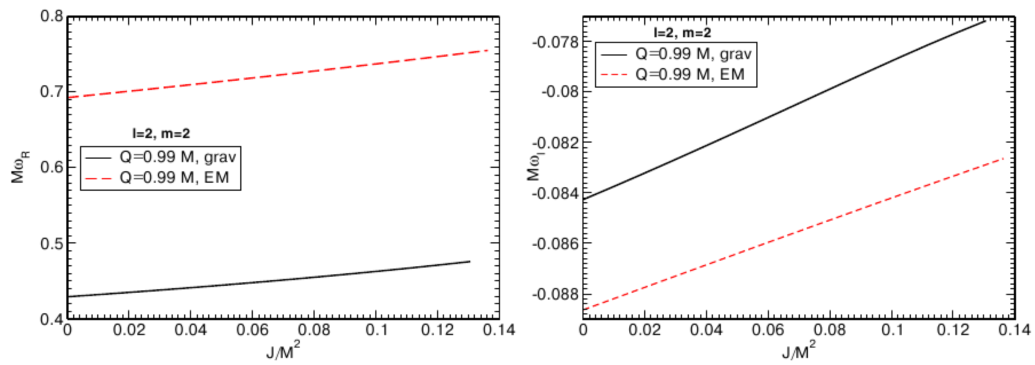
Depend very mildly on the fit coefficient and on the threshold

✸

$\tau_{Salpeter}$ → 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.

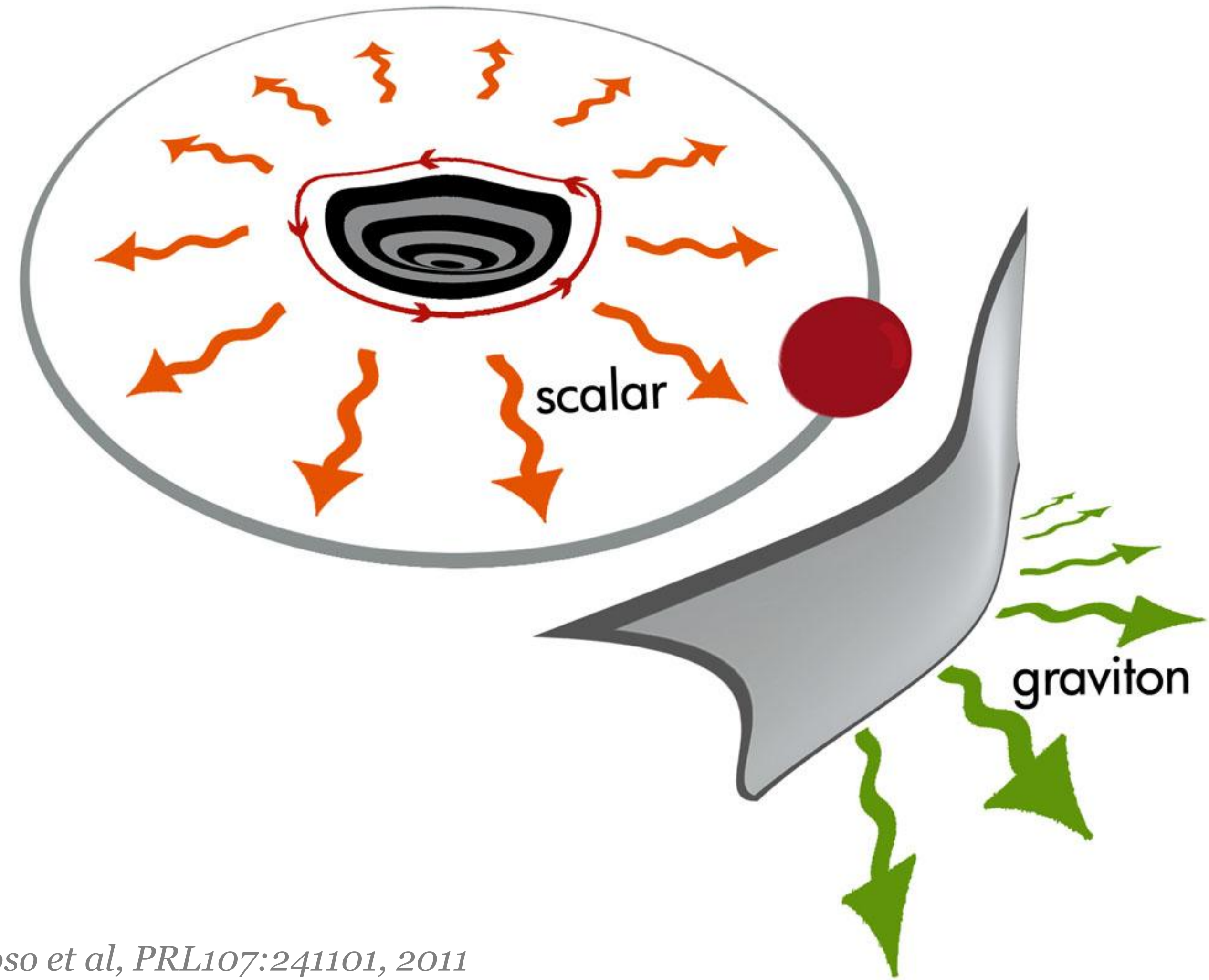
- 3rd order and higher in rotation, under way
- Gravito-EM perturbations of Kerr-Newman, under way



- 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

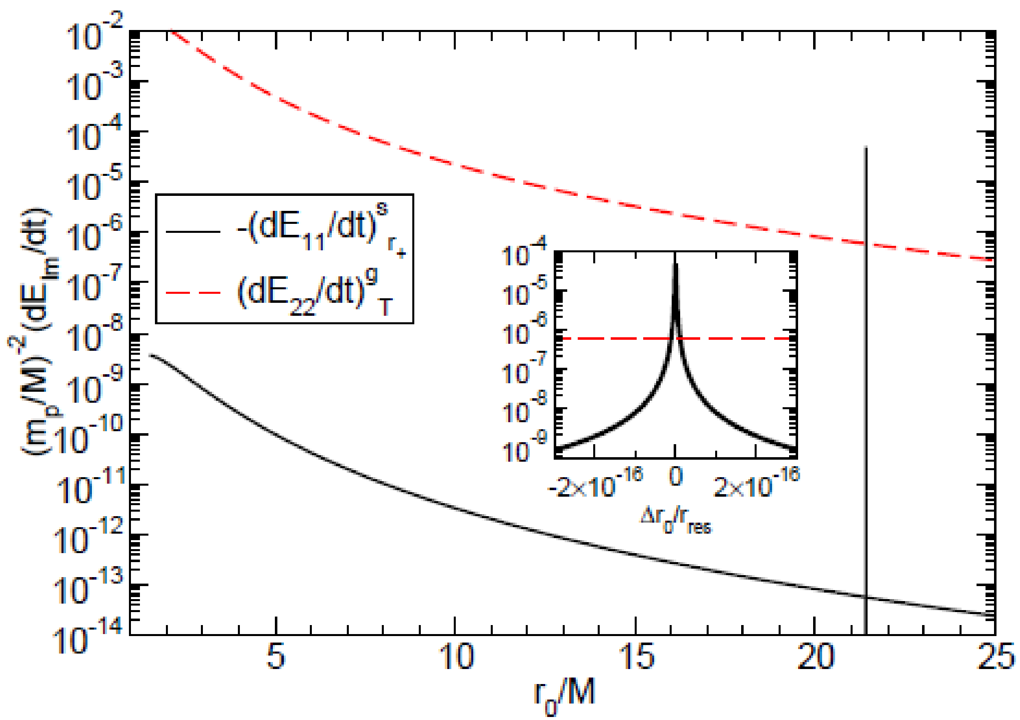


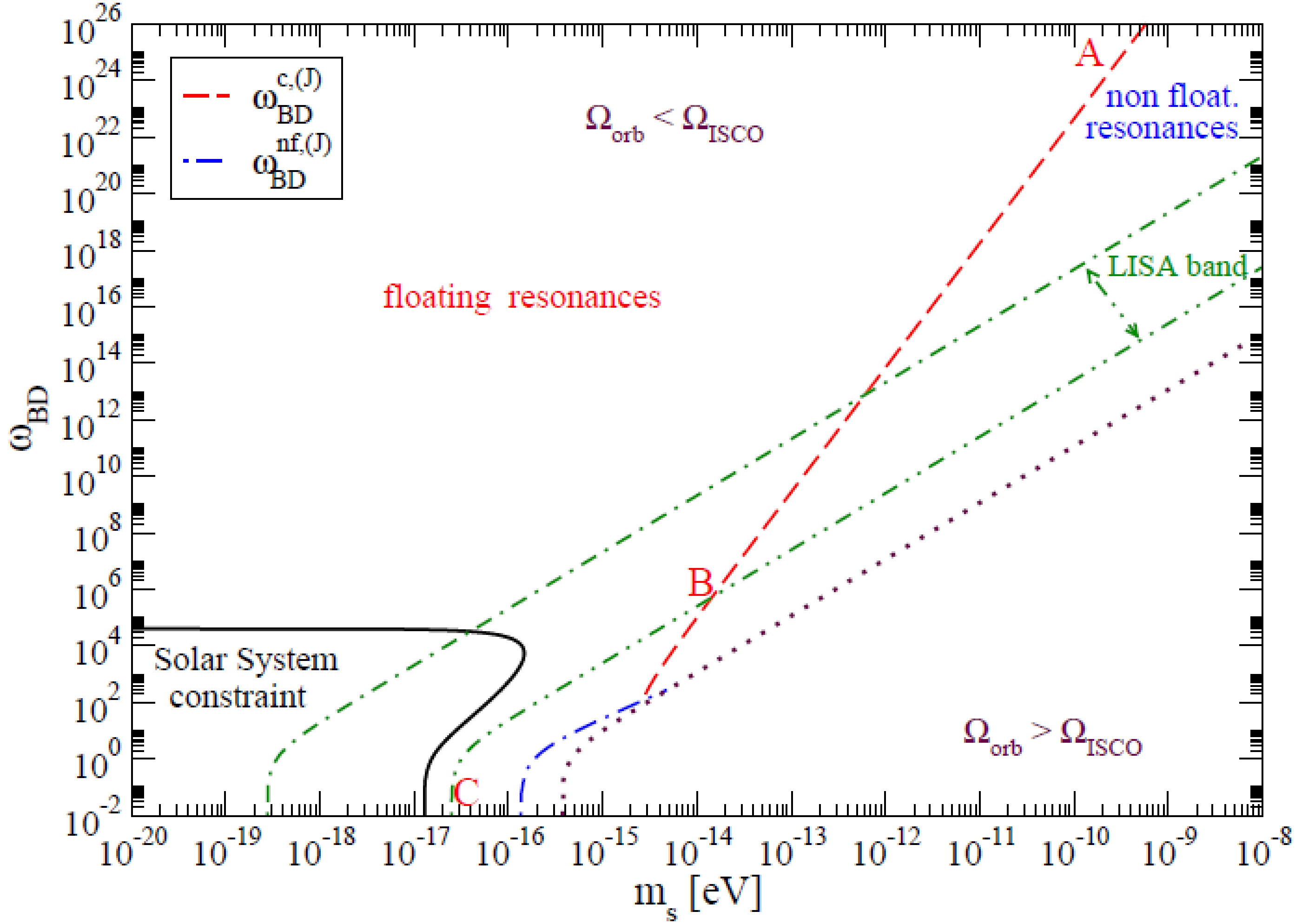
Cardoso et al, PRL107:241101, 2011

Yunes et al PRD81, 084052, 2012

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

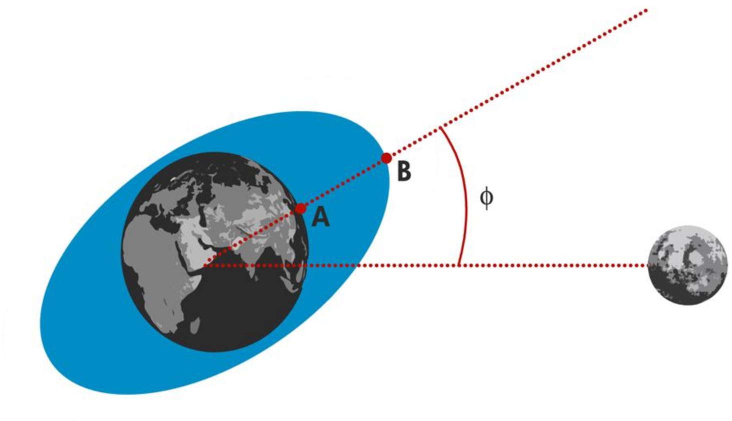
$$\dot{E}_{r_+}^{s,\mathrm{peak}} \sim -\frac{3\alpha^2 \sqrt{\frac{r_0}{M}} m_p^2 M}{16\pi r_+ \left(M^2 - a^2\right) \left(\frac{a}{2r_+} - (\frac{M}{r_0})^{3/2}\right) \mathcal{F}}$$

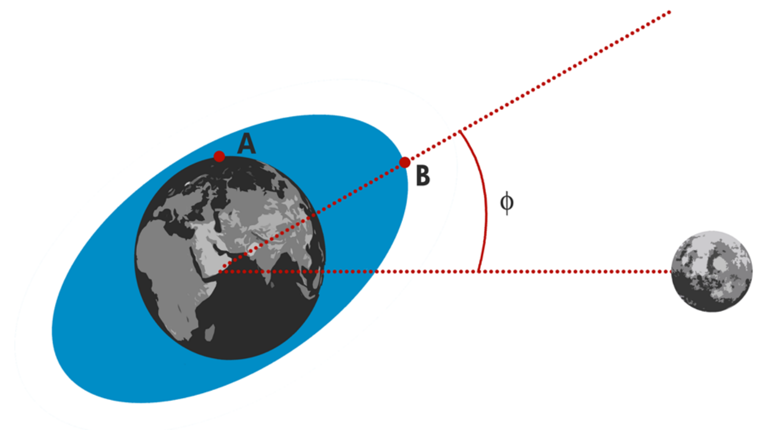




$\omega_{BD}^{c,(J)}$
$\omega_{BD}^{nf,(J)}$
A
B
C
$\Omega_{orb} < \Omega_{ISCO}$
non float.
resonances
floating resonances
LISA band
Solar System
constraint
$\Omega_{orb} > \Omega_{ISCO}$
ω_{BD}
m_s [eV]

Rotational energy: tidal acceleration





Earth-moon: 0.002s/cent

4cm/yr

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

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

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

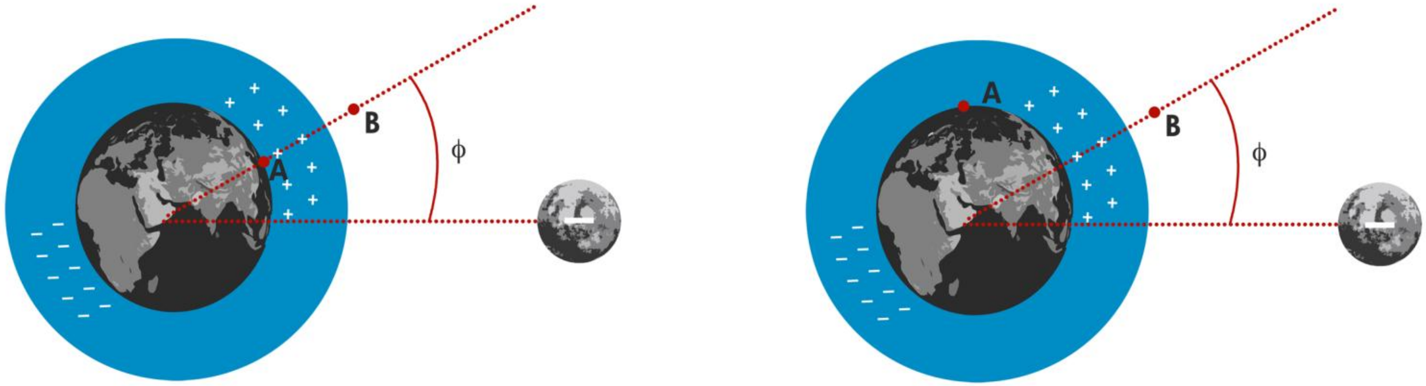
Tidal acceleration is in general impossible for BHs!

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

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

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

Press & Teukolsky, Nature (1973)



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

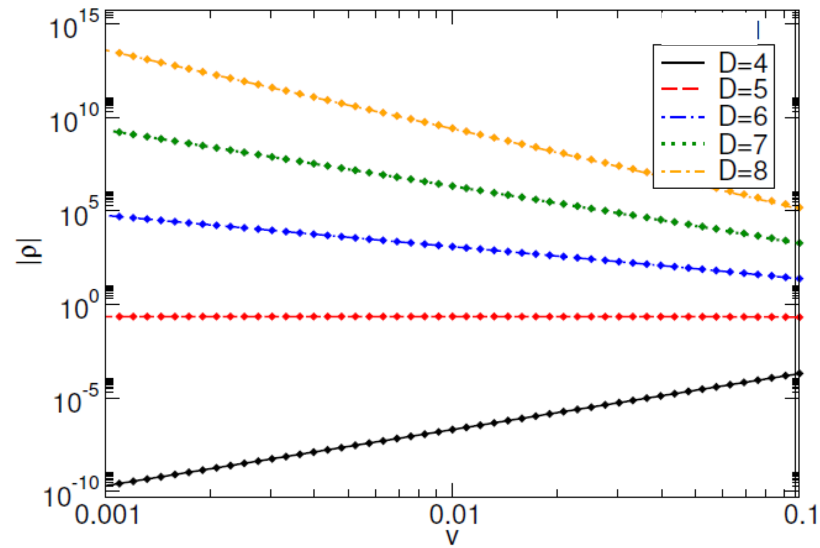
$$p \quad = 4\pi\epsilon_0 \left(\frac{\epsilon_r - 1}{2\epsilon_r + 1}\right) R^3 E_0$$

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

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

* * *

... 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?

Thank you

$$\cos\vartheta Y^{\ell} = \mathcal{Q}_{\ell+1} Y^{\ell+1} + \mathcal{Q}_{\ell} Y^{\ell-1} \,,$$

$$\sin\vartheta \partial_{\vartheta} Y^{\ell} = \mathcal{Q}_{\ell+1} \ell Y^{\ell+1} - \mathcal{Q}_{\ell} (\ell+1) Y^{\ell-1} \,,$$

$$\cos^2\vartheta Y^{\ell} = \left(\mathcal{Q}_{\ell+1}^2 + \mathcal{Q}_{\ell}^2\right) Y^{\ell} + \mathcal{Q}_{\ell+1} \mathcal{Q}_{\ell+2} Y^{\ell+2} + \mathcal{Q}_{\ell} \mathcal{Q}_{\ell-1} Y^{\ell-2}$$

$$\cos\vartheta \sin\vartheta \partial_{\vartheta} Y^{\ell} = \left(\ell \mathcal{Q}_{\ell+1}^2 - (\ell+1) \mathcal{Q}_{\ell}^2\right) Y^{\ell} + \mathcal{Q}_{\ell+1} \mathcal{Q}_{\ell+2} \ell Y^{\ell+2} - \mathcal{Q}_{\ell} \mathcal{Q}_{\ell-1} (\ell+1) Y^{\ell-2} \,,$$