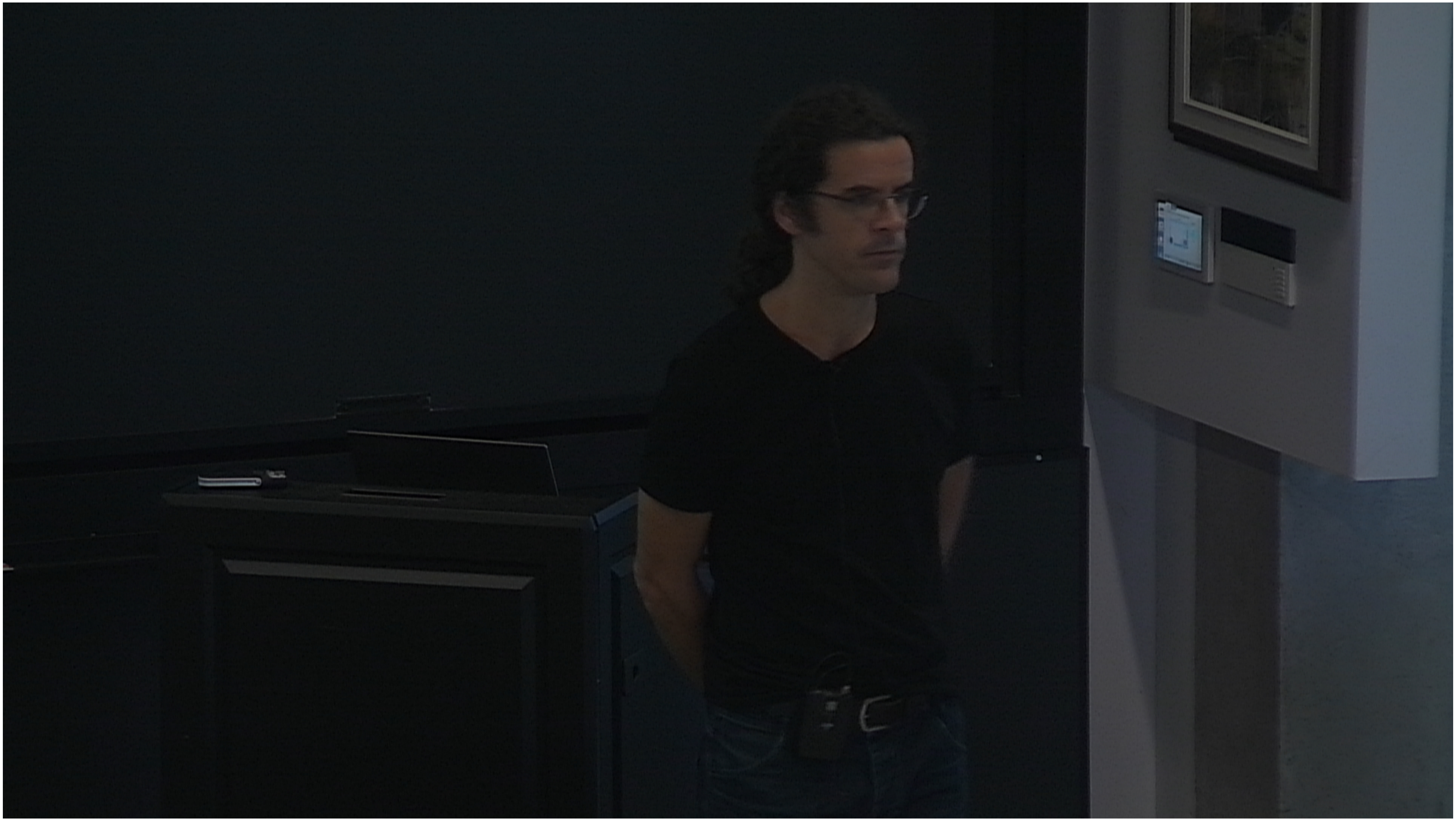
Title: The gravity of fundamental fields

Date: Sep 10, 2015 01:00 PM

URL: http://pirsa.org/15090023

Abstract: <p>Scalar fields are a useful proxy for other complex interactions, but also an attractive extension of General Relativity and a possible dark matter component. I will discuss some aspects of the gravitational interaction of scalar fields, in particular (i) the formation and growth of self-gravitating structures and their interaction with compact stars. and (ii) superradiance around black holes and how it can be used to constraint particle masses.</p>



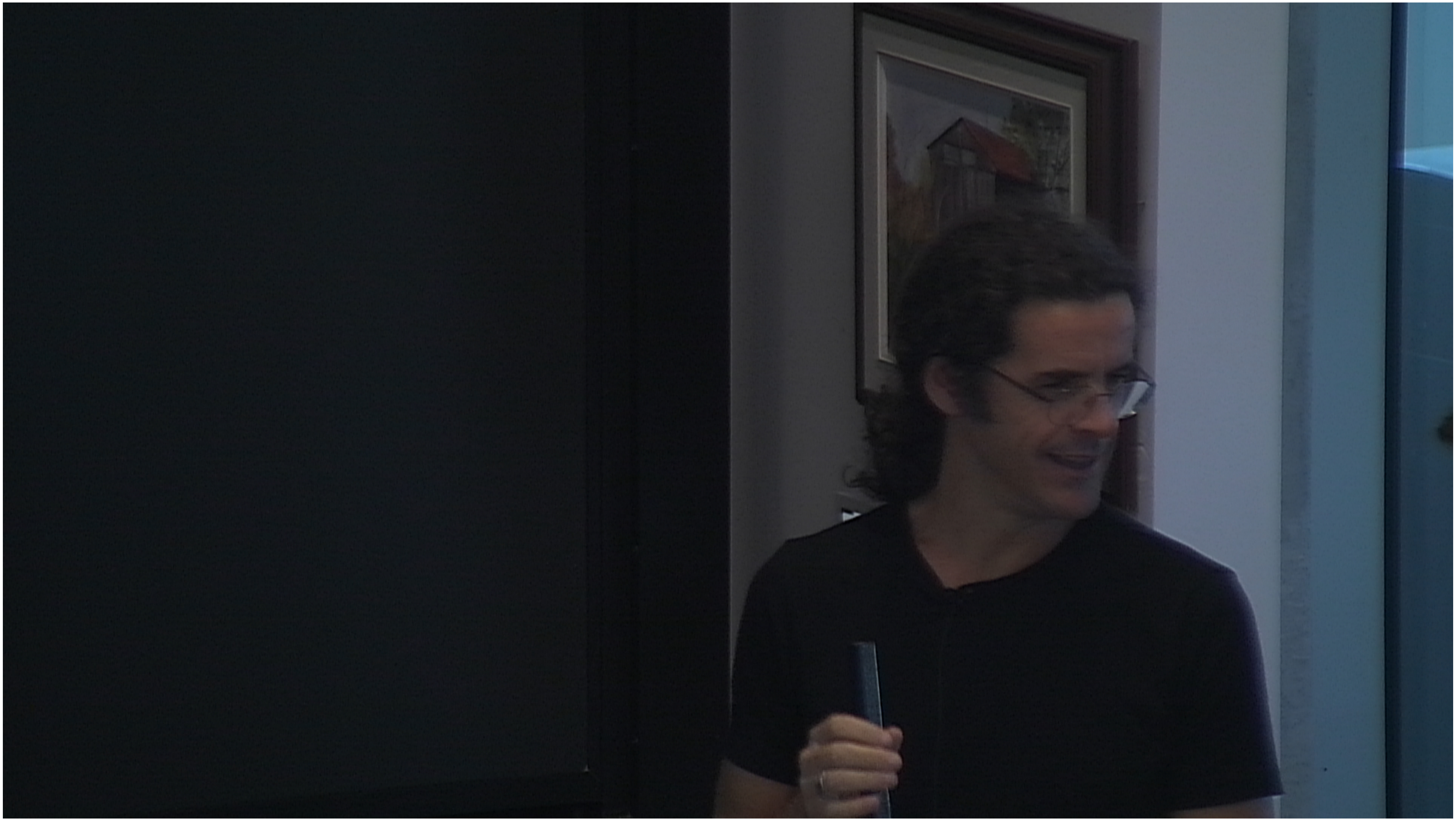
The gravity of fundamental fields

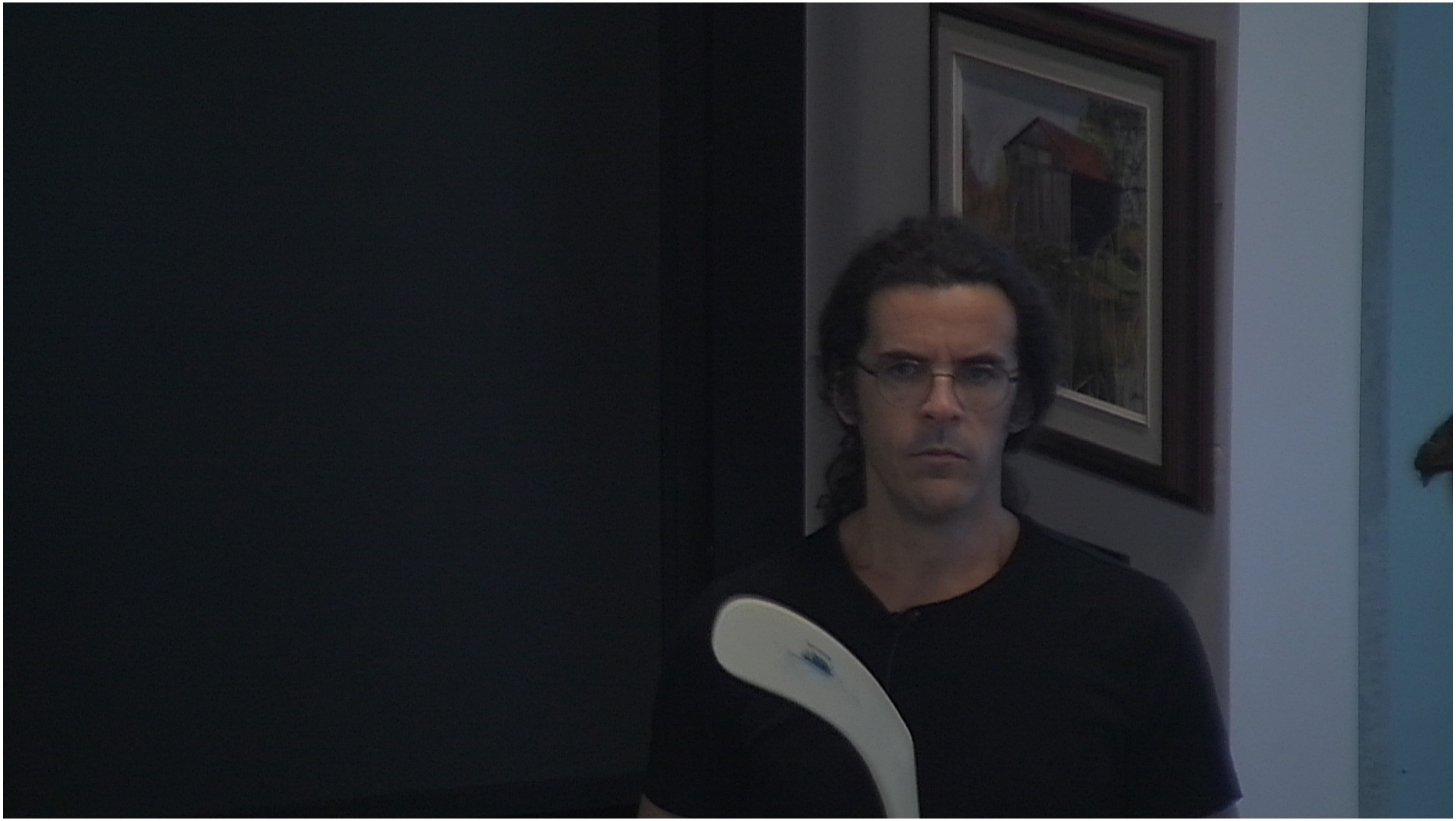
Vítor Cardoso
(CENTRA/Técnico & Perimeter)

...

Perimeter Institute

TÉCNICO LISBOA | centra | blackholes.ist.utl.pt | erc supports this project





Strong gravity and fundamental fields: (massive) scalars

Interesting as effective description; proxy for more complex interactions

Arise as interesting extensions of GR* *(BD or generic ST theories; f(R))*

They exist (Higgs)

They might exist *Peccei-Quinn (interesting because not invented to solve DM problem)*
Axiverse scenarios - moduli and coupling constant in string theory

..and one or more could be a component of DM

* *Poorly constrained for massive fields*

Okawa, Cardoso & Pani,
Collapse of self-interacting fields in asymptotically-flat spacetimes,
Phys.Rev.D89(2014) 4, 041502 ; arXiv:1311.1235

Okawa, Witek & Cardoso,
Black holes and fundamental fields in Numerical Relativity
Phys.Rev.D89 (2014) 10, 104032; arXiv:1401.1548

Brito, Cardoso & Okawa,
Dark matter accretion by stars,
Phys.Rev.Lett. 115: 111301 (2015); arXiv:1508.04773

Brito, Cardoso, Pani,
Superradiance,
Springer Lecture Notes in Physics vol. 906 (2015)

Solitons: existence

$$\mathcal{L} = R - \frac{g^{\mu\nu}}{2}\phi^*_{,\mu}\phi_{,\nu} - \frac{\mu_S^2}{2}\phi^*\phi - \frac{F^2}{4} - \frac{\mu_V^2}{2}A^2$$

$$\frac{G}{c\hbar}M\mu_{S,V} = 7.5 \cdot 10^4 \left(\frac{M}{M_\odot}\right)\left(\frac{m_B c^2}{10^{-5}eV}\right)$$

No time-independent solutions in Minkowski

[Derrick 1964]

No time-independent scalar or vector BH hair

[Bekenstein 1972]

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Time-dependent, complex bosons

$$\begin{aligned}\phi(t,r) &= \phi(r)e^{-i\omega t} \\ 8\pi T_{\mu\nu} &= \nabla_\nu\phi\nabla_\mu\phi^* + \nabla_\mu\phi\nabla_\nu\phi^* - g_{\mu\nu}\mu_S^2\,|\phi|^2 - g_{\mu\nu}(g^{ab}\nabla_b\phi\nabla_a\phi^*)\end{aligned}$$

$$\begin{aligned}ds^2 &= -e^\nu dt^2 + e^\lambda dr^2 + r^2\left(d\theta^2 + \sin^2\theta d\varphi^2\right) \\ \lambda' &= e^\lambda r\left(e^{-\nu}\omega^2 + \mu_S^2\right)\phi^2 + \frac{r^2\left(\phi'\right)^2 - e^\lambda + 1}{r} \\ \nu' &= e^\lambda r\left(e^{-\nu}\omega^2 - \mu_S^2\right)\phi^2 + \frac{r^2\left(\phi'\right)^2 + e^\lambda - 1}{r} \\ \phi'' &= \phi e^\lambda\left(\mu_S^2 - \omega^2 e^{-\nu}\right) + \frac{\phi'\left(r\lambda' - r\nu' - 4\right)}{2r}\end{aligned}$$

Prescribe scalar at origin, "shoot" for frequency w [Kaup 1968; Ruffini & Bonazzolla 1969]

Time-dependent, real bosons

$$\phi(t,r) = \sum_{j=0}^{\infty} \phi_{2j+1}(r)\ \cos\left[(2j+1)\,\omega t\right]$$

Prescribe scalar at origin, "shoot" for frequency w mode by mode [Seidel & Suen 1991]

Nonlinearities force cascade to high frequencies and eventually to mass loss [Page 2003]

$$T_{\mathrm{decay}} \sim 10^{324} \left(\frac{1\,\mathrm{meV}}{m_B \mathrm{c}^2}\right)^{11} \mathrm{yr}$$

Time-dependent, complex bosons

$$
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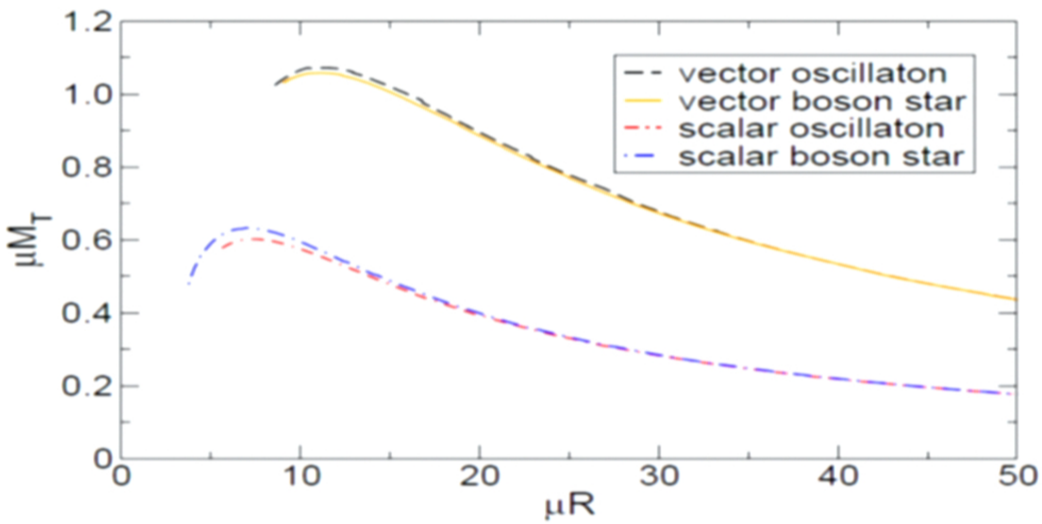
Prescribe scalar at origin, "shoot" for frequency w [Kaup 1968; Ruffini & Bonazzolla 1969]

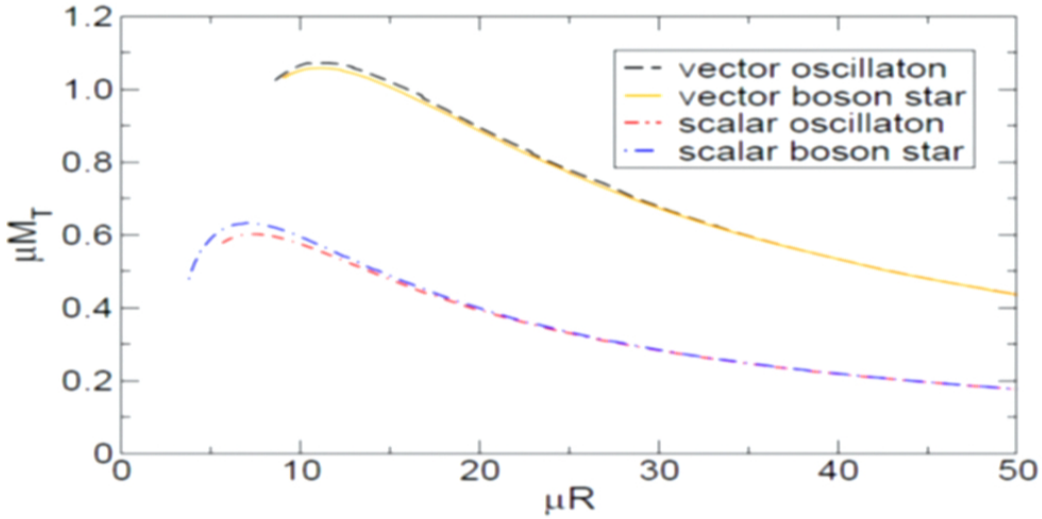
Nodeless solutions



Brito, Cardoso, Okawa, arXiv: 1508.04773

$$\frac{M_{\max}}{M_{\odot}} = 8 \times 10^{-11} \left(\frac{\mathrm{eV}}{m_B c^2} \right)$$

Nodeless solutions



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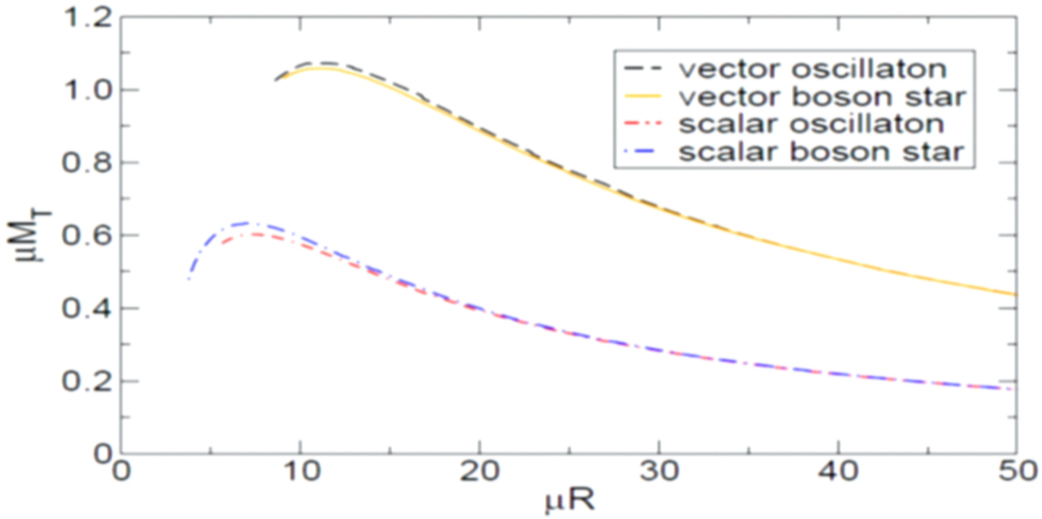

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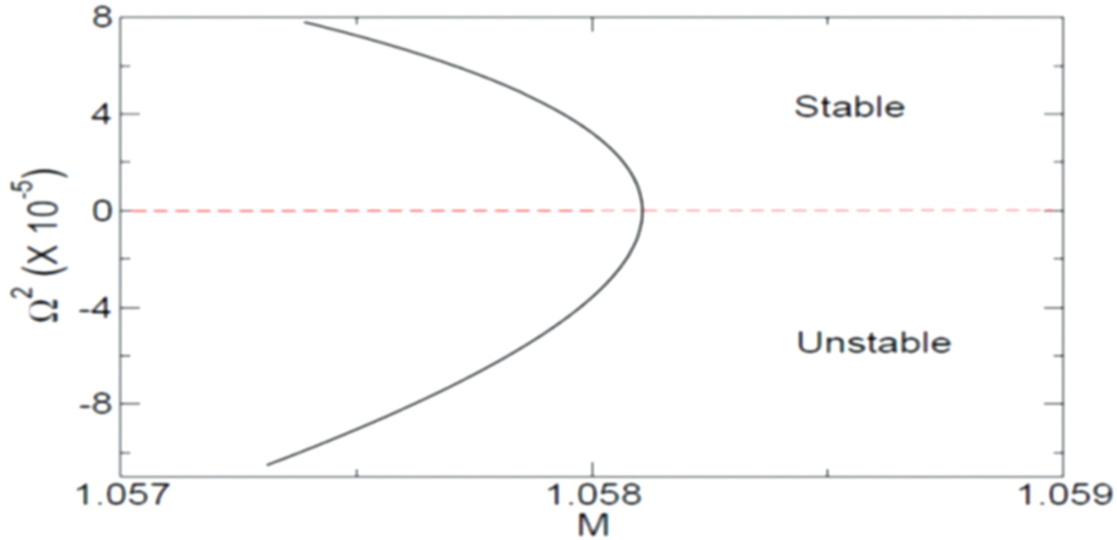
Solitons: existence
other theories

One needs mass

Scalar-tensor theories, non-minimally coupled theories etc

Solitons: stability

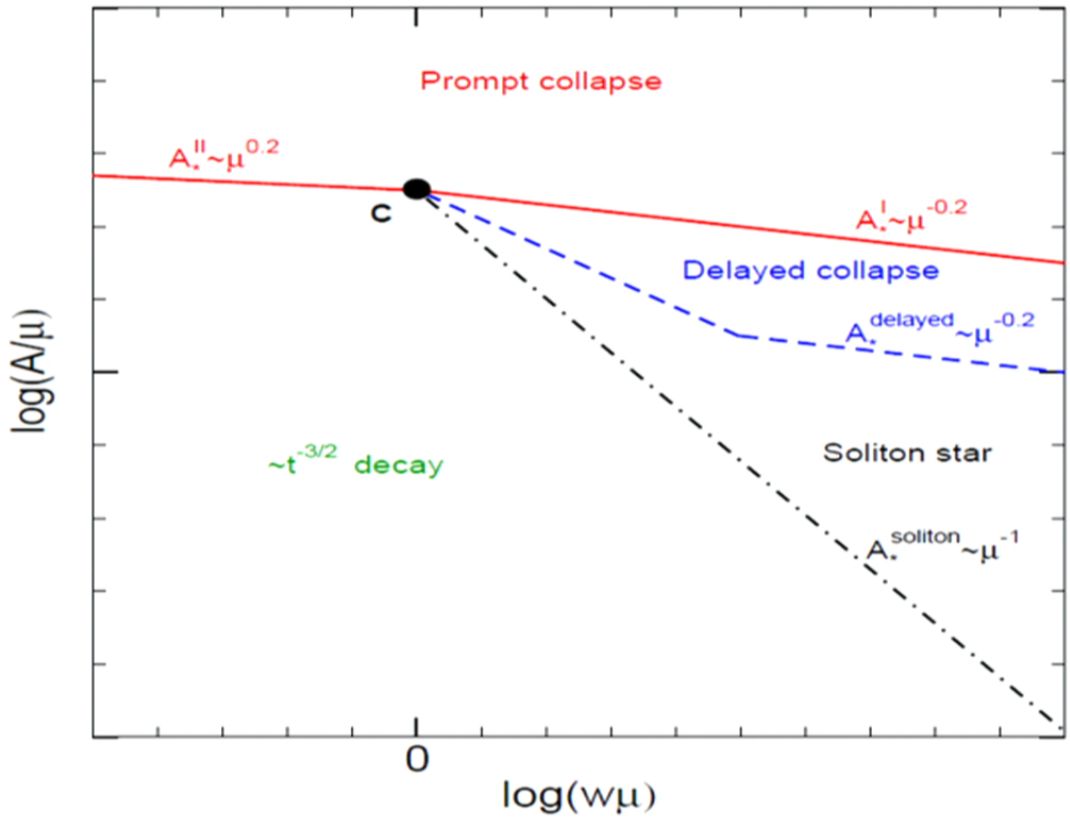
$$\delta\phi \sim e^{\Omega t}$$



For scalar case see Gleiser (1988) and Choptuik & Hawley (2000)

For vector see Brito, Cardoso, Herdeiro & Radu, arXiv:1508.05395

Formation of self-gravitating solutions:
gravitational collapse



Okawa et al PRD89, 041502 (2014)

Solitons: interaction and growth

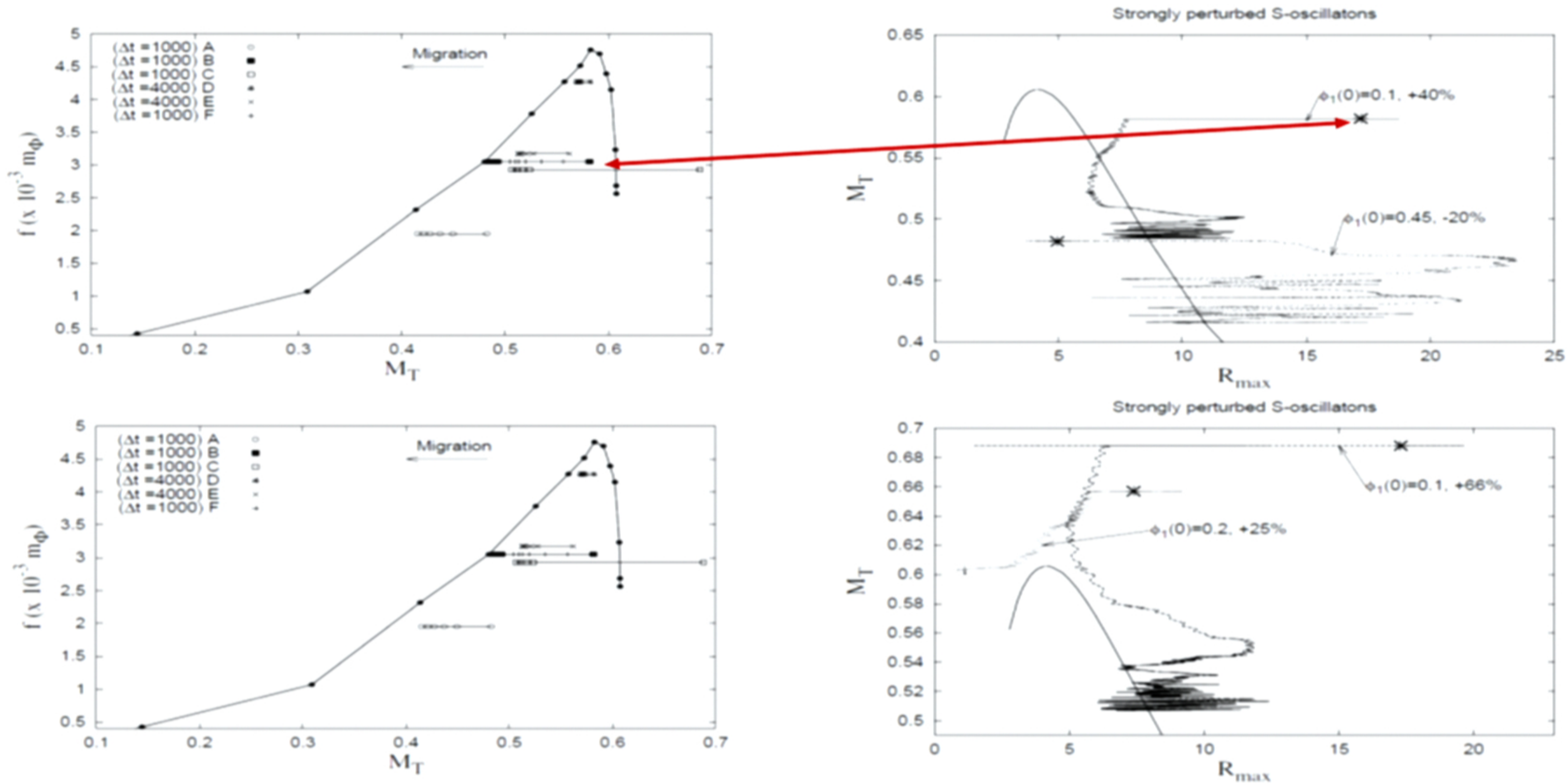
(i) Oscillatons to the right of the peak (S-branch) are stable when slightly perturbed

(ii) Perturbed oscillatons with mass smaller than critical migrate back to S-branch

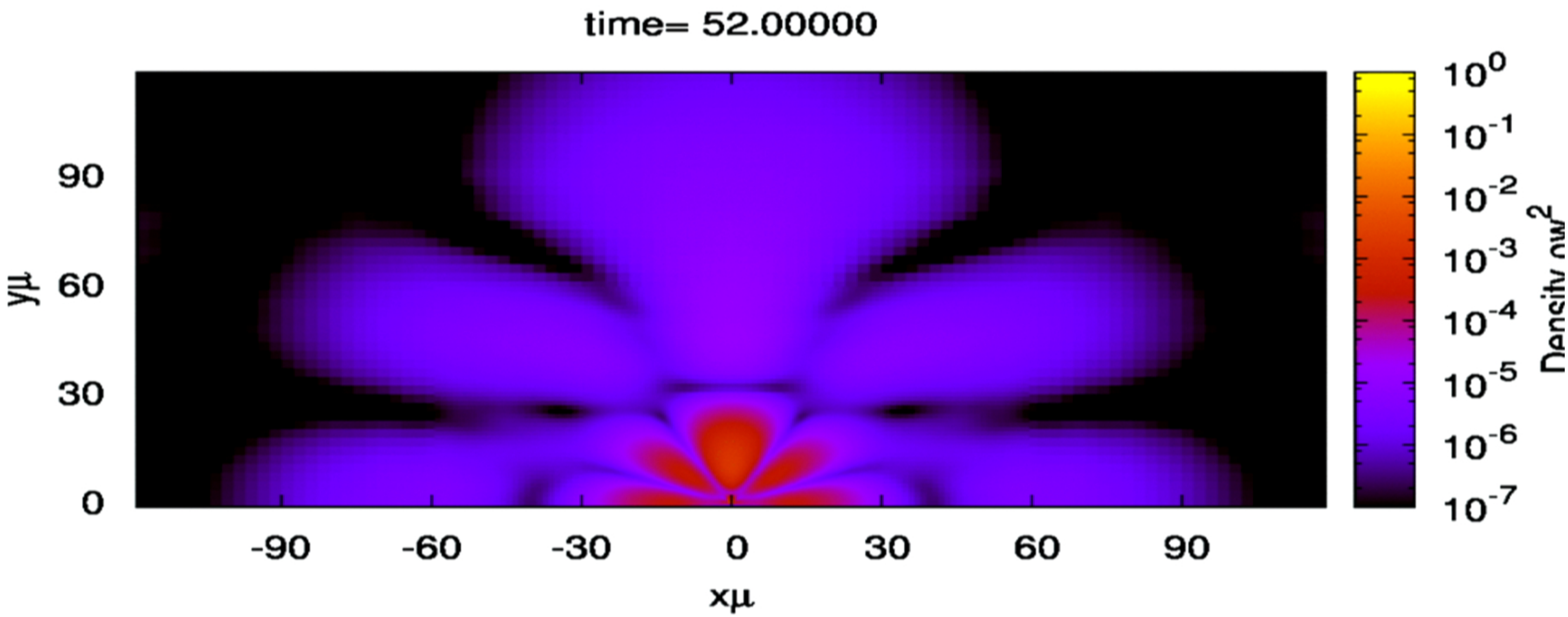
(iii) For masses larger than critical, either migrates back or collapses

Seidel and Suen 1990

Alcubierre et al 2003

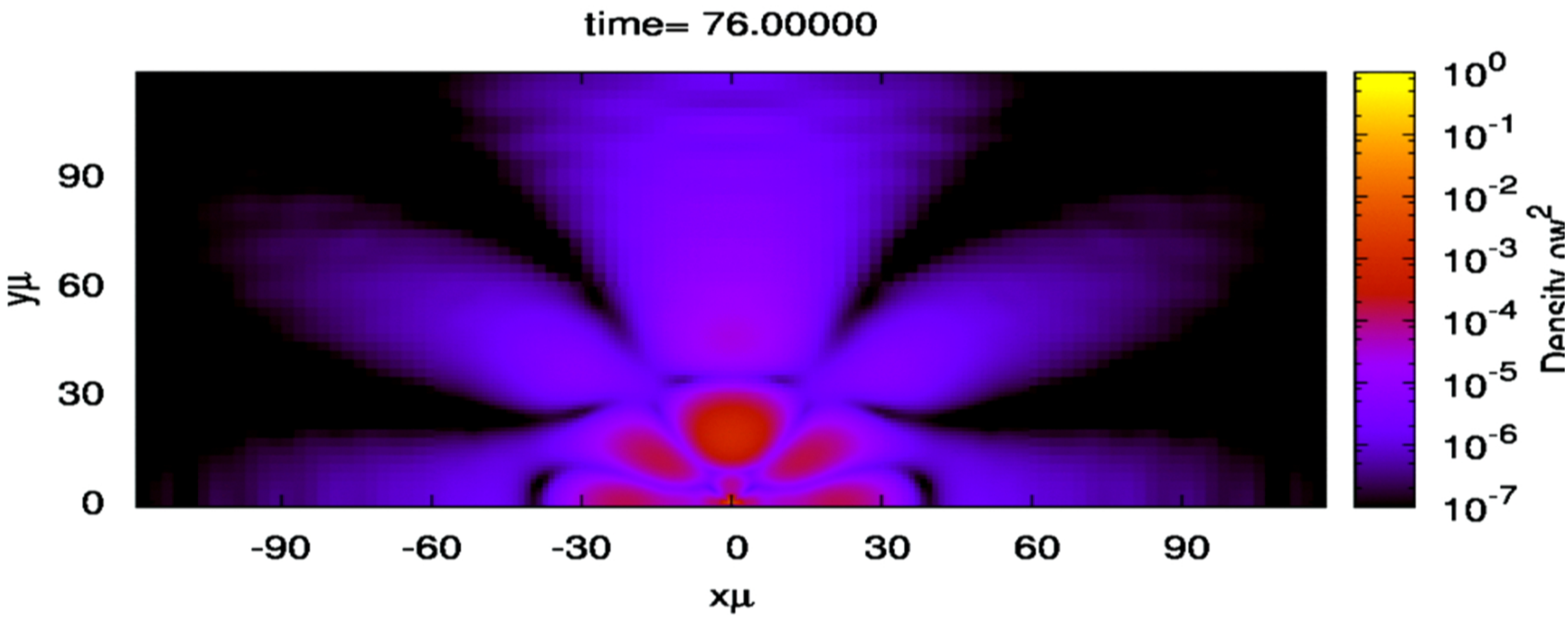


Alcubierre et al 2003



Parameters: μ=15, M μ =0.54 and R μ =4.5

Brito, Cardoso, Okawa, arXiv:1508.04773



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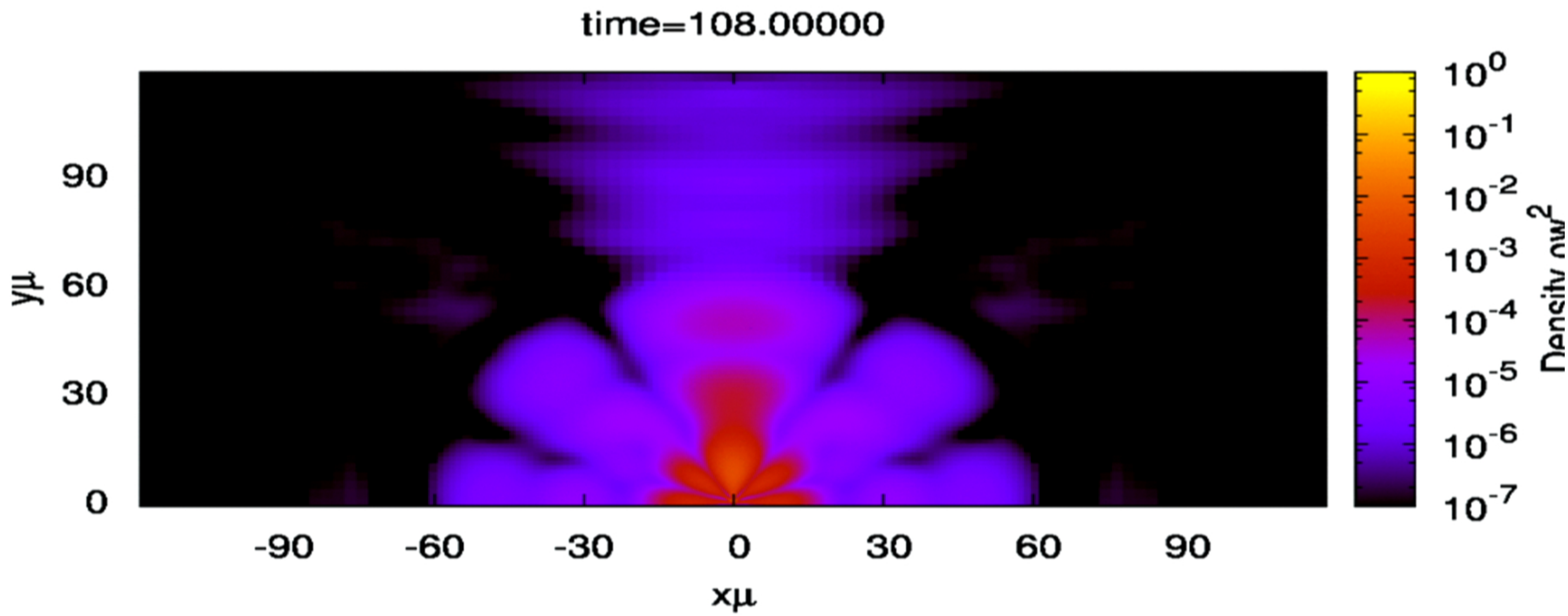

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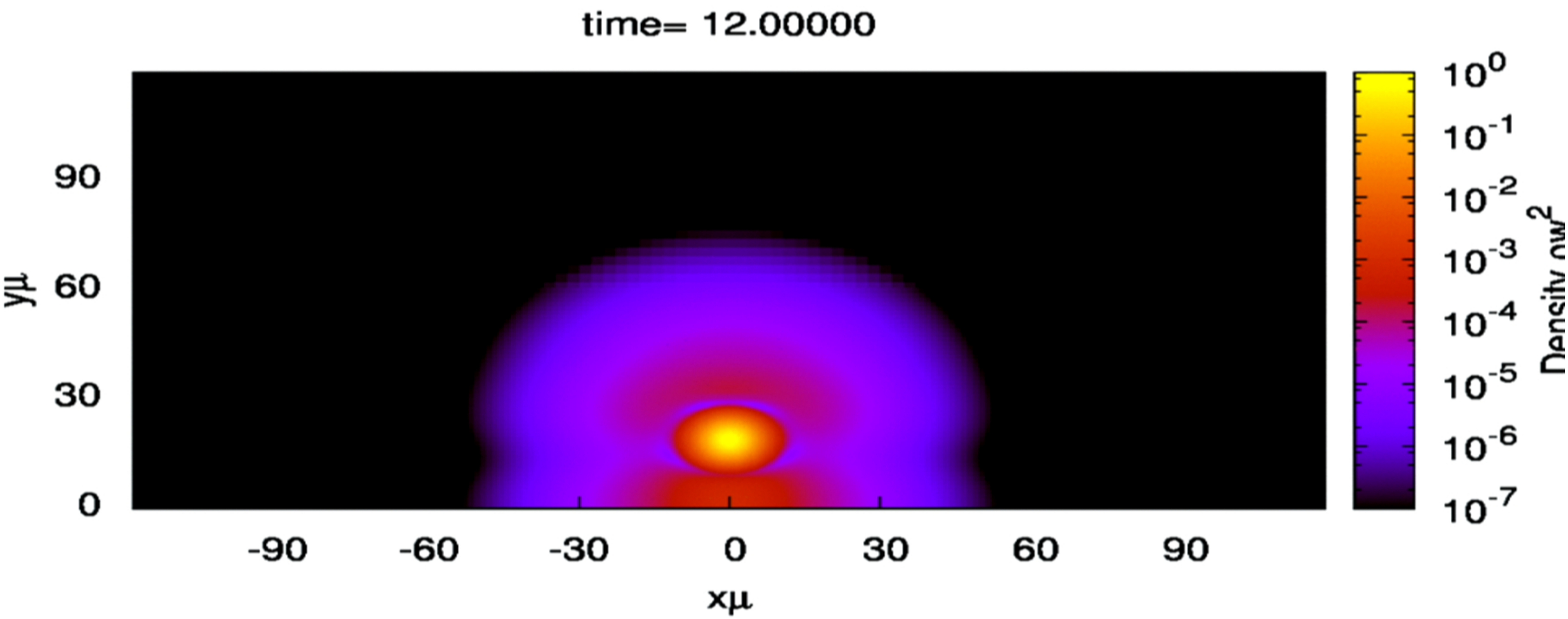

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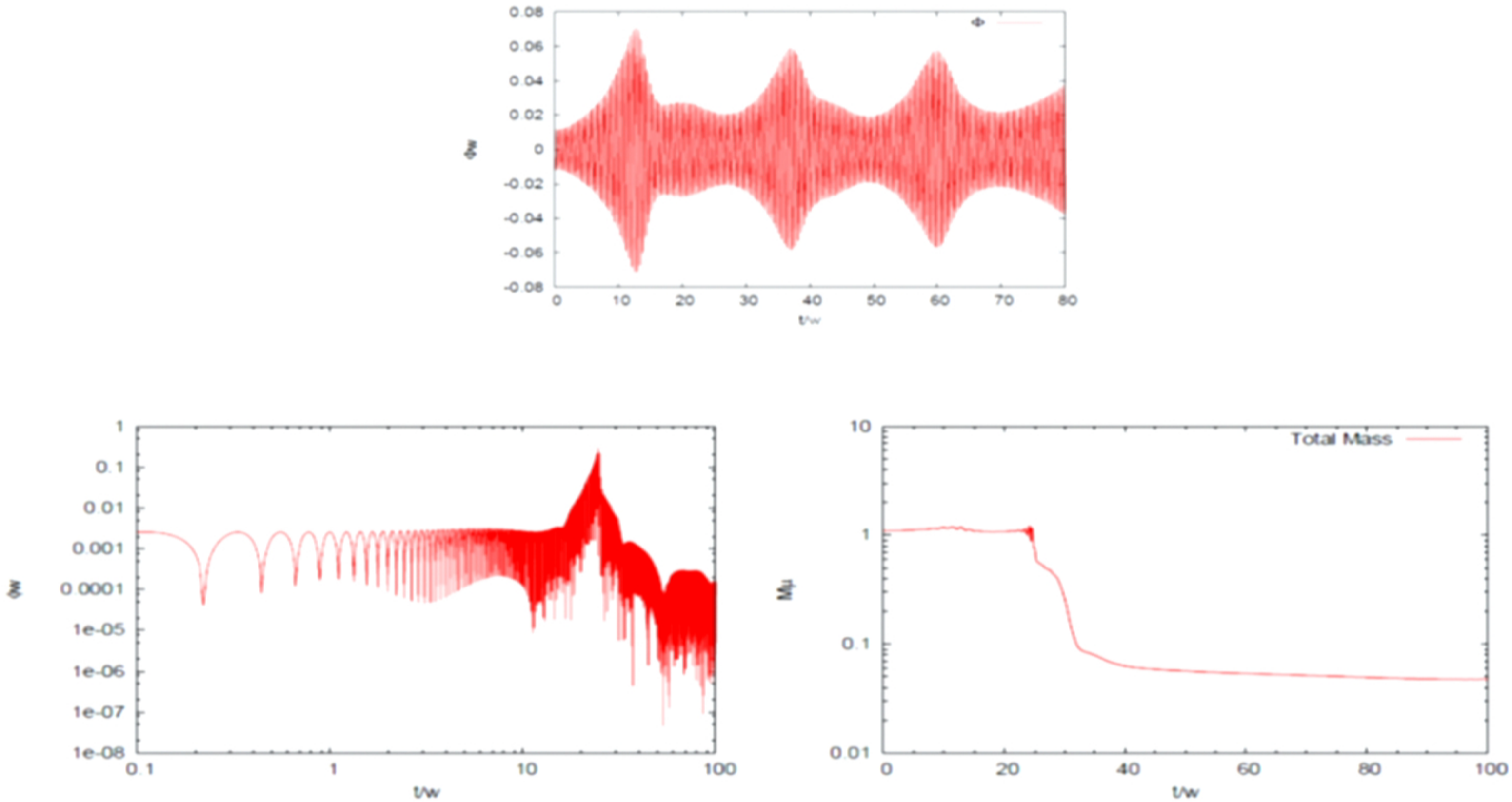


Brito, Cardoso, Okawa, arXiv:1508.04773

Growth of bosonic structures

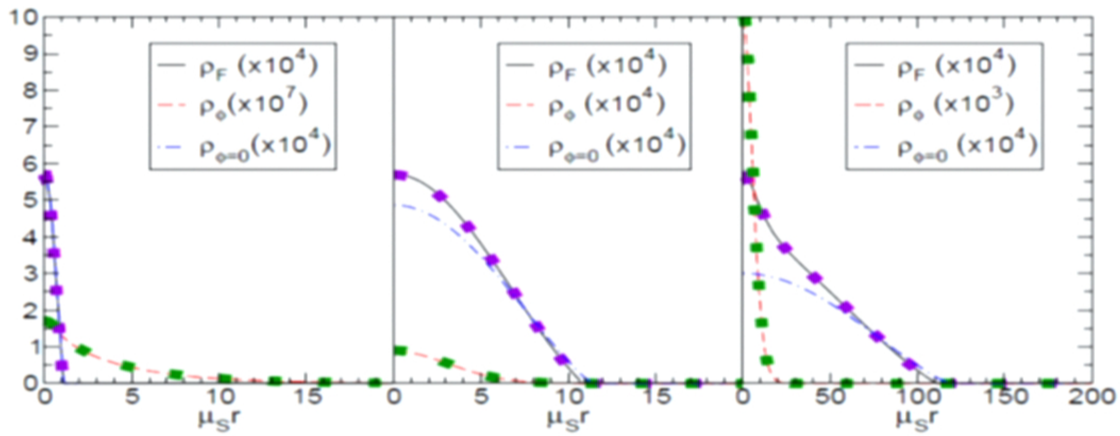
(i) Boson structures grow through mergers or minor mergers (more work welcome!)

(ii) The growth continues till threshold mass $\frac{M_{\rm max}}{M_\odot} = 8 \times 10^{-11} \left(\frac{\rm eV}{m_B c^2}\right)$ then halts

(iii) Collapse seems to be avoided by “gravitational cooling” mechanism

Brito, Cardoso, Okawa, arXiv:1508.04773

Accretion onto stars



Polytropic stars with a bosonic core at the center. Plots show (time-average) energy density for fluid and scalar field. Blue line is corresponding star for vanishing scalar. Squares denote same quantities for complex scalars. Left to right: μM=0.1, 1, 10

Brito, Cardoso, Okawa, arXiv:1508.04773

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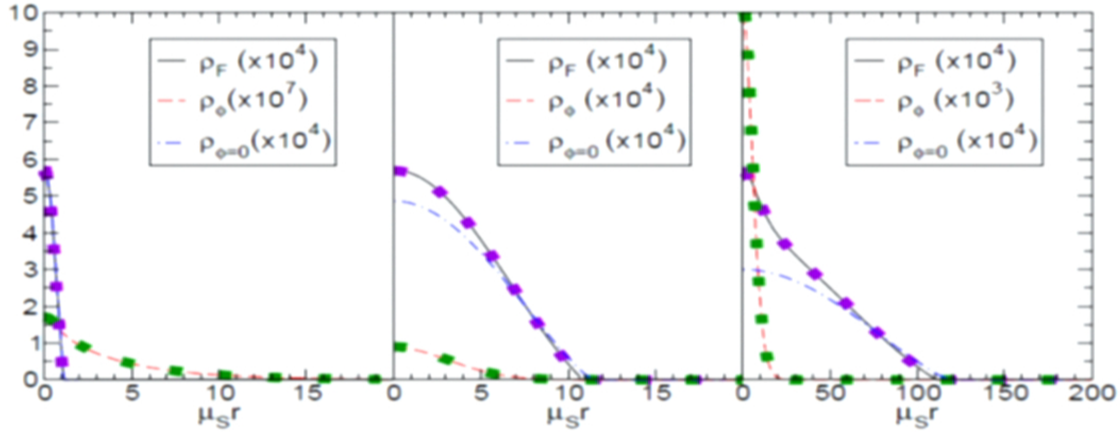

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Accretion onto stars

For Compton wavelengths smaller than size of star, boson core behaves as isolated oscillaton

Core grows through sequence of minor mergers, until peak mass

$$\frac{M_{\rm max}}{M_\odot} = 8 \times 10^{-11} \left(\frac{\rm eV}{m_B c^2}\right)$$

Core does *not* collapse to black hole

Gravitational coupling to matter drives oscillations of star at frequency

$$f = 2.5 \times 10^{14} \left(\frac{m_B c^2}{eV}\right) \text{ Hz}$$

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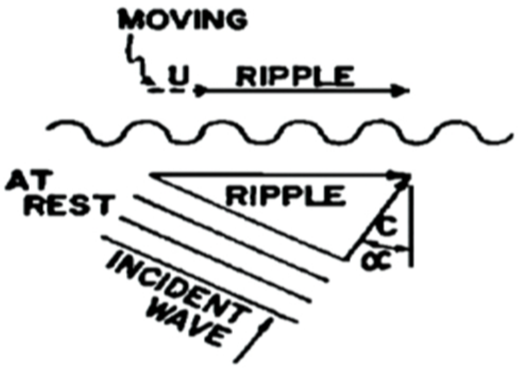
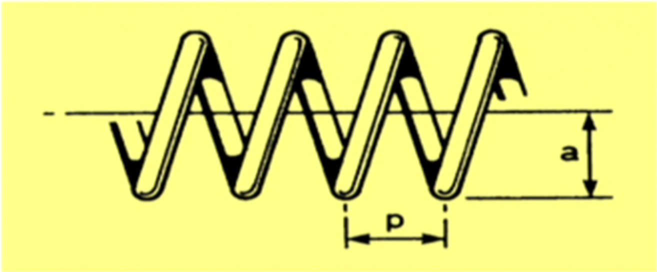
The strong gravity of fundamental fields

Friction & superradiance

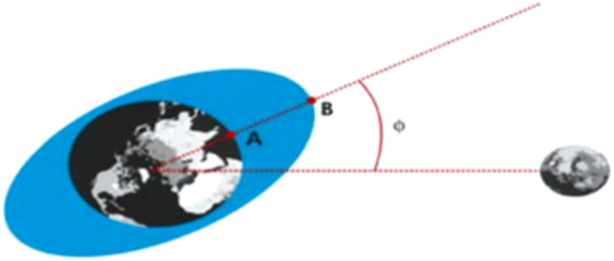


Ribner, J. Acous. Soc. Amer.29 (1957)

Tamm & Frank, Doklady AN SSSR 14 (1937)

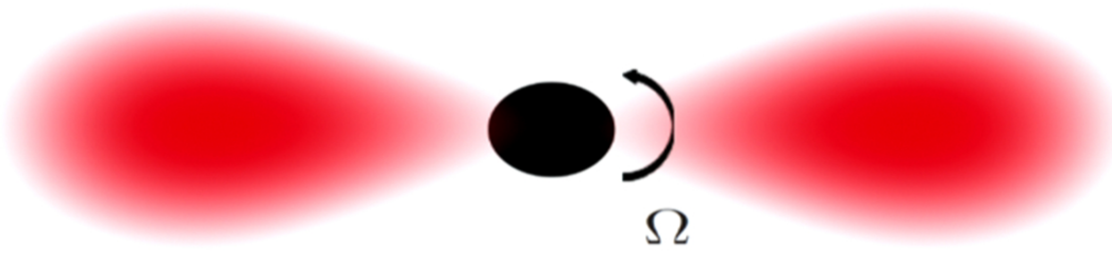


Pierce (& Kompfner), Bell Lab Series (1947)
Ginzburg, anomalous Doppler year



G. H. Darwin, Philos. Trans.
R. Soc. London 171 (1880)

$$\Phi \sim e^{-i\omega t + im\phi} \;\rightarrow\; (Angular)\, phase\, velocity = \frac{\omega}{m}$$

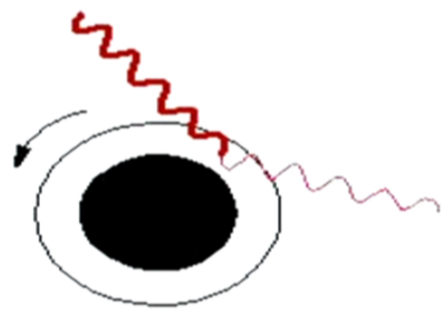


$$\omega < m\Omega$$

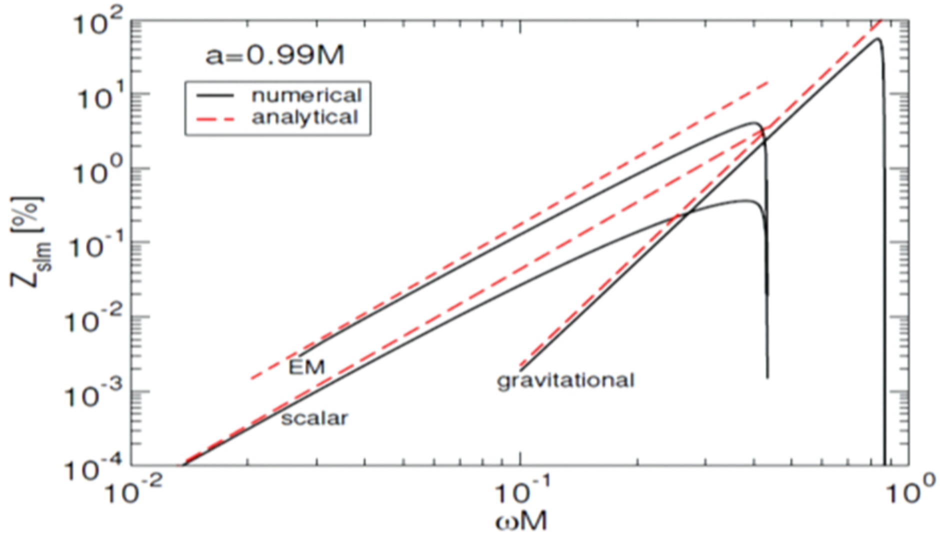
Zel'dovich, Pis'ma Zh. Eksp. Teor. Fiz. 14 (1971)

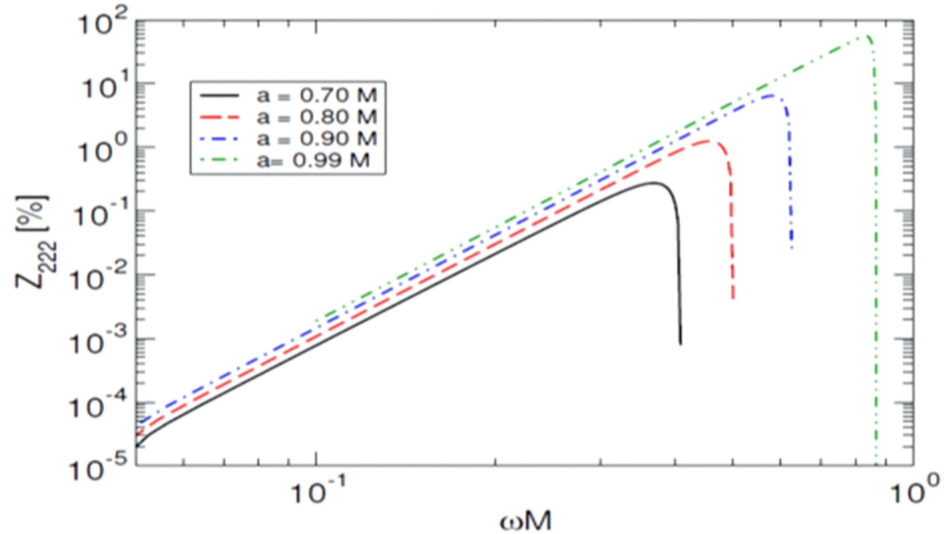
Black holes and superradiance

Friction built-in through one-way membrane (horizon)



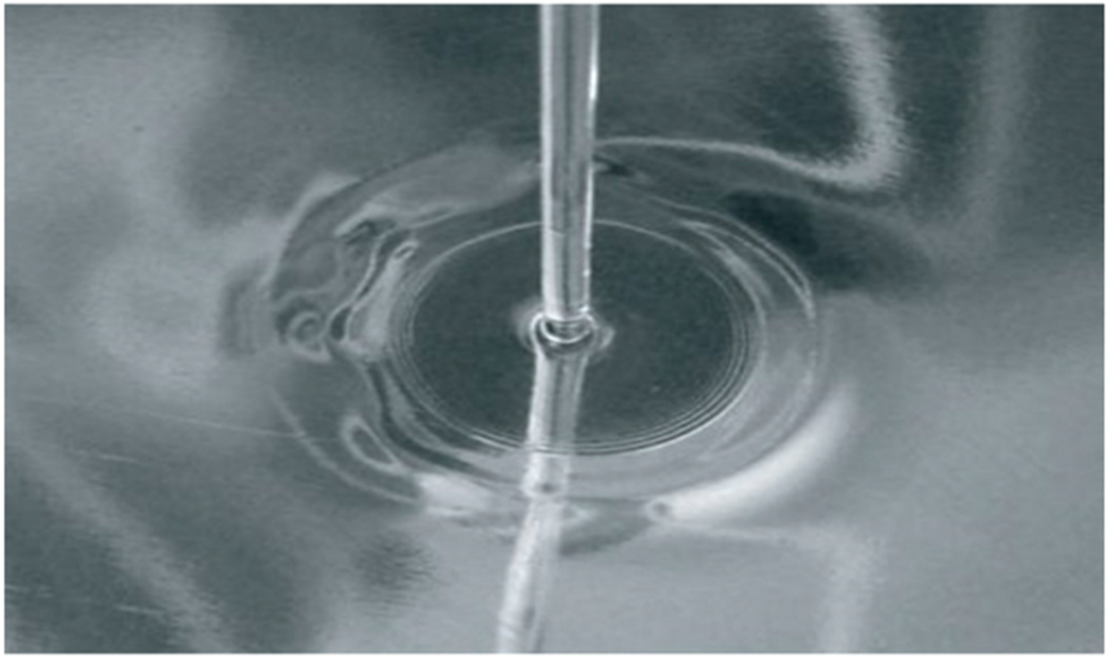
Zel'dovich, Pis'ma Zh. Eksp. Teor. Fiz. 14 (1971), Brito et al, arXiv:1501.06570





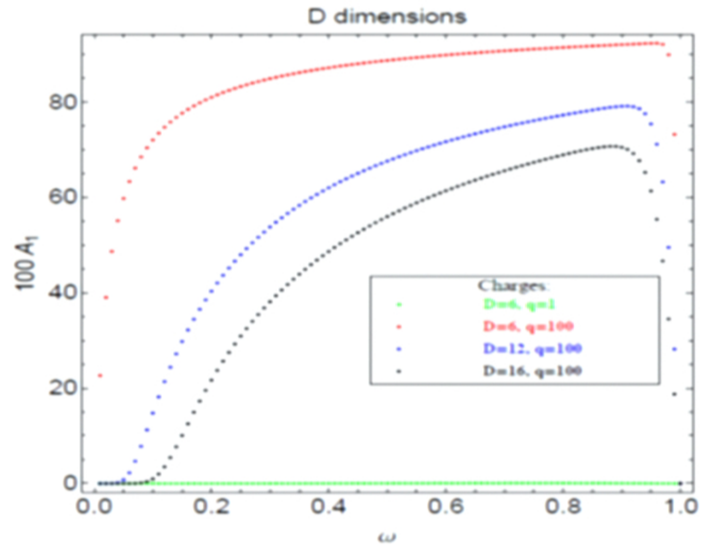
Brito, Cardoso & Pani , arXiv:1501.06570

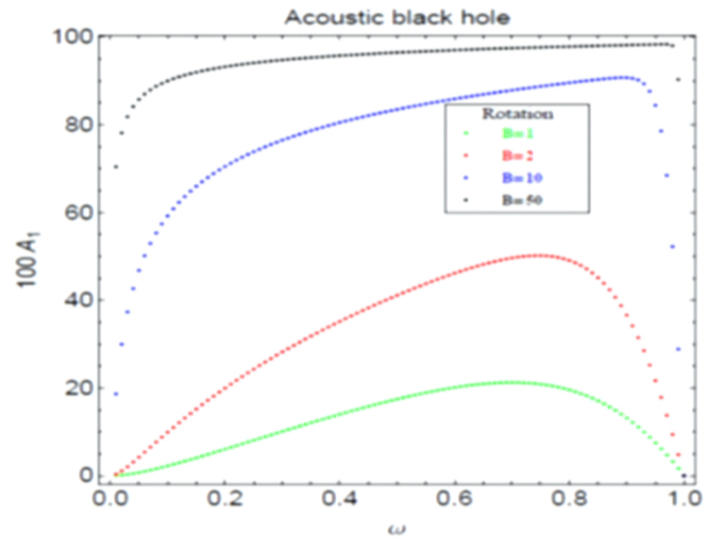
(Rotational) superradiance in the lab?



Need absorbing surface, characterized by complex acoustic impedance Z

Cardoso, Coutant , Richartz & Weinfurtner, in progress



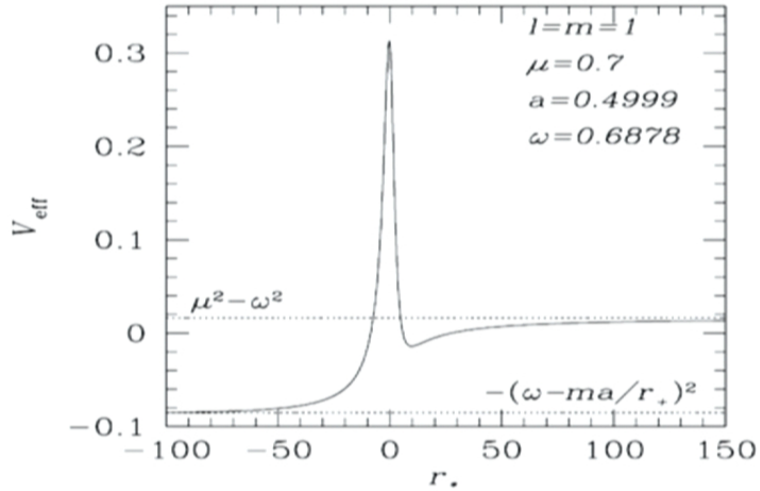


Amplification < 100%...fundamental bound on superradiance?

$$(\nabla_\mu - iqA_\mu)(\nabla^\mu - iqA^\mu)\Psi = 0$$

$$\frac{d^2X}{dx^2} + \left[(\omega - qA_0)^2 - V\right]X = 0$$

Baibhav, Cardoso and Emparan, in progress



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

Massive "states" around Kerr are linearly unstable

Damour et al '76; Detweiler PRD; Cardoso & Yoshida JHEP0507 (2005) 009

Witek et al, PRD87 (2013) 4, 043513;

Cardoso, Carucci, Pani, Sotiriou PRL111 (2013) 111101

See review Brito et al arXiv:1501.06570