Accretion of dark matter by stars

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...

GR100, Técnico, Lisbon

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

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

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

Brito, Cardoso, Herdeiro, Radu,
Proca Stars: gravitating Bose-Einstein condensates of massive spin-1 particles,
Phys.Lett.B752, 291 (2015); arXiv:1508.05395

Brito, Cardoso, Macedo, Okawa & Palenzuela,
Interaction between bosonic dark matter and stars,
arXiv:1512.00466

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*

Structure: 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]

Time-dependent, complex bosons

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

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

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

Time-dependent, real bosons

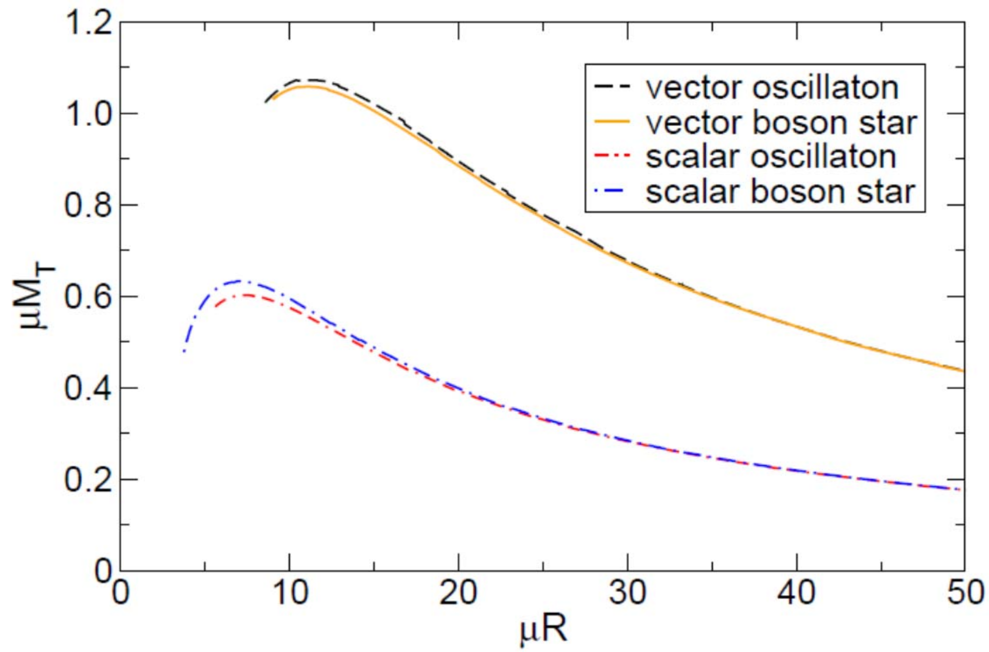
$$\phi(t,r) \quad = \quad \sum_{j=0}^{\infty} \phi_{2j+1}(r)\, \cos\left[(2j+1)\,\omega t\right]$$

Prescribe scalar at origin, “shoot” for frequency □ mode by mode [Seidel & Suen 1991]

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

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

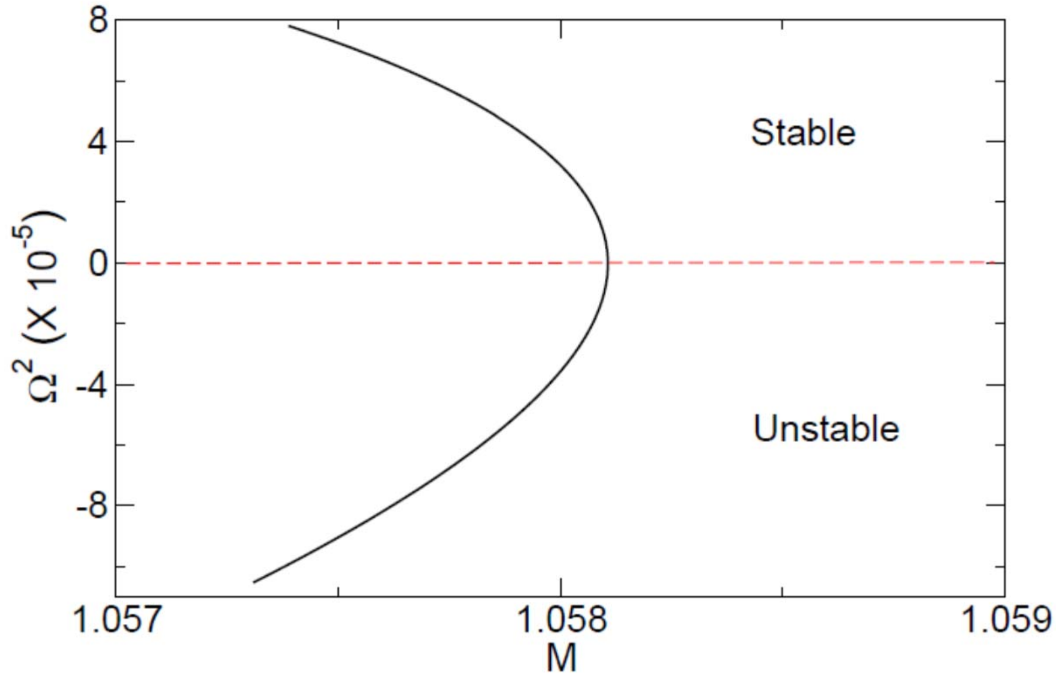
Nodeless solutions



Brito, Cardoso, Okawa, arXiv: 1508.04773

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

Solitons: stability

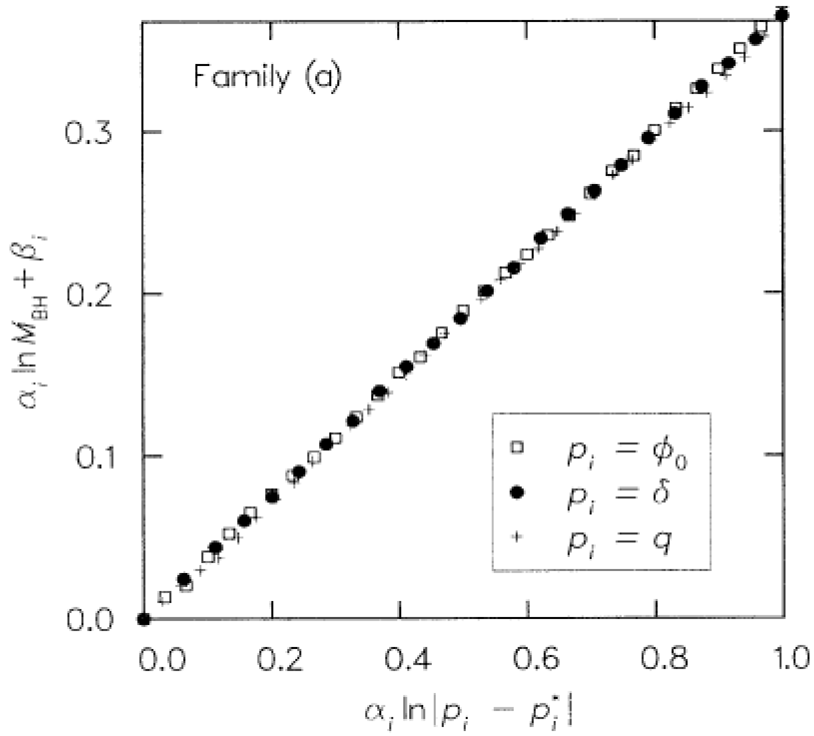


For scalar case see Gleiser (1988) and Choptuik & Hawley (2000)

Brito, Cardoso, Herdeiro & Radu (vector, arXiv:1508.05396*)*

Formation of self-gravitating solutions:

gravitational collapse

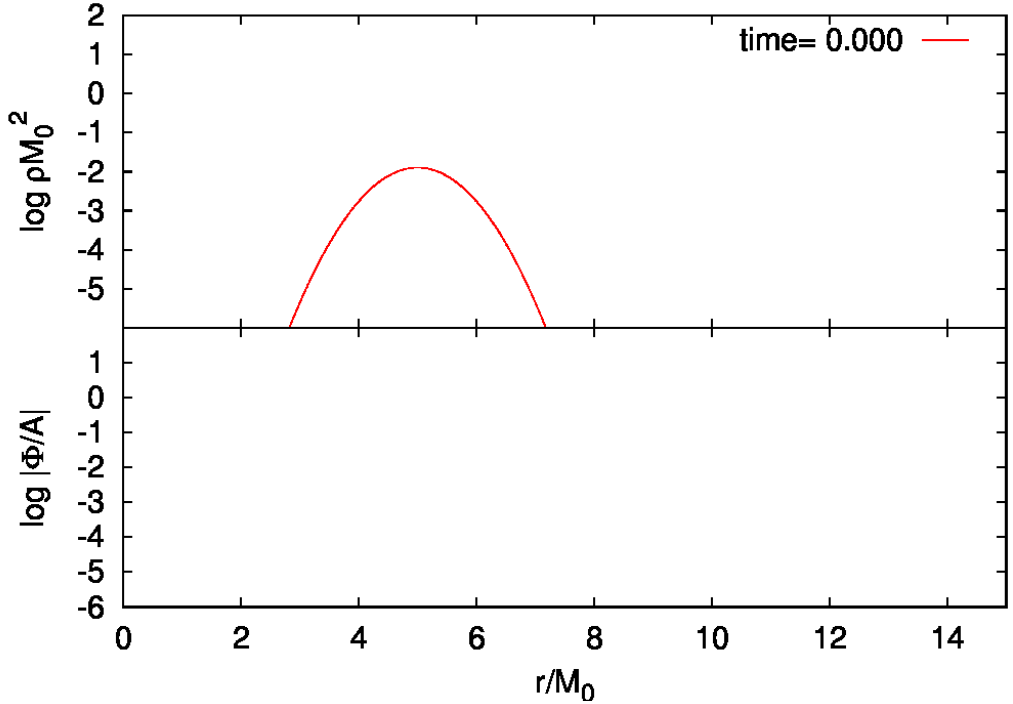


$$\phi = \phi_0 r^3 \exp\left(-\left[(r - r_0)/\delta\right]^q\right)$$

$$M \propto (p - p_*)^\gamma$$

Massless scalars, Choptuik 1993

$r_0 = 5, w = 1.25$ and $\mu = 2$

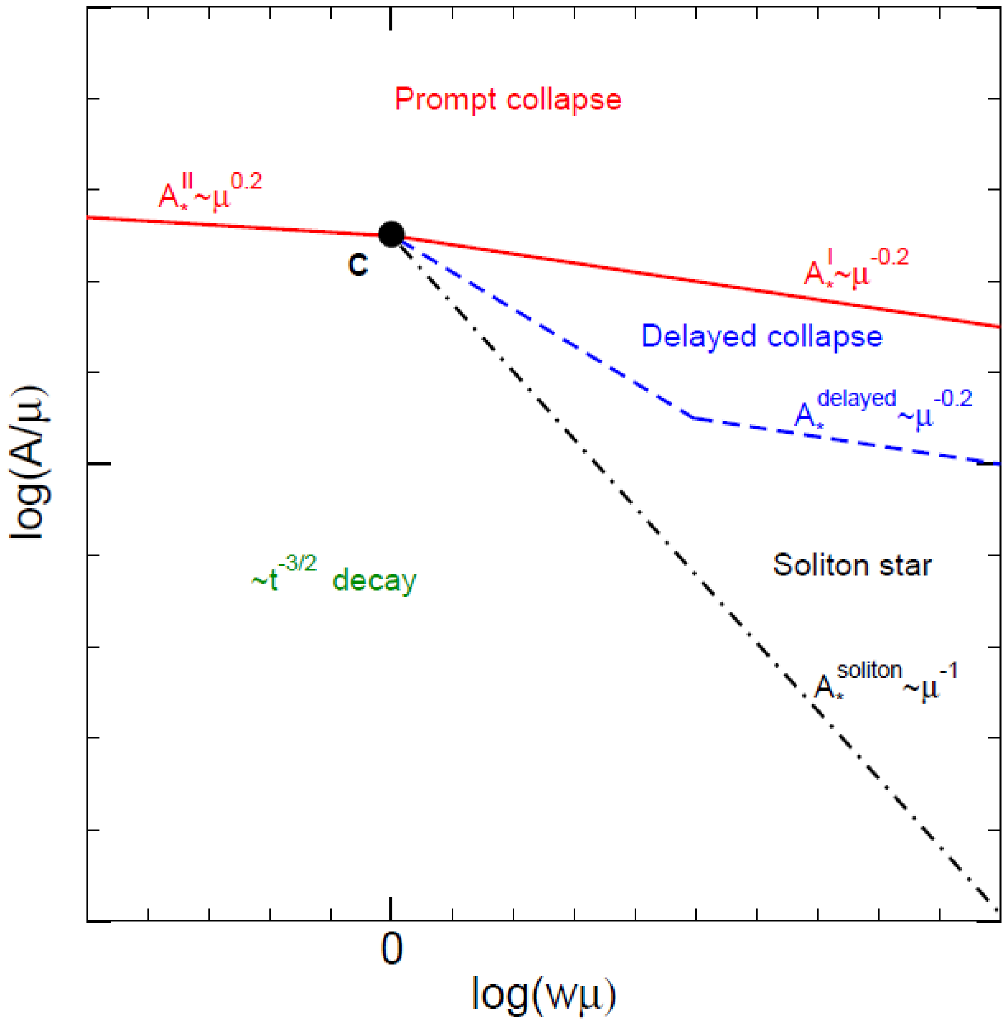


Seidel and Suen, Phys. Rev. Lett. 66:1659 (1991)

Okawa, Cardoso and Pani, Phys. Rev. D89 (4): 041502 (2014)

Collapse of massive scalar fields

Okawa et al PRD89, 041502 (2014)



Solitons: interaction and growth

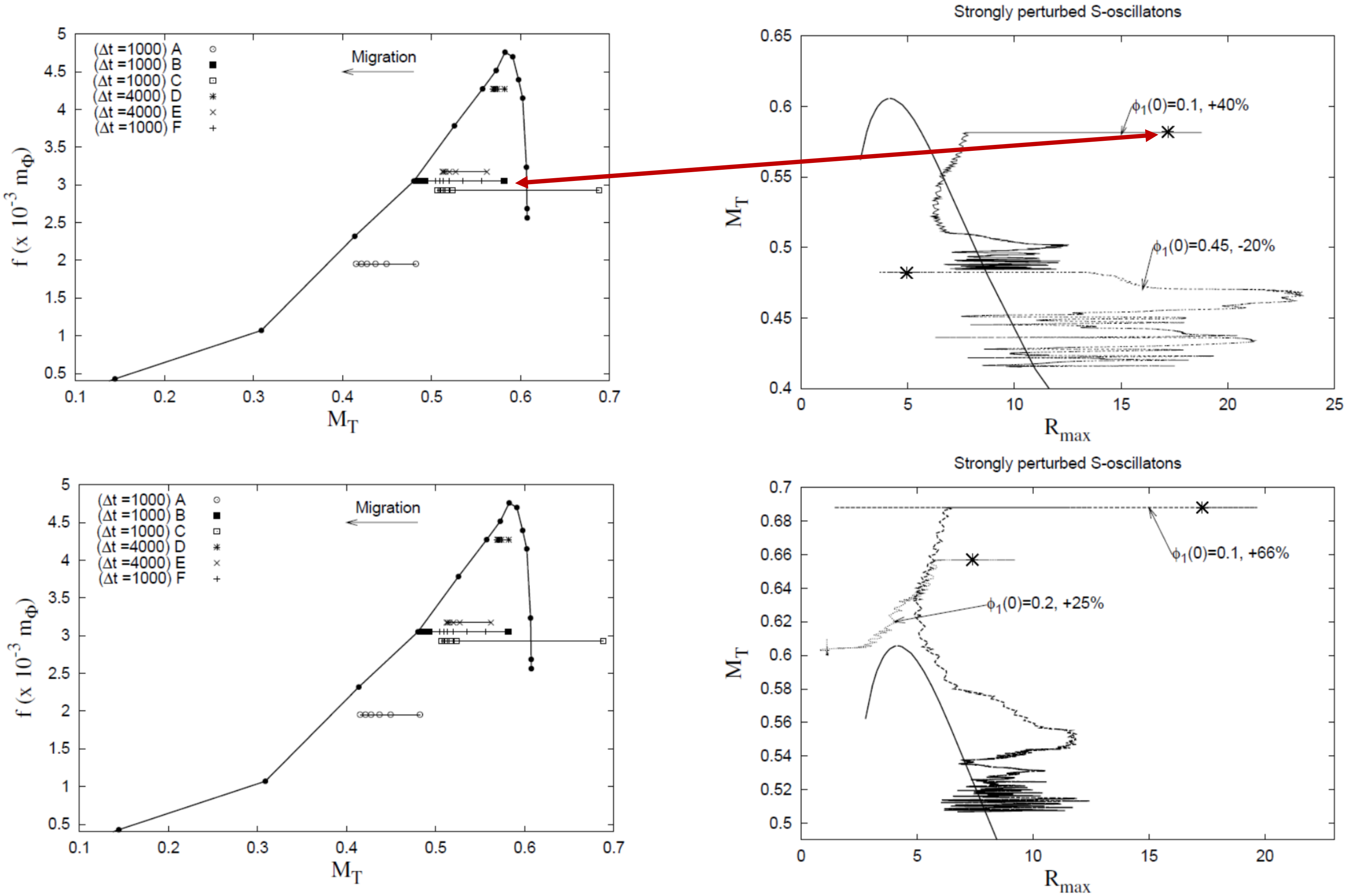
(i) Oscillatons to the right of the peak (S-branch) are stable when slightly perturbed

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

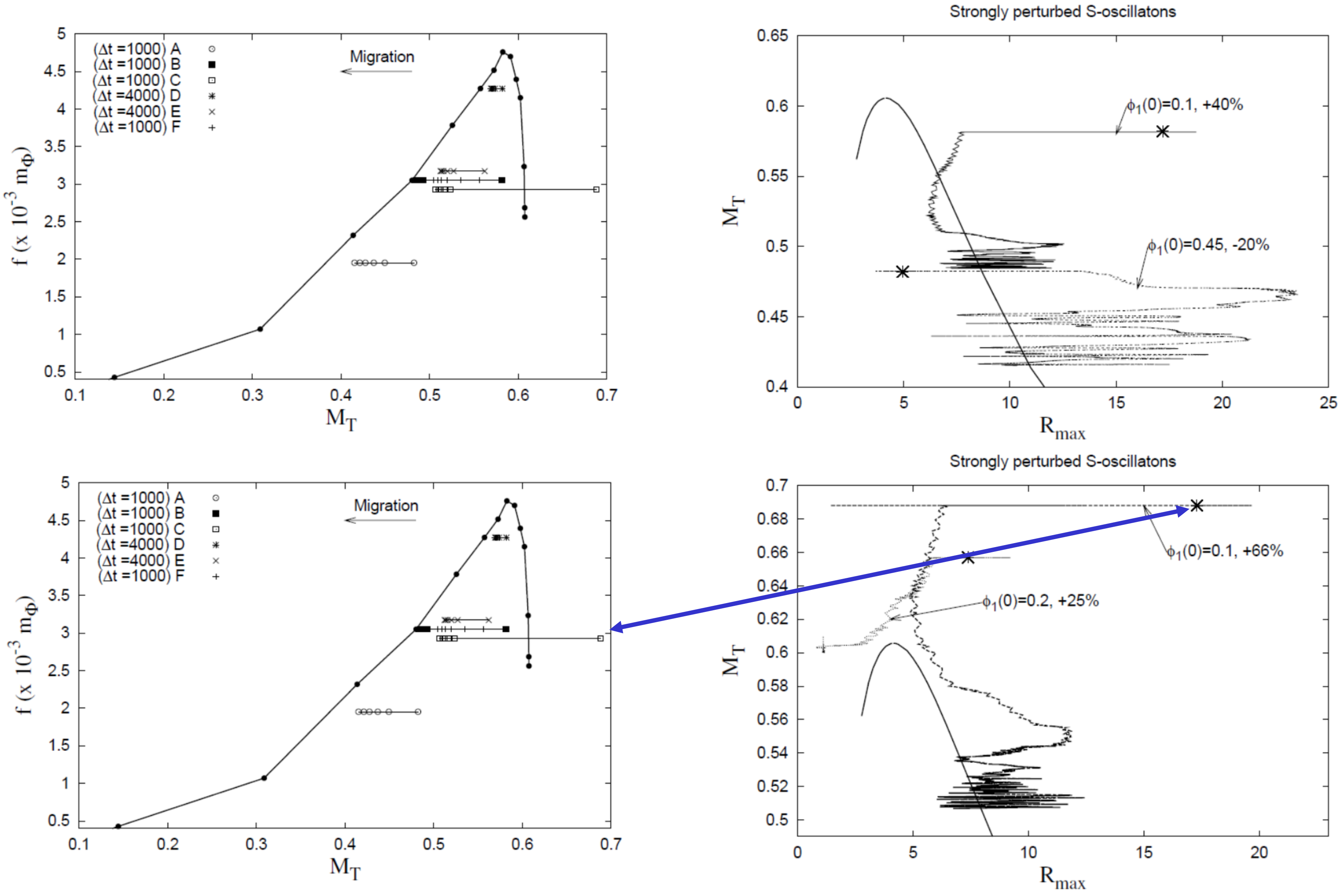
(iii) For masses larger than critical, either migrates back or collapses

Seidel and Suen 1990

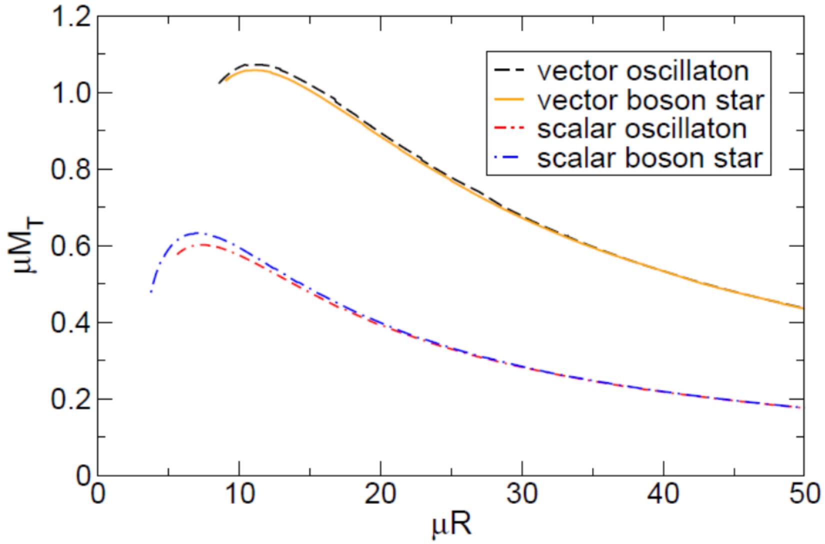
Alcubierre et al 2003

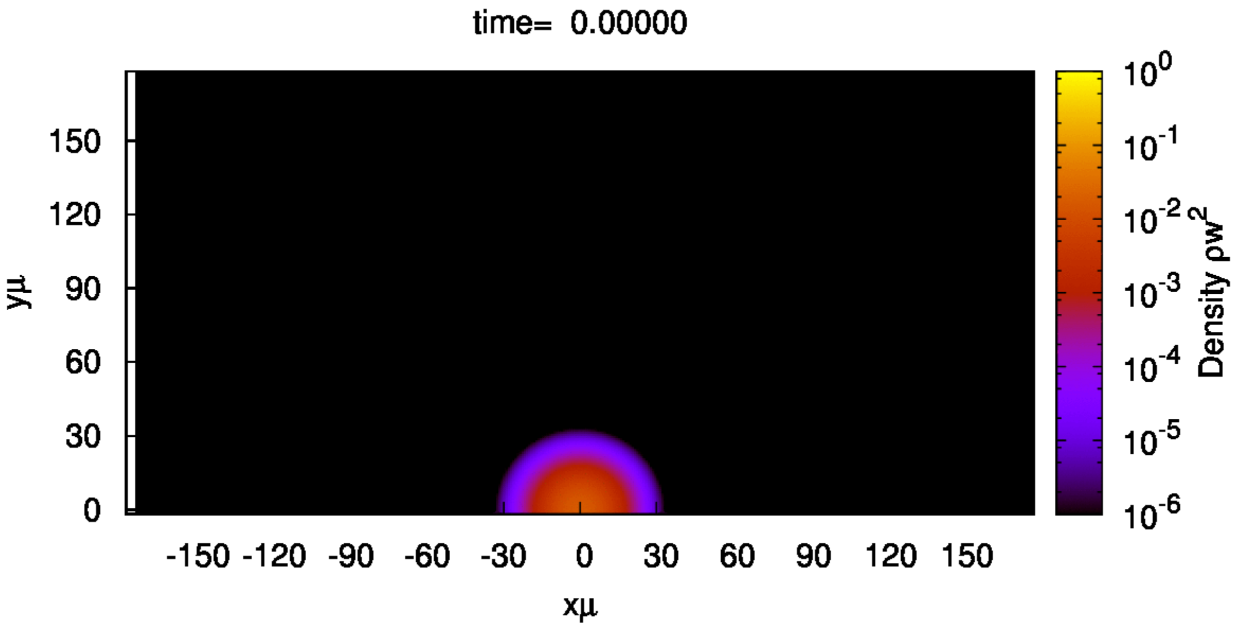


Alcubierre et al 2003

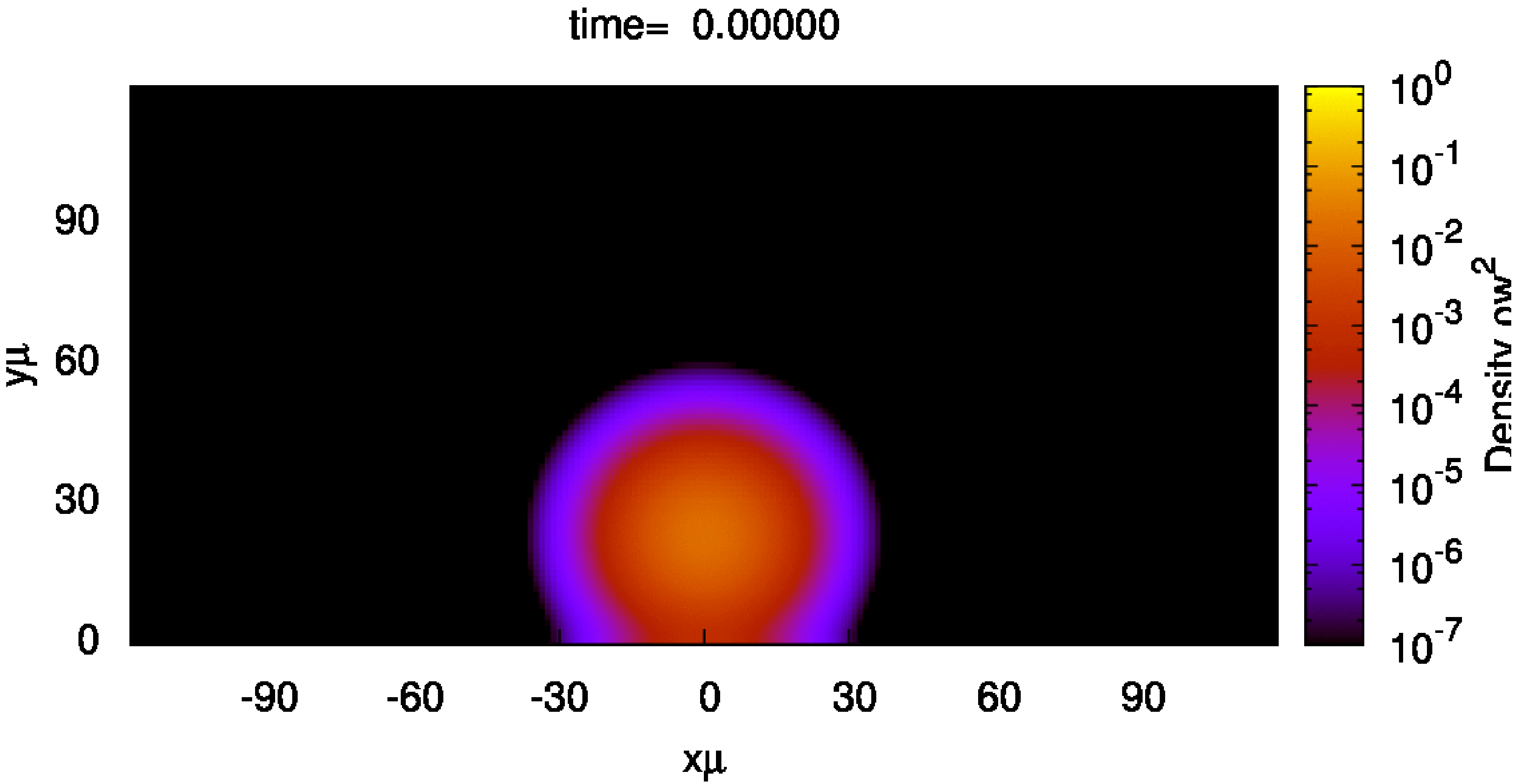


Alcubierre et al 2003





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



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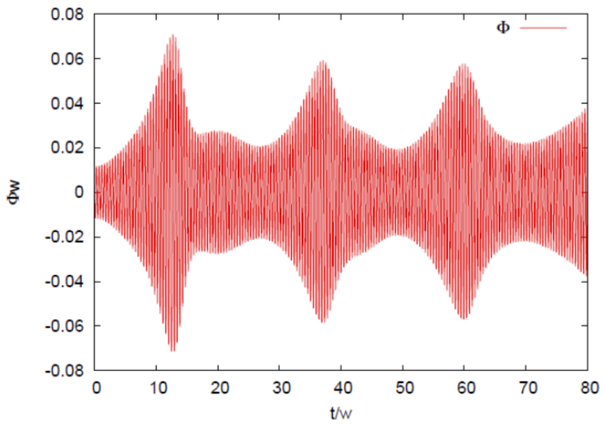
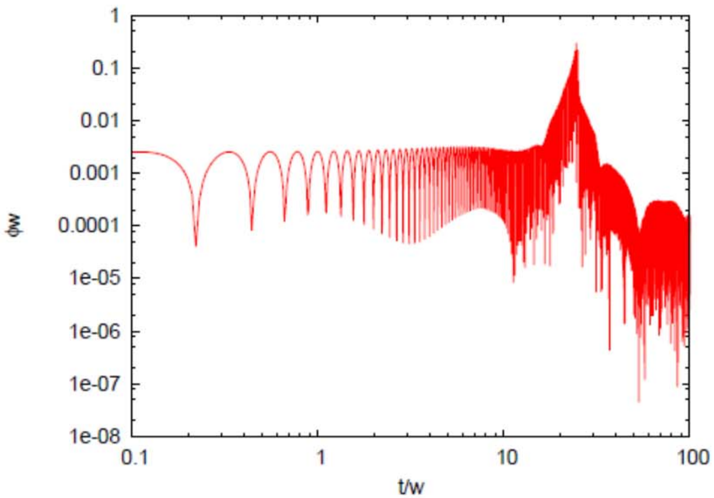
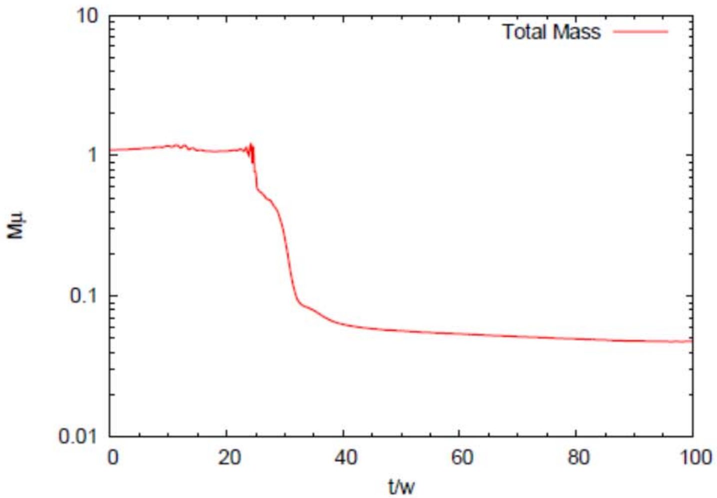
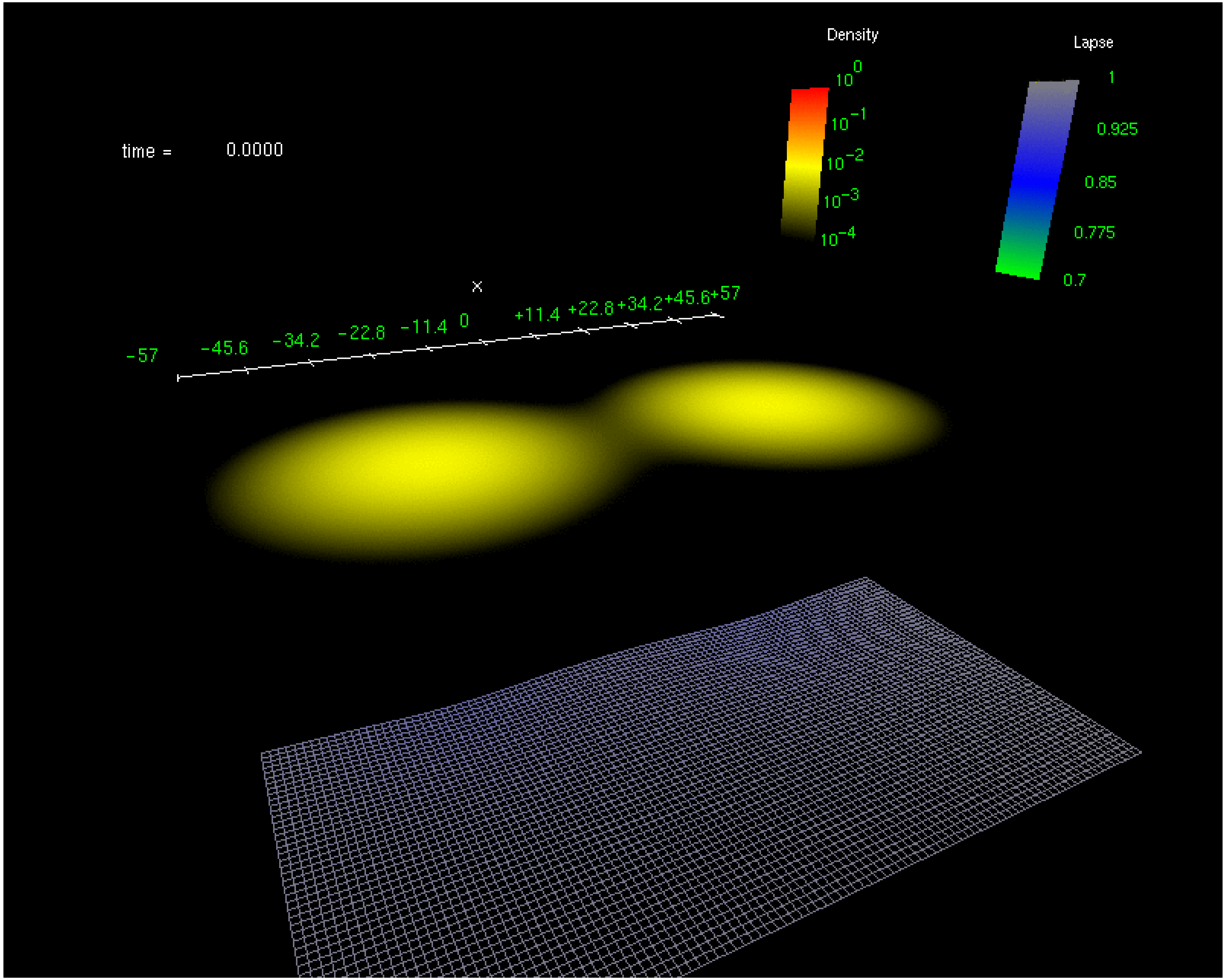
Brito, Cardoso, Okawa, arXiv:1508.04773







Brito, Cardoso, Okawa, arXiv:1508.04773



Density and lapse function sub-critical, equal-mass

Growth of bosonic structures

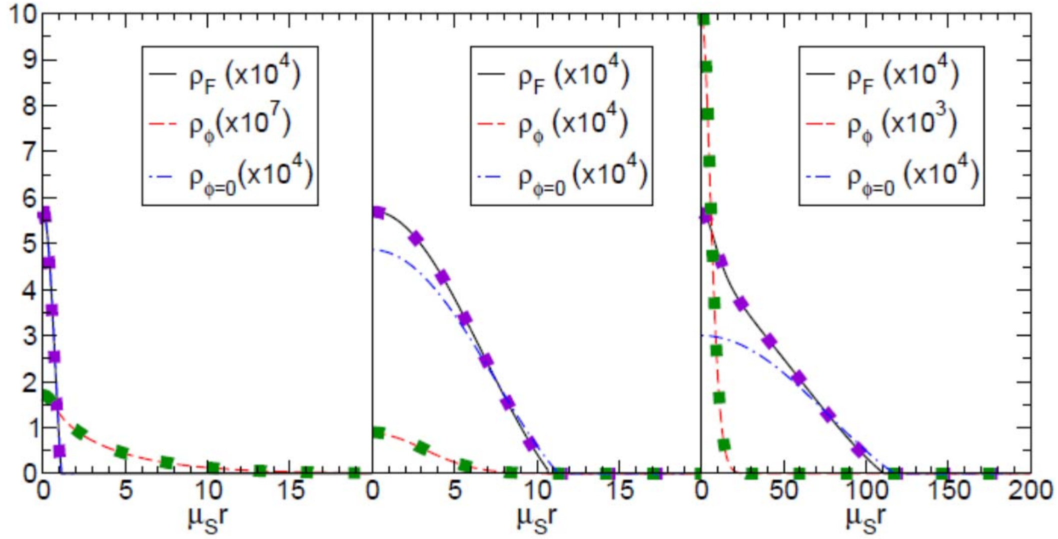
(i) Boson structures grow through mergers or minor mergers

(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

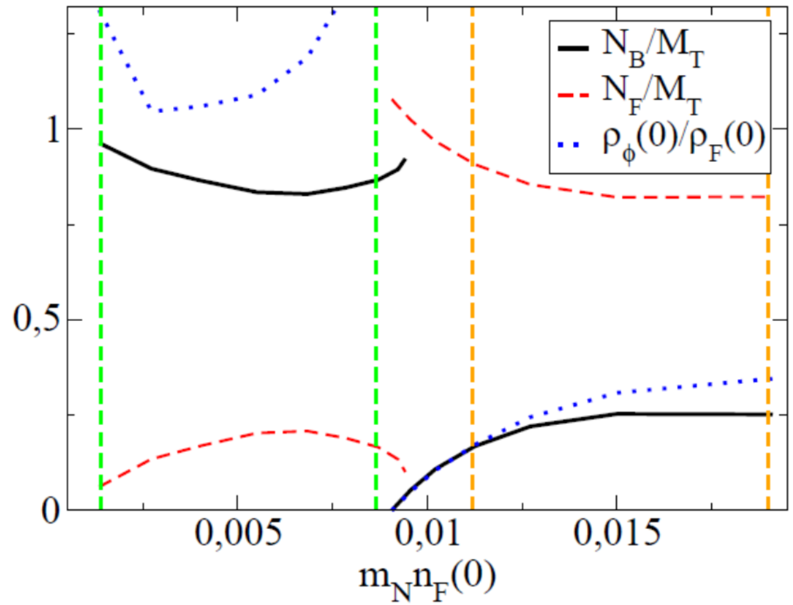
Accretion onto stars

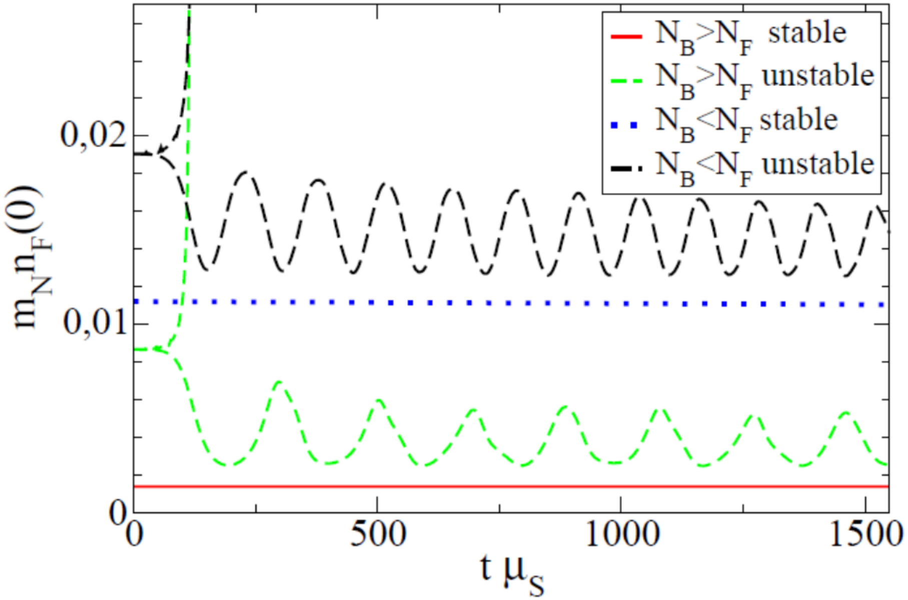


Polytropic stars with a bosonic core at the center. Plots show (time-average) energy density for fluid and scalar field. Blue line is corresponding star for vanishing scalar. Squares denote same quantities for complex scalars. Left to right: μM=0.1, 1, 10

Brito, Cardoso, Okawa, arXiv:1508.04773

Stability of stars with DM cores





$$\left.\frac{\partial N_F}{\partial n_F(0)}\right|_{M_T=M_c} = \left.\frac{\partial N_B}{\partial n_F(0)}\right|_{M_T=M_c} = 0$$

Brito, Cardoso, Macedo, Okawa, Palenzuela, arXiv: 1512.00466

Standard lore for interaction between DM and stars

1. Accumulation stage, thermalizing on radius $G\rho_{\rm star} r_{\rm th}^2 m_{\rm D} \sim k_B T$

2. Black hole phase, after DM core becomes self-gravitating

[Goldman and Nussinov PRD40, 3221 (1989); Bertone and Fairbairn PRD77, 043515 (2008); Bramante, PRL115, 141301 (2015); Kurita and Nakano, arXiv:1510.00893...etc]

Lack of rigorous framework to support these conclusions...

some of which are just plain wrong

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

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

Core does *not* collapse to black hole

Gravitational coupling to matter drives oscillations of star at frequency

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

Strong field gravity is truly a fascinating topic

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Fundamental fields, either in form of minimally coupled fields or under curvature couplings have a very rich and unexplored phenomenology: self-gravitating structures can form, grow and interact; condensates outside BHs and compact stars act as gravitational-wave lighthouses, but can also act as dark matter.

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Accretion onto stars might in principle lead to observable effects through a very definite oscillation pattern at the star's core...but it does not kill the host star!

Thank you

Evolution equations

$$
\begin{aligned}
ds^2 &= -\alpha^2 dt^2 + \psi^4 \eta_{ij} dx^i dx^j \\
K_{ij} &= \frac{1}{3}\psi^4 \eta_{ij} K
\end{aligned}
$$

η_{ij} is Minkowski 3-metric
K_{ij} is the extrinsic curvature of the conformally flat metric $\gamma_{ij} = \psi^4 \eta_{ij}$
The equations of motion yield the constraints

$$
\begin{aligned}
\frac{2}{3}K^2 - \frac{(8r^2\psi_{,r})_{,r}}{r^2\psi^5} - 8\pi\left[\Pi^2 + \psi^{-4}\Phi_{,r}^2 + \mu^2\Phi^2\right] &= 0 \\
\frac{2}{3}K_{,r} + 8\pi\Pi\Phi_{,r} &= 0
\end{aligned}
$$

and the evolution equations

$$
\begin{aligned}
\partial_t \psi_0 &= -\frac{1}{6}\alpha\psi K \\
\partial_t K &= -\psi^{-4}\alpha_{,rr} - 2\psi^{-5}\psi_{,r}\alpha_{,r} - \frac{2\alpha_{,r}}{r\psi^4} + \frac{1}{3}\alpha K^2 + 4\pi\alpha\left(2\Pi^2 - \mu^2\Phi^2\right), \\
\partial_t \Phi &= -\alpha\Pi, \\
\partial_t \Pi &= \alpha\Pi K - \psi^{-4}\alpha_{,r}\Phi_{,r} - \alpha\psi^{-4}\Phi_{,rr} - 2\alpha\psi^{-5}\psi_{,r}\Phi_{,r} - \frac{2\alpha\Phi_{,r}}{r\psi^4} + \alpha\mu^2\Phi,
\end{aligned}
$$

where Π is the momentum conjugate of Φ.

Evolution equations

We choose

$$\begin{aligned}
\Phi &= 0 \\
K &= 0 \quad \text{(maximal slicing)} \\
\Pi &= \frac{A}{2\pi}\psi^{-\frac{5}{2}} \exp\left\{-(r-r_0)^2/w^2\right\} \\
\psi &= 1 + \frac{u(r)}{\sqrt{4\pi r}}\,,
\end{aligned}$$

$$u''(r) + \frac{A^2 r}{\sqrt{4\pi}} \exp\left\{-(r-r_0)^2/w^2\right\} = 0\,.$$

A particular solution, which is regular at infinity, is

$$u_0(r) = A^2 w \frac{w^2 - 4r_0(r-r_0)}{16\sqrt{2}} \left[\left(\sqrt{2}(r-r_0)/w\right) - 1\right] - A^2 \frac{r_0 w^2}{8\sqrt{\pi}} \exp\left\{-2(r-r_0)^2/w^2\right\} + \text{const}$$

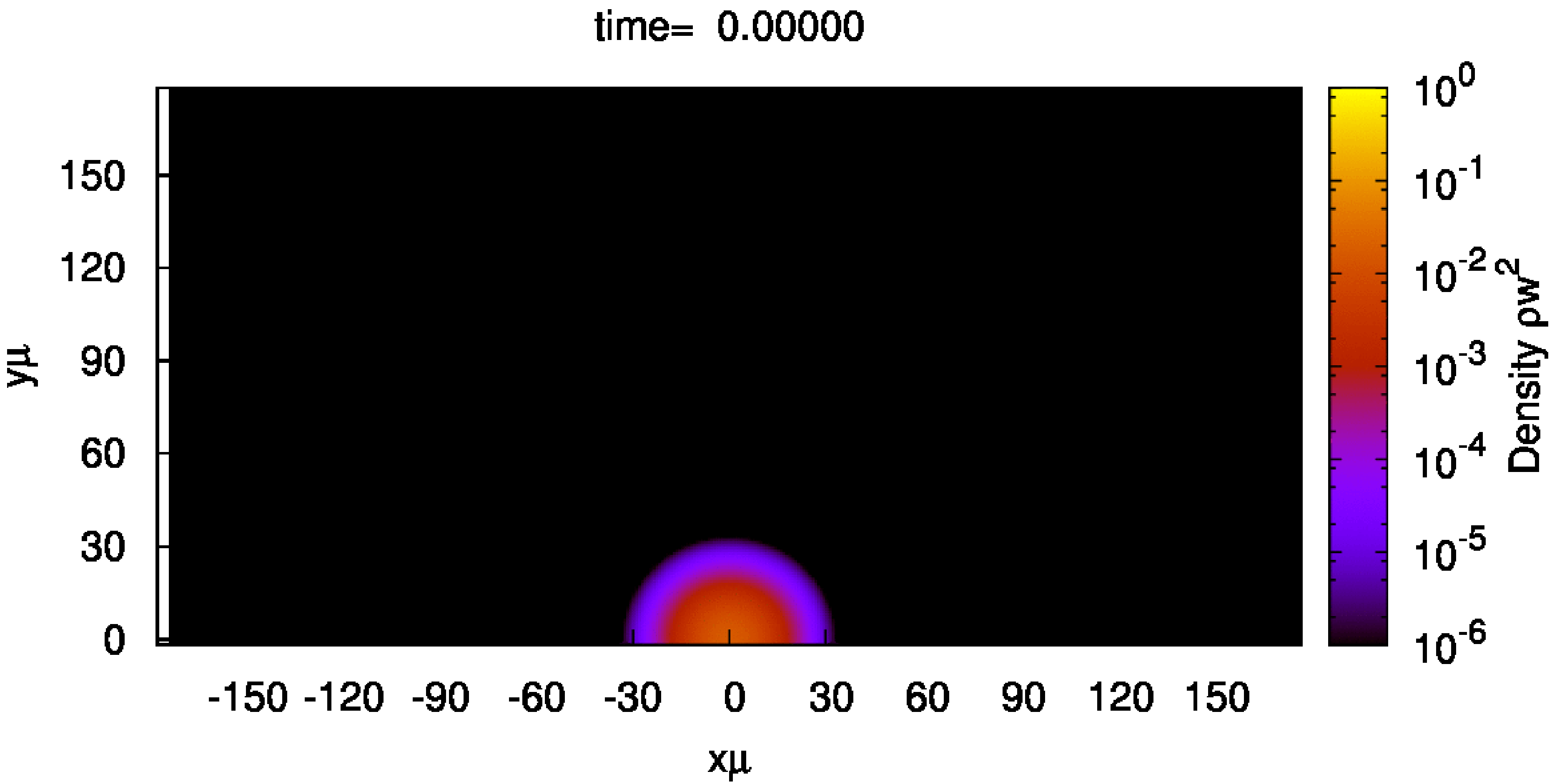
Solitons: existence
rotation

Exist

Schunk & Mielke 1998; Yoshida & Eriguchi 1997; Kleihaus et al 2005

Continuously connected to *hairy* black holes

Herdeiro & Radu 2014



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