grit
gravitation in técnico

TÉCNICO LISBOA

centra

Probing fundamental fields with compact stars

Richard Brito
CENTRA / IST
Lisbon, December 21

With V. Cardoso, H. Okawa, arXiv: 1508.04773
With V. Cardoso, H. Okawa, C. Macedo & C.Palenzuela, arXiv: 1512.00466

IDPASC

More info at http://blackholes.ist.utl.pt

Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, INOVAÇÃO E DO ENSINO SUPERIOR

Strong gravity & fundamental (bosonic) fields

The never ending search for dark matter…

Explore the rich phenomenology of fundamentals fields within full General Relativity.

Signatures of dark matter in strongly gravitating systems.

Can we use it to constrain (or even detect) dark matter candidates?

$$
\begin{aligned}
S &= \int d^4x\sqrt{-g}\left(\frac{R}{\kappa} - \frac{1}{4}F^{\mu\nu}\bar{F}_{\mu\nu} - \frac{\mu_V^2}{2}A_\nu\bar{A}^\nu\right. \\
&- \left.\frac{1}{2}g^{\mu\nu}\Phi^*_{,\mu}\Phi_{,\nu} - \frac{\mu_S^2|\Phi|^2}{2} + \mathcal{L}_{\text{matter}}\right)
\end{aligned}
$$

Solitonic stars

D.J. Kaup '68; Ruffini & Bonazzola '69; Seidel & Suen '91;
Brito, Cardoso, Herdeiro & Radu '15; Brito, Cardoso & Okawa '15

$$T^{\mu\nu}_{\rm scalar} = -\frac{1}{4} g^{\mu\nu}\left(\Phi^*_{,\alpha}\Phi^{,\alpha} + \mu_S^2\Phi^*\Phi\right) + \frac{1}{4}\left(\Phi^{*,\mu}\Phi^{,\nu} + \Phi^{,\mu}\Phi^{*,\nu}\right)$$

$$T^{\mu\nu}_{\rm vector} = F^{(\mu}_{\ \ \alpha}\bar{F}^{\nu)\alpha} - \frac{1}{4}\bar{F}^{\alpha\beta}F_{\alpha\beta}g^{\mu\nu} - \frac{1}{2}\mu_V^2 A_\alpha \bar{A}^\alpha g^{\mu\nu} + \mu_V^2 A^{(\mu}A^{\nu)}$$

Spherical symmetry: $ds^2 = -F(t,r)dt^2 + B(t,r)dr^2 + r^2 d\Omega^2$

Complex fields - Boson stars:

$$\begin{aligned} N^i(t,r) &= N(r) \\ \Phi(t,r) &= \phi(r)e^{-i\omega t} \end{aligned}$$

Real fields - Oscillatons:

$$\begin{aligned} N^i(t,r) &= \sum_{j=0}^{\infty} N^i_{2j}(r)\cos(2j\omega t) \\ \Phi(t,r) &= \sum_{j=0}^{\infty} \phi_{2j+1}(r)\cos\left[(2j+1)\,\omega t\right] \end{aligned}$$

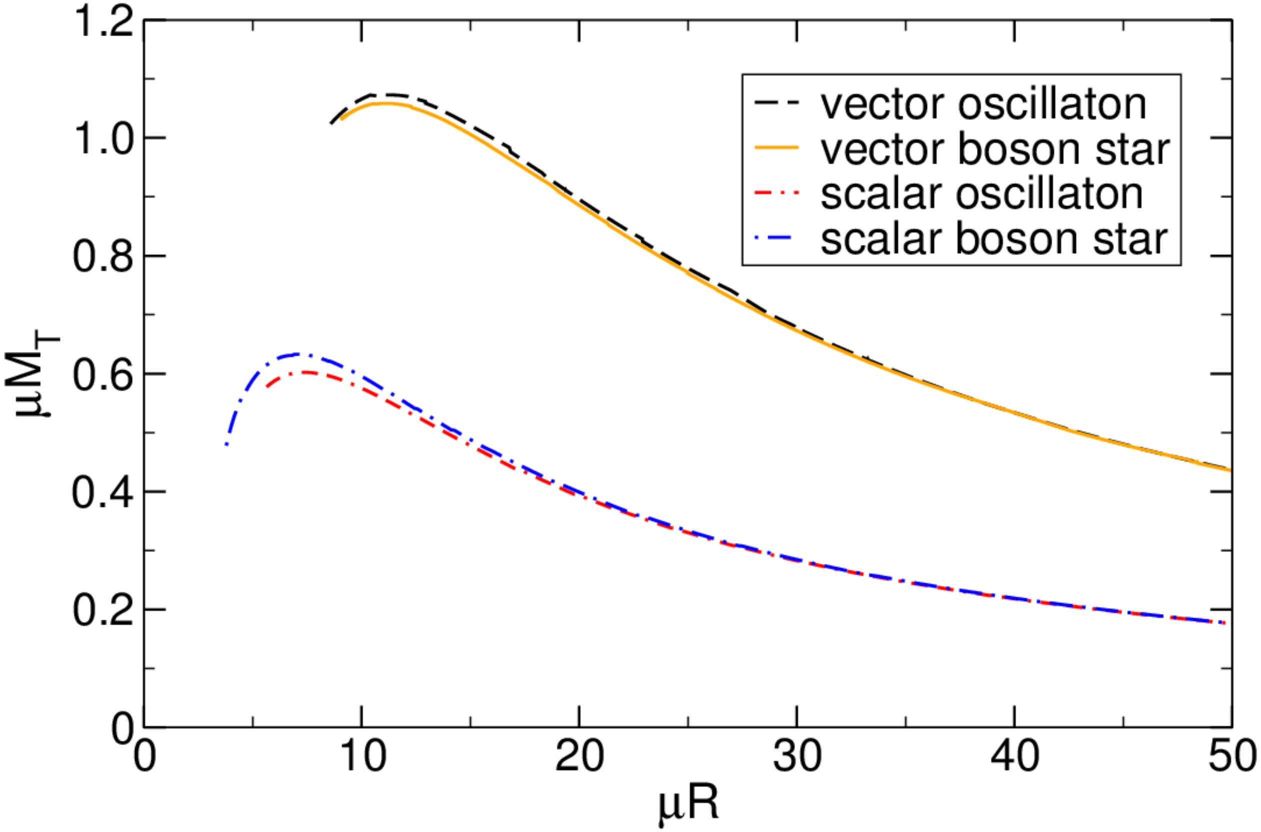
$$N^i = (B, F)$$

For rotating boson/Proca stars see:
Yoshida, Eriguchi '97; Schunck, Mielke '98
Brito, Cardoso, Herdeiro & Radu '15

Oscillatons and Boson/Proca stars

D.J. Kaup '68; Ruffini & Bonazzola '69; Seidel & Suen '91;
Brito, Cardoso, Herdeiro & Radu '15; Brito, Cardoso & Okawa '15

$$\frac{G}{c\hbar} M_T \mu = 7.5 \cdot 10^9 \left(\frac{M_T}{M_\odot}\right)\left(\frac{m_B c^2}{eV}\right)$$



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

Oscillatons: $T_{\rm decay} \sim 10^{324} \left(\frac{1\,{\rm meV}}{m_B c^2}\right)^{11}$ yr (Page '03)

Mixted boson-fluid stars

A. Henriques, A. R. Liddle & R. Moorhouse '89;
Brito, Cardoso & Okawa '15; Brito, Cardoso, Macedo, Okawa & Palenzuela, arXiv: 1512.00466

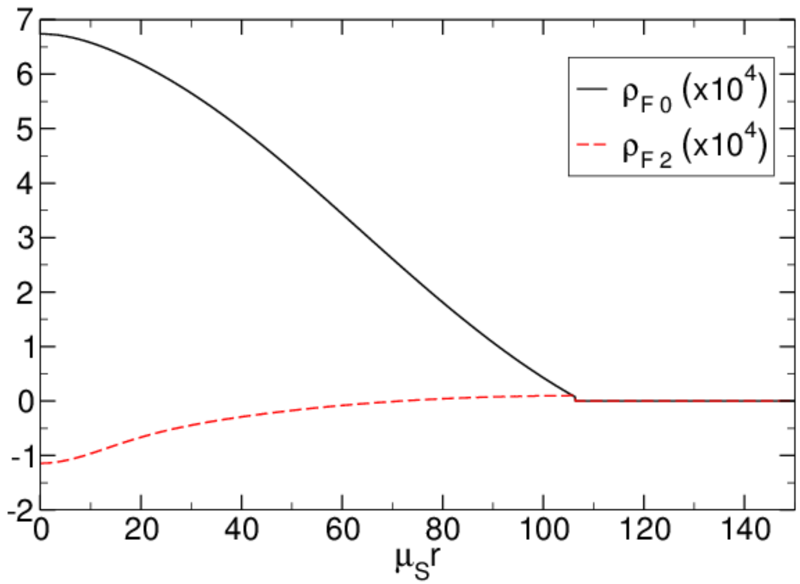
Perfect fluid star: $T^{\mu\nu}_{\text{fluid}} = (\rho_F + P)\, u^\mu u^\nu + P g^{\mu\nu}$

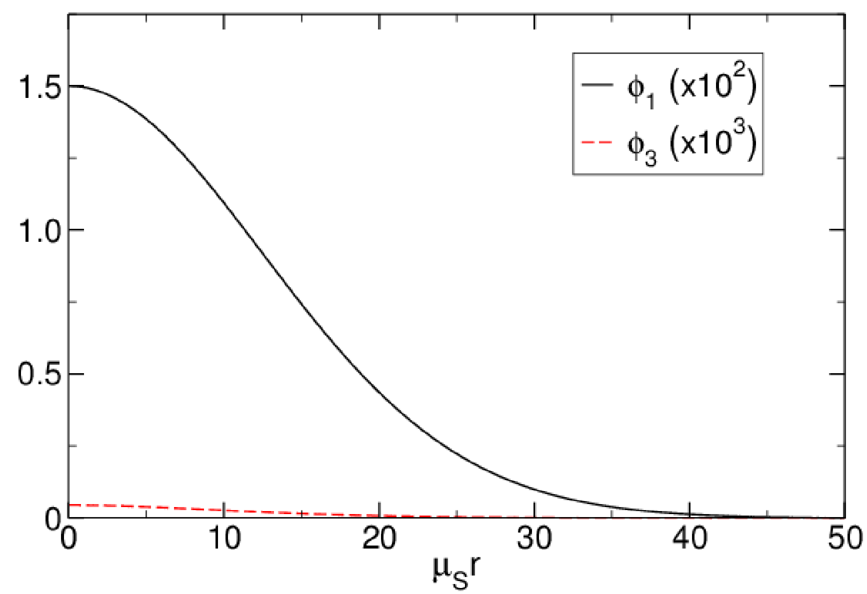
$$u^\mu = \frac{\Gamma}{\sqrt{-g_{tt}}}\,(1, V(t,r), 0, 0)$$

$$N^i = \sum_{j=0}^{\infty} N^i_{2j}(r)\, \cos(2j\omega t)$$

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

$$N^i = (g_{tt}, g_{rr}, n_F, \rho_F, P, V)$$

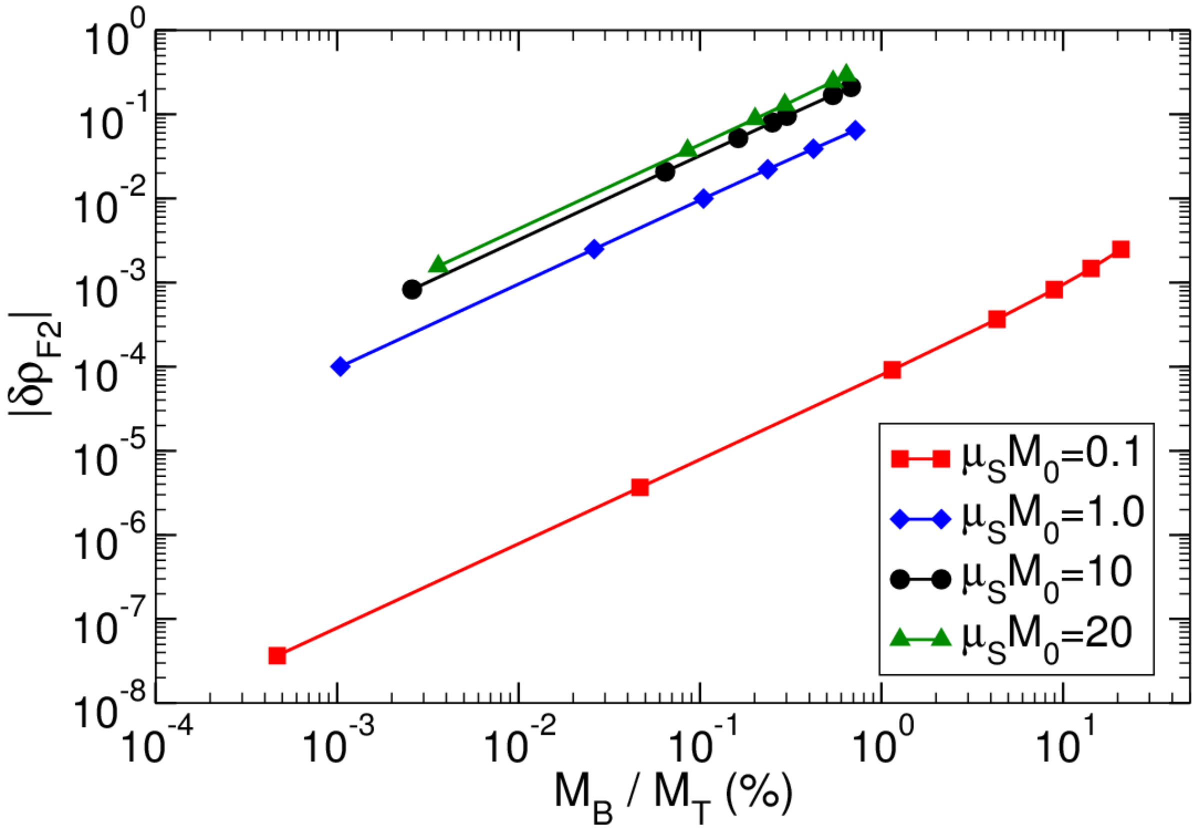




Fluid oscillations

Brito, Cardoso & Okawa ‘15;
Brito, Cardoso, Macedo, Okawa & Palenzuela, arXiv: 1512.00466

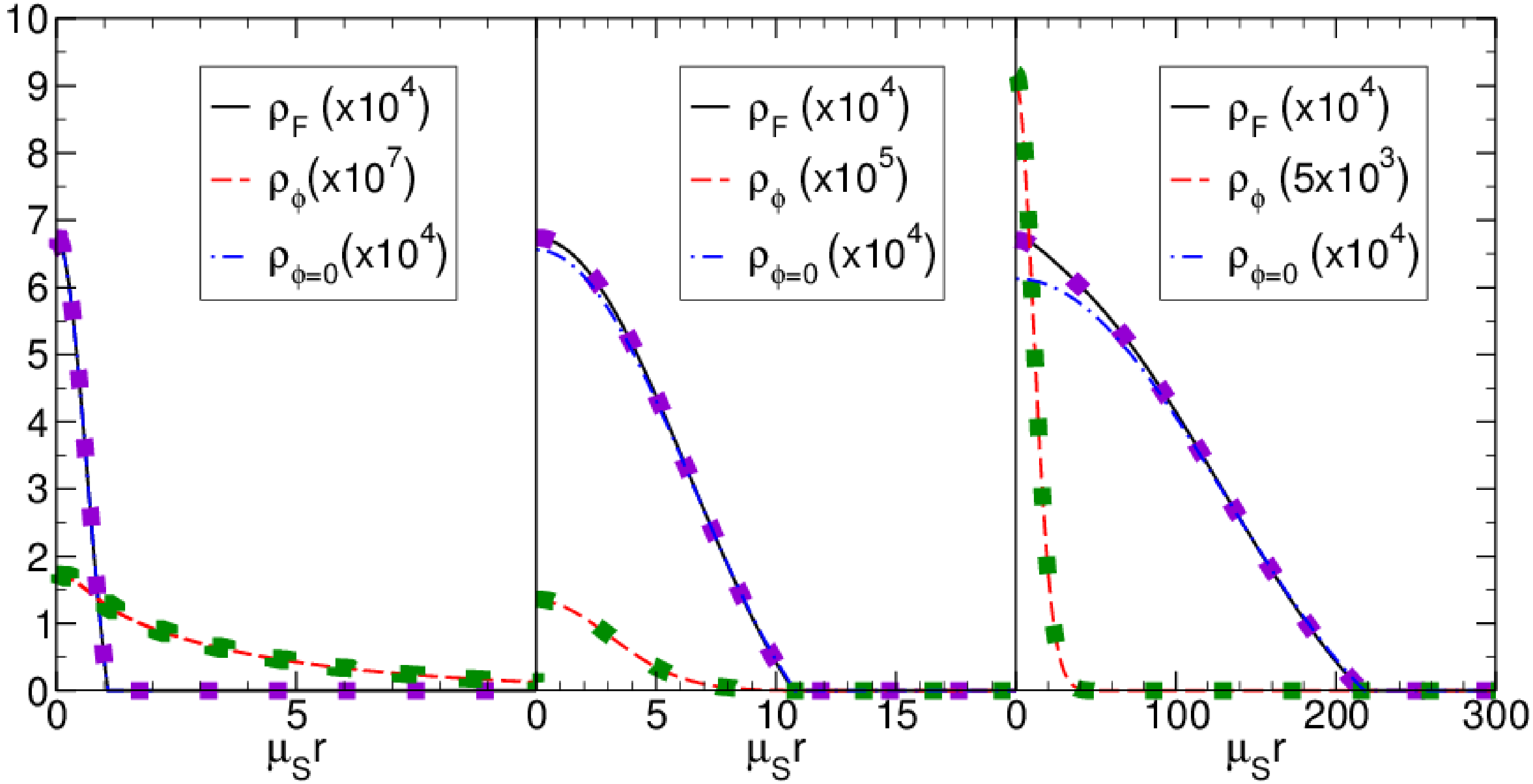
$$\rho_F = \sum_{j=0}^{\infty} \rho_{F\,2j}(r)\, \cos(2j\omega t) \qquad \delta\rho_{F\,2} \equiv \frac{\rho_{F\,2}(0)}{\rho_{F\,0}(0)}$$



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

Mixted boson-fluid stars

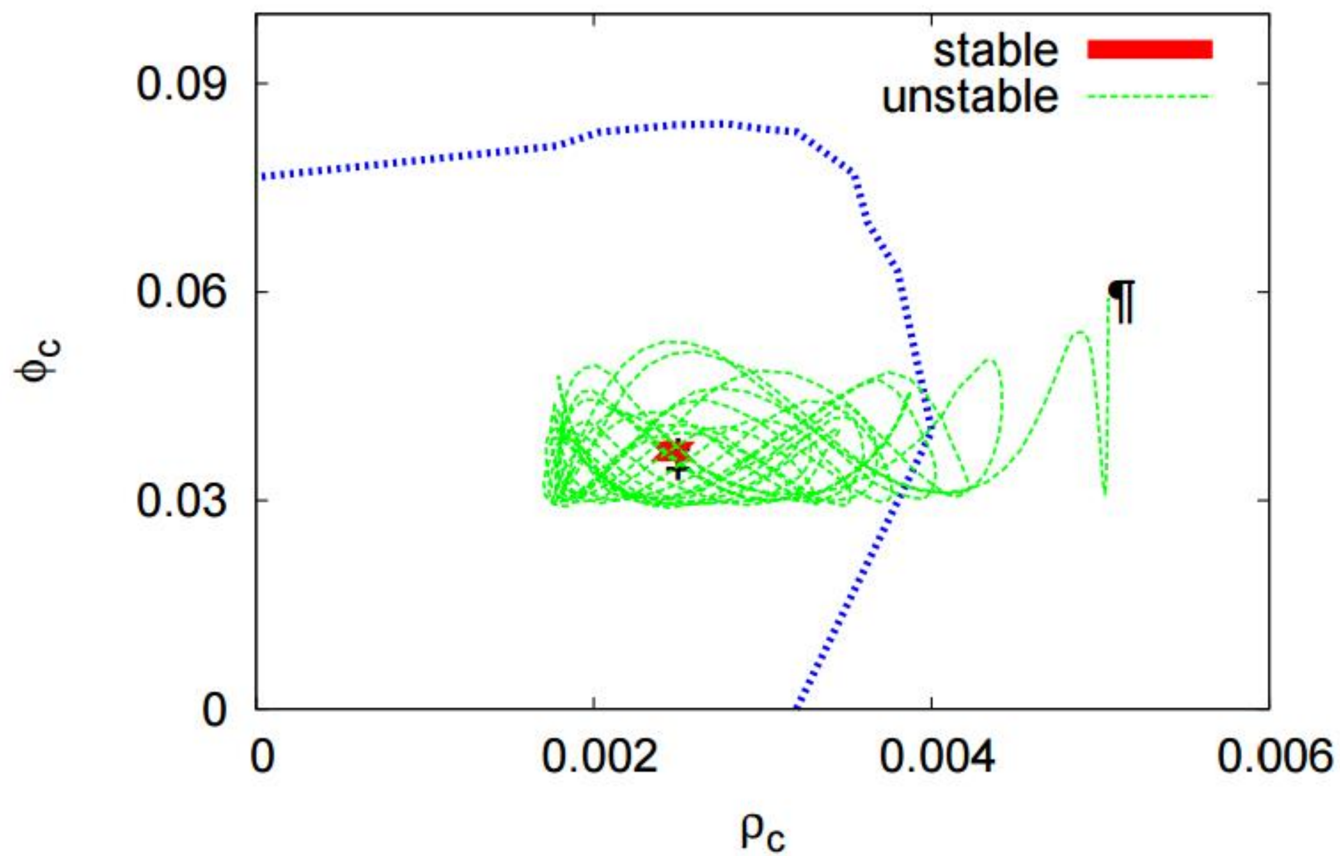
A. Henriques, A. R. Liddle & R. Moorhouse '89;
Brito, Cardoso & Okawa '15; Brito, Cardoso, Macedo, Okawa & Palenzuela, arXiv: 1512.00466



$M_0\mu_S = 0.1$	$M_0\mu_S = 1$	$M_0\mu_S = 20$
$M_B/M_T \approx 21\%$	$M_B/M_T \approx 0.66\%$	$M_B/M_T \approx 0.54\%$

Stability?

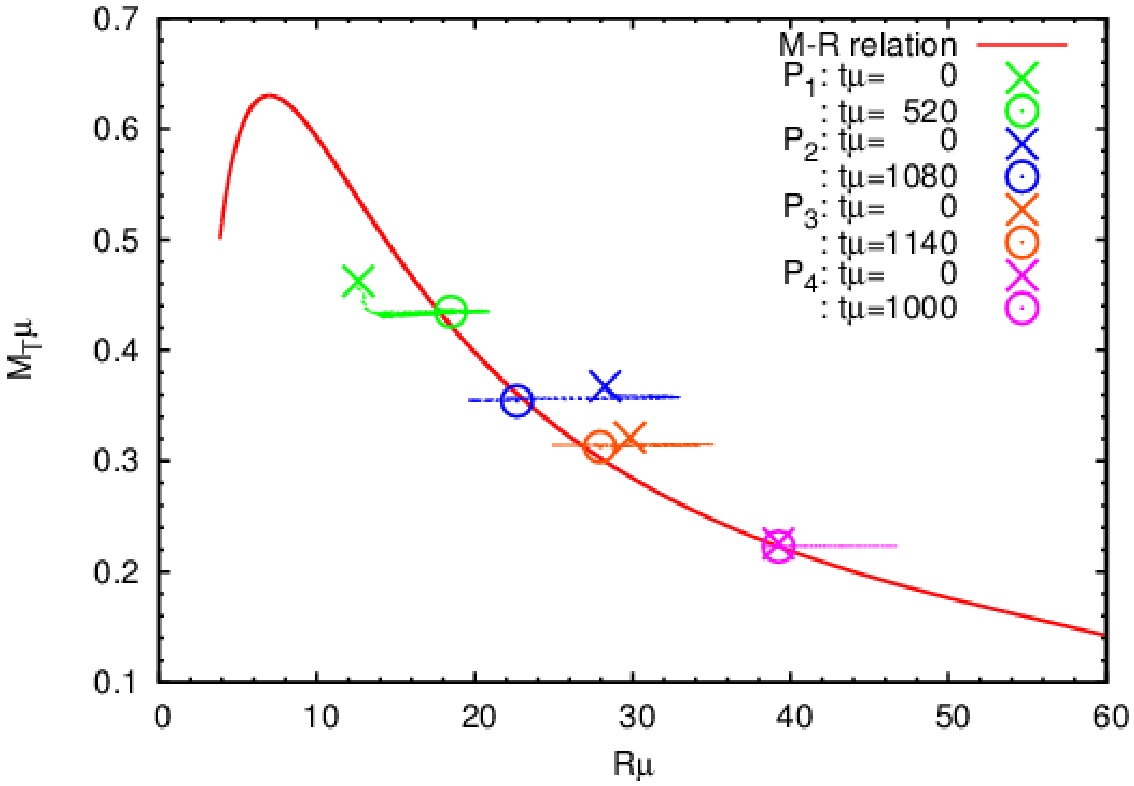
A. Henriques, A. R. Liddle & R. Moorhouse '90 ; Valdez-Alvarado, Palenzuela, Alic & Ureña-López '13; Brito, Cardoso, Macedo, Okawa & Palenzuela, arXiv: 1512.00466



From: Valdez-Alvarado, Palenzuela, Alic & Ureña-López, Phys.Rev. D87 (2013) 8, 084040

Stability? For sufficiently small scalar composites (or vice-versa) stability analysis of the host star is still valid. (A. Henriques, A. R. Liddle & R. Moorhouse PLB B251, 511 (1990))

Do they ever form?



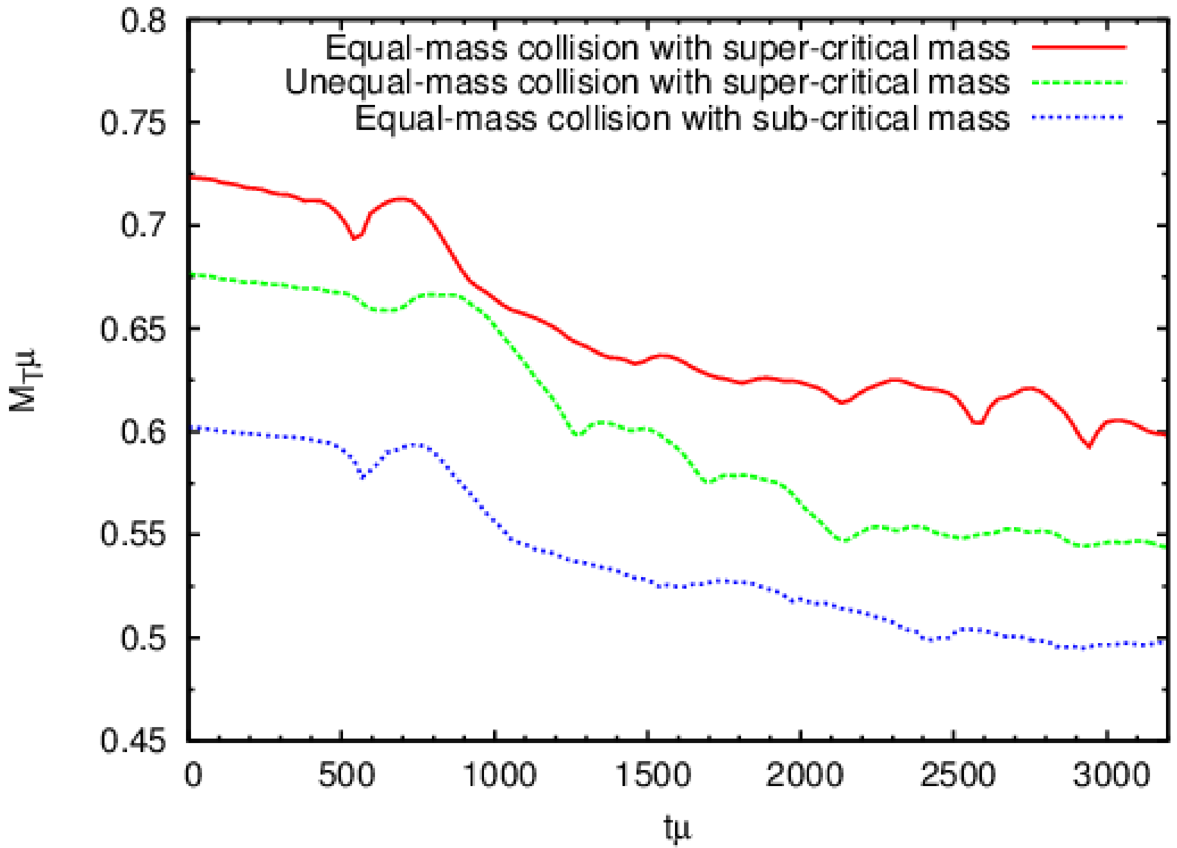
Purely bosonic states do.

Two channels for composite fluid-boson stars:

- Gravitational collapse in a bosonic environment;
- Capture and accretion of DM into the core of compact stars. Collapse to a black hole?

Collision (accretion) of oscillatons

Brito, Cardoso & Okawa ‘15;
Brito, Cardoso, Macedo, Okawa & Palenzuela, arXiv: 1512.00466



Collapse to a black hole can be avoided whenever gravitational cooling mechanism is efficient.

Conclusions

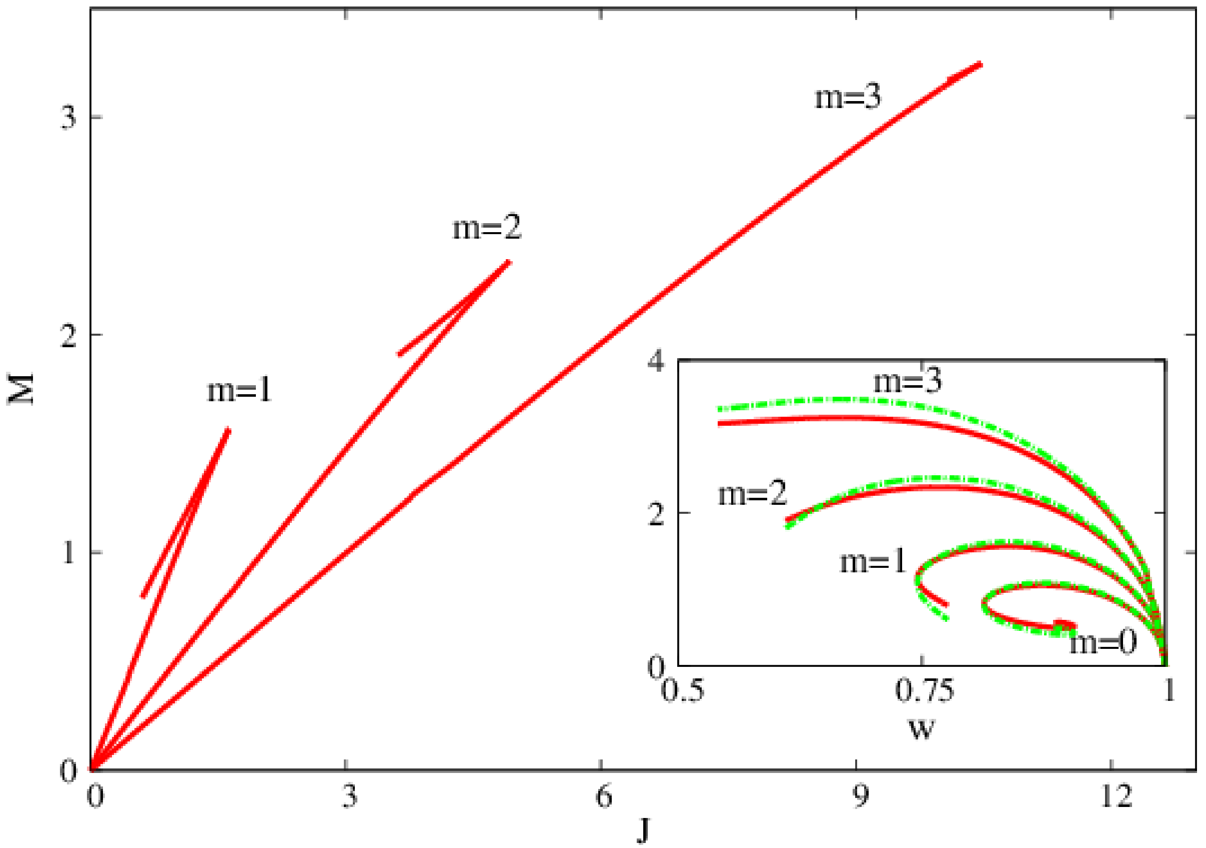
- Fundamental fields when coupled to gravity have a very rich and unexplored phenomenology.
- Accretion onto stars might in principle lead to stable periodically oscillating configurations and possible observable effects through a very definite oscillation frequency in the star's material.
- Collapse to a black hole can be avoided by an efficient gravitational cooling mechanism.

Thank you

Backup Slides

Rotating Boson/Proca stars

Yoshida, Eriguchi '97; Schunck, Mielke '98
Brito, Cardoso, Herdeiro & Radu '15

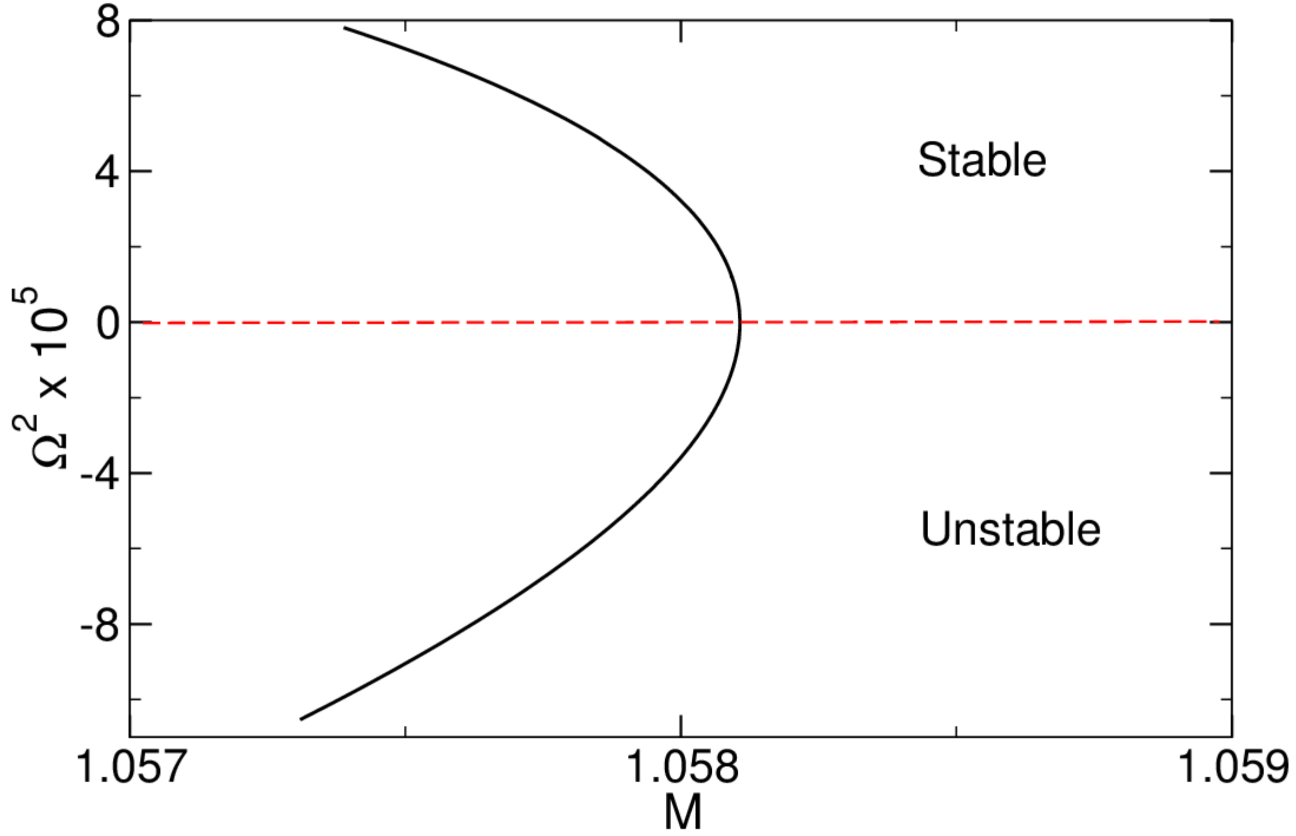


$$A = \mathcal{A}(r,\theta)e^{i(m\varphi - wt)}$$

Continuously connect to hairy black holes. (C. Herdeiro & E. Radu '13)

Stability

Gleiser'88;
Brito, Cardoso, Herdeiro & Radu '15



$$\delta A \sim e^{-i\Omega t}$$

Strong gravity & fundamental (bosonic) fields

$$S = \int d^4x\sqrt{-g}\left(\frac{R}{\kappa} - \frac{1}{4}F^{\mu\nu}\bar{F}_{\mu\nu} - \frac{\mu_V^2}{2}A_\nu\bar{A}^\nu - \frac{1}{2}g^{\mu\nu}\Phi^*_{,\mu}\Phi_{,\nu} - \frac{\mu_S^2|\Phi|^2}{2} + \mathcal{L}_{\rm matter}\right)$$

Natural candidates – QCD axion, axiverse scenario, dark photons…

Solitons

$$\mathcal{L} = \frac{R}{\kappa} - \frac{g^{\mu\nu}}{2}\Phi^*_{,\mu}\Phi_{,\nu} - \frac{\mu_S^2}{2}\Phi^*\Phi$$

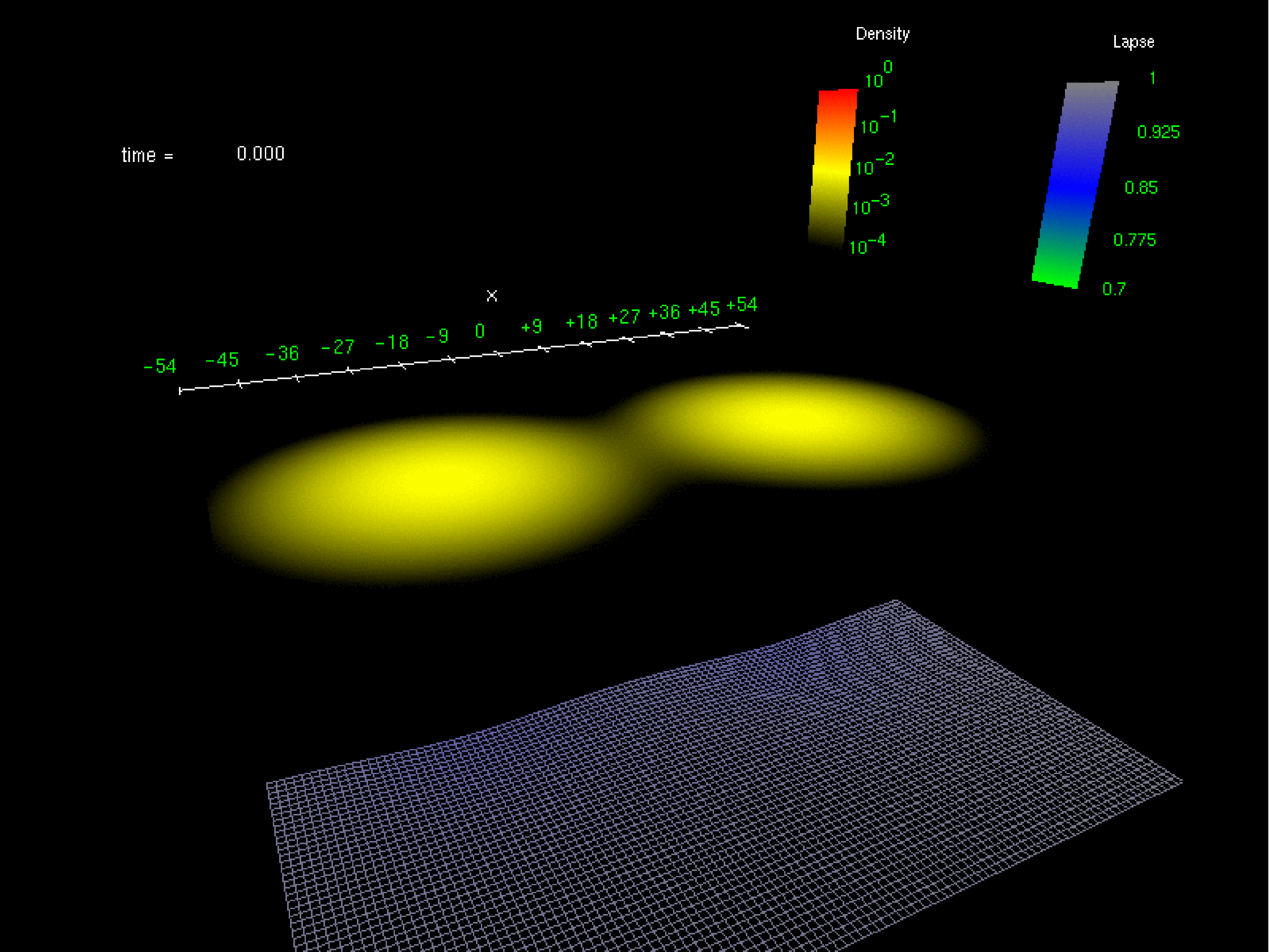
No stable time-independent regular solutions in Minkowski (and in fact not even when coupled to gravity).

(Derrick '64)

When coupling complex scalars to gravity, stable localized stationary solutions exist: Boson stars

(D.J. Kaup '68; Ruffini & Bonazzola '69)

$$\Phi(t,r) \quad = \quad \phi(r)e^{-i\omega t}$$


Density
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Lapse
1
0.925
0.85
0.775
0.7
time = 0.000
x
-54 -45 -36 -27 -18 -9 0 +9 +18 +27 +36 +45 +54