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Fundação para a Ciência e a Tecnologia

MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

Compact Objects in Generalized Proca Theories

Masato Minamitsuji

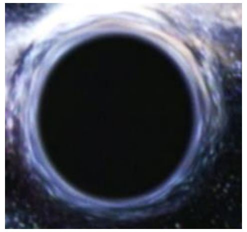
Heisenberg, Kase, Minamitsuji, and Tsujikawa; JCAP 1708, 08 (2017), PRD 96, 084049 (2017)

Minamitsuji; Phys. Rev. D96, 044017 (2017)

Compact Objects in Modified Gravity

$$G_{\mu\nu}(g) + H_{\mu\nu}(g_{\mu\nu}, \phi, A_\mu, f_{\mu\nu} \cdots) = 8\pi G T_{\mu\nu}$$

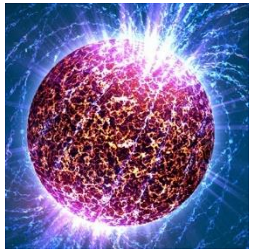
Black holes



$T_{\mu\nu} = 0$

Hairy solutions

Neutron stars



$T_{\mu\nu} \neq 0$

EOS-independent relations

Verified $\Leftarrow$

Boson stars

Kaup (68)
Ruffini & Bonazzola (69)
Jetzer (92)

Gravitationally bound solitonic objects

$\mu^2|\phi|^2$ $\quad M \sim M_p^2/\mu$

$\mu = 10^{-10} eV \Longrightarrow M \sim M_\odot$

$\Longrightarrow$**Not verified**

Generalized Proca Theories

Tasinato (14); Heisenberg (14) ;
Allys, Peter, & Rodriguez (16) ;
Beltran Jimenez, & Heisenberg (16)

Most general vector-tensor theories with 2nd order EOMs

$$S=\int d^4x\sqrt{-g}\left(F+\sum_{i=2}^{6}L_i\right)$$

$$X:=-\frac{1}{2}g^{\mu\nu}A_\mu A_\nu \qquad F:=-\frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

$$Y:=A^\mu A^\nu F_{\mu\alpha}F_\nu{}^\alpha \qquad L^{\mu\nu\alpha\beta}:=\frac{1}{4}\varepsilon^{\mu\nu\rho\sigma}\varepsilon^{\alpha\beta\gamma\delta}R_{\rho\sigma\gamma\delta}$$

$$L_2=G_2\,(X,F,Y) \qquad L_3=-G_3\,(X)\nabla_\mu A^\mu$$

$$L_4=G_4\,(X)R+G_{4X}(X)\left[\left(\nabla_\mu A^\mu\right)^2-\nabla_\mu A_\nu\nabla^\nu A^\mu\right]$$

Vector galileon couplings

→Horndeski theory $\left(A_\mu\to\partial_\mu\phi\right)$

$$L_5=G_5\,(X)G_{\mu\nu}\nabla^\mu A^\nu-\frac{G_{5X}(X)}{6}\left[\left(\nabla_\mu A^\mu\right)^3-3\nabla_\mu A^\mu\nabla_\rho A_\sigma\nabla^\sigma A^\rho+2\nabla_\rho A_\sigma\nabla^\gamma A^\rho\nabla^\sigma A_\gamma\right]$$
$$-g_5(X)\tilde{F}^{\alpha\mu}\tilde{F}^\beta{}_\mu\nabla_\alpha A_\beta$$

Intrinsic vector couplings

$$L_6=\frac{1}{4}G_6\,(X)L^{\mu\nu\alpha\beta}F_{\mu\nu}F_{\alpha\beta}+\frac{1}{2}G_{6X}(X)\tilde{F}^{\alpha\beta}\tilde{F}^{\mu\nu}\nabla_\alpha A_\mu\nabla_\beta A_\nu$$

Hairy Black Holes

$$ds^2 = -f(r)dt^2 + \frac{dr^2}{h(r)} + r^2 d\Omega^2 \qquad A_\mu dx^\mu = A_0(r)dt + A_1(r)dr$$

Charged stealth Schwarzschild solution

Chagoya, Niz, & Tasinato, 1602.08697

$$L = \frac{M_{pl}^2}{2}R + F + \beta G^{\mu\nu}A_\mu A_\nu \quad \leftrightarrow G_4(X) = \frac{1}{2}M_p^2 + \beta X$$

$\beta = \frac{1}{4}$:

$$f(r) = h(r) = 1 - \frac{2M}{r}$$

$$A_0(r) = P + \frac{Q}{r} \quad \Rightarrow F_{tr} = \frac{Q}{r^2}$$

$$A_1(r) = \pm \frac{\sqrt{Q^2 + 2PQr + 2MP^2 r}}{r}\frac{1}{f(r)}$$

Instability in the vicinity of horizon

Kase, Minamitsuji, Tsujikawa & Zhang, 1801.01787

Heisenberg, Kase, Minamitsuji, & Tsujikawa, 1705.09662, 1706. 05115

$$L = \frac{M_{pl}^2}{2} R - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} + L_i \qquad G_i(X), g_i(X) \propto X^n$$

1. Cubic vector Galileon: $G_3 = \beta_3 X$

$$f = 1 - \frac{2M}{r} - \frac{P^2 M^3}{6M_{\rm pl}^2 r^3} + \frac{M^4 P^2 (P^2 - 2M_{\rm pl}^2) + 3M_{\rm pl}^2 \tilde{b}_2^2}{3M_{\rm pl}^2 (2M_{\rm pl}^2 - P^2) r^4}$$

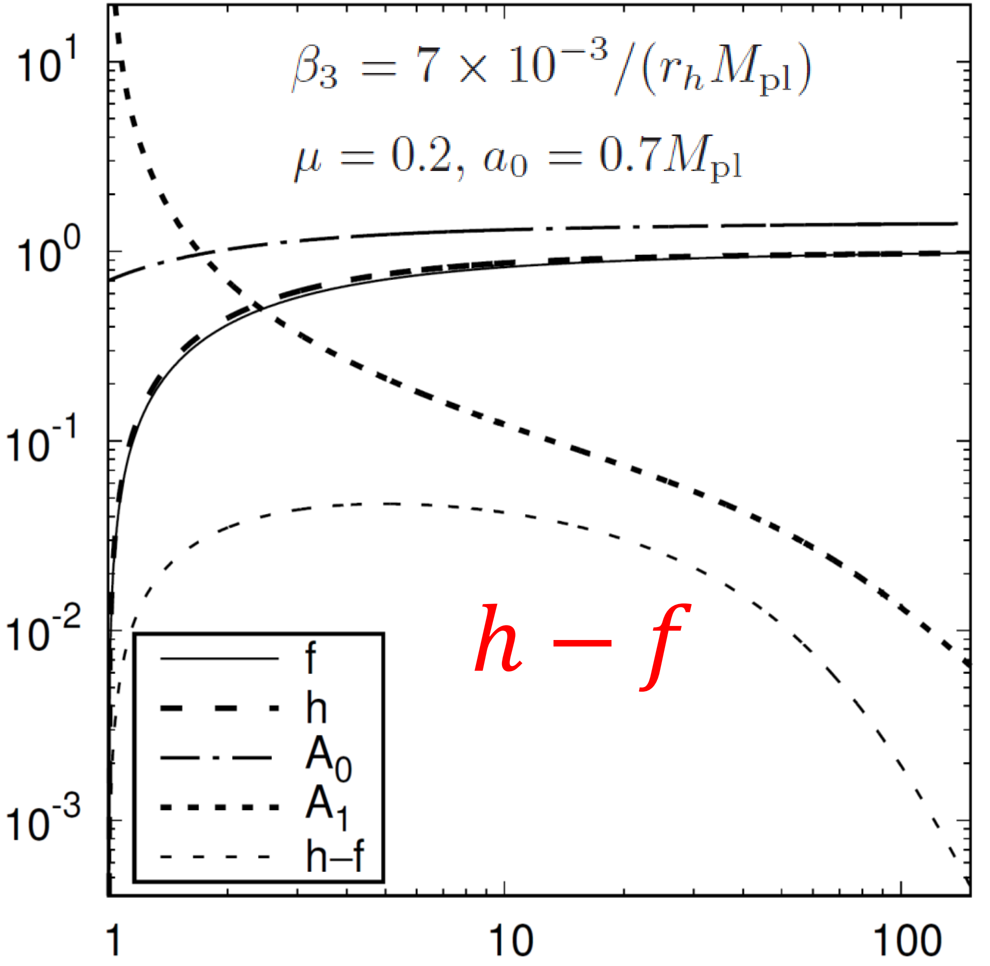
$$h = 1 - \frac{2M}{r} - \frac{P^2 M^2}{2M_{\rm pl}^2 r^2} - \frac{P^2 M^3}{2M_{\rm pl}^2 r^3} + \frac{2M^4 P^2 (P^2 - 2M_{\rm pl}^2) + 12 M_{\rm pl}^2 \tilde{b}_2^2}{3M_{\rm pl}^2 (2M_{\rm pl}^2 - P^2) r^4}$$

$$A_0 = P - \frac{PM}{r} - \frac{PM^2}{2r^2} - \frac{PM^3 (P^2 + 6M_{\rm pl}^2)}{12 M_{\rm pl}^2 r^3} - \frac{P^2 M^4 (2P^2 + 5M_{\rm pl}^2)(P^2 - 2M_{\rm pl}^2) + 8M_{\rm pl}^4 \tilde{b}_2^2}{8PM_{\rm pl}^2 (P^2 - 2M_{\rm pl}^2) r^4}$$

$$A_1 = \frac{\tilde{b}_2}{r^2} + \frac{M(M + 2\tilde{b}_2 \beta_3)}{\beta_3 r^3} + \frac{12 M^3 M_{\rm pl}^2 + \tilde{b}_2 M^2 (P^2 + 16 M_{\rm pl}^2) \beta_3}{4\beta_3 M_{\rm pl}^2 r^4}$$

$\tilde{b}_2, P$: primary vector hair

No ghost/Laplacian instabilities



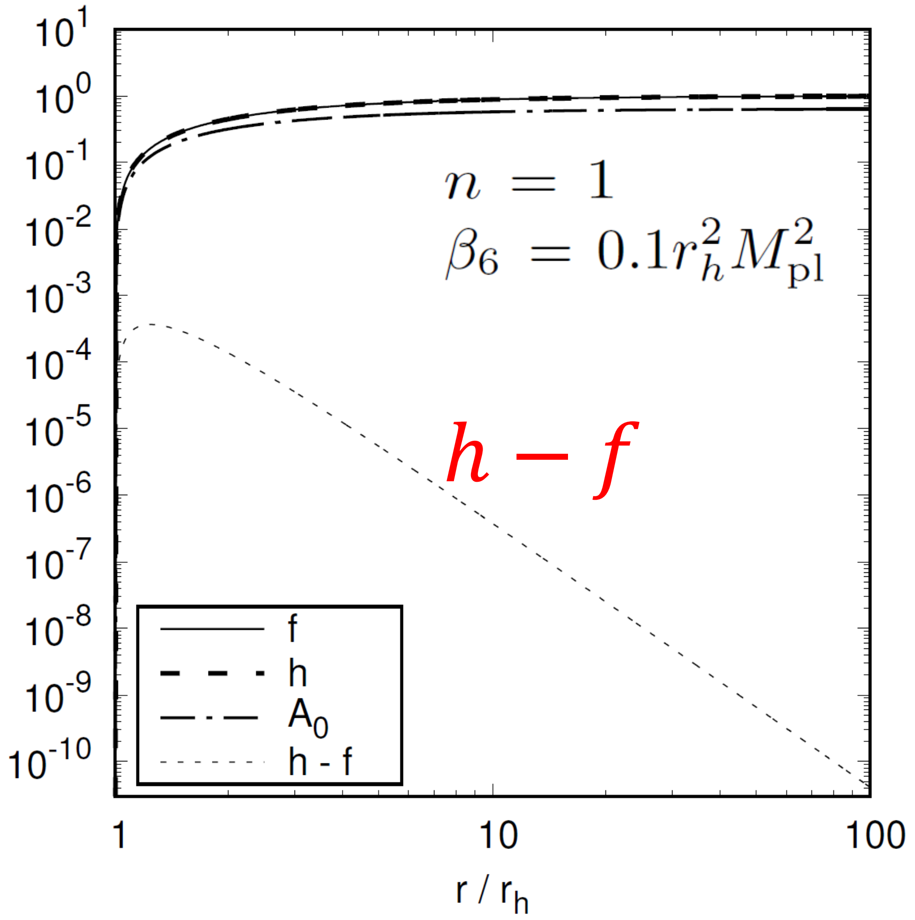
2. Intrinsic vector coupling: $G_6 = \frac{\beta_6}{M_{\rm pl}^2}\left(\frac{X}{M_{\rm pl}^2}\right)^n$

$A_1 = 0$

$$f = 1 - \frac{2M}{r} + \frac{Q^2}{2M_{\rm pl}^2 r^2} - \frac{\beta_6 P^{2n} Q^2}{2^{1+n} M_{\rm pl}^{4+2n} r^4} - \frac{2^{-n}\beta_6 P^{2n-1} Q^2 [MP(6n-5) + 8Qn]}{10 M_{\rm pl}^{4+2n} r^5}$$

$$h = 1 - \frac{2M}{r} + \frac{Q^2}{2M_{\rm pl}^2 r^2} + \frac{\beta_6 M P^{2n} Q^2 (2n-1)}{2^{1+n} M_{\rm pl}^{4+2n} r^5}$$

$$A_0 = P + \frac{Q}{r} - \frac{2^{-n}\beta_6 M P^{2n} Q}{M_{\rm pl}^{2+2n} r^4} - \frac{2^{-n}\beta_6 P^{2n-1} Q (32 M^2 M_{\rm pl}^2 P n + 28 M M_{\rm pl}^2 Q n - 3PQ^2}{20 M_{\rm pl}^{4+2n} r^5}$$



$P = P(M, Q)$: secondary vector hair

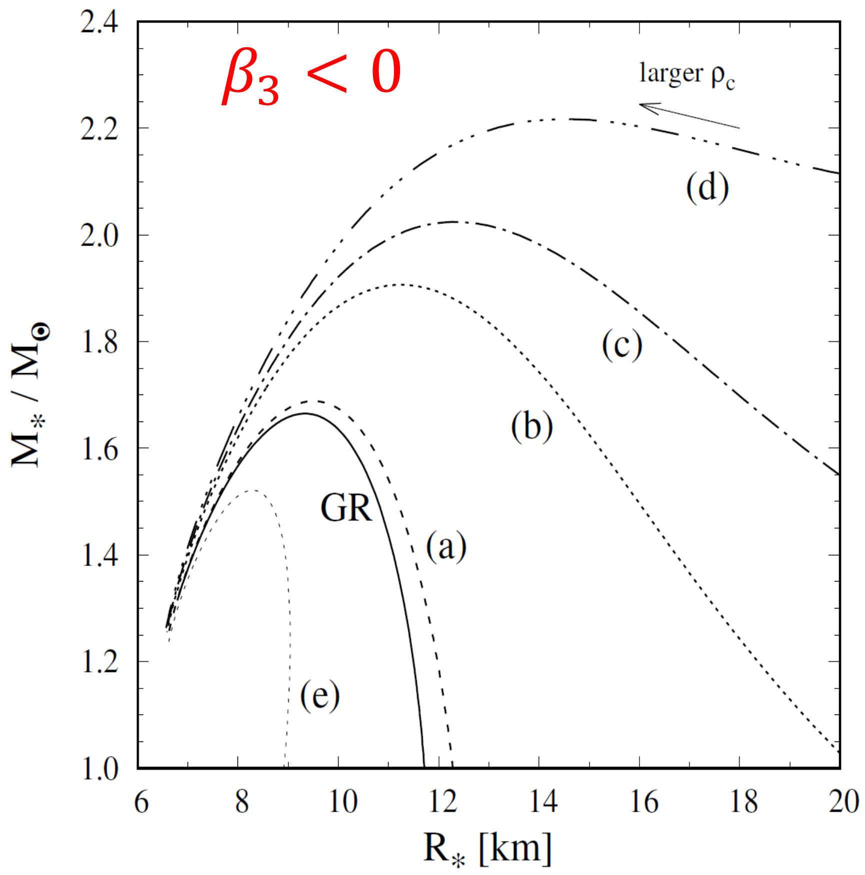
No ghost/ Laplacian instabilities

Secondary hair also for $G_2 = -g_4(X)F, g_5(X), G_6(X)$

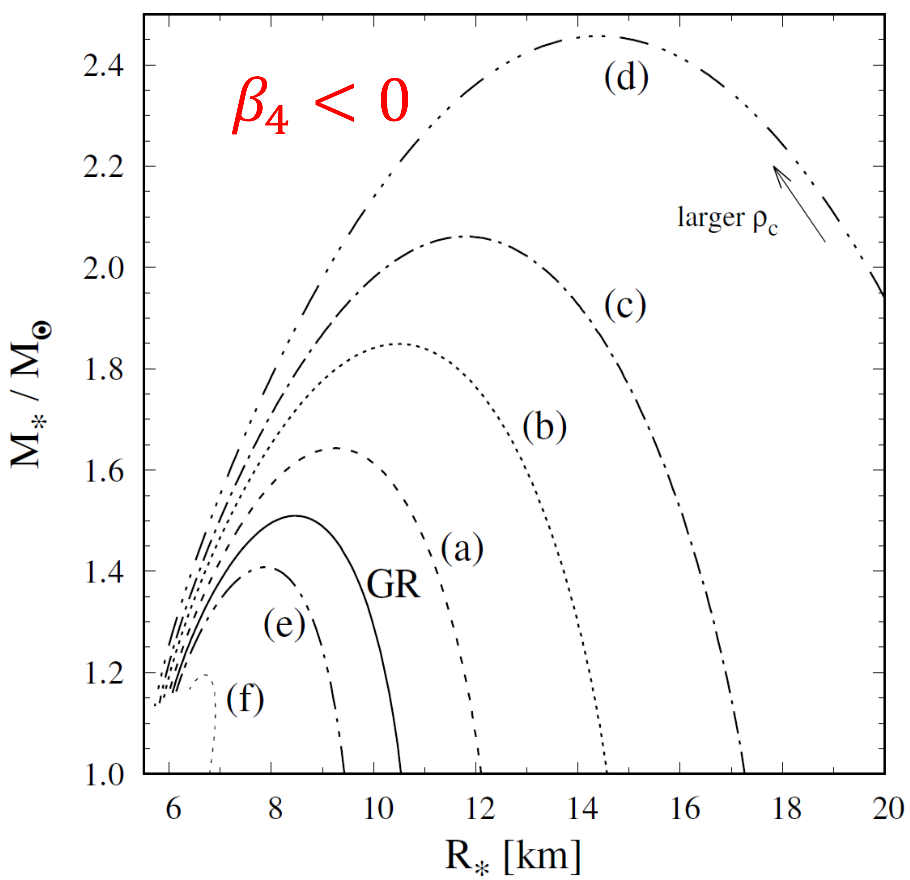
Relativistic Stars

$G_4 \supset \beta_4 X \Leftrightarrow G^{\mu\nu} A_\mu A_\nu$ Chagoya, Nitz, & Tasinato, 1703.09555

$G_3 = \beta_3 X$



$G_4 \supset \beta_4 X^2$



$G_2 = -g_4(X)F, g_5(X), G_6(X)$: No-hair properties for relativistic stars

Kase, Minamitsuji, & Tsujikawa, 1711.08713

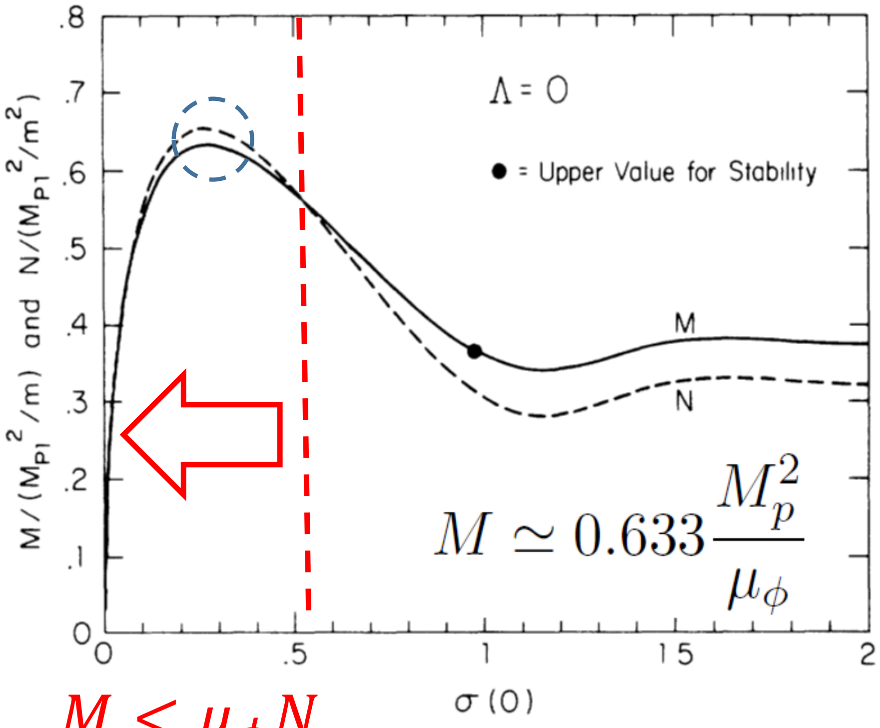
Scalar Boson Stars $\phi(t,r) = \sigma(r)e^{-i\omega t}$

$V = \mu^2|\phi|^2$ Kaup (68), Ruffini, & Bonazzola (69), Friedberg, Lee, & Pang (87)

$V = \mu^2|\phi|^2 + \lambda|\phi|^4 \quad \lambda\left(M_p/\mu\right)^2 \gg 1$

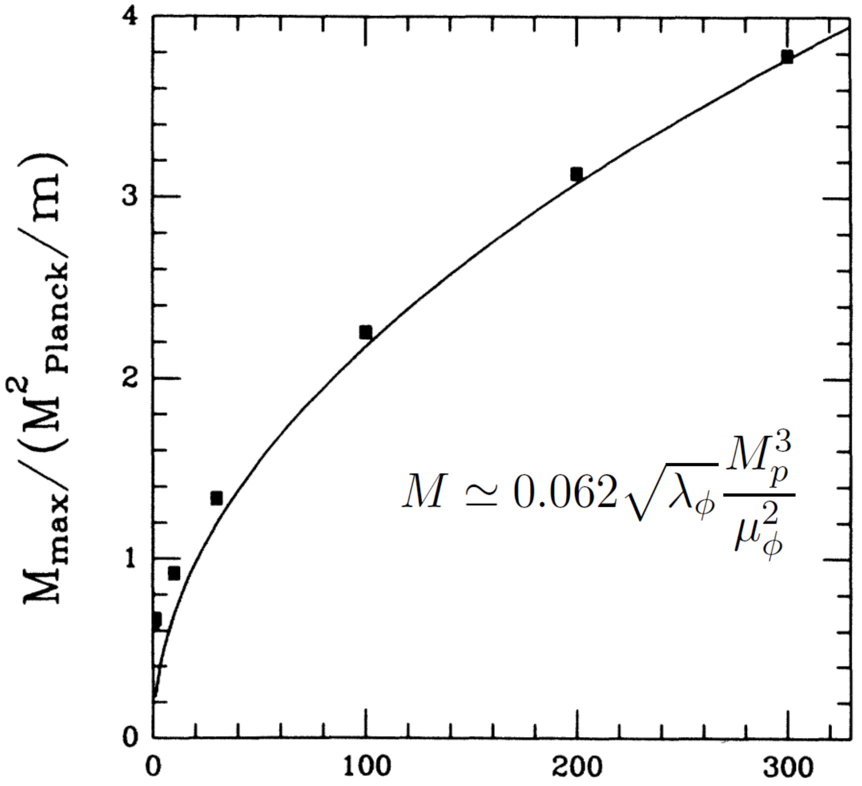
$M \sim M_p^2/\mu \ll M_{ch}$

$M \sim \sqrt{\lambda}\, M_p^3/\mu^2 \sim M_{ch}$



$M < \mu_\phi N$

Gleiser, PRD38, 2376(88)



$\Lambda = \lambda M^2_{Planck}/4\pi m^2$

Colpi, Shapiro, & Wasserman, PRL 57, 2485-2488 (86)

Massive Vector Boson Stars $\mathcal{A} = e^{-iwt}[f(r)dt + ig(r)dr]$

Brito, Cardoso, Herdeiro, & Radu, 1508.05395

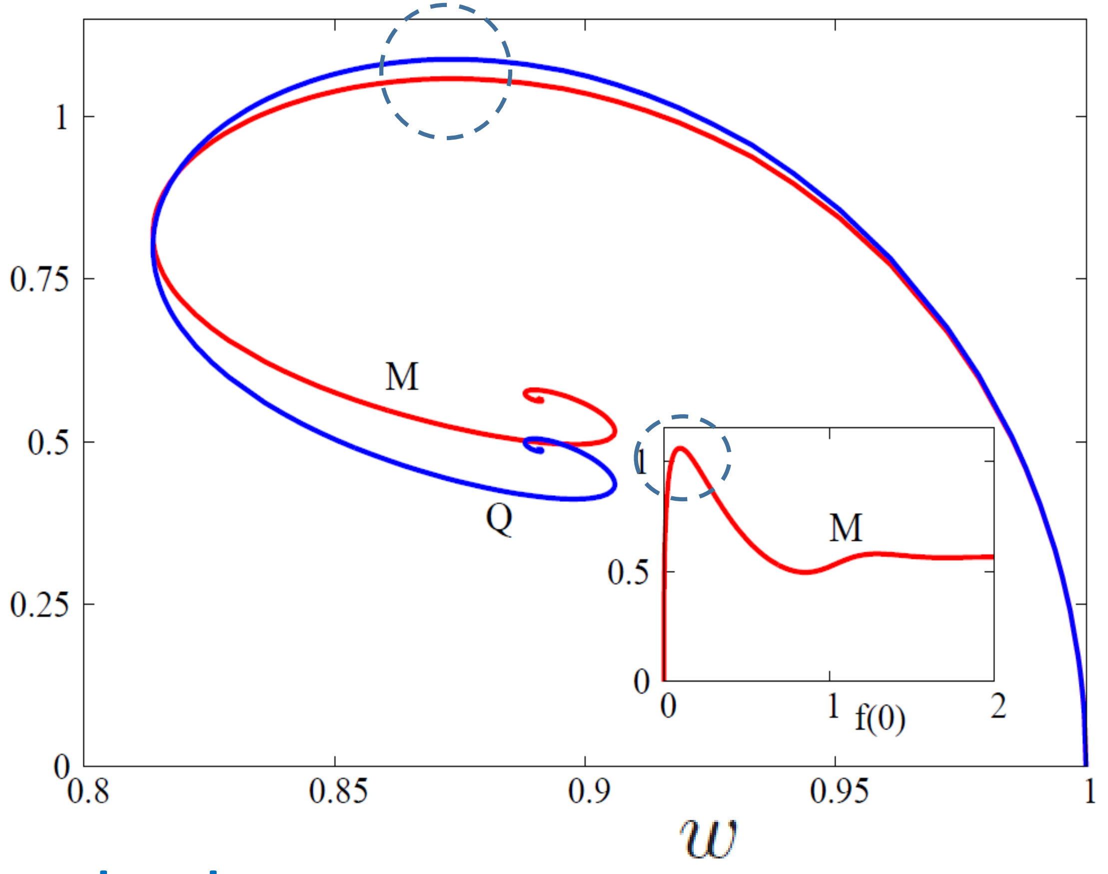
$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2\kappa^2}R - \frac{1}{4}F^{\mu\nu}\bar{F}_{\mu\nu} - \frac{1}{2}\mu^2 A^\mu \bar{A}_\mu\right]$$

Maximal mass and charge

$$M_{\max} \approx 1.058\frac{M_p^2}{\mu}$$

$$\mu Q_{\max} \approx 1.088\frac{M_p^2}{\mu}$$

$M \sim M_p^2/\mu$



Similar to massive scalar boson stars

Vector Boson Stars with Self Interactions

Minamitsuji, in progress

$$S=\int d^4x\sqrt{-g}\left[\frac{1}{2\kappa^2}R-\frac{1}{4}F^{\mu\nu}\bar{F}_{\mu\nu}-\frac{1}{2}\mu^2A^\mu\bar{A}_\mu-\frac{1}{4}\lambda\underline{\left(A^\mu\bar{A}_\mu\right)^2}\right]$$

Ansatz
$$g_{\mu\nu}dx^\mu dx^\nu=-\sigma(r)^2\left(1-\frac{2m(r)}{r}\right)d\hat{t}^2+\left(1-\frac{2m(r)}{r}\right)^{-1}dr^2+r^2d\Omega_2^2,$$

$$A_\mu dx^\mu=e^{-i\hat{\omega}\hat{t}}\left(a_0(r)d\hat{t}+ia_1(r)dr\right)$$

Around the center

$$a_0(r)=f_0-\frac{f_0}{6}\frac{f_0^2\lambda-\mu^2\sigma_0^2+\hat{\omega}^2}{\sigma_0^2}r^2+\mathcal{O}\left(r^4\right),\qquad m(r)=\frac{\kappa^2f_0^2}{24\sigma_0^4}\left(-3f_0^2\lambda+2\mu^2\sigma_0^2\right)r^3+\mathcal{O}\left(r^5\right),$$

$$a_1(r)=-\frac{f_0\hat{\omega}}{3\sigma_0^2}r+\mathcal{O}\left(r^3\right),\qquad \sigma(r)=\sigma_0+\frac{\kappa^2f_0^2}{4\sigma_0^3}\left(-f_0^2\lambda+\mu^2\sigma_0^2\right)r^2+\mathcal{O}\left(r^4\right).$$

$$f_0<f_{0,\mathrm{crit}}:=\frac{\mu\sigma_0}{\sqrt{\lambda}}$$

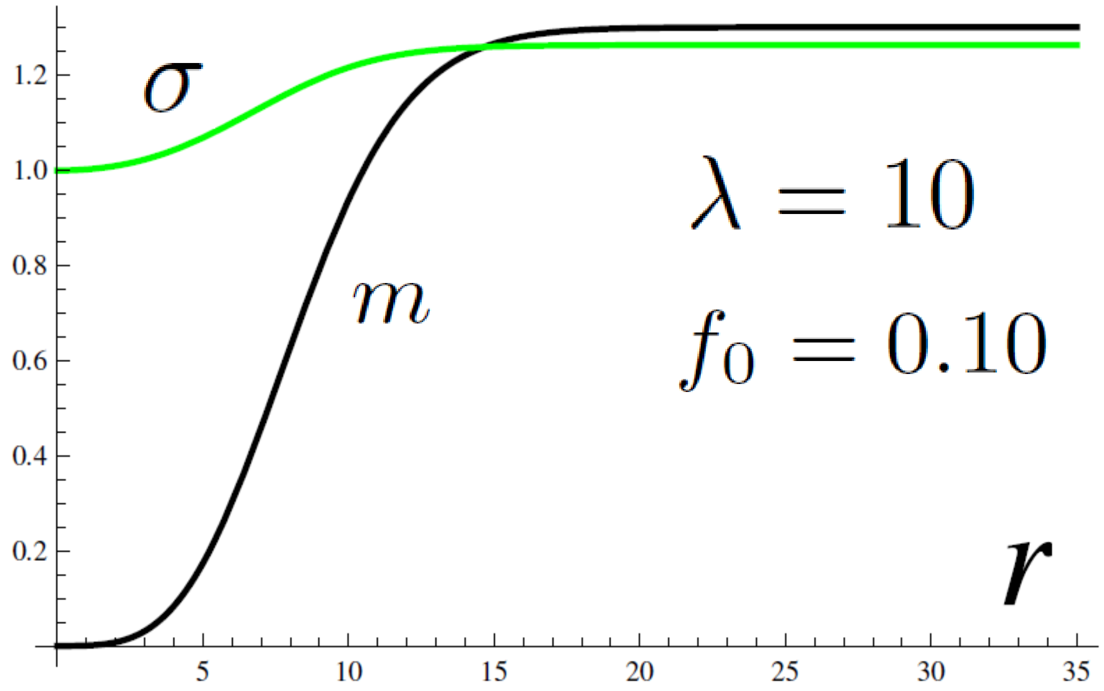
$$ds^2 \to -\sigma_\infty^2 \left(1 - \frac{2m_\infty}{r}\right) d\hat{t}^2 + \left(1 - \frac{2m_\infty}{r}\right)^{-1} dr^2 + r^2 d\Omega_2^2 \quad : \omega = \frac{\hat{\omega}}{\sigma_\infty} \leq \mu$$

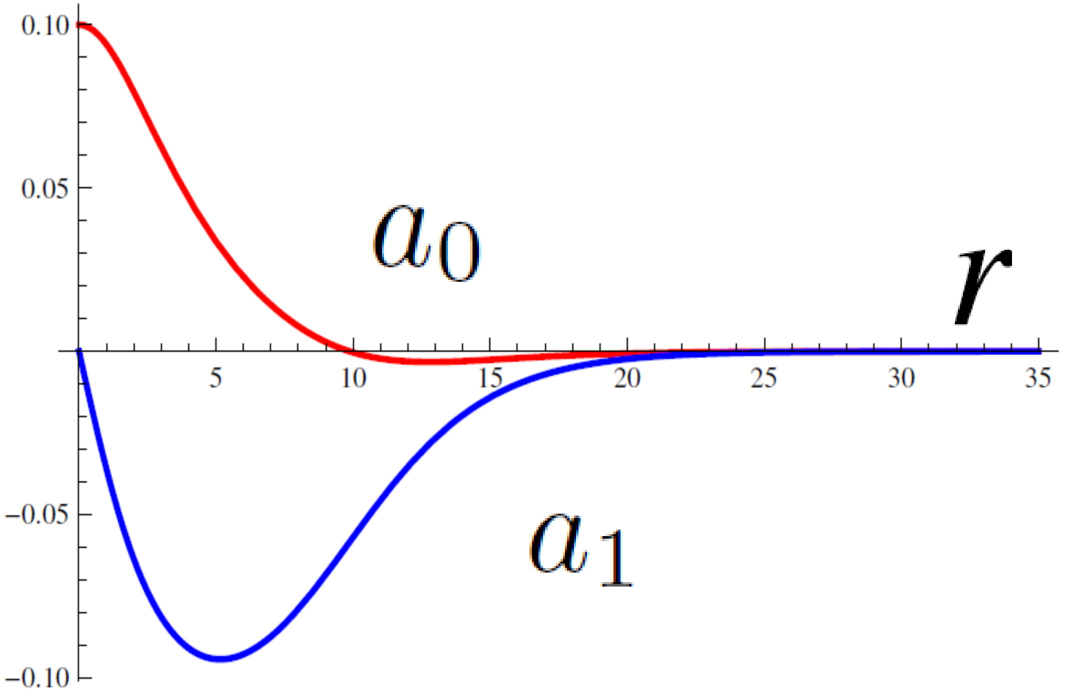
ADM mass $M := \dfrac{m_\infty}{G} = M_p^2 m_\infty$

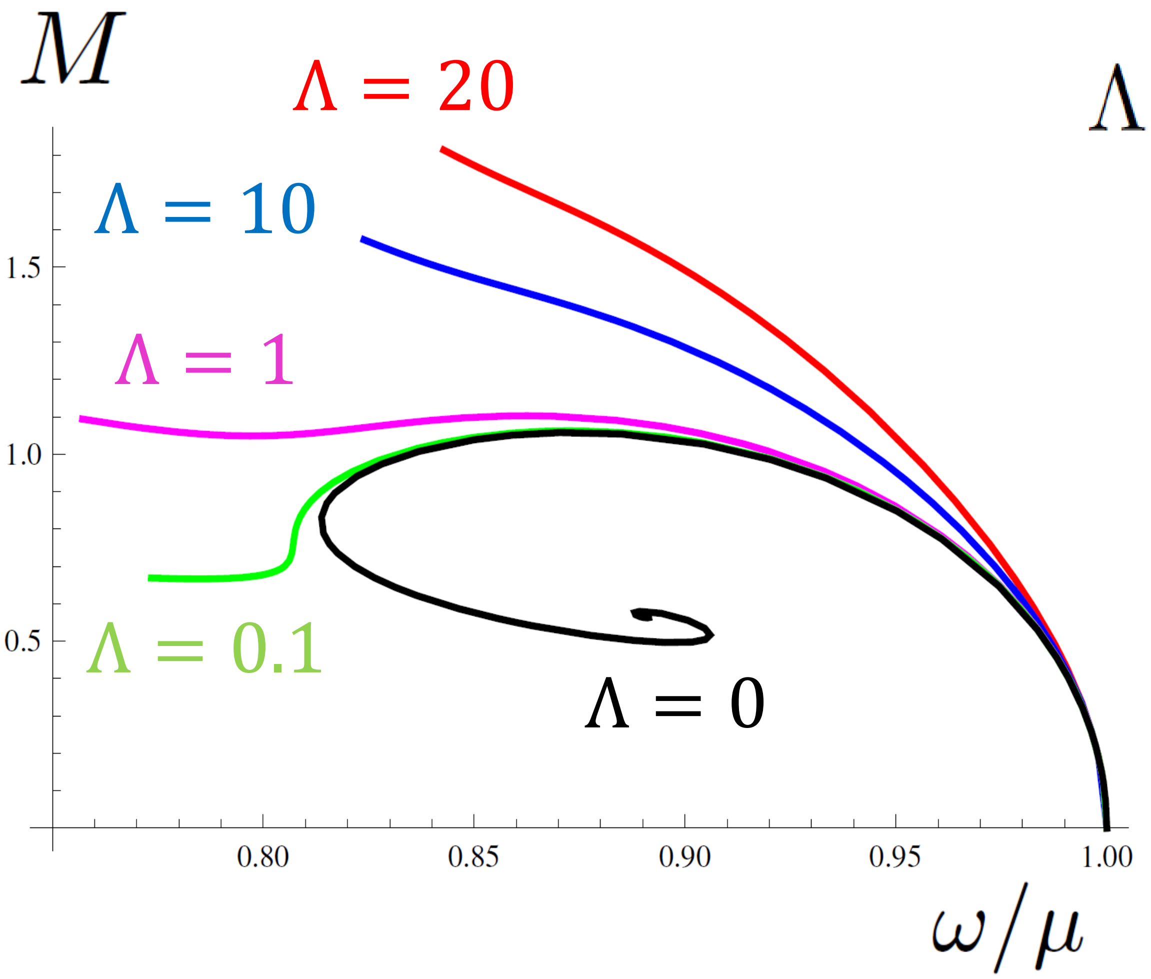
Noether charge $Q = \displaystyle\int_\Sigma d^3x \sqrt{-g} j^{\hat{t}}$

Binding energy $b := \dfrac{B}{M} = \dfrac{\mu Q}{M} - 1.$

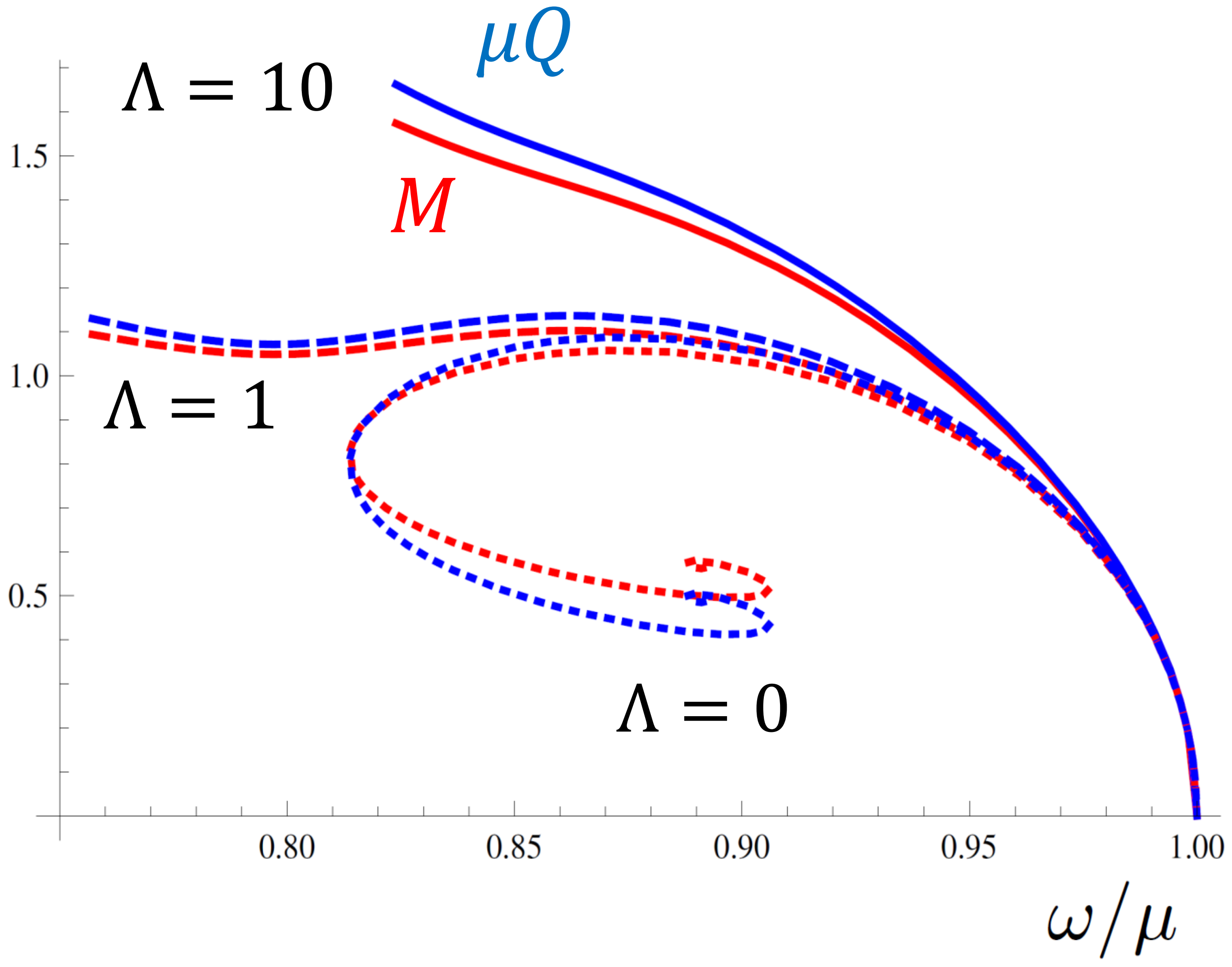
$\mu = \kappa = \sigma_0 = 1$





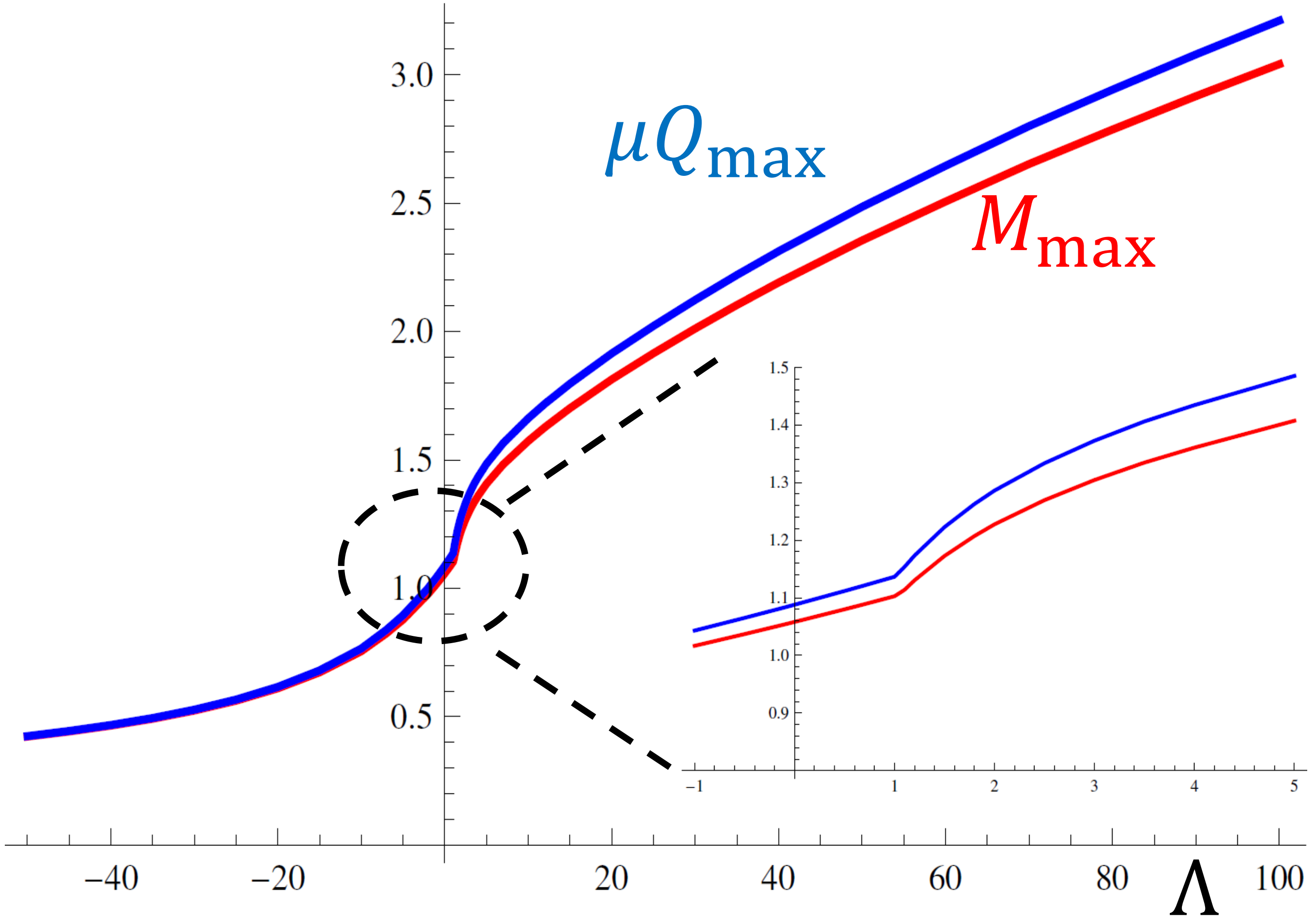


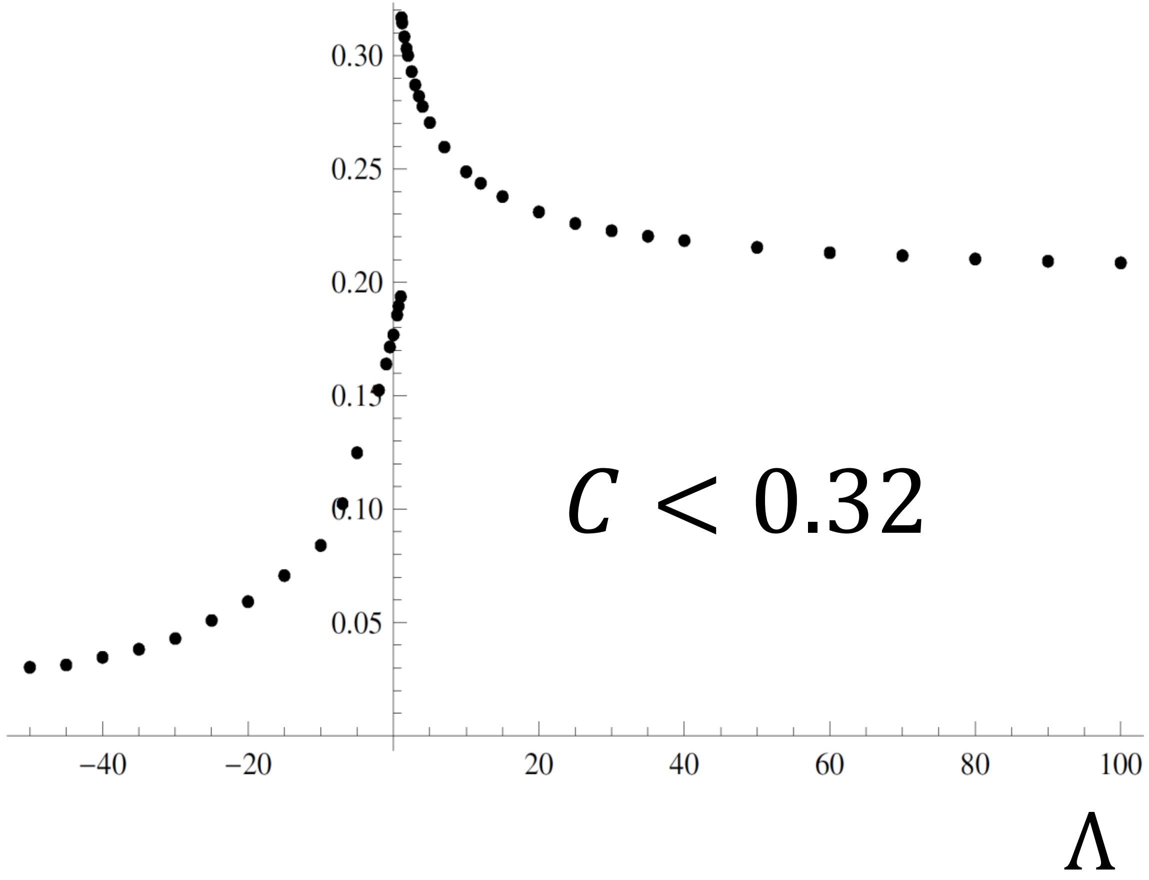
$$\Lambda := \frac{\lambda}{\mu^2\kappa^2} = \frac{M_p^2}{(8\pi)\mu^2}\lambda$$



Maximal mass and charge

$$\mathcal{C} := \frac{GM}{\mathcal{R}} \qquad \mathcal{R} := \frac{1}{Q}\int_\Sigma d^3x\sqrt{-g}\left(rj^{\hat{t}}\right)$$



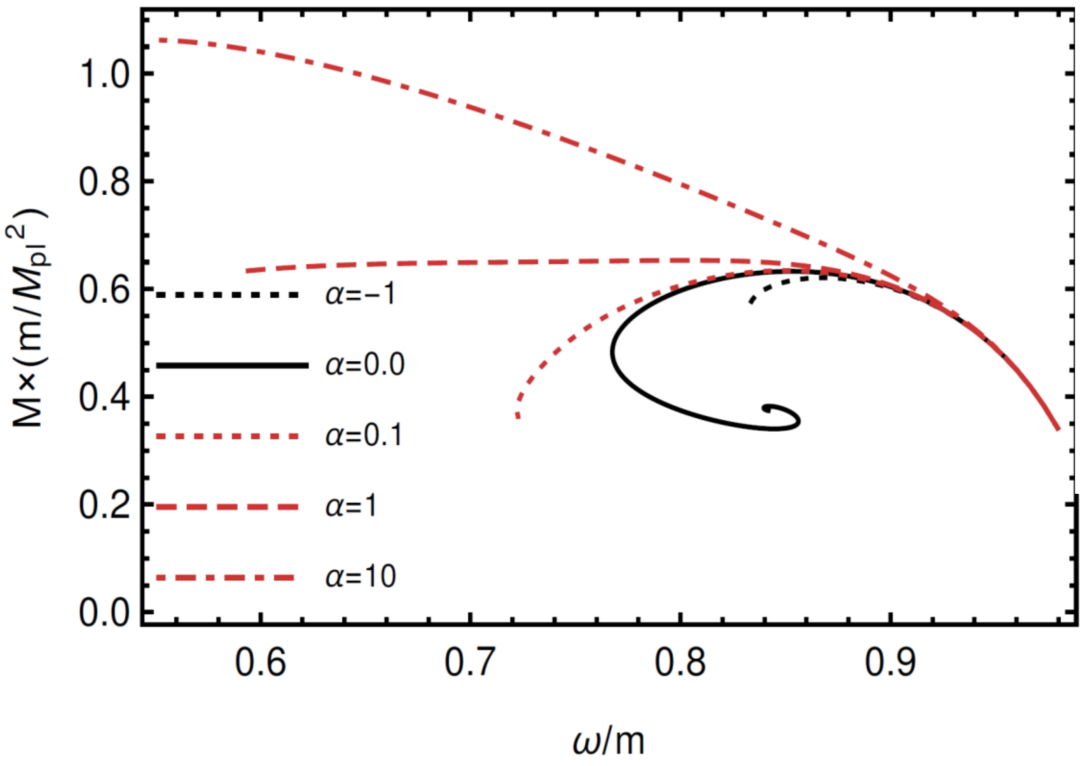


$$\Lambda \gg 1 \qquad M \sim \lambda M_p^4/\mu^3 \gg M_{ch}$$

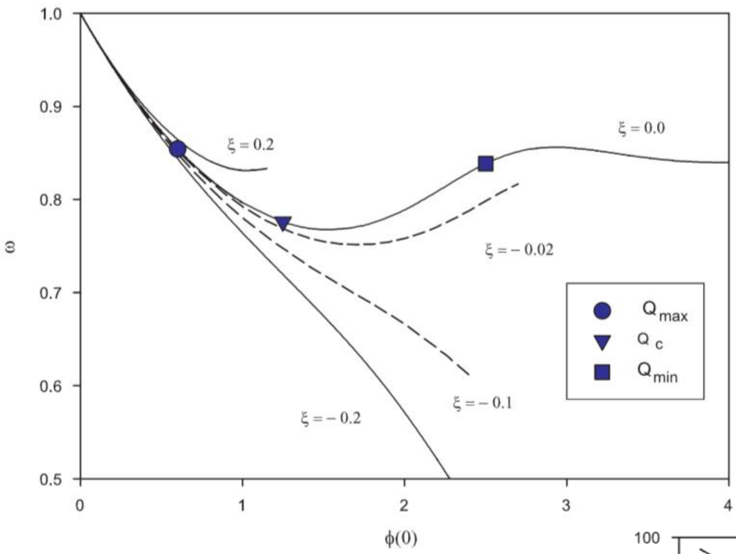
$$M_{\max} \approx \frac{M_p^2}{\mu}\left(0.9702 + 0.03526\frac{\sqrt{\lambda}M_p}{\mu} + 0.0001157\frac{\lambda M_p^2}{\mu^2}\right) \qquad \mu Q_{\max} \approx \frac{M_p^2}{\mu}\left(1.0058 + 0.03854\frac{\sqrt{\lambda}M_p}{\mu} + 0.0001019\frac{\lambda M_p^2}{\mu^2}\right)$$

Scalar Boson Stars with Derivative Couplings

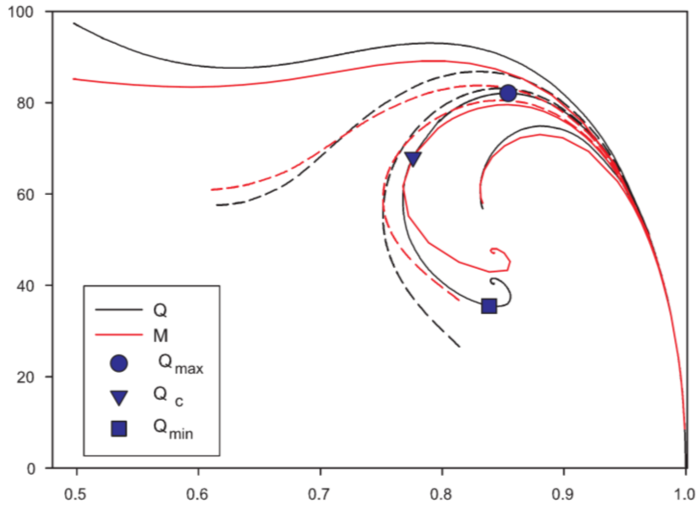
- $\alpha|\phi|^2 R_{GB}$ Baibhav & Maity, 1609.07225



- $\eta G^{\mu\nu}\partial_\mu\phi\partial_\nu\bar{\phi}$ Brihaye, Cisterna, & Erices, 1604.02121



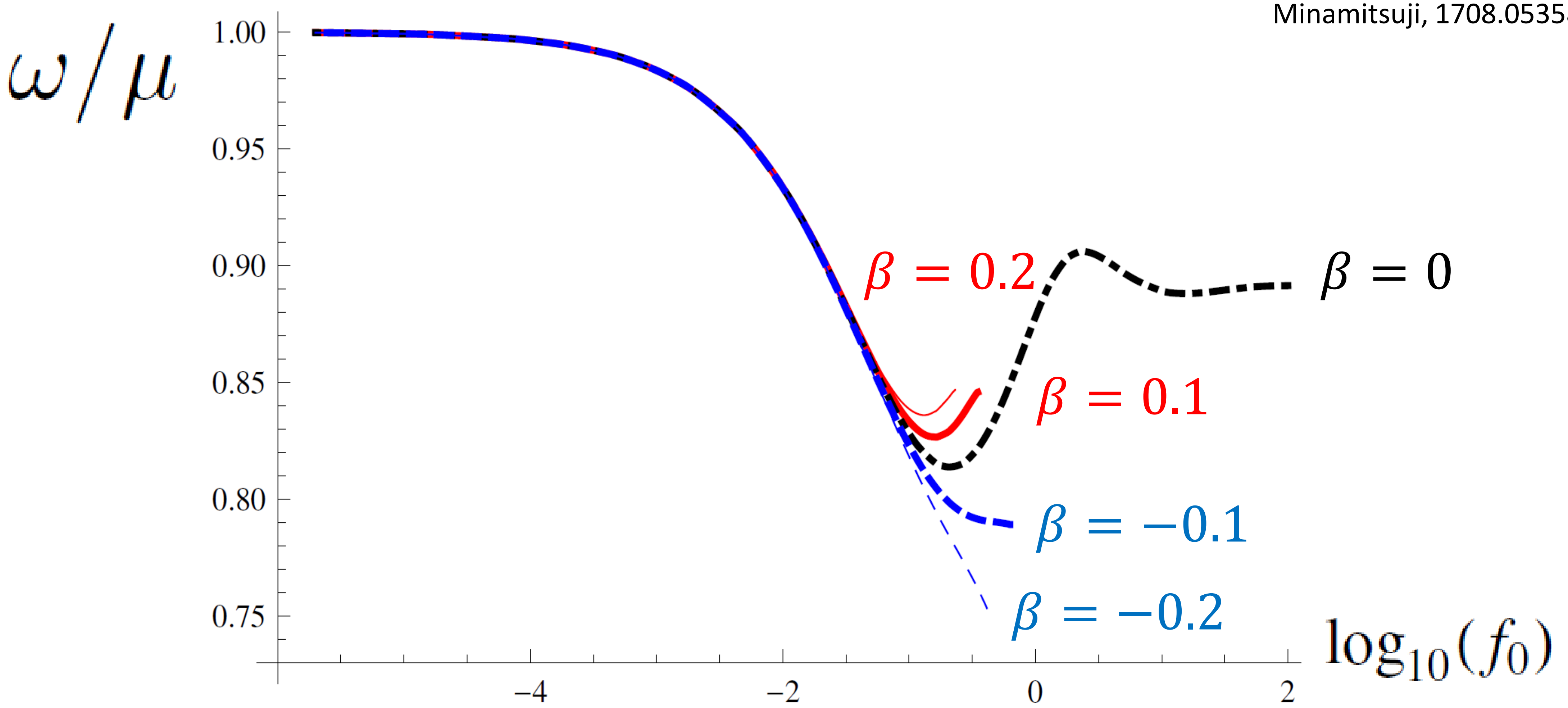
$$\xi = \eta/m^2$$

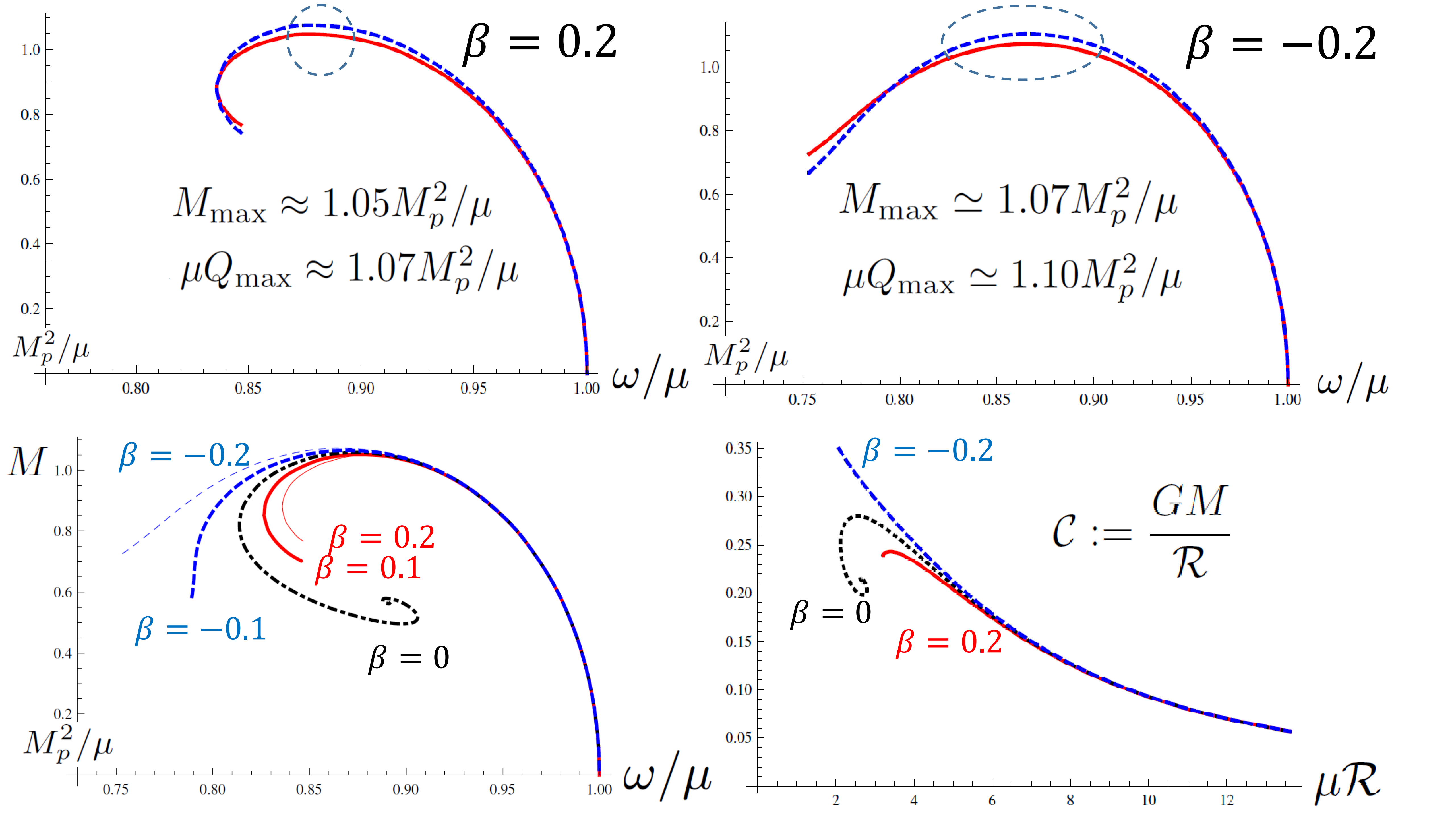


Vector Boson Star with Derivative Coupling

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2\kappa^2}R - \frac{1}{4}F^{\mu\nu}\bar{F}_{\mu\nu} - \frac{1}{2}\left(\mu^2 g^{\mu\nu} - \underline{\beta G^{\mu\nu}}\right)A_\mu \bar{A}_\nu\right]$$

Minamitsuji, 1708.05358





$\beta = 0.2$
$M_{\max} \approx 1.05 M_p^2/\mu$
$\mu Q_{\max} \approx 1.07 M_p^2/\mu$
M_p^2/μ
ω/μ
$\beta = -0.2$
$M_{\max} \simeq 1.07 M_p^2/\mu$
$\mu Q_{\max} \simeq 1.10 M_p^2/\mu$
M_p^2/μ
ω/μ
M
$\beta = -0.2$
$\beta = 0.2$
$\beta = 0.1$
$\beta = -0.1$
$\beta = 0$
M_p^2/μ
ω/μ
$\beta = -0.2$
$\mathcal{C} := \frac{GM}{\mathcal{R}}$
$\beta = 0$
$\beta = 0.2$
$\mu\mathcal{R}$

Summary

Black holes, Relativistic stars and Boson stars in generalized Proca theories.

- Hairy BHs in various class of generalized Proca theories

  ghost or Laplacian instabilities of charged stealth Schwarzschild BH

  stable BHs for other numerical solutions

- Relativistic Stars

  Modified structure of stars for vector Galileon couplings

  No-hair properties of stars for intrinsic vector mode couplings

- Boson Stars

  The existence of a critical central amplitude of the vector field

Thank you.