21st International Conference on General Relativity and Gravitation
Columbia University, New York

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Spontaneous scalarization of neutron stars in the unconstrained parameter regime of scalar-tensor theories

(Based on arXiv:1604.04175)

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GR21. New York City. July 11th, 2016.

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From Raissa's talk we have learned:

In Scalar-Tensor Theories (STT) with $\beta_0 > 0$, highly compact neutron stars (NS) obeying realistic equations of state (EoS) possess linearly unstable scalar modes.

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In the Einstein frame: $S = \frac{1}{16\pi}\int d^4x\sqrt{-g}\,(R - 2\nabla_\mu\phi\nabla^\mu\phi) + S_m[\Psi_m; a(\phi)^2 g_{\mu\nu}]$

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$$T^{\mu\nu} = \epsilon u^\mu u^\nu + p(\tilde{g}^{\mu\nu} + u^\mu u^\nu)$$

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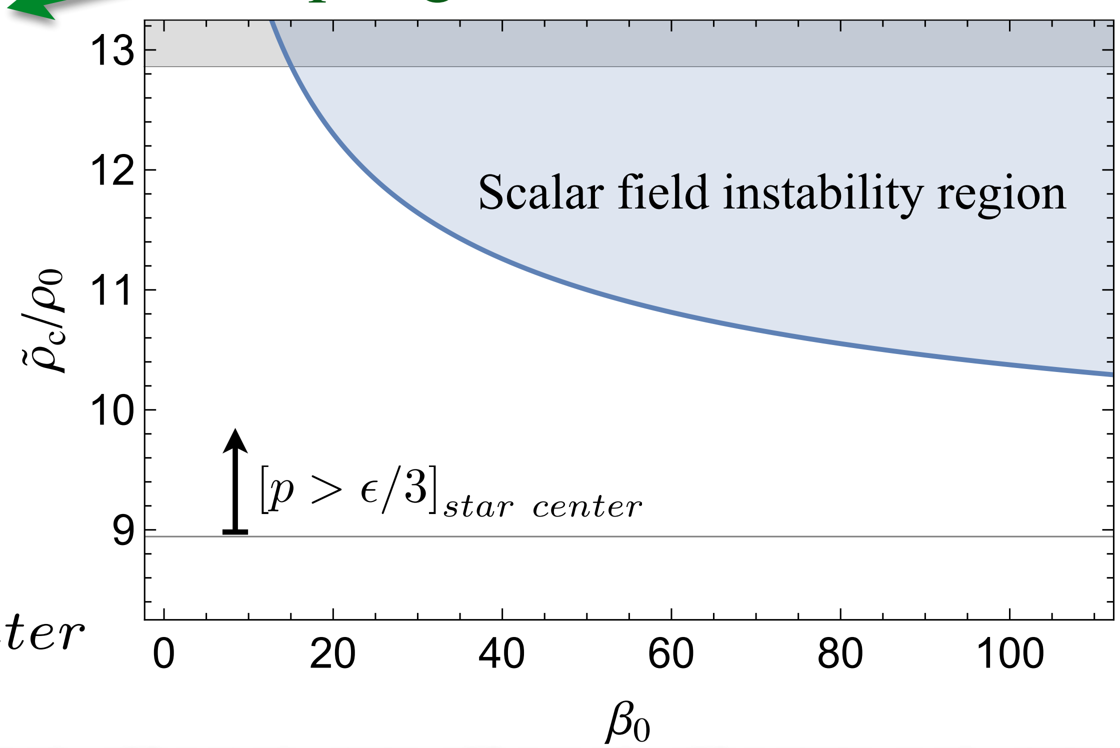

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Our strategies

* Energy balance analysis

* Full non-linear numerical simulations

Posing problem...

What we want to solve

Field equations

$$\begin{cases} G_{\mu\nu} - 2\nabla_\mu\phi\nabla_\nu\phi + g_{\mu\nu}\nabla_\sigma\phi\nabla^\sigma\phi = 8\pi a^2 T_{\mu\nu} \\ \nabla^\mu\nabla_\mu\phi = -4\pi a^4 \alpha T \end{cases}$$

Fluid equations

$$\begin{cases} \nabla_\mu(\rho u^\mu) = 0 \\ \nabla_\nu T^{\mu\nu} = 0 \end{cases}$$

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$$p(\rho) = K\rho_0(\rho/\rho_0)^\gamma$$

$$\gamma = 3,\ K = 0.005,$$

$$\rho_0 = 1.66 \times 10^{14}\mathrm{g/cm^3}$$

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Our approach: **3 + 1 Formalism**, **spherical symmetry** (reduction to 1+1D problem)

Radial gauge / Polar slicing $ds^2 = -N(t,r)^2dt^2 + A(t,r)^2dr^2 + r^2(d\vartheta^2 + \sin^2\vartheta d\varphi^2)$

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Requires fluid equations in flux-conservative form: $\frac{\partial}{\partial t}(A\mathbf{q}) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(NAr^2\mathbf{F}(\mathbf{q})\right) = \mathbf{S}(\mathbf{q})$

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Coupling function:

- **Model 1 (M1):** $\alpha(\phi) = \tanh[\sqrt{3}\beta(\phi-\phi_0)]/\sqrt{3}$ [mimics Nonminimally coupled (NMC) field]
- **Model 2 (M2):** $\alpha(\phi) = \beta(\phi-\phi_0)$ [Damour-Esposito-Farese (DEF)]

Relevant previous results

(Dynamic transition to scalarized states in the $\beta < 0$ case)

Nonminimally coupled fields (like M1): M. Alcubierre et al., 2010, M. Ruiz, 2012.

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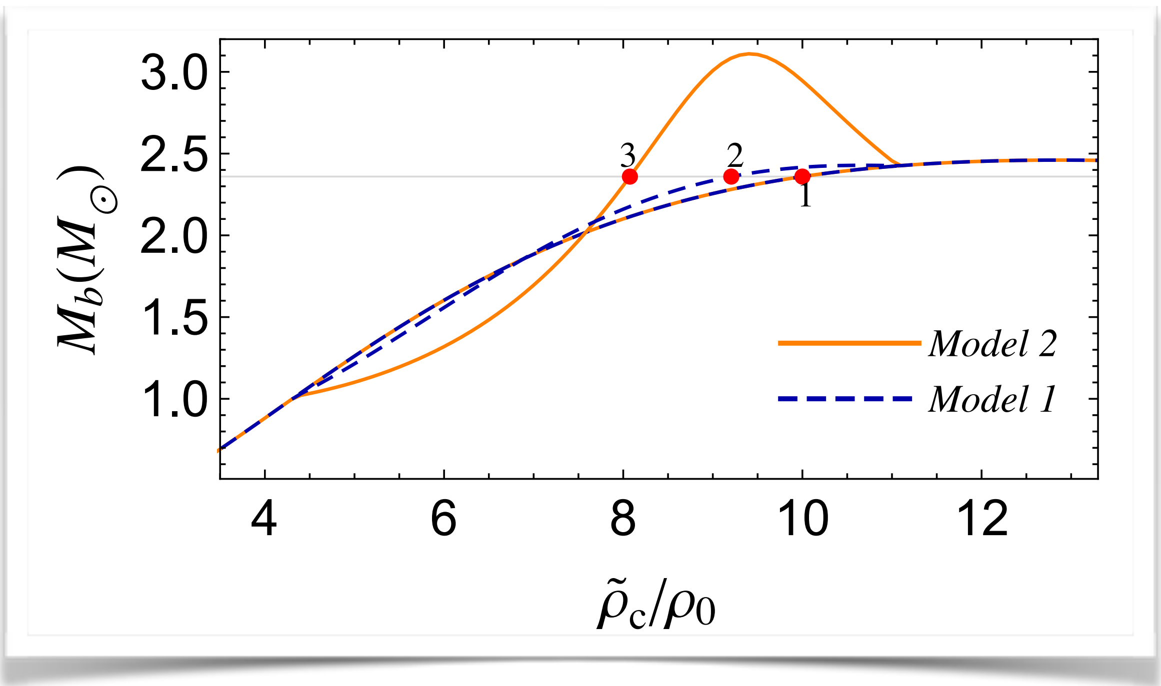

Solution	$\tilde{\rho}_c/\rho_0$	$M_b[M_\odot]$	$M[M_\odot]$	M/R_s	$\lvert\phi_c - \phi_0\rvert$	$\lvert\omega\rvert[M_\odot]$
1*	10.0	2.3594	1.9650	0.287	0	0
2 (M1)	9.2061	2.3594	1.9641	0.273	0.095	0.30
3 (M2)	8.0747	2.3594	1.9459	0.209	0.284	1.23

Table 1: Some equilibrium solutions with $\beta = -6$. The solution marked with a star is used as initial data for our numerical simulation.

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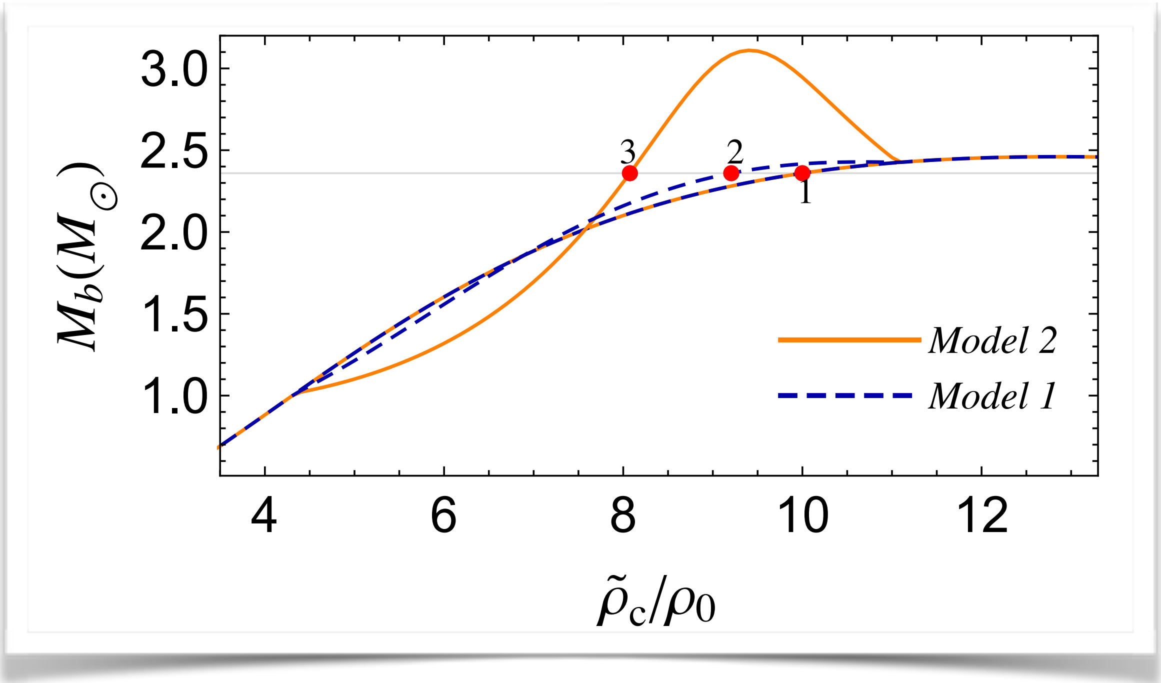

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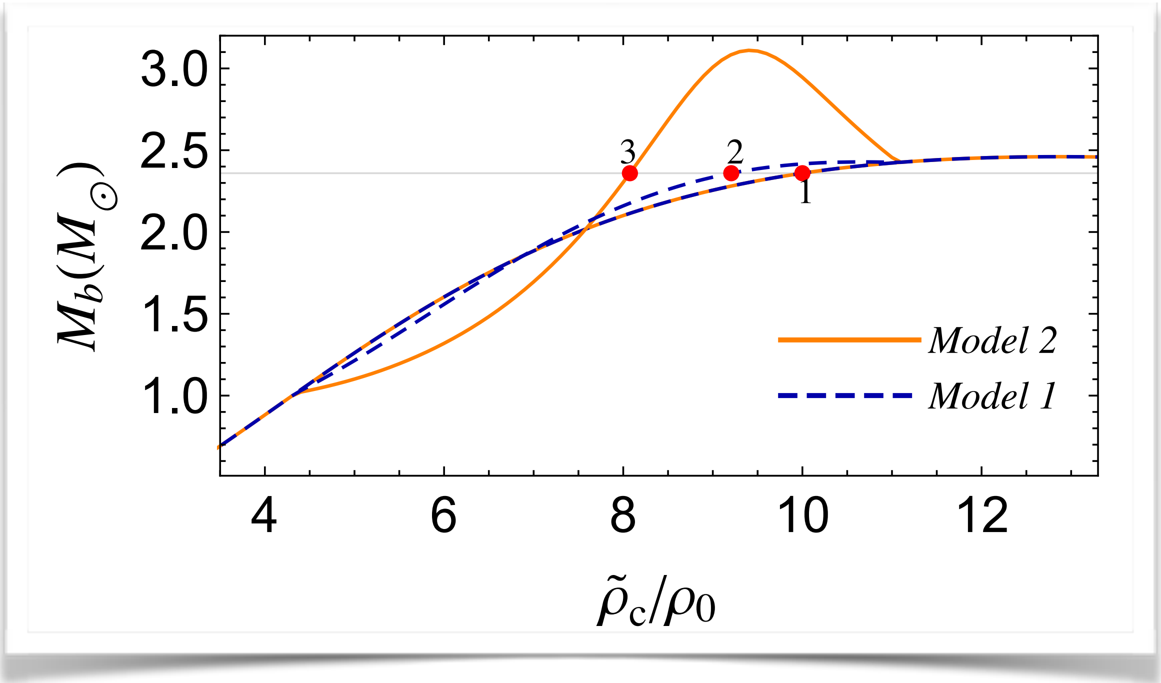

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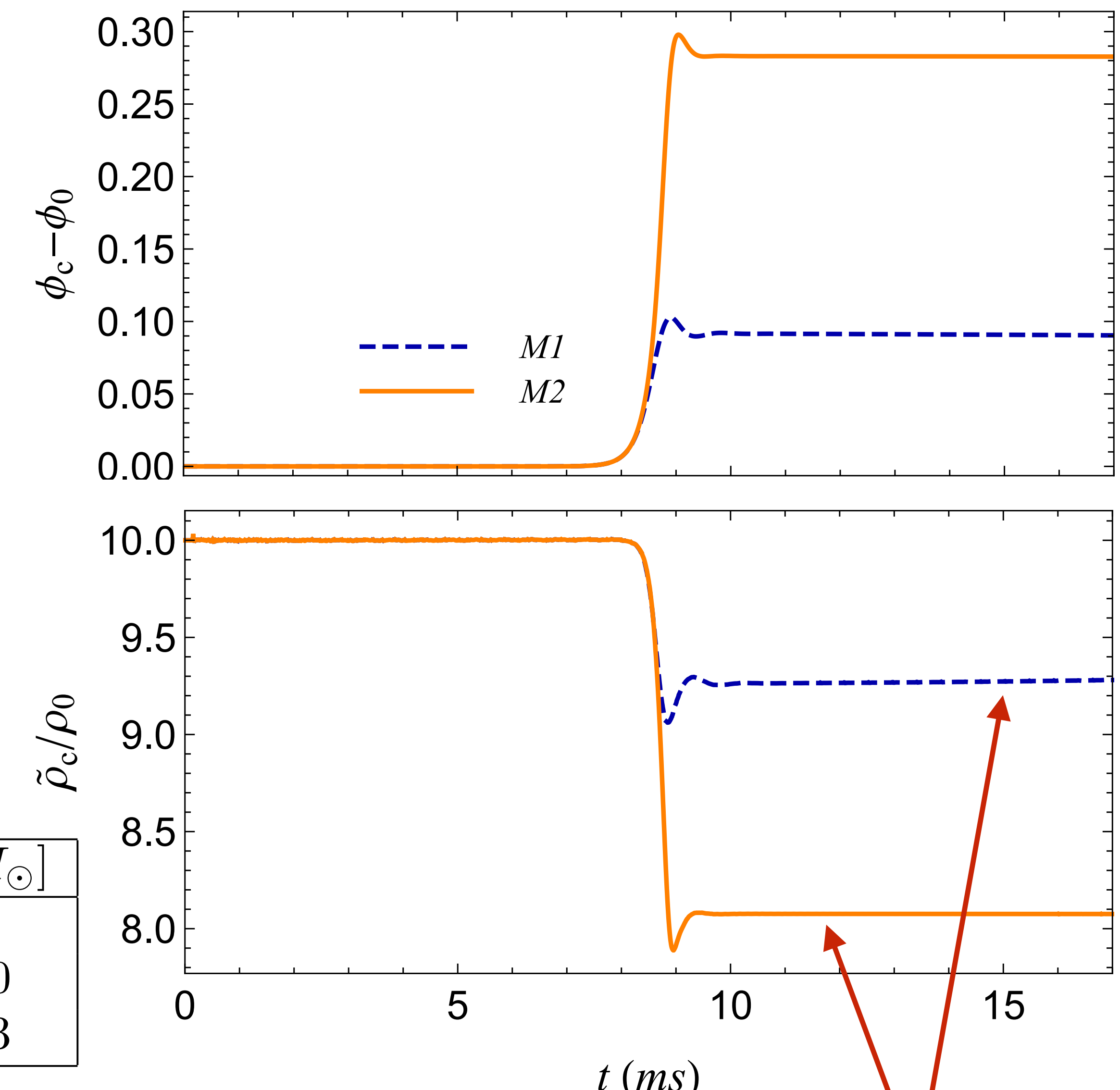

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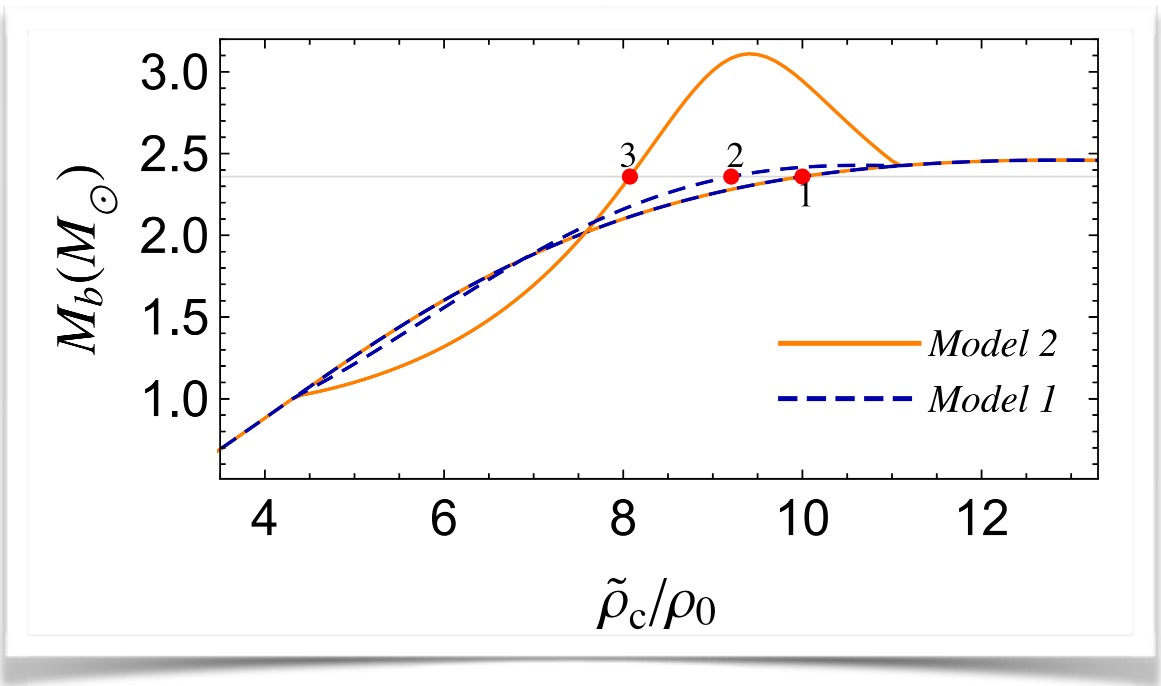

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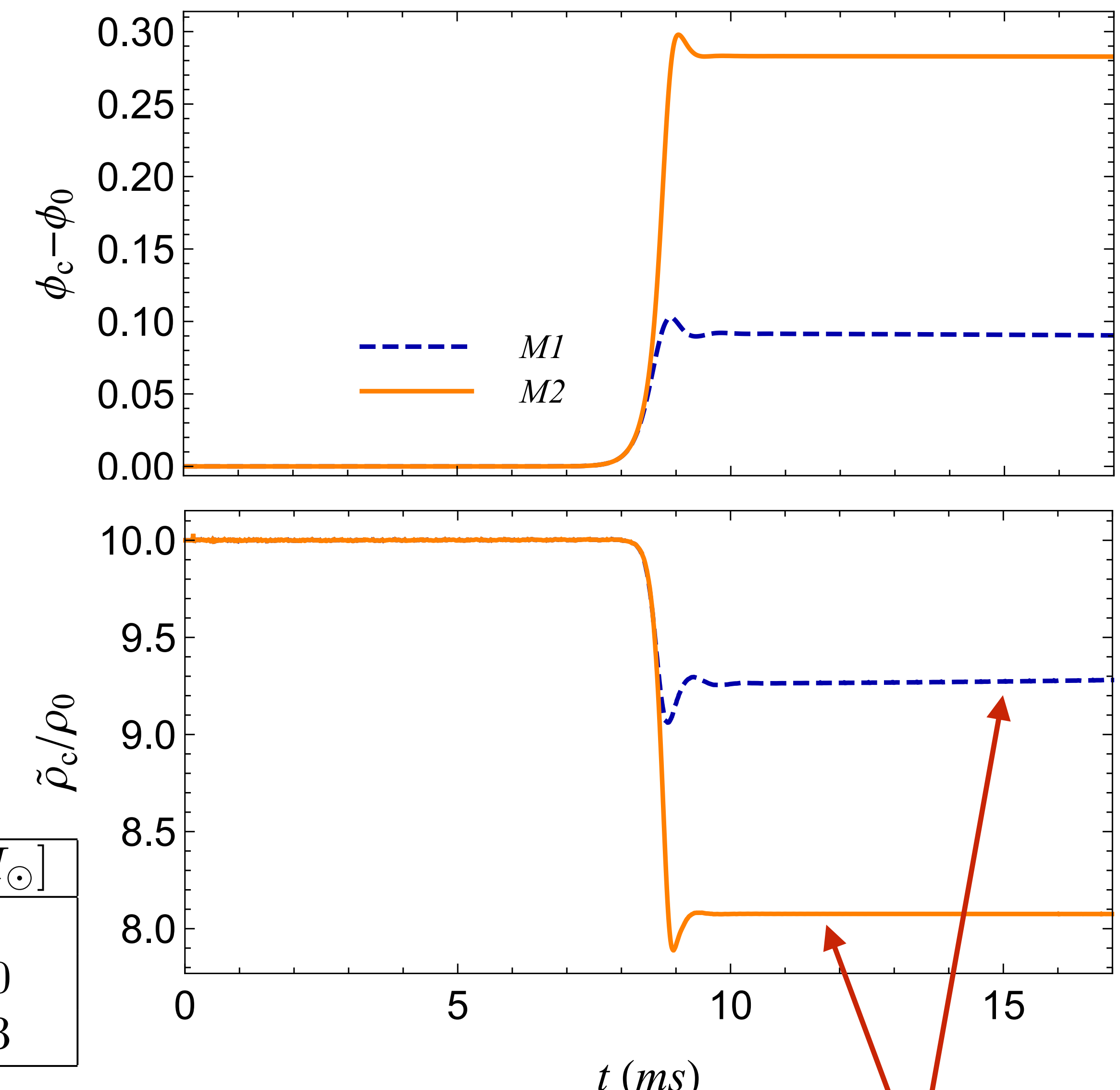

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Remark: The transition is generic regardless of the details of coupling function

New results

Exploring the $\beta > 0$ case

Model 1
(NMC field)

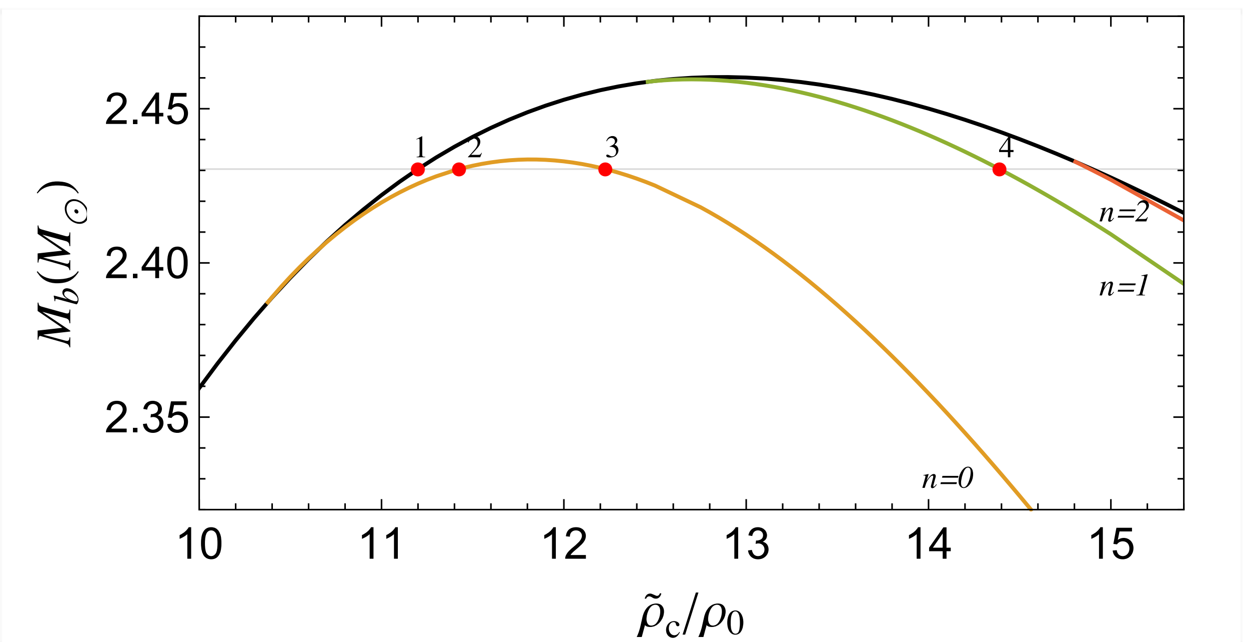

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Table 2: Some equilibrium solutions in M1 with $\beta = 100$. Solutions marked with stars are used as initial data for numerical simulations.

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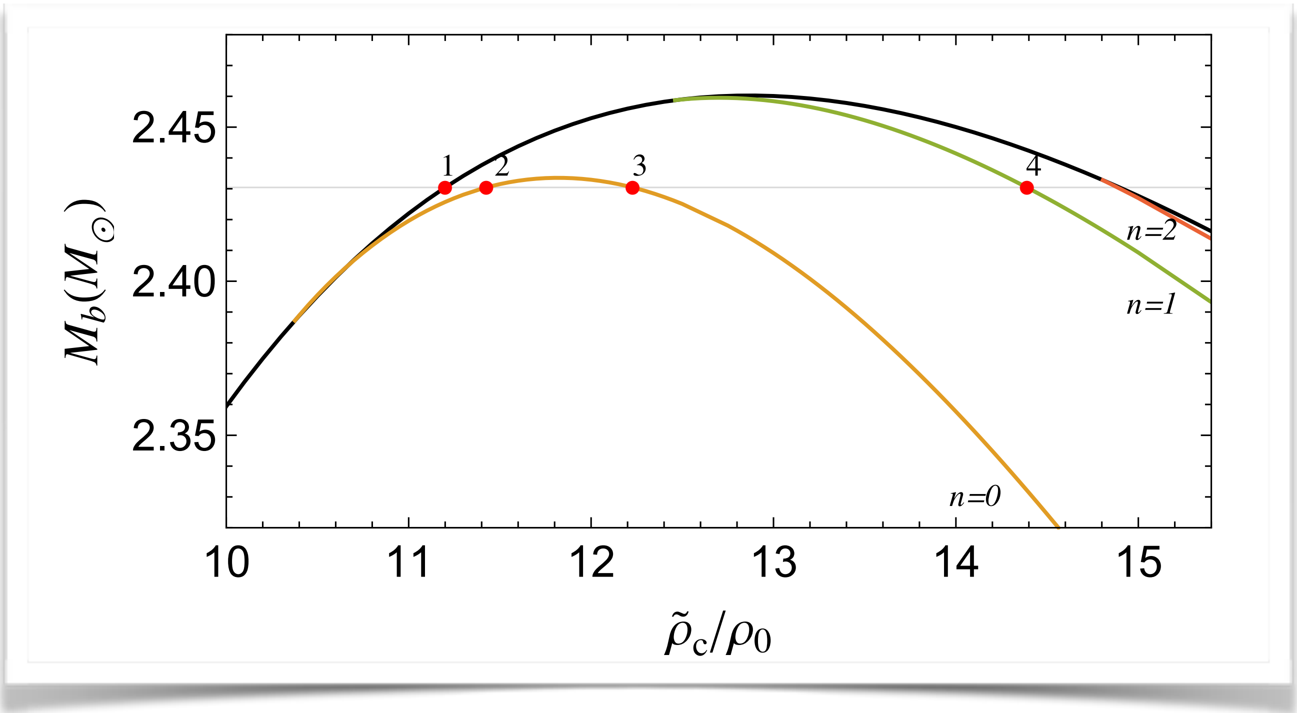

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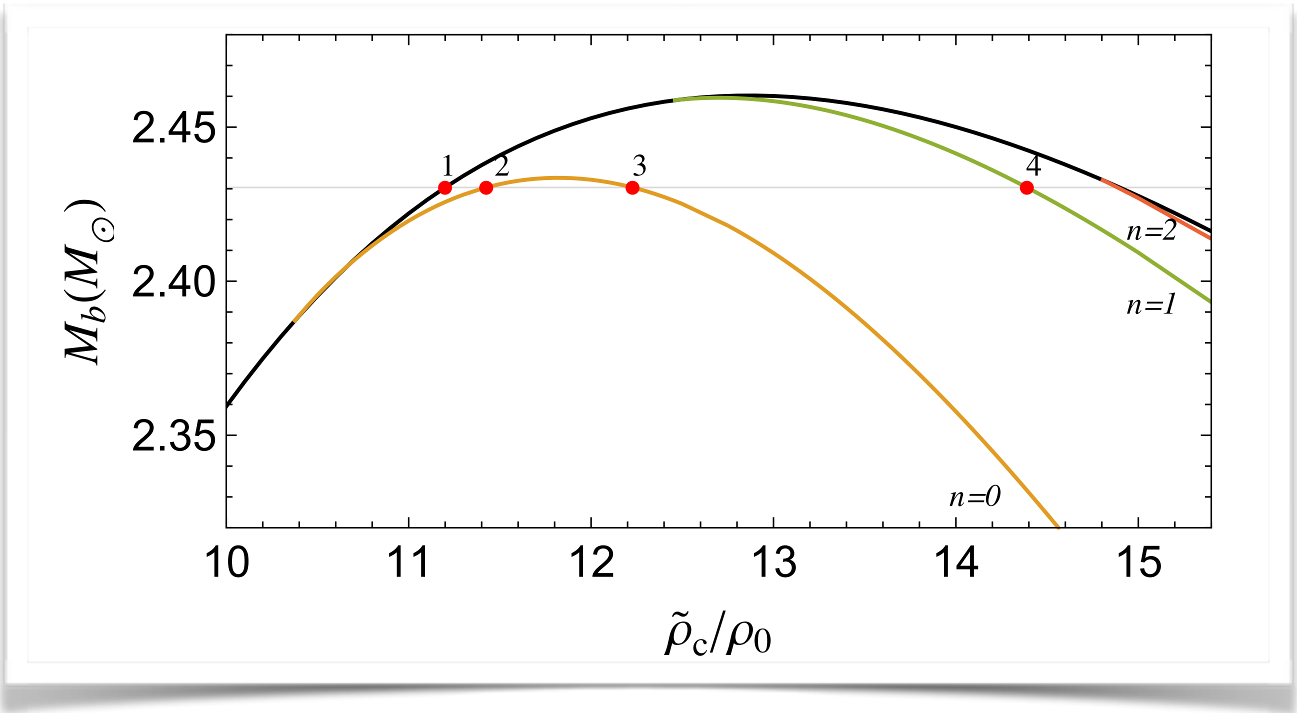

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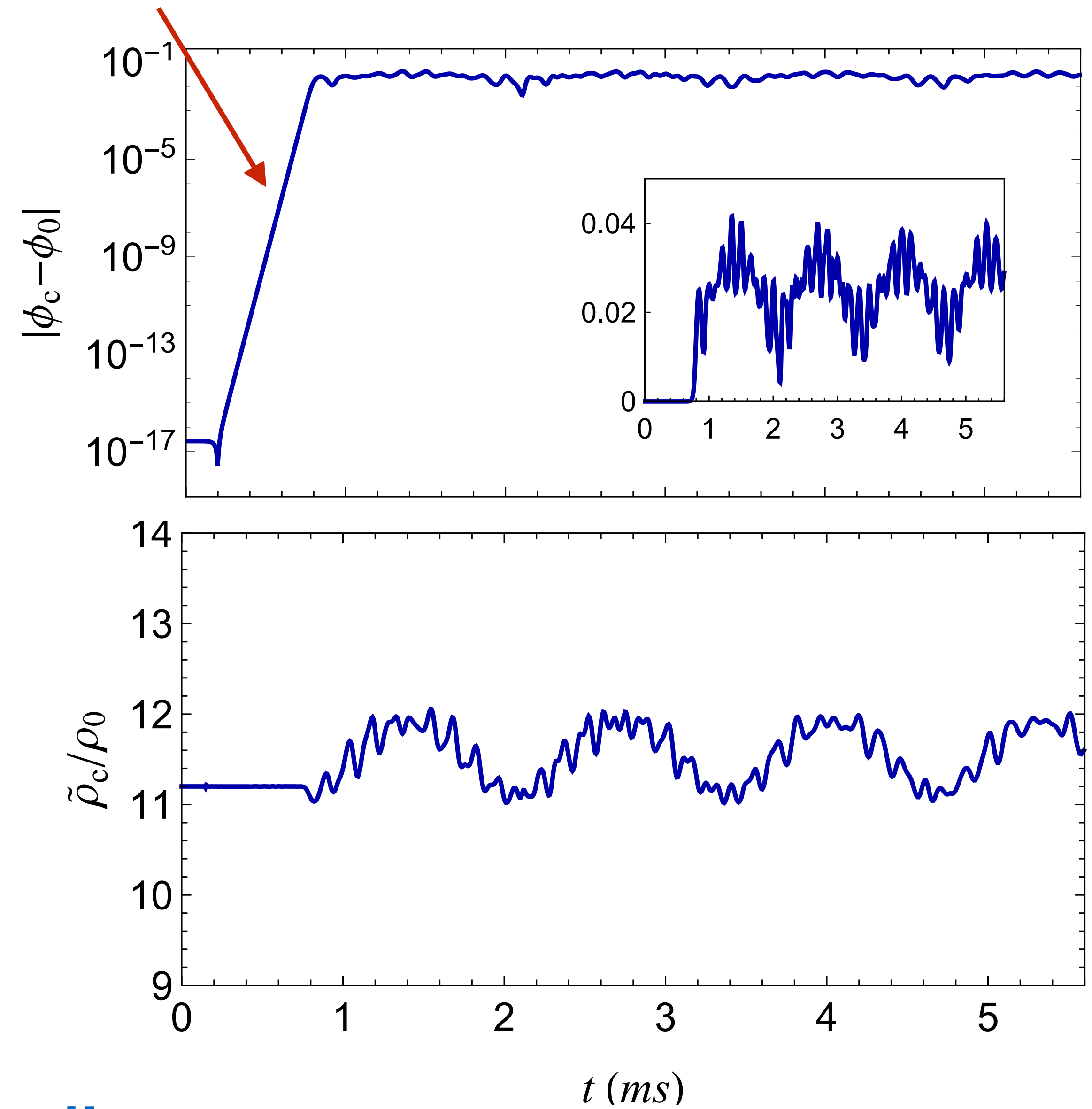
(consistent with solution 2 the Table 2)



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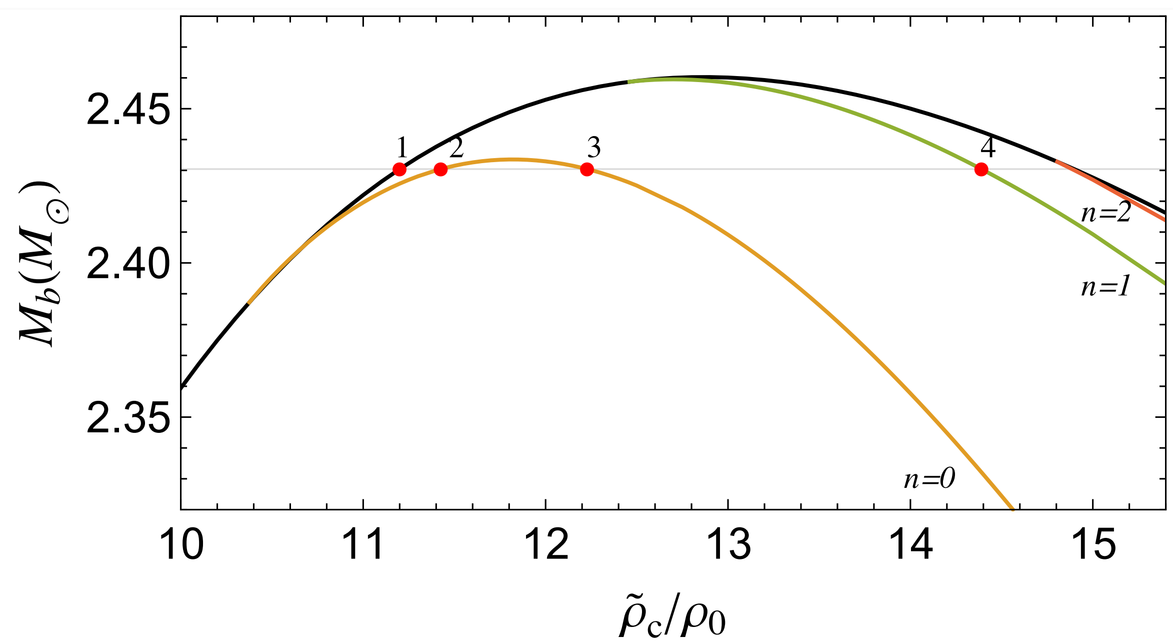

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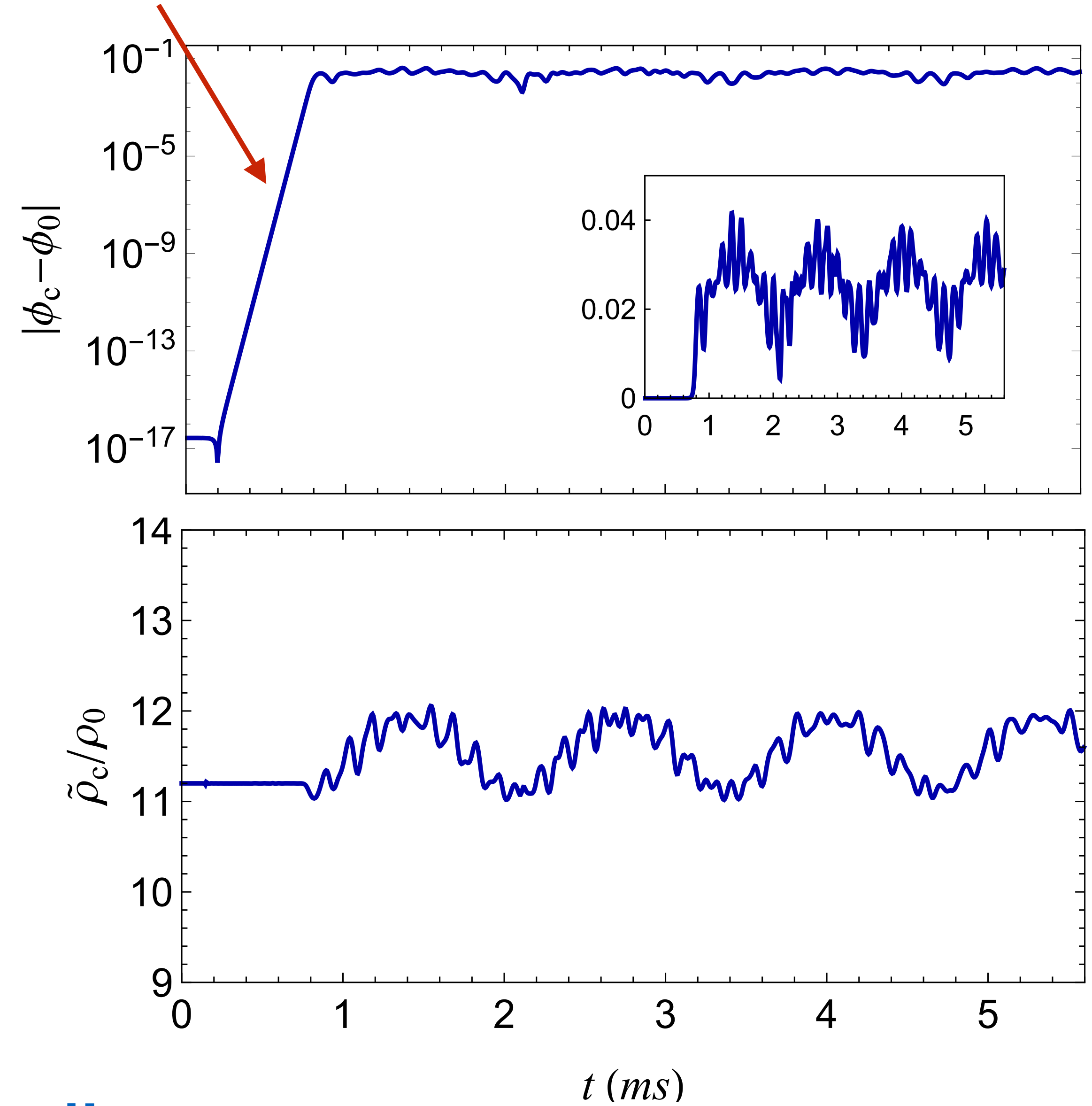

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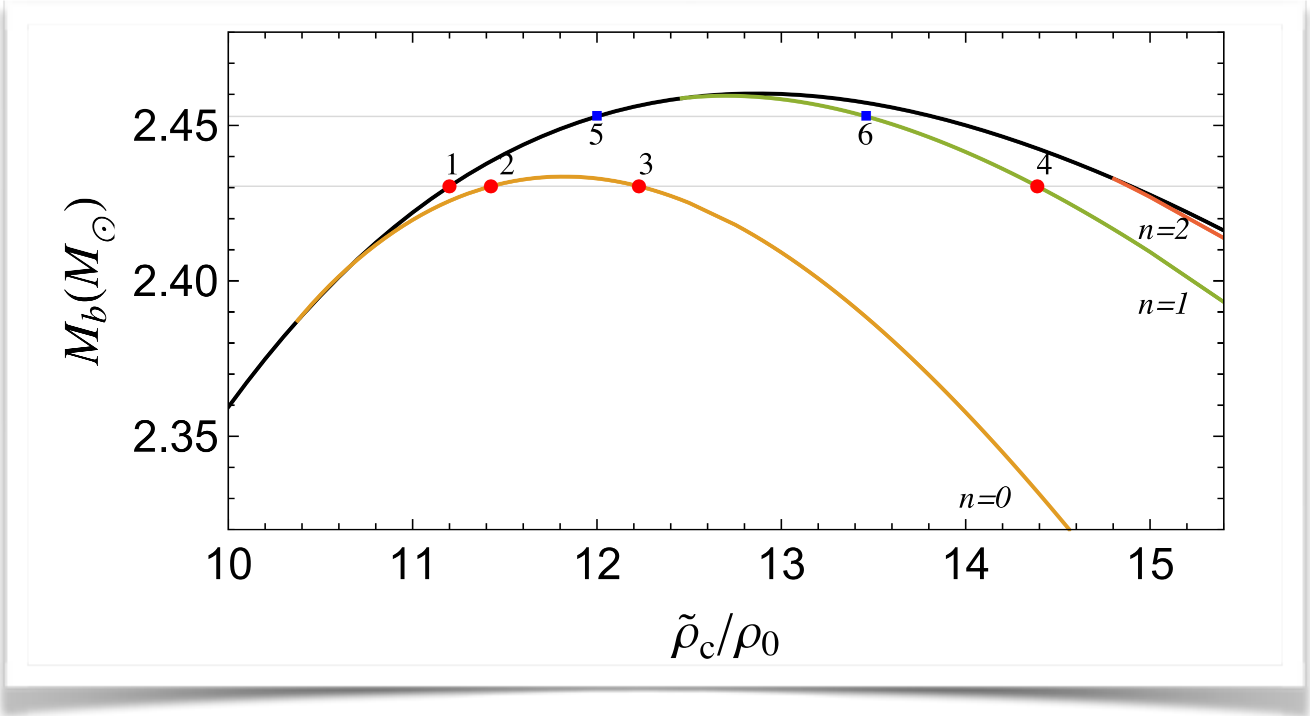

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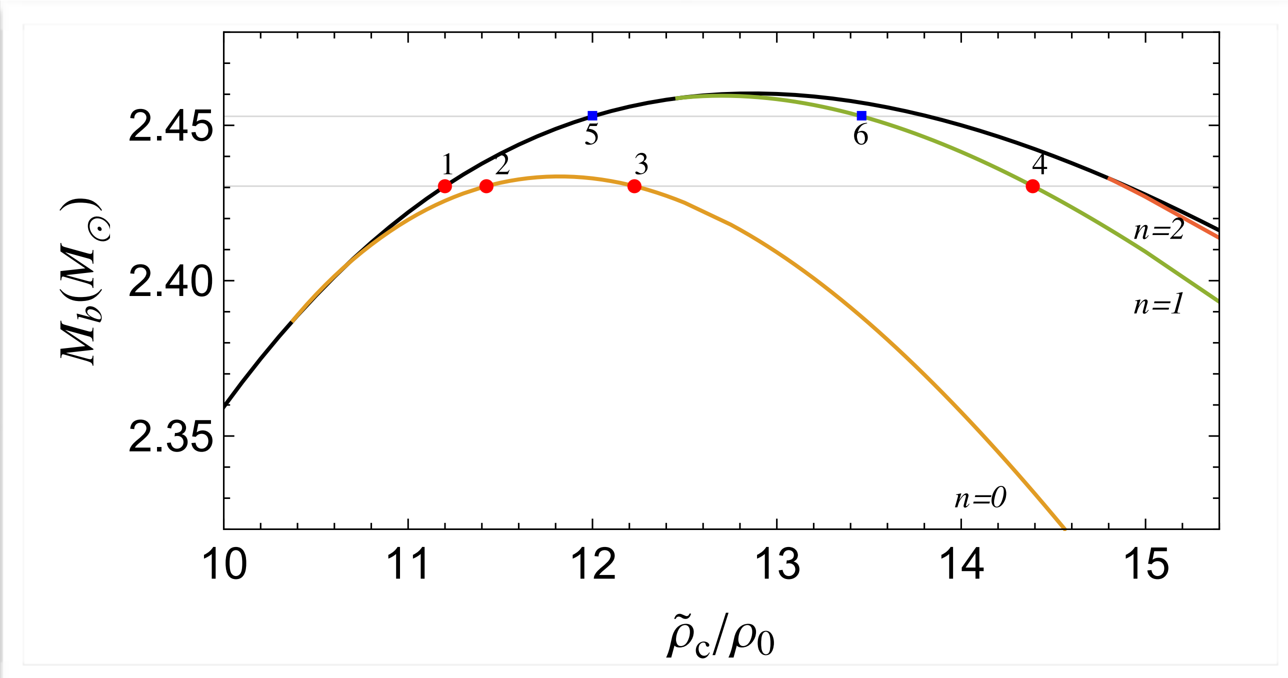

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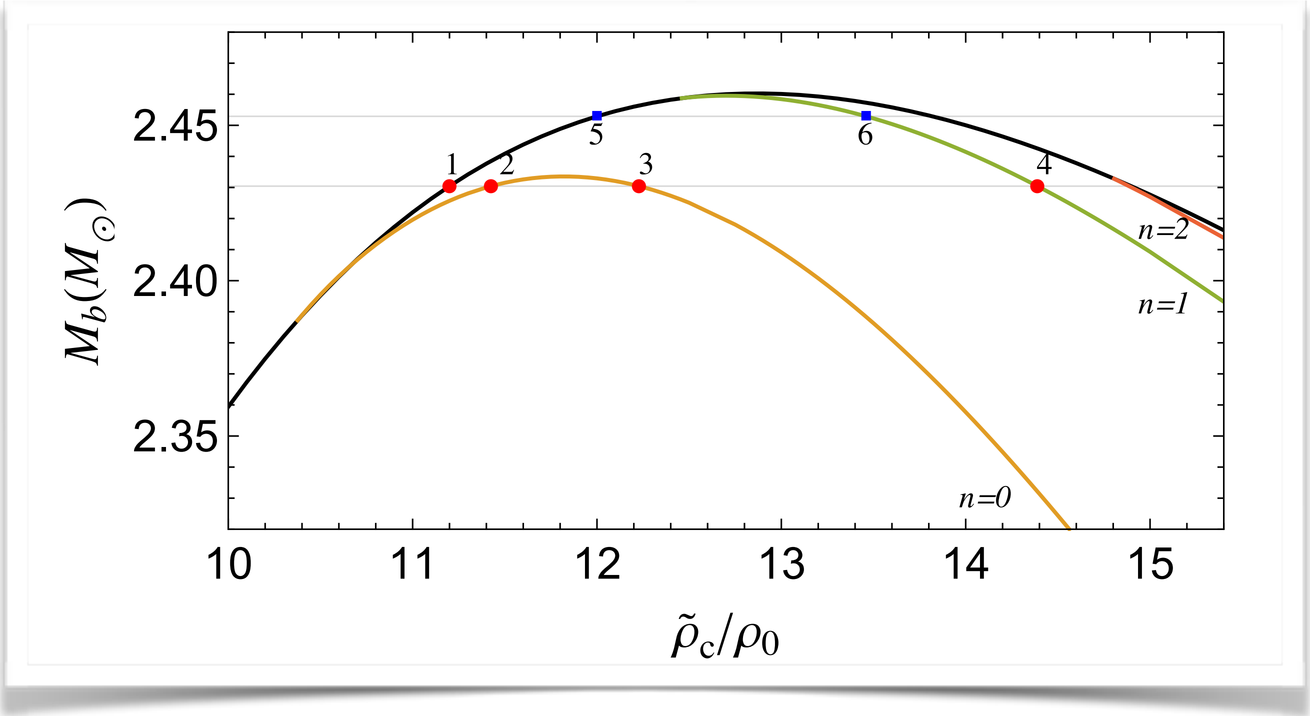
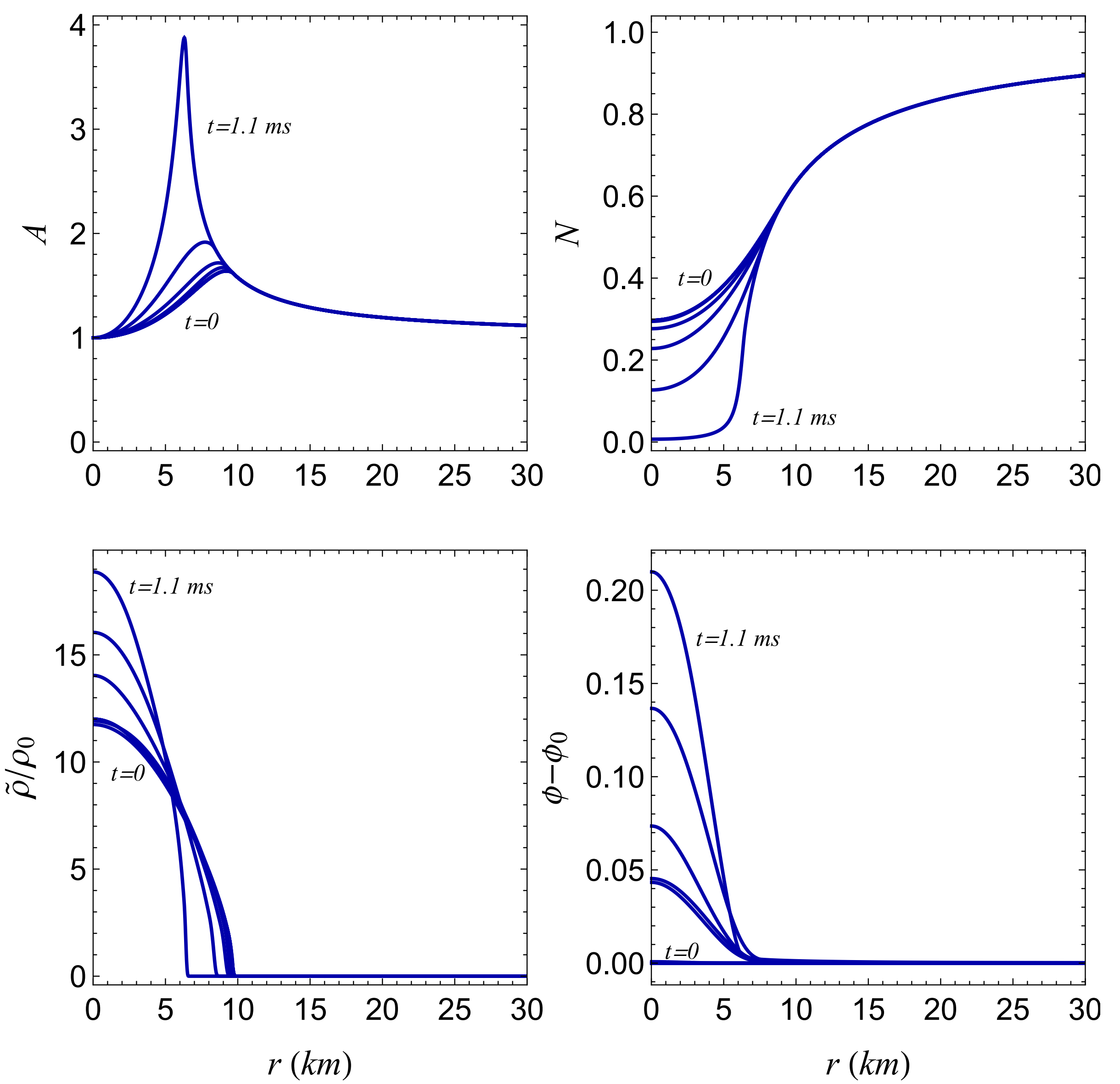


Gravitational collapse!



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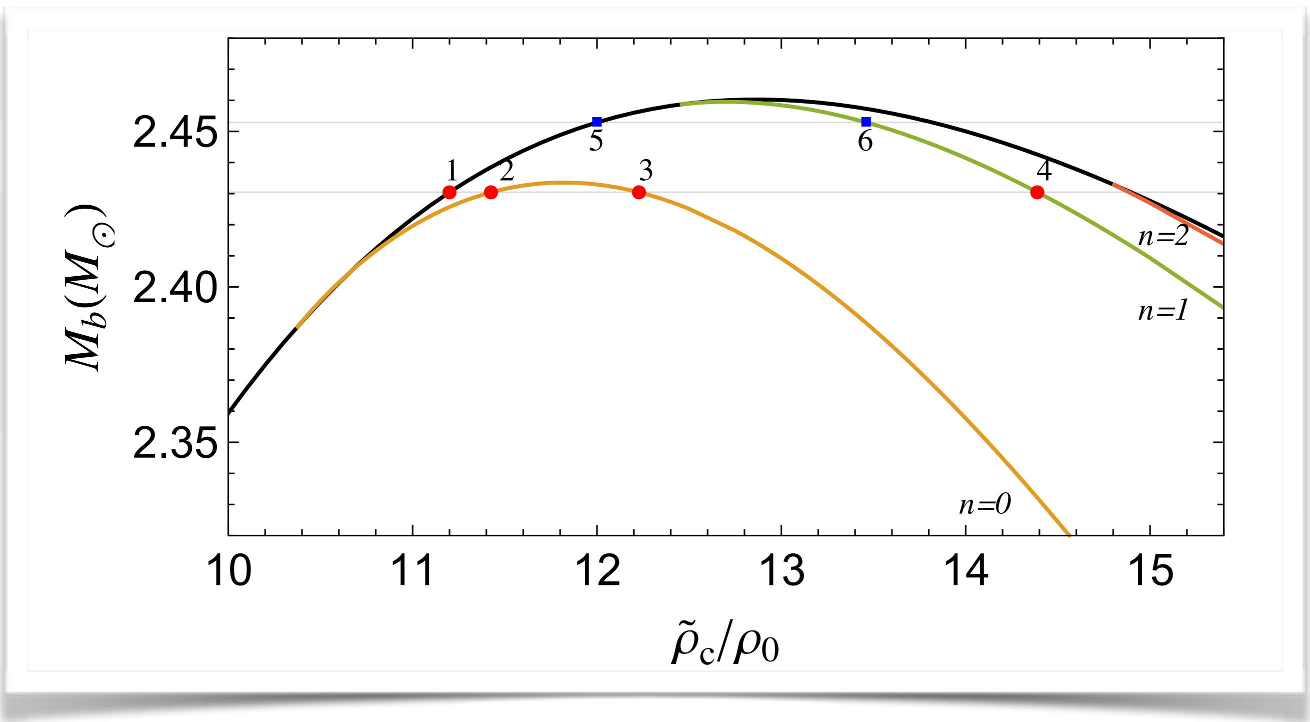

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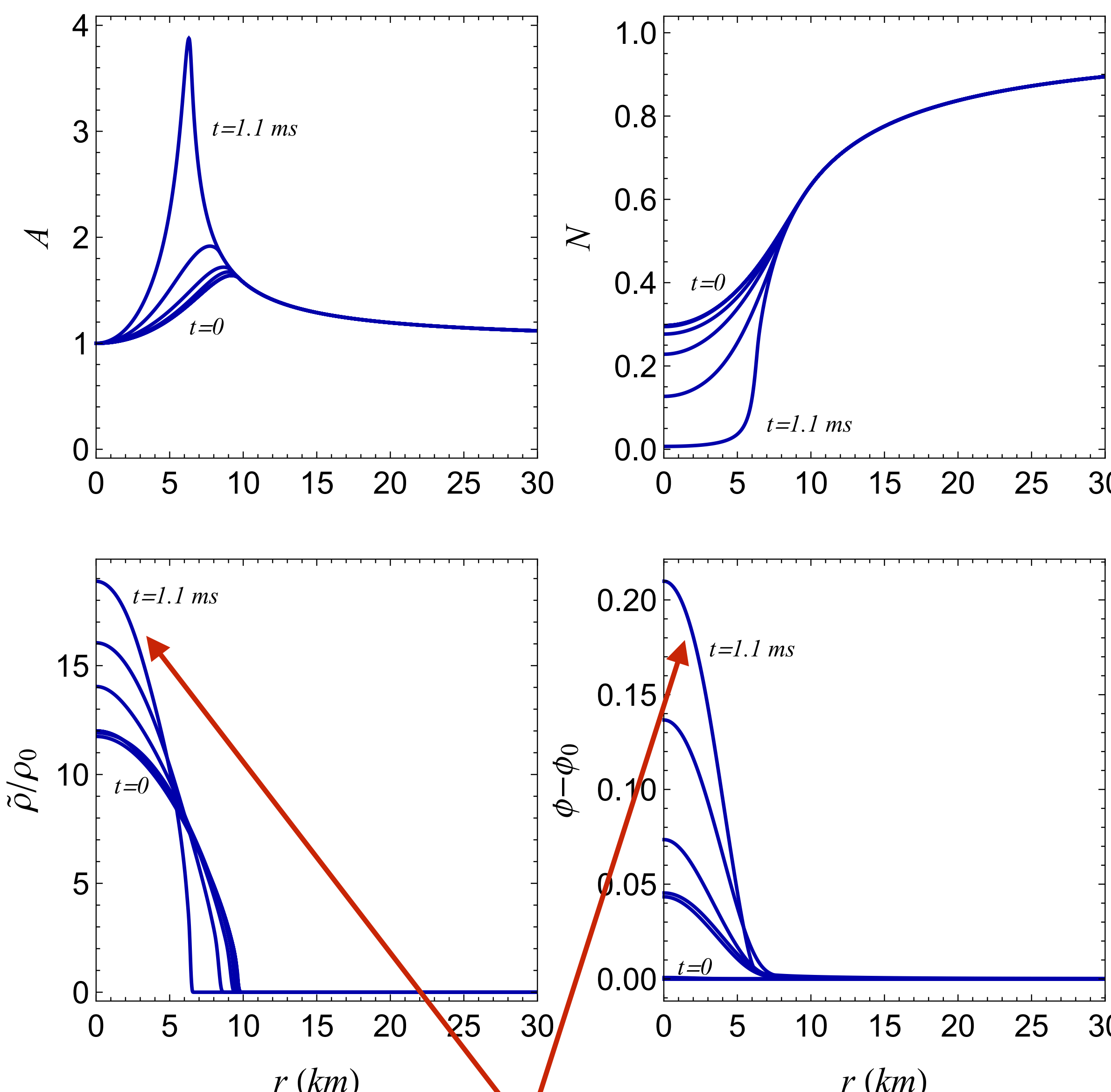

Unbounded growths in $r = 0$

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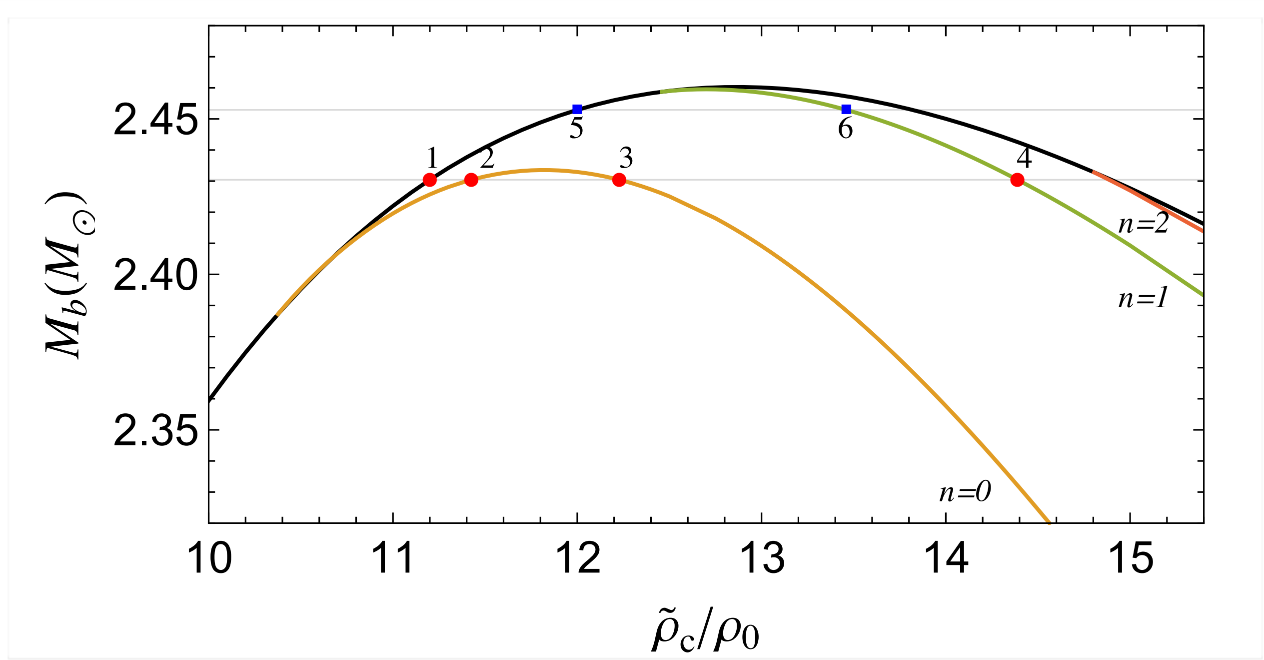
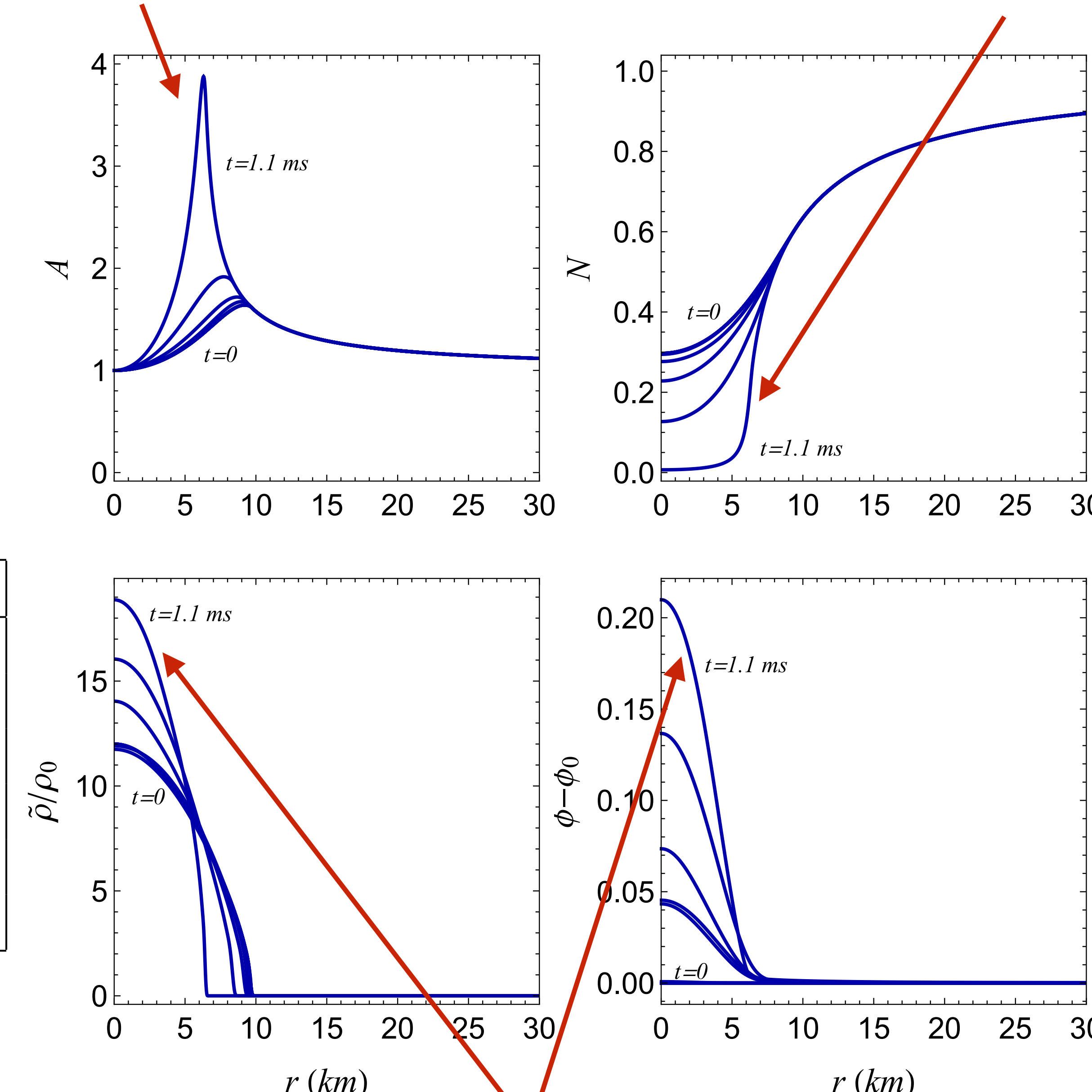


Gravitational collapse!

Slice stretching

Lapse function collapses



Solution	$\tilde{\rho}_c/\rho_0$	$M_b[M_\odot]$	$M[M_\odot]$	M/R_s	$\lvert\phi_c - \phi_0\rvert$
1*	11.20	2.4304	2.01058	0.302	0
2	11.4251	2.4304	2.01053	0.304	0.023159
3	12.2279	2.4304	2.01056	0.311	0.039036
4	14.3890	2.4304	2.01132	0.325	0.027827
5*	12.0	2.4529	2.02461	0.309	0
6	13.4600	2.4529	2.02469	0.320	0.017240

Table 2: Some equilibrium solutions in M1 with $\beta = 100$. Solutions marked with stars are used as initial data for numerical simulations.

Unbounded growths in $r = 0$

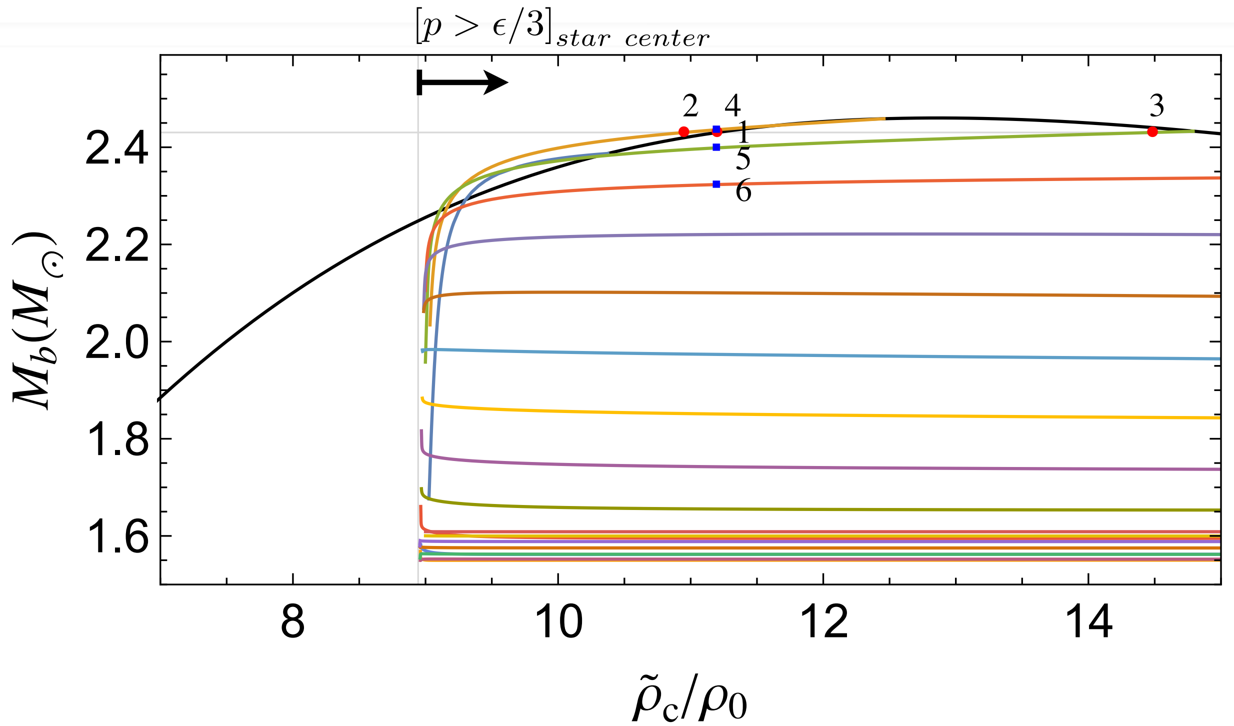
Solution 6 is energetically disfavored vs. solution 5: likely unphysical

New results

Exploring the $\beta > 0$ case

Model 2
(DEF)

(In agreement with C. Palenzuela and S. Liebling, 2016)



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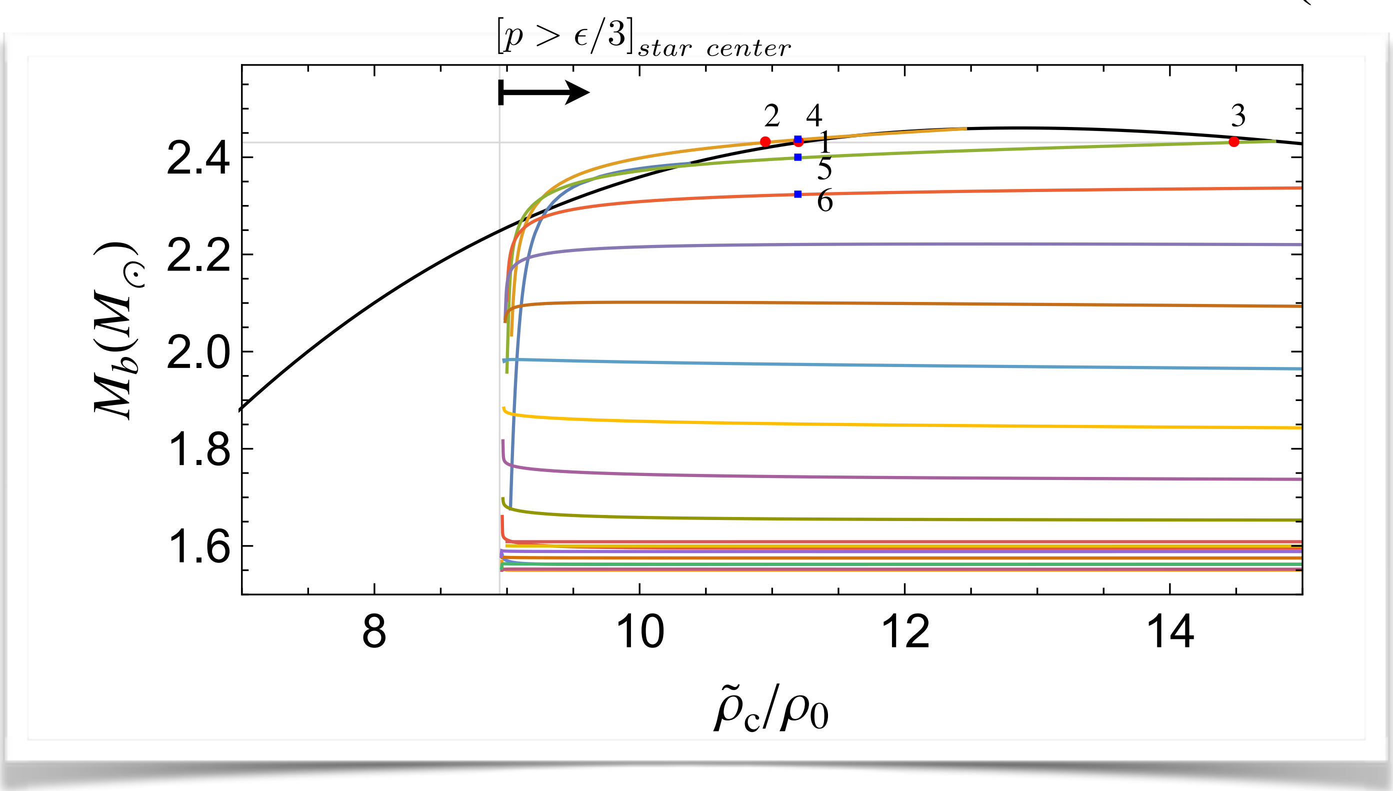

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1*	11.20	2.4304	2.01058	0.302	0
2	10.9493	2.4304	2.01087	0.312	0.055
3	14.4841	2.4304	2.01142	0.327	0.023
4*	11.20	2.43611	2.01435	0.313	0.050
5*	11.20	2.39877	1.99273	0.325	0.081
6*	11.20	2.32321	1.94928	0.332	0.104

Table 3: Some equilibrium solutions in M2 with $\beta = 100$. Solutions marked with stars are used as initial data for numerical simulations.

New results

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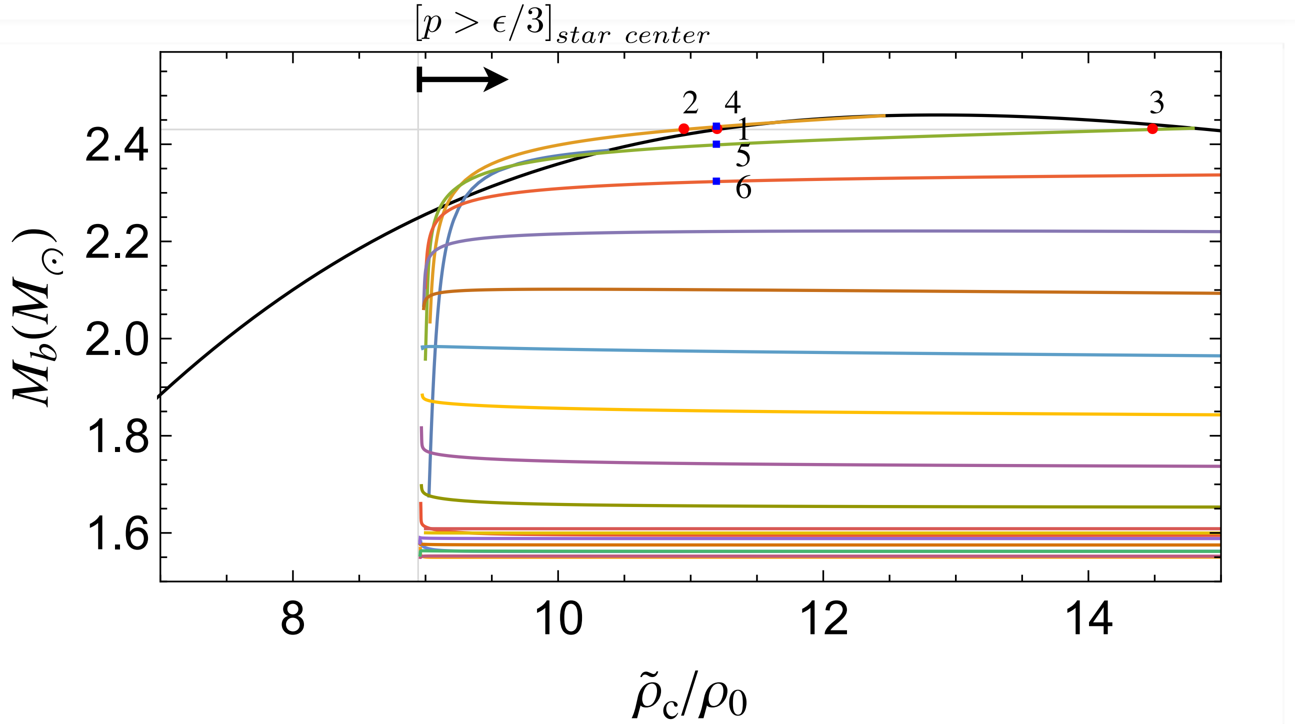

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Solutions 2 and 3 are energetically disfavored vs. solution 1: likely unphysical

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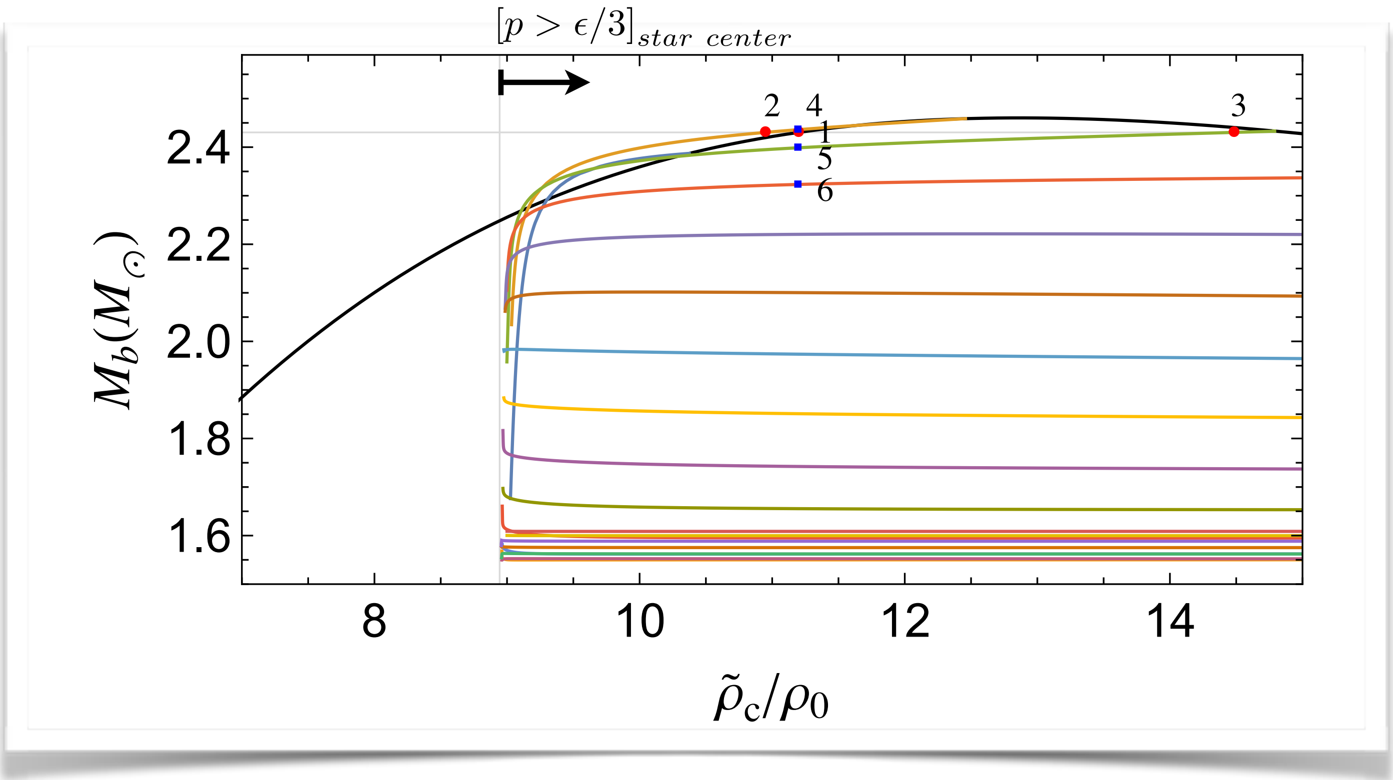
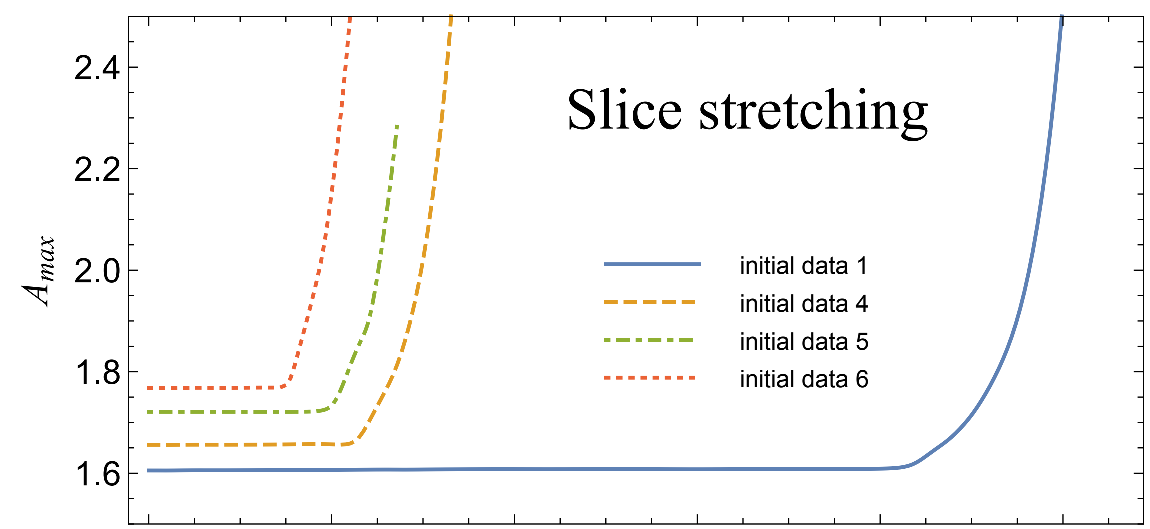
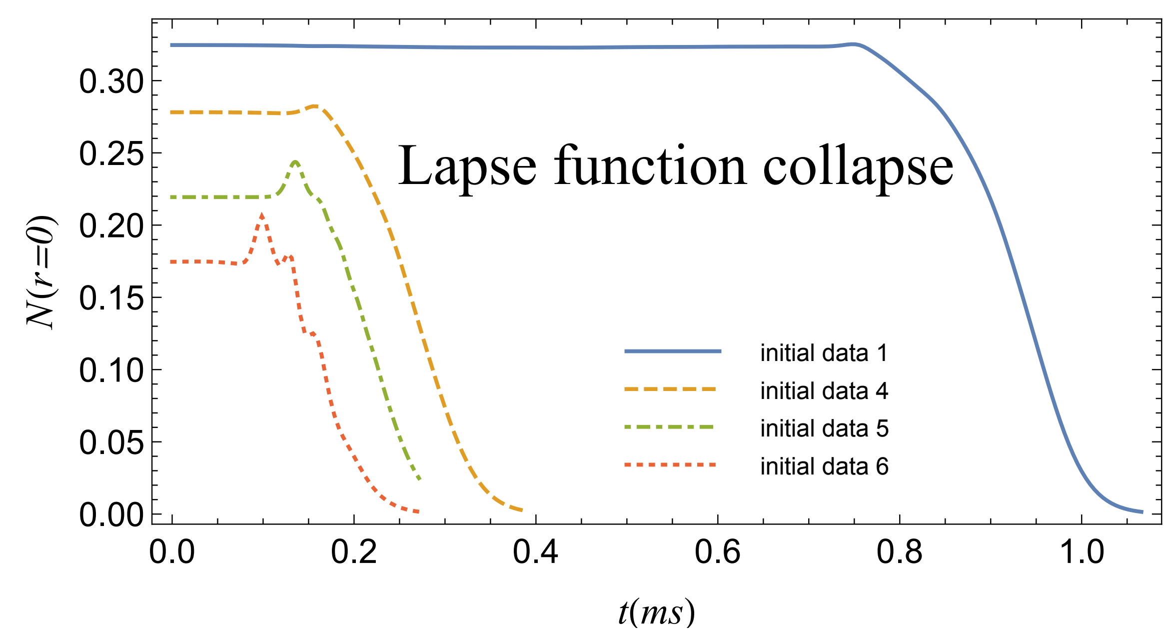


Gravitational collapse!





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Punch line:

First demonstration of spontaneous scalarization in STT with $\beta_0 > 0$

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Fell free to manipulate our plots is https://bitbucket.org/nestor_ortiz/highly-compact-neutron-stars-in-stts.git