NUMERICAL STUDY OF STELLAR COLLAPSE IN SCALAR-TENSOR THEORY

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Team

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Outline

- *ST Action and TOV ODEs*
- *Construct initial data*
- *Spontaneous scalarization*
- *Monopole Gravitational wave*
- *Suppression of massive scalar field*
- *Conclusion*

From GR to ST - Action

In scalar tensor theory,we set c=G=1

ST Action :

$$S = \int dx^4 \sqrt{-g}[\frac{F(\varphi)}{16\pi G}R - \frac{1}{2}g^{\mu\nu}(\partial_\mu\varphi)(\partial_\nu\varphi) - U(\varphi)] + S_m(\psi_m, g_{\mu\nu})$$

conformal transformation :

$$\tilde{g}_{\mu\nu} = Fg_{\mu\nu},\ \frac{\partial\phi}{\partial\varphi} = \sqrt{\frac{3}{4}\frac{F^2_{,\varphi}}{F^2} + \frac{4\pi G}{F}}$$

Coupling function :

$$F(\phi) = e^{(-2\alpha_0(\phi-\phi_0)-\beta_0(\phi-\phi_0)^2)},\ \alpha_0 = -\frac{1}{2}\frac{\partial lnF}{\partial\phi},\ \beta_0 = -\frac{1}{2}\frac{\partial^2 lnF}{\partial^2\phi}$$

Potential of massive scalar field :

$V(\phi) = \frac{\mu^2}{\hbar^2}\frac{\phi^2}{2} + \lambda\phi^4$ (we have some discussion with Pro. Geng and Dr. Luo)

Source: "Numerical simulations of stellar collapse in scalar-tensor theories of gravity", Davide Gerosa, Ulrich Sperhake,Christian D. Ott,

From GR to ST - The line element

restrict the equations of motion to spherical symmetry in radial-gauge, polar-slicing coordinates

$\underline{GR :}$

$$ds^2 = -e^{2\phi(r)}c^2dt^2 + (\frac{rc^2}{rc^2-2Gm(r)})dr^2 + r^2d\Omega^2$$

$\underline{ST :}$

$$ds^2 = -\alpha^2dt^2 + \frac{r}{F(r-2m)}dr^2 + \frac{r^2}{F}d\Omega^2$$

Source: ”Numerical simulations of stellar collapse in scalar-tensor theories of gravity”, Davide Gerosa, Ulrich Sperhake,Christian D. Ott,

arXiv, 1602.06952.

TOV ODEs in GR

in static equilibrium
polytropic EOS : $\rho = (p/K)^{1/\gamma}$
specific internal energy : $\epsilon = \frac{p}{(\gamma-1)\rho}$
ODEs :

$$\frac{dp}{dr} = -G(\rho(1+\epsilon/c^2) + p/c^2)\frac{d\phi}{dr}$$

$$\frac{dm}{dr} = 4\pi r^2 \rho(1+\epsilon/c^2)$$

$$\frac{d\phi}{dr} = \frac{m+4\pi r^3 p/c^2}{r(r-2Gm/c^2)}$$

$$\frac{dm_{bary}}{dr} = \frac{4\pi r^2 \rho}{\sqrt{1-\frac{2Gm}{rc^2}}}$$

Source: "https://en.wikipedia.org/wiki/Tolman

Modified TOV ODEs in ST

$$\textit{polytropic EOS}: \rho = (p/K)^{1/\Gamma}$$
$$\textit{Coupling function}: F = e^{(-2\alpha_0(\phi-\phi_0)-\beta_0(\phi-\phi_0)^2)}$$
$$\textit{derived from enclosed mass}: X = (\frac{r}{F(r-2m)})^{\frac{1}{2}}$$
$$\textit{specific internal energy}: \epsilon = \frac{K_1}{\Gamma_1-1}\rho^{\Gamma_1-1}$$
$$h = 1+\epsilon+\frac{P}{\rho}$$
$$\textit{ODEs}:$$
$$\frac{d\Phi}{dr} = FX^2(\frac{m}{r^2}+4\pi r\frac{P}{F^2}+\frac{r}{2F}\eta^2)$$
$$\frac{dm}{dr} = 4\pi r^2\frac{\rho h-P}{F^2}+\frac{r^2}{2F}\eta^2$$
$$\frac{dP}{dr} = -\rho hFX^2(\frac{m}{r^2}+4\pi r\frac{P}{F^2}+\frac{r}{2F}\eta^2)+\rho h\frac{F_{,\phi}}{2F}X\eta$$
$$\frac{d\phi}{dr} = X\eta$$
$$\frac{d\eta}{dr} = -2\frac{\eta}{r}-2\pi X\frac{\rho h-4P}{F^2}F_{,\phi}-\eta FX^2(\frac{m}{r^2}+4\pi r\frac{P}{F^2}+\frac{r}{2F}\eta^2)+\frac{XF_{,\phi}}{2F}\eta^2$$

Source: ”Numerical simulations of stellar collapse in scalar-tensor theories of gravity”, Davide Gerosa, Ulrich Sperhake,Christian D. Ott, *arXiv*, 1602.06952.

Compare ST with GR in Python

This result confirms that GR is recovered from ST for $\phi = 0$ (F=1), as a trivial limit of the ST TOVs.

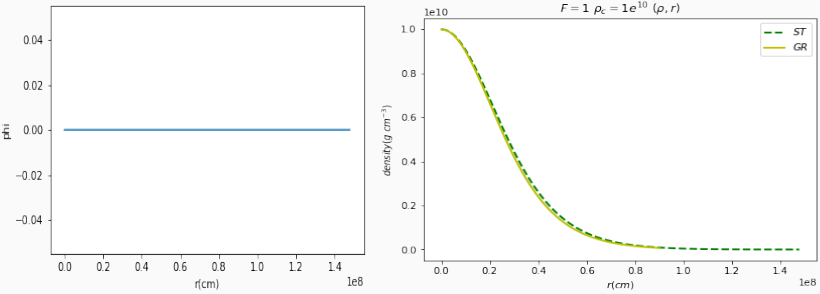


Figure: *scalar field* $\phi = 0, \rho_{ST} = \rho_{GR}$

Different initial conditions

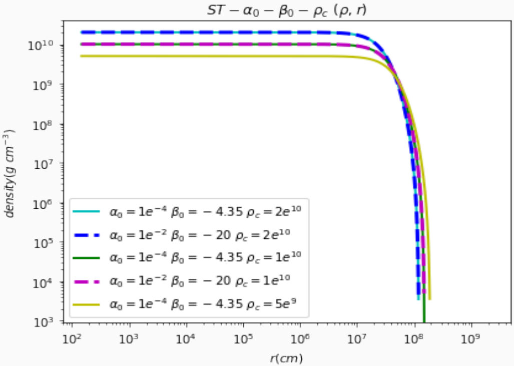


Figure: *density* ρ

Different initial conditions

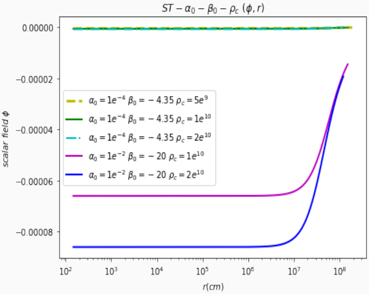


Figure: *scalar field* ϕ

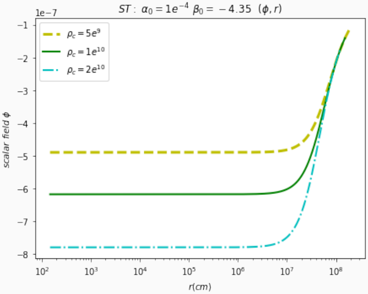


Figure: *scalar field* ϕ

Modified GR1D

- Simulate stellar collapse
- Parameters:
  - μ : the mass of the scalar field
  - λ : a coupling constant for the self-interaction
  - α_0, β_0 : parameters for the coupling function $F(\phi)$
  - Γ_1, Γ_2 : adiabatic indices for subnuclear, supranuclear polytropic EOS
  - Γ_{th} : the thermal adiabatic index for the thermal part pressure which models a mixture of relativistic and non-relativistic gas

Source: "A New Open-Source Code for Spherically-Symmetric Stellar Collapse to Neutron Stars and Black Holes",Evan O'Connor, Christian D. Ott , *arXiv*, 0912.2393.

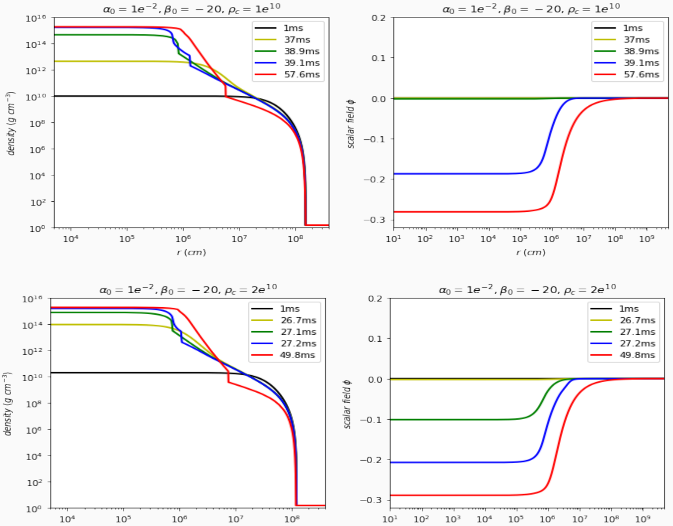
"Long-lived inverse chirp signals from core collapse in massive scalar-tensor gravity", *arXiv*, 1708.03651 [gr-qc], *PhysRevLett.*, 119.201103

Different α_0, β_0 can also cause some little variation of mass.

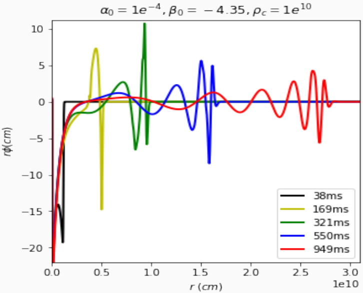
	Profile 1	Profile 2	Profile 3	Profile 4
$\rho\ (g \cdot cm^{-3})$	$1e^{10}$	$1e^{10}$	$2e^{10}$	$2e^{10}$
α_0	0.01	0.0001	0.01	0.0001
β_0	-20	-4.35	-20	-4.35
m ($M_\odot$)	1.4326(7)	1.4329(3)	1.4260(3)	1.4263(0)

Table: The energy of the massive scalar field in this study is $3 * 10^{-14} eV$

SPONTANEOUS SCALARIZATION



The monopole scalar wave in ST : $h(t) = \frac{2}{D}\alpha_0 r(\phi - \phi_0)$, where D is the distance between the detector and the source.



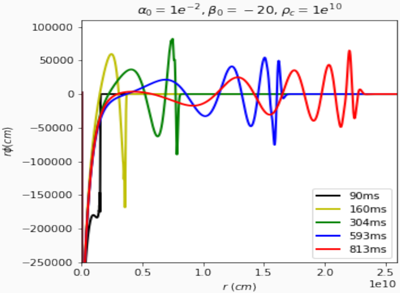


Figure: The emitted monopole gravitational waveform is take as $h(t) \propto r\phi$. Also, the Γ_{th} is 1.35.

Suppression of massive scalar field

Reduce the amplitude of the scalar field, GW signals and memory effect.

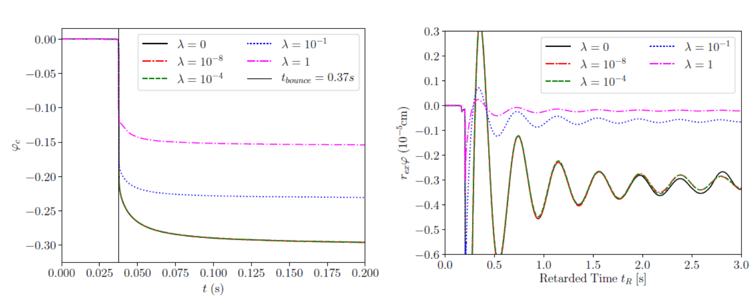


Figure: The scalar field $\phi(r, t)$ is at center of star and waveform $r\phi$ are extracted at $5 * 10^9$ (cm).

Source: "Numerical Studies on Core Collapse Supernova in Self-interacting Massive Scalar-Tensor Gravity",Patrick Chi-Kit Cheong, Tjonnie Guang Feng Li,*arXiv*: 1812.04835[gr-qc]

Conclusions

- Matter of star has some connections with scalar field.
- Spontaneous scalarization and the monopole gravitational waves occur in stellar core collapse.
- The compact degree of star can accelerate spontaneous scalarization.
- Self-interaction of massive scalar field suppress spontaneous scalarization and amplitude of GW signals and memory effect.
- LIGO-VIRGO detection and other ongoing process.

Thank You!