Core collapse and compact-object formation to test General Relativity

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Outline

1. **Why** scalar-tensor theory?
2. Action, equations, **numerics**
3. **Core collapse** and GW breathing mode
4. Ongoing: EOS, polarizations, massive field
Why testing GR?

~1919:
Journalist: “Herr Einstein, what if the theory turned out to be wrong?”
Einstein: “I would feel sorry for the dear Lord. The theory is correct.”

Theory:
• Where is quantum mechanics?
• Are there really singularities around?

Puzzling observations:
• Dark energy makes up most of the Universe
• Why is Lambda so small?

Tests
• GR is extremely well tested “in between” these two regimes $1 \text{ mm} \lesssim L \lesssim 1 \text{ AU}$

Extreme challenge for theorists
Why scalar-tensor theory?

Damour and Esposito-Farese 1992

- Modifications of GR from high-energy theory often lead to the introduction of **additional degrees of freedom** (Lovelock theorem)
  
  see eg. Sotiriou et al 2007

- **Scalar-tensor theories**: gravity mediated by the metric and one additional scalar field

- Some high-energy theories predict GR + scalars as their low-energy limit.
  
  cf e.g. review by Will 2014

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**Complicated enough**

to introduce testable modifications (e.g. the Eddington PPN parameters)

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**Simple enough**

to work out predictions (and even do full numerical simulations)
A tale of two formulations

**Jordan frame**

\[
S = \int dx^4 \sqrt{-g} \left[ \frac{F(\phi)}{16\pi} R - \frac{1}{2} g^{\mu\nu} (\partial_\mu \phi)(\partial_\nu \phi) - V(\phi) \right] + S_m(\psi_m, g_{\mu\nu})
\]

**The most general action...**

1. single scalar field coupled non-minimally
2. invariant under space-time diffeomorphisms
3. at most two space-time derivatives
4. satisfy the Weak Equivalence Principle (WEP)

**Moreover...**

1. Vanishing potential \( V(\phi) = 0 \)
2. **Coupling function** \( F = F(\phi) \)
3. Note the WEP!

**Conformal transformation:** \( \bar{g}_{\mu\nu} = F g_{\mu\nu} \)

**Einstein frame**

\[
S = \frac{1}{16\pi} \int dx^4 \sqrt{-\bar{g}} \left[ \bar{R} - 2\bar{g}^{\mu\nu} (\partial_\mu \varphi)(\partial_\nu \varphi) \right] + S_m[\psi_m, \bar{g}_{\mu\nu}/F]
\]
Dominant corrections to GR

**1PN corrections** in ST theories depend on two parameters only:

\[
\varphi_0 = \lim_{r \to \infty} \varphi
\]

\[
\alpha_0 = -\frac{1}{2} \left. \frac{\partial \log F}{\partial \varphi} \right|_{\varphi=\varphi_0}
\]

\[
\beta_0 = -\frac{1}{2} \left. \frac{\partial^2 \log F}{\partial \varphi^2} \right|_{\varphi=\varphi_0}
\]

**Experimental constraints**

Let's take this subset of ST theories

**coupling function**

\[
F = \exp \left[ -2\alpha_0 (\varphi - \varphi_0) - \beta_0 (\varphi - \varphi_0)^2 \right]
\]
Slowly rotating solutions particular case of the action recovers the usual minimally coupled massless scalar. The theory above can be obtained as a classical nature of the approximation were studied by Damour and Esposito-Farèse 1993, 1996. Spontaneous scalarization discussed above this quantum instability can be interpreted in terms of the spontaneous scalarization discussed and Damour and Esposito-Farese 1993, 1996.

Deviation from GR involves at least two factors between matter and the scalar field to be weak. On the other hand, constants built from the coefficients of a non-minimally coupled scalar field to be large enough, it is energetically favorable to have strongly coupled to two scalar fields. The body becomes thus strongly coupled to two scalar fields.

Perturbative corrections enters as…

$$\alpha_0^2 \times \left[ \lambda_0 + \lambda_1 \frac{Gm}{Rc^2} + \lambda_2 \left( \frac{Gm}{Rc^2} \right)^2 + \ldots \right]$$

If $$\alpha_0 \sim 0$$ the theory is perturbative equivalent to GR, but if $$\frac{Gm}{Rc^2} \sim 0.2$$ (so, neutron stars!)

**Strong-field non-linearities!**

**Fundamental threshold:**

$$\beta_0 \lesssim -4.35$$
Hydrodynamics in ST theories

Jordan frame

\[ S = \int dx^4 \sqrt{-g} \left[ \frac{F(\phi)}{16\pi} R - \frac{1}{2} g^{\mu\nu} (\partial_\mu \phi)(\partial_\nu \phi) - V(\phi) \right] + S_m(\psi_m, g_{\mu\nu}) \]

Einstein equations

\[ G_{\mu\nu} = \frac{8\pi}{F} \left( T^F_{\mu\nu} + T^\phi_{\mu\nu} + T_\mu \right) \]
\[ T^F_{\mu\nu} = \frac{1}{8\pi} \left( \nabla_\mu \nabla_\nu F - g_{\mu\nu} \nabla^\rho \nabla_\rho F \right) \]
\[ T^\phi_{\mu\nu} = \partial_\mu \phi \partial_\nu \phi - \frac{1}{2} g_{\mu\nu} \partial_\lambda \phi \partial^\lambda \phi \]

Wave equation

\[ \nabla^\rho \nabla_\rho \phi = -\frac{1}{16\pi} F,\phi R \]

Spherical symmetry...

Code built on top of GR1D

O'Connor & Ott 2010
Hybrid EOS

Quick analytic prescription to mimic all the nuclear physics I don’t understand:

$$P = P_c + P_{th}$$

$$P_c = \begin{cases} K_1 \rho^{\Gamma_1} & \text{if } \rho \leq \rho_{\text{nuc}} \\ K_2 \rho^{\Gamma_2} & \text{if } \rho > \rho_{\text{nuc}} \end{cases}$$

Piecewise polytropic
- Iron core collapse $\Gamma_1 \lesssim 4/3$
- Stiffening at nuclear densities $\Gamma_2 \approx 2.5 - 3$

Ideal gas
- Response of the heated post-shock material $4/3 < \Gamma_{\text{th}} < 5/3$

Real sims (you)

These sims (me)

Tested against finite-temperature EOS: Dimmelmeier+ 2007, 2008

Collapse, bounce, shock... and NS

Mass density

Scalar field

Initial profile: realistic SN progenitor $M_{ZAMS} = 12 M_\odot$ Woosley & Heger 2007

ST theory $\alpha_0 = 10^{-4}$ $\beta_0 = -4.35$

First collapse of realistic massive star through bounce in ST theory
Collapse, bounce, shock... and BH

Mass density

Scalar field

Initial profile: realistic SN progenitor $M_{\text{ZAMS}} = 40M_\odot$
ST theory $\alpha_0 = 10^{-4} \quad \beta_0 = -4.35$

First collapse of realistic massive star through bounce in ST theory

Woosley & Heger 2007
Breathing mode

In ST theories there are GWs in spherical symmetry

\[ h(t) = \frac{2}{D} \alpha_0 r (\varphi - \varphi_0) \]

-Damour and Esposito-Farese 1992

Time domain waveform
Distance
Scalar field
Extraction radius
Coupling with the detector

Breathing mode

In ST theories there are GWs in spherical symmetry.
**Microphysics**

**Hybrid EOS:**

\[ P = P_c + P_{th} \]

\[ P_c = \begin{cases} K_1 \rho^{\Gamma_1} & \text{if } \rho \leq \rho_{\text{nuc}} \\ K_2 \rho^{\Gamma_2} & \text{if } \rho > \rho_{\text{nuc}} \end{cases} \]

\[ P_{th} = (\Gamma_{th} - 1) \rho \epsilon_{th} \]

**(o)** Fast relaxation
initial profile is GR, not ST!

**(i)** Collapse

**(ii)** Bounce!

**(iii)** Core forms a NS

**(iv)** Collapse to a BH

\[ \alpha_0 = 10^{-4} \quad \beta_0 = -4.35 \]
**Monopolar GWs**

- $M_{\text{ZAMS}} = 12M_\odot$
  - Can’t get enough compactness for spontaneous scalarization
  - We need better microphysics!
  - Neutrino transfer and cooling?

- $M_{\text{ZAMS}} = 40M_\odot$
  - Powerful signal from BH formation

Source in the Milky Way: $D = 10\,\text{kpc}$

**Ongoing!**

with C. Ott
Different polarizations

- Three detectors are enough to distinguish plus, cross and breathing
- New polarizations mean different detector response!

How to fully exploit the detector response?

plots by Max Isi

Ongoing! with M. Isi
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