Particlelike distributions of the Higgs field nonminimally coupled to gravity

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Particlelike distributions of the Higgs field nonminimally coupled to gravity,
***A. Füzfa, M. Rinaldi, S.S.**, PRL **111** 121103 (2013)*

Particlelike solutions in modified gravity: The Higgs monopole,
***S.S., M. Rinaldi, F. Staelens, A. Füzfa**,*
*PRD **90** 044056 (2014)*

Higgs field and gravity (I)

- Standard Model: Higgs field = scalar boson
  - Elementary particles mass generation (+ QCD for bounded states)
  - Spontaneous symmetry breaking
  - Mass depends on the (local) value of the Higgs field
- Scalar-tensor theories: Scalar field partner of the metric

$$S = \int d^4x\sqrt{-g}\left[\frac{F(\phi)}{16\pi G_N}R - \frac{1}{2}(\partial\phi)^2 + V(\phi)\right] + S_M[\psi_M; g_{\mu\nu}]$$

  - Gravitational "constant" depends on the local value of ϕ, $G_{eff}(r) \propto F^{-1}(\phi)$
  - Cosmology: inflation (slow-roll), dark energy
  - Compact objects: spontaneous scalarization, particlelike solutions

Higgs field and gravity (II)

- Scalar-theory with Higgs-like scalar field

$$S = \int d^4x\sqrt{-g}\left[F(h)\frac{M_{pl}^2}{2}R - \frac{M_{pl}^2}{2}(\partial h)^2 + V(h)\right] + S_M[\psi_M; g_{\mu\nu}]$$

- Assumptions on the Higgs field
  - Unitary gauge (no Higgs doublet $\mathcal{H}$)

$$\mathcal{H} = \frac{h\,M_{pl}}{\sqrt{2}}$$

  - Higgs potential ($\lambda_{sm} \sim 0.1$ and $v = 246$ GeV)

$$V(h) = \frac{\lambda_{sm}M_{pl}^4}{4}\left(h^2 - \frac{v^2}{M_{pl}^2}\right)^2$$

  - No Yukawa coupling Higgs field-matter fields

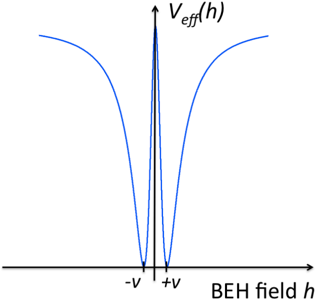
Higgs inflation

The Standard Model Higgs boson as the inflaton,
F. Bezrukov, M. Shaposhnikov
Phys.Lett.B 659 (2008) 703

Higgs inflation: the model

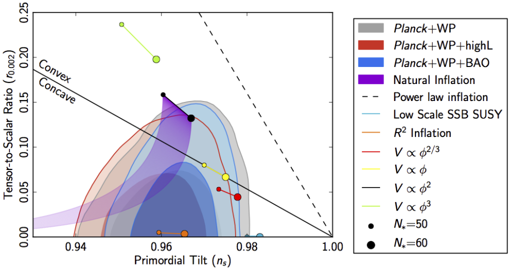
$$S = \int d^4x \sqrt{-g} \left[\left(1+\xi h^2\right) \frac{M_{pl}^2}{2} R - \frac{M_{pl}^2}{2} (\partial h)^2 + V(h) \right]$$

- Large field limit $\xi h^2 \gg 1$
  - Looks like induced gravity
  - Viable inflationary model
  - Fail to describe particle physics
- Small field limit $\xi h^2 \ll 1$
  - Minimally coupled scalar field
  - No viable inflation
  - SM is preserved



Higgs inflation: Observational constraints

- $n_s \simeq 0.97$, $r \simeq 0.0033$ (60 e-folds for $k_* = 0.002/$ Mpc)
- Normalization of the power spectrum implies $\xi > 10^4$
- Higgs inflation equivalent to Starobinsky model (not for reheating)
- Favoured by Planck data



Planck 2013 results.
XXII. Constraints on inflation

Higgs monopoles

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Combined constraints for compact objects

- **Distribution of the Higgs field around compact objects (made of baryonic matter)?**
- **Deviations from GR (solar system and compact objects)?**
- Solutions in a static and spherically symmetric spacetime

$$\mathcal{L} = \frac{m_{pl}^2}{16\pi}\left(1 + \frac{\xi}{m_{pl}^2} H^2\right) R - \frac{1}{2}(\partial H)^2 - V(H) + \mathcal{L}_{mat}\left[\psi_m, g_{\mu\nu}\right]$$

$$\text{with} \qquad H = m_{pl} h \tilde{v}, \qquad \tilde{v} = 246 \text{ GeV}/m_{pl}$$

$$V(H) = \frac{\lambda}{4}\left(H^2 - v^2\right)^2$$

- Standard Model Higgs potential parameters
- Matter = top-hat density profile

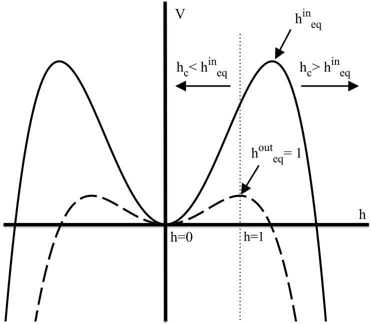
Effective dynamics

- Klein-Gordon equation $\Box h = -\frac{dV_{\text{eff}}}{dh}$ with $V_{\text{eff}} = -V + \frac{\xi h^2 R}{16\pi}$
- In cosmology (FLRW metric, scale factor $a(t)$)

$$\frac{d^2h}{dt^2} + \frac{3}{a}\frac{da}{dt}\frac{dh}{dt} = \frac{dV_{\text{eff}}}{dh}$$

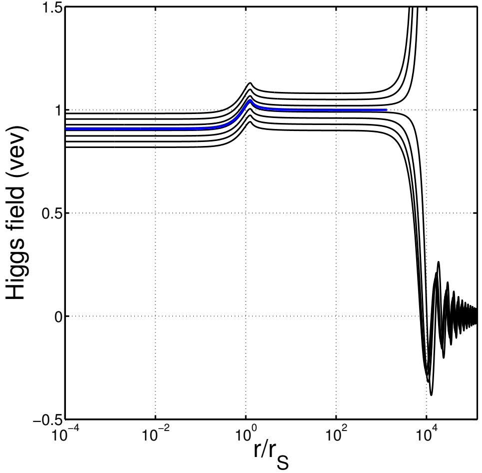
- For compact objects (Schwarzschild coordinates)

$$h'' - h'\left(\lambda' - \nu' - \frac{2}{r}\right) = -\frac{dV_{\text{eff}}}{dh}$$



Higgs monopole solutions

$\xi = 10$, $m = 10^6$ kg, $s = 0.75$



- Parameters:
  - compactness $s = r_s / r_*$,
  - baryonic mass m
  - NM coupling ξ
- Particlelike solutions:
  - Convergence towards the vev
  - Globally regular
  - Finite energy
  - Asympotically flat
- In GR, unrealistic homogeneous solution only ($h = 1$ everywhere)

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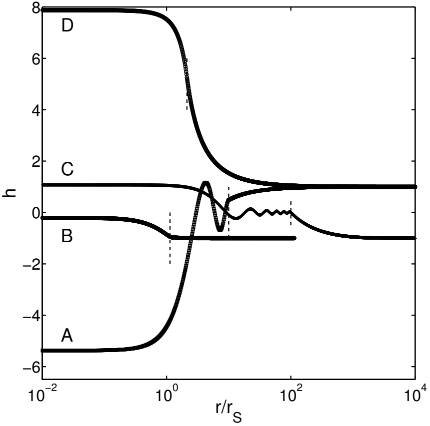
Monopole family



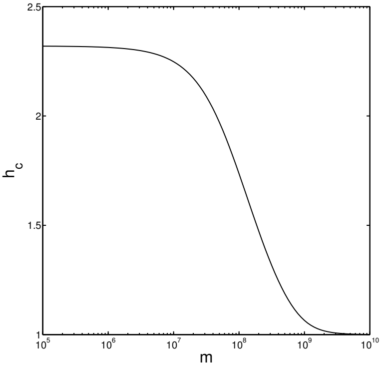
	h_c	ξ	m	s
A	- 5.37	10^4	10^3 kg	0.1
B	- 0.21	10	10^6 kg	0.88
C	1.077	10^6	10^6 kg	0.01
D	7.88	60	10^4 kg	0.47

Notice: no astrophysical objects

Deviations from GR

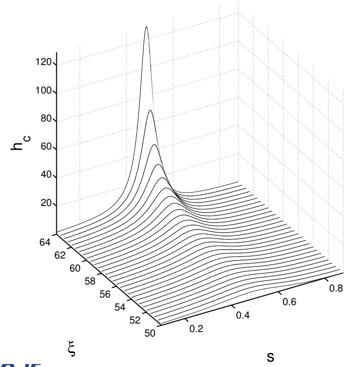
- $0 < |h_c| \leq |h_{eq}^{in}| = \sqrt{1 + \frac{3s^3\xi}{8\pi r_s^2 \lambda_{sm} m_{pl}^2 \tilde{v}^2}}$
- Astrophysical objects: $h_c \longrightarrow 1$
- PPN parameters ($\xi = 10^4$): $\gamma - 1 \ll 10^{-26}$; $\beta - 1 \ll 10^{-23}$
- Vev vs Planck scale ("hierarchy problem")
- **Only one solution, different than GR!**

$\xi = 60$, $s = 0.2$

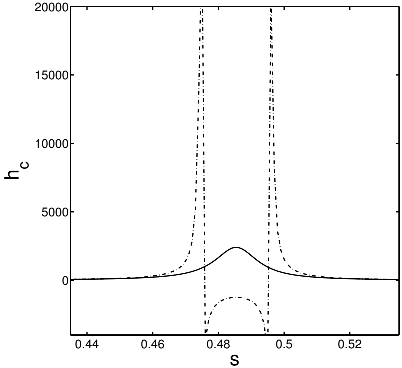


Amplification mechanism (I)

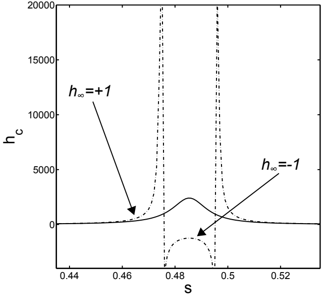
$$m = 10^3 \ \text{kg}$$



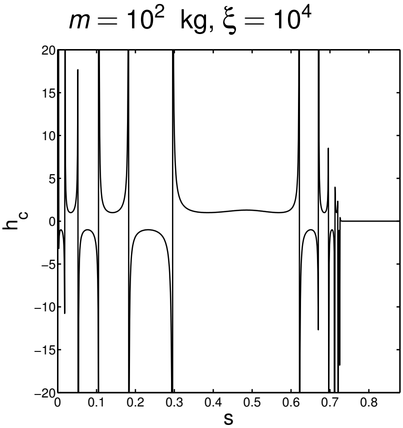
$\xi = 64.6$ (solid line)
$\xi = 64.7$ (dashed line)



Amplification mechanism (II)



- Critical ξ: $h_c \longrightarrow \infty$ for some s (or r_*)
- Phase transition $h_\infty \longrightarrow \pm 1$
- Constraint on ξ: forbidden s (or r_*)
  $\rightarrow$ No (monopole) solution !



Yukawa coupling

- **Phenomenological approach**:
  - Modelling of the Higgs field coupling to matter (perfect fluid):

$$\begin{aligned}\mathcal{L}_{mat}(g_{\mu\nu}) &= \mathcal{L}_{mat,0}(g_{\mu\nu}) + h\,\mathcal{L}_{mat,Y}(g_{\mu\nu}) \\ &= -\rho_0 - h\,\rho_Y\end{aligned}$$

  - QCD contribution and Yukawa coupling contributions
- **Field theory**:
  - Explicit gauge freedom (with gauge bosons)
  - Higgs doublet (multifield)
  - Coupling to fermions (spinors)

$$\mathcal{L} = \left(\frac{M_{pl}}{2} + \xi \mathcal{H}^\dagger \mathcal{H}\right) R - D_\mu \mathcal{H}^\dagger D^\mu \mathcal{H} - \frac{1}{4} F^2 - V(\mathcal{H}^\dagger \mathcal{H})$$

Greenwood, Kaiser, Sfakianakis, PRD 87 (2013): 064021
Rinaldi, Eur.Phys.J.Plus (2014) 129: 56

Take-away points

- New particlelike solution: the Higgs monopole
- Negligible deviations from GR
- Realistic Higgs distributions (in GR, $h = 1$ everywhere)
- General amplification mechanism

Open questions:

- Realistic Higgs field: coupling to matter and unitary gauge (*under progress*)
- Possible formation during gravitational collapse and stability
- Generalization of amplification mechanism