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, partner of the metric?

- Why the Higgs field?
  - Only fundamental **scalar** field detected
  - Elementary particles mass generation
  - Partner to gravity?
- What do we call the Higgs field?
  - Higgs potential parameters ($\lambda_{\mathrm{SM}} \sim 0.1$ and VEV=246 GeV)
  - Unitary gauge (no Higgs doublet)

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

  - (No) Yukawa coupling between the Higgs field to matter

Greenwood, Kaiser, Sfakianakis, PRD 87 (2013): 064021

Rinaldi, Eur.Phys.J.Plus (2014) 129: 56

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Scalar-tensor theories

- Scalar field counterpart of the metric $\rightarrow$ gravity
- Natural framework: Scalar-tensor theories of gravity
- Generalized "Brans-Dicke" like action (Jordan frame)
  - Effective gravitational constant $G_{eff} \propto G_N/\phi$
  - Violation of the Local Position Invariance

$$S = \int d^4x\sqrt{-g}\left(\frac{m_{pl}^2}{16\pi}\phi R - \frac{\omega(\phi)}{\phi}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right) + S_m\left[\phi, \psi_m, g_{\mu\nu}\right]$$

- Implications at different scales
  - High energy physics
  - Cosmological scales
  - Astrophysical scales, compact objects
- **Particlelike distributions of the Higgs field around compact objects**

Higgs monopoles

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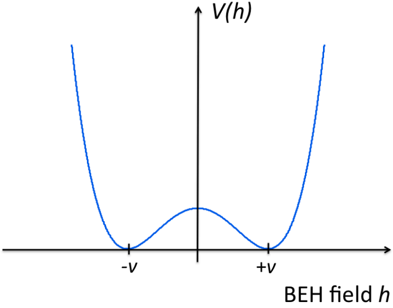
New Higgs inflation (*Bezrukov, Shaposhnikov, Phys.Lett.B 659 (2008) 703*)

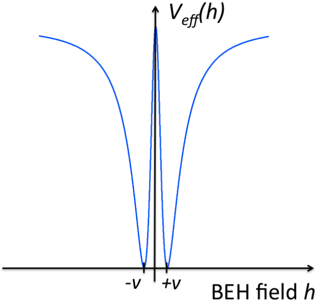
Very early model ('80):
"minimally coupled Higgs field"

$$\mathcal{L} = \frac{m_{pl}^2}{16\pi} R - \frac{1}{2} (\partial\phi)^2 - V(\phi)$$



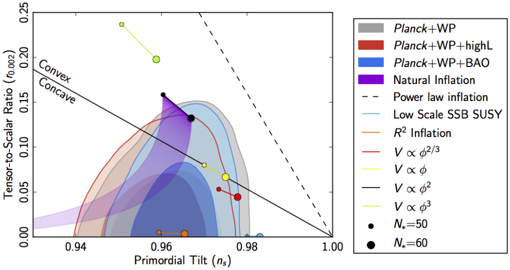
New Higgs inflation (2008):
"non-minimally coupled Higgs field"

$$\mathcal{L} = \frac{m_{pl}^2}{16\pi} \left(1 + \xi\phi^2\right) R - \frac{1}{2} (\partial\phi)^2 - V(\phi)$$



New Higgs inflation, a viable model?

- Constraint: Non-minimal coupling $\xi > 10^4$ (slow-roll)
- At high energy: equivalent to R^2 inflation
- Favoured by Planck data



Planck 2013 results.
XXII. Constraints on inflation

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

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

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

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

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

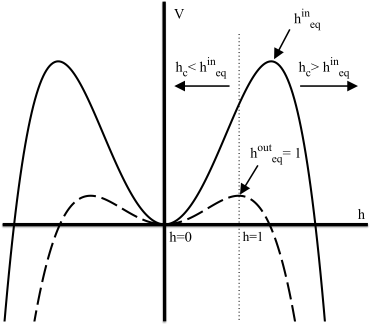
Effective dynamics

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

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

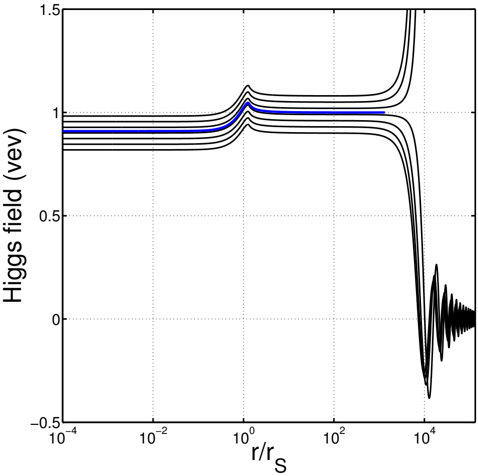
- For compact objects (Schwarzschild coordinates)

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



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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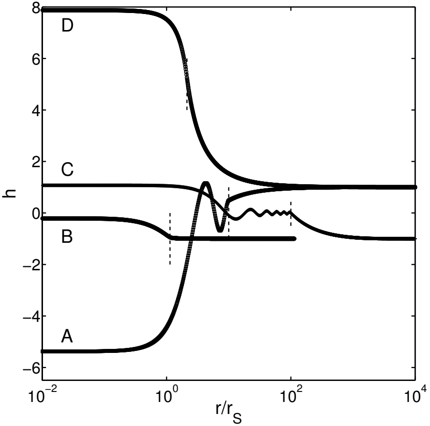
Monopole family



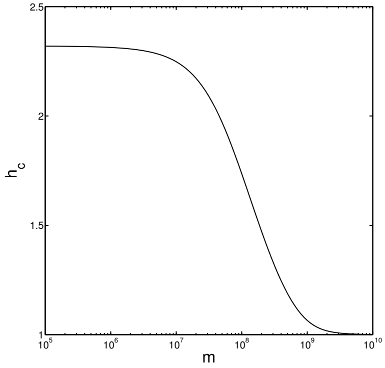
	h_c	ξ	m	s
A	- 5.37	10^4	10^3 kg	0.1
B	- 0.21	10	10^6 kg	0.88
C	1.077	10^6	10^6 kg	0.01
D	7.88	60	10^4 kg	0.47

Notice: no astrophysical objects

Deviations from GR

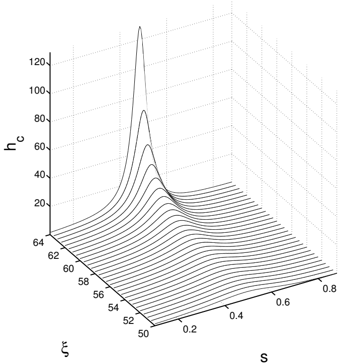
- $0 < |h_c| \leq |h_{eq}^{in}| = \sqrt{1 + \frac{3s^3\xi}{8\pi r_s^2 \lambda m_p^2 \tilde{v}^2}}$
- Astrophysical objects: $h_c \longrightarrow 1$
- PPN parameters ($\xi = 10^4$): $\gamma - 1 \ll 10^{-26}$; $\beta - 1 \ll 10^{-23}$
- Vev vs Planck scale ("hierarchy problem")
- **Only one solution, different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

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

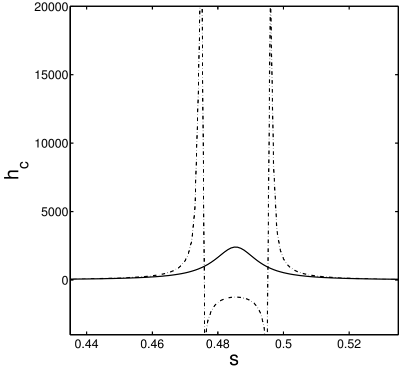


Amplification mechanism (I)

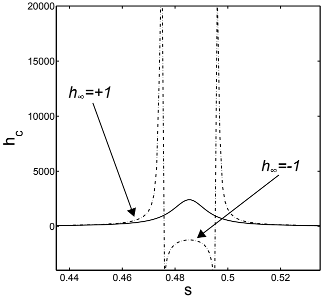
$$m = 10^3 \text{ kg}$$

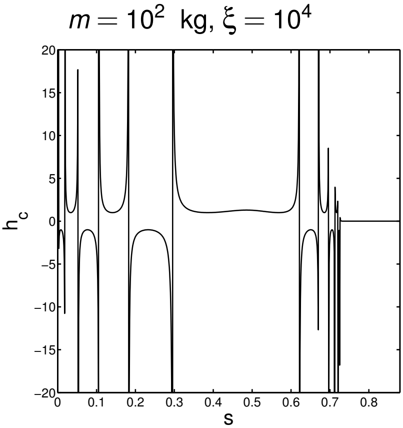


$\xi = 64.6$ (solid line)
$\xi = 64.7$ (dashed line)



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 !

Two approaches for matter coupled to the Higgs field

- Induced gravity approach

$$\mathcal{L} = Z(H^\dagger H)\frac{R}{2\kappa} - \frac{1}{2}D_\mu H^\dagger D^\mu H - V(H^\dagger H) + \mathcal{L}_M$$

with the covariant derivative $D_\mu H = \partial_\mu H + ig[A_\mu, H]$ and the matter component

$$\mathcal{L}_M = \frac{i}{2}\overline{\psi}\gamma^\mu_{L,R}D_\mu\psi + \text{h.c.} - F^a_{\mu\nu}F^{\mu\nu}_a - k\overline{\psi}_R H\widehat{x}\psi_L + \text{h.c.}$$

- **Effective approach**

$$\mathcal{L} = Z(h)\frac{R}{2\kappa} - \frac{m_h^2}{2}(\partial h) - V(h) + \mathcal{L}_M[g_{\mu\nu}, h, \psi_M] \quad (1)$$

with the matter Lagrangian,

$$\mathcal{L}_{\mathrm{mat}}(g_{\mu\nu},\ h) = \mathcal{L}_{\mathrm{mat},0}(g_{\mu\nu}) + h\mathcal{L}_{\mathrm{mat},Y}(g_{\mu\nu})$$

Effective approach

- Perfect fluid

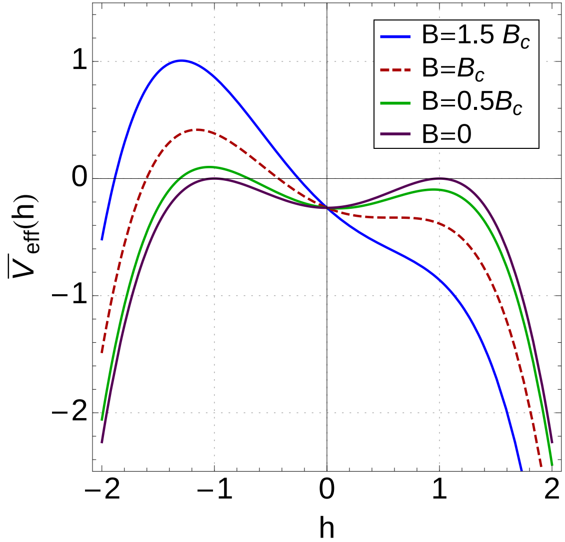
$$\mathcal{L}_{\rm mat}(g_{\mu\nu}, h) = -\rho(h) = -\rho_0 - h\rho_Y$$

- Assumption on the pressure $p(r,h) = p_0(r) + h\,p_{\rm Y}(r)$
- Decoupling of both sectors: TOV equations (analytical solutions)

$$\begin{aligned} p_0' + \nu'(p_0 + \rho_0) &= 0 \\ (h\,p_Y)' + \nu'(p_Y + \rho_Y) &= -h'\,\rho_Y \end{aligned}$$

- Effective dynamics: Extrema given by $\left(h_e^2 - 1\right) h_e = -B^2 = -\frac{\rho_Y}{m_h^4}$

Effective dynamics



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
- Application to boson stars (complex scalar field)