IV Black Holes Workshop
Aveiro University
Dec 19th, 2011

Astrophysical signatures of theories beyond GR

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http://blackholes.ist.utl.pt

Outline

Testing alternative theories of gravity

- Motivation
- Modified gravity
- Strategies
- Neutron stars as strong-curvature probes

Part I

Coupling to matter

- Non-relativistic phenomenology
- Eddington-inspired gravity

Part II

Coupling to scalars

- Quadratic gravity
- Spontaneous scalarization

GR is NOT well tested in the strong-field regime!

$$\frac{\Phi_{\rm Newton}}{c^2} = \frac{GM_\odot}{c^2\,1{\rm AU}} \sim 10^{-8}$$

Solar system tests

$$\frac{\Phi_{\rm Newton}}{c^2} \sim \frac{GM_\odot}{c^2\, r^{\rm periastron}_{\rm Hulse\text{-}Taylor}} \sim 10^{-6}$$

Millisecond binary pulsar

$$\frac{\Phi_{\rm Newton}}{c^2} \sim \frac{GM_{\rm BH}}{c^2\,\mathcal{O}(r_{\rm H})} \sim 10^{-1} - 1$$

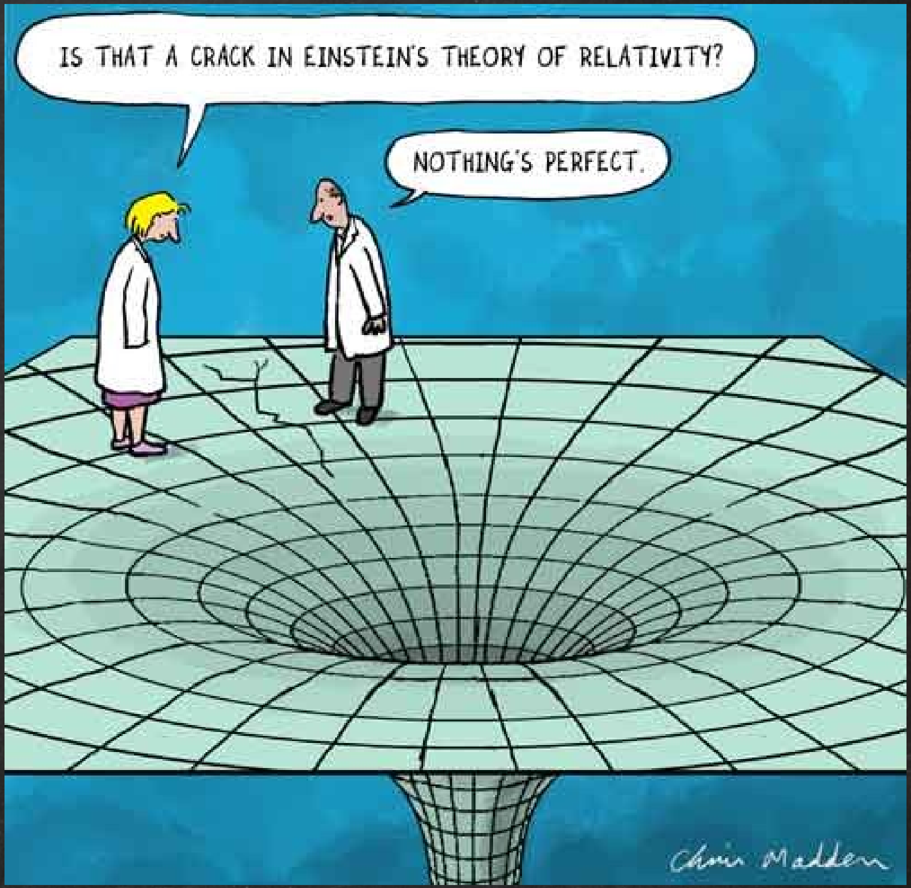
Binary black holes

Gravity: Current experiments — 10^{-6} — ? ? ? Black holes, Neutron stars ? ? → **Curvature**

Particle physics: Subnuclear physics — 10^{-6} — Atomic physics ← **Length**

Modifying GR: motivation

- **Phenomenologically: elusive sectors of Einstein theory**
  - Strong-field regime
  - Coupling with matter
- **Experimentally:**
  - Dark matter and dark energy
  - Gravitational waves
- **Theoretically: many issues**
  - Singularities ?
  - Gravity and QFT
  - Hints of UV completion



Modifying GR: strategies

- Imagination beats reality: plethora of alternative theories
- Unified approach VS case-by-case analysis:

1) Select a specific theory/effect and look for *"smoking guns"*

- *Floating orbits* in scalar-tensor theories [Cardoso's previous talk]
- *GWs birefringence* in parity-violating theories
- *Singularity avoidance* in cosmology and stellar collapse
- Spontaneous scalarization in scalar-tensor neutron stars

2) Parametrize a general action / field equations

- Quadratic couplings
- Scalar-tensor theories / f(R) theories
- Coupling with matter

3) Look for accumulated effects

- Two-body inspiral [Gualtieri's next talk]

Illustration by Krieg Barrie

Part I

Coupling to matter

Based on:

P. Pani, V. Cardoso, T. Delsate — Phys. Rev. Lett. 107 031101 (2011) & Work in Progress

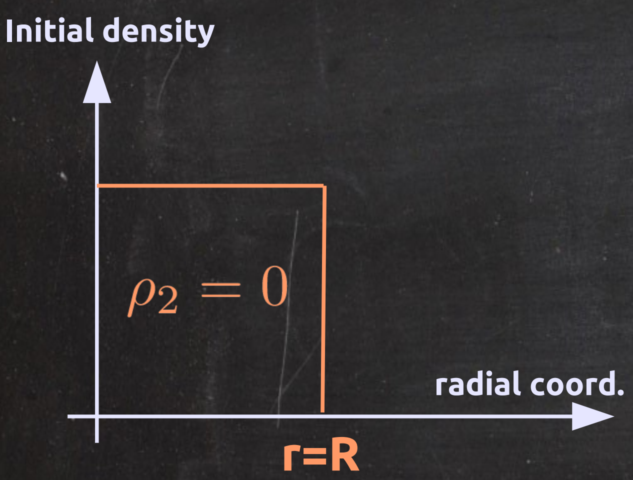
J. Casanellas, P. Pani, I. Lopes, V. Cardoso — ApJ (in press) astro-ph.SR/1109.0249

T. Delsate and J. Steinhoff — Work in progress

Singularities in GR

[Joshi and Malafarina 2000-2011, Joshi, Dadhich, Maartens 2002]

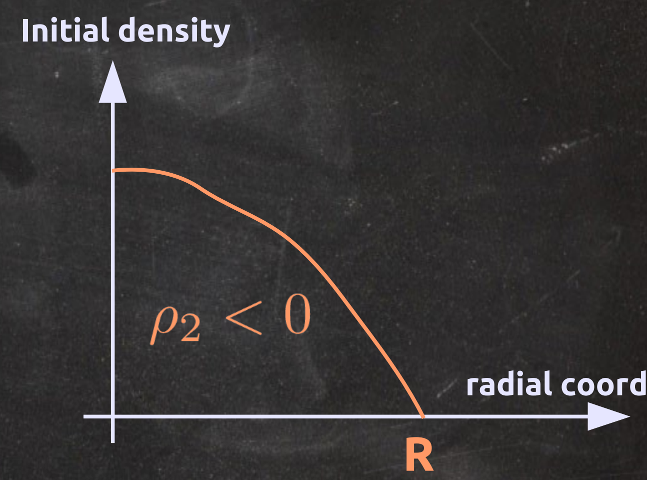
- Singularity are common in GR (Big Bang, black holes...)
  - Can be produced in dynamical processes (e.g. stellar collapse)
  - Cosmic Censorship
  - Naked singularities in realistic scenarios ?



$$\rho(r) \sim \rho_c + \rho_2 r^2 + \ldots$$

$$t_{\rm ah} \approx t_s - \rho_c r^3 - \rho_2 r^2$$

Time of formation of an apparent horizon



Density gradient produces a shear that postpones the apparent horizon formation

Locally naked singularities may be globally naked! [Joshi, Dwivedi, 2002]

In the whole process it is crucial how gravity is coupled to matter

Coupling to matter beyond GR

- In vacuum → $R_{\mu\nu} = 0 \quad \nabla_\mu T^{\mu\nu} = 0$
- Matter sector is extremely difficult to probe → caution (e.g. extra dims)
- Crucial to describe stars and cosmology

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu} + \underbrace{S_{\mu\nu}[g, T, \partial g, \partial T]}_{\text{Can become dominant at high density or high gradients}}$$

Can become dominant
at high density or high gradients

- No extra fundamental fields
- Vanishing in vacuum [Bertolami et al., 2007]
- Geodesic equation, minimal coupling → $\nabla_\mu T^{\mu\nu} = 0$
- Quadratic in T? Matter derivatives? Action principle?

Born-Infeld-Eddington gravity is a prototype of this kind of corrections

Have we tested Newtonian gravity enough?

- **Parametrized Post-Poissonian approach:**

Most general Poisson eq. which is covariant, perturbative to 2nd derivatives and reduces to Laplace eq. in vacuum:

standard — Linear corrections

$$\underbrace{\nabla^2\Phi = 4\pi G\rho}_{\text{standard}} \underbrace{+\frac{\kappa_g}{4}\nabla^2\rho}_{\text{Linear corrections}} +\alpha_g\epsilon^{ij}\nabla_i\Phi\nabla_j\rho+$$

$$\underbrace{+\eta\rho^2+\gamma\nabla\rho\cdot\nabla\rho+\epsilon_1\nabla\Phi\cdot\nabla\rho+\epsilon_2\Phi\nabla^2\rho+\epsilon_3\rho\nabla^2\Phi+\ldots}_{\text{Quadratic corrections}}$$

Quadratic corrections

- **Tests of the equivalence principle constrain many terms**

- **Linear corrections are compatible with all observations so far**

$$\nabla^2\Phi = 4\pi G\rho + \frac{\kappa}{4}\nabla^2\rho$$

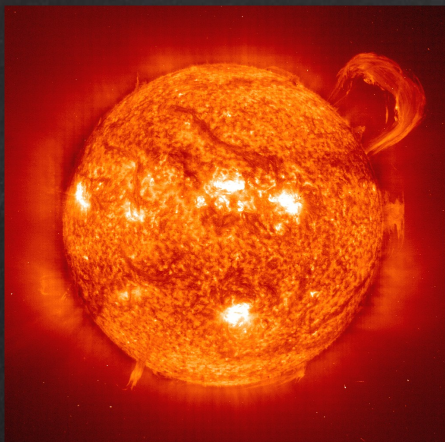
- **Precise measurements of solar neutrinos and helioseismology**

[Casanellas, Pani, Lopes, Cardoso, ApJ (in press) astro-ph.SR/1109.0249]

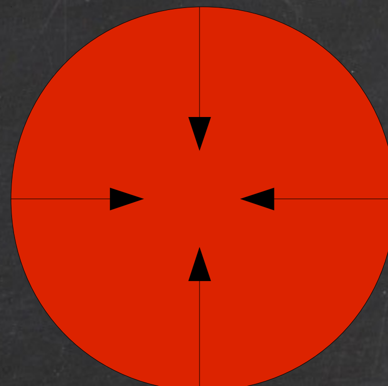
Collapse in modified Newtonian gravity

[Pani, Cardoso, Delsate, PRL 107, 2011]

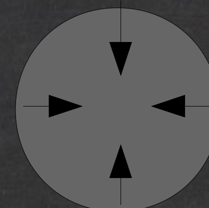
$$\nabla^2\Phi = 4\pi G\rho$$



Massive star

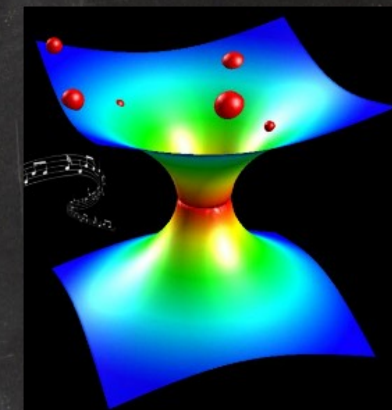


End of nuclear reactions



Collapse

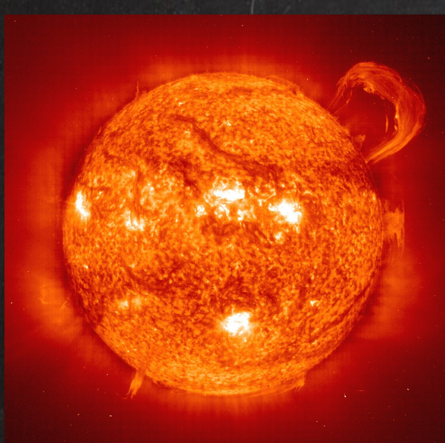
Singularity

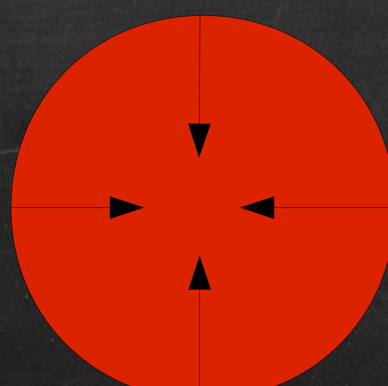


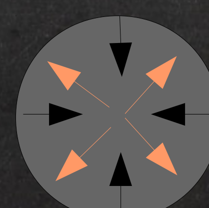
Black hole (?)

time

$$\nabla^2\Phi = 4\pi G\rho + \frac{\kappa}{4}\nabla^2\rho$$

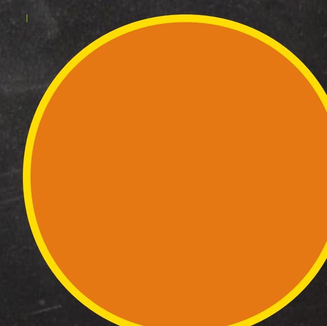






New repulsive gravity

NO Singularity!



Regular “star”

Collapse in modified Newtonian gravity

[Pani, Cardoso, Delsate, PRL 107, 2011]

- In GR, the Newtonian collapse of non-iteracting particles reproduces the Oppenheimer-Snyder collapse quantitatively [Florides 1977]

$$\frac{\partial u(t,r)}{\partial t} + u(t,r)\frac{\partial u(t,r)}{\partial r} = -\frac{GM(t,r)}{r^2} - \frac{\kappa}{4}\frac{\partial \rho(t,r)}{\partial r}$$

Modified Euler equation

$$\frac{\partial \rho(t,r)}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}\left[\rho(t,r) r^2 u(t,r)\right]$$

Continuity equation

$$\frac{\partial M(t,r)}{\partial r} = 4\pi r^2 \rho(t,r)$$

Mass function

- In practice:
  - Lagrangian formulation (less time consuming, "comoving coords.")
  - Artificial viscosity (to smear out fluid shocks)

Stellar collapse:
1+1 evolution of non-interacting particles

Stars in modified Newtonian gravity

$$\nabla^2\Phi = 4\pi G\rho + \frac{\kappa}{4}\nabla^2\rho$$

- **Modified hydrostatic equilibrium:**

$$\frac{dP}{dr} = -\frac{Gm(r)\rho}{r^2} - \frac{\kappa}{4}\rho\rho'$$

Equivalent to standard gravity with a polytropic EOS:

$$P(\rho) = \frac{\kappa}{8}\rho^2$$

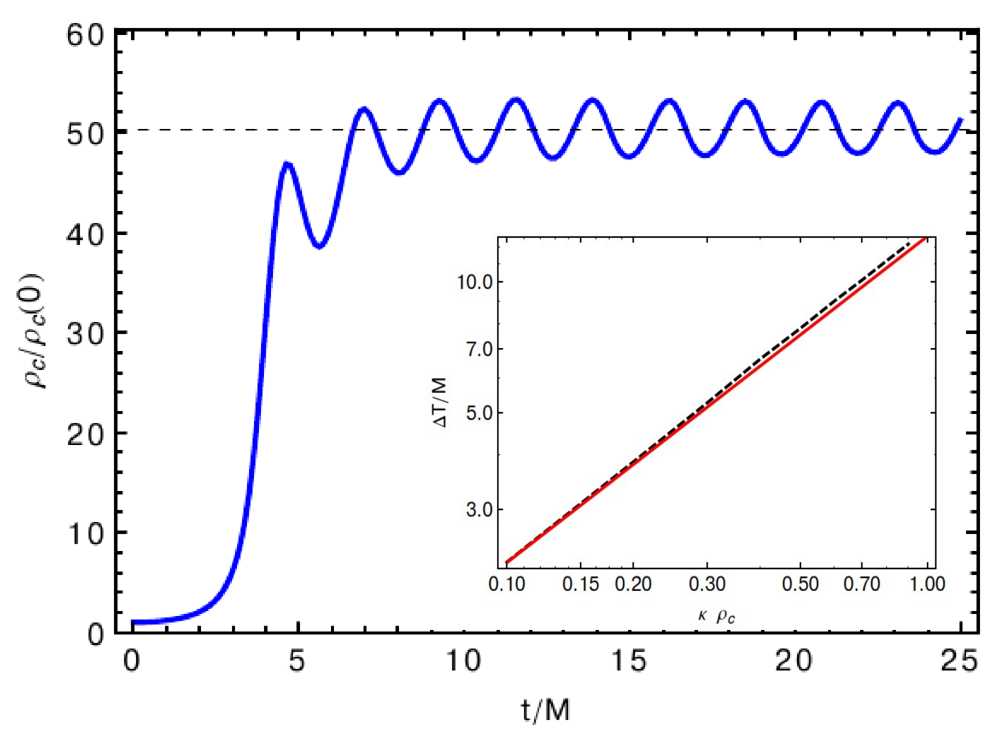
- **Admits "dark matter stars" (P=0 and κ>0)**

$$\rho(r) = \rho_c \frac{\sin \varpi r}{\varpi r} \qquad \varpi = 4\sqrt{\frac{\pi G}{\kappa}}$$

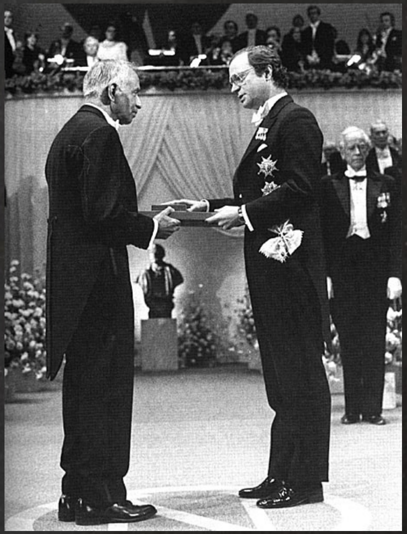
- **Linearly stable:**

$$\frac{\Delta T}{M} \approx \frac{\pi^{5/4}}{4.4}\left(\frac{\kappa}{M^2}\right)^{3/4}$$

- **No dissipation in the collapse**



Modified Chandrasekhar model



- Ultra-relativistic matter $P=K\rho^{4/3}$

- Energy:

$$\nabla^2\Phi = 4\pi G\rho + \frac{\kappa}{4}\nabla^2\rho$$

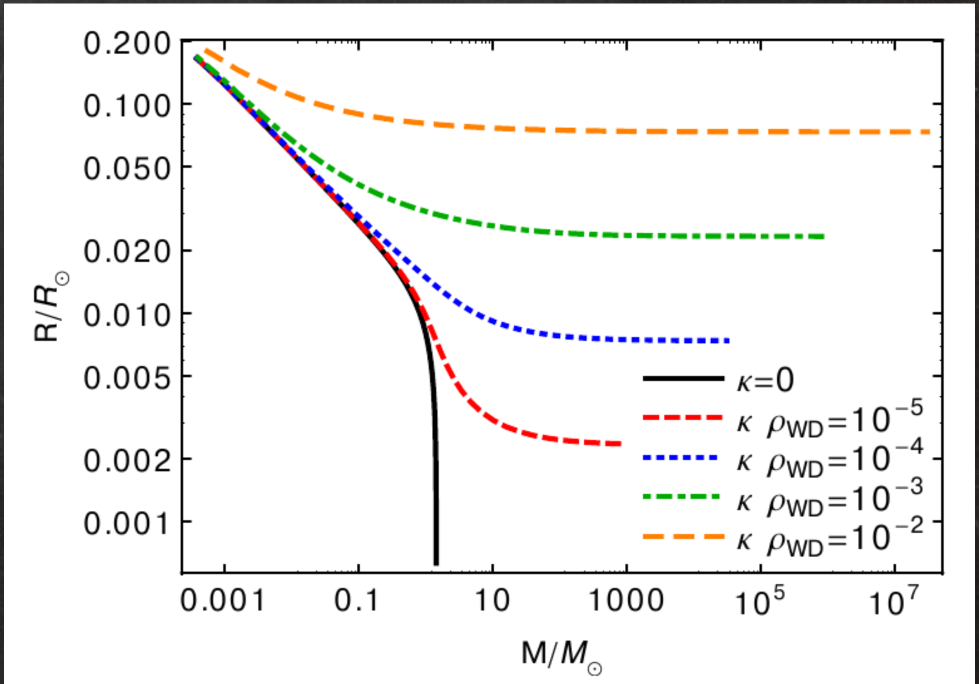
$$E = E_F + E_G \approx \underbrace{\frac{\hbar c N^{1/3}}{R}}_{\text{Fermi energy}} \underbrace{- \frac{G N m_b^2}{R} + \frac{3\kappa N m_b^2}{16\pi R^3}}_{\text{Gravitational energy per fermion}}$$

- If κ=0 (Chandra's result)

$$N_{\rm max} \approx \left(\frac{c\hbar}{G m_b^2}\right)^{3/2} \Rightarrow M_{\rm max} \approx 1.4 M_\odot$$

- If κ>0 (Eddington-inspired gravity)

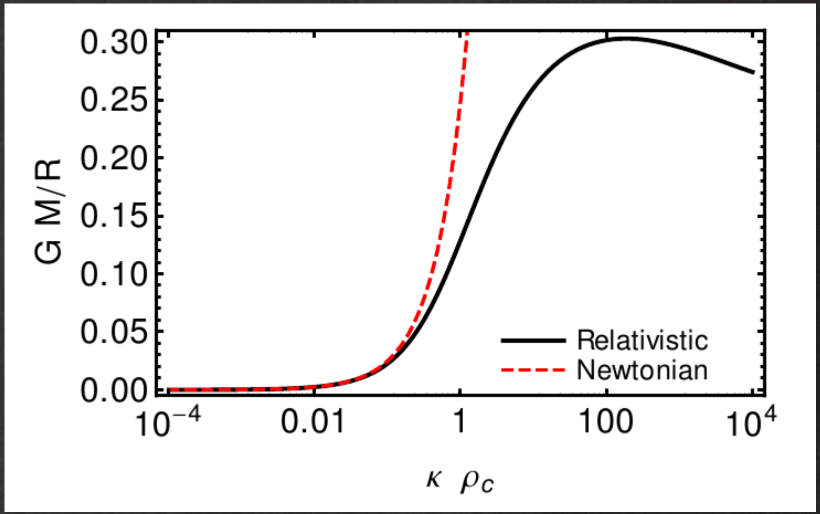
$$R_{\rm min} \approx \frac{3}{4}\sqrt{\frac{\kappa}{\pi G}}\sqrt{1-\frac{N_{\rm max}^{2/3}}{N^{2/3}}}$$



Open issues

Pressureless stars:

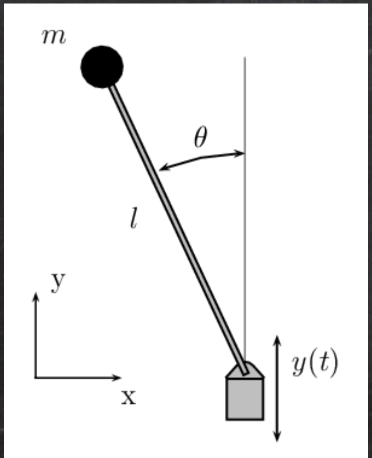
Maximum mass



- **Collapse when M>1.4 Msun?**

BHs are vacuum solutions, but can be formed in dynamical scenarios?

~ inverted pendolum:



To answer these questions, we need a fully relativistic theory which reduces to

$$\nabla^2\Phi = 4\pi G\rho + \frac{\kappa}{4}\nabla^2\rho$$

in the non-relativistic limit

- **Are BHs stable?**

Born-Infeld-Eddington (BEI) gravity

[Banados, Ferreira 2010]

$$S_{BEI}[g,\Gamma,\Psi] = \frac{2}{\kappa}\int d^4x\left[\sqrt{|g_{ab}+\kappa R_{ab}(\Gamma)|}-\lambda\sqrt{g}\right]+S_m[g,\Psi_m]$$

$$\Lambda = \frac{\lambda-1}{\kappa}$$

Field equations:

$$q_{\mu\nu} = g_{\mu\nu}+\kappa R^{(q)}_{\mu\nu}$$

$$\sqrt{-q}q^{\mu\nu} = \lambda\sqrt{-g}g^{\mu\nu}-\kappa\sqrt{-g}T^{\mu\nu}$$

- **q is the affine metric**
- **Equivalent to GR in vacuum**

- **Deviations only occur when coupled to matter**
- **Small κ limit →** $R^{(q)}_{\mu\nu} \approx \Lambda g_{\mu\nu}+T_{\mu\nu}-\frac{1}{2}Tg_{\mu\nu}+\kappa\left[S_{\mu\nu}-\frac{1}{4}Sg_{\mu\nu}\right]+\ldots$

  Derivatives corrections

  Quadratic in the matter fields

  $$S_{\mu\nu} = T^{\alpha}_{\mu}T_{\alpha\nu}-\frac{1}{2}TT_{\mu\nu}$$

- **Non-relativistic limit →** $\nabla^2\Phi = 4\pi G\rho+\frac{\kappa}{4}\nabla^2\rho$
- **Nonetheless, matter is minimally coupled to gravity →** $\nabla^{(g)}_{\mu}T^{\mu\nu} = 0$

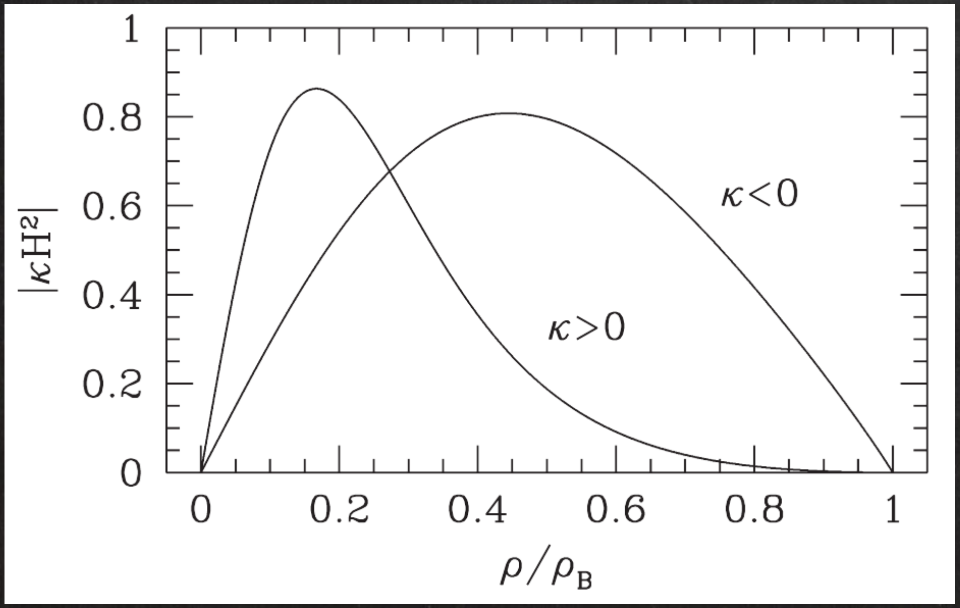
Cosmology in BIE gravity

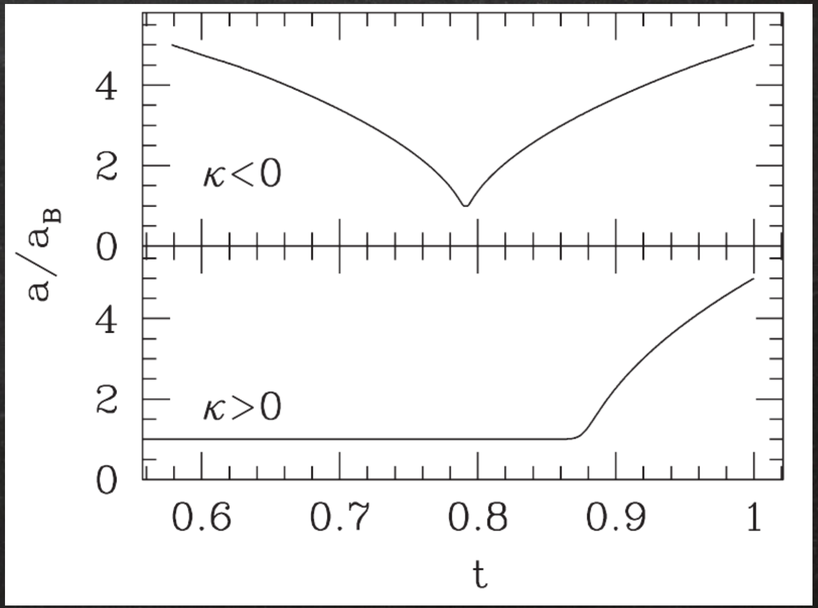
[Banados, Ferreira PRL 105, 2010]

- Same energy conservation
- Different Friedmann equation
- At early times:

$$3H^2(\rho) = \frac{1}{\kappa}\left[\kappa\rho - 1 + \frac{1}{3\sqrt{3}}\sqrt{(1+\kappa\rho)(3-\kappa\rho)^3}\right]$$

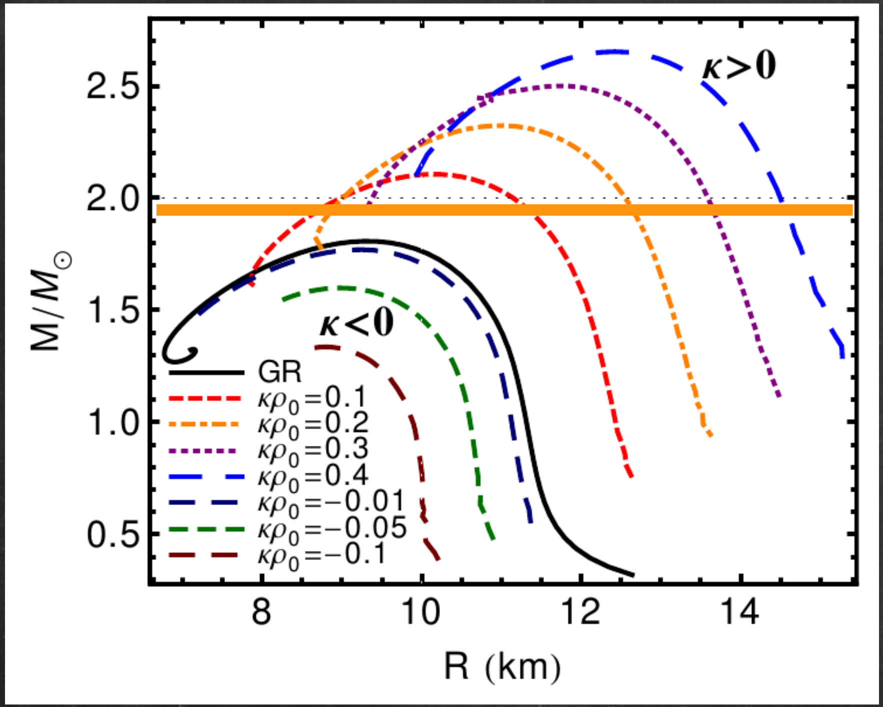
No Big Bang!



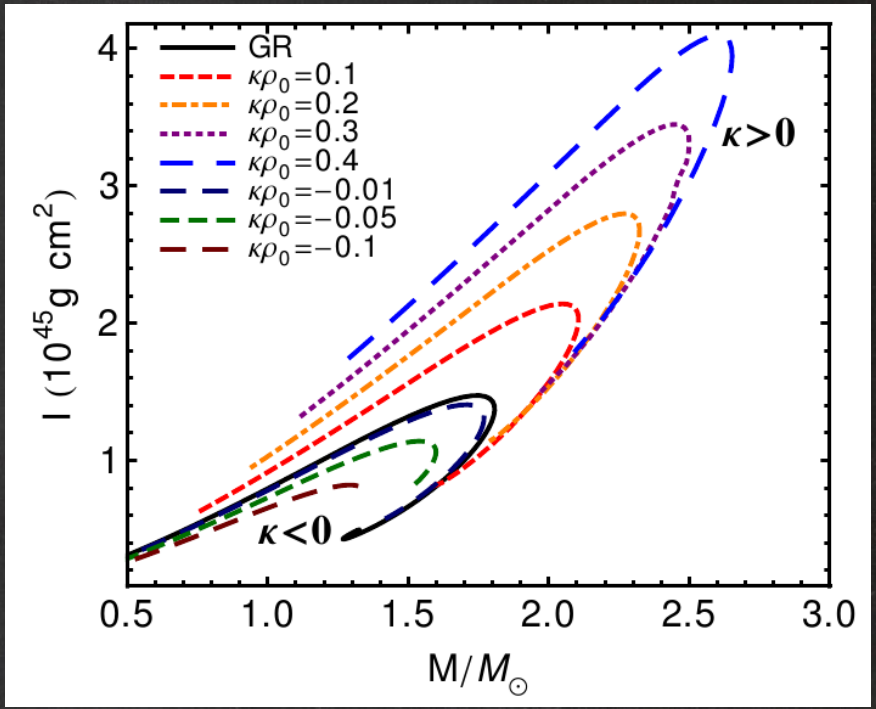


Standard neutron stars in BIE gravity:

Mass-radius relation



Moment of inertia



[Pani, Cardoso, Delsate, PRL 107, 2011]

Positive κ contribute to enhance the relativistic effects

- **Degeneracy between different equations of state!**
- **Can explain recent observations without assuming exotic EOS**
- **No compact objects when:**

$$\begin{cases} P_c\kappa < 1 & \kappa > 0 \\ \rho_c|\kappa| < 1 & \kappa < 0 \end{cases}$$

Conclusion

- Did we test the matter-gravity sector of GR enough??
- Currently hidden sectors of GR will be tested in the near-future
- Singularities in GR can be avoided modifying the coupling to matter
- Rich and viable phenomenology even in the non-relativistic limit
- Born-Infled-Eddington gravity has a very appealing features

  - Non-singular cosmology
  - Stable dark matter stars
  - Modified non-relativistic limit
  - Non-singular Newtonian collapse
  - Higher maximum mass in neutron stars
  - Constraints from solar physics

- Important to understand the relativistic collapse
- Non-linear, strong-field effects are “smoking guns” for next experiments

Boas férias e até o próximo ano!

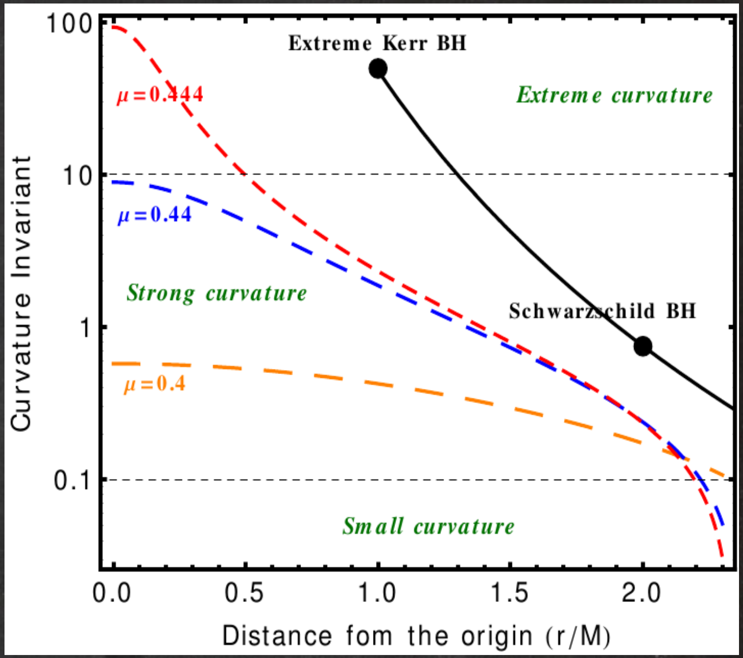
BHs V ? ?

Backup slides

“Nothing is More Necessary than the Unnecessary”

Compact stars as strong-field probes

- Intimately related: collapse, Chandra, etc..
- Even stronger curvatures than BHs
- New physics even at non-relativistic level
- Neutron stars (NSs) are common objects
- More accessible than black holes (BHs)



Compact stars as strong-field probes

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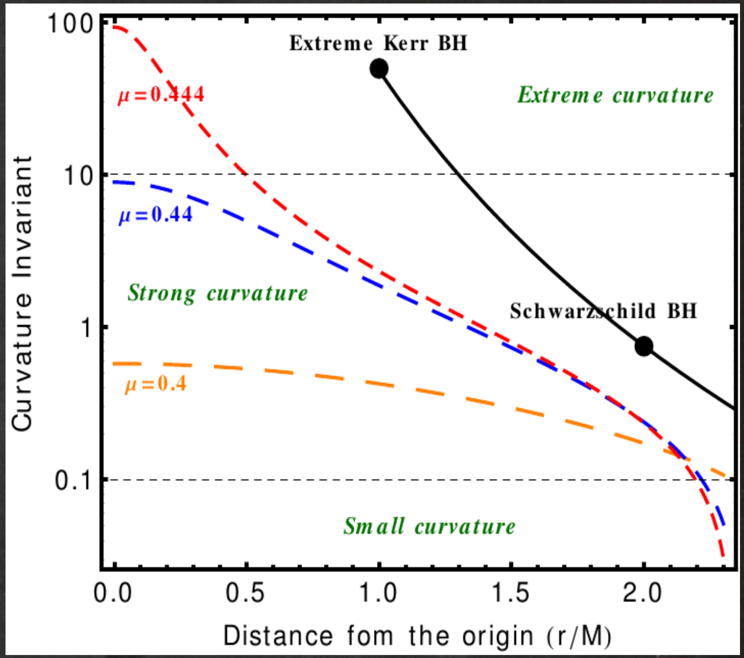
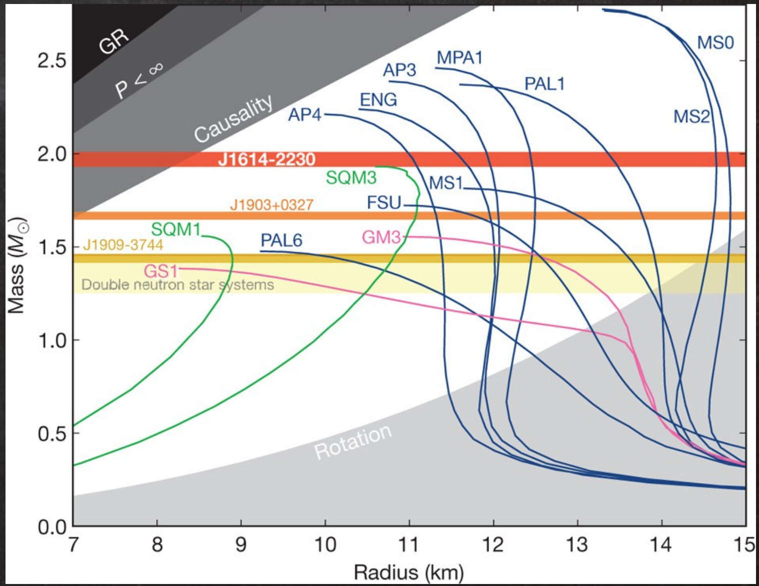


- However:
  - BHs are simple objects, NSs are not!
  - Equation of state of a NS?
- Future experiments (NICER)
- Theoretical insights may be EOS independent



Demorest et al. Nature 2010

Part II
Coupling to scalars

Based on:

P. Pani, E. Berti, V. Cardoso, J. Read — Phys. Rev. D 84, 104035 (2011)

P. Pani, E. Berti, V. Cardoso, J. Read, M. Salgado — Phys. Rev. D 83, 081501 (2011)

Quadratic corrections to GR

$$S=\kappa\int d^4x\sqrt{-g}R-\frac{1}{2}\int d^4x\sqrt{-g}\left[g^{ab}\nabla_a\phi\nabla_b\phi+V(\phi)\right]+\alpha_{\rm CS}\int d^4x\sqrt{-g}\phi\,{}^*RR$$

General Relativity — free scalar field — Chern-Simons term

$$+\alpha\int d^4x\sqrt{-g}\,e^{\beta\phi}\left(R^2-4R_{ab}R^{ab}+R_{abcd}R^{abcd}\right)$$

Gauss-Bonnet term

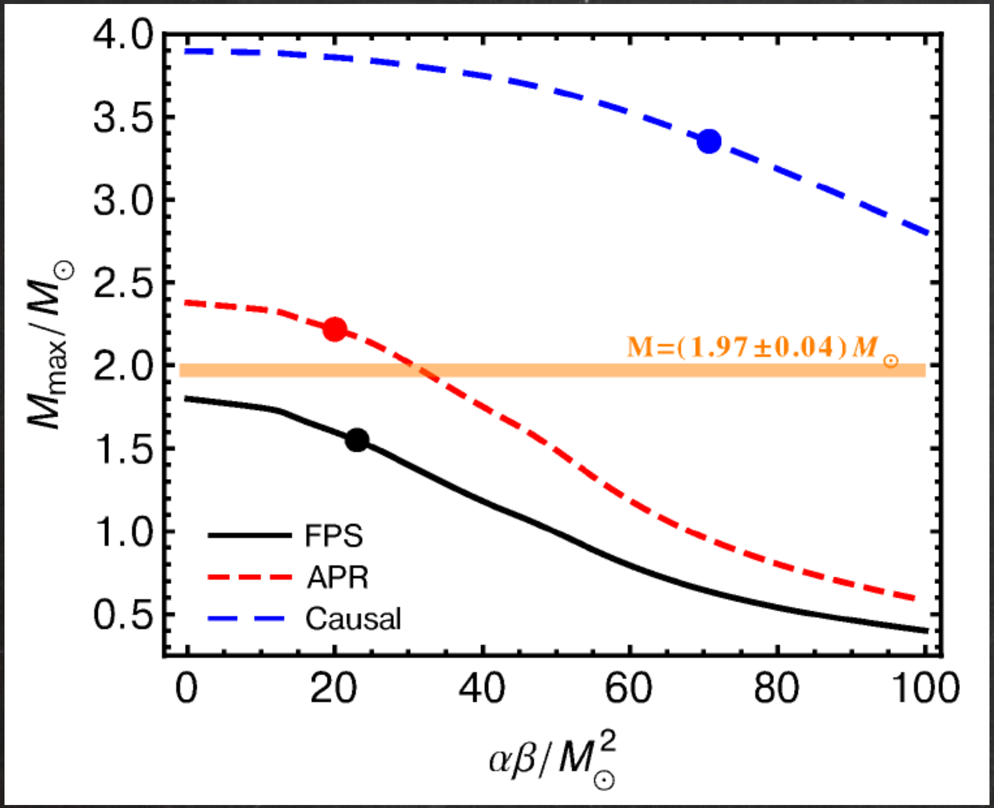
- **Well motivated (from HEP, string theory, etc..)**
- **Scalar field encoding modifications beyond GR**

- **Chern-Simons gravity** **[Gualtieri's next talk]** [Alexander & Yunes, Sopuerta & Yunes, ...]
  - **Modified rotating solutions** [Yunes & Pretorius (2009)] [Ali-Haimoud & Chen (2011)]
- **Gauss-Bonnet gravity**
  - **Modified static models** [Pani, Berti, Cardoso, Read (2011)] [Pani, Macedo, Crispino, Cardoso, (2011)]
- **Stability?** [Pani, Cardoso (2009)] [Motohashi, Suyama (2011)]

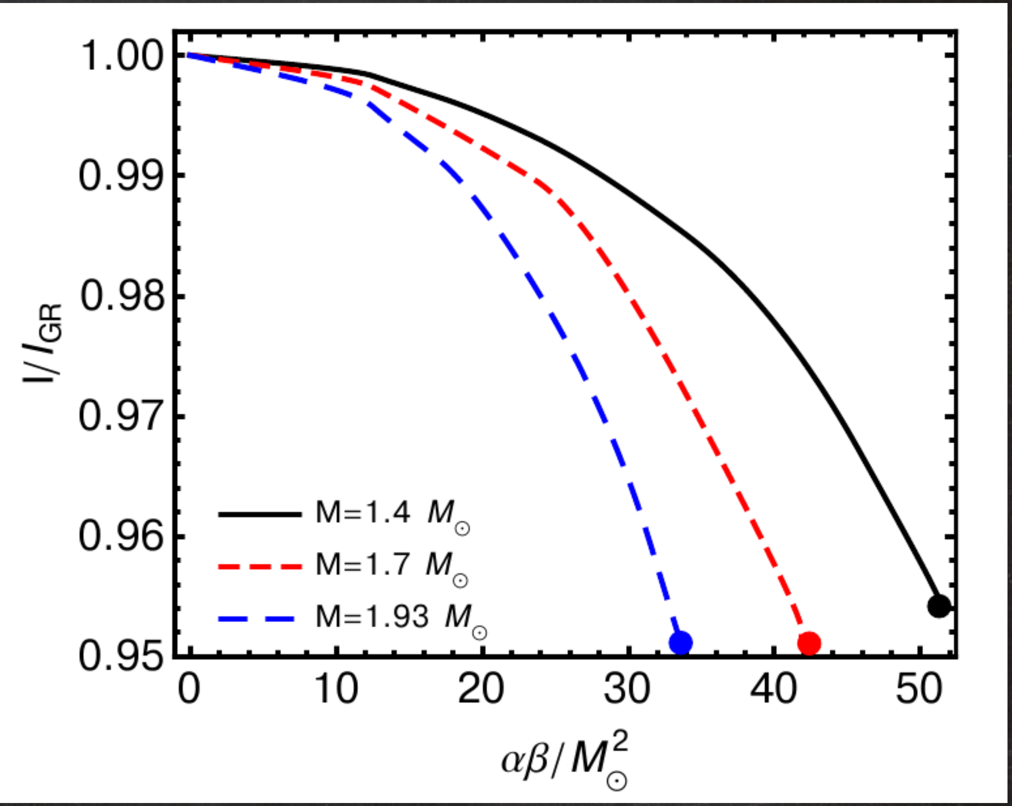
Neutron stars in Gauss-Bonnet gravity

[Pani, Berti, Cardoso, Read (2011)]

Maximum mass



Moment of inertia



Need to wait new observations to **disentangle** the **effects of different EOS** and put constraints

Scalar-tensor theories

[Fuji & Maeda book]

[Damour & Esposito-Farese, 90s]

"Physical" Jordan frame:

$$S_{(J)} = \frac{1}{16\pi}\int d^4x\sqrt{-g}\,[F(\phi)R - Z(\phi)g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - 2U(\phi)] + S_{\rm mat}(\Psi_m; g_{\mu\nu})$$

Conformal transformation → Einstein frame:

$$S_{(E)} = \int d^4x\sqrt{-g^{(E)}}\left(\frac{R^{(E)}}{16\pi} - \frac{1}{2}g^{(E)}_{\mu\nu}\partial^\mu\Phi\partial^\nu\Phi - \frac{V(\Phi)}{16\pi}\right) + S_{\rm mat}(\Psi_m; F(\Phi)g_{\mu\nu})$$

Spontaneous scalarization

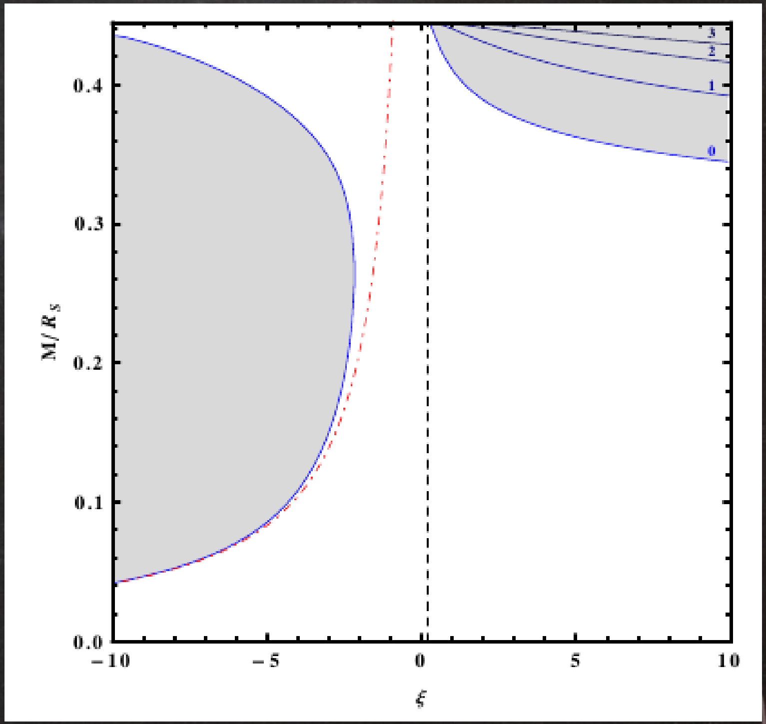
[Damour & Esposito-Farese (1992)]

[Harada 1997, Novak 1998]

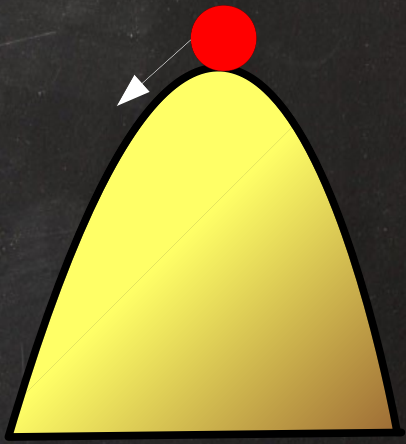
[Lima, Matsas, Vanzella, (2010))]

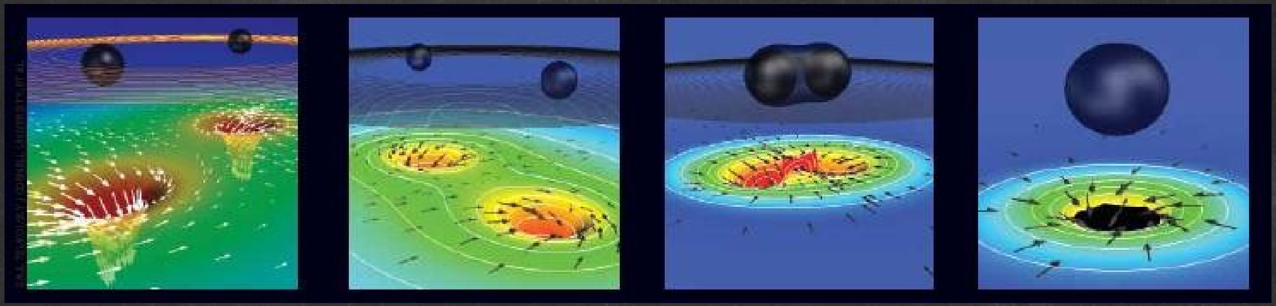
$$F(\phi) = 1 - \xi\phi^2 \qquad Z(\phi) = 1 \qquad U(\phi) = 0$$

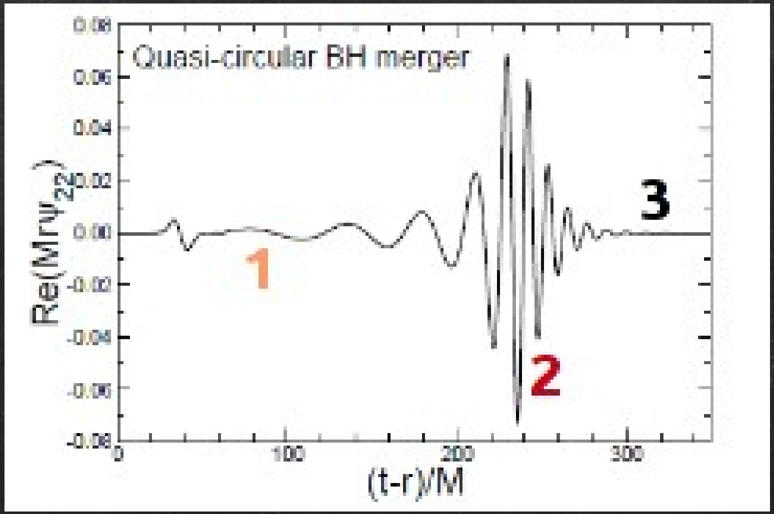
- Phenomenologically viable
- Scalar instability
- New "scalarized" star



[Pani, Berti, Cardoso, Read, Salgado, (2011))]

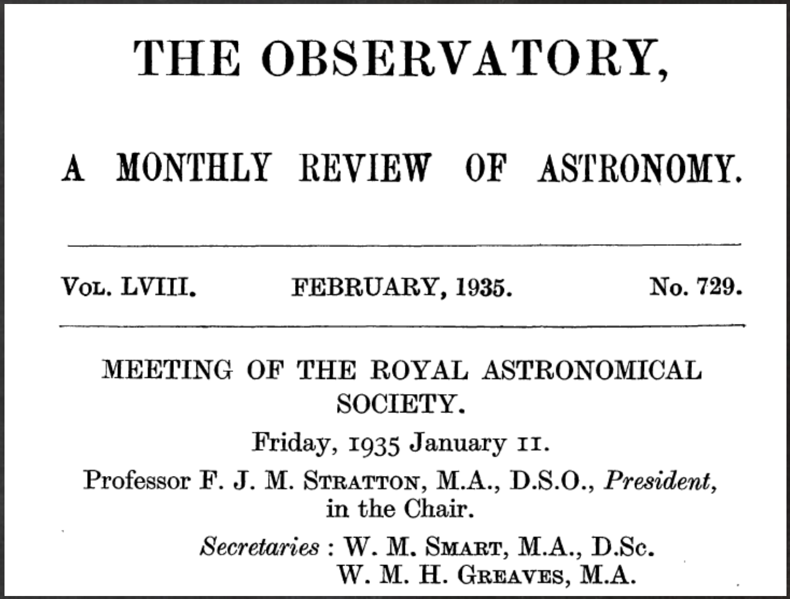





Quasi-circular BH merger
Re(MrΨ22)
(t-r)/M
0.08
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
0
100
200
300
1
2
3

Back to 1935:

The Observatory, Vol. 58, p. 33-41 (1935)



THE OBSERVATORY,

A MONTHLY REVIEW OF ASTRONOMY.

VOL. LVIII. FEBRUARY, 1935. No. 729.

MEETING OF THE ROYAL ASTRONOMICAL SOCIETY.

Friday, 1935 January 11.

Professor F. J. M. STRATTON, M.A., D.S.O., *President*, in the Chair.

Secretaries : W. M. SMART, M.A., D.Sc.
W. M. H. GREAVES, M.A.

- Meeting of the Royal Astronom. Society
- Chandrasekhar → theory of NS collapse
- Eddington → strong opposition

"[...] there should be a law of Nature to prevent a star from behaving in this absurd way!"

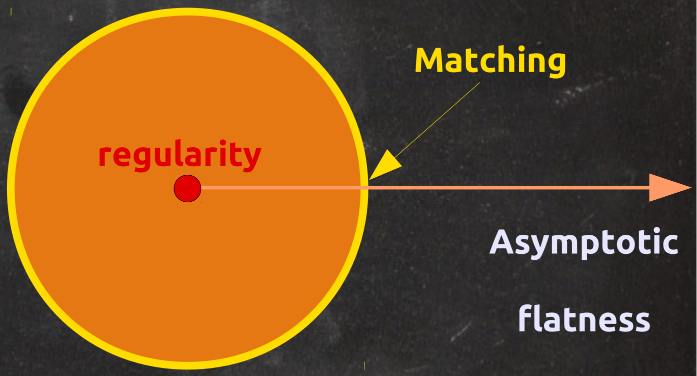
- Chandrasekhar had to move to U.S.A.
- Devastating impact for the development of astrophysics
- He was eventually right → standard theory of NSs

Relativistic stellar models

- It's not “just” modified gravity → many subtleties
  - Well-posedness of the field equations (cf. Palatini f(R) theories)
  - Matching conditions at the stellar surface
- Relativistic stellar collapse?
- Let us start with static configurations:

$$ds_q^2 = q_{ab}dx^a dx^b = -p(r)dt^2 + h(r)dr^2 + r^2 d\Omega^2$$

$$ds_g^2 = g_{ab}dx^a dx^b = -F(r)dt^2 + B(r)dr^2 + A(r)r^2 d\Omega^2$$



- Slowly-rotating models

$$q_{t\varphi} = -\eta(r)r^2 \sin^2\theta$$

$$g_{t\varphi} = -\zeta(r)r^2 \sin^2\theta$$

→ Field eqs can be solved perturbatively [Hartle '67]

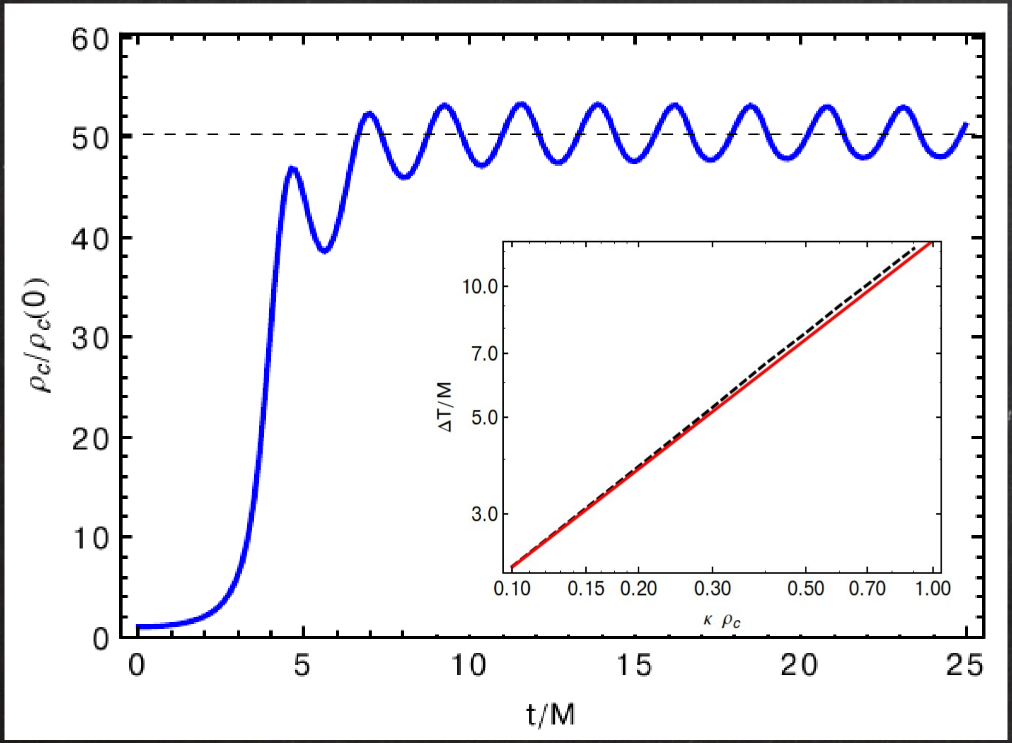
Stars in modified Newtonian gravity

- **Pressureless stars are the end-point of non-relativistic, P=0 collapse**

$$\ddot{\xi} - \frac{1}{\rho}\left[\frac{\gamma P}{r^2}(r^2\xi)'\right]' + \frac{4}{\rho r}\xi P' = -\frac{\kappa}{4}\left[\frac{2}{r}\xi\rho' - \xi'\rho' - \left[\frac{\rho}{r^2}(r^2\xi)'\right]'\right]$$

$\xi \sim e^{i\omega t} \rightarrow$ **Lagrangian displacement**

$\gamma \rightarrow$ **Adiabatic index of perturbations**



Oscillation period:

$$\frac{\Delta T}{M} \approx \frac{\pi^{5/4}}{4.4}\left(\frac{\kappa}{M^2}\right)^{3/4}$$

- **Dissipation would lead the system to a stationary configuration**