Spontaneous scalarization: a promising avenue for gravitational-wave astronomy

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arXiv:1602.????? (hopefully soon) with U. Sperhake, C. Ott

arXiv:1505.07462 (**CQG** 32:204001) with M. Horbatsch, H. Silva, P. Pani, E. Berti and L. Gualtieri, U. Sperhake

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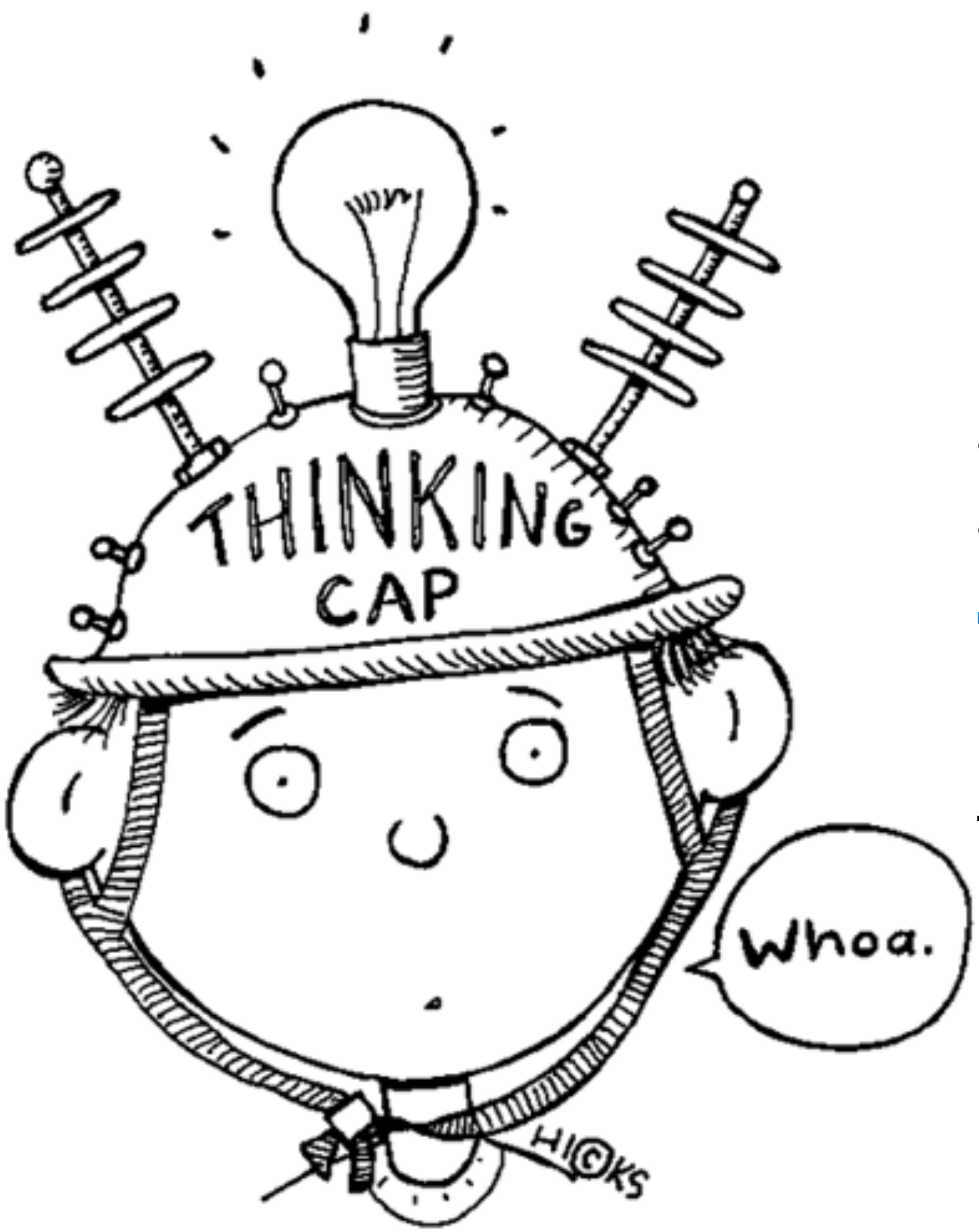
Outline

1. **Why** scalar-tensor theory?
2. Action, equations, **numerics**
3. **Core collapse** and GW breathing mode
4. **Multi-scalars** and target space

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:

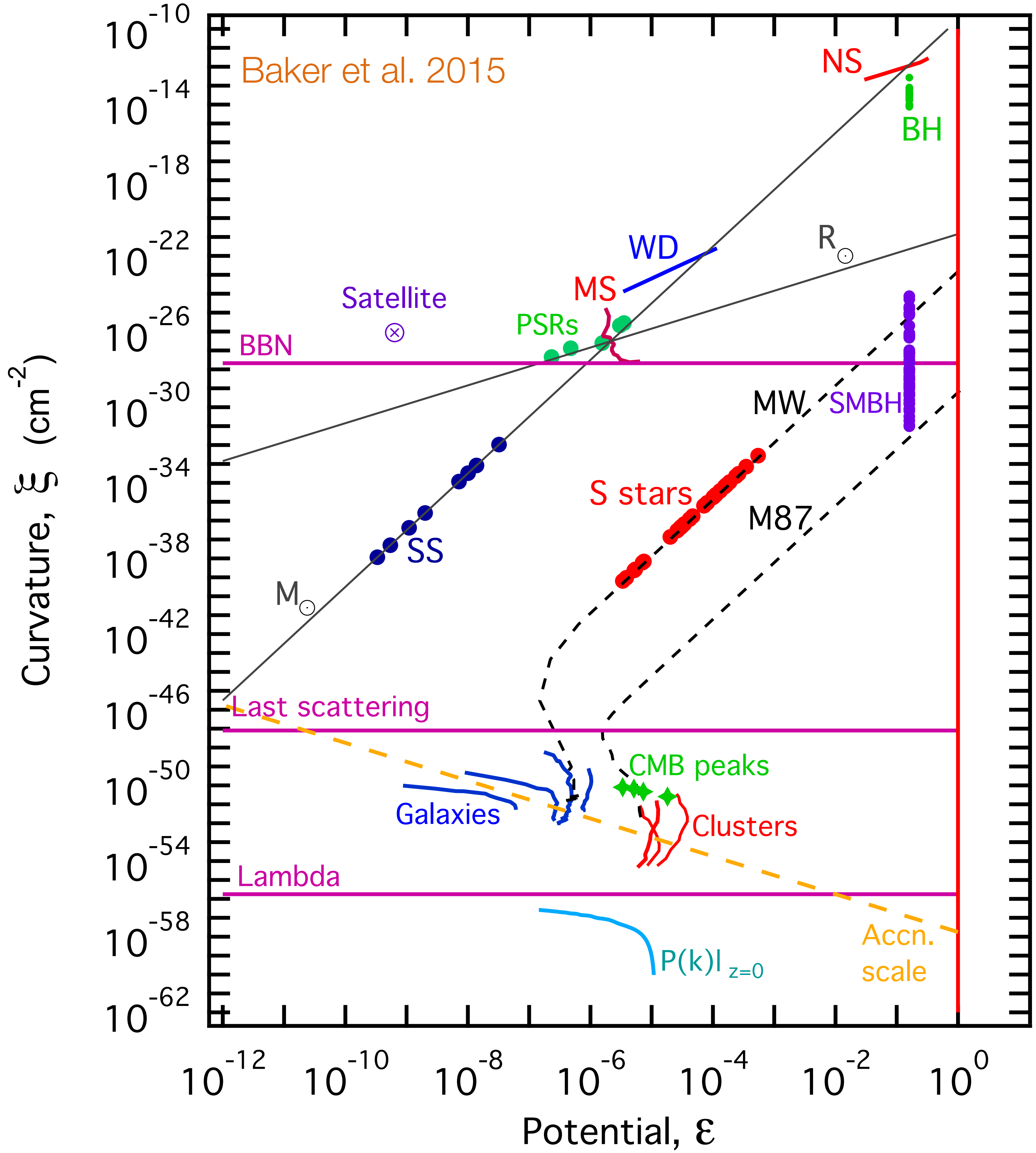
- Dark energy makes up most of the Universe
- Why is Lambda so small?

Tests

- GR is extremely well tested “in between” these two regimes $1\,\mathrm{mm} \lesssim L \lesssim 1\,\mathrm{AU}$

Extreme challenge for theorists

Strong-field test of gravity



Gravitational field

$$\epsilon \equiv \frac{GM}{rc^2}$$

Curvature (Kretschmann)

$$\xi = \left(R^{\alpha\beta\gamma\delta} R_{\alpha\beta\gamma\delta}\right)^{1/2} = \sqrt{48}\,\frac{GM}{r^3 c^2}$$

For a compass to navigate this alternative theory business: Berti et al. 2015

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
- **(Multi-)Scalar-tensor theories**: gravity mediated by the metric and additional scalar field(s)
- Some high-energy theories predict GR + scalars as their low-energy limit.

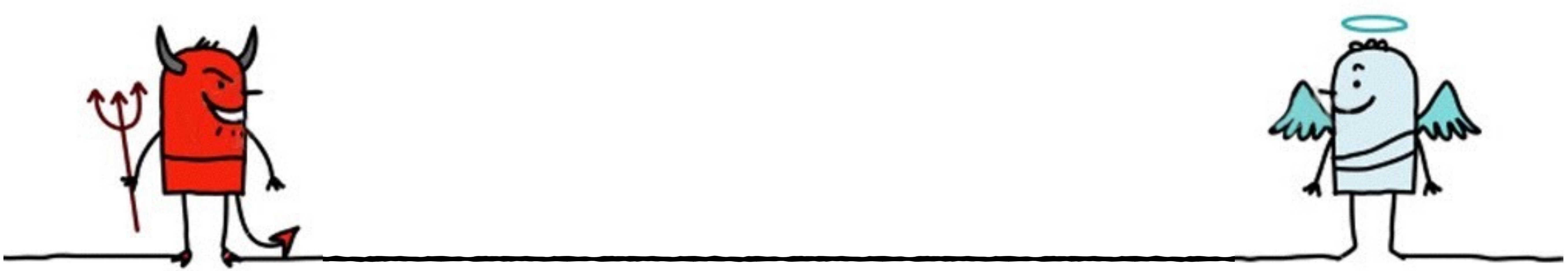
  cf e.g. review by Will 2014

Complicated enough

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

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)

Damour and Esposito-Farese 1992

Moreover…

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

Conformal tranformation: $\bar{g}_{\mu\nu} = F g_{\mu\nu}$

Einstein frame

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

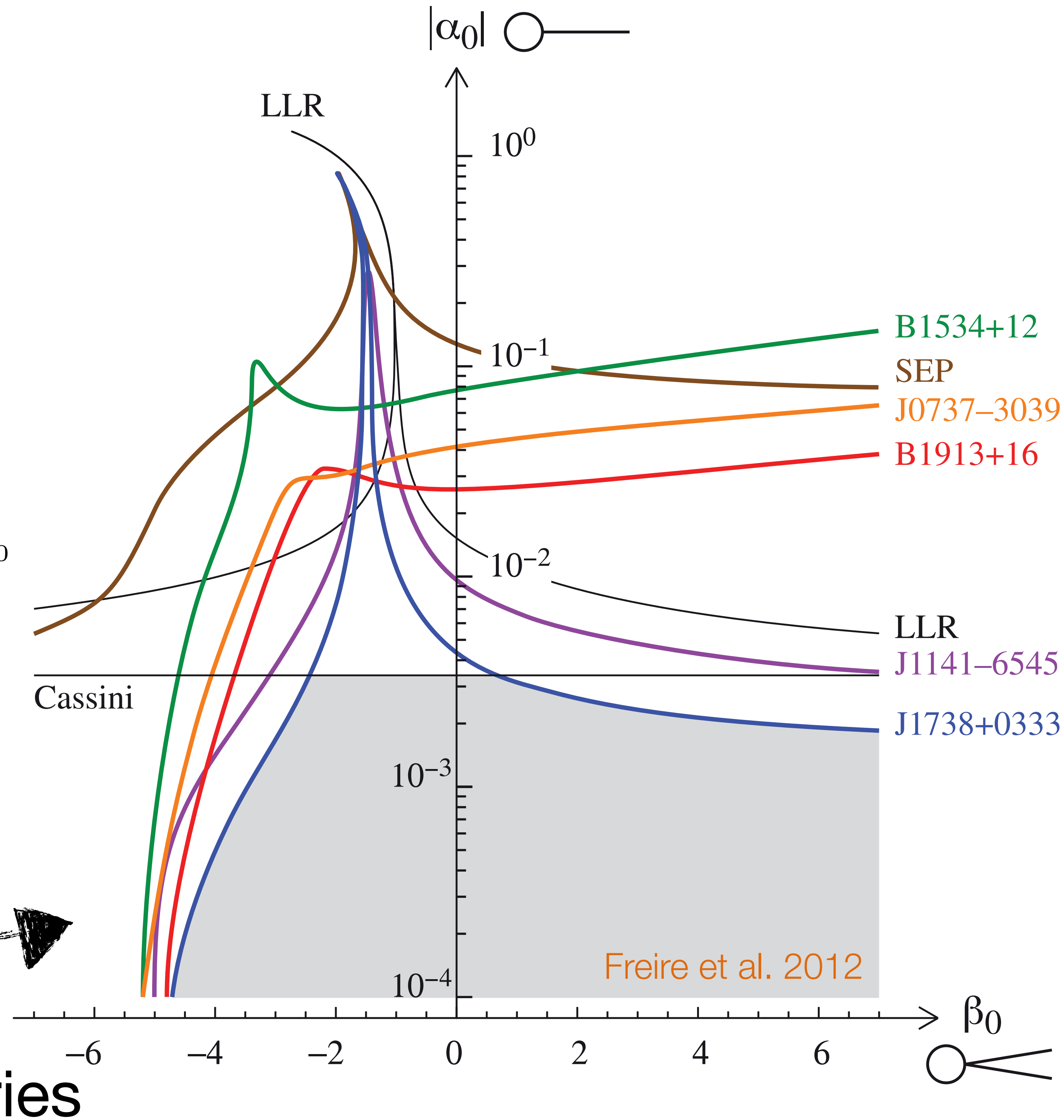
Dominant corrections to GR

1PN corrections in ST theories depend on two parameters only

$$\varphi_0 = \lim_{r\to\infty} \varphi$$

$$\alpha_0 = -\frac{1}{2}\frac{\partial \log F}{\partial \varphi}\bigg|_{\varphi=\varphi_0} \qquad \beta_0 = -\frac{1}{2}\frac{\partial^2 \log F}{\partial \varphi^2}\bigg|_{\varphi=\varphi_0}$$

Experimental constraints

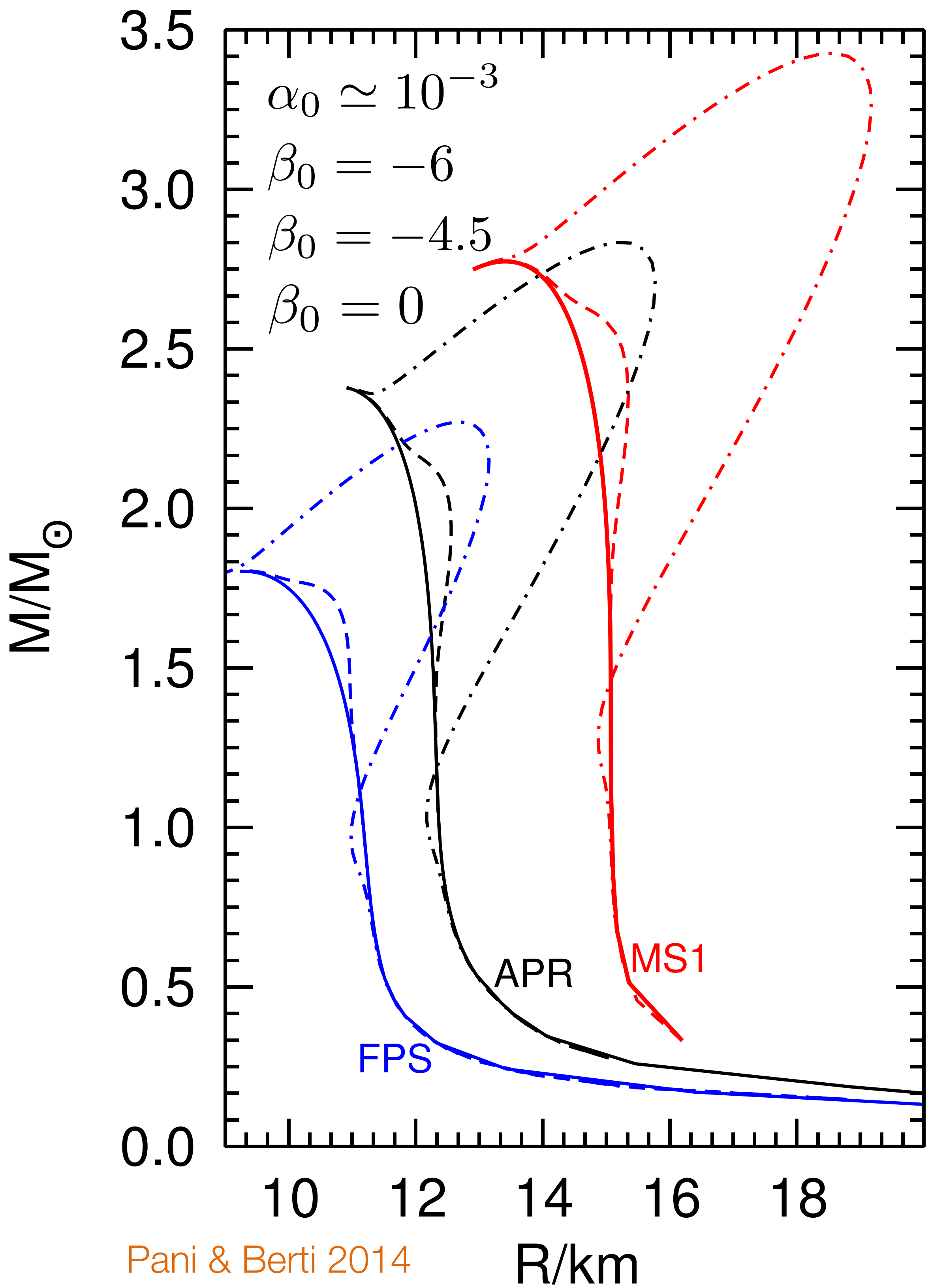


Let's take this subset of ST theories

coupling function $F = \exp\left[-2\alpha_0(\varphi-\varphi_0) - \beta_0(\varphi-\varphi_0)^2\right]$

Spontaneous scalarization

Damour and Esposito-Farese 1993, 1996



Pani & Berti 2014

Perturbative corrections enters as…

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

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!

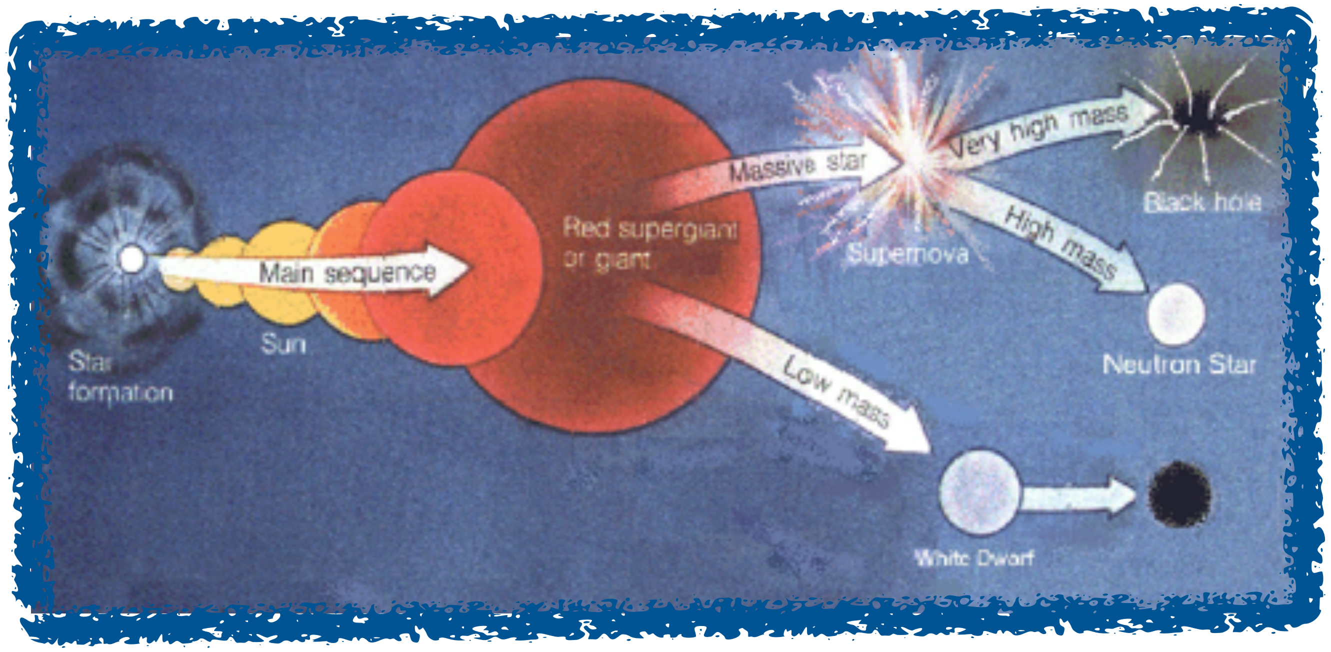
Fundamental threshold:

Novak 1998, Harada 1998

$$\beta_0 \lesssim -4.35$$

Core collapse in a nutshell

- End of star's life: iron core supported by **degenerate pressure of rel. electrons.**
- Collapse, outgoing shock, Type II supernova
- Core is left behind as a **neutron star**
- Accretion: **BH formation**



Type II SN are as luminous as entire galaxies

Are non-trivial scalar-field profiles excited following core-collapse?

How about GWs?

Hydrodynamics in ST theories

Jordan frame

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

$$G_{\mu\nu} = \frac{8\pi}{F}\left(T^F_{\mu\nu} + T^\phi_{\mu\nu} + T_{\mu\nu}\right)$$

$$T^F_{\mu\nu} = \frac{1}{8\pi}(\nabla_\mu\nabla_\nu F - g_{\mu\nu}\nabla^\rho\nabla_\rho F)$$

$$T^\phi_{\mu\nu} = \partial_\mu\phi\partial_\nu\phi - \frac{1}{2}g_{\mu\nu}\partial^\nu\phi\partial_\nu\phi$$

→ **Einstein equations**

$$\nabla^\rho\nabla_\rho\phi = -\frac{1}{16\pi}F_{,\phi}R$$

→ **Wave equation**

Radial gauge → $$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = -\alpha^2 dt^2 + X^2 dr^2 + \frac{r^2}{F}d\Omega^2$$

Perfect fluid → $$T_{\alpha\beta} = \rho h u_\alpha u_\beta + P g_{\alpha\beta} \qquad u^\mu = \frac{1}{\sqrt{1-v^2}}\left[\frac{1}{\alpha},\ \frac{v}{X},\ 0,\ 0\right]$$

cf. also Novak 1998a,b
Novak & Ibanez 2000

1. Curvature equations

Constraints for the enclosed mass and metric potential

2. Scalar-field wave equations

3 first-order PDEs

second-order finite differences + outgoing boundary condition

3. Matter equations

ρ : mass density
h : enthalpy
v : radial velocity

Primitive variables → **Conserved variables**

$$D = \frac{\rho X}{F\sqrt{F}\sqrt{1-v^2}},$$
$$S^r = \frac{\rho h v}{F^2(1-v^2)},$$
$$\tau = \frac{\rho h}{F^2(1-v^2)} - \frac{P}{F^2} - D$$

$$\partial_t \mathbf{U} + \frac{1}{r^2}\partial_r \left[r^2 \frac{\alpha}{X} \mathbf{f}(\mathbf{U}) \right] = \mathbf{s}(\mathbf{U})$$

Integrated with high-resolution shock-capturing schemes

Code built on top of GR1D O'Connor & Ott 2010

Mimicking nuclear physics

We need an **equation of state** to close the system

Hybrid EOS:

Janka, Zwerger, Moenchmeyer 1993
Zwerger, Mueller 1997

$$P = P_{\mathrm{c}} + P_{\mathrm{th}}$$

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

$$P_{\mathrm{th}} = (\Gamma_{\mathrm{th}} - 1) \rho \epsilon_{\mathrm{th}}$$

$$\epsilon_{\mathrm{th}} = \epsilon - \epsilon_c$$

Piecewise polytropic

- Iron core collapse

$$\Gamma_1 \lesssim 4/3$$

- Stiffening at nuclear densities

$$\Gamma_2 \simeq 2.5 - 3$$

Ideal gas

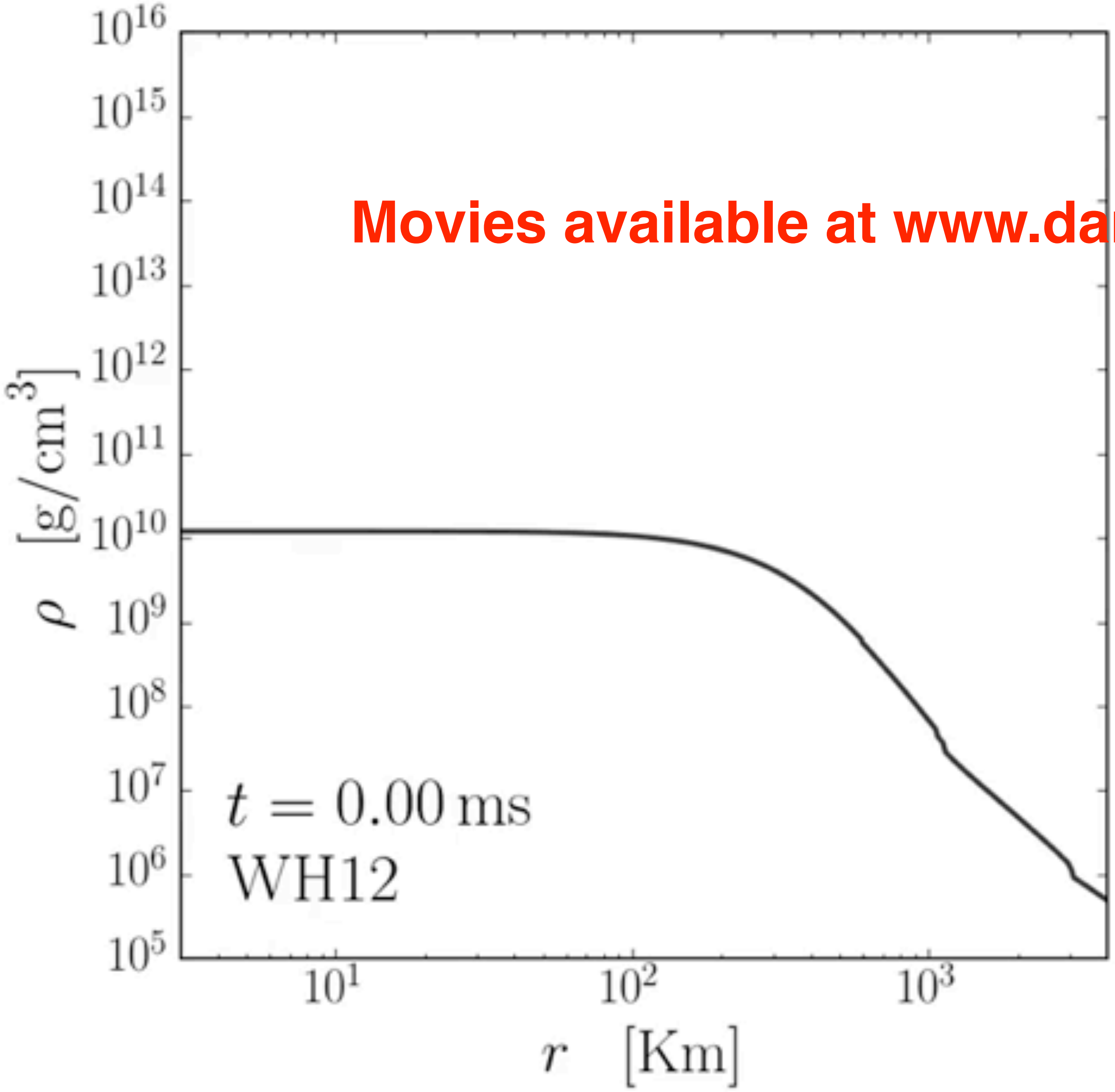
- Response of the heated post-shock material

$$4/3 < \Gamma_{\mathrm{th}} < 5/3$$

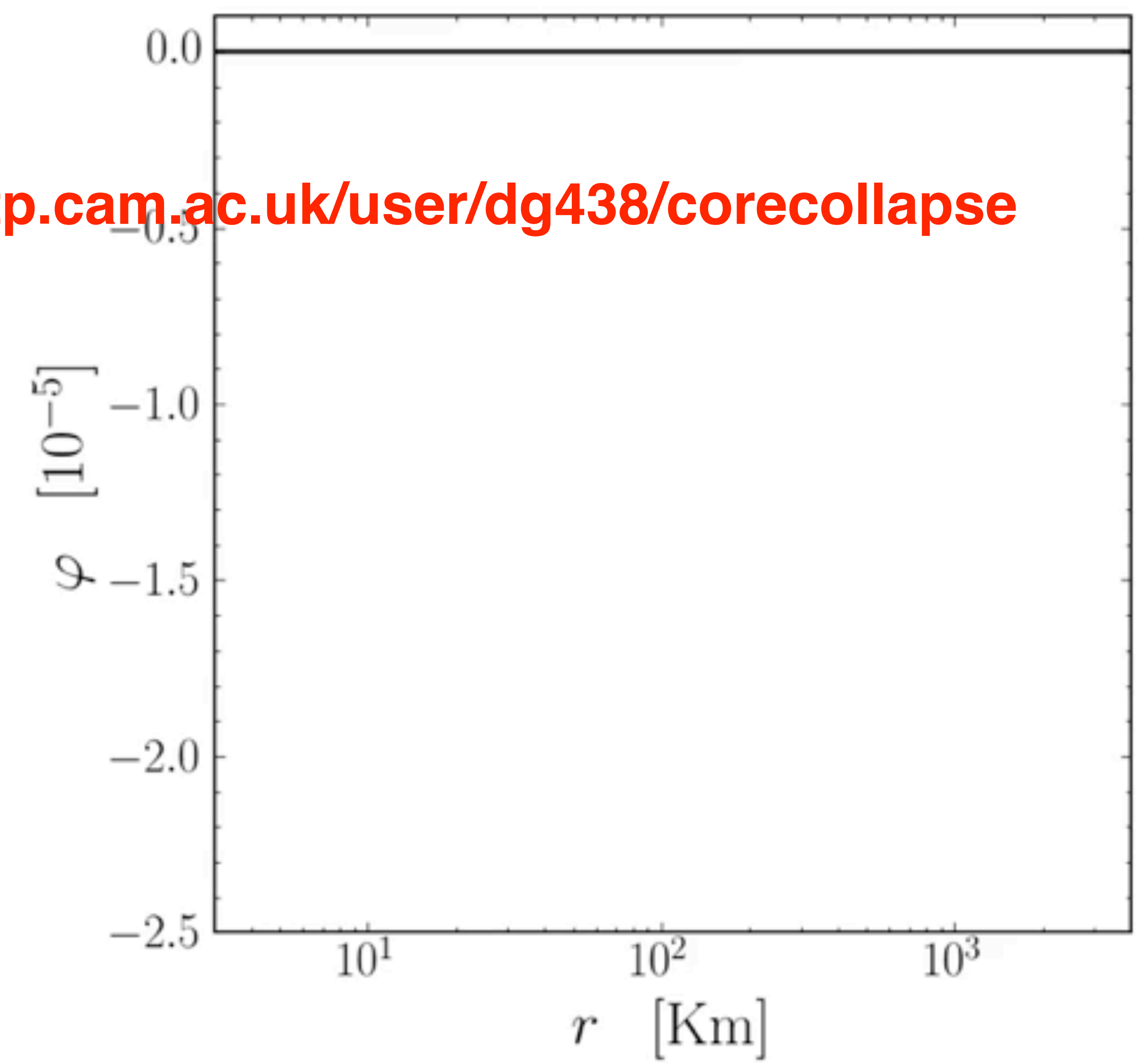
Tested against finite-temperature EOS: Dimmelmeier et al. 2007, 2008

Collapse, bounce, shock… and NS

Mass density | Scalar field



Movies available at www.damtp.cam.ac.uk/user/dg438/corecollapse



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

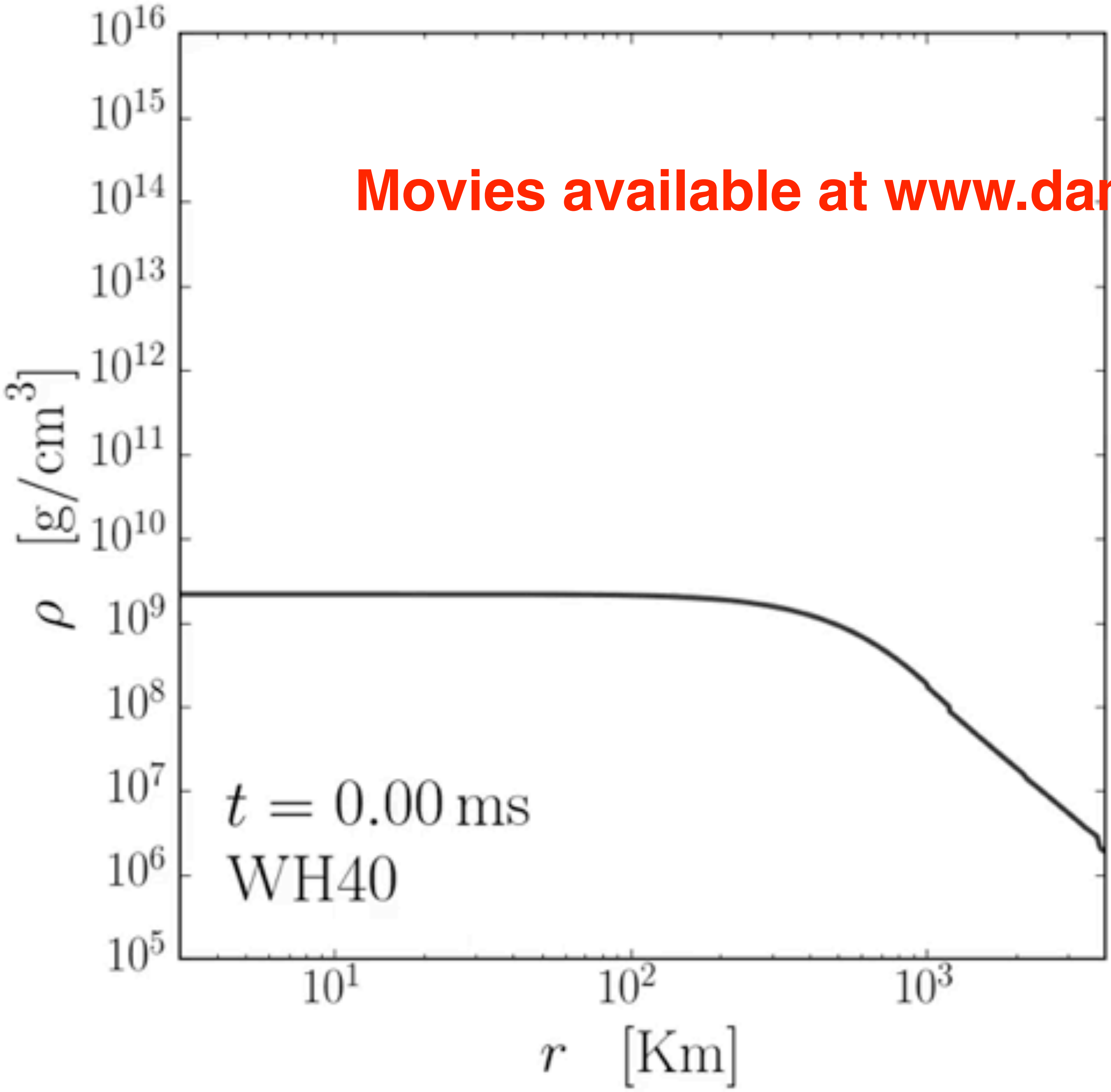
ST theory $\alpha_0 = 10^{-4}$ $\beta_0 = -4.35$

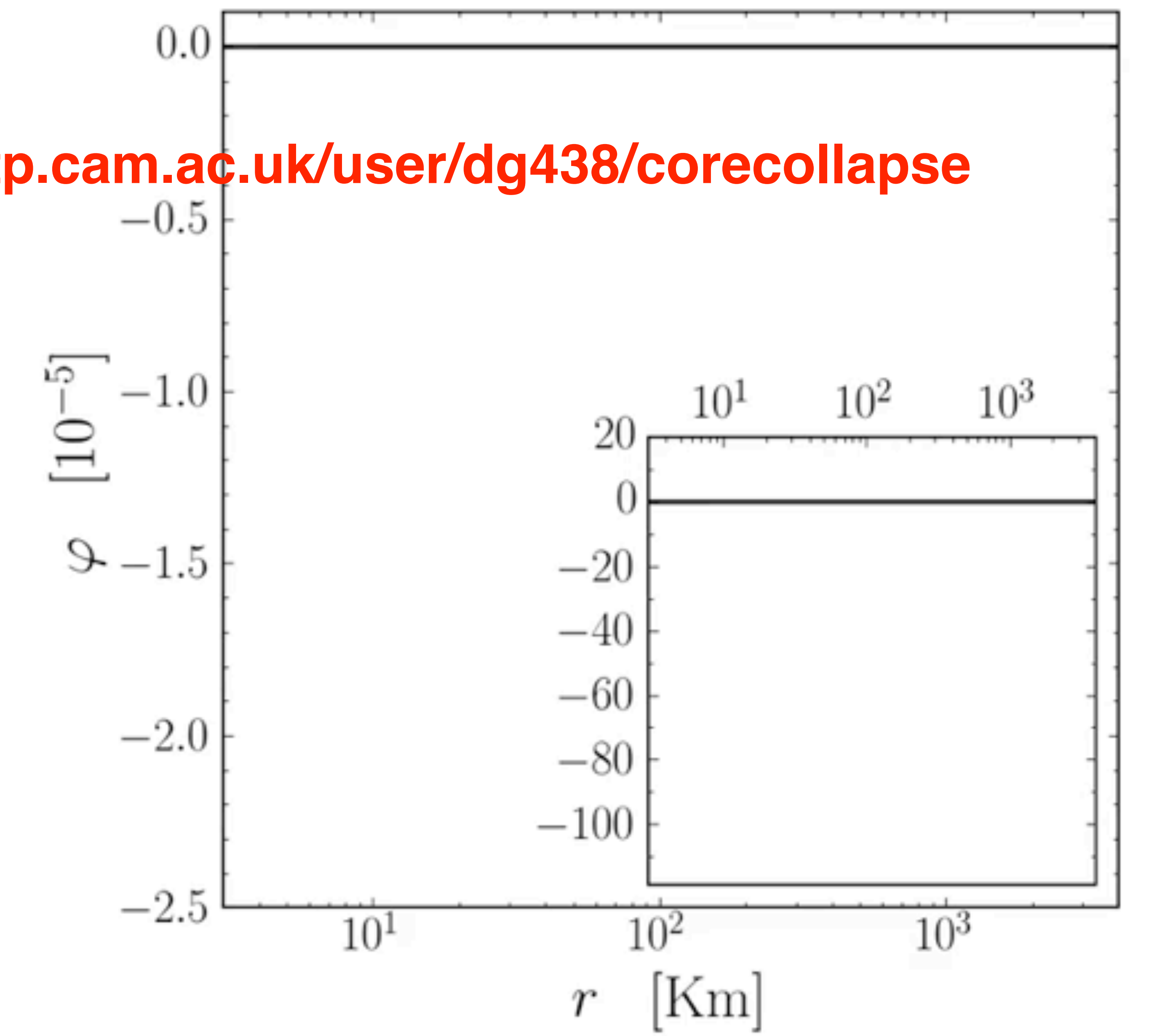
First collapse of realistic massive star through bounce in ST theory

Collapse, bounce, shock… and BH

Mass density | **Scalar field**

Movies available at www.damtp.cam.ac.uk/user/dg438/corecollapse





Initial profile: realistic SN progenitor $M_{\rm ZAMS} = 40 M_\odot$ Woosley & Heger 2007

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

First collapse of realistic massive star through bounce in ST theory

Proof of convergence

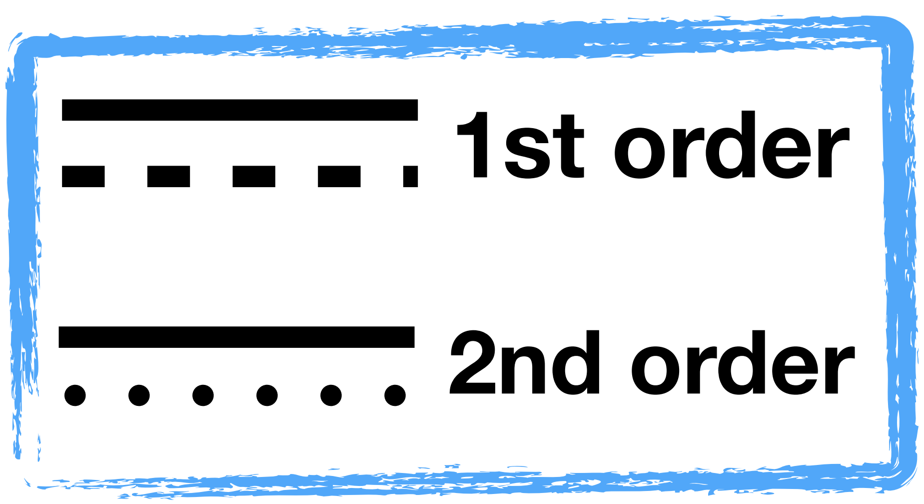
$\alpha_0 = 10^{-4}$
$\beta_0 = -4.5$

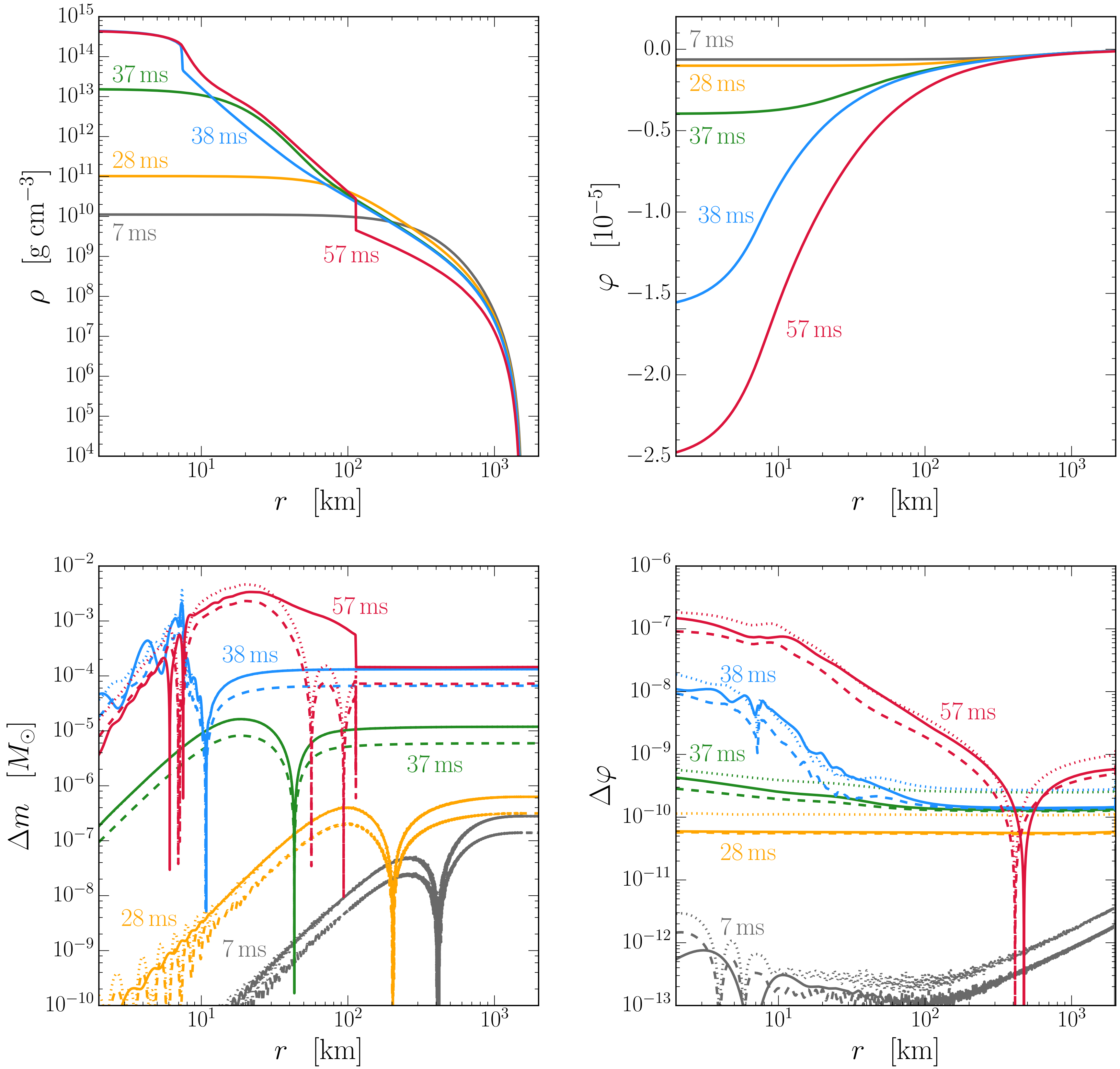
Self-convergence factor

$$Q = \frac{q_1 - q_2}{q_2 - q_3} = \frac{(dr_1)^n - (dr_2)^n}{(dr_2)^n - (dr_3)^n}$$

n: numerical scheme

- PREshock n=2
- POSTshock n=1





Breathing mode

In ST theories there are GWs in spherical symmetry

Damour and Esposito-Farese 1992

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

Time domain waveform

Scalar field

Extraction radius

Distance

Coupling with the detector

Microphysics

Hybrid EOS:

$$P = P_{\rm c} + P_{\rm th}$$

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

$$P_{\rm th} = (\Gamma_{\rm th} - 1)\rho\epsilon_{\rm th}$$

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

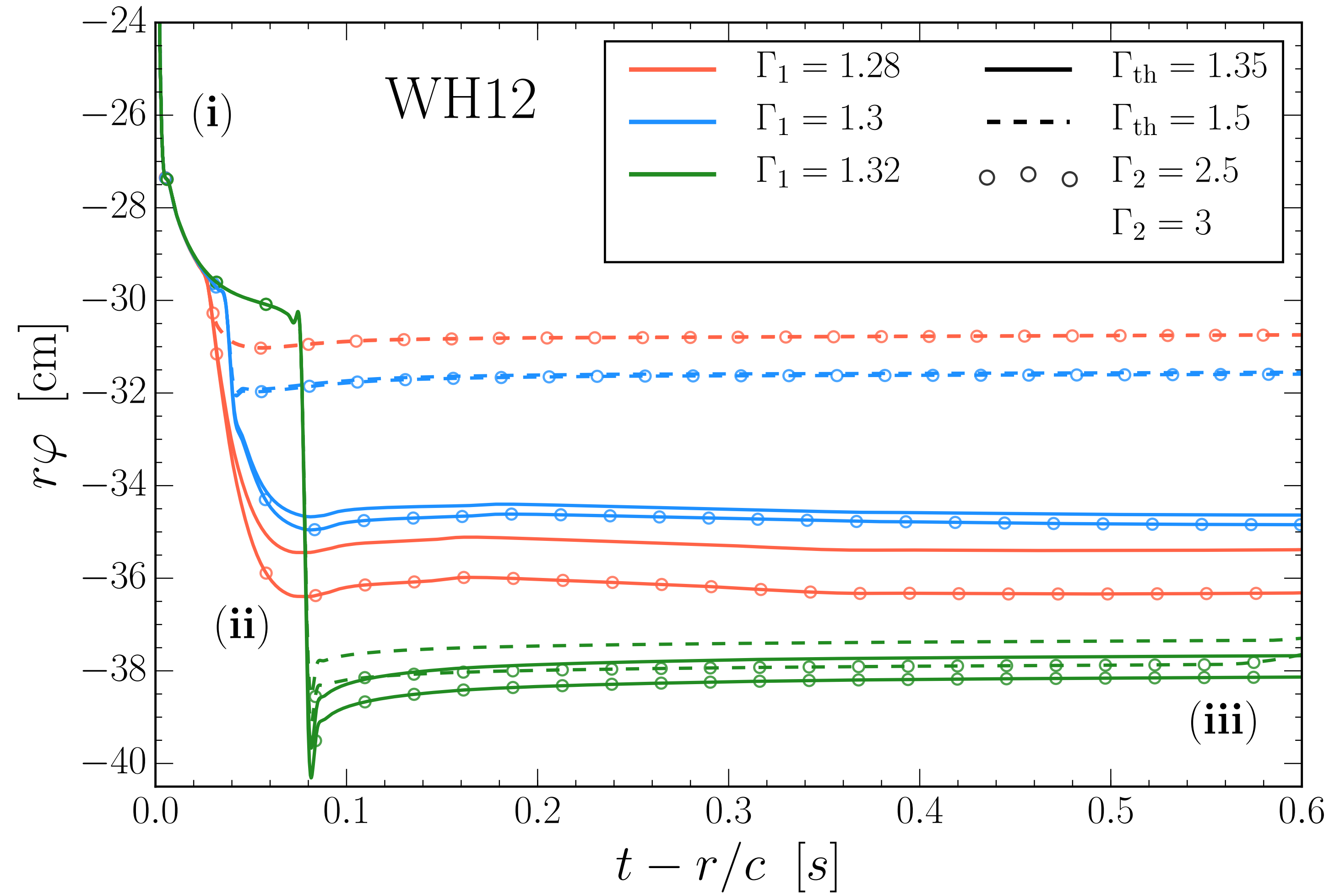
(i) Collapse

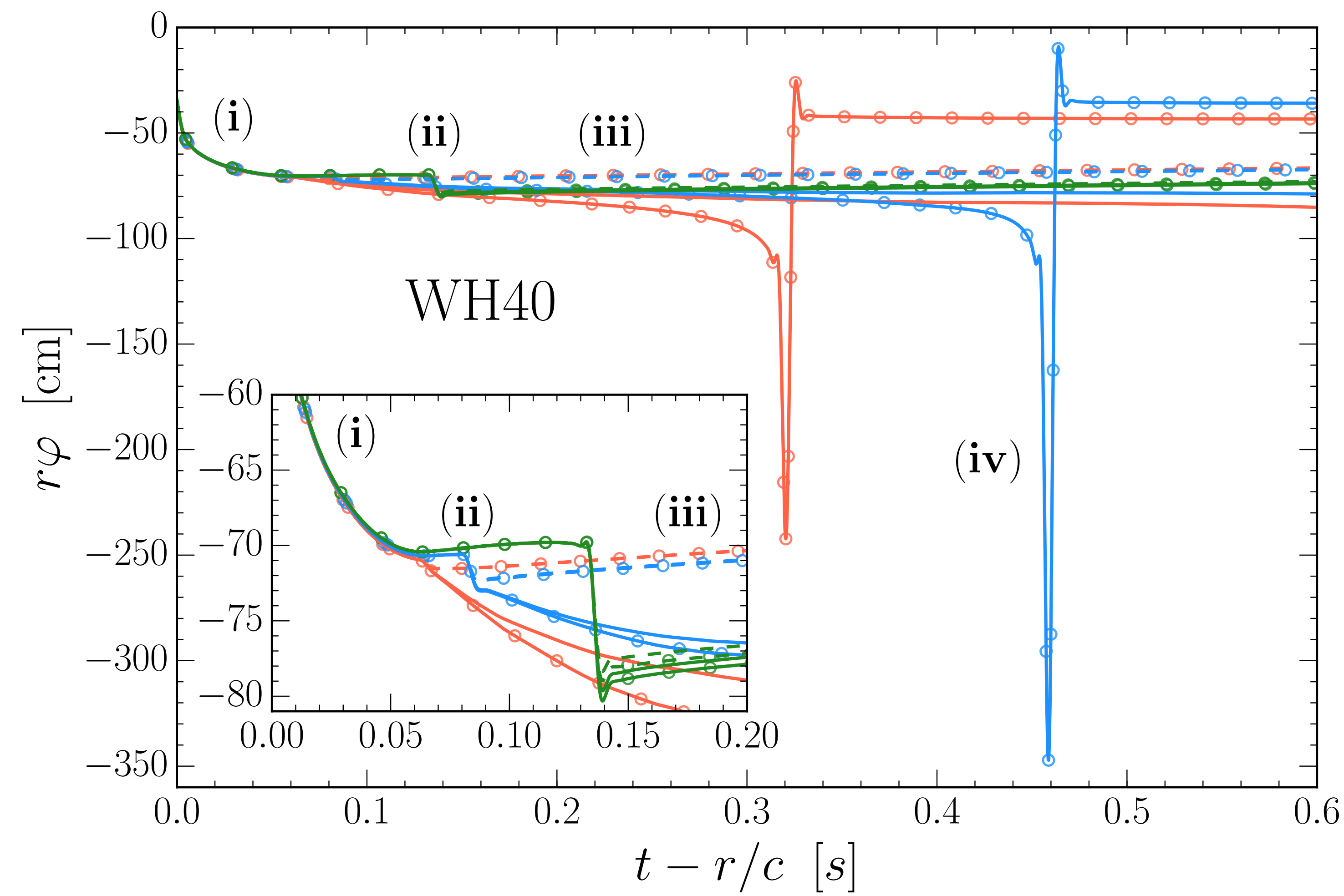
(ii) Bounce!

(iii) Core forms a NS

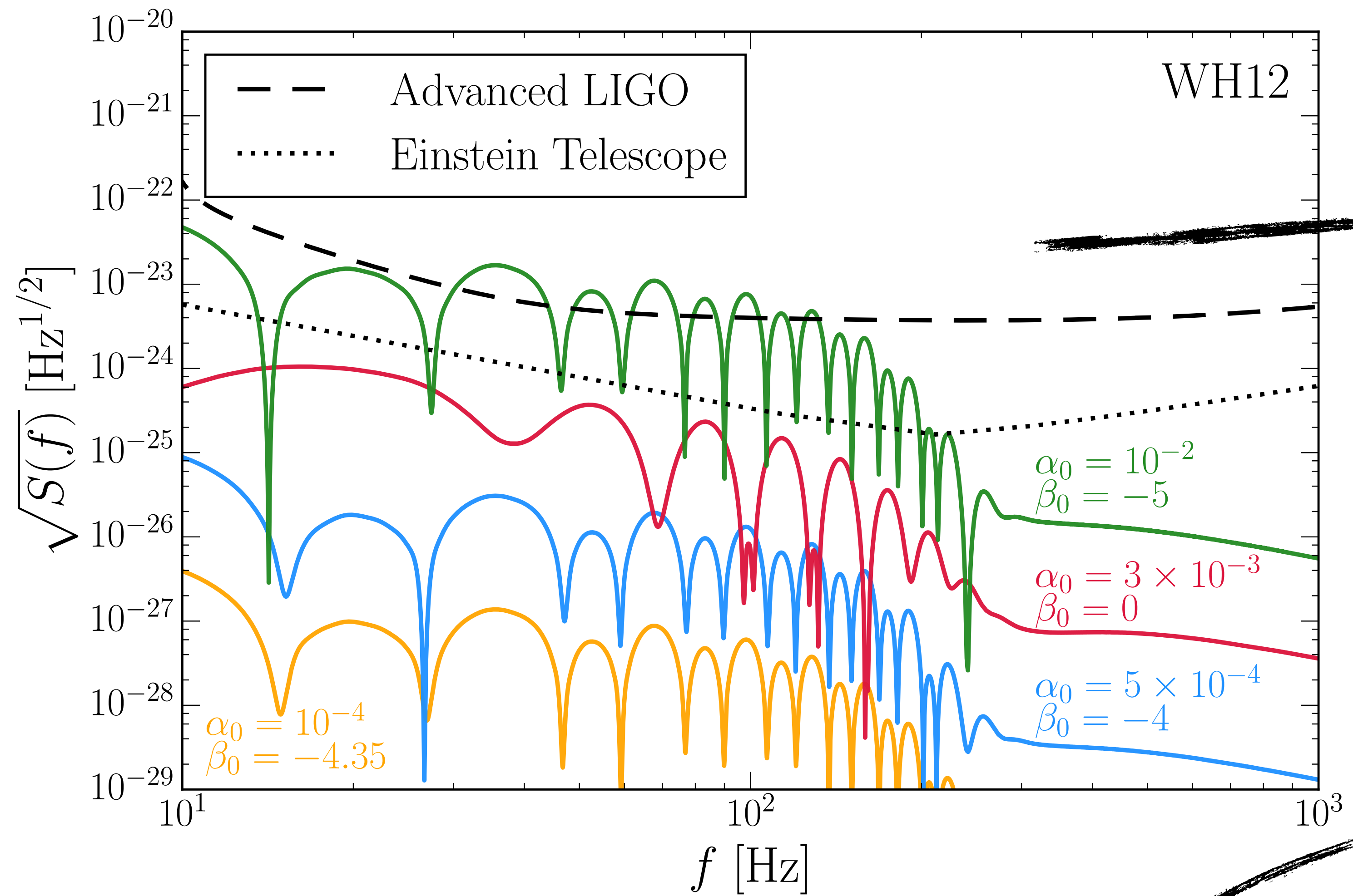
(iv) Collapse to a BH

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





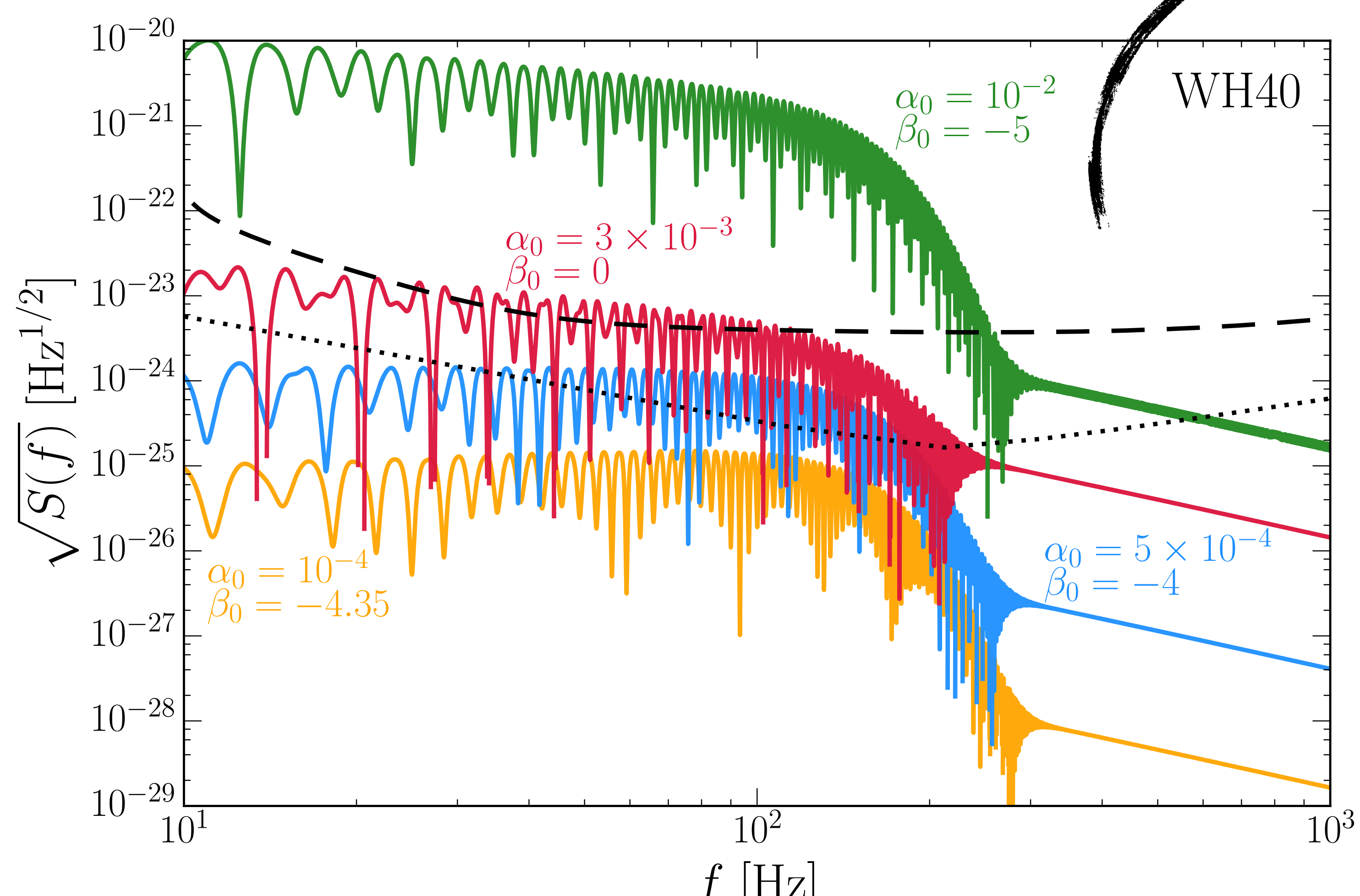
Monopolar GWs



$$M_{\rm ZAMS} = 12 M_\odot$$

Can't get enough compactness for spontaneous scalarization

- We need better microphysics! Neutrino transfer and cooling?



$$M_{\rm ZAMS} = 40 M_\odot$$

Powerful signal from BH formation

- Is transition to spontaneously scalarized star important?

Marginal detectability with Ad. LIGO for galactic sources

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

Horbatsch el at. 2015

One, two, many.

Tensor-multi-scalar theories

$$S = \frac{1}{4\pi G_\star}\int d^4x\sqrt{-g}\left[\frac{R}{4} - \frac{1}{2}g^{\mu\nu}\gamma_{AB}(\varphi)\partial_\mu\varphi^A\,\partial_\nu\varphi^B - V(\varphi)\right] + S_{\rm m}[A^2(\varphi)g_{\mu\nu};\Psi]$$

One example: **maximally symmetric two fields**

$$S = \frac{1}{4\pi G_\star}\int d^4x\sqrt{-g}\left[\frac{R}{4} - g^{\mu\nu}\gamma(\varphi,\bar\varphi)\nabla_\mu\bar\varphi\,\nabla_\nu\varphi - V(\varphi,\bar\varphi)\right] + S_{\rm m}[A^2(\varphi,\bar\varphi)g_{\mu\nu};\Psi]$$

$$\gamma(\varphi,\bar\varphi) = \frac{1}{2}\left(1+\frac{\bar\varphi\varphi}{4\mathfrak{r}^2}\right)^{-2}$$

$$\log A(\varphi,\bar\varphi) = \alpha^*\varphi + \bar\alpha^*\bar\varphi + \frac{1}{2}\beta_0\varphi\bar\varphi + \frac{1}{4}\beta_1^*\varphi^2 + \frac{1}{4}\bar\beta_1^*\bar\varphi^2$$

Curvature radius

Coupling function

Interactions between the fields: **target space**

Basically unconstrained! Genuine two-field physics?

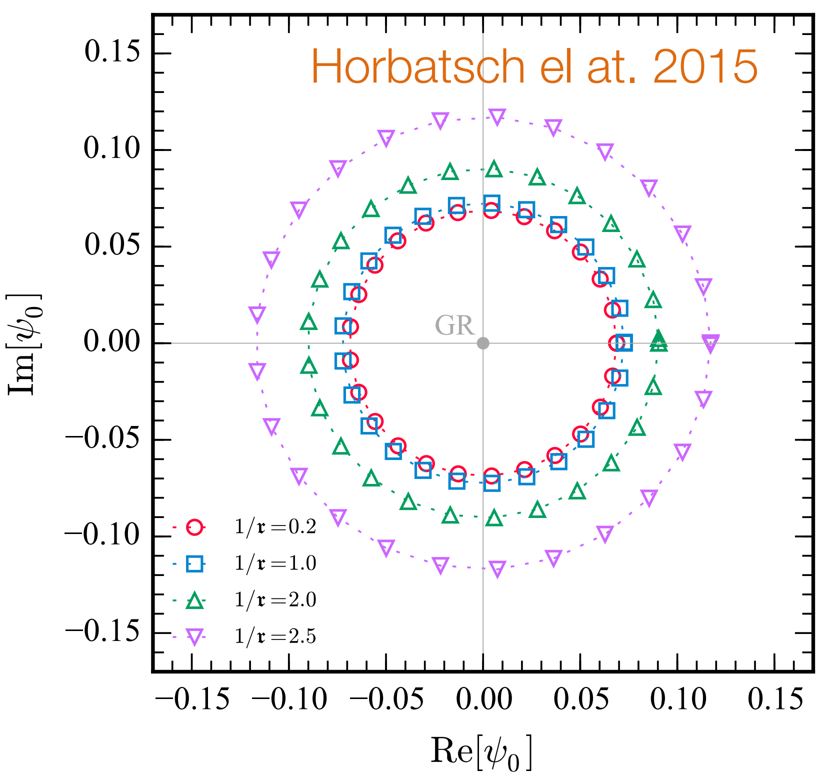
Curvature radius

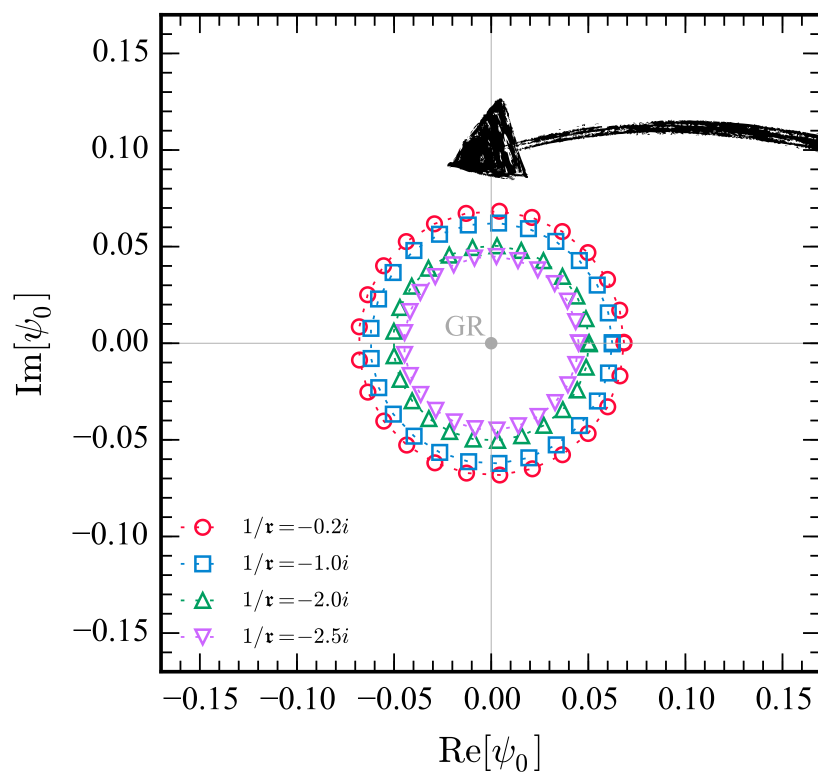
$$\log A(\psi, \bar{\psi}) = \alpha\psi + \bar{\alpha}\bar{\psi} + \frac{1}{2}\beta_0\psi\bar{\psi} + \frac{1}{4}\beta_1\psi^2 + \frac{1}{4}\beta_1\bar{\psi}^2$$

$$\alpha = 0 \quad \beta_1 = 0$$

Rotation symmetry

$$A(\psi, \bar{\psi}) = \exp\left(\frac{1}{2}\beta_0\psi\bar{\psi}\right)$$

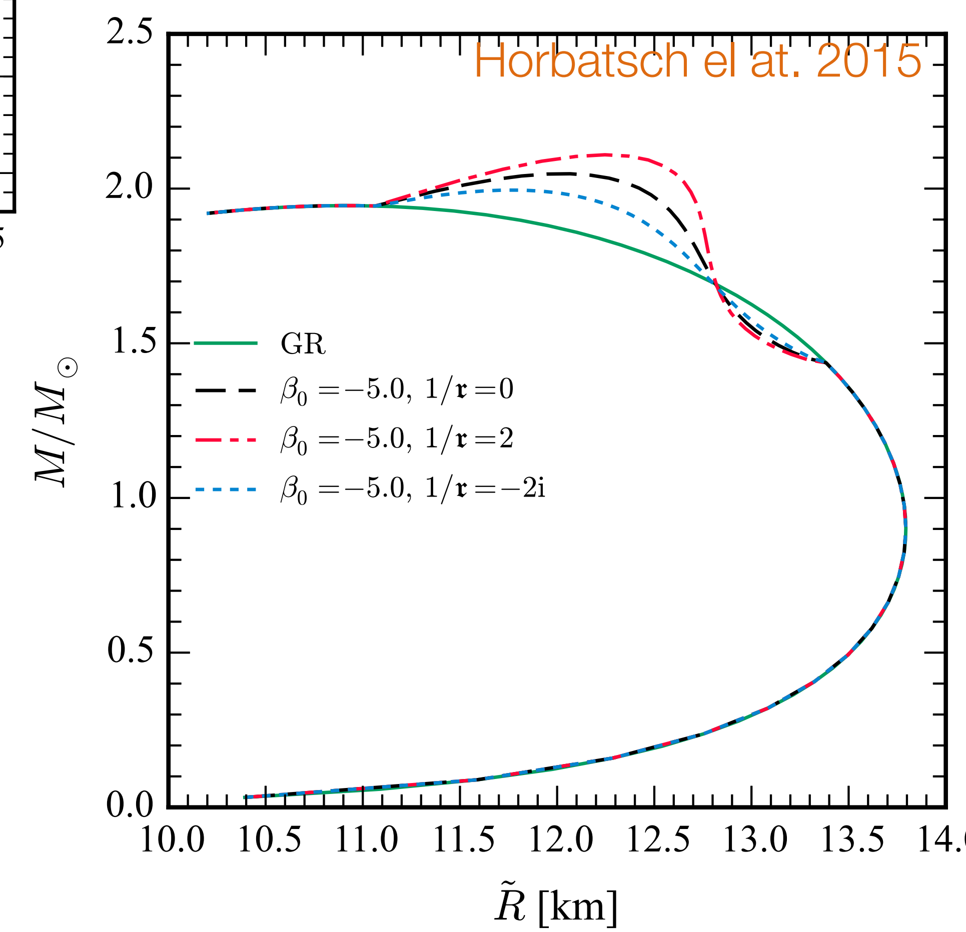




Central value of the scalar field

just a circle…

Neutron stars mass/radius



Neutron stars feel the target space!

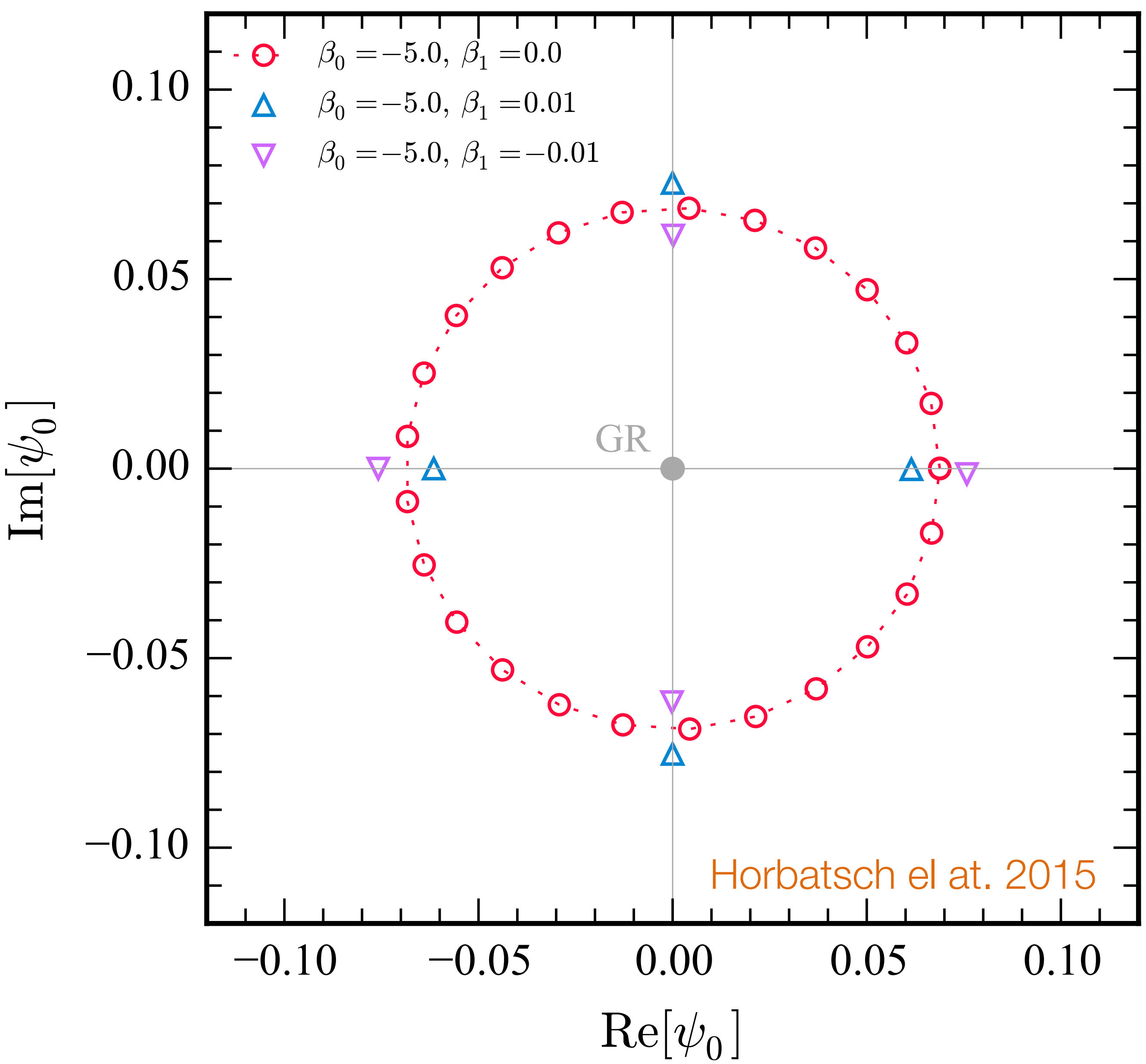
Breaking the symmetry

$$\log A(\psi,\bar{\psi}) = \alpha\psi + \bar{\alpha}\bar{\psi} + \frac{1}{2}\beta_0\psi\bar{\psi} + \frac{1}{4}\beta_1\psi^2 + \frac{1}{4}\beta_1\bar{\psi}^2$$

$\alpha = 0 \quad \beta_1 \neq 0$

~~Rotation symmetry~~

~~$A(\psi,\bar{\psi}) = \exp\left(\frac{1}{2}\beta_0\psi\bar{\psi}\right)$~~



Central value of the scalar field

The circle collapses to a cross… even for arbitrarily small β_1

Not yet understood…
genuine biscalarization found only for $\alpha \neq 0$

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4. **Multi-scalars** and target space **arXiv:1505.07462**