Instituto Argentino de Radioastronomía

Relativistic Astrophysics and Radio Astronomy Group (GARRA)

Black Hole Mimickers

Daniela Pérez and Gustavo E. Romero

Instituto Argentino de Radioastronomía (IAR-CCT CONICET)

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Contact: danielaperez@iar-conicet.gov.ar

Do black holes exist?

•**<u>The astrophysicist</u>**: yes, sure there is something like to black holes in the universe! They are an essential part of the current astrophysical mechanisms we use to explain a lot of facts: production of relativistic jets, stellar motions in the Galactic centre, tidal disruption of stars, galaxy formation, etc.

•**<u>The particle physicists</u>**: Black hole are disgusting entities. They should not exist. They destroy unitary evolution of quantum systems. A plethora of weird ideas: firewalls, fuzz balls, etc.

Is there an intermediate position?

•**The relativist**: well, black holes are objects of infinite redshifts and horizons, which are globally defined surfaces. In principle, you can mimick the behaviour of a black hole with arbitrary precision if you are ready to pay the price…

- **Mimicker**: an astrophysical object that behaves like a black hole for any possible astrophysical observation …but it is not. There is no event horizon neither trapped surfaces associated with it.

What price a mimicker?

You have to violate the conditions of the singularity theorem for gravitational collapse (Penrose 1965). This would mostly imply to violate some energy conditions.

You can do that in a variety of ways. Sometimes, you will need to add some new scalar or other fields to the ontology of the world. This approach is not recommended by Ockham's razor. The fewer are the entities we need to postulate to explain the universe, the better.

Some proposals:

•**Quark stars/ strange stars**: These are objects with a stiff equation of state that allows matter to exist in a hyper-dense regime. Objection: stable static compact stars require anisotropy stress (Cattoen et al. 2005).

•**Boson stars**: The particles in these objects do not obey Pauli's exclusion principle, so they can be very compact . Objection: you need to add a scalar field…and still you will have the stress problem.

•**Gravastars:** Hypothetical objects with a de Sitter core. Objection: plagued with instabilities.

All these are non-dynamical (static) systems

Dynamical mimickers?

One possibility are **Dark Stars** (e.g. Barceló et al. 2008): an ever collapsing objects that, nonetheless, never develops an horizon. To achieve this, quantum effects are usually invoked.

Another possibility is to explore gravitational collapse of matter with an equation of state such that a smooth transition is allowed from a polytropic state to a state of infinite rigidity in order to enforce a bounce.

An EoS of this type has been recently proposed by Mboyne & Kazanas (2005) and used to describe a regular black hole interior. This interior, however, was demonstrated to be dynamically and thermodynamically unstable by Pérez, Romero, & Perez Bergliaffa (2013).

Proposal:

A black hole can be mimicked by a bouncing system described by the M&K's EoS if the bounce occurs on timescales longer than the Hubble time.

…let's see.

Equation of state (Mbonye & Kazanas 2005):

$$p_r = \left[\alpha - (\alpha+1)\left(\frac{\rho}{\rho_{max}}\right)^2\right]\left(\frac{\rho}{\rho_{max}}\right)\rho$$

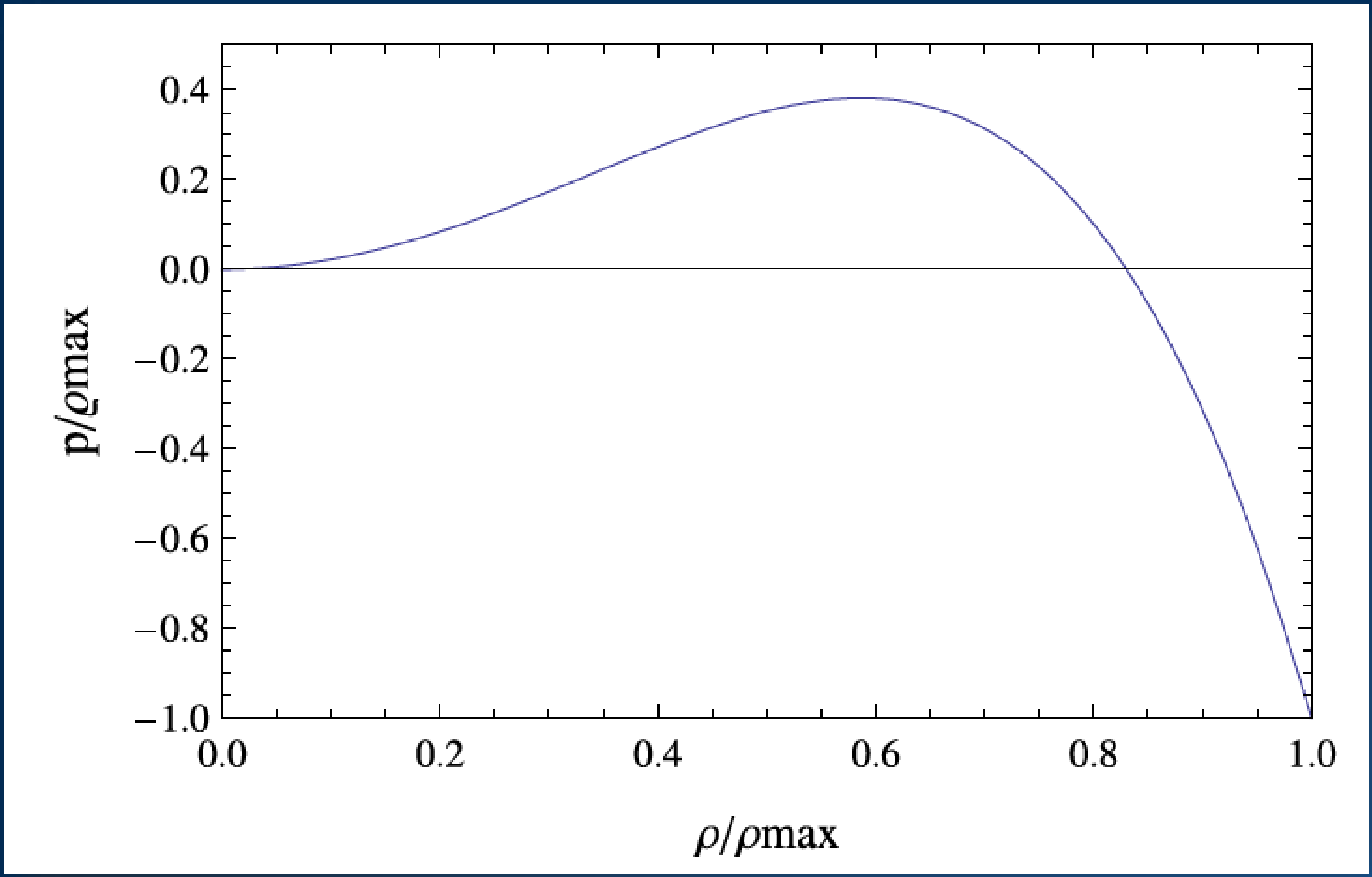
$\alpha = 2.2135$

Density profile (Dymnikova 1992, Yahil 1983)

$$\rho(r,t) = \rho_{max}\exp\left(-\frac{r}{R_*}\right)^3\left[\frac{1-\exp\left(-\frac{t}{T}\right)^2}{(t/T)^2}\right]$$

where the maximum density is the density at the bounce.
We adopt here a value of $0.2\ 10^{18}$ g/cm^3, higher than the highest densities probed at the LHC. It is conceivable that at such densities matter might undergo a change to some repulsive state as the one described by the M&K's EoS (p= - rho, which violates the energy conditions).

Pressure as a function of the density (Mbonye and Kazanas 2005)



Gravitational collapse and bounce

We study the Misner-Sharp equations along for a fluid described by M&K EoS.

We adopt the following initial conditions for the collapsing core of a massive star:

$M_{gravitational} = 4\ M_{sun}$
$R_{initial} = 30$ km

The metric has the diagonal form:

$$\begin{aligned} ds^2 &= -e^{2\phi}dt^2 + e^{\lambda}dr^2 + R^2 d\Omega^2, \\ d\Omega^2 &= d\theta^2 + \sin^2\theta d\varphi^2. \end{aligned}$$

Here [illegible] [illegible] and *R* are functions of the radial coordinate r and the coordin

$$U = D_t R \equiv e^{-\phi}\dot{R},$$

$$D_t = u^\mu \frac{\partial}{\partial x^\mu} = e^{-\phi}\left(\frac{\partial}{\partial t}\right)_r .$$

Full set of collapse equations (Misner & Sharp 1964)

$$\begin{aligned}
D_t R &= U, \\
D_t m &= -4\pi R^2 p U, \\
D_t U &= -\left[\frac{1 + U^2 - 2mR^{-1}}{\epsilon + p}\right]\left(\frac{\partial p}{\partial r}\right)_t \\
&\quad - \frac{m + 4\pi R^3 p}{R^2}, \\
\left(\frac{\partial m}{\partial R}\right)_t &= 4\pi R^2 \epsilon, \\
e^\phi &= (-g_{00})^{1/2} = 1/h, \\
\left(\frac{dA}{dr}\right)_{t=0} &= \frac{4\pi R^2 n}{(1 + U^2 - 2mR^{-1})^{1/2}} \frac{\partial R}{\partial r}.
\end{aligned}$$

with

$$e^{\lambda(r,t)} = g_{rr} = \left[1 + U^2 - \frac{2m(r,t)}{R}\right]^{-1} \left(\frac{\partial R}{\partial r}\right)^2 .$$

$$m(r,t) = \int_0^R 4\pi R^2 \, \epsilon \, dR,$$

In order to solve the Misner & Sharp equations, it is sufficient to specify:

p(n) equation of state.
ϵ(n) energy density of the matter

From these two quantities, we can calculate the enthalpy *h*

$$h = \left(\frac{\partial \epsilon}{\partial n}\right)_s .$$

From M&K EoS:

$$p(n) = \left[\alpha - (\alpha+1)\left(\frac{n}{n_{\mathrm{max}}}\right)^2\right]\left(\frac{n^2}{n_{\mathrm{max}}}\right),$$

$$e(n) = \left[\alpha - \frac{1}{3}(\alpha+1)\left(\frac{n}{n_{\mathrm{max}}}\right)^2\right]\left(\frac{n^2}{n_{\mathrm{max}}}\right),$$

$$h(n) = 2\left[\alpha - \frac{2}{3}(\alpha+1)\left(\frac{n}{n_{\mathrm{max}}}\right)^2\right]\left(\frac{n}{n_{\mathrm{max}}}\right).$$

From

$$D_t m = -4\pi R^2 p U$$

we obtain

$$\frac{\partial R}{\partial t} = -\frac{R}{3}\frac{\partial \epsilon}{\partial t}\frac{1}{(p+\epsilon)}$$

We replace the latter equation into:

$$D_t U = -\left[\frac{1+U^2-2mR^{-1}}{\epsilon+p}\right]\left(\frac{\partial p}{\partial r}\right)_t - \frac{m+4\pi R^3 p}{R^2},$$

We finally get:

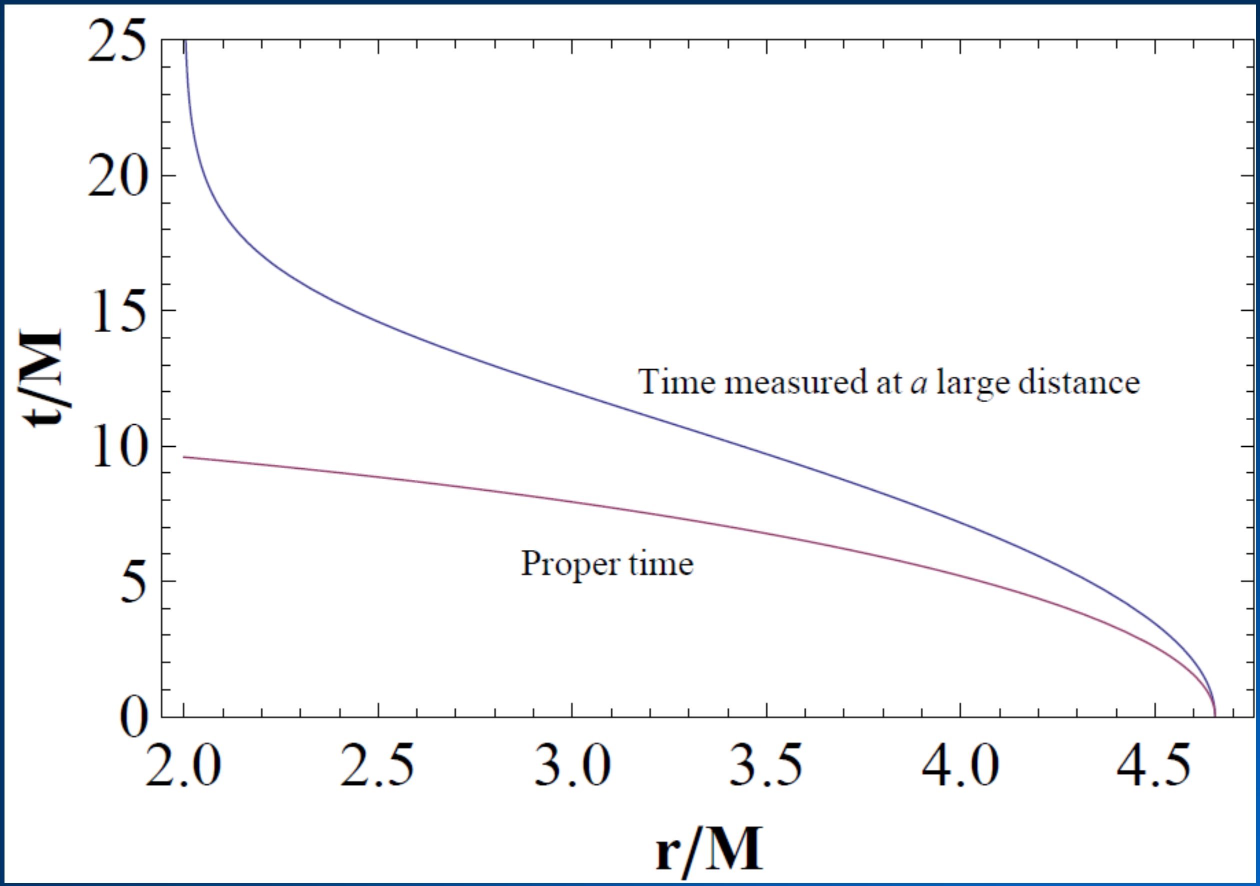
$$\alpha_0(r,t) + \alpha_1(r,t)R + \alpha_2(r,t)R^2 + \alpha_3(r,t)\dot{R} = 0$$

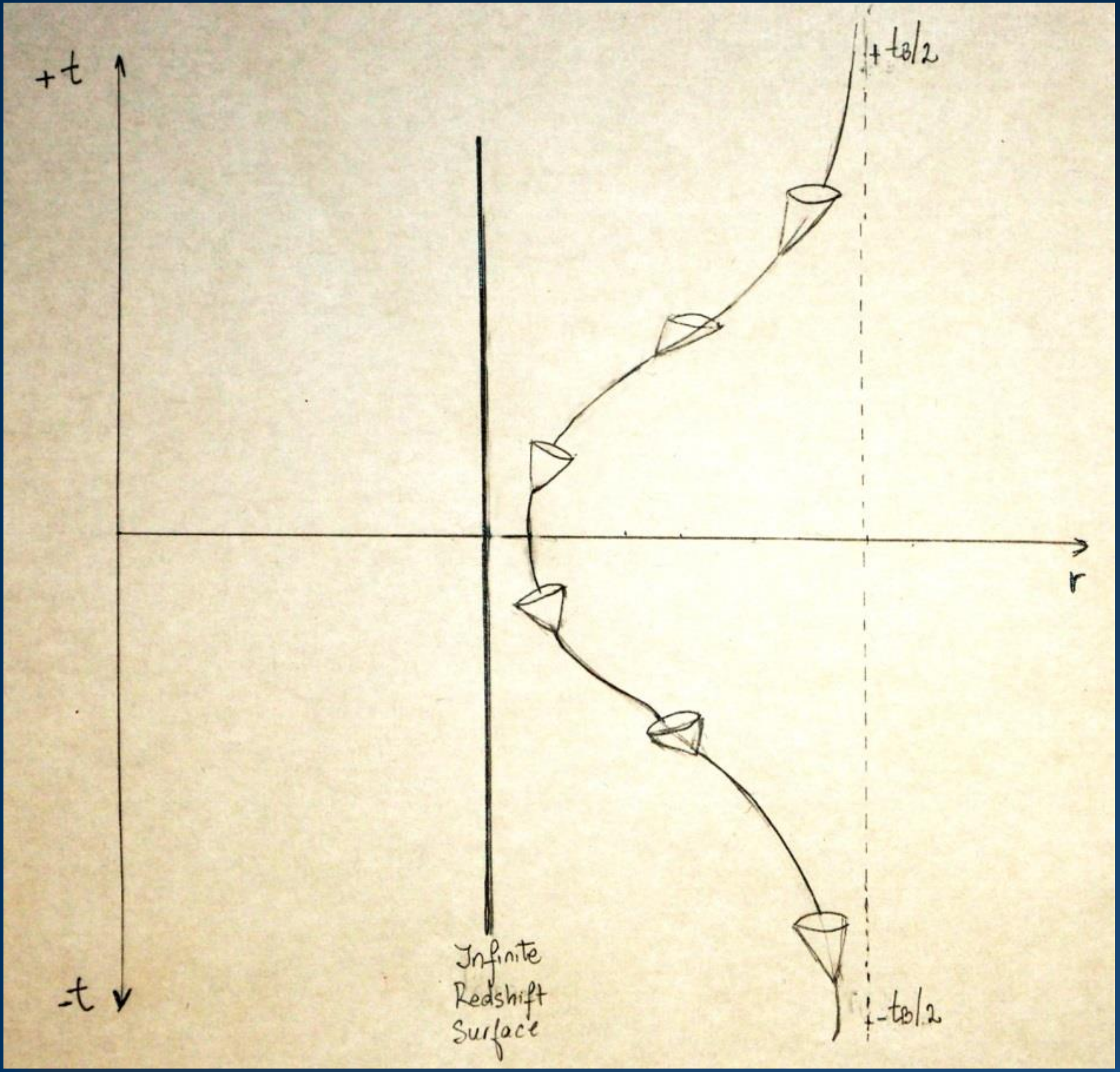
where α_i are functions of *r* and *t*

We can integrate numerically to obtain the radius of the bounce.

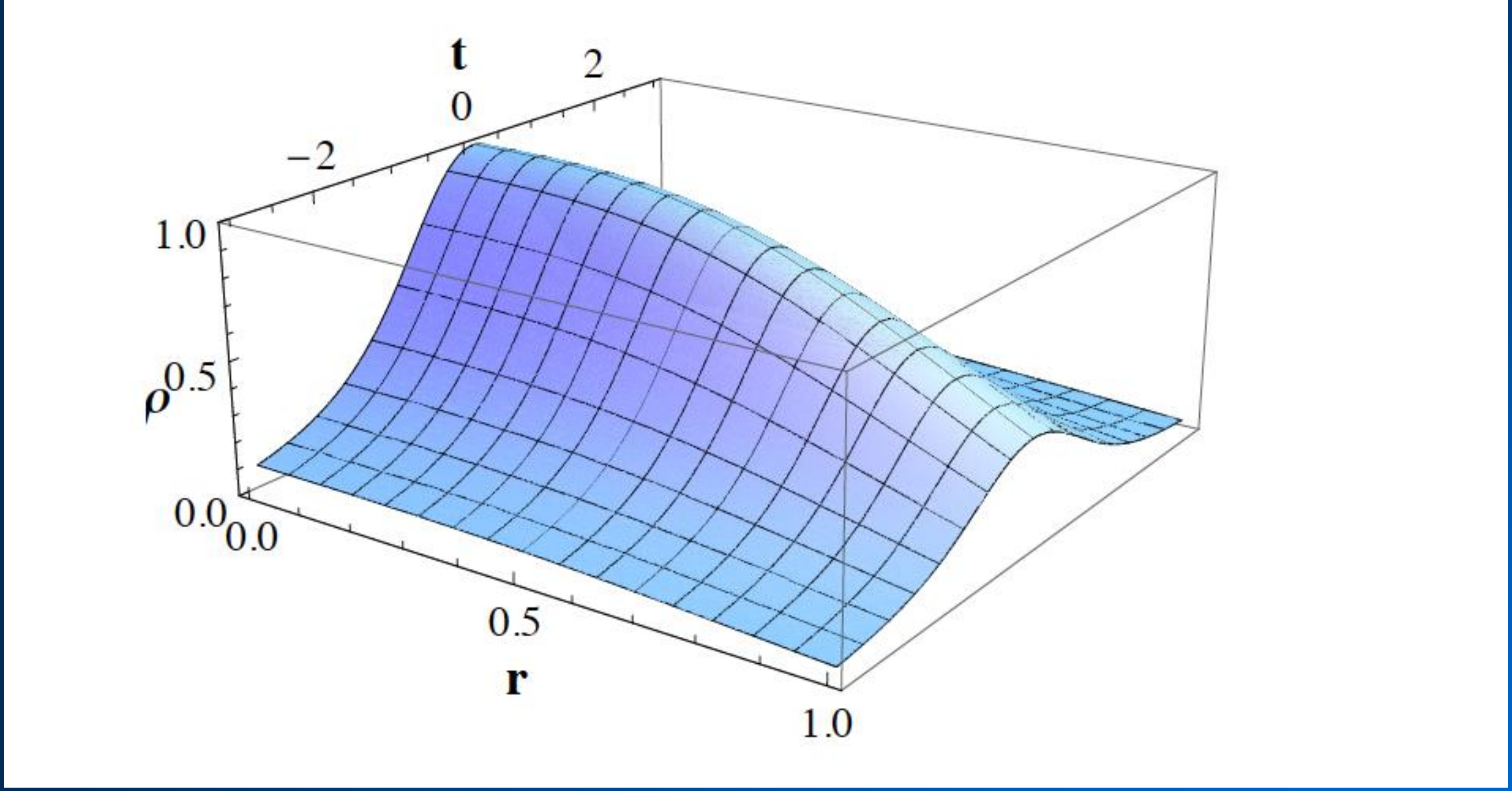
For $M = 4\ M_{sun}$ and $R_{initial} = 30$ km, the bounce occurs at distances larger than the Planck length for it to take a time of the order of the Hubble time as seen from infinity.

The bounce occurs in a regime where gravity is well within a classical regime.


25
20
15
10
5
0
t/M
2.0
2.5
3.0
3.5
4.0
4.5
r/M
Time measured at *a* large distance
Proper time


+t
-t
r
+tB/2
-tB/2
Infinite
Redshift
Surface

Evolution of the density of the mimicker in normalised units



Conclusions

- The M&K's EoS cannot support a stable regular black hole interior but can lead to a bounce and the formation of an evolving black hole mimicker.

- For typical values of the core of a massive star such a mimicker has a lifetime longer than the Hubble time.

- Is this EoS reasonable? Are evolving mimickers nothing else but mathematical trick? These questions can be probed, at least in part, through experiments at high energy colliders such the LHC, natural cosmic colliders, and, perhaps, through cosmological observations.

- In order to determine if there are trapped surfaces numerical calculations of the full collapse will be performed with the code COCONUT.

Back ups

$$\alpha_0(r,t) = \frac{1}{f_1}\frac{df_1}{dr}\frac{\left[\alpha - 2\left(\alpha+1\right){f_1}^2{f_2}^2\right]}{\left[\alpha - 2/3\left(\alpha+1\right){f_1}^2{f_2}^2\right]}$$

$$\alpha_1(r,t) = a_1(r,t)(b_1(r,t) + c_1(r,t)) + d_1(r,t)$$

$$\begin{aligned}
a_1(r,t) &= \frac{4}{3}\beta^2{f_1}^2{f_2}^2\left[\alpha - 2/3\left(\alpha+1\right){f_1}^2{f_2}^2\right]^2,\\
b_1(r,t) &= 4\beta^2{f_1}^2\left(\frac{df_2}{dt}\right)^2\left[\alpha - 10/3\left(\alpha+1\right){f_1}^2{f_2}^2\right]\left[\alpha - 2/3\left(\alpha+1\right){f_1}^2{f_2}^2\right]\\
c_1(r,t) &= \frac{1}{f_2}\left[\frac{1}{f_2}\left(\frac{df_2}{dt}\right)^2 - \frac{d^2f_2}{dt^2}\right],\\
d_1(r,t) &= \frac{8}{3}\pi\beta{f_1}^2{f_2}^2\left[2\alpha - 5/3\left(\alpha+1\right){f_1}^2{f_2}^2\right].
\end{aligned}$$

$$\alpha_2(r,t) = a_2(r,t)b_2(r,t)$$

$$a_2(r,t) = \frac{4}{3}f_1\beta\frac{df_1}{dr}\frac{\left[\alpha - 2\left(\alpha+1\right){f_1}^2{f_2}^2\right]}{\left[\alpha - 2/3\left(\alpha+1\right){f_1}^2{f_2}^2\right]},$$

$$b_2(r,t) = \frac{\beta}{3}\left(\frac{df_2}{dt}\right)^2\left[\alpha - 2/3\left(\alpha+1\right){f_1}^2{f_2}^2\right]^2 - 2\pi{f_2}^2\left[\alpha - 1/3\left(\alpha+1\right){f_1}^2{f_2}^2\right]$$

$$\alpha_3(r,t) = -\frac{4}{3}\beta^2{f_1}^2 f_2\left[\alpha - 2/3\left(\alpha+1\right){f_1}^2{f_2}^2\right]^2\frac{df_2}{dt}$$

$$f_1(r) = \exp\left(-\frac{r}{R_*}\right)^3$$

$$f_2(t) = \left[\frac{1-\exp\left(-\frac{t}{T}\right)^2}{(t/T)^2}\right]$$