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On the conditions for the formation of exotic compact objects from gravitational collapse

based on work done in collaboration with
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Abstract

Gravitational collapse models with semi-classical corrections in the strong field regime are known to lead to bouncing scenarios where the black hole turns into a white hole. Here we investigate under which conditions the complete collapse of an homogeneous and isotropic, spherical matter cloud with semi-classical corrections may lead to the formation of an exotic compact remnant. In particular we investigate the case of the so called 'dark energy star' and discuss its implications for astrophysical black holes.

Black Holes

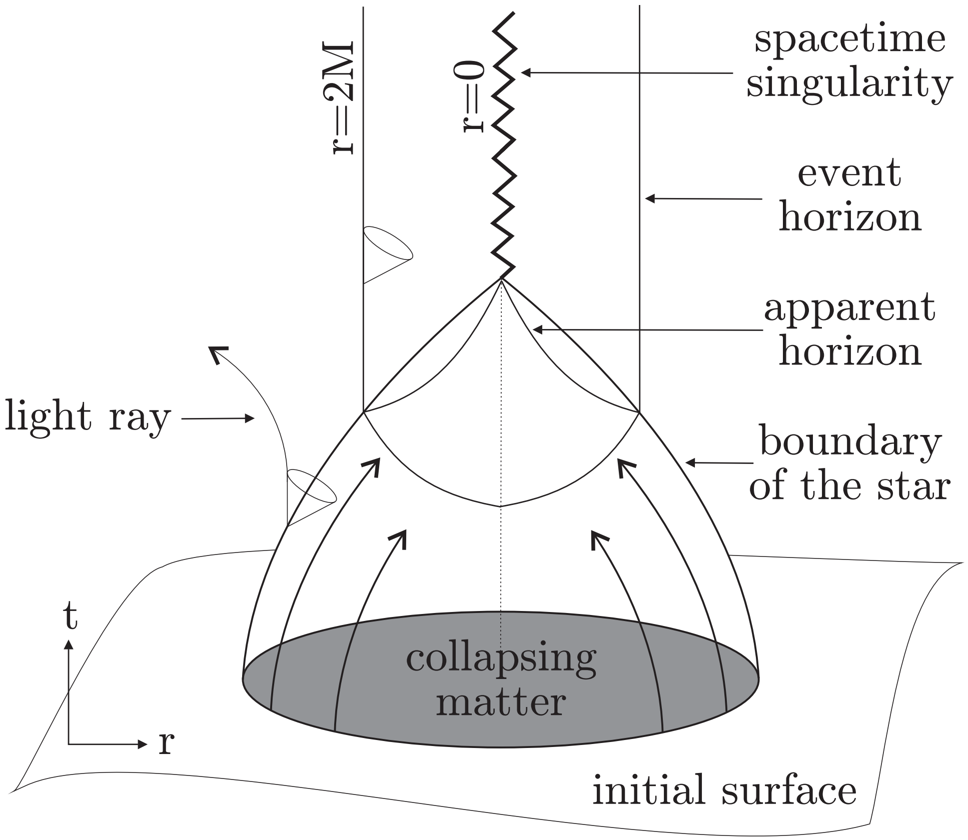
Theory:

- A black hole is a singularity of the spacetime covered by an event horizon.
- Under standard energy conditions GR predicts that singularities must form at the end of collapse.
- A black hole results when the infalling matter is trapped inside the horizon before the singularity forms.
- Is this picture still valid in the strong field regime?
- Singularities signal a breakdown of the theory and may not occur in the universe.

Observation:

- Strong indirect evidence that very compact objects exist in the universe.
- Detection of GW150914 is the first direct evidence of the existence of black holes.
- The processes that lead to the formation of such ultracompact objects are still widely unknown.
- Are astrophysical black holes and mathematical black holes the same thing?

Black Hole Formation



- The matter cloud collapses under its own gravity.
- The trapped surfaces develop before the singularity.
- The singularity curve remains always hidden within the horizon.
- No light ray can escape the singularity to reach far away observers.
- The first theoretical model to be studied was that of a spherical cloud of homogeneous dust.

[J. R. Oppenheimer and H. Snyder, Phys. Rev. 56 (1939) 455]

Open issues

Are black holes the only possible outcomes of complete collapse?

- Compact objects composed of ordinary or exotic matter?
- Bounce and complete dispersal?

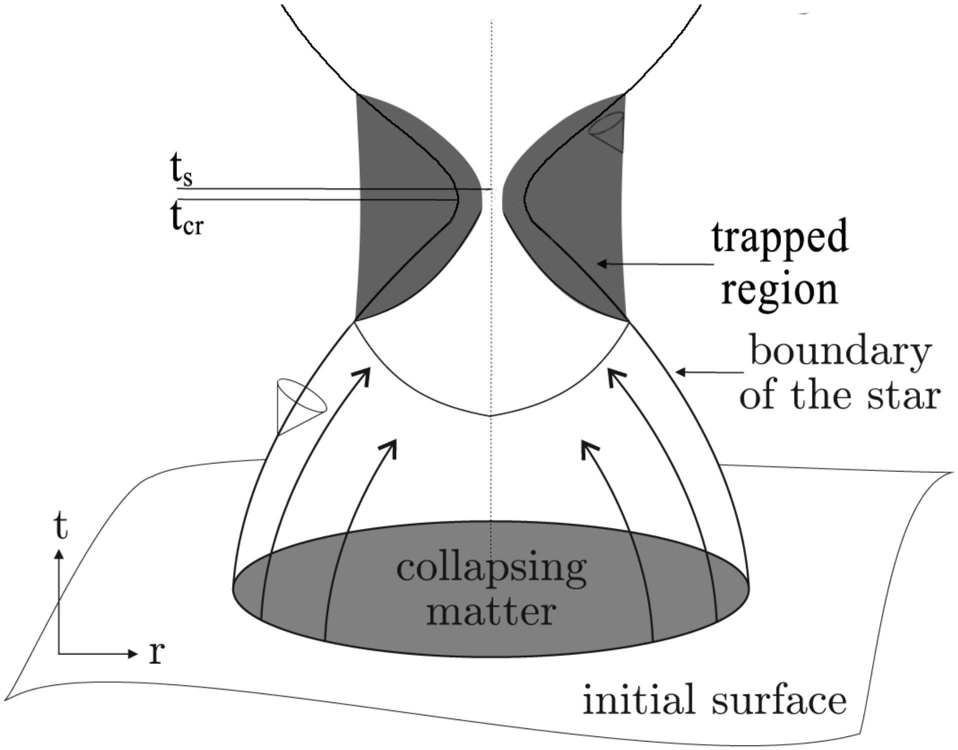
How do the mechanisms that can prevent the formation of singularities affect astrophysical objects?

- Can a bounce lead to the disappearance of black holes? Over what time scales?
- Can the matter remain trapped after the bounce thus forming a universe?

If exotic compact objects can exist in the universe then:

- What is the equation of state for matter of these objects?
- What kind of progenitor stars may lead to such outcomes?
- What observational features do these objects have?
- Is there any way to detect them?

No singularity



- Strong field effects influence weak field regions.
- The matter cloud bounces. No singularity forms.
- Energy conditions are violated in the strong field.
- The horizon disappears after a finite time.
- At the bounce the black hole turns into a white hole.

[L. Modesto, C. Bambi and DM, Phys. Rev. D 88, 044009 (2013)]

Gravitational collapse

Homogeneous perfect fluid cloud collapsing, in comoving coordinates.

-) Line element

$$ds^2 = -dt^2 + \frac{R'^2}{G(t,r)} dr^2 + R(t,r)^2 d\Omega^2$$

-) Energy-momentum tensor

$$T^\mu_\nu = \mathrm{diag}\{\rho(t), p(t), p(t), p(t)\}$$

-) Einstein's equations

$$\begin{aligned} p &= -\frac{\dot{F}}{R^2 \dot{R}} \\ \rho &= \frac{F'}{R^2 R'} \\ \dot{G} &= 0 \end{aligned}$$

-) Misner-Sharp mass:

$$F = r^3 M(r,t) = R(1 - G + \dot{R}^2)$$

Scale Factor

There is the gauge freedom to fix the scaling of the area-radius $R(r, t)$:

$$R = ra(r, t)$$

With this choice of the scaling factor ρ diverges only at the singularity.

- Initial time t_i: $a(r, t_i) = 1$.
- Collapse: $\dot{a} < 0$.

Trapped Surfaces

The apparent horizon is the surface that separates light rays directed outwards that are outgoing from those directed outwards that are ingoing. In vacuum it coincides with the event horizon.

$$1 - \frac{F}{R} = 1 - \frac{r^2 M}{a} = 0$$

Define the curve $t_{\mathrm{ah}}(r)$, time at which r becomes trapped.

Homogeneous dust collapse

Homogeneus if $\rho = \rho(t)$ and dust if $p = 0$. Then $M = M_0$

$$G = 1 + k \text{ (Marginally bound case for } k = 0)$$

Classically leads to the formation of a black hole.

Classical dust collapse

$$\rho = \frac{3M_0}{a^3}$$
$$M = M_0$$
$$M_0 = a\dot{a}^2$$
$$a(t) = \left(1 - \frac{3}{2}\sqrt{M_0}t\right)^{2/3}$$

Semiclassical corrections

$$G_{\mu\nu} + G^{\text{corr}}_{\mu\nu} = 8\pi T_{\mu\nu} \quad \longrightarrow \quad G_{\mu\nu} = 8\pi T_{\mu\nu} + 8\pi T^{\text{corr}}_{\mu\nu}$$

Introduce a classical effective density to model repulsive effects at small scales

$$\rho_{\text{eff}} = \rho + \rho_{\text{corr}} = \rho + \alpha_1 \rho^2 + \alpha_2 \rho^3 + o(\rho^3)\ ,\ \ \rho_{\text{eff}} = \rho\left(1 - \frac{\rho}{\rho_{\text{cr}}}\right)\ .$$

with α_i depending upon the critical density ρ_{cr}.

Dust collapse with semiclassical corrections

$$p_{\text{eff}} = -\frac{\rho^2}{\rho_{\text{cr}}}$$

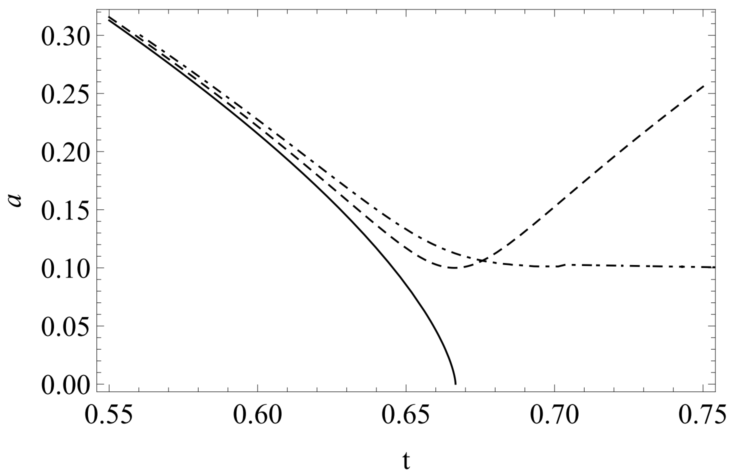
$$M_{\text{eff}} = M_0\left(1 - \frac{\rho}{\rho_{\text{cr}}}\right)$$

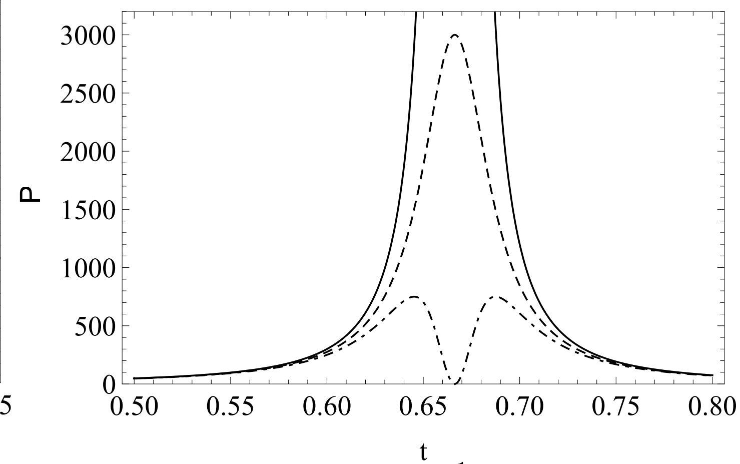
$$\dot{a}^2 = \frac{M_0}{a^4}\left(a^3 - a^3_{\text{cr}}\right)$$

$$a^3_{\text{cr}} = \frac{3M_0}{\rho_{\text{cr}}}$$

Minimum size and maximum density

The system reaches a critical scale at which ρ is finite and then bounces.

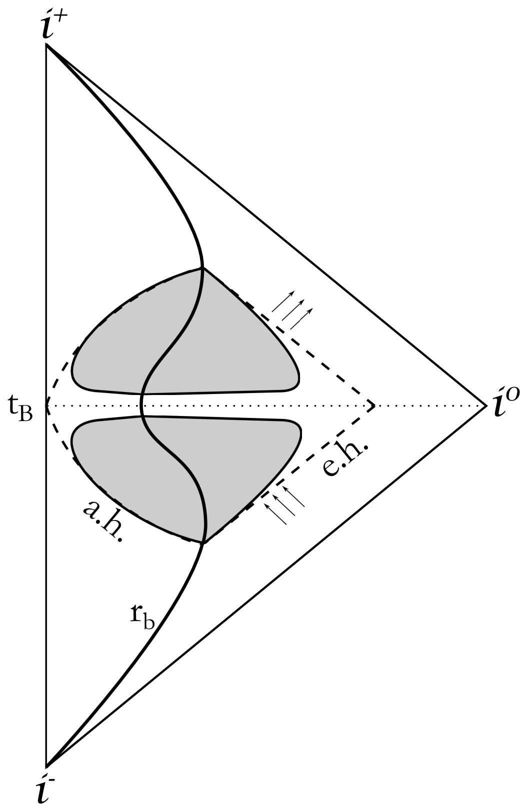




$$a(t) = \left[a_{\mathrm{cr}}^3 + \left(\sqrt{1 - a_{\mathrm{cr}}^3} - \frac{3\sqrt{M_0}}{2} t \right)^2 \right]^{\frac{1}{3}}$$

Bounce: From black hole to white hole

Collapse behaves classically until the strong field regime is reached, then halts at a critical radius $r_{\rm cr}$ and re-expands indefinitely.



- The density reaches maximum value at $t_{\rm cr} = t_B$.
- Each shell bounces at the co-moving time t_B.
- Trapped surfaces vanish before the critical radius is reached.
- Light rays can escape from the quantum-gravity region.
- For $t < t_B$ particles with $r < r_S$ are ingoing.
- For $t > t_B$ particles with $r < r_S$ are outgoing.

Conditions for compact objects

Conditions for collapse to halt

$$\dot{a} \longrightarrow 0$$

$$\ddot{a} \longrightarrow 0$$

as $a \to a_{\rm cr}$

$$\ddot{a} = \frac{a}{2}\left[p\left(2\frac{\rho}{\rho_{\rm cr}} - 1\right) - \frac{\rho}{3}\left(1 - 4\frac{\rho}{\rho_{\rm cr}}\right)\right]$$

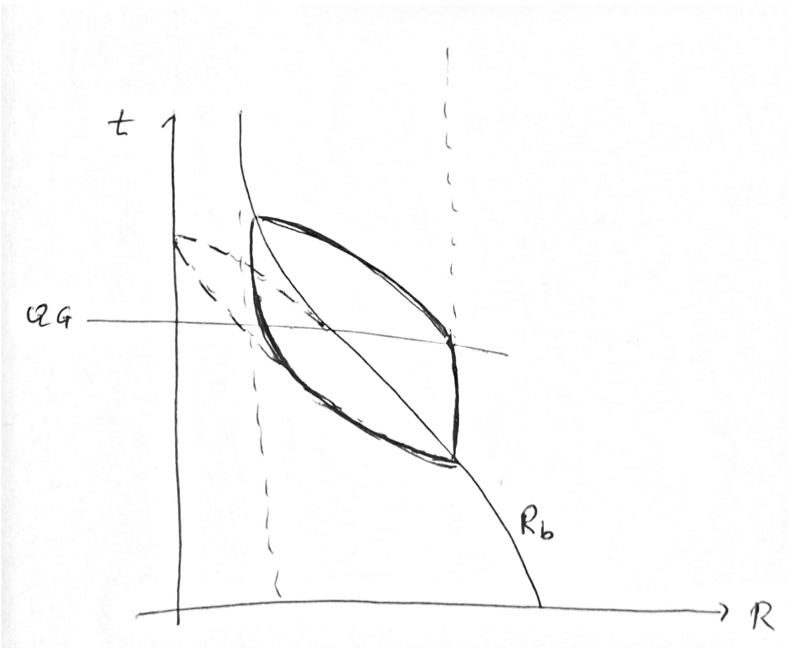
For semi-classical collapse of a perfect fluid this implies

$$p \to -\rho$$

The fluid must behave like a dark energy fluid.

Dark energy stars

We don't know how matter behaves in the strong field limit.



- Collapse halts as $t \to \infty$.
- No singularity and no bounce.
- The density reaches maximum value.
- The trapped region exists for a finite time.
- The exotic compact remnant is visible to far away observers.

If the asymptotic safe regime is equivalent to a low density regime then dark energy dominates and collapse can halt.

Summary

The term 'black hole' was first used around 50 years ago. Today we have direct evidence of their existence.

Astrophysical black holes may be different from mathematical black holes. No singularity. Horizon with finite lifespan.

Do exotic compact objects exist? Can they be distinguished from black holes?

Future perspectives

We don't have a viable theory of QG yet but many examples from different theories suggest similar results. How general are these scenarios? How relevant are they for astrophysics?

We are entering the era of multimessenger astronomy (gravitational waves, sub-millimiter observations, neutrinos). Soon we will have experimental data from regions where the gravitational field is strong.

These are exciting times!