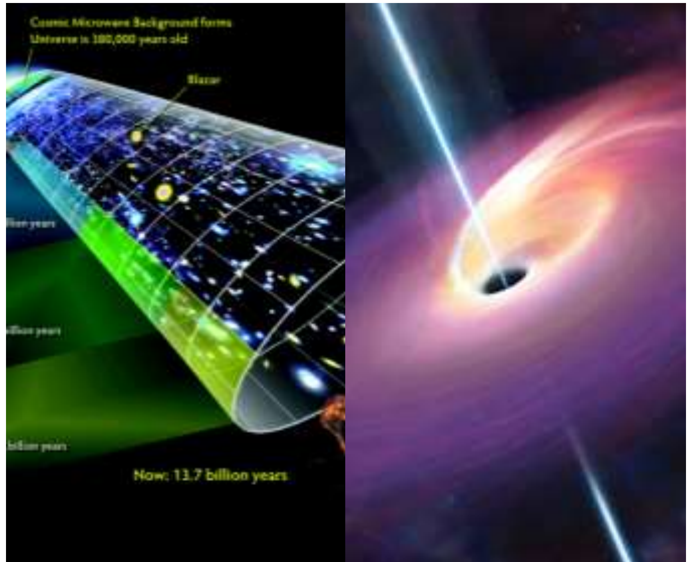
ULB



Albert Escrivà

Formation of PBHs during the QCD phase transition

Work in progress!

Service de Physique Théorique
Université Libre de Bruxelles

Cosmology from Home
Brussels, Belgium.
24th June, 2022

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What are PBHs????

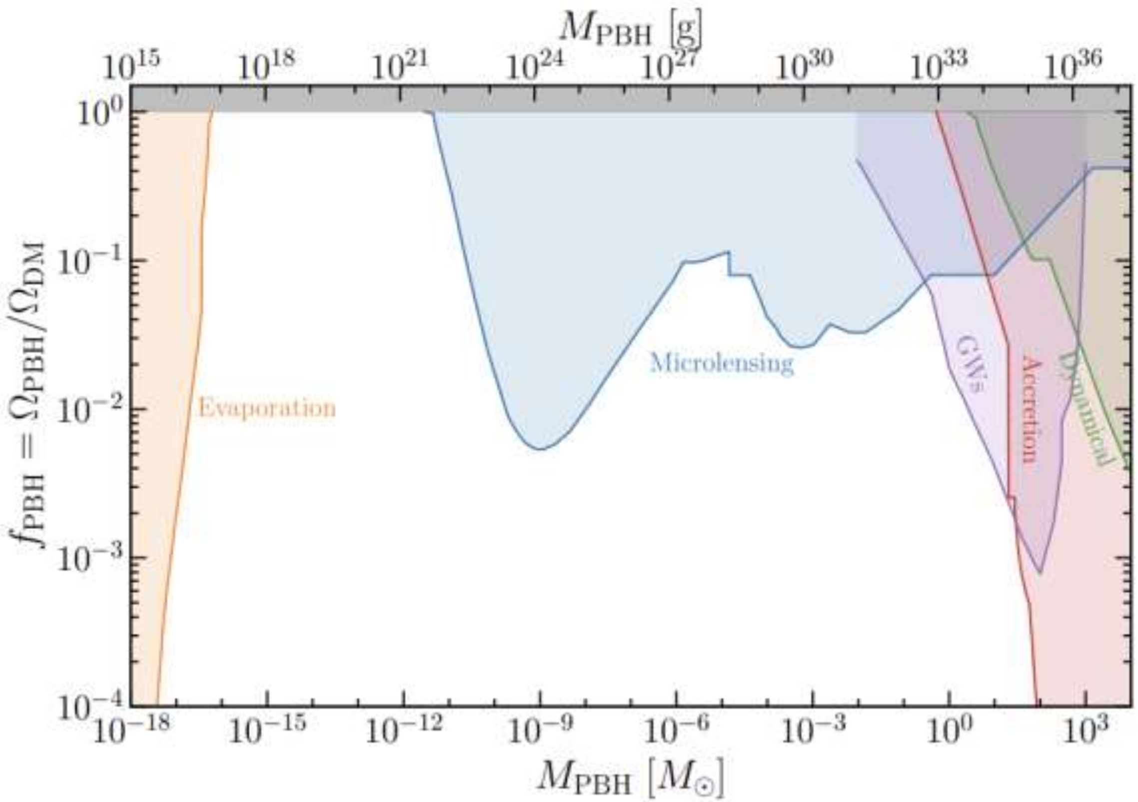
Black holes that could have been formed in the very early Universe (no estelar origin)

- First proposal by Novikov & Zel'dovič (1960), but refined later by Carr & Hawking (1974)

The dark matter and PBHs

- There is some missing matter in the Universe with an unknown composition

- The existence of dark matter can be explained through compact objects like Black Holes with a primordial origin



Green , A.M and Kavanagh, B.J
Arxiv:2007.10722

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A lot of mechanisms for PBH production!

- **<u>Large cosmological fluctuations from inflation</u>**
- Bubble collisions
- Cosmic strings
- Domain walls
- Q-balls
- Baby Universes

Etc…

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PBHs from cosmological fluctuations

- Some fluctuations generated during inflation could be sufficiently large (**very rare events**) and collapse during **radiation epoch** when they reenter the cosmological horizon

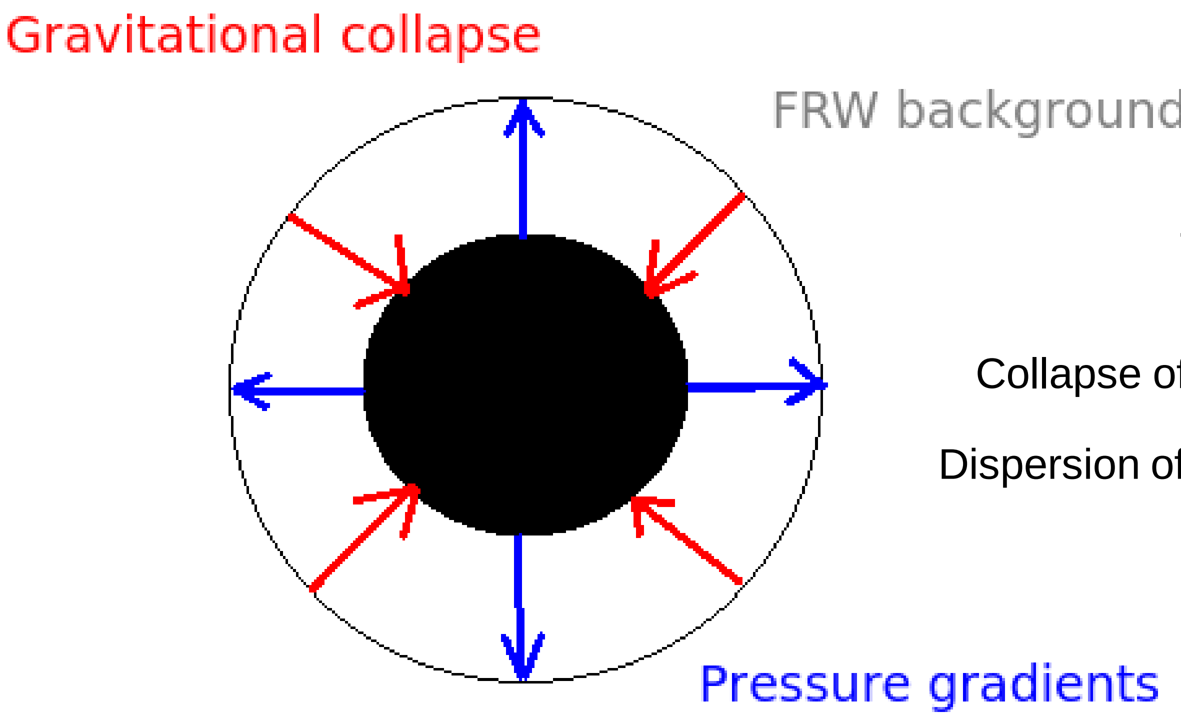
- These very rare fluctuations will have roughly spherical symmetry (spherical peaks)

J. M. Bardeen, J. R. Bond, N. Kaiser and A. S. Szalay 1986

Collapse of fluctuations

Some fluctuations generated during inflation could be sufficiently large (rare events) and collapse during **radiation epoch**

Spherical Collapse of cosmological perturbations leading to PBH formation



Threshold → δ_c

Collapse of the perturbation: $\delta > \delta_c$

Dispersion of the perturbation: $\delta < \delta_c$

"amplitude of the perturbation"

$$p = \omega \rho$$ Perfect fluid

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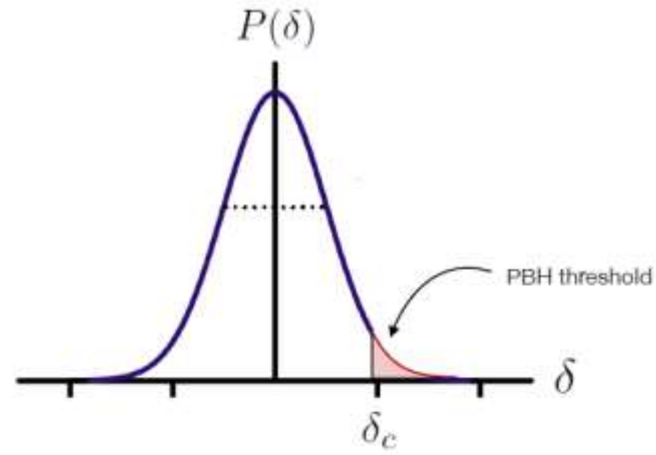
The abundance…

- Statistically, the prob. to have a large fluctuation is exponentially small

<u>**The abundance of PBHs is exponentially sensitive to the threshold**</u>

$$P(\delta) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{\delta^2}{2\sigma^2}}$$



$$\beta \equiv \frac{\rho_{\rm PBH}}{\rho_{\rm tot}} = 2\int_{\delta_c}^{\infty} \frac{M_{\rm PBH}}{M_{\rm H}} P(\delta) d\delta \sim {\rm erf}\left(\frac{\delta_{\rm c}}{\sqrt{2}\sigma}\right)$$

Press–Schechter formalism

The threshold…

- There are some analytical approximations,

Harada,Yoo,Kohri. 2013

$$\delta_{HYK} = \frac{3(1+w)}{5+3w}\sin^2\left(\frac{\pi\sqrt{w}}{1+3w}\right) \approx 0.41$$

(Jeans length aproximation), B. Carr 1975

$$\delta_{\rm Carr} = w = 1/3$$

In radiation

The threshold was considered time ago as a constant value, **but actually, it depends on the specific shape of the cosmological fluctuation**

Germani , Musco 2018

→

Only can be got numerically with accuracy!

⇓

Do simulations is essential!!

(ACTUALLY NOT!)

Escrivà, A., Germani C. and K. Sheth, Ravi. ArXiv:2007.05564.

Escrivà, A., Germani C. and K. Sheth, Ravi Arxiv:1907,13311

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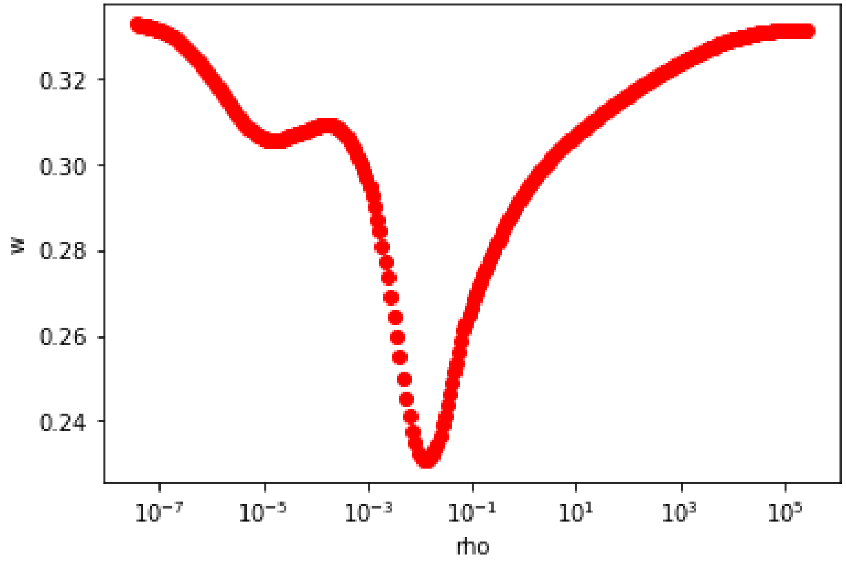
Background and Motivation

The problem for a constant eq. of state is very well studied

A. Escrivà. arXiv:2111.12693 (review paper)

BUT

Scenario with a QCD phase transition? → **enhances the probability of forming PBH with stellar masses**



We don't have analytical estimates for this case, we need to do simulations!

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How we form PBH numerically?
Solving Misner-Sharp equations

Misner,Sharp. Phys.Rev. 136 (1964)

- The Misner-Sharp equations describes the motion of a relativistic fluid under a curved spacetime

- We consider a perfect fluid with an equation of state $p = w(\rho)\rho$

QCD pase transition

$$T^{\mu\nu} = (\rho + p)u^\mu u^\nu + pg^{\mu\nu}$$

- Spherically symmetric spacetime

$$ds^2 = -A^2(r,t)dt^2 + B^2(r,t)dr^2 + R^2(r,t)d\Omega^2$$

- We can define an invariant quantities

$$D_t = u^\mu \partial_\mu = \frac{1}{A}\partial_t, D_r = v^\mu \partial_\mu = \frac{1}{B}\partial_r$$

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Misner-Sharp equations

$$D_t U = -\frac{\Gamma}{\rho + p} \boxed{D_r p} - \frac{M}{R^2} - 4\pi R p$$

$$D_t \rho = -\frac{\rho + p}{\Gamma R^2} D_r (R^2 U)$$

$$M = \int_0^R 4\pi R^2 \rho \, dR$$

$$D_t R = U$$

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

Hamiltonian constraint eq.

$$D_r M = 4\pi R^2 \Gamma \rho$$

$$\Gamma^2 = 1 + U^2 - 2\frac{M}{R}$$

$$D_r R = \Gamma$$

$$D_r A = -\frac{A}{\rho + p} \boxed{D_r p}$$

Numerical procedure

How can we solve this numerical problem???

- Until now: Using an hydrodynamic code , based on stellar/neutron collapse from ~1995. Uses FD, 2 order accuracy in time and space + AMR.

- Niemeyer & Jedamzik 1998
- Shibata & Sasaki 1999
- Hawke & Stewart 2002
- Musco & Miller & Rezolla 2005

(etc)

Essential when QCD phase transition is considered: solving the lapse equation is straighwordard!

Spectral methods!

Escrivà.ArXiv:1907.13065

RK4 for the time derivative

Spectral methods for spatial derivative

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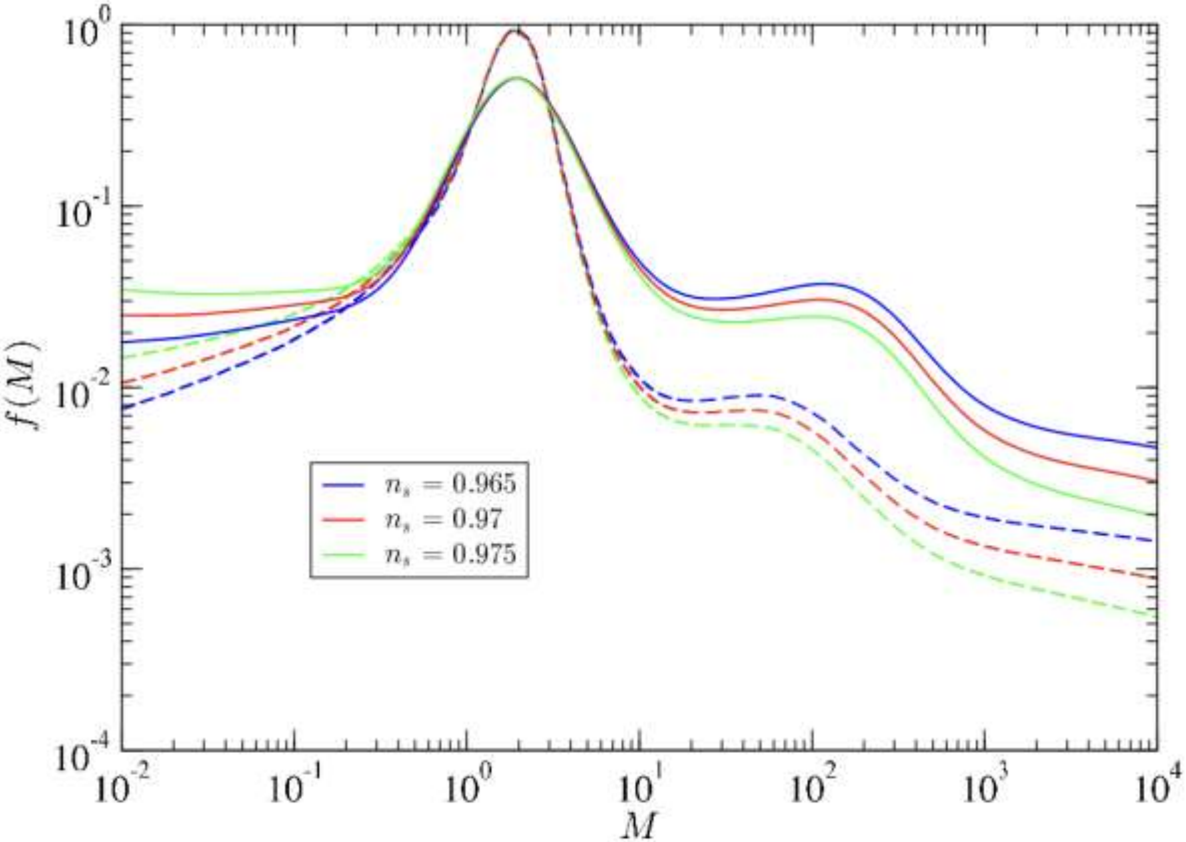
Crucial effect on the mass function



Fraction of PBHs to be the dark matter

$$\beta(M) = \mathrm{erfc}\left(\frac{\delta_c(M)}{\sqrt{2}\delta_{rms}(M)}\right)$$

Crucial difference!!

Computation of merging rates in progress!
(with E. Bagui and S. Clesse)

Mass function!

$$f(M) = \frac{1}{\rho_{DM}}\frac{d\rho_{PBH}}{d\ln(M)} \approx \frac{2.4}{f_{PBH}}\beta(M)\sqrt{\frac{M}{M_{eq}}}$$

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Conclusions

- The QCD phase transition affects the process of PBH formation significantly

- The thresholds of PBH formation are clearly smaller in comparison with the standard case of radiation

The threshold for PBH formation should be accurately computed to have precise results

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THANKS FOR YOUR ATTENTION!

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