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Primordial black holes as dark matter

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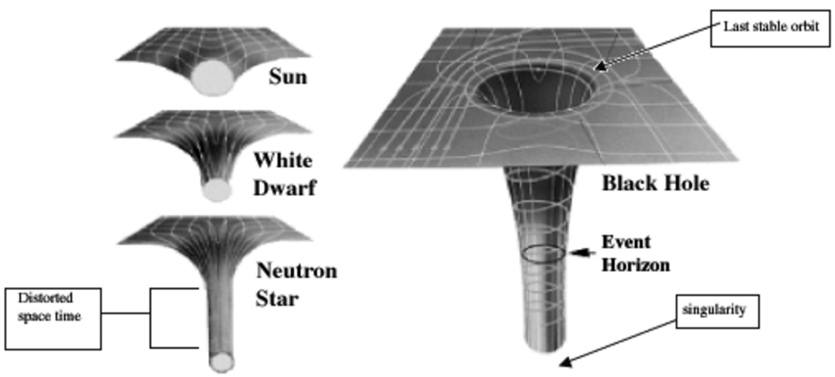
Primordial black holes

- Black holes are results of a gravitational collapse to a level it generates a potential so high not even light can escape. As such only 'extreme' objects, like very high mass stars, may eventually end up as black holes.

- However, extreme situations are common during the early universe. Quantum fluctuations during inflation might grow large enough to collapse, forming black holes as old as the universe and without any kind of stellar past. Thus the name “Primordial black holes”.

- Even outside this more standard formation process, a variety of other exotic formation mechanisms exist at the early universe, with considerable links to new physics.



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Dark matter and primordial black holes

- The existence of Dark Matter (DM) is one of the major mysteries in physics. Interacting with baryons through the grvavitational force, it is commonly theorized to be made up by particles outside the Standard Model.
- However, DM can also be explained through compact objects like black holes, that by themselves do not require new physics. Black holes in particular also interact almost purely gravitationally, but if they have a stellar origin their abundance is constrained by abundance of baryons.
- PBHs are free from these constraints. They are also not limited by stellar masses, meaning they can be as small as the Planck mass, and as large as 10^5 $M_\odot$, and very abundant depending on the formation mechanism.
- Even if they only make up a minority of the dark matter, their existence is still possible, as the formations mechanisms have few relation with dark matter itself. In fact, if PBHs exist and are the minority, their relation with particle DM can be very relevant.

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Formation

- The most common origin for PBHs is in the very early Universe, during radiation domination, where large curvature perturbations generated during inflation could have undergone gravitational collapse. The condition for this is the standard Schwarzschild radius, no new physics here.

- We can apply the condition to find the size of the density fluctuations δ we will need in order to generate these PBHs:

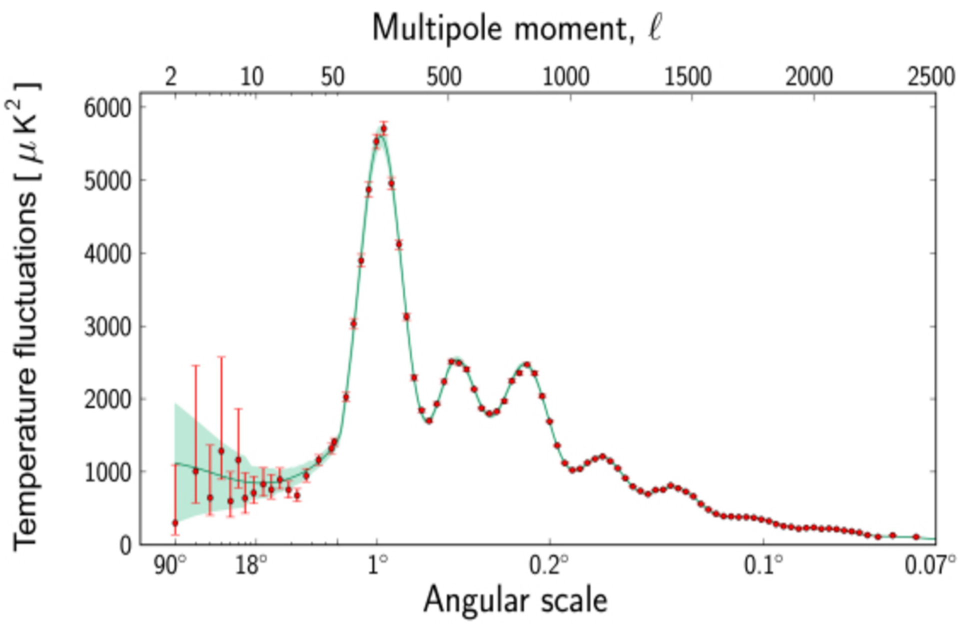
$$\delta = \frac{\mu - \mu_0}{\mu_0} \longrightarrow \delta \geq 1$$

- As the perturbations originate during inflation however, they will only collapse once they reenter the horizon. In effect this means that the mass of PBH that will form will reflect that of the horizon when the fluctuations collapse:

$$M_h \sim \frac{c\,t^3}{G} \sim 10^{15} \left[\frac{t}{10^{-23}\mathrm{s}}\right] \mathrm{g}$$

Formation

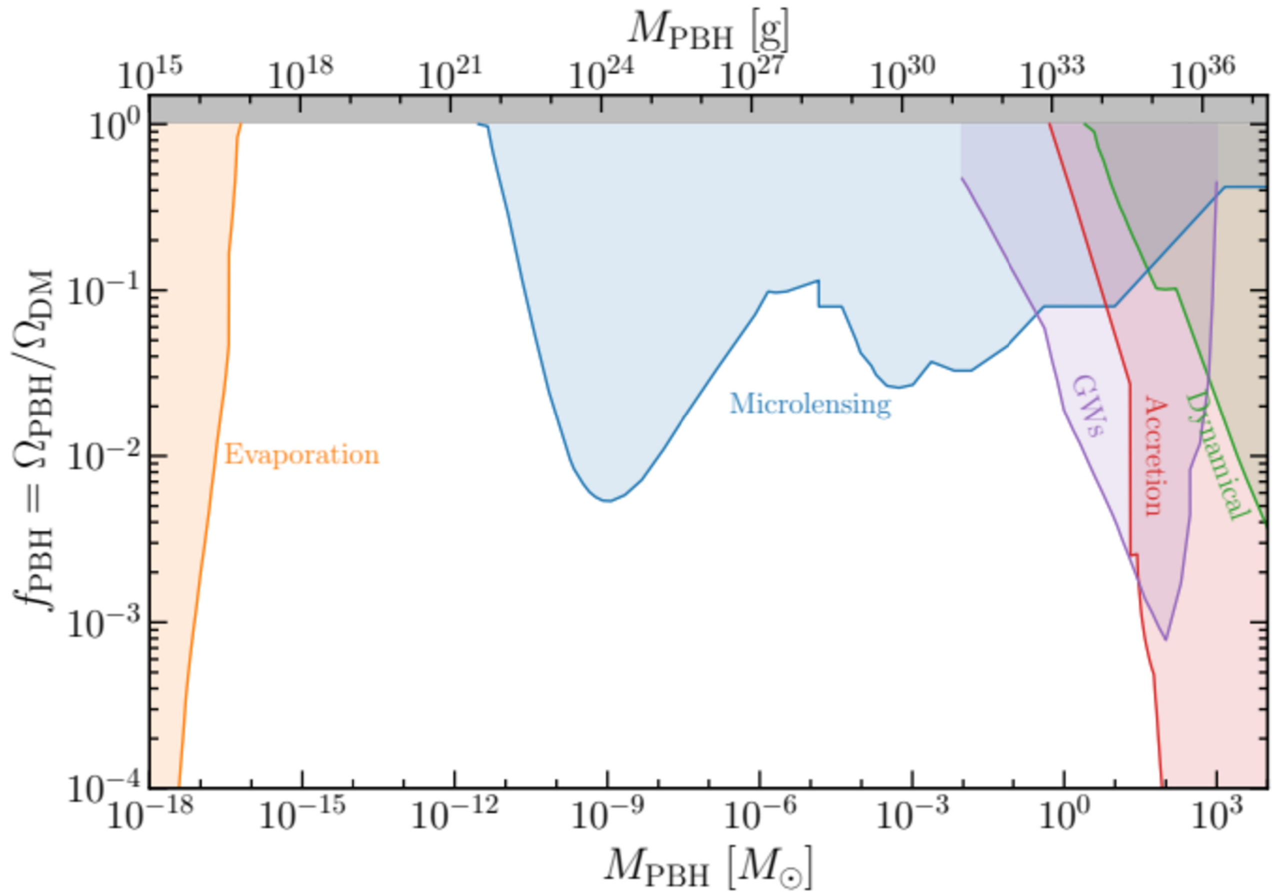
- However, analysis of the perturbations we see on the CMB, which also come from inflation, show only $\delta \sim 10^{-4}$, much smaller than required to form PBHs.
- Nonetheless, there are two significant ways in which PBH production is still possible:
  - Perturbation enhancement, where the inflation potential is non-standard, and therefore at some scales δ increases.
  - Non-gaussian tails, where the perturbations have a non-gaussian contribution that is big enough to create PBHs.



Temperature fluctuations in the CMB found by Planck.

- Both of the options **require** the presence of new physics. Therefore, beyond their relation with DM, PBHs can also act as probes of physics beyond the Standard Model. This doubly true for the more exotic formation models.

Constraints



From PBHbounds

Constraints come mainly from microlensing, gravitational waves and PBH evaporation.

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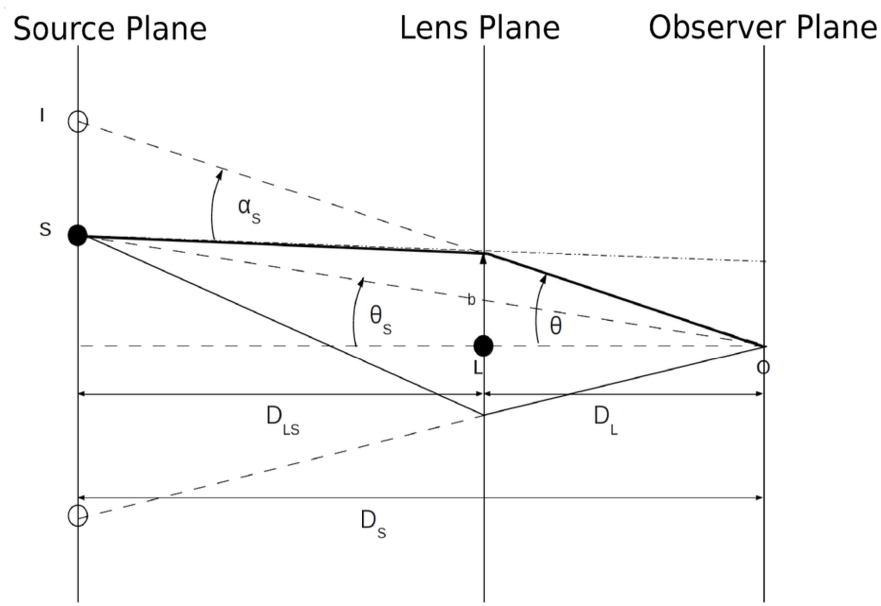
Microlensing

- The standard gravitational lensing case is well known. However, when the object and lens are very far away, or small, our resolution is unable to separate the two images. This is the particular case of microlensing, where the lensed image appears all on the same pixel rather than as two different images
- When geometric optics and point-like sources can be applied, microlensing is an extremely powerful tool, as we can compute a magnification from only masses and distances, and thus easily estimate microlensing events.
- However, when finite source effects start appearing, the microlensing effect is washed out.



$$\frac{\theta_S}{\theta_E} = \frac{R_s/D_s}{R_E/D_L} << 1$$

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Black hole evaporation

- PBH evaporation is a process resulting from Hawking radiation. The emission, mostly in terms of particles, is of an energy depending on the effective temperature of the Black Hole. This emitted radiation would have an almost thermal black body spectrum of the corresponding temperature, and this temperature depends on the mass. For a non-rotating zero charge black hole:

$$T_{bh} = \frac{hc^3}{16\pi G M_{bh} \sigma} \sim 10^{-7} \frac{M_\odot}{M} K$$

- From the temperature we can obtain its emission, which can only come from the black hole's own energy. Therefore the black hole will evaporate when it emits all of its energy, the majority of that energy being the one stored in the black hole's own mass. We can then define the lifetime of a black hole as the time it will take for it to evaporate:

$$\tau(M) \sim 10^{64} \mathrm{yr} \left(\frac{\mathrm{M}}{\mathrm{M}_\odot} \right)^3$$

Gravitational Waves

- LIGO detections of mergers are one of the reasons why PBHs returned to the limelight, and provide useful constraints on high mass PBHs.

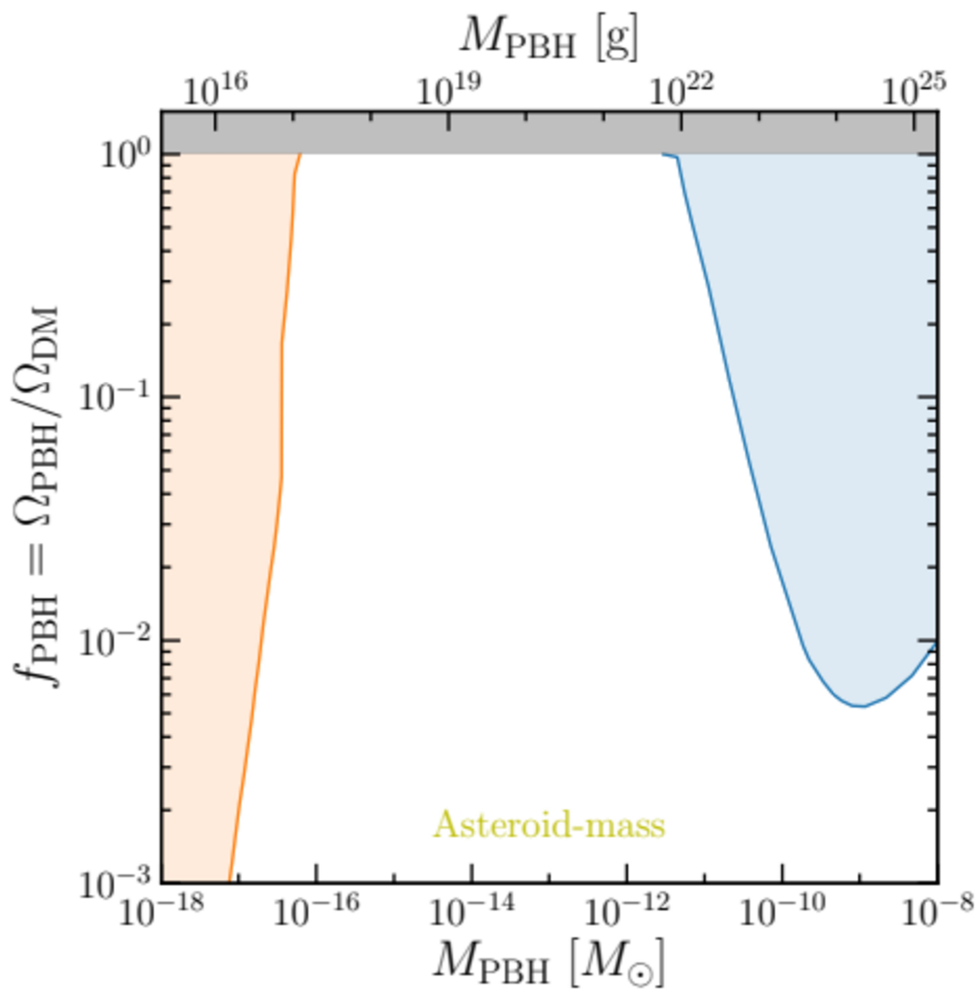
- However, current specifications are not enough to detect subsolar PBHs or mergers beyond z~1. Even future experiments like LISA will have difficulties to detect mergers in the lunar mass range or very far.

- A possibility however is the Stochastic Gravitational Wave Background (SGWB). This background could come in 2 forms for the case of PBHs, both exciting:
  - Being the addition of a lot of unidentified mergers. Even if they cannot be identified individually, if PBHs are the majority of these mergers then they would peak at high redshifts and be unrelated to the star formation rate.
  - From the formation of PBHs. As the perturbations reenter the horizon there is an emission of gravitational waves. The combination of all that GW emission would result in another background that could give information about the PBH generation and abundance

- While LIGO can only set small constraints, LISA should probe the expected ranges of various of the relevant SWGBs.

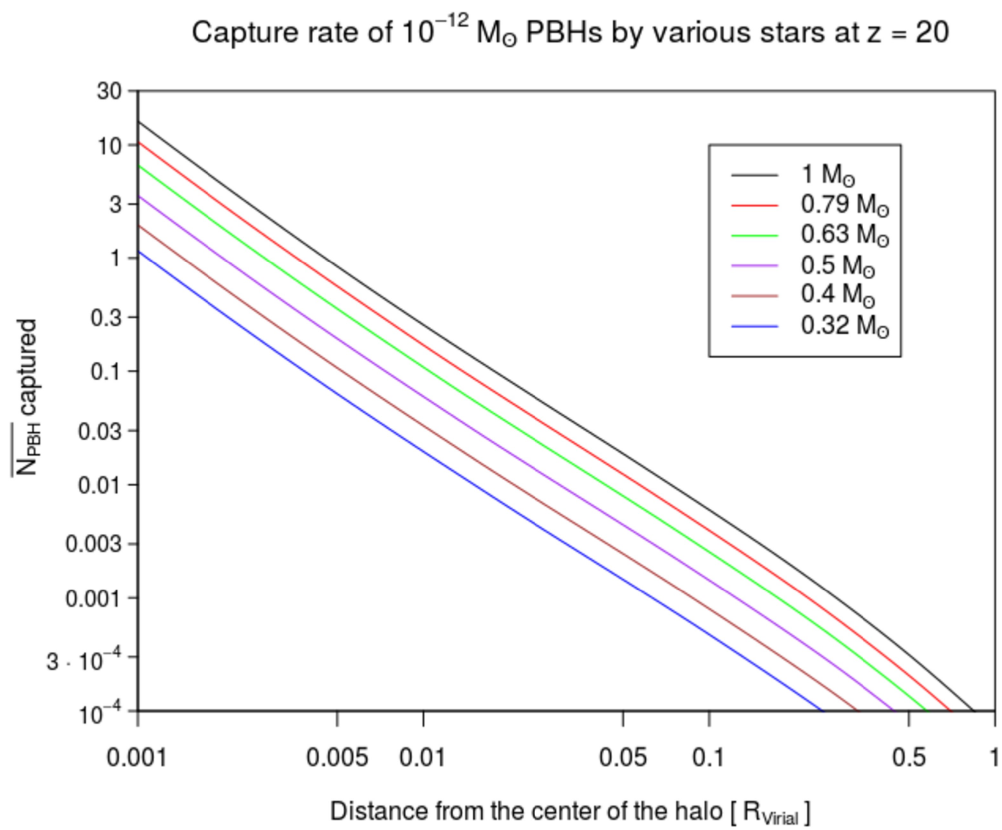
Windows remaining

- There is a window in the 10^{-16}-10^{-11} $M_\odot$ mass range where PBHs could still make up all of the Dark Matter
- Microlensing and PBH evaporation cannot constrain it.
- LISA will be able to probe the SGWBs of PBHs, but that requires waiting until 2040s.
- Previous constraints by neutron star capture are considered unreliable due to assumptions proved wrong regarding globular clusters



Capture by stars

Our work tries study the capture of small ($10^{-12}\, M_\odot$) PBH by main sequence stars in the very early universe, at z~20.



From M. Oncins & J. Miralda (in preparation)

By capturing PBHs, the stars will subsequently later be accreted in turn. We can estimate how common the process is for low mass stars that will reach our current time.

As the low mass stars are accreted, they will in turn become black holes below the Chandrasekhar mass that can only originate from PBHs, but are substantially larger and easier to detect.

Our results indicate if PBHs are all the DM we should also expect a large population of barely subsolar black holes.

Conclusions

- PBH are a DM candidate with peculiar properties that could explain a wide variety of phenomena without requiring new particles.

- Their formation requires new physics, particularly on inflation. However, by this same reason they are one of the only ways to probe non-standard inflation models.

- A large number of constraints exist from the observational consequences they would bring. However, previously extremely powerful tool like microlensing and PBH evaporation are reaching their limits.

- Gravitational waves observatories are the most promising tools, but current sensitivity is low and future experiments are very far off.

- There still exists an important window in the 10^{-16}-10^{-11} $M_\odot$ mass range where PBHs could be all the DM. Our work focuses on new ways to constrain or probe this range, but whilst results are promising more work needs to be done.