Early reionization from the accretion of Primordial Black Holes

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COSMOS meeting on astroparticle and fundamental physics with the CMB

Ferrara, 27/06/2018

General Properties of Primordial Black Holes (PBHs)

Proposed for the first time in 1972 by Stephen Hawking the PBHs are different from the ordinary BHs

- Different formation mechanisms:
  - Collapse of nonlinear perturbations reentering in the particle horizon.
  - Collapse of cosmic strings.
  - Phase transitions
- The mass depends on the formation time t_f:
  - $t_f = t_P \simeq 5.39 \times 10^{-44} s \rightarrow M_{pbh} = M_P \simeq 2.17 \times 10^{-15} g$.
  - $t_f \simeq 10^{-5} s \rightarrow M_{pbh} \simeq 1 M_\odot$.
  - $t_f \simeq 1 s \rightarrow M_{pbh} \simeq 10^5 M_\odot$.

Why introduce PBH in the model?

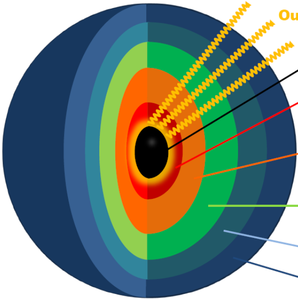
- They can account for dark matter, or a fraction of it $f_{pbh} = \dfrac{\Omega_{pbh}}{\Omega_{dm}}$.
- They can explain the existence of super massive black holes in the center of galaxies at high redshift ($z \simeq 6$).

Accretion into PBHs

Different observations tightly constrain the abundance of PBHs in different mass ranges. A particularly interesting region, thanks to the LIGO-VIRGO detection of merging binary black holes with mass around $30M_\odot$ is

$$1M_\odot \leq M_{pbh} \leq 100M_\odot$$

Matter falling towards the central region gets compressed $\rightarrow$ its density and temperature increases.
Near the event horizon, the temperature is very high and an **intense outgoing bremsstrahlung radiation is emitted**.



M. Sasaki, T. Suyama, T.Tanaka and S. Yokoyama

Accretion mechanism

The early energy injection from the bremsstrahlung radiation increases the free electron fraction and the primordial molecular hydrogen abundance after recombination.

In order to study the effects of PBHs on the reionization history we will consider Bondi accretion: for a point mass M in relative motion with velocity $v_{\rm rel}$ in a homogeneous gas with density $\rho_{b,\infty}$ and sound speed $c_{s,\infty}$ the Bondi accretion rate is

$$\dot{M}_B = 4\pi\lambda\rho_{b,\infty}v_{\rm eff}r_B^2 = 4\pi\lambda\rho_{b,\infty}\frac{(GM)^2}{v_{\rm eff}^3}$$

$v_{\rm eff} = \sqrt{c_{s,\infty}^2 + v_{\rm rel}^2}$, and λ is a numerical parameter that describes the deviation of the accretion from the Bondi idealized regime $\rightarrow$ quantifies non gravitational forces such as pressure, viscosity, etc.

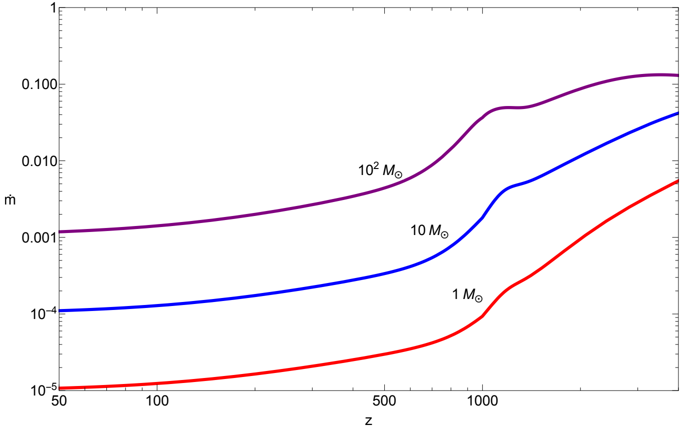
Bondi Accretion

The Bondi mechanism is characterized by

- Spherically symmetric accretion.
- Low accretion rate $\dot{m} = \frac{\dot{M}_{pbh}}{M_{Edd}} \ll 1.$

We further assume:

- Monochromatic distribution.
- Negligible merging rate.



Effects on reionization history

Standard reionization history

- Residual fraction of free electrons after recombination $x_e^{rec} = 2 \times 10^{-4}$.
- Dark Universe until the first stars of hydrogen and helium (population III) formed
- Intergalactic medium became fully ionized by stars at redshifts $z \lesssim 30$.

Modified reionization history

- Increasing free electron fraction after recombination.
- Enhanced formation rate of population III stars.
- Main contribution of PBH takes place $1000 \lesssim z \lesssim 100$

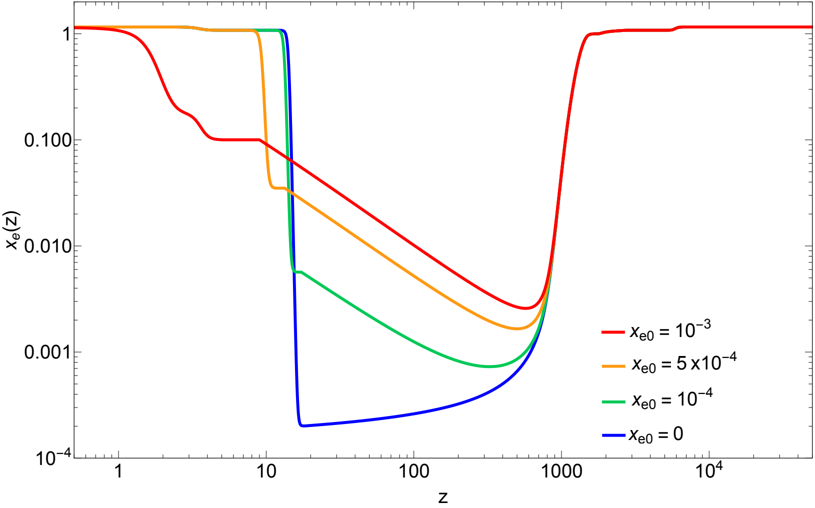
It is customary use an **Additional cosmological parameter** $x_{e0} \rightarrow$ deviation from the standard recombination history.

We have modified the Code for Anisotropies in the Microwave Background (CAMB) in order to parametrize the free electron fraction until the beginning of the stellar reionization ($z \geq z_{beg}$) as:

$$x_e(z) = x_e^{rec}(z) + x_e^{pbh}(z) = x_e^{rec}(z) + \text{min}\left[x_{e0}\left(\frac{1+z}{1000}\right)^{-1}, 0.1\right]$$

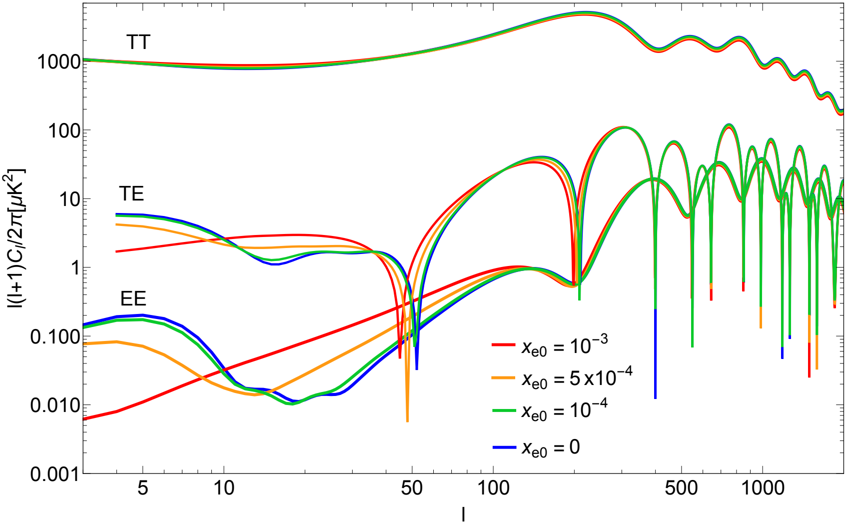
Effects on reionization history

Evolution of the free electron fraction for fixed reionization optical depth.



Effects on reionization history

The effect of the PBHs is much more evident in the polarization power spectra rather than in temperature



Effects on reionization history

The partial ionization due to PBHs and the ionization from the high redshift stars and galaxies produces different signatures on the CMB anisotropy spectra:

- PBHs affect angular scales $10 \lesssim l \lesssim 100$.
- Stars and Galaxies affect larger scales $l \lesssim 10$.

This two effects are almost uncorrelated and we can separate the total optical depth in two different contributions:

$$\tau = \tau_{rei} + \Delta\tau$$

were the contribution of the PBHs to the optical depth is:

$$\Delta\tau = \int_{z_{rec}}^{z_{dec}} \frac{x_e^{pbh}(z) n_H(z) \sigma_T}{H(z)(1+z)} \, dz$$

In the mass range range $1 M_\odot \leq M_{pbh} \leq 100 M_\odot$ the value of $\Delta\tau$ is related to the fractional abundance of PBH by the relation derived by M. Ricotti, J. P. Ostriker and K. J. Mack:

$$\Delta\tau \approx 0.05 \left(\frac{M_{pbh}}{M_\odot} \right) f_{pbh}^{1/2}$$

From $\Delta\tau$ is then possible to obtain f_{pbh}.

Constraints on PBHs relative abundance

We have used the Markov Chain Monte Carlo code CosmoMC to constrain the cosmological parameters for different combinations of the Planck 2015 data

- Planck TT+lowP.
- Planck TT,TE,EE+lowP.
- Planck TT,TE,EE+lowP+lensing.

Initial settings for the first cycle of runs:

- x_{e0} as free parameter.
- Fixed sum of the neutrino masses $\Sigma m_\nu = 0.06$ eV
- flat prior over x_{e0}.

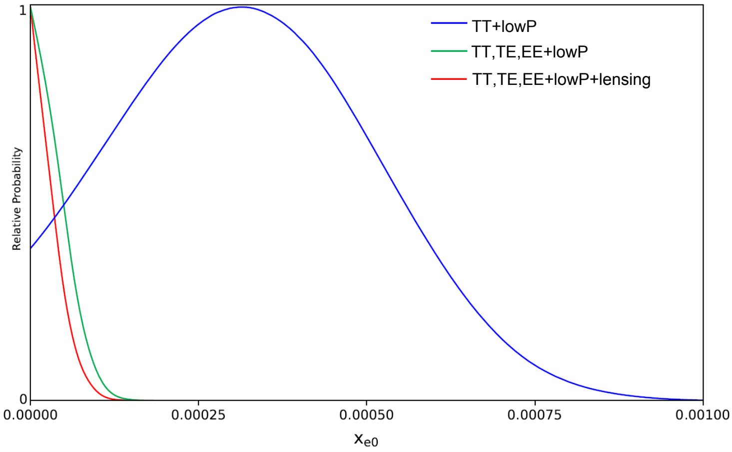
Assumptions:

- Spatial flatness.
- Adiabatic initial conditions.

We fitted the free parameters:

$\{\Omega_b h^2, \Omega_{dm} h^2, 100\theta_{MC}, \ln(10^{10} A_s), n_s, \tau_{rei}, x_{e0}\}$ and computed z_{rei} as a derived parameter

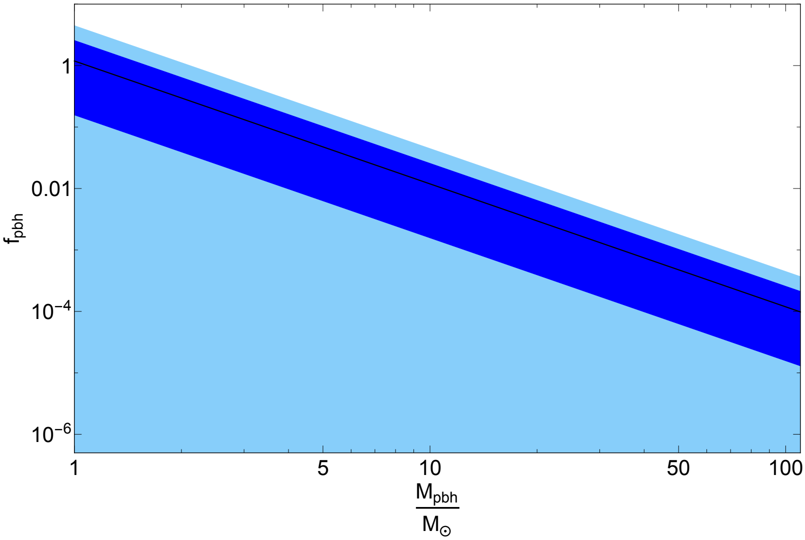
Constraints on PBHs relative abundance



We obtained upper limits at 95% C.L.

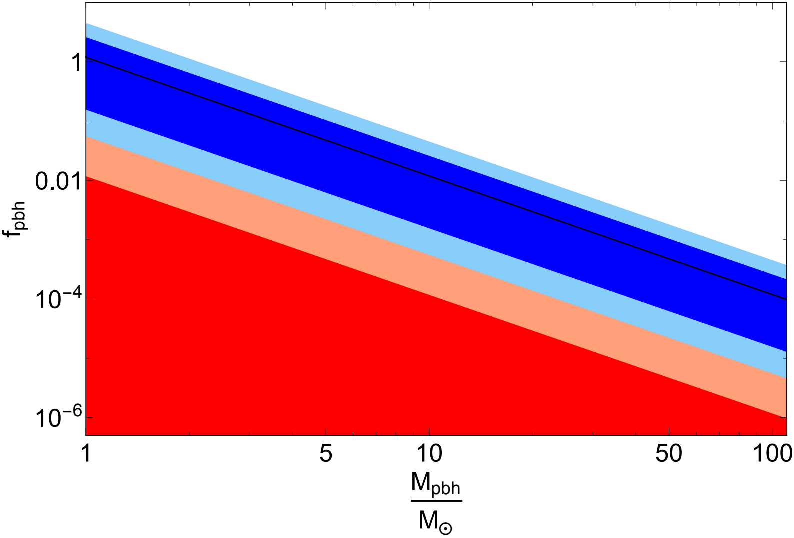
- $x_{e0} < 6.4 \times 10^{-4}$ TT+lowP
- $x_{e0} < 8.5 \times 10^{-5}$ TT,TE,EE+lowP
- $x_{e0} < 7.1 \times 10^{-5}$ TT,TE,EE+lowP+lensing

Constraints on PBHs relative abundance



TT+lowP $\quad f_{pbh} < 4.4 \left(\frac{M_{pbh}}{M_\odot} \right)^{-2}$ (95%C.L.)

Constraints on PBHs relative abundance



TT,TE,EE+lowP+lensing $\quad f_{pbh} < 0.04 \left(\frac{M_{pbh}}{M_\odot}\right)^{-2}$ (95%C.L.)

Σm_ν as additional free parameter

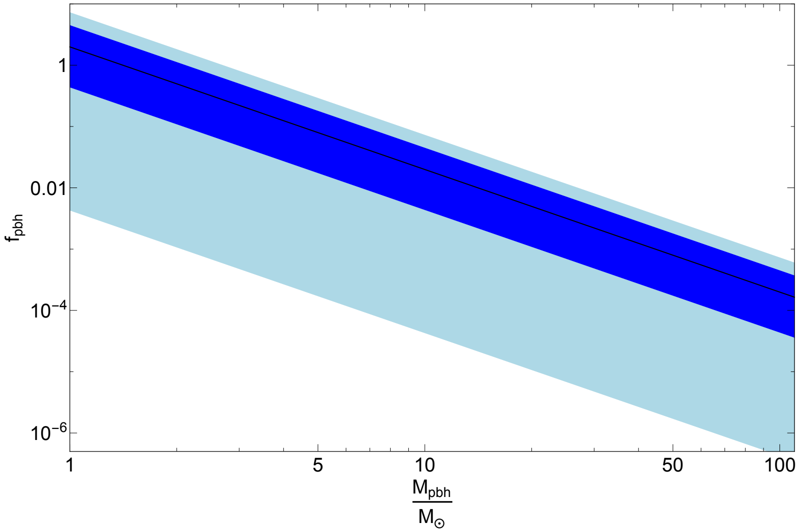
We have performed another series of runs with Σm_ν as an additional free parameter $\rightarrow$ degeneracy with x_{e0}
We found larger upper limits (at 95% C.L.) for:

- Σm_ν with respect to the standard case

Σm_ν [eV]	TT+lowP	TT,TE,EE+lowP	TT,TE,EE+lowP+lensing
extended ΛCDM	< 0.715	< 0.492	< 0.589
ΛPBH	< 1.252	< 0.557	< 0.683

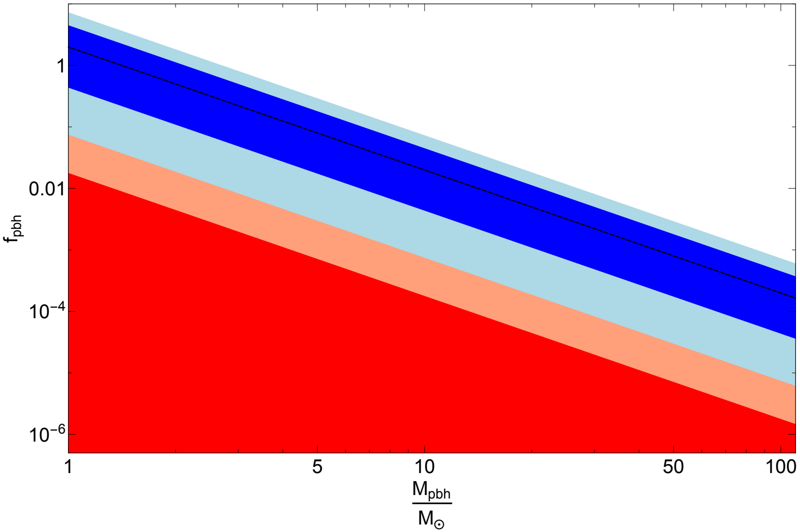
- x_{e0} with respect to the case with fixed Σm_ν

x_{e0}	TT+lowP	TT,TE,EE+lowP	TT,TE,EE+lowP+lensing
Fixed Σm_ν	$< 6.4 \times 10^{-4}$	$< 8.5 \times 10^{-5}$	$< 7.1 \times 10^{-5}$
Free Σm_ν	$< 8.2 \times 10^{-4}$	$< 8.8 \times 10^{-5}$	$< 8.3 \times 10^{-5}$



TT+lowP $\quad f_{pbh} < 6.7 \left(\frac{M_{pbh}}{M_\odot}\right)^{-2}$ (95%C.L.)

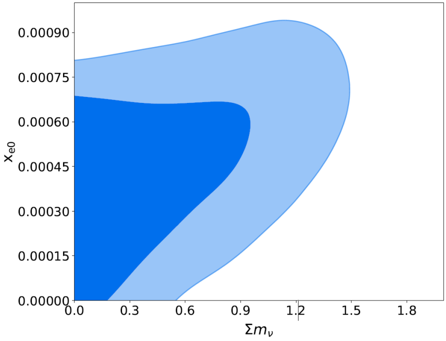
Constraints on PBHs relative abundance



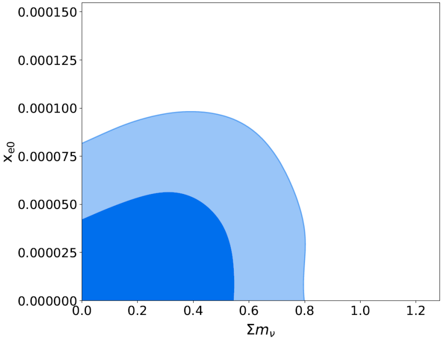
TT,TE,EE+lowP+lensing $\quad f_{pbh} < 0.06 \left(\frac{M_{pbh}}{M_\odot} \right)^{-2}$ (95%C.L.)

Degeneracy between x_{e0} and Σm_ν

TT+lowP



TT,TE,EE+lowP+lensing



Future prospects

We used relations derived by M. Ricotti, J. P. Ostriker and K. J. Mack in a seminal article published in 2008 https://arxiv.org/pdf/0709.0524.pdf

$$x_e^{pbh}(z) = \min\left[x_{e0}\left(\frac{1+z}{1000}\right)^{-1}, 0.1\right]$$

$$\Delta\tau_e = 0.05\left(\frac{M_{pbh}}{M_\odot}\right) f_{pbh}^{1/2}$$

Recent work by Ali-Hamoud and Kamionkowski https://arxiv.org/pdf/1612.05644.pdf refined the calculation suggesting the following improvements:

- Numerical parameter λ as a function of redshift.
- f_{pbh} can be obtained directly by calculating the energy injection rate in the plasma.
- The evolution of the free electron fraction after recombination can be obtained by calculating the energy injection deposition rate.

Conclusions

- No evidence for early reionization from PHBs.
- High-l polarization data put tight constraints on the abundance of PBH. Temperature data alone still allow $f_{pbh} = 1$.
- There is a degeneracy between the two free parameters x_{e0} and $\Sigma m_\nu \rightarrow$ a Universe with a larger value of Σm_ν allows larger values of f_{pbh}.
- More precise calculations that consider the energy injection and deposition rate could change this picture.
- Different accretion mechanisms are possible $\rightarrow$ Poulin et al. Recently suggested the Advection Dominated Accretion Flow (ADAF) as a possible alternative to the Bondi accretion https://arxiv.org/pdf/1707.04206.pdf.
- All the results obtained assuming:
  - spherical accretion
  - monochromatic mass function
  - negligible merging rate

Thanks for the attention