CMB constraints on (evaporating) primordial black holes

*An application of **ExoCLASS***

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in collaboration with:
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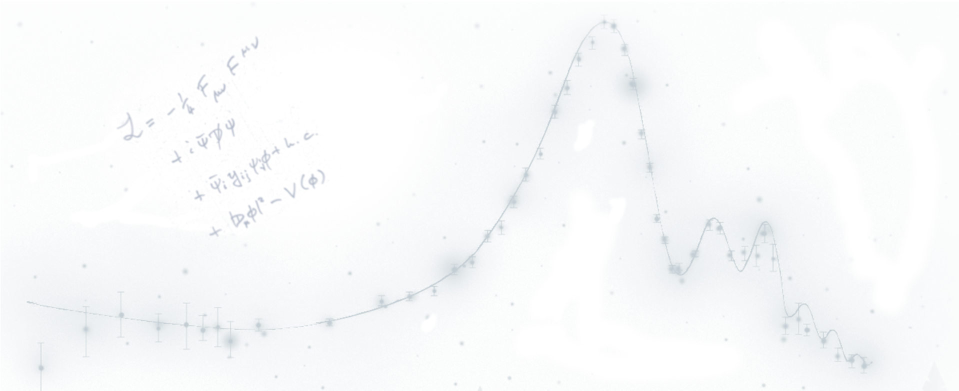
Outline

1. How does energy injected by dark matter influence the CMB?
   - Recombination in a nutshell
   - How to parametrize the model-specific influence on recombination
2. Constraining evaporating primordial black holes with the CMB
   - An alternative to the "DM is a particle"-paradigm
   - The influence of evaporating PBHs on recombination and the CMB
   - Results: Can DM be made up of evaporating primordial black holes?

Effect of DM induced energy injection on the early IGM

- Without loss of generality consider a model of DM χ which annihilates into the standard model $\chi\chi \to$ SM SM, most of these SM-particles decay and additional radiation is induced.

$$\chi\chi \to \text{SM SM} \to e^+, e^-, \gamma, \nu, p$$



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Evolution of the **ionization fraction** x_e and the **matter temperature** T_M

- Evolution **with**/without DM-induced energy injection:

$$\frac{\mathrm{d}x_e(z)}{\mathrm{d}z} = \frac{1}{(1+z)\,H(z)}\left(R(z) - I(z) - \boldsymbol{I(z)_X}\right)$$

and

$$\frac{\mathrm{d}T_M}{\mathrm{d}z} = \frac{1}{1+z}\left[2 \cdot T_M + \gamma(x_e)\,(T_M - T_{\mathrm{CMB}}) + \boldsymbol{K_h}\right]$$

- All additional contributions, ionization $I(z)_X$ and heating K_h, depend on the rate of energy **deposition** $\left.\frac{\mathrm{d}E(z,x_e)}{\mathrm{d}V\mathrm{d}t}\right|_{\mathrm{dep.}}$
- How does this rate relate to the rate of energy **injection**?

Relating the rate of energy *deposition* with the rate of energy *injection*

- The deposited energy rate $\left.\frac{\mathrm{d}E(z,x_e)}{\mathrm{d}V\mathrm{d}t}\right|_{\mathrm{dep.}}$ and injected energy rate $\left.\frac{\mathrm{d}E(z)}{\mathrm{d}V\ \mathrm{d}t}\right|_{\mathrm{inj.}}$ describe physics on two different energy scales. What happens in between?
- To infer the deposited energy rate (into a certain channel c) $\left.\frac{\mathrm{d}E(z,x_e)}{\mathrm{d}V\ \mathrm{d}t}\right|_{\mathrm{dep.\ (ch.)}}$, introduce the efficiency factor $f_c(z, x_e)$

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- $f_c(z)$ can be expressed by the spectrum of injected particles $\frac{\mathrm{d}\dot{N}(E,t(z))}{\mathrm{d}E}$, through convolution with precomputed transfer functions [Slatyer '12 & '15, *1211.0283, 1506.03811, 1506.03812*] $(\ell = e^+e^-, \gamma)$:

$$f_c(z) = \frac{\int\limits_z^\infty \mathrm{d}\ln(1+z') \frac{(1+z')^3}{H(z')} \quad \sum_\ell \int\limits_0^m \mathrm{d}E\ T_c^{(\ell)}(z',z,E) E \left.\frac{\mathrm{d}\dot{N}(E,t(z))}{\mathrm{d}E}\right|_{\mathrm{inj.}}^{(\ell)}}{\frac{(1+z)^3}{H(z)} \quad \int\limits_0^m \mathrm{d}E\ E \left.\frac{\mathrm{d}\dot{N}(E,t(z))}{\mathrm{d}E}\right|_{\mathrm{inj.}}^{\mathrm{tot.}}}$$

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- The deposited energy rate $\left.\frac{dE(z,x_e)}{dVdt}\right|_{dep.}$ and injected energy rate $\left.\frac{dE(z)}{dV\ dt}\right|_{inj.}$ describe physics on two different energy scales. What happens in between?
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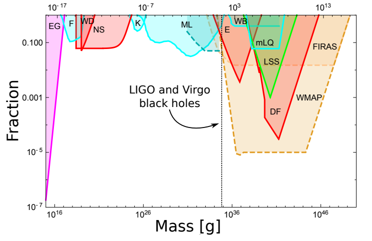
- →Development of **ExoCLASS**, an extension of the CMB-code CLASS, to incorporate the effect on the CMB for every exotic scenario of energy injection. *(Publication in preparation)*

The fuzz about primordial black holes as (subdominant) dark matter

- PBHs are black holes produced through density fluctuations in the early universe.
- Broad range of possible masses.→Broad phenomenology.
  (e.g. Constraints from CMB (accretion and evaporation), extragalactic γ-background, lensing and LSS)
- Possible origin of black hole-binary mergers measured by LIGO and VIRGO.

[Carr '16 *1607.06077*]



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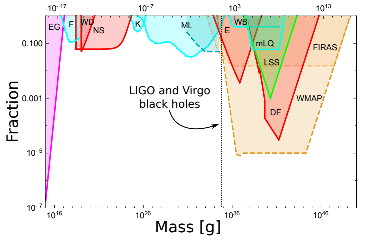


- Light PBHs ($M \sim 2 \times 10^{13} - 10^{17}$ g) have a temperature ($T_{\mathrm{BH}} \sim 1/M_{\mathrm{BH}}$) high enough to evaporate and to sizeably inject energy into the IGM through Hawking-radiation.
- Injected spectrum (for particle species with spin s) follows thermal distribution:

$$\frac{\mathrm{d}\dot{N}_s}{\mathrm{d}E}(E,z) \propto \frac{E/T_{\mathrm{BH}}(z)}{\exp\left(E/T_{\mathrm{BH}}(z)\right) - (-1)^{2s}}$$

- Evaporation in turn reduces the mass of the black hole

$$\frac{\mathrm{d}M}{\mathrm{d}t} \propto -\mathcal{F}(M)M^{-2}$$

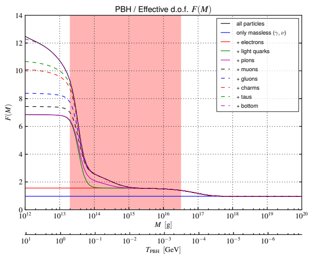
with $\mathcal{F}(M)$ being the effective degrees of freedom for a black hole with mass M.

The choice of $\mathcal{F}(M)$

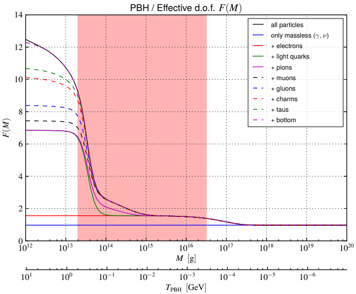
- In principle, take a sum of step-functions which kick in at $T_{\mathrm{BH}} = m_i$, weighted with the d.o.f. of the particle.
- We follow the prescription given in [J. H. MacGibbon '91 (PRD 44, 376)] and include the QCD-phase transition.

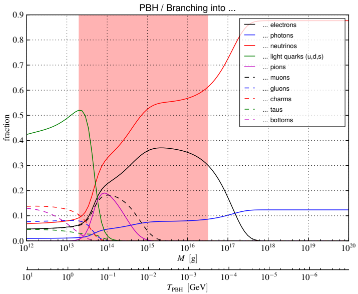
$$\mathcal{F}(M) = \sum_{\text{part. } i} \Pi_i \cdot f_{s,q} \cdot \exp\left(-\frac{M}{\beta_s \tilde{M}_i}\right) \cdot Q_i(T(M))$$

with Π_i being the internal degrees of freedom of the particle i, $\tilde{M}_i$ being the mass of a black hole with a temperature $T_{\mathrm{BH}} = m_i$ and $f_{s,q},\ \beta_s$ encoding the peak height and position of a black-body spectrum given the spin s and the charge q of the particle. (Takes the tail of the thermal distribution into account.)

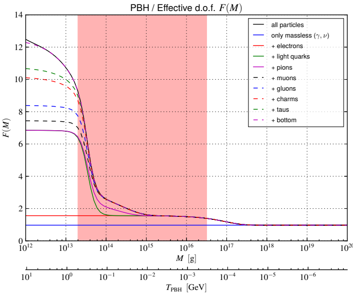


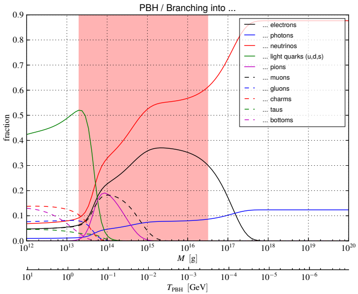
CMB-constraints on evaporating primordial black holes I





- So far, previous studies [Poulin ,Lesgourgues ,Serpico '16, *1610.1005*] ...
  - ... did not include the variation of the PBH-mass for initial masses below $\sim 10^{15}$ g.
  - ... only considered the primary electrons/positrons and photons. All other species are "inefficient".





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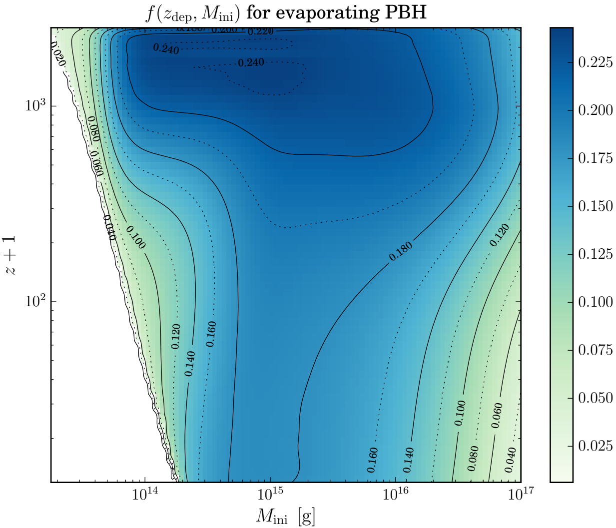
  - ... did not include the variation of the PBH-mass for initial masses below $\sim 10^{15}$ g.
  - ... only considered the primary electrons/positrons and photons. All other species are "inefficient". **But** in the mass range of our interest pions, muons and light quarks can have a non-negligible contribution to the energy injection and should be included
- The implementation in the **ExoCLASS**-package addresses both points above (*Still excluding the secondary of the quarks*).
  $\rightarrow$First precise analysis of CMB constraints on evaporating PBHs

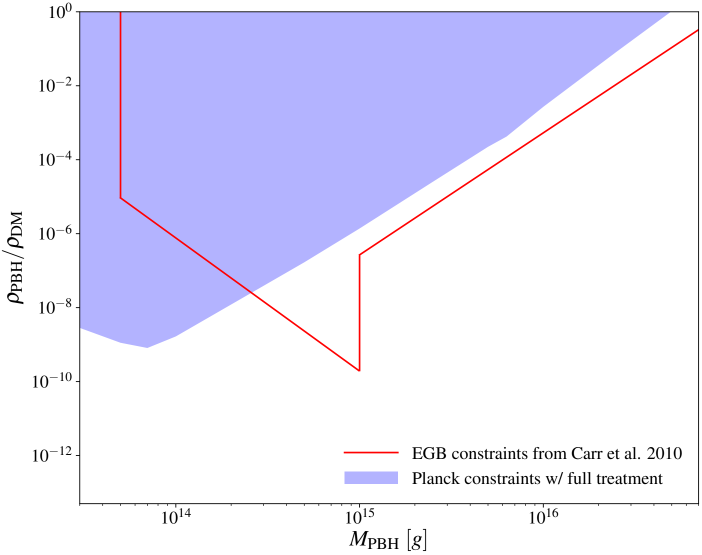
CMB-constraints on evaporating primordial black holes II

$f(z)$ as function of the initial mass



CMB-constraints on evaporating primordial black holes III

Constraint on the allowed DM-fraction



Conclusions

- Development of **ExoCLASS**, a package to calculate the influence of dark matter induced energy injection on the IGM during the "dark ages" for any generic model *(for any given injection spectrum)* and for any injection history *(for any z-dependence of the energy rate)*
- First detailed analyses on evaporating primordial black holes lead to the strongest results in the range of "short-lived" black holes ($M < 10^{15}$ g), where the PBH-mass significantly change with time and the black hole fully evaporates within the redshift-window the CMB is sensitive to.
- Lowest possible mass which has an effect on the CMB:

$$M_{\text{PBH}} > 2 \times 10^{13}\ \text{g}$$

- For "long-lived" black holes, constraints from extragalactic gamma-ray background are stronger by an order of magnitude.

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- For "long-lived" black holes, constraints from extragalactic gamma-ray background are stronger by an order of magnitude.
- The **ExoCLASS**-package and the PBH-results will be published soon (Together with the validation of the package in the scope of the Higgs-Portal model)

Thank You for Your Attention

Any Open Questions?

Backup

Recombination in a slightly bigger nutshell

Evolution of the **ionization fraction** x_e and the **matter temperature** T_M

- The easiest recombination-model assumes a three level atom (Ground state, excited state, continuum) [Peebles '68, Zeldovich et al. '69]
- Evolution **with**/without DM-induced energy injection:

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and

$$\frac{\mathrm{d}T_M}{\mathrm{d}z} = \frac{1}{1+z}\left[2\cdot T_M + \gamma(x_e)\,(T_M - T_{\mathrm{CMB}}) + \boldsymbol{K_h}\right]$$

- The additional ionization term $I(z)_X = I_{X_i} + I_{X_\alpha}$ is given by:

$$I_{X_i} = \frac{1}{n_H(z)E_i}\left.\frac{\mathrm{d}E(z,x_e)}{\mathrm{d}V\mathrm{d}t}\right|_{\mathrm{dep.\ (direct\ ion.)}} \quad \text{and} \quad I_{X_\alpha} = \frac{1-C}{n_H(z)E_\alpha}\left.\frac{\mathrm{d}E(z,x_e)}{\mathrm{d}V\mathrm{d}t}\right|_{\mathrm{dep.\ (excit.\ +\ ion.)}}$$

- The contribution to the heating term K_h is:

$$K_h = \frac{2}{H(z)3k_B n_H(z)\,(1+f_{He}+x_e)}\left.\frac{\mathrm{d}E(z,x_e)}{\mathrm{d}V\mathrm{d}t}\right|_{\mathrm{dep.\ (heat.)}}$$

Under the bonnet of **ExoCLASS**

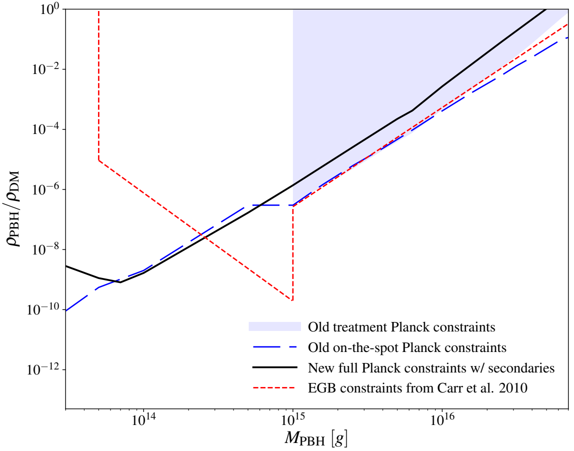
- **Cosmological constraints on a given DM-model can in principle be derived in three steps**
  1. Calculate, given the parameters of the model, the injected spectrum of $e^{\pm}, \gamma$ at given energy E (and at given redshift z').
  2. From this $f_c(z)$ is calculated by convolution of the spectra with the transfer function $T_c^{(\ell)}(z', z, E)$.
  3. Feed $f_c(z)$ into *CLASS* for the calculation of C_ℓ

- **In practice this looks like:**
  - The $f(z)$-backend of the **ExoCLASS**-package (written in Python) calculates $f_c(z)$ from a given injection spectra (e.g. from MadGraph / PYTHIA) (steps 1 and 2)
    - Possibility to derive $f(z)$ for different injection histories: 'Annihilation of particle DM','Decay of particle DM', 'Injection by black hole evaporation', ...
    - Spectra are automatically read and processed. (Automatic interpolation if spectra for different points in parameter space are given)
    - Inclusion of the cosmological background H_0, Ω_m, Ω_r into the convolution with the transfer functions

    →Can be also used as standalone-package.
  - This backend is interfaced with the CMB-anisotropy solver CLASS. (step 3)
    - DM model-parameters are input parameters of (Exo)CLASS. (Exo)CLASS sets up the call to the backend and processes the output.

CMB-constraints on evaporating primordial black holes

Comparison to previous analyses



- Previous analysis overestimated the relative impact of electrons and photons to other (ineffective) particles. Hence the constraints were too strong.

Spectra from PBH evaporation (Primary emission vs. secondary emission)