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Cosmic microwave background as a probe of dark relics

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I argue how cosmology (and the CMB in particular) is sensitive to even extremely suppressed interaction rates of (meta)stable species present in the cosmic soup. The case of dark relics decaying either in a dark sector or via some tiny visible branching ratio into visible form are reviewed. Applications to evaporating and merging primordial black holes are also covered. Finally, I conclude with some considerations on the CMB sensitivity to dark radiation.

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1. Introduction

Since a few decades, we are living a bizarre situation in fundamental physics: On the one hand, cosmological evidence definitively points to the existence of new physics unaccounted for in current theories of the fundamental constituents and their interactions (the celebrated "Standard Model", SM), for instance requiring large amounts of dark matter (DM) and a large baryon asymmetry. On the other hand, all searches at both the high-energy and the high-precision frontiers have come up empty-handed, with the long-sought new physics (NP) nowhere in sight.

At this point, we should assume as a concrete possibility that the NP required to address the cosmological conundrum is very weakly coupled with the SM and, for instance, that DM does little more than its job of... gravitating. Should we therefore conclude that this type of NP is essentially undetectable? Not necessarily so: My contribution to the Corfu Institute 2018 has been motivated at bringing some hope! I argue in the following that cosmological probes would still offer us some opportunity to discover rather *dark* relics, should this situation be realized in Nature. I will discuss in particular what the Cosmic Microwave Background (CMB) tells us about such scenarios, alone or supplemented by large-scale structure (LSS) data. All the results below concerning these observables were obtained by appropriate modifications of the CLASS code, `http://class-code.net/`.

2. "Dark matter" conversion into "dark radiation"

To convince ourselves that some optimism is justified, let us consider what is possibly the next-to-closest case to an "undiscoverable" relic: some component of the DM that merely decays into a dark radiation (DR) residing in an unspecified "dark sector" (DS). The DR may be constituted of new degrees of freedom (dof's) or "standard" dof's which are hard to identify, such as (low-energy) neutrinos or gravitational waves (GWs). For concreteness, let us assume that DM is made of a stable component (contributing Ω_s to the critical density) plus an unstable relic (contributing Ω_d to the critical density), with the latter amounting to a fraction f_d of the initial total DM fraction $\Omega_{\rm DM}^{\rm in}$. If $\Gamma_d^{-1} \equiv \tau_d$ is the lifetime of the unstable relic, in formulae we have

$$\Omega_{\rm DM} = \Omega_s + \Omega_d = (1 - f_d)\Omega_{\rm DM}^{\rm in} + f_d \Omega_{\rm DM}^{\rm in} \exp(-\Gamma_d t)\,. \tag{2.1}$$

This simple parameterization also describes the case where DM decays into a lighter (still non-relativistic) relic plus extra DR, although in this case additional and typically more stringent bounds follow from observables sensitive to the velocity distribution of the relic DM.

Cosmology is affected both at "zero-th" order, i.e. via an alteration of the homogeneous equations, and at higher-orders in perturbation theory. The equations for the average energy densities ρ_i of these species (d for DM, r for the DR product) can be easily derived e.g. from the Bianchi identity $\nabla_\mu T^{\mu\nu} = 0$ and write:

$$\rho_d' = -3\frac{a'}{a}\rho_d - a\Gamma_d\rho_d\,, \tag{2.2}$$

$$\rho_r' = -4\frac{a'}{a}\rho_r + a\Gamma_d\rho_r\,, \tag{2.3}$$

where a is the scale factor, a prime indicates a derivative with respect to conformal time, so that $a'/a = aH \equiv \mathscr{H}$, H being the Hubble expansion rate. For perturbations, we address the reader to [1], where a derivation is reported starting from Boltzmann equations, and some subtleties about gauge compatibility are discussed.

Concerning the phenomenological effect of decaying DM, let us have a look at the case $f_d = 1$, first. The CMB anisotropies are affected mostly by the late integrated Sachs-Wolfe effect, i.e. via the impact on metric fluctuations of a non-trivially evolving DM density at late times. The upper panel in Fig. 1 shows the effect of this dark decay model on the multipole coefficients C_ℓ (for benchmark parameters, see [2]). The addition of LSS data mostly helps in breaking partial degeneracies with other effects, such as curvature and tensor modes (compare upper and lower panel of Fig. 1). The resulting 95% CL bound (as all bounds quoted below) is $\tau_d \gtrsim 160-170\,\mathrm{Gyr}$ (depending exactly on the cosmological datasets used), i.e. the DM lifetime is constrained to be more than one order of magnitude longer than age of the universe! For more details, see [1, 2].

Let us move to the case $f_d < 1$; there are essentially three regimes:

- For a very long lifetime, i.e. if $H\tau_d \gg 1$, to first order the data are only sensitive to the product $\Gamma_d f_d$, since Eq.(2.1) rewrites

$$(1-f_d)\Omega_{\rm DM}^{\rm in} + f_d\Omega_{\rm DM}^{\rm in}\exp(-\Gamma_d t) \simeq \Omega_{\rm DM}^{\rm in}[1 - f_d\Gamma_d t + \mathscr{O}(\Gamma_d^2 t^2)]\,, \tag{2.4}$$

  and the bound is $f_d\Gamma_d < 0.0063\,(0.0059)\ \mathrm{Gyr}^{-1}$ for CMB only (adding consistent data).

- If the τ_d falls between recombination at $\sim \tau_{\rm CMB}$ and recent times, i.e. $H\tau_{\rm CMB} \ll H\tau_d \ll 1$, the data are practically insensitive to τ_d (see Fig. 2) and the constraint is $f_d \lesssim 0.038$. This bound thus also applies also to complicated, non-decaying DM models, where the DM abundance evolves due to other processes. An example could be DM in the form of primordial black holes (PBHs), subject to merging and emission of “dark radiation” in the form of GWs.

- For very short lifetimes, $\tau_d < \tau_{\rm CMB}$, the bound on f_d relaxes significantly, becoming weaker and weaker the shorter τ_d is, essentially degenerate with a higher (unmeasurable) value of $\Omega_{\rm DM}^{\rm in}$. No significant constraint exists if the lifetime is significantly shorter than the matter-radiation equality epoch.

Far from being academic curiosities, these constraints apply to numerous models discussed in the literature. For a partial and certainly incomplete list:

- Within supersymmetric scenarios (SUSY), think of cases where the lightest SUSY particle (LSP) and the next-to-lightest SUSY particles (NLSP) are a pair of particles among gravitinos, axions, saxions, axinos, right-handed sneutrinos, etc. A recent example of this sort has been discussed in [3].

- in SUSY models of NP accompanied by DS, including string-inspired ones, generically the lightest particle is expected in the DS, and the lightest “visible” SUSY partner is metastable [4].

- For a notable non SUSY example, think of the “invisible” Majoron model with keV-scale, mass and decaying into neutrinos, revisited e.g. in [5].

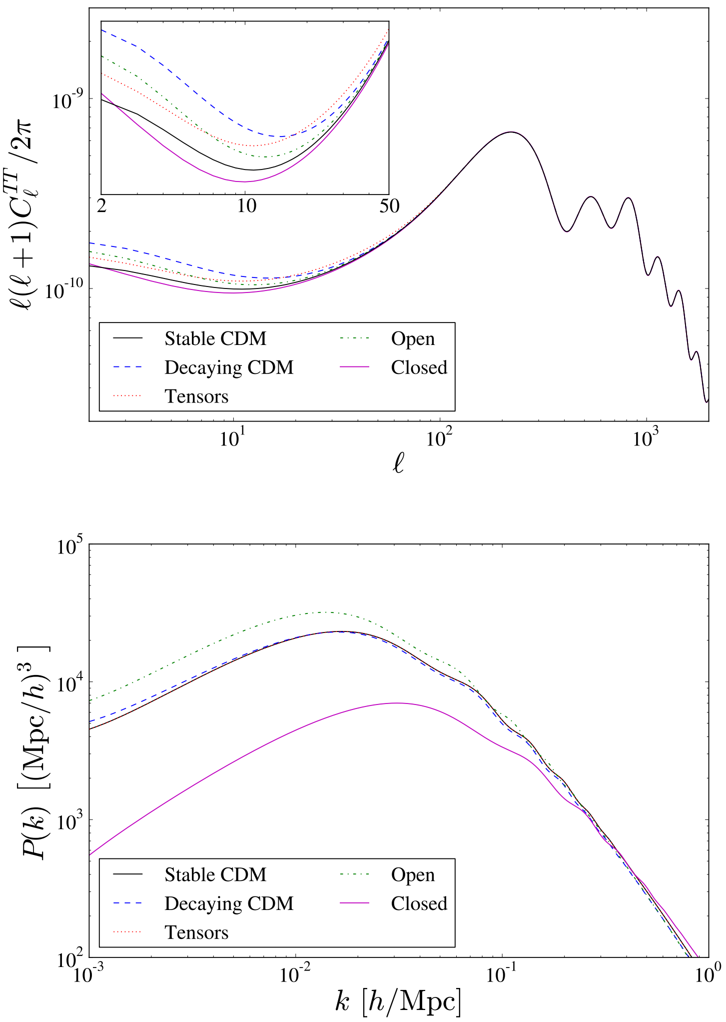

Figure 1: Effects of a dark decay scenario (dashed blue lines) on CMB temperature anisotropy multipoles (upper panel) and LSS power spectrum (lower panel), compared with the "concordance" ΛCDM model (solid black), a model with large tensor mode component (dotted red) and non-flat models (dash-dotted green and solid magenta, respectively, for open or closed universe). Adapted from [2].

- The field of application also extends to *non-particle* relics and *non-decaying* ones: the most notable case is the one of PBHs, where DR is nothing but GWs, and the process producing them is the merger of two PBHs into one. Since 4-5% of the initial mass of the system is converted into GWs in an equal-mass merger [6], either PBH do not make a sizable fraction of the DM or their mass function evolution over most of the history of the universe must be negligible, since on average they should have merged less than once (Fig. 2).

3. Massive relics injecting some electromagnetic energy

Let us now move to the more rich case where a relic injects some electromagnetic interacting SM

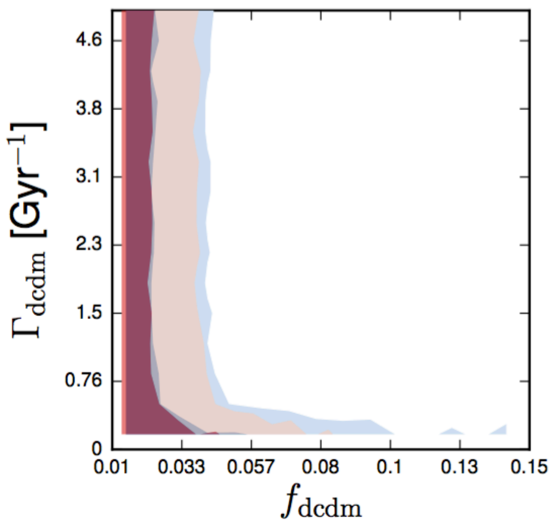

Figure 2: 68% and 95% exclusion regions in the $f_d - \Gamma_d$ plane for the intermediate lifetime regime $H\tau_{\rm CMB} \ll H\tau_d \ll 1$. Adapted from [1], which we address the reader to for further details.

particles. This is associated to a variety of particle physics or astrophysical processes, like

- Annihilating relics (like Weakly Interacting Massive Particle, or WIMP, DM).
- Decaying relics such as heavy sterile ν's or unstable WIMP particles (sometimes dubbed super-WIMPs).
- Evaporating PBHs (hence 'light' to ensure a non-negligible evaporation rate).
- Accreting PBHs (hence 'stellar mass or heavier', to ensure sizable accretion).

What happens to cosmological observables in this case? While the energy of the injected non-thermal particles is negligible with respect to the energy stored in the CMB photons, it is *not negligible* with respect to the kinetic energy of the baryonic gas, which can eventually be heated up (altering the gas temperature T_M) and ionized (altering the ionization fraction x_e). The latter, in particular, leads to alterations in the optical depth experienced by the CMB photons, to which CMB anisotropies are *very* sensitive! How sensitive? For a basic estimate, keep in mind that $\mathscr{O}(100)$ eV/baryon is more than enough to ionize all atoms (mostly hydrogen, with some Helium). In the DM sector, a rest mass energy of $\sim$5 GeV/baryon is available. In the standard thermal history of the Universe, the ionization fraction drops to $\sim 5\times10^{-4}$ in the dark ages following CMB recombination. Therefore, one can conclude that a 'visible' b.r. of $\mathscr{O}(10^{-11})$ may be sufficient to induce major alterations in x_e or T_M.

Of course, this is an 'optimal' sensitivity. Not all of the energy injected will be efficiently used to ionize the medium. Also, different processes differ in the amount and time-dependence of the ionizing radiation injected, leading to quantitative differences. In the rest of the section, let us explore a few benchmark scenarios.

3.1 Application to annihilating WIMPs

What do annihilating WIMPs do on CMB? Via annihilation byproducts, they inject energy in the medium at a rate

$$\left.\frac{dE}{dV\,dt}\right|_{\rm inj} = \rho_c^2(1+z)^6\Omega_{\rm DM}^2\frac{\langle\sigma v\rangle}{m_X} \tag{3.1}$$

which corresponds to a *deposited* energy

$$\left.\frac{dE}{dV\,dt}\right|_{\rm dep} = f(z)\left.\frac{dE}{dV\,dt}\right|_{\rm inj}, \tag{3.2}$$

which defines the energy deposition function $f(x_e(z),z)$. In general, these functions depend on the final state particle and on the medium properties, notably density of species (via z) and ionization state. In order to compute them, rather complex Monte Carlo treatments of the cascades induced by high-energy photons and $e^\pm$ in the cosmological medium are necessary, but these are ruled by SM processes, and tabulated results accurate to 10-20% level exist [7] [1]. In the above expressions, the key-parameter linked to particle physics is $p_{\rm ann}\equiv f(z)\langle\sigma v\rangle/m_X$, whose current bound—computed with ExoCLASS module [9]—from the latest Planck analysis is $p_{\rm ann}<3.2\times10^{-28}{\rm cm}^3\,{\rm s}^{-1}{\rm GeV}^{-1}$ [10]. Since $f(z)$ has typical values of $\mathscr{O}(0.1)$, the above limit implies a sensitivity in the $m_X-\langle\sigma v\rangle$ plane comparable to astrophysical constraints on WIMPs in the recent universe, such as gamma-ray ones, touching typical cross-section for S-wave thermal relics for masses of 10-30 GeV. Yet, it is much closer to a "calorimetric" bound, and pretty much independent of astrophysical details. Note that one may have expected that the large clumpiness of DM structures make the homogeneous DM distribution approximation implicit in Eq. (3.1) inadequate, but recent analyses (see e.g. [11] and refs. therein) clearly indicate that it is mostly the pristine energy injection at high-z that matters, when Eq. (3.1) is a very good proxy for the actual energy injection.

3.2 Application to decaying relics

As another application, consider a *decaying* relic. In this case,

$$\left.\frac{dE}{dV\,dt}\right|_{\rm inj} = \rho_c(1+z)^3\Omega_{\rm DM}\Xi\Gamma e^{-\Gamma t}, \tag{3.3}$$

where Ξ is the relative amount of energy (normalized to the DM one) released into e.m. for a single decay. For instance, a species constituting 1% of the total DM abundance decaying into $\nu\gamma$ corresponds to Ξ=1/200.

Analogously to the case of annihilating DM, we can define the efficiency functions $f(z)$, and compute the corresponding evolution of x_e and T_M. Compared to the annihilating case, they show a larger variety, notably due to the large range of Γ allowed. For very short lifetimes, the effect is rather similar to the one of annihilating WIMPs (see top panel in Fig. 3). For very long lifetimes (see bottom panel in Fig. 3), the effect may resemble an earlier and more slowly rising star formation, becoming partially degenerate with astrophysical scenarios. For intermediate lifetimes (see

[1]These results are also slightly conservative since energy depositions by protons and antiprotons (ultimate byproducts of the baryonic components of the showers) are usually neglected, albeit they could contribute as well at the $\sim$ 10% level, if DM mostly annihilates into quarks and/or gluons, see [8].

PoS(CORFU2018)094

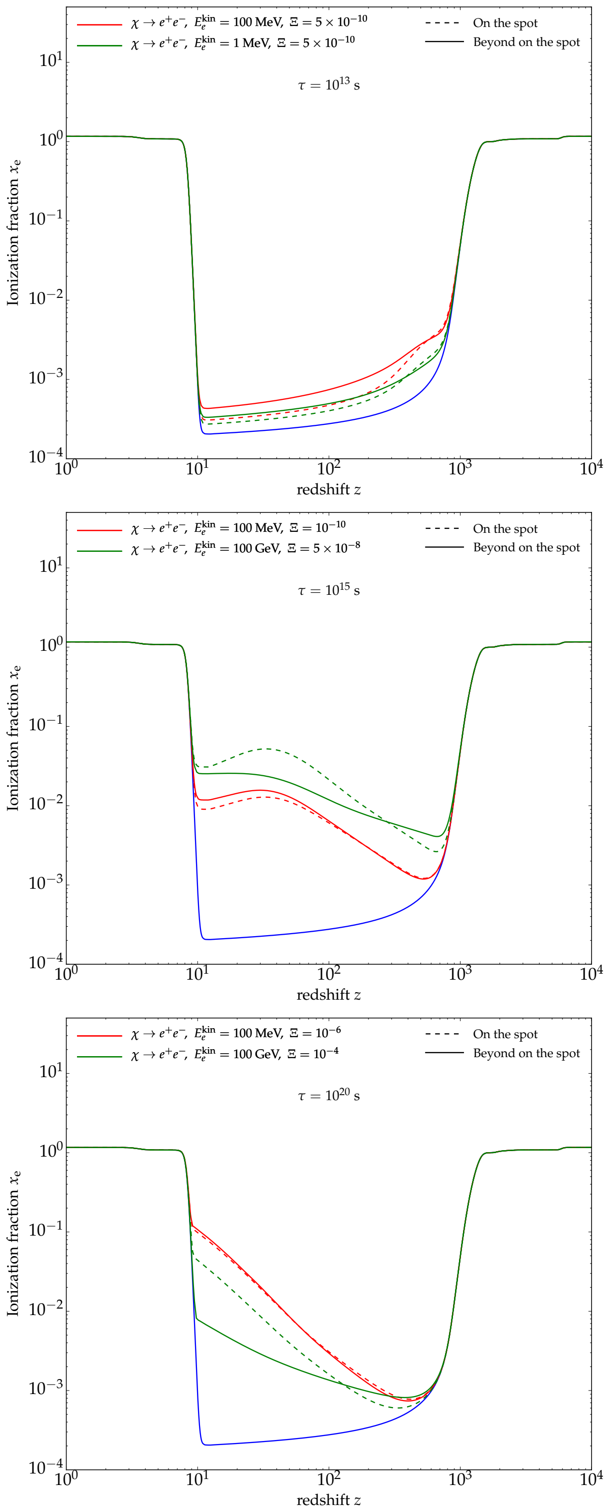

Figure 3: Ionization fraction x_e vs. redshift z for the fiducial ΛCDM model (blue curves) and for a decaying DM scenario with short (top panel), intermediate (middle panel) or long (bottom panel) lifetimes. Different energies and b.r. Ξ are considered. Dashed (as opposed to solid) lines are the result of a more approximated method of calculation. From [12].

middle panel in Fig. 3), very peculiar 'bumpy" features can arise. Unfortunately at the moment the CMB only provides an integrated bound on x_e, but future probes like the 21 cm tomography offer some hope to distinguish those scenarios.

In figure 4 we summarize the CMB bounds on this decaying scenario for a couple of final states (blue and green colors) roughly bracketing the possibilities of energy deposition efficiencies (width of shaded bands) and for an approximate ("on the spot") vs more refined treatment of the energy deposition (dashed vs. solid line styles; see [12] for details). We see that for lifetimes comparable with the CMB formation (recombination), one attains sensitivity to b.r. of $\mathcal{O}(10^{-11})$, as estimated above. For longer lifetimes, one loses sensitivity roughly proportionally to $\tau_{\rm CMB}/\tau_d$. One way to interpret this is that the bound mostly comes from energy injected at very early times after CMB formation, which is the most effective one. Note also the complementarity with bounds coming from dissociation of elements produced in primordial nucleosynthesis (shaded pink area) or CMB spectral distortions (above the solid cyan and red lines), which constrain instead relatively short lifetimes $\tau_d \ll \tau_{\rm CMB}$.

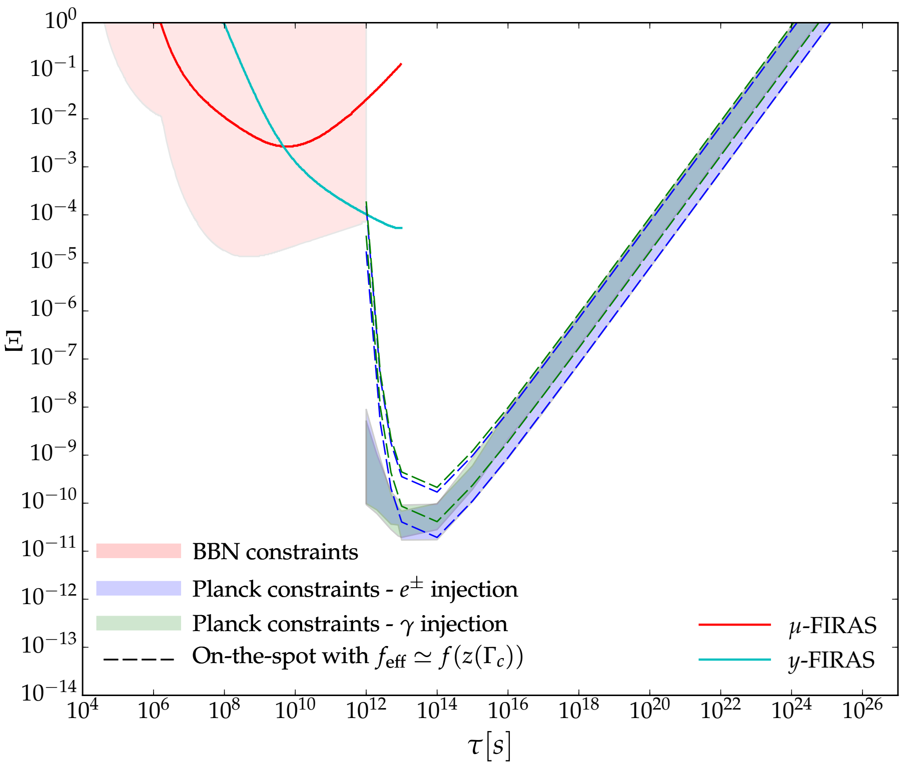

Figure 4: Summary plot of the CMB bounds on the decaying DM scenario, in terms of Ξ vs. τ_d, for $e^{\pm}$ or γ final states, and for an approximate or more refined treatment of the energy deposition. A comparison with other cosmological bounds at earlier lifetimes is also reported. From [12].

3.3 Applications to primordial BHs

When thinking of "early universe relics", we usually think of particles. Yet, PBHs are possibly macroscopic relics which can originate from the gravitational collapse of sufficiently large density fluctuations, at scales much smaller ($k \gg \mathrm{Mpc}^{-1}$) than the CMB ones, and are typically associated to non-trivial inflationary dynamics or phase transitions. Such scales are almost unconstrained, and avoiding PBH overproduction which would overclose the Universe is actually one of the few bounds available. For a recent review, see e.g. [13].

Sufficiently light PBHs evaporate via Hawking radiation at a cosmologically sizable rate (typically, if their mass is below $\sim 10^{17}$ g), emitting energetic $e^{\pm}$ and γ's. This may lead to peculiar modification of x_e, which are constrained by CMB similarly to decaying DM. Current CMB bounds are comparable or better than existing ones from studies of the diffuse gamma-ray background, at least for a certain range of PBH masses (see for instance [9, 12]).

However, PBH of *stellar mass* would also affect the CMB via non-thermal radiation emitted when accreting the baryonic gas. This is in fact the most efficient mechanism known in astrophysics to convert gravitational radiation into radiative power, and is virtually the only one known for powering quasars, for instance. In [14], the pioneering and very stringent bounds obtained a decade ago [15] have been shown to be incorrect and inconsistent. Very conservative bounds have then been derived, excluding the totality of DM in the form of PBH only for masses above 10-100 $M_{\odot}$. But are these *conservative* bounds also *plausible/realistic*, or even *self-consistent*?

The critical assumption entering these bounds is that the accretion of gas around a PBH is spherical. In [16], we have questioned this hypothesis, and derived realistic bounds (based on state of the art knowledge) assuming that the accretion proceeds via the formation of a disk. Loosely speaking, if the accreted material has sufficient angular momentum with respect to a BH to settle in Keplerian orbit at a distance $\gg 3R_{\mathrm{Schwarzschild}}$, the emission should be dominated by a disk, rather than a spherical region. This rather standard and undisputed criterion goes back to [17] (see also [18]). Unfortunately, the relative gas-PBH angular momentum cannot be computed exactly, since it depends ultimately upon non-linear physics. However, several independent arguments suggested us that it is likely that the above criterion is fulfilled. For instance, if PBHs constitute a sizable fraction of the DM in the universe, it is known that a large fraction of them should form bound structures (binaries or multiple systems in clusters) by the time CMB form (for a recent study, see [19]). The orbital motion of these PBHs is then enough to ensure that the gas falling onto them has enough angular momentum to form a disk [16]. Alternatively, a linear (but non-perturbative) analysis of the relative motion between DM and baryons at large scales can be performed [20]. This reveals that the motion is supersonic, with typical Mach number $\simeq 5$ at $z \simeq 1000$. If this can be extrapolated to small scales (as actually assumed in [14]), then simulations show that a disk will form [21].

In any case, if typical disk parameters are adopted, much stronger constraints follow, with CMB excluding PBHs as totality of DM down to the $M_{\odot}$ scale (below which lensing constraints become stronger). In summary, the debate on the actual CMB bounds on 'heavy' PBHs is far from over. But it appears likely that analytical toy models motivated essentially by their simplicity are not credible. State-of-the-art "recipes" calibrated to observations suggest strong bounds, but are not necessarily justified from first principles. To check and improve over them, dedicated simulations are required, specifically aiming at accretion onto PBHs in a cosmological setting.

PoS(CORFU2018)094

4. Sensitivity to dark radiation

CMB is not only sensitive to *massive* relics, but also to DR. The most obvious effect of adding some DR is to shift the matter-radiation equality. However, this is degenerate with a number of effects (like altering the amount of DM). If keeping the matter-radiation equality fixed, a more genuine effect of DR would be to increase the damping of perturbations at large ℓ's. This effect is still largely degenerate with an altered fraction of Helium Y_p in the pristine plasma. Yet, this does not mean that the DR has no specific effect: indeed, even adjusting Y_p to compensate the damping, there is still a characteristic shift of the oscillations at large ℓ, ultimately coming from the anisotropic stress due to free streaming of DR. This is in principle a clean signatures which may offer exquisite sensitivity to DR (For more details, see e.g. [22]).

The amount of DR is typically parameterized in terms of the effective number of neutrinos, $N_{\rm eff}$, or its alteration $\Delta N_{\rm eff}$ with respect to the standard value of 3.046. The latter value accounts for non-instantaneous, momentum-dependent decoupling of the neutrinos, for finite temperature QED corrections (including effective electron and photon masses, that in turn modify the equation of state of the plasma) as well as a fairly realistic description of neutrino oscillations effects, as first obtained in [23]. Recently, a new code, plus an improved treatment of off-diagonal damping terms in the density matrix evolution, lead to the almost indistinguishable result of 3.045, proving the robustness of this prediction [24]. Currently, the best bound available comes from Planck, supplemented by Baryon Acoustic Oscillation data: $\Delta N_{\rm eff} \lesssim 0.3$ [25].

One way to appreciate the strength of this is to rephrase it as follows: Not only we detect a DR background consistent with the three SM active neutrinos (at 10% level!), but we can exclude at 95% C.L. that at the CMB formation time there were any light thermal relics around that had frozen out after the QCD phase transition. The estimated sensitivity of future ground-based CMB-S4 surveys is about five times better than current bounds, resulting marginally sensitive (1 σ sensitivity of 0.03) to the non-instantaneous neutrino decoupling, and virtually to the presence of any NP relativistic thermal relic, no matter when it decoupled—unless the early universe cosmology in the electroweak epoch is greatly altered. See [22] for more details.

5. Conclusion

In my contribution to the Corfu Institute 2018, I have argued that:

- Cosmology (and the CMB in particular) is sensitive to even extremely suppressed interaction rates of (meta)stable species present in the cosmic soup.
- The example of an invisible decay mode of (a fraction of) DM is noteworthy: For instance, it limits to <3.8% the conversion of DM mass into dark radiation.
- If even a tiny fraction of the energy stored in the DM mass is released into "visible" (electromagnetic) form, CMB constraints can be quite tight, due to gas ionization and heating phenomena affecting temperature and polarization anisotropies. DM annihilation, DM decay, evaporating PBHs, accreting PBHs are examples to which this can be applied.

- CMB is also sensitive directly to relic relativistic species (dark radiation): currently, data detect pretty clearly the presence of species consistent with SM neutrinos, and exclude any additional *thermal* relic decoupling after the QCD phase transition. In the future, it is foreseen to achieve the sensitivity to *any* relativistic *thermal* relic decoupling even before the electroweak phase transition.

Definitely, we may expected a bright future, no matter how *dark* it may appear from Earth!

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