DEUTSCHES ELEKTRONEN-SYNCHROTRON
Ein Forschungszentrum der Helmholtz-Gemeinschaft

DESY 20-161
ULB-TH/20-16
arXiv:2011.06518
November 2020

ACROPOLIS: A **G**eneri**C** **F**R**amework** **f**O**r** P**hotodisintegration** O**f** LI**ght** **Element**S

P. F. Depta, K. Schmidt-Hoberg
Deutsches Elektronen-Synchrotron DESY, Hamburg

M. Hufnagel
Deutsches Elektronen-Synchrotron DESY, Hamburg
and
Service de Physique Théorique, Université Libre de Bruxelles, Belgium

ISSN 0418-9833

NOTKESTRASSE 85 – 22607 HAMBURG

Prepared for submission to JCAP

ACROPOLIS: A generiC fRamework fOr Photodisintegration Of LIght elementS

Paul Frederik Depta[a], Marco Hufnagel[a b], and Kai Schmidt-Hoberg[a]

[a]

[b]

Abstract:

$\sqrt{\quad}$

$\lesssim$

$\lesssim$

$\lesssim$

$\lesssim$

$\lesssim$

$\lesssim$

$\lesssim$

$\Bigg\{$

$\overline{}$ $\sum\int$

$\overline{}\Big(\sum\int \Big)$

$$\sum \left[\frac{\quad}{\quad} \int \right]$$

$$\sum \int \qquad \sum \int$$

$$\sum \left[\frac{}{} \int_{i} \right]$$

$$\sum \left[\frac{}{} - \left(\sum \right) \right]$$

$\sum$

$$\frac{}{} \sum \frac{}{}$$

$[\quad]$

$\rangle$

$\langle \sigma v \rangle$

ACROPOLIS

$

-
-

•

$

$ _

•

•

$

—

—

	—	—	—
	—	—	—
	—	—	—
	—	—	—
	—	—	—
	—	—	—
	—	—	—
	—	—	—
	—	—	—

–

$\mathcal{Y}$. ± . ×

/ . ± . ×

/ / . ± . ×

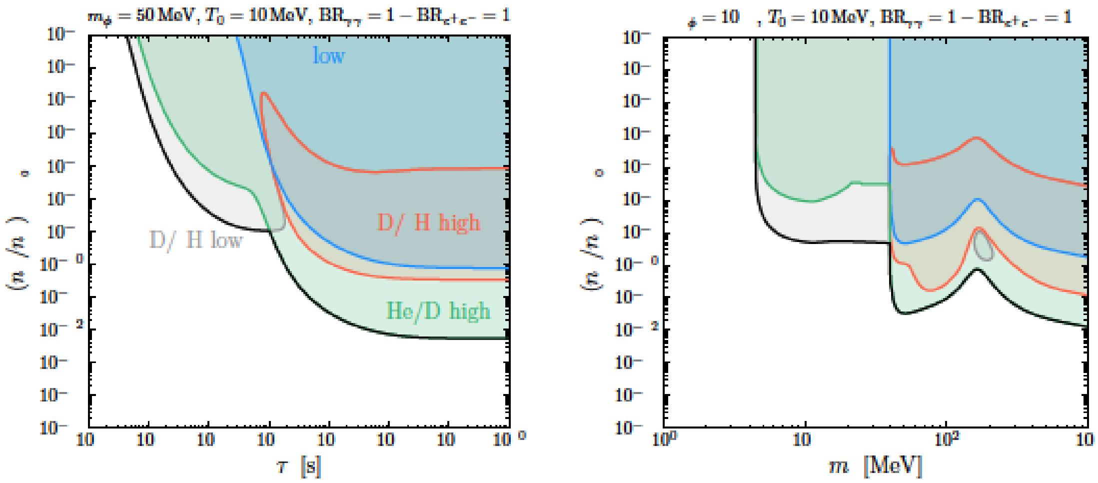

Figure 1. 95% C.L. constraints for decay of a decoupled MeV-scale BSM particle (implemented in `DecayModel`) into two photons ($\mathrm{BR}_{\gamma\gamma} = 1 - \mathrm{BR}_{e^+e^-} = 1$) in $\tau_\phi - (n_\phi/n_\gamma)|_{T=T_0}$ plane (left) and $m_\phi - (n_\phi/n_\gamma)|_{T=T_0}$ plane (right) with $T_0 = 10\,\mathrm{MeV}$ and $m_\phi = 50\,\mathrm{MeV}$ (left) as well as $\tau_\phi = 10^7\,\mathrm{s}$ (right). The limits from individual observables are shown separately: primordial deuterium abundance (orange high, grey low), helium-4 mass fraction $\mathcal{Y}_\mathrm{p}$ (blue), and helium-3 abundance normalised by deuterium (green). The overall 95% C.L. BBN limit is given by the black full line as an envelope of individual 95% C.L. constraints neglecting correlations. Using $(n_\phi/n_\gamma)|_{T=T_0}$, i.e. `n0a`, as a `fast` parameter on a single computing node with two `AMD EPYC 7402 24-Core Processors` the scans took ~ 40 min (left) and ~ 2 h (right) for a 200×200 grid.

deuterium, $m_\phi = 2E_\mathrm{D}^\mathrm{th} \approx 4.4\,\mathrm{MeV}$. Apart from some regions with more complex structure due to different disintegration reactions the limits become increasingly strong with larger m_ϕ as the energy density injected into the SM becomes larger.

The scans for figure 1 took ~ 40 min (left) and ~ 2 h (right) for a 200×200 grid on an `AMD EPYC 7402 24-Core Processors`, clearly highlighting the performance improvement due to the `fast` parameter $(n_\phi/n_\gamma)|_{T=T_0}$, i.e. `n0a`, making the number of points in this direction computationally inexpensive (cf. also appendix B). The runtime is thus determined mostly by the number of points in the direction of τ_ϕ or m_ϕ (not `fast`). Note that the longer runtime for the right panel is a result of the database files for the electromagnetic cascade reaction rates having an upper limit on the energy of $m_\phi/2 = E_0 = 100\,\mathrm{MeV}$, which often corresponds to the most interesting region in parameter space. For masses above the pion threshold in particular, $m_\phi \gtrsim 280\,\mathrm{MeV}$, hadrodisintegration may become relevant if ϕ has non-vanishing couplings to quarks, implying that $\mathrm{BR}_{\gamma\gamma} + \mathrm{BR}_{e^+e^-} < 1$ in general. Also muons are kinematically available in the mass region (which are currently not implemented in `ACROPOLIS`).

In figure 2 we show the constraints for residual annihilations of DM into two photons ($\mathrm{BR}_{\gamma\gamma} = 1 - \mathrm{BR}_{e^+e^-} = 1$) for purely s-wave annihilations (left, $b = 0$) and purely p-wave annihilations (right, $a = 0$, $T_\mathrm{kd} = 1\,\mathrm{MeV}$) as implemented in `AnnihilationModel`. These limits start at the disintegration threshold of deuterium, $m_\chi = E_\mathrm{D}^\mathrm{th} \approx 2.2\,\mathrm{MeV}$, and closely

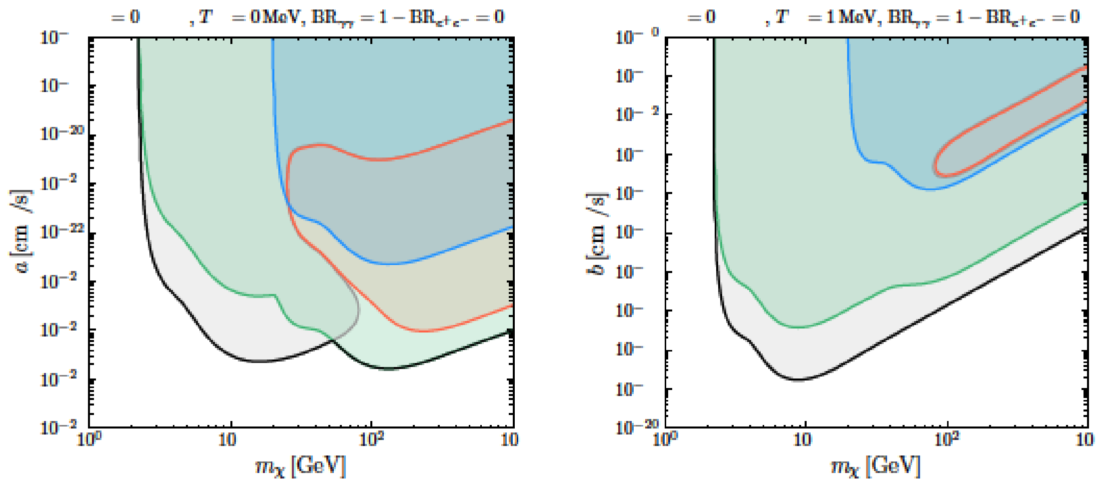

Figure 2. 95% C.L. constraints for residual annihilations of DM (implemented in `AnnihilationModel`) into two photons ($\mathrm{BR}_{\gamma\gamma} = 1 - \mathrm{BR}_{e^+e^-} = 1$) for purely s-wave annihilations (left, $b = 0$) and purely p-wave annihilations (right, $a = 0$, $T_{\mathrm{kd}} = 1\,\mathrm{MeV}$). For the explanation of the colour-coding see figure 1. Using $(n_\phi/n_\gamma)|_{T=T_0}$, i.e. `n0a`, as a `fast` parameter on a single computing node with two `AMD EPYC 7402 24-Core Processors` the scans took ~ 10 h each for a 200×200 grid.

resemble those presented in [26], albeit with updated observationally inferred primordial abundances. We therefore refer to [26] for a detailed discussion. The scans took ~ 10 h each for a 200×200 grid on the aforementioned computing node.

6 Implementing your own models

6.1 The model framework `acropolis.models`

While the provided example models should suffice to tackle most problems of interest, it may sometimes still happen that a scenario cannot directly be mapped to the standard implementation in `ACROPOLIS`. For such cases, `ACROPOLIS` provides further tools that allow for an easy implementation of additional models. The most important class in this context is `acropolis.models.AbstractModel`, which is an abstract base class containing most of the low-level implementation needed to run its method `run_disintegration()`. In fact, using this class as a base, any new model can be implemented in only two steps:

(i) create a new class, say `NewModel`, that uses `AbstractModel` as a base class, and

(ii) implement all abstract methods that are provided by `AbstractModel`, i.e.[7]

- `AbstractModel._temperature_range()`

[7]By default, the function `AbstractModel._source_positron()` simply returns the output of `AbstractModel._source_electron()`, which is justified for most scenarios. However, if your specific scenario predicts different source terms for electrons and positrons, it is always possible to simply overwrite the former function.

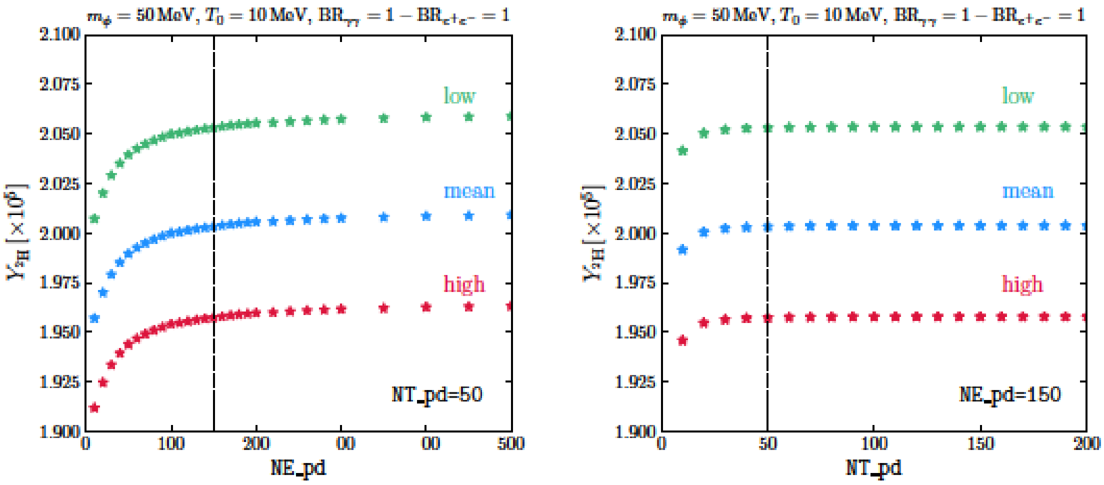

Figure 3. Convergence of the abundance of deuterium as a function of the grid points NE_pd and NT_pd. The dashed line indicates the default value in ACROPOLIS.

Acknowledgments

This work is supported by the ERC Starting Grant 'NewAve' (638528), the Deutsche Forschungsgemeinschaft under Germany's Excellence Strategy – EXC 2121 'Quantum Universe' – 390833306, and by the F.R.S. FNRS under the Excellence of Science (EoS) project No. 30820817 be.h 'The H boson gateway to physics beyond the Standard Model'.

A Rates for the cascade processes

In this appendix, we collect for completeness all relevant total and differential interaction rates $\Gamma_x(E)$ and $K_{x'\to x}(E, E')$ for the cascade processes of high-energetic photons, electrons, and positrons on the background photons, electrons, and nuclei (see eqs. (2.4) and (2.7)). Large parts are directly taken from [24].

Target densities

The thermal photon spectrum differential in energy $\mathrm{f}_\gamma(\bar\epsilon)$ is given by

$$\mathrm{f}_\gamma(\bar\epsilon) = \frac{\bar\epsilon^2}{\pi^2} \times \frac{1}{\exp(\bar\epsilon/T) - 1}\,, \tag{A.1}$$

while the total baryon number density can be calculated from the baryon-to-photon ratio η and the number density of photons $n_\gamma(T)$,

$$n_b(T) = \eta \times n_\gamma(T) = \eta \times \frac{2\zeta(3)}{\pi^2} T^3\,. \tag{A.2}$$

Via charge neutrality we obtain for the number density of background electrons

$$n_e(T) = \sum_N Z_N n_N \simeq \left[Y_p(T) + 2Y_{^4\mathrm{He}}(T)\right] \times n_b(T), \quad Y_N(T) = \frac{n_N(T)}{n_b(T)}\,. \tag{A.3}$$

$\gtrsim$

$\rightarrow \boldsymbol{e^+e^-\gamma}$

$\boldsymbol{\gamma\gamma_{\mathrm{th}} \rightarrow e^+e^-}$

$$\int_e \qquad \int_e \qquad \left(\sqrt{} \right)$$

$\gtrsim$

$$\int_e$$

$\gamma \rightarrow e$ $K_{x'} \; x$

$x \rightarrow x \in \{\gamma \rightarrow e \;, \gamma \rightarrow e \;\}$

$$\gamma\gamma_{\mathbf{th}} \to \gamma\gamma$$

$\lesssim$

$$\gamma N \to N e^{+} e^{-}$$

e

$$\gamma e^-_{\mathbf{th}} \to \gamma e^-$$

e

$e^{\pm}\gamma_{\mathrm{th}} \to e^{\pm}\gamma$

$$\int$$

$$\int \quad \int$$

$$\int$$

-
-
-
-

F E, E , ϵ $E < \epsilon$

+ −