Cosmological constraints on Dark Sector models for colliders

9th Large Hadron Collider Physics Conference, June 2021

Andreas Goudelis

LPC – Clermont Ferrand

Dark sectors

There is no strict definition of what constitutes a “dark sector”. The term has been used to describe, for example :

Anything that has not yet been experimentally observed

General but extremely vague, essentially includes all BSM physics

Exotic particles that are not charged under the SM gauge group

Motivated from various questions, often communicating with the SM through some “portal”

Particles that transform differently than the SM under some discrete symmetry

Mostly motivated from dark matter physics, the usual Z_2 – even/odd picture

Dark sectors

There is no strict definition of what constitutes a "dark sector". The term has been used to describe, for example :

Anything that has not yet been experimentally observed

General but extremely vague, essentially includes all BSM physics

Exotic particles that are not charged under the SM gauge group

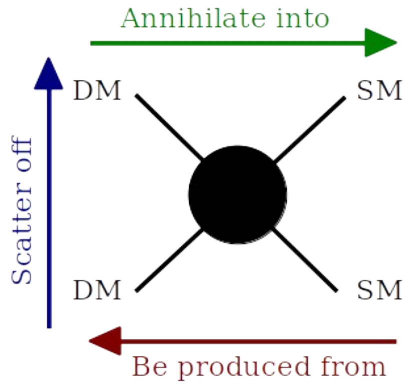
Motivated from various questions, often communicating with the SM through some "portal"

Particles that transform differently than the SM under some discrete symmetry

Mostly motivated from dark matter physics, the usual Z_2 – even/odd picture

· Whatever the definition, cosmology is a major driving force for model-building.
· It can suggest searches for New Physics at colliders.

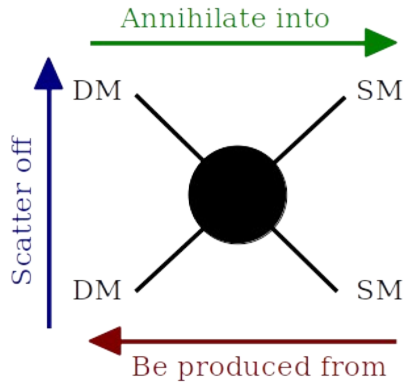
Dark matter: beyond WIMPs



Historically, dark matter physics has motivated numerous searches at colliders, most of them involving MET.
WIMPy idea: pair-produce DM along with visible state(s).

+ recycled a huge number of SUSY searches

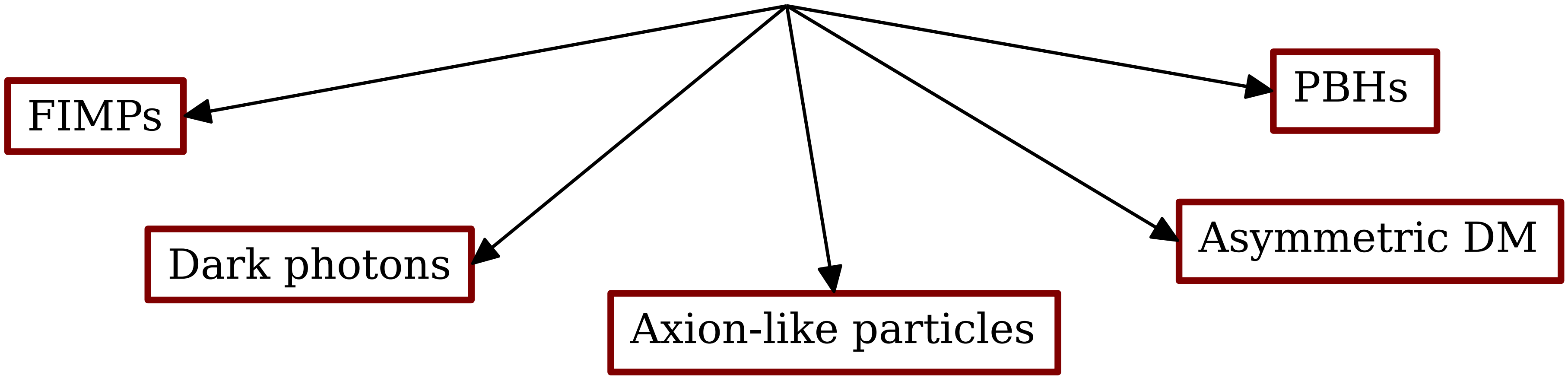
Dark matter: beyond WIMPs



Historically, dark matter physics has motivated numerous searches at colliders, most of them involving MET.
WIMPy idea: pair-produce DM along with visible state(s).

+ recycled a huge number of SUSY searches

But the LHC has searched for over a decade, idem direct/indirect detection, and no WIMPy state has been found so far. → Alternative ideas have gained traction.



· Most of these ideas are *not* new, just until recently less popular in the collider community. Freeze-out is still an option, but other options are been considered.

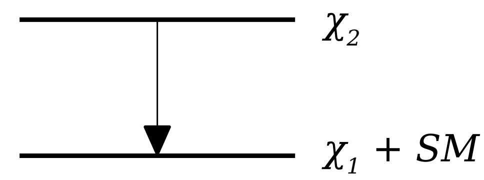
The LHC can only find what we (even inadvertedly) look for.

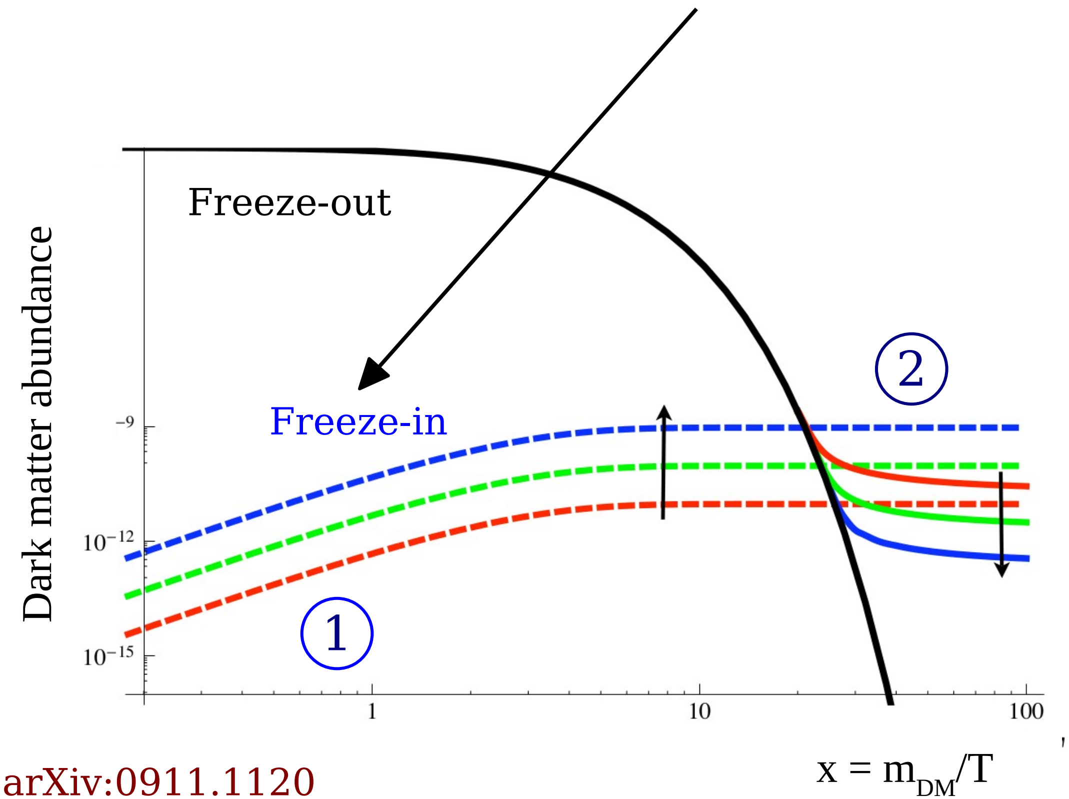
The freeze-in alternative

arXiv:hep-ph/0106249
arXiv:0911.1120

The freeze-in mechanism involves very weakly (“feebly”) interacting particles that don’t reach thermal equilibrium with the SM thermal bath in the early Universe.

· Such particles can be produced cosmologically *e.g.* from the decay of some heavier state.





arXiv:0911.1120

· Even though dark matter itself should be feebly interacting, this need not (at all!) be the case for the heavier state.

So what do we expect to observe at colliders ?

Freeze-in and long-lived particles

Example: consider the SM along with a real singlet scalar FIMP *s* and a charged SU(2)-singlet vector-like fermion *F*, both odd under a discrete $\mathbf{Z_2}$ symmetry:

arXiv:1811.05478

$$\mathcal{L} \supset +i\left(\bar{F}_L D F_L + \bar{F}_R D F_R\right) - \left(m_F \bar{F}_L F_R + y_{sFf}\, s \bar{F}_L f_R + \text{h.c.}\right)$$

Freeze-in and long-lived particles

Example: consider the SM along with a real singlet scalar FIMP s and a charged SU(2)-singlet vector-like fermion F, both odd under a discrete $\mathbf{Z_2}$ symmetry:

arXiv:1811.05478

$$\mathcal{L} \supset +i\left(\bar{F}_L D F_L + \bar{F}_R D F_R\right) - \left(m_F \bar{F}_L F_R + y_{sFf} s \bar{F}_L f_R + \text{h.c.}\right)$$

· If $F \rightarrow f + s$ is the main DM production mode, the lifetime of F is related to the abundance of s through:

$$c\tau \approx \underline{4.5\text{m}\ \xi}\ g_F \left(\frac{0.12}{\Omega_s h^2}\right)\left(\frac{m_s}{100\ \text{keV}}\right)\left(\frac{200\ \text{GeV}}{m_F}\right)^2 \left(\frac{102}{g_*(m_F/3)}\right)^{3/2} \left[\frac{\int_{m_F/T_R}^{m_F/T_0} dx\ x^3 K_1(x)}{3\pi/2}\right]$$

· F expected to be

→ Long-lived.

Esp. given m_s > 12 keV, from Lyman-alpha

→ Copiously produced at the LHC, if accessible.

Drell-Yan and/or strong production

Freeze-in and long-lived particles

Example: consider the SM along with a real singlet scalar FIMP s and a charged SU(2)-singlet vector-like fermion F, both odd under a discrete $\mathbf{Z_2}$ symmetry:

arXiv:1811.05478

$$\mathcal{L} \supset +i\left(\bar{F}_L D F_L + \bar{F}_R D F_R\right) - \left(m_F \bar{F}_L F_R + y_{sFf}\, s \bar{F}_L f_R + \text{h.c.}\right)$$

· If $F \to f + s$ is the main DM production mode, the lifetime of F is related to the abundance of s through:

$$c\tau \approx \underline{4.5\text{m}\ \xi\ g_F} \left(\frac{0.12}{\Omega_s h^2}\right)\left(\frac{m_s}{100\ \text{keV}}\right)\left(\frac{200\ \text{GeV}}{m_F}\right)^2 \left(\frac{102}{g_*(m_F/3)}\right)^{3/2} \left[\frac{\int_{m_F/T_R}^{m_F/T_0} dx\ x^3 K_1(x)}{3\pi/2}\right]$$

· F expected to be

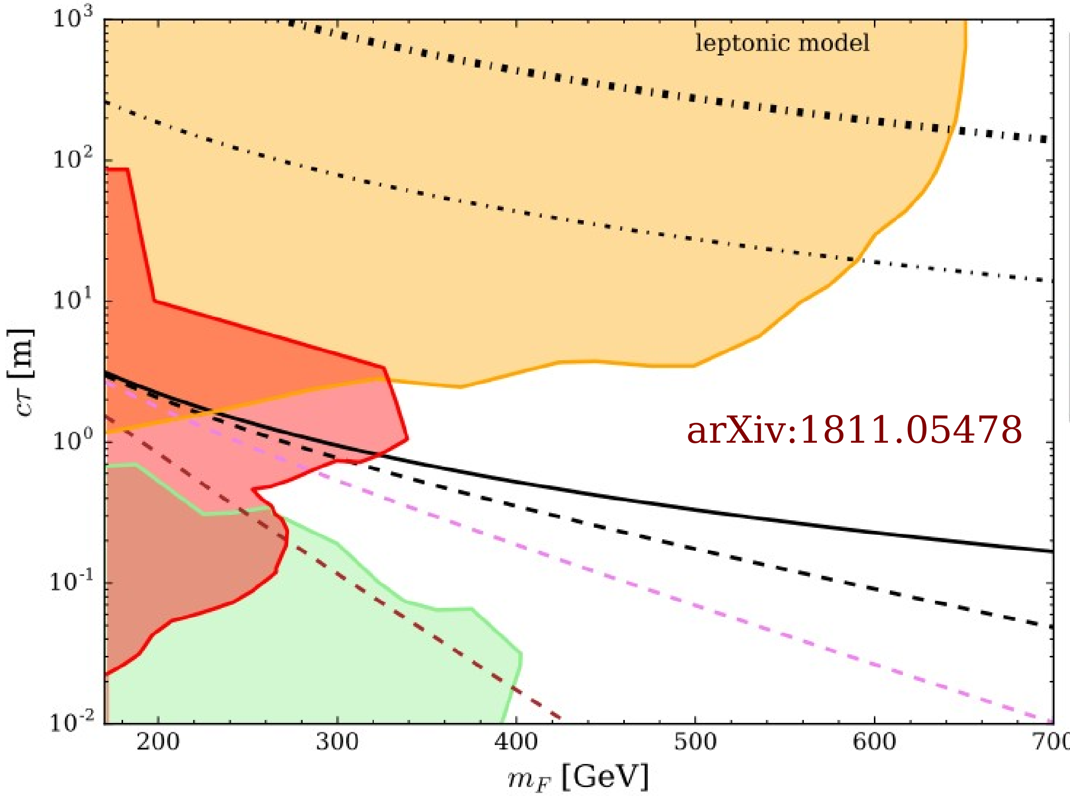
- Long-lived.
  Esp. given m_s > 12 keV, from Lyman-alpha
- Copiously produced at the LHC, if accessible.
  Drell-Yan and/or strong production

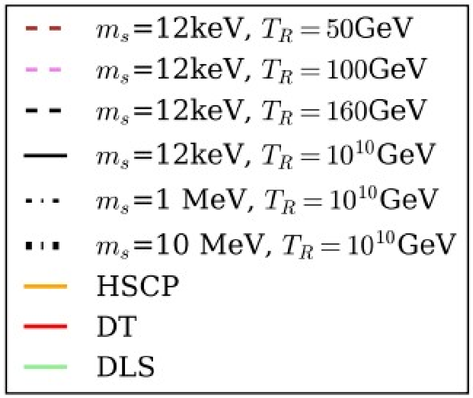
Dark matter freeze-in may involve LHC-accessible LLPs

cf e.g. also arXiv:0911.1120, 1611.09540, 1706.06815, 1805.04423

Charged parent example

Example constraints if the parent particle is colour-neutral but carries E/M charge:





For an example involving an E/M neutral parent particle, *cf e.g.* arXiv:1805.04423.

Discussion also partly applies to conversion-driven freeze-out, arXiv:1705.09292, 1705.08450

· Measuring the lifetime of F may be feasible – albeit tricky, and can provide information on its relevance for cosmology!

Cf e.g. arXiv:1912.06669

· But what if the parent particle were neutral and very long-lived?

Primordial nucleosynthesis

Consider an extension of the SM by a real singlet scalar s that mixes with the Higgs boson.

$$\mathcal{L} \supset \left(H^\dagger H\right)\left(As + \lambda s^2\right)$$

· Standard Higgs decay width constraints forbid $h \to ss$ to be larger than ~10%.

· At the same time, if $Av \ll \lambda v^2$, then s may be produced at substantial (but allowed) rates and only decay later on, potentially outside the LHC detectors.

· At which distance should we place a detector to observe s decays?

Primordial nucleosynthesis

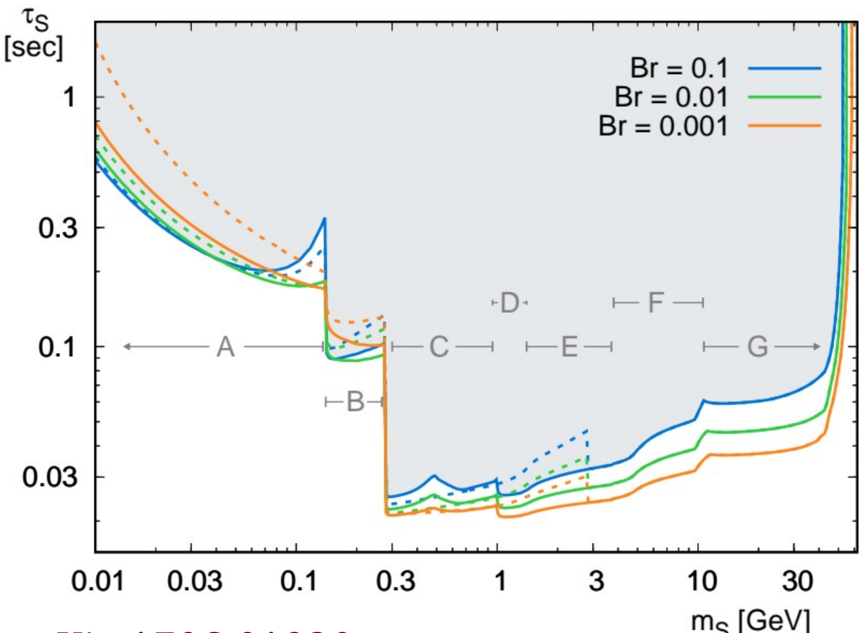
Consider an extension of the SM by a real singlet scalar *s* that mixes with the Higgs boson.

$$\mathcal{L} \supset \left(H^\dagger H\right)\left(As + \lambda s^2\right)$$

· Standard Higgs decay width constraints forbid $h \to ss$ to be larger than ~10%.

· At the same time, if $Av \ll \lambda v^2$, then *s* may be produced at substantial (but allowed) rates and only decay later on, potentially outside the LHC detectors.

· At which distance should we place a detector to observe *s* decays?



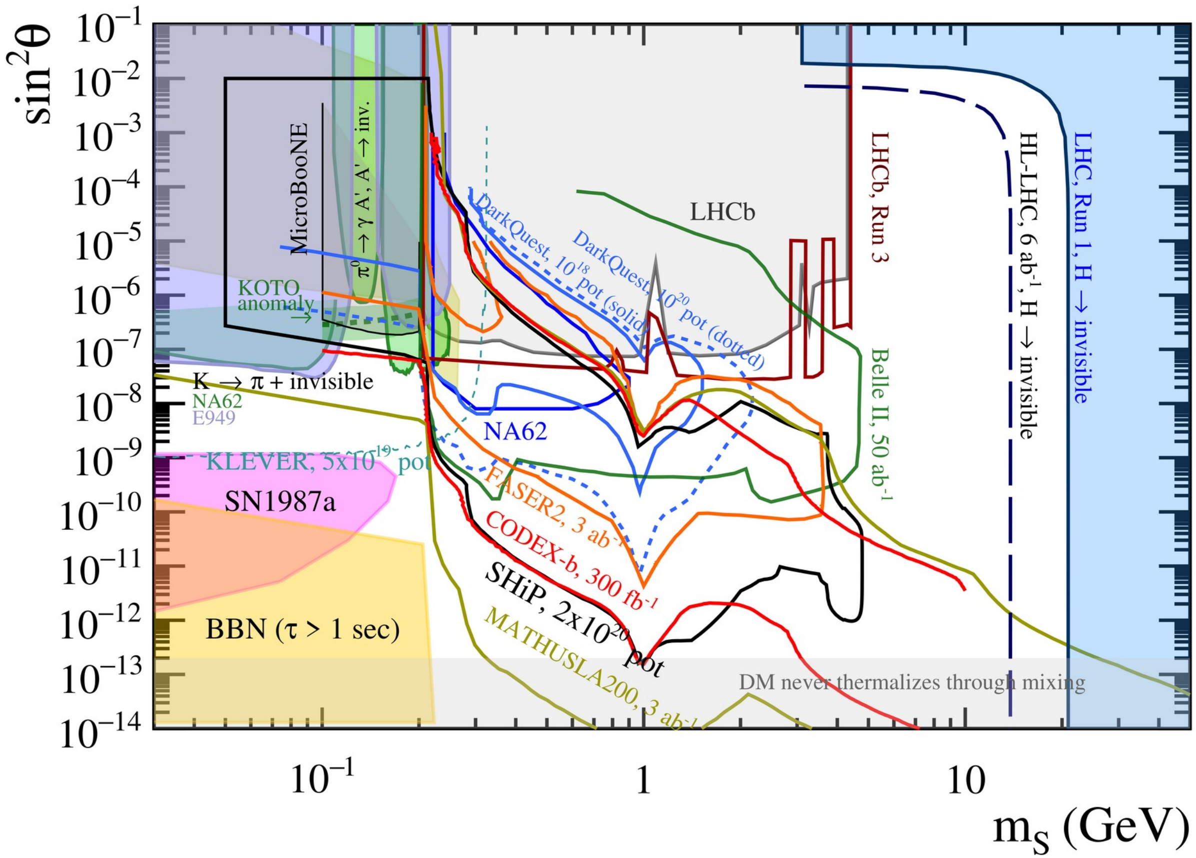
arXiv:1706.01920

· If *s* decays too late, then it may interfere with the formation of light elements in the Universe. This is very well-predicted by standard BBN theory.

Very long lifetimes are disfavoured by cosmology

Primordial nucleosynthesis *et al*

Summary of constraints/projections for the simplest scalar portal, assuming a Higgs branching fraction of $\sim 10^{-2}$



arXiv:2102.12143

Clear complementarity between BBN constraints and running/planned experiments

Summary and outlook

· Cosmology has traditionally been one of the major sources of inspiration for collider searches.

· Searches for “dark” particles have been carried out since decades, perhaps a bit less within the collider community. Given the LHC results so far and developments on the theory side, this is currently changing.

· Cosmological arguments can not only guide collider searches in the “traditional” (final state – based?) sense. It can also make suggestions for really technical issues (*e.g.* “where to build a detector”).

· I gave only two examples, based on dark matter and primordial nucleosynthesis. There are many more, based on other open questions in cosmology (*e.g.* baryogenesis).

· Cosmology can provide guidance. Is the outcome guaranteed? No, but my view is that it never was :) .

Thank you!