(Not even) Feebly Interacting Massive Particles as Non-Cold Dark matter

Laura Lopez Honorez

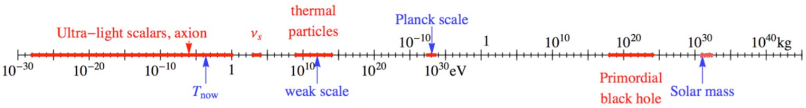
mainly inspired by `arXiv:2004.14773` and `arXiv:2012.XXXXX`
in collaboration with I. Baldes, L. Calibbi, **Q. Decant**,
F. d'Eramo, D.C. Hooper, **S. Junius** & A. Mariotti.

online workshop on New Trends in Dark Matter
ICTP-SAIFR (Dec. 7 - 9, 2020)

What is the Nature of Dark Matter?

Dark Matter should be essentially:

- Neutral
- Massive
- Beyond the Standard Model (non baryonic)



Courtesy of M.Cirelli

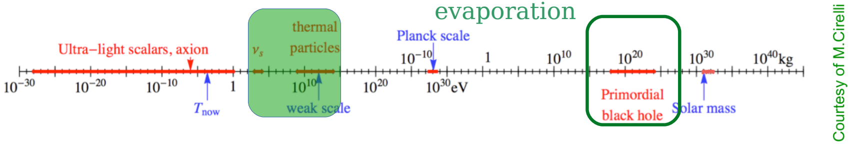
What is the Nature of Dark Matter?

Dark Matter should be essentially:

- Neutral
- Massive
- Beyond the Standard Model (non baryonic)

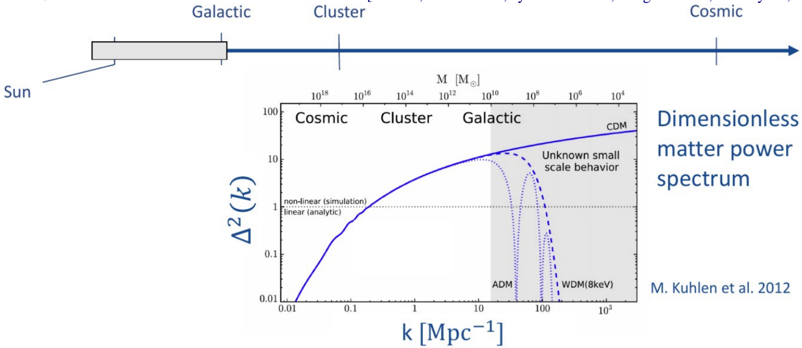
FIMPs: focus of this talk

& not even FIMPs from PBH evaporation



Non-Cold Dark Matter

see also [Silk'67, Boehm'00+,Cyr-Racine'12+,Bringman'12+,Buckley'14, etc]

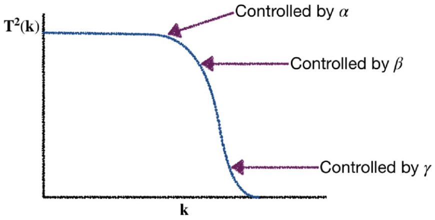


- WDM free-streaming from overdense to underdense regions
  $\rightsquigarrow$ Smooth out inhomegeneities for $\lambda \lesssim \lambda_{FS} \sim \int_{t_{dec}}^{t_0} v/adt$
  Also e.g. collisional damping due to DM coupling to light species see [Boehm'00, etc]

Non-Cold Dark Matter see also [Silk'67, Boehm'00+,Cyr-Racine'12+,Bringman'12+,Buckley'14, etc]

$$T^2(k) = \frac{P(k)_{\mathrm{nCDM}}}{P(k)_{\mathrm{CDM}}} = \left[1 + (\alpha k)^{\beta}\right]^{2\gamma}$$

[Murgia'17]

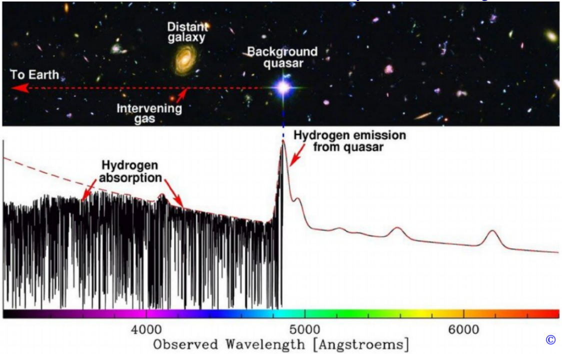


[Courtesy DC Hooper]

- WDM free-streeming from overdense to underdense regions
  $\rightsquigarrow$ Smooth out inhomegeneities for $\lambda \lesssim \lambda_{FS} \sim \int_{t_{dec}}^{t_0} v/a dt$
  Also e.g. collisional damping due to DM coupling to light species see [Boehm'00, etc]
- Effects $P(k)$ and $T(k)$ generalized to Non-Cold DM see e.g. [Bode'00, Viel'05, Murgia'17], including non-thermal DM from freeze-in or PBH evaporation.

Non-Cold Dark Matter

see also [Silk'67, Boehm'00+,Cyr-Racine'12+,Bringman'12+,Buckley'14, etc]



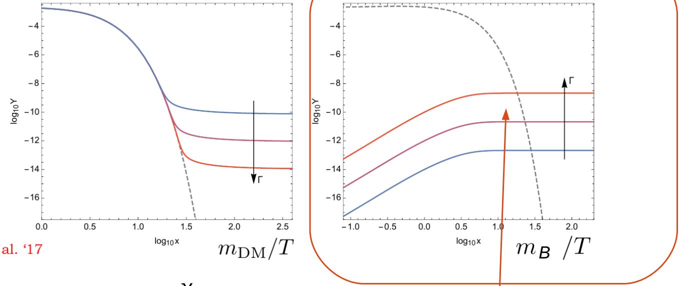
© M. Murphy

- WDM free-streeming from overdense to underdense regions
  $\rightsquigarrow$ Smooth out inhomegeneities for $\lambda \lesssim \lambda_{FS} \sim \int_{t_{dec}}^{t_0} v/adt$
  Also e.g. collisional damping due to DM coupling to light species see [Boehm'00, etc]
- Effects $P(k)$ and $T(k)$ generalized to Non-Cold DM see e.g. [Bode'00, Viel'05, Murgia'17], including non-thermal DM from freeze-in or PBH evaporation.
- Tested against Lyman-α: absorption lines along l.o.s. to distant quasars probe smallest structures $\rightsquigarrow$ $m_{\rm WDM}^{\rm thermal} > 1.9$-$5.3$ keV [Viel'05, Yeche'17, Palanque-Del'19,Garzilli'19]

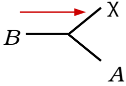
NCDM FIMPs from Freeze-in

WIMP Freeze-out vs e.g. FIMP Freeze-in

DM abundance: Freeze-out versus Freeze-in (through decay)



Bernal et al. '17



$$\mathcal{R}_{B\to\chi} \propto \frac{m_B}{T}\Gamma_{B\to\chi} \sim H(T)$$

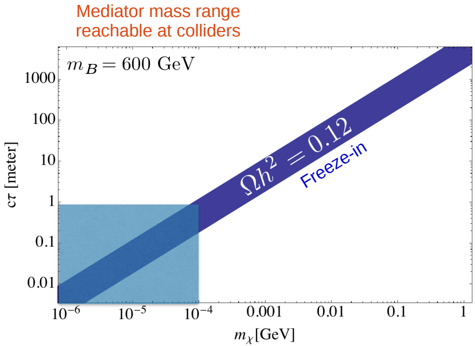
$$\Omega_\chi h^2 \propto 0.12 \times \left(\frac{\Gamma_B}{4\times 10^{-15}\,\mathrm{GeV}}\right)\left(\frac{600\,\mathrm{GeV}}{m_B}\right)^2\left(\frac{m_\chi}{10\,\mathrm{keV}}\right)$$

$$\text{for } \Gamma_B \sim \frac{y^2}{4\pi}m_B \Rightarrow y \sim 10^{-8}$$

FIMP: displaced vertices and cosmology interplay

e.g. [Hall'09, Co'15, Hessler'16, d'Eramo'17, Heeck'17, Boulebnane'17, Brooijmans'18, Garny'18, Calibbi'18, No'19, Belanger 18, etc]

$$\Omega h^2 \sim 0.12 \left(\frac{5\ \text{cm}}{c\tau_B}\right) \left(\frac{600\ \text{GeV}}{m_B}\right)^2 \left(\frac{m_\chi}{10\ \text{keV}}\right)$$

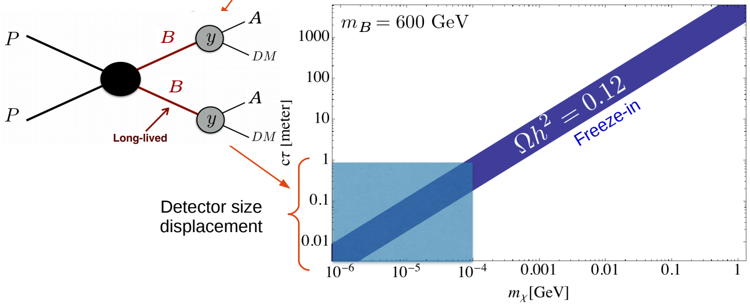


FIMP: displaced vertices and cosmology interplay

e.g. [Hall'09, Co'15, Hessler'16, d'Eramo'17, Heeck'17, Boulebnane'17, Brooijmans'18, Garny'18, Calibbi'18, No'19, Belanger 18, etc]

$$\Omega h^2 \sim 0.12 \left(\frac{5\ \text{cm}}{c\tau_B}\right)\left(\frac{600\ \text{GeV}}{m_B}\right)^2\left(\frac{m_\chi}{10\ \text{keV}}\right)$$

Mediator mass range
reachable at colliders



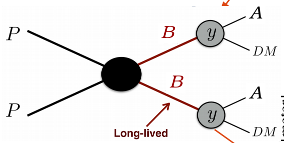
Detector size
displacement

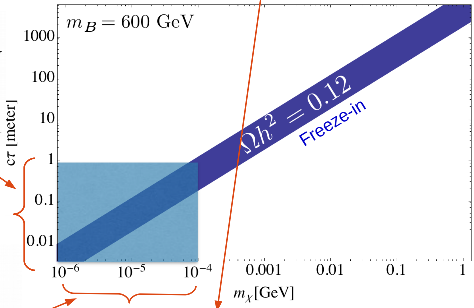
FIMP: displaced vertices and cosmology interplay

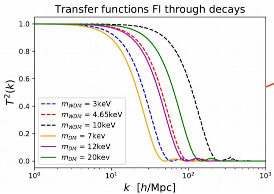
e.g. [Hall'09, Co'15, Hessler'16, d'Eramo'17, Heeck'17, Boulebnane'17, Brooijmans'18, Garny'18, Calibbi'18, No'19, Belanger 18, etc]

$$\Omega h^2 \sim 0.12 \left(\frac{5\ \mathrm{cm}}{c\tau_B}\right)\left(\frac{600\ \mathrm{GeV}}{m_B}\right)^2\left(\frac{m_\chi}{10\ \mathrm{keV}}\right)$$

Mediator mass range reachable at colliders



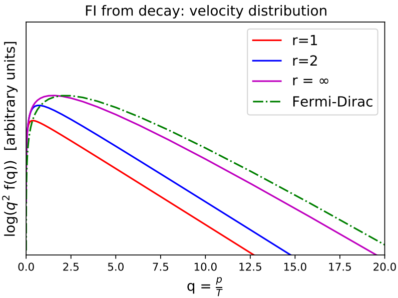




Warm DM like signatures
Suppressing small scale structures

NCDM FIMPs from FI

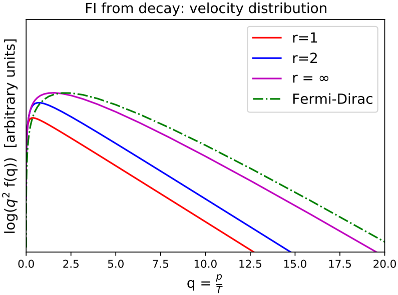
see also [Heeck'17, Boulebnane'17, Kamada'19, Baumholzer'19, Ballesteros'20, d'Eramo'20]

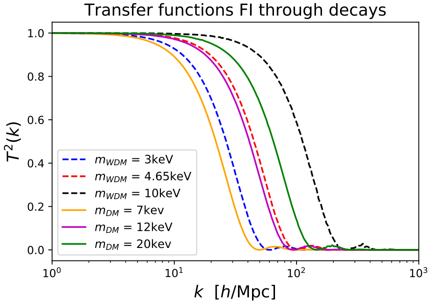


- Contrarily to "usual" WDM, FIMPs are non-thermaly produced.
  still they inherit "thermal like" distrib. fn. from the mediator B in equilibrium.

NCDM FIMPs from FI

see also [Heeck'17, Boulebnane'17, Kamada'19, Baumholzer'19, Ballesteros'20, d'Eramo'20]





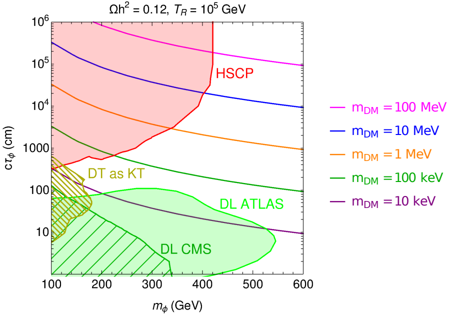
- Contrarily to "usual" WDM, FIMPs are non-thermaly produced. still they inherit "thermal like" distrib. fn. from the mediator B in equilibrium.
- The FIMPs transfer function is similar to thermal WDM for FI through decay. Tested against Lyman-α:

$$\Rightarrow m_{\rm DM}^{\rm FI} \geq 12\,{\rm keV} \quad \text{for } m^{\rm Ly-\alpha} > 4.65\text{ keV} \quad \text{[Boulebnane'17]}$$

Leptophilic DM: Collider vs NCDM Constraints

see also e.g. [Hall'09, Belanger 18, etc]

$$\mathcal{L} \subset \mathcal{L}_K - \frac{m_\chi}{2}\bar{\chi}\chi - m_\phi \phi^\dagger \phi \; - \; \lambda_\chi \phi \bar{\chi} l_R \; + \; h.c.$$



DM FI via B decays: $c\tau_B \simeq 3.3 \times 10^6 \text{cm} \left(\frac{m_\chi}{10\,\text{GeV}}\right) \left(\frac{1\,\text{TeV}}{m_B}\right)^2$.

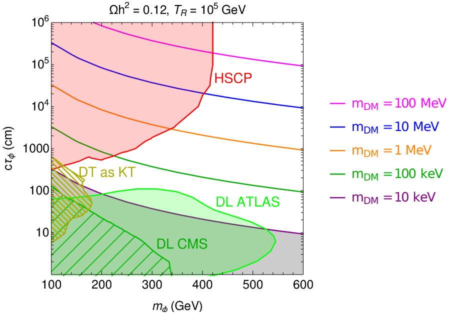
$\Rightarrow$ B decays usually beyond detector size ($\sim$ 10 m)

unless DM saturates the Lyman-α constraints

Leptophilic DM: Collider vs NCDM Constraints

see also e.g. [Hall'09, Belanger 18, etc]

$$\mathcal{L} \subset \mathcal{L}_K - \frac{m_\chi}{2}\bar{\chi}\chi - m_\phi \phi^\dagger \phi \; - \; \lambda_\chi \phi \bar{\chi} l_R \; + \; h.c.$$



DM FI via B decays: $c\tau_B \simeq 3.3 \times 10^6 \text{cm} \left(\frac{m_\chi}{10\,\text{GeV}}\right) \left(\frac{1\,\text{TeV}}{m_B}\right)^2$.

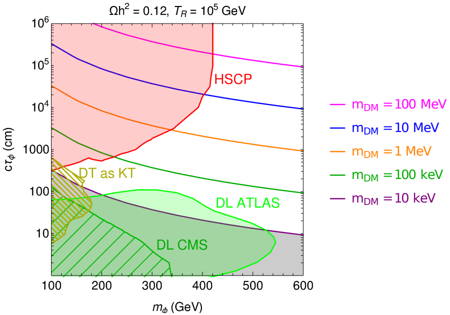
$\Rightarrow$ B decays usually beyond detector size ($\sim$ 10 m)

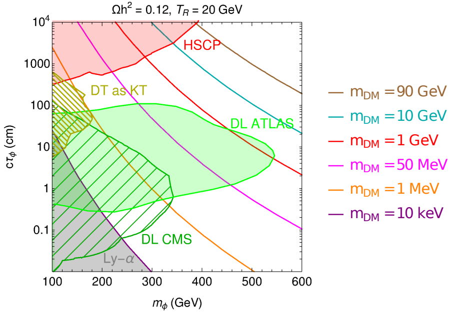
unless DM saturates the Lyman-α constraints

Leptophilic DM: Collider vs NCDM Constraints

see also e.g. [Hall'09, Belanger 18, etc]

$$\mathcal{L} \subset \mathcal{L}_K - \frac{m_\chi}{2}\bar{\chi}\chi - m_\phi \phi^\dagger \phi \; - \; \lambda_\chi \phi \bar{\chi} l_R \; + \; h.c.$$





DM FI via B decays: $c\tau_B \simeq 3.3 \times 10^6 \mathrm{cm} \left(\frac{m_\chi}{10\,\mathrm{GeV}}\right) \left(\frac{1\,\mathrm{TeV}}{m_B}\right)^2$.

$\Rightarrow$ B decays usually beyond detector size ($\sim$ 10 m)

unless DM saturates the Lyman-α constraints

Dislaced events at colliders might point to freeze-in with modified early universe cosmology beyond (e.g. early MD era with low T_R.)

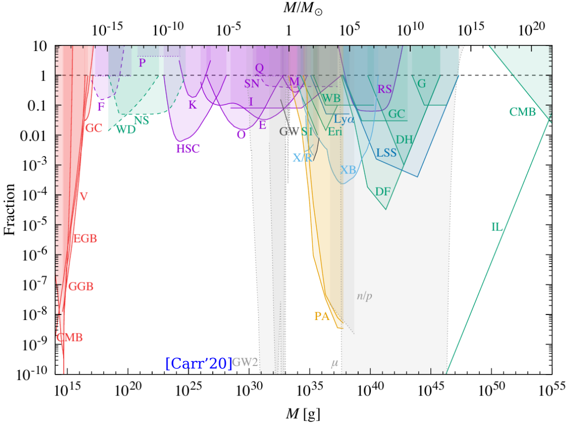
Not even FIMP from PBH evaporation

PBH and Dark Matter

see also e.g. [Bauman'07,Fujita'14,Allahverdi'17, Lennon'17,Morrison'17, Hooper'19+, Masina'20,Keith'20, Gondolo'20,Bernal'20+]

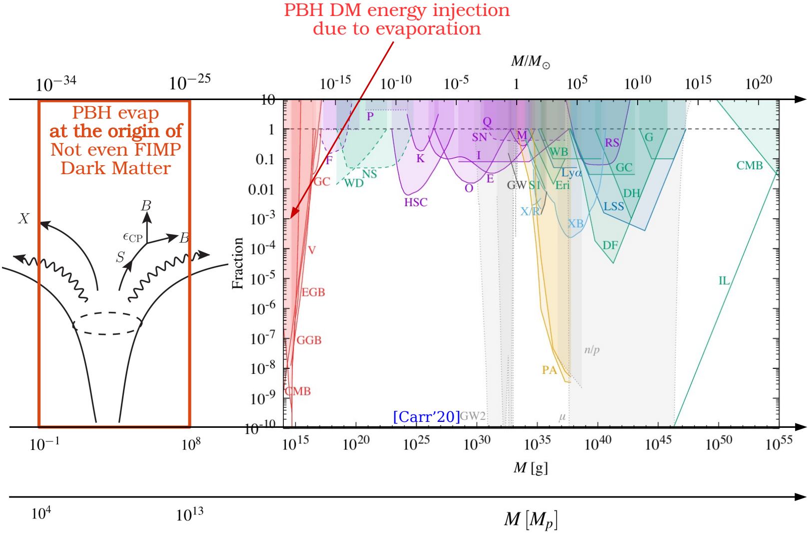
PBH fully Evaporated Before BBN

PBH stable on Cosmological scales



PBH and Dark Matter

see also e.g. [Bauman'07,Fujita'14,Allahverdi'17, Lennon'17,Morrison'17, Hooper'19+, Masina'20,Keith'20, Gondolo'20,Bernal'20+]



NCDM from PBH evaporation

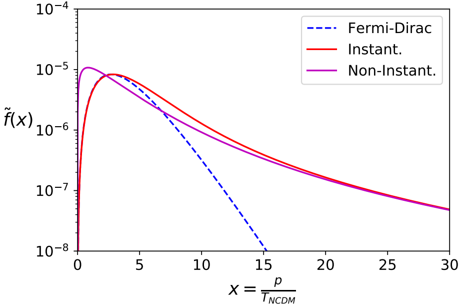
PBHs may be light enough to decay via **Hawking radiation** at an early enough epoch to avoid all previous constraints.

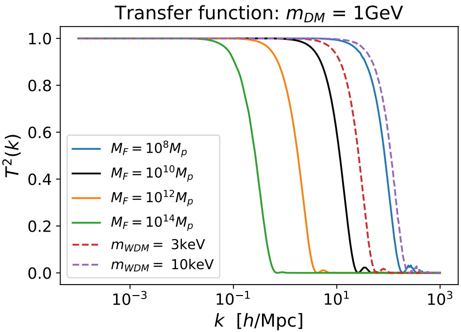
- DM particles (and SM) will be produced from PBH evaporation given **gravitational interactions** (not even FIMPs needed).
- For $m_{DM} < T_{BH}^{init} = M_p^2/(8\pi M_{BH}^{init})$, behave as non-thermal NCDM.

NCDM from PBH evaporation

PBHs may be light enough to decay via **Hawking radiation** at an early enough epoch to avoid all previous constraints.

- DM particles (and SM) will be produced from PBH evaporation given **gravitational interactions** (not even FIMPs needed).
- For $m_{DM} < T_{BH}^{init} = M_p^2/(8\pi M_{BH}^{init})$, behave as non-thermal NCDM.





$$\Rightarrow m_{\rm DM}^{\rm PBH} \geq 2\,{\rm GeV} \times \left(M_F/(10^{10} M_p)\right)^{1/2}$$ [for $m^{\rm Ly-\alpha} > 3$ keV and $\beta > \beta_c$]

PBH evaporating after inflation and before BBN

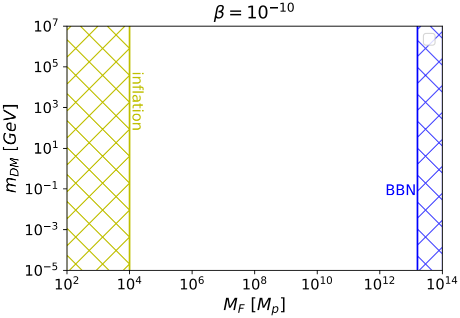
PBH generation: during radiation domination (after inflation) an initially large density perturbation at sufficiently small scale can collapse to form a PBH with mass of order the horizon mass. [Zeldovich & Novikov; Hawking; Carr & Hawking]

$$M_{BH}^{init} \equiv M_F = M_{\rm horiz} = \gamma \rho_{\rm tot} \times 4\pi/(3H_F^3)$$

PBH evaporating after inflation and before BBN

PBH generation: during radiation domination (after inflation) an initially large density perturbation at sufficiently small scale can collapse to form a PBH with mass of order the horizon mass. [Zeldovich & Novikov; Hawking; Carr & Hawking]

$$M_{BH}^{init} \equiv M_F = M_{\rm horiz} = \gamma \rho_{\rm tot} \times 4\pi/(3H_F^3)$$

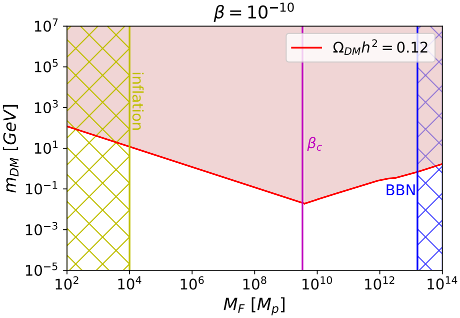


- PBH formed after inflation:
  $t_F > t_{\rm infl} \rightarrow M_F > 10^4 M_p$
- PBH evaporate before BBN:
  $t_{\rm ev} < t_{BBN} \rightarrow M_F < 2 \times 10^{13} M_p$

PBH evaporating after inflation and before BBN

PBH generation: during radiation domination (after inflation) an initially large density perturbation at sufficiently small scale can collapse to form a PBH with mass of order the horizon mass. [Zeldovich & Novikov; Hawking; Carr & Hawking]

$$M_{BH}^{init} \equiv M_F = M_{\rm horiz} = \gamma \rho_{\rm tot} \times 4\pi/(3H_F^3)$$

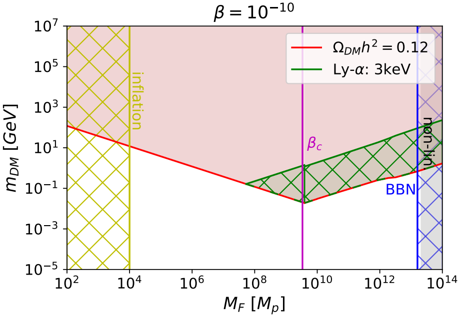


- PBH formed after inflation: $t_F > t_{\rm infl} \rightarrow M_F > 10^4 M_p$
- PBH evaporate before BBN: $t_{\rm ev} < t_{BBN} \rightarrow M_F < 2 \times 10^{13} M_p$
- DM abundance depends on the initial BH fraction: $\beta \equiv \rho_{\rm PBH}/\rho_{\rm tot}|_{t_F} \leq 1$

PBH evaporating after inflation and before BBN

PBH generation: during radiation domination (after inflation) an initially large density perturbation at sufficiently small scale can collapse to form a PBH with mass of order the horizon mass. [Zeldovich & Novikov; Hawking; Carr & Hawking]

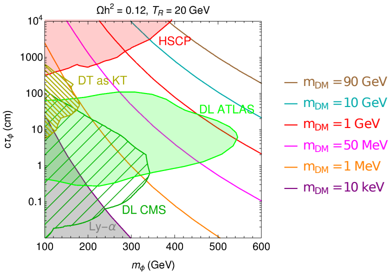
$$M_{BH}^{init} \equiv M_F = M_{\rm horiz} = \gamma \rho_{\rm tot} \times 4\pi/(3H_F^3)$$

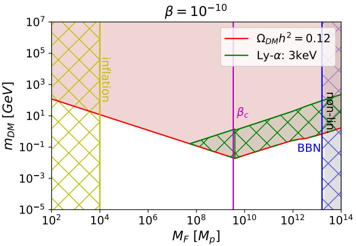


- PBH formed after inflation: $t_F > t_{\rm infl} \rightarrow M_F > 10^4 M_p$
- PBH evaporate before BBN: $t_{\rm ev} < t_{BBN} \rightarrow M_F < 2 \times 10^{13} M_p$
- DM abundance depends on the initial BH fraction: $\beta \equiv \rho_{\rm PBH}/\rho_{\rm tot}|_{t_F} \leq 1$

Lyman-α bound: NCDM account for all the DM if $\beta \lesssim 5 \times 10^{-7}$ and $m_{\rm DM} \gtrsim 2\,{\rm MeV}$.

Conclusion





- FIMPs from freeze-in: Reheating and Colliders
  - LLP at colliders with displaced signatures for $\sim keV$ DM only.
  - FIMPs $\sim$ NCDM and Lyman-α forest constrains $m_{DM} \gtrsim 10$ keV
  - Lower T_{RH} increase the testable parameter space
    $\rightsquigarrow$ colliders might indirectly probe early universe cosmology
- not even FIMPs from PBH evaporation
  - Gravitational interactions only source DM production
  - DM properties are testable due to their NCDM Cosmological imprint: $m_{DM} \gtrsim 2$ MeV and $\beta \lesssim 5 \times 10^{-7}$ if all DM from PBH

We are Hiring!

Postdoc positions at ULB:

https://inspirehep.net/jobs/1824263

https://inspirehep.net/jobs/1832772

Thank you for your attention!

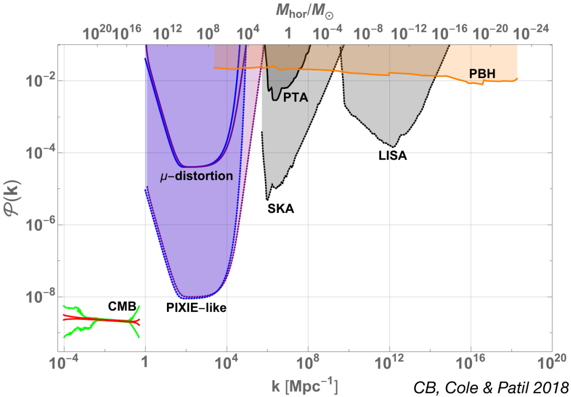
Backup

Lyman-α forest

Absorption lines produced by the inhomogeneous IGM along different line of sights to distant quasars: a fraction of photons is absorbed at the Lyman-α wavelength (corresponding to $\lambda_\alpha \sim 121$ nm), resulting in a depletion of the observed spectrum at a given frequency ($\lambda_{abs} < \lambda_\alpha$).

- Allows us to trace neutal hydrogen clouds, i.e. smallest structures
- Provides a tracer of the matter power spectrum at high redshifts ($2 < z < 6$) and small scales ($0.5\ h/\text{Mpc} < k < 20\ h/\text{Mpc}$).
- IGM modelling requires nonlinear evolution: this needs N-body hydrodynamical simulations. Computational expensive and only available for few benchmark models.

Power spectrum constraints

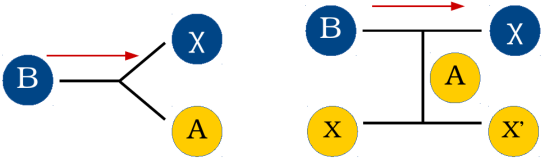


If PBHs form from large amplitude perturbations, we will either detect PBHs, or else (almost) rule out their existence at late times

[Byrnes'19]

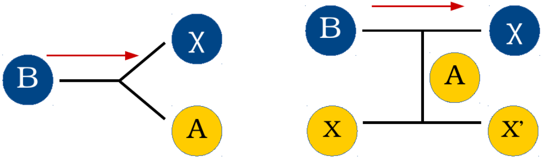
Minimal models for 3 body interactions

Production in the early universe



Minimal models for 3 body interactions

Production in the early universe

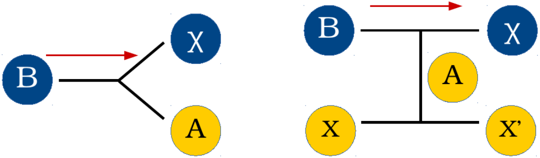


A_{SM}	Spin DM	Spin B	Interaction	Label
ψ_{SM}	0	1/2	$\bar{\psi}_{SM}\Psi_B\phi$	$\mathcal{F}_{\psi_{SM}\phi}$
	1/2	0	$\bar{\psi}_{SM}\chi\Phi_B$	$\mathcal{S}_{\psi_{SM}\chi}$
$F^{\mu\nu}$	1/2	1/2	$\bar{\Psi}_B\sigma_{\mu\nu}\chi F^{\mu\nu}$	$\mathcal{F}_{F\chi}$
H	0	0	$H^\dagger\Phi_B\phi$	$\mathcal{S}_{H\phi}$
	1/2	1/2	$\bar{\Psi}_B\chi H$	$\mathcal{F}_{H\chi}$

[Calibbi in prep]

Minimal models for 3 body interactions

Production in the early universe

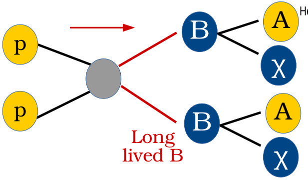


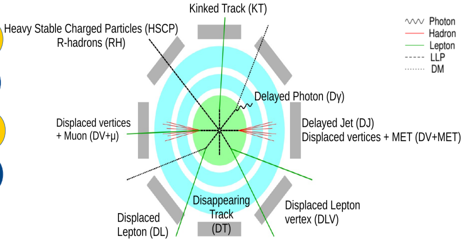
A_{SM}	Spin DM	Spin B	Interaction	Label
ψ_{SM}	0	1/2	$\bar{\psi}_{SM}\Psi_B\phi$	$\mathcal{F}_{\psi_{SM}\phi}$
	1/2	0	$\bar{\psi}_{SM}\chi\Phi_B$	$\mathcal{S}_{\psi_{SM}\chi}$
$F^{\mu\nu}$	1/2	1/2	$\bar{\Psi}_B\sigma_{\mu\nu}\chi F^{\mu\nu}$	$\mathcal{F}_{F\chi}$
H	0	0	$H^\dagger\Phi_B\phi$	$\mathcal{S}_{H\phi}$
	1/2	1/2	$\bar{\Psi}_B\chi H$	$\mathcal{F}_{H\chi}$

[Calibbi in prep]

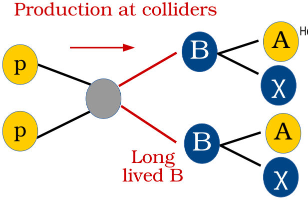
Colliders sensitivity to LLPs

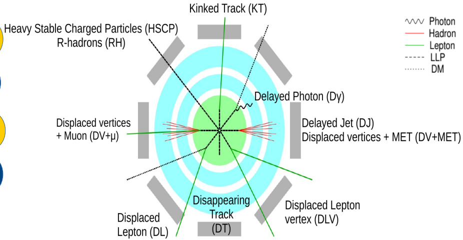
Production at colliders





Colliders sensitivity to LLPs





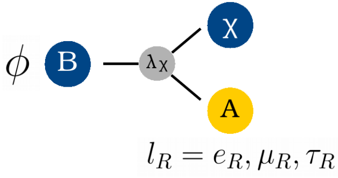
Displaced B decay ⟷ Stable B ⟷

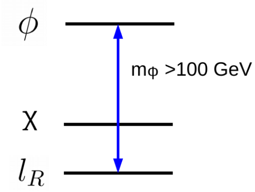
Label	DV + MET	DJ + MET	DJ + μ	DL	DLV	Dγ	DT	RH	HSCP	KT
$\mathcal{F}_{l\phi}$ & $\mathcal{S}_{l\chi}$				✓					✓	✓
$\mathcal{F}_{\tau\phi}$ & $\mathcal{S}_{\tau\chi}$	✓	✓		✓					✓	✓
$\mathcal{F}_{q\phi}$ & $\mathcal{S}_{q\chi}$	✓	✓						✓		
$\mathcal{F}_{t\phi}$ & $\mathcal{S}_{t\chi}$	✓	✓	✓	✓				✓		
$\mathcal{F}_{G\chi}$	✓	✓						✓		
$\mathcal{F}_{W\chi}$	✓	✓	✓	✓	✓	✓	✓			✓
$\mathcal{S}_{H\phi}$ & $\mathcal{F}_{H\chi}$	✓	✓	✓	✓	✓		✓			✓

[Calibbi, D'Eramo, Junius, LLH,Mariotti in prep]

The case of leptophilic DM

see also [Bergstrom '89+, Bringmann '08+, Ciafaloni '11, Garny '11+,Toma '13, Giacchino'13++, Ibarra'14, Belanger'18, Calibbi'18...]

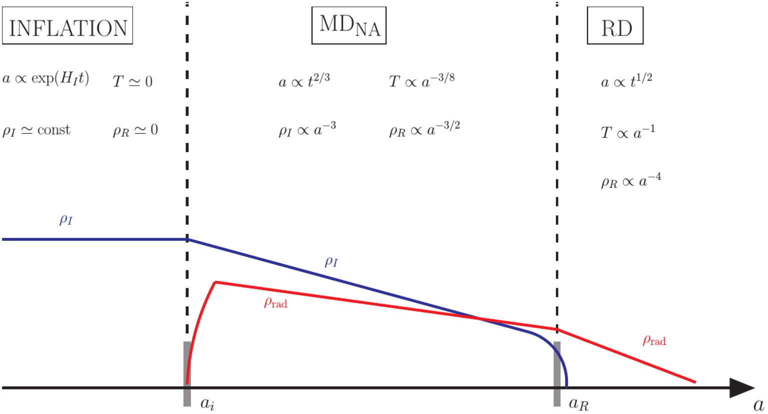




$$\mathcal{L} \subset \mathcal{L}_K - \frac{m_\chi}{2}\bar{\chi}\chi - m_\phi \phi^\dagger \phi - \lambda_\chi \phi \bar{\chi} l_R + h.c.$$

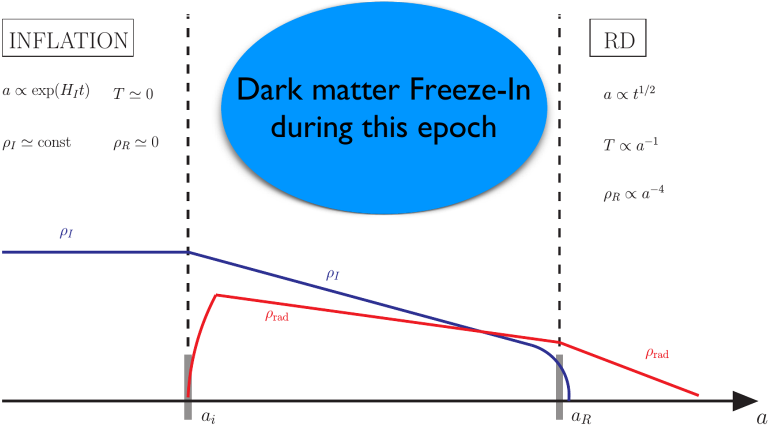
- SM + 1 charged dark scalar ϕ + 1 Majorana dark fermions χ (Z_2 symmetry for DM stability)
- Cosmo: minimal DM mass $\sim$ 12 keV
- Colliders: Heavy stable charged ϕ (HSCP) [ATLAS'19], Kinked tracks (KT) making use of DT of [CMS'20] & displaced lepton searches (DL)[CMS'16]

Freeze-in in early Matter Dominated era



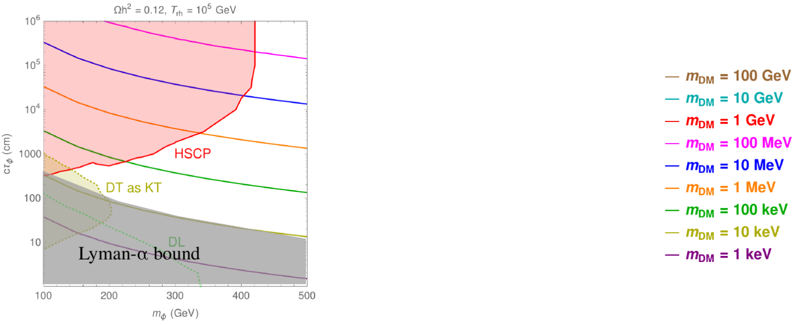
For FI in early Matter Dominated era (MD), the relic density depends on the reheating temperature T_{RH} [Co'15].

Freeze-in in early Matter Dominated era



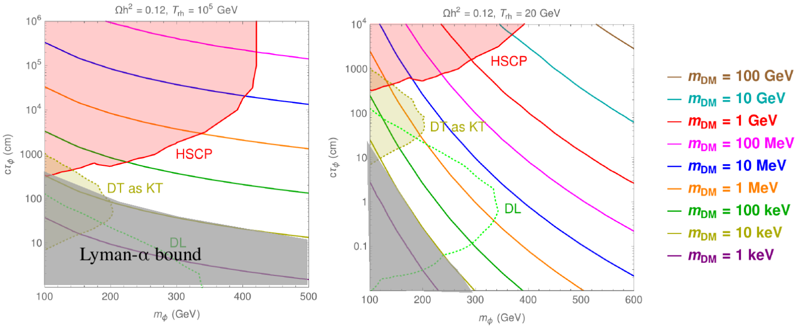
For FI in early Matter Dominated era (MD), the relic density depends on the reheating temperature T_{RH} [Co'15].

Leptophilic DM: Collider Constraints and Reheating



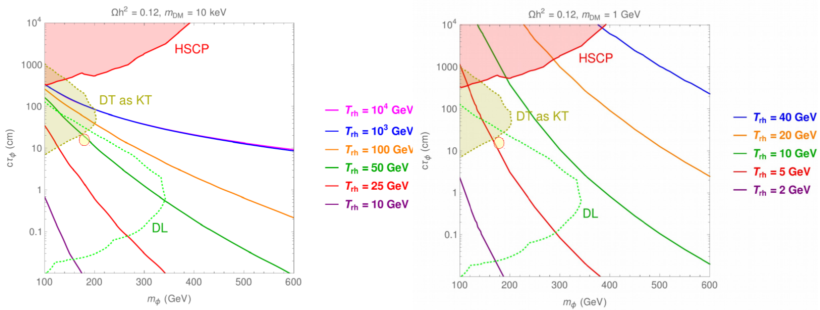
- The lower T_{RH}, the lower is Y_X^∞ (for fixed m_ϕ and m_χ)
  $\rightsquigarrow$ the higher λ_χ must be to account for DM abundance and the lower is $c\tau_B$.

Leptophilic DM: Collider Constraints and Reheating

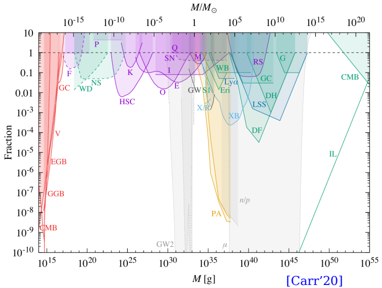


- The lower T_{RH}, the lower is Y_X^∞ (for fixed m_ϕ and m_χ)
  $\rightsquigarrow$ the higher λ_χ must be to account for DM abundance and the lower is $c\tau_B$.
- Lowering T_{RH} allows for displaced signatures at colliders with larger DM masses. see also [Belanger'18]

Leptophilic DM: Collider Constraints and Reheating



- The lower T_{RH}, the lower is Y_X^∞ (for fixed m_ϕ and m_χ)
  $\rightsquigarrow$ the higher λ_χ must be to account for DM abundance and the lower is $c\tau_B$.
- Lowering T_{RH} allows for displaced signatures at colliders with larger DM masses. see also [Belanger'18]
- If $(m_\phi, c\tau_\phi)$ can be reconstructed at colliders, T_{RH} giving rise to all the dark matter for the lowest DM mass might serve as an upper bound on T_{RH}



[Carr'20]

FIG. 10. Constraints on $f(M)$ from evaporation (red), lensing (magenta), dynamical effects (green), accretion (light blue), CMB distortions (orange), large-scale structure (dark blue) and background effects (grey). Evaporation limits come from the extragalactic gamma-ray background (EGB), the Galactic gamma-ray background (GGB) and Voyager $e^{\pm}$ limits (V). Lensing effects come from femtolensing (F) and picolensing (P) of gamma-ray bursts, microlensing of stars in M31 by Subaru (HSC), in the Magellanic Clouds by MACHO (M) and EROS (E), in the local neighbourhood by Kepler (K), in the Galactic bulge by OGLE (O) and the Icarus event in a cluster of galaxies (I), microlensing of supernova (SN) and quasars (Q), and millilensing of compact radio sources (RS). Dynamical limits come from disruption of wide binaries (WB) and globular clusters (GC), heating of stars in the Galactic disk (DH), survival of star clusters in Eridanus II (Eri) and Segue 1 (S1), infalling of halo objects due to dynamical friction (DF), tidal disruption of galaxies (G), and the CMB dipole (CMB). Accretion limits come from X-ray and radio (X/R) observations, CMB anisotropies measured by Planck (PA) and gravitational waves from binary coalescences (GW). Background constraints come from CMB spectral distortion (μ), 2nd order gravitational waves (GW2) and the neutron-to-proton ratio (n/p). The incredulity limit (IL) corresponds to one hole per Hubbble volume. Constraints shown by broken lines are insecure and probably wrong but included for historical completeness; those shown by a dotted line depend upon some additional assumptions.

PBH evaporation and Greybody factors

BH temperature and Evaporation see [Hawking 74-75, Bardeen 1973,Page 1976 & Mc Gibbon1990]

$$T_{\rm BH} = \frac{M_p^2}{8\pi M_{\rm BH}} \quad \text{and} \quad \frac{dN_j}{dtdE} = \frac{g_j}{2\pi}\frac{\Gamma_j(E, M_{\rm BH})}{\exp\left(E/T_{\rm BH}\right) \pm 1},$$

where $\Gamma_j(E, M_{\rm BH})$ are spin and energy dependent greybody factors. We use the high energy limit $\Gamma_j \to 27E^2M_{\rm BH}^2/M_p^4$.

$$\frac{dM_{\rm BH}}{dt} = -\sum_j \int_0^\infty E\frac{dN_j}{dtdE}dE = -e_T\frac{M_p^4}{M_{\rm BH}^2},$$

$$N_j = -\int_{t_F}^\tau dt \int_0^\infty dEE\frac{dN_j}{dtdE} = g_j\frac{81\zeta(3)}{4096\pi^4 e_T}\frac{M_F^2}{M_p^2}$$

with a lifetime $\tau = \frac{1}{3e_T}\frac{M_F^3}{M_p^4}$.

Including the full treatment of the greybody factors [Mc Gibbon1990] , our e_T is approximatively twice as large as the correct $\tilde{e}_T$ for dM/dt. This implies that we underestimated τ by a factor of 2. The corrected $\tilde{\Omega}_{\rm DM}(t_0)$ to differ from $\Omega_{\rm DM}(t_0)$ by a factor $1.8 \times X'_{\rm DM}$ for $\beta < \beta_c$ and a factor $1.3 \times X'_{\rm DM}$ for $\beta > \beta_c$. It would also imply a strengthening of the Ly-α bounds obtained by $\sim 25\,\%$ aside from the shift in the peak velocity to higher velocities that would strengthen this bound even further.

NCDM from PBH evaporation

PBHs may be light enough to decay via **Hawking radiation** at an early enough epoch to avoid all previous constraints.

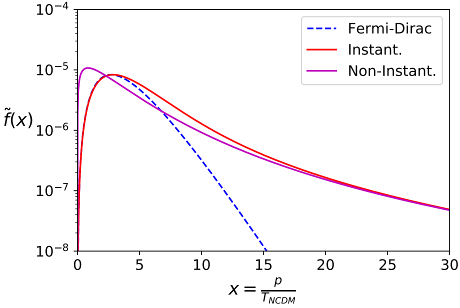
- DM particles (and SM) will be produced from PBH evaporation given **gravitational interactions** (not even FIMPs needed).
- For $m_{DM} < T_{BH}^{init} \propto M_p^2/(8\pi M_{BH}^{init})$, behave as non-thermal NCDM.

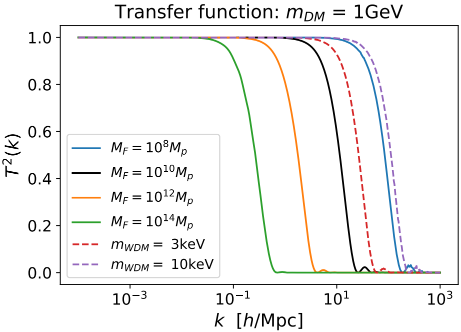
NCDM from PBH evaporation

PBHs may be light enough to decay via **Hawking radiation** at an early enough epoch to avoid all previous constraints.

- DM particles (and SM) will be produced from PBH evaporation given **gravitational interactions** (not even FIMPs needed).
- For $m_{DM} < T_{BH}^{init} \propto M_p^2/(8\pi M_{BH}^{init})$, behave as non-thermal NCDM.

$$N_{\rm DM} = 3.2 \times 10^{-2} g_{\rm DM} \left(M_{BH}^{init}/M_p\right)^2 \quad \text{and} \quad \langle p_{\rm DM}\rangle|_{t_{\rm ev}} \approx 5 \times T_{BH}^{init}$$





NCDM from PBH: Lyman-α & $\Delta N_{\rm eff}$

- Suppressed power at small scales:

$$T_X(k) = (1 + (\alpha_X k)^{2\nu})^{-5/\nu}$$

with $\nu = 1.2$ and WDM and PBH breaking scale are given by:

$\alpha_{\rm WDM} = 0.049 \left(\frac{m_{\rm WDM}}{1\,{\rm keV}}\right)^{-1.11} \left(\frac{\Omega_{\rm WDM}}{0.25}\right)^{0.11} \left(\frac{h}{0.7}\right)^{1.22} h^{-1}{\rm Mpc}$ [Viel'05]

$\alpha_{\rm PBH} = 53.2 \left(\frac{m_{\rm DM}}{1\,{\rm eV}}\right)^{-0.83} \left(\frac{M_{\rm F}}{M_p}\right)^{0.42} h^{-1}{\rm Mpc}$ [our result for $\beta > \beta_c$ using CLASS]

$$\rightsquigarrow m_{\rm DM} \geq 4.4\,{\rm keV} \times \left(\frac{m_{\rm WDM}^{\rm Ly-\alpha}}{\rm keV}\right)^{4/3} \left(\frac{M_F}{M_p}\right)^{1/2}$$

NCDM from PBH: Lyman-α & $\Delta N_{\rm eff}$

- Suppressed power at small scales:

$$T_X(k) = (1 + (\alpha_X k)^{2\nu})^{-5/\nu}$$

with $\nu = 1.2$ and WDM and PBH breaking scale are given by:

$\alpha_{\rm WDM} = 0.049 \left(\frac{m_{\rm WDM}}{1\,{\rm keV}}\right)^{-1.11} \left(\frac{\Omega_{\rm WDM}}{0.25}\right)^{0.11} \left(\frac{h}{0.7}\right)^{1.22} h^{-1}{\rm Mpc}$ [Viel'05]

$\alpha_{\rm PBH} = 53.2 \left(\frac{m_{\rm DM}}{1\,{\rm eV}}\right)^{-0.83} \left(\frac{M_{\rm F}}{M_p}\right)^{0.42} h^{-1}{\rm Mpc}$ [our result for $\beta > \beta_c$ using CLASS]

$$\rightsquigarrow m_{\rm DM} \geq 4.4\,{\rm keV} \times \left(\frac{m_{\rm WDM}^{{\rm Ly}-\alpha}}{\rm keV}\right)^{4/3} \left(\frac{M_F}{M_p}\right)^{1/2}$$

- Extra relativistic dof at recombination or BBN [Merle '15]:

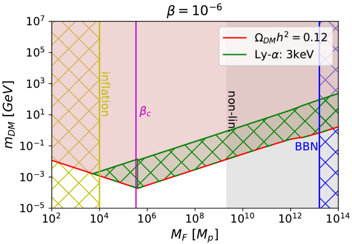
$$\Delta N_{\rm eff}(T) = \frac{\rho_{\rm DM}(T) - m_{\rm DM} n_{\rm DM}(T)}{\rho_{rel\,\nu}(T)/N^{\nu}_{\rm eff}(T)}$$

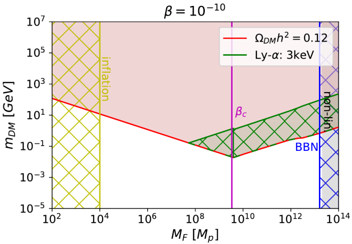
$\rightsquigarrow \Delta N_{\rm eff} < 4.1 \times 10^{-2}$ (independently of M_F)

too small to be detected by CMB experiments (for $g_{\rm DM} = 2$)

($\Delta N_{\rm eff}(T_{\rm CMB}) < 0.28$ at 95 % C.L. [Planck'18] and ~ 0.06 for CMB Stage IV [Abazajian'19])

PBH: summary

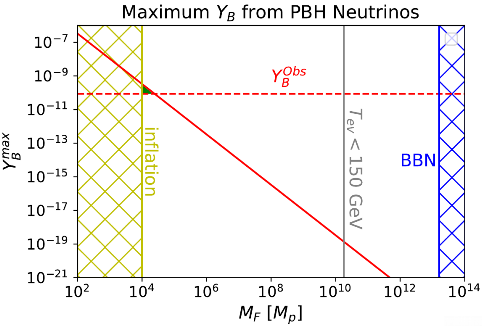




$$M_{\rm BH}(t) = M_F \left(1 - \frac{(t - t_F)}{\tau}\right)^{1/3} \qquad \tau = \frac{1}{3e_T} \frac{M_F^3}{M_p^4} .$$

$$\beta_c = \sqrt{\frac{3e_T}{\gamma} \frac{M_p}{M_F}} .$$

PBH: Leptogenesis



Davidson-Ibarra bound on the CP violation $\quad \epsilon \lesssim \frac{3 M_N \delta m_\nu}{8\pi v_\phi^2}$

baryon yield from the heavy neutrinos $\quad Y_B = \epsilon \kappa N_N Y_{\rm BH}$

the NCDM produced by the PBH accounts for $\Omega_{\rm DM} h^2 = 0.12$

$$\beta < 0.016\, \beta_c \qquad Y_B < 3.3 \times 10^{-4} \left(\frac{\delta m_\nu}{0.05\,{\rm eV}}\right) \left(\frac{M_p}{M_F}\right)^{3/2}$$

PBH: DM abundance and $\Delta N_{\rm eff}$

$$\Omega_{\rm DM}(t_0) = \frac{m_{\rm DM} n_{\rm DM}(t_{\rm ev})}{\rho_c} \times \left(\frac{a_{\rm ev}}{a_0}\right)^3 \qquad a_{\rm ev} \propto M_F^{3/2}$$

$$\frac{\Omega_{\rm DM}(t_0)h^2}{0.12} = \left(\frac{m_{\rm DM}}{1\,\rm MeV}\right) \times \begin{cases} \left(\frac{M_F}{1.1\times 10^7 M_p}\right)^{1/2}\left(\frac{\beta}{3.6\times 10^{-8}}\right) & \text{if } \beta < \beta_c\,, \\ \left(\frac{M_F}{1.1\times 10^7 M_p}\right)^{-1/2} & \text{if } \beta > \beta_c\,. \end{cases}$$

$$\left.\frac{dN_j}{dp}\right|_{t=t_{\rm ev}} = \int_0^\tau dt' \, \frac{a(\tau)}{a(t')} \times \frac{dN_j}{dp'dt'}\left(p\frac{a(\tau)}{a(t')}, t'\right) \qquad \tilde{f}(x) = \frac{T_F^3}{M_p^2 g_j} \left.\frac{dN_j}{dp}\right|_{t=t_{\rm ev}}$$

Contribution to $\Delta N_{\rm eff}$ $\qquad \Delta N_{\rm eff}(t_{\rm CMB}) < 0.28$ at 95 % C.L.

$$\Delta N_{\rm eff}(T) = \frac{\rho_{\rm DM}(T) - m_{\rm DM} n_{\rm DM}(T)}{\rho_{rel\,\nu}(T)/N_{\rm eff}^{\nu}(T)}$$

$$\Delta N_{\rm eff}^{\rm rel}(T) \simeq \frac{g_{\rm DM}}{2} \begin{cases} 1.2\times 10^{-1}\beta \times \frac{M_F}{M_p} & \text{if } \beta < \beta_c\,, \\ 4.1 \times 10^{-2} & \text{if } \beta > \beta_c\,. \end{cases}$$

PBH: Lyman-α

Estimate for the Lyman-α constraint

$$\langle v\rangle|_{t=t_0} = a_{\rm ev} \times \frac{\langle p\rangle|_{t=\tau}}{m_{\rm DM}} = \left(\frac{\rm keV}{m_{\rm DM}}\right)\left(\frac{M_F}{M_p}\right)^{1/2} \times \begin{cases} 6.4\times 10^{-7} & \text{for } \beta < \beta_c\,, \\ 5.5\times 10^{-7} & \text{for } \beta > \beta_c\,, \end{cases}$$

$$v_{\rm WDM}|_{t=t_0} \approx 3.9\times 10^{-8}\left(\frac{\rm keV}{m_{\rm WDM}}\right)^{4/3} .$$

$$m_{\rm DM} \gtrsim \left(\frac{m_{\rm WDM}^{\rm Ly-\alpha}}{\rm keV}\right)^{4/3}\left(\frac{M_F}{M_p}\right)^{1/2} \times \begin{cases} 16\,{\rm keV} & \text{for } \beta < \beta_c\,, \\ 14\,{\rm keV} & \text{for } \beta > \beta_c\,. \end{cases}$$

Lyman-α constraints from the transfer function

$$T_X(k) = \left(1 + (\alpha_X k)^{2\mu}\right)^{-5/\mu}$$

$$\alpha_{\rm WDM} = 0.049\left(\frac{m_{\rm WDM}}{1\,{\rm keV}}\right)^{-1.11}\left(\frac{\Omega_{\rm WDM}}{0.25}\right)^{0.11}\left(\frac{h}{0.7}\right)^{1.22} h^{-1}{\rm Mpc}\,,$$

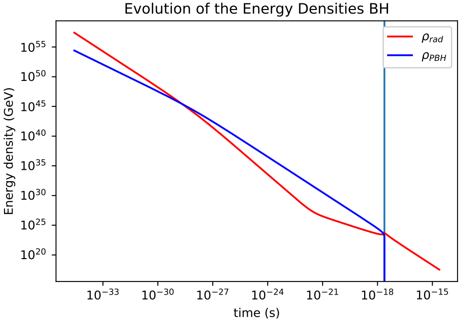
$$\alpha_{\rm PBH} = \left(\frac{m_{\rm DM}}{1\,{\rm eV}}\right)^{-0.83}\left(\frac{M_F}{M_p}\right)^{0.42} \times \begin{cases} 60.4\,{\rm Mpc}\,h^{-1} & \text{if } \beta < \beta_c\,, \\ 53.2\,{\rm Mpc}\,h^{-1} & \text{if } \beta > \beta_c\,, \end{cases}$$

$$m_{\rm DM} \geq \left(\frac{m_{\rm WDM}^{\rm Ly-\alpha}}{\rm keV}\right)^{4/3}\left(\frac{M_F}{M_p}\right)^{1/2} \times \begin{cases} 5.2\,{\rm keV} & \text{if } \beta < \beta_c\,, \\ 4.4\,{\rm keV} & \text{if } \beta > \beta_c\,. \end{cases}$$

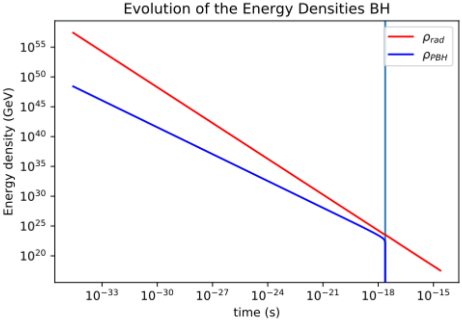
Evaporation in Radiation of Matter dom. era

The initial PBH fraction: $\beta \equiv \rho_{\rm PBH}/\rho_{\rm tot}|_{t_F} \leq 1$ will affect evaporation scale factor and the initial dark matter number density:

Matter (PBH) dominated era for $\beta > \beta_c(M_F)$



Radiation dominated era for $\beta > \beta_c(M_F)$



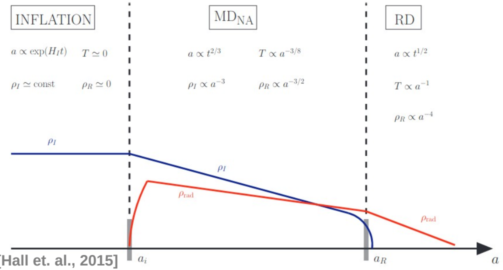
The dynamics of the reheating era

- Reheating through decay of inflaton (matter) to SM radiation

$$\frac{d\rho_I}{dt} + 3H\rho_I = -\Gamma_I \rho_I$$

$$\frac{d\rho_R}{dt} + 4H\rho_R = \Gamma_I \rho_I$$

$$\Gamma_I = H(T_{rh}) = \frac{\sqrt{\rho_R(T_{rh})}}{M_{Pl}\sqrt{3}}$$



[Hall et. al., 2015]

Effects of reheating on freeze-in

- Rewrite Boltzmann equation to capture effects of reheating
- For $T \sim a^{-1}$, usual Boltzmann equation is recovered

$$\frac{dN_{DM}}{dT} = \frac{\gamma(T)}{H(T)} \frac{1}{3} \frac{da^3}{dT}$$

$$N_{DM} = n_{DM} a^3$$

$$\gamma_{i \to jk} = n_i^{eq} \langle \Gamma_{i \to jk} \rangle$$

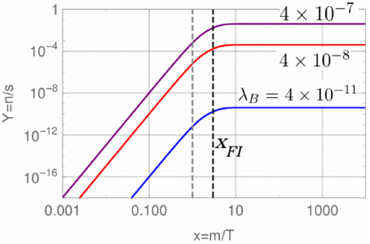
$$\gamma_{ij \to kl} = n_i^{eq} n_j^{eq} \langle \sigma_{ij \to kl} v_{ij} \rangle$$

13

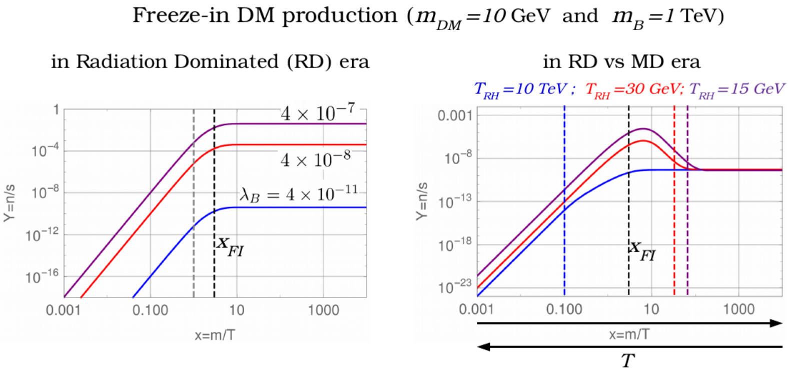
Reheating after FI and smaller $c\tau_B$

Freeze-in DM production ($m_{DM}=10$ GeV and $m_B=1$ TeV)

in Radiation Dominated (RD) era



Reheating after FI and smaller $c\tau_B$



DM yield is diluted due to extra entropy production from inflaton decay:

$$Y_X(T_{FI})/Y_X^\infty \propto (T_{FI}/T_{RH})^5 \,,$$

$\rightsquigarrow$ The lower T_{RH}, the longer is the dilution and the lower is Y_X^∞ compared to $Y_X(T_{FI})$, the higher is λ_χ to account for DM abundance and the lower is $c\tau_B$.

UV freeze-in

- For operator of dimension d, contributions of scattering processes to Boltzmann equation scale as:

$$\frac{dN_{DM}}{dT} \sim \frac{T^{2d-17}}{\Lambda^{2d-8}} \quad \text{during RH era}$$
$$\sim \frac{T^{2d-10}}{\Lambda^{2d-8}} \quad \text{during RD era}$$

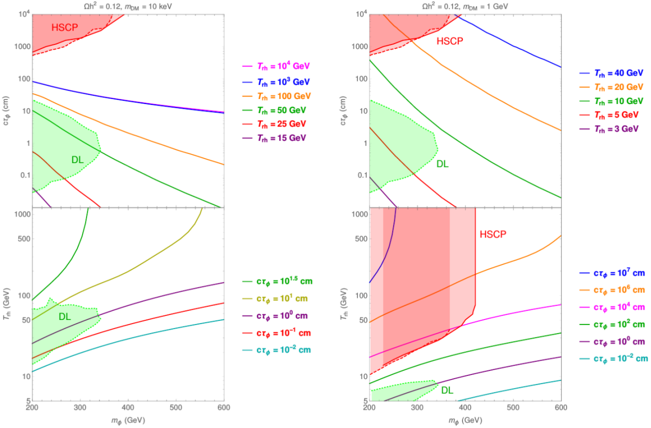
28

Collider searches

Signature	Exp. & Ref.	$\mathcal{L}$	Maximal sensitivity	Label
R-hadrons Heavy stable charged particle	CMS [48] ATLAS [49]	12.9 fb^{-1} 36.1 fb^{-1}	$c\tau \gtrsim 10$ m	RH HSCP
Disappearing tracks	ATLAS [50] CMS [51, 52]	36.1 fb^{-1} 140 fb^{-1}	$c\tau \approx 30$ cm $c\tau \approx 60$ cm	DT
Displaced leptons	CMS [53] CMS [54] ATLAS [55]	19.7 $fb^{-1\dagger}$ 2.6 fb^{-1} 139 fb^{-1}	$c\tau \approx 2$ cm $c\tau \approx 5$ cm	DL
Displaced vertices + MET	ATLAS [56]	32.8 fb^{-1}	$c\tau \approx 3$ cm	DV+MET
Delayed jets + MET	CMS [57]	137 fb^{-1}	$c\tau \approx 1-3$ m	DJ+MET
Displaced vertices + μ	ATLAS [58]	136 fb^{-1}	$c\tau \approx 3$ cm	DV+μ
Displaced dilepton vertices	ATLAS [59]	32.8 fb^{-1}	$c\tau \approx 1-3$ cm	DLV
Delayed photons	CMS [60]	77.4 fb^{-1}	$c\tau \approx 1$ m	Dγ

Leptophilic DM

$$\mathcal{L} \supset \frac{1}{2}\bar{\chi}\gamma^\mu\partial_\mu\chi - \frac{m_\chi}{2}\bar{\chi}\chi + (D_\mu\phi)^\dagger\, D^\mu\phi - m_\phi^2|\phi|^2 \;-\; \lambda_\chi\phi\bar{\chi}l_R \;+\; h.c.\,,$$



Leptophilic DM: comparaison to previous works

Comparing a cut in the integral over time to a full integration of the Boltzmann equations in EMDE

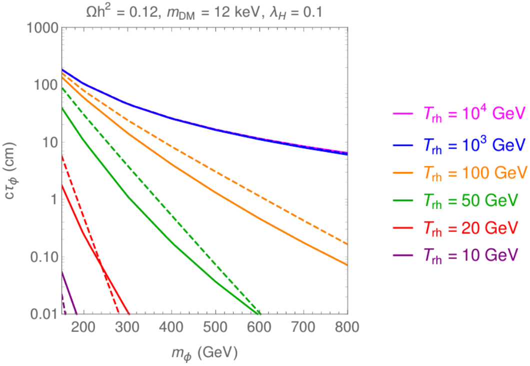
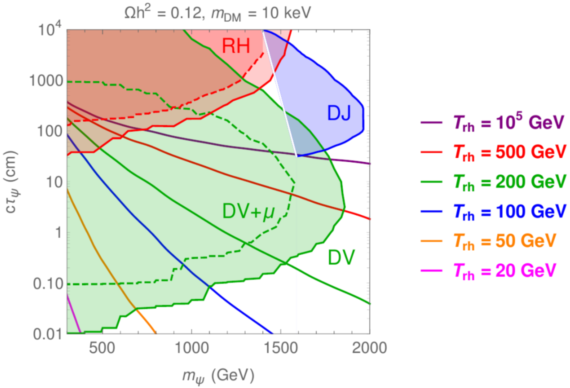


Figure 9: Comparison between our implementation of T_{RH} (continous curve) and a cut in the time integration of the DM yield as in e.g. [13, 32].

Topphilic DM

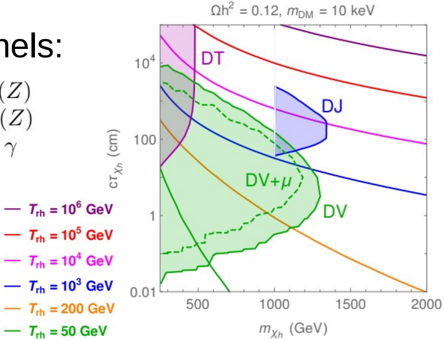
$$\mathcal{L} \supset \partial_\mu \phi\, \partial^\mu \phi - \frac{m_\phi^2}{2}\phi^2 + \frac{1}{2}\bar{\psi}\gamma^\mu D_\mu \psi - m_\psi^2 \bar{\psi}\psi \; - \; \lambda_\phi \phi \bar{\psi} t_R \; + \; h.c.\,,$$



Singlet-Triplet model: LHC bounds

- Possible decay channels:

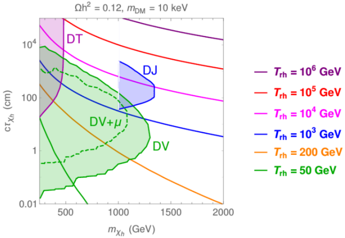
$$
\begin{aligned}
\chi^{\pm} \;\to\; & \chi_h \pi^{\pm} \;\to\; \chi_l \; l(Z) \\
& \phantom{\chi_h \pi^{\pm}} \;\to\; \chi_l \; j(Z) \\
& \phantom{\chi_h \pi^{\pm}} \;\to\; \chi_l \; \gamma \\
\to\; & \chi_l \; l(W) \\
\to\; & \chi_l \; j(W)
\end{aligned}
$$

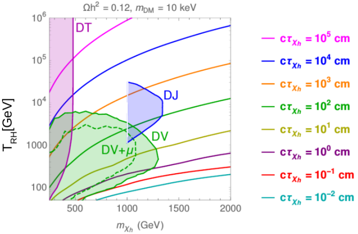


Singlet-Triplet DM

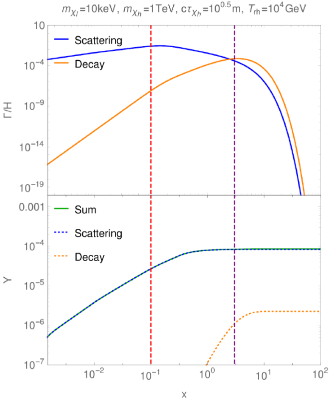
$$\mathcal{L}_{BSM} = -\frac{m_S}{2}\bar{\chi_S}\chi_S - \frac{m_T}{2}Tr\left[\bar{\chi_T}\chi_T\right] + \frac{1}{2}Tr\left[\bar{\chi_T}i\not{D}_\mu\chi_T\right]$$
$$+\frac{\kappa}{\Lambda}(W^a_{\mu\nu}\bar{\chi_S}\sigma^{\mu\nu}\chi^a_T + \text{h.c.}),$$

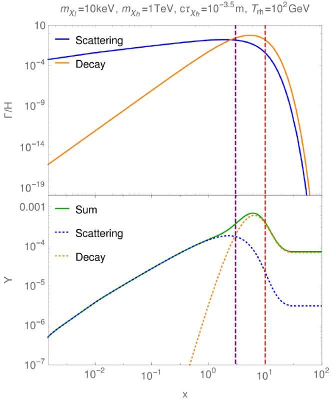
$$\chi_S = \chi^0_l, \qquad \chi_T = \begin{pmatrix} \chi^0_h/\sqrt{2} & \chi^+ \\ \chi^- & -\chi^0_h/\sqrt{2} \end{pmatrix}$$





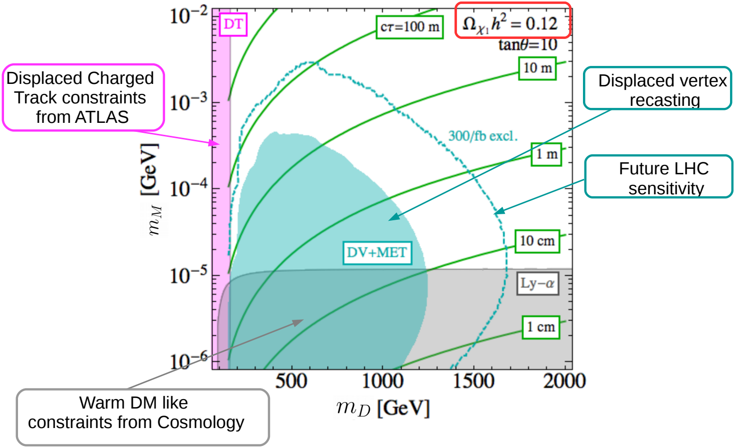
Singlet-Triplet DM





LHC & Cosmo complementarity: Singlet doublet

At each point y is fixed to get the DM abundance



Simplified Model for FIMPs: 3 extra parameters m_χ, m_B, y

FIMP as dark matter, χ ($\sim$ neutral), would be a fermion/scalar coupled to dark A and SM B through 3 body interactions

$$\mathcal{L} \subset y\, \chi\, A_{SM} B$$

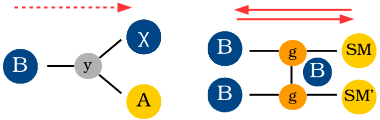
- Dark sector (Z_2 odd): $m_B > m_\chi$

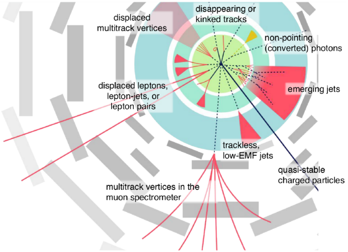
Simplified Model for FIMPs: 3 extra parameters m_χ, m_B, y

FIMP as dark matter, χ ($\sim$ neutral), would be a fermion/scalar coupled to dark A and SM B through 3 body interactions

$$\mathcal{L} \subset y\,\chi\,A_{SM}B$$

- Dark sector (Z_2 odd): $m_B > m_\chi$
- B is $SU(3) \times SU(2) \times U(1)$ charged
  - fast $B^\dagger A \leftrightarrow$ SM SM through gauge interactions at early time
  - B is produced at colliders today
- χ-B-SM interactions:
  - $\chi \equiv$ FIMP $\leftrightarrow y \ll 10^{-4}$
  - long lived B at colliders through $B \to A\chi$





[Figure from Heather Russell]

[See also 1903.04497]

bla

This is really the end