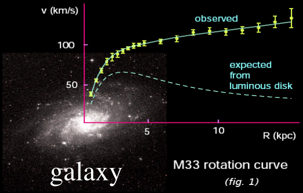
When Cosmology meets
Feebly Interacting dark matter Particles

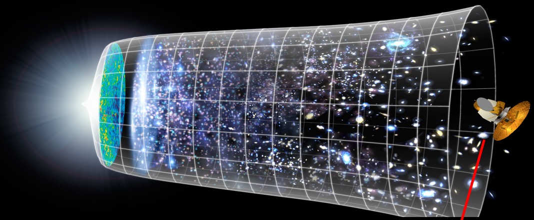
Laura Lopez Honorez

mainly inspired by `arXiv:2004.14773` and `arXiv:2005.XXXXX`
in collaboration with I. Baldes, L. Calibbi, **Q. Decant**,
F. d'Eramo, D.C. Hooper, **S. Junius** & A. Mariotti.

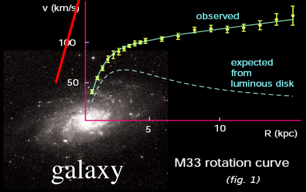
virtual Curie-Colloqium - MPIK - Heidelberg



The Quest to determine the Composition of our Universe



Dark matter



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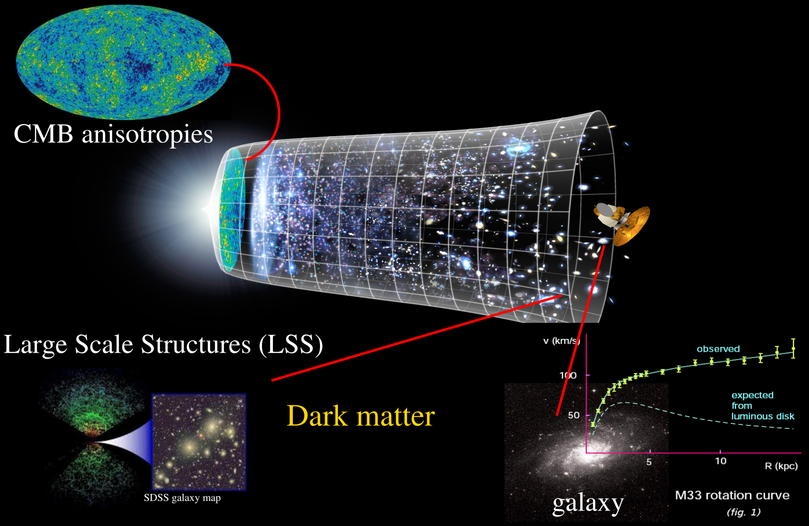

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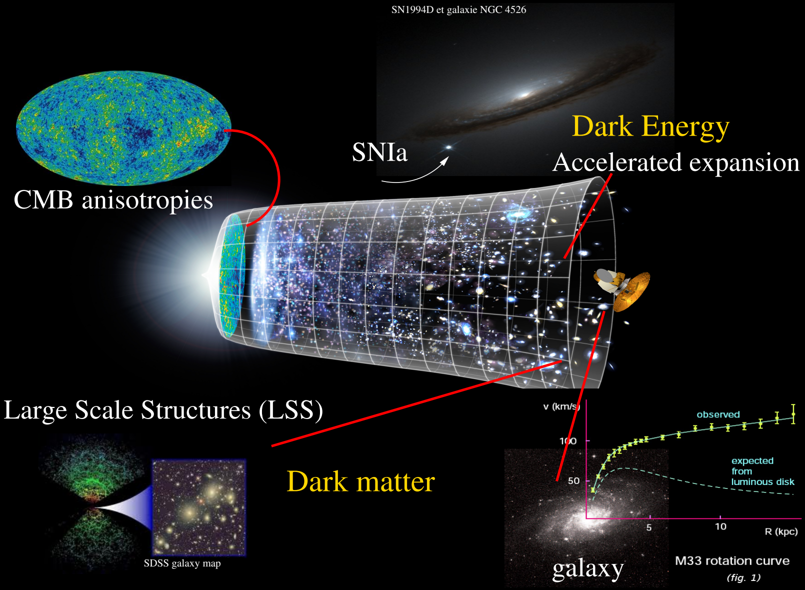


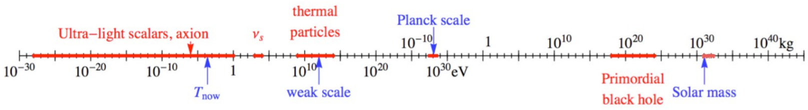
The Quest to determine the Composition of our Universe

80% of the matter content is made of Dark Matter

What is the Nature of Dark Matter?

Dark Matter should be essentially:

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



Courtesy of M.Cirelli

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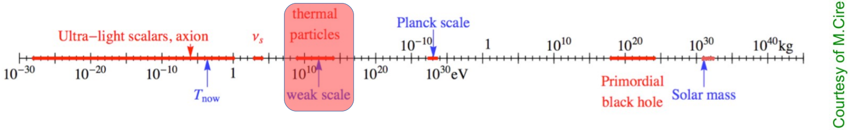
WIMPs: focus of the last ∼30 years



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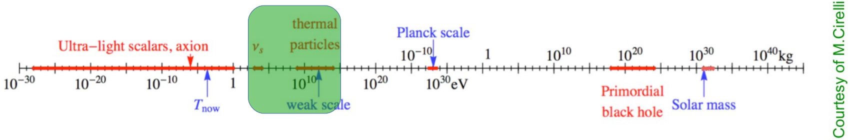
FIMPs: focus of this talk



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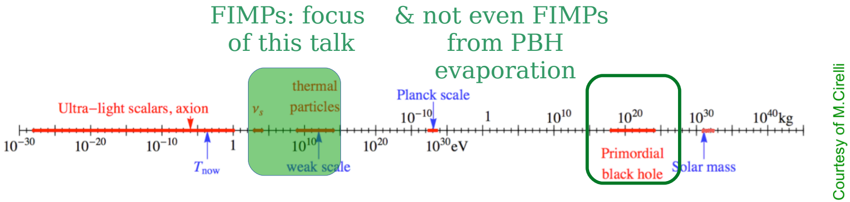
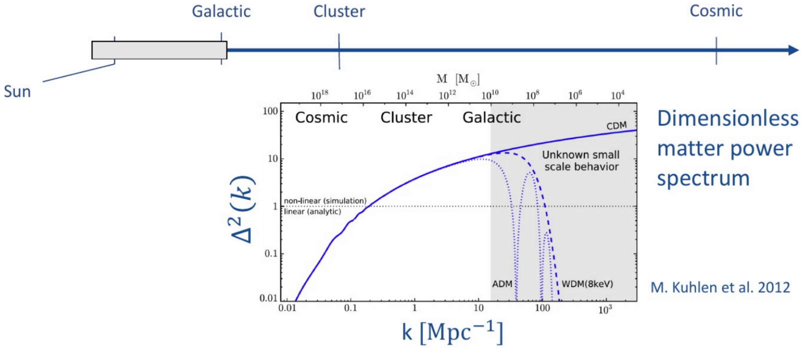


Non-Cold Dark Matter

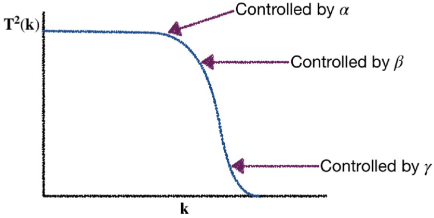


- WDM free-streeming from overdense to underdense regions
  $\rightsquigarrow$ Smooth out inhomegeneities for $\lambda \lesssim \lambda_{FS} \sim \int v/adt$
- Effects $P(k)$ and $T(k)$ generalized to Non-Cold DM see e.g. [Bode'00, Viel'05, Murgia'17], including non-thermal DM from freeze-in or PBH evaporation.

Non-Cold Dark Matter

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

[Murgia'17]



[Courtesy DC Hooper]

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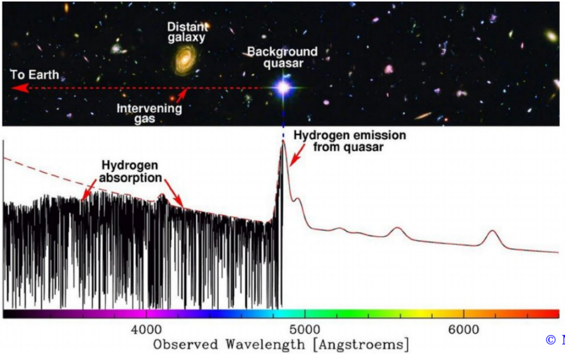

© M. Murphy

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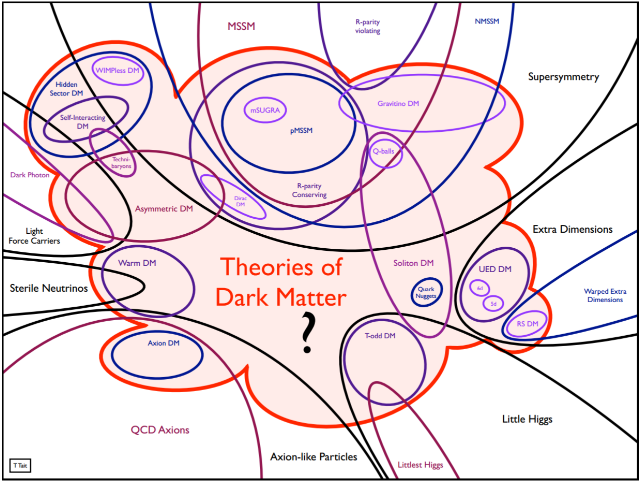
- Effects $P(k)$ and $T(k)$ generalized to Non-Cold DM see e.g. [Bode'00, Viel'05, Murgia'17], including non-thermal DM from freeze-in or PBH evaporation.
- Tested against Lyman-α: absorption lines along line of sights to distant quasars probe smallest structures $\rightsquigarrow$ $m_{\rm WDM}^{\rm thermal} > 1.9\text{-}5.3$ keV

see e.g. [Viel'05, Yeche'17, Palanque-Delabrouille'19,Garzilli'19]

Feebly interacting massive particles:
Interplay Cosmology and Particle physics experiments

Beyond the Standard Model?



Beyond the Standard Model: Simplified Model

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WIMP Freeze-out: Simple picture

SM + 1 extra DM particle χ

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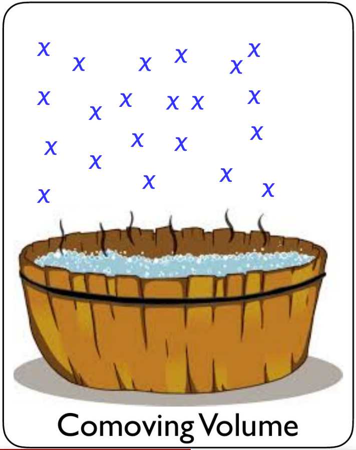

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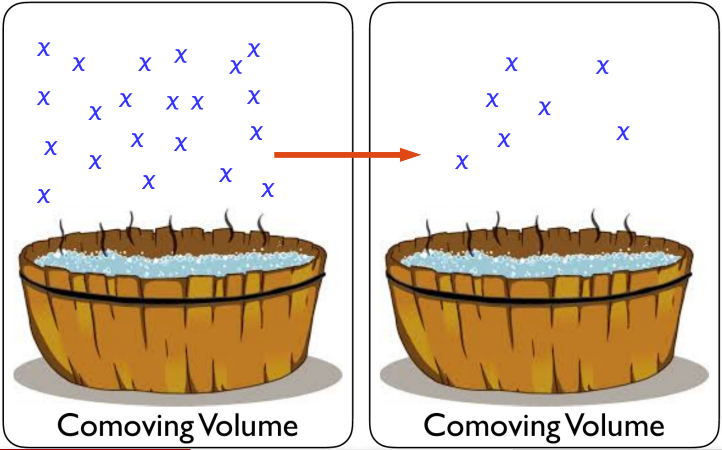
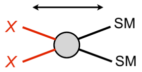


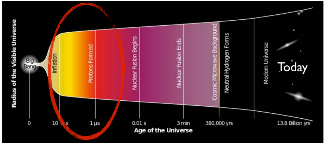
WIMP Freeze-out: Simple picture

$$\mathcal{R}_{\chi\chi\to XX} \propto n_\chi \langle \sigma v \rangle \sim H(T_{dec})$$

Rate of thermalizing processes:



Expansion with Hubble rate H



[Stolen from J. Heisig Moriond 2018]

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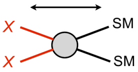

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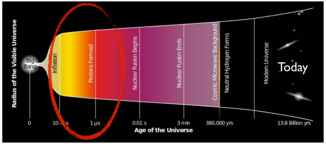

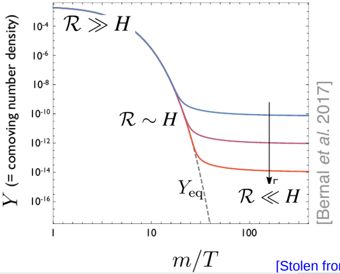

[Stolen from J. Heisig Moriond 2018]

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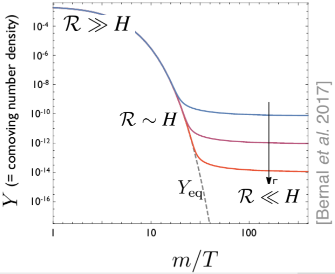
$$\mathcal{R}_{\chi\chi\to XX} \propto n_\chi \langle \sigma v \rangle \sim H(T_{dec})$$

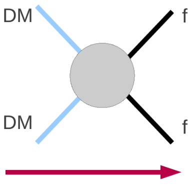
$$Y_\chi^\infty \sim \frac{n_\chi}{T^3} \propto \frac{H(T_{dec})}{\langle \sigma v \rangle} \longrightarrow \Omega_\chi h^2 \propto 0.12 \times \frac{\text{Pb}}{\langle \sigma v \rangle}$$

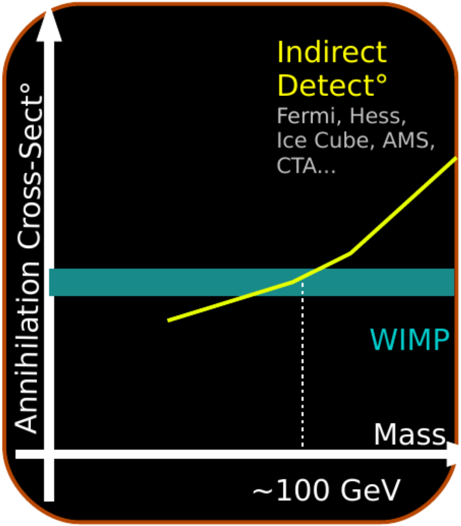
$$\langle \sigma v \rangle \sim \text{Pb} \times \frac{g_W^2}{4\pi} \left(\frac{\text{TeV}}{m_\chi} \right)^2$$

Typical cross-section probed by indirect detect° searches or CMB



Testing WIMPS: the "simple" picture





⇝ WIMPs at the verge of discovery/exclusion

see e.g. [Arcadi'17]

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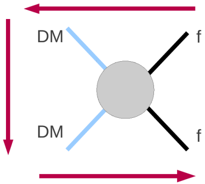

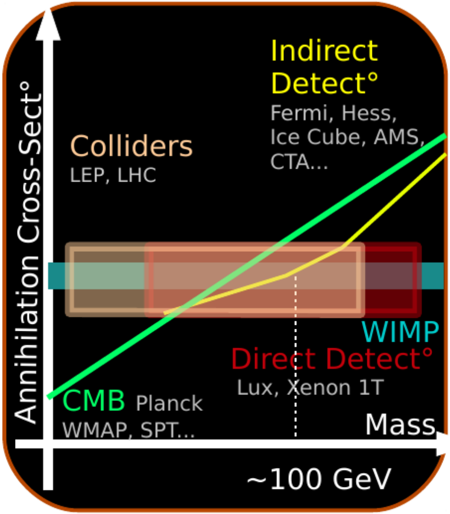

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SM + 2 extra dark sector particles: a bath particle B and a DM particle χ

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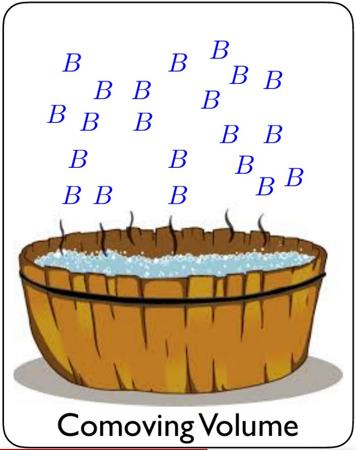

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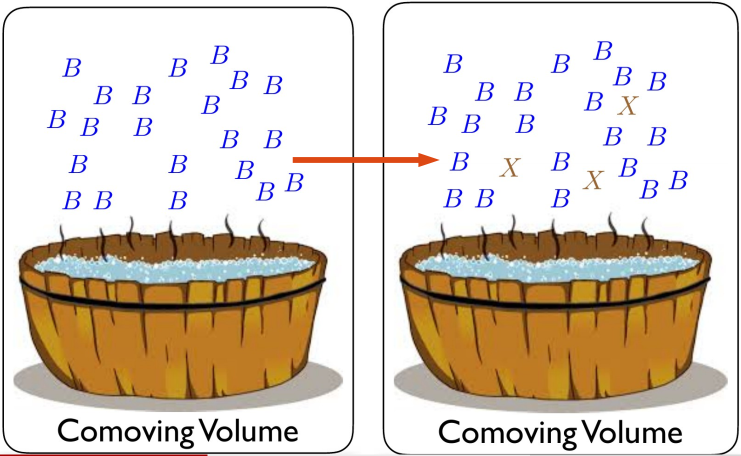

Simplified Model for FIMPs: 3 extra parameters m_χ, m_B, y

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): $m_B > m_\chi$

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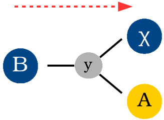
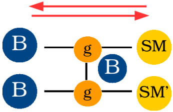
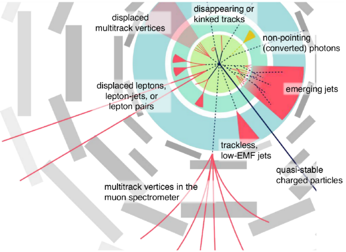
$$\mathcal{L} \subset y\,\chi\,A_{SM}B$$

- 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 $B \to A\chi$







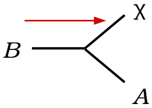
[Figure from Heather Russell]

[See also 1903.04497]

FIMP Freeze-in : Simple picture

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

Production processes



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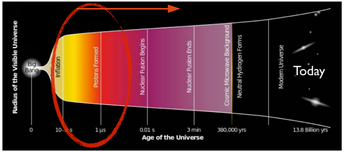

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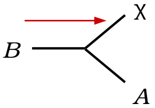

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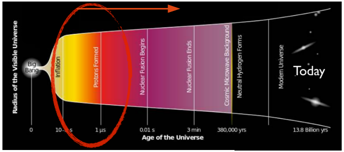

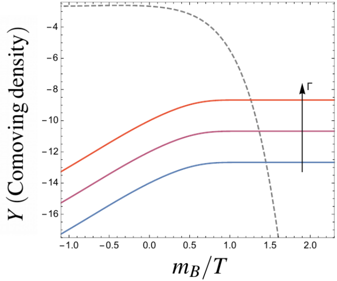

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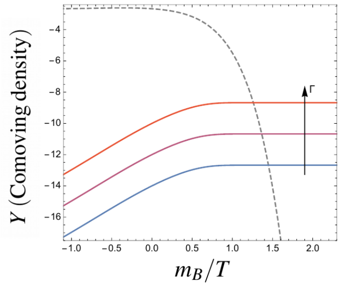
$$Y_X(T) \simeq \mathcal{R}_{B\to\chi} \times t(T) \sim \frac{m_B\,\Gamma_{B\to X}\,M_{\rm Pl}}{T^3}$$

IR dominated



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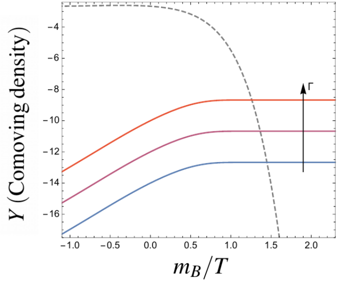
$$\Omega_\chi h^2 \propto 0.12 \times \left(\frac{\Gamma_B}{4\times 10^{-15}\,\text{GeV}}\right)\left(\frac{600\,\text{GeV}}{m_B}\right)^2\left(\frac{m_\chi}{10\,\text{keV}}\right)$$

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

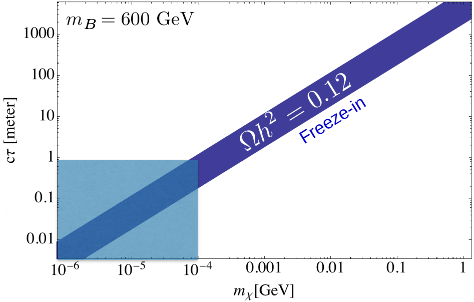


FIMP: displaced vertices and cosmology interplay

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]

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

Mediator mass range
reachable at colliders



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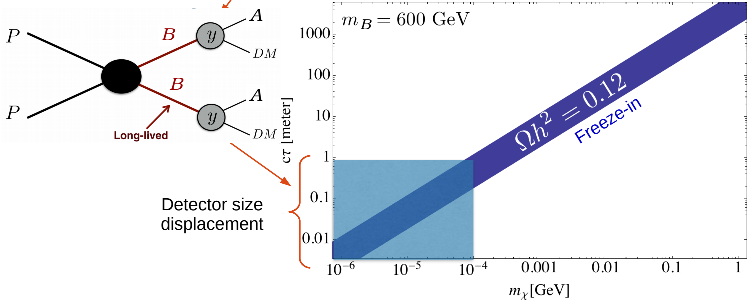

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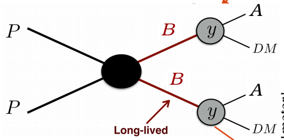
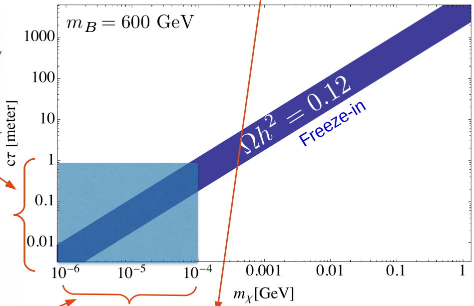
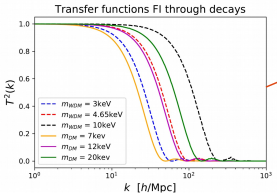
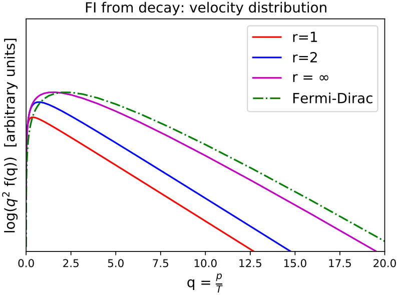






Warm DM like signatures
Suppressing small scale structures

FIMPs from FI through decay as NCDM



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

  see e.g. [Bauholzer’19] for interesting extra features.

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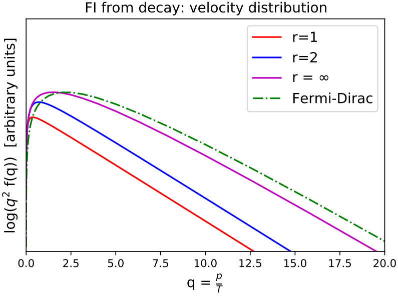

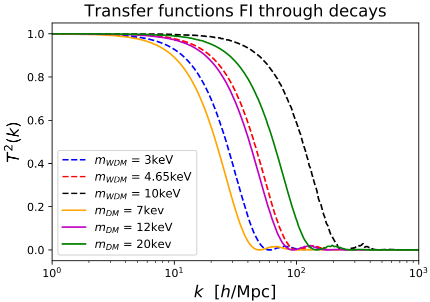

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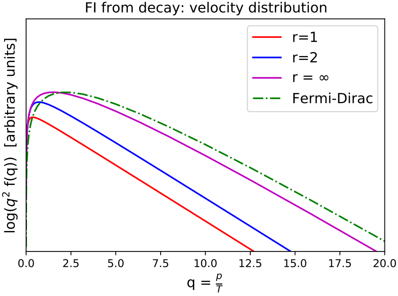

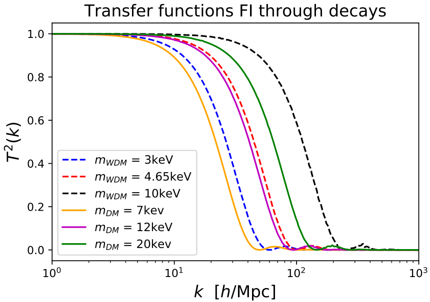

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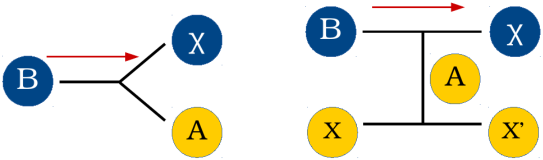
  still they inherit “thermal like” distrib. fn. from the mediator B in equilibrium.
  see e.g. [Bauholzer'19] for interesting extra features.
- The FIMPs transfer function is similar to thermal WDM for FI through decay.
  Tested against Lyman-α: $m_{\rm DM}^{\rm FI} \gtrsim 10$ keV [Boulebnane'17]

Minimal models for 3 body interactions

Production in the early universe



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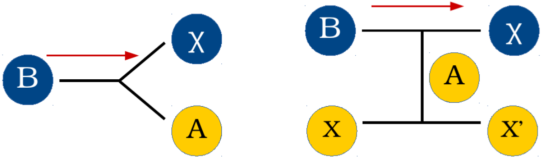
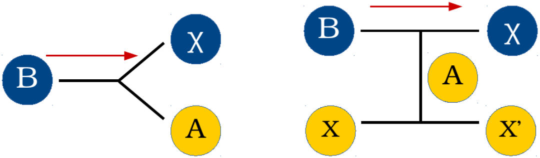


A_{SM}	Spin DM	Spin B	Interaction	Label
ψ_{SM}	0	1/2	$\bar{\psi}_{SM}\Psi_B\phi$	$\mathcal{F}_{\psi_{SM}\phi}$
	1/2	0	$\bar{\psi}_{SM}\chi\Phi_B$	$\mathcal{S}_{\psi_{SM}\chi}$
$F^{\mu\nu}$	1/2	1/2	$\bar{\Psi}_B\sigma_{\mu\nu}\chi F^{\mu\nu}$	$\mathcal{F}_{F\chi}$
H	0	0	$H^\dagger\Phi_B\phi$	$\mathcal{S}_{H\phi}$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



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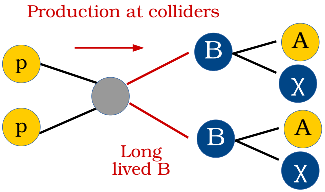
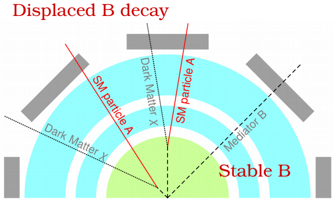
[Calibbi in prep]

Colliders sensitivity to LLPs





[Calibbi in prep]

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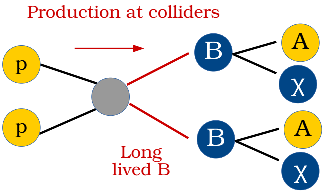
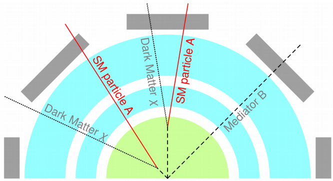


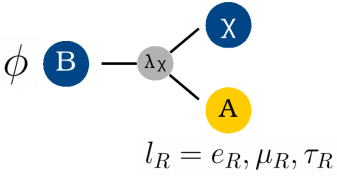


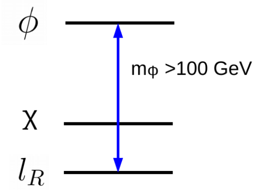
	Displaced B decay							Stable B	
Label	DV + MET	DJ + MET	DJ + μ	DL	DLV	Dγ	DT	RH	HSCP
$\mathcal{F}_{l\phi}$ & $\mathcal{S}_{l\chi}$				✓					✓
$\mathcal{F}_{\tau\phi}$ & $\mathcal{S}_{\tau\chi}$	✓	✓		✓					✓
$\mathcal{F}_{q\phi}$ & $\mathcal{S}_{q\chi}$	✓	✓						✓	
$\mathcal{F}_{t\phi}$ & $\mathcal{S}_{t\chi}$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

[Calibbi 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...]

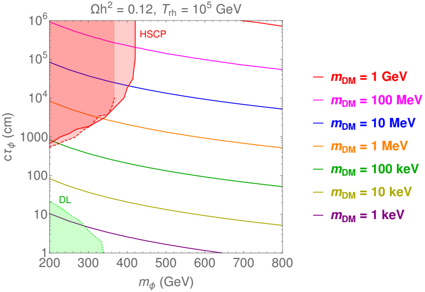




$$\mathcal{L} \subset \mathcal{L}_K - \frac{m_\chi}{2}\bar{\chi}\chi - m_\phi \phi^\dagger \phi \; - \; \lambda_\chi \phi \bar{\chi} l_R \; + \; h.c.$$

- SM + 1 charged dark scalar ϕ + 1 Majorana dark fermions χ (Z_2 symmetry for DM stability)
- Cosmo: minimal DM mass $\sim$ 10 keV
- Colliders: Heavy stable charged ϕ (HSCP) [ATLAS'19] & displaced lepton searches (DL)[CMS'16]

Leptophilic DM: Collider Constraints



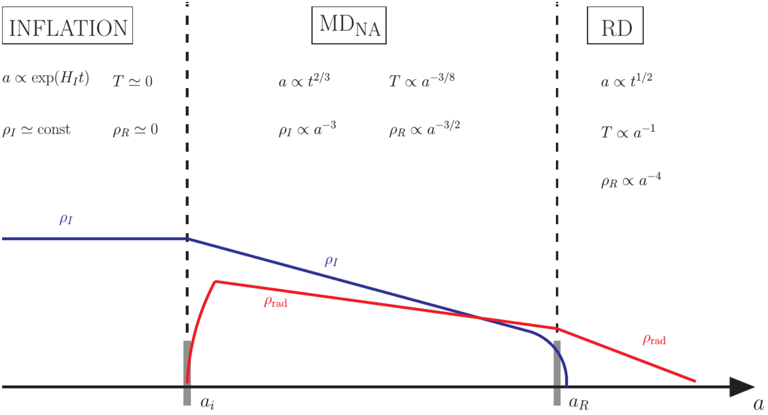
- for $m_{DM} > 10$ keV out of range for Displaced Searches
- Testing mediator masses up to ~ 400 GeV

Imposing DM relic abundance from CMB, we need $c\tau_B = 8\pi m_B/\lambda_\chi$:

$$c\tau_B \simeq 3.3 \times 10^6 \text{cm} \left(\frac{m_\chi}{10\ \text{GeV}}\right)\left(\frac{1\ \text{TeV}}{m_B}\right)^2 .$$

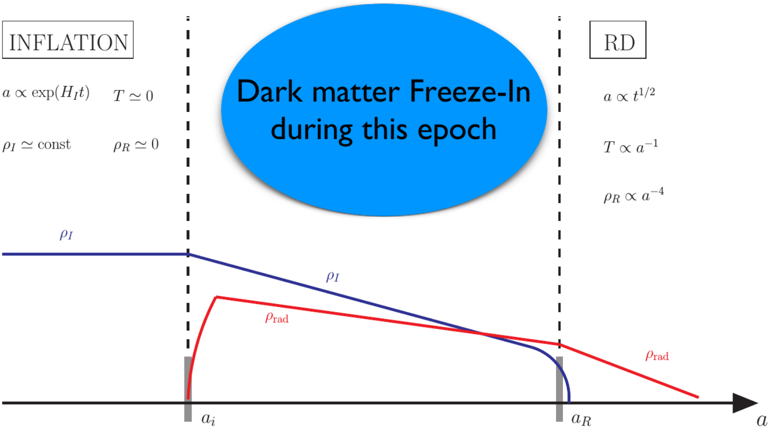
$\rightsquigarrow$ Generic statement: for freeze-in B decays beyond detector size (~ 10 m) unless light DM ($\sim$ keV) is considered.

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



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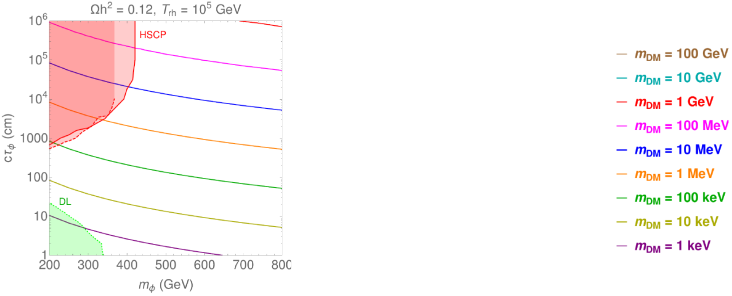
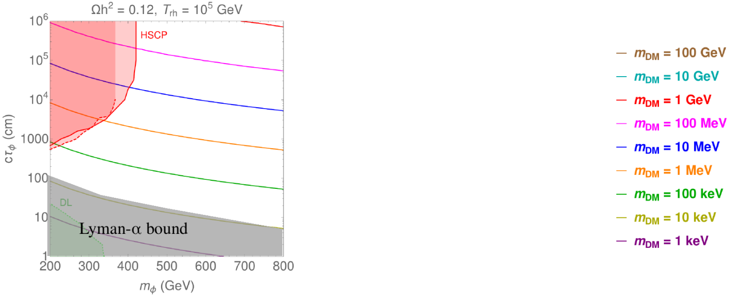
Leptophilic DM: Collider Constraints and Reheating



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

Leptophilic DM: Collider Constraints and Reheating



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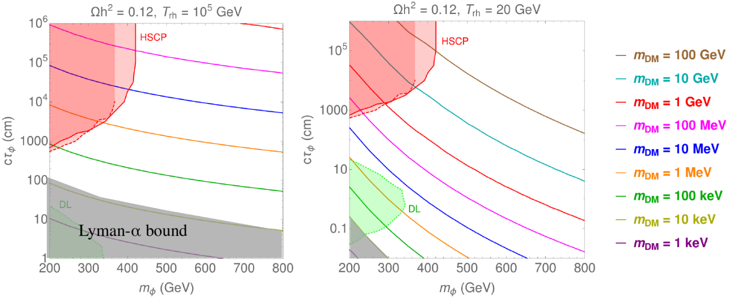

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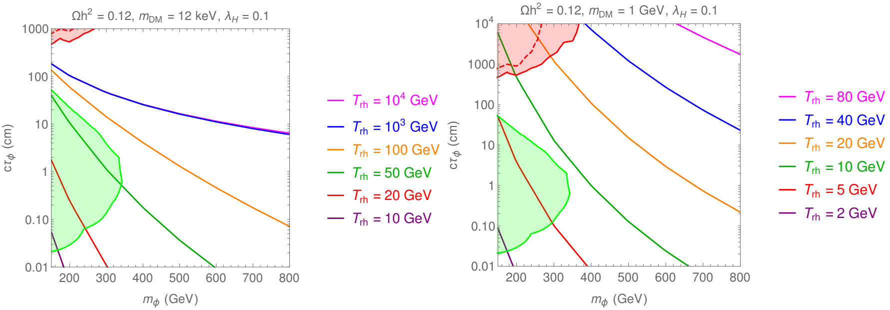

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  $\rightsquigarrow$ the higher λ_B must be to account for DM abundance and the lower is $c\tau_B$.
- Lowering T_{RH} allows for displaced signatures at colliders with larger DM masses. see also [Belanger'18]
- If $(m_\phi, c\tau_\phi)$ can be reconstructed 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}

Not even Feebly coupled DM from PBH evaporation: Cosmological imprint

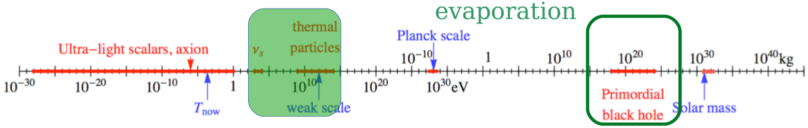
Remember the introduction

Dark Matter should be essentially:

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

FIMPs: focus of this talk

& not even FIMPs from PBH evaporation



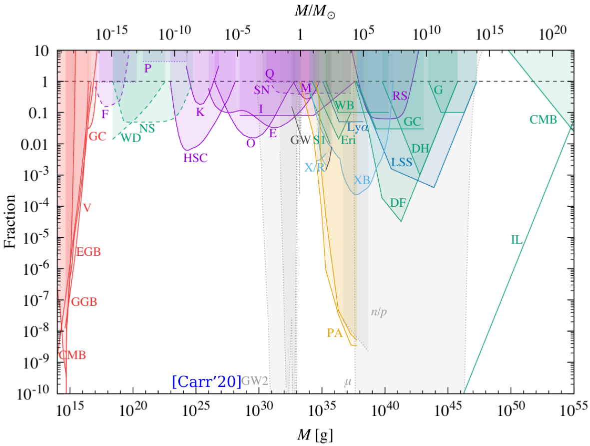
Courtesy of M.Cirelli

PBH and Dark Matter

see also e.g. [Matsas'98, Bell'98,Bauman'07,Fujita'14,Allahverdi'17, Lennon'17,Morrison'17, Hooper'19+, Masina'20]

PBH fully Evaporated Before BBN

PBH stable on Cosmological scales



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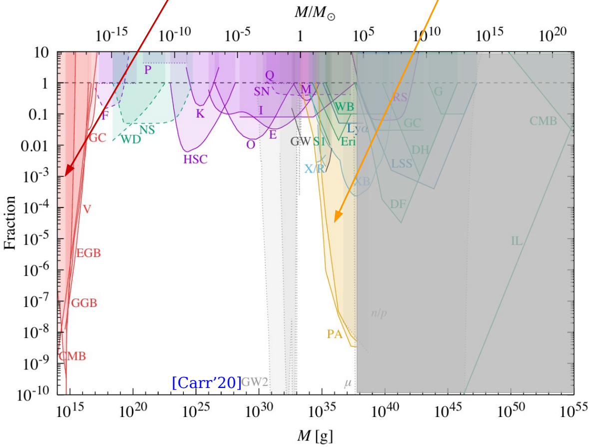
PBH DM energy injection due to evaporation

PBH DM energy injection due to accretion



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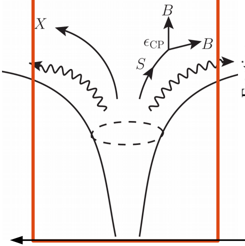
PBH evap
at the origin of
Not even FIMP
Dark Matter



PBH DM energy injection
due to evaporation

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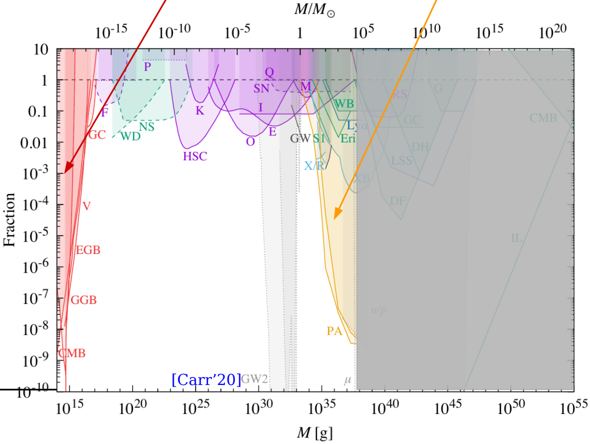
due to accretion



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 $m_{DM} < T_F \propto M_p^2/(8\pi M_F)$, behave as non-thermal NCDM.

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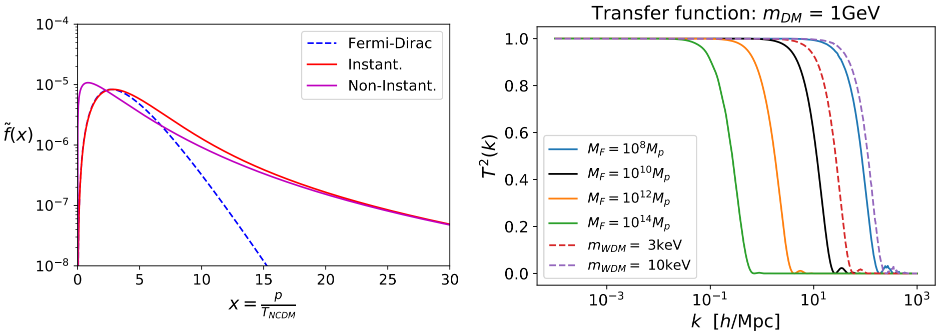
$$N_{\rm DM} = 3.2 \times 10^{-2} g_{\rm DM} M_F^2/M_p^2 \quad \text{and} \quad \langle p_{\rm DM}\rangle|_{t_{\rm ev}} \approx 5 \times T_F$$



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]

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

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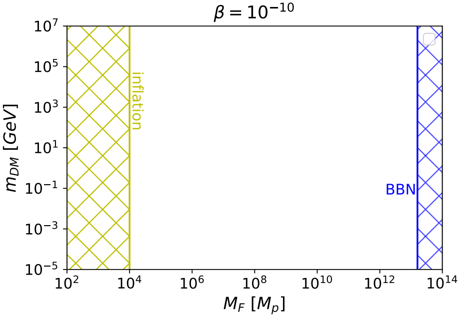

- PBH formed after inflation: $t_F > t_{\rm infl} \rightarrow M_F > 10^4 M_p$
- PBH evaporate before BBN: $t_{\rm ev} < t_{BBN} \rightarrow M_F < 2 \times 10^{13} M_p$

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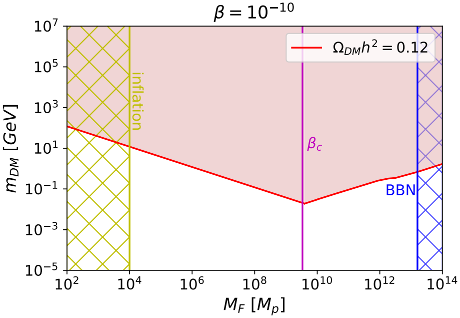

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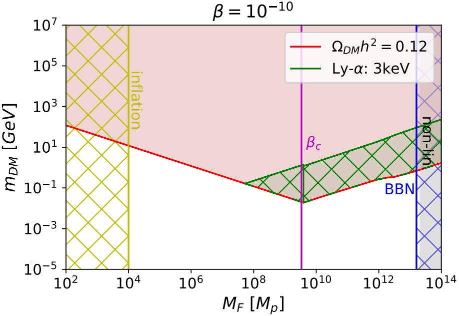

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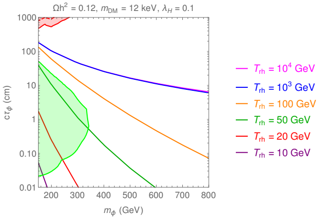
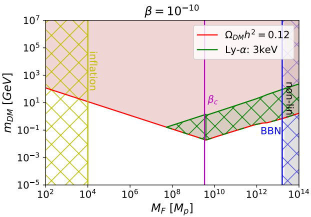
Lyman-α bound: NCDM account for all the DM if $\beta \lesssim 5\times 10^{-7}$ and $m_{\rm DM} \gtrsim 2\,{\rm MeV}$.

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
- NCDM and future experiments: 21cm Cosmology ?

Thank you for your attention!

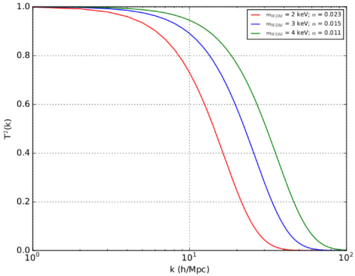
Backup

Warm Dark Matter

- Warm dark matter: DM that is non-relativistic at freeze-out, but has a non-negligible velocity ($m_{\rm WDM} \sim 1\,{\rm keV}$)

- If WDM was in thermal equilibrium, freeze-out took place before neutrino decoupling $\rightarrow \lambda_{\rm fs} \sim {\rm Mpc}$ (< than for neutrinos)

- This free-streaming washes out structures on small scales → introduces a suppression of the matter power spectrum

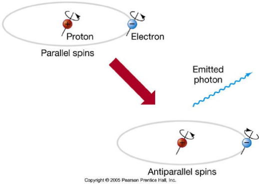


Lyman-α forest

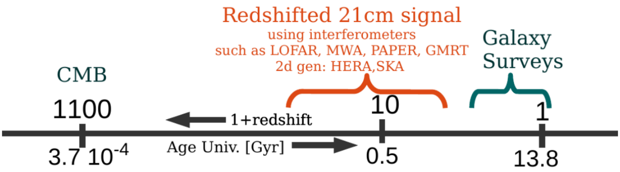
Absorption lines produced by the inhomogeneous IGM along different line of sights to distant quasars: a fraction of photons is absorbed at the Lyman-α wave- length (corresponding to $\lambda_\alpha \sim 121$ nm), resulting in a depletion of the observed spectrum at a given frequency ($\lambda_{abs} 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

- 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 ($0.5\ h/\mathrm{Mpc} < k < 20\ h/\mathrm{Mpc}$).
- IGM modelling requires nonlinear evolution: this needs N-body hydrodynamical simulations. Computational expensive and only available for few benchmark models.

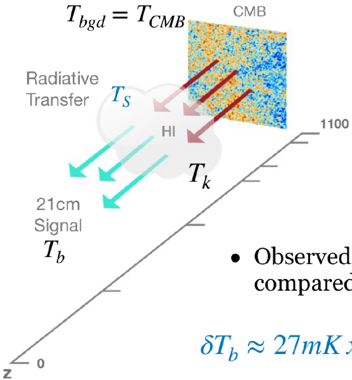
21 cm signal?



- Transitions between the two ground state energy levels of neutral hydrogen HI
  $\rightsquigarrow$ 21 cm photon ($\nu_0 = 1420$ MHz)
- 21 cm photon from HI clouds during dark ages & EoR redshifted to $\nu \sim 100$ MHz
  $\rightsquigarrow$ new cosmology probe



21 cm in practice



credit : [Kovetz]

- 21cm signal observed as CMB spectral distortions
- The spin temperature (= excitation T of HI) charaterises the relative occupancy of HI gnd state

$$n_1/n_0 = 3\exp(-h\nu_0/k_B T_S)$$

- Observed brightness of a patch of HI compared to CMB at $\nu = \nu_0/(1+z)$

$$\delta T_b \approx 27mK\, x_{HI}(1+\delta)\sqrt{\frac{1+z}{10}}\left(1 - \frac{T_{CMB}}{T_S}\right)$$

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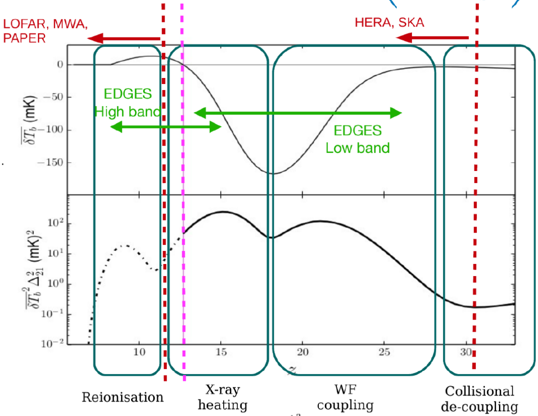


$$\langle\tilde{\delta}_{21}(\mathbf{k},z)\tilde{\delta}^*_{21}(\mathbf{k}',z)\rangle \equiv (2\pi)^3\delta^D(\mathbf{k}-\mathbf{k}')P_{21}(k,z) \qquad \Delta^2_{21}(k,z)=\frac{k^3}{2\pi^2}P_{21}(k,z)$$

NCDM linear regime: suppressed power at small scale

■ WDM: free-streeming (collision-less damping): collisionless particles can stream out of overdense to underdense regions

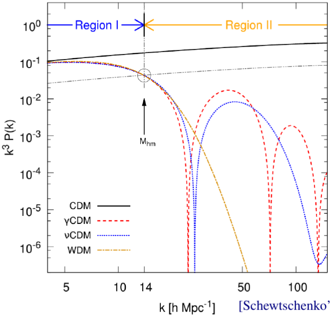
■ IDM: collisional damping (Silk damping): damping length associated to diffusion processes (depend distance traveled by coll. particles during random walk)

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

with $\nu = 1.2$ and define the scales

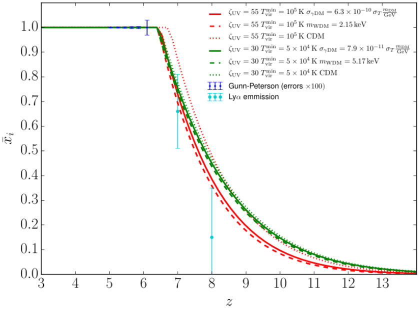
- $\alpha_{IDM} \propto (\sigma_{IDM}/m_{DM})^{0.48}$ [Bhoem'01] for IDM with γ induced damping $\alpha_{WDM} \propto (1/m_{WDM})^{1.15}$ [Bode'00]
- half mode mass : $T_X(k_{hm}) = 1/2$ $\rightsquigarrow M_{hm} = M_{hm}(\sigma_{IDM}/m_{DM})$ or $M_{hm}(m_{WDM})$

$\rightsquigarrow$ IDM & WDM suppress power at small scales (large k) characterized by α_X or equiv M_{hm} functions of σ_{IDM}/m_{DM} or m_{WDM} see also [Murgia'17-18]



[Schewtschenko'14]

21cm could help to discriminate between Non-CDM



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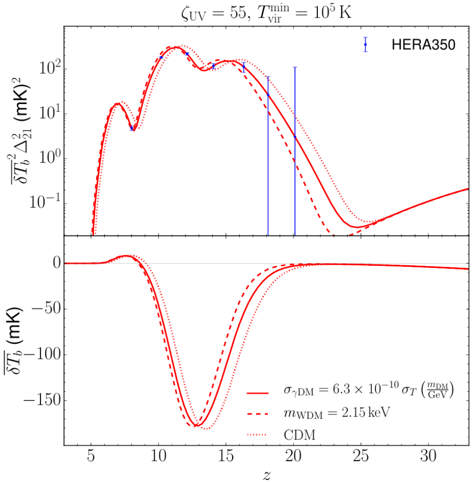
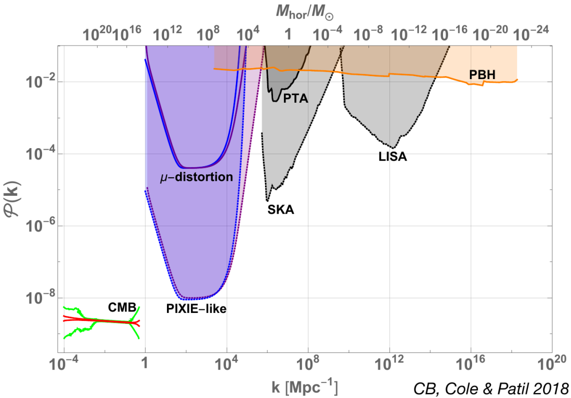


Power spectrum constraints



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

[Byrnes'19]

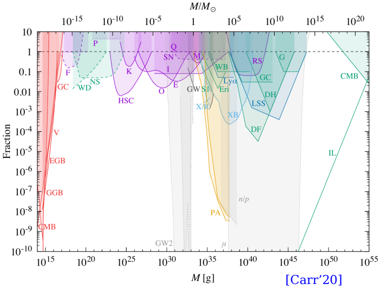
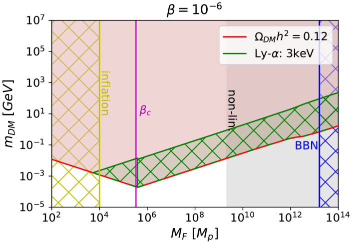
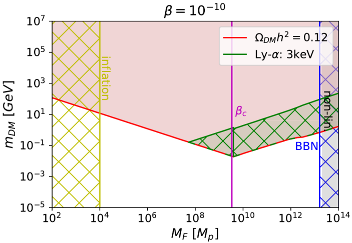


FIG. 10. Constraints on $f(M)$ from evaporation (red), lensing (magenta), dynamical effects (green), accretion (light blue), CMB distortions (orange), large-scale structure (dark blue) and background effects (grey). Evaporation limits come from the extragalactic gamma-ray background (EGB), the Galactic 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: summary

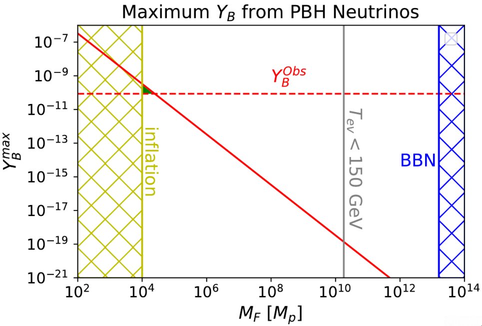




$$M_{\rm BH}(t) = M_F \left(1 - \frac{(t - t_F)}{\tau}\right)^{1/3} \qquad \tau = \frac{1}{3e_T}\frac{M_F^3}{M_p^4}\,.$$

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

PBH: Leptogenesis



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

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

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

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

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

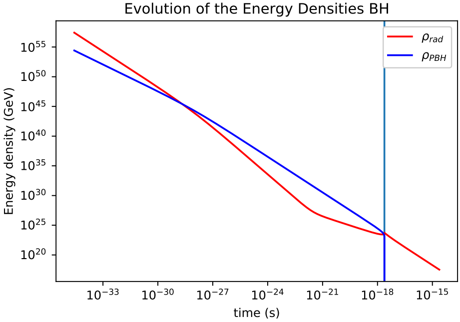
$$\alpha_{\rm PBH} = \left(\frac{m_{\rm DM}}{1\,{\rm eV}}\right)^{-0.83}\left(\frac{M_F}{M_p}\right)^{0.42} \times \begin{cases} 60.4\,{\rm Mpc}\,h^{-1} & \text{if } \beta<\beta_c\,, \\ 53.2\,{\rm Mpc}\,h^{-1} & \text{if } \beta>\beta_c\,, \end{cases}$$

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

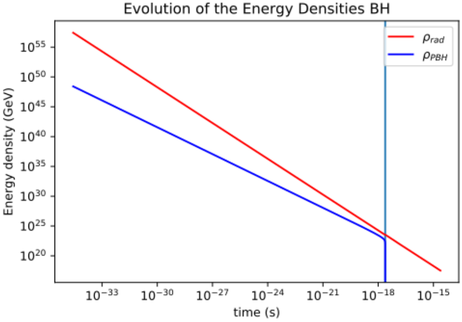
Evaporation in Radiation of Matter dom. era

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 $\beta > \beta_c(M_F)$



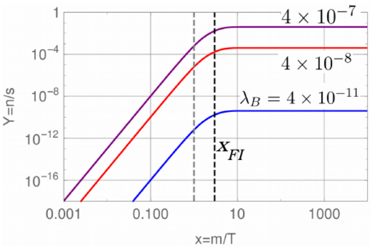
Radiation dominated era for $\beta > \beta_c(M_F)$



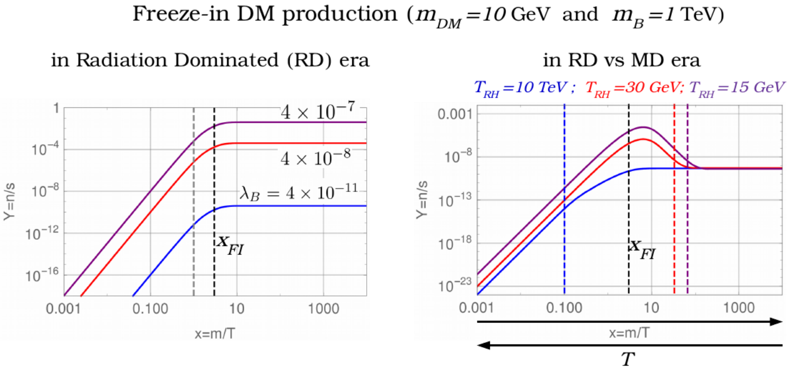
Reheating after FI and smaller $c\tau_B$

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:

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

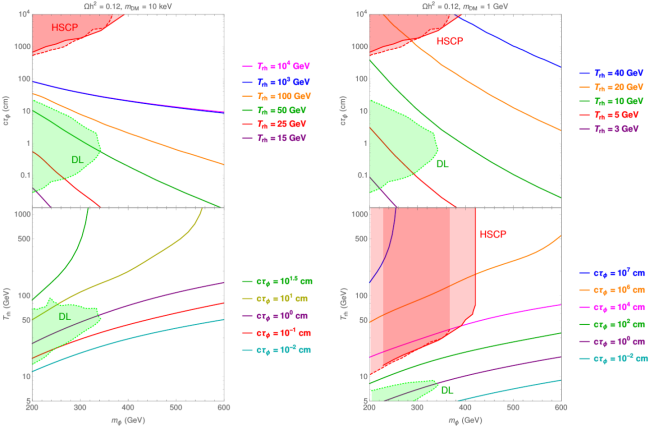
$\rightsquigarrow$ The lower T_{RH}, the longer is the dilution and the lower is Y_X^∞ compared to $Y_X(T_{FI})$, the higher is λ_B to account for DM abundance and the lower is $c\tau_B$.

Collider searches

Signature	Exp.	Document	$\sqrt{s}$	$\mathcal{L}$	Label
R-Hadrons	CMS	EXO-16-036	$13TeV$	$12.9fb^{-1}$	RH
HSCP	ATLAS	1902.01636	$13TeV$	$36.1fb^{-1}$	HSCP
Disappearing tracks	ATLAS	1712.02118	$13TeV$	$36.1fb^{-1}$	DT
	CMS	1804.07321	$13TeV$	$38.4fb^{-1}$	
Displaced leptons ($e\mu$)	CMS	1409.4789	$8TeV$	$19.7fb^{-1}$	DL
		EXO-16-022	$13TeV$	$2.6fb^{-1}$	
Displaced vertices + MET	ATLAS	1710.04901	$13TeV$	$32.8fb^{-1}$	DV+MET
Delayed jets + MET	CMS	1906.06441	$13TeV$	$137fb^{-1}$	DJ+MET
Displaced jets + μ	ATLAS	2003.11956	$13TeV$	$136fb^{-1}$	DJ+μ
Displaced dilepton vertices	ATLAS	1907.10037	$13TeV$	$32.8fb^{-1}$	DLV
Delayed photons	CMS	1909.06166	$13TeV$	$77.4fb^{-1}$	Dγ
Monojet	ATLAS	1711.03301	$13TeV$	$36.1fb^{-1}$	MJ
Kinked Tracks	/	/	/	/	KT

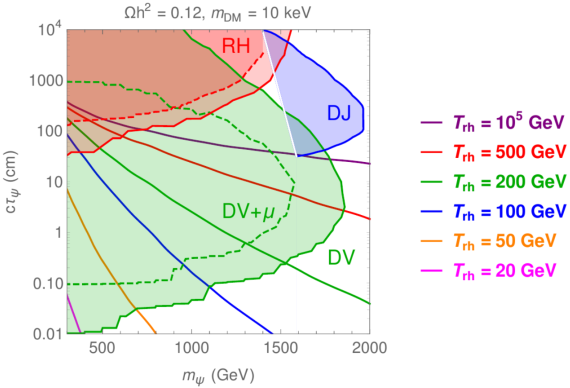
Leptophilic DM

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



Topphilic DM

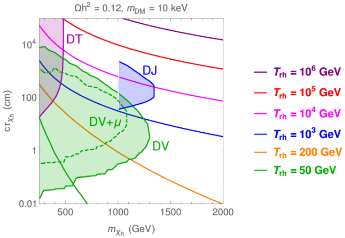
$$\mathcal{L} \supset \partial_\mu\phi\,\partial^\mu\phi - \frac{m_\phi^2}{2}\phi^2 + \frac{1}{2}\bar{\psi}\gamma^\mu D_\mu\psi - m_\psi^2\bar{\psi}\psi \;-\; \lambda_\phi\phi\bar{\psi}t_R \;+\; h.c.\,,$$

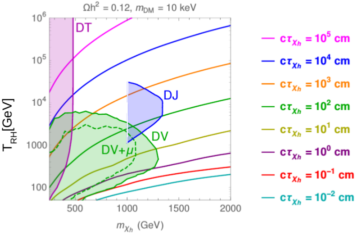


Singlet-Triplet DM

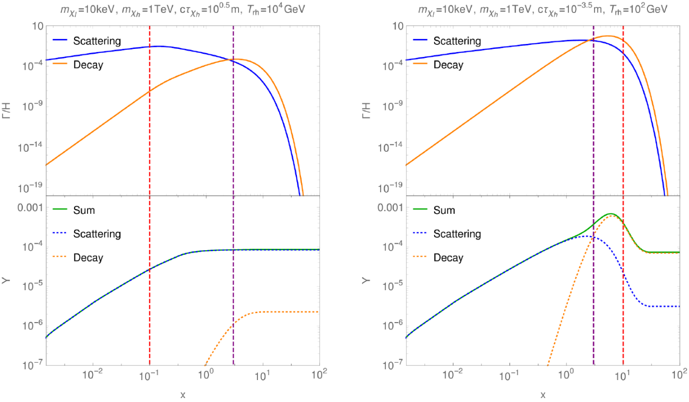
$$\mathcal{L}_{BSM} = -\frac{m_S}{2}\bar{\chi_S}\chi_S - \frac{m_T}{2}Tr\left[\bar{\chi_T}\chi_T\right] + \frac{1}{2}Tr\left[\bar{\chi_T} i\not{D}_\mu \chi_T\right]$$
$$+\frac{\kappa}{\Lambda}(W^a_{\mu\nu}\bar{\chi_S}\sigma^{\mu\nu}\chi^a_T + \text{h.c.}),$$

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



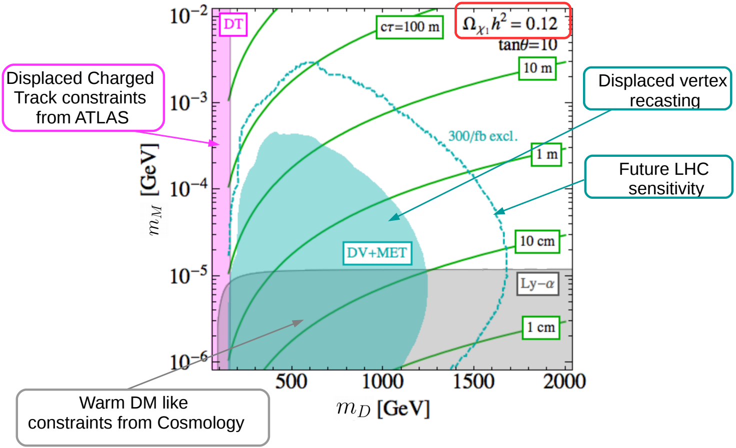


Singlet-Triplet DM

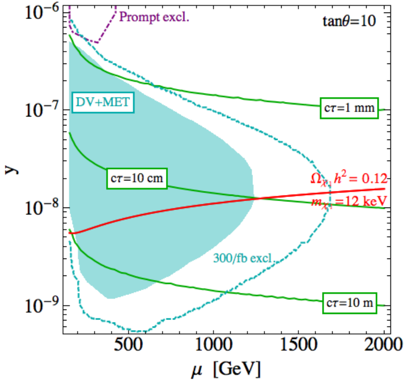


LHC & Cosmo complementarity: Singlet doublet

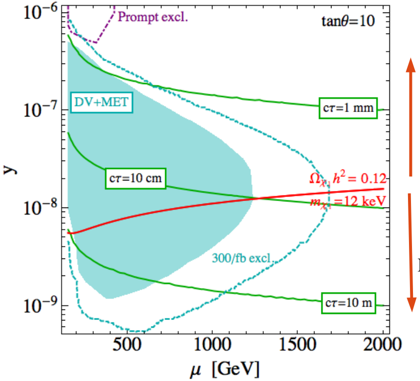
At each point y is fixed to get the DM abundance



LHC & Cosmology complementarity



LHC & Cosmology complementarity

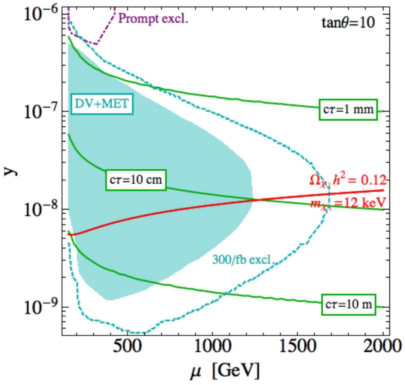


Fixed DM mass: overabundant
Fixed DM abundance: need lower mass

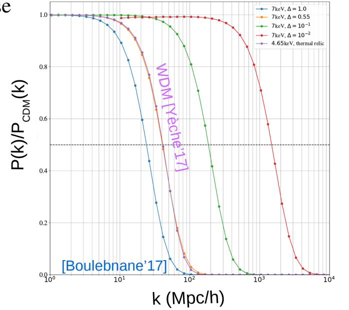
Fixed DM mass: underabundant
Fixed DM abundance: need higher mass

LHC & Cosmology complementarity

Light FIMP can behave as WDM:
Freestreams from overdense to underdense regions in the early universe



$A \to B$ DM with different $\Delta = 1 - m_B^2/m_A^2$



LHC & Cosmology complementarity

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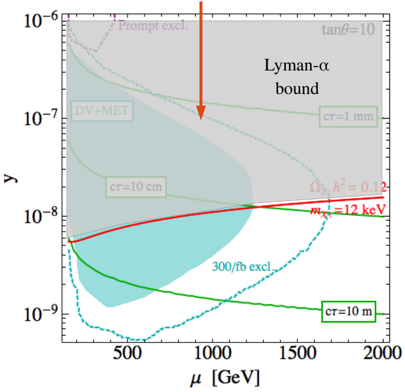
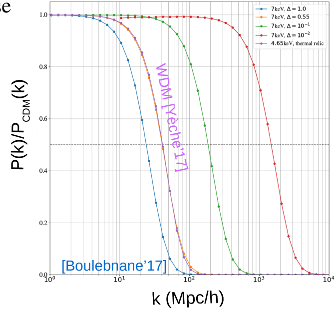
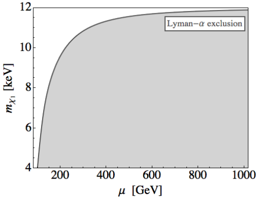


$A \to B$ DM with different $\Delta = 1 - m_B^2/m_A^2$

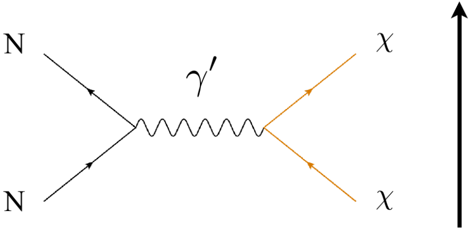




recoil energy

E_R

in keV range

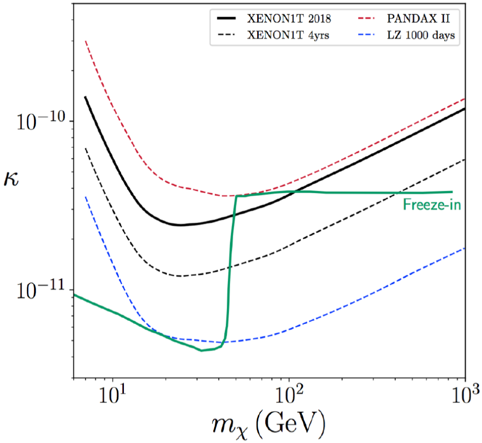


t-channel

v ~ 200 km/s (halo DM)

$$\frac{d\sigma}{dE_R} \propto \frac{m_N \kappa^2 \alpha^2 Z^2}{(2 m_N E_R + m_{\gamma'}^2)^2} \sim \frac{1}{E_R^2}$$

Huge enhancement if $m_{\gamma'} \lesssim 40 \text{ MeV}$



n.b.:
Not the same spectrum as a WIMP,
Must recasti the direct detection constraints

Very first direct detection test of a FI scenario !

Hambye, M.T., Vandecasteele, Vanderheyden '18

bla

This is really the end