FIMPs imprint on Cosmology as Non Cold Dark Matter

Laura Lopez Honorez

mainly inspired by JCAP 03 (2022) 03, 041
in collaboration with Q. Decant, J. Heisig, D. Hooper.

LLP Bethe Forum Bonn
13-17/11/23 - Bonn

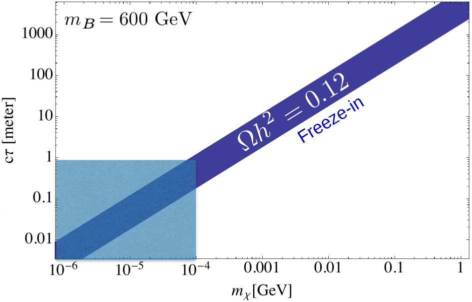
Why FIMPs & Non-Cold DM in a LLP workshop?

Exemplary case of Freeze-in: LLPs and NCDM

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, Decant'22,Becker'23, 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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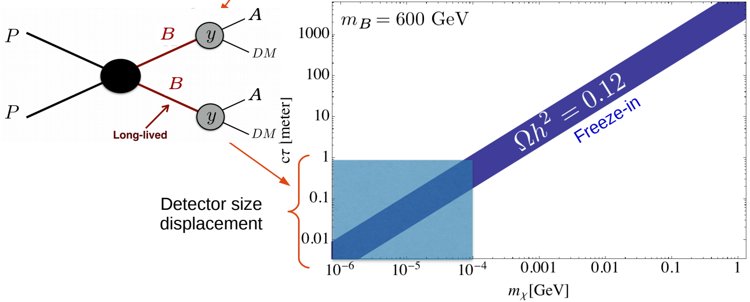

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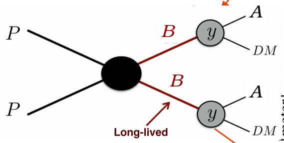
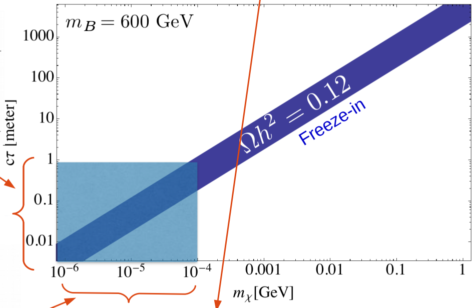
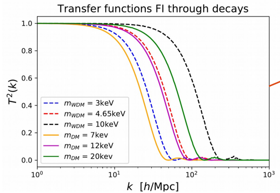


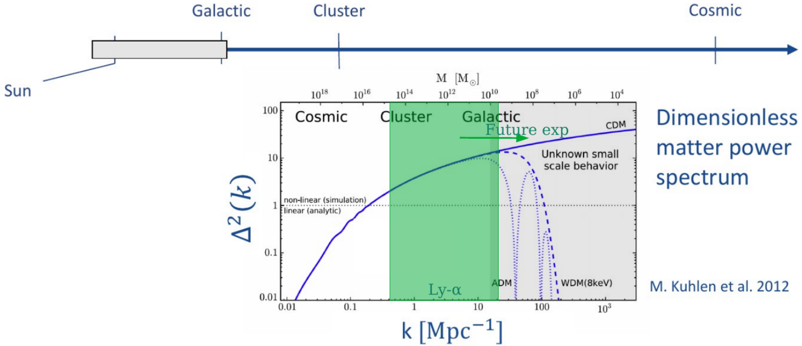




Warm DM like signatures
Suppressing small scale structures

Non-Cold Dark Matter??

Non-Cold Dark Matter erases small scale structures

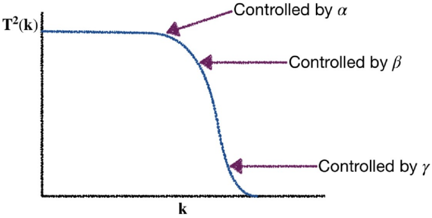


- WDM free-streaming from overdense to underdense regions
  $\rightsquigarrow$ Smooth out inhomegeneities for $\lambda \lesssim \lambda_{FS} \sim \int v/a dt$
- Effects $P(k)$ and $T(k)$ generalized to Non-Cold DM see e.g. [Bode'00, Viel'05, Murgia'17], including non-thermal DM from freeze-in, superWIMP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

Non-Cold Dark Matter erases small scale structures

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

[Murgia'17]



[Courtesy DC Hooper]

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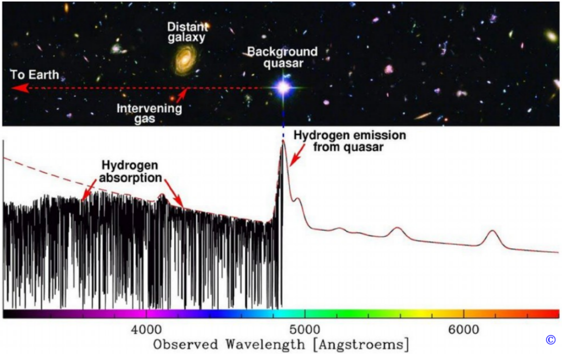

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- Tested against Lyman-α: absorption lines along line of sights to distant quasars probe smallest structures $\rightsquigarrow$ $m_{\rm WDM}^{\rm thermal} > 1.9$-$5.3$ keV

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

NCDM: (un-)usual suspects production in the early universe

NCDM: thermal WIMP vs non-thermal FIMP

Cosmology

Particle Physics

$$\boxed{\frac{df_\chi(t,p)}{dt}} = \boxed{\mathcal{C}[f_\chi]}$$

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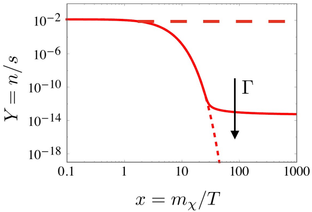
$\Gamma_{\chi\leftrightarrow \mathrm{SM}} > H$

"Thermal DM" (incl. WIMP)

$f_\chi(t,p) = f_\chi(t,p)^{fD,BE}$



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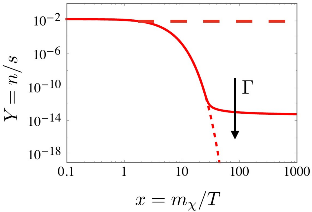
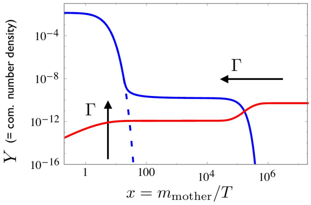
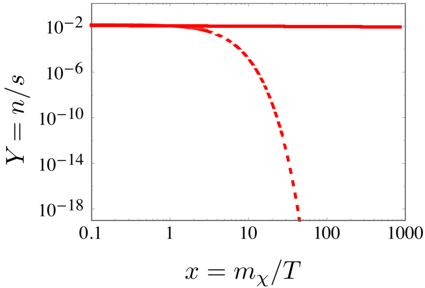




Thermal DM from relativistic freeze-out (WDM)

$$\frac{df_\chi}{dt} = \mathcal{C}_{\chi\chi\leftrightarrow AA'}[f_\chi] \quad \rightsquigarrow \quad n_\chi \propto \frac{g^0_{*,S}}{g_{*,S}(T_D)}$$

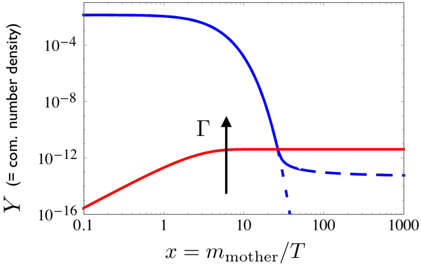


- DM annihilation driven freeze-out
- DM is weakly coupled: $\lambda_\chi \sim g_{\rm EW}$ $\rightsquigarrow$ χ chem. & kin. equilibrium
- DM decouples while relativistic: $x_D = m_B/T_D$ and $x_D < 3$
- $\Omega_\chi h^2 = 0.12 \frac{g^{(n)}_\chi m_\chi}{6\,\text{eV}} \frac{g^0_{*,S}}{g_{*,S}(T_D)}$

Non-thermal DM from Freeze-in

see also [McDonald '02; Covi'02; Choi'05; Asaka'06; Frère'06; Petraki'08; Hall'09; etc]

$$\frac{df_\chi}{dt} = \mathcal{C}_{B\to\chi A}[f_\chi] \quad \rightsquigarrow \quad n_\chi \propto \Gamma_{B\to\chi} M_p/m_B^2 = R_\Gamma$$



- Freeze-in from B decays
- B in chem. & kin. equilibrium
- $\Omega_\chi h^2 = 0.12 \rightsquigarrow \lambda_\chi \lesssim 10^{-8}$ i.e. χ decoupled
- $x = m_B/T$ and $x_{\rm FI} \sim 3$
- $\Omega_\chi h^2 \propto m_\chi R_\Gamma$

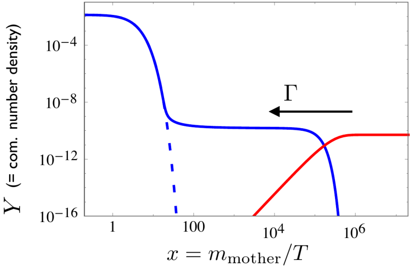
Careful: late decay (SW), production via scattering, early matter dominated era (T_R small), non renormalisable operators and thermal corrections for ultra-relativistic DM not taken into account.

Zero χ initial abundance assumed.

Non thermal DM from superWIMP

see also [Covi '99 ;Feng '03]

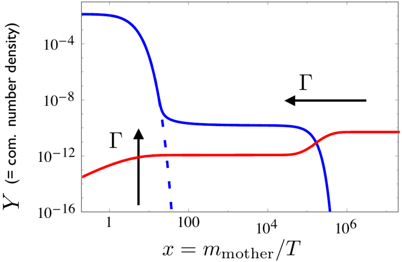
$$\frac{df_\chi}{dt} = \mathcal{C}_{B\to\chi A}[f_\chi] \;(\text{for}\, x > x_{\rm FO}) \quad \rightsquigarrow \quad n_\chi = n_B(x_{\rm FO})$$



- superWIMP from late B decays
- B chem. decoupled at $x = x_{\rm FO}$ & χ decoupled
- $x = \frac{m_B}{T}$ and $x_{\rm SW} \sim R_\Gamma^{-1/2} > x_{\rm FO}$
- $\Omega_\chi h^2 = m_\chi/m_B \times \Omega_B h^2|_{\rm FO}$ if $B \to A_{\rm SM} A'_{SM}$ not open

FIMPs from FI & superWIMP

Careful: both SW and FI contributions
are always present for production via B decays!!



- χ decoupled
- χ population slowly builds up from B before and after FO.
- $\Omega_\chi h^2 = \Omega_\chi h^2|_{\text{FI}} + \Omega_\chi h^2|_{\text{SW}}$

Substancial FI and SW contributions may arise from the very same process $B \to A\chi$ but FI and SW take place at very different times: $x_{\text{FI}} < x_{\text{SW}}$

Free streaming Velocity
Rule of Thumb

Can we translate WDM bound to FIMP?

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

Naive estimate for "similar velocity distributions" :

$$\langle v_\chi \rangle|_{t_0}^{\rm NCDM} \geq \langle v_\chi \rangle|_{t_0}^{\rm WDM\, lim}$$

$$\text{with} \quad \langle v_\chi \rangle|_{t_0} = \left.\frac{\langle p_\chi \rangle}{m_\chi}\right|_{t_0} = \left.\frac{\langle p_\chi \rangle}{T}\right|_{t_{\rm prod}} \times \left(\frac{g_{*S}(t_0)}{g_{*S}(t_{\rm prod})}\right)^{1/3} \times \frac{T_0}{m_\chi}$$

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- FI: $T_{\text{prod}} \sim m_B/3$ and $\langle p_\chi \rangle|_{t_{\text{prod}}} \sim m_B/2$
  $\Rightarrow \langle v_\chi \rangle|_{t_0}^{\text{FI}} \propto m_\chi^{-1}$

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- SW: $T_{\rm prod} \sim \sqrt{\Gamma_B M_{Pl}}$ and $\langle p_\chi \rangle|_{t_{\rm prod}} \sim m_B/2$
  $\Rightarrow \langle v_\chi \rangle|_{t_0}^{\rm SW} \propto m_\chi^{-1} \times R_\Gamma^{-1/2}$

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$$m_\chi \gtrsim \left(m_{\text{WDM}}^{\text{lim}}\right)^{4/3} \begin{cases} \#_{\text{FI}} & \text{for FI,} \\ \#_{\text{SW}} \times (R_\Gamma)^{-1/2} & \text{for SW,} \end{cases}$$

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$$m_\chi \gtrsim \begin{cases} 16\,{\rm keV} & \text{for FI,} \\ 0.38\,{\rm GeV} \times \sqrt{10^{-4}/R_\Gamma} & \text{for SW,} \end{cases} \quad \text{for } m_{\rm WDM}^{\rm Ly-\alpha} > 5.3\,{\rm keV}$$

Velocity Distributions: Impact on overdensities

WDM vs FIMP distributions

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Particle Physics

$$\boxed{\frac{df_\chi(t,p)}{dt}} = \boxed{\mathcal{C}[f_\chi]}$$

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"Thermal" DM

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Decouple still relativistic and freestream while struct. forms

"Thermal Warm" Dark Matter (WDM)

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Decouple still relativistic and freestream while struct. forms

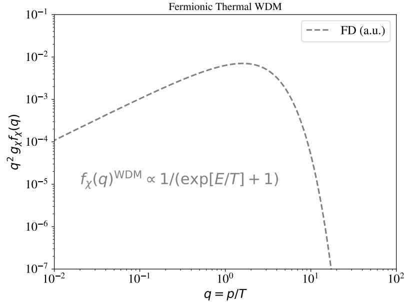
Produced through feeble interactions with large boost and freestream while struct. forms

"Thermal Warm" Dark Matter (WDM)

"Feebly Interacting Massive Particles" (FIMPS)

Thermal WDM: exponential cut in $P(k)$ at small scales

see also [Bode'00,Viel'05]



- Thermal WDM is in kinetic equilibrium thanks to fast elastic scatterings with thermal plasma: $\frac{d}{dt}f_\chi = \mathcal{C}_{el}[f_\chi] \rightsquigarrow f_\chi \propto f_\chi^{eq}(q)$

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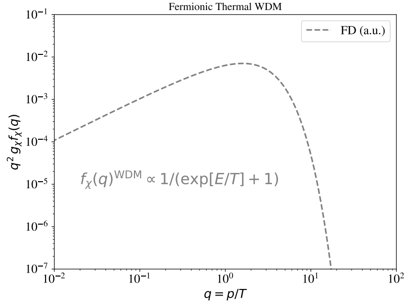

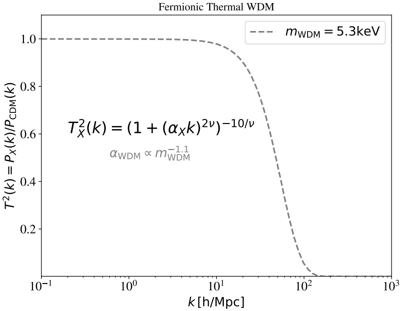

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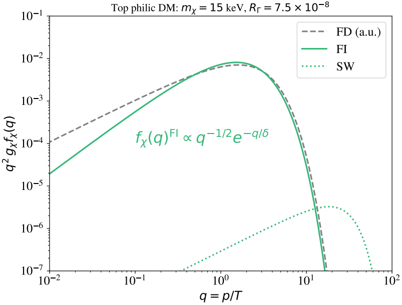
- Evolve f_χ up to 1st order pert. (w/ Boltzmann code):

Free-streaming scale: $\alpha_{\rm WDM} \sim 0.045\left(\frac{m_{\rm WDM}}{\rm keV}\right)^{-1.11}$ Mpc$/h$

“Pure” FI & SW: WDM-like

see also [Petraki’16,Heeck’17, Boulebnane’17, Kamada’19, Baumholzer’19, Ballesteros’20, d’Eramo’20]



- Contrarily to “usual” WDM, FIMPs are non-thermaly produced. Distribution $f_\chi \propto q_\star^{-\alpha} \exp(-q_\star^\beta)$ with $\alpha = \frac{1}{2}, 1$ and $\beta = 1, 2$ for FI, SW.

[Decant, Heisig, Hooper,LLH’21]

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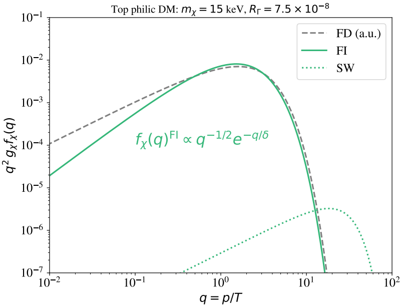
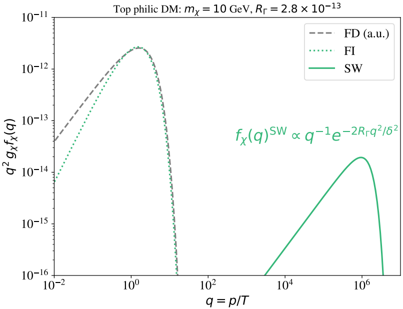
see also [Petraki'16,Heeck'17, Boulebnane'17, Kamada'19, Baumholzer'19, Ballesteros'20, d'Eramo'20]





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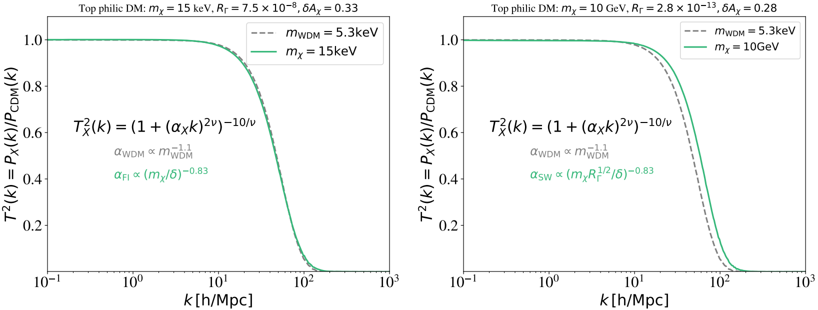
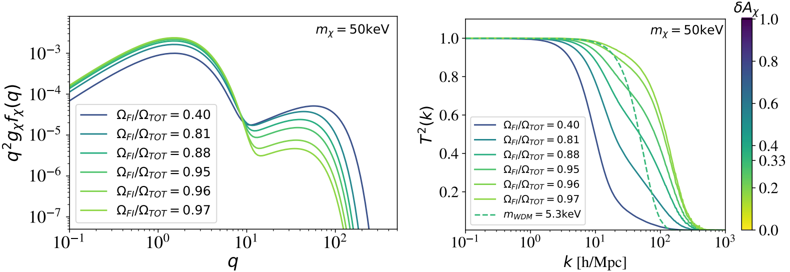


- Contrarily to “usual” WDM, FIMPs are non-thermaly produced. Distribution $f_\chi \propto q_\star^{-\alpha} \exp(-q_\star^\beta)$ with $\alpha = \frac{1}{2}, 1$ and $\beta = 1, 2$ for FI, SW.
- Modified CLASS: Pure FI/SW transfer functions similar to thermal WDM. $\rightsquigarrow$ Lower mass bound from Lyman-α $(m_B \ll m_A, T_{\rm prod} > T_{\rm EW})$:

$$m_\chi \gtrsim \begin{cases} 15\,\text{keV} & \text{for FI,} \\ 0.38\,\text{GeV} \times \sqrt{10^{-4}/R_\Gamma} & \text{for SW,} \end{cases} \quad \text{for } m_{\rm WDM}^{\rm Ly-\alpha} > 5.3\,\text{keV}$$

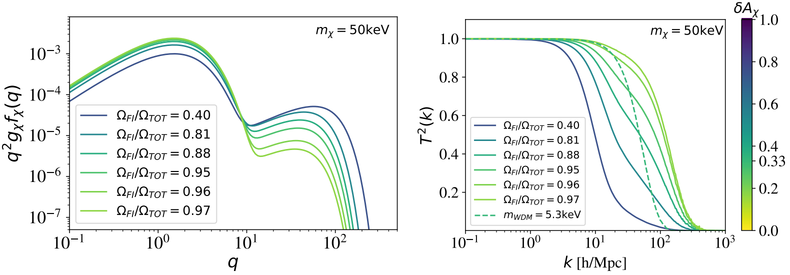
[Decant, Heisig, Hooper,LLH’21]

Mixed FI & SW: significant deviations from WDM



- Mixed FI-SM $q^2 f_\chi$ is multimodal $\rightsquigarrow T^2(k) = P_{\mathrm{FIMP}}(k)/P_{\mathrm{CDM}}(k)$ can significantly deviate from e.g. WDM, α, β, γ param. or CDM+WDM

Mixed FI & SW: significant deviations from WDM



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- We use the area criterion [Murgia'17] measuring the relative $P_{1D}(k)$ deviation over $0.5h/\text{Mpc} < k < 20h/\text{Mpc}$: $\delta A_\chi < \delta A^{ly-\alpha}_{\rm WDM} = 0.33$ for $m^{\rm Ly-\alpha}_{\rm WDM} > 5.3$ keV

see also [Schneider'16] and e.g. [D'Eramo'20, Egana-Ugrinovic'21]

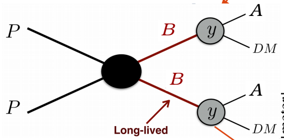
NCDM FIMPs: Complementarity with LLP searches

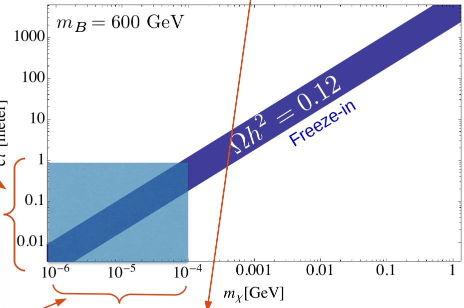
FIMPs: LLPs and NCDM

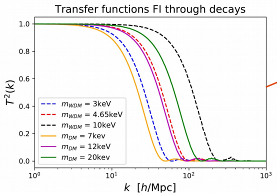
e.g. [Hall'09, Co'15, Hessler'16, d'Eramo'17, Heeck'17, Boulebnane'17, Brooijmans'18, Garny'18, Calibbi'18, No'19, Belanger 18, etc]

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

Mediator mass range
reachable at colliders

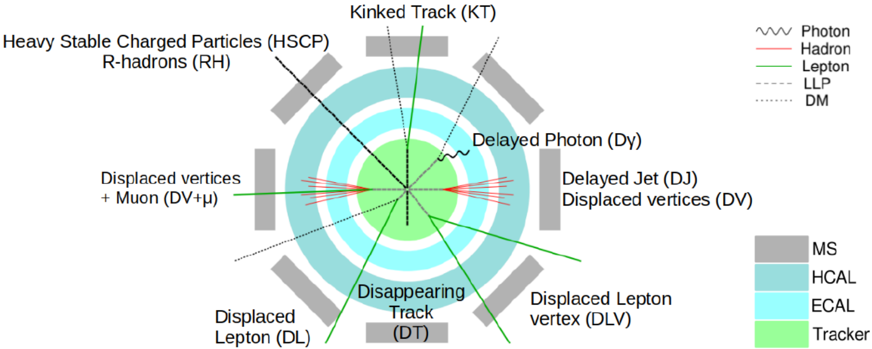






Warm DM like signatures
Suppressing small scale structures

Collider searches for LLP's



[Calibbi,d'Eramo,Junius,LLH '21]

Illustrative frameworks

Illustrative frameworks

Illustrative framework: minimal FIMP models

Dark matter χ coupled to dark B and SM A through Yukawa-like interactions

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

- Dark sector (Z_2 odd): $m_B > m_\chi$
- B is $SU(3) \times SU(2) \times U(1)$ charged
  - fast $B^\dagger B \leftrightarrow$ SM SM through gauge interactions at early time
  - B is produced at colliders today

Illustrative framework: minimal FIMP models

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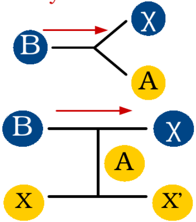
  - B is produced at colliders today
- Minimal scenarios:

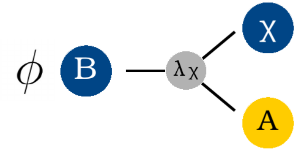
$A_{\rm SM}$	Spin DM	Spin B	Interaction	Label
$\psi_{\rm SM}$	0	1/2	$\bar{\psi}_{\rm SM}\Psi_B\phi$	$\mathcal{F}_{\psi_{\rm SM}\phi}$
	1/2	0	$\bar{\psi}_{\rm SM}\chi\Phi_B$	$\mathcal{S}_{\psi_{\rm SM}\chi}$
$F^{\mu\nu}$	1/2	1/2	$\bar{\Psi}_B\sigma_{\mu\nu}\chi F^{\mu\nu}$	$\mathcal{F}_{F\chi}$
H	0	0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

[Calibbi, D'Eramo, Junius, LLH,Mariotti 21]

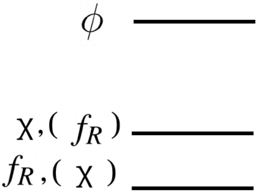
Production in the early universe



Top philic DM



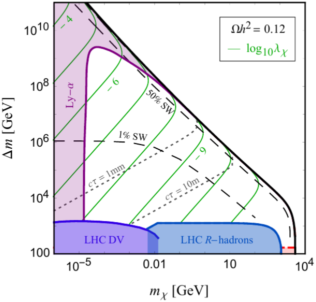
$f_R = l_R, t_R$

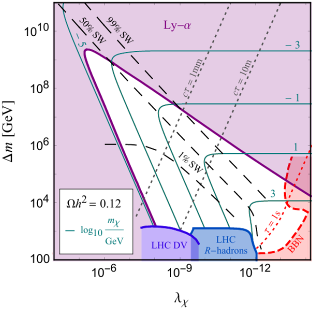


$$\mathcal{L} \subset \mathcal{L}_K - \frac{m_\chi}{2}\bar{\chi}\chi - m_\phi \phi^\dagger \phi \; - \; \lambda_\chi \phi \bar{\chi} f_R \; + \; h.c.$$

- SM + 1 charged/colored dark scalar ϕ + 1 Majorana dark fermions χ (Z_2 symmetry for DM stability) an $f_R = t_R$
- Sommerfeld and BSF taken into account to account for SW [Harz& Petraki'18]
- $\Omega_\chi h^2|_{\rm FI}$ driven by $\phi \to t\chi$ gets an extra 15-25% contribution from scatterings from $t\phi \to g\chi$ and $g\phi \to t\chi$.

Exemplary case of top-philic DM





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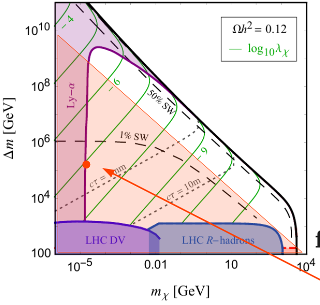
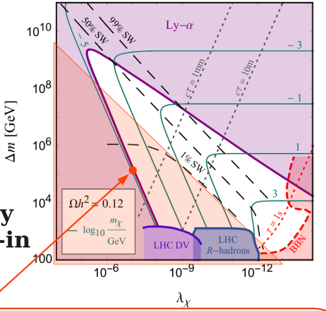
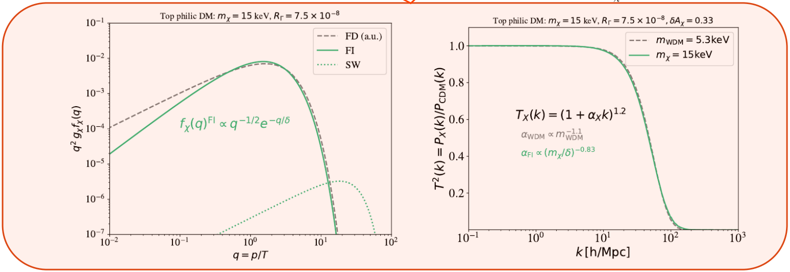


Mostly freeze-in





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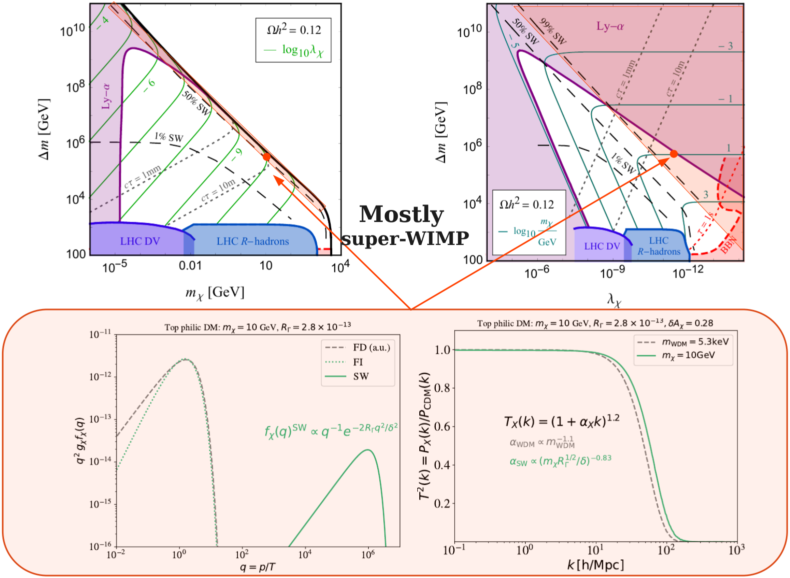

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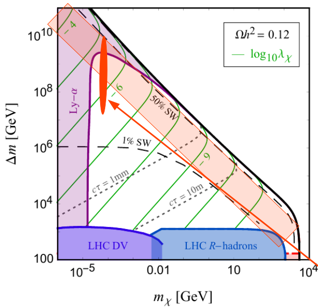
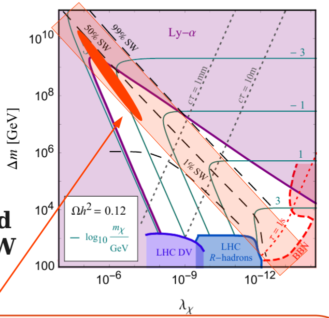
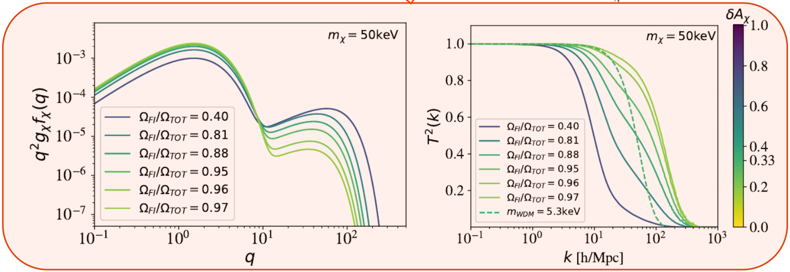


Mixed FI-SW

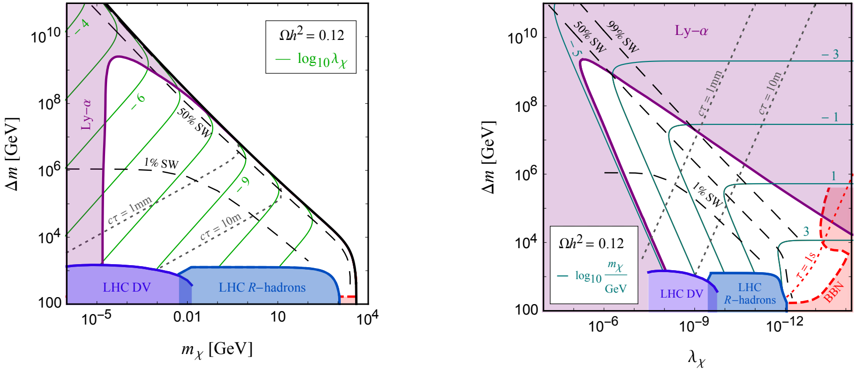




Exemplary case of top-philic DM

see also e.g. [Hall'09; Co'15; Hessler'16; d'Eramo'17, Buchmueller'17; Brooijmans'18; Belanger'18; No'19; Garny'18; Calibbi'18,21; etc]

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



- Topphilic DM: Parameter space cornered by particle (DV + R-hadron searches at LHC - for top-philic) and cosmology (Lyman-α, BBN) probes.
- Lyman-α constraints play a key role and excludes DM over a large range of λ_χ, complementary to BBN for $m_\chi \sim$ few 100 GeV.

Take home message

Even if dark matter would be (not even) very feebly interacting with the SM if can leave distinctive cosmology signature in the form of NCDM.
NCDM can be free-steaming (focus of today's talk) and/or experiencing collisional damping and give rise to suppressed stucture formation at small scales.

- NCDM is not necessarily thermal WDM and can have a mass much larger than few keV.
- Multiple NCDM production mechanisms can give rise to the same/similar features in Cosmology observations. Lyman-α forest data can probe a large parts of the DM parameter space.
- Complementary observations are necessary to pin point the DM nature.

To do extra:

- Modified cosmology can change prospects for LLP signatures (low T_R, etc) it will also change Ly$-\alpha$ constraints.
- Future radio telescopes (21cm Cosmology) might put stringent constraints on NCDM and distinguish between NCDM scenarios (might depend on T_{vir}^{min} [Giri'22])

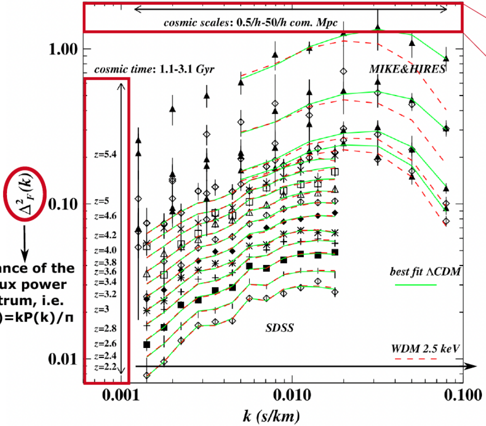
Thank you the invitation
and for your attention!!

Backup

Lyman-α forest

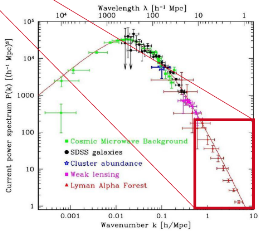
Absorption lines produced by the inhomogeneous IGM along different line of sights to distant quasars: a fraction of photons is absorbed at the Lyman-α wave- length (corresponding to $\lambda_\alpha \sim 121$ nm), resulting in a depletion of the observed spectrum at a given frequency ($\lambda_{abs} 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

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



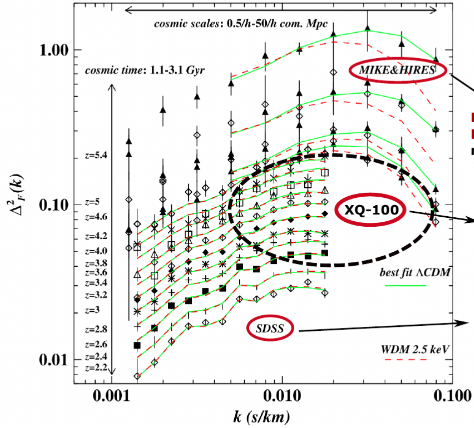
Variance of the 1D flux power spectrum, i.e. $\Delta^2(k)=kP(k)/\pi$

Adapted from Tegmark et al. 2004



The higher the z of the source,
1) the more absorbtion one gets,
2) the lower the mean transmission is,
3) the more the density fluctuations amplify,
4) the larger the amplitude of the spectrum

Adapted from Viel et al. 2013



Ref: Viel et al. 2013
Lkl: Publicly available and rather model-intependent

Ref: Irsic et al. 2017
Lkl: None publicly available yet

Ref: sdss.org (currently DR17)
Lkl: Publicly available but outdated (DR7, 2009) and halofit-dependent

Adapted from Viel et al. 2013 5/25

Matteo Lucca

Area criterium [Schneider 2016, Murgia, Merle, Viel, Totzauer, Schneider 2017]

- Consider ratio of 1D power spectra, computed with CLASS

$$r(k) = \frac{P^X_{1D}(k)}{P^{\rm CDM}_{1D}(k)} \quad \text{with} \quad P^X_{1D}(k) = \int_k^\infty dk'\, k'\, P_X(k')\,,$$

- Compute area under the curve

$$A_X = \int_{\rm k_{min}}^{k_{\rm max}} dk'\, r(k')$$

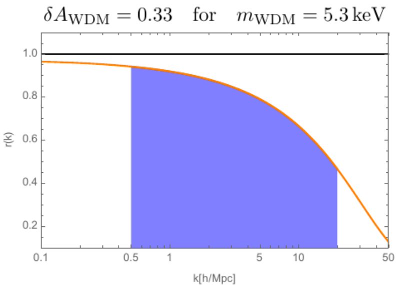
and

$$\delta A_X = \frac{A_{\rm CDM} - A_X}{A_{\rm CDM}}$$

- For freeze-in ($\delta = 1$):

$$m_{\rm FI} > 15.3\,{\rm keV}$$

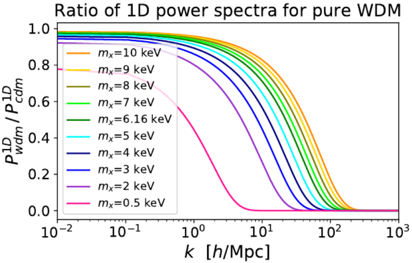
- Suitable for mixed scenario

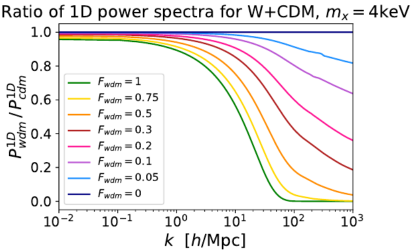


[see *also* D'Eramo, Lenoci, 2020; Egana-Ugrinovic, Essig, Gift, LoVerde 2021]

C+WDM mixed scenarios

preliminary results from Eva Punter master thesis at ULB, 2022, see also [Murgia'17]





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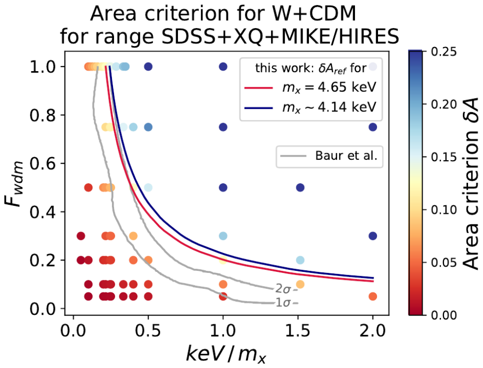


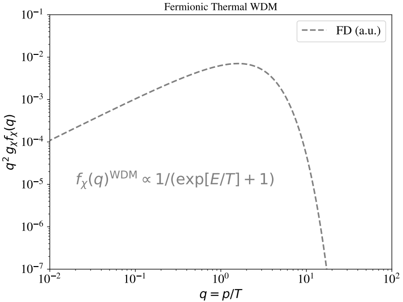
(b)

Figure 5.2: The area difference δA for W+CDM is shown for different WDM masses m_x and fractions F_{wdm}. The range of k over which is integrated is (a) $[0.001 - 0.02]$ s km^{-1} or $[0.046 - 0.92]$ h Mpc^{-1}. and (b) $[0.001 - 0.08]$ s km^{-1} or $[0.046 - 3.68]$ h Mpc^{-1}. The blue and red solid lines represent the reference values δA_{ref} for a different m_x throughout the

The area criterium put conservative constraints on mixed W+CDM scenario.
We can expect similar conclusions for FI+SW scenarios.

Thermal WDM: exponential cut in $P(k)$ at small scales

see also [Bode'00,Viel'05]



- Thermal WDM is in kinetic equilibrium thanks to fast elastic scatterings with thermal plasma: $\frac{d}{dt}f_\chi = \mathcal{C}_{el}[f_\chi] \rightsquigarrow f_\chi \propto f_\chi^{eq}(q)$

Thermal WDM: exponential cut in $P(k)$ at small scales

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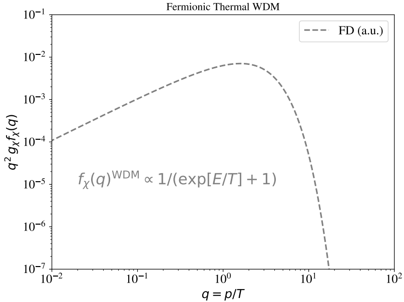
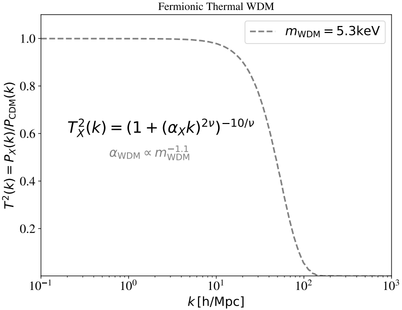




- Thermal WDM is in kinetic equilibrium thanks to fast elastic scatterings with thermal plasma: $\frac{d}{dt} f_\chi = \mathcal{C}_{el}[f_\chi] \rightsquigarrow f_\chi \propto f_\chi^{eq}(q)$
- Evolve f_χ up to 1st order pert. (w/ Boltzmann code as e.g. CLASS): Transfer function $T(k) = (1 + (\alpha_{\rm WDM} k)^{2\nu})^{-5/\nu}$ with $\nu = 1.12$ [Viel'05]

Free-streaming scale: $\alpha_{\rm WDM} \sim 0.045 \left(\frac{m_{\rm WDM}}{\rm keV}\right)^{-1.11}$ Mpc$/h$

DM cosmo probes

see [2203.06380]

Snowmass2021 Theory Frontier: Astrophysical and Cosmological Probes of Dark Matter

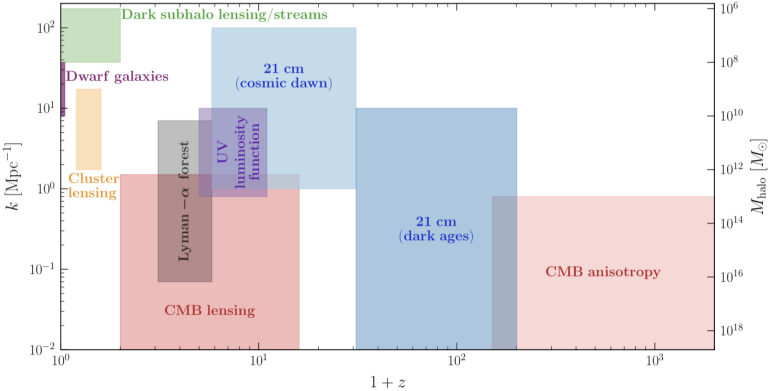
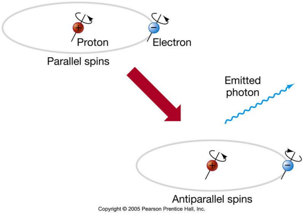


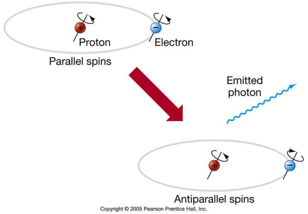
Figure 3: Schematic representation of the coverage of current and future probes of dark matter physics across various ranges of redshift z (i.e., eras that observable photons or signals primarily originate from), wave number k, and the corresponding halo mass M_{halo}. The ranges of individual probes are approximate. Note that some of the listed probes

21 cm Cosmology

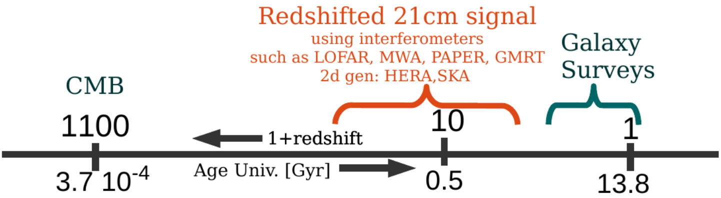


- Transitions between the two ground state energy levels of neutral hydrogen HI $\rightsquigarrow$ 21 cm photon ($\nu_0 = 1420$ MHz)

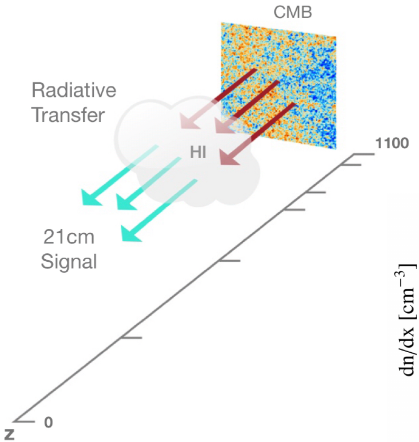
21 cm Cosmology



- 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



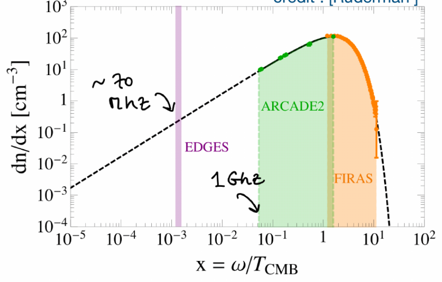
21 cm in practice



credit : [Kovetz]

- 21cm signal observed as CMB spectral distortions

credit : [Ruderman]



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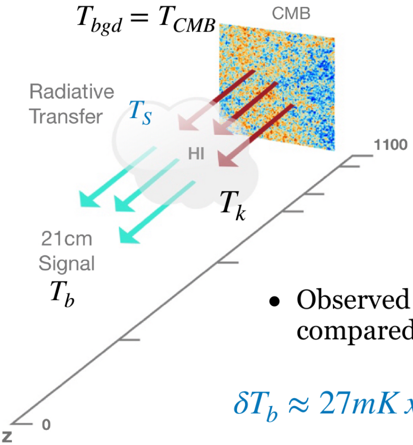


credit : [Kovetz]

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

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

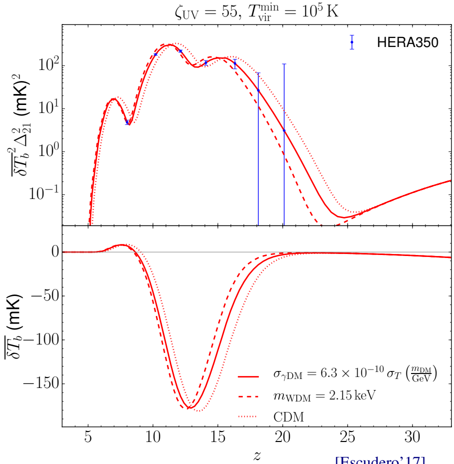
- Observed brightness of a patch of HI compared to CMB at $\nu = \nu_0/(1+z)$

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

Delayed 21cm features for Non-CDM

see also [Sitwell'13,Escudero'18, Schneider'18,Safarzadeh'18,Lidz'18, LLH'18, Muñoz'20,Schneider'22, Giri'22, etc]

Halo suppression can lead to delayed astro processes giving rise to reionization or 21cm features. Stronger delay for WDM than IDM.

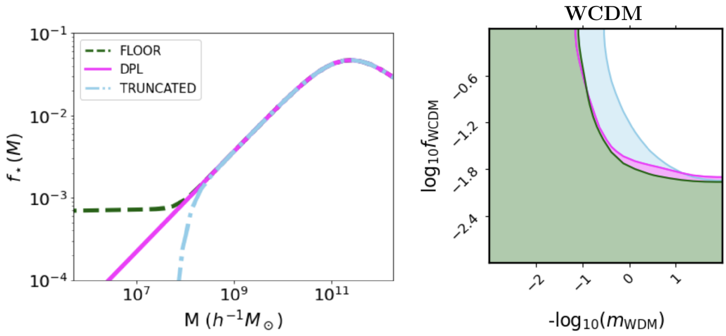


[Escudero'17]

Forecast SKA constraints on WDM+CDM

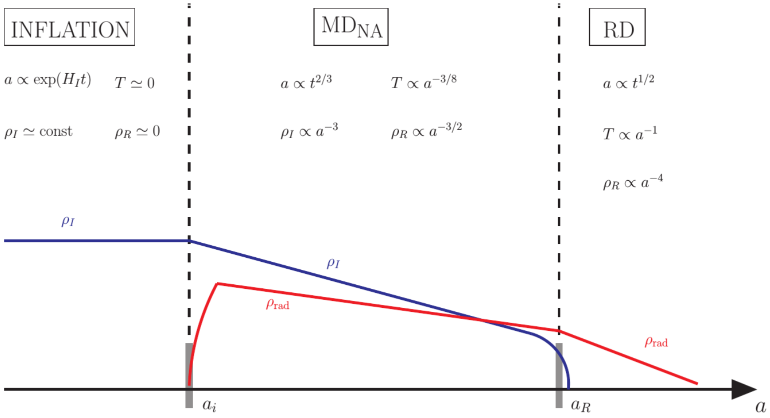
see also [Munoz'19,Hibbard'22, Giri'22, etc]

[Giri'22] (MCMC analysis): For low minimum virial mass ($T_{vir}^{min} < 10^4$K) and in the case that minihaloes are populated with stars, stringent constraints can be obtained on e.g. 100% WDM: up to $m_{\rm WDM} < 15$ keV.



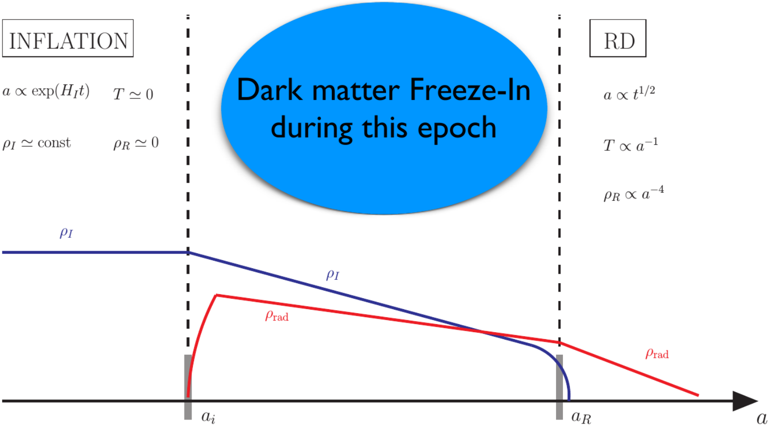
For $T_{vir}^{min} \sim 10^4$ K it will be difficult to distinguish between an inefficient source models and a universe filled with NCDM.

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].

Minimal Frameworks: 3 extra parameters $m_\chi, m_B, \lambda_\chi$

Dark matter χ coupled to dark B and SM A through Yukawa-like interactions

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

- Dark sector (Z_2 odd): $m_B > m_\chi$
- B is $SU(3) \times SU(2) \times U(1)$ charged
  - fast $B^\dagger B \leftrightarrow$ SM SM through gauge interactions at early time
  - B is produced at colliders today

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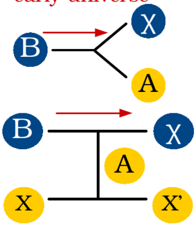
- Minimal scenarios:

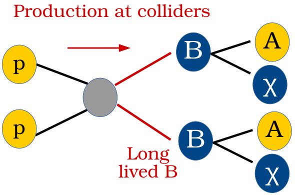
$A_{\rm SM}$	Spin DM	Spin B	Interaction	Label
$\psi_{\rm SM}$	0	1/2	$\bar{\psi}_{\rm SM}\Psi_B\phi$	$\mathcal{F}_{\psi_{\rm SM}\phi}$
	1/2	0	$\bar{\psi}_{\rm SM}\chi\Phi_B$	$\mathcal{S}_{\psi_{\rm SM}\chi}$
$F^{\mu\nu}$	1/2	1/2	$\bar{\Psi}_B\sigma_{\mu\nu}\chi F^{\mu\nu}$	$\mathcal{F}_{F\chi}$
H	0	0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

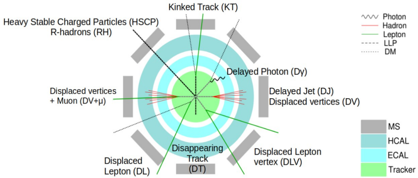
[Calibbi, D'Eramo, Junius, LLH,Mariotti 21]

Production in the early universe



Model dependent signatures





Displaced B decay ⟷ Stable B

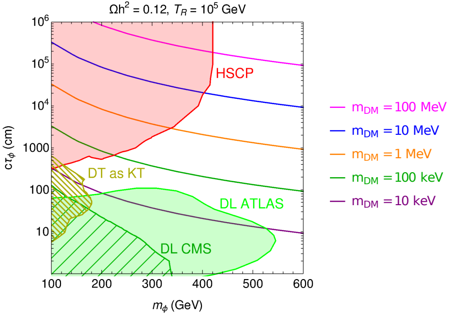
Label	DV + MET	DJ + MET	DJ + μ	DL	DLV	Dγ	DT	RH	HSCP	KT
$\mathcal{F}_{l\phi}$ & $\mathcal{S}_{l\chi}$				✓					✓	✓
$\mathcal{F}_{\tau\phi}$ & $\mathcal{S}_{\tau\chi}$	✓	✓		✓					✓	✓
$\mathcal{F}_{q\phi}$ & $\mathcal{S}_{q\chi}$	✓	✓						✓		
$\mathcal{F}_{t\phi}$ & $\mathcal{S}_{t\chi}$	✓	✓	✓	✓				✓		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

[Calibbi, D'Eramo, Junius, LLH,Mariotti '21]

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

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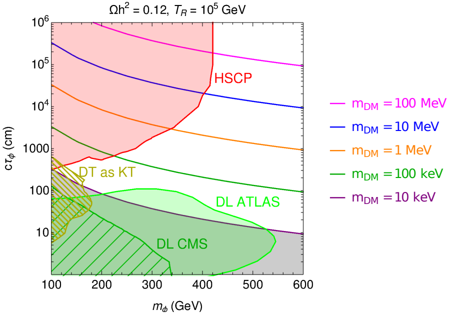

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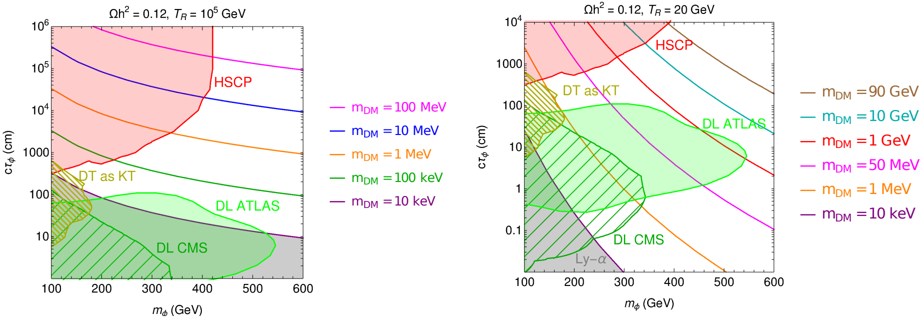

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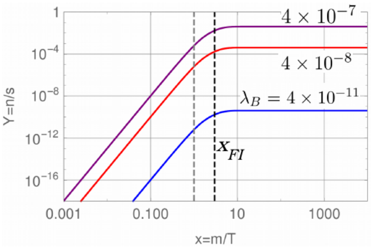
unless DM saturates the Lyman-α constraints

Dislaced events at colliders might point to freeze-in with modified early universe cosmology diluting DM (e.g. EMDE with low T_R. see Calibbi'21, also Arias'20)

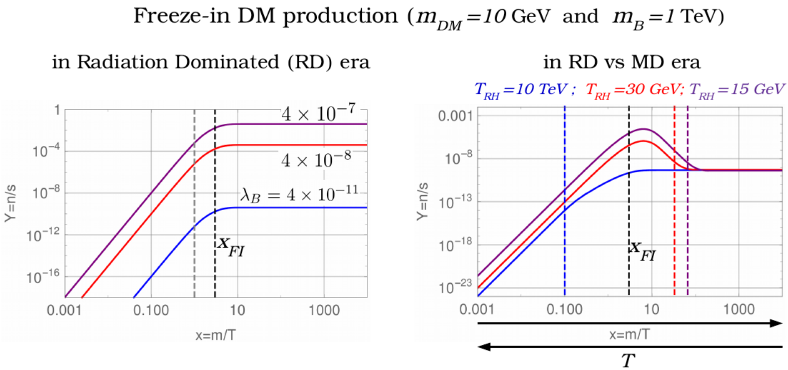
Reheating after FI and smaller $c\tau_B$

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:

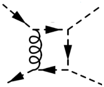
$$Y_X(T_{FI})/Y_X^\infty \propto (T_{FI}/T_{RH})^5 \,,$$

$\rightsquigarrow$ 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 $c\tau_B$.

Effects impacting the relic abundance

$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\rm eff} v \rangle}$$

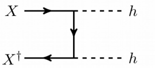
Higher order corrections



$$\sigma_{\rm eff} v_{\rm rel} = \sigma^{\rm NLO} v_{\rm rel}$$

can lead to corrections of around 20% to the DM abundance

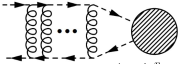
Born level annihilation



$$\sigma_{\rm eff} v_{\rm rel} = \sigma^{\rm tree} v_{\rm rel}$$

usual DM codes include *only* born level calculation

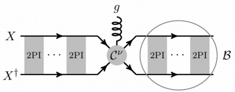
Sommerfeld enhancement



$$\left(\frac{\alpha}{v_{\rm rel}}\right)^n \sim 1$$

$$\sigma_{\rm eff} v_{\rm rel} = \sigma^{\rm tree} v_{\rm rel} \times S_0$$

Bound state formation



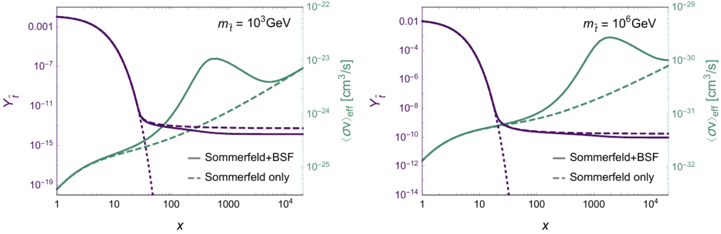
$$\langle \sigma_{\rm eff} v_{\rm rel} \rangle = \langle \sigma_{\rm ann} v_{\rm rel} \rangle + \langle \sigma_{\rm BSF} v_{\rm rel} \rangle_{\rm eff}$$

bound state formation and subsequent decay open up a new effective DM annihilation channel

Non perturbative effects on mediator annihilation/Freeze-out due to massless gauge boson (g) exchange

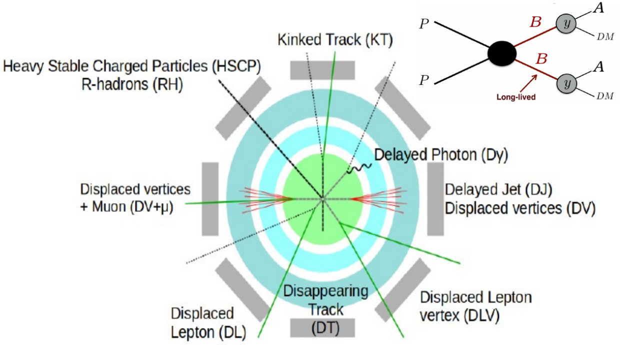
$$\langle \sigma_{\tilde{t}\tilde{t}^\dagger} v\rangle_{\rm eff} = \boxed{\langle \sigma_{\tilde{t}\tilde{t}^\dagger\to gg} v\rangle \times S_{\rm Som}} + \langle \sigma_{\tilde{t}\tilde{t}^\dagger\to q\bar{q}} v\rangle + \boxed{\langle \sigma_{\tilde{t}\tilde{t}^\dagger\to \mathcal{B}g} v\rangle \times \frac{\Gamma_{\mathcal{B},\rm dec}}{\Gamma_{\mathcal{B},\rm ion}+\Gamma_{\mathcal{B},\rm dec}}}$$

We took into accounts the Sommerfeld enhancement factor and the thermally averaged bound state formation cross-section ($\Gamma_{\mathcal{B},\rm ion}$ is the respective ionization rate $\mathcal{B}g \to \tilde{t}\tilde{t}^\dagger$ while $\Gamma_{\mathcal{B},\rm dec}$ its decay rate, $\mathcal{B} \to gg$) following [Harz, Petraki'18]. Annihilation into q is p-wave suppressed.



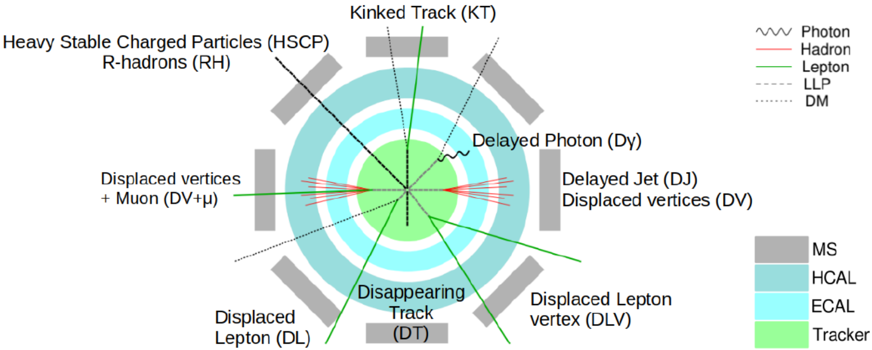
Prolonged Freeze-out due to late time enhancement of mediator annihilation

LLP signatures are framework dependent



- FIMP= feebly interacting massive particle, i.e. $\lambda_\chi \ll 1$
- $\lambda_\chi \ll 1$ and $\Delta m/m < 1 \rightsquigarrow$ possibly $c\tau_B \gtrsim$ collider detector size.
- B long lived particle (LLP), heavy stable particle and displaced events

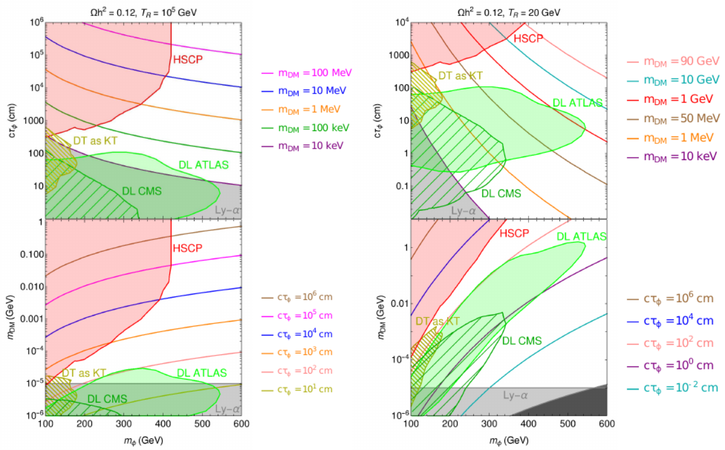
Collider searches



Collider searches

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

Leptophilic DM



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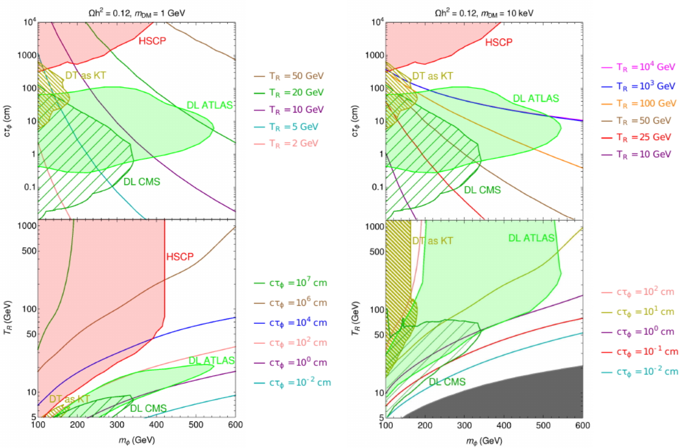
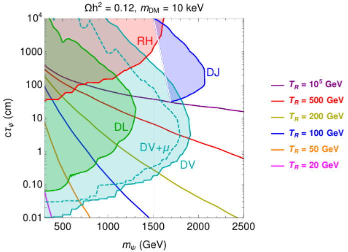
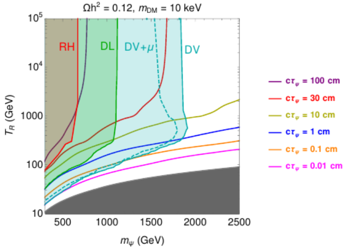


Topphilic DM

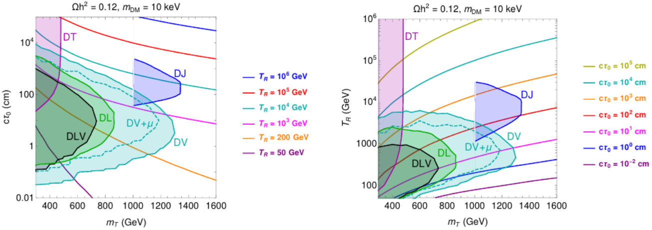




Singlet-Triplet DM

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

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



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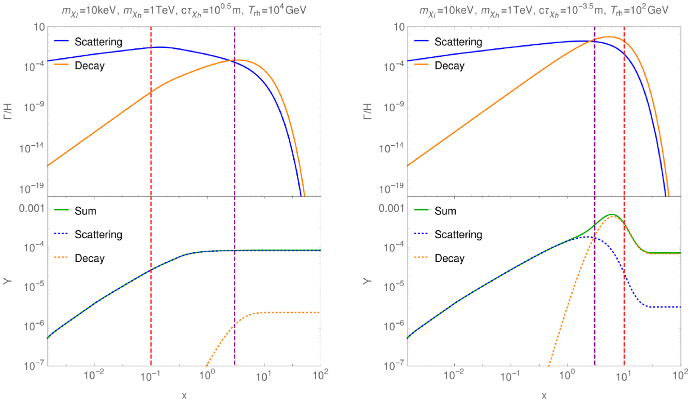
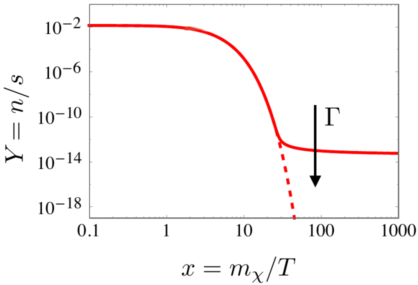


Thermal DM from non-relativistic Freeze-out (WIMP)



- DM annihilation driven freeze-out
- χ chem. & kin. equilibrium
- $\Omega_\chi \propto 1/\langle\sigma v\rangle_{\chi\chi}$
- $\Omega_\chi h^2 = 0.12$
  $\rightsquigarrow \langle\sigma v\rangle_{\chi\chi} = 3 \times 10^{-26}\,\text{cm}^3/\text{s}$
- $x = m_\chi/T$ and $x_{\text{FO}} \sim 25$

Carefull,

- coannihilations, velocity suppressed $\langle\sigma v\rangle$, potential large contributions from higher order processes, etc, not taken into account in this simple picture.
- WIMP still free-stream after kinetic decoupling: for e.g. 100 GeV DM with $T_{KD} \sim 30$ MeV, you expect $M_{fs} \sim 10^{-6} M_\odot$.

bla

This is really the end