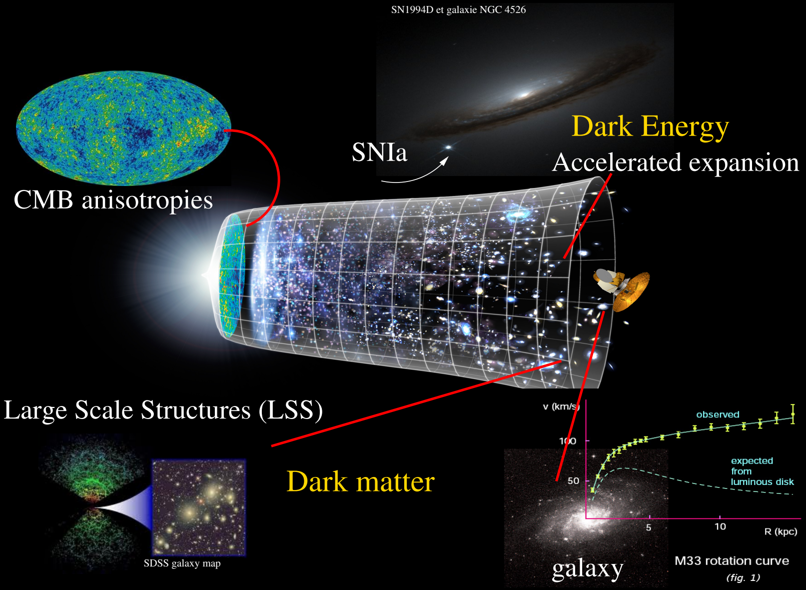
Feebly Interacting Dark Matter
a Non Cold Dark Matter candidate

Laura Lopez Honorez

FNRS FREEDOM TO RESEARCH   ULB

mainly inspired by JHEP 05 (2021) 234 and JCAP 03 (2022) 03, 041
in collaboration with L. Calibbi, Q. Decant, F. d'Eramo,
J. Heisig, D. Hooper, S. Junius and A. Mariotti.

Seminar at the Theoretical Particle Physics & Cosmology group
King's College London



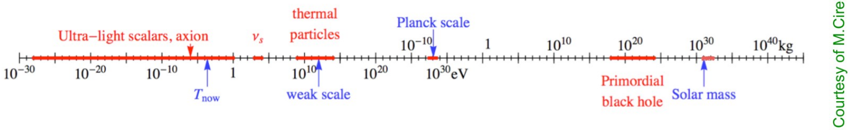
The Quest to determine the Composition of our Universe

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)



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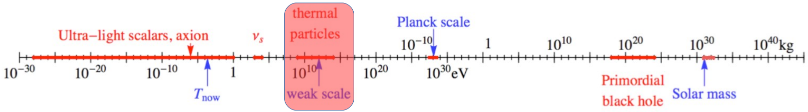
WIMPs: focus of the last ~30 years



Courtesy of M.Cirelli

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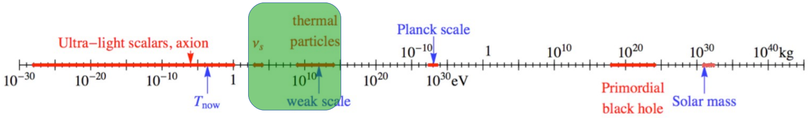
FIMPs: focus of this talk



Courtesy of M.Cirelli

FIMPs

from Freeze-in and superWIMP

WIMP versus FIMP

Cosmology

Particle Physics

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

WIMP versus FIMP

Cosmology

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

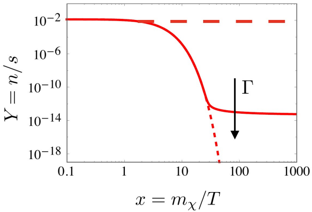
Particle Physics

Weak coupling
to SM

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

"Thermal DM" (incl. WIMP)

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



WIMP versus FIMP

Cosmology

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

Particle Physics

Weak coupling to SM

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

Feeble coupling to SM

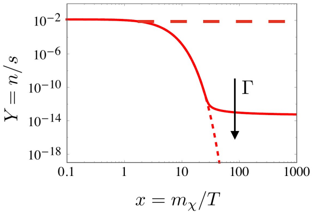
$\Gamma_{\chi\leftrightarrow \mathrm{SM}} < H$

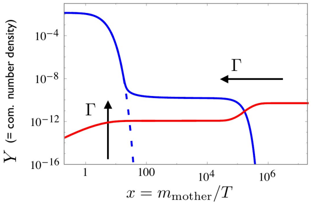
"Thermal DM" (incl. WIMP)

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

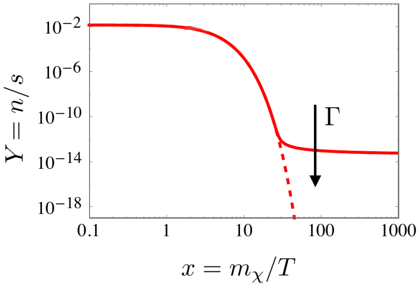
"Non-Thermal" FIMP

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





The simple picture of WIMP Freeze-out

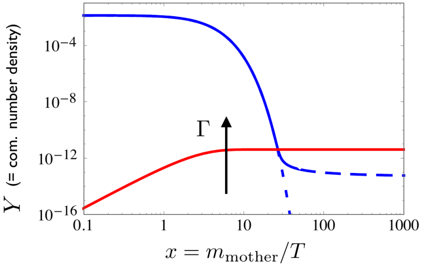


- DM annihilation driven freeze-out
- χ chem. & kin. equilibrium
- $\Omega_\chi \propto 1/\langle\sigma v\rangle_{\chi\chi}$
- $\Omega_\chi h^2 = 0.12$
  $\rightsquigarrow \langle\sigma v\rangle_{\chi\chi} = 3 \times 10^{-26}\,\text{cm}^3/\text{s}$
- $x = m_\chi/T$ and $x_{\text{FO}} \sim 25$

Careful: coannihilations, velocity suppressed $\langle\sigma v\rangle$, potential large contributions from higher order processes, etc, not taken into account in this simple picture.

The simple picture of FIMP Freeze-in

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



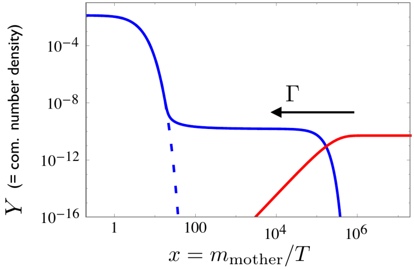
- Freeze-in from B decays
- χ decoupled
- B in chem. & kin. equilibrium
- $\Omega_\chi h^2 \propto \Gamma_{B\to\chi} M_p/m_B^2 \sim R_\Gamma$
- $\Omega_\chi h^2 = 0.12 \rightsquigarrow \lambda_\chi \lesssim 10^{-8}$
- $x = m_B/T$ and $x_{\rm FI} \sim 3$

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.

FIMPs from superWIMP

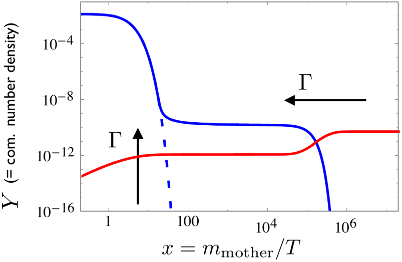
see also [Covi '99 ;Feng '03]



- superWIMP from late B decays
- χ decoupled
- B chem. decoupled
- $\Omega_\chi h^2 = m_\chi/m_B \times \Omega_B h^2|_{\rm FO}$
  if $B \to A_{\rm SM} A'_{SM}$ not open
- $x = m_B/T$ and $x_{\rm SW} \sim R_\Gamma^{-1/2} > 3$

FIMPs from FI & superWIMP

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

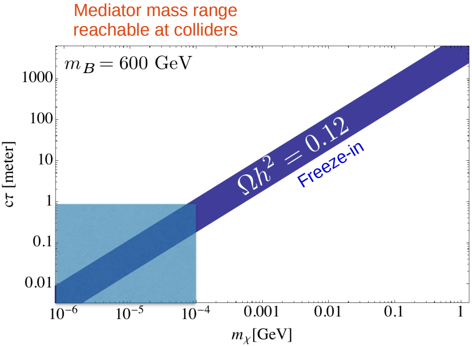


- χ decoupled
- χ population slowly builds up from B before and after FO.
- $\Omega_\chi h^2 = \Omega_\chi h^2|_{\rm FI} + \Omega_\chi h^2|_{\rm SW}$

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]

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



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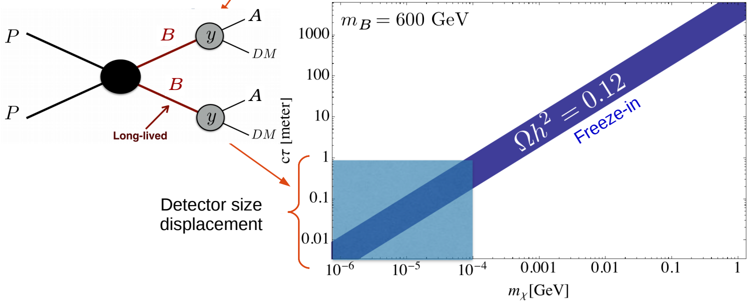
Mediator mass range reachable at colliders



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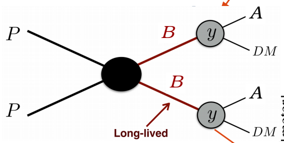

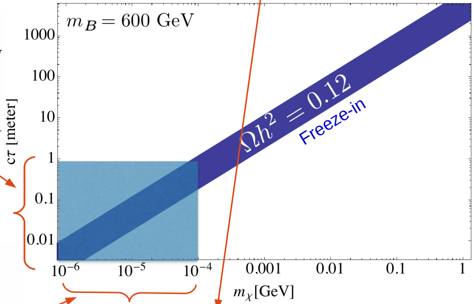

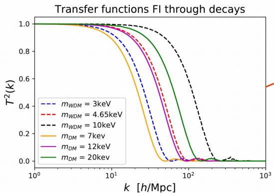

Warm DM like signatures
Suppressing small scale structures

Framework

Beyond the Standard Model: Minimal Models

Beyond the Standard Model: Minimal Models

Minimal Models: 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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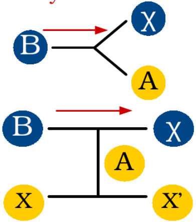
  - B is produced at colliders today
- Minimal scenarios:

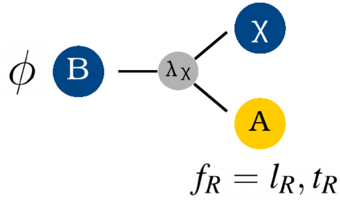
$A_{\rm SM}$	Spin DM	Spin B	Interaction	Label
$\psi_{\rm SM}$	0	1/2	$\bar{\psi}_{\rm SM}\Psi_B\phi$	$\mathcal{F}_{\psi_{\rm SM}\phi}$
	1/2	0	$\bar{\psi}_{\rm SM}\chi\Phi_B$	$\mathcal{S}_{\psi_{\rm SM}\chi}$
$F^{\mu\nu}$	1/2	1/2	$\bar{\Psi}_B\sigma_{\mu\nu}\chi F^{\mu\nu}$	$\mathcal{F}_{F\chi}$
H	0	0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

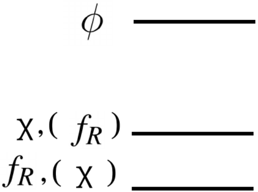
[Calibbi, D'Eramo, Junius, LLH,Mariotti 21]

Production in the early universe



Fermionic DM coupling to $f_R = l_R$ or t_R



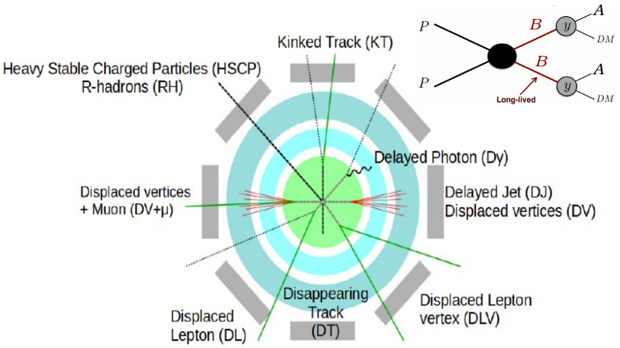


$$\mathcal{L} \subset \mathcal{L}_K - \frac{m_\chi}{2}\bar{\chi}\chi - m_\phi \phi^\dagger \phi \; - \; \lambda_\chi \phi \bar{\chi} f_R \; + \; h.c.$$

- SM + 1 charged/colored dark scalar ϕ + 1 Majorana dark fermions χ (Z_2 symmetry for DM stability)
- We work in the small coupling limit $\lambda_\chi < 10^{-7}$
- Here we focus on $f_R = l_R, t_R$.

Displaced Signatures

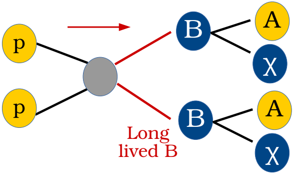
FIMPs and Long lived Mediators

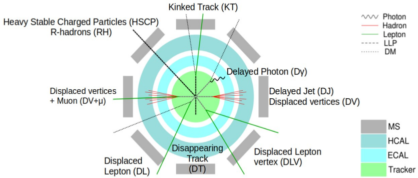


- FIMP= feebly interacting massive particle, i.e. $\lambda_\chi \ll 1$
- $\lambda_\chi \ll 1$ and $\Delta m/m < 1 \rightsquigarrow$ possibly $c\tau_B \gtrsim$ collider detector size.
- B long lived particle (LLP), heavy stable particle and displaced events

Model dependent signatures

Production at colliders





Displaced B decay ←→ Stable B

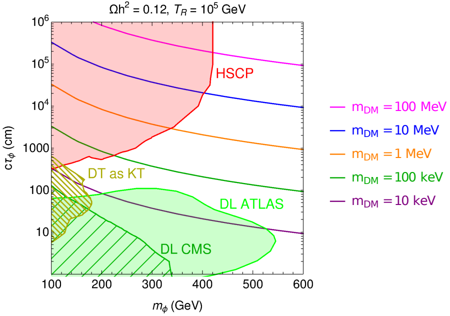
Label	DV + MET	DJ + MET	DJ + μ	DL	DLV	Dγ	DT	RH	HSCP	KT
$\mathcal{F}_{l\phi}$ & $\mathcal{S}_{l\chi}$				✓					✓	✓
$\mathcal{F}_{\tau\phi}$ & $\mathcal{S}_{\tau\chi}$	✓	✓		✓					✓	✓
$\mathcal{F}_{q\phi}$ & $\mathcal{S}_{q\chi}$	✓	✓						✓		
$\mathcal{F}_{t\phi}$ & $\mathcal{S}_{t\chi}$	✓	✓	✓	✓				✓		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

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

Exemplary case of Leptophilic DM

see also e.g. [Hall'09, Belanger'18, Calibbi'21, etc]

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



- Leptophilic DM: displaced leptons (DL), disappearing tracks (DT) and heavy stable charge particle (HSCP) searches

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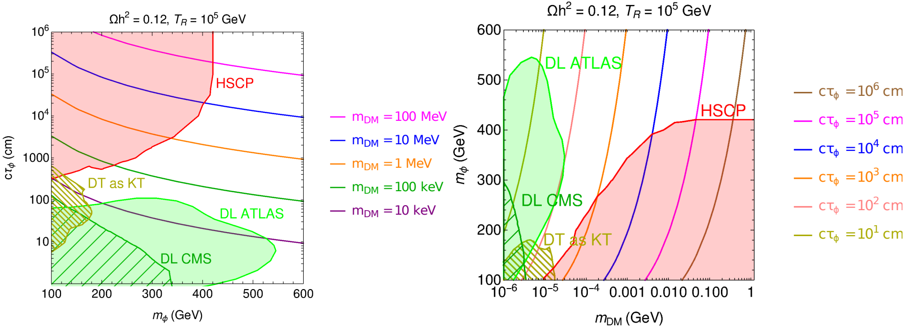
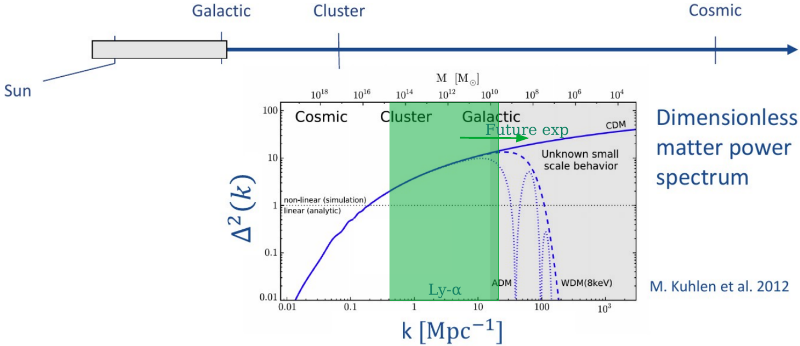


- Leptophilic DM: displaced leptons (DL), disappearing tracks (DT) and heavy stable charge particle (HSCP) searches
- Top-philic DM: displaced vertices (DV), delayed jets (DJ) and R-hadron searches are the most sensitive/complementary.

Where is the Cosmology bound from "WDM-like" free-steaming effect ?

Non-Cold Dark Matter

Non-Cold Dark Matter

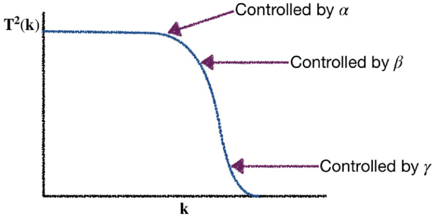


- WDM free-streeming from overdense to underdense regions
  $\rightsquigarrow$ Smooth out inhomegeneities for $\lambda \lesssim \lambda_{FS} \sim \int v/adt$
- Effects $P(k)$ and $T(k)$ generalized to Non-Cold DM see e.g. [Bode'00, Viel'05, Murgia'17], including non-thermal DM from freeze-in or superWIMP.

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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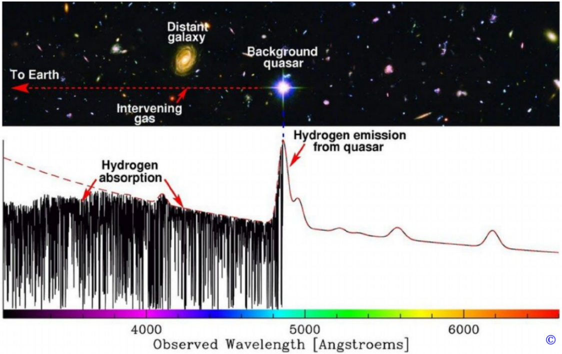

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- Effects $P(k)$ and $T(k)$ generalized to Non-Cold DM see e.g. [Bode'00, Viel'05, Murgia'17], including non-thermal DM from freeze-in or superWIMP.
- Tested against Lyman-α: absorption lines along line of sights to distant quasars probe smallest structures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

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

Translating WDM bound to NCDM?

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

Naive estimate for "similar velocity distributions" :

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

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

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- WDM: $\Omega_\chi h^2 = 0.12 \rightsquigarrow g_{*,S}(T_D) \simeq 10^3 \times \frac{m_\chi}{\rm keV}$
  $\Rightarrow \langle v_\chi \rangle|_{t_0}^{\rm WDM} \propto m_{\rm WDM}^{-4/3}$

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

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

Translating WDM bound to NCDM?

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

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

Translating WDM bound to NCDM?

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

Naive estimate for "similar velocity distributions" :

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

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

- WDM: $\Omega_\chi h^2 = 0.12 \rightsquigarrow g_{*,S}(T_D) \simeq 10^3 \times \frac{m_\chi}{\text{keV}}$
  $\Rightarrow \langle v_\chi \rangle |_{t_0}^{\text{WDM}} \propto m_{\text{WDM}}^{-4/3}$
- FI: $T_{\text{prod}} \sim m_B/3$ and $\langle p_\chi \rangle |_{t_{\text{prod}}} \sim m_B/2$
  $\Rightarrow \langle v_\chi \rangle |_{t_0}^{\text{FI}} \propto m_\chi^{-1}$
- SW: $T_{\text{prod}} \sim \sqrt{\Gamma_B M_{Pl}}$ and $\langle p_\chi \rangle |_{t_{\text{prod}}} \sim m_B/2$
  $\Rightarrow \langle v_\chi \rangle |_{t_0}^{\text{SW}} \propto m_\chi^{-1} \times R_\Gamma^{-1/2}$

$$m_\chi \gtrsim \begin{cases} 16\,\text{keV} & \text{for FI,} \\ 3.8\,\text{keV} \times (R_\Gamma)^{-1/2} & \text{for SW,} \end{cases} \quad \text{for } m_{\text{WDM}}^{\text{Ly}-\alpha} > 5.3\,\text{keV}$$

Non-Cold Dark Matter vs Warm Dark Matter Distributions

Cosmology

Particle Physics

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

Non-Cold Dark Matter vs Warm Dark Matter Distributions

Cosmology

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

Particle Physics

Weak coupling to SM

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

"Thermal" DM

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

Decouple still relativistic and freestream while struct. forms

"Thermal Warm" Dark Matter (WDM)

Non-Cold Dark Matter vs Warm Dark Matter Distributions

Cosmology

Particle Physics

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

Weak coupling to SM

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

Feeble coupling to SM

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

“Thermal” DM

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

“Non-Thermal” DM

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

Decouple still relativistic
and freestream while struct. forms

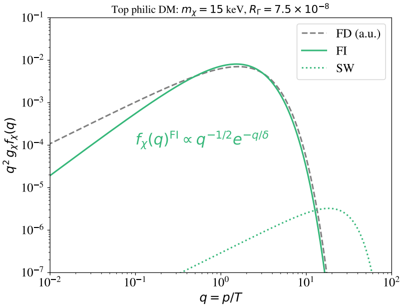
Produced through feeble interactions with large boost
and freestream while struct. forms

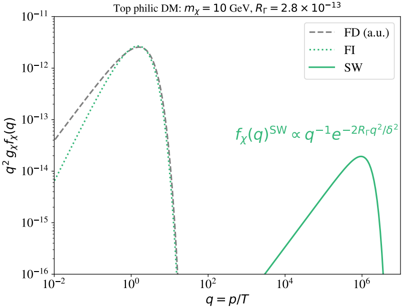
“Thermal Warm” Dark Matter (WDM)

“Feebly Interacting Massive Particles” (FIMPS)

Pure FI & SW: WDM-like

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



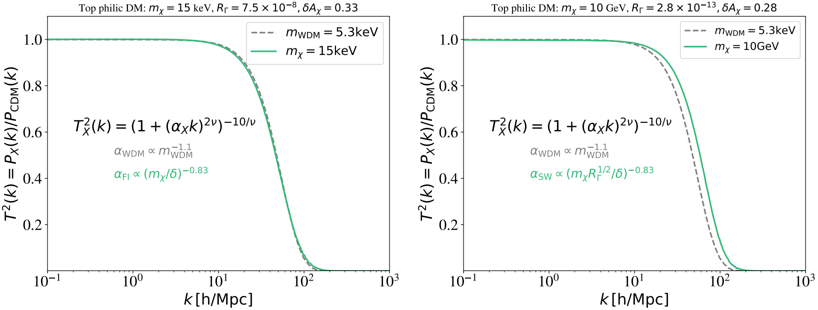


- Contrarily to "usual" WDM, FIMPs are non-thermaly produced. Distribution $f_\chi \propto q_\star^{-\alpha} \exp(-q_\star^\beta)$ with $\alpha = \frac{1}{2}, 1$ and $\beta = 1, 2$ for FI, SW.

[Decant, Heisig, Hooper,LLH'21]

Pure FI & SW: WDM-like

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

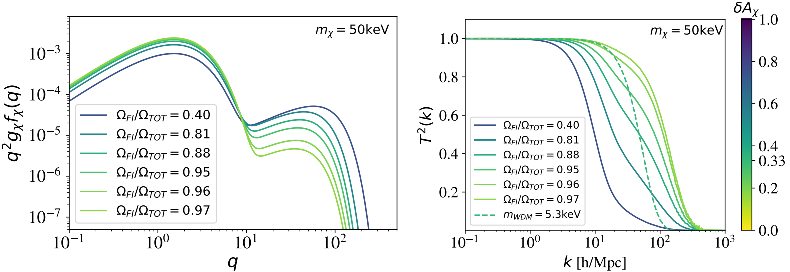


- Contrarily to "usual" WDM, FIMPs are non-thermaly produced. Distribution $f_\chi \propto q_\star^{-\alpha} \exp(-q_\star^\beta)$ with $\alpha = \frac{1}{2}, 1$ and $\beta = 1, 2$ for FI, SW.
- Using CLASS: Pure FI/SW transfer functions similar to thermal WDM. $\rightsquigarrow$ Lower mass bound from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

$$m_\chi \gtrsim \begin{cases} 15\,\text{keV} & \text{for FI,} \\ 3.8\,\text{keV} \times (R_\Gamma)^{-1/2} & \text{for SW,} \end{cases} \quad \text{for } m_{\rm WDM}^{\rm Ly-\alpha} > 5.3\,\text{keV}$$

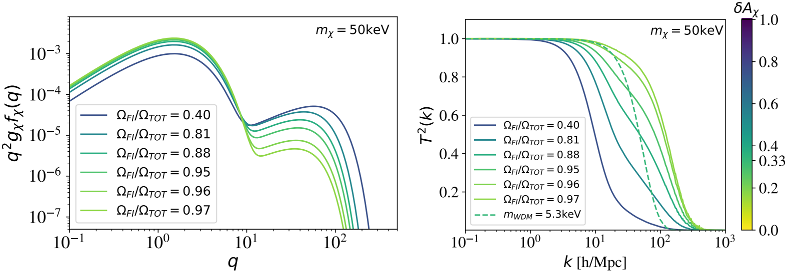
[Decant, Heisig, Hooper,LLH'21]

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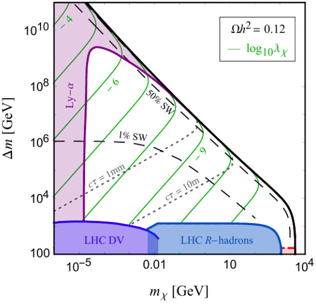
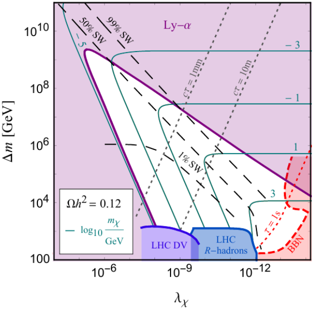
- We use the area criterion [Murgia'17] measuring the relative $P_{1D}(k)$ deviation over $0.5h/\text{Mpc} < k < 20h/\text{Mpc}$: $\delta A_\chi < \delta A^{ly-\alpha}_{\rm WDM} = 0.33$ for $m^{\rm Ly-\alpha}_{\rm WDM} > 5.3$ keV

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

Exemplary case of top-philic DM





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

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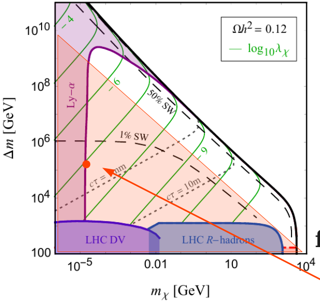
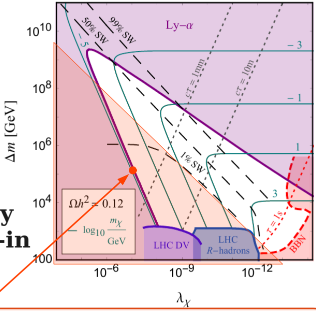
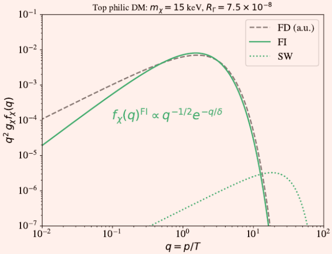
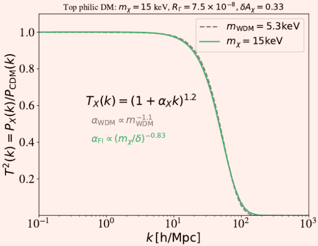


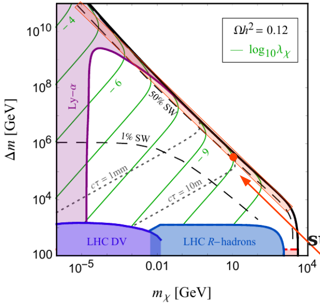
Mostly freeze-in



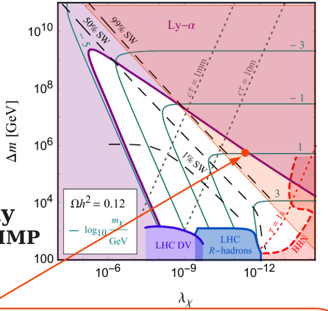


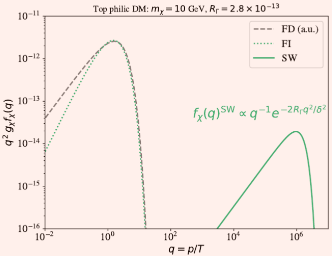


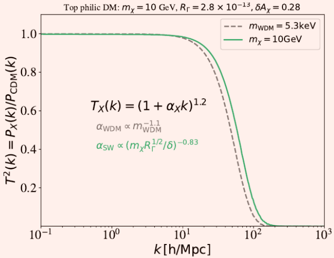
Exemplary case of top-philic DM



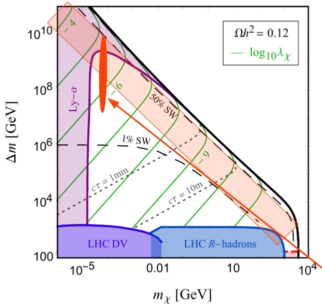
Mostly super-WIMP



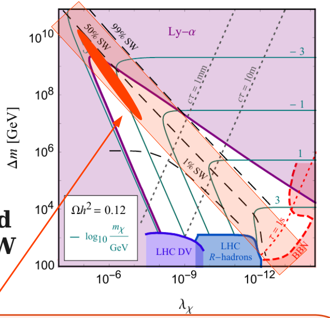


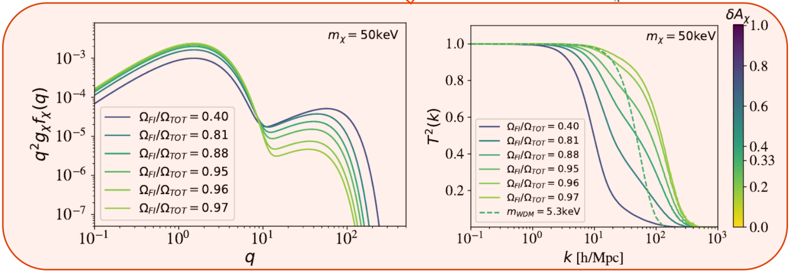


Exemplary case of top-philic DM



Mixed FI-SW

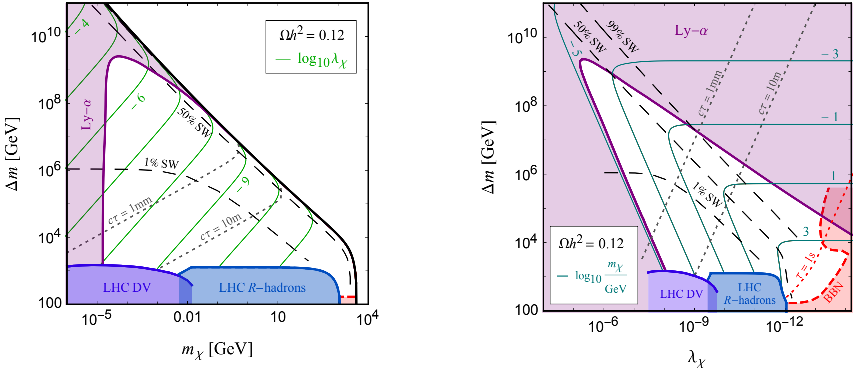




Exemplary case of top-philic DM

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

Despite very feeble couplings to SM, DM models FIMPs from freeze-in, & superWIMP are viable and testable:

- LLP at colliders with displaced signatures.
- FI & SW: FIMPs $\sim$ NCDM and Lyman-α forest constraints $m_{\rm DM} \gtrsim 15$ keV (FI) or up to few 100 GeV (SW).

Displaced events at colliders might already be ruled out by Lyman-α searches for a standard cosmology. However, if an event was detected, it might also point out to a different early Cosmology.

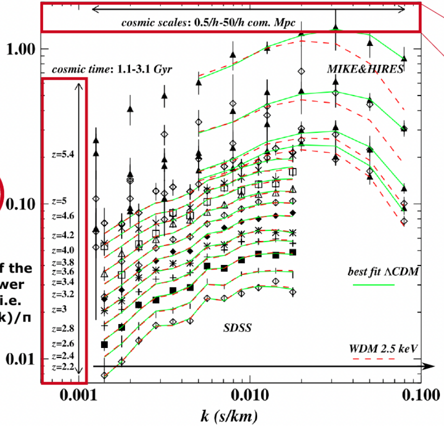
Thank you the invitation
and for your attention!!

Backup

Lyman-α forest

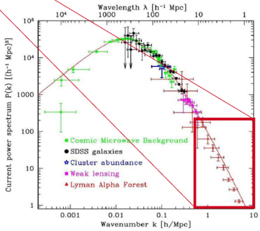
Absorption lines produced by the inhomogeneous IGM along different line of sights to distant quasars: a fraction of photons is absorbed at the Lyman-α wave- length (corresponding to $\lambda_\alpha \sim 121$ nm), resulting in a depletion of the observed spectrum at a given frequency ($\lambda_{abs} 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

- 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.



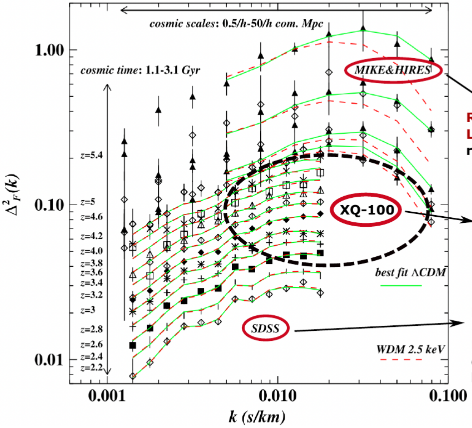
Variance of the 1D flux power spectrum, i.e. $\Delta^2(k)=kP(k)/\pi$

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

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

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

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

- Compute area under the curve

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

and

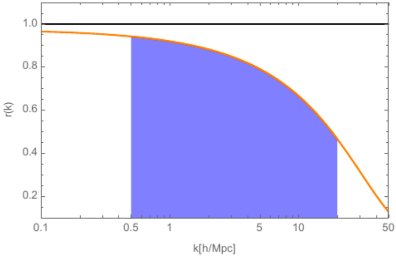
$$\delta A_X = \frac{A_{\rm CDM} - A_X}{A_{\rm CDM}}$$

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

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

- Suitable for mixed scenario

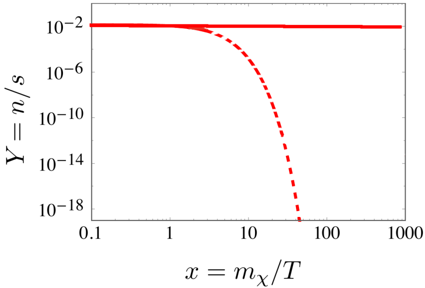
$\delta A_{\rm WDM} = 0.33 \quad \text{for} \quad m_{\rm WDM} = 5.3\,{\rm keV}$



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

Thermal WDM freeze-out

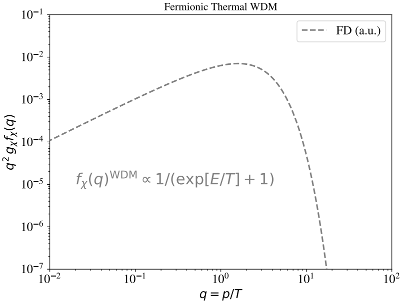
$$\frac{df_\chi}{dt} = \mathcal{C}_{ann}[f_\chi] \quad \rightsquigarrow \quad n_\chi \propto \frac{g^0_{*,S}}{g_{*,S}(T_D)}$$



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

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

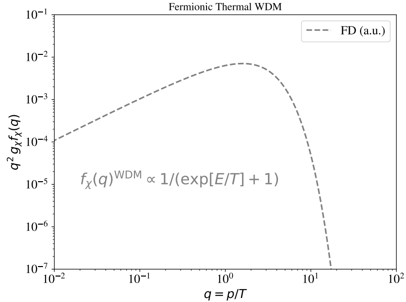
see also [Bode'00,Viel'05]

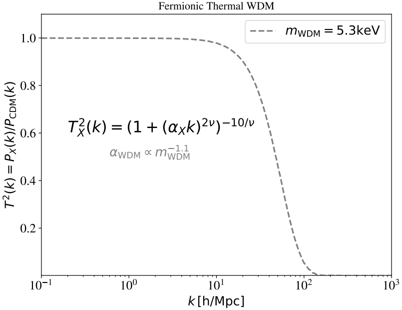


- Thermal WDM is in kinetic equilibrium thanks to fast elastic scatterings with thermal plasma: $\frac{d}{dt} f_\chi = \mathcal{C}_{el}[f_\chi] \rightsquigarrow f_\chi \propto f_\chi^{eq}(q)$

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

see also [Bode'00,Viel'05]

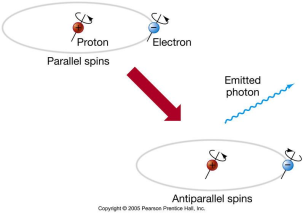




- Thermal WDM is in kinetic equilibrium thanks to fast elastic scatterings with thermal plasma: $\frac{d}{dt} f_\chi = \mathcal{C}_{el}[f_\chi] \rightsquigarrow f_\chi \propto f_\chi^{eq}(q)$
- Evolve f_χ up to 1st order pert. (w/ Boltzmann code as e.g. CLASS): Transfer function $T(k) = (1+(\alpha_{\rm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

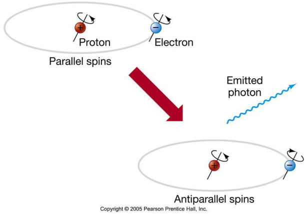
Free-streaming scale: $\alpha_{\rm WDM} \sim 0.045\left(\frac{m_{\rm WDM}}{\rm keV}\right)^{-1.11}$ Mpc$/h$

21 cm Cosmology

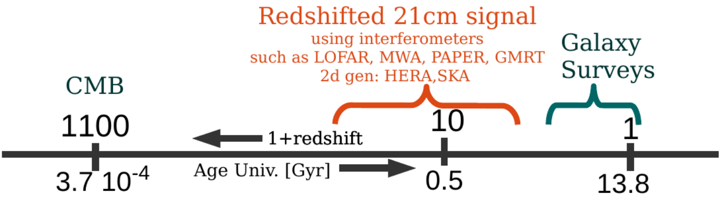


- Transitions between the two ground state energy levels of neutral hydrogen HI $\rightsquigarrow$ 21 cm photon ($\nu_0 = 1420$ MHz)

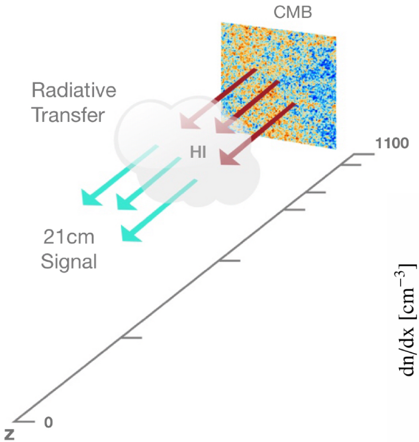
21 cm Cosmology



- 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

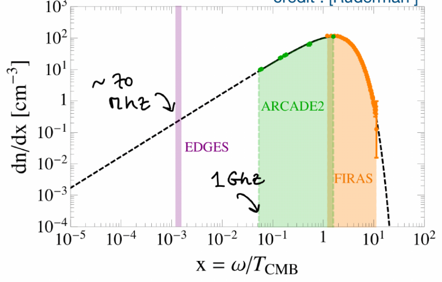


21 cm in practice



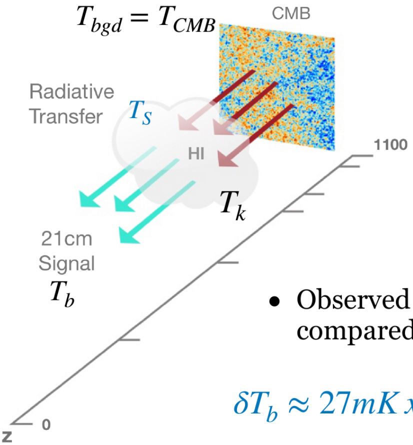
credit : [Kovetz]

- 21cm signal observed as CMB spectral distortions



credit : [Ruderman]

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

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

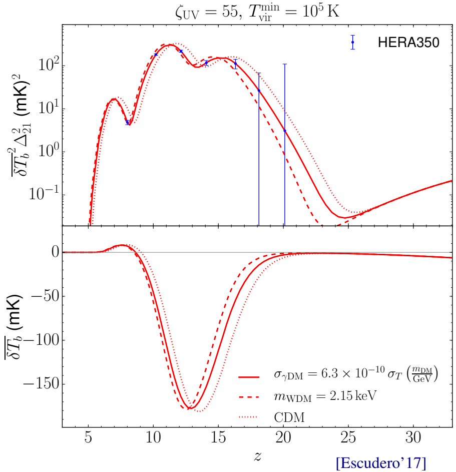
- Observed brightness of a patch of HI compared to CMB at $\nu = \nu_0/(1+z)$

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

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.

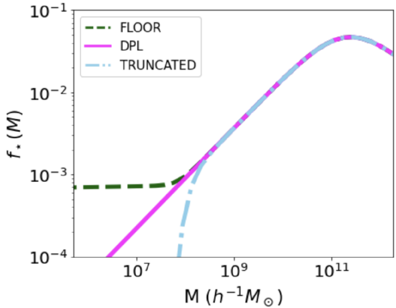


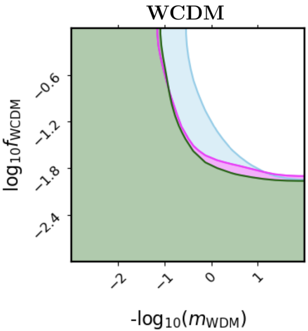
[Escudero'17]

Forecast SKA constraints on WDM+CDM

[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.

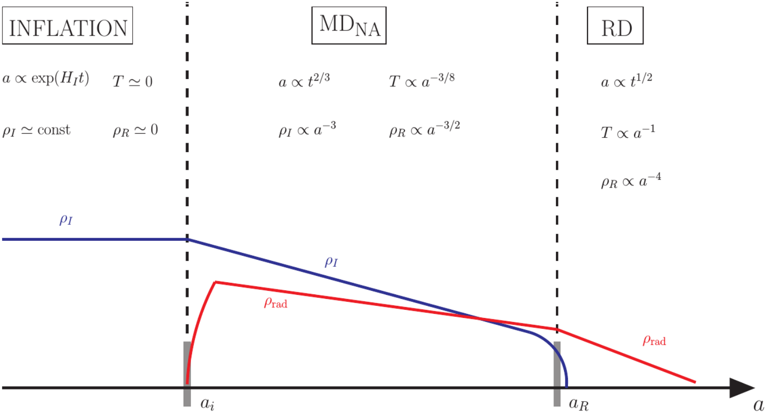
see also [Munoz'19,Hibbard'22, Giri'22, etc]





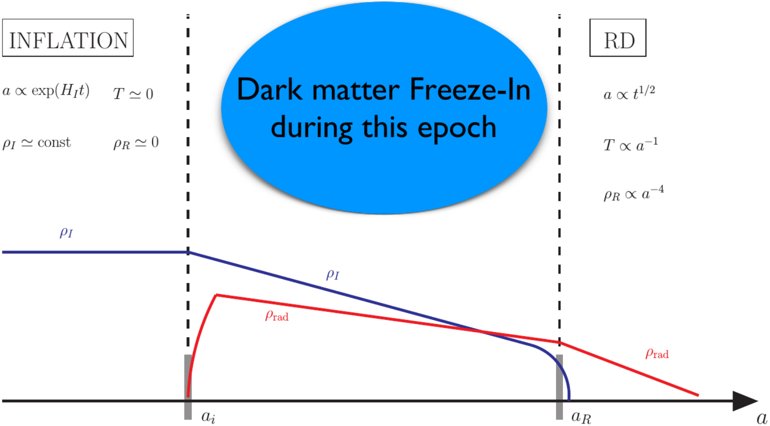
For $T_{vir}^{min} \sim 10^4$ K it will be difficult to distinguish between an inefficient source models and a universe filled with NCDM.

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



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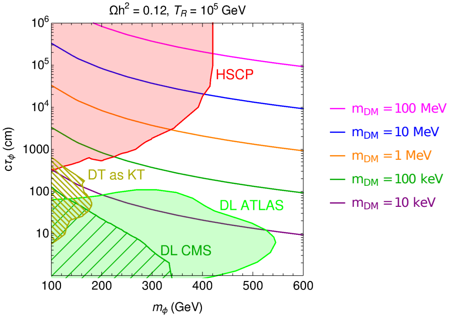
Leptophilic DM: Collider vs NCDM Constraints

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

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



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

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

unless DM saturates the Lyman-α constraints

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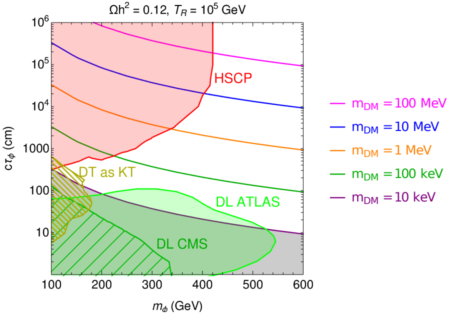

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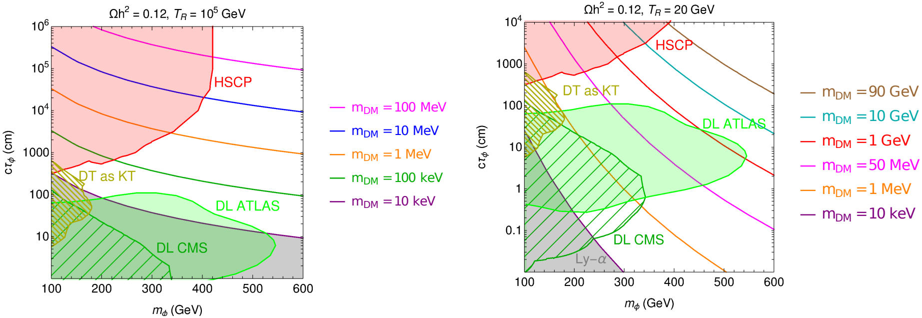

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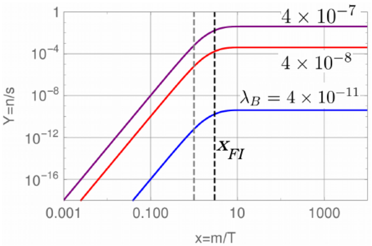
unless DM saturates the Lyman-α constraints

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)

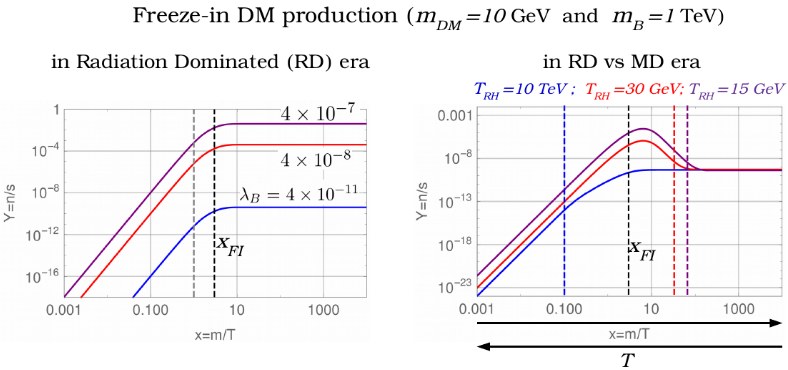
Reheating after FI and smaller $c\tau_B$

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:

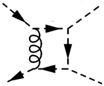
$$Y_X(T_{FI})/Y_X^\infty \propto (T_{FI}/T_{RH})^5 \,,$$

$\rightsquigarrow$ 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

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

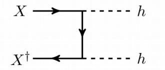
Higher order corrections



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

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

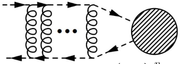
Born level annihilation



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

usual DM codes include *only* born level calculation

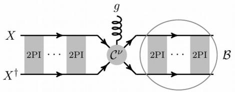
Sommerfeld enhancement



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

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

Bound state formation



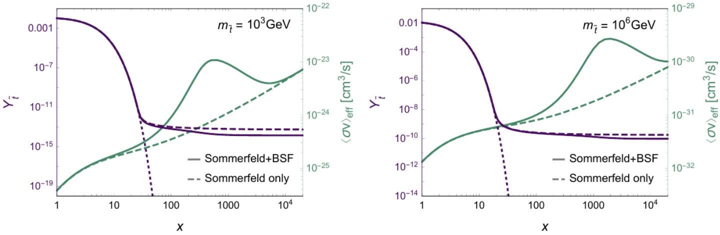
$$\langle \sigma_{\text{eff}} v_{\text{rel}} \rangle = \langle \sigma_{\text{ann}} v_{\text{rel}} \rangle + \langle \sigma_{\text{BSF}} v_{\text{rel}} \rangle_{\text{eff}}$$

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

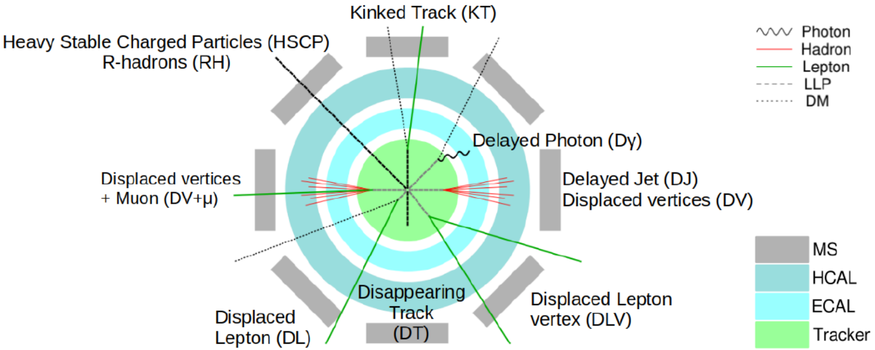
$$\langle \sigma_{\tilde{t}\tilde{t}^\dagger} v \rangle_{\rm eff} = \boxed{\langle \sigma_{\tilde{t}\tilde{t}^\dagger \to gg} v \rangle \times S_{\rm Som}} + \langle \sigma_{\tilde{t}\tilde{t}^\dagger \to q\bar{q}} v \rangle + \boxed{\langle \sigma_{\tilde{t}\tilde{t}^\dagger \to \mathcal{B}g} v \rangle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

We took into accounts the Sommerfeld enhancement factor and the thermally averaged bound state formation cross-section (ΓB,ion is the respective ionization rate Bg → t̃t̃† while ΓB,dec its decay rate, B → gg) following [Harz, Petraki'18]. Annihilation into q is p-wave suppressed.



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

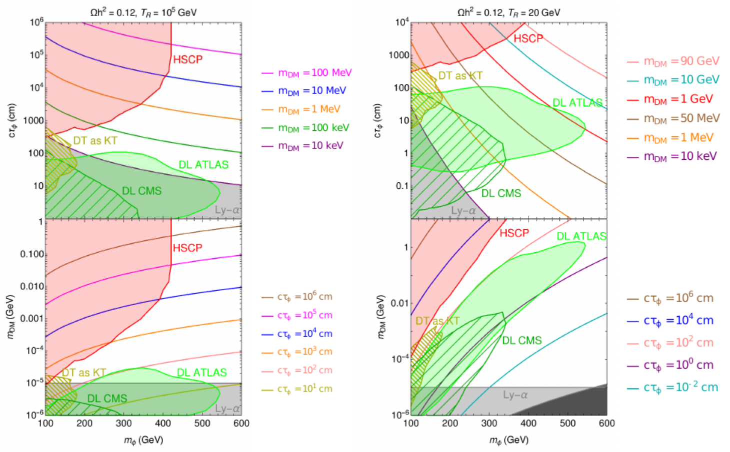
Collider searches



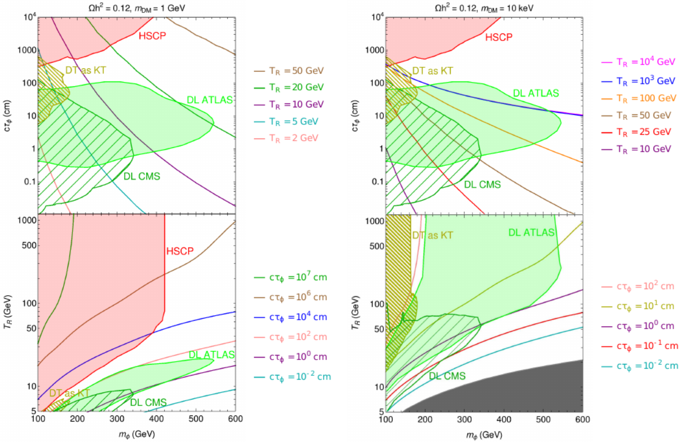
Collider searches

Signature	Exp. & Ref.	$\mathcal{L}$	Maximal sensitivity	Label
R-hadrons	CMS [48]	12.9 fb^{-1}	$c\tau \gtrsim 10$ m	RH
Heavy stable charged particle	ATLAS [49]	36.1 fb^{-1}		HSCP
Disappearing tracks	ATLAS [50]	36.1 fb^{-1}	$c\tau \approx 30$ cm	DT
	CMS [51, 52]	140 fb^{-1}	$c\tau \approx 60$ cm	
Displaced leptons	CMS [53]	19.7 $\text{fb}^{-1\dagger}$	$c\tau \approx 2$ cm	DL
	CMS [54]	2.6 fb^{-1}		
	ATLAS [55]	139 fb^{-1}	$c\tau \approx 5$ cm	
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

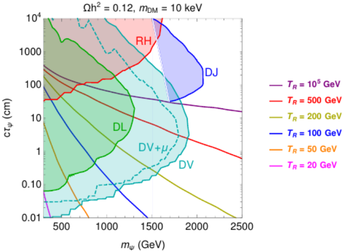
Leptophilic DM

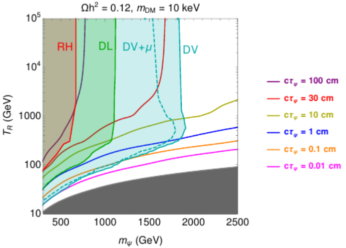


Leptophilic DM



Topphilic DM

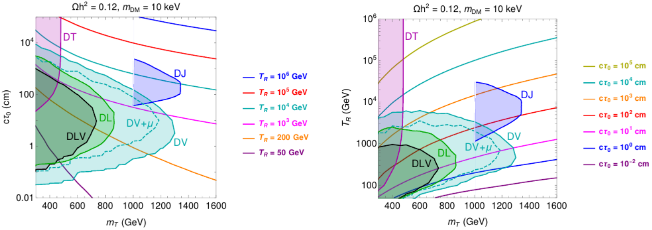




Singlet-Triplet DM

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

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



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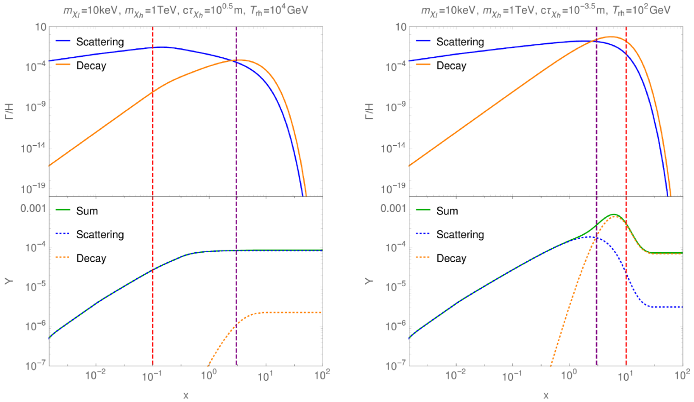

bla

This is really the end