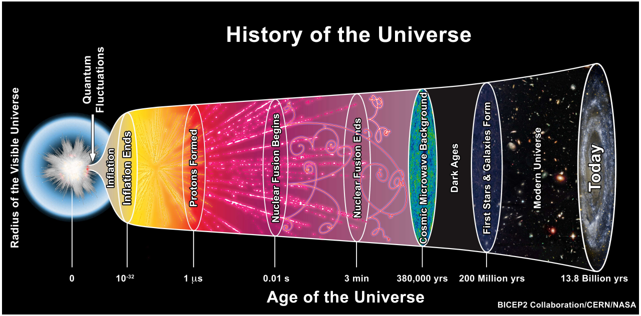
Cosmology versus Colliders: Dark Matter as an illustrative case

Laura Lopez Honorez

inspired by JCAP 10 (2013) 025, JHEP 07 (2019) 136, JHEP 05 (2021) 234 and JCAP 03 (2022) 041 in collab. with L. Calibbi, Q. Decant, F. d'Eramo, F. Giacchino, J. Heisig, D. Hooper, S. Junius, A. Mariotti, and M. Tytgat.

LFC22: Strong interactions from QCD to new strong dynamics at LHC and Future Colliders (ECT Trento - 29-02/08/22)

Universe history and Cosmology probes



- EW breaking scale $T \sim 150$ GeV and QCD breaking $T \sim 200$ MeV
- BBN at $T \sim 0.1$ MeV and $z_{\rm BBN} \sim 10^{10}$
- CMB at $T \sim$ eV and $z_{\rm CMB} \sim 10^3$
- Galaxy surveys probe $z \lesssim 5$,...
- SNIa (DE etc) , GW (sym. breaking, BH, etc), 21 cm surveys ($z \sim 5 - 20$), etc

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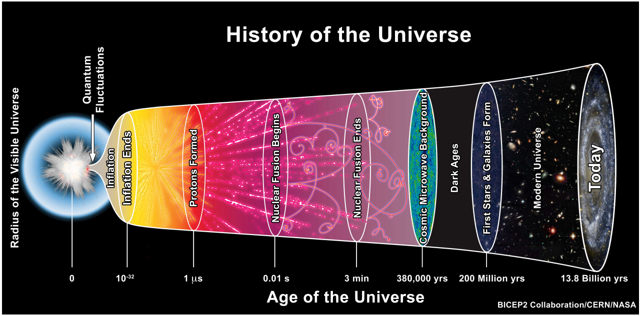

- EW breaking scale $T \sim 150$ GeV and QCD breaking $T \sim 200$ MeV
- BBN at $T \sim 0.1$ MeV and $z_{\rm BBN} \sim 10^{10} \rightsquigarrow$ constrains Ω_b, $\tau_{\rm exotic} \gtrsim t_{BBN}$,...
- CMB at $T \sim$ eV and $z_{\rm CMB} \sim 10^3 \rightsquigarrow \Omega_{\rm DM}, \Omega_{\rm b}$ to sub% precision, $\sigma v_{\rm ann}$ bound, ...
- Galaxy surveys probe $z \lesssim 5$ $\rightsquigarrow \Omega_m$, Matter distribution, WDM,...
- SNIa (DE etc) , GW (sym. breaking, BH, etc), 21 cm surveys ($z \sim 5 - 20$), etc

Complementary Cosmology Probes: Universe Content

Only 5% of the Universe is made of Baryonic Matter
80% of the Matter content is made of Dark Matter

Beyond the Standard Model: Minimal Models

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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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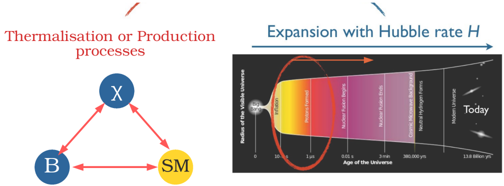
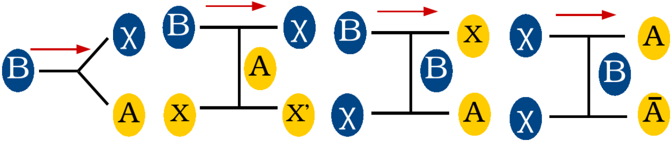
- DM production at early times: Particle Physics vs Cosmology

$$\mathcal{R}_{\text{thermal.,prod.}} \sim H(T)$$



“t-channel” DM coupling to $\psi_{\rm SM} = l_R$ or t_R

Production in the early universe



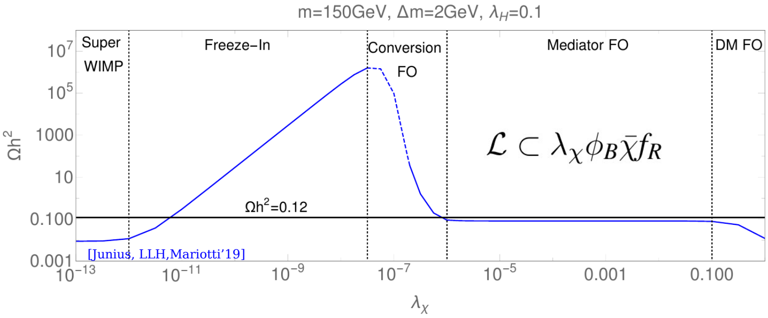
$A_{\rm SM}$	Spin DM	Spin B	Interaction	Label
$\psi_{\rm SM}$	0	1/2	$\bar\psi_{\rm SM}\Psi_B\phi$	$\mathcal{F}_{\psi_{\rm SM}\phi}$
	1/2	0	$\bar\psi_{\rm SM}\chi\Phi_B$	$\mathcal{S}_{\psi_{\rm SM}\chi}$
$F^{\mu\nu}$	1/2	1/2	$\bar\Psi_B\sigma_{\mu\nu}\chi F^{\mu\nu}$	$\mathcal{F}_{F\chi}$
H	0	0	$H^\dagger\Phi_B\phi$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

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

In this talk illustrative case of $\psi_{\rm SM} = t_R, l_R$ coupling to:

- “mediator” (Φ_B/Ψ_B) = charged/colored dark scalar/fermion (Z_2 odd)
- DM (χ)= dark Majorana fermion/real scalar singlet (Z_2 odd)

DM cosmo production: from freeze-out to superWIMP



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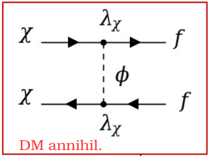

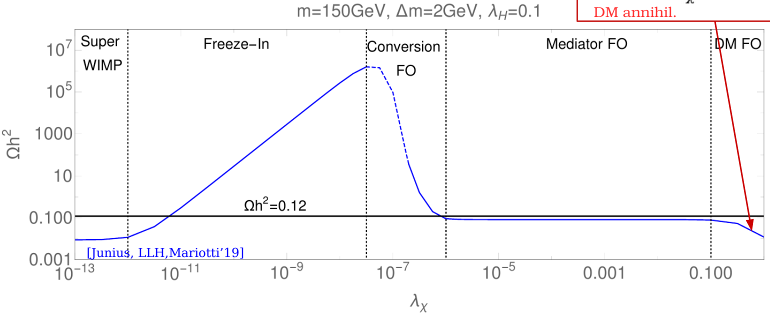

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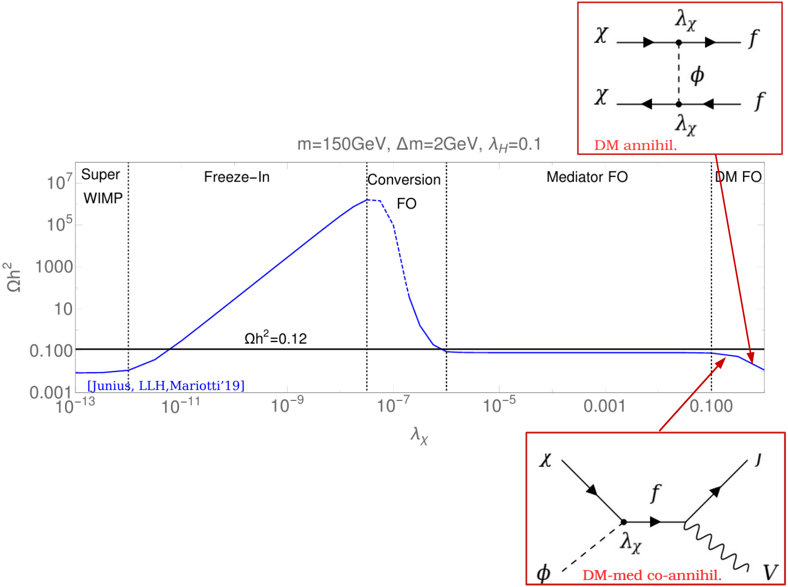

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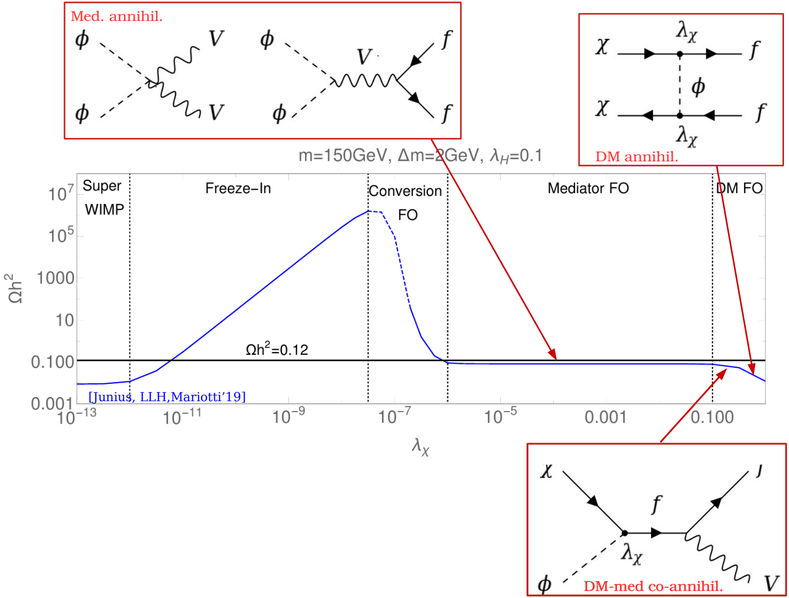

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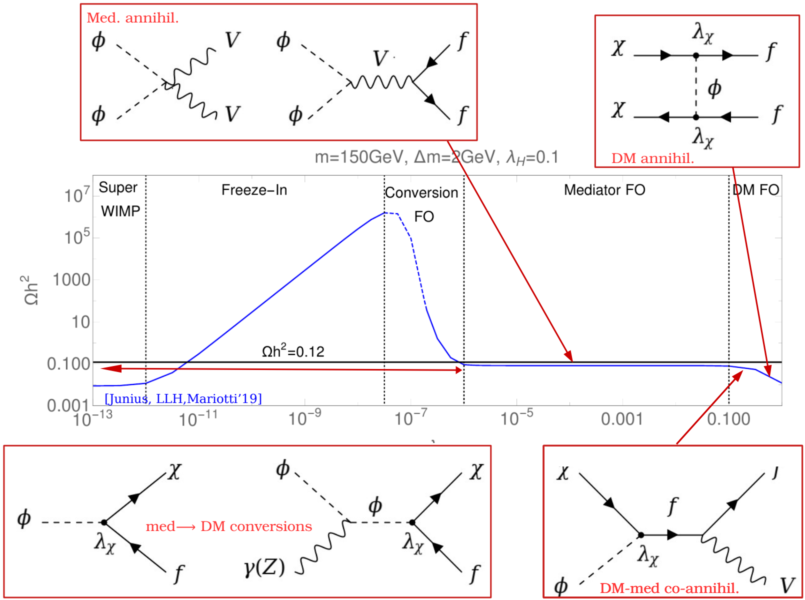
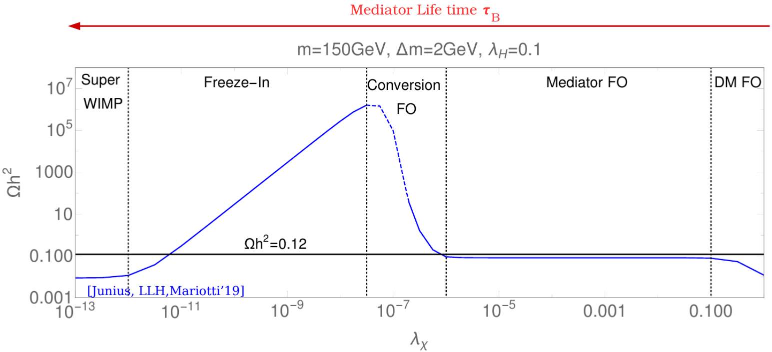


DM cosmo production: Colliders vs Cosmology



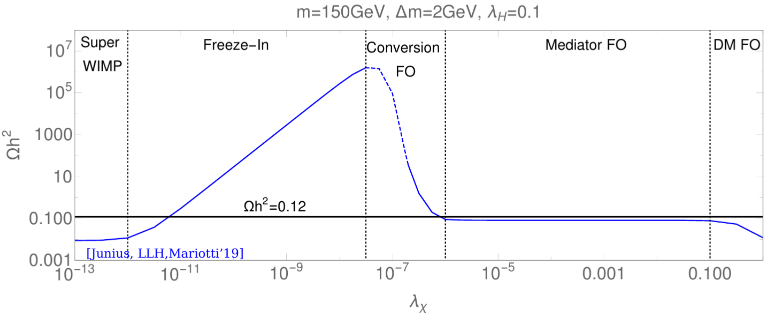
DM cosmo production: Colliders vs Cosmology

Collider Searches

Prompt searches: Monojet +MET, Multjet +MET, ttbar+ MET etc

Displaced searches: R-hadrons, HSCP, DV, DJ, DT, Kinked tracks, etc

Mediator Life time τ_B



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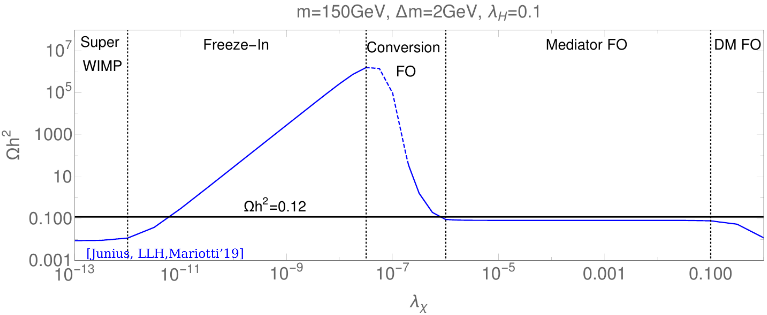


Cosmology constraints

DM relic abundance (CMB +LSS)

DM free-streeming (Lyman-alpha)

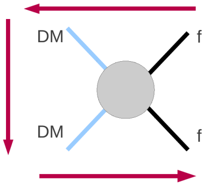
DM annihilation (CMB)

B late decay into EM, hadrons, rad (BBN, CMB)

Freeze-outs

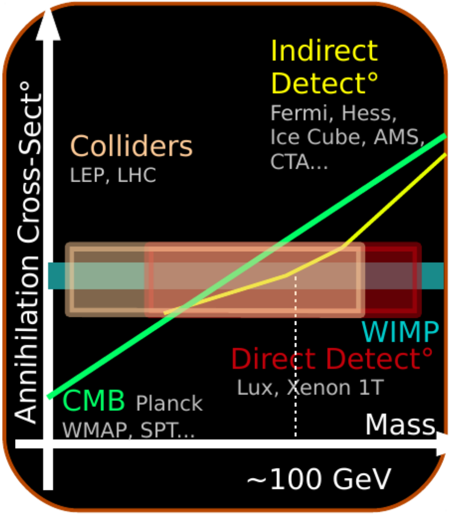
mainly based on JCAP 10 (2013) 025,
JCAP 08 (2014) 046, JHEP 07 (2019) 136
in collab. w/ F. Colucci, B. Fuks, F. Giacchino, M. Tytgat & J. Vandecasteele

The “simple” picture of WIMP freeze-out

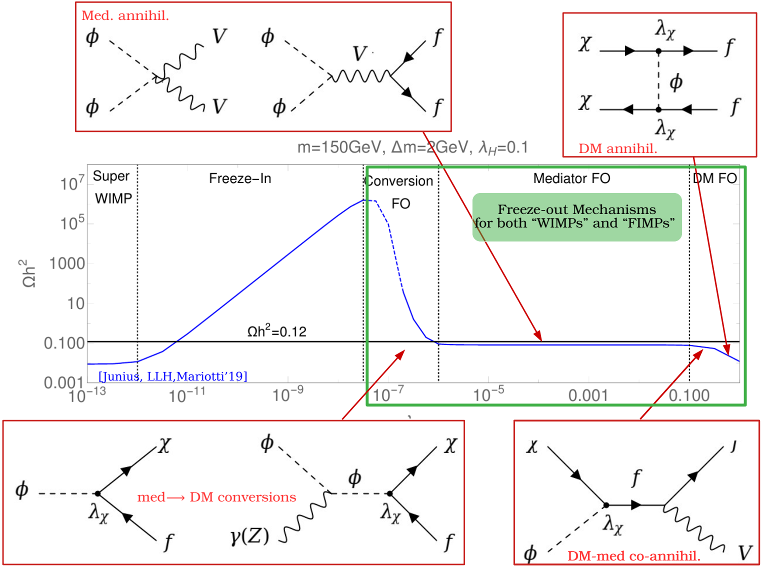


⇝ WIMPs at the verge of discovery/exclusion

see e.g. [Arcadi'17]

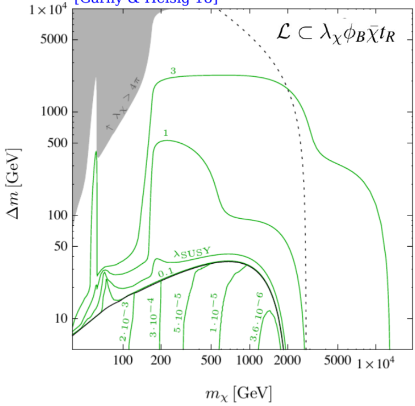


DM freeze-outs: much more than the simplest WIMP

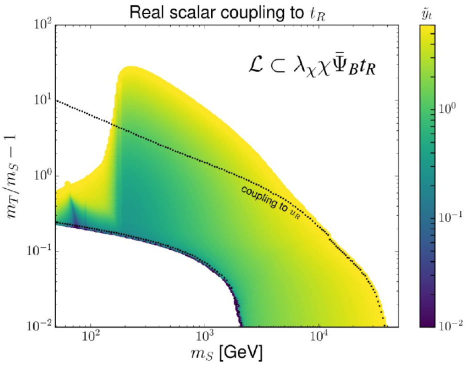


Freeze-out parameter space & particle physics constraints

[Garny & Heisig'18]



[Colucci, Fuks,Giacchino, LLH, VandeCasteele'18]



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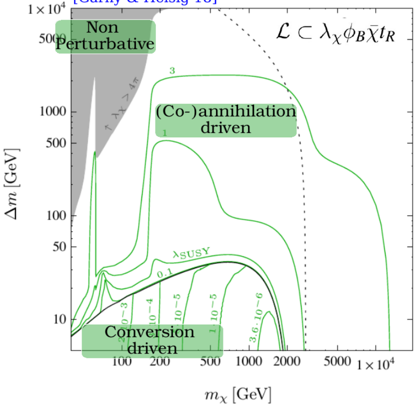

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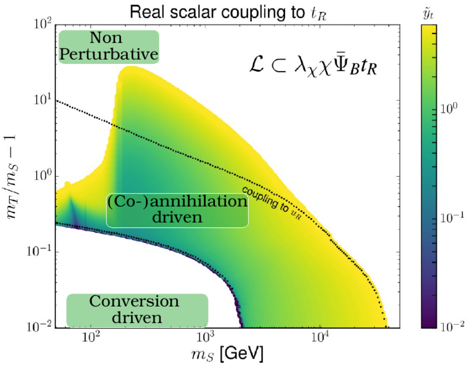

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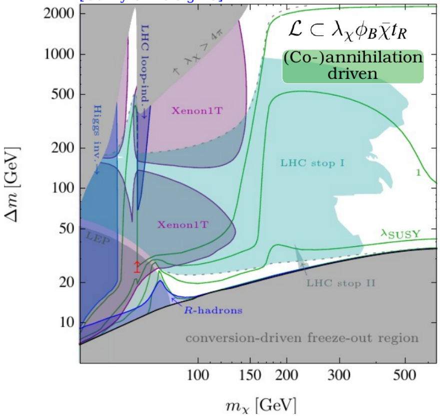

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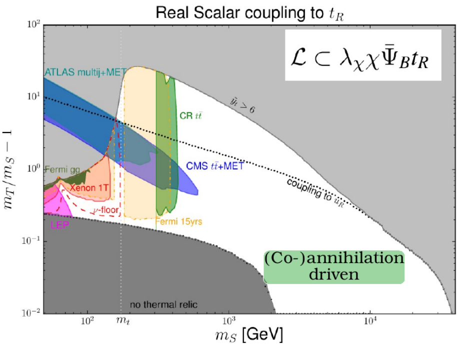

- Top-philic DM: Colliders probe a large parameter space, Direct and Indirect DM as well. see [Garny'18-22; Colucci'18], see also [Arina'20]
- Lepto-philic DM: Interesting line-like signal from $\chi\chi \to \gamma ll$ (VIB stronger for real scalar DM!)+ LEP Collider

see also [Bergstrom'89,Flores'89,Bringmann et al'12, Toma'13, Giacchino'13-15; Garny'11-17; etc]

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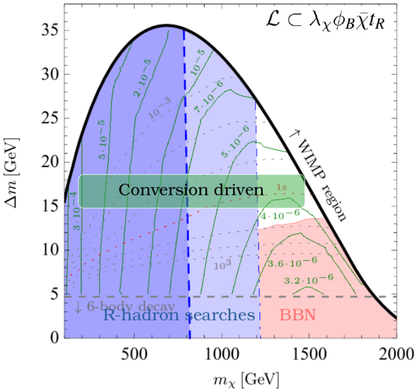

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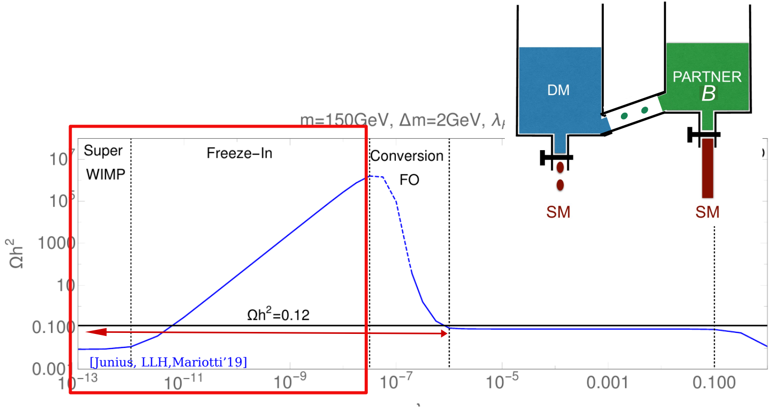
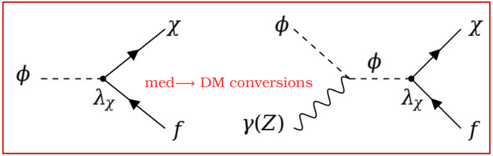
FIMPs from Freeze-in and SuperWIMP

Q. Decant, J. Heisig, D.C Hooper & LLH, arXiv:2111.09321

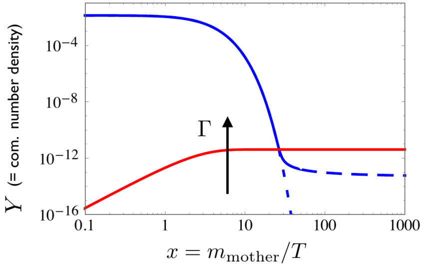
FIMPs from FI & superWIMP





FIMPs from freeze-in

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



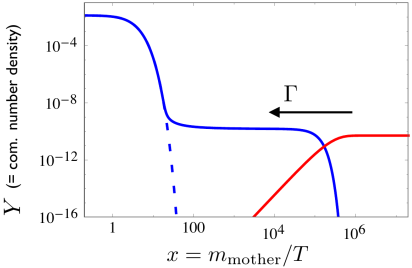
- χ decoupled
- B in chem. & kin. equilibrium
- $\Omega_\chi h^2 \propto \Gamma_{B\to\chi} M_p / m_B^2 \sim R_\Gamma$
- $\Omega_\chi h^2 = 0.12 \rightsquigarrow \lambda_\chi \lesssim 10^{-8}$
- $x = m_B/T$ and $x_{\rm FI} \sim 3$

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

Zero χ initial abundance assumed.

FIMPs from superWIMP

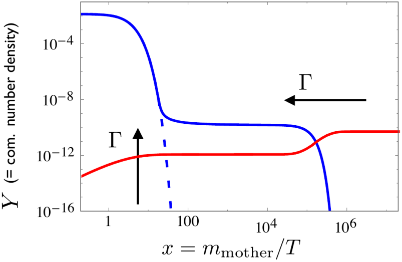
see also [Covi '99 ;Feng '03]



- 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 $x_{\rm SW} \sim R_\Gamma^{-1/2} > 3$

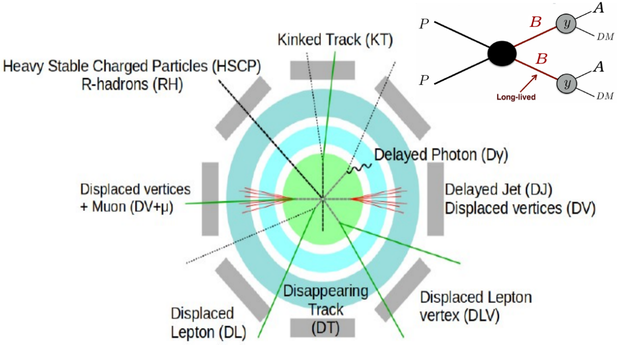
FIMPs from FI & superWIMP

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 and Long lived Mediators



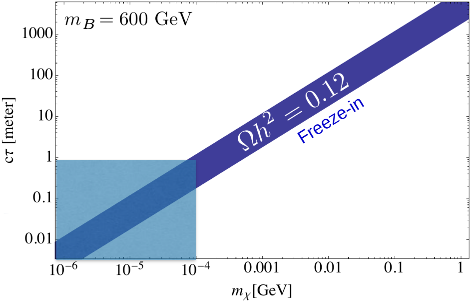
- FIMP= feebly interacting massive particle, i.e. $\lambda_\chi \ll 1$
- $\lambda_\chi \ll 1$ and $\Delta m/m < 1 \rightsquigarrow$ possibly $c\tau_B >$ collider detector size.
- B long lived particle (LLP), heavy stable particle and displaced events

FIMPs: LLPs and Non Cold DM (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



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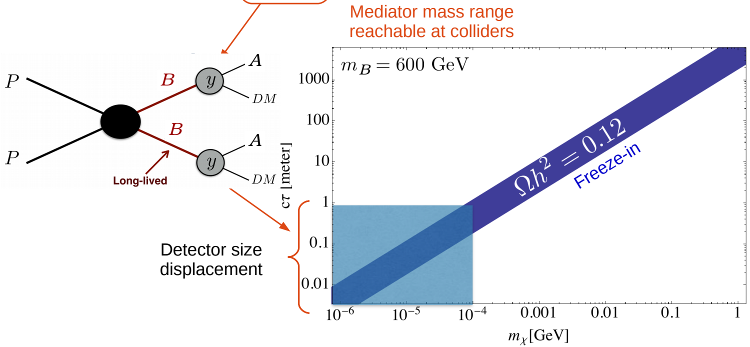

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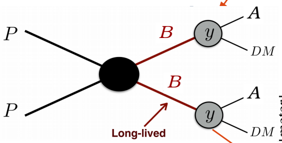
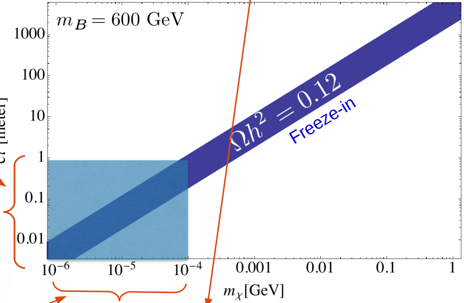
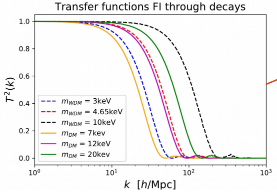
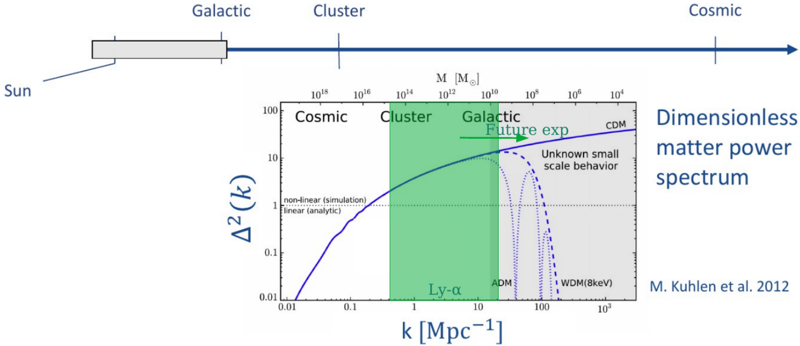






Warm DM like signatures
Suppressing small scale structures

Non-Cold Dark Matter

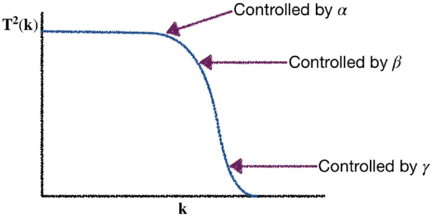


- WDM free-streeming from overdense to underdense regions
  $\rightsquigarrow$ Smooth out inhomegeneities for $\lambda \lesssim \lambda_{FS} \sim \int v/adt$
- Effects $P(k)$ and $T(k)$ generalized to Non-Cold DM see e.g. [Bode'00, Viel'05, Murgia'17], including non-thermal DM from freeze-in or superWIMP.

Non-Cold Dark Matter

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

[Murgia'17]



[Courtesy DC Hooper]

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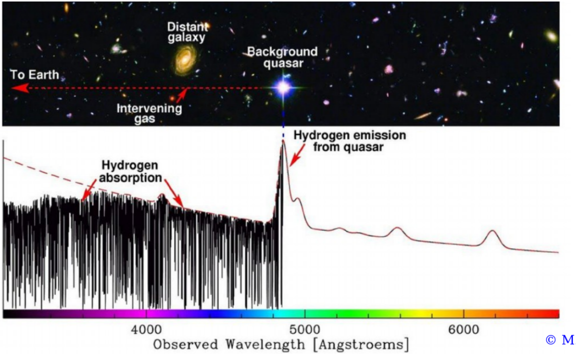

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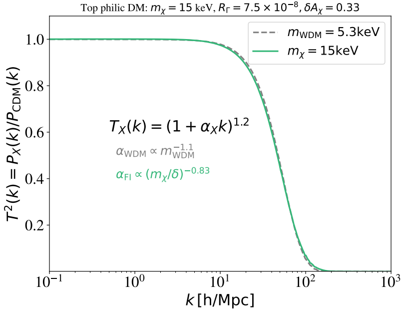
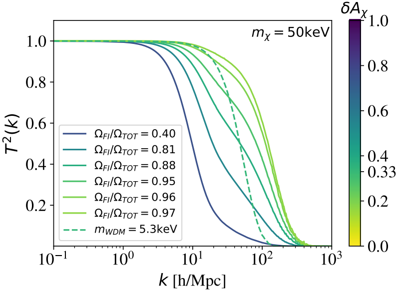
- Effects $P(k)$ and $T(k)$ generalized to Non-Cold DM see e.g. [Bode'00, Viel'05, Murgia'17], including non-thermal DM from freeze-in or superWIMP.
- Tested against Lyman-α: absorption lines along line of sights to distant quasars probe smallest structures $\rightsquigarrow$ $m_{\rm WDM}^{\rm thermal}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

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

FI & SW: WDM-like and deviations

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





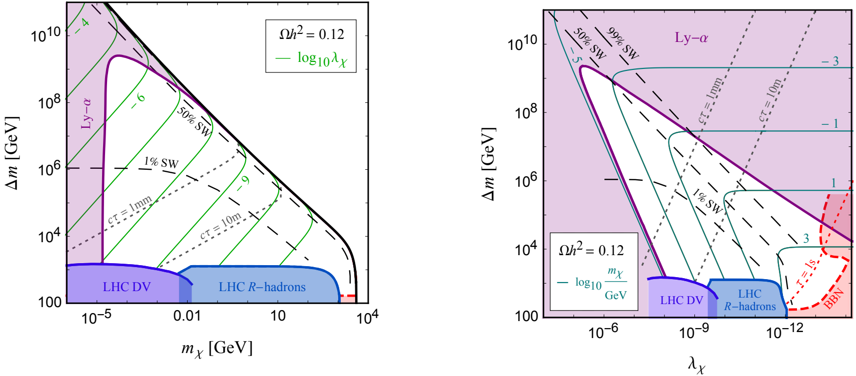
- Contrarily to "usual" WDM, FIMPs are non-thermaly produced.
- Using CLASS: Pure FI/SW transfer functions similar to thermal WDM.
  $\rightsquigarrow$ Lower mass bound from Lyman-α $(m_B \ll m_A,\, T_{\rm prod} > T_{\rm EW})$:

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

[Decant, Heisig, Hooper,LLH'21]

FIMPs: very nice Interplay Cosmo-Colliders

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]



- 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.

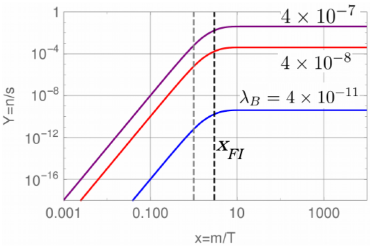
FIMPs from Freeze-in in an Early Matter Dominated Era (low T_{RH})

Calibbi, d'Eramo, Junius, LLH & Mariotti, JCAP 05 (2021) 234

lower T_{RH} implies smaller $c\tau_B$

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

in Radiation Dominated (RD) era



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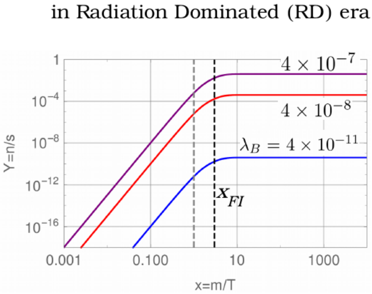
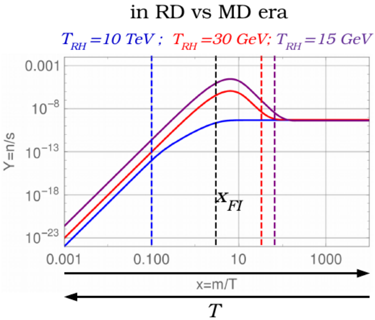




DM yield is diluted due to extra entropy production from inflaton decay:

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

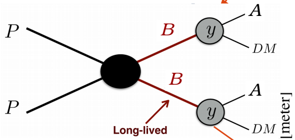
$\rightsquigarrow$ The lower T_{RH}, the longer is the dilution and the lower is Y_X^∞ compared to $Y_X(T_{FI})$, the higher is λ_B to account for DM abundance and the lower is $c\tau_B$.

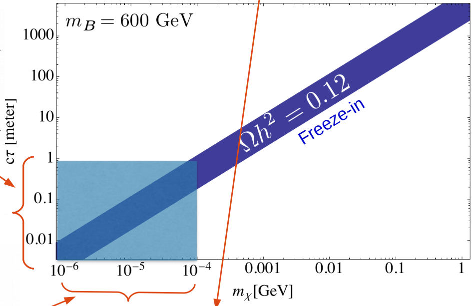
FI in MD era can evade "Ly-α constraints"

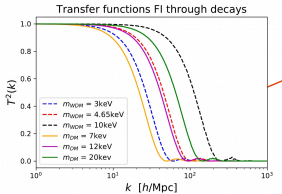
e.g. [Hall'09, Co'15, Hessler'16, d'Eramo'17, Heeck'17, Boulebnane'17, Brooijmans'18, Garny'18, Calibbi'18, No'19, Belanger 18, etc]

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

Mediator mass range
reachable at colliders







Warm DM like signatures
Suppressing small scale structures

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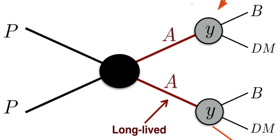
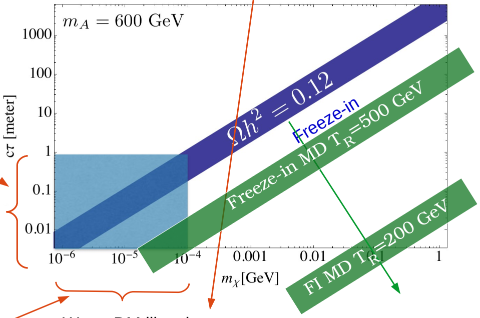
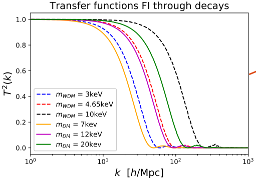
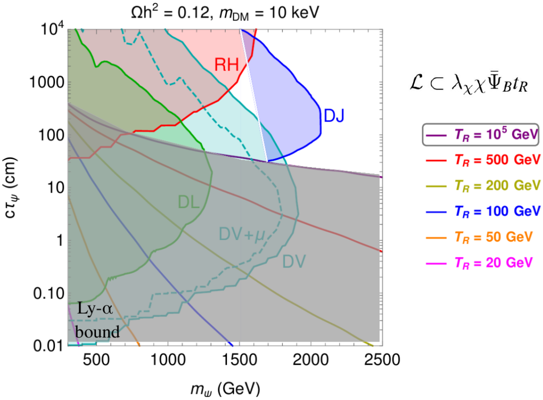






Warm DM like signatures
Suppressing small scale structures

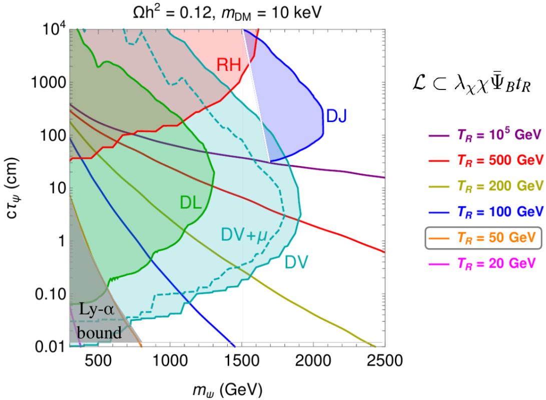
Unexpected displaced events



$\mathcal{L} \subset \lambda_\chi \chi \bar{\Psi}_B t_R$

Unexpected dislaced events at colliders might point to freeze-in with modified early universe cosmology diluting DM (e.g. EMDE with low T_{RH} see [Calibbi'21], also [Arias'20])

Unexpected displaced events



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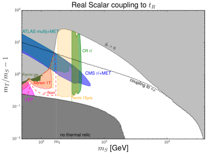
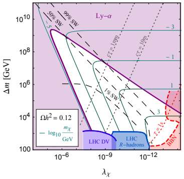
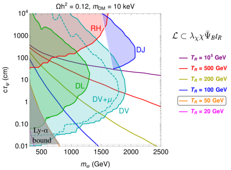
Conclusion







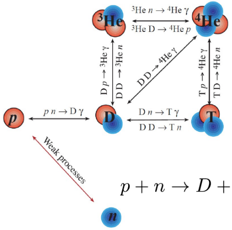
The exemplary "Simple" t-chanel DM scenario are quite rich in the end:

- WIMPs from freeze-out: still quite much viable parameter space open:
  - higher order processes ($\chi\chi \to V\bar{f}f, VV$) have to be taken into account
  - Colliders and Indirect DM searches can play a key role
- FIMPs from conversion-driven FO, freeze-in, & superWIMP: Despite very feeble couplings to SM, DM models are viable
  - LLP at colliders with displaced signatures.
  - Changing cosmology (T_R) may lead to unexpected displaced events.
  - FI & SW: FIMPs ~ NCDM and Lyman-α forest constraints $m_{\rm DM} \gtrsim 15$ keV (FI) or up to few 100 GeV (SW).

Thank you the invitation
and for your attention!!

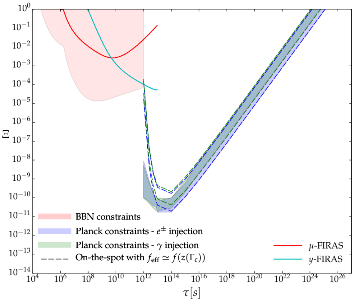
Backup

Big Bang Nucleosynthesis and light elements abundance



$$p + n \to D + \gamma$$

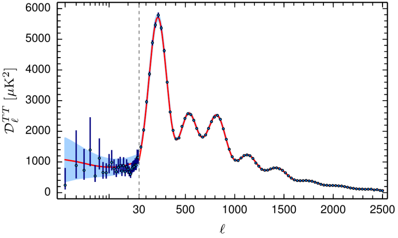
$$T^D_{\rm nuc} \approx \frac{B_D}{\log {\eta_B}^{-1}}$$



SM and BSM constraints

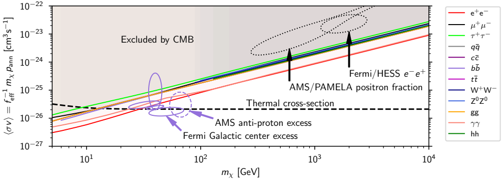
- Baryon asymmetry $\eta_B = \frac{n_b - n_{\bar{b}}}{n_\gamma} = (6.9 \pm 0.06) \times 10^{-10}$ and abundance
- Expansion rate $H(z)$ and number of relativistic dof ($N_{\rm eff}$)
- MeV BSM particles interactions with γ, e, ν
- Decay of exotic long lived particles with $\tau \gtrsim t_{\rm BBN}$
- etc

Cosmic Microwave Background

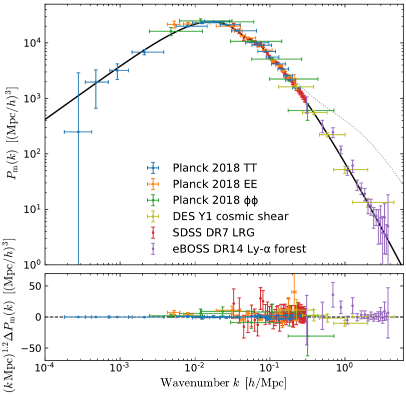


SM and BSM constraints

- Precise content of the ΛCDM (to sub% level)
- Expansion rate ($H(z)$) and nb of relativistic dof ($N_{\rm eff}$)
- Exotic energy injection into CMB (annihilation, decay, tec)
- etc

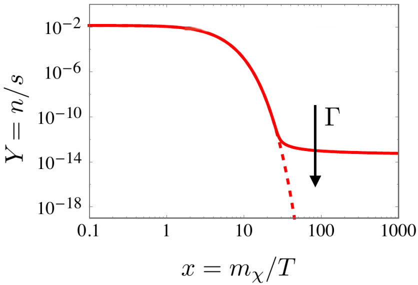


Galaxy surveys



- Precise measurements of BA0 at $z \sim 0.2 - 0.5$ and $k \sim 0.15/h$ Mpc $\rightsquigarrow$ independent measurement of Ω_b, Ω_m and $H(z)$.
- Quasar spectra from $z \sim 2 - 5$ and $k \sim 0.5 - 20/h$ Mpc $\rightsquigarrow$ Lyman-α forest constrs on Warm DM mass
- etc

Freeze-outs: from WIMP to FIMP



- DM annihilation FO:
  $\Omega_\chi \propto 1/\langle\sigma v\rangle_{\chi\chi}$
  "WIMP" simple picture
  $\lambda_\chi \gtrsim 10^{-2}$

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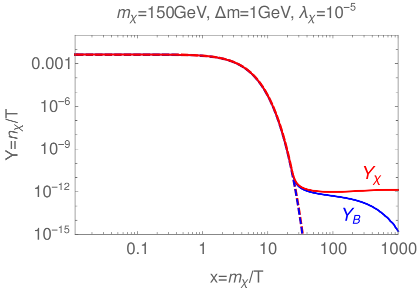

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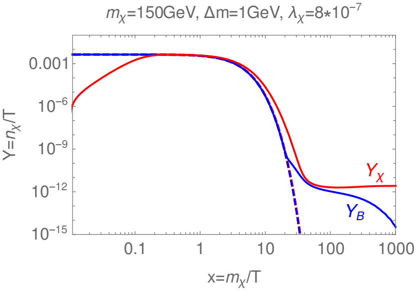
- Mediator (co-)ann. FO:
  $\Omega_\chi \propto 1/\langle\sigma v\rangle_{eff}$
  $\langle\sigma v\rangle_{eff} \sim \sigma v_{ij}$ weight $e^{-x(\Delta m_{i,j}/m)}$
  $\Delta m/m \lesssim 0.1$
  $10^{-2} \gtrsim \lambda_\chi \gtrsim 10^{-5}$

Freeze-outs: from WIMP to FIMP



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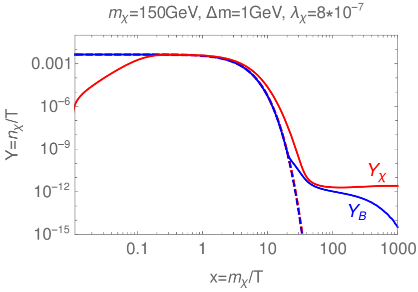

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Careful: for t-channel scenarios, potential large contributions from annihilations in $2 \to 3$ with Virtual Internal Bremsstrahlung (VIB) or loop induced $2 \to 2$, Sommerfeld and bound state formation.

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.

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

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

Can we translate WDM bound to FIMP?

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

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  $\Rightarrow \langle v_\chi \rangle|_{t_0}^{\rm SW} \propto m_\chi^{-1} \times R_\Gamma^{-1/2}$

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

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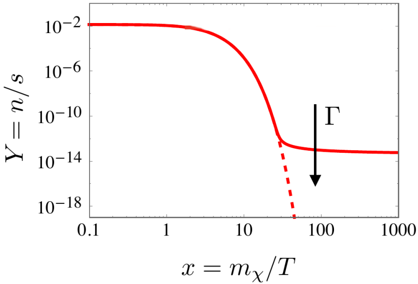
  $\Rightarrow \langle v_\chi \rangle|_{t_0}^{\rm SW} \propto m_\chi^{-1} \times R_\Gamma^{-1/2}$

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

WIMP: χ annihilation driven freeze-out

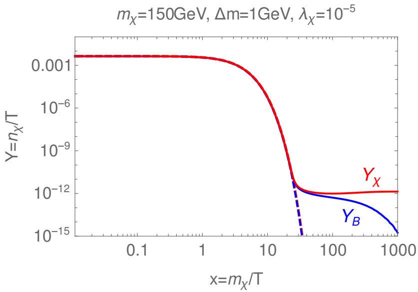


- $\Omega_\chi \propto 1/\langle\sigma v\rangle_{\chi\chi}$
- $\Omega_\chi h^2 = 0.12$
  $\rightsquigarrow \langle\sigma v\rangle_{\chi\chi} = 3 \times 10^{-26}\,\mathrm{cm^3/s}$
- DM annihilation driven freeze-out (FO)
- $x = m_\chi/T$ and $x_{\rm FO} \sim 25$

Careful: for t-channel scenarios, potential large contributions from annihilations in $2 \to 3$ with Virtual Internal Bremsstrahlung (VIB) or loop induced $2 \to 2$.

WIMP to FIMP: *B* (co-)annihilations driven FO

[Griest '91, Gondolo'91, Edsjo'97 etc]



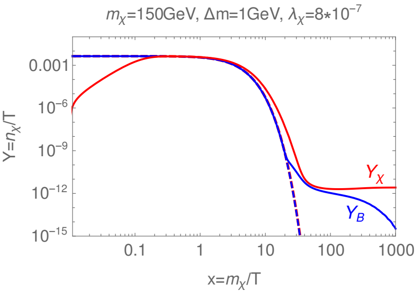
- $\Omega_\chi \propto 1/\langle\sigma v\rangle_{eff}$
  σv_{eff} is a weighted sum of $\exp(-x(\Delta_j + \Delta_i)) \times \sigma v_{ij}$
- $\Omega_\chi h^2 = 0.12$ possible for $\langle\sigma v\rangle_{\chi\chi} \ll 3 \times 10^{-26}\,\text{cm}^3/\text{s}$
- possible co-annihilation/partner annihilation driven FO
- $x = m_\chi/T$ and $x_{\text{FO}} \simeq x^B_{\text{FO}} \sim 25$

For compressed spectra $\Delta_i = (m_i - m_\chi)/m_i \lesssim 0.1$ with $i = B$
co-annihilations play an important role

Careful: for t-channel scenarios, potential large corrections from Sommerfeld and Bound states effects on σv_{BB}!

"FIMP": Conversion driven freeze-out

see also [Garny'17-22, D'Agnolo'17-18, Junius'19, Herms'21, Filimonova'22, MicrOMEGAs'22]



- $\Delta m/m \lesssim 1$ **and** $\lambda_\chi < 10^{-5}$
- suppressed conversions: $\langle\Gamma_{B\to\chi}\rangle^{\text{dec,scat}} \lesssim H$
- conversion driven FO
- $\Omega_\chi h^2$ increases for decreasing λ_χ
- $x = m_\chi/T$ and possibly $x_{\text{FO}} \gg x^B_{\text{FO}} \sim 25$

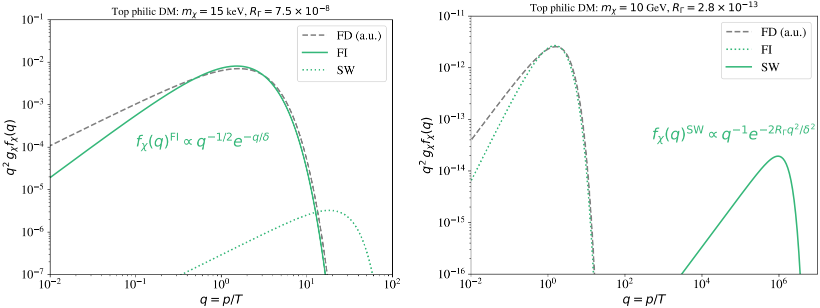
Beyond standard co-annihilation/partner annihilation FO:

$B \leftrightarrow \chi$ are prevented, i.e. $\chi - B$ chemical decoupling well before FO:

$n_\chi > n_\chi^{eq}$ for $x \lesssim x_{\text{FO}}, x^B_{\text{FO}}$

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]

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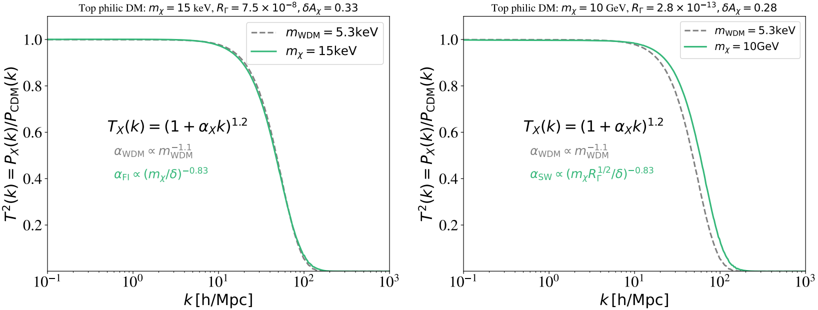

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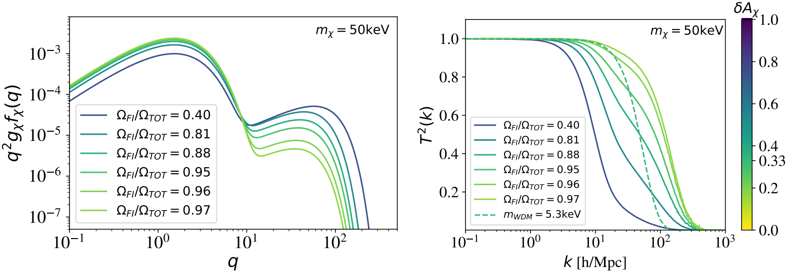
- Using CLASS: Pure FI/SW transfer functions similar to thermal WDM. $\rightsquigarrow$ Lower mass bound from Lyman-α ($m_B \ll m_A$, $T_{\rm prod} > T_{\rm EW}$) :

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

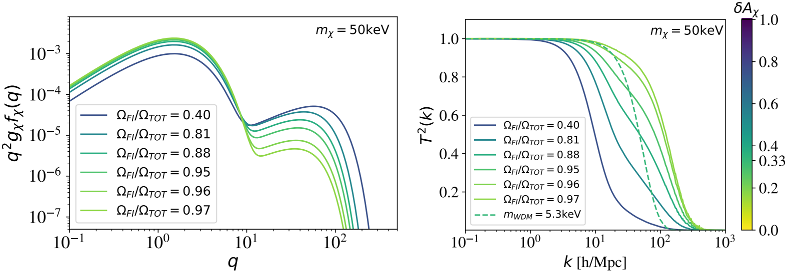
[Decant, Heisig, Hooper,LLH'21]

Mixed FI & SW: significant deviations from WDM



- Mixed FI-SM $q^2 f_\chi$ is multimodal $\rightsquigarrow T^2(k) = P_{\rm FIMP}(k)/P_{\rm CDM}(k)$ 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 $0.5h/\text{Mpc} < k < 20h/\text{Mpc}$: $\delta A_\chi < \delta A_{\rm WDM}^{ly-\alpha} = 0.33$ for $m_{\rm WDM}^{\rm Ly-\alpha} > 5.3$ keV

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

Minimal models for 3 body interactions

$A_{\rm SM}$	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	$\psi_{\rm SM}\chi\Phi_B$	$\mathcal{S}_{\psi_{\rm SM}\chi}$
$F^{\mu\nu}$	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]

Possible processes for DM production in the early universe:

- (co-)annihilations: $\chi\chi \to XX'$, $\chi B \to XX'$ & $BB \to XX'$
- conversions: $B \to A\chi$ & $BB' \to \chi A$

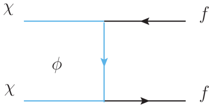
Leptophilic DM: Annihilation in Chiral limit ($m_f \to 0$)

[Bergstrom '89+, Bringmann '08+, Ciafaloni '11, Garny '11+,Toma '13, Giacchino'13+, Ibarra'14]

DM = Majorana χ

$\mathcal{L} \supset \lambda_\chi \phi^\dagger \chi f_R + h.c.$

$$Z_2 \,:\, \chi \to -\chi, \Phi \to -\Phi$$



$$r = \frac{M_\phi}{M_\chi}$$

$$\sigma v_{ff}|_\chi = \frac{\lambda_\chi^4}{48\pi} \frac{v^2}{M_\chi^2} \frac{1 + r^4}{(1 + r^2)^4}$$

p-wave suppressed ($\propto v^2$ for $m_f \to 0$)

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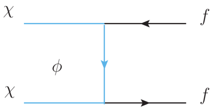

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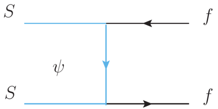
p-wave suppressed ($\propto v^2$ for $m_f \to 0$)

DM = Real Scalar S

$$\mathcal{L} \supset y \, S \, \bar{\psi} f_R + h.c..$$

$$Z_2 \; : \; S \to -S, \Psi \to -\Psi$$



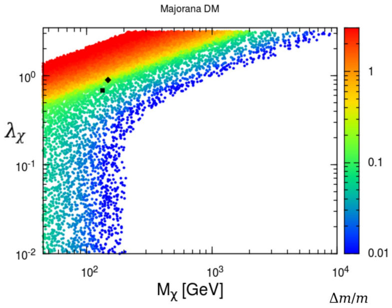
$$r = \frac{M_\psi}{M_S}$$

$$\sigma v_{ff}|_S = \frac{y^4}{60\pi} \frac{v^4}{M_S^2} \frac{1}{(1 + r^2)^4}$$

d-wave suppressed ($\propto v^4$ for $m_f \to 0$)

- DM DM $\to \bar{l}l$ is chirally ($\propto (m_f/M_{\rm dm})^2$) or velocity suppressed
- Annihilation processes show a dependence in $r = M_{\rm NLZP}/M_{\rm dm} \geq 1$
- At f.o. $\langle \sigma v \rangle_{ll}|_S / \langle \sigma v \rangle_{ll}|_\chi \lesssim 0.16 \rightsquigarrow$ larger Yukawas for S to match $\Omega_{\rm dm}$

Viable param. space for coupling to e_R



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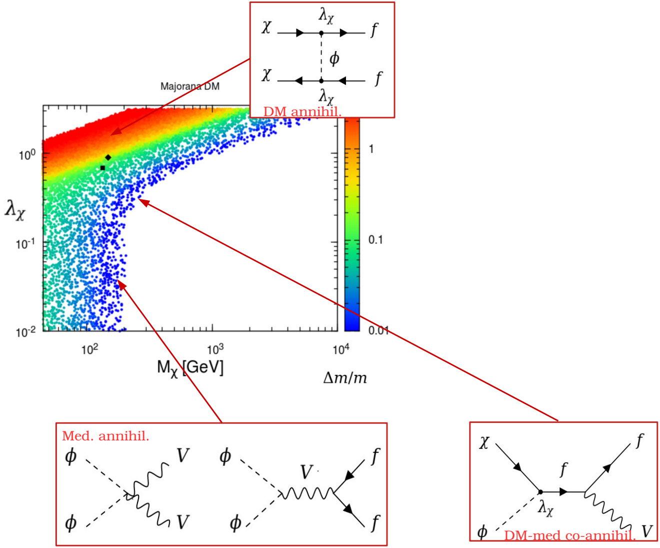

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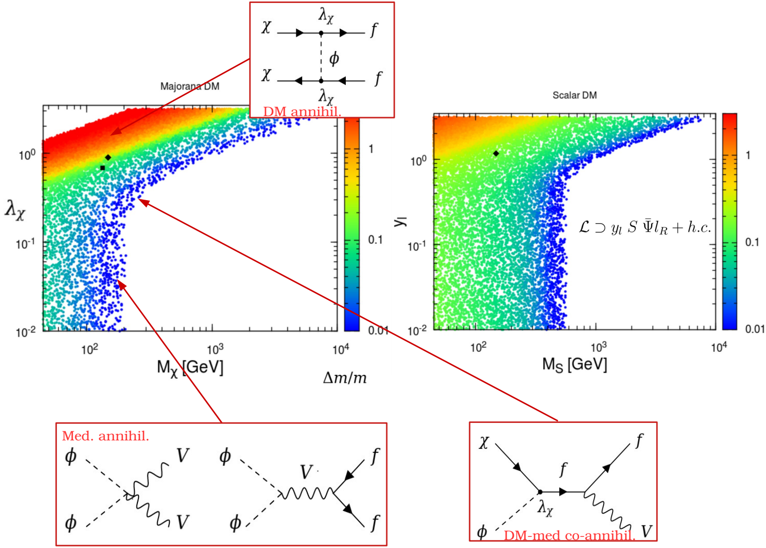
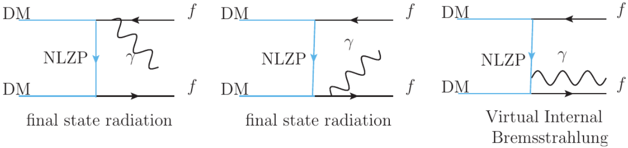


Sharp spectral feature from Internal Bremsstrahlung



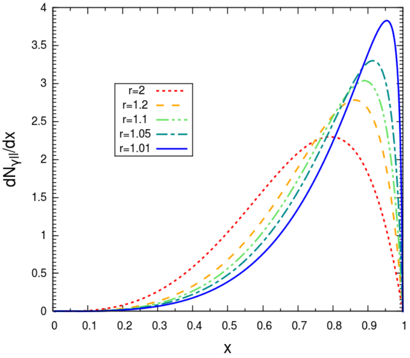
The γ spectrum

$$\frac{dN_{\gamma ll}}{dx} = \frac{M_{\rm dm}}{\sigma_{\gamma ll}} \frac{d\sigma_{\gamma ll}}{dE_\gamma}$$

as a fn of $x = \frac{E_\gamma}{M_{\rm dm}}$ and $r = \frac{M_{\rm NLZP}}{M_{\rm dm}}$

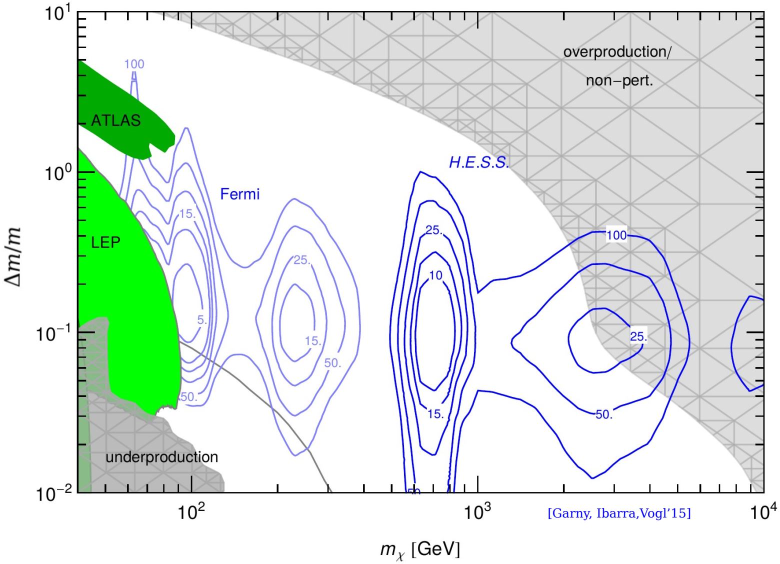
- peaked at $E_\gamma \sim M_{\rm dm}$ for $r \to 1$
- Identical for Scalar & Majonana

[see also Barger'11]



⇝ "γ line"-like feature with Bremsstrahlung emission

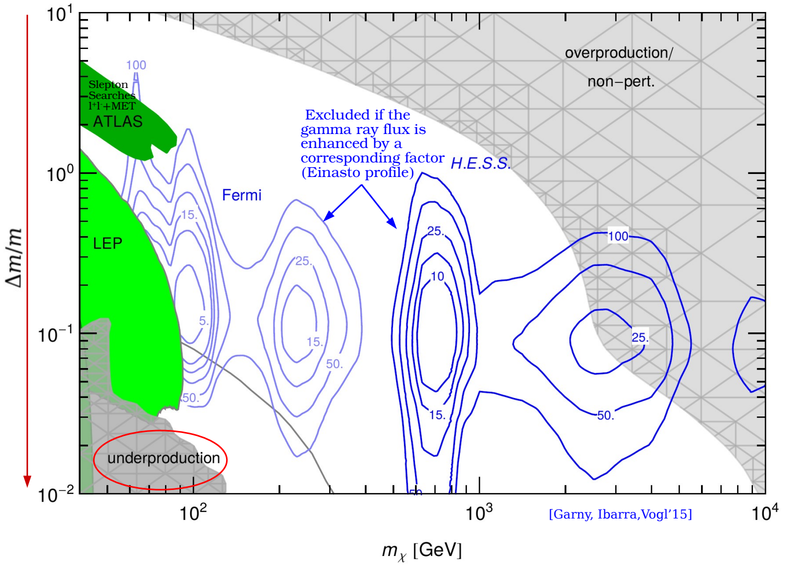
Leptophilic Fermionic DM: WIMP summary



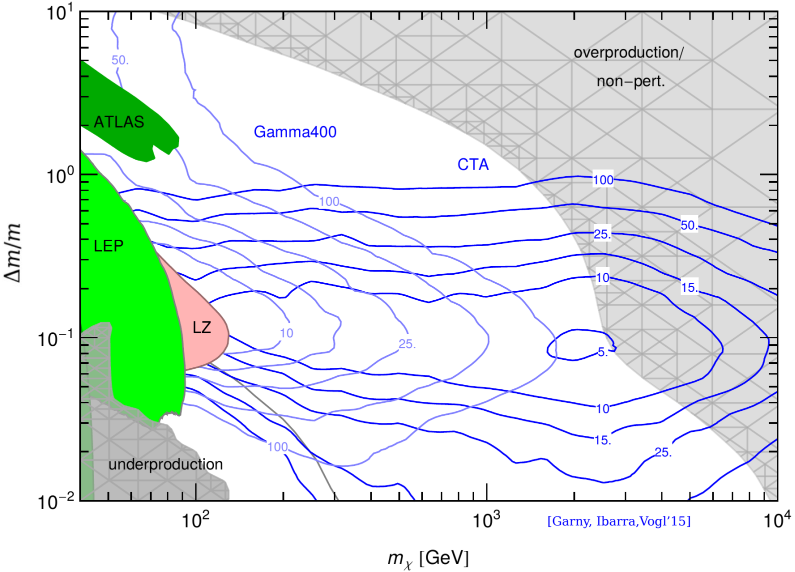
[Garny, Ibarra,Vogl'15]

Leptophilic Fermionic DM: WIMP summary

More Compressed→ smaller coupling needed



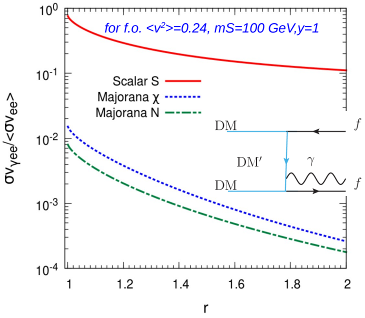
Leptophilic Fermionic DM: WIMP summary

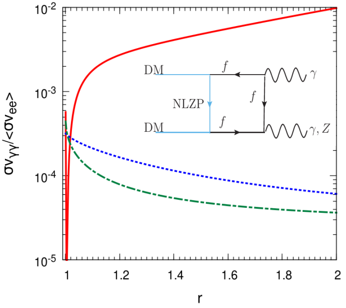


[Garny, Ibarra,Vogl'15]

Enhanced radiative processes for Scalars

see [Giacchino, LLH & Tytgat '13 &'14]
see also [Toma'13 & Ibarra'14]





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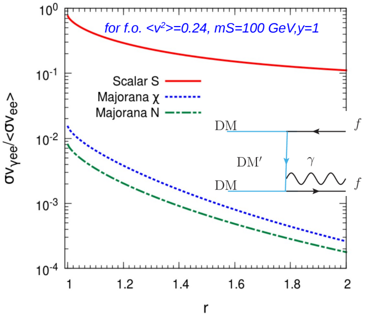
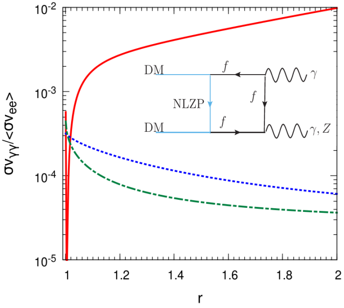




Relative enhancement min $\sim$ 50 of the Bremsstrahlung signal for scalar DM !!
Radiative processes $\gamma\gamma$, γee always more relevant for Real Scalar DM

$$\mathscr{L}_{\text{eff}} \supset \frac{d_M}{2}\,\bar{\chi}\sigma^{\mu\nu}\chi\,F_{\mu\nu} + \frac{d_E}{2}\,\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi\,F_{\mu\nu} + \mathcal{A}\,\bar{\chi}\gamma^{\mu}\gamma^5\chi\,\partial^{\nu}F_{\mu\nu}\,,$$

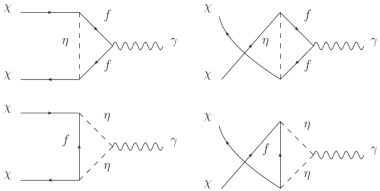
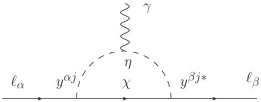


FIG. 3: The one loop diagrams generating the effective dark matter–photon coupling for Majorana DM. For Dirac DM, the two diagrams on the right are absent.

[Kopp,Michaels,Smirnov'14]

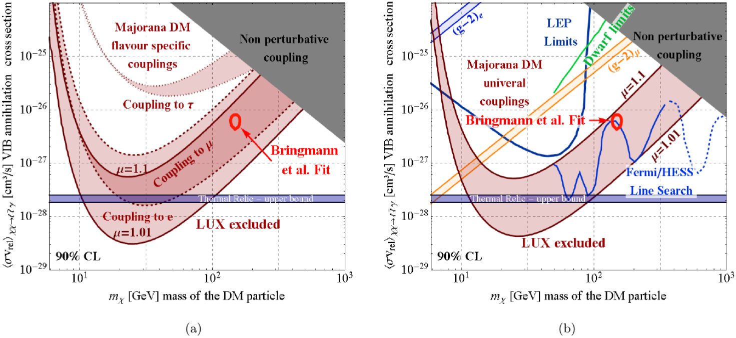
$$\mathcal{A} = -\frac{ey^2}{32\pi^2 m_\chi^2}\left[\frac{-10 + 12\log\xi - (3+9\mu)\log(\mu-1) - (3-9\mu)\log\mu}{9(\mu-1)}\right], \qquad (|q^2| \gg m_\ell^2)\,.$$



Process	Coupling	Limit
$\mu \to e\gamma$	$\left[\sum_j (y_R^{\mu j} y_R^{ej*})^2\right]^{1/2}$	$< 1.0 \times 10^{-4}$
$\tau \to \mu\gamma$	$\left[\sum_j (y_R^{\tau j} y_R^{\mu j*})^2\right]^{1/2}$	$< 7.0\ 10^{-2}$
$\tau \to e\gamma$	$\left[\sum_j (y_R^{\tau j} y_R^{ej*})^2\right]^{1/2}$	$< 6.1\ 10^{-2}$

[Kopp,Michaels,Smirnov'14]

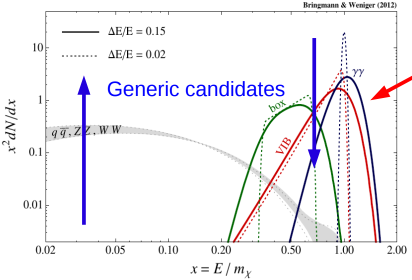
FIG. 8: New physics contribution to the lepton magnetic dipole moment ($\alpha = \beta$) and to flavor violating lepton decays ($\alpha \neq \beta$) in our simplified model.



Smoking gun evidences for WIMP DM

e.g. sharp spectral features, such as lines, in the gamma ray spectrum:

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\psi) = \frac{1}{8\pi}\int_{\Delta\psi}\frac{d\Omega}{\Delta\psi}\int_{\rm l.o.s} d\ell(\psi)\rho_\chi^2(\mathbf{r}) \times \left(\frac{\langle\sigma v\rangle_{\rm ann}}{m_\chi^2}\sum_f B_f \frac{dN_\gamma^f}{dE_\gamma}\right)$$



Careful!!

The importance of the "line" compared to the continuum depends on their relative contribution to the total annihilation cross-section

Conversion processes can affect the DM abundance

DM and mediator annihilation
and Co-annihilation processes

$$\frac{dY_{DM}}{dx} = \frac{s\langle\sigma v_{\rm eff}\rangle}{Hx}\left(Y_{DM}^2 - Y_{DM,eq}^2\right)$$

Conversion processes can affect the DM abundance

DM and mediator annihilation and Co-annihilation processes

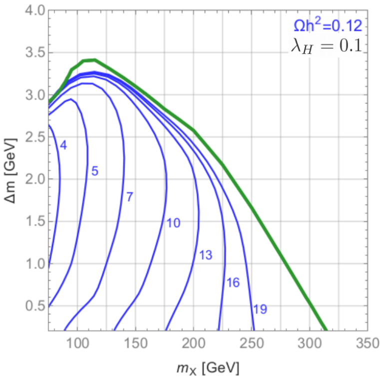
$$\frac{dY_\chi}{dx} = \frac{-2}{Hxs}\left[\gamma_{\chi\chi}\left(\frac{Y_\chi^2}{Y_{\chi,eq}^2}-1\right)+\gamma_{\chi\phi}\left(\frac{Y_\chi Y_\phi}{Y_{\chi,eq}Y_{\phi,eq}}-1\right)\right.$$
$$\left.+\gamma_{\chi\to\phi}\left(\frac{Y_\chi}{Y_{\chi,eq}}-\frac{Y_\phi}{Y_{\phi,eq}}\right)+\gamma_{\chi\chi\to\phi\phi^\dagger}\left(\frac{Y_\chi^2}{Y_{\chi,eq}^2}-\frac{Y_\phi^2}{Y_{\phi,eq}^2}\right)\right],$$

$$\frac{dY_\phi}{dx} = \frac{-2}{Hxs}\left[\gamma_{\phi\phi^\dagger}\left(\frac{Y_\phi^2}{Y_{\phi,eq}^2}-1\right)+\gamma_{\chi\phi}\left(\frac{Y_\chi Y_\phi}{Y_{\chi,eq}Y_{\phi,eq}}-1\right)\right.$$
$$\left.-\gamma_{\chi\to\phi}\left(\frac{Y_\chi}{Y_{\chi,eq}}-\frac{Y_\phi}{Y_{\phi,eq}}\right)-\gamma_{\chi\chi\to\phi\phi^\dagger}\left(\frac{Y_\chi^2}{Y_{\chi,eq}^2}-\frac{Y_\phi^2}{Y_{\phi,eq}^2}\right)\right],$$

DM and mediator Conversion processes

Conversion driven FO: Viable parameter space

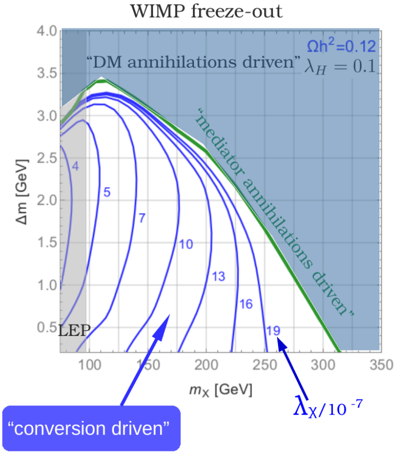
$\lambda_\chi \lesssim$ few $\times 10^{-6}$, $\Delta m <$ few GeV and $m_\chi \sim$ few $\times$ 100 GeV



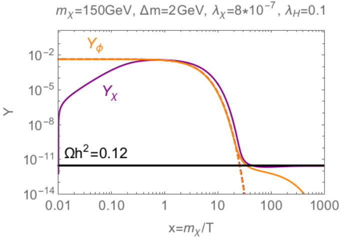
Conversion driven FO: Viable parameter space

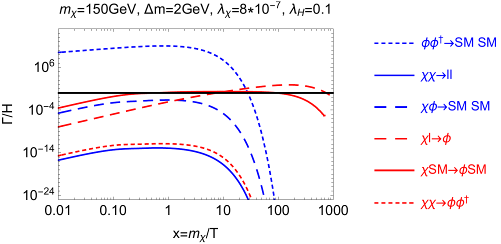
$\lambda_\chi \lesssim$ few $\times 10^{-6}$, $\Delta m <$ few GeV and $m_\chi \sim$ few $\times$ 100 GeV

- right limit: freeze-out driven by mediator annihilations
- left limit: LEP constraints on charged mediators
- bottom limit: $\Delta m > m_l$ (or beyond $2 \to 2$)

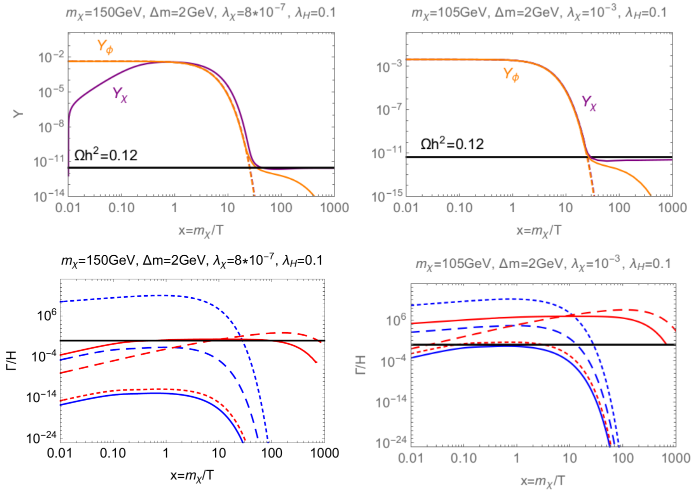


Conversion driven

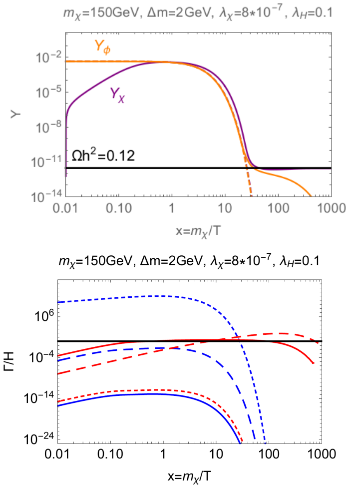




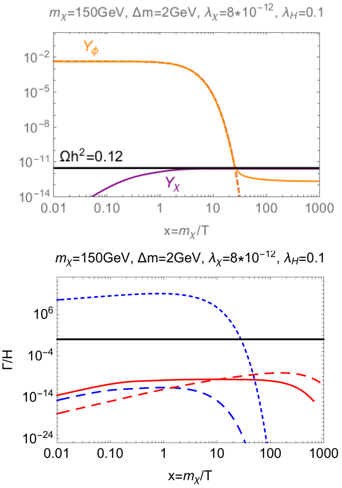
Conversion driven | Co-annihilation driven



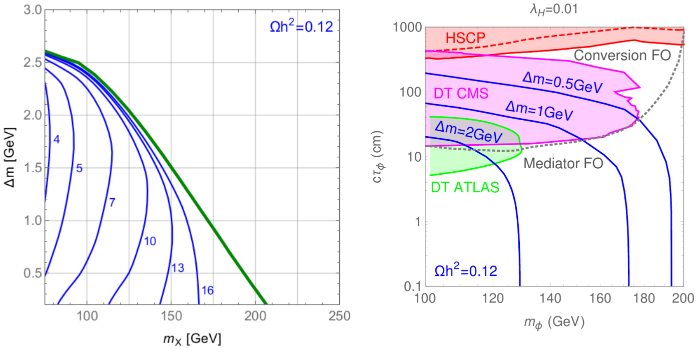
Conversion driven



Freeze-in

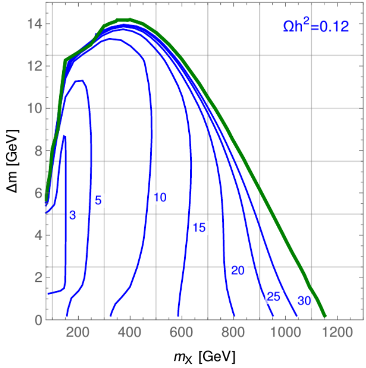


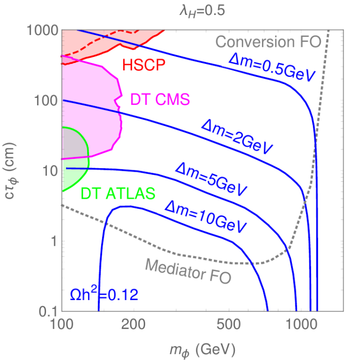
Conversion driven freeze-out



$$\lambda_H = 0.01$$

Conversion driven freeze-out

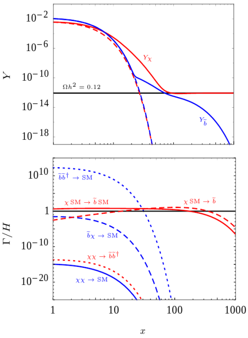




$$\lambda_H = 0.5$$

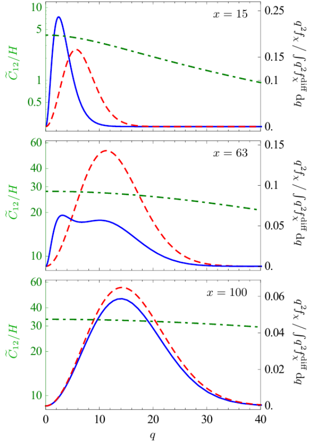
Conversion driven freeze-out

arXiv:1705.09292 Mathias Garny,[1] Jan Heisig,[2] Benedikt Lülf,[2] and Stefan Vogl[3]



$$\frac{dY_\chi}{dx} = \frac{1}{3H}\frac{ds}{dx}\Bigg[\langle\sigma_{\chi\chi}v\rangle\left(Y_\chi^2 - Y_\chi^{\mathrm{eq}\,2}\right) + \langle\sigma_{\chi\tilde b}v\rangle\left(Y_\chi Y_{\tilde b} - Y_\chi^{\mathrm{eq}}Y_{\tilde b}^{\mathrm{eq}}\right) + \frac{\Gamma_{\chi\to\tilde b}}{s}\left(Y_\chi - Y_{\tilde b}\frac{Y_\chi^{\mathrm{eq}}}{Y_{\tilde b}^{\mathrm{eq}}}\right) - \frac{\Gamma_{\tilde b}}{s}\left(Y_{\tilde b} - Y_\chi\frac{Y_{\tilde b}^{\mathrm{eq}}}{Y_\chi^{\mathrm{eq}}}\right) + \langle\sigma_{\chi\chi\to\tilde b\tilde b^\dagger}v\rangle\left(Y_\chi^2 - Y_{\tilde b}^2\frac{Y_\chi^{\mathrm{eq}\,2}}{Y_{\tilde b}^{\mathrm{eq}\,2}}\right)\Bigg]$$

$$\frac{dY_{\tilde b}}{dx} = \frac{1}{3H}\frac{ds}{dx}\Bigg[\frac{1}{2}\langle\sigma_{\tilde b\tilde b^\dagger}v\rangle\left(Y_{\tilde b}^2 - Y_{\tilde b}^{\mathrm{eq}\,2}\right) + \langle\sigma_{\chi\tilde b}v\rangle\left(Y_\chi Y_{\tilde b} - Y_\chi^{\mathrm{eq}}Y_{\tilde b}^{\mathrm{eq}}\right) - \frac{\Gamma_{\chi\to\tilde b}}{s}\left(Y_\chi - Y_{\tilde b}\frac{Y_\chi^{\mathrm{eq}}}{Y_{\tilde b}^{\mathrm{eq}}}\right) + \frac{\Gamma_{\tilde b}}{s}\left(Y_{\tilde b} - Y_\chi\frac{Y_{\tilde b}^{\mathrm{eq}}}{Y_\chi^{\mathrm{eq}}}\right) - \langle\sigma_{\chi\chi\to\tilde b\tilde b^\dagger}v\rangle\left(Y_\chi^2 - Y_{\tilde b}^2\frac{Y_\chi^{\mathrm{eq}\,2}}{Y_{\tilde b}^{\mathrm{eq}\,2}}\right)\Bigg]$$



$$Hx\partial_x f_\chi(q,x) = \widetilde C(q,x)\left(f_\chi^{\mathrm{eq}}\frac{Y_{\tilde b}}{Y_{\tilde b}^{\mathrm{eq}}} - f_\chi\right)$$

Conversion driven freeze-out

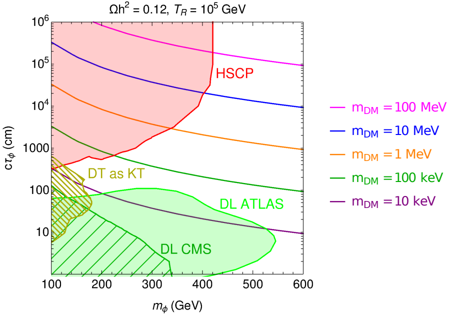
Reaction densities

$$\begin{aligned}
\gamma_{ij\to kl} &= \int\int d\phi_i d\phi_j f_i^{eq} f_j^{eq} \int\int d\phi_k d\phi_l (2\pi)^4 \delta^4(p_i + p_j - p_k - p_l) |\mathcal{M}_{ij\to kl}|^2 \\
&= n_i^{eq} n_j^{eq} \langle \sigma_{ij\to kl} v_{ij} \rangle \\
\gamma_{ij\to k} &= \int\int d\phi_i d\phi_j \int d\phi_k f_k^{eq} (2\pi)^4 \delta^4(p_i + p_j - p_k) |\mathcal{M}_{k\to ij}|^2 = n_k^{eq} \Gamma_{k\to ij} \frac{K_1(x)}{K_2(x)}
\end{aligned}$$

Leptophilic DM: Collider vs NCDM Constraints

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

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



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

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

unless DM saturates the Lyman-α constraints

Leptophilic DM: Collider vs NCDM Constraints

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

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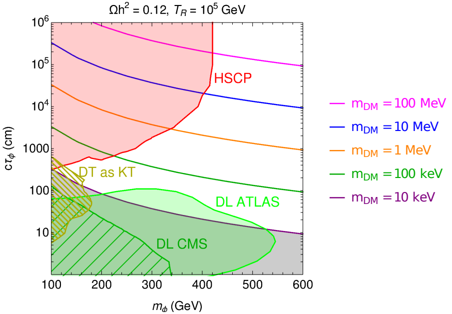

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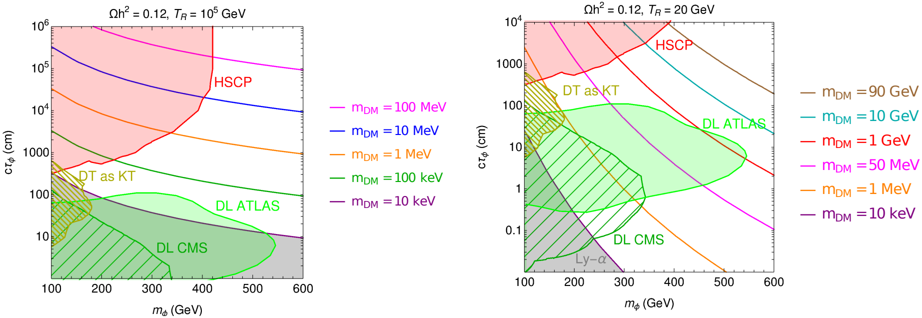

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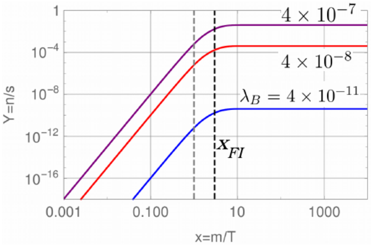
unless DM saturates the Lyman-α constraints

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)

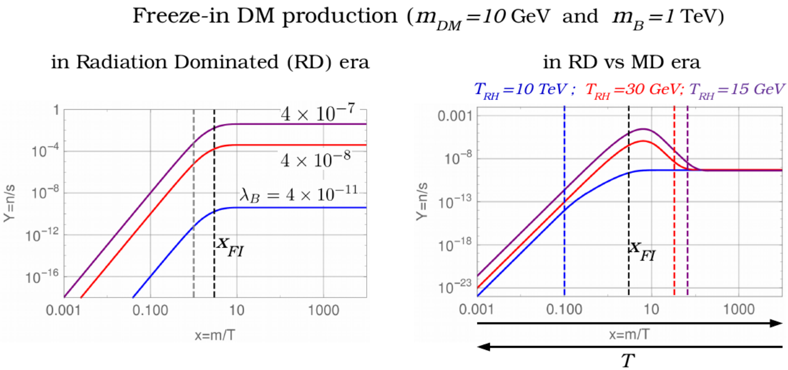
Reheating after FI and smaller $c\tau_B$

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

in Radiation Dominated (RD) era



Reheating after FI and smaller $c\tau_B$

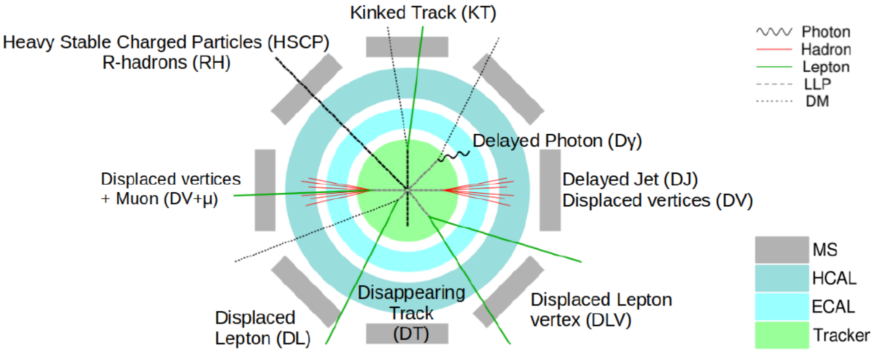


DM yield is diluted due to extra entropy production from inflaton decay:

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

$\rightsquigarrow$ 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 $c\tau_B$.

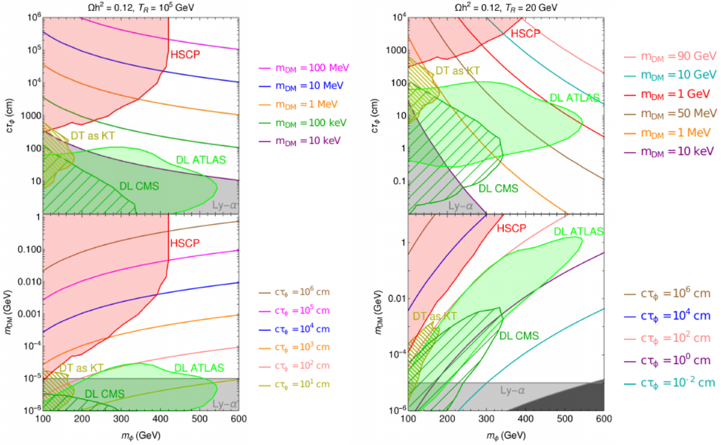
Collider searches



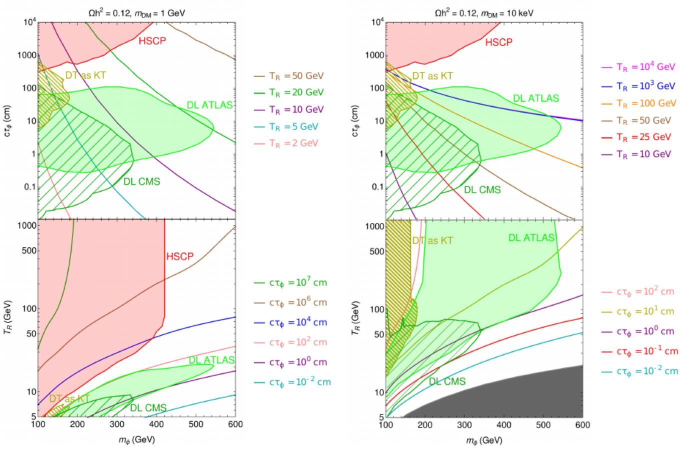
Collider searches

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

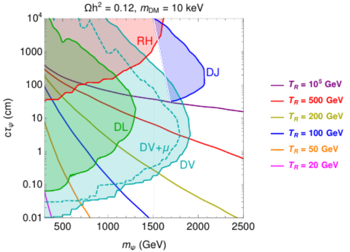
Leptophilic DM

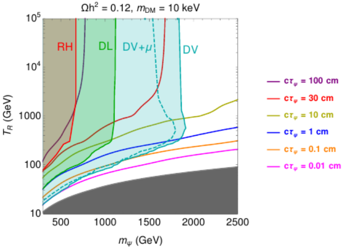


Leptophilic DM



Topphilic DM

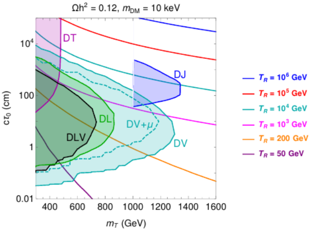


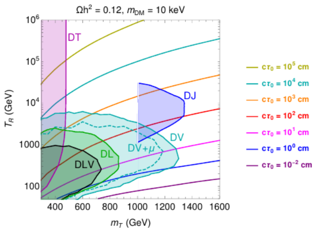


Singlet-Triplet DM

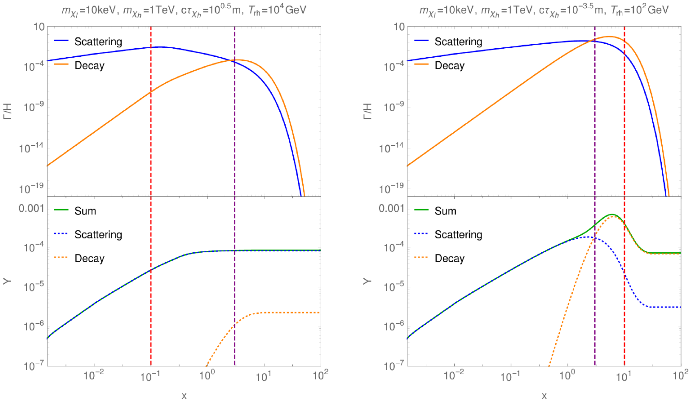
$$\mathcal{L}_{BSM} = -\frac{m_S}{2}\bar{\chi_S}\chi_S - \frac{m_T}{2}Tr\left[\bar{\chi_T}\chi_T\right] + \frac{1}{2}Tr\left[\bar{\chi_T}i\not{D}_\mu\chi_T\right]$$
$$+\frac{\kappa}{\Lambda}(W^a_{\mu\nu}\bar{\chi_S}\sigma^{\mu\nu}\chi^a_T + \text{h.c.}),$$

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





Singlet-Triplet DM



bla

This is really the end