Instituto de Física Teórica UAM-CSIC

Freeze-in Dark Matter
&
Long-Lived Particle Searches

Jose Miguel No
IFT-UAM/CSIC, Madrid

Based on **1811.05478** *(w. Belanger, Desai, Goudelis, Harz, Lessa, Pukhov, Sekmen, Sengupta, Zaldivar & Zurita)*

1908.11387 *(w. Tunney & Zaldivar)*

6th LLP Workshop, Ghent
27/11/19

UNIVERSIDAD AUTONOMA DE MADRID

In the next 15 min...

➔ **Freeze-In Production of Dark Matter**

➔ **Simple Freeze-In DM Models ("LHC-friendly")**

➔ **Long-Lived Particle searches: LHC and MATHUSLA**

In the next 15 min...

➔ Freeze-In Production of Dark Matter

Why non-thermal Dark Matter motivates LLP searches?

➔ **Simple Freeze-In DM Models ("LHC-friendly")**

➔ **Long-Lived Particle searches: LHC and MATHUSLA**

In the next 15 min...

➔ Freeze-In Production of Dark Matter

Why non-thermal Dark Matter motivates LLP searches?

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➔ **Long-Lived Particle searches: LHC and MATHUSLA**

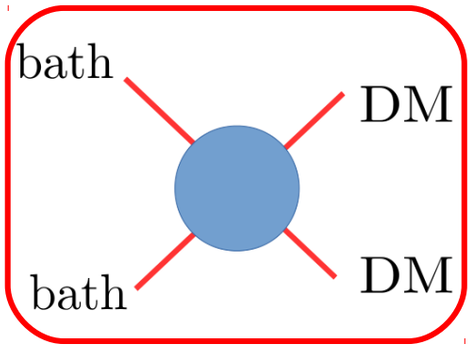
Dark Matter Freeze-In in a Nutshell

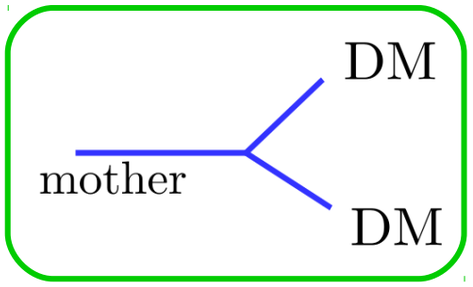
Hall et al, 0911.1120

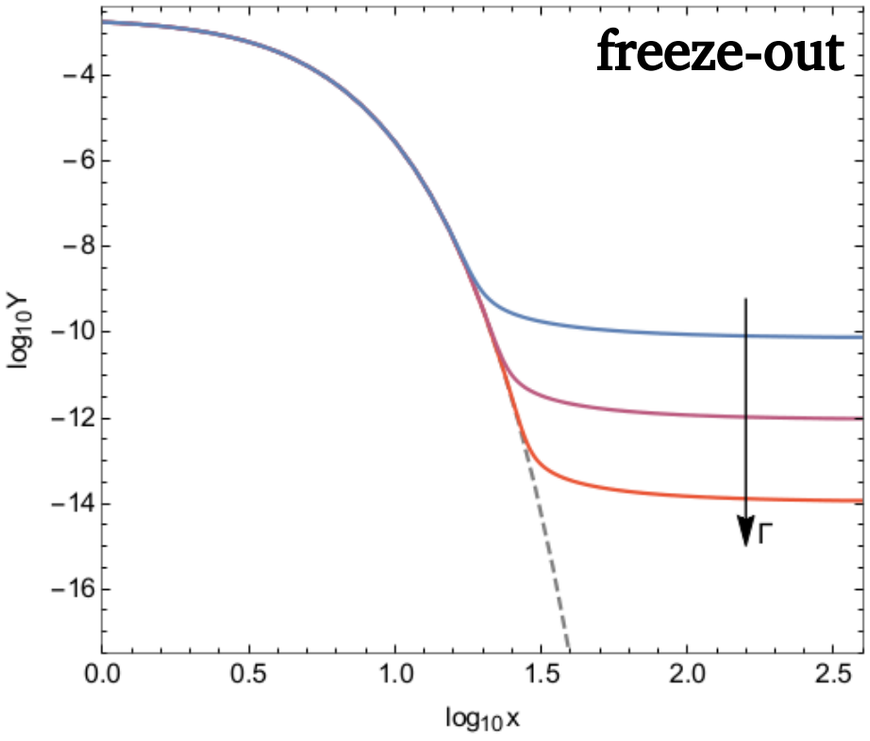
$$\frac{dn_{\rm DM}}{dt} + 3Hn_{\rm DM} = n_{\rm bath}\underbrace{\Gamma_{\rm prod} - \cancel{n_{\rm DM}\Gamma_{\rm ann}}}_{\text{interaction rates}}$$

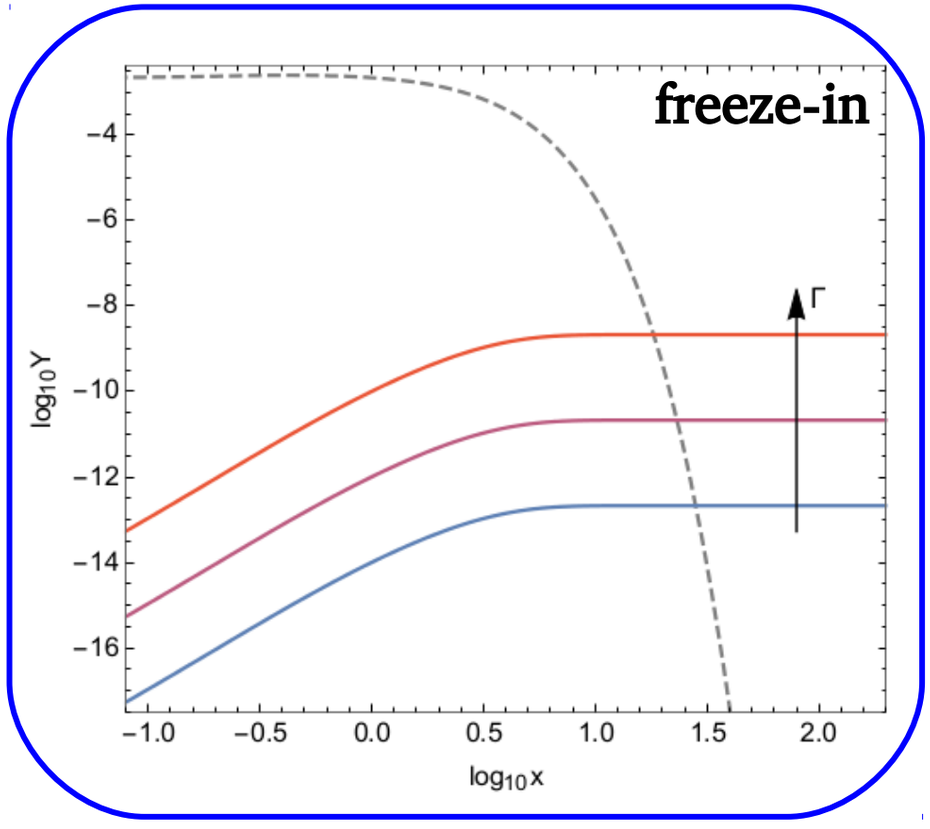
negligible

- ➔ Initial negligible DM abundance (+ DM never thermalizes)
- ➔ Production from **scatterings** or **decays**









$$Y = n_{\rm DM}/s$$

$$x = m/T$$

Bernal et al, 1706.07442

Dark Matter Freeze-In in a Nutshell

Hall et al, 0911.1120

➔ Freeze-in from **decays** $\boxed{Y \;\to\; X_{\rm SM}\,\chi}$

mother DM

$$\frac{dn_\chi}{dt} + 3H\,n_\chi = \Gamma_Y\,n_Y^{\rm eq}\,\frac{K_1(m_Y/T)}{K_2(m_Y/T)} \longrightarrow Y_\chi \approx \frac{135\,g_Y\,\xi\,M_{\rm Pl}\,\Gamma_Y}{8\pi^3\,m_Y^2}\,\frac{1}{1.66\,g_*^s(m_Y/3)\sqrt{g_*(m_Y/3)}}$$

Dark Matter Freeze-In in a Nutshell

Hall et al, 0911.1120

➔ Freeze-in from **decays** $Y \to X_{\rm SM}\,\chi$

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DM Relic Density: $\lambda \sim (10^{-12} - 10^{-13})\sqrt{\frac{m_Y}{m_\chi}}$

Long-lived particle signatures

(Y decays)

$$c\tau_Y \sim 3.6\,m\left(\frac{0.12}{\Omega_\chi h^2}\right)\left(\frac{m_\chi}{100\,{\rm KeV}}\right)\left(\frac{300\,{\rm GeV}}{m_Y}\right)^2$$

Simple Freeze-In DM Models

VS

Simple Freeze-In DM Models

$$y_\chi \, Y \, X_{\rm SM} \, \chi \rightarrow \text{DM}$$

($\mathbb{Z}_2$-odd)

Mother Particle

↓

mirrors SM gauge properties of X_{SM}

Quarks
Leptons → charged

Belanger et al, 1811.05478

Higgs → neutral

Calibbi, Lopez-Honorez, Mariotti, Lowette, 1805.04423

JMN, Tunney, Zaldivar, 1908.11387

DM Freeze-In from SM Quarks/Leptons

$\mathbb{Z}_2$-odd sector

Mother Particle → $Y = F$ Charged fermion (SU(2) singlet)

Dark Matter → $\chi = s$ Singlet scalar

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \partial_\mu s\, \partial^\mu s - \frac{\mu_s^2}{2} s^2 + \frac{\lambda_s}{4} s^4$$
$$+ \bar{F}\left(i\not{D}\right) F - m_F \bar{F} F - \sum_f y_s^f \left(s \bar{F} \left(\frac{1+\gamma^5}{2} \right) f + \text{h.c.} \right)$$

Freeze-in DM interactions

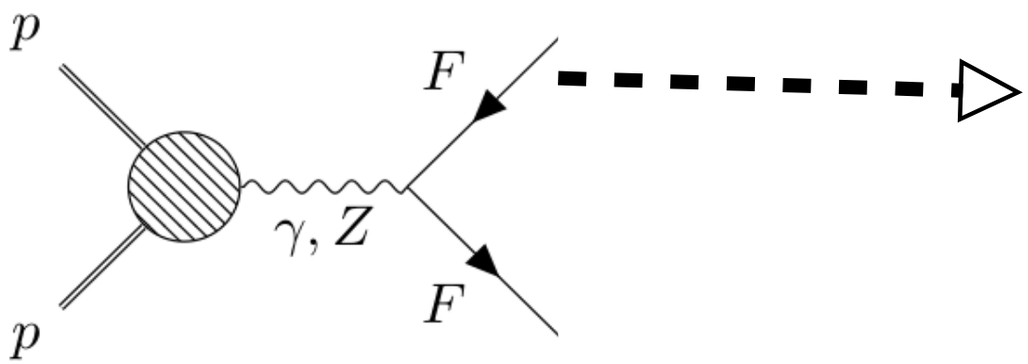
$f = \{e, \mu, \tau\}$, $\{u, c, t\}$ or $\{d, s, b\}$

leptons quarks

SM Quarks

Probing Freeze-in at LHC

SM Leptons



$$c\tau[\mathrm{m}] \approx 4.5\ \xi\ g_F \left(\frac{0.12}{\Omega_s h^2}\right)\left(\frac{m_s}{100\ \mathrm{keV}}\right)\left(\frac{200\ \mathrm{GeV}}{m_F}\right)^2 \times \left(\frac{102}{g_*(m_F/3)}\right)^{3/2}\left[\frac{\int_{m_F/T_R}^{m_F/T_0} dx\ x^3 K_1(x)}{3\pi/2}\right]$$

Heavy Stable Charged Particle (HSCP) Searches

Displaced Lepton (DL) Searches

CMS search(es) for (different flavour, ***e μ***) **lepton pairs with large impact parameters**

Disappearing track (DT) Searches

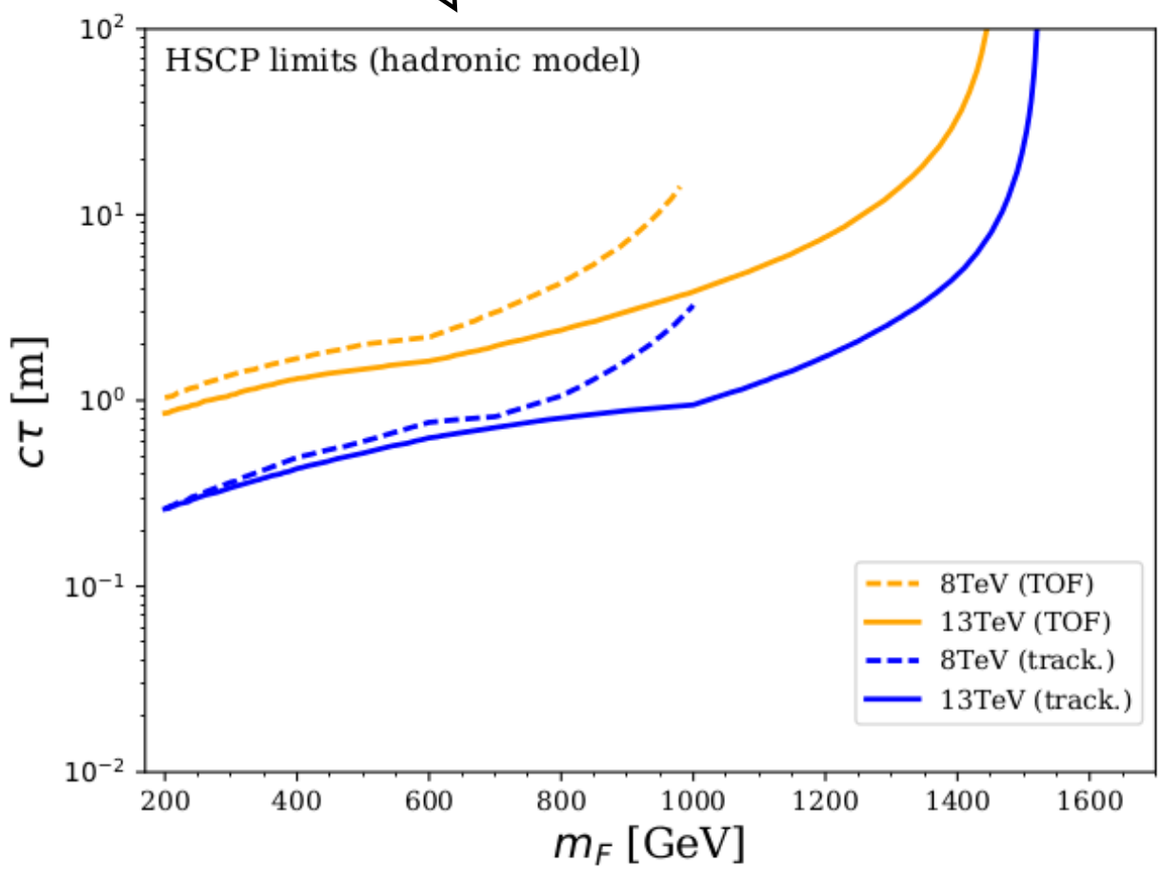
Displaced vertices (DV) + MET Searches

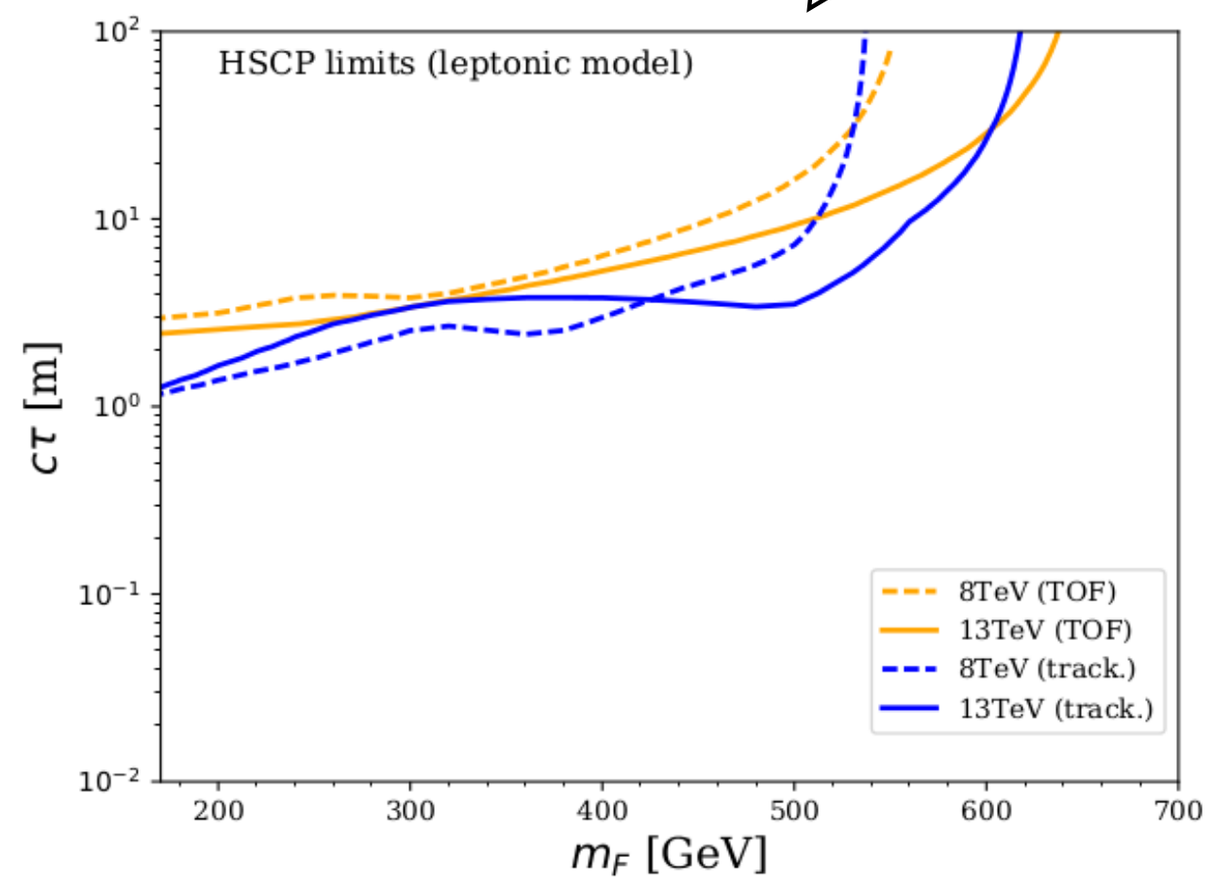
Probing Freeze-in at LHC

SM Quarks

SM Leptons

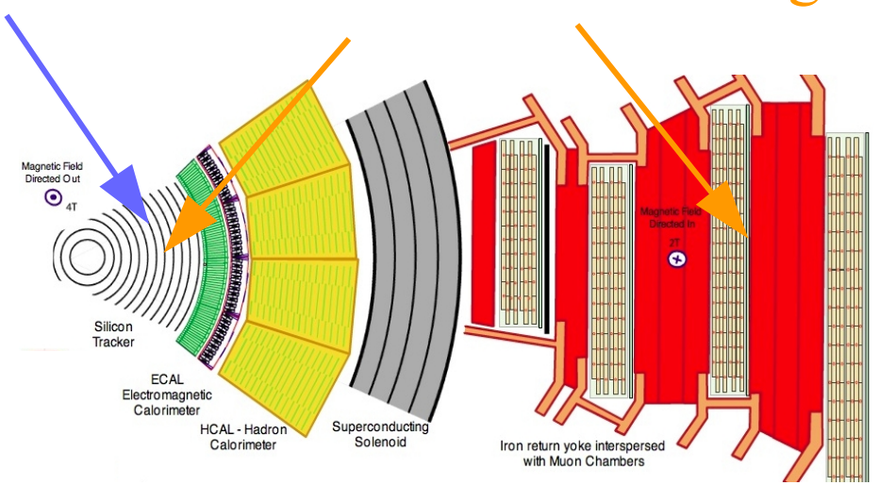
Heavy Stable Charged Particle (HSCP) Searches





Tracker

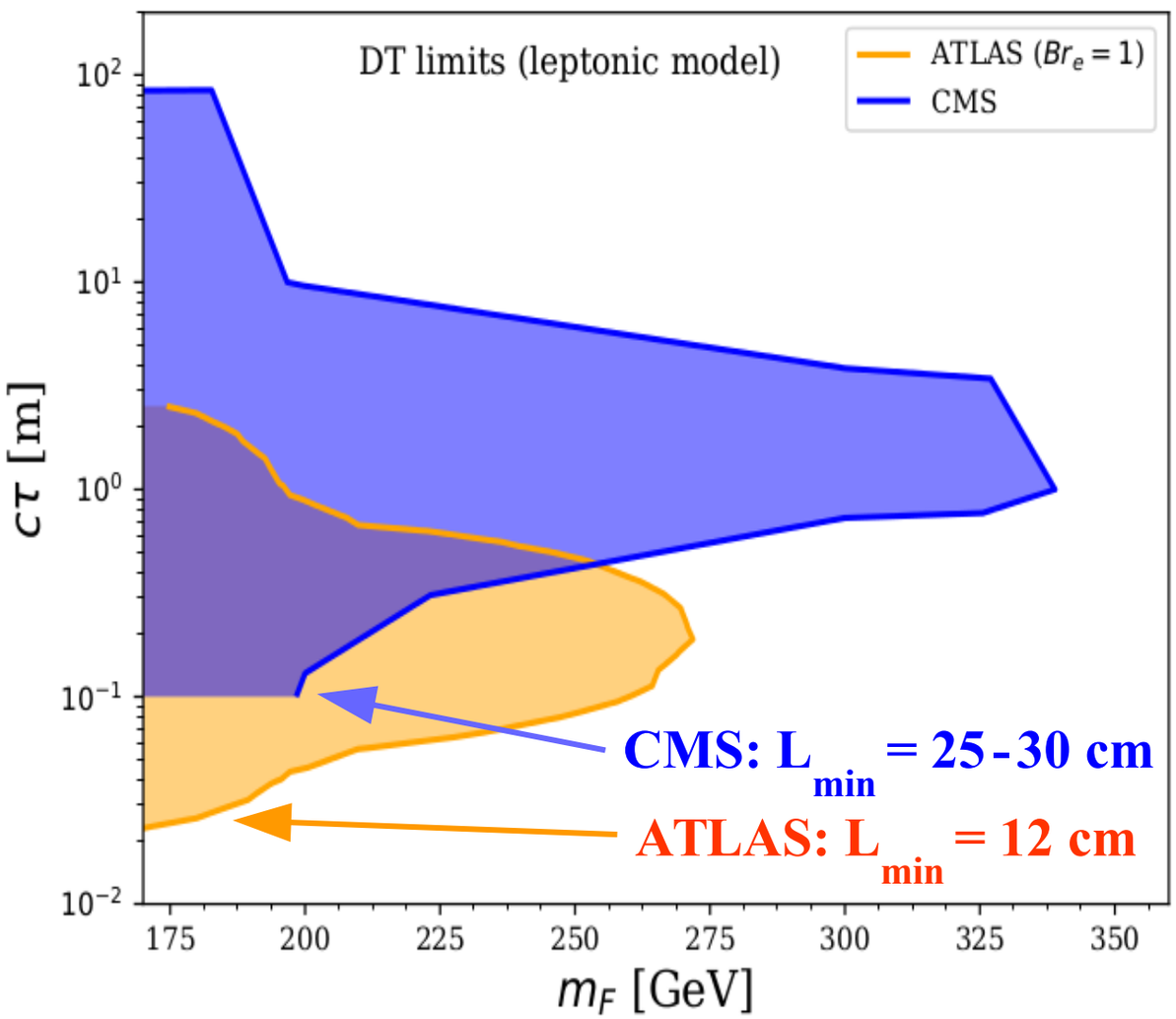
Tracker + Time of flight (TOF)



CMS 8 TeV, 18.8 fb^{-1} (1305.0491)
CMS 13 TeV, 12.9 fb^{-1} (CMS-PAS-EXO-16-036)

Probing Freeze-in at LHC

Disappearing track (DT) Searches



ATLAS 13 TeV, 36.1 fb^{-1} (1712.02118)
CMS 13 TeV, 38.4 fb^{-1} (1804.07321)

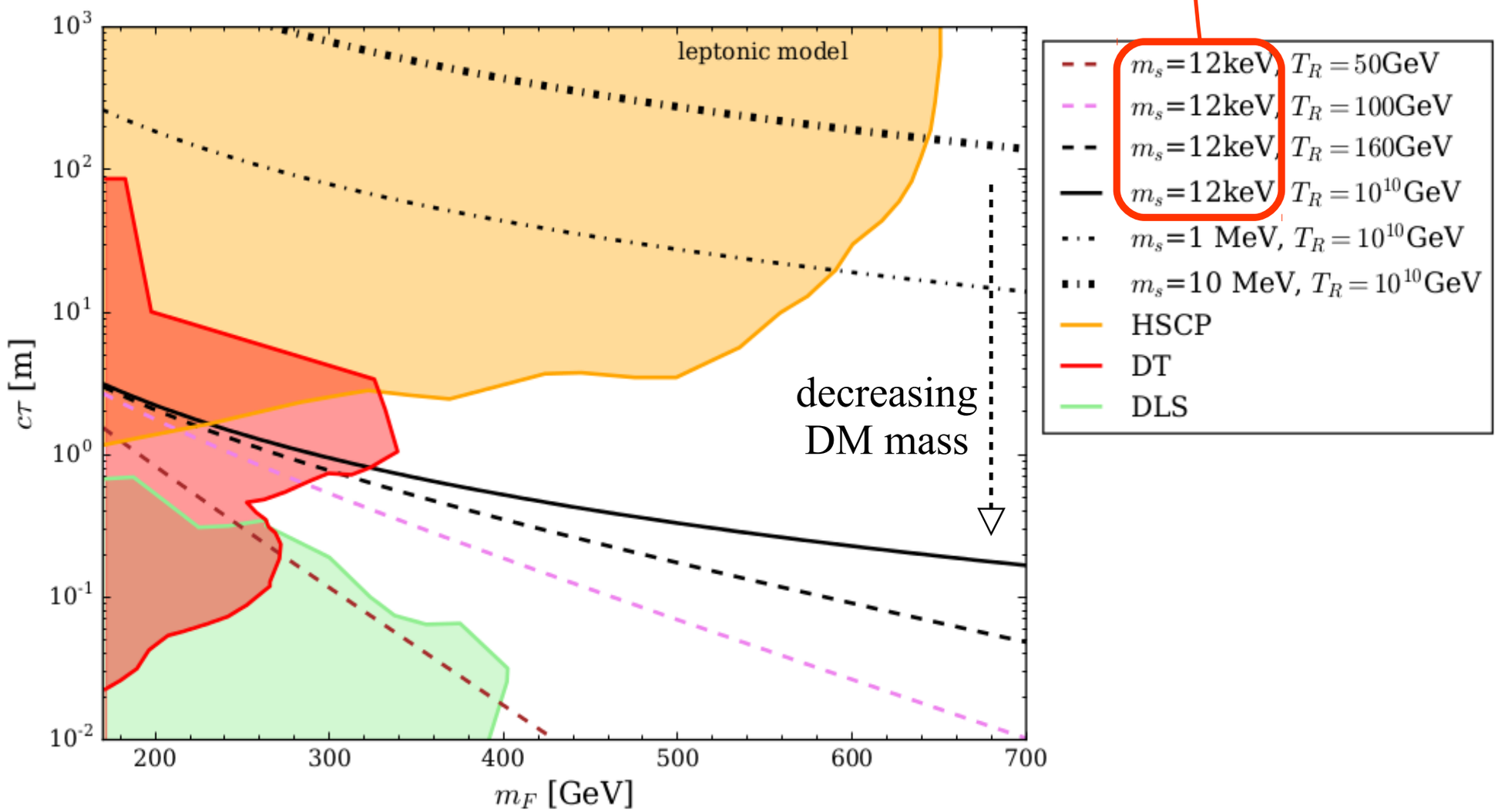
Minimum reconstructed track length L_{min}

Probing Freeze-in at LHC

SM Leptons: Combination

Lower bound on DM mass from Lyman-α

"warm" DM suppressing small-scale structure



Probing Freeze-in at LHC

SM Leptons: Combination

Lower bound on DM mass from Lyman-α

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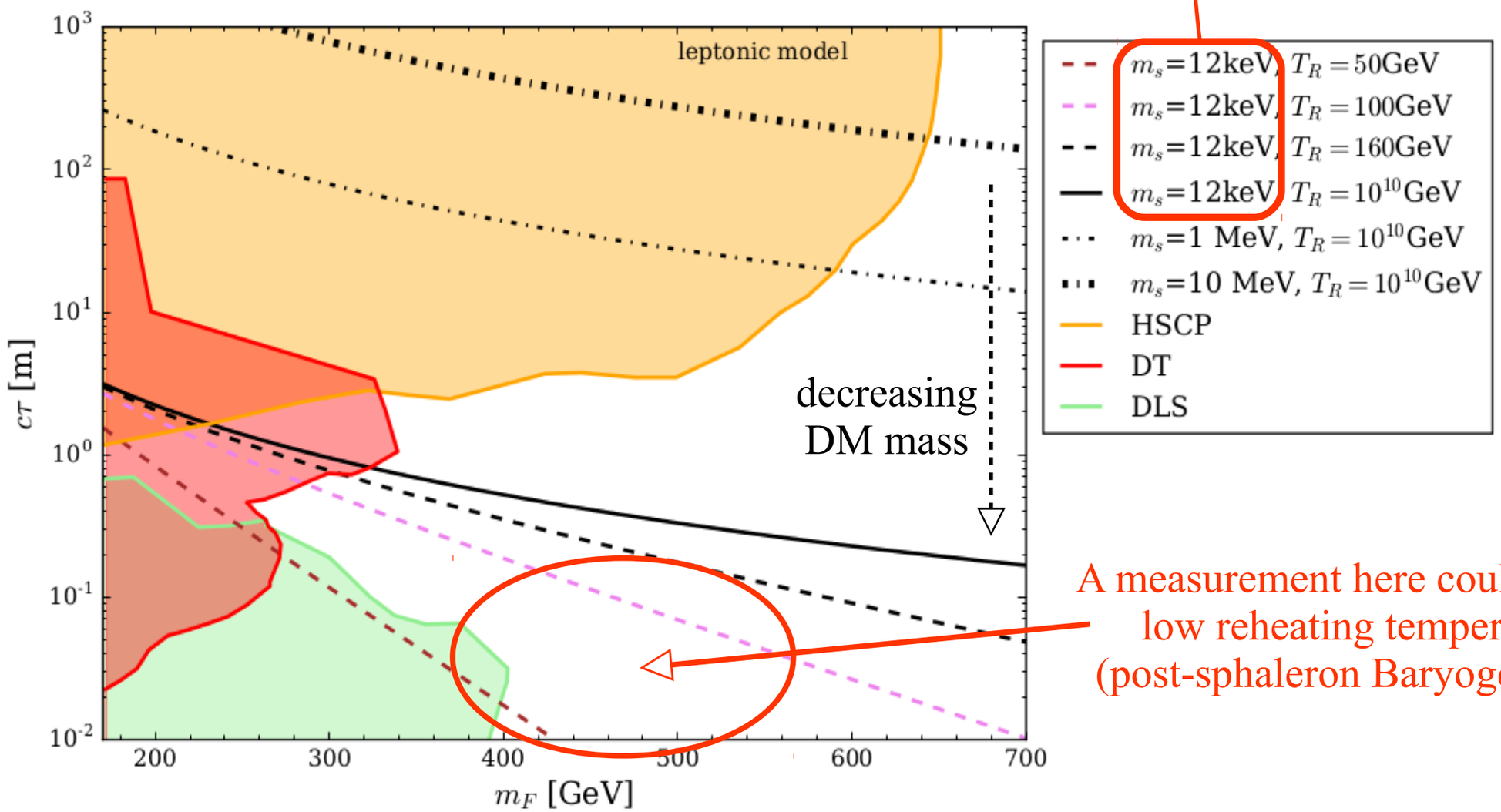


A measurement here could favour low reheating temperature (post-sphaleron Baryogenesis?)

$$c\tau[\mathrm{m}] \approx 4.5\ \xi\ g_F \left(\frac{0.12}{\Omega_s h^2}\right)\left(\frac{m_s}{100\ \mathrm{keV}}\right)\left(\frac{200\ \mathrm{GeV}}{m_F}\right)^2 \times \left(\frac{102}{g_*(m_F/3)}\right)^{3/2} \left[\frac{\int_{m_F/T_R}^{m_F/T_0} dx\ x^3 K_1(x)}{3\pi/2}\right]$$

[source: PhD Comics]

Freeze-In DM from the Higgs

Calibbi, Lopez-Honorez, Mariotti, Lowette, 1805.04423
Filimonova, Westhoff, 1812.04628
JMN, Tunney, Zaldivar, 1908.11387

$\mathbb{Z}_2$-odd sector

SU(2) Singlet SU(2) Doublet "Higgs Portal"

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\,\bar{\chi}\gamma^\mu\partial_\mu\chi + i\,\bar{\psi}\gamma^\mu D_\mu\psi - m_s\,\bar{\chi}\chi - m_D\bar{\psi}\psi - \boxed{y_\chi\,\bar{\psi}H\chi + h.c.}$$

Simple DM version of complete setups (e.g. Higgsino-Axino, Higgsino-Singlino)

Co et al, 1506.07532

Decays of χ_2 (doublet-like mother)

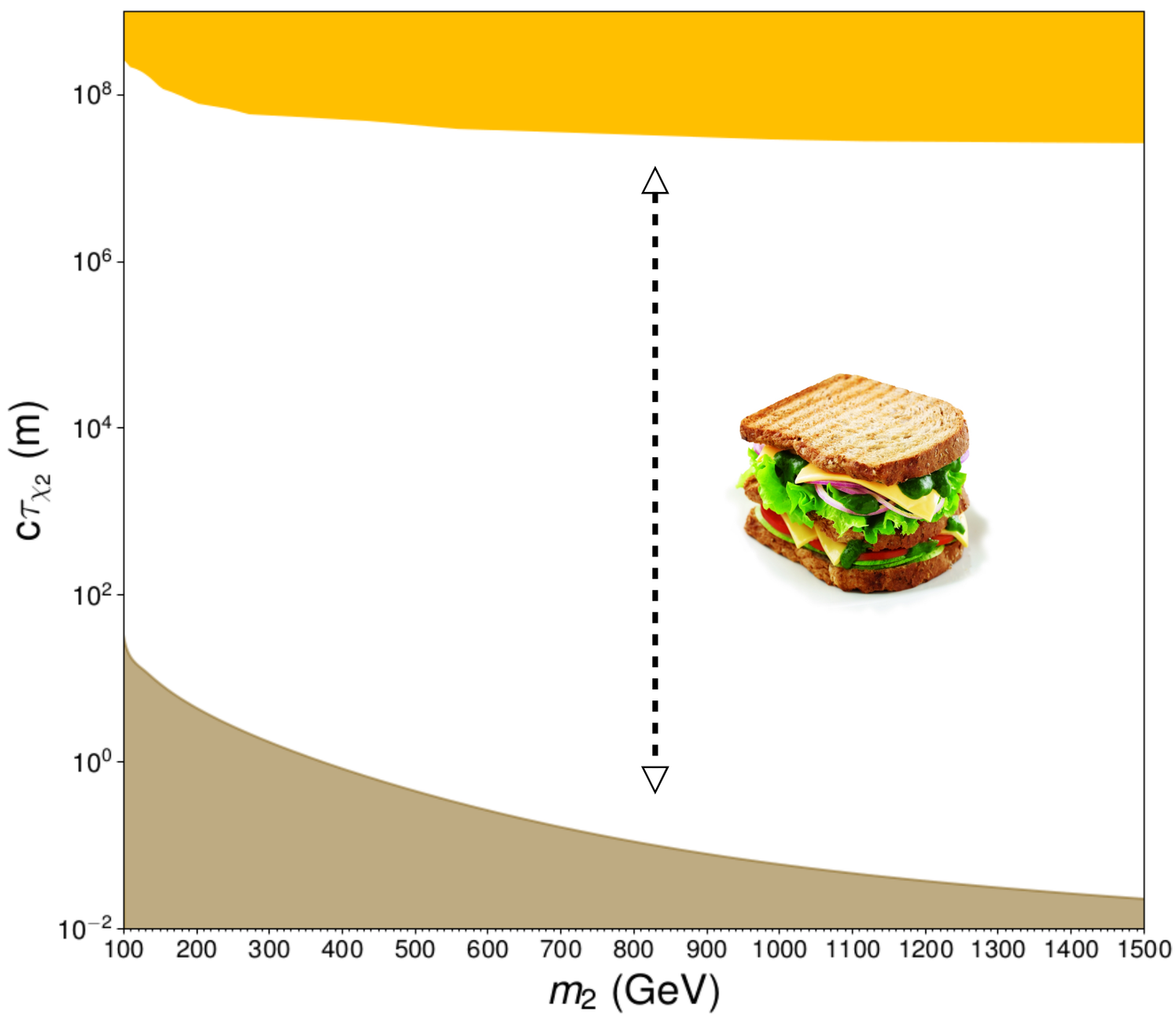
$$\chi_2 \to h\chi_1$$
$$\chi_2 \to Z\chi_1$$

(singlet-like DM)

Constraints from Cosmology

- ▷ **Lyman-α forest observations**
- ▷ **Big-bang nucleosynthesis**

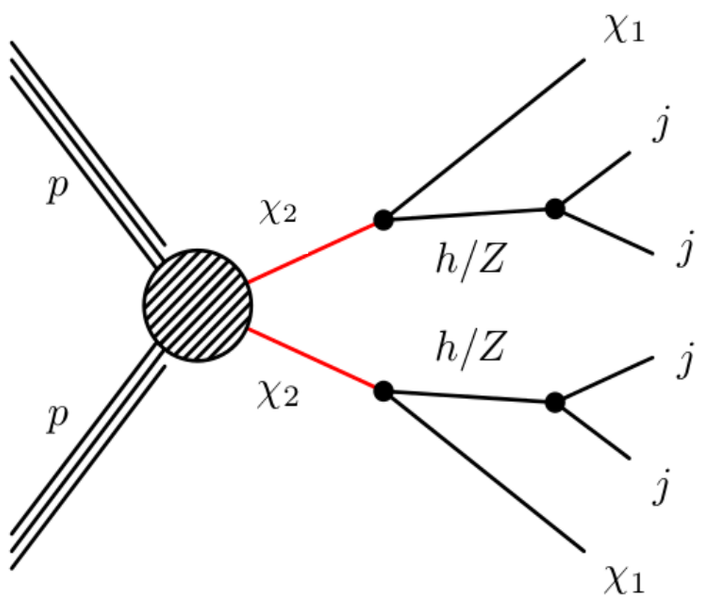
Constrain washout of small-scale structure by partially relativistic ("*warm*") DM

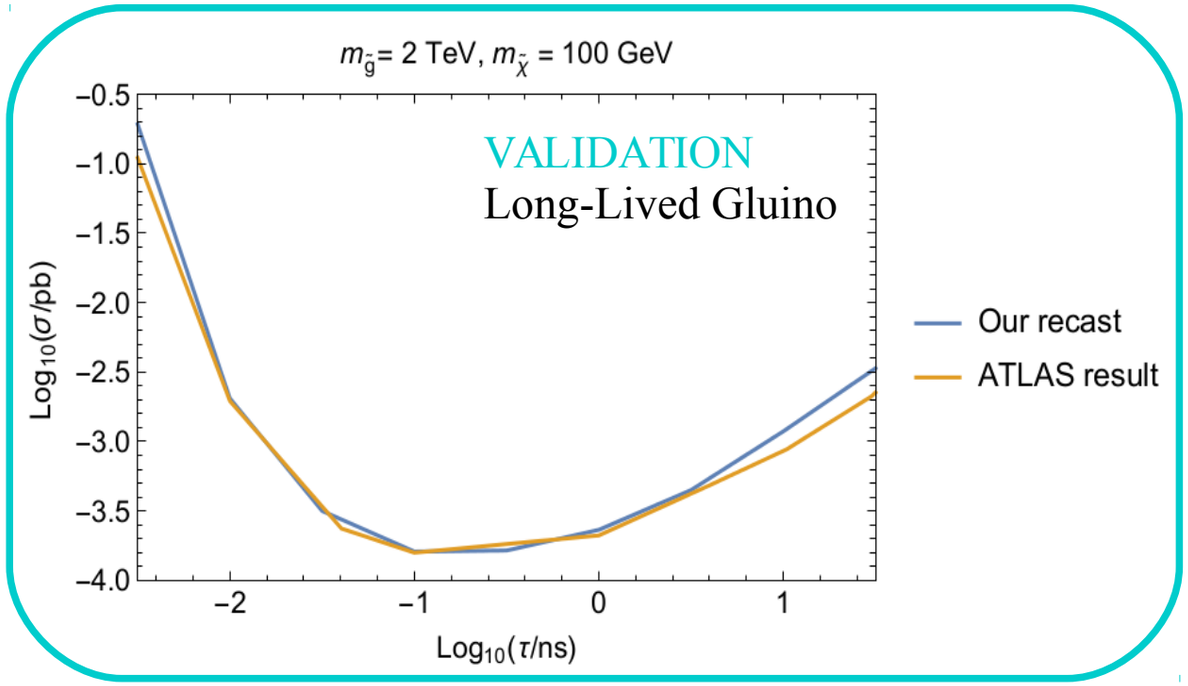


Probing Freeze-in at LHC

Displaced vertices (DV) + MET Searches

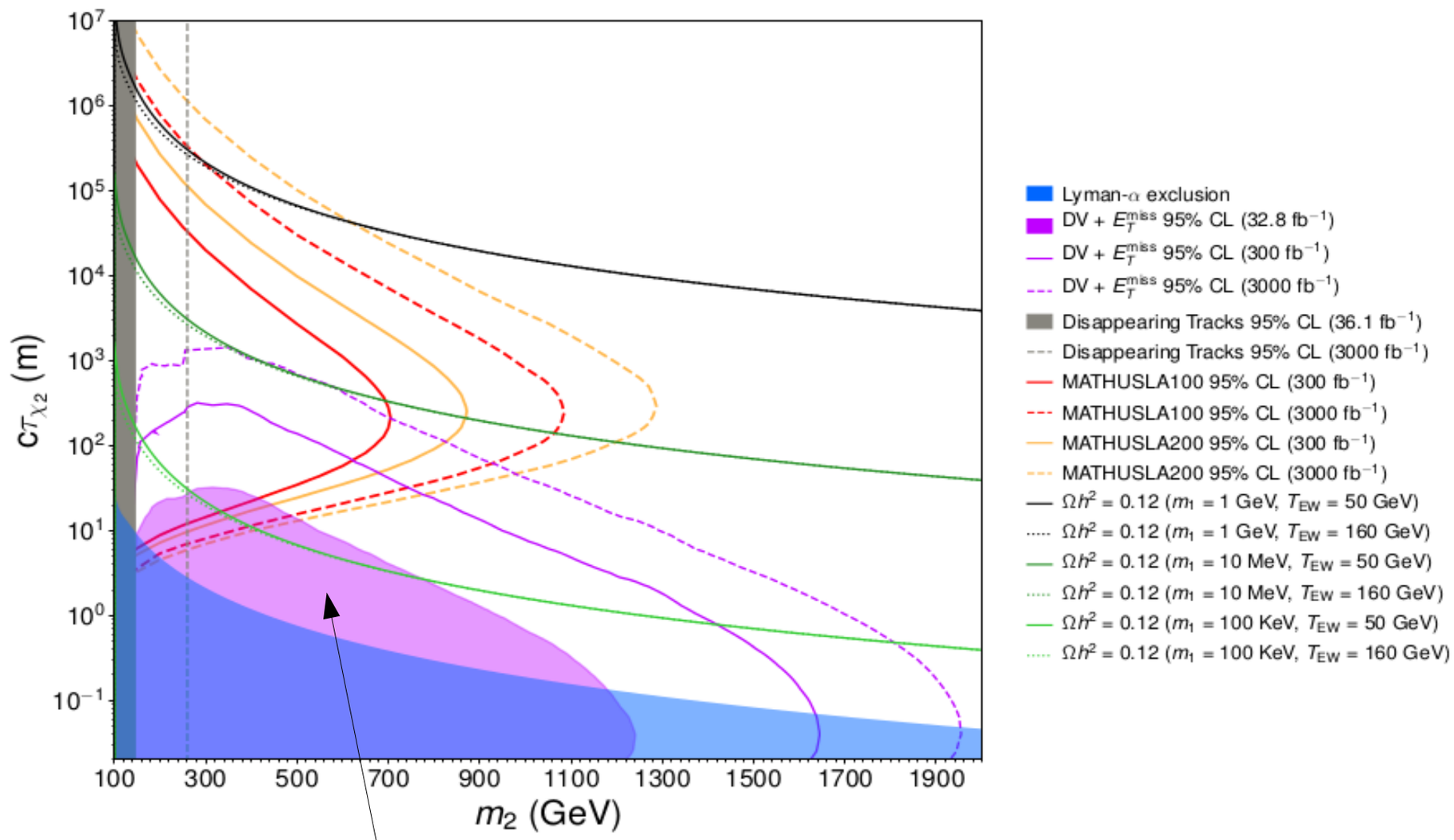
ATLAS 13 TeV, 32.8 fb^{-1} (1710.04901)





Calibbi, Lopez-Honorez, Mariotti, Lowette, 1805.04423
JMN, Tunney, Zaldivar, 1908.11387

Probing Freeze-in at LHC



Displaced vertices (DV) + MET Searches

Probing Freeze-in at LHC & MATHUSLA

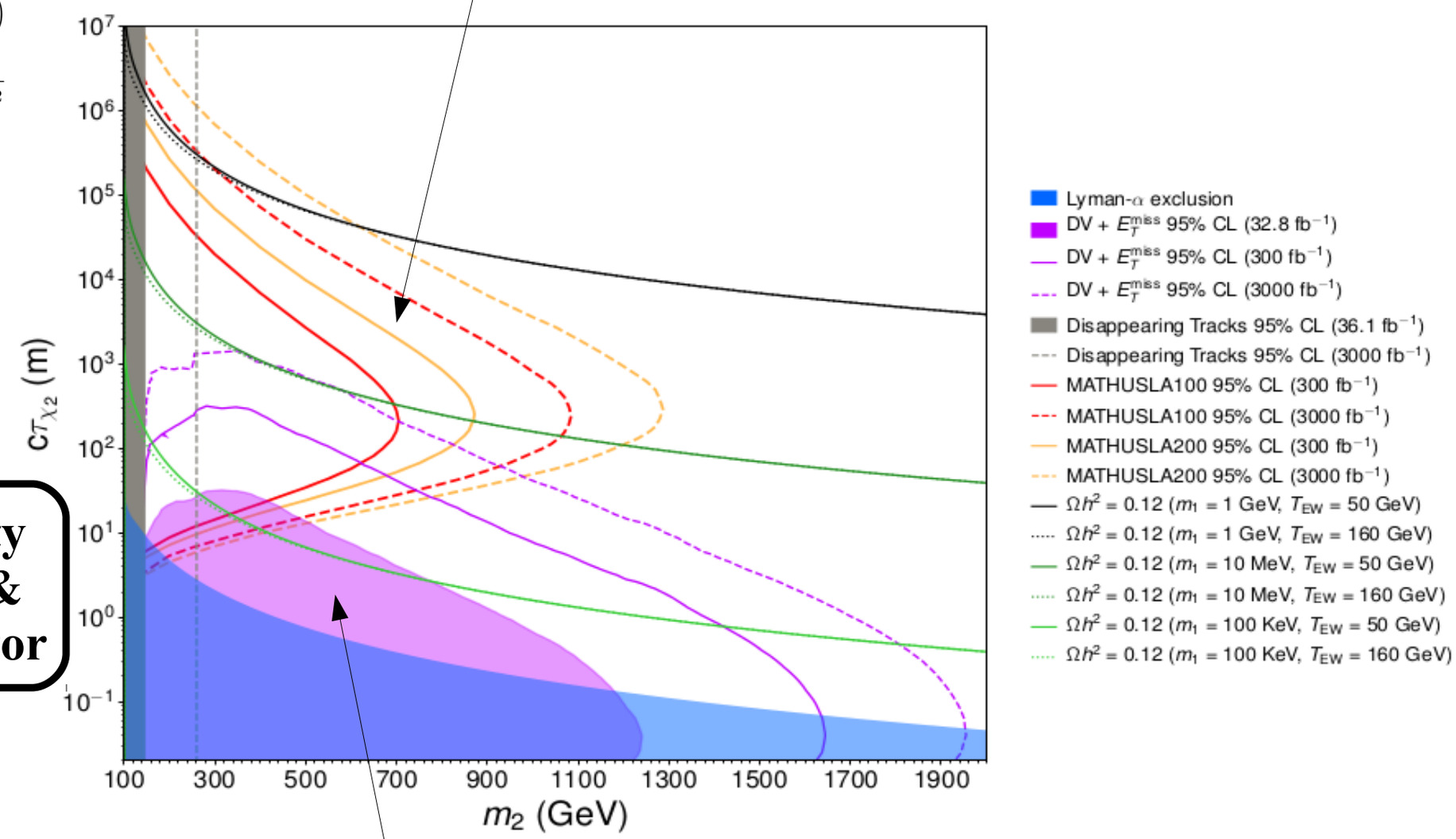
MATHUSLA solid angle from interaction point

$$P_{\text{decay}}^{\text{MATH}} = \epsilon_{\text{geometric}} \times P_{\text{decay}}(\beta\, c\tau_2, L_a, L_b)$$

$$P_{\text{decay}}(\beta\, c\tau_2, L_a, L_b) = e^{-\frac{L_a}{\beta\, c\tau_2}} - e^{-\frac{L_b}{\beta\, c\tau_2}}$$

$$|\vec{p}_{\chi_2}|/m_2$$

MATHUSLA 100 / 200



Strong Complementarity between ATLAS/CMS & MATHUSLA LLP detector

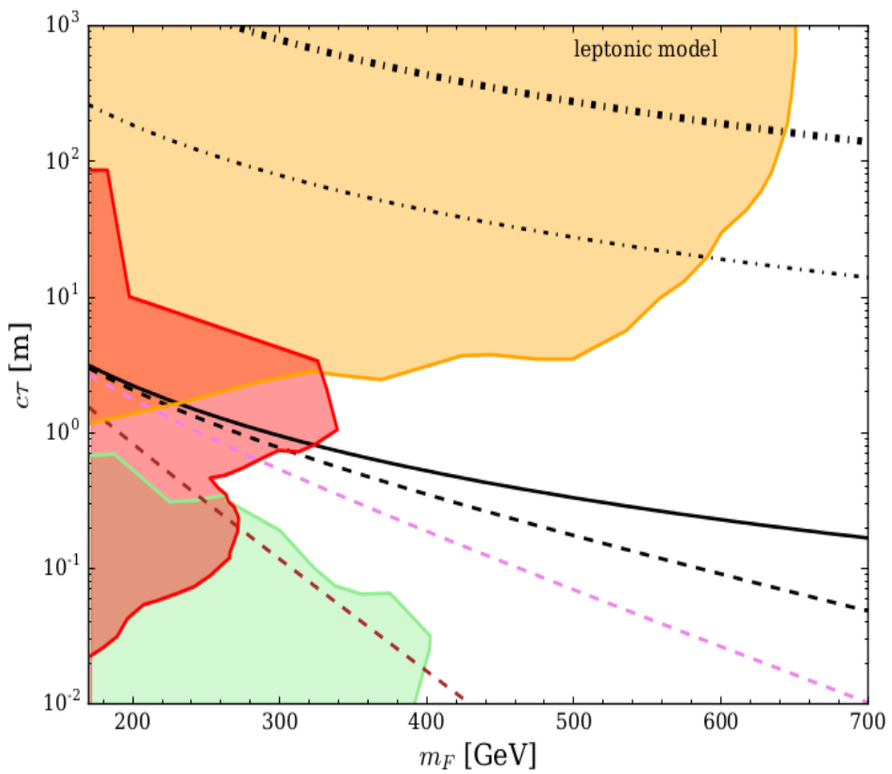
Displaced vertices (DV) + MET Searches

Summary & wrap-up

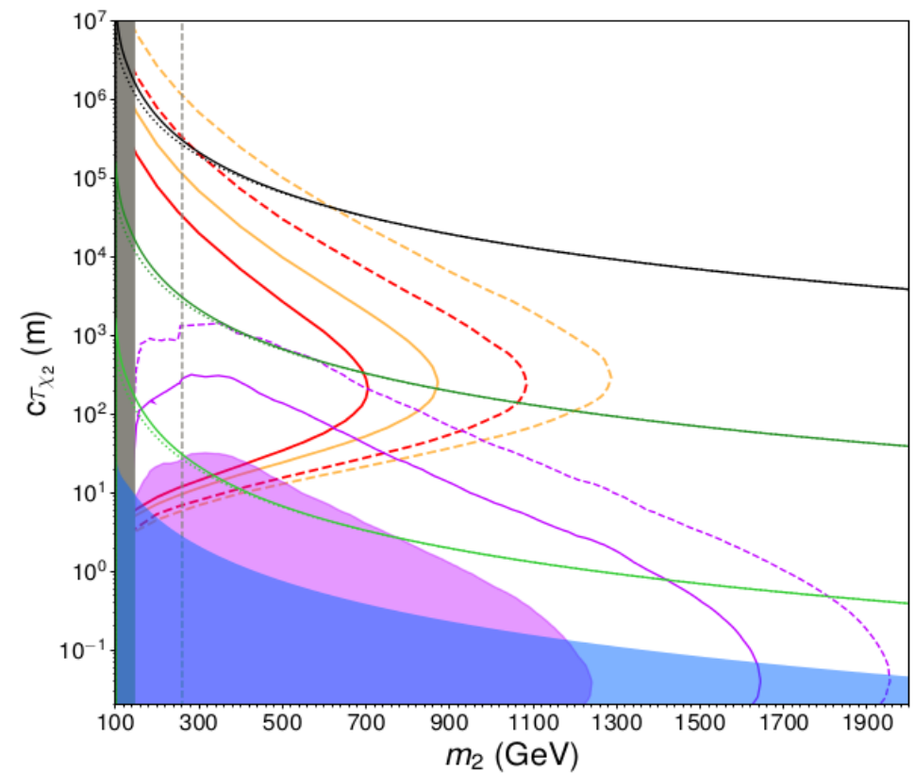
▷ Possible to explore Freeze-in DM @LHC

Use simple (minimal) models

Charged partner (quarks/leptons)



Neutral partner (Higgs)



▷ Interplay between Cosmology, LHC (ATLAS/CMS) & Dedicated LLP detector

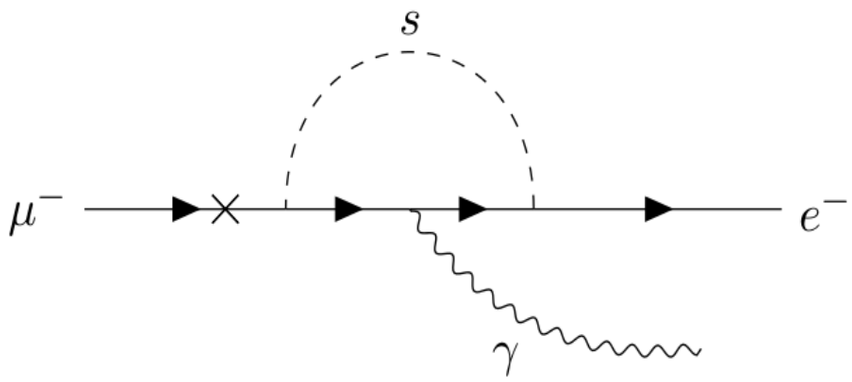
MATHUSLA

KEEP
CALM
AND
BACKUP
YOUR
WORK

DM Freeze-In from SM Quarks/Leptons

"Typical" Constraints VERY weak

e.g. SM Lepton scenario $\longrightarrow$ $\mu \to e\gamma$



$$Br(\mu \to e\gamma) \approx \frac{2v^4 (y_s^e)^2 (y_s^\mu)^2}{3m_F^4 (16\pi)^2}$$

$$Br(\mu \to e\gamma) \sim \mathcal{O}(10^{-46})$$

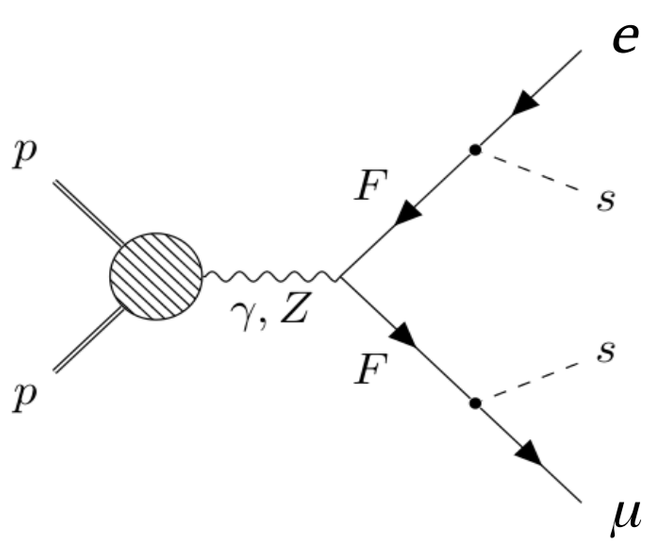
$$Br(\mu \to e\gamma) < 4.2 \times 10^{-13} \ (90\% \ C.L.)$$

MEG Collaboration, 1605.05081

Probing Freeze-in at LHC

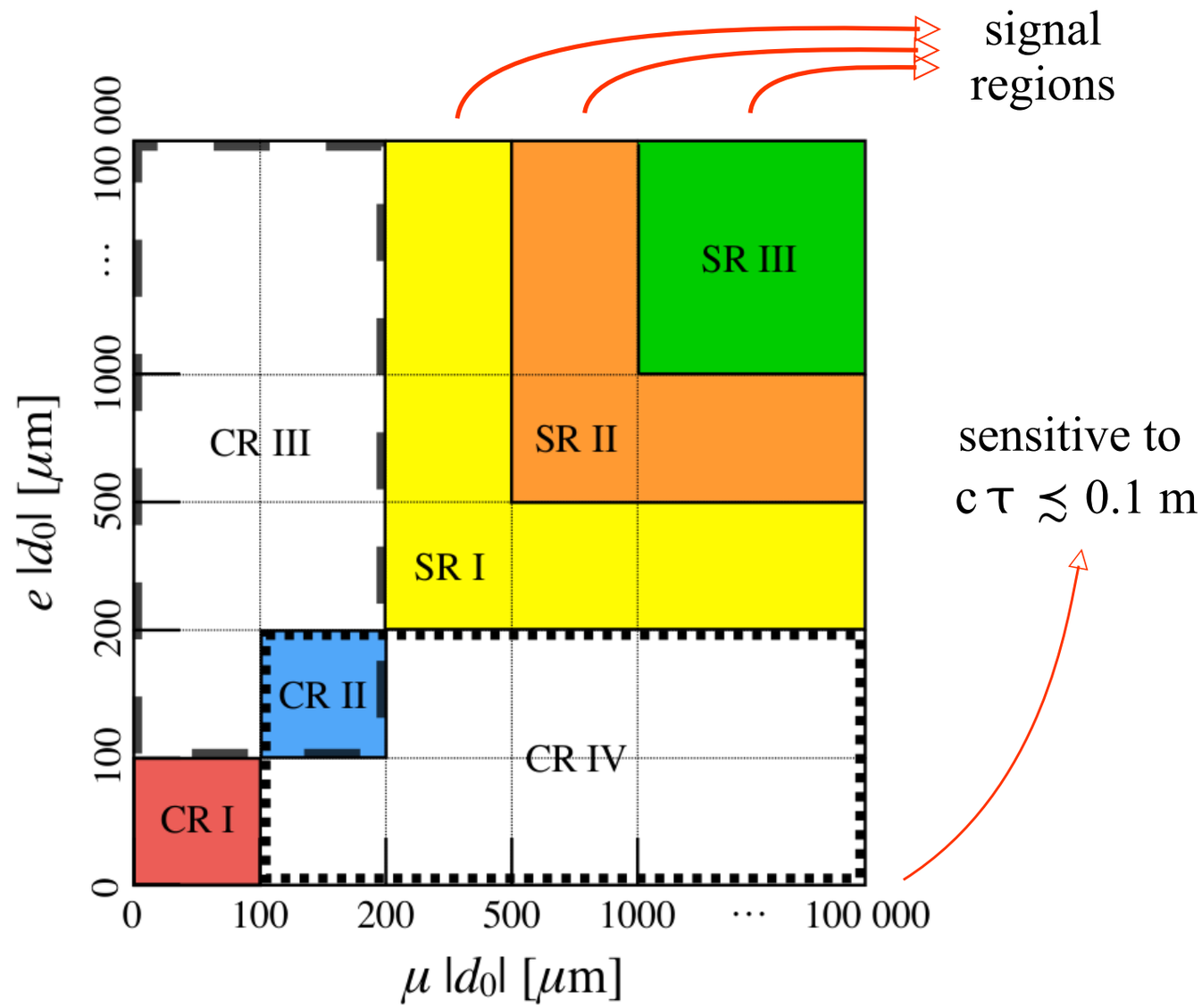
Displaced Lepton (DL) Searches

CMS searches for (different flavour, $e\,\mu$) lepton pairs with large impact parameters



Transverse Impact Parameter:

$$d_0^\ell = \frac{\left|p_x^\ell L_y - p_y^\ell L_x\right|}{p_T^\ell}$$



CMS Collaboration, 1409.4789 (8 TeV)

CMS-PAS-EXO-16-022 (13 TeV)

DM Production

(assume standard thermal history)

Freeze-In:

$$\Gamma_{\rm FI} = \Gamma(\chi_2 \to h\chi_1) + \Gamma(\chi_2 \to Z\chi_1) + \Gamma(\psi^\pm \to W^\pm\chi_1)$$

$$\Omega_1 h^2 \simeq \frac{m_1}{\rho_c/s_0} \frac{135\, M_{\rm Pl}\, \Gamma_{\rm FI}}{2 \times 1.66\, \pi^3\, m_2^2\, [g_*(m_2/3)]^{3/2}}$$

$$\rho_c/s_0 = 3.6 \times 10^{-9}\ \text{GeV}$$

Super-WIMP: χ_2 freezes-out and then decays *(Higgsino-like freeze-out)*

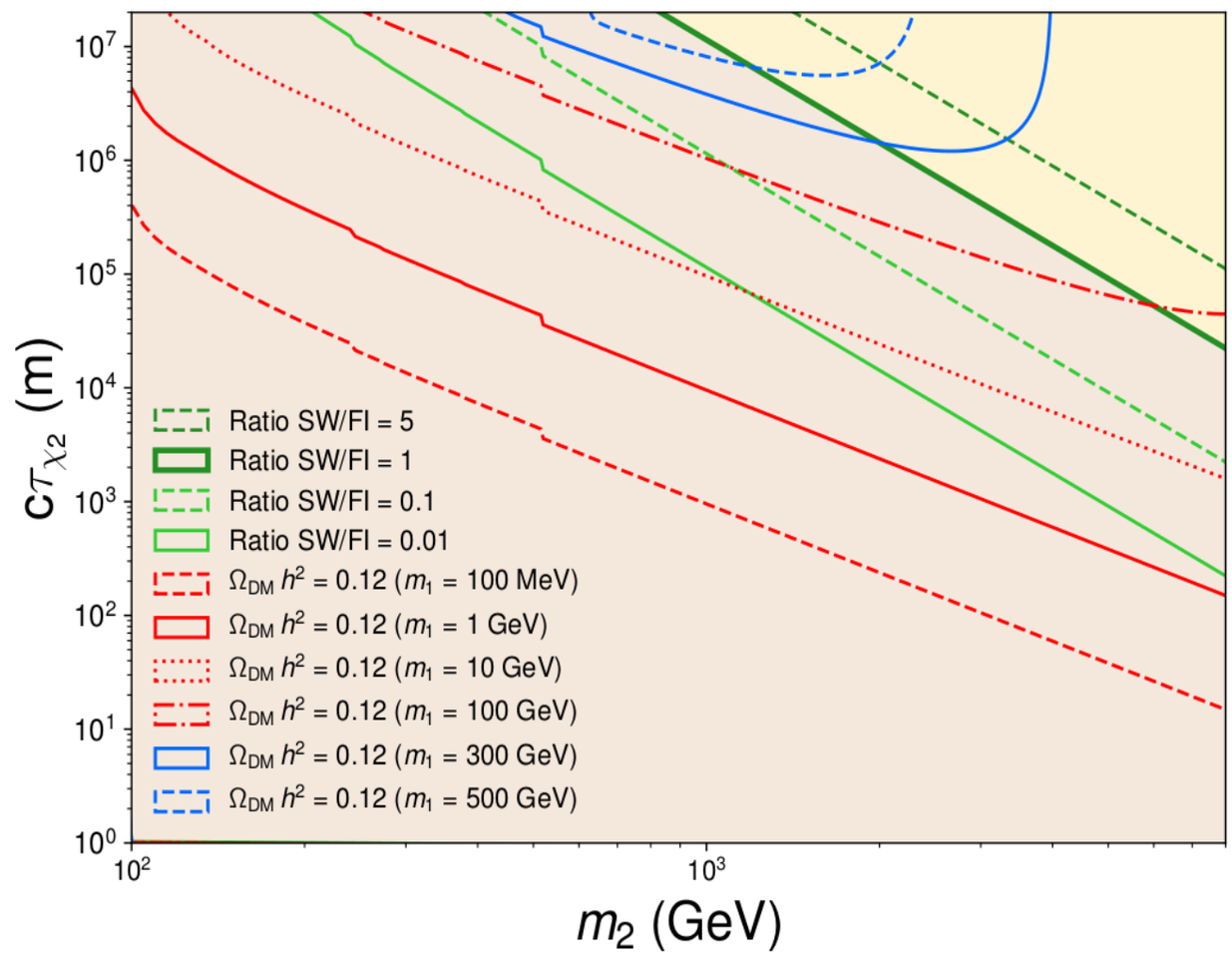
Feng et al, hep-ph/0302215

$$\Omega_2\, h^2 \simeq 0.1 \left(\frac{m_2}{\text{TeV}}\right)^2$$

$$\Omega_{\rm DM}\, h^2 = \Omega_1\, h^2 + \Omega_2\, h^2 \times \frac{m_1}{m_2}$$

Note however that if Super-WIMP component dominant and mass ratio large, DM would be quite relativistic!

Garny et al, 1809.10135



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$\mathbb{Z}_2$-odd sector

SU(2) Singlet SU(2) Doublet "Higgs Portal"

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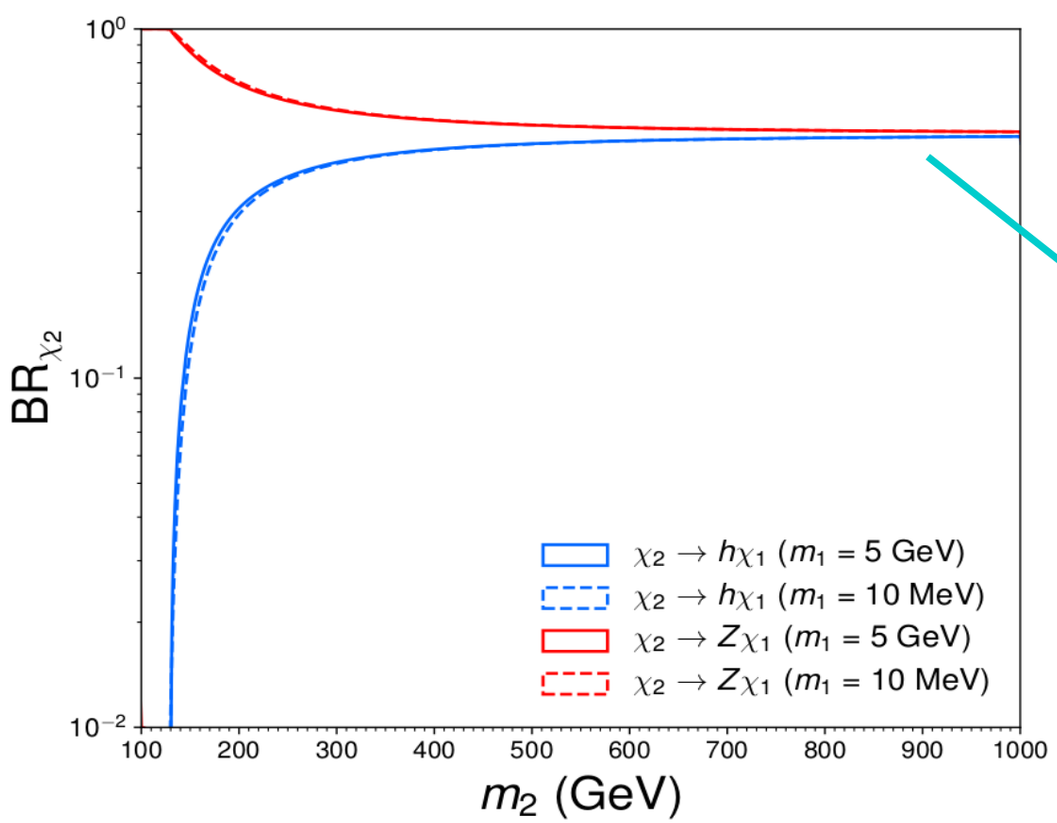
Simple DM version of complete setups (e.g. Higgsino-Axino, Higgsino-Singlino)

Co et al, 1506.07532

Tiny singlet-doublet mixing (DM is singlet-like) $\sin\theta \simeq \dfrac{y_\chi v}{\sqrt{2}(m_2 - m_1)}$



50% BR

Decays of χ_2

$\chi_2 \to h\chi_1$
$\chi_2 \to Z\chi_1$

Freeze-In DM from the Higgs

Calibbi, Lopez-Honorez, Mariotti, Lowette, 1805.04423
Filimonova, Westhoff, 1812.04628
JMN, Tunney, Zaldivar, 1906.xxxxx

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Simple DM version of complete setups (e.g. Higgsino-Axino, Higgsino-Singlino)

Co et al, 1506.07532

Also note the charged component of SU(2) doublet $\psi^\pm$

Radiative mass splitting

$$\delta m = m_{\psi^\pm} - m_2 \in [260, 340]\ \text{MeV}$$

Dominant decay

$$\psi^\pm \to \pi^\pm\chi_2$$
$$\psi^\pm \to \ell^\pm\nu\chi_2$$
$$\psi^\pm \to W^\pm\chi_1$$

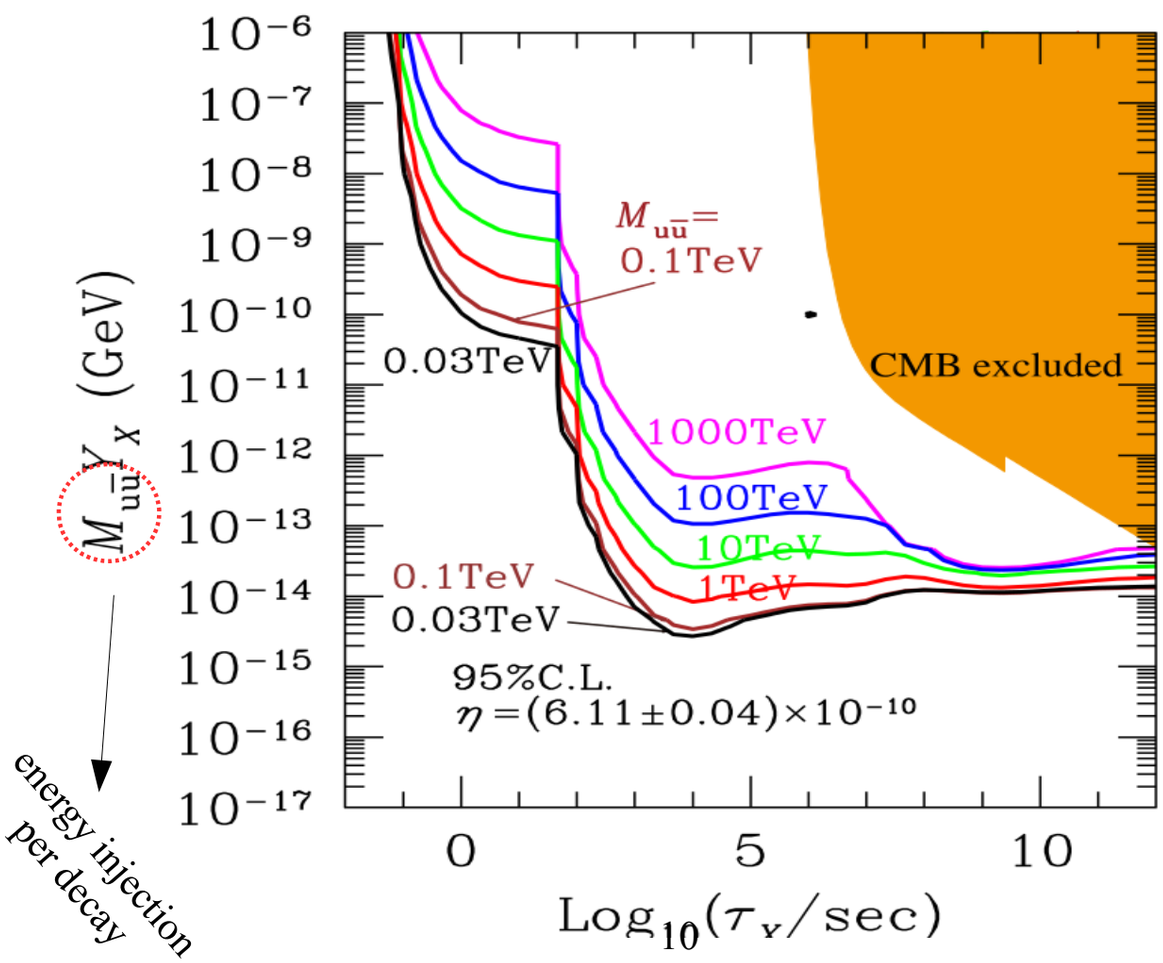
DM production

Constraints from Cosmology

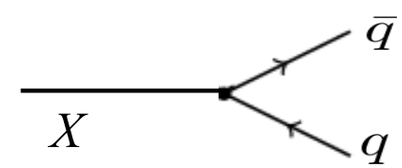
▷ Big-bang nucleosynthesis

If long-lived, χ_2 visible decay products can affect BBN predictions

Constrain (hadronic) energy injection from the decay of χ_2



Kawasaki, Kohri, Moroi, Takaesu, 1709.01211



$$E_{\bar{q}q} \sim m_X$$

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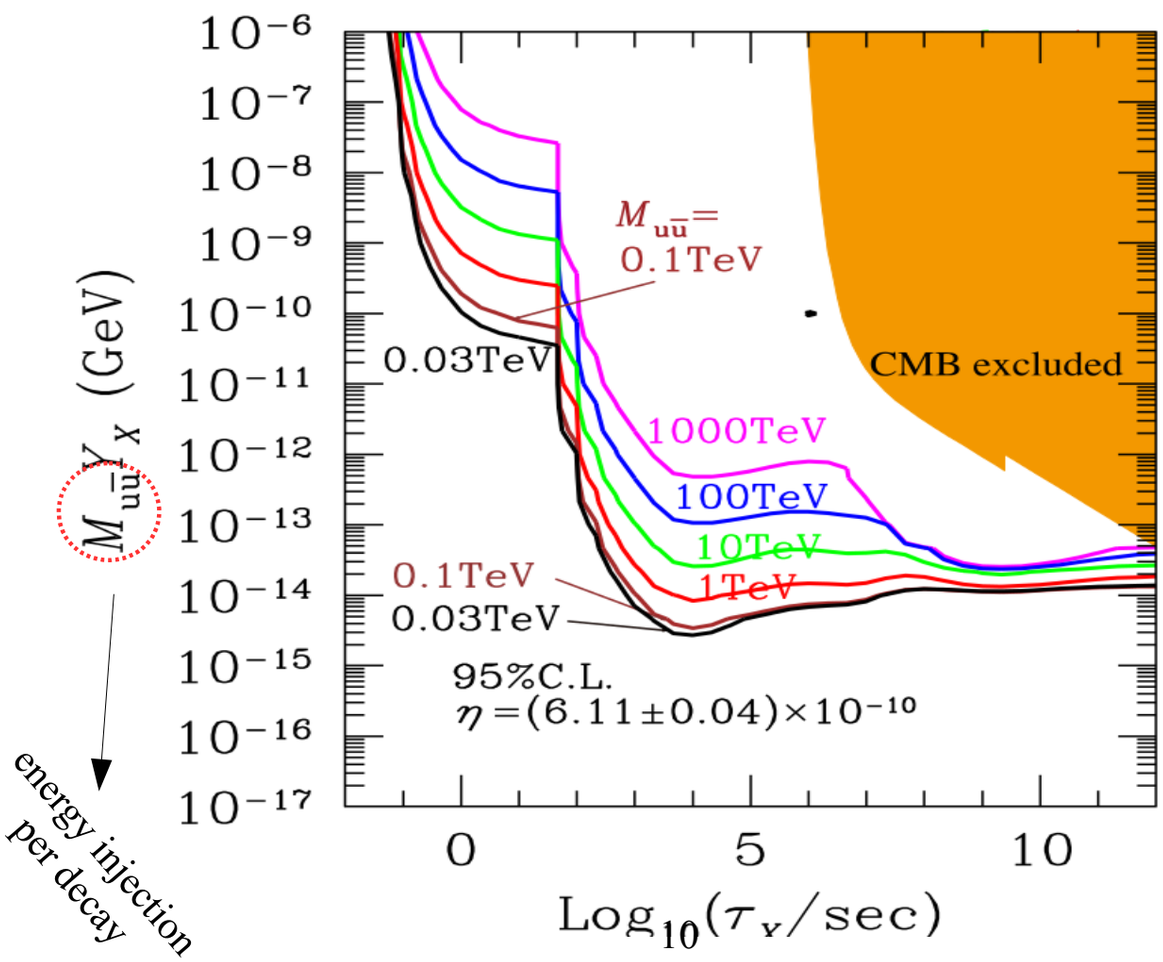
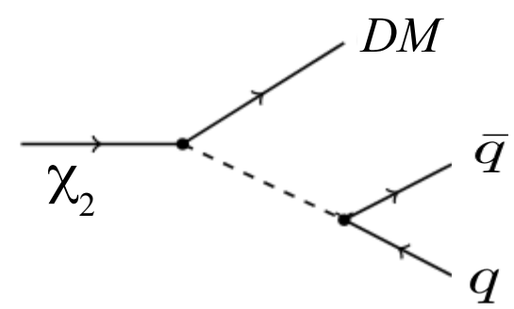


Kawasaki, Kohri, Moroi, Takaesu, 1709.01211

Energy injection per decay



$$E_{\bar{q}q} \simeq \sqrt{m_Z^2 + \frac{m_2^2}{4}\left[(1-\xi_z-\xi_1)^2 - 4\xi_z\xi_1\right]} \qquad (\chi_2 \to Z\chi_1)$$

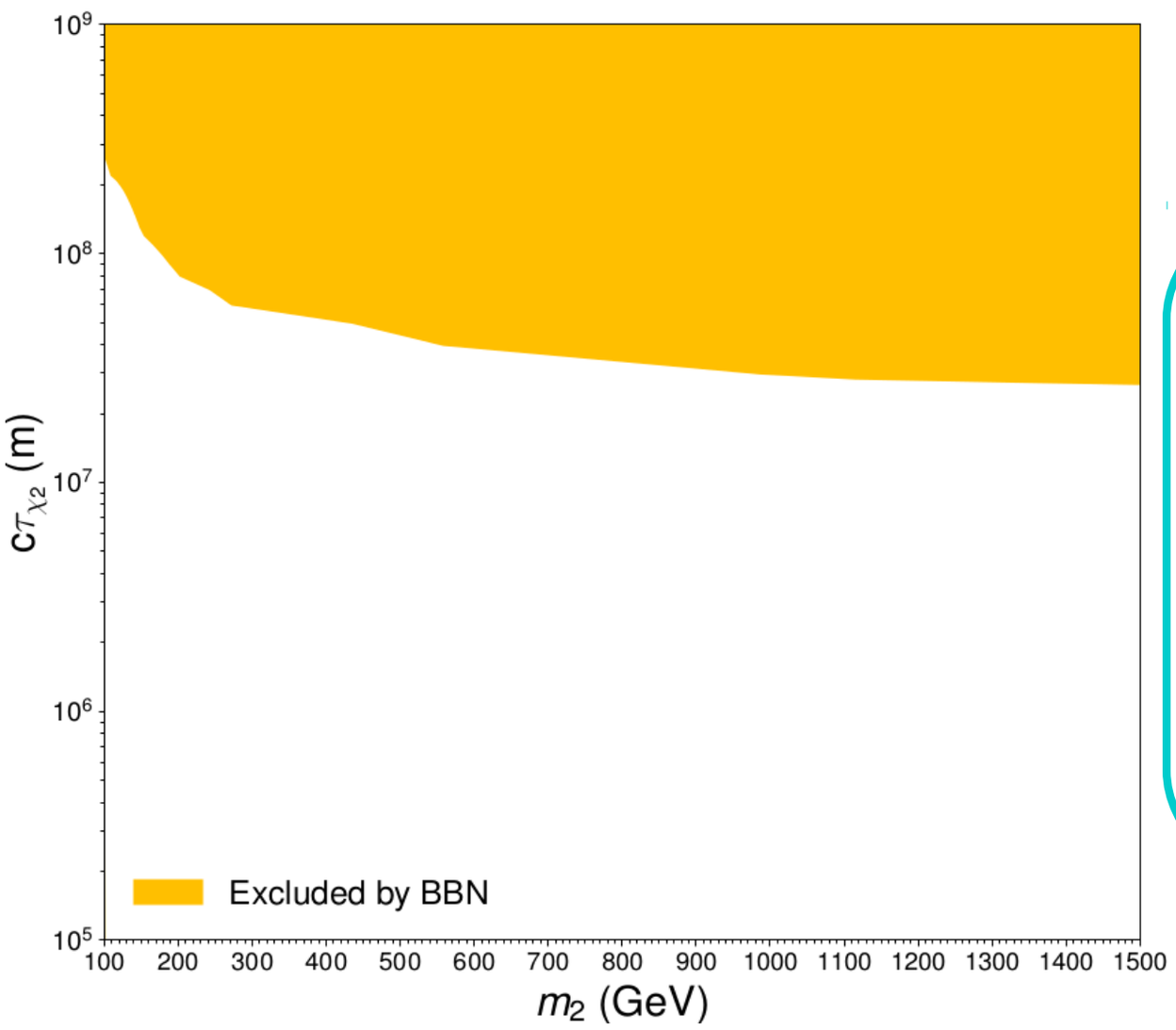
Constrain $\dfrac{\Omega_2 h^2}{m_2} \times \sum_{a=h,Z} E^a_{\bar{q}q} \times \mathrm{BR}(\chi_2 \to a\,\chi_1)\ \mathrm{BR}(a \to \mathrm{hadrons})$

Constraints from Cosmology

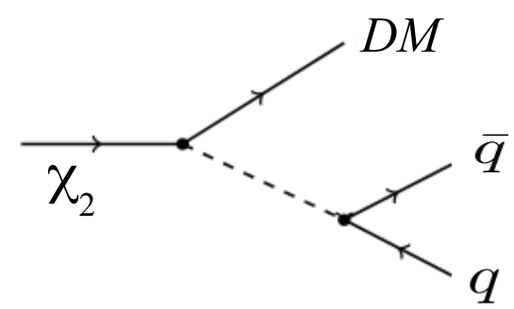
▷ Big-bang nucleosynthesis

If long-lived, χ_2 visible decay products can affect BBN predictions

Constrain (hadronic) energy injection from the decay of χ_2



Energy injection per decay



$$E_{\bar{q}q} \simeq \sqrt{m_Z^2 + \frac{m_2^2}{4}\left[(1-\xi_z-\xi_1)^2 - 4\xi_z\xi_1\right]} \qquad (\chi_2 \to Z\chi_1)$$

Constrain $\dfrac{\Omega_2 h^2}{m_2} \times \sum_{a=h,Z} E^a_{\bar{q}q} \times \mathrm{BR}(\chi_2 \to a\,\chi_1)\ \mathrm{BR}(a \to \mathrm{hadrons})$

Constraints from Cosmology

▷ Lyman-α forest observations

Constrain washout of small-scale structure by partially relativistic ("*warm*") DM

Assumes DM relic abundance is saturated

$m_{\rm DM} \gtrsim 4.65$ keV

Thermal warm DM

Baur et al, 1706.03118

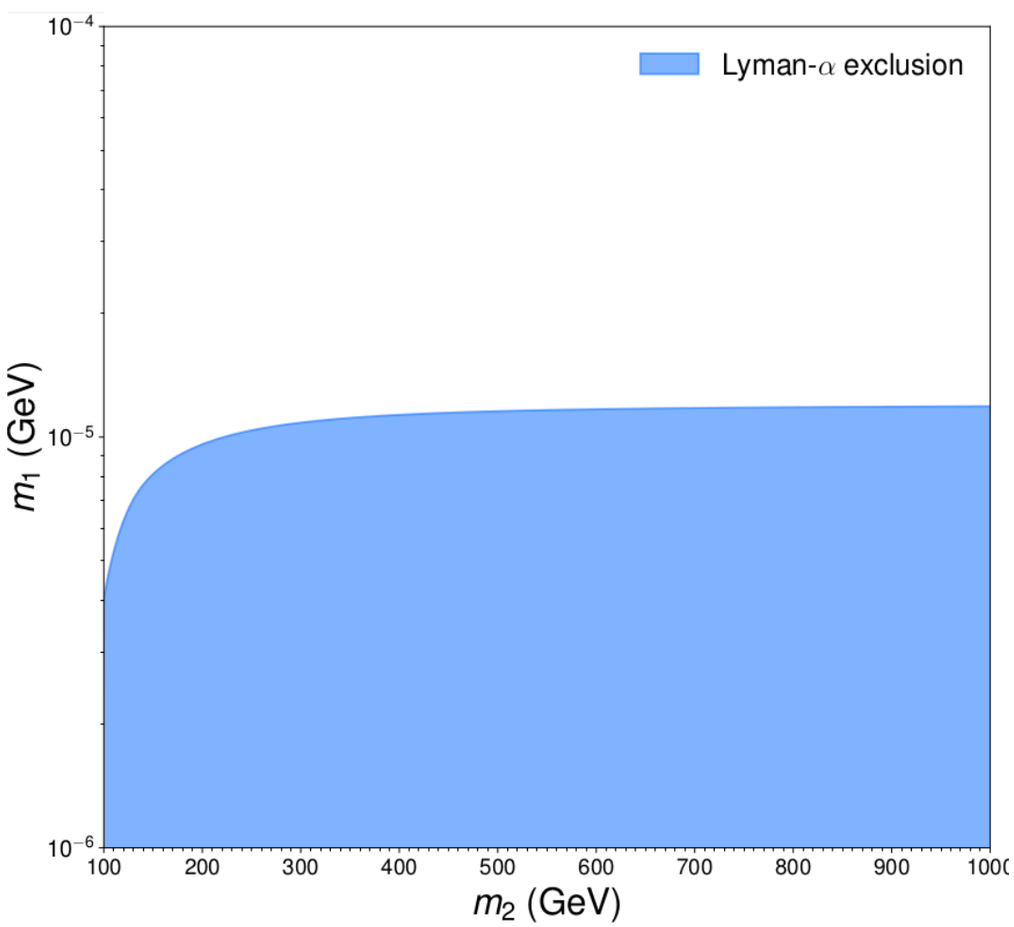
$$m_{\rm DM} \gtrsim 12 \text{ keV} \left(\frac{\sum_{ij} g_i \Gamma_{ij} \Delta_{ij}^{\eta}}{\sum_{ij} g_i \Gamma_{ij}} \right)^{1/\eta}$$

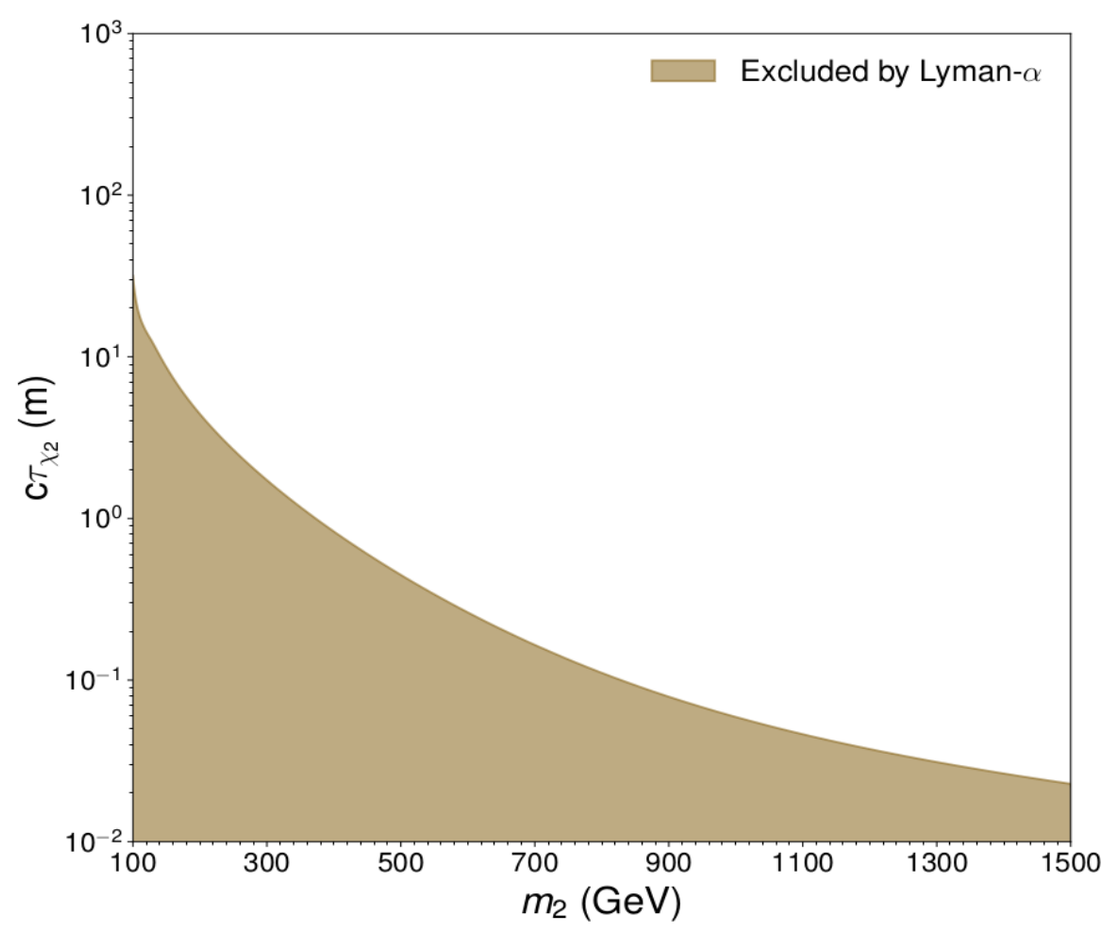
Freeze-in DM from 2-body decay

Boulebnane, Heeck, Nguyen, Teresi, 1709.07283

$\Gamma(A_i \to B_j \chi_1)$

$$1 - \frac{m_{B_j}^2}{m_{A_i}^2}$$

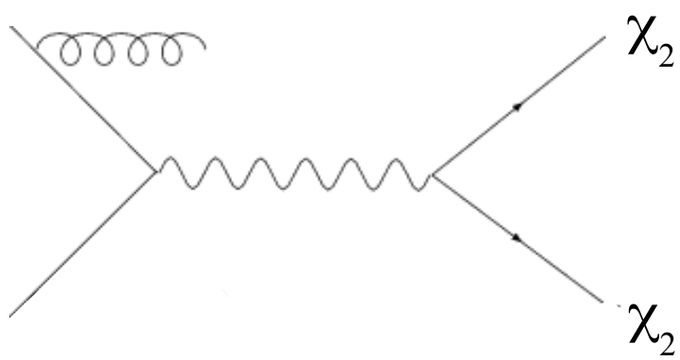




Probing Freeze-in at LHC

▷ Mono-X (mono-jet)

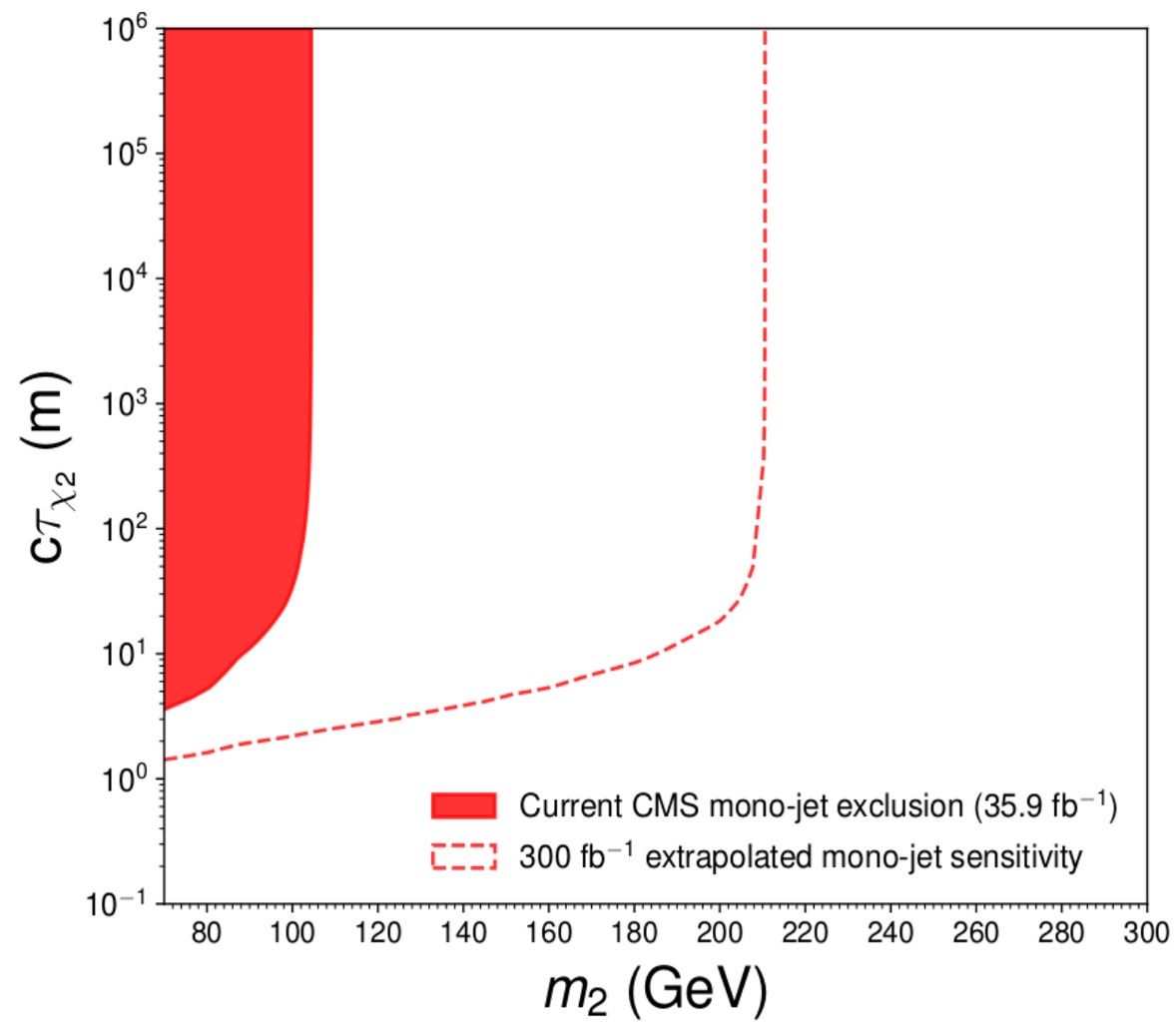
Consider χ_2 as effectively stable on LHC



$$\mathcal{L} \supset Z'_\mu \left(g_{\rm SM}\, \bar{q}\gamma^\mu q + g_\chi\, \bar{\chi}\gamma^\mu \chi \right)$$

(Re)interpret CMS bounds for DM simplified models with vector mediator with $m = m_Z$

CMS *1712.02345* (35.9 fb^{-1})



▷ Disappearing tracks

$$\psi^\pm \to \pi^\pm \chi_2$$

$$\delta m = m_{\psi^\pm} - m_2 \in [260, 340]\ \text{MeV}$$

few *cm* decay length

ATLAS DT analysis for pure Higgsino production

ATL-PHYS-PUB-2017-019 (36.1 fb^{-1})

$$m_{\psi^\pm} > 145\ \text{GeV}$$