LHC-Friendly Avenues
for
Freeze-in Dark Matter

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Outline

➔ **Freeze-In Production of Dark Matter** (*in a nutshell*)

➔ **LHC-friendly Freeze-In DM Models**
  (A Model of Dark Matter Freeze-In via the Higgs Field)

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

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[source: PhD Comics]

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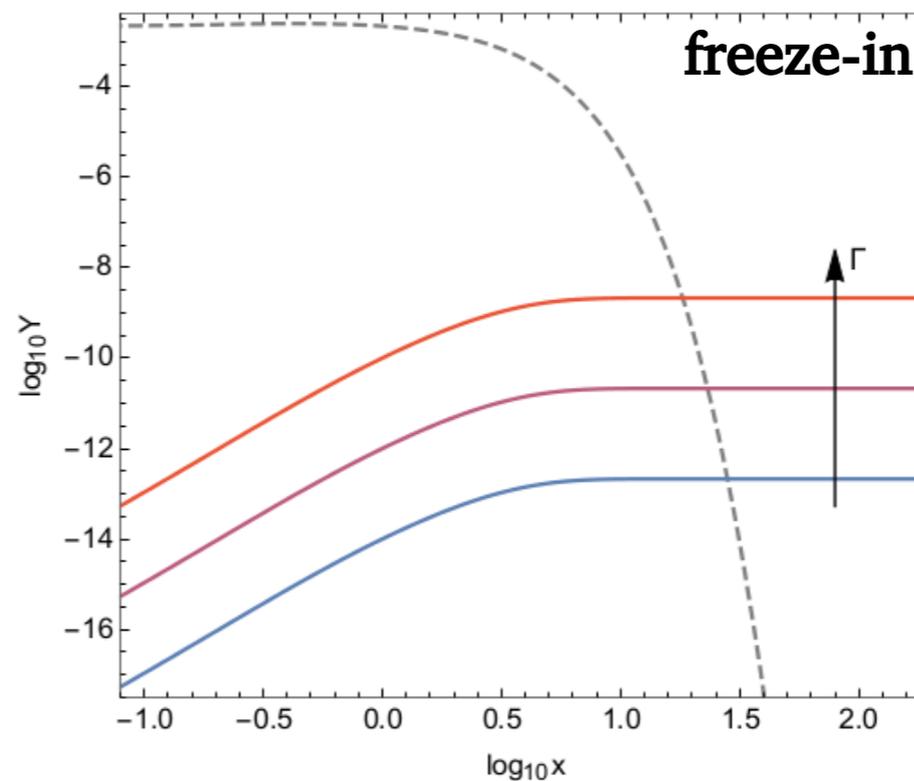
➔ **Long-Lived Particle searches:** LHC **and** MATHUSLA
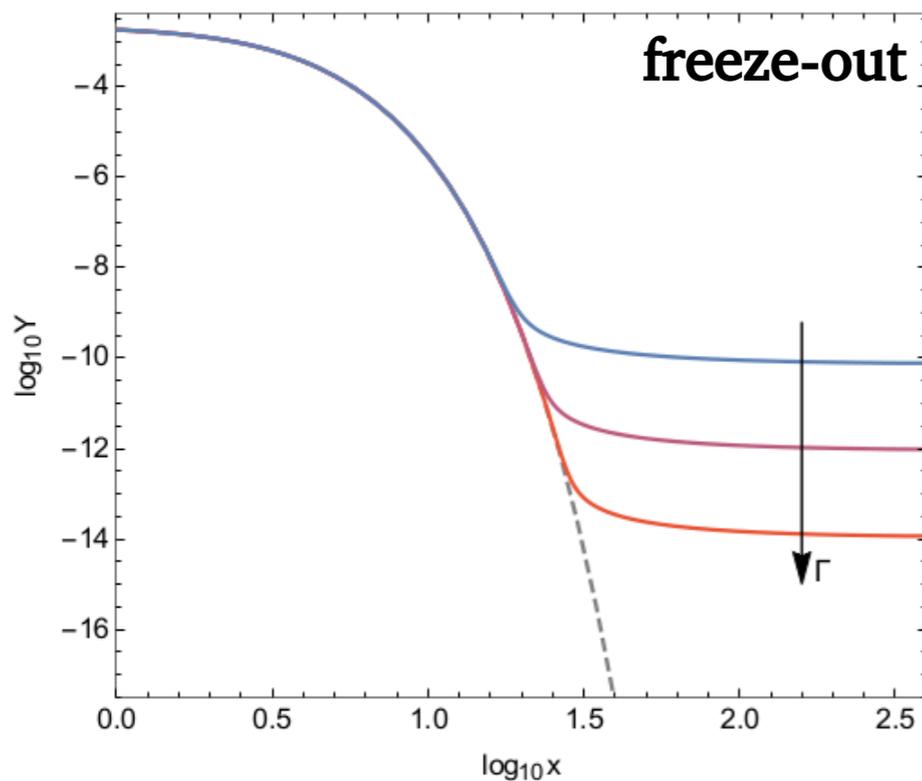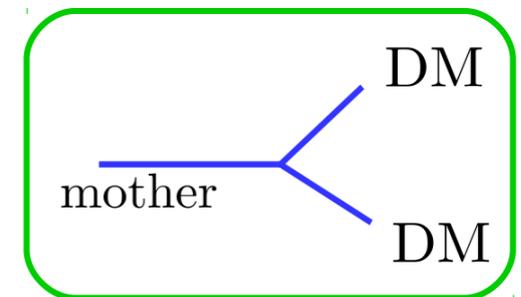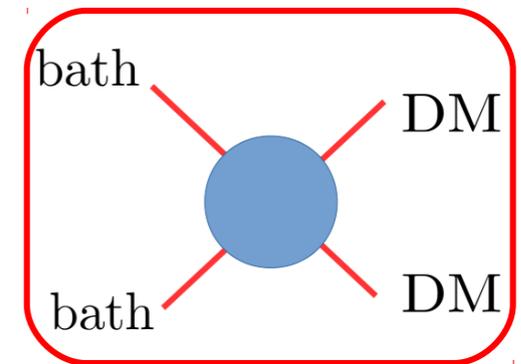
Dark Matter Freeze-In in a Nutshell

Hall et al, 0911.1120

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

negligible

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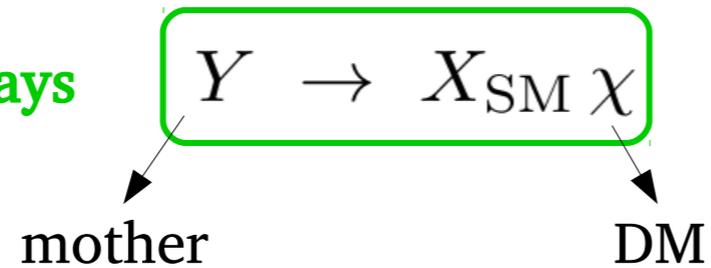➜ Production from **scatterings** or **decays**

$$Y = n_{\mathrm{DM}}/s$$
$$x = m/T$$

Bernal et al, 1706.07442

Hall et al, 0911.1120

➜ Freeze-in from **decays**

$$Y \; \rightarrow \; X_{\mathrm{SM}}\, \chi$$

mother   DM

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

Hall et al, 0911.1120

➡ Freeze-in from **decays** $\quad Y \;\to\; X_{\mathrm{SM}}\,\chi$

$\qquad\qquad\qquad\qquad$ mother $\qquad\qquad\qquad\qquad$ DM

$$\frac{dn_\chi}{dt} + 3H\,n_\chi = \Gamma_Y\,n_Y^{\mathrm{eq}}\,\frac{K_1(m_Y/T)}{K_2(m_Y/T)} \qquad\longrightarrow\qquad Y_\chi \approx \frac{135\,g_Y\,\xi\,M_{\mathrm{Pl}}\,\Gamma_Y}{8\pi^3\,m_Y^2}\,\frac{1}{1.66\,g_*^s(m_Y/3)\sqrt{g_*(m_Y/3)}}$$
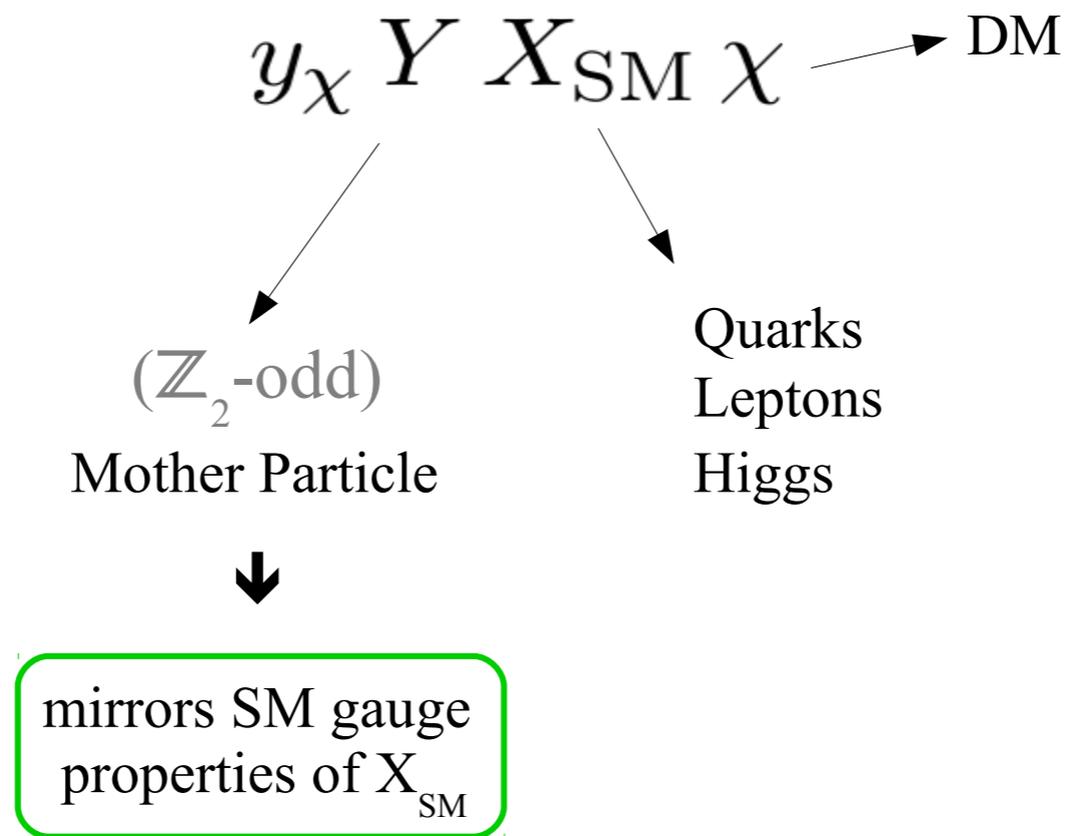
DM Relic Density: $\quad \lambda \sim (10^{-12}-10^{-13})\sqrt{\dfrac{m_Y}{m_\chi}}$

Long-lived particle signatures (e.g. LHC) from Y decays!

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

Simple Freeze-In DM Models

Belanger et al, 1811.05478

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

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

Mother Particle

Quarks
Leptons
Higgs

⬇

mirrors SM gauge
properties of X_{SM}

Freeze-In DM from the Higgs

$\mathbb{Z}_2$-odd sector

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

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

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

Co et al, 1506.07532

See also: *Calibbi et al, 1505.03867* (freeze-out)
Calibbi et al, 1805.04423 (freeze-in)

Freeze-In DM from the Higgs

$\mathbb{Z}_2$-odd sector

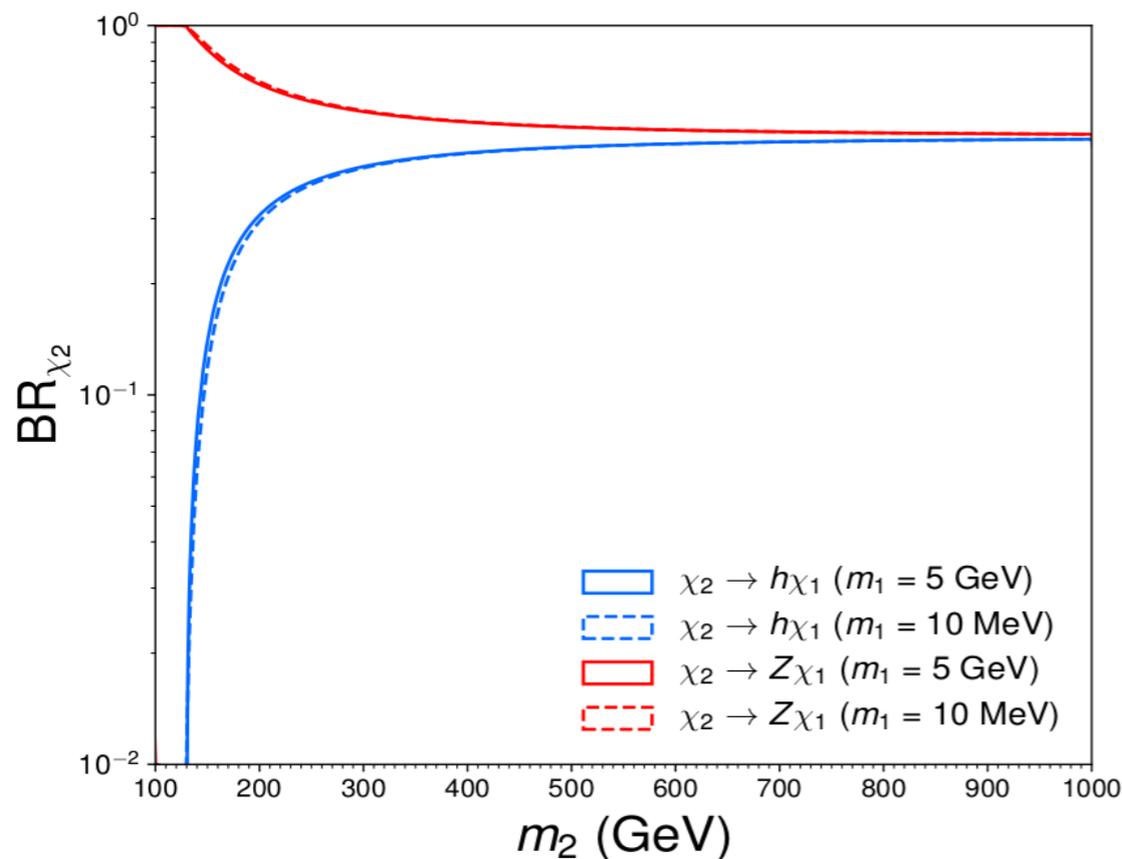SU(2) Singlet   SU(2) Doublet   "Higgs Portal"

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

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

Co et al, 1506.07532

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

Decays of χ_2

$$\boxed{\begin{array}{l} \chi_2 \to h\chi_1 \\ \chi_2 \to Z\chi_1 \end{array}}$$

Legend (figure):
- $\chi_2 \to h\chi_1$ ($m_1 = 5$ GeV)
- $\chi_2 \to h\chi_1$ ($m_1 = 10$ MeV)
- $\chi_2 \to Z\chi_1$ ($m_1 = 5$ GeV)
- $\chi_2 \to Z\chi_1$ ($m_1 = 10$ MeV)

Axes: BR_{χ_2} vs m_2 (GeV)

Freeze-In DM from the Higgs

$\mathbb{Z}_2$-odd sector

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

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

Co et al, 1506.07532

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

Radiative mass splitting

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

Decays of $\psi^\pm$ Dominant decay

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

Relevant for DM production

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Freeze-In DM from the Higgs

$\mathbb{Z}_2$-odd sector

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

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

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

Co et al, 1506.07532

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

Freeze-in Production of DM

(assume standard thermal history)

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

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

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

Constraints from Cosmology

➔ **Lyman-α forest observations**

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

➔ **Big-bang nucleosynthesis**

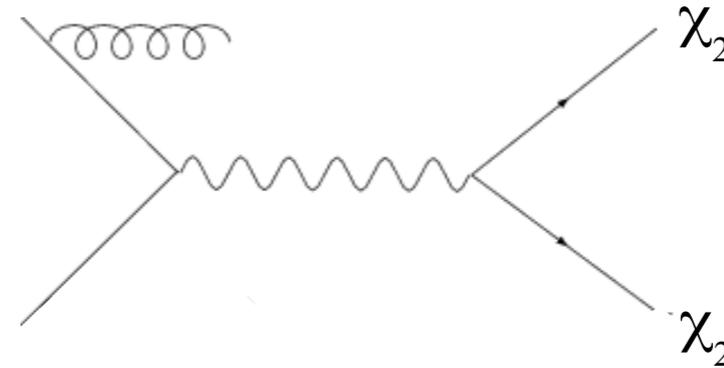If long-lived, χ_2 visible decay products can affect BBN predictions

Constrain (hadronic) energy injection from the decay of χ_2

Probing Freeze-in at LHC

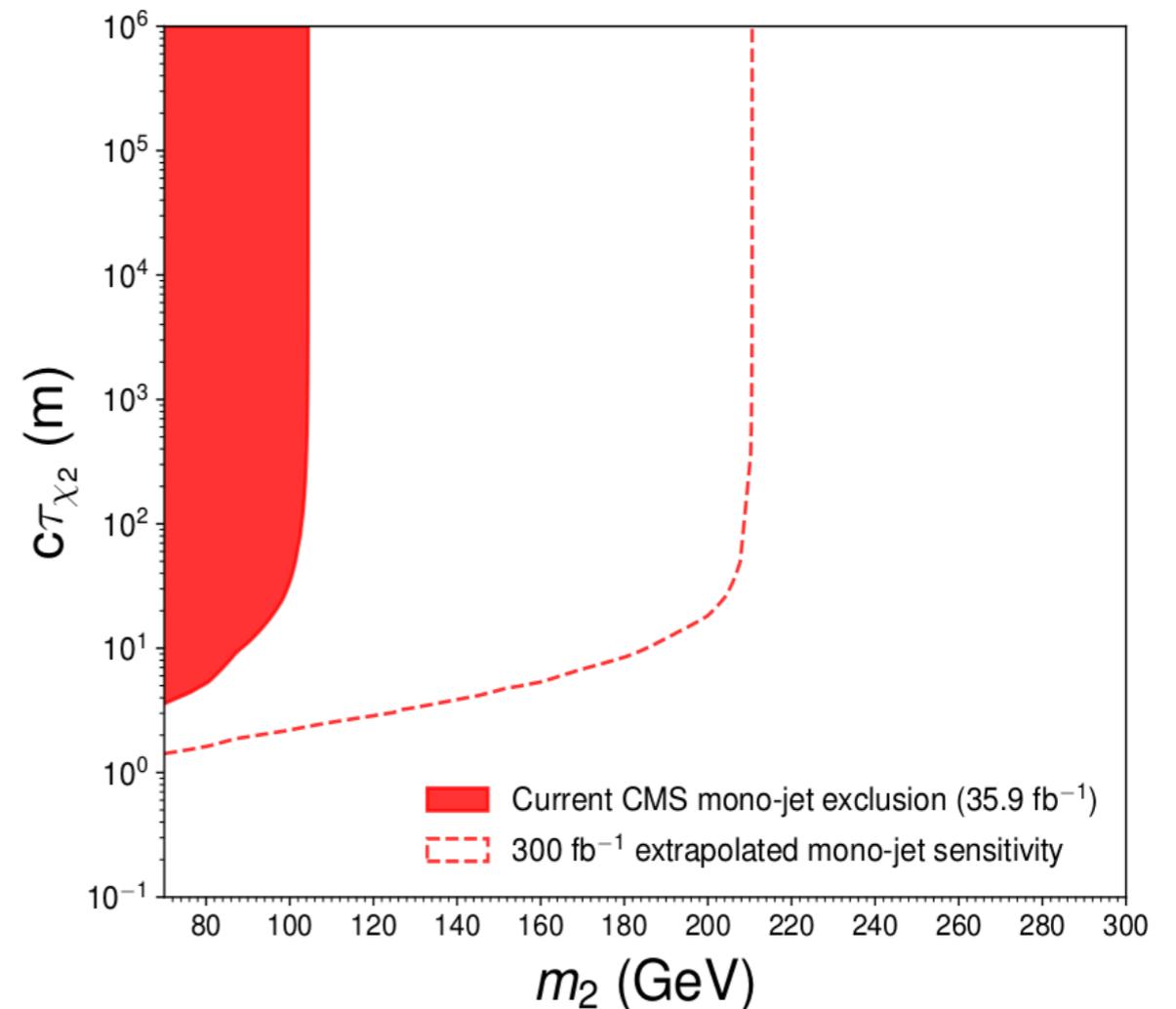➔ **Mono-X (mono-jet)**

Consider χ_2 as effectively stable on LHC

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

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

Search for new physics in final states with an energetic jet or a hadronically decaying W or Z boson and transverse momentum imbalance at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration[*]

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

- ■ Current CMS mono-jet exclusion (35.9 fb^{-1})
- ⬚ 300 fb^{-1} extrapolated mono-jet sensitivity

Probing Freeze-in at LHC

➔ **Disappearing tracks:** $\psi^{\pm} \to \pi^{\pm} \chi_2$ $\delta m = m_{\psi^{\pm}} - m_2 \in [260, 340]$ MeV

few *cm* decay length

ATLAS disappearing track analysis for pure Higgsino production

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

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

[Courtesy of Livia Soffi, CMS Collaboration]

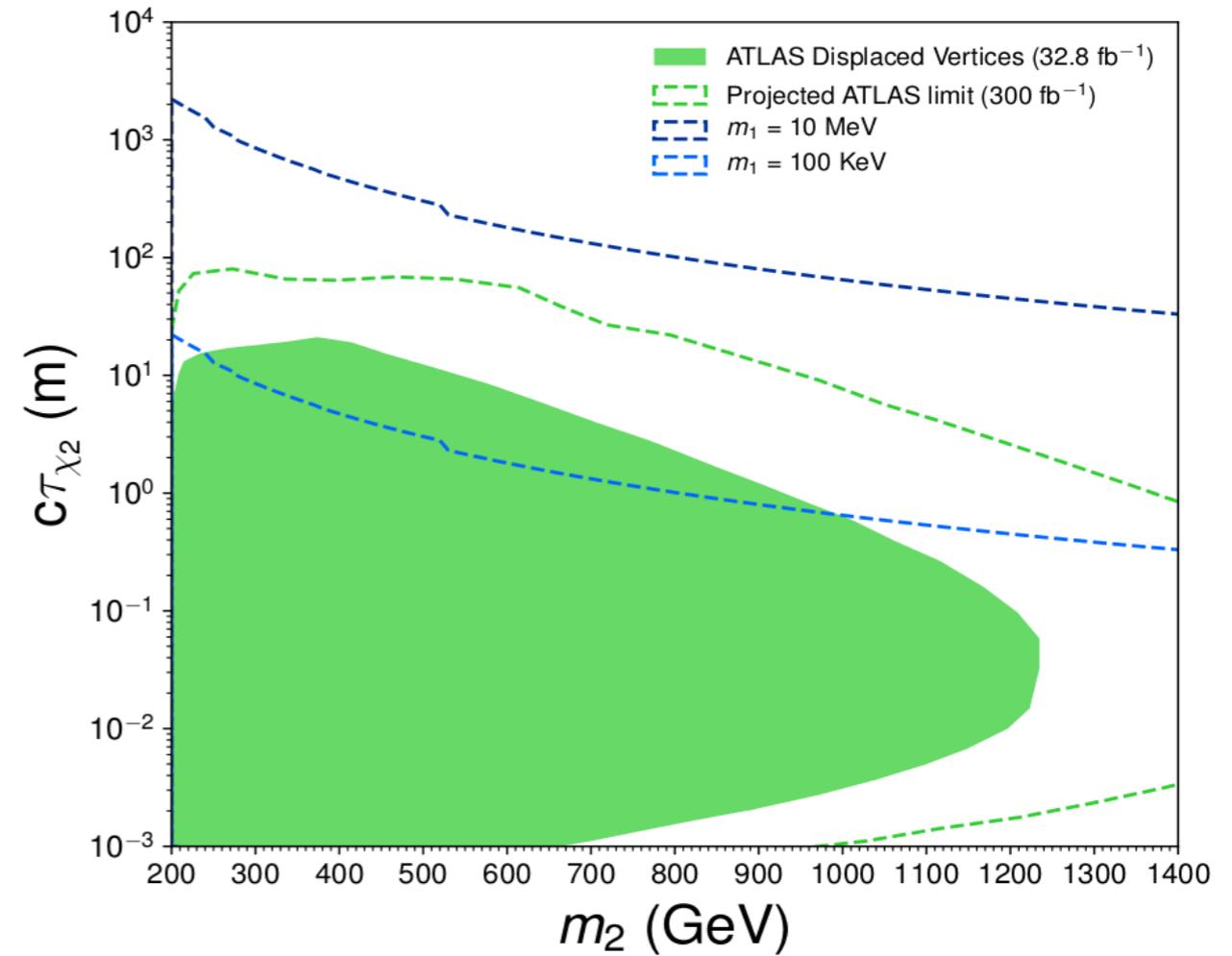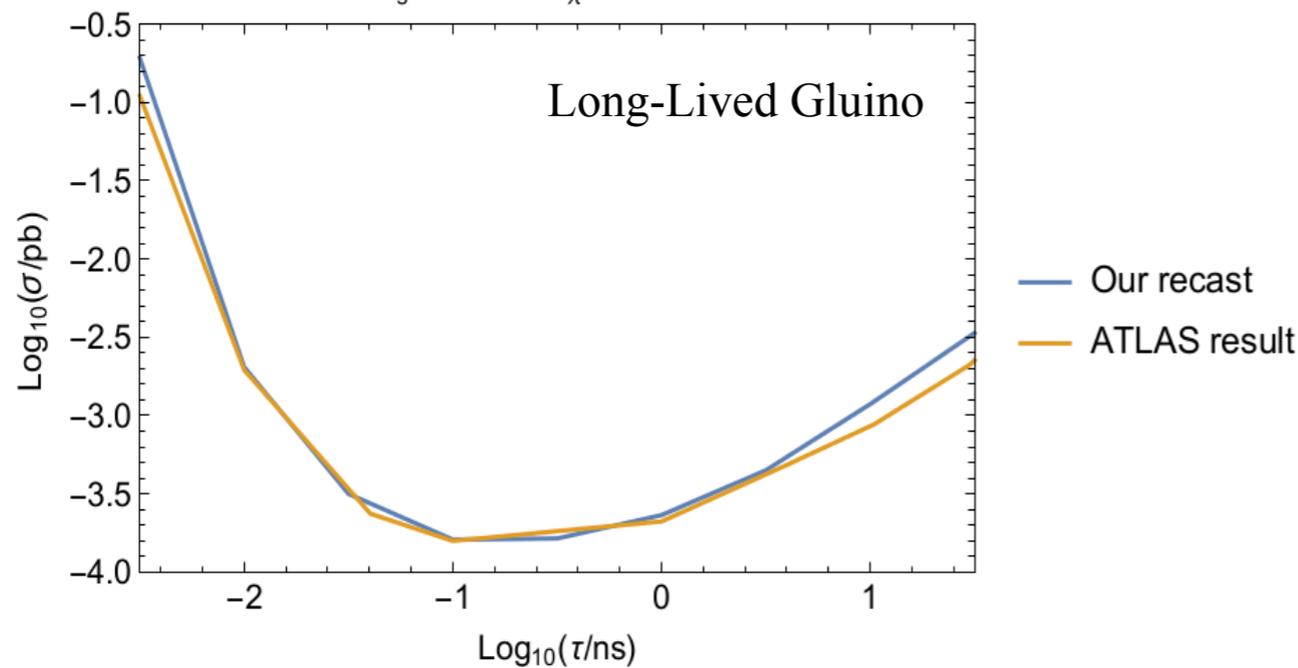# Probing Freeze-in at LHC

➜ **Displaced vertices (jets) + MET**

ATLAS *1710.04901* (32.8 fb^{-1})

Calibbi et al, 1805.04423

JMN, Tunney, Zaldivar, 1906.xxxxx

$m_{\tilde{g}}$ = 2 TeV, $m_{\tilde{\chi}}$ = 100 GeV

Long-Lived Gluino

— Our recast
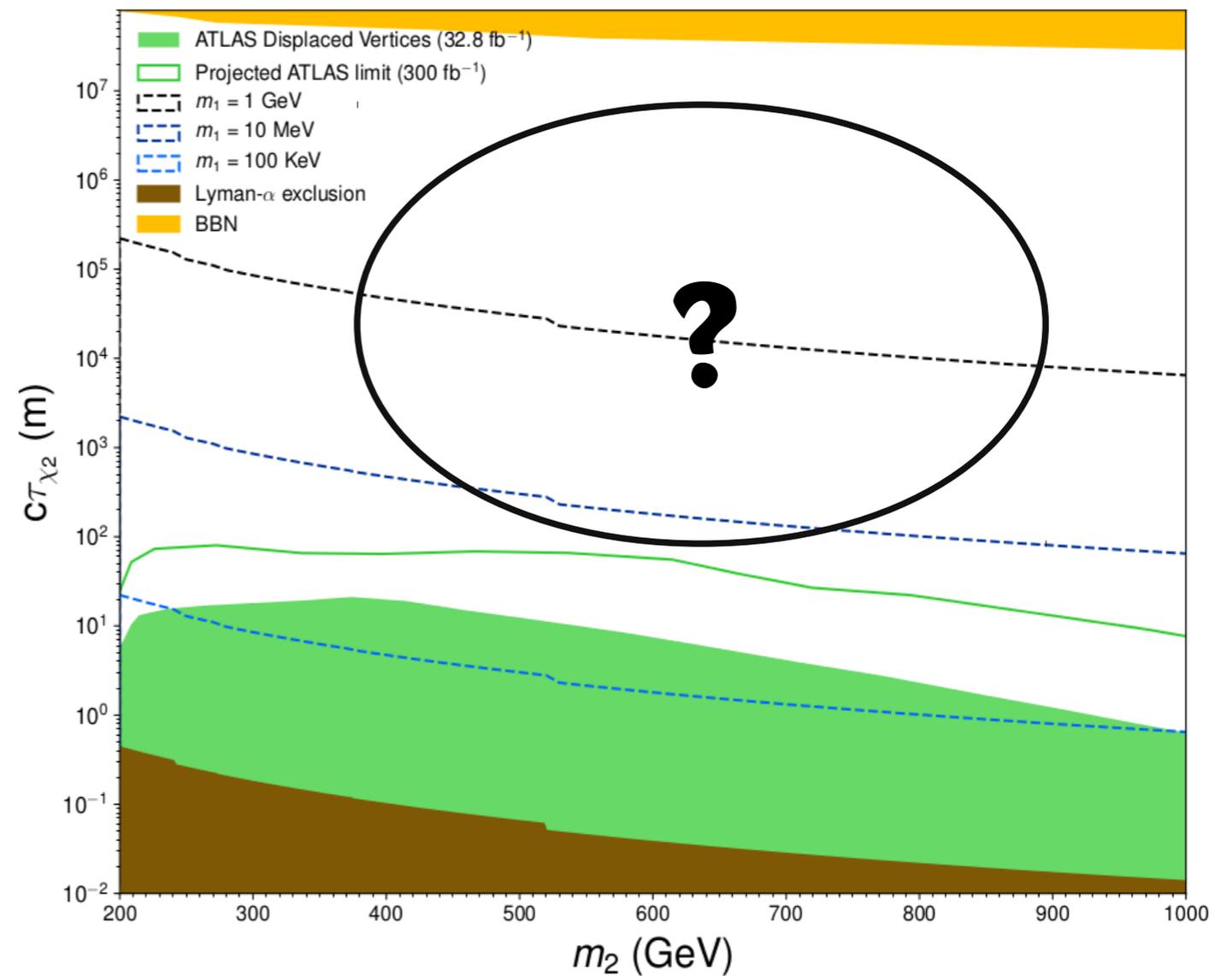— ATLAS result

Probing Freeze-in at LHC

➜ Displaced vertices (jets) + MET

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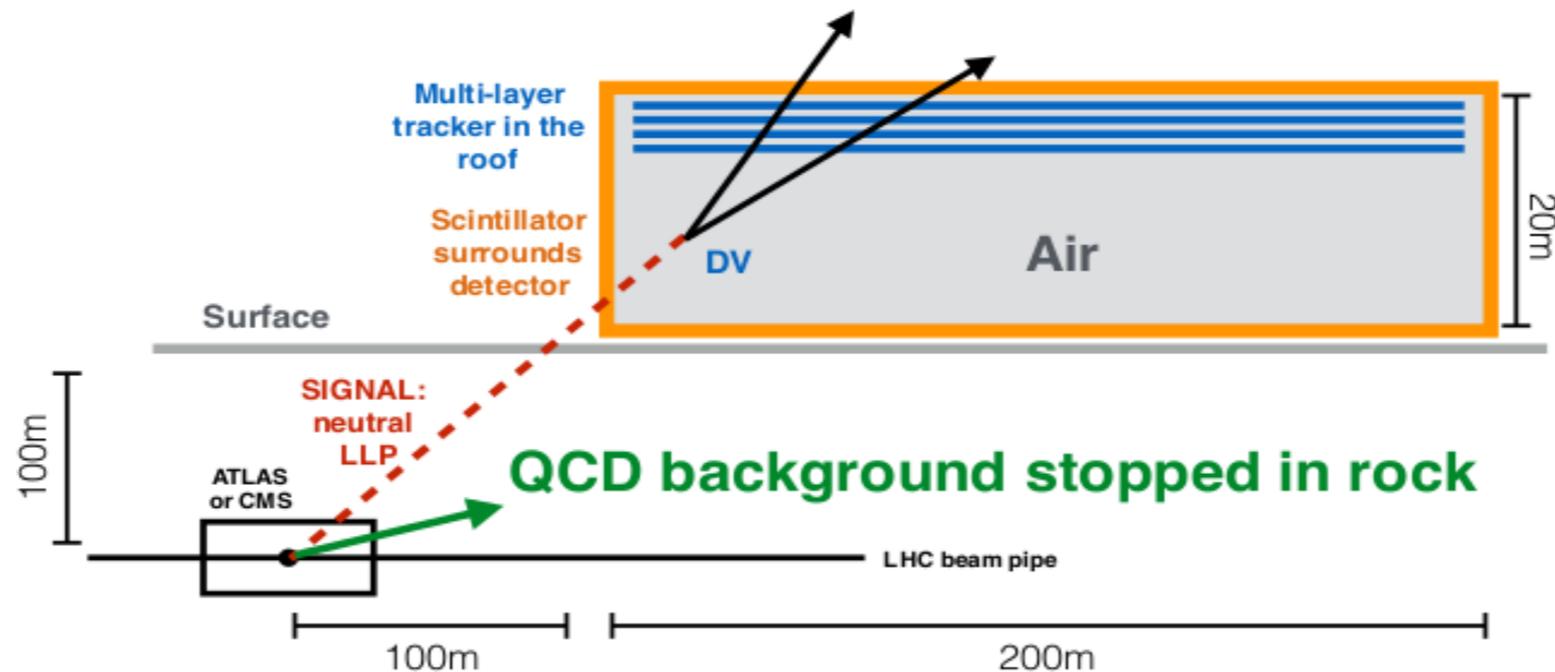*Calibbi et al, 1805.04423*

JMN, Tunney, Zaldivar, 1906.xxxxx

Probing Freeze-in at LHC

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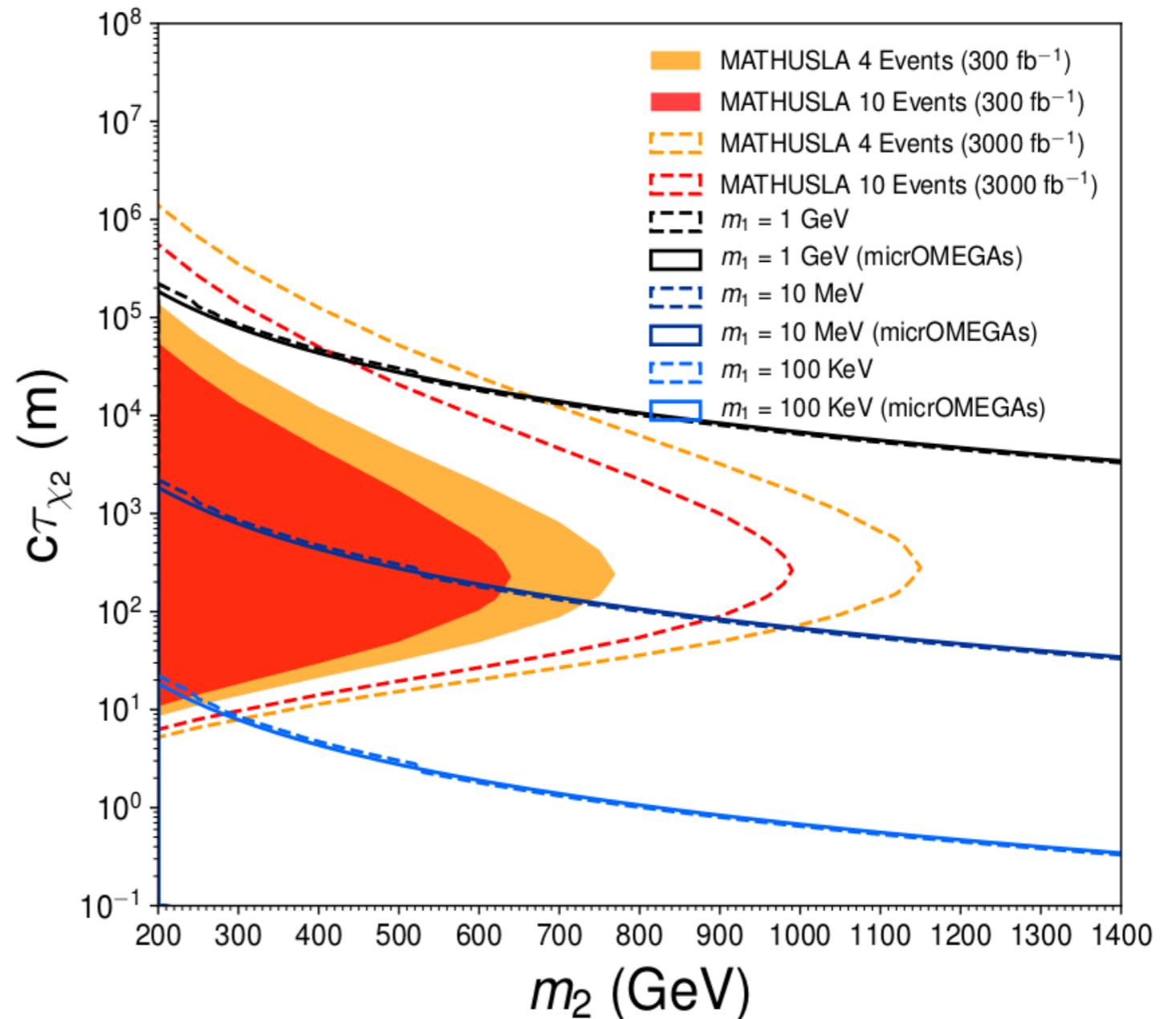# Probing Freeze-in at MATHUSLA

Probing Freeze-in at MATHUSLA

$$c\tau_2 \simeq 3500 \text{ m } \left(\frac{m_1}{100 \text{ MeV}}\right)\left(\frac{500 \text{ GeV}}{m_2}\right)^2$$
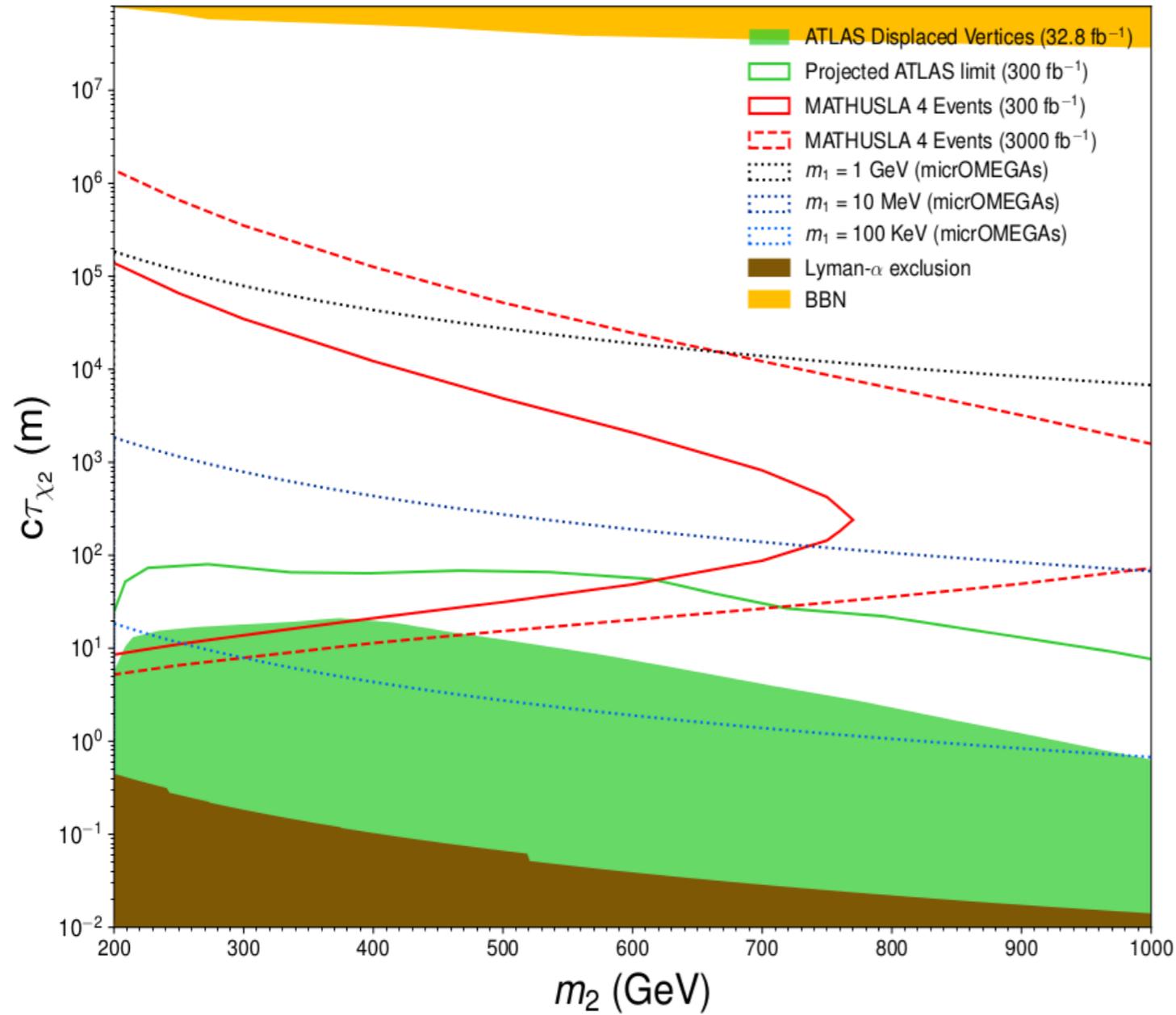
MATHUSLA solid angle
from interaction point

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

$$P_{\text{decay}}(\beta\, c\tau_2, L_a, L_b) = e^{-\frac{L_a}{\beta\, c\tau_2}} - e^{-\frac{L_b}{\beta\, c\tau_2}}$$
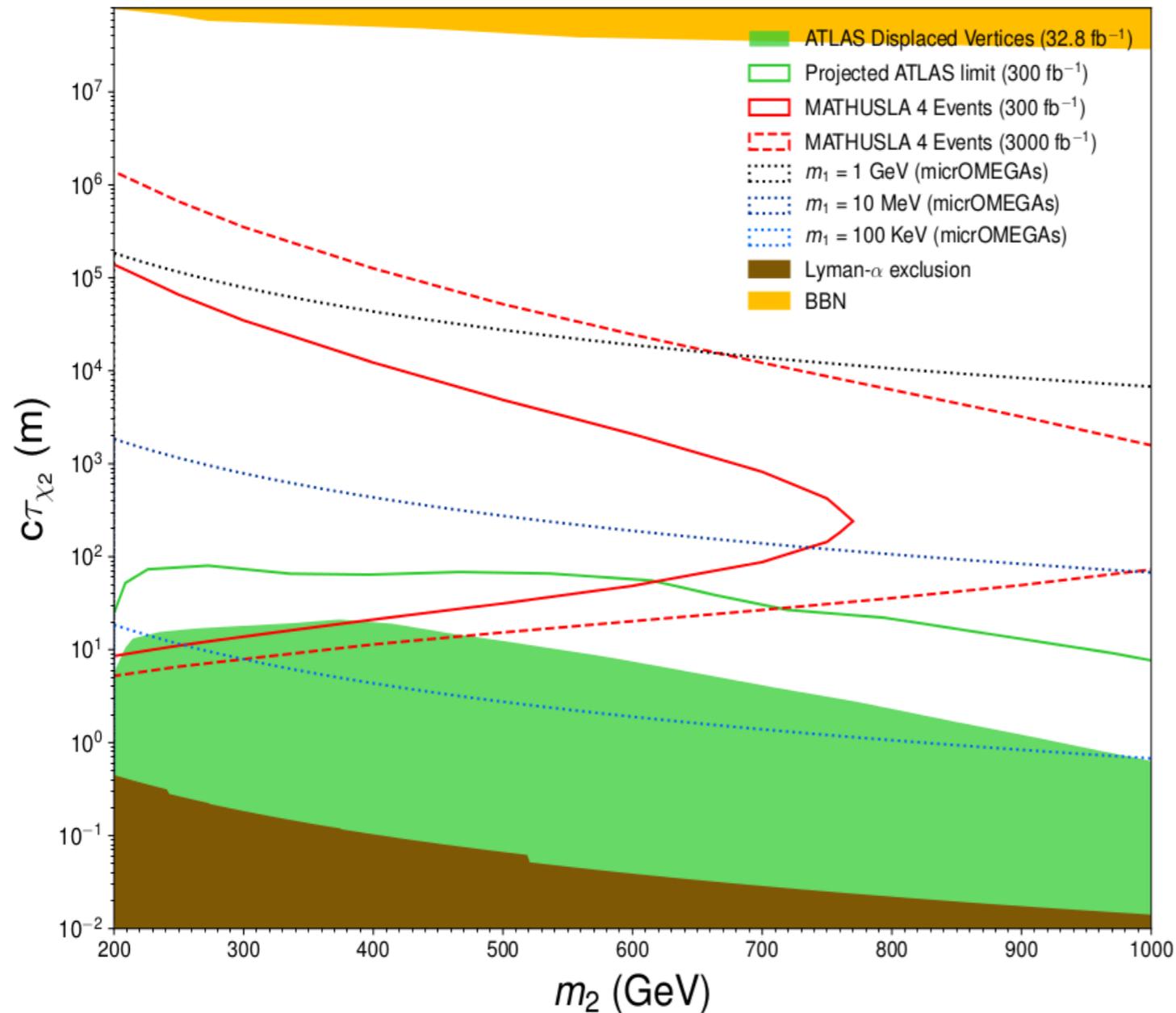
$$|\vec{p}_{\chi 2}|/m_2$$

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Putting it all together & wrapping up...

Putting it all together & wrapping up...

→ Freeze-in well-motivated alternative to WIMP

→ Explore freeze-in DM probes @LHC with simple (minimal) models
 e.g. **Higgs "portal"**

→ Possible to probe freeze-in DM with long-lived particle searches!

LHC

MATHUSLA (*advantage of dedicated LLP detector*)

Thank you!

Constraints from Cosmology

➜ **Lyman-α forest observations**

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

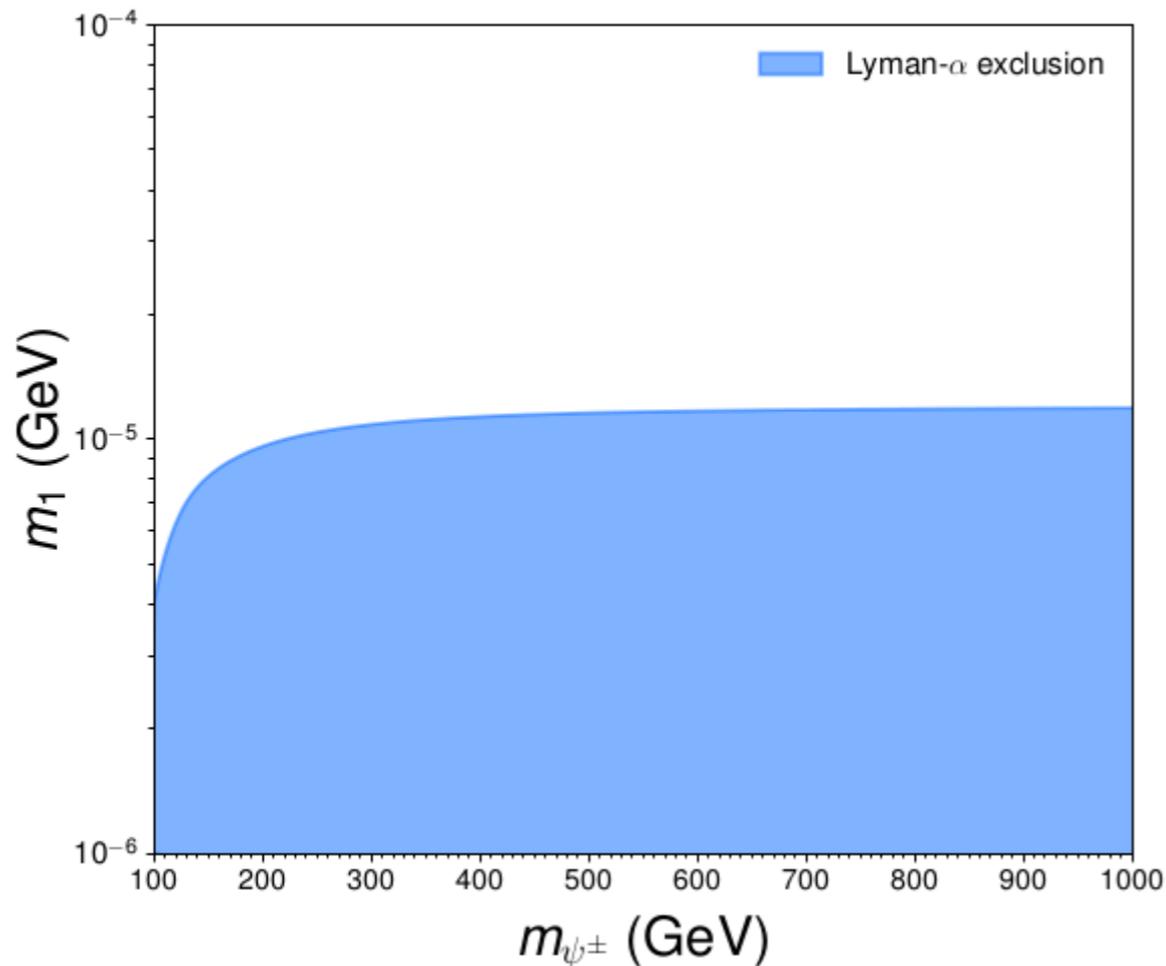$$\boxed{m_{\rm DM} \gtrsim 4.65 \text{ keV}} \quad \xrightarrow{\hspace{2cm}} \quad \boxed{m_{\rm DM} \gtrsim 12 \text{ keV} \left(\frac{\sum_{ij} g_i \Gamma_{ij} \Delta_{ij}^\eta}{\sum_{ij} g_i \Gamma_{ij}} \right)^{1/\eta}}$$

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

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

Thermal warm DM

Freeze-in DM from 2-body decay

Baur et al, 1706.03118

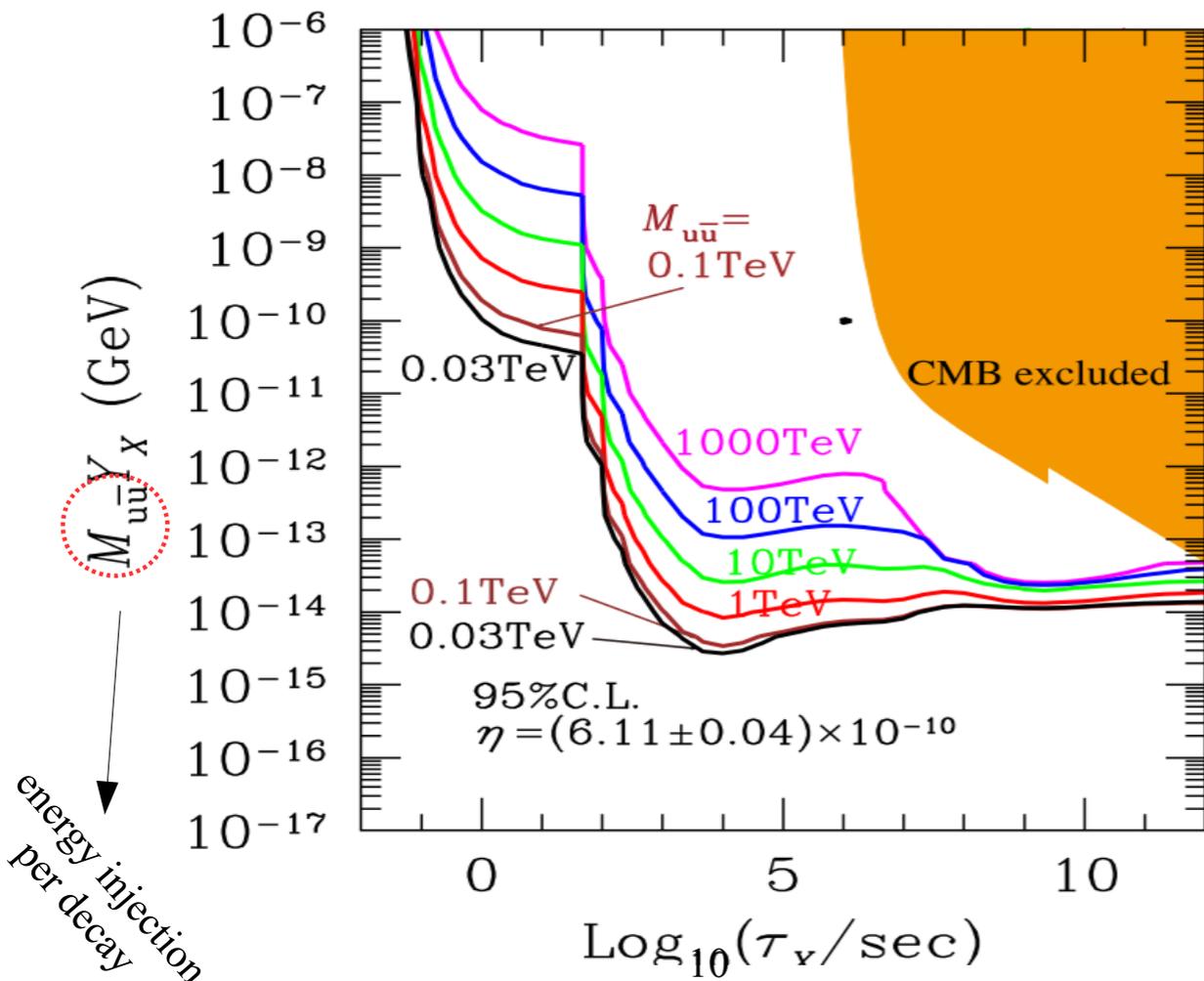*Heeck et al, 1706.09909*

Assumes DM relic abundance is saturated!

Constraints from Cosmology

➜ **Big-bang nucleosynthesis**

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

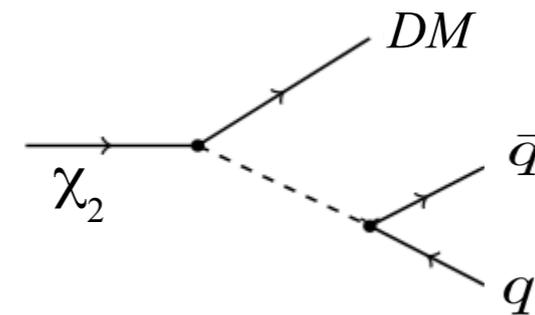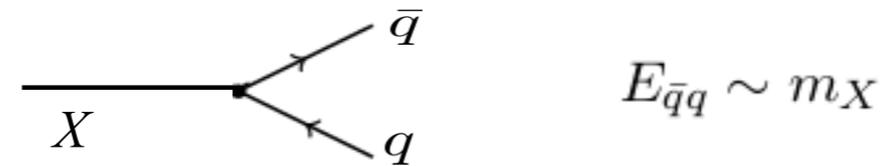Constrain (hadronic) energy injection from the decay of χ_2

$M_{u\bar{u}} =$
0.1 TeV

0.03 TeV

CMB excluded

1000 TeV
100 TeV
10 TeV
0.1 TeV 1 TeV
0.03 TeV

95% C.L.
$\eta = (6.11 \pm 0.04) \times 10^{-10}$

$M_{u\bar{u}} Y_X$ (GeV)

energy injection per decay

Kawasaki et al, 1709.01211

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

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

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

Freeze-In DM Production

➡ Production of DM in early Universe (assume standard thermal history)

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

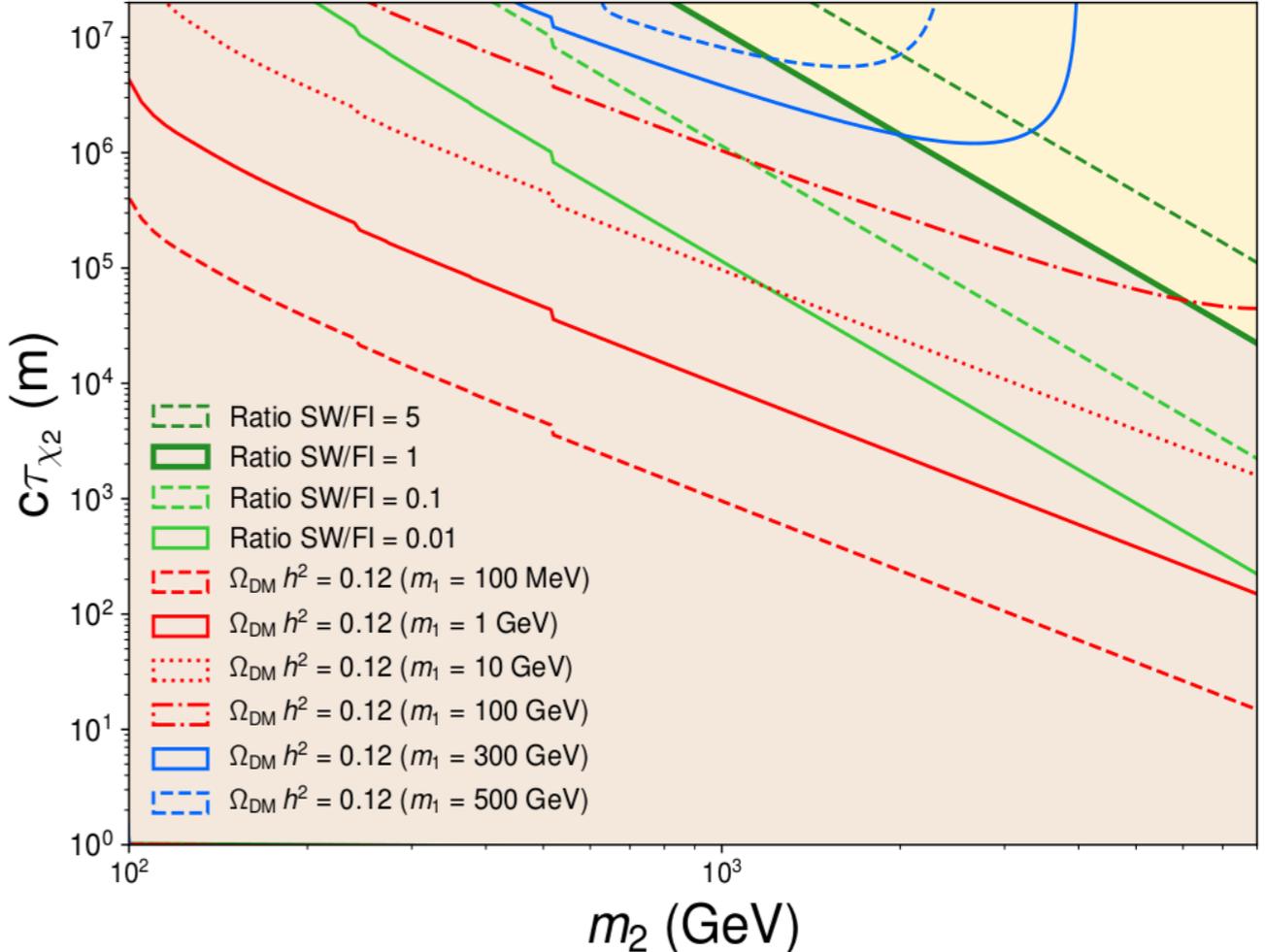Super-WIMP:

Feng et al, hep-ph/0302215

χ_2 freezes-out and then decays

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

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

Note however that if Super-WIMP component dominant and mass ratio large, DM would be quite relativistic!
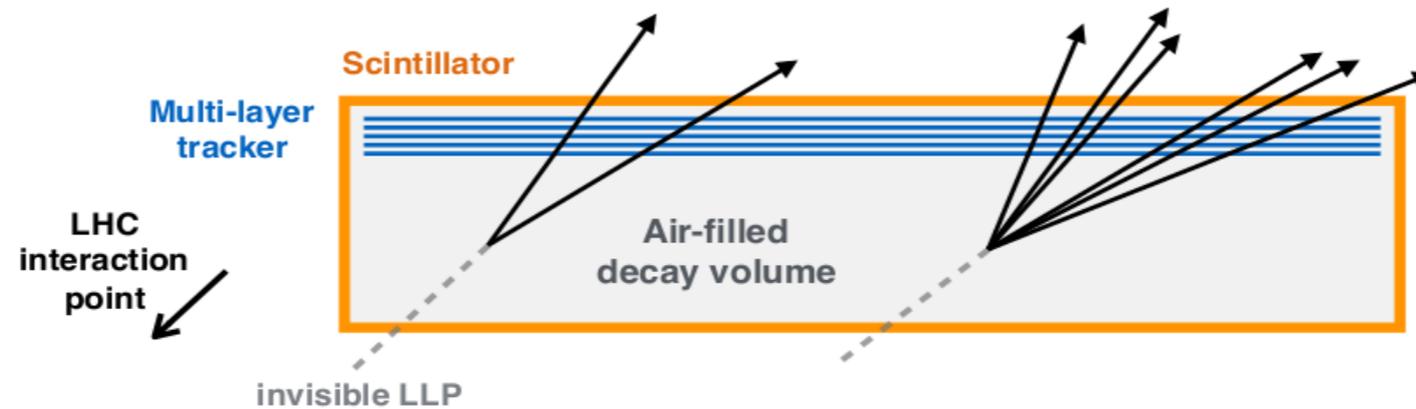
Garny et al, 1809.10135

Legend:
- Ratio SW/FI = 5
- Ratio SW/FI = 1
- Ratio SW/FI = 0.1
- Ratio SW/FI = 0.01
- $\Omega_{\rm DM}\, h^2 = 0.12$ (m_1 = 100 MeV)
- $\Omega_{\rm DM}\, h^2 = 0.12$ (m_1 = 1 GeV)
- $\Omega_{\rm DM}\, h^2 = 0.12$ (m_1 = 10 GeV)
- $\Omega_{\rm DM}\, h^2 = 0.12$ (m_1 = 100 GeV)
- $\Omega_{\rm DM}\, h^2 = 0.12$ (m_1 = 300 GeV)
- $\Omega_{\rm DM}\, h^2 = 0.12$ (m_1 = 500 GeV)

Axes: $c\tau_{\chi_2}$ (m) versus m_2 (GeV)
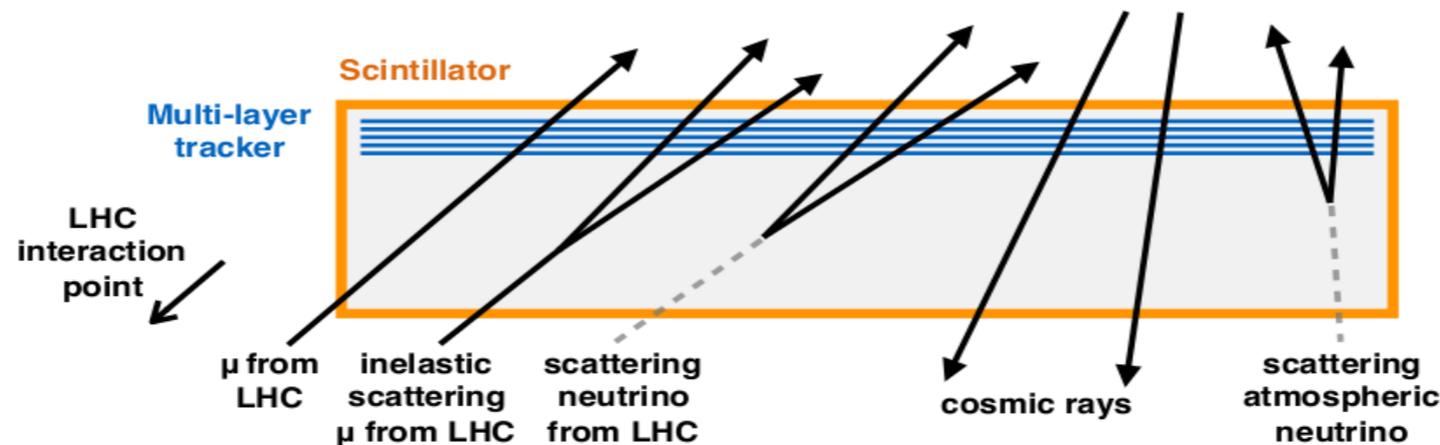
Signal Reconstruction

~5% geometric coverage, but much deeper than ATLAS/CMS
→ similar geometric acceptance for LLP decays (but no BG!)

Charged particle tracks are reconstructed with
~cm spatial resolution and ~ns timing resolution.

→ determine charged particle *speed* with ~0.05c precision.

LLP decays are reconstructed as Displaced Vertices (DV)
in both **space** and **time**, with strict **geometric requirements** and vetoes.

Reject using tight DV signal requirements, geometry & timing.

~Zero background regime can be reached!

*Cosmic backgrounds can be measured and studied during
beam down-time to verify rejection strategies.*