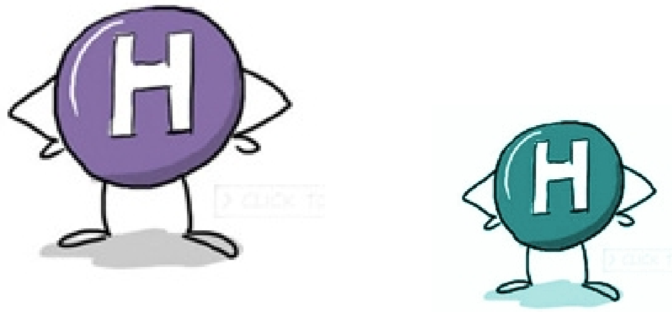

Long Live(d) the Higgs Portal to Dark Matter

(Freeze-in DM with LHC and MATHUSLA)

Jose Miguel No

IFT-UAM/CSIC, Madrid

w. Patrick Tunney & Bryan Zaldivar, soon to appear on ArXiv!

Comunidad de Madrid

HPNP 2019, Osaka

20/02/19

UAM UNIVERSIDAD AUTONOMA DE MADRID

ift Instituto de Física Teórica UAM-CSIC

Outline

- ➔ **Freeze-In Production of Dark Matter** (*in a nutshell*)
- ➔ **A Model of Dark Matter Freeze-In via the Higgs Field**
- ➔ **Constraints from Cosmology**
- ➔ **Long-Lived Particle searches: LHC and MATHUSLA**

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

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HPNP2019 The 4th International Workshop on "Higgs as a Probe of New Physics"

➔ **Constraints from Cosmology**

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

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Dark Matter Freeze-In in a Nutshell

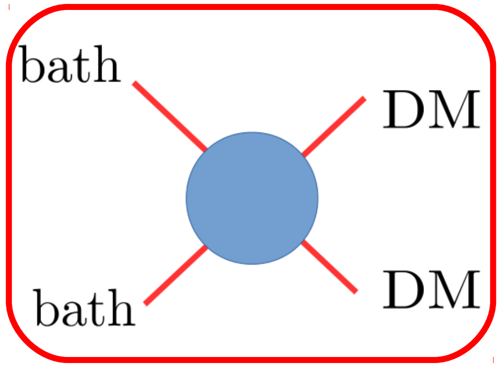
Hall et al, 0911.1120

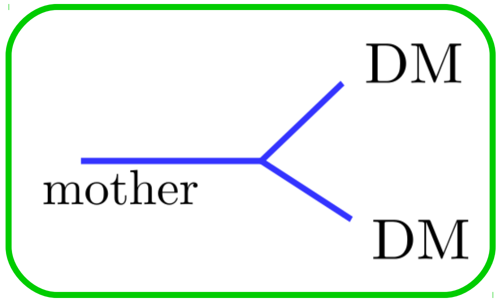
$$\frac{dn_{\rm DM}}{dt} + 3Hn_{\rm DM} = n_{\rm bath}\Gamma_{\rm prod} - n_{\rm DM}\Gamma_{\rm ann}$$

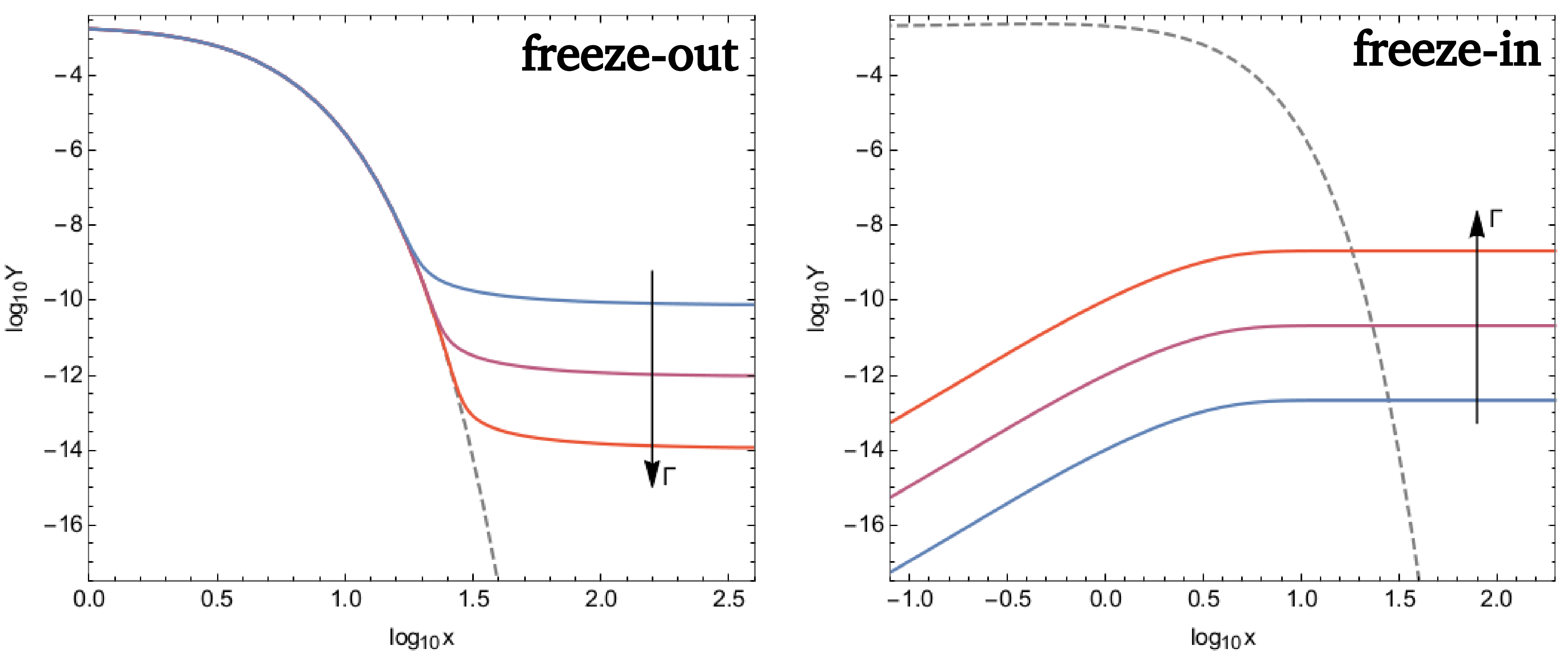
negligible

interaction rates

- ➔ 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** $Y \to X_{\rm SM}\,\chi$

mother — Y; DM — χ

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

Dark Matter Freeze-In in a Nutshell

Hall et al, 0911.1120

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

mother (Y) — DM (χ)

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

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

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

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

Freeze-In DM from the Higgs

$\mathbb{Z}_2$-odd sector

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

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

➔ 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

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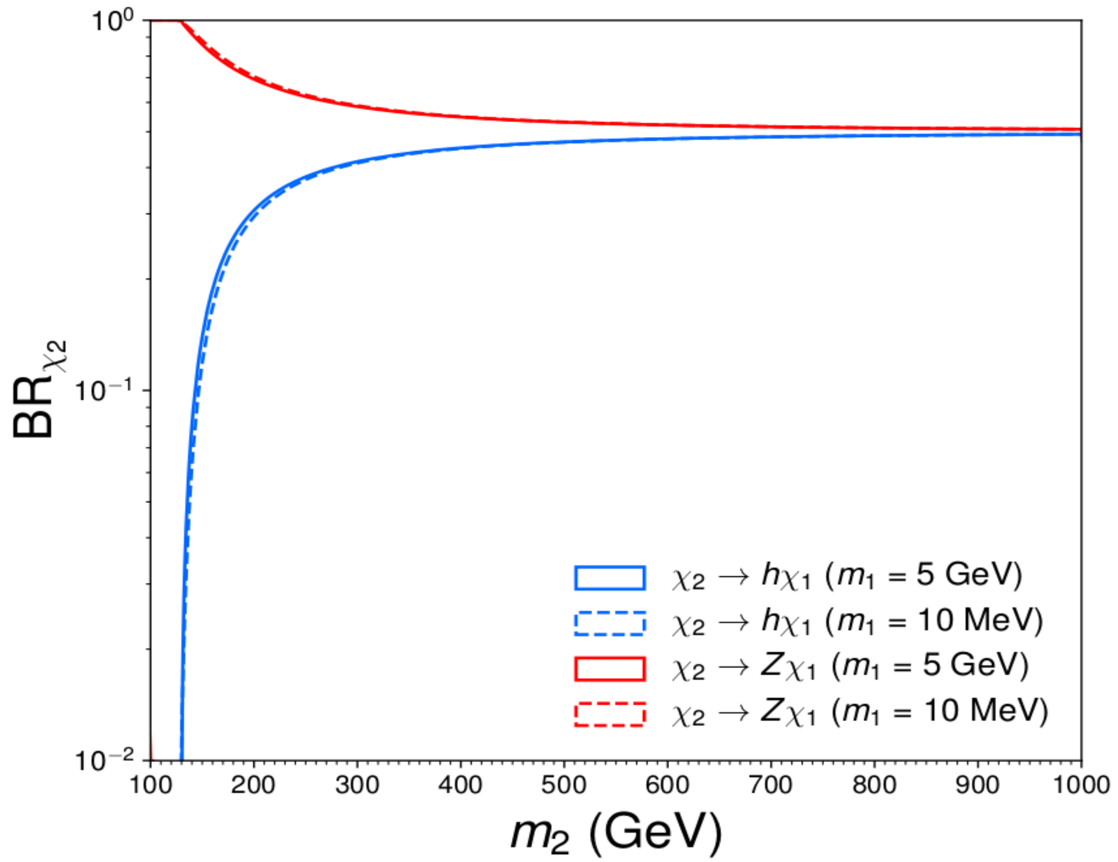
➔ Simple DM version of complete setups (e.g. Higgsino-Axino, Higgsino-Singlino)

Co et al, 1506.07532

➔ Tiny singlet-doublet mixing (DM is singlet-like)

$$\sin\theta \simeq \frac{y_\chi v}{\sqrt{2}(m_2 - m_1)}$$



Decays of χ_2

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

Freeze-In DM from the Higgs

$\mathbb{Z}_2$-odd sector

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

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

➔ 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

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

Decays of $\psi^\pm$

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

Dominant decay

$$\psi^\pm \to \ell^\pm \nu \chi_2$$

$$\psi^\pm \to W^\pm \chi_1$$

Relevant for DM production

Freeze-In DM from the Higgs

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

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

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

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

Freeze-In DM from the Higgs

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Super-WIMP:

Feng et al, hep-ph/0302215

χ_2 freezes-out and then decays

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

(Higgsino-like freeze-out)

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

Freeze-In DM from the Higgs

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

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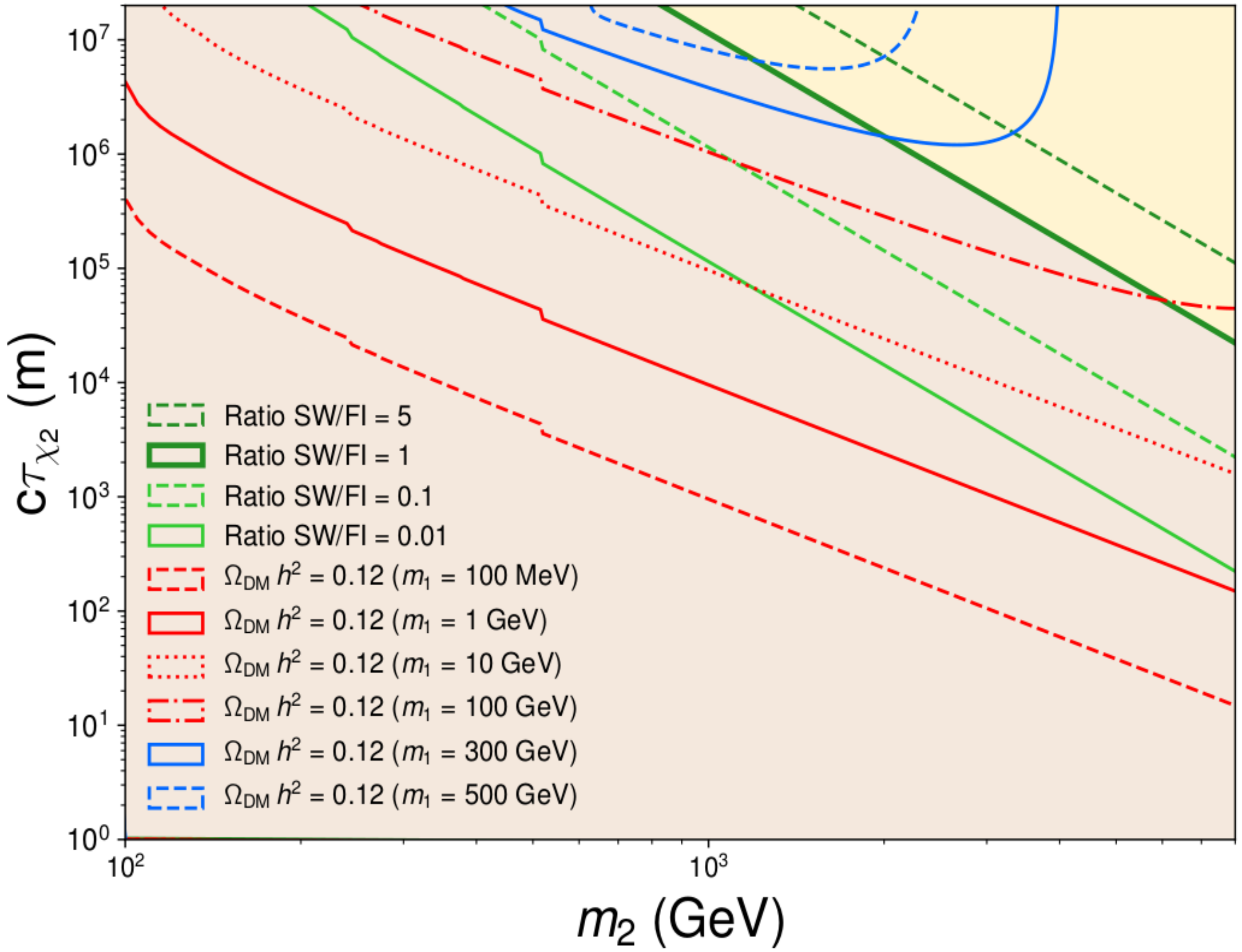

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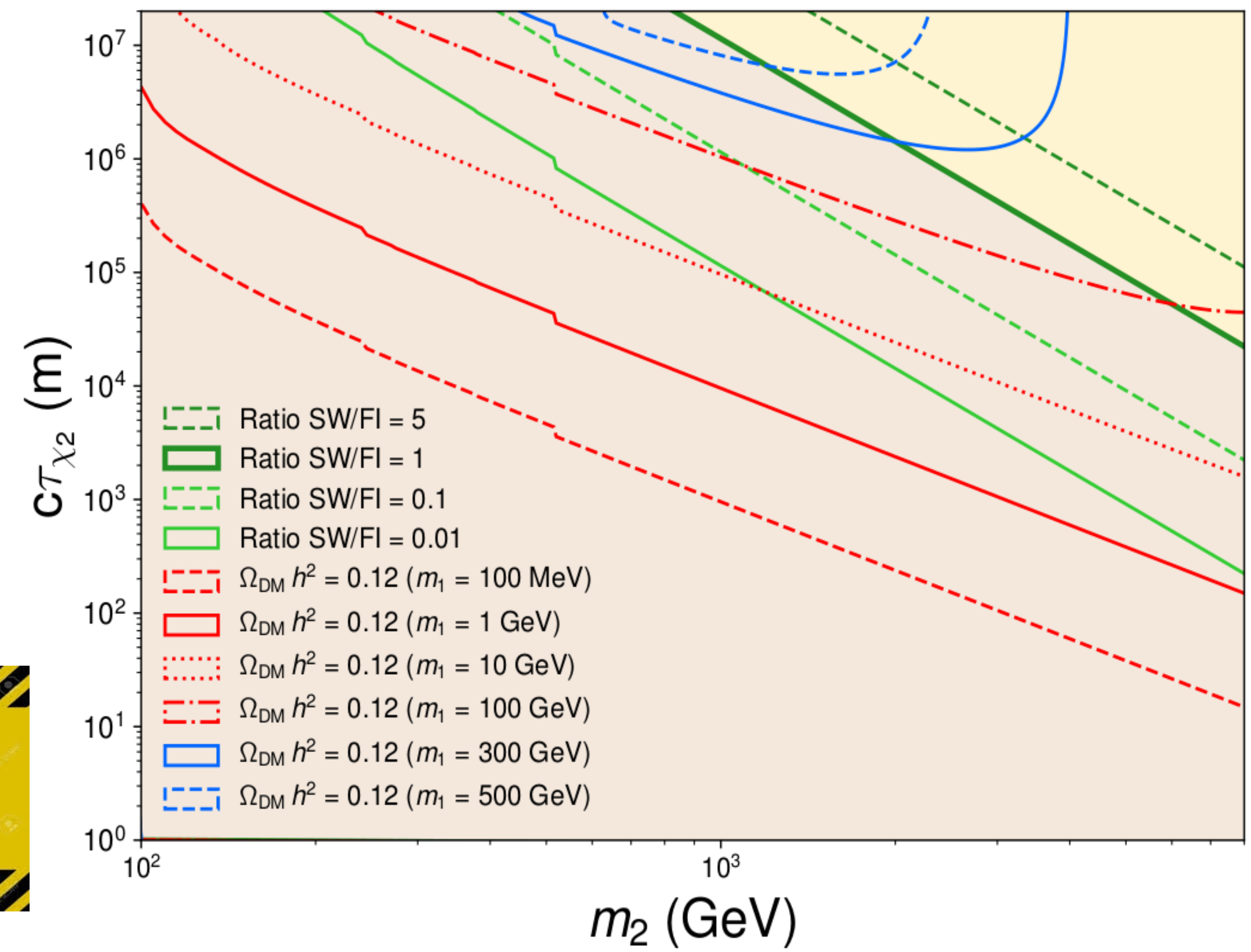
Feng et al, hep-ph/0302215

χ_2 freezes-out and then decays

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

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

Garny et al, 1809.10135



Constraints from Cosmology

➔ Lyman-α forest observations

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

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

Thermal warm DM

Baur et al, 1706.03118

→

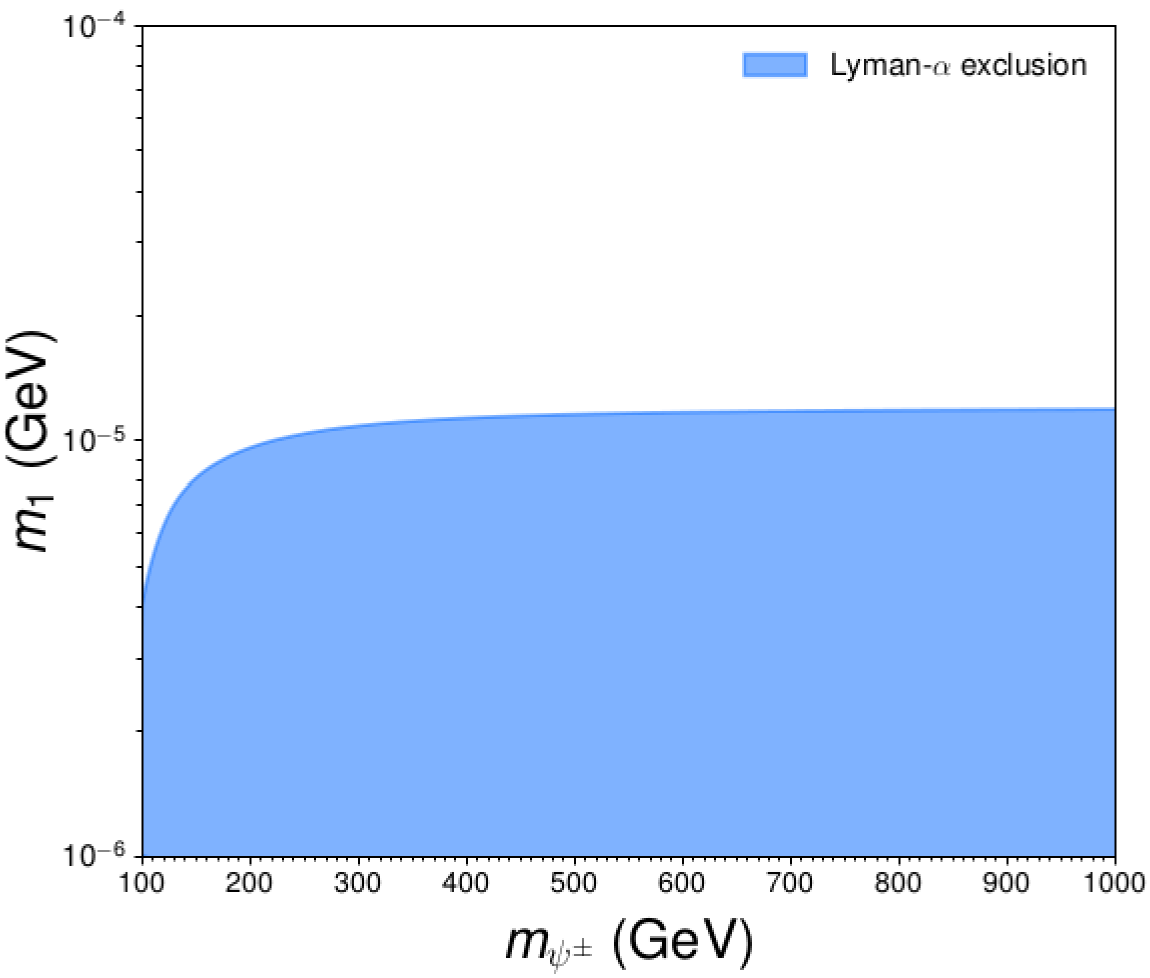
$$m_{\rm DM} \gtrsim 12\ \text{keV} \left(\frac{\sum_{ij} g_i \Gamma_{ij} \Delta_{ij}^{\eta}}{\sum_{ij} g_i \Gamma_{ij}} \right)^{1/\eta}$$

Freeze-in DM from 2-body decay

Heeck et al, 1706.09909

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

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



Assumes DM relic abundance is saturated!

Constraints from Cosmology

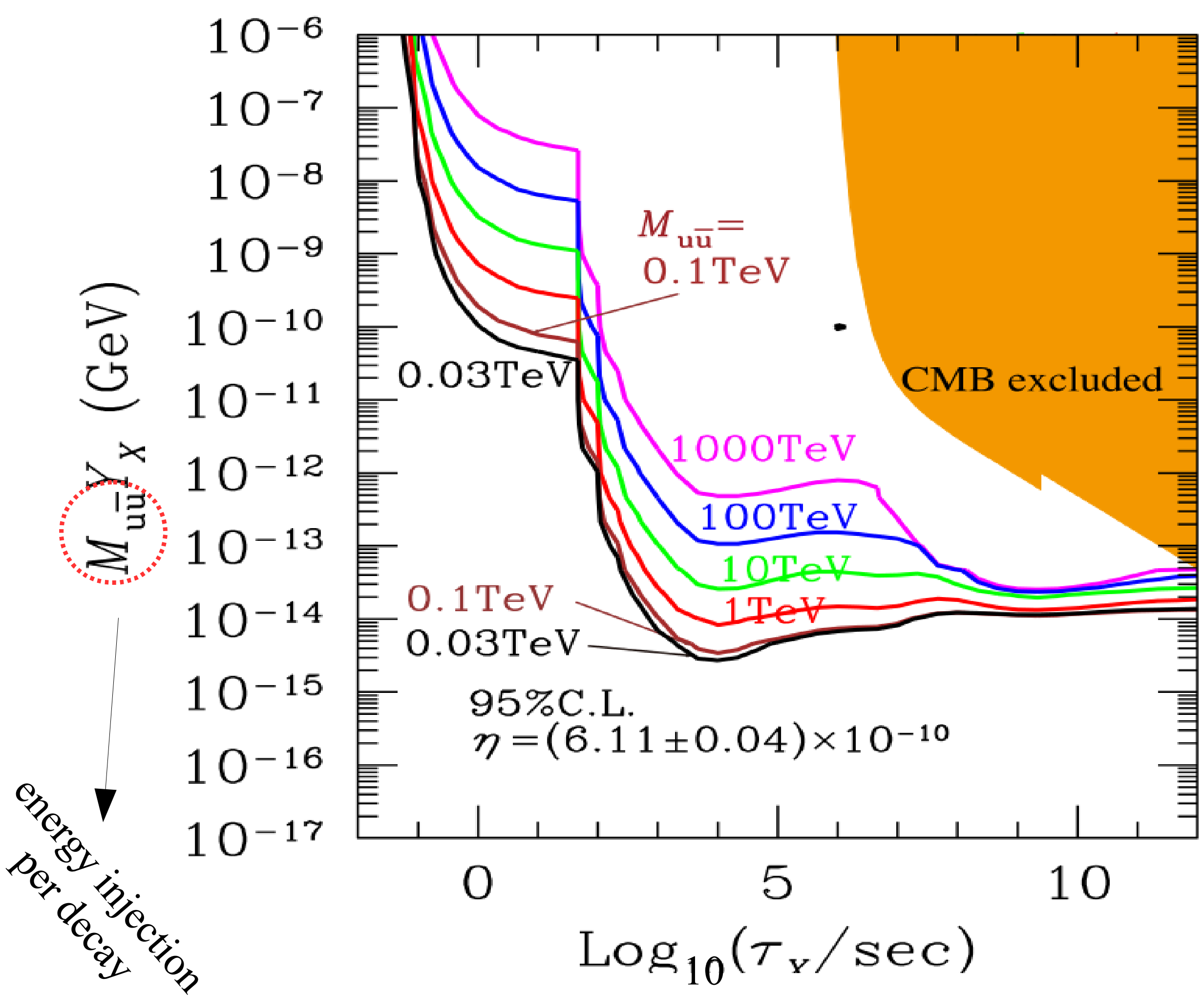
➔ **Lyman-α forest observations**

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

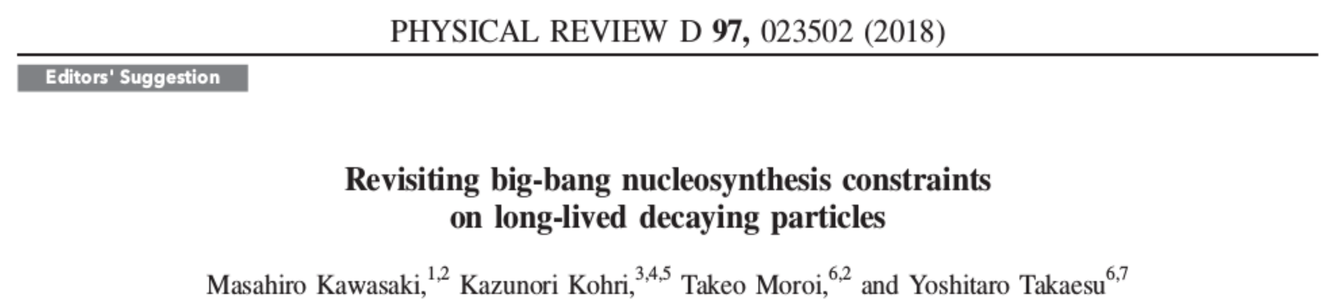
➔ **Big-bang nucleosynthesis**

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

Constrain (hadronic) energy injection from the decay of χ_2



Kawasaki et al, 1709.01211

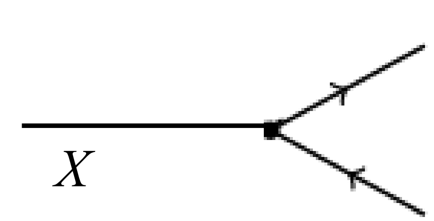


PHYSICAL REVIEW D **97,** 023502 (2018)

Editors' Suggestion

Revisiting big-bang nucleosynthesis constraints on long-lived decaying particles

Masahiro Kawasaki,[1,2] Kazunori Kohri,[3,4,5] Takeo Moroi,[6,2] and Yoshitaro Takaesu[6,7]



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

Constraints from Cosmology

➔ Lyman-α forest observations

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

➔ Big-bang nucleosynthesis

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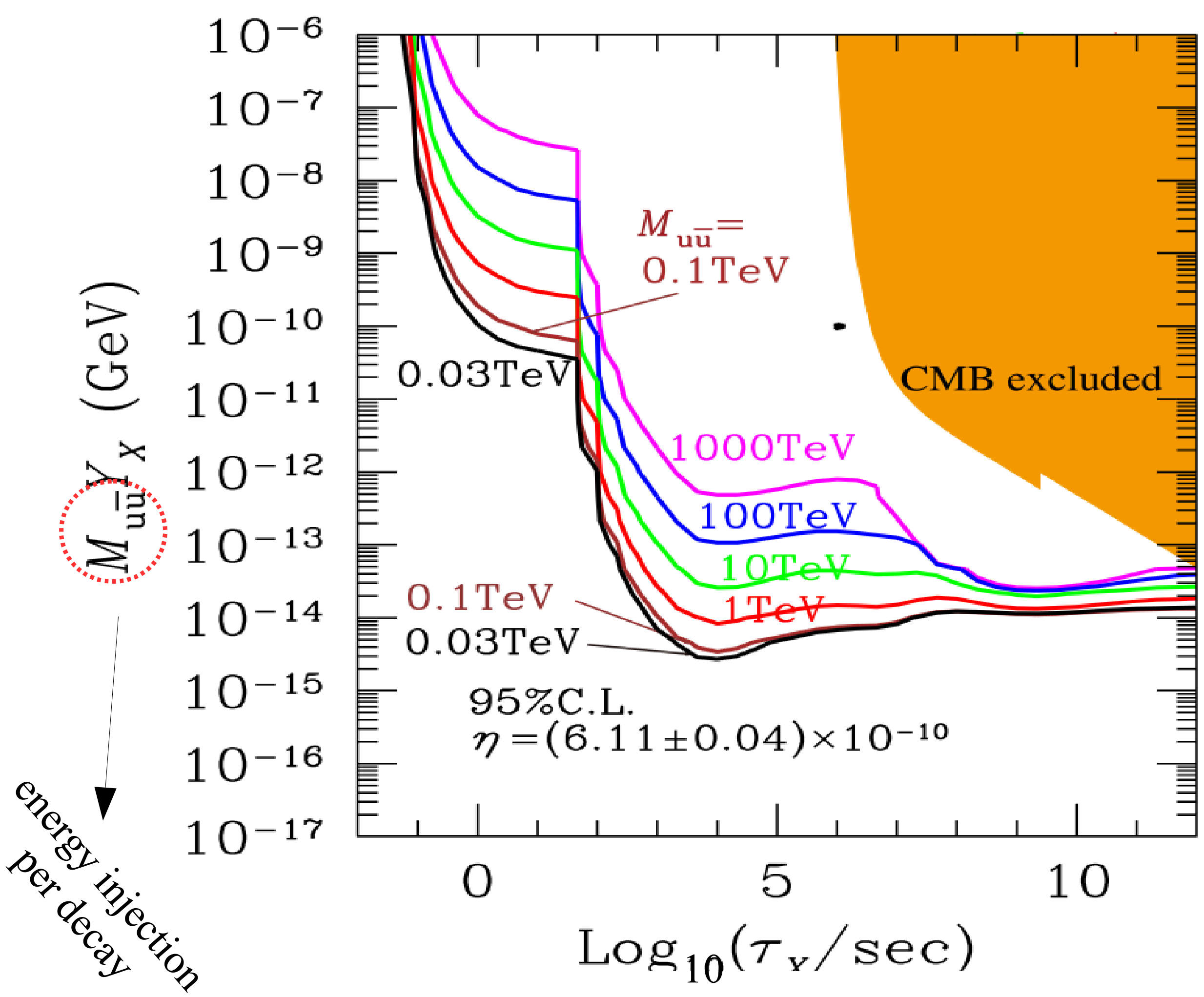
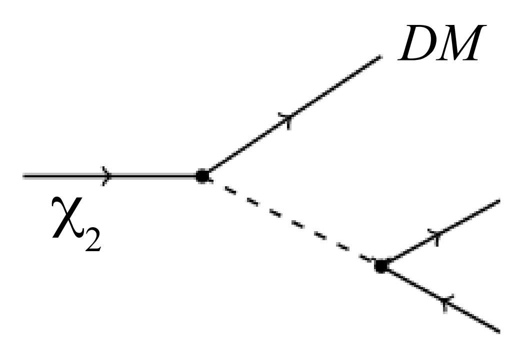


Kawasaki et al, 1709.01211



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

$$\xi_z = m_Z^2/m_2^2$$

$$\xi_1 = m_1^2/m_2^2$$

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

Constraints from Cosmology

➔ Lyman-α forest observations

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

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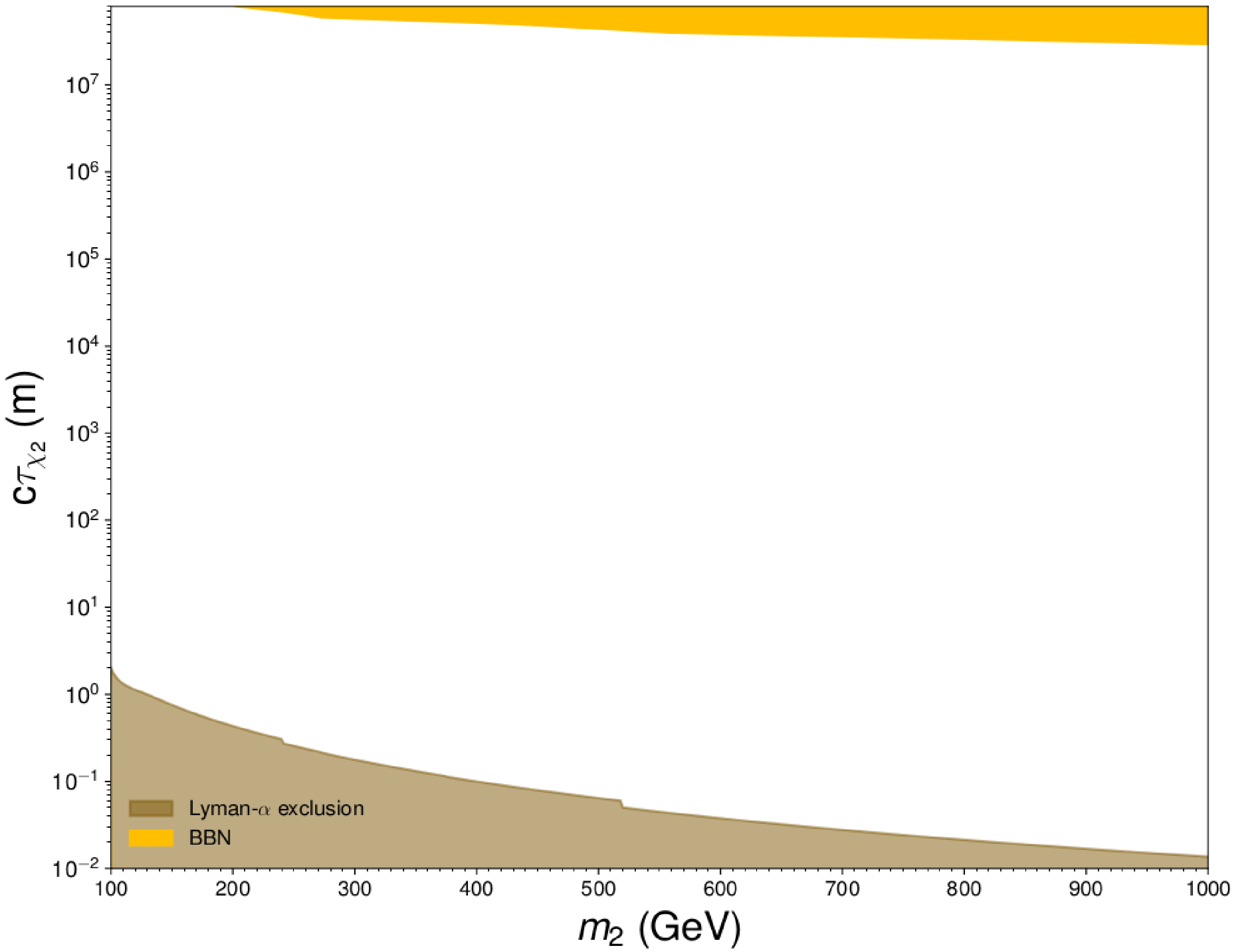
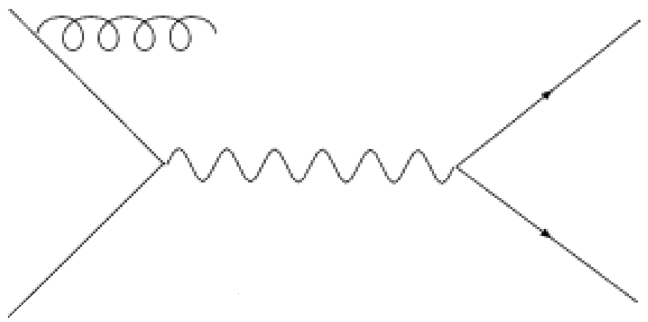
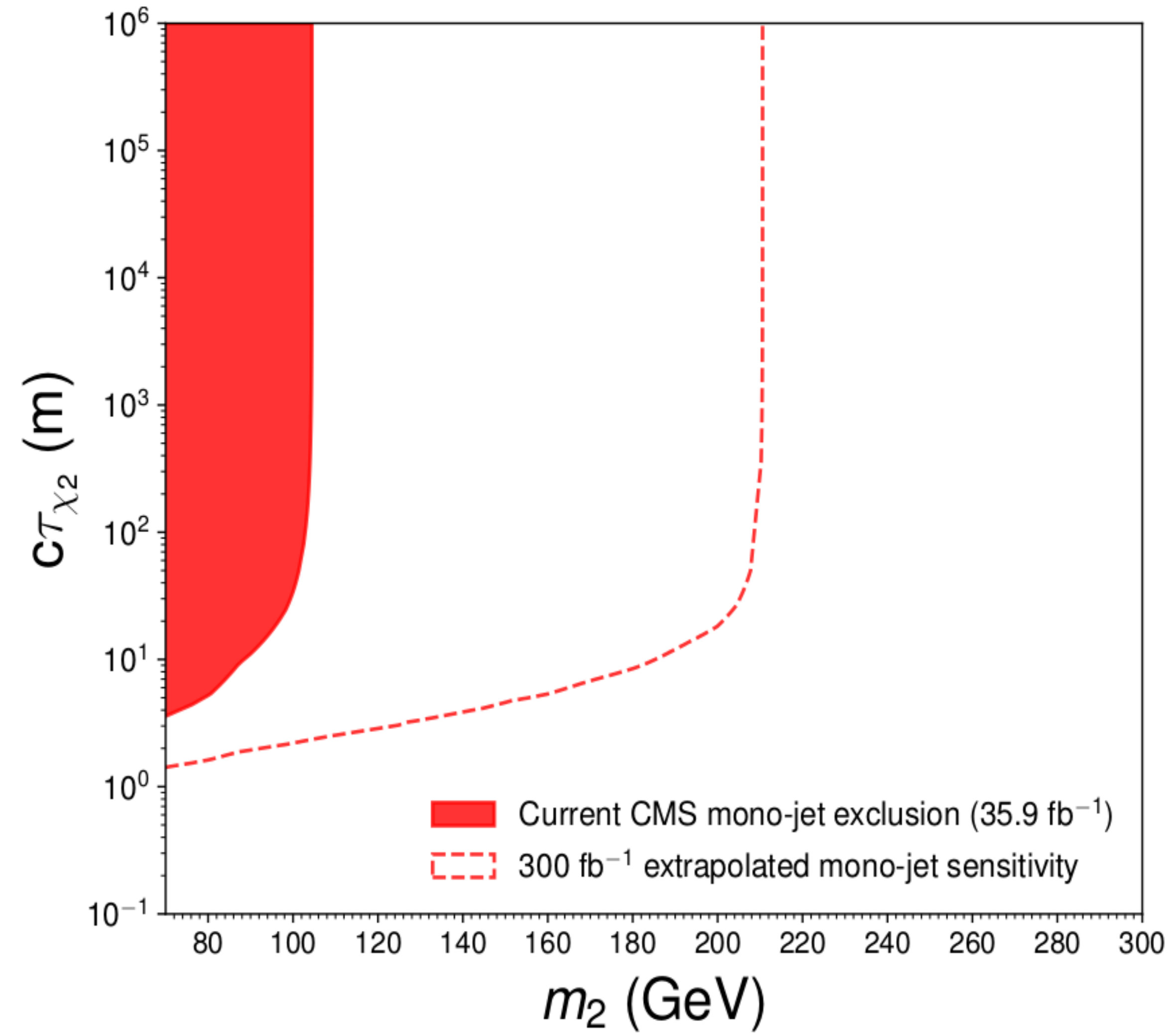


Probing Freeze-in at LHC

➔ 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

Probing Freeze-in at LHC

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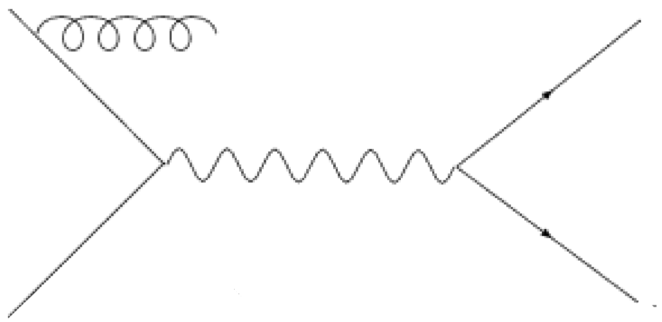


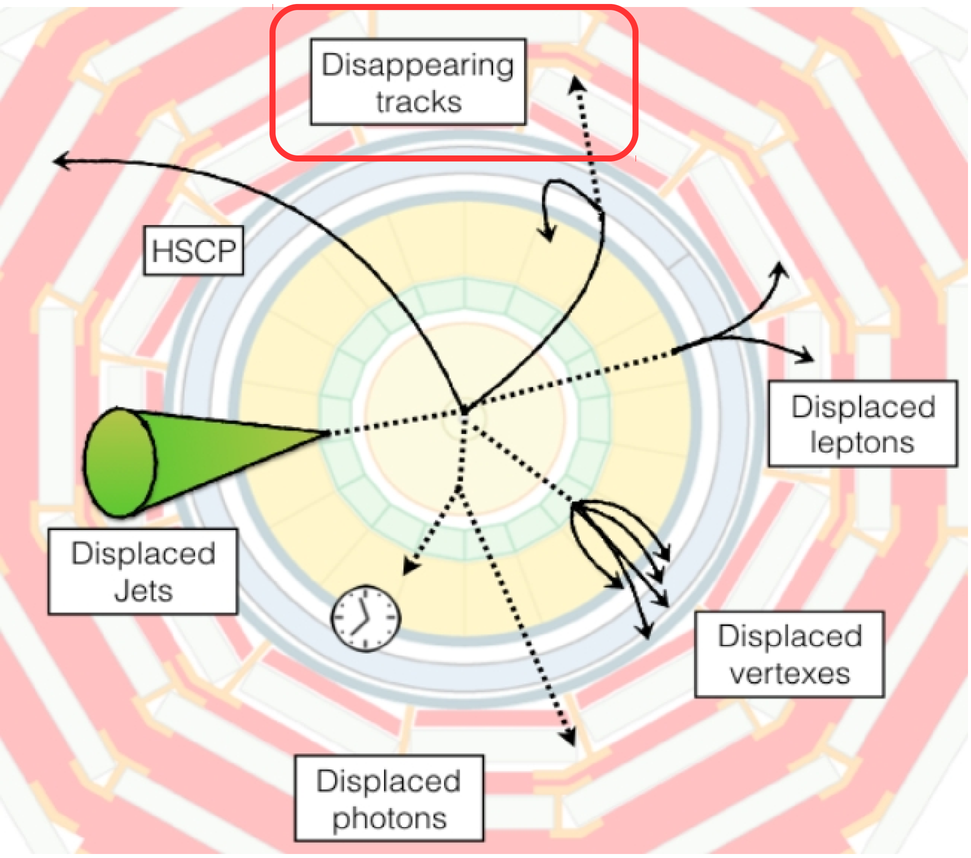
- ➔ Disappearing tracks: $\psi^{\pm} \to \pi^{\pm}\chi_2$

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

few *cm* decay length

ATLAS disappearing track analysis for pure Higgsino production → $m_{\psi^{\pm}} > 145$ GeV

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



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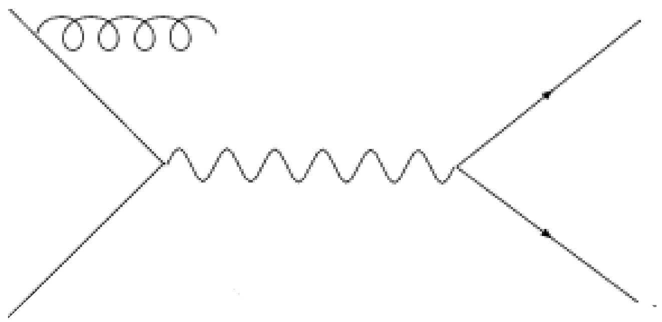
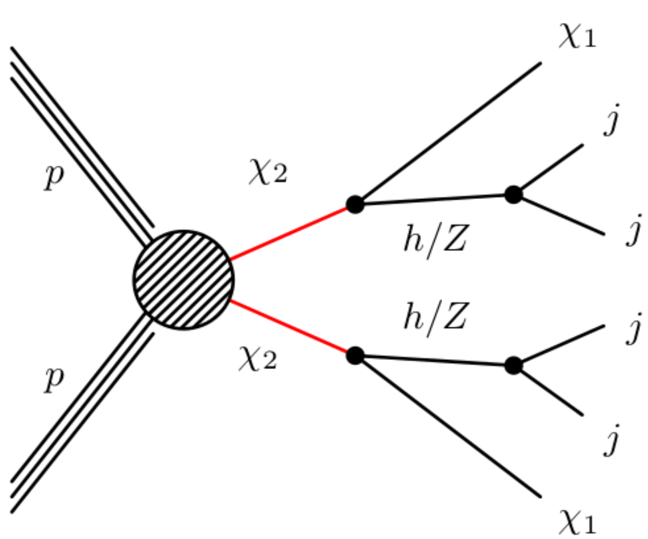


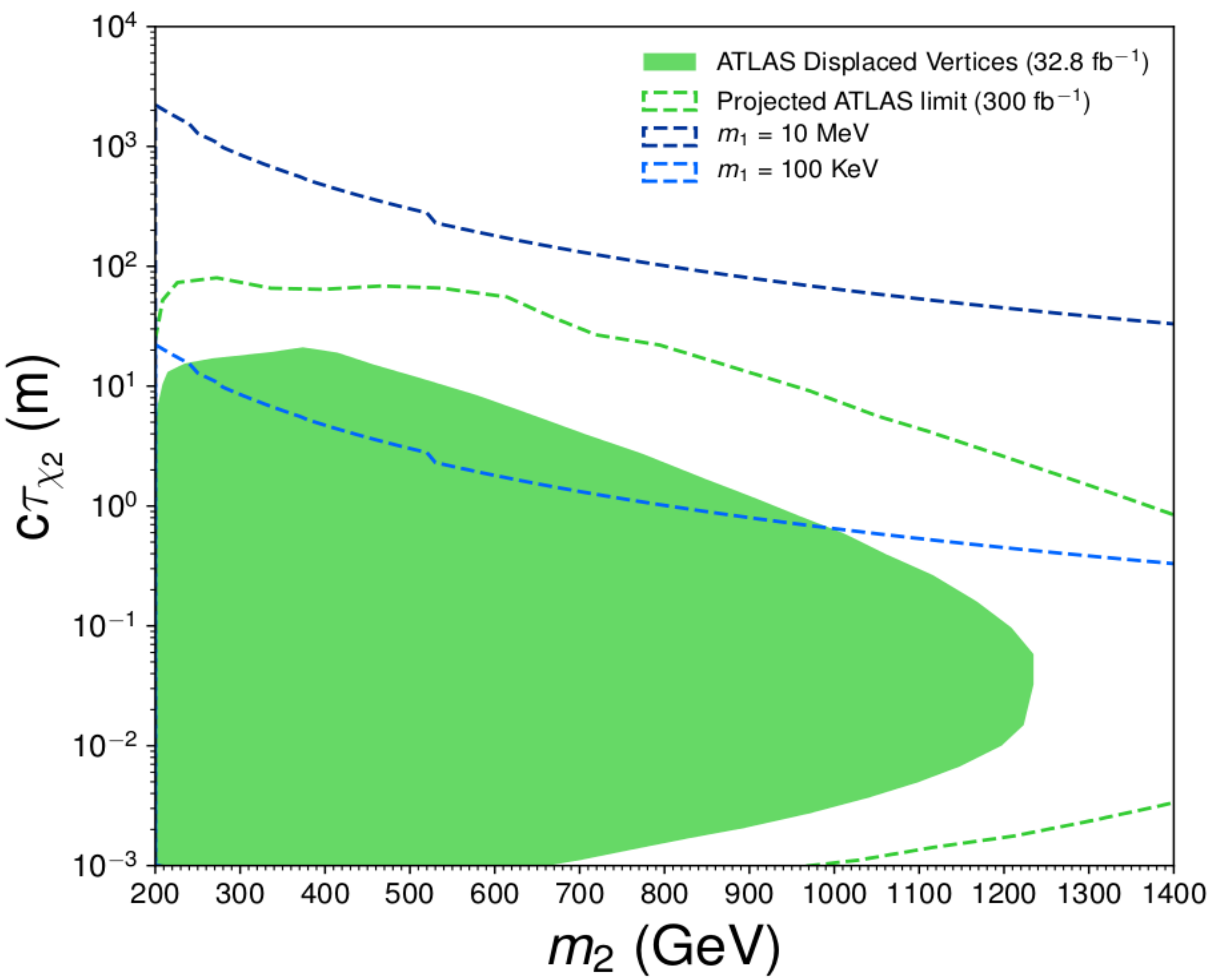
➔ Disappearing tracks: $\psi^{\pm} \to \pi^{\pm}\chi_2$

➔ Displaced vertices (jets) + MET

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



Calibbi et al, 1805.04423



Probing Freeze-in at LHC

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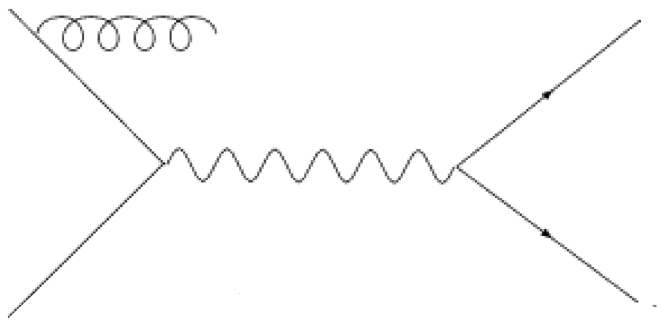

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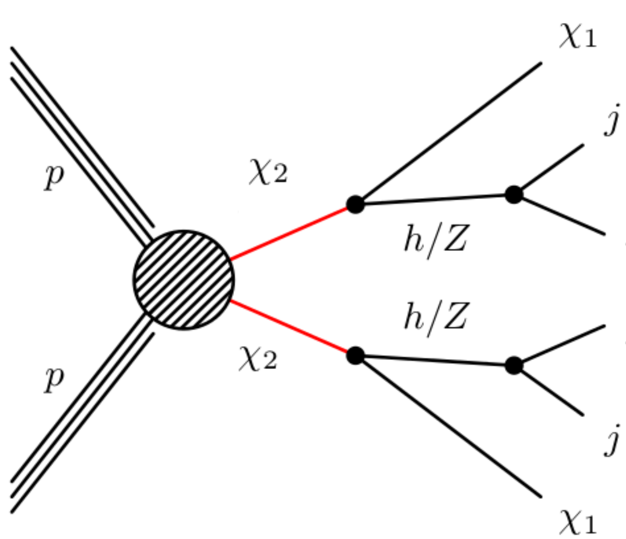

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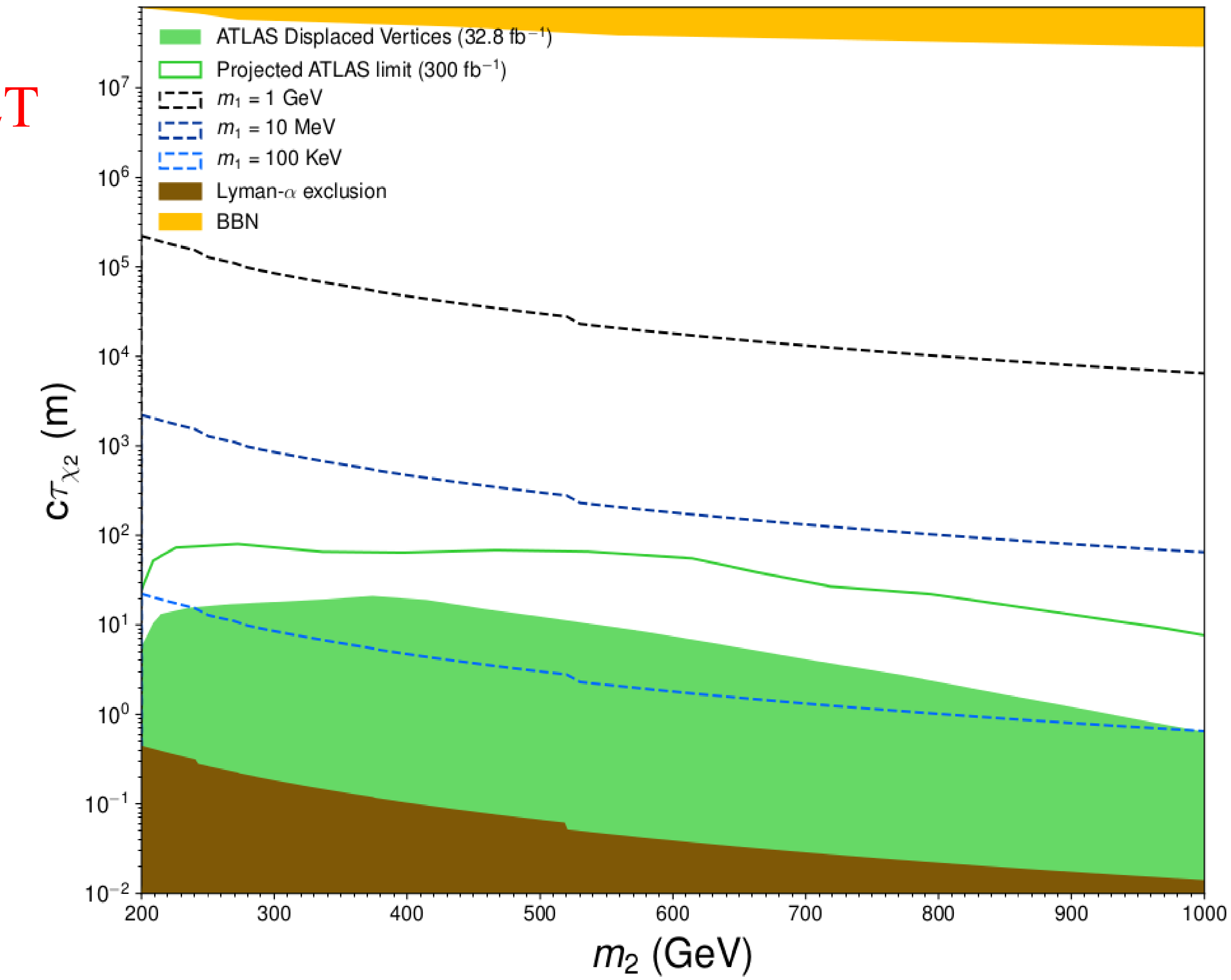

Probing Freeze-in at LHC

- **Mono-X (mono-jet)**
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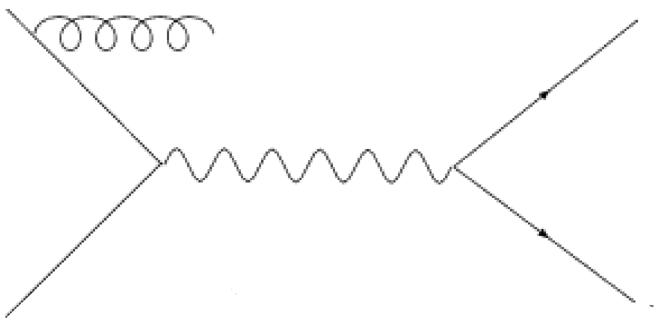

- **Disappearing tracks:** $\psi^{\pm} \to \pi^{\pm}\chi_2$

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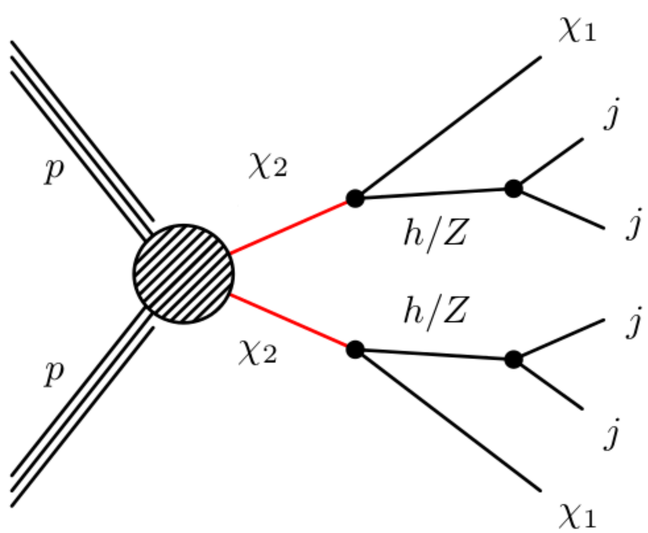
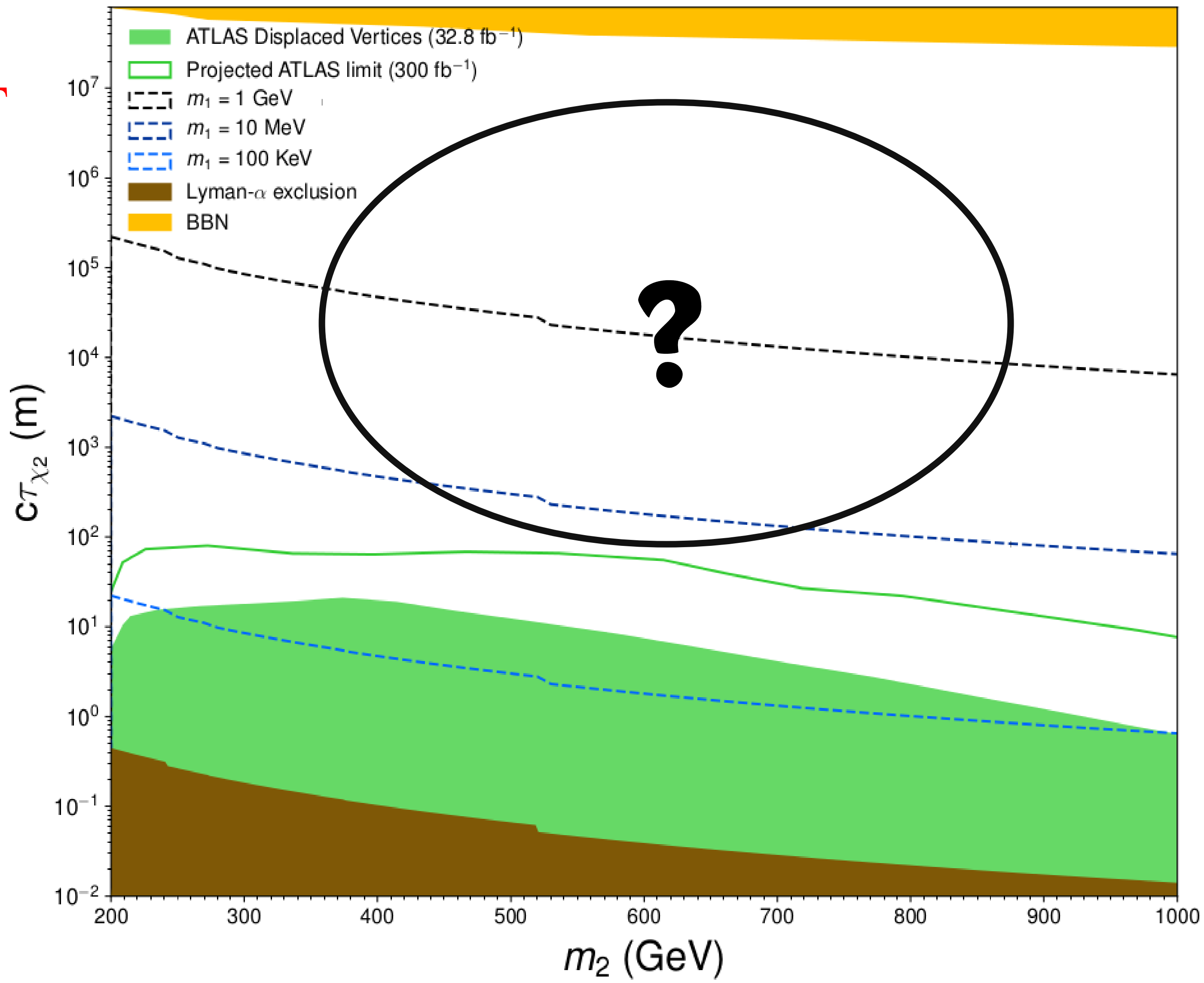


Calibbi et al, 1805.04423

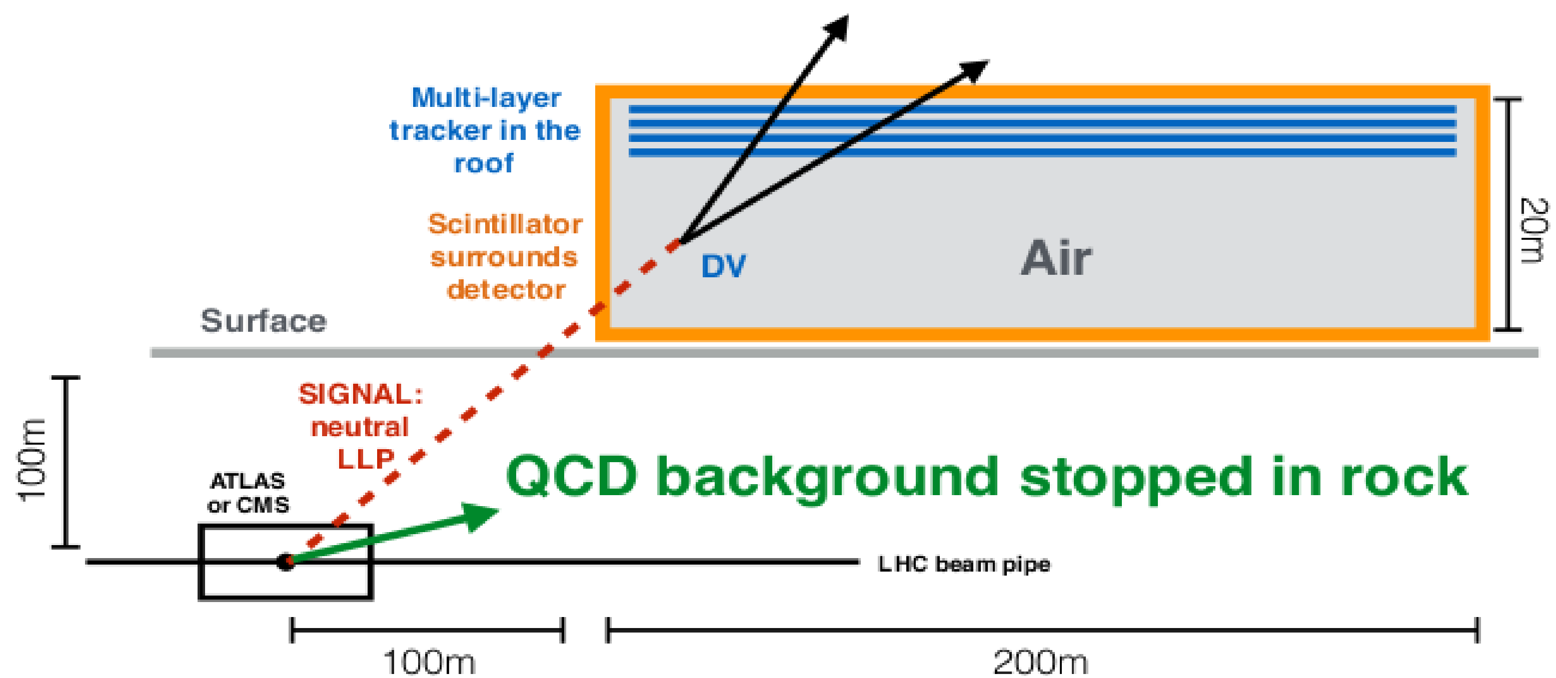


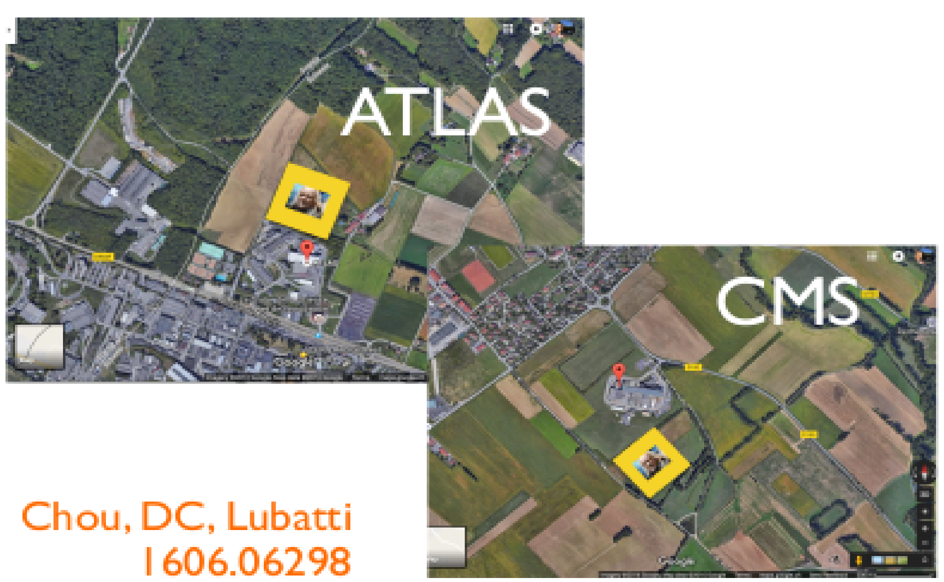
Probing Freeze-in at MATHUSLA

Courtesy of David Curtin

MATHUSLA

An external LLP detector for the HL- or HE-LHC





Chou, DC, Lubatti
1606.06298

Reliance on well-understood technology (RPC, plastic scintillators) means this could be implemented in time for the HL-LHC. **But design not set in stone, will explore other options!**

Unofficial cost estimates of current design: ~ 50 million USD

Probing Freeze-in at MATHUSLA

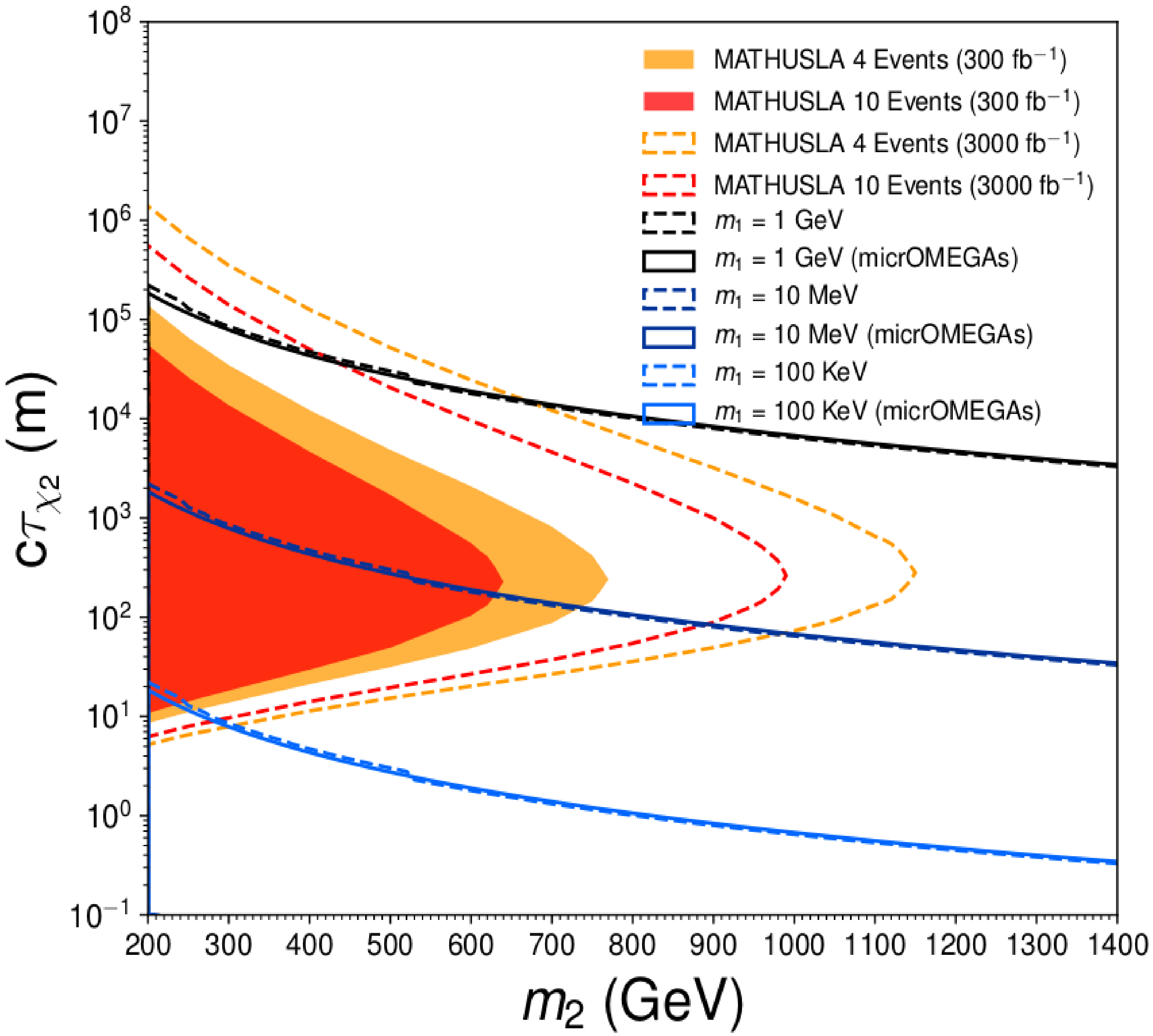
$$c\tau_2 \simeq 3500 \text{ m} \left(\frac{m_1}{100 \text{ MeV}}\right)\left(\frac{500 \text{ GeV}}{m_2}\right)^2$$

MATHUSLA solid angle from interaction point

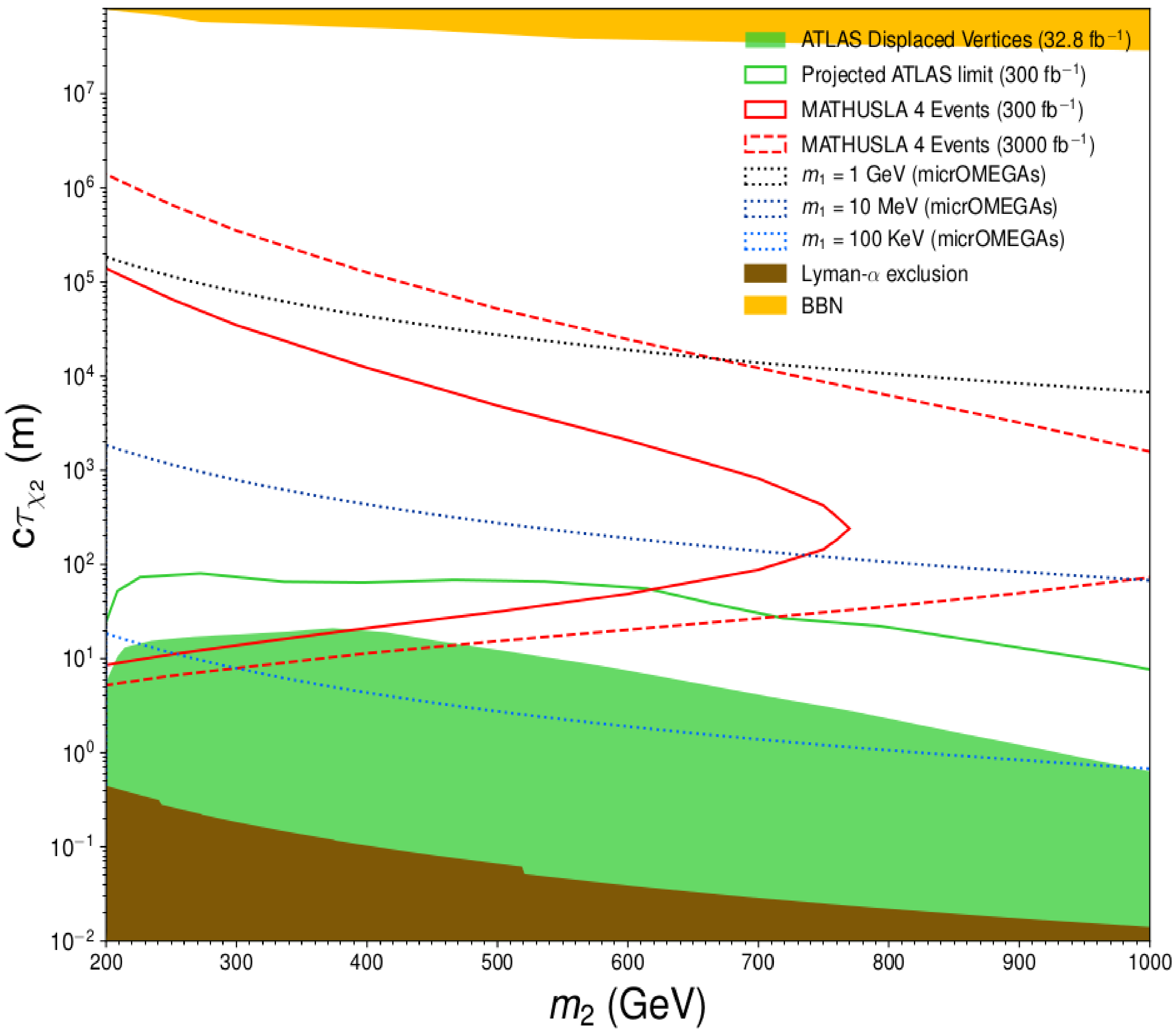
$$P_{\rm decay}^{\rm MATH} = \epsilon_{\rm geometric} \times P_{\rm decay}(\beta\, c\tau_2, L_a, L_b)$$

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

$|\vec{p}_{\chi 2}|/m_2$



Putting it all together & wrapping up...



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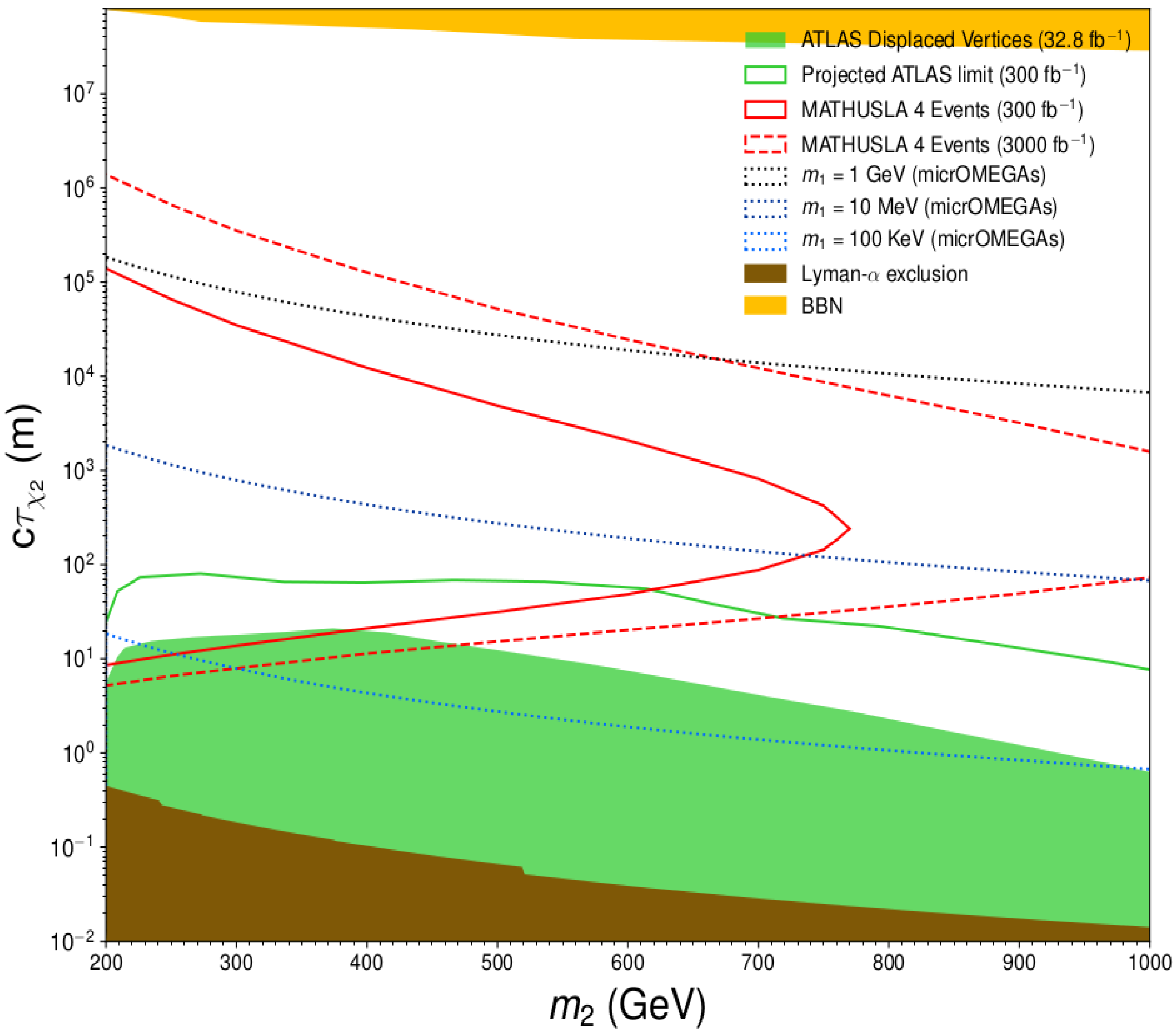


- ➔ Higgs is well-motivated "portal" to DM
- ➔ Explore its role in DM scenarios beyond WIMP

  e.g. **Freeze-In**
- ➔ Possible to probe freeze-in DM with long-lived particle searches!

  LHC

  MATHUSLA (*advantage of dedicated LLP detector*)

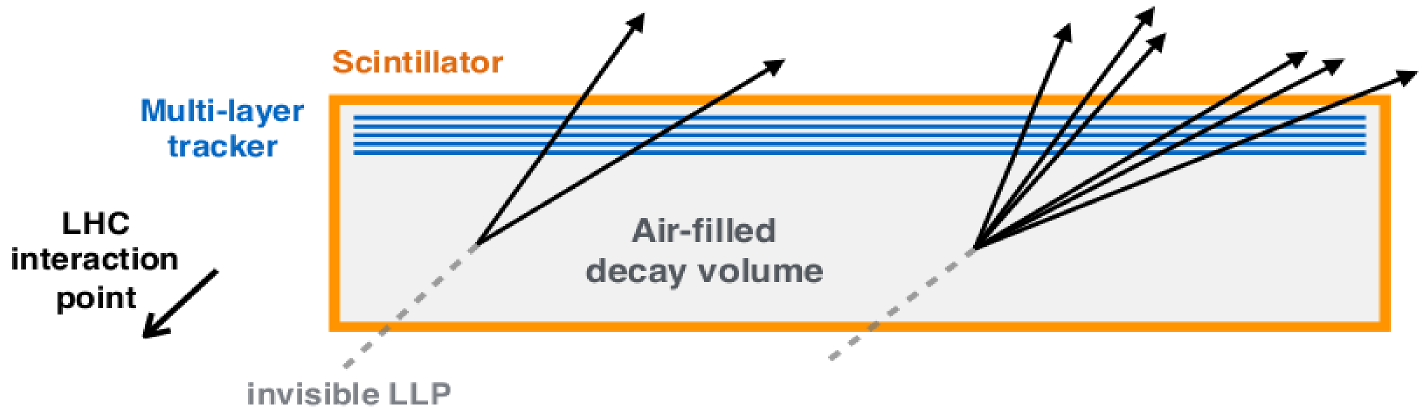
Thank you!


KEEP
CALM
AND
BACKUP
YOUR
WORK

Signal Reconstruction

Chou, DC, Lubatti
1606.06298

Courtesy of David Curtin

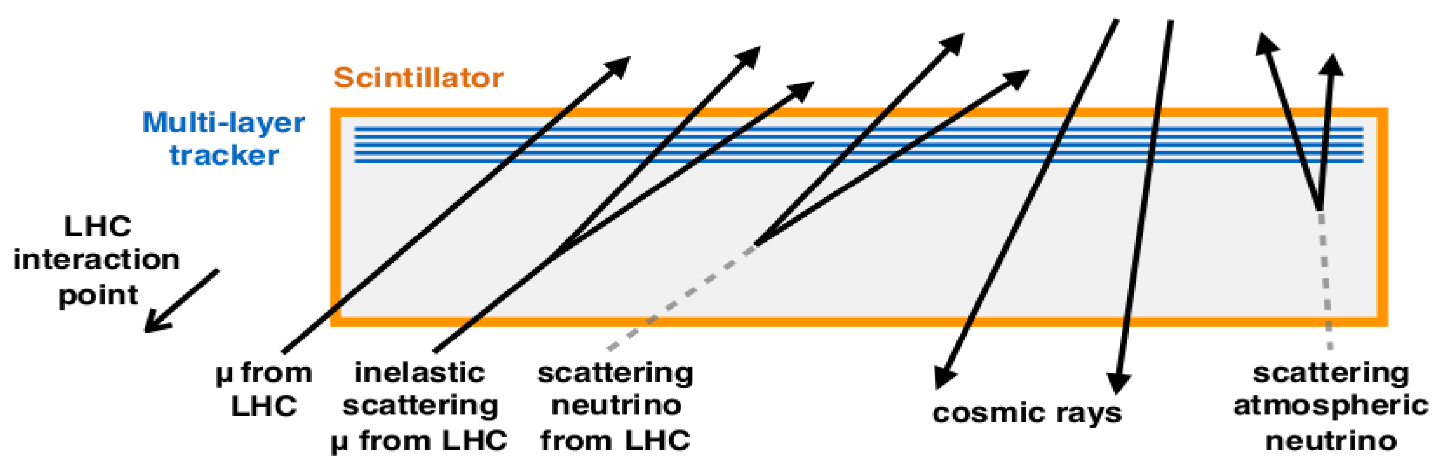


~5% geometric coverage, but much deeper than ATLAS/CMS
→ similar geometric acceptance for LLP decays (but no BG!)

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.