Dark Matter Freeze-out Beyond the WIMP Paradigm

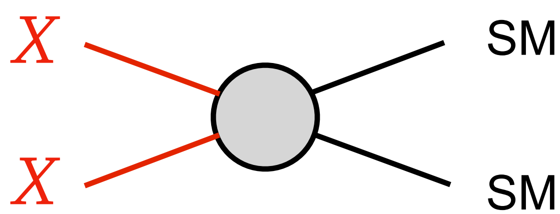
Jan Heisig

Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

The Dark Side of the Universe - DSU2024
Corfu, September 8-14, 2024

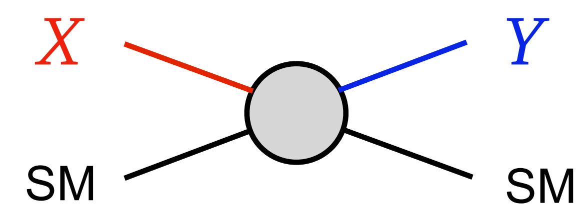
Freeze-out of dark matter

annihilation



vs

conversion

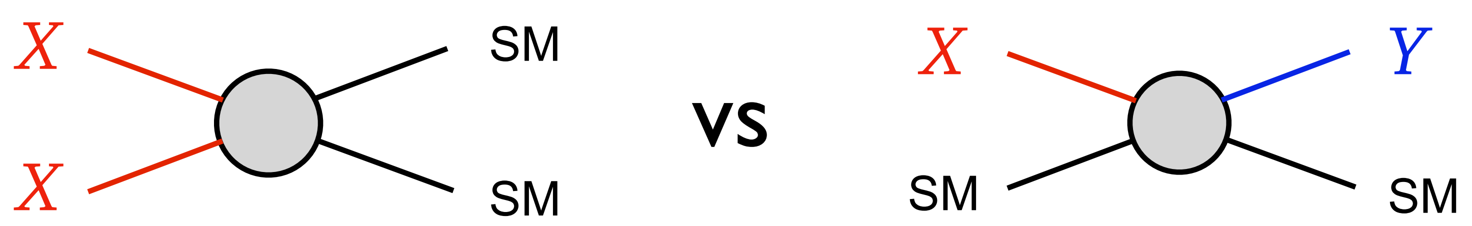


WIMP

beyond WIMP

Freeze-out of dark matter

annihilation | conversion



WIMP | beyond WIMP

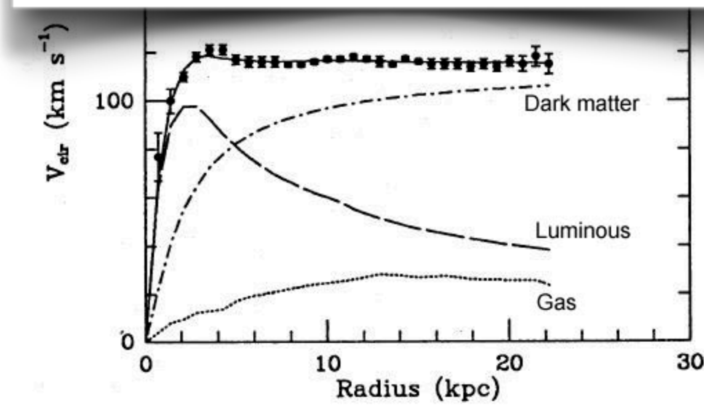
Outline

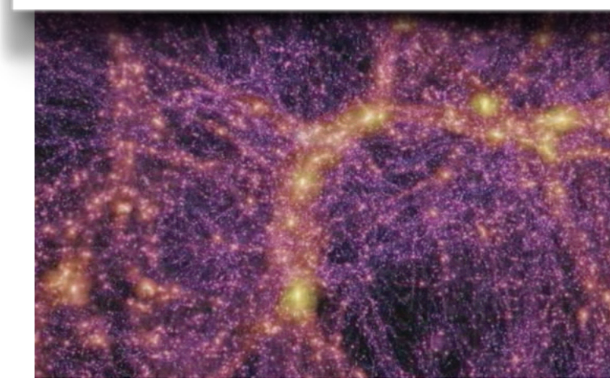
- Conversion-driven freeze-out
- How to search for it at LHC
- Intriguing link to baryogenesis

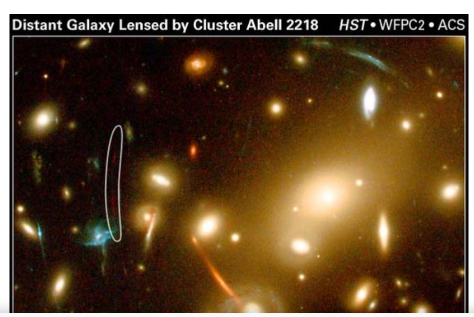
The phenomena of Dark Matter

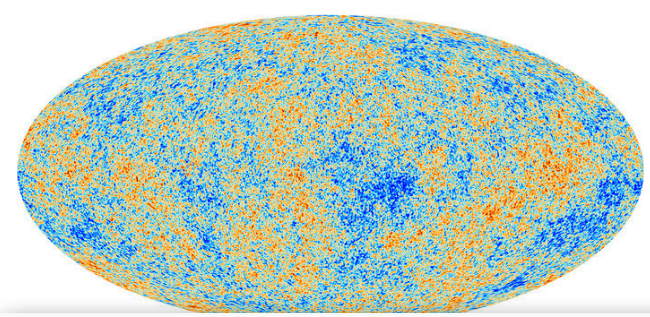
Galaxy (cluster) dynamics

Structure formation







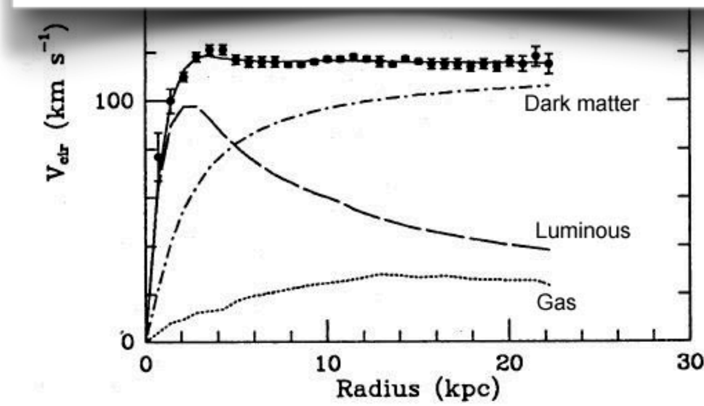


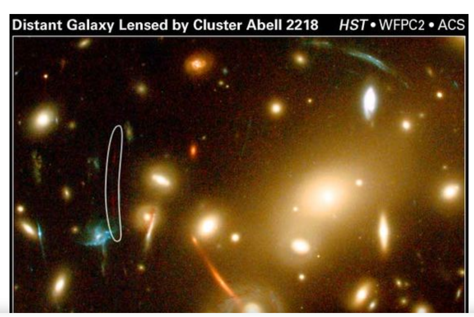
Gravitational lensing

CMB anisotropies

The phenomena of Dark Matter

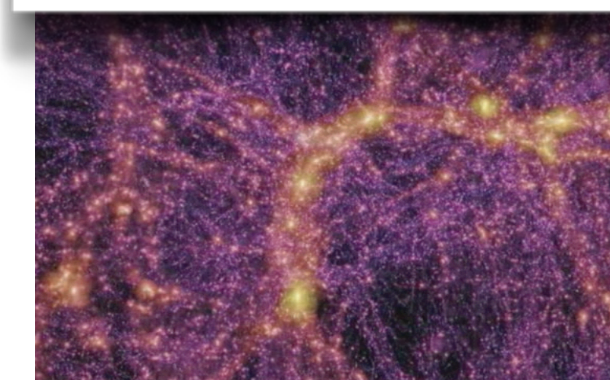
Galaxy (cluster) dynamics

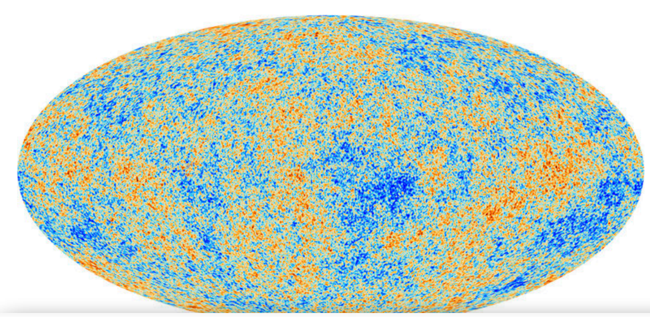




Gravitational lensing

Structure formation



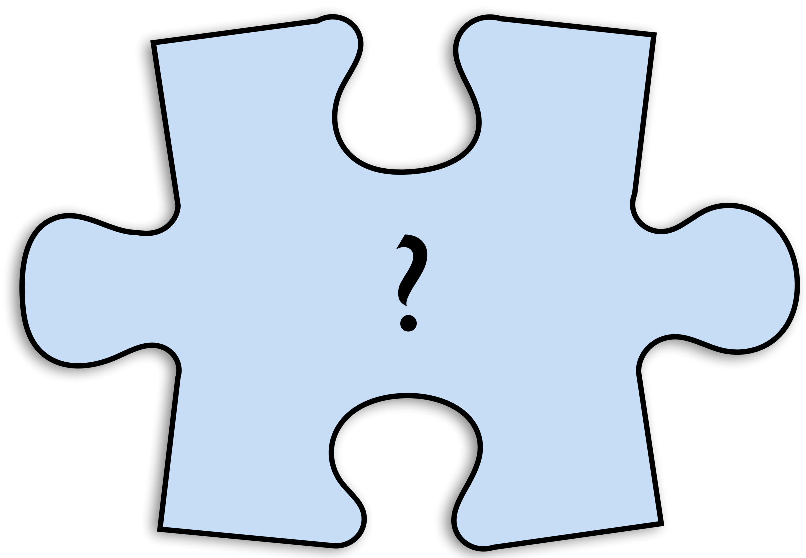


CMB anisotropies

[Planck 2020]

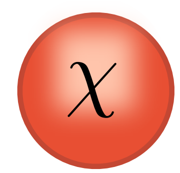
$$\Omega_{\mathrm{DM}} h^2 = 0.12 \pm 0.001$$

The nature of Dark Matter



The nature of Dark Matter

New particle(s) beyond the SM



The nature of Dark Matter

New particle(s) beyond the SM

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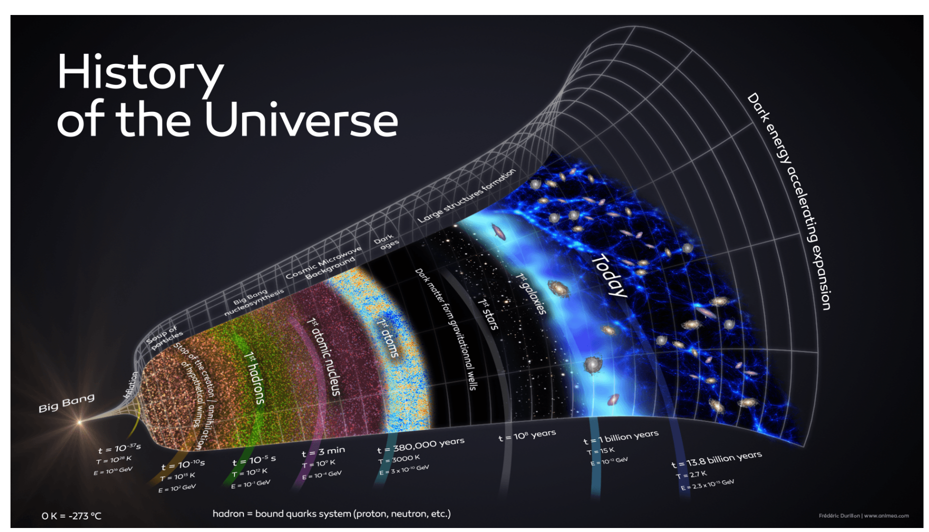
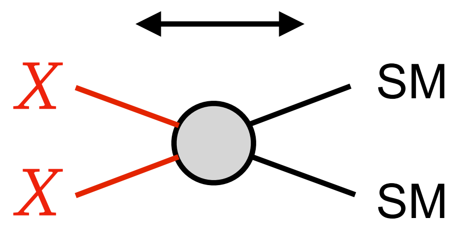
Thermal relic

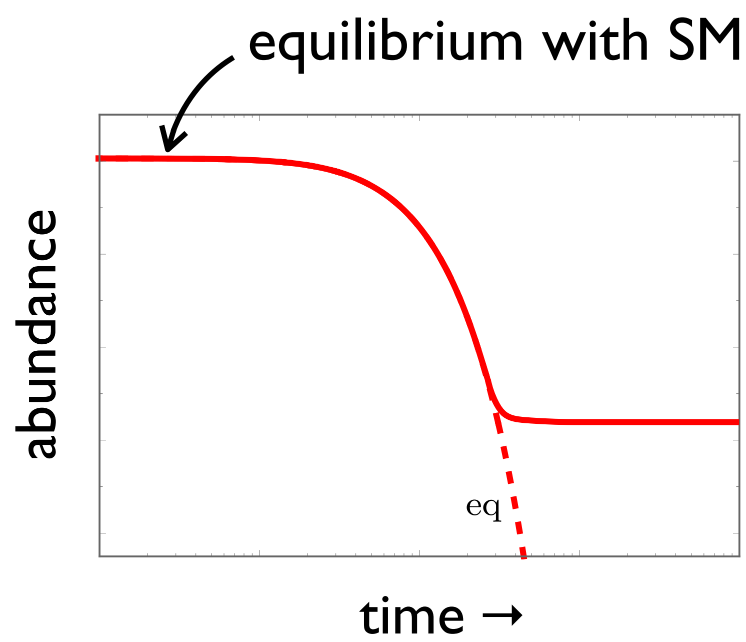


CEA/Irfu 2018

Thermal relic dark matter

Thermalised

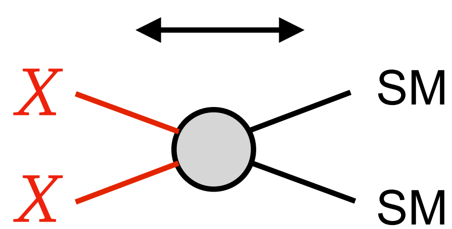


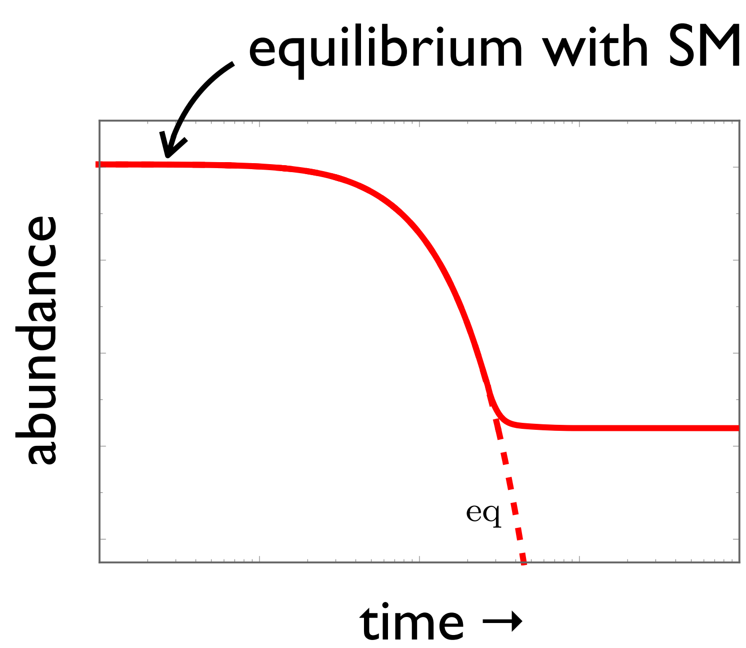


WIMP(-like)

Thermal relic dark matter

Thermalised



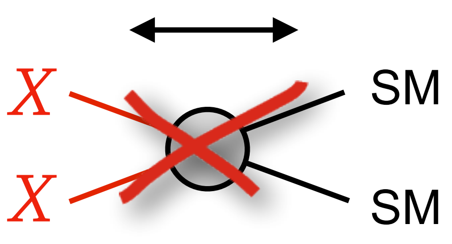


WIMP(-like)

- Thermalization: predictive power
- Provides cold dark matter
- Testable (but facing null-results)

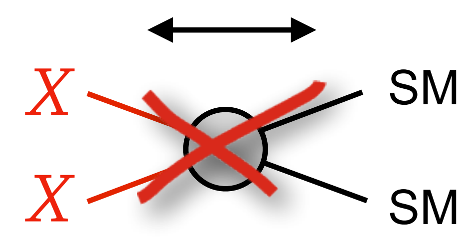
Thermal relic dark matter

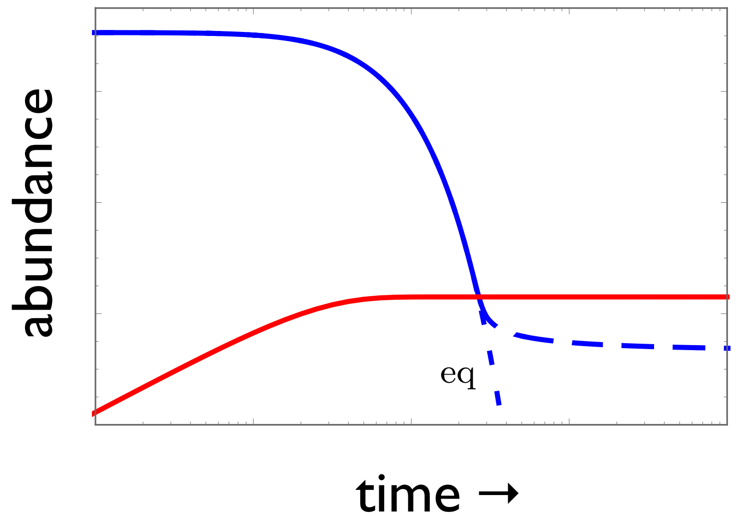
Non-thermalised



Thermal relic dark matter

Non-thermalised



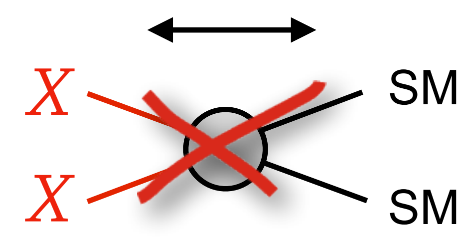


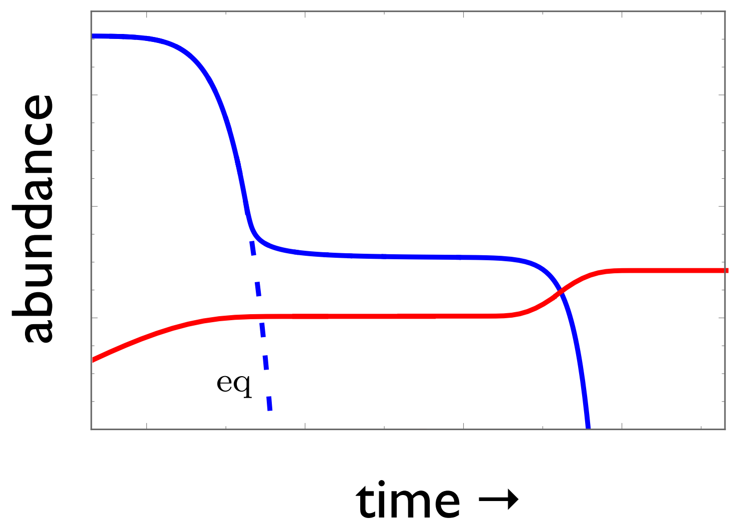
Freeze-in production

[McDonald 2002; Asaka *et al.* 2006; Hall *et al.* 2009]

Thermal relic dark matter

Non-thermalised





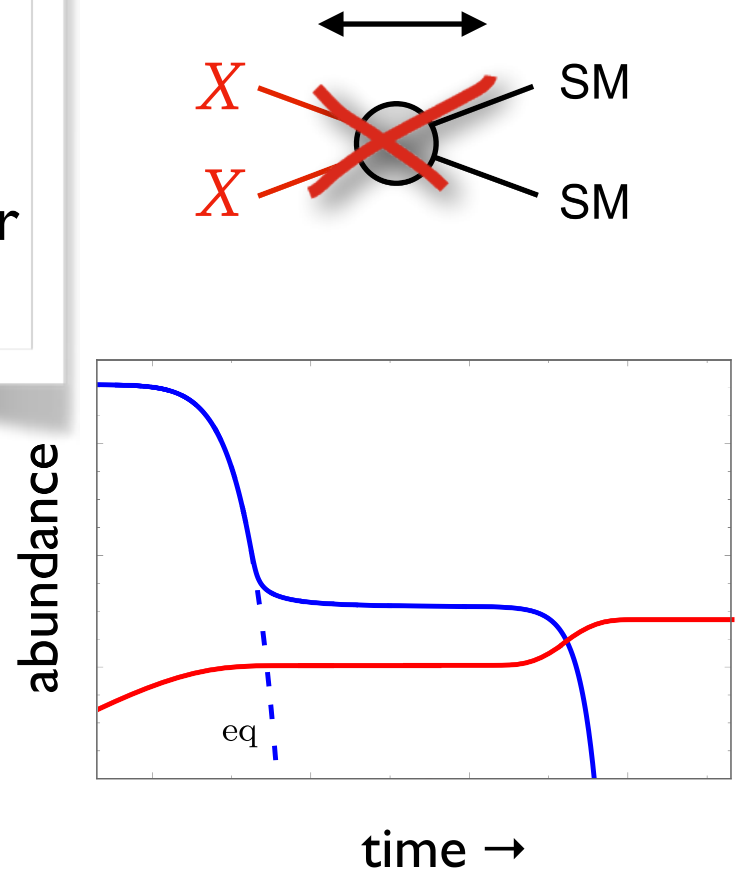
superWIMP production

[Covi *et al.* 1999; Feng *et al.* 2003]

Thermal relic dark matter

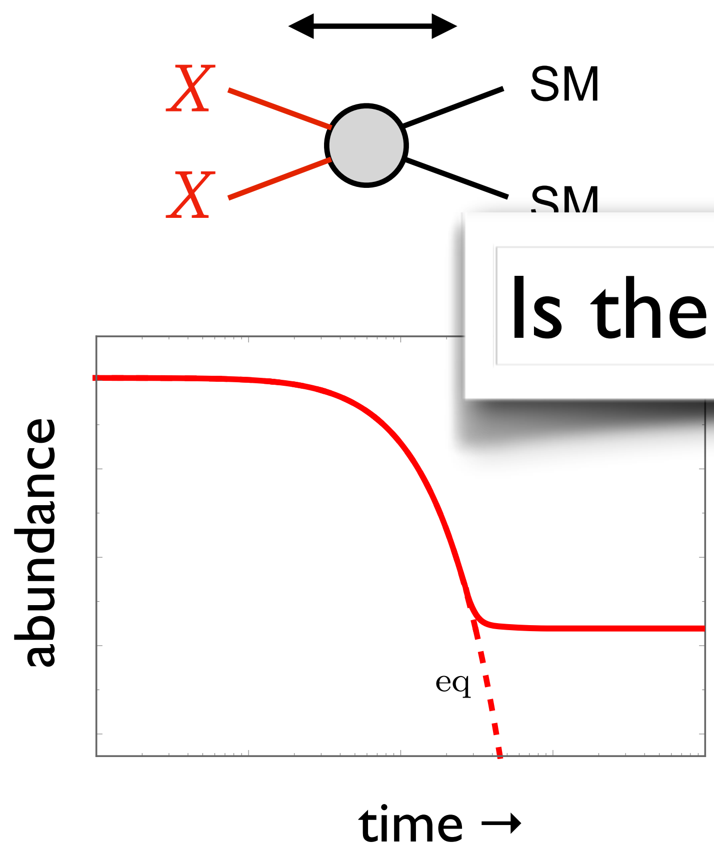
Non-thermalised

- Fine with null-results
- Depend on initial conditions
- Not necessarily cold dark matter
- Only partly testable

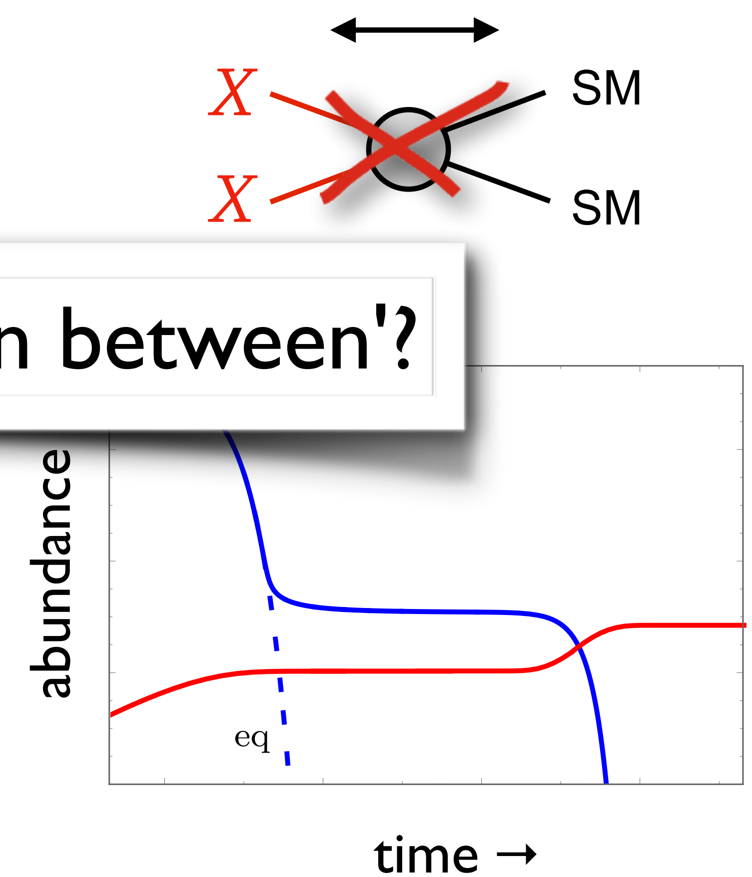


Thermal relic dark matter

Thermalised



Non-thermalised



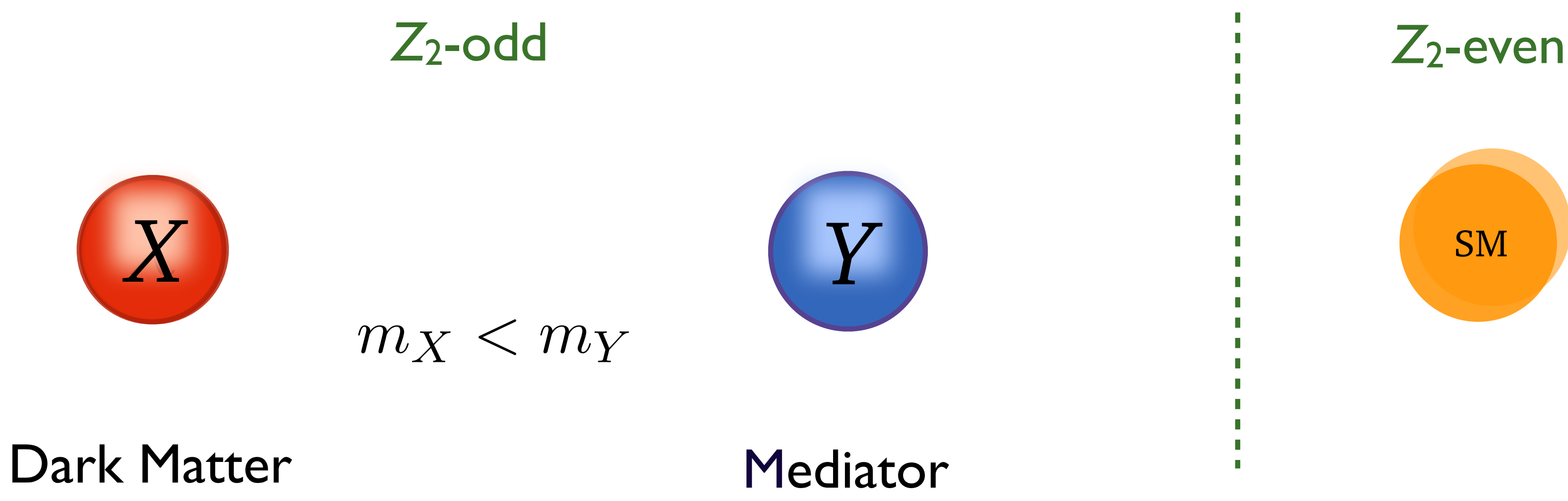
Is there something 'in between'?

Conversion-driven freeze-out

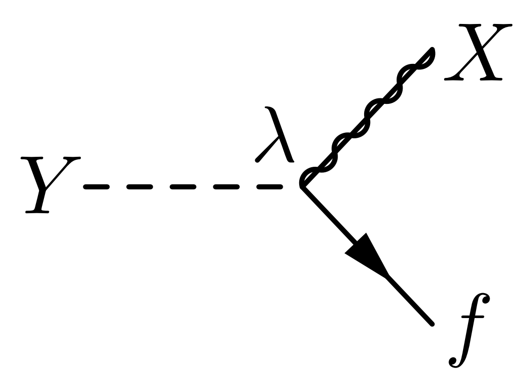
(aka co-scattering)

[Garny, JH, Lülf, Vogl 1705.09292; D'Agnolo, Pappadopulo, Ruderman 1705.08450]

Minimal *t*-channel mediator model



$$\mathcal{L} \supset \lambda Y \bar{f} X$$



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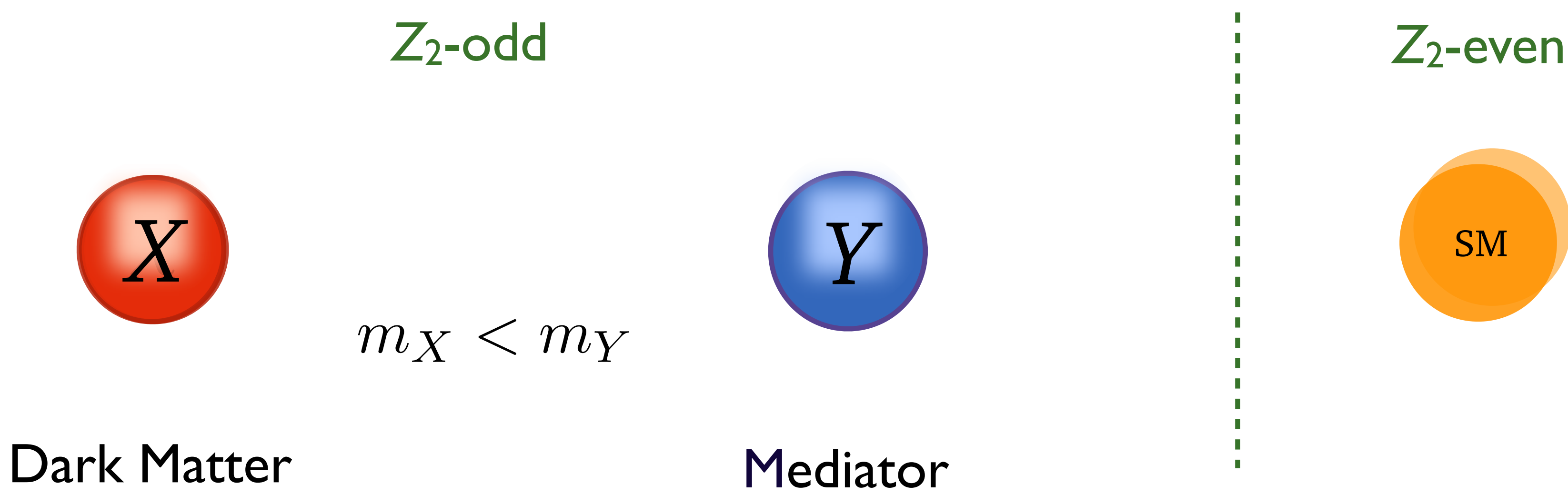

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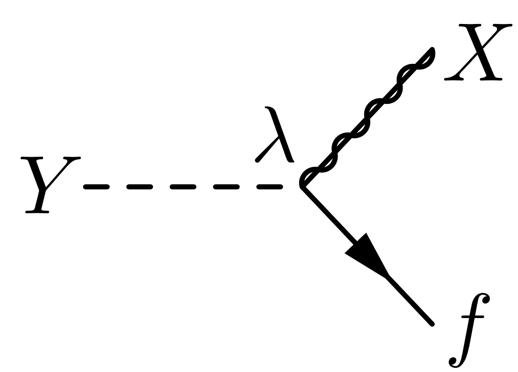
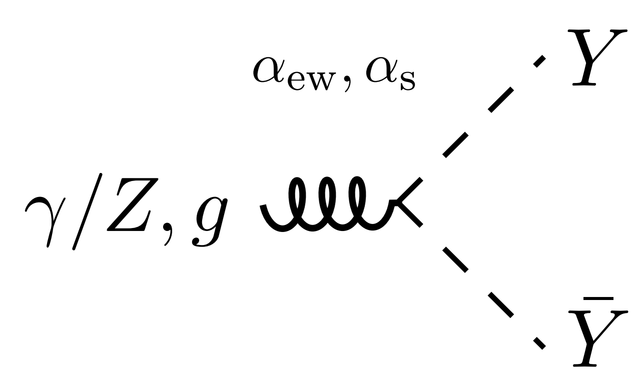
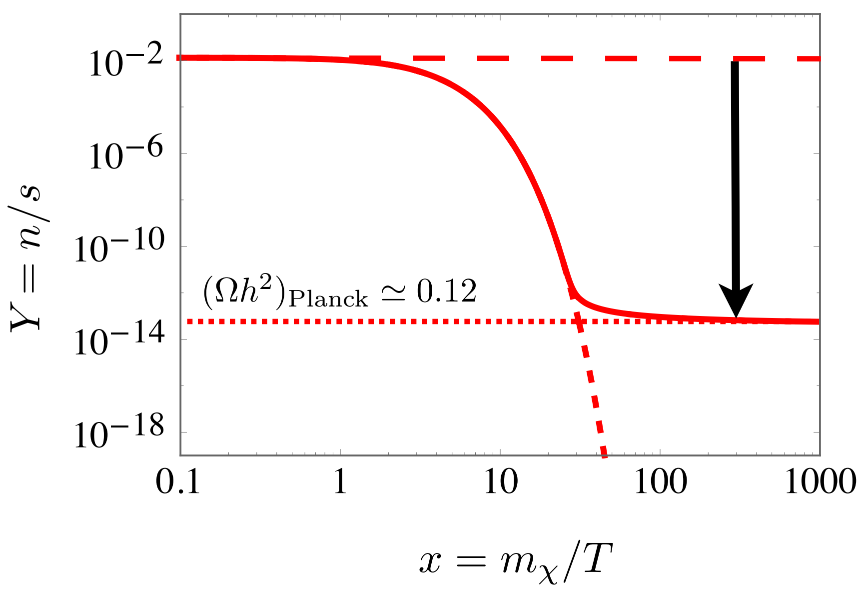


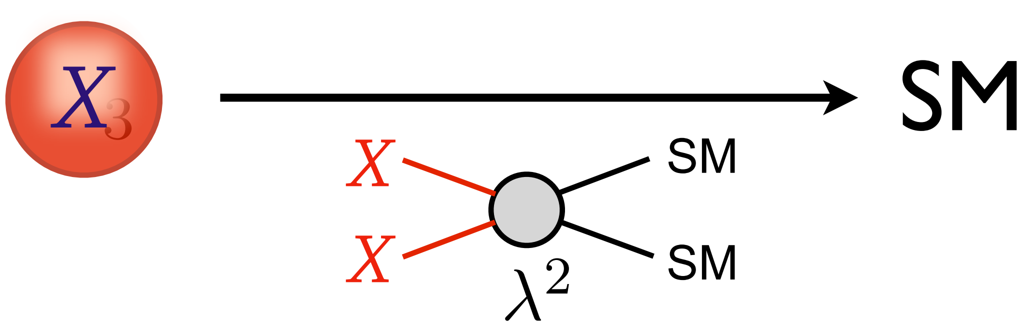
Mediator same gauge quantum no. as $f \Rightarrow$ (color-)charged:



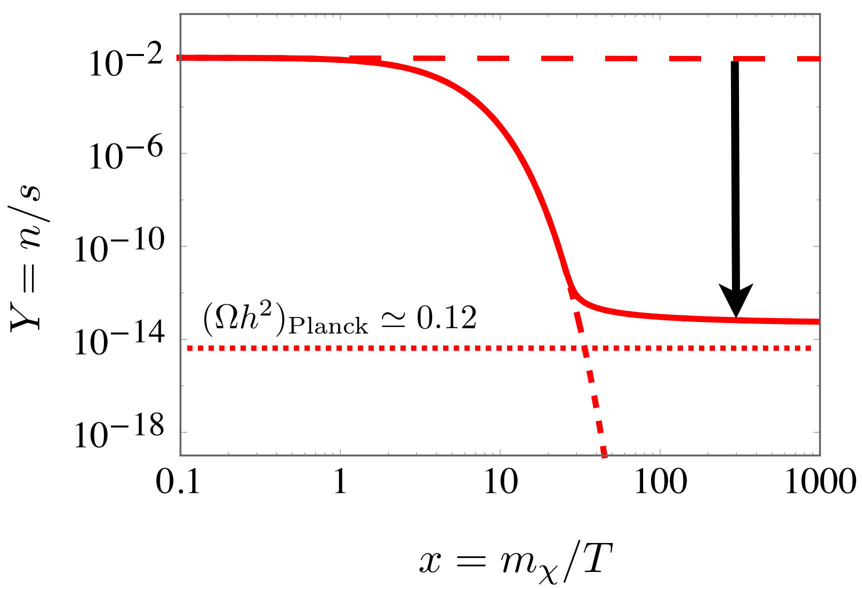
Dark matter freeze-out



(time →)



Dark matter freeze-out



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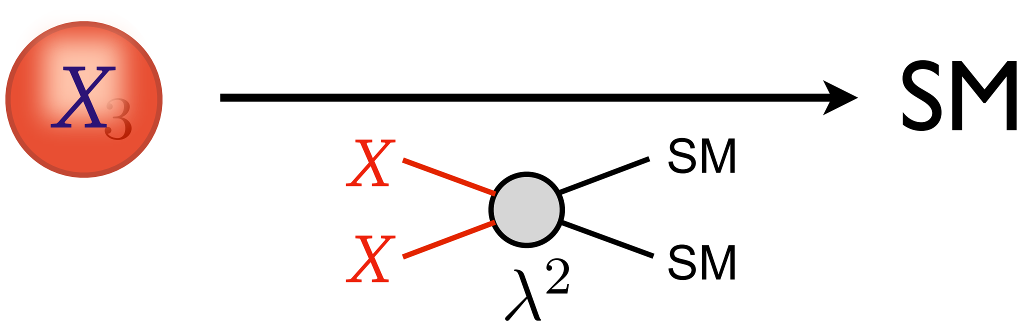
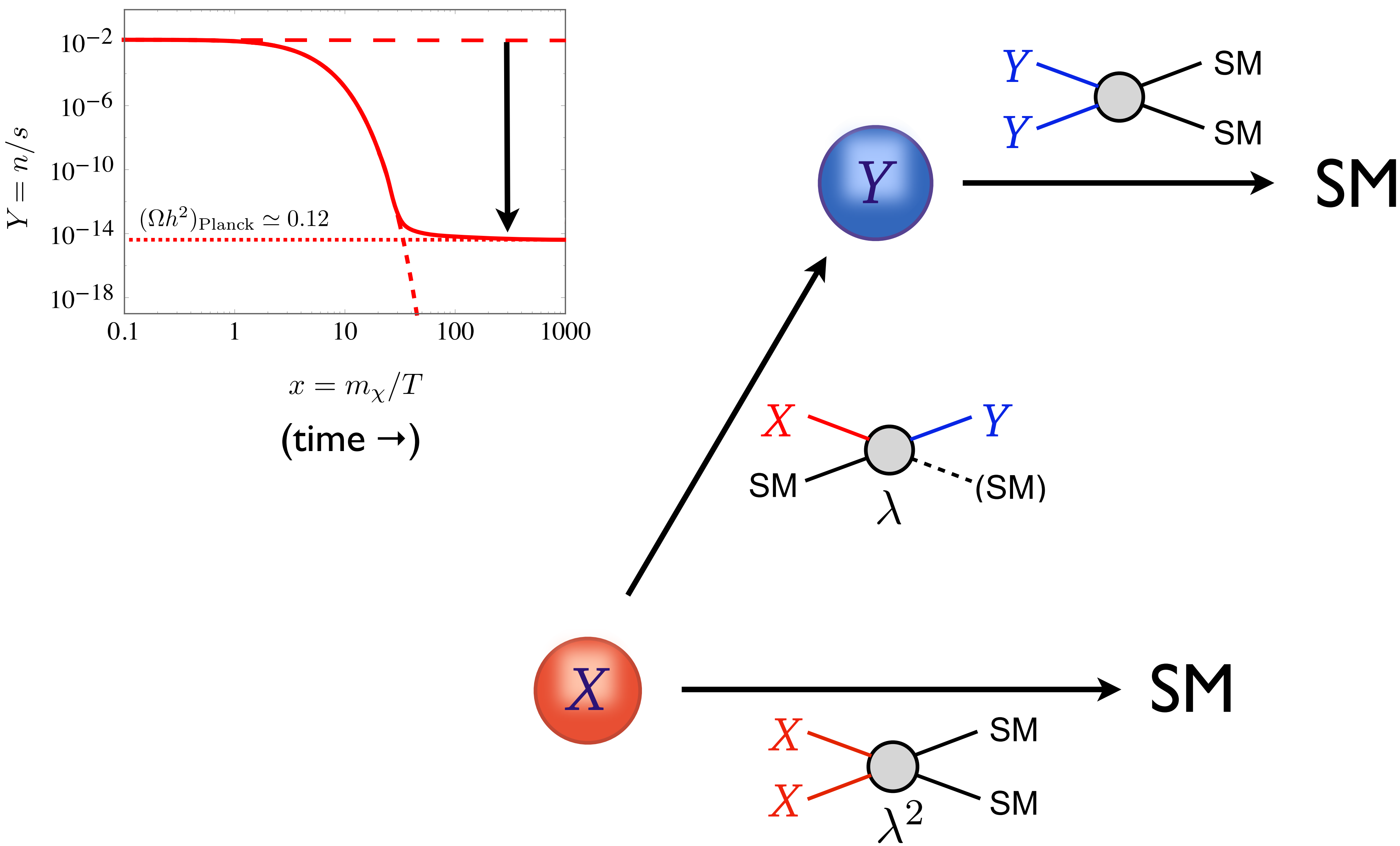


Dark matter freeze-out: coannihilation



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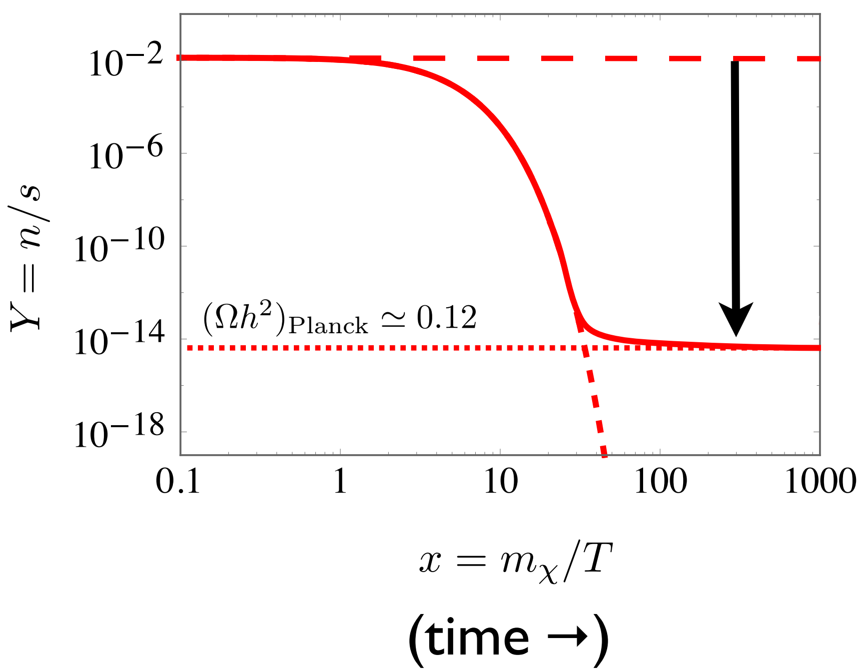

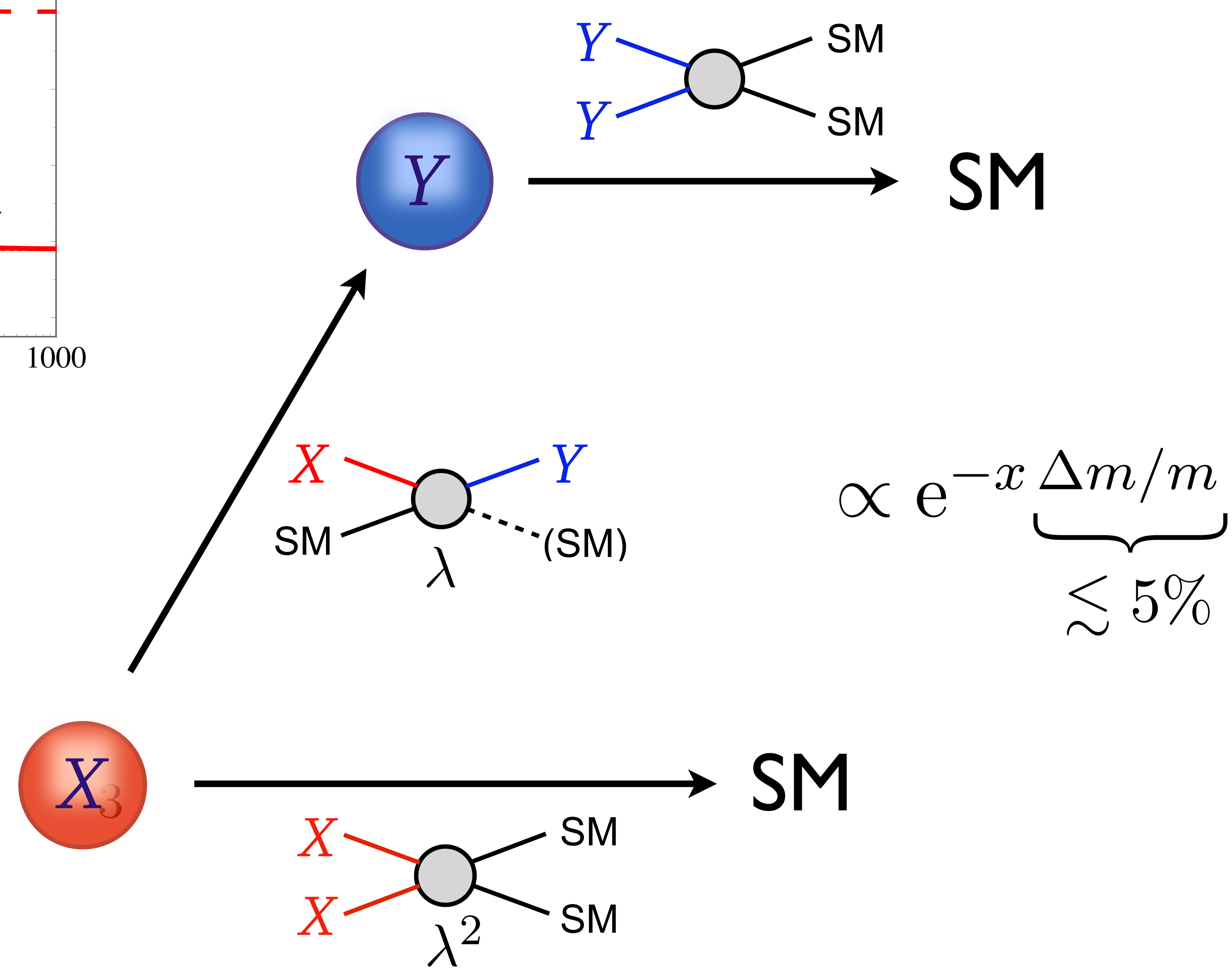

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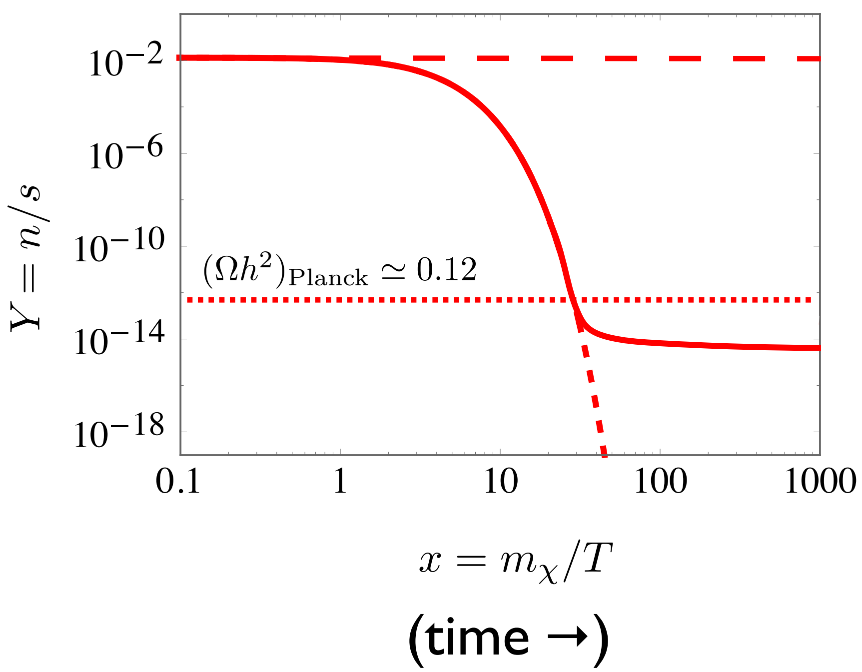
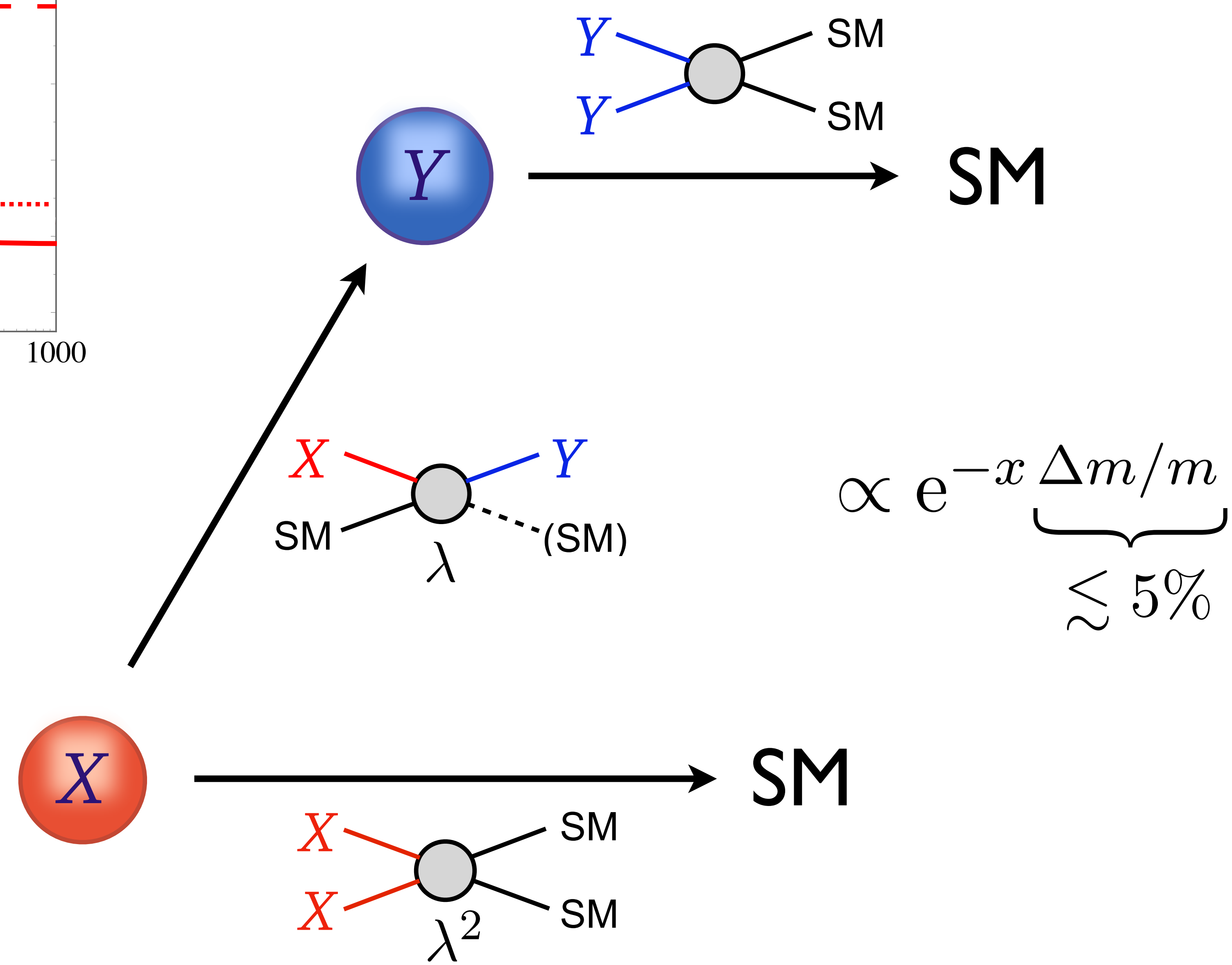
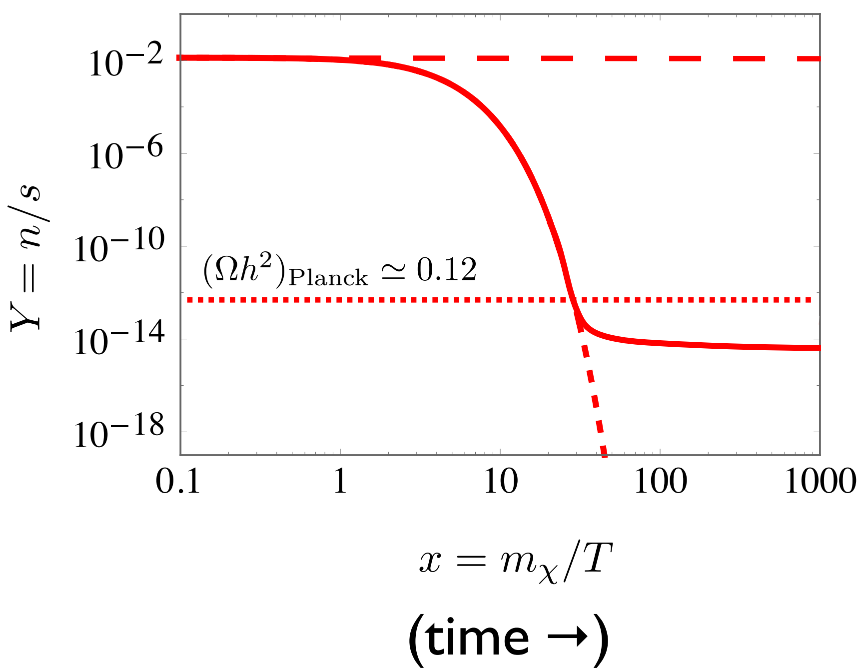
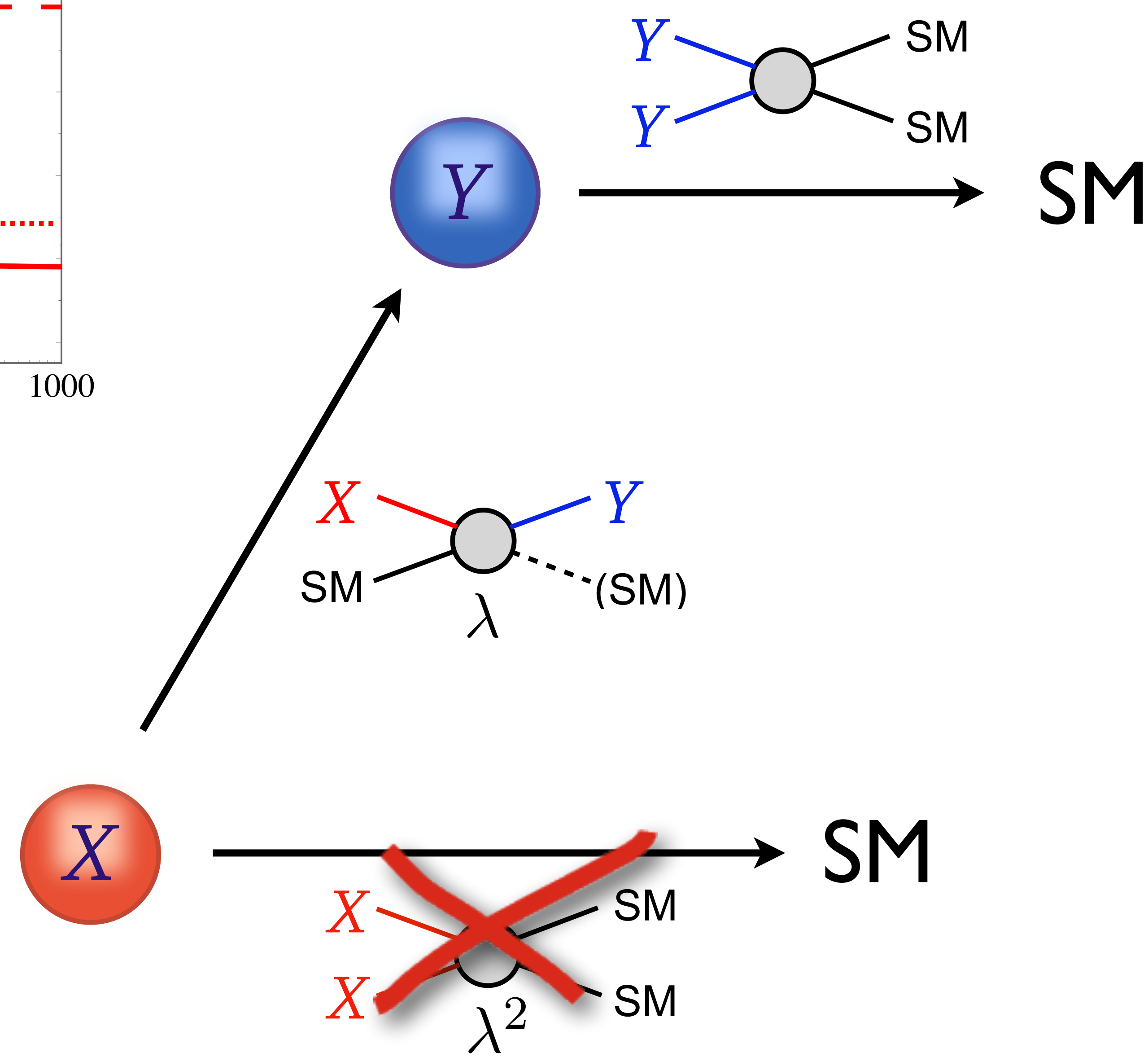


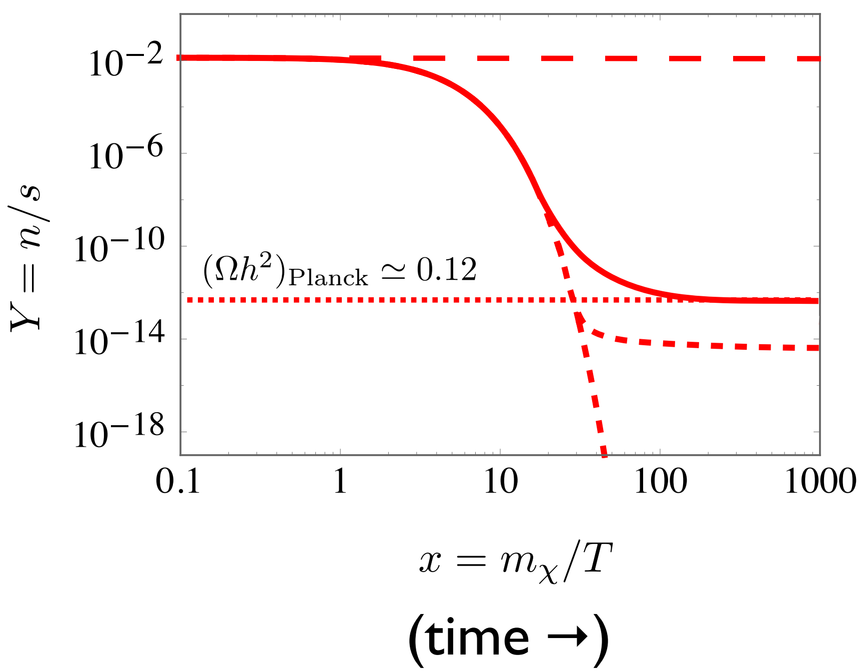


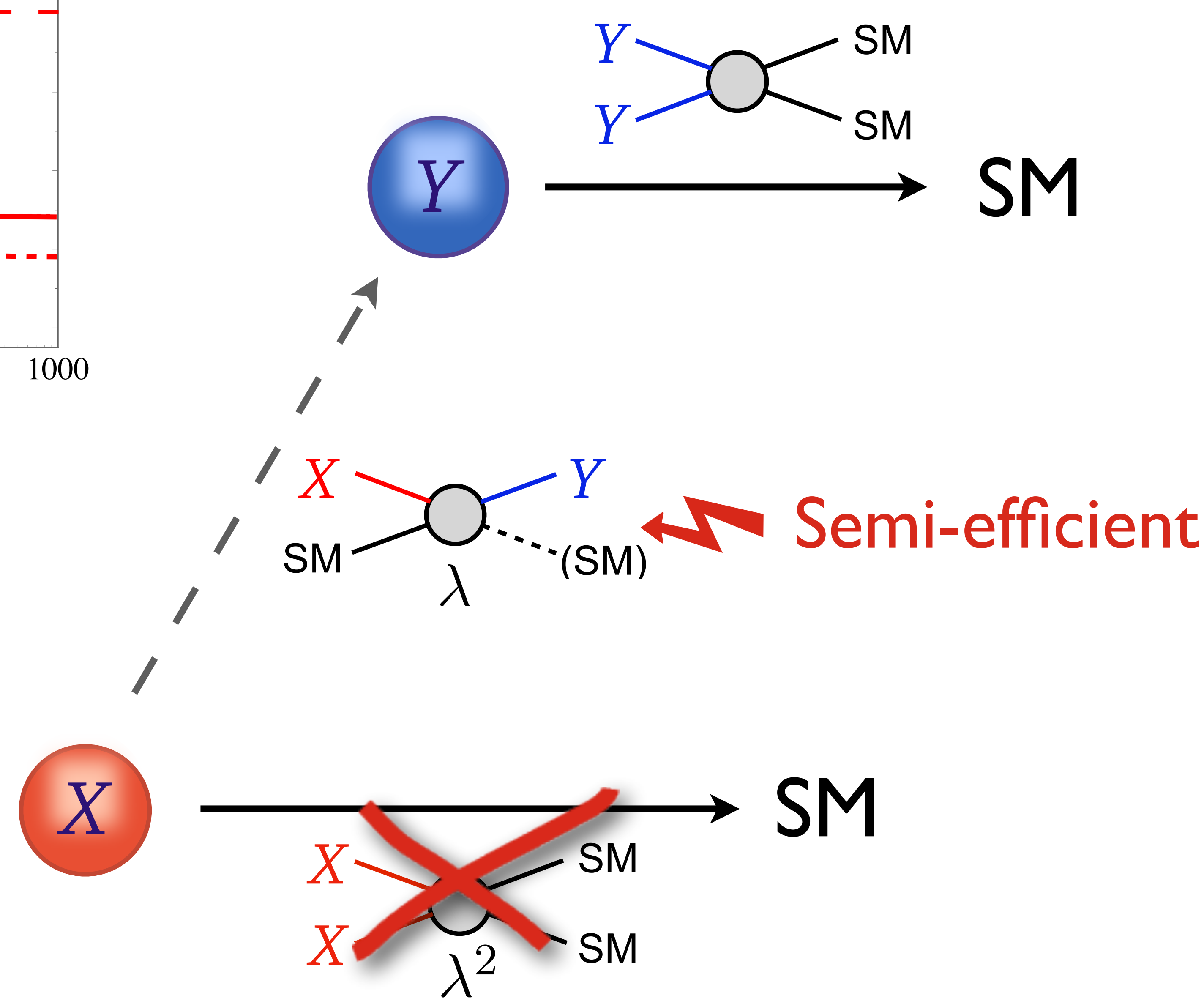
Dark matter freeze-out: small λ





Dark matter freeze-out: very small λ





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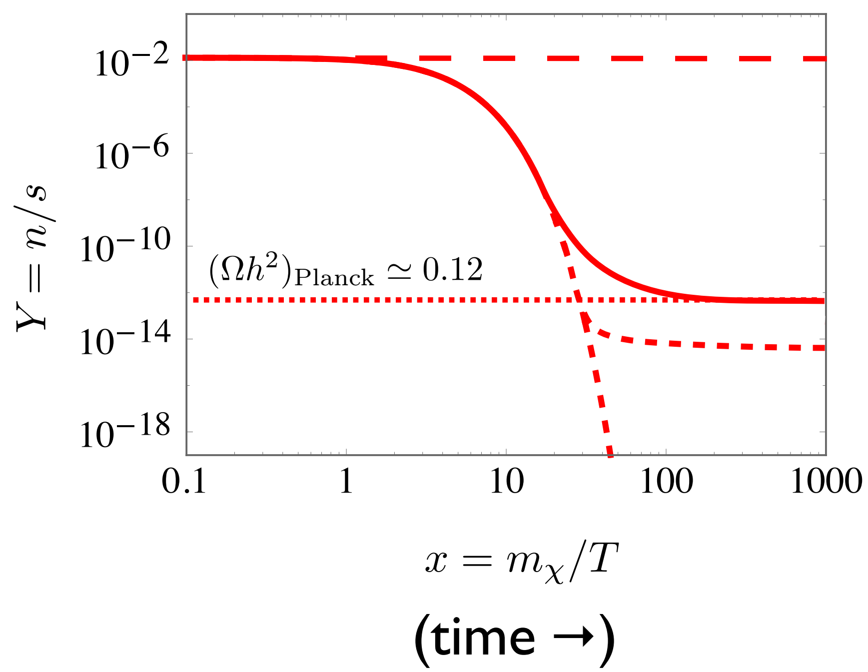
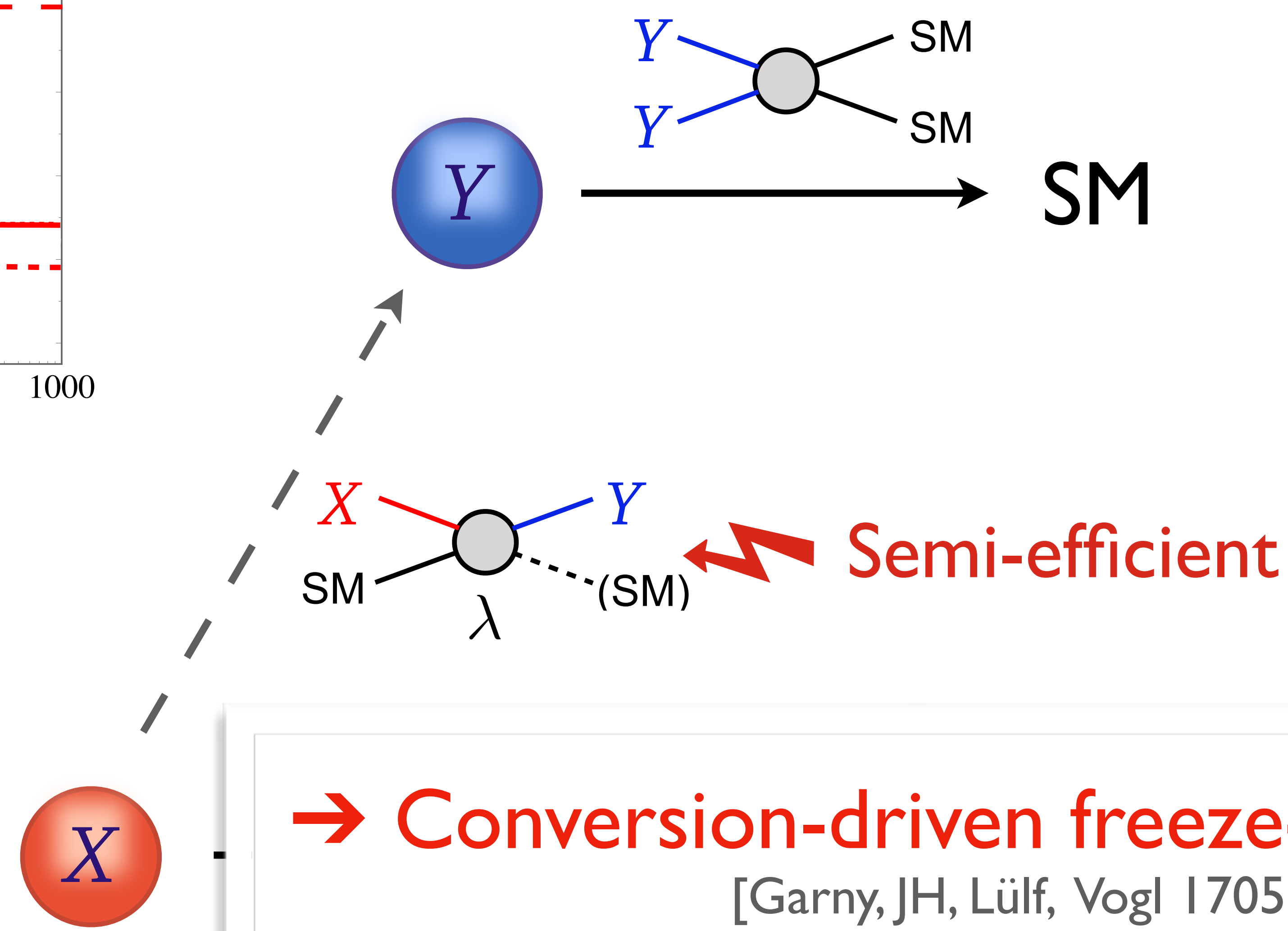
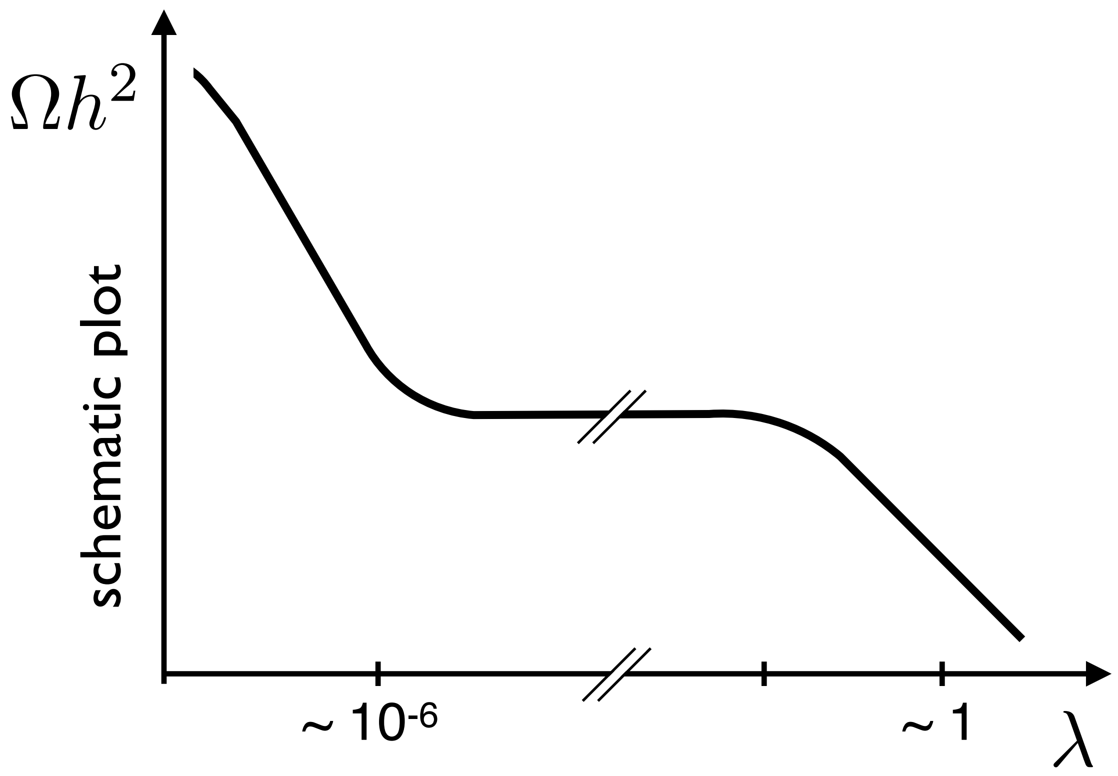


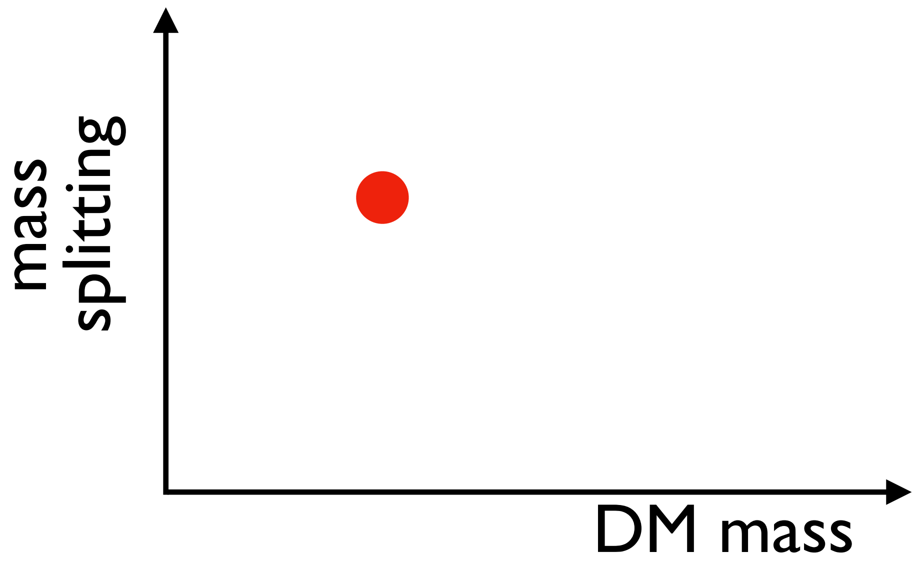


→ Conversion-driven freeze-out

[Garny, JH, Lülf, Vogl 1705.09292;
D'Agnolo, Pappadopulo, Ruderman 1705.08450]

Accessible parameter space





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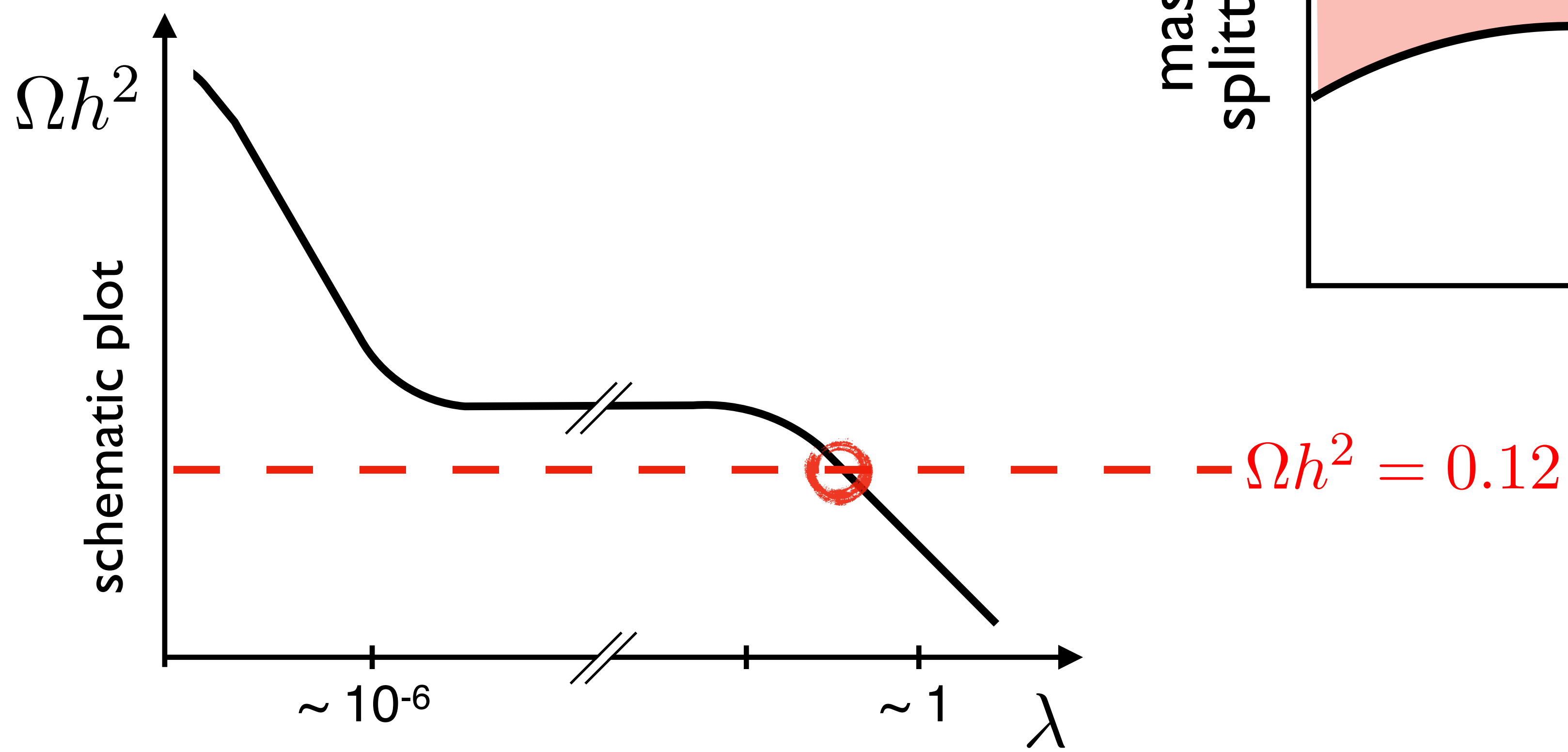

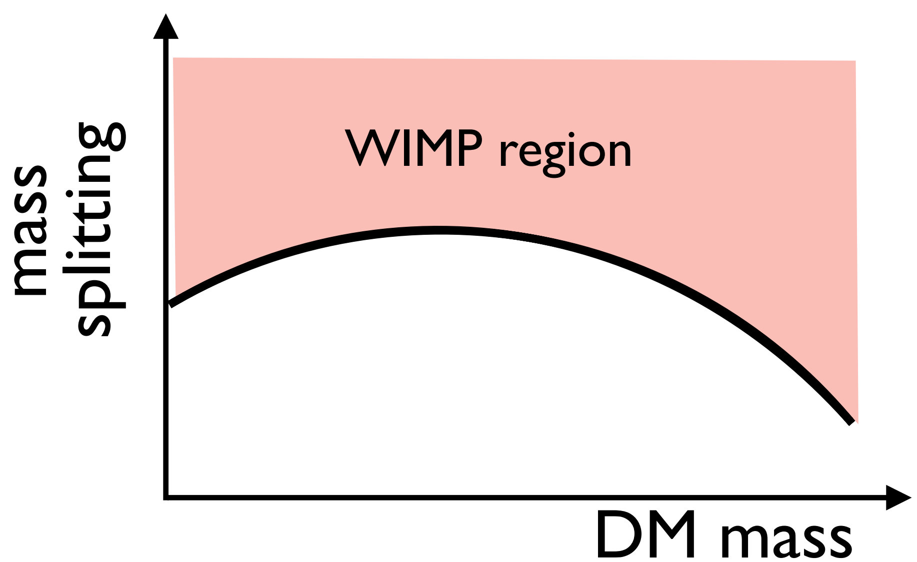

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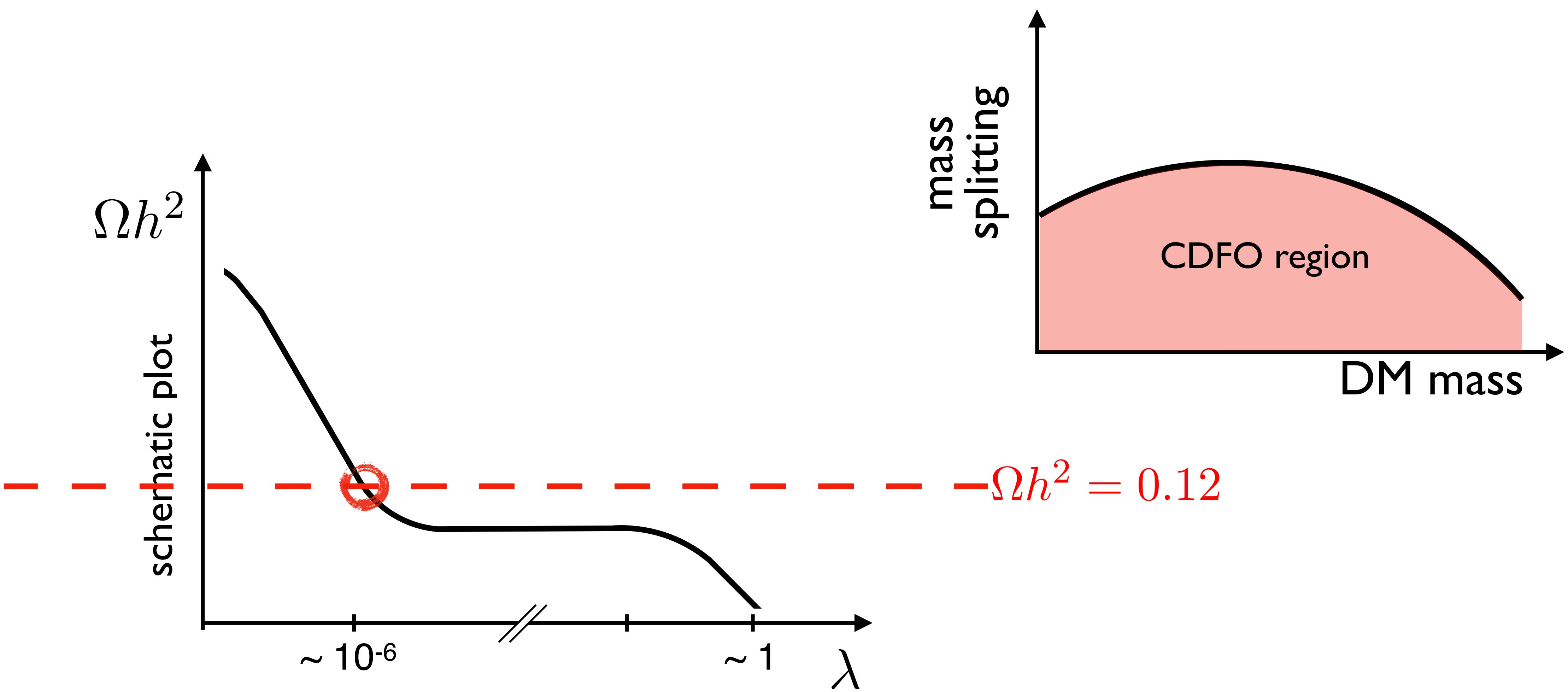

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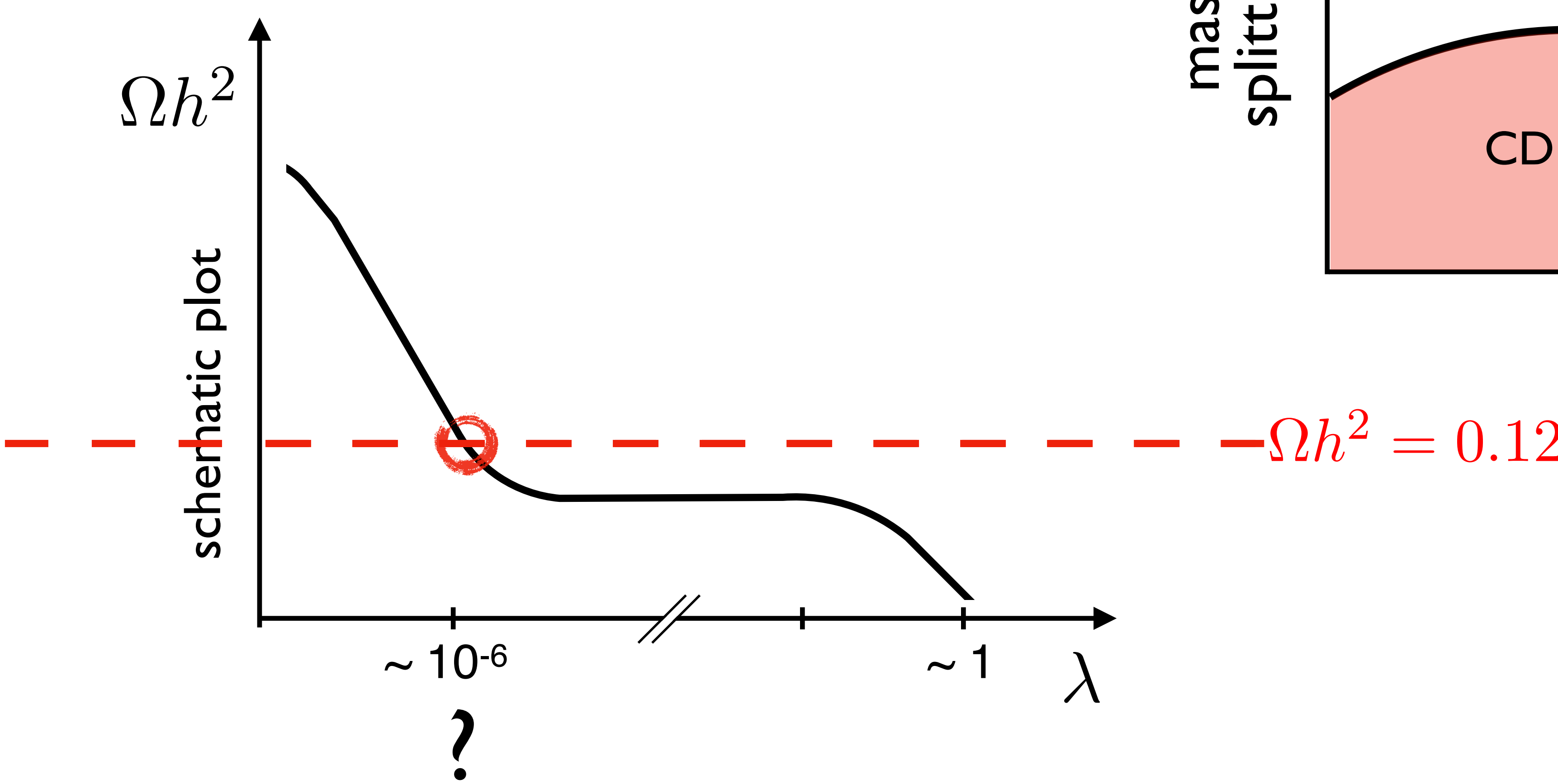
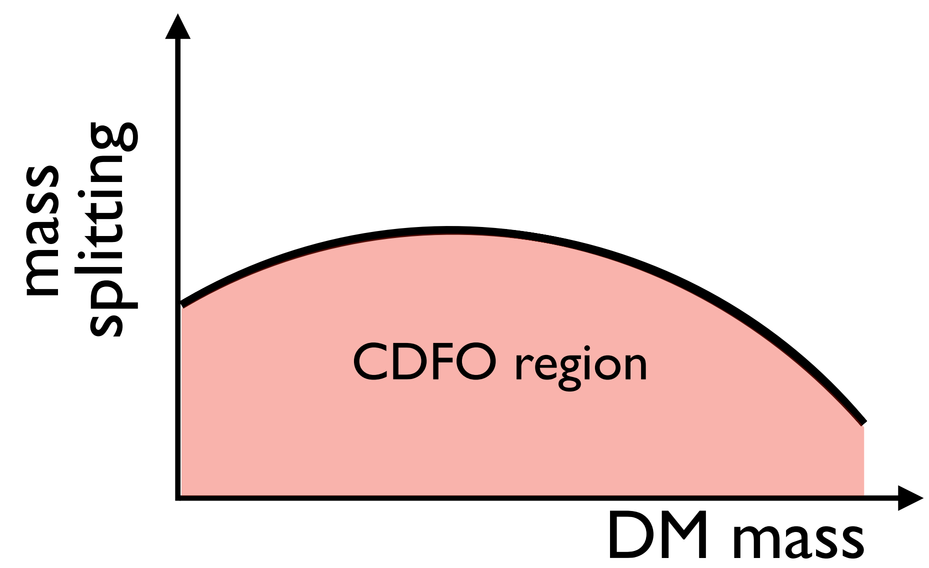
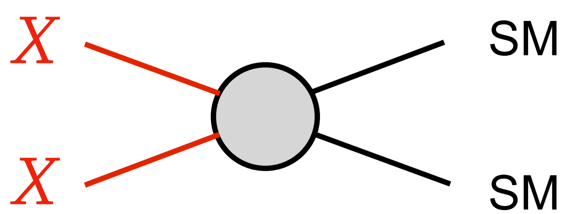




Typical coupling



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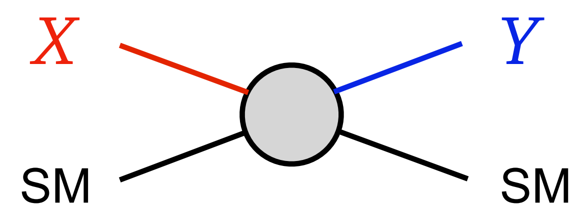
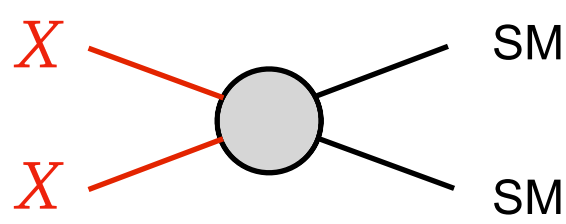


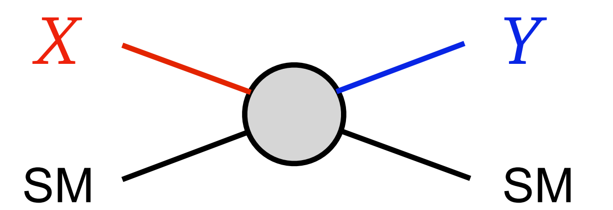
$$\Gamma_{\mathrm{ann}} = n_X \langle \sigma v \rangle_{\mathrm{ann}}$$

$$\Gamma_{\mathrm{con}} = n_{\mathrm{SM}} \langle \sigma v \rangle_{\mathrm{con}}$$

Typical coupling



vs

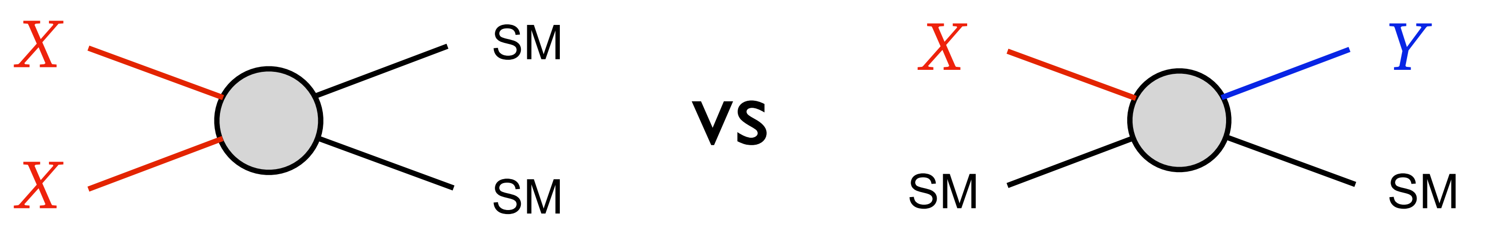


$$\Gamma_{\rm ann} = n_X \langle \sigma v \rangle_{\rm ann}$$

$$\Gamma_{\rm con} = n_{\rm SM} \langle \sigma v \rangle_{\rm con}$$

$\mathrm{e}^{-m_X/T_{\rm fo}} \sim 10^{-12}$

Typical coupling



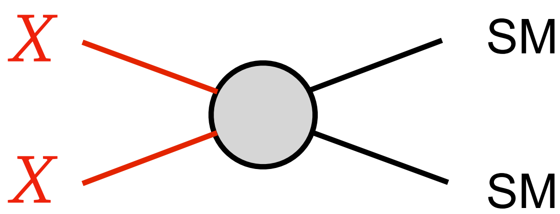
$\Gamma_{\rm ann} = n_X \langle \sigma v \rangle_{\rm ann}$ $\qquad$ $\Gamma_{\rm con} = n_{\rm SM} \langle \sigma v \rangle_{\rm con}$

$\uparrow$

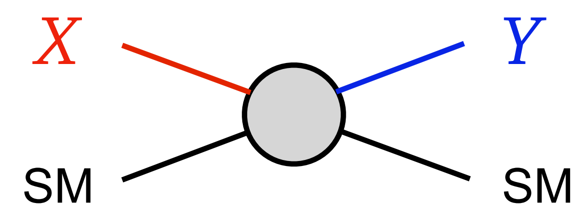
$\mathrm{e}^{-m_X/T_{\rm fo}} \sim 10^{-12}$

Thermal decoupling condition: $\Gamma \sim H$

Typical coupling



vs



$$\Gamma_{\rm ann} = n_X \langle \sigma v \rangle_{\rm ann}$$

$$\Gamma_{\rm con} = n_{\rm SM} \langle \sigma v \rangle_{\rm con}$$

$\uparrow$ $e^{-m_X/T_{\rm fo}} \sim 10^{-12}$

Thermal decoupling condition: $\Gamma \sim H$

$$\frac{\langle \sigma v \rangle_{\rm con}}{\langle \sigma v \rangle_{\rm ann}} \sim 10^{-12} \qquad \Rightarrow \lambda \sim 10^{-6}$$

Conversion-driven freeze-out – summary

- Conversions initiate thermal decoupling $\lambda \sim 10^{-6}$
- Accommodate null-results of WIMP searches
- Still, conversions supply thermalisation

Conversion-driven freeze-out – summary

- Conversions initiate thermal decoupling $\lambda \sim 10^{-6}$
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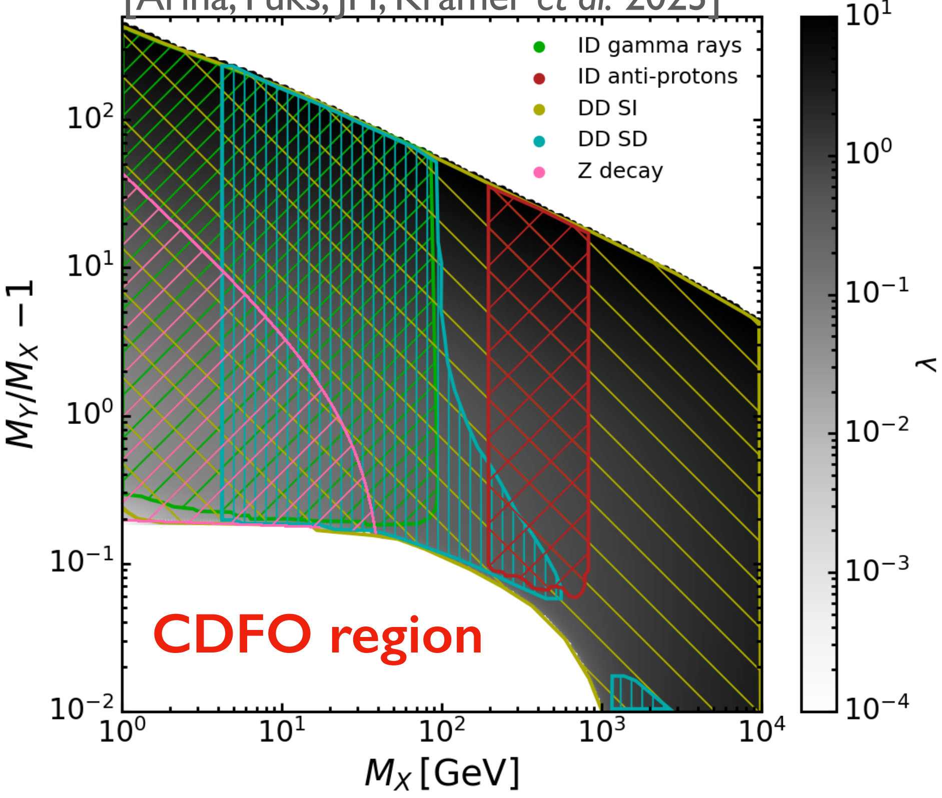
- Still, conversions supply thermalisation

- Wide range of viable model realizations
  [Garny+ 2018, Bharucha+ 2018, D'Agnolo+ 2018, Cheng+ 2018, Junius+ 2019, Belanger+ 2022, Alguero+ 2022, Díaz Sáez 2024, …]
- Link to neutrino masses [Heeck, JH, Thapa 2023]
- Link to baryogensis [JH 2024]

[Arina, Fuks, JH, Krämer *et al.* 2023]



How to search for it at LHC

How to search for it at LHC?

Conversion rate on the edge of being efficient:

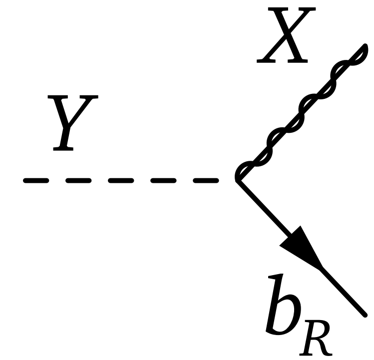
$$\Gamma_{\rm con} \sim H$$
$$\Rightarrow \quad \Gamma_{\rm dec} \lesssim H$$

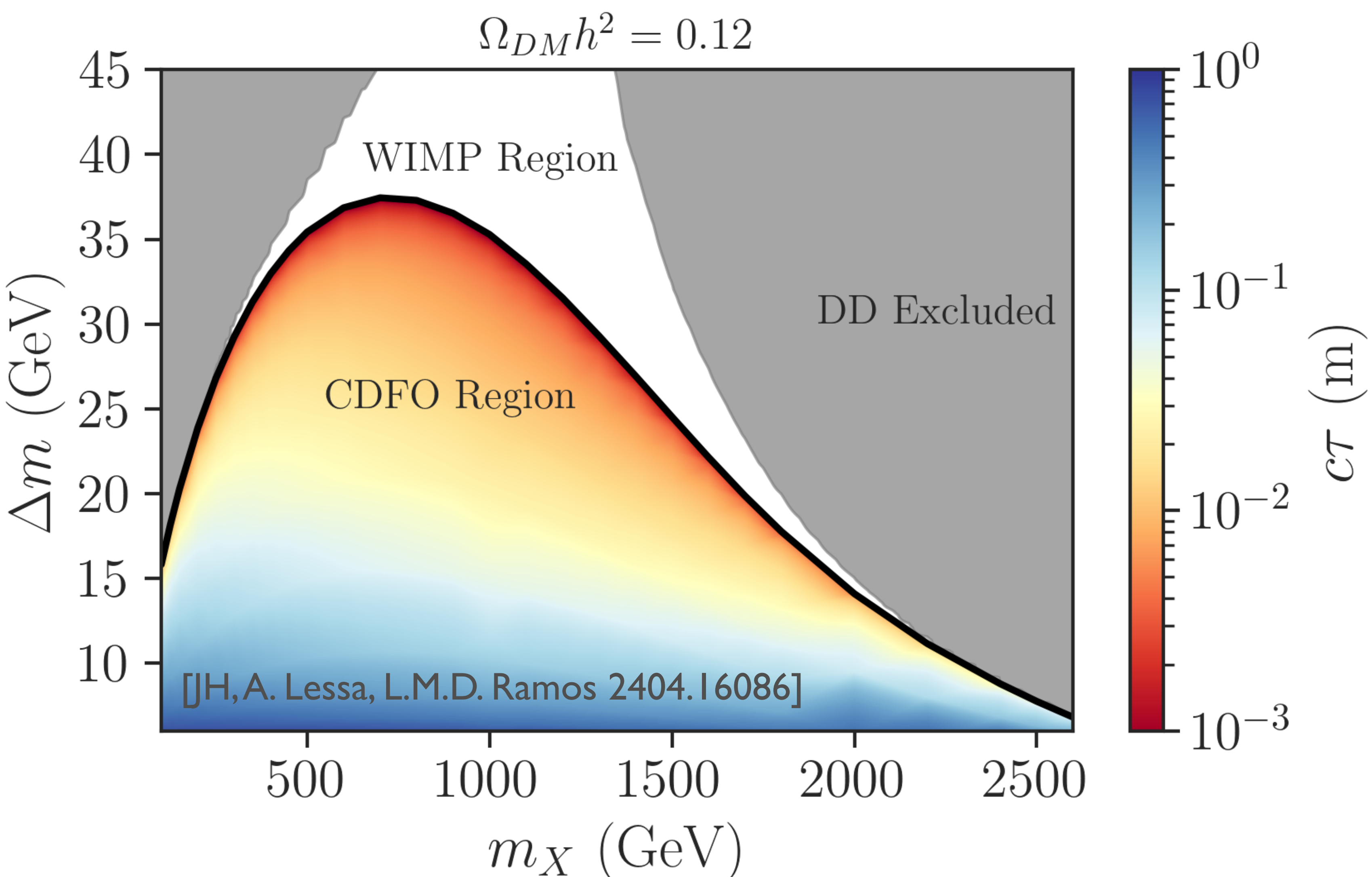
$$c\tau \gtrsim H^{-1} \simeq 1.5\,{\rm cm}\left(\frac{(100\,{\rm GeV})^2}{T_{\rm fo}^2}\right)$$

⇒ Long-lived particles (LLPs) at LHC!

Bottom-philic example

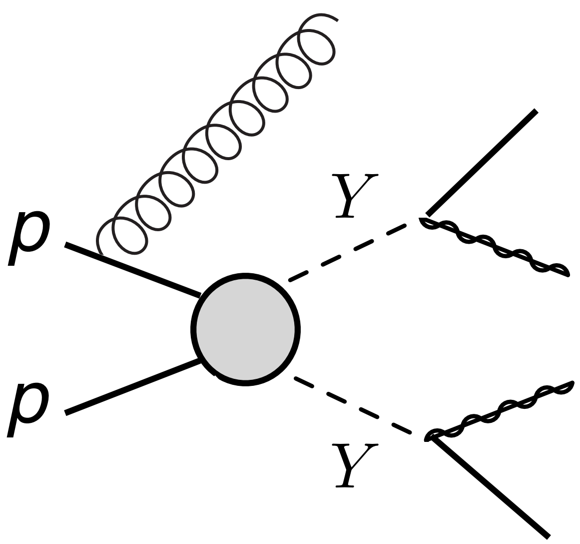
X: Majorana dark matter
Y: Scalar mediator (bottom-partner)

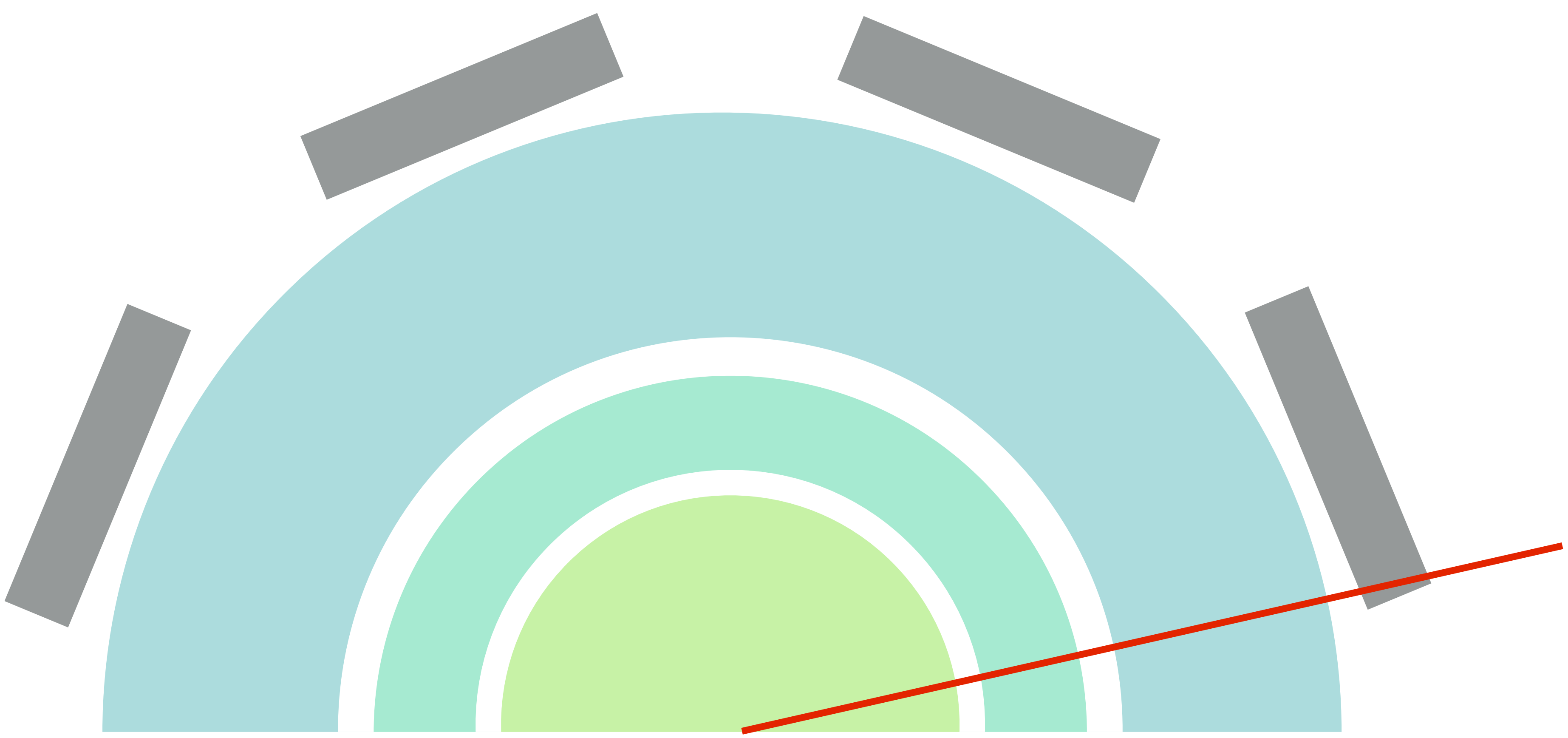




[cf. Garny, JH, Lülf, Vogl 1705.09292;
bound state effects from Garny, JH 2112.01499]

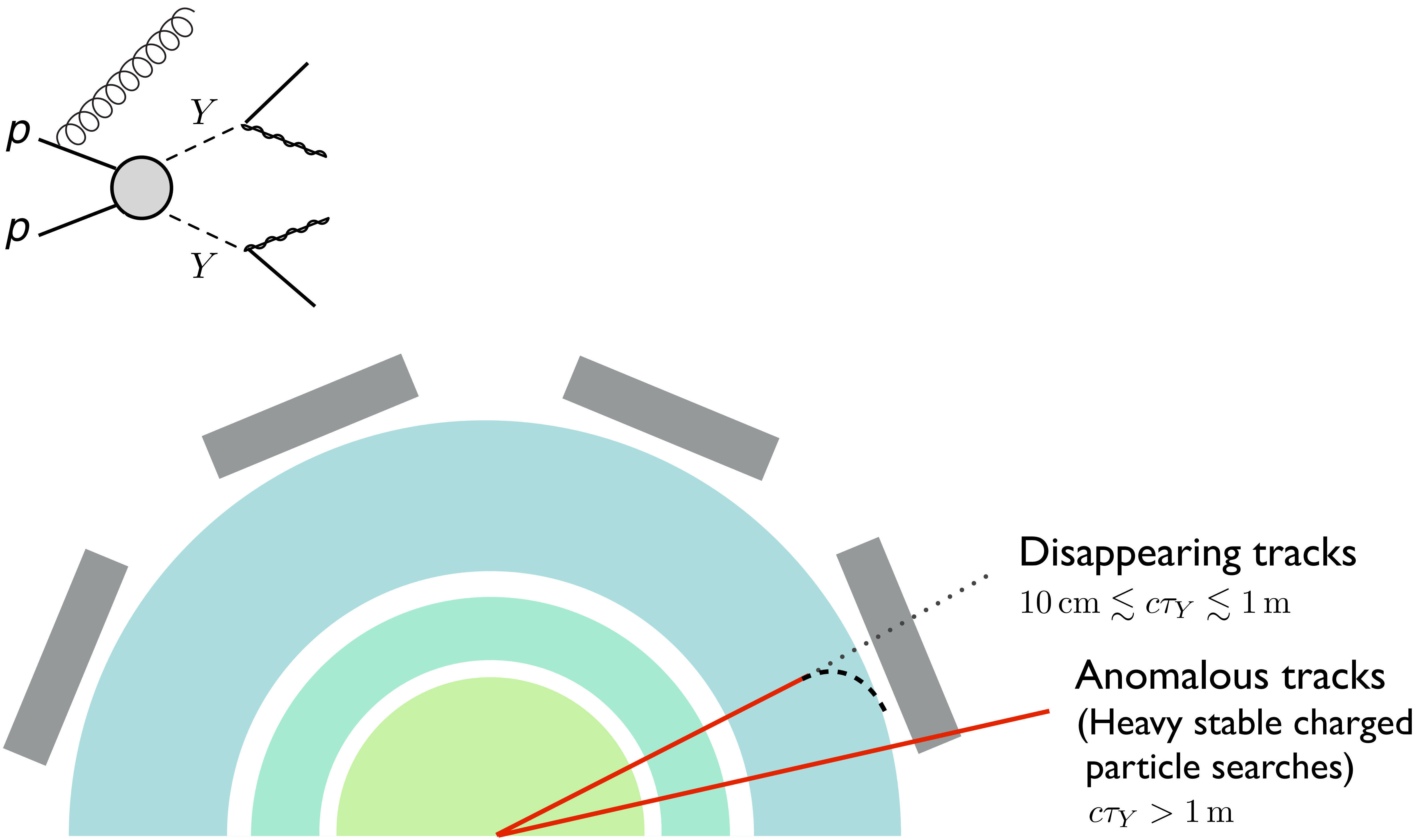
LHC Signature





Anomalous tracks
(Heavy stable charged particle searches)
$c\tau_Y > 1\,\mathrm{m}$

LHC Signature



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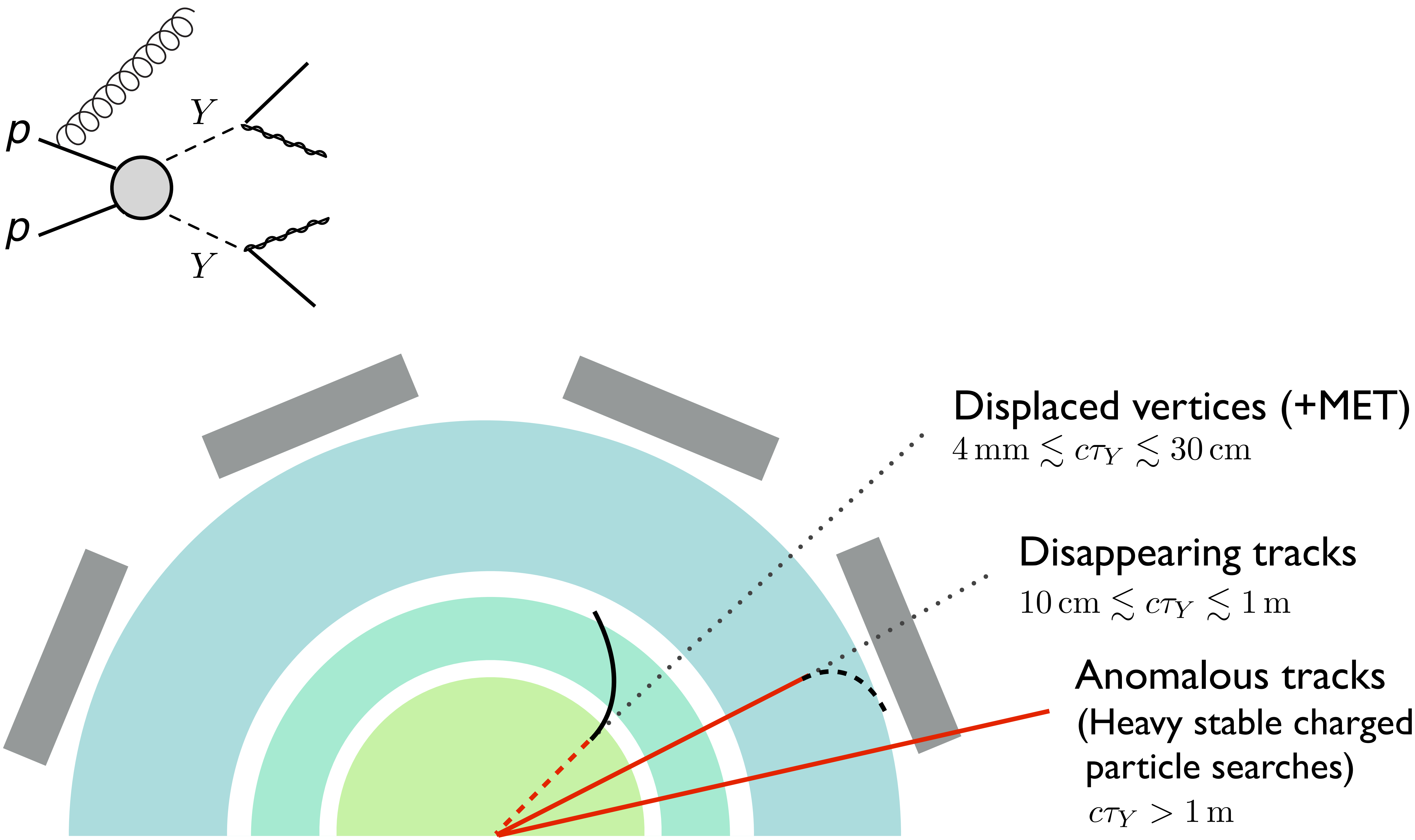

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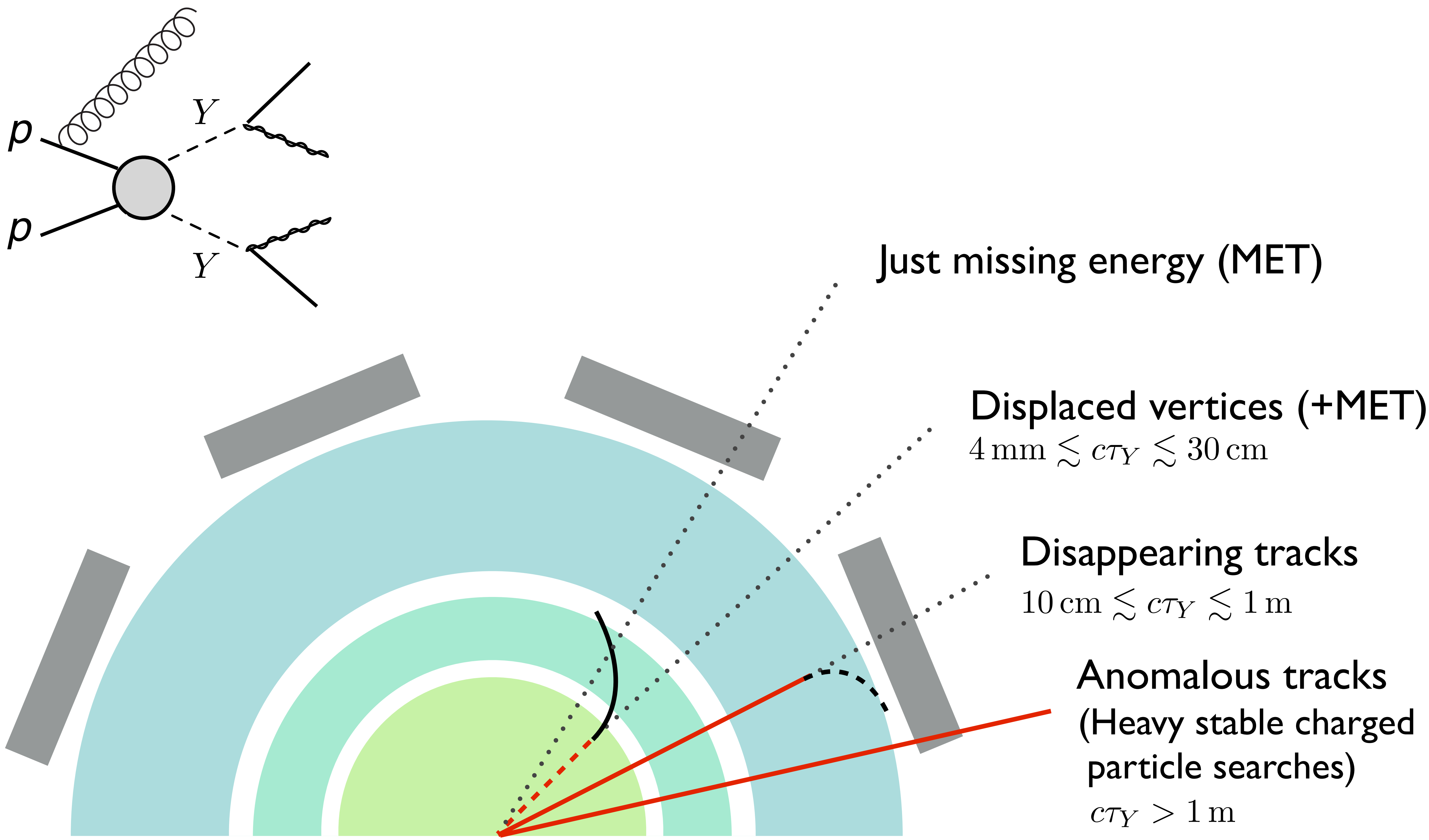
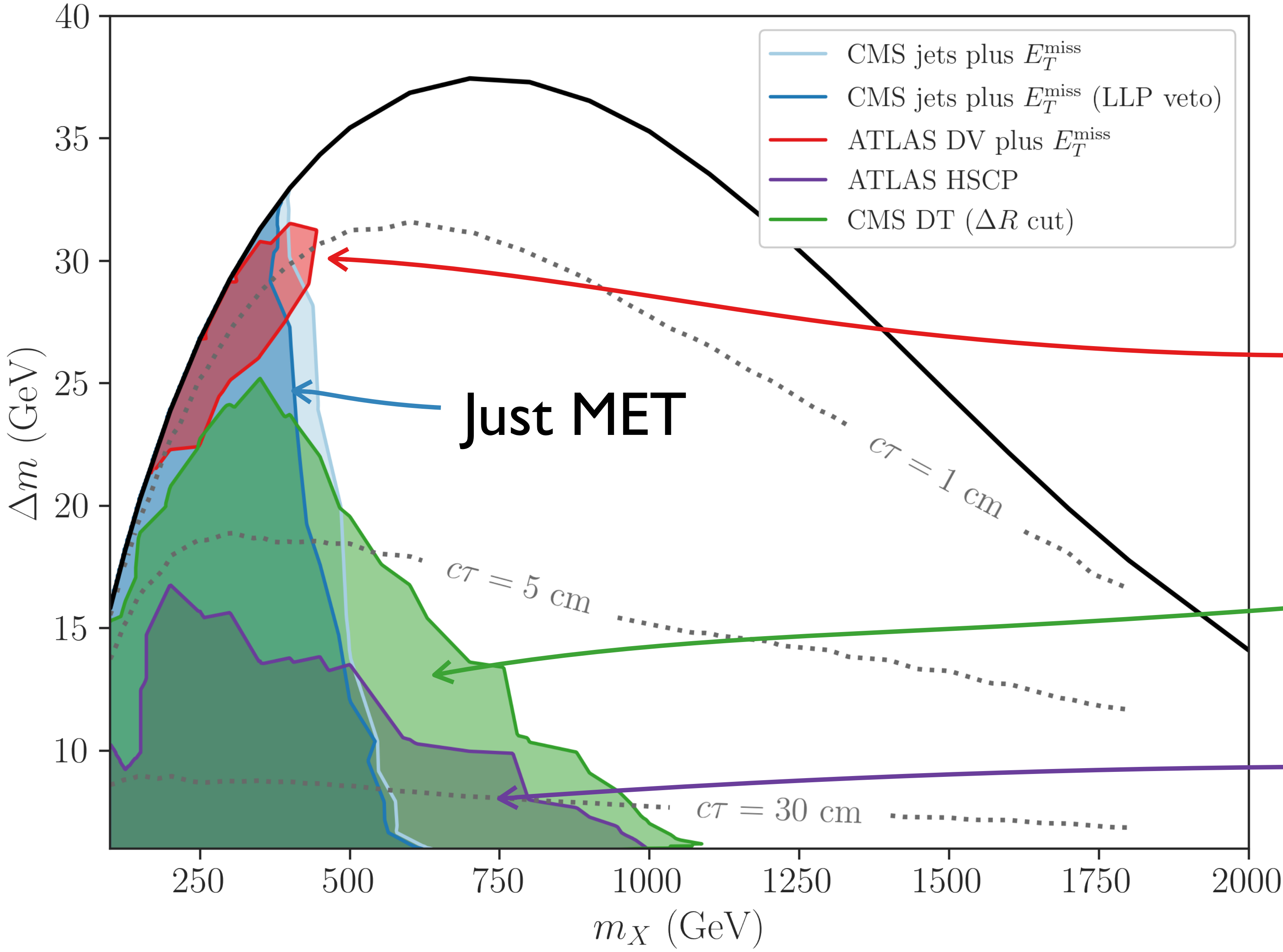


Current LHC constraints

[JH, A. Lessa, L.M.D. Ramos 2404.16086]



Displaced vertices (+MET)
$4\,\text{mm} \lesssim c\tau_Y \lesssim 30\,\text{cm}$

Disappearing tracks
$10\,\text{cm} \lesssim c\tau_Y \lesssim 1\,\text{m}$

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[see also Fuks *et al.*, contr. 7 in 2002.12220]

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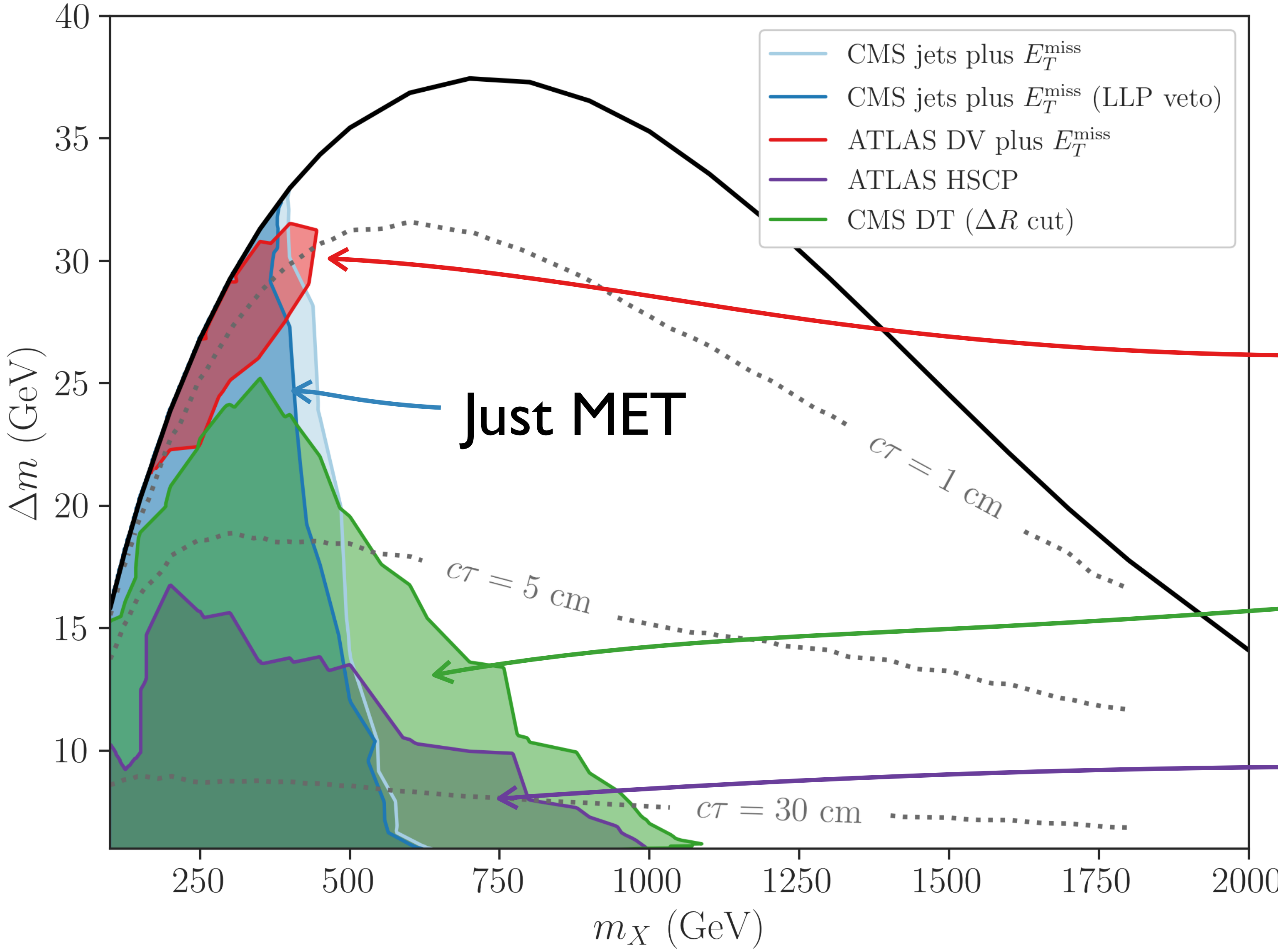

Why poor performance?

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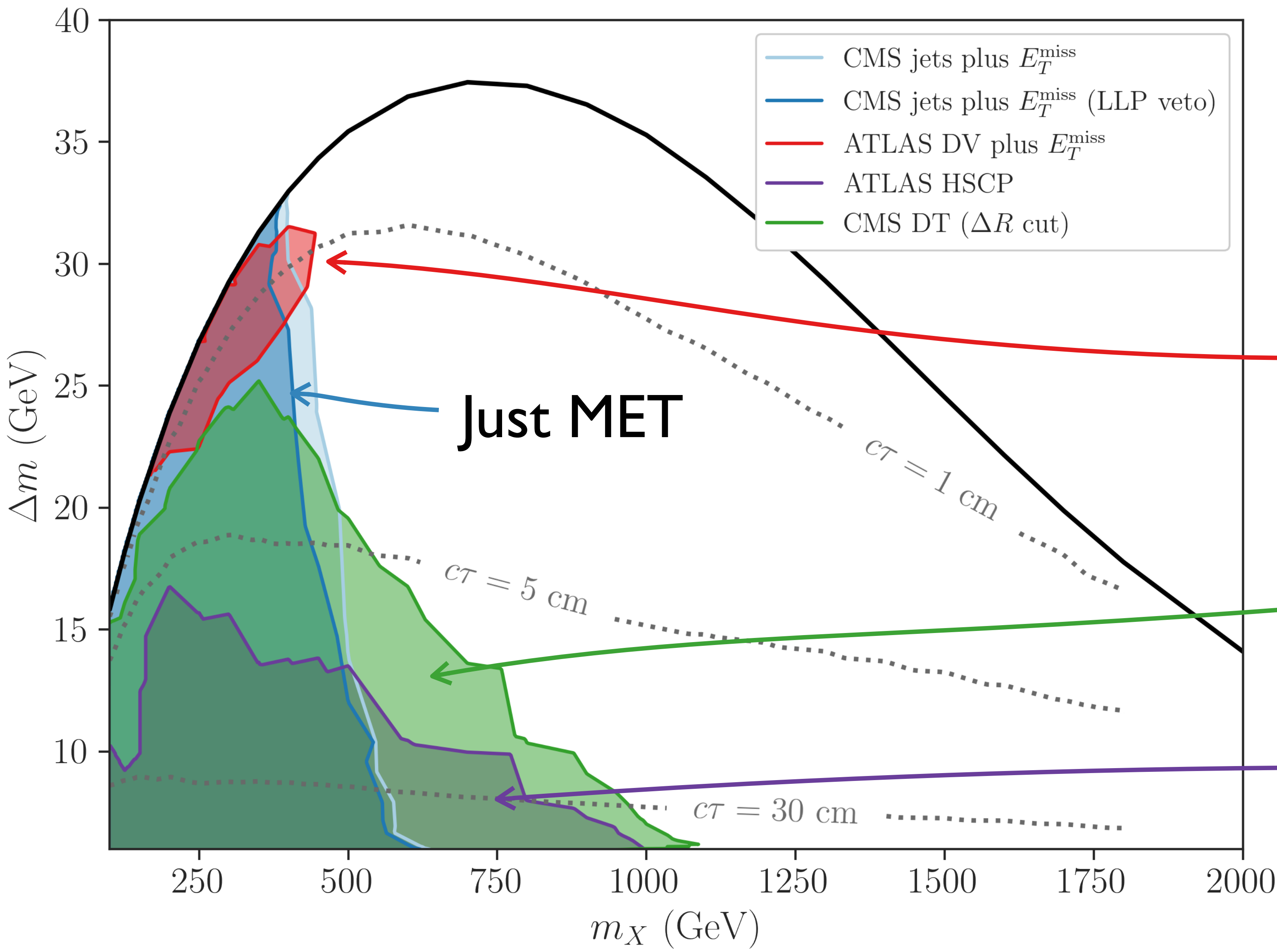

Targeted to harder jets (split SUSY)

$m_{\mathrm{DV}} > 10\,\mathrm{GeV}$

Displaced vertices (+MET)

$4\,\mathrm{mm} \lesssim c\tau_Y \lesssim 30\,\mathrm{cm}$

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$10\,\mathrm{cm} \lesssim c\tau_Y \lesssim 1\,\mathrm{m}$

Anomalous tracks (Heavy stable charged particle searches)

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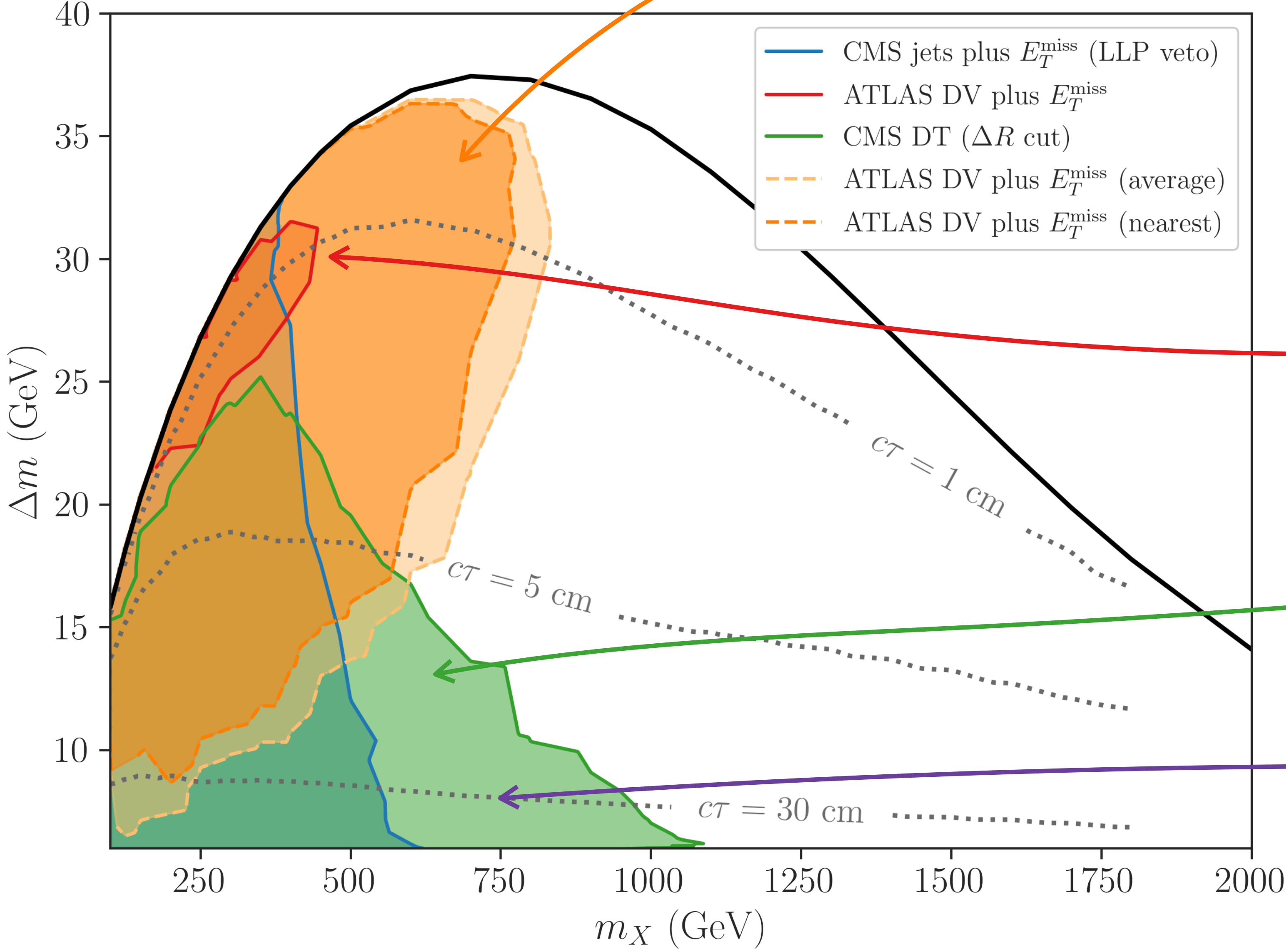
[see also Fuks *et al.*, contr. 7 in 2002.12220]

Current LHC constraints

[JH, A. Lessa, L.M.D. Ramos 2404.16086]

Proposed displaced vertices +MET search

$m_{\rm DV} > 5\,{\rm GeV}$



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Anomalous tracks

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HL-LHC projections

[JH, A. Lessa, L.M.D. Ramos 2404.16086]

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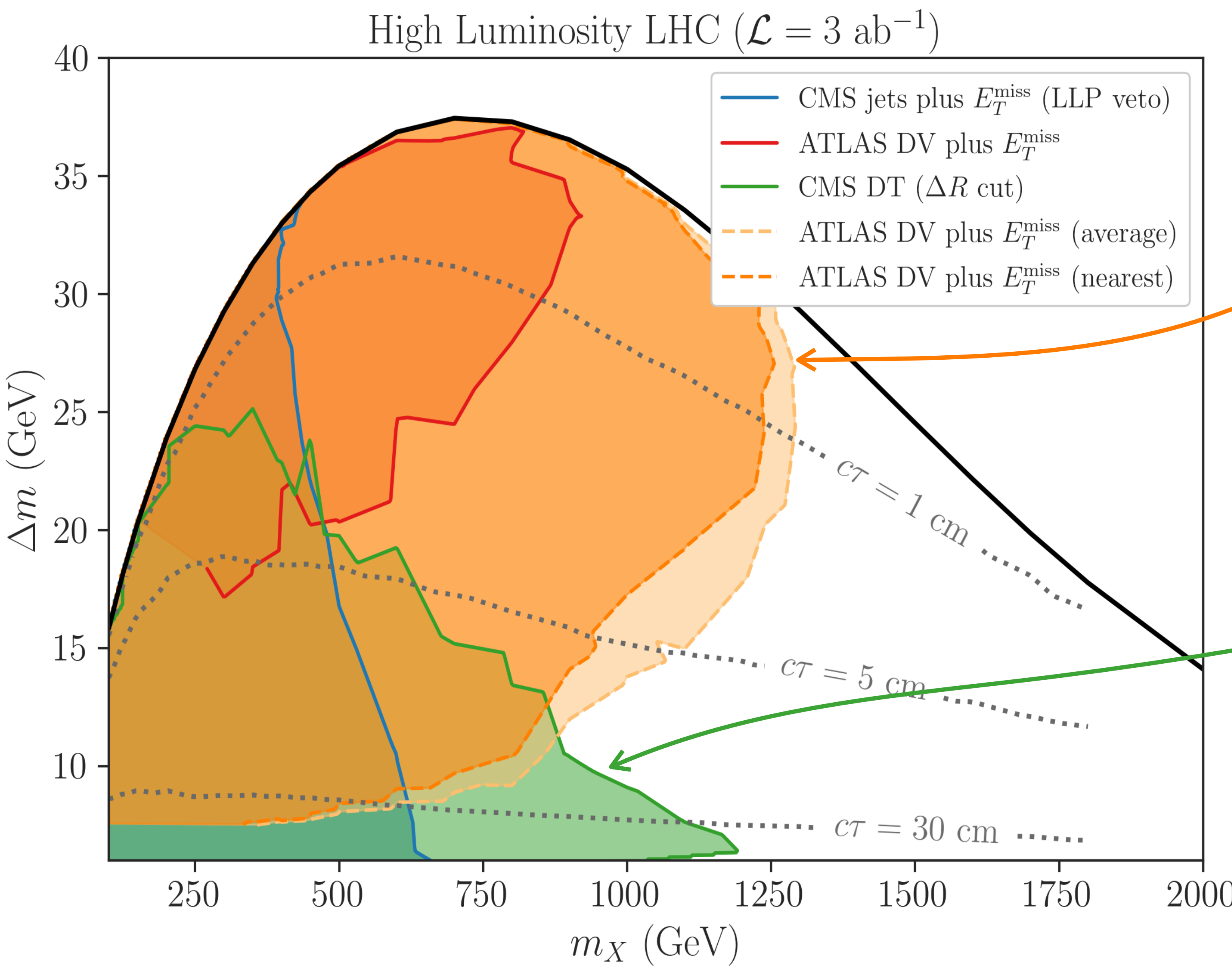


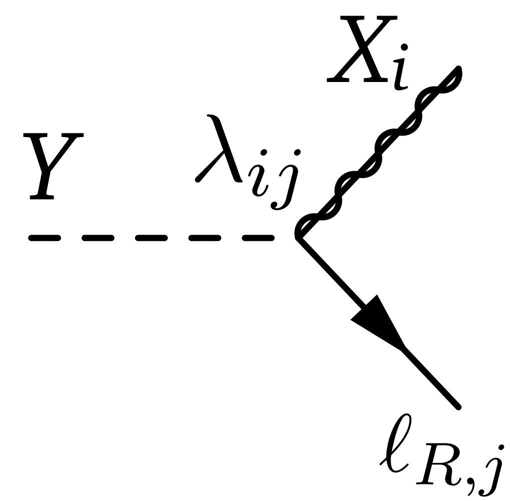
Disappearing tracks

$10\,{\rm cm} \lesssim c\tau_Y \lesssim 1\,{\rm m}$

Link to baryogenesis

Link to baryogenesis

Charged mediator | Dark Matter Multiplet

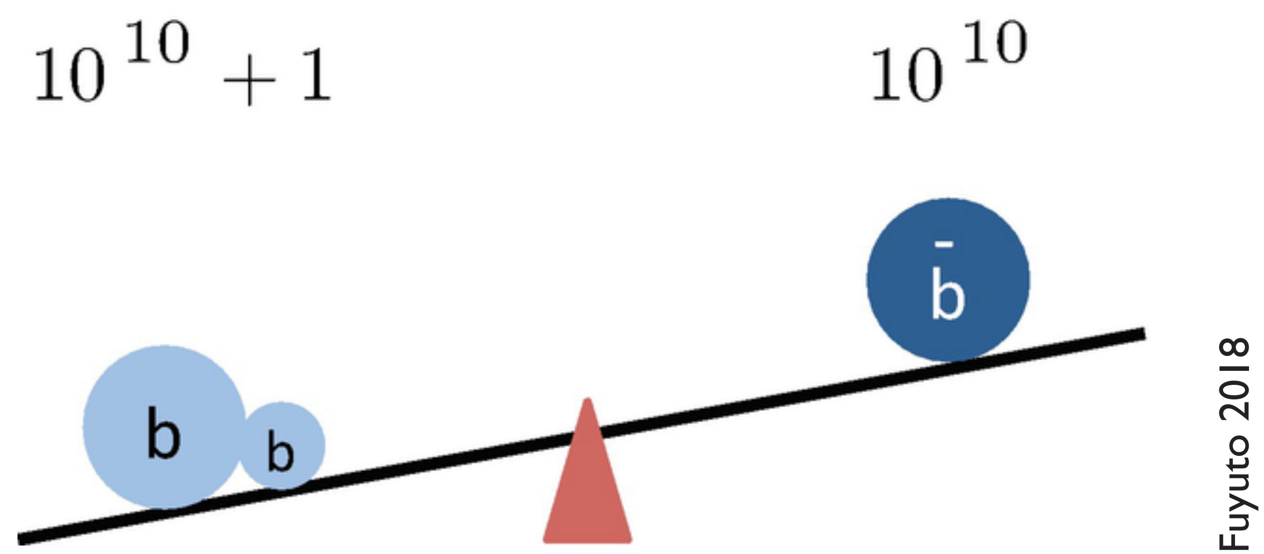


Motivation:

Simultaneously explain dark matter and baryon asymmetry via *conversion-driven leptogenesis*

[JH 2404.12428]

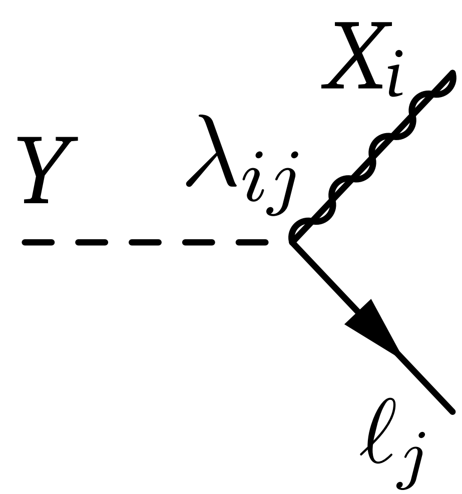
Baryon asymmetry



Sakharov conditions:

- *C*/*CP*-violation
- Baryon number violation
- Out-of-equilibrium processes

New source of *CP*-violation



$\lambda \sim 10^{-6}$: large *CP*-phases allowed

Not challenged by constraints from charge lepton flavor violation and EDMs

Baryon number violation

In SM, sphaleron processes violate B by washing out $B + L$

$B - L$ effectively conserved at TeV scale

Used in leptogenesis: break $L \Rightarrow \Delta L \to \Delta B$

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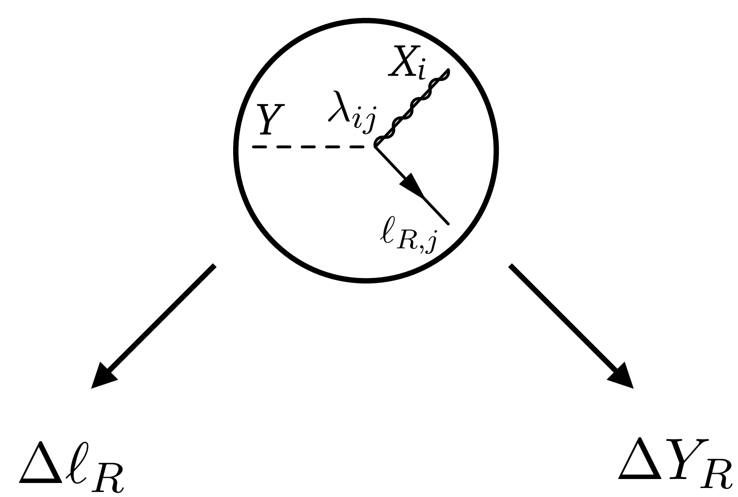
Conversion-driven leptogenesis w/o need to break L



$$\Delta\ell_{R,j} = -\Delta Y_R$$

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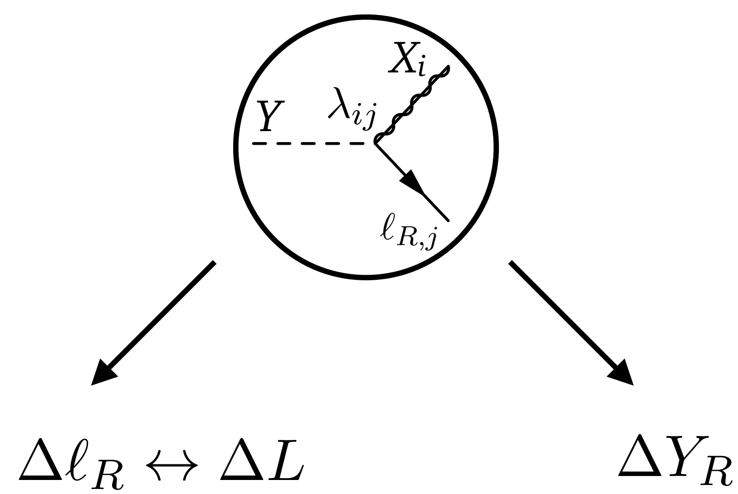

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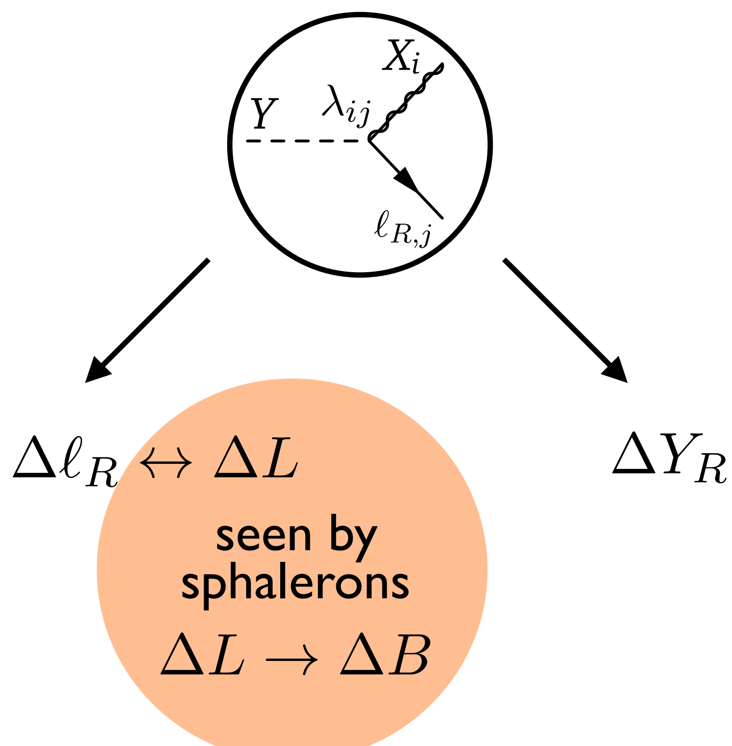

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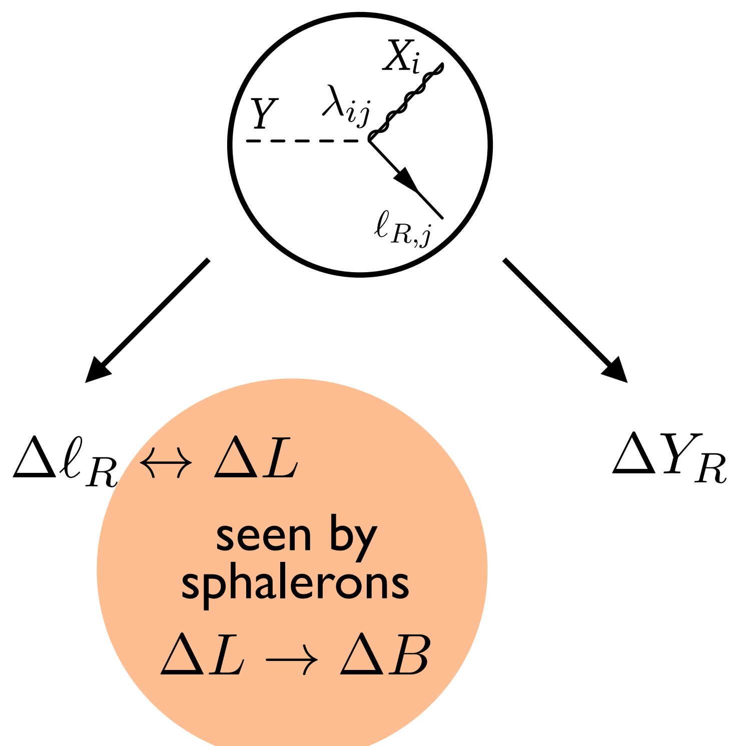
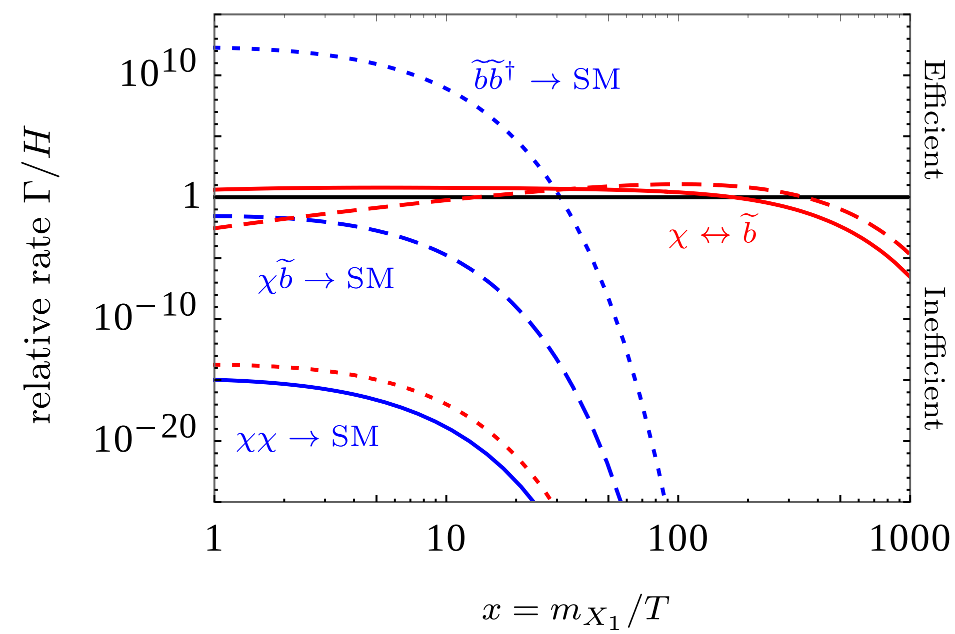
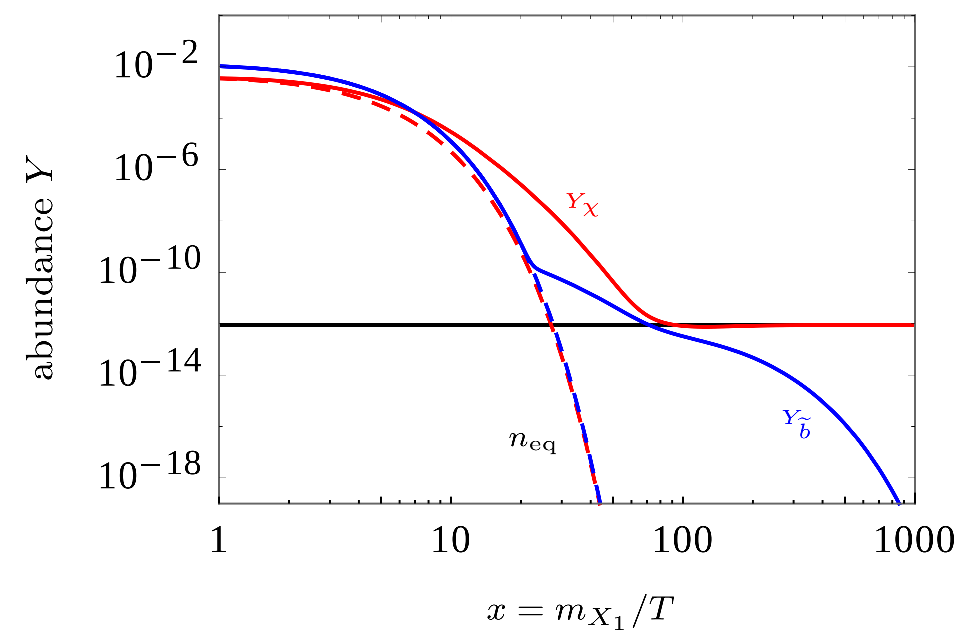


Similar to Dirac leptogenesis
[Dick, Lindner, Ratz, Wright, 2000]

Out-of-equilibrium processes

Conversion rates: shallower in *1/T* than annihilations, early departure from equilibrium





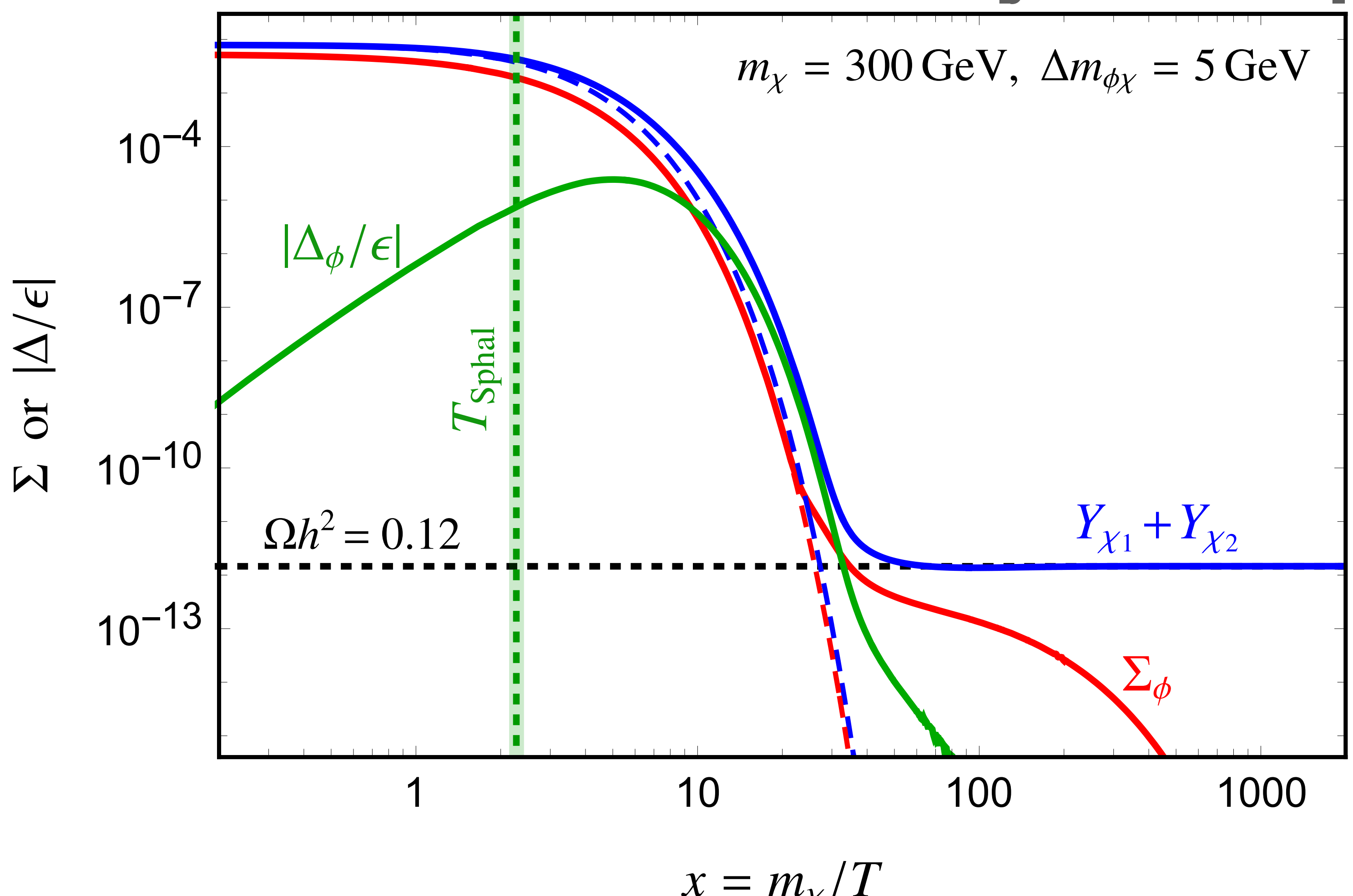
abundances still large ⇒ sizeable asymmetries!

(Source term of Δ_Y) $\propto \left(Y_Y - Y_Y^{\rm eq} \frac{Y_{\chi_i}}{Y_{\chi_i}^{\rm eq}} \right)$

Abundances and asymmetry

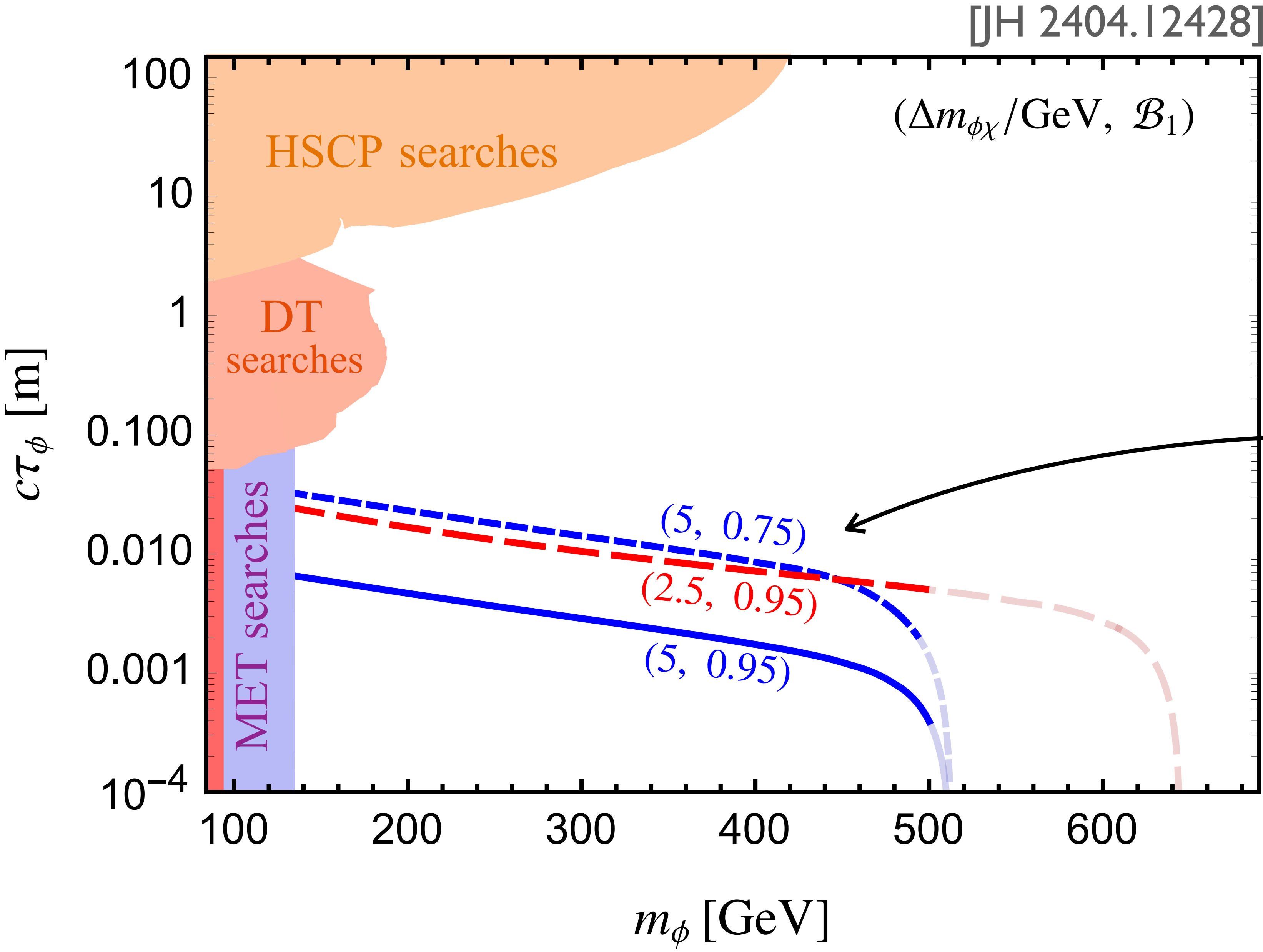
Viable parameter point yielding $\Omega h^2 = 0.12$, $Y_{\Delta B} = 0.9 \times 10^{-10}$
for quasi mass-degenerate X_i

[JH 2404.12428]



[CP-asymmetry in resonant scenario: Hambye, Teresi 2016;
Frossard, Garny, Hohenegger, Kartavtsev, Mitrouskas 2013

Testability at colliders



Parameter slices yielding:

$\Omega h^2 = 0.12$

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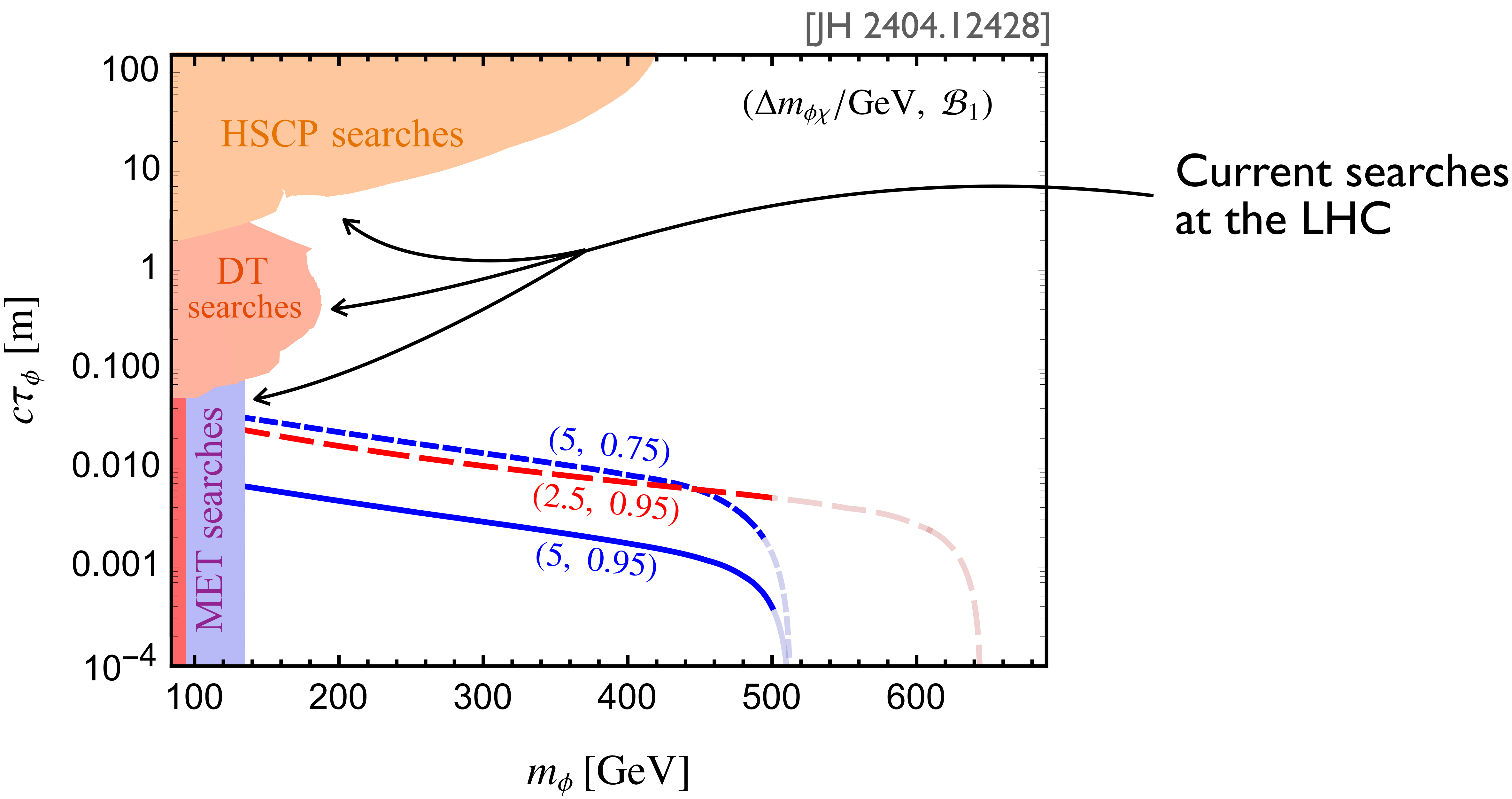

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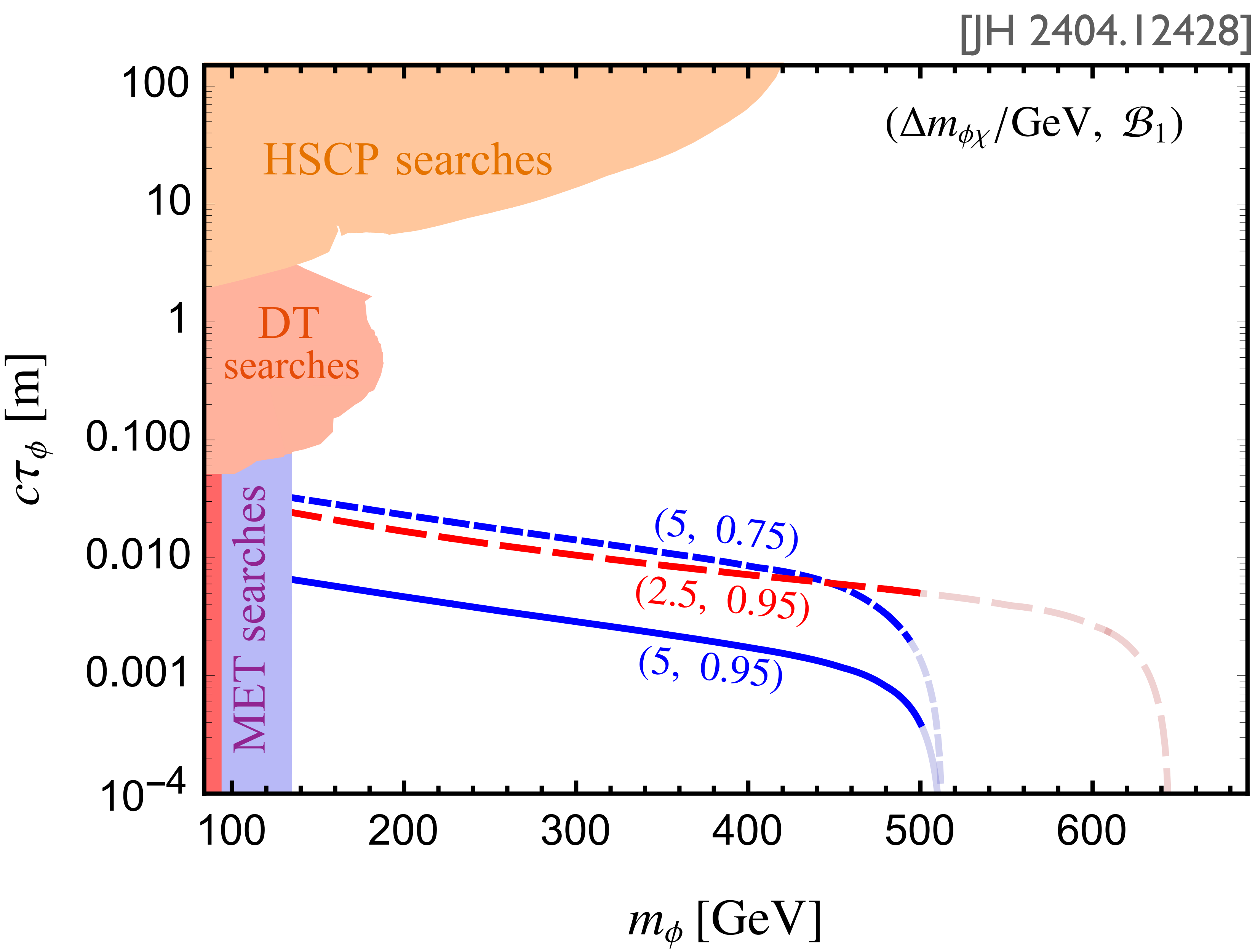


Displaced leptons?

$p_{\mathrm{T}} > 65\,\mathrm{GeV}$

[ATLAS 2011.07812]

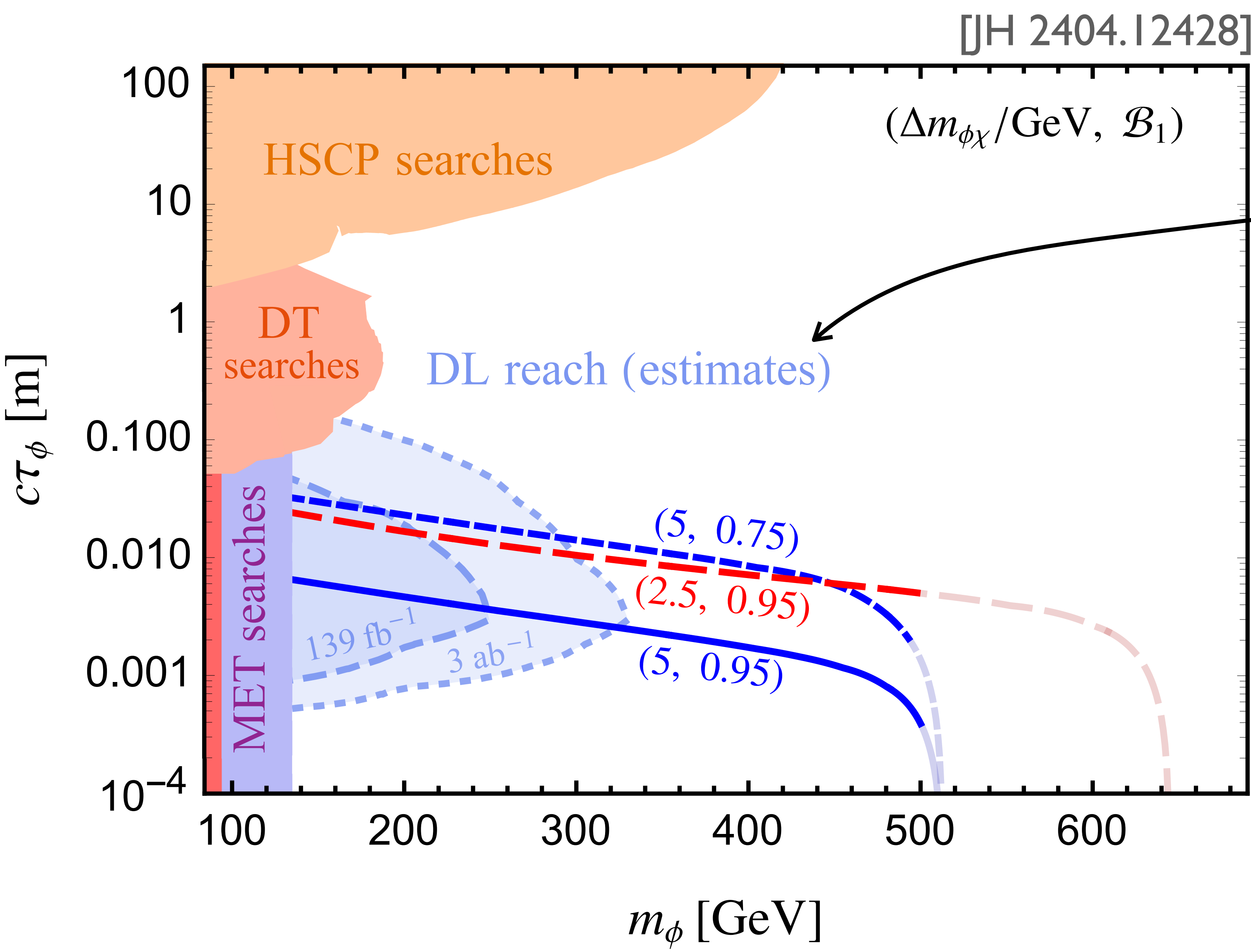
or dileptons with

$p_{\mathrm{T}} > 20\,\mathrm{GeV}$,

$m_{\mathrm{inv}} > 200\,\mathrm{GeV}$

[ATLAS 2305.02005]

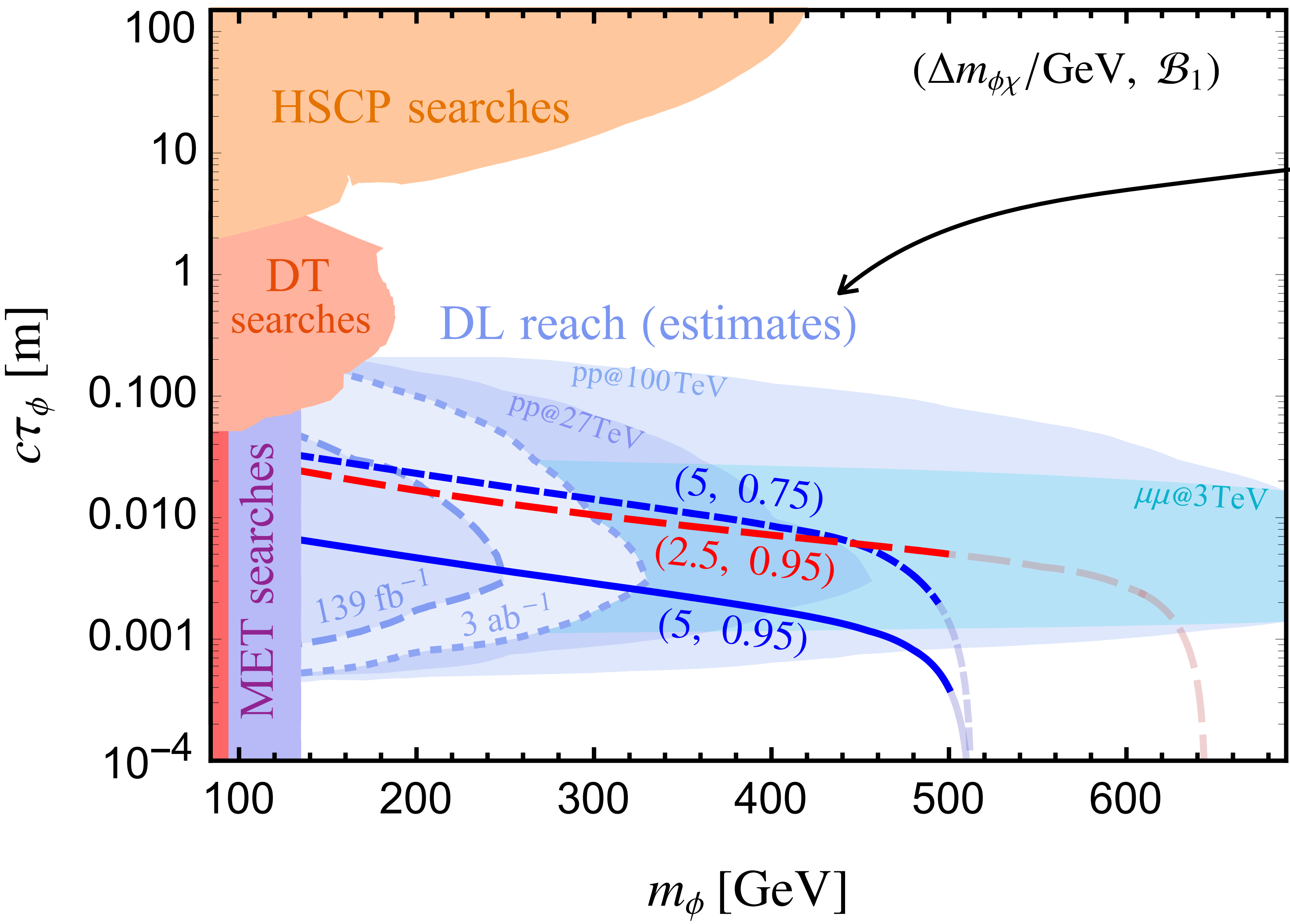
Testability at colliders



Assuming similar background reduction with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ but exploiting MET (maybe timing?)

Testability at colliders

[JH 2404.12428]



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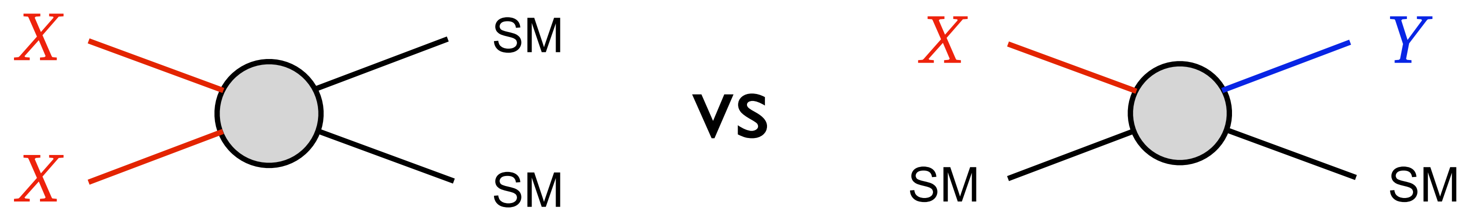
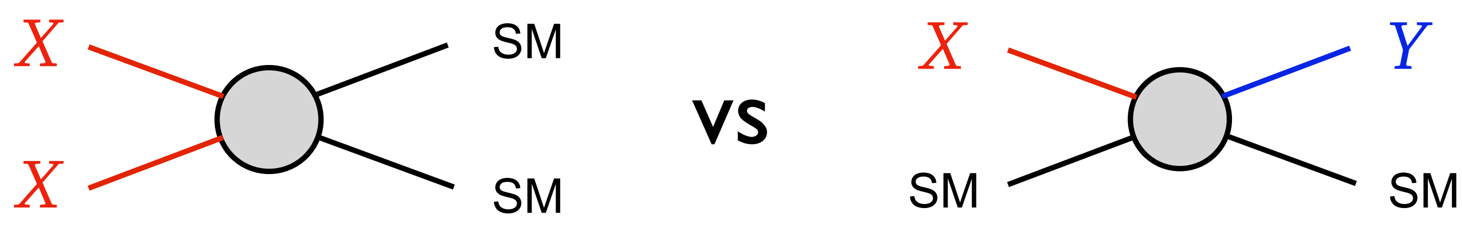
Conclusion



- Conversion-driven freeze-out viable scenario, $\lambda \sim 10^{-6}$
- Evade WIMP constraints, but still thermalize

Conclusion



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  - accessible parameter space
  - soft displaced objects not well covered yet

  $\Rightarrow$ prime target for future investigations

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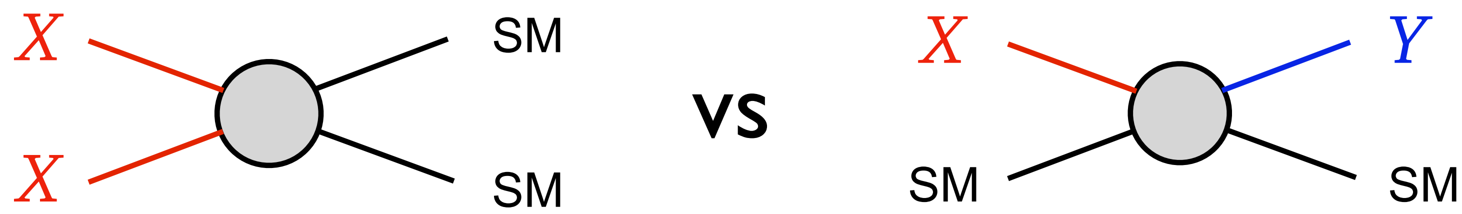

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  $\Rightarrow$ prime target for future investigations

- Conversion-driven leptogenesis:
  - asymmetry in mediator abundance hidden
  - early out-of-equilibrium provides large asymmetries
  - testable at colliders

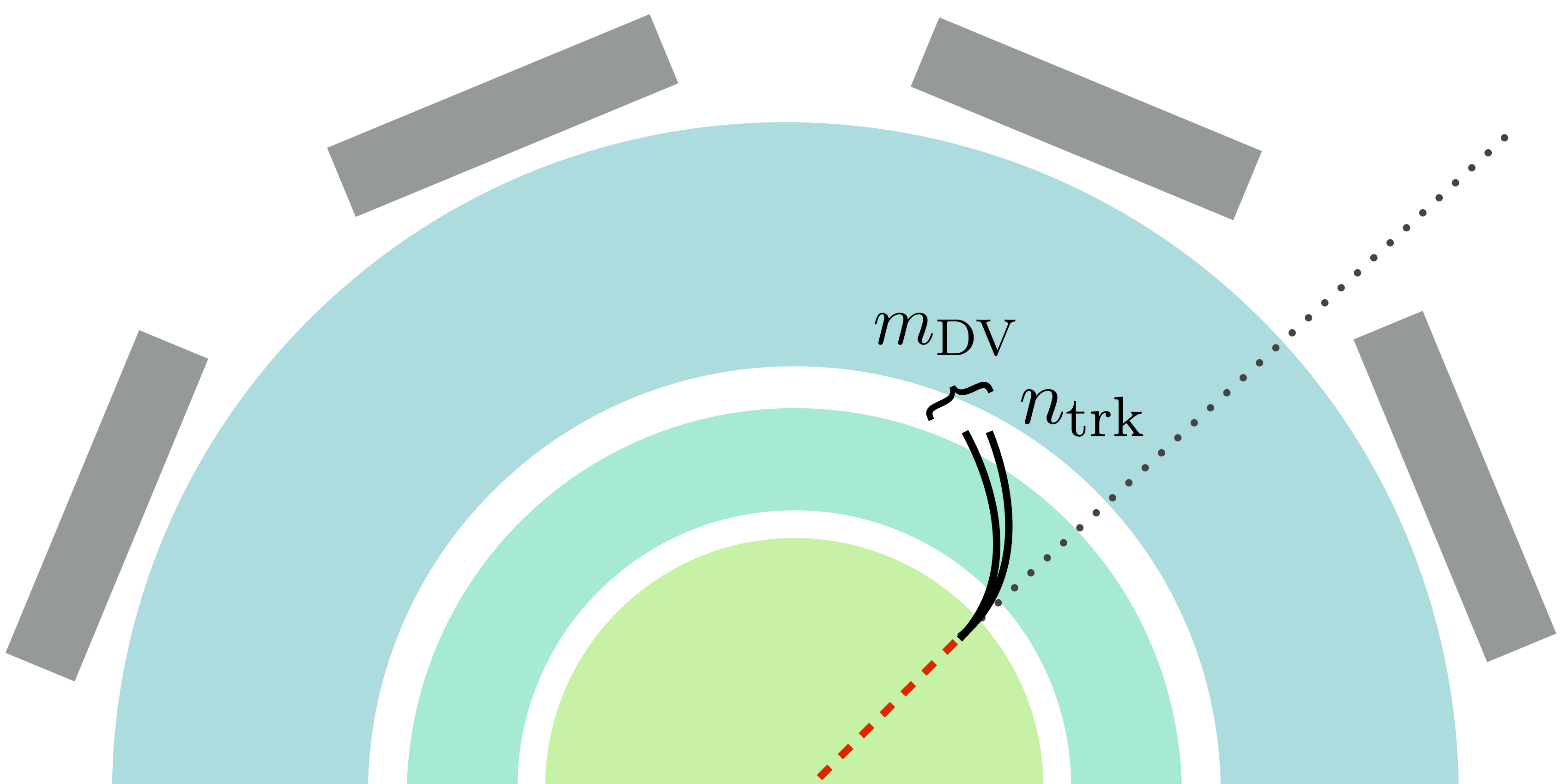
Backup slides

Potential of displaced vertices search

[ATLAS-SUSY-2016-08, 1710.04901]

Search requires:

- Number of displaced tracks: $n_{\mathrm{trk}} \geq 5$
- Invariant mass of displaced vertex: $m_{\mathrm{DV}} > 10\,\mathrm{GeV}$



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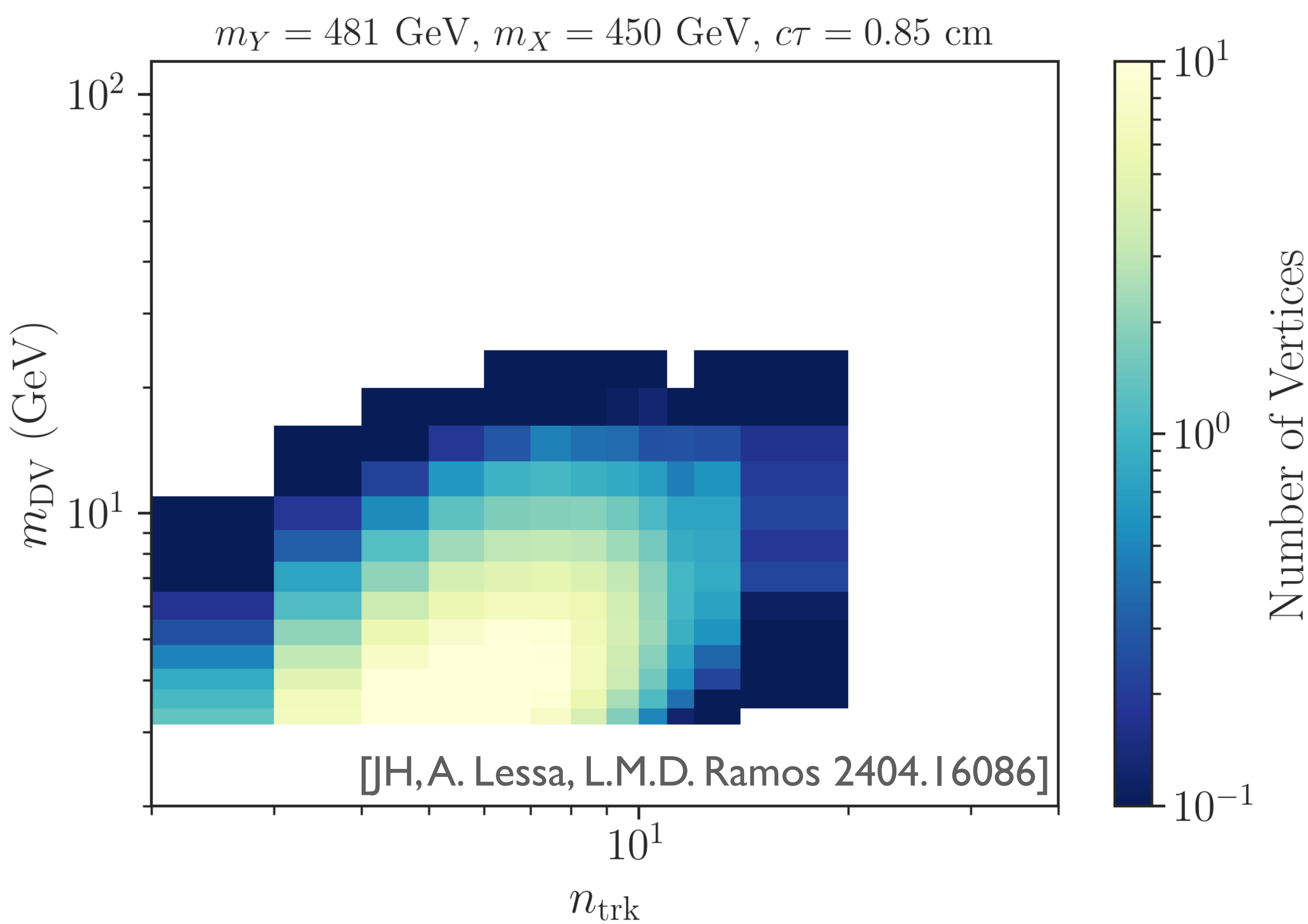

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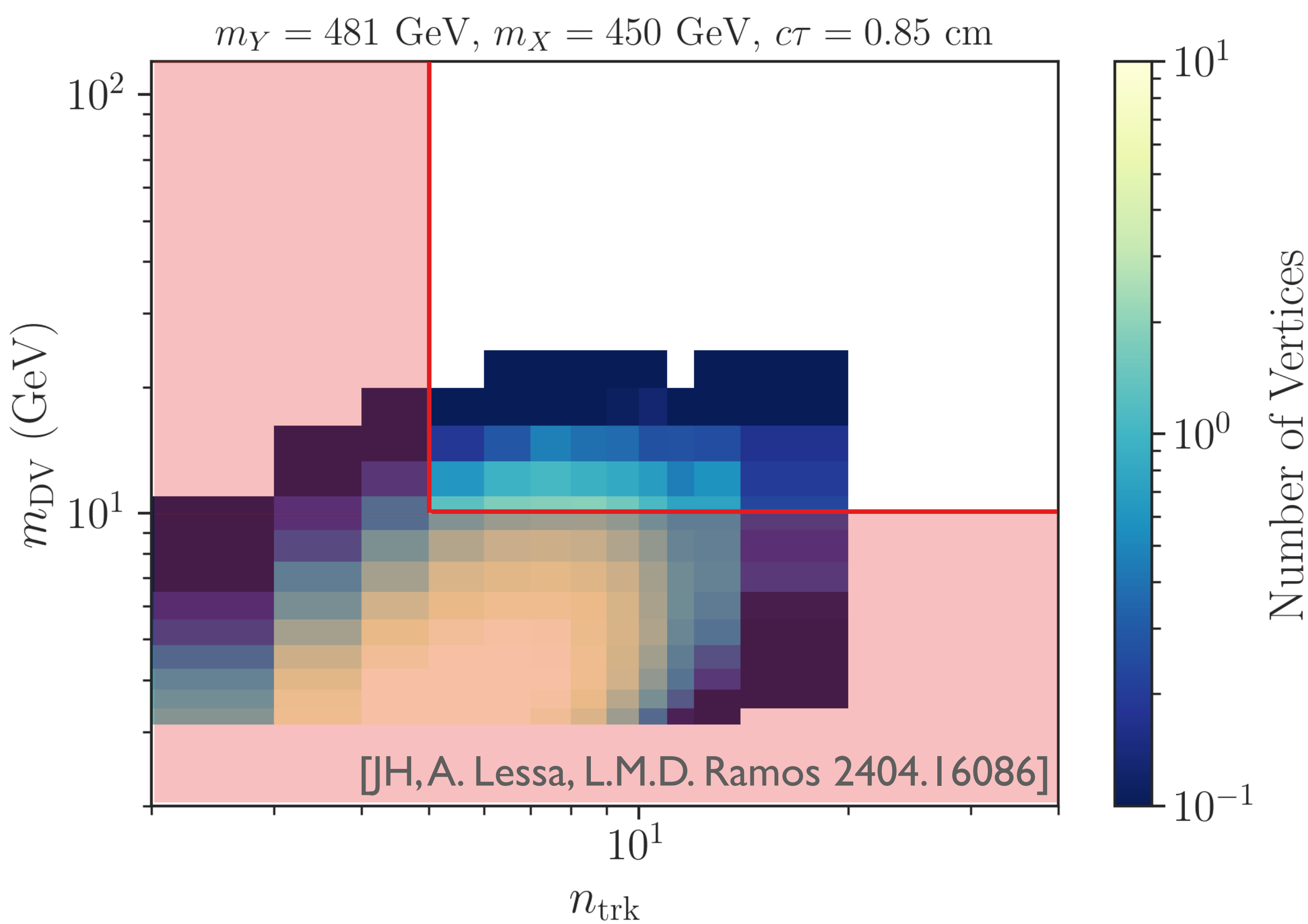

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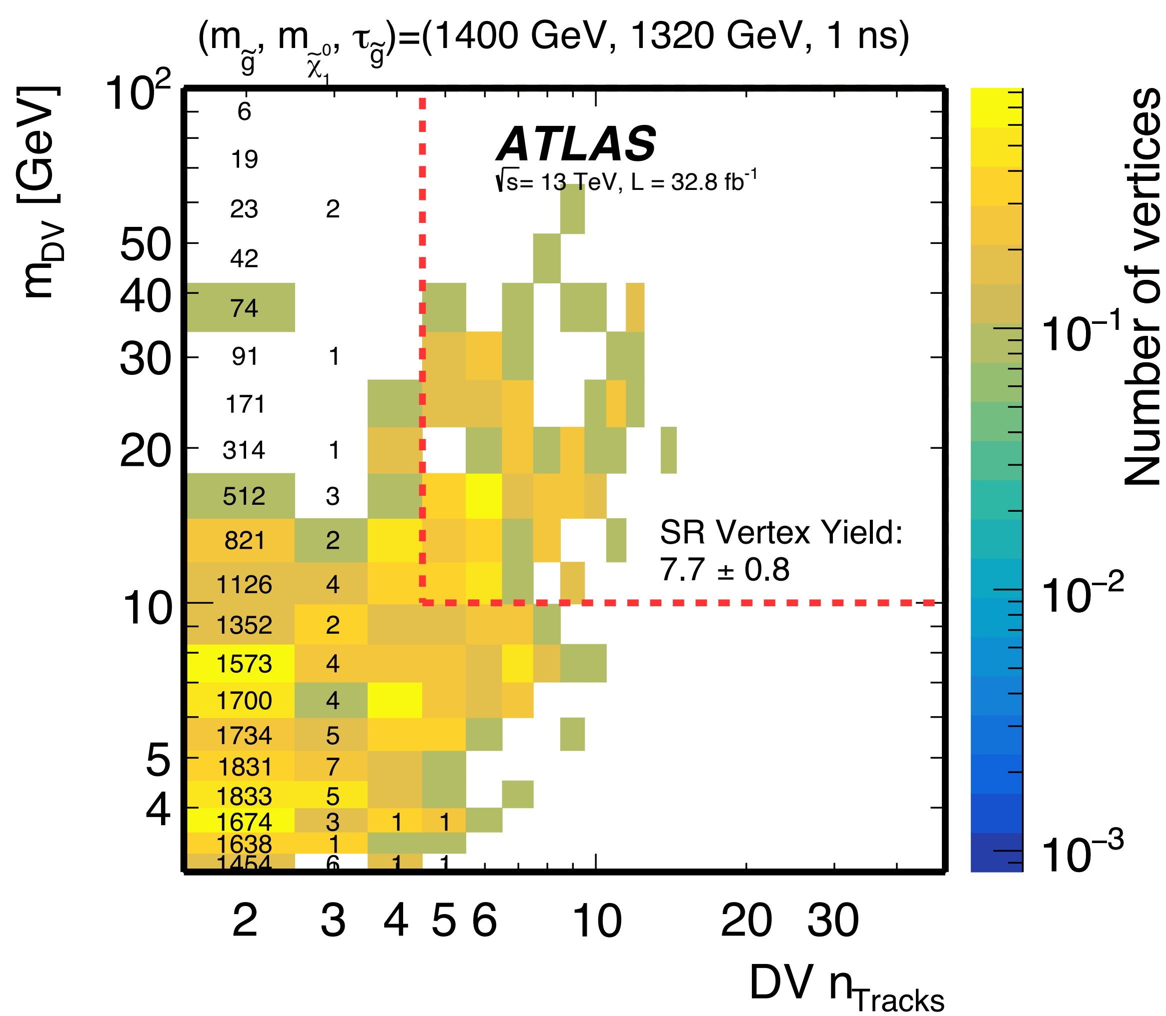

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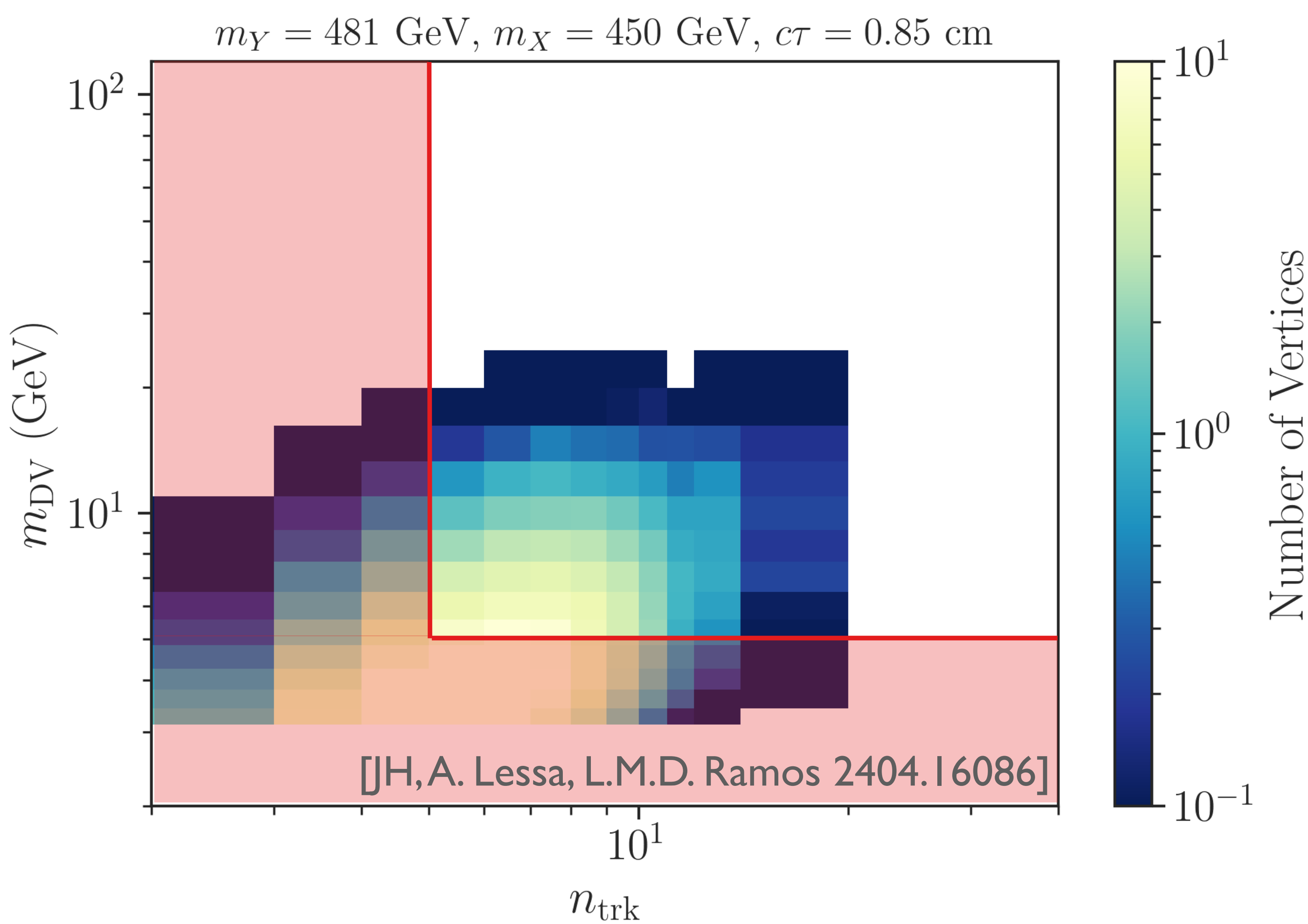
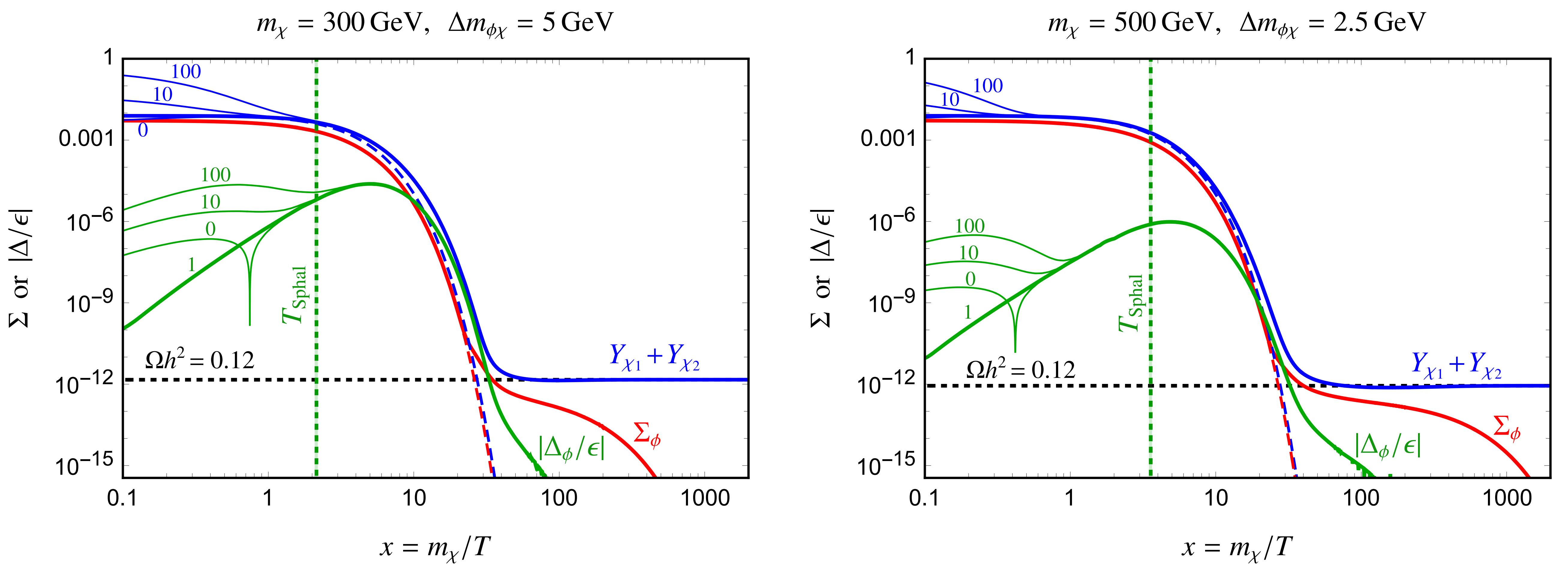
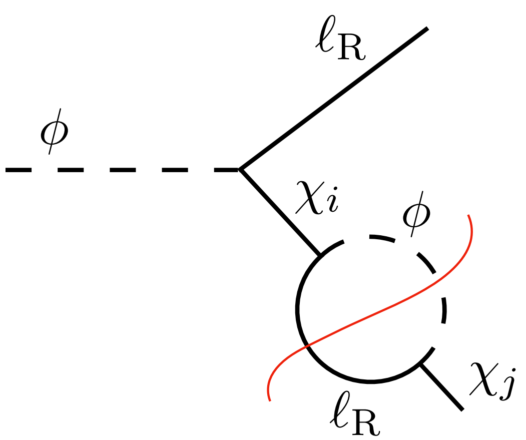
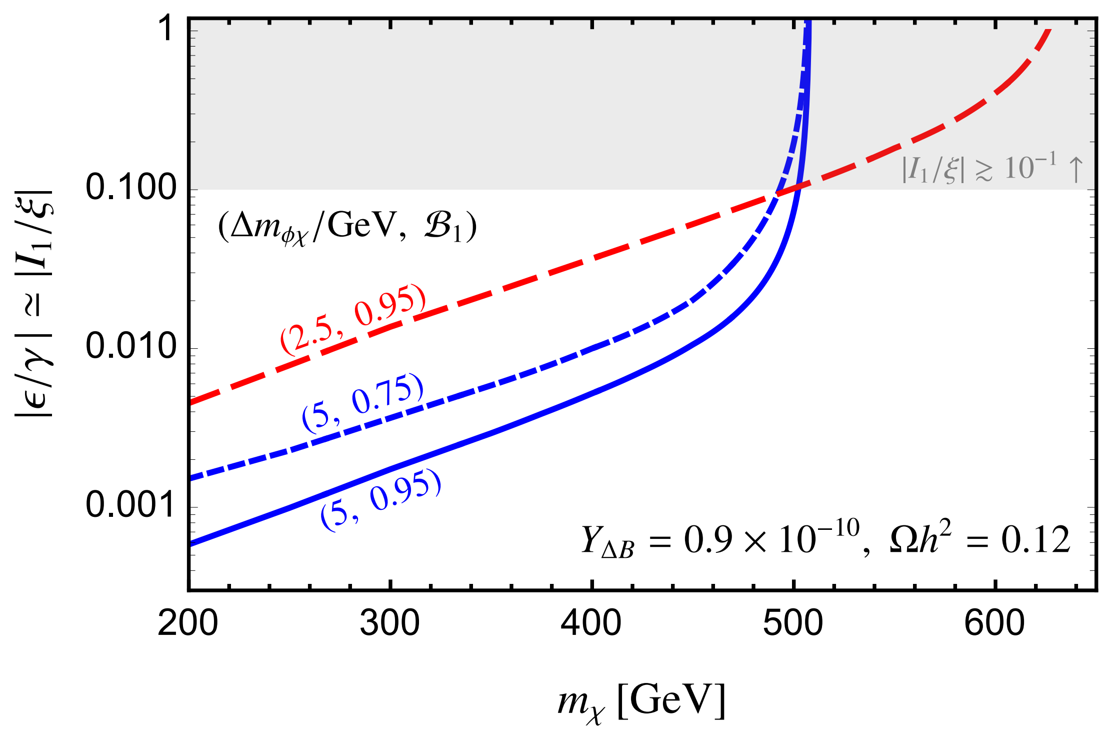


Dependence on initial conditions



CP-asymmetry

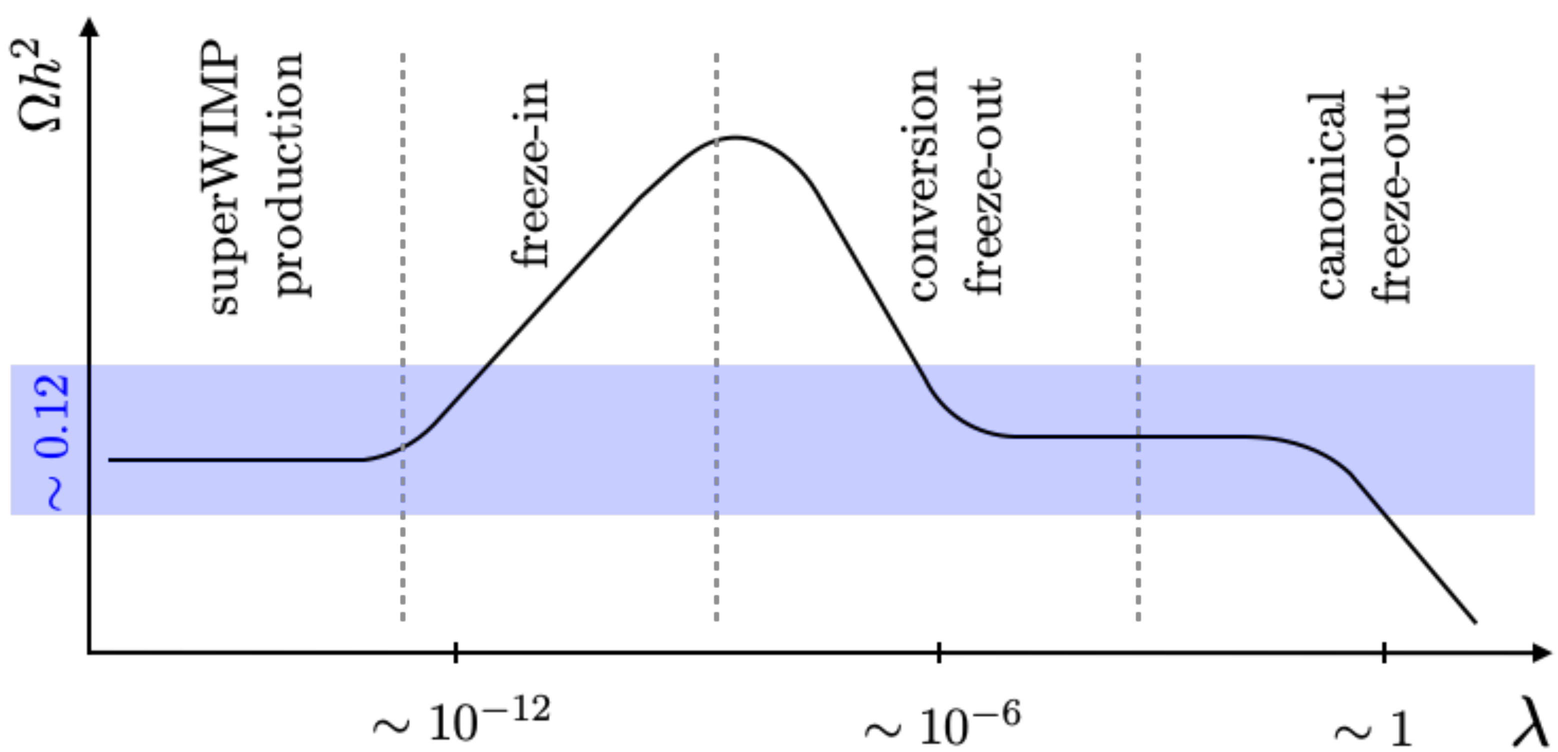




[CP-asymmetry in resonant scenario: Hambye, Teresi 2016; Frossard, Garny, Hohenegger, Kartavtsev, Mitrouskas 2013

$I_1 = \Im[(\lambda^\dagger\lambda)^2_{12}]/(|\lambda^\dagger\lambda|_{11}|\lambda^\dagger\lambda|_{22}),\ \xi = 2\Delta m_{12}/\Gamma^0_{\chi_2}$

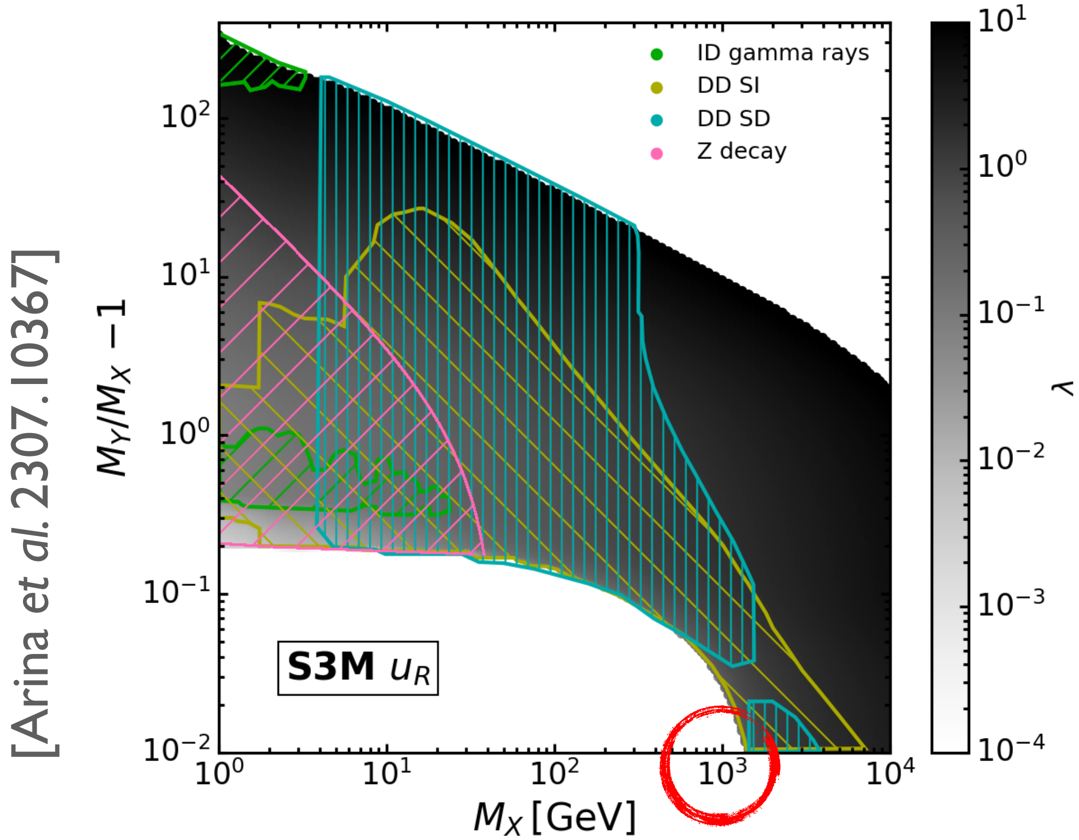
Cosmologically viable regions



Testability

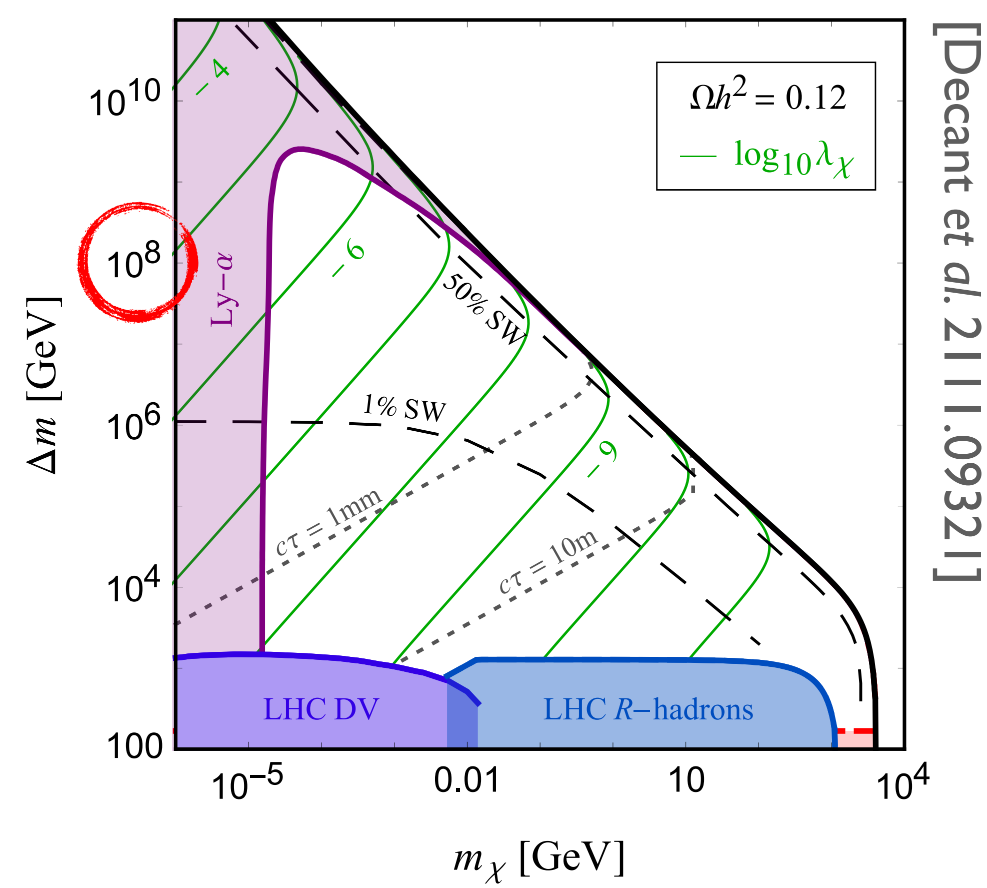
masses: few TeV
⇒ testable at colliders

Minimal t-channel models
thermalised DM:



masses up to 10^9 GeV
⇒ mostly out of reach

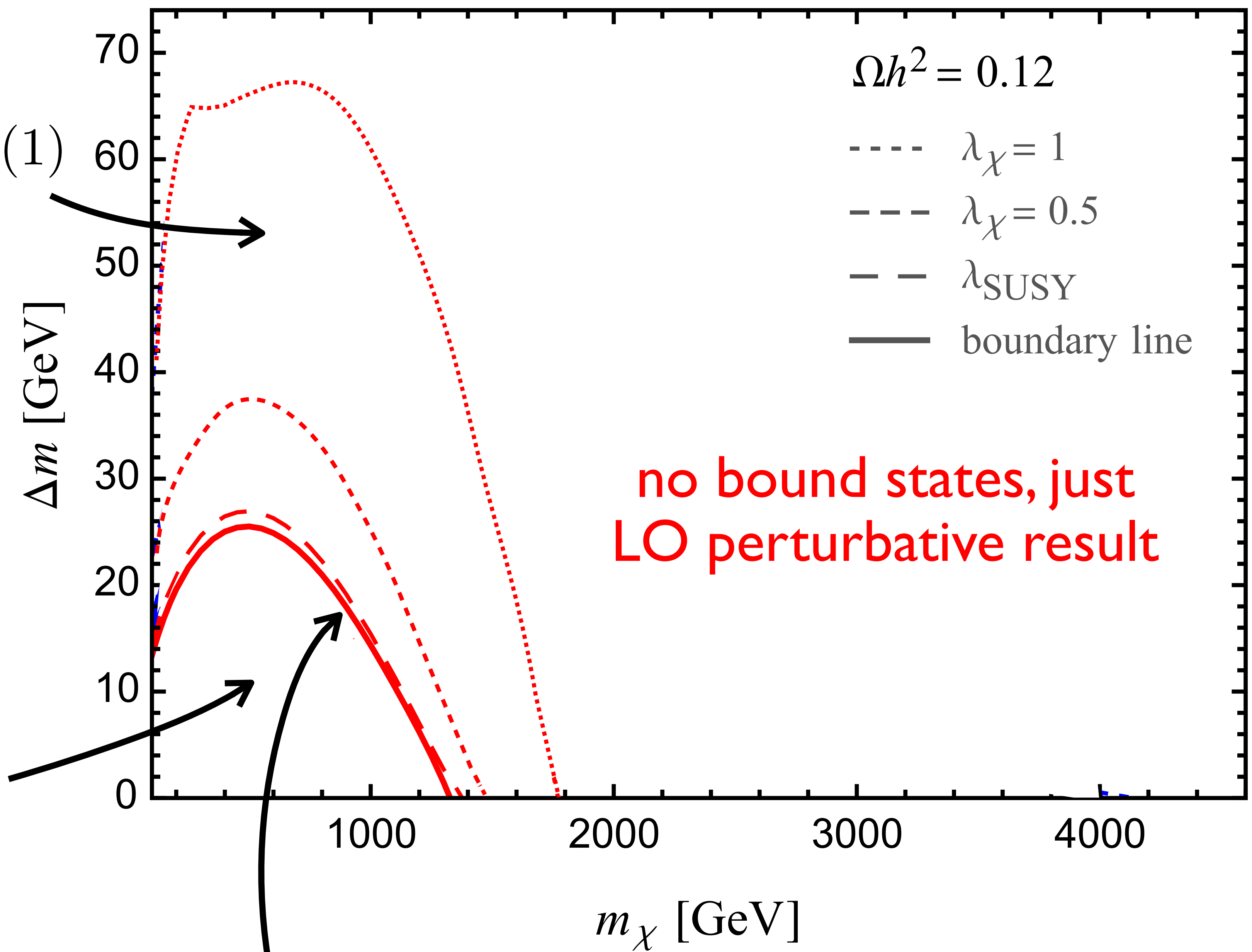
Minimal t-channel models
non-thermalised DM:



Bound state effects on the parameter space

[Garny, JH 2112.01499]

WIMP region $\lambda_\chi \sim \mathcal{O}(1)$



Conversion-driven freeze-out region, $\lambda_\chi \sim 10^{-6}$

Boundary, λ_χ drops from $\mathcal{O}(1)$ to $\sim 10^{-6}$

Bound state effects on the parameter space

[Garny, JH 2112.01499]

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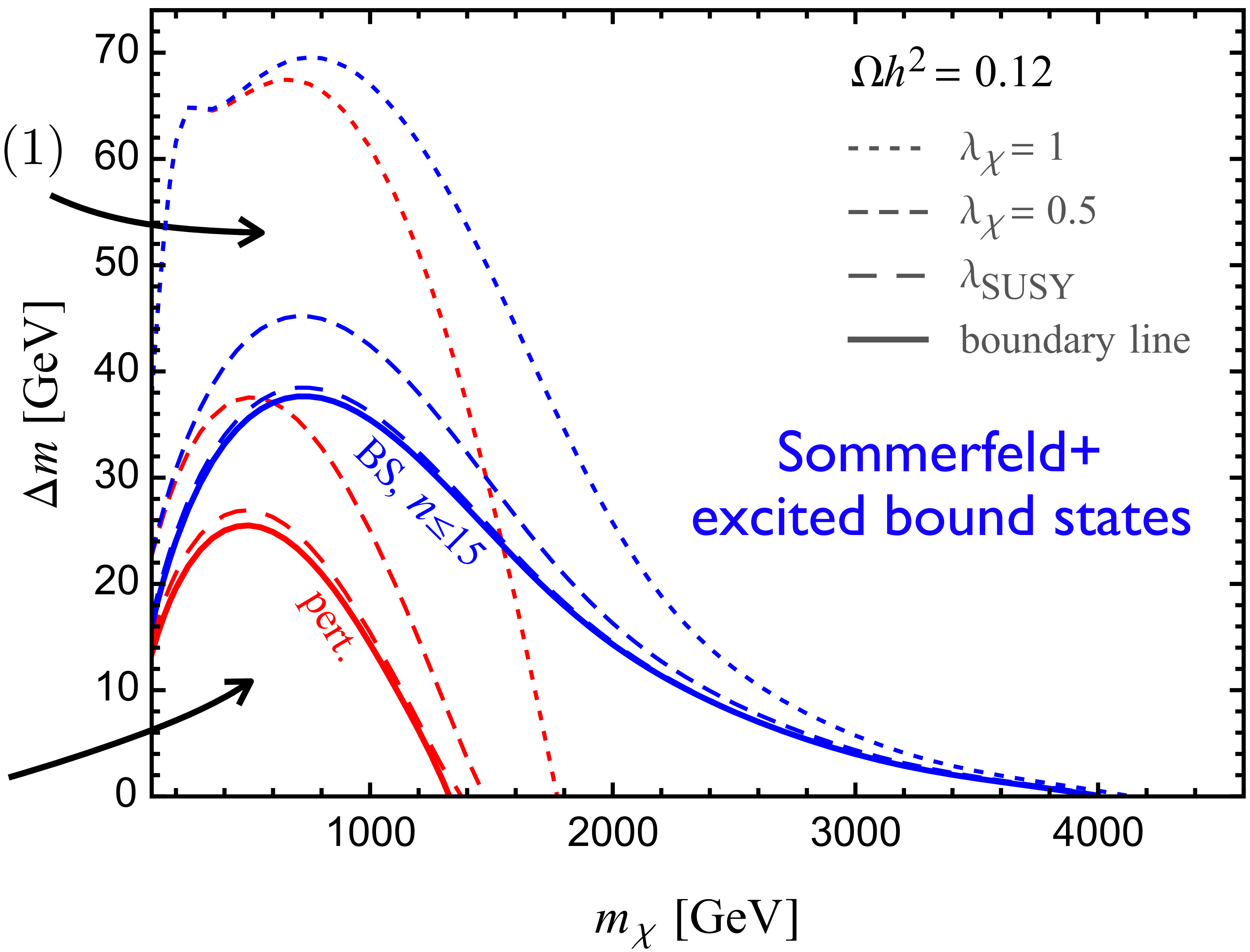


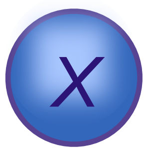
Conversion-driven freeze-out region, $\lambda_\chi \sim 10^{-6}$

here: no transition limit

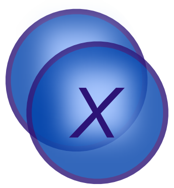
Boltzmann equations with excitations

[Binder Filimonova, Petraki, White 2112.00042; Garny, JH 2112.01499]

X pair-annihilation (hard process+Sommerfeld) — Bound state formation



$$: \quad \frac{\mathrm{d}Y_X}{\mathrm{d}x} = \frac{1}{3Hs}\frac{\mathrm{d}s}{\mathrm{d}x}\left[\frac{1}{2}\langle\sigma_{XX^\dagger}v\rangle\left(Y_X^2 - Y_X^{\mathrm{eq}\,2}\right) + \sum_i \frac{1}{2}\langle\sigma_{\mathrm{BSF},i}v\rangle\left(Y_X^2 - Y_X^{\mathrm{eq}\,2}\frac{Y_{\mathcal{B}_i}}{Y_{\mathcal{B}_i}^{\mathrm{eq}}}\right)\right]$$



$$: \quad \frac{\mathrm{d}Y_{\mathcal{B}_i}}{\mathrm{d}x} = \frac{1}{3Hs}\frac{\mathrm{d}s}{\mathrm{d}x}\left[\Gamma^i_{\mathrm{ion}}\left(Y_{\mathcal{B}_i} - Y_{\mathcal{B}_i}^{\mathrm{eq}}\frac{Y_X^2}{Y_X^{\mathrm{eq}\,2}}\right) + \Gamma^i_{\mathrm{dec}}\left(Y_{\mathcal{B}_i} - Y_{\mathcal{B}_i}^{\mathrm{eq}}\right) - \sum_{j\neq i}\Gamma^{j\to i}_{\mathrm{trans}}\left(Y_{\mathcal{B}_j} - Y_{\mathcal{B}_i}\frac{Y_{\mathcal{B}_j}^{\mathrm{eq}}}{Y_{\mathcal{B}_i}^{\mathrm{eq}}}\right)\right]$$

$=0$ (left-hand side crossed out)

Ionization — Decay — Bound-to-bound transition

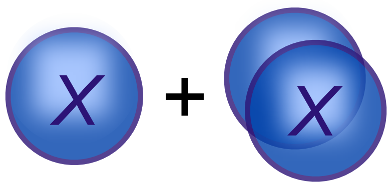
steady-state

Solve for $Y_{\mathcal{B}_i}$ algebraically → system of linear equations

[*cf.* Ellis, Luo, Olive 1503.07142;
Mitridate, Redi, Smirnov, Strumia 1702.01141]

Boltzmann equations with excitations

[Binder Filimonova, Petraki, White 2112.00042; Garny, JH 2112.01499]



: $$\frac{\mathrm{d}Y_X}{\mathrm{d}x} = \frac{1}{3Hs}\frac{\mathrm{d}s}{\mathrm{d}x}\,\frac{1}{2}\langle\sigma_{XX^\dagger}v\rangle_{\rm eff}\left(Y_X^2 - Y_X^{\mathrm{eq}\,2}\right)$$

$$\langle\sigma_{XX^\dagger}v\rangle_{\rm eff} = \langle\sigma_{XX^\dagger}v\rangle + \sum_i \langle\sigma_{\mathrm{BSF},i}v\rangle R_i\,, \quad 0 \le R_i \le 1$$

Contains all rates

[*cf.* Ellis, Luo, Olive 1503.07142;
Mitridate, Redi, Smirnov, Strumia 1702.01141]

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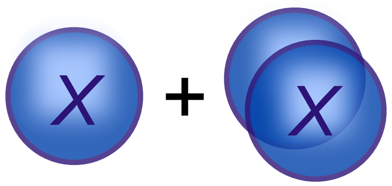


:

$$\frac{\mathrm{d}Y_X}{\mathrm{d}x} = \frac{1}{3Hs}\frac{\mathrm{d}s}{\mathrm{d}x}\frac{1}{2}\langle \sigma_{XX^\dagger} v\rangle_{\mathrm{eff}}\left(Y_X^2 - Y_X^{\mathrm{eq}\,2}\right)$$

$$\langle \sigma_{XX^\dagger} v\rangle_{\mathrm{eff}} = \langle \sigma_{XX^\dagger} v\rangle + \sum_i \langle \sigma_{\mathrm{BSF},i} v\rangle R_i\,, \quad 0 \leq R_i \leq 1$$

No transition limit:

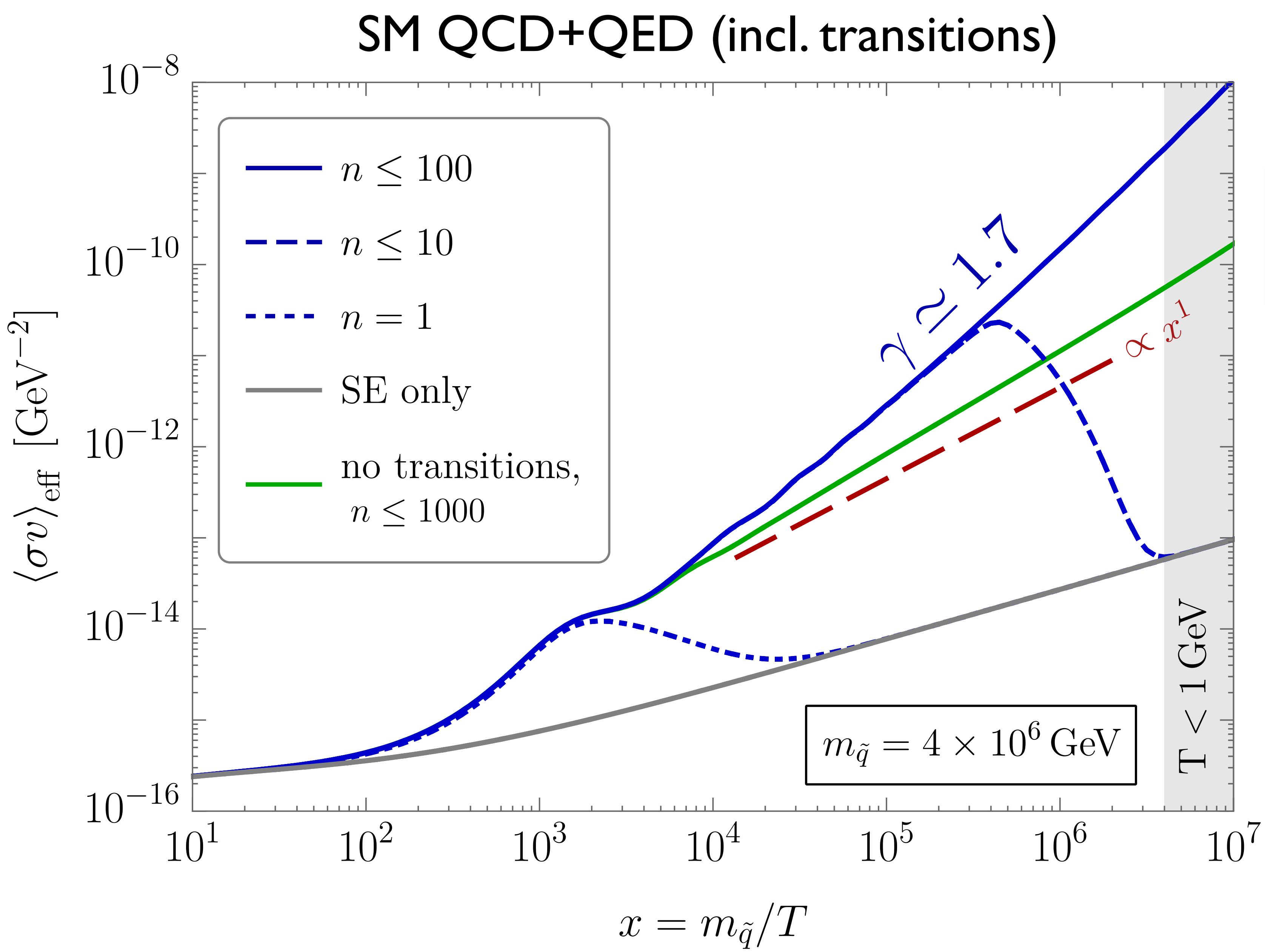
$$\langle \sigma_{XX^\dagger} v\rangle_{\mathrm{eff}} = \langle \sigma_{XX^\dagger} v\rangle + \sum_i \underbrace{\langle \sigma_{\mathrm{BSF},i} v\rangle \frac{\Gamma^i_{\mathrm{dec}}}{\Gamma^i_{\mathrm{ion}} + \Gamma^i_{\mathrm{dec}}}}$$

$$\Gamma^i_{\mathrm{ion}} \gg \Gamma^i_{\mathrm{dec}}: \qquad \propto \mathrm{e}^{E_{\mathcal{B}_i}/T}\,\Gamma^i_{\mathrm{dec}}$$

[*cf.* Ellis, Luo, Olive 1503.07142;
Mitridate, Redi, Smirnov, Strumia 1702.01141]

Effective annihilation cross section

[Binder, Garny, JH, Lederer, Urban 2308.01336]



$$\langle \sigma v \rangle_{\rm eff} \propto x^{\gamma}$$