When Annihilation Takes a Back Seat: Conversion-Driven Freeze-Out

Jan Heisig
RWTH Aachen University

DISCRETE 2026 · Bratislava · November 2026

DISCRETE 2026
November 12-18, 2026, Comenius University Bratislava



Dark matter

Baryon asymmetry

[Garny, JH+1705.09292
D'Agnolo+1705.08450]

[JH 2404.12428
Belfatto, JH+2607.11147]

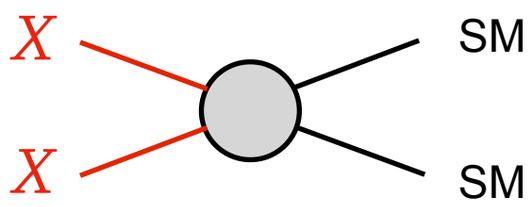
Conversion-driven freeze-out
(aka coscattering)

[Heeck, JH+2211.13013]

Neutrino masses

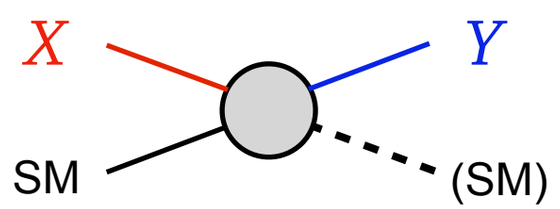
What is conversion-driven freeze-out?

annihilation



vs

conversion



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

when particles X,Y become non-relativistic:

Boltzmann suppressed

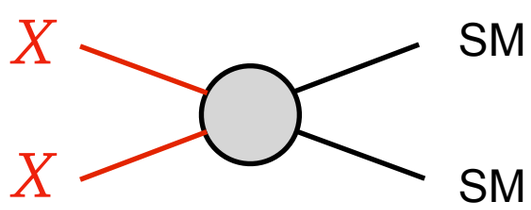
$\mathrm{e}^{-m_X/T_{\rm fo}} \sim 10^{-12}$

No suppression

$\Rightarrow \langle \sigma v \rangle_{\rm con}$ could be tiny

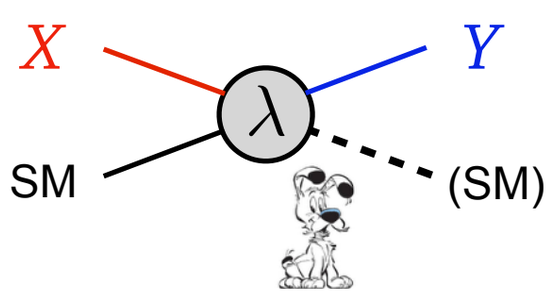
What is conversion-driven freeze-out?

annihilation



vs

conversion



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

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

when particles X,Y become non-relativistic:

Boltzmann suppressed

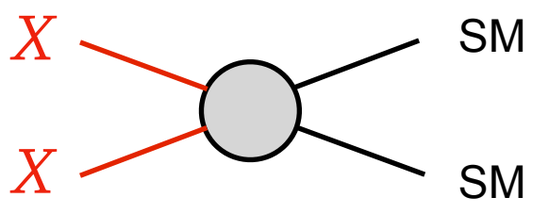
$$e^{-m_X/T_{\rm fo}} \sim 10^{-12}$$

No suppression

$\Rightarrow \langle \sigma v \rangle_{\rm con}$ could be tiny 

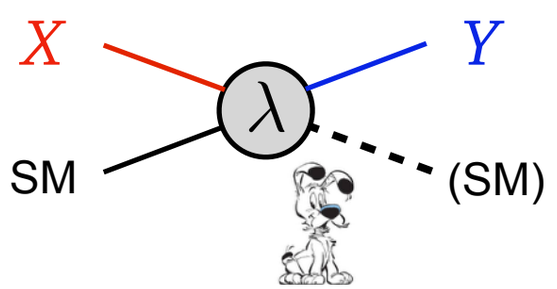
What is conversion-driven freeze-out?

annihilation



vs

conversion



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

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

when particles X,Y become non-relativistic:

Boltzmann suppressed

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

No suppression

$\Rightarrow \langle \sigma v \rangle_{\rm con}$ could be tiny 

Interesting, distinct phenomenology!

Why was this only studied in 2017?

Neutralino Relic Density including Coannihilations

Joakim Edsjö*

Department of Theoretical Physics, Uppsala University
Box 803, SE-751 08 Uppsala, Sweden

Paolo Gondolo†

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)
Föhringer Ring 6, 80805 München, Germany

hep-ph/9704361

$$\begin{aligned}\frac{dn_i}{dt} &= -3Hn_i - \sum_{j=1}^{N}\langle\sigma_{ij}v_{ij}\rangle\left(n_in_j - n_i^{\rm eq}n_j^{\rm eq}\right)\\ &\quad -\sum_{j\neq i}\left[\langle\sigma'_{Xij}v_{ij}\rangle\left(n_in_X - n_i^{\rm eq}n_X^{\rm eq}\right) - \langle\sigma'_{Xji}v_{ij}\rangle\left(n_jn_X - n_j^{\rm eq}n_X^{\rm eq}\right)\right]\\ &\quad -\sum_{j\neq i}\left[\Gamma_{ij}\left(n_i - n_i^{\rm eq}\right) - \Gamma_{ji}\left(n_j - n_j^{\rm eq}\right)\right].\end{aligned}$$

Why was this only studied in 2017?

hep-ph/9704361

Neutralino Relic Density including Coannihilations

Joakim Edsjö*
Department of Theoretical Physics, Uppsala University
Box 803, SE-751 08 Uppsala, Sweden

Paolo Gondolo†
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)
Föhringer Ring 6, 80805 München, Germany

$$\frac{dn_i}{dt} = -3Hn_i - \sum_{j=1}^{N} \langle \sigma_{ij} v_{ij} \rangle \left(n_i n_j - n_i^{\rm eq} n_j^{\rm eq} \right)$$

annihilations

$$- \sum_{j \neq i} \left[\langle \sigma'_{Xij} v_{ij} \rangle \left(n_i n_X - n_i^{\rm eq} n_X^{\rm eq} \right) - \langle \sigma'_{Xji} v_{ij} \rangle \left(n_j n_X - n_j^{\rm eq} n_X^{\rm eq} \right) \right]$$

$$- \sum_{j \neq i} \left[\Gamma_{ij} \left(n_i - n_i^{\rm eq} \right) - \Gamma_{ji} \left(n_j - n_j^{\rm eq} \right) \right].$$

Why was this only studied in 2017?

Neutralino Relic Density including Coannihilations

Joakim Edsjö*
Department of Theoretical Physics, Uppsala University
Box 803, SE-751 08 Uppsala, Sweden

Paolo Gondolo†
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)
Föhringer Ring 6, 80805 München, Germany

hep-ph/9704361

$$\frac{dn_i}{dt} = -3Hn_i - \sum_{j=1}^{N} \langle \sigma_{ij} v_{ij} \rangle \left(n_i n_j - n_i^{\rm eq} n_j^{\rm eq} \right)$$

annihilations

$$- \sum_{j \neq i} \left[\langle \sigma'_{Xij} v_{ij} \rangle \left(n_i n_X - n_i^{\rm eq} n_X^{\rm eq} \right) - \langle \sigma'_{Xji} v_{ij} \rangle \left(n_j n_X - n_j^{\rm eq} n_X^{\rm eq} \right) \right]$$

$$- \sum_{j \neq i} \left[\Gamma_{ij} \left(n_i - n_i^{\rm eq} \right) - \Gamma_{ji} \left(n_j - n_j^{\rm eq} \right) \right].$$

conversions

Why was this only studied in 2017?

Neutralino Relic Density including Coannihilations

Joakim Edsjö*
Department of Theoretical Physics, Uppsala University
Box 803, SE-751 08 Uppsala, Sweden

Paolo Gondolo†
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)
Föhringer Ring 6, 80805 München, Germany

hep-ph/9704361

$$\frac{dn_i}{dt} = -3Hn_i - \sum_{j=1}^{N} \langle \sigma_{ij} v_{ij} \rangle \left(n_i n_j - n_i^{\rm eq} n_j^{\rm eq} \right)$$

annihilations

$$- \sum_{j \neq i} \left[\langle \sigma'_{Xij} v_{ij} \rangle \left(n_i n_X - n_i^{\rm eq} n_X^{\rm eq} \right) - \langle \sigma'_{Xji} v_{ij} \rangle \left(n_j n_X - n_j^{\rm eq} n_X^{\rm eq} \right) \right]$$

$$- \sum_{j \neq i} \left[\Gamma_{ij} \left(n_i - n_i^{\rm eq} \right) - \Gamma_{ji} \left(n_j - n_j^{\rm eq} \right) \right].$$

conversions

assuming conversions are fully efficient $\Gamma_{\rm con} \gg \Gamma_{\rm ann}$

[Honorable exceptions exist, e.g. Ellis+ 1503.07142]

Why was this only studied in 2017?

Neutralino Relic Density including Coannihilations

Joakim Edsjö*
Department of Theoretical Physics, Uppsala University
Box 803, SE-751 08 Uppsala, Sweden

Paolo Gondolo†
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)
Föhringer Ring 6, 80805 München, Germany

hep-ph/9704361

$$\frac{dn}{dt} = -3Hn - \langle\sigma_{\rm eff} v\rangle \left(n^2 - n_{\rm eq}^2\right)$$ annihilations

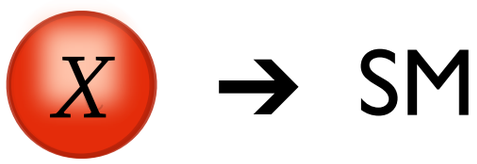
$$- \sum_{j\neq i} \left[\langle\sigma'_{Xij} v_{ij}\rangle \left(n_i n_X - n_i^{\rm eq} n_X^{\rm eq}\right) - \langle\sigma'_{Xji} v_{ij}\rangle \left(n_j n_X - n_j^{\rm eq} n_X^{\rm eq}\right)\right]$$

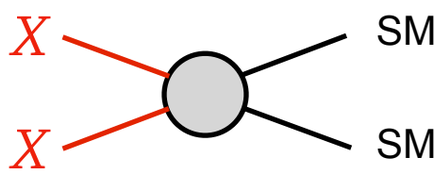
$$- \sum_{j\neq i} \left[\Gamma_{ij} \left(n_i - n_i^{\rm eq}\right) - \Gamma_{ji} \left(n_j - n_j^{\rm eq}\right)\right].$$ conversions

assuming conversions are fully efficient $\Gamma_{\rm con} \gg \Gamma_{\rm ann}$

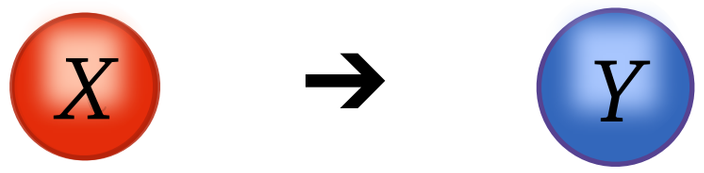
[Honorable exceptions exist, e.g. Ellis+ 1503.07142]

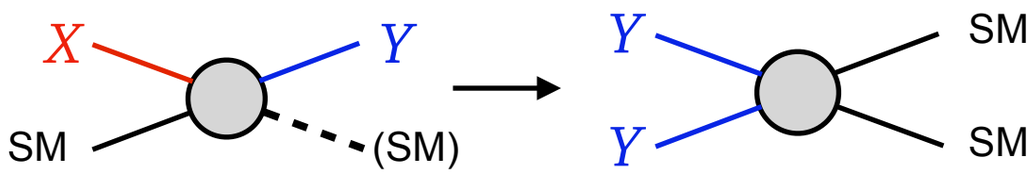
What does it look like?





...

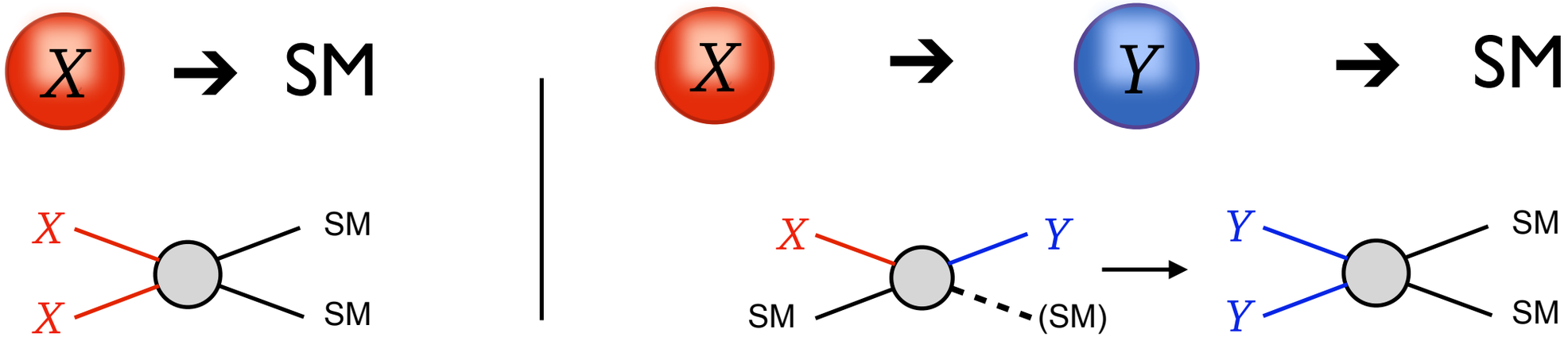




...

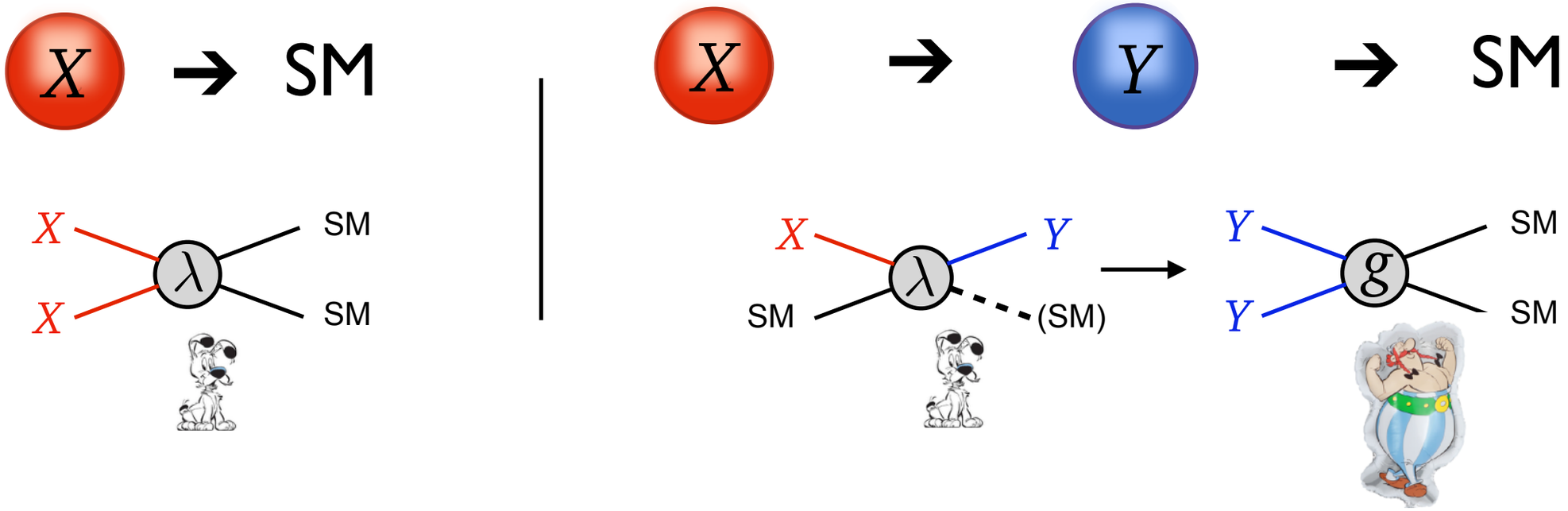
...

What does it look like?

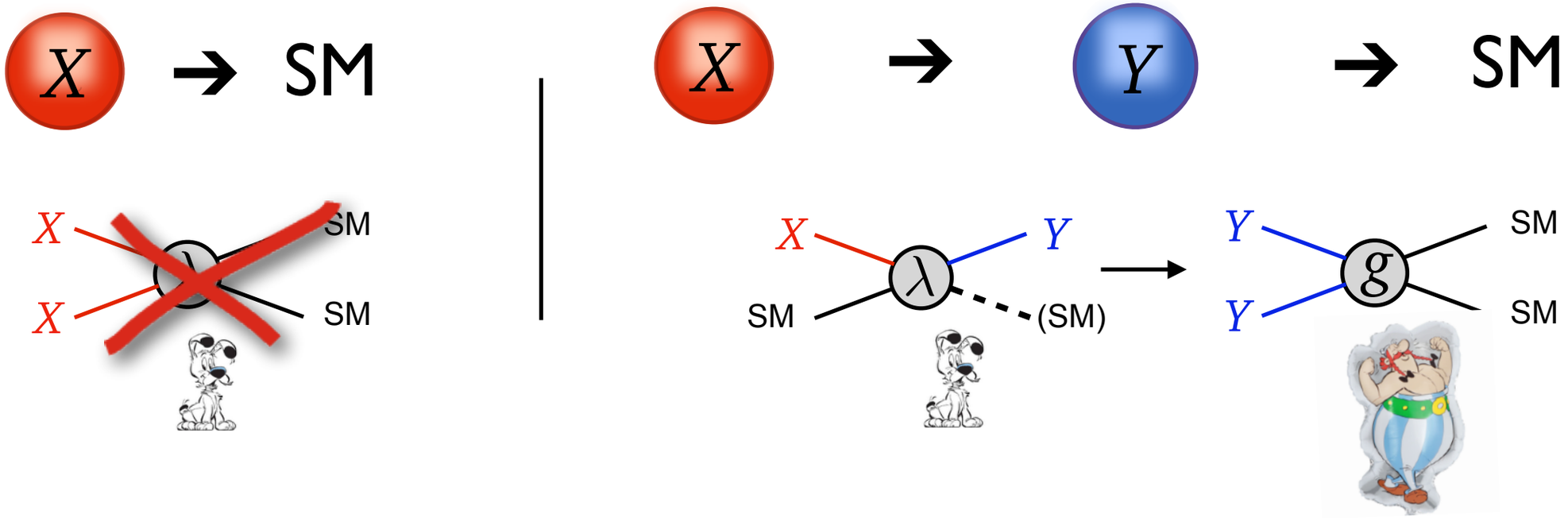


fully efficient

What does it look like?



What does it look like?



$\Gamma_{\rm con} \lesssim \Gamma_{\rm ann}$

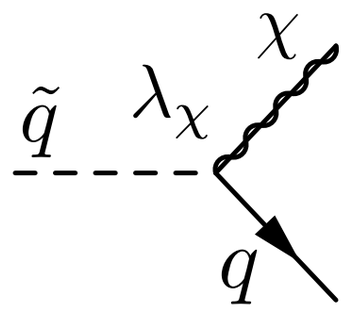
can initiate freeze-out

SUSY-inspired t-channel mediator model

Majorana DM χ $\quad m_X \lesssim m_{\tilde{Y}}$ $\quad \tilde{q}$ scalar quark-partner

λ_X 

g_s 

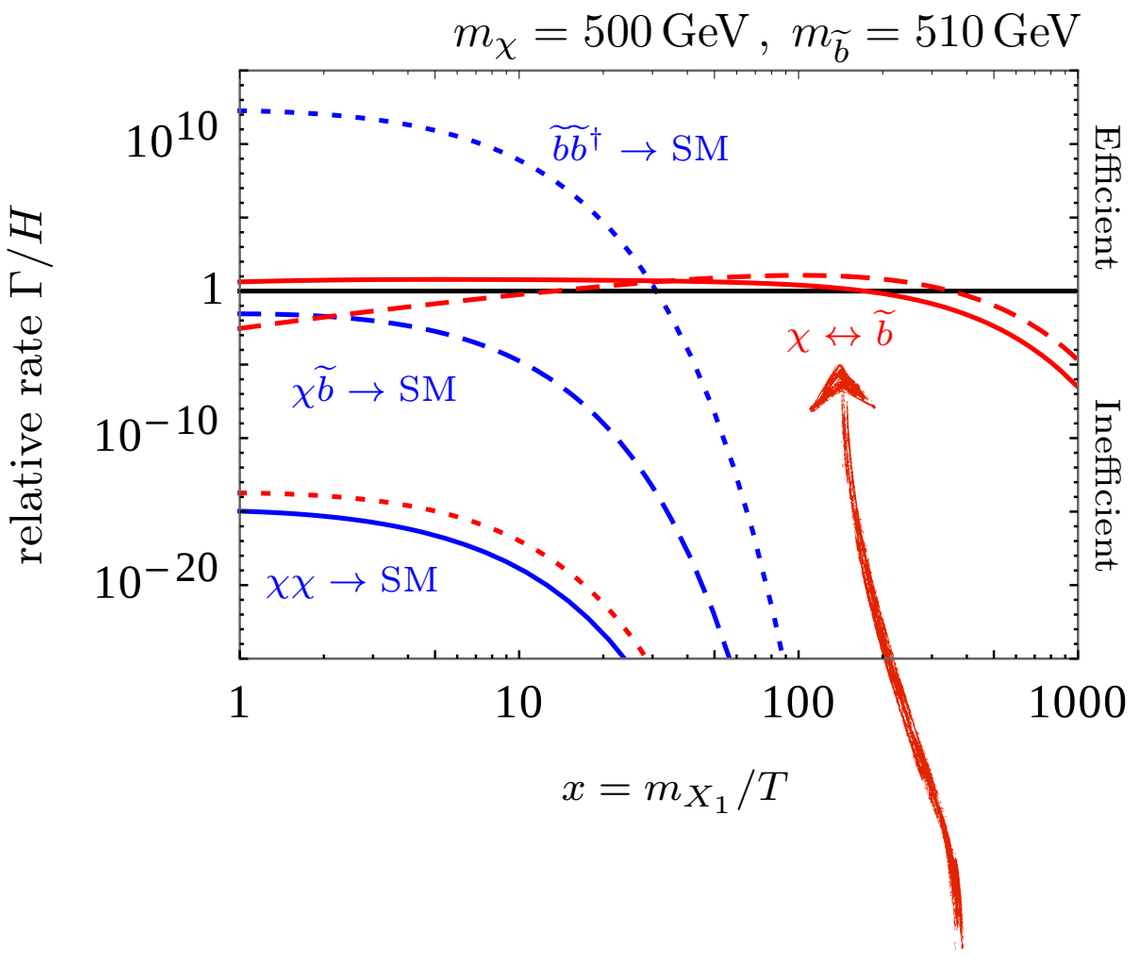
Yukawa-type interaction: 

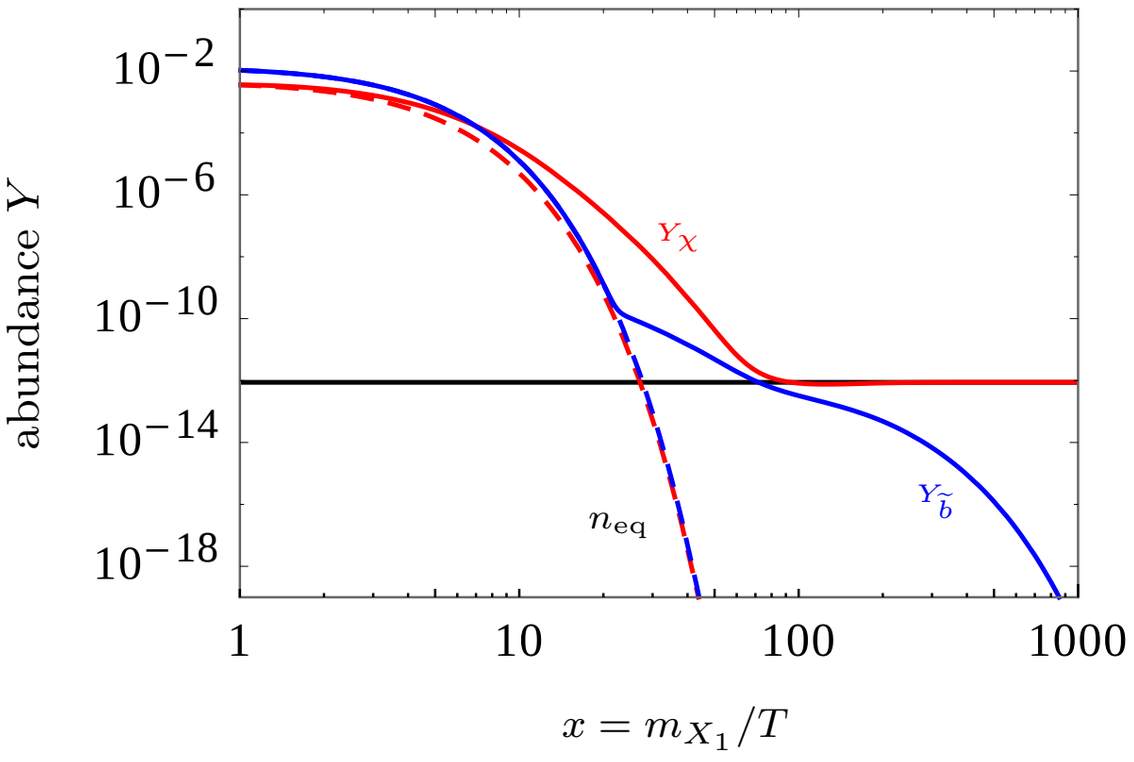
Evolution of abundances

[Garny, JH, Lülf, Vogl 1705.09292]

$$\Omega h^2 = 0.12 \quad \Rightarrow \quad \lambda_\chi \simeq 2.6 \times 10^{-7}$$







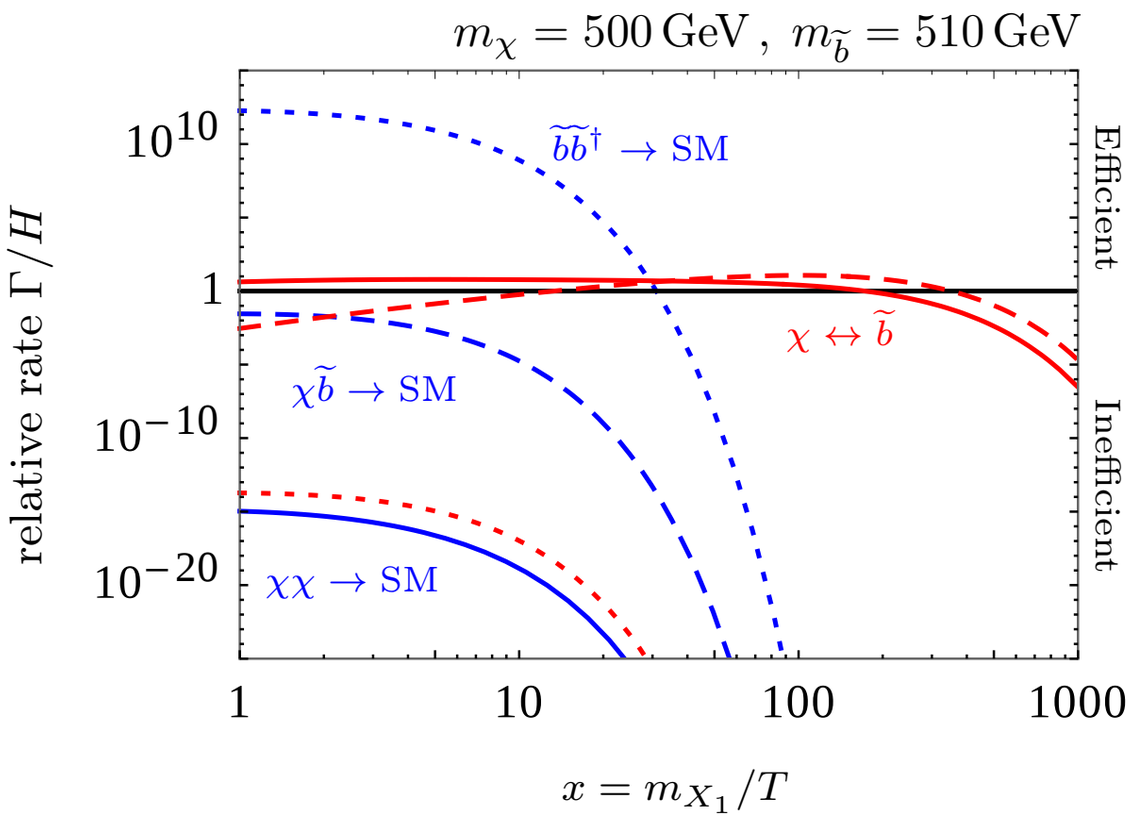
conversions on the edge of being efficient

Evolution of abundances

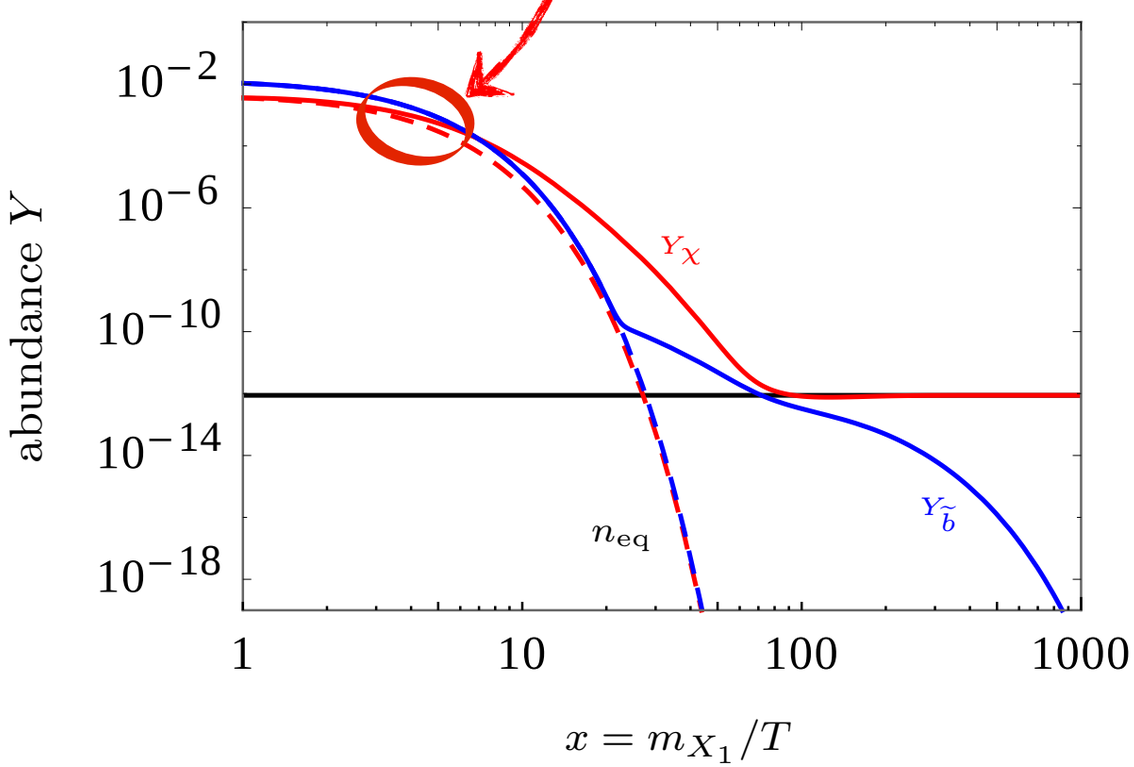
[Garny, JH, Lülf, Vogl 1705.09292]

$$\Omega h^2 = 0.12 \quad \Rightarrow \quad \lambda_\chi \simeq 2.6 \times 10^{-7}$$





Early departure from equilibrium



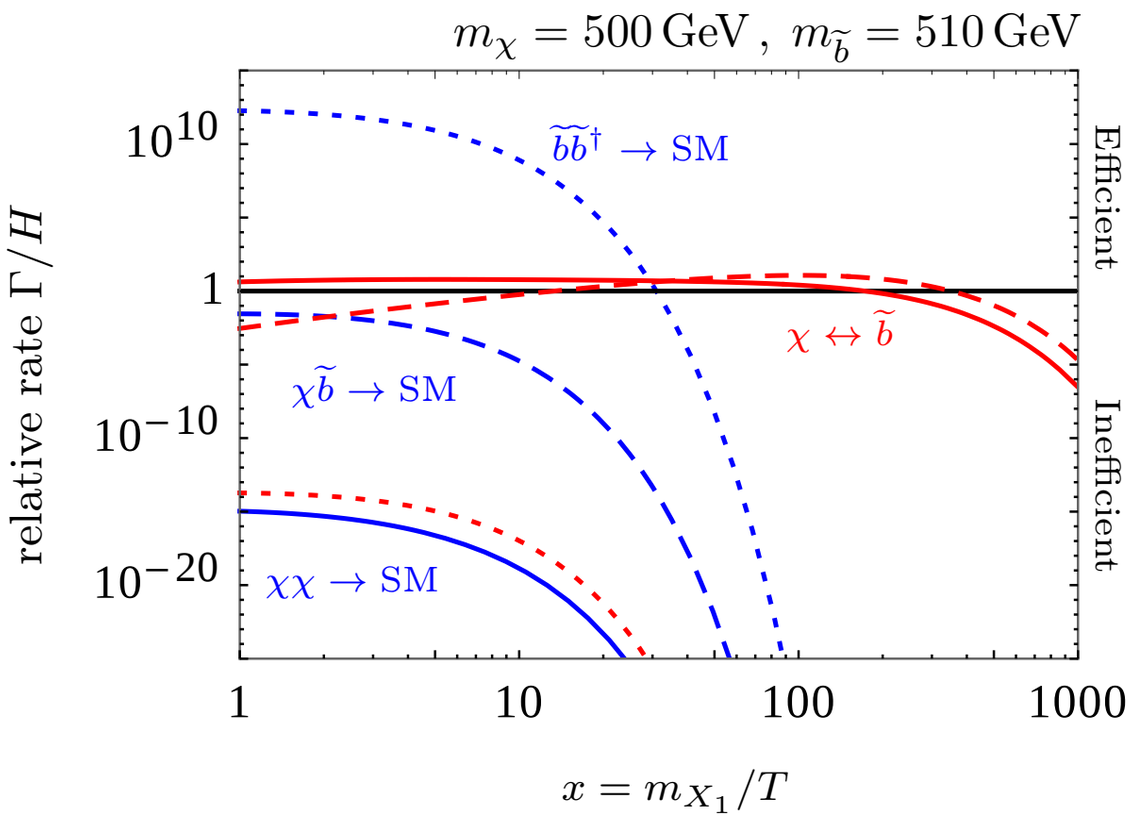
Evolution of abundances

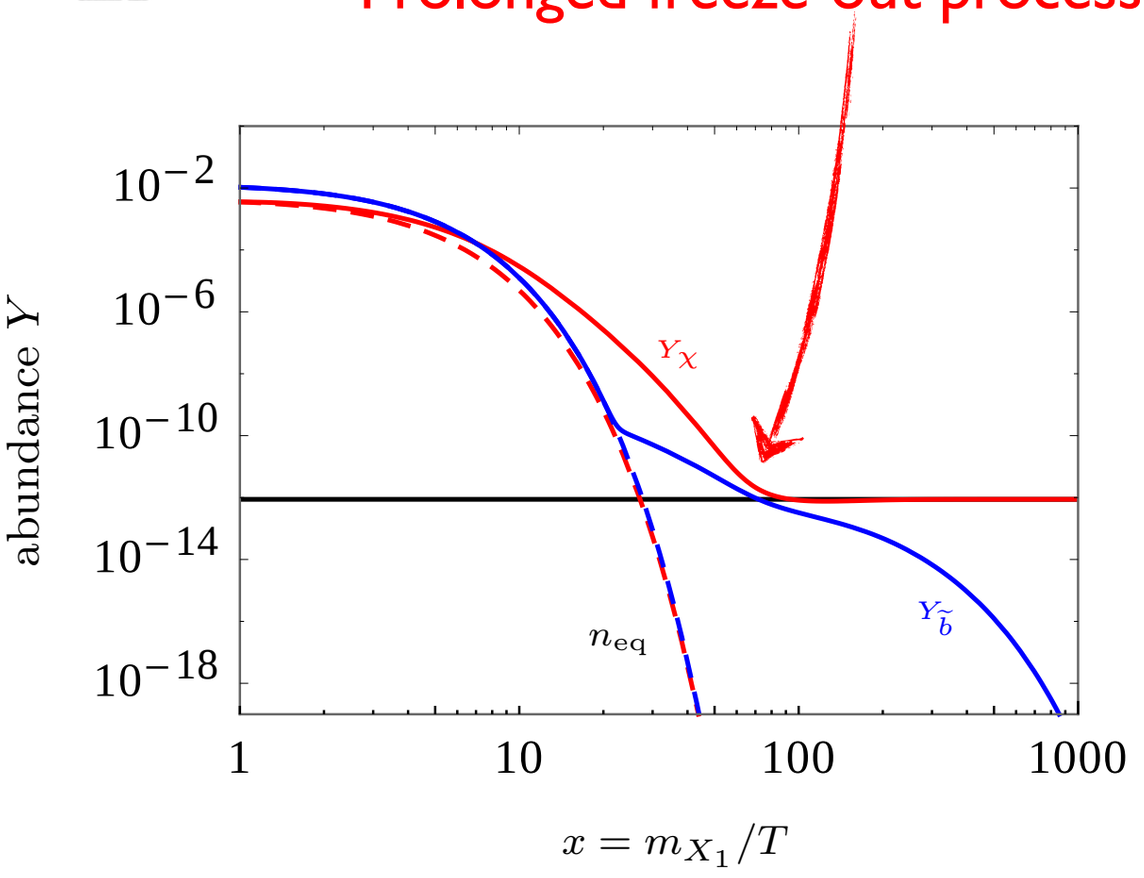
[Garny, JH, Lülf, Vogl 1705.09292]

$$\Omega h^2 = 0.12 \quad \Rightarrow \quad \lambda_\chi \simeq 2.6 \times 10^{-7}$$



Prolonged freeze-out process

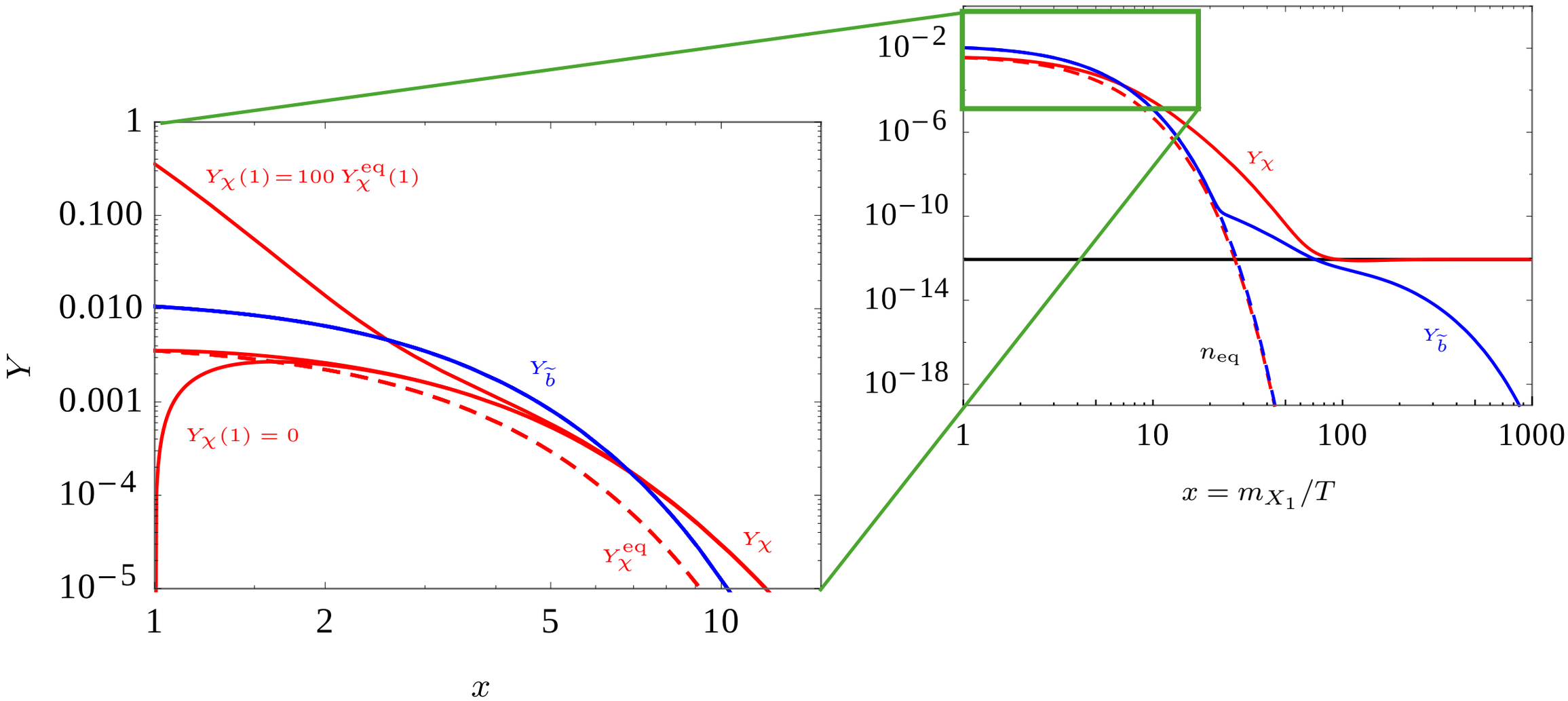




Evolution of abundances

[Garny, JH, Lülf, Vogl 1705.09292]

- Washes out initial conditions
- Converges directly to early out-of-equilibrium abundance



Rich phenomenology

CDFO occupies an interesting spot in parameter space:

- Small couplings 10^{-7}–10^{-6} avoid all conventional WIMP-constraints
- Despite tiny couplings: thermalisation
- Prolonged freeze-out: bound state effects of Y become important
  [Garny, JH 2112.01499]
- Couplings 10^{-7}–10^{-6}: sweet spot for radiative neutrino mass generation in scotogenic models [Heeck, JH+2211.13013]
- Early departure from equilibrium before significant dilution
  ⇒ opportunities for simultaneous baryogenesis [JH 2404.12428; Belfatto, JH+2607.11147]
- $\Gamma_{\rm con} \sim H$ at freeze-out ⇒ LLP at colliders: $c\tau \gtrsim 1\,\mathrm{mm}$

Rich phenomenology

CDFO occupies an interesting spot in parameter space:

- Small couplings 10^{-7}–10^{-6} avoid all conventional WIMP-constraints
- Despite tiny couplings: thermalisation
- Prolonged freeze-out: bound state effects of Y become important
  [Garny, JH 2112.01499]
  - Couplings 10^{-7}–10^{-6}: sweet spot for radiative neutrino mass generation in scotogenic models [Heeck, JH+2211.13013]

★Early departure from equilibrium before significant dilution
⇒ opportunities for simultaneous baryogenesis [JH 2404.12428; Belfatto, JH+2607.11147]

★$\Gamma_{\rm con} \sim H$ at freeze-out ⇒ LLP at colliders: $c\tau \gtrsim 1\,\mathrm{mm}$

How to search for it at LHC

How to search for it at the LHC?

Conversion rate on the edge of being efficient:

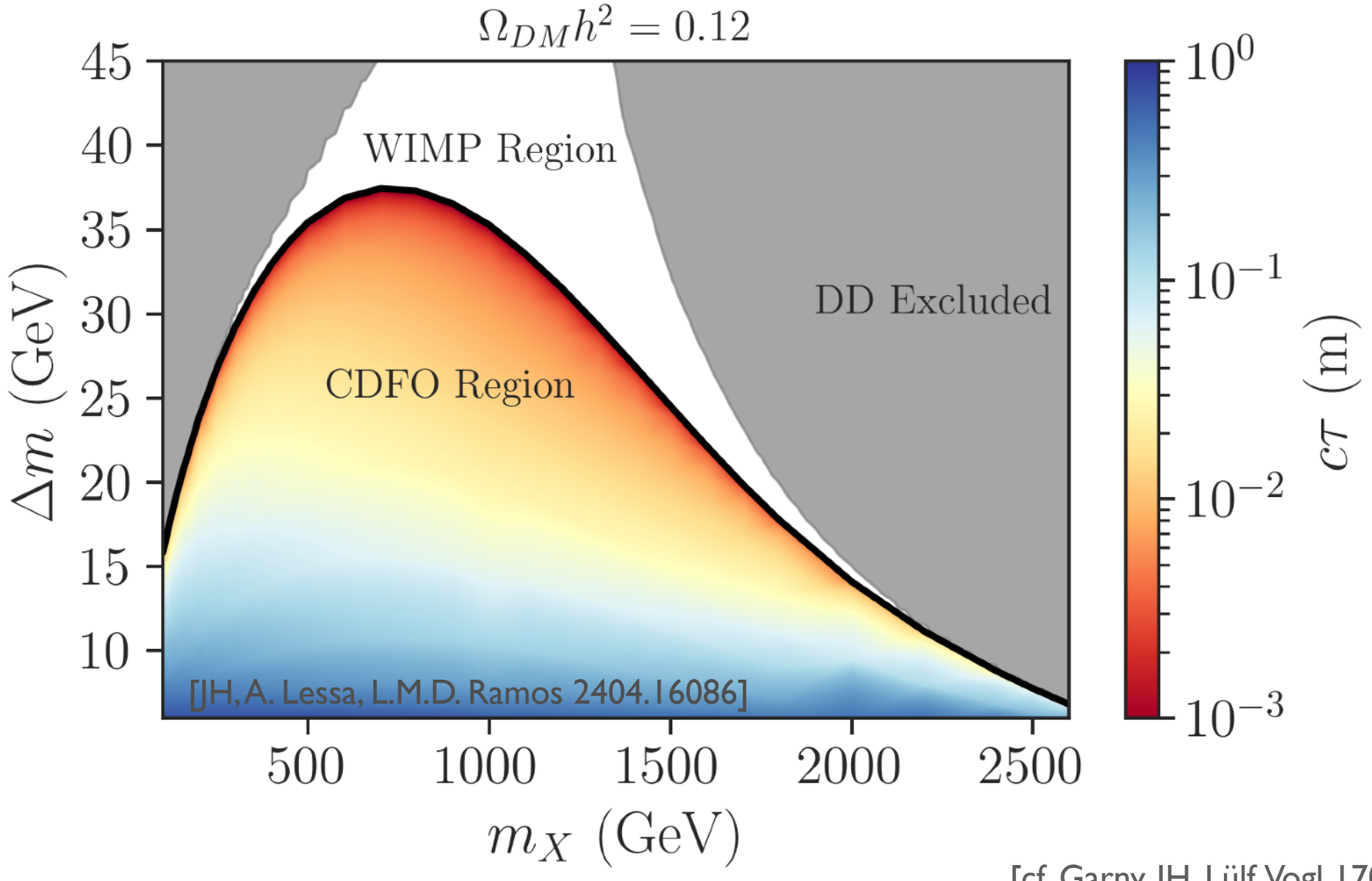
$$\Gamma_{\rm con} \sim H$$

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

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

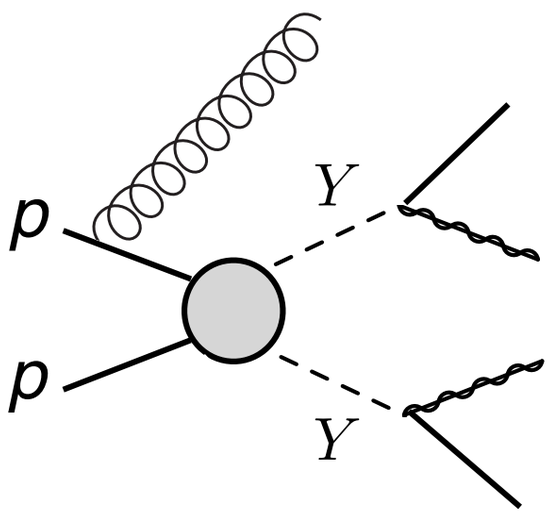
⇒ Long-lived particles (LLPs) at the LHC!

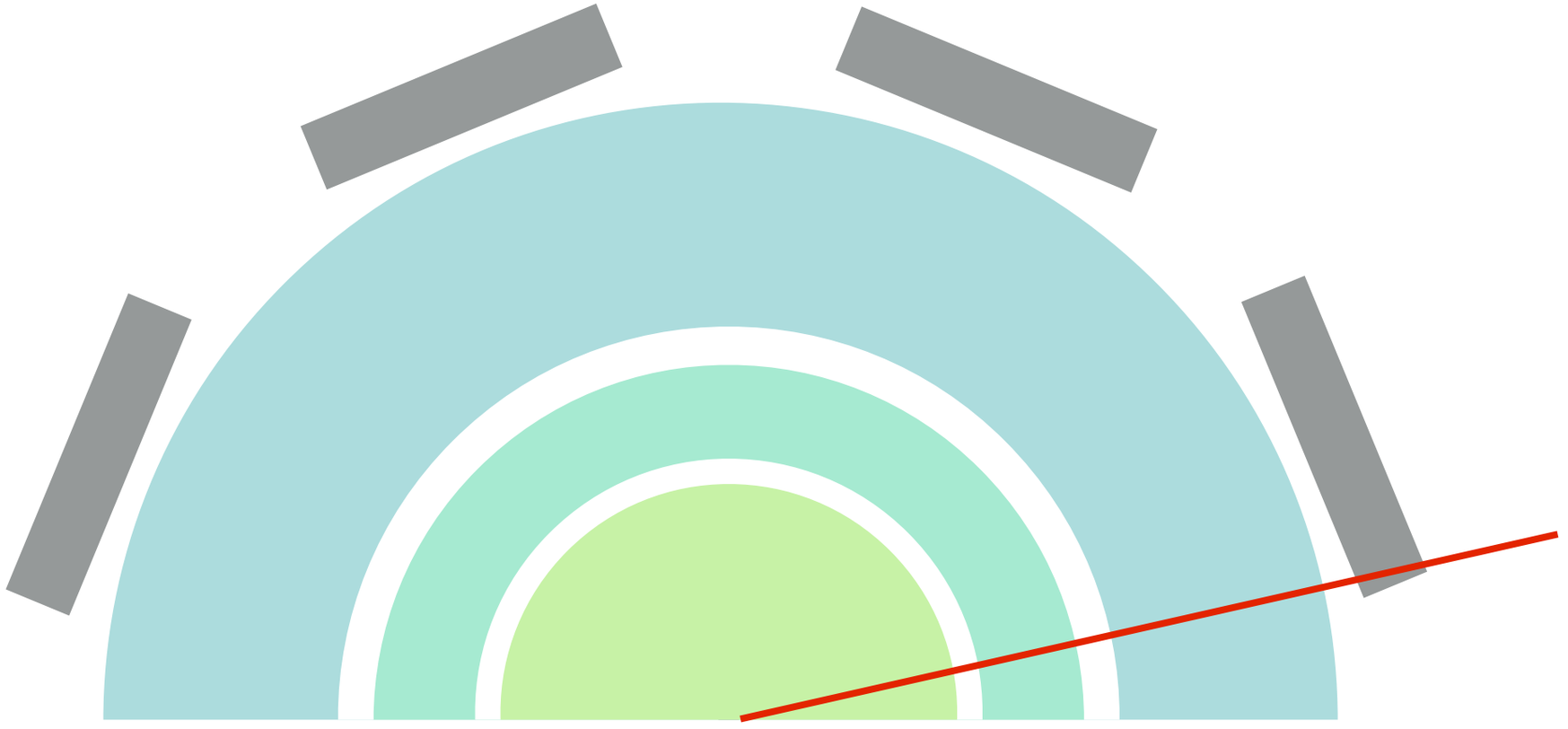
Bottom-philic example



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

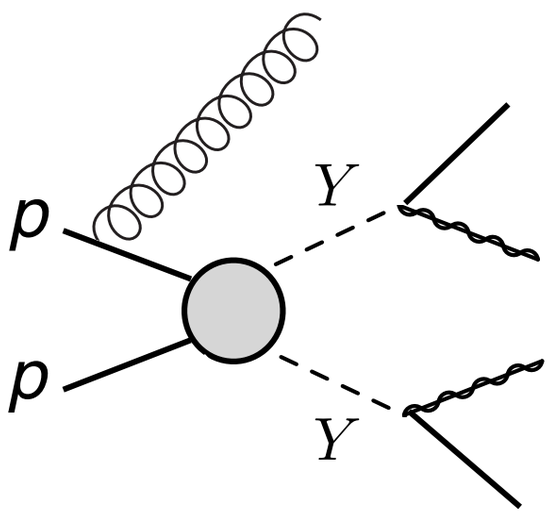
LHC Signature

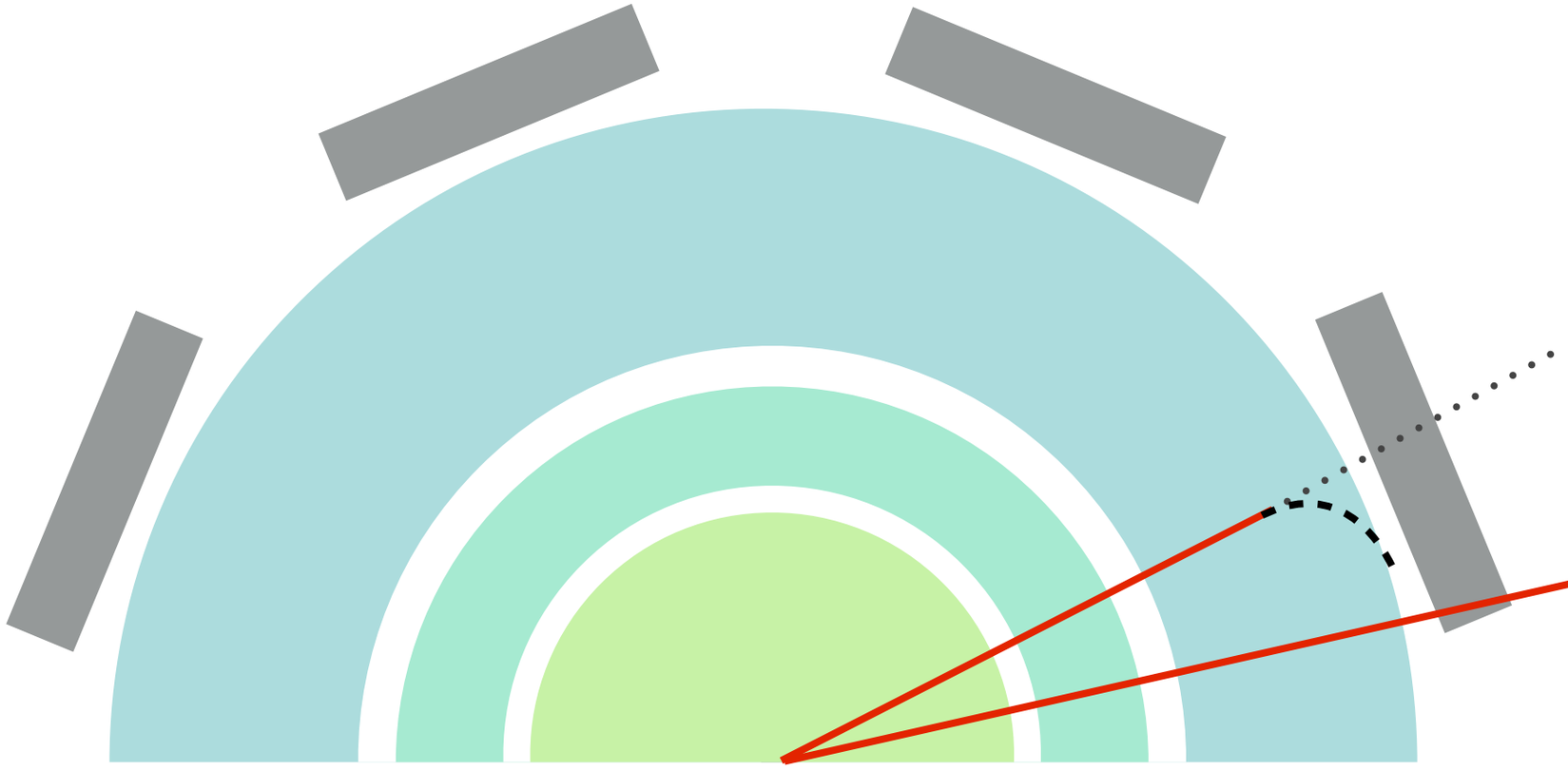




Anomalous tracks
(Heavy stable charged particle searches)
$c\tau_Y > 1\,\mathrm{m}$

LHC Signature





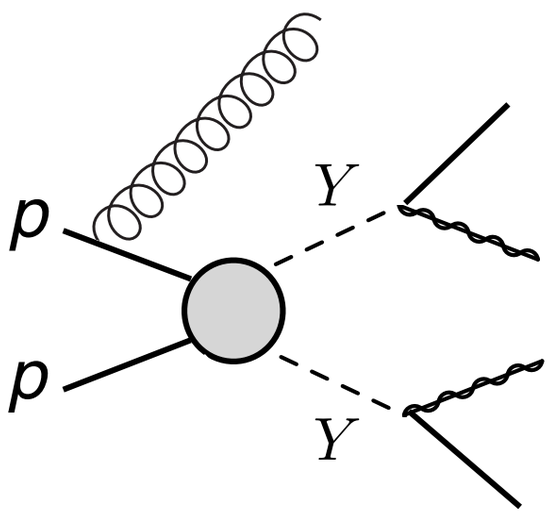
Disappearing tracks

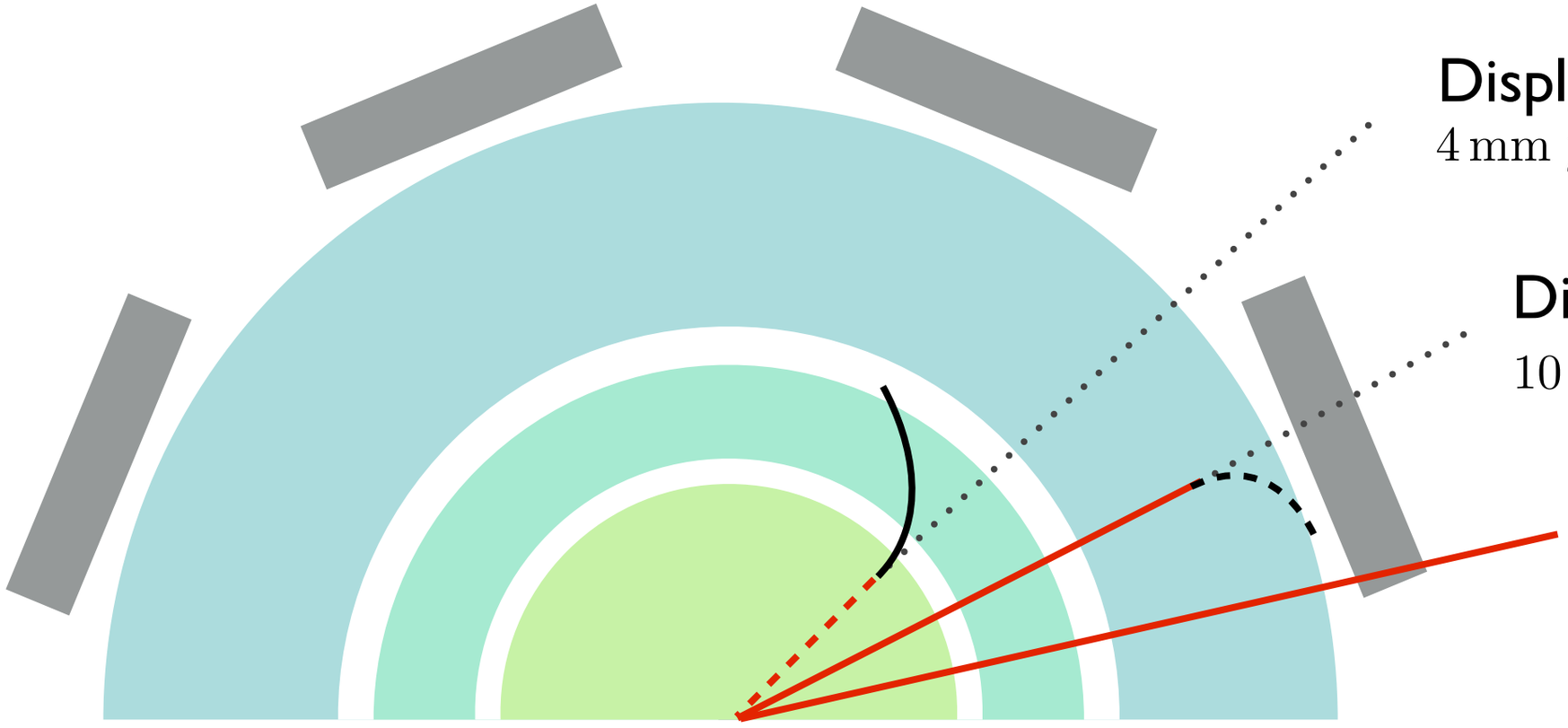
$10\,\mathrm{cm} \lesssim c\tau_Y \lesssim 1\,\mathrm{m}$

Anomalous tracks
(Heavy stable charged particle searches)

$c\tau_Y > 1\,\mathrm{m}$

LHC Signature





Displaced vertices (+MET)

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

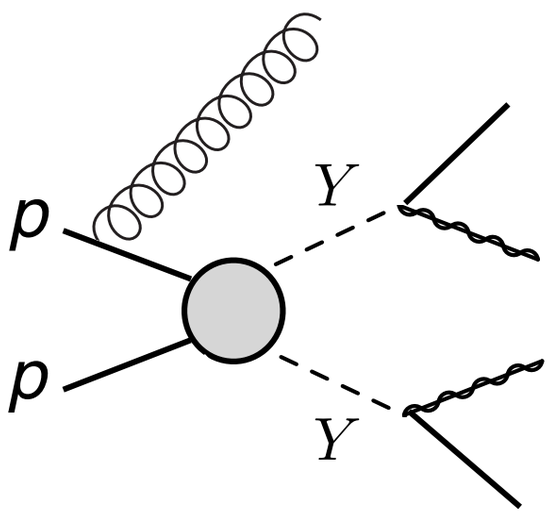
Disappearing tracks

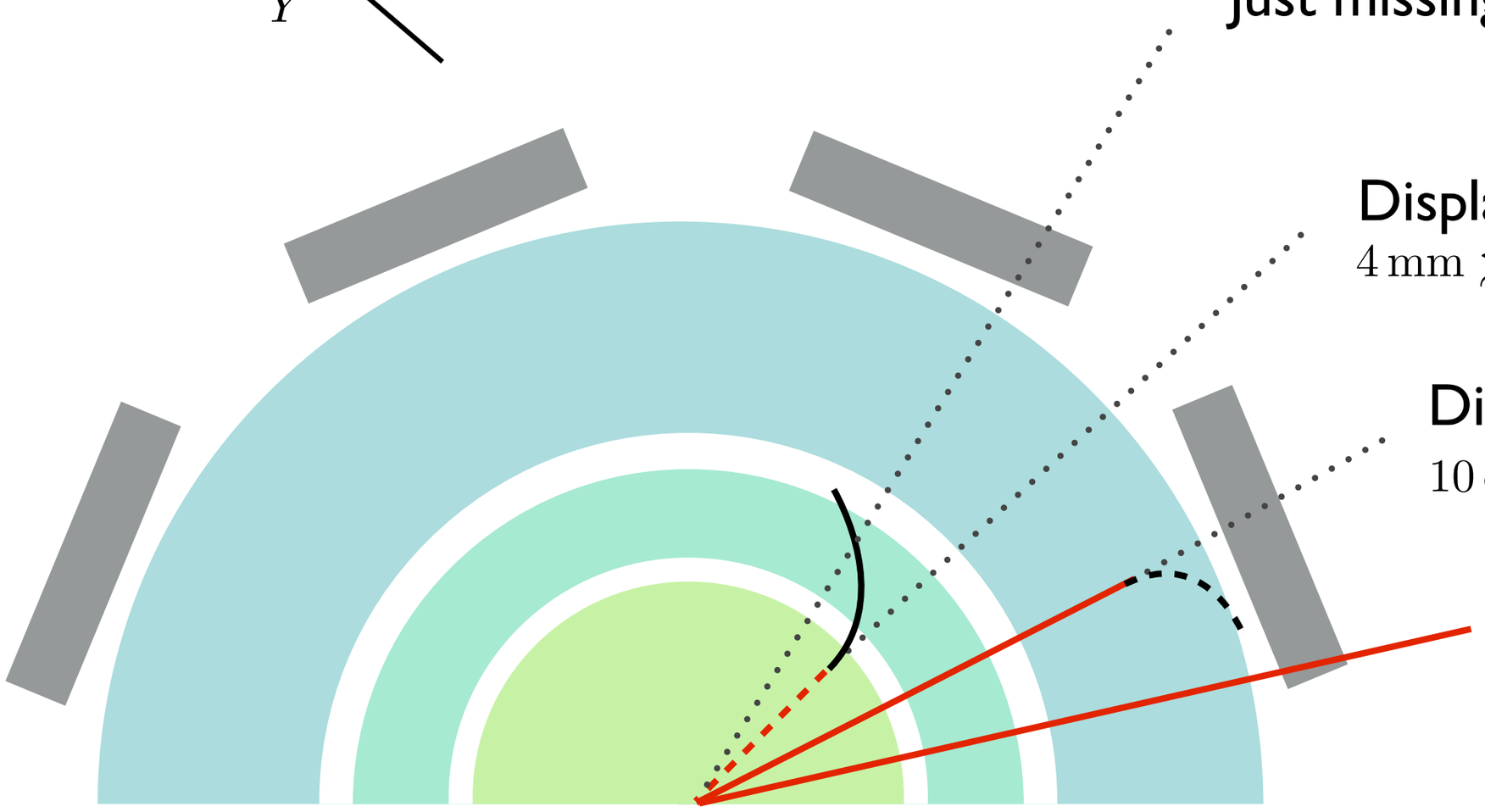
$10\,\mathrm{cm} \lesssim c\tau_Y \lesssim 1\,\mathrm{m}$

Anomalous tracks
(Heavy stable charged particle searches)

$c\tau_Y > 1\,\mathrm{m}$

LHC Signature





Just missing energy (MET)

Displaced vertices (+MET)

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

Disappearing tracks

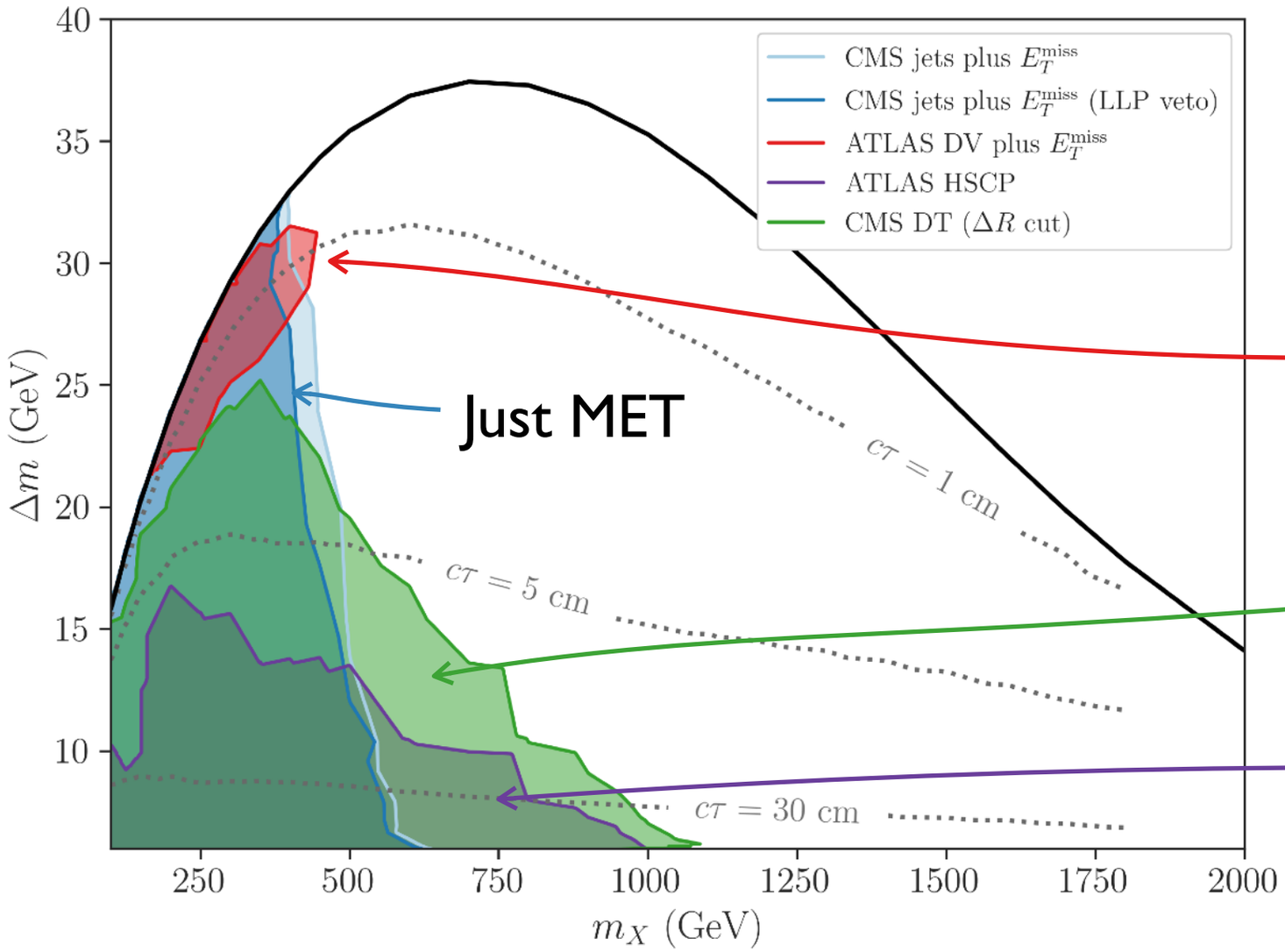
$10\,\mathrm{cm} \lesssim c\tau_Y \lesssim 1\,\mathrm{m}$

Anomalous tracks
(Heavy stable charged particle searches)

$c\tau_Y > 1\,\mathrm{m}$

Current LHC constraints

[JH, Lessa, Ramos 2404.16086]



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

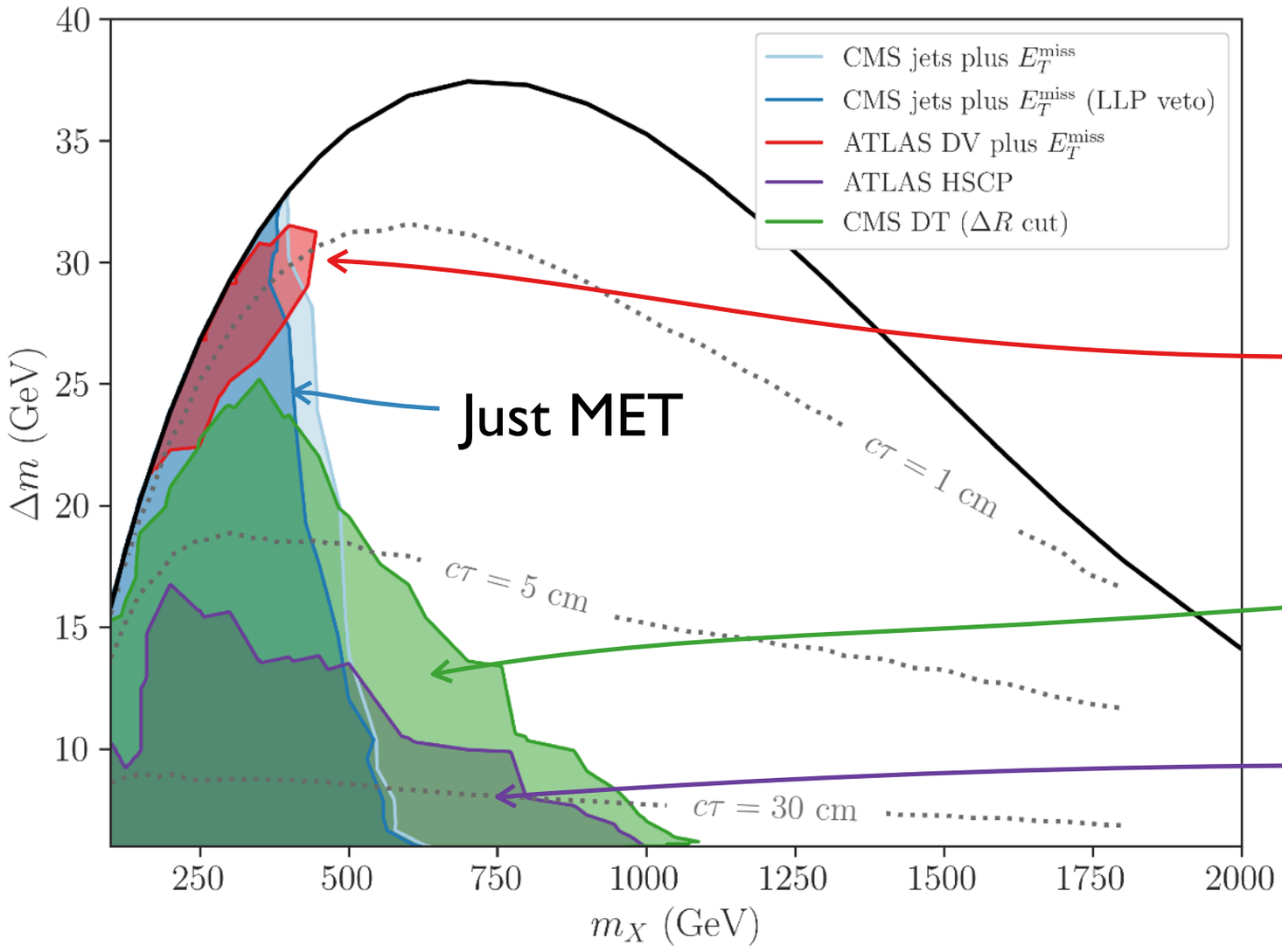
Disappearing tracks
$10\,\mathrm{cm} \lesssim c\tau_Y \lesssim 1\,\mathrm{m}$

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

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

Current LHC constraints

[JH, Lessa, Ramos 2404.16086]



Why poor performance?

Displaced vertices (+MET)

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

Disappearing tracks

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

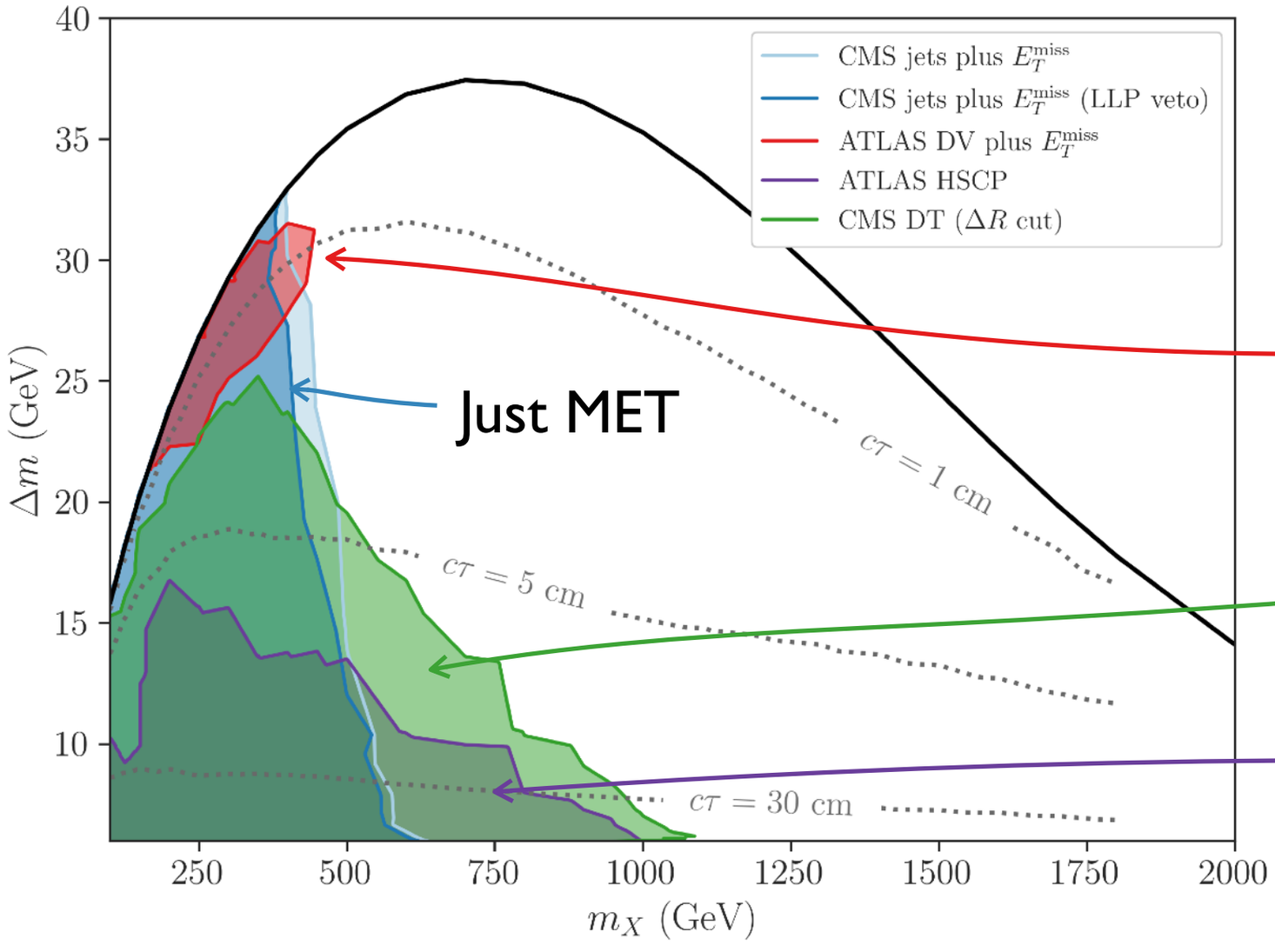
Anomalous tracks
(Heavy stable charged particle searches)

$c\tau_Y > 1\,\mathrm{m}$

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

Current LHC constraints

[JH, Lessa, Ramos 2404.16086]



Targeted at harder jets (split SUSY)

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

Displaced vertices (+MET)

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

Disappearing tracks

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

Anomalous tracks (Heavy stable charged particle searches)

$c\tau_Y > 1\,{\rm m}$

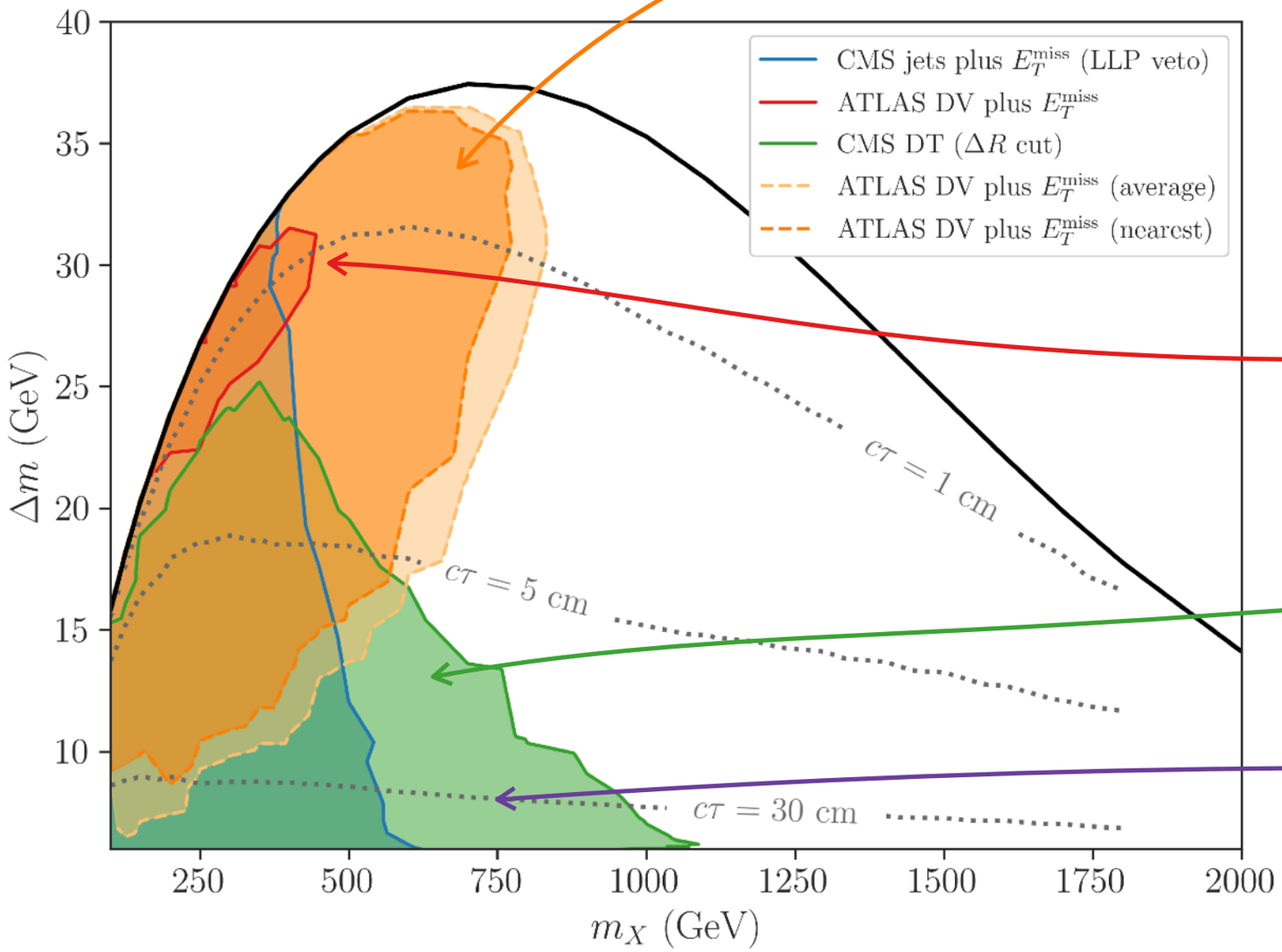
[see also Fuks *et al.*, contr. 7 in 2002.12220]

Current LHC constraints

[JH, Lessa, Ramos 2404.16086]

Proposed displaced vertices +MET search

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



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

Displaced vertices (+MET)

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

Disappearing tracks

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

Anomalous tracks (Heavy stable charged particle searches)

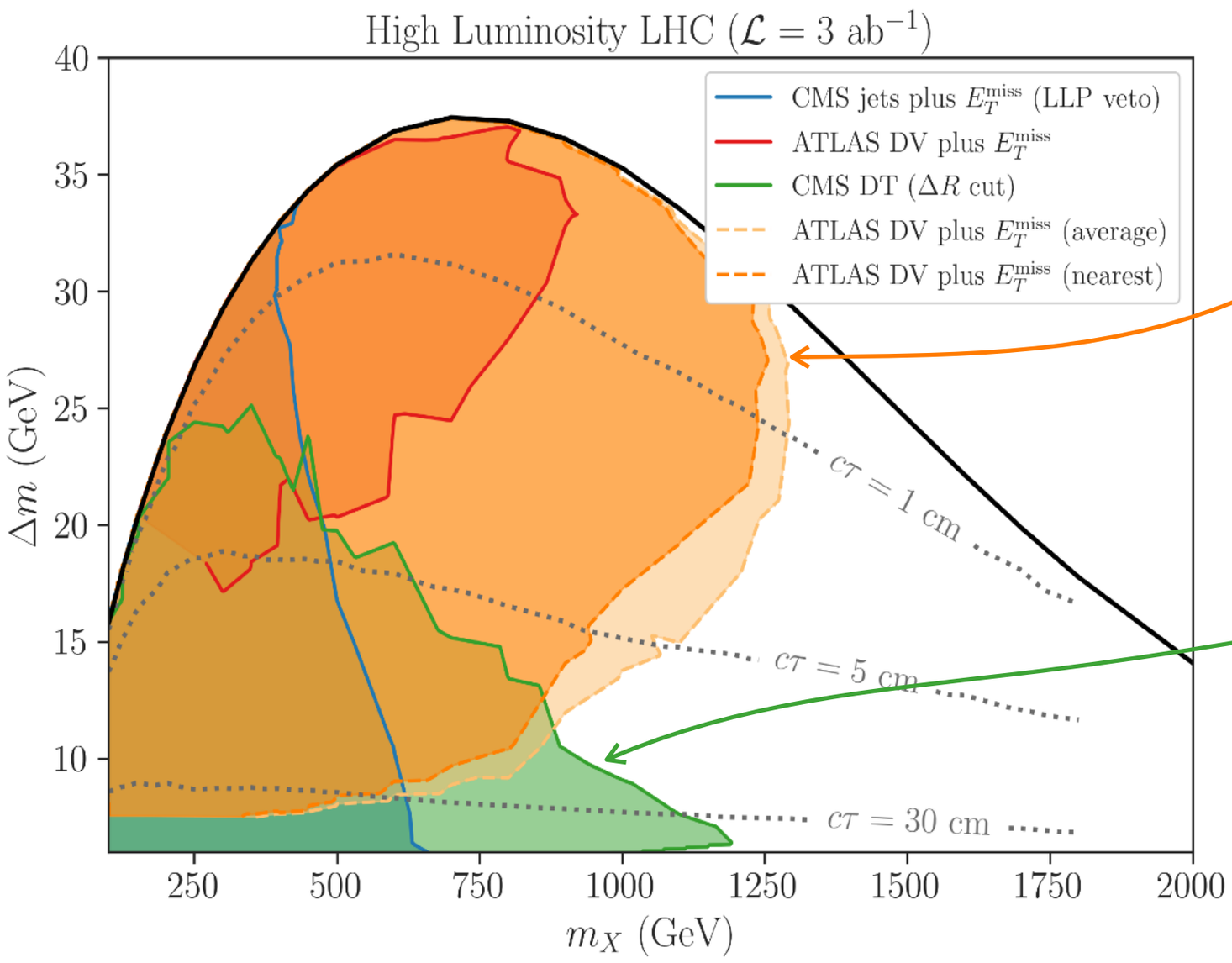
$c\tau_Y > 1\,{\rm m}$

HL-LHC projections

[JH, Lessa, Ramos 2404.16086]

Proposed displaced vertices +MET search

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



Disappearing tracks

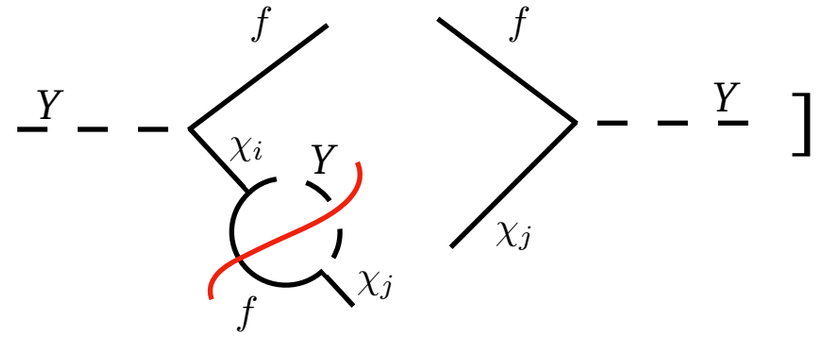
$10\,{\rm cm} \lesssim c\tau_Y \lesssim 1\,{\rm m}$

Flavoured Models and baryogenesis

Conversion-driven baryogenesis

[JH 2404.12428; Belfatto, JH+ 2607.11147]

Idea: CP-asymmetry from the same conversions

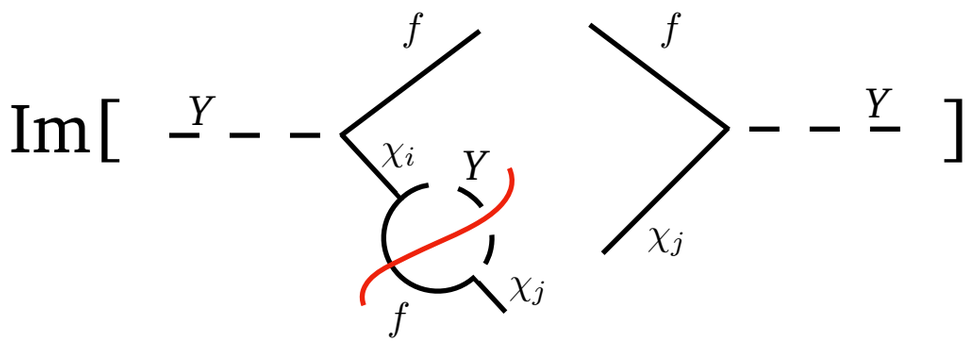
Leading contribution: $\mathrm{Im}[$  $]$

Conversion-driven baryogenesis

[JH 2404.12428; Belfatto, JH+ 2607.11147]

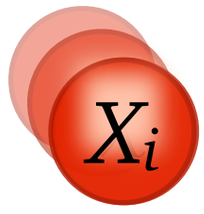
Idea: CP-asymmetry from the same conversions

Leading contribution:





Charged mediator



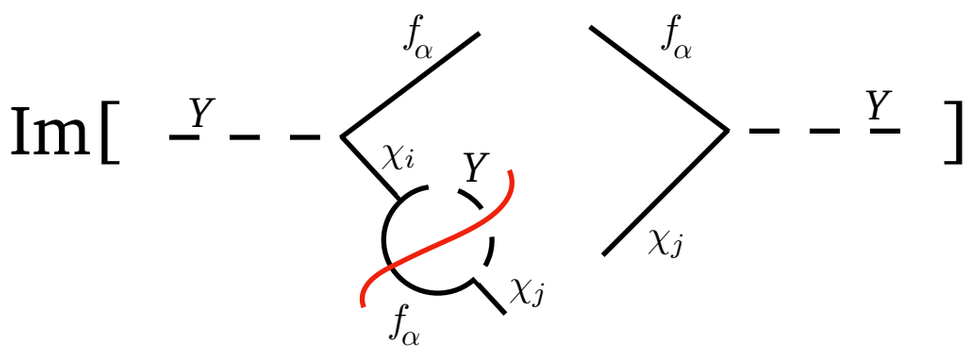
Dark Matter Multiplet

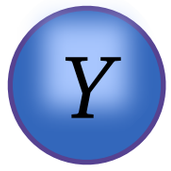
Conversion-driven baryogenesis

[JH 2404.12428; Belfatto, JH+ 2607.11147]

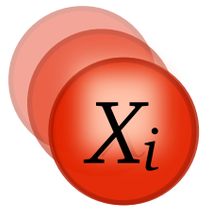
Idea: CP-asymmetry from the same conversions

Leading contribution:





Charged mediator



Dark Matter Multiplet

⇒ realisations of CDFO in 'flavoured' dark matter

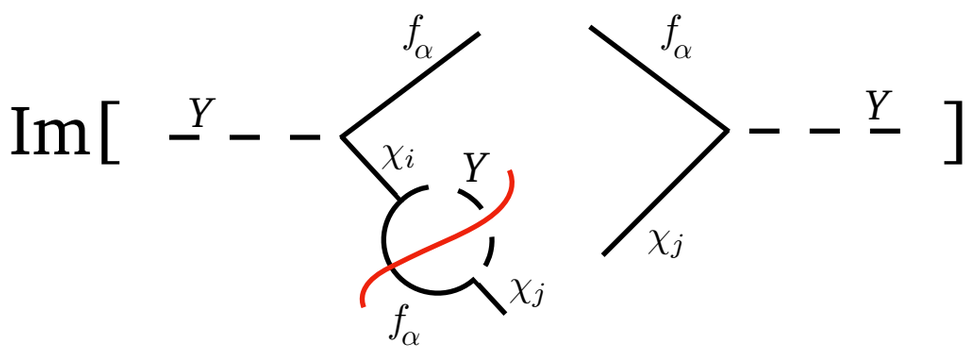
⇒ $\lambda_{i\alpha}$ coupling matrix

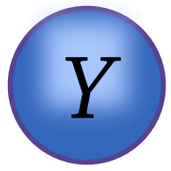
Conversion-driven baryogenesis

[JH 2404.12428; Belfatto, JH+ 2607.11147]

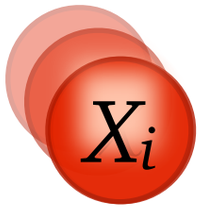
Idea: CP-asymmetry from the same conversions

Leading contribution:





Charged mediator



Dark Matter Multiplet

⇒ realisations of CDFO in 'flavoured' dark matter

⇒ $\lambda_{i\alpha}$ coupling matrix



Conversion-driven baryogenesis

[JH 2404.12428; Belfatto, JH+ 2607.11147]

Idea: CP-asymmetry from the same conversions:

- Require quasi-degenerate multiplet $\Delta m_\chi \sim m_\chi \lambda^2$ (resonant regime)

Conversion-driven baryogenesis

[JH 2404.12428; Belfatto, JH+ 2607.11147]

Idea: CP-asymmetry from the same conversions:

- Require quasi-degenerate multiplet $\Delta m_\chi \sim m_\chi \lambda^2$ (resonant regime)
- Non-vanishing only at finite temperature
- Computed for Higgs-lepton interactions [Hambye+2016; Frossard+2013]

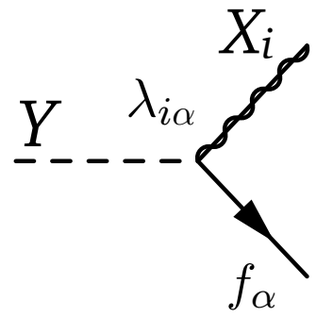
Conversion-driven baryogenesis

[JH 2404.12428; Belfatto, JH+ 2607.11147]

Idea: CP-asymmetry from the same conversions:

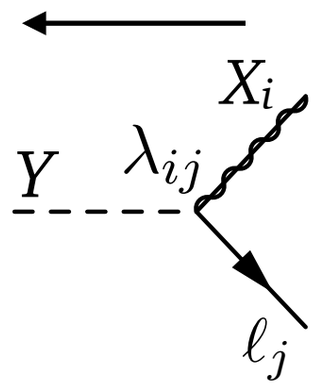
- Require quasi-degenerate multiplet $\Delta m_\chi \sim m_\chi \lambda^2$ (resonant regime)
- Non-vanishing only at finite temperature
- Computed for Higgs-lepton interactions [Hambye+2016; Frossard+2013]

- *CP*-violation ✓
- Out-of-equilibrium processes ✓
- Baryon number violation ?



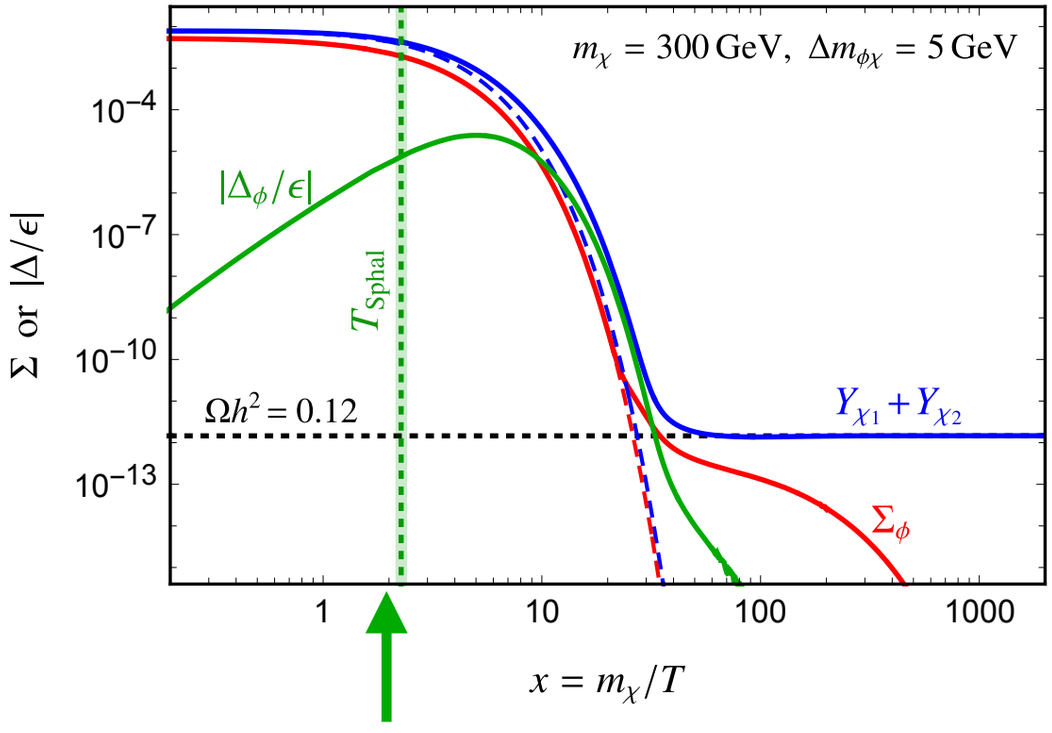
No B or L violation
But Sphalerons violate $B+L$

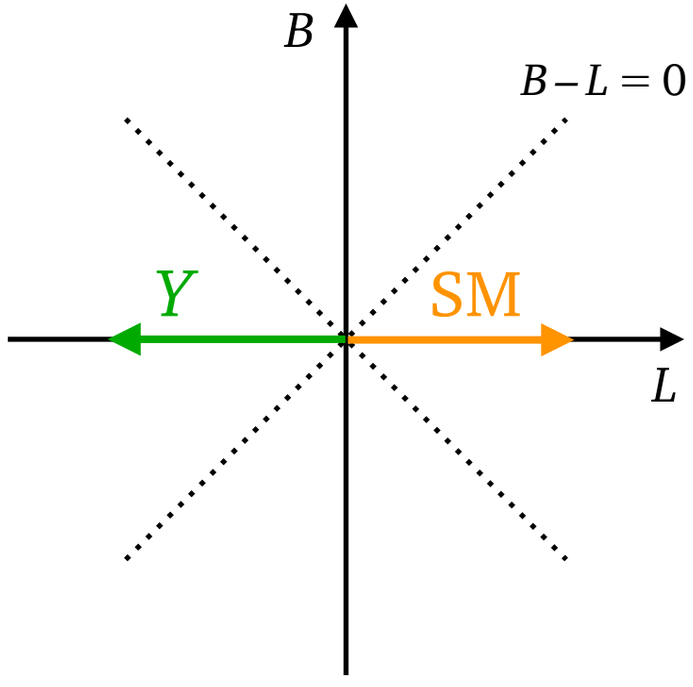
Abundances and asymmetry



[JH 2404.12428]

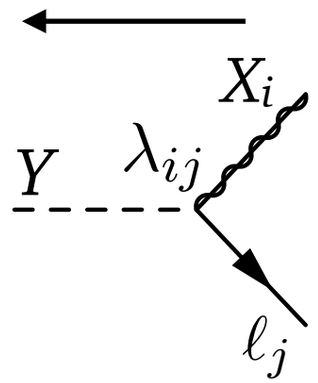
$\Omega h^2 = 0.12 \;\; Y_{\Delta B} = 0.9 \times 10^{-10}$





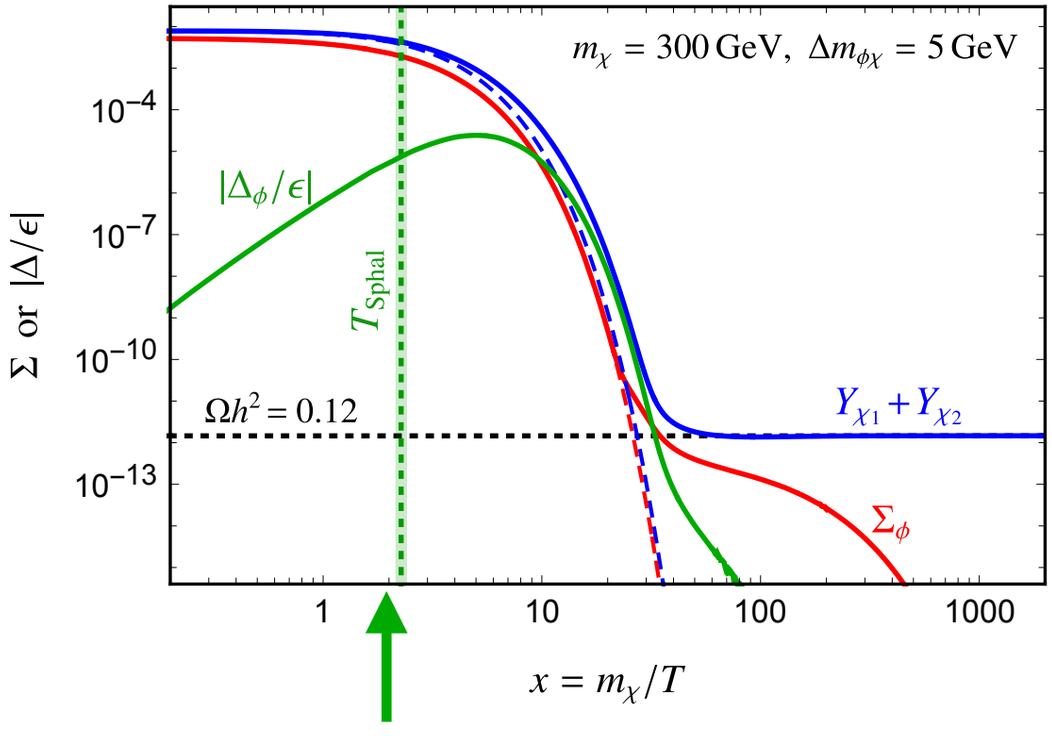
(Source term of Δ_Y) $\propto \left(Y_Y - Y_Y^{\mathrm{eq}} \dfrac{Y_{\chi_i}}{Y_{\chi_i}^{\mathrm{eq}}} \right)$

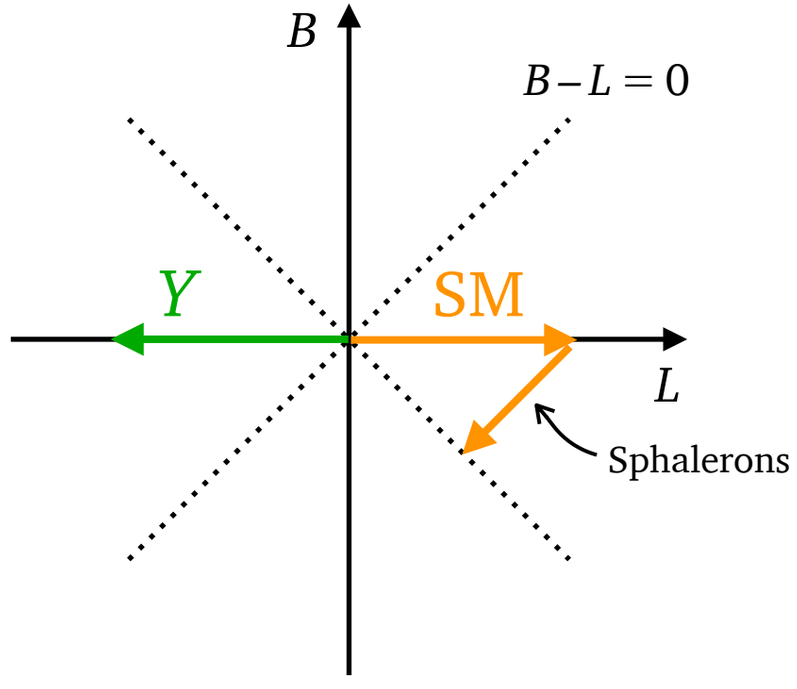
Abundances and asymmetry



[JH 2404.12428]

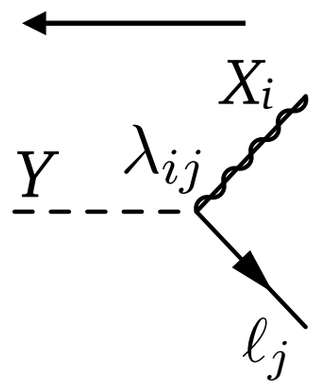
$\Omega h^2 = 0.12 \;\; Y_{\Delta B} = 0.9 \times 10^{-10}$





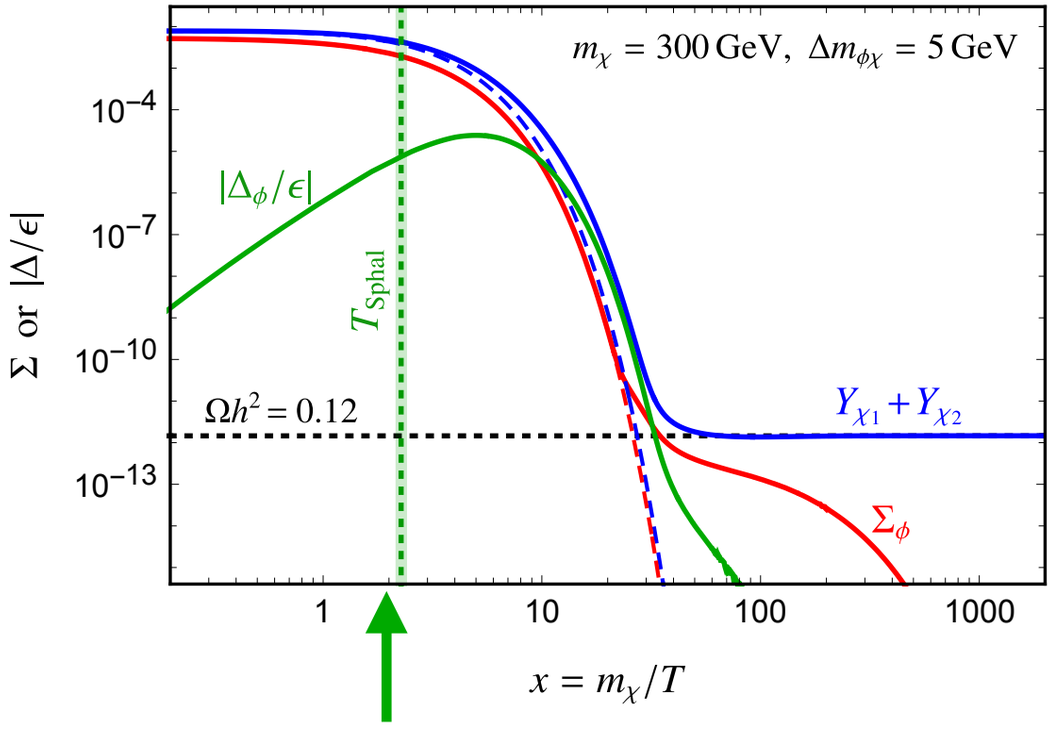
[Similarity to Dirac leptogenesis
Dick, Lindner, Ratz, Wright, 2000]

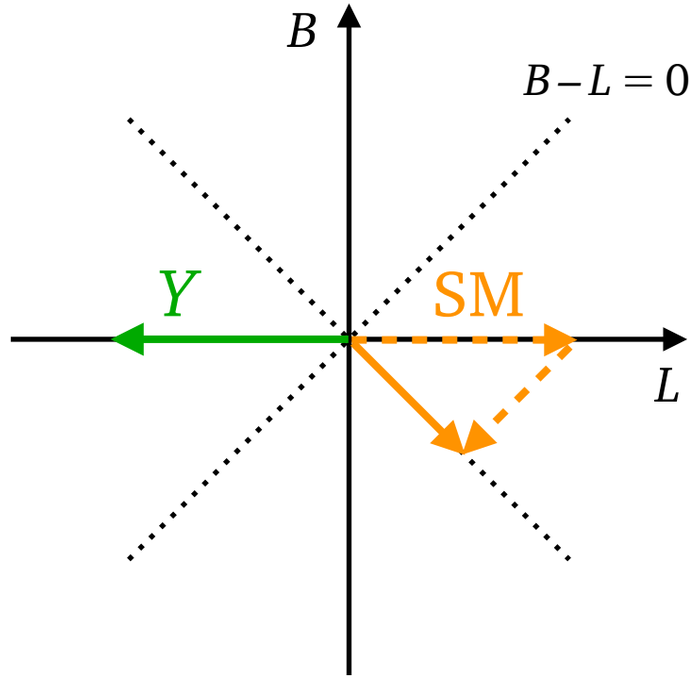
Abundances and asymmetry



[JH 2404.12428]

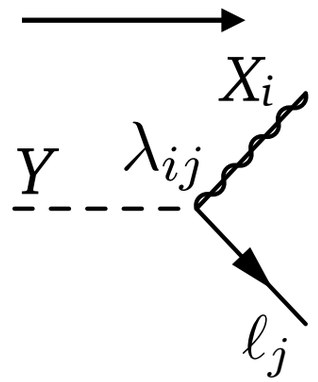
$\Omega h^2 = 0.12 \;\; Y_{\Delta B} = 0.9 \times 10^{-10}$





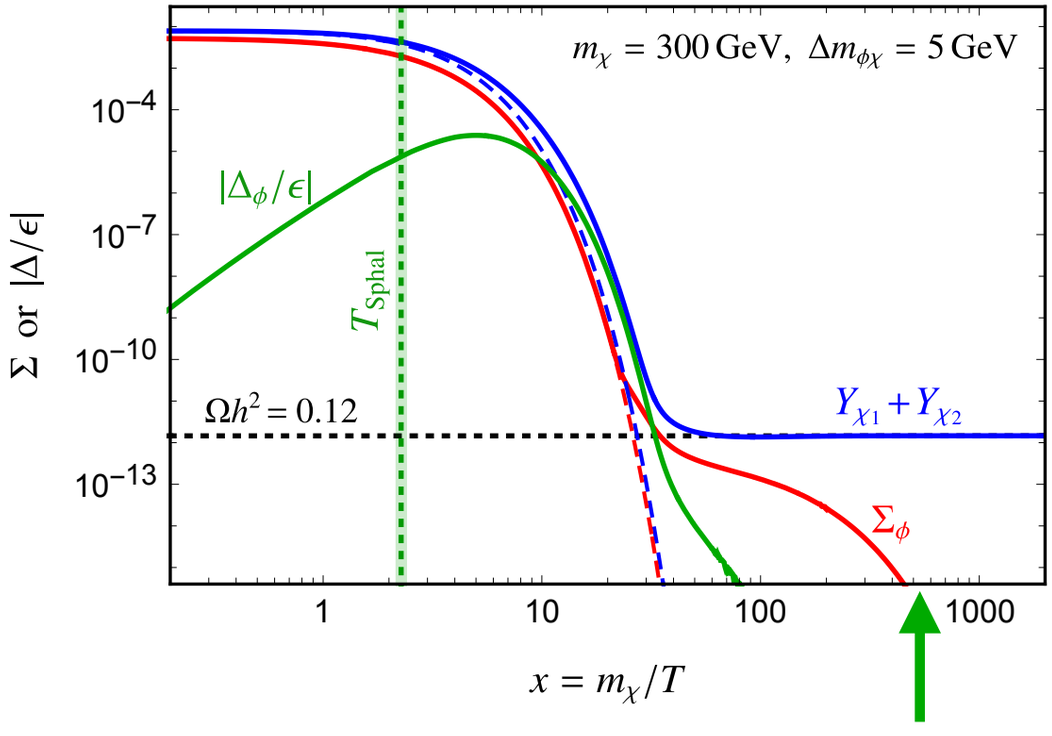
[Similarity to Dirac leptogenesis
Dick, Lindner, Ratz, Wright, 2000]

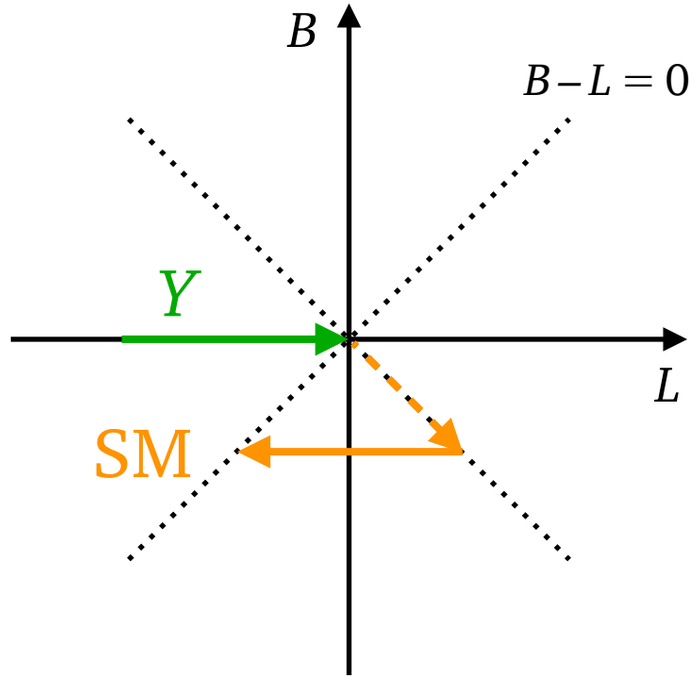
Abundances and asymmetry



[JH 2404.12428]

$\Omega h^2 = 0.12 \;\; Y_{\Delta B} = 0.9 \times 10^{-10}$

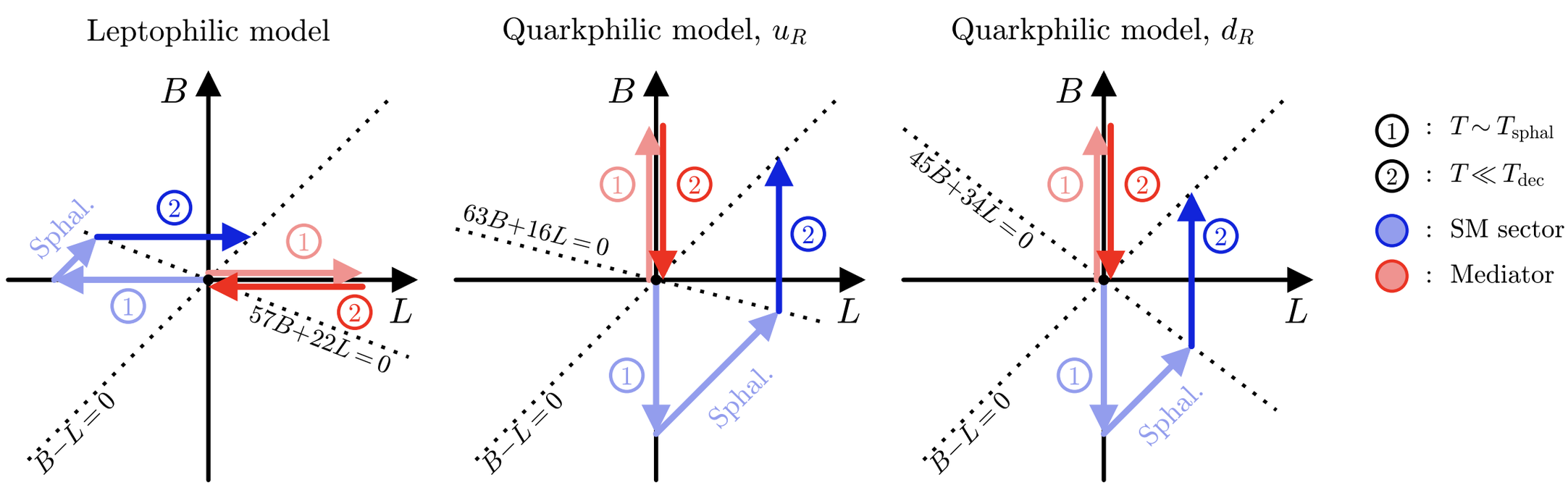




[Similarity to Dirac leptogenesis
Dick, Lindner, Ratz, Wright, 2000]

Leptophilic and Quarkphilic realisations

[Belfatto, Blanke, JH, Rathmann, Wilsch 2607.11147]

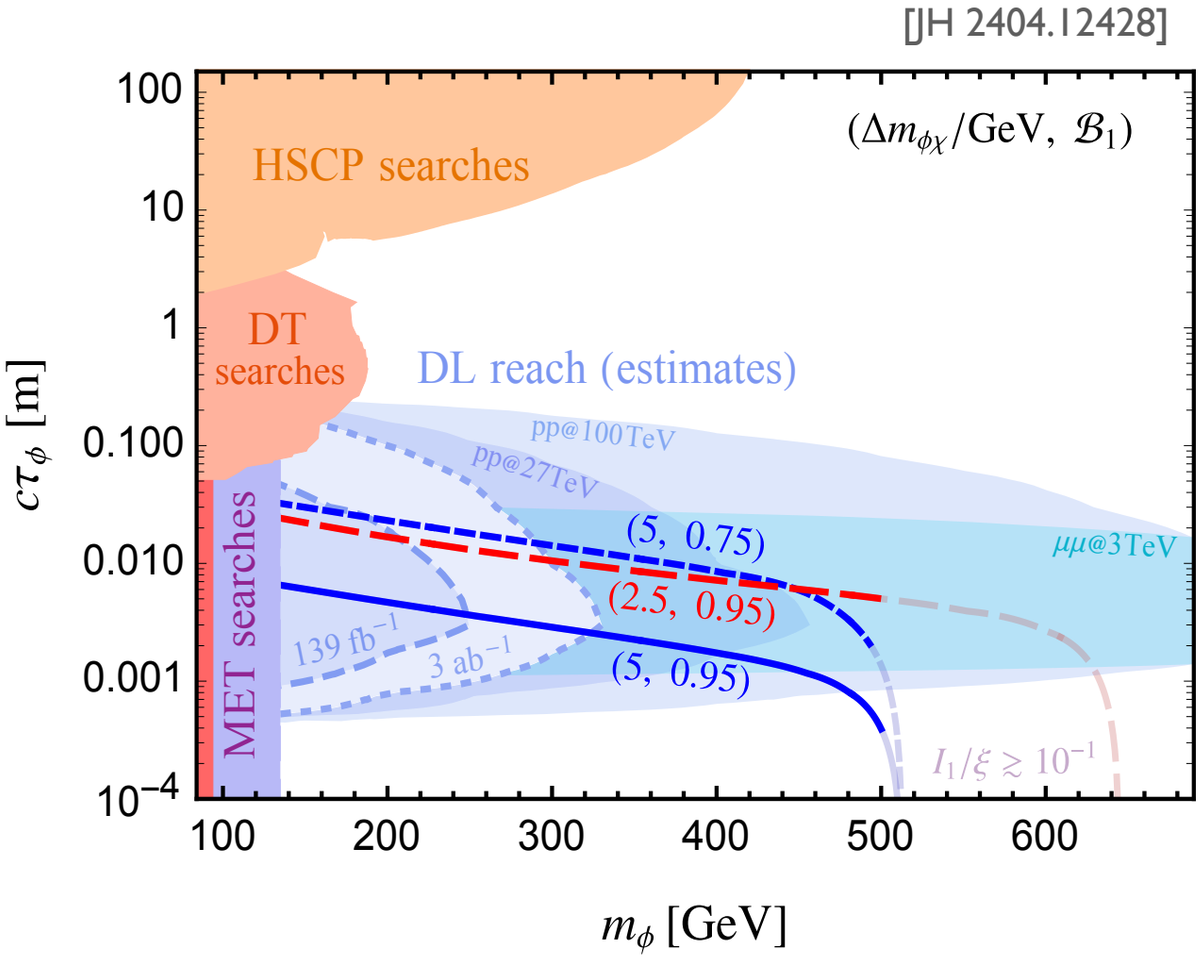


Viable parameter space and constraints

$$\Omega h^2 = 0.12 \;\; Y_{\Delta B} = 0.9 \times 10^{-10}$$

Leptophilic model:

[JH 2404.12428]

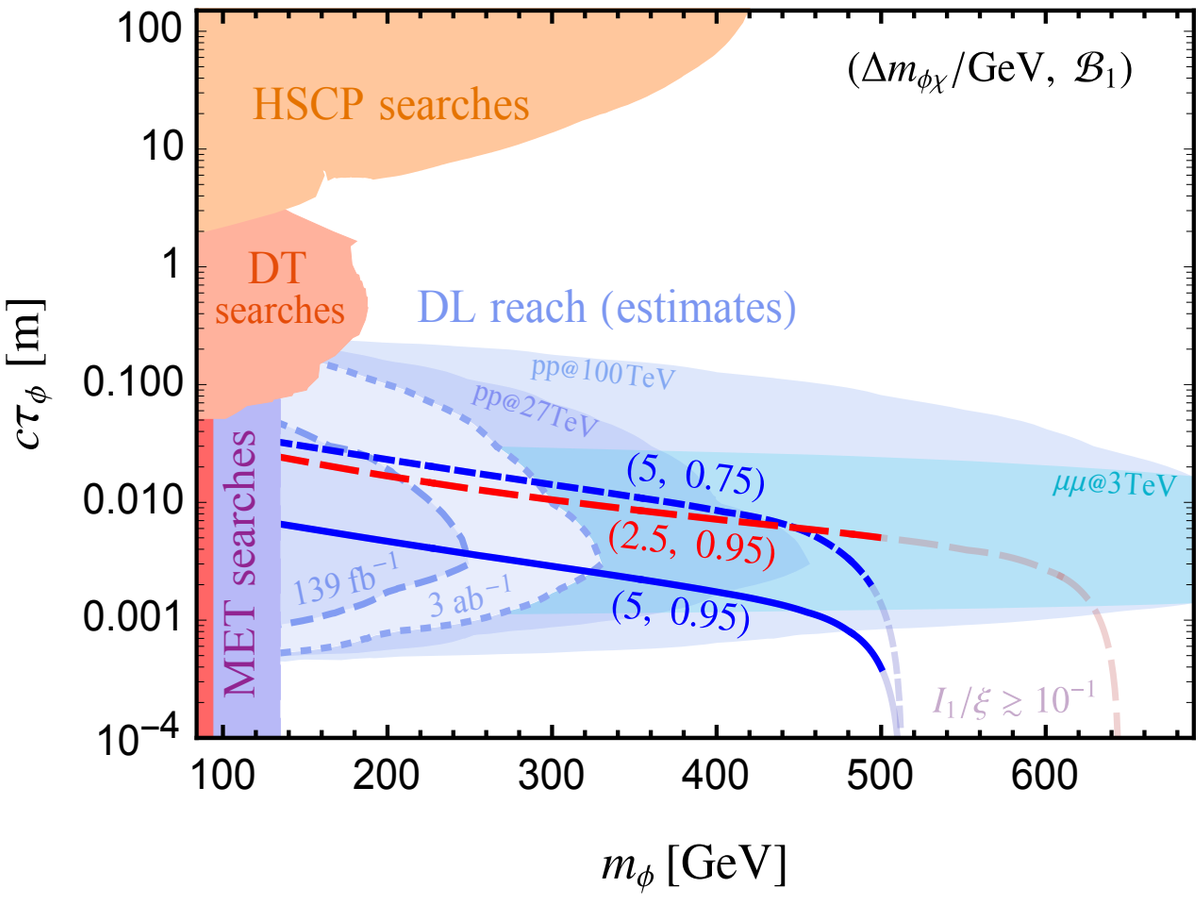


Viable parameter space and constraints

$$\Omega h^2 = 0.12 \;\; Y_{\Delta B} = 0.9 \times 10^{-10}$$

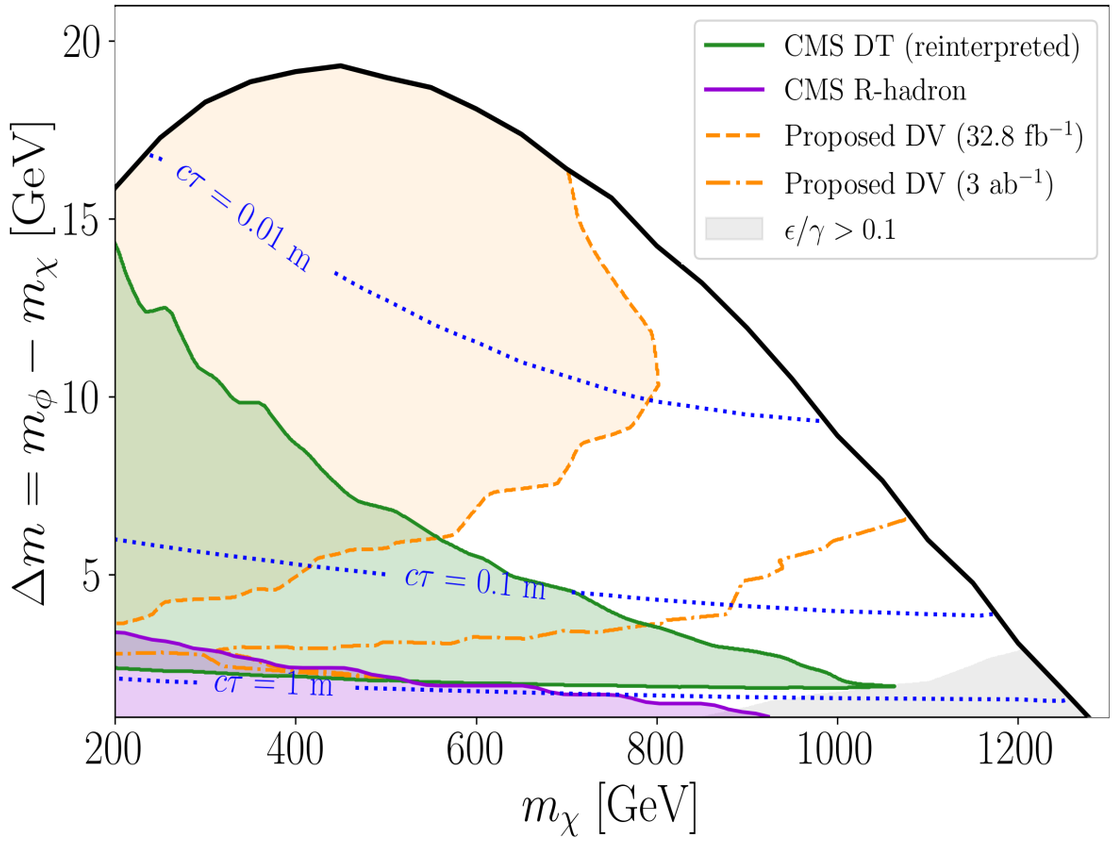
Leptophilic model:

[JH 2404.12428]



Quarkphilic model (down-type):

[Belfatto, Blanke, JH, Rathmann, Wilsch 2607.11147]



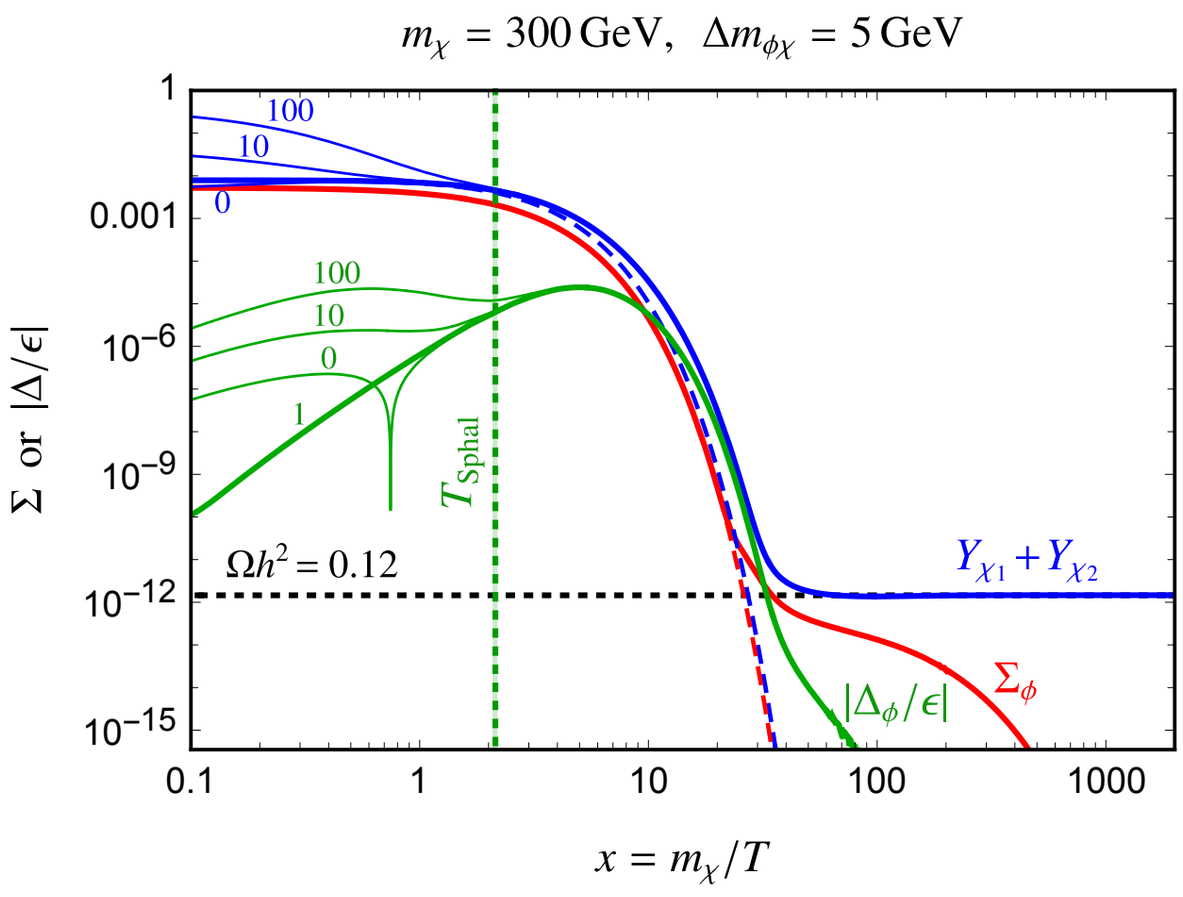
Conclusions

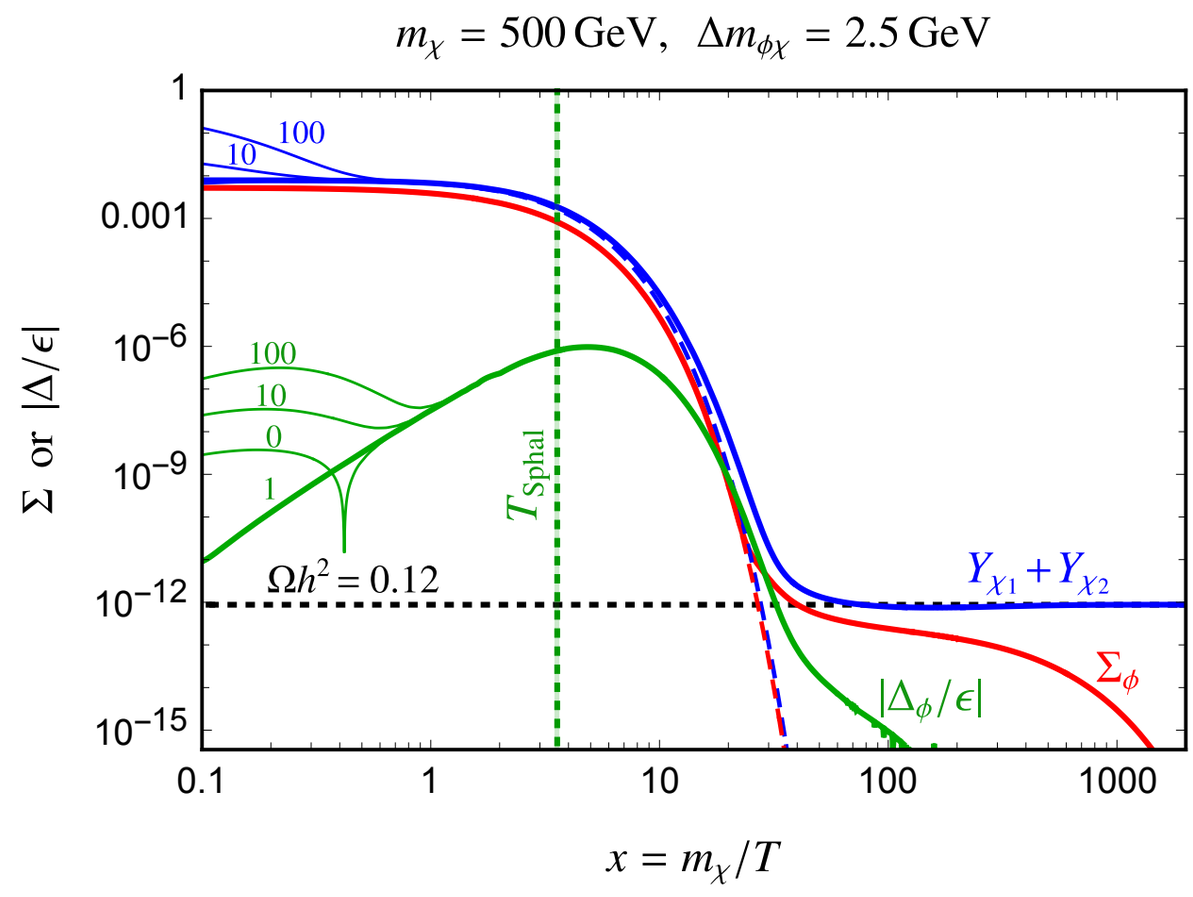
- CDFO points to very small couplings, $\lambda \sim 10^{-6}$ 
- Evades conventional WIMP constraints
- Naturally implies LLPs at colliders: soft displaced signatures not well covered yet ⇒ prime targets for future searches
- Interesting regime on the edge of thermal equilibrium
  - provide thermalization
  - sufficient departure for baryogenesis
  - technically challenging
- In flavored realizations: CP violation and flavor breaking
- Leptophilic realizations: a route toward a common explanation of dark matter, baryogenesis, and neutrino masses

Thank you!

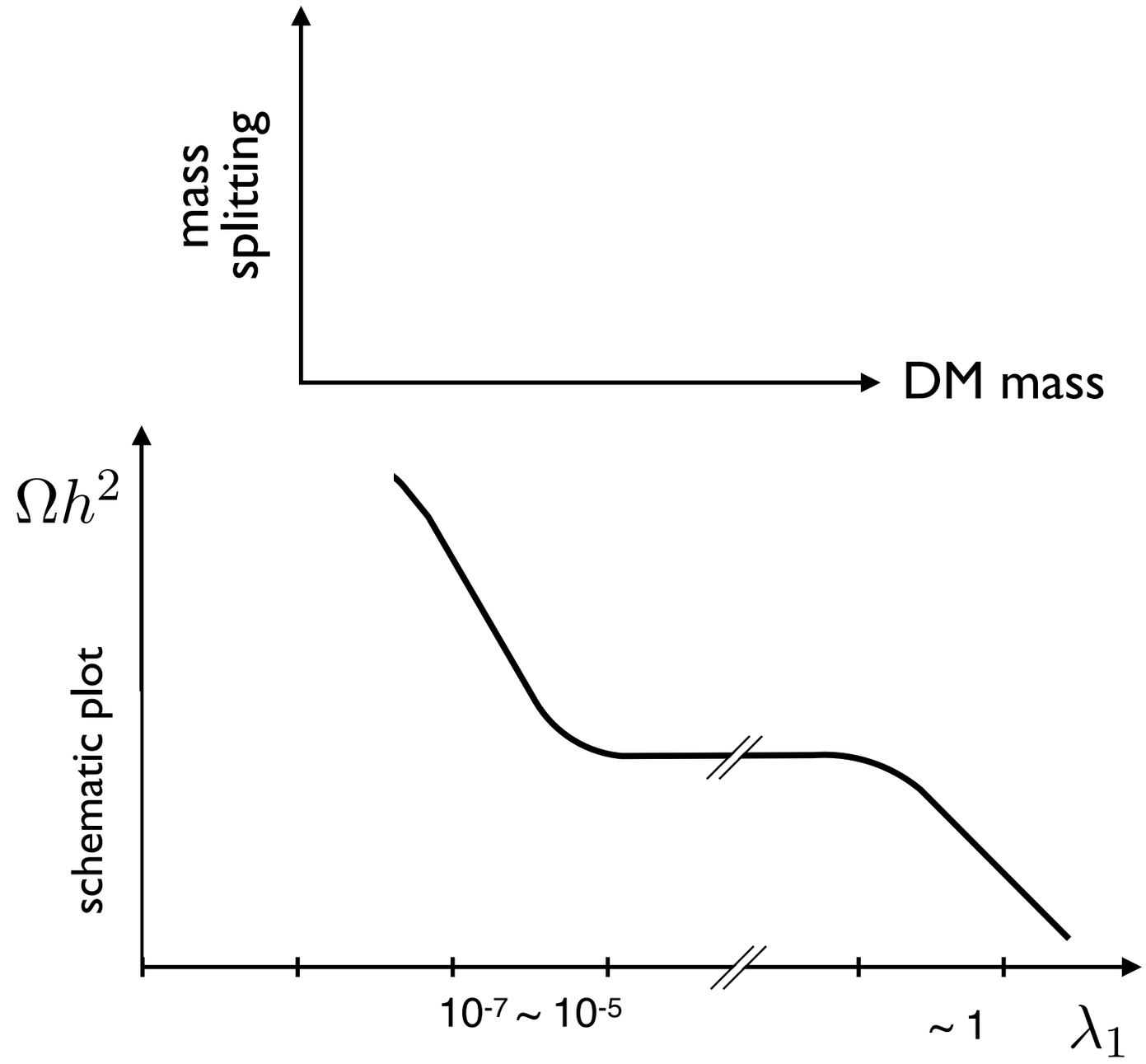
Backup slides

Conversion-driven leptogenesis: Dependence on initial conditions

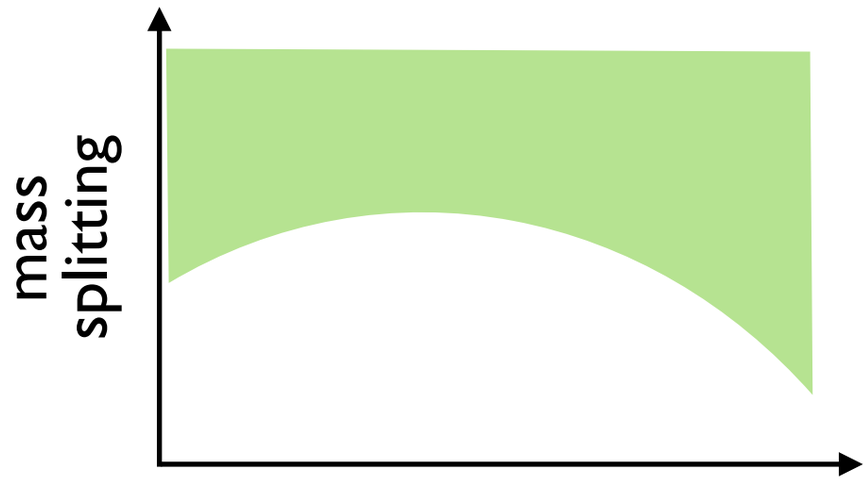


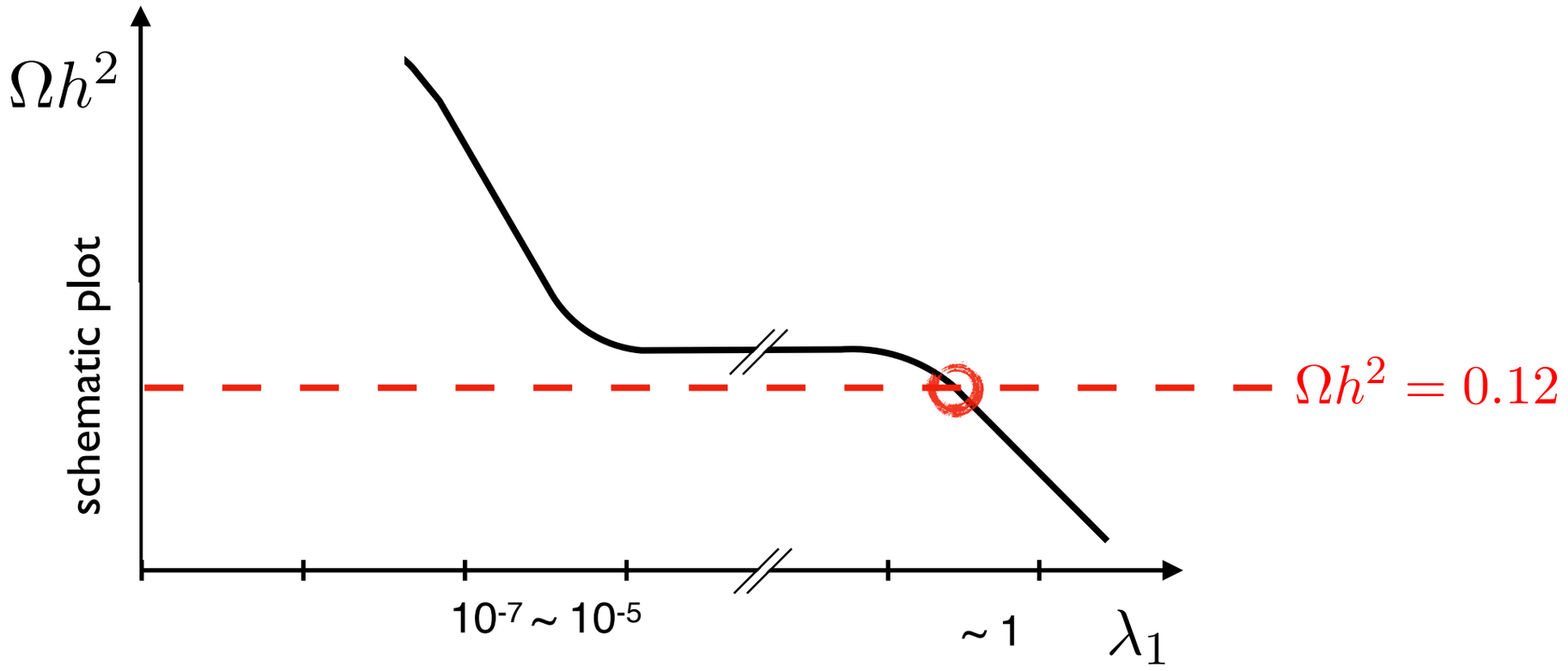


Viable CDFO parameter space

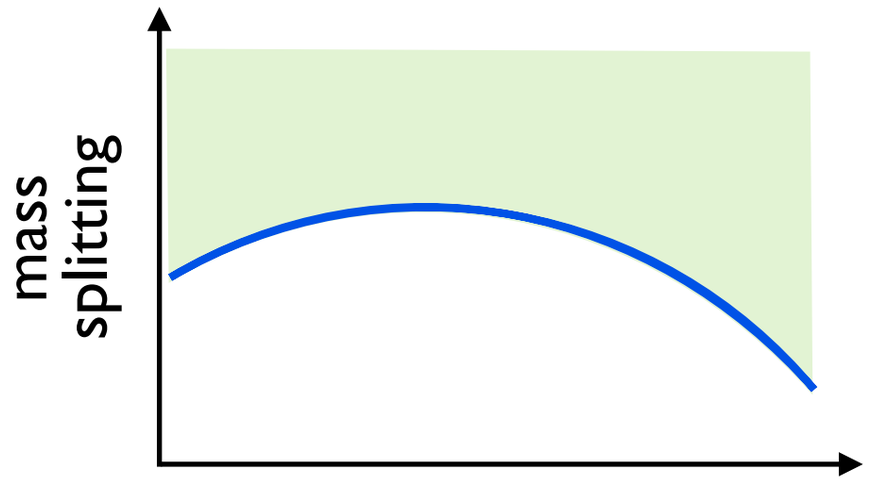


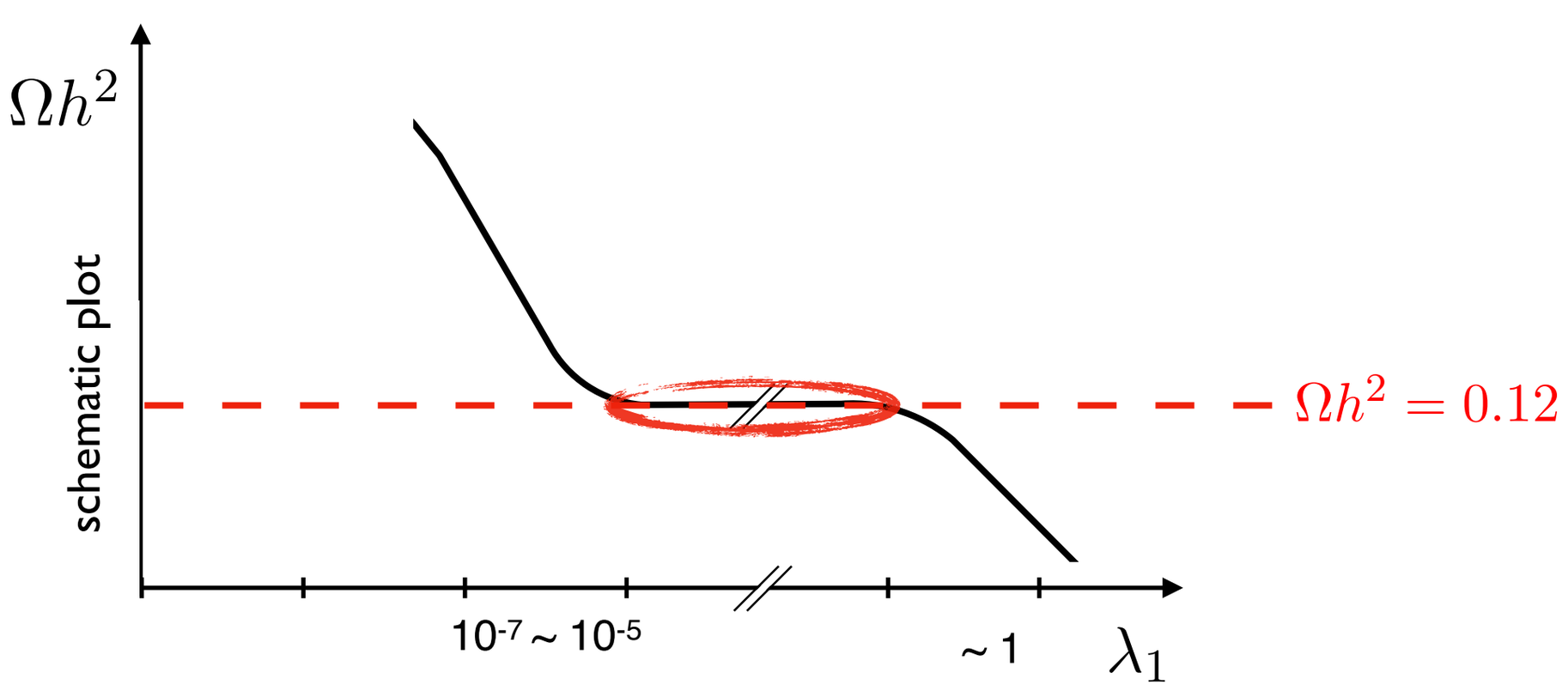
Viable CDFO parameter space



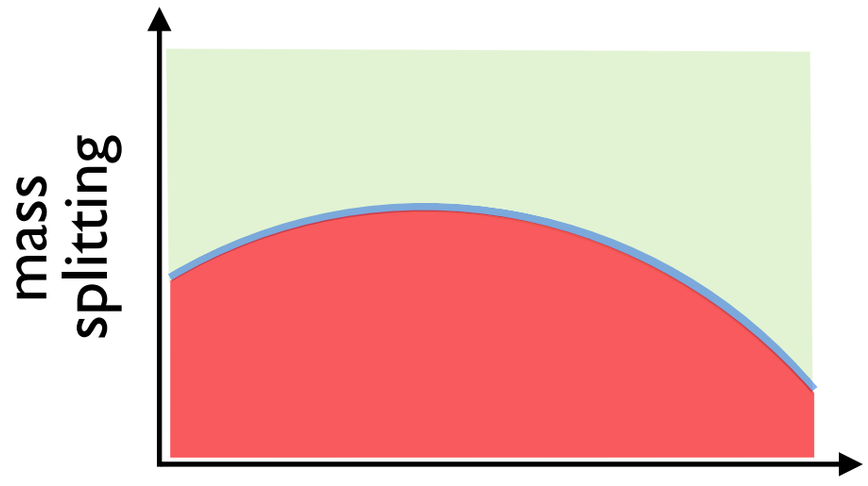


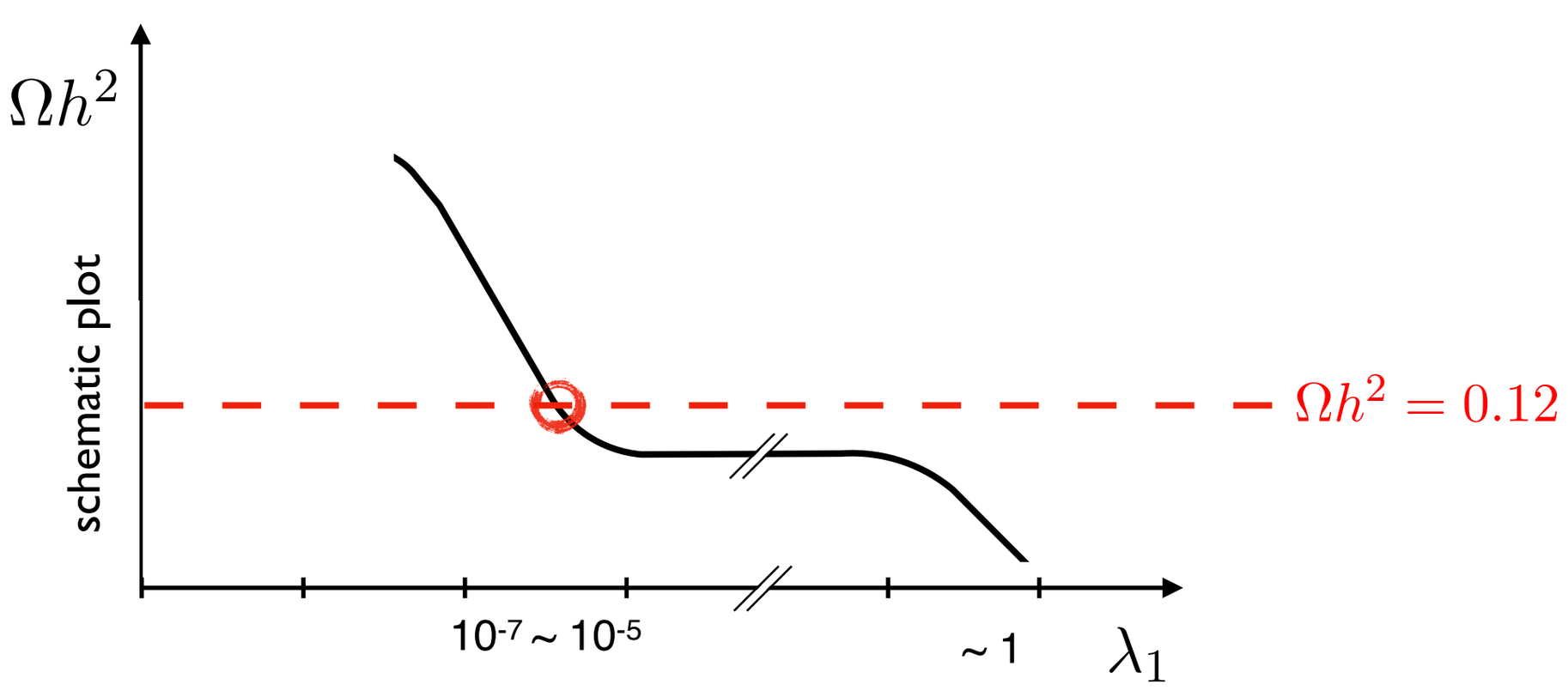
Viable CDFO parameter space



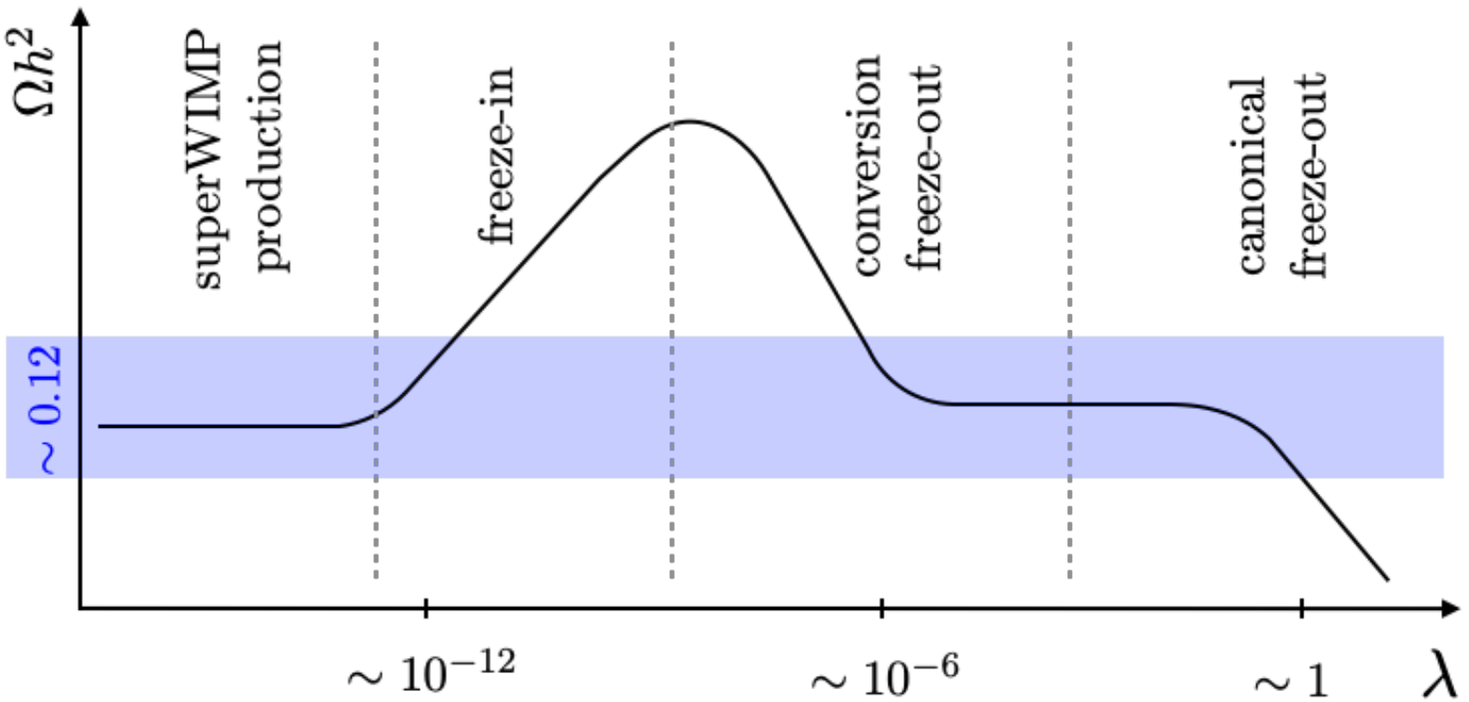


Viable CDFO parameter space





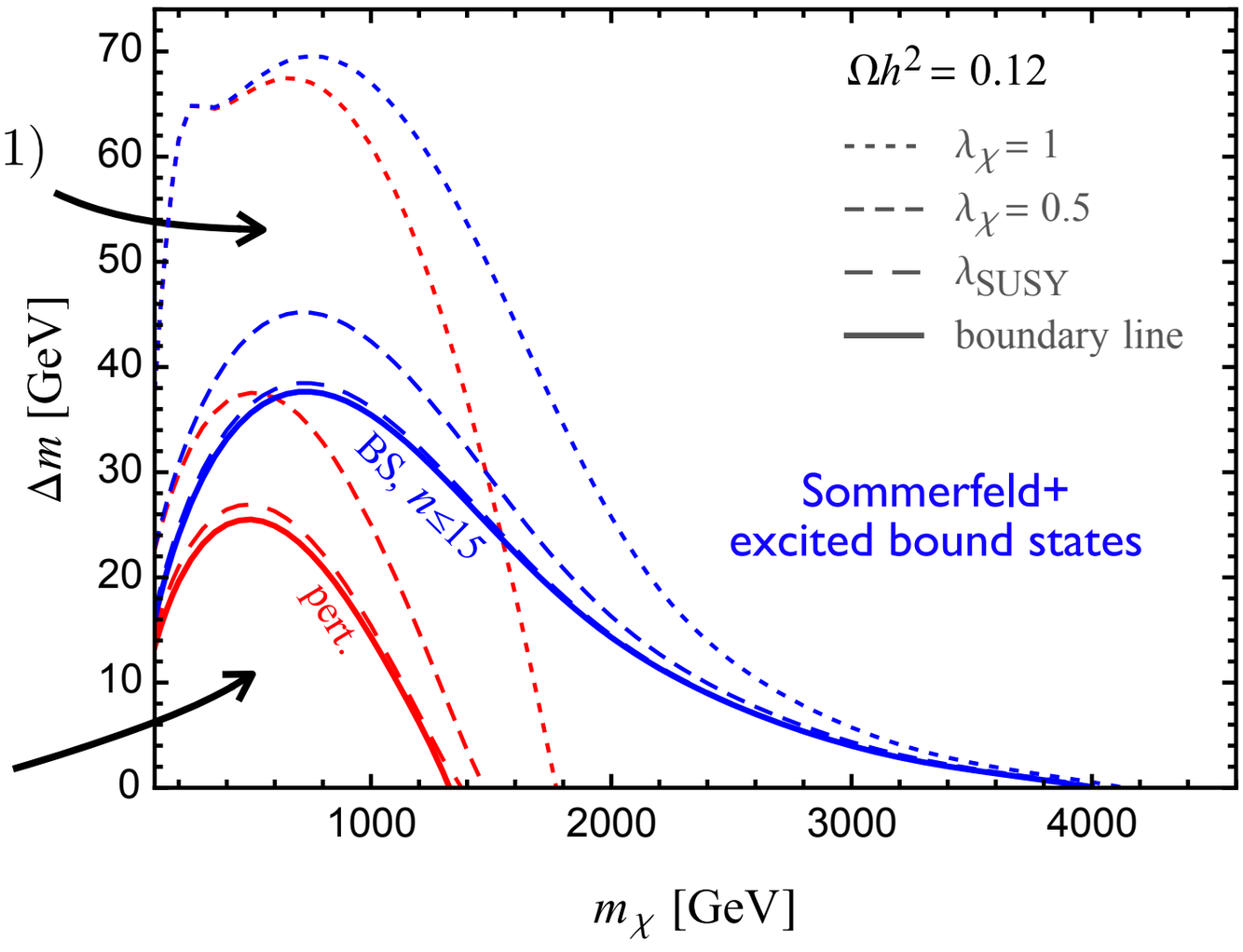
Cosmologically viable regions across various regimes



Bound state effects on the parameter space

[Garny, JH 2112.01499]

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

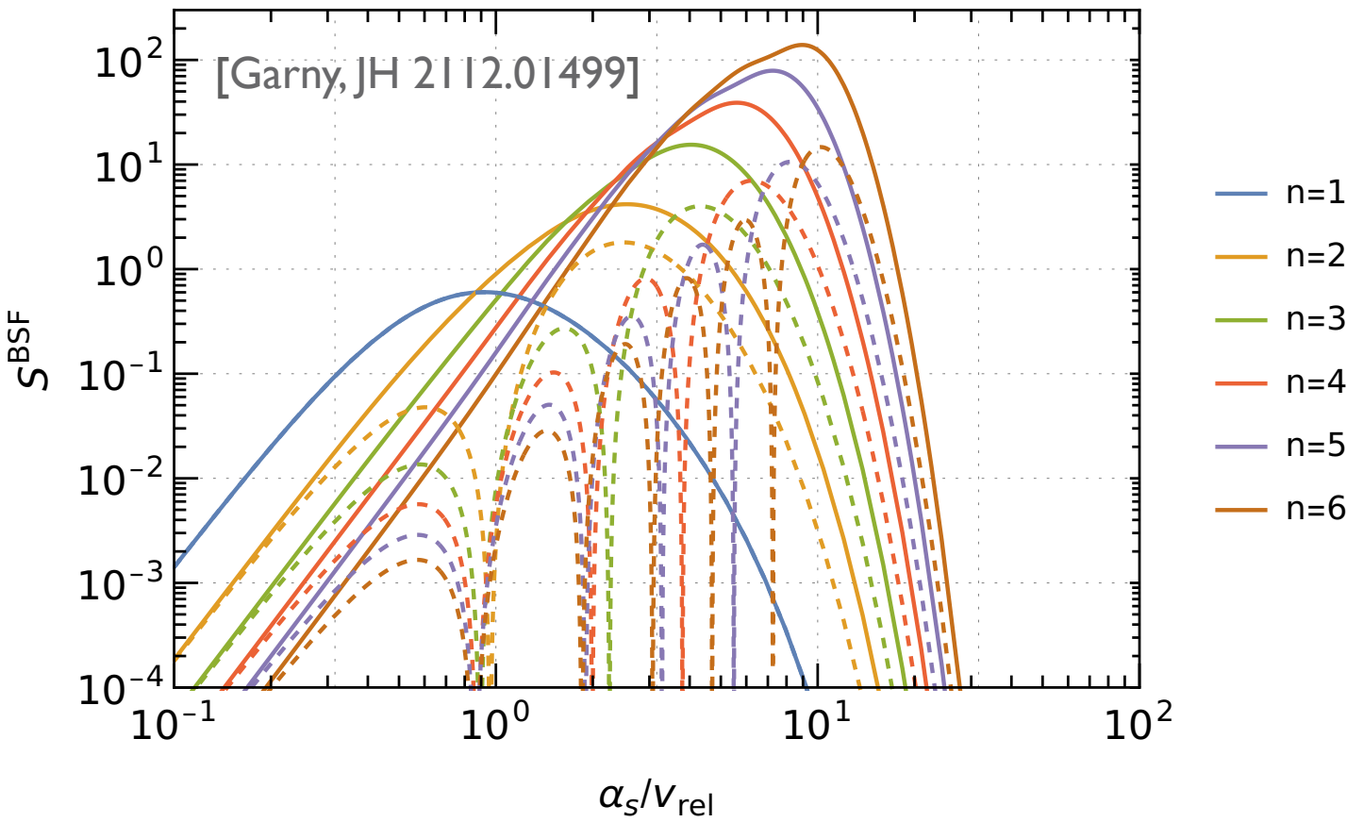


Conversion-driven freeze-out region, $\lambda_\chi \sim 10^{-6}$

Bound state formation cross section

$$\sigma^{\tilde{q}\tilde{q}^\dagger \to \mathcal{B}g}_{\mathrm{BSF},n\ell} v_{\mathrm{rel}} \;\propto\; \alpha_{\mathrm{s}}\omega^3 \left|\langle \psi^{[\mathbf{1}]}_{n\ell} | \boldsymbol{r} | \psi^{[\mathbf{8}]}_{\boldsymbol{p}_{\mathrm{rel}}} \rangle\right|^2$$

[Color-electric dipol operator, computed in potential nonrel. QCD, see e.g. X. Yao, B. Müller 1811.09644]



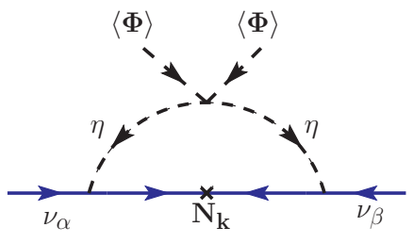
small velocities ~ relevant for small temperatures

Neutrino mass link [J. Heeck, JH, A. Thapa, 2211.13013]

Scotogenic model:
[E. Ma, 2006]

Dark matter multiplet N_i $\quad m_{N_1} < m_{H^+,H,A}$ $A\ H\ H^+$ Scalar ‘mediators’

$$|Y|_{2,3} \sim \frac{(10^{-6}\text{–}10^{-5})}{\lambda_5^{1/4}} \qquad g_{\rm ew}\,,\,\lambda_i$$



- Natural conversion-driven regime for O(1) scalar couplings
  [J. Heeck, JH, A. Thapa, 2211.13013]
- Provides all ingredients for leptogenesis

Neutrino mass link [J. Heeck, JH, A. Thapa, 2211.13013]

- Relate to neutrino masses using Casas-Ibarra parametrization:

$$y = U_{\rm PMNS}\sqrt{\mathcal{M}_\nu}^{\rm diag} R^\dagger \sqrt{\Lambda^{-1}}$$

- Use best-fit parameters from NuFit 5.1 [Esteban *et al.* 2020]

$m_H < m_{H^+}$, benchmark point ★

