Long-lived particles and *t*-channel models

Jan Heisig (RWTH Aachen / UVA)

University of Virginia

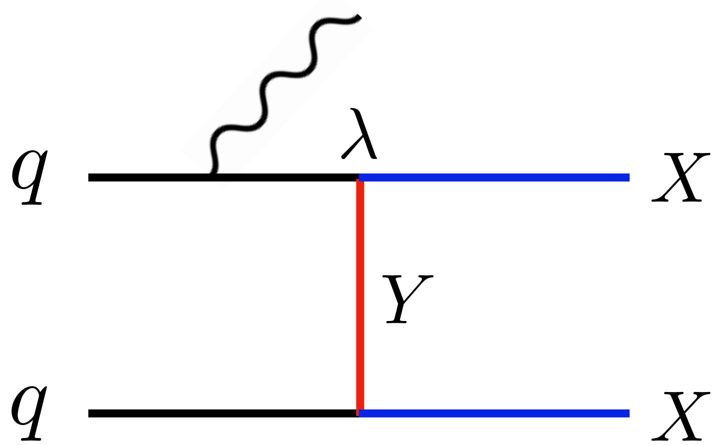
TTK Institute for Theoretical Particle Physics and Cosmology | RWTH Aachen University

Alexander von Humboldt Stiftung

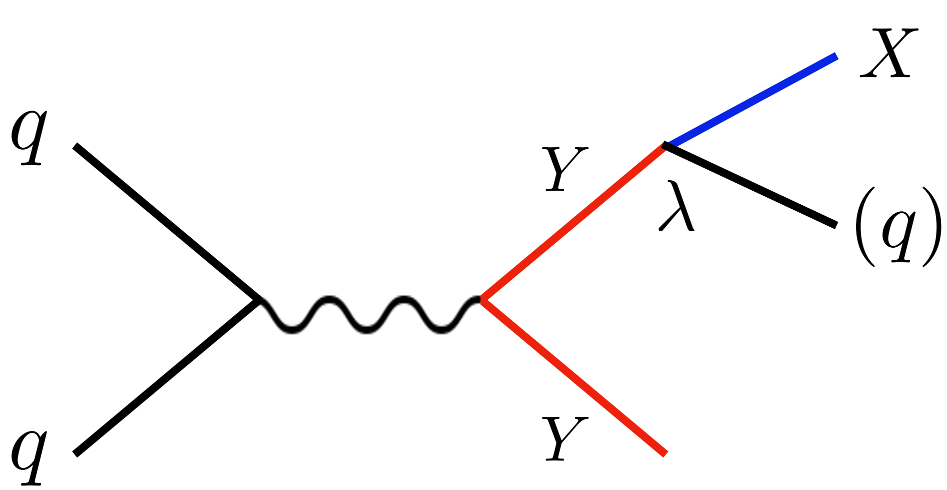
Towards a t-channel DM whitepaper
– status report meeting –

Why long-lived particles (LLPs)?

- Minimal quark-philic models:



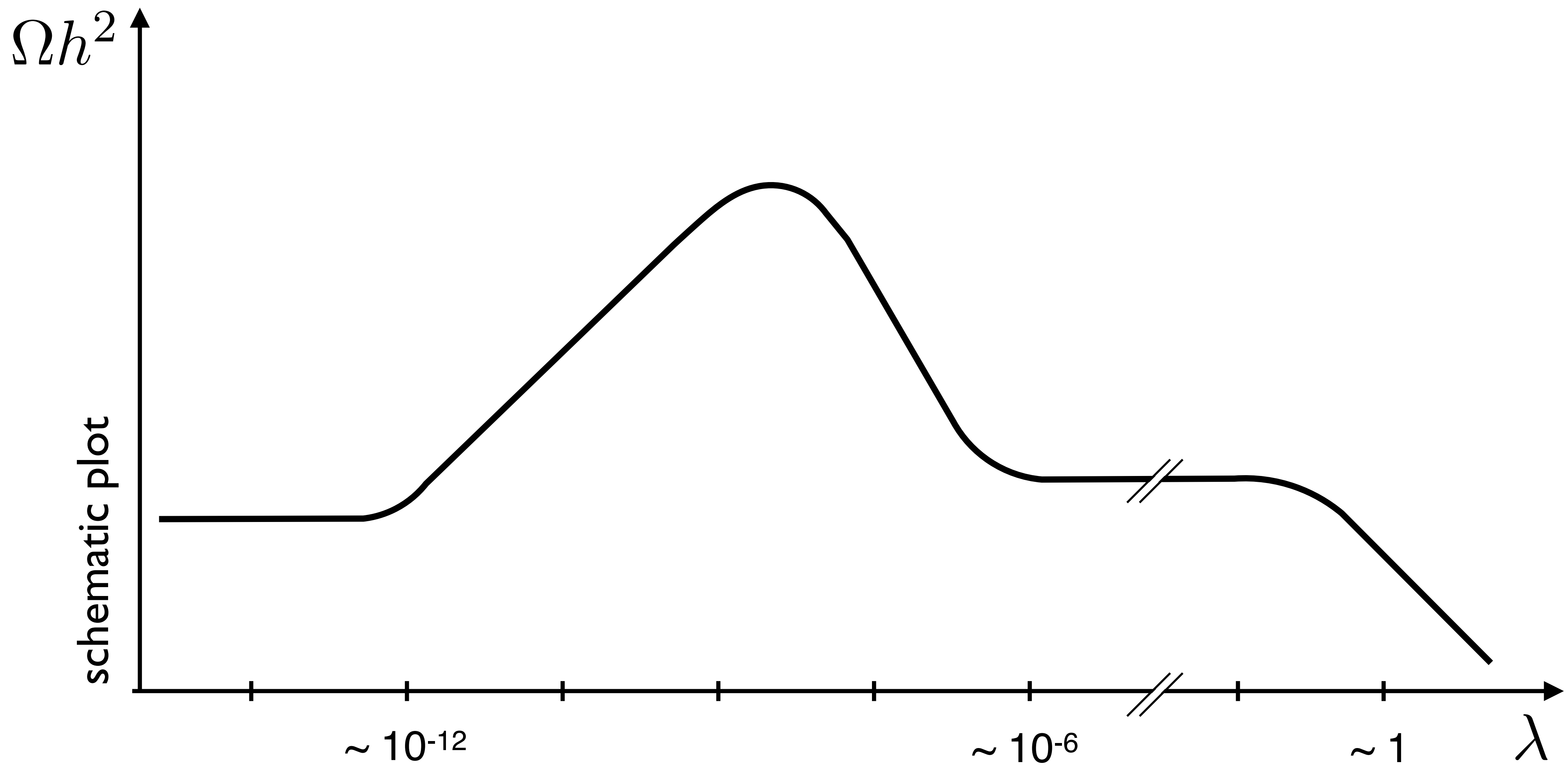
$\Rightarrow$ MET signature



$\Rightarrow$ LLPs if:

- λ small or/and
- Small mass splitting, in particular: $\Delta m = m_Y - m_X < m_{(q)}$

Range of dark matter couplings



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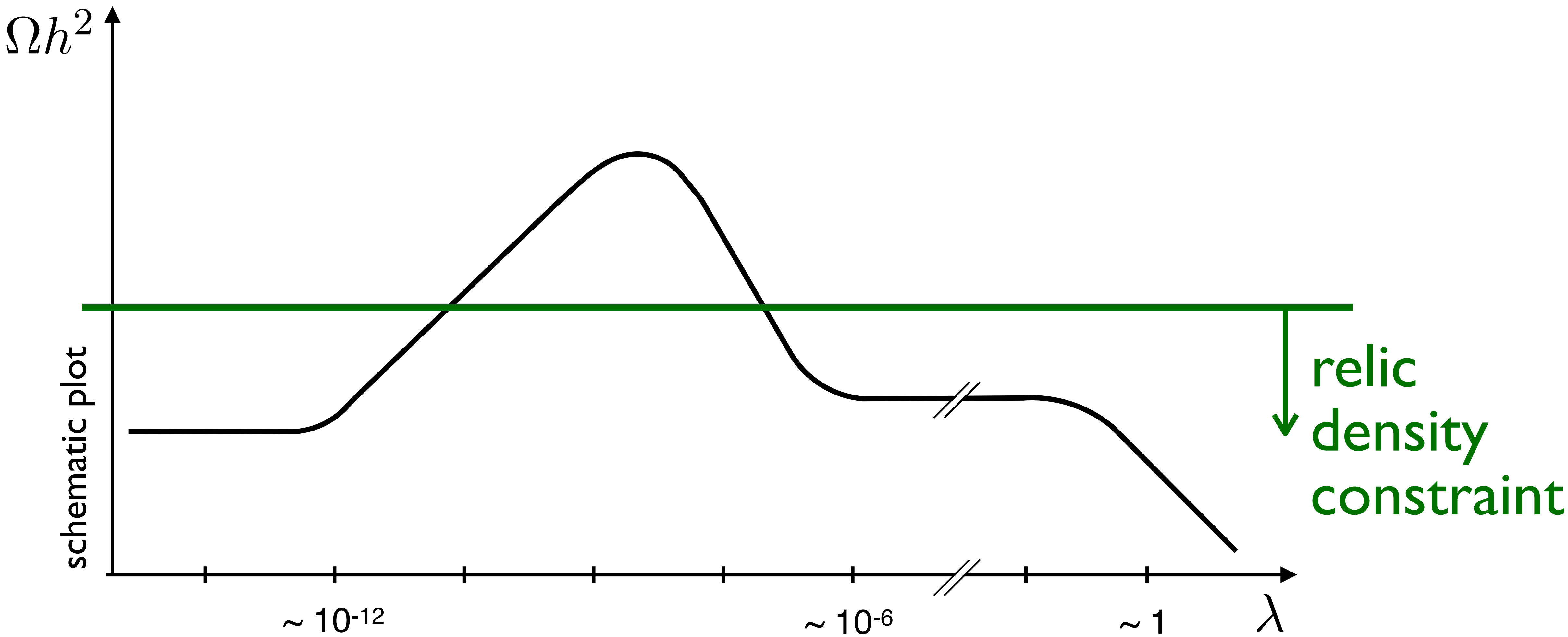

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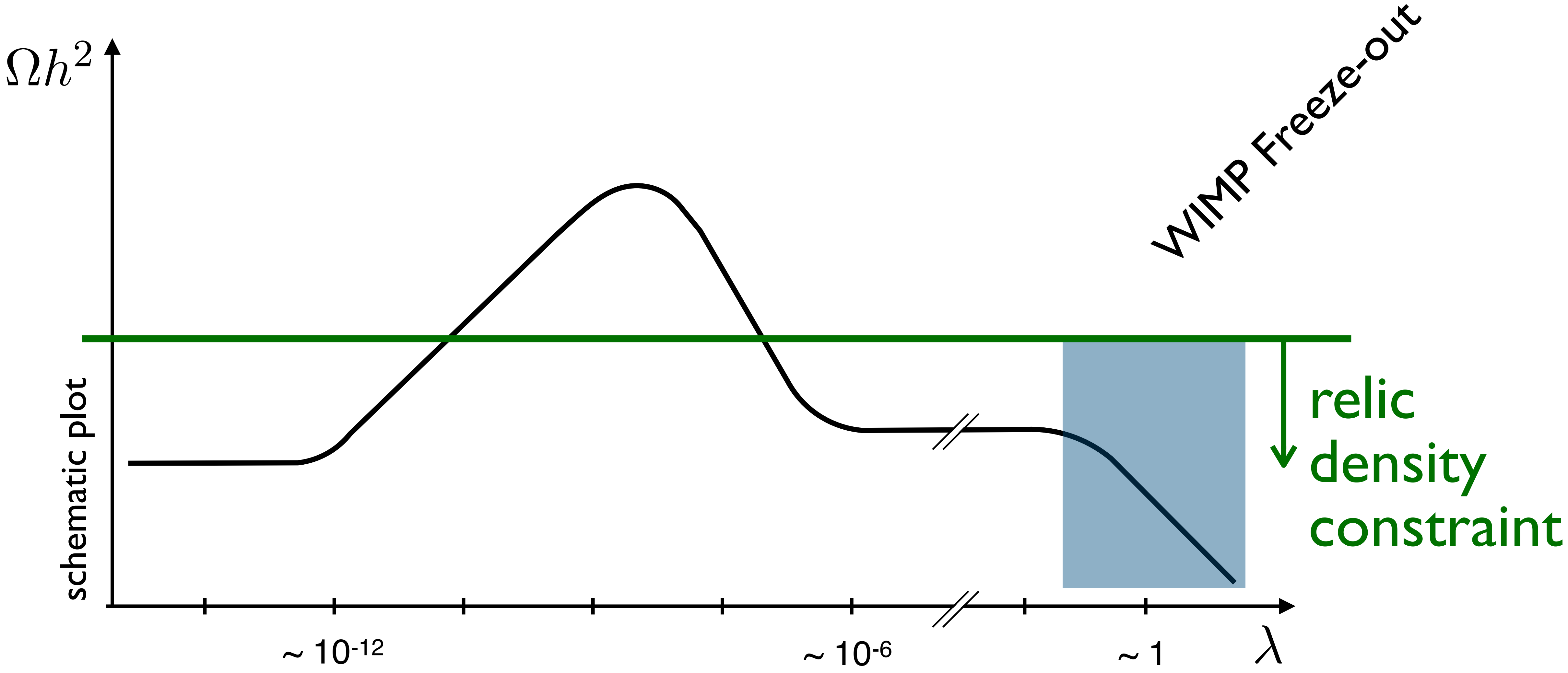

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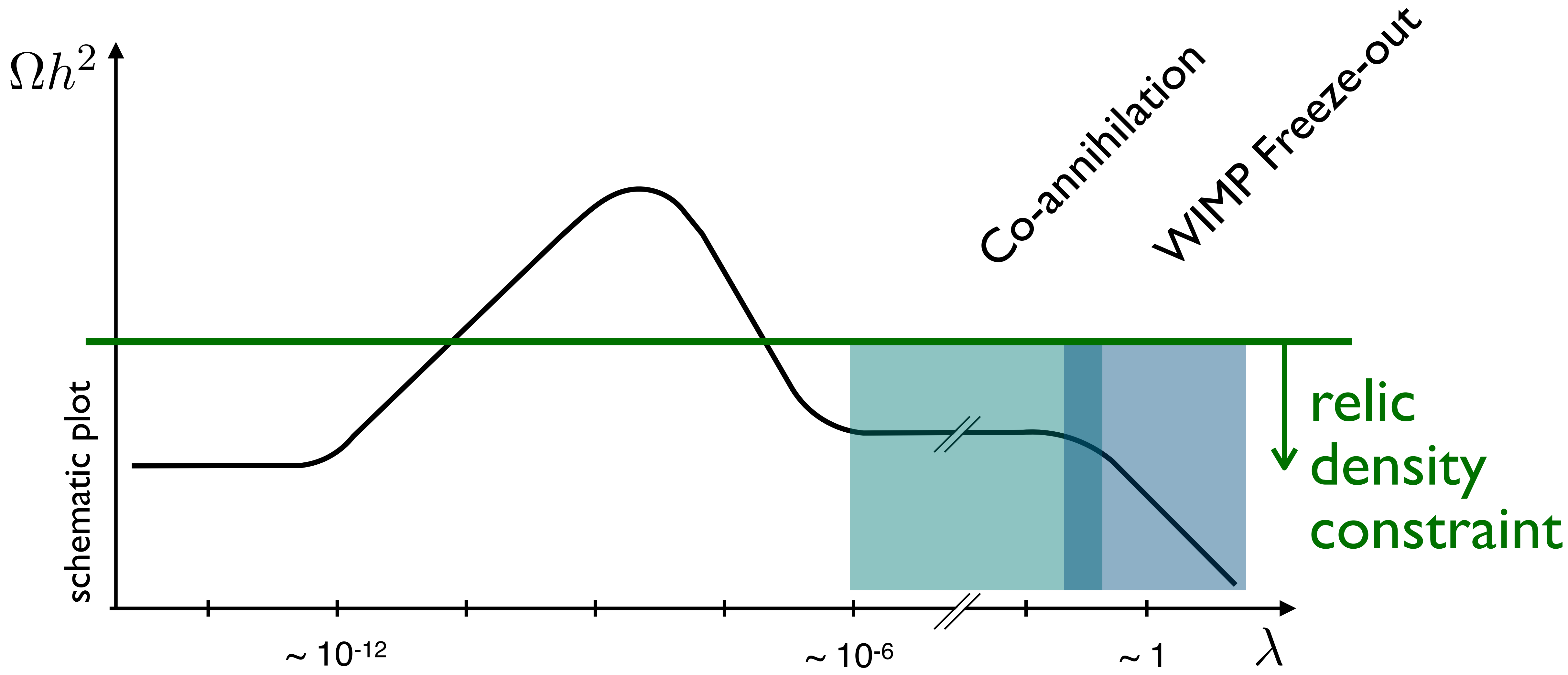

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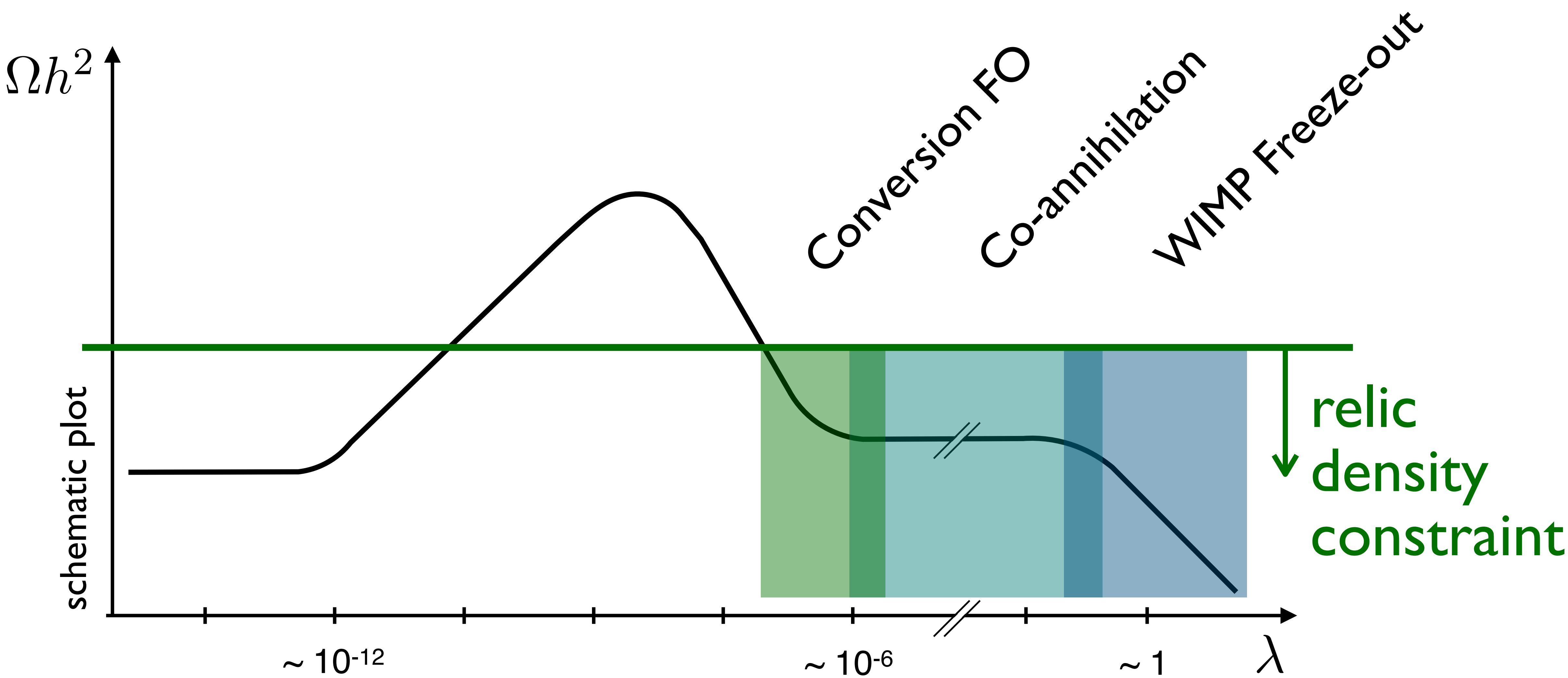

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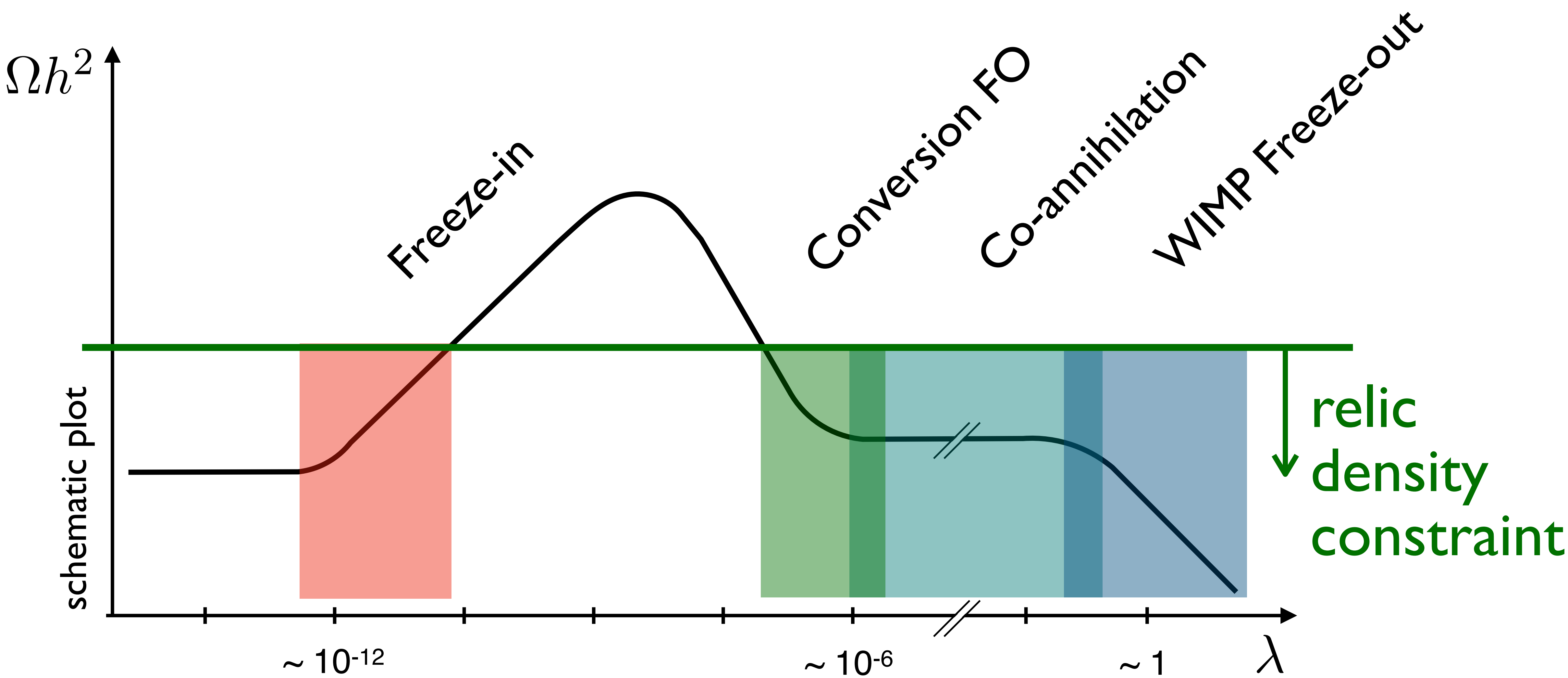

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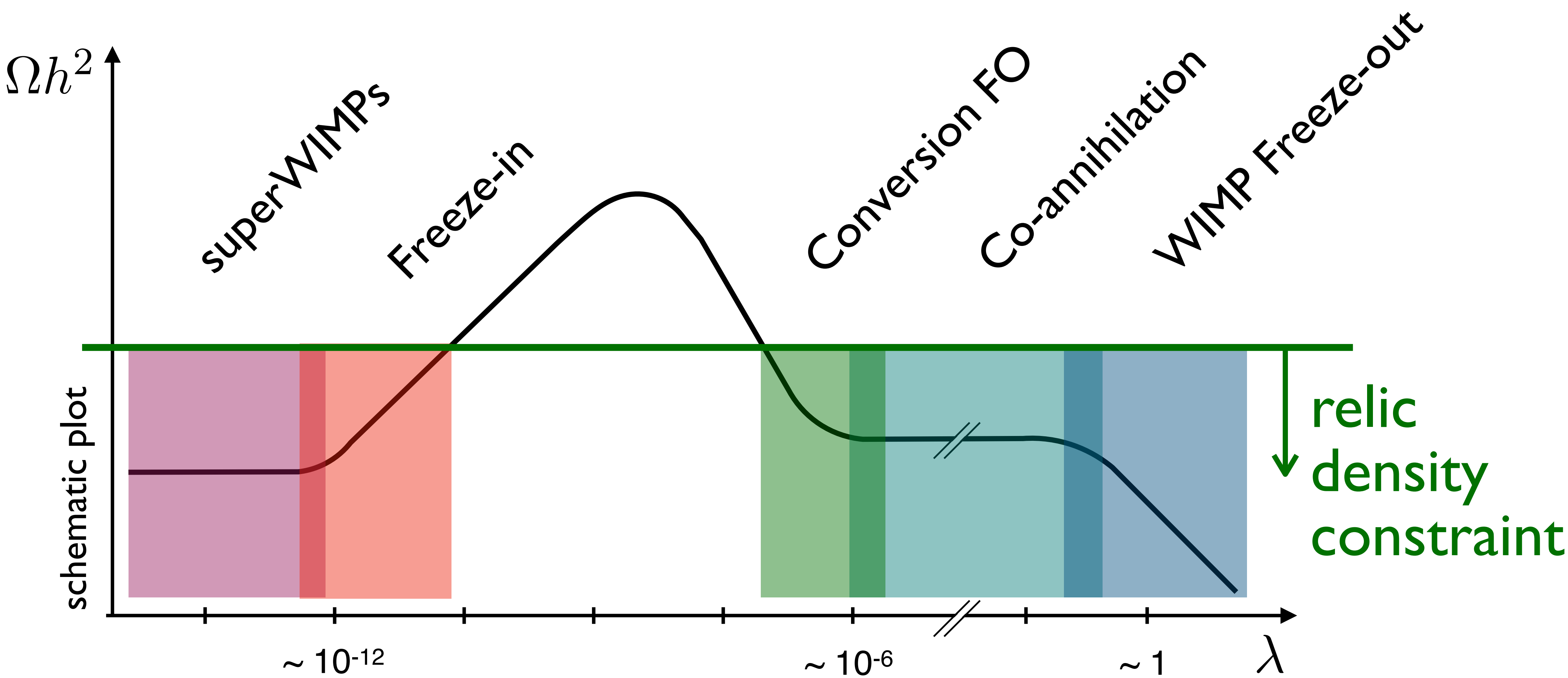

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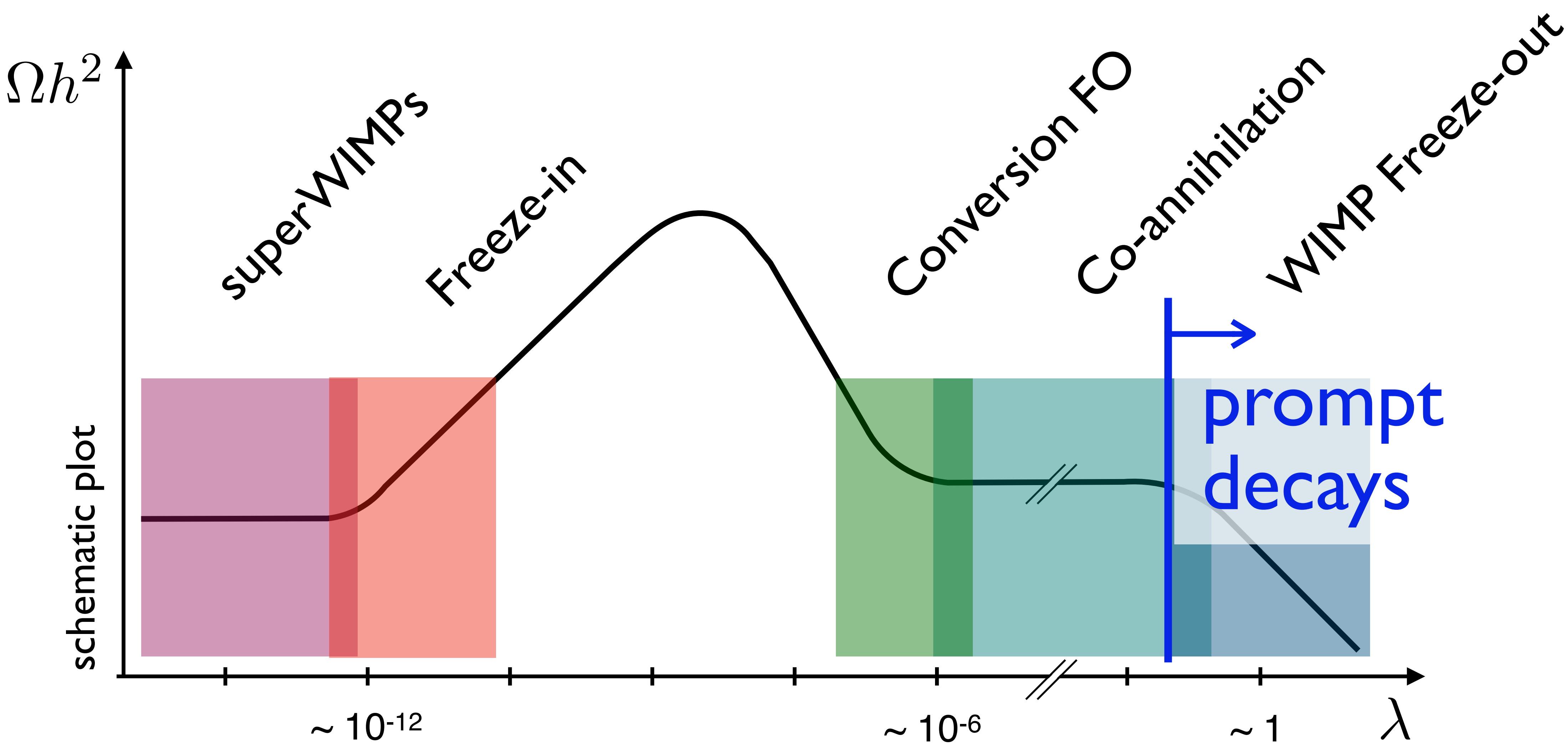

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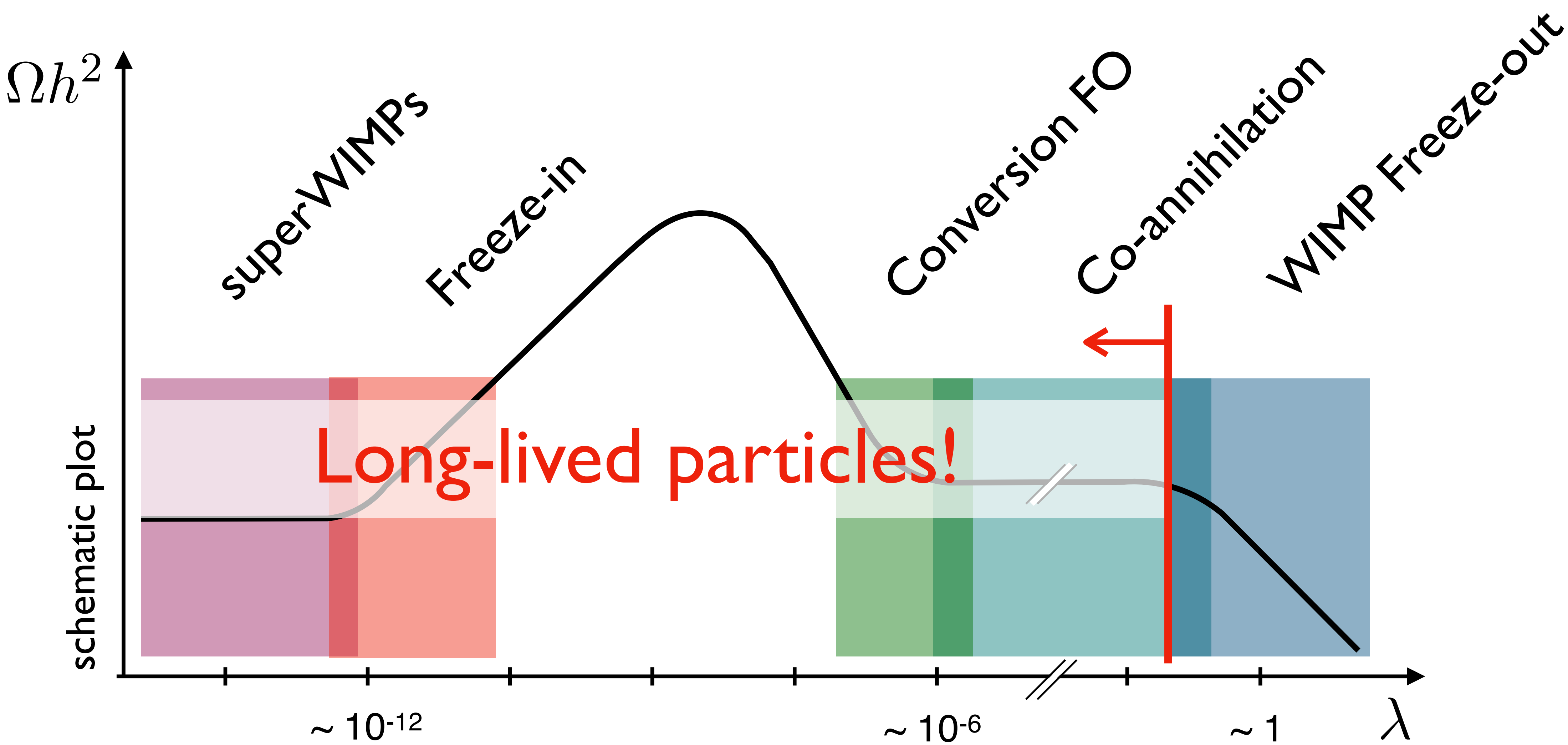

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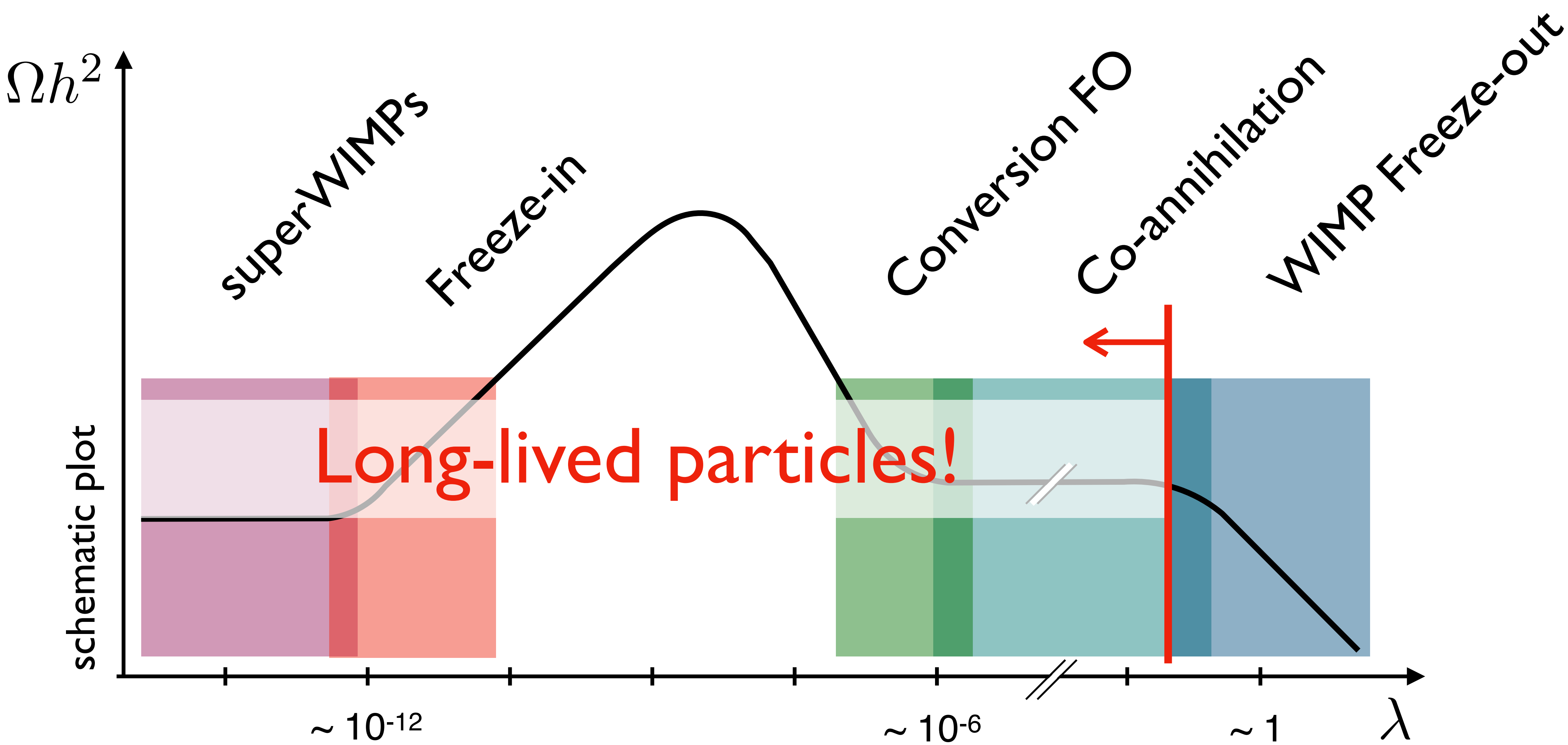
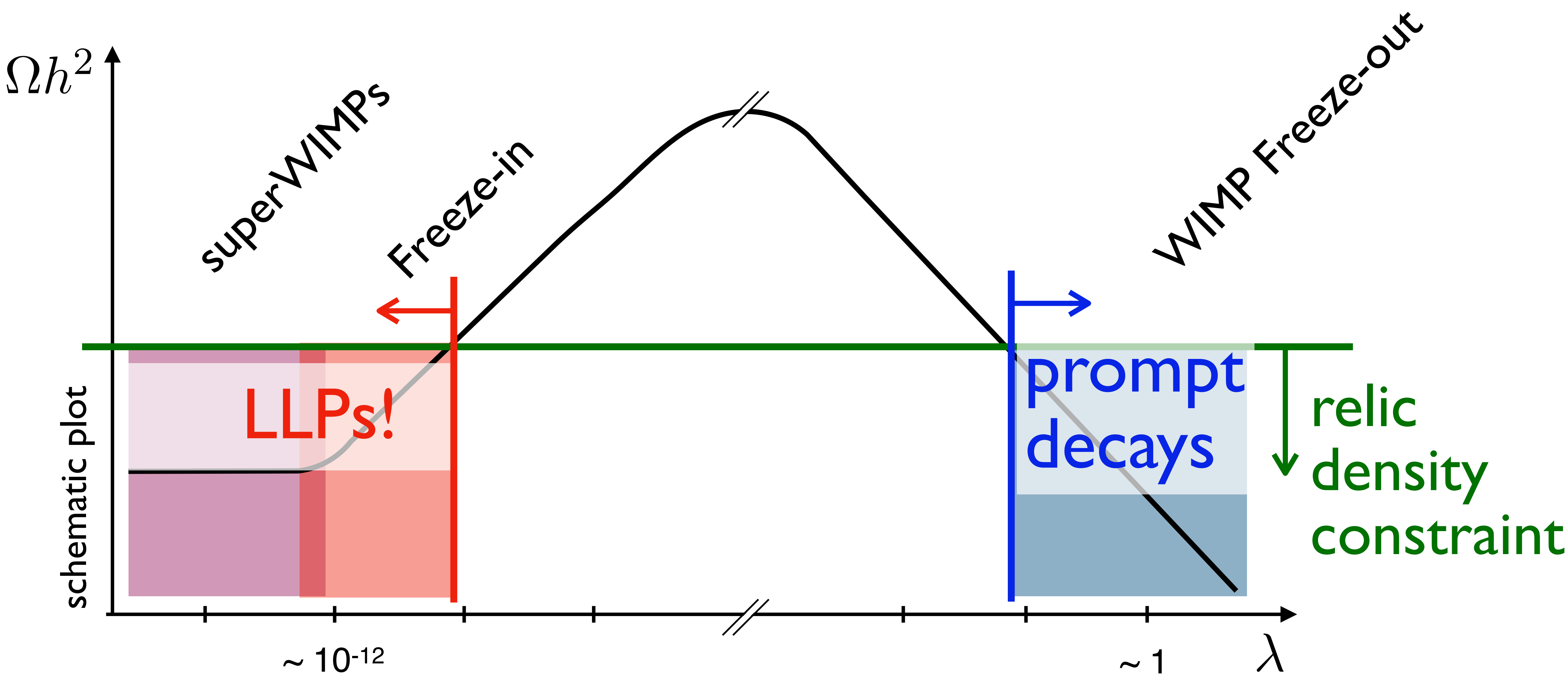


Plot only for small mass splittings, $\Delta m \lesssim 0.1 m_Y$!

Range of dark matter couplings (large mass splittings)



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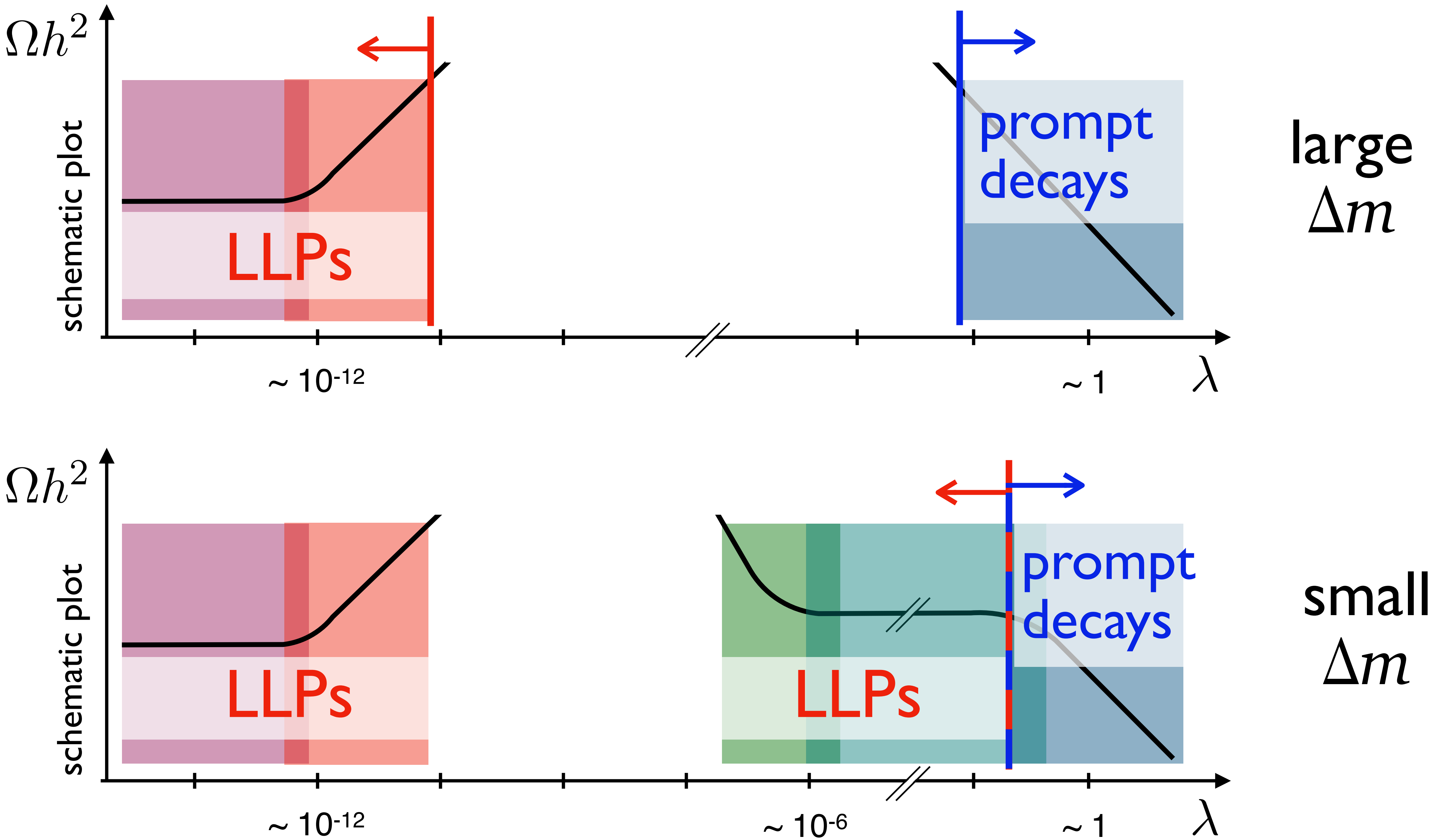

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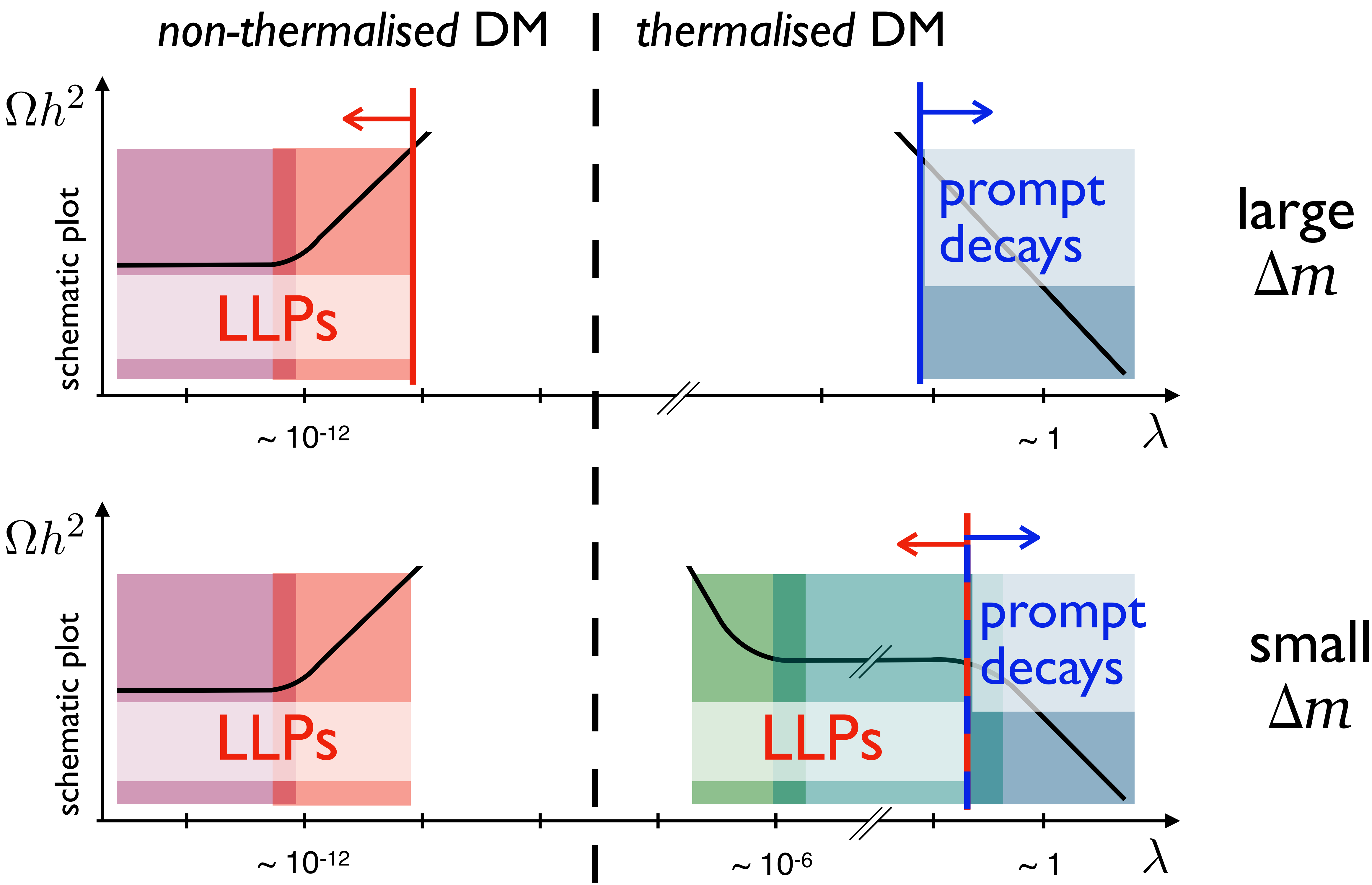
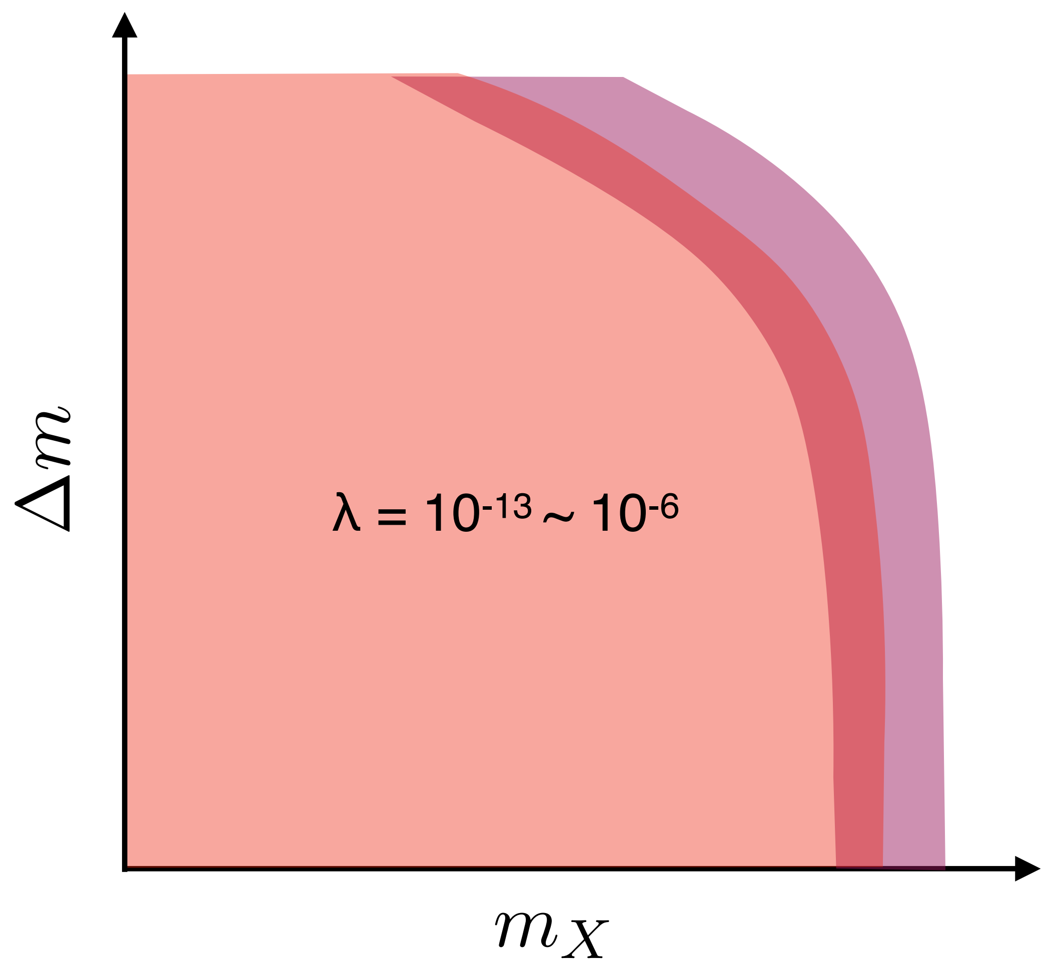
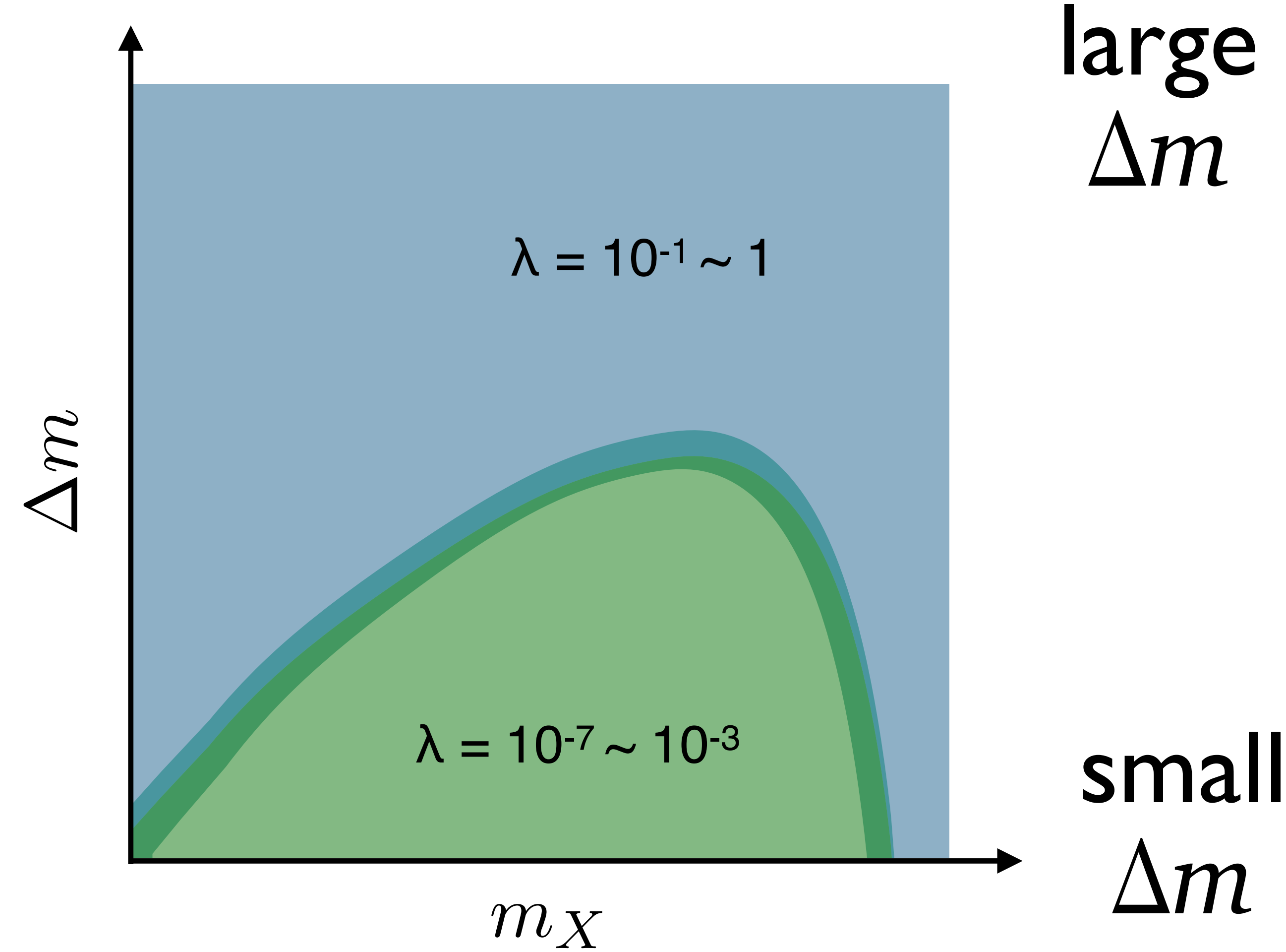


Range of dark matter couplings

non-thermalised DM | *thermalised* DM





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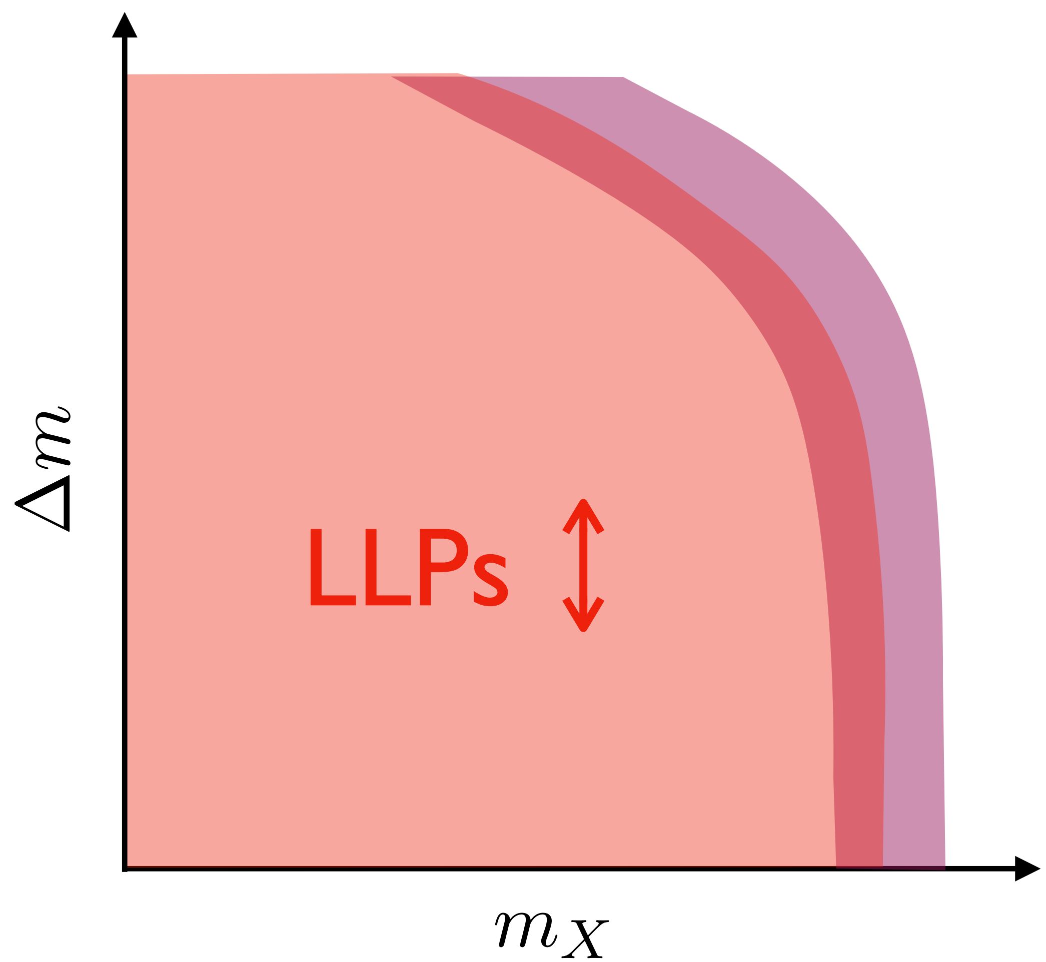

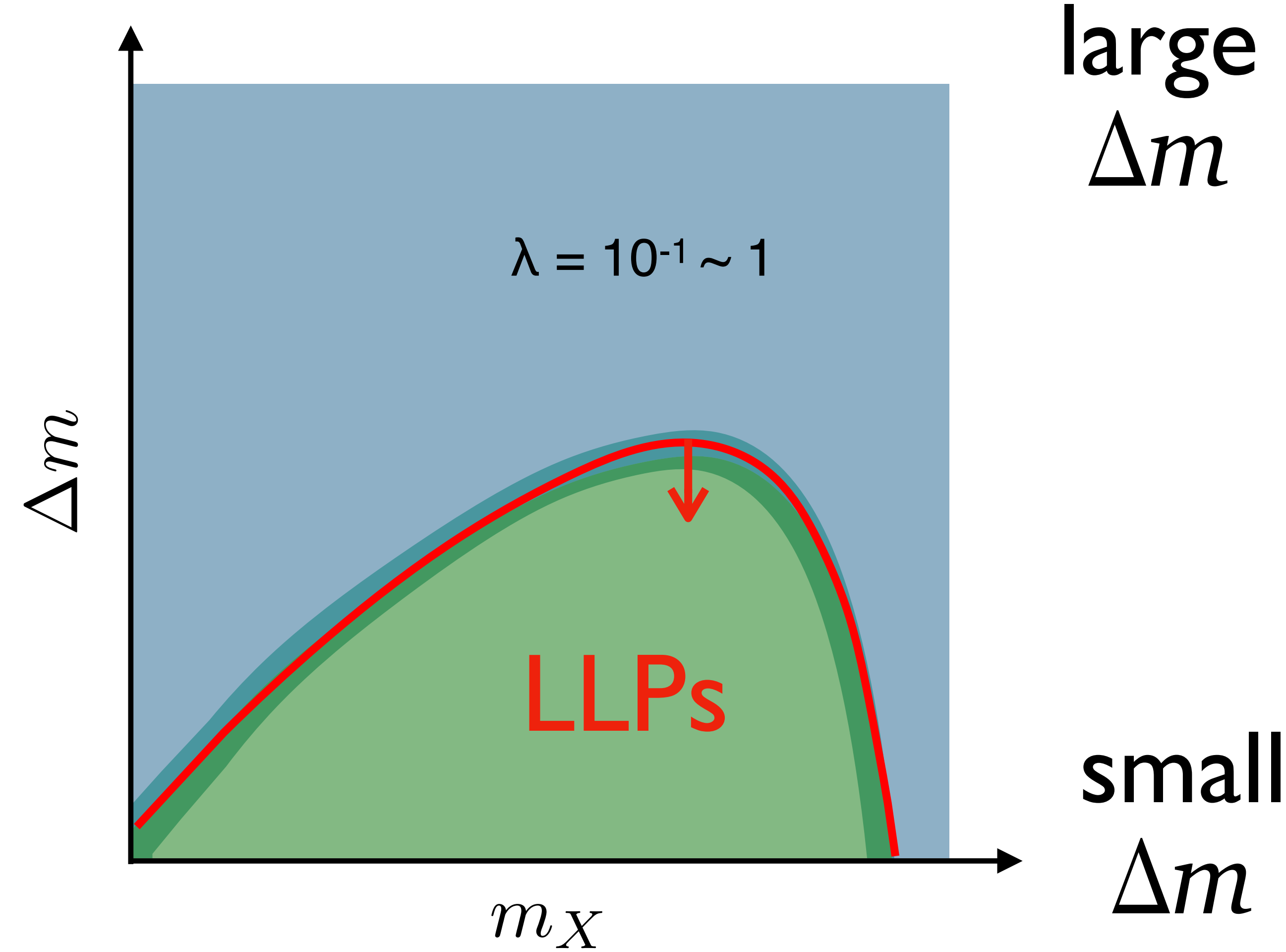

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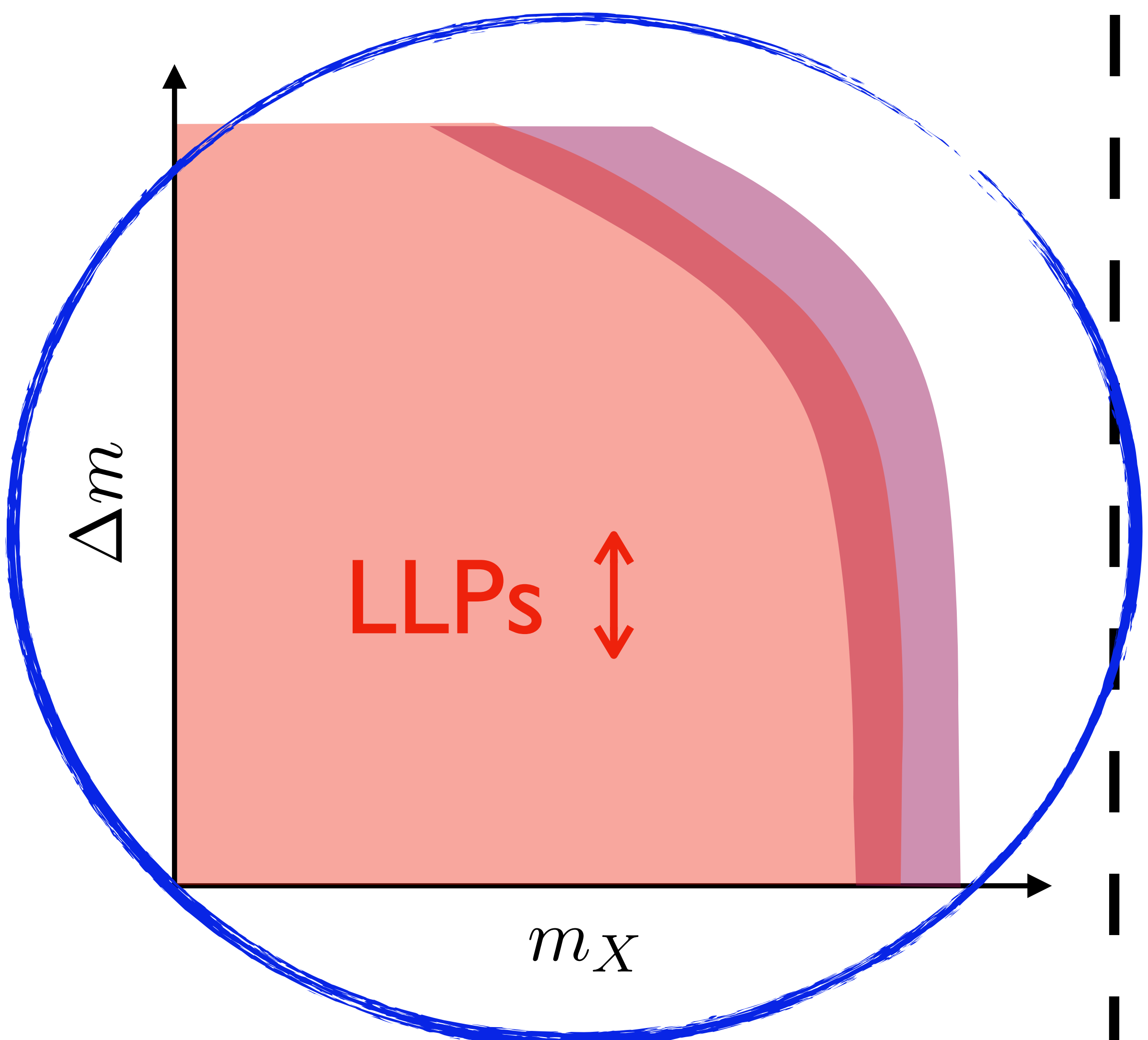
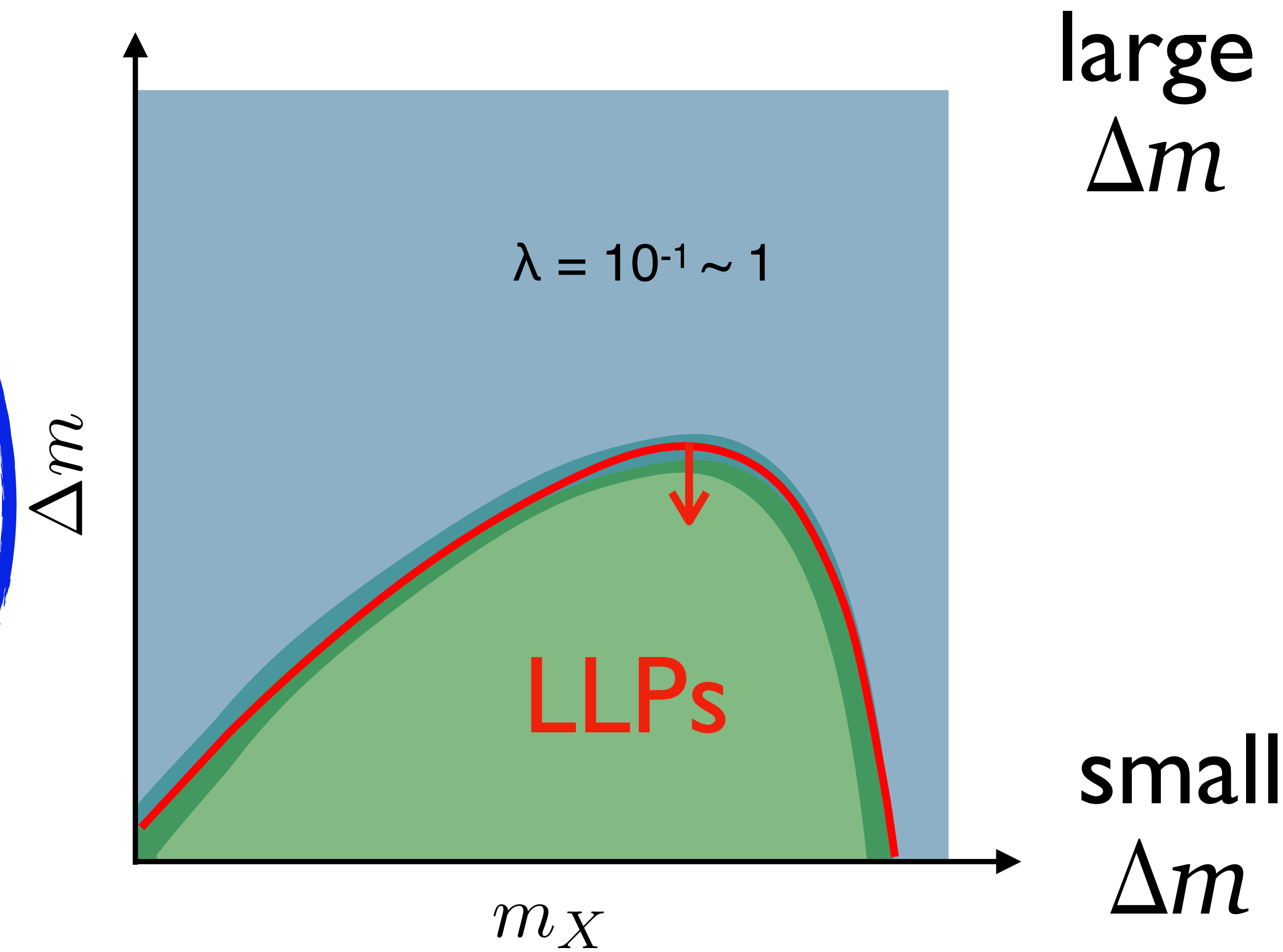
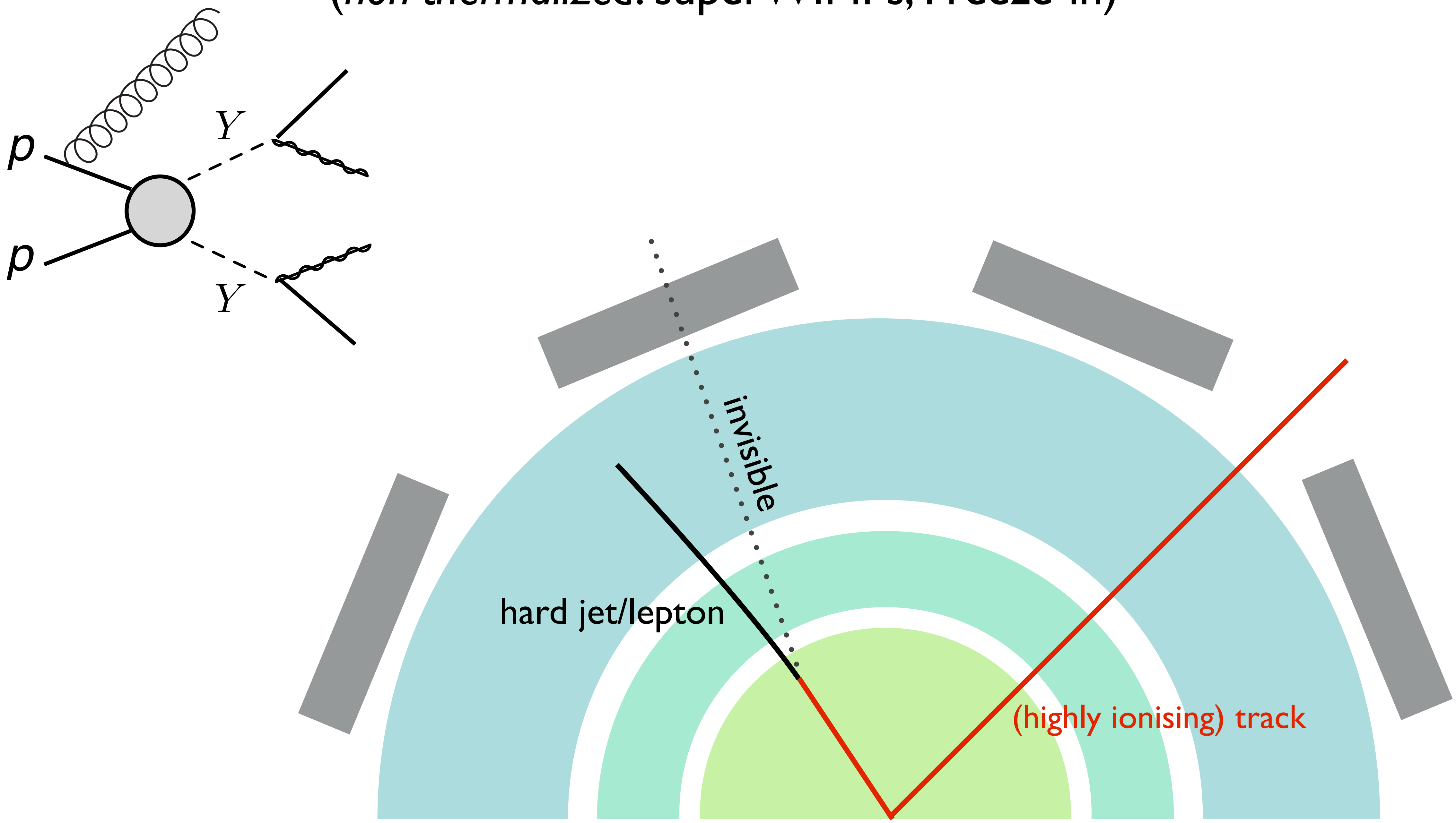
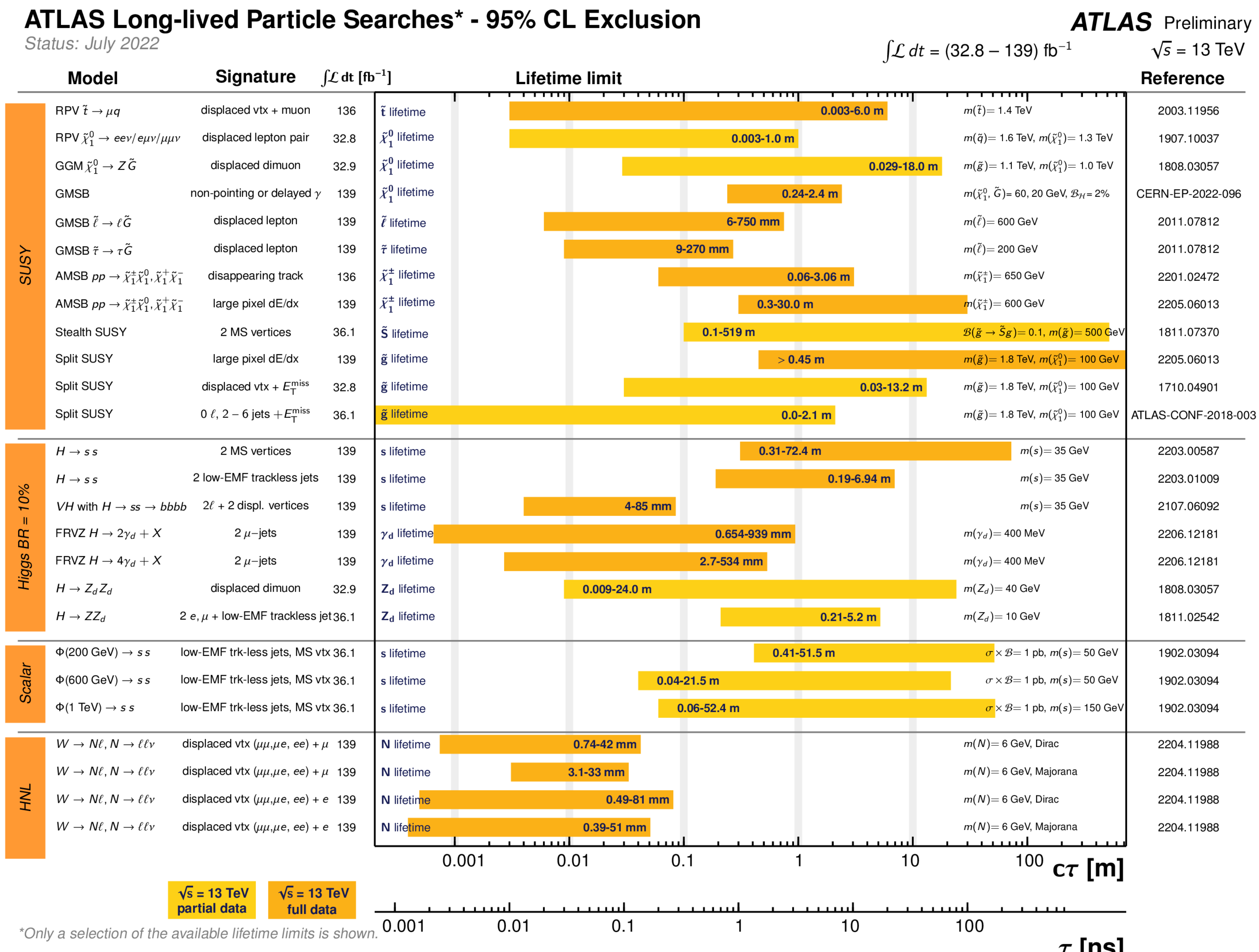




LLP Signatures: large Δm

(*non-thermalized*: superWIMPs, Freeze-in)





ATLAS Long-lived Particle Searches* - 95% CL Exclusion
Status: July 2022
ATLAS Preliminary
$\int\mathcal{L}\,dt = (32.8 - 139)\ \text{fb}^{-1}$
$\sqrt{s}$ = 13 TeV
Model
Signature
$\int\mathcal{L}\,dt\ [\text{fb}^{-1}]$
Lifetime limit
Reference
SUSY
RPV $\tilde{t} \to \mu q$ | displaced vtx + muon | 136 | $\tilde{t}$ lifetime | 0.003-6.0 m | $m(\tilde{t})$= 1.4 TeV | 2003.11956
RPV $\tilde{\chi}_1^0 \to ee\nu/e\mu\nu/\mu\mu\nu$ | displaced lepton pair | 32.8 | $\tilde{\chi}_1^0$ lifetime | 0.003-1.0 m | $m(\tilde{q})$= 1.6 TeV, $m(\tilde{\chi}_1^0)$= 1.3 TeV | 1907.10037
GGM $\tilde{\chi}_1^0 \to Z\tilde{G}$ | displaced dimuon | 32.9 | $\tilde{\chi}_1^0$ lifetime | 0.029-18.0 m | $m(\tilde{g})$= 1.1 TeV, $m(\tilde{\chi}_1^0)$= 1.0 TeV | 1808.03057
GMSB | non-pointing or delayed γ | 139 | $\tilde{\chi}_1^0$ lifetime | 0.24-2.4 m | $m(\tilde{\chi}_1^0, \tilde{G})$= 60, 20 GeV, $\mathcal{B}_H$= 2% | CERN-EP-2022-096
GMSB $\tilde{\ell} \to \ell\tilde{G}$ | displaced lepton | 139 | $\tilde{\ell}$ lifetime | 6-750 mm | $m(\tilde{\ell})$= 600 GeV | 2011.07812
GMSB $\tilde{\tau} \to \tau\tilde{G}$ | displaced lepton | 139 | $\tilde{\tau}$ lifetime | 9-270 mm | $m(\tilde{\ell})$= 200 GeV | 2011.07812
AMSB $pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_1^0, \tilde{\chi}_1^{+}\tilde{\chi}_1^{-}$ | disappearing track | 136 | $\tilde{\chi}_1^{\pm}$ lifetime | 0.06-3.06 m | $m(\tilde{\chi}_1^{\pm})$= 650 GeV | 2201.02472
AMSB $pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_1^0, \tilde{\chi}_1^{+}\tilde{\chi}_1^{-}$ | large pixel dE/dx | 139 | $\tilde{\chi}_1^{\pm}$ lifetime | 0.3-30.0 m | $m(\tilde{\chi}_1^{\pm})$= 600 GeV | 2205.06013
Stealth SUSY | 2 MS vertices | 36.1 | $\tilde{S}$ lifetime | 0.1-519 m | $\mathcal{B}(\tilde{g} \to \tilde{S}g)$= 0.1, $m(\tilde{g})$= 500 GeV | 1811.07370
Split SUSY | large pixel dE/dx | 139 | $\tilde{g}$ lifetime | > 0.45 m | $m(\tilde{g})$= 1.8 TeV, $m(\tilde{\chi}_1^0)$= 100 GeV | 2205.06013
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Higgs BR = 10%
$H \to s\,s$ | 2 MS vertices | 139 | s lifetime | 0.31-72.4 m | $m(s)$= 35 GeV | 2203.00587
$H \to s\,s$ | 2 low-EMF trackless jets | 139 | s lifetime | 0.19-6.94 m | $m(s)$= 35 GeV | 2203.01009
VH with $H \to ss \to bbbb$ | 2ℓ + 2 displ. vertices | 139 | s lifetime | 4-85 mm | $m(s)$= 35 GeV | 2107.06092
FRVZ $H \to 2\gamma_d + X$ | 2 μ–jets | 139 | γ_d lifetime | 0.654-939 mm | $m(\gamma_d)$= 400 MeV | 2206.12181
FRVZ $H \to 4\gamma_d + X$ | 2 μ–jets | 139 | γ_d lifetime | 2.7-534 mm | $m(\gamma_d)$= 400 MeV | 2206.12181
$H \to Z_dZ_d$ | displaced dimuon | 32.9 | Z_d lifetime | 0.009-24.0 m | $m(Z_d)$= 40 GeV | 1808.03057
$H \to ZZ_d$ | 2 e, μ + low-EMF trackless jet | 36.1 | Z_d lifetime | 0.21-5.2 m | $m(Z_d)$= 10 GeV | 1811.02542
Scalar
Φ(200 GeV) $\to s\,s$ | low-EMF trk-less jets, MS vtx | 36.1 | s lifetime | 0.41-51.5 m | $\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV | 1902.03094
Φ(600 GeV) $\to s\,s$ | low-EMF trk-less jets, MS vtx | 36.1 | s lifetime | 0.04-21.5 m | $\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV | 1902.03094
Φ(1 TeV) $\to s\,s$ | low-EMF trk-less jets, MS vtx | 36.1 | s lifetime | 0.06-52.4 m | $\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 150 GeV | 1902.03094
HNL
$W \to N\ell, N \to \ell\ell\nu$ | displaced vtx ($\mu\mu$,μe, ee) + μ | 139 | N lifetime | 0.74-42 mm | $m(N)$= 6 GeV, Dirac | 2204.11988
$W \to N\ell, N \to \ell\ell\nu$ | displaced vtx ($\mu\mu$,μe, ee) + μ | 139 | N lifetime | 3.1-33 mm | $m(N)$= 6 GeV, Majorana | 2204.11988
$W \to N\ell, N \to \ell\ell\nu$ | displaced vtx ($\mu\mu$,μe, ee) + e | 139 | N lifetime | 0.49-81 mm | $m(N)$= 6 GeV, Dirac | 2204.11988
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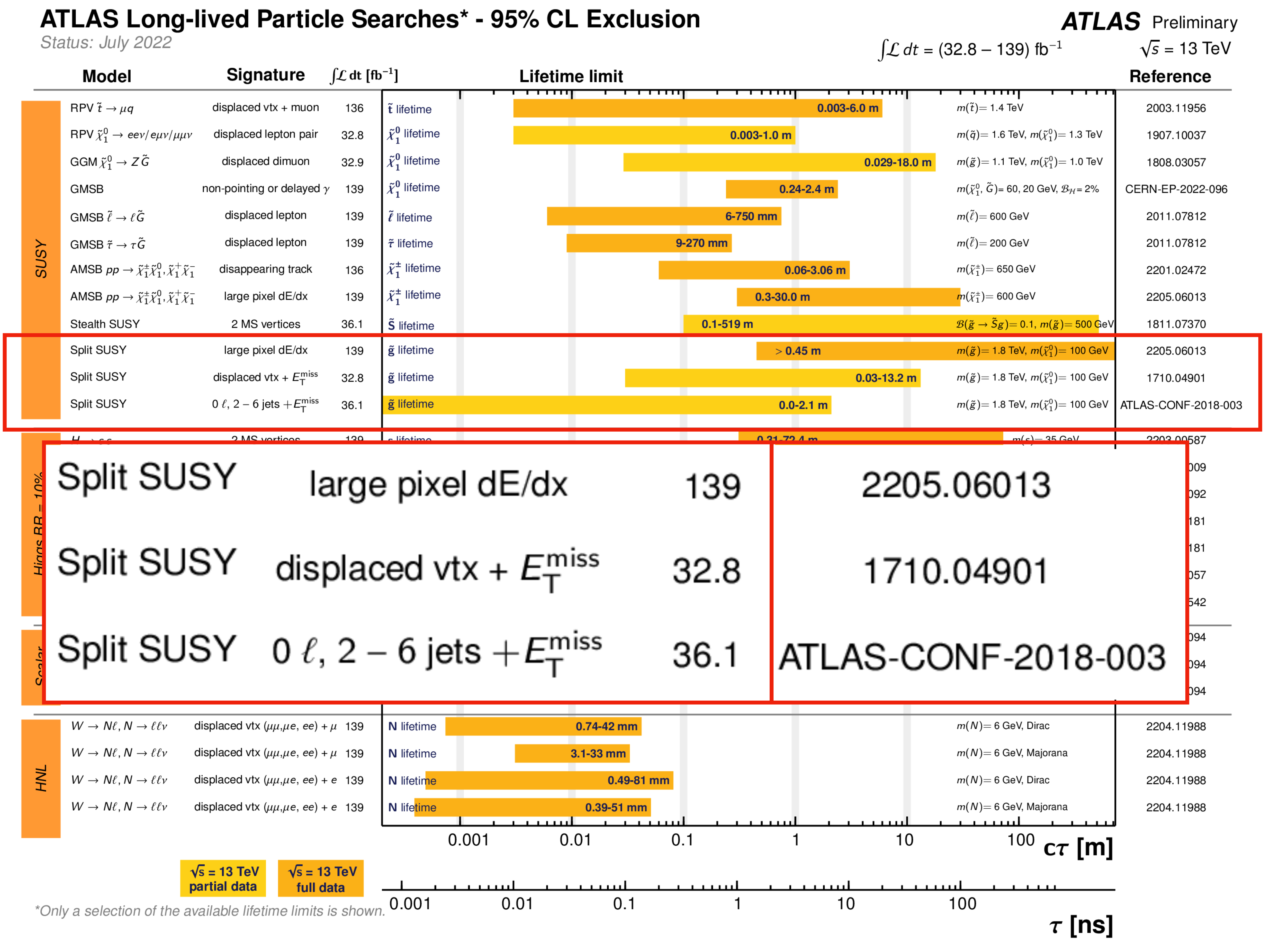
0.001
0.01
0.1
1
10
100
$c\tau$ [m]
$\sqrt{s}$ = 13 TeV partial data
$\sqrt{s}$ = 13 TeV full data
0.001
0.01
0.1
1
10
100
τ [ns]
*Only a selection of the available lifetime limits is shown.



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τ [ns]
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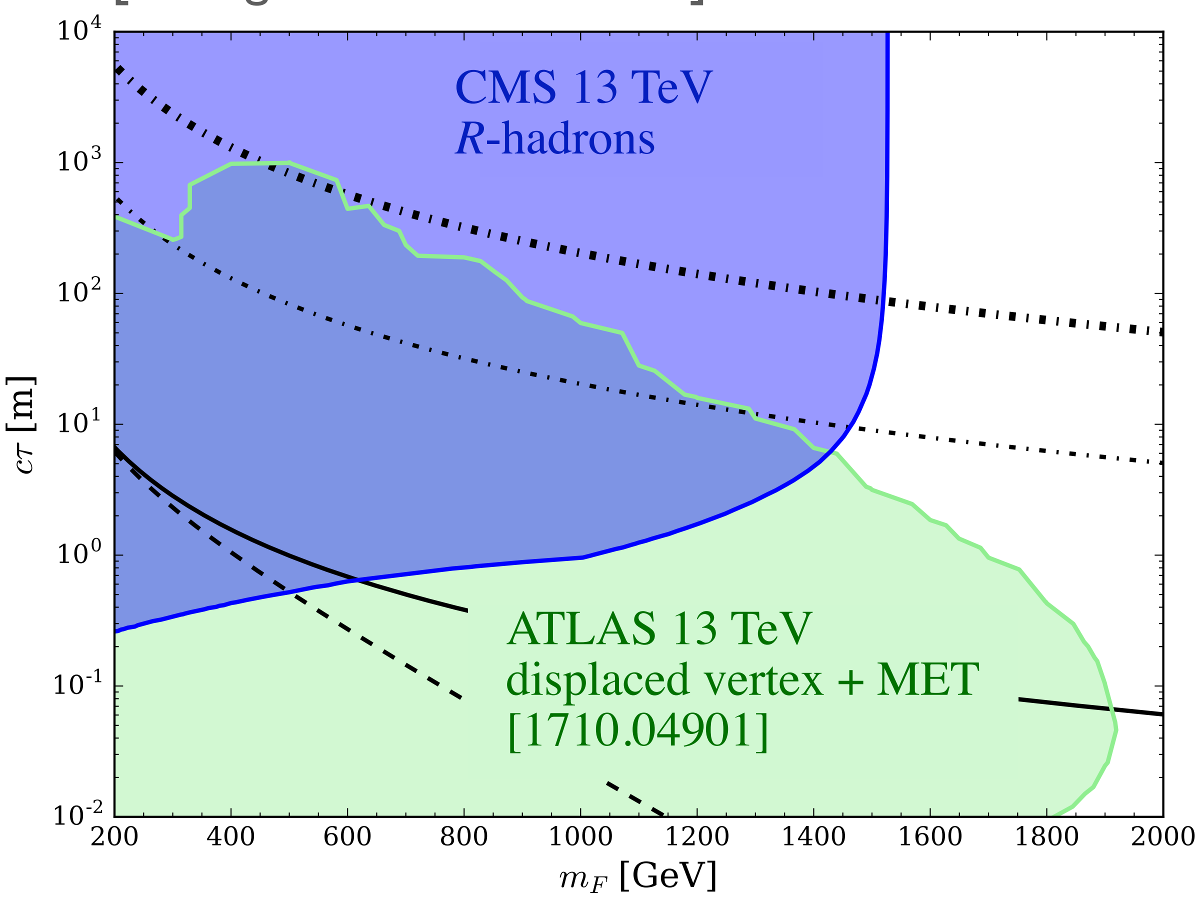
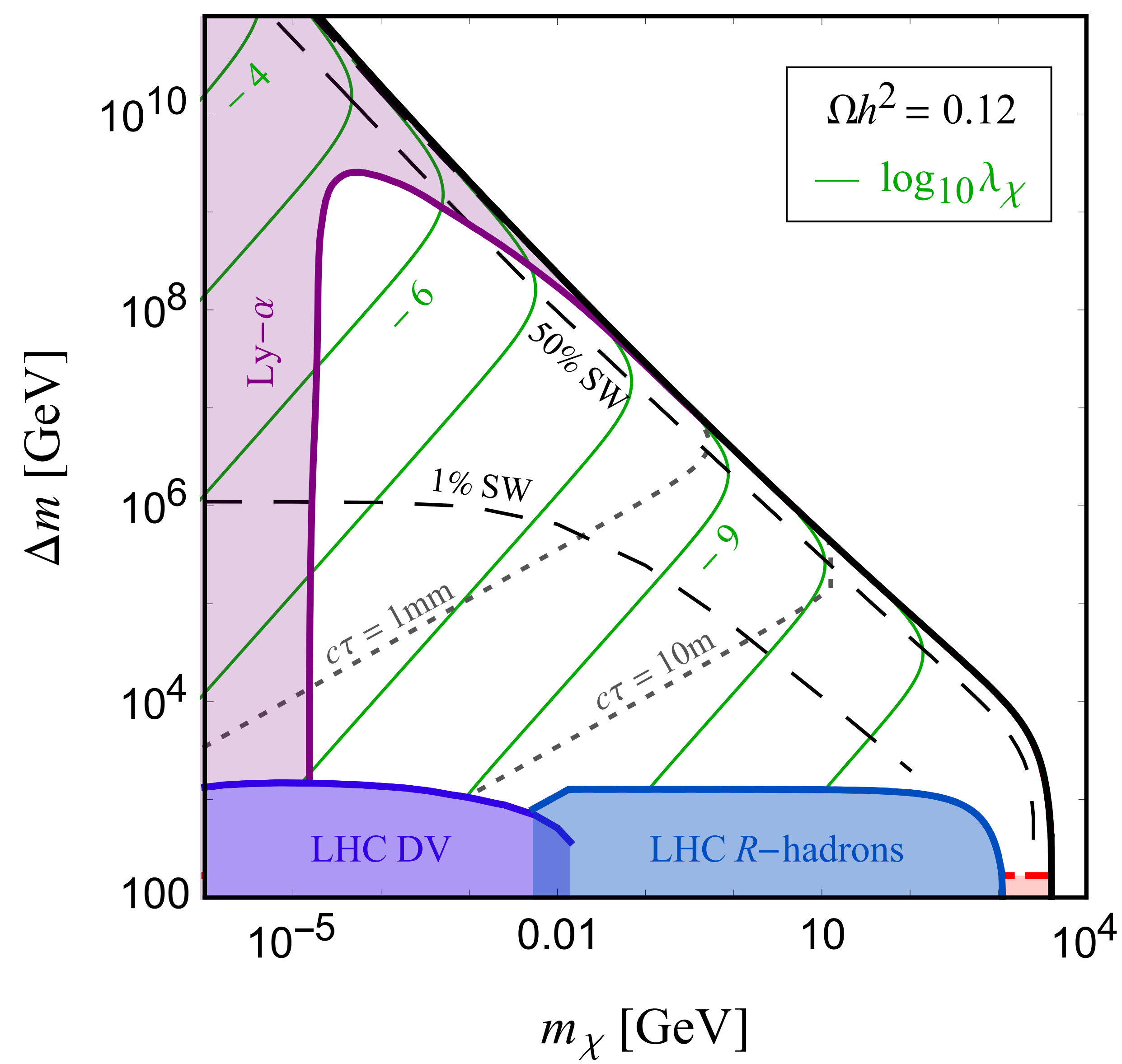
Reinterpretation of searches

(*non-thermalized*: superWIMPs, Freeze-in)

[Bélanger *et al.* 1811.05478]



[Decant *et al.* 2111.09321]



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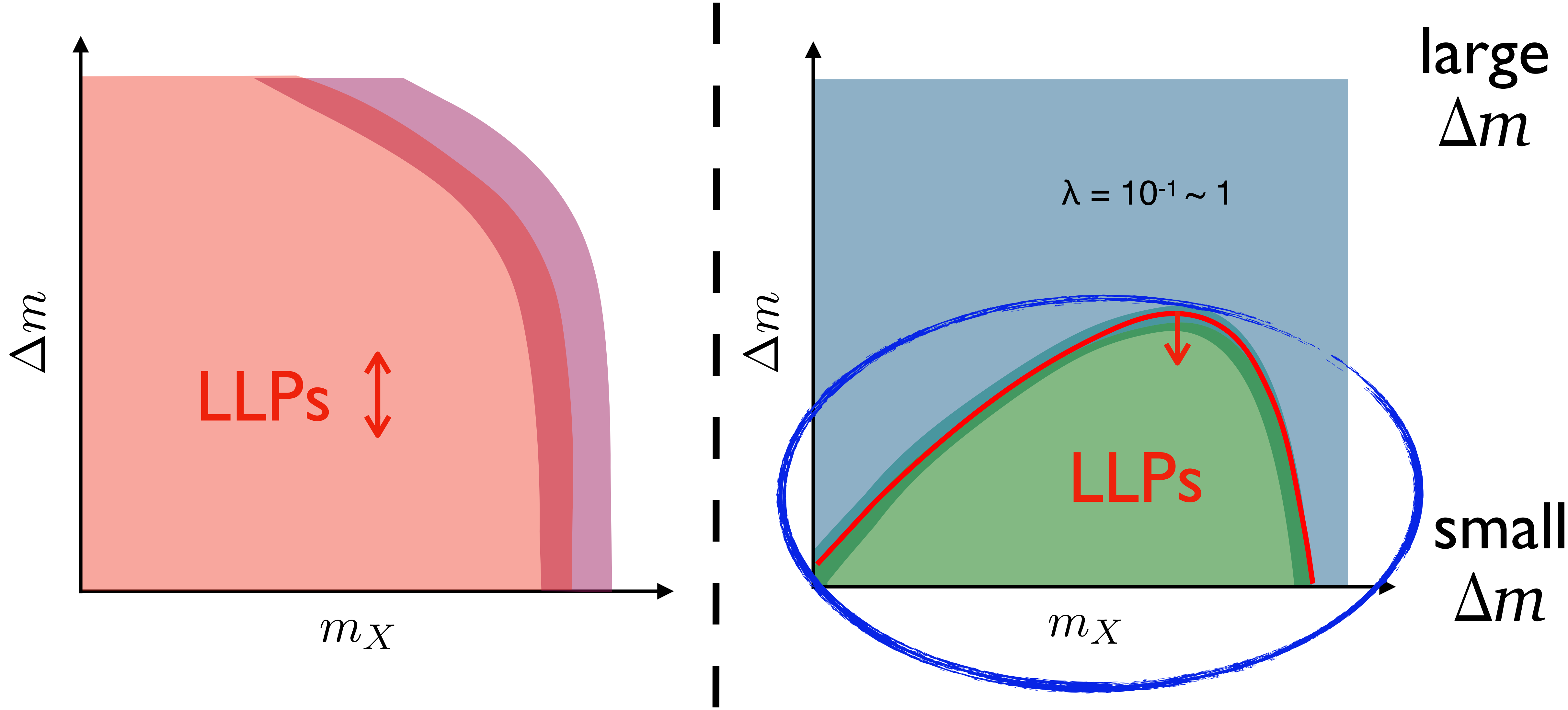
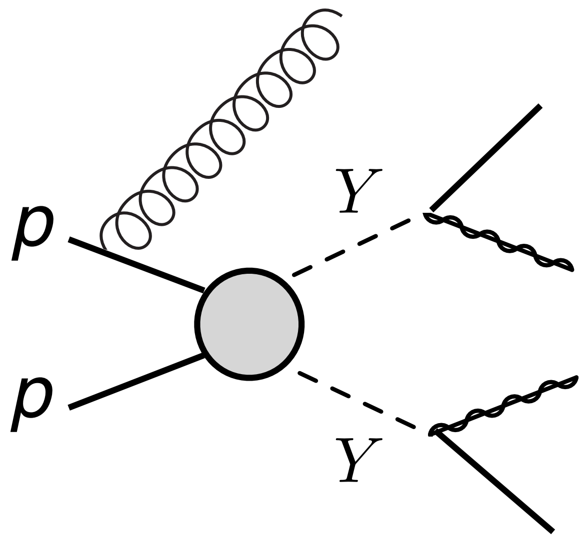
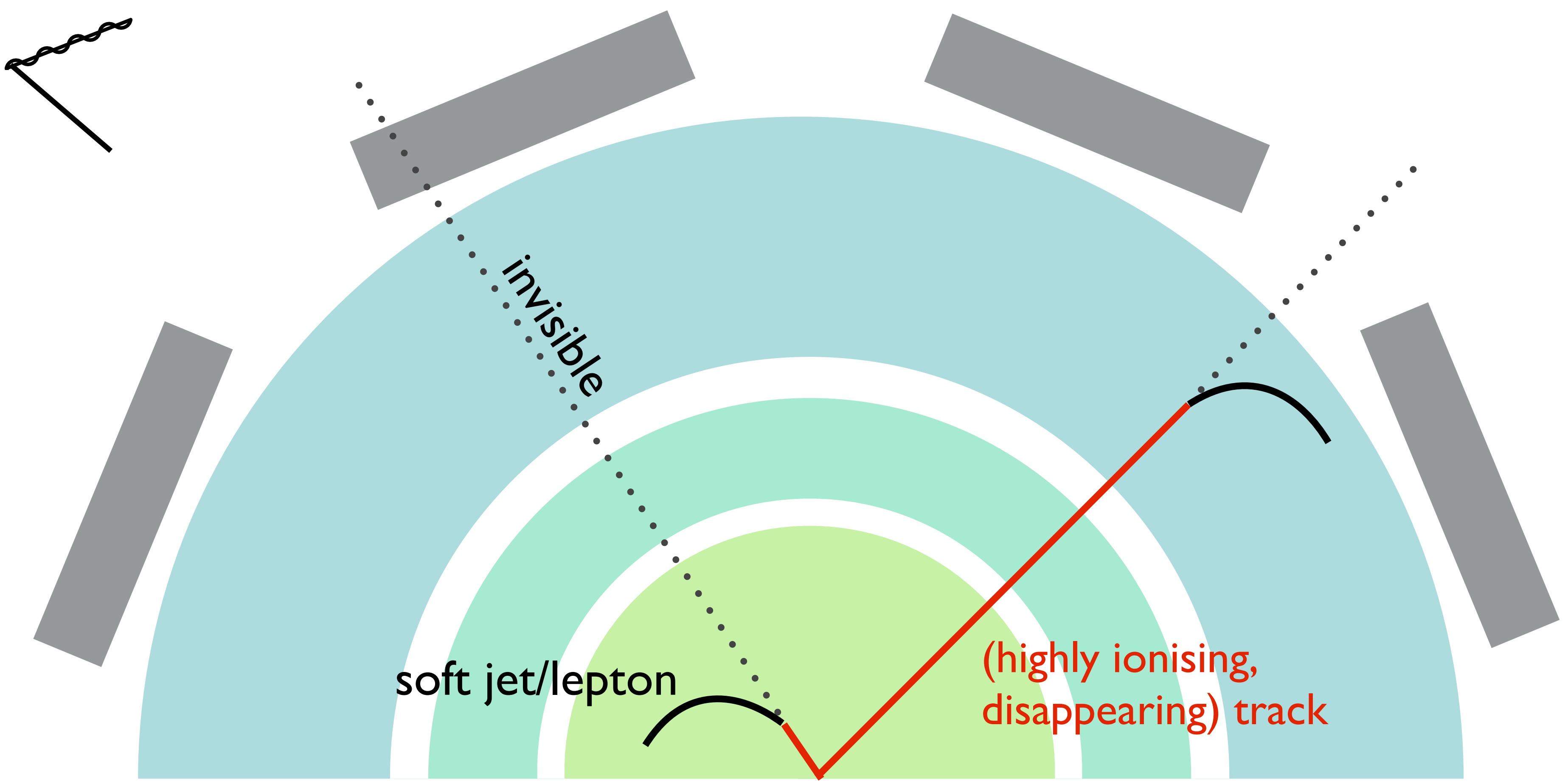
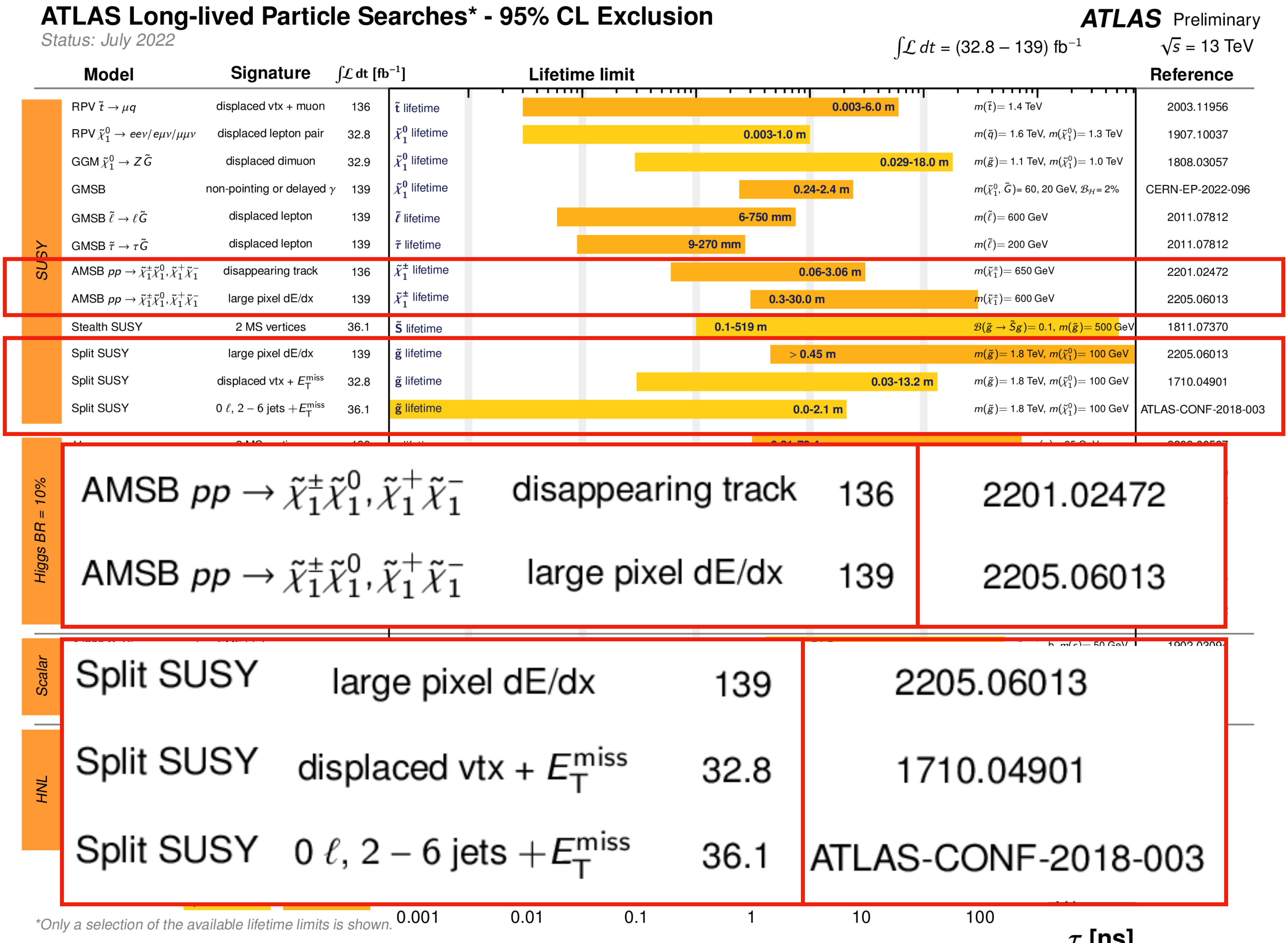


LLP Signatures: small Δm

(*thermalized*: conversion-driven FO, co-annihilation)







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0.001
0.01
0.1
1
10
100
τ [ns]
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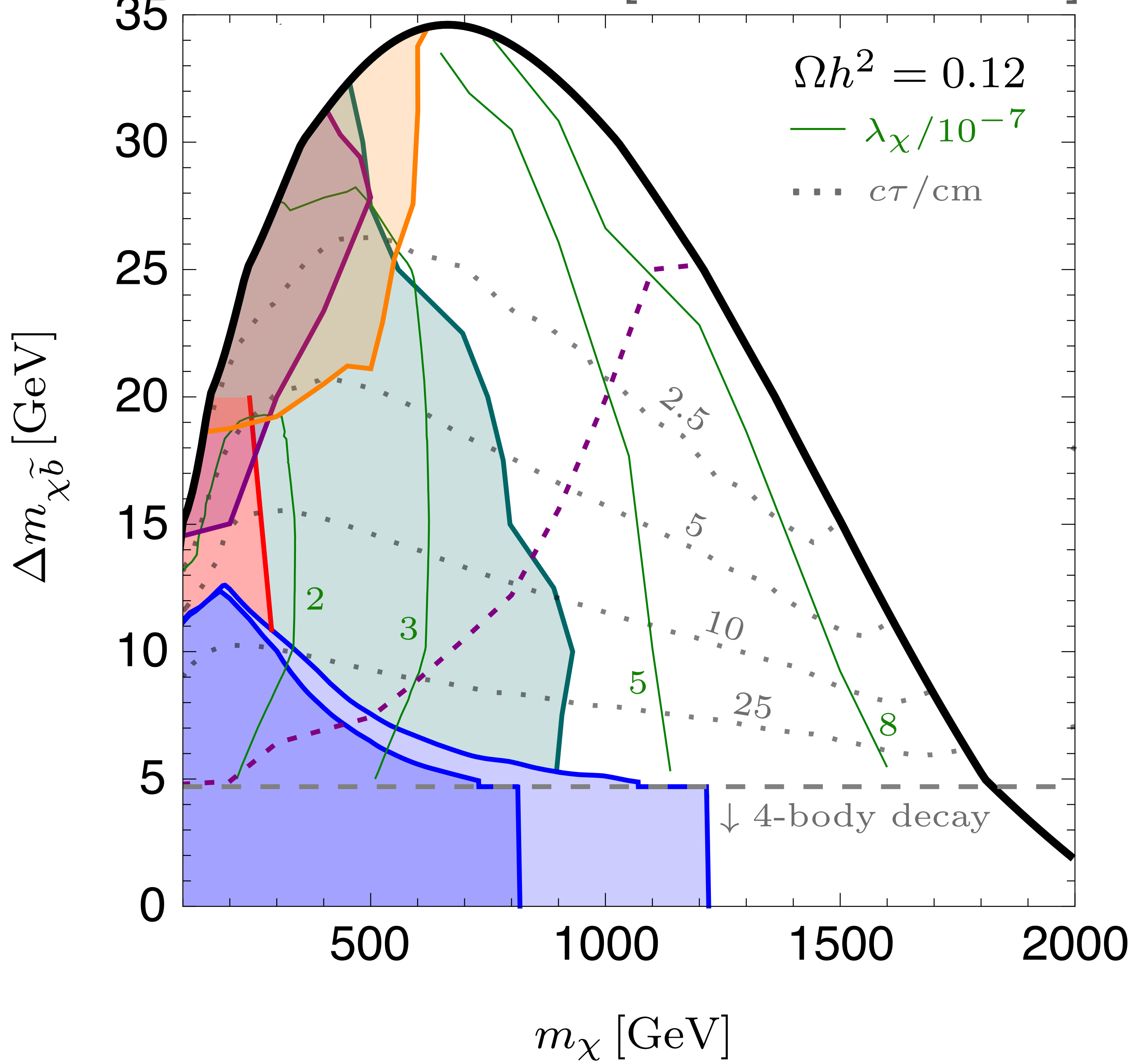
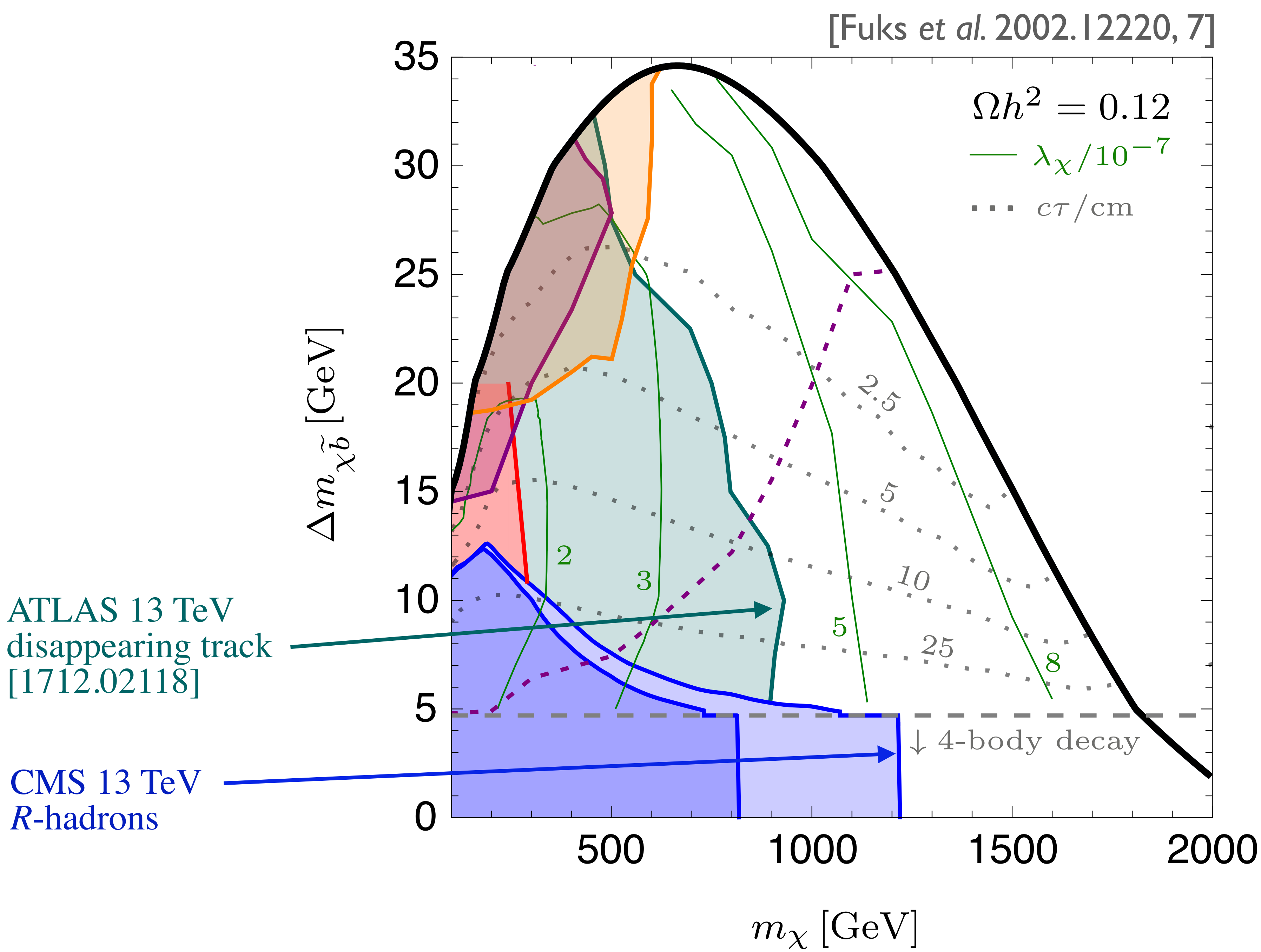
(*thermalized*: conversion-driven FO, co-annihilation)

[Fuks *et al.* 2002.12220, 7]



Reinterpretation of searches

(*thermalized*: conversion-driven FO, co-annihilation)



Reinterpretation of searches

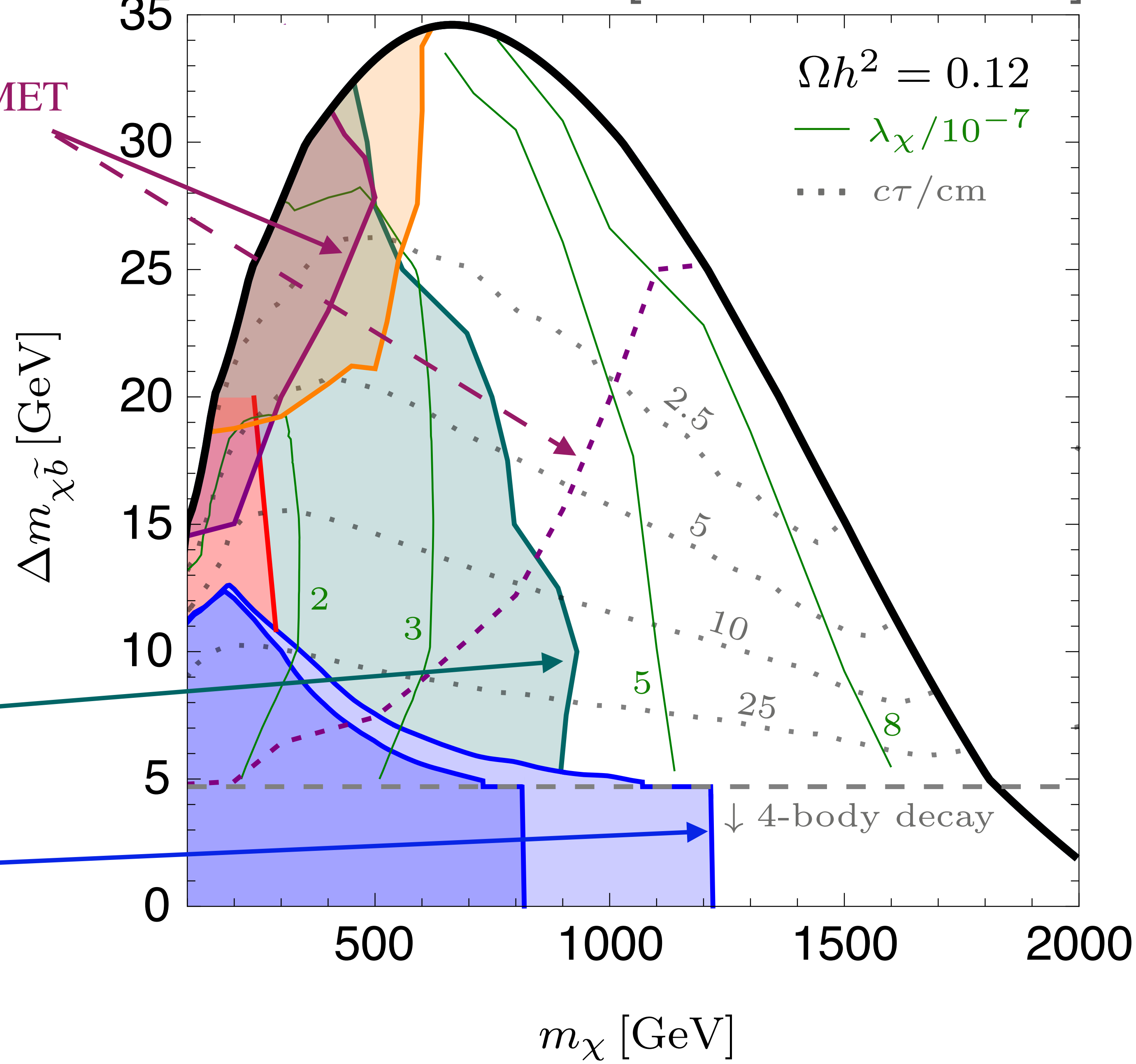
(*thermalized*: conversion-driven FO, co-annihilation)

[Fuks *et al.* 2002.12220, 7]

ATLAS 13 TeV
displaced vertex + MET
[1710.04901]

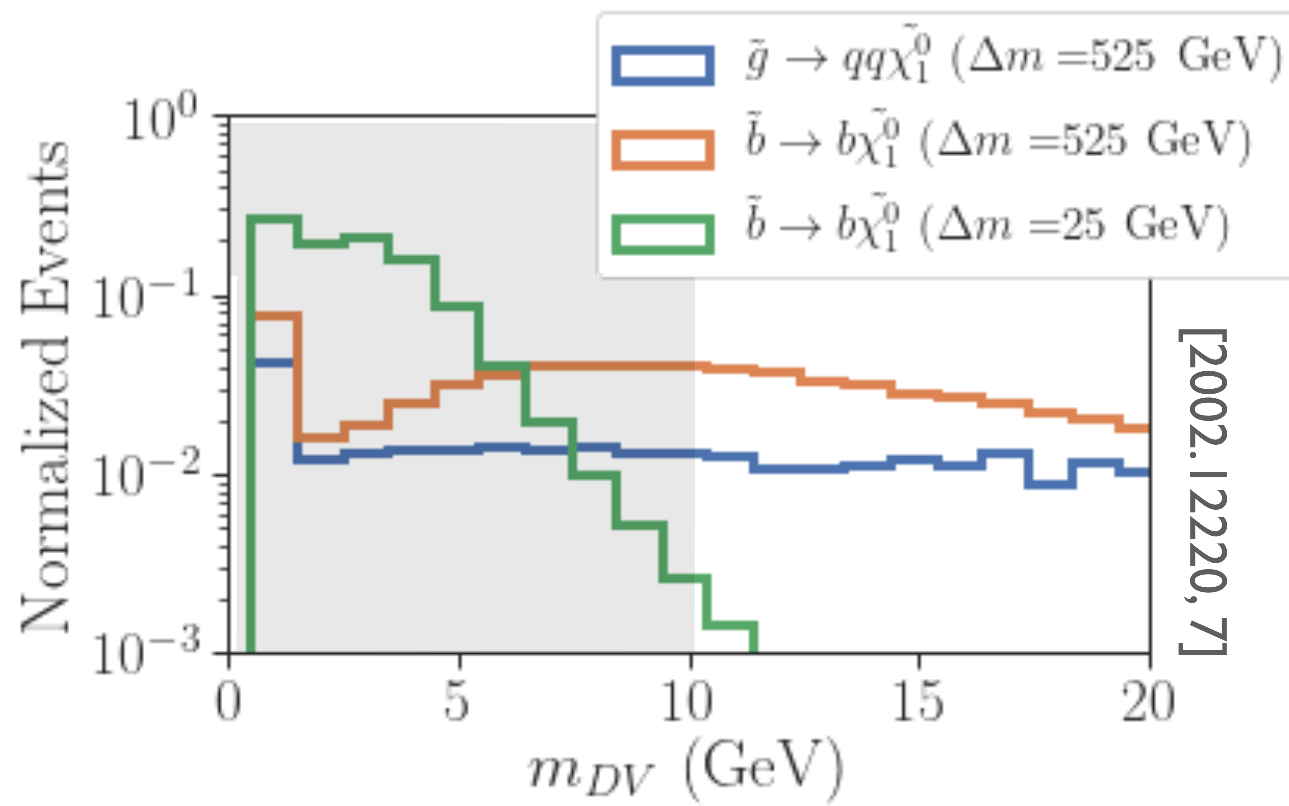
ATLAS 13 TeV
disappearing track
[1712.02118]

CMS 13 TeV
R-hadrons



Reinterpretation of searches

(*thermalized*: conversion-driven FO, co-annihilation)



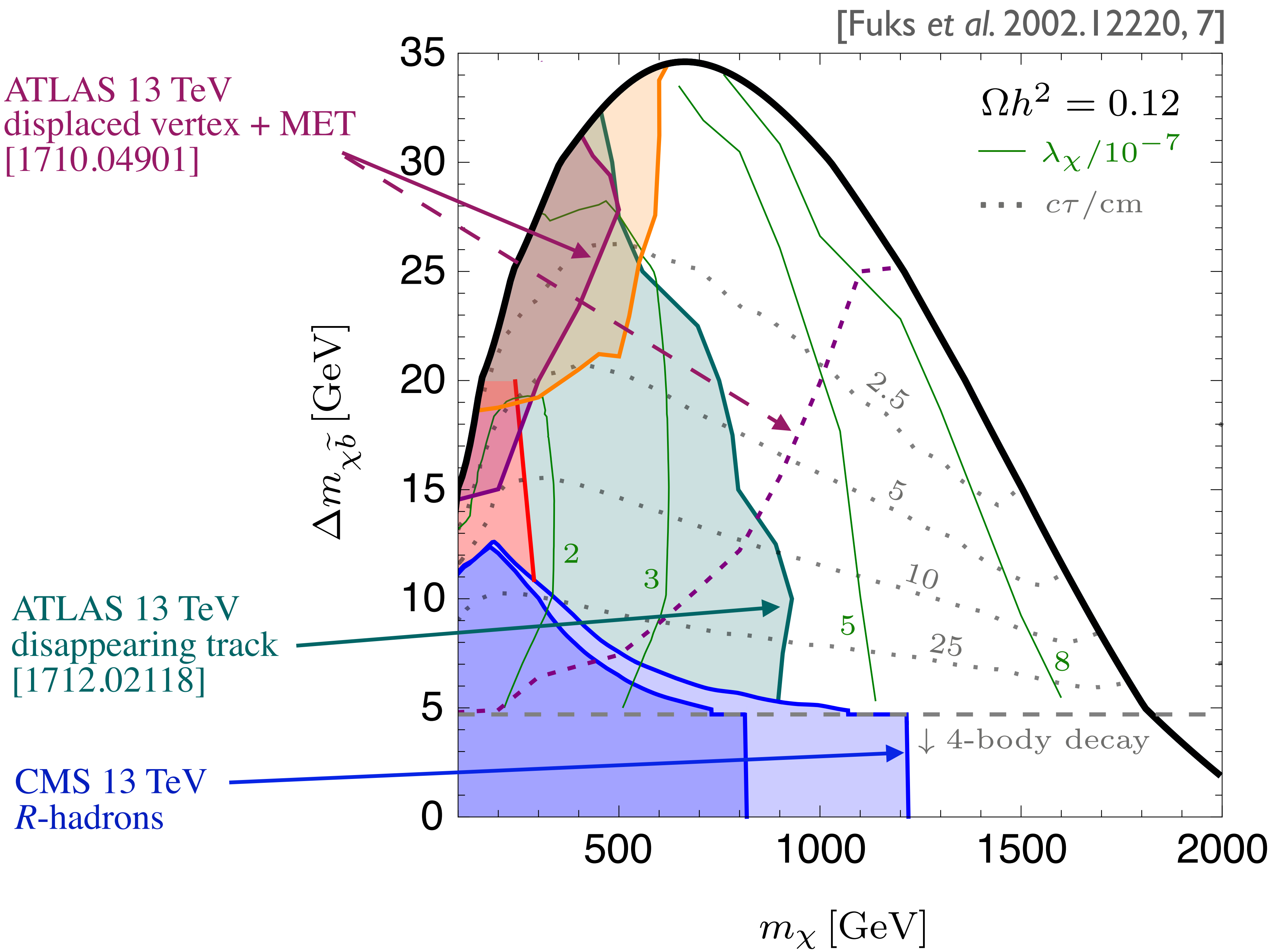
[2002.12220, 7]

- Displaced jets+MET suffers from m_{inv}-cut!

[ATLAS, 1710.04901]

Reinterpretation of searches

(*thermalized*: conversion-driven FO, co-annihilation)



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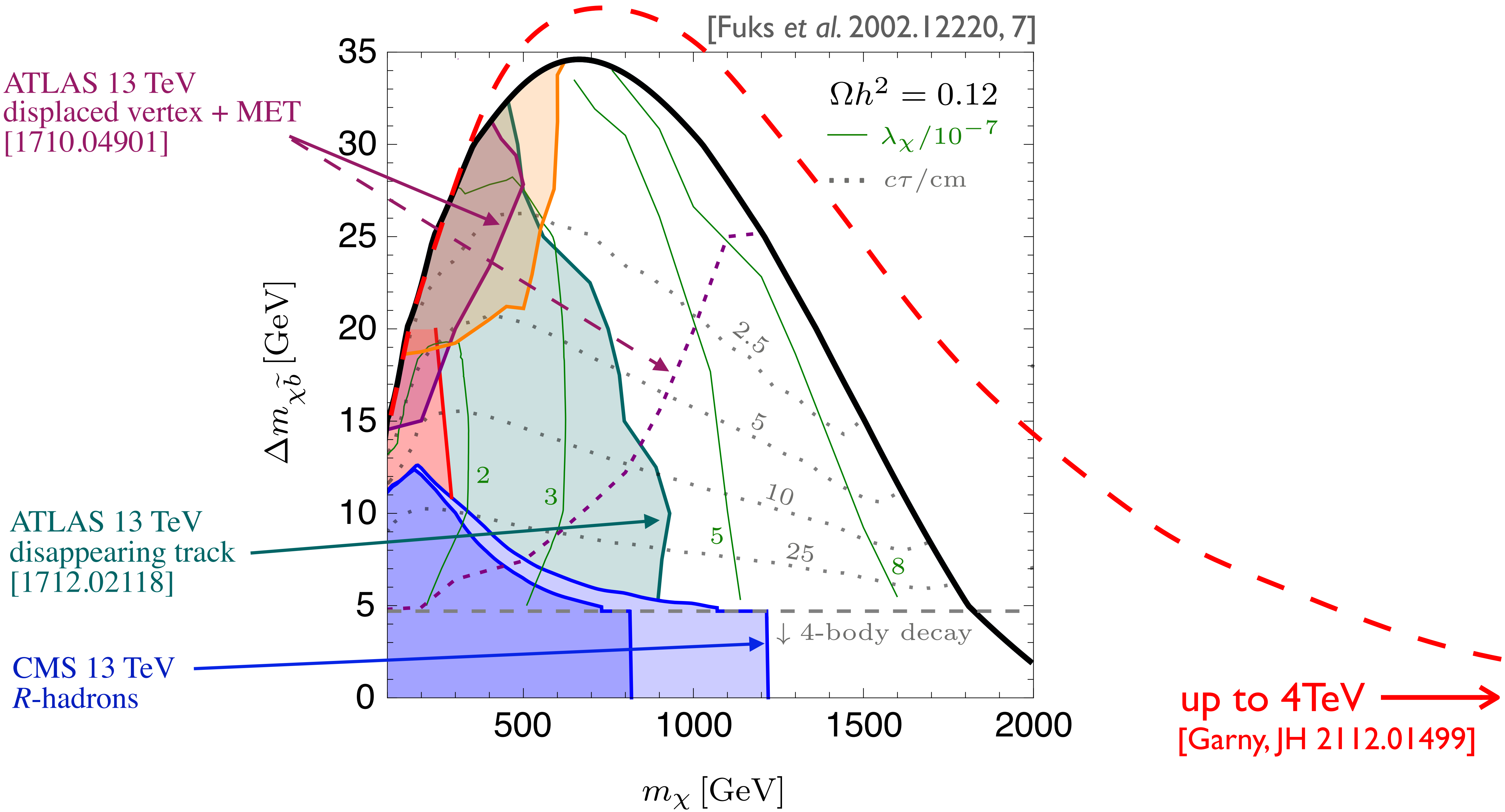

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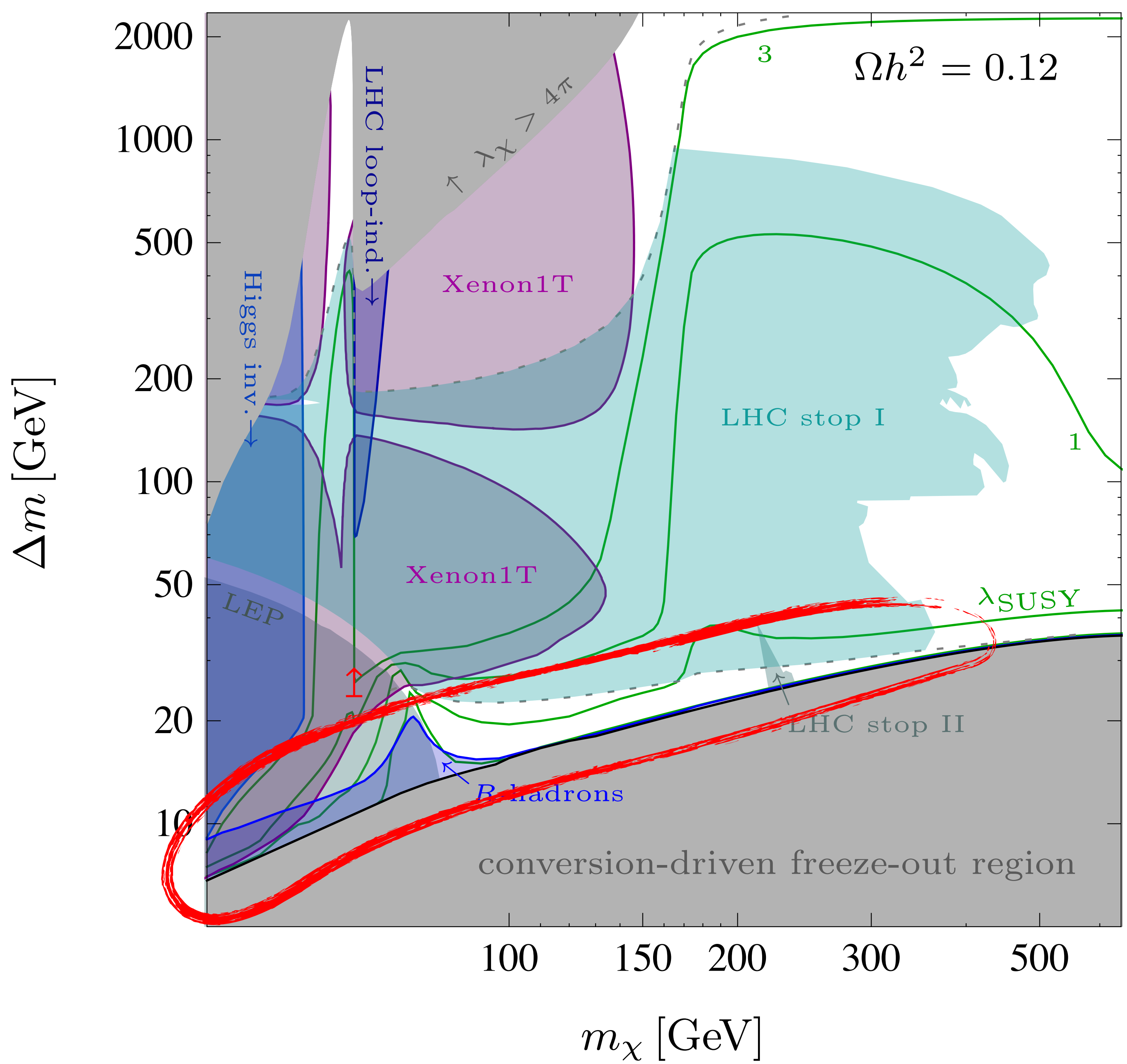
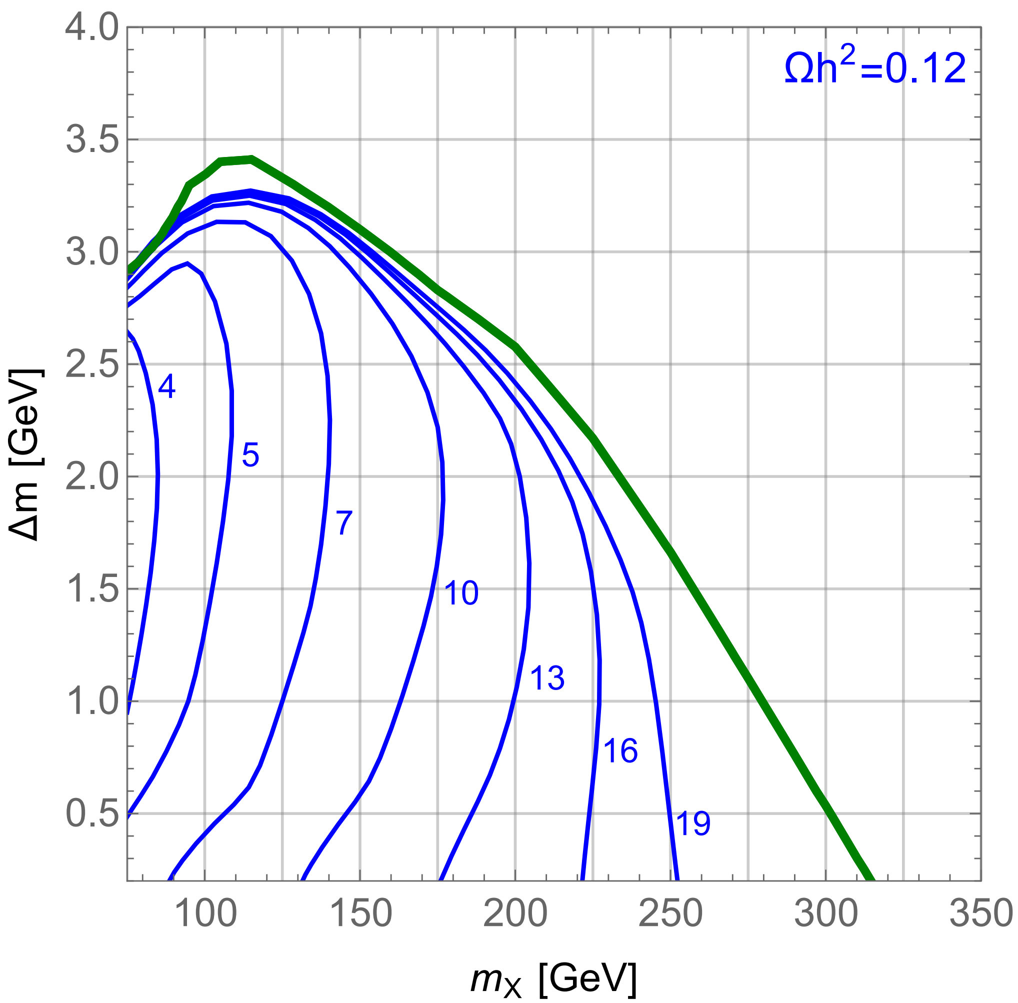


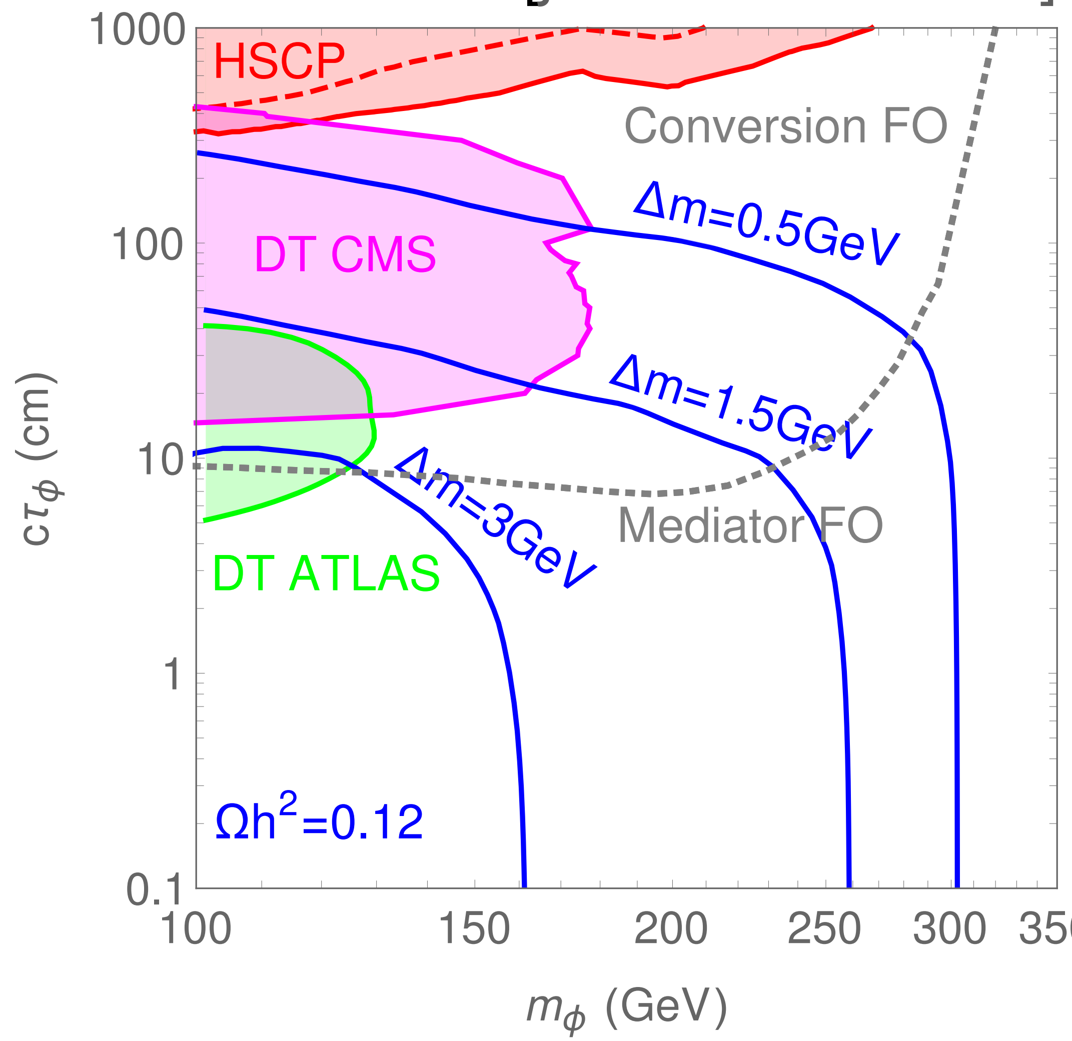
Challenging: transition between prompt/long-lived

Beyond minimal quark-philic models

- Leptophilic *t*-channel models:
  Similar pheno, e.g. conversion-driven freeze-out:

[Junius *et al.* 1904.07513]

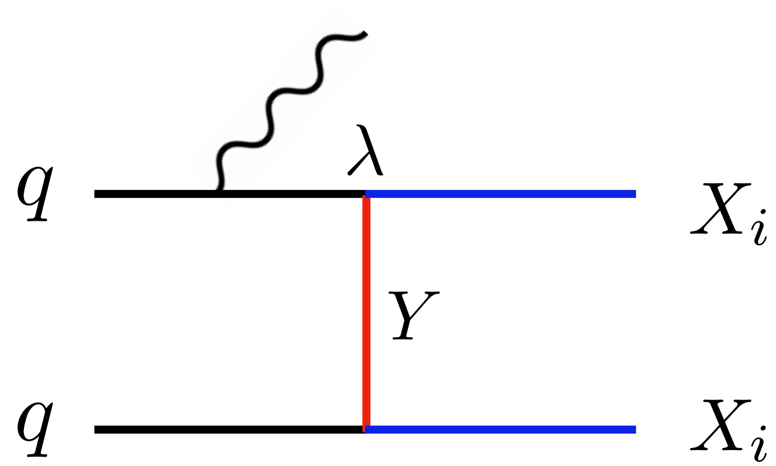




Beyond minimal quark-philic models

- Non-minimal models:
  e.g. Dark Minimal Flavour Violation [Acaroglua, Blanke 2109.10357]

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\left(i\bar{\chi}\partial\!\!\!/\chi - M_\chi\bar{\chi}\chi\right) - \left(\lambda_{ij}\,\bar{u}_{Ri}\chi_j\,\phi + \text{h.c.}\right)$$



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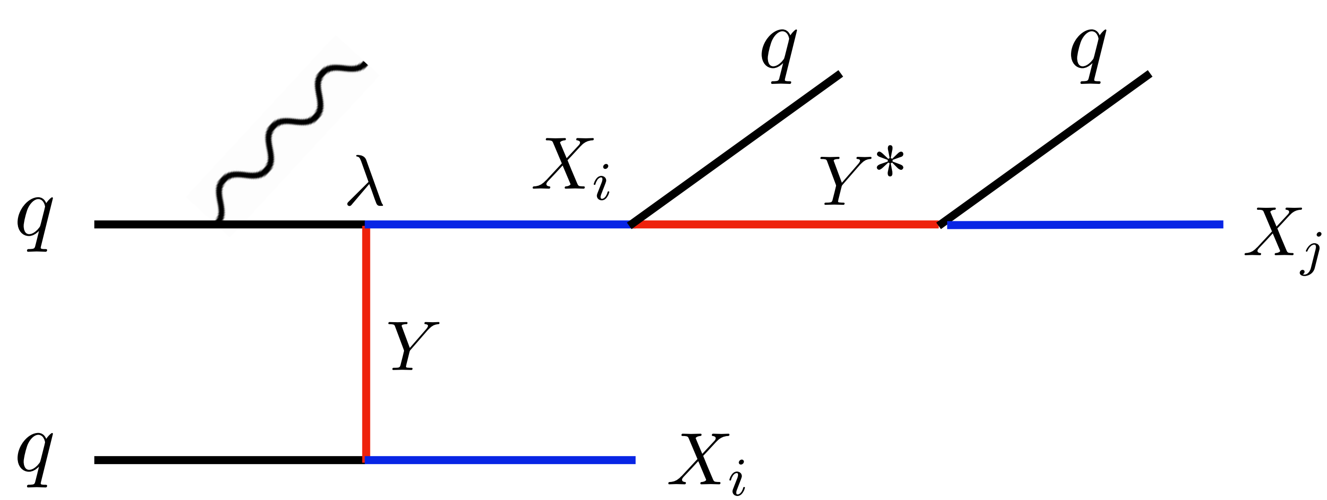

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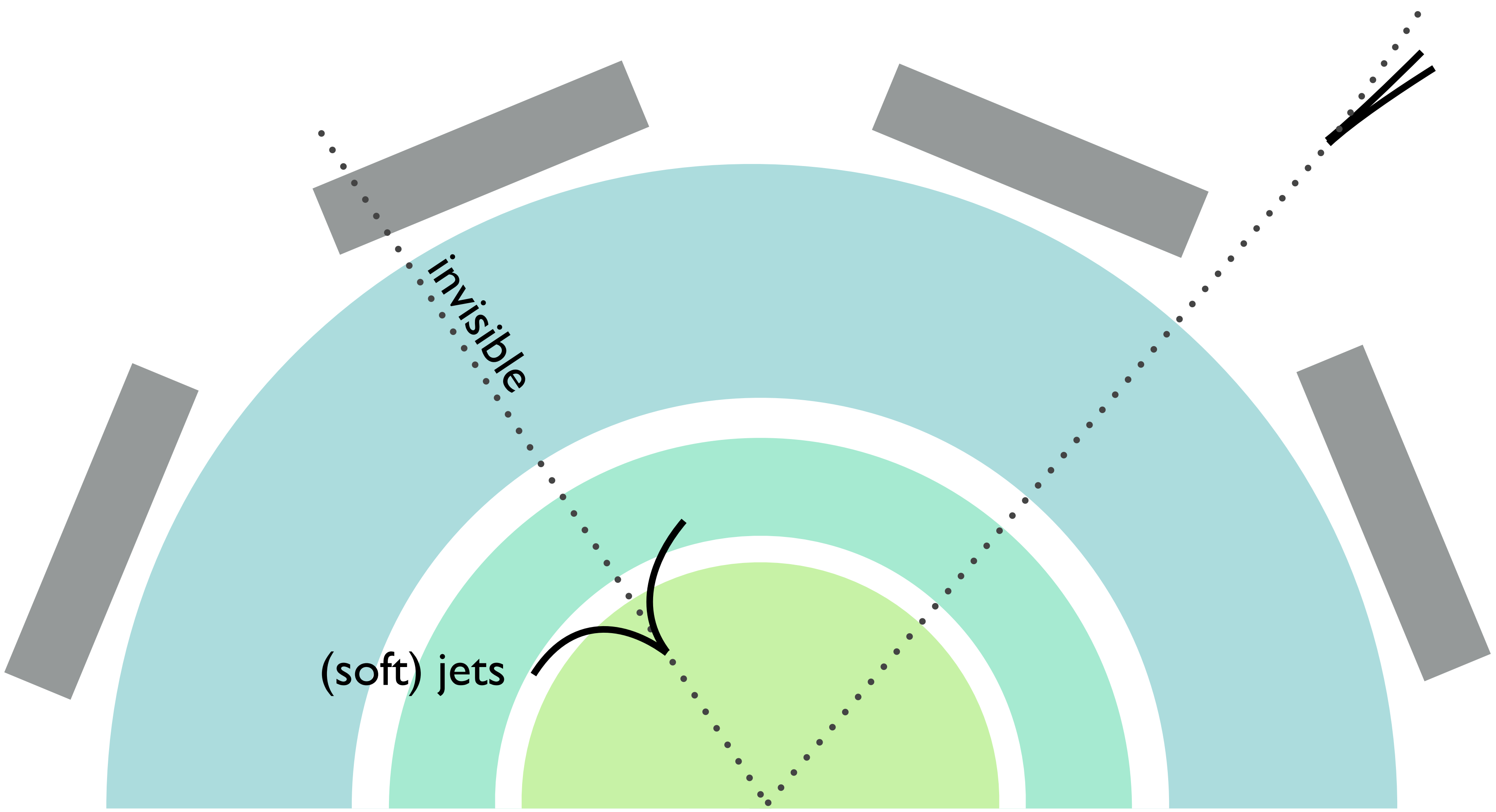

Conclusion

- Minimal quark-philic models
  - SuperWIMP / freeze-in:
    Light DM, current searches apply
  - Conversion-driven freeze-out:
    Small mass splitting O(10GeV) challenging
  - Coannihilation:
    Transition between prompt and long-lived
- Beyond minimal quark-philic models
  - Leptophilic: Similar pheno
  - Dark Minimal Flavor Violation: more variety

- Current table of contents (very preliminary):

Contents

- Contribution to LLP section very welcome!
  please contact me at heisig@virginia.edu