

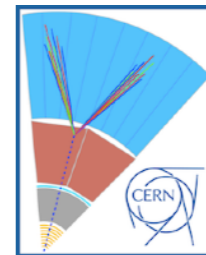
Heavy charged particles: a theory perspective

Jan Heisig (UCL)

Chargé de
recherches



Searching for long-lived particles at the LHC:
Fourth workshop of the LHC LLP Community
October 23-25, 2018, Amsterdam Science Park



I. Cosmological point of view

→ Link to dark matter

II. Reinterpretation of searches

→ Use of simplified models

LLP signatures at LHC

$$1 \text{ mm} \lesssim c\tau \lesssim 10 \text{ m}$$

$$c\tau \gtrsim 10 \text{ m}$$

neutral

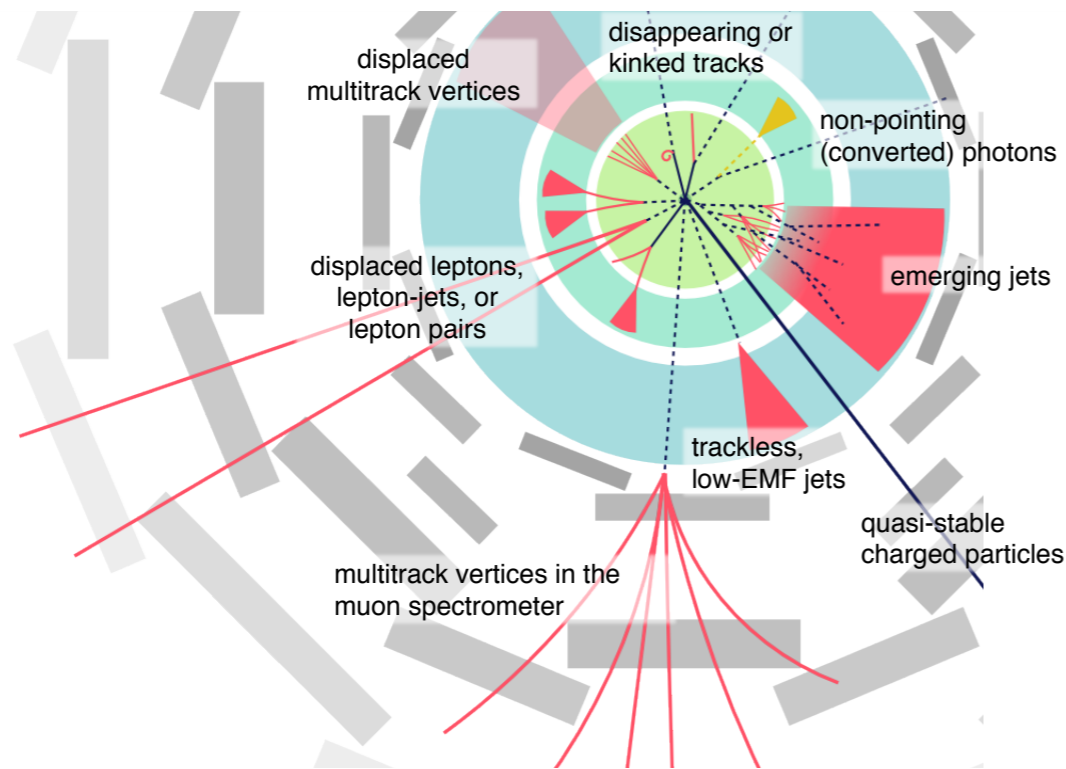
displaced objects

(MET)

charged

displaced objects/
disappearing tracks

highly-ionizing
tracks/ToF (HSCP)



[Figure from Heather Russell]

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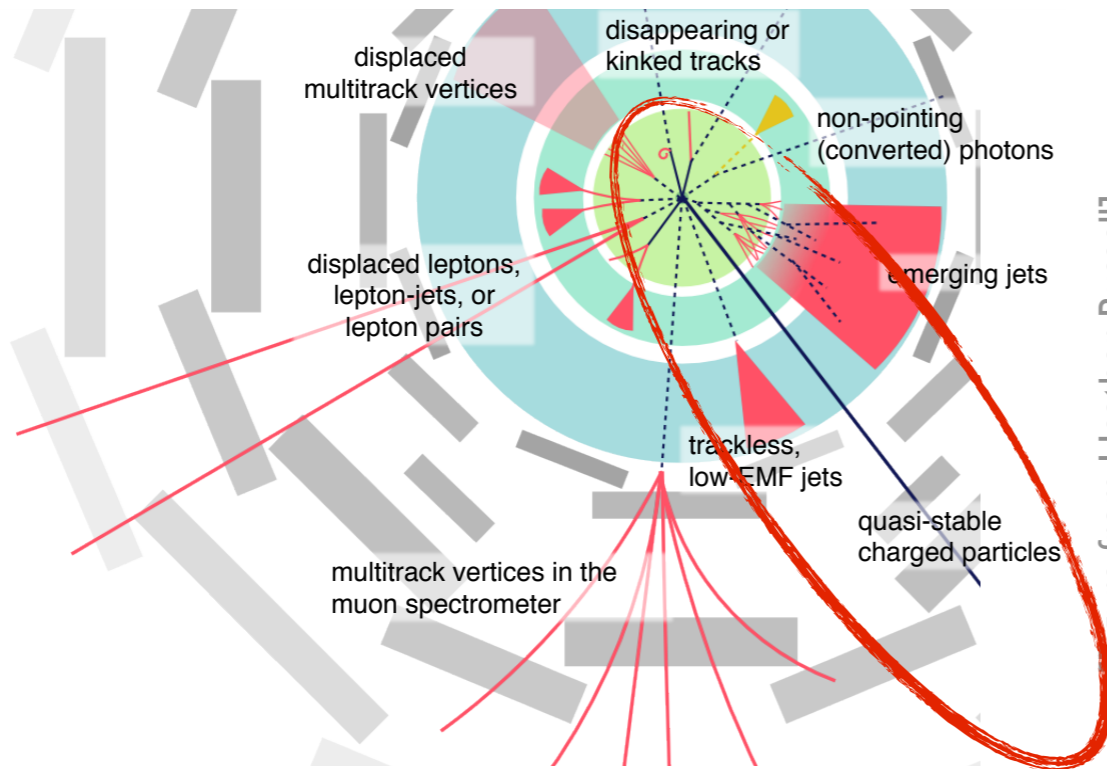
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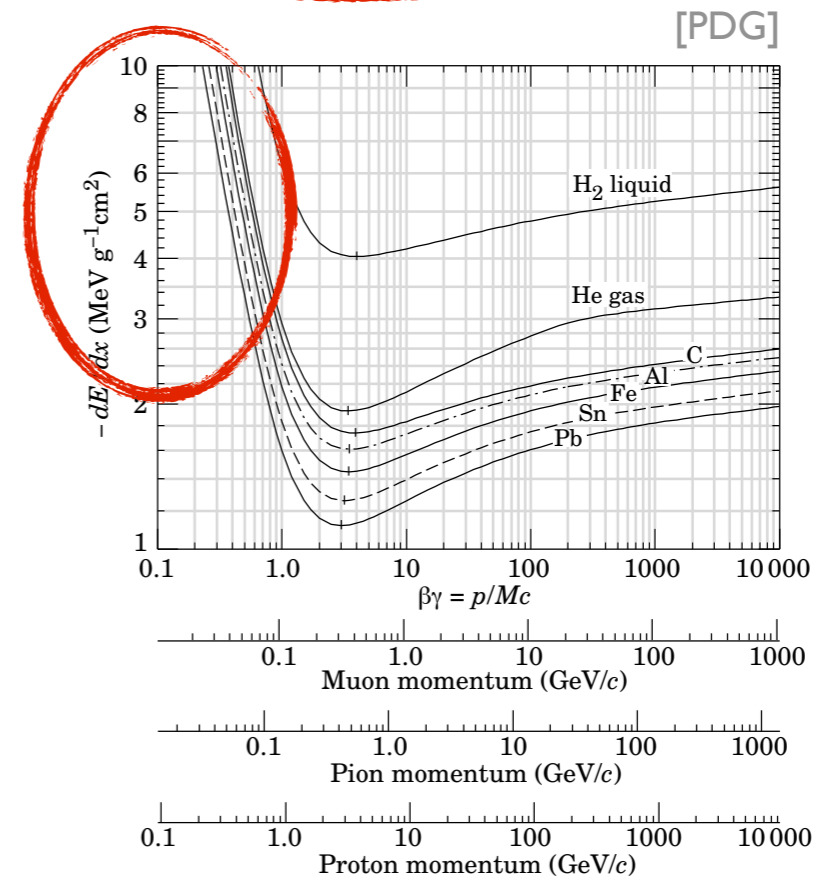
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[Figure from Heather Russell]



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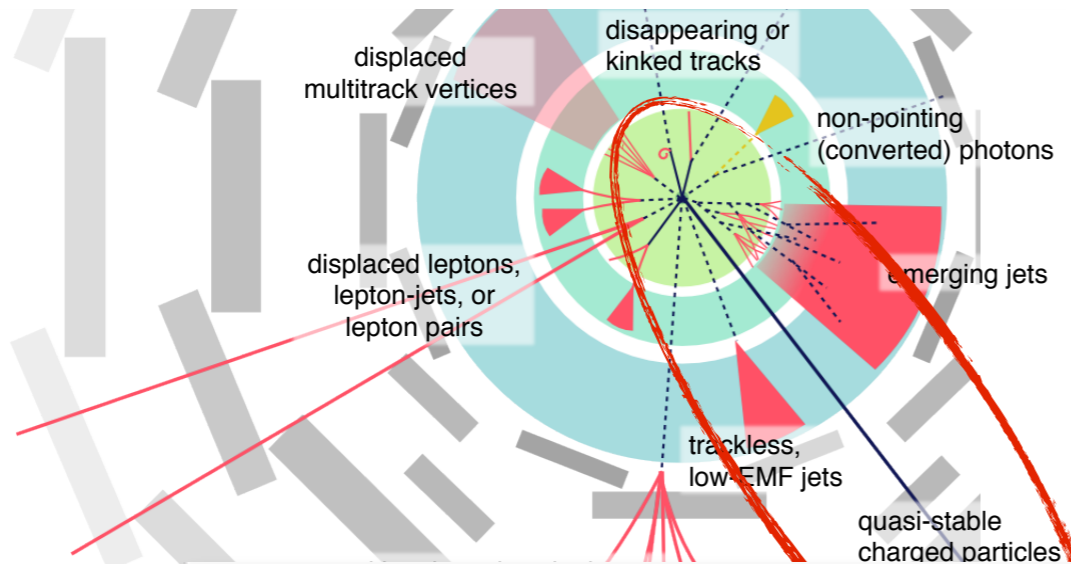
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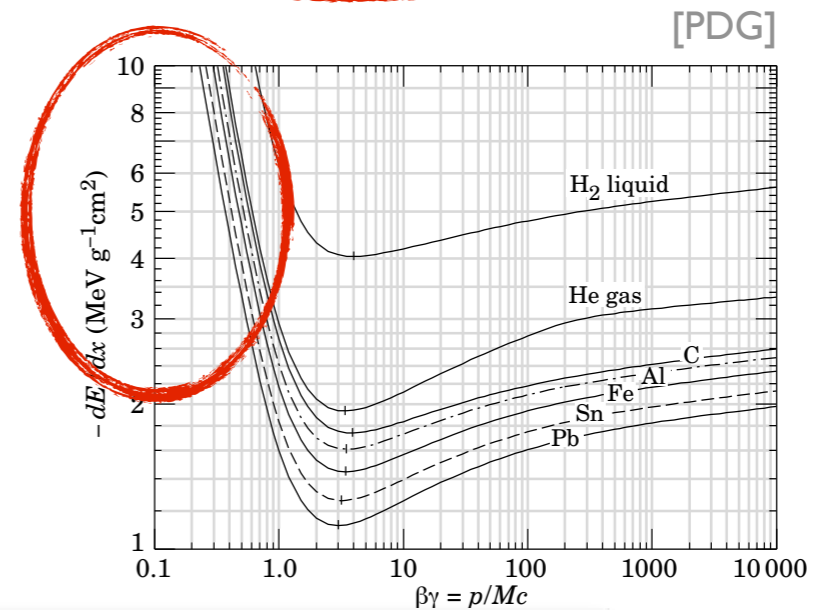
charged

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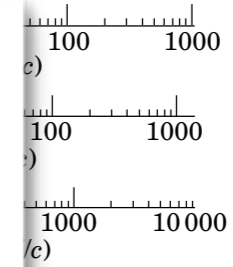


from Heather Russell



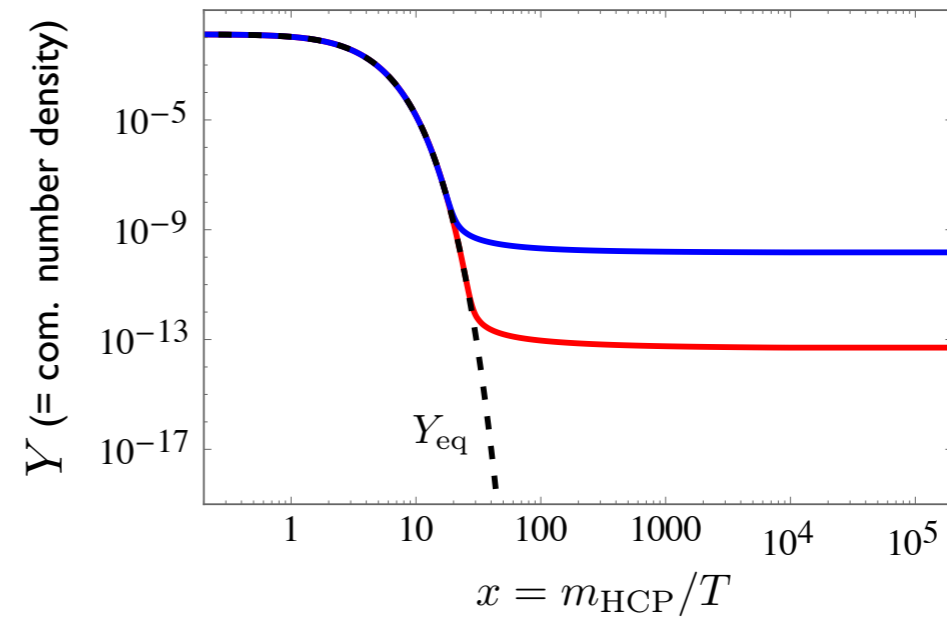
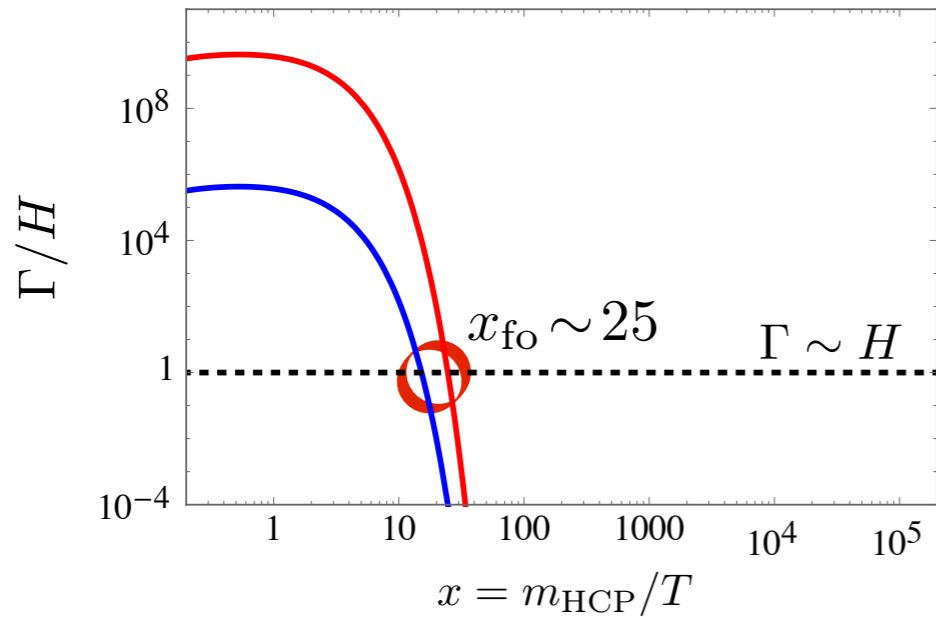
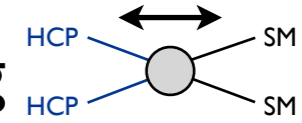
[PDG]

- Extremely inclusive
- Targets a large region in "theory space"

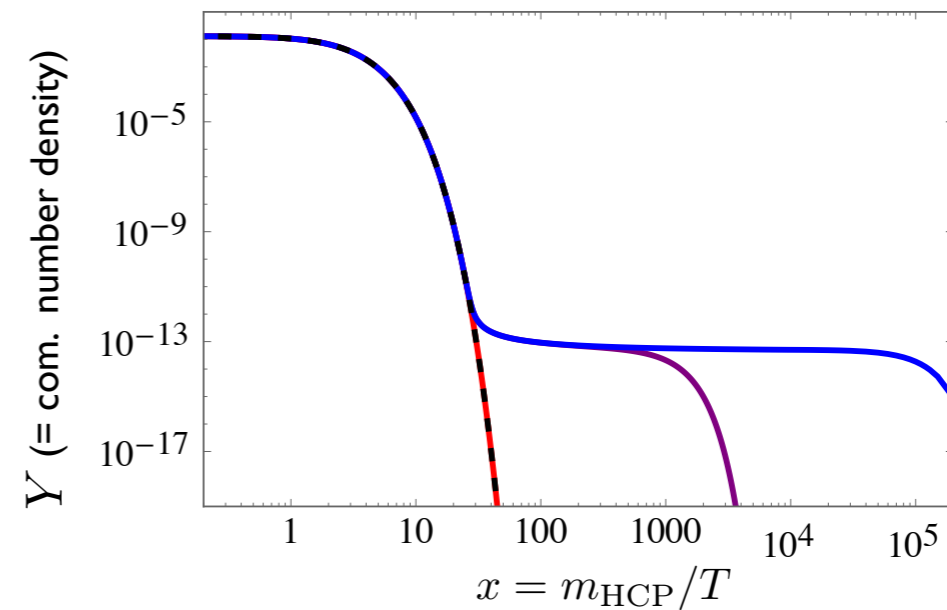
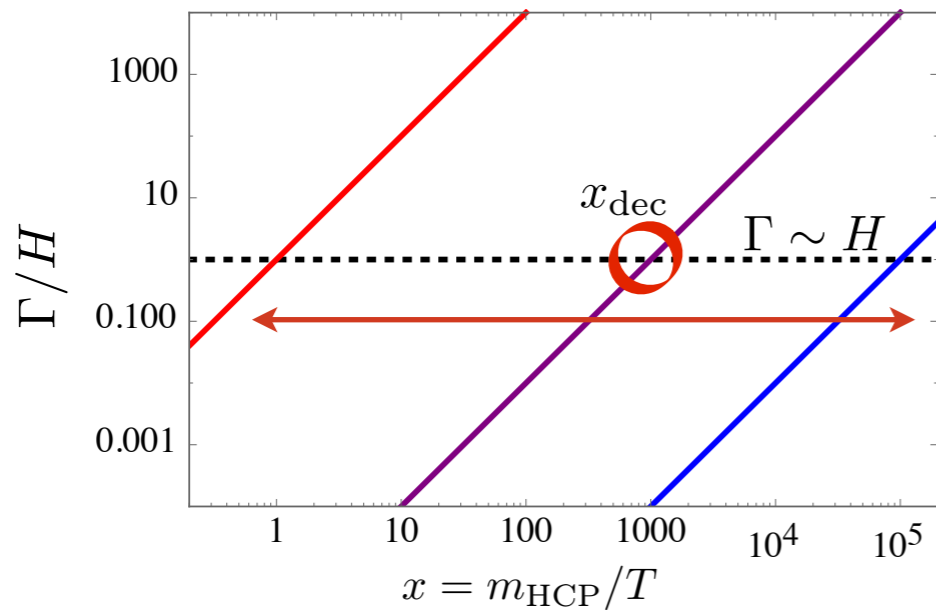
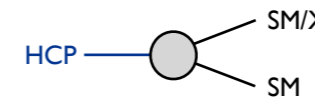


Cosmological point of view

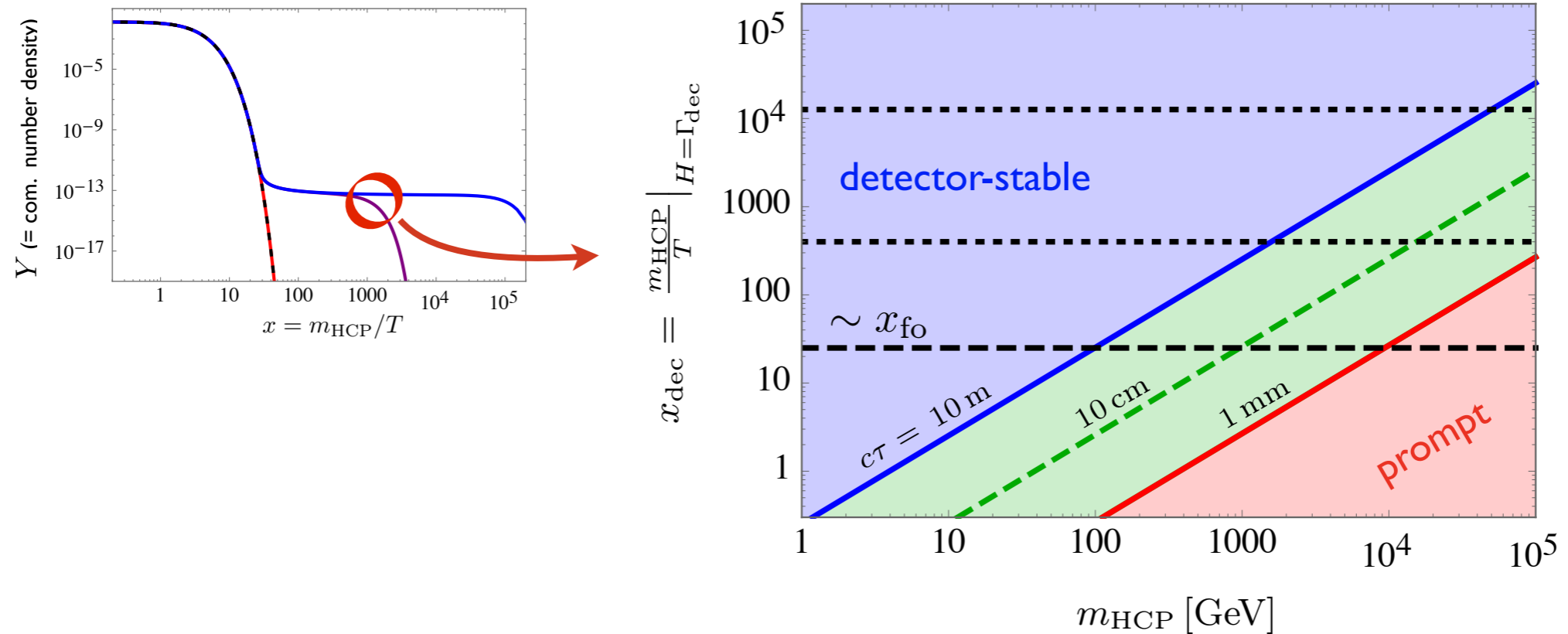
Charged: kinetic term induces efficient $2 \rightarrow 2$ scattering



Model-dependent: Decay of the HCP

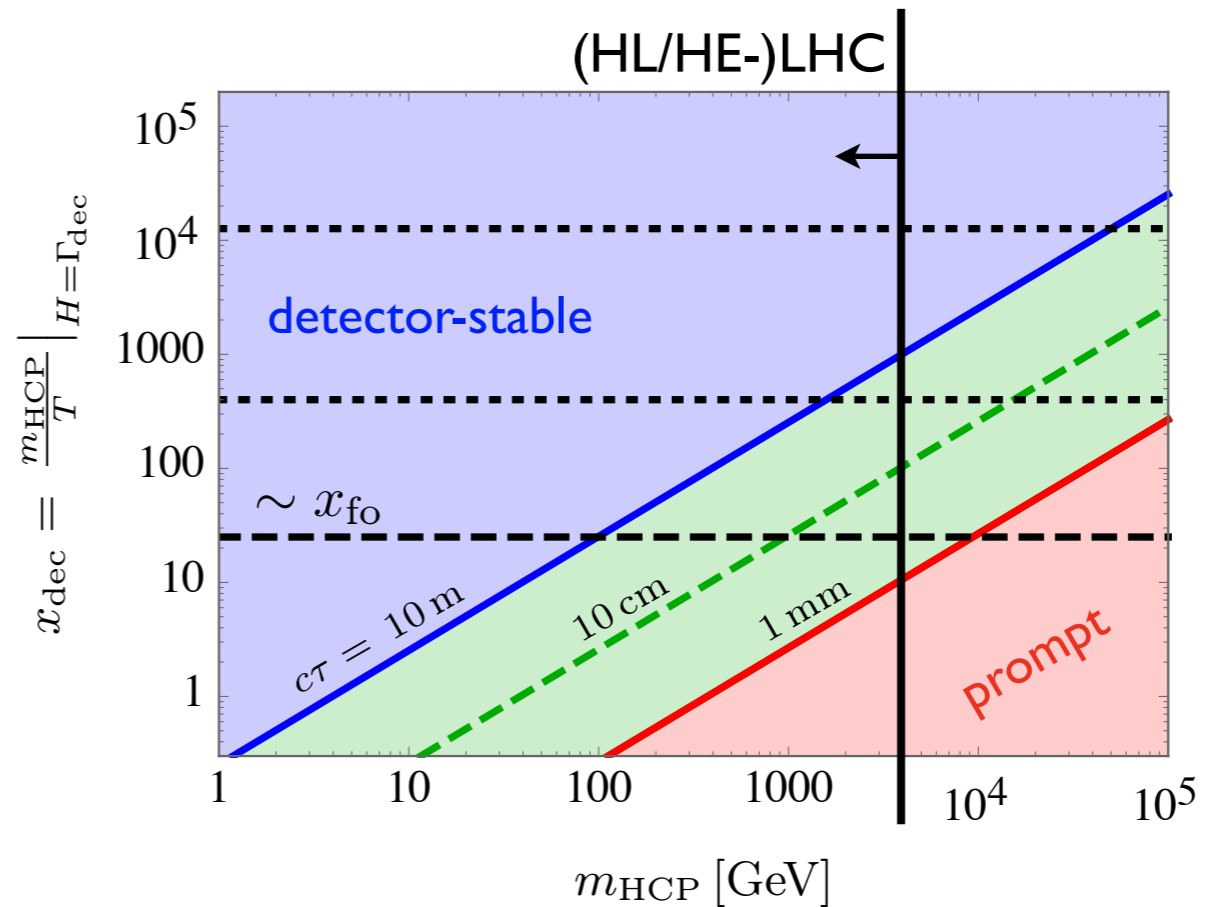
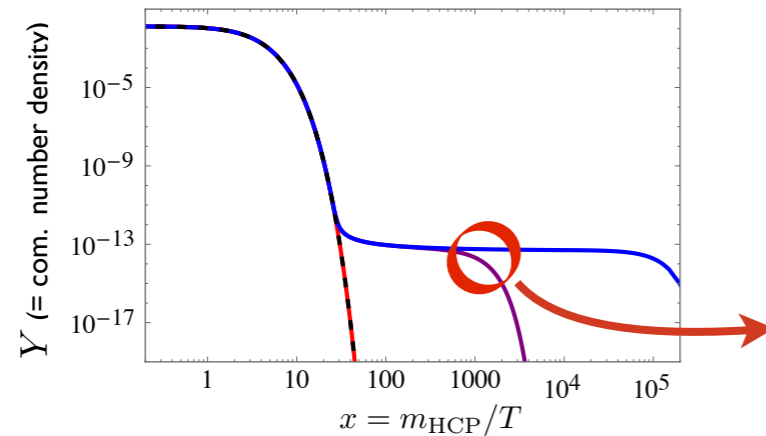


Cosmological point of view



- Very general (assuming standard cosmological history)

Cosmological point of view



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Cosmological point of view

- Z_2 -symmetry:

$$\text{HCP} \rightarrow \chi \text{ SM}$$

- Dark matter:

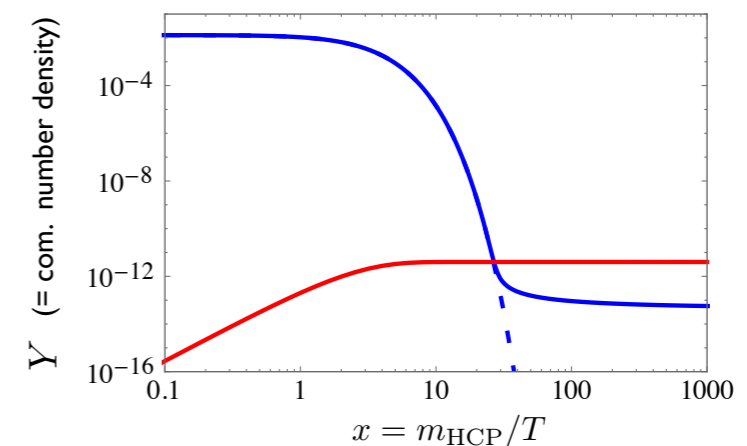
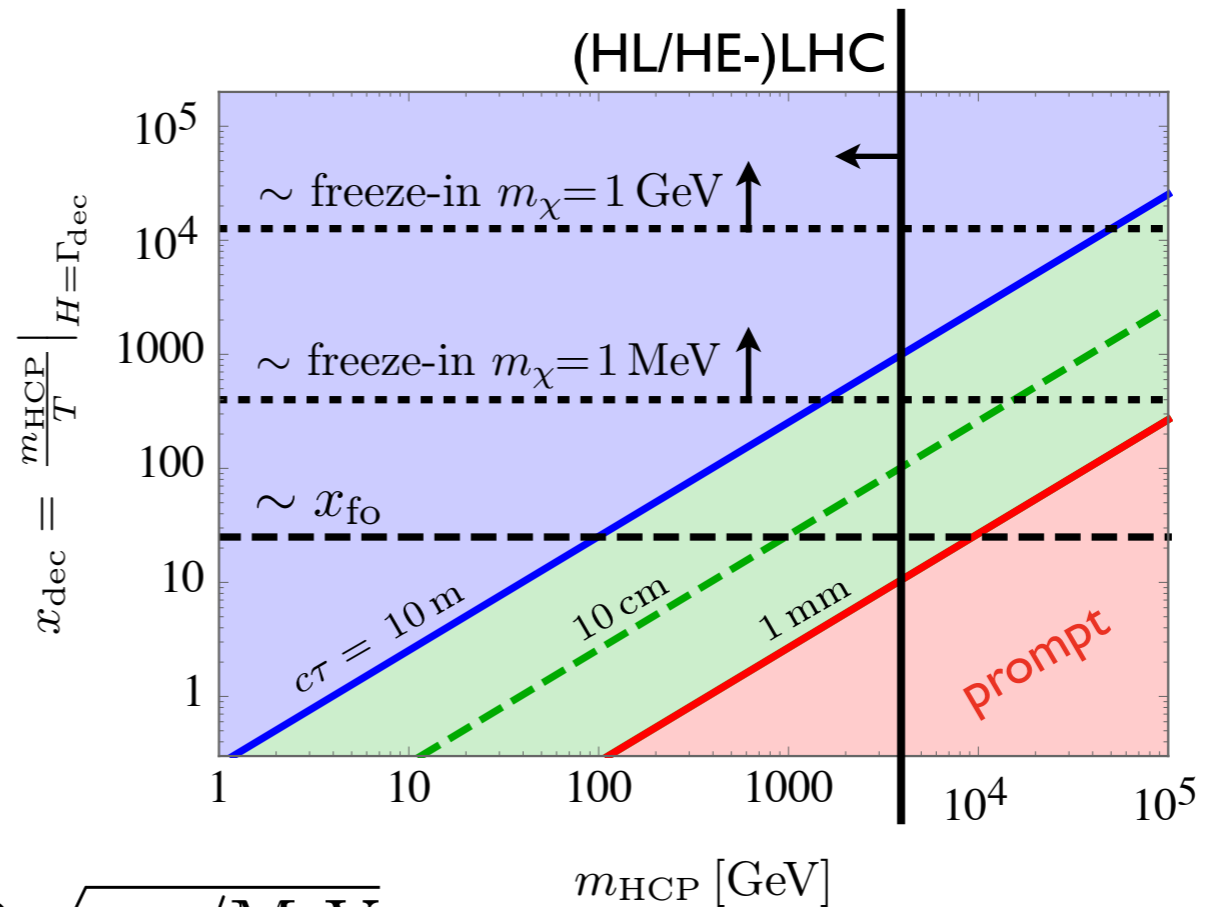
$$\Omega h^2 = 0.12$$



- freeze-in: $x_{\text{dec}} \sim 400 \sqrt{m_\chi / \text{MeV}}$

[Garny, JH 1809.10135]

[McDonald 2002; Choi, Roszkowski 2005; Petraki, Kusenko 2008; Hall, Jedamzik, March-Russell, West, 2009]



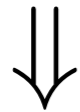
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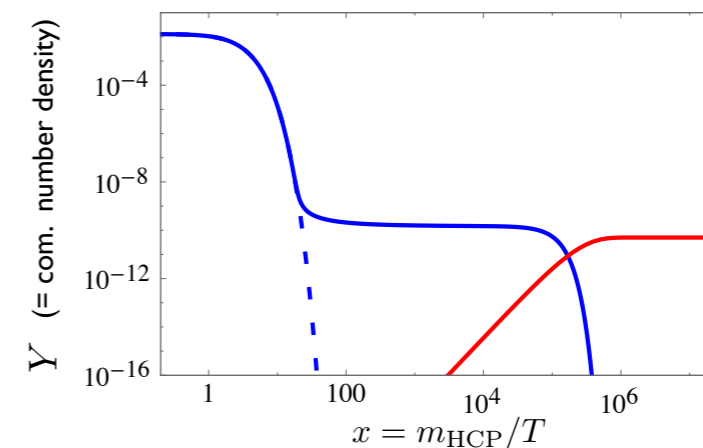
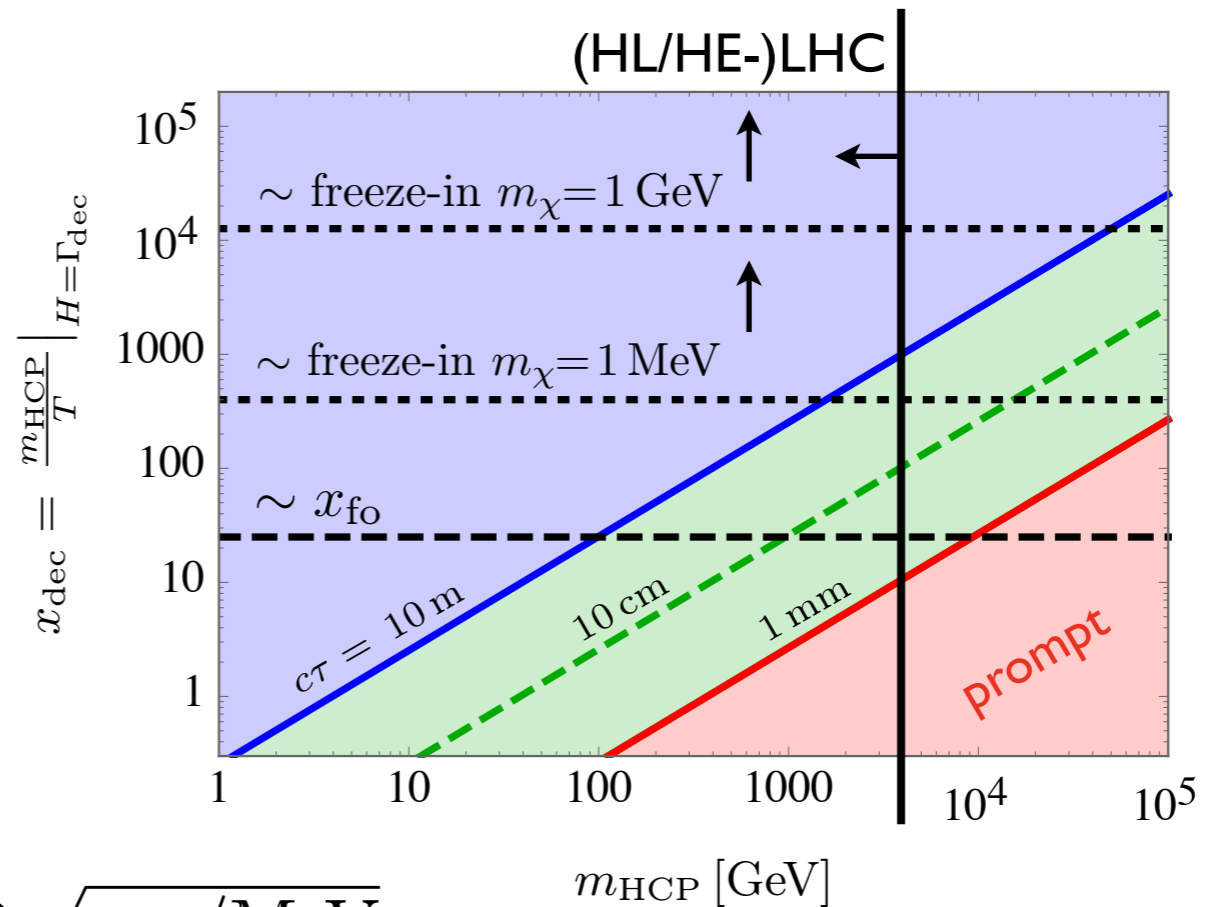
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- freeze-in: $x_{\text{dec}} \sim 400 \sqrt{m_\chi / \text{MeV}}$

- superWIMP: $x_{\text{dec}} \gg 400 \sqrt{m_\chi / \text{MeV}}$

[Feng, Rajaraman, Takayama 2003]



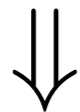
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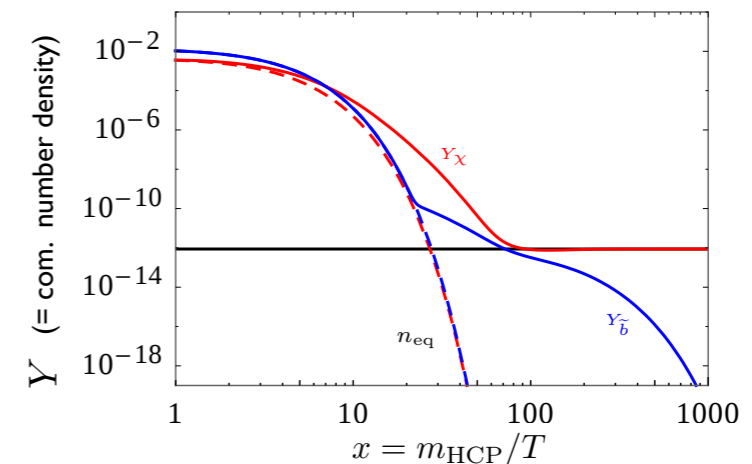
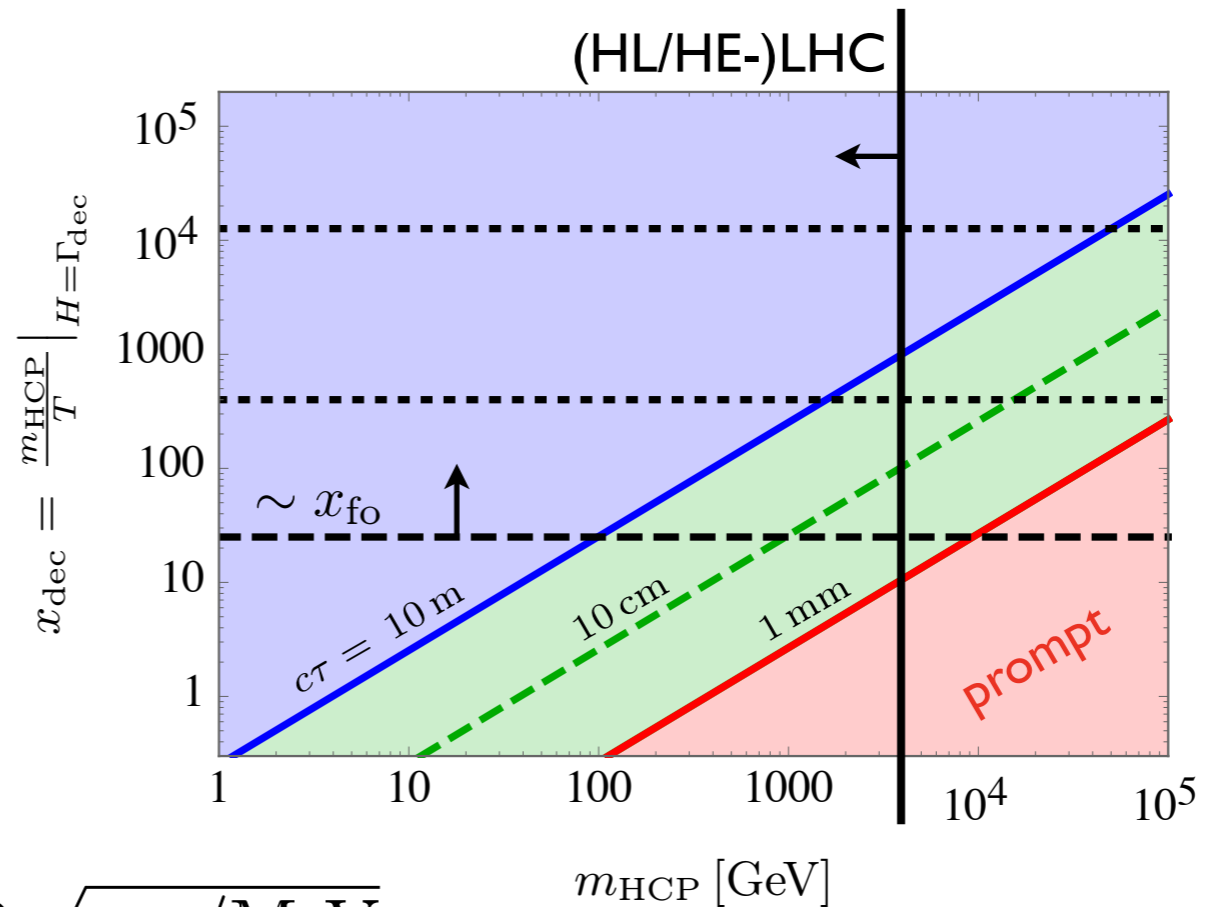


- freeze-in: $x_{\text{dec}} \sim 400 \sqrt{m_\chi / \text{MeV}}$

- superWIMP: $x_{\text{dec}} \gg 400 \sqrt{m_\chi / \text{MeV}}$

- conversion-driven freeze-out: $x_{\text{dec}} \gtrsim x_{\text{fo}}$

[Garny, JH, Lülf, Vogl 2017, D'Agnolo, Pappadopulo, Ruderman, 2017]



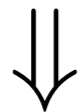
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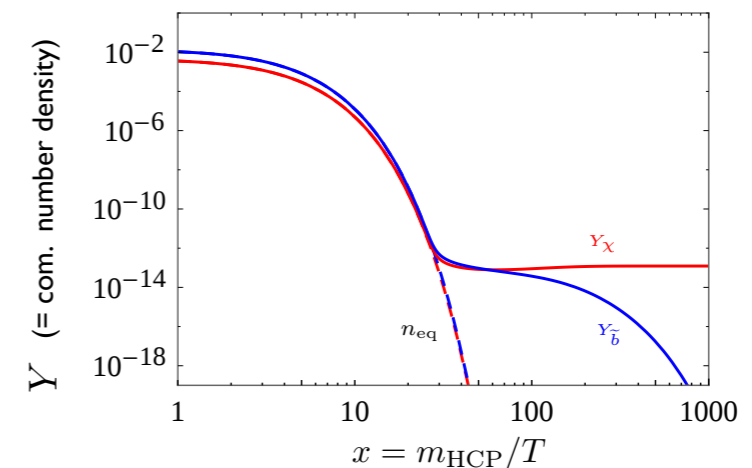
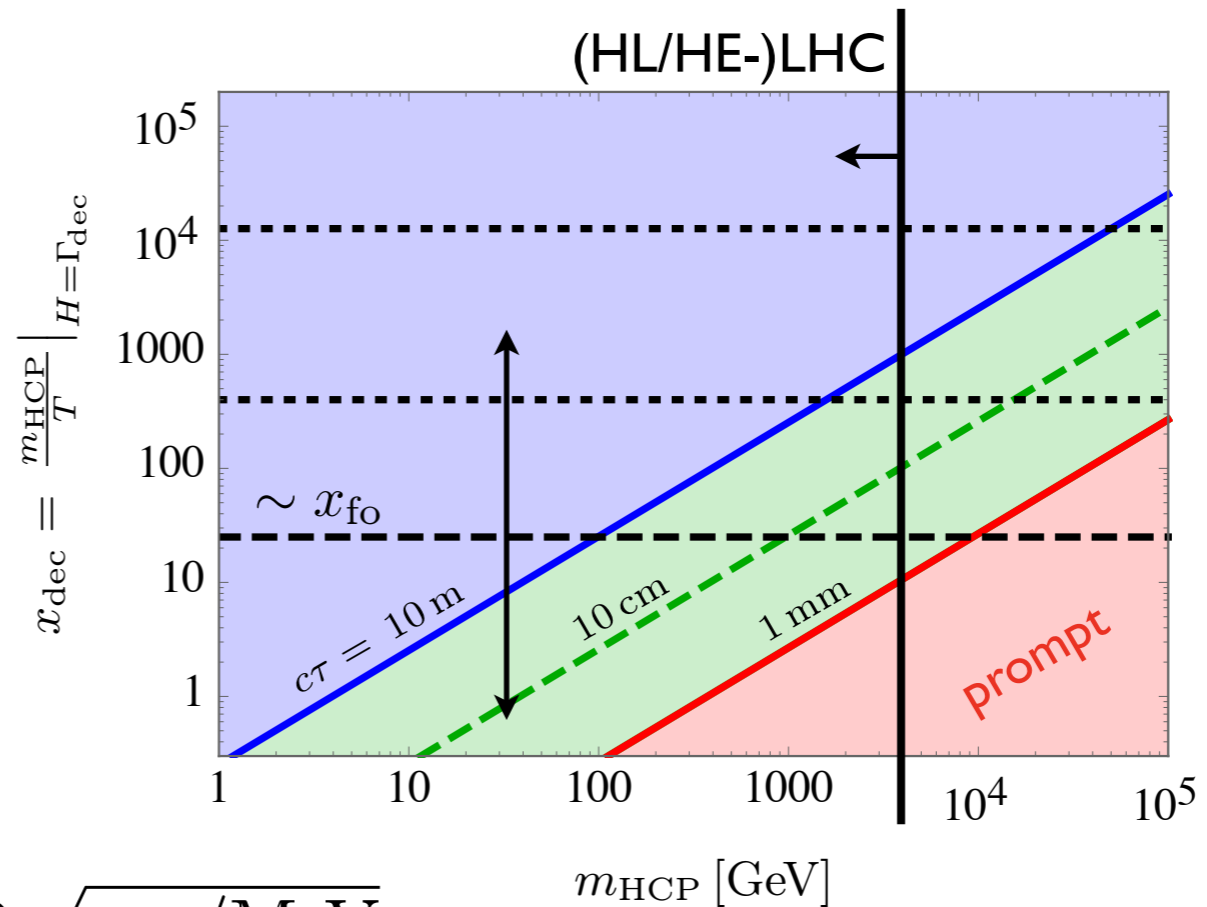


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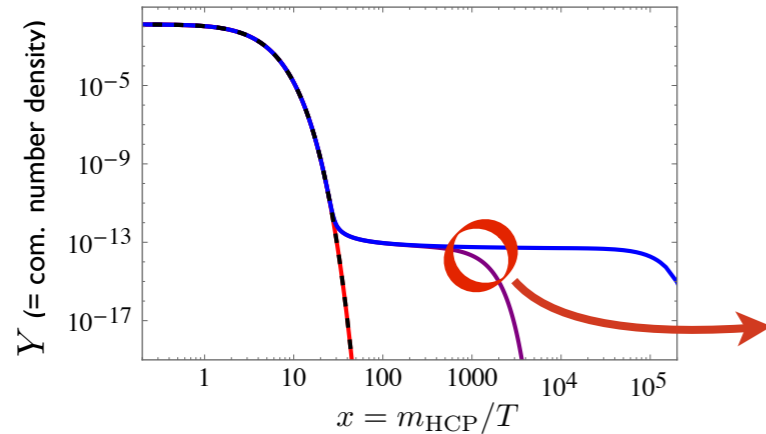
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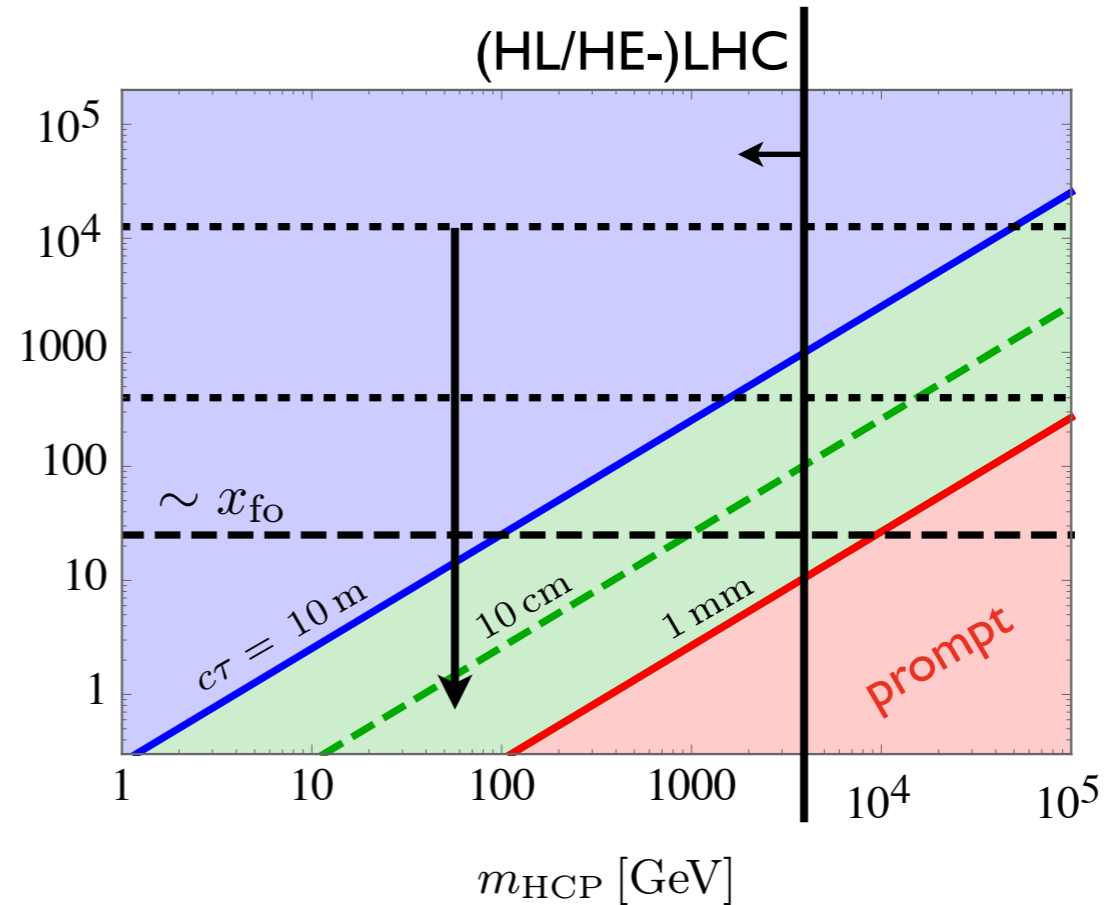
- co-annihilation: $x_{\text{dec}} \lesssim x_{\text{fo}}$
[Griest, Seckel 1991; Edsjo, Gondolo 1997]



Cosmological point of view



$$x_{\text{dec}} = \frac{m_{\text{HCP}}}{T} \Big|_{H=\Gamma_{\text{dec}}}$$



- No Z_2 -symmetry:

HCP \rightarrow SM SM

- Connection to dark matter?

- freeze-in:

e.g. HCP \rightarrow $\chi\chi$ SM

$\Gamma_\chi \leftarrow$ relic density

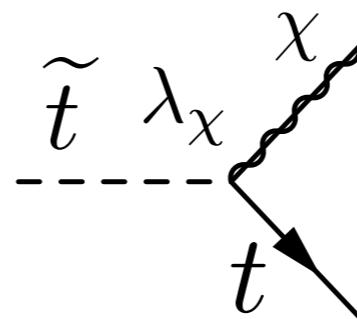
$\Gamma_{\text{tot}} \leftarrow$ lifetime

An explicit example

- Specific model: $\mathcal{L}_{\text{int}} = |D_\mu \tilde{q}|^2 - \lambda_\chi \tilde{q} \bar{q} \frac{1 - \gamma_5}{2} \chi + \text{h.c.}$
- SUSY-inspired simplified model:
Choose Majorana DM and scalar top-partner



- Yukawa-type interaction:

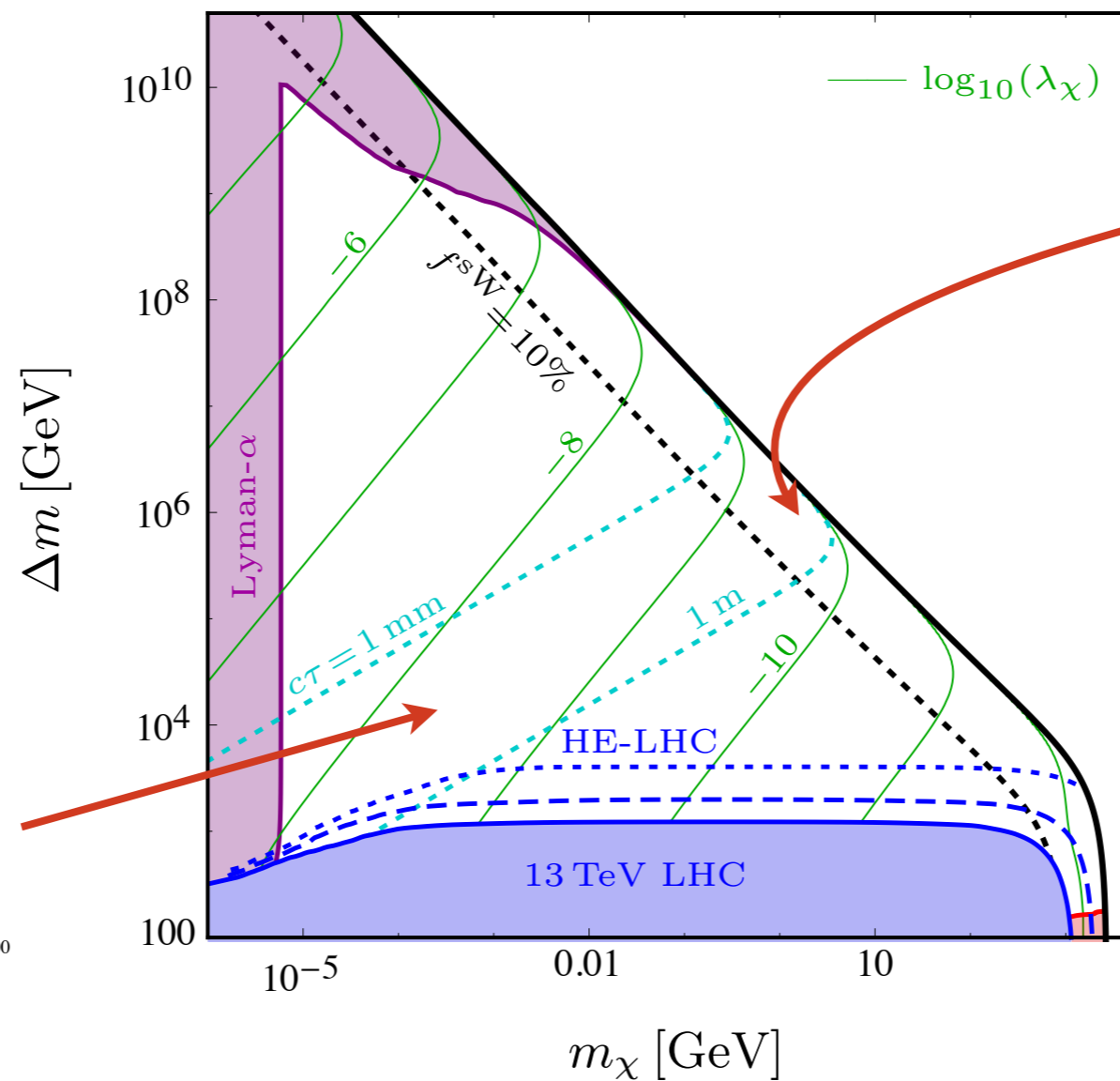


λ_χ is a free parameter here [see Ibarra et al. 2009 for SUSY realization]

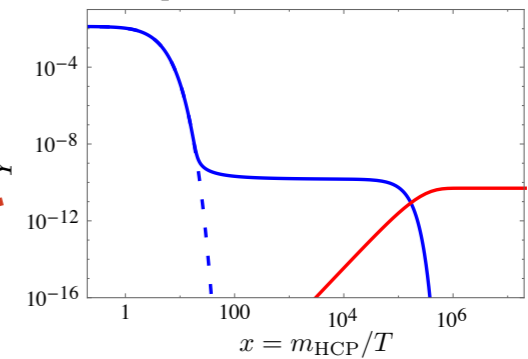
Freeze-in and superWIMP

[Garny, JH 1809.10135]

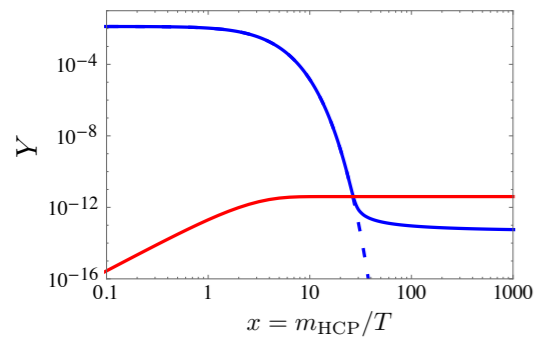
$$(\Omega h^2)_{\chi}^{\text{fi}}(\lambda_{\chi}) + (\Omega h^2)_{\chi}^{\text{sW}} = 0.12$$



superWIMP



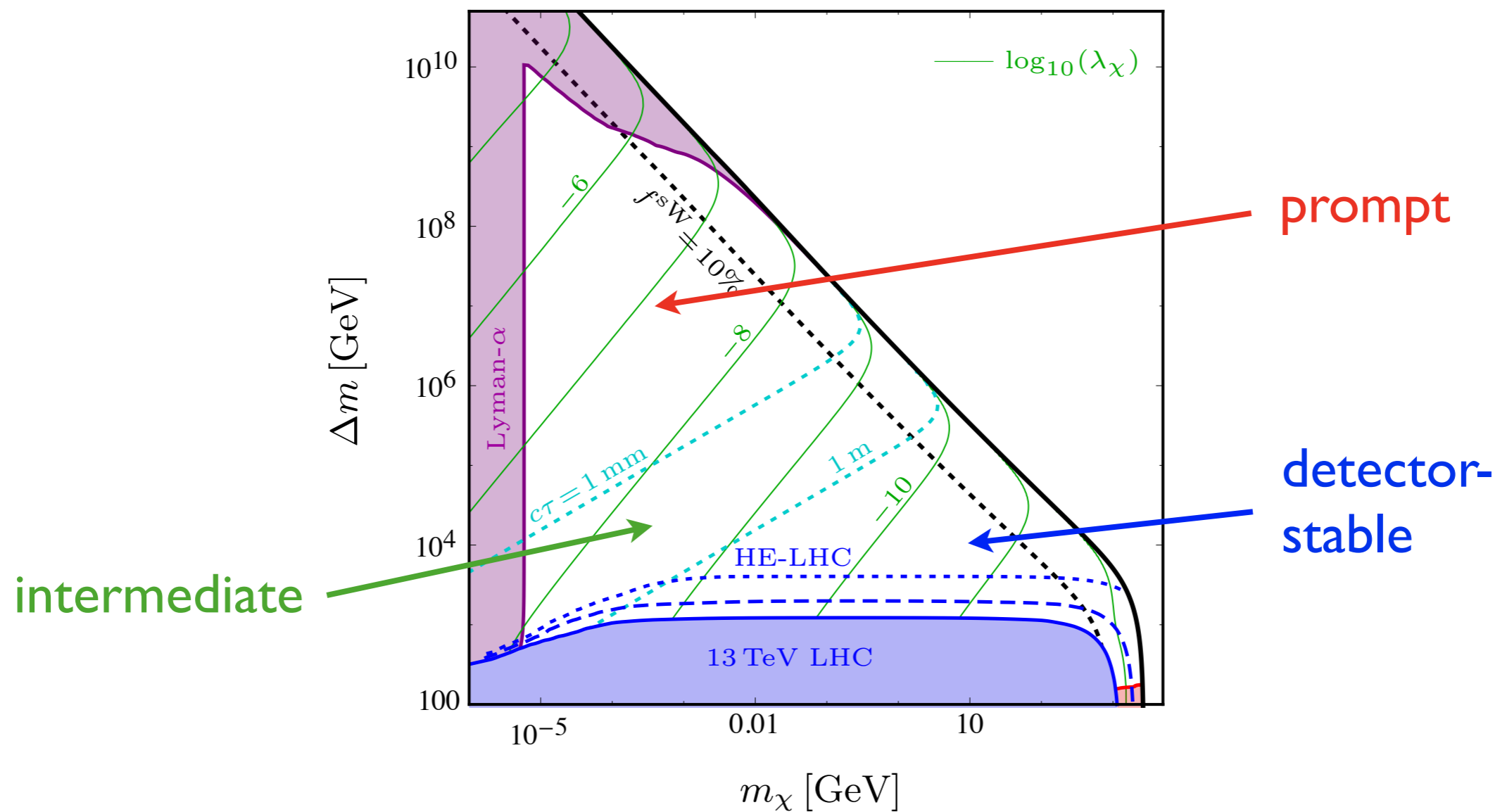
freeze-in



Freeze-in and superWIMP

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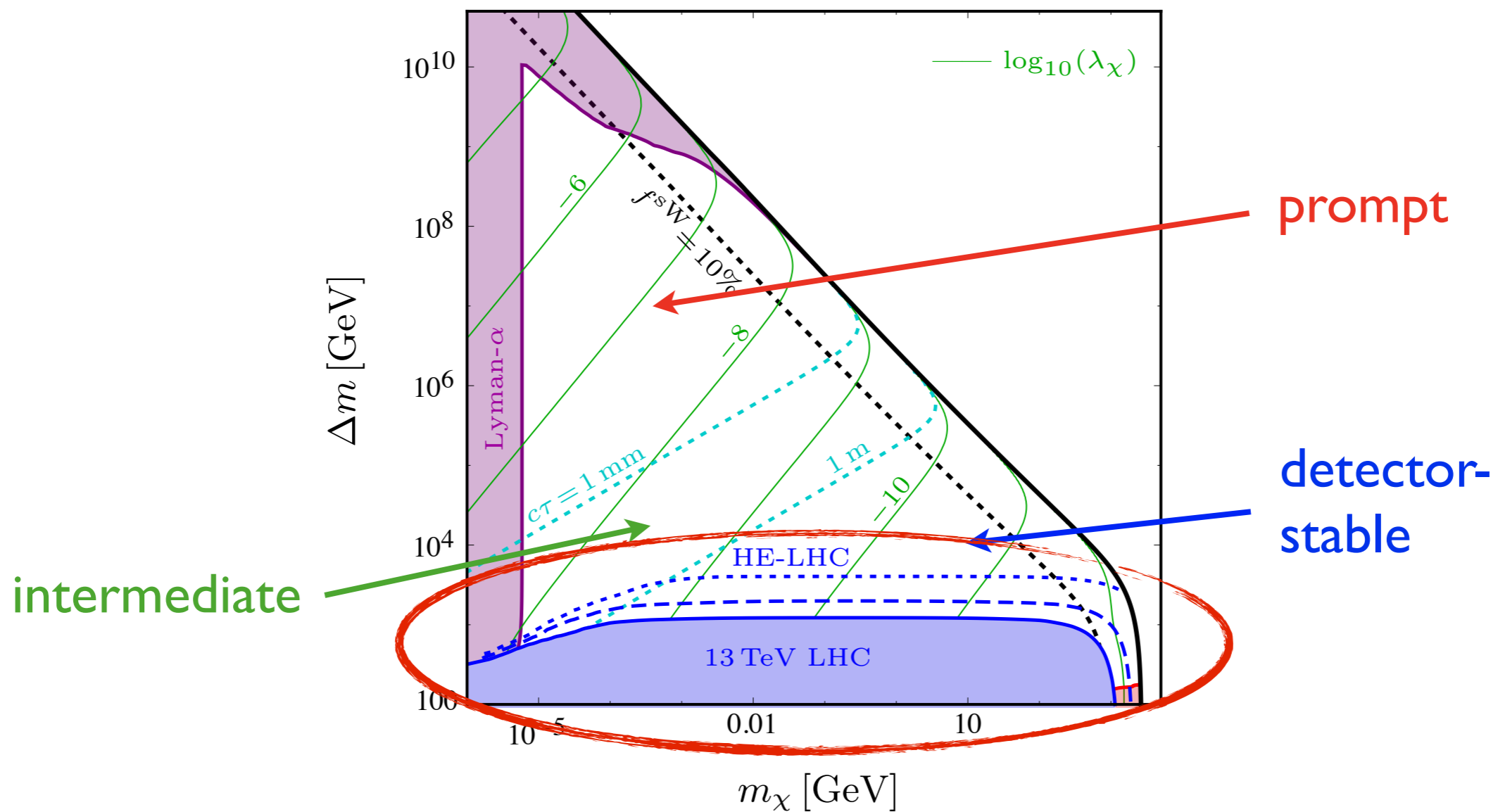
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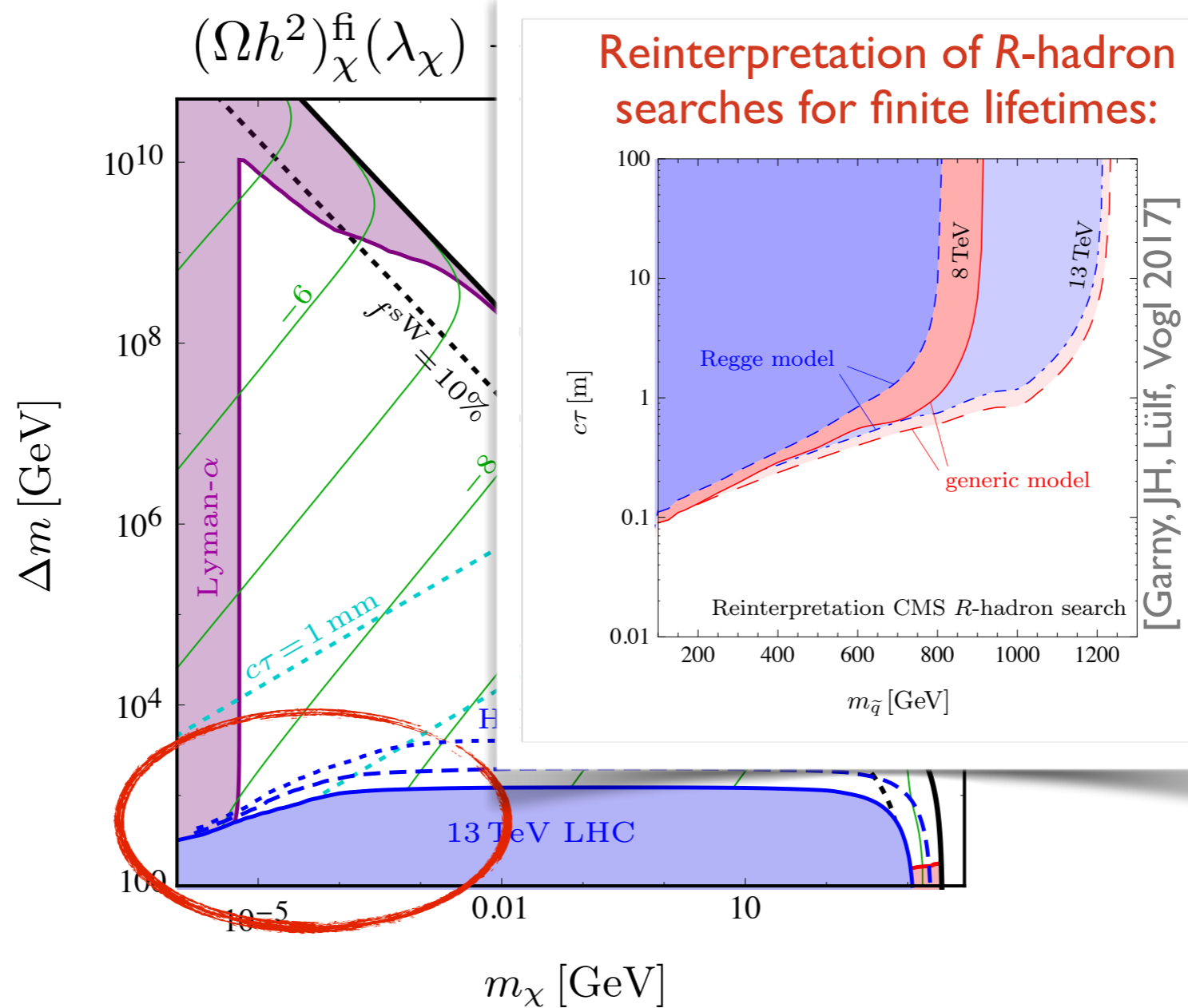
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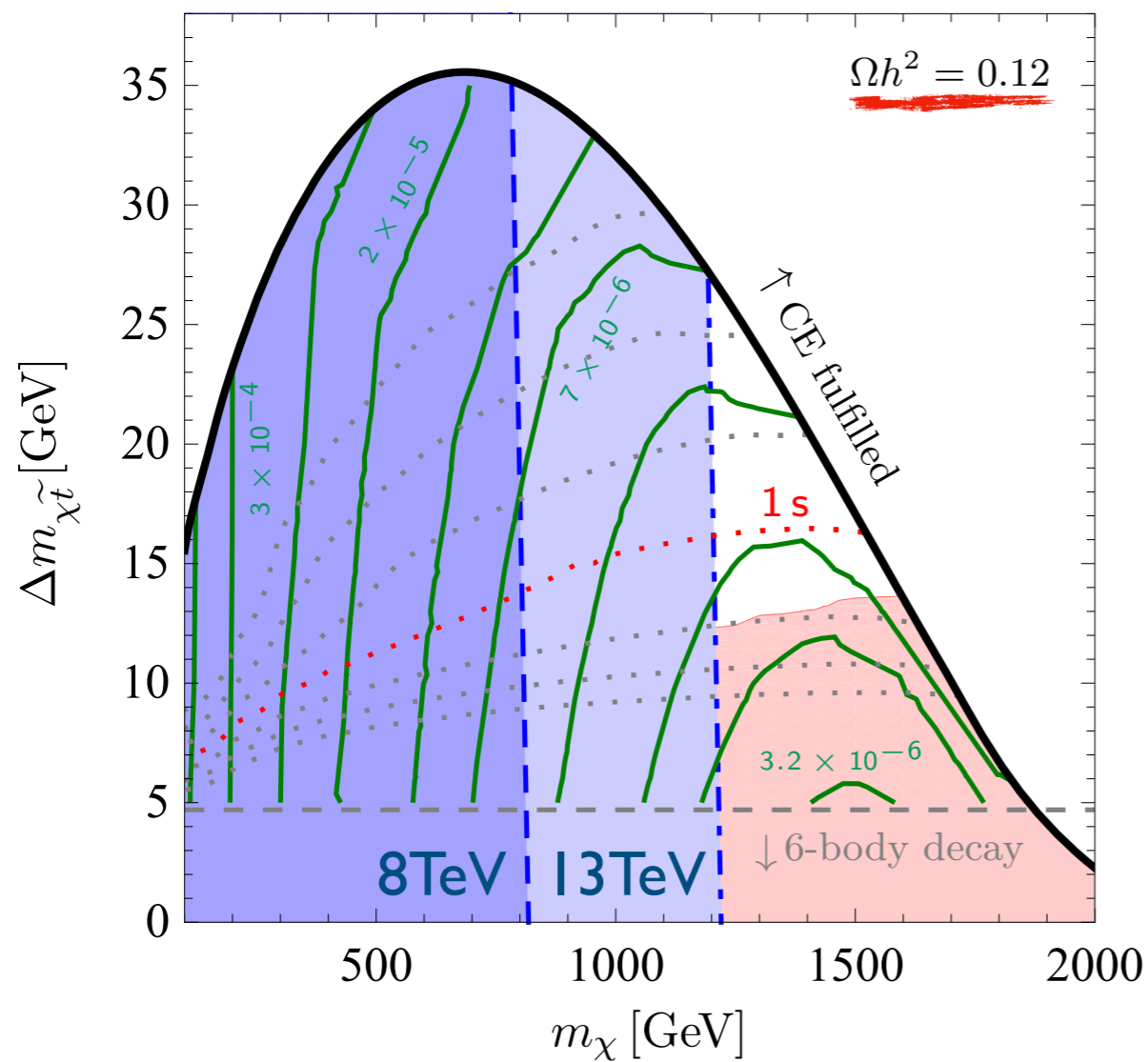


[Garny, JH, Lülfi, Vogl 2017]

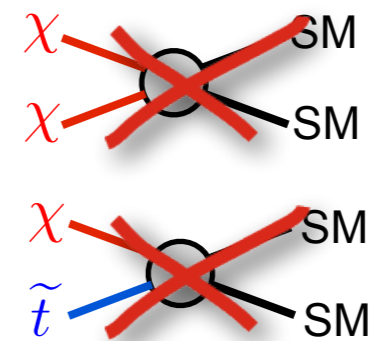
Conversion-driven freeze-out

[Garny, JH, Hufnagel, Lulf 2018]

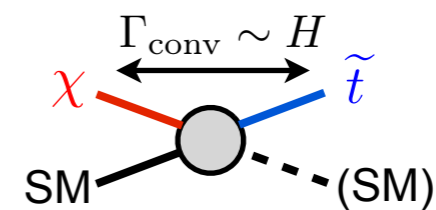
Allowed parameter space



- Thermalized dark matter
- Chemical decoupling not via annihilations...



...but via conversions:

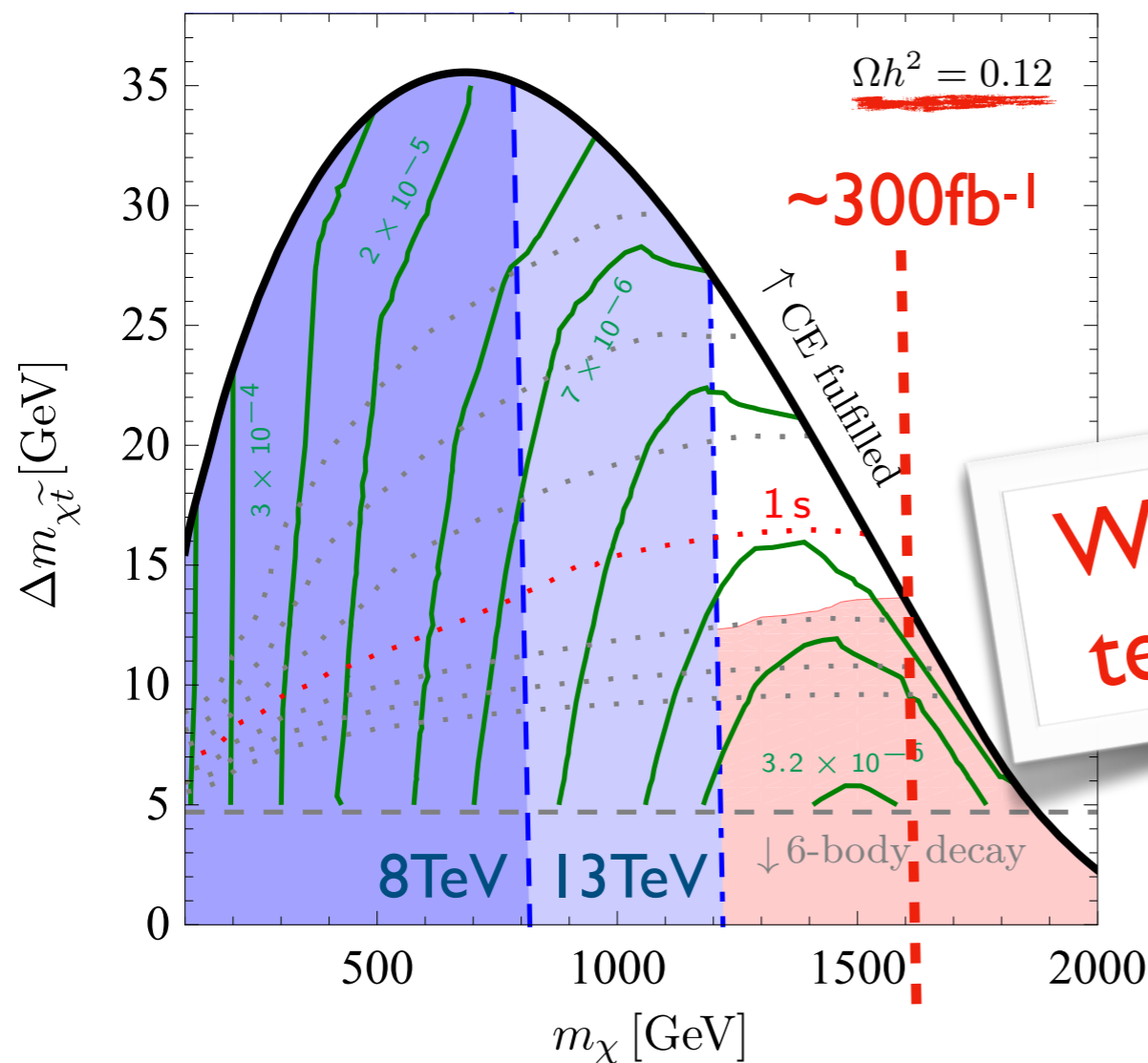


- Typical couplings $O(10^{-6})$

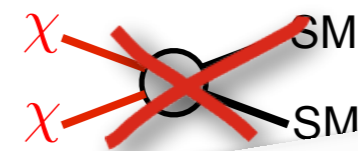
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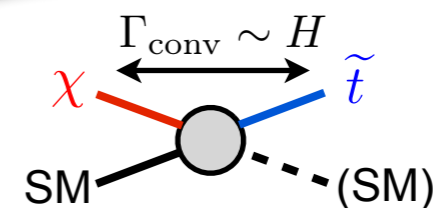
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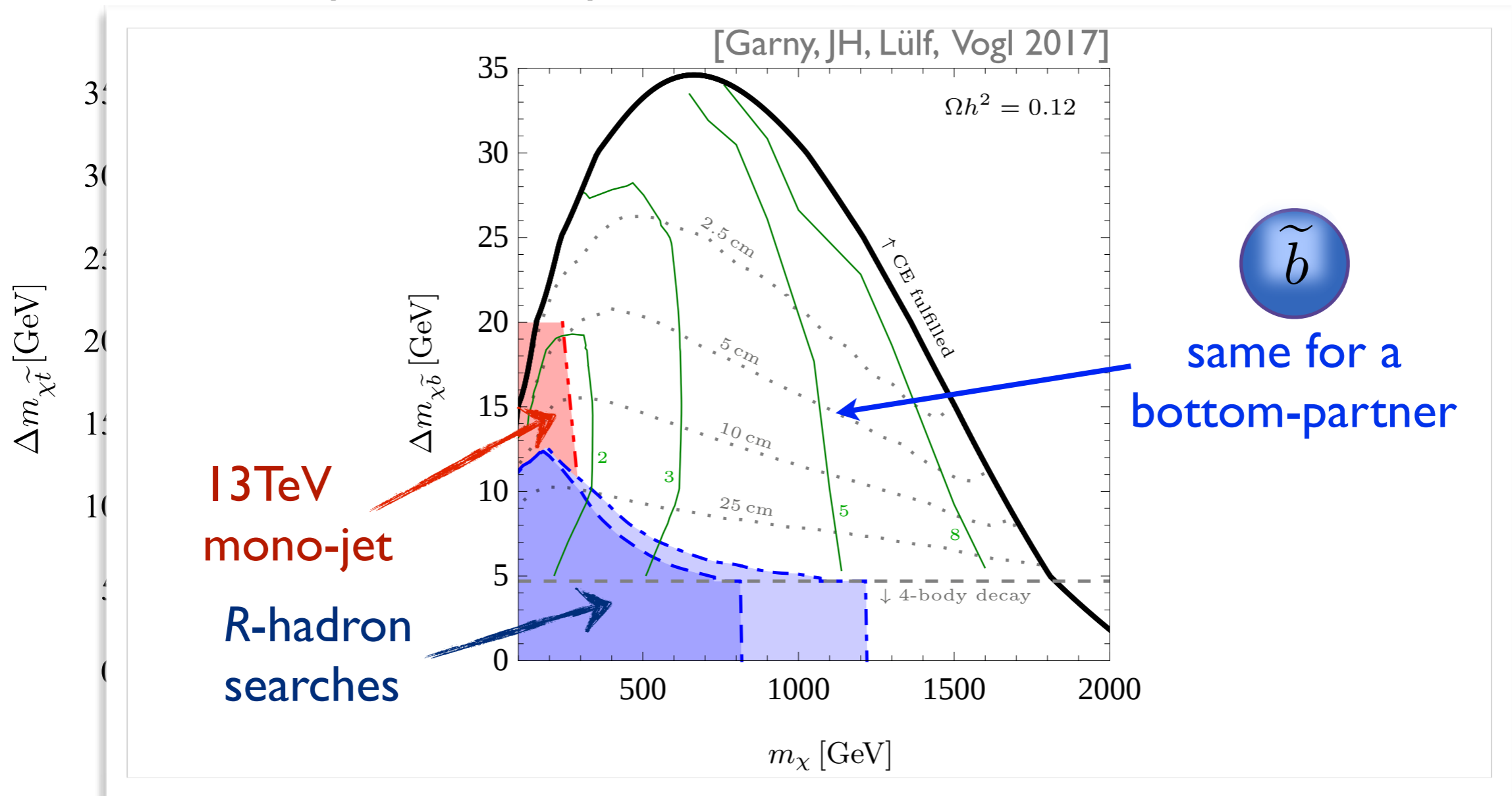
Whole allowed region testable with 300 fb⁻¹!



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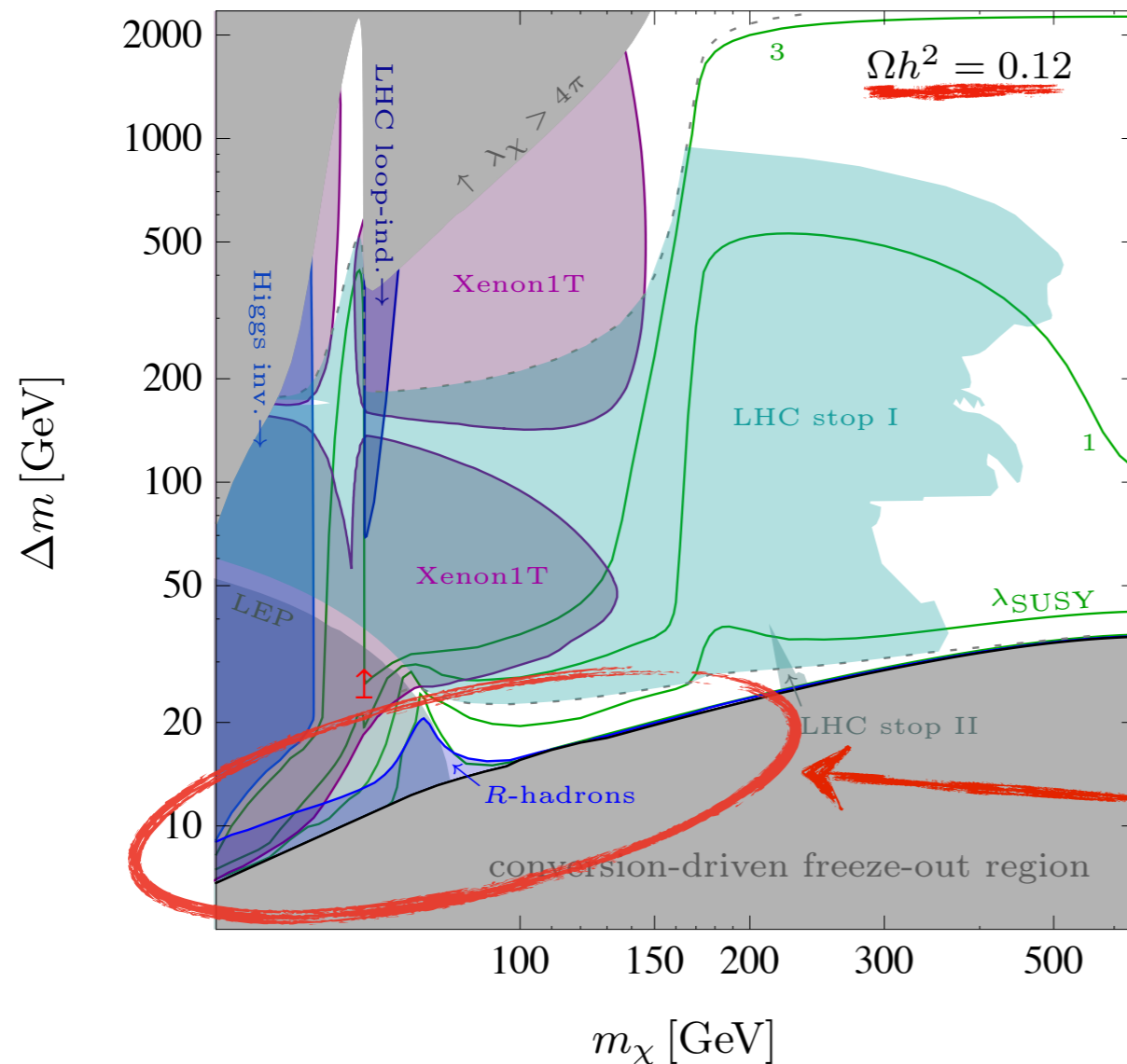
Allowed parameter space



Co-annihilation (WIMP dark matter)

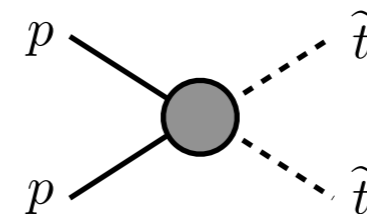
[Garny, JH, Hufnagel, Lülf 2018]

"WIMP region"



LHC:

- Searches for top-squarks
- Monojet searches
- Higgs invisible decay



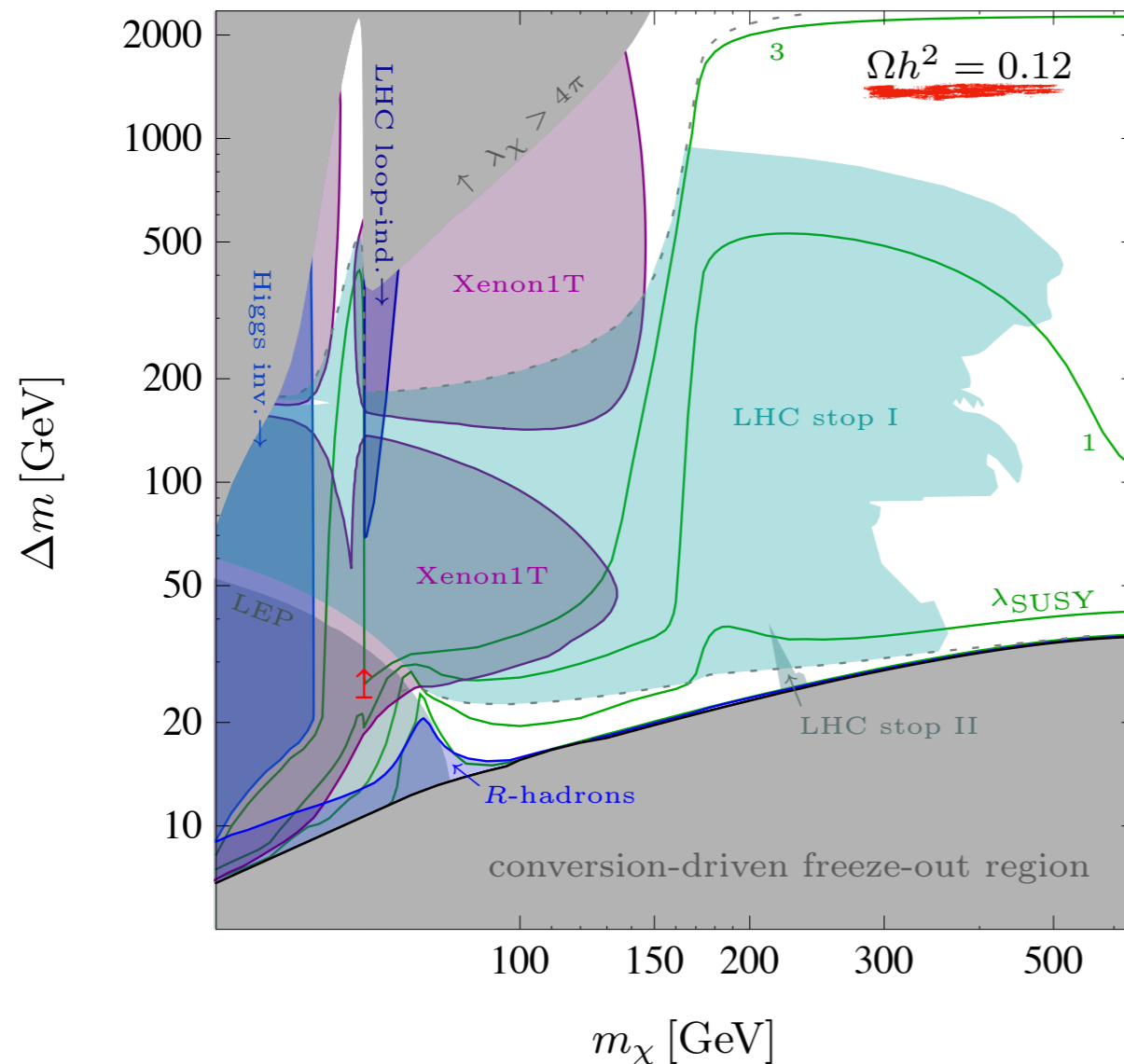
- **R-hadron searches**

[CMS 1305.0491, CMS-PAS-EXO-16-036]

Co-annihilation (WIMP dark matter)

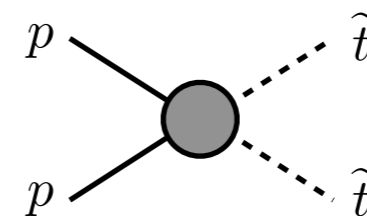
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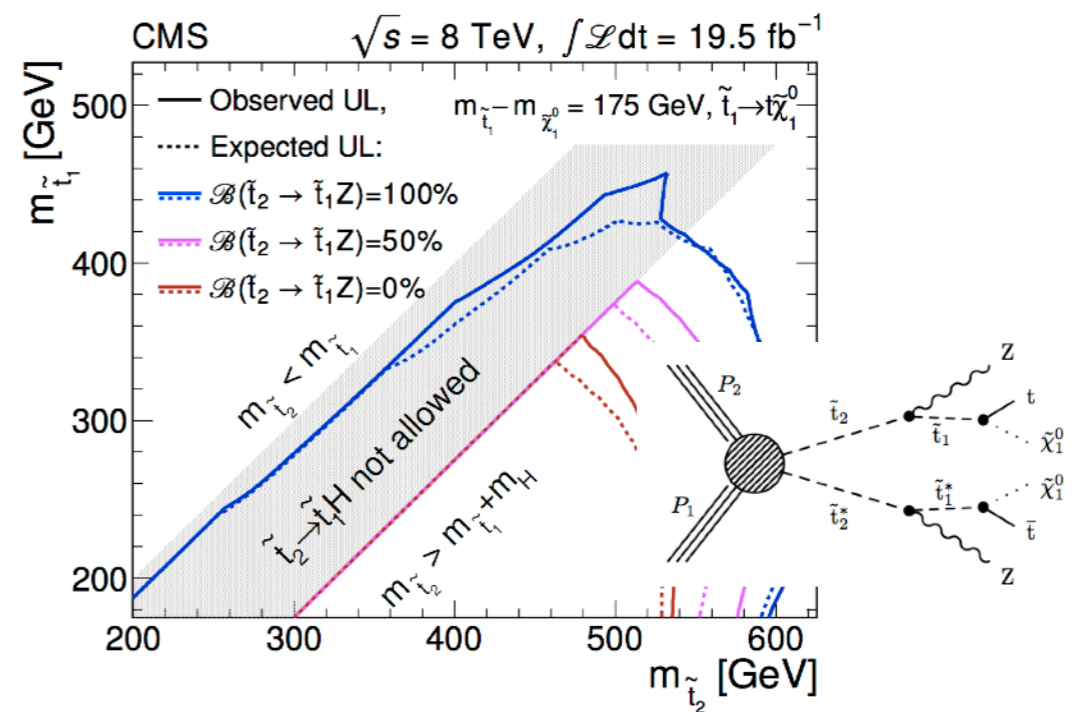
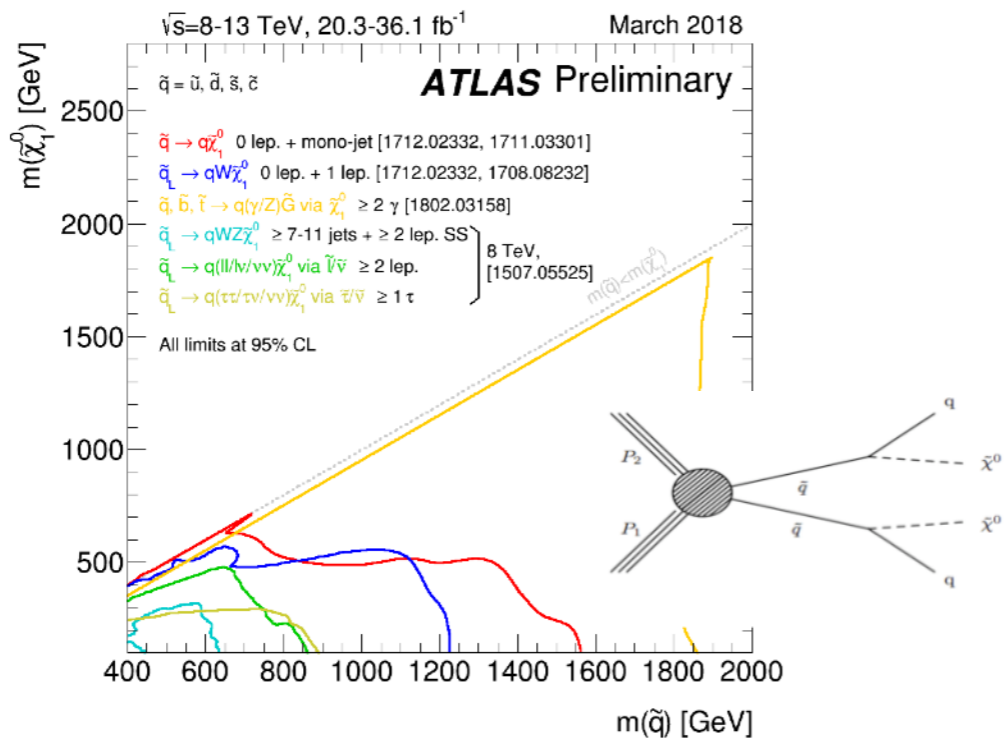
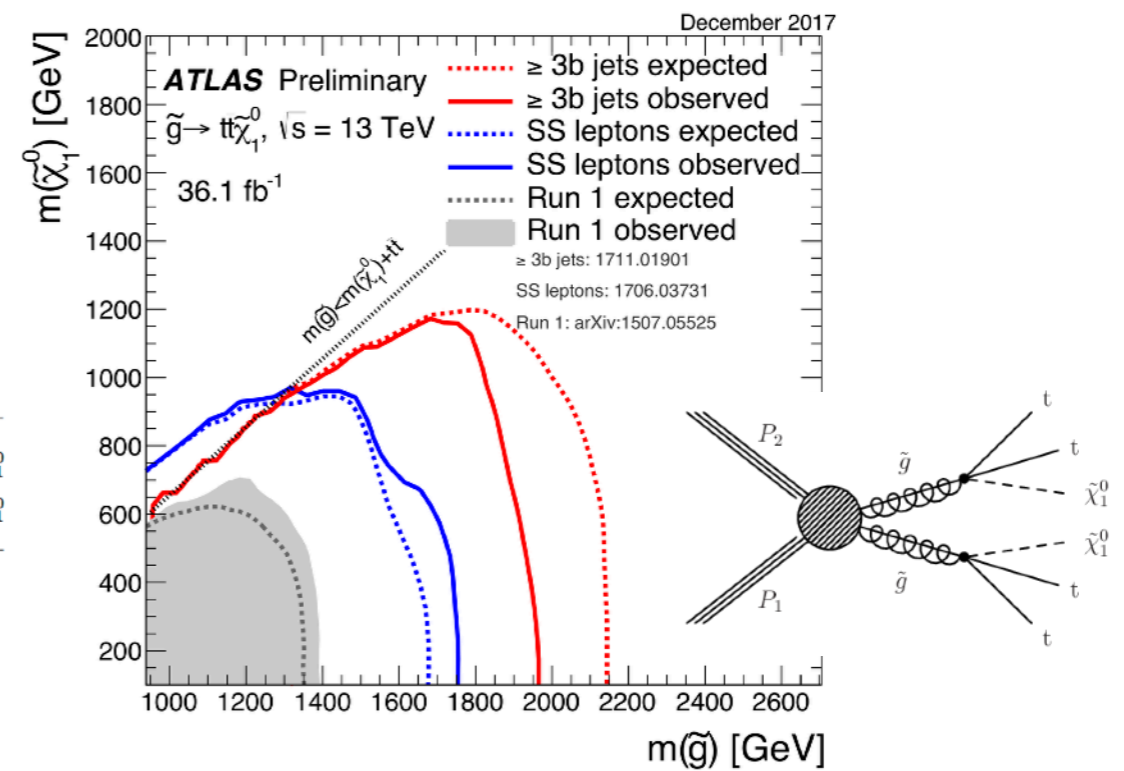
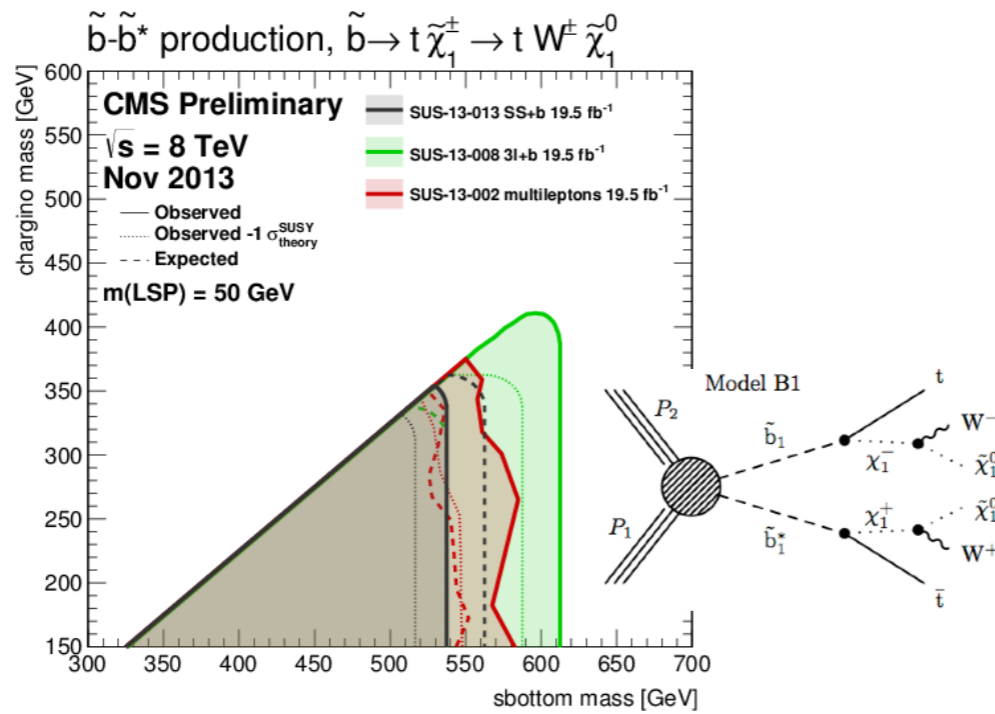


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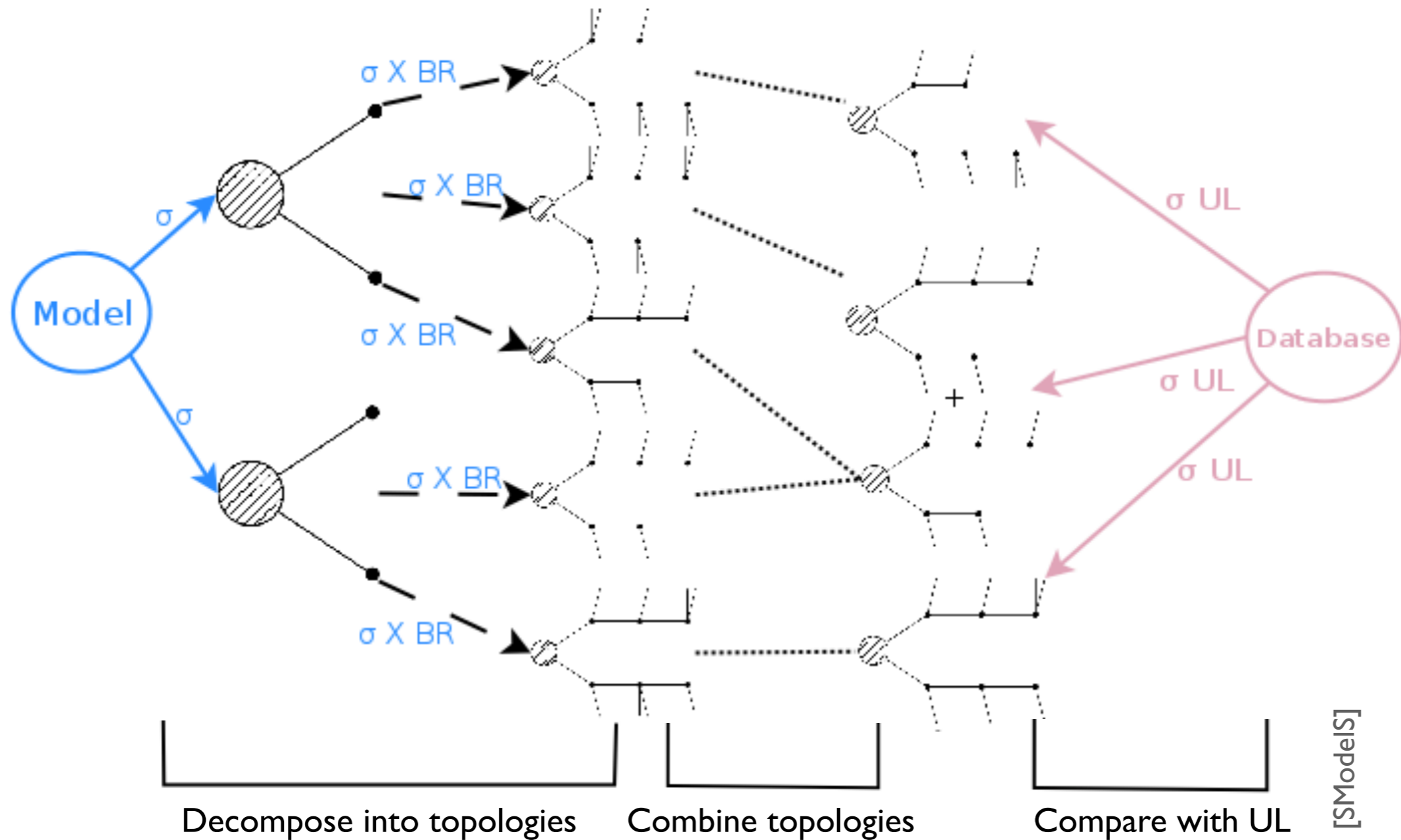
Reinterpretation of HSCP searches

Reinterpretation via simplified models



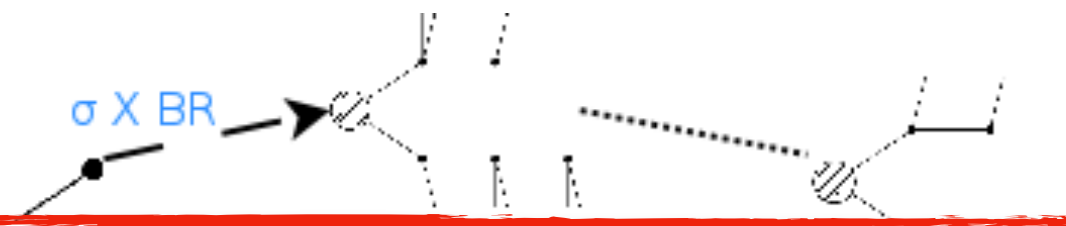
Systematic use of simplified model results

[SModelS: Federico Ambrogi, Juhi Dutta, JH, Sabine Kraml, Suchita Kulkarni, Ursula Laa, Andre Lessa, Veronika Magerl, Wolfgang Magerl, Doris Proschofsky, Humberto Reyes-Gonzalez, Jory Sonneveld, Michael Traub, Wolfgang Waltenberger, Matthias Wolf, Alicia Wongel] [Fastlim: Michele Papucci, Kazuki Sakurai, Andreas Weiler, Lisa Zeune]

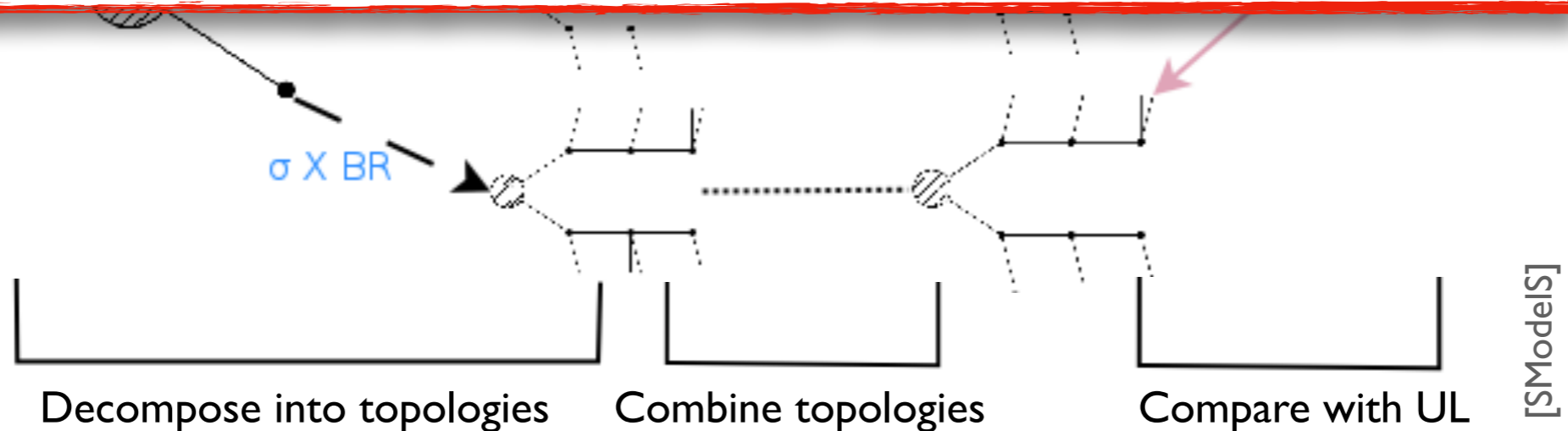


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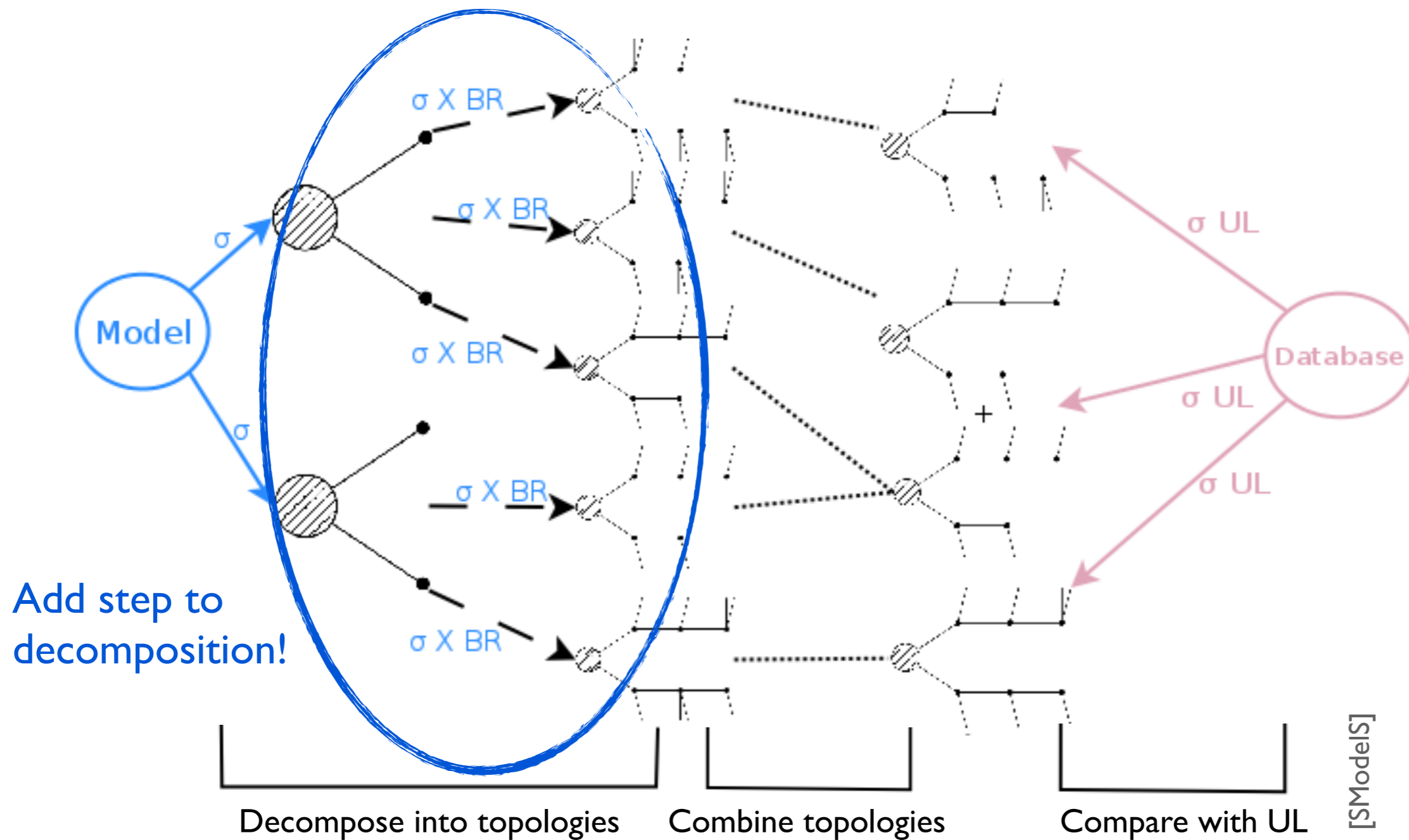
- 
- Diagram showing a particle decaying into two particles, with a label $\sigma X BR$ and an arrow pointing to the decay vertex. The diagram is part of a larger set of Feynman diagrams illustrating the process.
- No Monte Carlo simulation need \rightarrow Fast!
 - Applicable to any BSM
 - Uses approximations (only masses, topologies)

[see e.g. Edelhäuser et al. 1410.0965, 1501.03942]



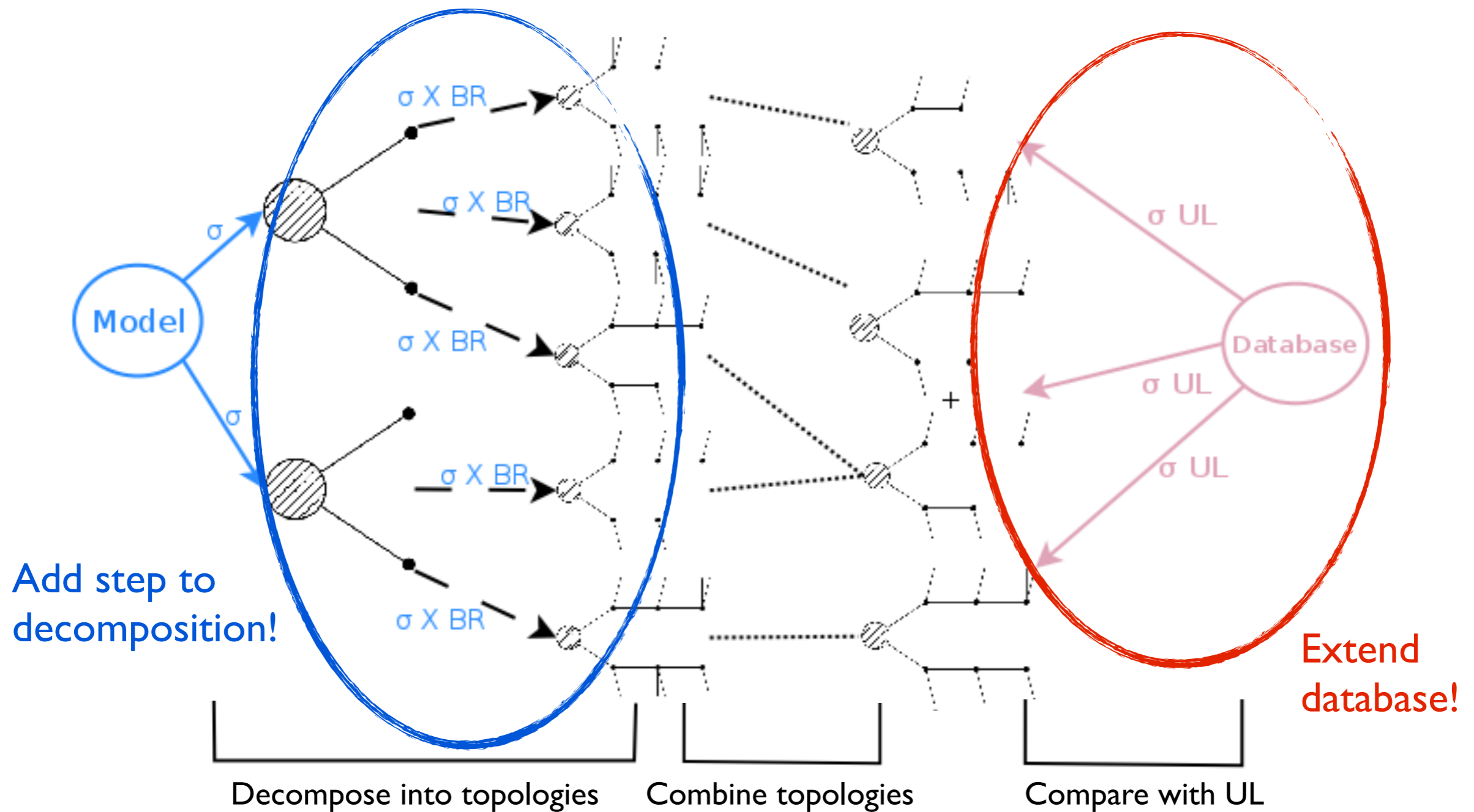
Extension for long-lived particles

[SModelS 1.2: <http://smodels.hephy.at>; JH, Sabine Kraml, Andre Lessa | 808.05229]



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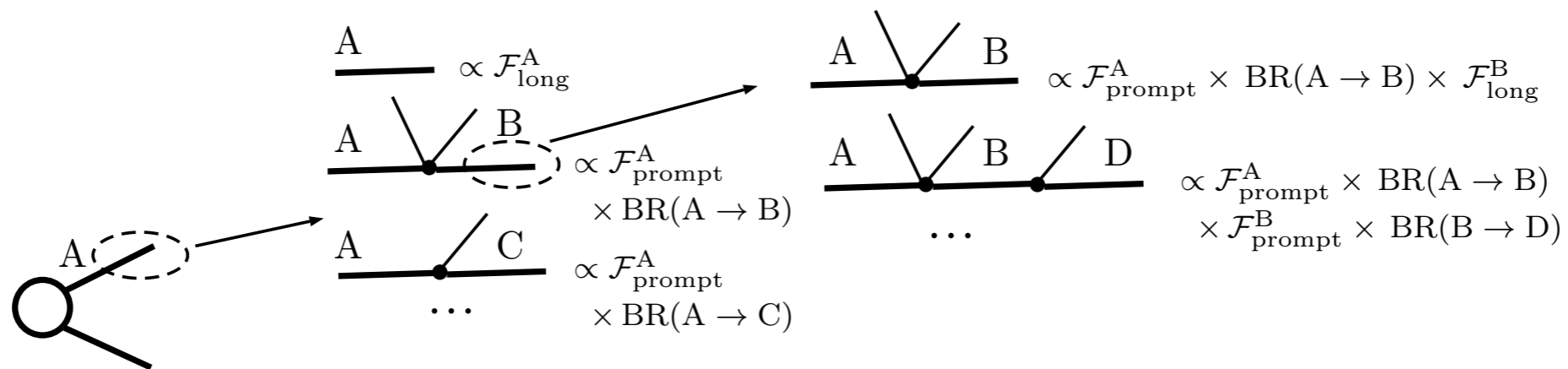
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- Add step to decomposition:

Probability to decay promptly: $\mathcal{F}_{\text{prompt}} = 1 - \exp\left(-\Gamma \left\langle \frac{\ell_{\text{inner}}}{\gamma\beta} \right\rangle_{\text{eff}}\right)$

or appear metastable: $\mathcal{F}_{\text{long}} = \exp\left(-\Gamma \left\langle \frac{\ell_{\text{outer}}}{\gamma\beta} \right\rangle_{\text{eff}}\right)$



[see also JH, Lessa, Quertenmont, | 509.00473]

- End up with:

pure MET, mixed MET/HSCP and pure HSCP (or R-hadrons)

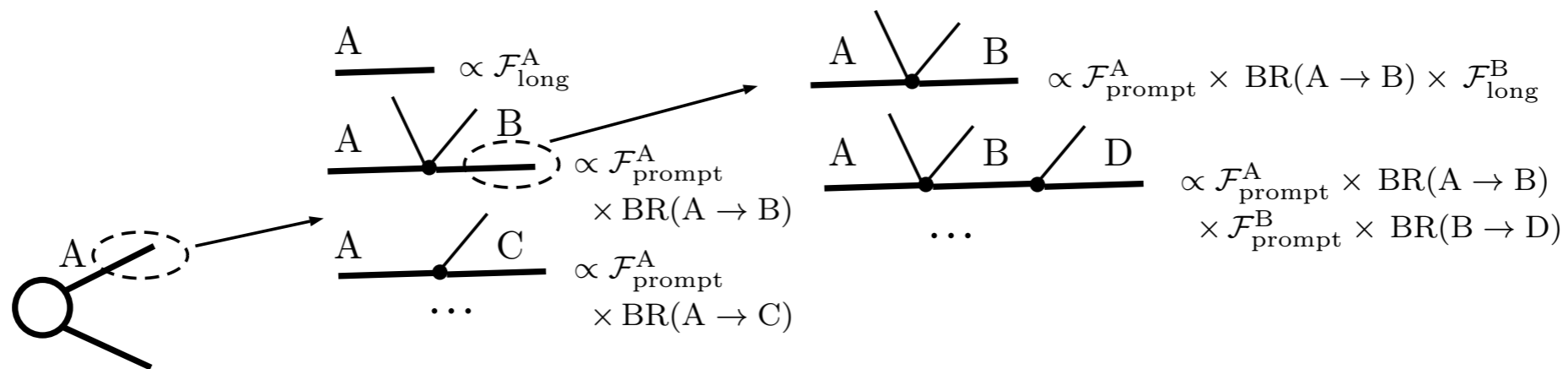
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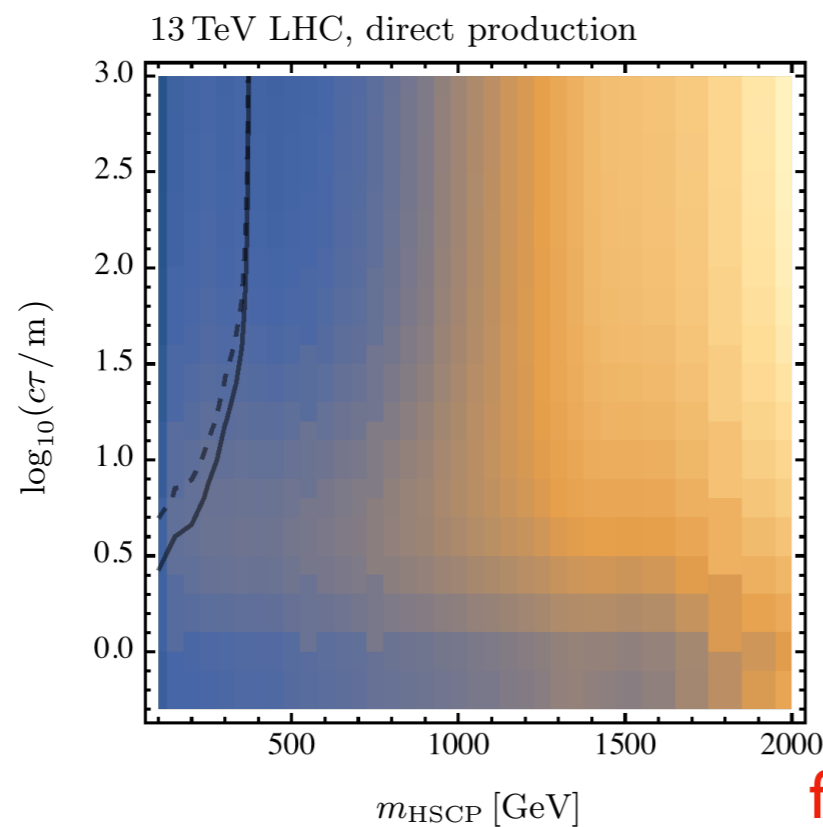
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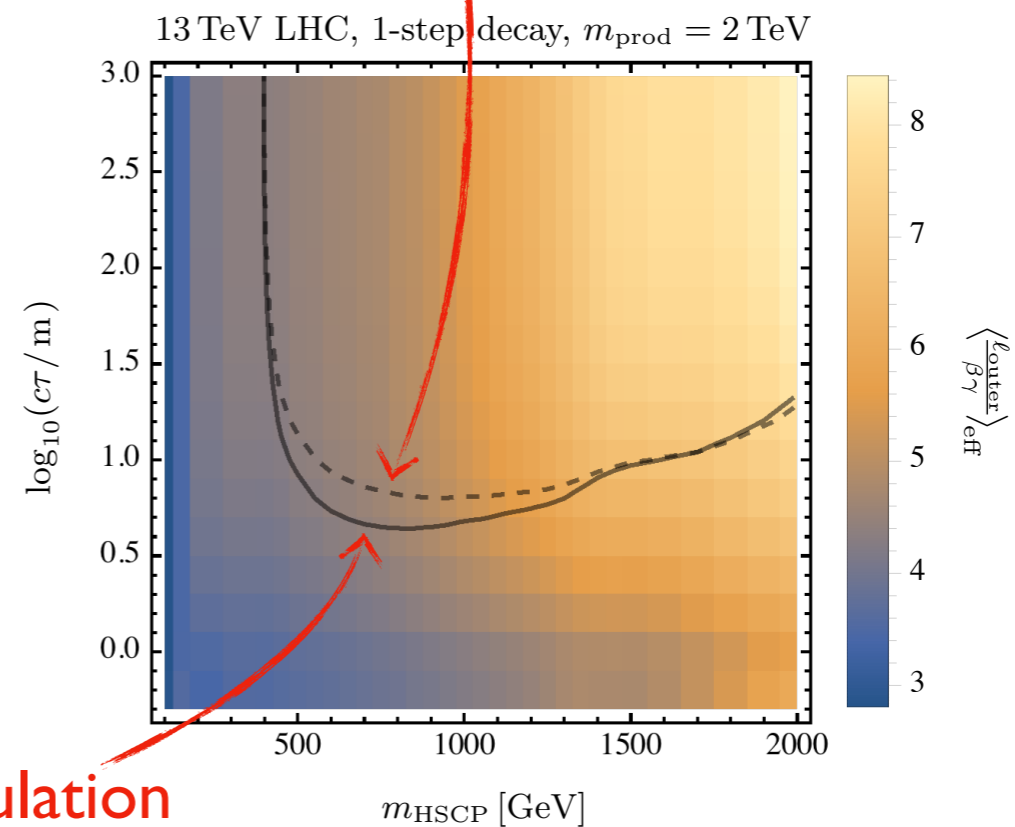
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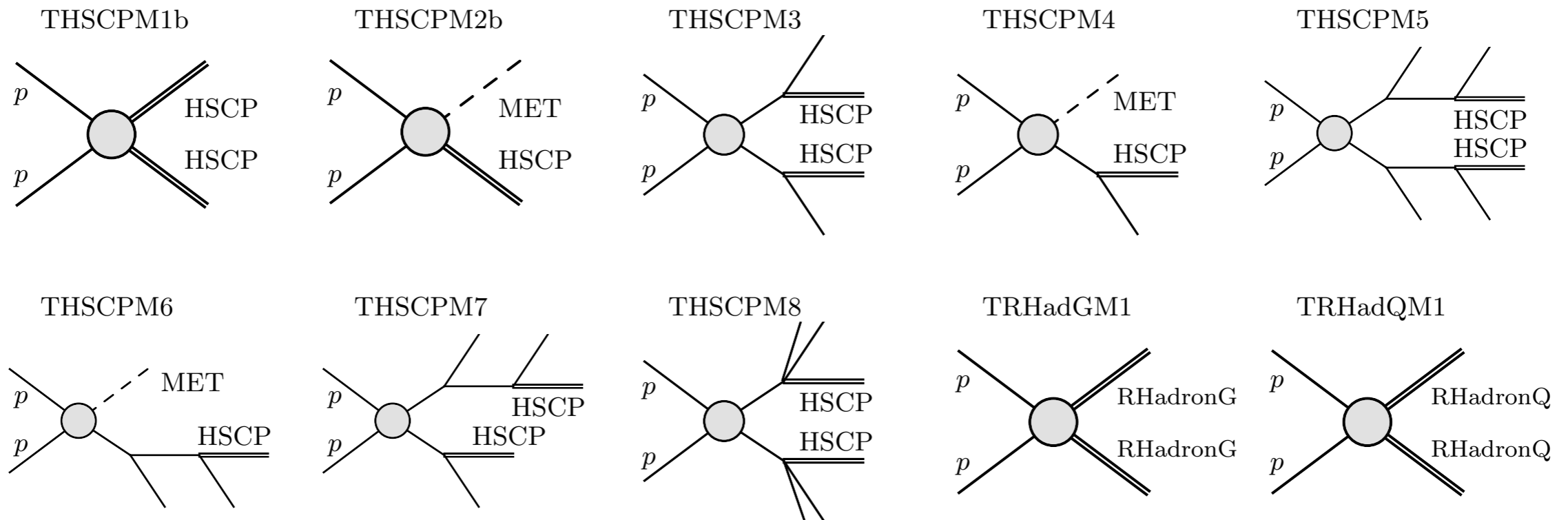
full simulation



Extension for long-lived particles

[SModelS 1.2: <http://smodels.hephy.at>; JH, Sabine Kraml, Andre Lessa | 808.05229]

- **Extend database:**
 - Generate our own efficiency maps
 - Use existing upper limits (direct production only)



Example I: Inert Doublet Model (IDM)

[Deshpande, Ma '78; Ma '06; Barbieri, Hall, Rychkov: '06; ...]

- Add second Higgs doublet Φ and Z_2 -symmetry:

$$V = \mu_1^2 |H|^2 + \mu_2^2 |\Phi|^2 + \lambda_1 |H|^4 + \lambda_2 |\Phi|^4 + \lambda_3 |H|^2 |\Phi|^2 \\ + \lambda_4 |H^\dagger \Phi|^2 + \frac{\lambda_5}{2} \left[(H^\dagger \Phi)^2 + \text{h.c.} \right]$$

- five free parameters: m_{H^0} , m_{A^0} , m_{H^\pm} , λ_L , λ_2

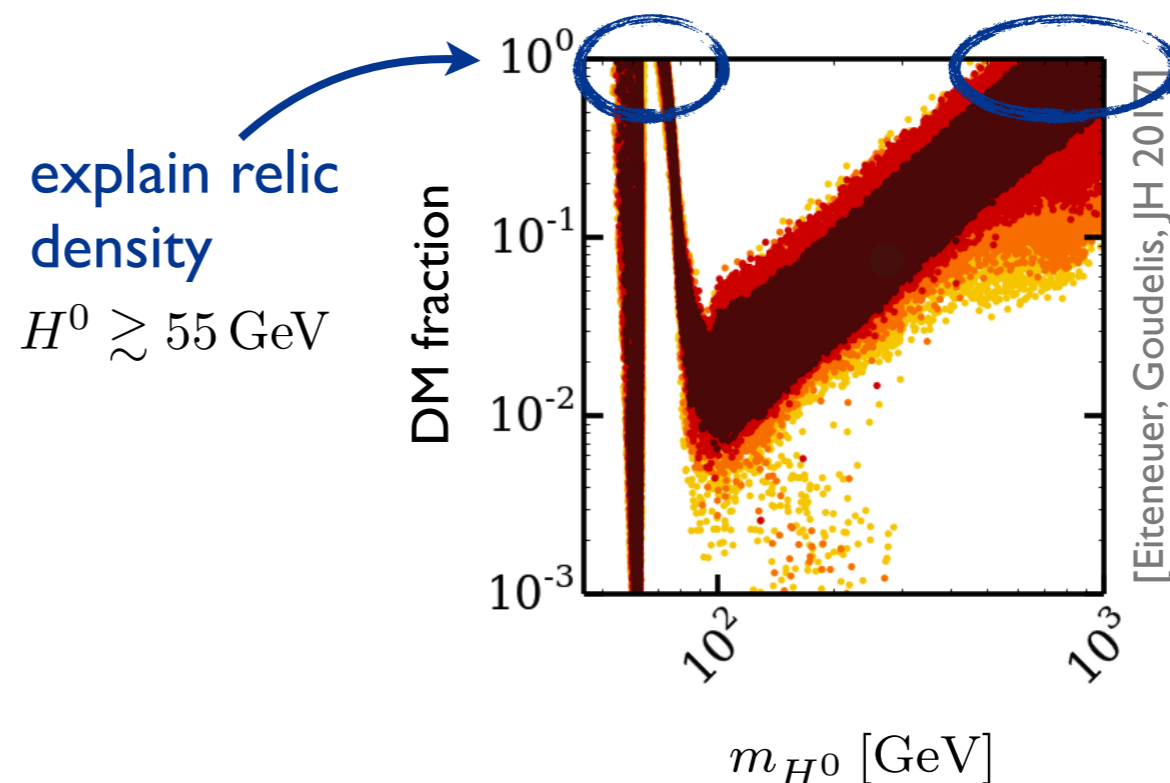
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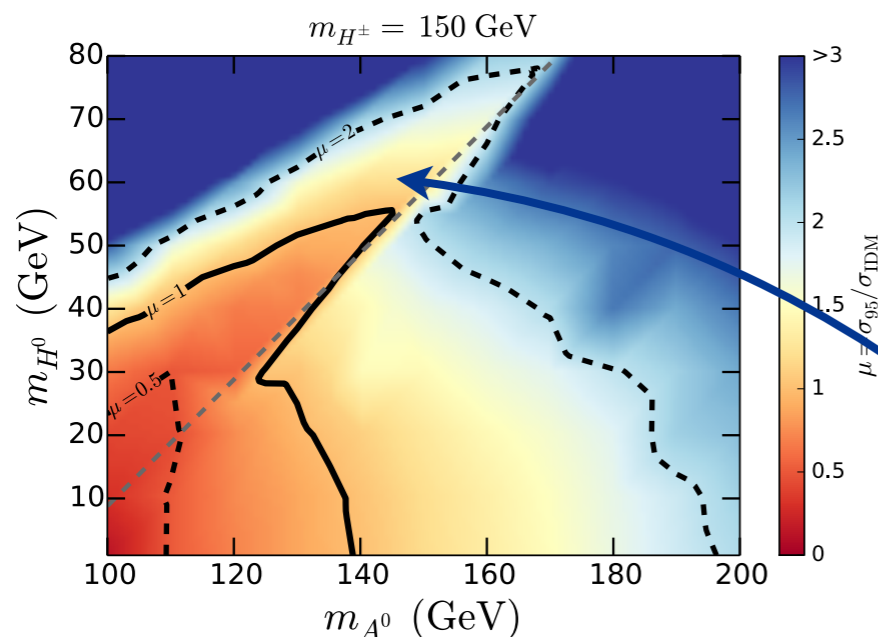
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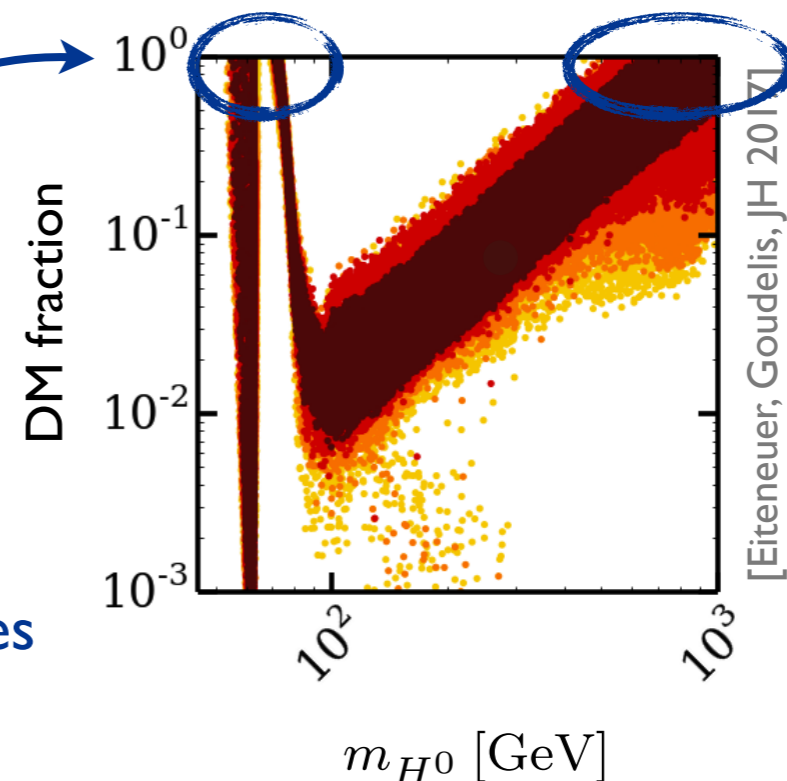
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[Belanger, Dumont, Goudelis, Herrmann, Kraml, Sengupta 2015]

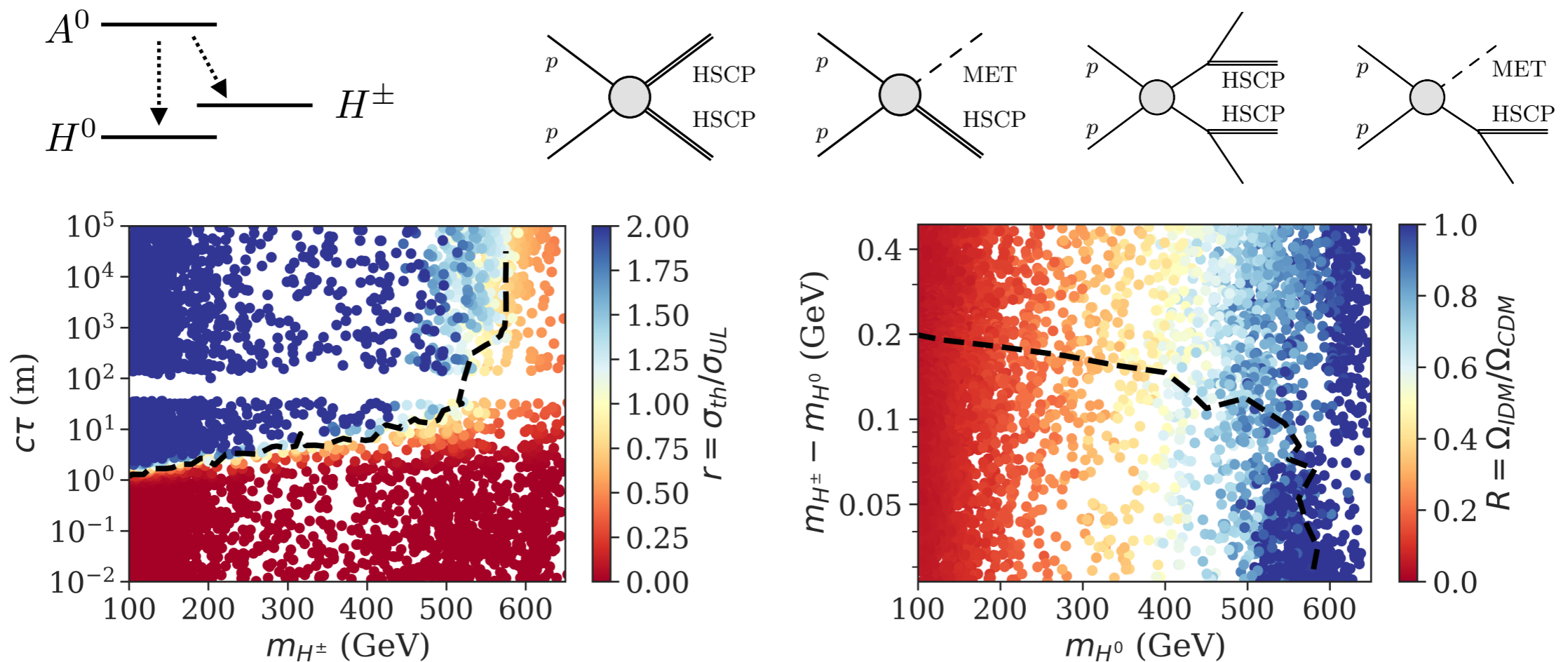
explain relic density
 $H^0 \gtrsim 55$ GeV
 not challenged by MET searches



Example I: Inert Doublet Model (IDM)

[JH, Sabine Kraml, Andre Lessa | 808.05229]

- Very compressed region $m_{H^\pm} \sim m_{H^0}$

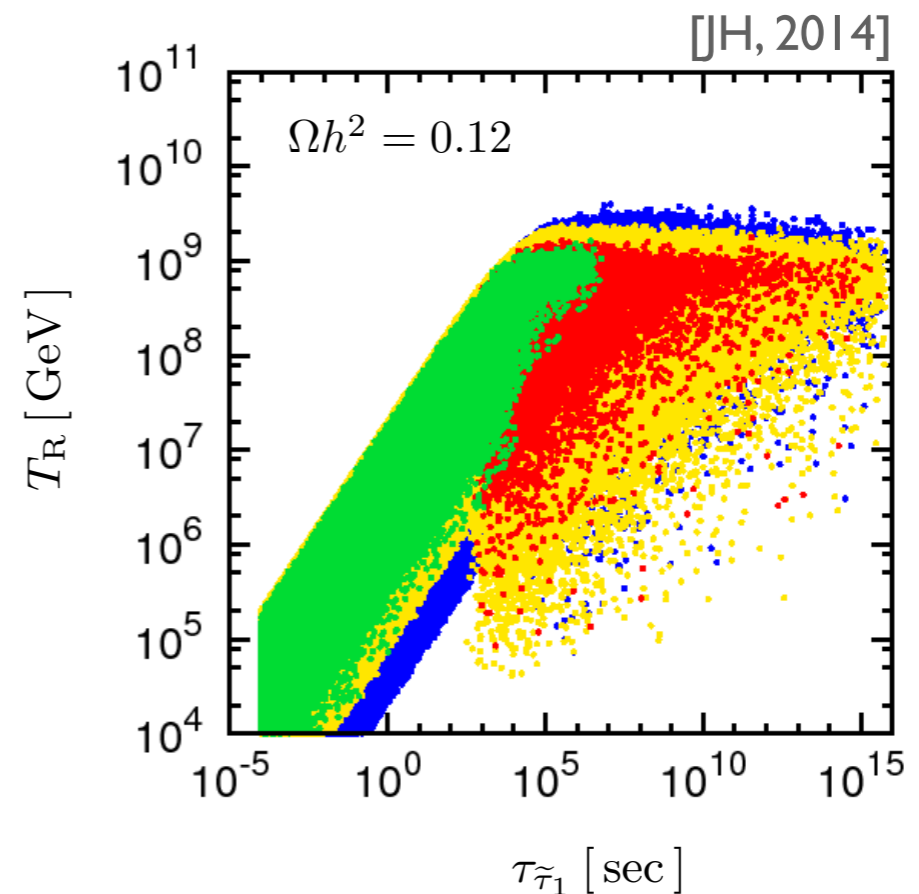


- Sensitive to DM masses of up to 580 GeV

Example II: MSSM gravitino DM, stau NLSP

[JH, Sabine Kraml, Andre Lessa | 808.05229]

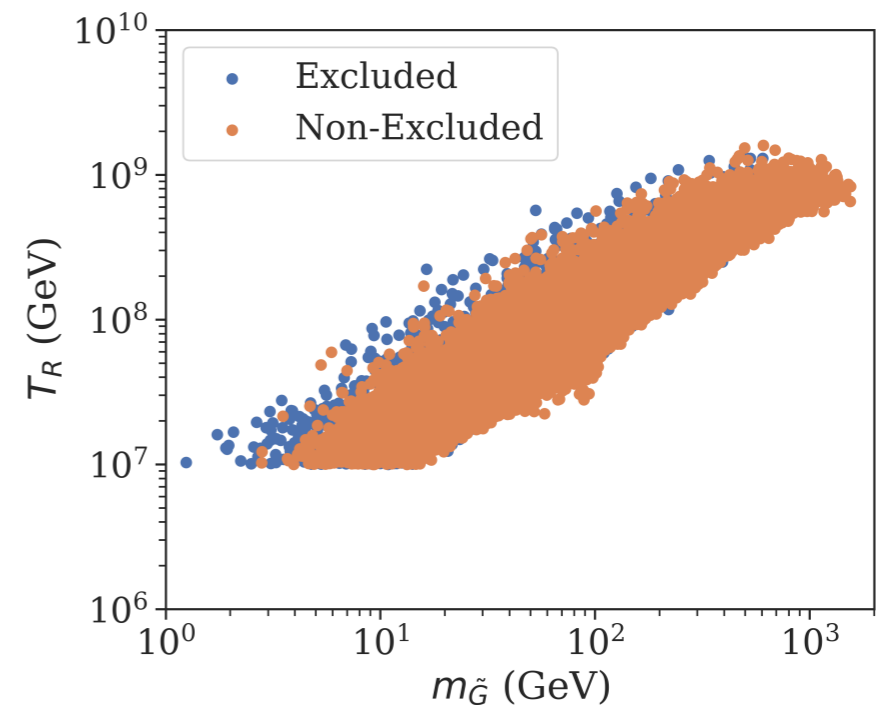
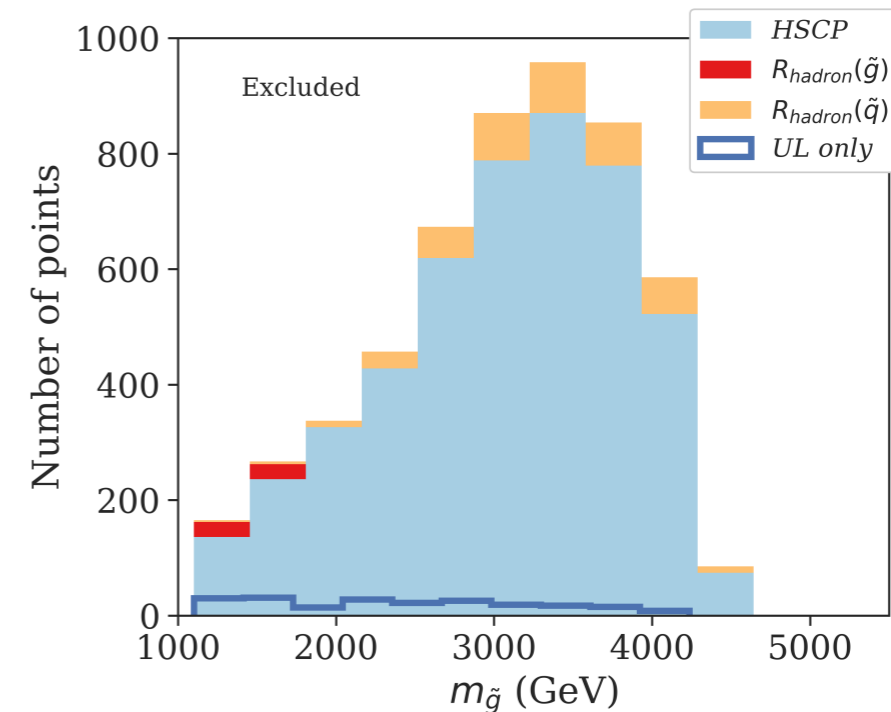
- NLSP detector-stable
- large number of production and decay channels contribute
- in pMSSM scan other meta-stable sparticles occur frequently e.g. long-lived gluinos



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Summary

- Highly ionizing charged tracks very well motivated
 - Covers a large range in "theory space"
 - Important benchmark for future detector updates
 - Connection to (FIMP) dark matter
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- Reinterpretation via simplified models useful
- UV complete theories like MSSM:
 - Large number of production and decay channels
 - several long-lived particles
- SModelS 1.2: Automatic computation of LHC limits
- Work in progress (SModelS 2.0) more general LLPs
smodels.hephy.at