Dark matter and long-lived particles at the LHC

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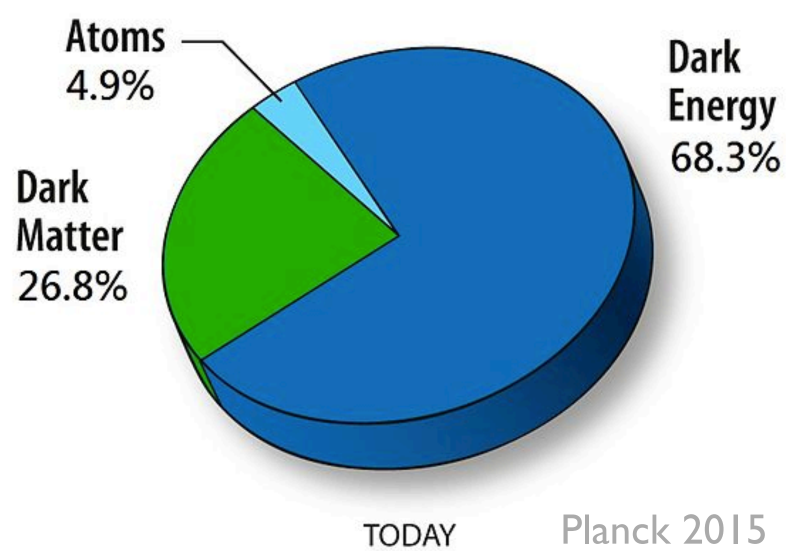
53rd Rencontres de Moriond session on
Electroweak Interactions and Unified Theories
La Thuile, Aosta Valley, Italy, March 10−17, 2018

Among key scientific goals of LHC:

- Pinpoint the nature of dark matter!

Energy density of the universe:



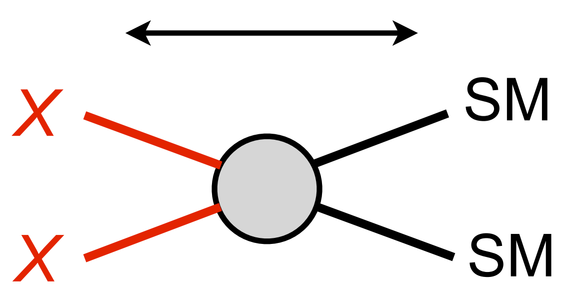
Planck 2015

<u>Needed</u>: Predictions for possible signatures of dark matter models

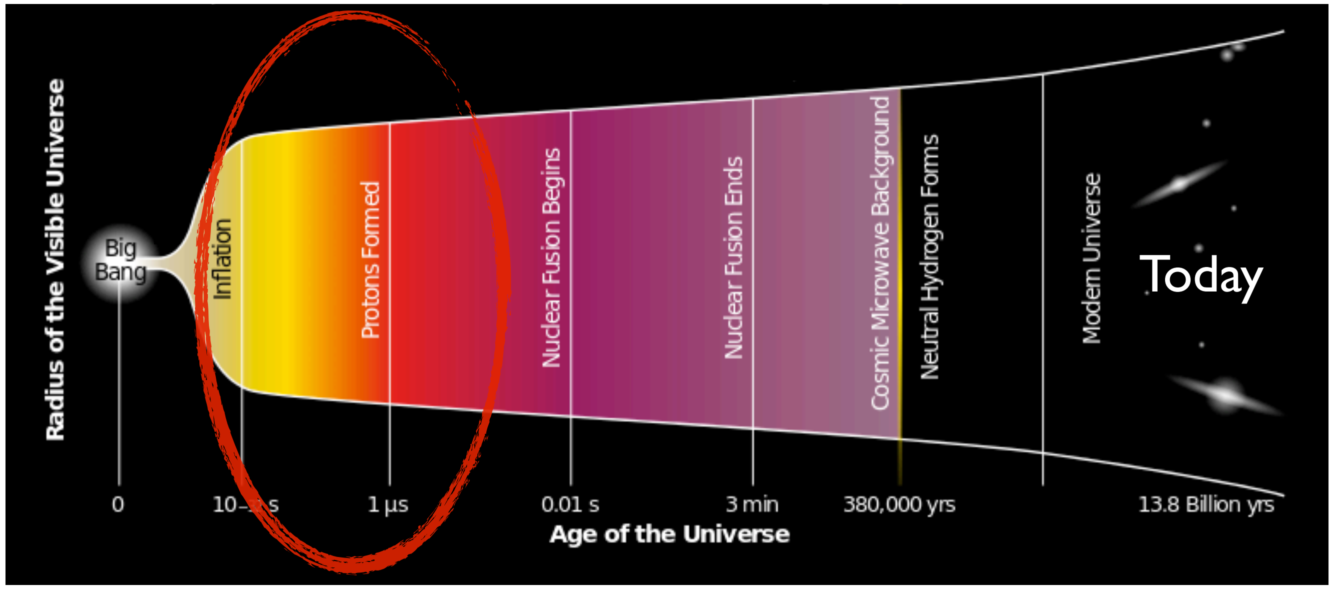
Decisive property: Dark matter thermalized in expanding early Universe?

$$\Gamma_{\mathrm{ann}} \gtrsim H$$

Rate of thermalizing processes:



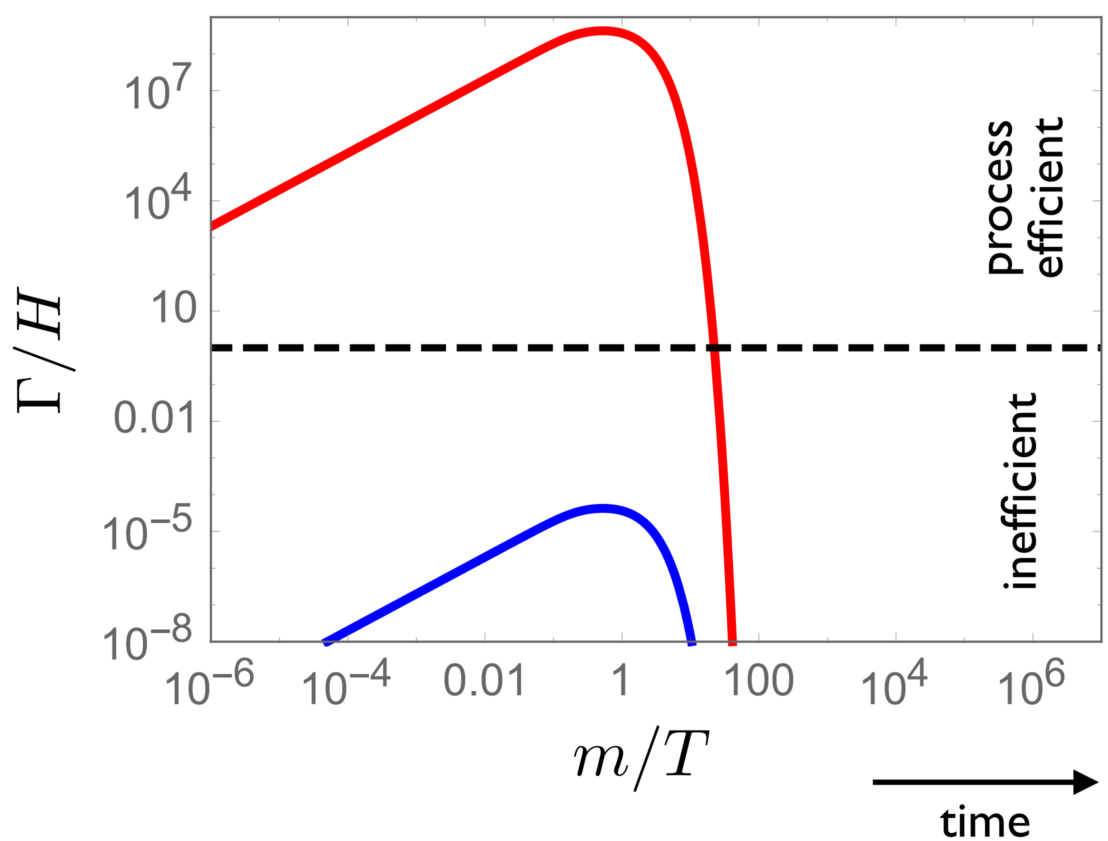
Expansion with Hubble rate H



Decisive property: Dark matter thermalized in expanding early Universe?

$$H \propto T^2 \,, \qquad \Gamma_{\rm ann} \propto \begin{cases} T & , \; T \gg m \;\; (\text{ultra-rel.}) \\ \mathrm{e}^{-m/T} & , \; T < m \;\; (\text{non-rel.}) \end{cases}$$

- $2 \rightarrow 2$ processes maximum, thermalization processes can remain inefficient:



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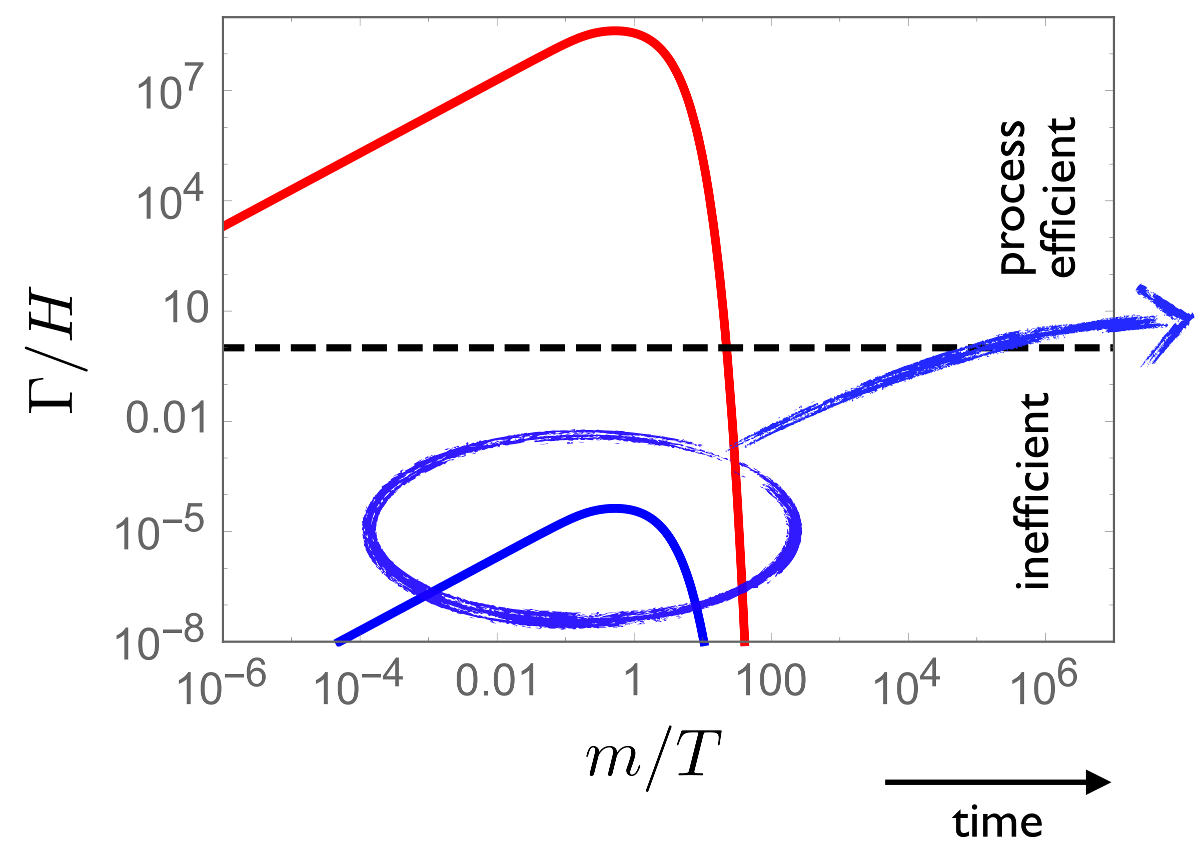

Non-th. dark sector:
No LHC signal!
[see Kahlhoefer 1801.07621]

Decisive property: Dark matter thermalized in expanding early Universe?

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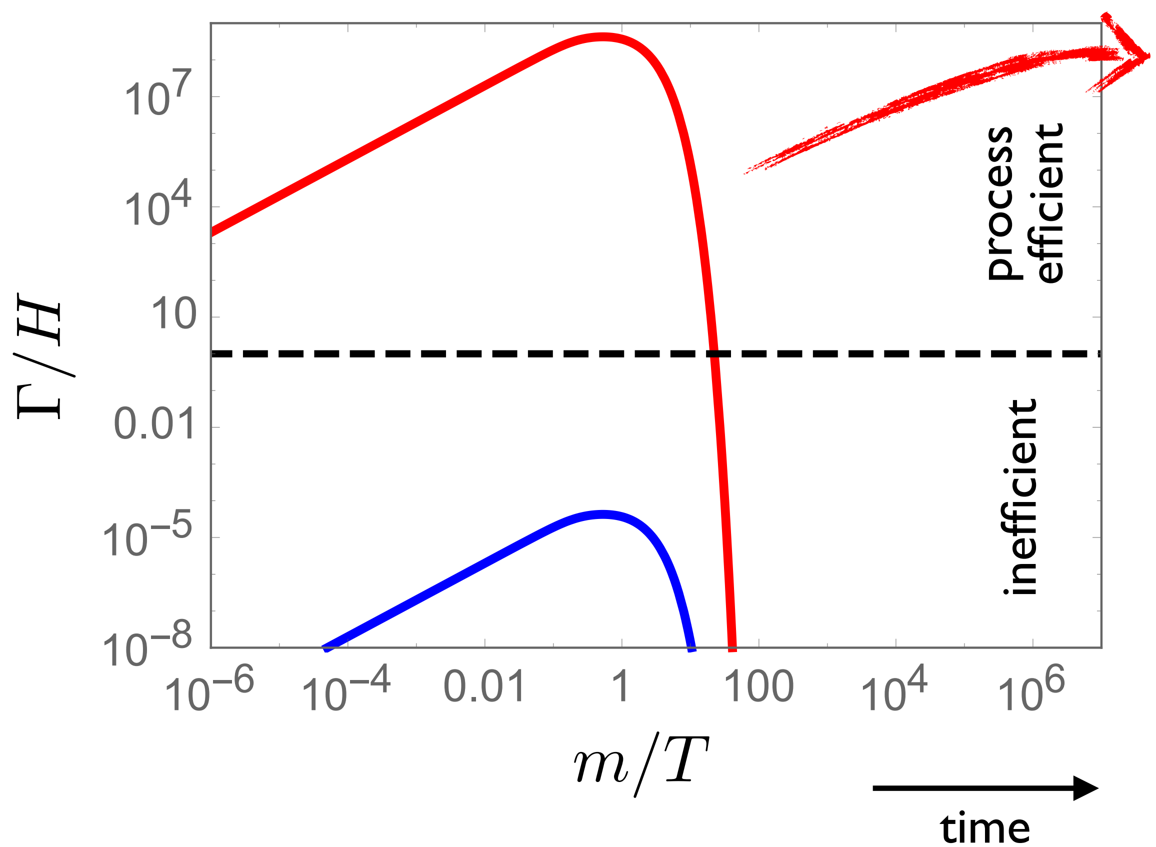
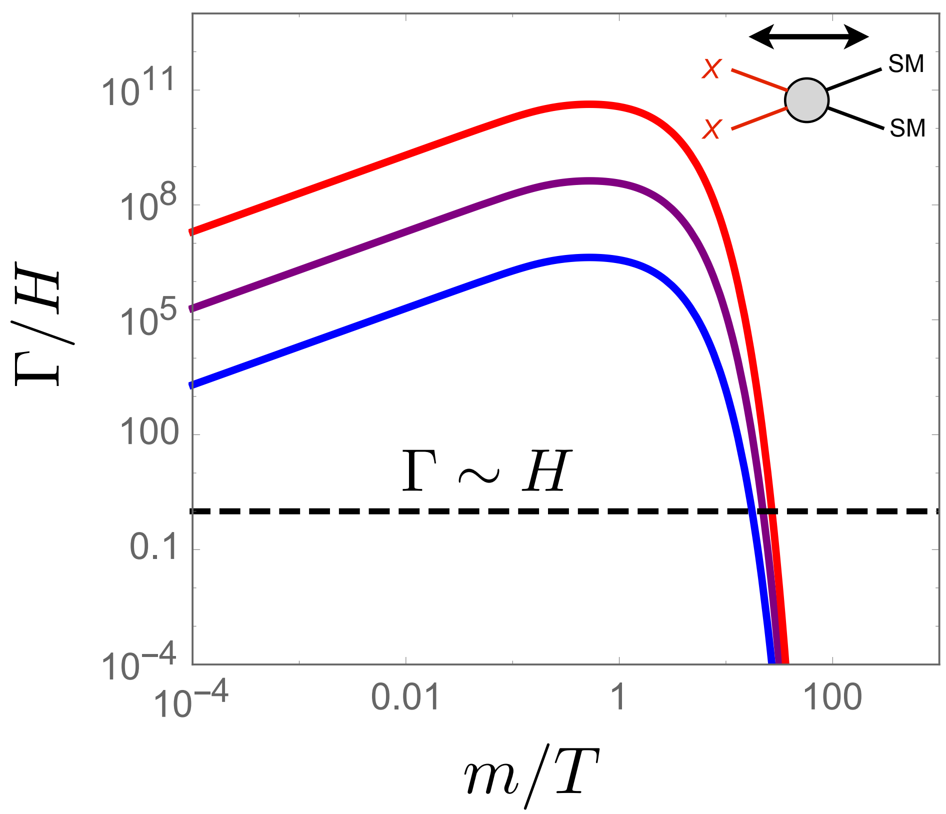
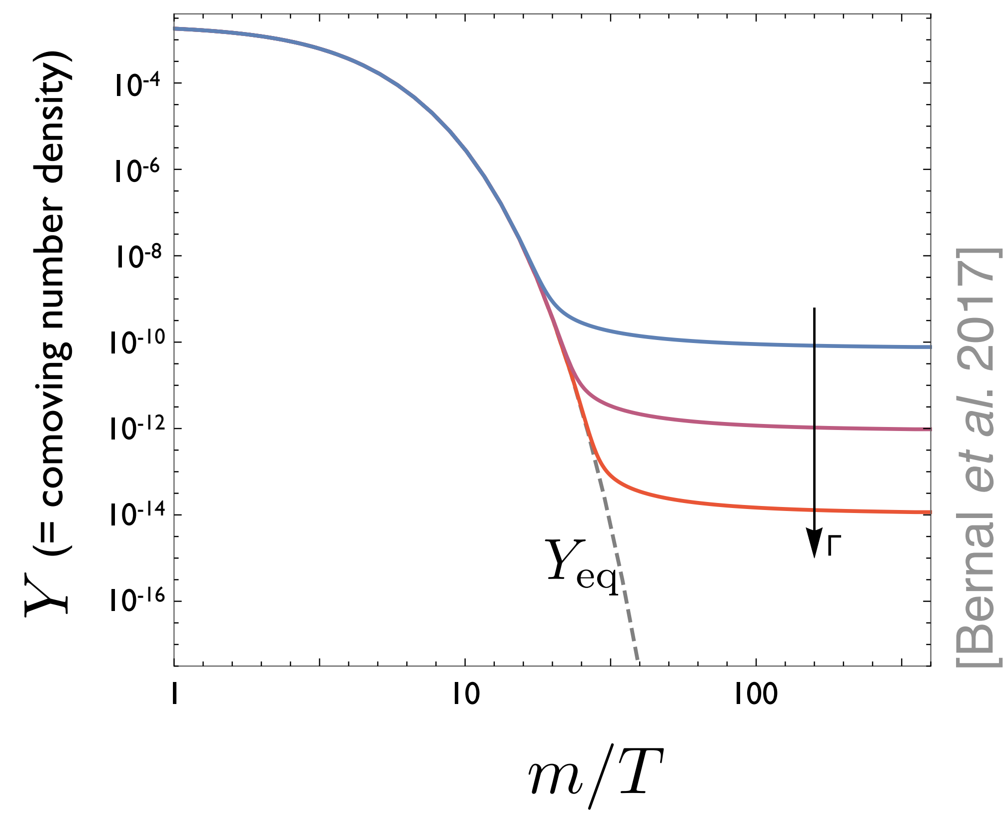


At least part of dark sector thermalized: Of interest for LHC

Vanilla WIMP

- Weak couplings: well thermalized! ➔ independent of initial cond.
- Well-known freeze-out picture:
  Leaves equilibrium density when $\Gamma \sim H$ ➔ cold DM





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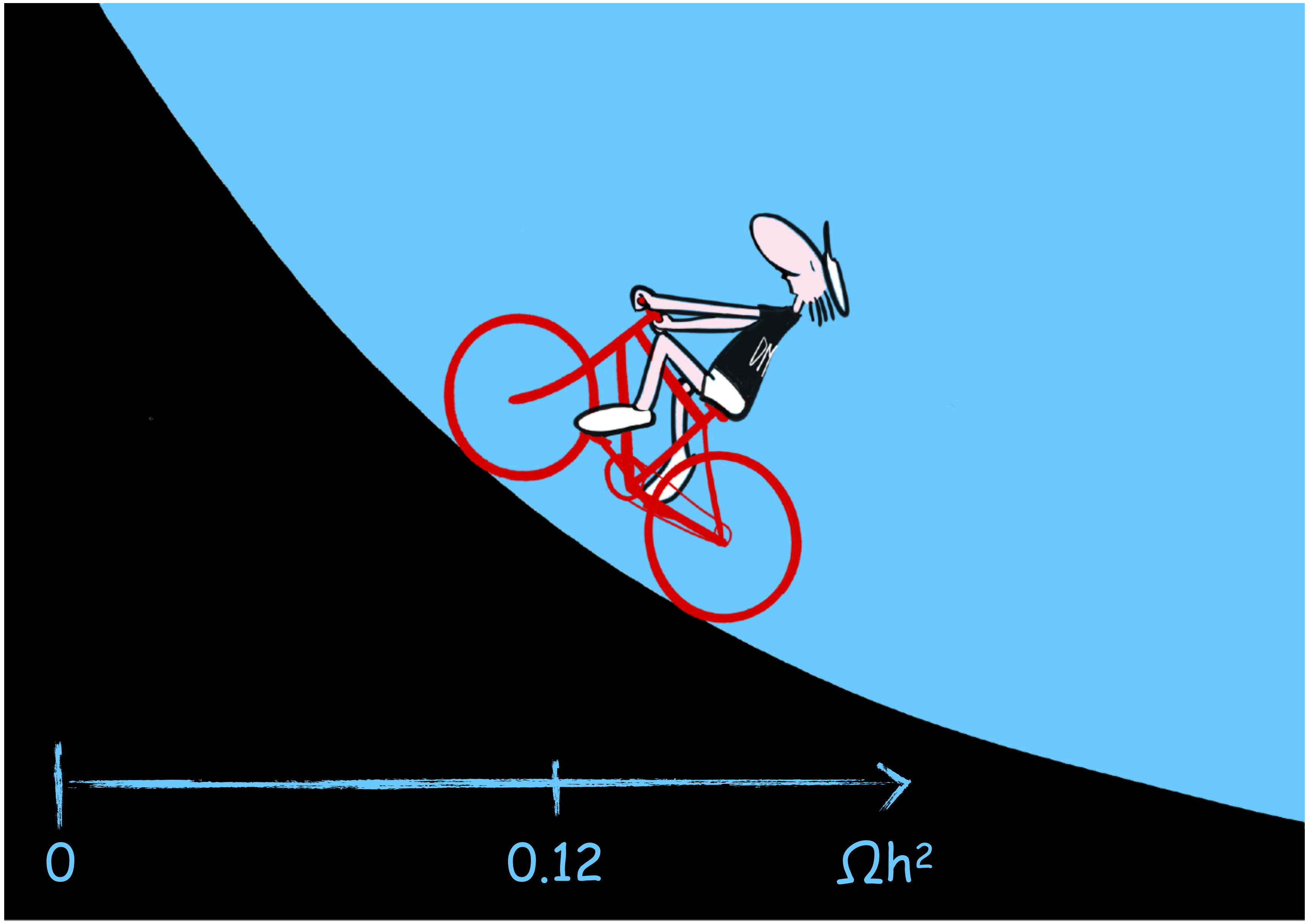
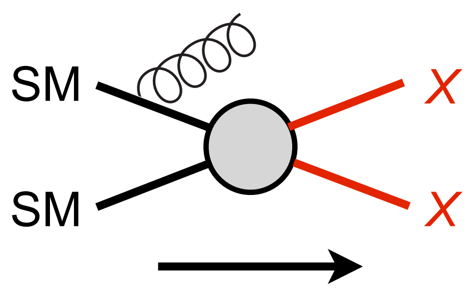
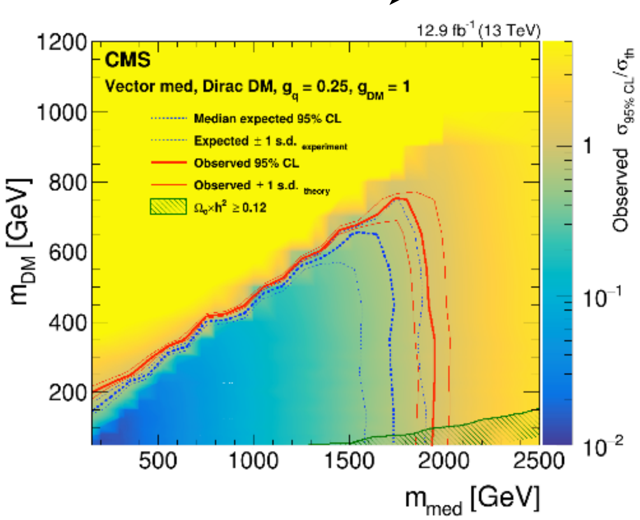


Dark Matter searches
WIMPs (weakly interacting massive particles)

Direct production

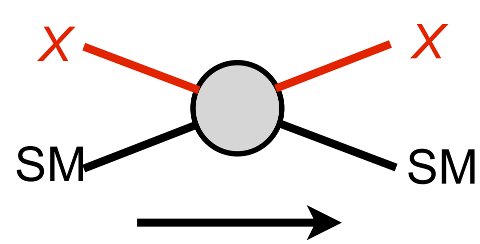


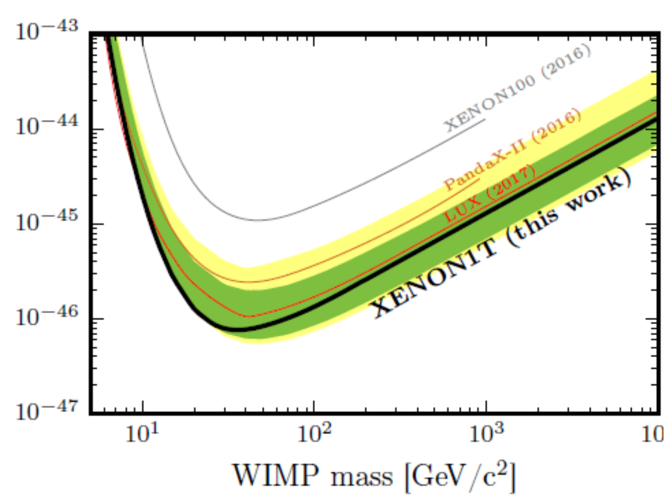


[CMS EXO-16-039]

→ talk of Francesco

Direct detection

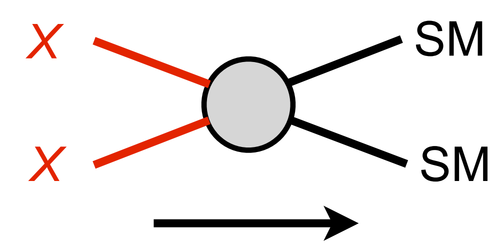


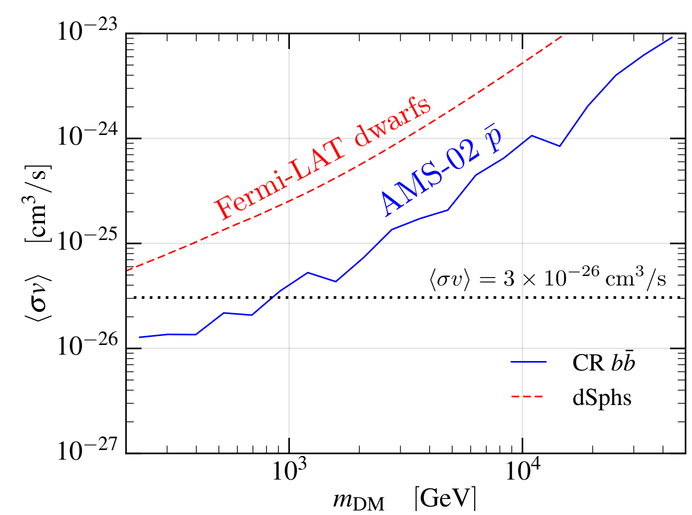


[Xenon1T 1705.06655]

→ talk of Daniel

Indirect detection





[Cuoco, JH, Korsmeier, Krämer 2017]

→ talk of Michael (YSF)

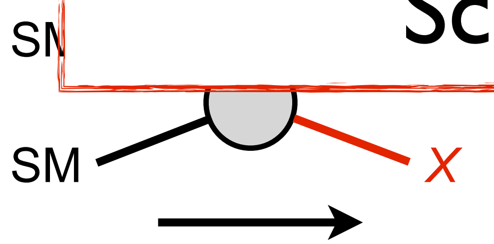
Dark Matter searches
WIMPs (weakly interacting massive particles)

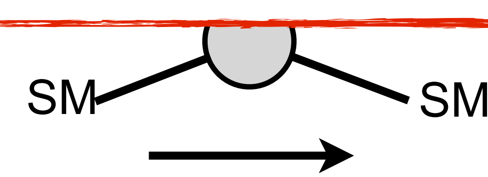
Direct production

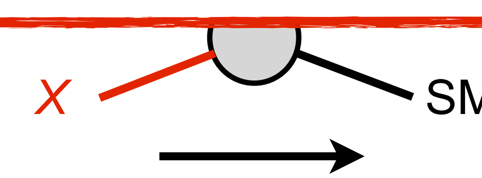
Direct detection

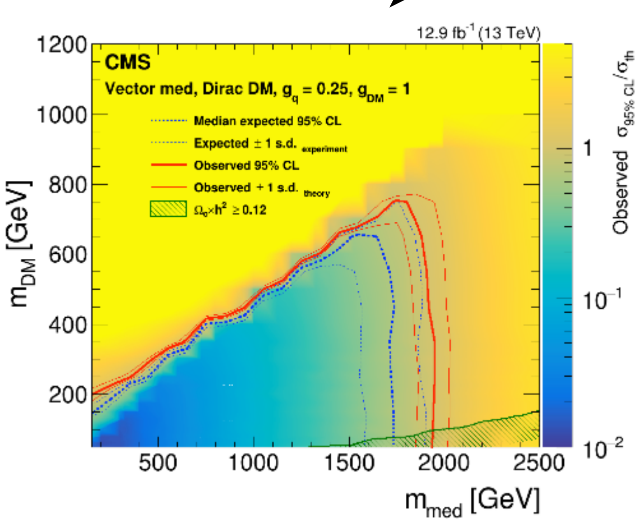
Indirect detection

WIMPs strongly constraint by current searches
Scenarios with other signatures?

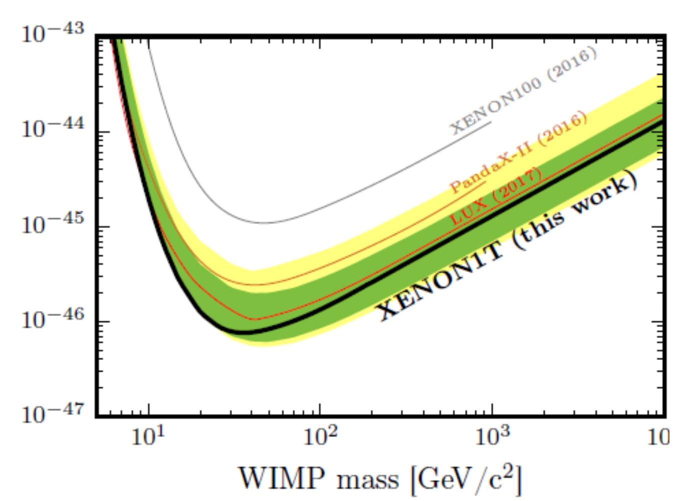




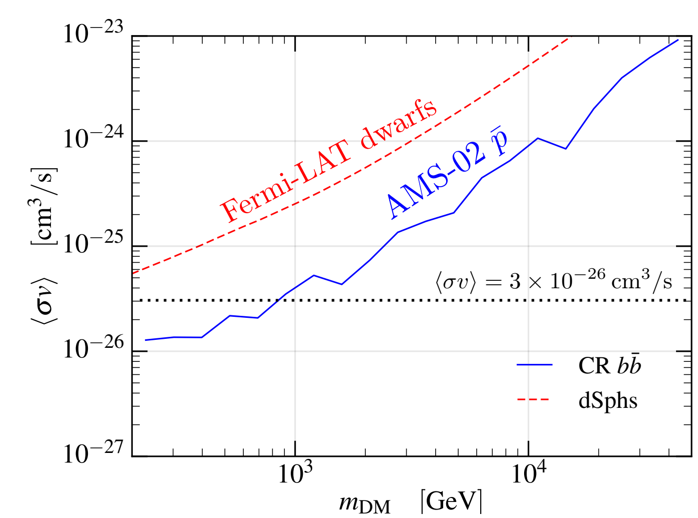




[CMS EXO-16-039]



[Xenon1T 1705.06655]



[Cuoco, JH, Korsmeier, Krämer 2017]

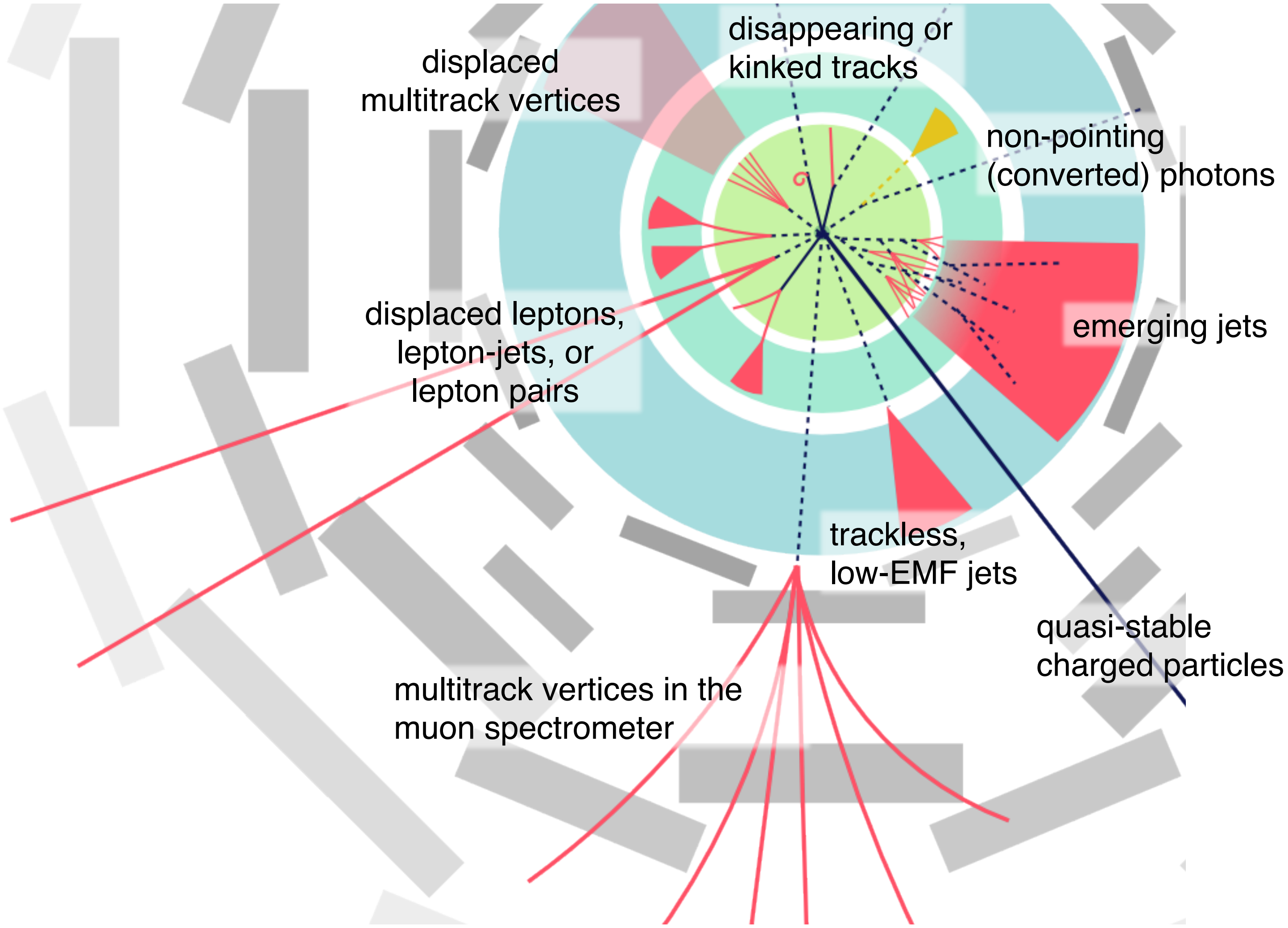
➔ talk of Francesco

➔ talk of Daniel

➔ talk of Michael (YSF)

Long-lived particles (LLPs) at the LHC

- Metastable BSM particles (except neutral detector-stable particles ➔ MET)
- Wide range of possible signatures:



[Figure from Heather Russell]

- Many LLP signatures low background ➔ high sensitivity

LLP searches at the LHC: challenges

- Cover spectrum of possible LLP signatures and kinematic ranges
  so far mostly SUSY related scenarios
- Hard to trigger
  often additional signature needed for triggering
- Interpretation of results
  applicability for a large set of models required
- Recasting difficult
  exchange of additional information needed

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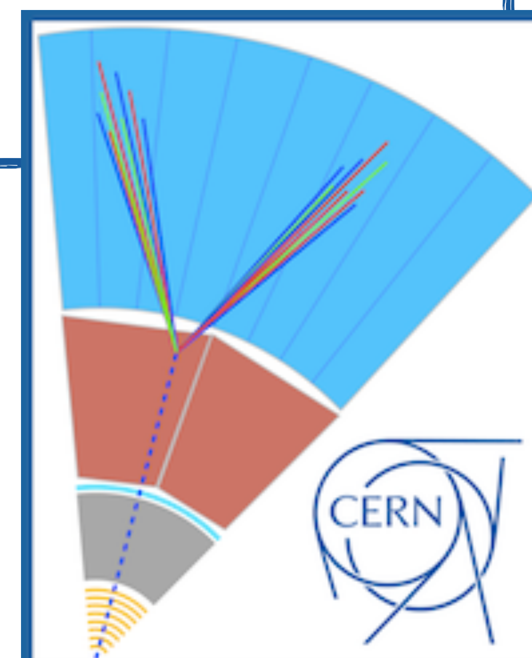


LHC LLP Community Workshops:

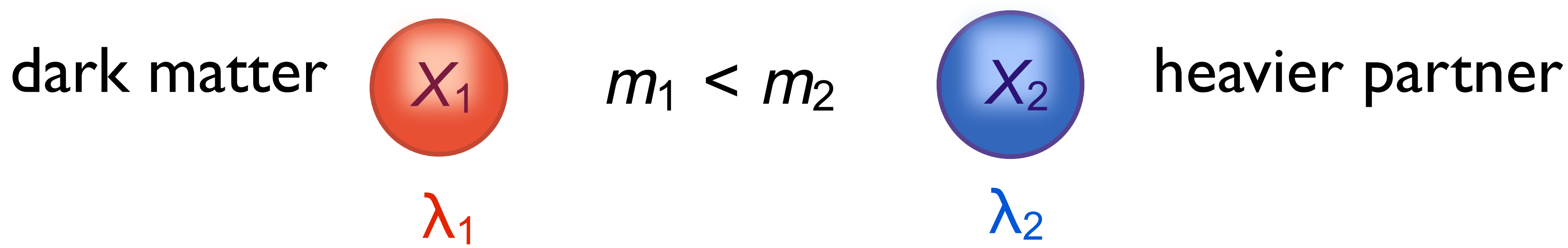
April 2017: https://indico.cern.ch/event/607314/
October 2017: https://indico.cern.ch/event/649760/

Next Workshop: 16-18 May 2018 at CERN
Community white paper in preparation

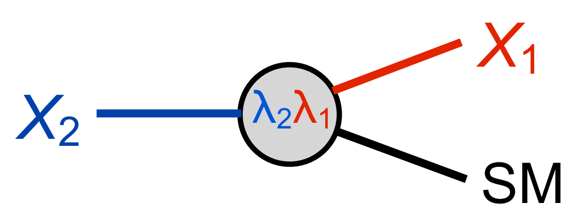
LLPs and dark matter

LLPs and dark matter

- Consider Z_2-odd dark sector

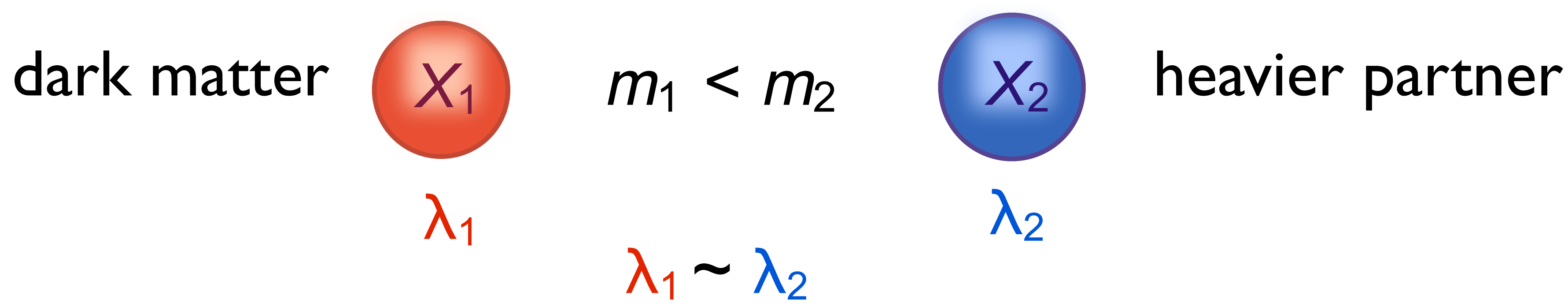


- Decay only in Z_2-odd states:



- Consider: next heavier state X_2 involved in freeze-out!

Coannihilation [Griest, Seckel 1991; Edsjo, Gondolo 1997]



Number densities during freeze-out:

$$\frac{Y_2^{\mathrm{eq}}}{Y_1^{\mathrm{eq}}} \propto \mathrm{e}^{-\Delta m/T_{\mathrm{f}}} \sim \mathrm{e}^{-25\,\Delta m/m}$$

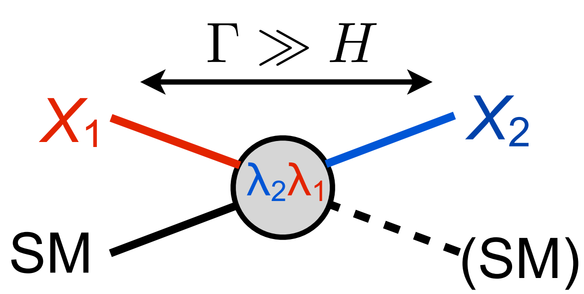
$$\Delta m/m \lesssim 10\%$$

[for an interesting exception see D'Agnolo *et al.* 1803.02901]

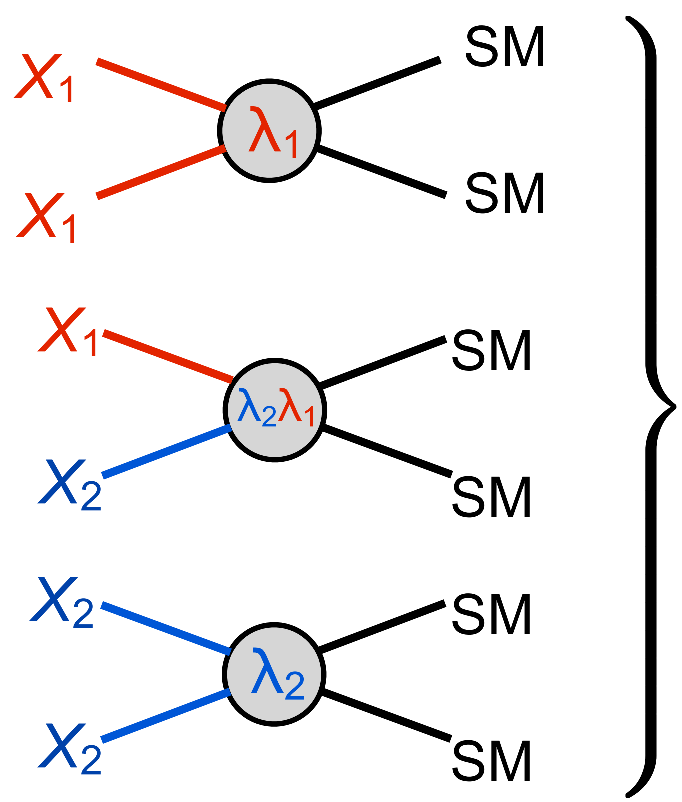
➔ X_2 still "around" during freeze-out

Coannihilation

Number densities "tied" together through efficient conversions:

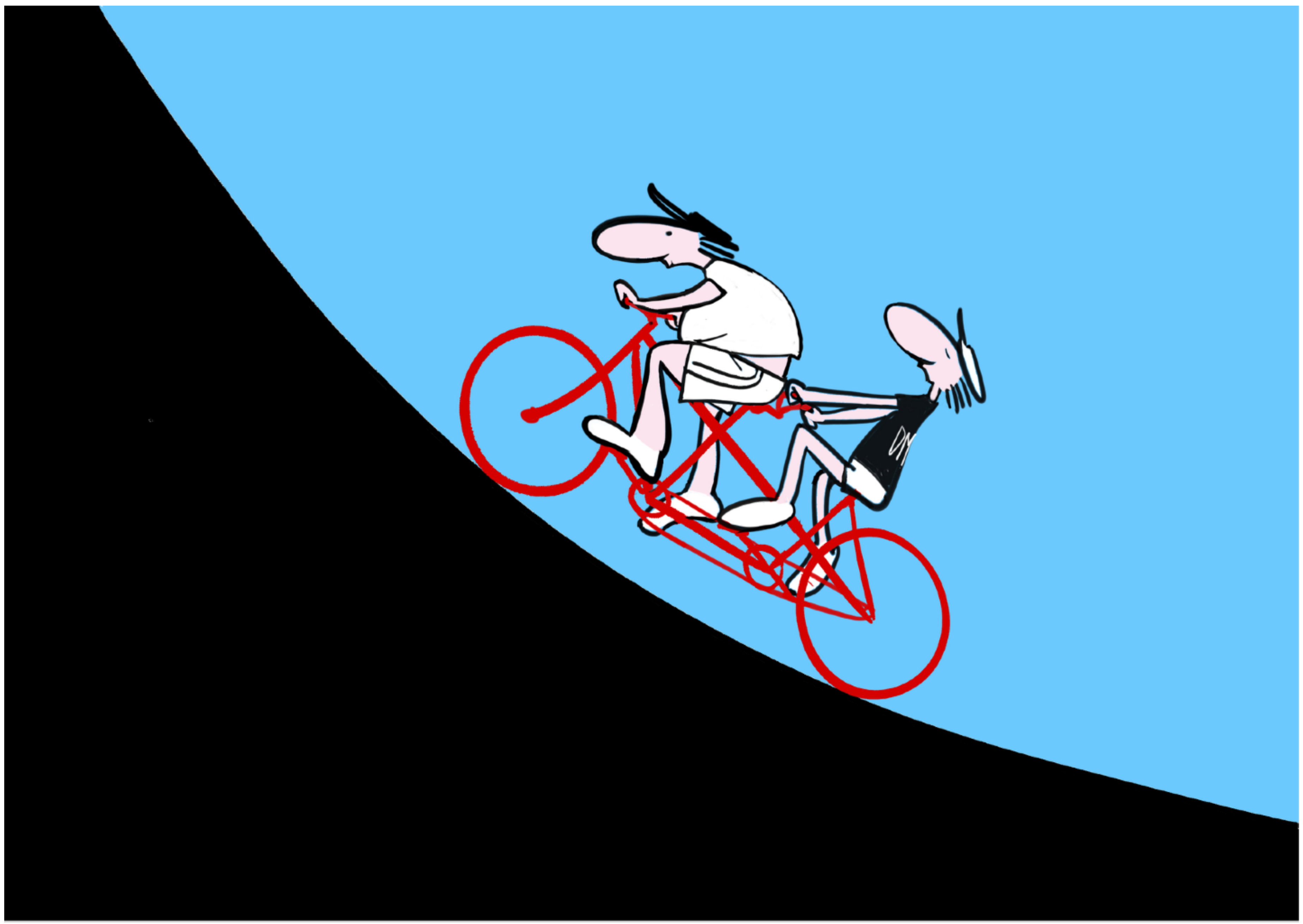


$$\Rightarrow \quad \frac{Y_2}{Y_1} = \frac{Y_2^{\mathrm{eq}}}{Y_1^{\mathrm{eq}}}$$



efficient annihilation
of dark sector

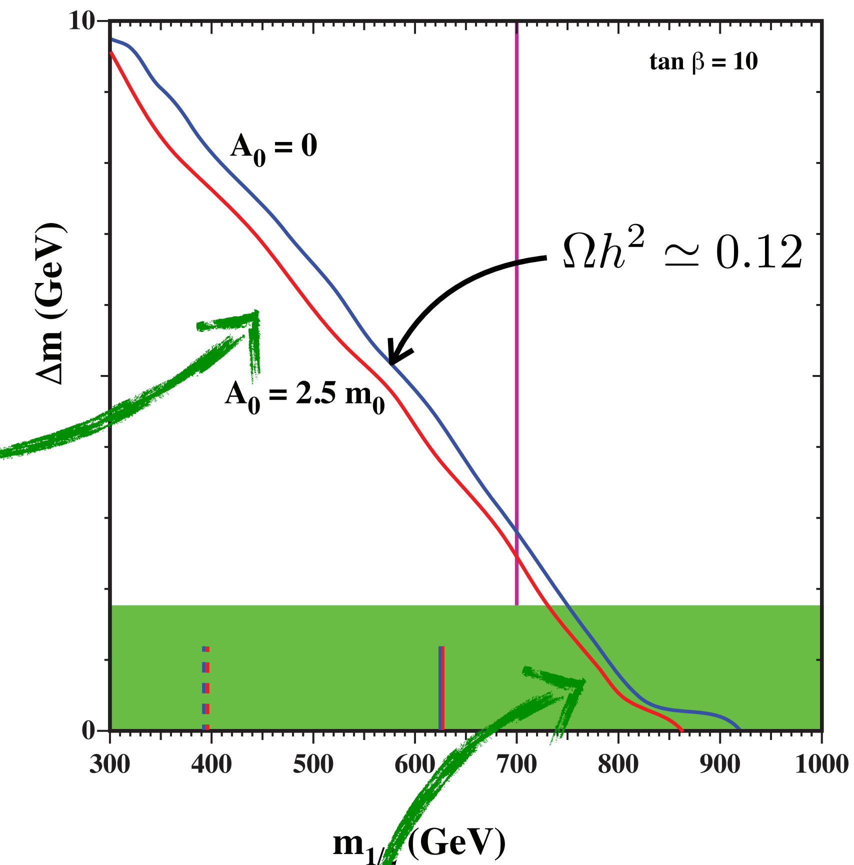
Coannihilation



Coannihilation and LLPs

- SUSY: stau coannihilation strip

[Citron *et al.* 1212.2886]

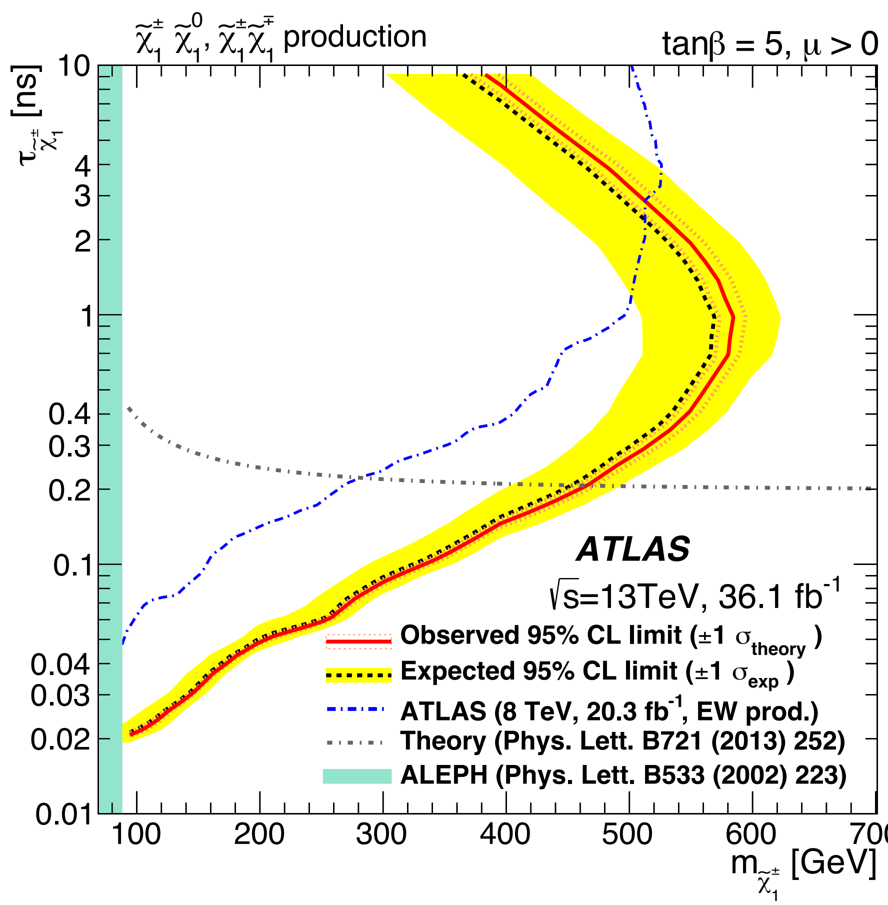


Prompt decays

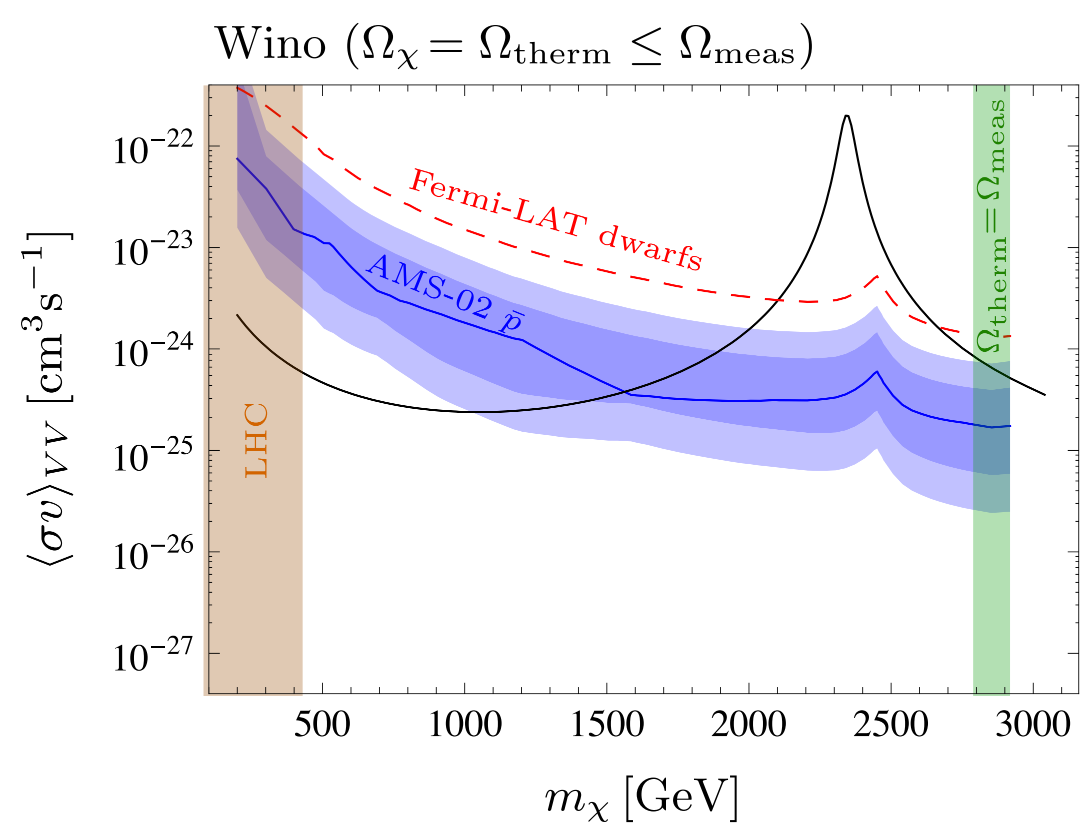
Long-lived staus

Coannihilation and LLPs

- SUSY: stau coannihilation strip
- Minimal dark matter, e.g. pure wino:
  [Cirelli *et al.* hep-ph/0512090]



[Cuoco, JH, Korsmeier, Krämer 1711.05274]



Coannihilation and LLPs

- SUSY: stau coannihilation strip
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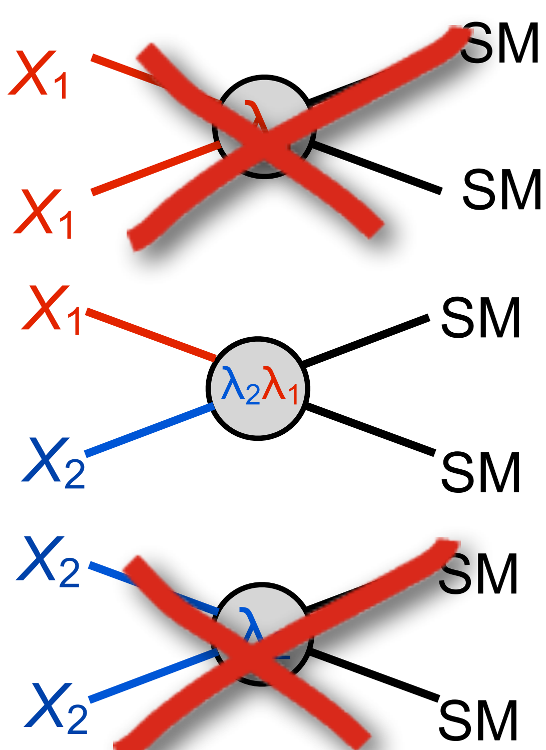
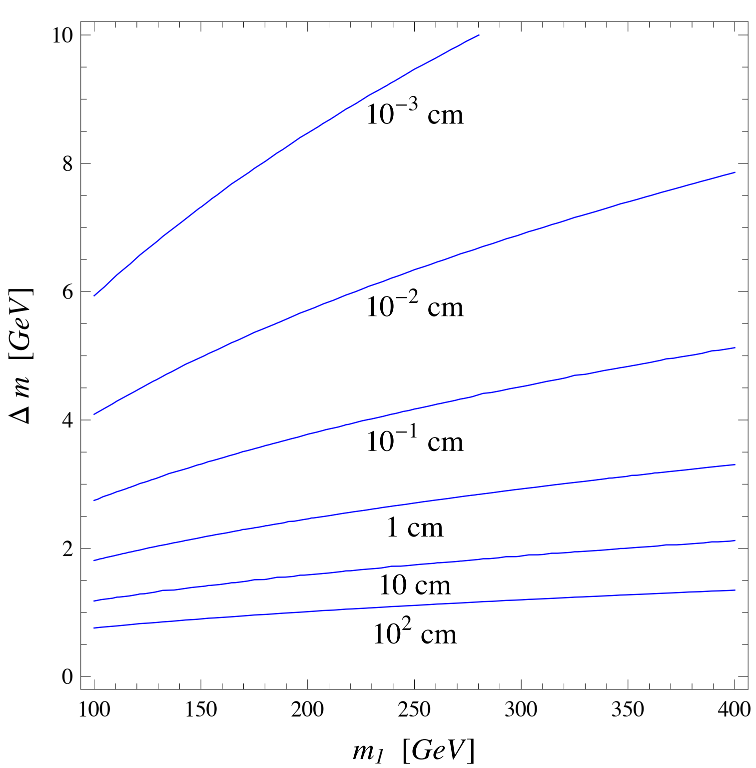
  [Cirelli *et al.* hep-ph/0512090]
- Pseudo Dirac dark matter
  [De Simone, Sanz, Sato 2010; Davolia, De Simone, Jacquesa, Sanz 2017]



→ evade direct and indirect detection bounds
→ predicts LLPs



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- ...

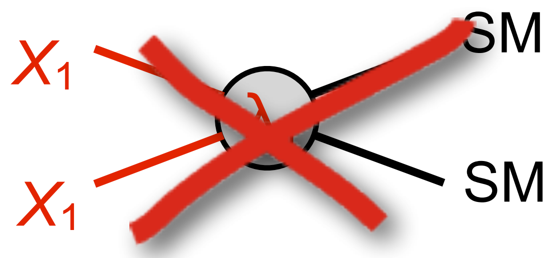
LLP due to small mass splittings

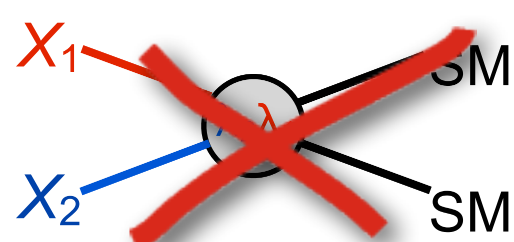
Small dark matter couplings

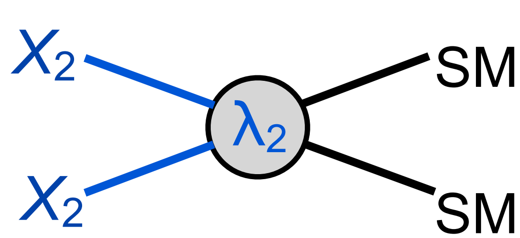
dark matter X_1 $m_1 < m_2$ X_2 heavier partner

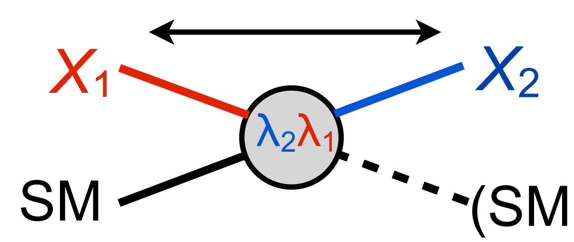
λ_1 λ_2

$\lambda_1 \ll \lambda_2$





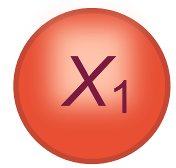


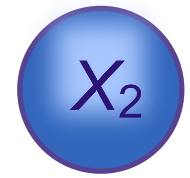


conversions efficient $\Gamma \gg H$

$$\Rightarrow \frac{Y_2}{Y_1} = \frac{Y_2^{\mathrm{eq}}}{Y_1^{\mathrm{eq}}}$$

Small dark matter couplings

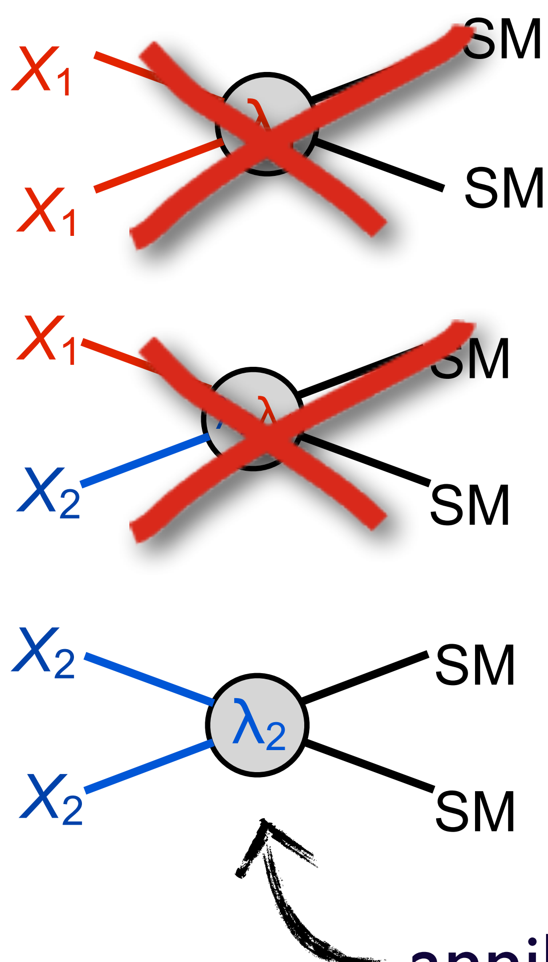
dark matter 

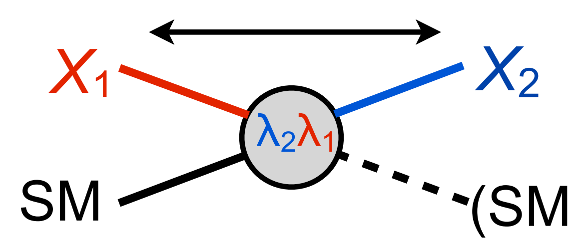
$m_1 < m_2$ 

heavier partner

λ_1 λ_2

$\lambda_1 \ll \lambda_2$



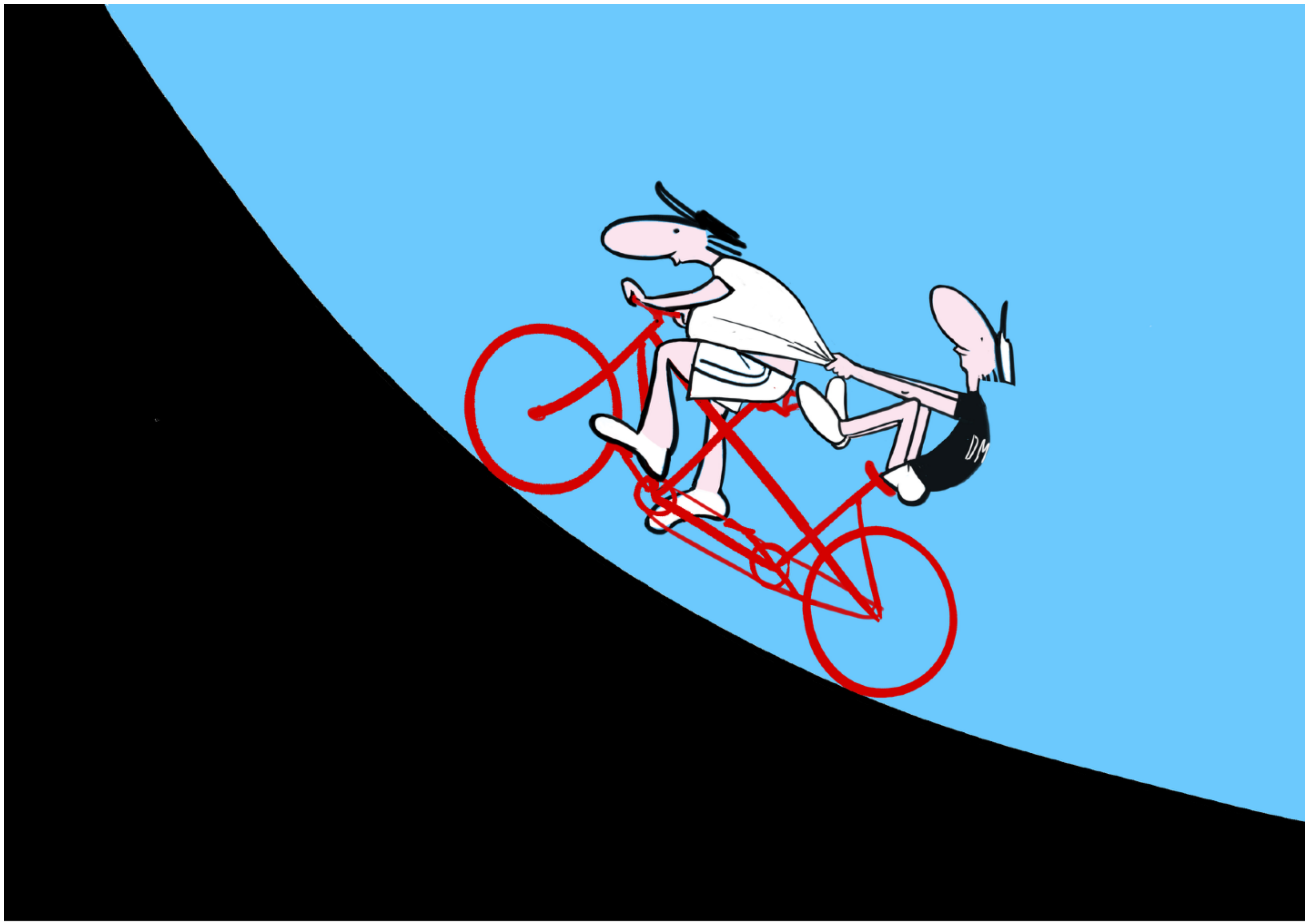


conversions efficient $\Gamma \gg H$

$$\Rightarrow \frac{Y_2}{Y_1} = \frac{Y_2^{\mathrm{eq}}}{Y_1^{\mathrm{eq}}}$$

annihilation of X_2 alone sets relic density

Freeloader's freeze-out



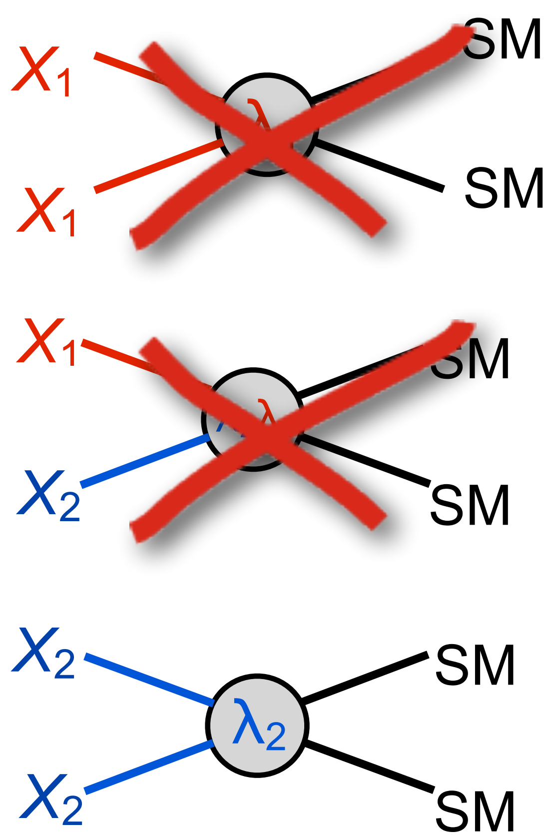
Even smaller dark matter couplings

[Garny, JH, Lülf, Vogl 1705.09292; D'Agnolo, Pappadopulo, Ruderman 1705.08450; Garny, JH, Hufnagel, Lülf 1802.00814]

dark matter χ_1 $m_1 < m_2$ χ_2 heavier partner

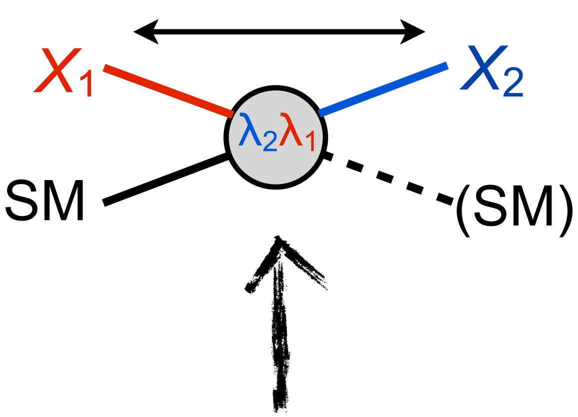
λ_1 λ_2

$\lambda_1 \ll \lambda_2$



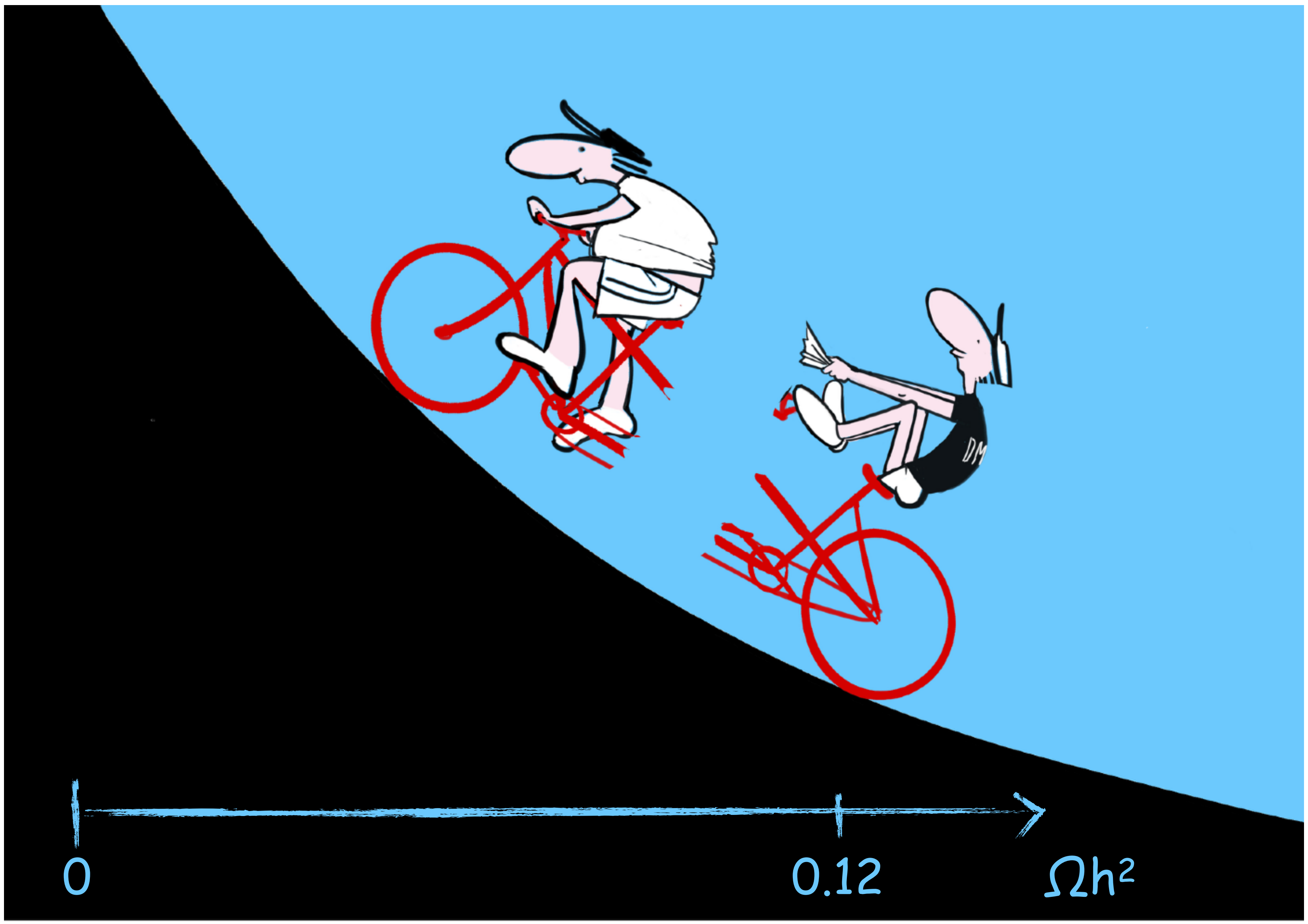
conversions become inefficient ↯

$$\Gamma_{\text{conv}} \sim H$$



conversion sets relic density

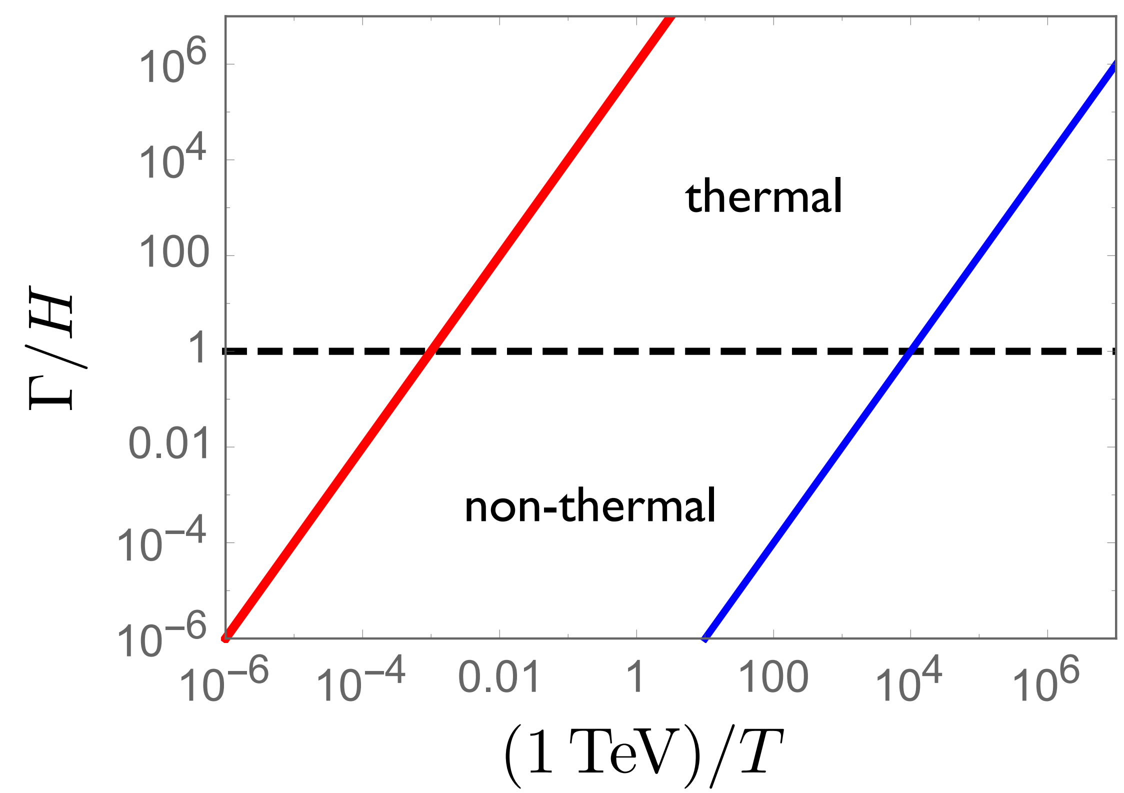
Conversion-driven freeze-out



Pheno of conversion-driven freeze-out

- Consider decay:

$$H \propto T^2 \; , \qquad \Gamma_{\text{dec}} \sim \text{const.}$$



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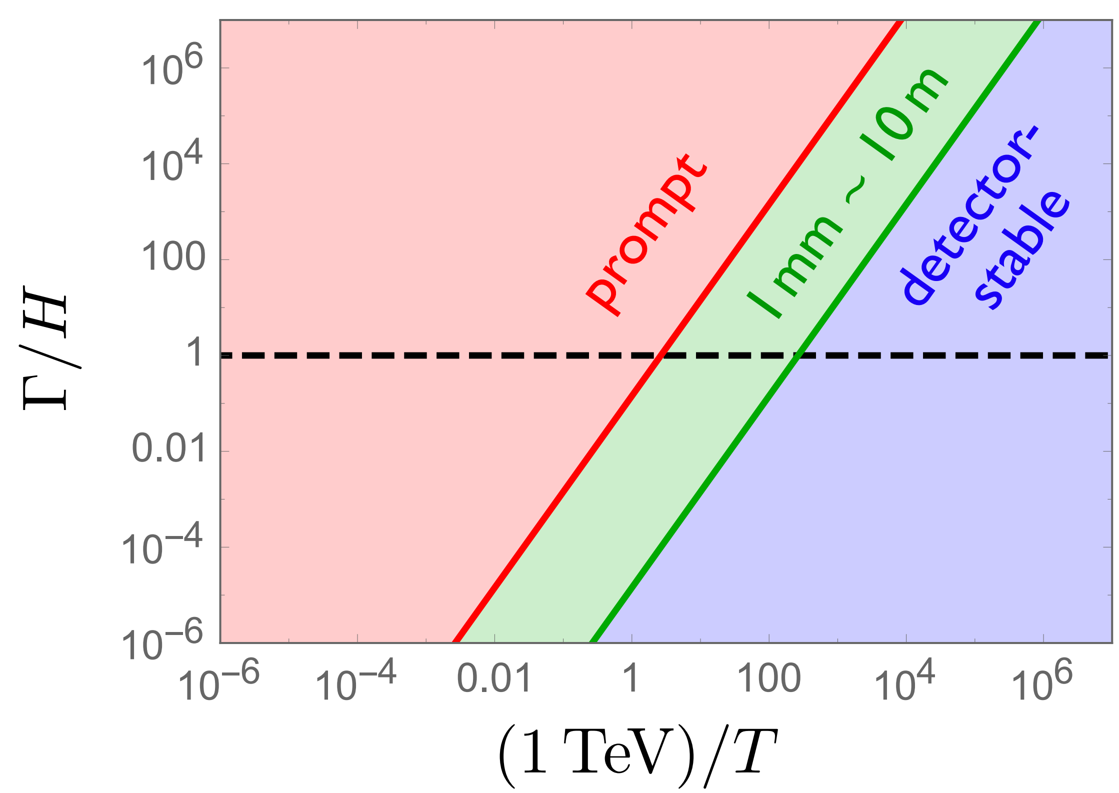

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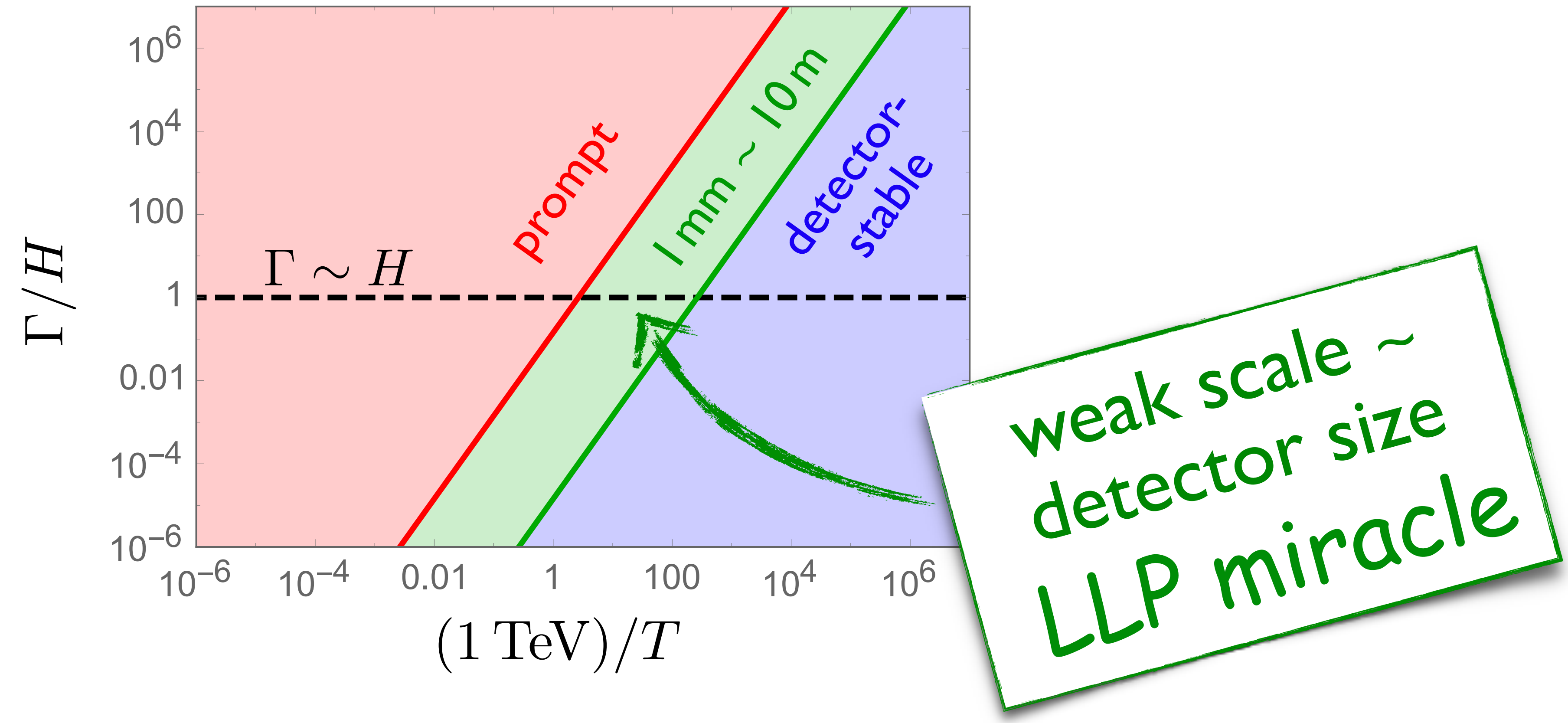
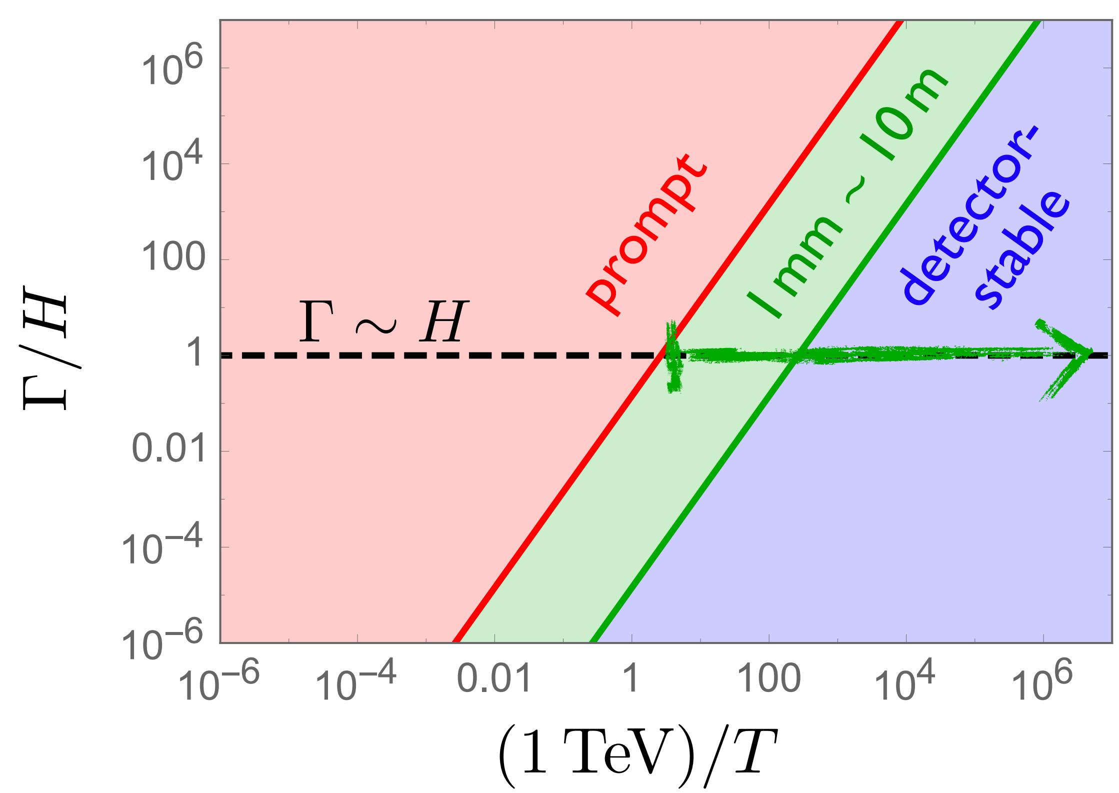


Pheno of conversion-driven freeze-out

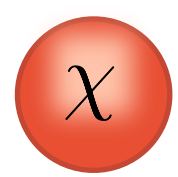
Neither decay nor 2 → 2 scattering can be efficient around freeze-out: Decay non-prompt!

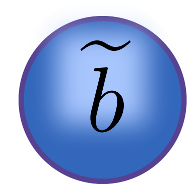


A concrete example

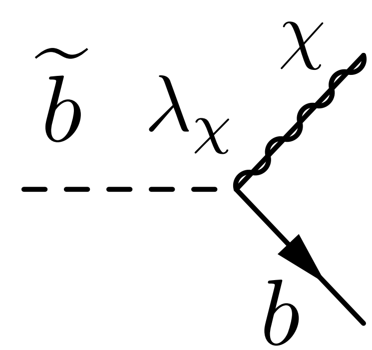
- Specific model: $\mathcal{L}_{\text{int}} = |D_\mu \widetilde{q}|^2 - \lambda_\chi \widetilde{q} \bar{q} \frac{1-\gamma_5}{2} \chi + \text{h.c.}$

- SUSY-inspired simplified model:
  Choose Majorana DM and scalar bottom-partner





- Yukawa-type interaction:

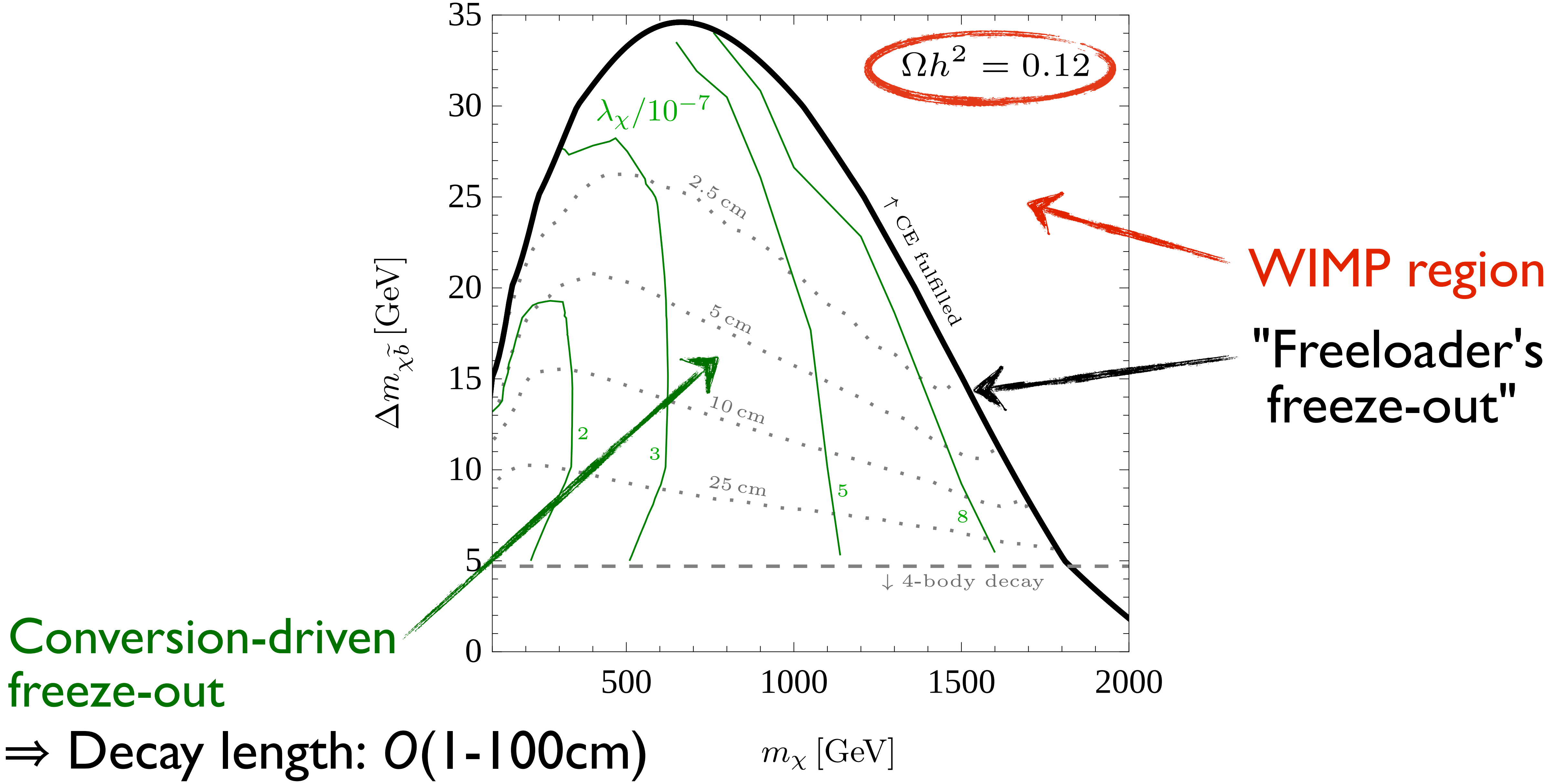


λ_χ is a free parameter here [see Ibarra et al. 2009 for SUSY realization]

Allowed parameter space

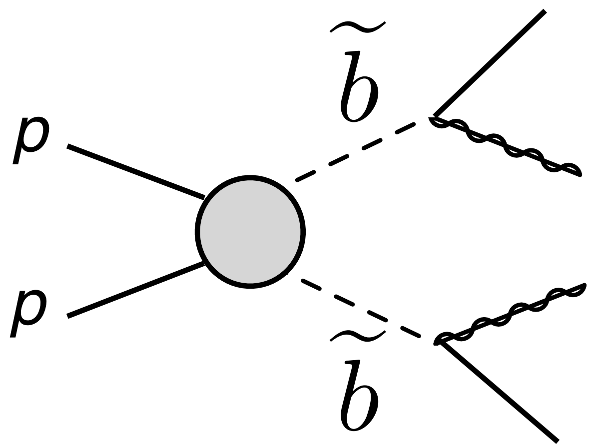
- Require Planck relic density

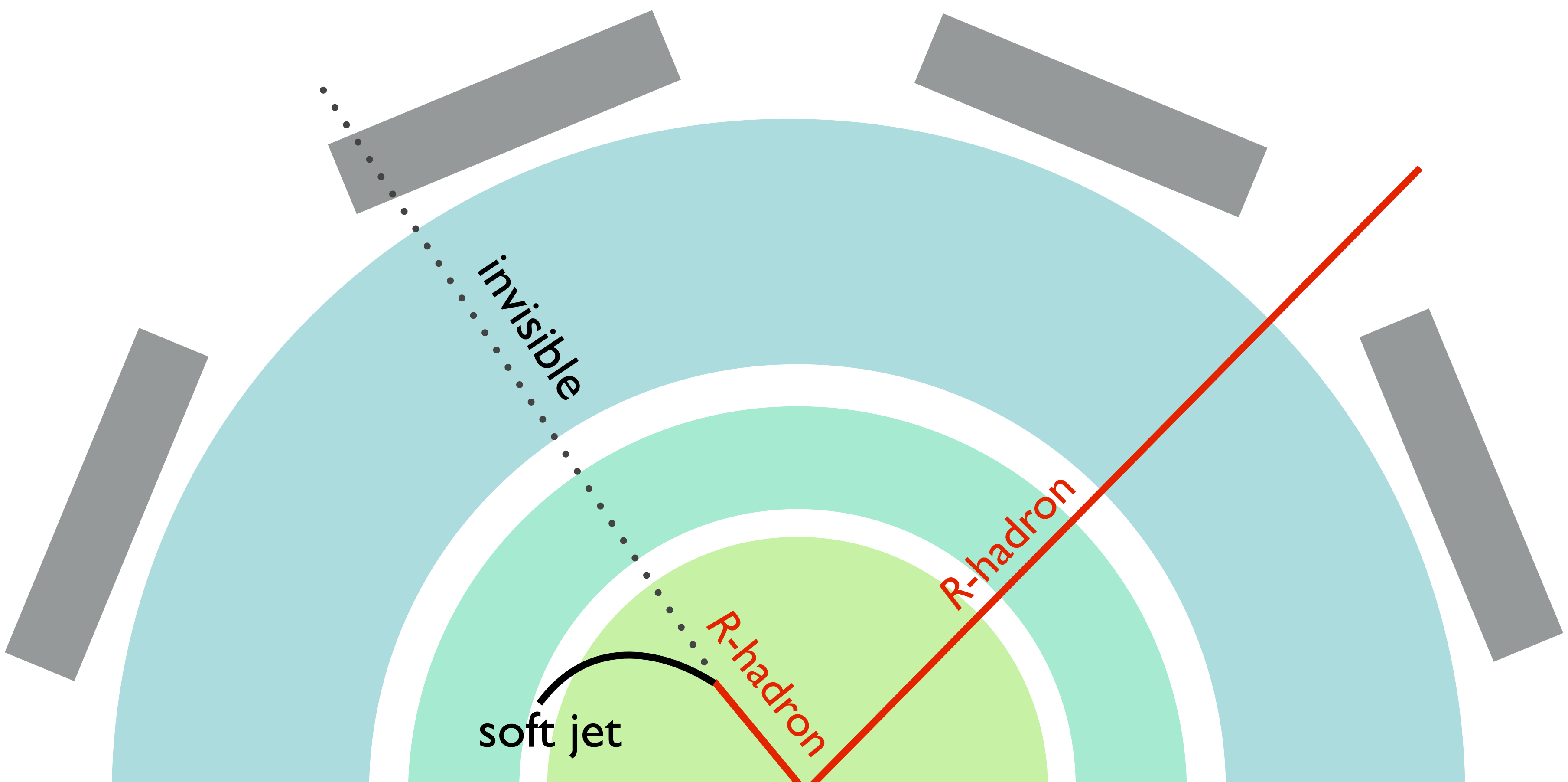
[Garny, JH, Lülf, Vogl 2017]



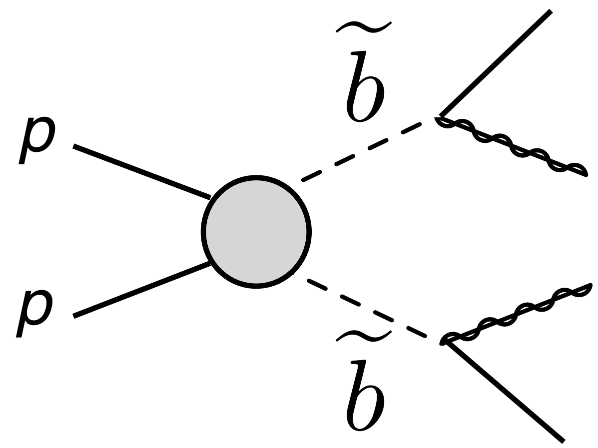
⇒ Decay length: *O*(1-100cm)

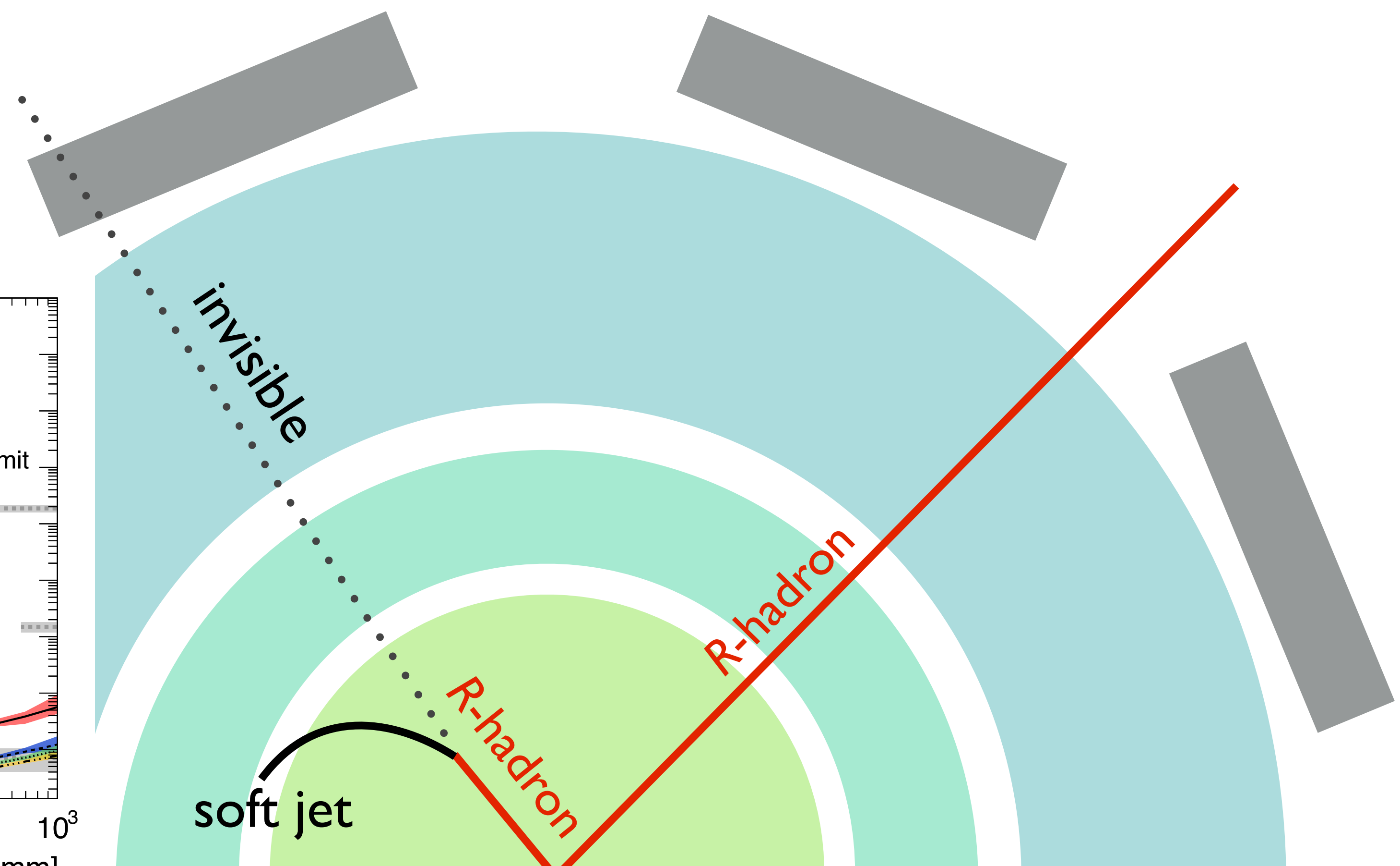
LHC constraints



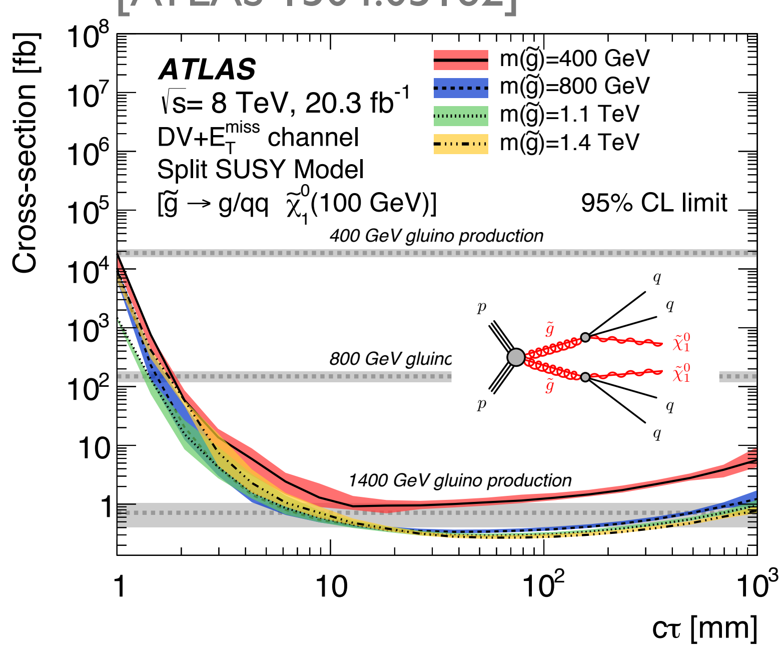


LHC constraints

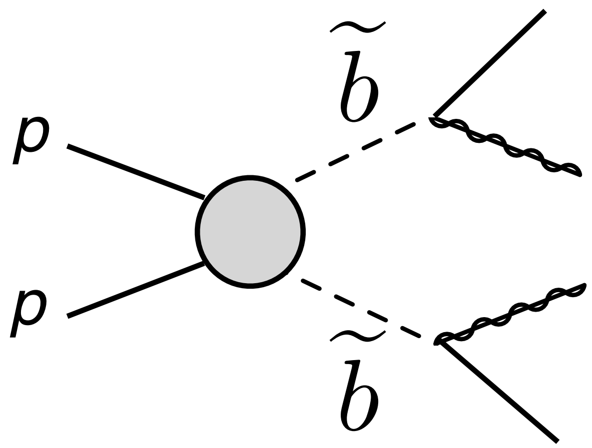




[ATLAS 1504.05162]



LHC constraints



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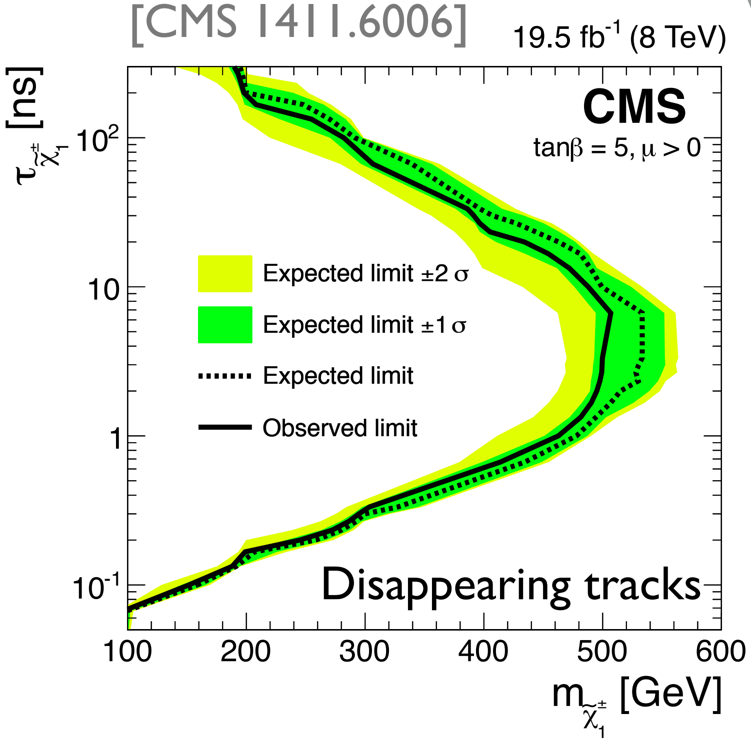
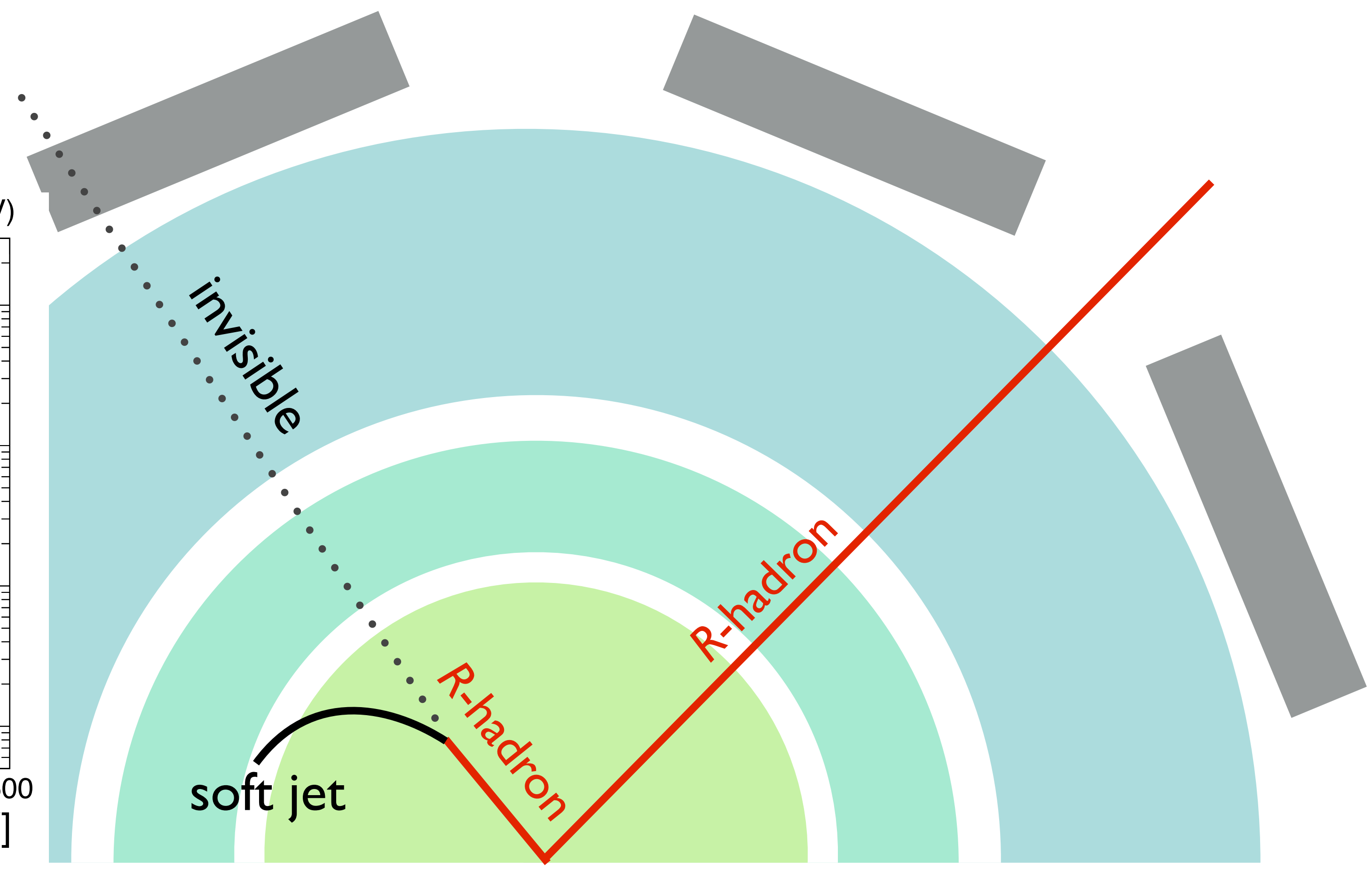
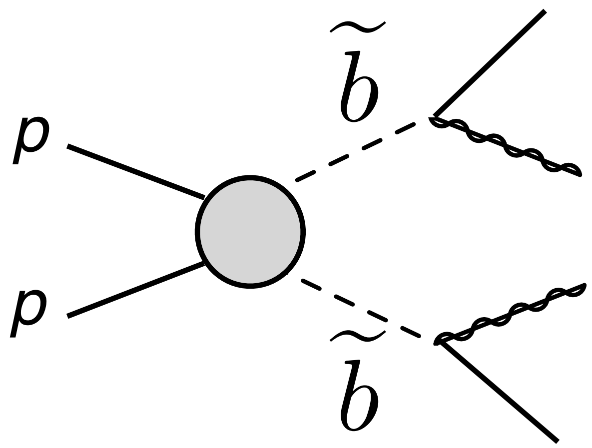
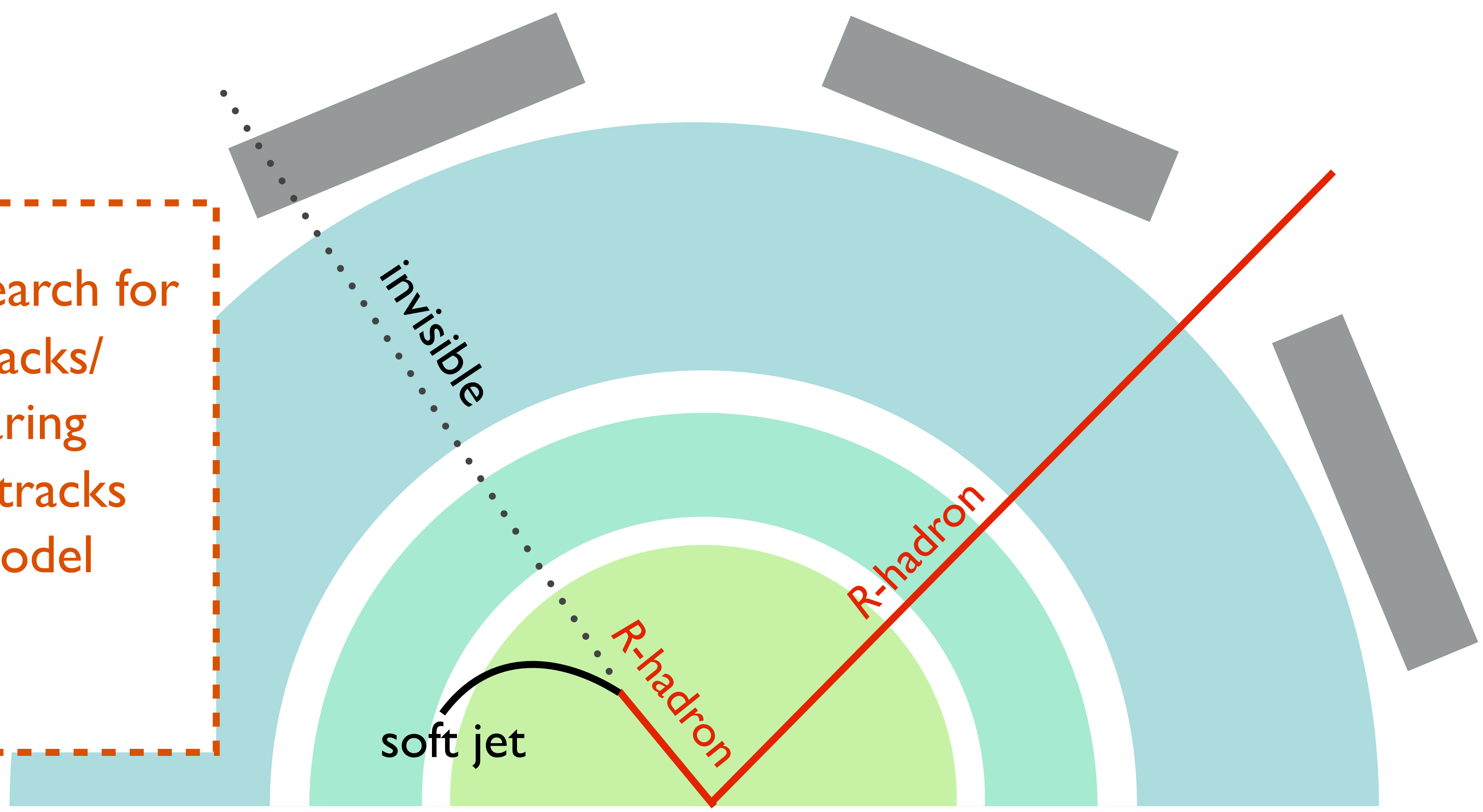




LHC constraints



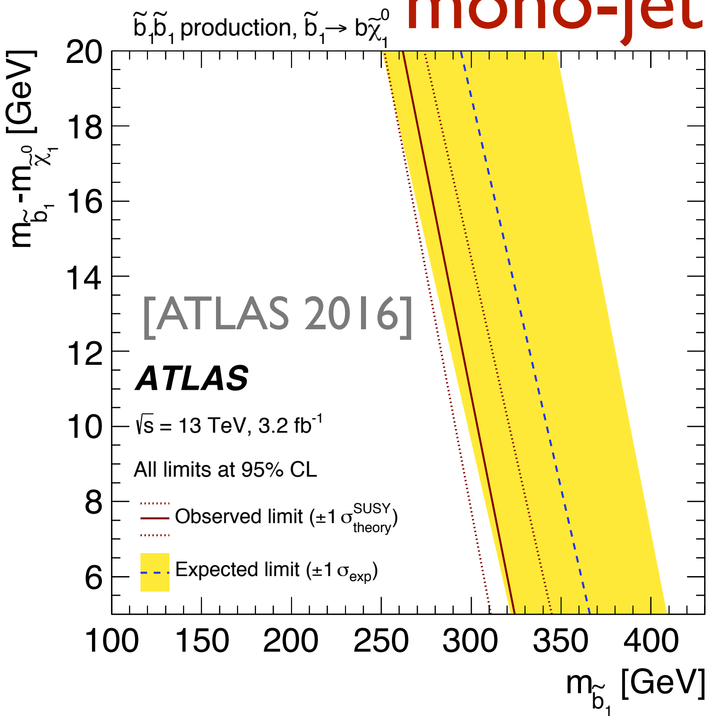


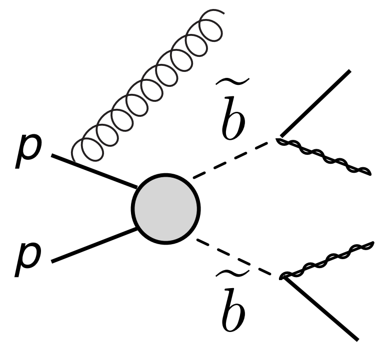
Dedicated search for kinked tracks/ disappearing R-hadron tracks within model

?

LHC constraints

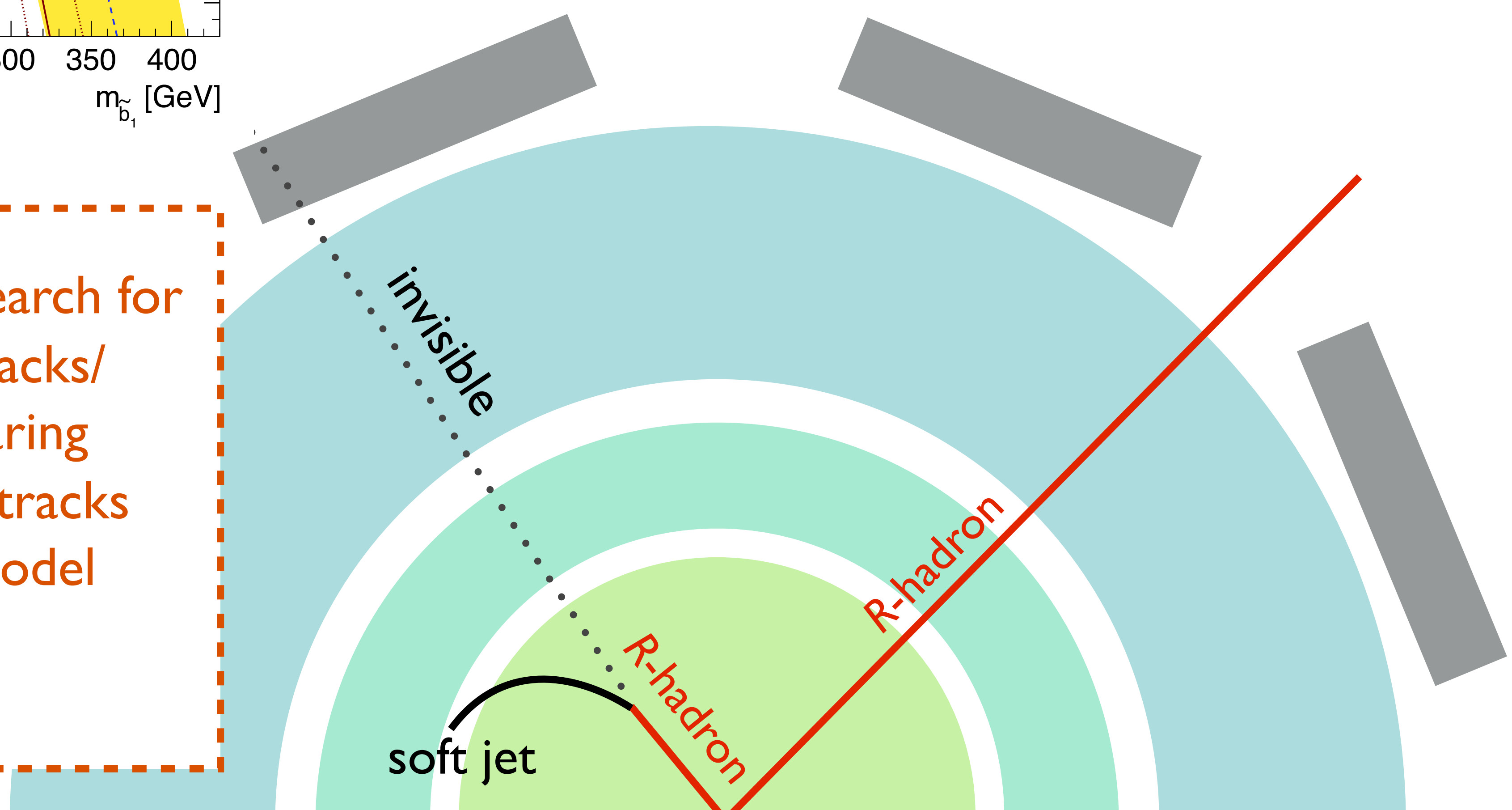
mono-jet





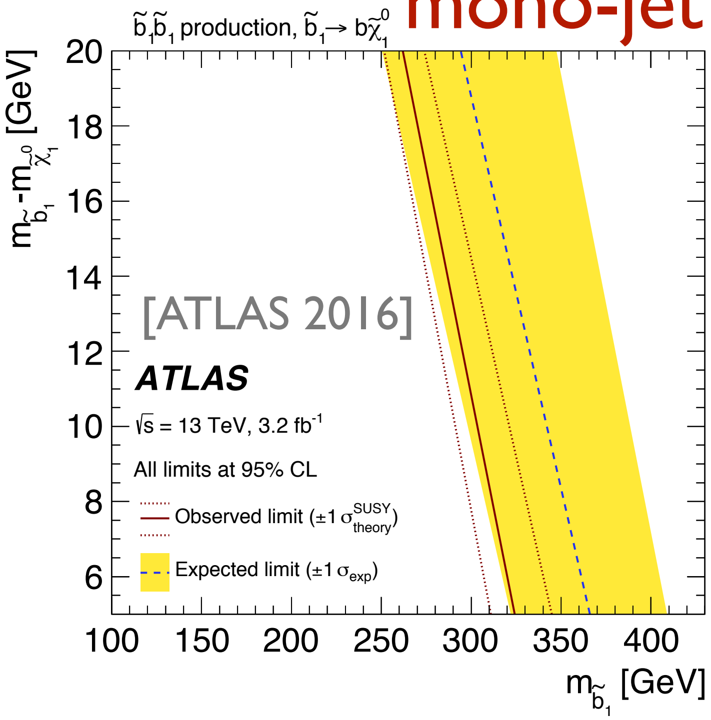
Dedicated search for kinked tracks/ disappearing R-hadron tracks within model

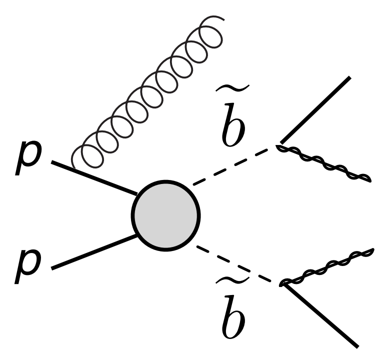
?

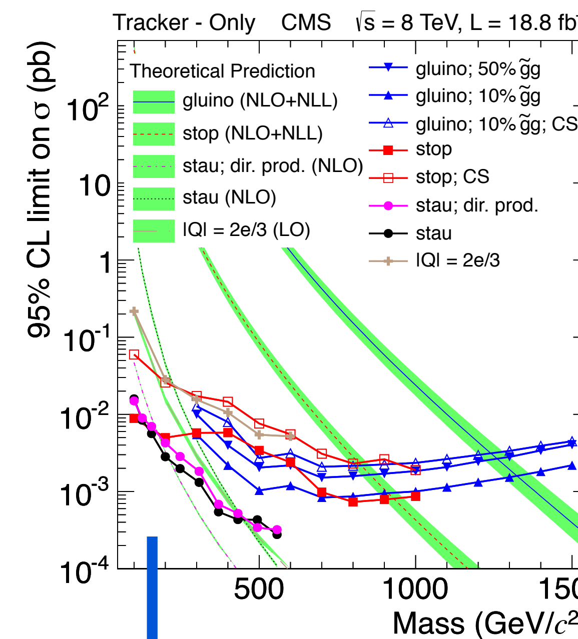


LHC constraints

mono-jet



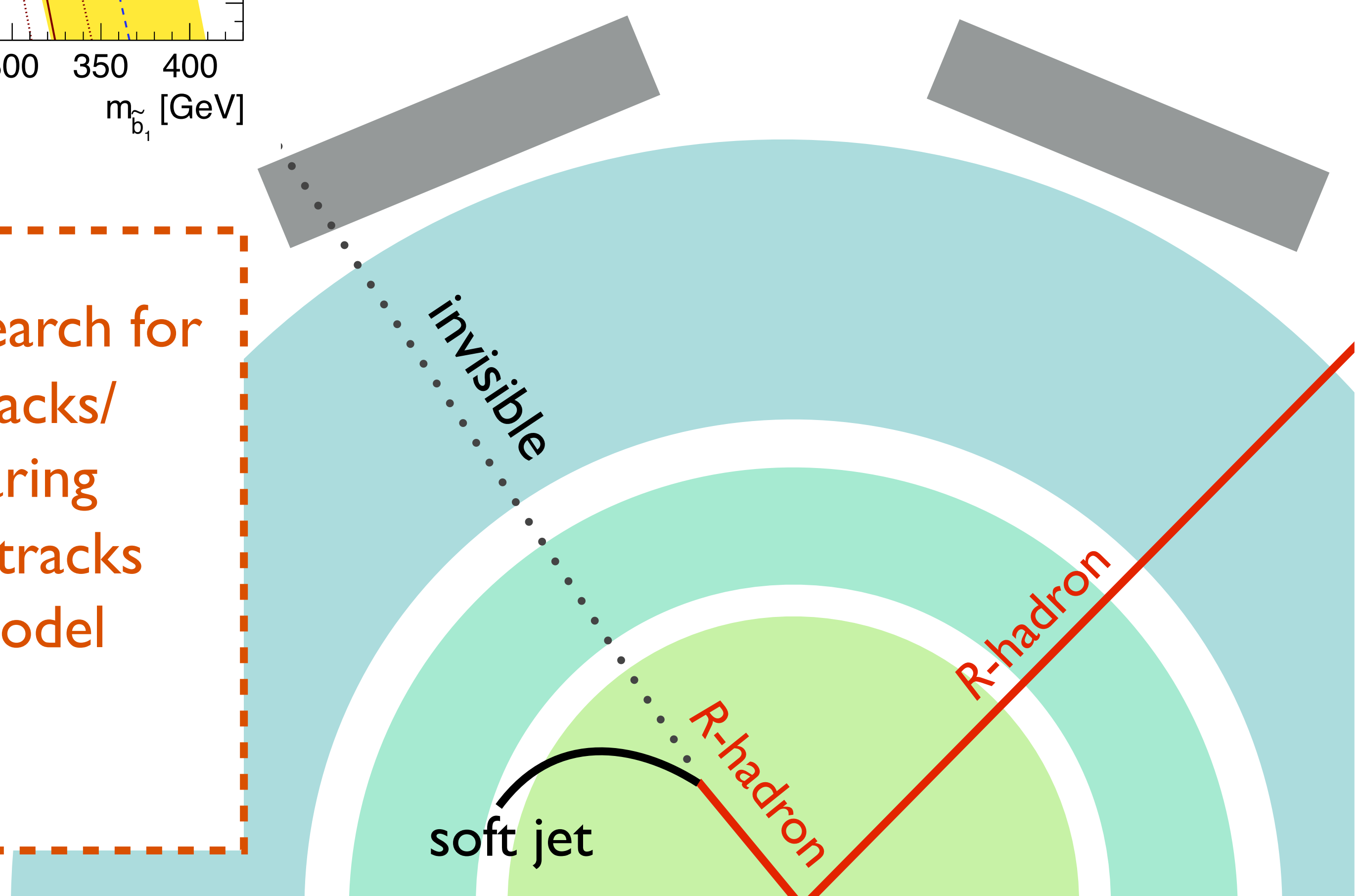


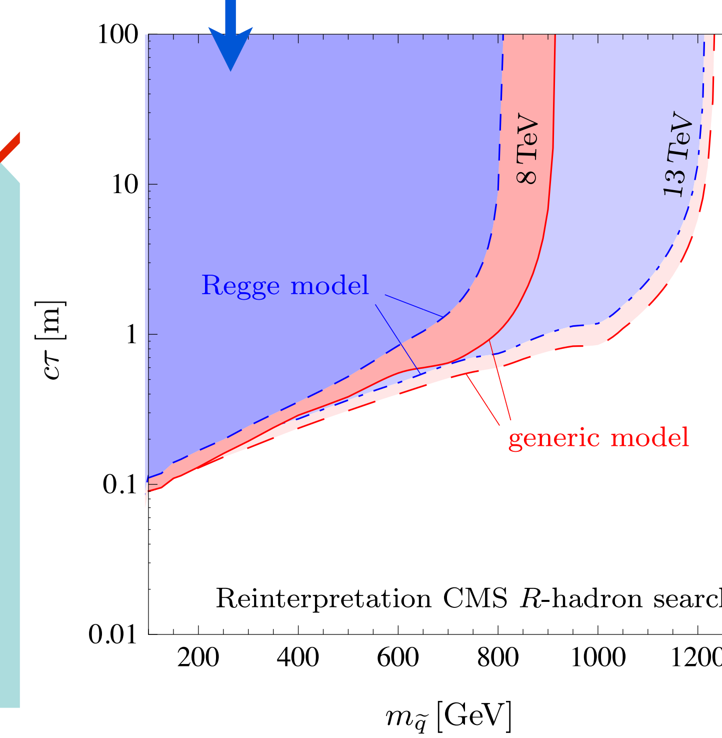


[CMS 2013]

Reinterpretation of *R*-hadron searches for finite lifetimes

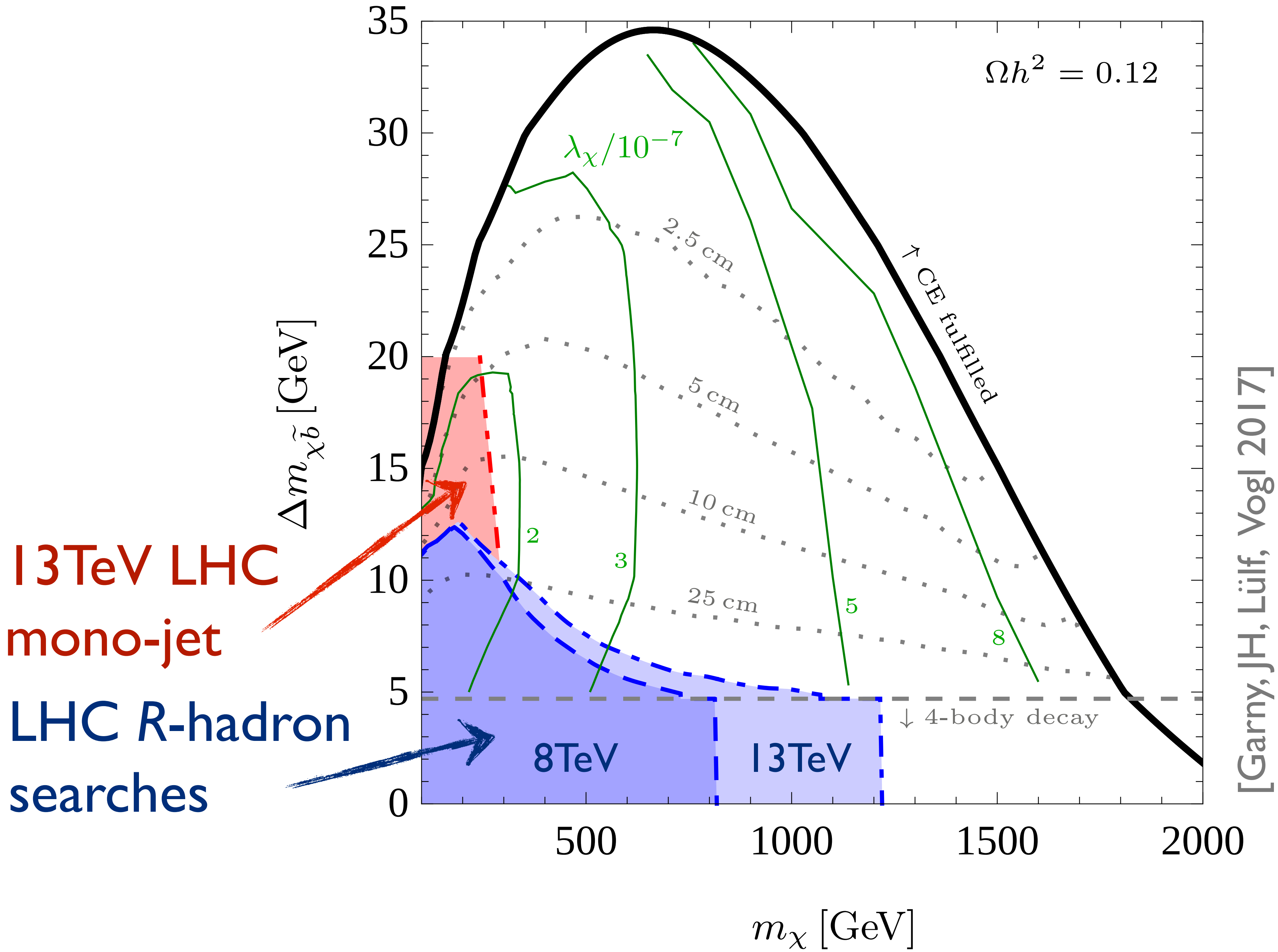
Dedicated search for kinked tracks/ disappearing R-hadron tracks within model ?



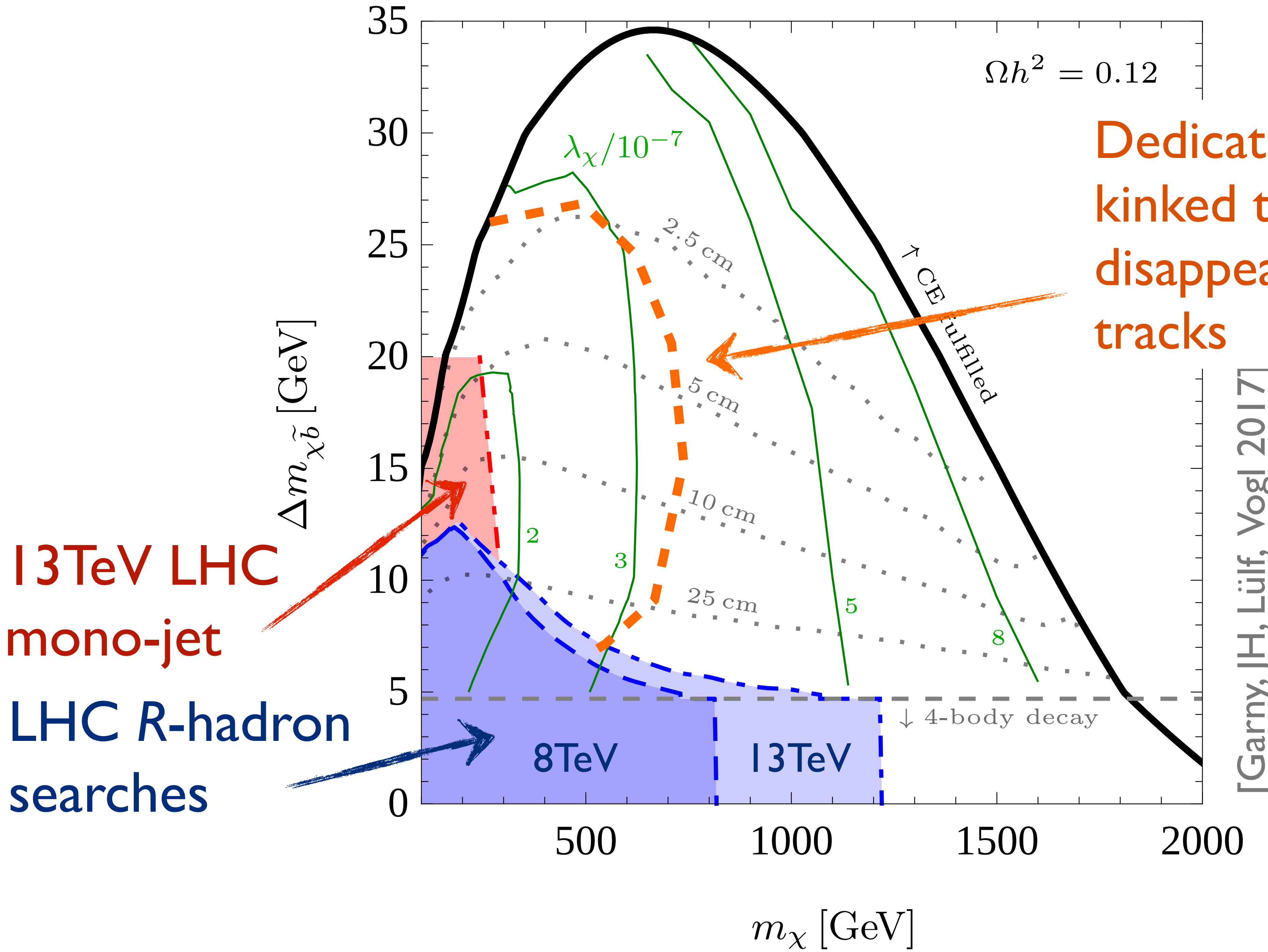


[Garny, JH, Lülf, Vogl 2017]

Allowed parameter space

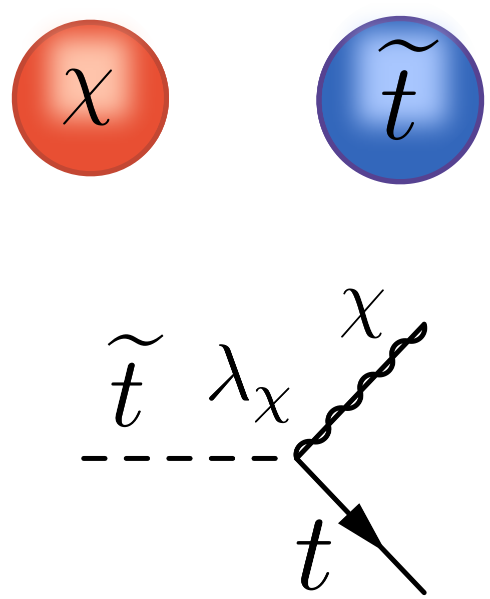


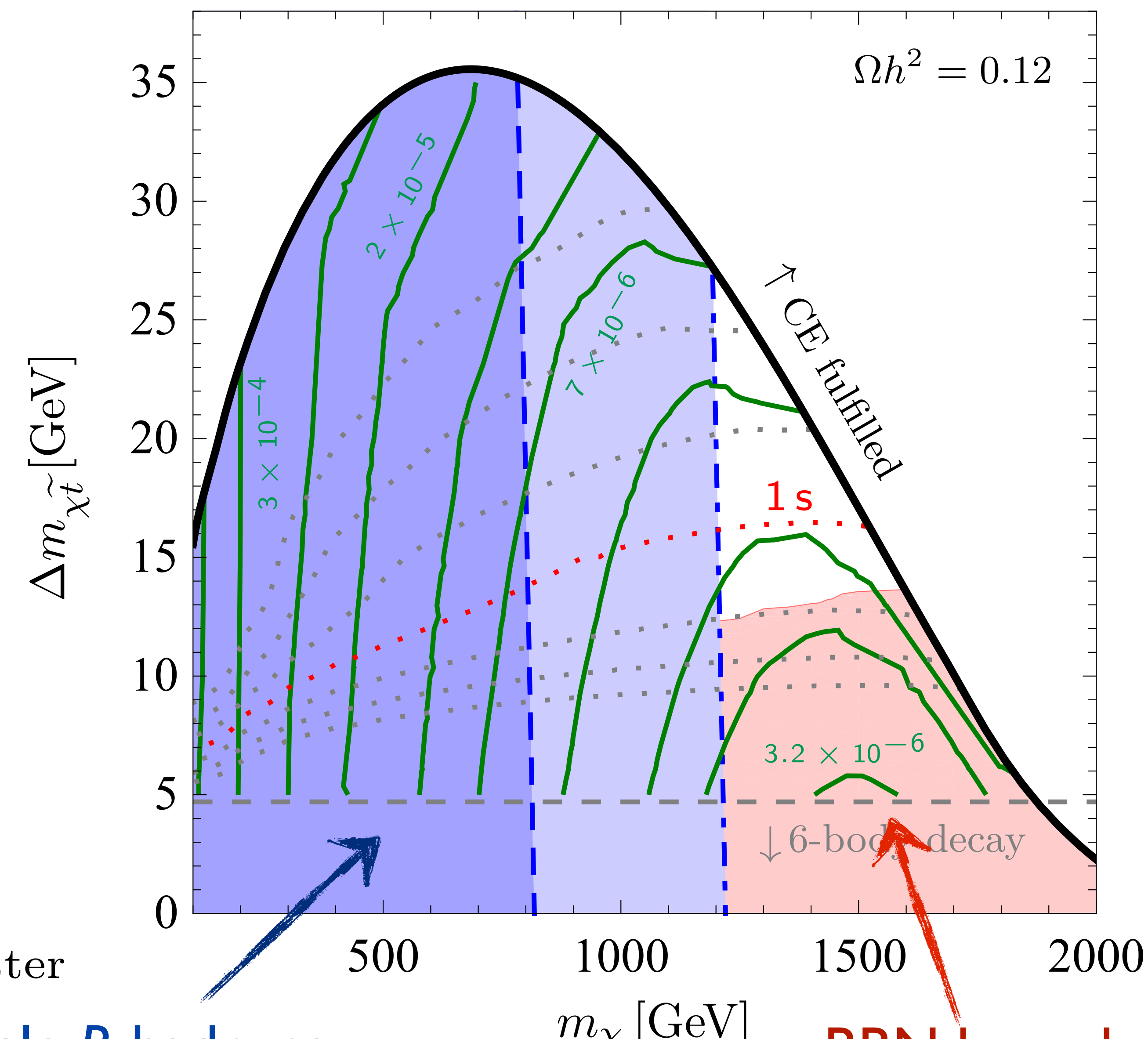
Allowed parameter space



Allowed parameter space: top-partner model

[Garny, JH, Hufnagel, Lülf 1802.00814]





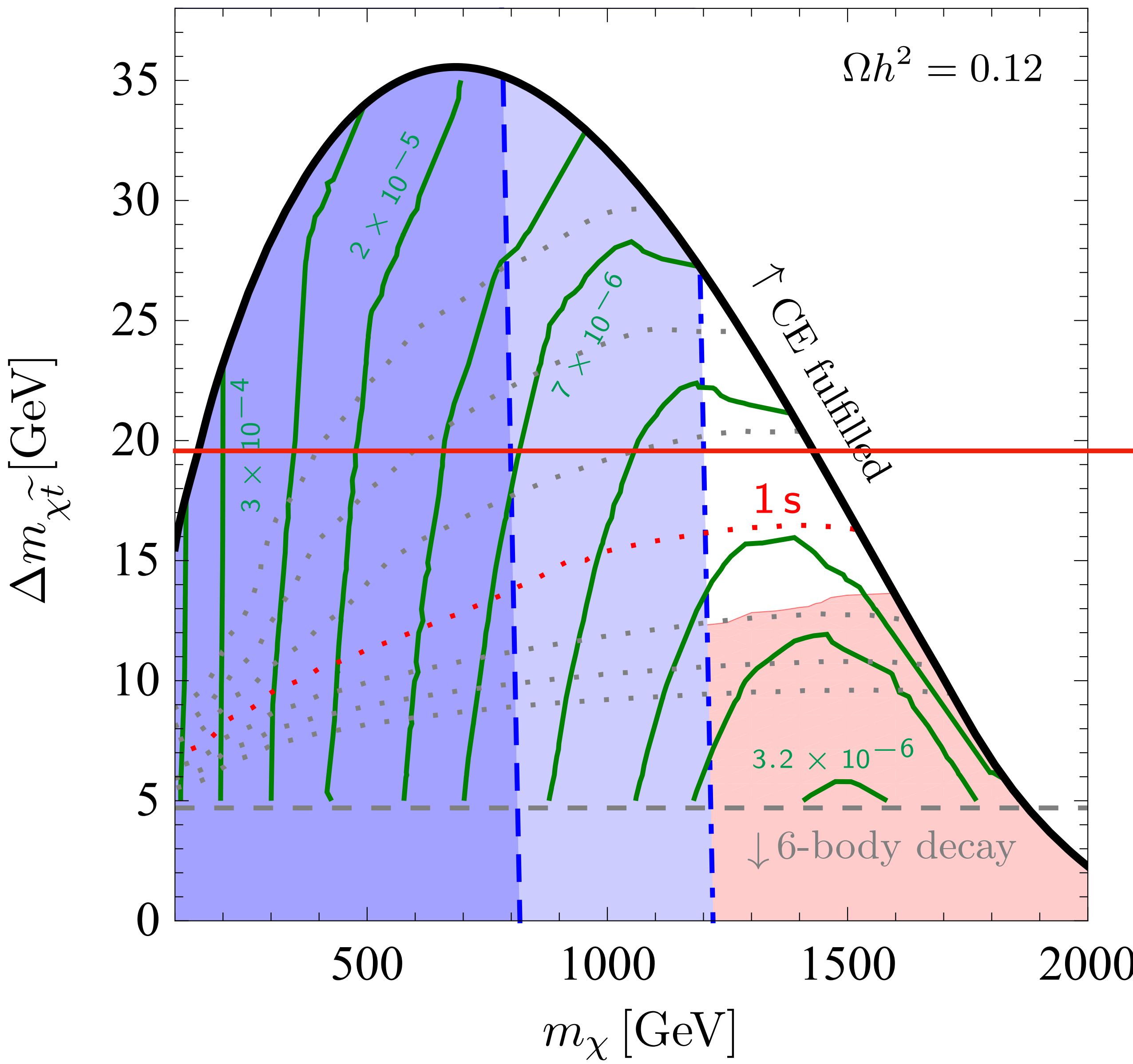
$\Gamma_{\mathrm{decay}} \ll \Gamma_{\mathrm{scatter}}$

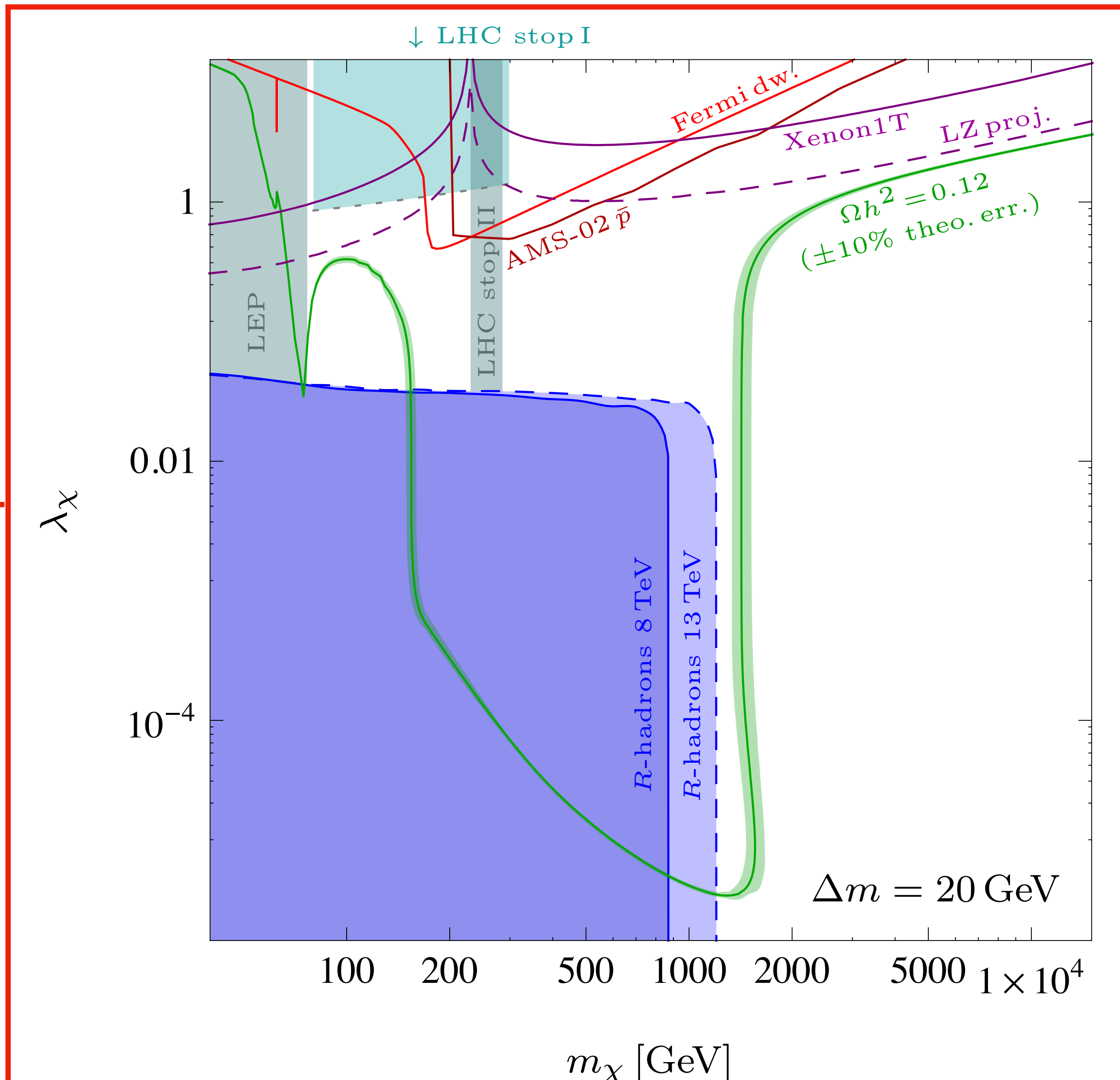
⇒ Detector-stable *R*-hadrons

BBN bounds

Allowed parameter space: top-partner model

[Garny, JH, Hufnagel, Lülf 1802.08814]





Summary

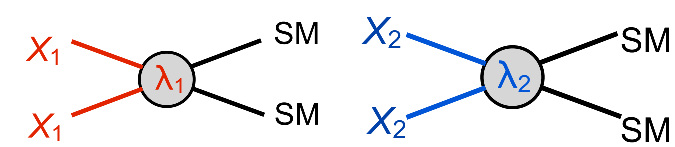
- Vanilla WIMP strongly constrained: Watch out for new avenues beyond WIMPs
- Variety long-lived particle signatures: Exploit LHC potential
- Coannihilation with small mass splitting or couplings
- Coincidence: weak scale decays ~ detector size
- Conversion-driven freeze-out:
  - Shares nice features of WIMPs!
  - Accommodates null-results from WIMP-searches
  - Dedicated searches needed

Thanks for your attention!

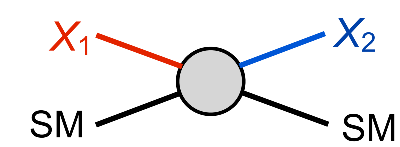
Backup slides

Coupled set of Boltzmann equations

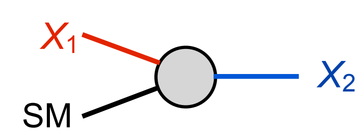
$$\frac{\mathrm{d}n_i}{\mathrm{d}t} + 3Hn_i = -\sum_{j=1}^{N} \langle \sigma_{ij} v_{ij} \rangle \left(n_i n_j - n_i^{\mathrm{eq}} n_j^{\mathrm{eq}} \right)$$ annihilations



$$- \sum_{j \neq i} \left[\langle \sigma'_{Xij} v_{ij} \rangle \left(n_i n_X - n_i^{\mathrm{eq}} n_X^{\mathrm{eq}} \right) - (i \leftrightarrow j) \right]$$ conversions (scattering)



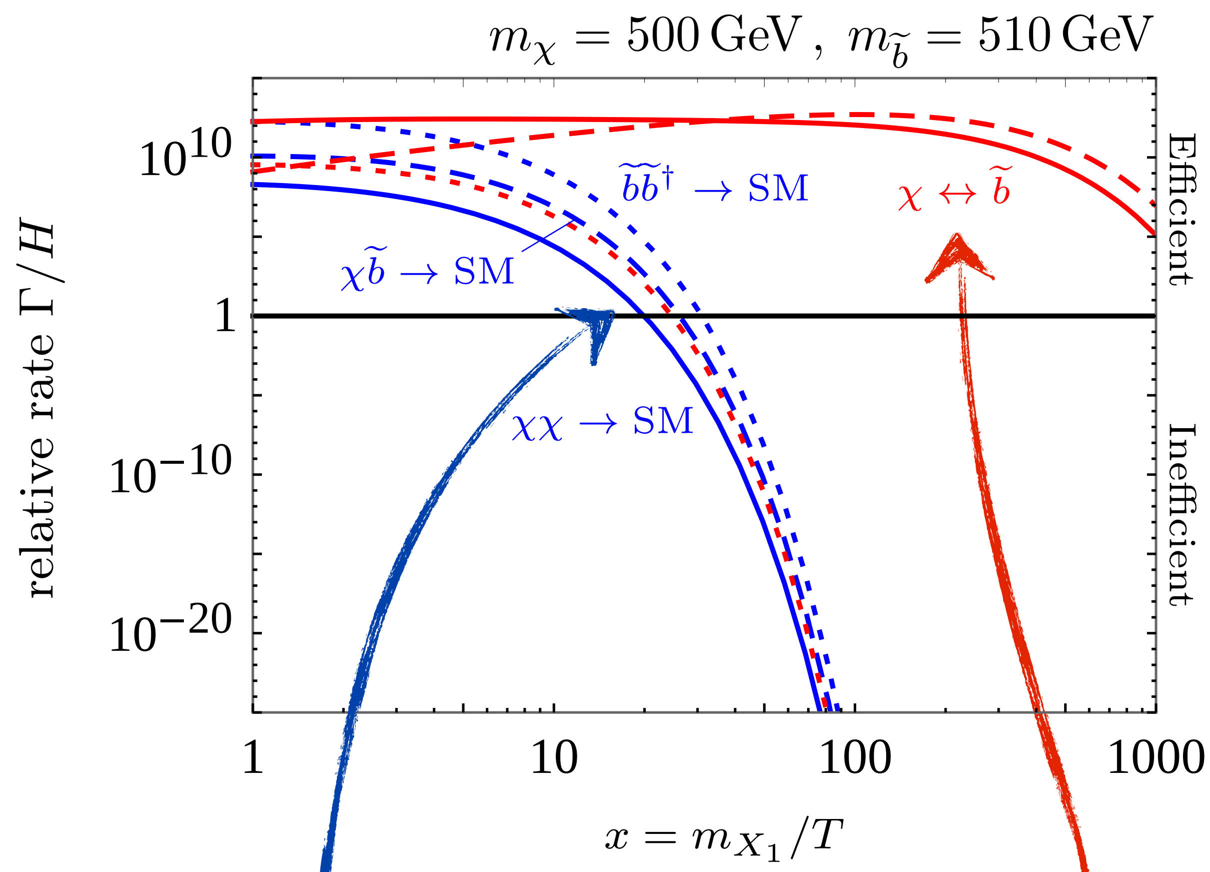
$$- \sum_{j \neq i} \left[\Gamma_{ij} \left(n_i - n_i^{\mathrm{eq}} \right) - (i \leftrightarrow j) \right]$$ conversions (decay)

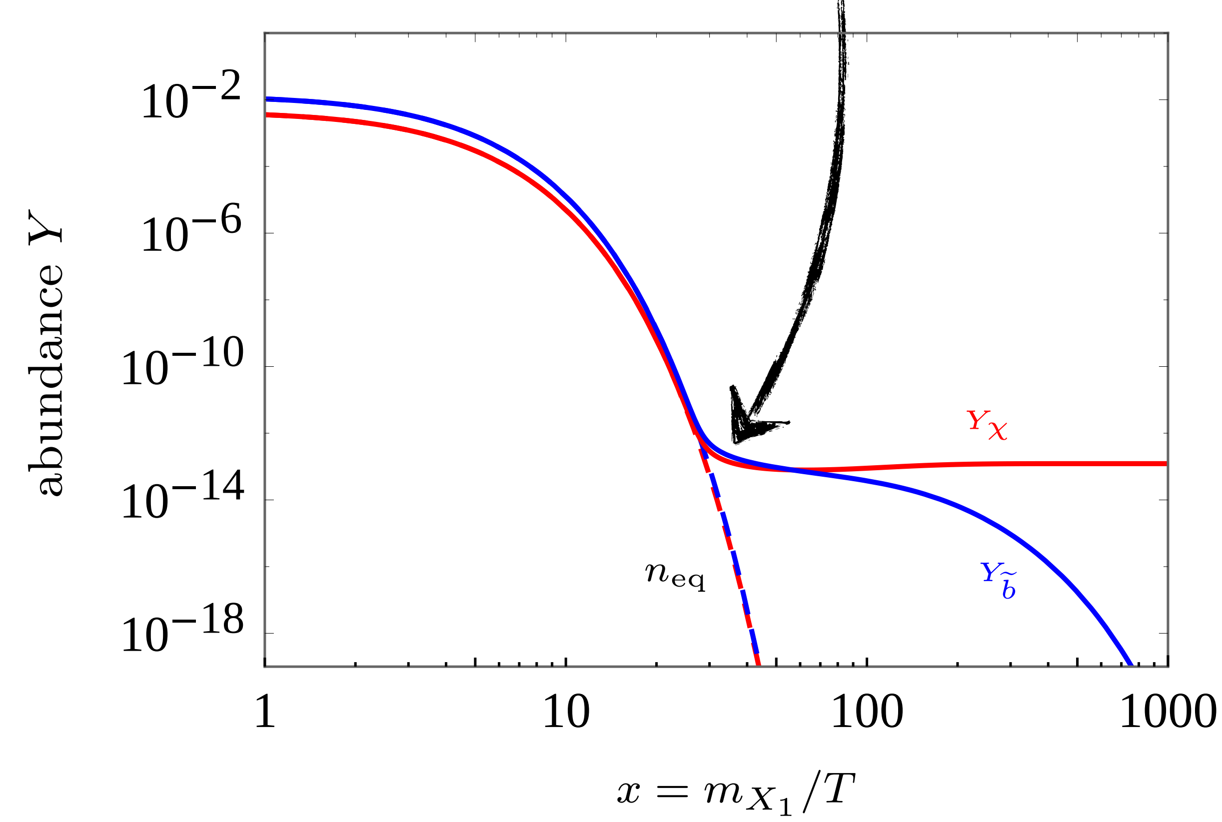


Numerical solution of full coupled system

- SUSY coupling $\lambda_\chi \simeq 0.17$:

DM and mediator freeze-out simultaneously (chemical eq.)





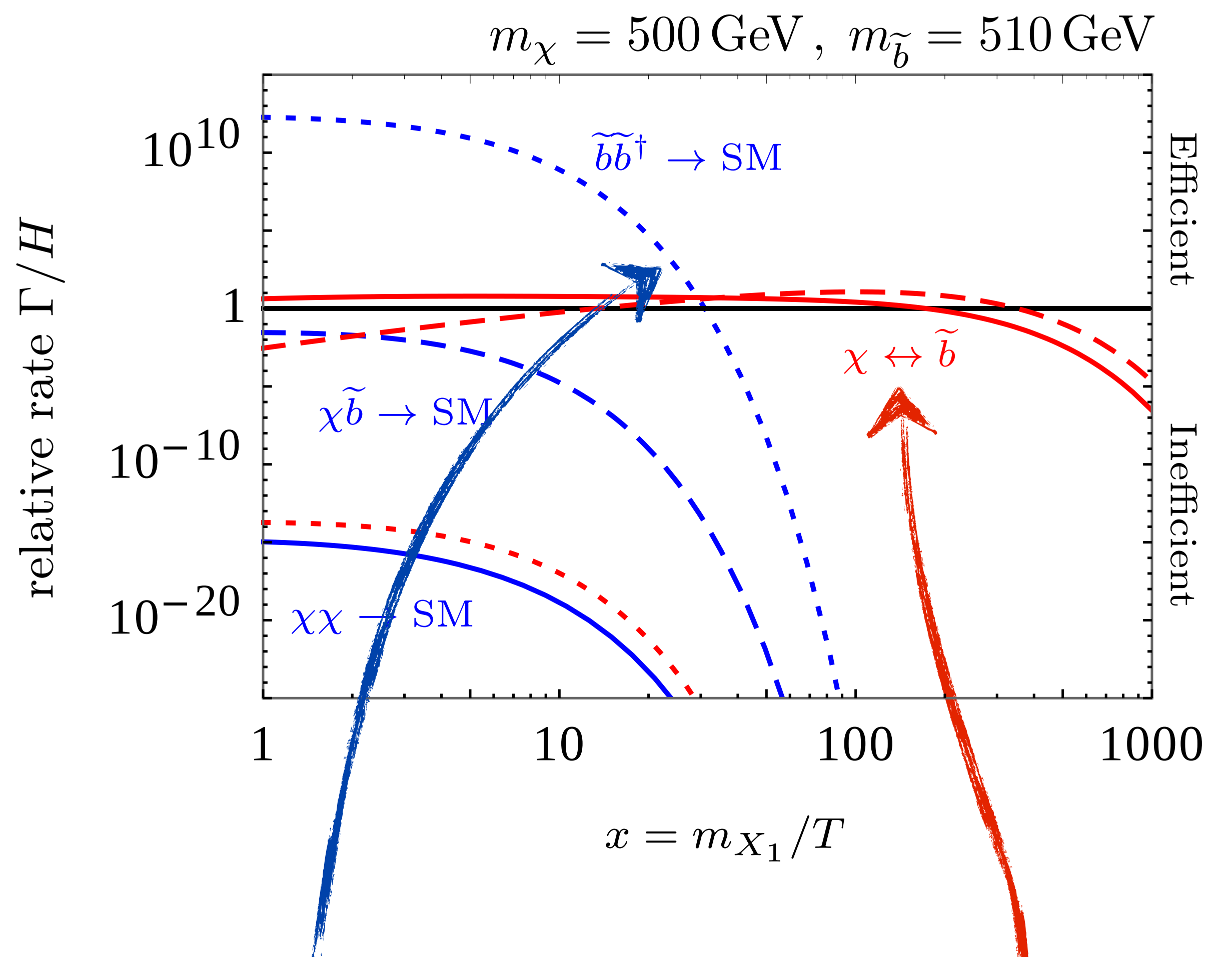
all annihilations contribute

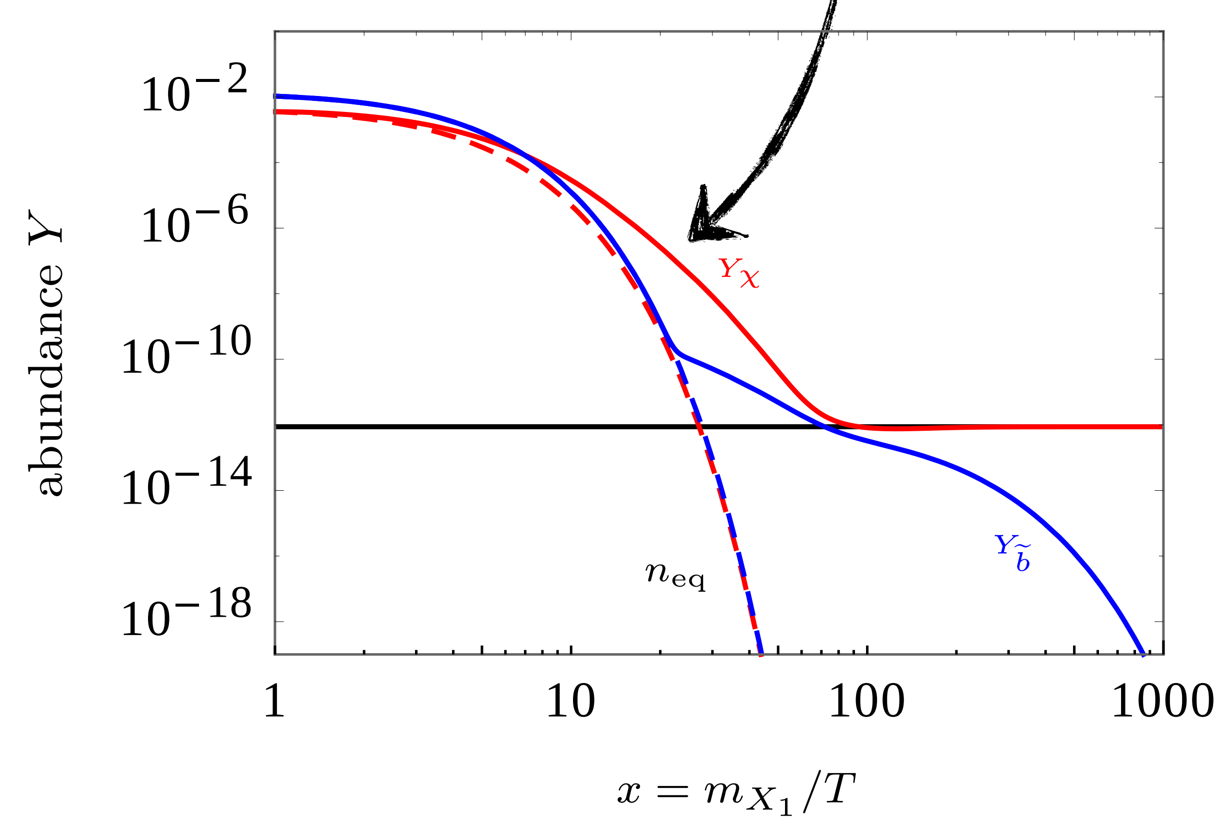
conversion thoroughly efficient

Numerical solution of full coupled system

- Very small coupling $\lambda_\chi \simeq 2.6 \times 10^{-7}$:

DM and mediator freeze-out at different x (no chem. eq.)



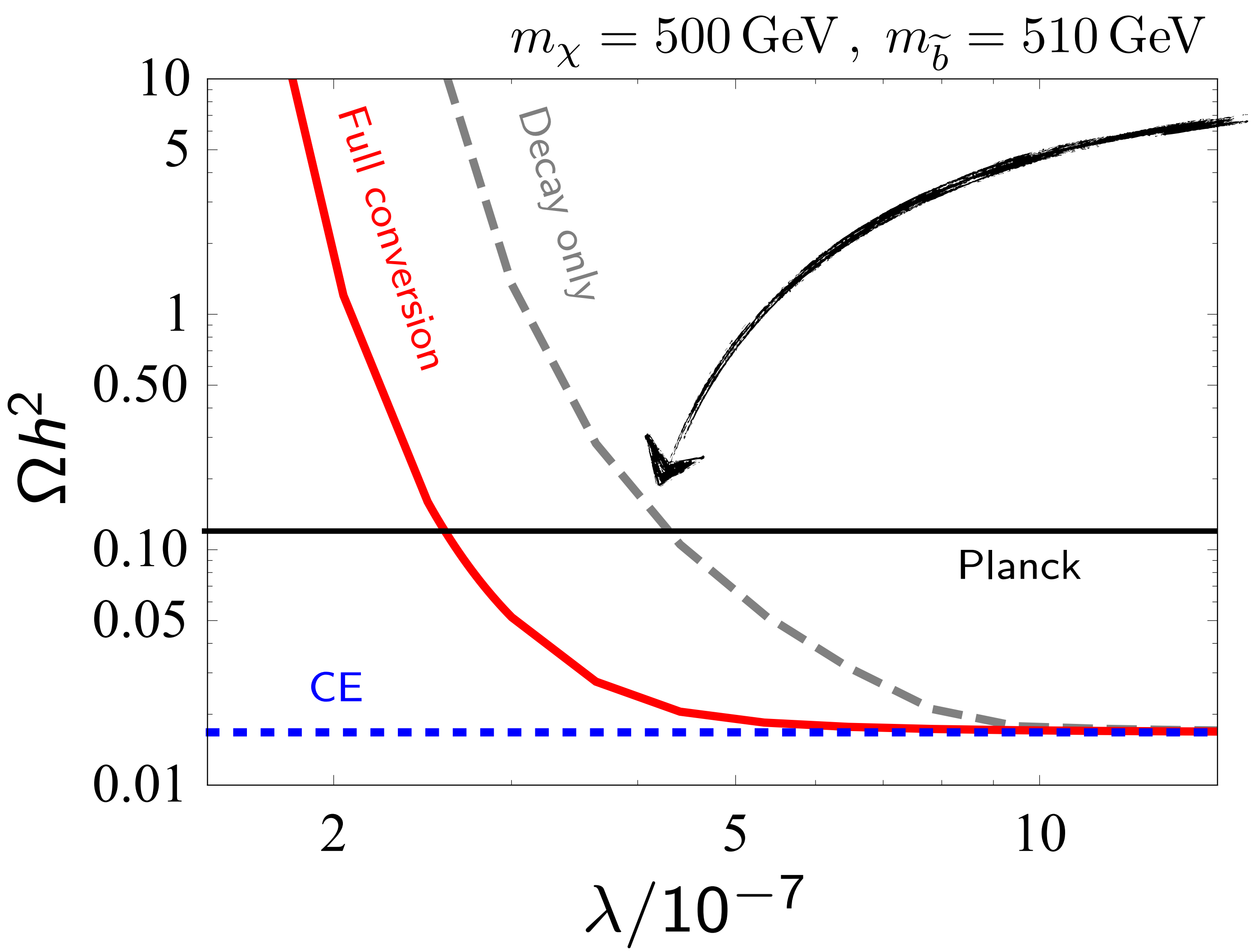


mediator-annihilation contributes only

conversion on the edge of being efficient

Numerical solution of full coupled system

- Scan of the coupling:



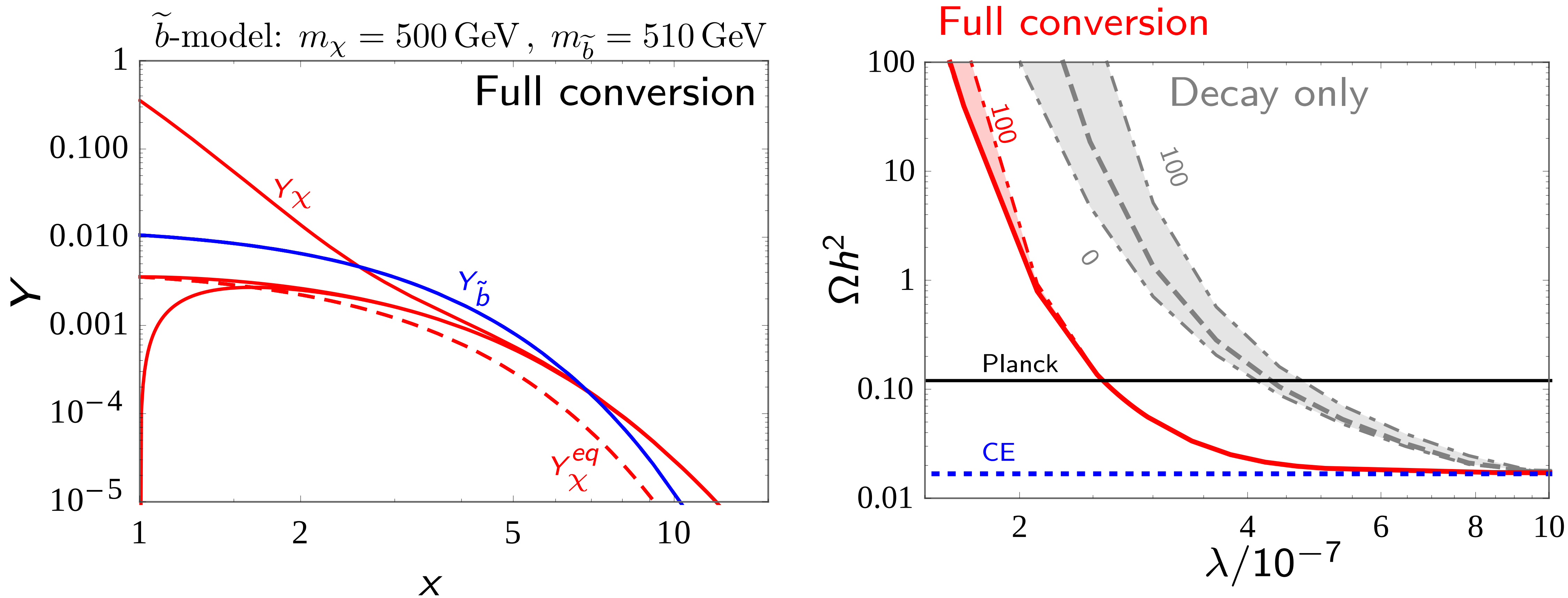
Decay only similar

$\Gamma_{\rm decay} \sim \Gamma_{\rm scatter}$

Scrutinizing some assumptions

Dependence on Initial Conditions

- So far equilibrium density at x=1 assumed
- Does DM thermalize?



- Insensitive in range $Y_\chi(1) = (0\text{–}100) \times Y_\chi^{\mathrm{eq}}(1)$

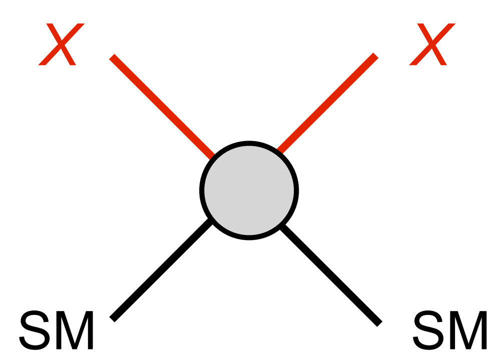
$\Rightarrow$ Independent of thermal history prior to freeze-out!

Kinetic equilibrium

- Assumption of thermal distributions (via kinetic equilibrium)

$$f_\chi(t,p) = f^{\rm eq}(t,p)\,\frac{n(t)}{n^{\rm eq}(t)}$$

- WIMPs: kinetic equilibrium established through efficient elastic scatterings with SM particles:



(kinetic decoupling takes place well after freeze-out)

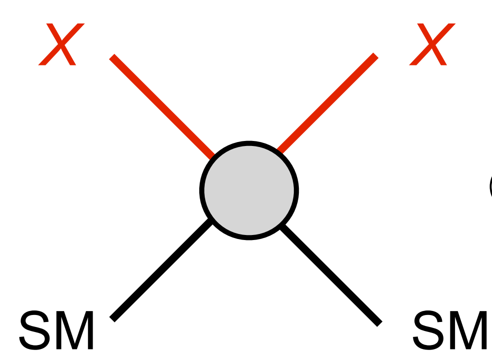
[*cf.* Chen, Kamionkowski, Zhang 2001, Bringmann, Hofmann 2006; Borzumati, Bringmann, Ullio 2007]

Kinetic equilibrium

- Assumption of thermal distributions (via kinetic equilibrium)

$$f_\chi(t,p) = f^{\mathrm{eq}}(t,p)\,\frac{n(t)}{n^{\mathrm{eq}}(t)}$$

- WIMPs: kinetic equilibrium established through efficient elastic scatterings with SM particles:



$$\propto \lambda_\chi^4$$

- Inefficient for DM in conversion-driven freeze-out!
- Mediator is in kinetic equilibrium

Boltzmann equations for particle densities

[Lee, Weinberg 1977; Binetruy, Girardi, Salati 1984; Bernstein, Brown, Feinberg 1985; Srednicki, Watkins, Olive 1988; Kolb, Turner 1990; Griest, Seckel 1991; Gondolo, Gelmini 1991; Edsjo, Gondolo 1997]

DM distribution functions

$$E_\chi \left(\partial_t - H p \, \partial_p\right) f_\chi(p,t) = C\left[f_\chi\right]$$

Relativistic Liouville operator for homogeneous, isotropic Universe

Collision operator

Cosmology

Particle Physics

Unintegrated Boltzmann equation

- Consider unintegrated Boltzmann equation for χ:

$$H x \partial_x f_\chi(q,x) = \widetilde{C}(q,x)\left(f_\chi^{\rm eq}\frac{Y_{\tilde{b}}}{Y_{\tilde{b}}^{\rm eq}} - f_\chi\right)$$

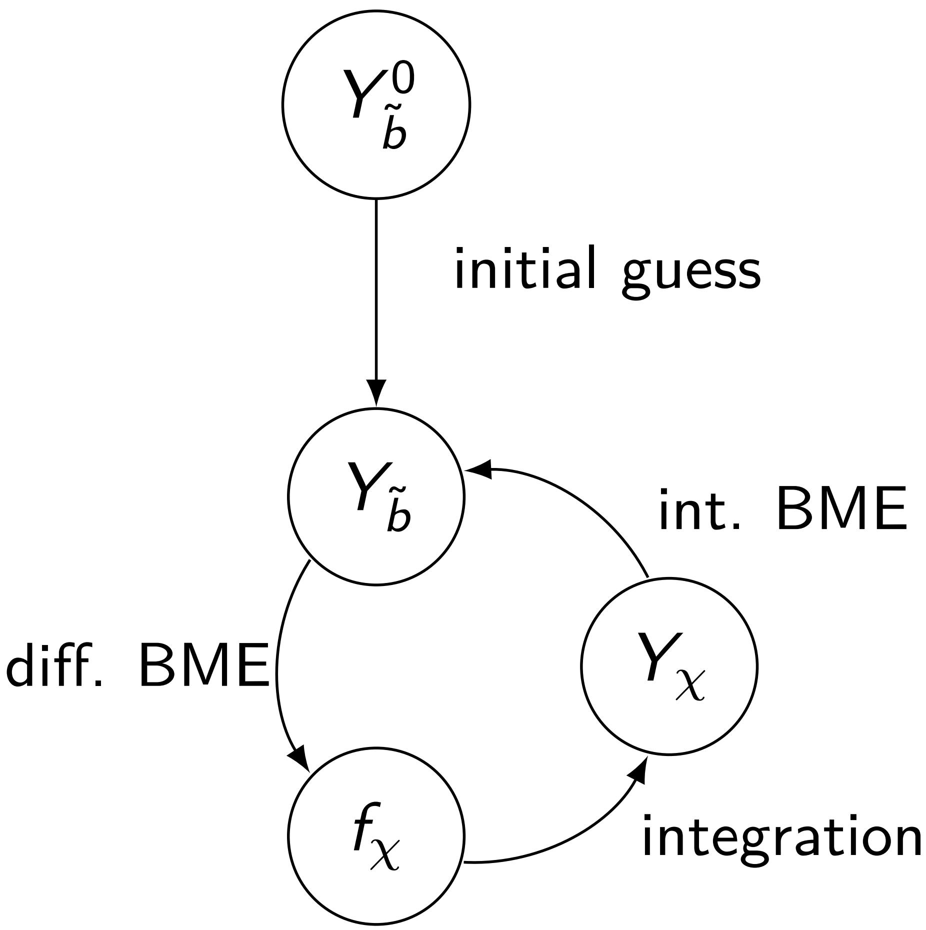
- Conversion only: linear in f_χ
- Can be solved by separation of variables and variation of constants:

$$f_\chi(q,x) = f_\chi^{\rm eq}(q,x)\frac{Y_{\tilde{b}}}{Y_{\tilde{b}}^{\rm eq}} - \int_{x_0}^{x}\frac{{\rm d}\big(f_\chi^{\rm eq}(q,y)\,Y_{\tilde{b}}(y)/Y_{\tilde{b}}^{\rm eq}(y)\big)}{{\rm d}y}\times\exp\left(-\int_y^x\frac{\widetilde{C}(q,z)}{zH(z)}{\rm d}z\right){\rm d}y$$

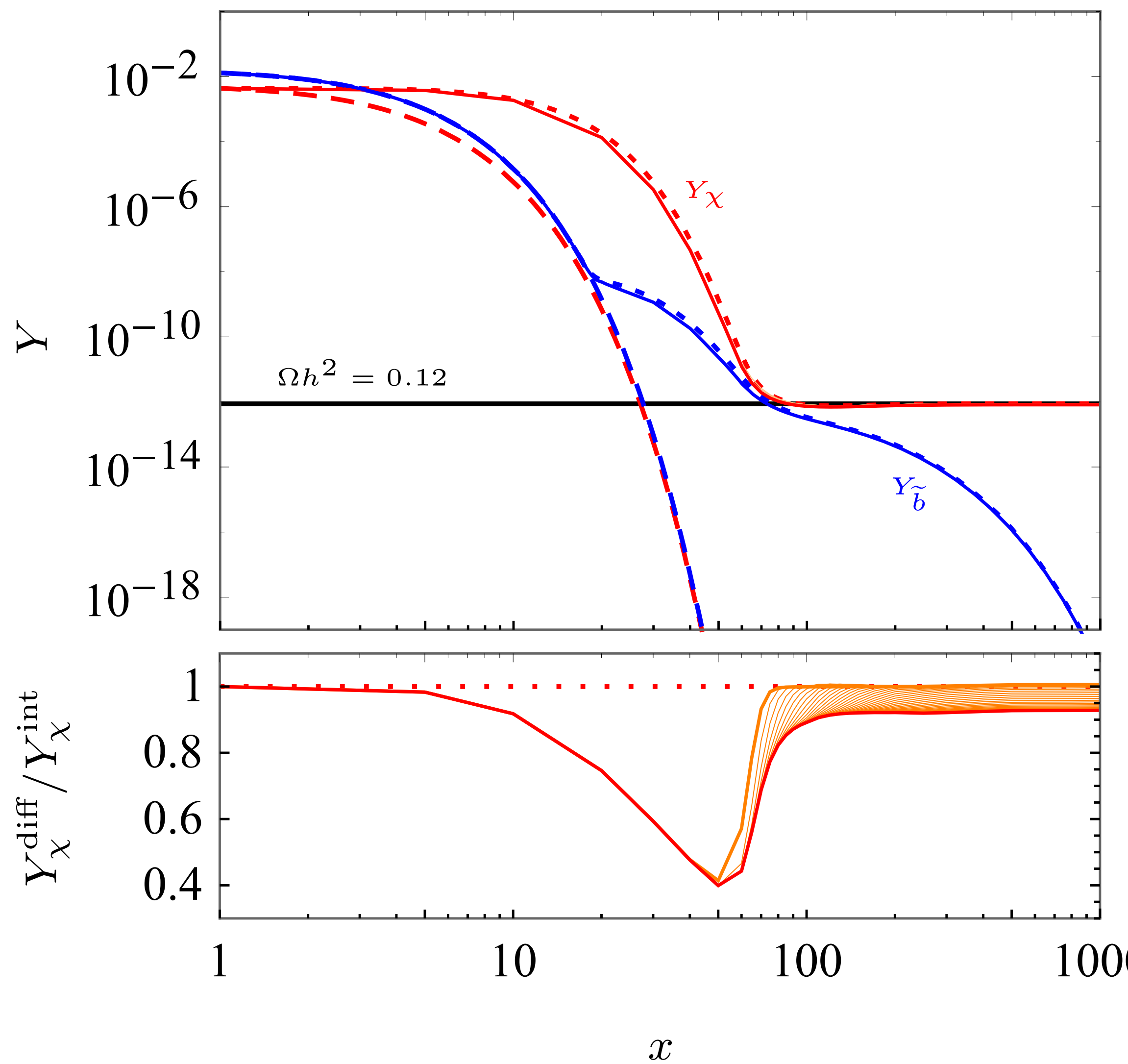
Involves $Y_{\tilde{b}}$ ➔ still coupled system

Iterative solution

- Do not solve coupled system at once but iteratively
- Start with "guess" for $Y_{\tilde{b}}$: solution of integrated equations

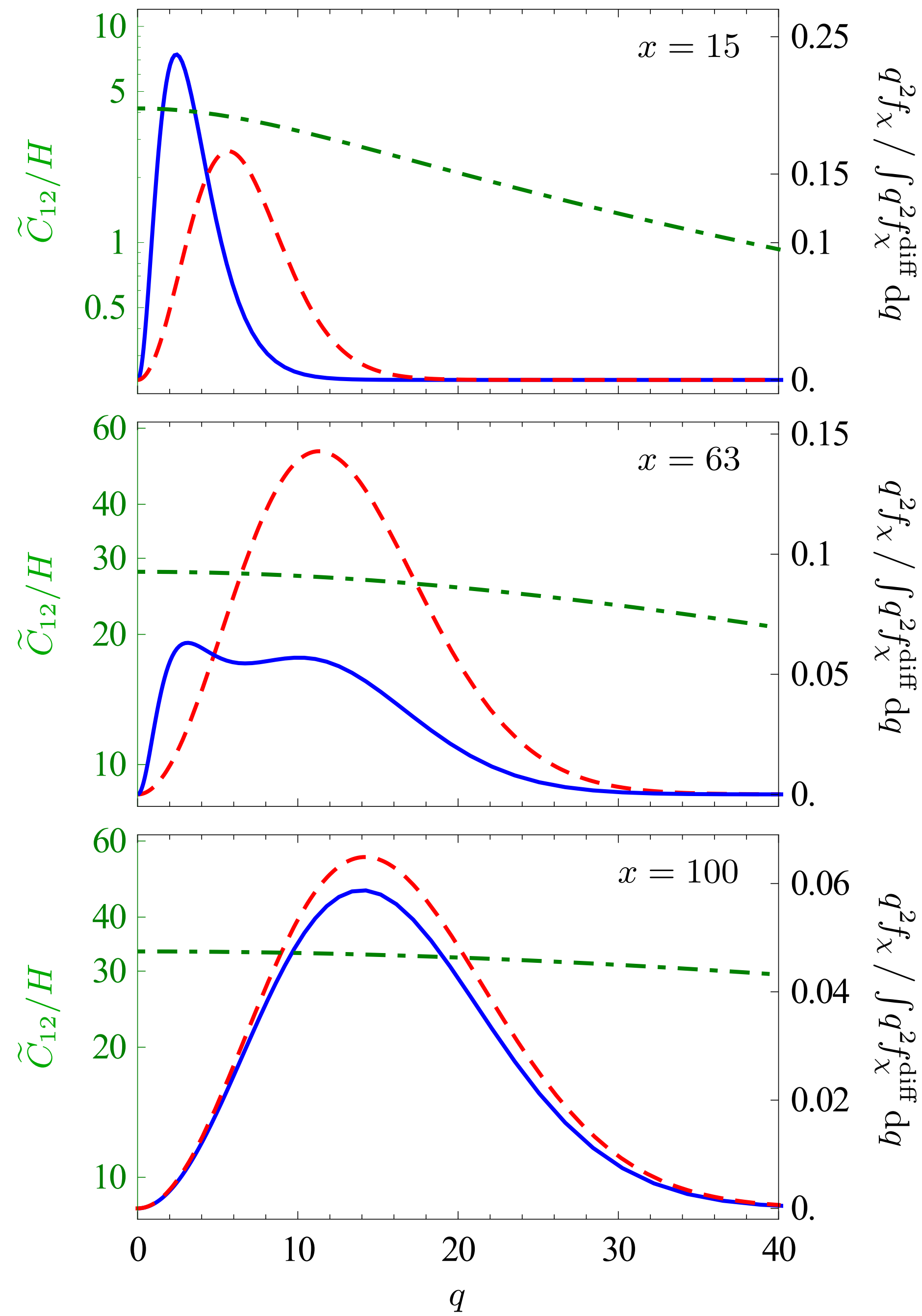


B. Lülf



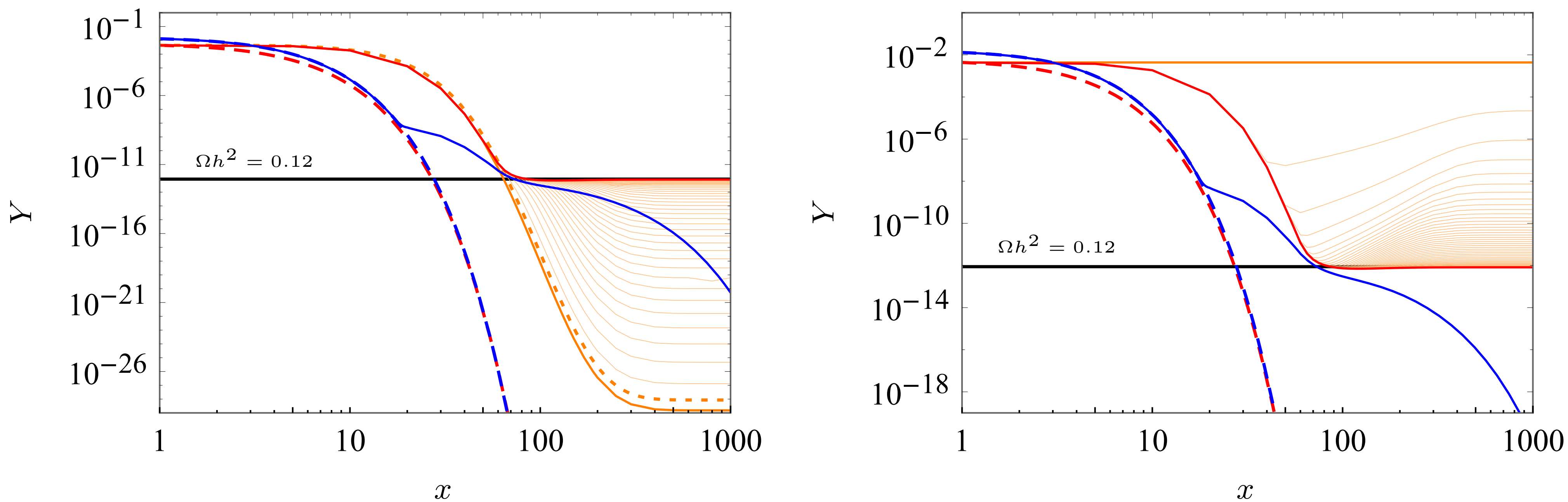
Deviation from thermal distribution

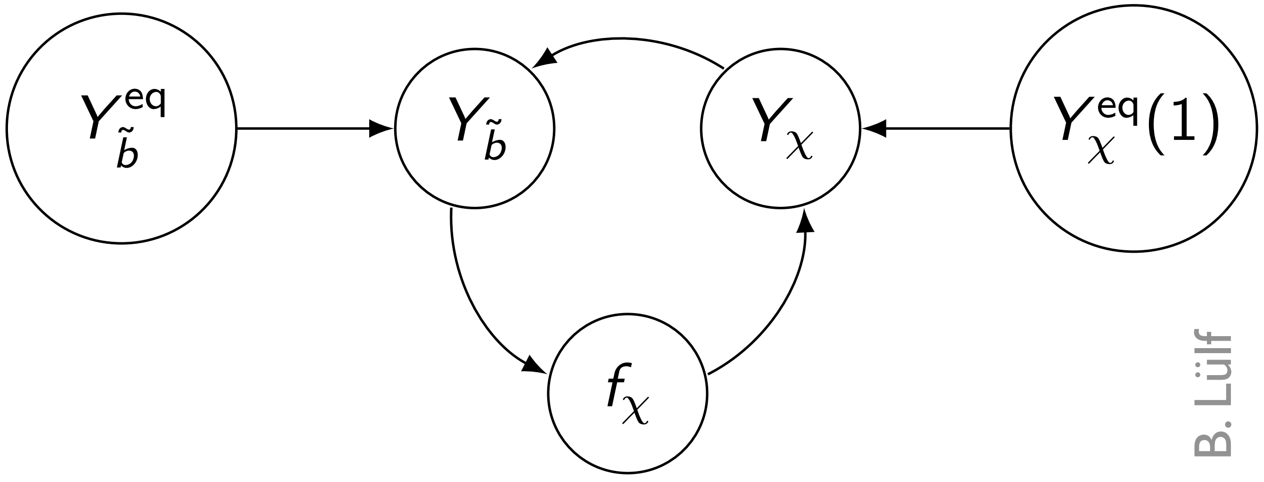
- small x: redshift only
- Conversion inset: thermalization starts
- Close-to-thermal distribution



Testing initial guess

- Extreme cases for initial evolutions of abundances
- Converge to same solution:



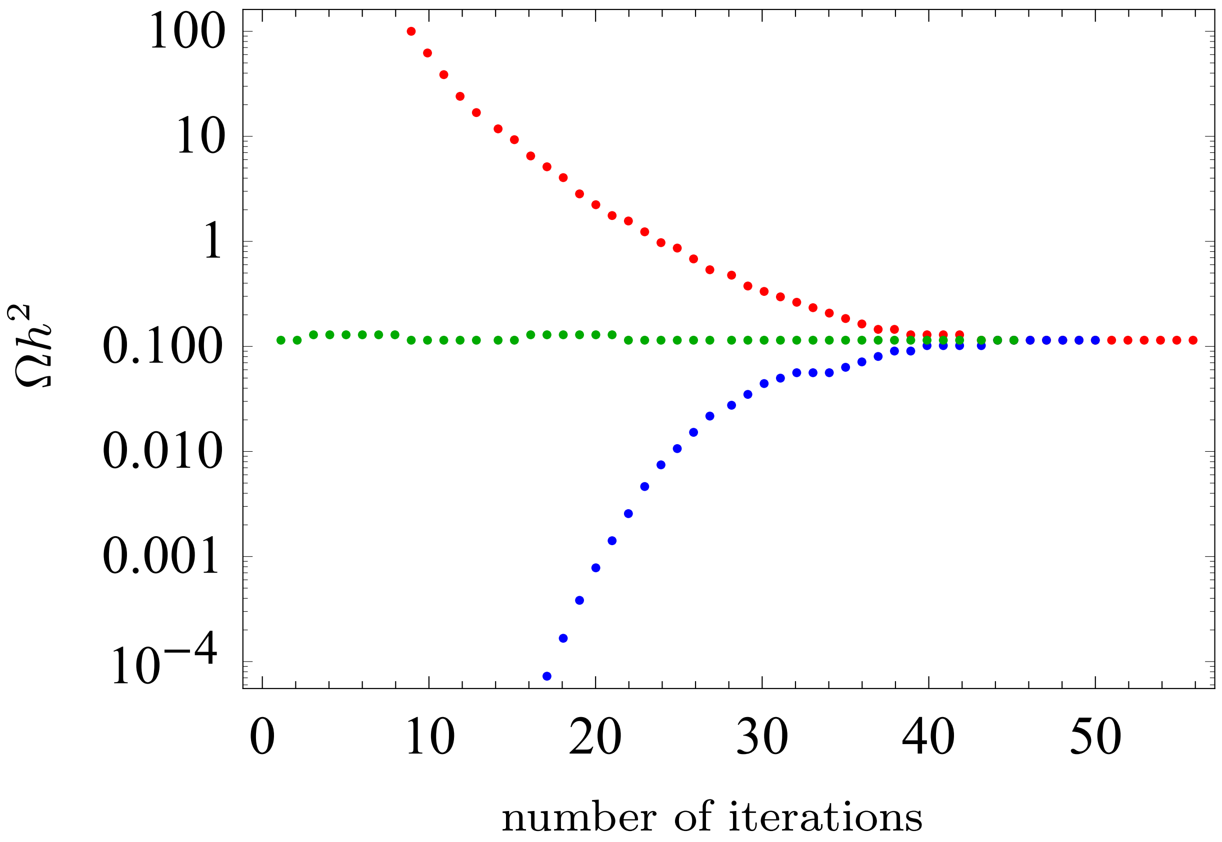


B. Lülf

Iterative solution

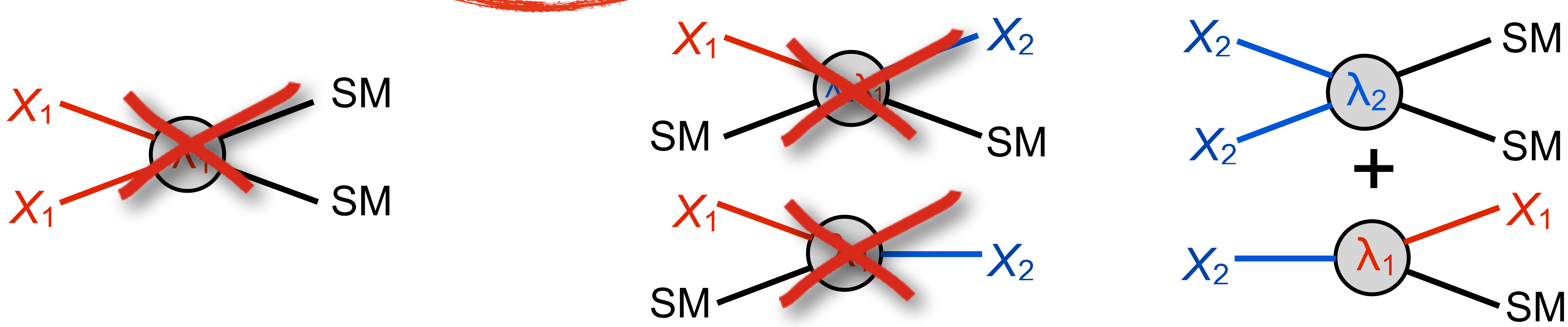
- All initial guesses converge to the same solution
- Difference to integrated treatment below 10%
- Solution of coupled system more important

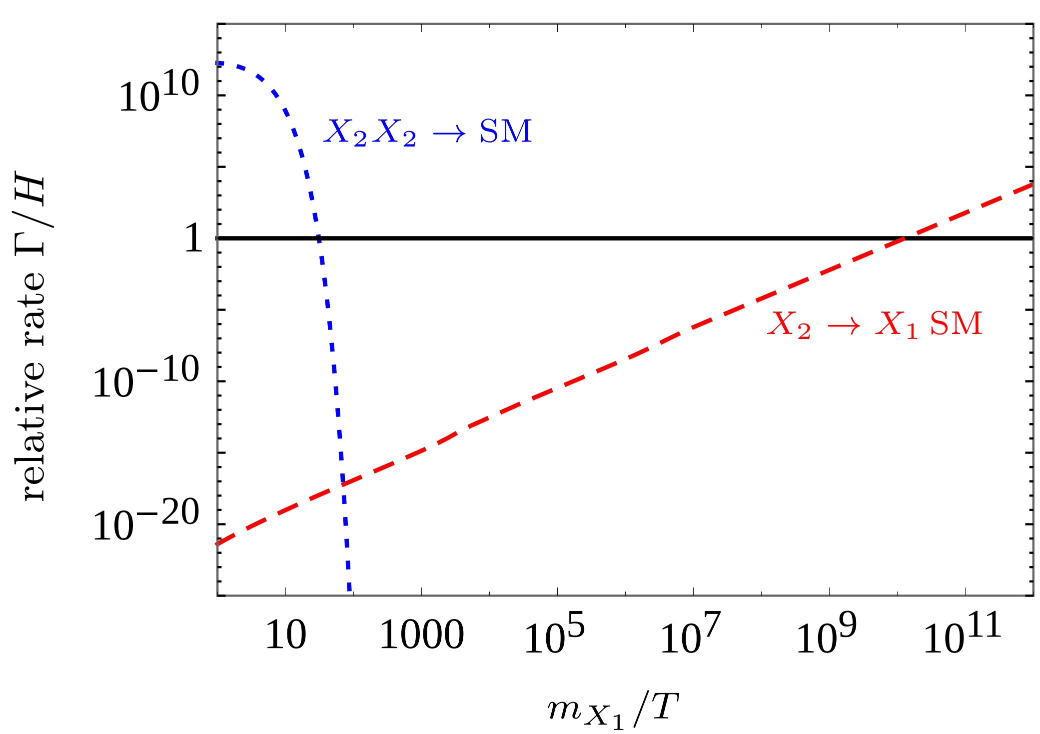
[cf. D'Agnolo, Pappadopulo, Ruderman, 2017]

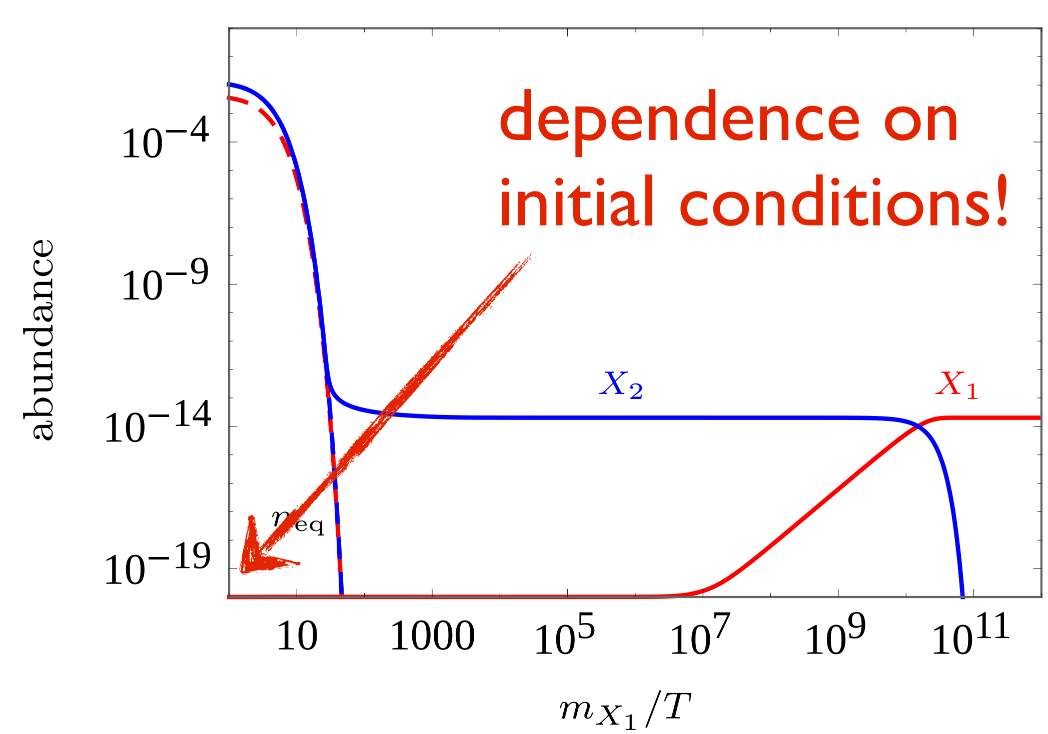


superWIMP scenario

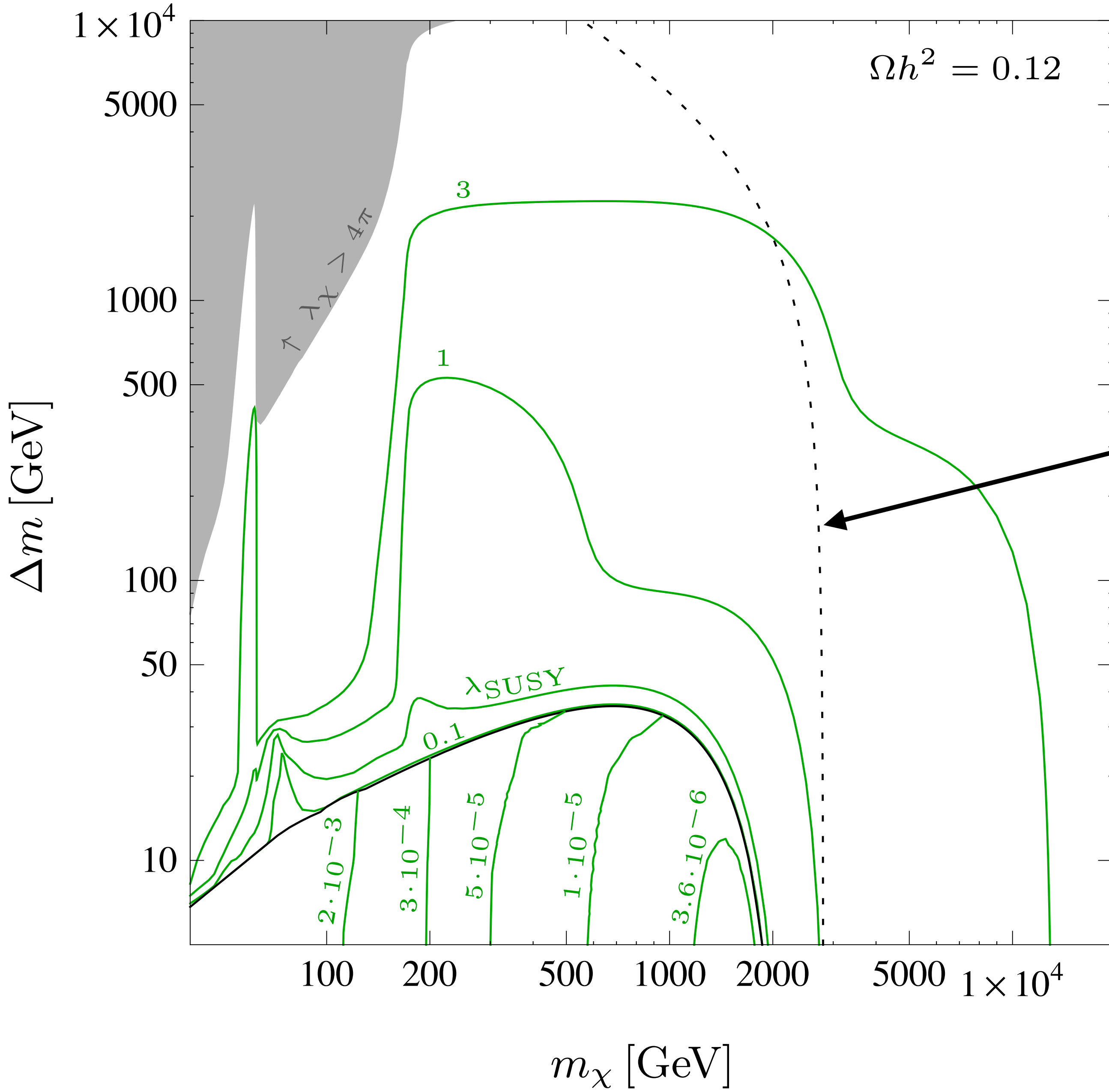
Annihilation: $\lambda_1 \lll \lambda_2$ Conversion: + Co-annihilation:







superWIMP scenario



superWIMP
zero initial
abundance