Dark matter genesis beyond the WIMP paradigm: Conversion-driven freeze-out

[M. Garny, JH, B. Lülf, S.Vogl, **1705.09292**, *PRD*; Garny, JH, M. Hufnagel, B. Lülf, **1802.00814**, *PRD*]

Jan Heisig (RWTH Aachen University)

Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

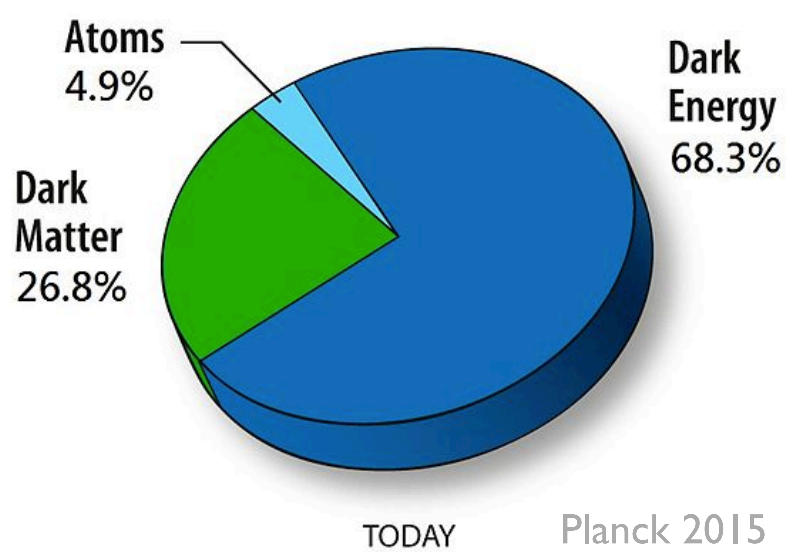
supported by the DAAD Deutscher Akademischer Austauschdienst German Academic Exchange Service

Talk at the Workshop on the Standard Model and Beyond, Corfu, September 8, 2018

Among key scientific goals of LHC:

- Pinpoint the nature of dark matter!

Energy density of the universe:

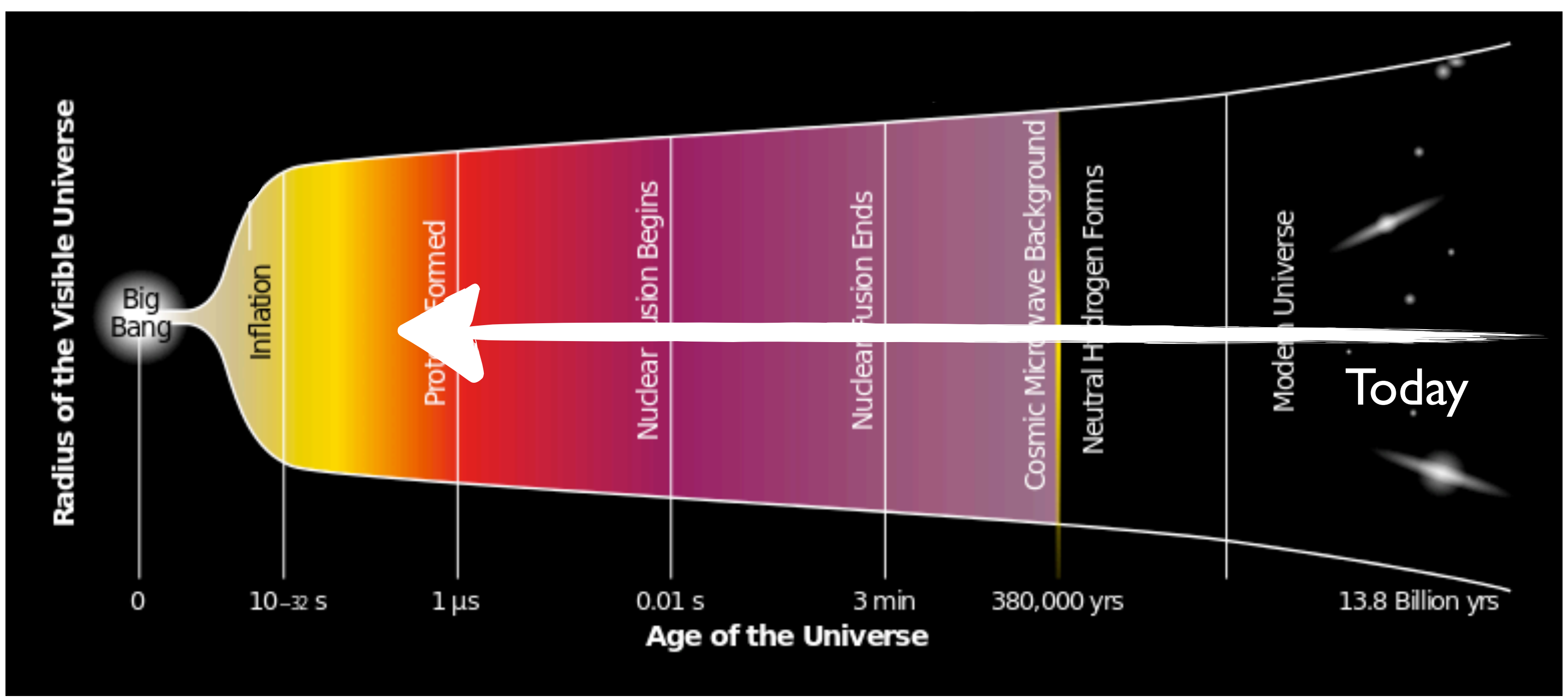


Dark matter $\stackrel{?}{=}$ WIMP

⇒ More possibilities
(even among thermal relics)

Goal: explain the dark matter density

- Relic from thermal abundance
- Consider cosmological history of Universe:



Particle physics +cosmology: Extrapolate to early hot Universe

Expansion with Hubble rate *H*

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

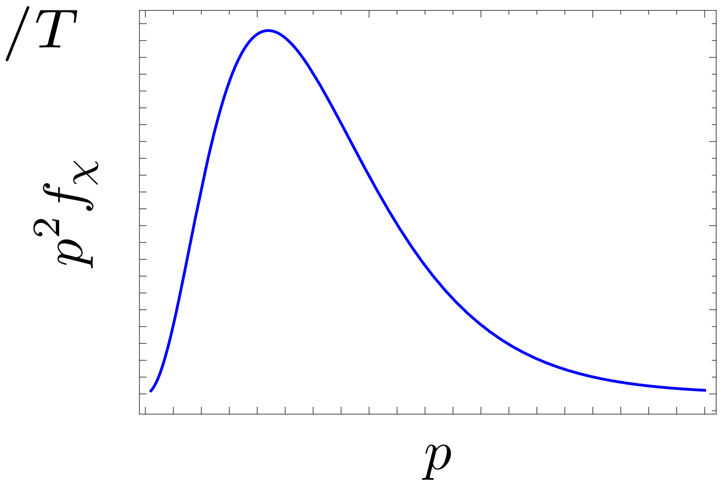
Boltzmann equations for particle densities

[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]

Assumption: $f_\chi(p) \propto f_{\rm BM} = {\rm e}^{-E_p/T}$

(Boltzmann distribution established in kinetic equilibrium)

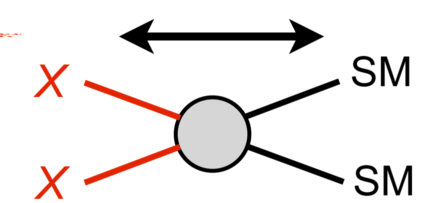
[see e.g. Binder, Bringmann, Gustafsson, Hryczuk 2017 for general solutions without kinetic eq.]



Integrated equation for $n_\chi(t) = \int {\rm d}\Pi_p \, f_\chi(p,t)$:

$$\frac{{\rm d}n_\chi}{{\rm d}t} + 3Hn_\chi = -\langle\sigma v\rangle_{\rm ann}\left(n_\chi^2 - n_\chi^{\rm eq\,2}\right)$$

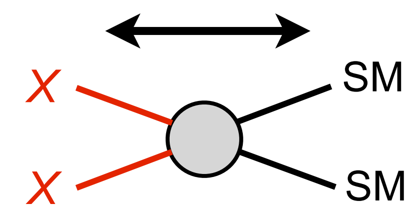
Cosmology — Particle Physics



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]

$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + \underline{3Hn_\chi} = \underline{-\langle\sigma v\rangle_{\mathrm{ann}}\left(n_\chi^2 - n_\chi^{\mathrm{eq}\,2}\right)}$$



$$\Gamma_{\mathrm{ann}} := n_\chi \langle\sigma v\rangle_{\mathrm{ann}}$$

annihilation rate

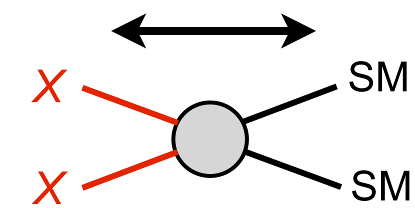
$\Gamma_{\mathrm{ann}} \gg H$: efficient

$\Gamma_{\mathrm{ann}} \ll H$: inefficient

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]

$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + 3Hn_\chi = -\langle\sigma v\rangle_{\mathrm{ann}}\left(n_\chi^2 - n_\chi^{\mathrm{eq}\,2}\right)$$

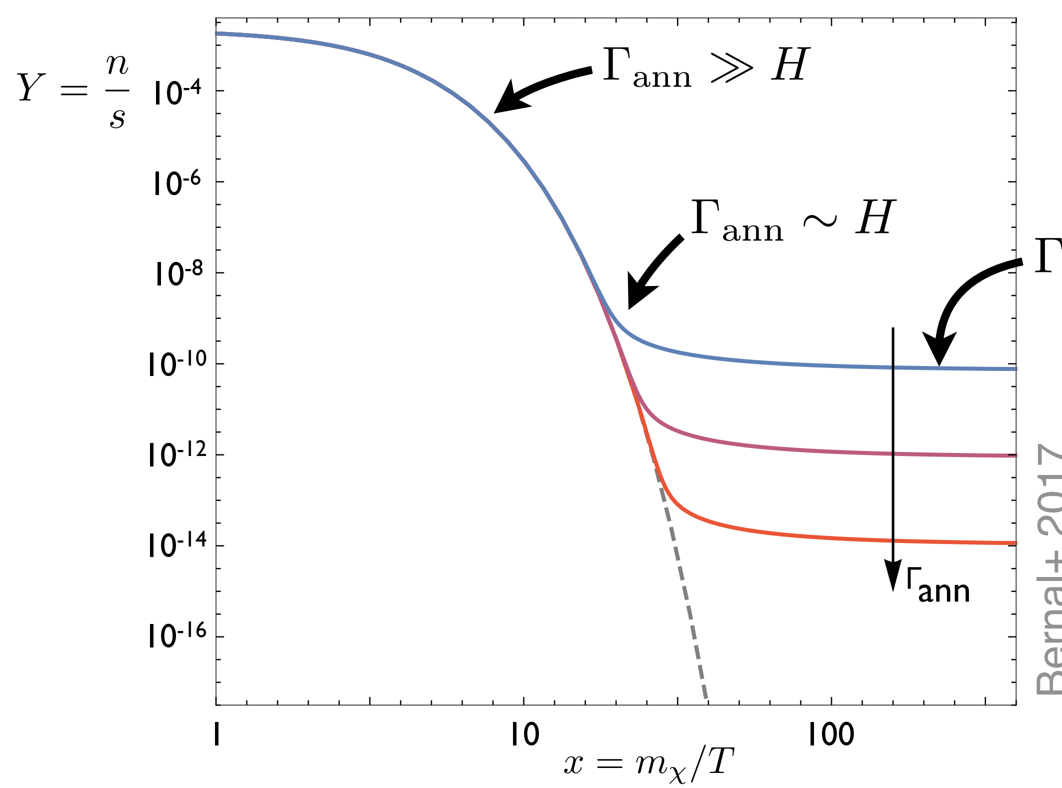


$$\Gamma_{\mathrm{ann}} := n_\chi\langle\sigma v\rangle_{\mathrm{ann}}$$

annihilation rate

$\Gamma_{\mathrm{ann}} \gg H$: efficient

$\Gamma_{\mathrm{ann}} \ll H$: inefficient

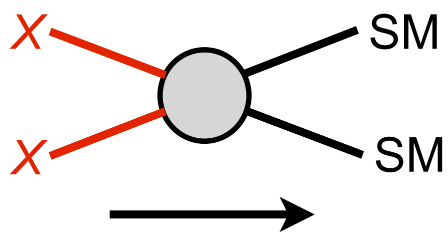


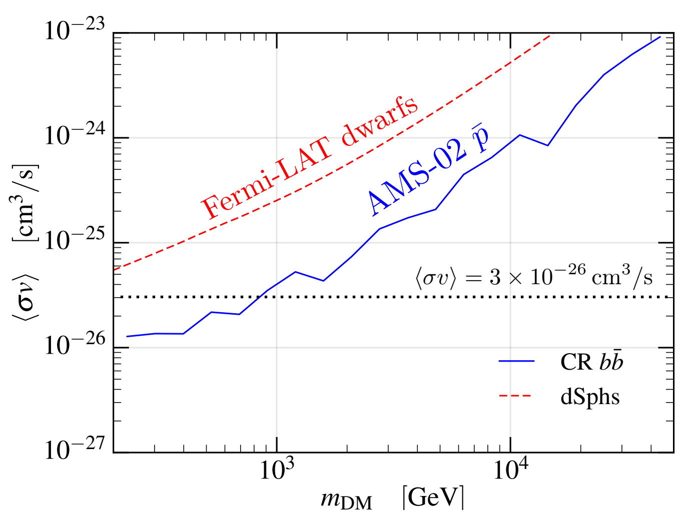
WIMP paradigm attractive:

- Works with simple/natural models ("WIMP miracle")
- Leads to a cold relic
- Independent of largely unconstrained/unknown physics of the very early universe (inflation/reheating)
- Robust predictions
- Testable at collider, direct and indirect detection experiments

WIMP Dark Matter: searches

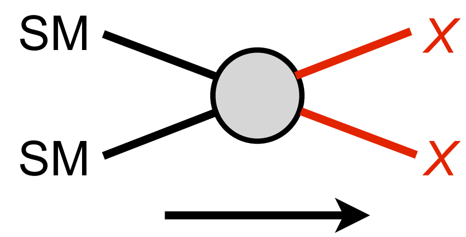
Indirect detection

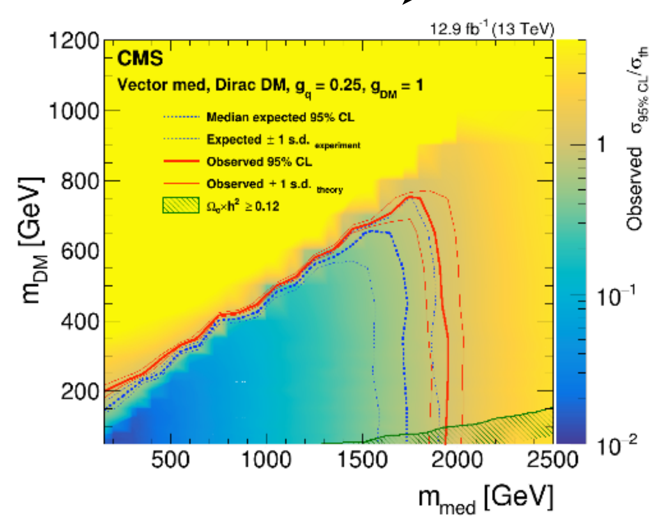




[Cuoco, JH, Korsmeier, Krämer 2017]

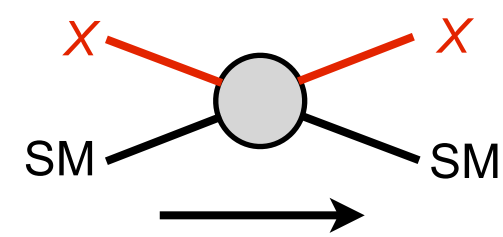
Direct production

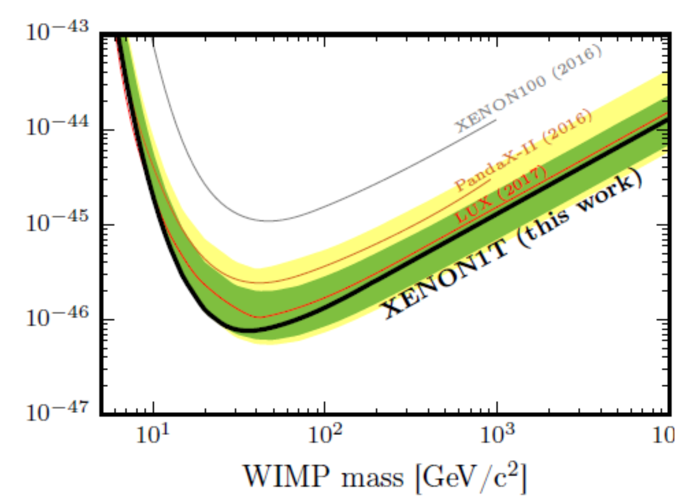




[CMS EXO-16-039]

Direct detection





[Xenon1T 1705.06655]

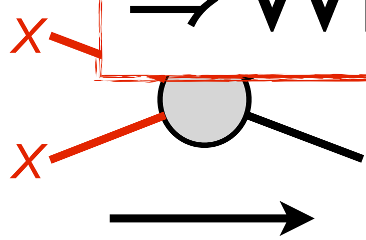
WIMP Dark Matter: searches

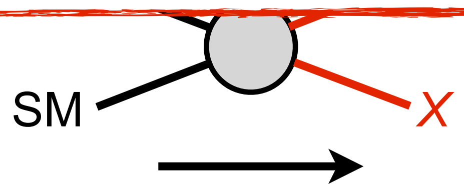
Indirect detection

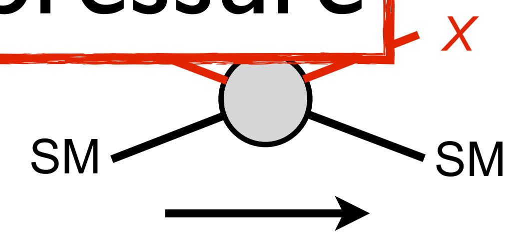
Direct production

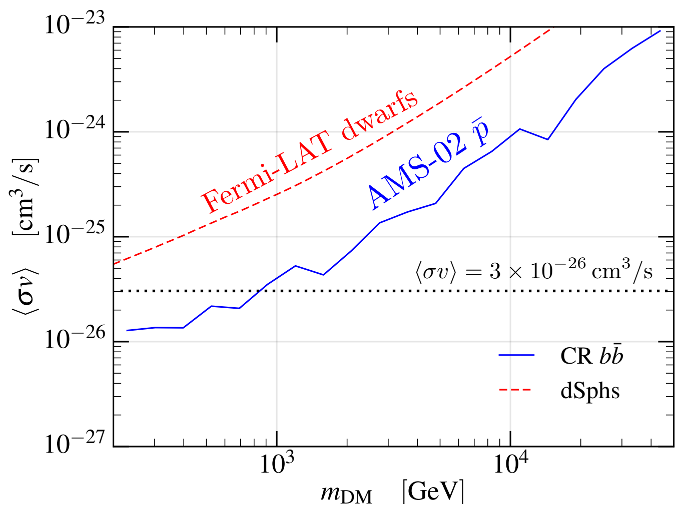
Direct detection

⇒ WIMP dark matter under pressure

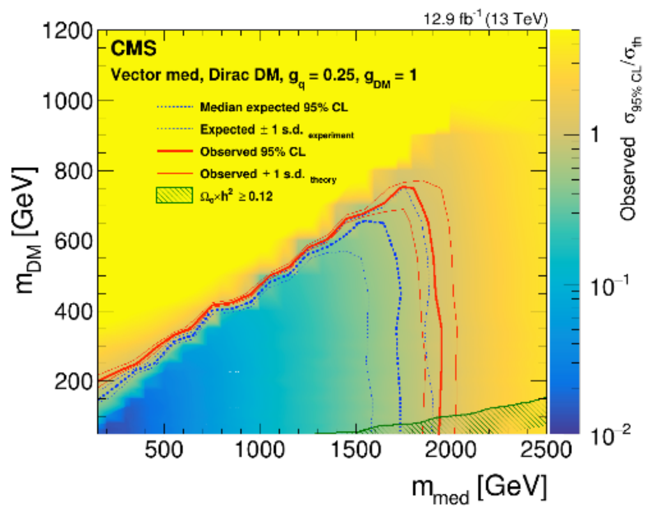




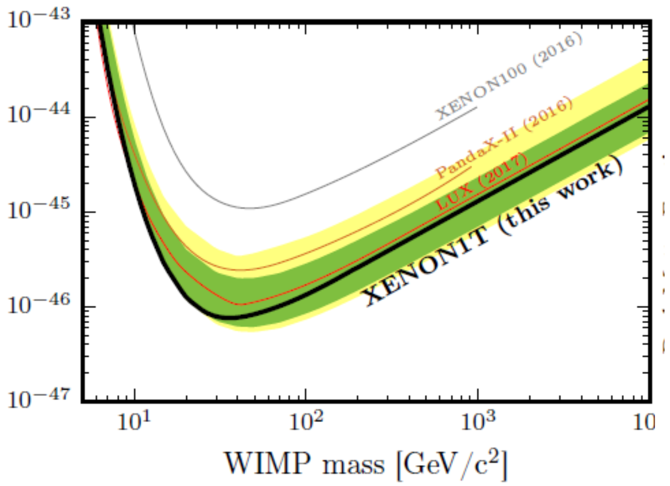




[Cuoco, JH, Korsmeier, Krämer 2017]

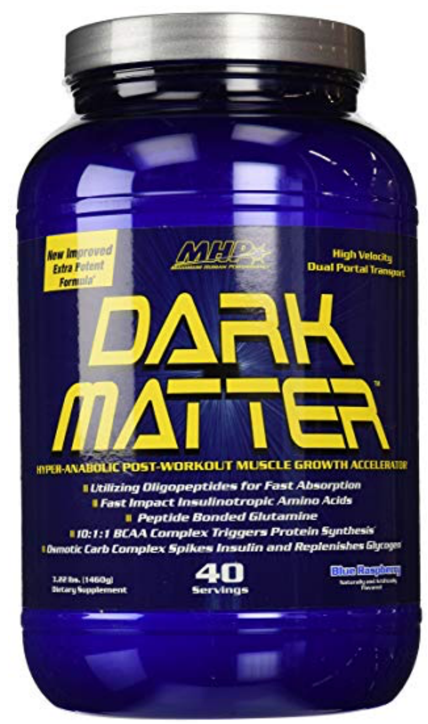


[CMS EXO-16-039]



[Xenon1T 1705.06655]

Dark matter beyond WIMPs

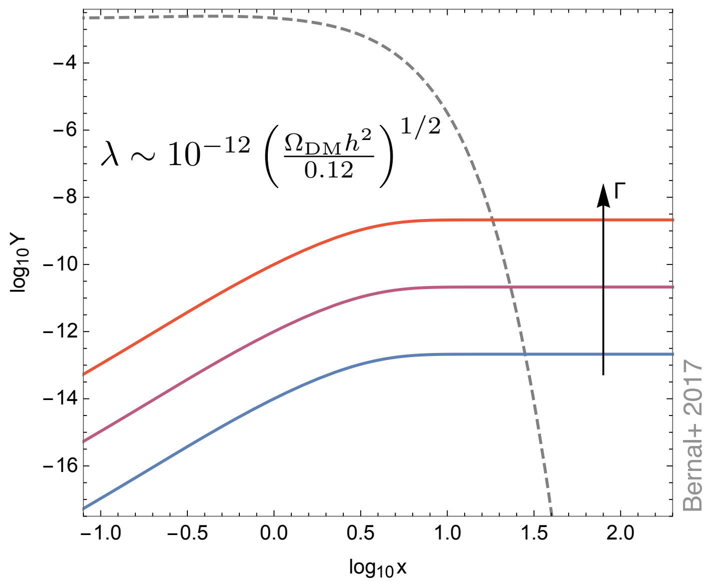


Thermal relics beyond WIMPs

- Non-thermalized dark matter:

Freeze-in scenario

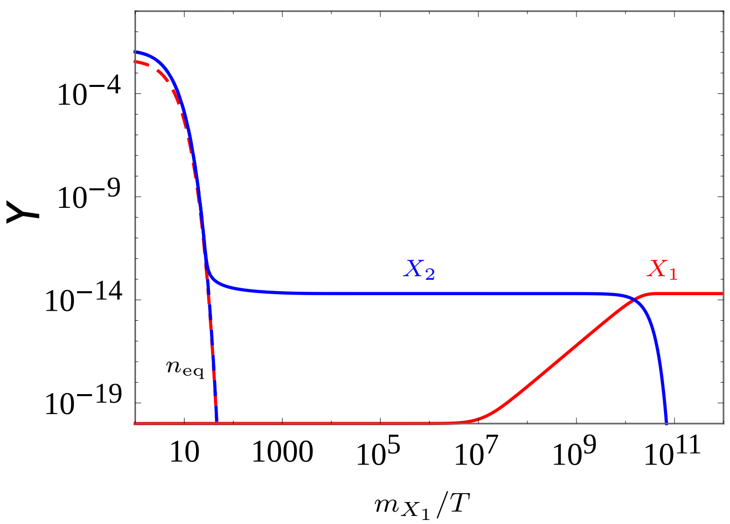
[McDonald 2002; Choi, Roszkowski 2005; Petraki, Kusenko 2008; Hall, Jedamzik, March-Russell, West, 2009]



SuperWIMP scenario

[Feng, Rajaraman, Takayama 2003]

DM production from decay of heavier thermal relic:



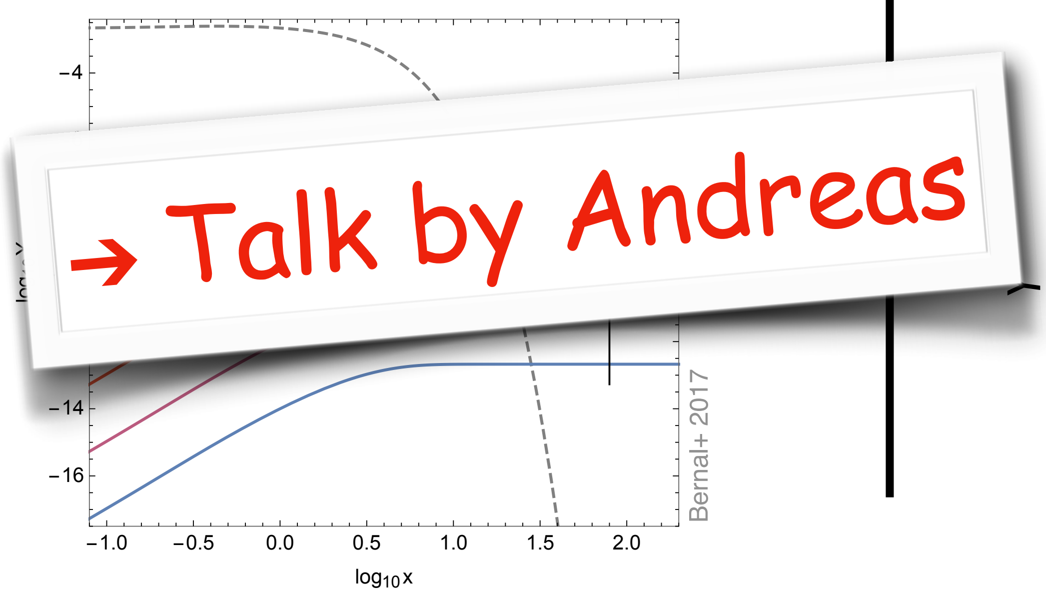
- Thermalized dark matter, but very small couplings
  How is that?

Thermal relics beyond WIMPs

- Non-thermalized dark matter:

Freeze-in scenario

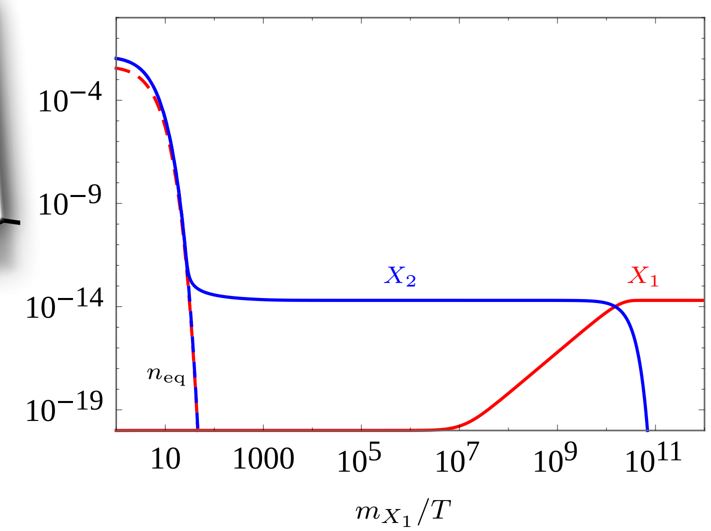
[McDonald 2002; Choi, Roszkowski 2005; Petraki, Kusenko 2008; Hall, Jedamzik, March-Russell, West, 2009]



SuperWIMP scenario

[Feng, Rajaraman, Takayama 2003]

DM production from decay of heavier thermal relic:



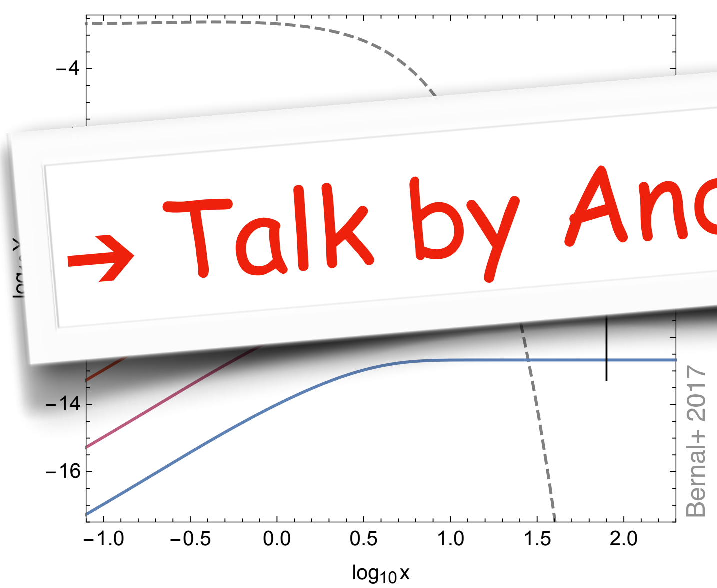
- Thermalized dark matter, but very small couplings
  How is that?

Thermal relics beyond WIMPs

- Non-thermalized dark matter:

Freeze-in scenario

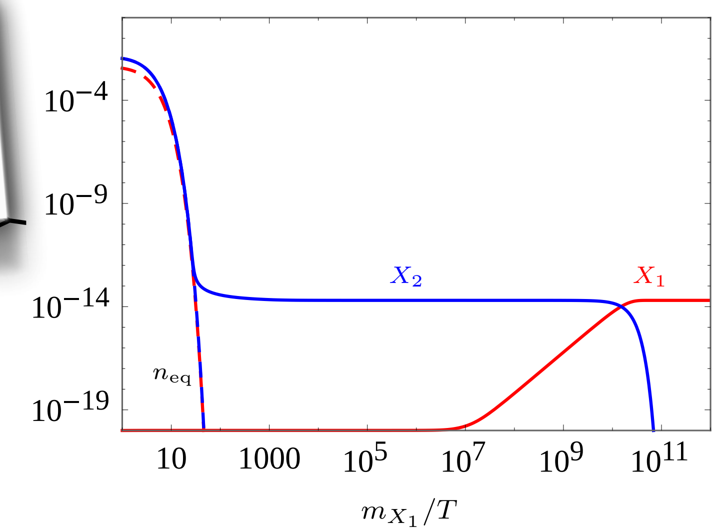
[McDonald 2002; Choi, Roszkowski 2005; Petraki, Kusenko 2008; Hall, Jedamzik, March-Russell, West, 2009]



SuperWIMP scenario

[Feng, Rajaraman, Takayama 2003]

DM production from decay of heavier thermal relic:



- Thermalized dark matter, but very small couplings
  How is that?

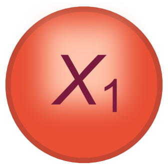
→ Conversion-driven freeze-out

[Garny, JH, Lülf, Vogl 2017]

[see also D’Agnolo, Pappadopulo, Ruderman, 2017]

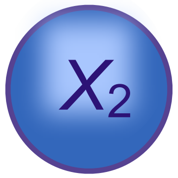
Revisiting WIMP co-annihilation

[Griest, Seckel 1991; Edsjo, Gondolo 1997]

dark matter 

λ_1

$m_1 < m_2$

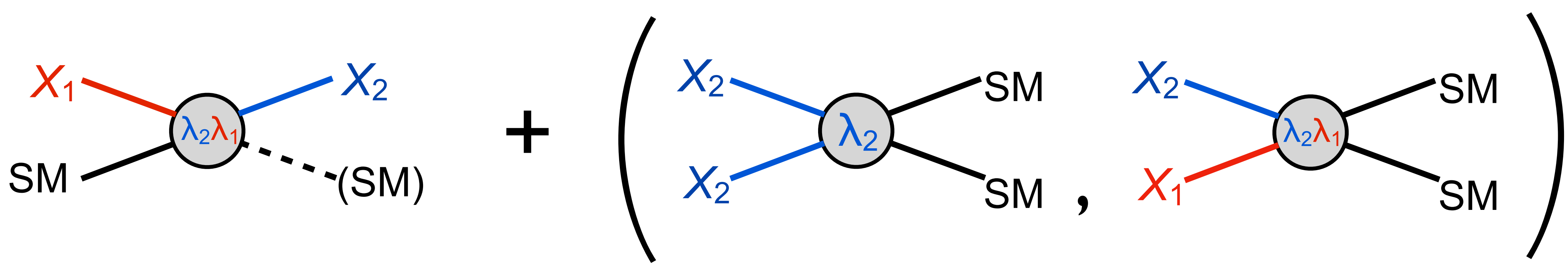


co-annihilation partner
λ_2

$$\frac{n_2^{\mathrm{eq}}}{n_1^{\mathrm{eq}}} \propto \mathrm{e}^{-\Delta m/T_{\mathrm{f}}}\,, \quad \Delta m \lesssim 0.1\, m_{1,2} \;:$$

Conversion
$X_1 \to X_2$

Co-annihilation
$X_2 \to$ SM

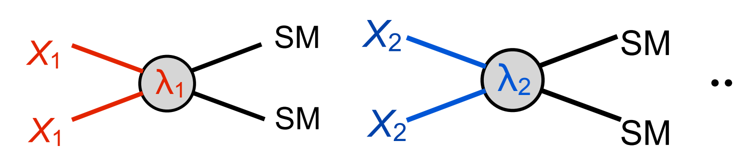


Revisiting WIMP co-annihilation

[Griest, Seckel 1991; Edsjo, Gondolo 1997]

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



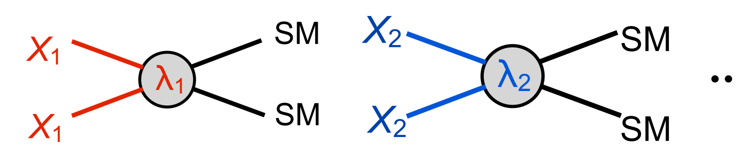
Revisiting WIMP co-annihilation

[Griest, Seckel 1991; Edsjo, Gondolo 1997]

Coupled set of Boltzmann equations:

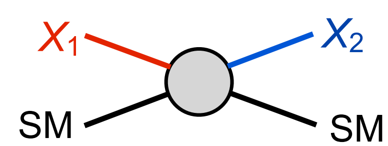
$$\frac{\mathrm{d}n_i}{\mathrm{d}t} + 3Hn_i = -\sum_{j=1}^{N} \langle \sigma_{ij} v_{ij} \rangle \left(n_i n_j - n_i^{\mathrm{eq}} n_j^{\mathrm{eq}} \right)$$

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)

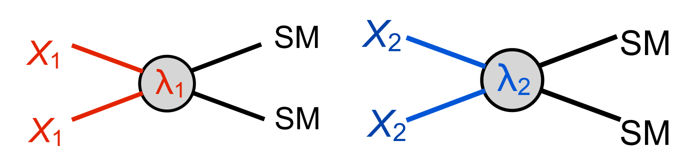


Revisiting WIMP co-annihilation

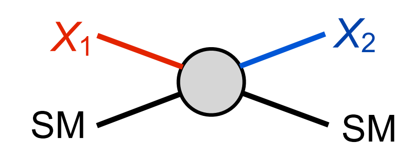
[Griest, Seckel 1991; Edsjo, Gondolo 1997]

Coupled set of Boltzmann equations:

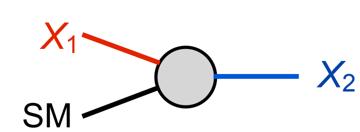
$$\frac{\mathrm{d}n_i}{\mathrm{d}t} + 3Hn_i = -\sum_{j=1}^{N} \langle \sigma_{ij} v_{ij} \rangle \left(n_i n_j - n_i^{\mathrm{eq}} n_j^{\mathrm{eq}} \right)$$ annihilations



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



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

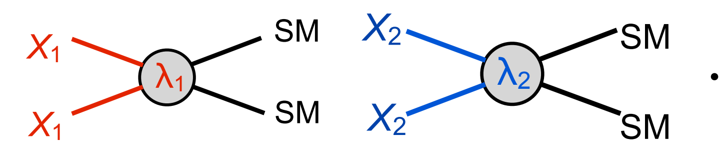


Revisiting WIMP co-annihilation

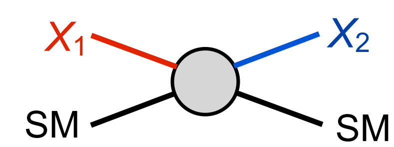
[Griest, Seckel 1991; Edsjo, Gondolo 1997]

Coupled set of Boltzmann equations:

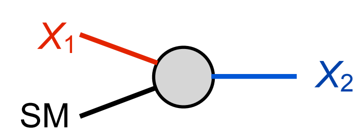
$$\frac{\mathrm{d}n_i}{\mathrm{d}t} + 3Hn_i = -\sum_{j=1}^{N} \langle \sigma_{ij} v_{ij} \rangle \left(n_i n_j - n_i^{\mathrm{eq}} n_j^{\mathrm{eq}} \right) \quad \text{annihilations}$$



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



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



Usually (e.g. SUSY): $\lambda_1 \sim \lambda_2 \sim g_{\mathrm{SM}}$ $\Rightarrow$ conversions always efficient

- Drives solutions into chemical equilibrium in dark sector, i.e.

$$\frac{n_i}{n_j} = \frac{n_i^{\mathrm{eq}}}{n_j^{\mathrm{eq}}}$$

Revisiting WIMP co-annihilation

[Griest, Seckel 1991; Edsjo, Gondolo 1997]

Assumption of chemical equilibrium

⇒ reduction to single, uncoupled Boltzmann equation*:

$$\frac{\mathrm{d}n}{\mathrm{d}t} + 3Hn = -\langle\sigma v\rangle_{\mathrm{eff}} \left(n^2 - n_{\mathrm{eq}}^2\right)$$

$n := \sum_i n_i$ entire dark sector

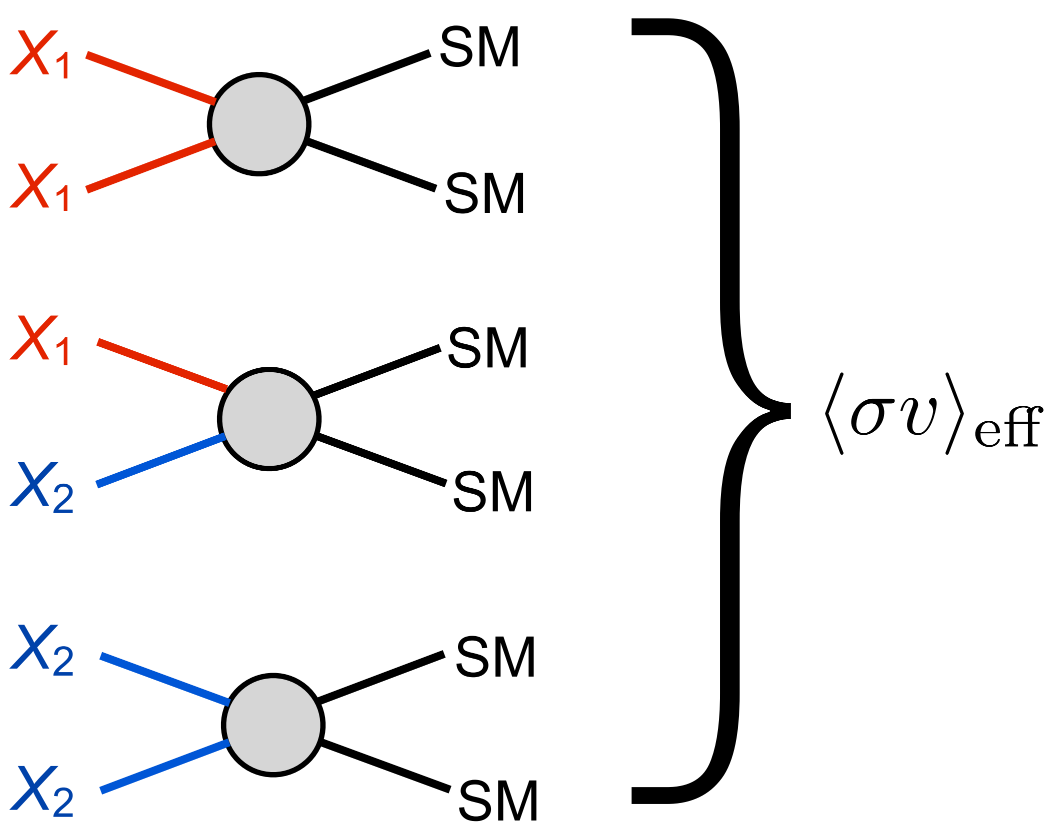
$\langle\sigma v\rangle_{\mathrm{eff}}$ effective dark sector annihilation

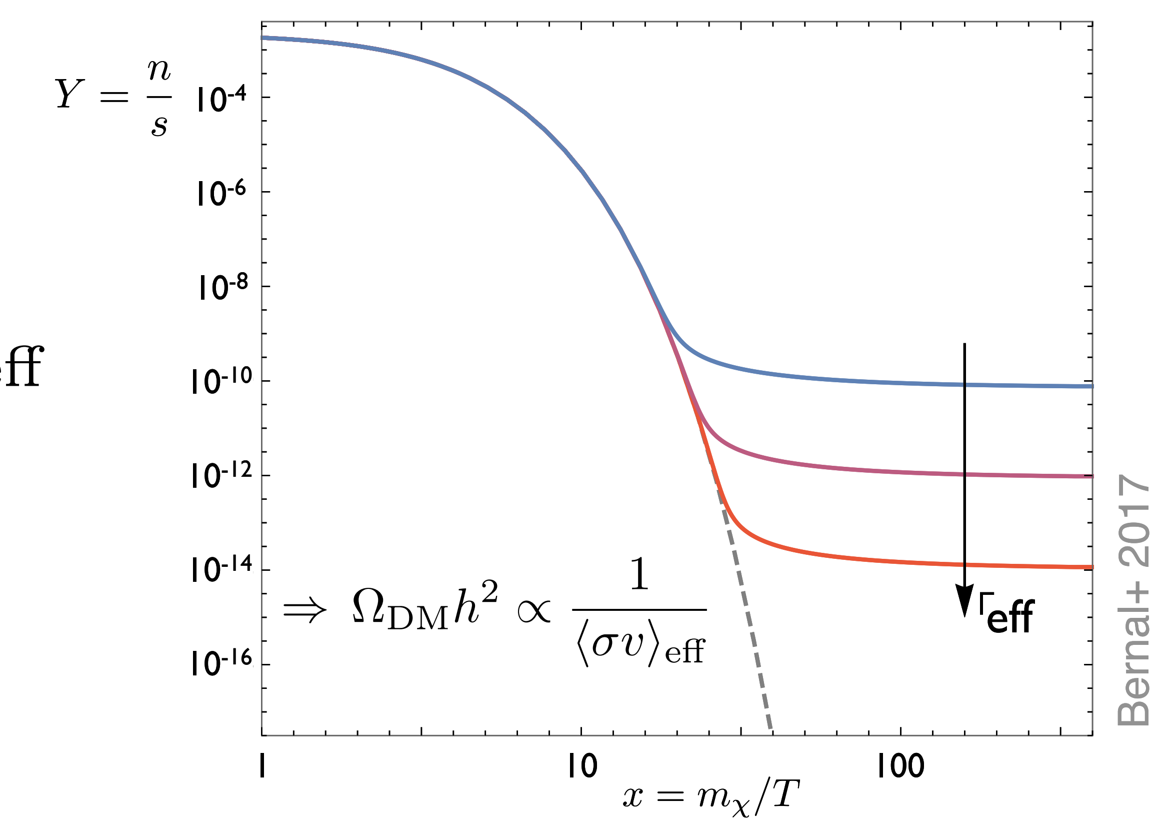
*) Solved by numerical tools [MadDM, DarkSUSY, micrOMEGAs]

Revisiting WIMP co-annihilation

[Griest, Seckel 1991; Edsjo, Gondolo 1997]

$$\langle \sigma v \rangle_{\rm eff} = \sum_{i,j} \langle \sigma v \rangle_{i,j} \frac{n_i^{\rm eq}}{n^{\rm eq}} \frac{n_j^{\rm eq}}{n^{\rm eq}}$$

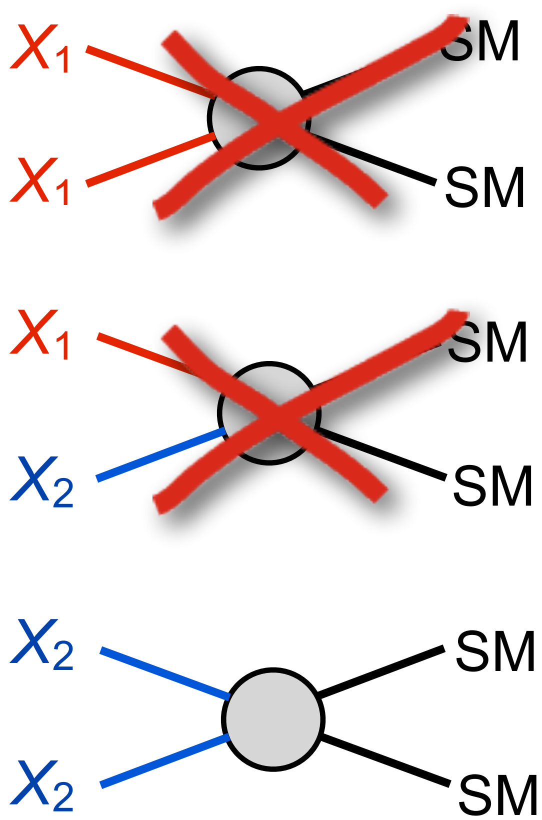




Small dark matter couplings

$$\langle \sigma v \rangle_{\rm eff} = \sum_{i,j} \langle \sigma v \rangle_{i,j} \frac{n_i^{\rm eq}}{n^{\rm eq}} \frac{n_j^{\rm eq}}{n^{\rm eq}} \simeq \langle \sigma v \rangle_{22} \frac{n_2^{\rm eq}}{n^{\rm eq}} \frac{n_2^{\rm eq}}{n^{\rm eq}}$$

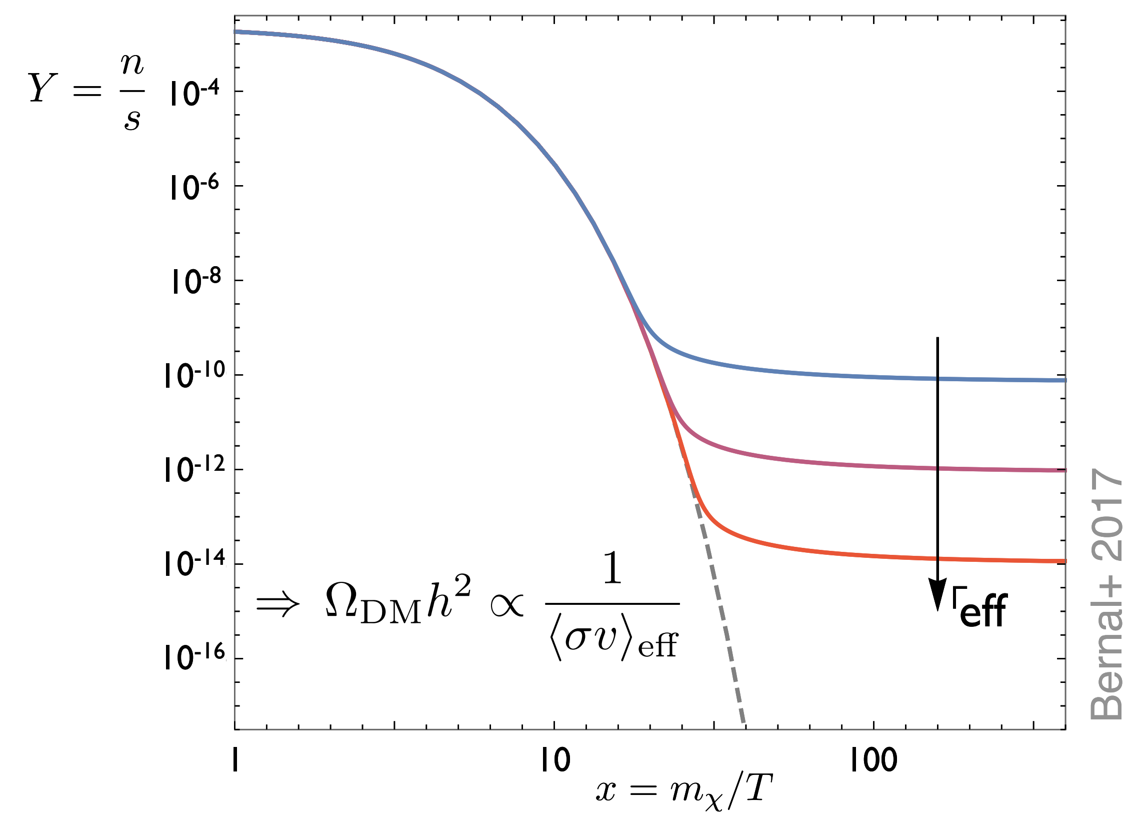
$\lambda_1 \ll \lambda_2$



$\propto \lambda_1^2$

$\propto \lambda_1 \lambda_2$

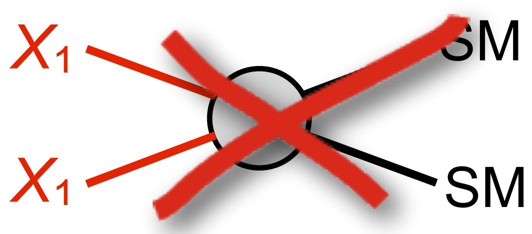
$\propto \lambda_2^2$



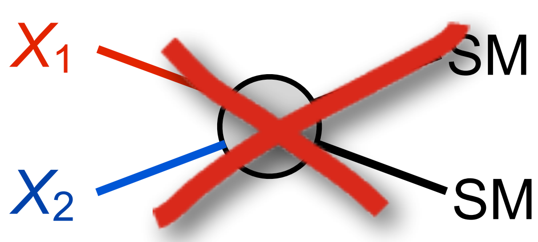
Small dark matter couplings

$$\langle \sigma v \rangle_{\text{eff}} = \sum_{i,j} \langle \sigma v \rangle_{i,j} \frac{n_i^{\text{eq}}}{n^{\text{eq}}} \frac{n_j^{\text{eq}}}{n^{\text{eq}}} \simeq \langle \sigma v \rangle_{22} \frac{n_2^{\text{eq}}}{n^{\text{eq}}} \frac{n_2^{\text{eq}}}{n^{\text{eq}}}$$

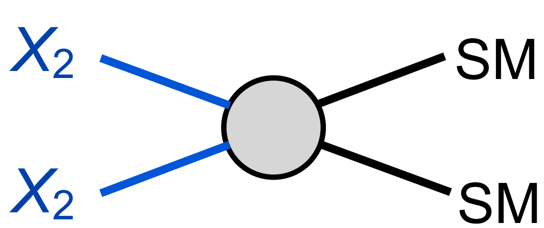
$$\lambda_1 \ll \lambda_2$$



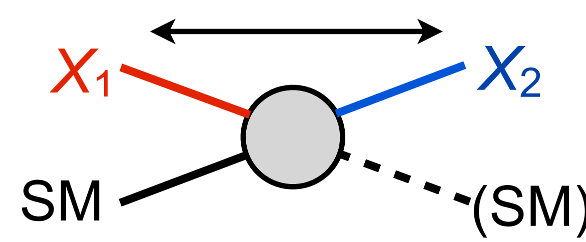
$\propto \lambda_1^2$



$\propto \lambda_1 \lambda_2$



$\propto \lambda_2^2$



$\propto \lambda_1 \lambda_2$

conversions efficient $\Gamma \gg H$

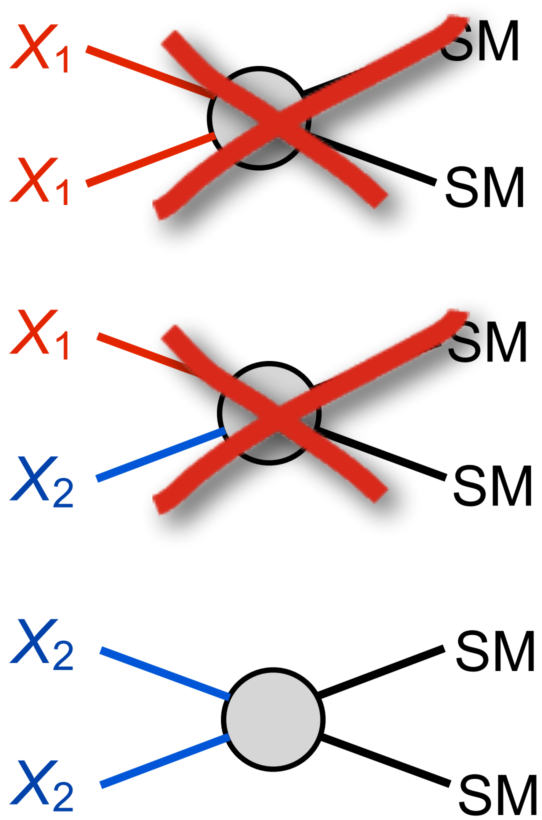
$$\Rightarrow \frac{n_1}{n_1^{\text{eq}}} = \frac{n_2}{n_2^{\text{eq}}}$$

Even smaller dark matter couplings

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

$$\langle \sigma v \rangle_{\text{eff}} = \sum_{i,j} \langle \sigma v \rangle_{i,j} \frac{n_i^{\text{eq}}}{n^{\text{eq}}} \frac{n_j^{\text{eq}}}{n^{\text{eq}}} \simeq \langle \sigma v \rangle_{22} \frac{n_2^{\text{eq}}}{n^{\text{eq}}} \frac{n_2^{\text{eq}}}{n^{\text{eq}}}$$

$$\lambda_1 \ll \lambda_2$$

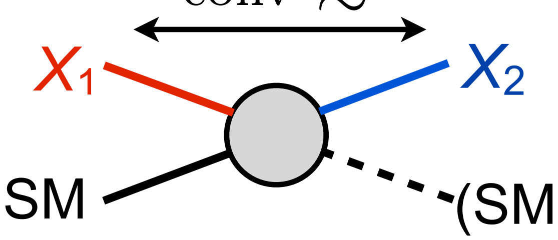


$\propto \lambda_1^2$

$\propto \lambda_1 \lambda_2$

$\propto \lambda_2^2$

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



$\propto \lambda_1 \lambda_2$

conversions become inefficient

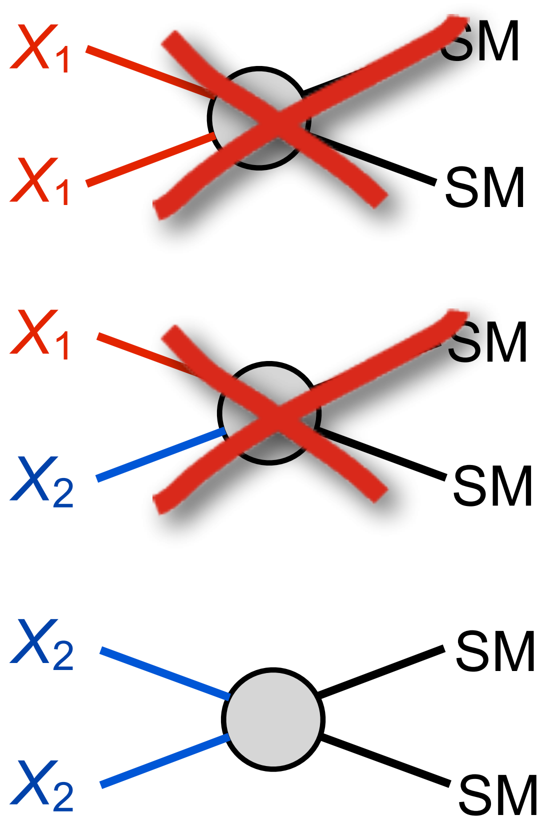
$$\Rightarrow \quad \frac{n_1}{n_1^{\text{eq}}} \;\lightning\!\!=\; \frac{n_2}{n_2^{\text{eq}}}$$

Even smaller dark matter couplings

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

$$\langle\sigma v\rangle_{\rm eff} = \sum_{i,j}\langle\sigma v\rangle_{i,j}\frac{n_i^{\rm eq}}{n^{\rm eq}}\frac{n_j^{\rm eq}}{n^{\rm eq}} \simeq \langle\sigma v\rangle_{22}\frac{n_2^{\rm eq}}{n^{\rm eq}}\frac{n_2^{\rm eq}}{n^{\rm eq}}$$

$$\lambda_1 \ll \lambda_2$$

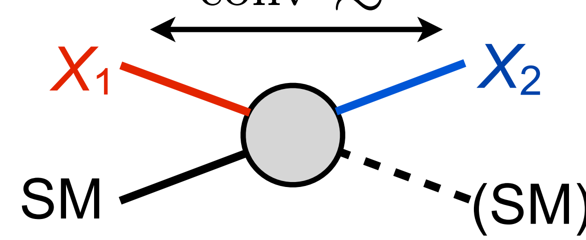


$\propto \lambda_1^2$

$\propto \lambda_1\lambda_2$

$\propto \lambda_2^2$

$\Gamma_{\rm conv} \lesssim H$



$\propto \lambda_1\lambda_2$

conversions become inefficient

$$\Rightarrow \quad \frac{n_1}{n_1^{\rm eq}} \neq \frac{n_2}{n_2^{\rm eq}}$$

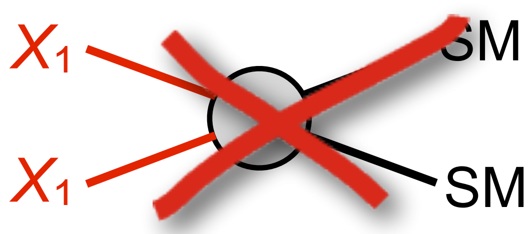
Conversion rate sets relic density!

Even smaller dark matter couplings

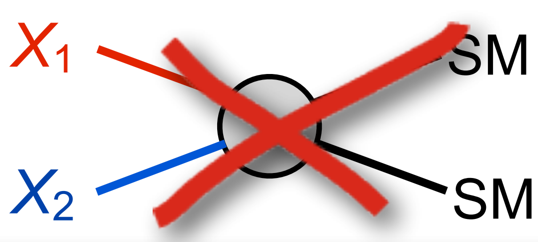
[Garny, JH, Lülf, Vogl 1705.09292; D'Agnolo, Pappadopulo, Ruderman 1705.08450]

$$\langle \sigma v \rangle_{\rm eff} = \sum_{i,j} \langle \sigma v \rangle_{i,j} \frac{n_i^{\rm eq}}{n^{\rm eq}} \frac{n_j^{\rm eq}}{n^{\rm eq}} \simeq \langle \sigma v \rangle_{22} \frac{n_2^{\rm eq}}{n^{\rm eq}} \frac{n_2^{\rm eq}}{n^{\rm eq}}$$

$$\lambda_1 \ll \lambda_2$$

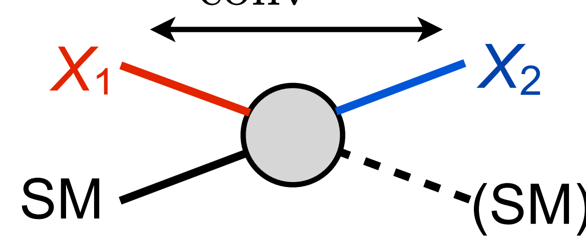


$\propto \lambda_1^2$



$\propto \lambda_1 \lambda_2$

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

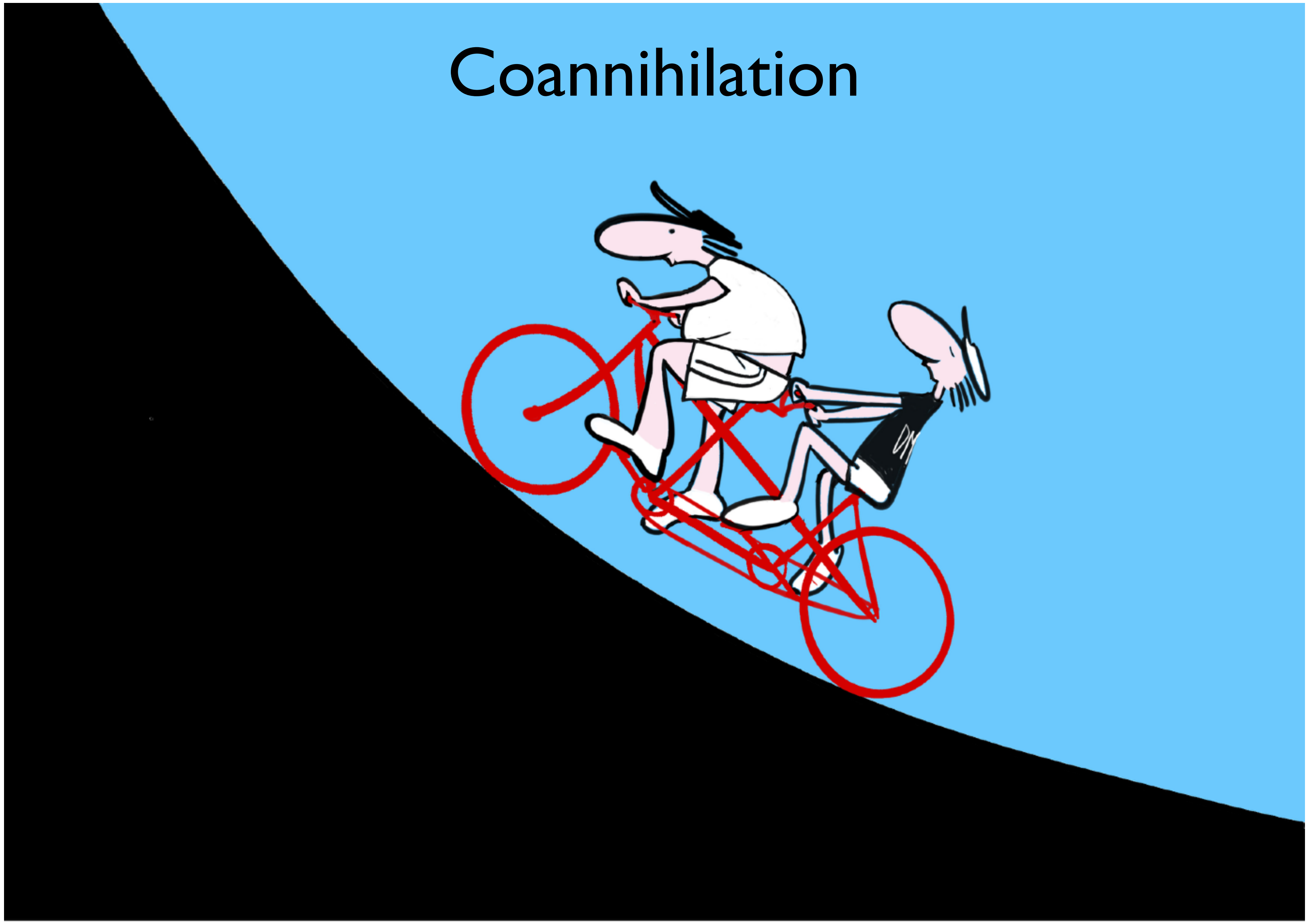


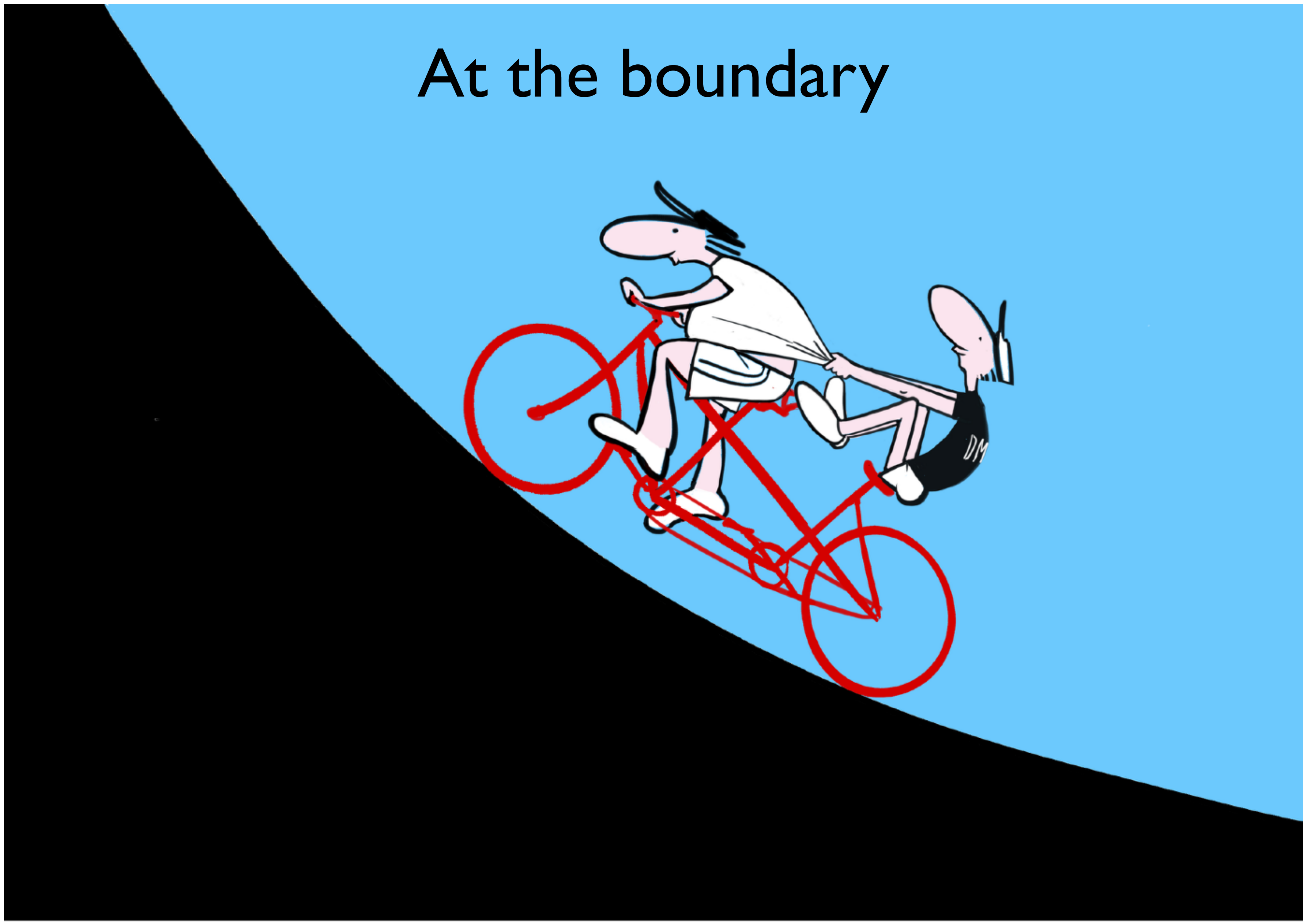
$\propto \lambda_1 \lambda_2$

conversions become inefficient

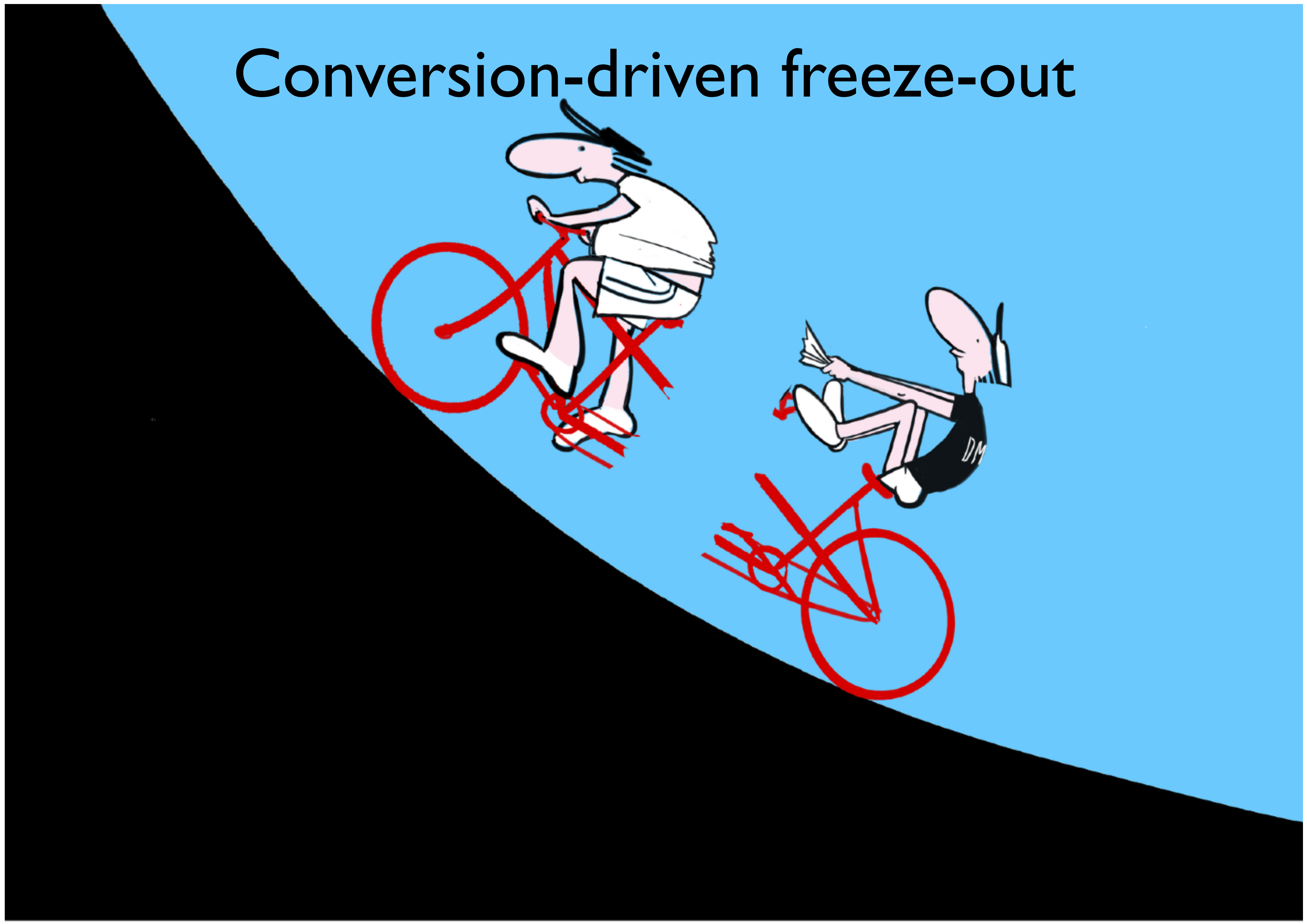
→ Conversion-driven freeze-out

Conversion rate sets relic density!


Coannihilation


At the boundary

Conversion-driven freeze-out



General back-of-the-envelope estimate:

Conversion rate on the edge of being efficient:

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

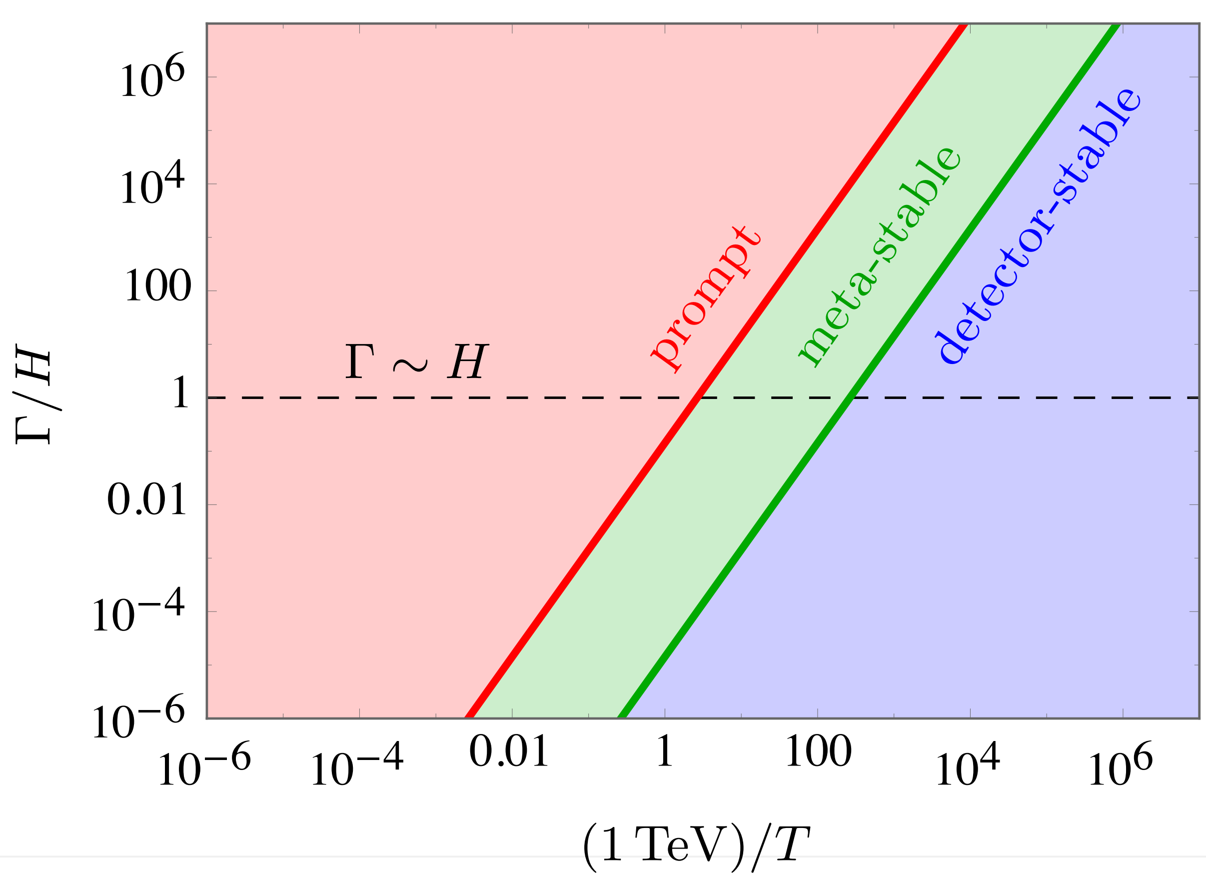
$$\Rightarrow \; \Gamma_{\rm dec} \lesssim H$$

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

$$T \lesssim (10\text{–}100)\,{\rm GeV}$$

⇒ Long-lived particles at LHC!

General back-of-the-envelope estimate:

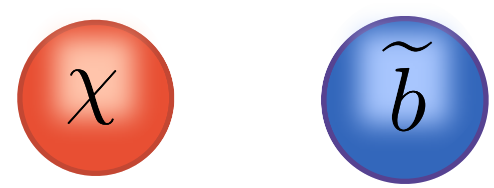


$$T \lesssim (10\text{–}100)\,\text{GeV}$$

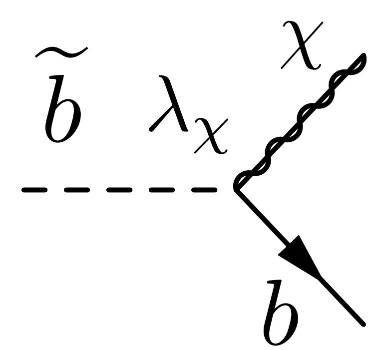
⇒ Long-lived particles at LHC!

An explicit 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:

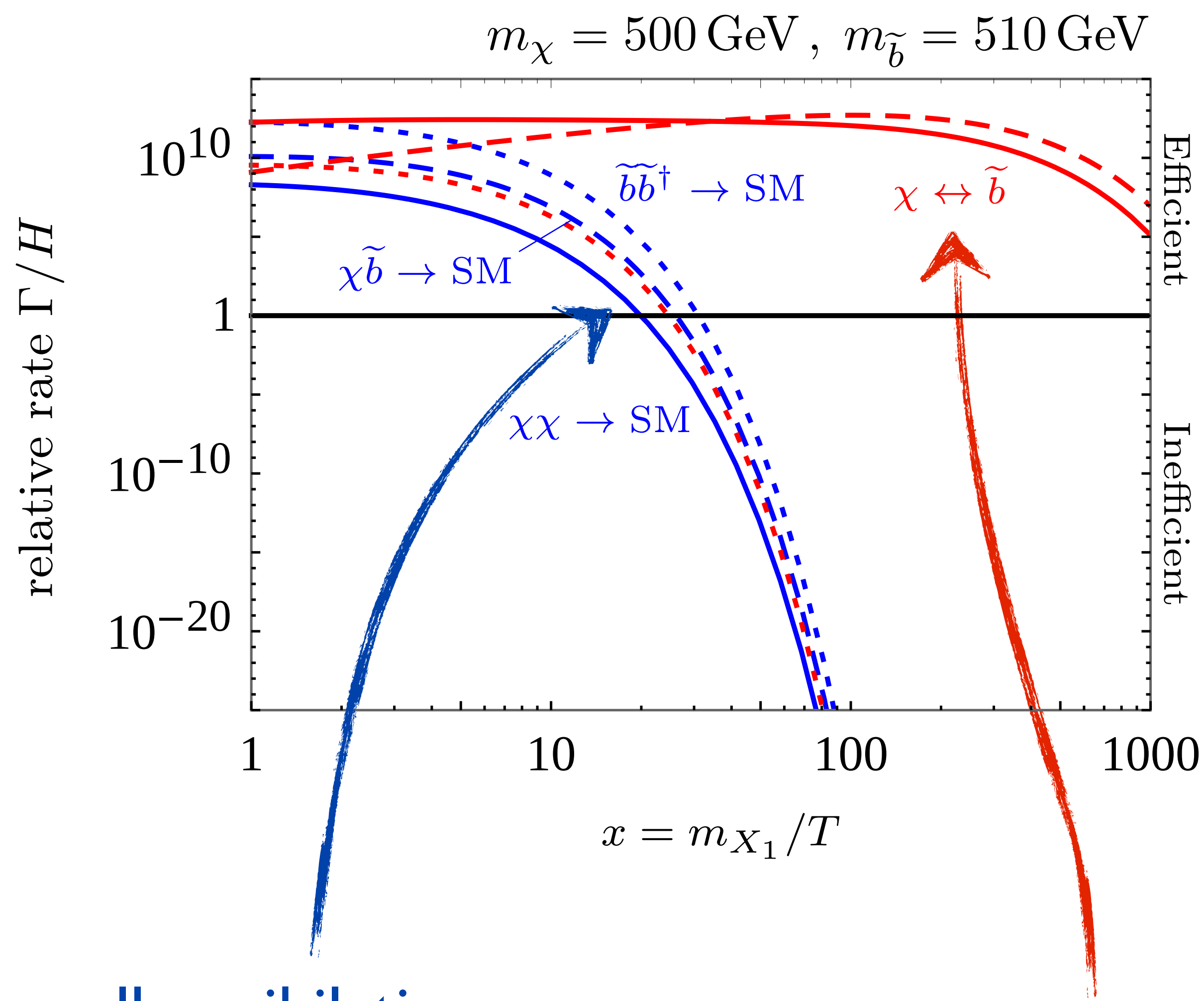


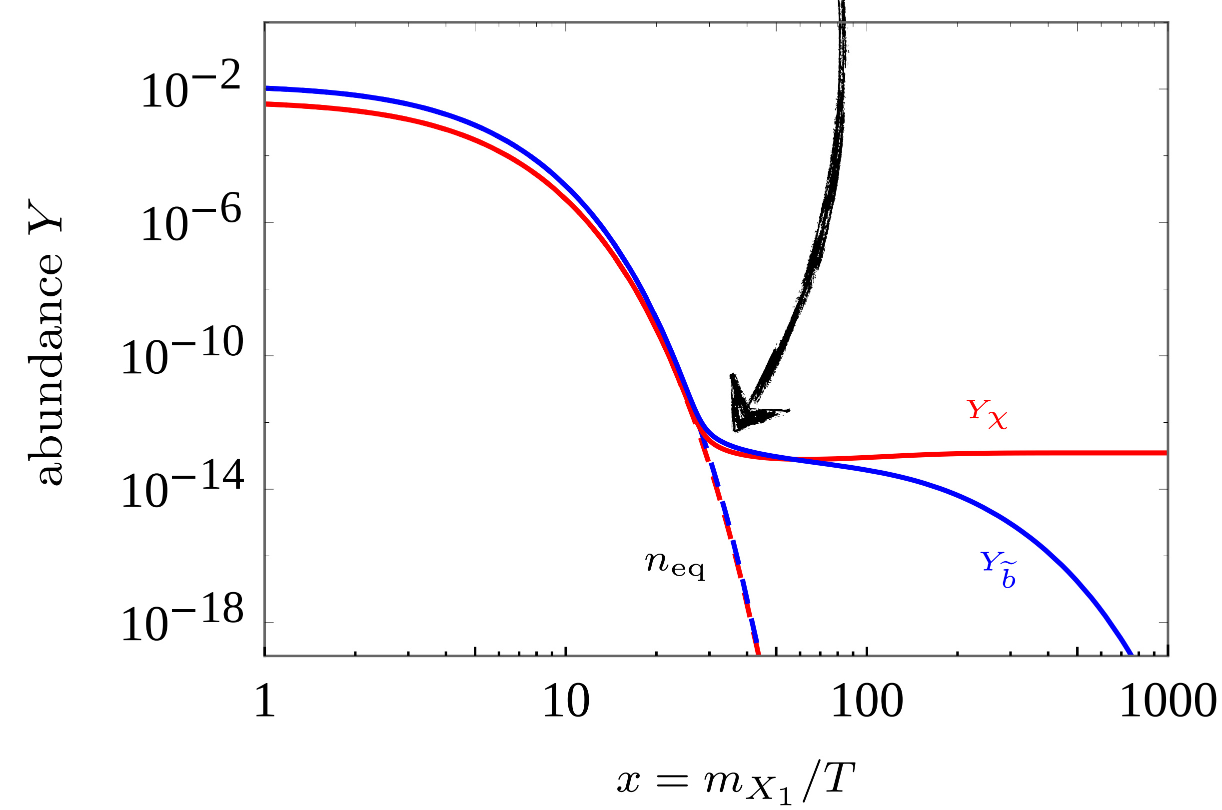
λ_χ is a free parameter here [see Ibarra et al. 2009 for SUSY realization]

Numerical solution of full coupled system

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

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





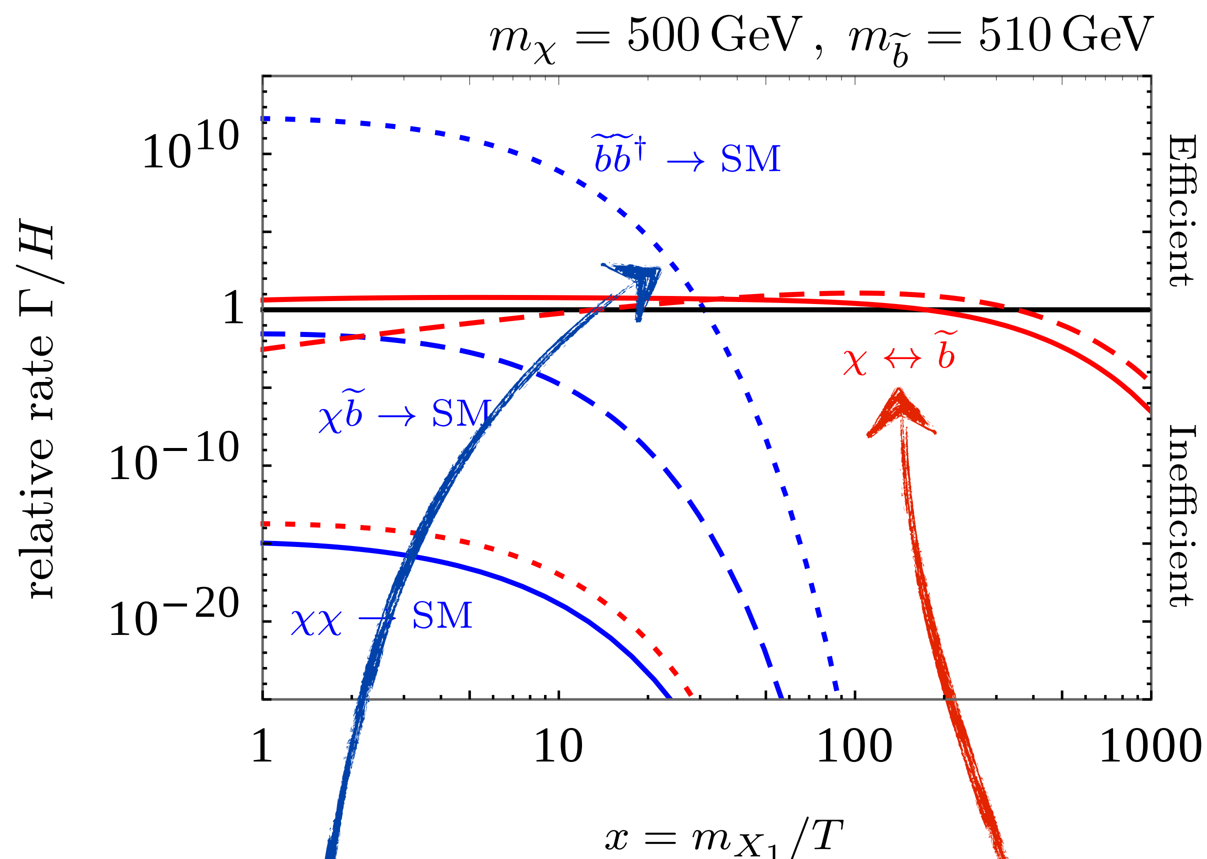
all annihilations contribute

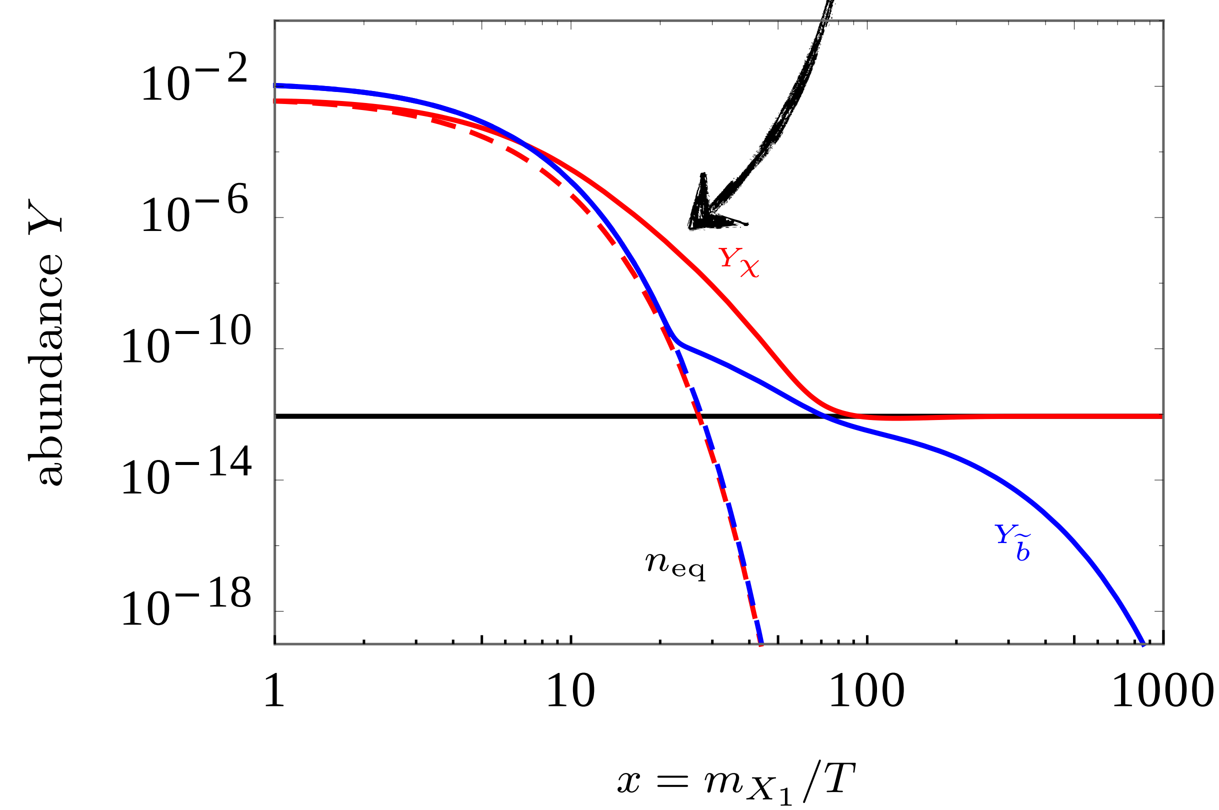
conversion thoroughly efficient

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.)



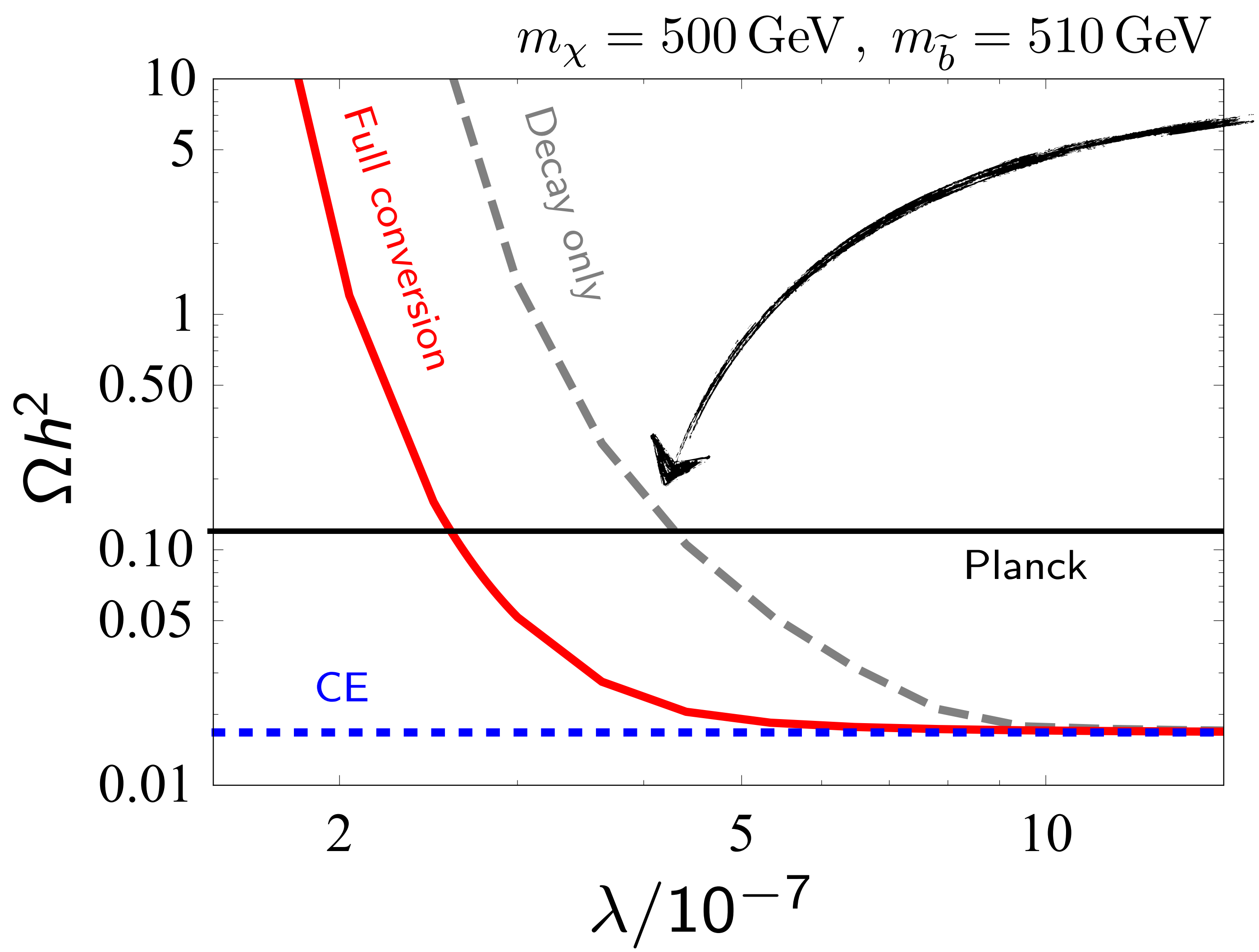


mediator-annihilation contributes only

conversion on the edge of being efficient

Numerical solution of full coupled system

- Scan of the coupling:

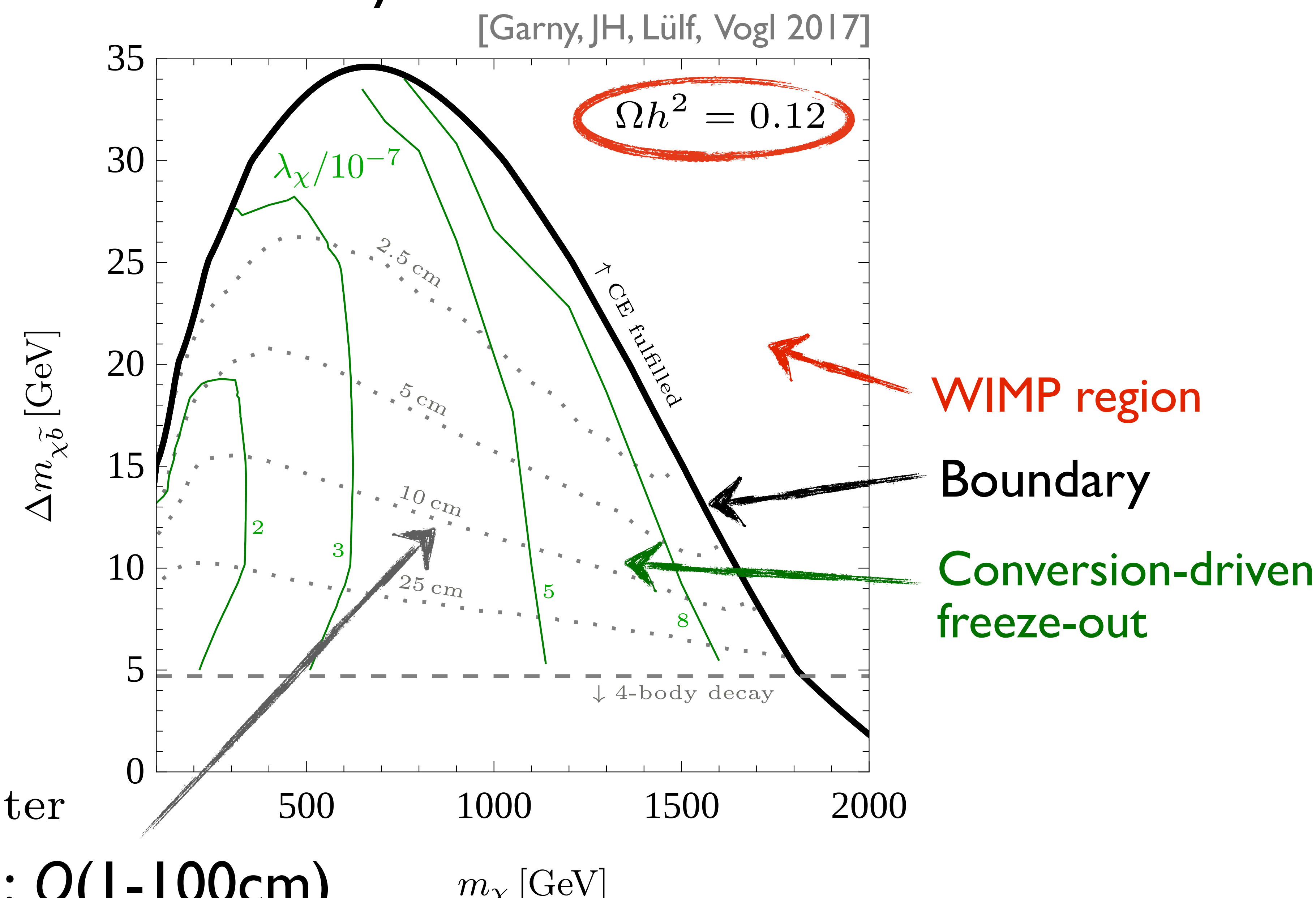


Decay only: similar

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

Allowed parameter space

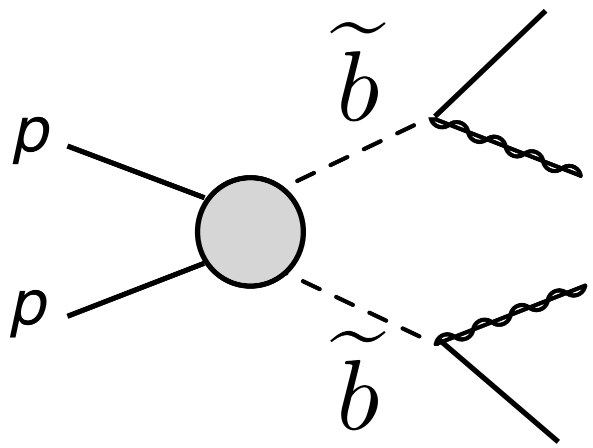
- Require Planck relic density

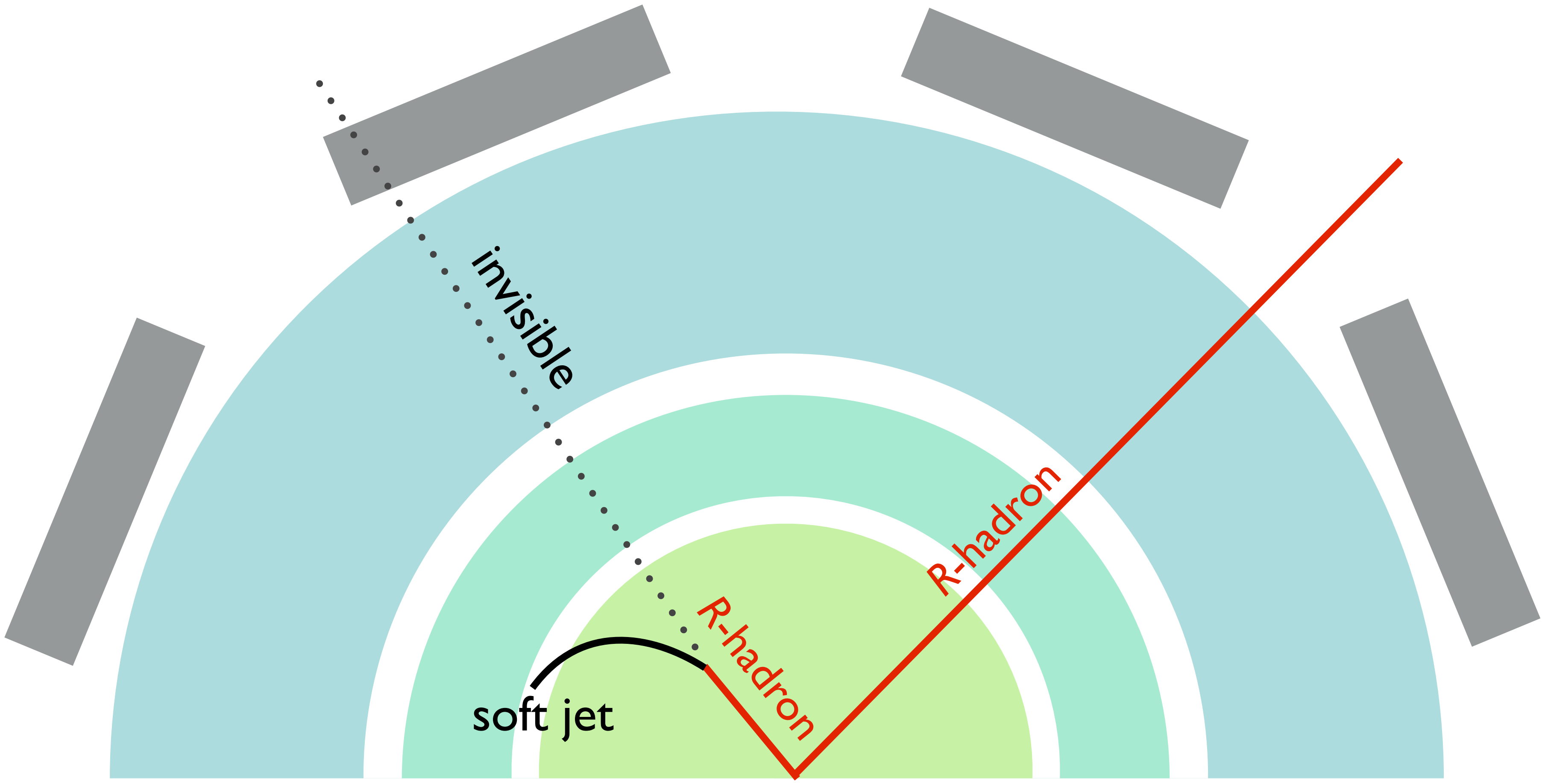


$$\Gamma_{\rm decay} \sim \Gamma_{\rm scatter}$$

⇒ Decay length: O(1-100cm)

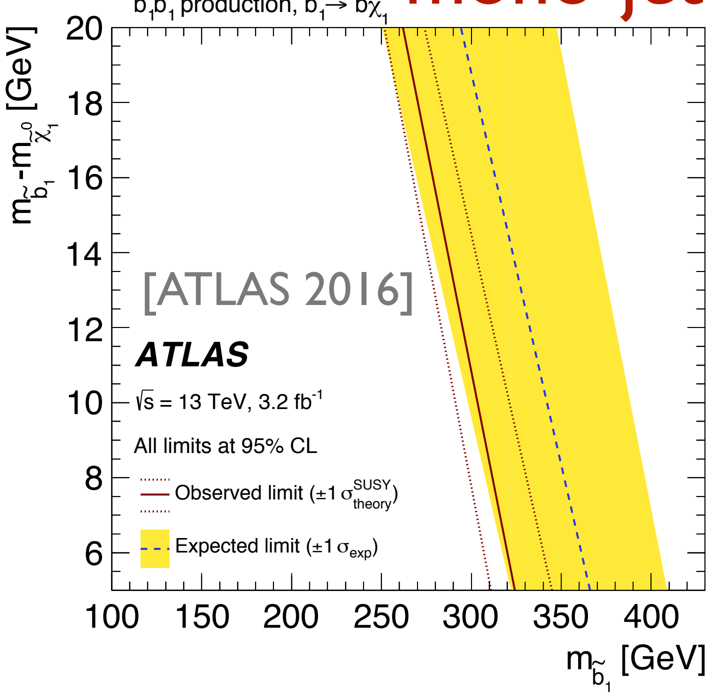
LHC constraints

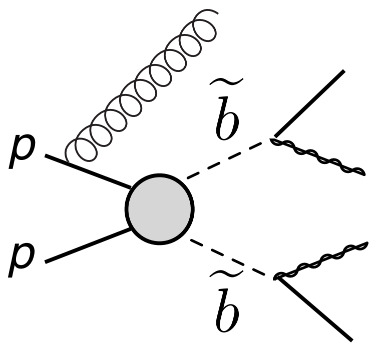


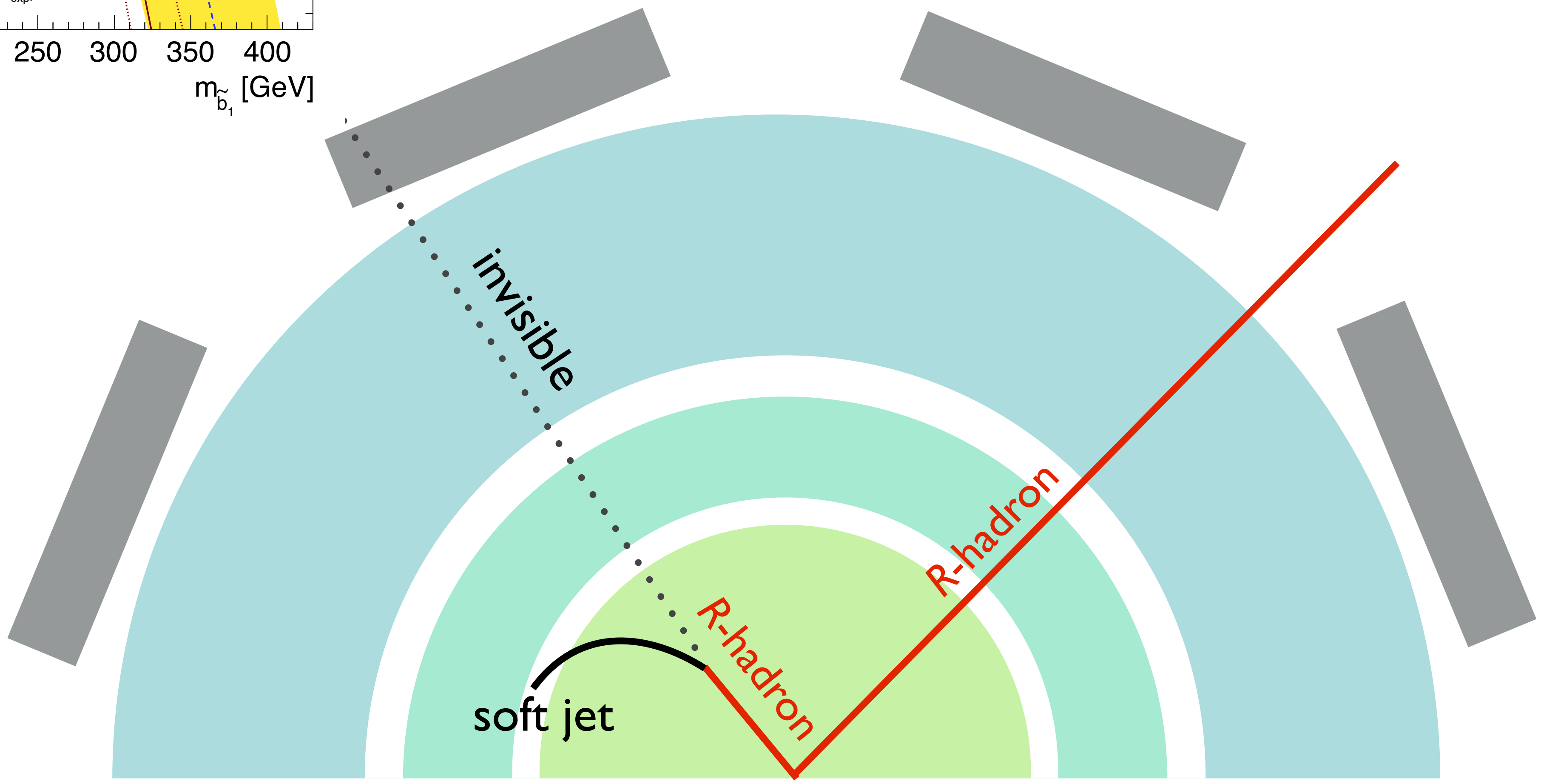


LHC constraints

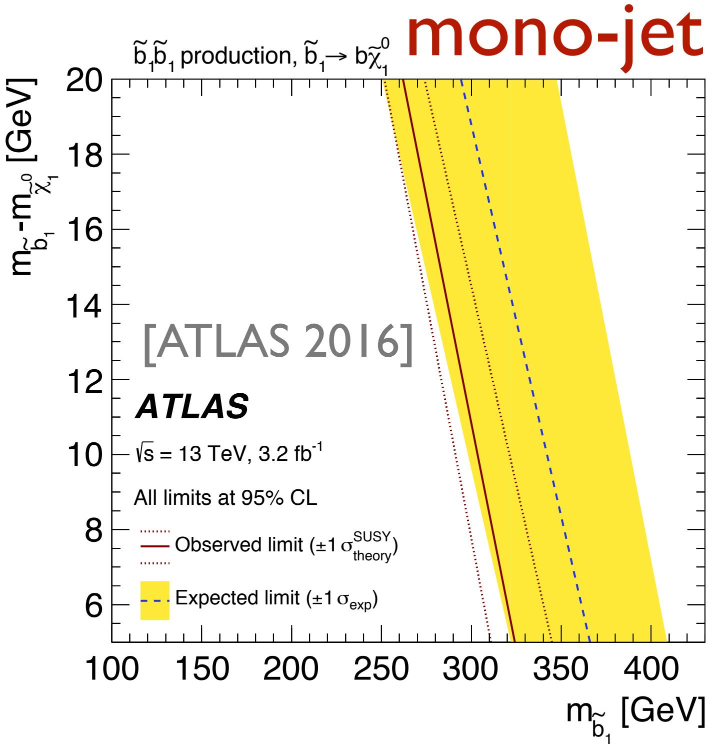
mono-jet

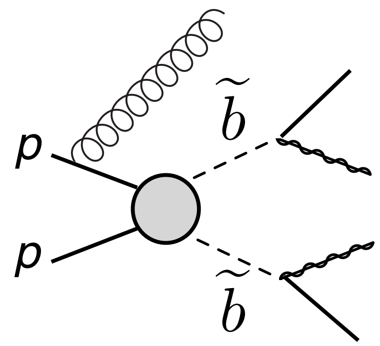


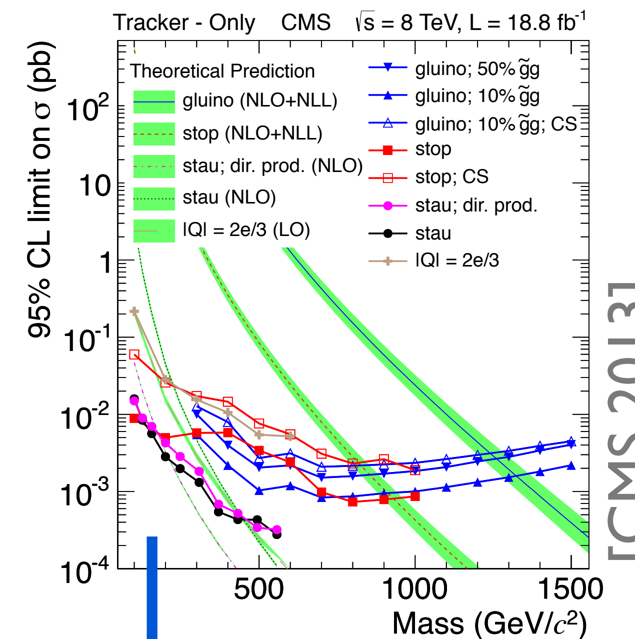




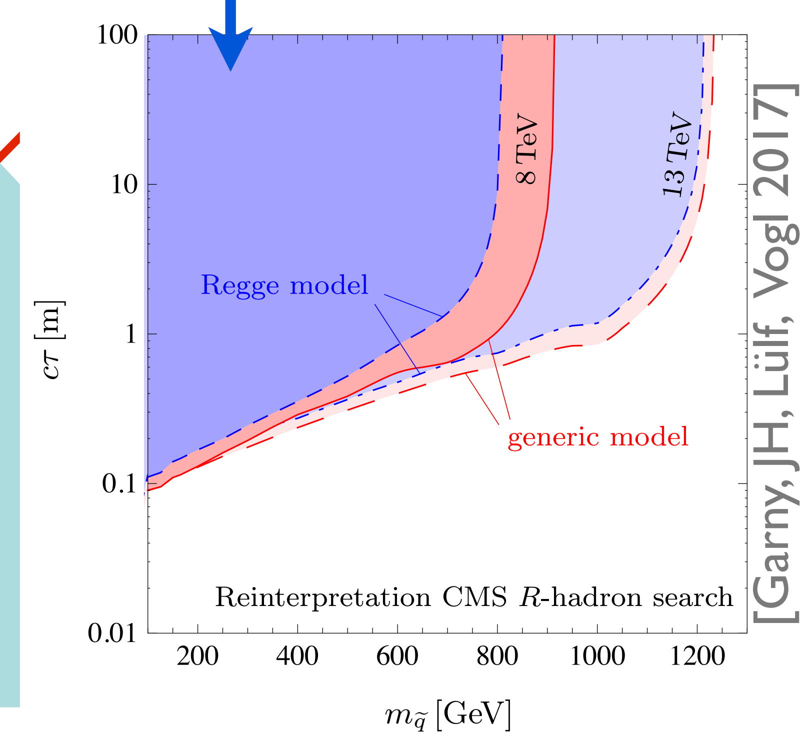
LHC constraints

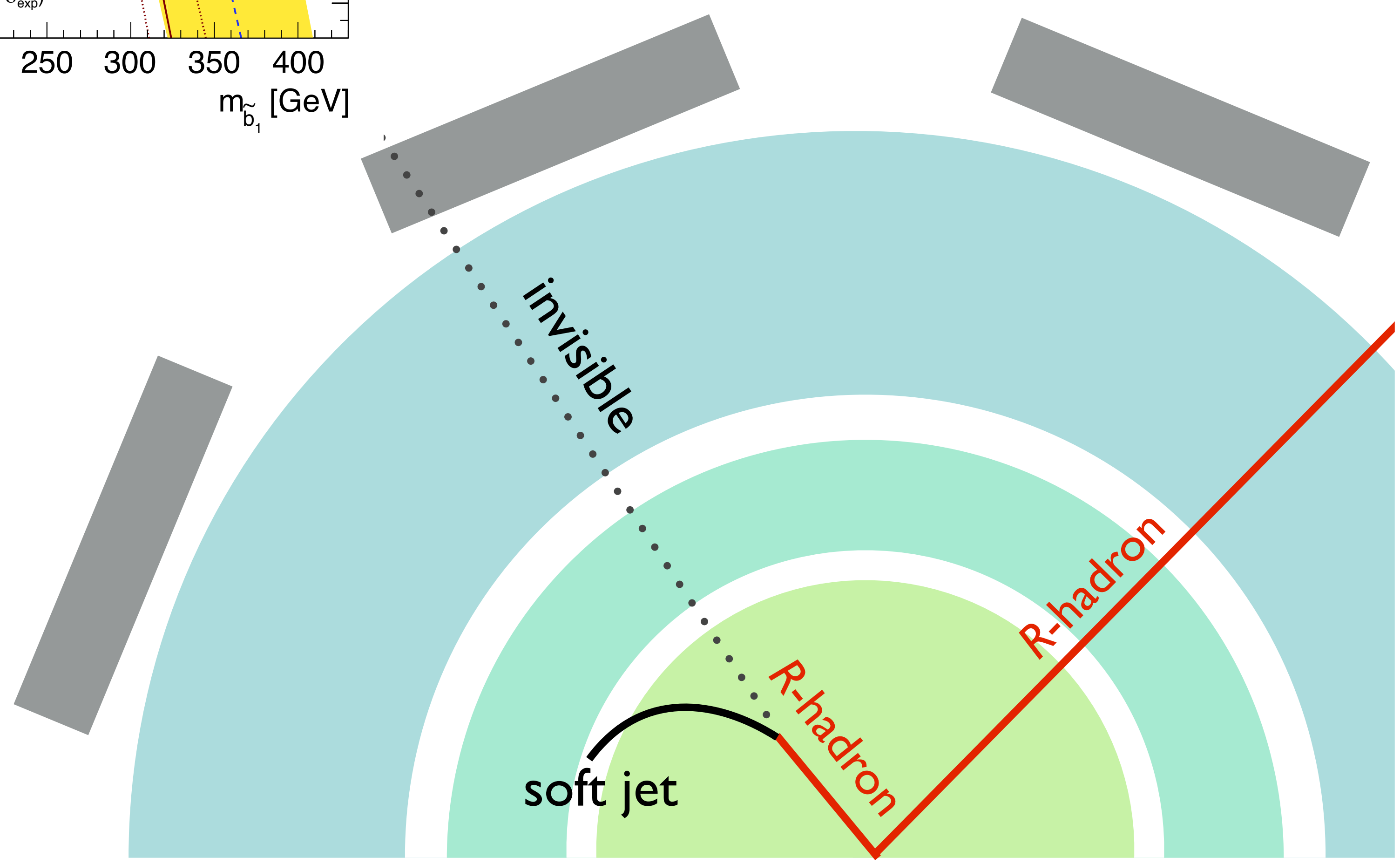




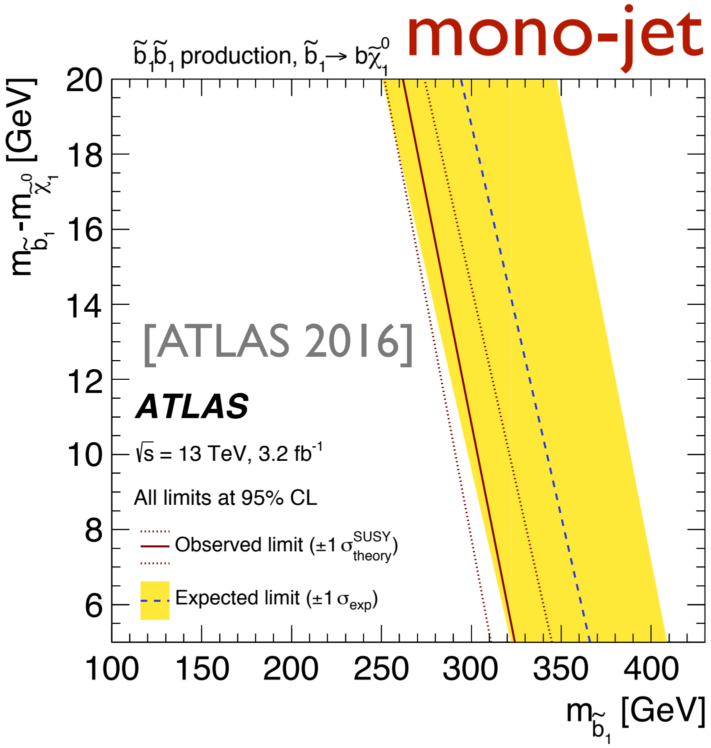


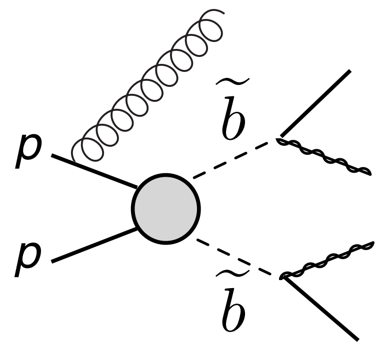
Reinterpretation of *R*-hadron searches for finite lifetimes

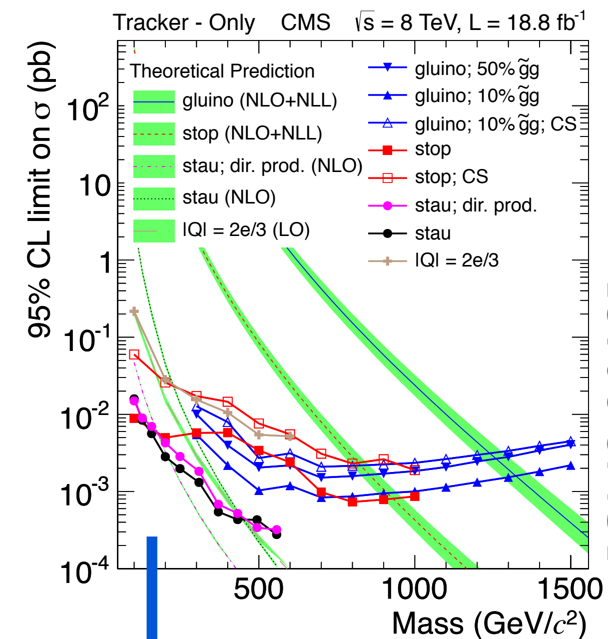




LHC constraints



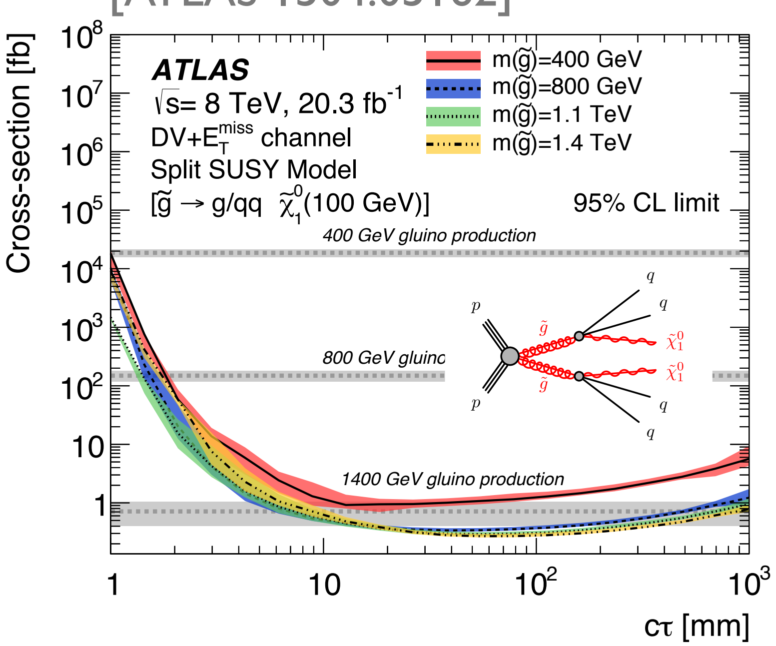


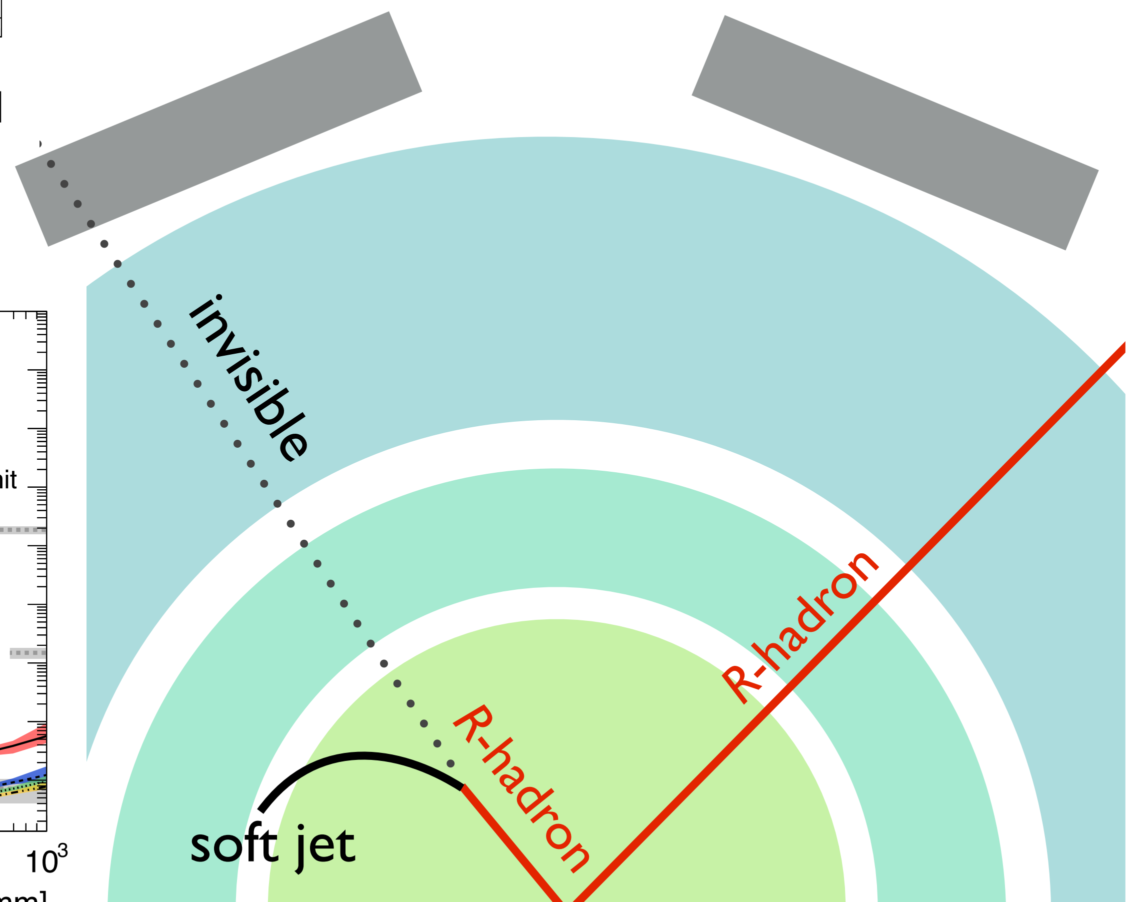


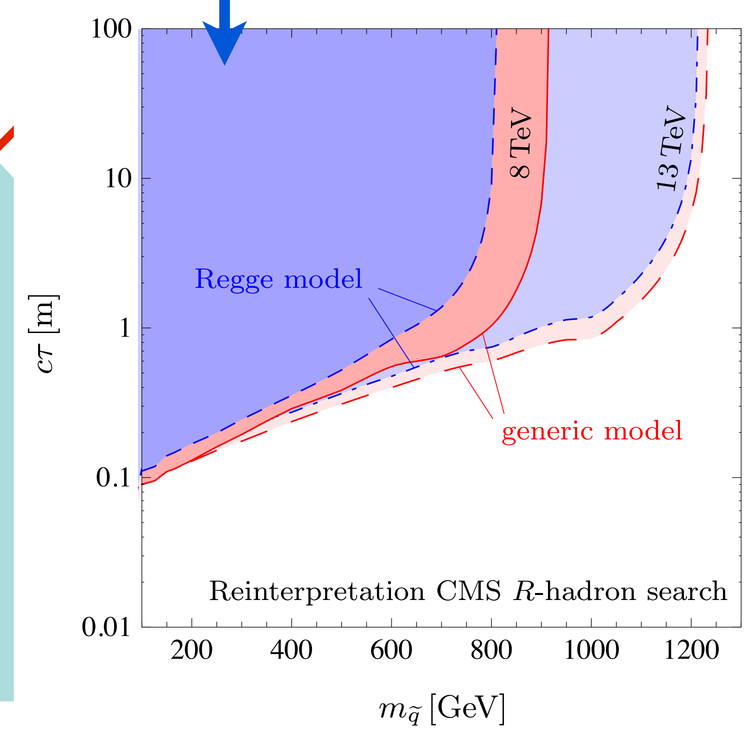
[CMS 2013]

Reinterpretation of *R*-hadron searches for finite lifetimes

[ATLAS 1504.05162]



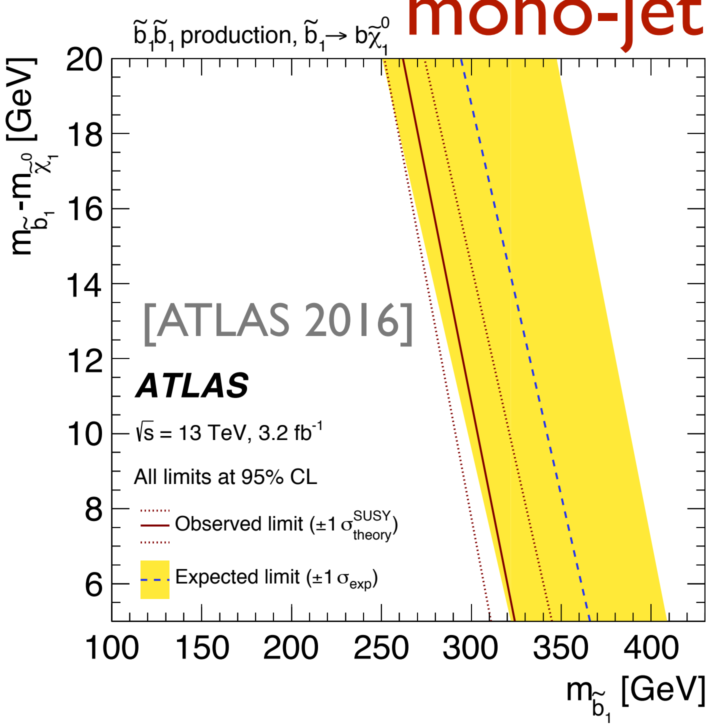


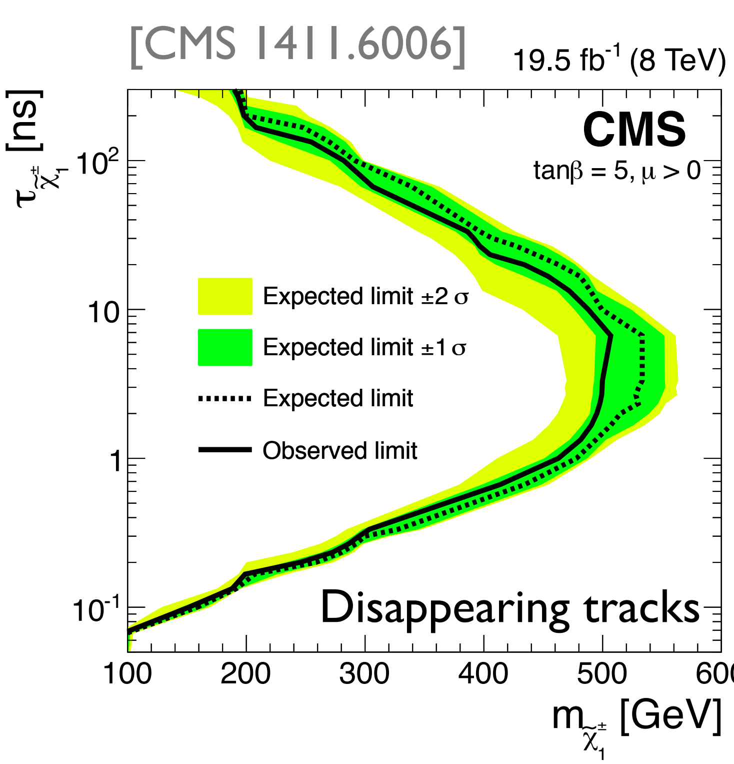


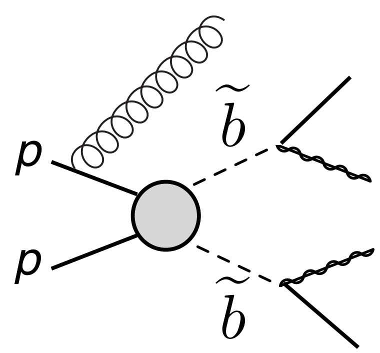
[Garny, JH, Lülf, Vogl 2017]

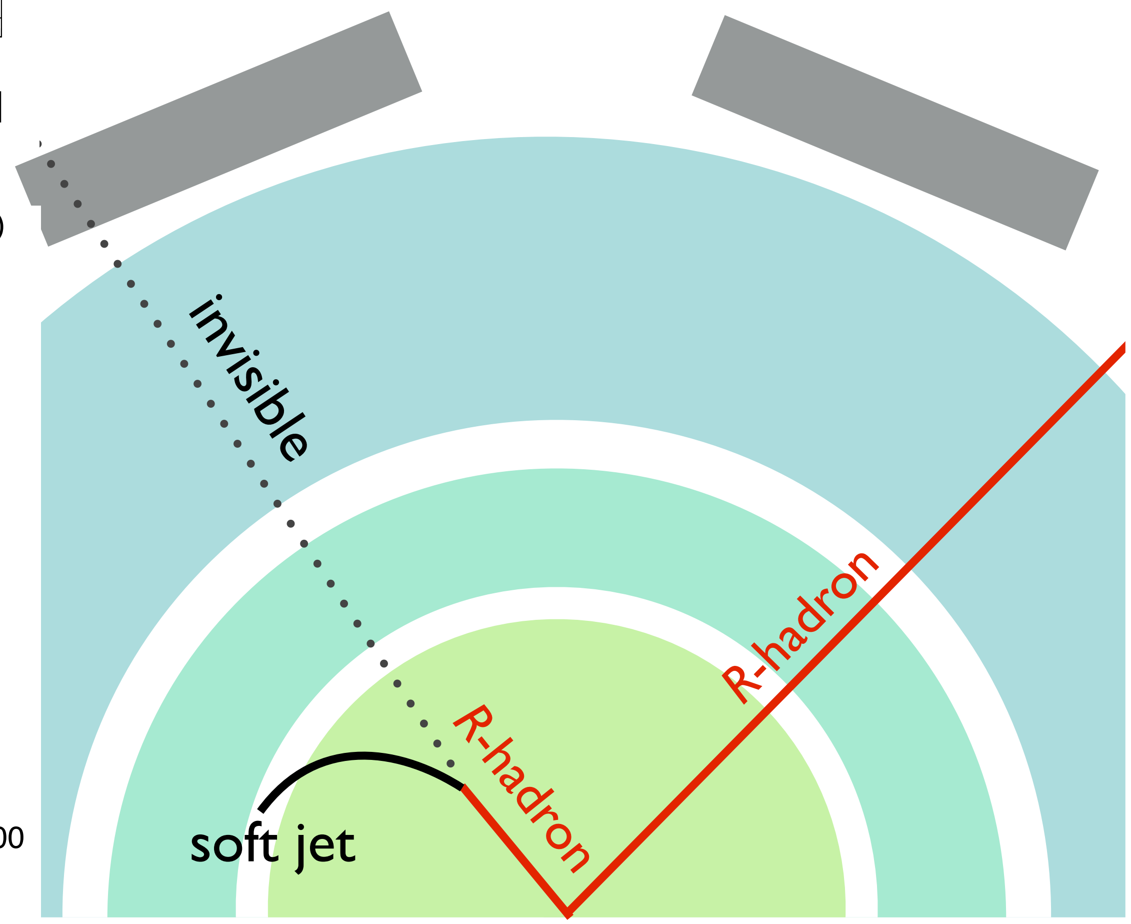
LHC constraints

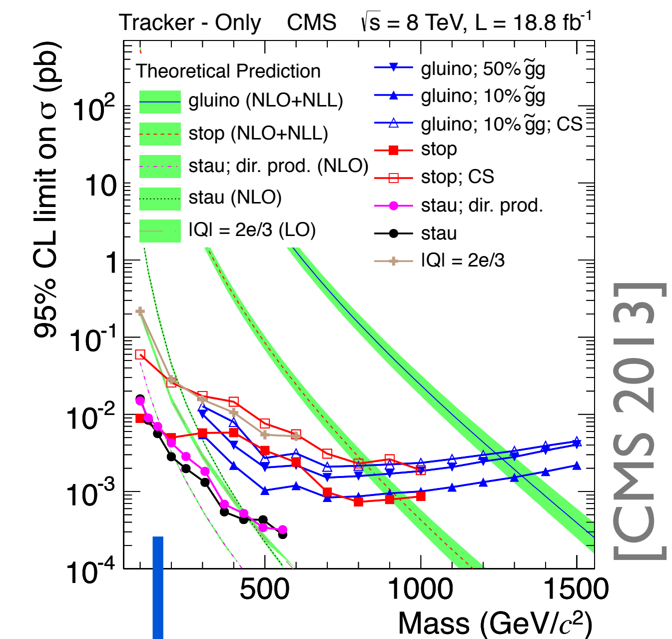
mono-jet



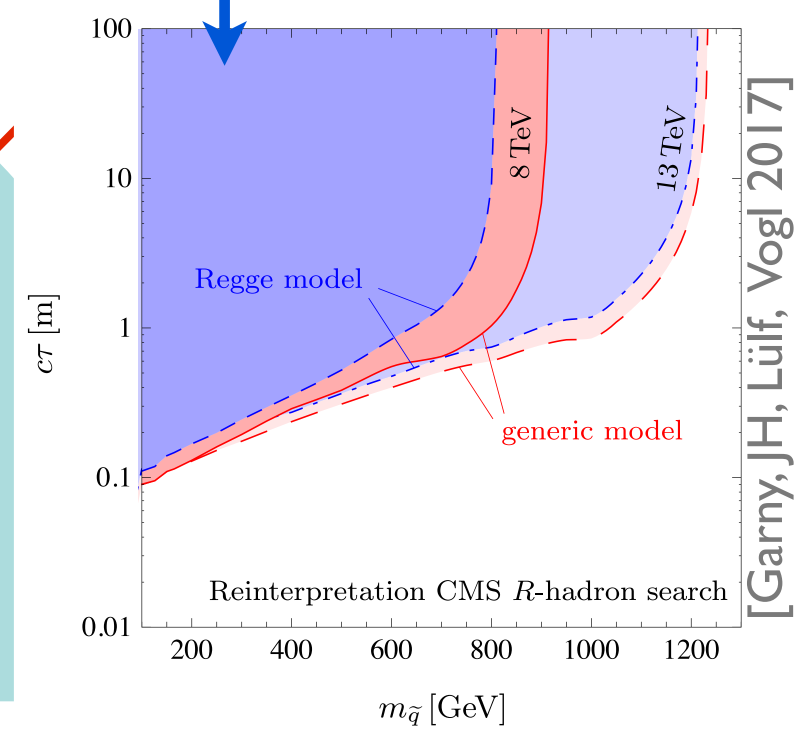






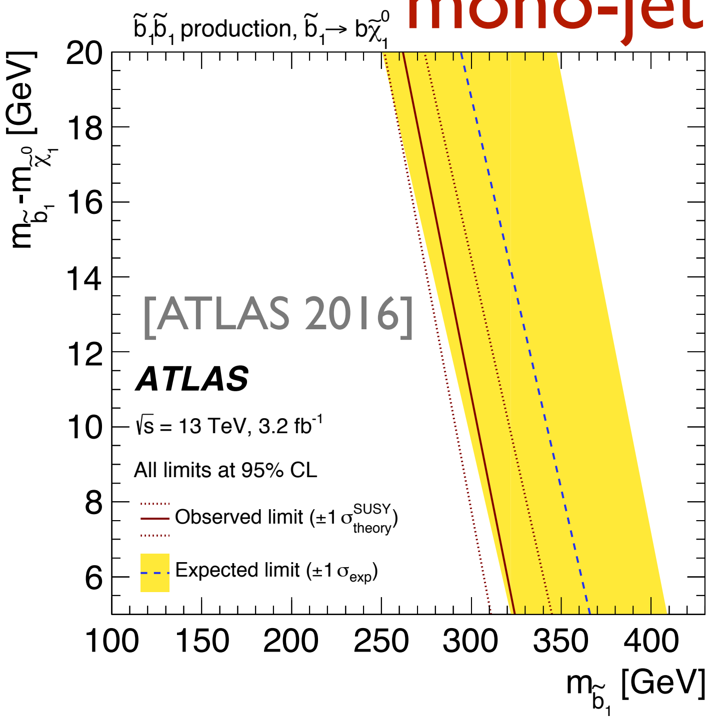


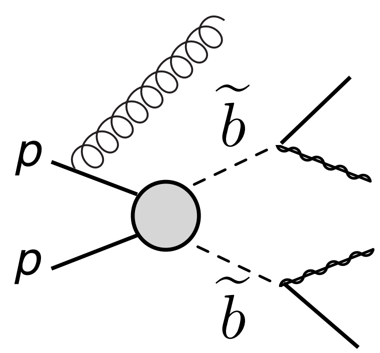
Reinterpretation of *R*-hadron searches for finite lifetimes

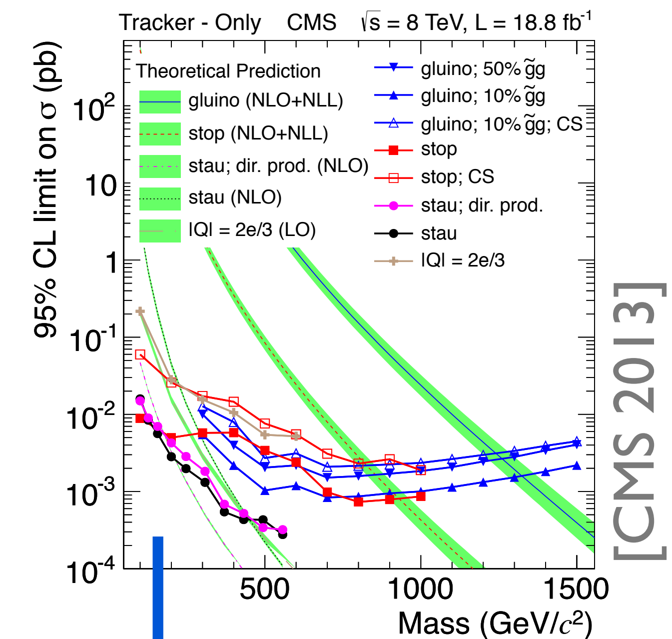


LHC constraints

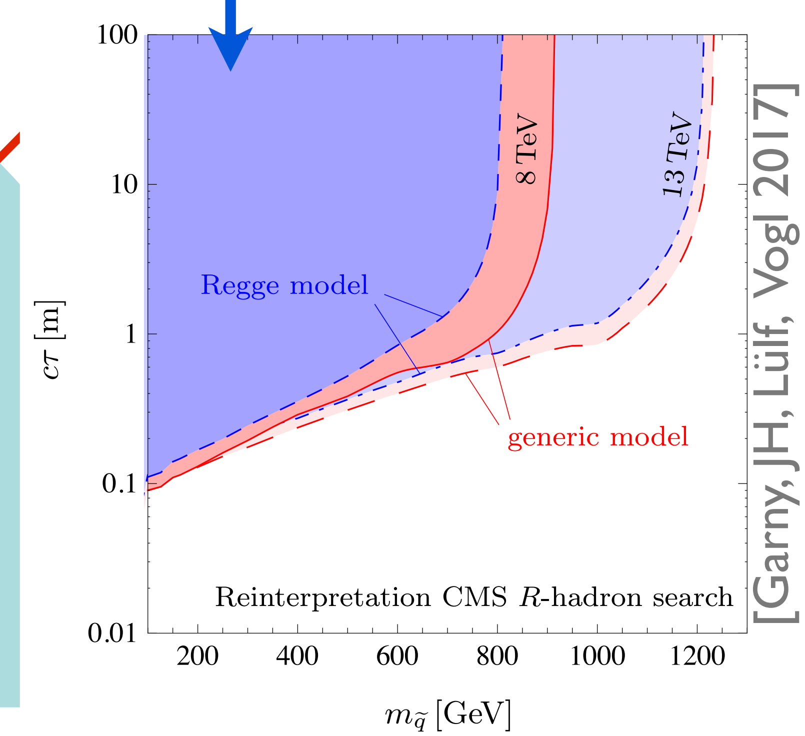
mono-jet



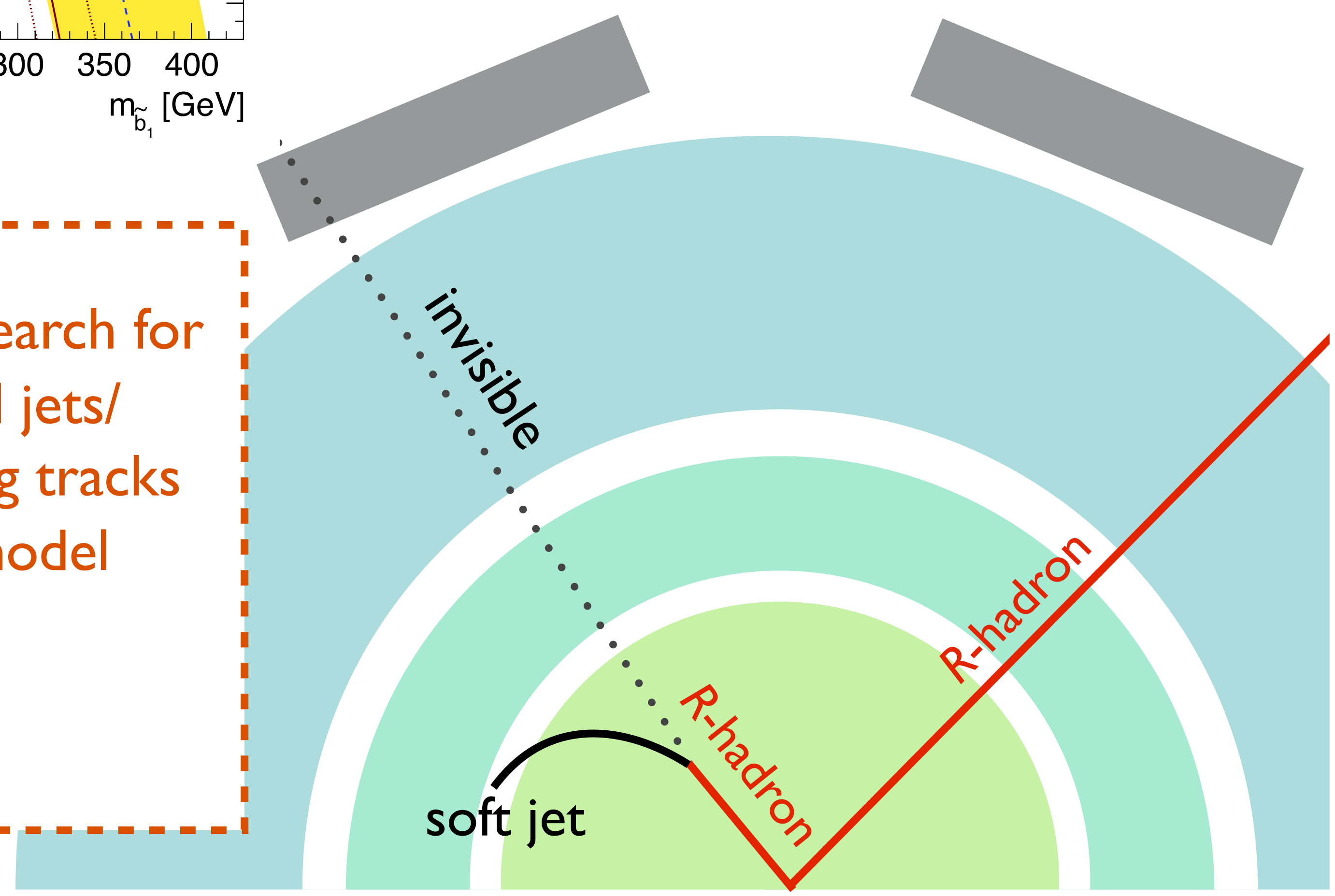




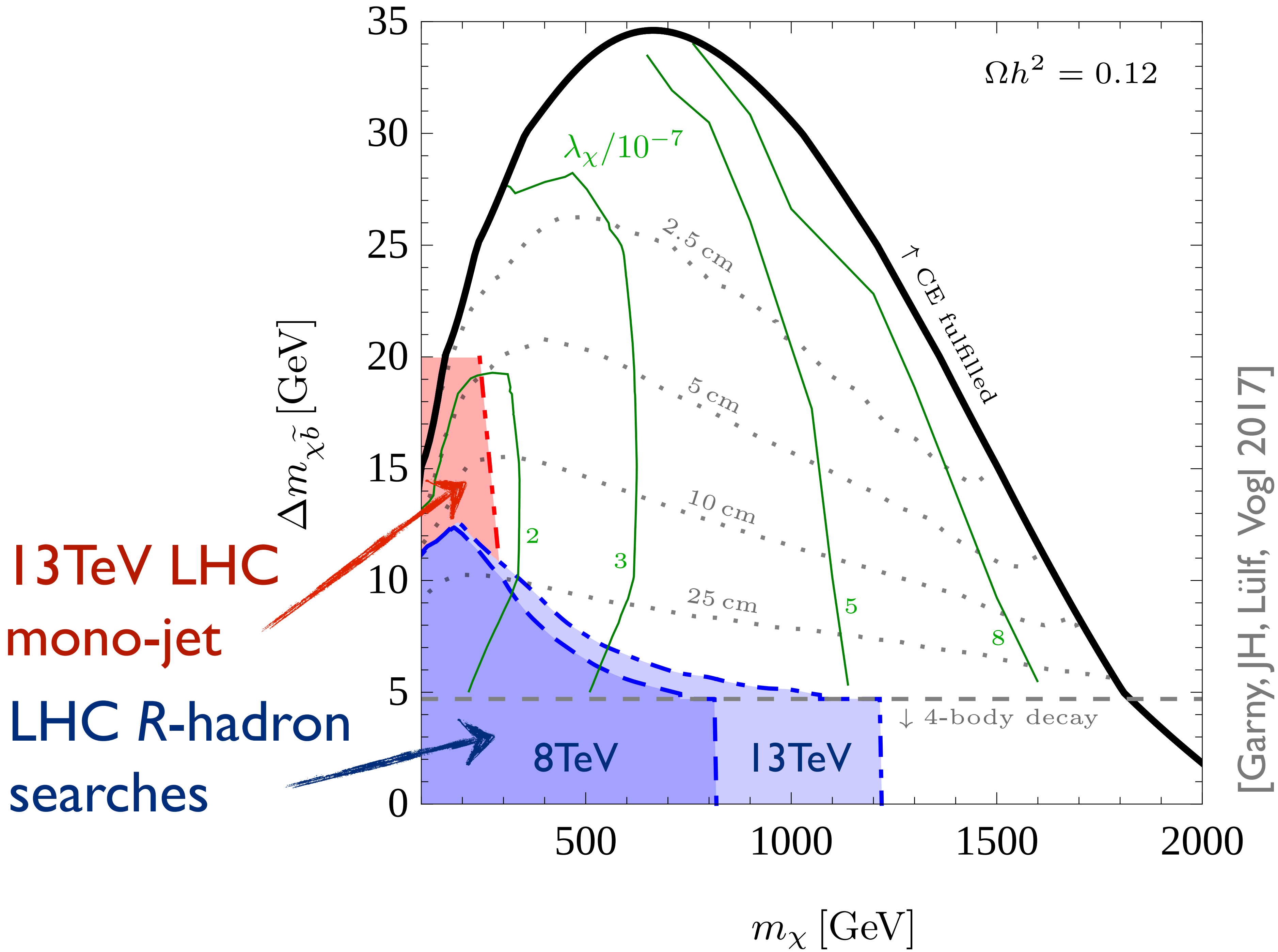
Reinterpretation of *R*-hadron searches for finite lifetimes



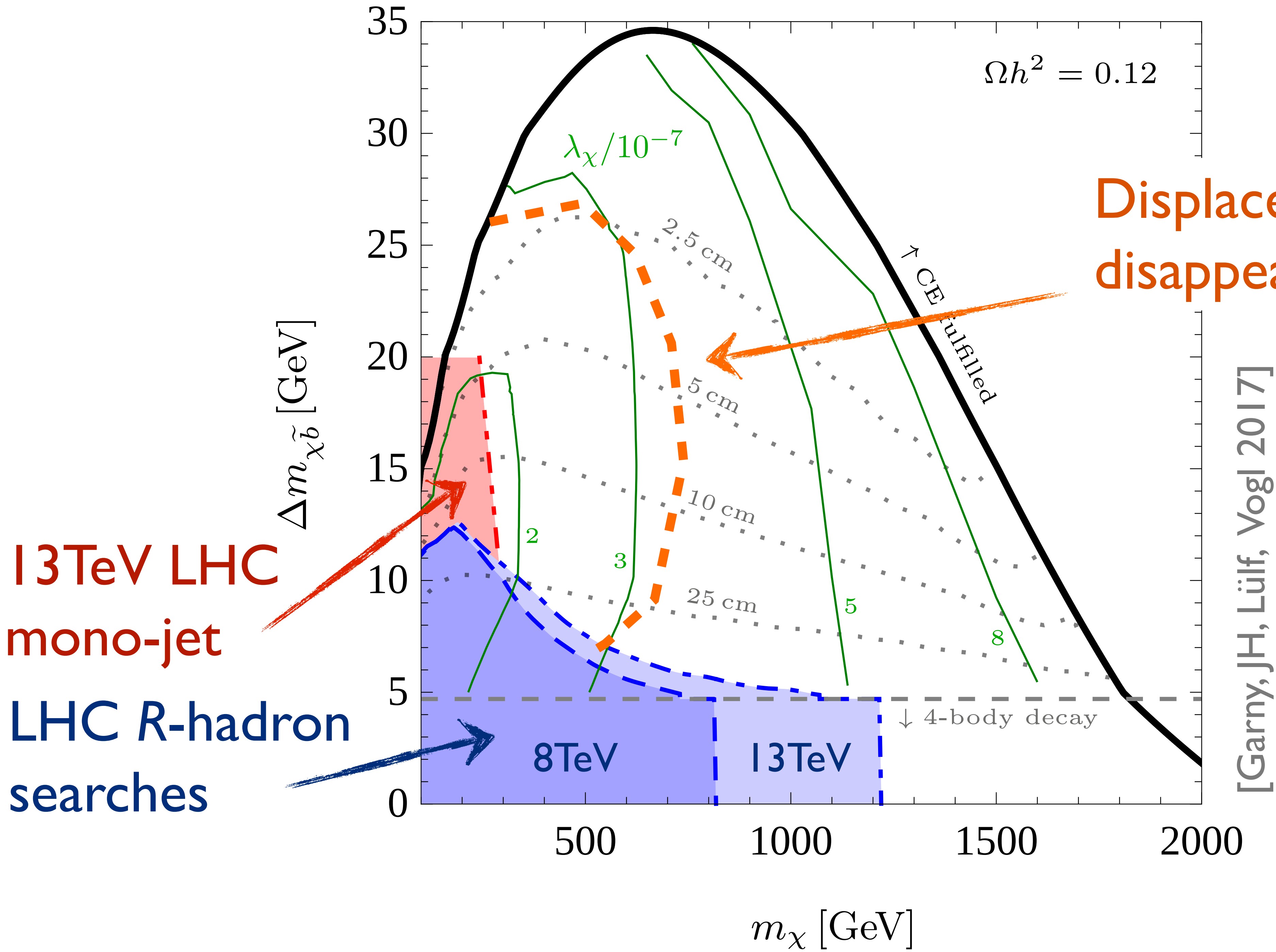
Dedicated search for displaced jets/ disapperaing tracks within model ?



Allowed parameter space



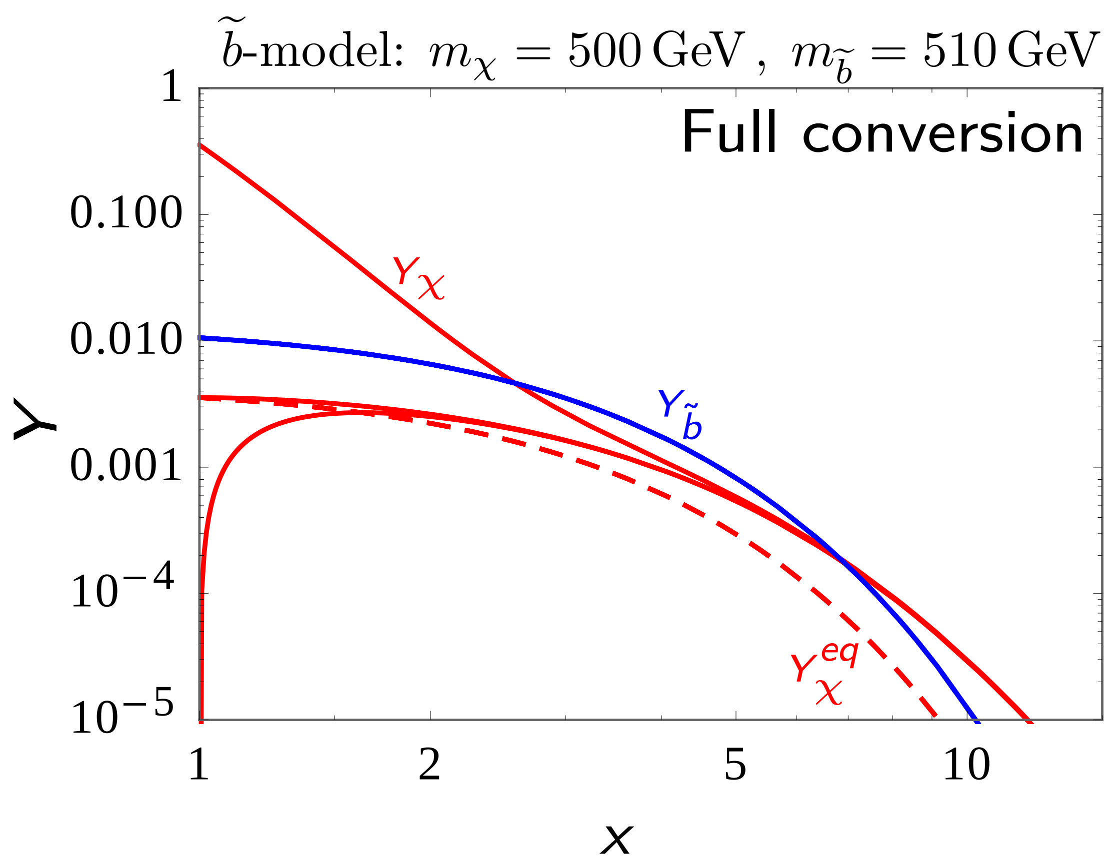
Allowed parameter space

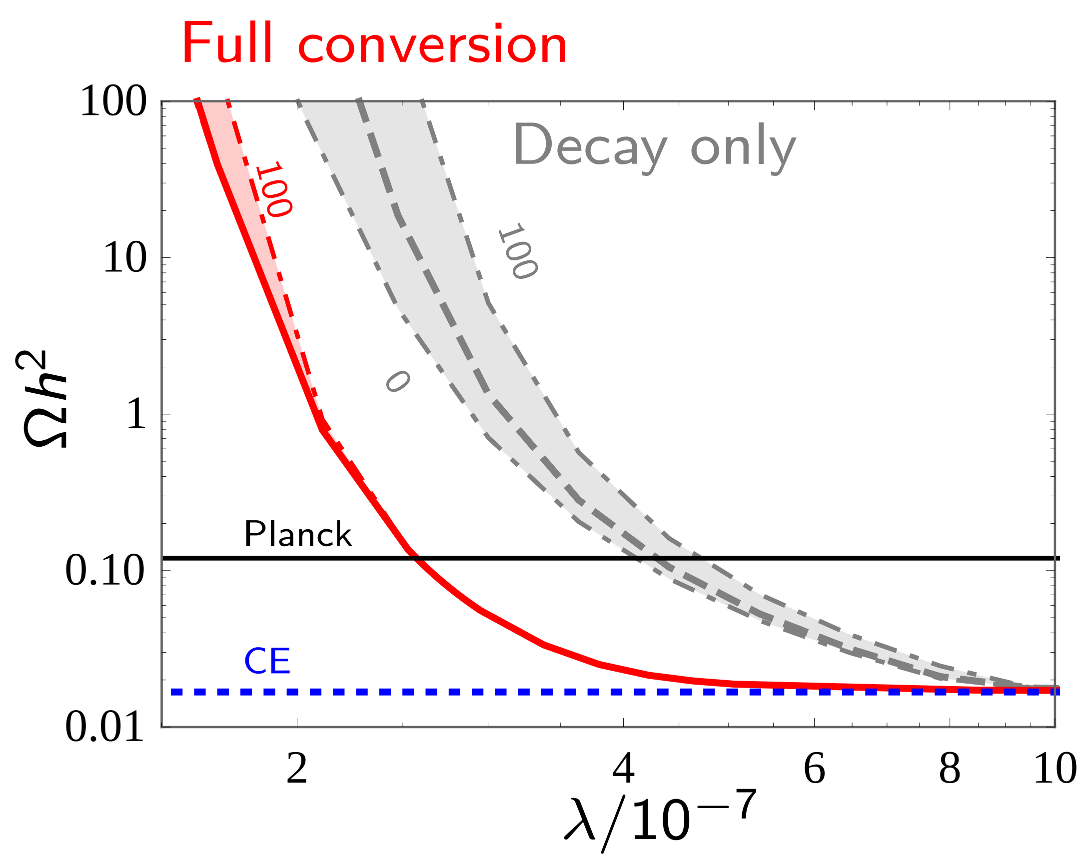


Scrutinizing some assumptions

Dependence on Initial Conditions

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





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

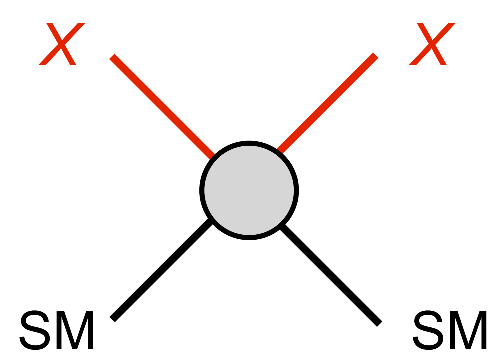
⇒ Independent of thermal history prior to freeze-out!

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:



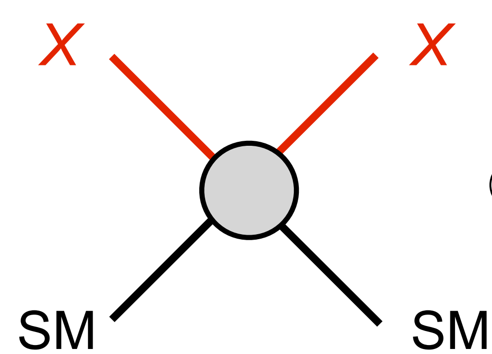
(kinetic decoupling takes place well after freeze-out)
[*cf.* Chen, Kamionkowski, Zhang 2001, Bringmann, Hofmann 2006; Borzumati, Bringmann, Ullio 2007]

Kinetic equilibrium

- Assumption of thermal distributions (via kinetic equilibrium)

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

- 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

Unintegrated Boltzmann equation

- Consider unintegrated Boltzmann equation for χ:

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

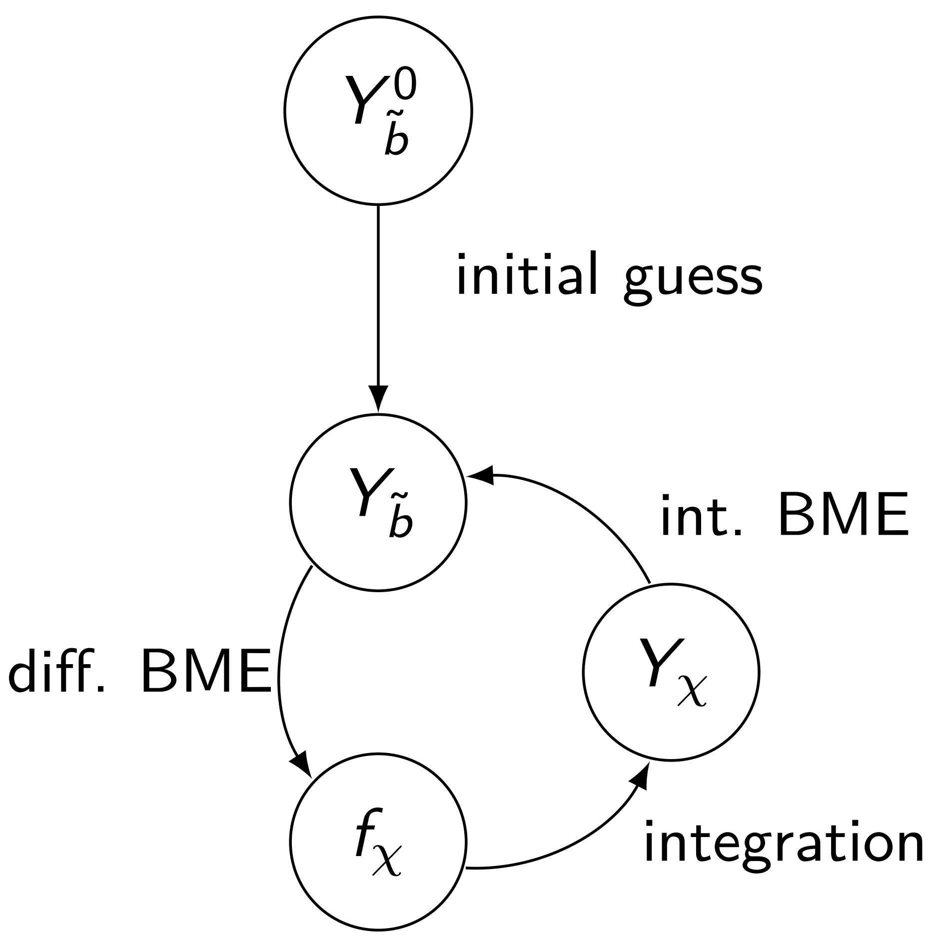
- Conversion only: linear in f_χ
- Can be solved by separation of variables and variation of constants:

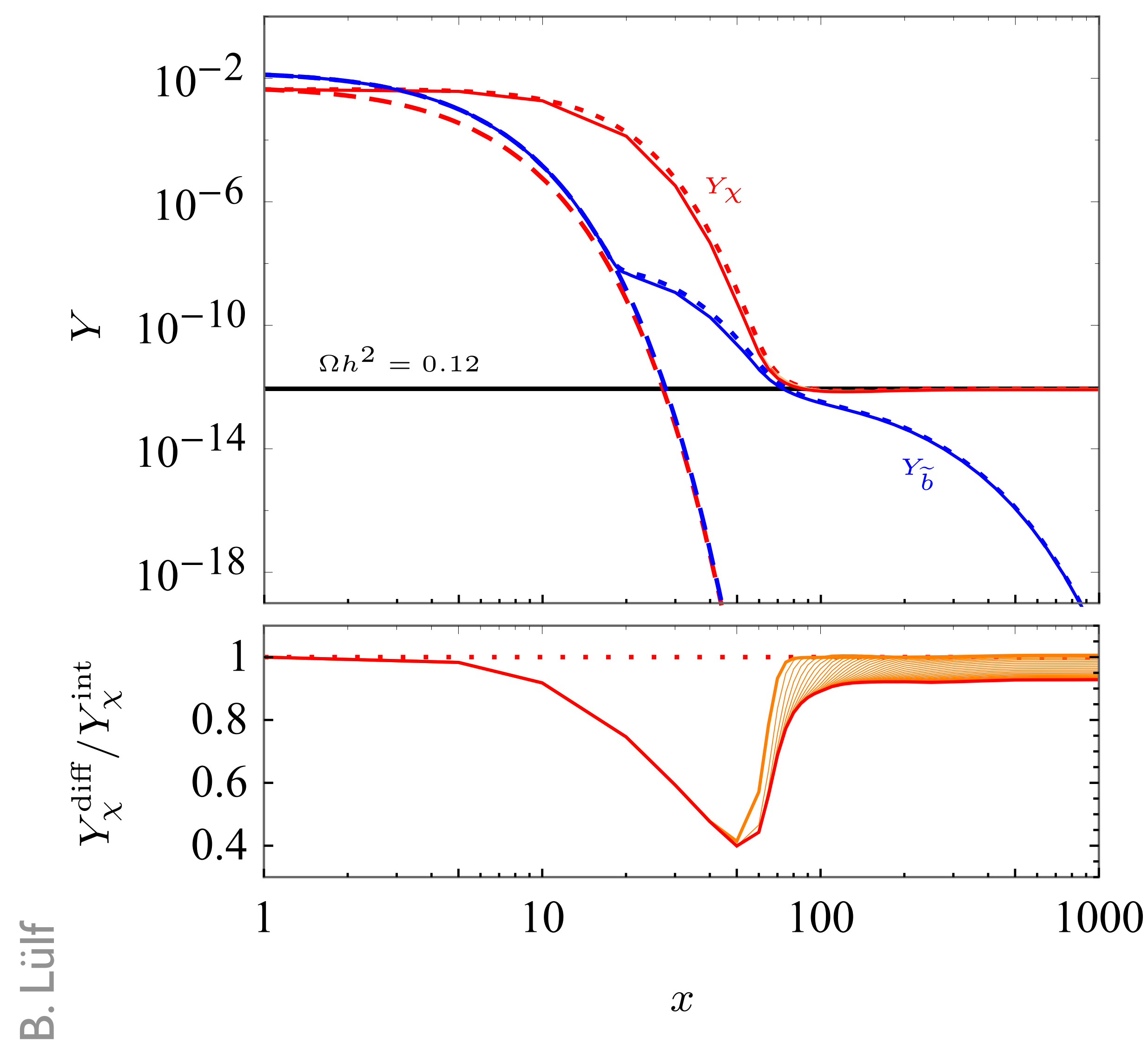
$$f_\chi(q,x) = f_\chi^{\mathrm{eq}}(q,x)\frac{Y_{\tilde{b}}}{Y_{\tilde{b}}^{\mathrm{eq}}} - \int_{x_0}^{x} \frac{\mathrm{d}\left(f_\chi^{\mathrm{eq}}(q,y)\, Y_{\tilde{b}}(y)/Y_{\tilde{b}}^{\mathrm{eq}}(y)\right)}{\mathrm{d}y} \times \exp\left(-\int_y^x \frac{\widetilde{C}(q,z)}{zH(z)}\mathrm{d}z \right)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

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

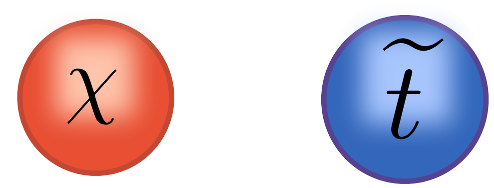




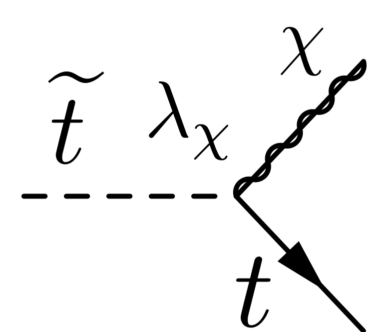
Another explicit example

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

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



- Yukawa-type interaction:

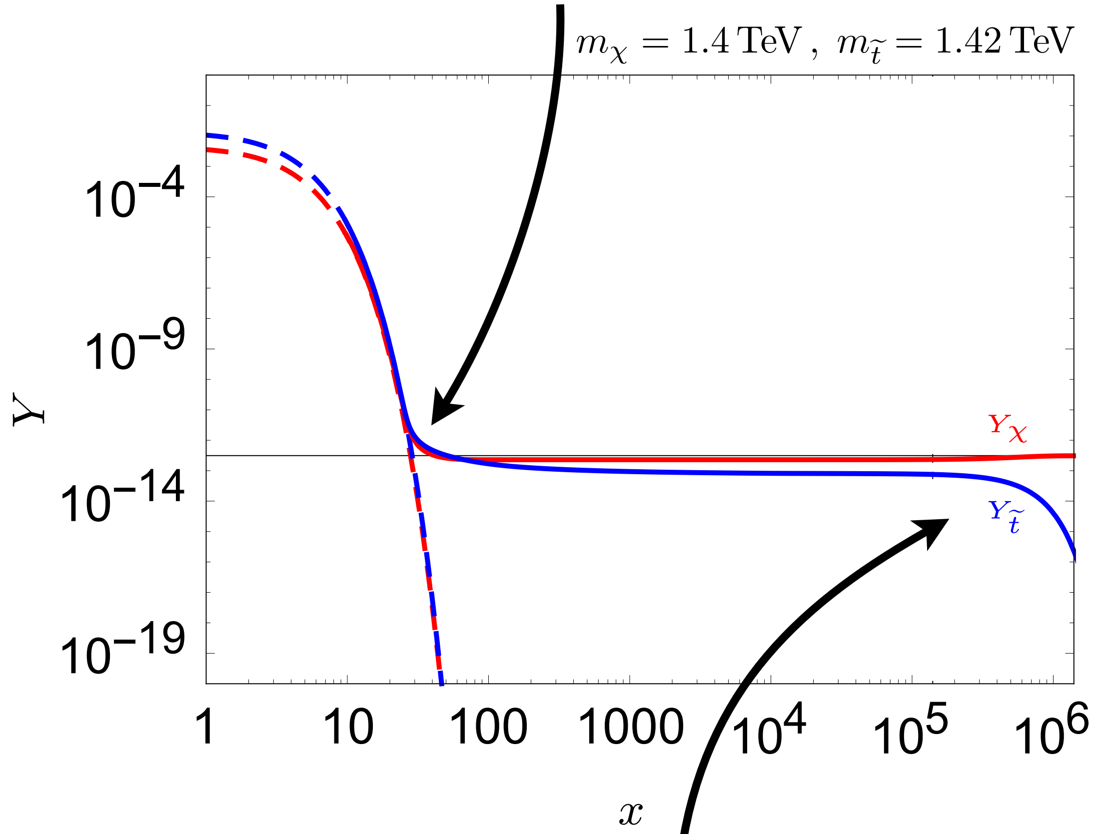


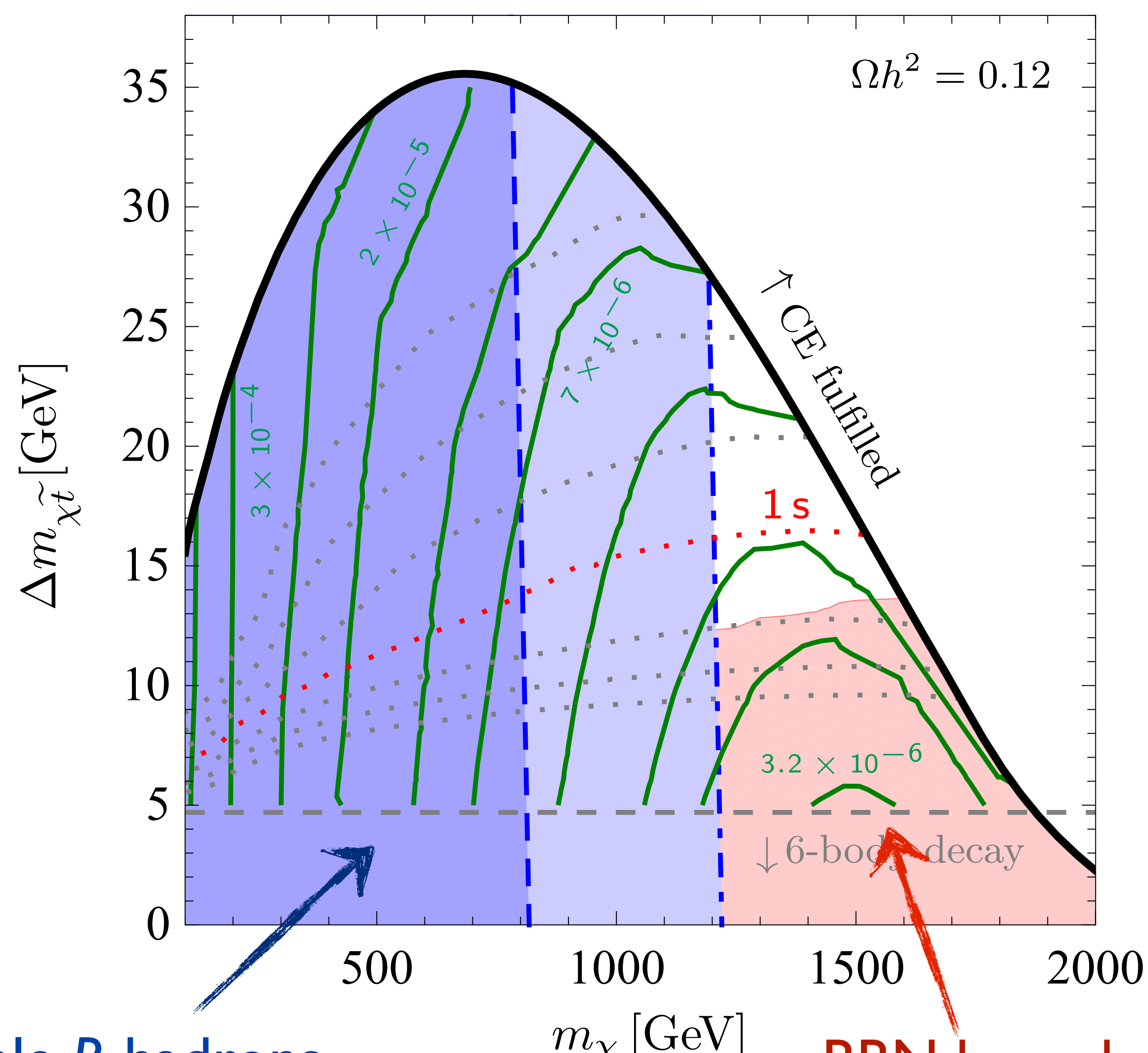
- Difference: Top-quark non-negligible mass!

Allowed parameter space: top-partner model

[Garny, JH, Hufnagel, Lülf 2018]

Scatterings dominate conversions





Decay efficient much later

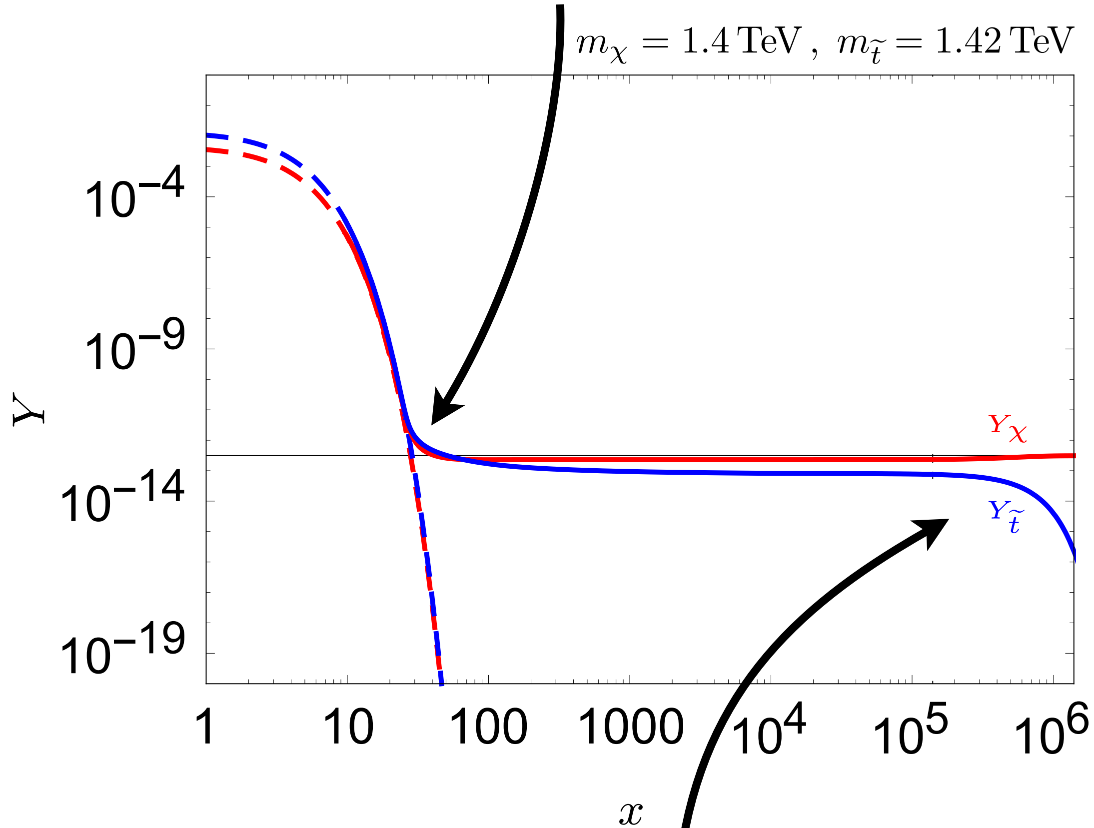
$\Gamma_{\text{decay}} \ll \Gamma_{\text{scatter}}$ $\Rightarrow$ Detector-stable *R*-hadrons

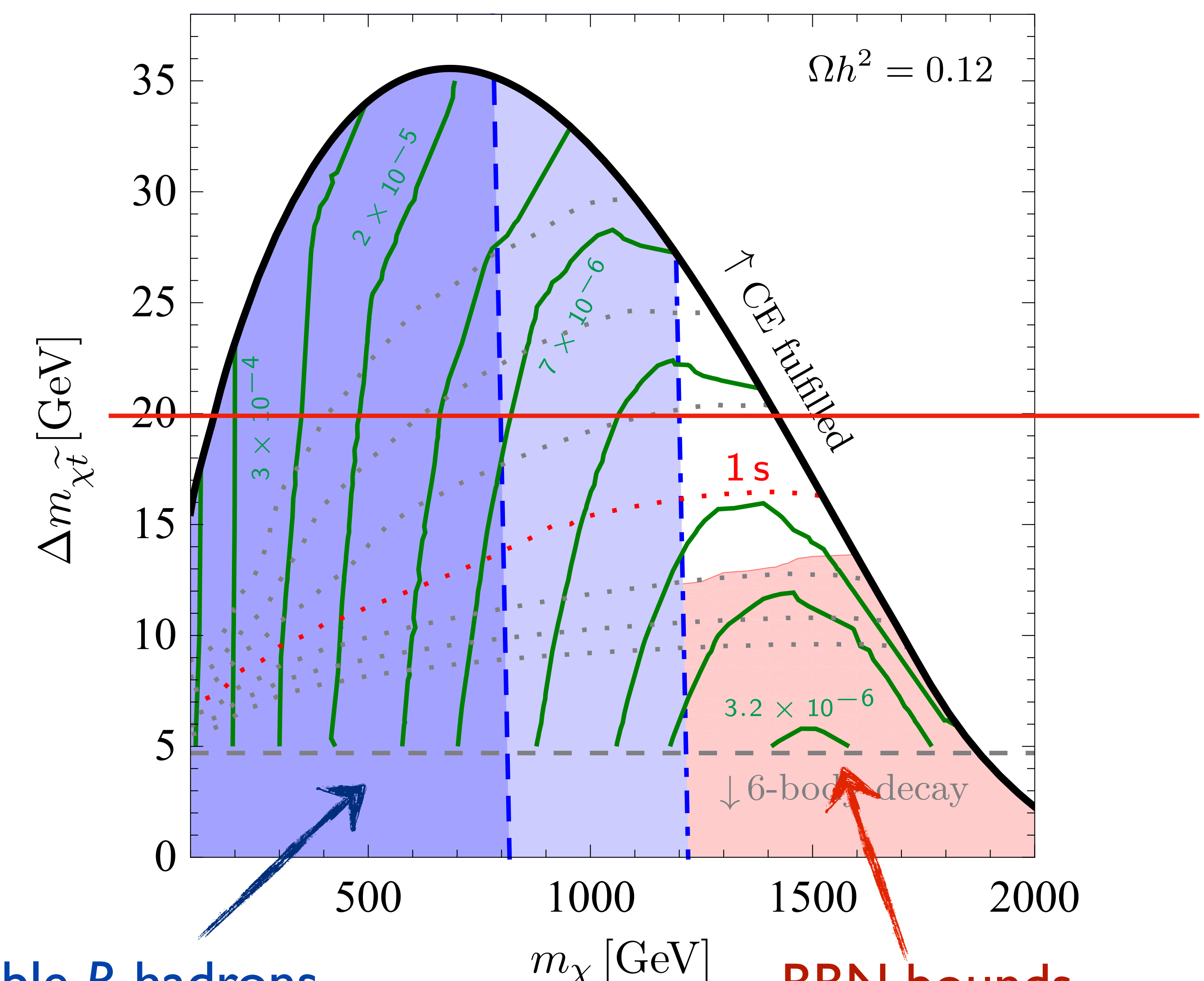
BBN bounds

Allowed parameter space: top-partner model

[Garny, JH, Hufnagel, Lülf 2018]

Scatterings dominate conversions





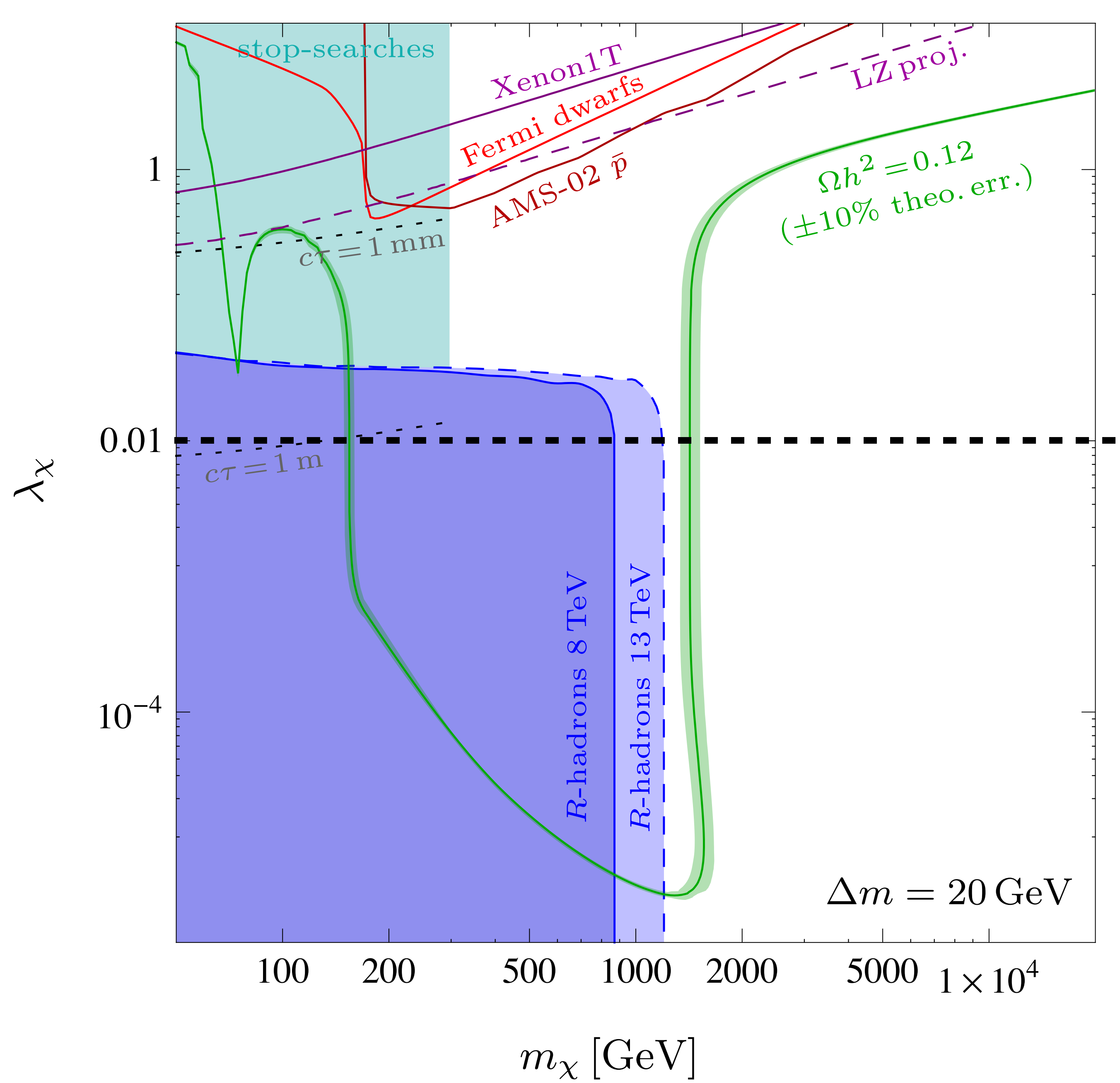
Decay efficient much later

$\Gamma_{\mathrm{decay}} \ll \Gamma_{\mathrm{scatter}}$ $\Rightarrow$ Detector-stable *R*-hadrons

BBN bounds

Allowed parameter space: top-partner model

[Garny, JH, Hufnagel, Lülf 2018]



WIMP freeze-out

Conversion-driven freeze-out

Summary

- Vanilla WIMP under pressure: Watch out for avenues beyond WIMPs with new LHC signatures!
- Conversion-driven freeze-out:
  - Shares nice features of WIMPs!
  - Accommodates null-results from WIMP-searches
  - $H \sim \Gamma$: Lifetimes naturally O(1-100cm)

    $\Rightarrow$ Strong motivation for long-lived particles at LHC
- Interesting times for dark matter hunters lie ahead

Recent effort to identify gaps, systematically cover LLP signatures

LHC LLP Community Workshops:

April 2017: https://indico.cern.ch/event/607314/
October 2017: https://indico.cern.ch/event/649760/
May 2018: https://indico.cern.ch/event/714087/
Next Workshop: https://indico.cern.ch/event/744951/
Community white paper to appear soon

Reinterpretation of heavy-stable charged particle/ *R*-hadron searches for arbitrary BSM models:

Now public at
http://smodels.hephy.at

arXiv:1808.05229v1

Constraining new physics with searches for long-lived particles: Implementation into SModelS

Jan Heisig[a], Sabine Kraml[b], Andre Lessa[c]

[a] Institute for Theoretical Particle Physics and Cosmology, RWTH Aachen University, 52056 Aachen, Germany
[b] Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, 53 Avenue des Martyrs, F-38026 Grenoble, France
[c] Centro de Ciências Naturais e Humanas, Universidade Federal do ABC, Santo André, 09210-580 SP, Brazil

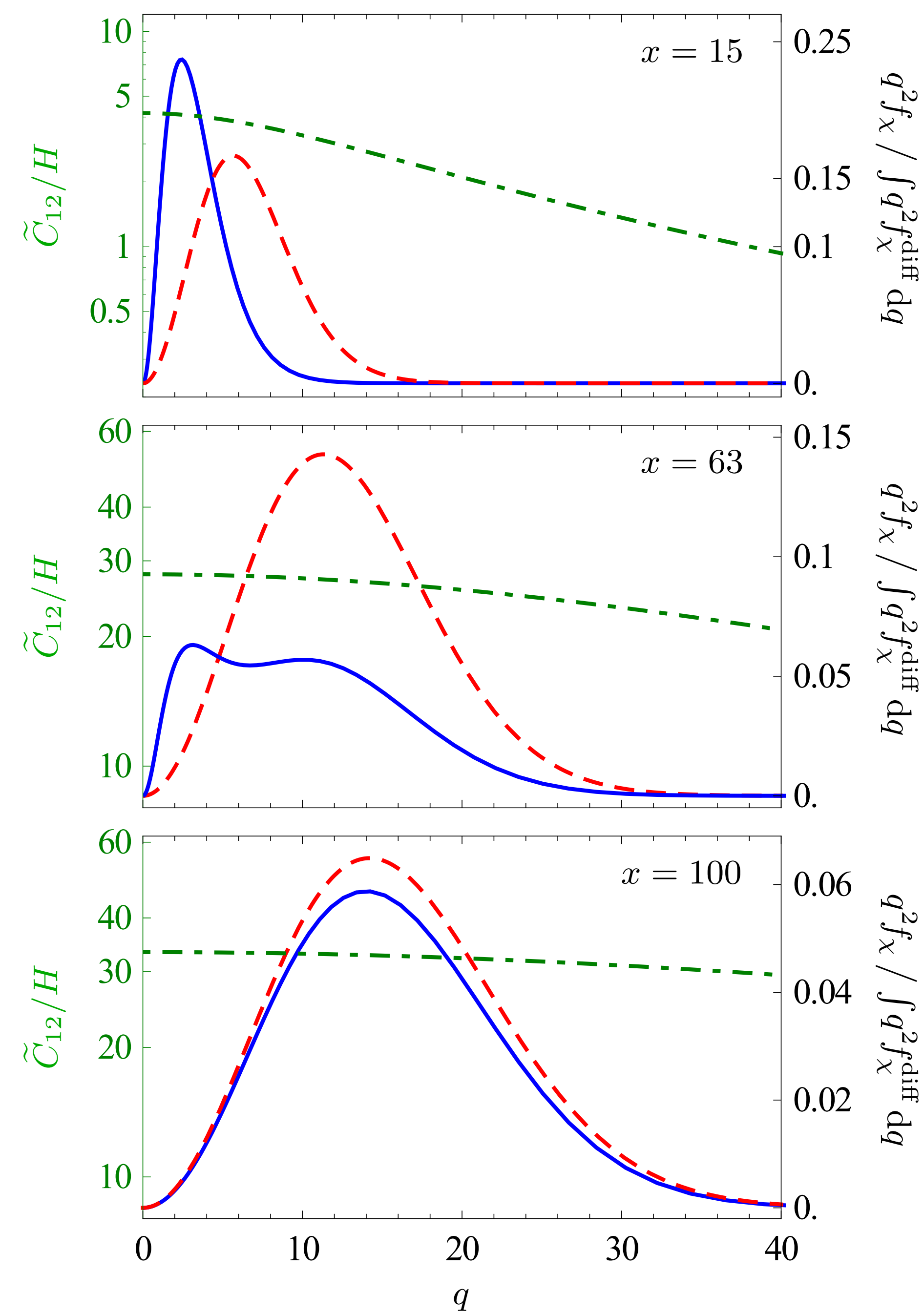
Abstract

We present the implementation of heavy stable charge particle (HSCP) and *R*-hadron signatures into SModelS v1.2. We include simplified-model results from the 8 and 13 TeV LHC and demonstrate their impact on two new physics scenarios motivated by dark matter: the inert doublet model and a gravitino dark matter scenario. For the former, we find sensitivity up to dark matter masses of 580 GeV for small mass splittings within the inert doublet, while missing energy searches are not able to constrain any significant part of the cosmologically preferred parameter space. For the gravitino dark matter scenario, we show that both HSCP and *R*-hadron searches provide important limits, allowing to constrain the viable range of the reheating temperature.

Backup slides

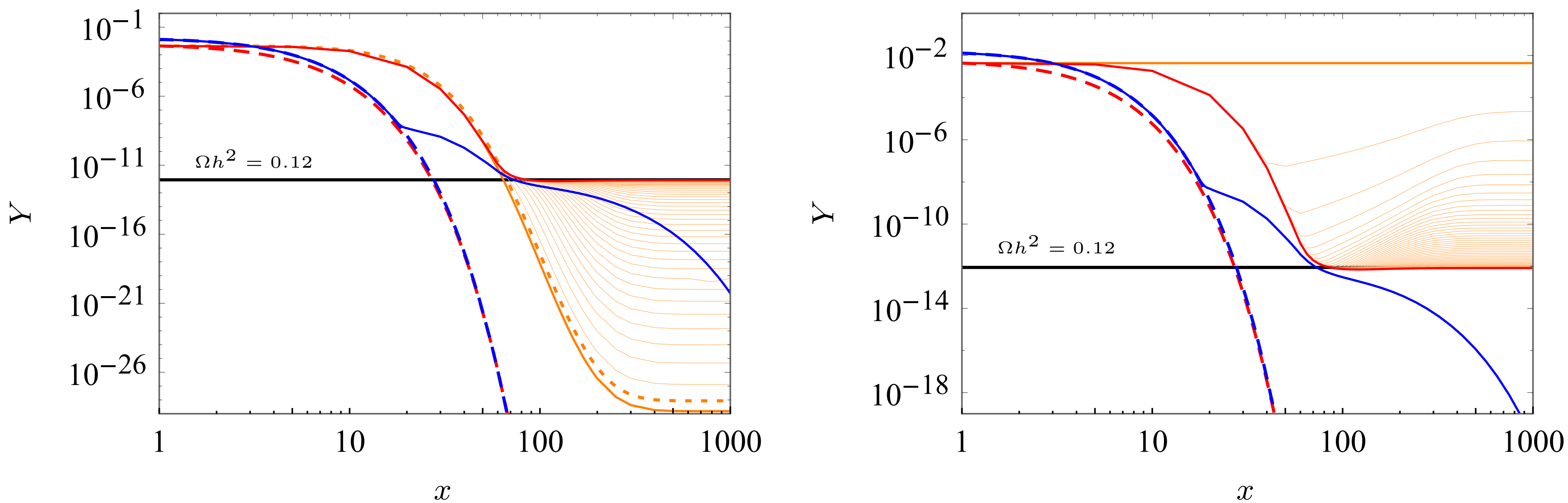
Deviation from thermal distribution

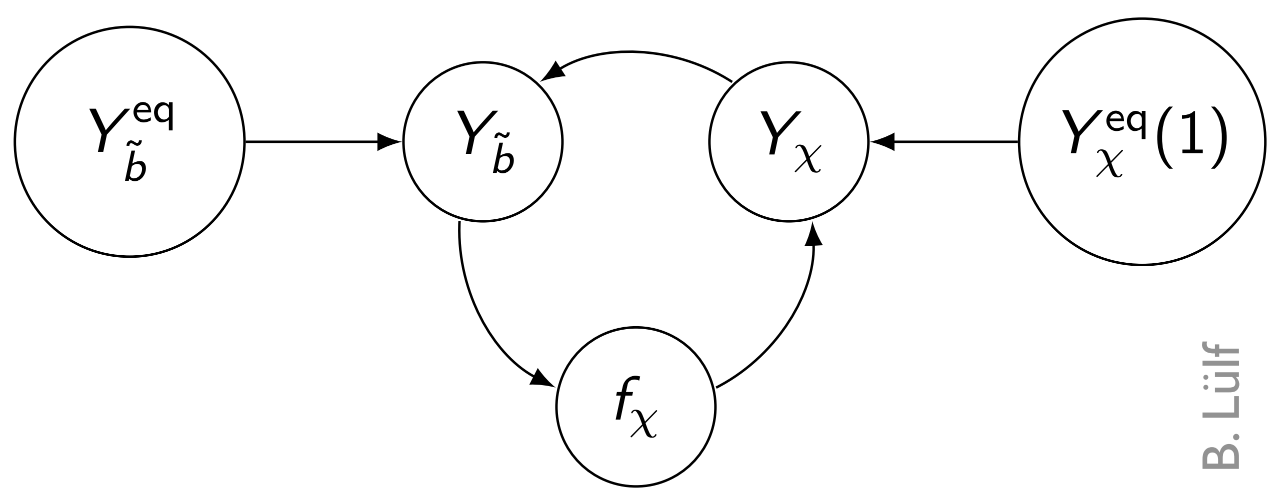
- small x: redshift only
- Conversion inset: thermalization starts
- Close-to-thermal distribution



Testing initial guess

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





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]