Dark matter freeze-out beyond the WIMP paradigm

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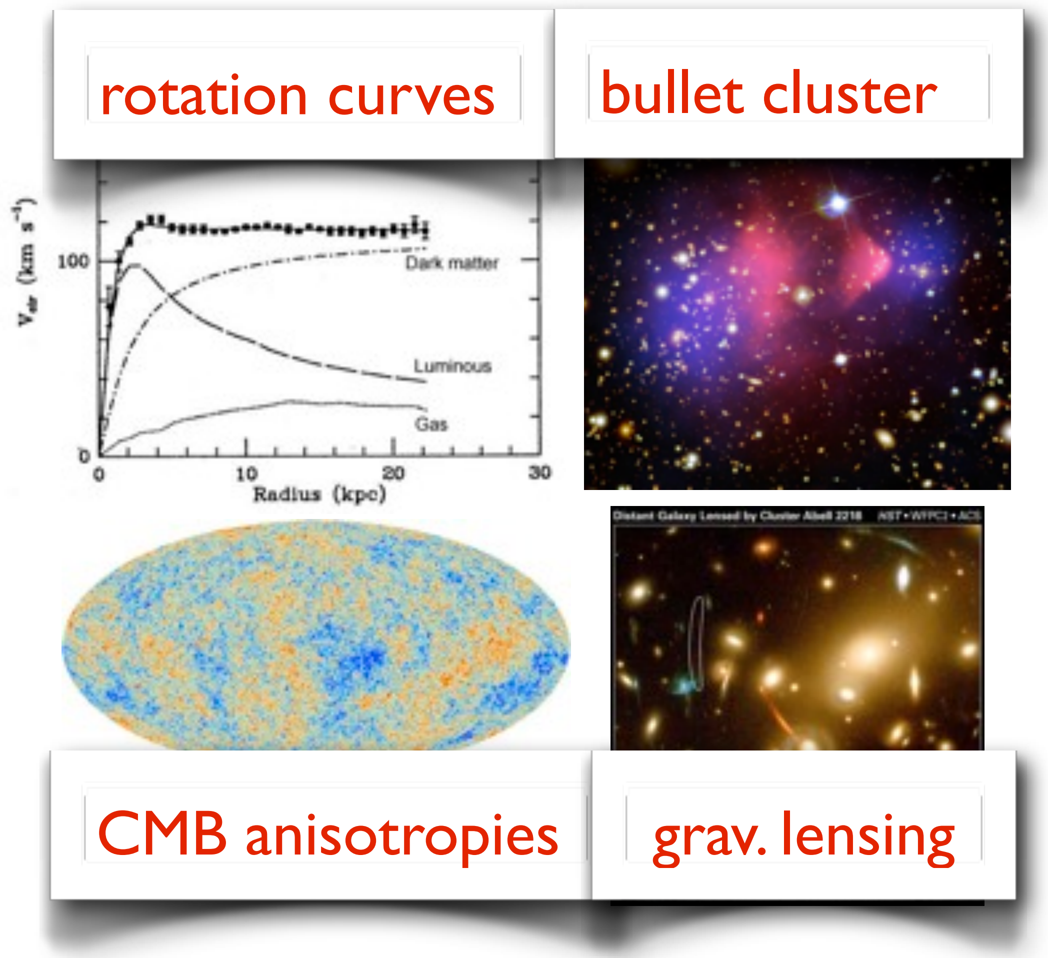
November 22, 2017

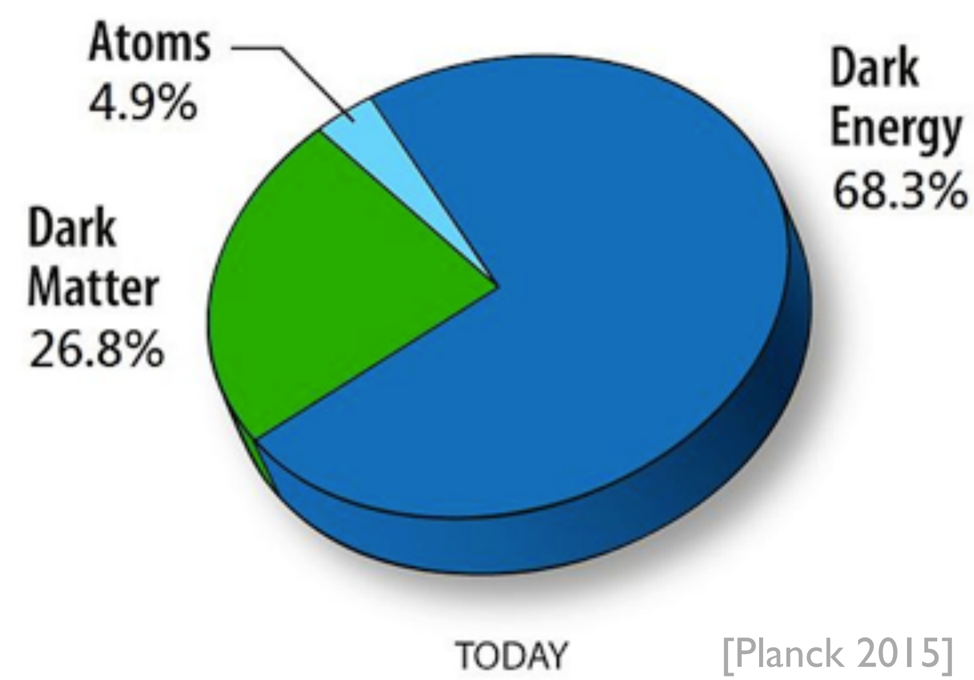
Theory Seminar/SDI Seminar

UiO : Department of Physics
University of Oslo

What is Dark Matter?



Energy density of the universe:



$$\Omega_{\rm DM} h^2 = 0.1198 \pm 0.0015$$

- Overwhelming evidence for gravitational interaction of dark matter
- No conclusive hint for other interactions with the Standard Model
- Electrically and color-neutral: Interactions at most via weak force

Dark matter = a WIMP ?

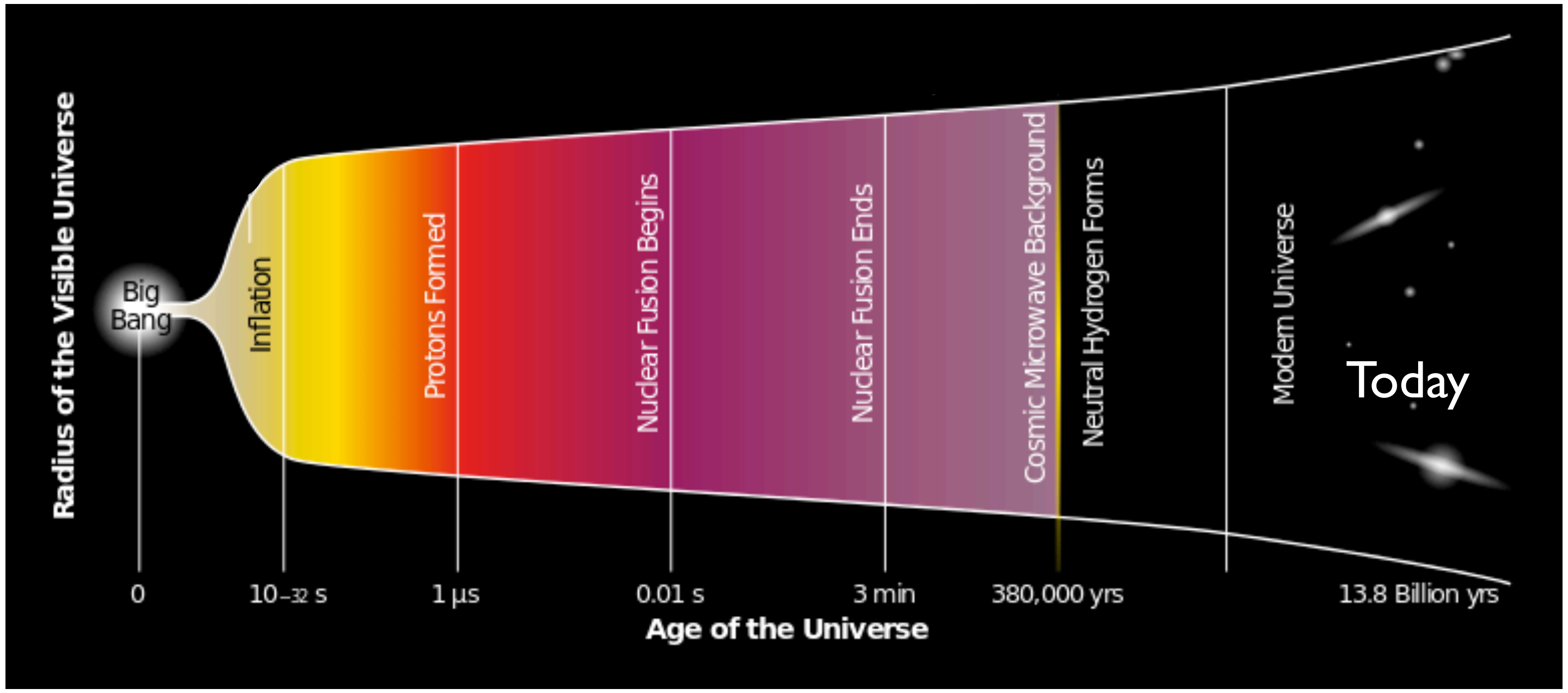
(Weakly Interacting Massive Particle)

WIMP paradigm attractive:

- Works with simple/natural models ("WIMP miracle")
- Independent of largly unconstrained/unknown physics of the very early universe (inflation/reheating)
- Robust predicions
- Testable at collider, direct and indirect detection experiments

WIMP paradigm: How to explain the dark matter density?

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



Expansion with Hubble rate: $H = \frac{\dot{R}}{R}, \quad R =$ scale factor

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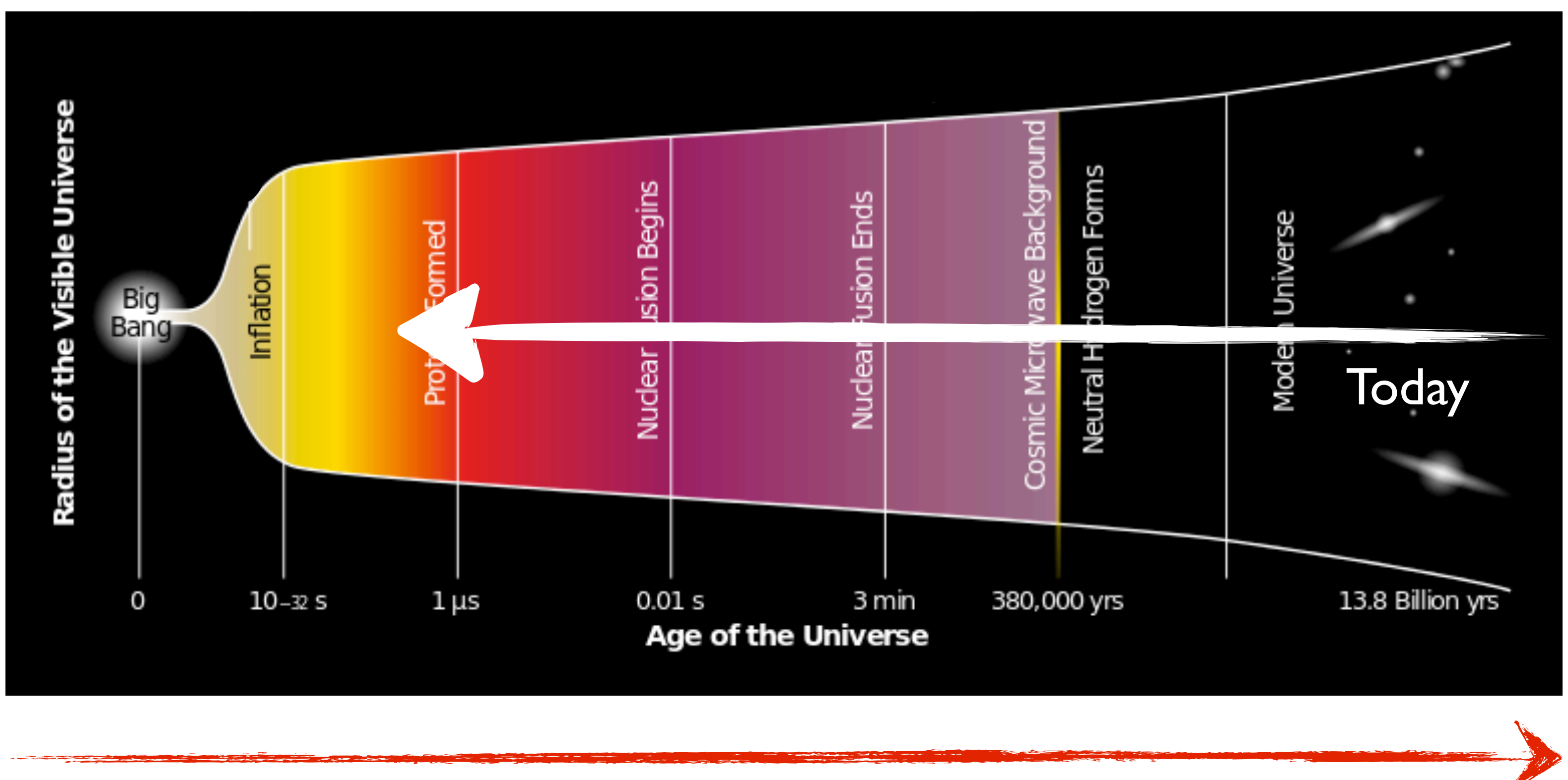
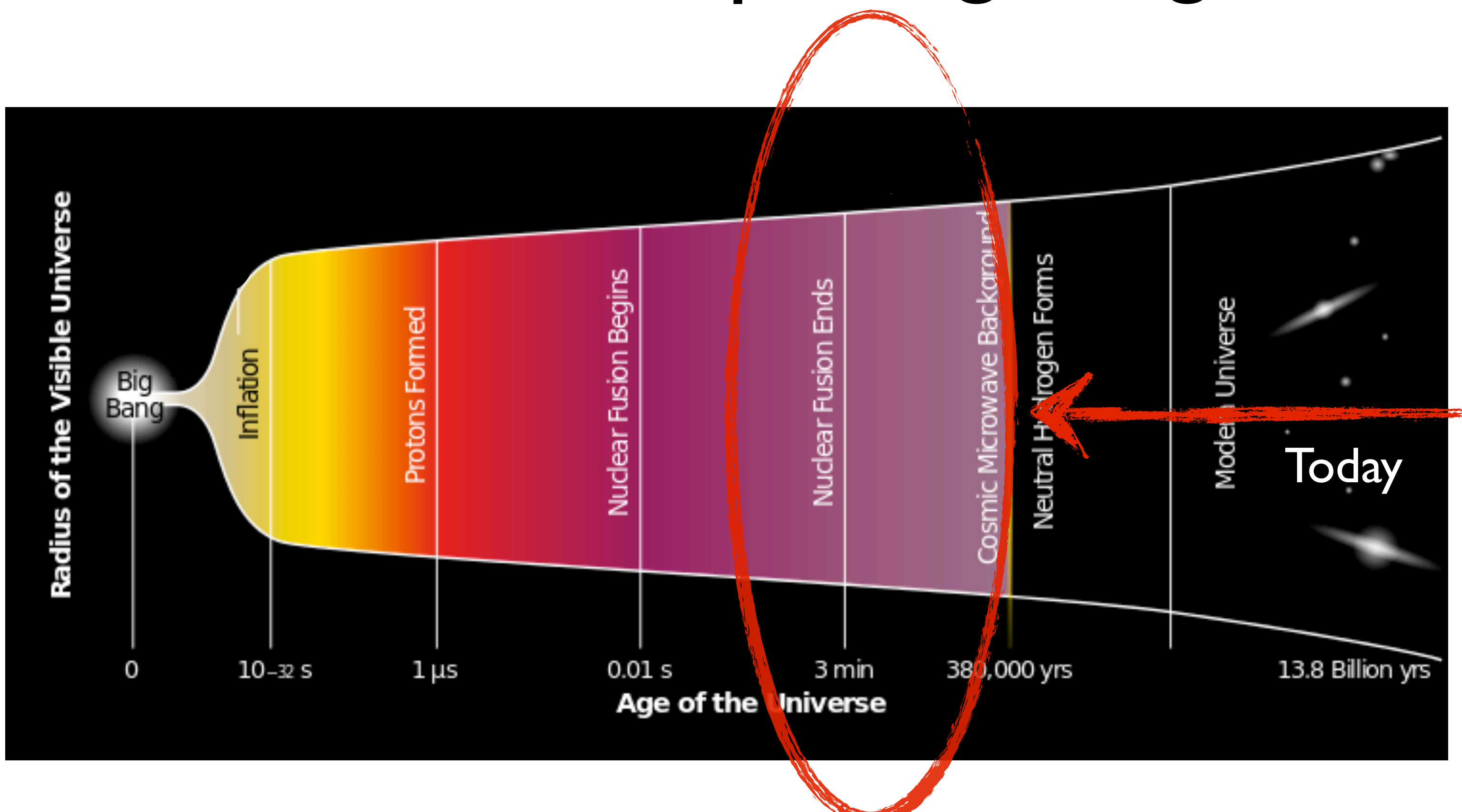


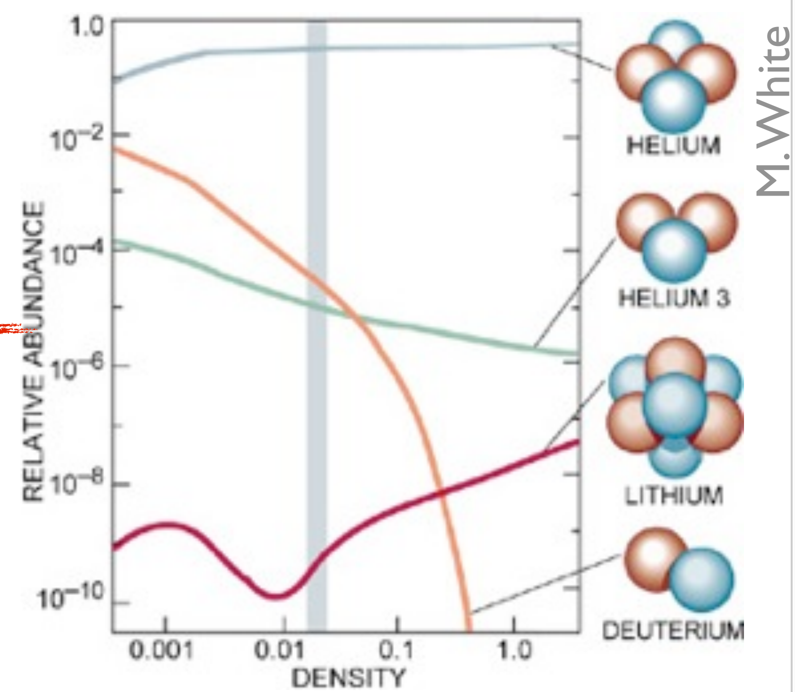
Particle physics +cosmology: Extrapolate to early hot Universe

Expansion with Hubble rate: $H = \frac{\dot{R}}{R}\,, \quad R =$ scale factor

WIMP paradigm: How to explain the dark matter density?

- Successful example: Big Bang Nucleosynthesis

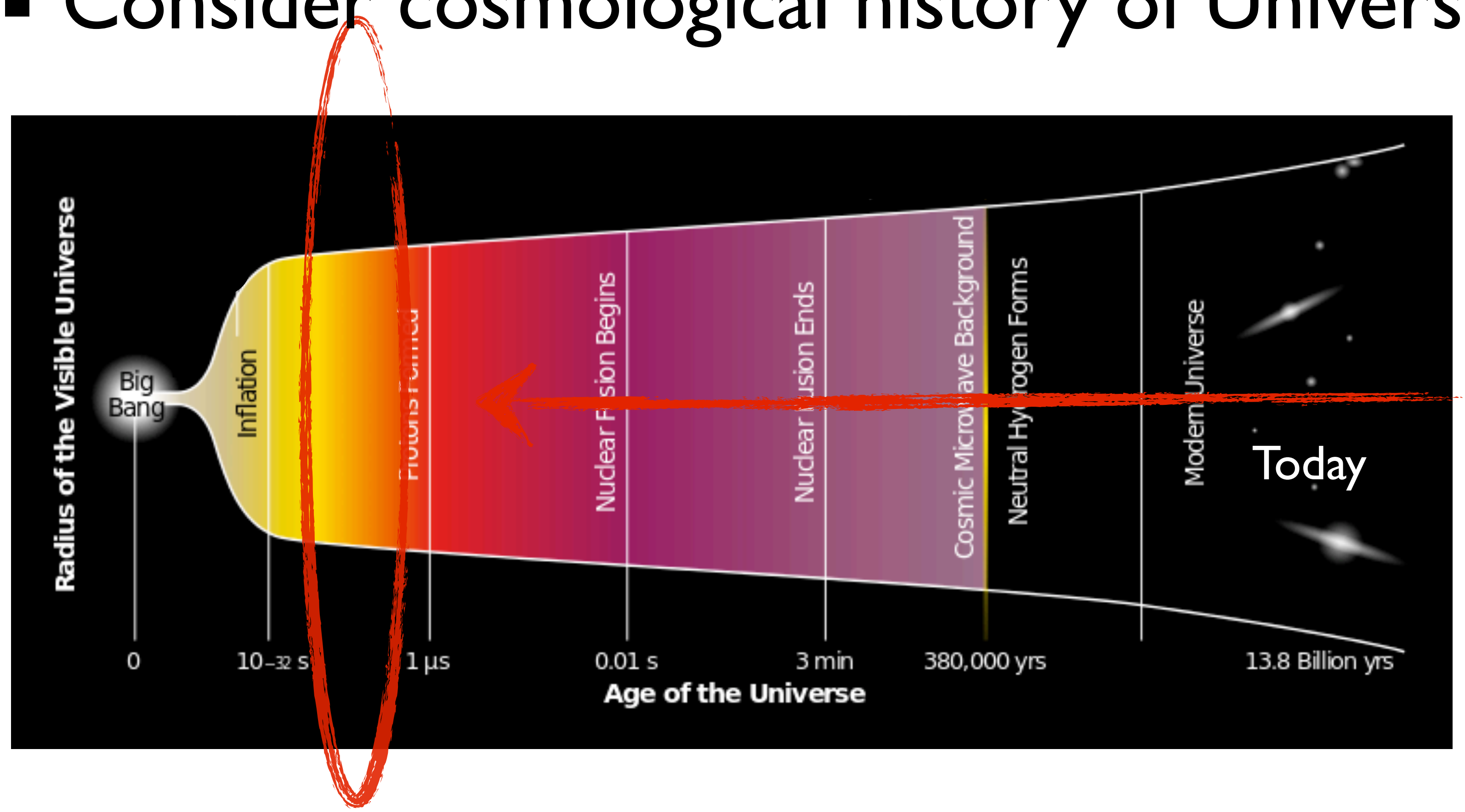




→ Explains primordial abundances of light elements

WIMP paradigm: How to explain the dark matter density?

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



Particle physics +cosmology: Extrapolate to early hot Universe

Temperatures 1-100 GeV (~10^{13}-10^{15} K)

WIMP freeze-out

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

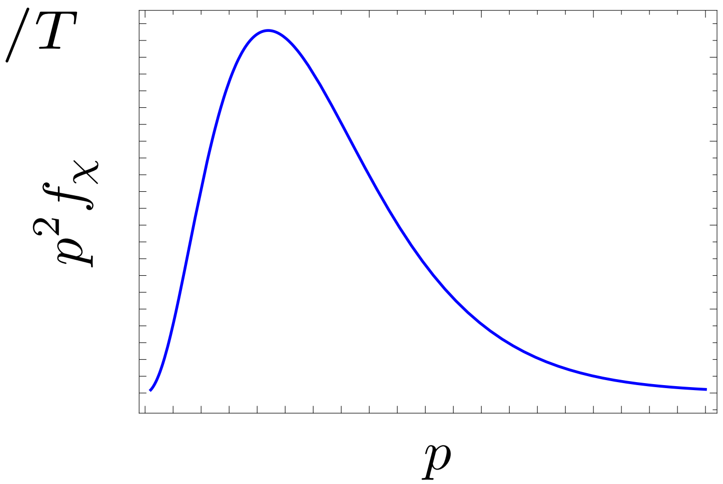
Boltzmann equations for particle densities

[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)

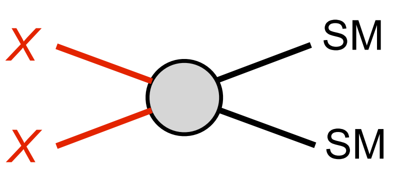
[see e.g. Binder, Bringmann, Gustafsson, Hryczuk 2017 for general solutions without kinetic eq.]



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

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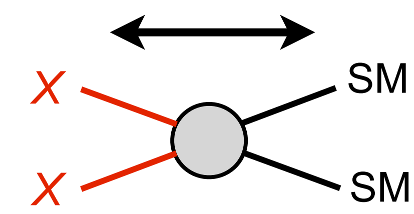
$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + 3Hn_\chi = -\langle\sigma v\rangle_{\rm ann}\left(n_\chi^2 - n_\chi^{\rm eq\,2}\right)$$

Annihilation rate: $\Gamma_{\rm ann} := n_\chi \langle\sigma v\rangle_{\rm ann}$



$$H \gtrless \Gamma_{\rm ann}$$

Boltzmann equations for particle densities

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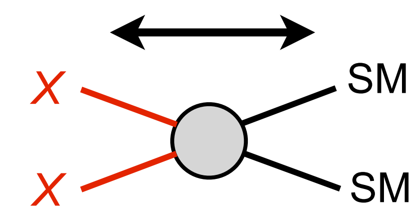

$$\Gamma_{\rm ann} \gg H \quad \Rightarrow \quad n_\chi = n_\chi^{\rm eq} \overset{\text{non-rel.}}{\propto} T^{3/2}\mathrm{e}^{-m_\chi/T}$$

Boltzmann equations for particle densities

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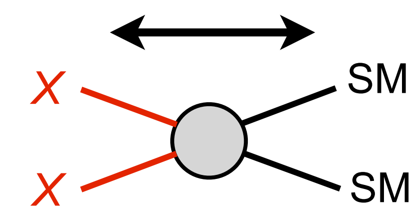

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$$H \gg \Gamma_{\mathrm{ann}} \quad \Rightarrow \quad n_\chi \propto T^3$$

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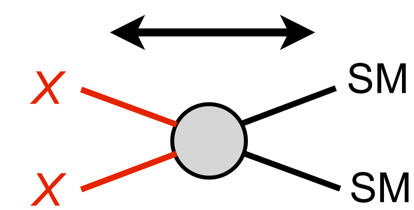

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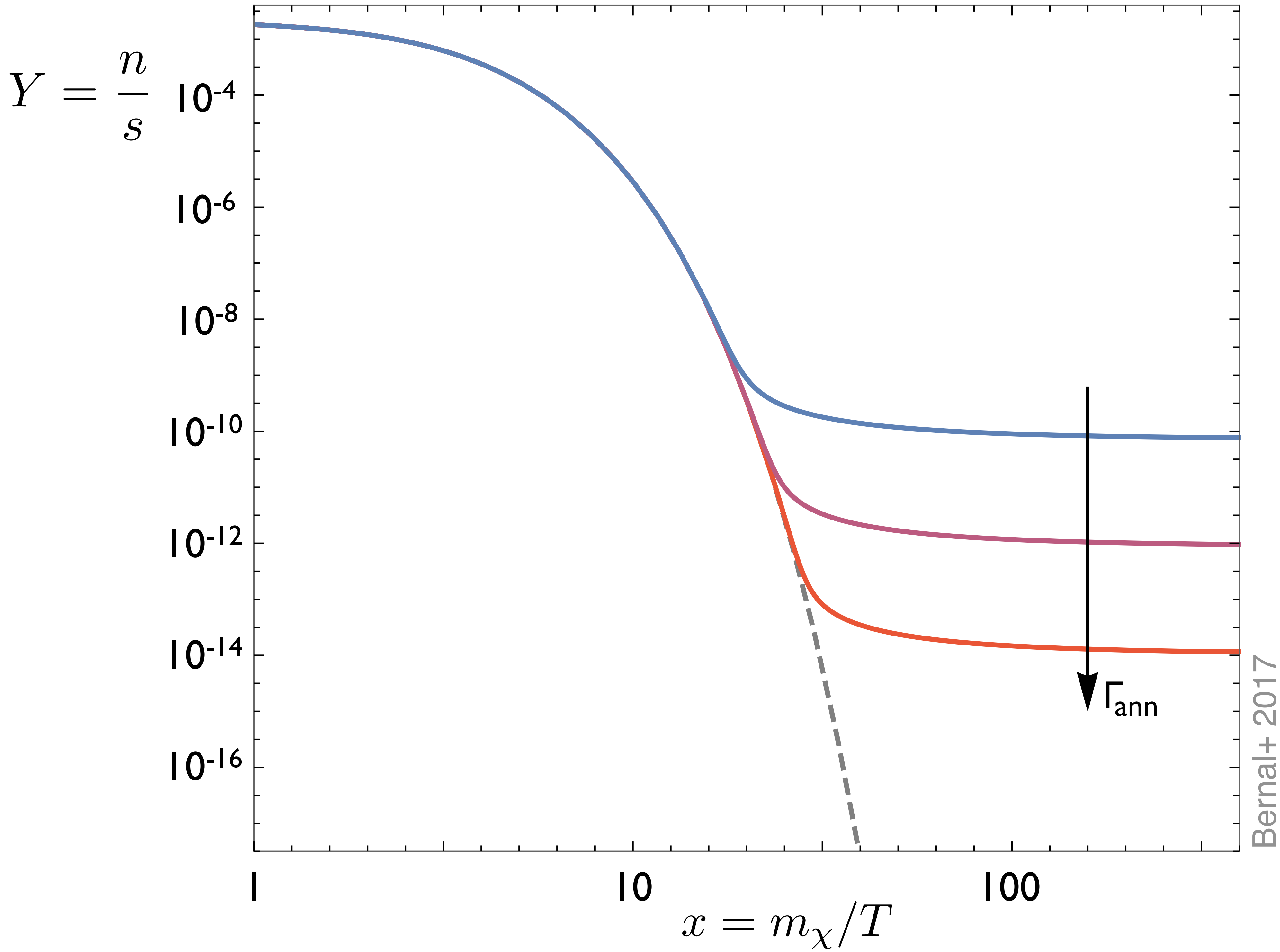
$$H \gg \Gamma_{\mathrm{ann}} \quad \Rightarrow \quad n_\chi \propto T^3$$

$$H \propto T^2 \qquad \langle\sigma v\rangle_{\mathrm{ann}} \propto T^0 + \mathcal{O}(T^2)$$

⇒ For late times (small T) Hubble expansion dominates

WIMP dark matter freeze-out



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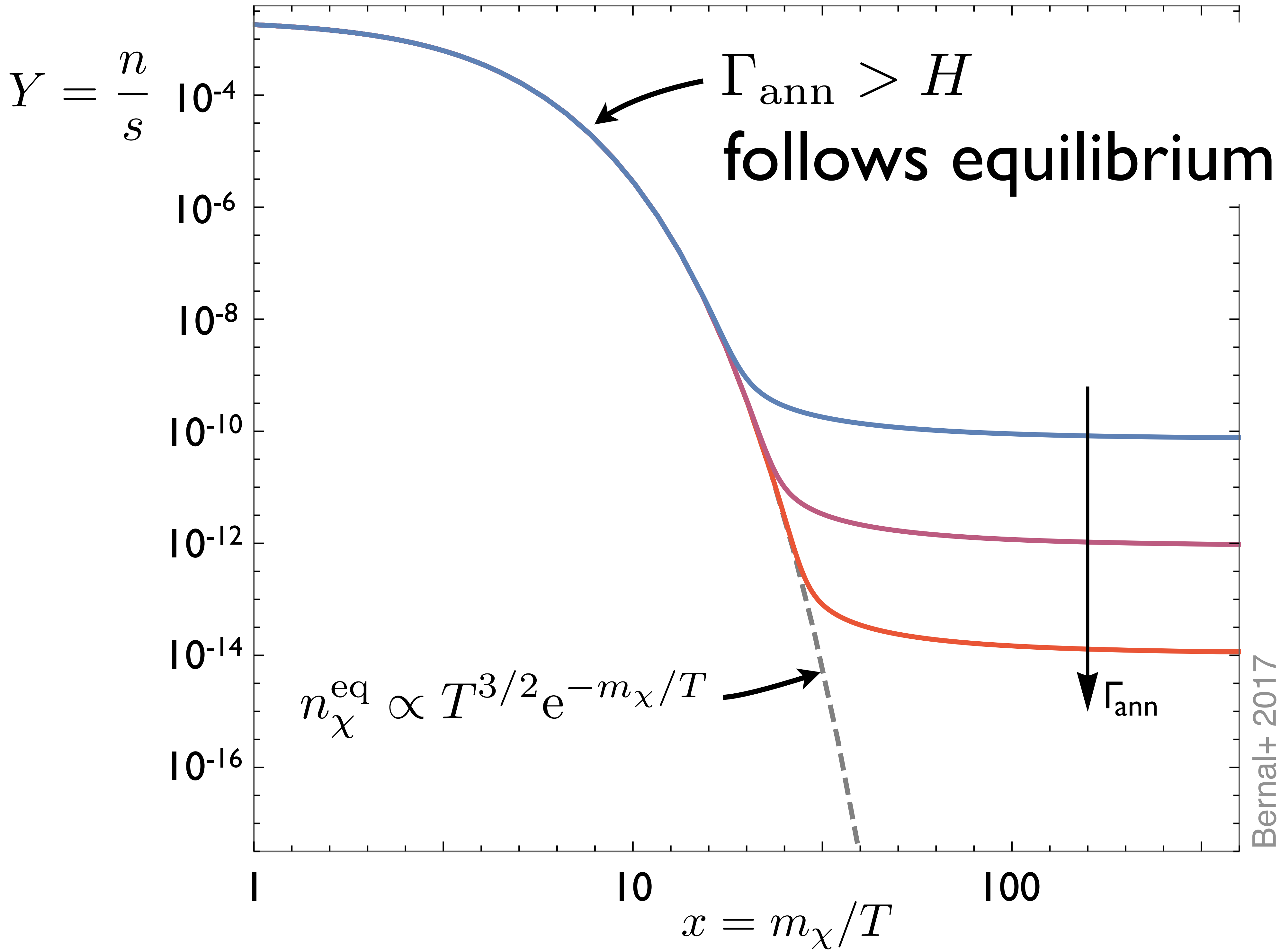

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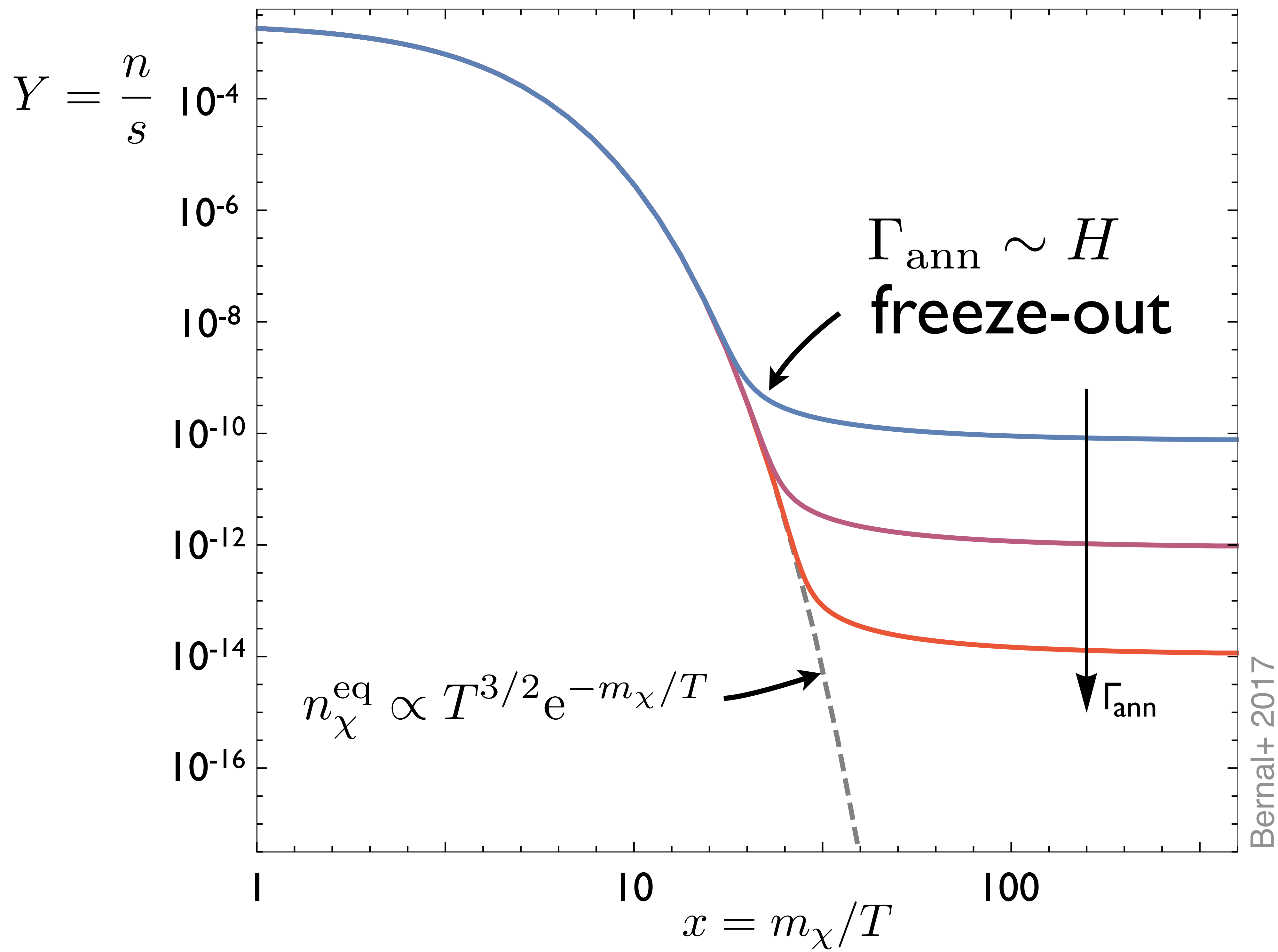

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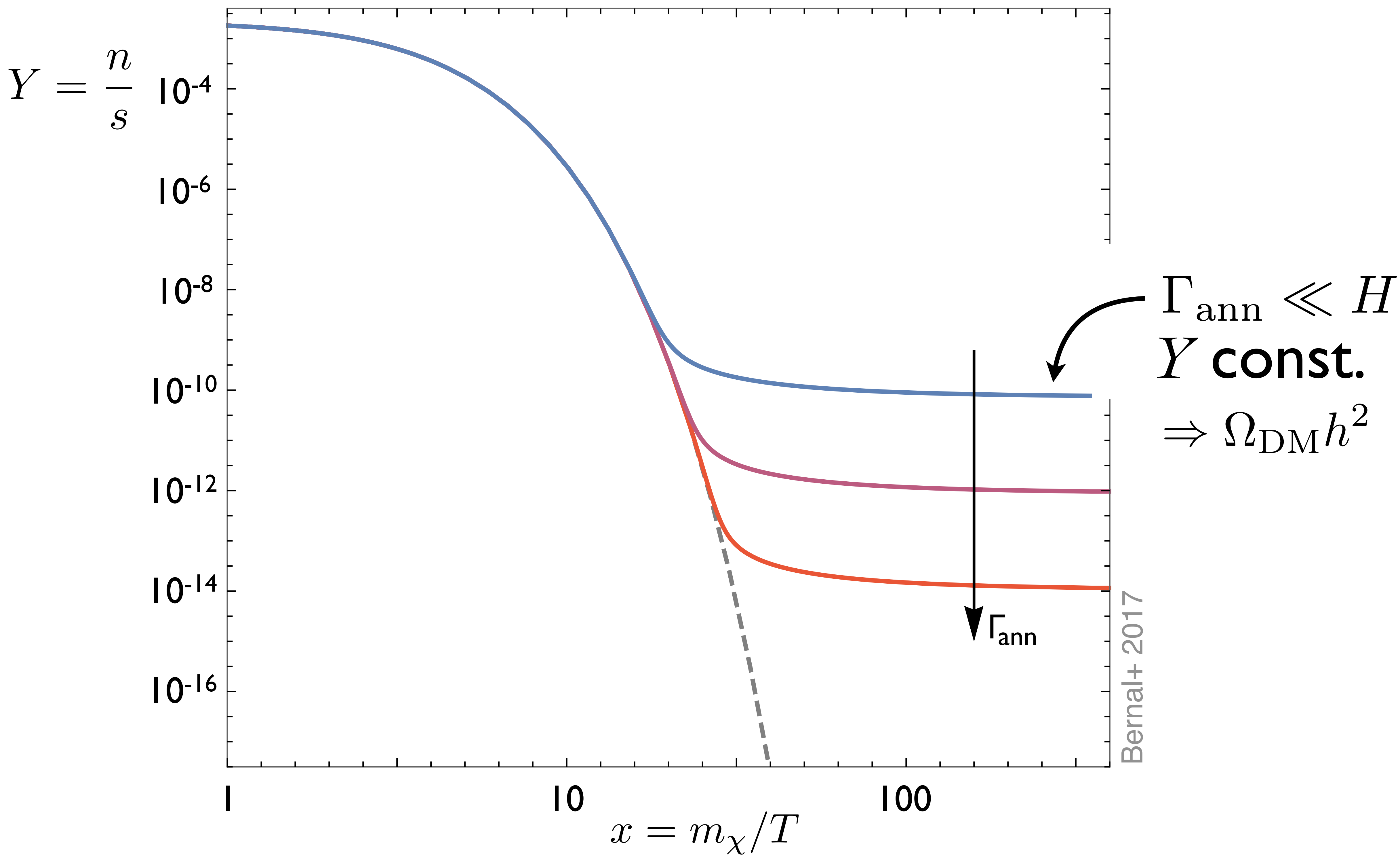

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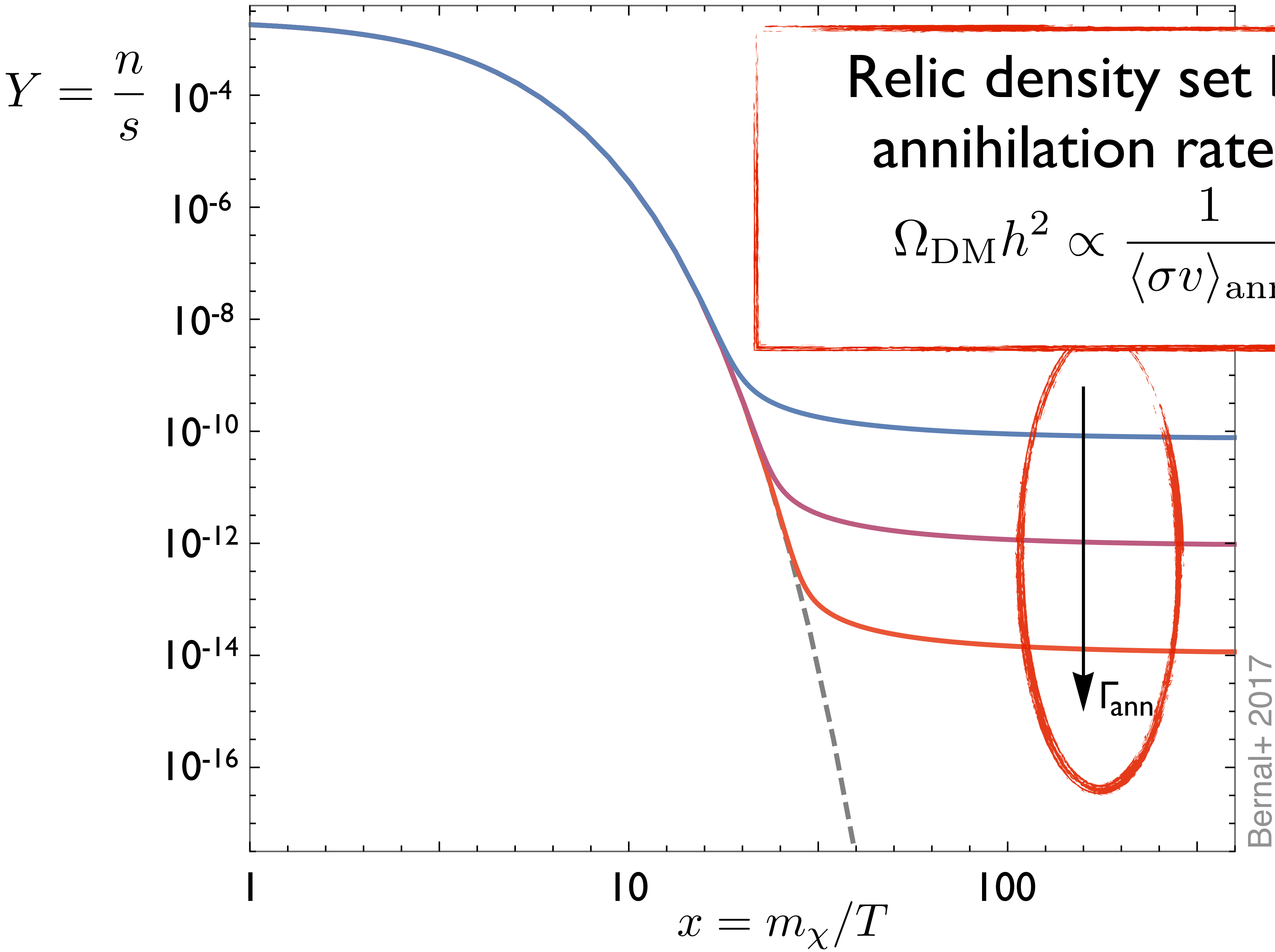
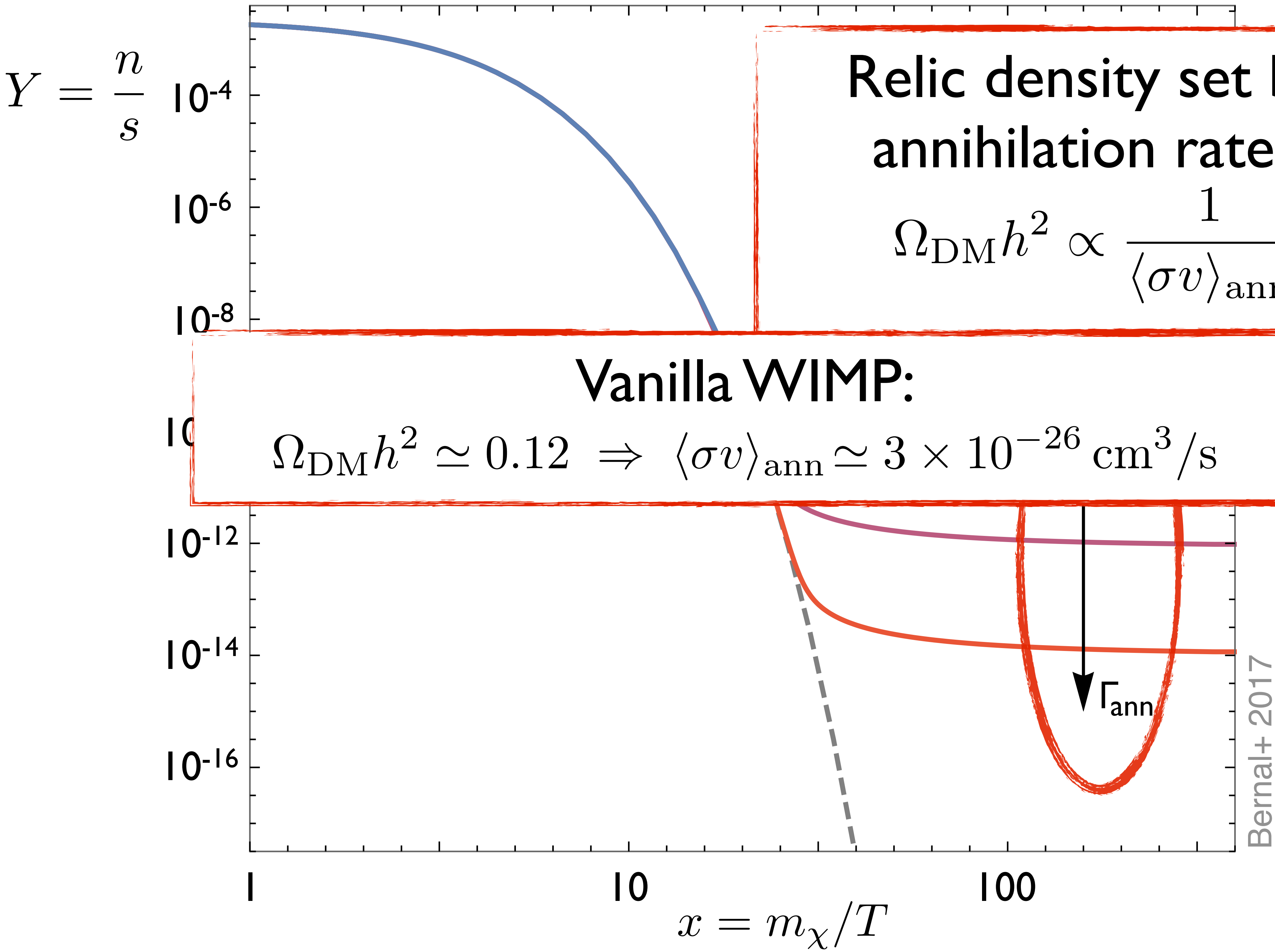


Relic density set by annihilation rate:

$$\Omega_{\rm DM}h^2 \propto \frac{1}{\langle \sigma v \rangle_{\rm ann}}$$

WIMP dark matter freeze-out



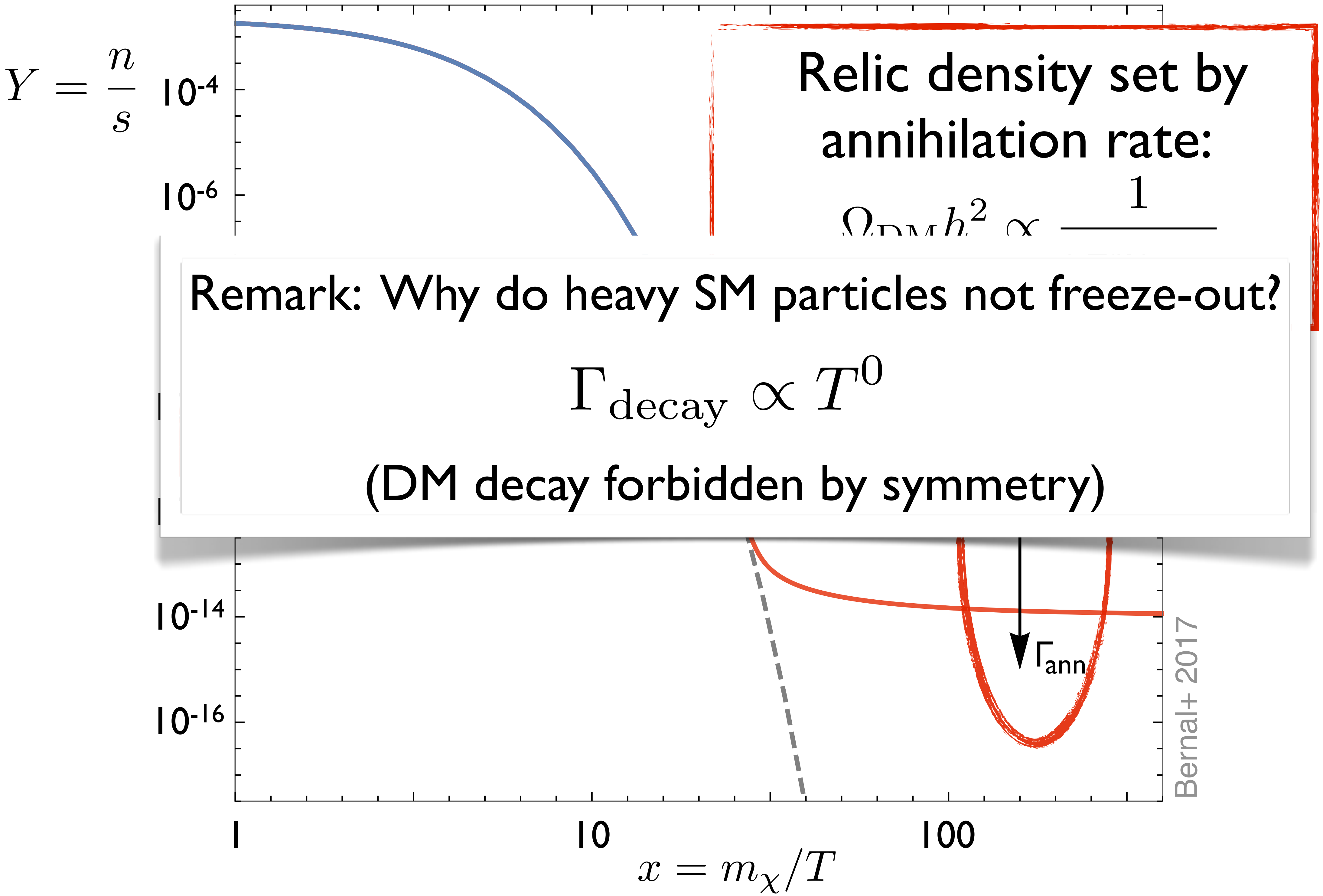
Relic density set by annihilation rate:

$$\Omega_{DM} h^2 \propto \frac{1}{\langle \sigma v \rangle_{ann}}$$

Vanilla WIMP:

$$\Omega_{DM} h^2 \simeq 0.12 \;\Rightarrow\; \langle \sigma v \rangle_{ann} \simeq 3 \times 10^{-26}\,\mathrm{cm^3/s}$$

WIMP dark matter freeze-out



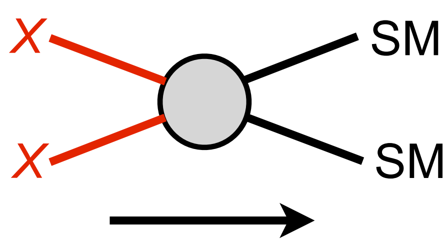
Remark: Why do heavy SM particles not freeze-out?

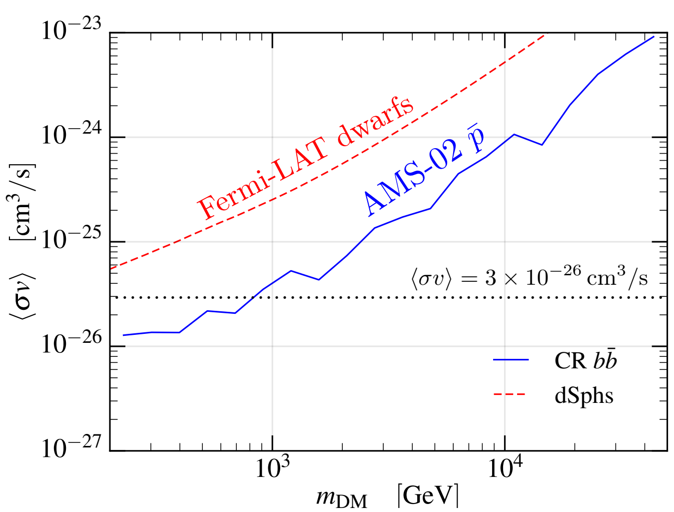
$$\Gamma_{\rm decay} \propto T^0$$

(DM decay forbidden by symmetry)

WIMP Dark Matter: searches

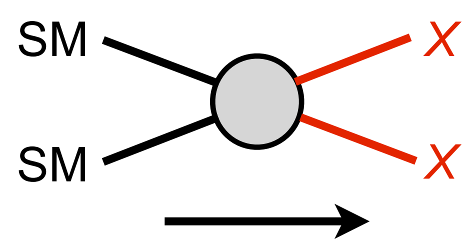
Indirect detection*

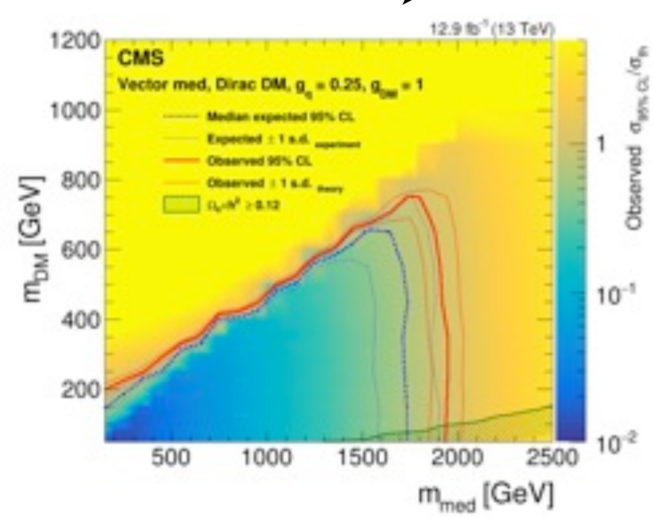




[Cuoco, JH, Korsmeier, Krämer 2017]

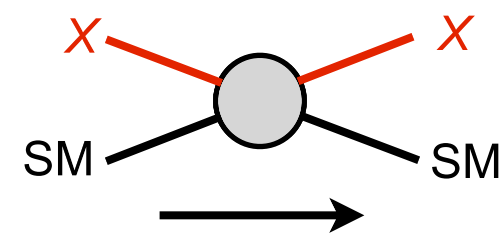
Direct production

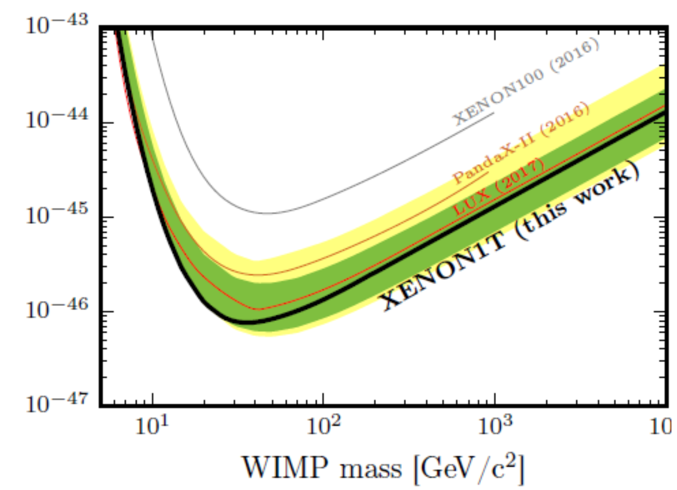




[CMS EXO-16-039]

Direct detection





[Xenon1T 1705.06655]

*) Possible inconclusive hints for DM seen in gamma rays [Hooper, Goodenough 2009; Gordon+ 2013; Abazajian+ 2014; Calore+ 2015; Daylan+ 2016...] and cosmic rays [Cuoco+ 2016, 2017; Cui+ 2016]

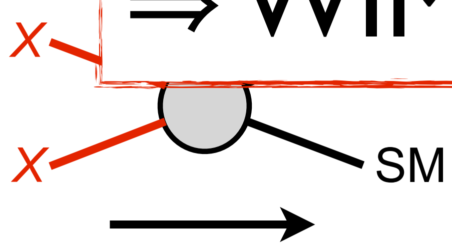
WIMP Dark Matter: searches

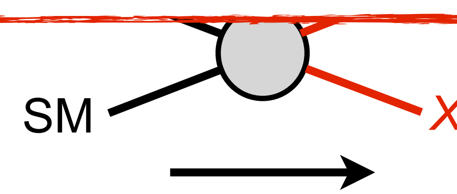
Indirect detection*

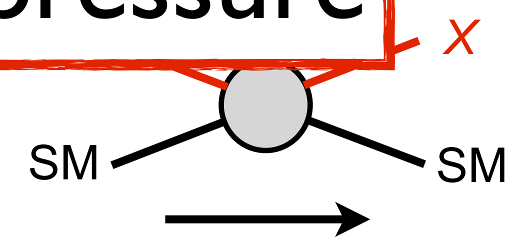
Direct production

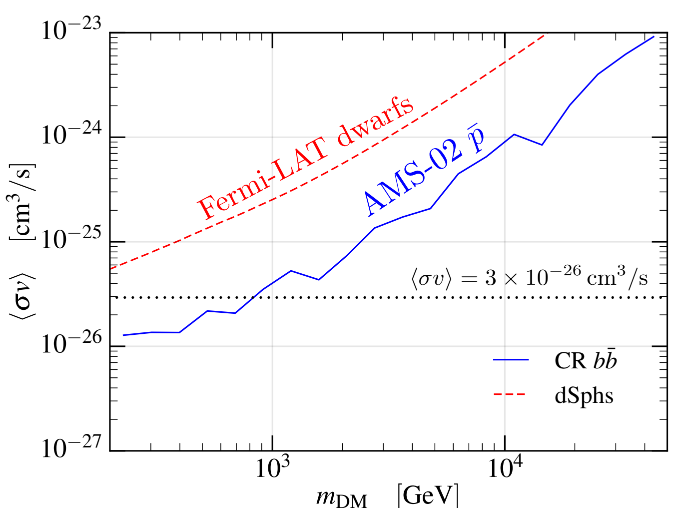
Direct detection

⇒ WIMP dark matter under pressure

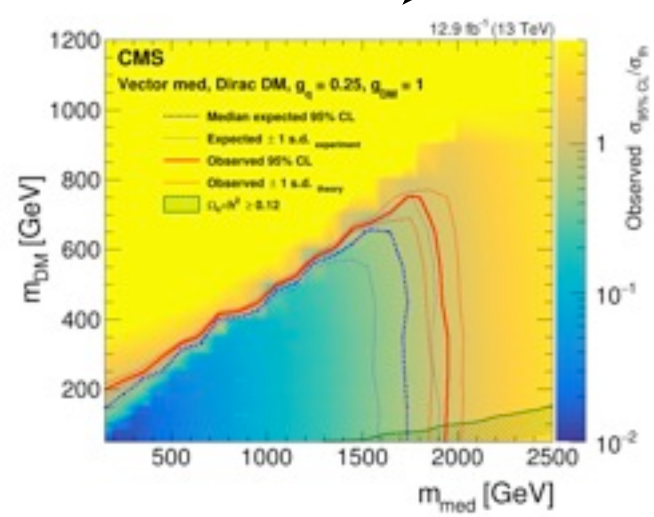








[Cuoco, JH, Korsmeier, Krämer 2017]



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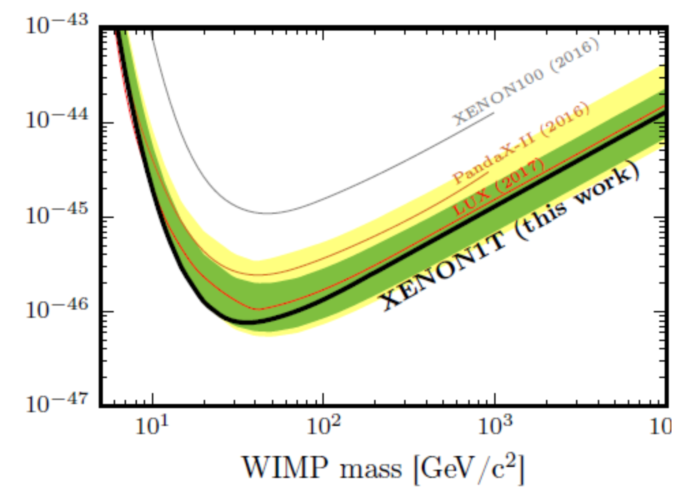

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Dark matter beyond WIMPs

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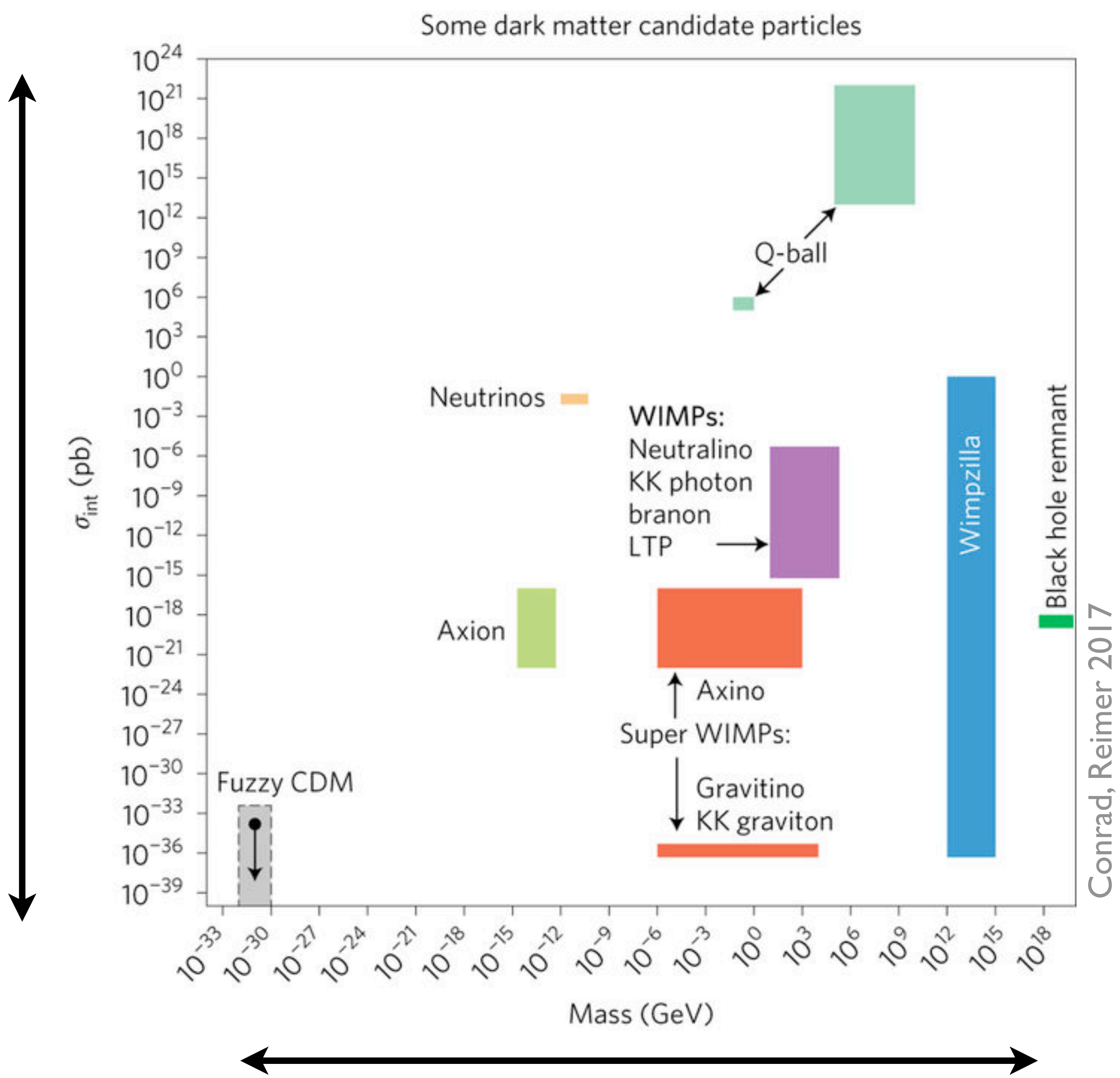


DM Models span huge range in mass and coupling!

Dark matter beyond WIMPs

Some dark matter candidate particles

Here: Focus on GeV-TeV range (WIMP-like)

but explore smaller couplings

➔ naturally accomodate WIMP search null-results

- small coupling ⇒ overproduction of DM?

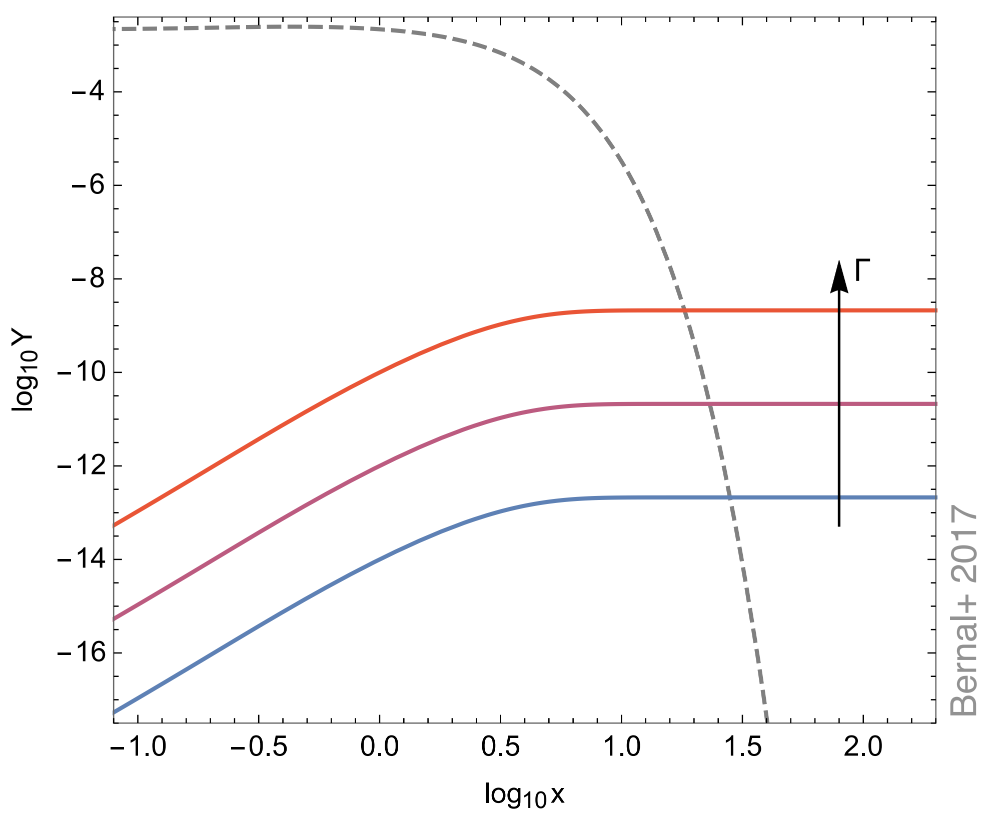
- briefly review two such scenarios
- present conversion-driven freeze-out

Other avenues beyond WIMPs: Secluded dark matter [Pospelov, Ritz, Voloshin 2007; Feng, Kumar 2008], Asymmetric dark matter [Kaplan, Luty, Zurek, 2009], SIMPs [Hochberg, Kuflik, Volansky, Wacker, 2014], Co-Decaying dark matter [Dror, Kuflik, Ng, 2016], Forbidden dark matter [D'Agnolo, Ruderman, 2015], Pseudo-Dirac dark matter [Davolia, De Simone, Jacquesa, Sanz 2017], ELDERs [Kuflik, Perelstein, Rey-Le Lorier, Tsai, 2016 & 2017], ...

DM Models span huge range in mass and coupling!

Freeze-in scenario

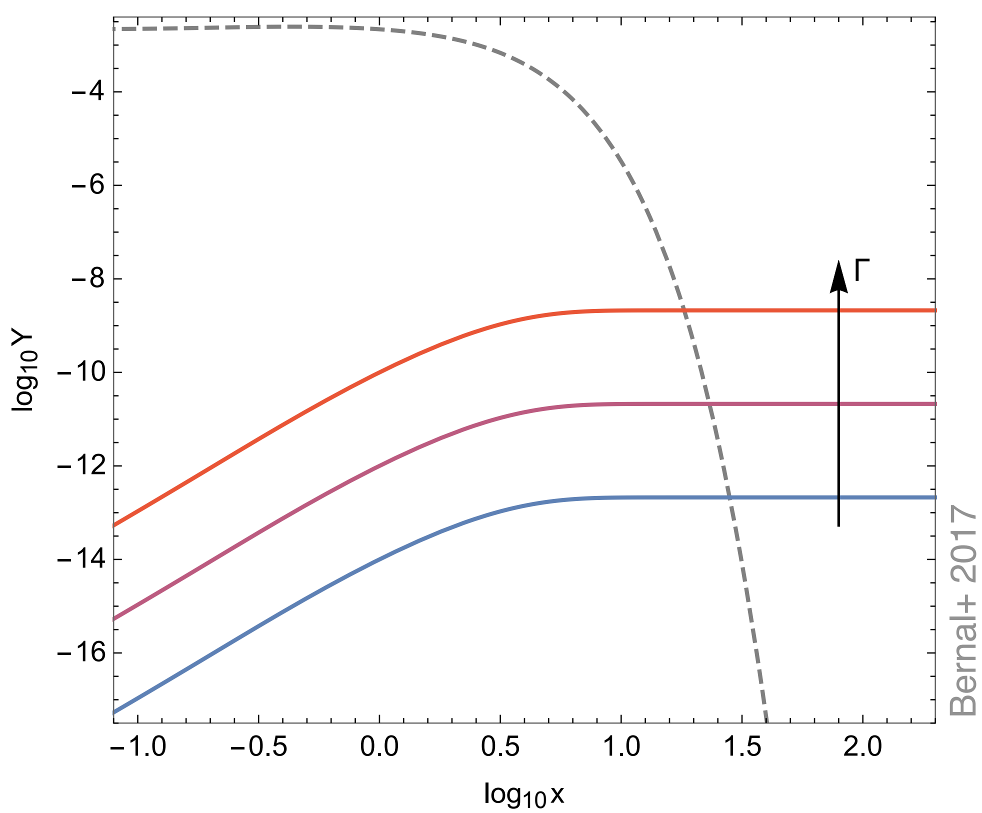
[McDonald 2002; Choi, Roszkowski 2005; Petraki, Kusenko 2008; Hall, Jedamzik, March-Russell, West, 2009]



$$\lambda \sim 10^{-12} \left(\frac{\Omega_{\rm DM} h^2}{0.12}\right)^{1/2}$$

Freeze-in scenario

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

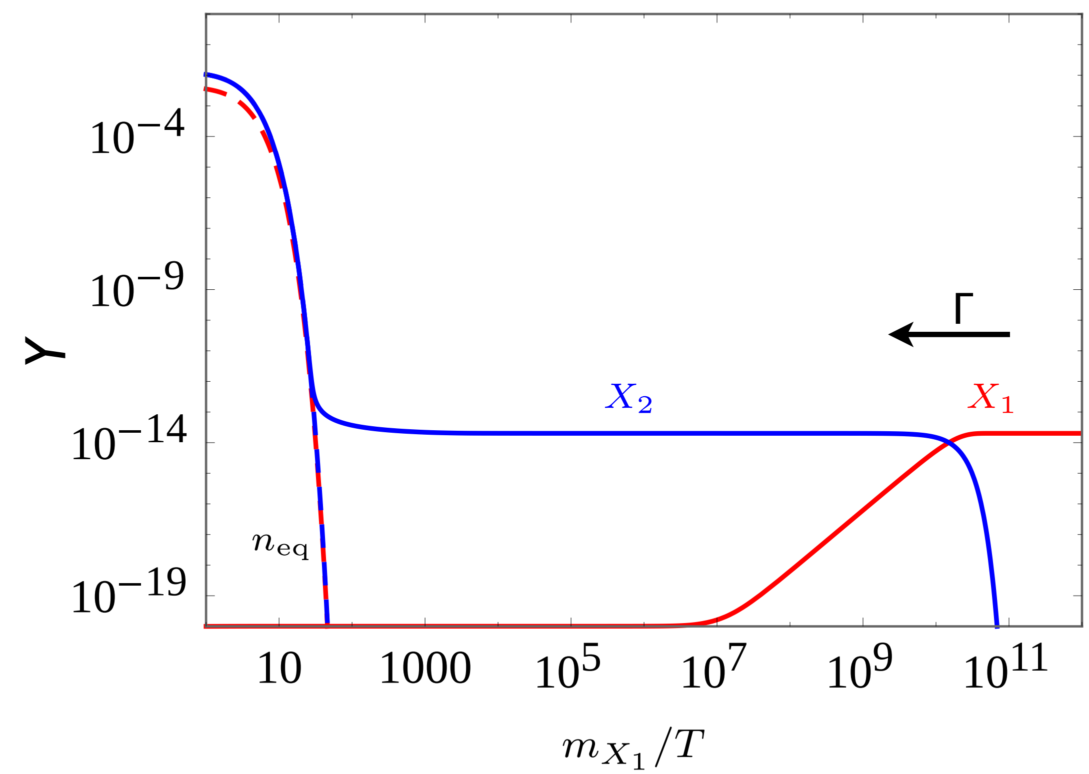


$$\lambda \sim 10^{-12} \left(\frac{\Omega_{\rm DM} h^2}{0.12} \right)^{1/2}$$

SuperWIMP scenario

[Feng, Rajaraman, Takayama 2003]

DM production from decay of heavier thermal relic



➔ even smaller couplings

Freeze-in scenario

[McDonald 2002; Choi, Roszkowski 2005;
Pe
Ru

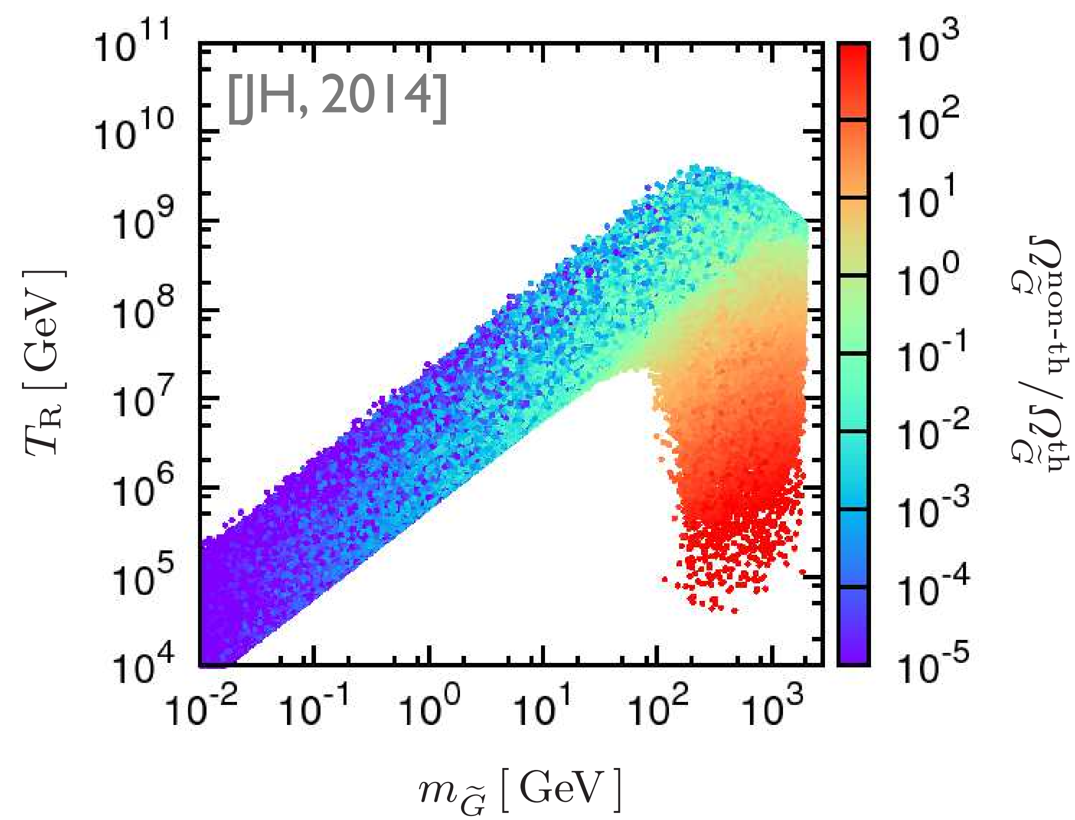
SuperWIMP scenario

[Feng, Rajaraman, Takayama 2003]

Assumes zero abundance initially
→ dependence on initial conditions

E.g. gravitino as
a superWIMP:

thermal scattering
during reheating



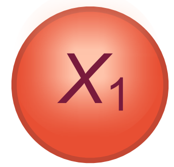
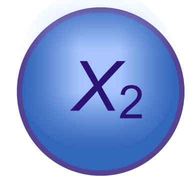
Conversion-driven freeze-out

[Garny, JH, Lülf, Vogl 2017]

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

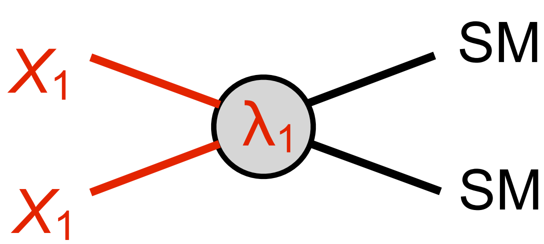
Revisiting WIMP co-annihilation

[Griest, Seckel 1991; Edsjo, Gondolo 1997]

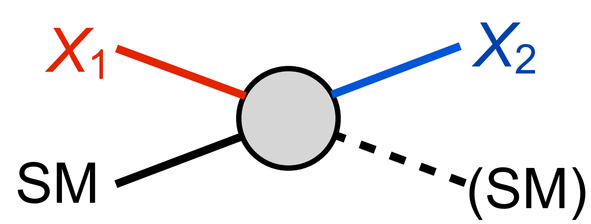
dark matter  $m_1 < m_2$  co-annihilation partner

λ_1 $\Delta m \ll m_{1,2}$ λ_2

Annihilation
$X_1 \to \mathrm{SM}$

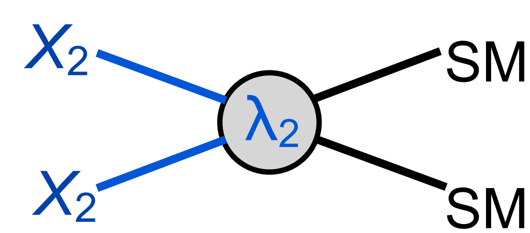


Conversion
$X_1 \to X_2$



+

Co-annihilation
$X_2 \to \mathrm{SM}$

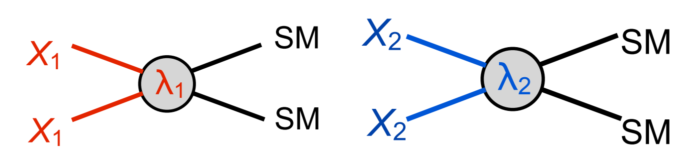


Revisiting WIMP co-annihilation

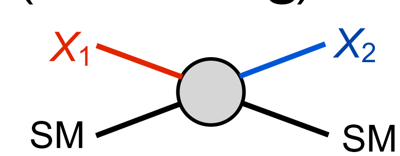
[Griest, Seckel 1991; Edsjo, Gondolo 1997]

Coupled set of Boltzmann equations:

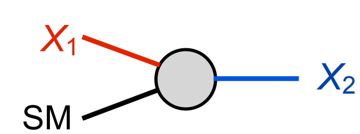
$$\frac{\mathrm{d}n_i}{\mathrm{d}t} + 3Hn_i = -\sum_{j=1}^{N} \langle \sigma_{ij} v_{ij} \rangle \left(n_i n_j - n_i^{\mathrm{eq}} n_j^{\mathrm{eq}} \right)$$ annihilations



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



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



Usually (e.g. SUSY): $\lambda_1 \sim \lambda_2 \sim g_{SM}$ ⇒ 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

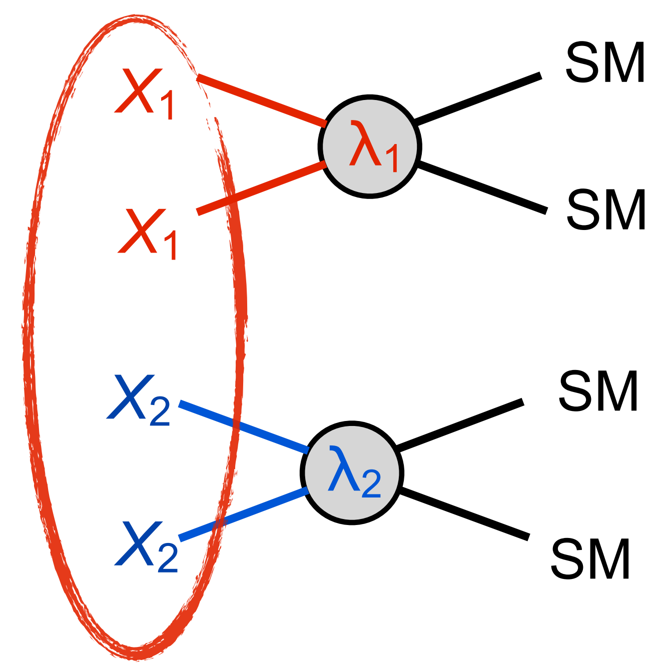
⇒ reduction to single, uncoupled Boltzmann equation*:

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

$n := \sum_i n_i$ entire dark sector

$\langle \sigma v \rangle_{\mathrm{eff}}$ effective ann. cross section

$$\Omega h^2 \propto \frac{1}{\langle \sigma v \rangle_{\mathrm{eff}}}$$



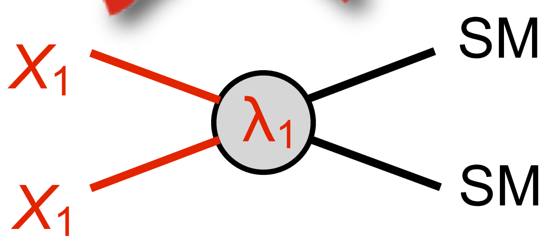
*) Solved by numerical tools [DarkSUSY, micrOMEGAs, MadDM]

Conversion-driven freeze-out

[Garny, JH, Lülf, Vogl 2017]

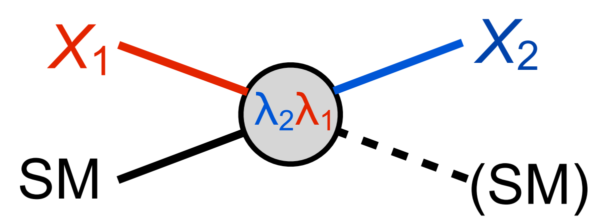
Consider $\lambda_1 \ll \lambda_2$: $X_1 \overset{\text{eq.?}}{\longleftrightarrow} X_2$

~~Annihilation~~
~~$X_1 \to$ SM~~

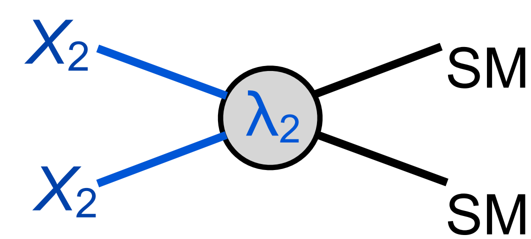


negligable

Conversion
$X_1 \to X_2$



Co-annihilation
$X_2 \to$ SM



large rate

Conversion-driven freeze-out

[Garny, JH, Lülf, Vogl 2017]

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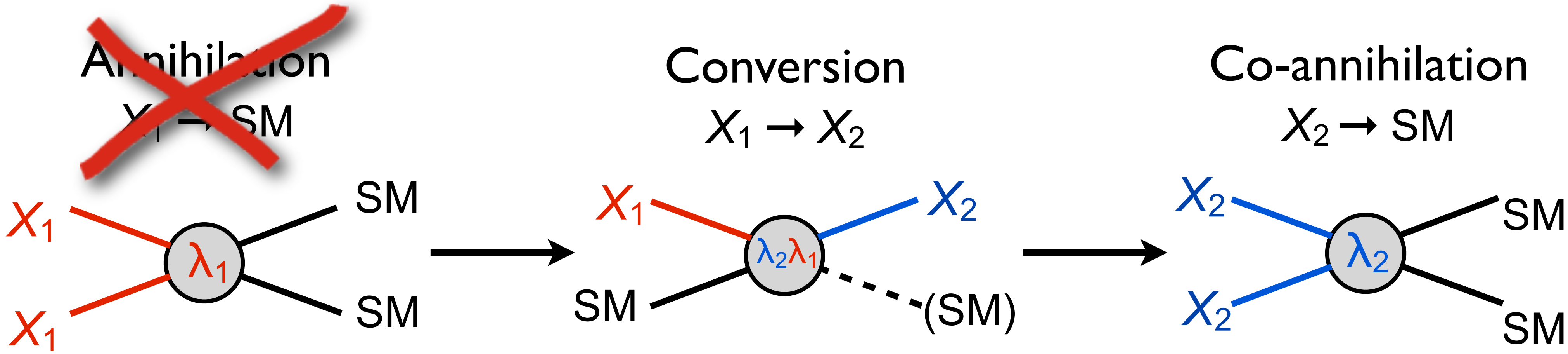

negligable

large rate

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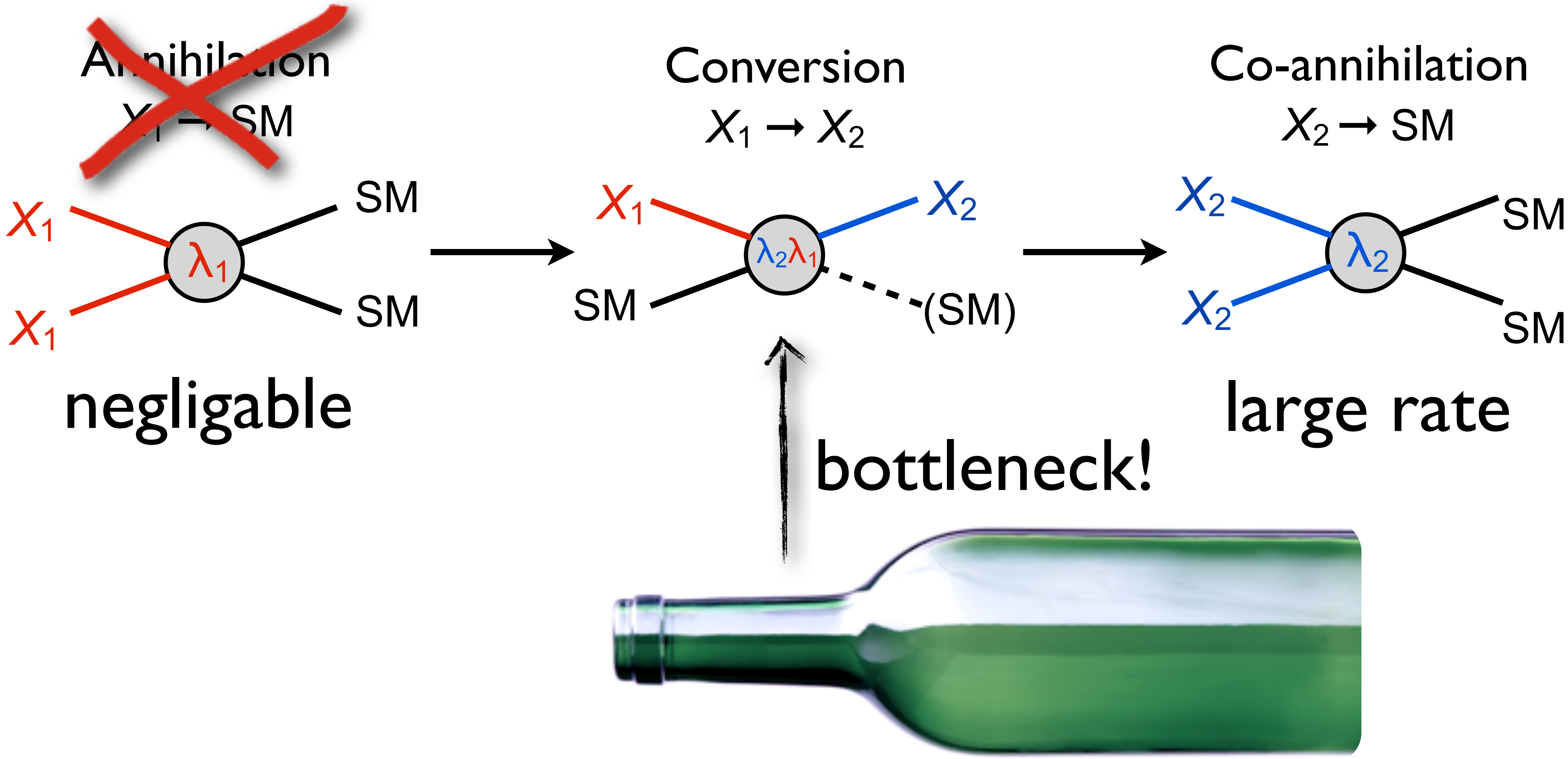


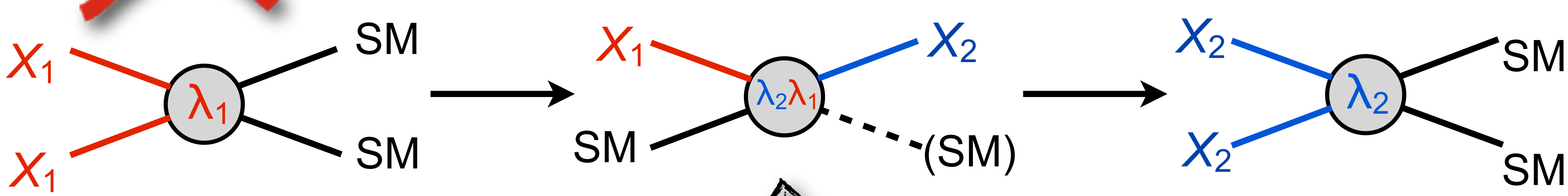
➔ Relic density is set by the size of the conversion rate

Conversion-driven freeze-out

[Garny, JH, Lülf, Vogl 2017]

Consider $\lambda_1 \ll \lambda_2$: $X_1 \overset{\text{eq.?}}{\longleftrightarrow} X_2$

~~Annihilation $X_1 \to$ SM~~ | Conversion $X_1 \to X_2$ | Co-annihilation $X_2 \to$ SM



negligable | bottleneck! | large ra…

No chemical equilibrium!
Coupled system to be solved

➔ Relic density is set by the size of the conversion rate

General back-of-the-envelope estimate:

Conversion rate (just) efficient at freeze-out:

$$\Gamma_{\rm conv} = \Gamma_{\rm decay} + \Gamma_{\rm scatter} \sim H(x \simeq 30)$$

⇒ X_2 decay-length:

$$c\tau = \frac{1}{\Gamma_{\rm decay}} \gtrsim \frac{1}{H(x \simeq 30)} \sim 1\text{–}100\,{\rm cm}$$

(for masses 100GeV to a few TeV)

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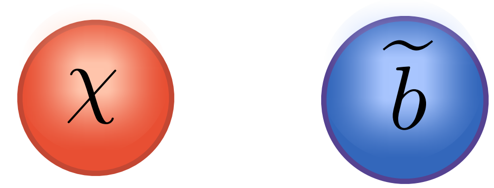
(for masses 100GeV to a few TeV)

⇒ Long-lived particles at LHC!

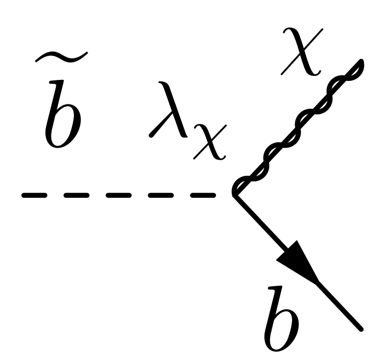
"LLP-miracle"

An explicit example

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



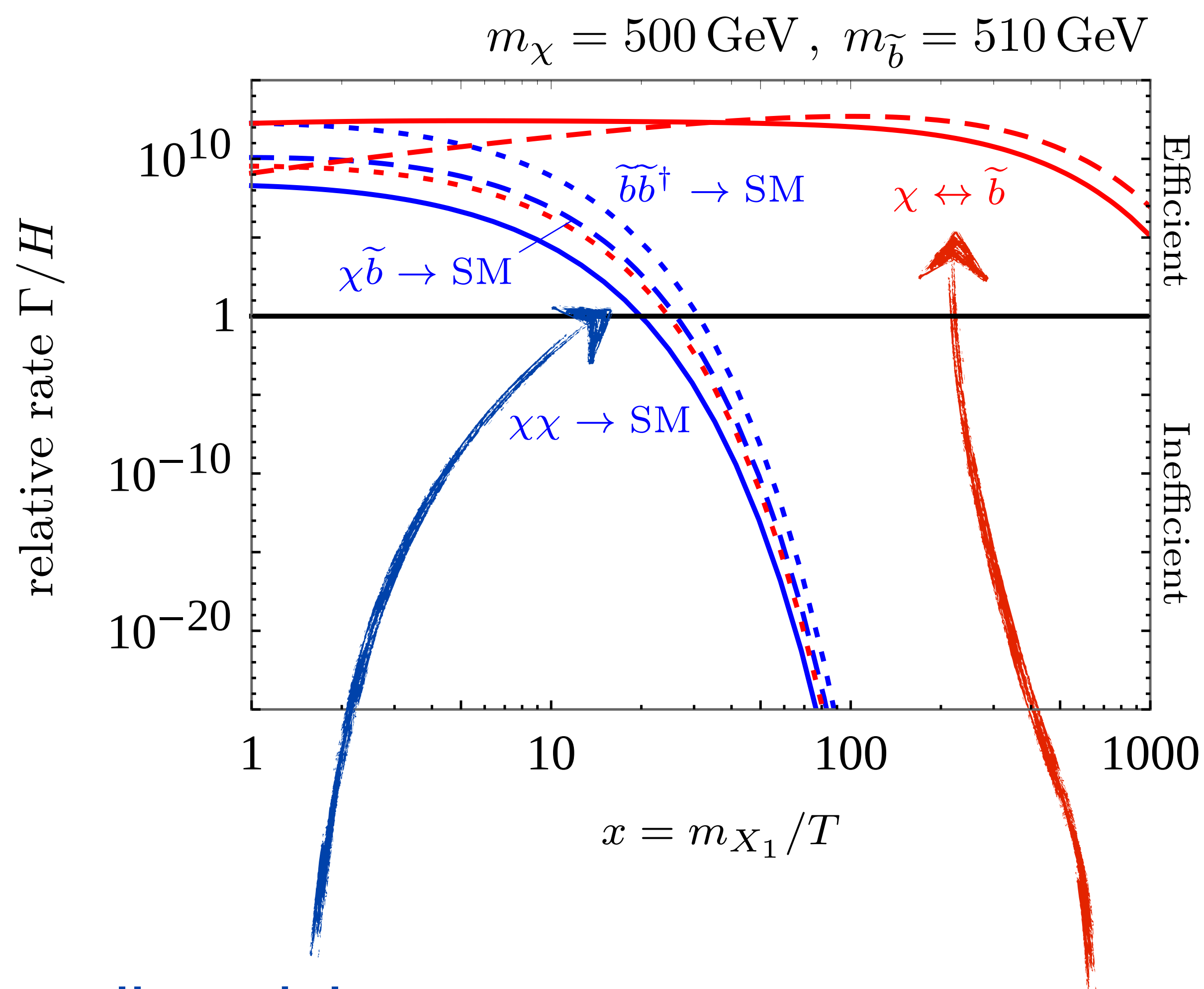
- Yukawa-type interaction:



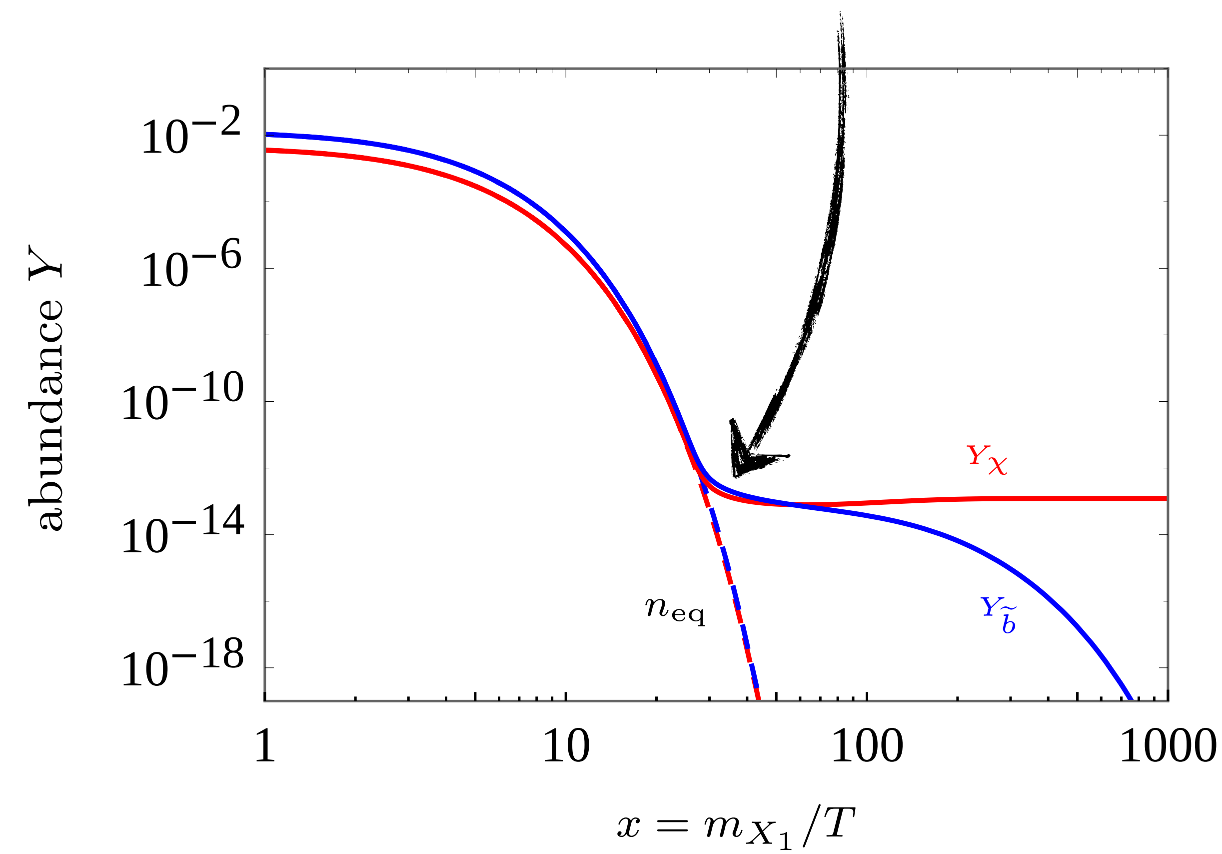
λ_χ is a free parameter here [see Ibarra et al. 2009 for SUSY realization]

Numerical solution of full coupled system

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



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



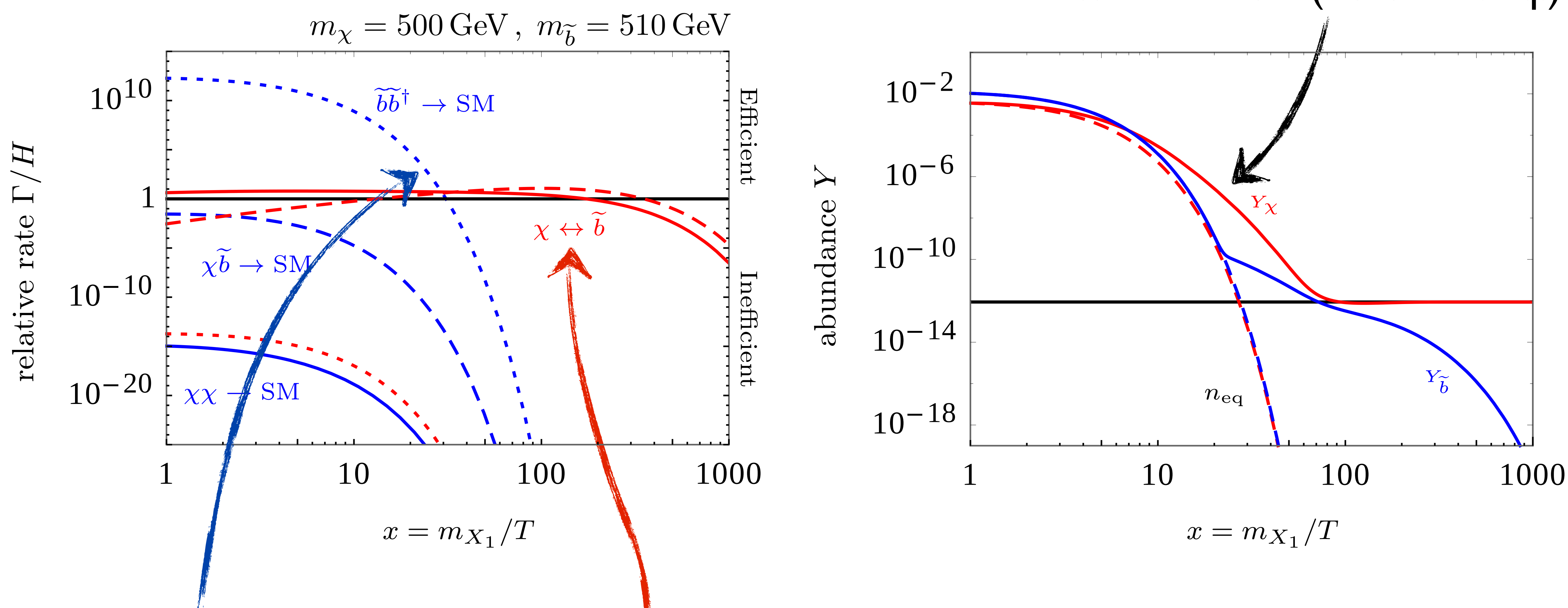
all annihilations contribute

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.)

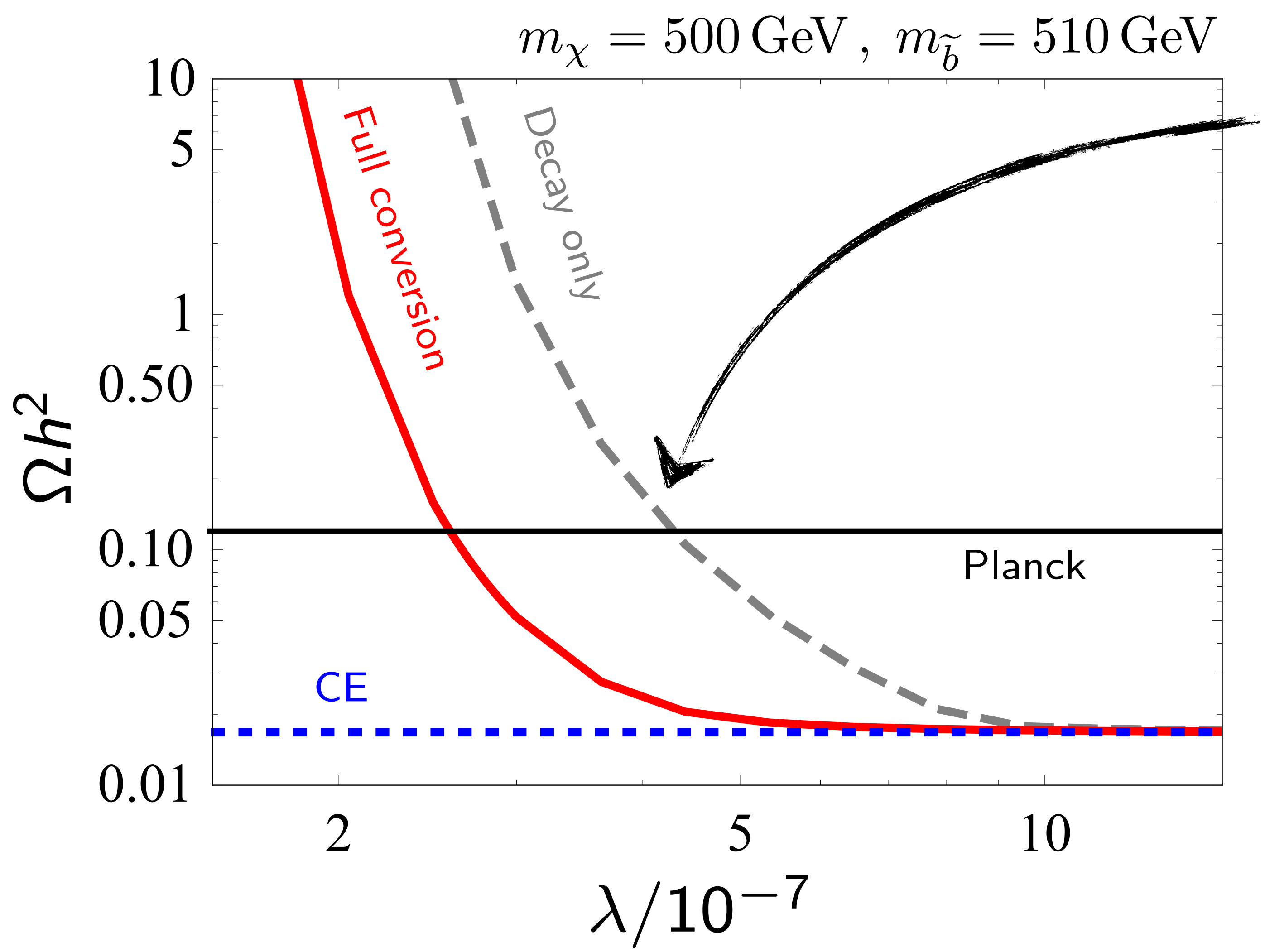


mediator-annihilation contributes only

conversion on the edge of being efficient

Numerical solution of full coupled system

- Scan of the coupling:

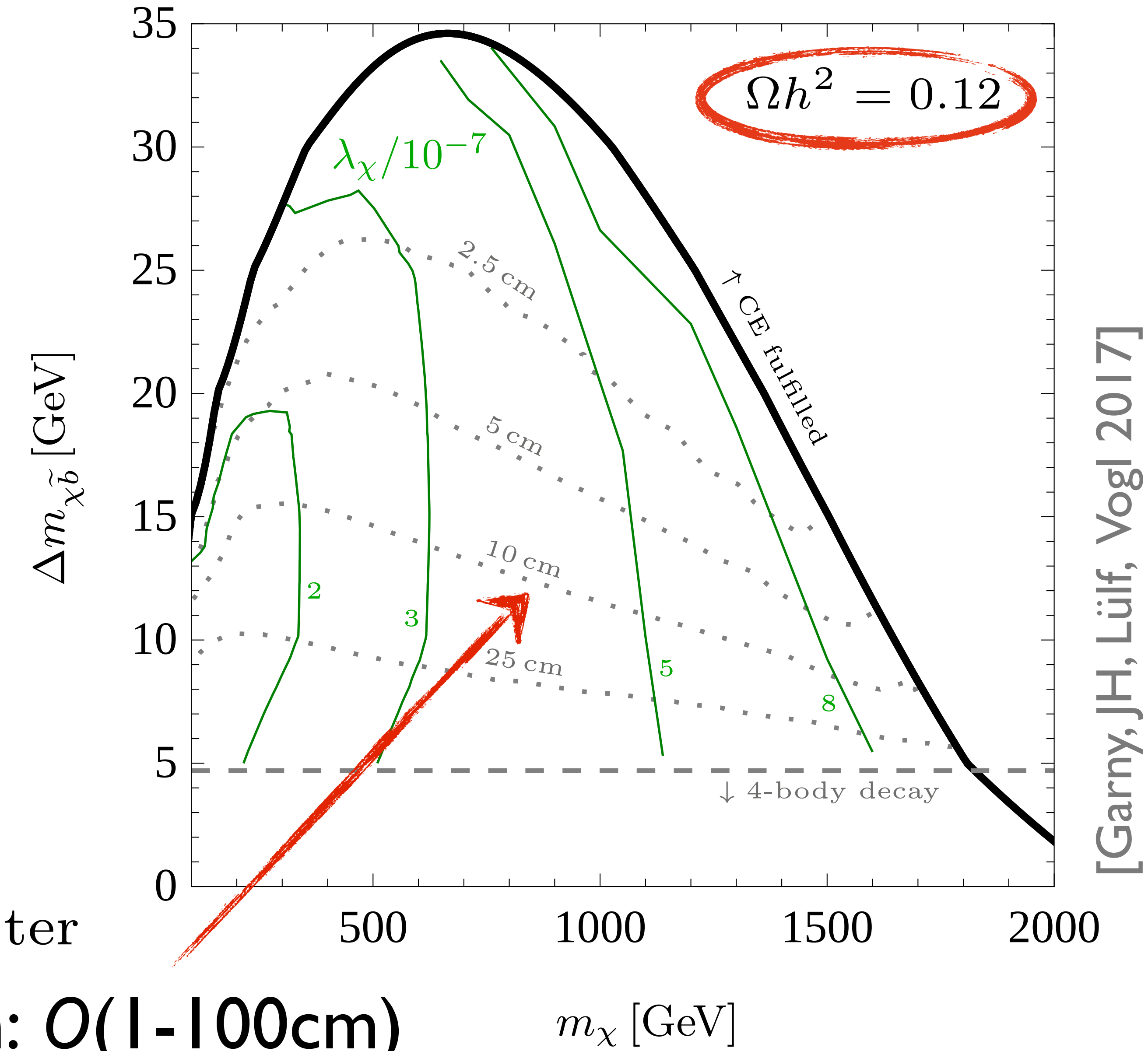


Decay only similar

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

Allowed parameter space

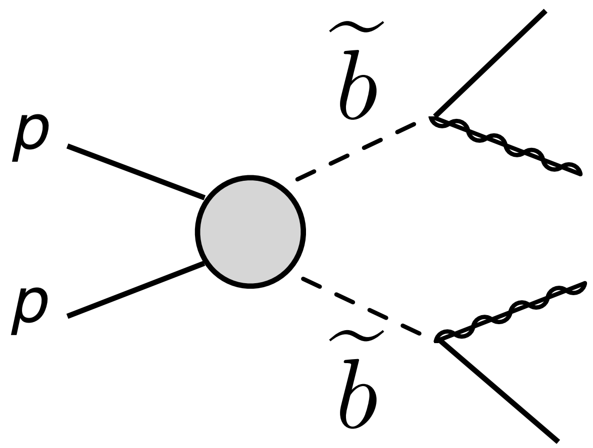
- Require Planck relic density

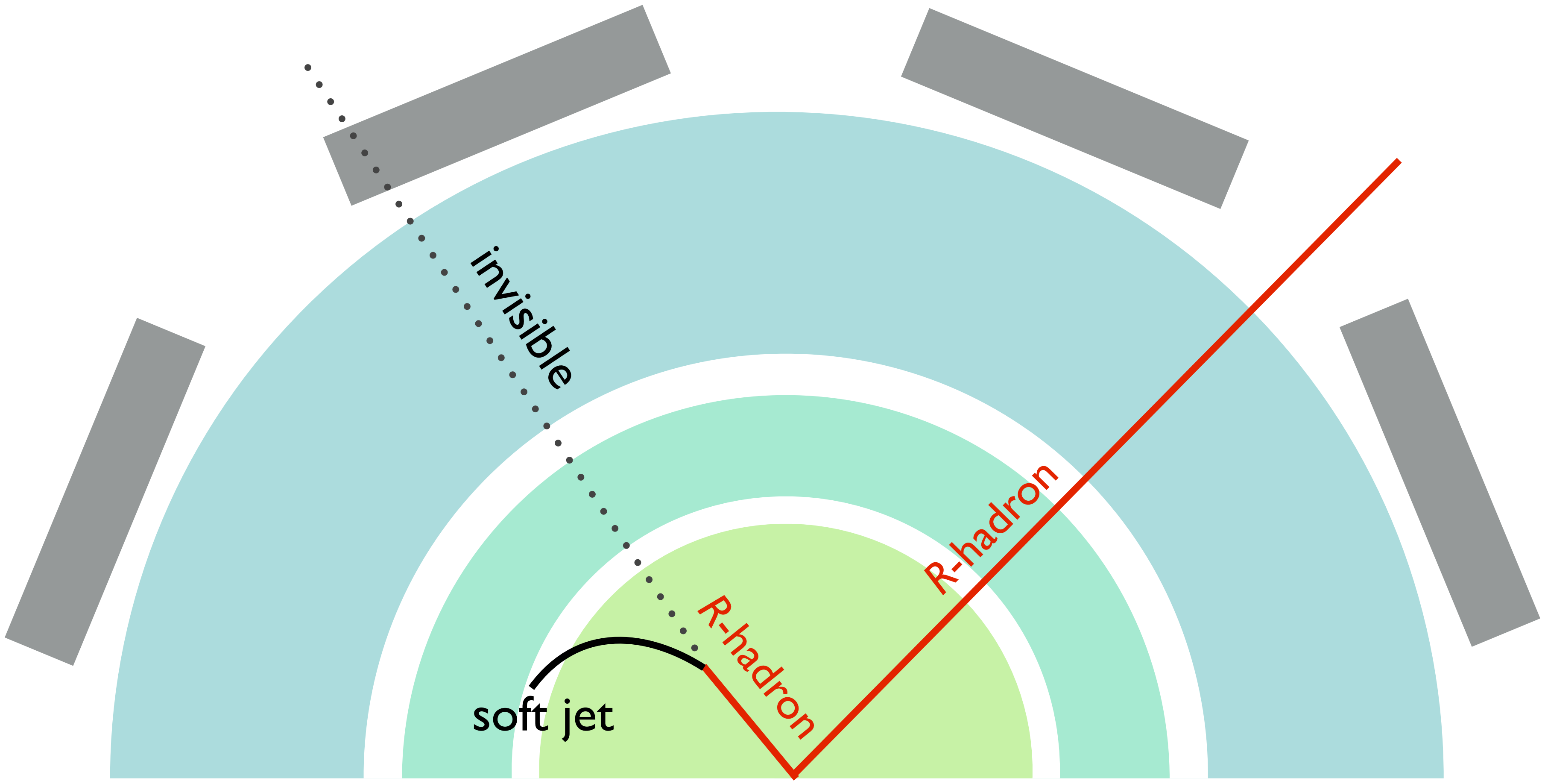


$\Gamma_{\text{decay}} \sim \Gamma_{\text{scatter}}$

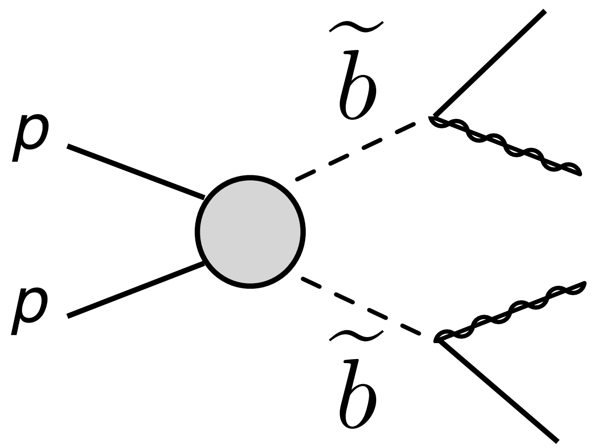
⇒ Decay length: *O*(1-100cm)

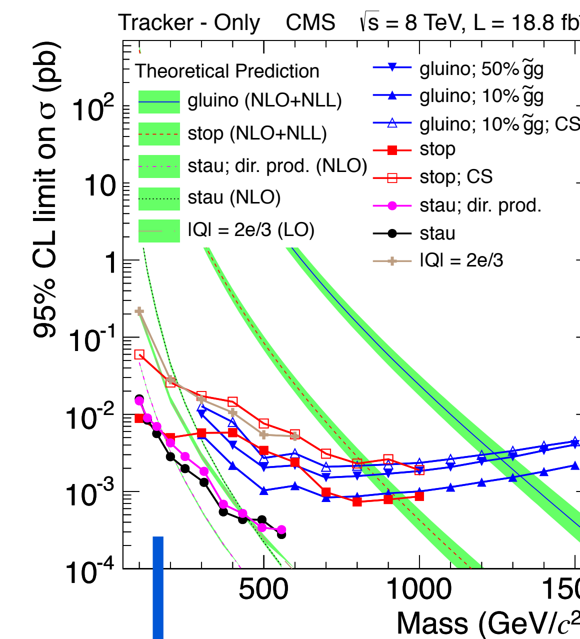
LHC constraints





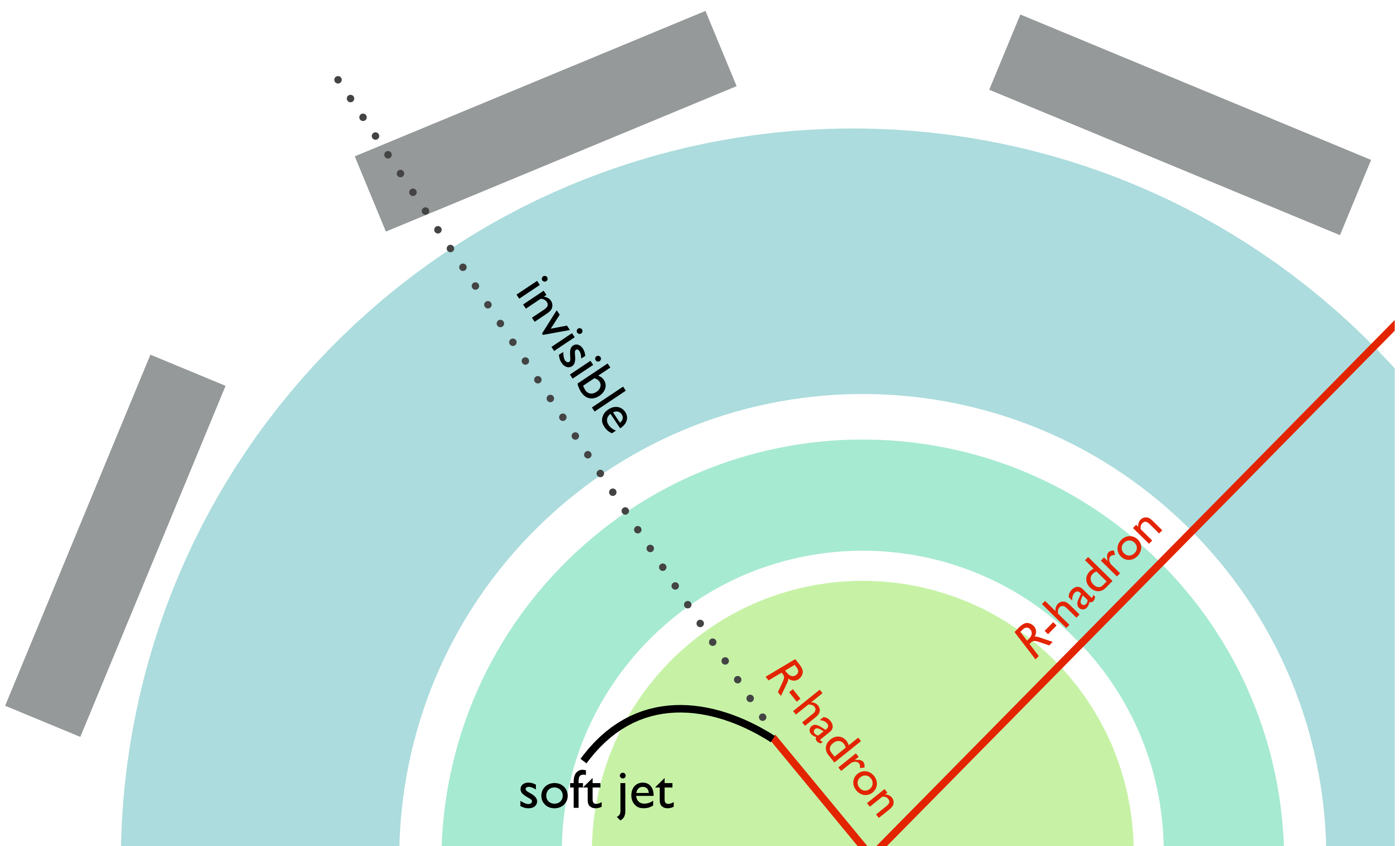
LHC constraints

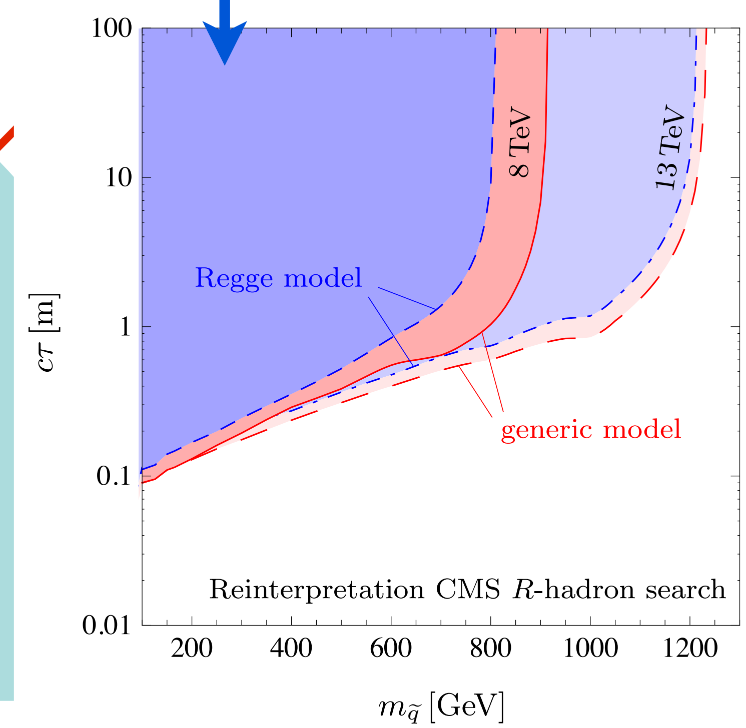




[CMS 2013]

Reinterpretation of *R*-hadron searches for finite lifetimes

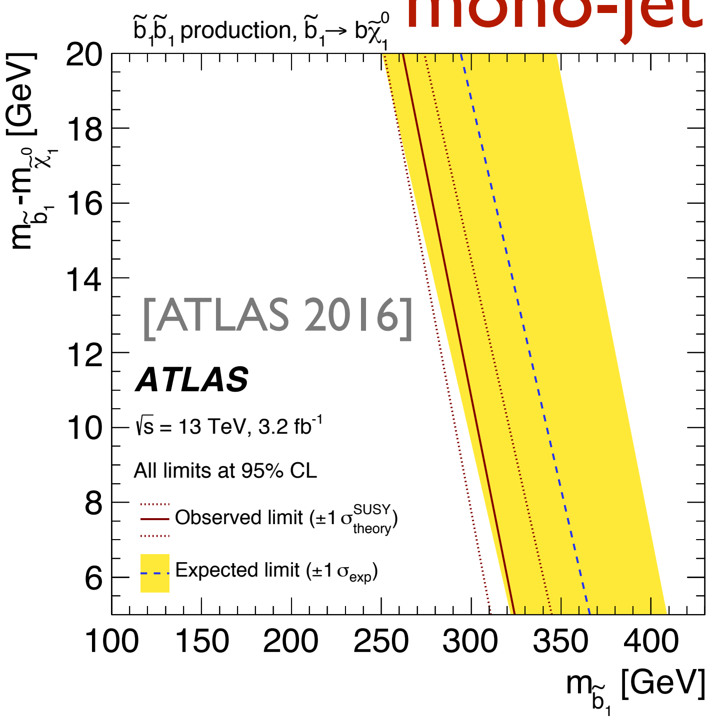


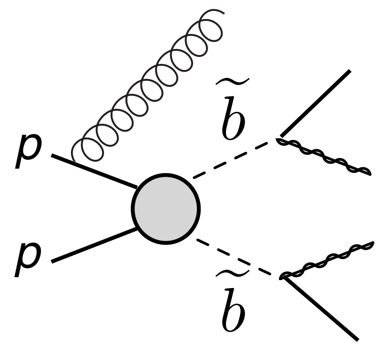


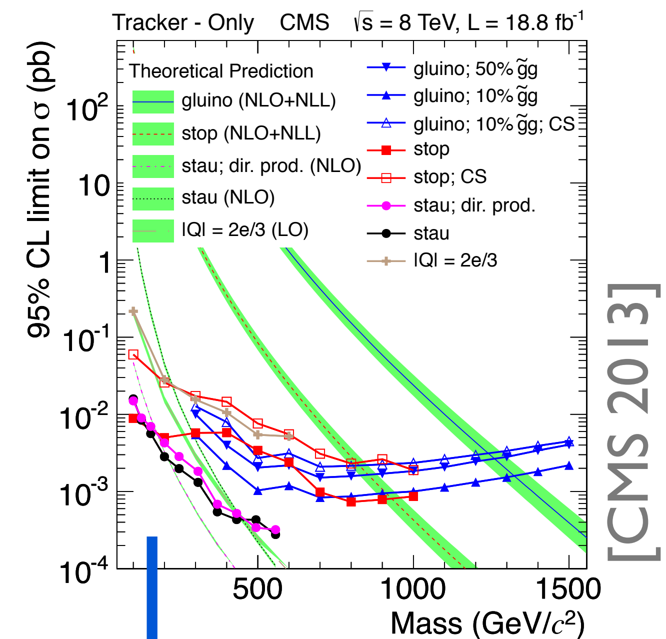
[Garny, JH, Lülf, Vogl 2017]

LHC constraints

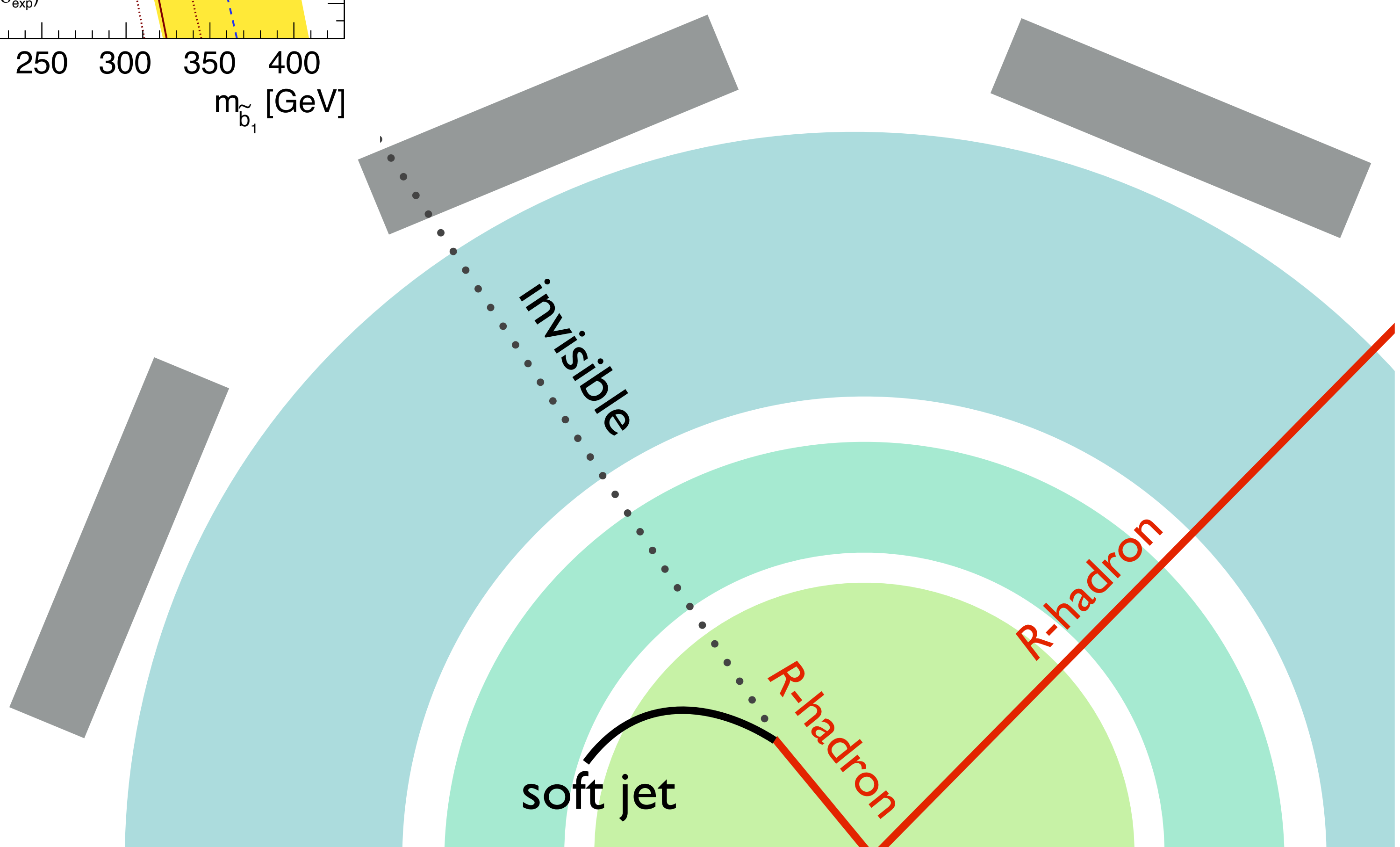
mono-jet

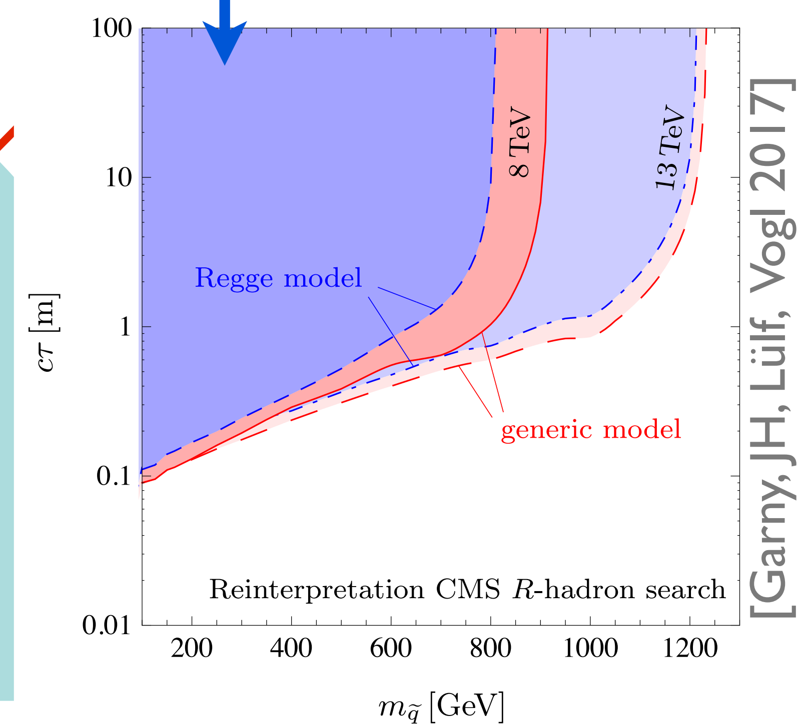






Reinterpretation of *R*-hadron searches for finite lifetimes





LHC constraints

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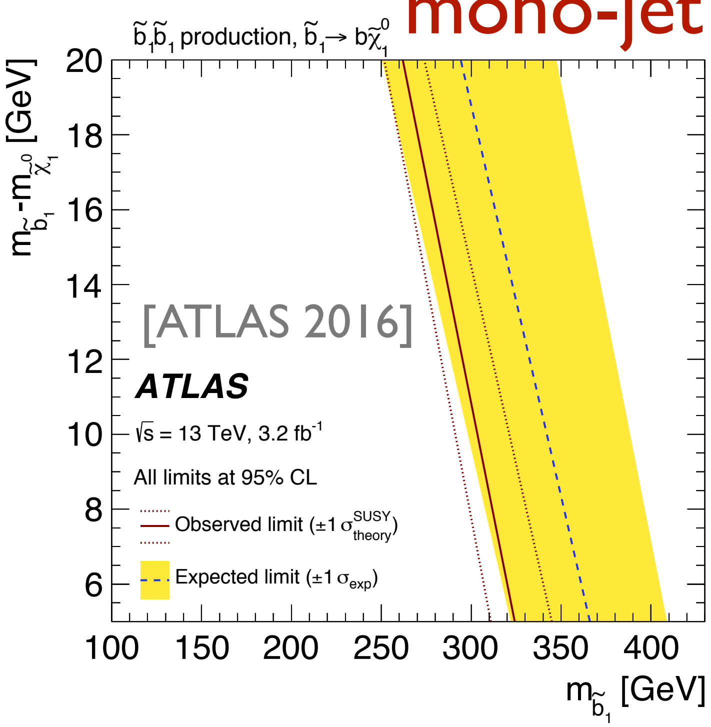

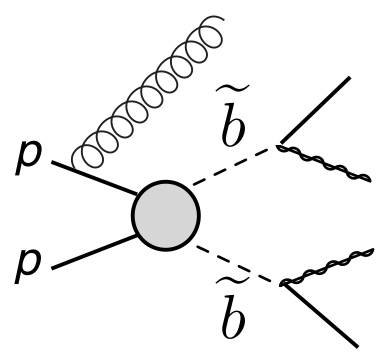

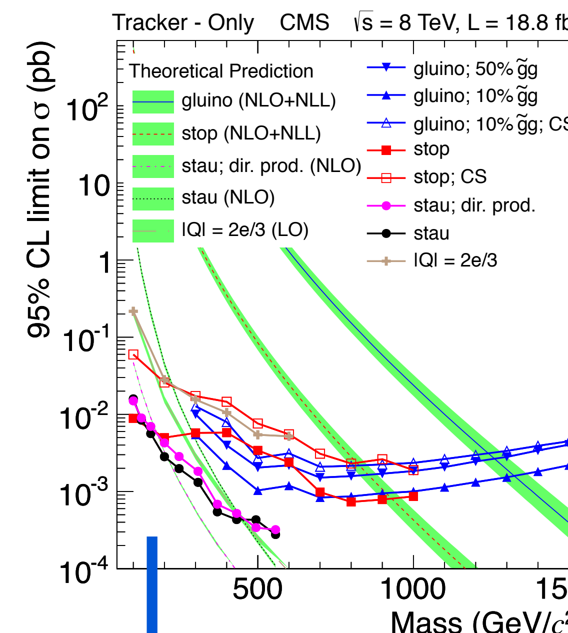

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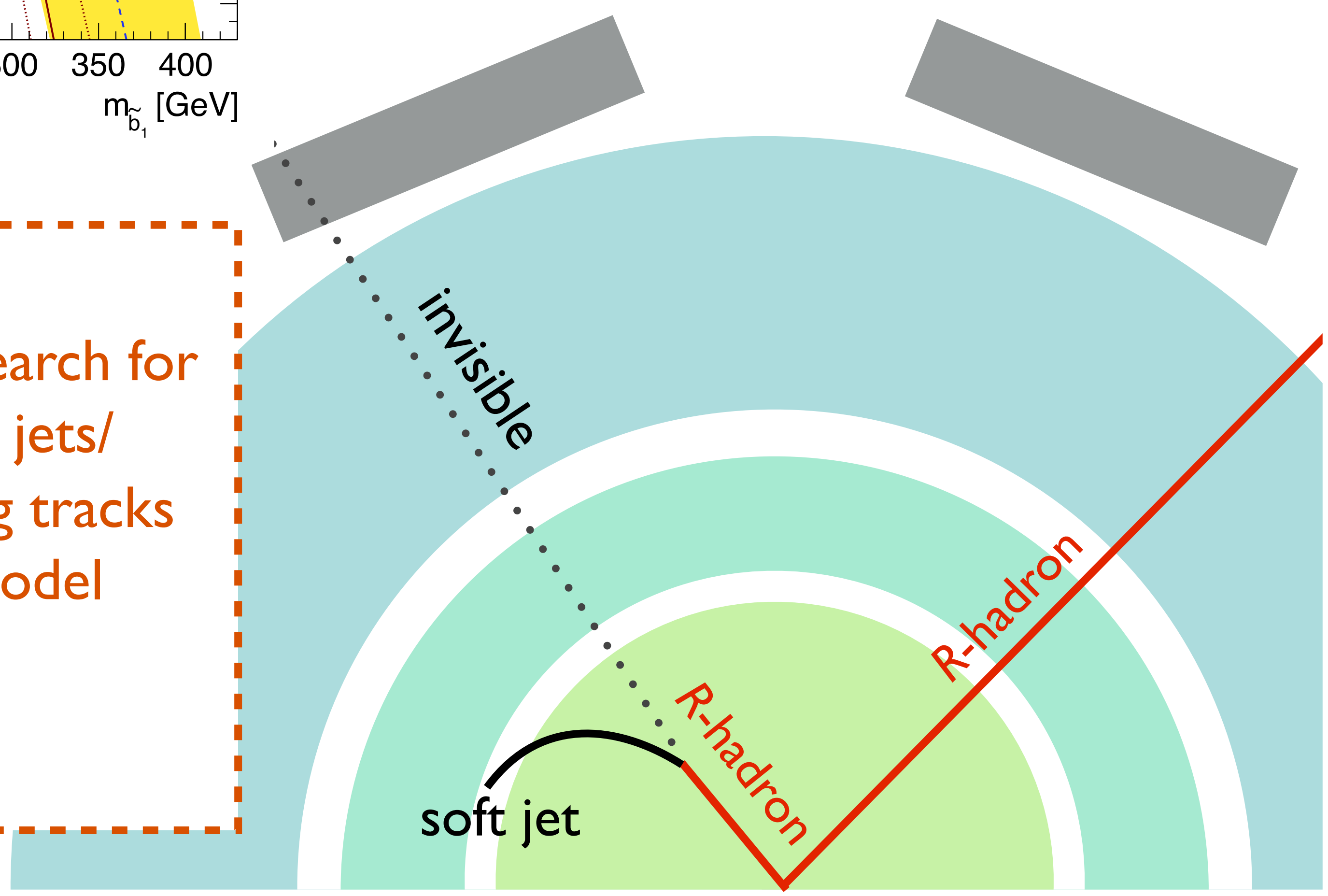
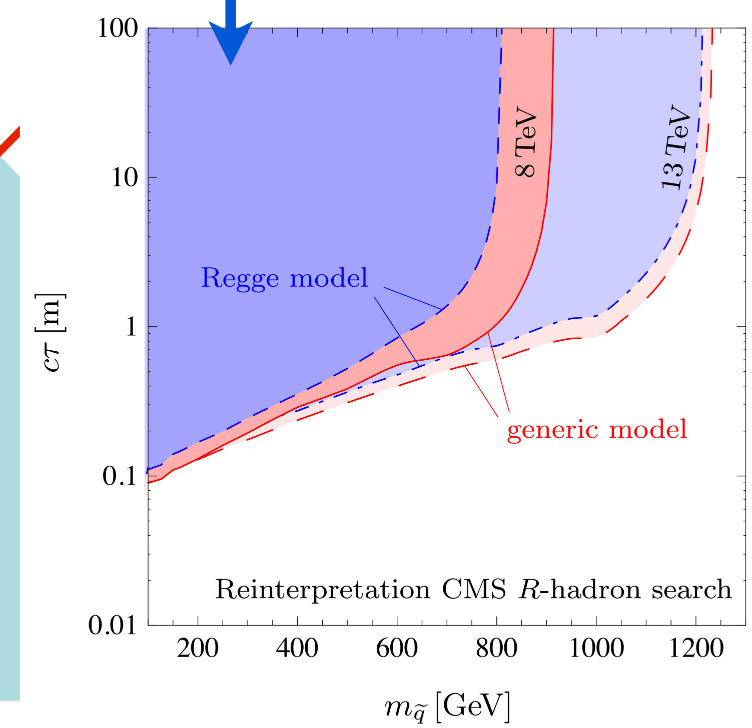


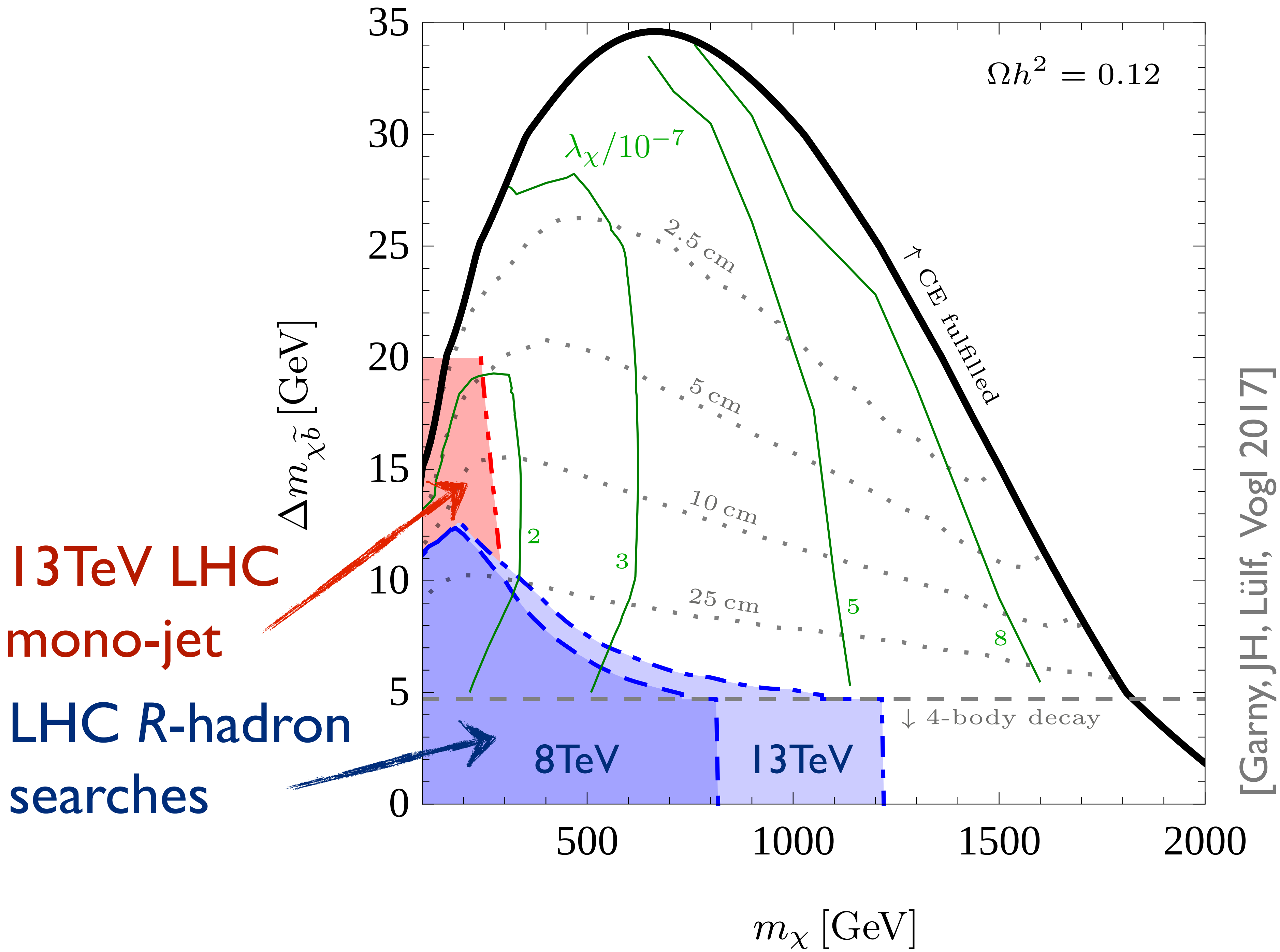
Dedicated search for displaced jets/ disapperaing tracks within model

?

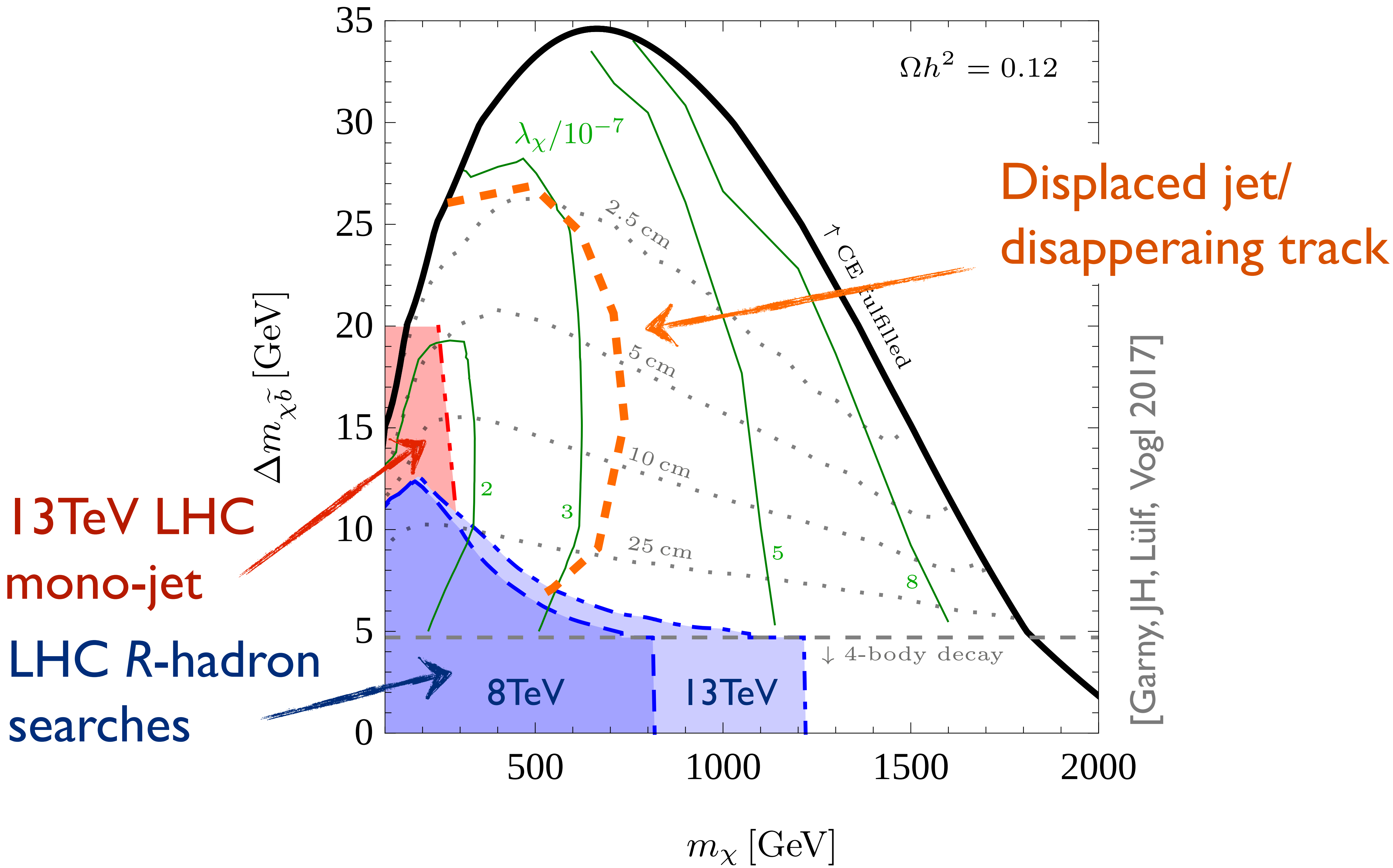


[Garny, JH, Lülf, Vogl 2017]

Allowed parameter space



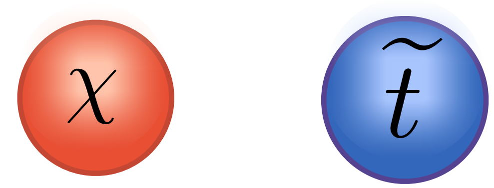
Allowed parameter space



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



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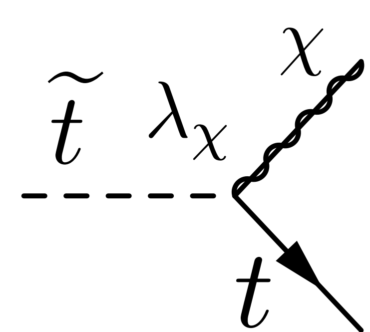
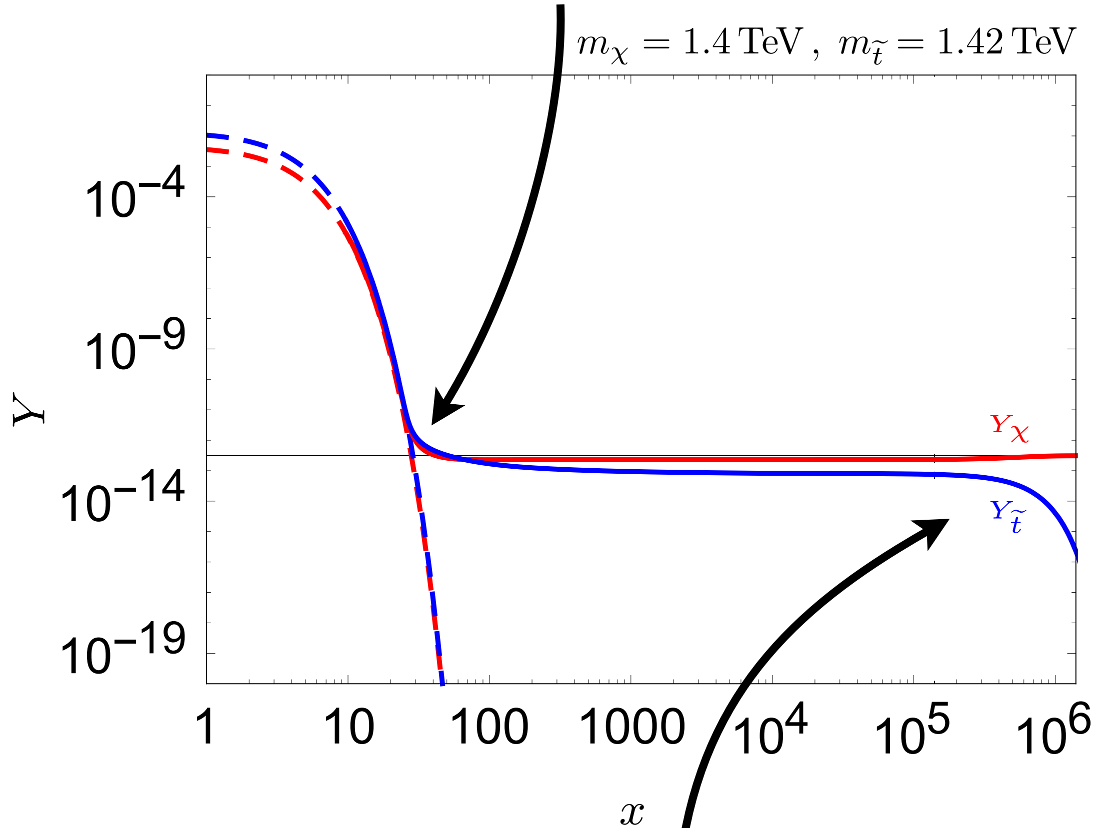
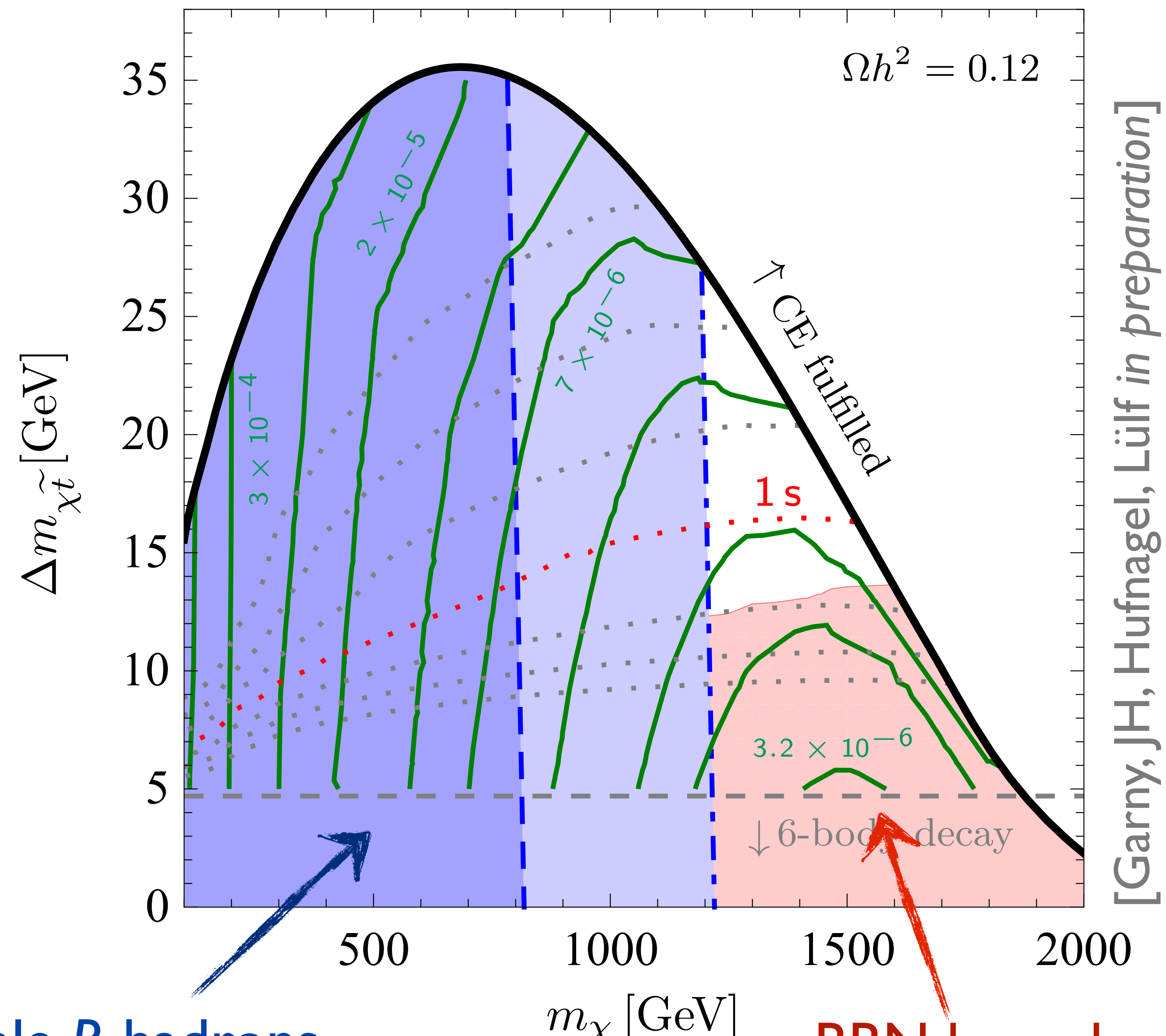


- Difference: Top-quark non-negligible mass!

Allowed parameter space: top-partner model

Scatterings dominate conversions





Decay efficient much later

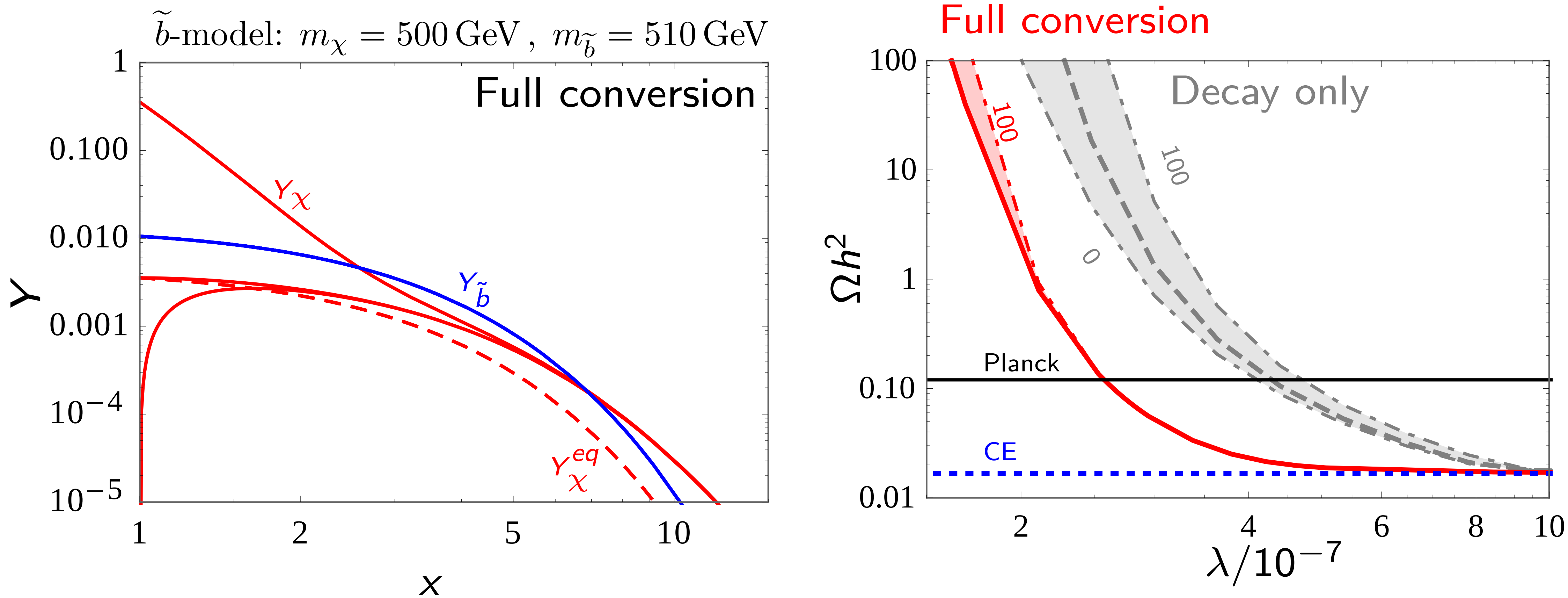
$\Gamma_{\text{decay}} \ll \Gamma_{\text{scatter}}$ ⇒ Detector-stable *R*-hadrons

BBN bounds

Scrutinizing some assumptions

Dependence on Initial Conditions

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



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

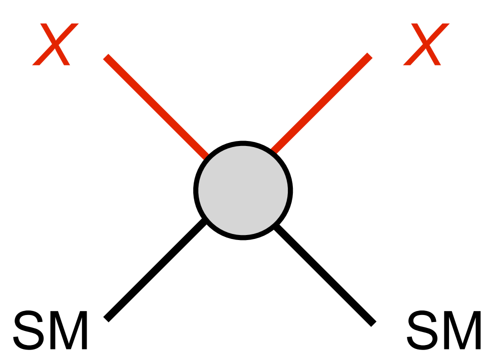
$\Rightarrow$ Independent of thermal history prior to freeze-out!

Kinetic equilibrium

- Assumption of thermal distributions (via kinetic equilibrium)

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

- WIMPs: kinetic equilibrium estabished 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

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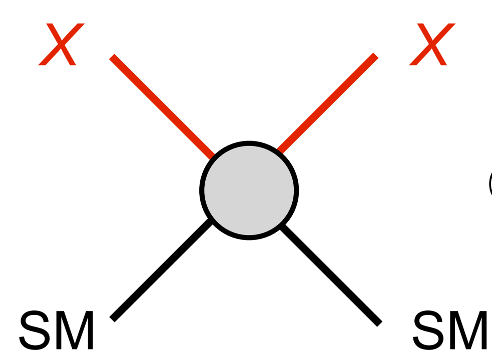


$$\propto \lambda_\chi^4$$

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

Unitegrated Boltzmann equation

- Consider unintegrated BME for χ ($g_{\rm eff} = $ const., only conversions, no annihilations)

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

- For decay with massless b-quark: $\widetilde{C}$ available **analytically**!
- Use separation of variables and variation of constants to find solution

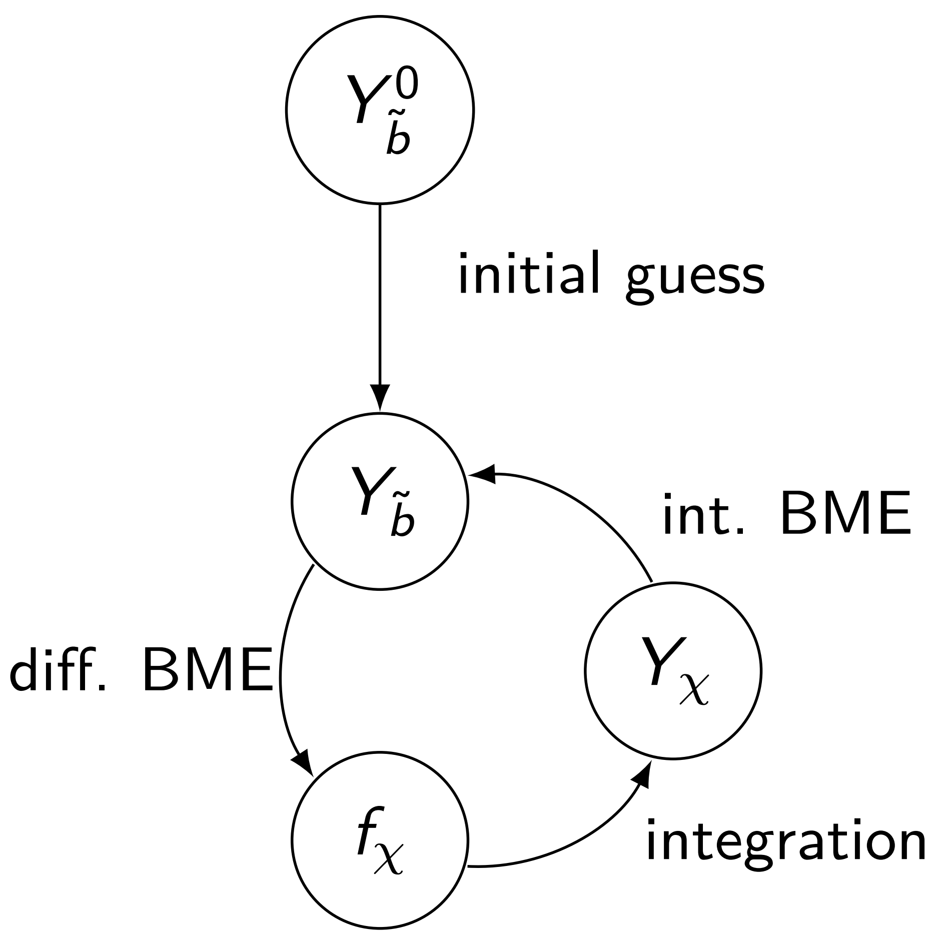
$$f_\chi(q,x) = f_\chi^{\rm eq}(q,x)\frac{Y_{\tilde{b}}}{Y_{\tilde{b}}^{\rm eq}} - \int_{x_0}^{x}\frac{\mathrm{d}\left(f_\chi^{\rm eq}(q,y)Y_{\tilde{b}}(y)/Y_{\tilde{b}}^{\rm eq}(y)\right)}{\mathrm{d}y}\times\exp\left(-\int_y^x\frac{\widetilde{C}(q,z)}{zH(z)}\mathrm{d}z\right)\mathrm{d}y$$

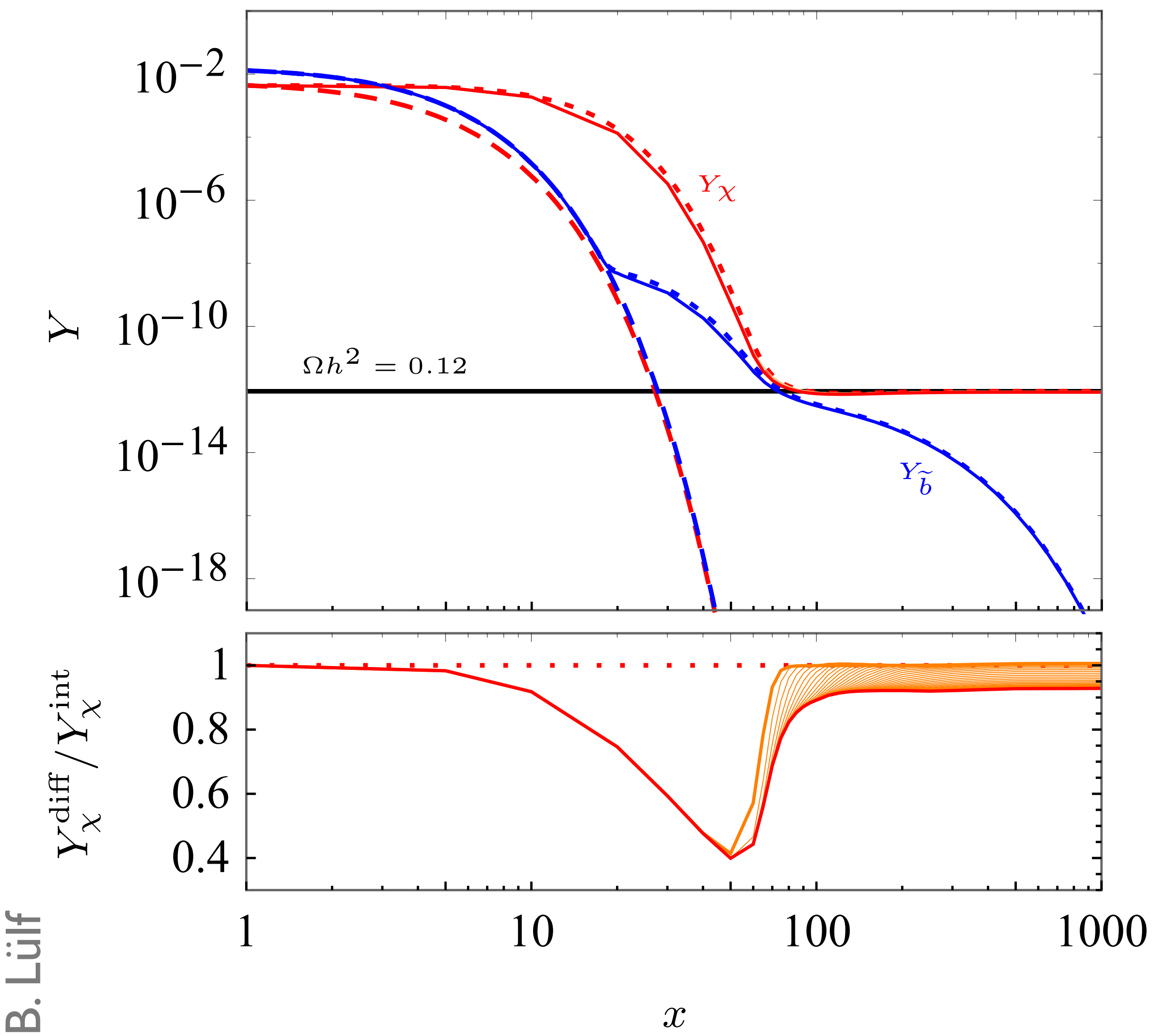
Slide: credits to B. Lülf

Caution: $Y_{\tilde{b}}$ needed!

Iterative solution

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

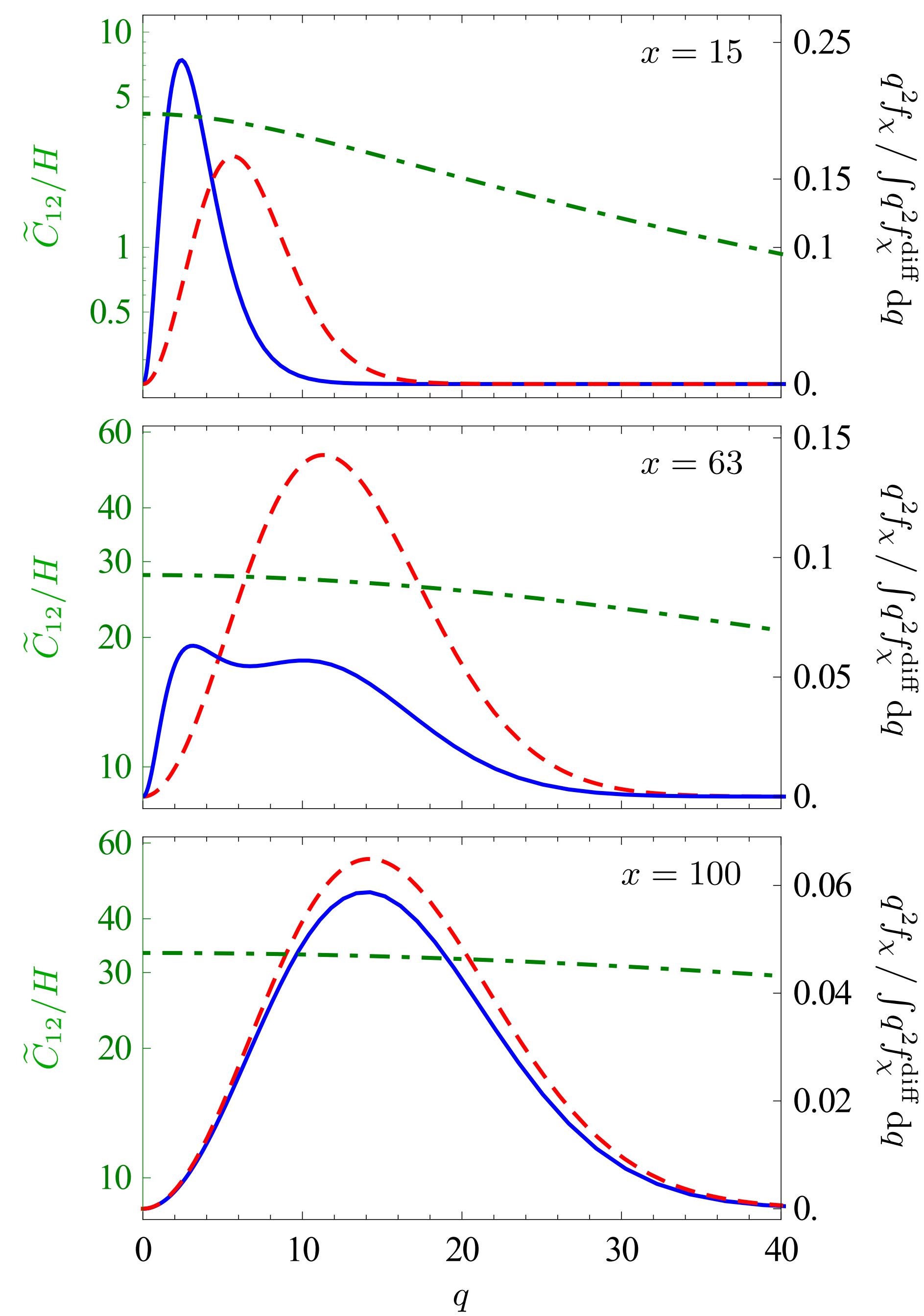




B. Lülf

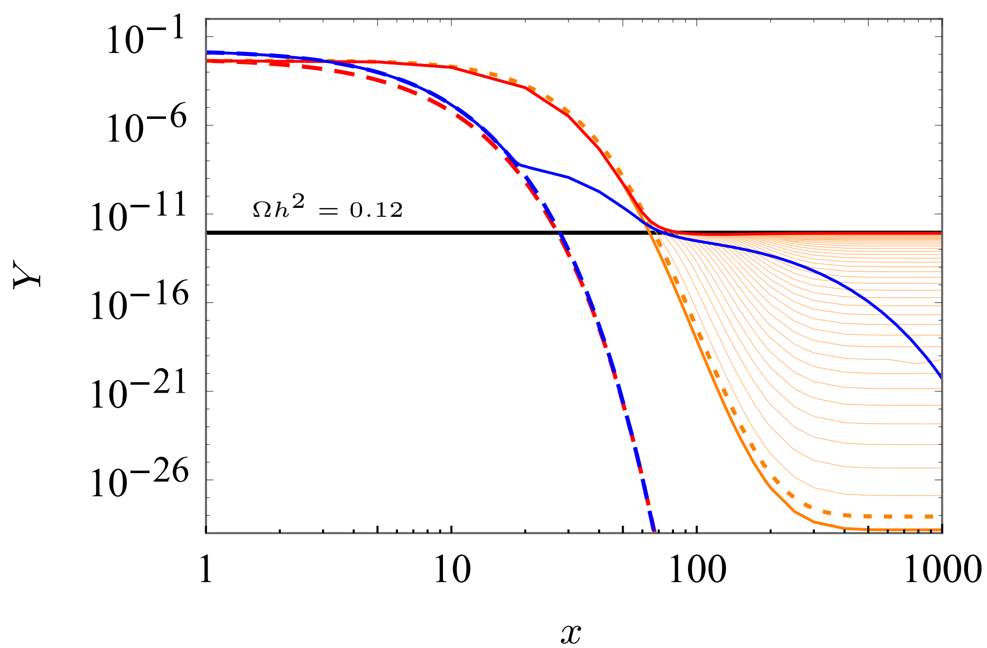
Deviation from thermal distribution

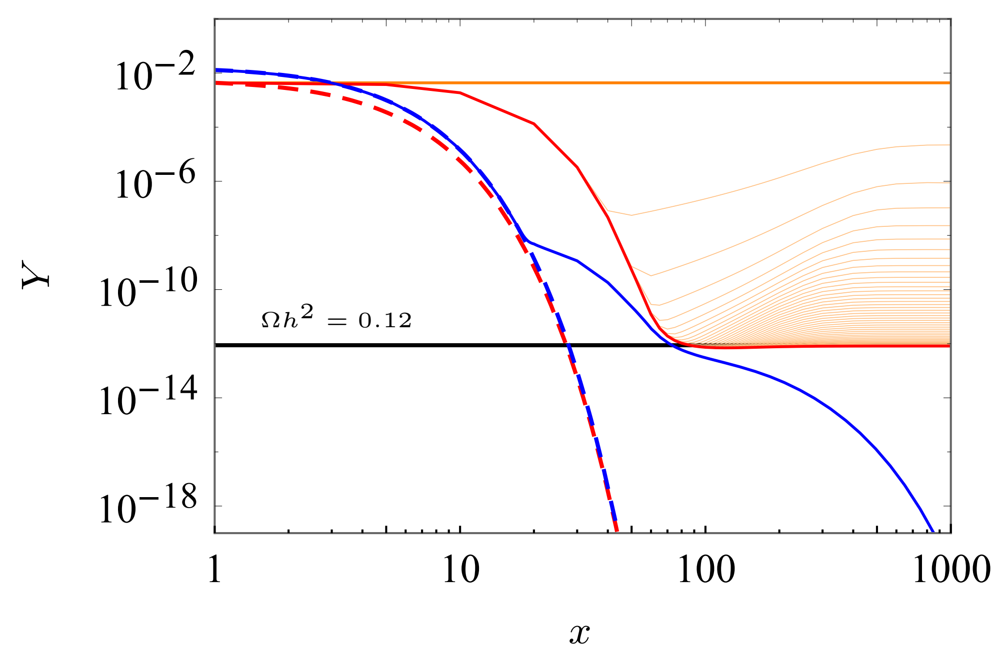
- small x: redshift only
- Conversion inset: thermalization starts
- Close-to-thermal distribution

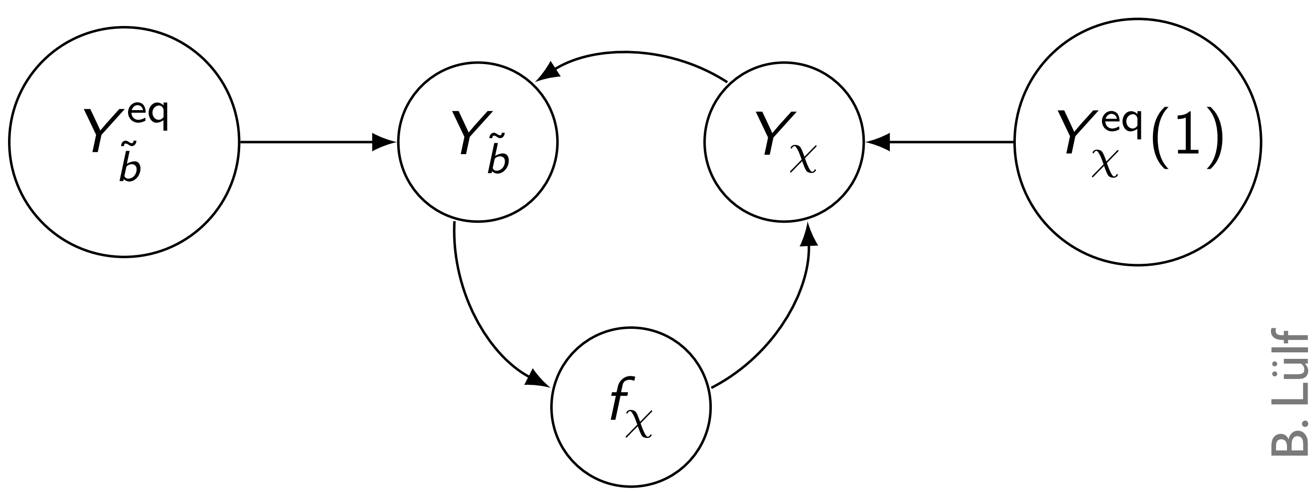


Testing initial guess

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



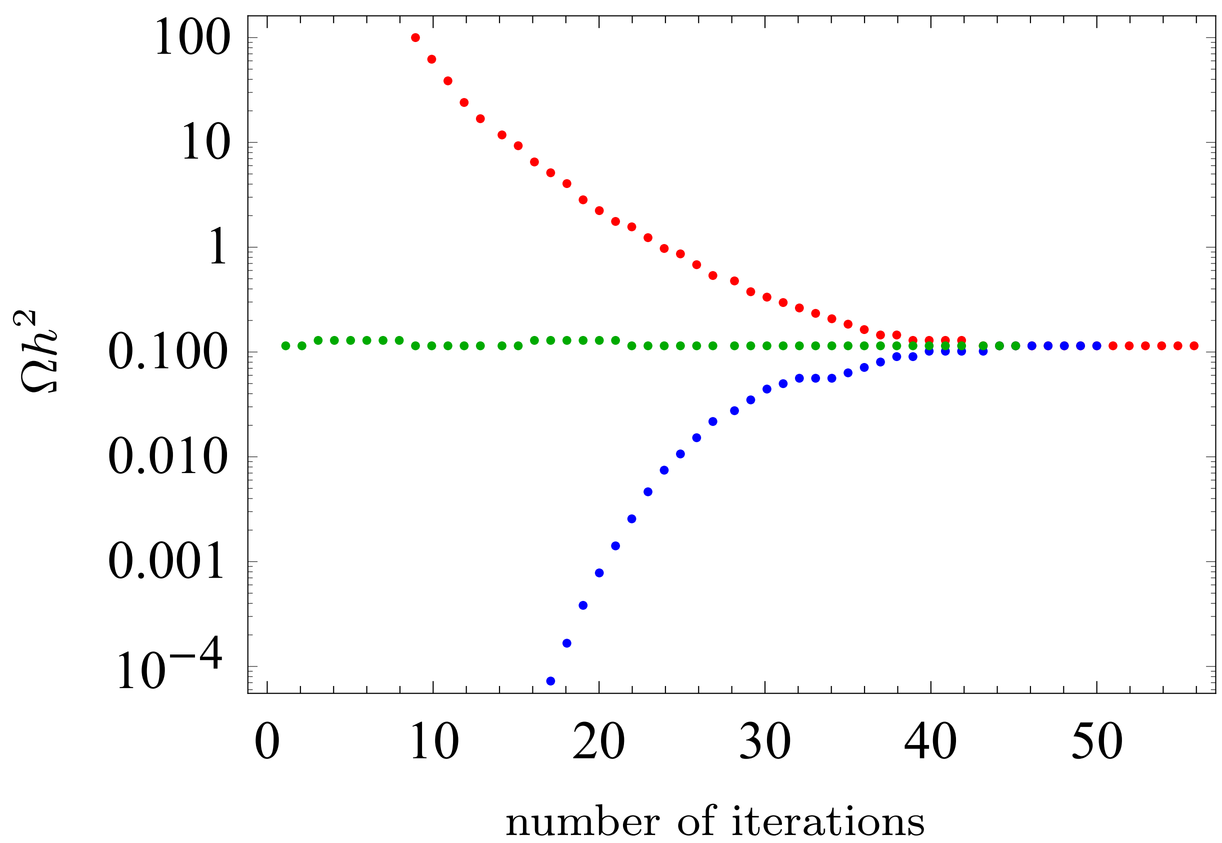




Iterative solution

- 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]



Summary

- Dark matter among key scientific questions
- 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
- Thermalization through mediator establishes kinetic equilibrium