Precision calculation of relic abundance for two-component dark matter: out-of-kinetic equilibrium effects

Shiuli Chatterjee
National Centre for Nuclear Research (NCBJ), Warszawa

based on ongoing work with Andrzej Hryczuk

September 12th, 2024

Outline

- Brief recap of the standard calculation of Dark Matter (DM) abundance
- Towards a more precise calculation when the underlying assumption of kinetic equilibrium as in the canonical case is not met
  - When does DM freeze-out outside of kinetic equilibrium
  - How is the Boltzmann equation solved without this simplifying assumption: challenges and solutions
- Non minimal dark sector: two-component
- Summary

Production of DM by freeze-out

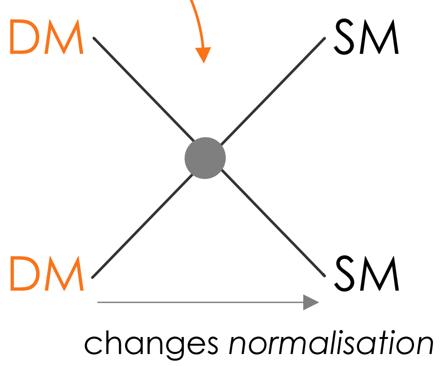
Dark matter relic density measurement from the CMB is a well-measured quantity

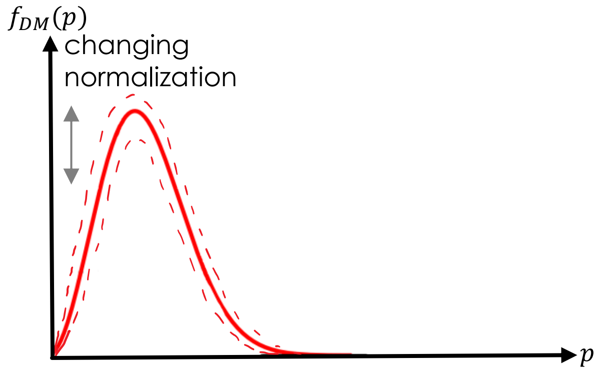
$$\Omega_c h^2 = 0.1198 \pm 0.0012 \quad \text{PLANCK 2018}$$

- Obtained from solving the Boltzmann equation

$$L[f_{DM}] = C[f_{DM}]$$

$$\partial_t f_{DM} - Hp\partial_p f_{DM} = C_{el}[f_{DM}] + C_{ann}[f_{DM}] + \dots$$





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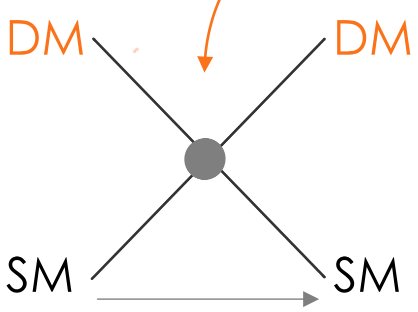
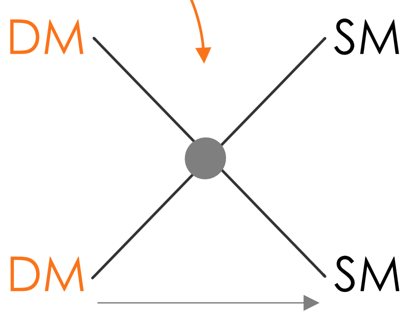
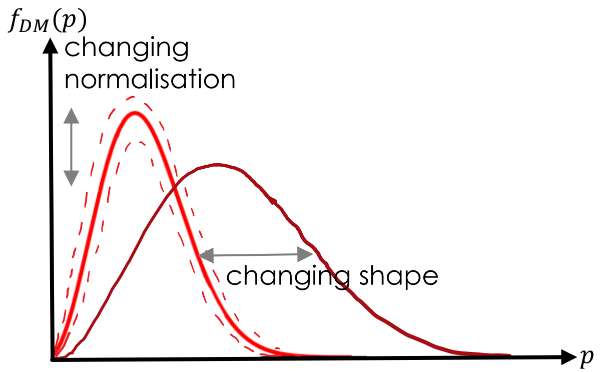


changes *shape*



changes *normalisation*



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$$\dot{n} + 3Hn = -\langle\sigma v\rangle(n^2 - n_{eq}^2)$$

Kinetic equilibrium Bernstein, Brown, Feinberg 1985

$$f_{DM}(T) \propto f_{eq}(T)$$

- Although typically a good assumption for $m_{DM} \gg m_{SM}$ …

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there exist scenarios where kinetic decoupling PRECEEDES freeze-out

When can Kinetic Decoupling precede freeze-out?

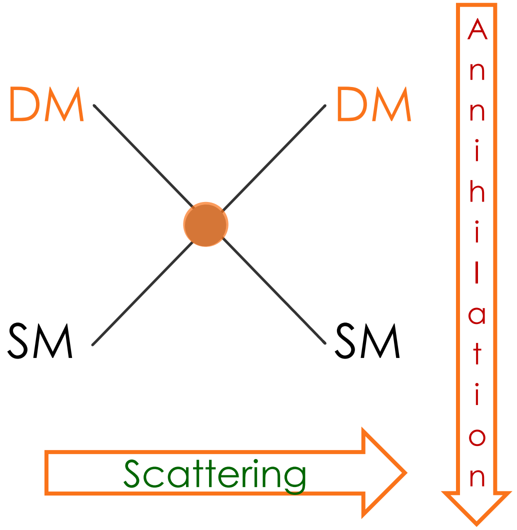
Bringmann, Hoffman 2006
Binder, Bringmann, Gustafsson, Hryczuk 2017
Duch, Grządkowski 2017
Ala-Mattinen, Kaunilainen 2019
Gondolo, Hisano, Kadota 2012
Binder, Covi, Kamada, Murayama, Takahashi '12

When can Kinetic Decoupling precede Freeze-out?

Freeze-out (FO) occurs in Kinetic Equilibrium in typical WIMP models when:

$$n_{SM}^{eq}\langle\sigma v\rangle_s \gg n_{DM}^{eq}\langle\sigma v\rangle_a \simeq H \qquad \text{with} \qquad \langle\sigma v\rangle_a \simeq \langle\sigma v\rangle_s \,, n_{SM}^{eq} \gg n_{DM}^{eq}$$

1. Same coupling fully controls annihilation and elastic scattering
2. # scattering partners (n_{SM}) >> # annihilating partners (n_{DM}) at FO

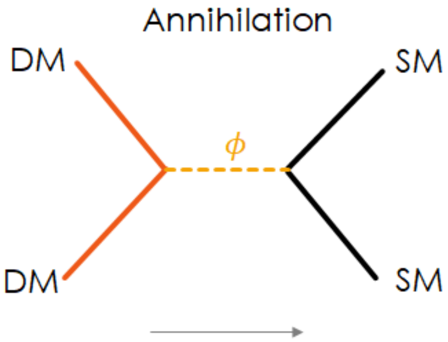


When can Kinetic Decoupling precede Freeze-out?

(I) Resonant annihilation:

Same coupling fully controls annihilation and elastic scattering

scattering partners (n_{SM}) >> # annihilating partners (n_{DM}) at FO



Resonance for $m_\phi \simeq 2m_{DM}$

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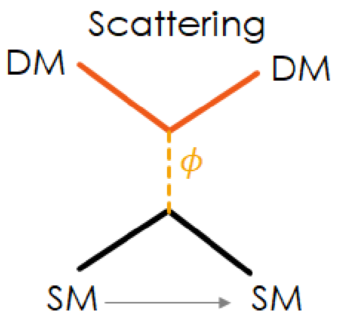

no resonance for $m_\phi \simeq 2m_{DM}$

$$n_{SM}^{eq}\langle\sigma v\rangle_s \not\gg n_{DM}^{eq}\langle\sigma v\rangle_a \simeq H \qquad \text{with} \qquad \langle\sigma v\rangle_a \not\simeq \langle\sigma v\rangle_s \,, n_{SM}^{eq} \gg n_{DM}^{eq}$$

I. Resonant annihilation
II. Sommerfeld enhanced annihilation
III. Heavy scattering partner
IV. DM stabilized by Z_3
V. Multicomponent dark sector …

(Binder, Bringmann, Gustafsson, Hryczuk '17, '21)
Duch, Grządkowski '17

When can Kinetic Decoupling precede Freeze-out?

(II) Sommerfeld enhanced annihilation:

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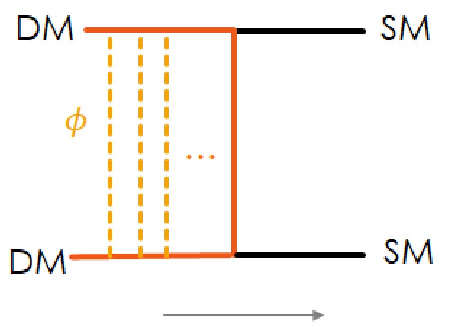
Sommerfeld enhancement in annihilation



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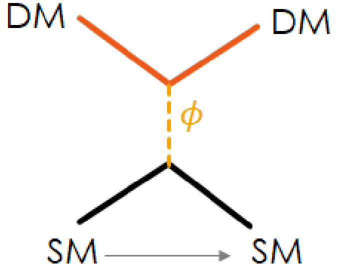
Scattering



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When can Kinetic Decoupling precede Freeze-out?

(III) Scattering partner is heavy and also Boltzmann suppressed at FO

✓ Same coupling fully controls annihilation and elastic scattering

✗ # scattering partners (n_{SM}) >> # annihilating partners (n_{DM}) at FO

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$$m_{DM} \sim m_{SM} \Longrightarrow n_{DM}^{eq} \simeq n_{SM}^{eq}$$

$$n_{SM}^{eq} \langle \sigma v \rangle_s \not\gg n_{DM}^{eq} \langle \sigma v \rangle_a \simeq H \qquad \text{with} \qquad \langle \sigma v \rangle_a \simeq \langle \sigma v \rangle_s \, , n_{SM}^{eq} \not\gg n_{DM}^{eq}$$

(Binder, Bringmann, Gustafsson, Hryczuk '17, '21)
Gondolo, Hisano, Kadota 2012

When can Kinetic Decoupling precede Freeze-out?

(IV) Non-minimal dark sector – DM stabilised by Z_3 or larger group

- I. Resonant annihilation
- II. Sommerfeld enhanced annihilation
- III. Heavy scattering partner
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- V. Multicomponent dark sector …

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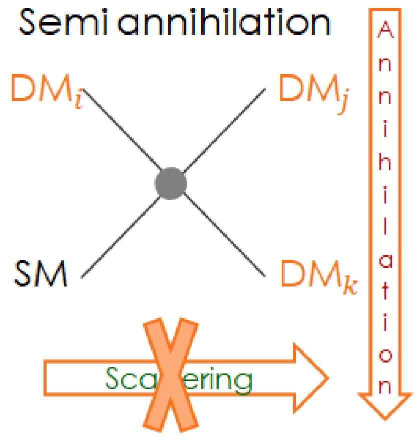

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(Eramo, Thaler 2010; Belanger, Kannike, Pukhov, Raidal 2012; Cai, Spray 2016)

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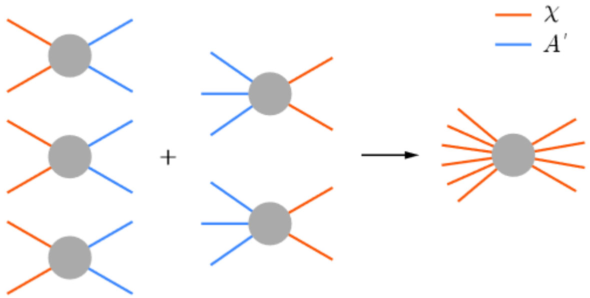

FIG. 1. Schematic illustration of the catalyzed annihilation of DM χ (red line) with a catalyst A' (blue line). Three $2\chi \to 2A'$ processes plus two $3A' \to 2\chi$ effectively deplete the number of DM particles by two.

fig. from Xing, Zhu '21; hep-ph: 2102.02447

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Dark Matter Freeze-out production out of Kinetic Equilibrium

solve for *one* variable n → *two* variables n and T

Review of current literature in solving for abundance of DM out of Kinetic equilibrium:

1. Solve for DM temperature along with abundance (coupled BE)
   assume: DM distribution still has an equilibrium shape, only at a temperature $T_{DM} \neq T_{SM}$
   (Binder, Bringmann, Gustafsson, Hryczuk 2017, 2021; Hryczuk, Laletin 2021; Benincasa, Hryczuk, Kannike, Laletin 2023)

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solve for *one* variable n → *two* variables n and T→ *full phase space* with approximations (maintaining detailed balance)

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2. A generalized relaxation approximation agrees with fBE in specific cases; but not justified In full generality
   assume: $f_{DM}(p,t) = g(t)f_{eq}(p,t) + \delta f(p,t)$ and that the integrated difference between the exact collision term and this momentum dependent approximation is small
   (Ala-Mattinen, Kainulainen 2019; Ala-Mattinen, Heikinheimo, Kainulainen, Tuominen 2022)
3. Langevin simulations confirms the predictions from cBE in studied case
   Stochastic differential equation for studying the efficiency of kinetic equilibration in the non-relativistic regime (Kim, Laine 2023)

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4. Solving the DM distribution function at the full phase space level: numerically very challenging

$$\partial_t f_{DM} - Hp\partial_p f_{DM} = C_{el}[f_{DM}] + C_{ann}[f_{DM}]$$

(Du, Huang, Li, Li, Yu '21; Hryczuk, Laletin '22; Ala-Mattinen, Heikinheimo, Kainulainen, Tuominen '22; Aboubrahim, Klasen, Wiggering '23; Brahma, Heeba, Schutz '23)

Boltzmann equation at the phase space level

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CAN proceed fully numerically but it is time and CPU costly, due to the multidimensional integrations in the collision operators:

$$C_{el}[f_{DM}] = \int d\Pi \, |M|^2_{DM,SM\to DM,SM} \left(f_{DM}(p_1) f_{eq}(p_3) - \boldsymbol{f_{DM}(p_2)} f_{eq}(p_4)\right)$$

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$$\delta^{(3)}(\vec{p_3} + \vec{p_4} - \vec{p_1} - \vec{p_2}) \approx \sum_n \left(\frac{1}{n!} \left(\vec{q}.\vec{\nabla}_{p_3}\right)^n \delta^{(3)}(\vec{p_3} - \vec{p_1}) \right)$$

$$\frac{\Delta\vec{p}}{\vec{p}} < 1, \frac{p_1}{E_1} < 1$$

$$C_{el}[f_{DM}] = C_2 + C_4 + C_6 + C_8 + \cdots$$

Bringmann, Hoffman '06
Gondolo, Hisano, Kadota '12
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$$C_{el}[f_{DM}] = \underbrace{C_2 + C_4}_{C_{FP}} + C_6 + C_8 + \cdots$$

$$C_{FP} = \frac{1}{2E_1}\gamma\left(f_{eq}\right)\widehat{FP}(p_1).\boldsymbol{f_{DM}(p_1)}$$

Has all the nice features:

- ✓ no integration on f_{DM}
- ✓ number conserving
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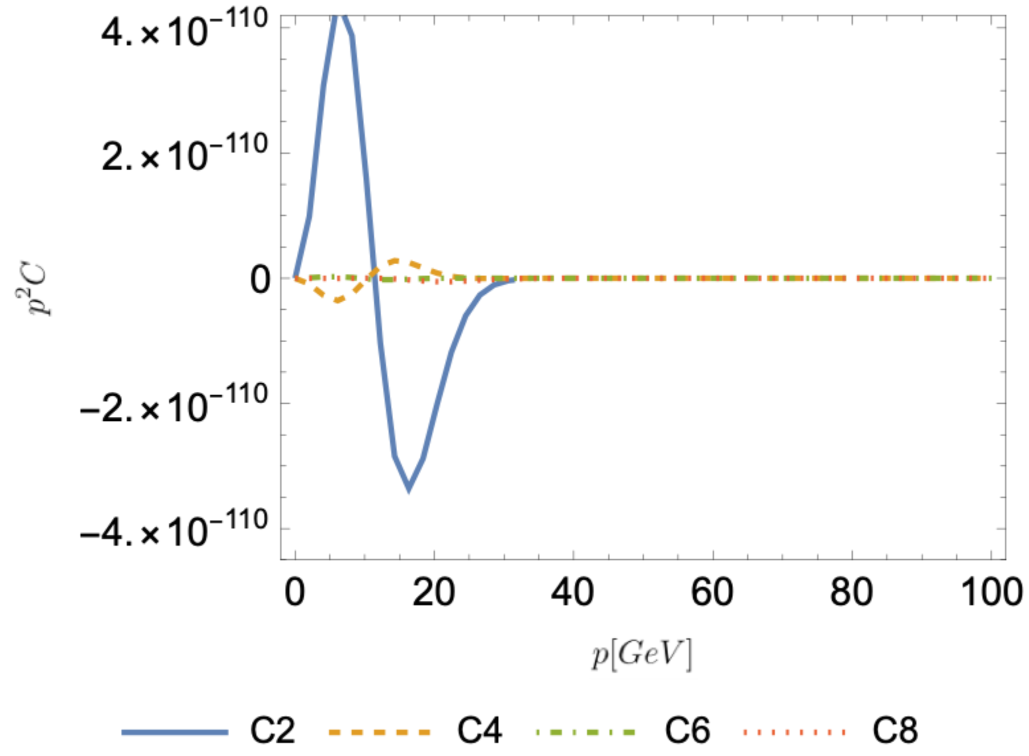

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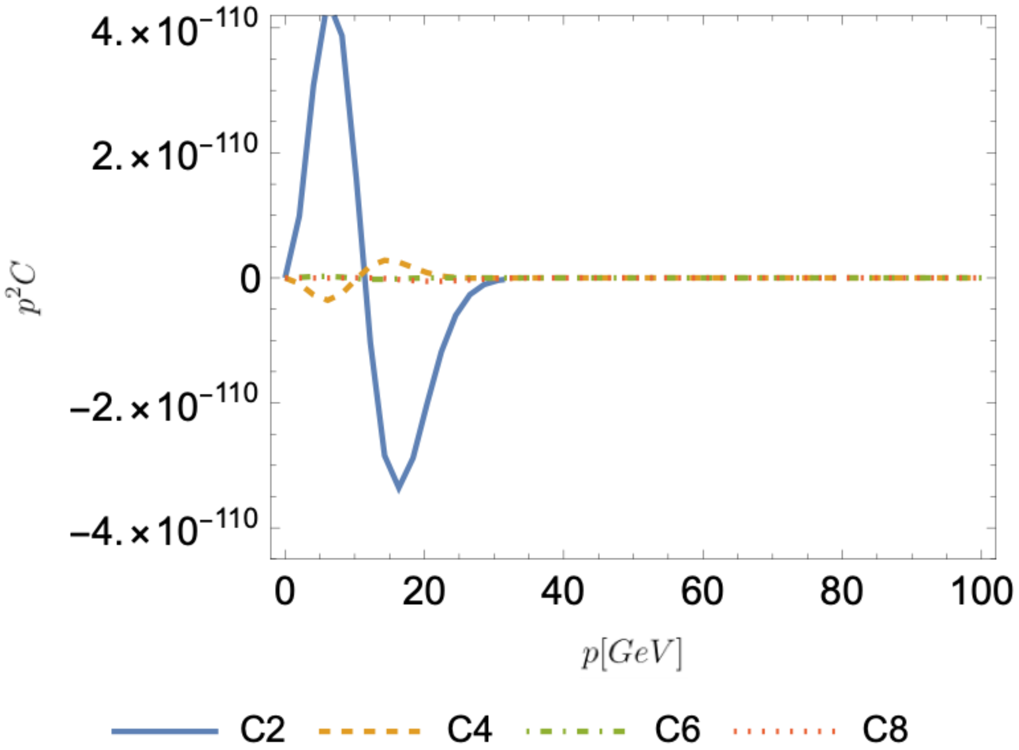

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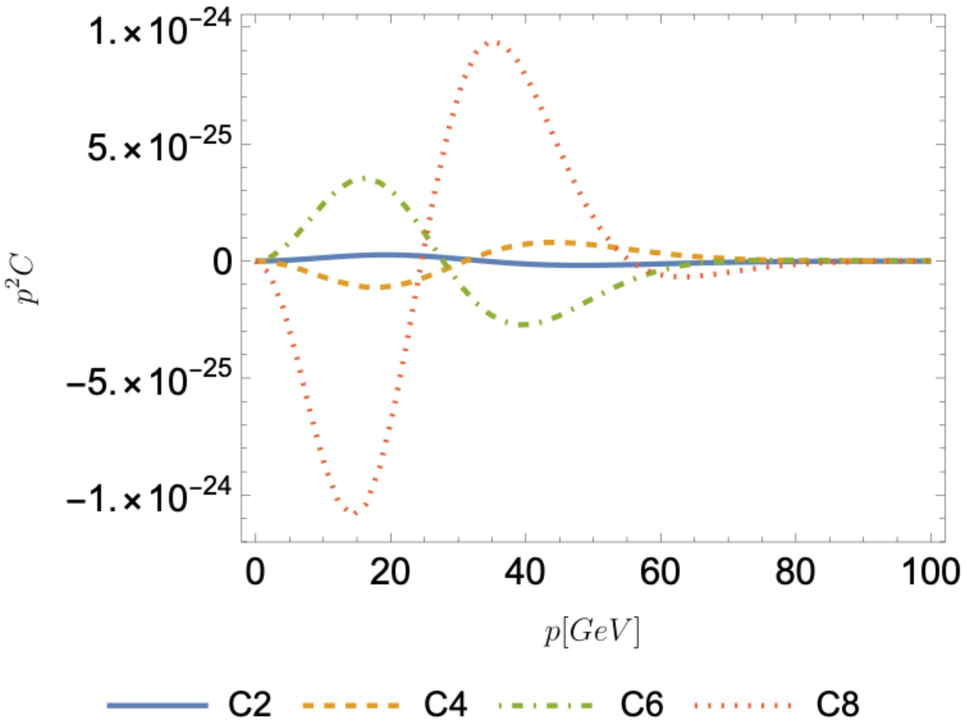

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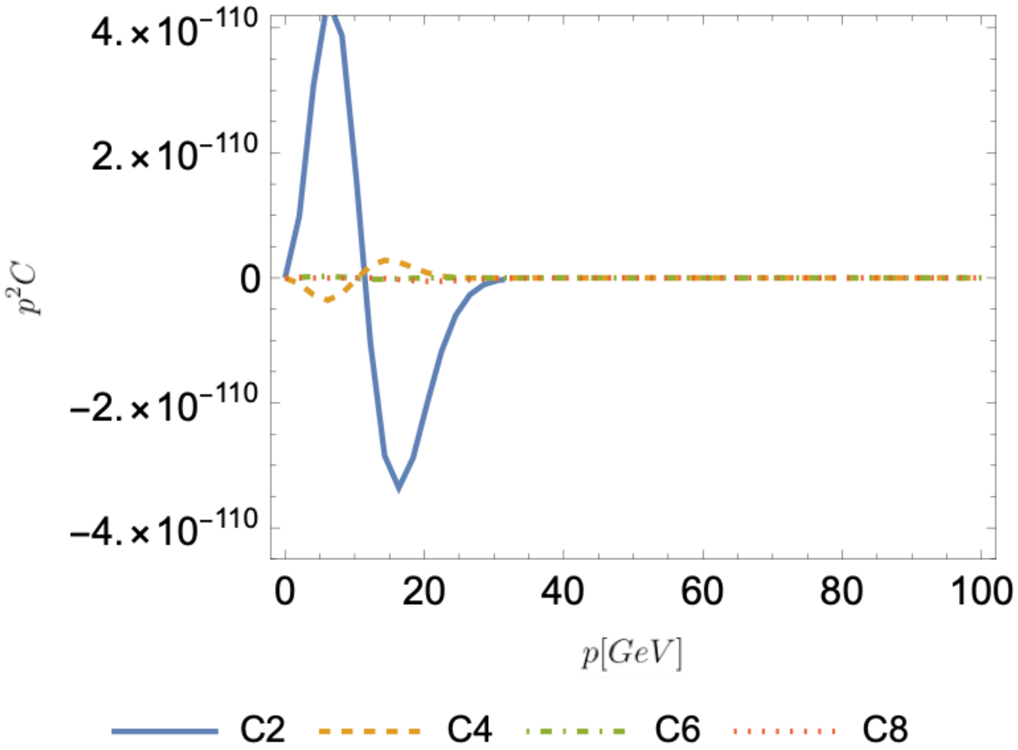

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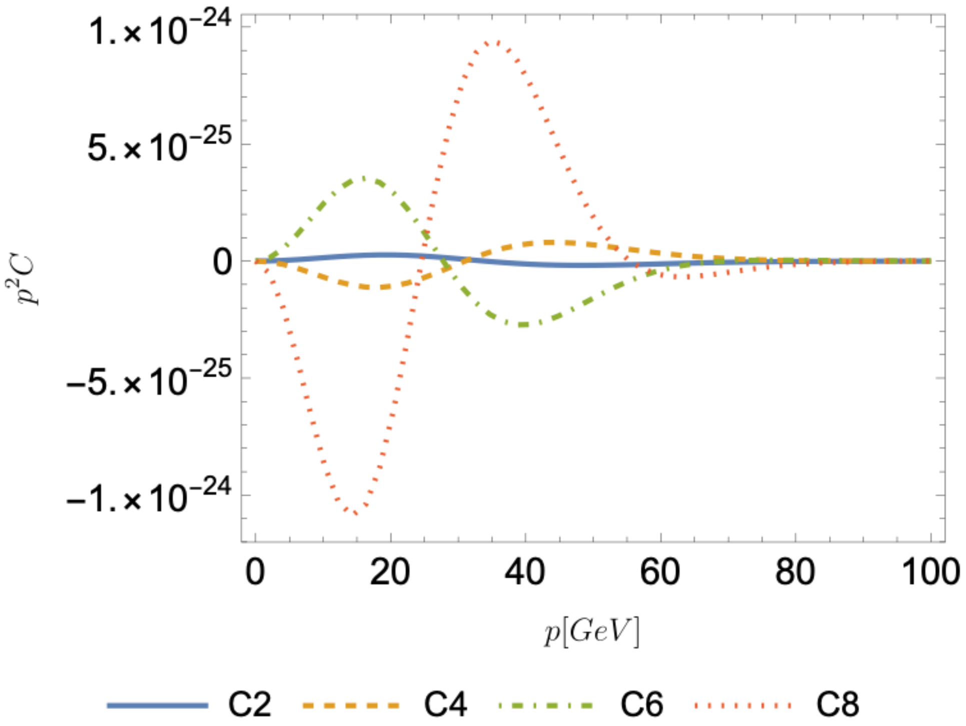

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When does the Fokker Planck approx. work?

- Arrived at by *dropping higher order terms* in $\Delta\vec{p}/\vec{p}$ and p_1/E_1.
- Very good "approximation" (O(1%)) while the conditions of the expansion hold true.

Q: How to know when the FP approximation works?

$$|M|^2 \longrightarrow \underbrace{t^{n_1}}_{\propto \text{ transfer momentum}} \underbrace{(s-(m_{DM}+m_{SM})^2)^{n_2}}_{\propto \text{ relative velocity}} \underbrace{(u-(m_{DM}-m_{SM})^2)^{n_3}}_{\propto \text{ velocities}}$$

With an efficiently implemented fully numerical[1] solver for the Boltzmann equation into DRAKE, we find that The Fokker Planck approximation works well for:

1. Scattering particle with masses significantly smaller than DM mass (small reduced mass ⇒ small momentum transfer

   &

2. DM temperatures close to the SM temperature (eg.: near kinetic decoupling)

   &

3. Scattering amplitudes that aren't strongly dependent on momentum transfer (the dropped higher order terms are more relevant for an amplitude sensitive to said dropped quantity)

[1] Ala-Mattinen, Kainulainen '19
Hryczuk, Laletin '20
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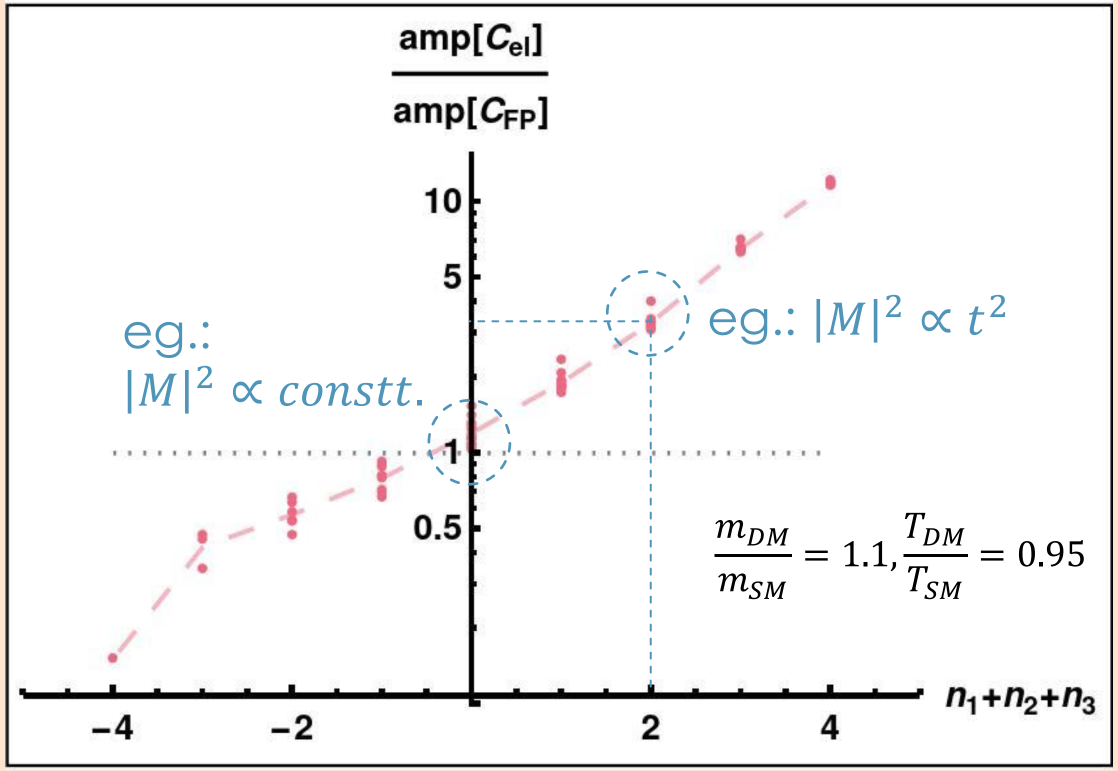

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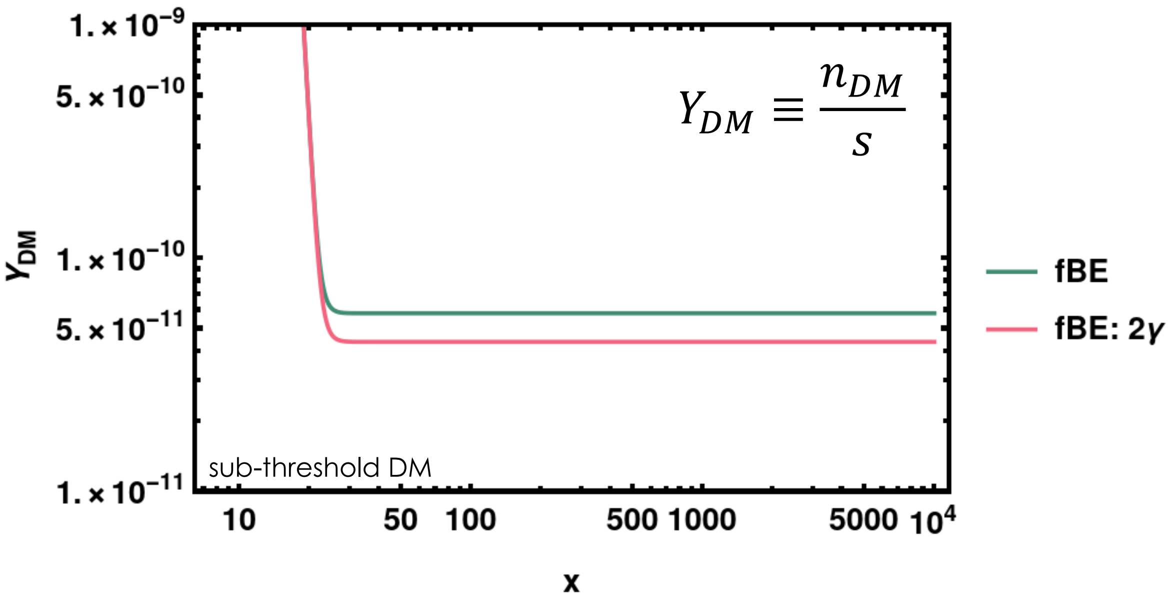
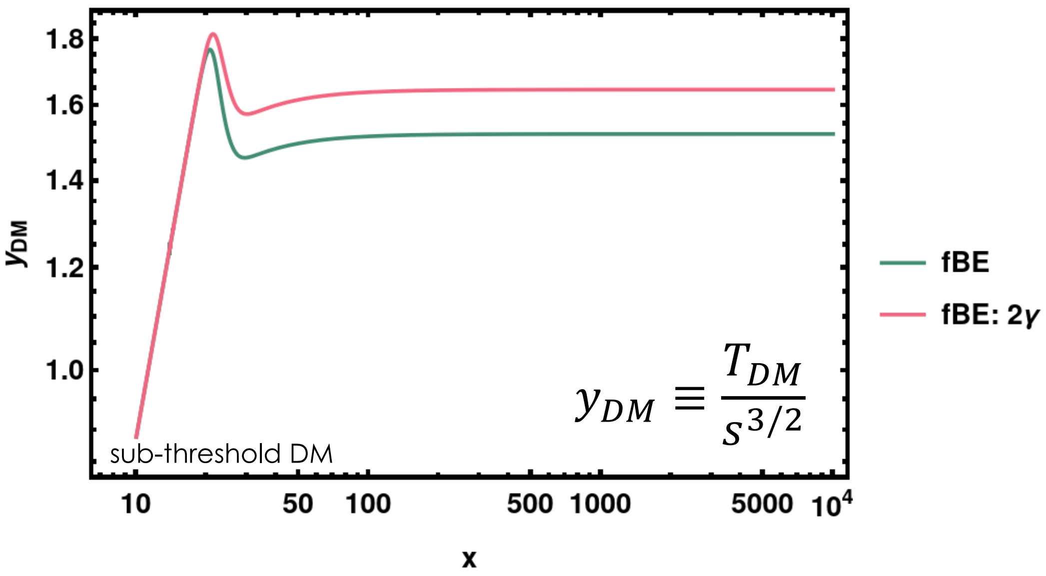
Improvement on Fokker Planck: Relic density

$$\partial_t f_{DM} - Hp\partial_p f_{DM} = C_{el}[f_{DM}] + C_{ann}[f_{DM}]$$

$$C_{el}[f_{DM}] \simeq C_{FP} = \frac{1}{2E_1}\gamma(f_{eq})\,\widehat{FP}(p_1).\boldsymbol{f_{DM}(p_1)}$$

An overall factor 2 at the level of collision operator $\Longrightarrow$ 25% change in DM relic density

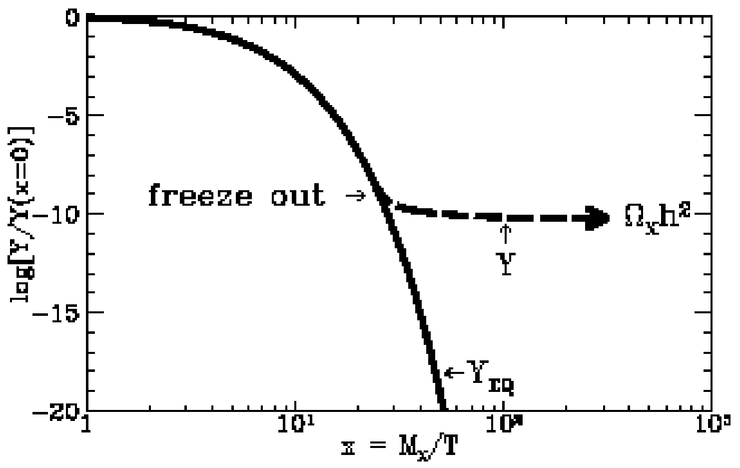


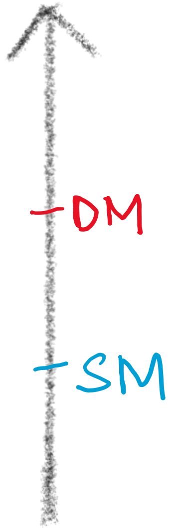


Non-minimal Dark Sector

Dark Matter production:

- In the simplest freeze-out production of WIMP (weakly interacting massive particle) DM, there is one DM particle, initially in kinetic and chemical equilibrium with the SM plasma.





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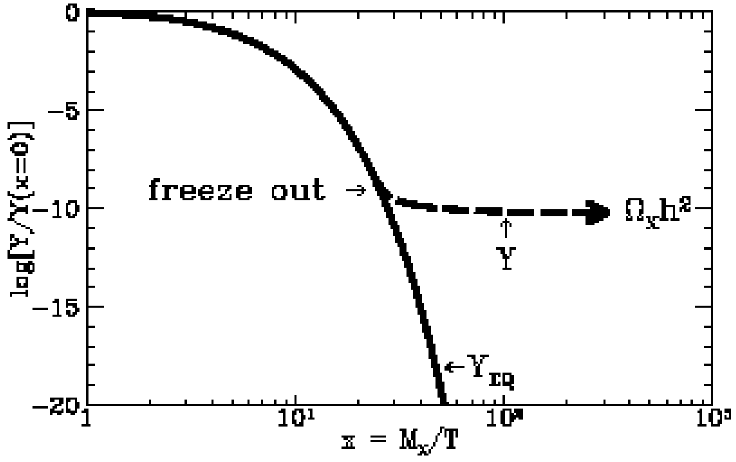

- DM could be part of a sector of particles charged under the parity that stabilizes the DM particles.

- If the DM is well separated from the rest --- the one-particle freeze-out picture holds

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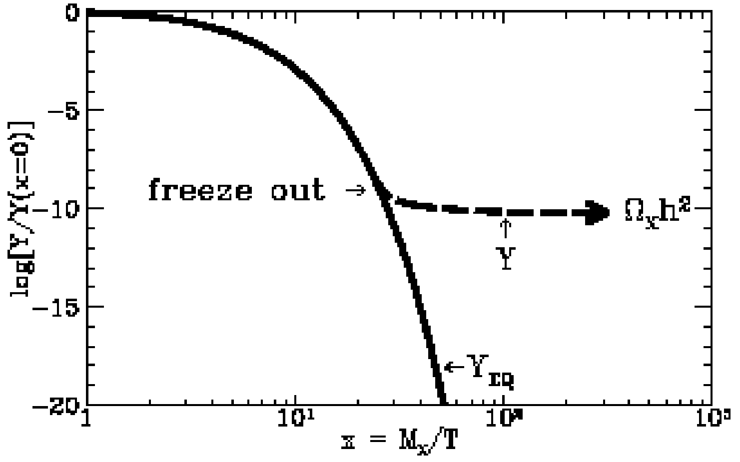

- DM could be part of a sector of particles charged under the parity that stabilizes the DM particles.

- If the DM is well separated from the rest --- the one-particle freeze-out picture holds

- $m_{NLSP} \simeq m_{DM}$ $\Longrightarrow$ "multiparticle" freeze-out

What if dark sector had more than one particle

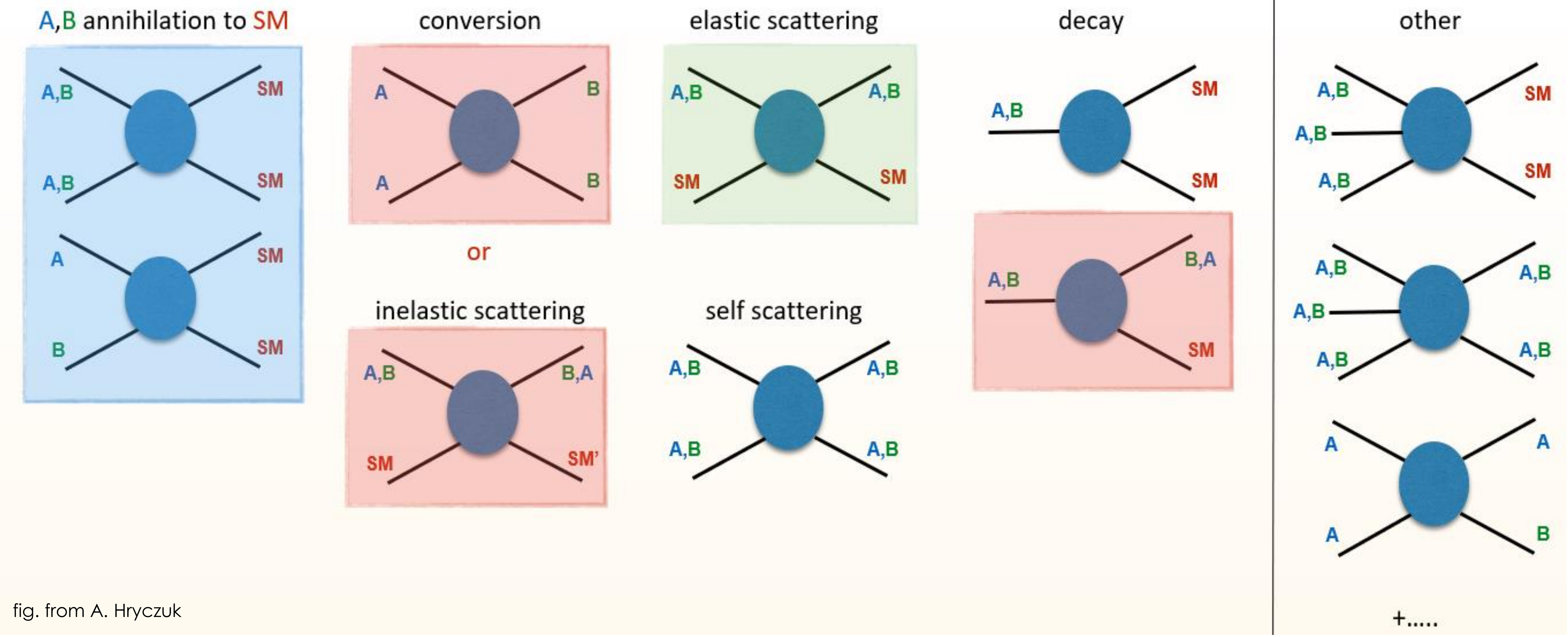

fig. from A. Hryczuk

computationally more challenging…

2-particle freeze-out:

$\mathrm{A} = \chi_1;\ \ \mathrm{B} = \chi_2;\ \ m_{\chi_2} > m_{\chi_1}$

Coupled Boltzmann equation:

$$\frac{dY_1}{dT} = \frac{1}{3H}\frac{ds}{dx}\left[\langle\sigma_{11}v\rangle\left(Y_1^2 - Y_{1,eq}^2\right) + \langle\sigma_{12}v\rangle\left(Y_1 Y_2 - Y_{1,eq}Y_{2,eq}\right) + \frac{\Gamma_{1\to2}}{s}\left(Y_1 - Y_2\frac{Y_{1,eq}}{Y_{2,eq}}\right) - \frac{\Gamma_2}{s}\left(Y_2 - Y_1\frac{Y_{2,eq}}{Y_{1,eq}}\right) + \langle\sigma_{11\to22}v\rangle\left(Y_1^2 - Y_2^2\frac{Y_{1,eq}^2}{Y_{2,eq}^2}\right)\right]$$

$$\frac{dY_2}{dT} = \frac{1}{3H}\frac{ds}{dx}\left[\langle\sigma_{22}v\rangle\left(Y_2^2 - Y_{2,eq}^2\right) + \langle\sigma_{12}v\rangle\left(Y_1 Y_2 - Y_{1,eq}Y_{2,eq}\right) - \frac{\Gamma_{1\to2}}{s}\left(Y_1 - Y_2\frac{Y_{1,eq}}{Y_{2,eq}}\right) + \frac{\Gamma_2}{s}\left(Y_2 - Y_1\frac{Y_{2,eq}}{Y_{1,eq}}\right) - \langle\sigma_{11\to22}v\rangle\left(Y_1^2 - Y_2^2\frac{Y_{1,eq}^2}{Y_{2,eq}^2}\right)\right]$$

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$\Gamma_{\chi_{1,SM}\leftrightarrow\chi_{2,SM}} \gg H$ Coannihilation

Edsjo, Gondolo '97

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$\Gamma_{\chi_{1,SM}\leftrightarrow\chi_{2,SM}} \simeq H$: Conversion-driven

Talk yesterday by Jan Heisig

Garny, Heisig, Lulf, Vogl '17;
D'Agnnolo et al '17;
Garny, Heisig, Hufnagel, Lulf, Vogl '19;

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$\frac{\Gamma_{\chi_1,SM\to\chi_1,SM}}{H} \gg 1$ & $\Gamma_{\chi_1,SM\leftrightarrow\chi_2,SM} \simeq H$: Conversion-driven

Assumes efficient processes to restore equilibrium distribution

Garny, Heisig, Lulf, Vogl '17;
D'Agnnolo et al '17;
Garny, Heisig, Hufnagel, Lulf, Vogl '19;

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- Process to restore equilibrium distribution is inefficient

Garny, Heisig, Lulf, Vogl '17;
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full Boltzmann equation (fBE) must be solved when:

- Process to restore equilibrium distribution is inefficient
- Strongly momentum dependent/ selective processes

Brummer '19;
Garny, Heisig, Lulf, Vogl '17;
D'Agnolo et al '17;
Garny, Heisig, Hufnagel, Lulf, Vogl '19;

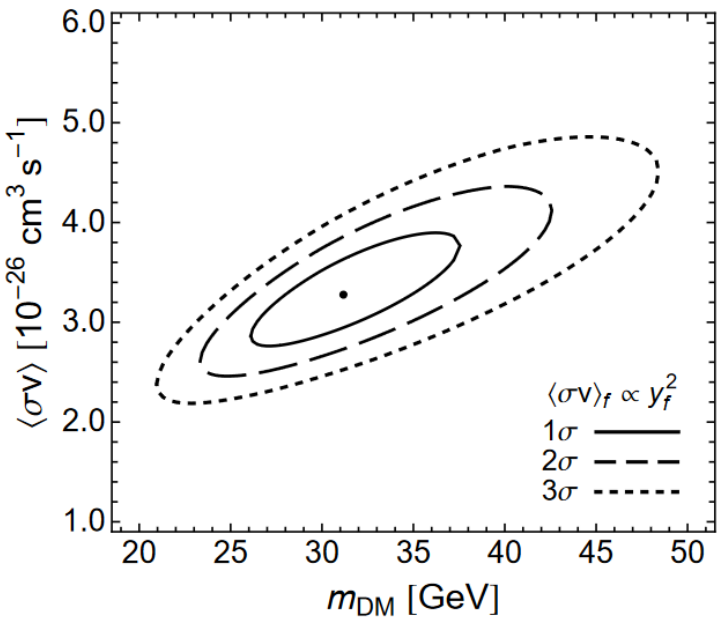
Coy Dark Matter:

1. A DM interpretation of the extended Galactic gamma-ray excess from Fermi-LAT

2. Dirac DM (χ) with interaction mediated by a light pseudoscalar, with couplings to SM particles proportional to Yukawa couplings per Minimal Flavour Violation (MFV)

3. Direct detection rates suppressed by square of the nuclear recoil energy

$$\mathcal{L} \supset -i\frac{g_{DM}}{\sqrt{2}}\, a\, \bar{\chi}\gamma^5\chi - i\sum_{f\in SM}\frac{g_f}{\sqrt{2}} a\, \bar{f}\gamma^5 f$$



Boehm et al 2014

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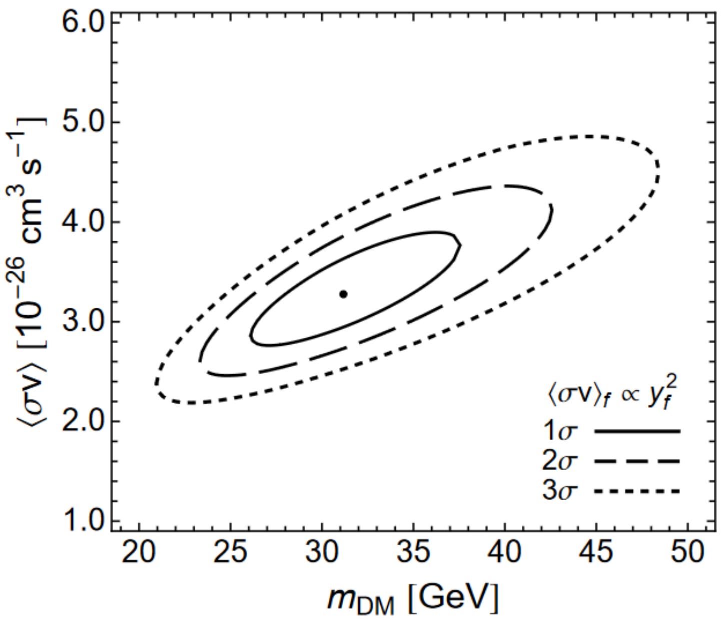

Boehm et al 2014

hep-ph: 1612.05687

Coy Dark Matter: 2-component

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$\Rightarrow$

Solve full coupled Boltzmann equation to investigate all the effects of conversions, annihilations and scatterings.

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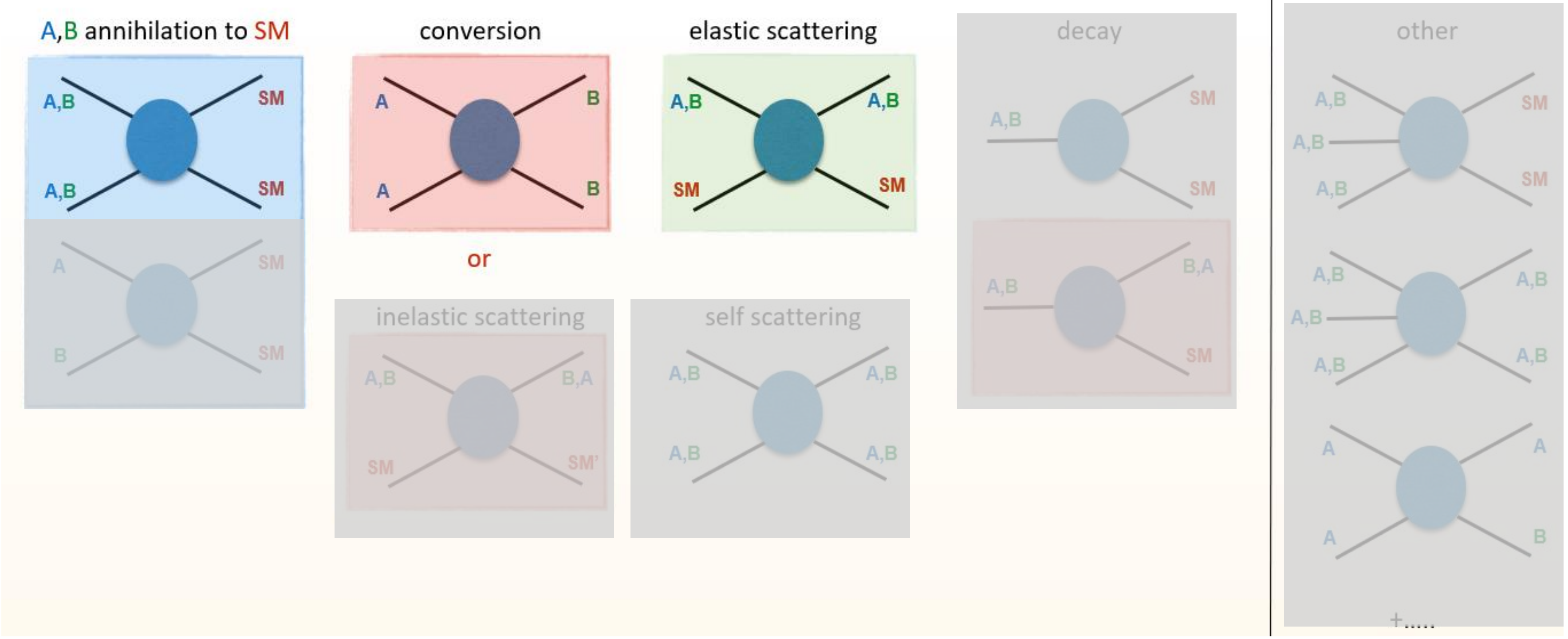

- Code to solve at Yield level: micrOMEGAs 6.0: N-component DM
- We develop a code to solve for this multicomponent DM at phase space level: extending the publicly available code DRAKE

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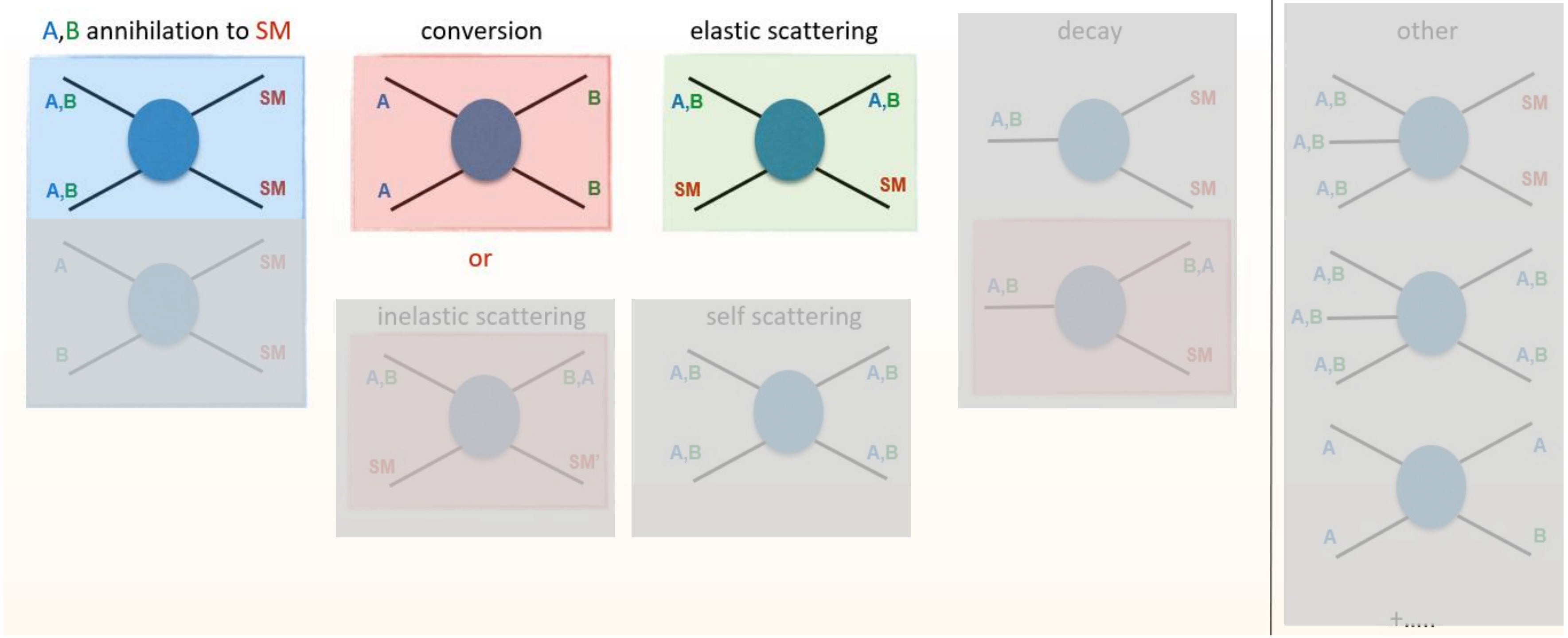
Coy Dark Matter: 2-component



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Collision operators:

$$C_{el}[f_{DM}] = \int d\Pi\, |M|^2_{DM,SM\to DM,SM}\left(f_{DM;A,B}(p_1) f_{eq}(p_3) - \boldsymbol{f_{DM;A,B}(p_2)} f_{eq}(p_4)\right)$$

$$C_{ann}[f_{DM}] = \int d\Pi\, |M|^2_{DM,DM\to SM,SM}\left(f_{DM;A,B}(p_1)\boldsymbol{f_{DM;A,B}(p_2)} - f_{eq}(p_3) f_{eq}(p_4)\right)$$

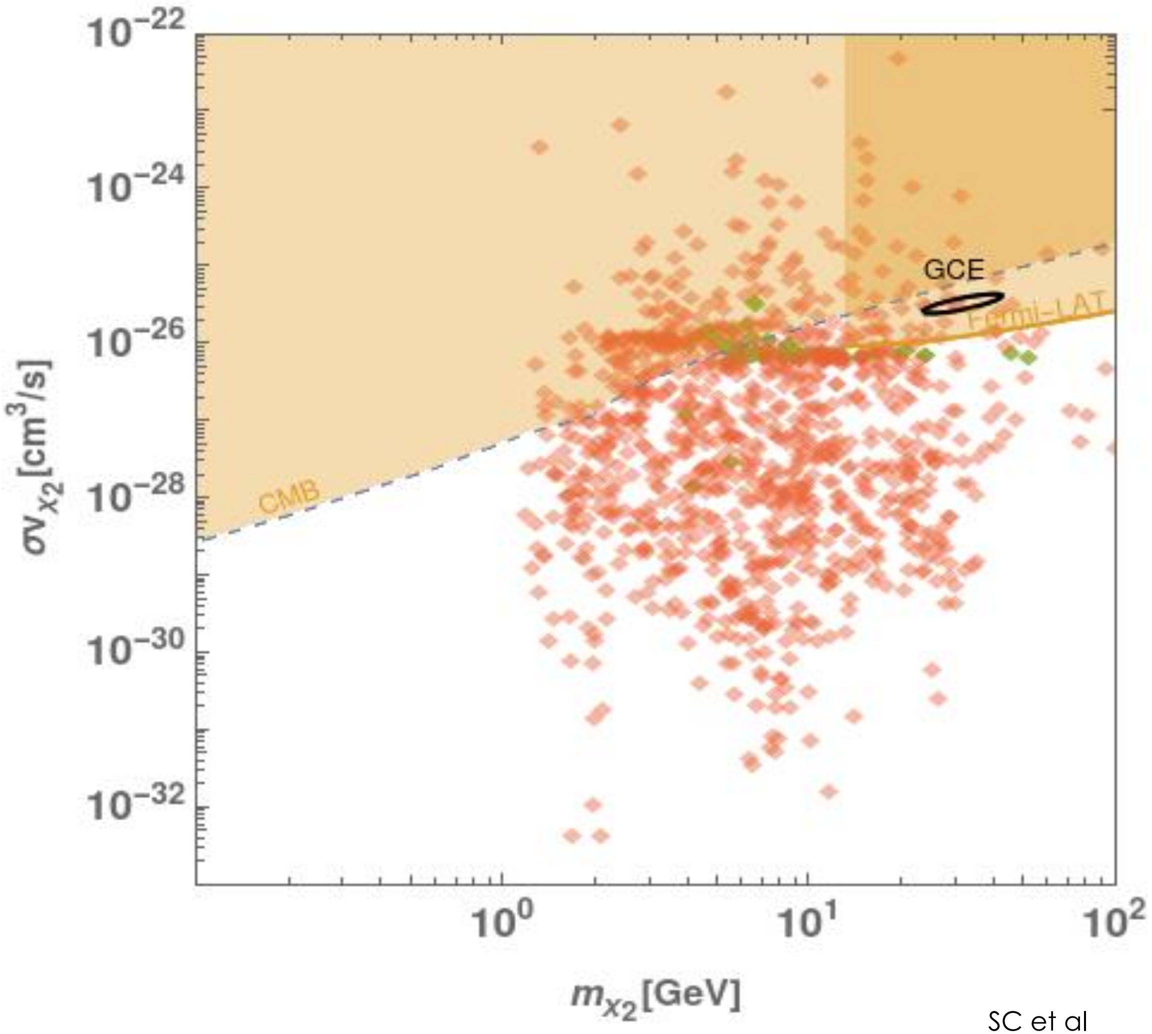
$$C_{conv}[f_{DM}] = \int d\Pi\, |M|^2_{A,A\to B,B}\left(f_{DM,A}(p_1)\boldsymbol{f_{DM,A}(p_2)} - \boldsymbol{f_{DM,B}(p_3) f_{DM,B}(p_4)}\right)$$

$$\mathcal{L} \supset -i\lambda_1 a\, \bar{\chi}_1\gamma^5\chi_1 - i\lambda_2 a\, \bar{\chi}_2\gamma^5\chi_2$$

$$-i\lambda_y \sum_{f\in SM} y_f\, a\, \bar{f}\gamma^5 f$$

Coy Dark Matter: 2-component

Indirect Detection:



SC et al

Scan results: $m_{\chi_2} \leq m_{\chi_1}, m_a \geq 1GeV$

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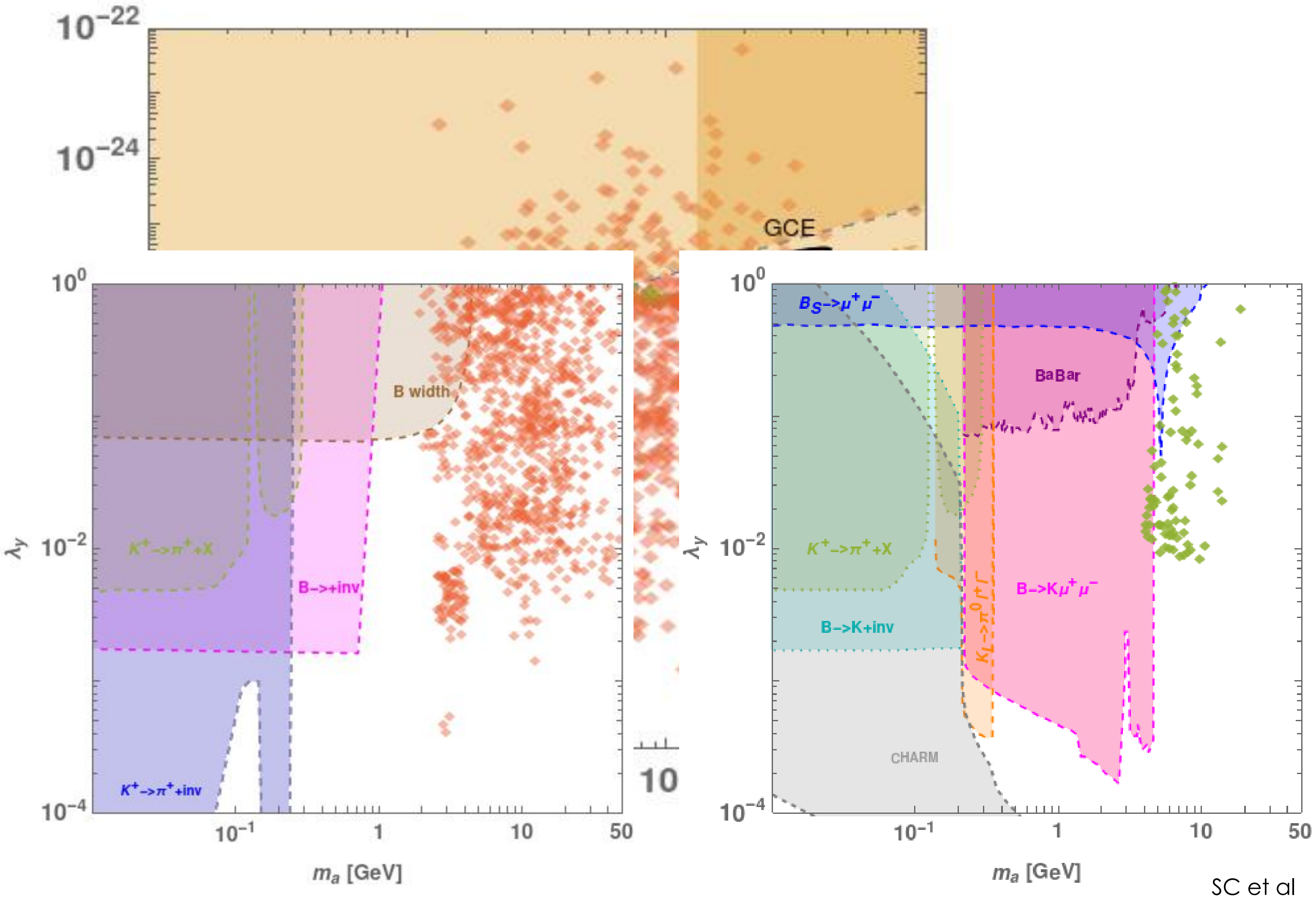
- Indirect detection constraint on χ_2 which is the dominant relic
- Red-- $m_{\chi_2} < \frac{m_a}{2}$: a decays dominantly to SM
- Green-- $m_{\chi_2} > \frac{m_a}{2}$: a decays dominantly to DM
- Shown is the 2σ preferred region to explain the Galactic Centre excess (Boehm et al 2014)

MFV pseudoscalar cnstraints from Dolan et al 1412.5174

Coy Dark Matter: 2-component

Indirect Detection:



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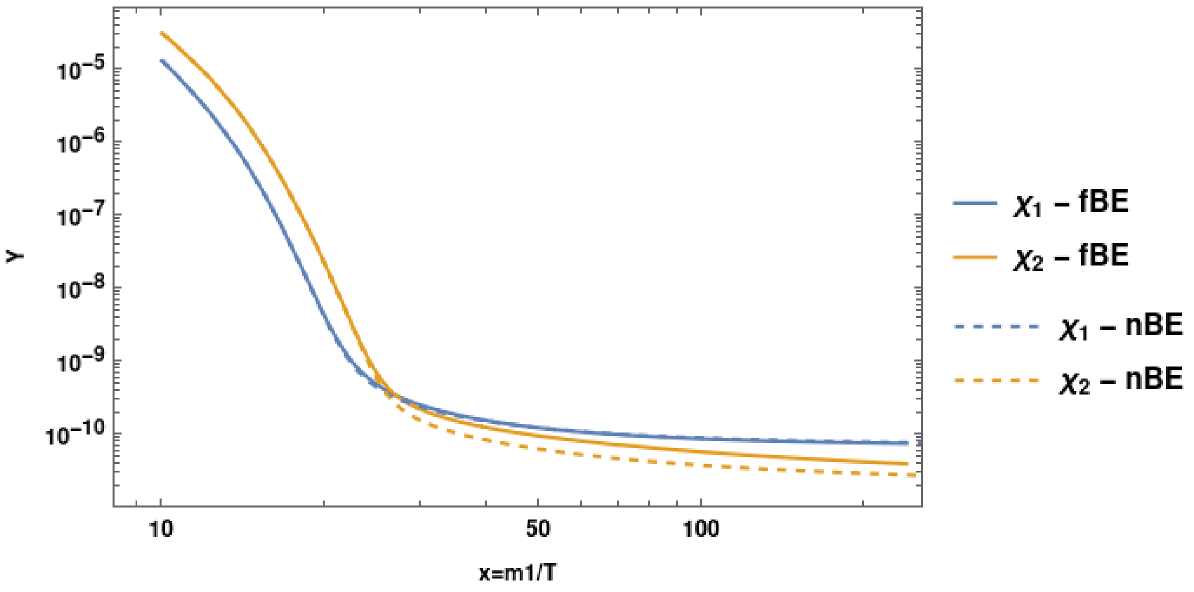
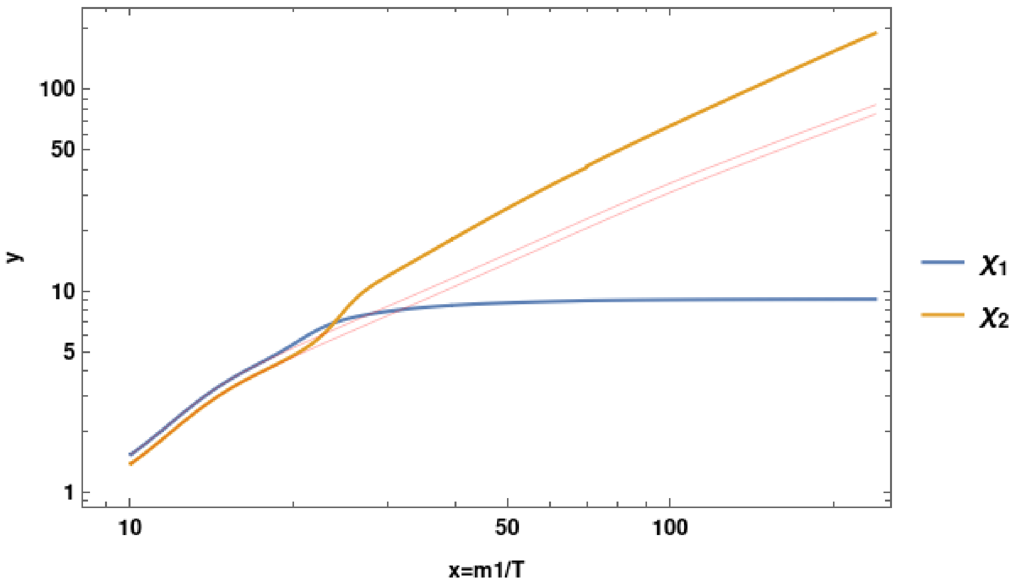
- Bounds on pseudoscalar a from flavor factories and fixed-target experiments (MFV interaction with SM) (Dolan et al 1412.5174)

2-component Coy Dark Matter: Near-resonant BM

$$Y_i \equiv \frac{n_i}{s}, \quad y_i \equiv \frac{m_1 T_i}{s^{2/3}}$$





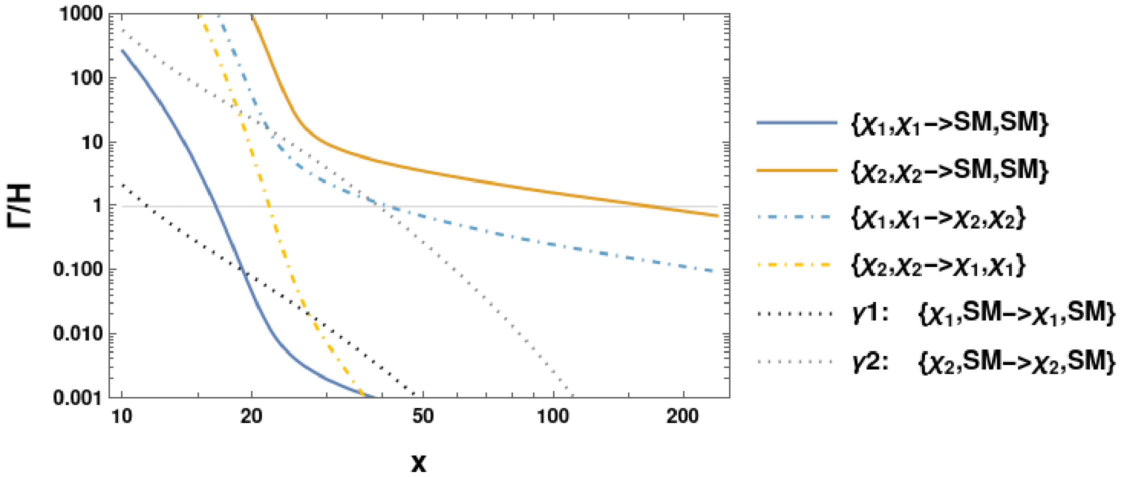
$$m_{\chi_1} = 1.86\ GeV$$
$$m_{\chi_2} = 1.67\ GeV$$
$$m_a = 3.31\ GeV$$
$$\lambda_1 = 0.0067, \lambda_2 = 0.11, \lambda_y = 0.17$$

$$\delta_1 \equiv \left(\frac{2m_{\chi_1}}{m_a}\right)^2 - 1 = 0.262$$
$$\delta_2 \equiv \left(\frac{2m_{\chi_2}}{m_a}\right)^2 - 1 = 0.019$$

$$\frac{Y_1^{nBE}}{Y_1^{fBE}} = 1.02, \frac{Y_2^{nBE}}{Y_2^{fBE}} = 0.71$$

nBE: $(\Omega h^2)_1 = 0.092, (\Omega h^2)_2 = 0.035$

Rates:



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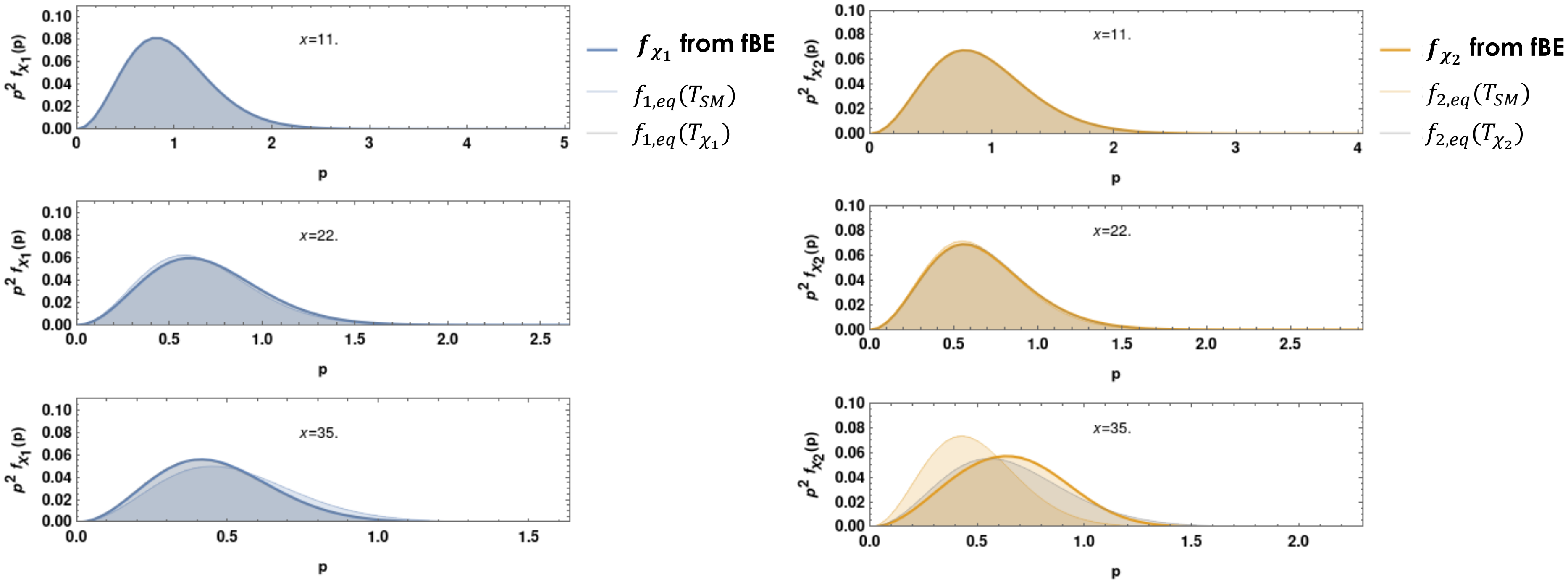

$x = m_{DM}/T_{SM}$

$(m_2^2 - m_1^2)^{1/2} \simeq 0.8\ GeV$

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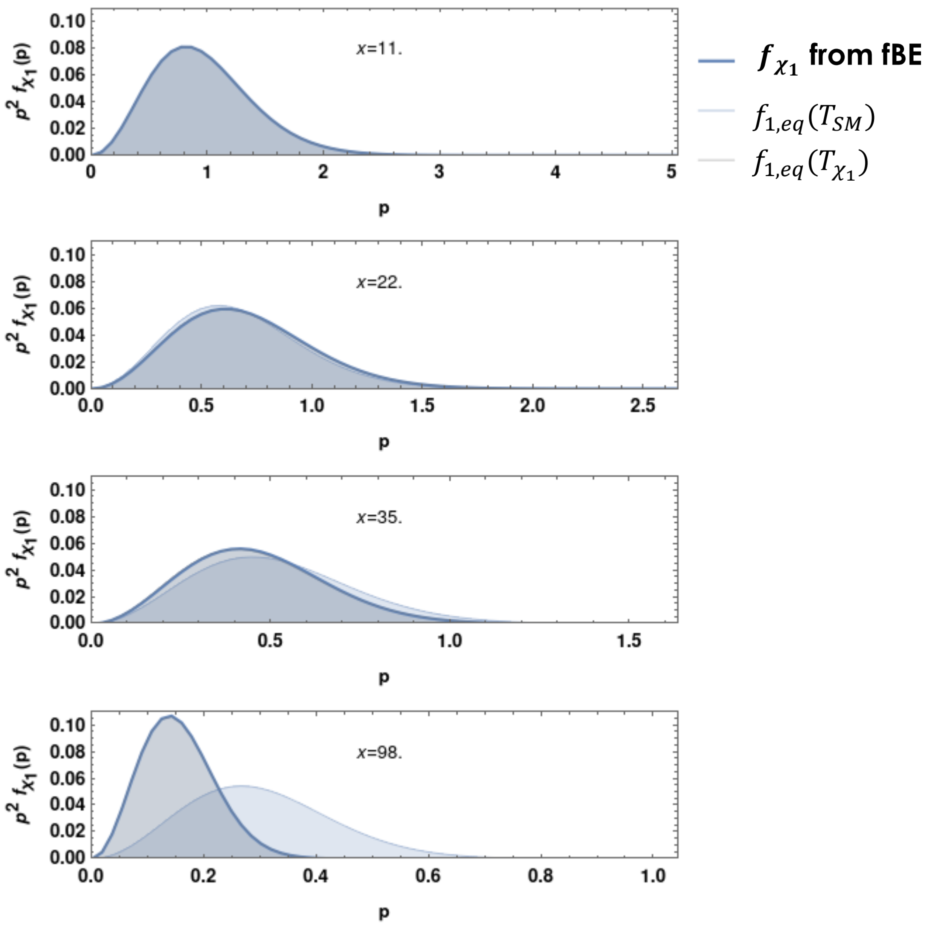

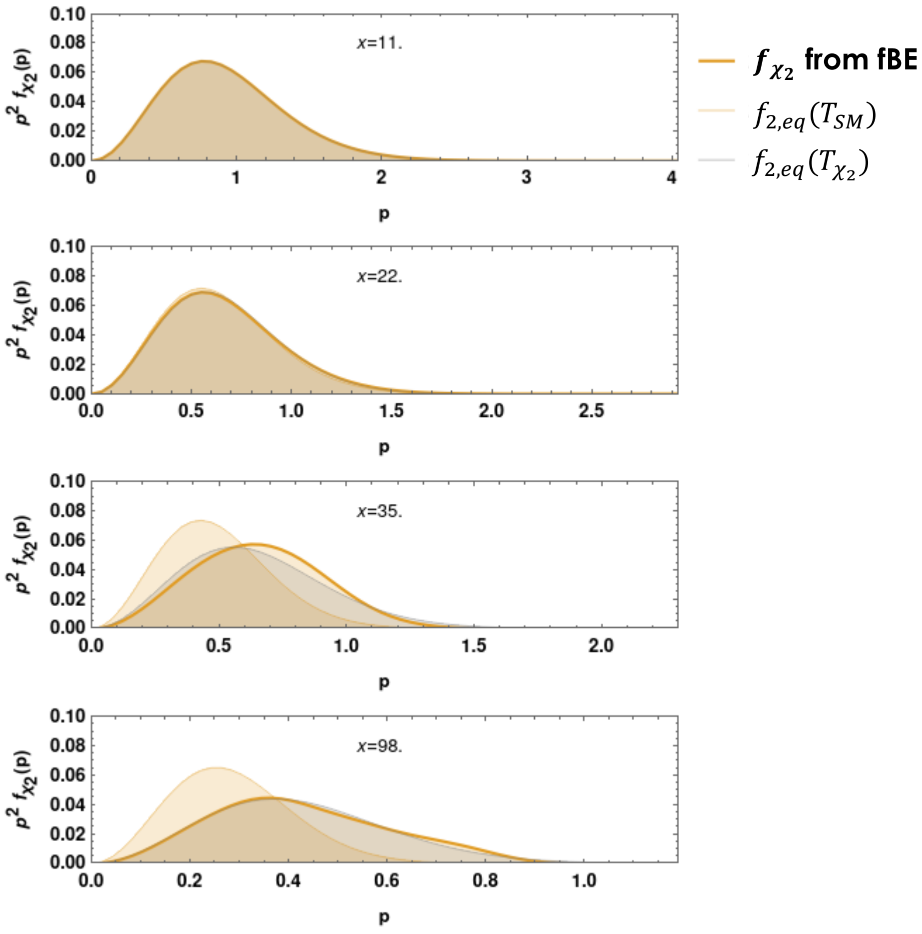

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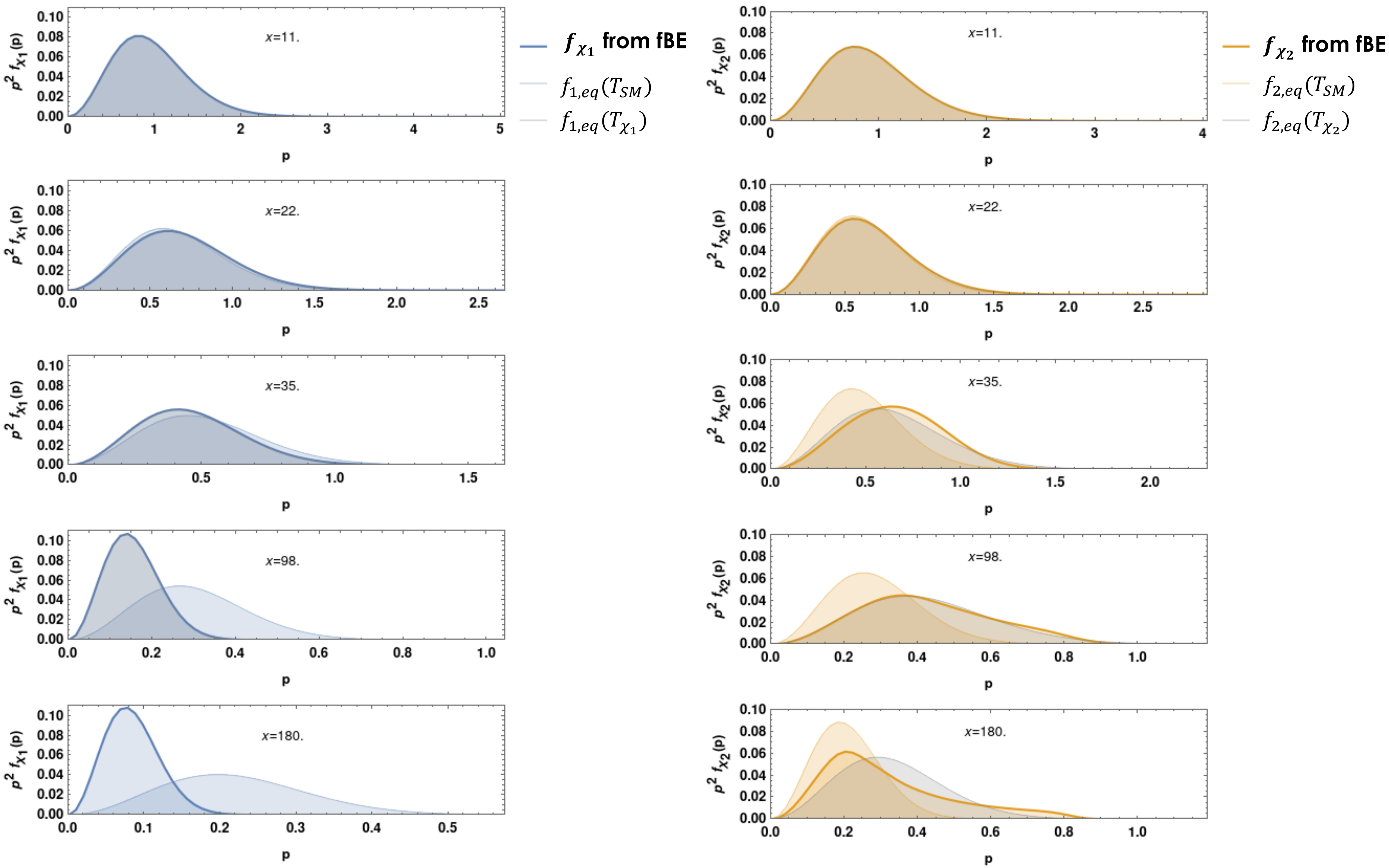

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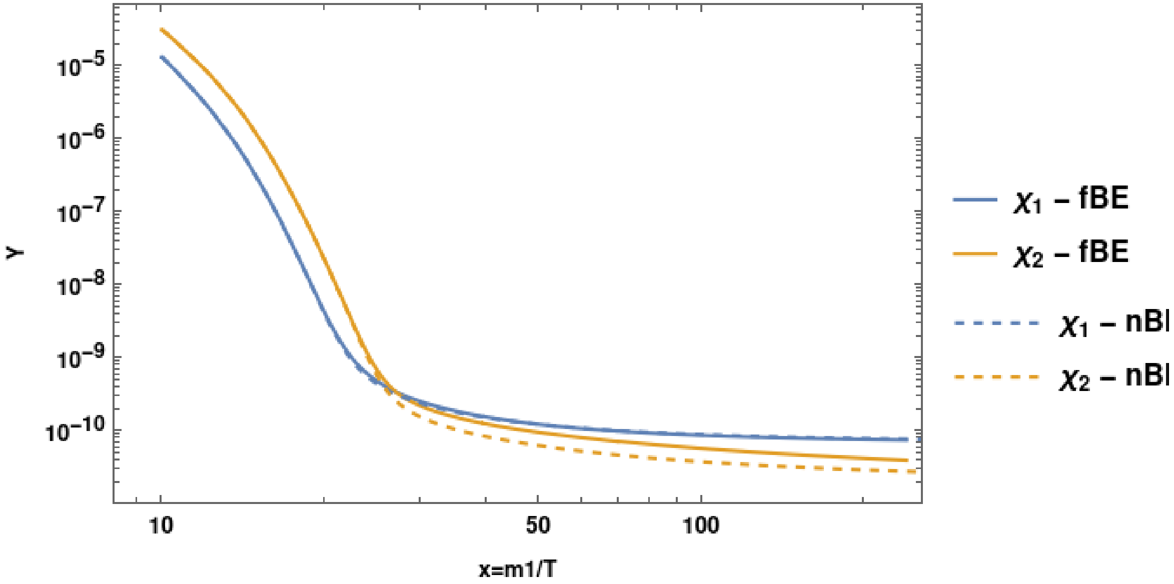

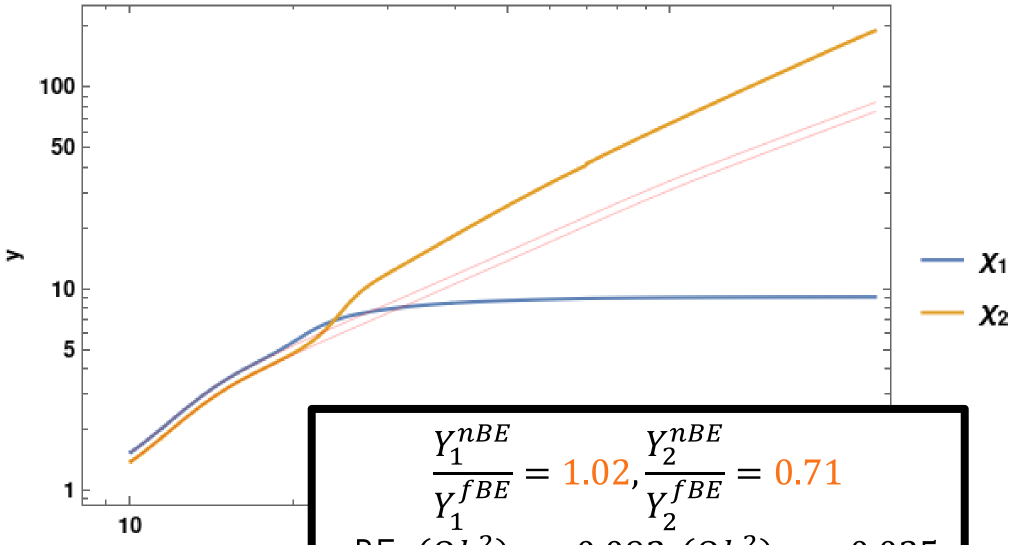

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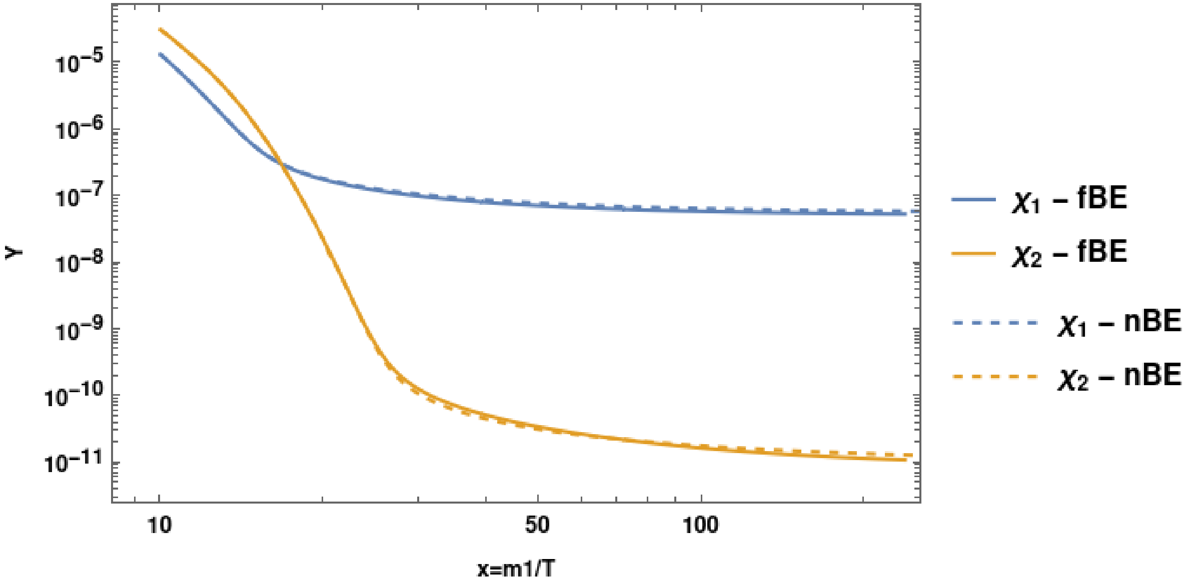

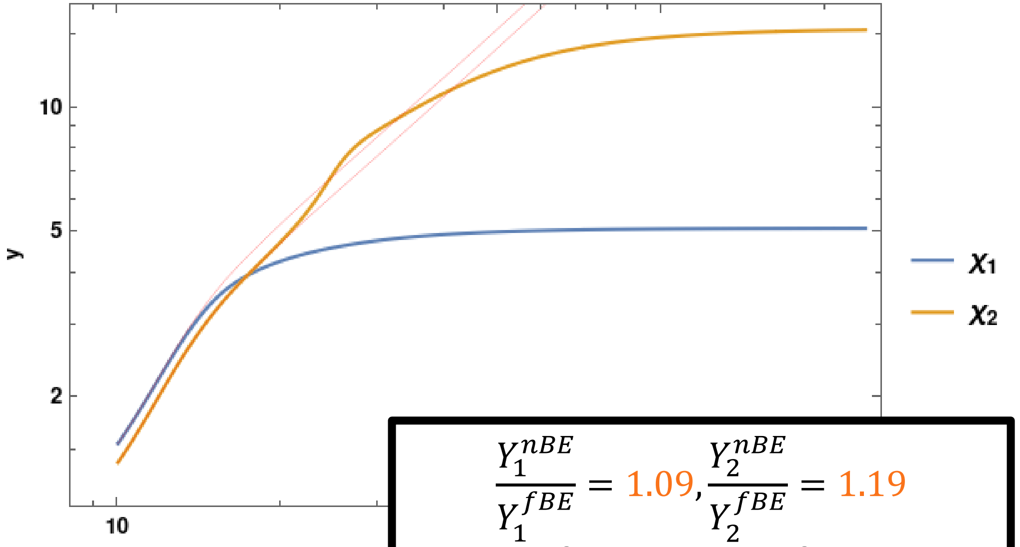

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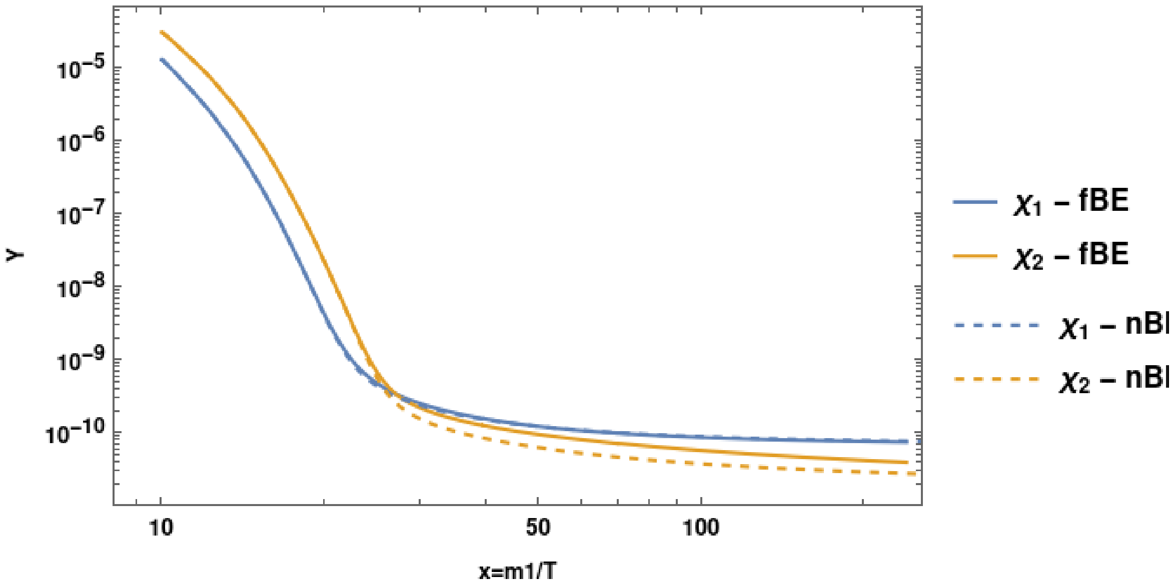
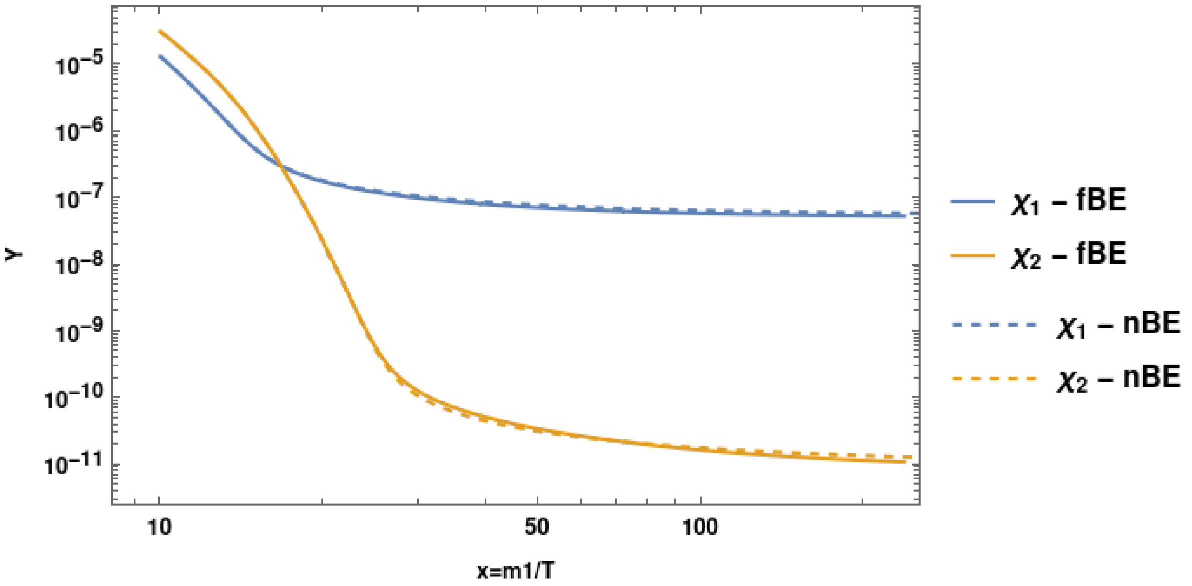
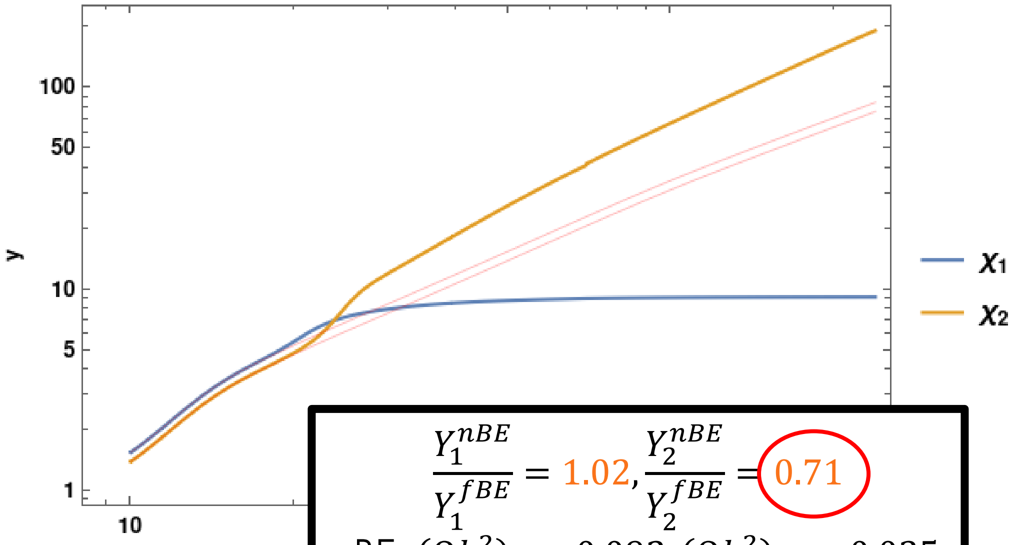


Without conversions:





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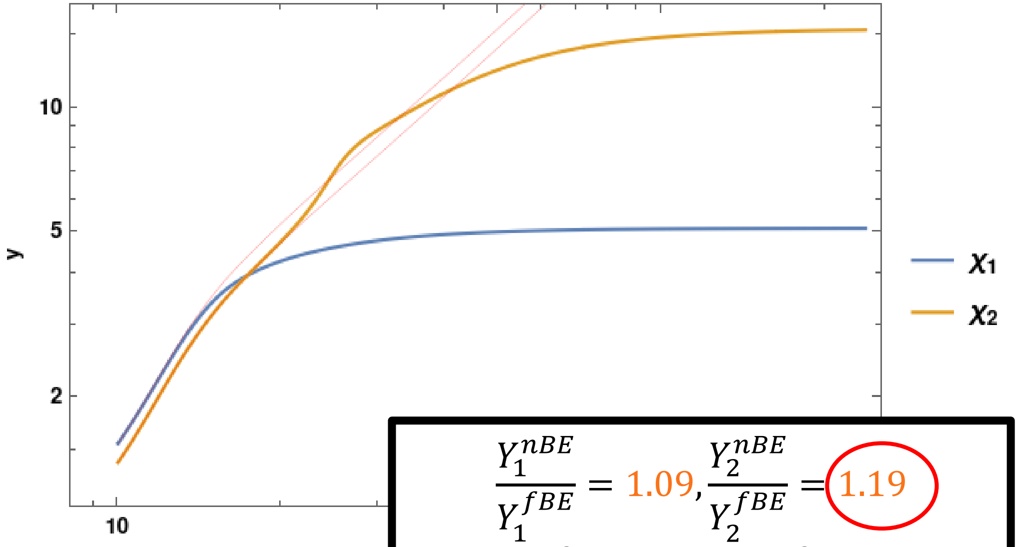

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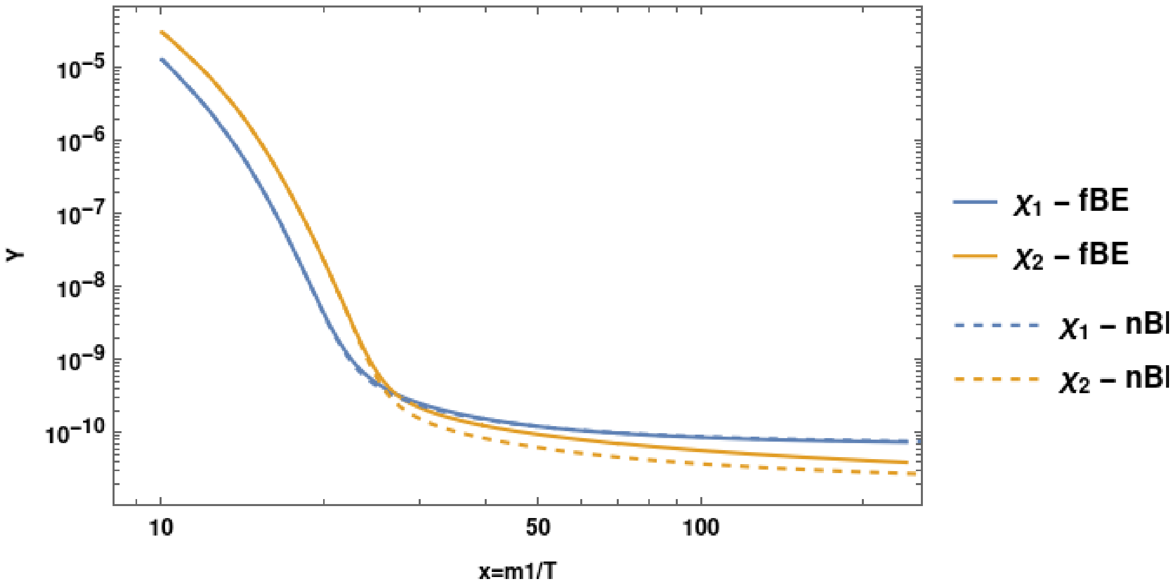

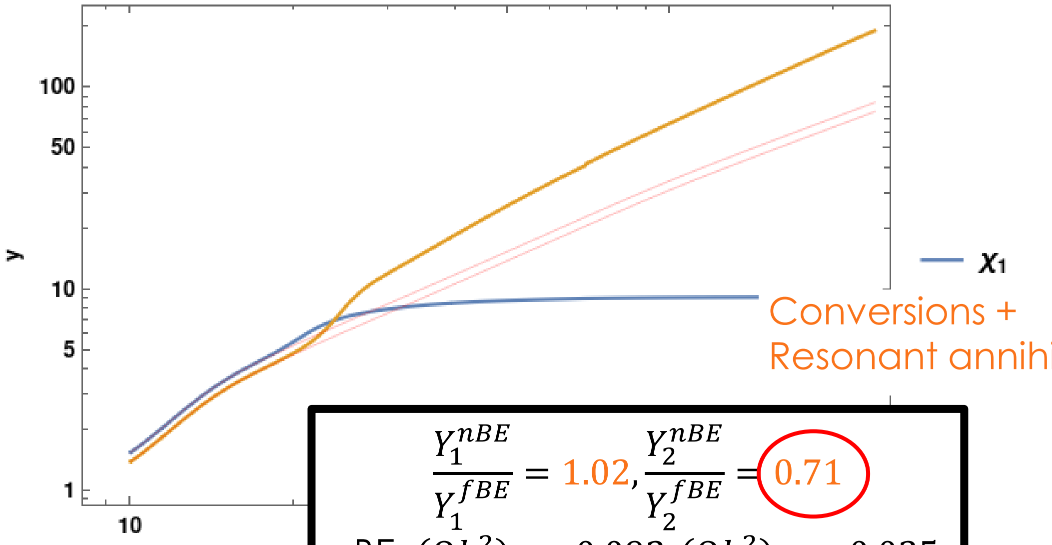

Conversions +
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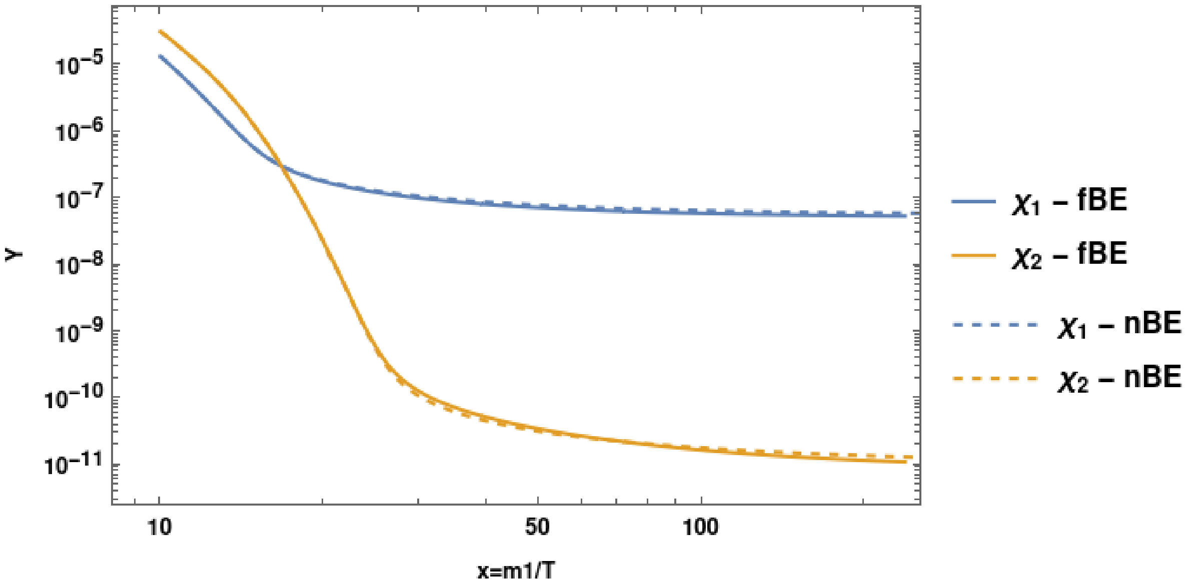

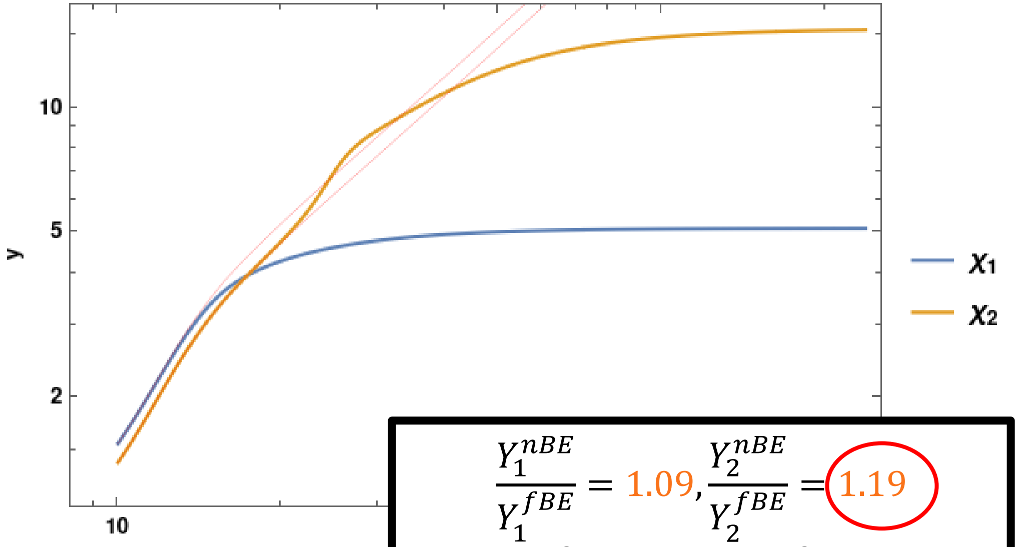

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Summary

- The sector containing DM can *in general* be richly populated with multiple particles.

- The canonical picture of a single WIMP falling out of equilibrium with the SM plasma (freeze-out) is then an approximation to the full picture: typically a good approximation, but *not always*.

- For the parameter spaces where this separation of particles cannot be made, the coupled Boltzmann equation for all particles and processes relevant to the DM freeze-out must be solved.

- Additionally, if the kinetic equilibrium of DM with SM cannot be guaranteed, a precise determination of the relic abundance requires for a solution of the full Boltzmann equation (fBE) at the phase-space level. These effects would be larger still for momentum dependent DM interactions.
- With a 2-component Coy DM model--featuring momentum dependent DM-SM scattering:
  - O(10)% deviation in relic densities of either particle is frequently observed
  - For specific points with strong resonance-effects, O(10) deviation is observed

  between the relic densities obtained from solutions of full Boltzmann equation at phase space level to the (integrated Boltzmann) equation in Yield.

- A code to solve the two-component DM Boltzmann equation at phase space level for precision calculation (to be included in a future version of the publicly available code DRAKE)

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Thank you!

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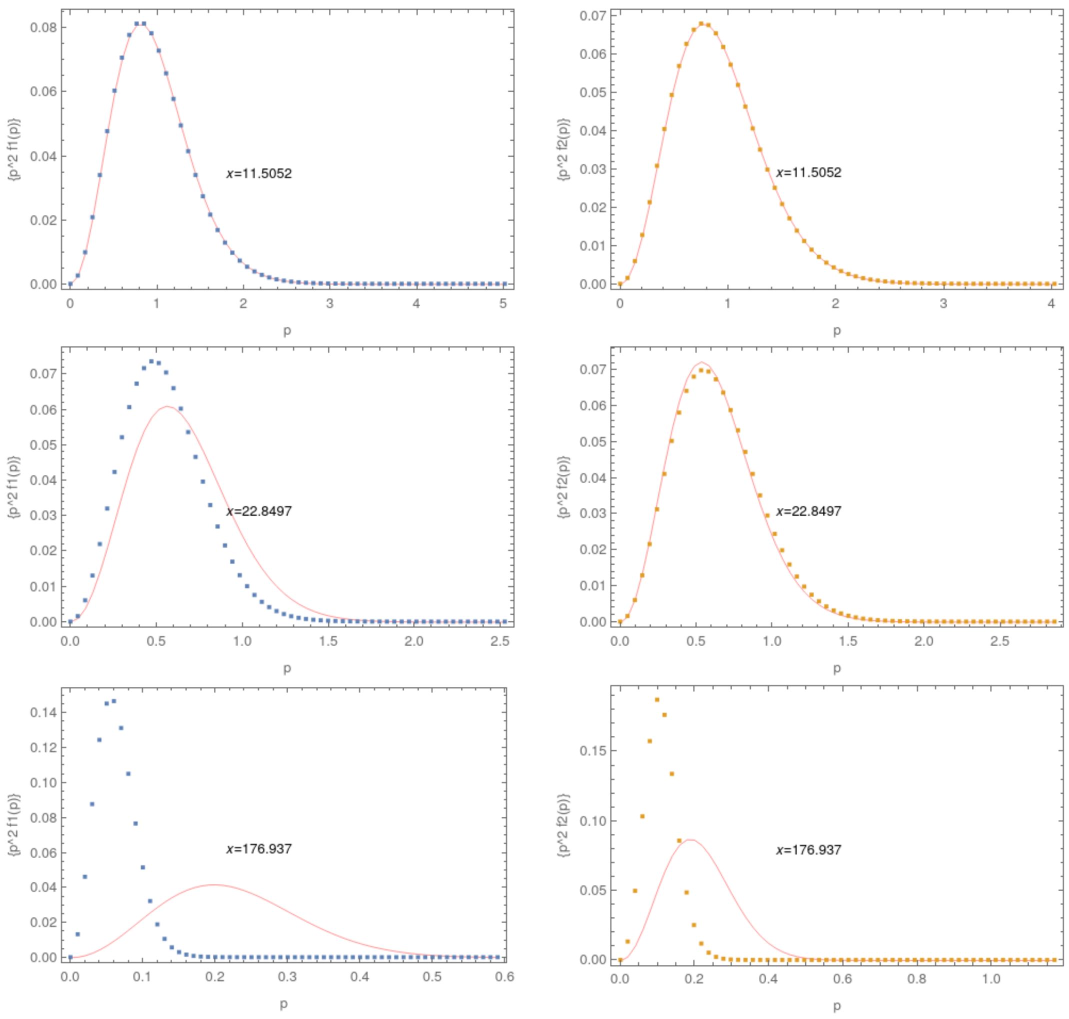
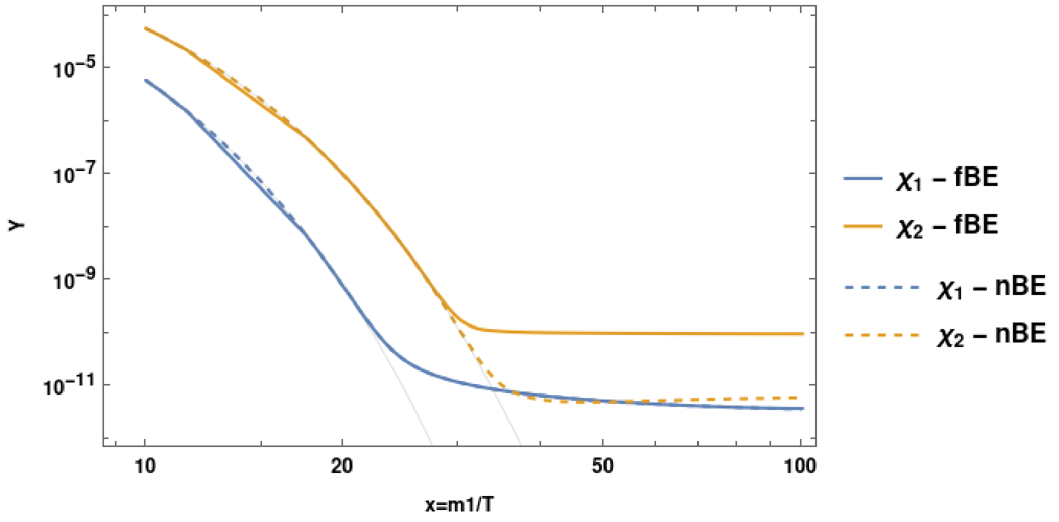
Backup

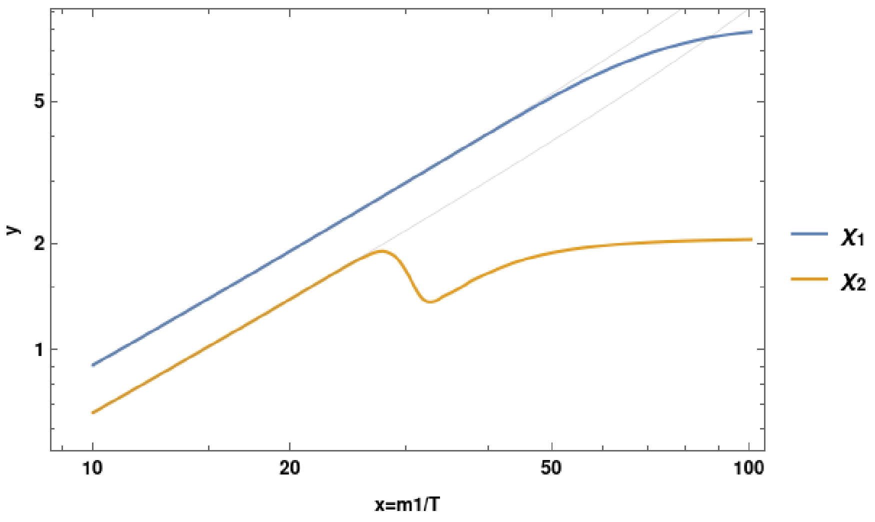
2-component Coy Dark Matter: Near-resonant

w/o conversions



2-component Coy Dark Matter: Resonant case





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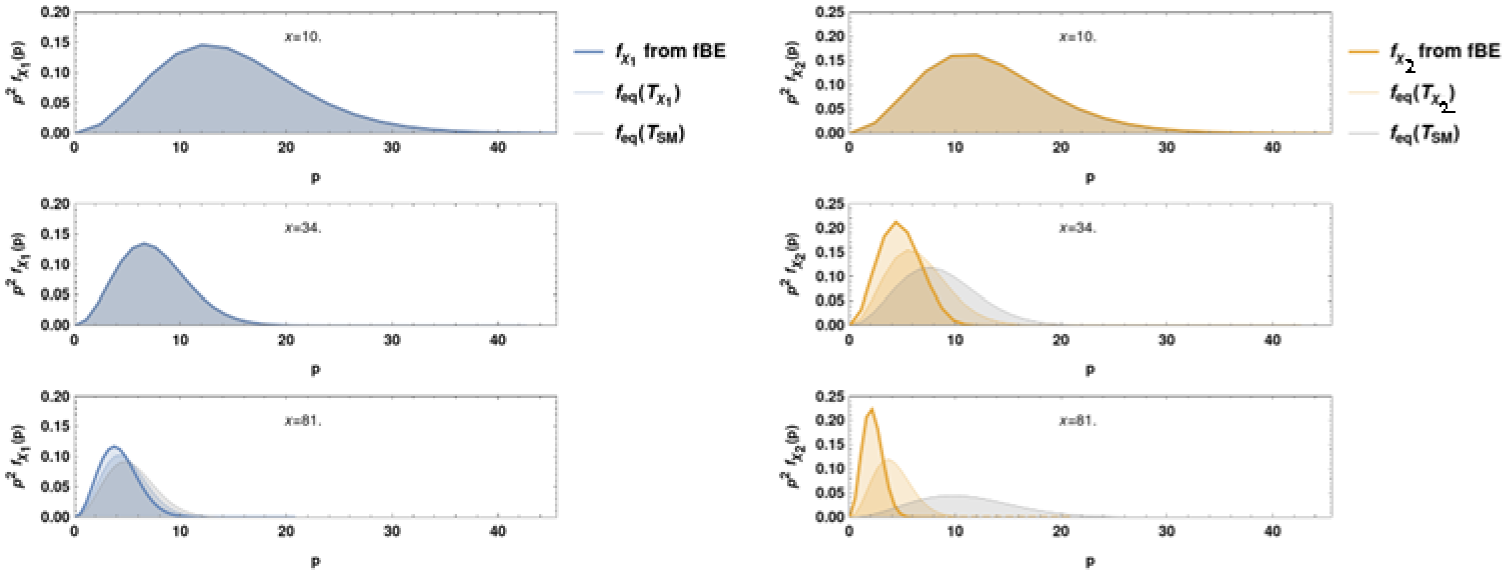


$m_{\chi_1} = 26.6 GeV$
$m_{\chi_2} = 19.54 GeV$
$m_a = 43.34 GeV$
$\lambda_1 = 0.4, \lambda_2 = 0.28, \lambda_y = 0.16$

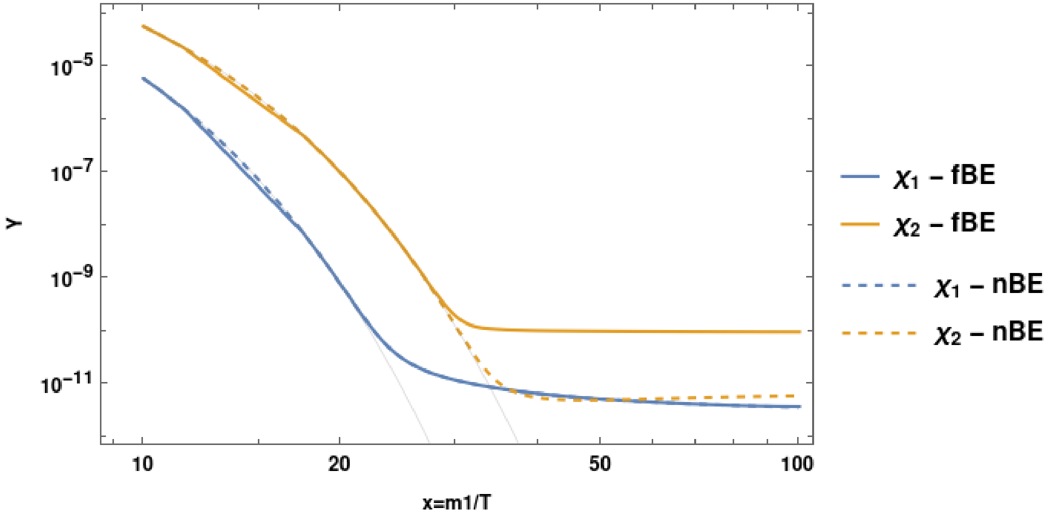
Resonant annihilation of χ_2

$$\frac{Y_1^{nBE}}{Y_1^{fBE}} = 0.975, \frac{Y_2^{nBE}}{Y_2^{fBE}} = 0.058$$

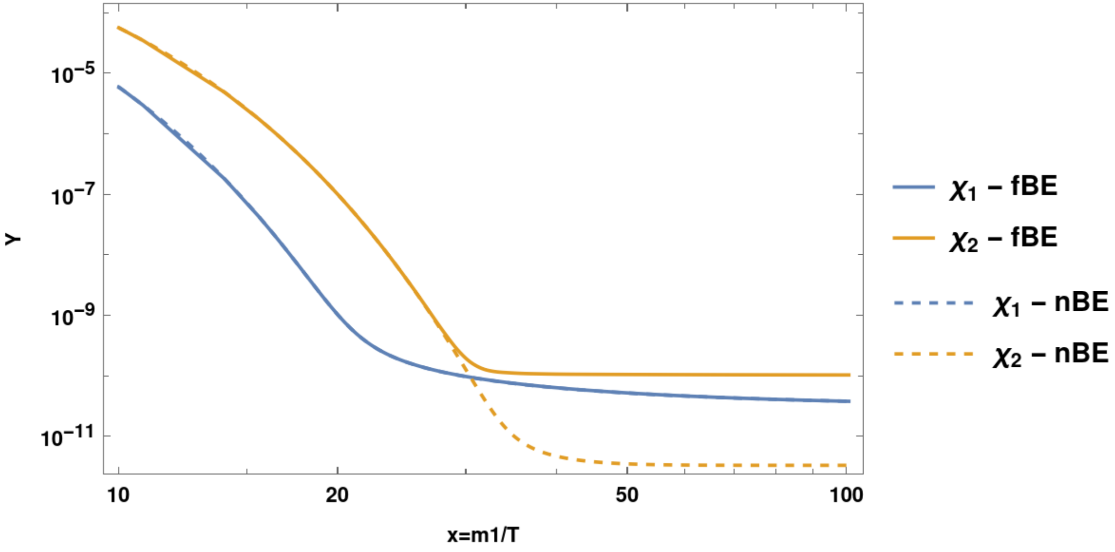
nBE: $(\Omega h^2)_1 = 0.05, (\Omega h^2)_2 = 0.06$

2-component Coy Dark Matter: Resonant case

With conversions:



Without conversions:



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nBE: $(\Omega h^2)_1 = 0.054, (\Omega h^2)_2 = 0.067$

$$\frac{Y_1^{nBE}}{Y_1^{fBE}} = 1.00, \frac{Y_2^{nBE}}{Y_2^{fBE}} = 0.03$$

nBE: $(\Omega h^2)_1 = 0.57, (\Omega h^2)_2 = 0.036$

2-component Coy Dark Matter: Resonant case

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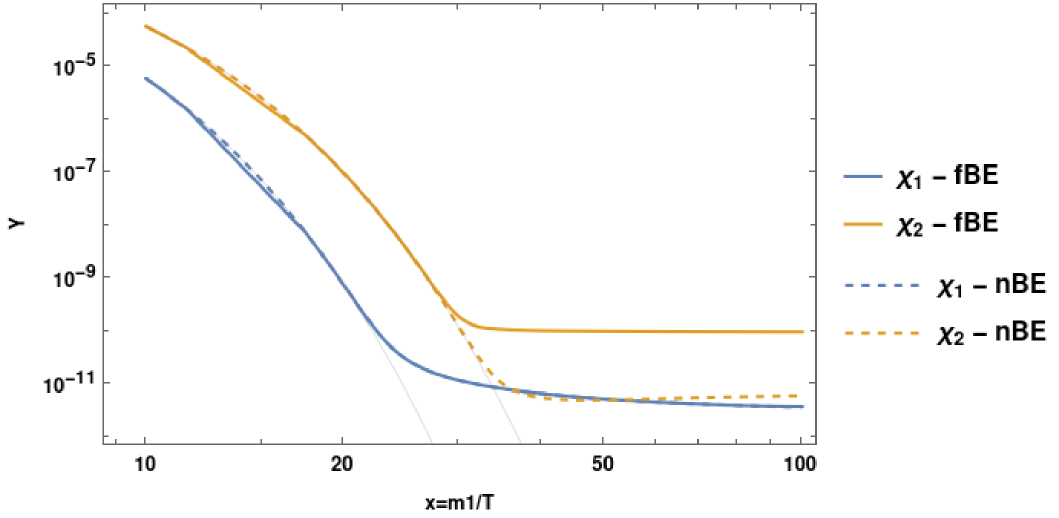

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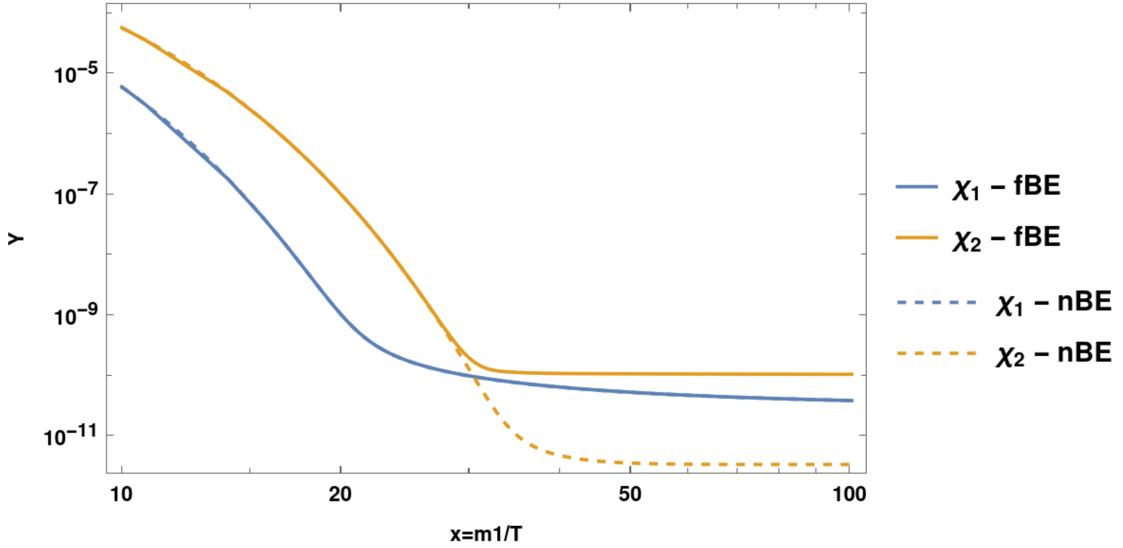

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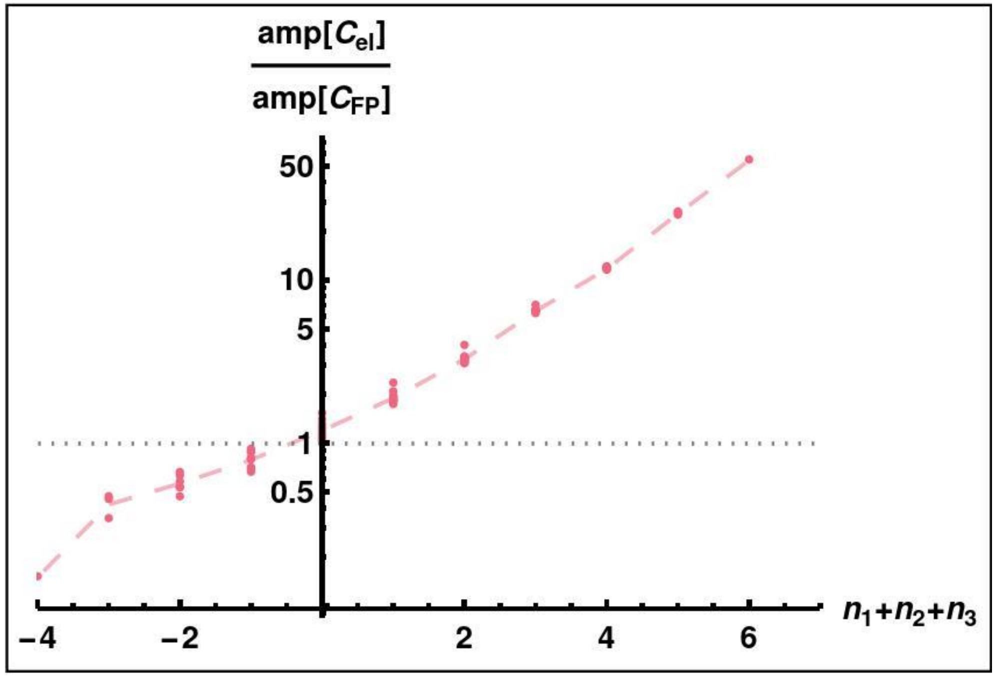
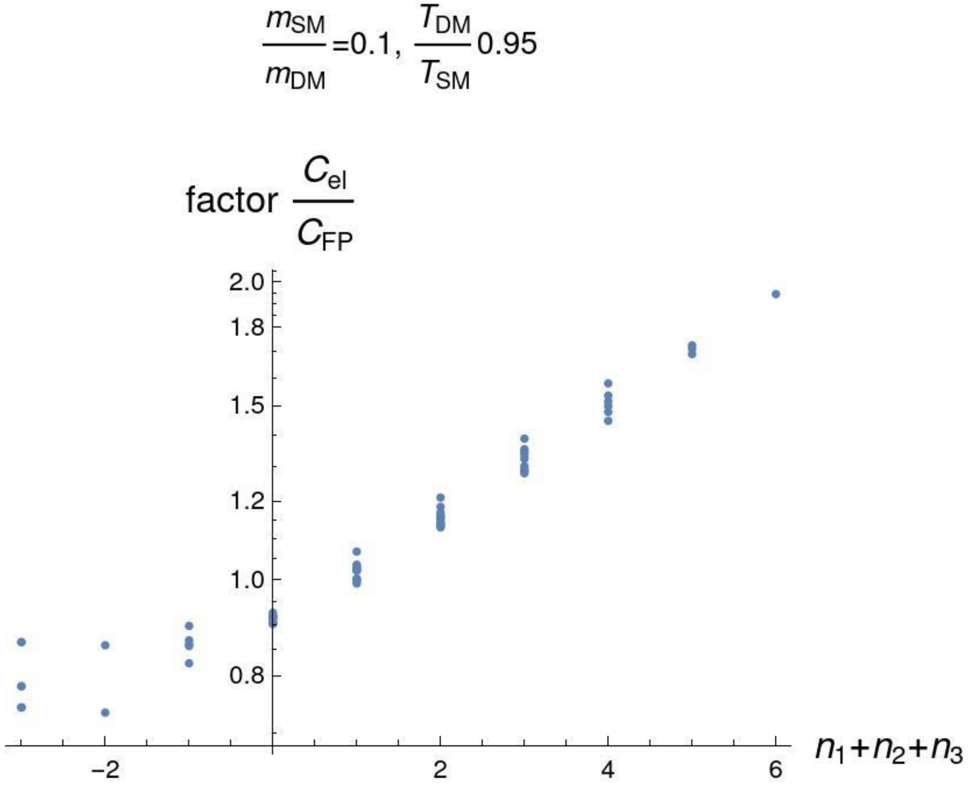
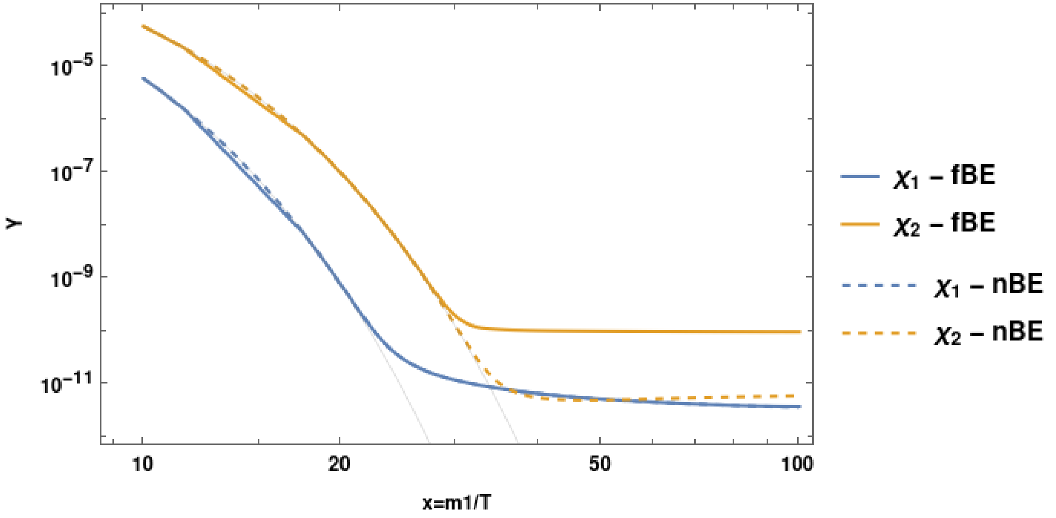

amp[C_el] / amp[C_FP]
50
10
5
1
0.5
−4
−2
2
4
6
n1+n2+n3


m_SM / m_DM =0.1, T_DM / T_SM 0.95
factor C_el / C_FP
2.0
1.8
1.5
1.2
1.0
0.8
−2
2
4
6
n1+n2+n3

2-component Coy Dark Matter: Results phase space solutions

With conversions:



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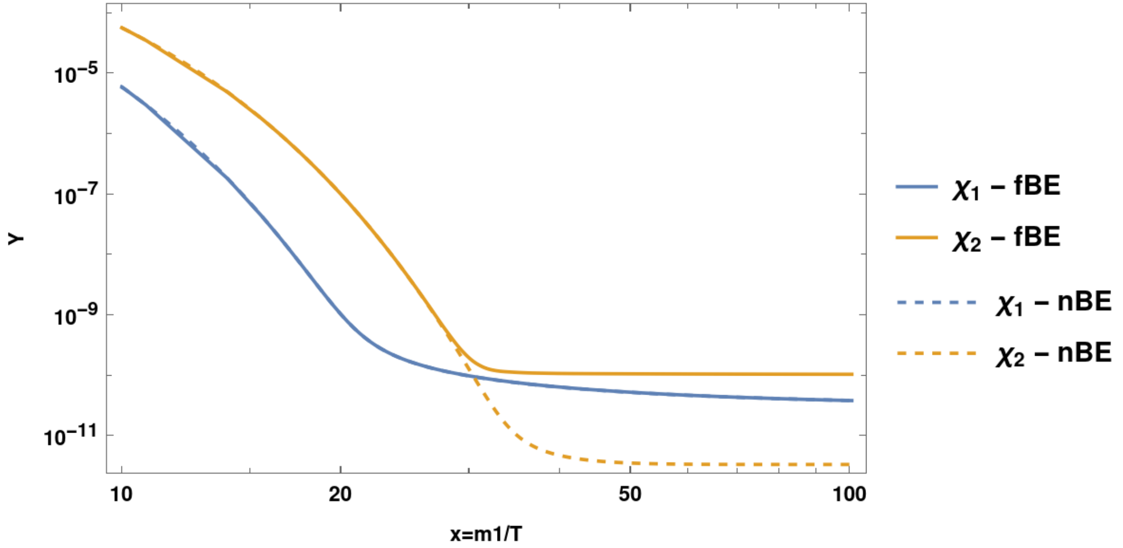

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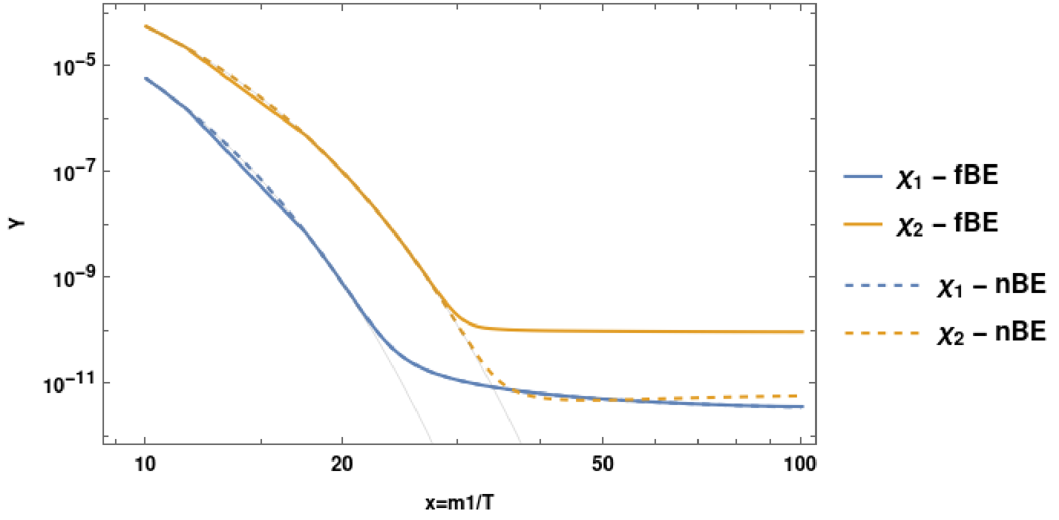

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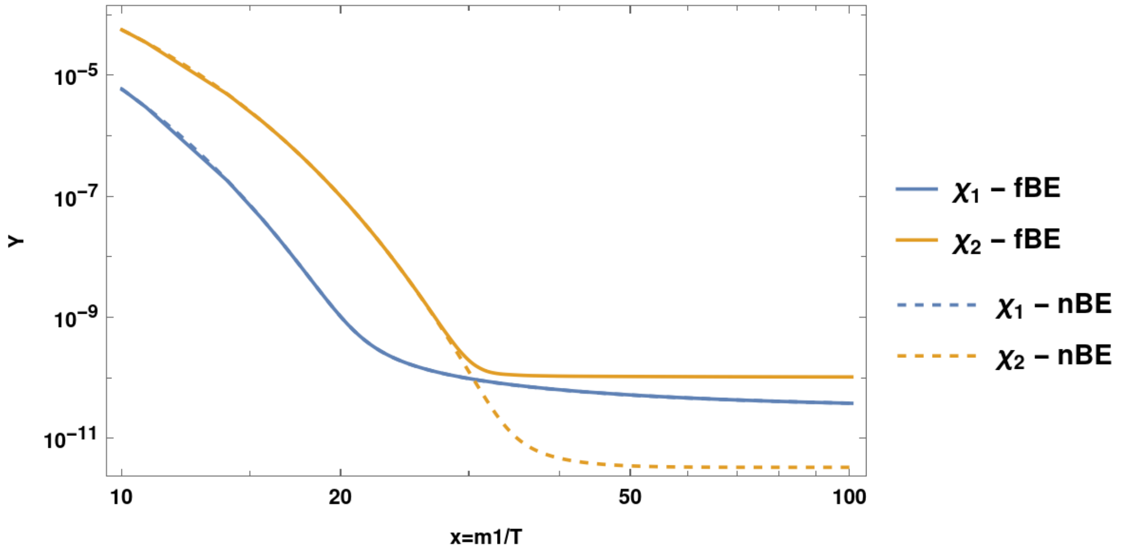

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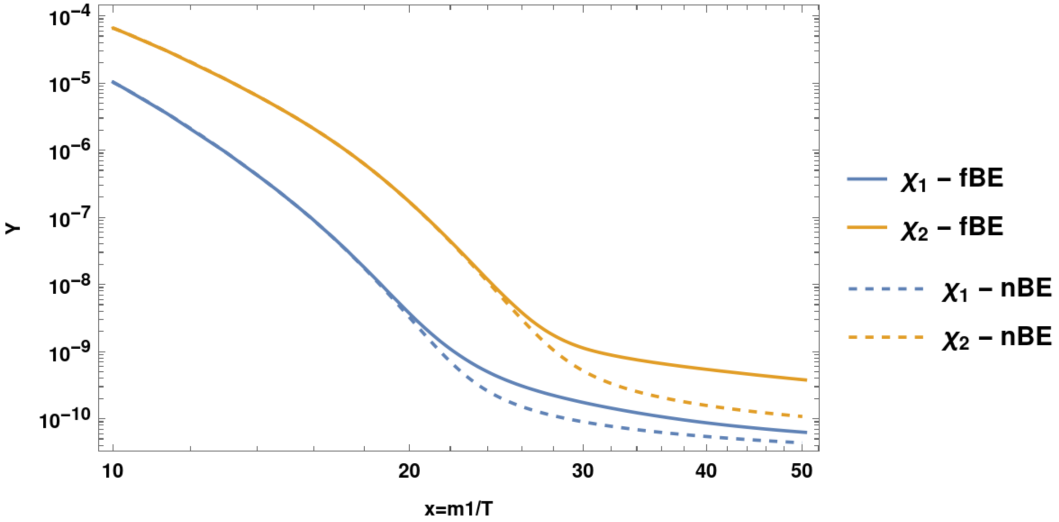

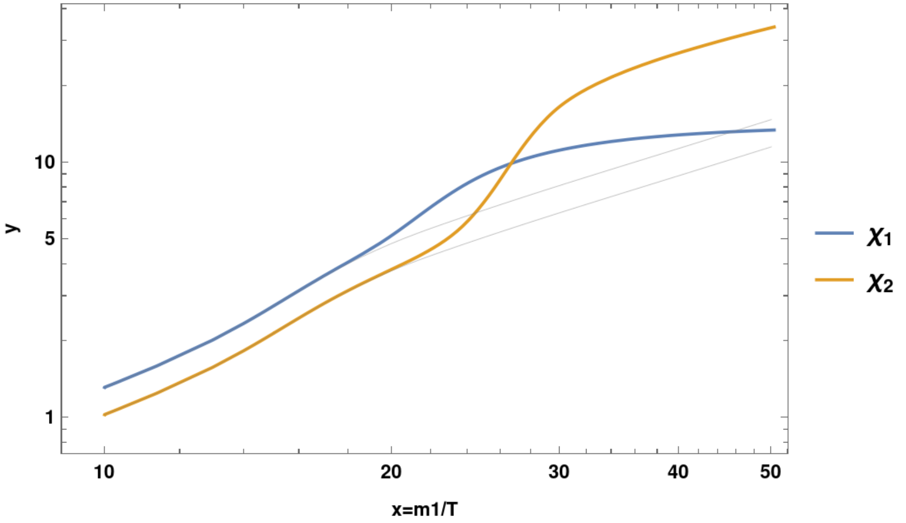

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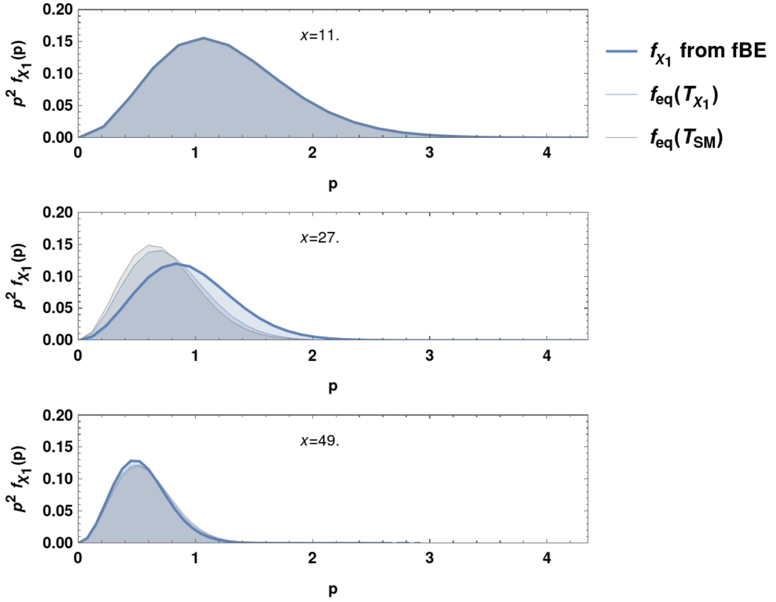

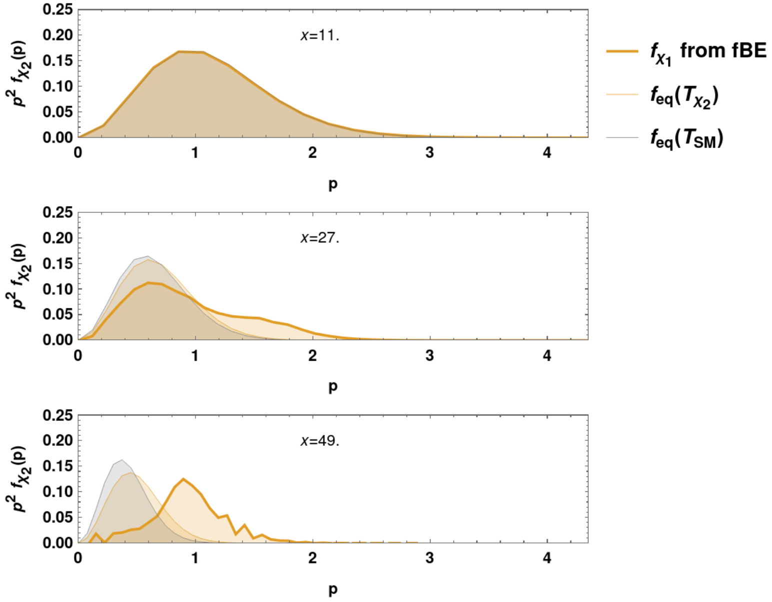

$m_{\chi_1} = 2.41\ GeV$
$m_{\chi_2} = 1.88\ GeV$
$m_a = 3.82\ GeV$
$\lambda_1 = 0.09, \lambda_2 = 0.02, \lambda_y = 0.0027$

Resonant annihilation of χ_2

$$\frac{Y_1^{nBE}}{Y_1^{fBE}} = 0.699, \frac{Y_2^{nBE}}{Y_2^{fBE}} = 0.29$$

nBE: $(\Omega h^2)_1 = 0.043, (\Omega h^2)_2 = 0.07$