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

Shiuli Chatterjee
NCBJ, Warszawa

based on ongoing work with Andrzej Hryczuk

SUSY Conference, 2024

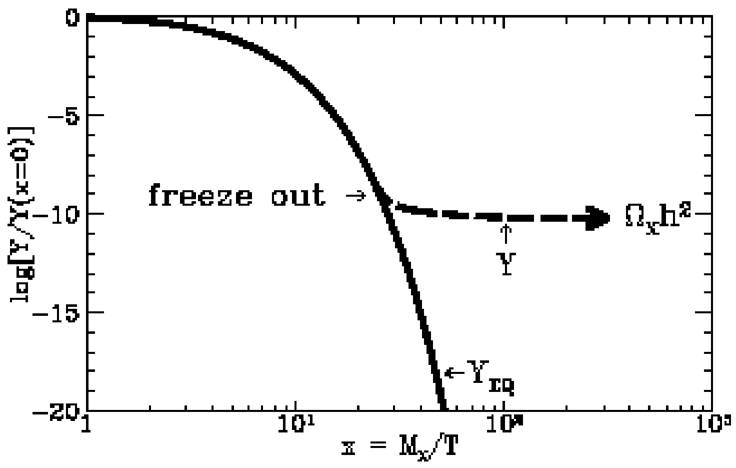
June 10th, 2024

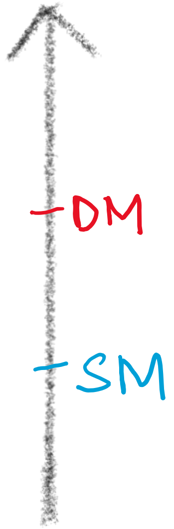
Outline

- Motivation to study multi-particle freeze-out of Dark Matter (DM): SUSY and beyond
- Processes involved in a multiparticle freeze-out: full Boltzmann equation
  effects from DM phase space distribution
- Two-component Coy DM (pseudoscalar mediated)
- Results and discussion

Dark Matter production:

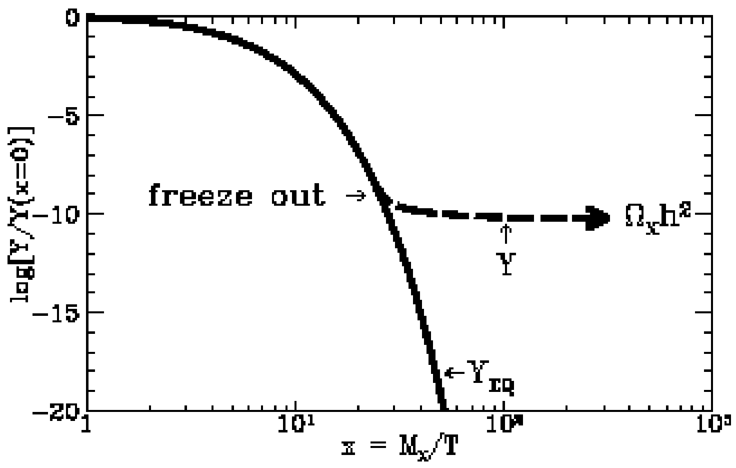
- In the simplest freeze-out production of WIMP (weakly interacting massive particle) DM, there is one DM particle, initially kinetic and chemical equilibrium with the SM plasma.





Dark Matter production: why multiparticle?

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

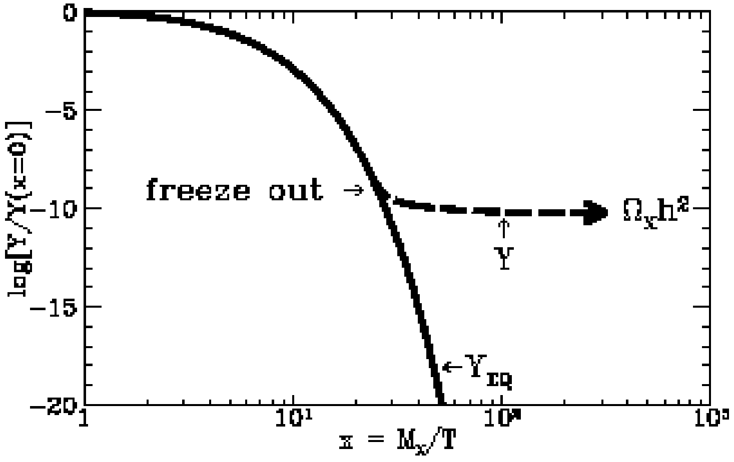


- DM could be part of a sector of particles charged under the parity that stabilizes the DM particles.

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

Dark Matter production: why multiparticle?

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



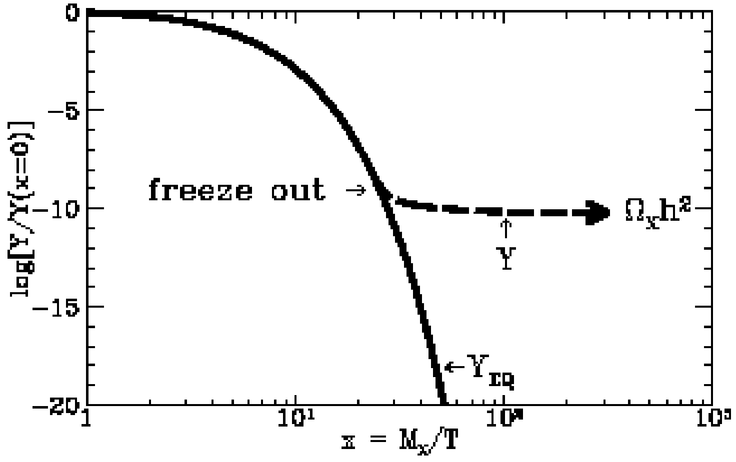
- DM could be part of a sector of particles charged under the parity that stabilizes the DM particles.

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

- $m_{NLSP} \simeq m_{LSP} \implies$ coannihilations i.e. "multiparticle" freeze-out

Dark Matter production: why multiparticle?

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



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

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

- $m_{NLSP} \simeq m_{LSP} \implies$ coannihilations i.e. "multiparticle" freeze-out

Compressed SUSY spectra

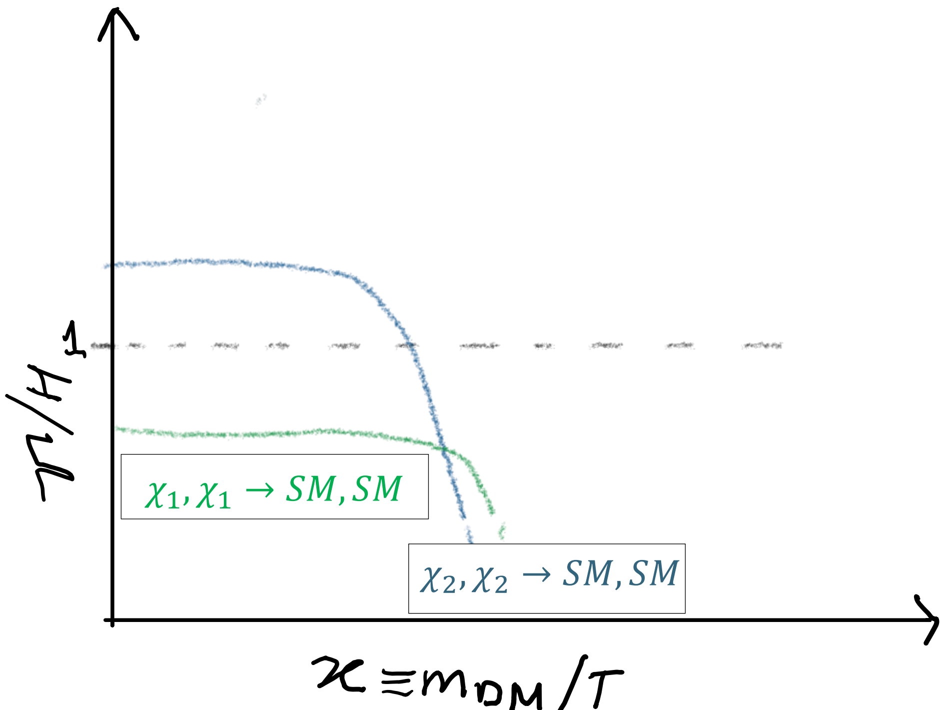
Multiparticle Freeze-out: SUSY

χ_1= DM = LSP; χ_2= NLSP; $m_{\chi_2} > m_{\chi_1}$

- Stau Coannihilation, Compressed Spectrum and SUSY Discovery at the LHC - Aboubrahim et al (2017). Neutralino DM, stau co-annihilation

- Connecting Particle Physics and Cosmology: Measuring the Dark Matter Relic Density in Compressed Supersymmetry at the LHC –Avila et al (2018). Neutralino DM, stau co-annihilation

$\Gamma \equiv n_{eq} < \sigma v >$
H ≡Hubble rate



Multiparticle Freeze-out: SUSY

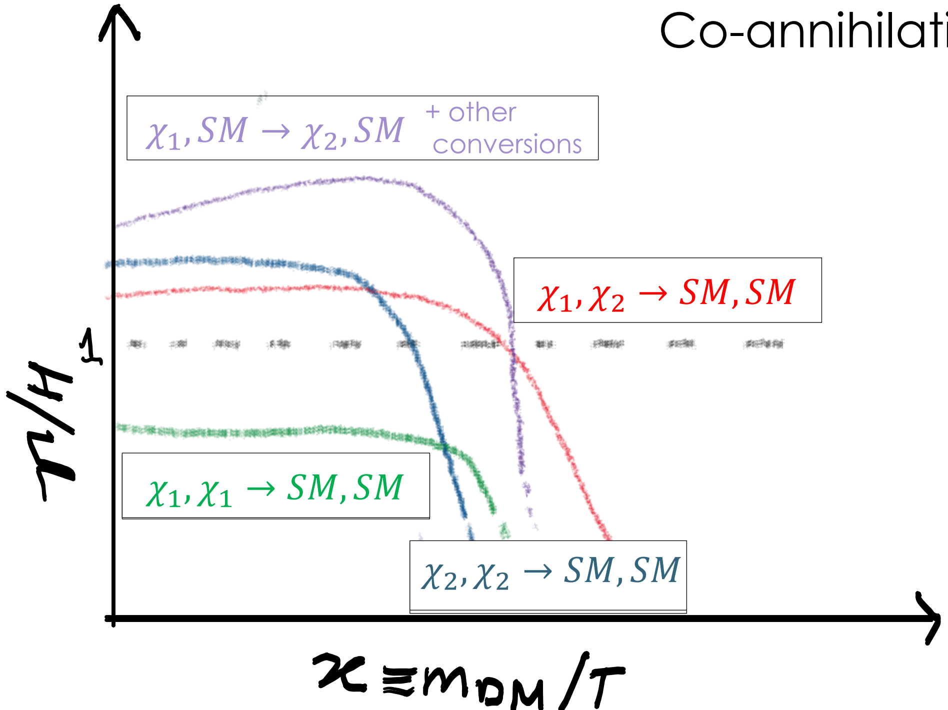
χ_1= DM = LSP; χ_2= NLSP; $m_{\chi_2} > m_{\chi_1}$

- Stau Coannihilation, Compressed Spectrum and SUSY Discovery at the LHC - Aboubrahim et al (2017). Neutralino DM, stau co-annihilation

- Connecting Particle Physics and Cosmology: Measuring the Dark Matter Relic Density in Compressed Supersymmetry at the LHC –Avila et al (2018). Neutralino DM, stau co-annihilation

$\Gamma \equiv n_{eq} < \sigma v >$
H ≡Hubble rate

Co-annihilations



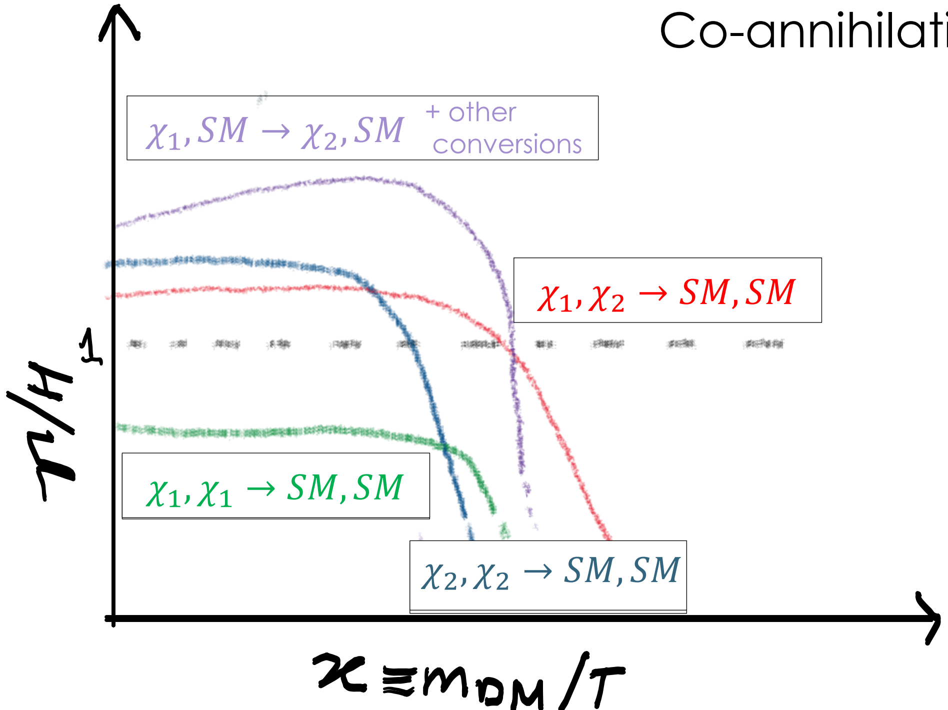
Multiparticle Freeze-out: SUSY

χ_1= DM = LSP; χ_2= NLSP; $m_{\chi_2} > m_{\chi_1}$

- Stau Coannihilation, Compressed Spectrum and SUSY Discovery at the LHC - Aboubrahim et al (2017). Neutralino DM, stau co-annihilation
- Connecting Particle Physics and Cosmology: Measuring the Dark Matter Relic Density in Compressed Supersymmetry at the LHC –Avila et al (2018). Neutralino DM, stau co-annihilation

$\Gamma \equiv n_{eq} < \sigma v >$

H ≡Hubble rate



Co-annihilations

$$\frac{dY_1}{dT} = \frac{1}{3H}\frac{ds}{dx}\left[\langle\sigma_{11}v\rangle(Y_1^2 - Y_{1,eq}^2) + \langle\sigma_{12}v\rangle(Y_1Y_2 - Y_{1,eq}Y_{2,eq}) + \frac{\Gamma_{1\to2}}{s}\left(Y_1 - Y_2\frac{Y_{1,eq}}{Y_{2,eq}}\right) - \frac{\Gamma_2}{s}\left(Y_2 - Y_1\frac{Y_{2,eq}}{Y_{1,eq}}\right) + \langle\sigma_{11\to22}v\rangle\left(Y_1^2 - Y_2^2\frac{Y_{1,eq}^2}{Y_{2,eq}^2}\right)\right]$$

$$\frac{dY_2}{dT} = \frac{1}{3H}\frac{ds}{dx}\left[\langle\sigma_{22}v\rangle(Y_2^2 - Y_{2,eq}^2) + \langle\sigma_{12}v\rangle(Y_1Y_2 - Y_{1,eq}Y_{2,eq}) - \frac{\Gamma_{1\to2}}{s}\left(Y_1 - Y_2\frac{Y_{1,eq}}{Y_{2,eq}}\right) + \frac{\Gamma_2}{s}\left(Y_2 - Y_1\frac{Y_{2,eq}}{Y_{1,eq}}\right) - \langle\sigma_{11\to22}v\rangle\left(Y_1^2 - Y_2^2\frac{Y_{1,eq}^2}{Y_{2,eq}^2}\right)\right]$$

$$\frac{n_i}{n} \simeq \frac{n_{i,eq}}{n_{eq}}$$

$$\frac{dY}{dx} \propto \langle\sigma_{eff}v\rangle(Y^2 - Y_{eq}^2)$$

Edsjo, Gondolo '97

Multiparticle Freeze-out: SUSY

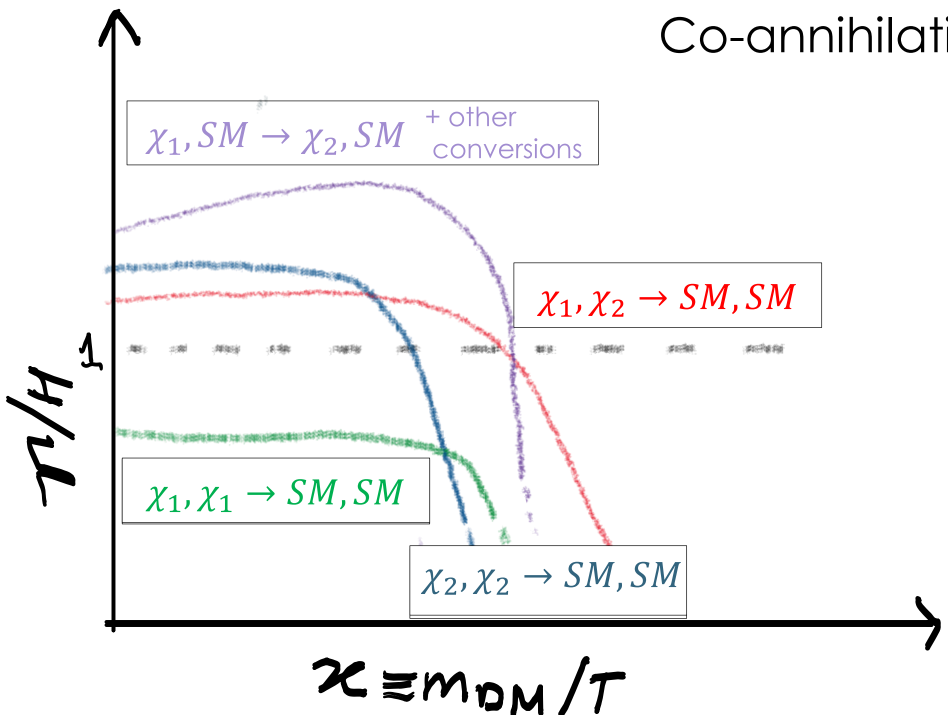
χ_1= DM = LSP; χ_2= NLSP; $m_{\chi_2} > m_{\chi_1}$

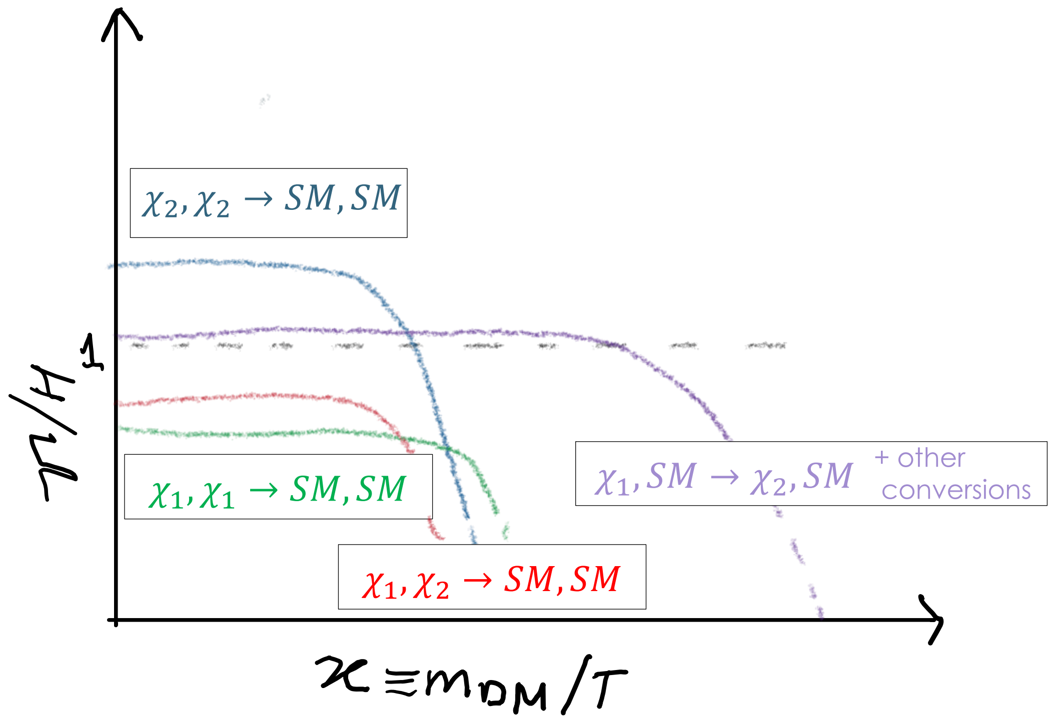
- Stau Coannihilation, Compressed Spectrum and SUSY Discovery at the LHC - Aboubrahim et al (2017). Neutralino DM, stau co-annihilation
- Connecting Particle Physics and Cosmology: Measuring the Dark Matter Relic Density in Compressed Supersymmetry at the LHC - Avila et al (2018). Neutralino DM, stau co-annihilation
- Coscattering in next-to-minimal dark matter and split supersymmetry – F. Brummer (2019). bino-like LSP coannihilating/coscattering with a wino-like neutralino and chargino

$\Gamma \equiv n_{eq} < \sigma v >$

$H \equiv$Hubble rate

Co-annihilations





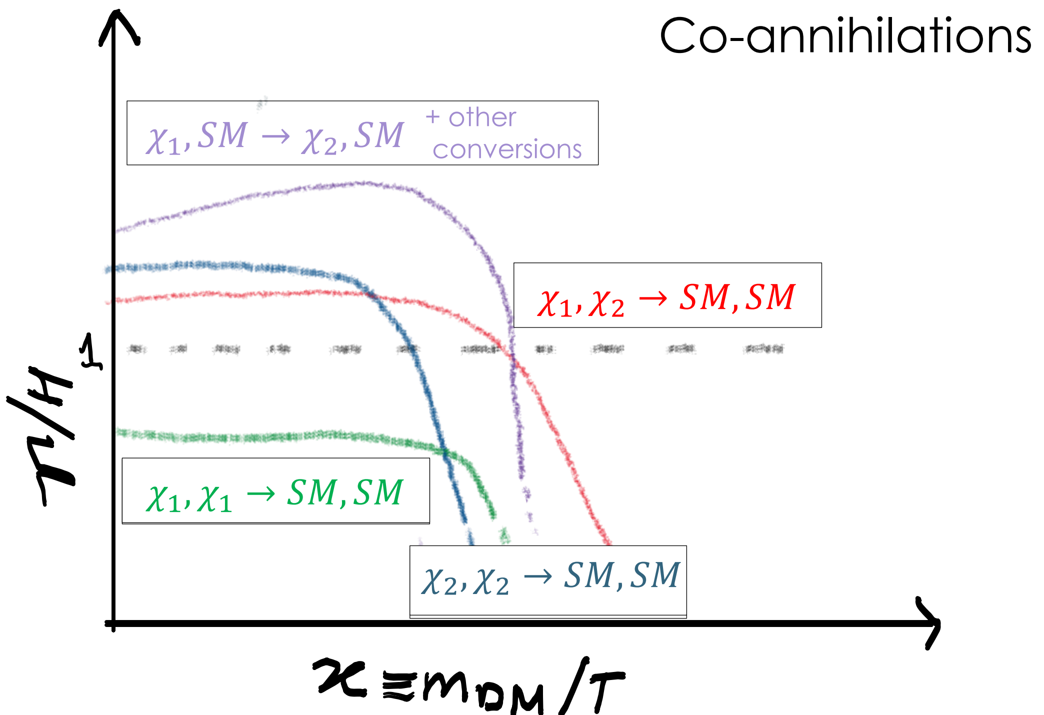
Multiparticle Freeze-out: SUSY

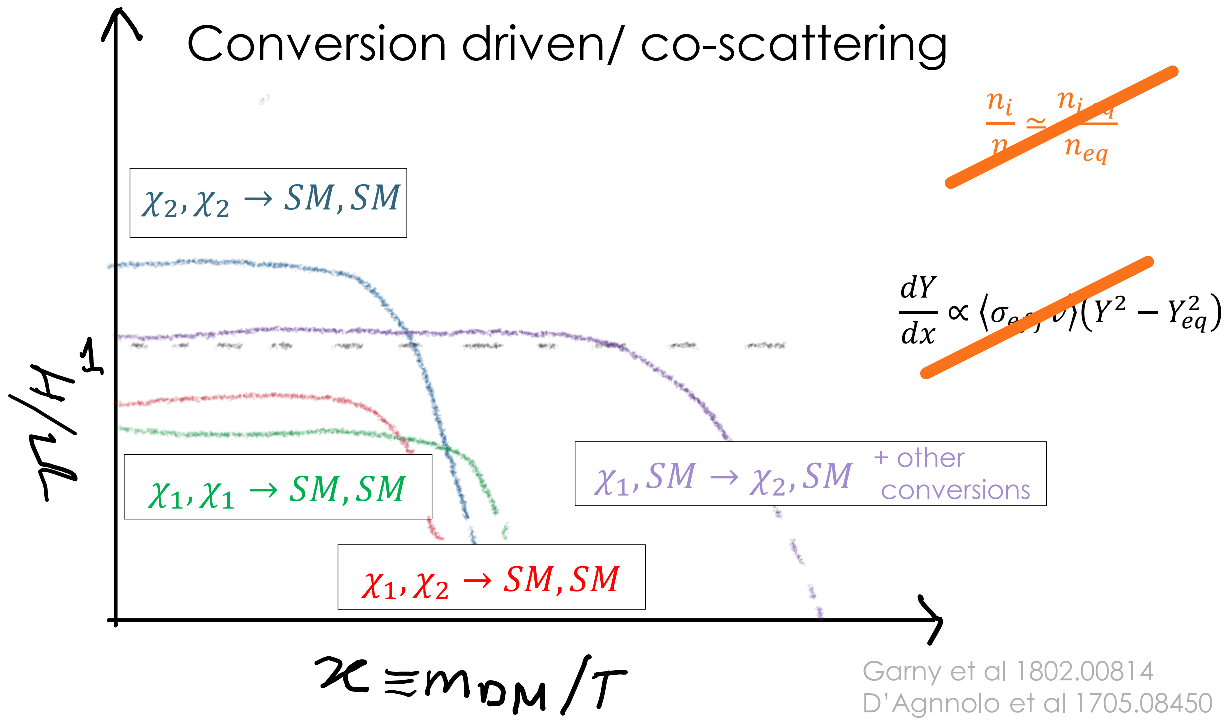
χ_1= DM = LSP; χ_2= NLSP; $m_{\chi_2} > m_{\chi_1}$

- Stau Coannihilation, Compressed Spectrum and SUSY Discovery at the LHC - Aboubrahim et al (2017). Neutralino DM, stau co-annihilation
- Connecting Particle Physics and Cosmology: Measuring the Dark Matter Relic Density in Compressed Supersymmetry at the LHC - Avila et al (2018). Neutralino DM, stau co-annihilation
- Coscattering in next-to-minimal dark matter and split supersymmetry – F. Brummer (2019). bino-like LSP coannihilating/coscattering with a wino-like neutralino and chargino

$\Gamma \equiv n_{eq} < \sigma v >$

H ≡Hubble rate





Garny et al 1802.00814
D'Agnolo et al 1705.08450

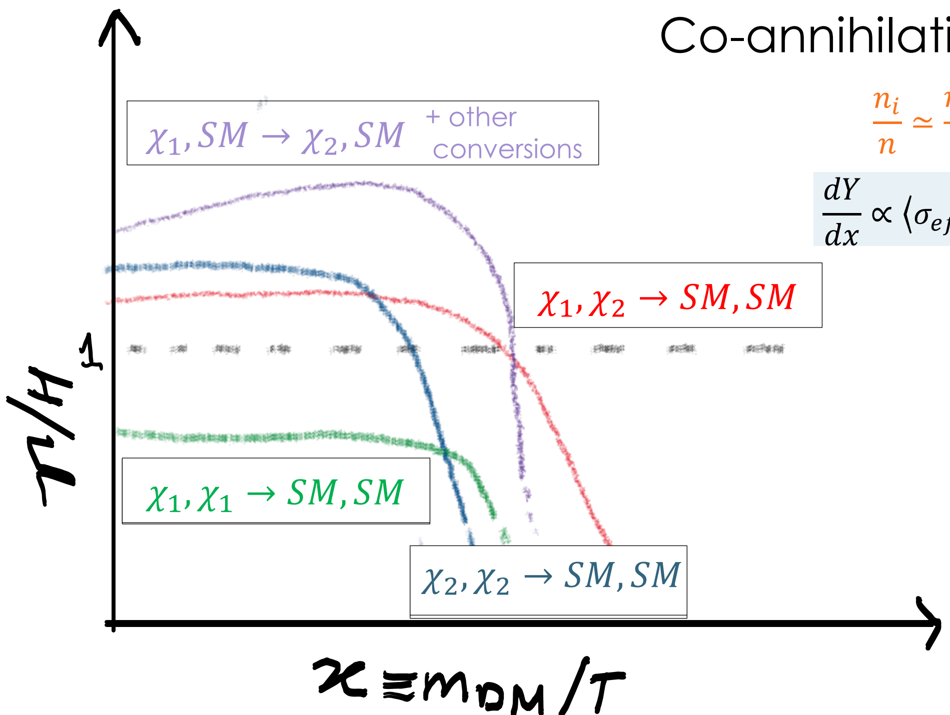
Multiparticle Freeze-out: SUSY

χ_1 = DM = LSP; χ_2 = NLSP; $m_{\chi_2} > m_{\chi_1}$

- Stau Coannihilation, Compressed Spectrum and SUSY Discovery at the LHC - Aboubrahim et al (2017). Neutralino DM, stau co-annihilation
- Connecting Particle Physics and Cosmology: Measuring the Dark Matter Relic Density in Compressed Supersymmetry at the LHC - Avila et al (2018). Neutralino DM, stau co-annihilation
- Coscattering in next-to-minimal dark matter and split supersymmetry – F. Brummer (2019). bino-like LSP coannihilating/coscattering with a wino-like neutralino and chargino

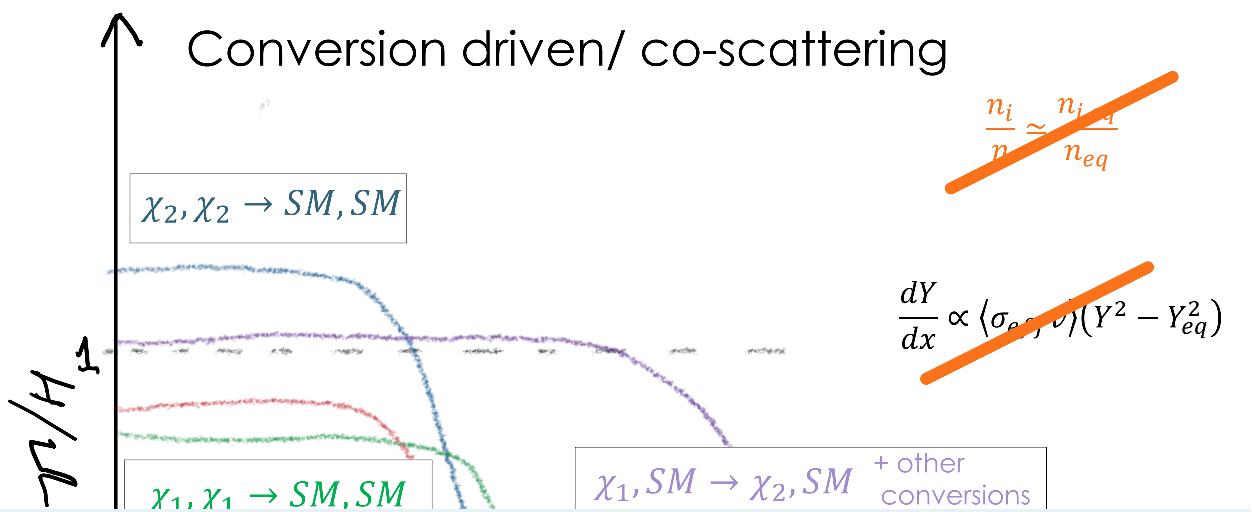
$\Gamma \equiv n_{eq} < \sigma v >$

H ≡Hubble rate



$\frac{n_i}{n} \simeq \frac{n_{i,eq}}{n_{eq}}$

$\frac{dY}{dx} \propto \langle \sigma_{eff} v \rangle (Y^2 - Y_{eq}^2)$



$$\frac{dY_i}{dT} = \frac{1}{3H}\frac{ds}{dx}\left[\langle \sigma_{ii} v \rangle (Y_i^2 - Y_{i,eq}^2) + \langle \sigma_{ij} v \rangle (Y_i Y_j - Y_{i,eq} Y_{j,eq}) + \frac{\Gamma_{i \to j}}{s}\left(Y_i - Y_j \frac{Y_{i,eq}}{Y_{j,eq}}\right) - \frac{\Gamma_j}{s}\left(Y_j - Y_i \frac{Y_{j,eq}}{Y_{i,eq}}\right) + \langle \sigma_{11 \to 22} v \rangle \left(Y_1^2 - Y_2^2 \frac{Y_{1,eq}^2}{Y_{2,eq}^2}\right) \right]$$

For all relevant i; $j \neq i$

Multiparticle Freeze-out: SUSY

χ_1= DM = LSP; χ_2= NLSP; $m_{\chi_2} > m_{\chi_1}$

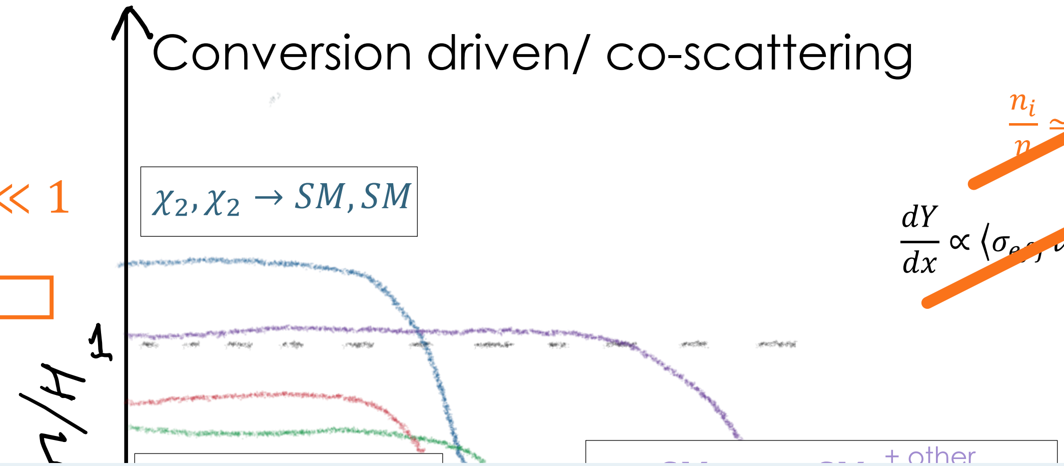
- Stau Coannihilation, Compressed Spectrum and SUSY Discovery at the LHC - Aboubrahim et al (2017). Neutralino DM, stau co-annihilation
- Connecting Particle Physics and Cosmology: Measuring the Dark Matter Relic Density in Compressed Supersymmetry at the LHC - Avila et al (2018). Neutralino DM, stau co-annihilation
- Coscattering in next-to-minimal dark matter and split supersymmetry – F. Brummer (2019). bino-like LSP coannihilating/coscattering with a wino-like neutralino and chargino
- Mixed (Cold+Warm) Dark Matter in the Bino-Wino co-annihilation scenario – Ibe et al (2013).

$\Gamma \equiv n_{eq} < \sigma v >$

H ≡Hubble rate

$$(\partial_t - p_i H \partial_{p_i}) f_i(p_i,t) = \underbrace{\hat{C}_{\chi_i,SM\to\chi_i,SM}(p_i,t)}_{Elastic\ scattering} + \underbrace{\hat{C}_{\chi_i\chi_i\to SM,SM}(p_i,t)}_{Annihilations} + \underbrace{\sum_{j\neq i}\hat{C}_{\chi_i\chi_j\to SM,SM}(p_i,t)}_{Co-annihilations} + \underbrace{\hat{C}_{\chi_i\chi_i\to\chi_j\chi_j}(p_i,t)}_{Conversions}$$

$$\frac{\Gamma_{\chi_1,SM\to\chi_1,SM}}{H} \ll 1$$



$\frac{n_i}{n} \simeq \frac{n_{i,eq}}{n_{eq}}$

$\frac{dY}{dx} \propto \langle\sigma_{eff} v\rangle (Y^2 - Y_{eq}^2)$

$$\frac{dY_i}{dT} = \frac{1}{3H}\frac{ds}{dx}\left[\langle\sigma_{ii}v\rangle(Y_i^2 - Y_{i,eq}^2) + \langle\sigma_{ij}v\rangle(Y_iY_j - Y_{i,eq}Y_{j,eq}) + \frac{\Gamma_{i\to j}}{s}\left(Y_i - Y_j\frac{Y_{i,eq}}{Y_{j,eq}}\right) - \frac{\Gamma_j}{s}\left(Y_j - Y_i\frac{Y_{j,eq}}{Y_{i,eq}}\right) + \langle\sigma_{11\to 22}v\rangle\left(Y_1^2 - Y_2^2\frac{Y_{1,eq}^2}{Y_{2,eq}^2}\right)\right]$$

For all relevant i; $j \neq i$

Multiparticle Freeze-out: SUSY

χ_1= DM = LSP; χ_2= NLSP; $m_{\chi_2} > m_{\chi_1}$

- Stau Coannihilation, Compressed Spectrum and SUSY Discovery at the LHC - Aboubrahim et al (2017). Neutralino DM, stau co-annihilation
- Connecting Particle Physics and Cosmology: Measuring the Dark Matter Relic Density in Compressed Supersymmetry at the LHC - Avila et al (2018). Neutralino DM, stau co-annihilation
- Coscattering in next-to-minimal dark matter and split supersymmetry – F. Brummer (2019). bino-like LSP coannihilating/coscattering with a wino-like neutralino and chargino
- Mixed (Cold+Warm) Dark Matter in the Bino-Wino co-annihilation scenario – Ibe et al (2013).

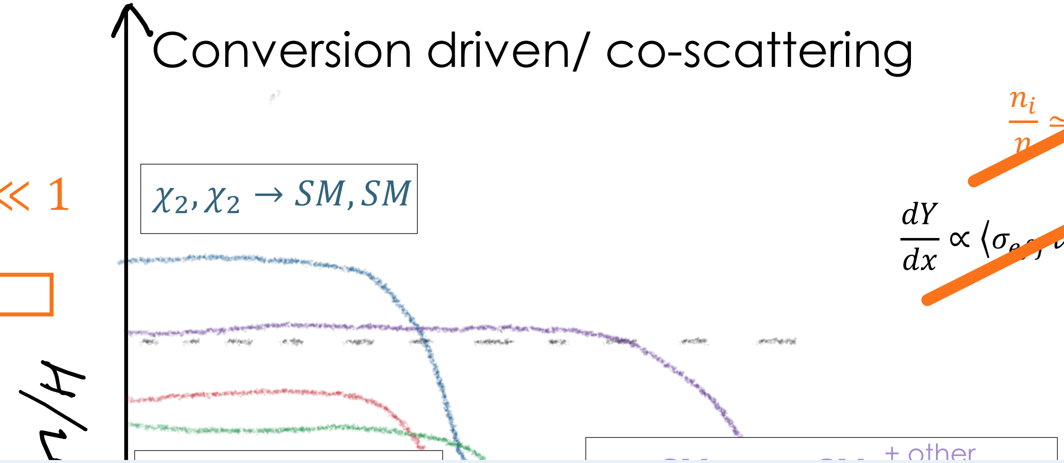
$\Gamma \equiv n_{eq} < \sigma v >$

H ≡Hubble rate

full Boltzmann equation (fBE)

$$(\partial_t - p_i H \partial_{p_i}) f_i(p_i,t) = \underbrace{\hat{C}_{\chi_i,SM\to\chi_i,SM}(p_i,t)}_{Elastic\ scattering} + \underbrace{\hat{C}_{\chi_i,\chi_i\to SM,SM}(p_i,t)}_{Annihilations} + \underbrace{\sum_{j\neq i}\hat{C}_{\chi_i,\chi_j\to SM,SM}(p_i,t)}_{Co-annihilations} + \underbrace{\hat{C}_{\chi_i,\chi_i\to\chi_j,\chi_j}(p_i,t)}_{Conversions\ \&\ self\ sc.}$$

$$\frac{\Gamma_{\chi_1,SM\to\chi_1,SM}}{H} \ll 1$$



$\frac{n_i}{n} \simeq \frac{n_{i,eq}}{n_{eq}}$

$\frac{dY}{dx} \propto \langle\sigma_{eff} v\rangle (Y^2 - Y_{eq}^2)$

- No process to restore equilibrium distribution
- Strongly momentum dependent/ selective processes

$$\frac{dY_i}{dT} = \frac{1}{3H}\frac{ds}{dx}\left[\langle\sigma_{ii}v\rangle(Y_i^2 - Y_{i,eq}^2) + \langle\sigma_{ij}v\rangle(Y_iY_j - Y_{i,eq}Y_{j,eq}) + \frac{\Gamma_{i\to j}}{s}\left(Y_i - Y_j\frac{Y_{i,eq}}{Y_{j,eq}}\right) - \frac{\Gamma_j}{s}\left(Y_j - Y_i\frac{Y_{j,eq}}{Y_{i,eq}}\right) + \langle\sigma_{11\to22}v\rangle\left(Y_1^2 - Y_2^2\frac{Y_{1,eq}^2}{Y_{2,eq}^2}\right)\right]$$

For all relevant i; $j \neq i$

Multiparticle Freeze-out: SUSY and beyond

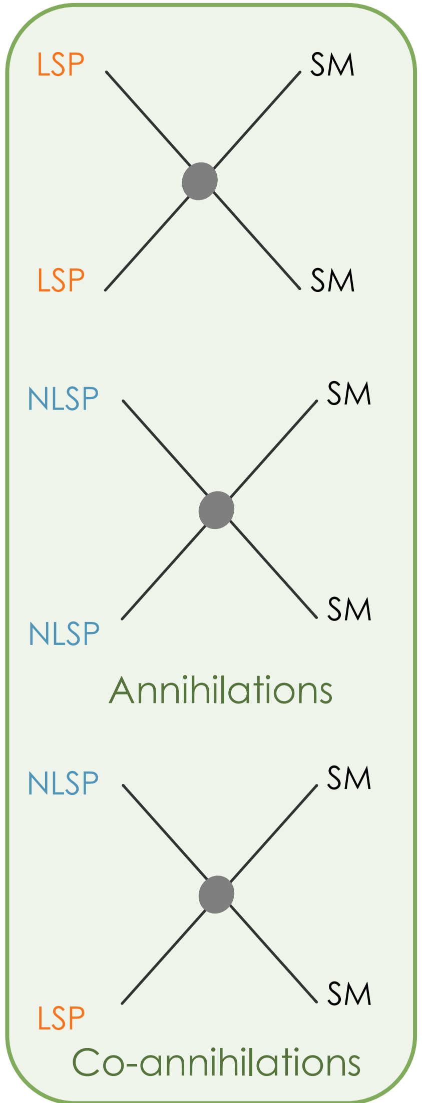
- Stau Coannihilation, Compressed Spectrum and SUSY Discovery at the LHC - Aboubrahim et al (2017). Neutralino DM, stau co-annihilation
- Connecting Particle Physics and Cosmology: Measuring the Dark Matter Relic Density in Compressed Supersymmetry at the LHC - Avila et al (2018). Neutralino DM, stau co-annihilation
- Coscattering in next-to-minimal dark matter and split supersymmetry – F. Brummer (2019). bino-like LSP coannihilating/coscattering with a wino-like neutralino and chargino
- Mixed (Cold+Warm) Dark Matter in the Bino-Wino co-annihilation scenario – Ibe et al (2013).
- Coscattering/Coannihilation Dark Matter in a Fraternal Twin Higgs Model –Cheng et al (2018). Twin neutrino DM, scattering and annihilations with twin tau, and twin photon
- Co-decaying DM-Dror et al (2016)
- Secluded DM – Pospelov et al (2007)
- Coscattering in the Extended Singlet-Scalar Higgs Portal – talk in this session by Jayita Lahiri

full Boltzmann equation (fBE) must be solved when:

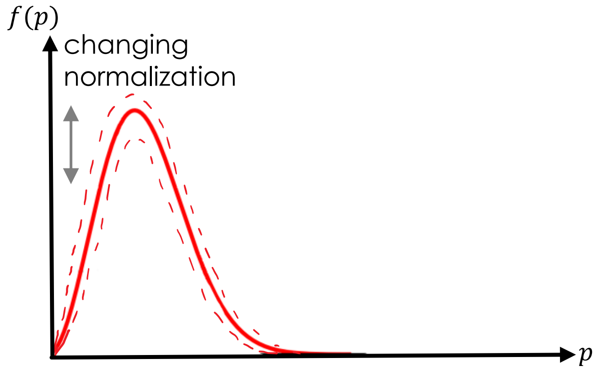
- No process to restore equilibrium distribution
- Strongly momentum dependent/ selective processes

Dark Matter production: multiparticle Freeze-out

$$(\partial_t - p_i H \partial_{p_i}) f_i(p_i,t) = \underbrace{\hat{C}_{\chi_i,SM\to\chi_i,SM}(p_i,t)}_{Elastic\ scattering} + \underbrace{\hat{C}_{\chi_i,\chi_i\to SM,SM}(p_i,t)}_{Annihilations} + \underbrace{\sum_{j\neq i} \hat{C}_{\chi_i,\chi_j\to SM,SM}(p_i,t)}_{Co-annihilations} + \underbrace{\sum_{j} \hat{C}_{\chi_i,\chi_i\to\chi_j,\chi_j}(p_i,t)}_{Conversions\&\ self\ scattering}$$

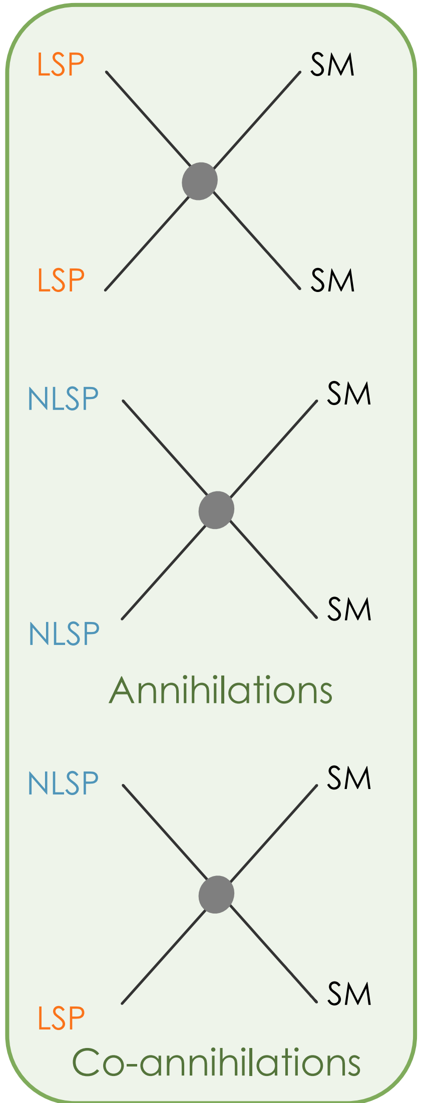


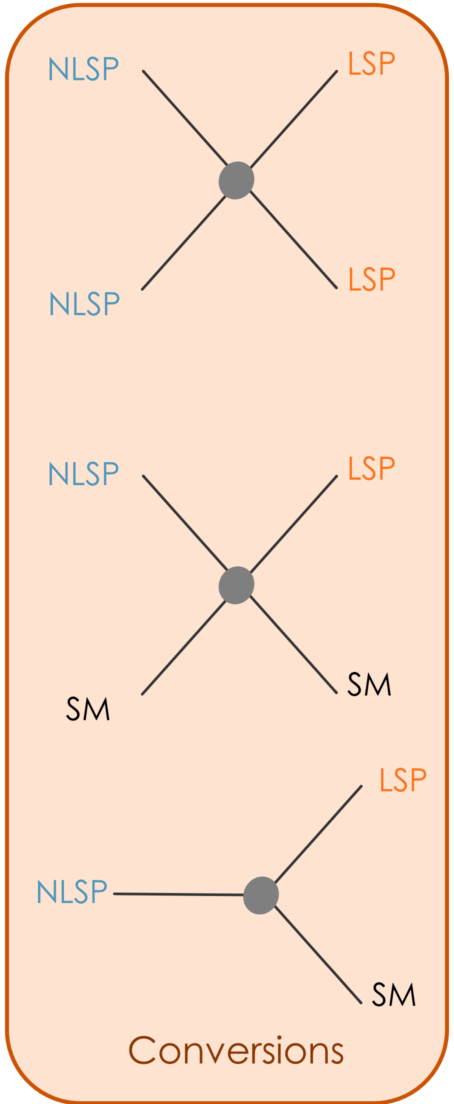
LSP=DM=χ_1; NLSP=χ_2; $m_{\chi_2} > m_{\chi_1}$



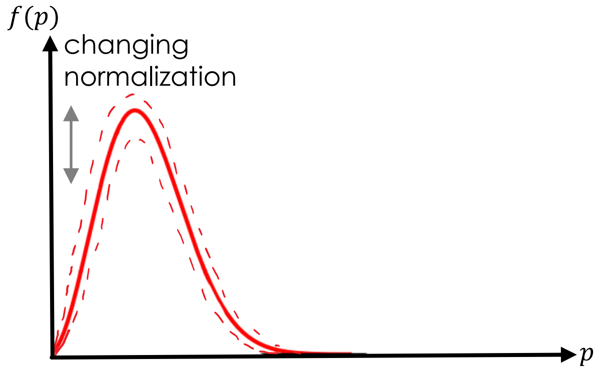
Dark Matter production: multiparticle Freeze-out

$$(\partial_t - p_i H \partial_{p_i}) f_i(p_i,t) = \underbrace{\hat{C}_{\chi_i, SM \to \chi_i, SM}(p_i,t)}_{Elastic\ scattering} + \underbrace{\hat{C}_{\chi_i \chi_i \to SM, SM}(p_i,t)}_{Annihilations} + \underbrace{\sum_{j \neq i} \hat{C}_{\chi_i \chi_j \to SM, SM}(p_i,t)}_{Co-annihilations} + \underbrace{\sum_{j} \hat{C}_{\chi_i \chi_i \to \chi_j \chi_j}(p_i,t)}_{Conversions\&\ self\ scattering}$$





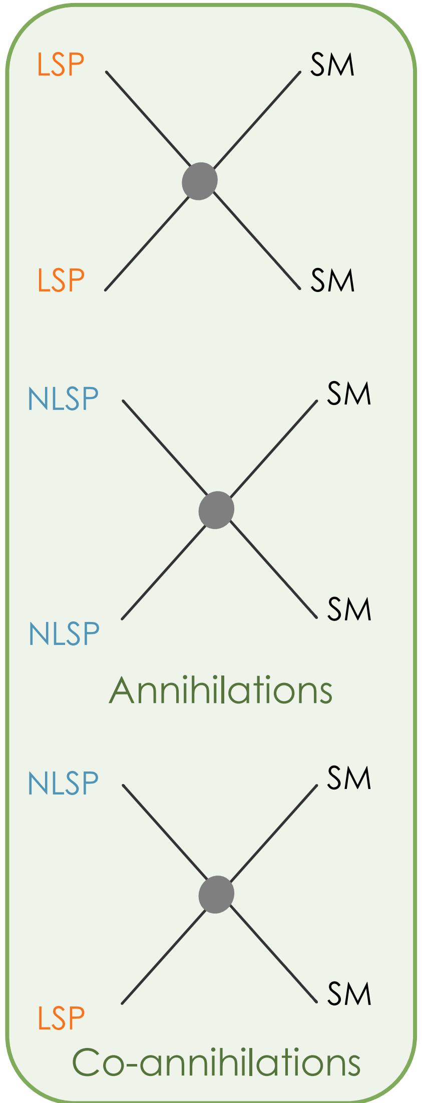
LSP=DM=χ_1; NLSP=χ_2; $m_{\chi_2} > m_{\chi_1}$

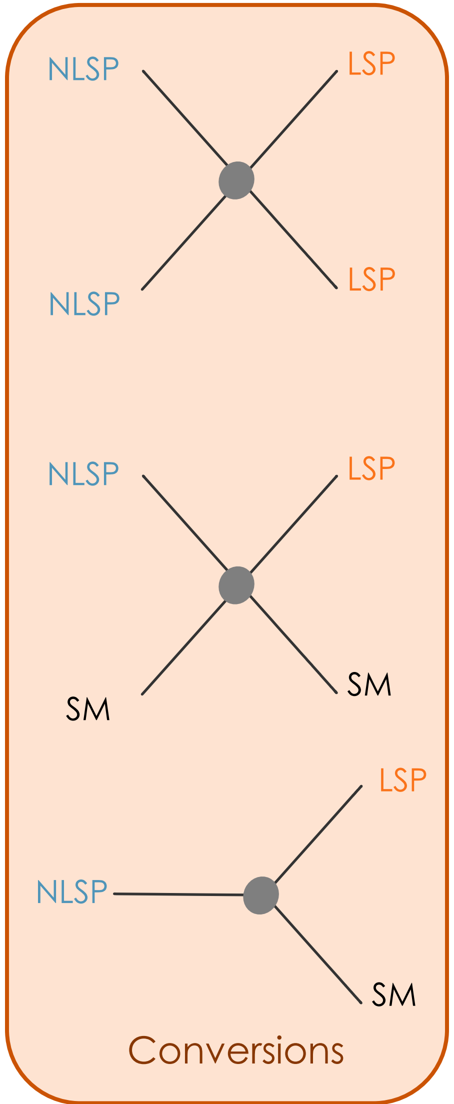


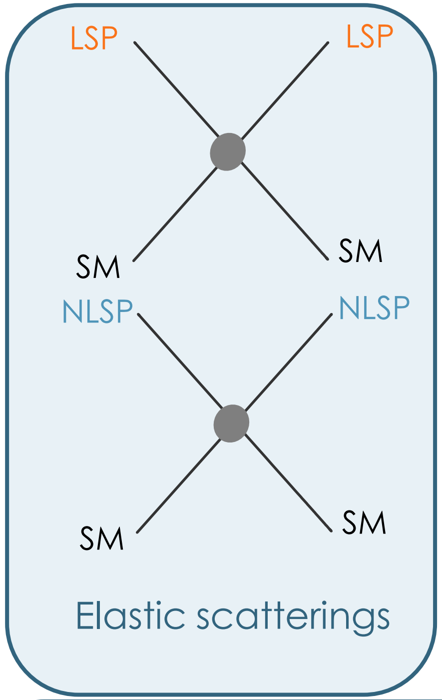
Dark Matter production: multiparticle Freeze-out

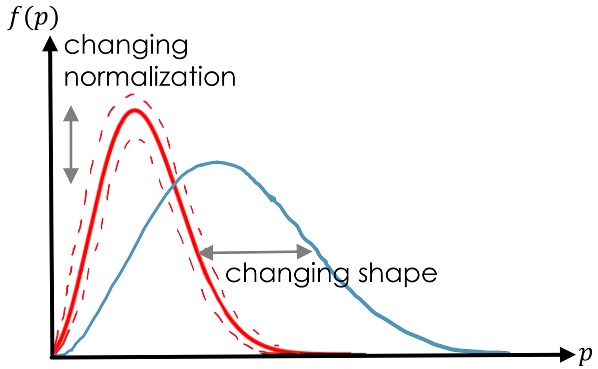
$$(\partial_t - p_i H \partial_{p_i}) f_i(p_i,t) = \underbrace{\hat{C}_{\chi_i,SM\to\chi_i,SM}(p_i,t)}_{Elastic\ scattering} + \underbrace{\hat{C}_{\chi_i,\chi_i\to SM,SM}(p_i,t)}_{Annihilations} + \underbrace{\sum_{j\neq i} \hat{C}_{\chi_i,\chi_j\to SM,SM}(p_i,t)}_{Co-annihilations} + \underbrace{\sum_{j} \hat{C}_{\chi_i,\chi_i\to\chi_j,\chi_j}(p_i,t)}_{Conversions\,\&\,self\ scattering}$$

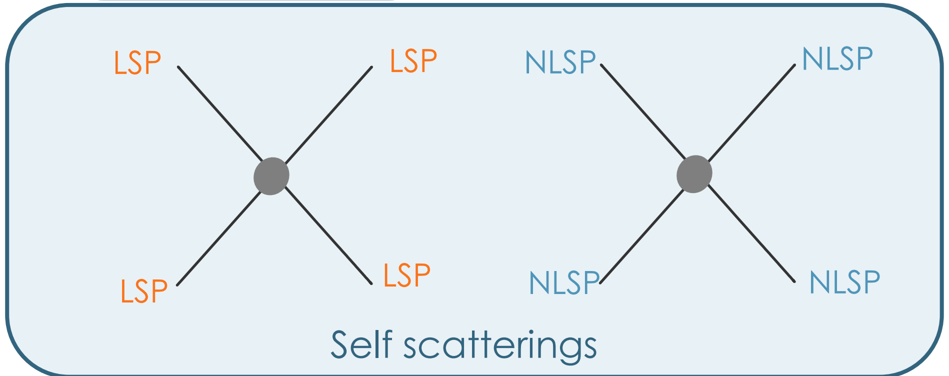
LSP=DM=χ_1; NLSP=χ_2; $m_{\chi_2} > m_{\chi_1}$







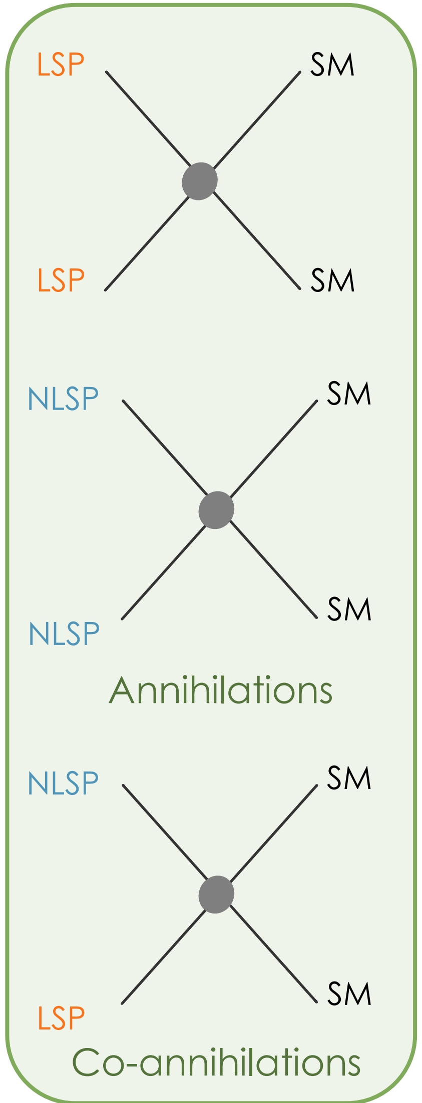


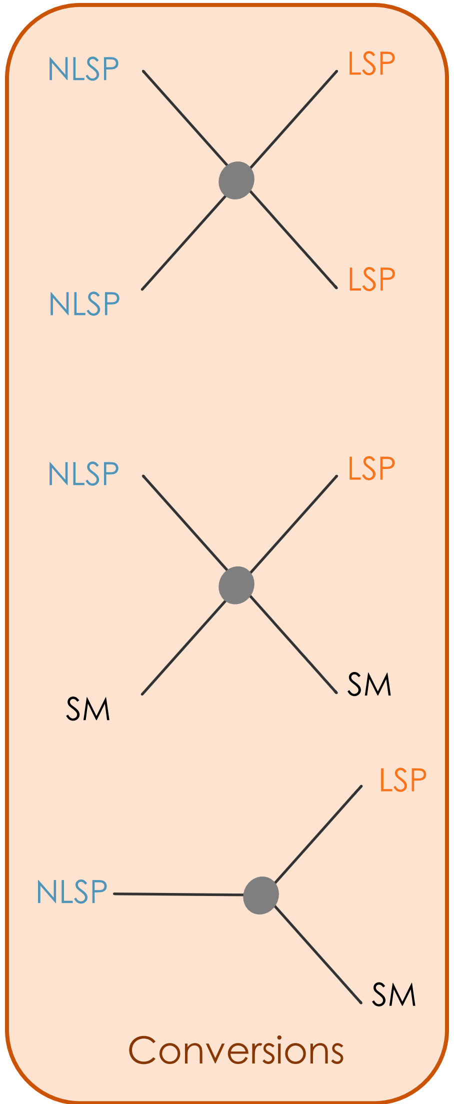


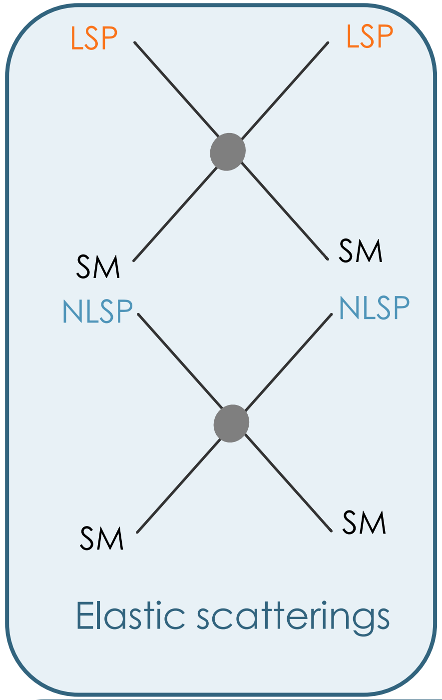
Dark Matter production: multiparticle Freeze-out

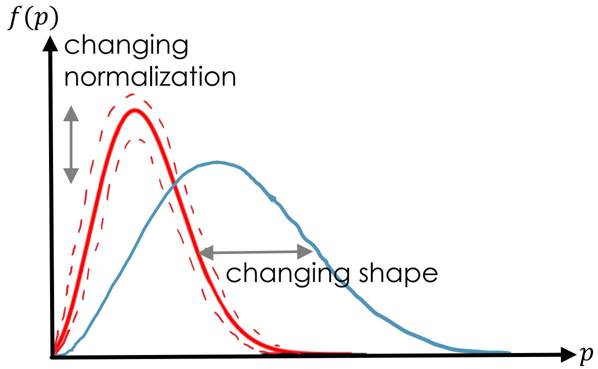
$$(\partial_t - p_i H \partial_{p_i}) f_i(p_i,t) = \underbrace{\hat{C}_{\chi_i,SM\to\chi_i,SM}(p_i,t)}_{Elastic\ scattering} + \underbrace{\hat{C}_{\chi_i,\chi_i\to SM,SM}(p_i,t)}_{Annihilations} + \underbrace{\sum_{j\neq i}\hat{C}_{\chi_i,\chi_j\to SM,SM}(p_i,t)}_{Co-annihilations} + \underbrace{\sum_{j}\hat{C}_{\chi_i,\chi_i\to\chi_j,\chi_j}(p_i,t)}_{Conversions\,\&\,self\ scattering}$$

LSP=DM=χ_1; NLSP=χ_2; $m_{\chi_2} > m_{\chi_1}$





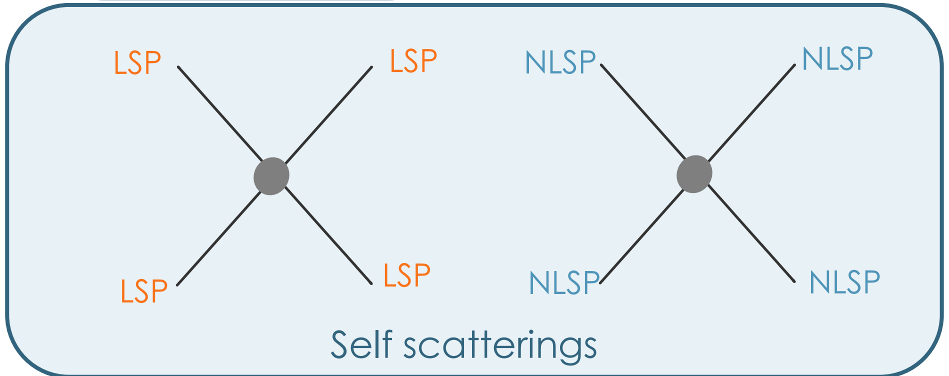




Semi annihilations: $DM, DM \to DM, SM$

Cannibal: $DM, DM, DM \to DM, DM$

$+\cdots$

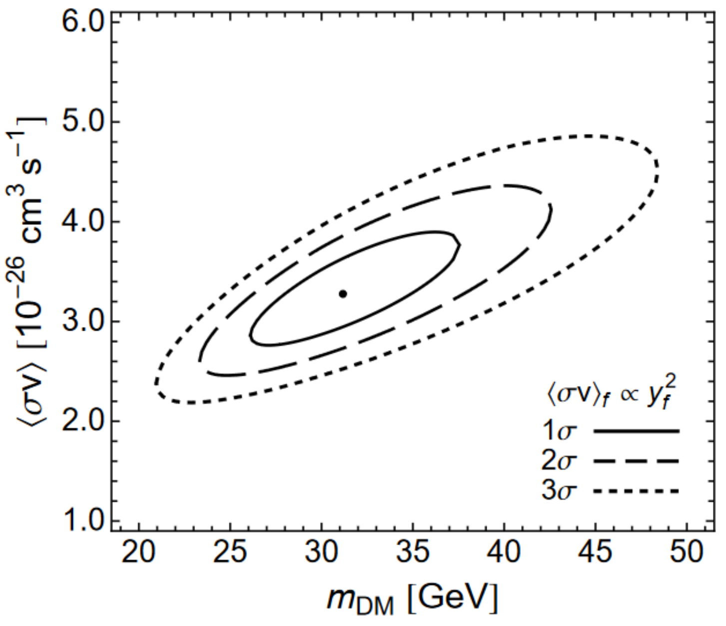


Coy Dark Matter:

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)
   a) Direct detection rates suppressed by square of the nuclear recoil energy
   b) Suppressed couplings to massive vector bosons weaken direct search constraints from colliders

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



Boehm et al 2014

hep-ph: 1612.05687

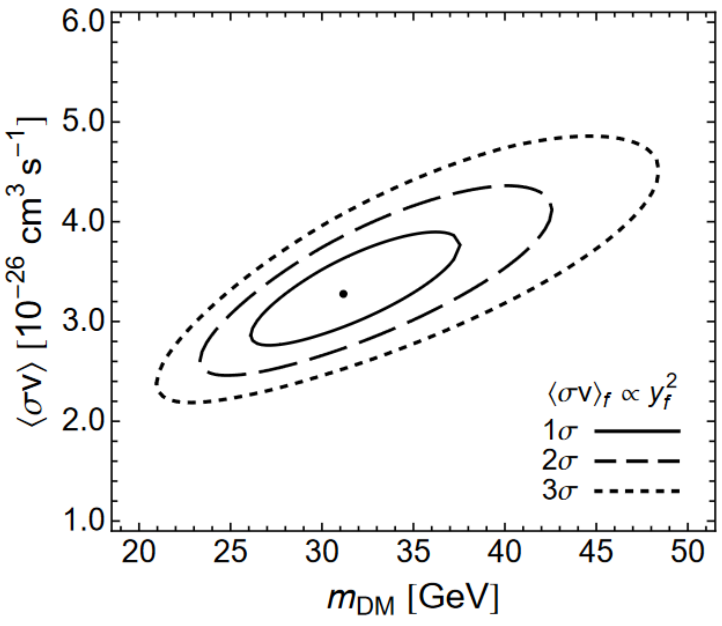
Coy Dark Matter:

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)
   a) Direct detection rates suppressed by square of the nuclear recoil energy
   b) Suppressed couplings to massive vector bosons weaken direct search constraints from colliders

- momentum-dependent scattering rates
- "crossing symmetry" between annihilation and scattering is broken $\Longrightarrow$ DM distribution can veer away from equilibrium shape

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



Boehm et al 2014

Coy Dark Matter: 2-component

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

2. Dirac fermions (χ_1, χ_2) with interaction mediated by a light pseudoscalar (a), with couplings to SM particles proportional to Yukawa couplings per Minimal Flavour Violation (MFV)
   a) Direct detection rates suppressed by square of the nuclear recoil energy
   b) Suppressed couplings to massive vector bosons weaken direct search constraints from colliders

- momentum-dependent scattering rates
- "crossing symmetry" between annihilation and scattering is broken $\Longrightarrow$ DM distribution can veer away from equilibrium shape

Can potentially depend on particle momentum distributions

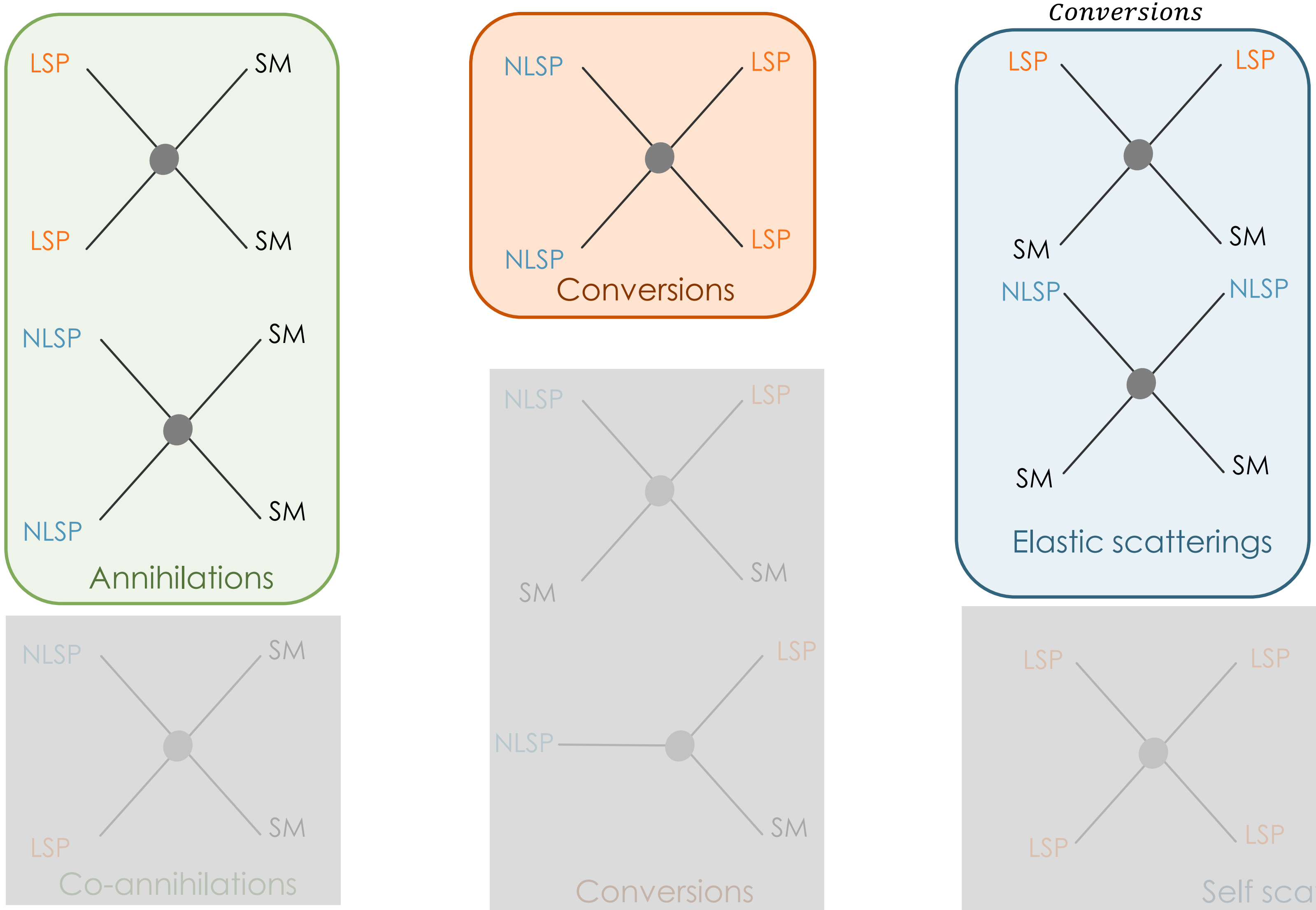
$\Downarrow$

Requires full coupled Boltzmann equation to be solved to capture all the effects of conversions, annihilations and scatterings.

$$\mathcal{L} \supset -i\lambda_1 a\, \bar{\chi}_1 \gamma^5 \chi_1 - i\lambda_2 a\, \bar{\chi}_2 \gamma^5 \chi_2 - i\lambda_y \sum_{f \in SM} y_f\, a\, \bar{f} \gamma^5 f$$

Two-particle Freeze-out

$$(\partial_t - p_i H \partial_{p_i}) f_i(p_i,t) = \underbrace{\hat{C}_{\chi_i,SM\to\chi_i,SM}(p_i,t)}_{\textit{Elastic scattering}} + \underbrace{\hat{C}_{\chi_i\chi_i\to SM,SM}(p_i,t)}_{\textit{Annihilations}} + \underbrace{\sum_{i\neq j}\hat{C}_{\chi_i\chi_i\to\chi_j\chi_j}(p_i,t)}_{\textit{Conversions}}$$



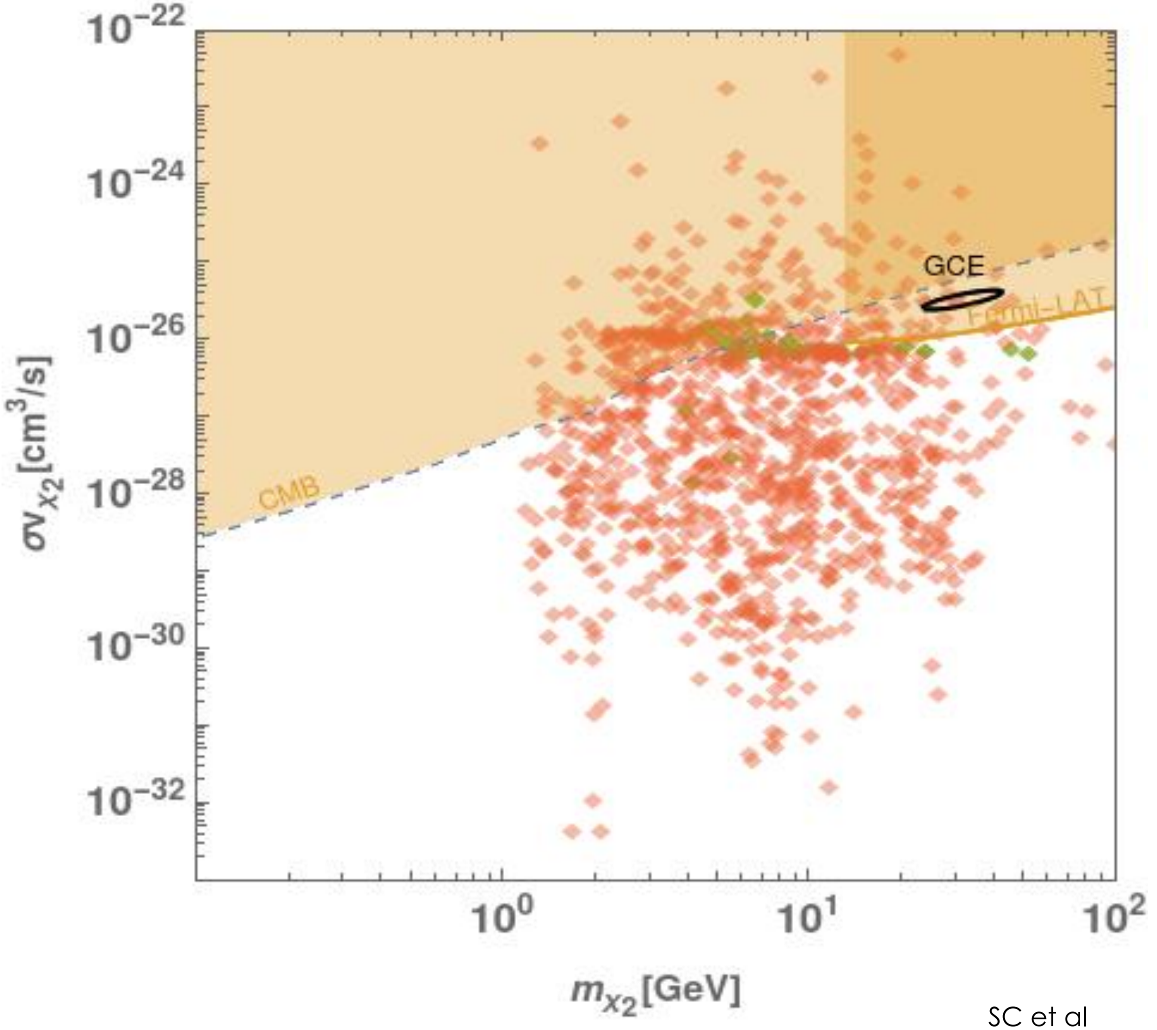
Code to solve at Yield level:

- 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

Coy Dark Matter: 2-component

Indirect Detection:



SC et al

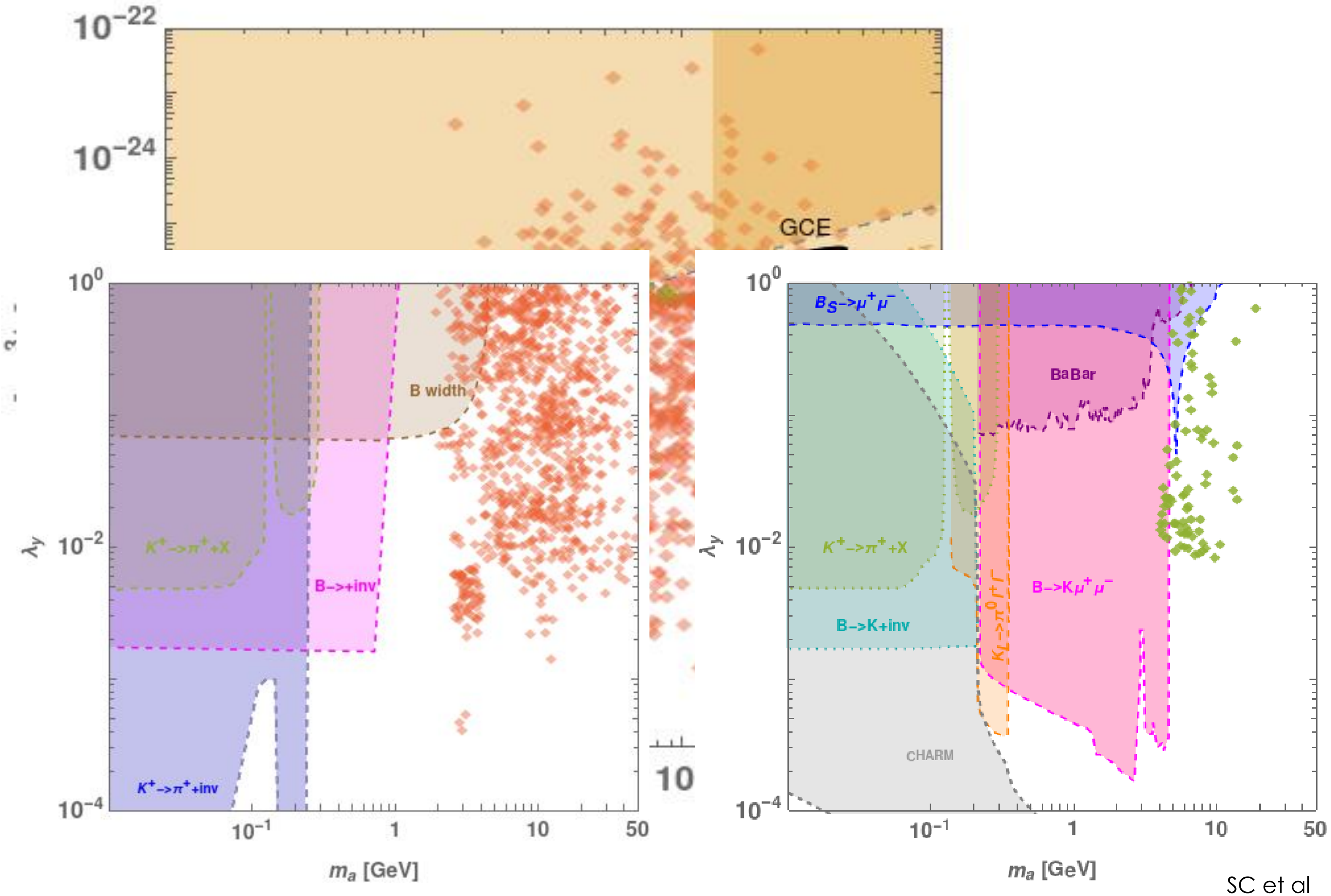
Scan results: $m_{\chi_2} \leq m_{\chi_1}, m_a \geq 1GeV$

- Sum of χ_1, χ_2 relic densities reproduces observed $\Omega h^2 = 0.12 \pm 0.012$
- 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:



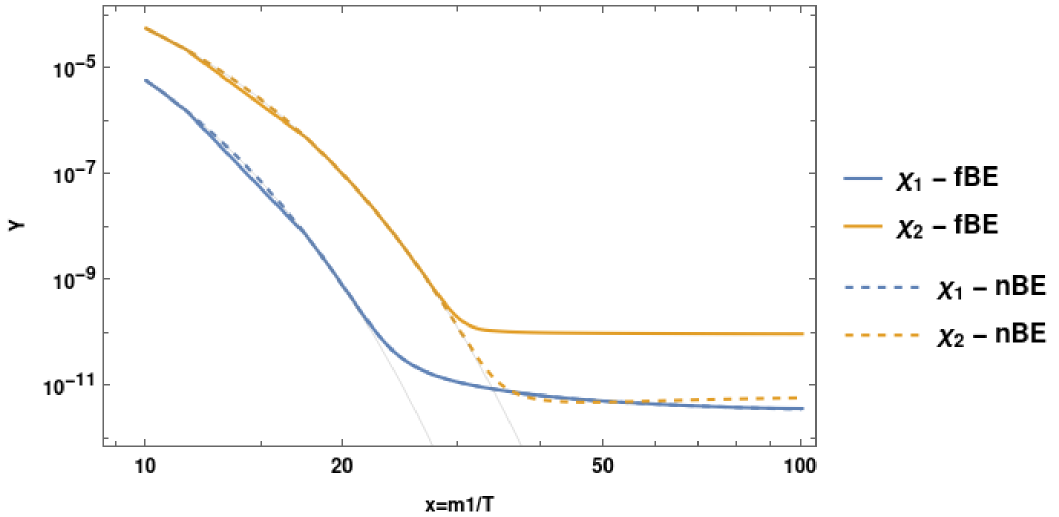
SC et al

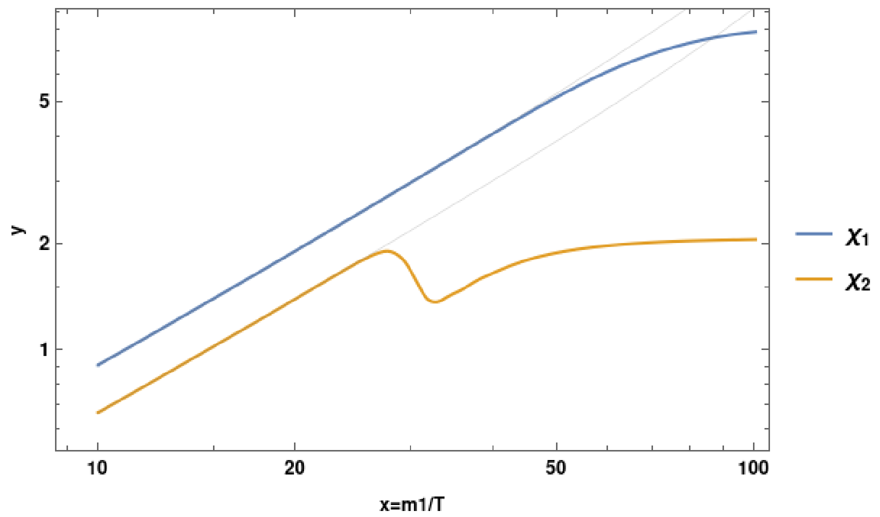
Scan results: $m_{\chi_2} \leq m_{\chi_1}, m_a \geq 1GeV$

- Sum of χ_1, χ_2 relic densities reproduces observed $\Omega h^2 = 0.12 \pm 0.012$
- 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)

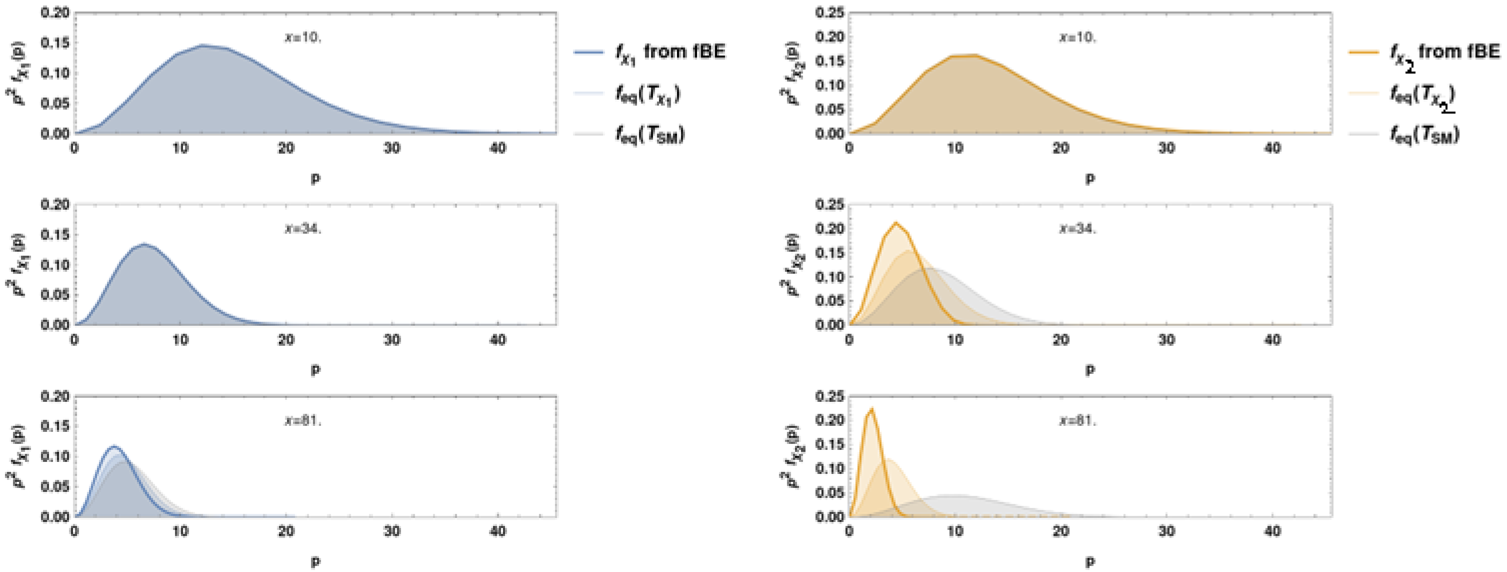
- Bounds on pseudoscalar a from flavor factories and fixed-target experiments (MFV interaction with SM) (Dolan et al 1412.5174)

2-component Coy Dark Matter: Results phase space solutions





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



$m_{\chi_1} = 26.6GeV$

$m_{\chi_2} = 19.54GeV$

$m_a = 43.34GeV$

$\lambda_1 = 0.4, \lambda_2 = 0.28, \lambda_y = 0.16$

Resonant annihilation of χ_2

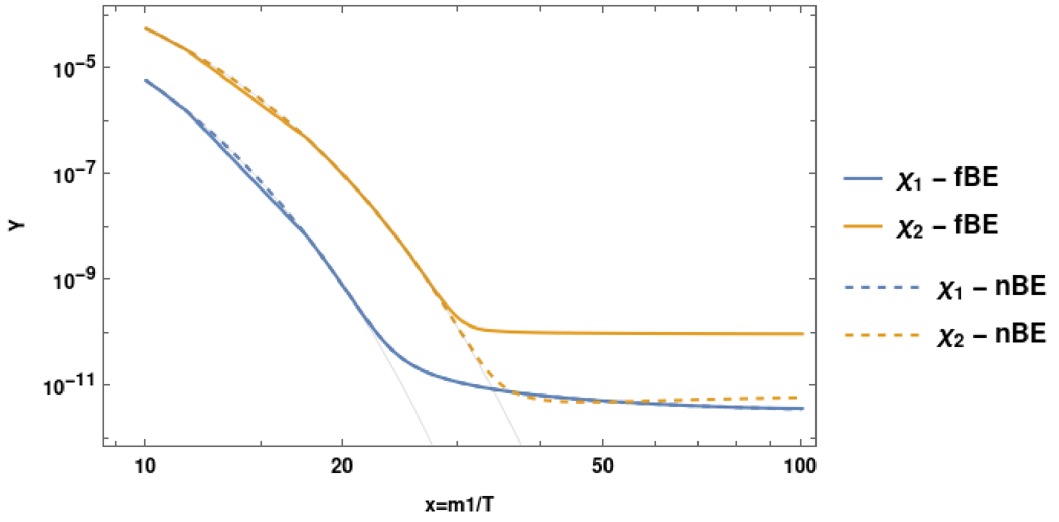
$$\frac{Y_1^{nBE}}{Y_1^{fBE}} = 0.975, \frac{Y_2^{nBE}}{Y_2^{fBE}} = 0.058$$

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

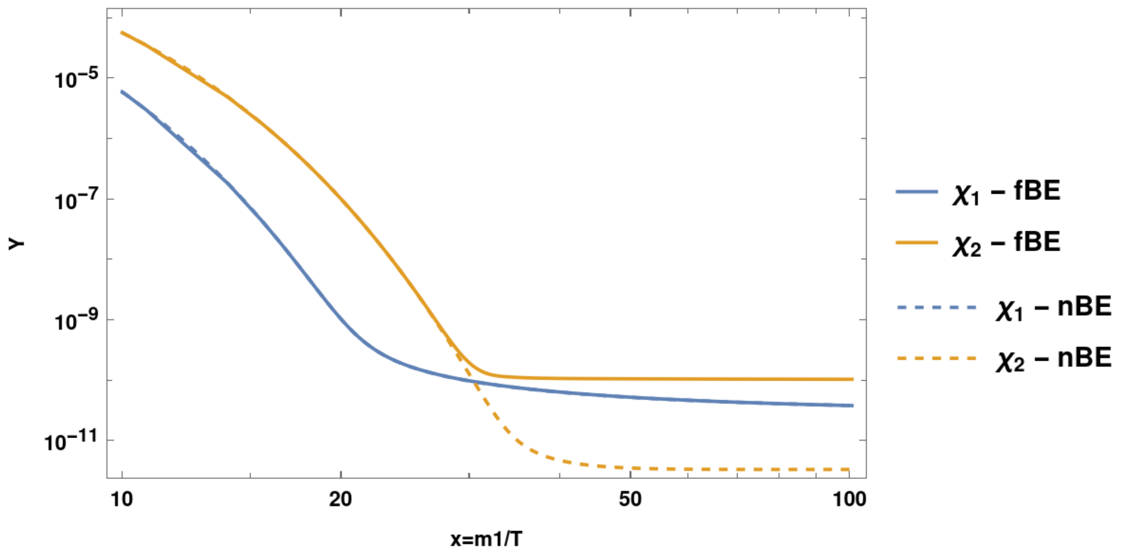
2-component Coy Dark Matter: Results phase space solutions

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

With conversions:



Without conversions:



$m_{\chi_1} = 26.6GeV$

$m_{\chi_2} = 19.54GeV$

$m_a = 43.34GeV$

$\lambda_1 = 0.4, \lambda_2 = 0.28, \lambda_y = 0.16$

Resonant annihilation of χ_2

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

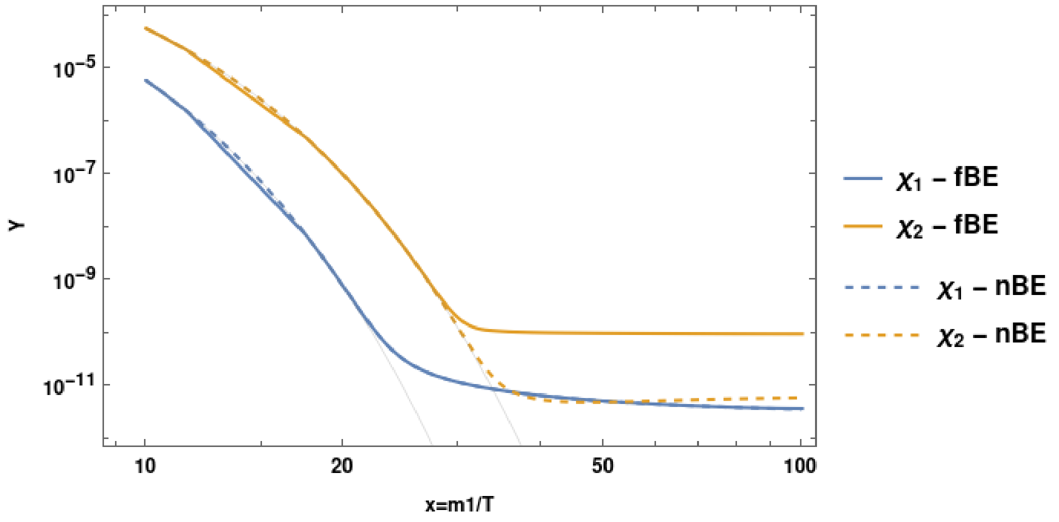
nBE: $(\Omega h^2)_1 = 0.05, (\Omega h^2)_2 = 0.06$

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

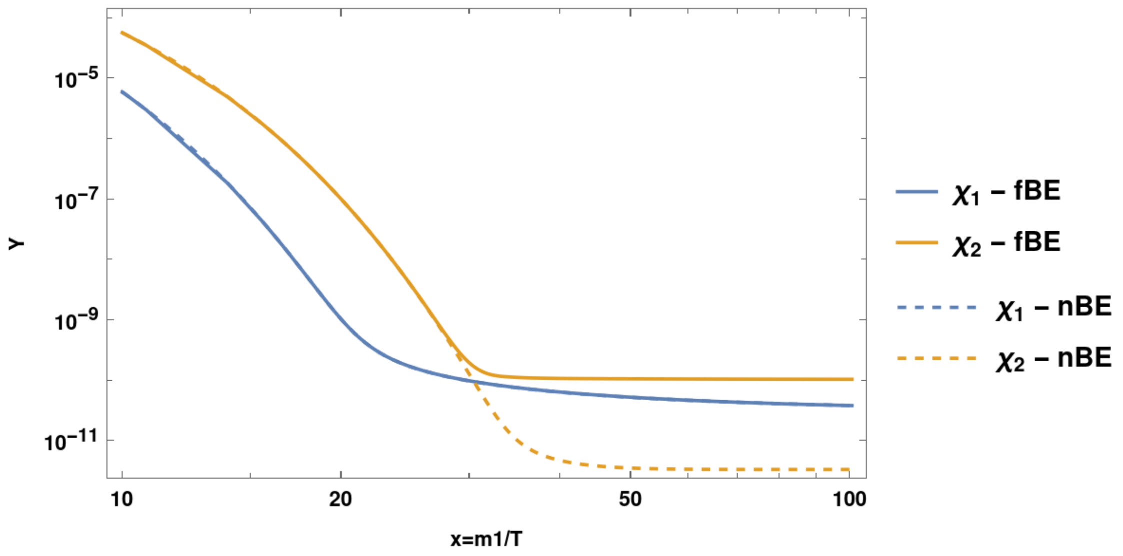
nBE: $(\Omega h^2)_1 = 0.57, (\Omega h^2)_2 = 0.036$

2-component Coy Dark Matter: Results phase space solutions

With conversions:



Without conversions:



$Y_i \equiv \frac{n_i}{s},$

$y_i \equiv \frac{m_1 T_i}{s^{2/3}}$

$m_{\chi_1} = 26.6 GeV$

$m_{\chi_2} = 19.54 GeV$

$m_a = 43.34 GeV$

$\lambda_1 = 0.4, \lambda_2 = 0.28, \lambda_y = 0.16$

Resonant annihilation of χ_2

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

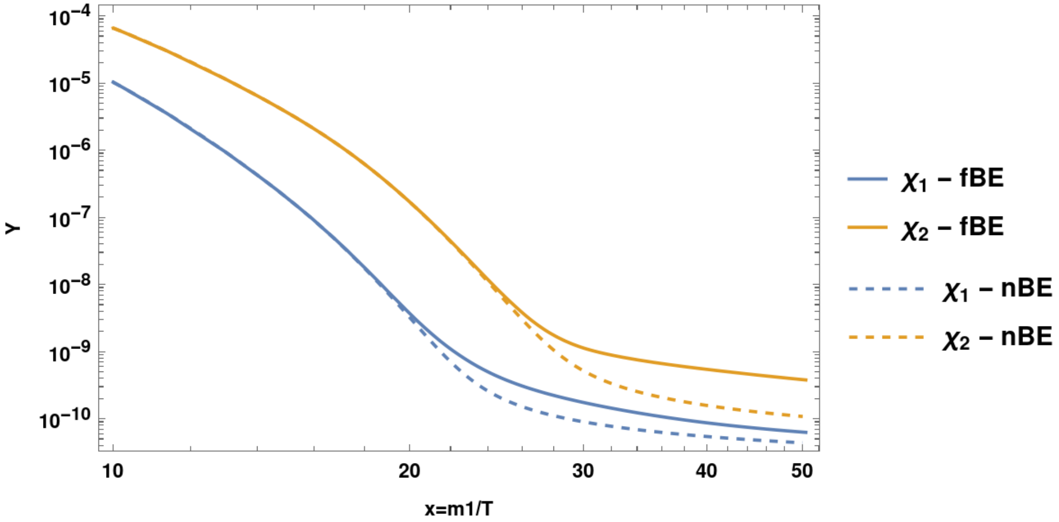
Conversions + Resonant annihilation

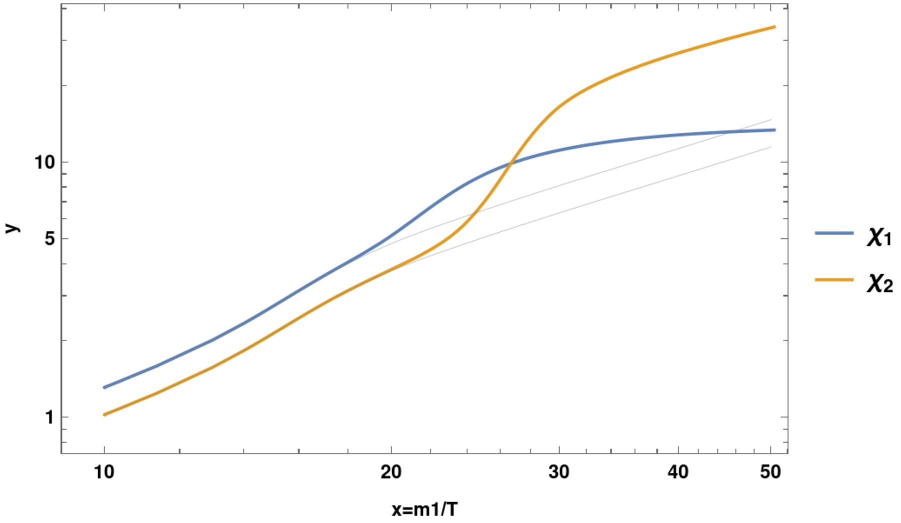
nBE: $(\Omega h^2)_1 = 0.05, (\Omega h^2)_2 = 0.06$

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

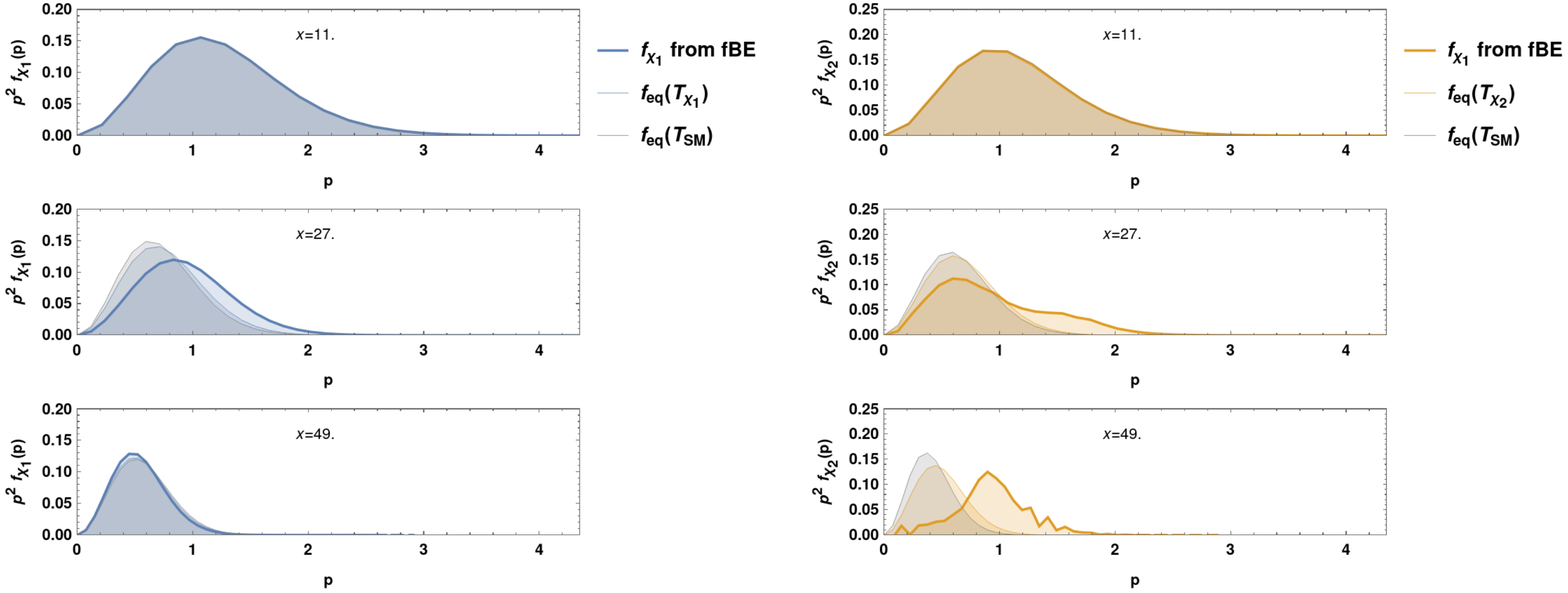
nBE: $(\Omega h^2)_1 = 0.57, (\Omega h^2)_2 = 0.036$

Coy Dark Matter: 2-component





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



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

Resonant annihilation of χ_2

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

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

Summary

- Much as in SUSY, 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* (e.g. bino-like DM, compressed spectra, DM production from late time decays of heavier particles)

- 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--features momentum dependent DM-SM scattering:
    - O(10)% deviation in relic densities of each particles 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)

Summary

- Much as in SUSY, 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* (e.g. bino-like DM, compressed spectra, DM production from late time decays of heavier particles)

- 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, o... ise determination of the relic abundance requires for a solution of the full Boltzm... (fBE) at the phase-space level. These effects would be larger still for momentum dep... interactions.

$$\Omega_c h^2 = 0.1198 \pm 0.0012$$

PLANCK 2015

- With a 2-component Coy DM model--features momentum dependent DM-SM scattering:
  - O(10)% deviation in relic densities of each particles 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)

Summary

- Much as in SUSY, 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* (e.g. bino-like DM, compressed spectra, DM production from late time decays of heavier particles)

- 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, c ... ise determination of the relic abundance requires for a solution of the full Boltzm ... n (fBE) at the phase-space level. These effects would be larger still for momentum de ... interactions.

$\Omega_c h^2 = 0.1198 \pm 0.0012$

PLANCK 2015

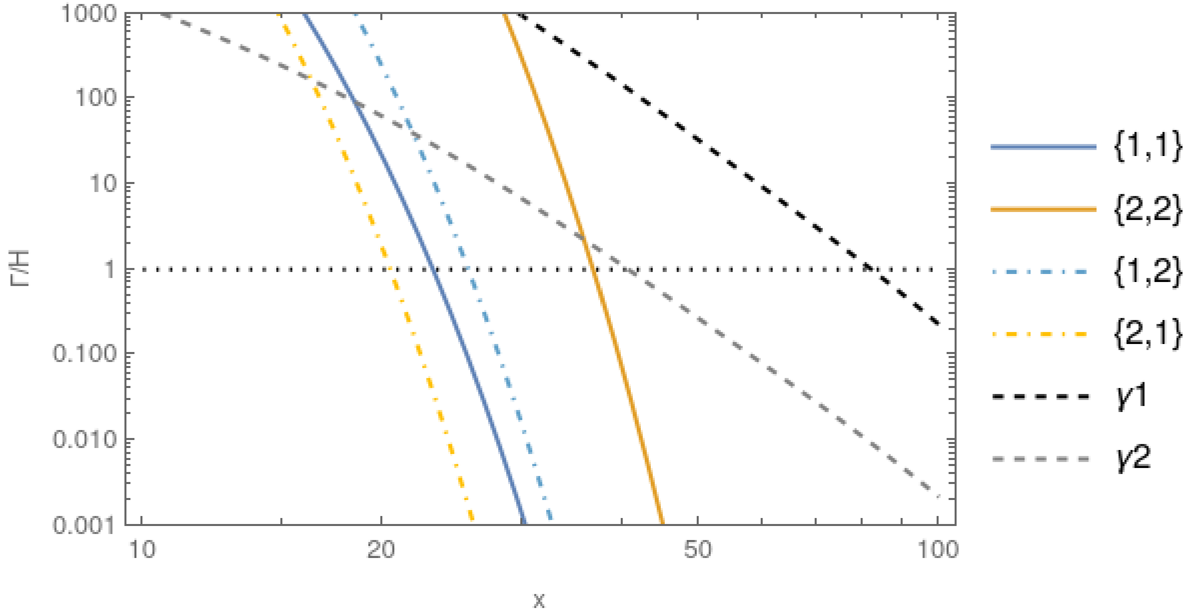
- With a 2-component Coy DM model--features momentum dependent DM-SM scattering:
  - O(10)% deviation in relic densities of each particles is frequently observed
  - For specific points with strong resonance-effects O(10) deviation is observed between the relic densities obtained from solutions of full 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)

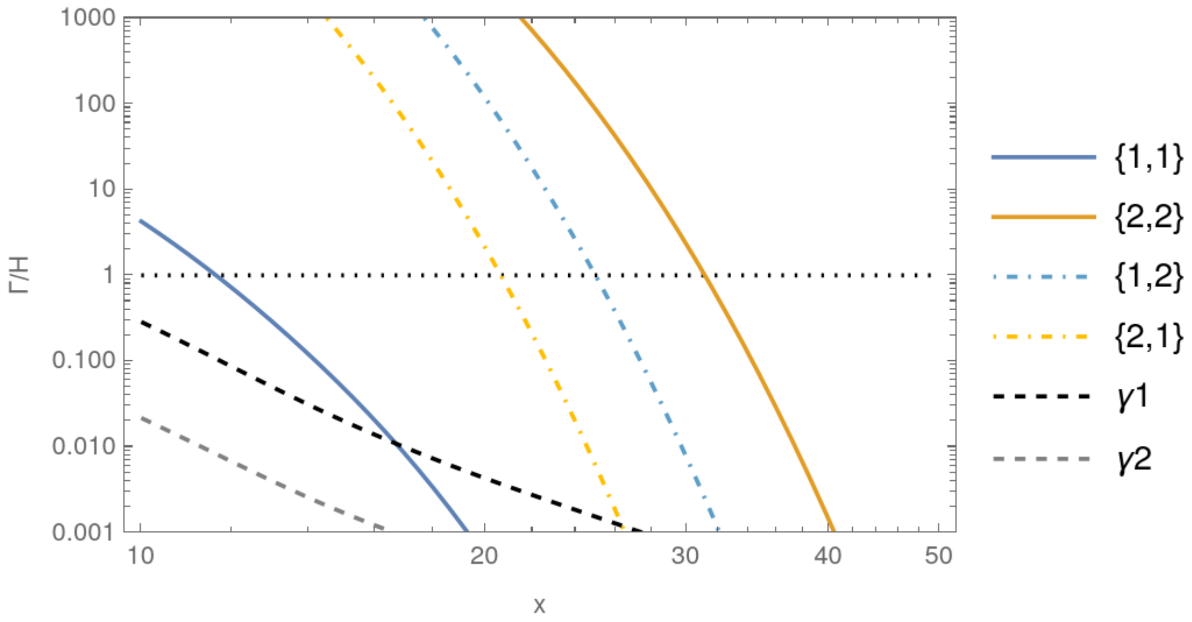
THANK YOU!

Back-up

Rates: BM1

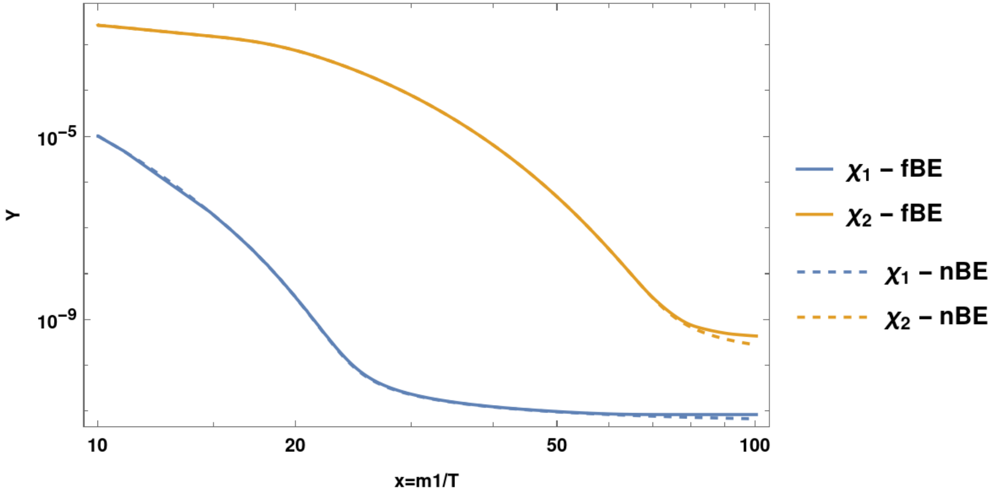


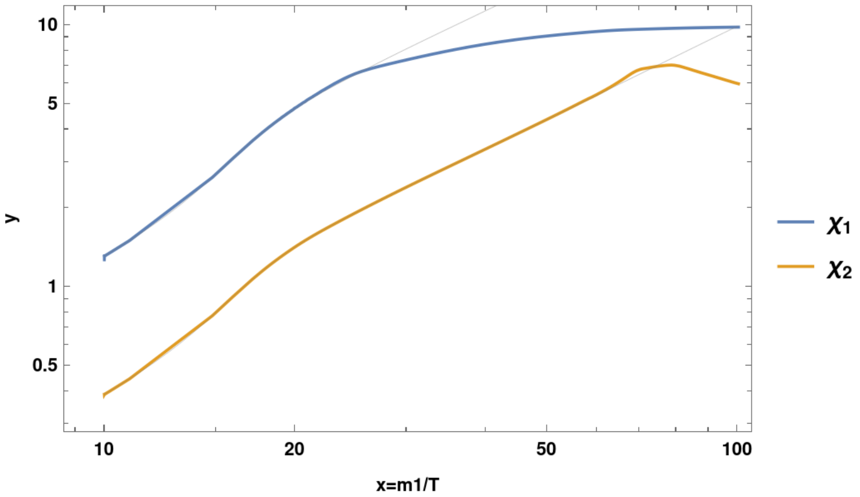
Rates: BM2

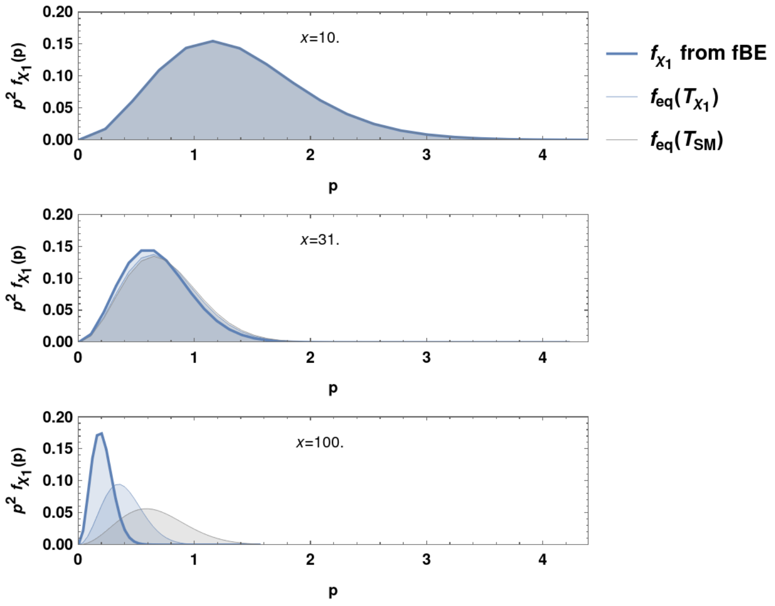


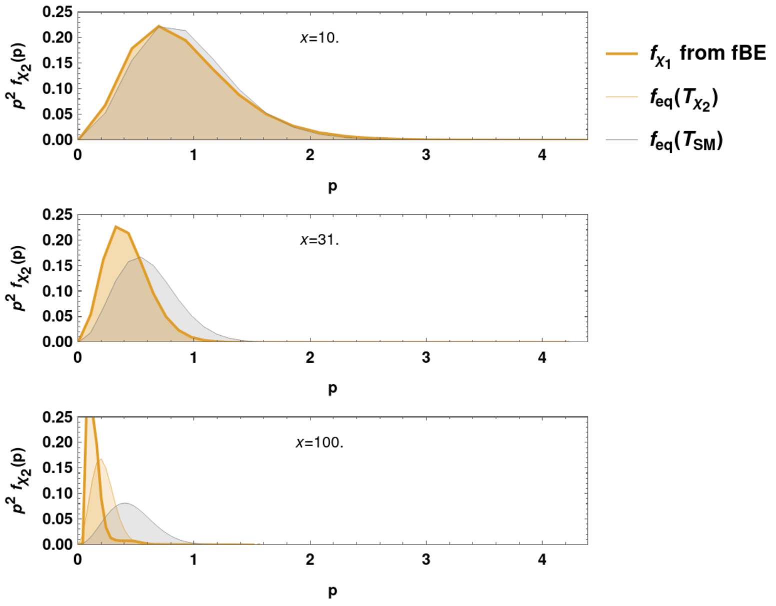
Coy Dark Matter: 2-component

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









$m_{\chi_1} = 2.43\ GeV$

$m_{\chi_2} = 0.72\ GeV$

$m_a = 1.49\ GeV$

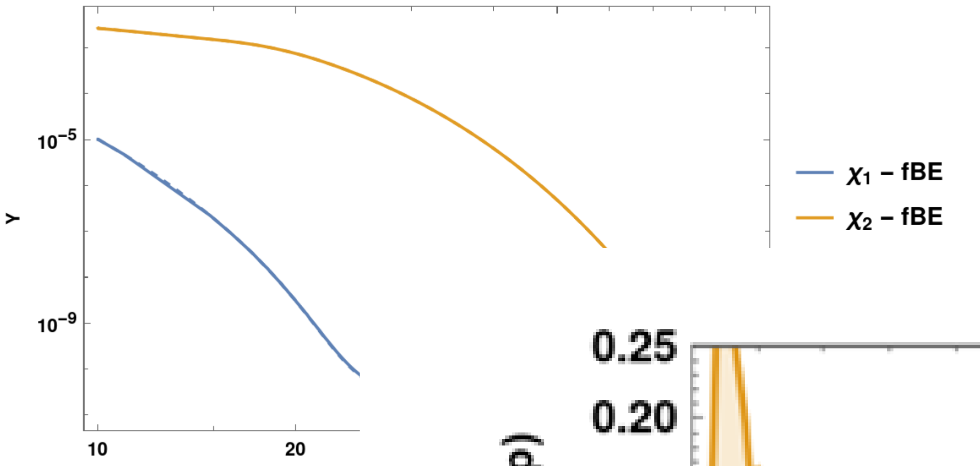
$\lambda_1 = 0.11, \lambda_2 = 0.08, \lambda_y = 0.026$

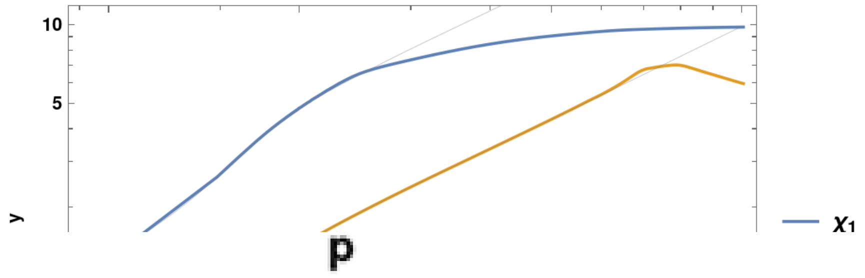
Resonant annihilation of χ_2

$$\frac{Y_1^{nBE}}{Y_1^{fBE}} = 0.81, \frac{Y_2^{nBE}}{Y_2^{fBE}} = 0.64$$

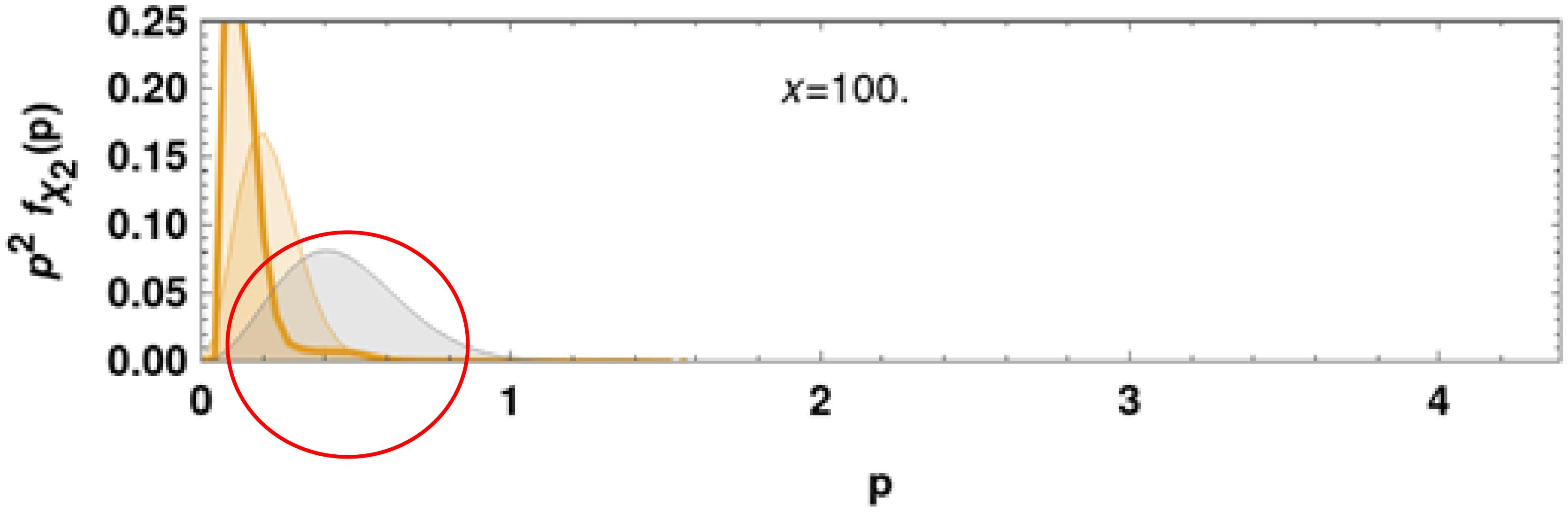
nBE: $(\Omega h^2)_1 = 0.009, (\Omega h^2)_2 = 0.114$

Coy Dark Matter: 2-component





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



m_{χ_1} =

m_{χ_2} =

m_a =

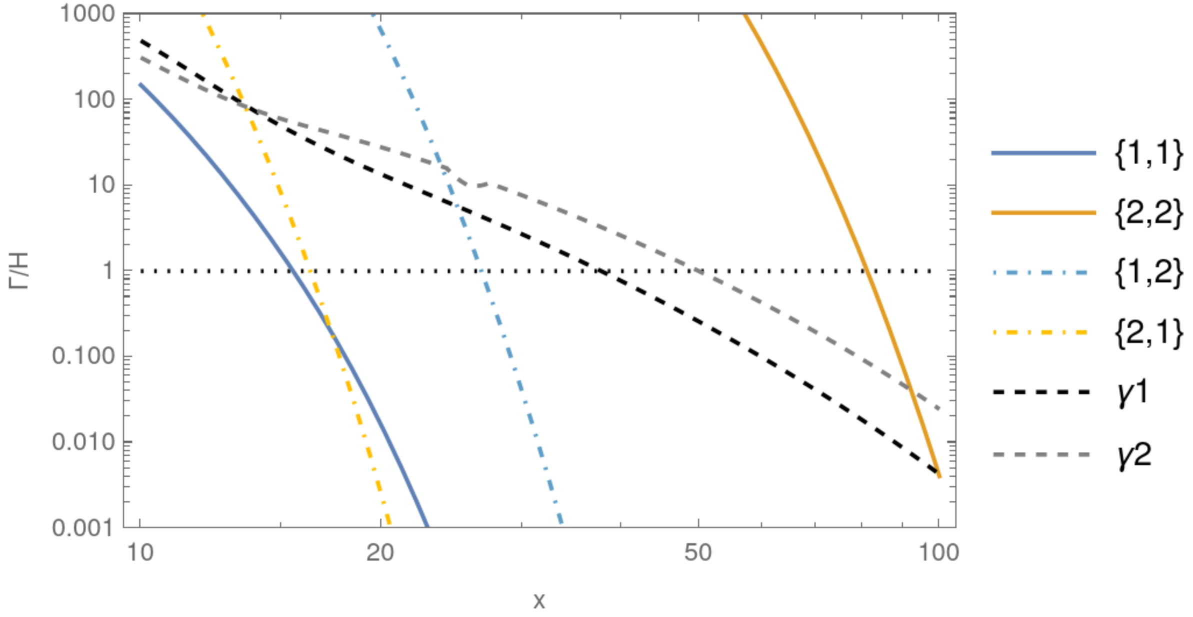
$\lambda_1 = 0.11, \lambda_2$ =

Resonant annihilation of χ_2 and conversions

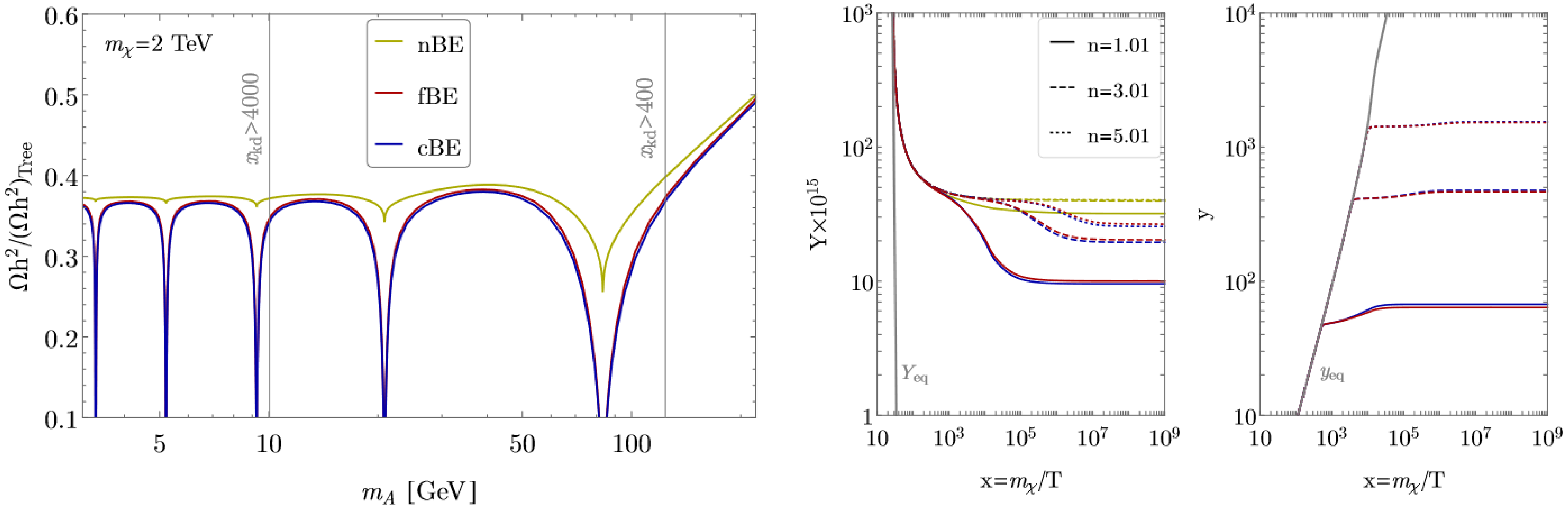
$$\frac{Y_1^{nBE}}{Y_1^{fBE}} = 0.81\,, \frac{Y_2^{nBE}}{Y_2^{fBE}} = 0.64$$

nBE: $(\Omega h^2)_1 = 0.009, (\Omega h^2)_2 = \ 0.114$

Rates: BM2



Sommerfeld enhanced



Sub-threshold model