NATIONAL SCIENCE CENTRE
POLAND
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RELIC ABUNDANCE THEORY:

NEW DEVELOPMENTS

Andrzej Hryczuk

NCBJ

A personal selection of recent ideas in the field

+ some results based on:

T. Binder, T. Bringmann, M. Gustafsson & A.H. 1706.07433, 2103.01944

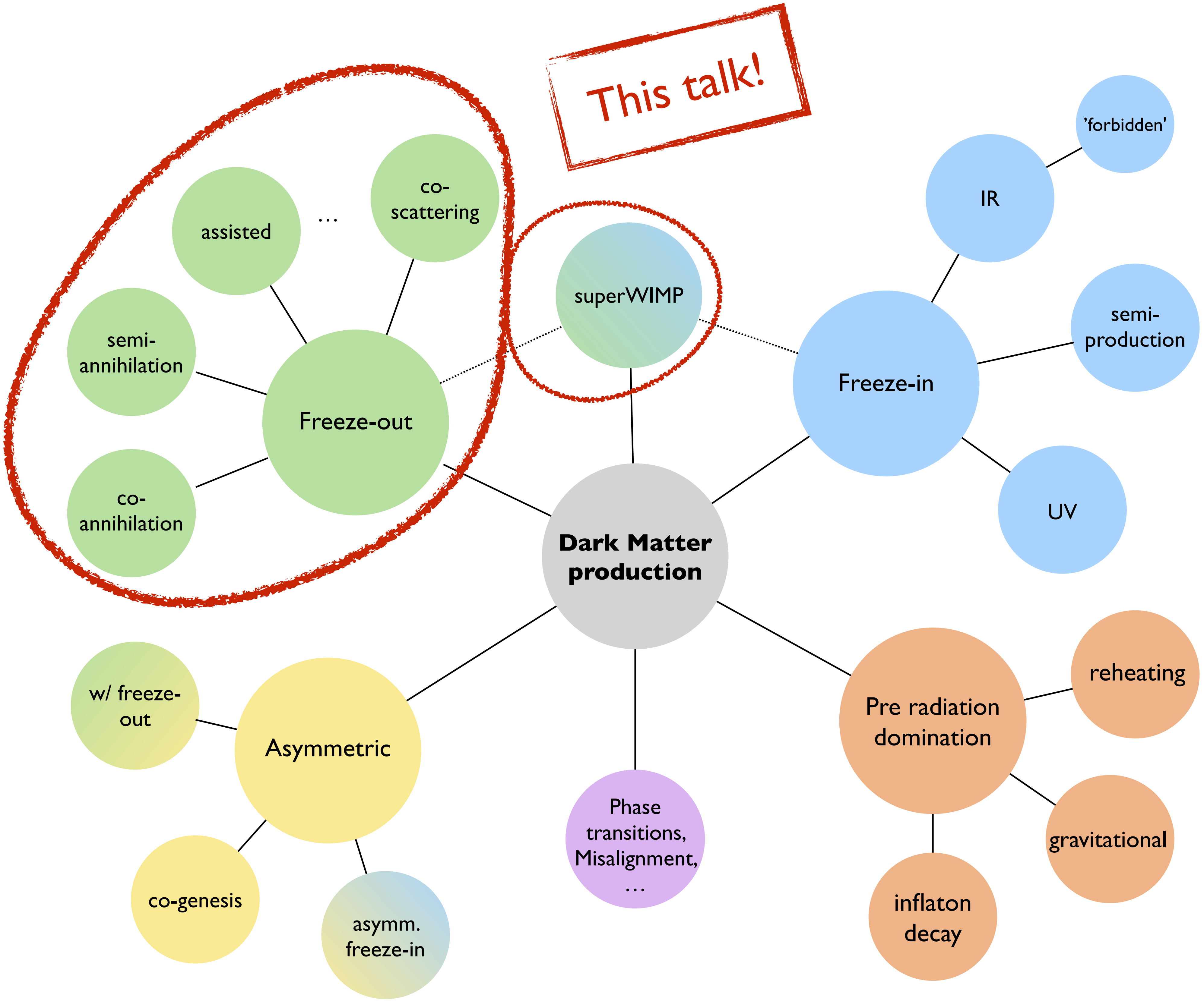
A.H. & M. Laletin 2204.07078

DM^3 @ RIKEN, Kiobe (online)

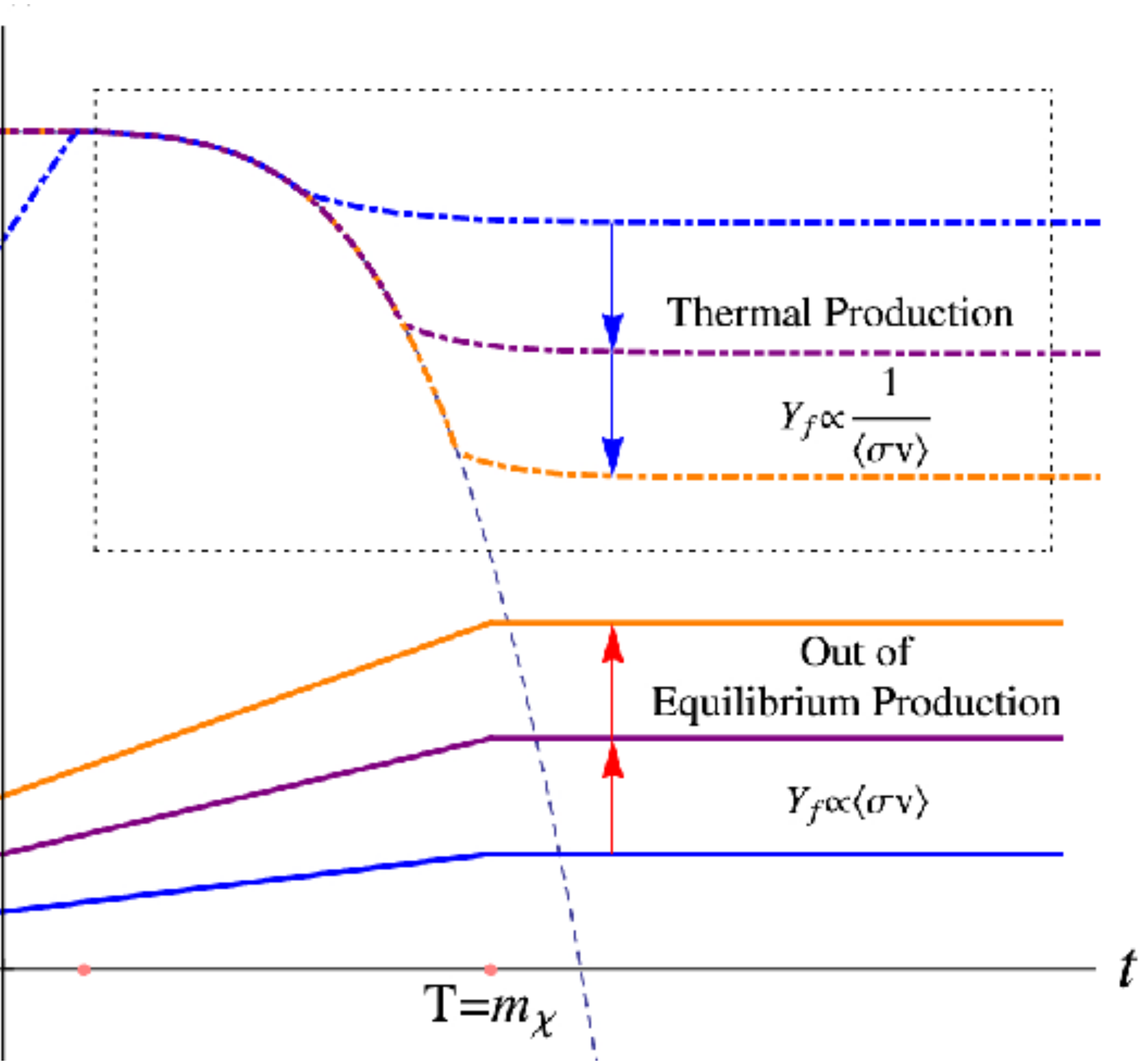
andrzej.hryczuk@ncbj.gov.pl

16th September 2022

DARK MATTER ORIGIN



FREEZE-IN *VS.* FREEZE-OUT



freeze-out

freeze-in

THERMAL RELIC DENSITY

STANDARD SCENARIO & BEYOND

modified expansion rate

e.g., relentless DM, D'Eramo et al. '17, …

numerical codes e.g.,
DarkSUSY, micrOMEGAs, MadDM, SuperISOrelic, …

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_{\chi\bar{\chi}\to ij}\sigma_{\rm rel}\rangle^{\rm eq}\left(n_\chi n_{\bar{\chi}} - n_\chi^{\rm eq} n_{\bar{\chi}}^{\rm eq}\right) + \ldots\ldots\ldots$$

general multi-component dark sector →

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_{\chi\bar{\chi}\to ij}\sigma_{\rm rel}\rangle^{\rm eq}\left(n_\chi n_{\bar{\chi}} - n_\chi^{\rm eq} n_{\bar{\chi}}^{\rm eq}\right) + \ldots\ldots\ldots$$

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_{\chi\bar{\chi}\to ij}\sigma_{\rm rel}\rangle^{\rm eq}\left(n_\chi n_{\bar{\chi}} - n_\chi^{\rm eq} n_{\bar{\chi}}^{\rm eq}\right) + \ldots\ldots\ldots$$

modified cross section

Sommerfeld enhancement
Bound State formation
NLO
finite T effects

breakdown of necessary assumptions leading to different form of the equation, e.g. violation of kinetic equilibrium

where the thermally averaged cross section:

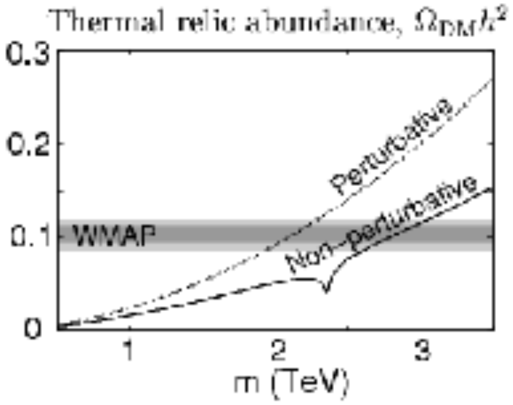
$$\langle\sigma_{\chi\bar{\chi}\to ij}v_{\rm rel}\rangle^{\rm eq} = -\frac{h_\chi^2}{n_\chi^{\rm eq} n_{\bar{\chi}}^{\rm eq}}\int\frac{d^3\vec{p}_\chi}{(2\pi)^3}\frac{d^3\vec{p}_{\bar{\chi}}}{(2\pi)^3}\,\sigma_{\chi\bar{\chi}\to ij}v_{\rm rel}\; f_\chi^{\rm eq} f_{\bar{\chi}}^{\rm eq}$$

CHAPTER I:

PARTICLE PHYSICS EFFECTS

THE SOMMERFELD EFFECT

FROM EW INTERACTIONS

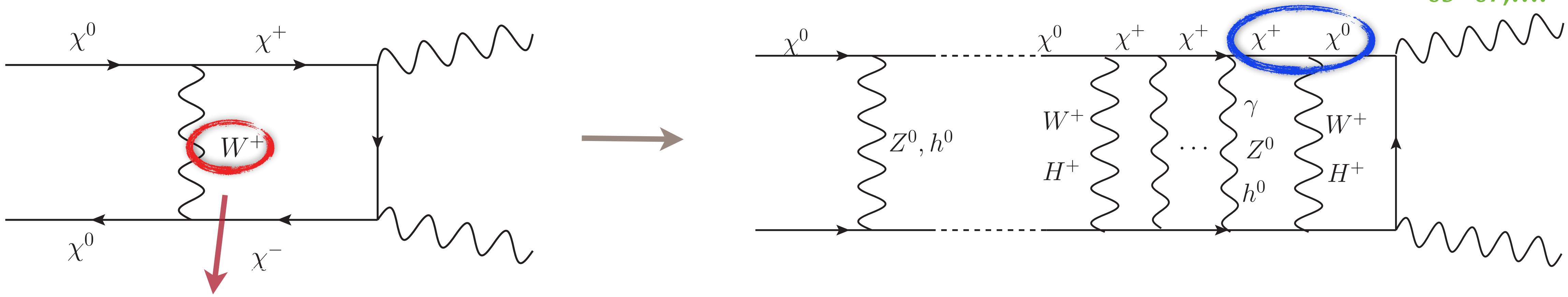


seminal papers by
Hisano, Matsumoto, Nojiri, saito, Nagai, Senami, Sato, Sato, '03-'07,….

force carriers in the MSSM:

$\cancel{\gamma},\ W^{\pm},\ Z^0,\ h_1^0,\ h_2^0,\ H^{\pm}$

$\delta m \ll m_\chi$



$m_\chi \gg m_W$

at TeV scale $\Rightarrow$ generically effect of $\mathcal{O}(1-100\%)$

on top of that resonance structure

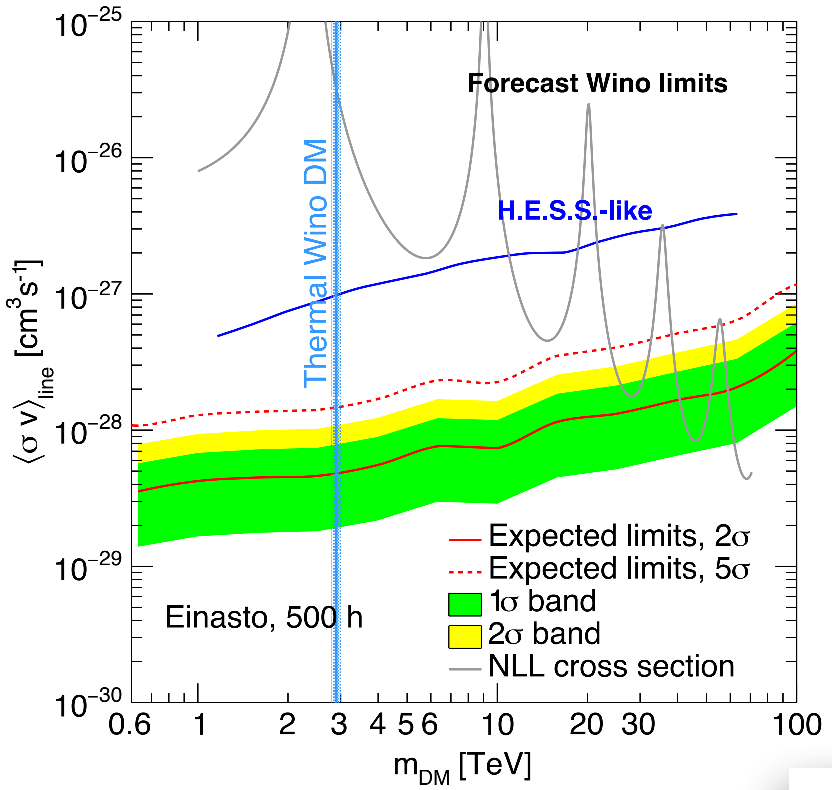
→ effect of $\mathcal{O}(\text{few})$
for the relic density

can be understood as being close to
a threshold of lowest bound state

AH, R. Iengo, P. Ullio. '10; AH '11
AH *et al.* '17, M. Beneke *et al.*; '16

THE SOMMERFELD EFFECT

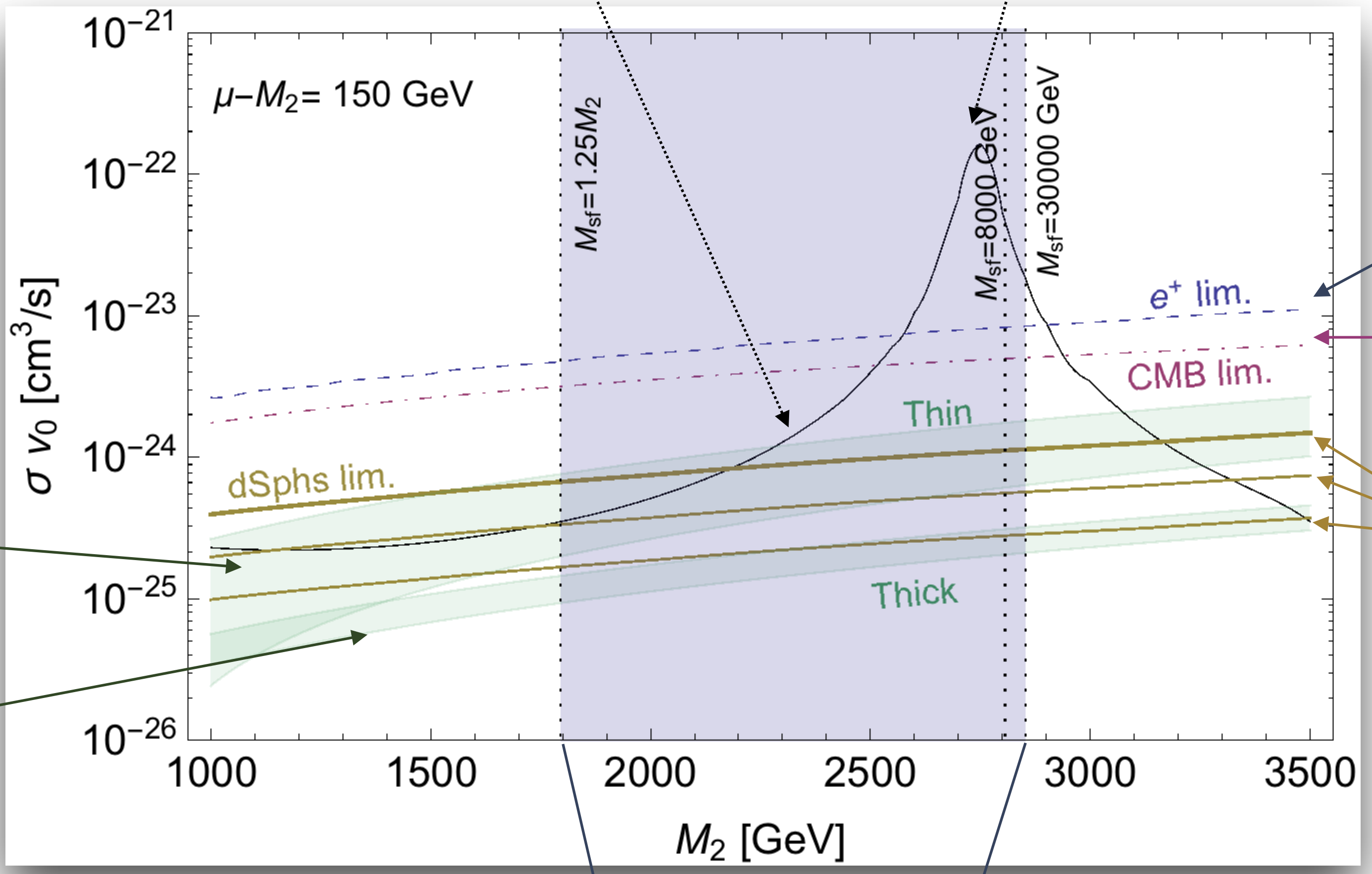
INDIRECT DETECTION



Slatyer *et al.*, '21

actual
cross section

resonance moves
to the right
w.r.t. pure wino



Limits:

AMS leptons

CMB limits
from Planck

Fermi +
MAGIC
dSphs

Antiproton fits:

Thin
prop. model

Thick
prop. model

Beneke, …AH, … *et al.*, '16

**correct RD can be achieved:
when varying sfermion masses**

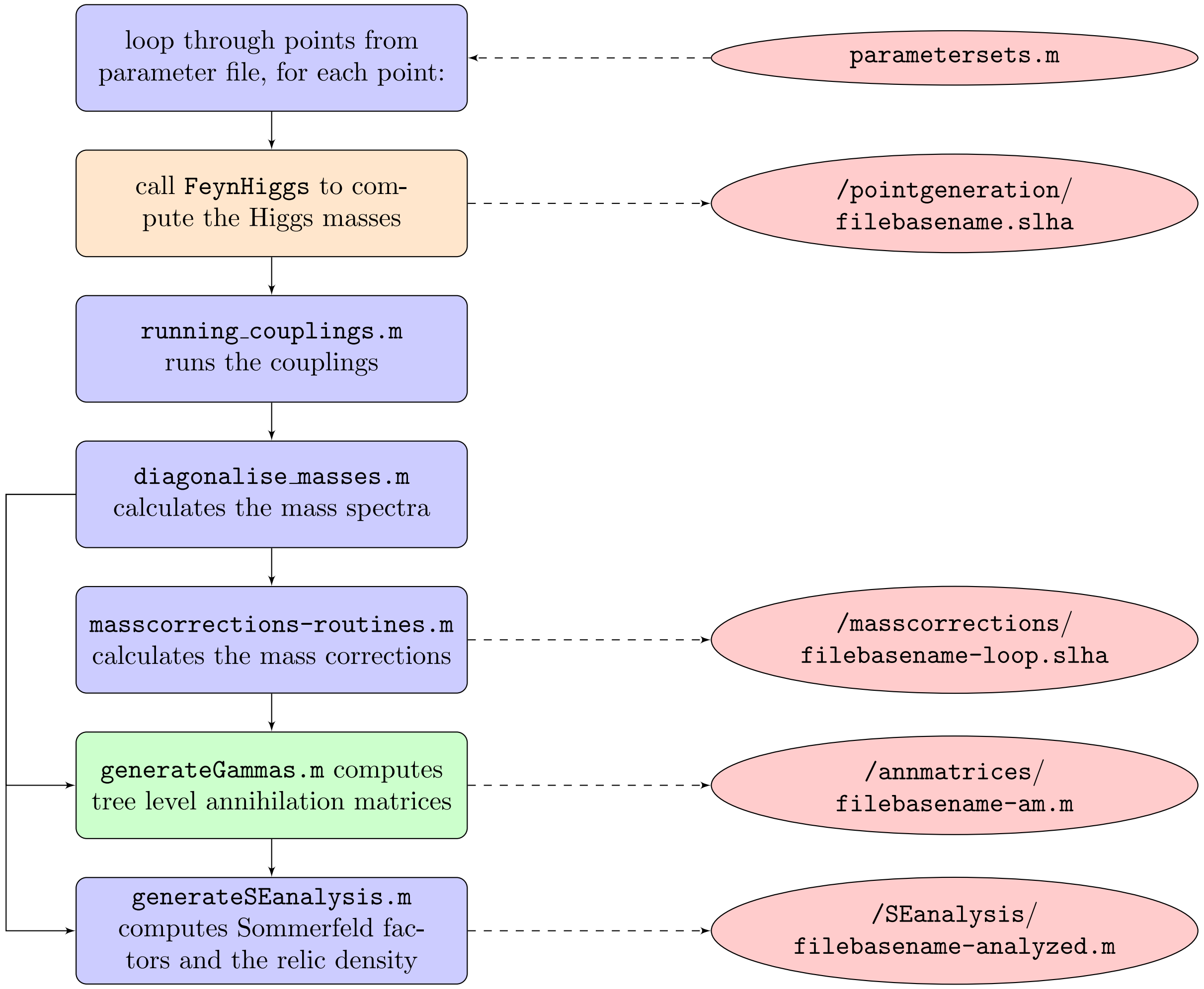
similar study, pure Wino case: Ibe *et al*. '15

NEW NUMERICAL TOOL

based on EFT, improving accuracy in numerous ways

- suitable for (large scale) scans
- implemented full MSSM
- one-loop on-shell mass splittings and running couplings
- the Sommerfeld effect for P- and $O(v^2)$ S-wave
- off-diagonal annihilation matrices
- present day annihilation in the halo (for ID)
- possibility of including thermal corrections
- …
- accuracy at O(%), dominated by theoretical uncertainties of EFT

not present in DarkSE
AH, ′11



loop through points from parameter file, for each point: ← `parametersets.m`

call **FeynHiggs** to compute the Higgs masses → `/pointgeneration/filebasename.slha`

`running_couplings.m` runs the couplings

`diagonalise_masses.m` calculates the mass spectra

`masscorrections-routines.m` calculates the mass corrections → `/masscorrections/filebasename-loop.slha`

`generateGammas.m` computes tree level annihilation matrices → `/annmatrices/filebasename-am.m`

`generateSEanalysis.m` computes Sommerfeld factors and the relic density → `/SEanalysis/filebasename-analyzed.m`

Status: all works as intended, making the code ready for public release

Beneke,…, AH,… *et al.* in preparation

BOUND STATE FORMATION

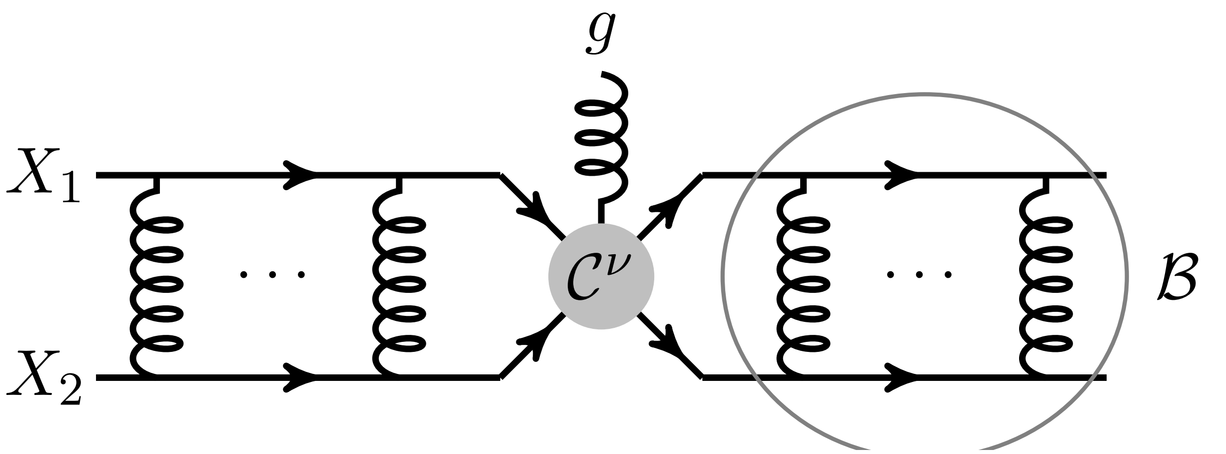
As noticed before Sommerfeld effect has resonances when Bohr radius ~ potential range, i.e. when close to a bound state threshold →

Can DM form actual bound states from such long range interactions?

↓

Yes, it can!

Q: How to describe such bound states and their formation?



free DM states DM bound state

*the effect was first studied in simplified models with light mediators, then gradually extended to non-Abelian interactions, double emissions, co-annihilations, etc.

see papers by **K. Petraki** *et al.* '14-19

**vide also "WIMPonium"
March-Russel, West '10

EXAMPLE: BSF FOR TEV SCALE WIMP

Electroweak interactions are stronger and longer ranged than Higgs mediated…
but also more complicated (non-Abelian + massive mediators)

here as far as I know work is still in progress…

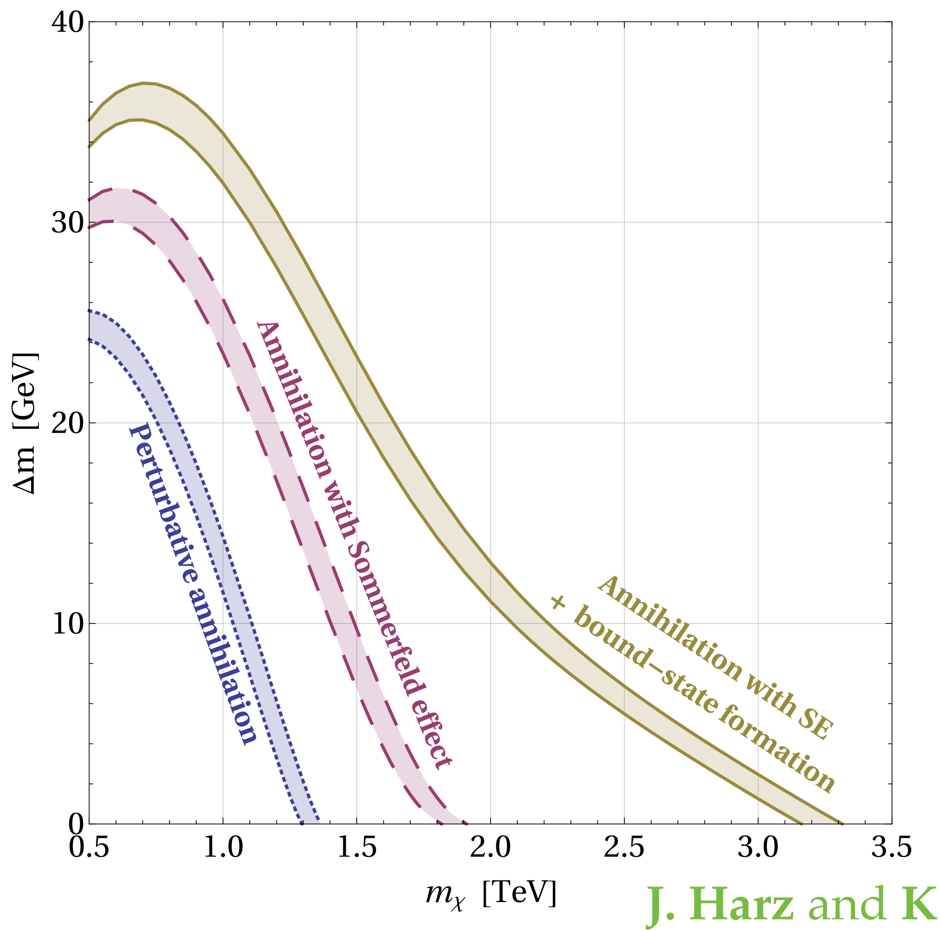
Higgs mediated ⇒ Could lead to DM bound states, but for usual TeV DM models, biggest effect observed is more indirect

e.g. produces tighter bound states of squarks - less inefficient dissociation - more efficient DM depopulation

J. Harz and **K. Petraki** '19

but e.g.: co-annihilation with squarks and QCD squark bound states

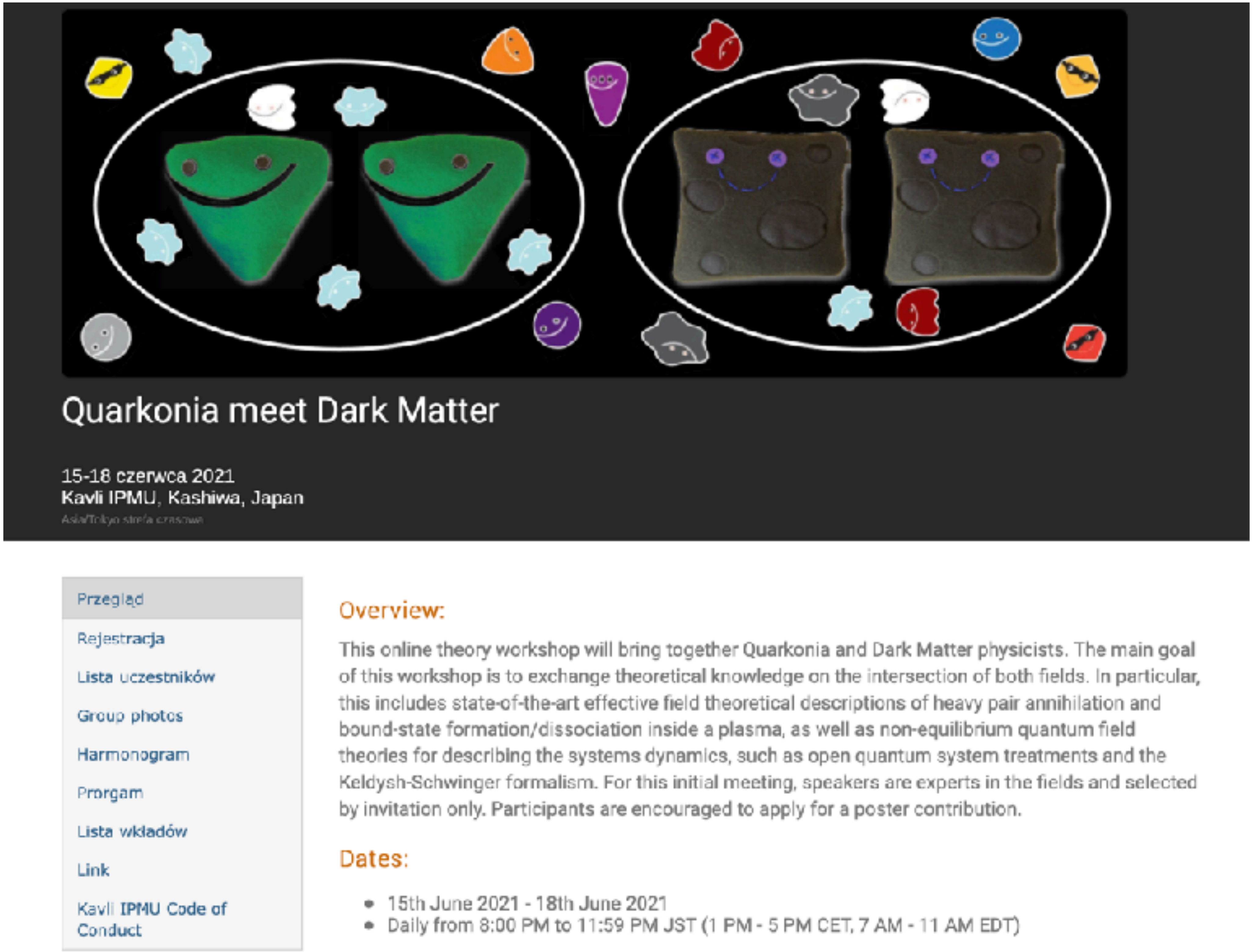
significant modification of the annihilation rate - large effects on the DM models, especially in the TeV scale



J. Harz and **K. Petraki** '18

Bound states in DM workshop last June 2021 @ IMPU

https://indico.ipmu.jp/event/389/



Quarkonia meet Dark Matter

15-18 czerwca 2021
Kavli IPMU, Kashiwa, Japan
Asia/Tokyo strefa czasowa

Overview:

This online theory workshop will bring together Quarkonia and Dark Matter physicists. The main goal of this workshop is to exchange theoretical knowledge on the intersection of both fields. In particular, this includes state-of-the-art effective field theoretical descriptions of heavy pair annihilation and bound-state formation/dissociation inside a plasma, as well as non-equilibrium quantum field theories for describing the systems dynamics, such as open quantum system treatments and the Keldysh-Schwinger formalism. For this initial meeting, speakers are experts in the fields and selected by invitation only. Participants are encouraged to apply for a poster contribution.

Dates:

- 15th June 2021 - 18th June 2021
- Daily from 8:00 PM to 11:59 PM JST (1 PM - 5 PM CET, 7 AM - 11 AM EDT)

DARK MATTER AT NLO

Bergstrom ’89; Drees et al., 9306325; Ullio & Bergstrom, 9707333	helicity suppression lifting
⋮	
Bergstrom et al., 0507229; Bringmann et al., 0710.3169	spectral features in indirect searches
⋮	
Ciafaloni et al., 1009.0224 Cirelli et al., 1012.4515 Ciafaloni et al., 1202.0692 AH & Iengo, 1111.2916	large EW corrections
⋮	
Chatterjee et al., 1209.2328 Harz et al., 1212.5241 Ciafaloni et al., 1305.6391 Hermann et al., 1404.2931 Boudjema et al., 1403.7459 Bringmann et al., 1510.02473 Klasen et al., 1607.06396	***thermal relic density***

$$\Omega_{DM}h^2 = 0.1187 \pm 0.0017.$$

<1.5% uncertainty!

Planck+WMAP pol.+highL+BAO; 1303.5062

⋮	
SloopS, DM@NLO, PPC4DMID	NLO codes

RELIC DENSITY AT NLO

Recall at LO:

$$C_{\rm LO} = -h_\chi^2 \int \frac{d^3\vec{p}_\chi}{(2\pi)^3}\frac{d^3\vec{p}_{\bar\chi}}{(2\pi)^3}\, \sigma_{\chi\bar\chi\to ij}v_{\rm rel}\, \left[f_\chi f_{\bar\chi}(1\pm f_i)(1\pm f_j) - f_i f_j (1\pm f_\chi)(1\pm f_{\bar\chi})\right]$$

crucial point:

$$\boxed{p_\chi + p_{\bar\chi} = p_i + p_j \Rightarrow f_\chi^{\rm eq} f_{\bar\chi}^{\rm eq} \approx f_i^{\rm eq} f_j^{\rm eq}}$$

in Maxwell approx.

at NLO both virtual one-loop and 3-body processes contribute:

$$C_{1-{\rm loop}} = -h_\chi^2 \int \frac{d^3\vec{p}_\chi}{(2\pi)^3}\frac{d^3\vec{p}_{\bar\chi}}{(2\pi)^3}\, \sigma^{1-{\rm loop}}_{\chi\bar\chi\to ij}v_{\rm rel}\, \left[f_\chi f_{\bar\chi}(1\pm f_i)(1\pm f_j) - f_i f_j (1\pm f_\chi)(1\pm f_{\bar\chi})\right]$$

$$C_{\rm real} = -h_\chi^2 \int \frac{d^3\vec{p}_\chi}{(2\pi)^3}\frac{d^3\vec{p}_{\bar\chi}}{(2\pi)^3}\, \sigma_{\chi\bar\chi\to ij\gamma}v_{\rm rel}\, \left[f_\chi f_{\bar\chi}(1\pm f_i)(1\pm f_j)(1+f_\gamma) - f_i f_j f_\gamma (1\pm f_\chi)(1\pm f_{\bar\chi})\right]$$

$$p_\chi + p_{\bar\chi} = p_i + p_j \pm p_\gamma \Rightarrow$$

photon can be arbitrarily soft

$$f_\gamma \sim \omega^{-1}$$

Maxwell approx. not valid anymore...

...problem: *T*-dependent IR divergence!

RELIC DENSITY

WHAT REALLY HAPPENS AT NLO?

Beneke, Dighera, AH, 1409.3049

typically only this used in NLO literature

$$C_{\rm NLO} \sim \int d\Pi_{\chi\bar{\chi}ij} \;\; f_\chi f_{\bar{\chi}} \; \boxed{\Big\{ |\mathcal{M}^{\rm LO}_{\chi\bar{\chi}\to ij}|^2 + |\mathcal{M}^{{\rm NLO}\; T=0}_{\chi\bar{\chi}\to ij}|^2 + \int d\Pi_\gamma |\mathcal{M}_{\chi\bar{\chi}\to ij\gamma}|^2 +}$$

$$|\mathcal{M}^{{\rm NLO}\; T\neq 0}_{\chi\bar{\chi}\to ij}|^2 + \int d\Pi_\gamma \left[f_\gamma \left(|\mathcal{M}_{\chi\bar{\chi}\to ij\gamma}|^2 + |\mathcal{M}_{\chi\bar{\chi}\gamma\to ij}|^2 \right) \right.$$

$$\left. - f_i \left(|\mathcal{M}_{\chi\bar{\chi}\to ij\gamma}|^2 + |\mathcal{M}_{\chi\bar{\chi}i\to j\gamma}|^2 \right) - f_j \left(|\mathcal{M}_{\chi\bar{\chi}\to ij\gamma}|^2 + |\mathcal{M}_{\chi\bar{\chi}j\to i\gamma}|^2 \right) \right] \Big\}$$

thermal
1-loop

photon
absorption

photon
emission

SM fermions
emission

SM fermions
absorption

$$-f_i f_j \Big\{ |\mathcal{M}^{\rm LO}_{ij\to\chi\bar{\chi}}|^2 + |\mathcal{M}^{{\rm NLO}\; T=0}_{ij\to\chi\bar{\chi}}|^2 + \int d\Pi_\gamma |\mathcal{M}_{ij\to\chi\bar{\chi}\gamma}|^2 +$$

$$|\mathcal{M}^{{\rm NLO}\; T\neq 0}_{ij\to\chi\bar{\chi}}|^2 + \int d\Pi_\gamma \left[f_\gamma \left(|\mathcal{M}_{ij\to\chi\bar{\chi}\gamma}|^2 + |\mathcal{M}_{ij\gamma\to\chi\bar{\chi}}|^2 \right) \right.$$

$$\left. - f_\chi \left(|\mathcal{M}_{ij\to\chi\bar{\chi}\gamma}|^2 + |\mathcal{M}_{ij\chi\to\chi\gamma}|^2 \right) - f_{\bar{\chi}} \left(|\mathcal{M}_{ij\to\chi\bar{\chi}\gamma}|^2 + |\mathcal{M}_{ij\bar{\chi}\to\bar{\chi}\gamma}|^2 \right) \right] \Big\}$$

SOLUTION: non-equilibrium thermal field theory

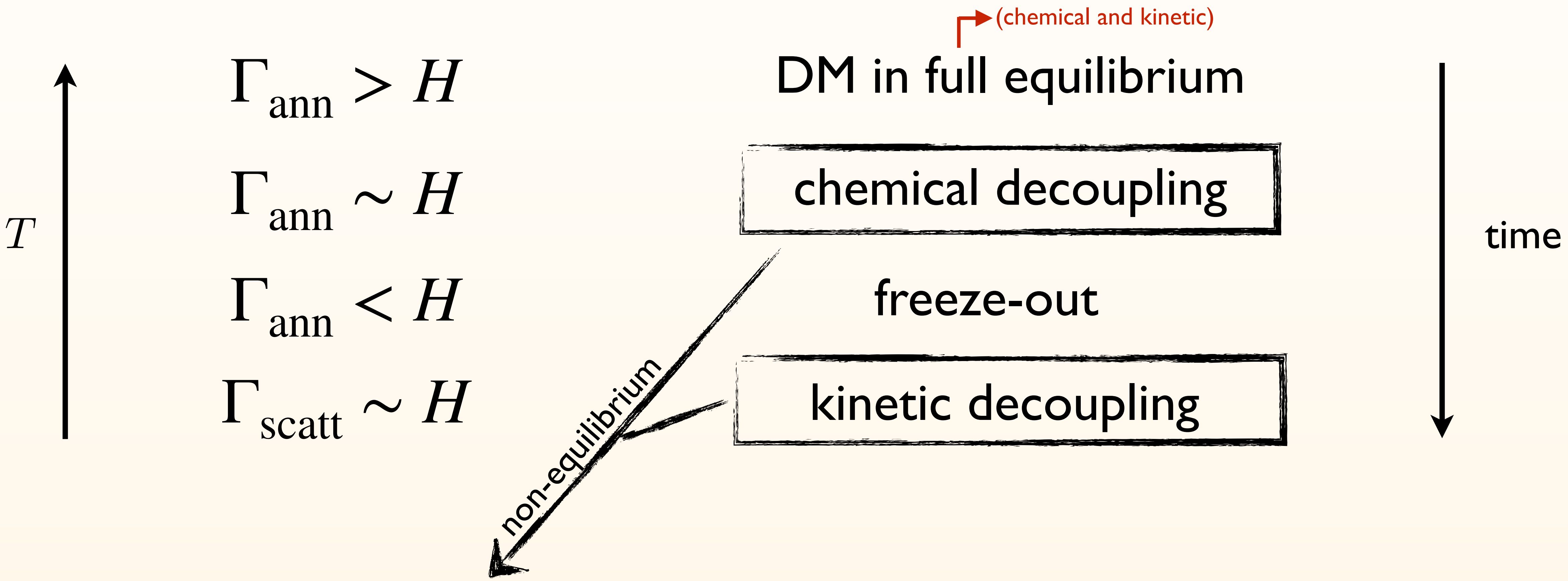
in the DM context some results available, lot more to be done…
but typically not that relevant for phenomenology

CHAPTER II:

NON-EQUILIBRIUM EFFECTS

THERMAL RELIC DENSITY

STANDARD SCENARIO



T

$\Gamma_{\text{ann}} > H$ DM in full equilibrium

$\Gamma_{\text{ann}} \sim H$ chemical decoupling

$\Gamma_{\text{ann}} < H$ freeze-out

$\Gamma_{\text{scatt}} \sim H$ kinetic decoupling

time

time evolution of $f_\chi(p)$ in kinetic theory:

$$\boxed{E\left(\partial_t - H\vec{p}\cdot\nabla_{\vec{p}}\right)} f_\chi = \mathcal{C}[f_\chi]$$

Liouville operator in FRW background

the collision term

THERMAL RELIC DENSITY

STANDARD APPROACH

Boltzmann equation for $f_\chi(p)$:

$$E\left(\partial_t - H\vec{p}\cdot\nabla_{\vec{p}}\right) f_\chi = \mathcal{C}[f_\chi]$$

*assumptions for using Boltzmann eq:
classical limit, molecular chaos,...

…for derivation from thermal QFT
see e.g., 1409.3049

$\Downarrow$ integrate over p
(i.e. take 0th moment)

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_{\chi\bar{\chi}\to ij}\sigma_{\rm rel}\rangle^{\rm eq}\left(n_\chi n_{\bar{\chi}} - n_\chi^{\rm eq} n_{\bar{\chi}}^{\rm eq}\right)$$

$\Downarrow$

Critical assumption:
kinetic equilibrium at chemical decoupling

$$f_\chi \sim a(T) f_\chi^{\rm eq}$$

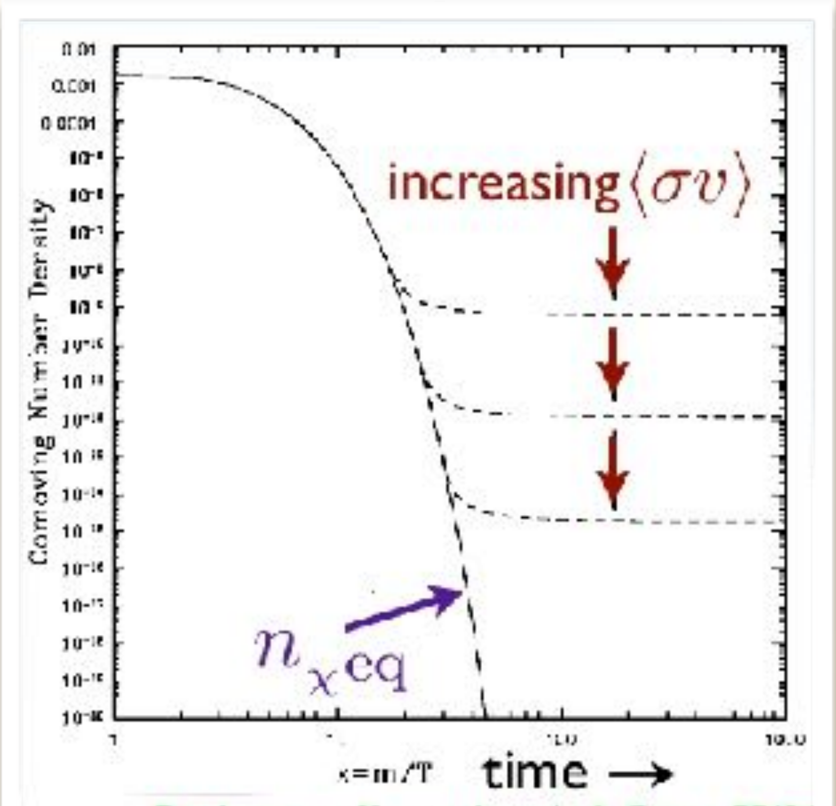
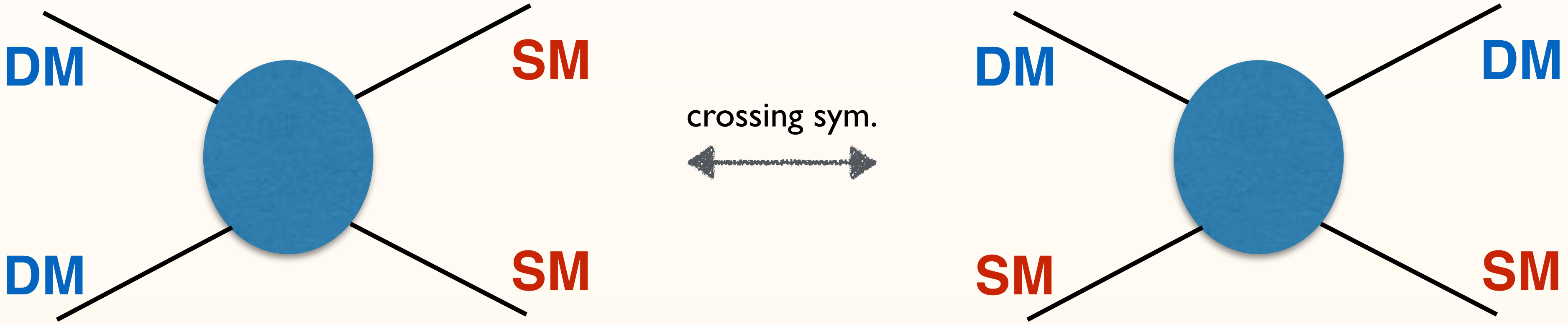


Fig.: Jungman, Kamionkowski & Griest, PR'96

FREEZE-OUT *VS.* DECOUPLING

annihilation (elastic) scattering



$$\sum_{\text{spins}} \left|\mathcal{M}^{\text{pair}}\right|^2 = F(p_1, p_2, p_1', p_2') \quad \sim \quad \sum_{\text{spins}} \left|\mathcal{M}^{\text{scatt}}\right|^2 = F(k, -k', p', -p)$$

Boltzmann suppression of DM vs. SM $\Rightarrow$ scatterings typically more frequent

dark matter frozen-out but typically still kinetically coupled to the plasma

$$\boxed{\tau_{\text{r}}(T_{\text{kd}}) \equiv N_{\text{coll}}/\Gamma_{\text{el}} \sim H^{-1}(T_{\text{kd}})}$$

Schmid, Schwarz, Widern '99; Green, Hofmann, Schwarz '05

Two consequences:

1. During freeze-out (chemical decoupling) typically: $f_\chi \sim a(\mu) f_\chi^{\text{eq}}$
2. If kinetic decoupling much, much later: possible impact on the matter power spectrum

i.e. kinetic decoupling can have observable consequences and affect e.g. missing satellites problem

see e.g., Bringmann, Ihle, Karsten, Walia '16

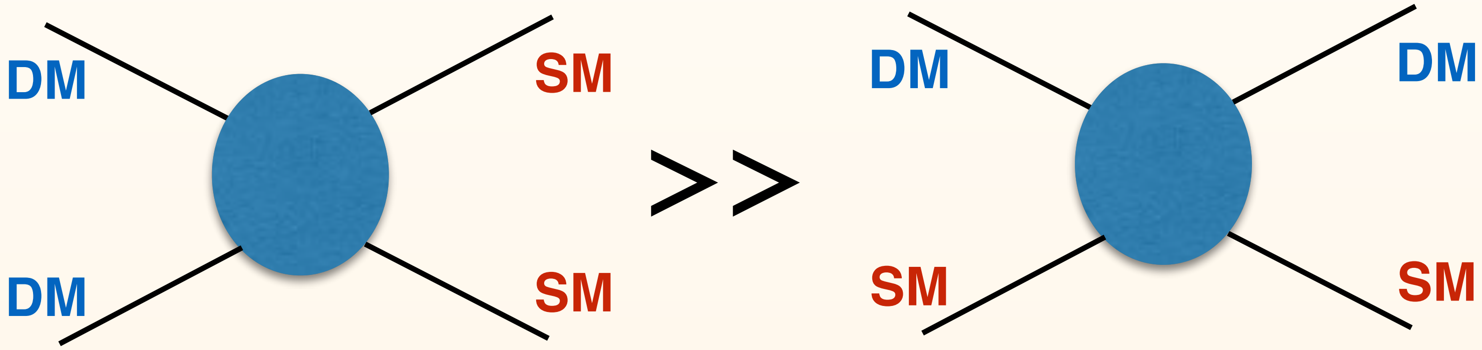
EARLY KINETIC DECOUPLING?

A necessary and sufficient condition: scatterings weaker than annihilation

i.e. rates around freeze-out: $H \sim \Gamma_{\rm ann} \gtrsim \Gamma_{\rm el}$

Possibilities:

A)



e.g., resonant annihilation

B) Boltzmann suppression of SM as strong as for DM

e.g., below threshold annihilation (forbidden-like DM)

C) Scatterings and annihilation have different structure

e.g., semi-annihilation, 3 to 2 models,…

D) Multi-component dark sectors

e.g., additional sources of DM from late decays, …

HOW TO GO BEYOND KINETIC EQUILIBRIUM?

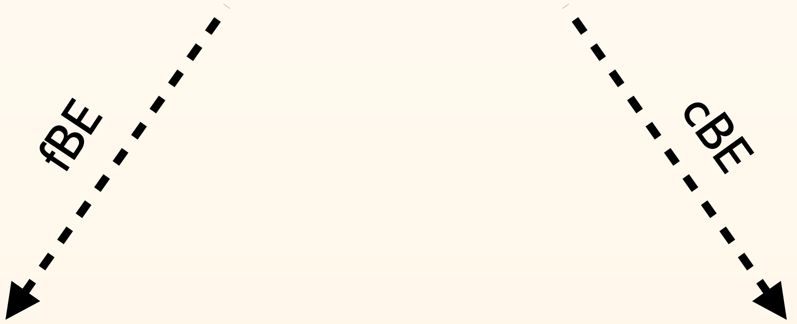
All information is in the full BE:

both about chemical (”normalization”) and kinetic (”shape”) equilibrium/decoupling

$$E\,(\partial_t - H\vec{p}\cdot\nabla_{\vec{p}})\,f_\chi = \mathcal{C}[f_\chi]$$

contains both scatterings and annihilations

Two possible approaches:



0-th moment: n_χ
2-nd moment: T_χ
…

solve numerically for full $f_\chi(p)$

have insight on the distribution
no constraining assumptions

numerically challenging
often an overkill

consider system of equations for moments of $f_\chi(p)$

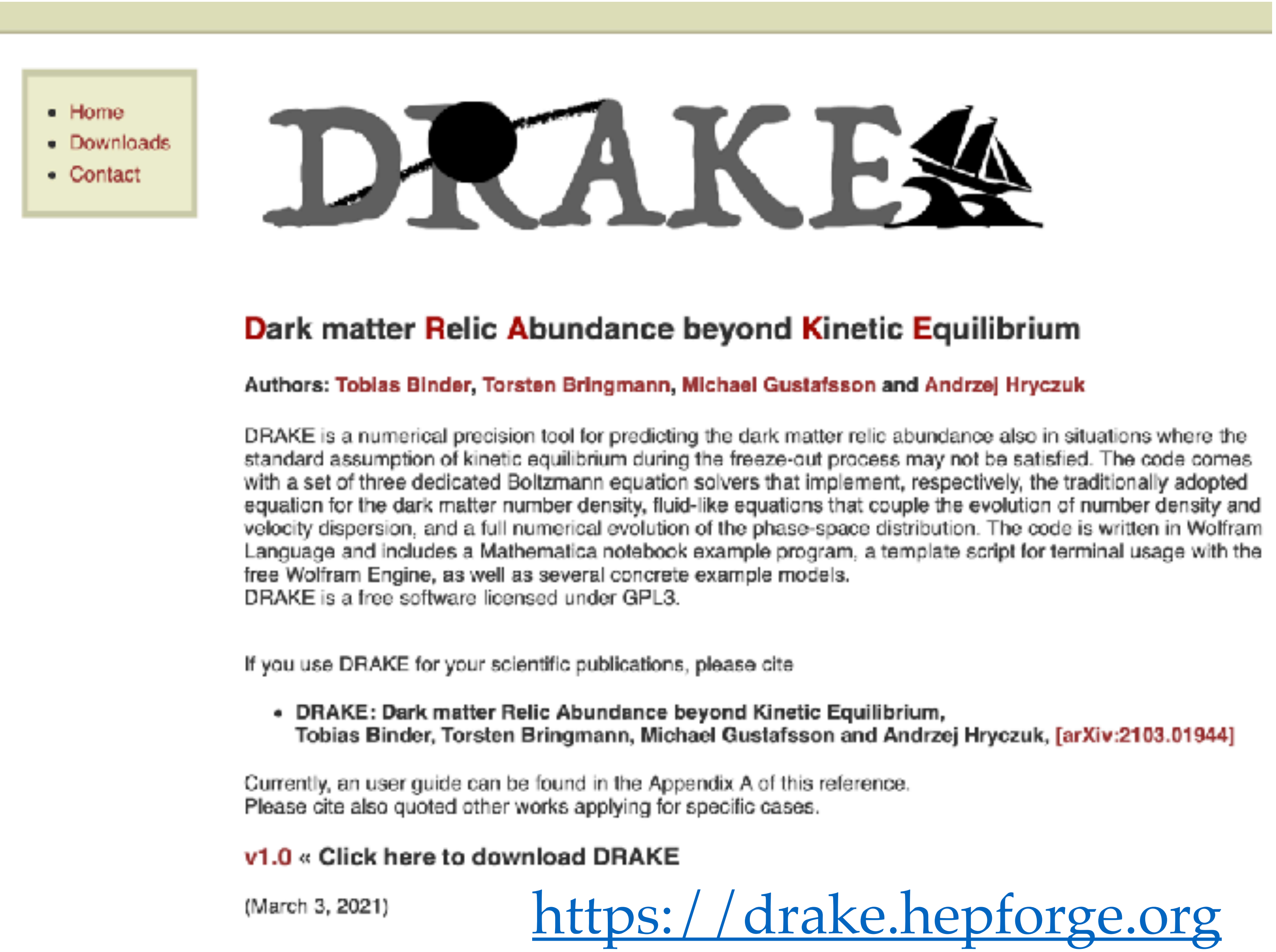
partially analytic/much easier numerically
manifestly captures all of the relevant physics

finite range of validity
no insight on the distribution

NEW TOOL!

T. Binder, T. Bringmann,
M. Gustafsson & A.H. 2103.01944

GOING BEYOND THE STANDARD APPROACH



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DRAKE

Dark matter Relic Abundance beyond Kinetic Equilibrium

Authors: Tobias Binder, Torsten Bringmann, Michael Gustafsson and Andrzej Hryczuk

DRAKE is a numerical precision tool for predicting the dark matter relic abundance also in situations where the standard assumption of kinetic equilibrium during the freeze-out process may not be satisfied. The code comes with a set of three dedicated Boltzmann equation solvers that implement, respectively, the traditionally adopted equation for the dark matter number density, fluid-like equations that couple the evolution of number density and velocity dispersion, and a full numerical evolution of the phase-space distribution. The code is written in Wolfram Language and includes a Mathematica notebook example program, a template script for terminal usage with the free Wolfram Engine, as well as several concrete example models.
DRAKE is a free software licensed under GPL3.

If you use DRAKE for your scientific publications, please cite

- **DRAKE: Dark matter Relic Abundance beyond Kinetic Equilibrium,**
  Tobias Binder, Torsten Bringmann, Michael Gustafsson and Andrzej Hryczuk, [arXiv:2103.01944]

Currently, an user guide can be found in the Appendix A of this reference.
Please cite also quoted other works applying for specific cases.

v1.0 « Click here to download DRAKE

(March 3, 2021)

https://drake.hepforge.org

Applications:

DM relic density for
any (user defined) model*

Interplay between chemical and
kinetic decoupling

Prediction for the DM
phase space distribution

Late kinetic decoupling
and impact on cosmology

see e.g., 1202.5456

…

(only) prerequisite:
Wolfram Language (or *Mathematica*)

*at the moment for a single DM species and w/o co-annihlations… but stay tuned for extensions!

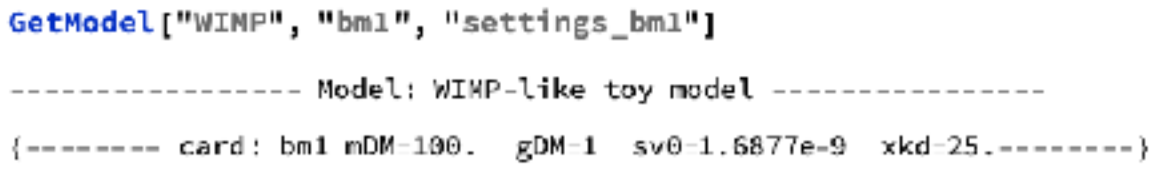
DRAKE
Dark matter Relic Abundance beyond Kinetic Equilibrium
https://drake.hepforge.org

SNAPSHOTS FROM AN EXAMPLE NOTEBOOK

1. Load DRAKE

```
Needs["DRAKE`"]
```

2. Initialize model



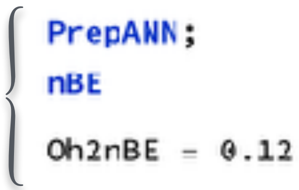
```
GetModel["WIMP", "bm1", "settings_bm1"]

----------------- Model: WIMP-like toy model ----------------

{-------- card: bm1 mDM=100.  gDM=1  sv0=1.6877e-9  xkd=25.--------}
```

3. Run

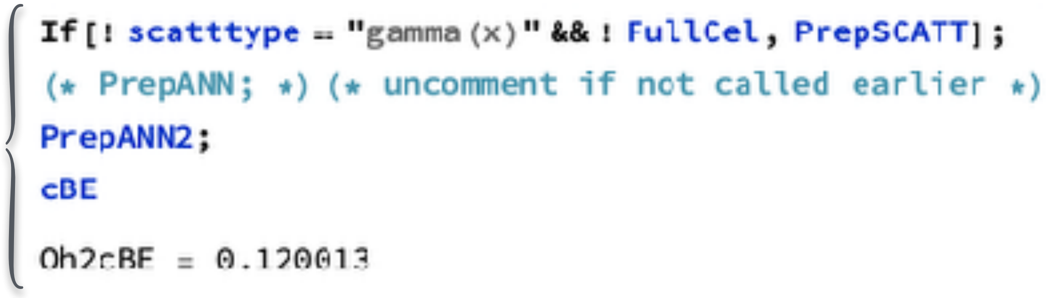
nBE



```
PrepANN;
nBE

Oh2nBE = 0.12
```

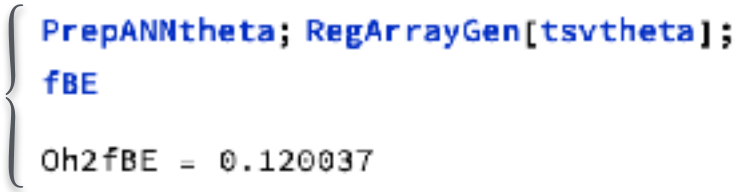
cBE



```
If[! scatttype == "gamma(x)" && ! FullCel, PrepSCATT];
(* PrepANN; *) (* uncomment if not called earlier *)
PrepANN2;
cBE

Oh2cBE = 0.120013
```

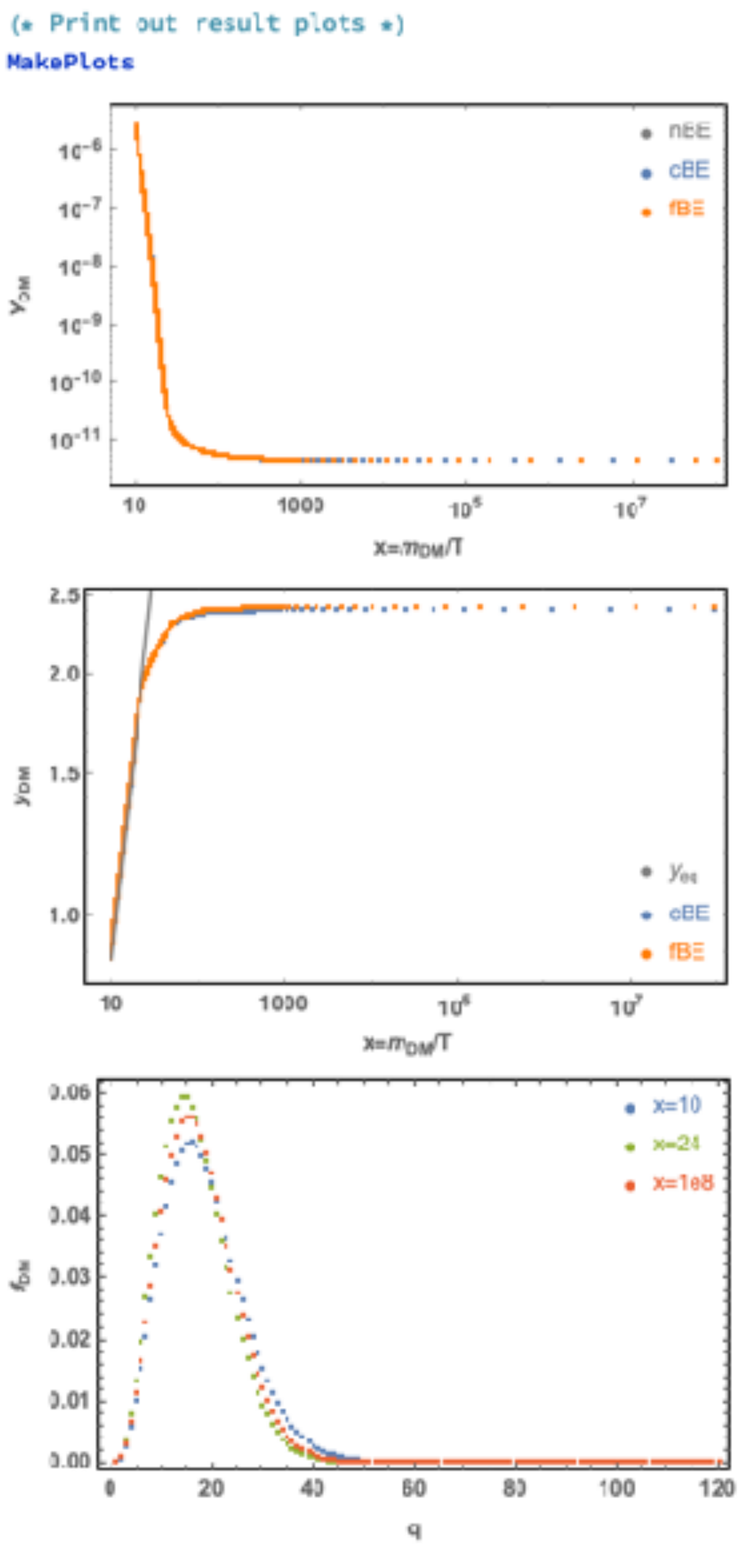
fBE



```
PrepANNtheta; RegArrayGen[tsvtheta];
fBE

Oh2fBE = 0.120037
```

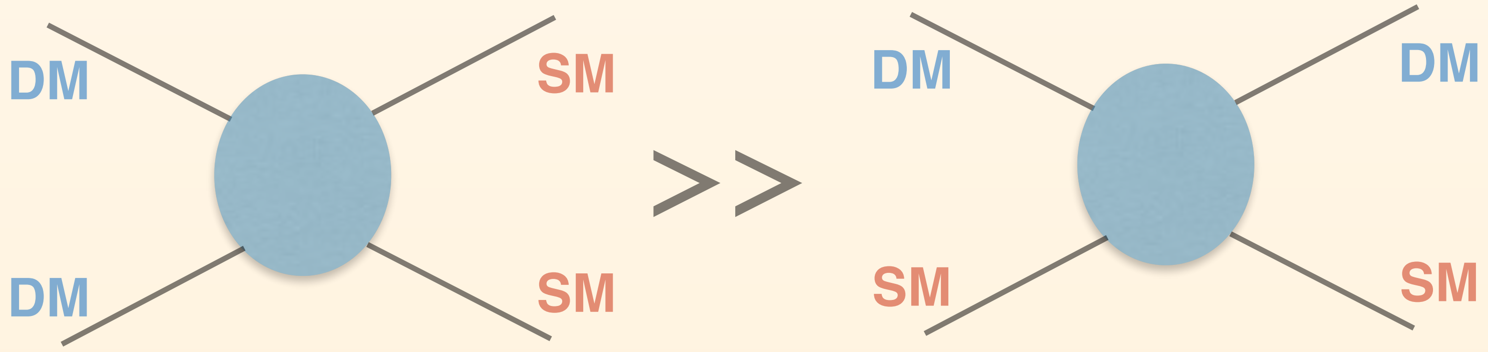
4. Print plots



```
(* Print out result plots *)
MakePlots
```

EXAMPLE A:
SCALAR SINGLET DM

A)



EXAMPLE A

SCALAR SINGLET DM

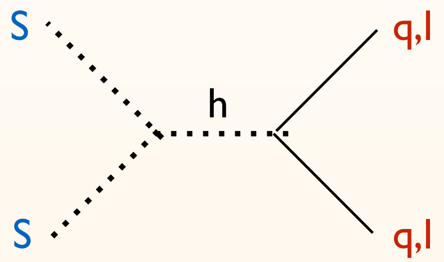
To the SM Lagrangian add one singlet scalar field *S* with interactions with the Higgs:

$$\mathcal{L}_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}\mu_S^2 S^2 - \frac{1}{2}\lambda_s S^2 |H|^2$$

$$m_s = \sqrt{\mu_S^2 + \frac{1}{2}\lambda_s v_0^2}$$

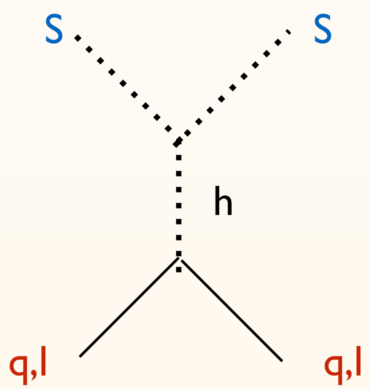
Annihilation processes:

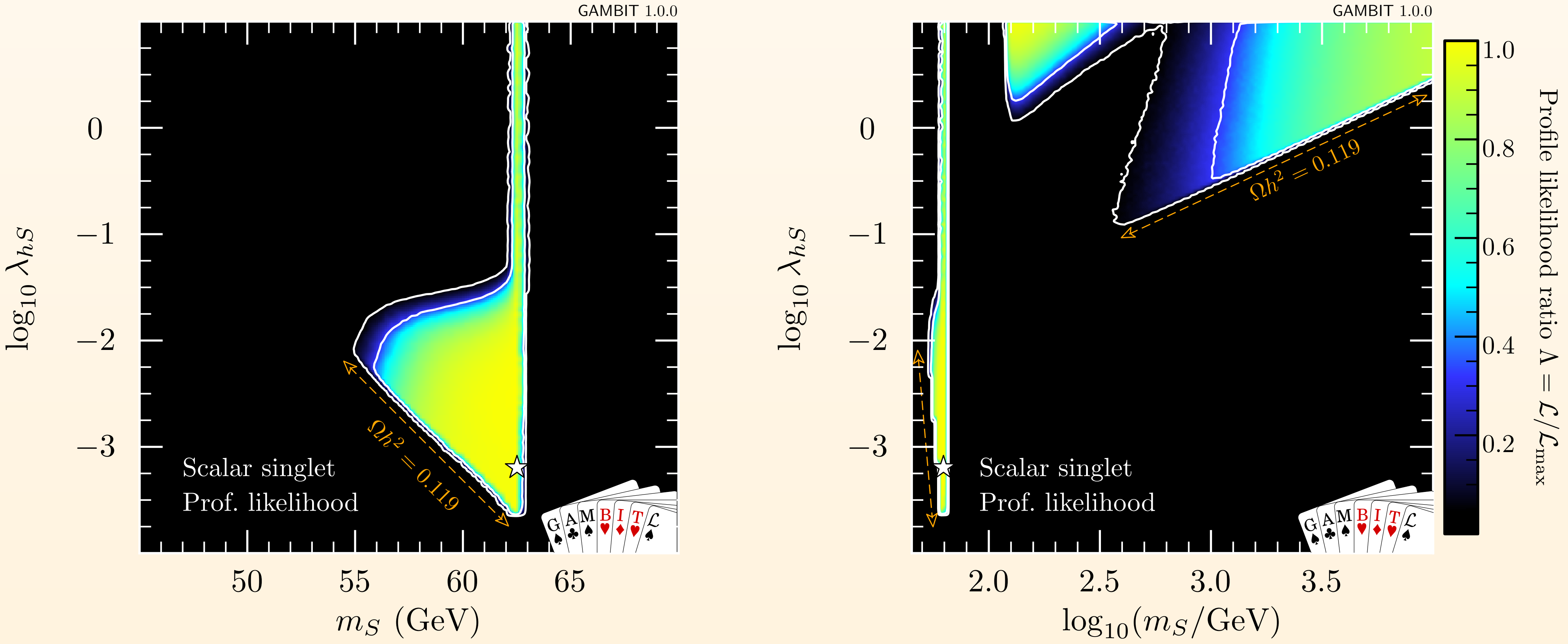
resonant



El. scattering processes:

non-resonant



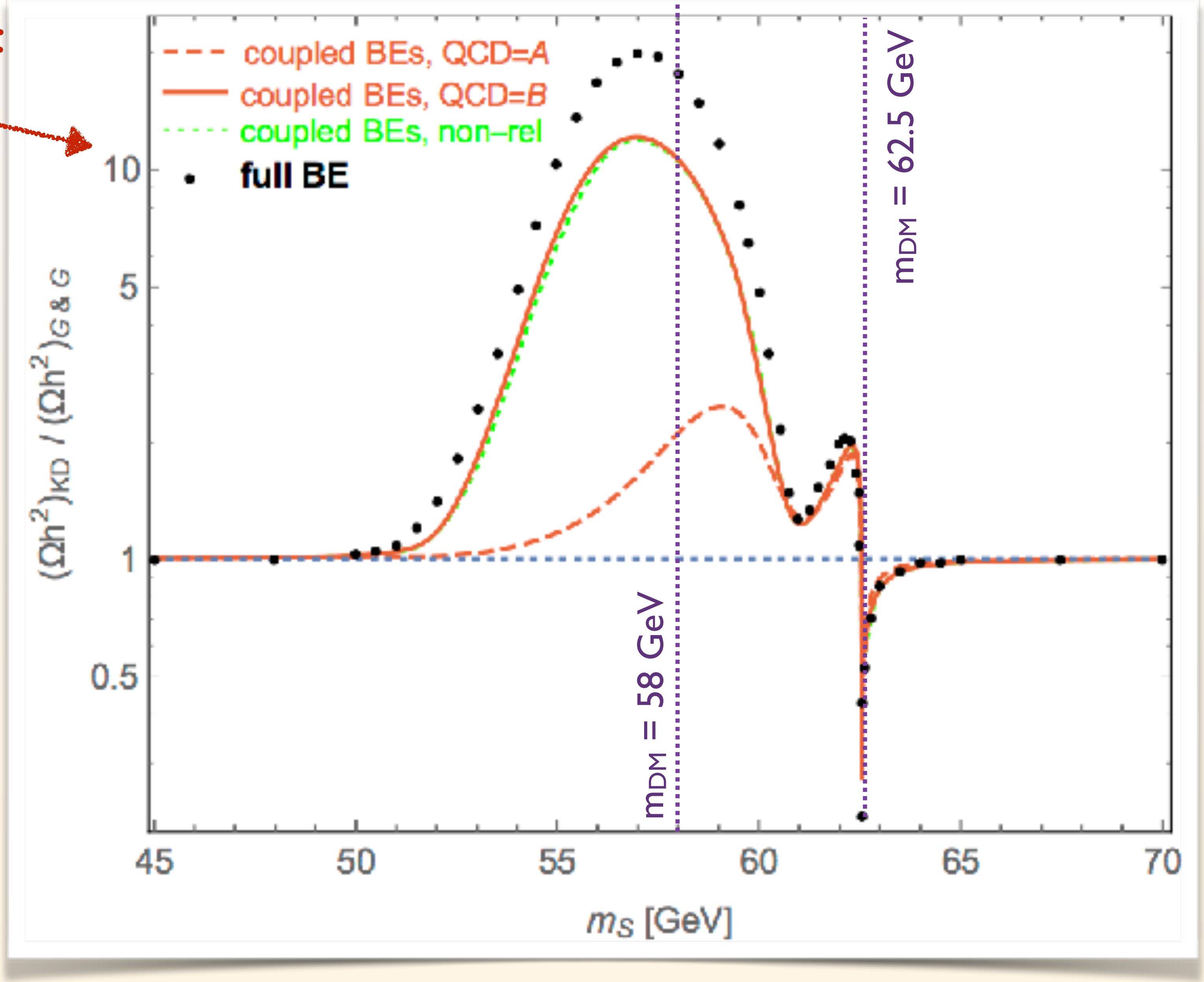


GAMBIT collaboration
1705.07931

RESULTS

EFFECT ON THE Ωh^2

effect on relic density:
up to O(~10)



T. Binder, T. Bringmann, M. Gustafsson & A.H. 1706.07433

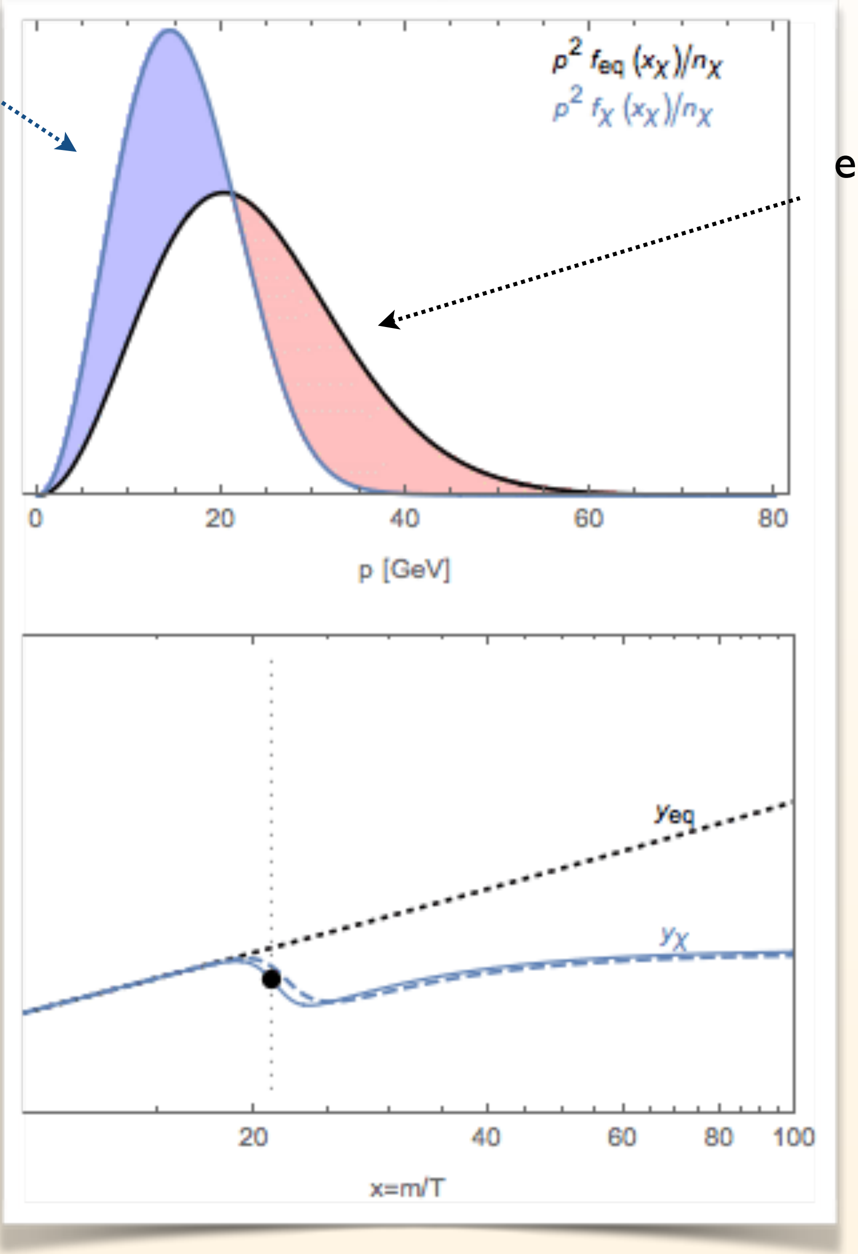
[… Freeze-out at few GeV ⟶ what is the abundance of heavy quarks in QCD plasma?

two scenarios:
QCD = A - all quarks are free and present in the plasma down to T_c =154 MeV
QCD = B - only light quarks contribute to scattering and only down to $4T_c$ …]

FULL PHASE-SPACE EVOLUTION

m_{DM} = 58 GeV

blue - full solution for f_{DM} at T_{DM}

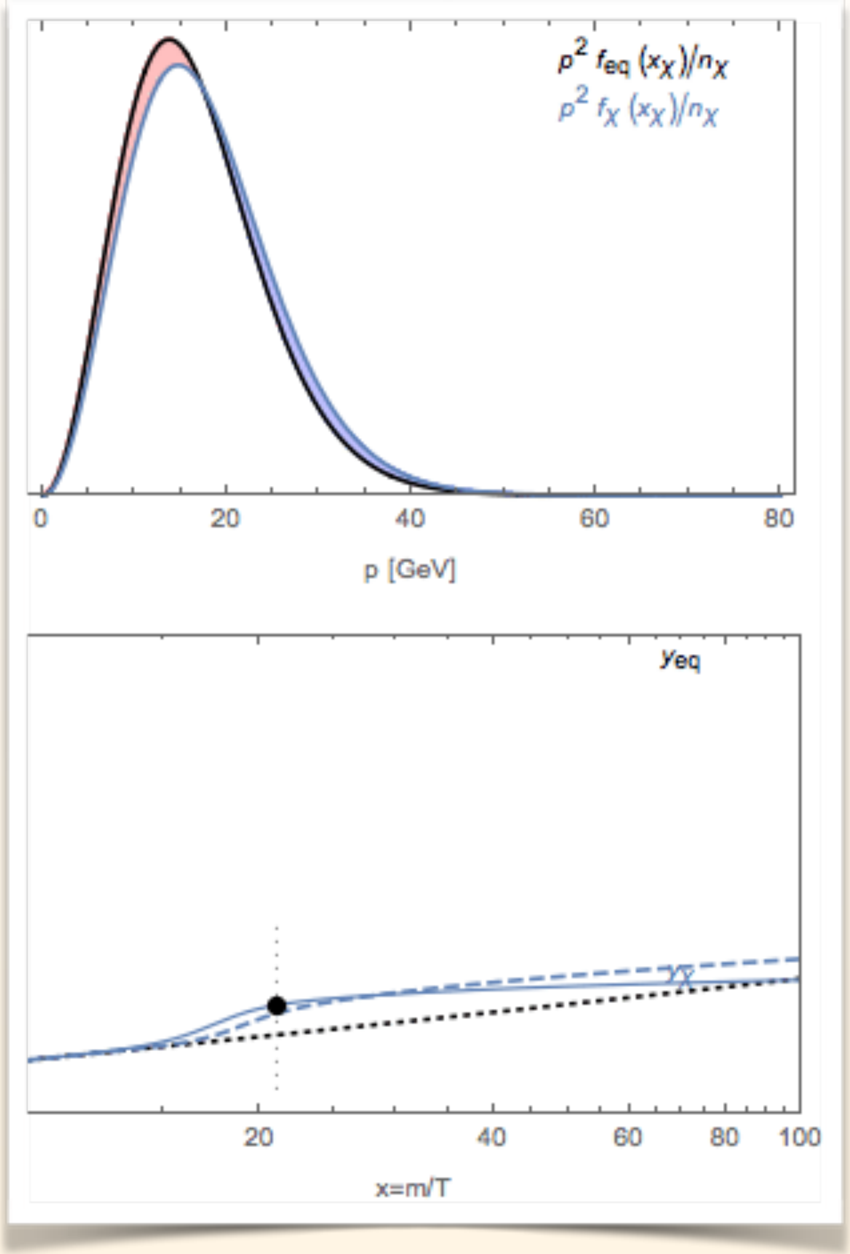


black - equilibrium at T_{DM}

significant deviation from equilibrium shape already around freeze-out

⟶ effect on relic density largest, both from different T and f_{DM}

m_{DM} = 62.5 GeV



large deviations at later times, around freeze-out not far from eq. shape

⟶ effect on relic density ~only from different T

cBE vs. fBE

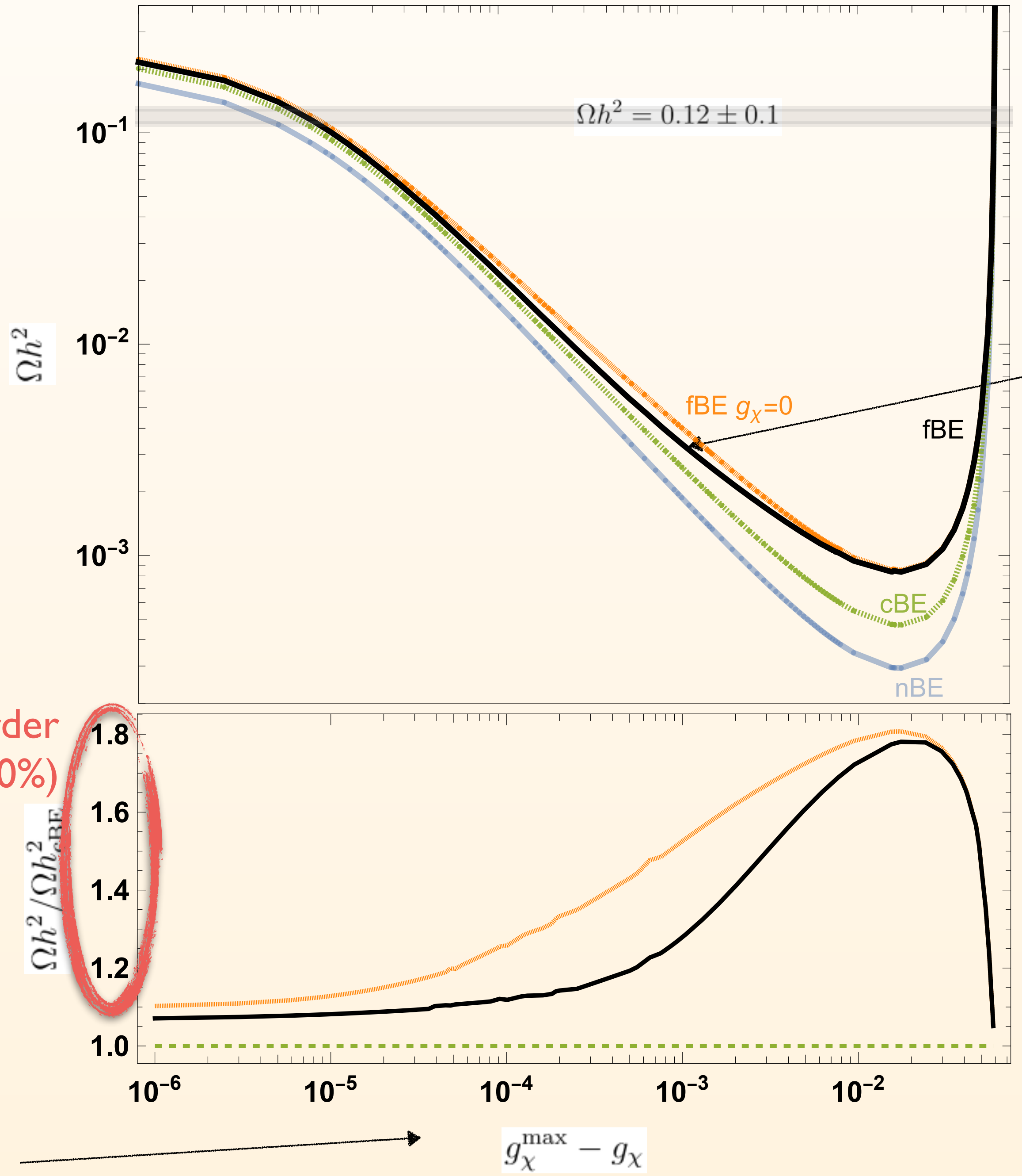
WHICH IS MORE ACCURATE?! **A.H. & M. Laletin** 2204.07078

They correspond to the opposite limits of self-interaction strengths:

very efficient - **cBE**

inefficient - f**BE**

Which limit is closer to reality depends on the model, but it seems that fBE is typically more accurate, unless self-scattering is tuned up, e.g:



black line gives the result including self-scattering processes! (being between pure fBE and cBE)

difference of order O(10%)

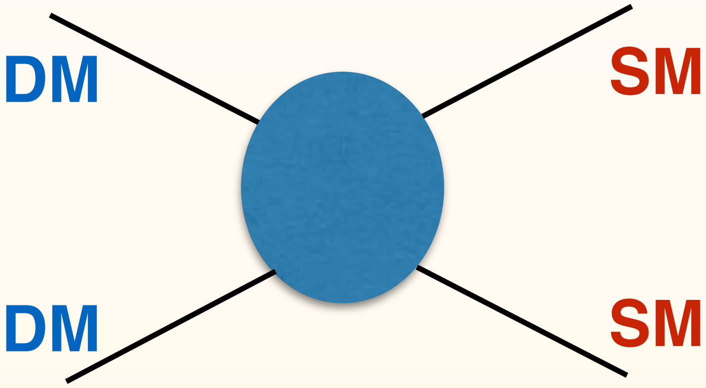
coupling to the mediator; governs self-scatterings

CHAPTER III:

MULTI-COMPONENT DARK MATTER

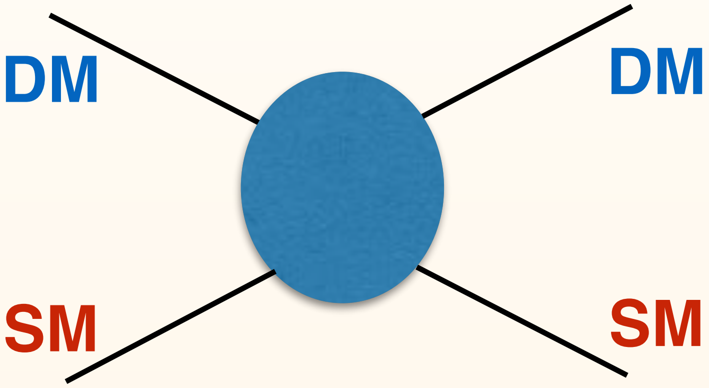
WHAT IF A NON-MINIMAL SCENARIO?

In a minimal WIMP case only two types of processes are relevant:



annihilation

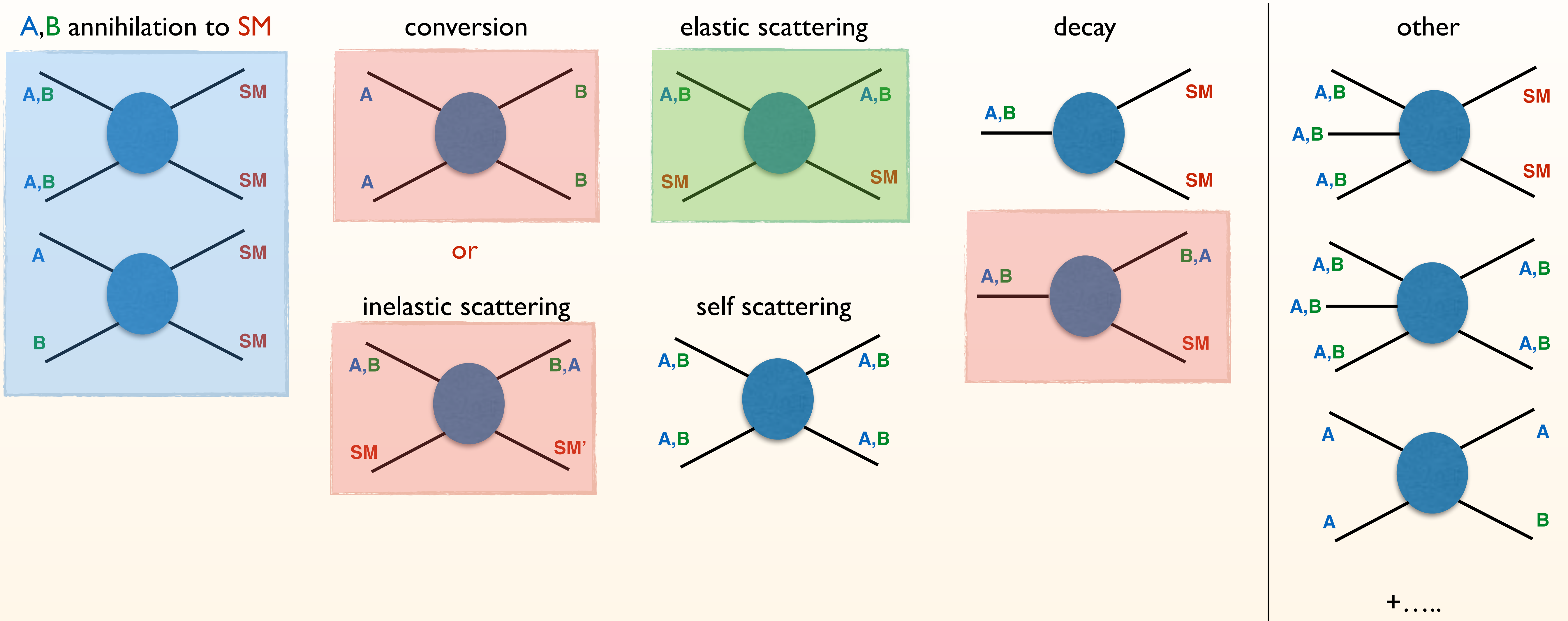
drives number density evolution



(elastic) scattering

keeping the distribution to be
in local thermal eq.

WHAT IF A NON-MINIMAL SCENARIO?



↳ typically forbidden by symmetry

Co-annihilation ⟶ due to efficient conversion processes one can trace only number density of sum of the states with shared conserved quantum number using weighted annihilation cross section

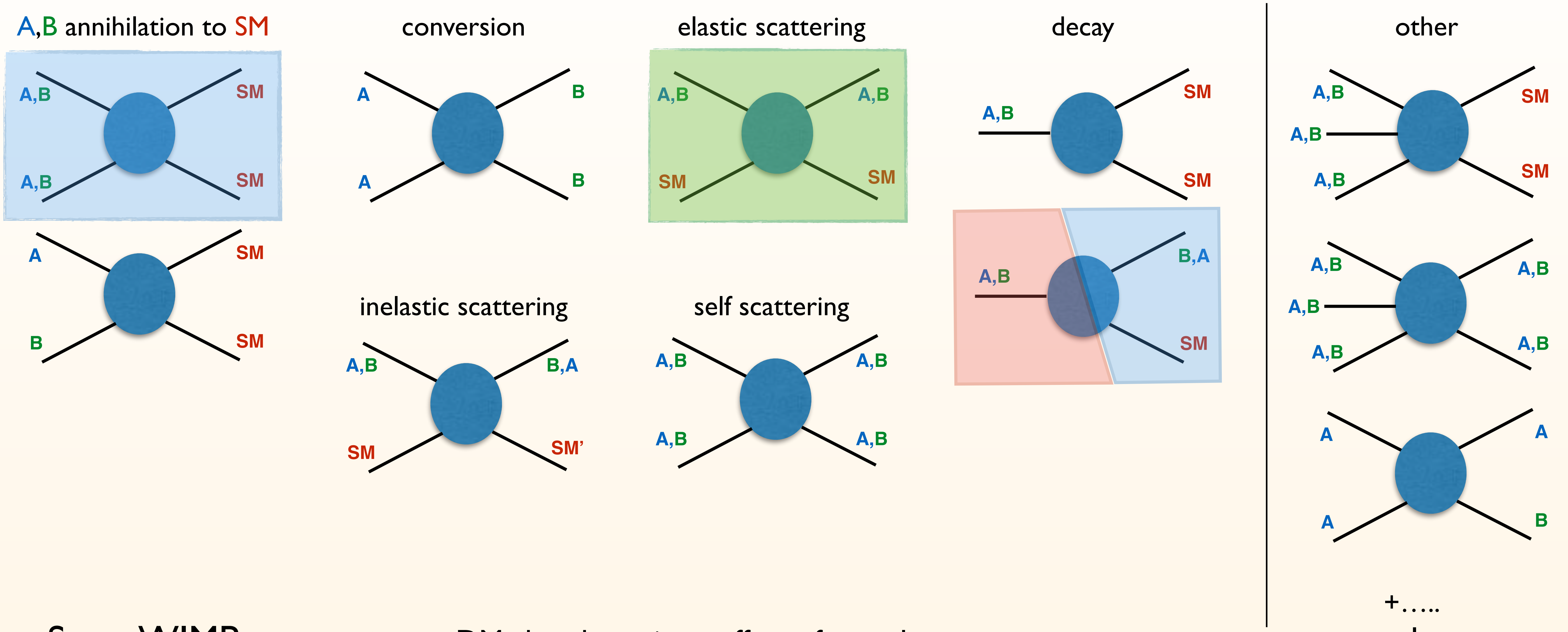
Griest, Seckel '91

🟦 what one calculates

🟥 „defines" the mechanism (necessary for it to work)

🟩 assumed in calculation (but not necessary)

WHAT IF A NON-MINIMAL SCENARIO?



+…..

↳ typically forbidden by symmetry

SuperWIMP → DM abundance is an effect of complete decay of heavier state which freezes-out as standard WIMP

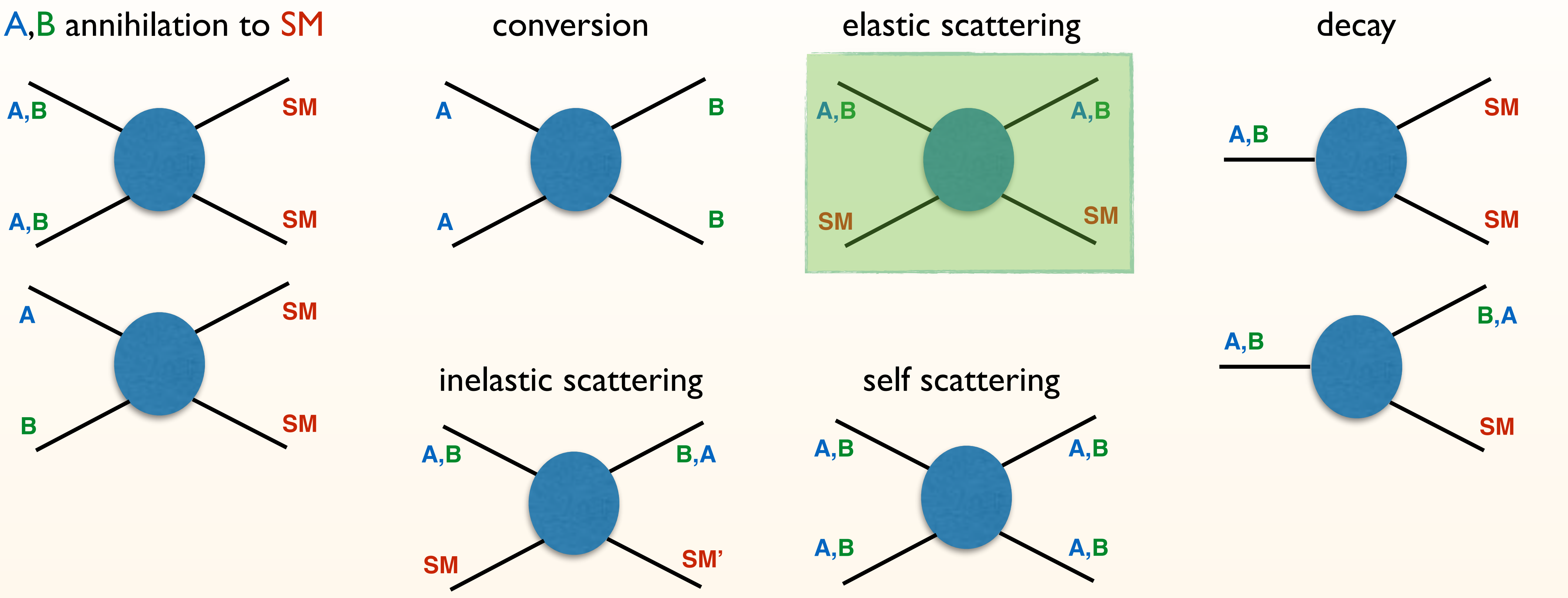
Feng, Rajaraman, Takayama '03

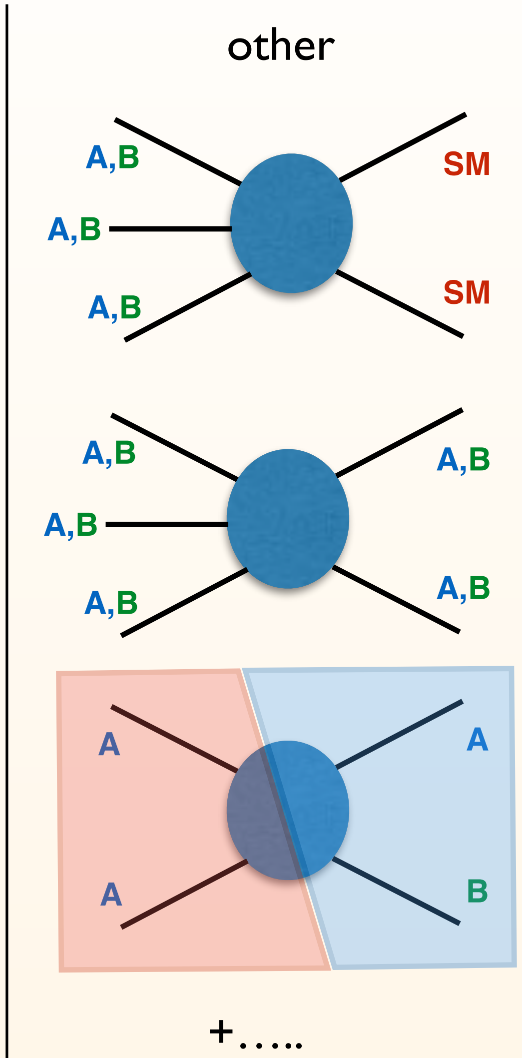
🟦 what one calculates

🟥 „defines" the mechanism (necessary for it to work)

🟩 assumed in calculation (but not necessary)

WHAT IF A NON-MINIMAL SCENARIO?





Semi-annihilation ⟶ new type of annihilation precess that can dominate the freeze-out dynamics; occurs when new „flavour" or „baryon" structure in dark sector

D'Eramo, Thaler '10

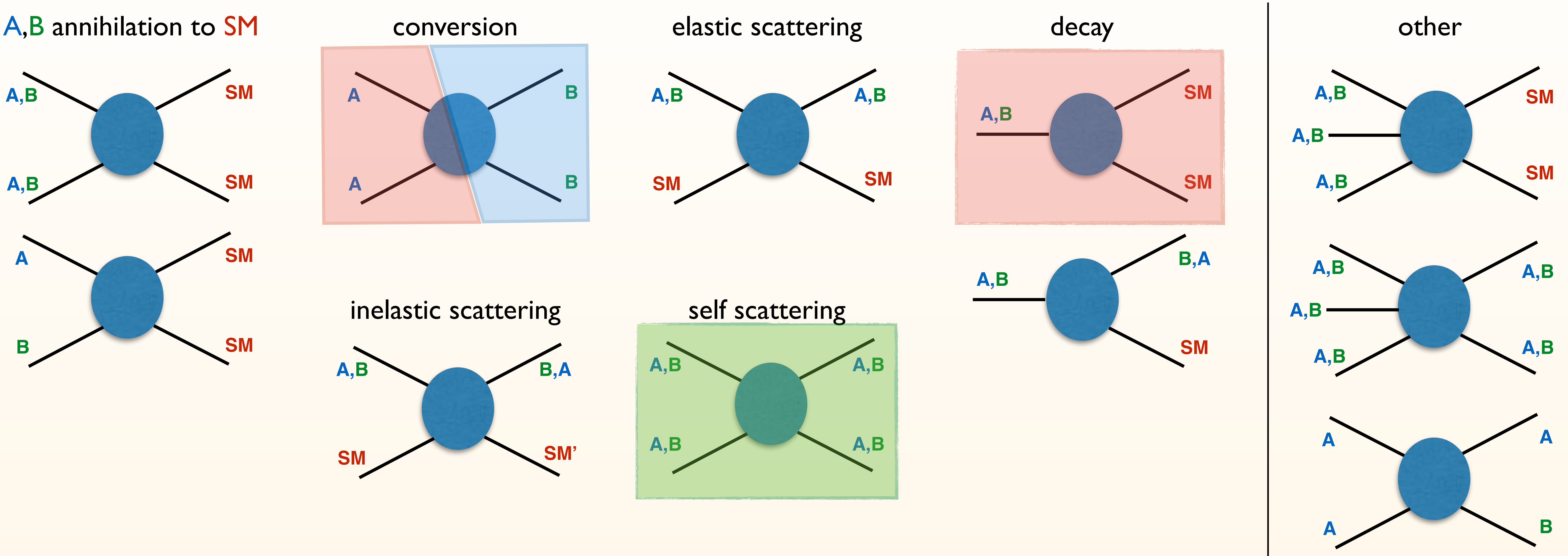
↳ typically forbidden by symmetry

🟦 what one calculates

🟥 „defines" the mechanism (necessary for it to work)

🟩 assumed in calculation (but not necessary)

WHAT IF A NON-MINIMAL SCENARIO?



+…..

↳ typically forbidden by symmetry

Co-decaying → dark sector decouples when relativistic but then one of its states decays and this affect DM density as long as conversions are efficient

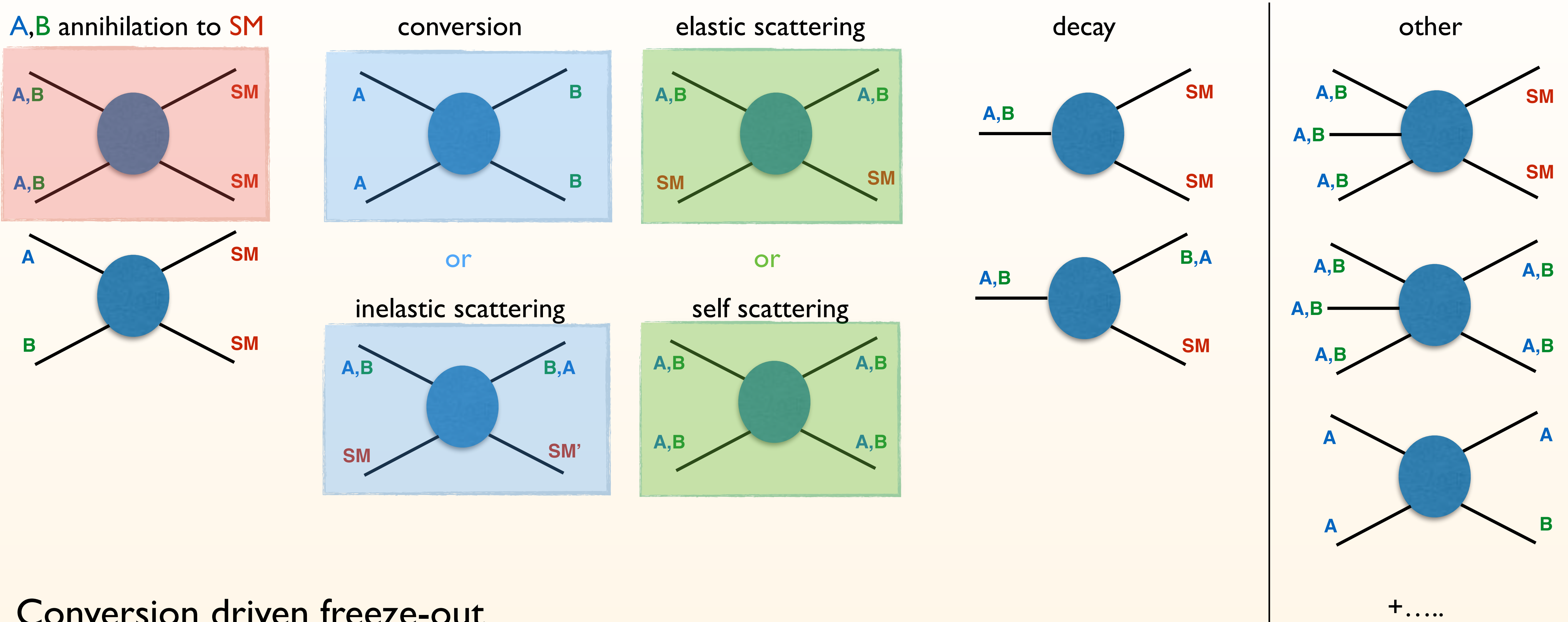
Dror, Kuflik, Ng ’16

🟦 what one calculates

🟥 „defines” the mechanism (necessary for it to work)

🟩 assumed in calculation (but not necessary)

WHAT IF A NON-MINIMAL SCENARIO?



A,B annihilation to SM

conversion

or

inelastic scattering

elastic scattering

or

self scattering

decay

other

+…..

↳ typically forbidden by symmetry

Conversion driven freeze-out

Garny, Heisig, Lulf, Vogl '17

Co-scattering

D'Agnolo, Pappadopulo, Ruderman '17

→

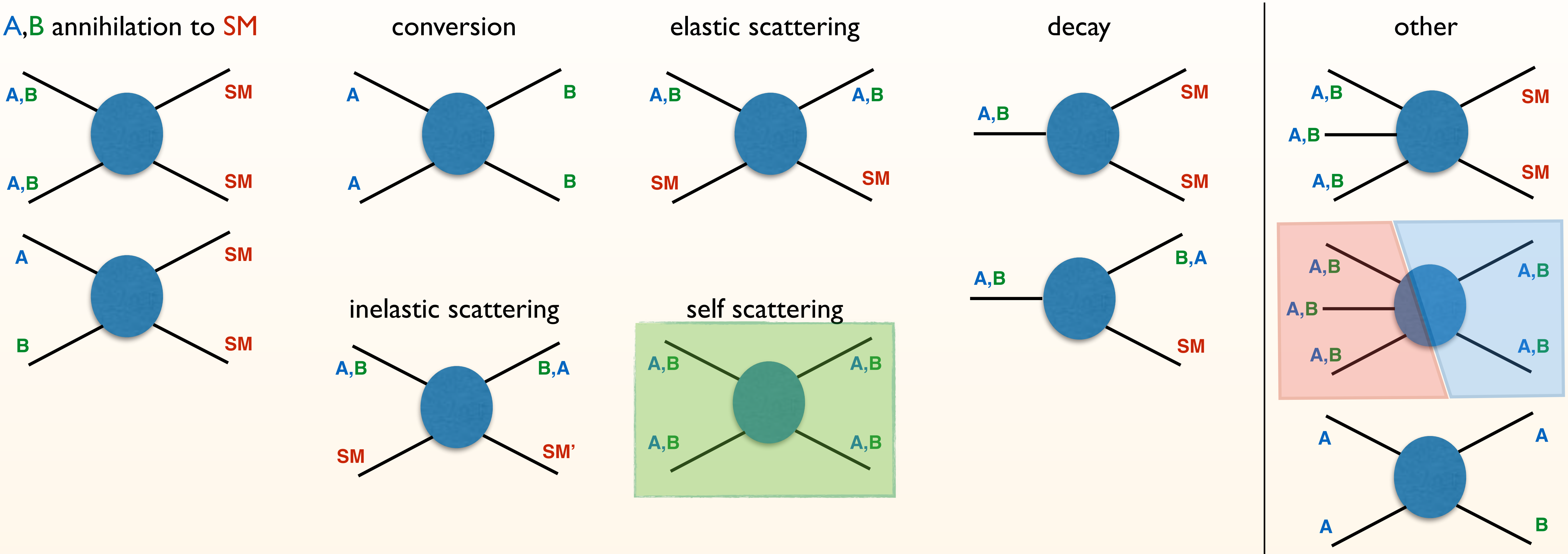
one of the dark sector states annihilates very efficiently, but conversions stop being efficient which blocks co-annihilation

🟦 what one calculates

🟥 „defines" the mechanism (necessary for it to work)

🟩 assumed in calculation (but not necessary)

WHAT IF A NON-MINIMAL SCENARIO?


A,B annihilation to SM

conversion

elastic scattering

decay

other

inelastic scattering

self scattering

+…..

↳ typically forbidden by symmetry

Cannibalization → secluded dark sector, with efficient 3-2 annihilation leading to DM zero chemical potential and keeping DM at much higher temperature than SM plasma

Kuflik et al. '15

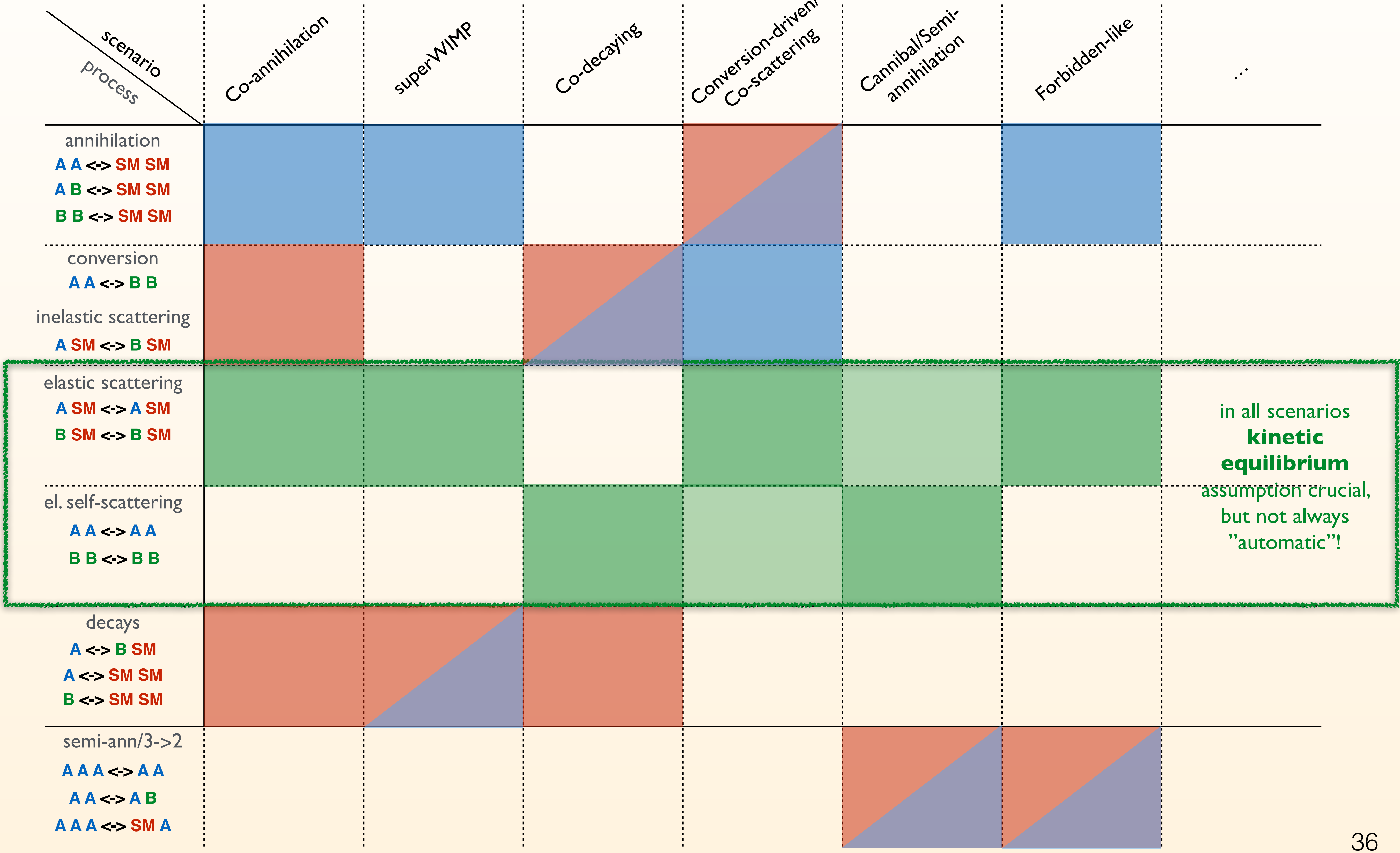
🟦 what one calculates

🟥 „defines" the mechanism (necessary for it to work)

🟩 assumed in calculation (but not necessary)

WHAT IF A NON-MINIMAL SCENARIO?

Example: assume two particles in the dark sector: A and B



scenario / process	Co-annihilation	superWIMP	Co-decaying	Conversion-driven/ Co-scattering	Cannibal/Semi-annihilation	Forbidden-like	…
annihilation A A <-> SM SM A B <-> SM SM B B <-> SM SM	🟦	🟦		🟥/🟪		🟦	
conversion A A <-> B B inelastic scattering A SM <-> B SM	🟥		🟥/🟪	🟦			
elastic scattering A SM <-> A SM B SM <-> B SM	🟩	🟩		🟩	(🟩)	🟩	
el. self-scattering A A <-> A A B B <-> B B			🟩	(🟩)	🟩		
decays A <-> B SM A <-> SM SM B <-> SM SM	🟥	🟥/🟪	🟥				
semi-ann/3->2 A A A <-> A A A A <-> A B A A A <-> SM A					🟥/🟪	🟥/🟪	

in all scenarios **kinetic equilibrium** assumption crucial, but not always "automatic"!

EXAMPLE D:

WHEN ADDITIONAL INFLUX OF DM ARRIVES

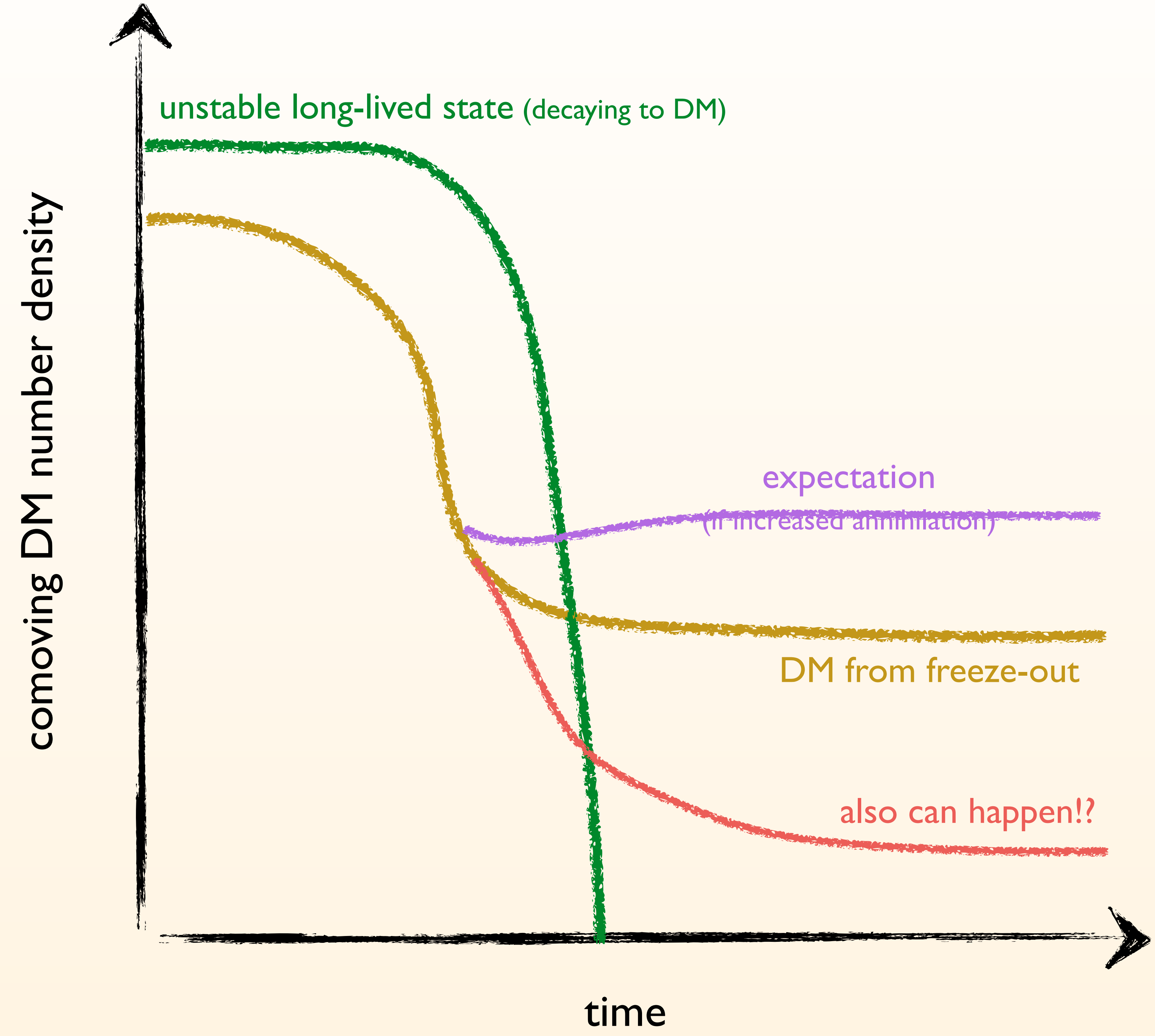
D) Multi-component dark sectors

Sudden injection of more DM particles distorts $f_\chi(p)$

(e.g. from a decay or annihilation of other states)

- this can modify the annihilation rate (if still active)
- how does the thermalization due to elastic scatterings happen?

WEIRD THINGS CAN HAPPEN…

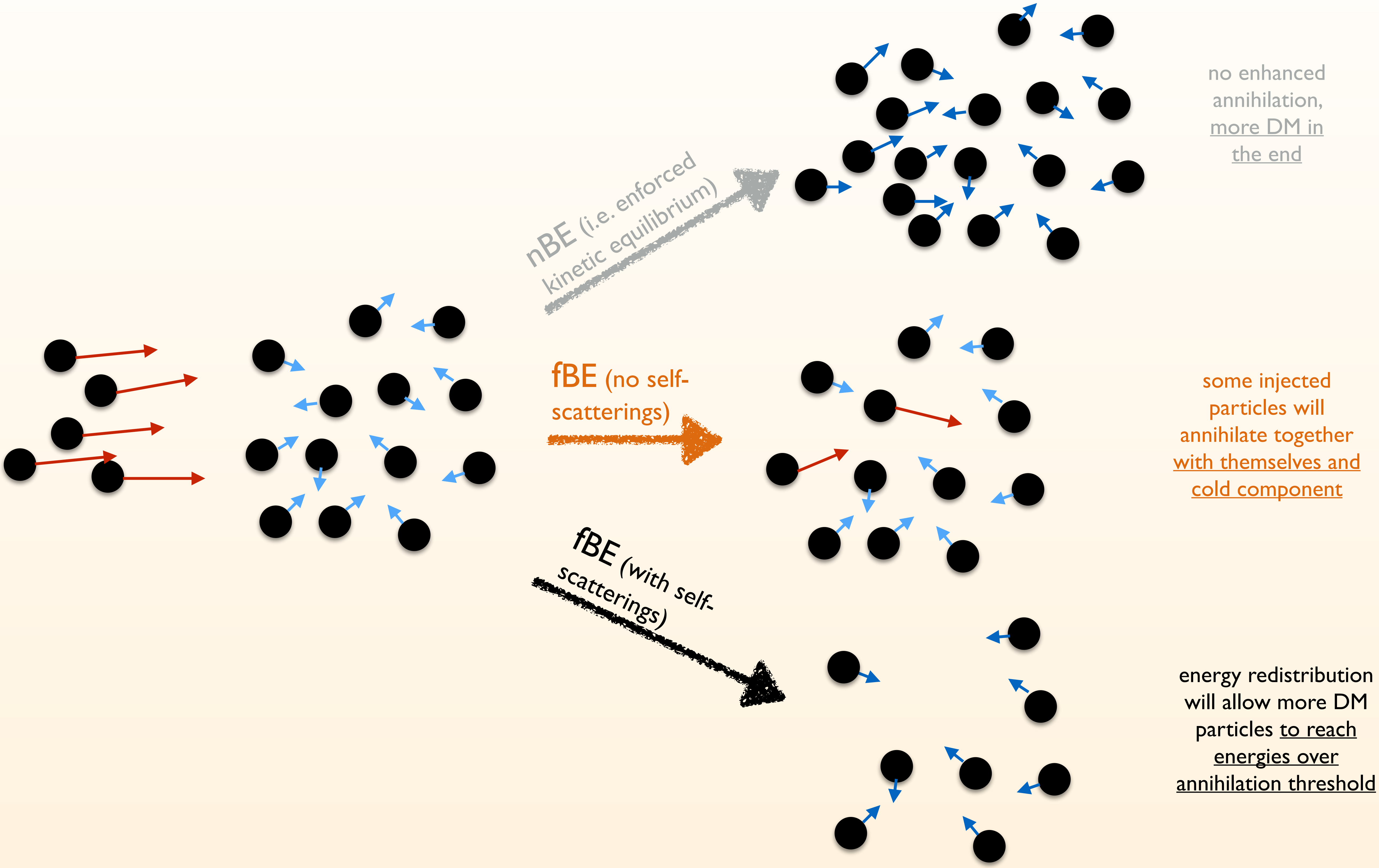


1) DM produced via:

- 1st component from thermal freeze-out
- 2nd component from a decay $\phi \to \bar{\chi}\chi$

2) DM annihilation has a threshold

e.g. $\chi\bar{\chi} \to f\bar{f}$ with $m_\chi \lesssim m_f$



nBE (i.e. enforced kinetic equilibrium)

no enhanced annihilation, more DM in the end

fBE (no self-scatterings)

some injected particles will annihilate together with themselves and cold component

fBE (with self-scatterings)

energy redistribution will allow more DM particles to reach energies over annihilation threshold

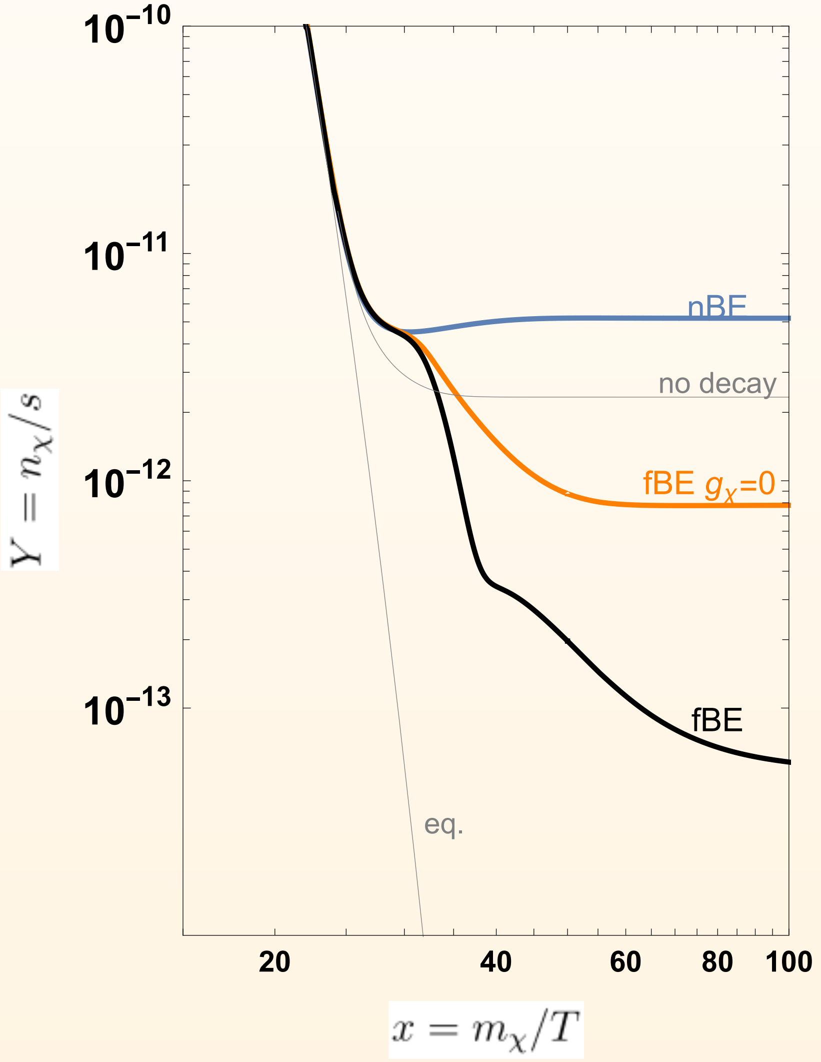
A.H. & M. Laletin 2204.07078

DM produced via:
- 1st component from thermal freeze-out
- 2nd component from a decay $\phi \to \bar{\chi}\chi$

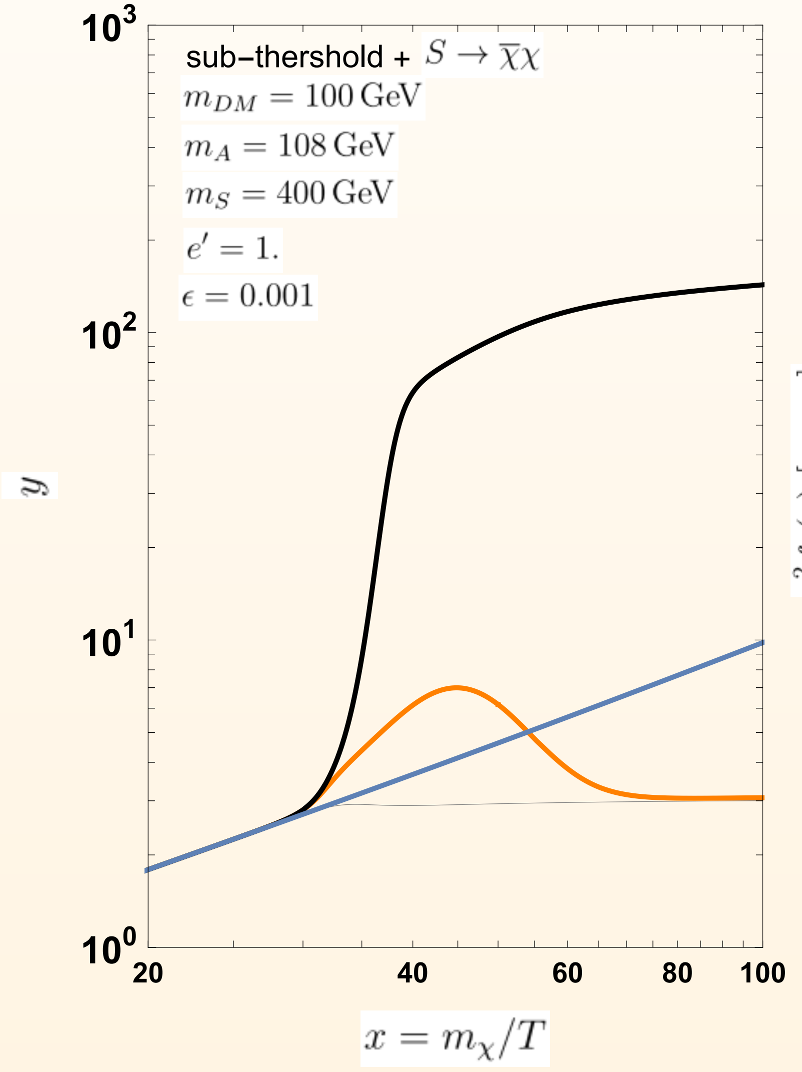
2) DM annihilation has a threshold

e.g. $\chi\bar{\chi} \to f\bar{f}$ with $m_\chi \lesssim m_f$

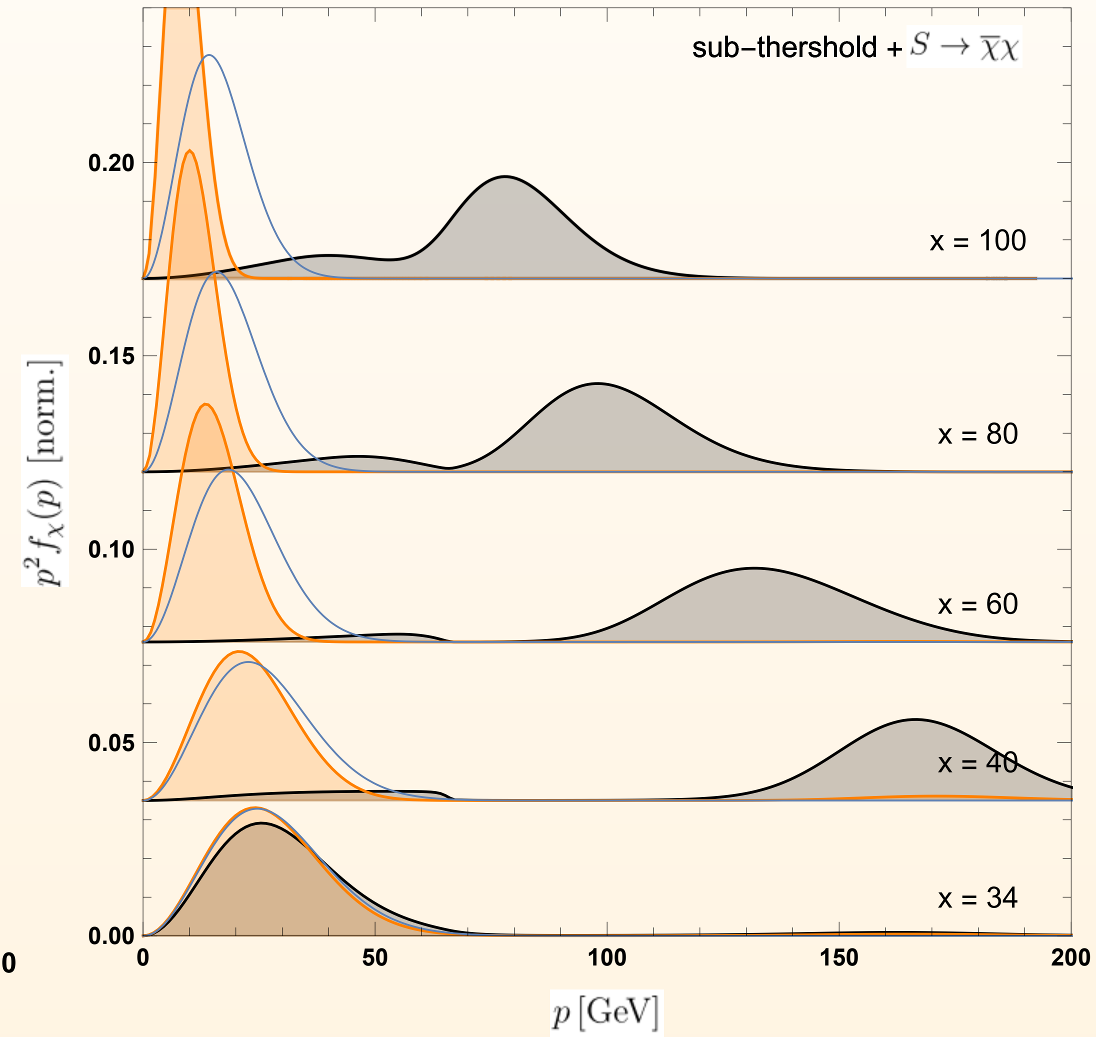
$Y \sim$ number density



$y \sim$ temperature

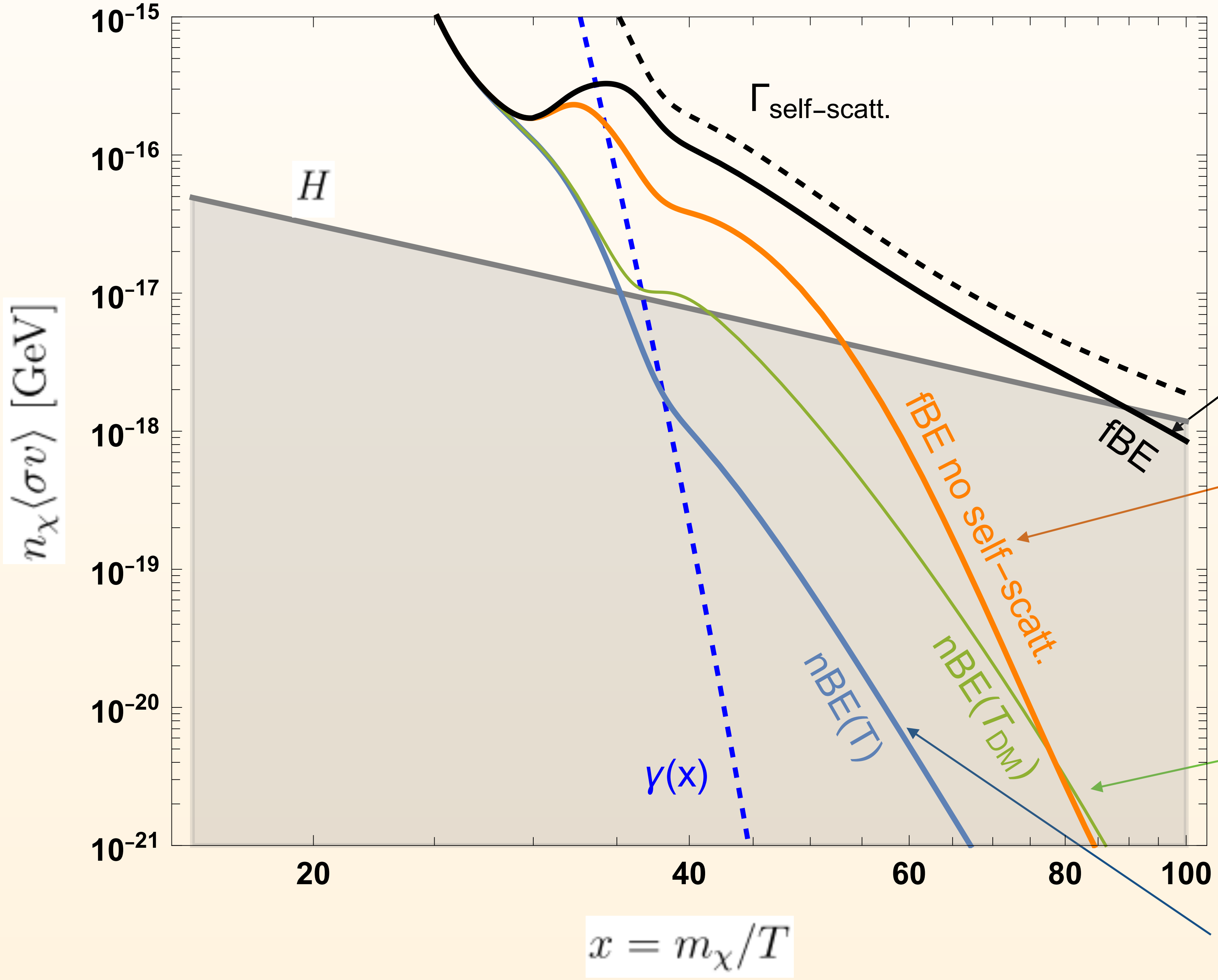


$p^2 f(p) \sim$ momentum distribution



WHY DOES INJECTING MORE DM PARTICLES CAN LEAD TO DECREASE OF THE RELIC ABUNDANCE?

Let's look on the interaction rates for different cases:



full

w/o self-interactions

only number density but at modified T

only number density at SM plasma temperature

CHAPTER IV:
CONCLUSION

TAKEAWAY MESSAGE

When computing relic density of dark matter one needs carefully to check if the standard treatment is sufficient for the case at hand

”Everything should be made as simple as possible, but no simpler.”

attributed to* **Albert Einstein**

*The published quote reads:
”It can scarcely be denied that the supreme goal of all theory is to make the irreducible basic elements as simple and as few as possible without having to surrender the adequate representation of a single datum of experience.”
„On the Method of Theoretical Physics" ,The Herbert Spencer Lecture, delivered at Oxford (10 June 1933); also published in *Philosophy of Science*, Vol. 1, No. 2 (April 1934), pp. 163-169., p. 165