NON-STANDARD DARK MATTER FREEZE-OUT

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Review Part:

a personal selection of new interesting ideas in the topic

Results Part:

A.H. & M. Laletin 2204.07078

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

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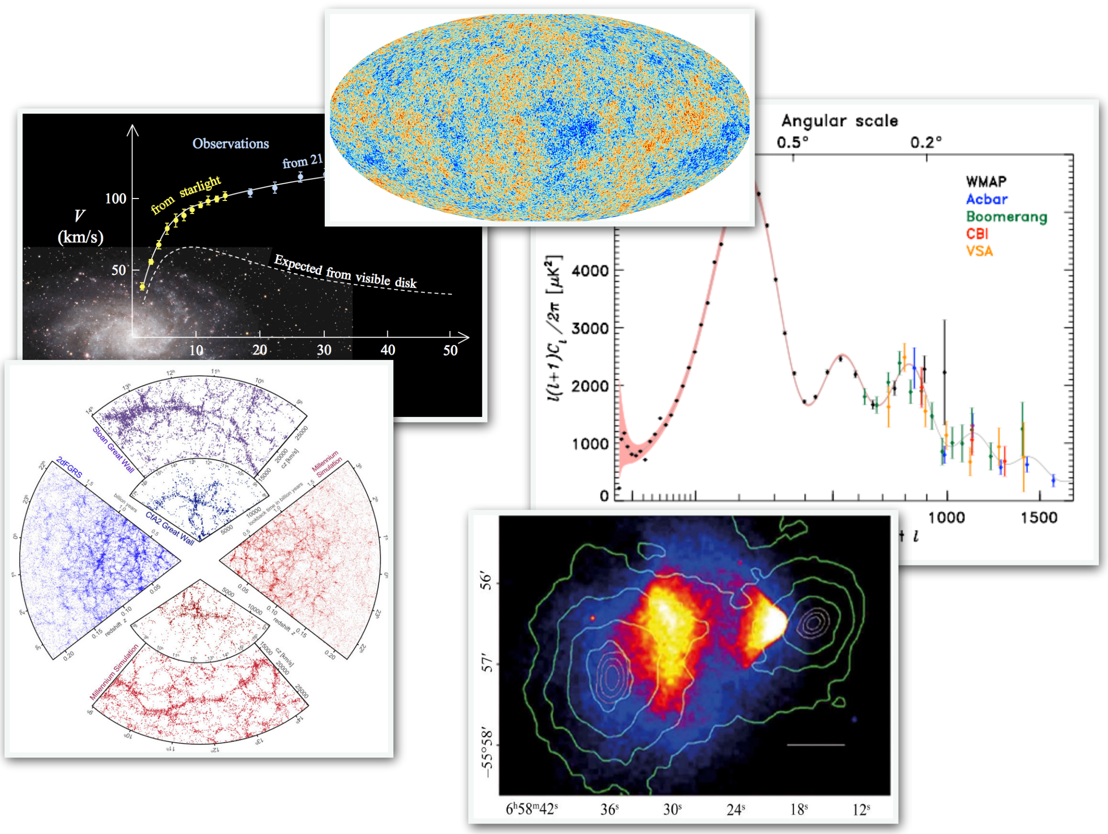
Dark Matter origin

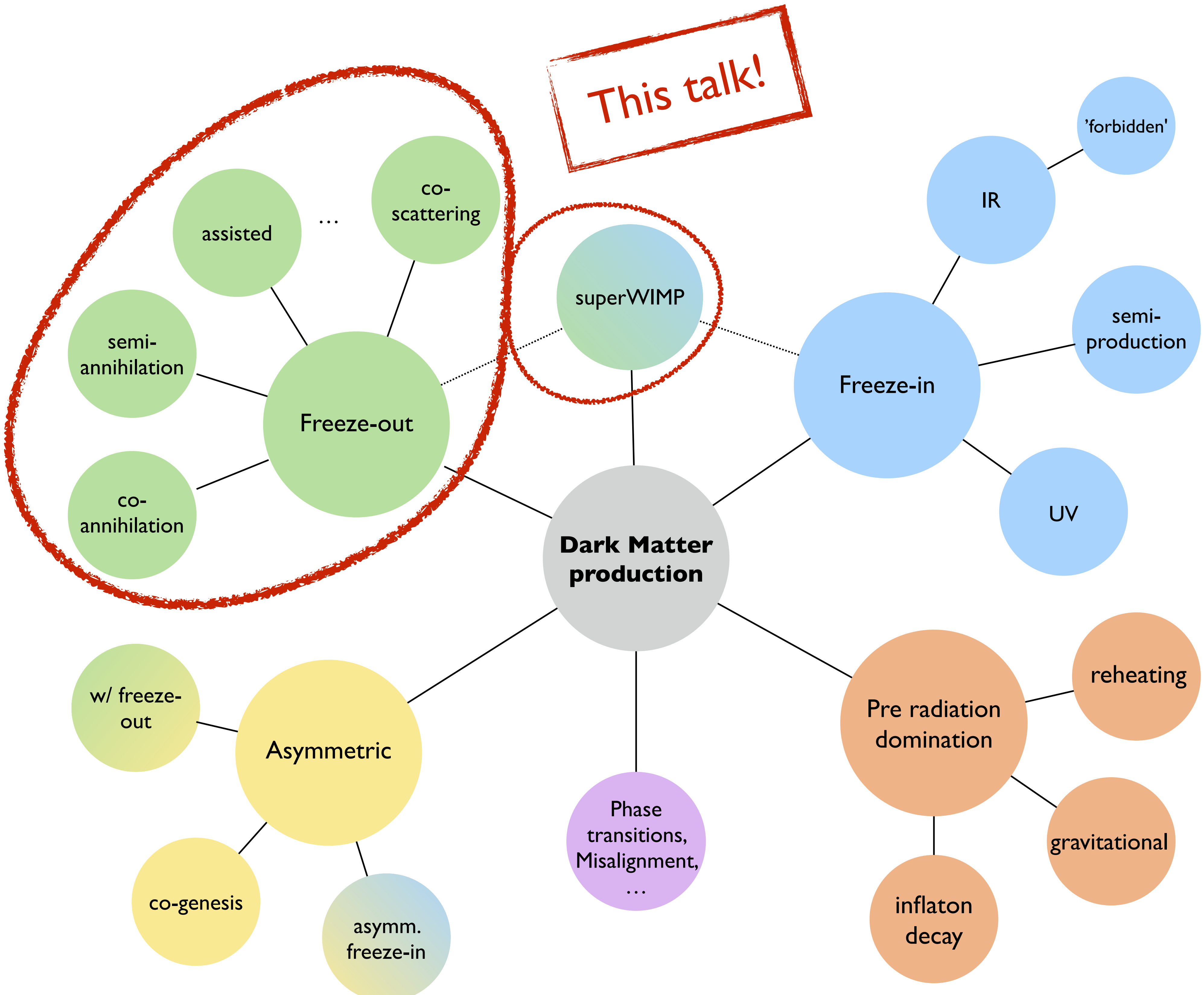


Evidence on all scales!

Any successful theory must explain the origin of DM, i.e. provide a mechanism for its production with the abundance in agreement with observations

There are, of course, quite a few mechanisms known in the literature…

DARK MATTER ORIGIN



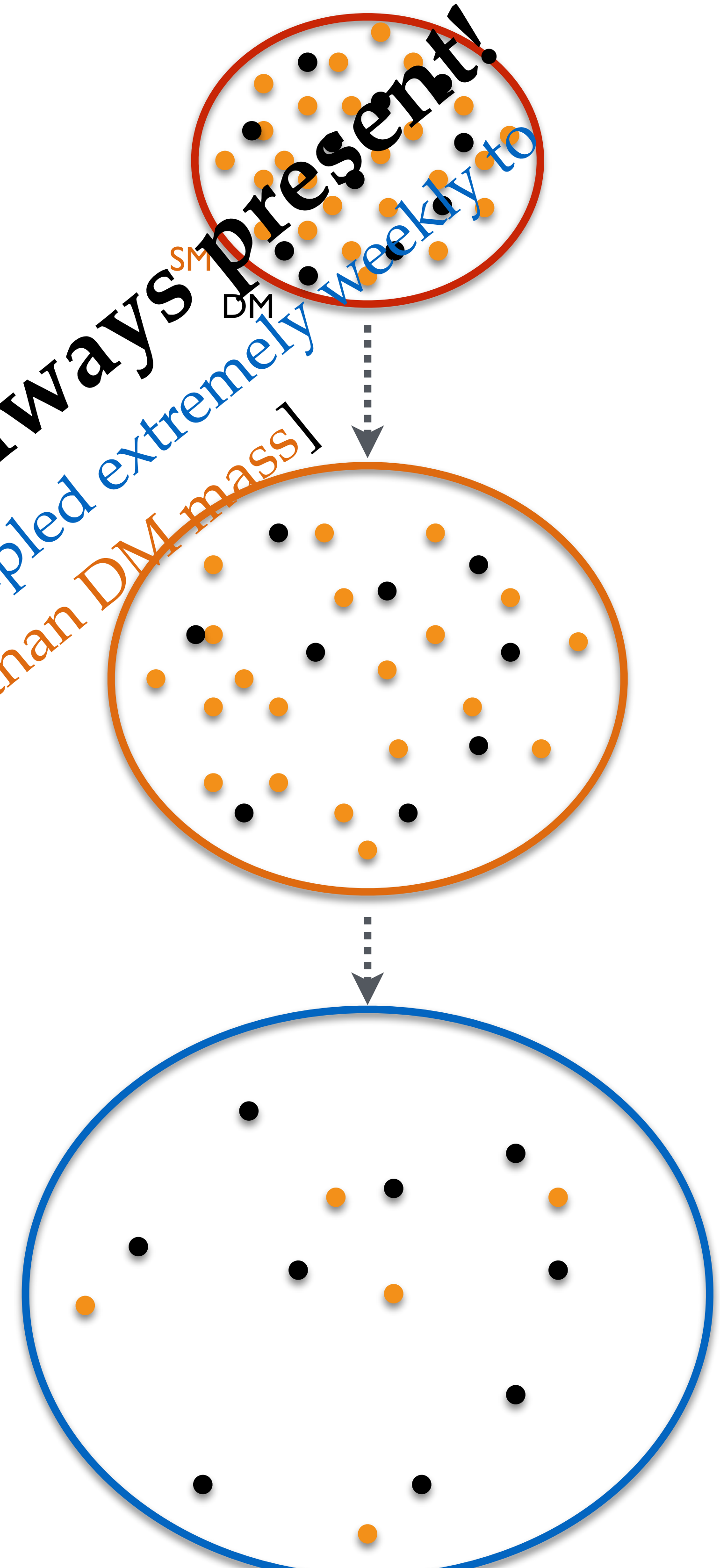
THERMAL RELIC DENSITY
A.K.A. FREEZE-OUT

T

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

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

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



time

This process is (essentially) always present!

[Only exceptions: DM is not a particle or coupled extremely weekly to SM or reheating T is smaller than DM mass]

THERMAL RELIC DENSITY

STANDARD SCENARIO

T			time
↑	$\Gamma_{\text{ann}} > H$	DM in full equilibrium (chemical and kinetic)	↓
	$\Gamma_{\text{ann}} \sim H$	chemical decoupling	
	$\Gamma_{\text{ann}} < H$	freeze-out	
	$\Gamma_{\text{scatt}} \sim H$	kinetic decoupling	

non-equilibrium

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

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

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 0[th] moment)

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

for a process of DM DM ↔ SM SM

Critical assumption:
kinetic equilibrium at chemical decoupling

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

$\Downarrow$

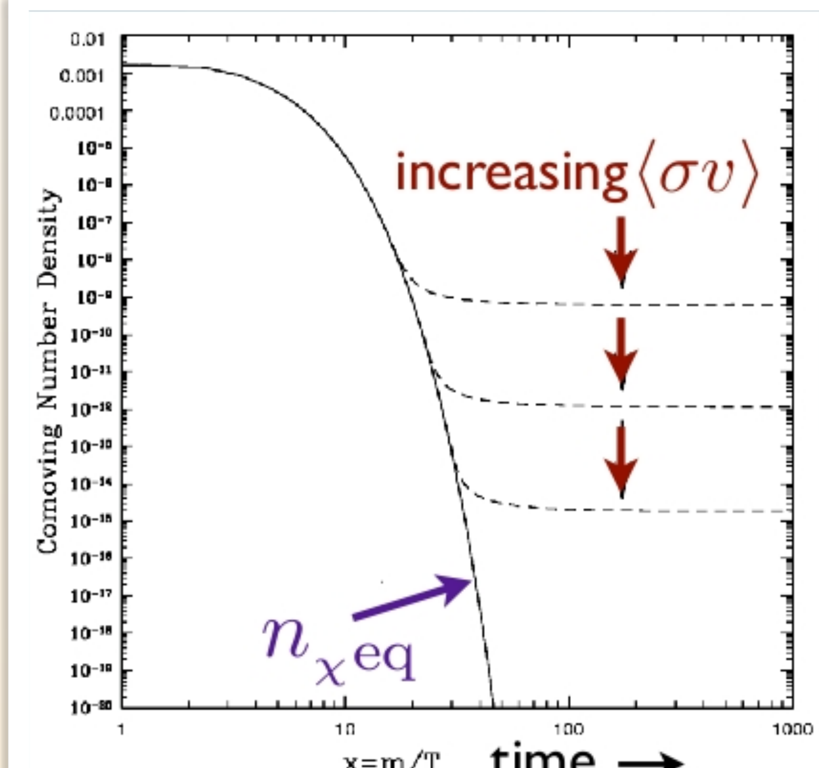


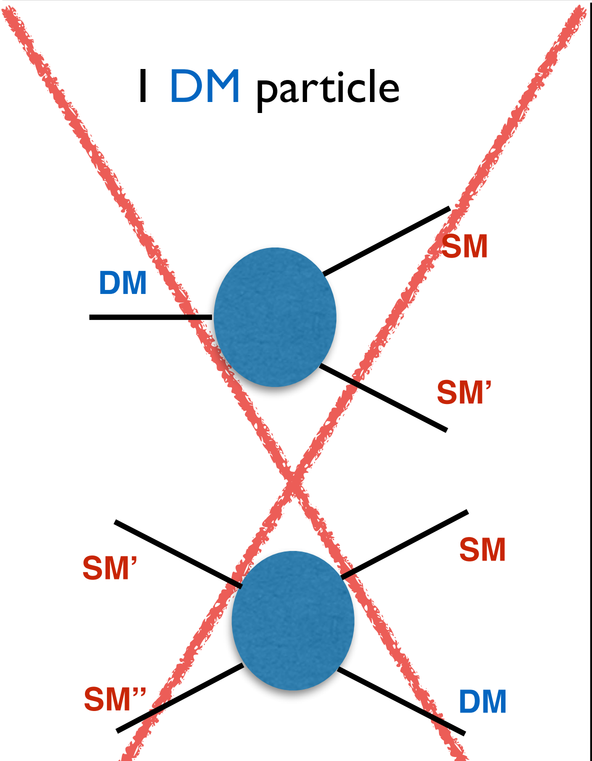
Fig.: Jungman, Kamionkowski & Griest, PR'96

WHAT GOES INTO C IN GENERAL?

For now assume a minimal theory of SM + <u>one</u> DM field

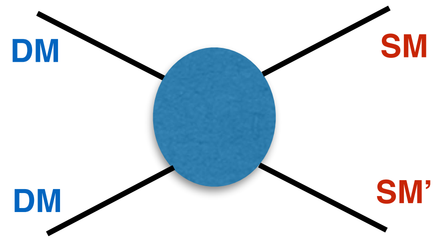
<u>changing</u> processes ⇒ number density

1 DM particle



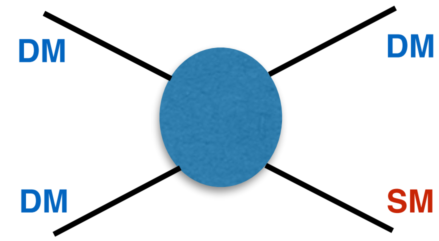
stability

2 DM particles



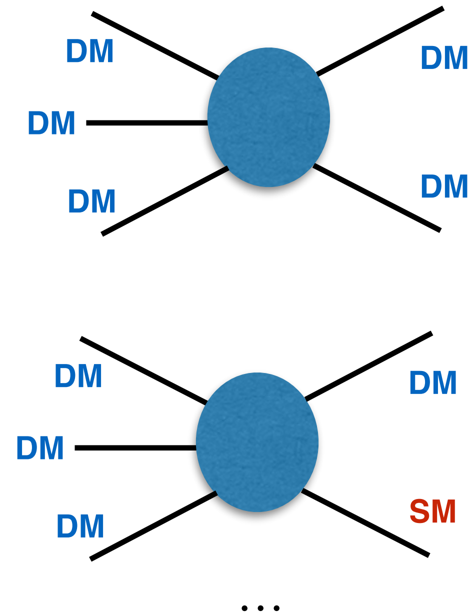
annihilation

3 DM particles



semi-annihilation

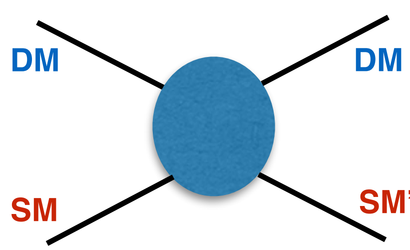
4+ DM particles



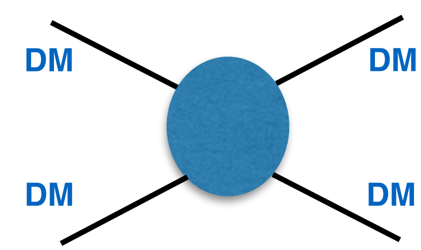
cannibalization

…

<u>conserving</u> processes ⇒ energy density



elastic scattering



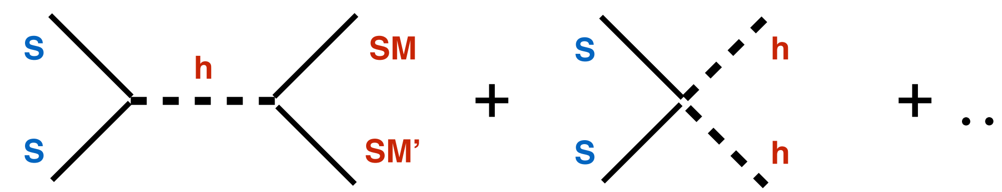
self scattering

EXAMPLES:
STANDARD DM MODELS

Simple WIMP (e.g. scalar singlet model)

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

one coupling governing production & detection



… but still not ruled out

$m_S \sim (\sim 55 - 63)$ GeV & > 3 TeV

SUSY

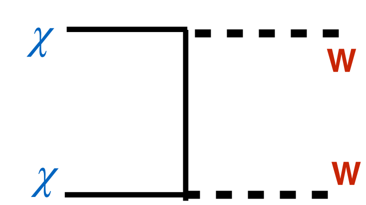
Neutralino

$$\chi = \alpha_1 \tilde{B} + \alpha_2 \tilde{W} + \alpha_3 \tilde{H}_1 + \alpha_4 \tilde{H}_2$$

SU(2): singlet triplet doublet $\Rightarrow$

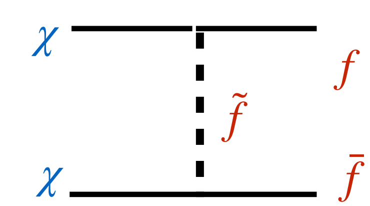
has SM gauge interactions with fixed strength… but unknown mixing

$m_\chi \sim \mathcal{O}(100 - \text{few } 1000)$ GeV



\+ …

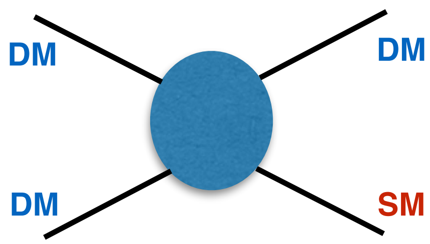
in particular:



EXAMPLES:
NON-STANDARD SINGLE DM MODELS

Semi-annihilation

D'Eramo, Thaler '10



Typically occurs when new „flavour" or „baryon" structure in dark sector, but also present in scalar models, e.g. with $\mathbb{Z}_3$ symmetry

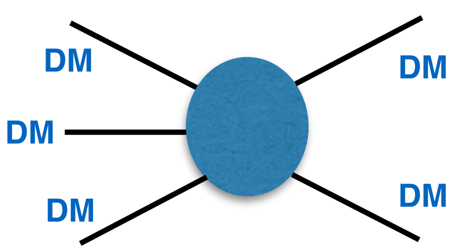
$$\lambda_S |S|^4 + \lambda_{SH} |S|^2 |H|^2 + \frac{\mu_3}{2}(S^3 + S^{\dagger 3}).$$

This interaction does not directly give a direct detection signal
and leads to self-heating of DM → implications for: ID (Cai, Spray '18); core formation (Chu, Garcia-Cely '18)

Kamada et al. '18

Cannibal DM

Calrson, Machacek, Hall '92



…

Idea: completely secluded dark sector, no non-gravitational interactions

$$\Downarrow$$

Freeze-out still possible and natural for $m_{DM} \sim \mathcal{O}(10-100)$ MeV

This process also heats up DM, making original proposal incompatible with structure formation…
but revived after including additional (very weak) interactions with SM as „the SIMP miracle"

Hochberg et al. '14; …

EXAMPLES:
NON-STANDARD DM+MEDIATOR MODELS

Dark freeze-out

If in the dark sector a light state with $\mu = 0$ is present $\Rightarrow$ a completely secluded $2 \leftrightarrow 2$ freeze-out is possible

Differences:

- dark sector can have different temperature T'
- Hubble rate & d.o.f. need to be modified
- no direct connections to indirect nor direct detection

see e.g. Bringmann et al. '21

Inverse decays - INDY DM

Frumkin et al. '21

$$\psi \longleftrightarrow \chi + \phi$$

$\mathbb{Z}_2:$	-1	-1	1
	DS	DM	SM

Boltzmann equation:

$$\dot{n}_\chi + 3Hn_\chi = \Gamma \left(n_\psi - n_\chi \frac{n_\psi^{\rm eq}}{n_\chi^{\rm eq}} \right)$$

No direct signals of DM; one can look for the mediator in (typically) light long-lived particle searches

OTHER:

…, ELDER, KINDER, co-scattering, co-decay, zombie, pandemic, co-SIMP, forbidden, superWIMP, squirrel, catalyzed, dynamical, reproductive, …

*only one of these is a joke DM candidate…

Thermal Relic Density
Other Exceptions

modified expansion rate

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

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

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

general multi-component dark sector

$$\frac{dn_\chi}{dt} + 3Hn_\chi \quad \ldots \quad n_{\bar{\chi}} - n_\chi^{\mathrm{eq}} n_{\bar{\chi}}^{\mathrm{eq}})$$

$$\frac{dn_\chi}{dt} + 3Hn_\chi \quad \ldots \quad n_{\bar{\chi}} - n_\chi^{\mathrm{eq}} n_{\bar{\chi}}^{\mathrm{eq}})$$

modified cross

Sommer

Bound St

NLO

finite T e

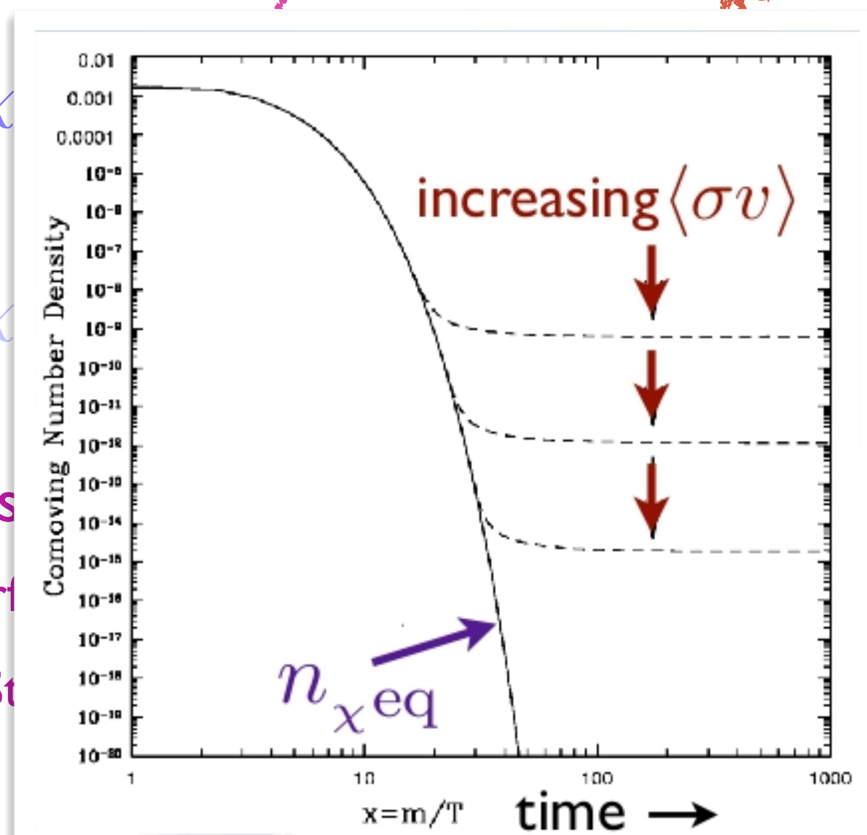


Fig.: Jungman, Kamionkowski & Griest, PR'96

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

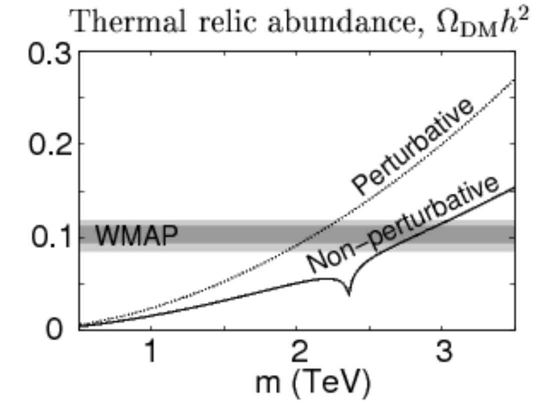
where the thermally averaged cross section:

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

I:

Particle Physics Effects

THE SOMMERFELD EFFECT
FROM EW INTERACTIONS

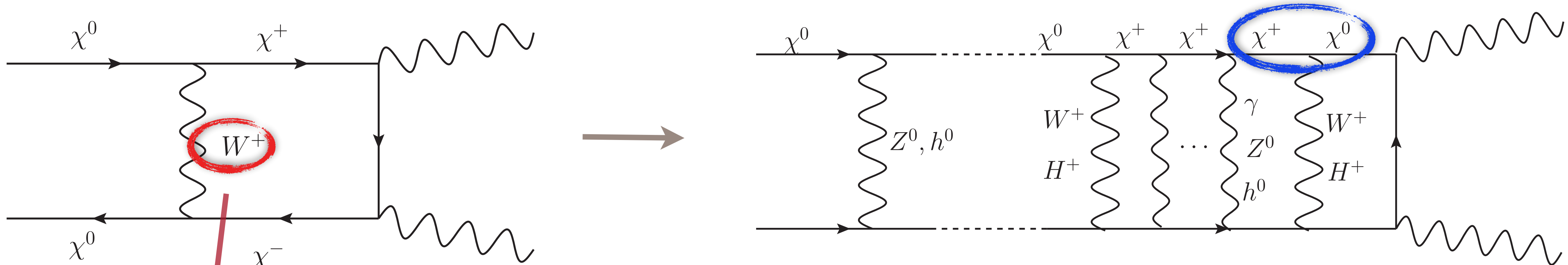


force carriers in the MSSM:

~~γ~~, $W^\pm$, Z^0, h_1^0, h_2^0, $H^\pm$

$\delta m \ll m_\chi$

seminal papers
Hisano *et al.* '04,'06,...



$m_\chi \gg m_W$

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

on top of that resonance structure

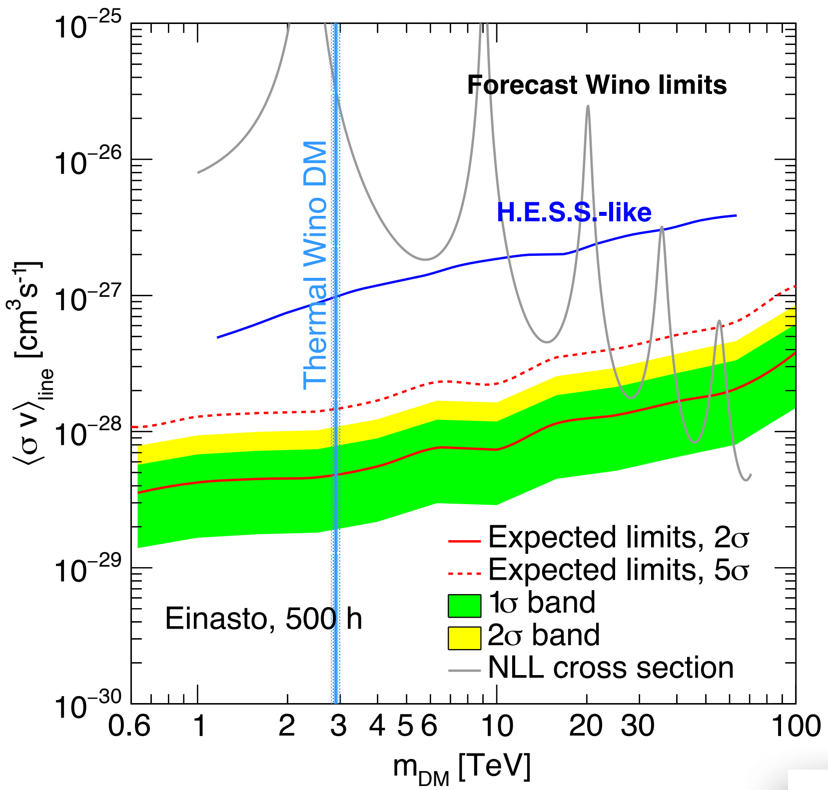
$\rightarrow$ effect of $\mathcal{O}(\text{few})$
for the relic density

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

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

The Sommerfeld effect

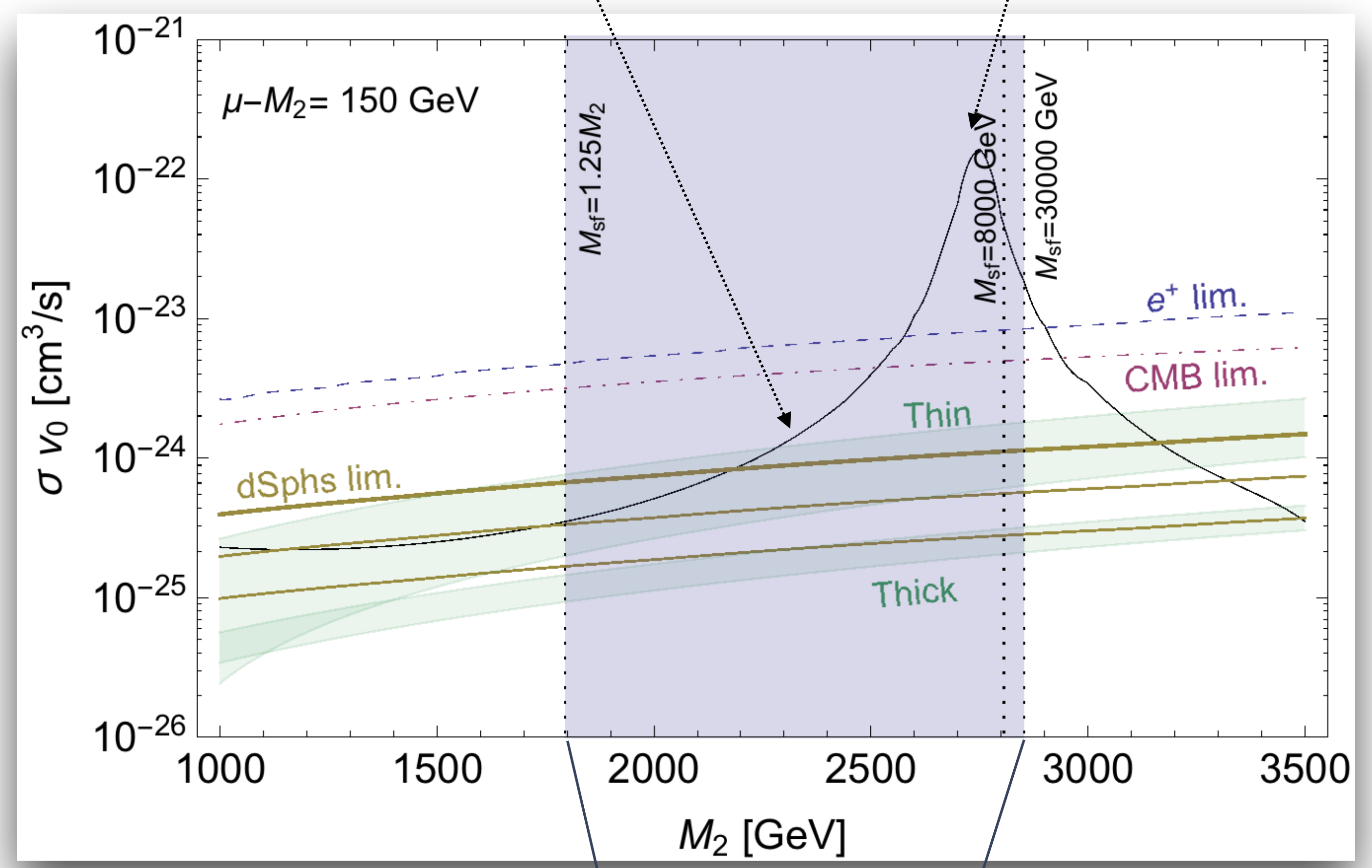
Indirect Detection



Slatyer *et al.*, '21

actual cross section

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



Beneke, …AH, … *et al.*, '16

correct RD can be achieved: when varying sfermion masses

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

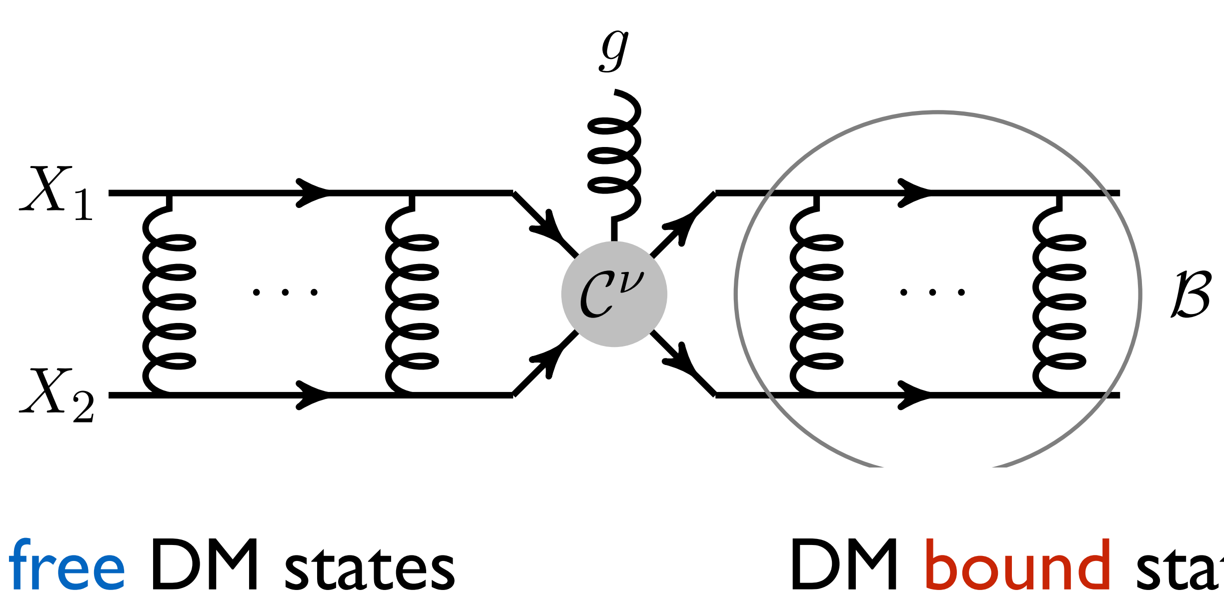
BOUND STATE FORMATION

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?



*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:
IMPACT ON THE UNITARITY BOUND

Conservation of probability (for any partial wave) $\Longrightarrow$ $(\sigma v_{\rm rel})^J_{\rm total} < (\sigma v)^J_{\rm max} = \dfrac{4\pi(2J+1)}{M^2_{\rm DM} v_{\rm rel}}$

$\Longrightarrow$ upper limit on DM mass if thermally produced: "$M_{\rm DM} < 340\,{\rm TeV}$" (for a Majorana fermion and $\Omega h^2 = 1$)

$M_{\rm DM} < 200\,{\rm TeV}$ (updated)

Griest and **Kamionkowski** '89

With the bound state annihilation taken into account:

$$(\sigma v_{\rm rel})_{\rm total} = (\sigma v_{\rm rel})_{\rm ann} + \underline{\textstyle\sum_I (\sigma_I v_{\rm rel})_{\rm BSF}}$$

but some of the bound states dissociate before they are able to annihilate!

$\Downarrow$

$(\sigma v_{\rm rel})_{\rm total}$ overestimates the cross section in the Boltzmann eq.

$\Leftarrow$

maximal attainable mass for thermal DM is lower

$M_{\rm DM} < 144\,{\rm TeV}$ $\Leftarrow$
(for a Majorana fermion coupled vis $SU(2)_L$)

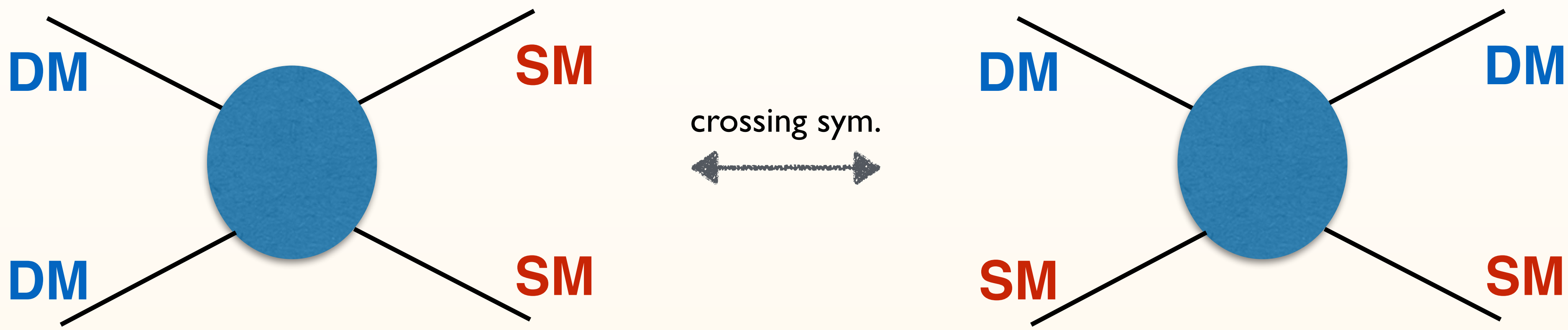
Smirnov, Beacom '19
(see also **von Harling, Petraki** '14, **Cirelli** *et al.* '16, …)

II:

Non-Equilibrium effects

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 <u>typically</u> more frequent

dark matter frozen-out but <u>typically</u> still kinetically coupled to the plasma

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

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

Two consequences:

1. During freeze-out (chemical decoupling) <u>typically</u>: $f_\chi \sim a(\mu) f_\chi^{\text{eq}}$
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

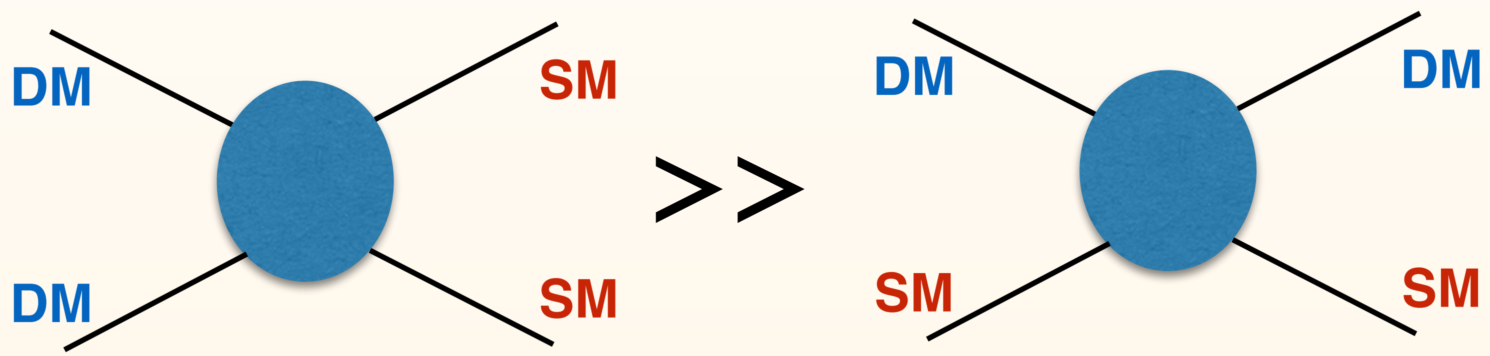
EARLY KINETIC DECOUPLING?

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

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

→ contains both scatterings and annihilations

Two possible approaches:

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

- have insight on the distribution
- no constraining assumptions
- numerically challenging
- often an overkill

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

0-th moment: n_χ
2-nd moment: T_χ
$\ldots$

- partially analytic/much easier numerically
- manifestly captures all of the relevant physics
- finite range of validity
- no insight on the distribution

NEW TOOL!

GOING BEYOND THE STANDARD APPROACH

- Home
- Downloads
- Contact

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!

EXAMPLE A:
SCALAR SINGLET DM

A)

EXAMPLE A

SCALAR SINGLET DM

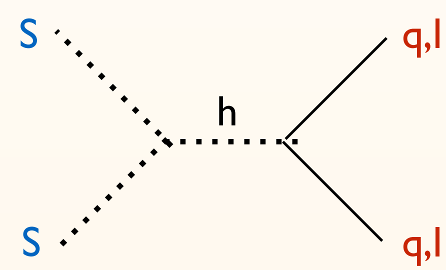
To the SM Lagrangian add one singlet scalar field *S* with interactions with the Higgs:

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

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

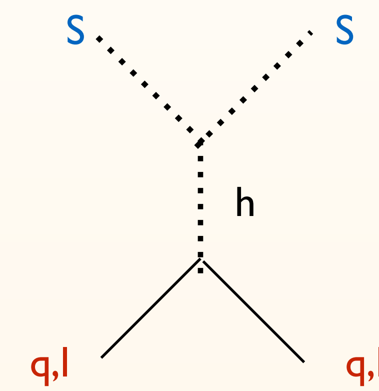
Annihilation processes:

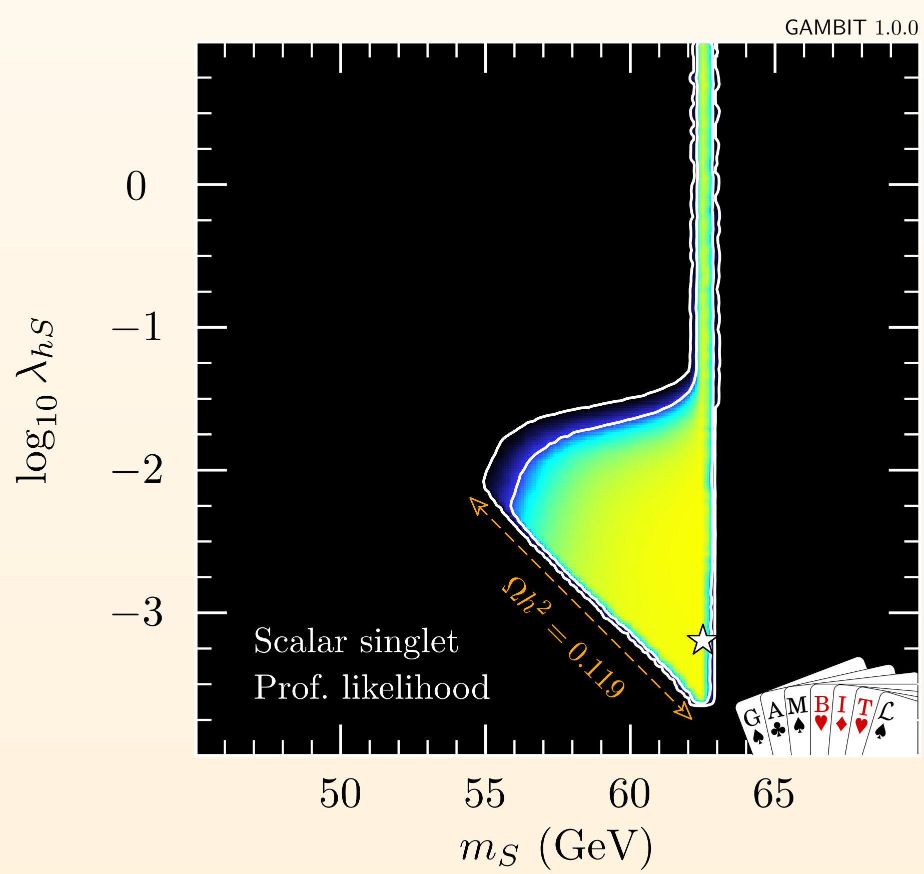
resonant

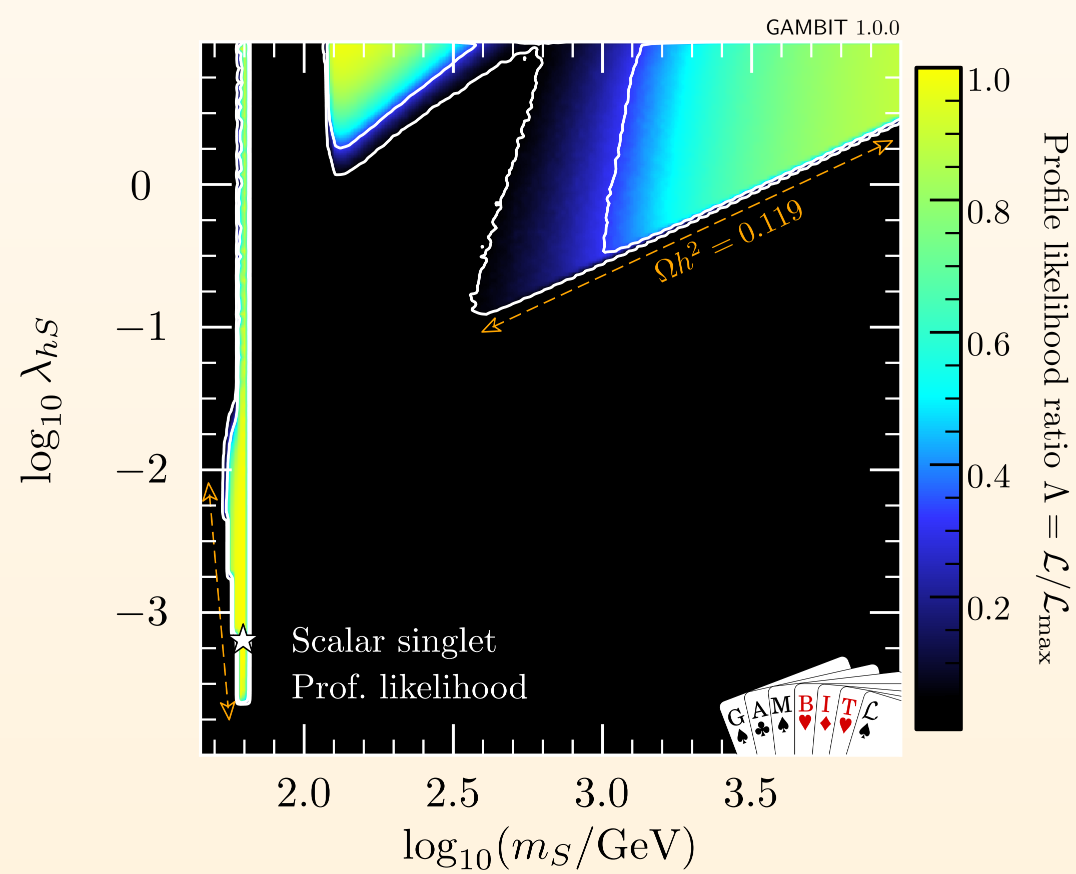


El. scattering processes:

non-resonant





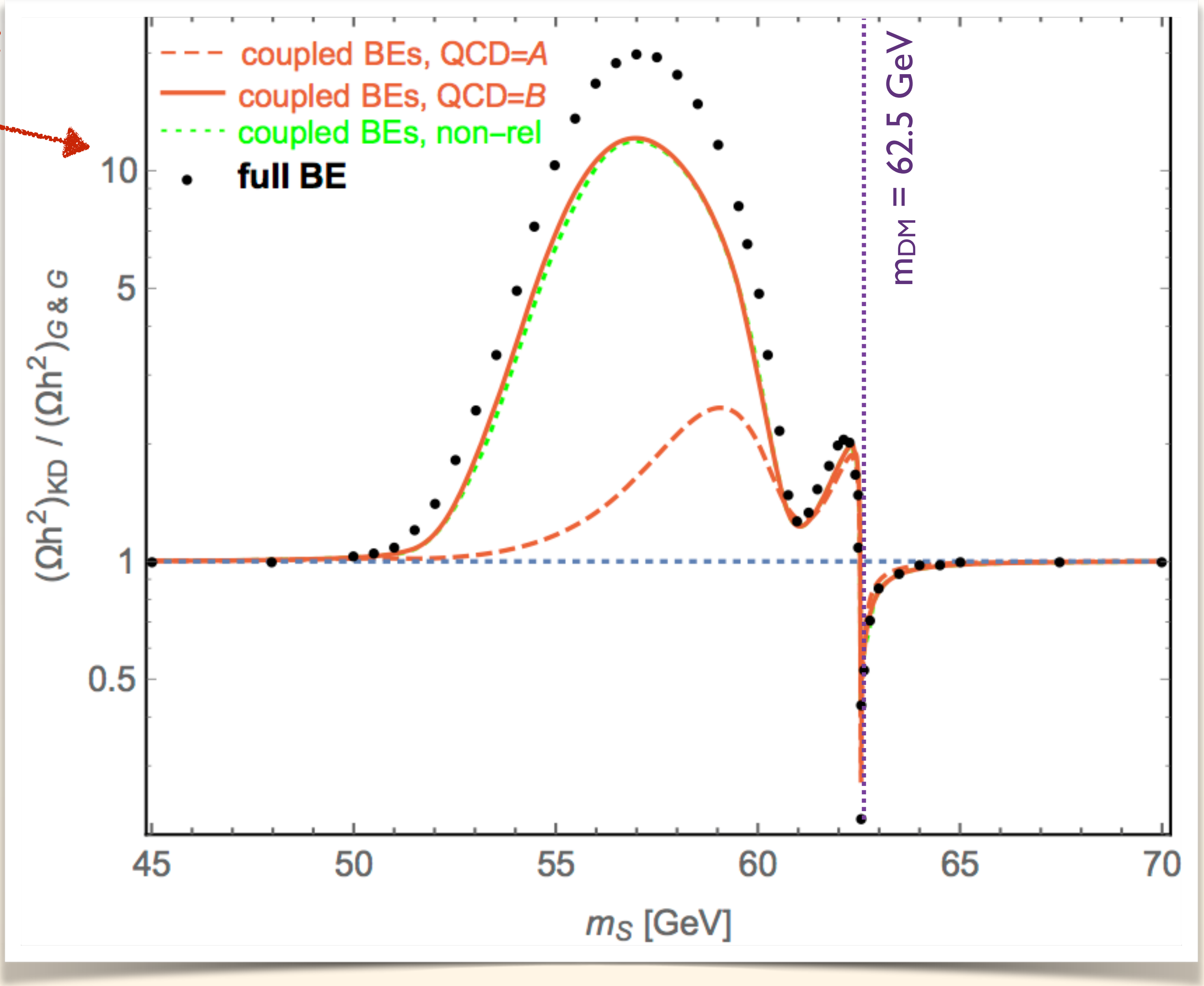


GAMBIT collaboration
1705.07931

Results

Effect on the Ωh^2

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

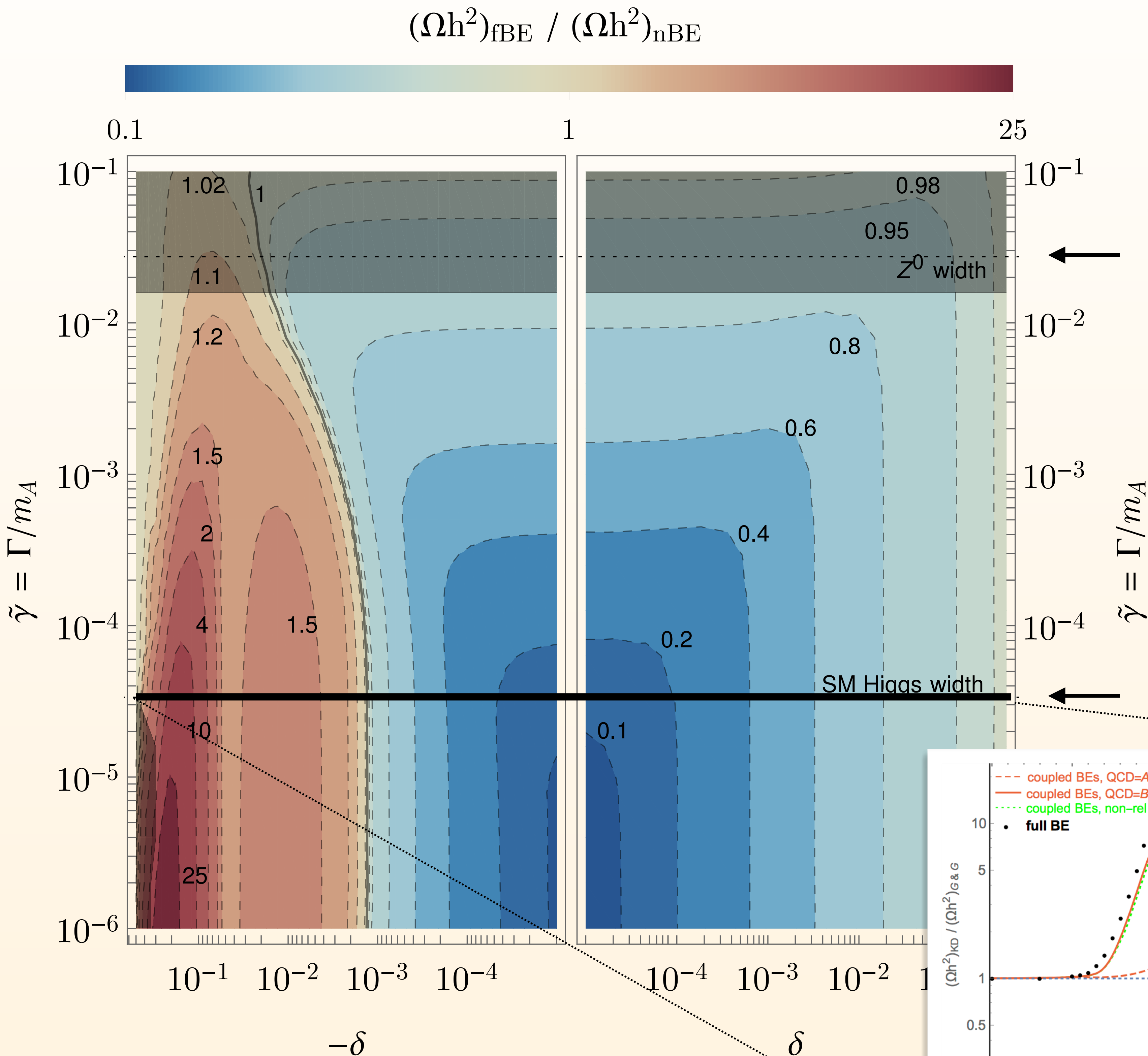


[… Freeze-out at few GeV ⟶ what is the abundance of heavy quarks in QCD plasma?

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 $4T_c$ …]

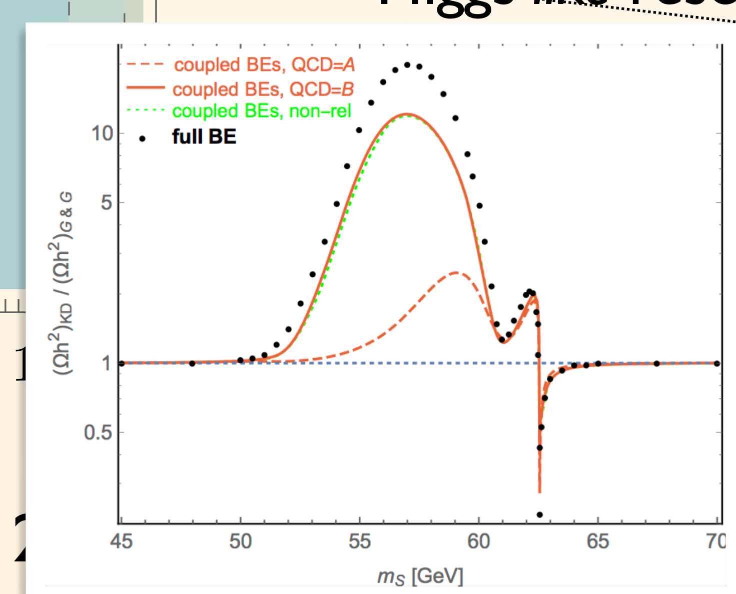
GENERIC RESONANT ANNIHILATION
EXAMPLE EFFECT OF EARLY KD ON RELIC DENSITY

resonance **width** normalized to m_{DM}



can reach O(10%) even for *Z-like* resonance

very large effect for Higgs-*like* resonance

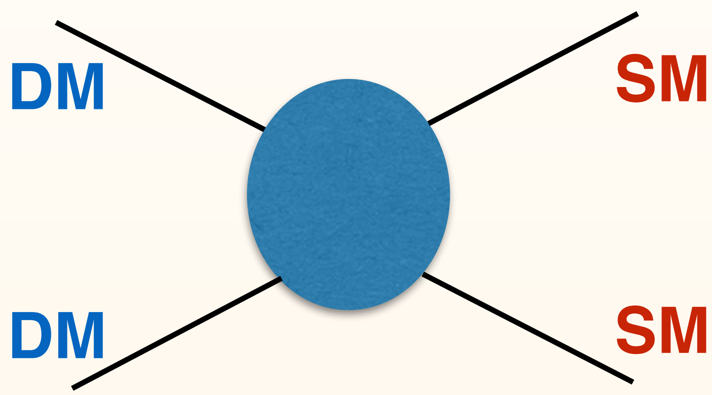


distance in mass from the exact condition 2

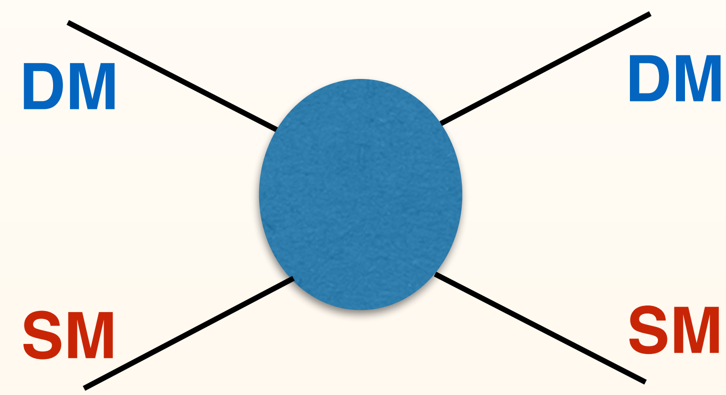
III:
Multi-component Dark Matter

What if a non-minimal scenario?

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



crossing sym.



annihilation

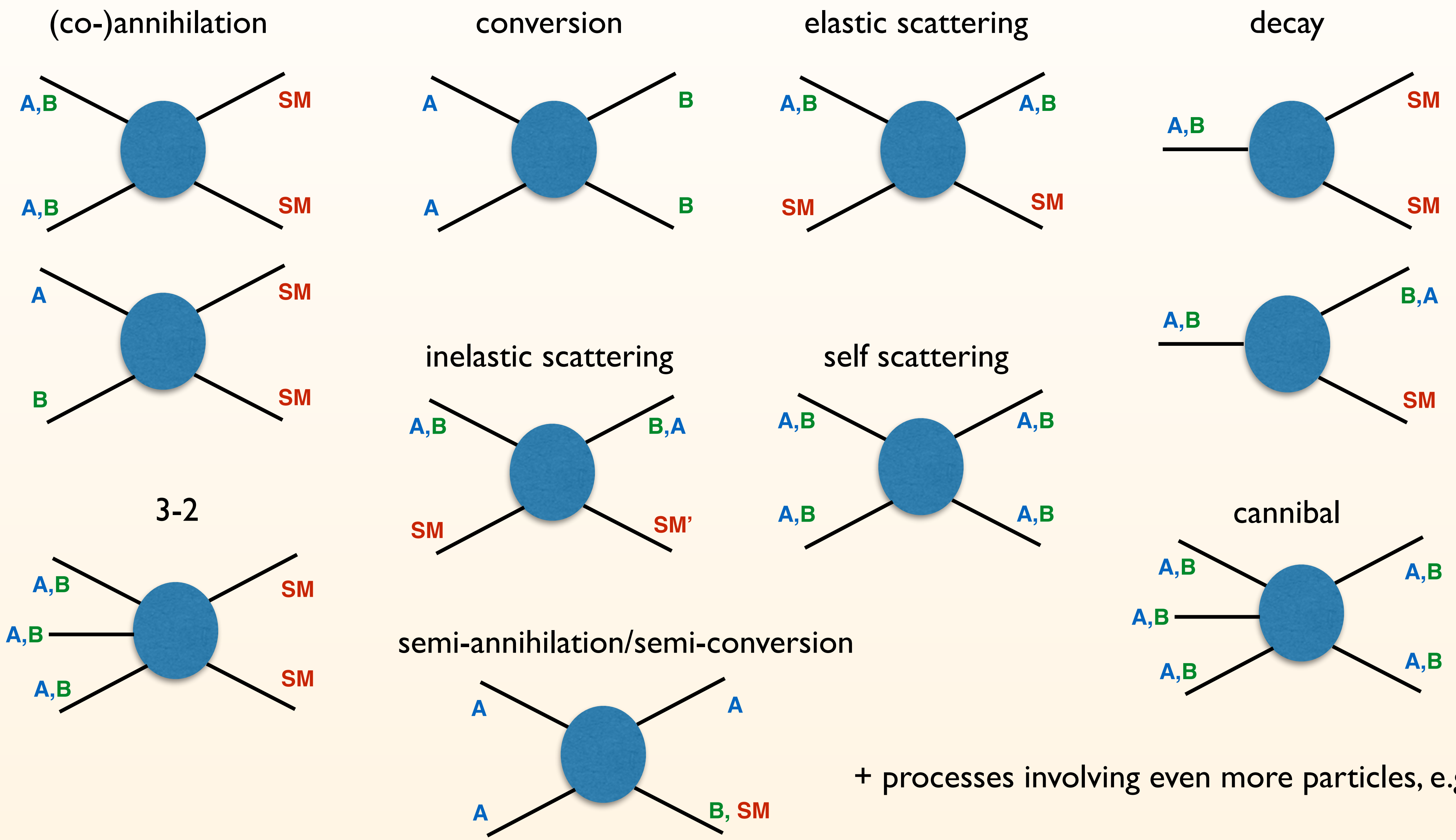
(elastic) scattering

drives number density evolution

scatterings typically more frequent
(keeping the distribution to be in local thermal eq.)
Schmid, Schwarz, Widern '99; Green, Hofmann, Schwarz

WHAT IF A NON-MINIMAL SCENARIO?

A,B — two different dark sector states (at least one needs to be stable)



+ processes involving even more particles, e.g. $2 \leftrightarrow 4\ldots$

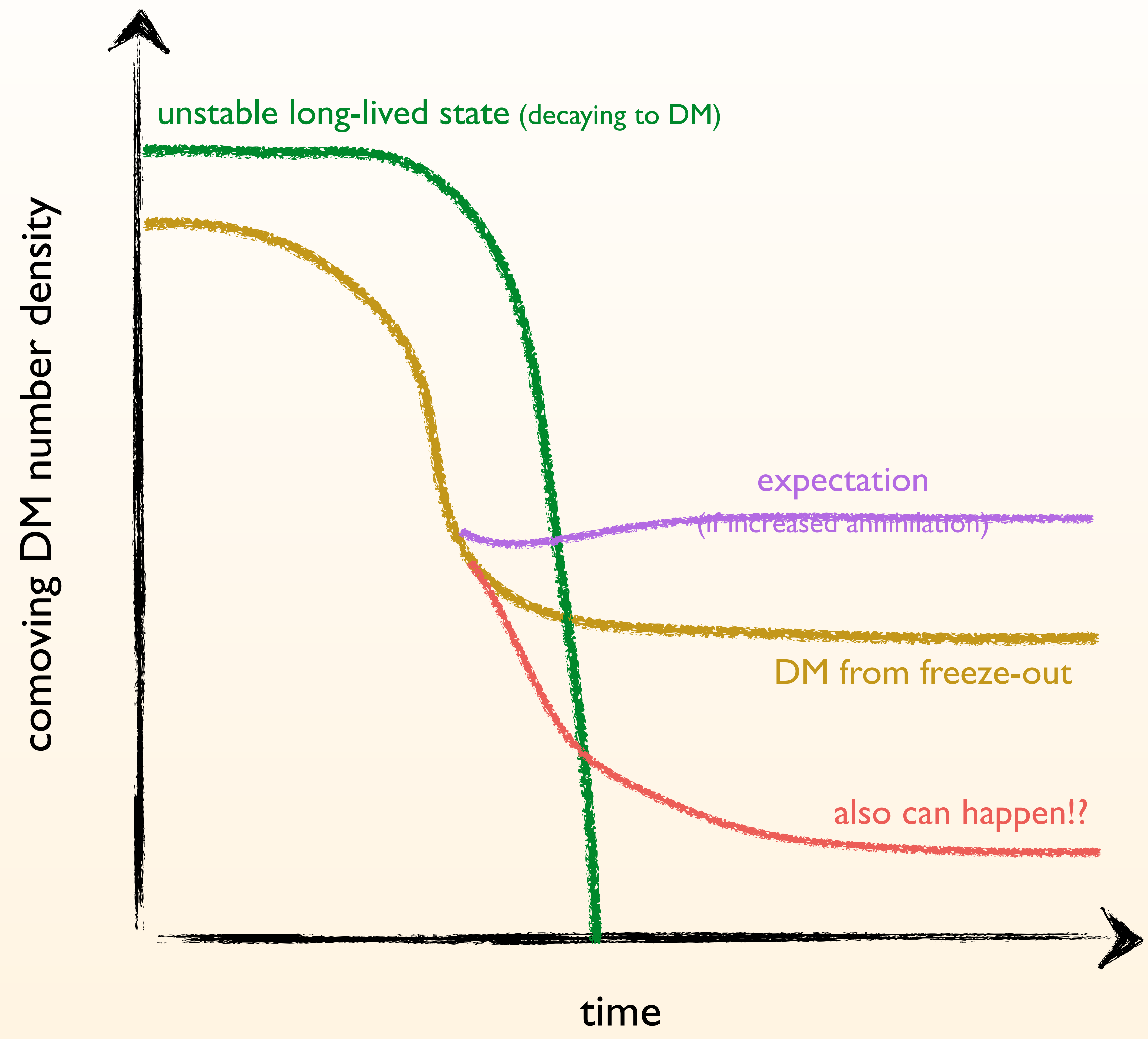
Note: some of these processes affect not only # density, but also strongly modify the energy distribution of DM particles!

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)

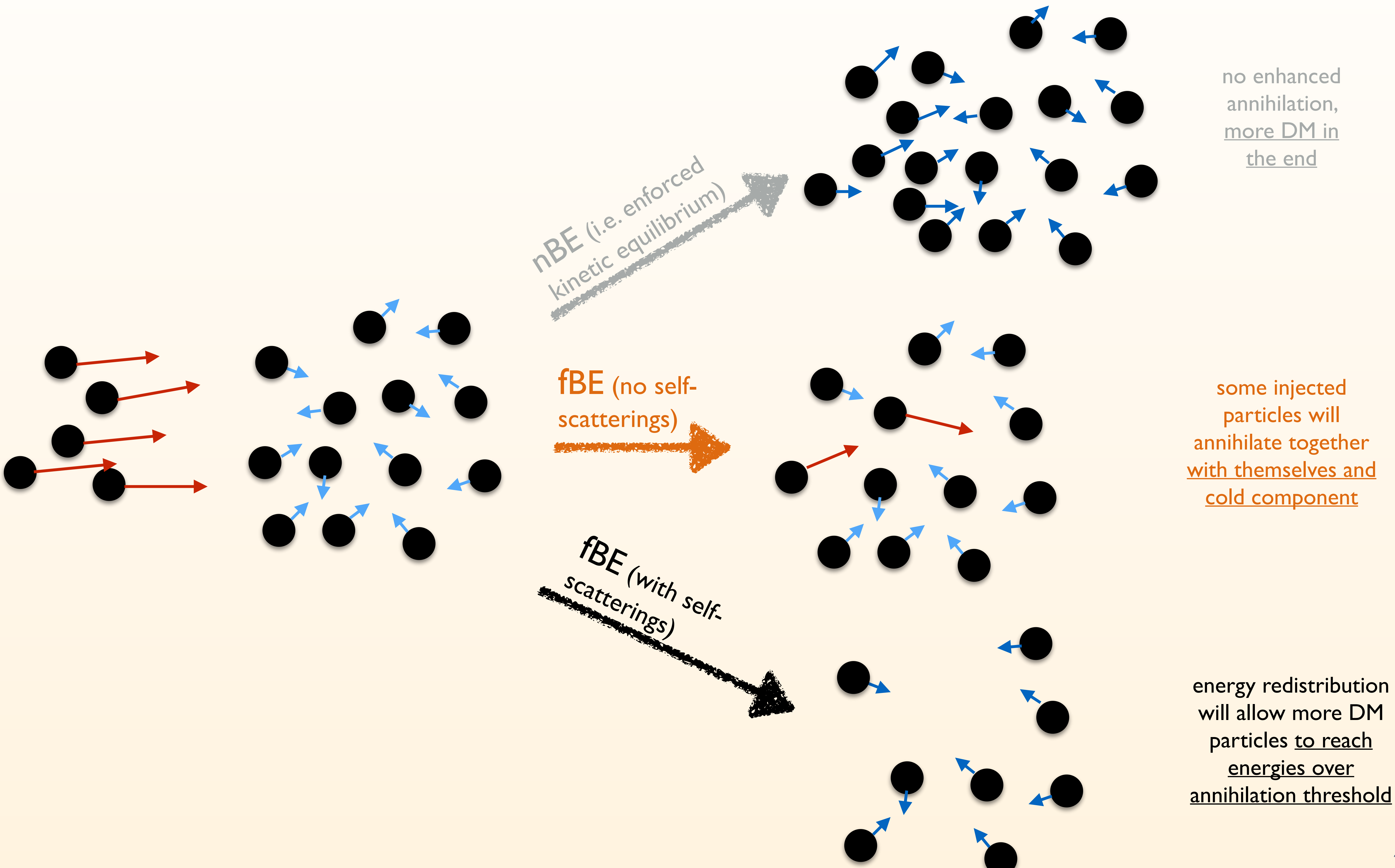
- this can modify the annihilation rate (if still active)
- how does the thermalization due to elastic scatterings happen?


unstable long-lived state (decaying to DM)
comoving DM number density
expectation
(if increased annihilation)
DM from freeze-out
also can happen!?
time

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 $m_\chi \lesssim m_f$



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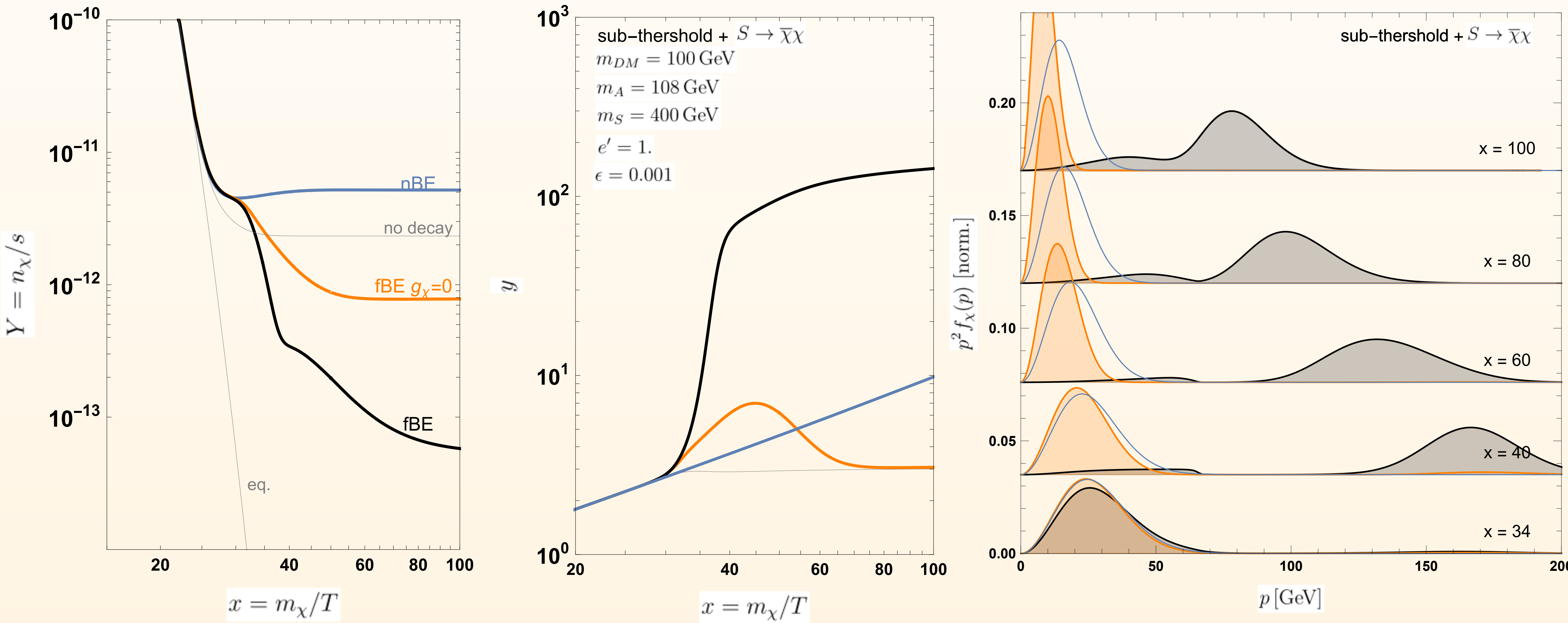
EXAMPLE EVOLUTION

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 $m_\chi \lesssim m_f$

$Y \sim$ number density | $y \sim$ temperature | $p^2 f(p) \sim$ momentum distribution



SUMMARY

1. Non-standard freeze-out encompasses a plethora of models, ideas and possibilities, that have a similar theoretical standing to the standard WIMP-like freeze-out, while possibly quite different phenomenology

2. In recent years a significant progress in refining the relic density calculations (not yet fully implemented in public codes!)

3. Kinetic equilibrium is a necessary (often implicit) assumption for standard relic density calculations in all the numerical tools…
…while it is not always warranted!

(we also introduced DRAKE a new tool to extend the current capabilities to the regimes beyond kinetic equilibrium)