EARLY KINETIC DECOUPLING OF DARK MATTER

WHEN THE STANDARD WAY OF CALCULATING THE THERMAL RELIC DENSITY FAILS

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based on: **T. Binder, T. Bringmann, M. Gustafsson and AH,**
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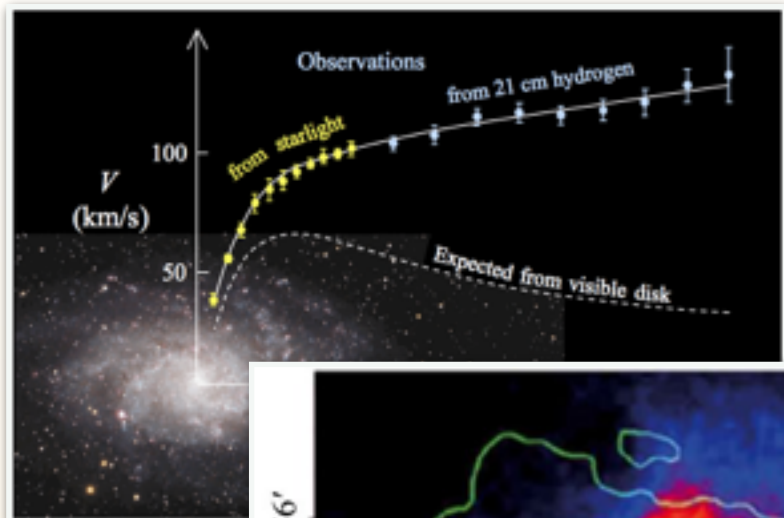
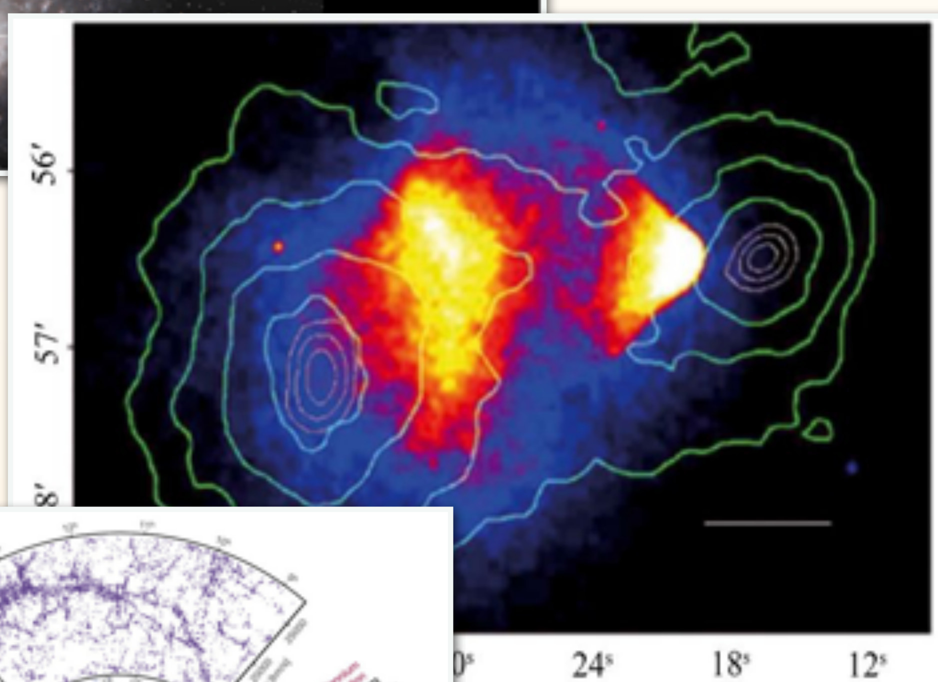
Outline

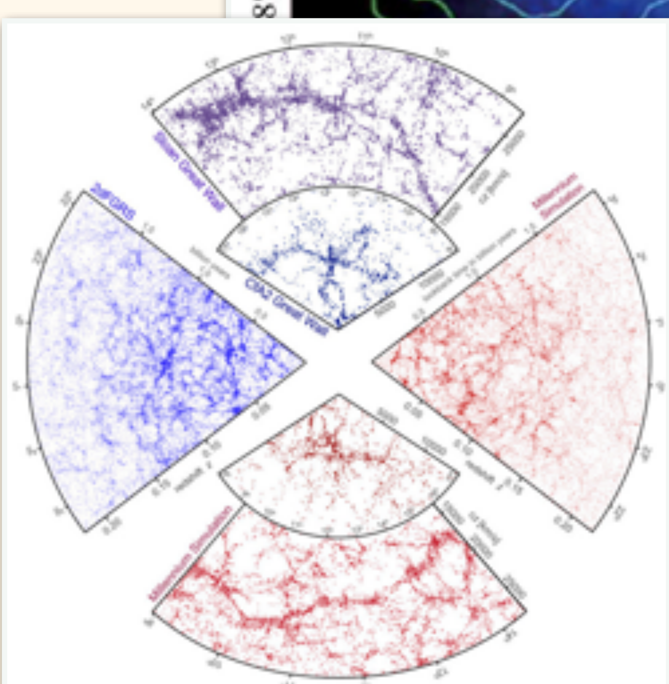
1. Introduction
   - standard approach to thermal relic density
   - recent novel models/ideas
2. Kinetic decoupling
   - freeze-out vs. decoupling
   - significance for cosmology
3. Our work
   - early kinetic decoupling with
   - velocity dependent annihilation
4. Summary

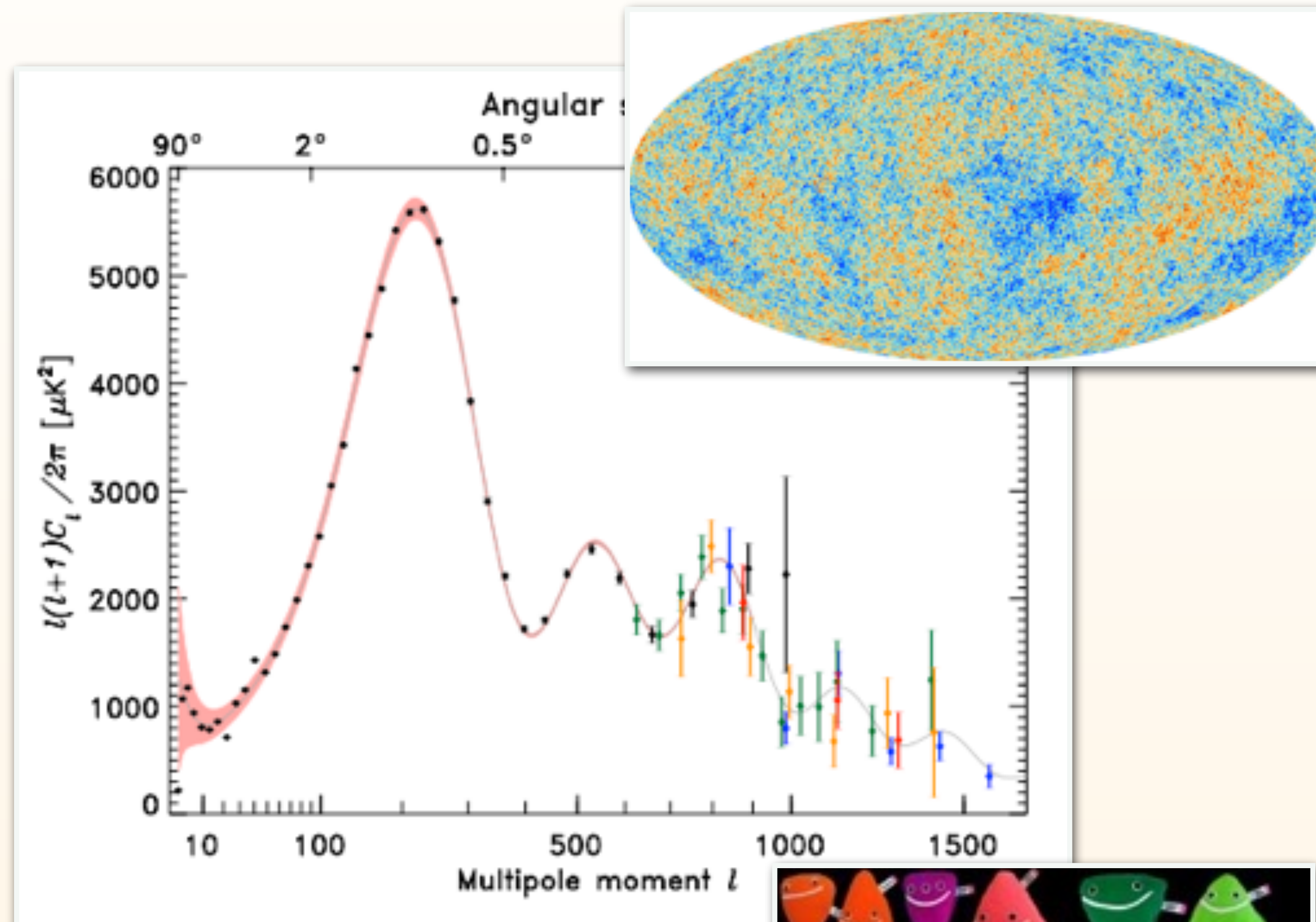
DARK MATTER

IS EVERYWHERE!









⇒ Evidence on all scales!

…want to know more?! join the DM course, starting Thursday 22nd

The Origin of Dark Matter

Dark matter could be created in many different ways…

…but <u>every</u> massive particle with not-too-weak interactions with the SM will be produced thermally, with relic abundance:

Lee, Weinberg '77; + others

$$\Omega_\chi h^2 \approx 0.1 \, \frac{3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma v \rangle}$$

It is very natural to expect that this mechanism is responsible for the origin of all of dark matter

…but even if not, it still is present nevertheless and it's important to be able to correctly determine thermal population abundance

Thermal Relic Density

standard approach

T ↑

$\Gamma_{\rm ann} > H$ — DM in equilibrium

$\Gamma_{\rm ann} \sim H$ — **chemical decoupling**

$\Gamma_{\rm ann} < H$ — freeze-out

↓ time

non-equilibrium

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

$$E\,(\partial_t - H\vec{p}\cdot\nabla_{\vec{p}})\,f_\chi = \mathcal{C}[f_\chi] \quad\Rightarrow\quad \frac{dn_\chi}{dt} + 3Hn_\chi = C$$

Liouville operator in FRW background

the collision term

integrated

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

…for derivation from thermal QFT see e.g., M. Beneke, F. Dighera, AH; JHEP 1410 (2014) 45

Thermal Relic Density

THE COLLISION TERM

for $2 \leftrightarrow 2$ CP invariant process:

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

assuming kinetic equilibrium at chemical decoupling: $f_\chi \sim a(\mu) f_\chi^{\rm eq}$

$$C_{\rm LO} = -\langle \sigma_{\chi\bar{\chi}\to ij} v_{\rm rel}\rangle^{\rm eq} \left(n_\chi n_{\bar{\chi}} - n_\chi^{\rm eq} n_{\bar{\chi}}^{\rm eq}\right)$$

where the thermally averaged cross section:

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

THERMAL RELIC DENSITY

BOLTZMANN EQ.

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

Re-written for the comoving number density:

$$\frac{dY}{dx} = \sqrt{\frac{g_* \pi m_\chi^2}{45G}}\,\frac{\langle \sigma_{\chi\bar\chi\to ij}\sigma_{\rm rel}\rangle^{\rm eq}}{x^2}\left(Y^2 - Y_{\rm eq}^2\right)$$

$$\lim_{x\to 0} Y = Y_{\rm eq} \qquad \lim_{x\to\infty} Y = {\rm const}$$

Recipe:
compute annihilation cross-section,
take a thermal bath average,
throw it into BE… and voilà

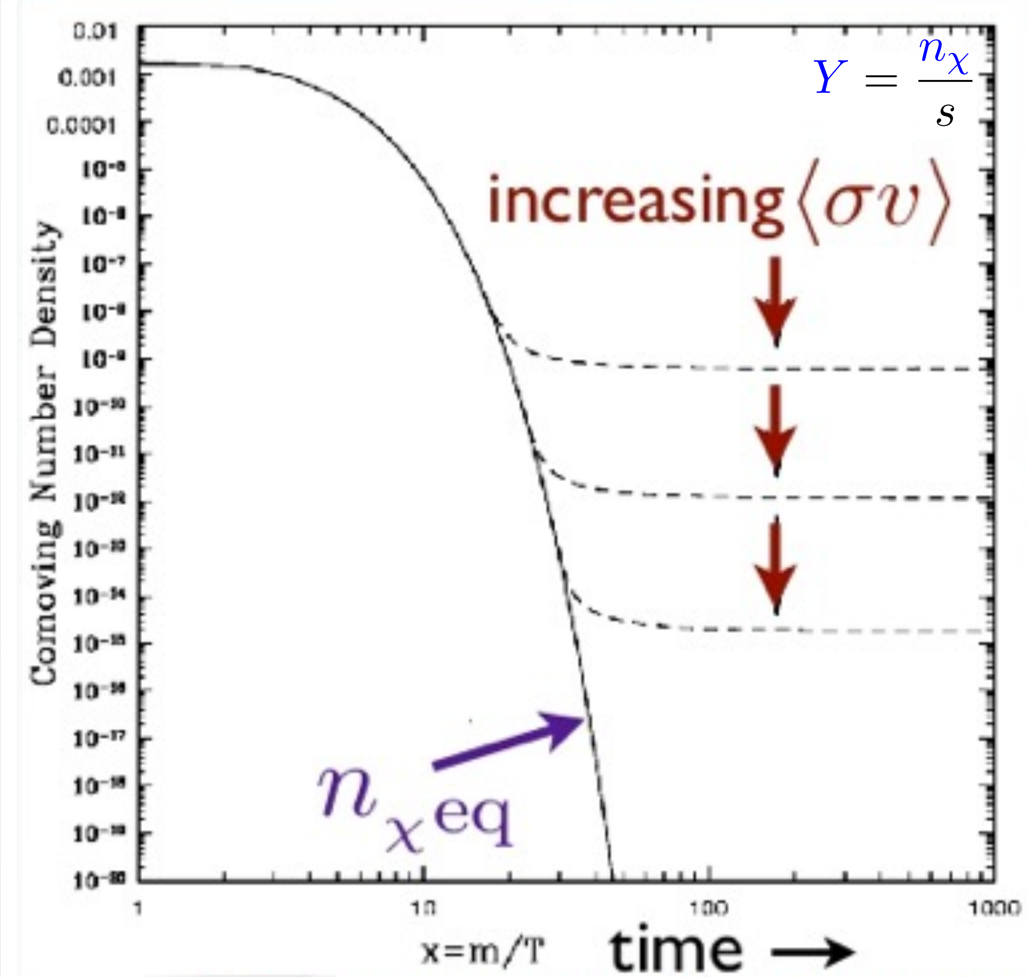


Fig.: Jungman, Kamionkowski & Griest, PR'96

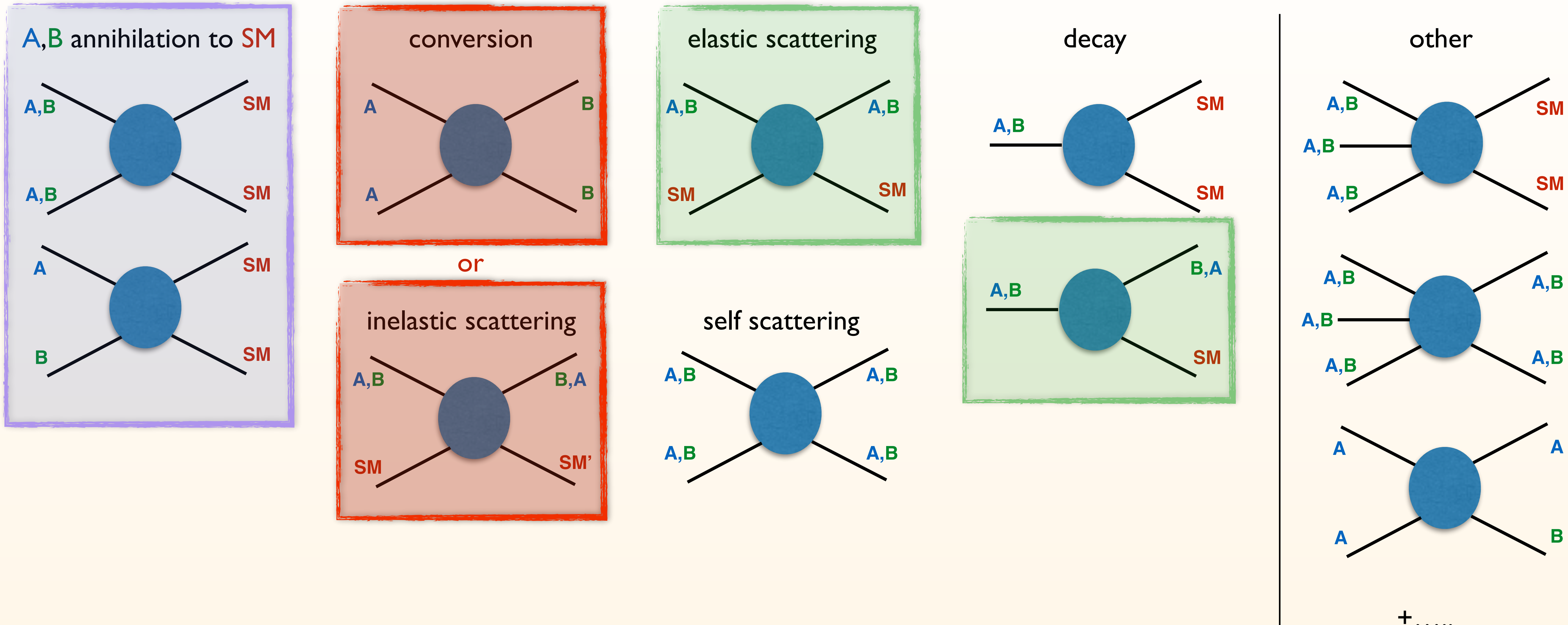
THERMAL RELIC DENSITY

"EXCEPTIONS"

1. Three "exceptions"
   Griest, Seckel '91
2. Non-standard cosmology
   many works… very recent e.g., D'Eramo, Fernandez, Profumo '17
3. Bound State Formation
   recent e.g., Petraki at al. '15, '16;   An et al. '15, '16;   Cirelli et al. '16; …
4. $3 \rightarrow 2$ and $4 \rightarrow 2$ annihilation
   e.g., D'Agnolo, Ruderman '15;   Cline at al. '17; Choi at al. '17; …
5. Second era of annihilation
   Feng et al. '10;   Bringmann et al. '12; …
6. Semi-annihilation
   D'Eramo, Thaler '10; …
7. Cannibalization
   e.g., Kuflik et al. '15;   Pappadopulo et al. '16; …
8. …

In other words: whenever studying non-minimal scenarios "exceptions" appear — but most of them come from interplay of new added effects, while do not affect the foundations of modern calculations

WHAT IF NON-MINIMAL SCENARIO?



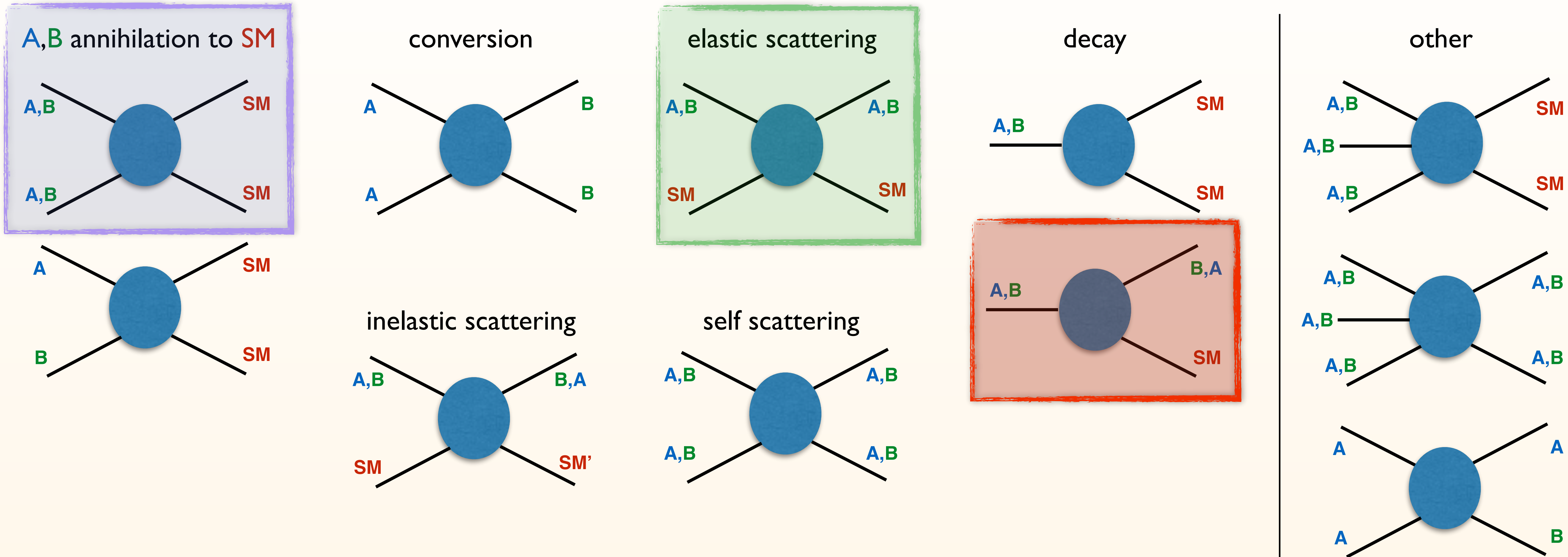
↳ typically forbidden by symmetry

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

- needed to be efficient for mechanism to work
- setting the relic density
- assumed in computation

What if 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

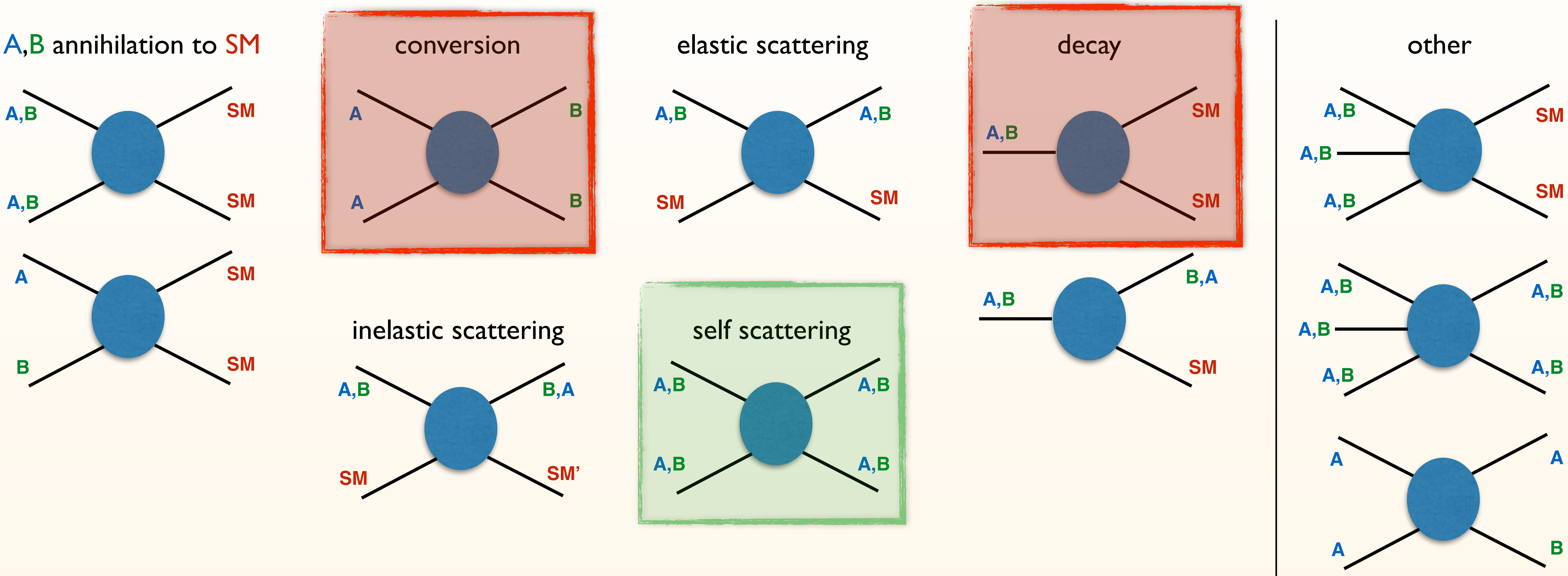
Feng, Rajaraman, Takayama '03

needed to be efficient for mechanism to work

setting the relic density

assumed in computation

WHAT IF NON-MINIMAL SCENARIO?



+…..

↳ typically forbidden by symmetry

Co-decaying → DM decouples when relativistic but then one of the dark sector states decays and this effect important as long as conversions are

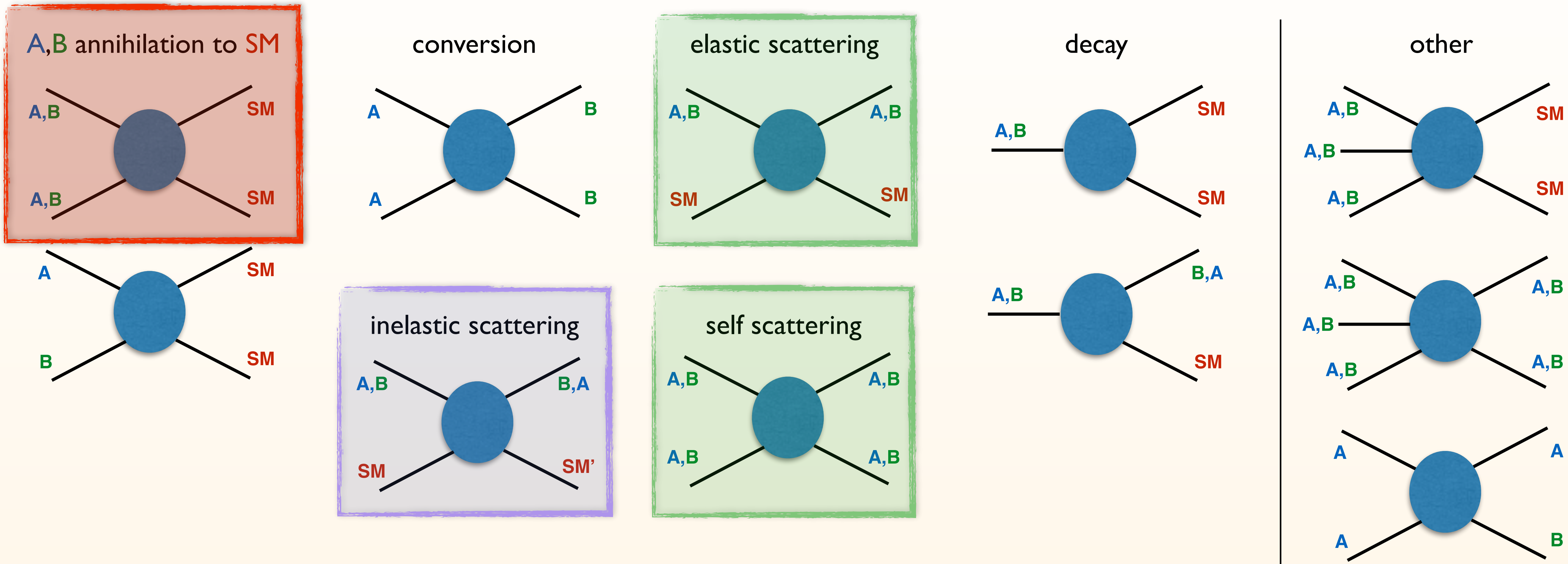
Dror, Kuflik, Ng '16

needed to be efficient for mechanism to work

setting the relic density

assumed in computation

WHAT IF NON-MINIMAL SCENARIO?



+…..

↳ typically forbidden by symmetry

Conversion driven freeze-out

Garny, Heisig, Lulf, Vogl '17

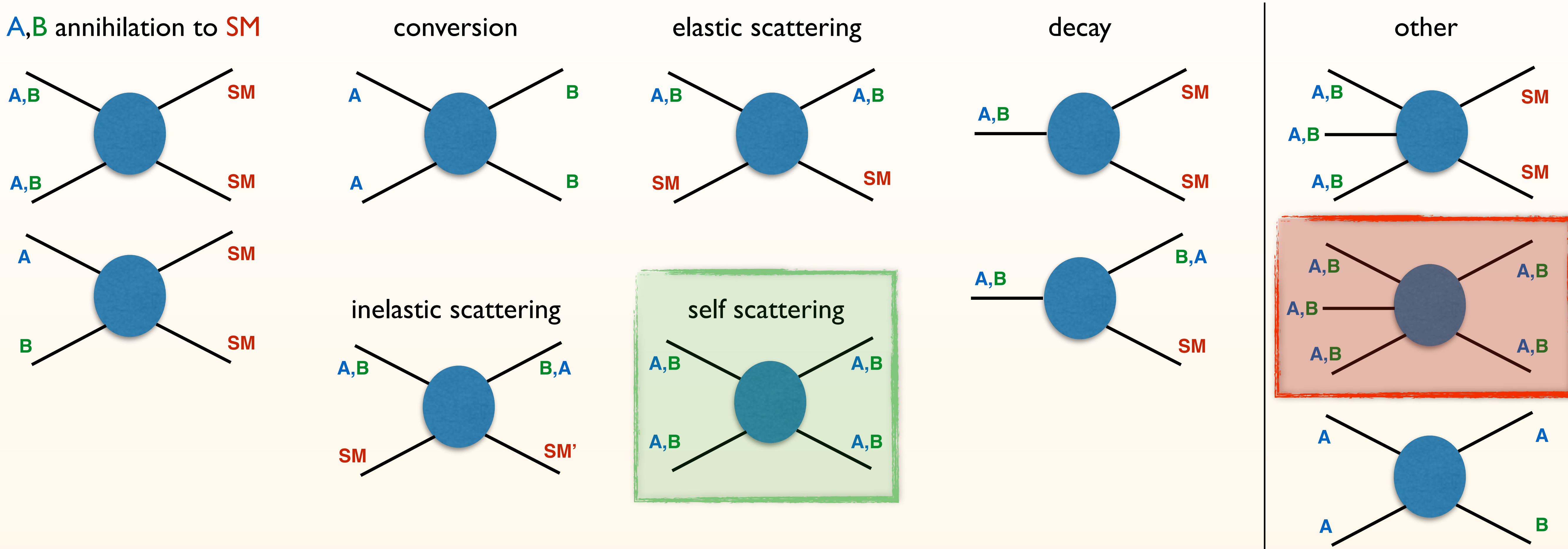
Co-scattering

D'Agnolo, Pappadopulo, Ruderman '17

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

- needed to be efficient for mechanism to work
- setting the relic density
- assumed in computation

WHAT IF NON-MINIMAL SCENARIO?



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

+.....

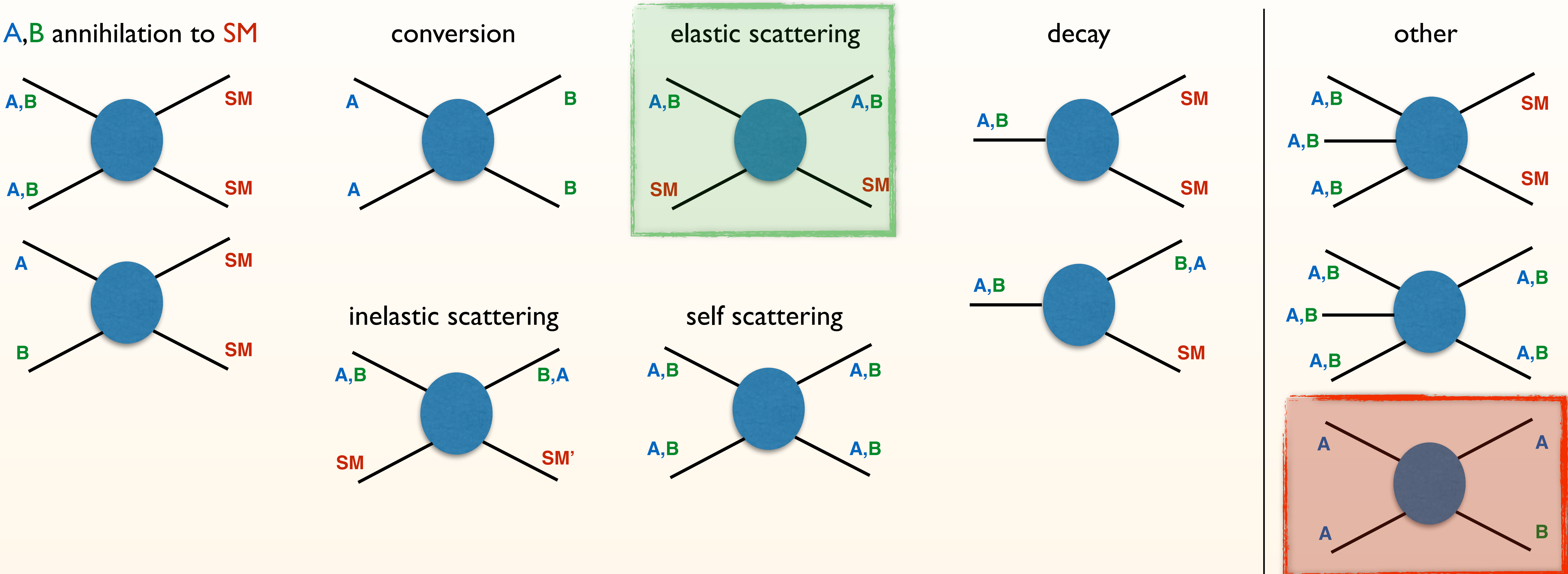
↳ typically forbidden by symmetry

needed to be efficient for mechanism to work

setting the relic density

assumed in computation

What if 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

+…..

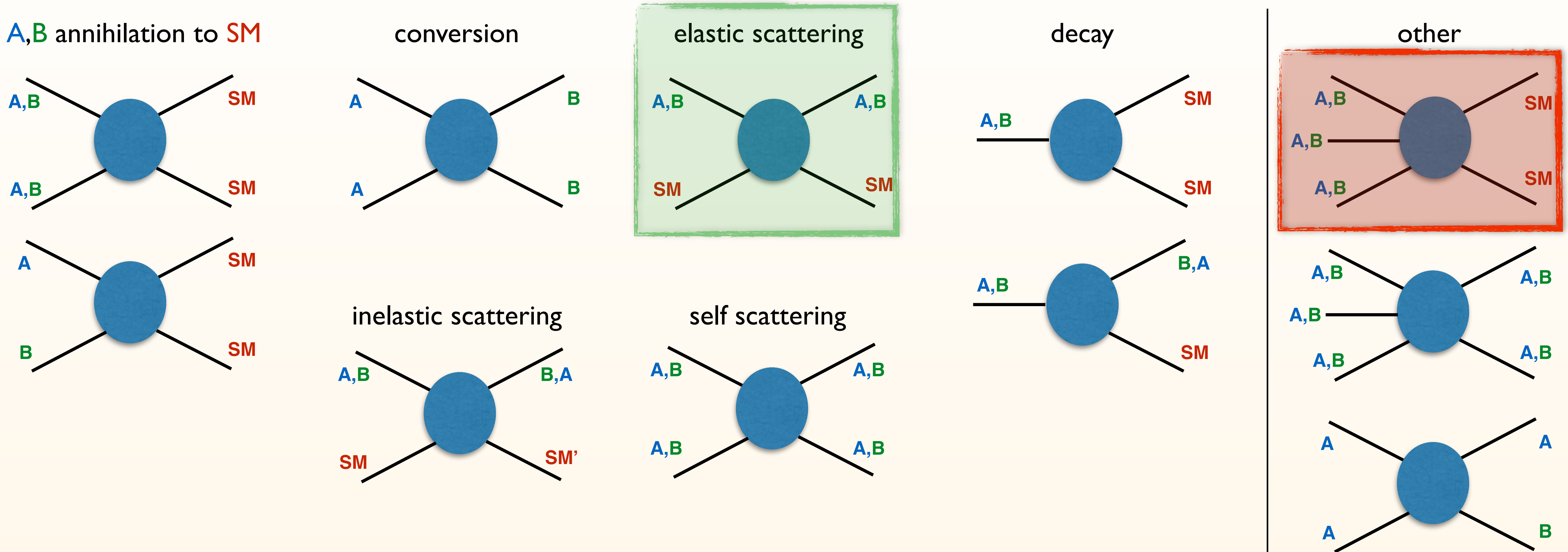
↳ typically forbidden by symmetry

needed to be efficient for mechanism to work

setting the relic density

assumed in computation

What if non-minimal scenario?



+.....

typically forbidden by symmetry

Forbidden-like DM → annihilation to a state heavier than DM, possible from tail of the Boltzmann distribution or when 3-2 processes are non-negligible

e.g., D'Agnolo, Ruderman '15; Cline at al. '17; Choi at al. '17;

needed to be efficient for mechanism to work

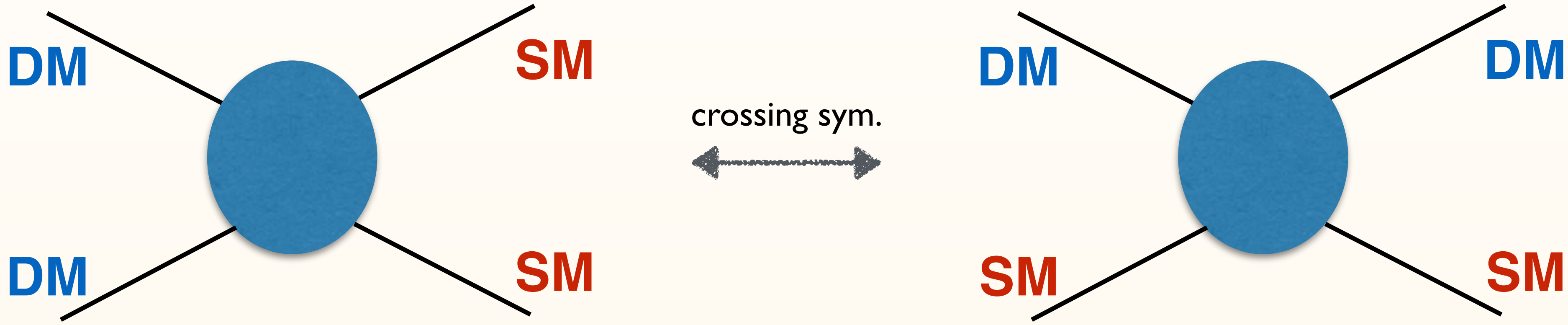
setting the relic density

assumed in computation

Kinetic Decoupling

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:

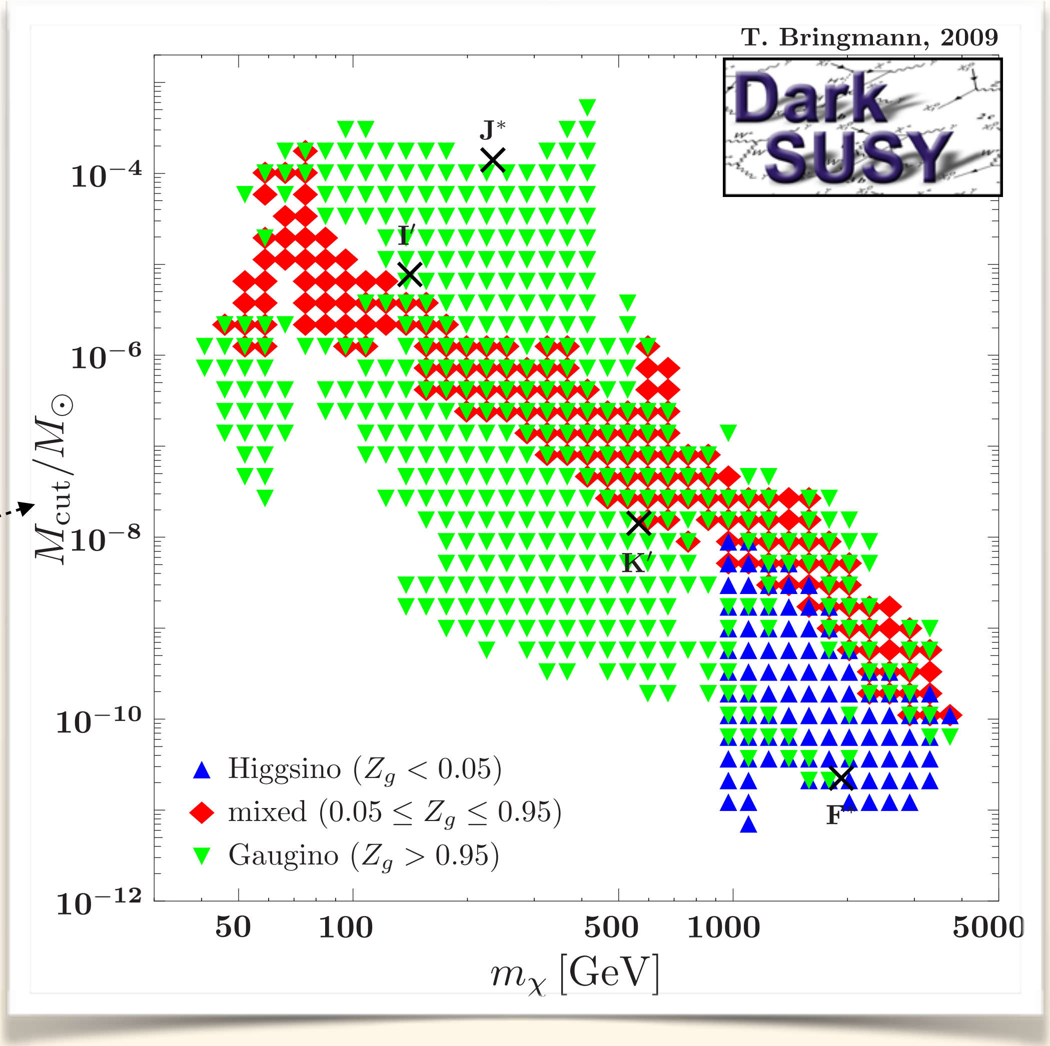
1. During freeze-out (chemical decoupling) <u>typically</u>: $f_\chi \sim a(\mu) f_\chi^{\text{eq}}$
2. If kinetic decoupling much, much later: possible impact on the matter power spectrum

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

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

Implications of Kinetic Decoupling

E.g. for SUSY neutralino: Bringmann '09



Free-streaming of DM after KD washes out density contrasts at small scales (similarly to baryonic oscillations)

Green, Hofmann, Schwarz '05

Cut-off in the power spectrum corresponding to smallest gravitationally bound objects

„Typical" values for WIMPs are relatively small ⟶ small substructures expected

⟶ but bad for missing satellites problem

$\Longrightarrow$ moment of KD leaves important imprint on the Universe

A Pitfall in a Nutshell

T ↑

$\Gamma_{\rm ann} > H$ — DM in equilibrium

$\Gamma_{\rm ann} \sim H$ — chemical decoupling

$\Gamma_{\rm ann} < H$ — freeze-out

time ↓

can it happen?

typically

kinetic decoupling

If KD happens around CD ⟶ what would be the relic density?

↓

how to even compute that? ⟹ need for refined treatment of solving the Boltzmann eq.

assuming kinetic equilibrium at chemical decoupling: $f_\chi \sim a(\mu) f_\chi^{\rm eq}$

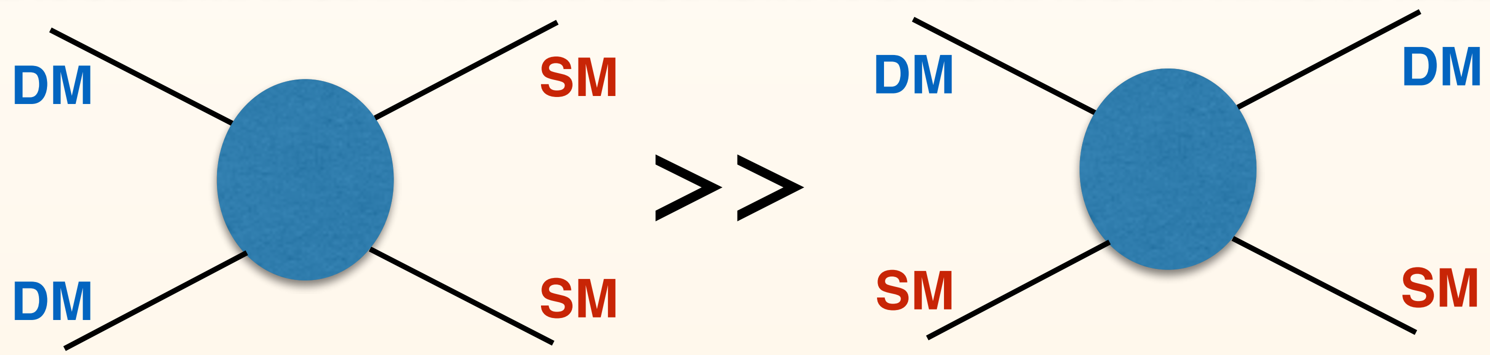
$$C_{\rm LO} = -\langle \sigma_{\chi\bar{\chi}\to ij} v_{\rm rel}\rangle^{\rm eq} \left(n_\chi n_{\bar{\chi}} - n_\chi^{\rm eq} n_{\bar{\chi}}^{\rm eq}\right)$$

EARLY KINETIC DECOUPLING?

A necessary and sufficient condition: scatterings weaker than annihilation

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

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,…

Early KD and resonance

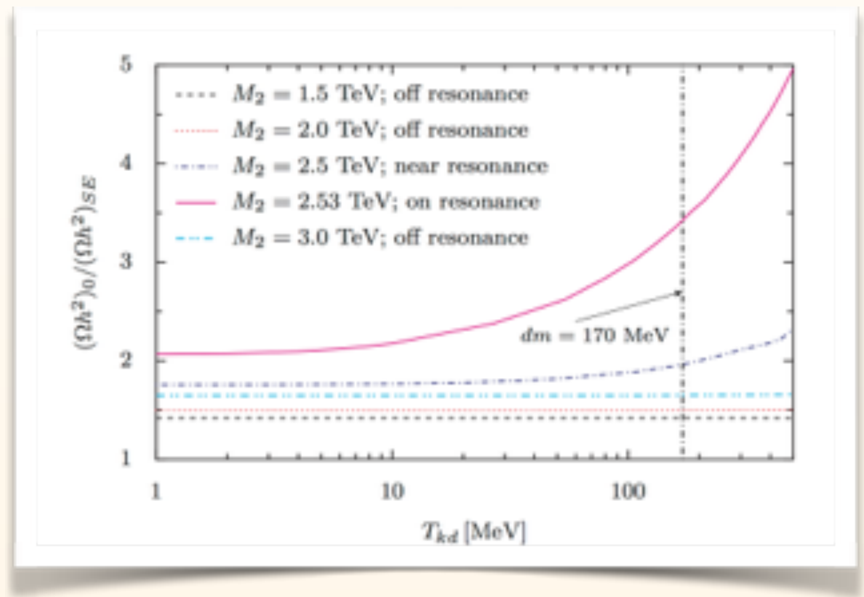
our work wasn't the first to realize that resonant annihilation can lead to early kinetic decoupling…

Feng, Kaplinghat, Yu '10 — noted that for Sommerfeld-type resonances KD can happen early

Dent, Dutta, Scherrer '10 — looked at potential effect of KD on thermal relic density

Since then people were aware of this effect and sometimes tried to estimate it assuming instantaneous KD, e.g., in the case of Sommerfeld effect in the MSSM:

but no systematic studies of decoupling process were performed, until…



AH, Iengo, Ullio '11

…models with very late KD become popular, in part to solve „missing satellites" problem

van den Aarssen et al '12; Bringmann et al '16, x2; Binder et al '16

this progress allowed for better approach to early KD scenarios as well and was applied to the resonant annihilation case in

Duch, Grządkowski '17

… but we developed a dedicated accurate method/code to deal with this and other similar situations

How to describe KD?

All information is in 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 annihilation

Two possible approaches:

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

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

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

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

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

SCATTERING

The elastic scattering collision term:

$$C_{\rm el} = \frac{1}{2g_\chi}\int\frac{d^3k}{(2\pi)^3 2\omega}\int\frac{d^3\tilde{k}}{(2\pi)^3 2\tilde{\omega}}\int\frac{d^3\tilde{p}}{(2\pi)^3 2\tilde{E}}$$
$$\times(2\pi)^4\delta^{(4)}(\tilde{p}+\tilde{k}-p-k)|\mathcal{M}|^2_{\chi f\leftrightarrow\chi f}$$
$$\times\left[(1\mp g^\pm)(\omega)\,g^\pm(\tilde{\omega})f_\chi(\tilde{\mathbf{p}})-(\omega\leftrightarrow\tilde{\omega},\mathbf{p}\leftrightarrow\tilde{\mathbf{p}})\right]$$

→ equilibrium functions for SM particles

Expanding in **NR** and small **momentum transfer**: Bringmann, Hofmann '06

$$C_{\rm el}\simeq\frac{m_\chi}{2}\gamma(T)\left[Tm_\chi\partial_p^2+\left(p+2T\frac{m_\chi}{p}\right)\partial_p+3\right]f_\chi$$

More generally, Fokker-Planck scattering operator (relativistic, but still small **momentum transfer**): Binder et al. '16

physical interpretation: scattering rate

$$C_{\rm el}\simeq\frac{E}{2}\nabla_{\mathbf{p}}\cdot\left[\gamma(T,\mathbf{p})\left(ET\nabla_{\mathbf{p}}+\mathbf{p}\right)f_\chi\right]$$

Semi-relativistic: assume that scattering $\gamma(T,\mathbf{p})$ is momentum independent

KINETIC DECOUPLING 101

DM temperature Definition:

$$T_\chi \equiv \frac{g_\chi}{3 m_\chi n_\chi} \int \frac{\mathrm{d}^3 p}{(2\pi)^3} p^2 f_\chi(p) \qquad y \equiv \frac{m_\chi T_\chi}{s^{2/3}}$$

actually: normalized average NR energy - equals temperature at equilibrium

First take late KD scenario and consider only temperature evolution - i.e. leave out feedback **on/from** changing number density:

then 2nd moment of full BE (up to terms p^2/m_χ^2) gives:

$$\frac{y'}{y} = -\frac{Y'}{Y}\left(1 - \frac{\langle \sigma v_{\rm rel}\rangle_2}{\langle \sigma v_{\rm rel}\rangle}\right) - \left(1 - \frac{x}{3}\frac{g'_{*S}}{g_{*S}}\right)\frac{2 m_\chi c(T)}{H x}\left(1 - \frac{y_{\rm eq}}{y}\right)$$

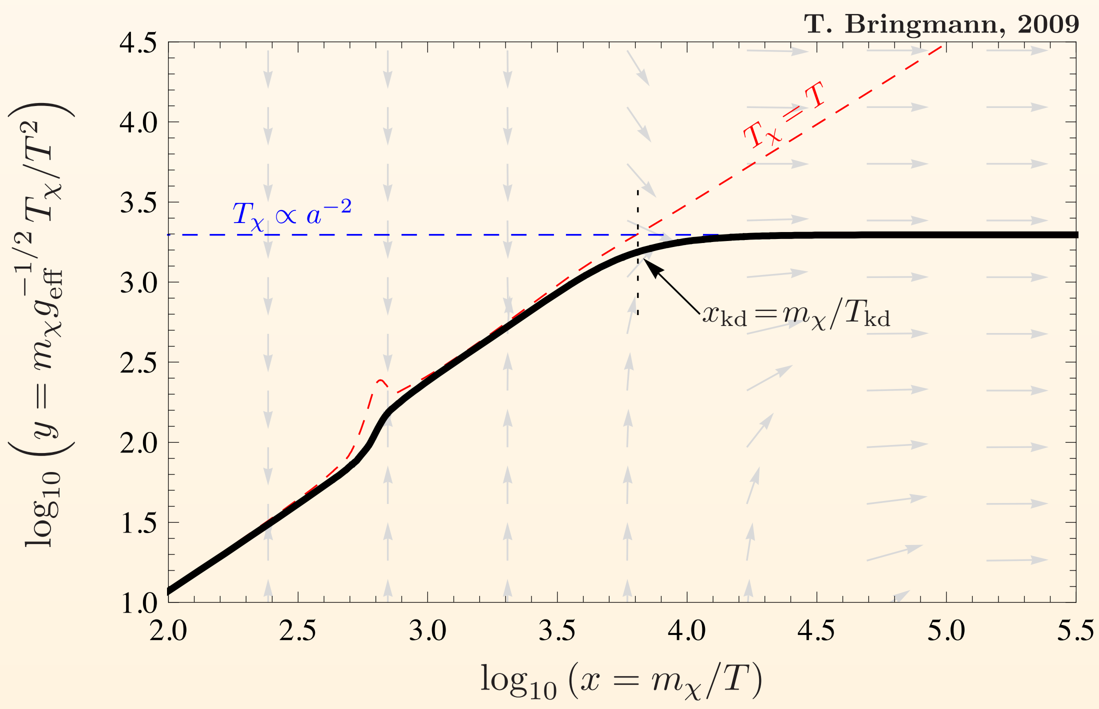
where:

$$\langle \sigma v_{\rm rel}\rangle_2 \equiv \frac{g_\chi^2}{3 T m_\chi n_\chi^2} \int \frac{d^3 p}{(2\pi)^3} \int \frac{d^3 \tilde{p}}{(2\pi)^3}\, p^2 v_{\rm rel} \sigma_{\bar{\chi}\chi \to \bar{X}X} f(E) f(\tilde{E})$$

impact of annihilation

$$c(T) = \frac{1}{12(2\pi)^3 m_\chi^4 T} \sum_X \int dk\, k^5 \omega^{-1} g^{\pm}\left(1 \mp g^{\pm}\right) \int_{-4k^2}^{0} (-t) \frac{1}{8k^4} |\mathcal{M}_{\rm el}|^2$$

impact of elastic scatterings



ONE STEP FURTHER…

Now consider general KD scenario, i.e. coupled temperature and number density evolution:

annihilation and production thermal averages done at different T — feedback of modified y evolution

$$\frac{Y'}{Y} = -\frac{1-\frac{x}{3}\frac{g'_{*S}}{g_{*S}}}{Hx} sY \left(\langle\sigma v_{\rm rel}\rangle|_{x=m_\chi^2/(s^{2/3}y)} - \frac{Y_{\rm eq}^2}{Y^2}\langle\sigma v_{\rm rel}\rangle|_x \right)$$

$$\frac{y'}{y} = -\frac{1-\frac{x}{3}\frac{g'_{*S}}{g_{*S}}}{Hx} \left[2m_\chi c(T)\left(1-\frac{y_{\rm eq}}{y}\right) - sY\left(\left(\langle\sigma v_{\rm rel}\rangle - \langle\sigma v_{\rm rel}\rangle_2\right)_{x=m_\chi^2/(s^{2/3}y)} - \frac{Y_{\rm eq}^2}{Y^2}\left(\langle\sigma v_{\rm rel}\rangle - \frac{y_{\rm eq}}{y}\langle\sigma v_{\rm rel}\rangle_2\right)_x \right) \right]$$

$$+\frac{1-\frac{x}{3}\frac{g'_{*S}}{g_{*S}}}{3m_\chi}\langle p^4/E^3\rangle_{x=m_\chi^2/(s^{2/3}y)}$$

"relativistic" term

$$T_\chi \equiv \frac{g_\chi}{3n_\chi}\int\frac{d^3p}{(2\pi)^3}\frac{p^2}{E}f_\chi(p)$$

elastic scatterings term

impact of annihilation

These equations still assume the equilibrium shape of $f_\chi(p)$ — but with variant temperature

or more accurately: that the thermal averages computed with true non-equilibrium distributions don't differ much from the above ones

NUMERICAL APPROACH

… or one can just solve full phase space Boltzmann eq.

$$
\begin{aligned}
\partial_x f_\chi(x,q) \;&=\; \frac{m_\chi^3}{\tilde{H}x^4}\frac{g_{\bar\chi}}{2\pi^2}\int d\tilde{q}\;\tilde{q}^2\,\frac{1}{2}\int d\cos\theta\;\; v_{\text{Møl}}\sigma_{\bar\chi\chi\to\bar f f} \\
&\quad \times\left[f_{\chi,\text{eq}}(q)f_{\chi,\text{eq}}(\tilde q) - f_\chi(q)f_\chi(\tilde q)\right] \\
&\quad + \frac{2m_\chi c(T)}{2\tilde{H}x}\left[x_q\partial_q^2 + \left(q+\frac{2x_q}{q}+\frac{q}{x_q}\right)\partial_q + 3\right] f_\chi \\
&\quad + \tilde{g}\frac{q}{x}\partial_q f_\chi,
\end{aligned}
$$

fully general

expanded in NR and small momentum transfer
(semi-relativistic!)

discretization,
~1000 steps

$$
\begin{aligned}
\partial_x f_i \;&=\; \\
&\frac{m_\chi^3}{\tilde{H}x^4}\frac{g_{\bar\chi}}{2\pi^2}\sum_{j=1}^{N-1}\frac{\Delta\tilde q_j}{2}\Big[\tilde q_j^2\,\langle v_{\text{Møl}}\sigma_{\bar\chi\chi\to\bar f f}\rangle_{i,j}^\theta\left(f_i^{\text{eq}}f_j^{\text{eq}} - f_i f_j\right) \\
&+\; \tilde q_{j+1}^2\,\langle v_{\text{Møl}}\sigma_{\bar\chi\chi\to\bar f f}\rangle_{i,j+1}^\theta\left(f_i^{\text{eq}}f_{j+1}^{\text{eq}} - f_i f_{j+1}\right)\Big] \\
&+\; \frac{2m_\chi c(T)}{2\tilde H x}\left[x_{q,i}\partial_q^2 + \left(q_i+\frac{2x_{q,i}}{q_i}+\frac{q_i}{x_{q,i}}\right)\partial_q + 3\right] f_i \\
&+\; \tilde g\frac{q_i}{x}\partial_q f_i,
\end{aligned}
$$

Solved numerically with MatLab

Note:

can be extended to e.g. self-scatterings

very stiff, care needed with numerics

EXAMPLE:

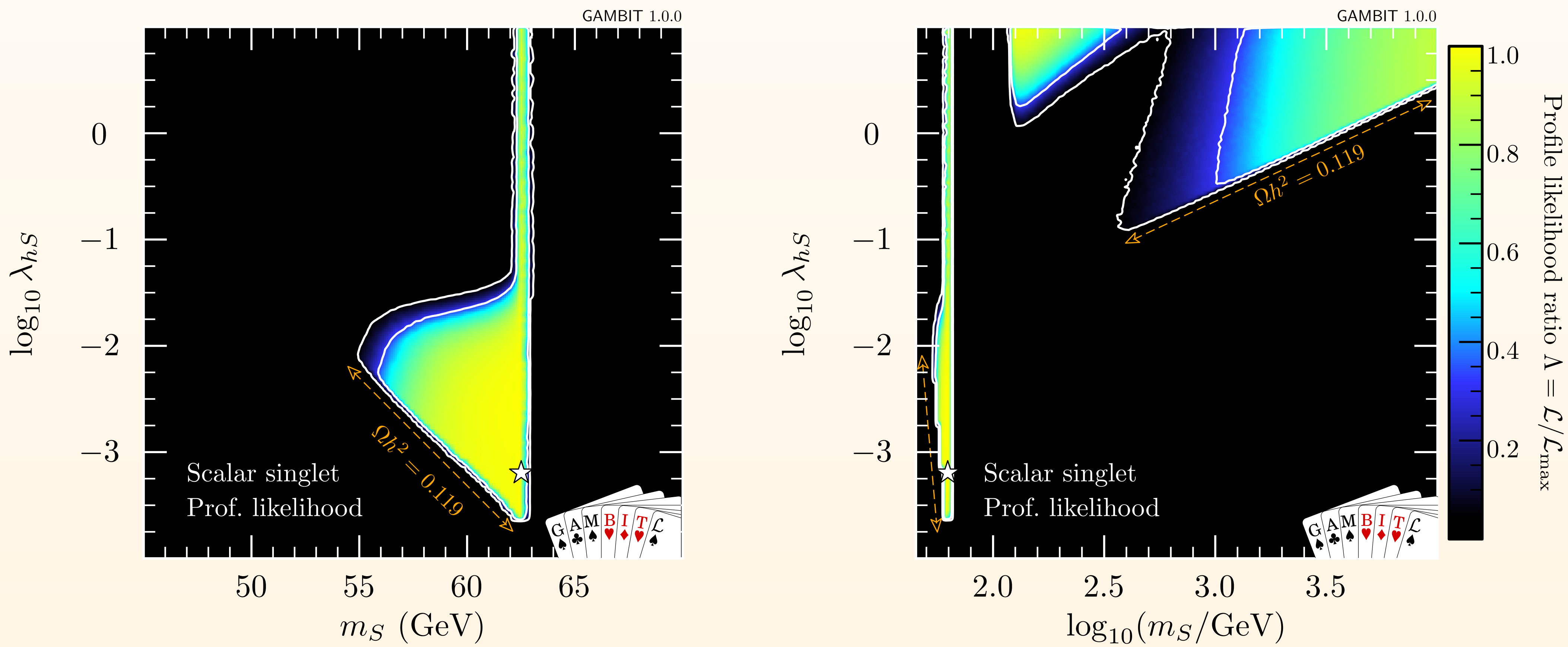
SCALAR SINGLET DM

SCALAR SINGLET DM

VERY SHORT INTRODUCTION

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

$$\mathcal{L}_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}\mu_S^2 S^2 - \frac{1}{2}\lambda_s S^2 |H|^2 \qquad m_s = \sqrt{\mu_S^2 + \frac{1}{2}\lambda_s v_0^2}$$



GAMBIT collaboration
1705.07931

Most of the parameter space excluded, but… even such a simple model is hard to kill

SCALAR SINGLET DM

ANNIHILATION VS. SCATTERINGS

$$\sigma v_{\rm rel} = \frac{2\lambda_s^2 v_0^2}{\sqrt{s}} |D_h(s)|^2 \Gamma_h(\sqrt{s})$$

tabulated Higgs width

with:

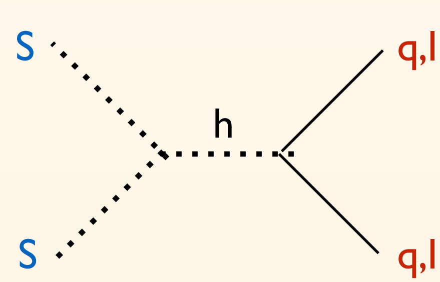
$$|D_h(s)|^2 \equiv \frac{1}{(s-m_h^2)^2 + m_h^2 \Gamma_h^2(m_h)}$$

$$\left\langle |\mathcal{M}|^2 \right\rangle_t = \sum_f \frac{N_f \lambda_S^2 m_f^2}{8k^4} \Big[\frac{2k_{\rm cm}^2 - 2m_f^2 + m_h^2}{1 + m_h^2/(4k_{\rm cm}^2)} - \left(m_h^2 - 2m_f^2\right) \log\left(1 + 4k_{\rm cm}^2/m_h^2\right) \Big] .$$

Hierarchical Yukawa couplings: strongest coupling to more Boltzmann suppressed quarks/leptons

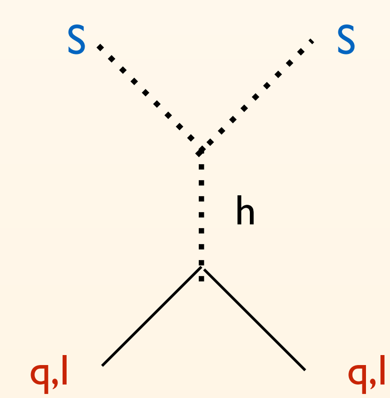
Annihilation processes:

resonant



El. scattering processes:

non-resonant



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

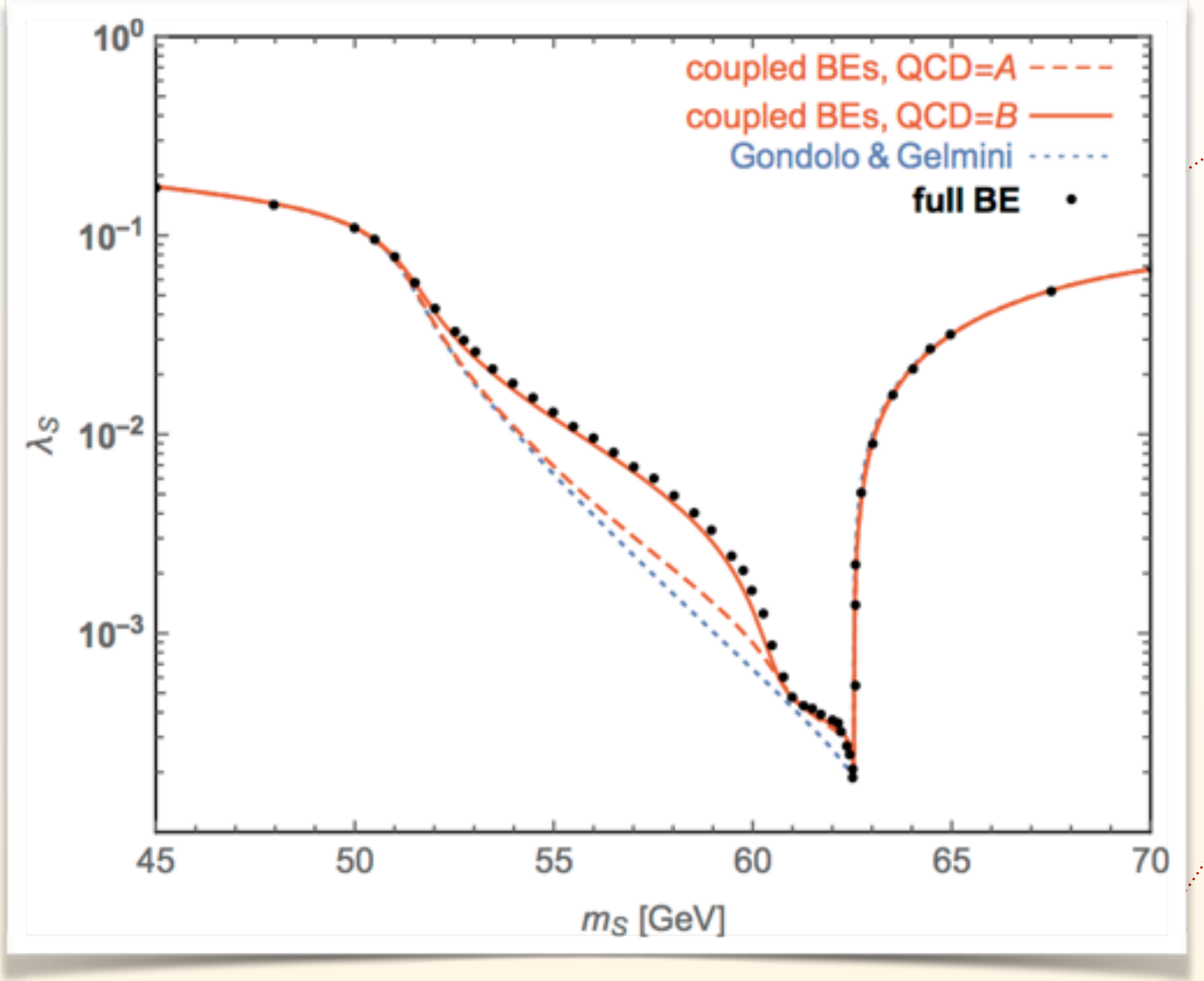
two scenarios:

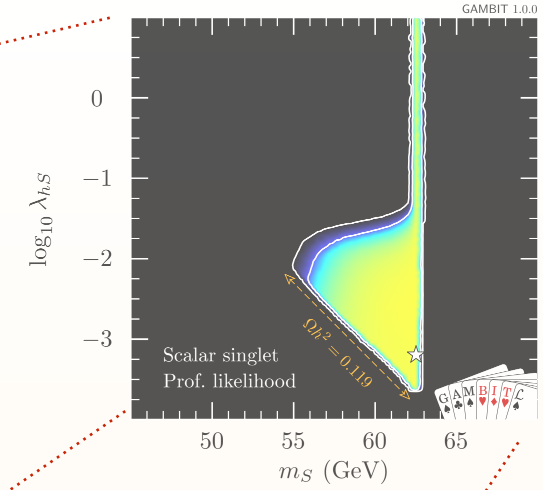
QCD = A - all quarks are free and present in the plasma down to T_c =154 MeV

QCD = B - only light quarks contribute to scattering and only down to $4T_c$

RESULTS

RD CONTOURS





essentially the only region left for this model

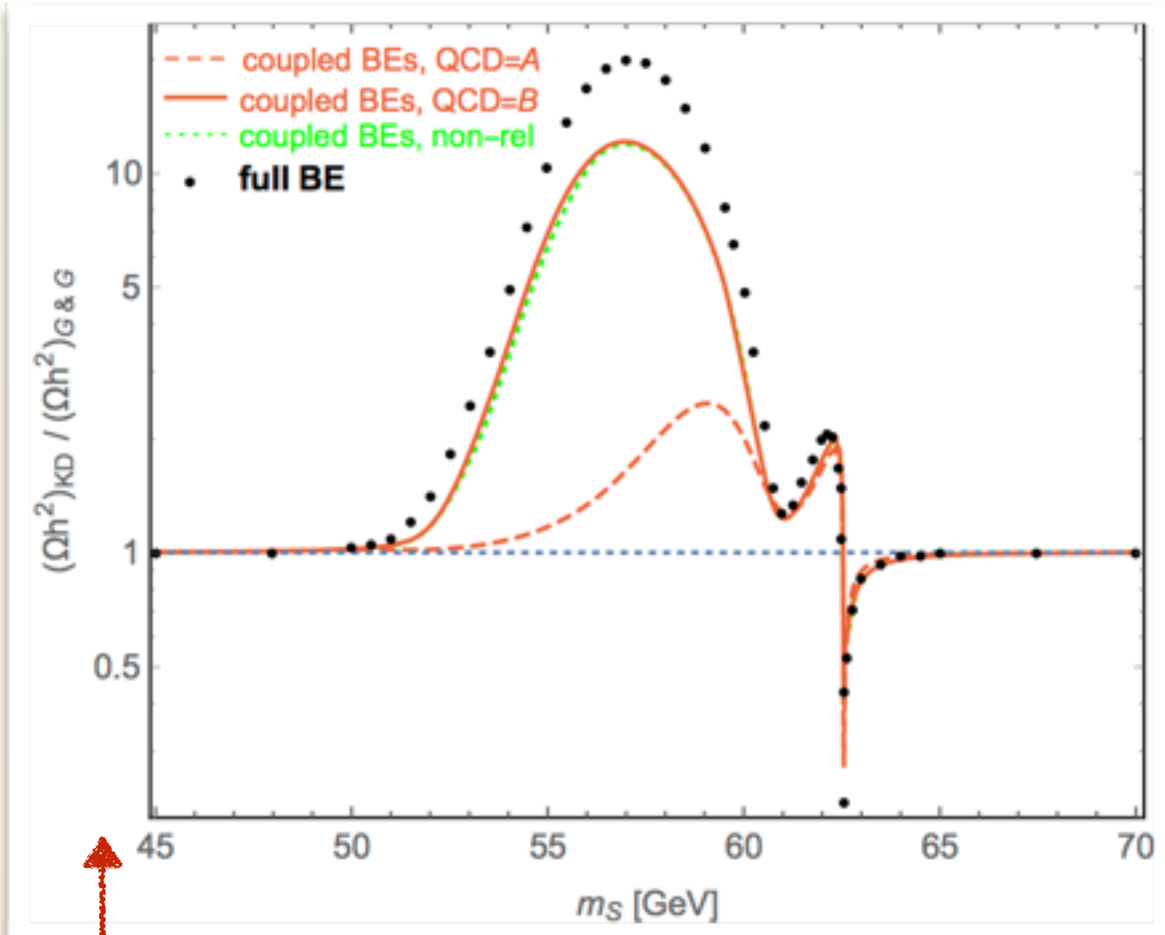
Significant modification of the observed relic density contour in the Scalar Singlet DM model

→ larger coupling needed → better chance for closing the last window

RESULTS

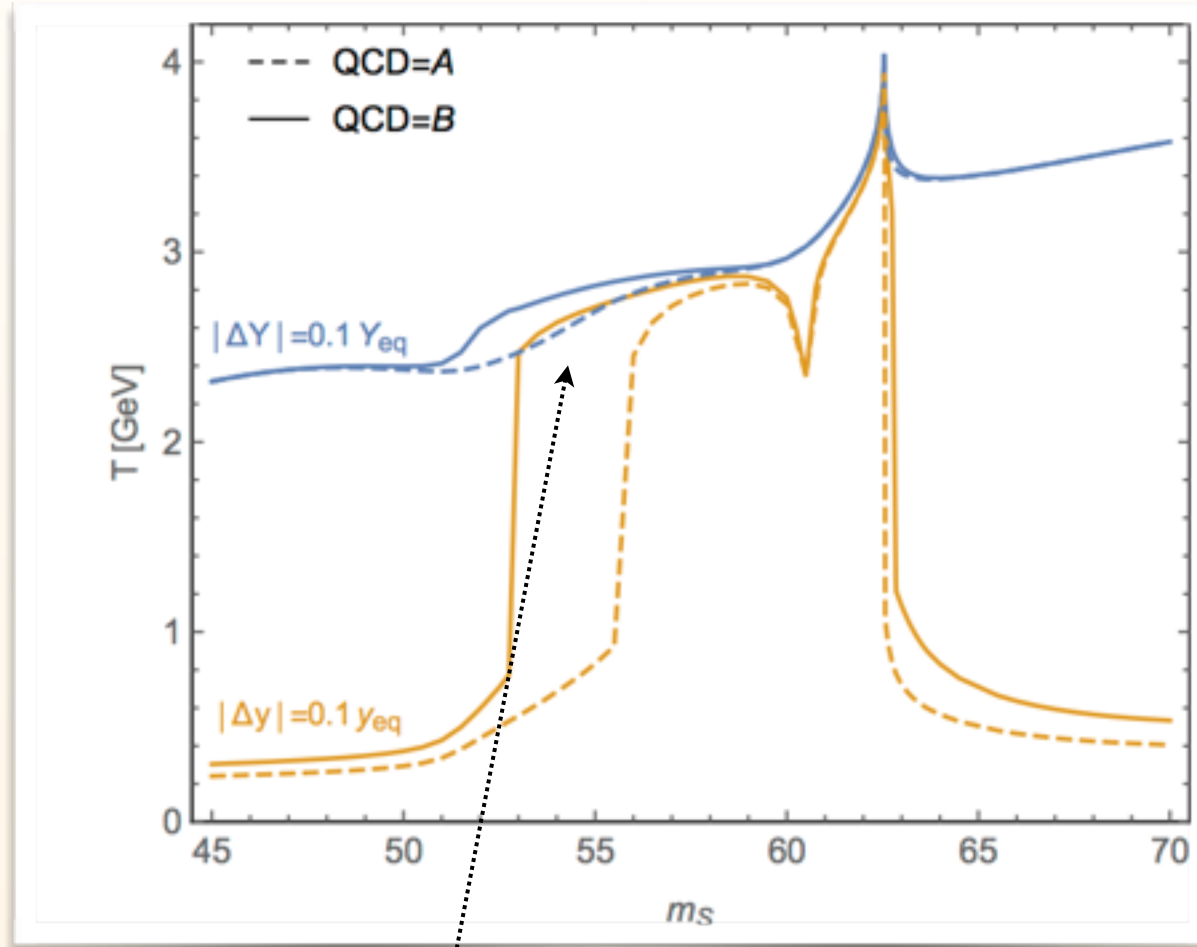
EFFECT

effect on relic density:



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

kinetic and chemical decoupling:



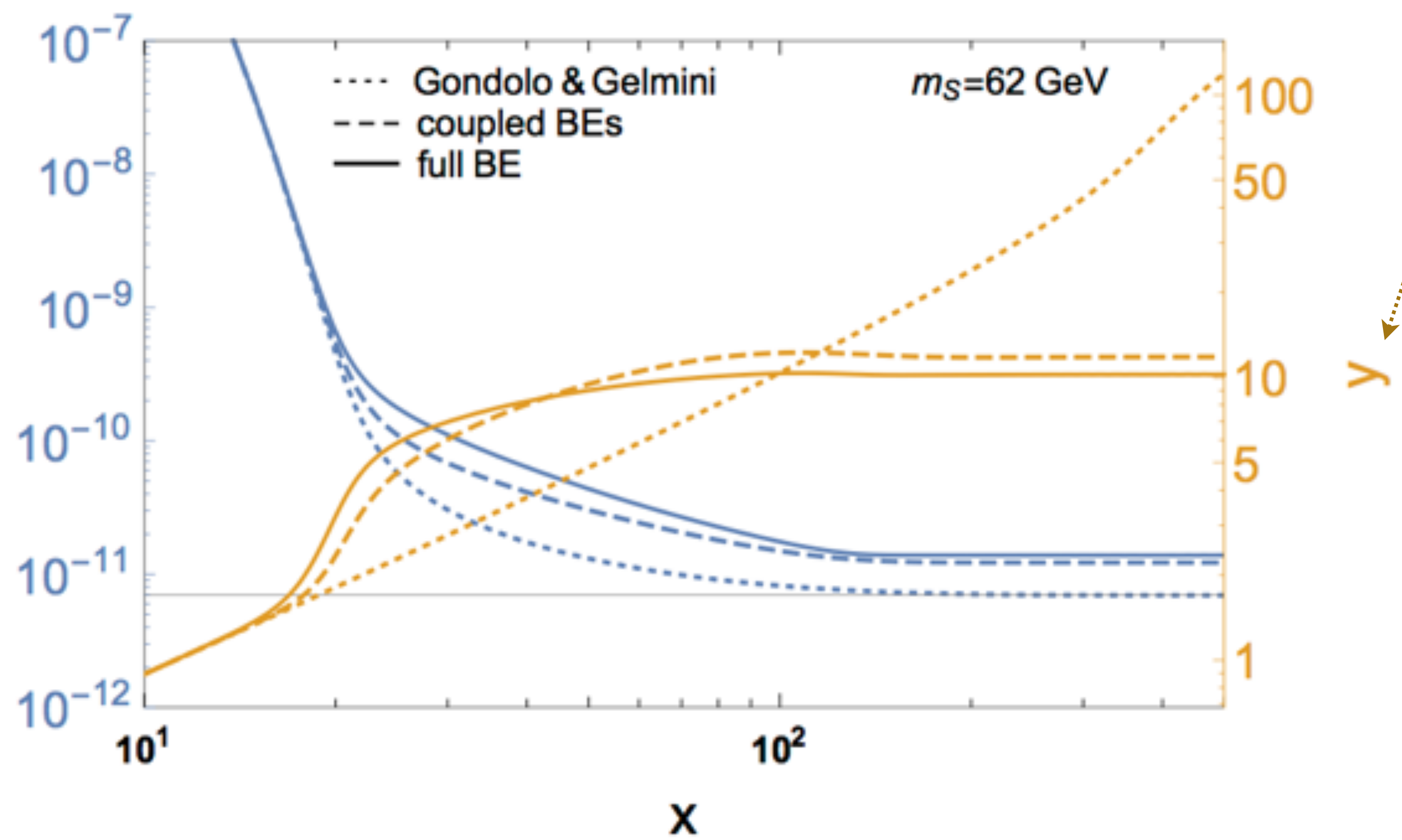
ratio approaches 1,
but does not reach it!

Why such non-trivial shape of the effect of early kinetic decoupling?

→ we'll inspect the y and Y evolution…

DENSITY AND T_{DM} EVOLUTION

for m_{DM} = 62 GeV,   i.e. just below the resonance:



co-moving number density

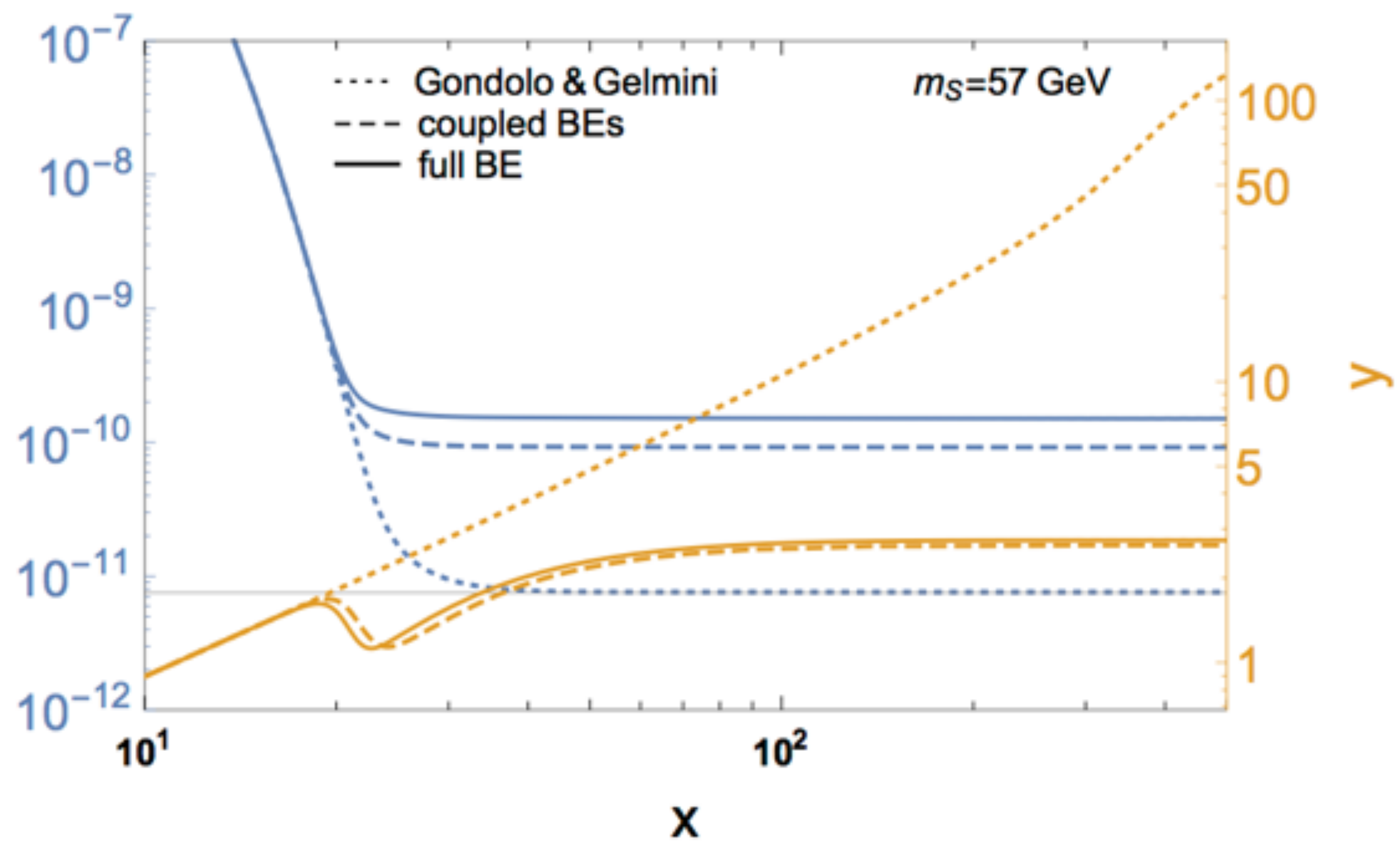
DM temperature

Resonant annihilation **most effective** for **low momenta**

⟶ DM fluid goes through "heating" phase before leaves kinetic equilibrium

DENSITY AND T_{DM} EVOLUTION

for m_{DM} = 57 GeV, i.e. further away from the resonance:

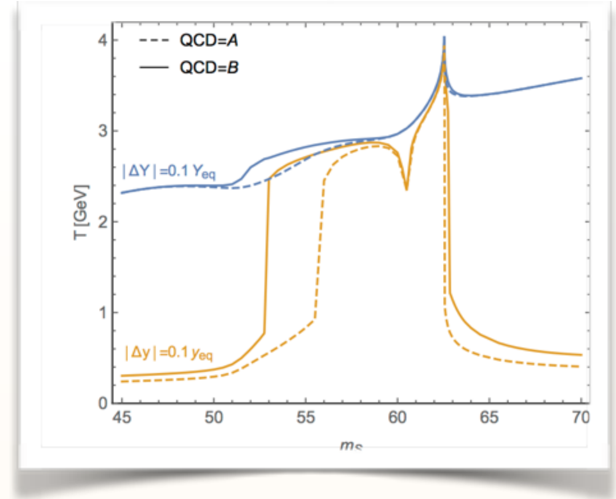


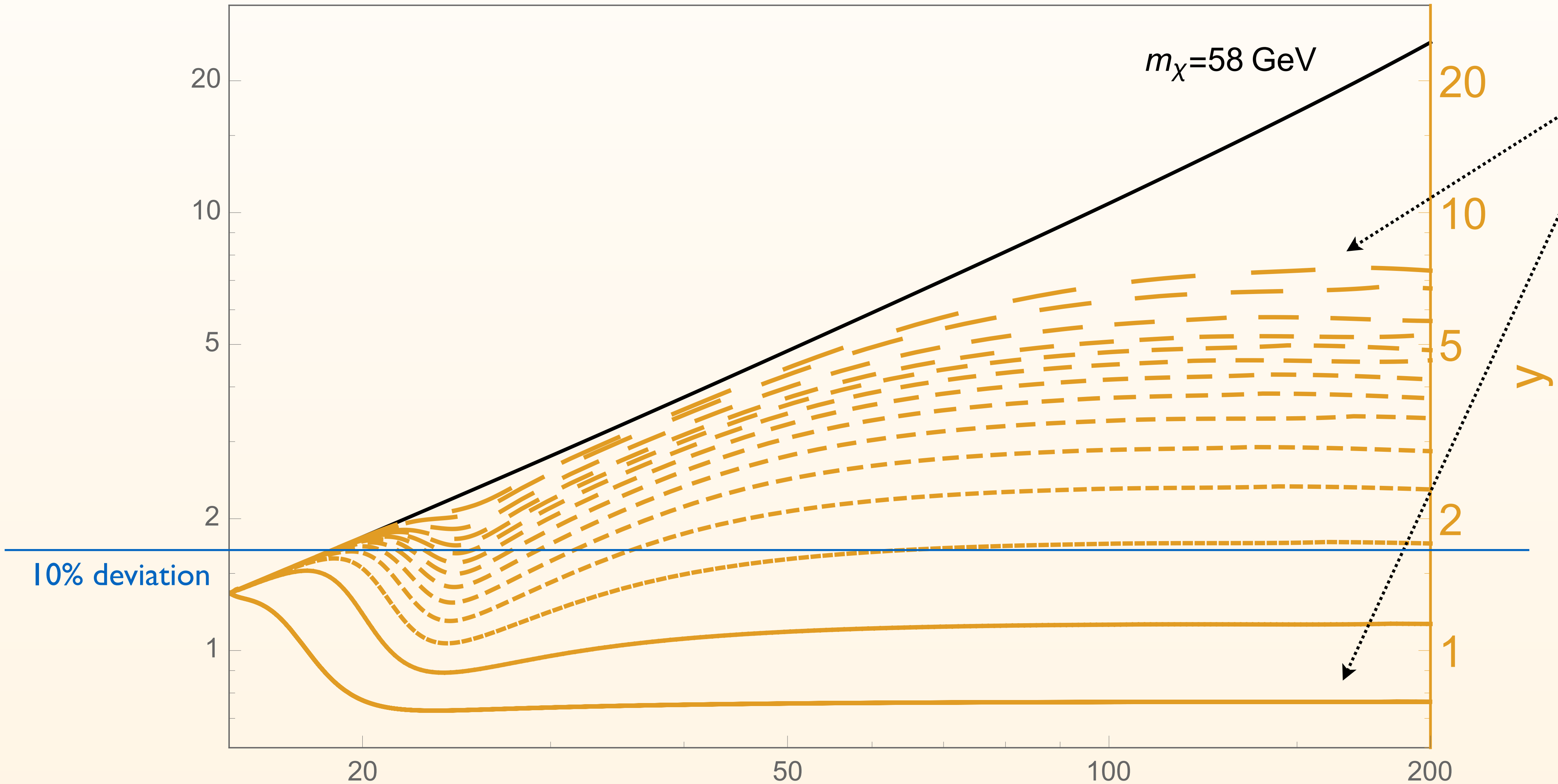
Resonant annihilation **most effective** for **high momenta**

⟶ DM fluid goes through fast "cooling" phase

after that when T_{DM} drops to much annihilation not effective anymore

WHY SPIKES IN T_{KD}?

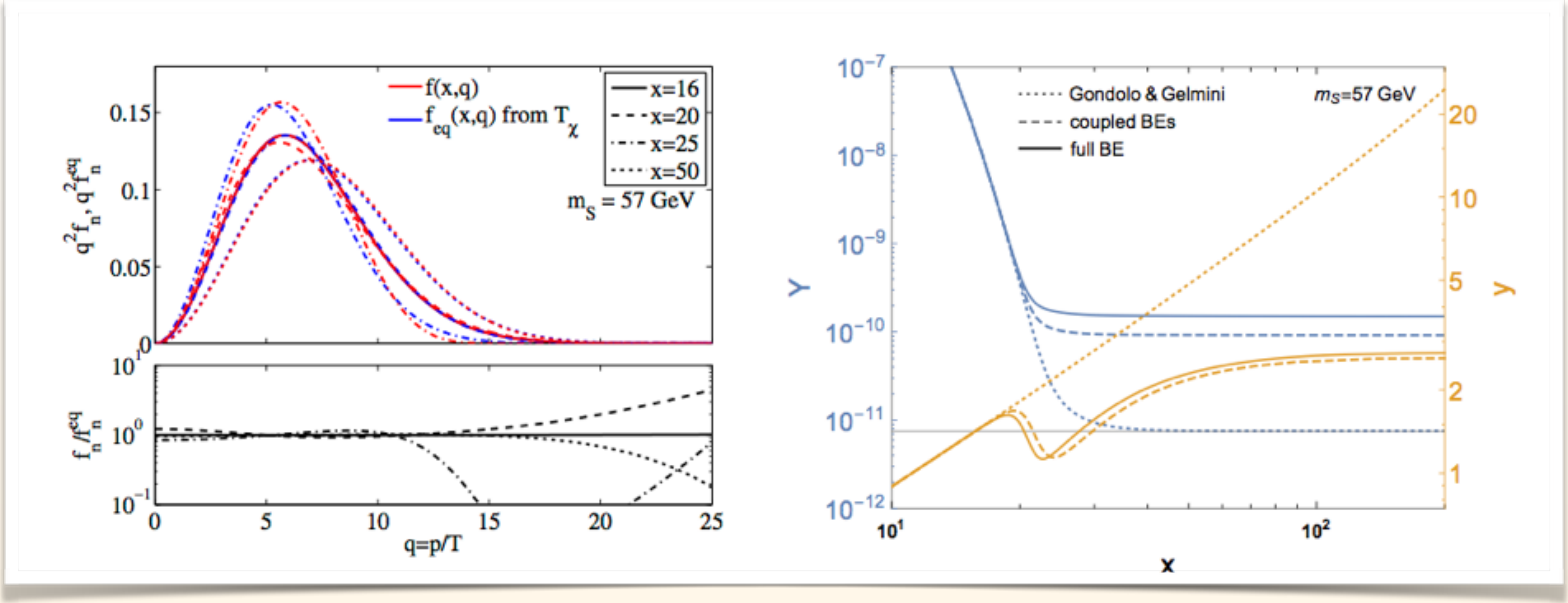




Effect resembling first order „phase transition” —
artificial as dependent on a particular choice of T_{KD} definition

Full phase-space BE solver

Solutions for full phase-space distribution function:



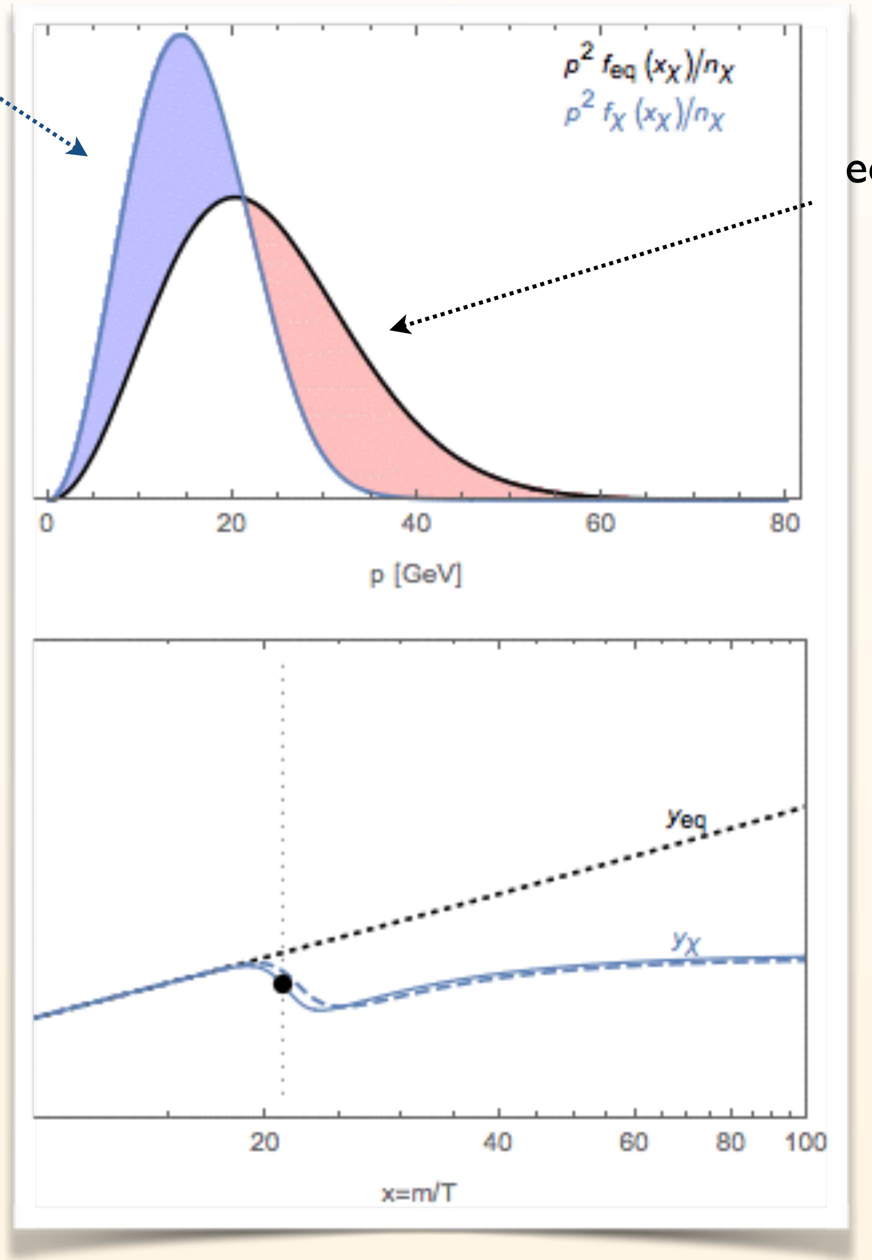
Results of both approaches compatible:
some deviation from equilibrium shape mildly affects the Y and y evolution

Allows to study the evolution of $f_\chi(p)$ and
the interplay between scatterings and annihilation!

FULL PHASE-SPACE EVOLUTION

m_{DM} = 58 GeV

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

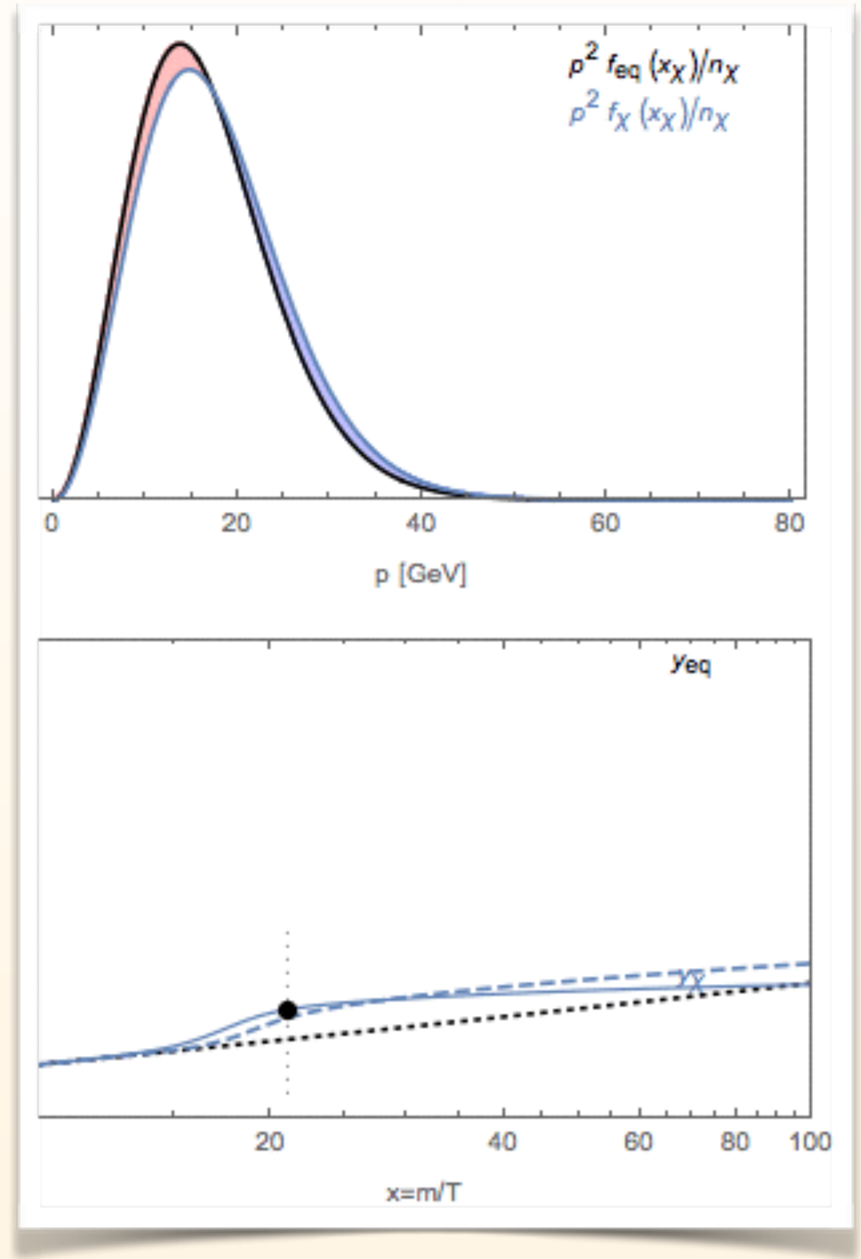


black - equilibrium at T_{DM}

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

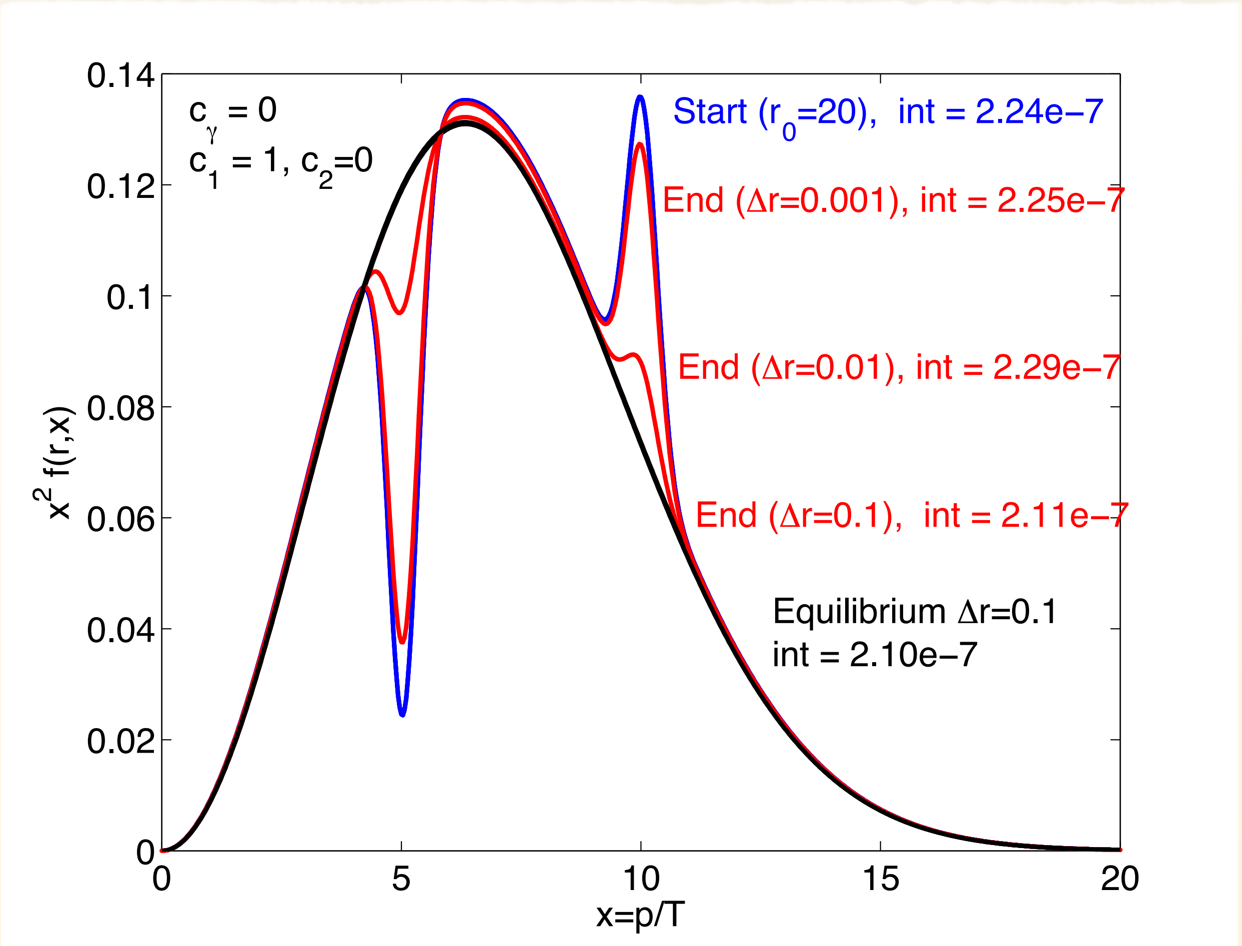
⟶ effect on relic density ~only from different T

KD BEFORE CD?

Obvious issue:
How to <u>define exactly</u> the kinetic and chemical decouplings and what is the significance of such definitions?

$\Downarrow$

Improved question:
Can kinetic decoupling happen <u>much earlier</u> than chemical?



we have already seen that even if scatterings were very inefficient compared to annihilation, departure from equilibrium for both Y and y happened around the same time…

← <u>turn off scatterings</u> and take s-wave annihilation; look at local disturbance

annihilation/production precesses drive to restore kinetic equilibrium!

What next?

1. Extend the numerical full phase space BE code to the case of scattering on heavy particles

(no small momentum transfer approximation!)

2. Prepare a public release and study some more examples

3. Work on extension to self-scattering

(none of the particles in scattering term has equilibrium phase space density)

4. Maybe: in-ealstic scatterings, semi-annihilation, cannibal, …

Conclusions

1. One needs to remember that kinetic equilibrium is a necessary assumption for standard relic density calculations

2. Coupled system of Boltzmann equations for 0th and 2nd moments allow for a very accurate treatment of the kinetic decoupling and its effect on relic density

3. In special cases the full phase space Boltzmann equation can be necessary — especially if one wants to trace DM temperature as well