Non-equilibrium effects in the evolution of Dark Matter

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based on: **T. Binder, T. Bringmann, M. Gustafsson and AH** 1706.07433
A. Hektor, AH and K. Kannike 1901.08074
+ work in progress with **T. Binder, T. Bringmann, M. Gustafsson**

CPT/CPPM Seminar

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Dark Matter

1. We know nearly nothing at all about dark matter

(we don't know *what it is*)

- origin
- nature
- interactions
- structure
- …

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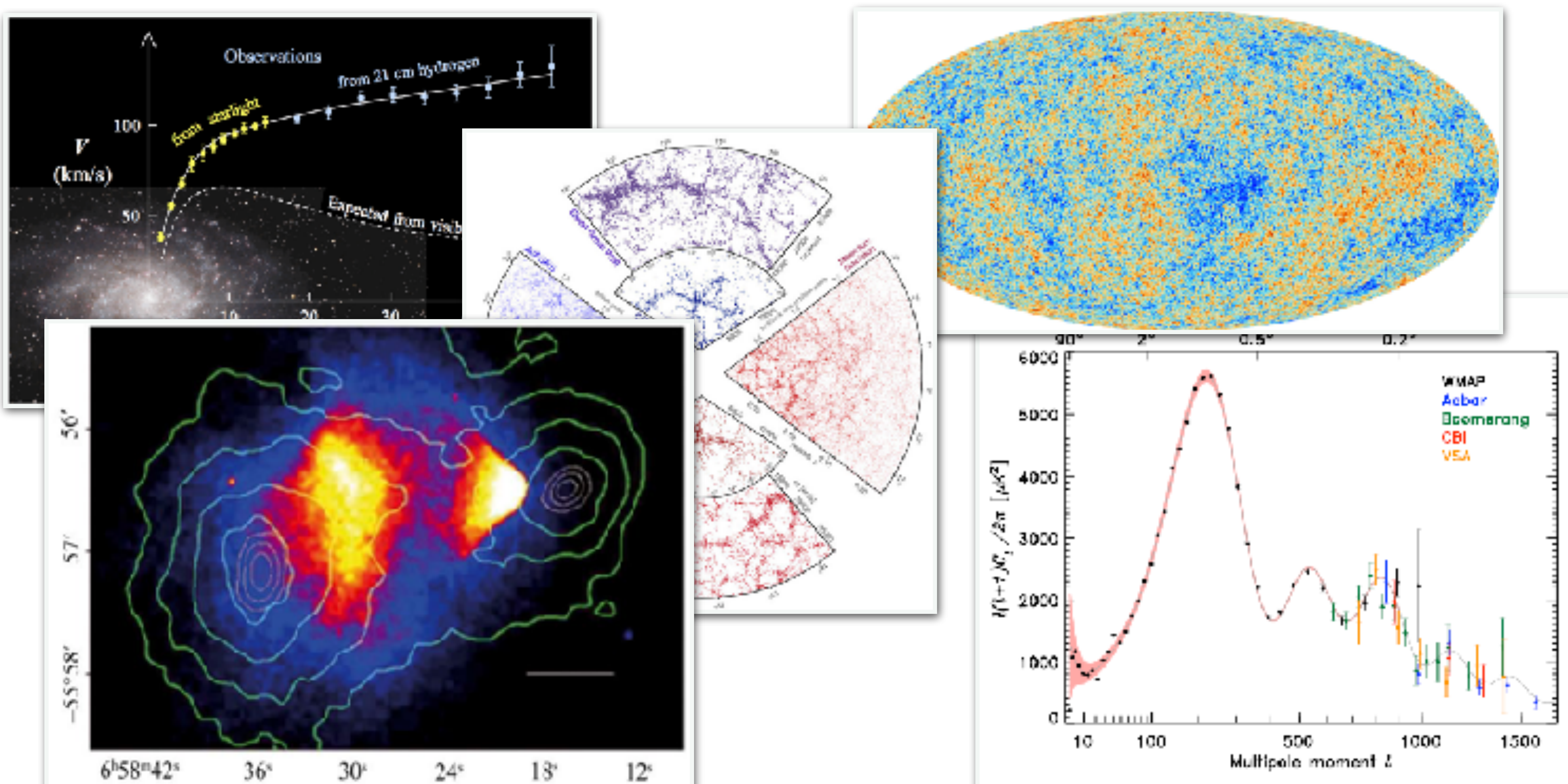
2. We know quite a lot about dark matter

(but we know *what it isn't*)

- it is there!
- particle(s) vs. sth else
- large scale structure
- limits on interactions
- mechanisms of origin
- …

DARK MATTER

I don't think there is any need for convincing you that DM exists…



$\Longrightarrow$ Evidence on all scales!

… but perhaps I should argue why particle DM

Particle Dark Matter

We <u>know</u> that the Standard Model (of particle physics) in <u>not</u> complete*

*neutrino masses, baryogenesis, quantum gravity, …

its extension could *in principle* be extremely minimal… but it is <u>far more likely</u> that there are (many?) new particles we do not know yet

it is quite possible that some of them are stable and then they are **<u>a</u>** dark matter

if so it is very natural to expect that they constitute **<u>the</u>** dark matter

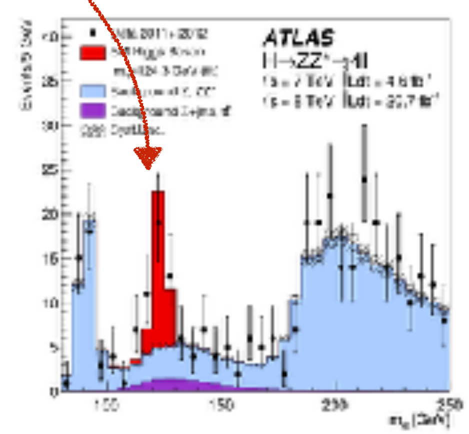
$\Downarrow$

particle DM in not an anomaly
it is a generic prediction
(at least on a qualitative level)

New Physics

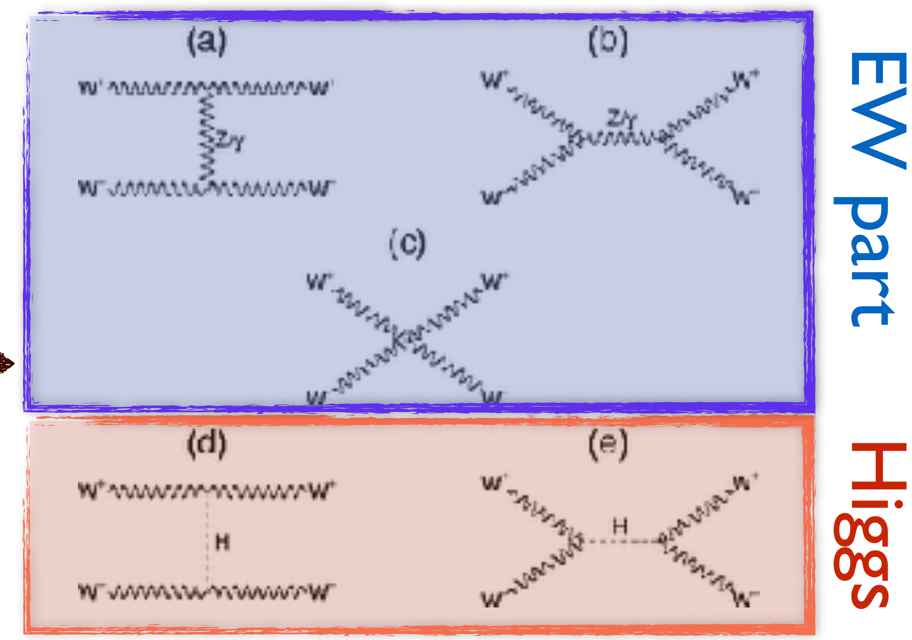
(is always) AROUND THE CORNER

July 2012 - the Higgs boson



since then:

but then we <u>knew</u> sth is there: *vide* so-called unitarization of the WW scattering cross section



Now, after the Higgs was found - **The Hierarchy Problem**

$$\Delta m_h^2 = \frac{3\Lambda^2}{8\pi^2 v^2}\left[4m_t^2 - 2m_W^2 - m_Z^2 - m_h^2\right] + \mathcal{O}\left(\log\frac{\Lambda}{v}\right)$$

or in other words: why is the Higgs boson so light?

THE ORIGIN OF DARK MATTER
AND THE „WIMP MIRACLE"

Dark matter could be created in many different ways…

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

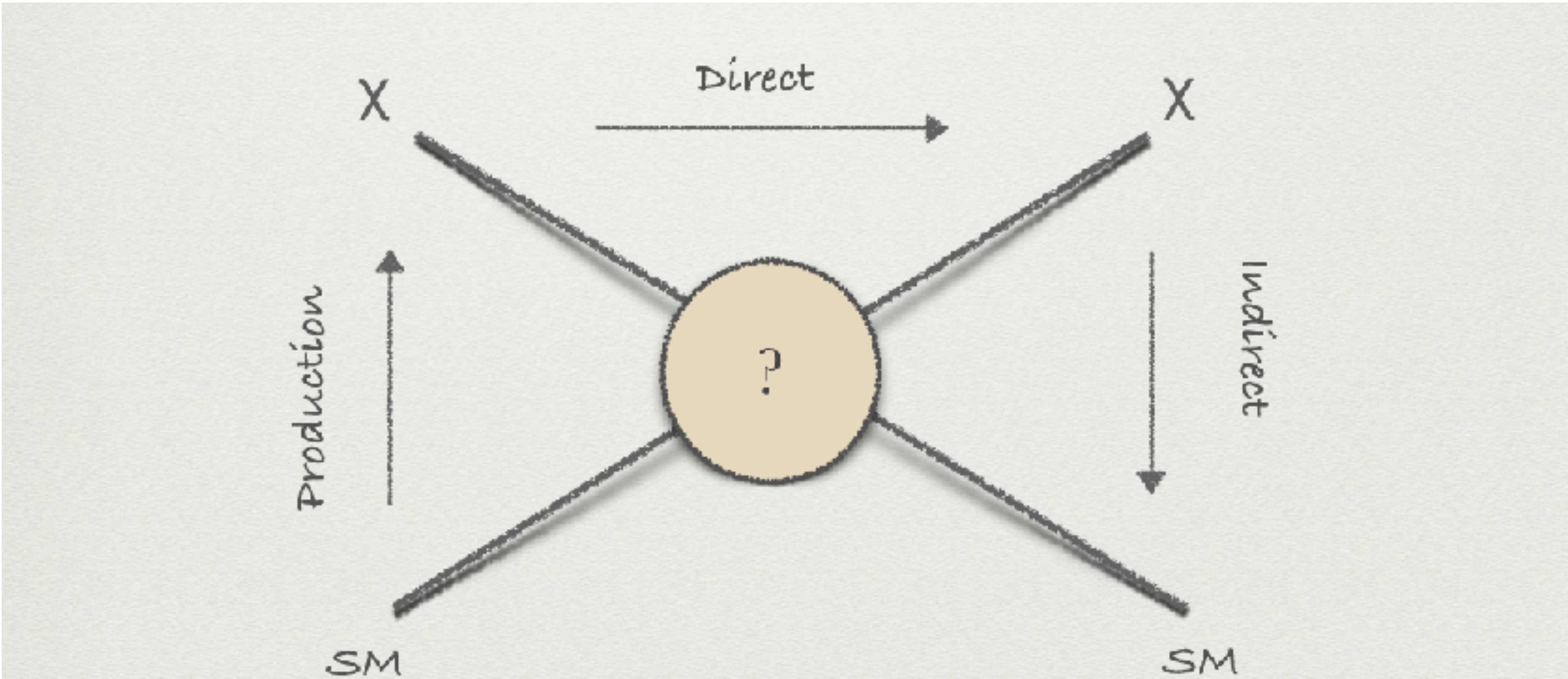
Lee, Weinberg '77; + others

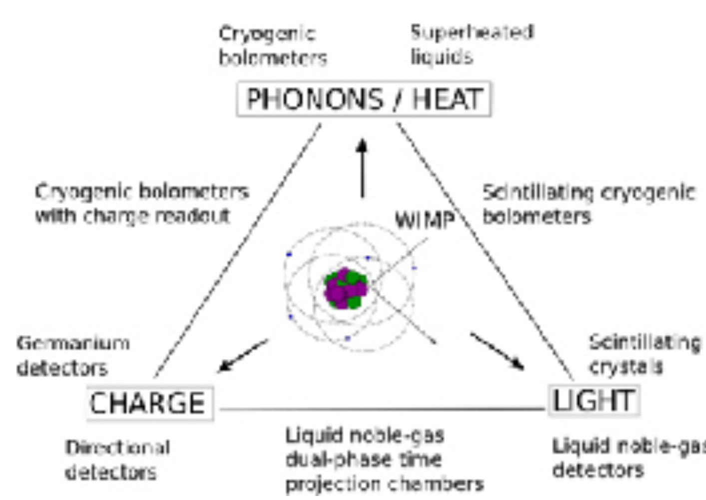
$$\Omega_\chi h^2 \approx 0.1 \, \frac{3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma v \rangle}$$

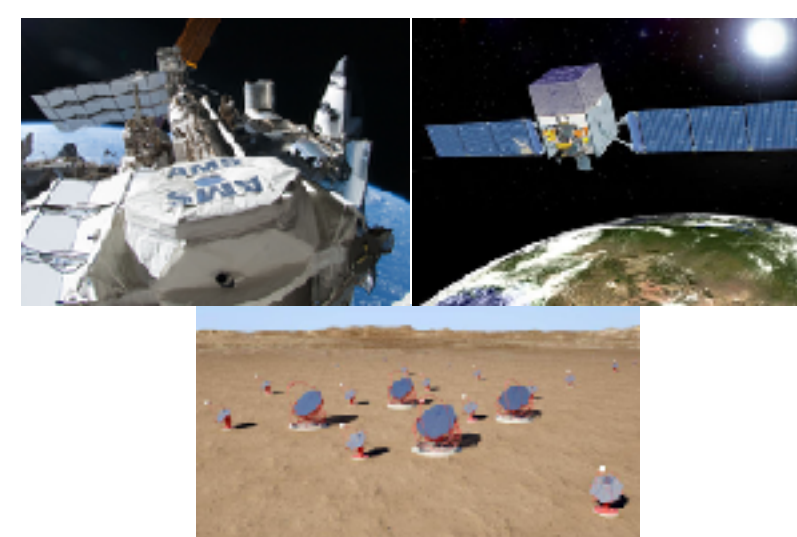
This is dubbed the *WIMP miracle* because it coincidentally seem to point at the same energy scale as suggested by the Hierarchy Problem

T ↑			time ↓
	$\Gamma_{\mathrm{ann}} > H$	DM in equilibrium	
	$\Gamma_{\mathrm{ann}} \sim H$	chemical decoupling	
	$\Gamma_{\mathrm{ann}} < H$	freeze-out	

WIMP DETECTION



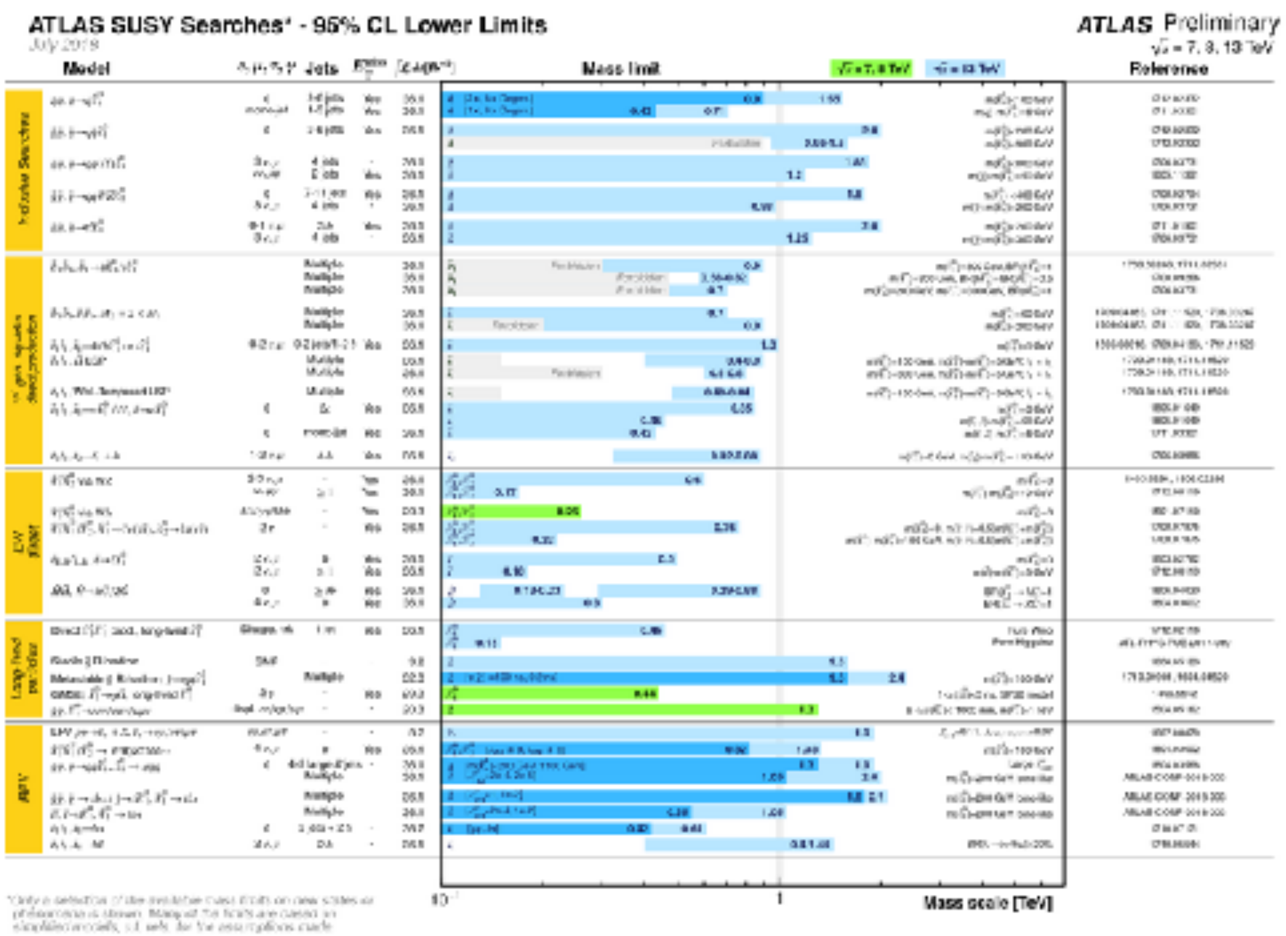


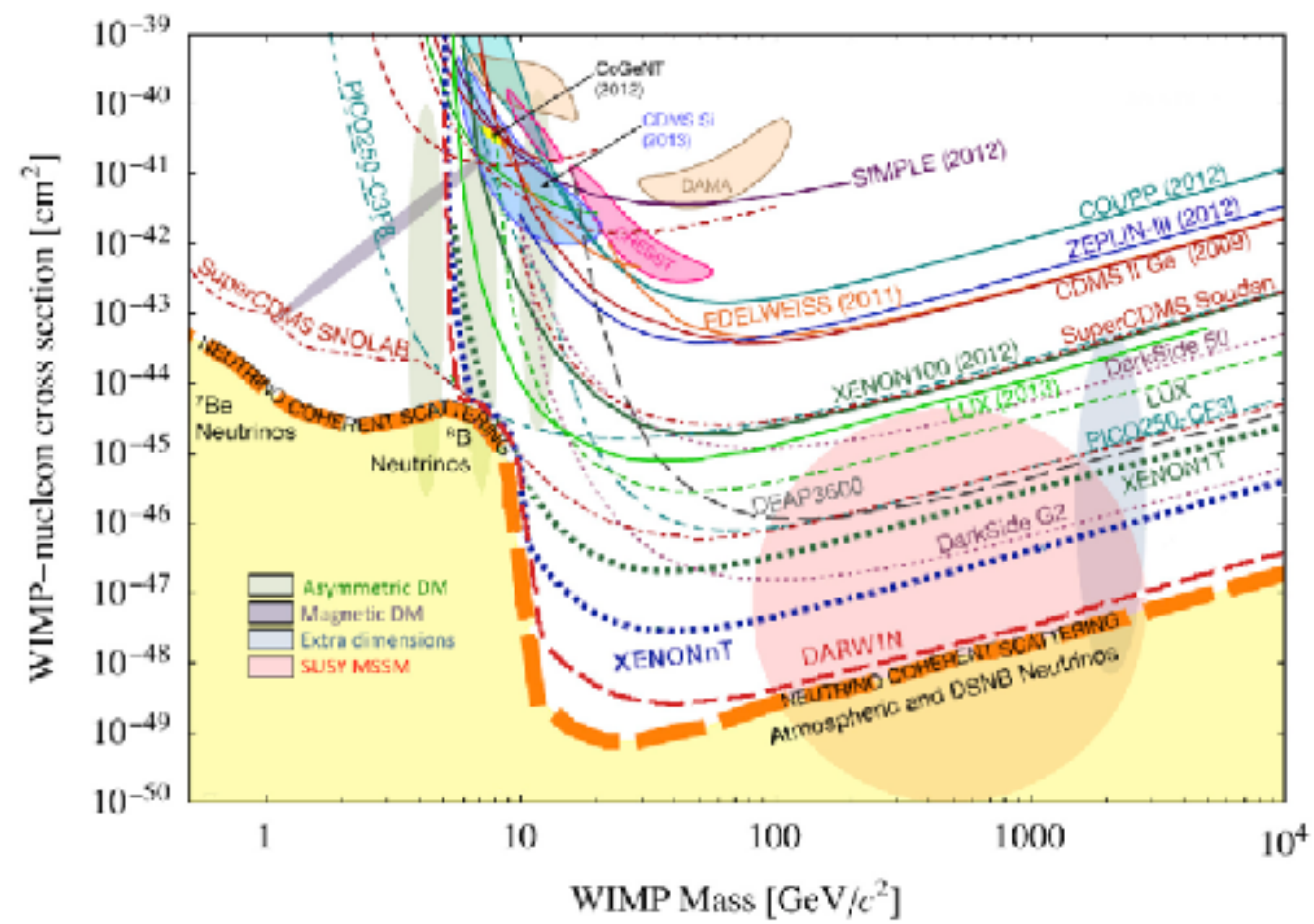


CURRENT LIMITS
AND DECLINE OF THE WIMP PARADIGM

"The great tragedy of science - the slaying of a beautiful hypothesis by an ugly fact"
Aldous Huxley

On both Direct Detection and LHC front no* signal of DM particle!





*convincing

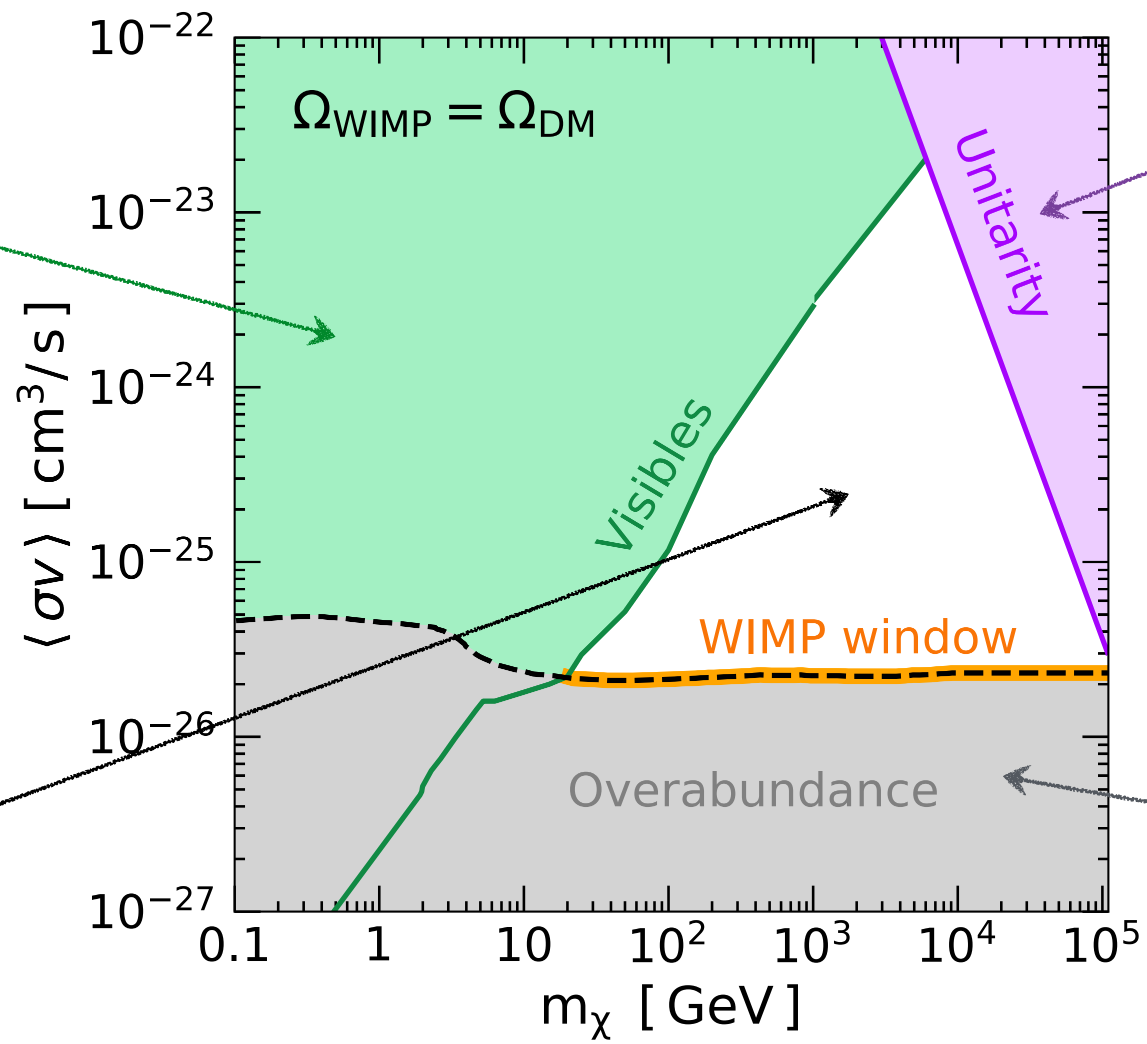
… BUT IN FACT WIMP
NOT EVEN SLIGHTLY DEAD

Most of the (strongest) limits are based on assumptions motivated by theoretical prejudice (or convenience)

→ this can lead to a very broad-brush conclusions

excluded by observations

predicted probabilities can be >1



all fine!

too much dark matter

R. Leane *et al*; 1805.10305

TIME FOR A NEW PARADIGM?

A New Era in the Quest for Dark Matter

Gianfranco Bertone[1] and Tim M.P. Tait[1,2]

ABSTRACT

There is a growing sense of 'crisis' in the dark matter community, due to the absence of evidence for the most popular candidates such as weakly interacting massive particles, axions, and sterile neutrinos, despite the enormous effort that has gone into searching for these particles. Here, we discuss what we have learned about the nature of dark matter from past experiments, and the implications for planned dark matter searches in the next decade. We argue that diversifying the experimental effort, incorporating astronomical surveys and gravitational wave observations, is our best hope to make progress on the dark matter problem.

Nature, volume 562, pages 51–56 (2018)

From HEP perspective it all may feel quite depressing…

(…) the new guiding principle should be "no stone left unturned".

→ i.e. test all ideas in all possible ways…

… but precision cosmology & astrophysics has a potential to provide the so-much needed observational input and show which way to follow

Outline

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

MOTIVATION
THERMAL RELIC DENSITY

Theory:

I. Natural

Comes out automatically from the expansion of the Universe

Naturally leads to cold DM

II. Predictive

No dependence on initial conditions

Fixes coupling(s) $\Rightarrow$ signal in DD, ID & LHC

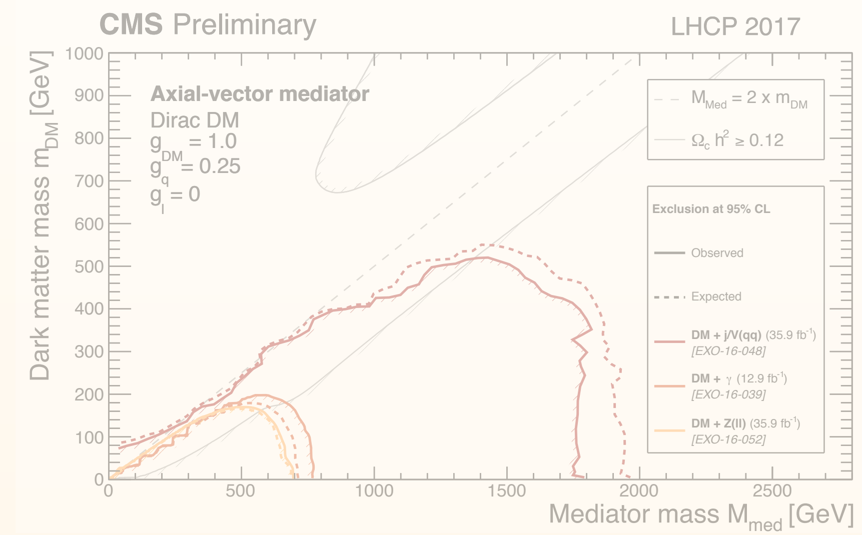
III. It is <u>not</u> optional

Overabundance constraint

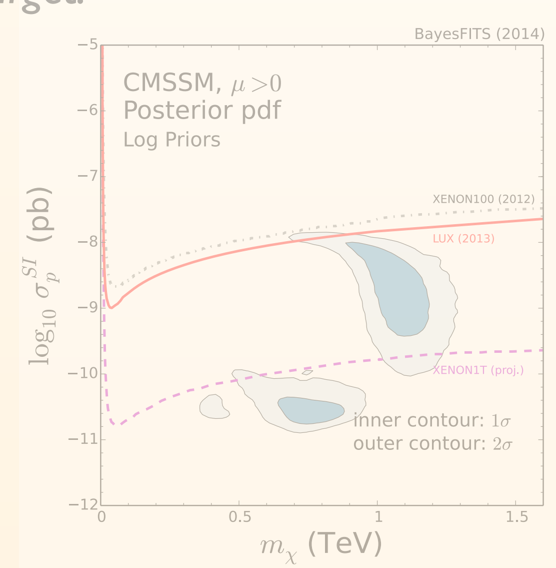
To avoid it one needs quite significant deviations from standard cosmology

Experiment:

…as a constraint:



…as a target:



"(…) besides the Higgs boson mass measurement and LHC direct bounds, the constraint showing **by far the strongest impact** on the parameter space of the MSSM is the **relic density**"

Roszkowski et al. '14

…as a pin:

When a dark matter signal is (finally) found: relic abundance can pin-point the particle physics interpretation

THERMAL RELIC DENSITY

STANDARD APPROACH

T ↑		↓ time
$\Gamma_{\rm ann} > H$	DM in equilibrium
$\Gamma_{\rm ann} \sim H$	**chemical decoupling**
$\Gamma_{\rm ann} < H$	freeze-out

non-equilibrium

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

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

Liouville operator in FRW background

the collision term

integrated

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)

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

where the thermally averaged cross section:

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

$\Downarrow$

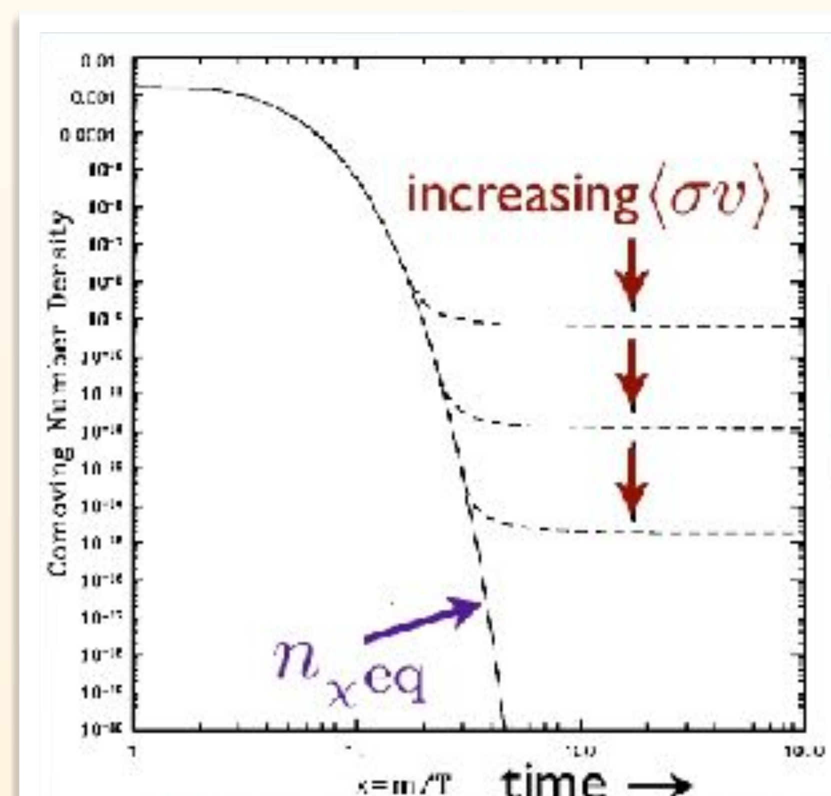


Fig.: Jungman, Kamionkowski & Griest, PR'96

Critical assumption:
kinetic equilibrium at chemical decoupling

$$f_\chi \sim a(\mu) f_\chi^{\mathrm{eq}}$$

Historical Prelude

Three Exceptions

Griest & Seckel '91

1. Co-annihilations

if more than one state share a conserved quantum number making DM stable

$$\langle \sigma_{\rm eff} {\rm v} \rangle = \sum_{ij} \langle \sigma_{ij} {\rm v}_{ij} \rangle \frac{n_i^{\rm eq} n_j^{\rm eq}}{n_{\rm eq}^2}$$

with: $\sigma_{ij} = \sum_X \sigma(\chi_i \chi_j \to X)$

e.g., SUSY

2. Annihilation to forbidden channels

if DM is slightly below mass threshold for annihilation $\Longrightarrow$ „forbidden" channel can still be accessible in thermal bath

recent e.g., 1505.07107

3. Annihilation near poles

expansion in velocity (s-wave, p-wave, etc.) not safe

(more historical issue: these days most people use numerical codes)

THERMAL RELIC DENSITY

MODERN "EXCEPTIONS"

1. Non-standard cosmology

   many works… very recent e.g., D'Eramo, Fernandez, Profumo '17

2. Bound State Formation

   recent e.g., Petraki at al. '15, '16; An et al. '15, '16; Cirelli et al. '16; …

3. 3 → 2 and 4 → 2 annihilation

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

4. Second era of annihilation

   Feng et al. '10; Bringmann et al. '12; …

5. Semi-annihilation

   D'Eramo, Thaler '10; …

6. Cannibalization

   e.g., Kuflik et al. '15; Pappadopulo et al. '16; …

7. …

…in other words: whenever studying non-minimal scenarios "exceptions" appear

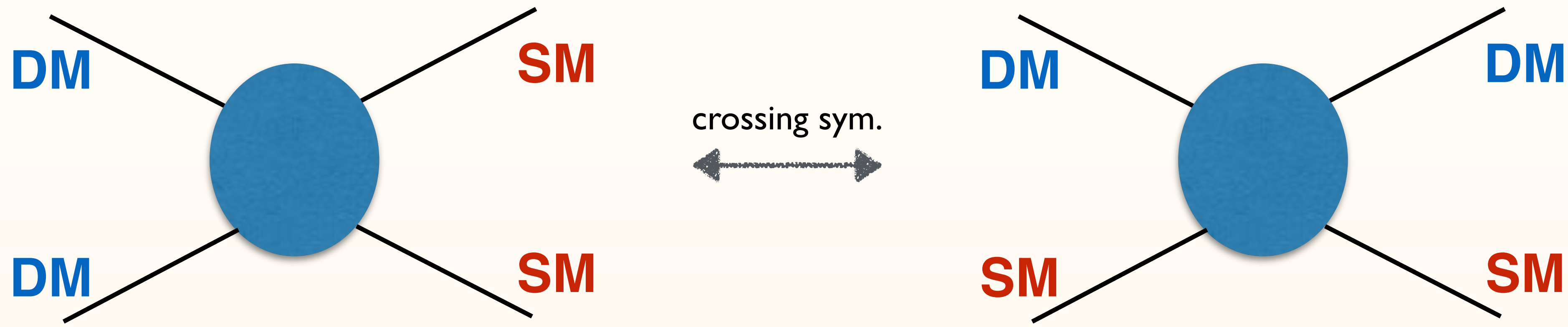
WHAT IF NON-MINIMAL SCENARIO?

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

process \ scenario	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	**first efficient then stops**						
conversion A A <-> B B inelastic scattering A SM <-> B SM	**efficient always**						
elastic scattering A SM <-> A SM B SM <-> B SM	**assumed to be very efficient**						in all scenarios **kinetic equilibrium** assumption crucial, but not always "automatic"!
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							

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

Recall: in *standard* thermal relic density calculation:

Critical assumption:
kinetic equilibrium at chemical decoupling

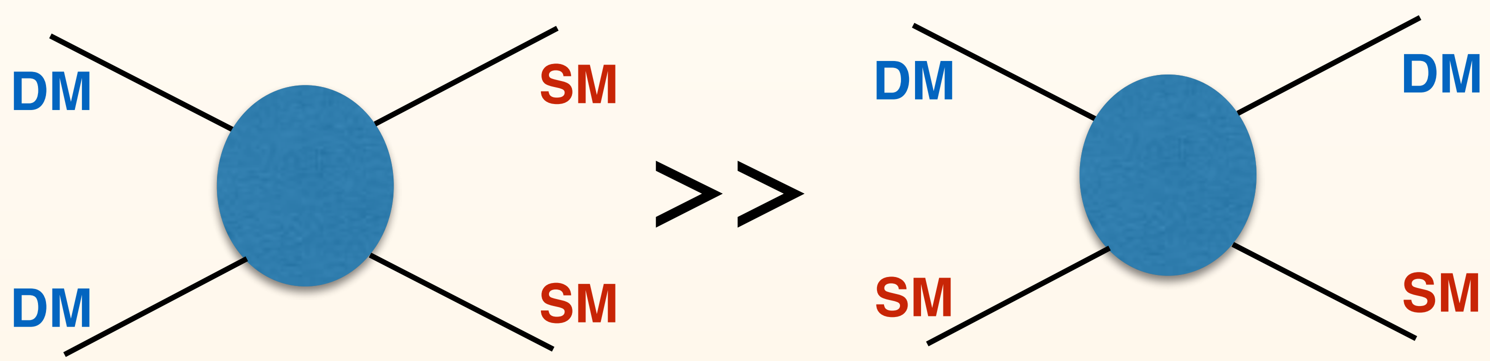
$$f_\chi \sim a(\mu) f_\chi^{\text{eq}}$$

EARLY KINETIC DECOUPLING?

A necessary and sufficient condition: <u>scatterings weaker than annihilation</u>

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,…

How to describe KD?

All information is in 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 annihilation

Two possible approaches:

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

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 $f_\chi(p)$

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

finite range of validity
no insight on the distribution

Kinetic Decoupling 101

DM temperature Definition:

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

actually: normalized average NR energy - equals temperature at equilibrium

First take consider only temperature evolution - then 2nd moment of full BE (up to terms p^2/m_χ^2) gives:

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

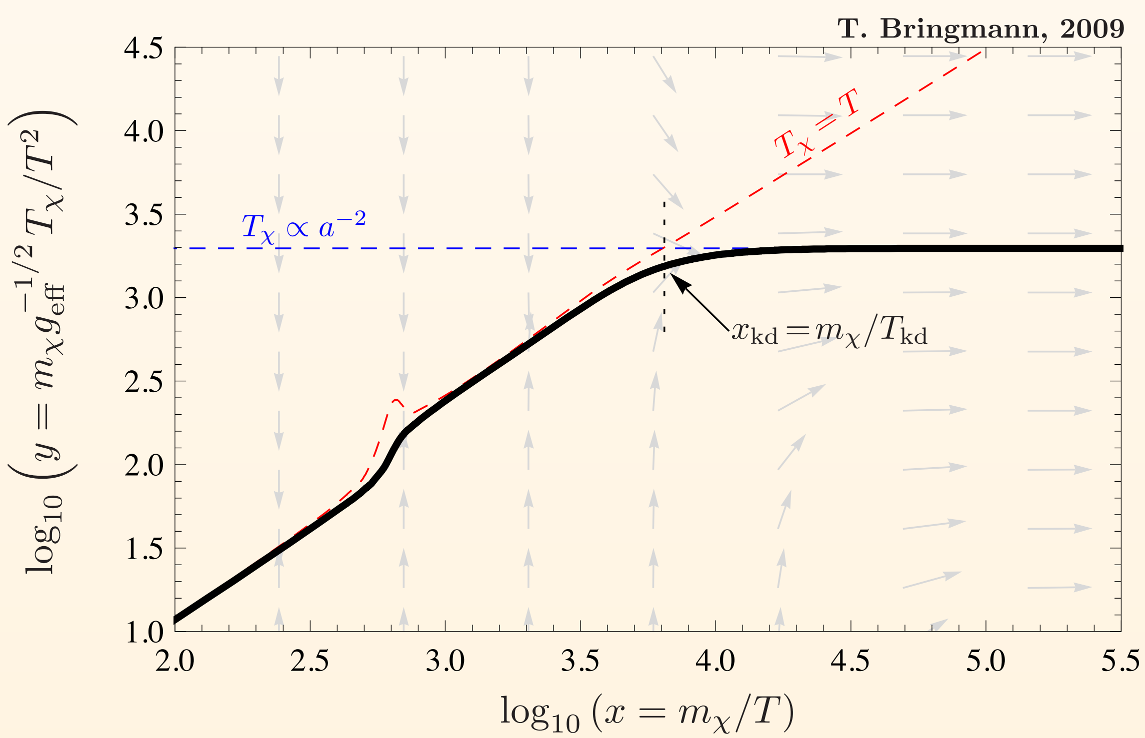
where:

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

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.

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

fully general

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

discretization,
~1000 steps

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

Solved numerically with MatLab

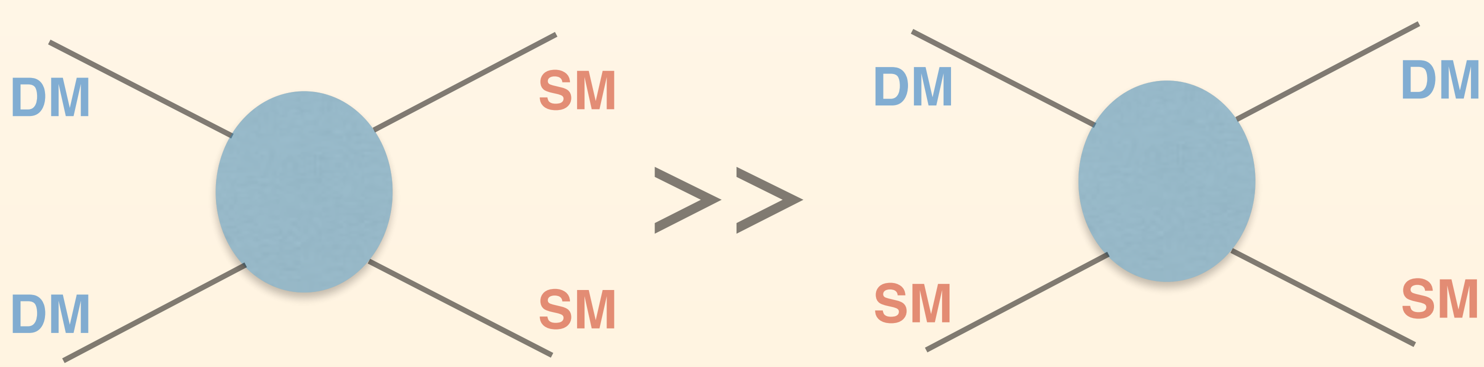
Note:

can be extended to e.g. self-scatterings

very stiff, care needed with numerics

EXAMPLE A:
SCALAR SINGLET DM

A)



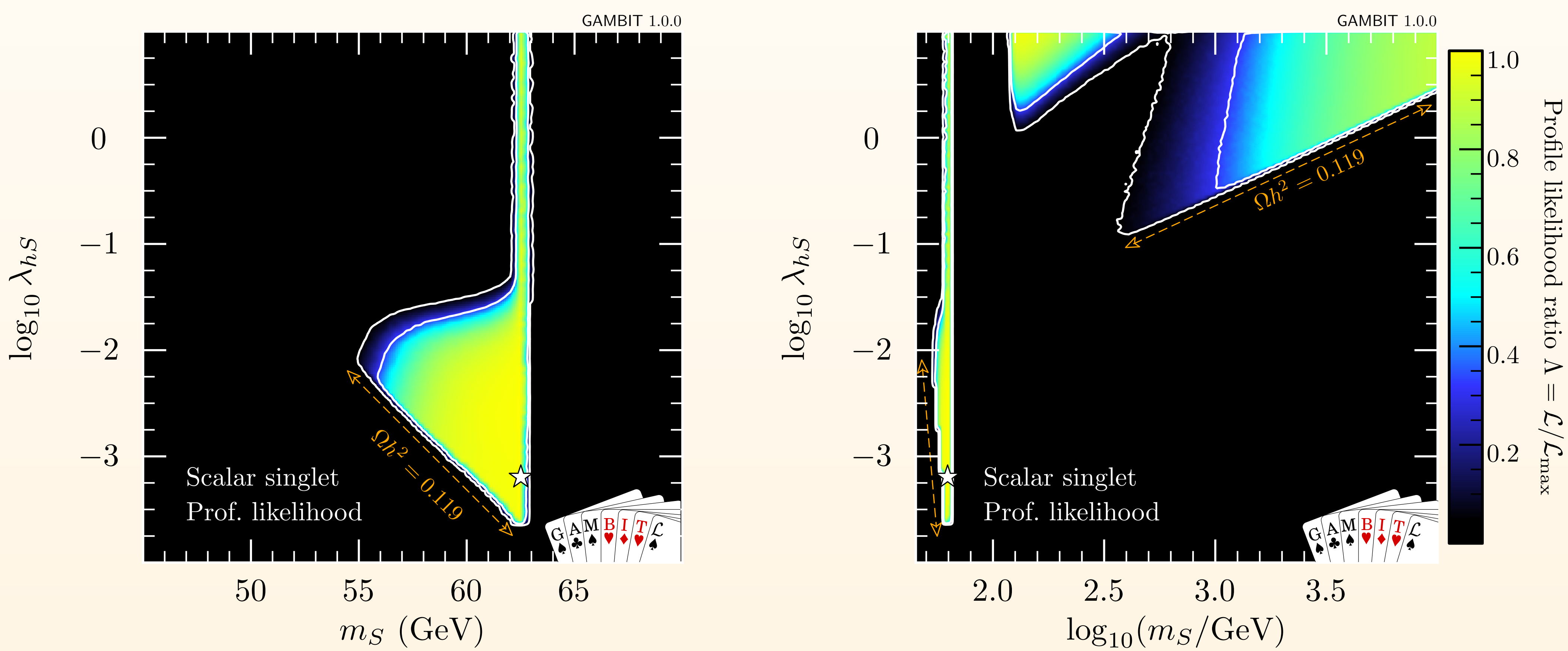
SCALAR SINGLET DM

VERY SHORT INTRODUCTION

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

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

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



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

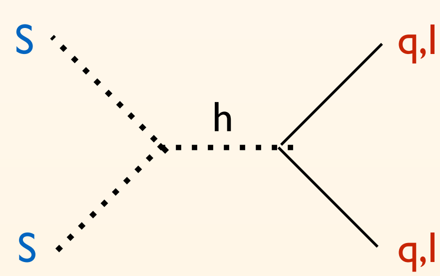
with:

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

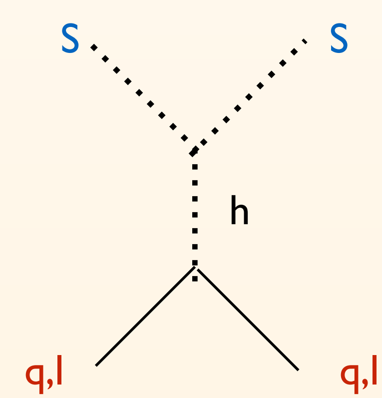
$$\left\langle |\mathcal{M}|^2 \right\rangle_t = \sum_f \frac{N_f \lambda_S^2 m_f^2}{8k^4} \left[\frac{2k_{\rm cm}^2 - 2m_f^2 + m_h^2}{1 + m_h^2/(4k_{\rm cm}^2)} - \left(m_h^2 - 2m_f^2\right) \log\left(1 + 4k_{\rm cm}^2/m_h^2\right) \right].$$

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

Annihilation processes:
resonant



El. scattering processes:
non-resonant



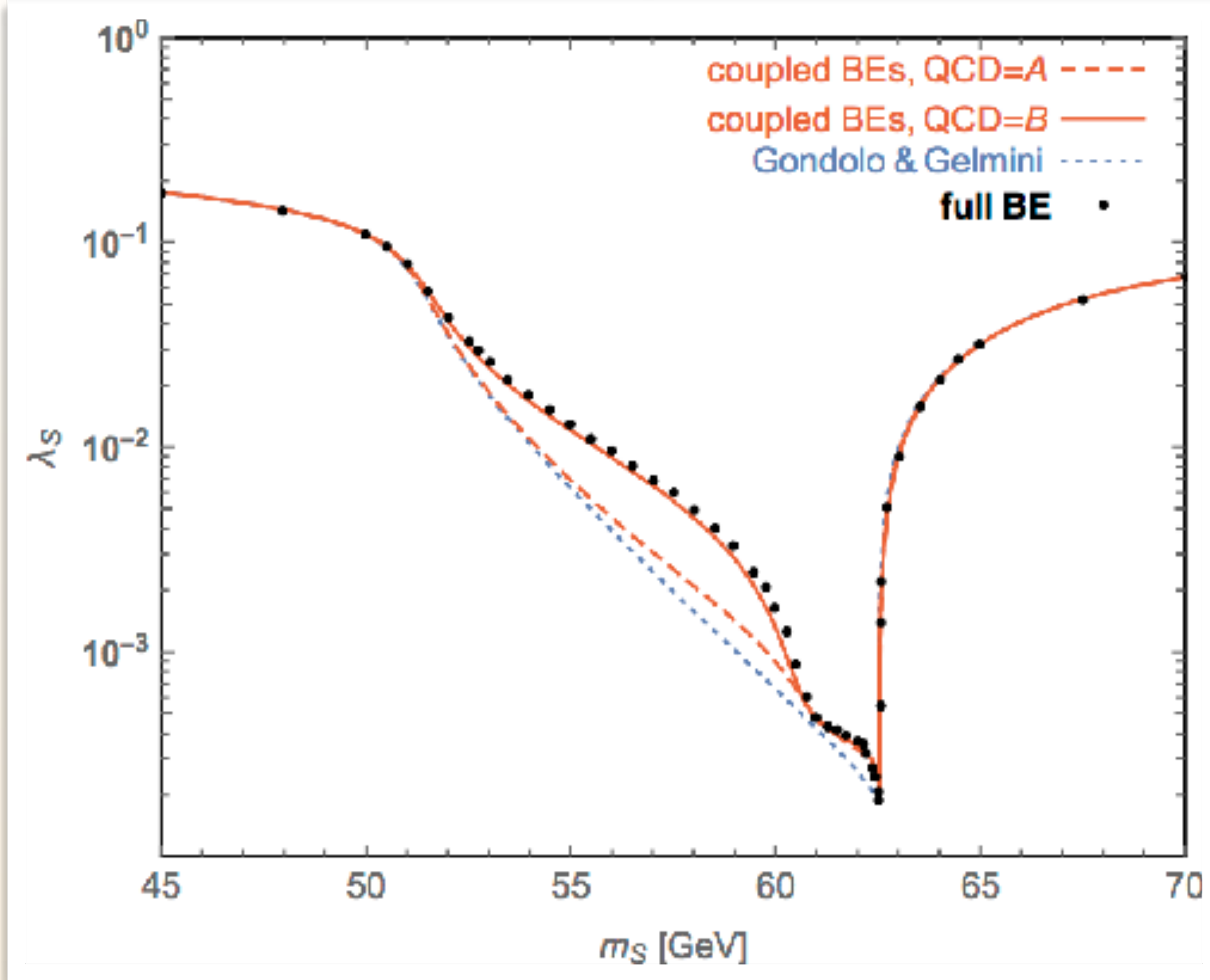
Freeze-out at few GeV ⟶ what is the abundance of heavy quarks in QCD plasma?

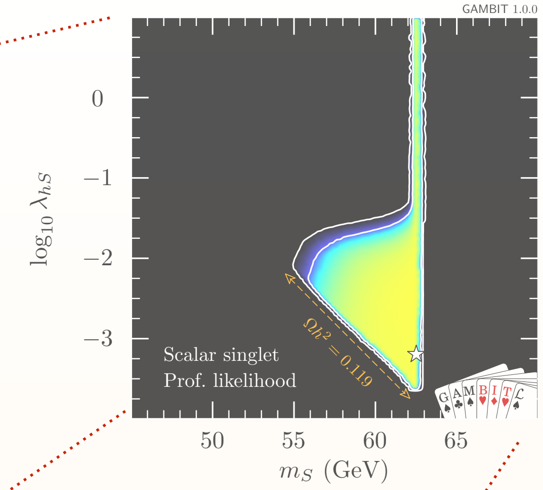
two scenarios:

- 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

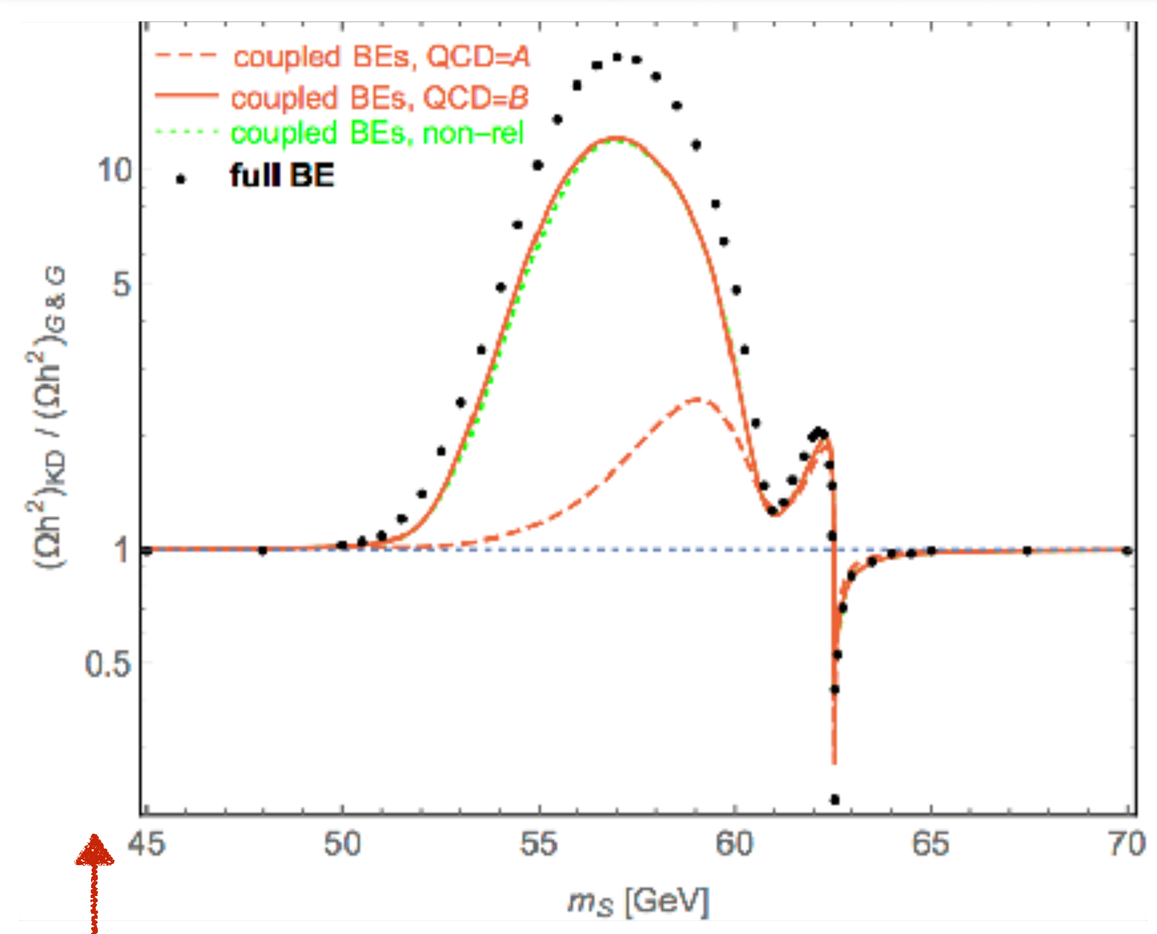
Significant modification of the observed relic density contour in the Scalar Singlet DM model

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

RESULTS

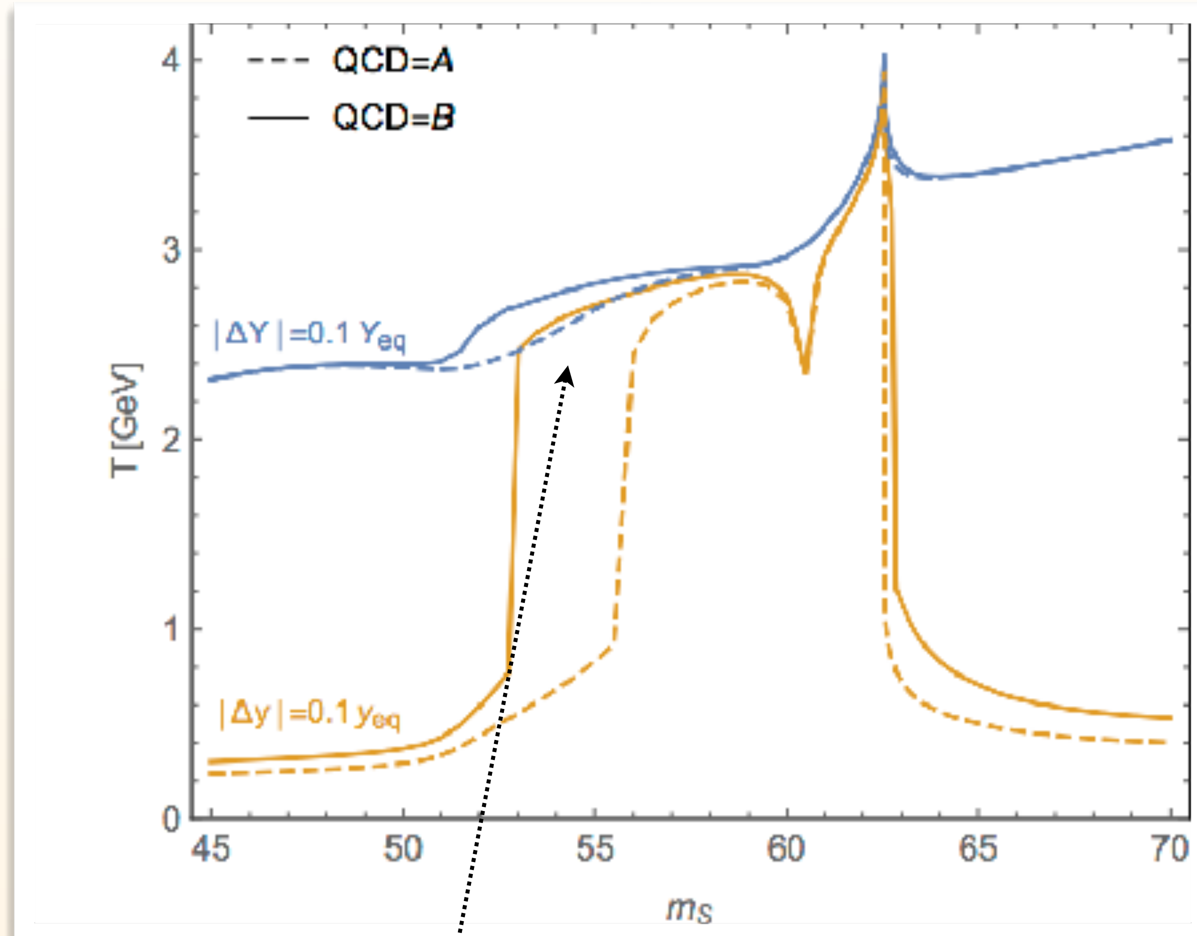
EFFECT

effect on relic density:



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

kinetic and chemical decoupling:



ratio approaches 1,
but does not reach it!

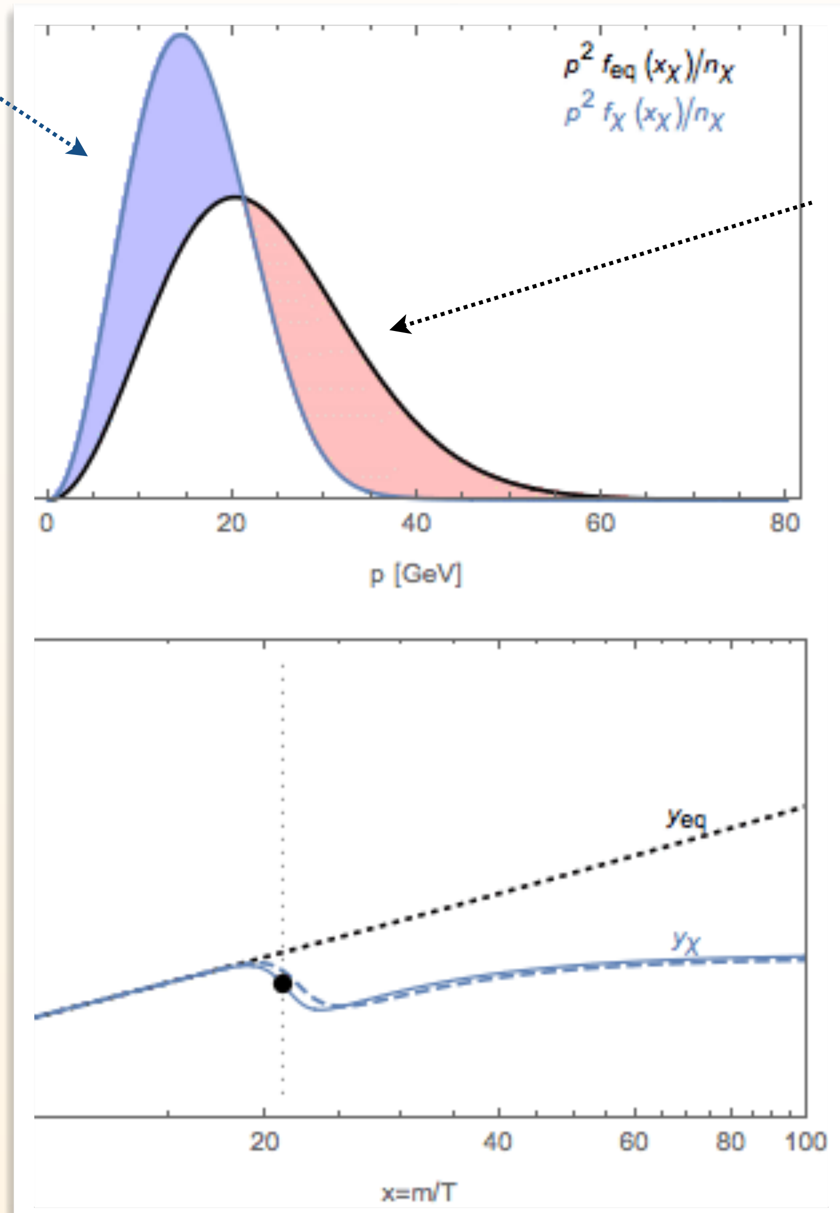
Why such non-trivial shape of the effect of early kinetic decoupling?

→ we'll inspect the y and Y evolution…

FULL PHASE-SPACE EVOLUTION

m_{DM} = 58 GeV

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

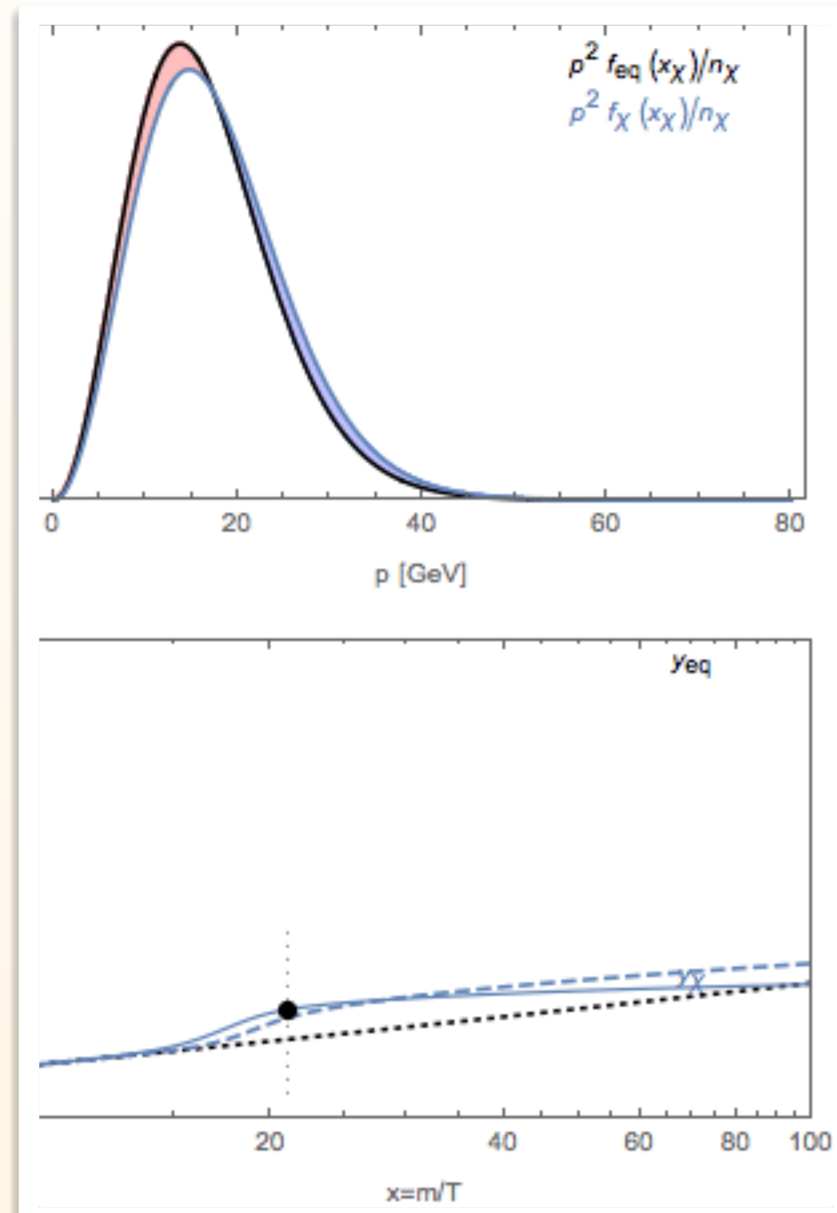


black - equilibrium at T_{DM}

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



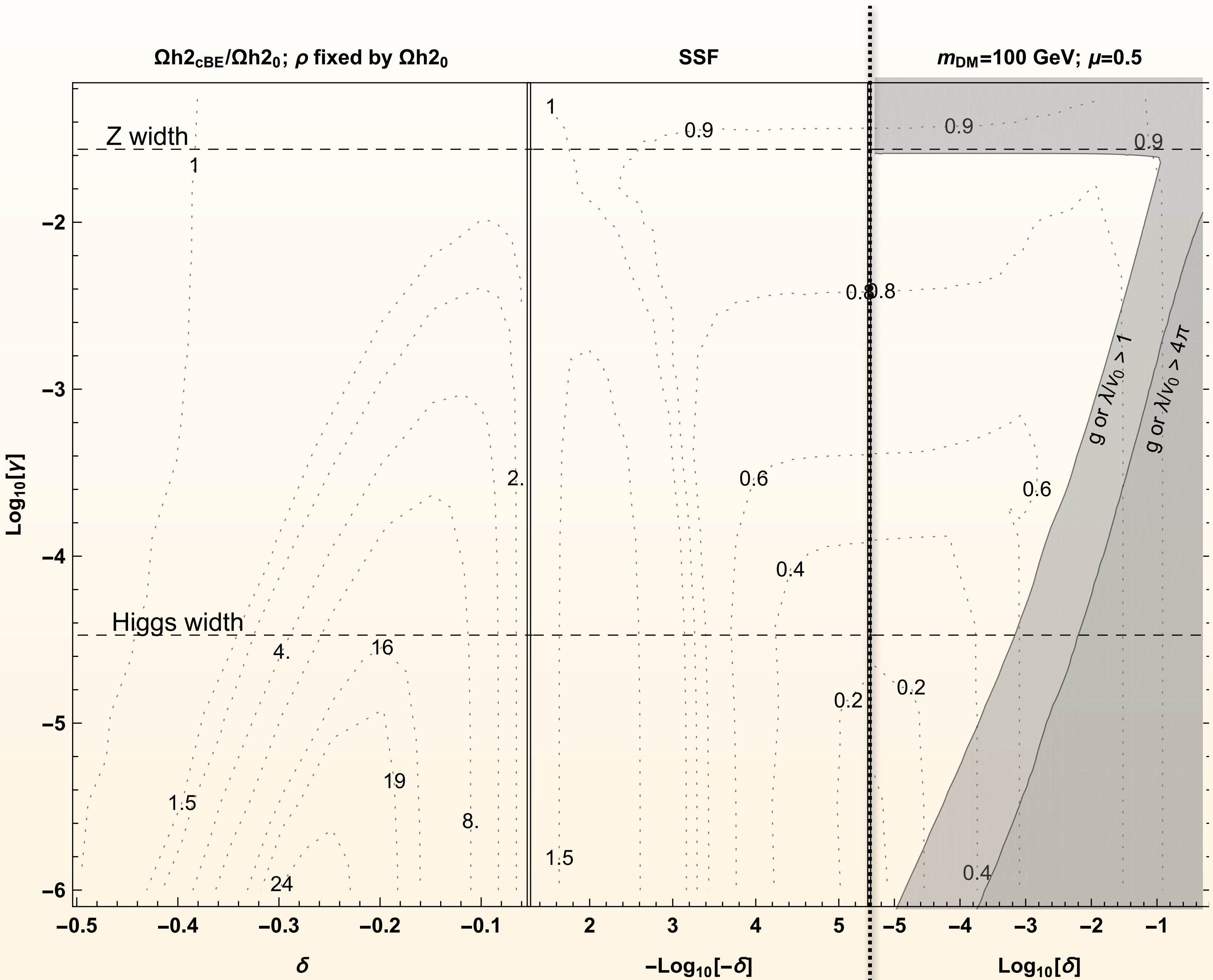
large deviations at later times, around freeze-out not far from eq. shape

⟶ effect on relic density ~only from different T

Generic Resonant Annihilation

Example effect on early KD on relic density

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



can reach O(10%) even for Z resonance

very large effect for Higgs resonance

distance in mass from the exact condition $2m_{DM}=m_R$

*calculated with the coupled BEs method

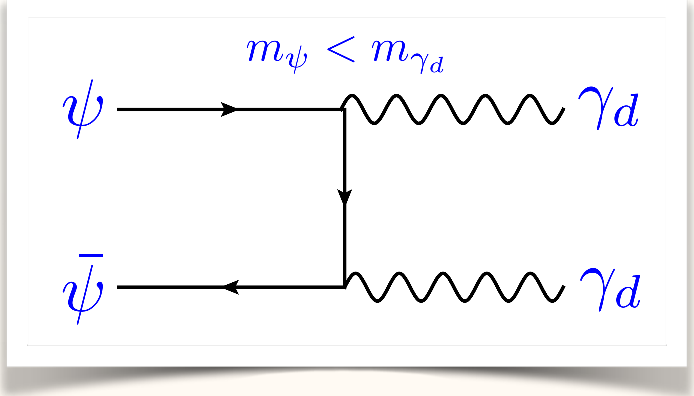
EXAMPLE B:
FORBIDDEN DM

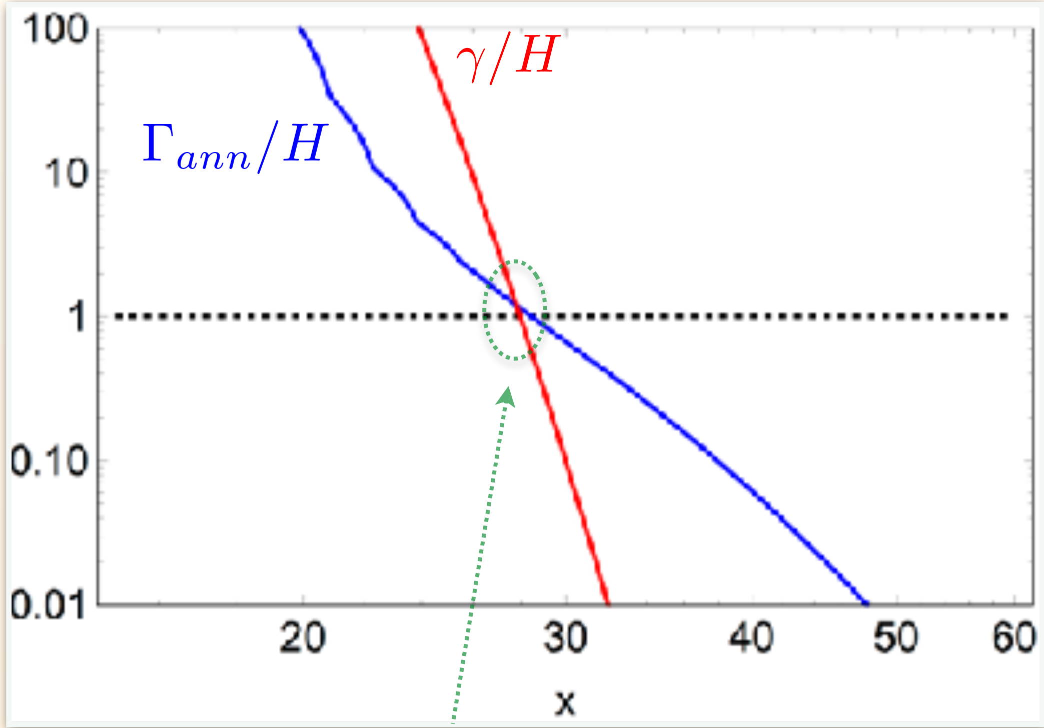
B) Boltzmann suppression of SM as strong as for DM

FORBIDDEN DARK MATTER

DM is a thermal relic that annihilates <u>only</u> to heavier states
(forbidden in zero temperature)

…, D'Agnolo, Ruderman '15, …



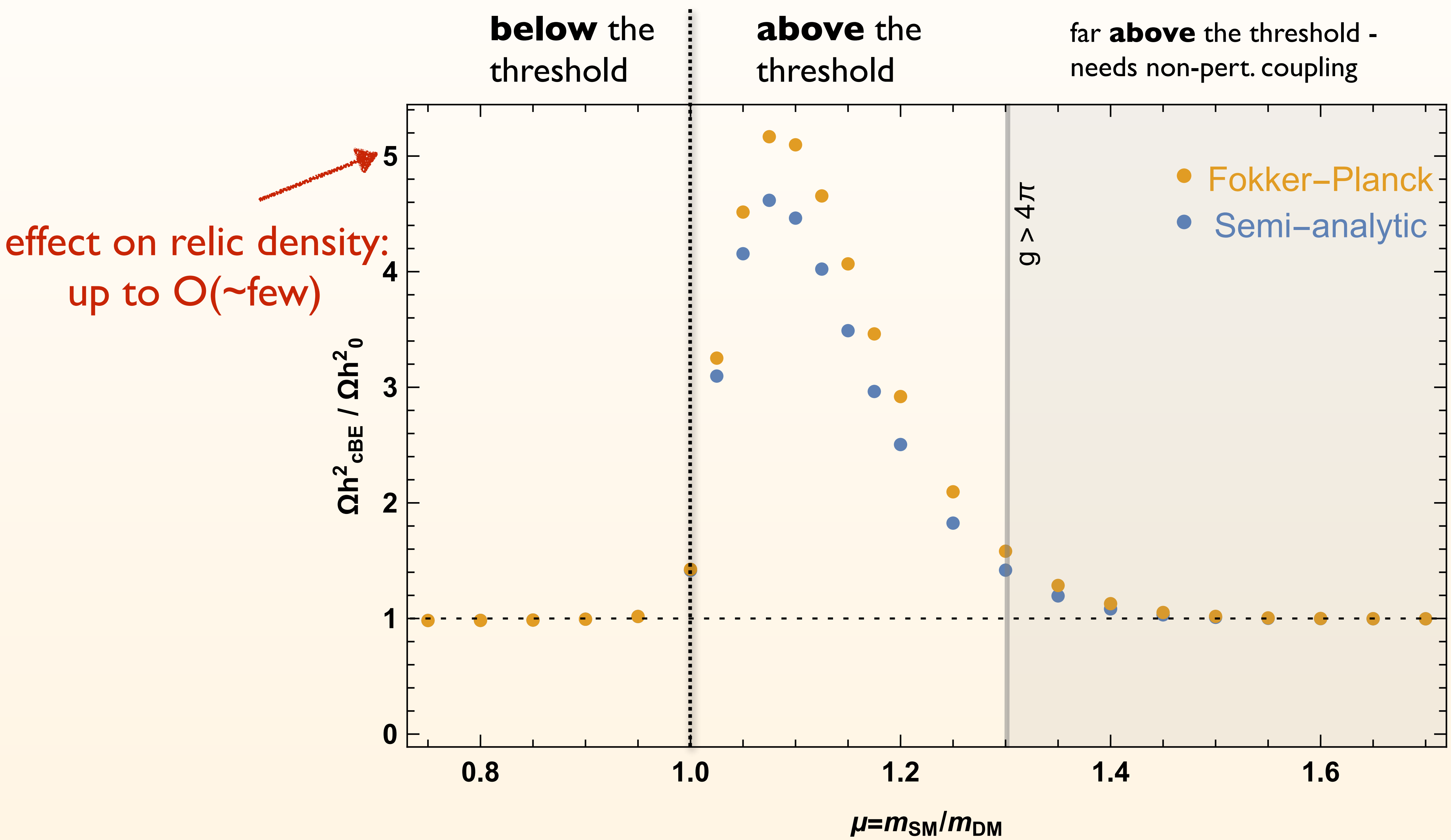


kinetic and chemical
decoupling close

Annihilation threshold	→	velocity dependence
"heavy" SM particle	→	scattering rate low

Forbidden Dark Matter

Example effect on early KD on relic density



*calculated with the coupled BEs method

EXAMPLE C:
SEMI-ANNIHILATION

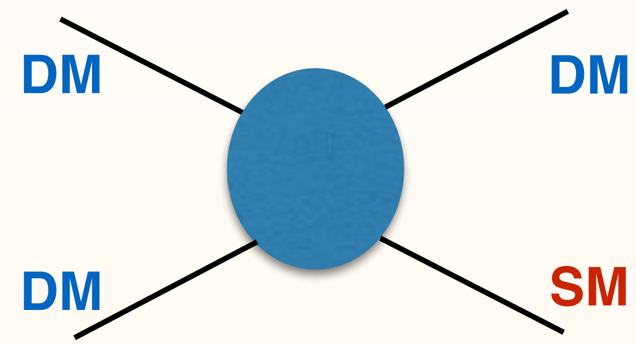
C) Scatterings and annihilation have different structure

Dark Matter Semi-Annihilation

and its simplest realization

DM is a thermal relic but with freeze-out governed by the semi-annihilation process

D'Eramo, Thaler '10; …



Z_3 complex scalar singlet:

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

just above the Higgs threshold semi-annihilation dominant!

Belanger, Kannike, Pukhov, Raidal '13

very weak elastic scatterings → semi-annihilation by itself does not equilibrate DM

↓

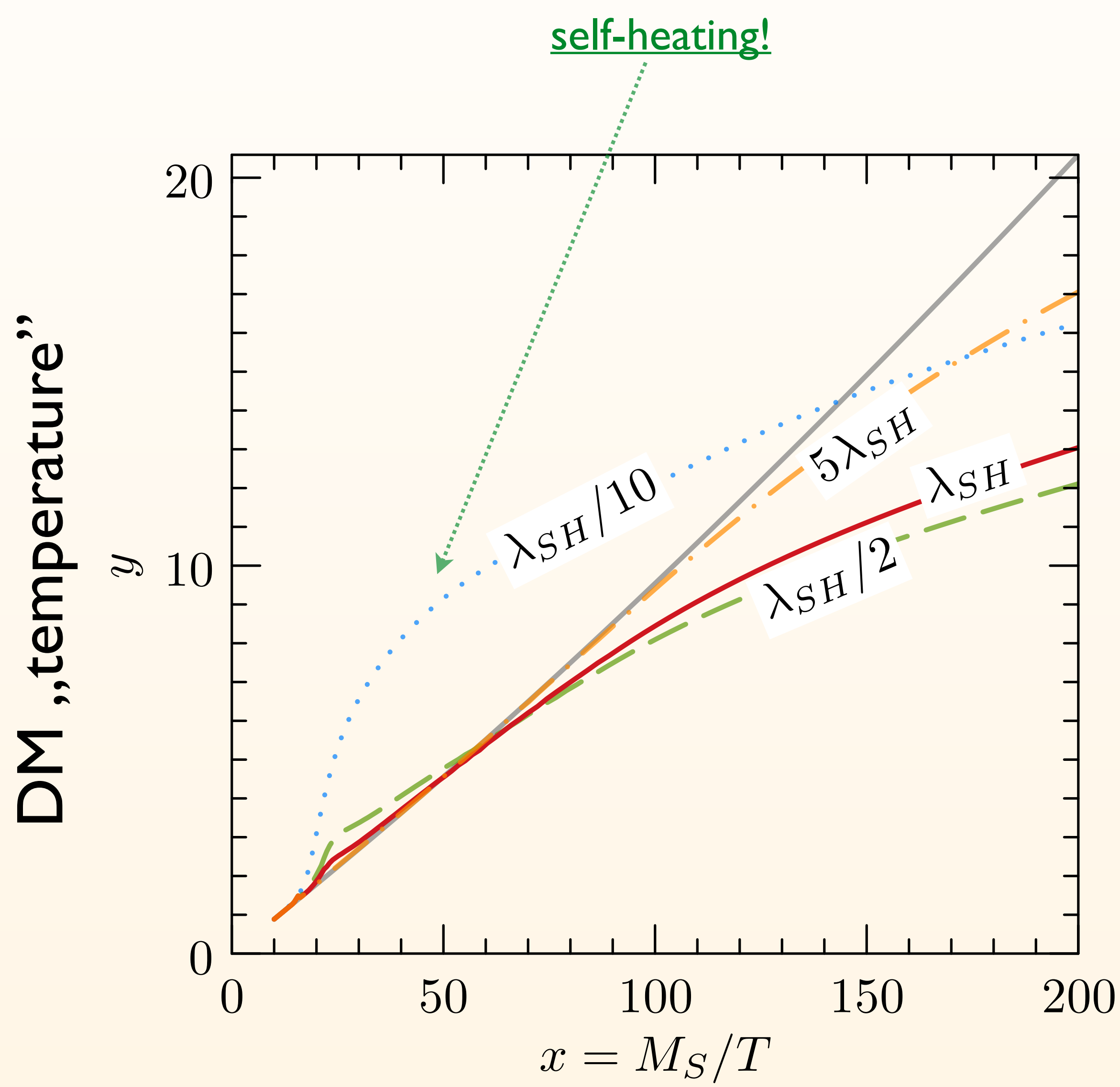
but rather leads to self-heating!

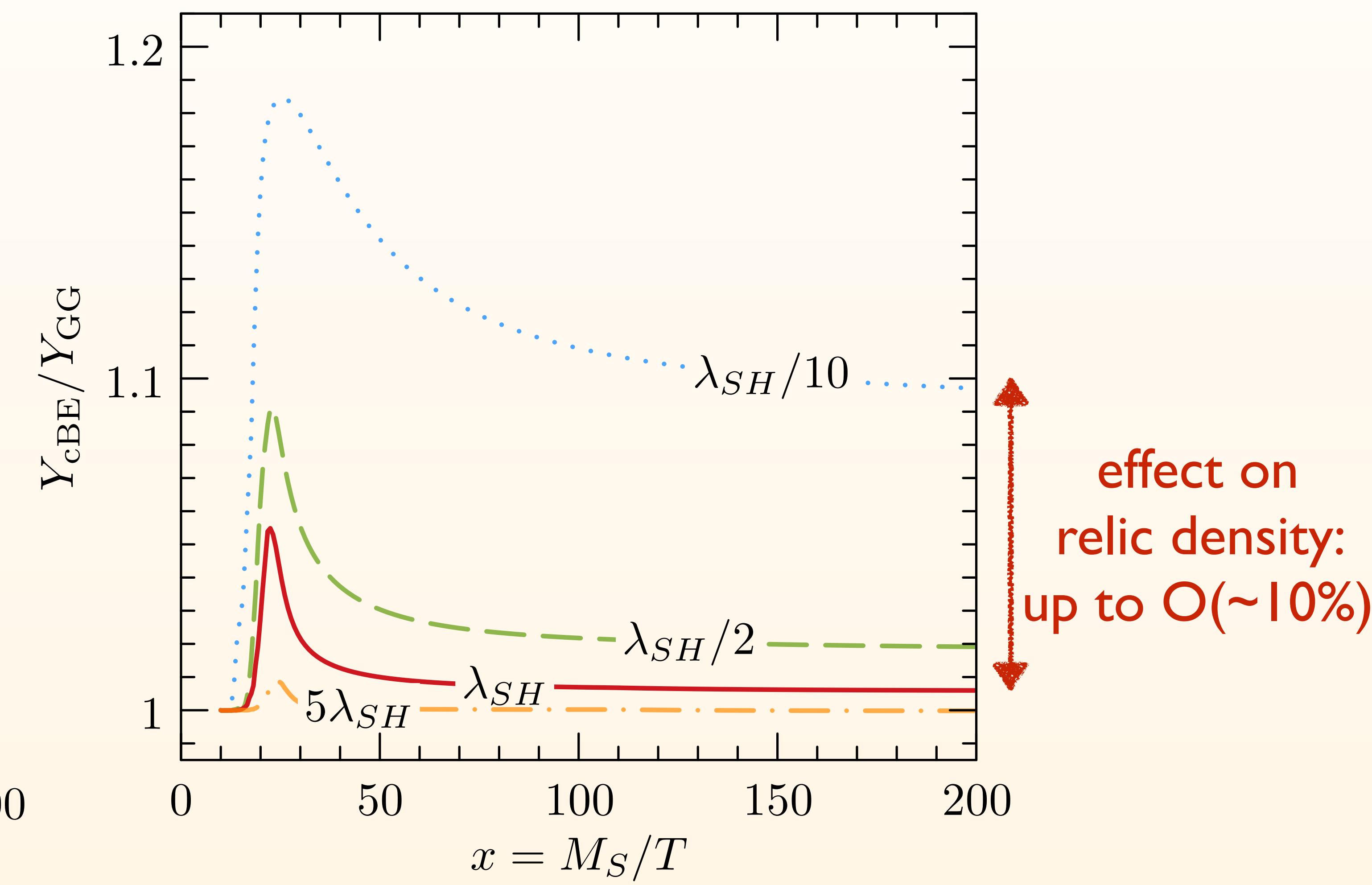
implications for ID

see also Cai, Spray 1807.00832

SEMI-ANNIHILATION
EXAMPLE EFFECT ON EARLY KD ON RELIC DENSITY

A. Hektor, AH and K. Kannike 1901.080





Note: here the final effect is relatively mild (though still larger than the observational error), but only because in the simplest model the velocity dependence of annihilation is mild as well…

*calculated with the (modified) coupled BEs method

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

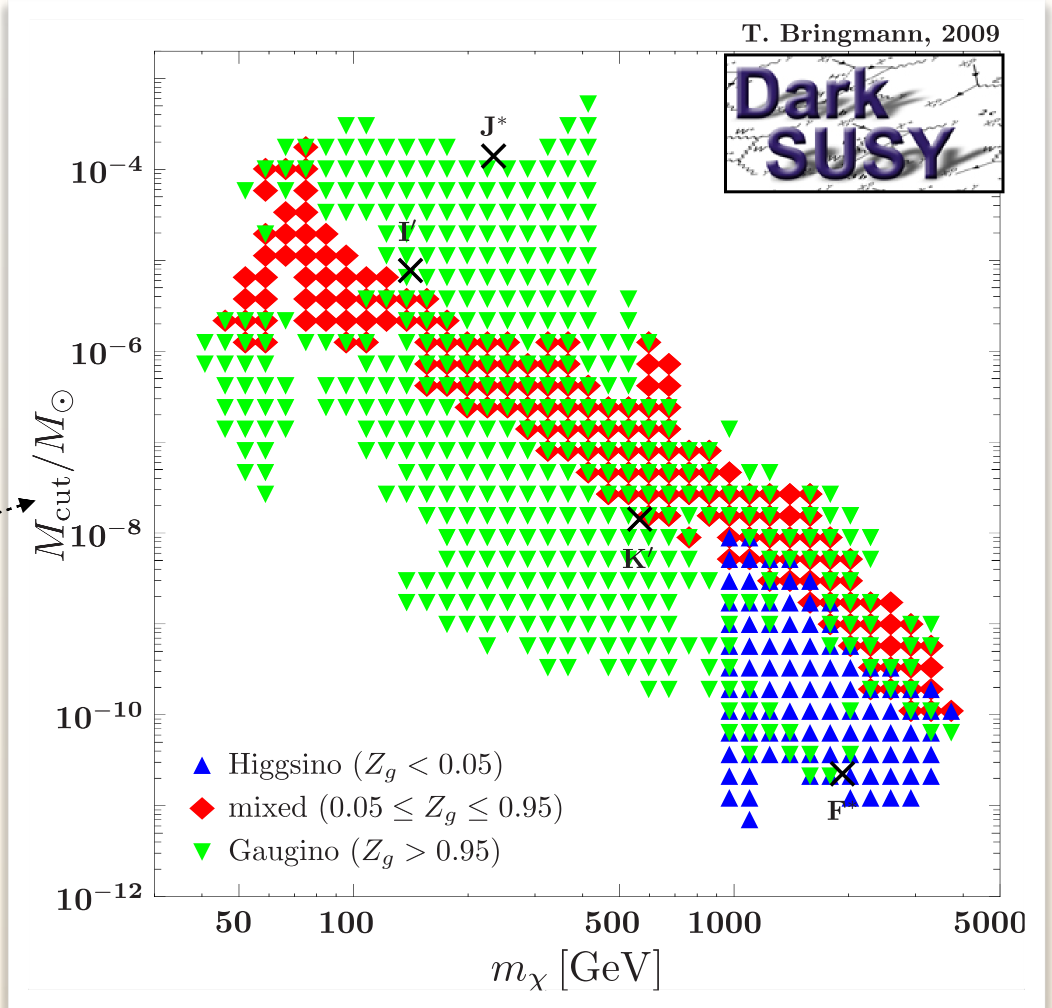
3. In special cases the full phase space Boltzmann equation can be necessary — especially if one wants to trace DM temperature as well

…a step towards more fundamental and reliable relic density determination

BACKUP

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

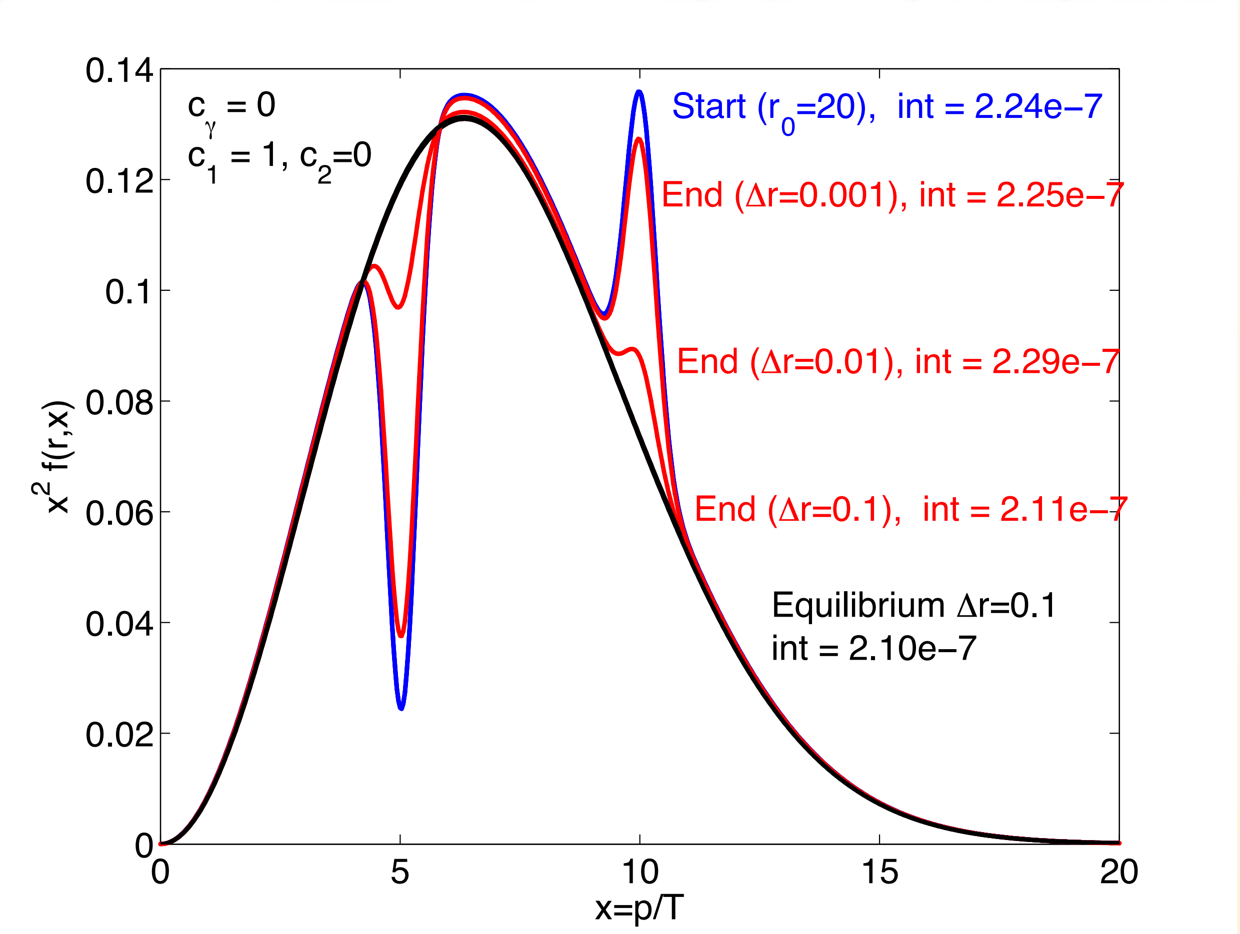
$\Longrightarrow$ moment of KD leaves important imprint on the Universe

KD BEFORE CD?

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

⇓

Improved question:
Can kinetic decoupling happen much earlier 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…

← turn off scatterings and take s-wave annihilation; look at local disturbance

annihilation/production precesses drive to restore kinetic equilibrium!

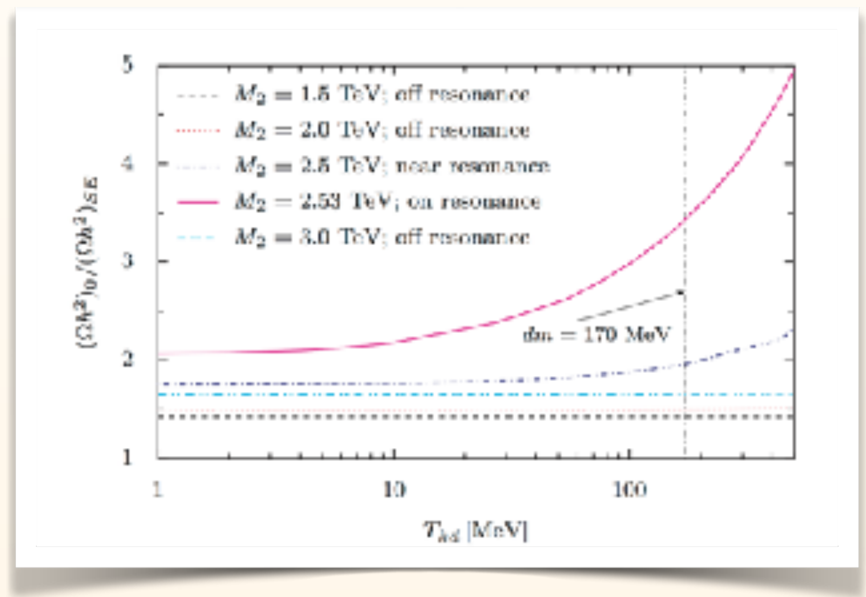
Early KD and resonance

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:



AH, Iengo, Ullio '11

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

…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

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

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

physical interpretation: scattering rate

More generally, Fokker-Planck scattering operator (relativistic, but still small **momentum transfer**):

Binder et al. '16

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

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