NATIONAL SCIENCE CENTRE
POLAND

TOWARDS ROBUST PREDICTIONS FOR THERMAL PRODUCTION

OF

MULTICOMPONENT DARK MATTER

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NCBJ

Based on:

work in progress with **S. Chatterjee**

+ some earlier results from:

N. Benincasa, A.H, K. Kannike & M. Laletin 2312.04627
A.H. & M. Laletin 2104.05684, 2204.07078
T. Binder, T. Bringmann, M. Gustafsson & A.H. 1706.07433, 2103.01944

Seminar @ FUW

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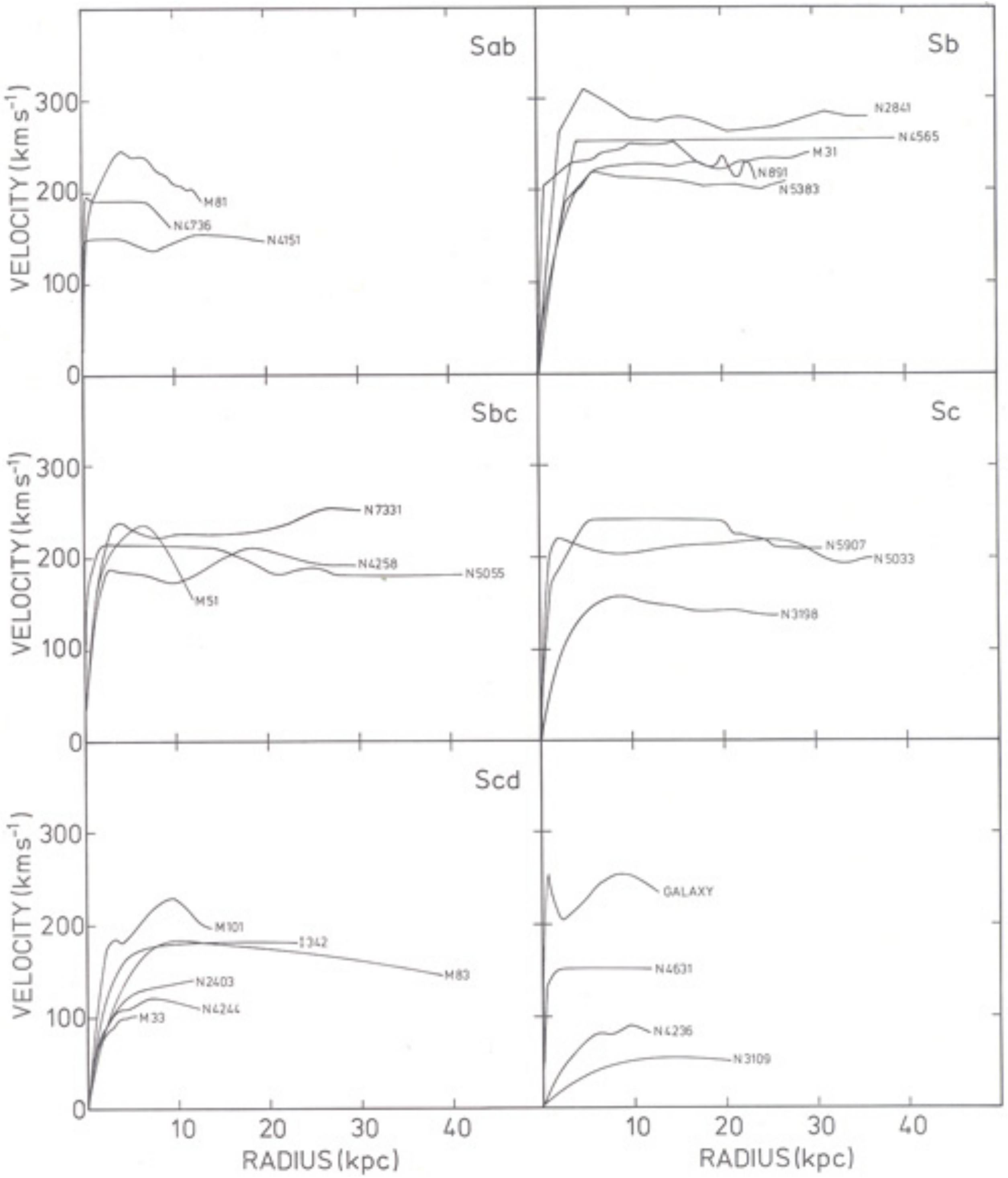
4th April 2024

HISTORY & EVIDENCE



A. Bosma ’78

Idea that there is some „dark matter” in the Universe has a very long history

Suggested read: Bertone & Hooper ’16

But for the most part the „dark” has been understood as a mere adjective…

Indeed, even the historical milestone of establishing that the rotation curves of galaxies are close to flat at large distances, did not cement the idea that there is a „new kind of matter”

What made it to the transition to a proper noun?

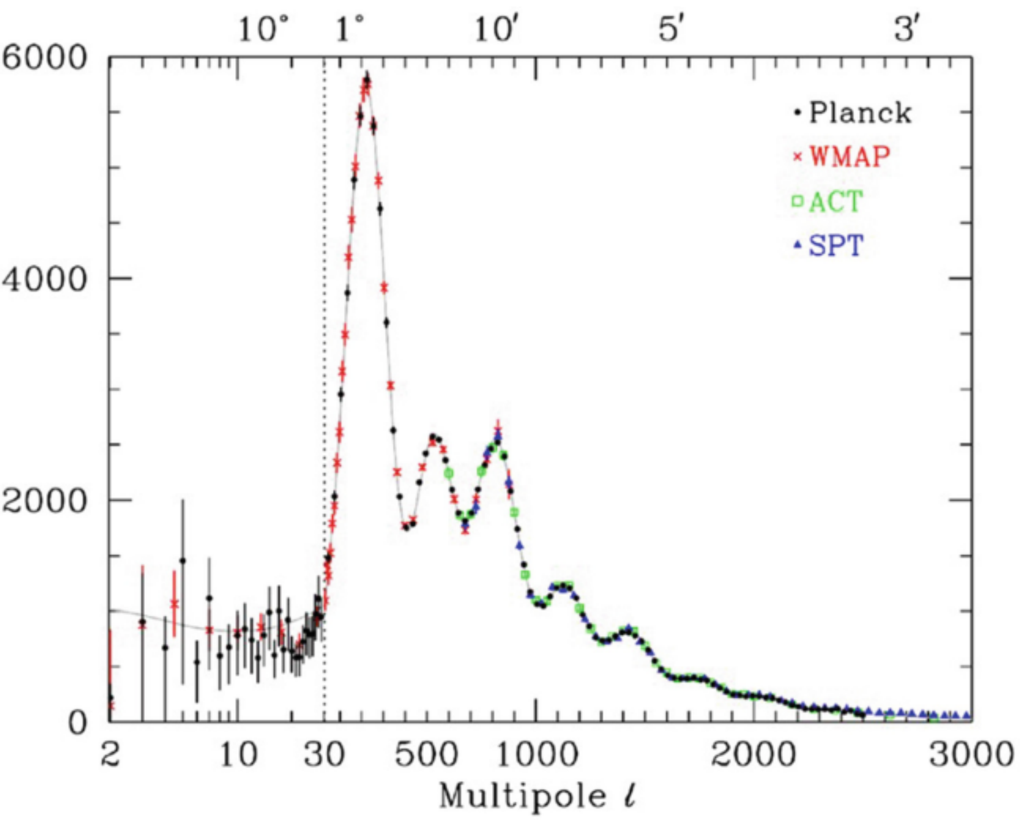
HISTORY & EVIDENCE

Rotation curves are commonly seen as the most direct evidence of the existence of DM

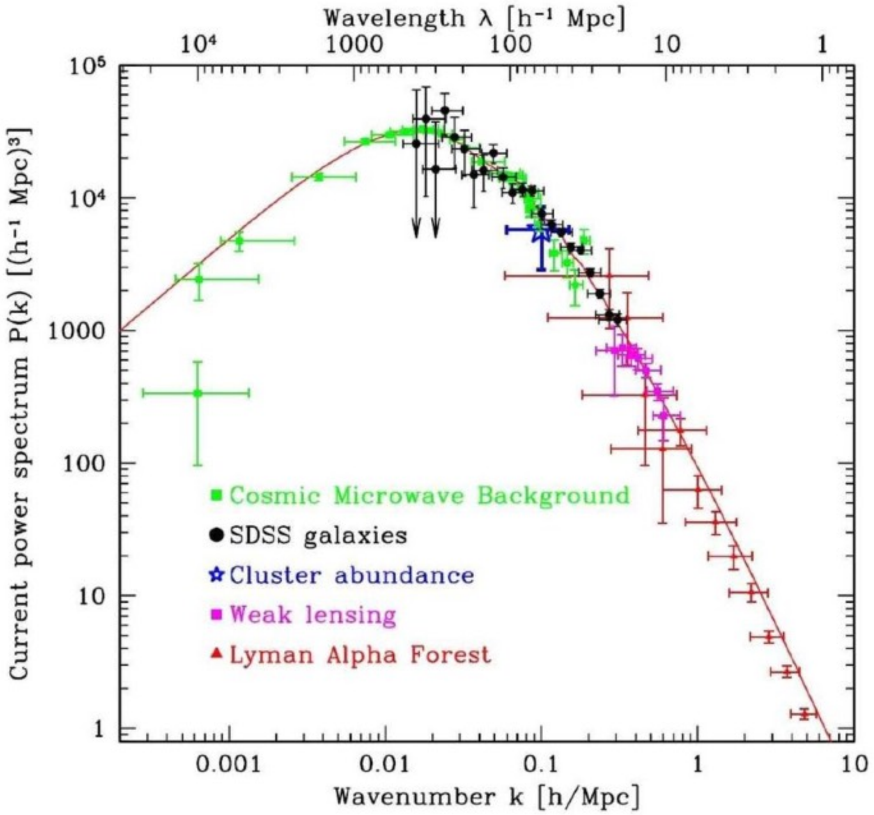
… but this frames DM as an astrophysical „issue”

(cf. phrase like „missing mass problem”)

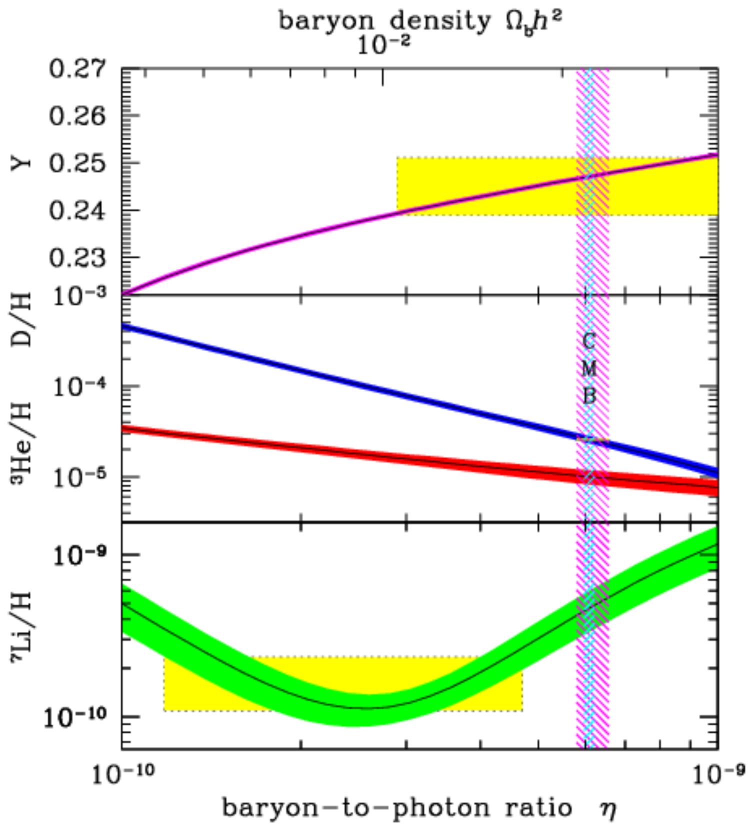
From HEP or cosmology perspective the most important pieces of evidence:



CMB anisotropies



Matter power spectrum

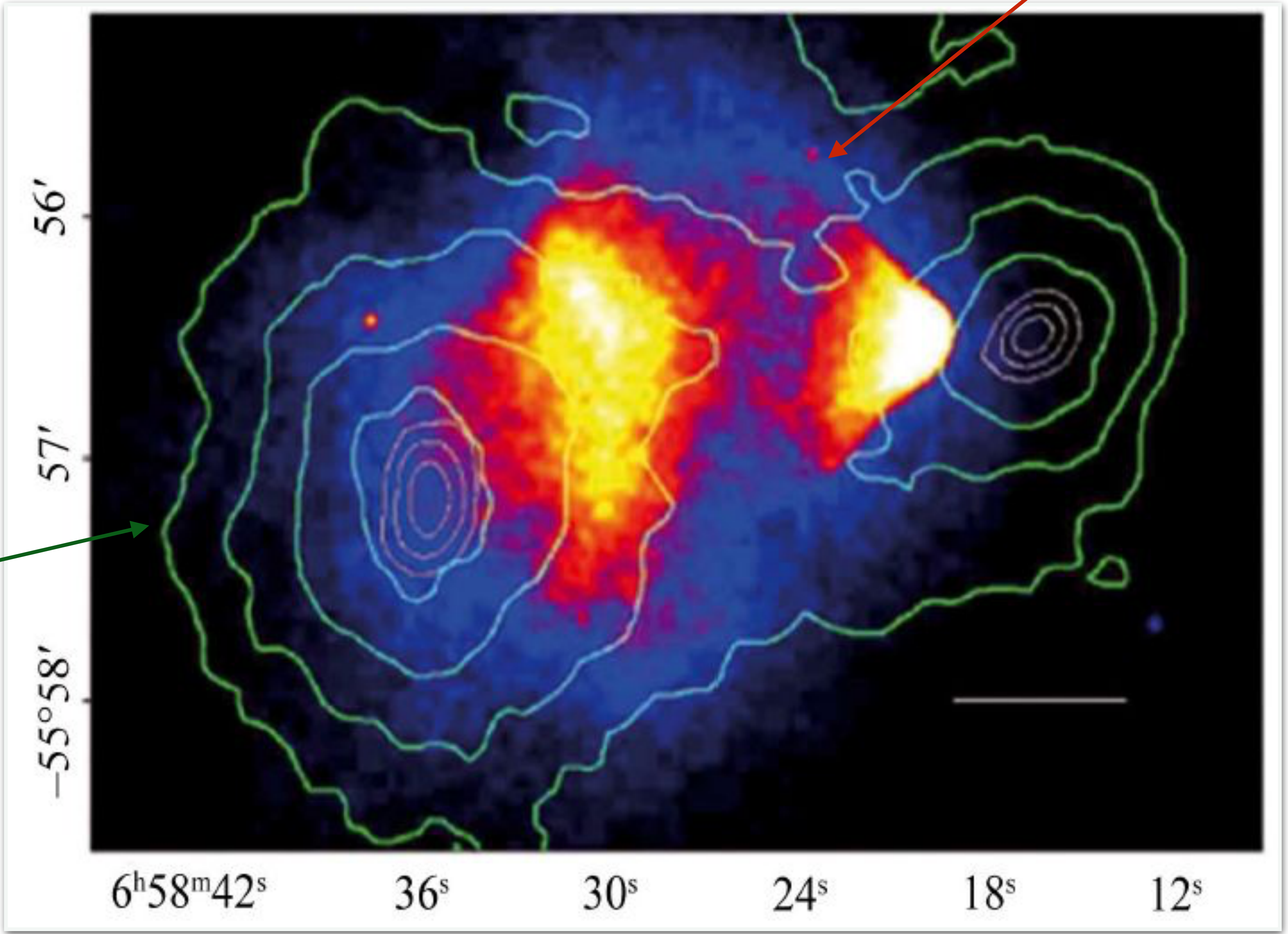


BBN

(and missing baryons)

HISTORY & EVIDENCE

And then there is also of course:



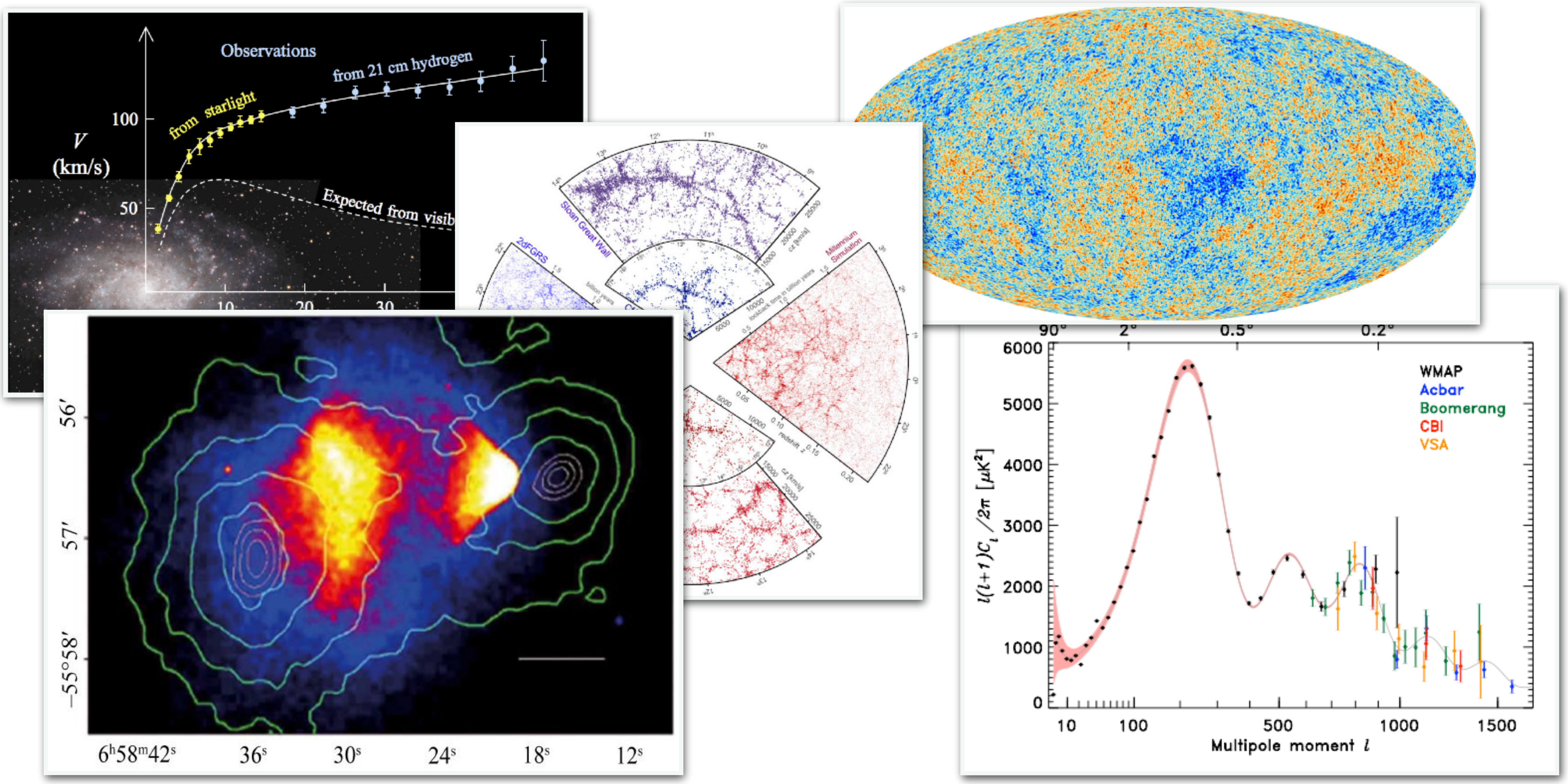
hot gas from X-ray observations

mass distribution from lensing

The Bullet Cluster

DARK MATTER

There is plenty of evidence on astrophysical and cosmological length scales that DM exists…



⇒ Qualitatively convergent picture!

… but no direct evidence that it is a particle DM

ALTERNATIVES TO PARTICLE DM

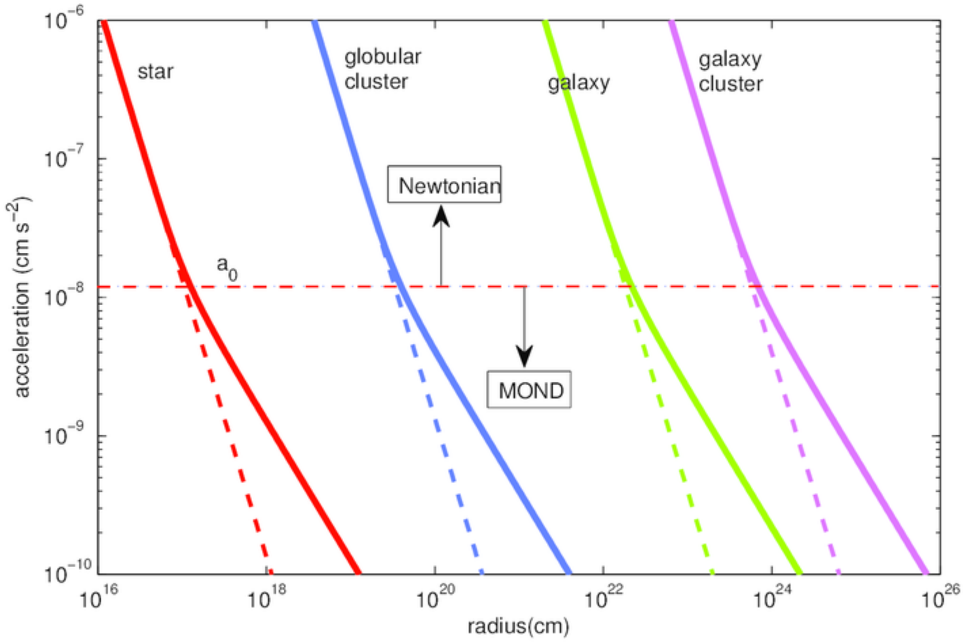
Modification of gravity

(leading to a MOND limit)

$$F = ma \cdot \mu(a/a_0)$$

$$a_0 \approx \frac{cH_0}{2\pi} \qquad \mu(x) = \begin{cases} x, & \text{if } 0 < x \ll 1 \\ 1, & \text{if } x \gg 1 \end{cases}$$

new (fundamental) constant



e.g. **TeVeS**
Bekenstein '04

(problem with cosmology and GWs)

RMOND
Skordis, Złośnik '21

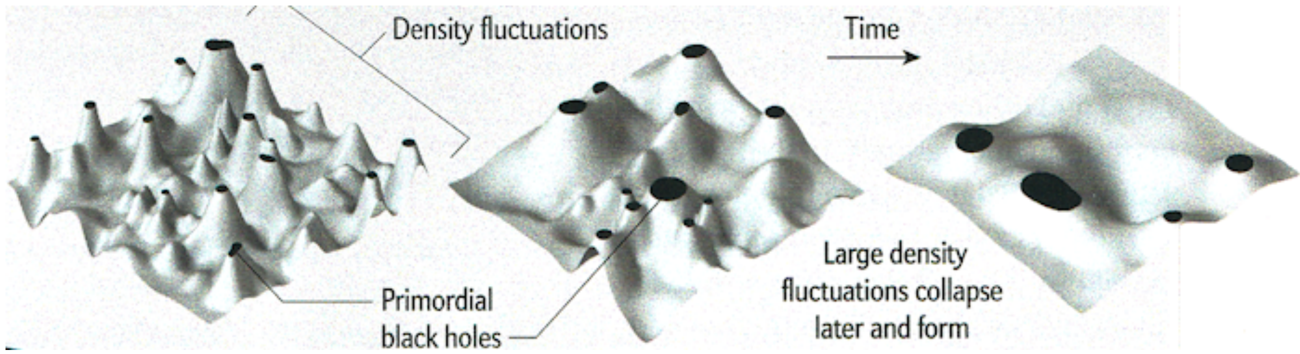
$$S = \int d^4x \frac{\sqrt{-g}}{16\pi\tilde{G}} \Big[R - \frac{K_B}{2} F^{\mu\nu} F_{\mu\nu} + 2(2 - K_B) J^\mu \nabla_\mu \phi - (2 - K_B)\mathcal{Y} - \mathcal{F}(\mathcal{Y}, \mathcal{Q}) - \lambda(A^\mu A_\mu + 1) \Big] + S_m[g]$$

MACHOs

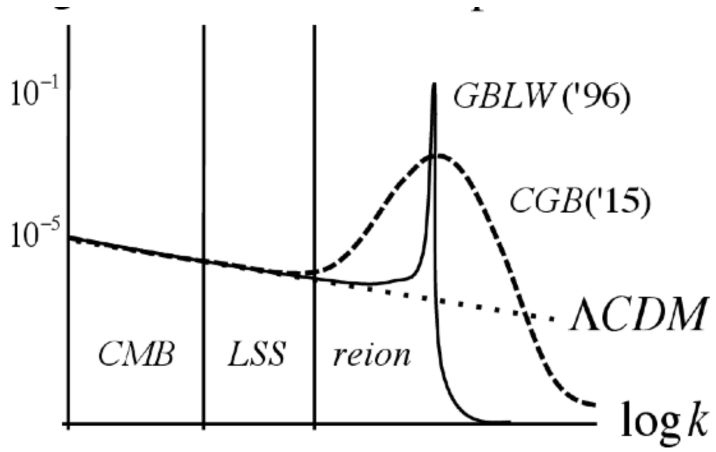
(Massive Compact Halo Objects)

<u>They do exist</u>, but number strongly constrained by lensing & most of them cannot be baryonic if to play the role of DM

what about **Primordial Black Holes**?

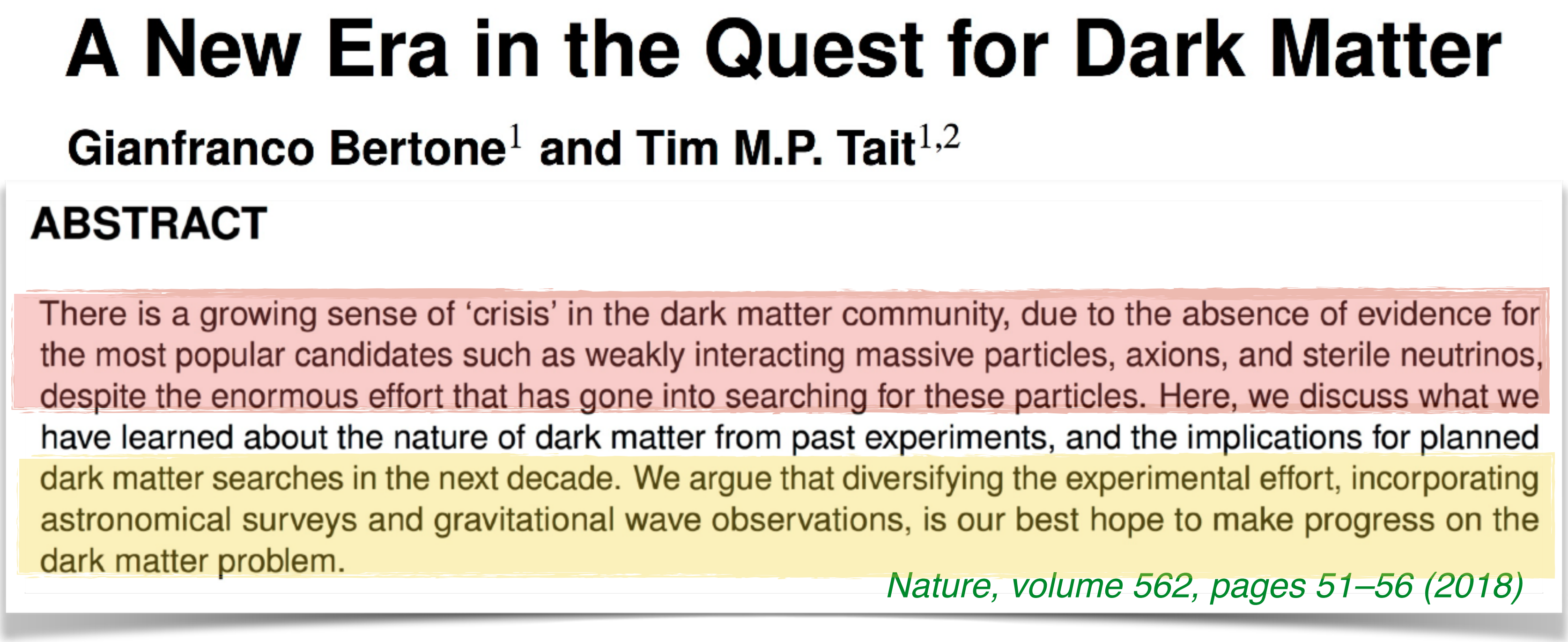


ΛCDM compatible with (close to) scale invariant power spectrum: if extrapolated to small scales PBHs formation negligible



Garcia-Bellido '17

DARK MATTER CRISIS?



A New Era in the Quest for Dark Matter

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

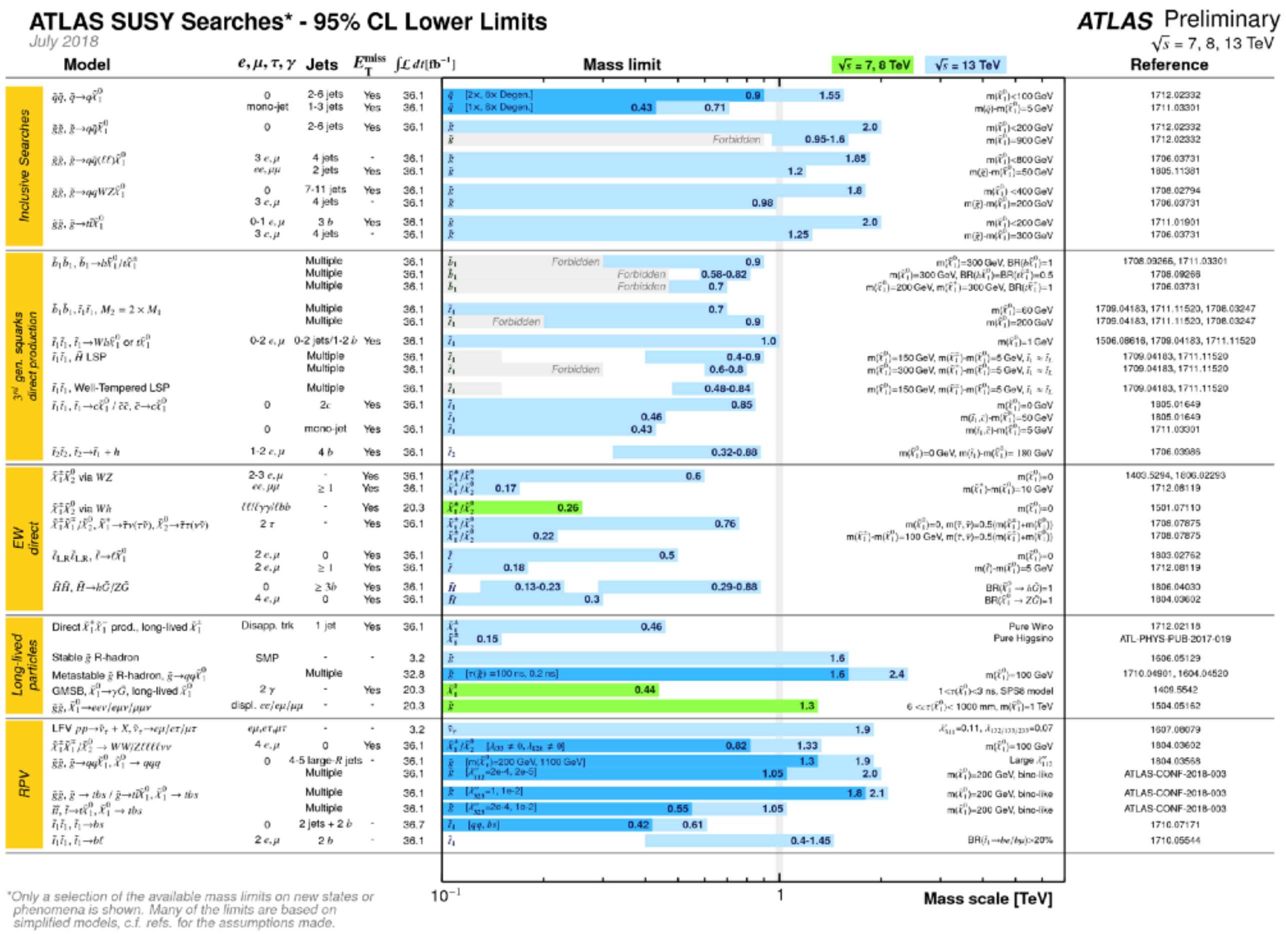
ABSTRACT

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”.



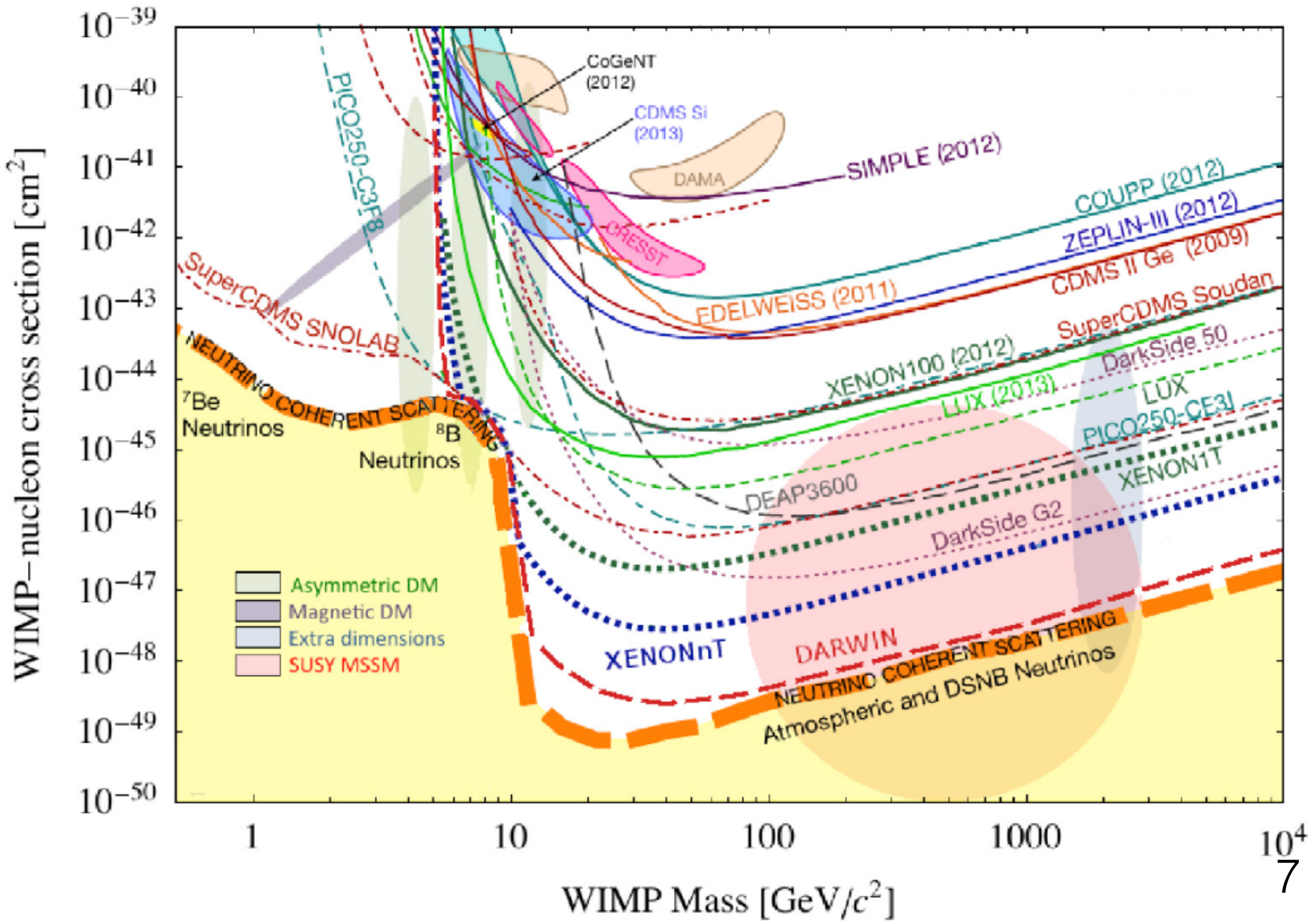
ATLAS SUSY Searches* - 95% CL Lower Limits

July 2018

ATLAS Preliminary

$\sqrt{s}$ = 7, 8, 13 TeV

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.



DARK MATTER CRISIS?

BELIEFS OF XX CENT.

„DM is nearly certainly WIMPs
(or perhaps axions or sterile ν's)"

„SUSY is just around the corner"

⇒ Studying BSM models and their phenomenology in direct & indirect detection makes a lot of sense

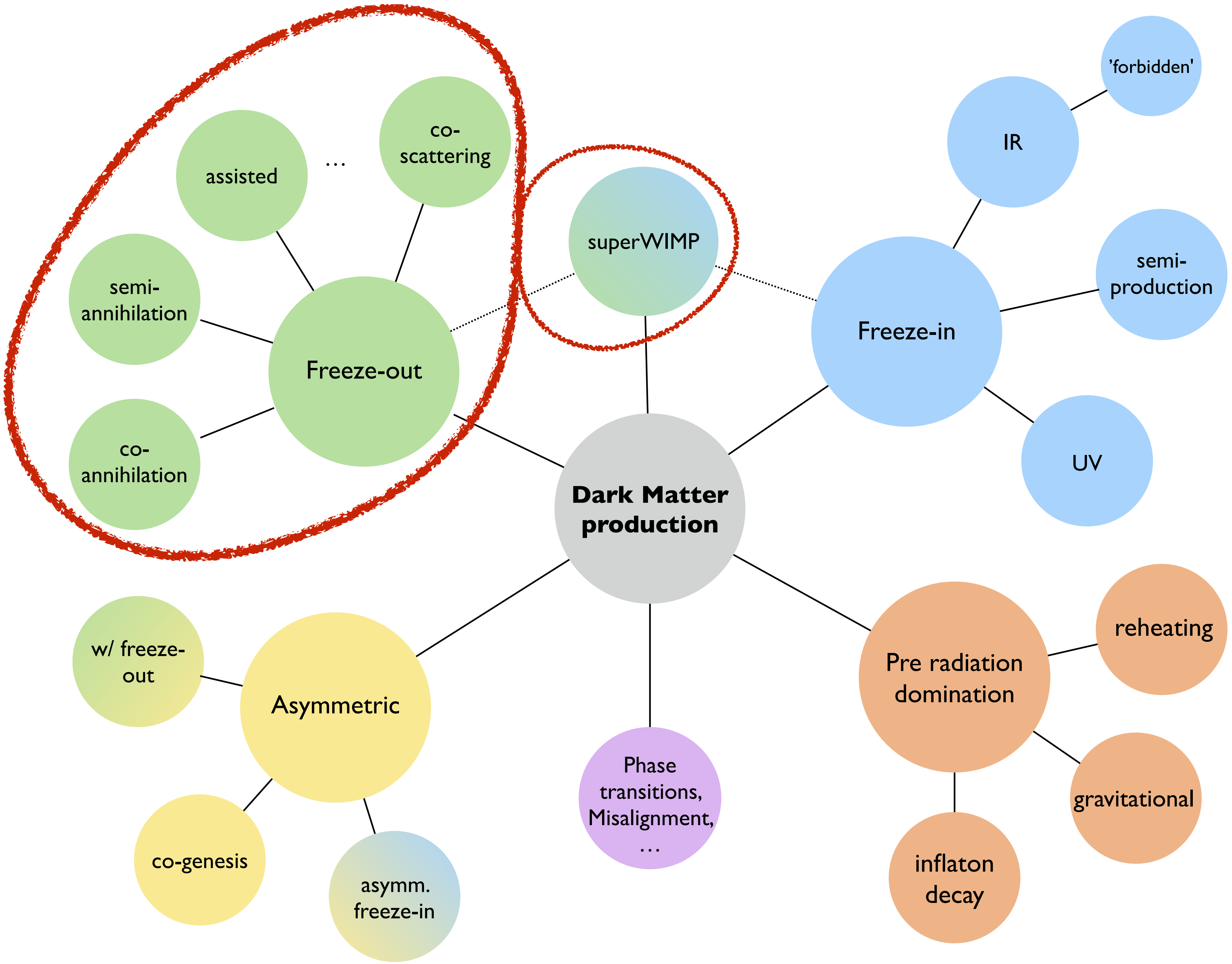
BELIEFS OF XXI CENT.

Realisation that we actually have no idea what DM is starts to sink in

Options:

- New detection ideas
- Double down and propose/study new models
- Make an effort to improve our understanding of relevant processes

DARK MATTER ORIGIN



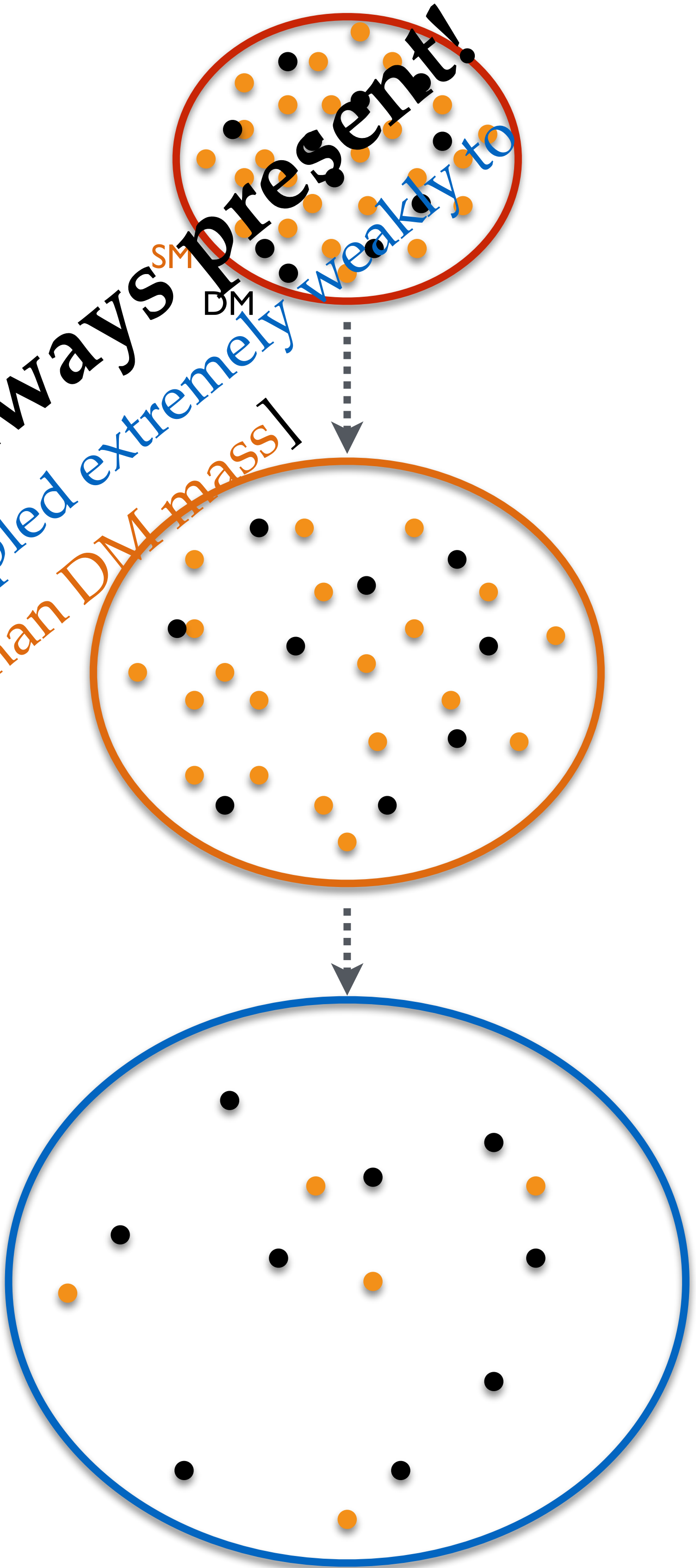
THERMAL RELIC DENSITY
A.K.A. FREEZE-OUT

T

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

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

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



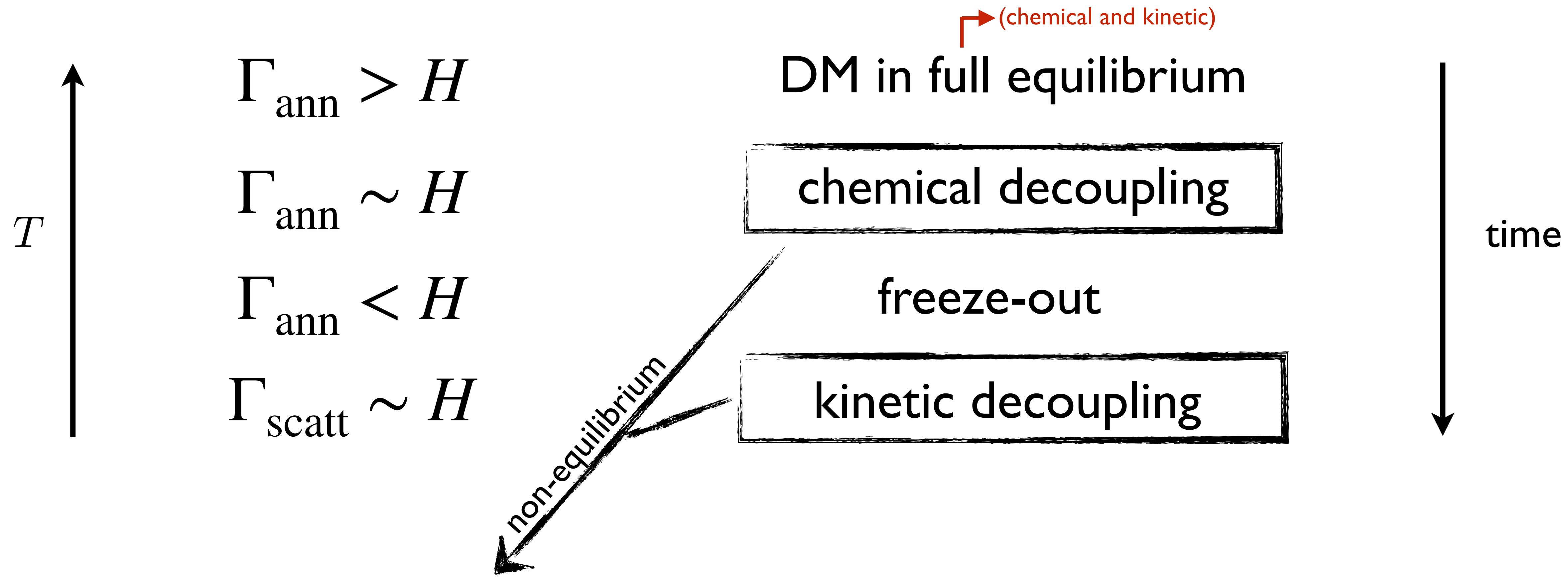
time

This process is (essentially) always present!

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

THERMAL RELIC DENSITY

STANDARD SCENARIO



T

$\Gamma_{\text{ann}} > H$

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

$\Gamma_{\text{ann}} < H$

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

(chemical and kinetic)

DM in full equilibrium

chemical decoupling

freeze-out

kinetic decoupling

non-equilibrium

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)

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

for a process of DM DM ↔ SM SM

$\Downarrow$

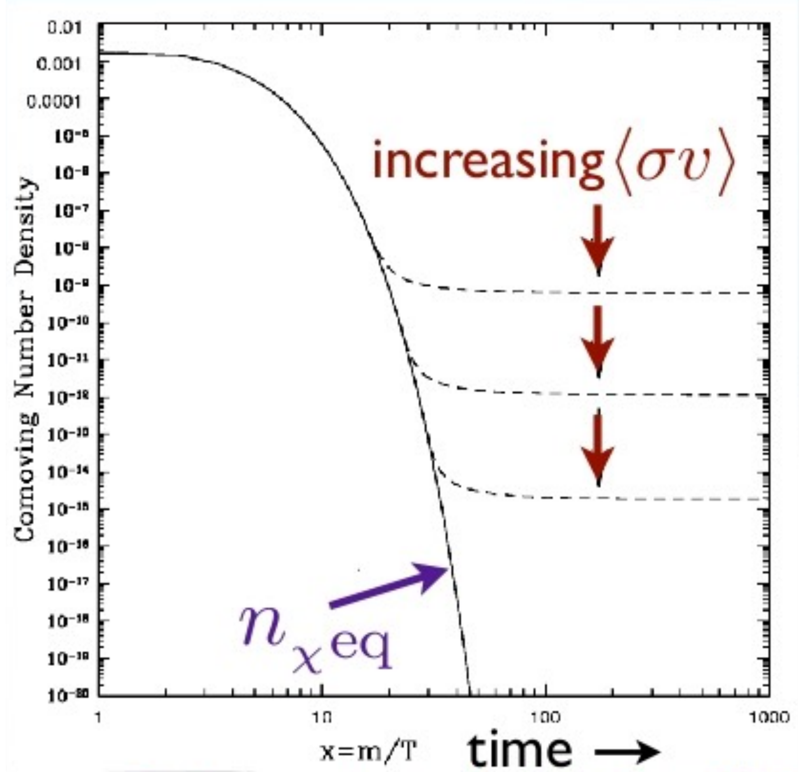


Fig.: Jungman, Kamionkowski & Griest, PR'96

Critical assumption:

kinetic equilibrium at chemical decoupling

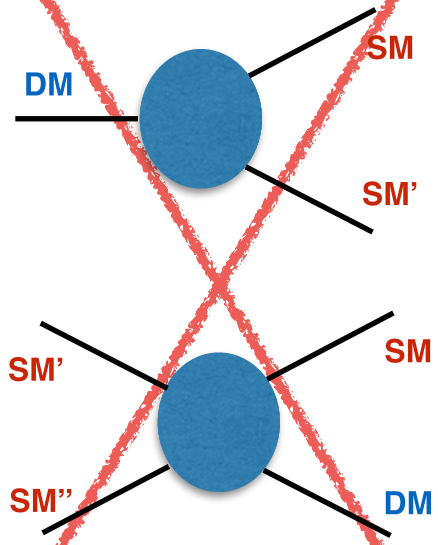
$$f_\chi \sim a(T) f_\chi^{\rm eq}$$

WHAT GOES INTO C IN GENERAL?

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

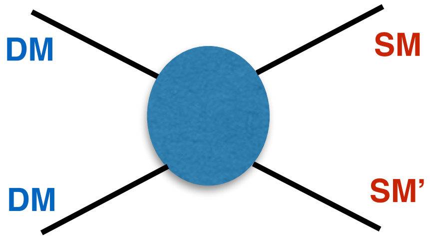
changing processes ⇒ number density

1 DM particle



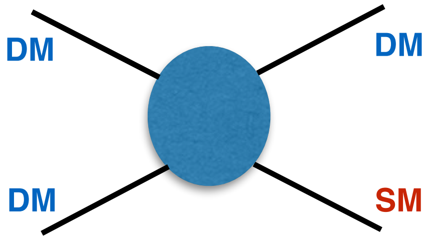
stability

2 DM particles



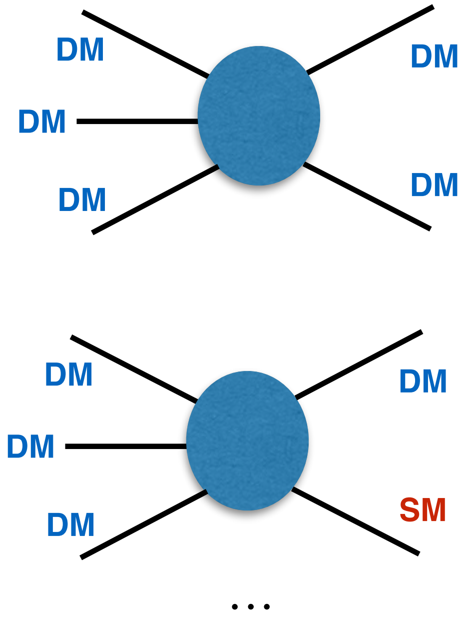
annihilation

3 DM particles



semi-annihilation

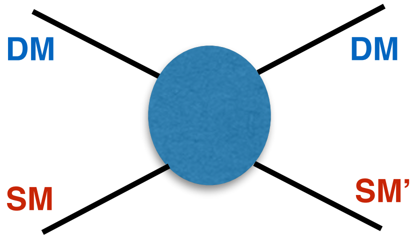
4+ DM particles



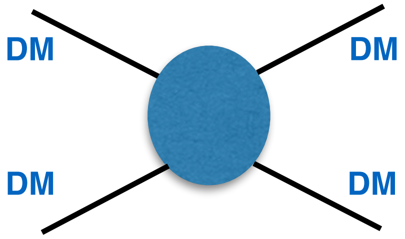
cannibalization

…

conserving processes ⇒ energy density



elastic scattering



self scattering

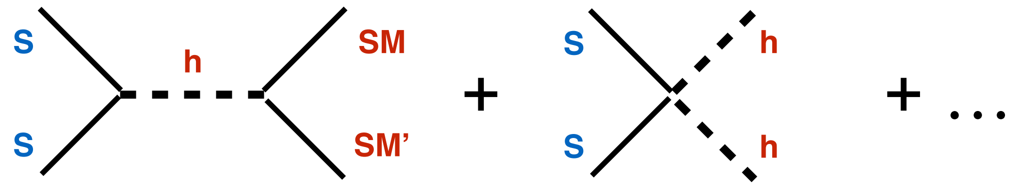
EXAMPLES:

STANDARD DM MODELS

Simple WIMP (e.g. scalar singlet model)

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

one coupling governing production & detection



… but still not ruled out

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

SUSY

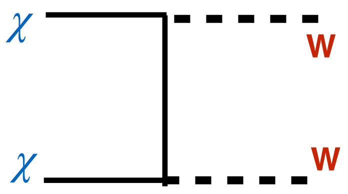
Neutralino

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

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

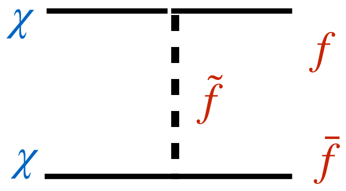
has SM gauge interactions with fixed strength… but unknown mixing

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



+ …

in particular:

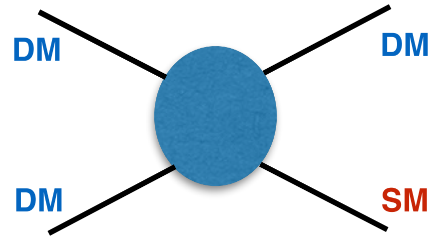


EXAMPLES:

NON-STANDARD SINGLE DM MODELS

Semi-annihilation

D'Eramo, Thaler '10

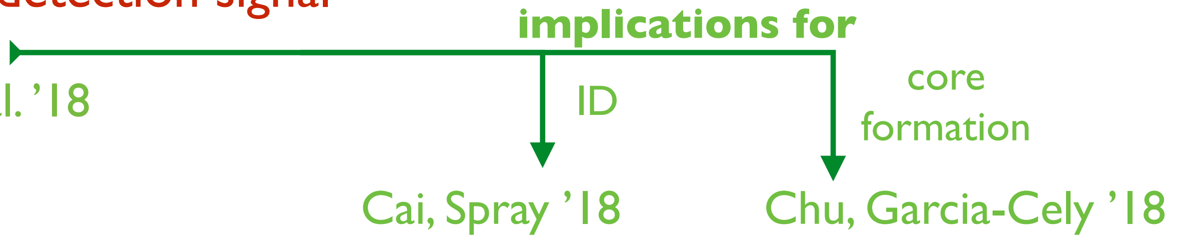


Typically occurs when new „flavour" or „baryon" structure in dark sector, but also present in scalar models, e.g. with $\mathbb{Z}_3$ symmetry

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

This interaction does not directly give a direct detection signal and leads to self-heating of DM

Kamada et al. '18



implications for

ID

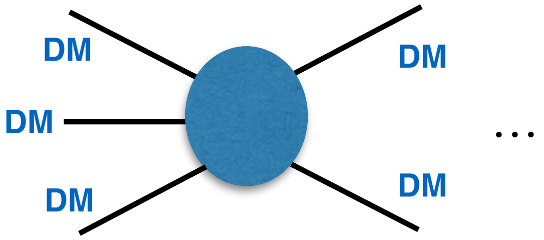
Cai, Spray '18

core formation

Chu, Garcia-Cely '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 ⇒ 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, …

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

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

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

general
multi-
component
dark sector

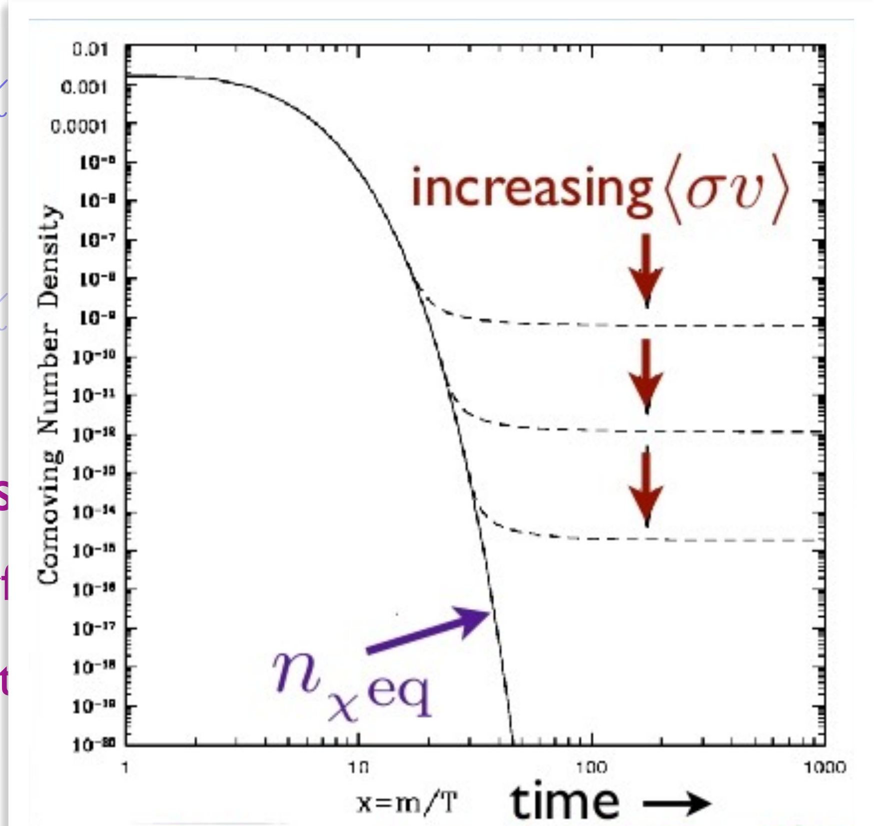


Fig.: Jungman, Kamionkowski & Griest, PR'96

modified cross

Sommerf

Bound St

NLO

finite T e

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

where the thermally averaged cross section:

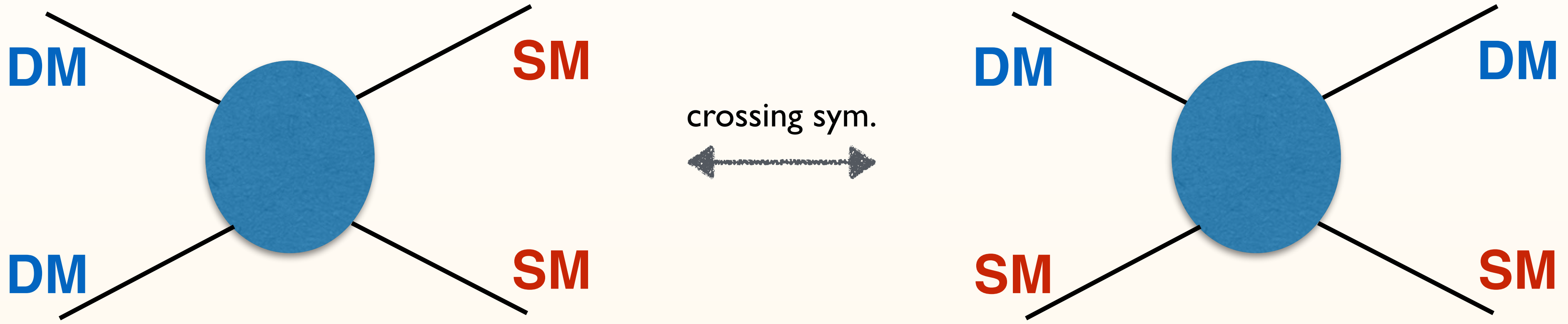
$$\langle\sigma_{\chi\bar\chi\to ij}v_{\rm rel}\rangle^{\rm eq} = -\frac{h_\chi^2}{n_\chi^{\rm eq} n_{\bar\chi}^{\rm eq}}\int\frac{d^3\vec p_\chi}{(2\pi)^3}\frac{d^3\vec p_{\bar\chi}}{(2\pi)^3}\,\sigma_{\chi\bar\chi\to ij}v_{\rm rel}\; f_\chi^{\rm eq} f_{\bar\chi}^{\rm eq}$$

I:

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 typically more frequent

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

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

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

Two consequences:

1. During freeze-out (chemical decoupling) typically: $f_\chi \sim a(\mu) f_\chi^{\rm eq}$
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

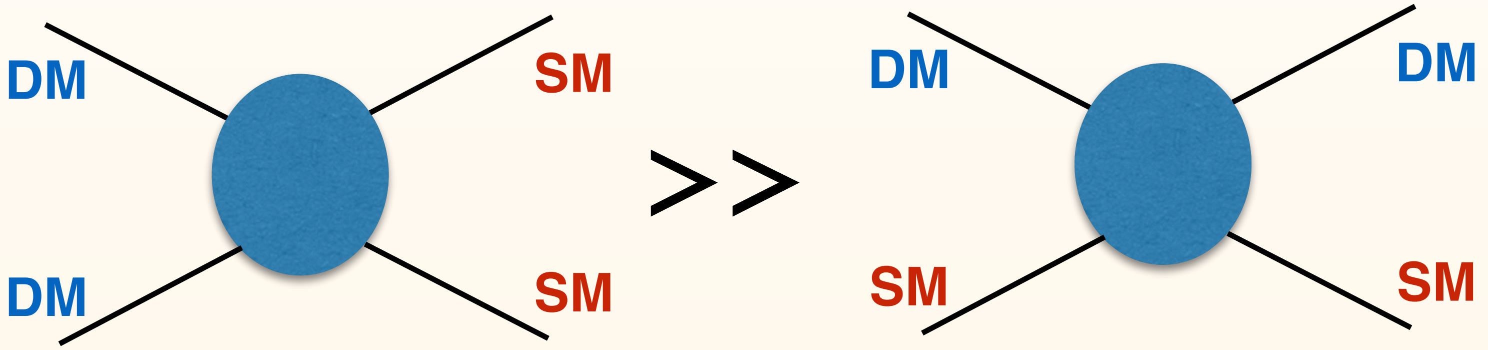
EARLY KINETIC DECOUPLING?

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

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

$\mathcal{C}[f_\chi]$ → 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
…

partially analytic/much easier numerically

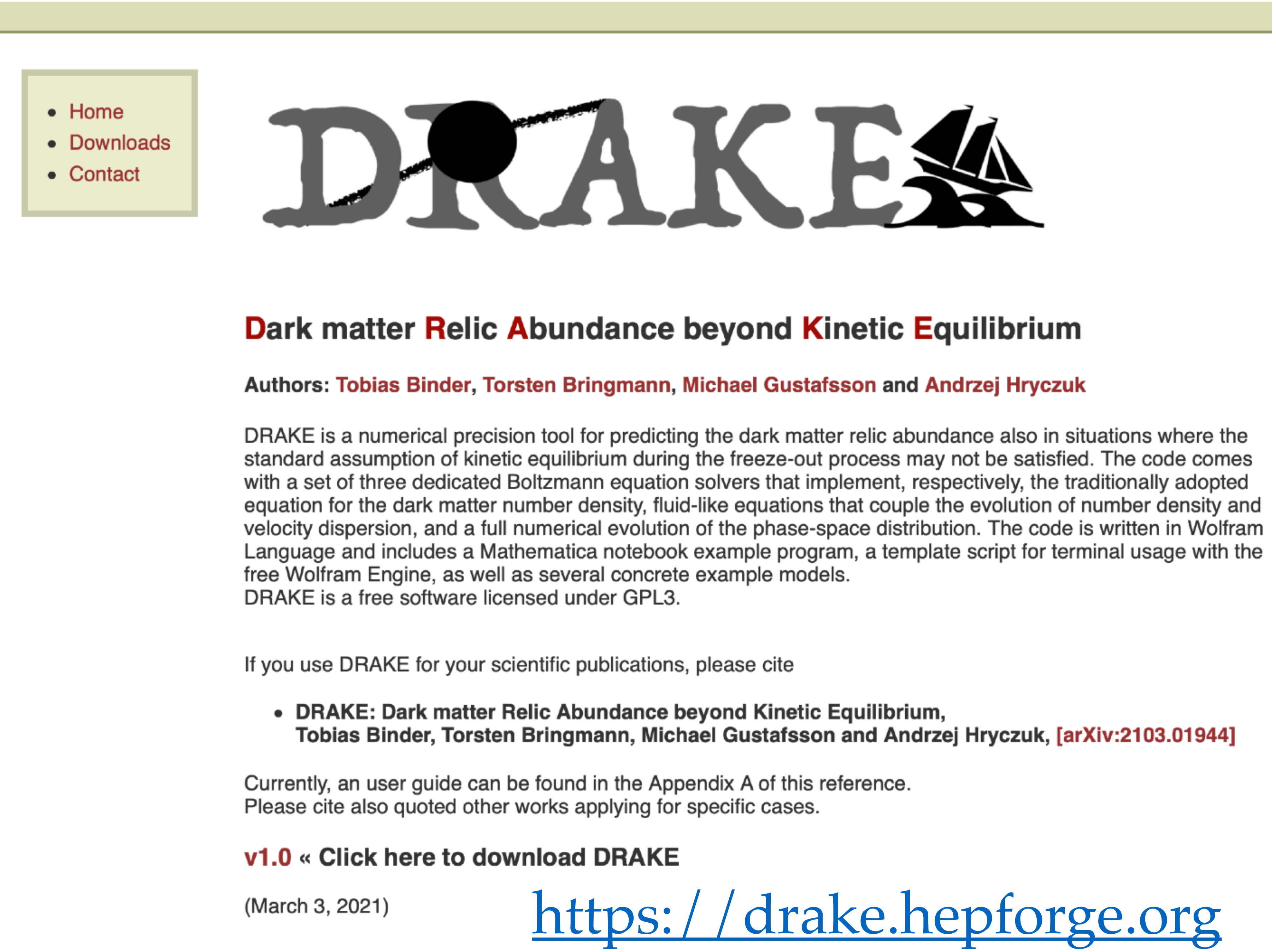
manifestly captures all of the relevant physics

finite range of validity

no insight on the distribution

NEW TOOL!

GOING BEYOND THE STANDARD APPROACH



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

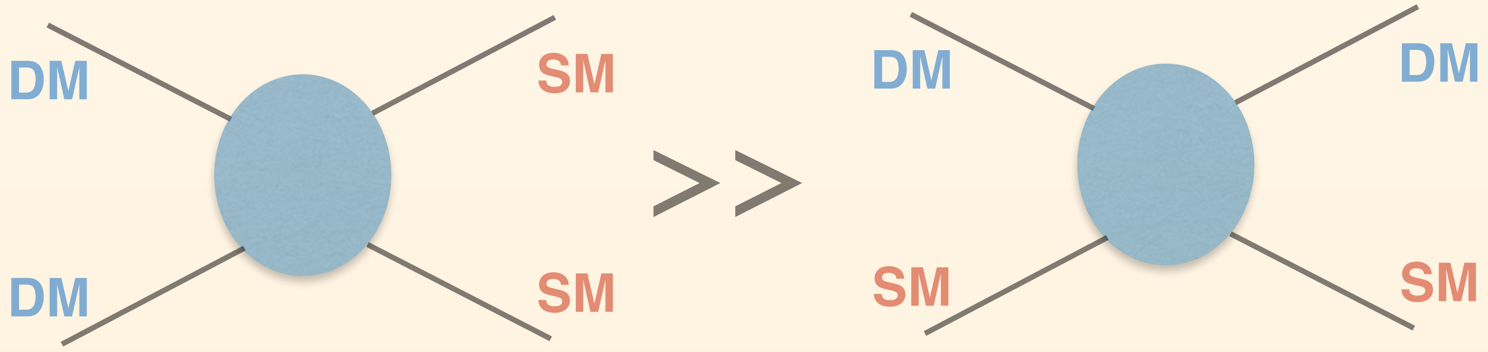
…

(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

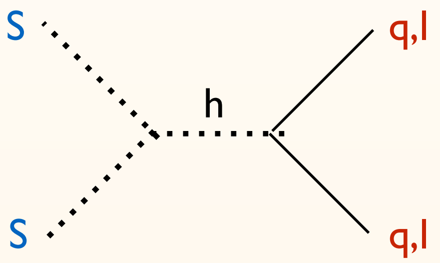
To the SM Lagrangian add one singlet scalar field *S* with interactions with the Higgs:

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

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

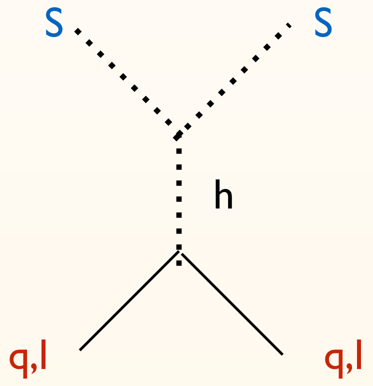
Annihilation processes:

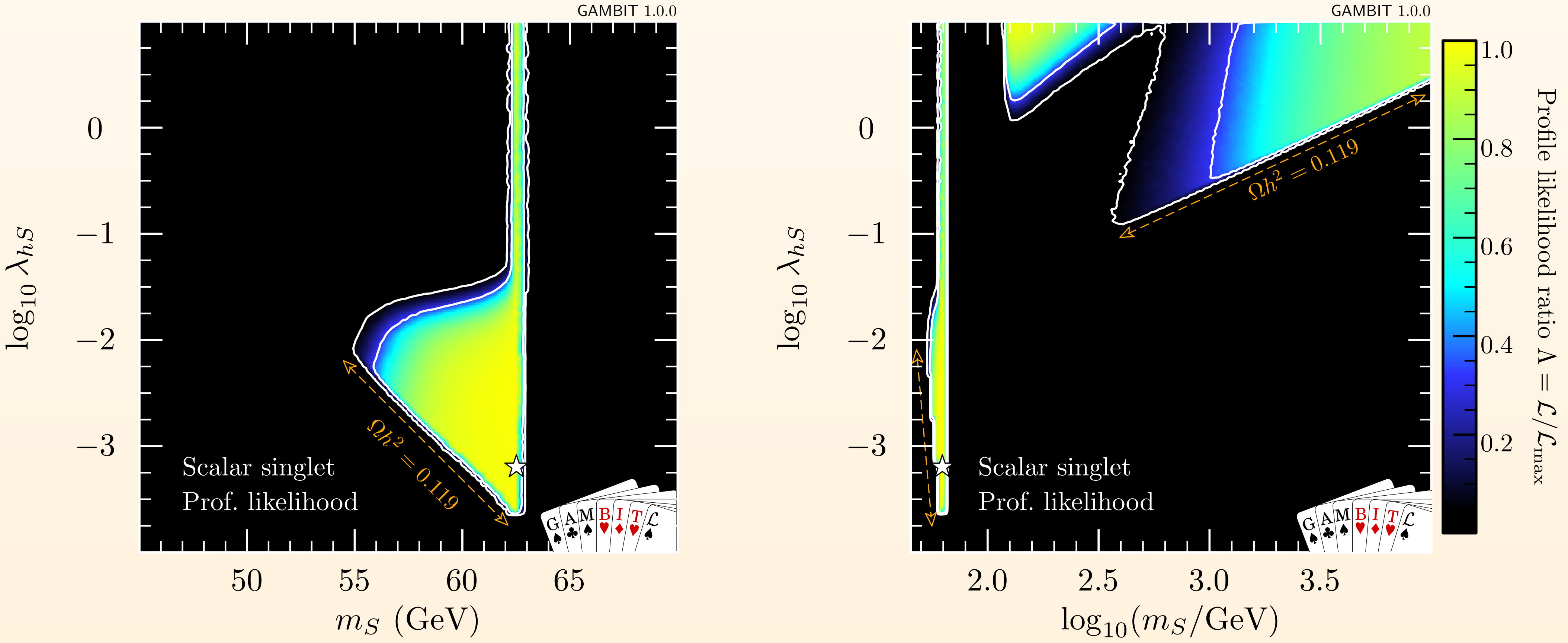
resonant



El. scattering processes:

non-resonant



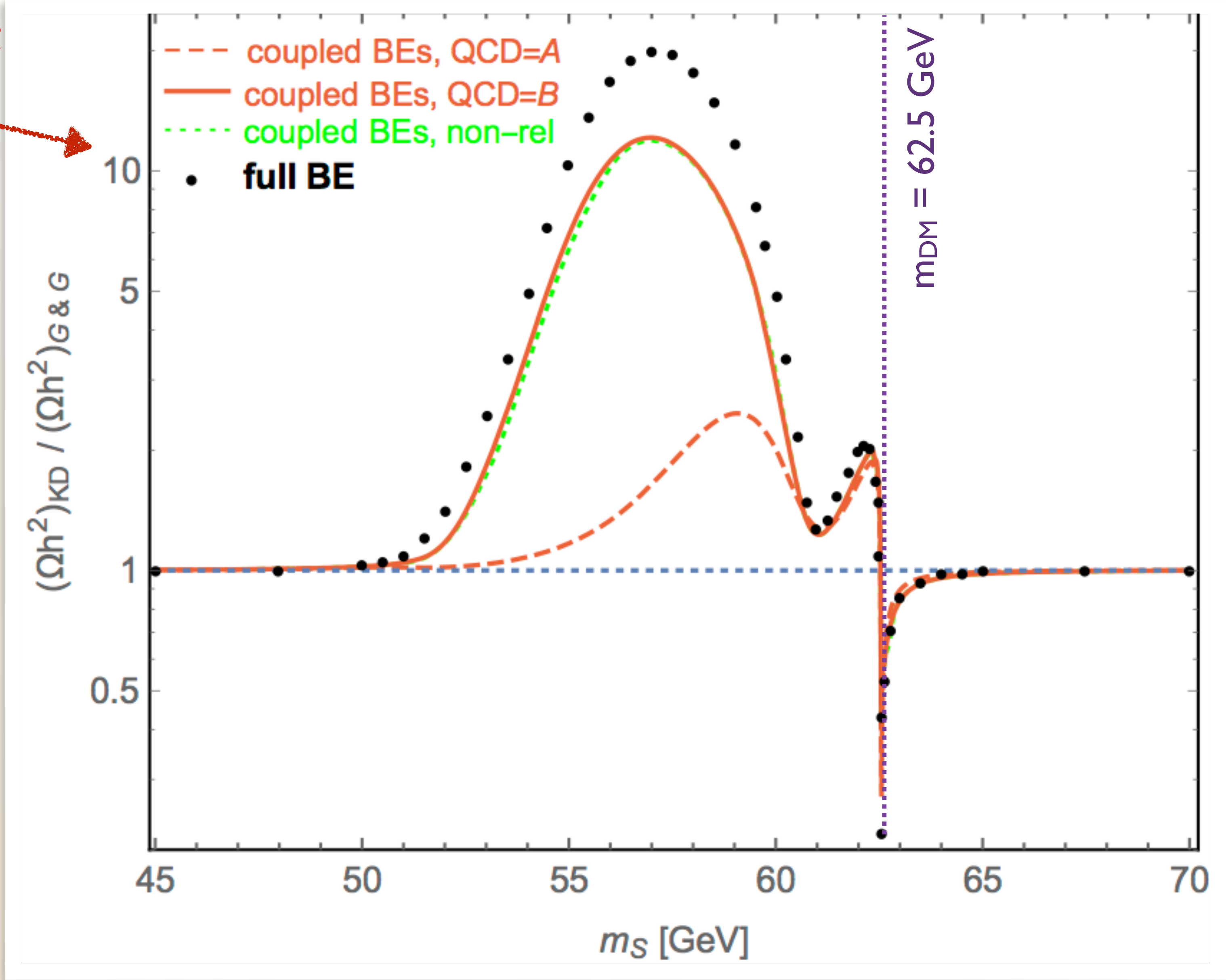


GAMBIT collaboration
1705.07931

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 $4T_c$ …]

DM ELASTIC SCATTERINGS

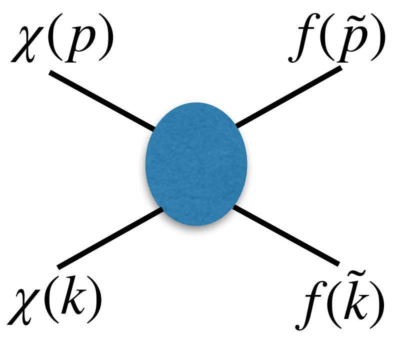
(FEW DETAILS AND CHALLENGES…)

ELASTIC SCATTERING COLLISION TERM

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

→ contains both scatterings and annihilations

Annihilation:



$$C_{\rm ann} \sim \int d\tilde{\Pi}\, |\mathscr{M}|^2_{\chi\chi\leftrightarrow f\bar{f}} \Big(\underbrace{f_f^{\rm eq}(\tilde{p}) f_f^{\rm eq}(\tilde{k})}_{\text{easy}} - \underbrace{f_\chi(p) f_\chi(k)}_{\text{easy}}\Big)$$

easy: no unknown f_χ under integral

⇒ 1D integration

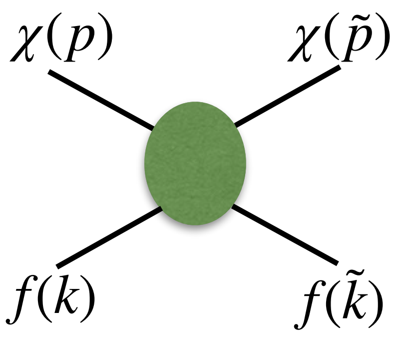
medium: no unknown f_χ under integral

⇒ 2-3D integration

hard: unknown f_χ under integral

⇒ 2-4D integration

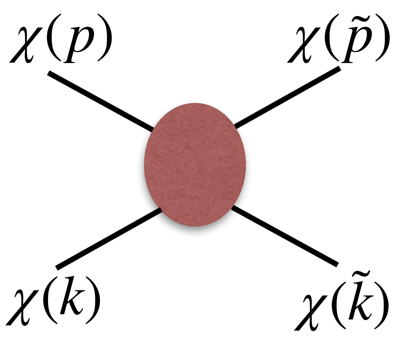
El. scattering (on SM particles):



$$C_{\rm el} \sim \int d\tilde{\Pi}\, |\mathscr{M}|^2_{\chi f\leftrightarrow \chi f} \Big(\underbrace{f_\chi(\tilde{p}) f_f^{\rm eq}(\tilde{k})(1 \pm f_f^{\rm eq}(k))}_{\text{hard}} - \underbrace{f_\chi(p) f_f^{\rm eq}(k)(1 \pm f_f^{\rm eq}(\tilde{k}))}_{\text{medium}}\Big)$$

An approximate method needed!

El. self-scattering (DM on DM):



$$C_{\rm self} \sim \int d\tilde{\Pi}\, |\mathscr{M}|^2_{\chi\chi\leftrightarrow \chi\chi} \Big(\underbrace{f_\chi(\tilde{p}) f_\chi(\tilde{k}) - f_\chi(p) f_\chi(k)}_{\text{hard}}\Big)$$

$$d\tilde{\Pi} = d\Pi_{\tilde{p}}\, d\Pi_k\, d\Pi_{\tilde{k}}\, \delta^{(4)}(\tilde{p} + p - \tilde{k} - k)$$

APPROACHES

I) Expand in „small momentum transfer"

$$M_{\mathrm{DM}} \gg |\vec{q}\,| \sim T \gg m_{\mathrm{SM}}$$

typical momentum transfer

Bringmann, Hofmann '06

$$\delta^{(3)}(\tilde{\mathbf{p}}+\tilde{\mathbf{k}}-\mathbf{p}-\mathbf{k}) \approx \sum_n \frac{1}{n!}(\mathbf{q}\nabla_{\tilde{\mathbf{p}}})^n \delta^{(3)}(\tilde{\mathbf{p}}-\mathbf{p})$$

Kasahara '09; Binder, Covi, Kamada, Murayama, Takahashi, Yoshida '16

$$f_3 \simeq f_1 + \tilde{\mathbf{q}}_i \frac{\partial f_1}{\partial \mathbf{p}_{1i}} + \frac{1}{2}\tilde{\mathbf{q}}_i \tilde{\mathbf{q}}_j \frac{\partial^2 f_1}{\partial \mathbf{p}_{1i}\partial \mathbf{p}_{1j}}$$

A.H. & S. Chatterjee, *work in progress…*
(on different expansion schemes)

$\Longrightarrow$ all lead to Fokker-Planck type eq.

II) Replace the backward term with a simpler one (i.e. a relaxation-like approximation)

$\Longrightarrow$ simpler, but generally incorrect

Ala-Mattinen, Kainulainen '19
Ala-Mattinen, Heikinheimo, Kainulainen, Tuominen '22

$$\begin{aligned}\hat{C}_{\mathrm{E},m}(p_1,t) &\to -\delta f(p_1,t)\,\Gamma^m_{\mathrm{E}}(p_1,t)\\ &= \big(\,g_m(t) f_{\mathrm{eq}}(p_1,t) - f(p_1,t)\,\big)\,\Gamma^m_{\mathrm{E}}(p_1,t)\end{aligned}$$

III) Langevin simulations

$$(\hat{p}^i)' = -\hat{\eta}\,\hat{p}^i + \hat{f}^i\,, \quad \langle\, \hat{f}^i(x_1)\,\hat{f}^j(x_2)\,\rangle = \hat{\zeta}\,\delta^{ij}\,\delta(x_1-x_2)$$

$\Longrightarrow$ very new, promising (?)…

stochastic term, taking care of detailed balance

Kim, Laine '23

IV) Fully numerical implementation

A.H. & M. Laletin 2204.07078 (focus on DM self-scatterings)
Ala-Mattinen, Heikinheimo, Kainulainen, Tuominen '22
Du, Huang, Li, Li, Yu '21

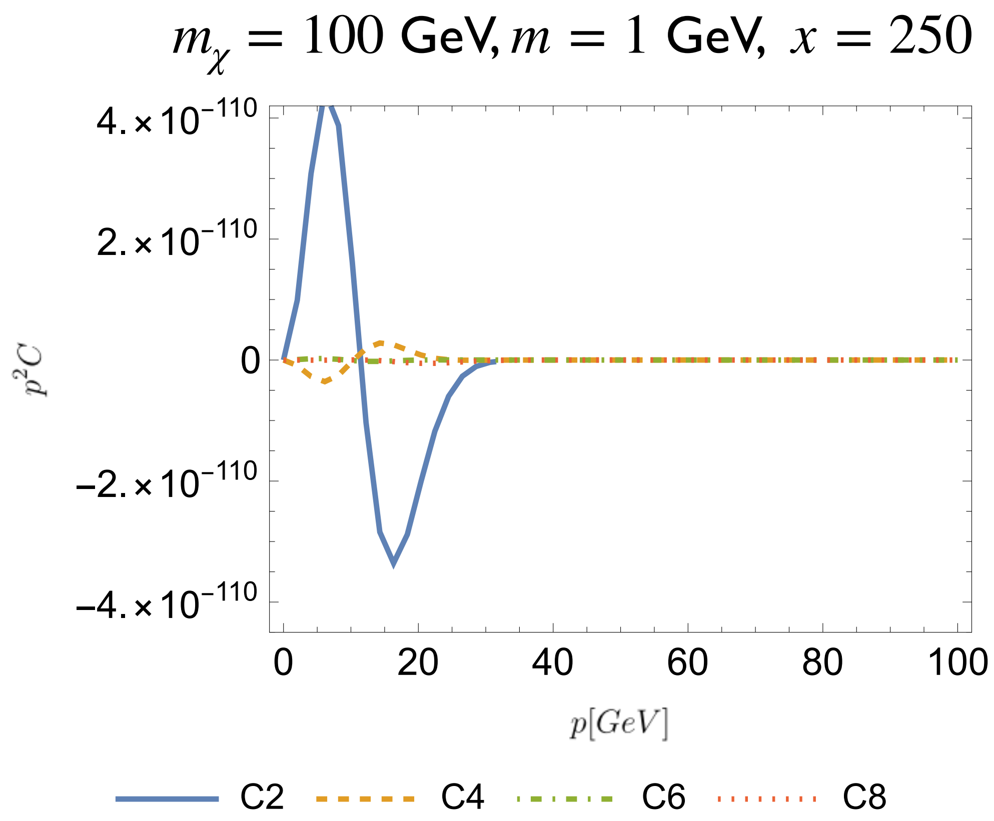
$\Longrightarrow$ doable, but very CPU expensive

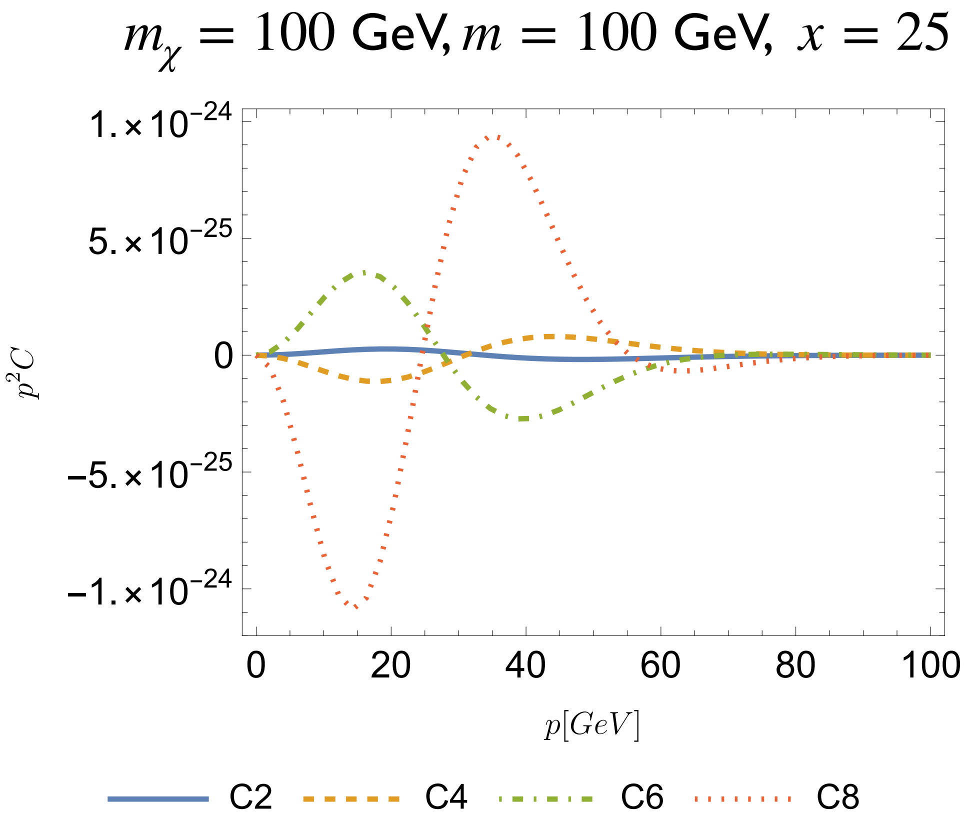
ISSUES…

I) Expand in „small momentum transfer"

Bringmann, Hofmann '06

$$\delta^{(3)}(\tilde{\mathbf{p}}+\tilde{\mathbf{k}}-\mathbf{p}-\mathbf{k}) \approx \sum_n \frac{1}{n!}(\mathbf{q}\nabla_{\tilde{\mathbf{p}}})^n \delta^{(3)}(\tilde{\mathbf{p}}-\mathbf{p}) \quad \Rightarrow C_{el} = C_0 + C_2 + C_6 + \ldots$$





Kasahara '09;
Binder, Covi, Kamada, Murayama, Takahashi, Yoshida '16

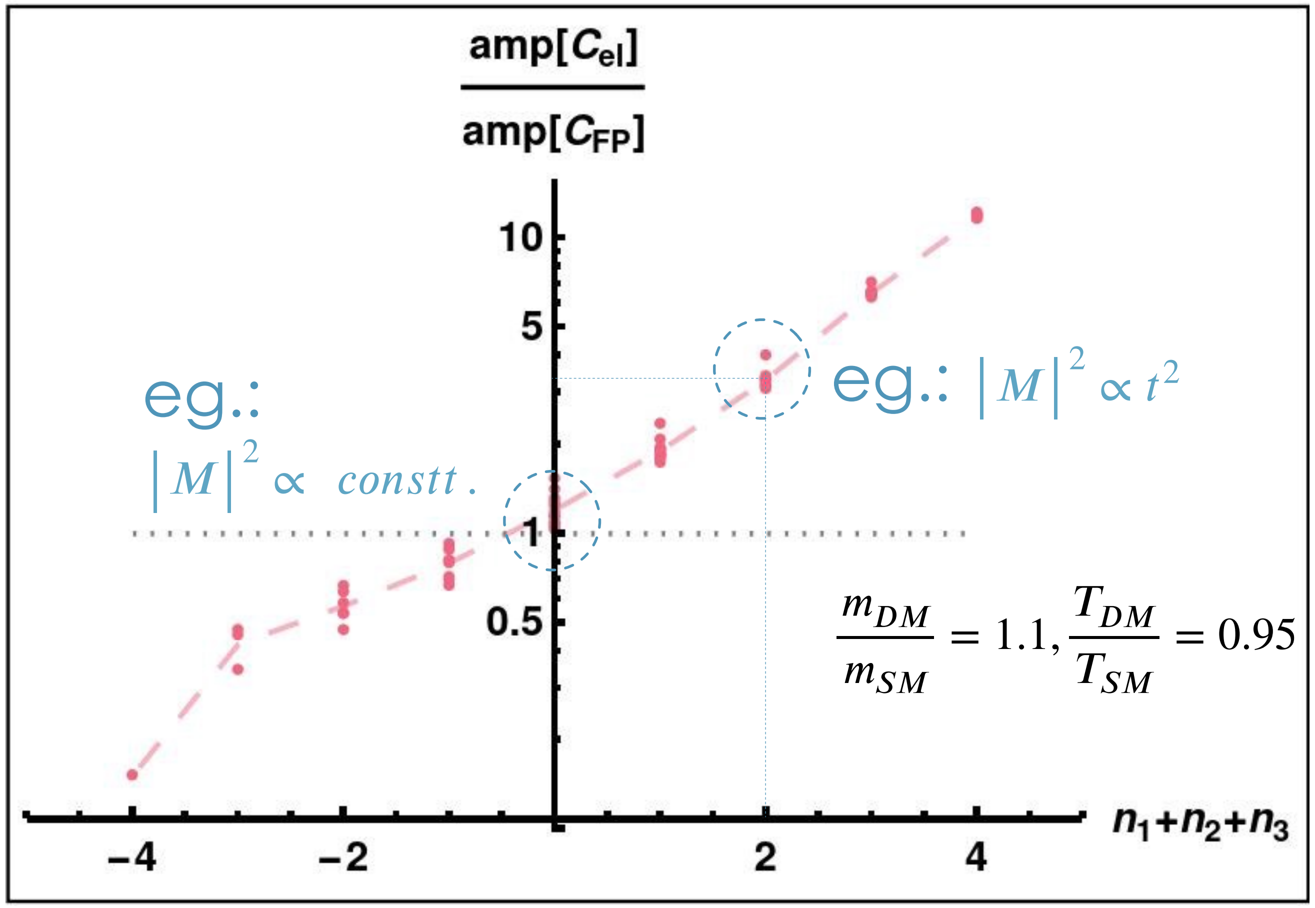
$$f_3 \simeq f_1 + \tilde{\mathbf{q}}_i \frac{\partial f_1}{\partial \mathbf{p}_{1i}} + \frac{1}{2}\tilde{\mathbf{q}}_i\tilde{\mathbf{q}}_j \frac{\partial^2 f_1}{\partial \mathbf{p}_{1i}\partial \mathbf{p}_{1j}}$$

approx.: plasma frame → CM frame

(not justified for all collisions in the plasma)

WHEN DOES THE FOKKER-PLANCK APPROX. WORK?

$$|M|^2 \longrightarrow \underbrace{t^{n_1}}_{\propto\ \text{transfer momentum}} \underbrace{\left(s-\left(m_{DM}+m_{SM}\right)^2\right)^{n_2}}_{\propto\ \text{relative velocity}} \underbrace{\left(u-\left(m_{DM}-m_{SM}\right)^2\right)^{n_3}}_{\propto\ \text{velocities}}$$



1. Scattering particle with masses significantly smaller than DM mass (small reduced mass⇒small momentum transfer)

&

2. DM temperatures close to the SM temperature (eg.: near kinetic decoupling)

&

3. Scattering amplitudes that aren’t strongly dependent on momentum transfer (the dropped higher order terms are more relevant for an amplitude sensitive to said dropped quantity)

work in progress with **S. Chatterjee**

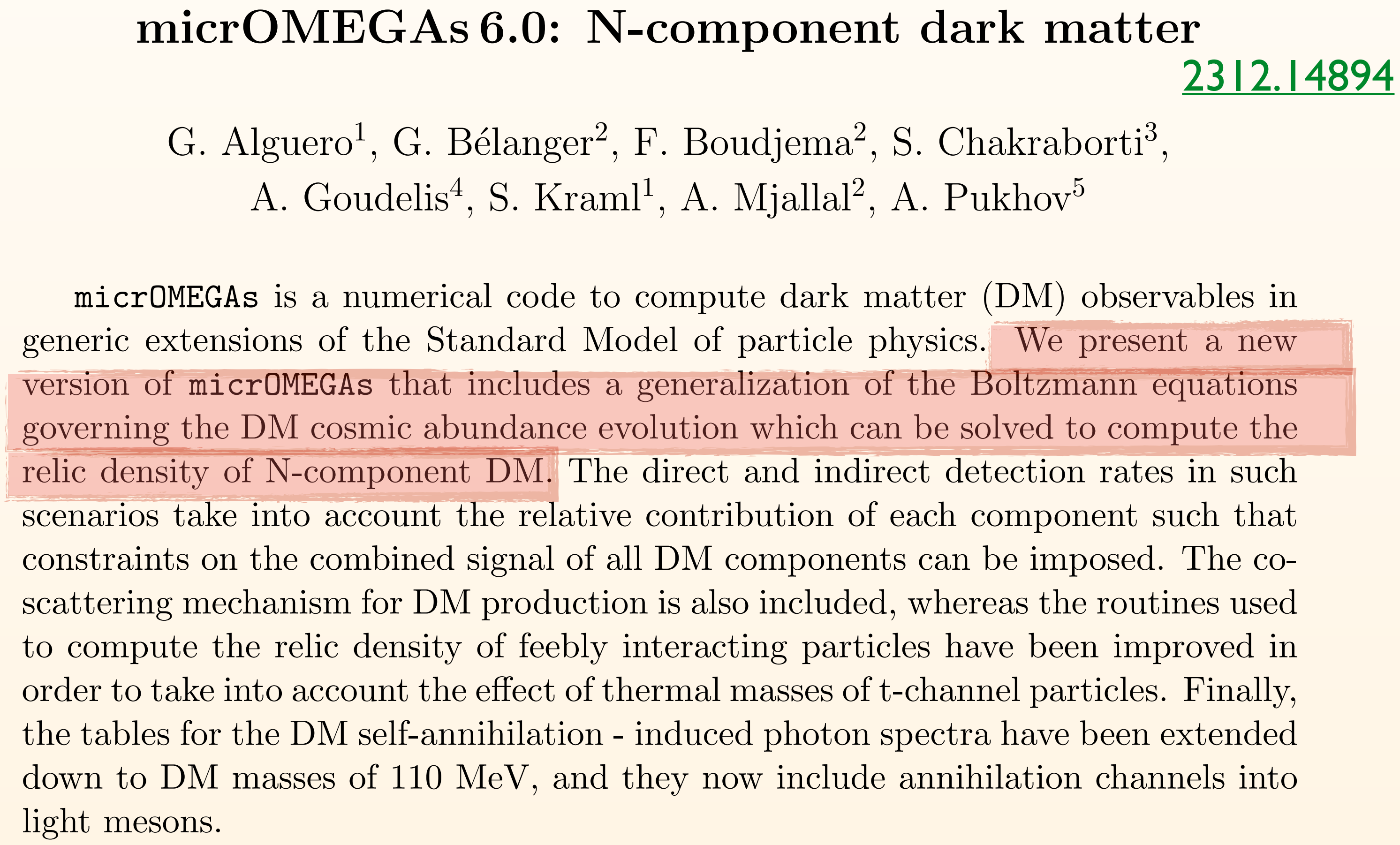
II:

MULTI-COMPONENT DARK MATTER

STATE-OF-THE-ART…

There are numerous results for two-component dark sectors… but without full generality and in fact narrowly tailored to specific models

The most general tool so far is the newly released:



micrOMEGAs 6.0: N-component dark matter

2312.14894

G. Alguero[1], G. Bélanger[2], F. Boudjema[2], S. Chakraborti[3],
A. Goudelis[4], S. Kraml[1], A. Mjallal[2], A. Pukhov[5]

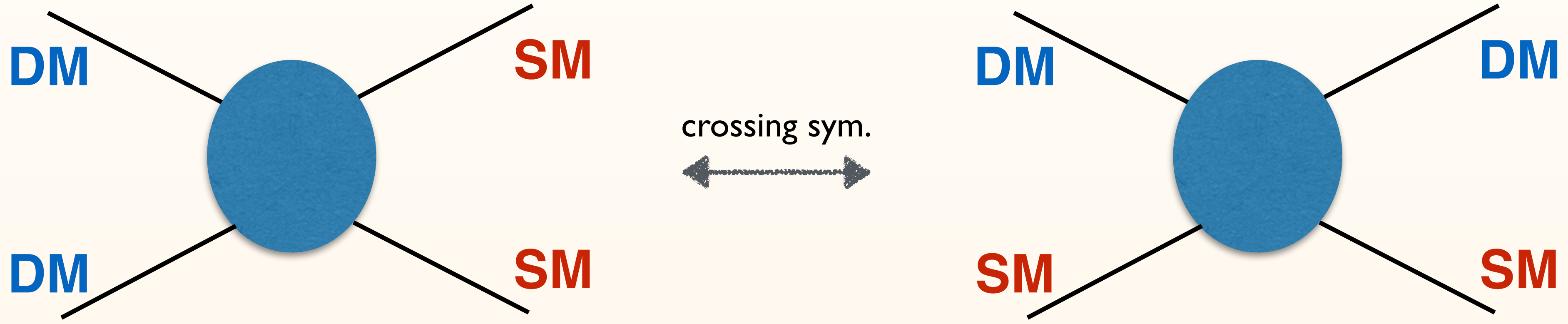
`micrOMEGAs` is a numerical code to compute dark matter (DM) observables in generic extensions of the Standard Model of particle physics. We present a new version of `micrOMEGAs` that includes a generalization of the Boltzmann equations governing the DM cosmic abundance evolution which can be solved to compute the relic density of N-component DM. The direct and indirect detection rates in such scenarios take into account the relative contribution of each component such that constraints on the combined signal of all DM components can be imposed. The co-scattering mechanism for DM production is also included, whereas the routines used to compute the relic density of feebly interacting particles have been improved in order to take into account the effect of thermal masses of t-channel particles. Finally, the tables for the DM self-annihilation - induced photon spectra have been extended down to DM masses of 110 MeV, and they now include annihilation channels into light mesons.

Solves set of equations for the yields (only):

$$3H\frac{dY_\mu}{d\mathfrak{s}} = \sum_{\alpha\leq\beta;\,\gamma\leq\delta} Y_\alpha Y_\beta C_{\alpha\beta}\langle v\sigma_{\alpha\beta\gamma\delta}\rangle(\delta_{\mu\alpha}+\delta_{\mu\beta}-\delta_{\mu\gamma}-\delta_{\mu\delta})\,.$$

WHAT IF A NON-MINIMAL SCENARIO?

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



annihilation

(elastic) scattering

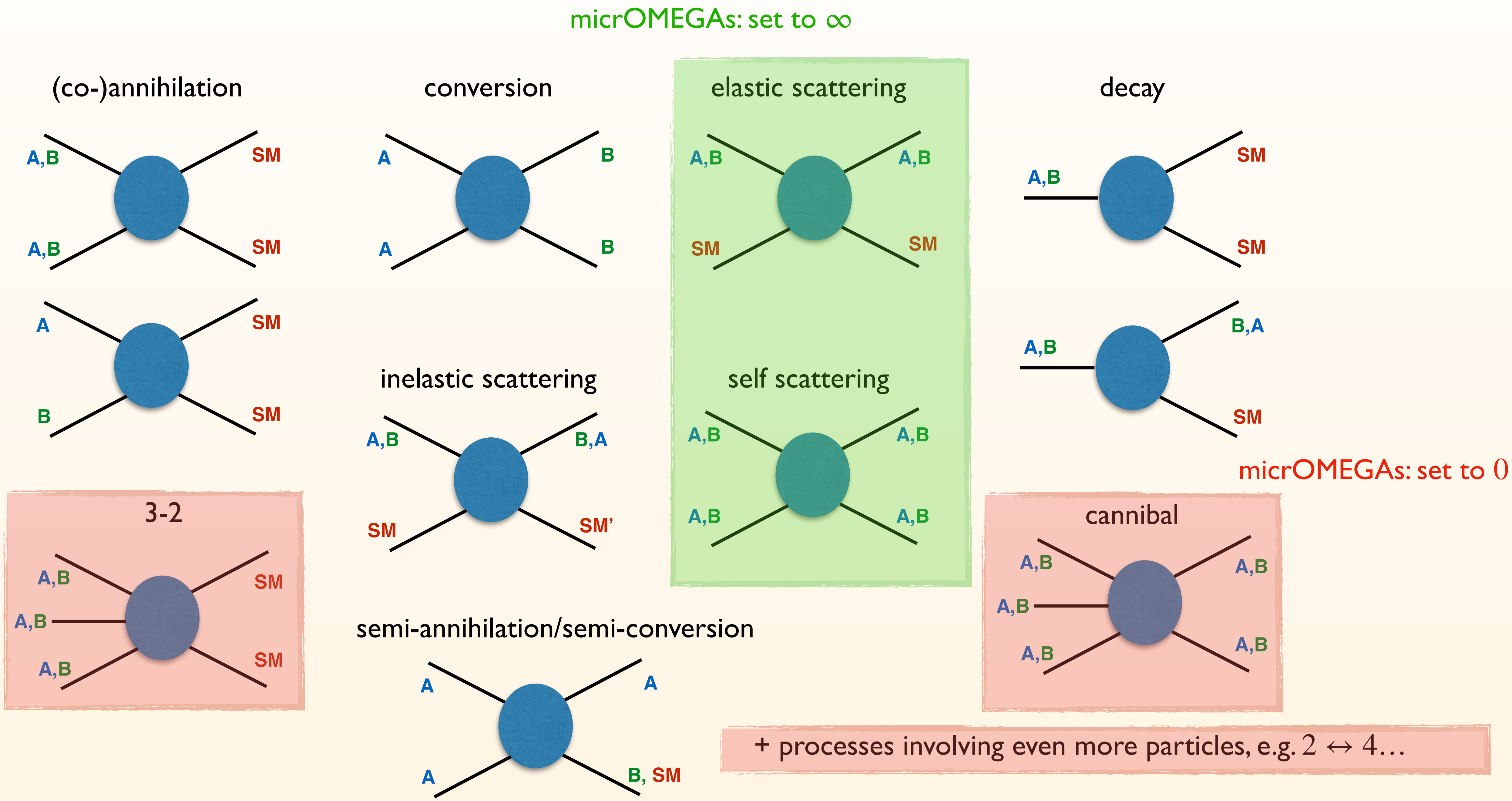
drives number density evolution

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)



micrOMEGAs: set to ∞

(co-)annihilation

conversion

elastic scattering

decay

inelastic scattering

self scattering

micrOMEGAs: set to 0

3-2

cannibal

semi-annihilation/semi-conversion

+ 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 C:

SEMI-ANNIHILATION

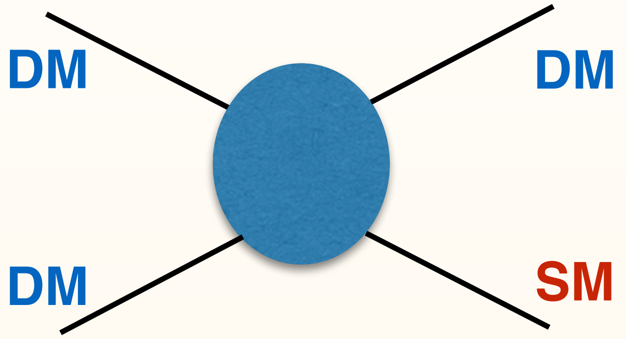
C) Scatterings and annihilation have different structure

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:

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

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!

Kamada et al. 1707.09238

implications for ID

see also Cai, Spray 1807.00832

LESS SIMPLE EXAMPLE

Inert doublet model H_1, H_2 an with additional scalar singlet S:

$$\mathbb{Z}_3 \qquad H_1 \to H_1,\ S \to \omega S,\ H_2 \to \omega H_2 \qquad \omega^3 = 1$$

SM Higgs

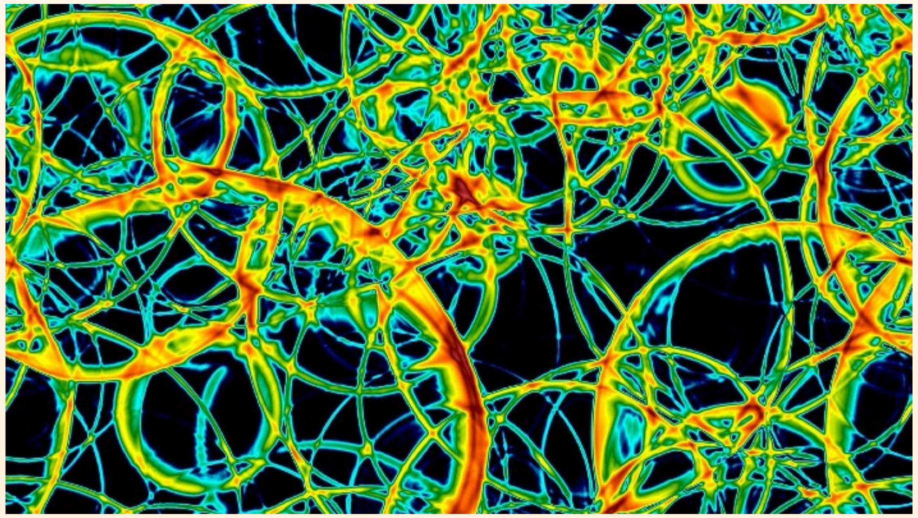
Classical Inert Doublet Model

Classical Scalar Singlet Model (**Z₂**)

$$\begin{aligned} V = &\boxed{\mu_1^2|H_1|^2 + \lambda_1|H_1|^4} + \boxed{\mu_2^2|H_2|^2 + \lambda_2|H_2|^4} + \boxed{\mu_S^2|S|^2 + \lambda_S|S|^4} \\ &\boxed{+ \lambda_{S1}|S|^2|H_1|^2} + \lambda_{S2}|S|^2|H_2|^2 + \boxed{\lambda_3|H_1|^2|H_2|^2 + \lambda_4(H_1^\dagger H_2)(H_2^\dagger H_1)} \\ &\boxed{+ \frac{\mu_S''}{2}(S^3 + S^{\dagger 3}) + \frac{\lambda_{S12}}{2}(S^2 H_1^\dagger H_2 + S^{\dagger 2} H_2^\dagger H_1) + \frac{\mu_{SH}}{2}(S H_2^\dagger H_1 + S^\dagger H_1^\dagger H_2)} \end{aligned}$$

Z₃ mixing terms

Such a scalar potential allows
for FOPT ⇒ nucleation of bubbles
& stochastic GW background →

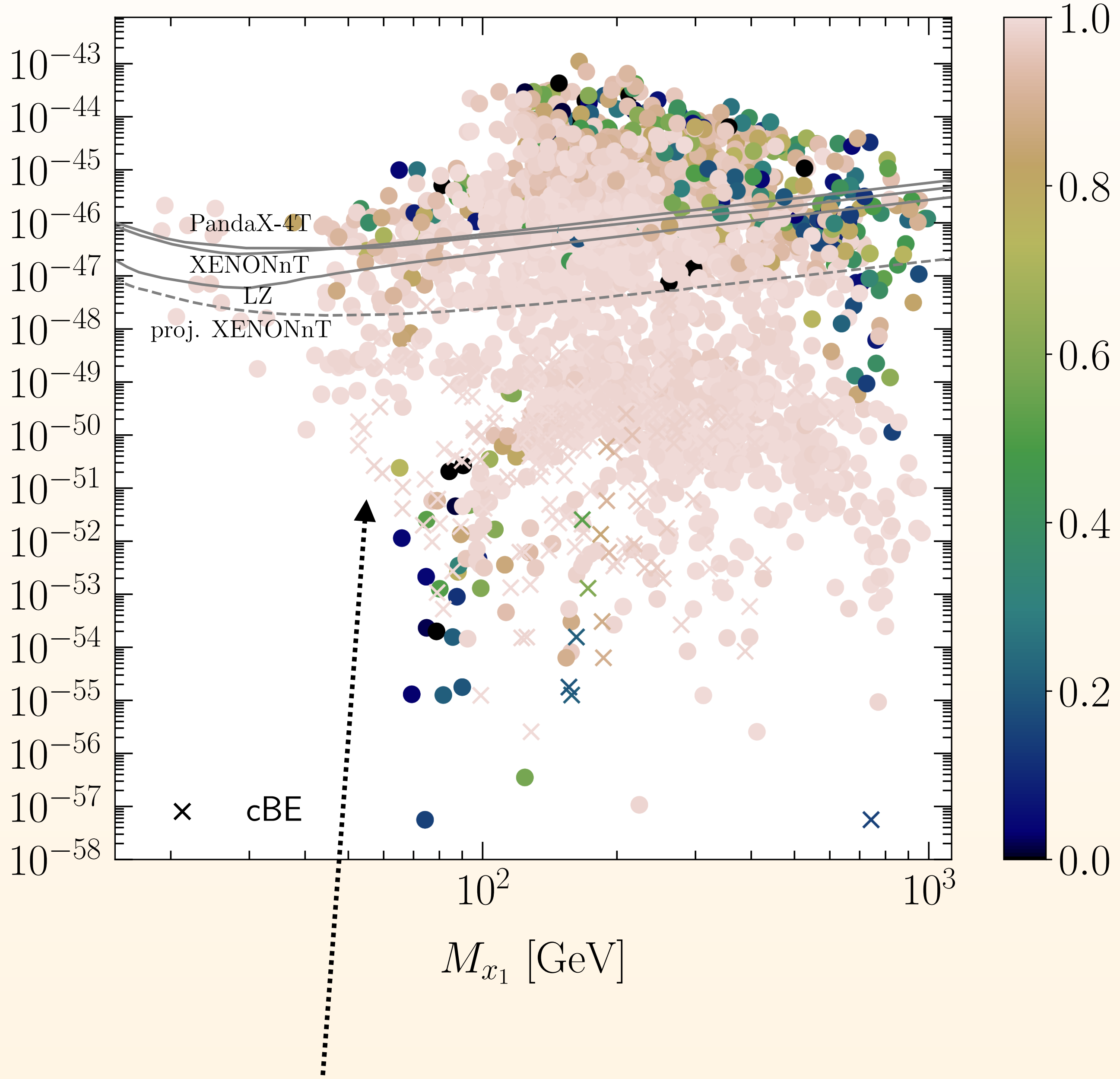


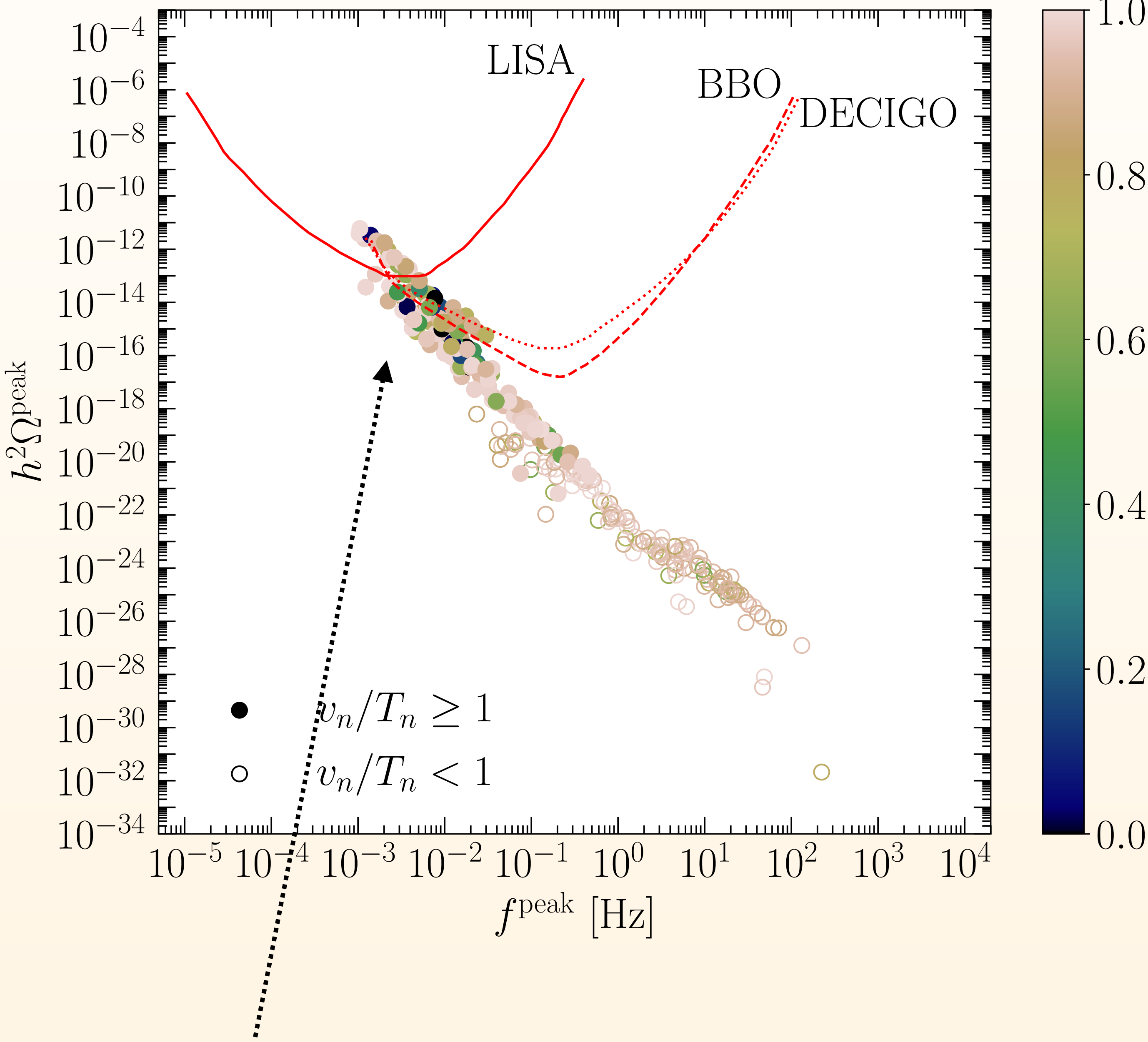
Credit: D. Weir

N. Benincasa, A.H, K. Kannike & M. Laletin 2312.04627

SCAN RESULTS

color: strength of semi-annihilation vs. annihilation





Significant fraction of points has early kinetic decoupling

Some (small) portion of the allowed parameter space will be detectable with future GW instruments

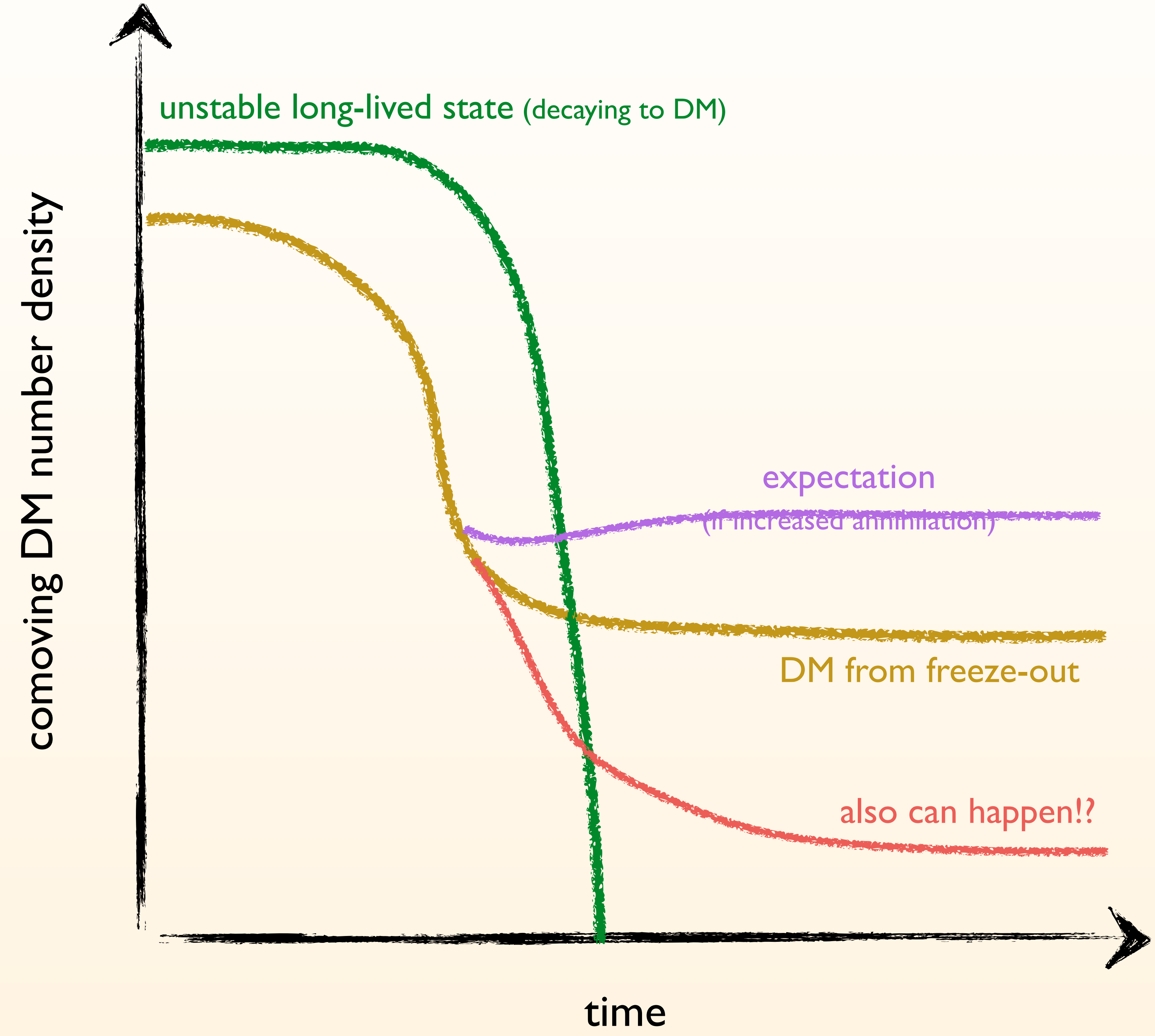
EXAMPLE D:

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)

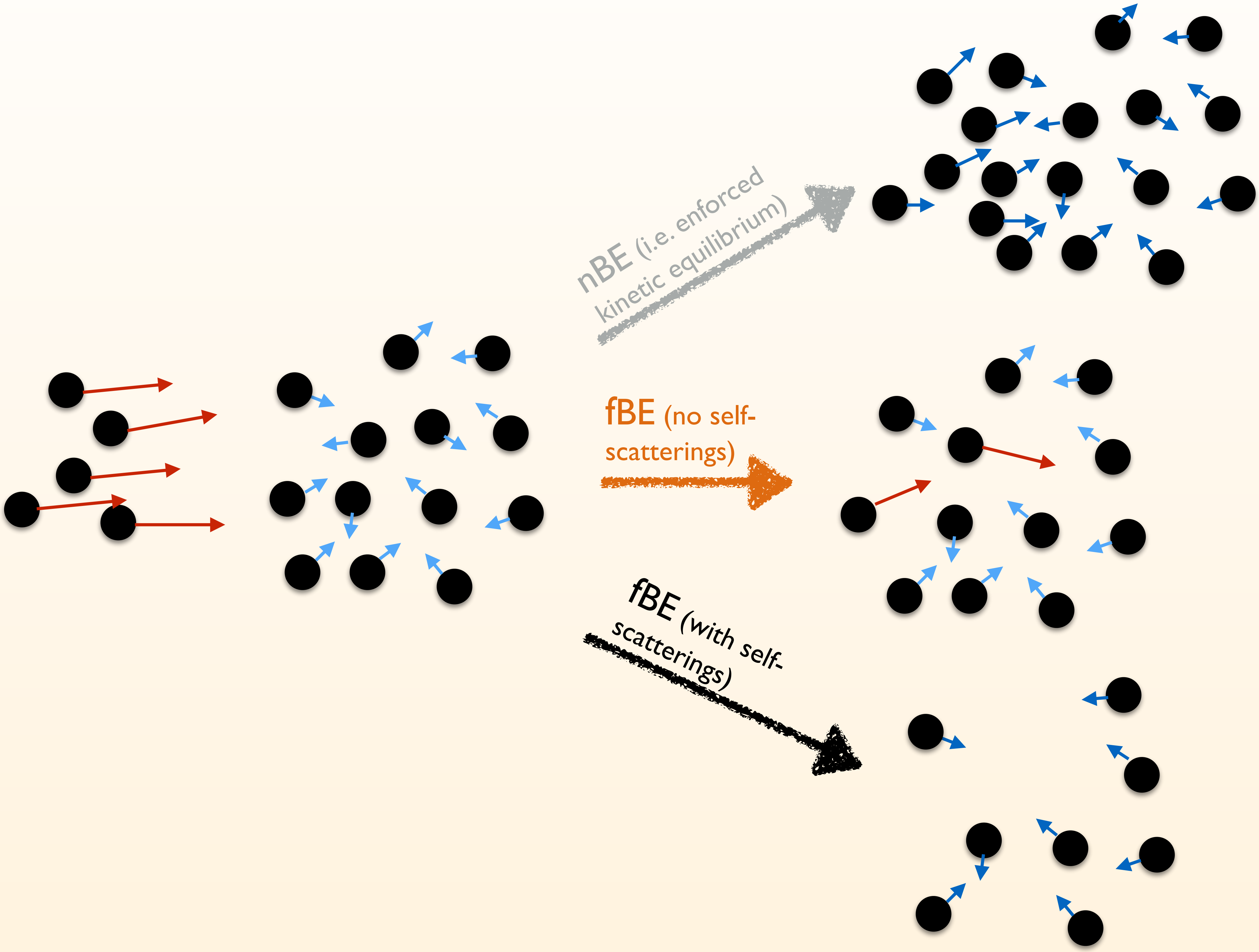
- this can modify the annihilation rate (if still active)
- how does the thermalization due to elastic scatterings happen?


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

I) 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

AH, Laletin 2204.07078

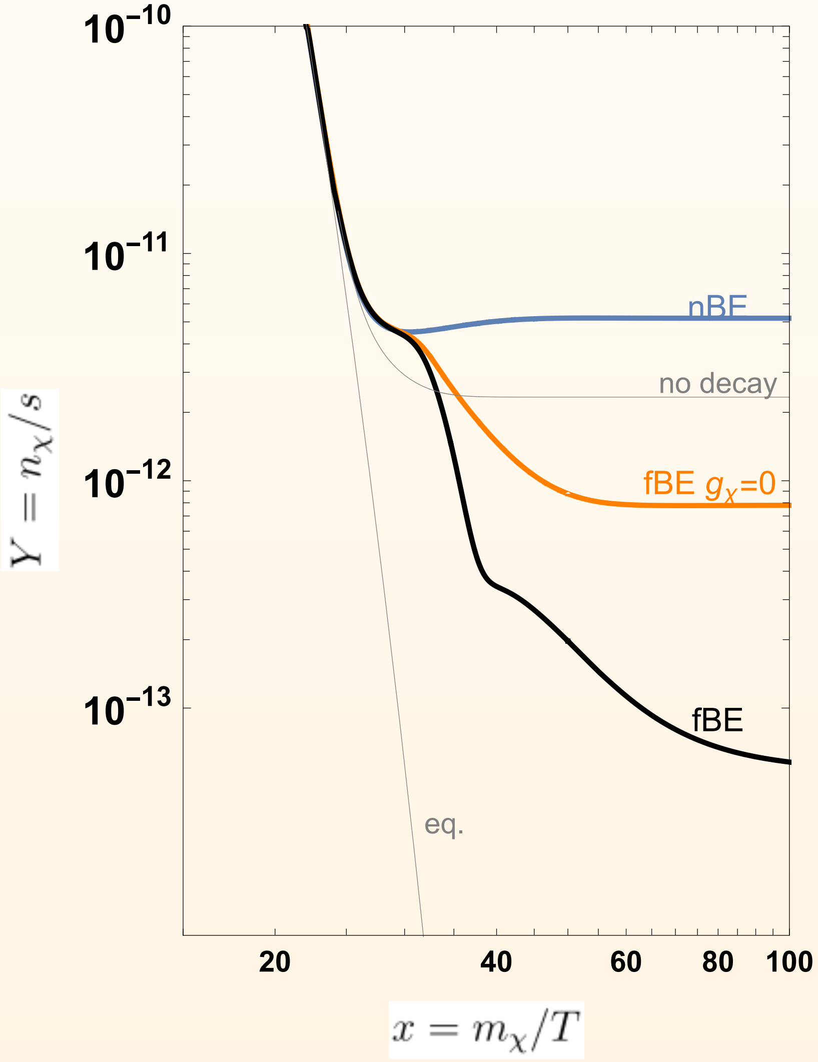
EXAMPLE EVOLUTION

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

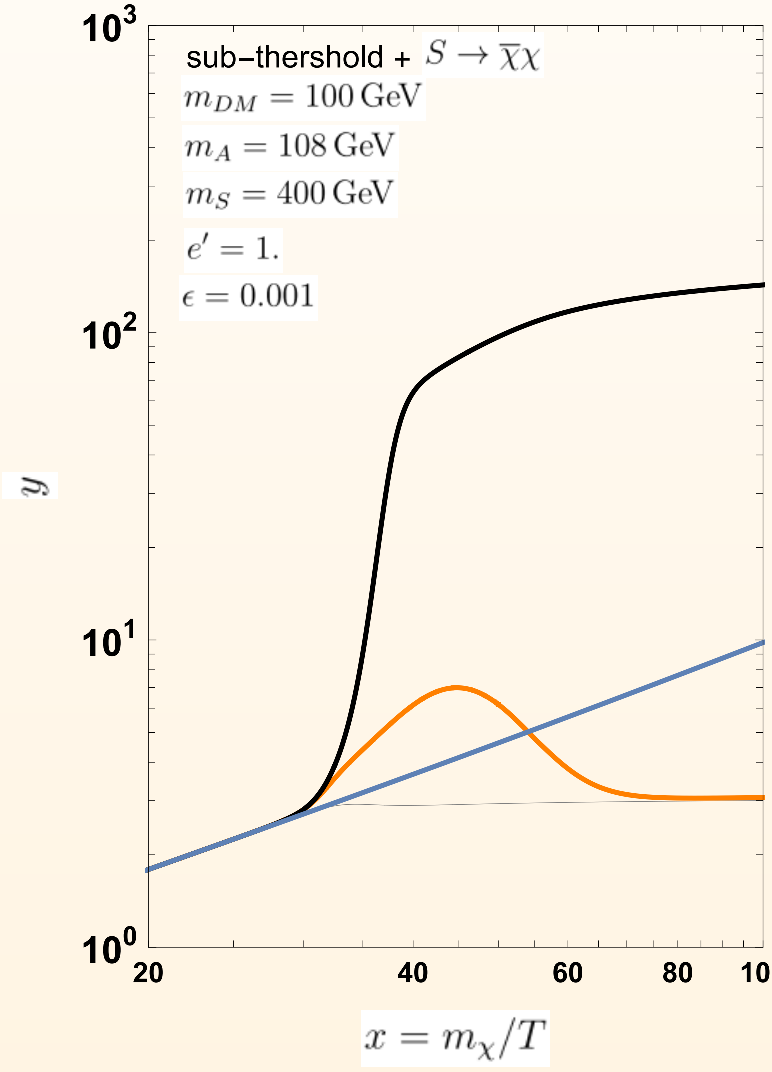
2) DM annihilation has a threshold

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

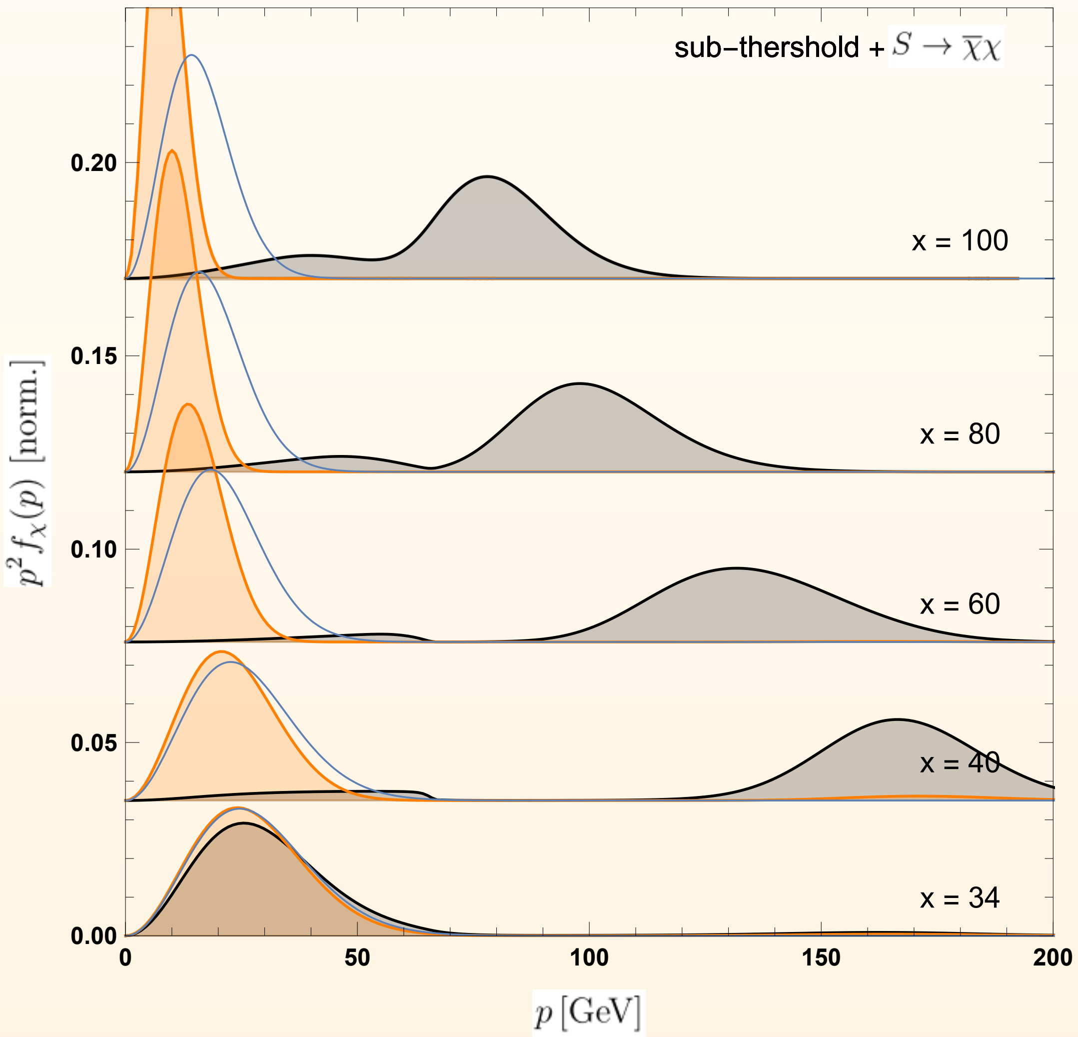
$Y \sim$ number density



$y \sim$ temperature



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

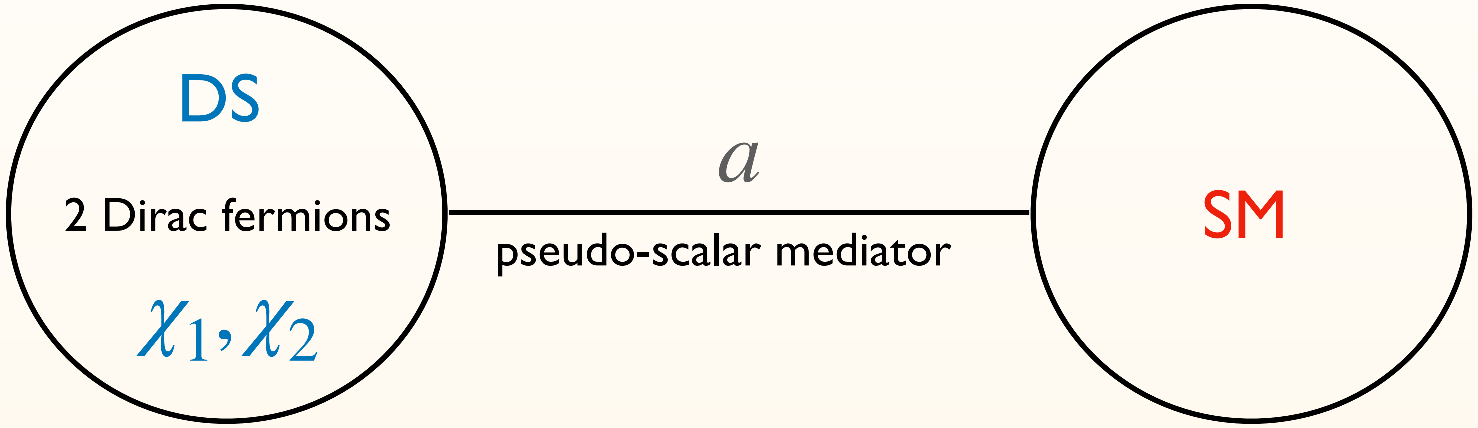


EXAMPLE D:

EFFECT OF CONVERSION PROCESSES

THE MODEL

Let’s take one <u>of the simplest</u> two-component DM models:



$$\mathscr{L}_{int} = -i\lambda_1 \, a\bar{\chi}_1\gamma^5\chi_1 - i\lambda_2 \, a\bar{\chi}_2\gamma^5\chi_2 \quad - i\lambda \, a\bar{f}\gamma^5 f$$

coupled directly to SM fermions in a MFV way

Main motivation (for models in the literature with pseudo-scalar mediator):

Evasion of the direct detection bounds while giving strong signal in indirect detection, in particular for explaining the Galactic Centre excess

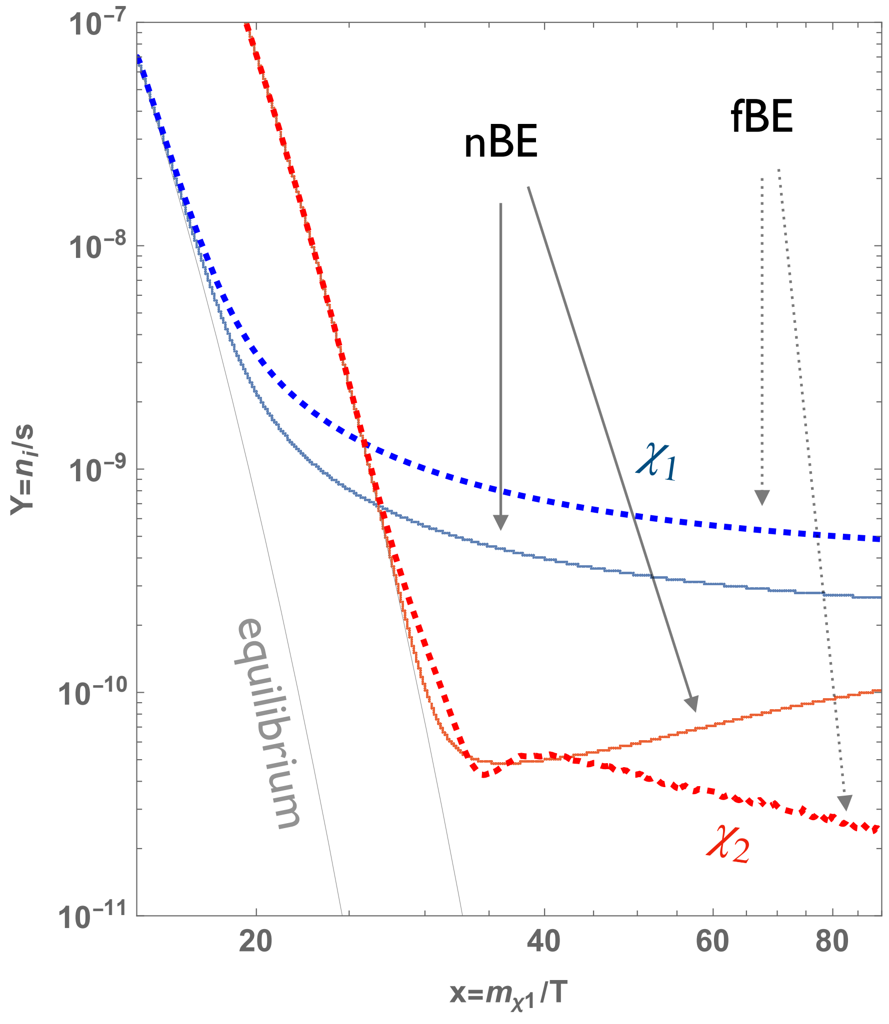
(see e.g. „Coy DM”)

C. Boehm et al. 1401.6485, …

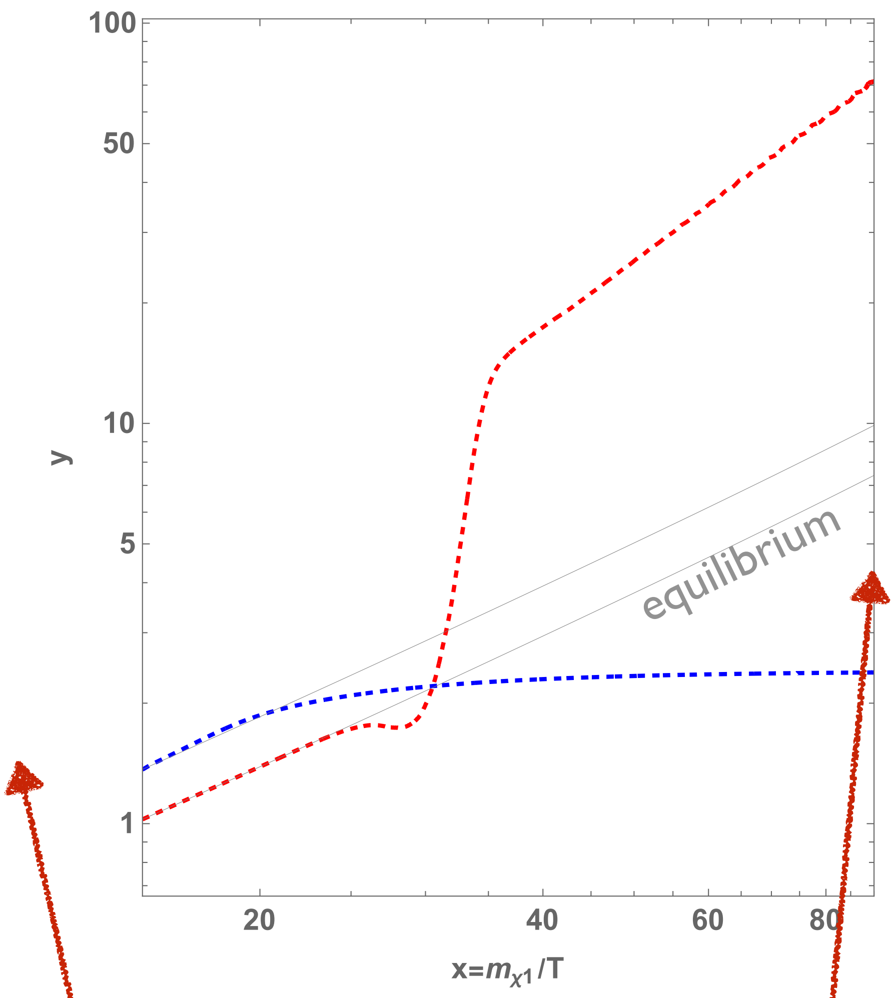
work in progress with **S. Chatterjee**

EXAMPLE CASE

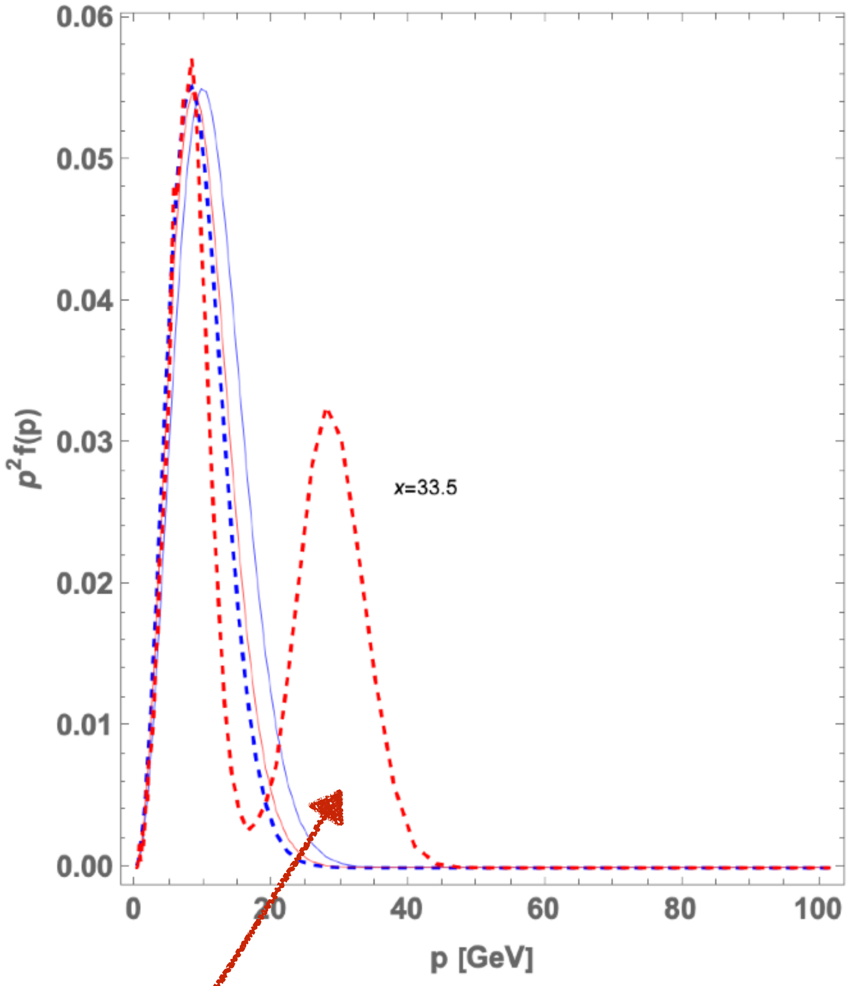
$Y \sim$ number density



$y \sim$ temperature



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



effect on relic density: O(~5)

Large shift in temperature & distribution function

	Mass [GeV]		Coupling
M1	40.	λ_1	0.04
M2	30.	λ_2	0.02
Ma	65.	λ	0.001
Mf	10.		

Note: conversions are ubiquitous in multicomponent models…

TAKEAWAY MESSAGES

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 are working on extending DRAKE to multi-component models with regimes beyond kinetic equilibrium)