Sequential freeze-in: A new phase of dark matter production out of equilibrium

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03/06/2020

based on: *"Dark Matter Abundance from Sequential Freeze-in Mechanism"*
arXiv: 2005.06294
in collab. with G. Bélanger, C. Delaunay, A. Pukhov

Outline

- Generic introduction to dark matter

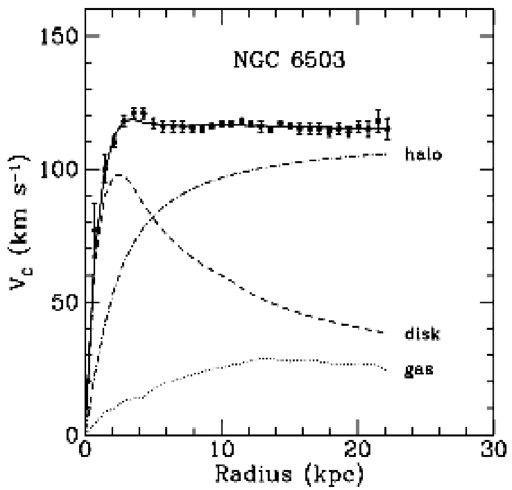
- DM production regimes

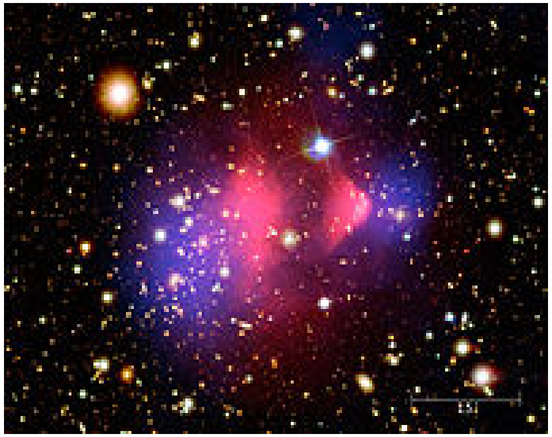
- Sequential freeze-in regime

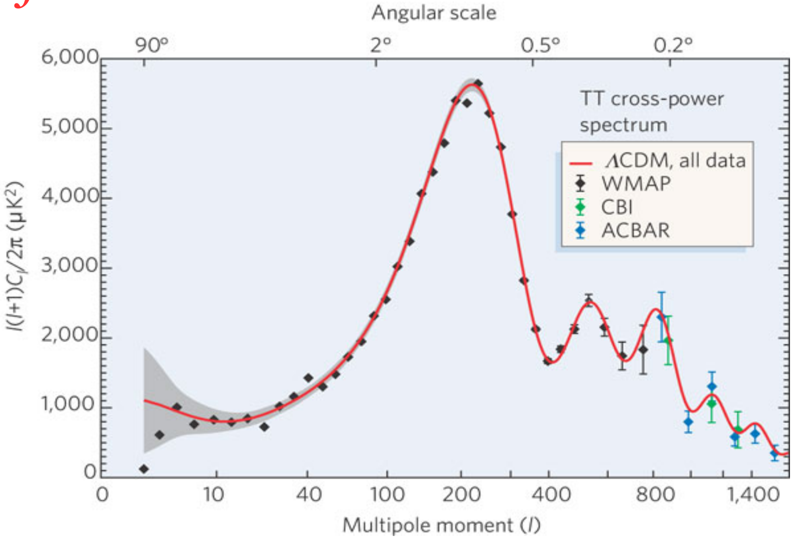
- Conclusions

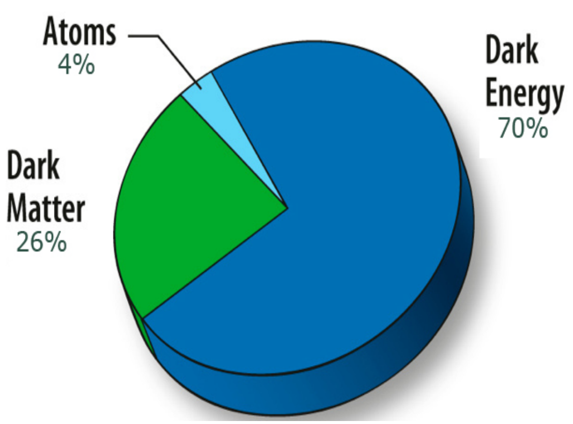
Dark Matter

Compelling evidence ***(only gravitational)*** *of non-luminous matter*









6 times more abundant than visible matter

We know…

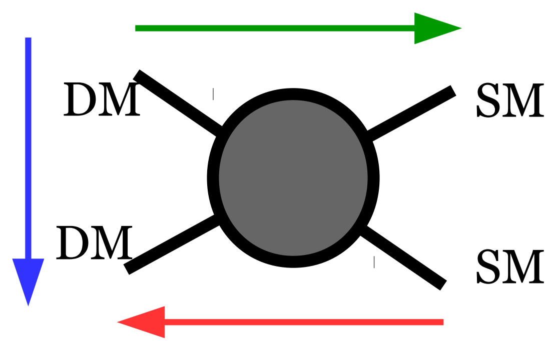
- its abundance
- presureless
- long-lived enough
- neutral enough

We don't know…

- fundamental particle?
- spin, mass?
- non-gravitational interactions?
- **thermal relic?**
- when was it produced?
- …

DM non-gravitational interactions?

- DM annihilating/decaying into SM particles? (Gunn, Lee, Lerche, Schramm and Steigman **1978**, Astrophys.J. 223, 1015)
  (DM not mentioned explicitely here)
  DM indirect detection

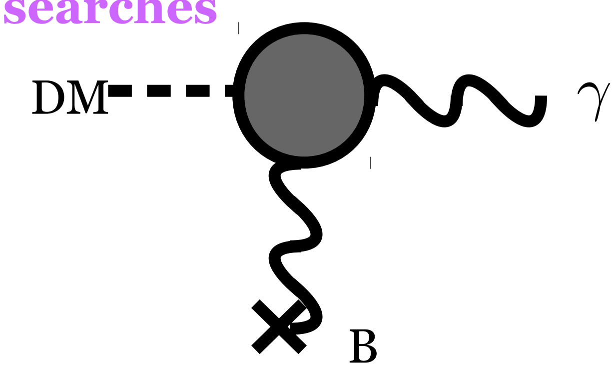


- DM scattering off nuclei ? (Goodman & Witten **1985**, Phys.Rev. D31, 3059)
  DM direct detection

- DM produced in particle collisions (Ellis, Frère, Hagelin, Kane, Petcov, **1983**, Phys.Lett.B 132 436-442)
  (DM not mentioned explicitely here)
  DM collider searches

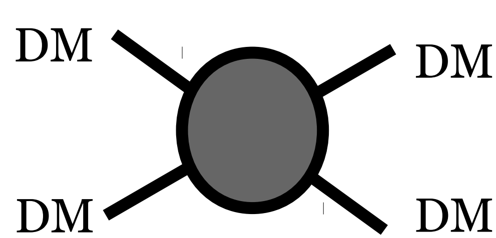
(not sure if this is the very first paper)

- Axion DM experiments (Sikivie, P., **1983**, Phys.Rev.Lett. 51, 1415.)
  Axion searches



- DM self-interactions (Spergel and Steinhardt, **1999**, Phys.Rev.Lett. 84, 3760-3763)

Gravitational lensing



Thermal vs. Non-thermal DM

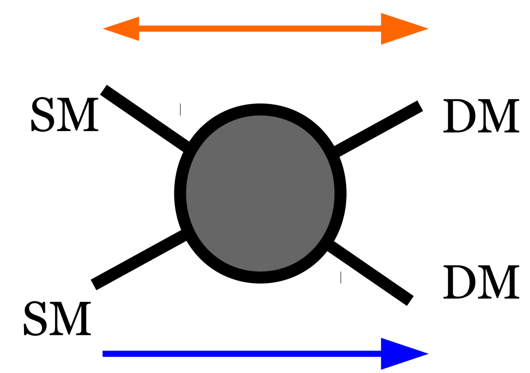
...whether or not the DM particles have been in thermal equilibrium with the SM bath

At early times...

If thermal DM:

$$H < \Gamma(\mathrm{DM}+\mathrm{DM} \to \mathrm{SM}+\mathrm{SM}) = \Gamma(\mathrm{SM}+\mathrm{SM} \to \mathrm{DM}+\mathrm{DM})$$

H : expansion rate $\quad\quad$ Γ : reaction rate



If non-thermal DM:

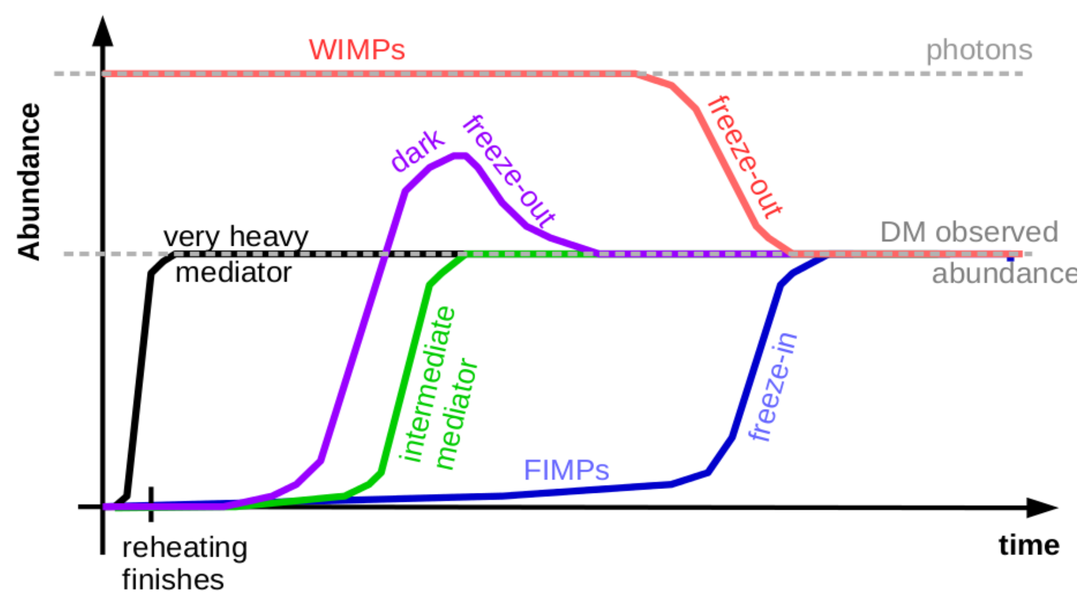
$$\Gamma(\mathrm{DM}+\mathrm{DM} \to \mathrm{SM}+\mathrm{SM}) < H < \Gamma(\mathrm{SM}+\mathrm{SM} \to \mathrm{DM}+\mathrm{DM})$$

At later times...

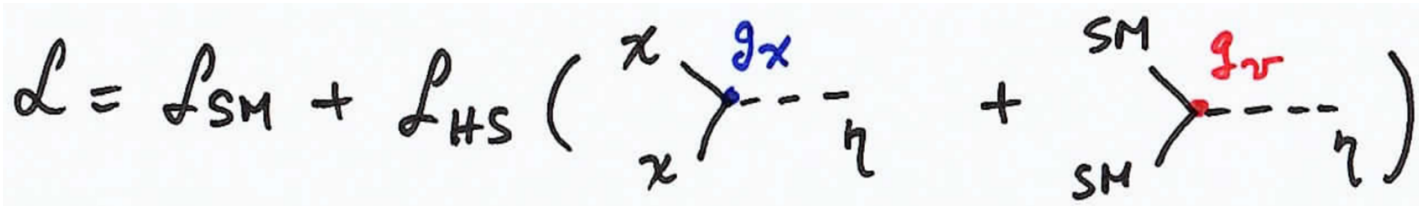
$\Gamma(\mathrm{SM}+\mathrm{SM} \to \mathrm{DM}+\mathrm{DM}) < H$ (thermal)

At the end of the day....

$\Gamma \ll H$ **...so DM freezes-out (in)**

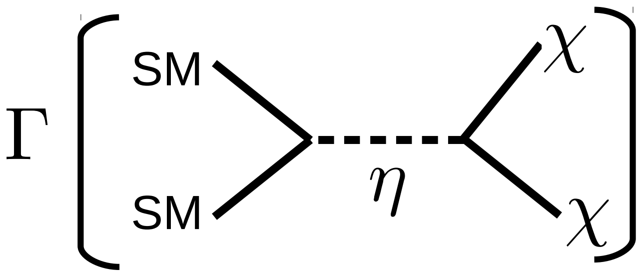


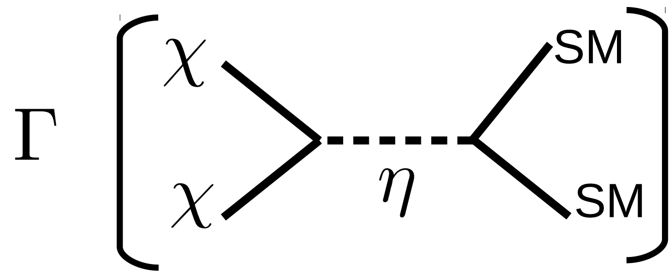
…it is mostly about couplings…



If $g_\chi \cdot g_v$
very tiny

If $g_\chi \cdot g_v$
sizeable

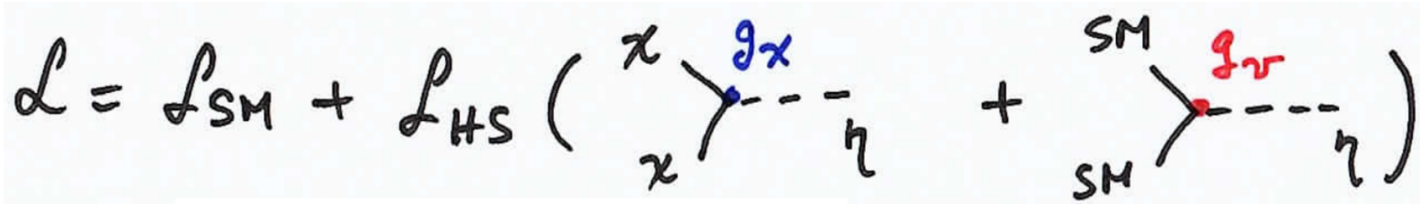




If $g_\chi \gg g_v$

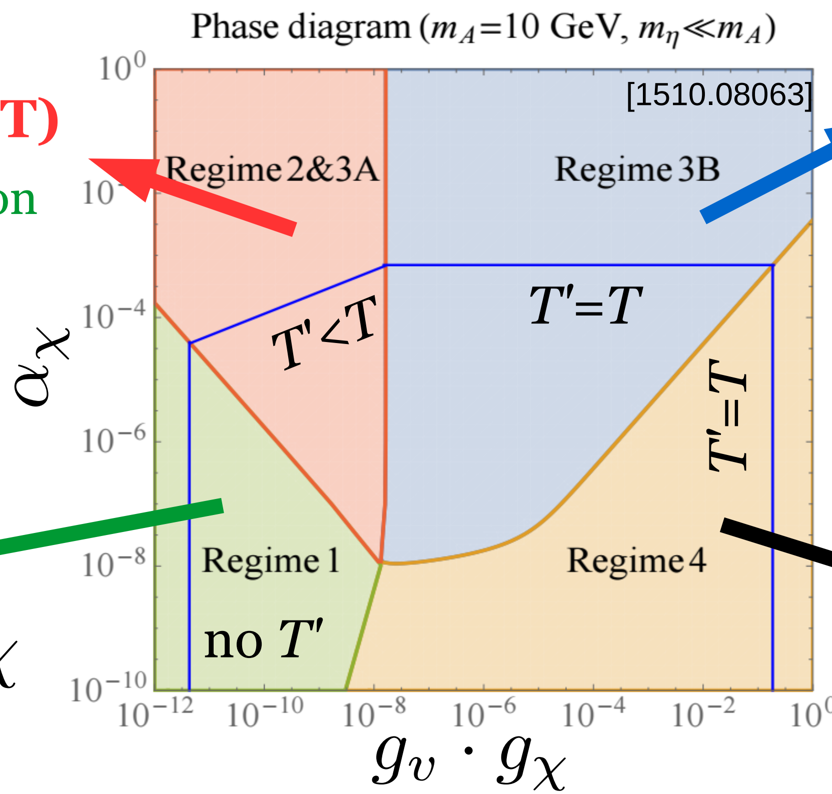
dynamics is more complex, mix between freeze-in and freeze-out

Different thermal histories of DM

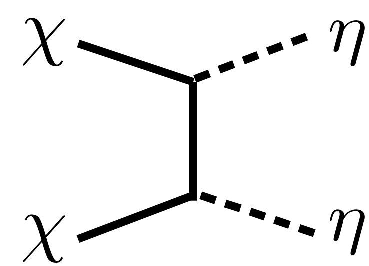


Dark Freeze-out (T' < T)

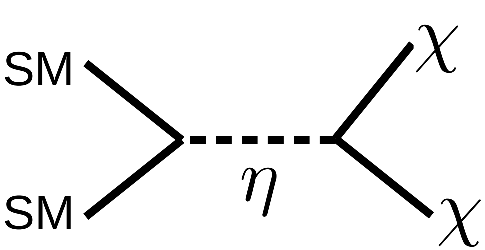
- Freeze-in production
+ dark annihilation



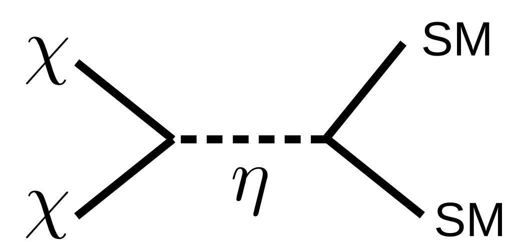
Dark Freeze-out (T' = T)



Freeze-in



usual Freeze-out



Chu, Hambye & Tytgat, 1112.0493
Bernal, Chu, García-Cely, Hambye & Zaldivar, 1510.08063

T': temperature of dark sector
T: temperature of visible sector

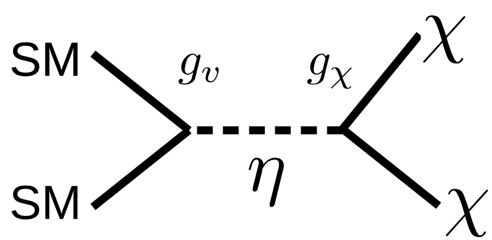
So what is 2005.06294 about?

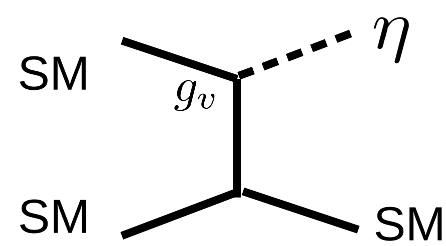
Note: we work in the framework of a particular model (up-philic scalar mediator, lighter than fermionic DM), however the mechanism is pretty generic

"Sequential freeze-in"

[Hambye, Tytgat, Vandecasteele, Vanderheyden, 1908.09864]
[this work]

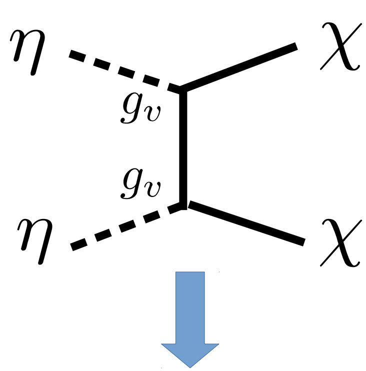
At the beginning... (assuming zero abundance of both mediator & DM)





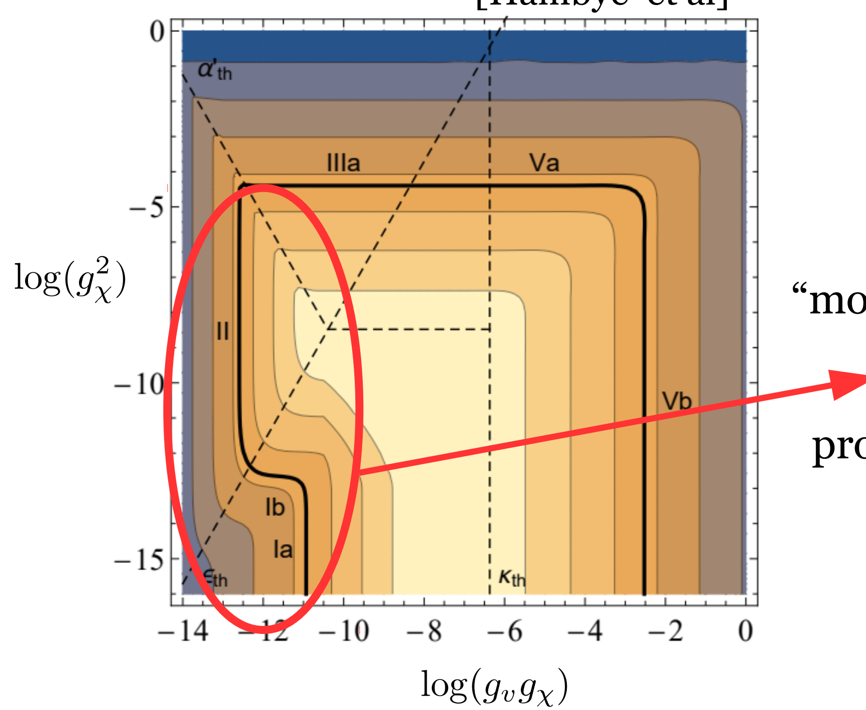
η in thermal eq. with SM or not, depending on size of g_v

Soon after... if $g_\chi \gg g_v$



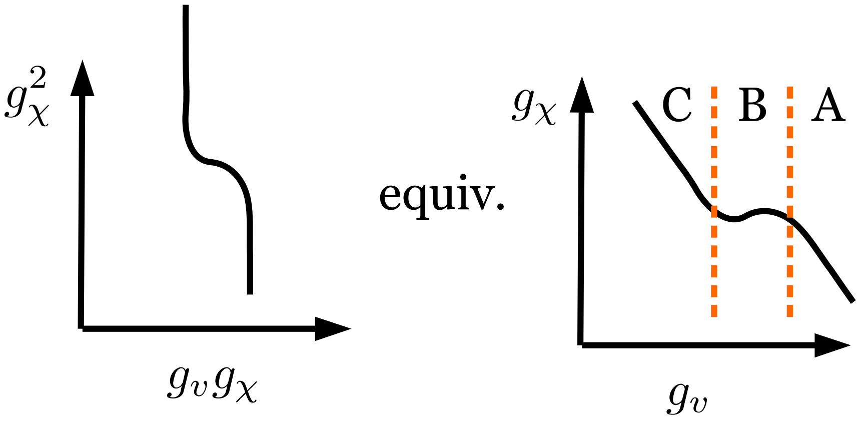
becomes the dominant DM production mode
even if η is not in thermal eq.!

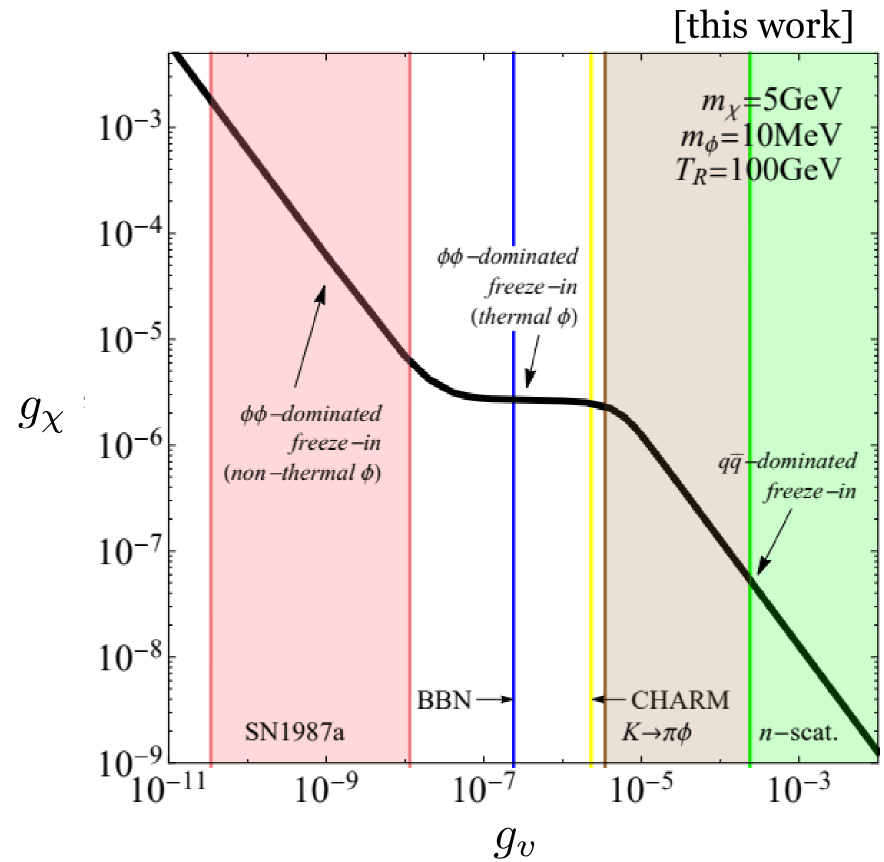
[Hambye et al]



"mooring bollard" shape due to the production from mediators

“Sequential freeze-in”





A) standard freeze-in

$\mathrm{SM} + \mathrm{SM} \to \chi + \chi$

$$\Gamma \propto n_{\rm SM}^2 \langle \sigma v \rangle_A \sim 1 \cdot (g_v g_\chi)^2$$

B) mediator-dom. freeze-in (med. is thermal)

$\phi + \phi \to \chi + \chi$

$$\Gamma \propto n_\phi^2 \langle \sigma v \rangle_B \sim 1 \cdot (g_\chi)^4$$

C) mediator-dom. freeze-in (med. is not thermal) $\phi + \phi \to \chi + \chi$

$$\Gamma \propto n_\phi^2 \langle \sigma v \rangle_C \sim (n_{\rm SM}^2 \langle \sigma v \rangle_\phi)^2 \langle \sigma v \rangle_C \sim 1 \cdot (g_v)^4 \cdot (g_\chi)^4$$

Mediator production

Boltzmann Equation $\hat{L}[f_\phi] = C[f_\phi]$

Liouville operator, dealing with the expansion rate and gravity

collision term, where the reaction rates enter

f_ϕ : mediator's distribution function

For FRW universe

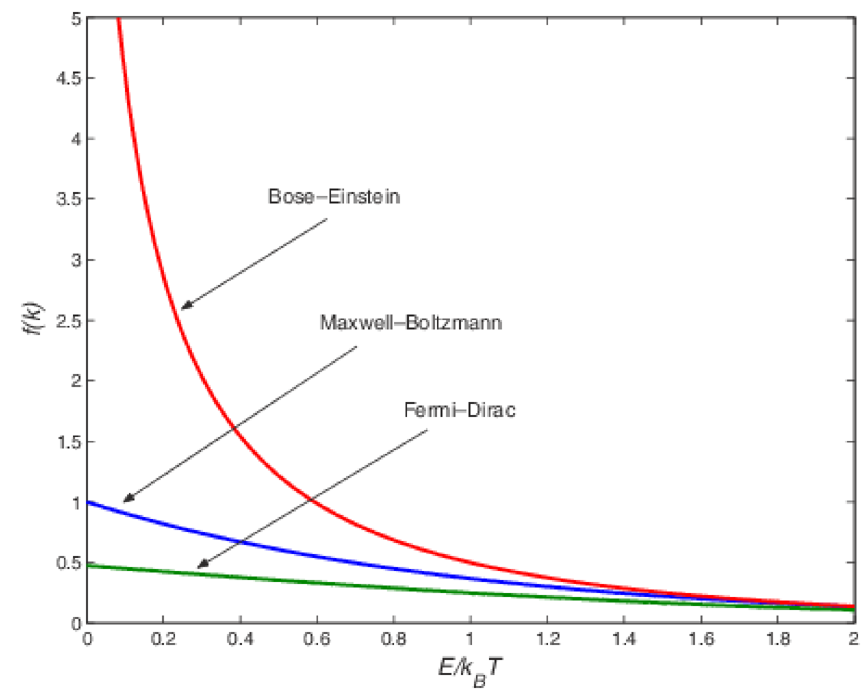
$$E(\partial_t - Hp\partial_p) f_\phi = C[f_\phi] \quad \text{(I)}$$

For species in thermal eq., f has a known shape, completely determined by the temperature and the energy

So it is convenient to integrate the Boltzmann Eq. to get an Eq. for number density n

$$n \propto \int f_\phi \, d^3p$$

$$\dot{n} + 3Hn \propto \int C[f_\phi] \, d^3p/E \quad \text{(II)}$$

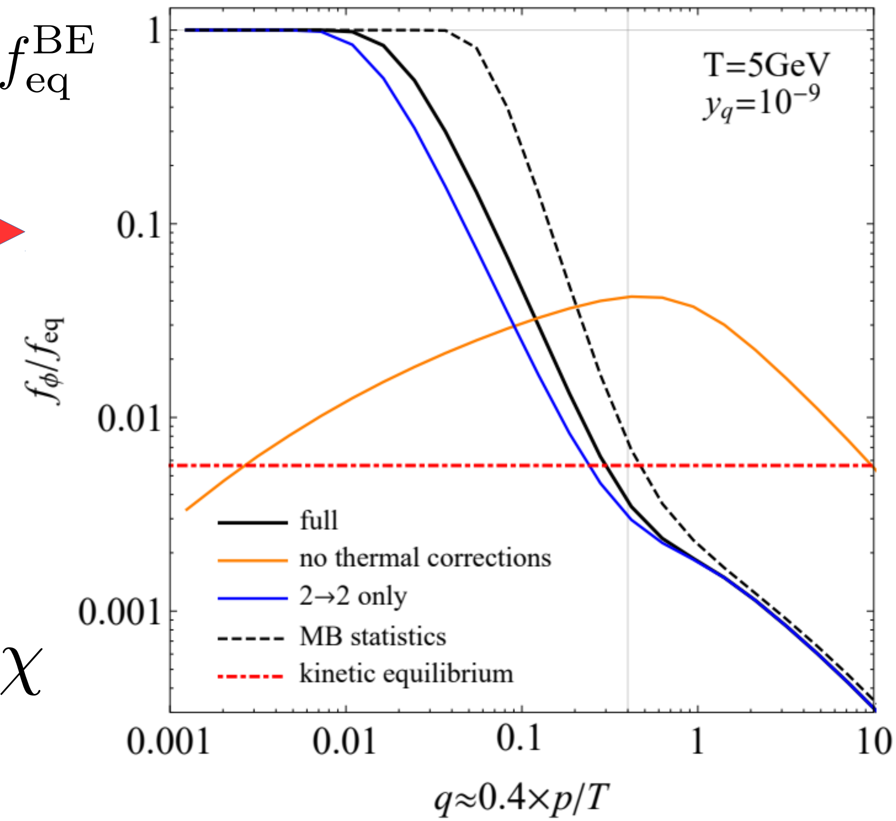


When med. is not in eq., a priori (I) should be used

Mediator production for DM

Sometimes in the literature it is assumed $f_\phi \propto f_{\rm eq}^{\rm BE}$
so as to avoid solving (I)   (kinetic eq. approx.)

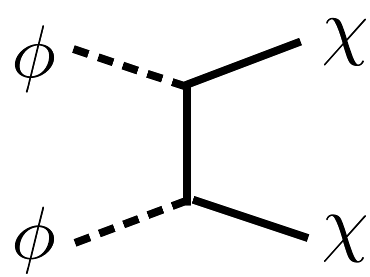
As for med. itself, this is far from correct →



If assuming MB distrib. for the SM particles

$$\frac{f_\phi}{f_{\rm eq}} \sim 1 - \exp\left[-\frac{g_v^2 M_{\rm Pl}}{p}\left(1+\log\frac{p}{T}\right)\right]$$

DM production from mediator:



$$\Gamma_{\phi\phi\to\chi\chi} \propto f_\phi(p_1) f_\phi(p_2)$$

since $m_\chi \gg m_\phi$

$p_1 + p_2$ should be sizeable → DM prod. is maximised for $p_1 \gg p_2$

Thus, as for DM is concerned, kinetic eq. approx. actually gives correct order of magnitude
[off by factor ~2 for low coupling g_v]

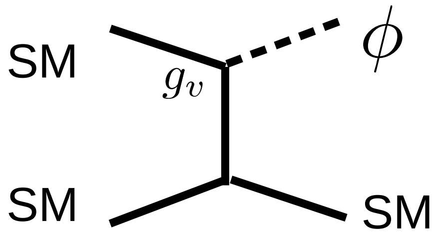
About thermal corrections

Since “freeze-in” was first proposed (Hall et al, 2009, although see McDonald 2001) thermal corrections were neglected until few years ago

Here thermal corrections are a priori relevant, since DM production is out of eq., (so no washout of initial conditions) starting from very high temperatures

In finite-temperature QFT:
- particles acquire temperature-dependent masses
- interaction vertices are also temperature-dependent
- other effects apparently less relevant…

As for the mediator-production is concerned:



- cross-section’s forward divergence regulated by thermal masses at **high momenta**

- Enhancement of med. production at **low momenta** (soft phi), which is absent when no thermal corr. are included

As for DM production is concerned:
O(1) change in the abundance, wrt not considering such corrections

Probes with Direct Detection experiments

$\sigma_{\rm SI} \propto (g_v g_\chi)^2$

while requiring good relic abundance

A) standard freeze-in

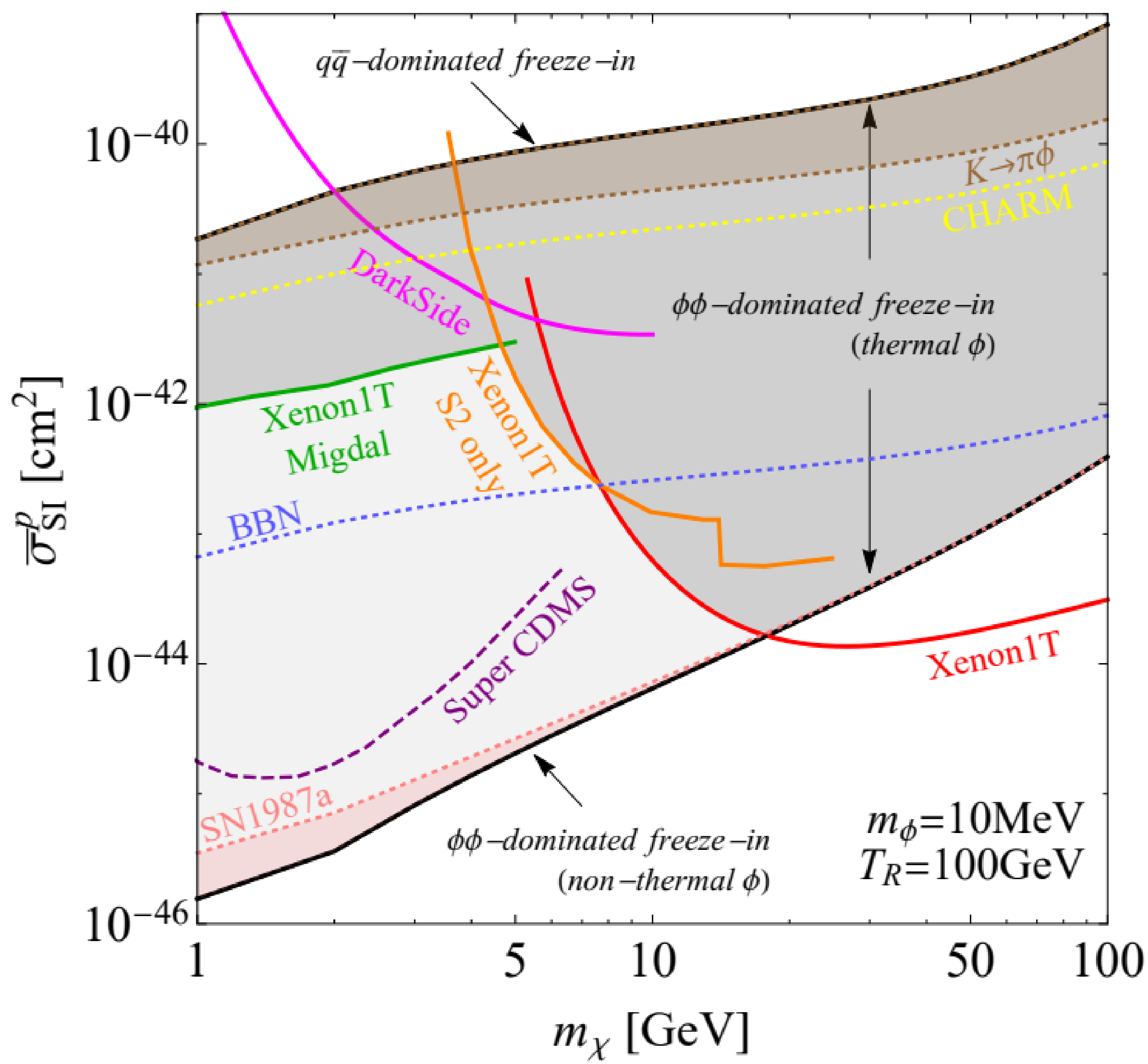
$\Omega_\chi \propto (g_v g_\chi)^2$

C) non-thermal mediator -driven freeze-in

$\Omega_\chi \propto (g_v g_\chi)^4$

B) thermal mediator -driven freeze-in

infinite combinations



Summary

- Sequential freeze-in is a recently discovered DM production regime at work when $g_\chi \gg g_\upsilon$

- Interestingly, values of coupling combinations much smaller than the standard freeze-in can still deliver good relic abundance

- Case of mediator out of equilibrium is very important, although a priori technically challenging (still, some assumptions may give reasonable results)

- Thermal corrections are very important a priori, but do not change the order of magnitude of the DM abundance

- Direct Detection experiments are able to probe a large part of the parameter space of sequential freeze-in

Thanks!