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Sequential freeze-in of light dark matter and its possible probes

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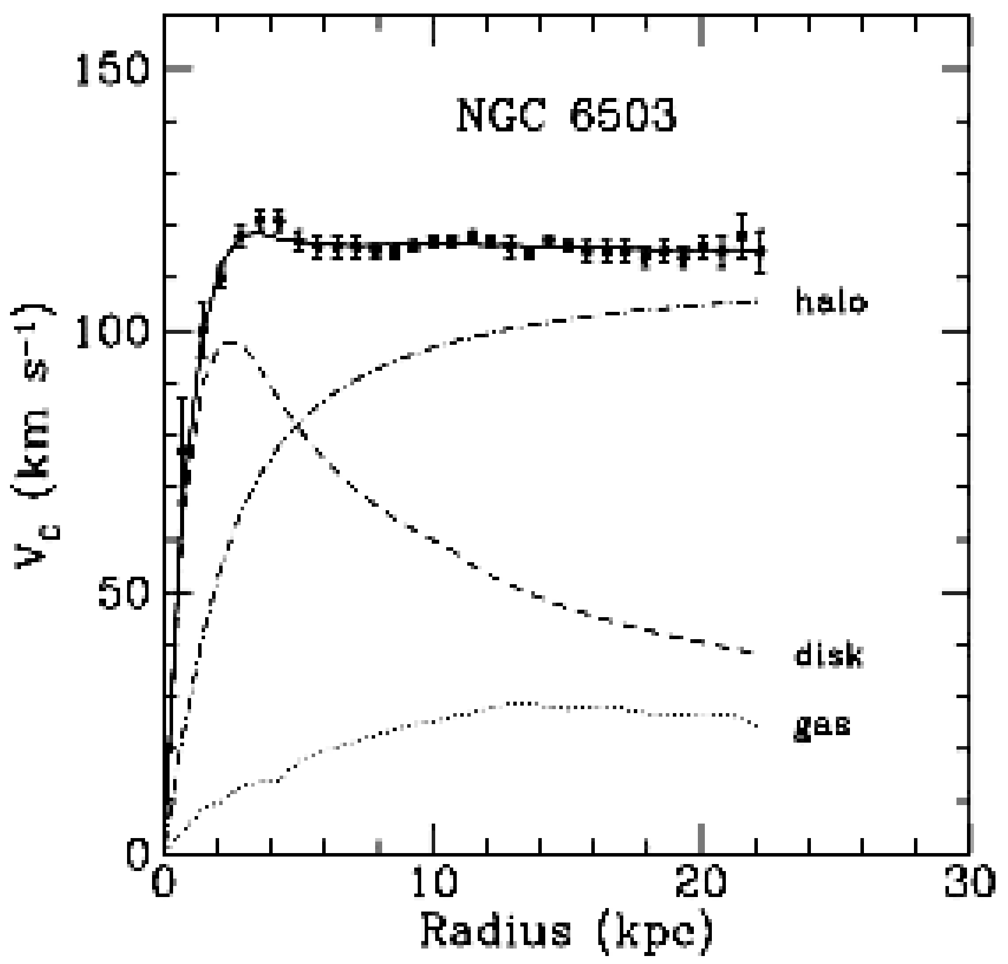
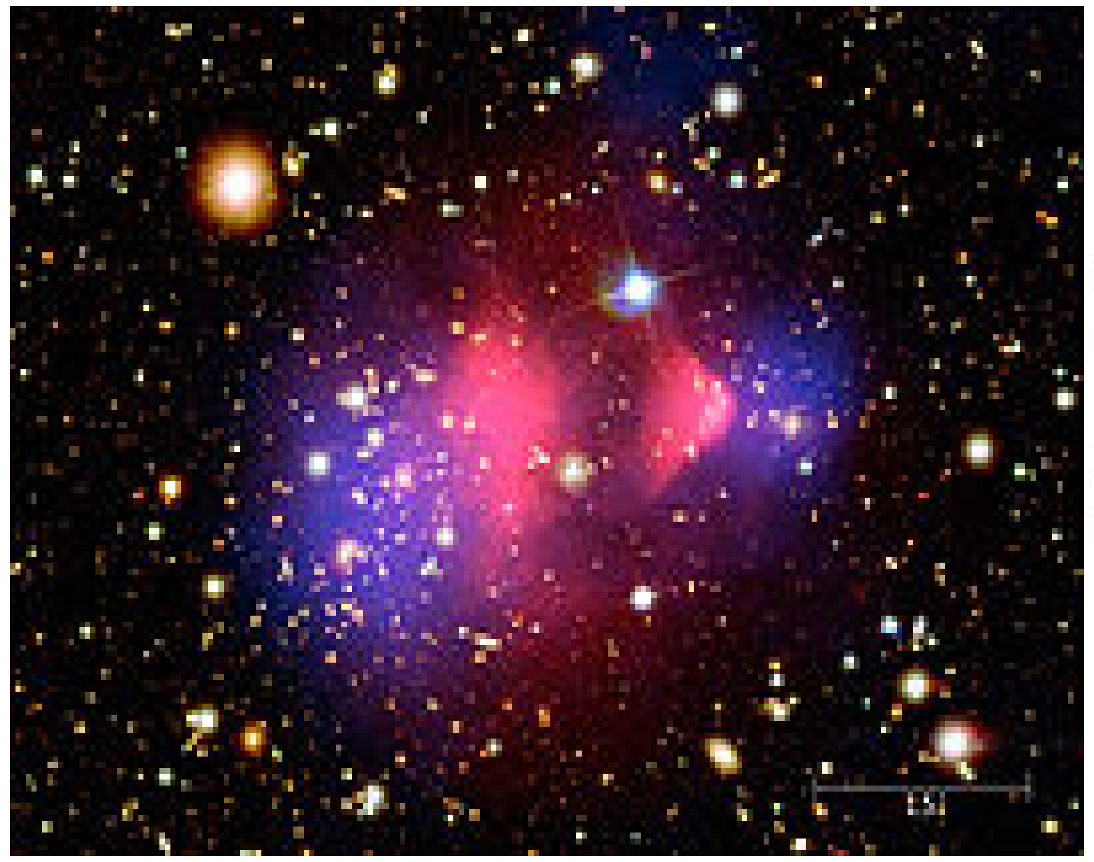
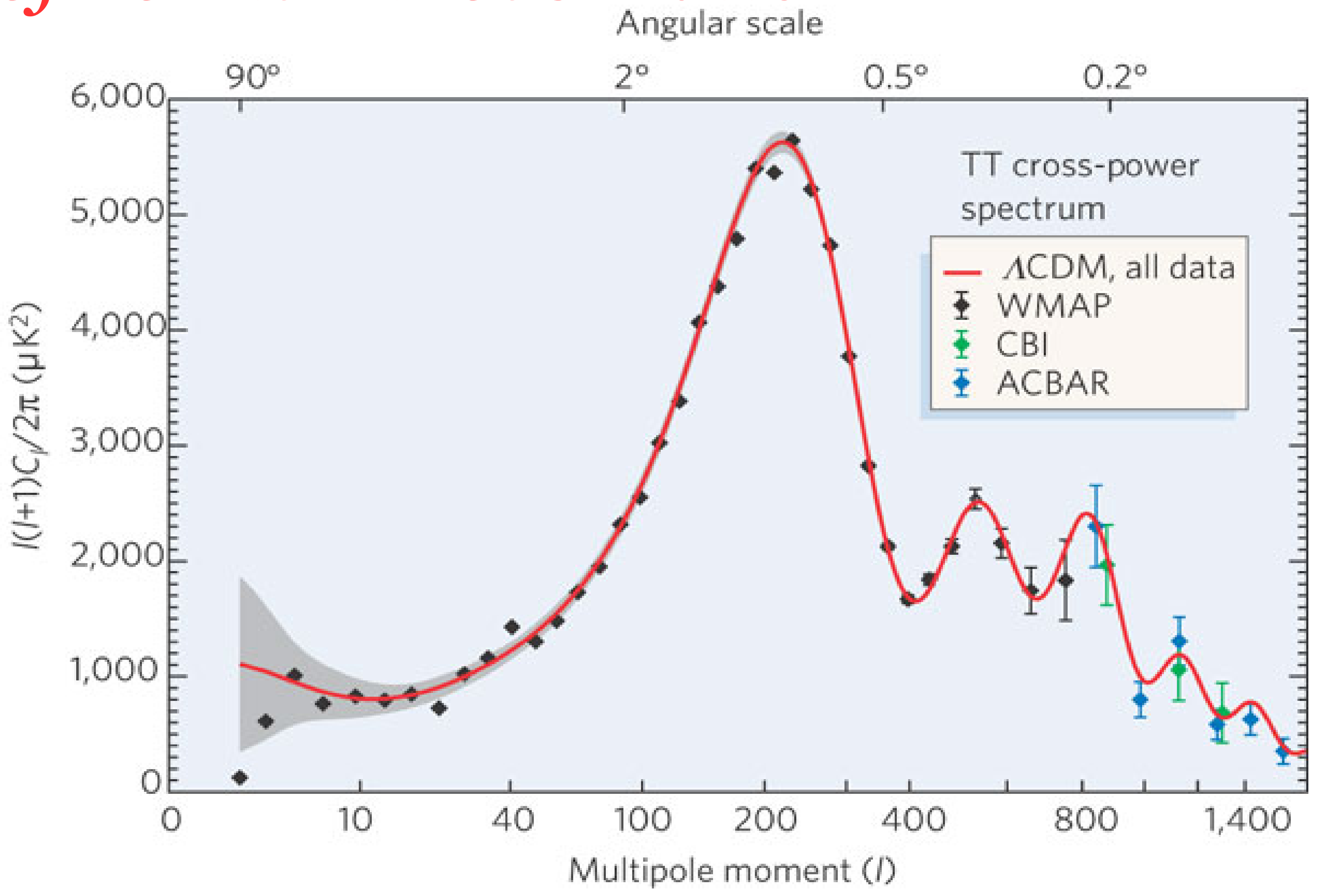
Photo by Karim Benakli

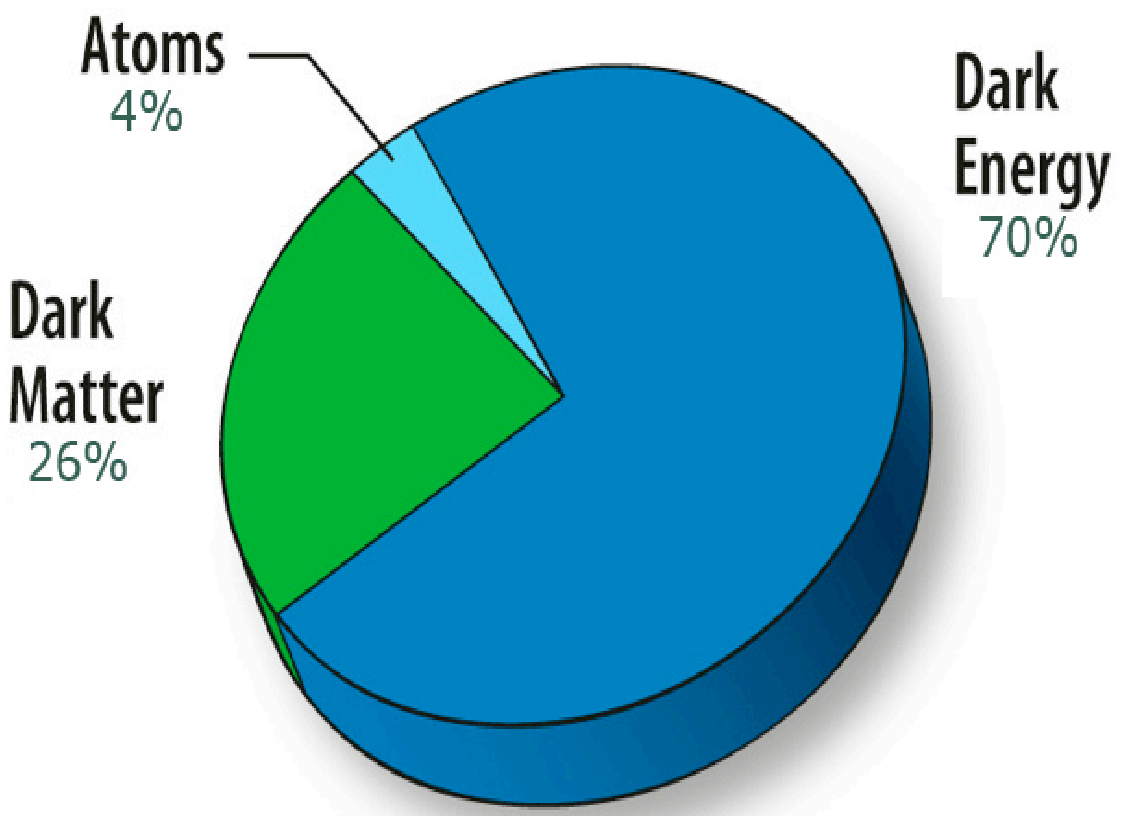
Dark matter

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









Courtesy: Bryan Zaldívar, 2020

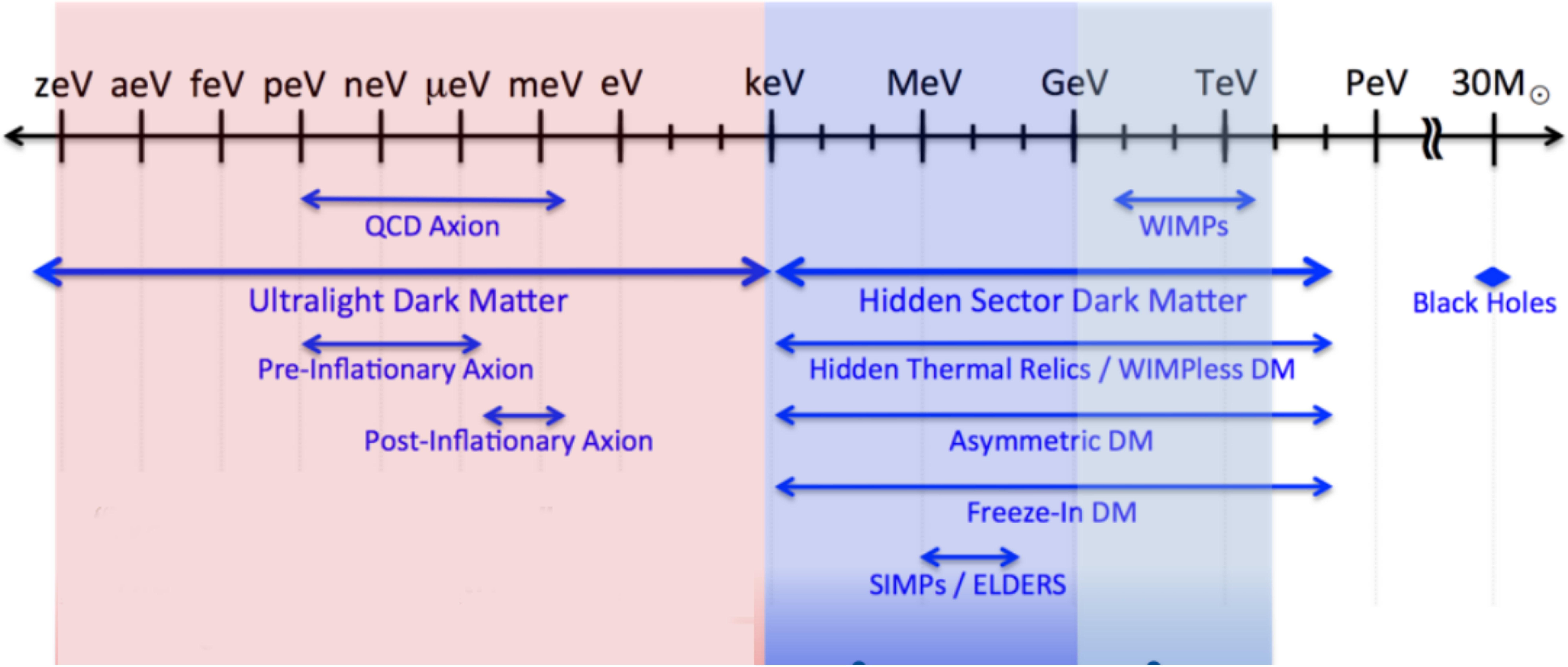
We know…

- 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?
- …

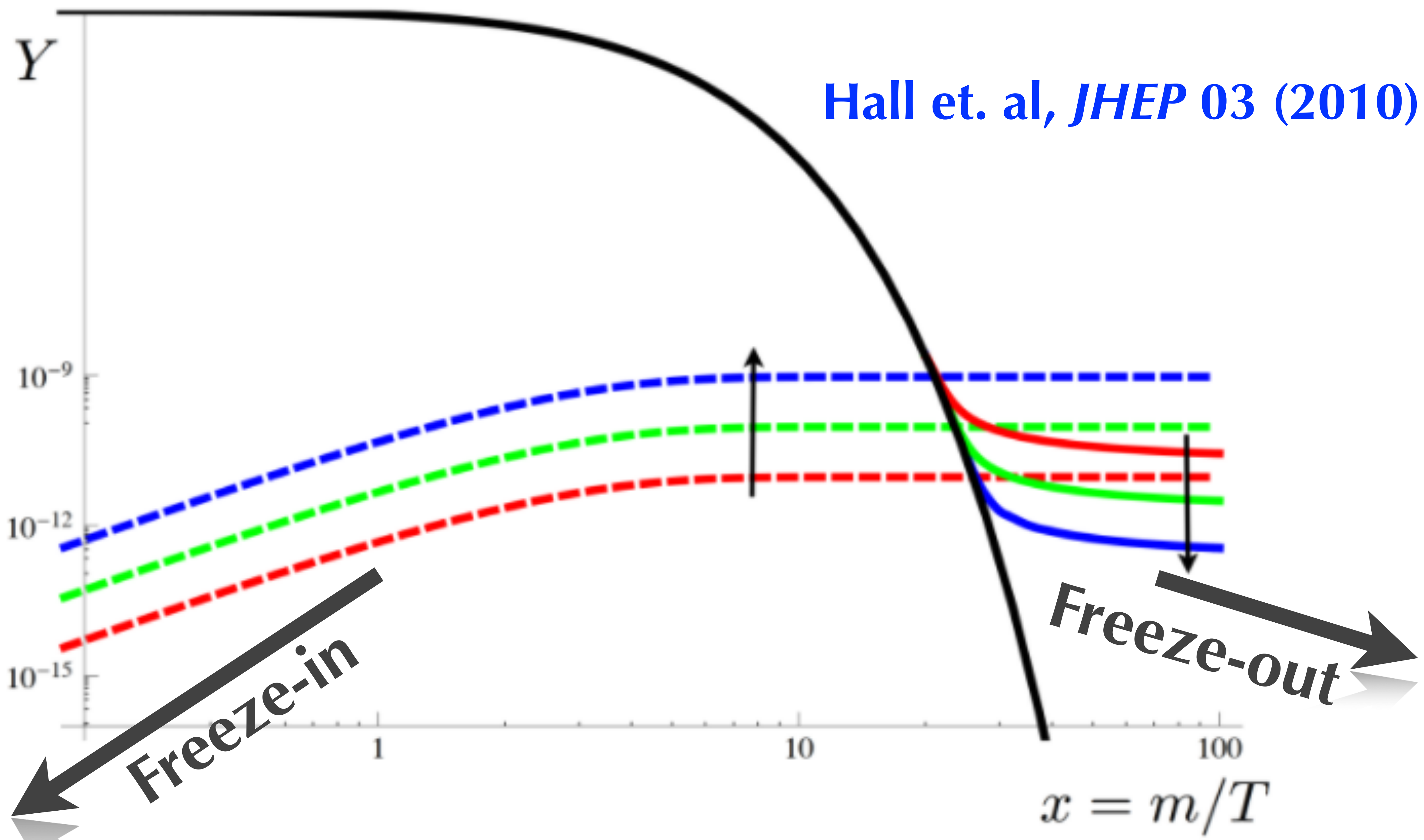
Particle nature of dark matter



Thermal OR non-thermal?

- Depends on whether DM is in thermal equilibrium with the SM bath

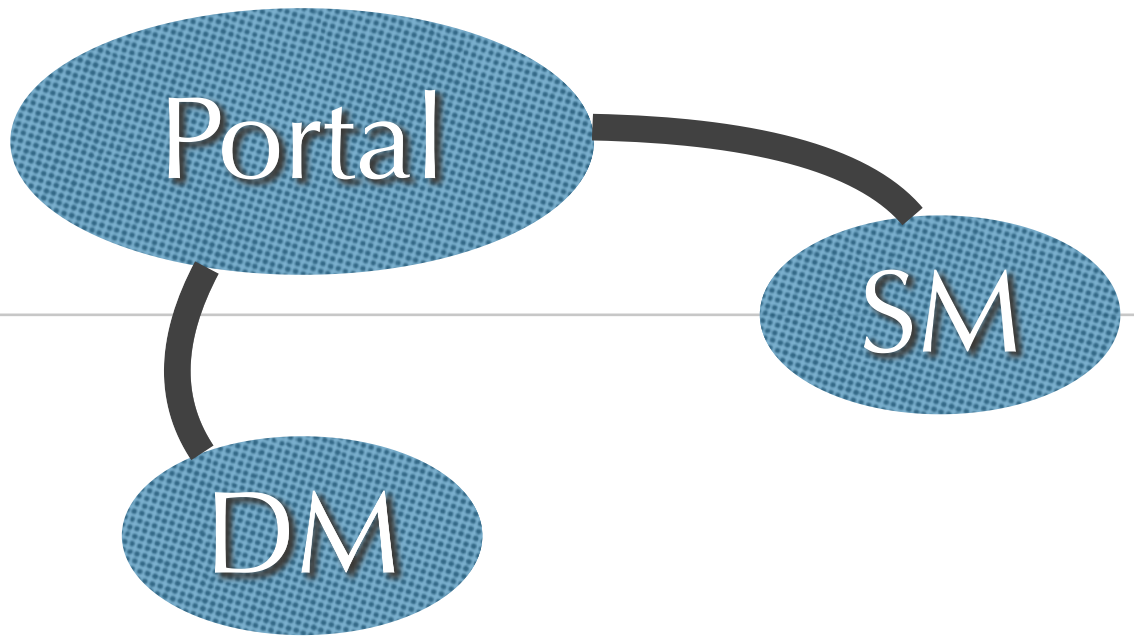
Hall et. al, *JHEP* 03 (2010) 080



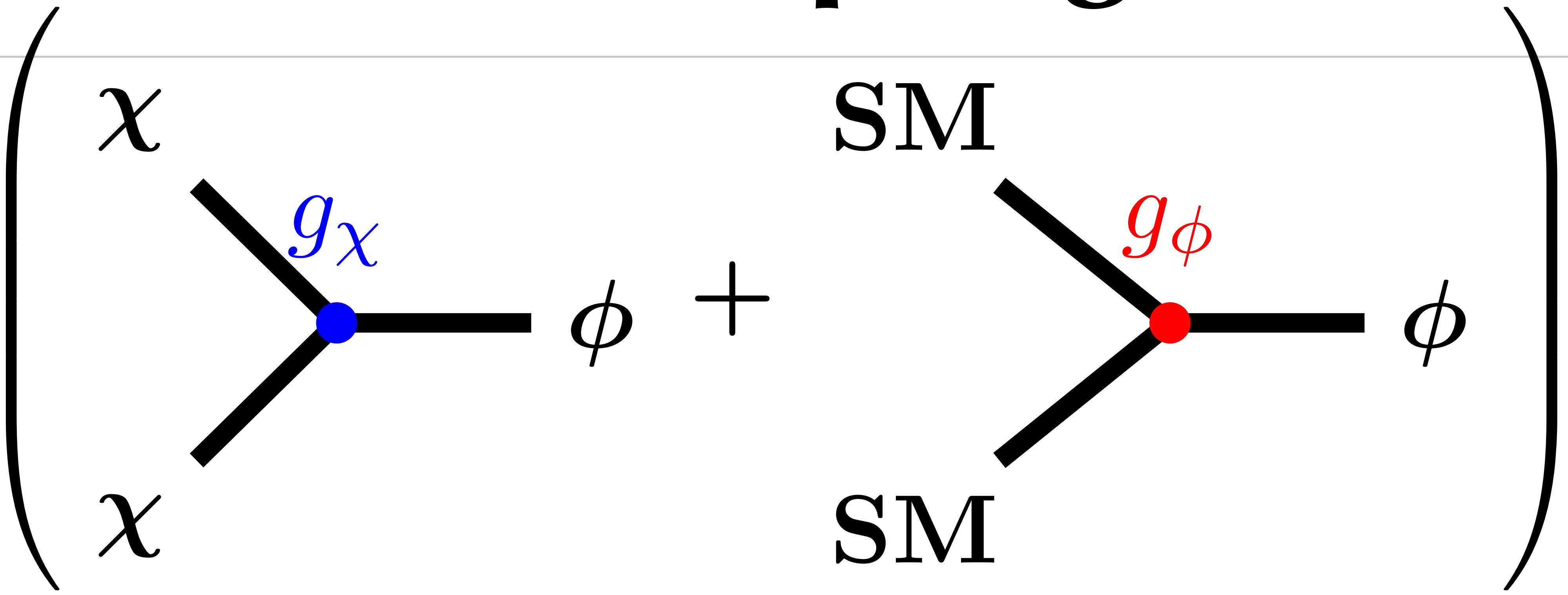
- In early Universe
$H < \Gamma(\mathrm{DM\ DM} \to \mathrm{SM\ SM})$
$= \Gamma(\mathrm{SM\ SM} \to \mathrm{DM\ DM})$
- In later times
$\Gamma(\mathrm{SM\ SM} \to \mathrm{DM\ DM}) < H$

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

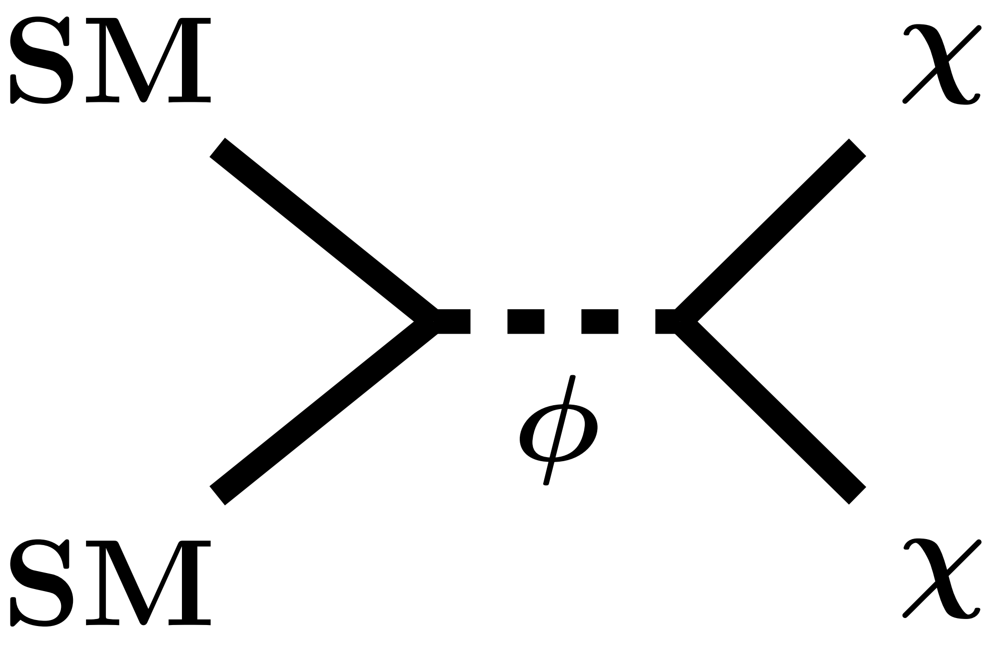
… and it all depends on couplings !!!



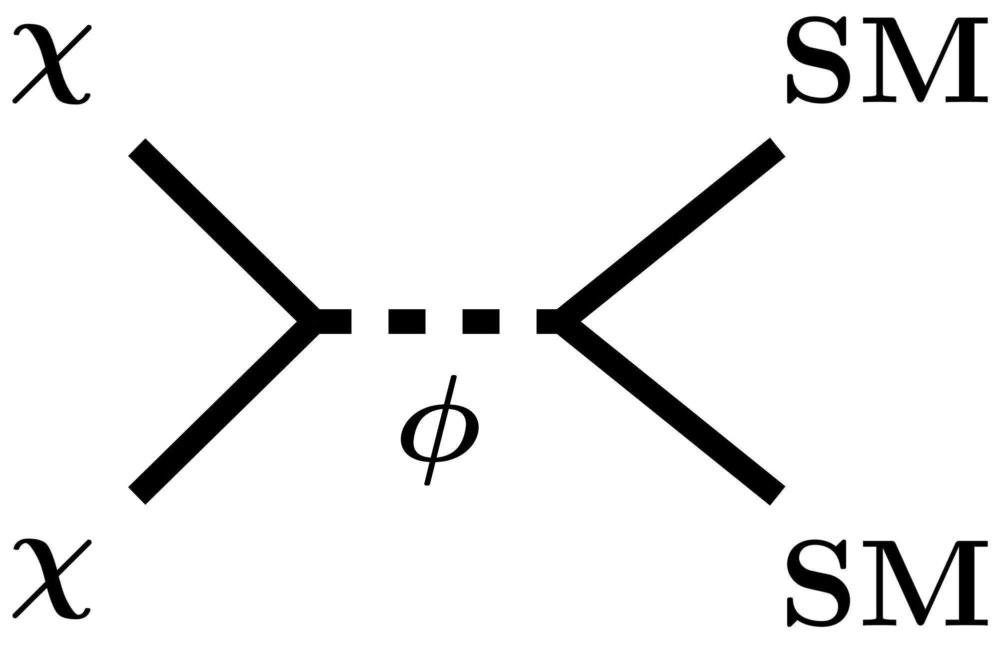
$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{HS}}$



If $g_\chi \cdot g_\phi$ very tiny



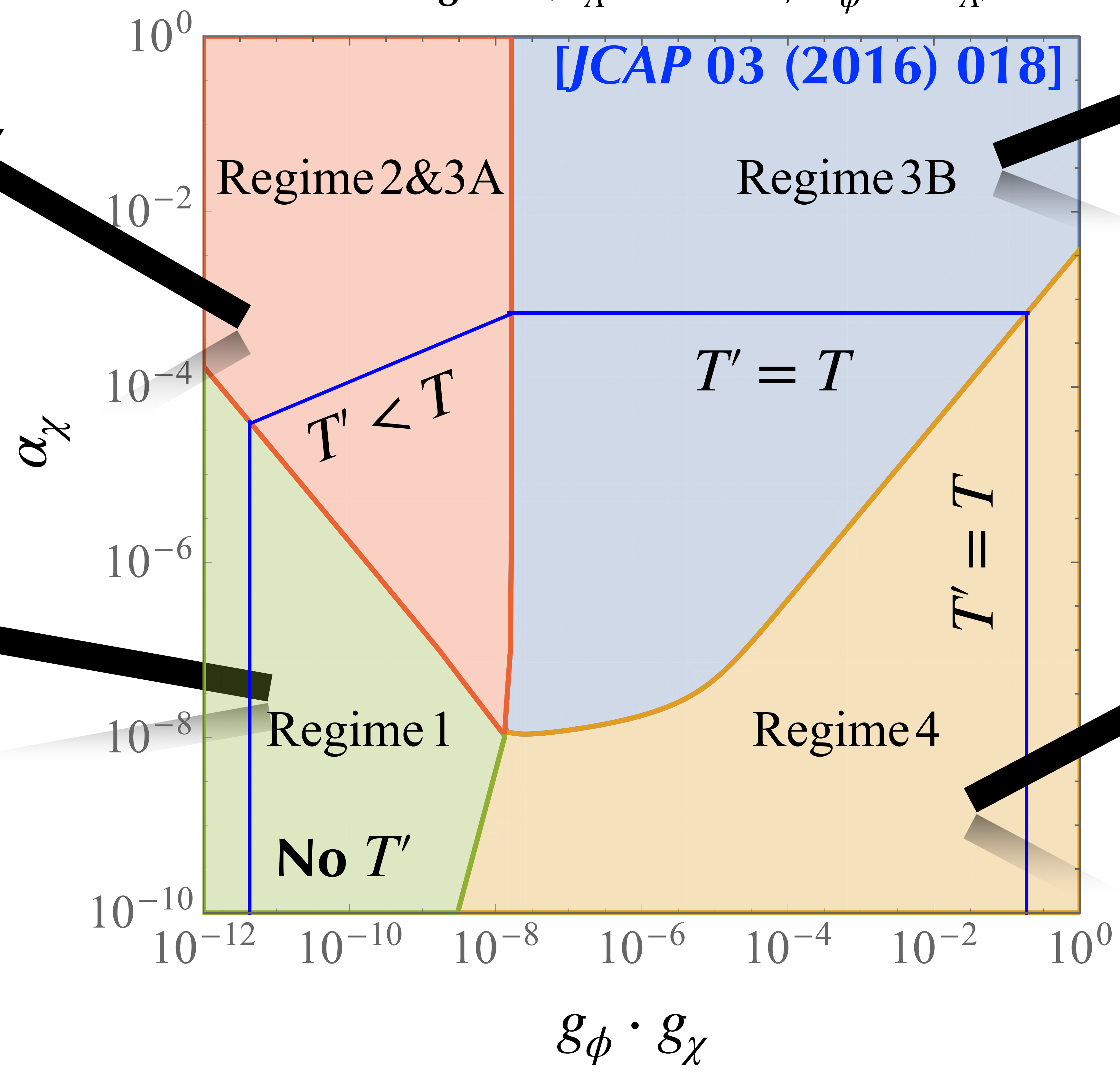
If $g_\chi \cdot g_\phi$ sizable



If $g_\chi \gg g_\phi$, dynamics is far more complex!!

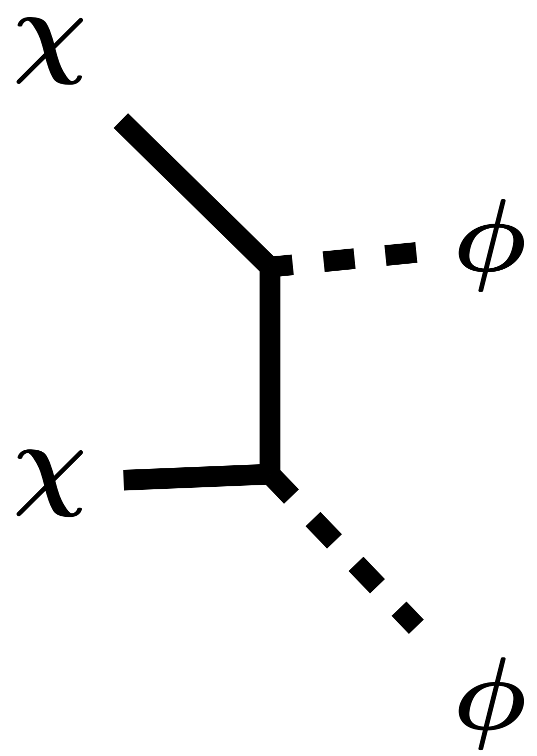
Different thermal histories of DM

Phase diagram (m_A = 10 GeV, $m_\phi \ll m_A$)

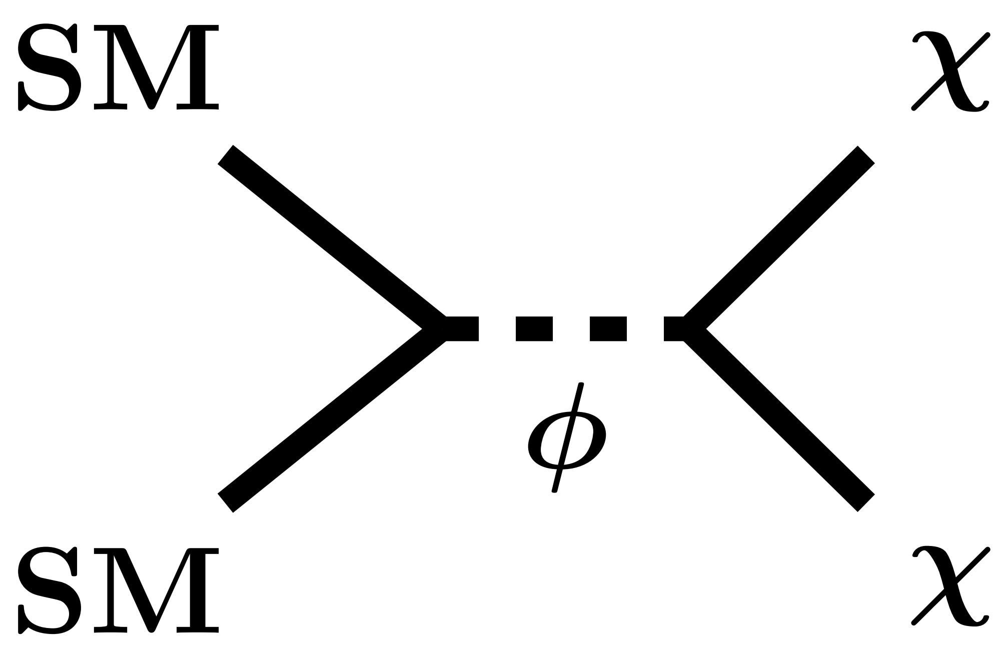


Dark Freeze-out ($T' < T$)
− Freeze-in production
+ Dark annihilation

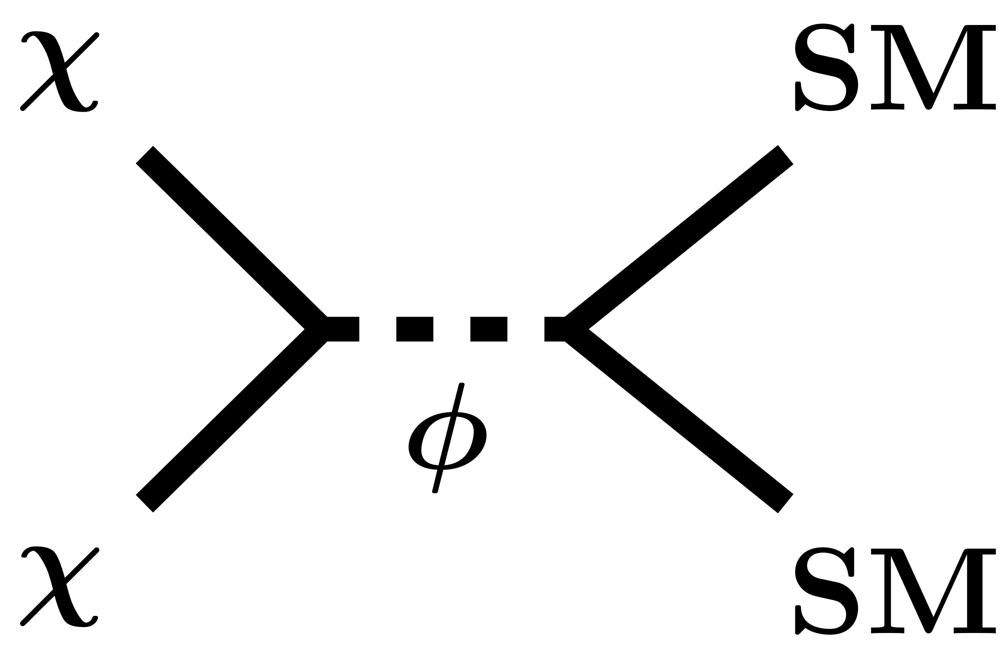
Dark Freeze-out ($T' = T$)



Freeze-in



Usual Freeze-out



Chu, Hambye & Tytgat, *JCAP* 05 (2012) 034
Bernal, Chu, García-Cely, Hambye & Zaldivar, *JCAP* 03 (2016) 018

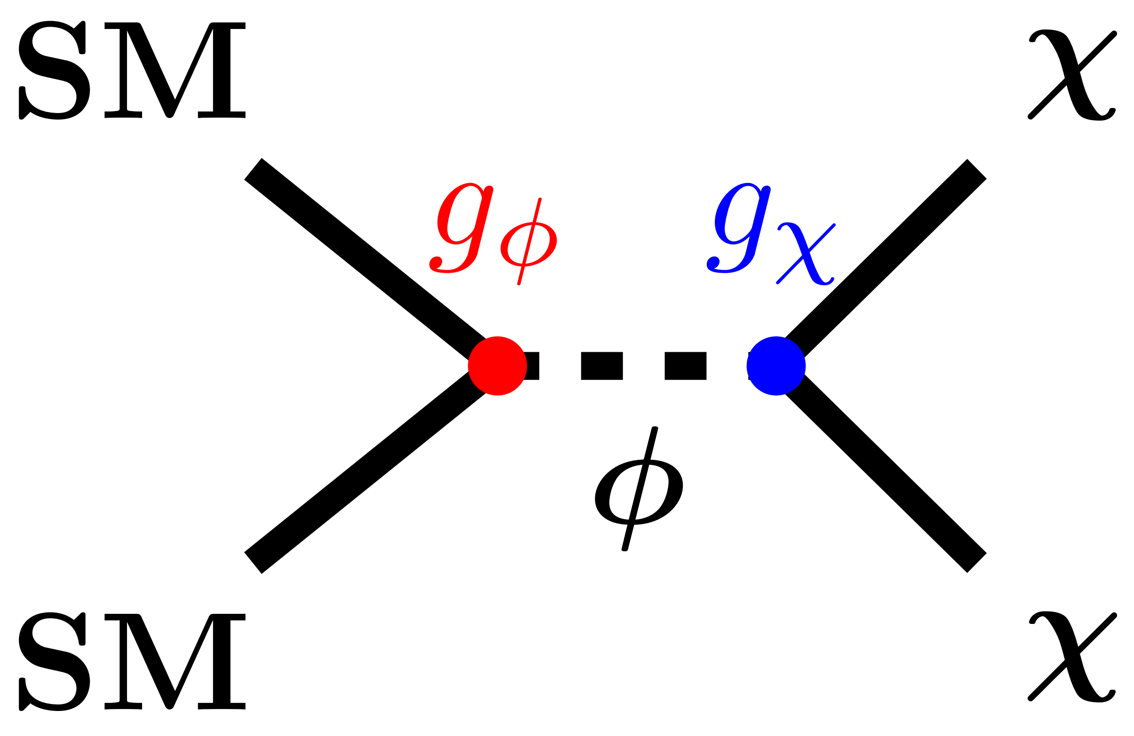
$T' \rightarrow$ temperature of dark sector
$T \rightarrow$ temperature of visible sector

Sequential freeze-in

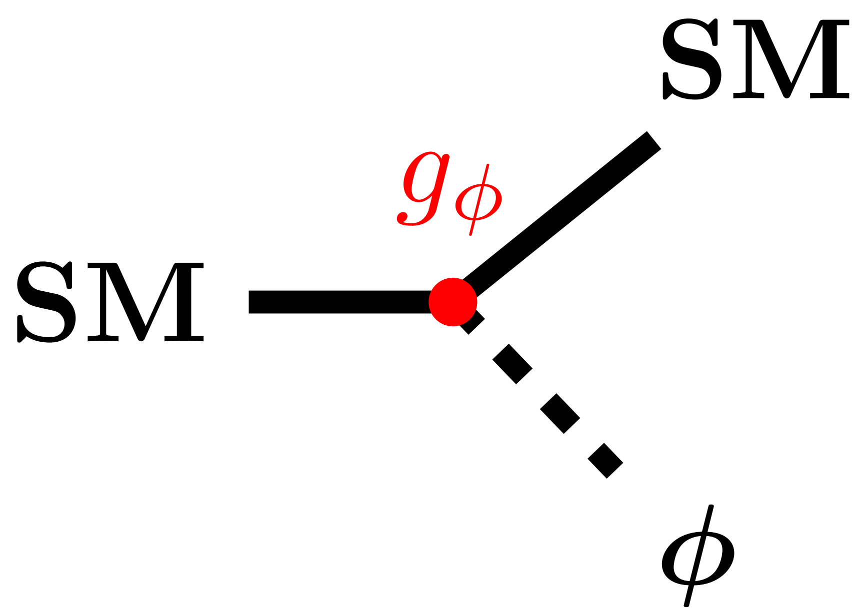
Hambye et. al, *Phys.Rev.D* 100 (2019) 9, 095018

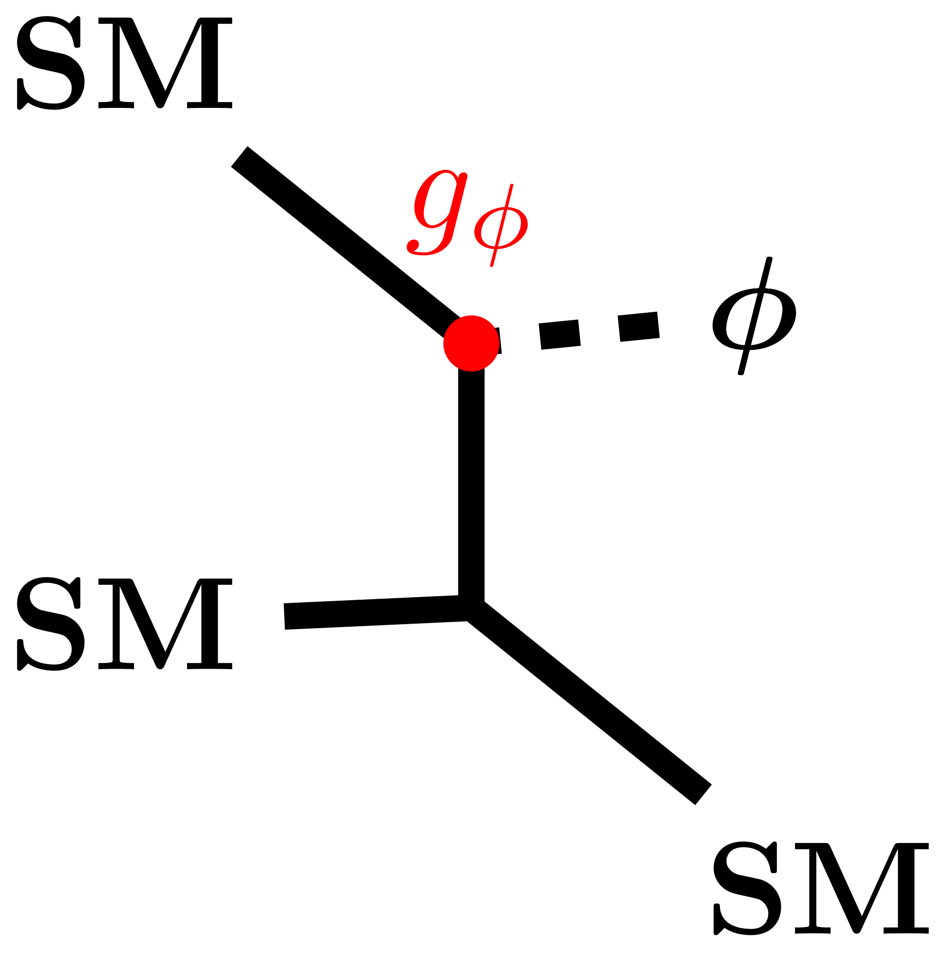
- A fifth stage in the phase diagram
- Zero initial abundance for mediator & DM

DM Production



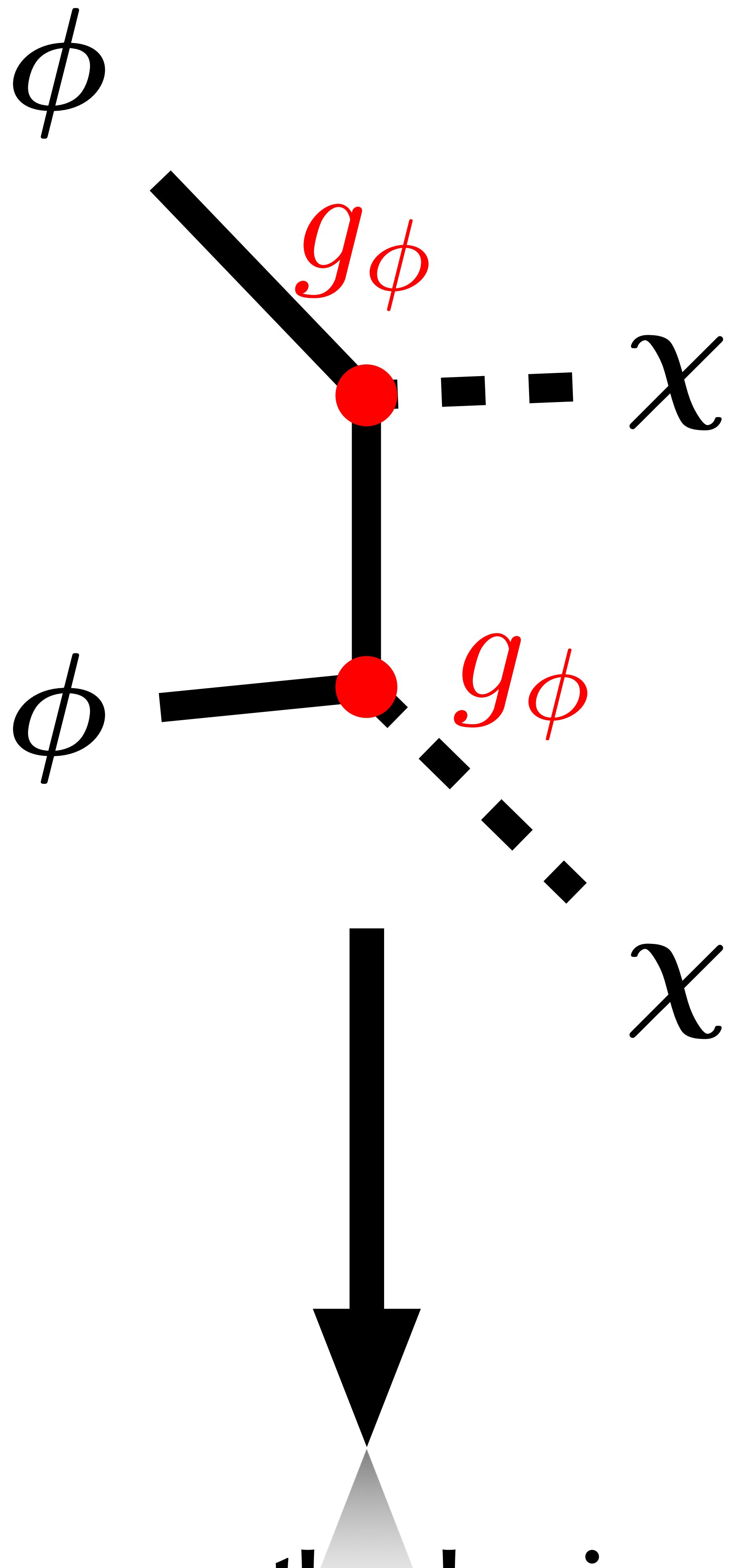
Mediator Production





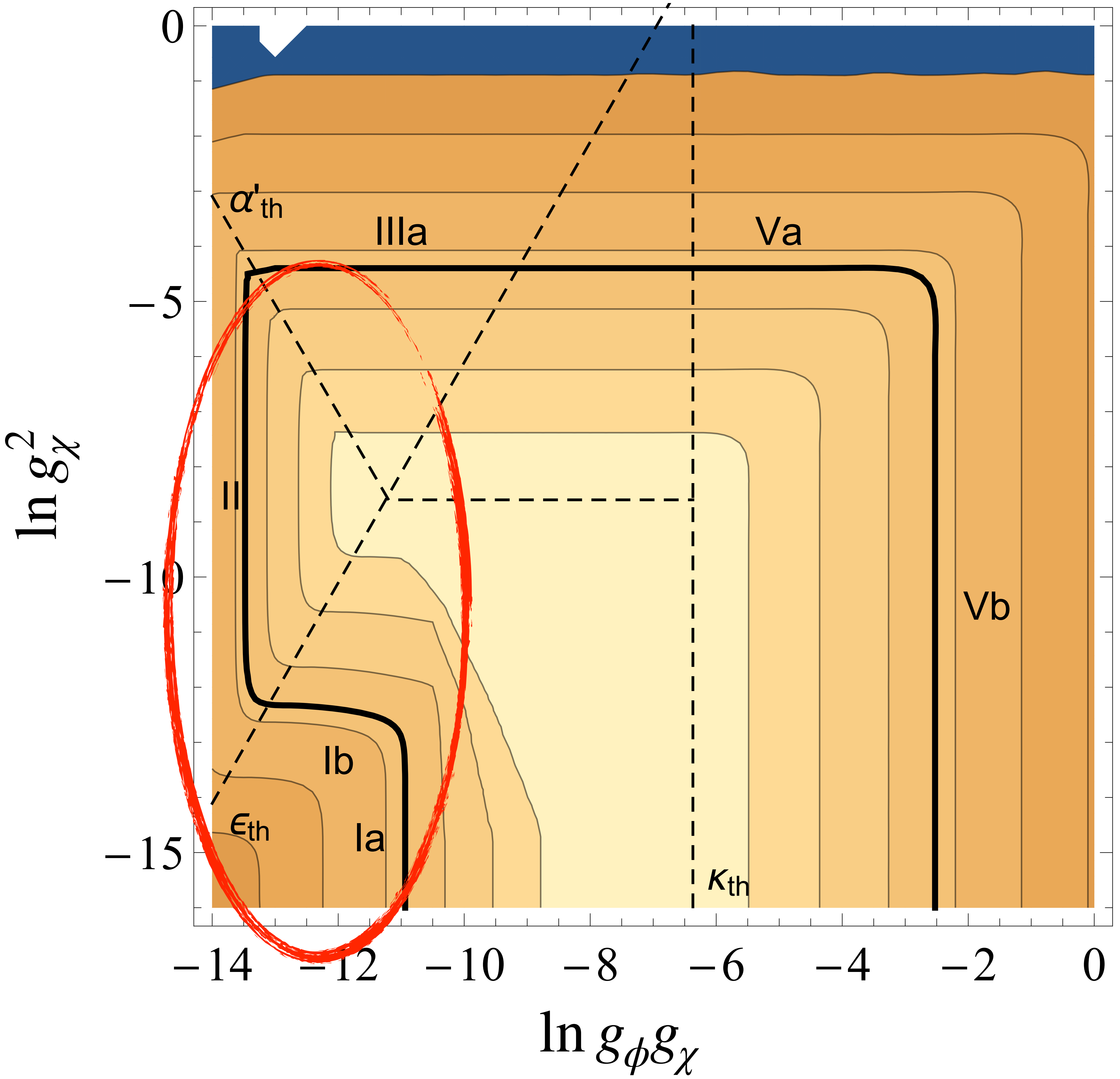
ϕ in thermal equilibrium or not depends on g_ϕ

Soon after… if $g_\chi \gg g_\phi$



becomes the dominant DM production channel

Hambye et. al, *Phys.Rev.D* 100 (2019) 9, 095018



A Toy Model

Bélanger et. al, *Phys.Rev.D* 102 (2020) 3, 035017

$$-\mathscr{L}_{\mathrm{int}} = y_\chi \phi \bar{\chi}\chi + y_q \phi \bar{u} u$$

↓ Similar Hadrophilic model

Batell et. al, *Phys.Rev.D* 100 (2019) 9, 095020

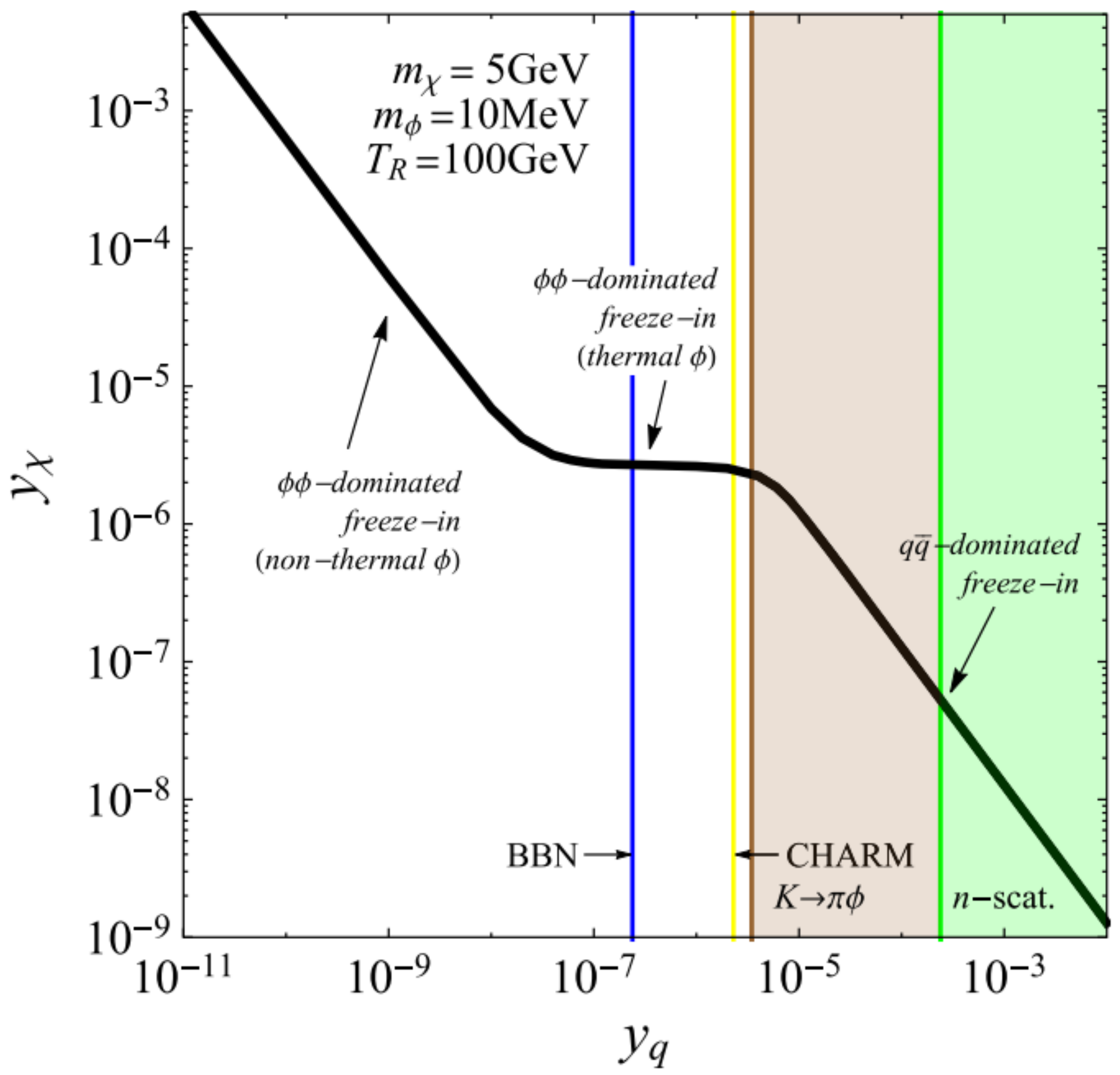
Mediator Production

- $ug \to u\phi$
- $u\bar{u} \to g\phi$
- $g \to u\bar{u}\phi$
- & QED counterparts

DM Production

- $u\bar{u} \to \bar{\chi}\chi$
- $\phi\phi \to \bar{\chi}\chi$

Phase diagram



Phase diagram

- standard freeze-in

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

$\Gamma \propto n_{\text{SM}}^2 \langle \sigma v \rangle \sim (y_q y_\chi)^2$

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

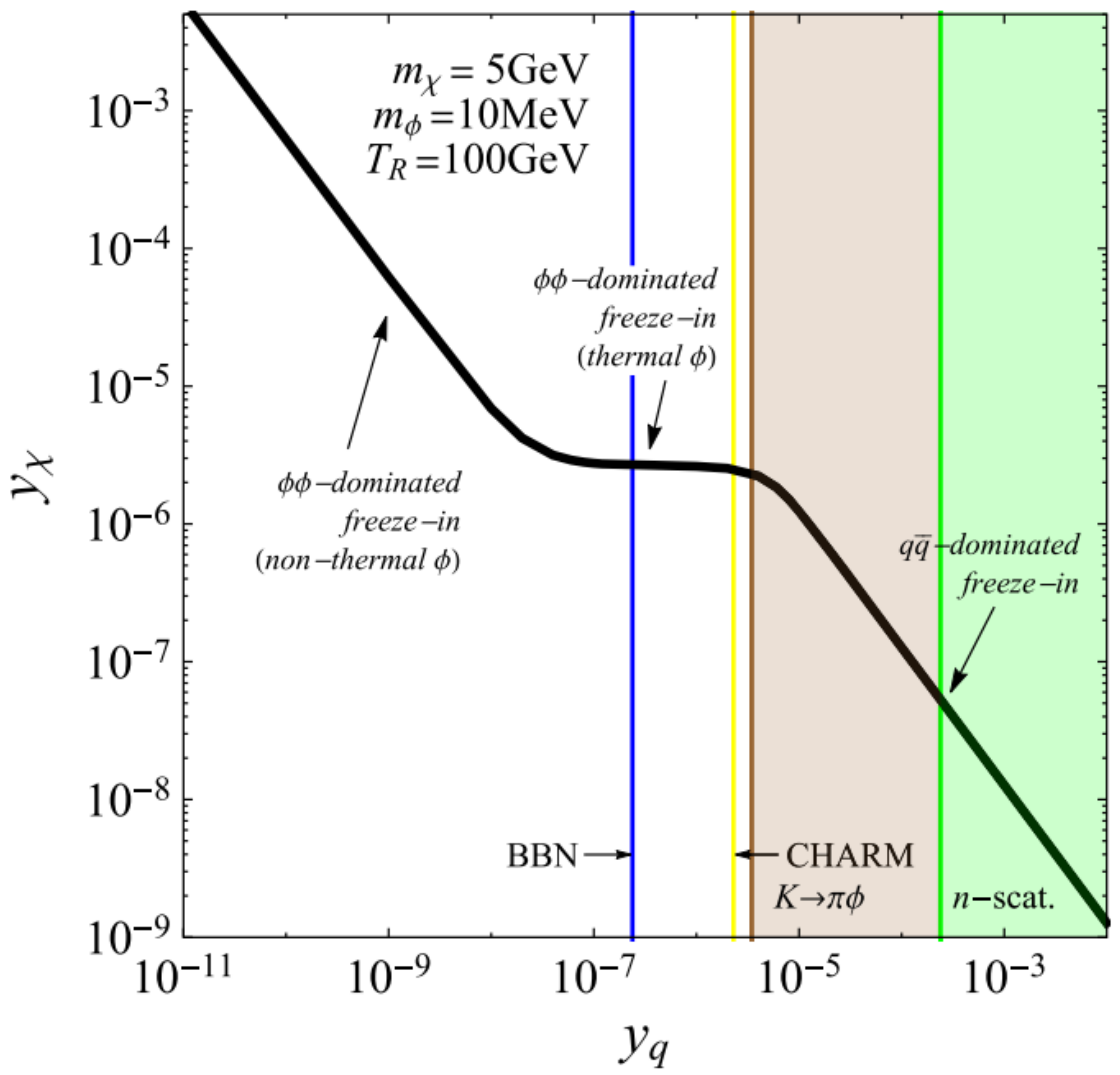
$\phi\phi \to \chi\chi$

$\Gamma \propto n_\phi^2 \langle \sigma v \rangle \sim (y_\chi)^4$

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

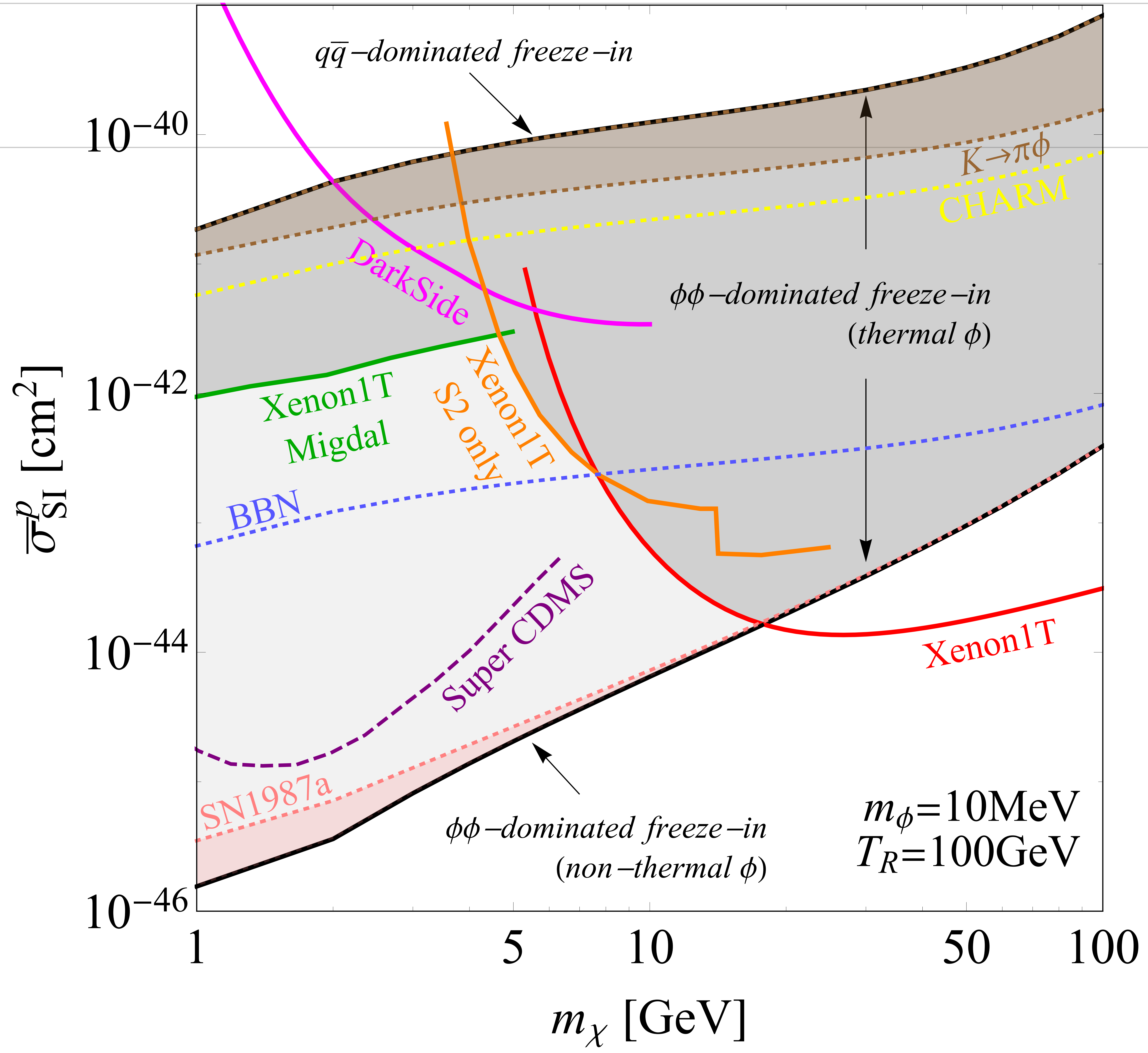
$\phi\phi \to \chi\chi$

$$\Gamma \propto n_\phi^2 \langle \sigma v \rangle \sim \left(n_{\text{SM}}^2 \langle \sigma v \rangle_\phi \right)^2 \langle \sigma v \rangle \sim \left(\frac{y_q y_\chi}{y_q^{\text{eq}}} \right)^4$$



Probes

$\sigma_{\mathbf{SI}} \propto (g_\phi g_\chi)^2$



A leptophilic extension

G. Bélanger, SC, C. Delaunay (this work!)

$$-\mathscr{L}_{\rm int} = y_\chi \phi \bar{\chi}\chi + y_q \phi \bar{u} u + y_e \phi \bar{e} e$$

- Towards a more generic model
- Exploring complementarity between Direct Detection, electron beam dumps and proton beam dumps
- Alternate probes like atomic spectroscopy

Phenomenology

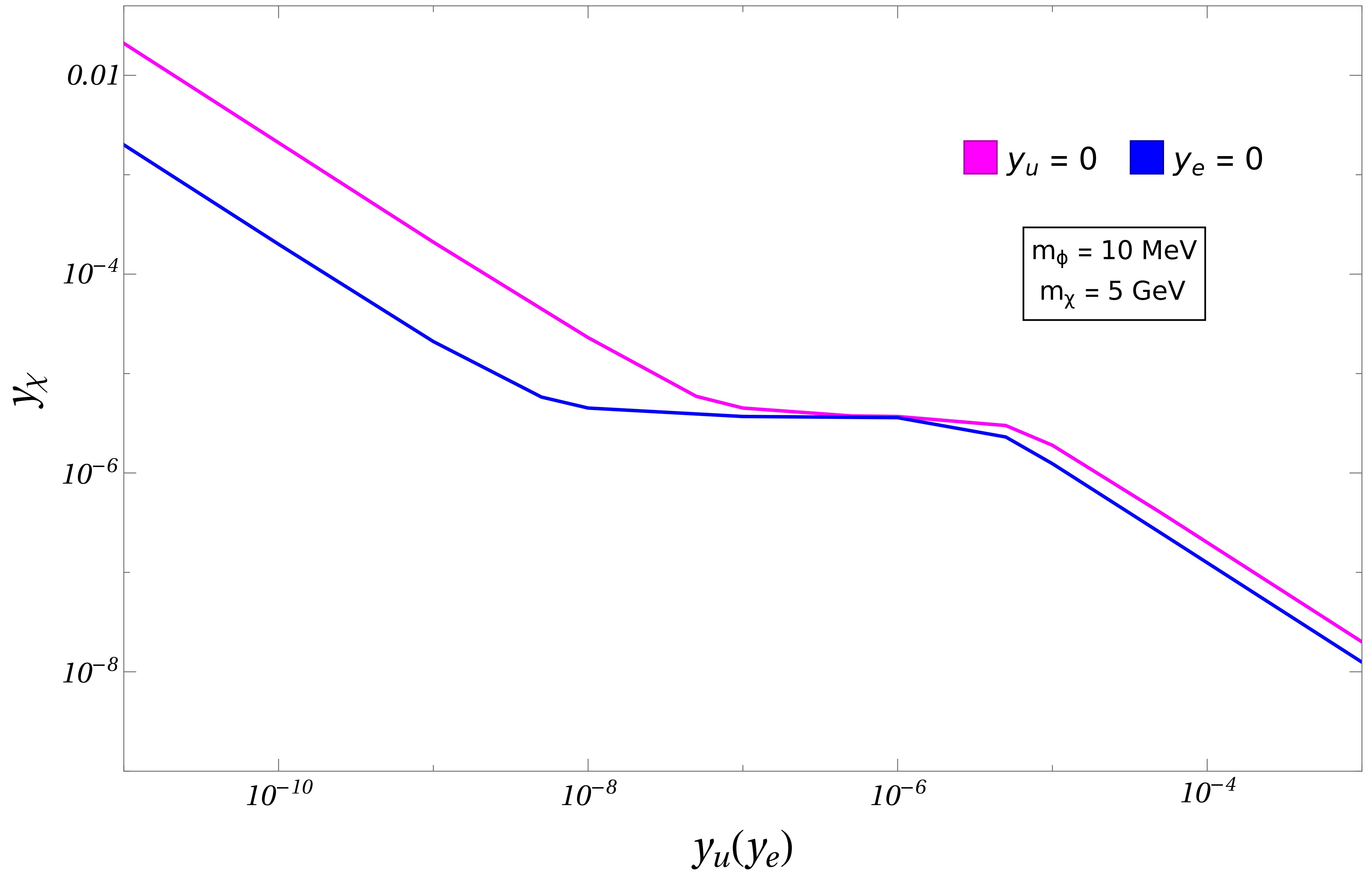
(only) Hadrophilic vs. leptophilic

Extra ϕ production channel(s)

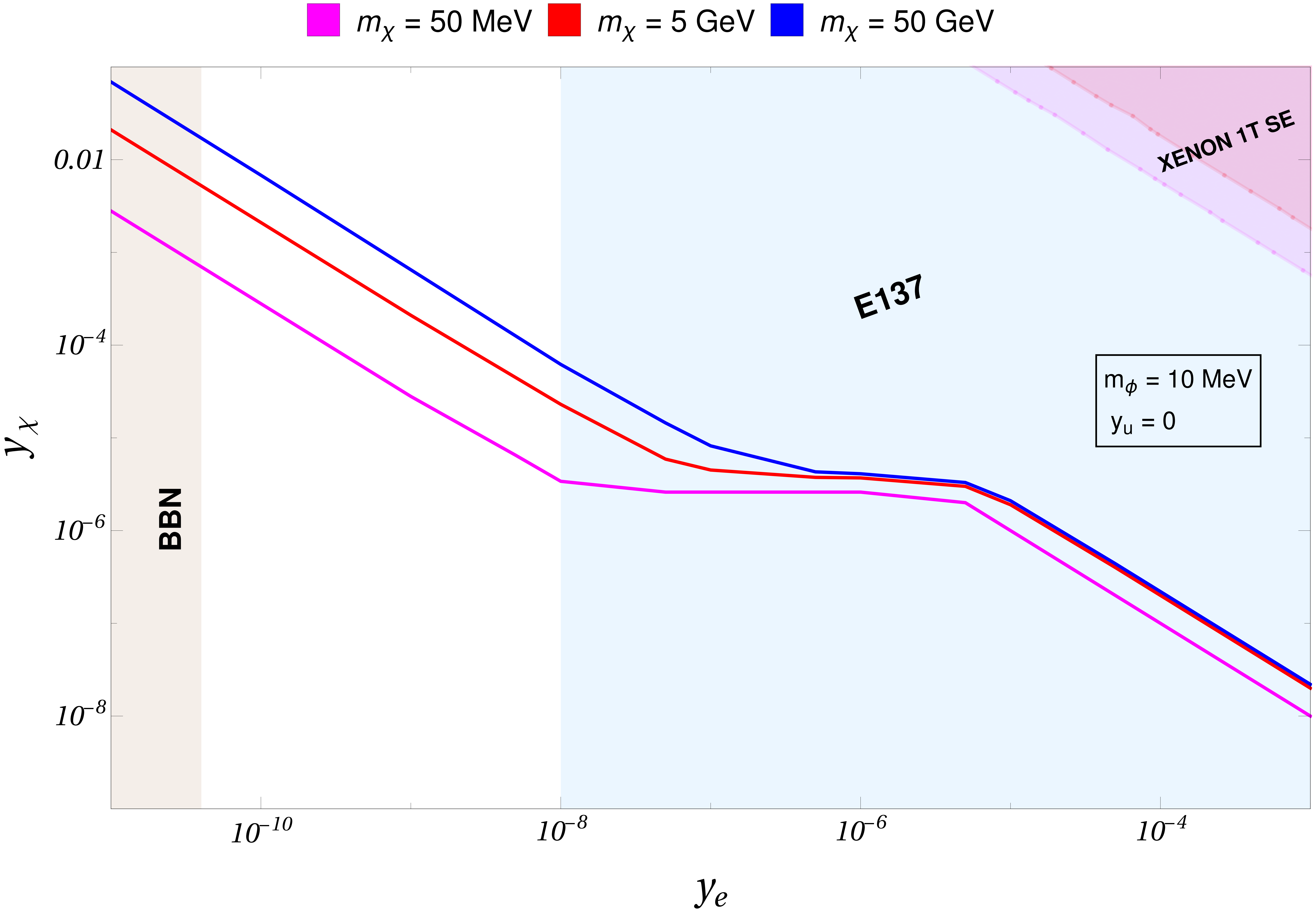
- $e^+e^- \to \gamma\phi$
- $e\gamma \to e\phi$
- $\gamma \to e^+e^-\phi$

Extra χ production channel(s)

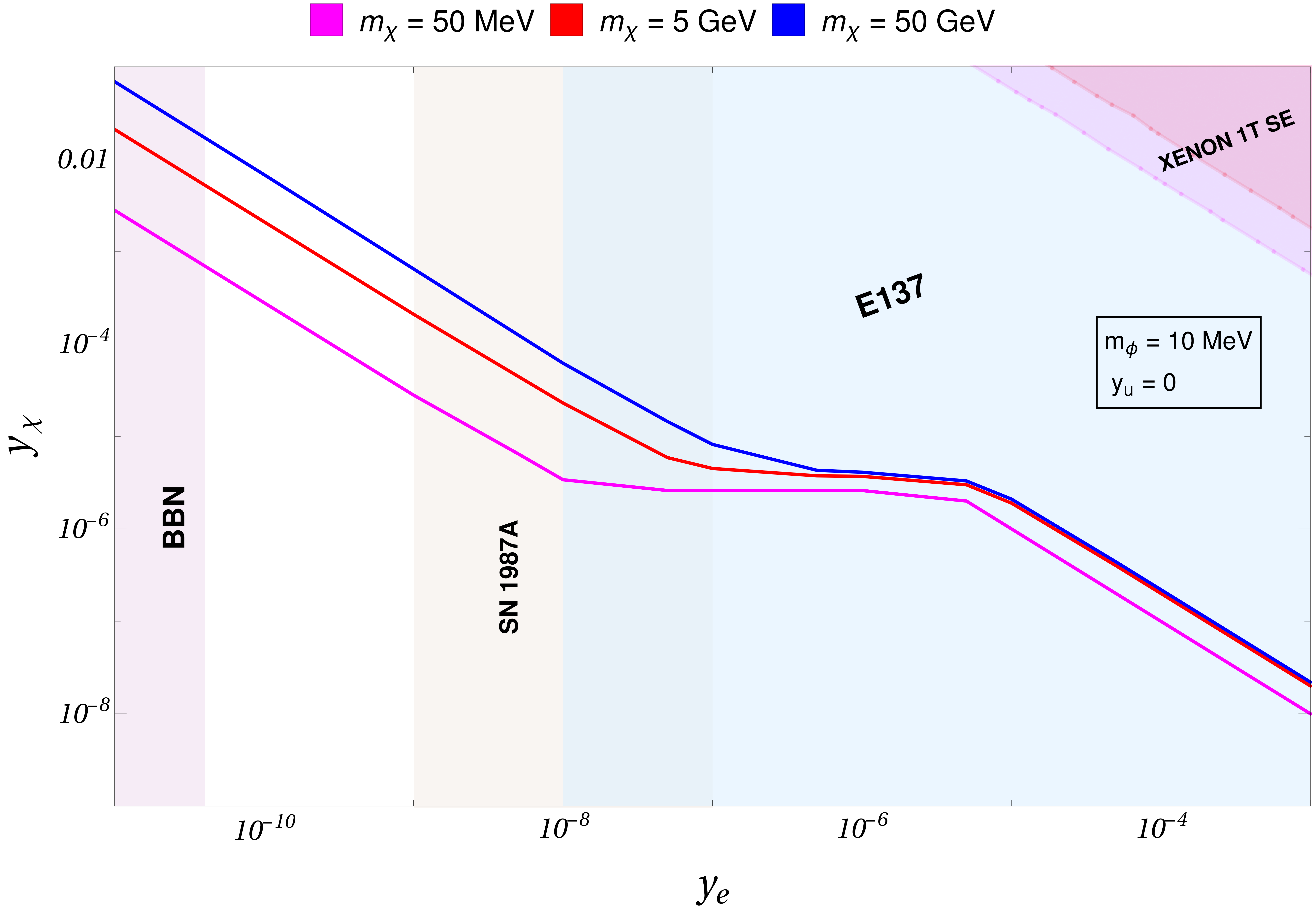
- $e^+e^- \to \chi\bar{\chi}$



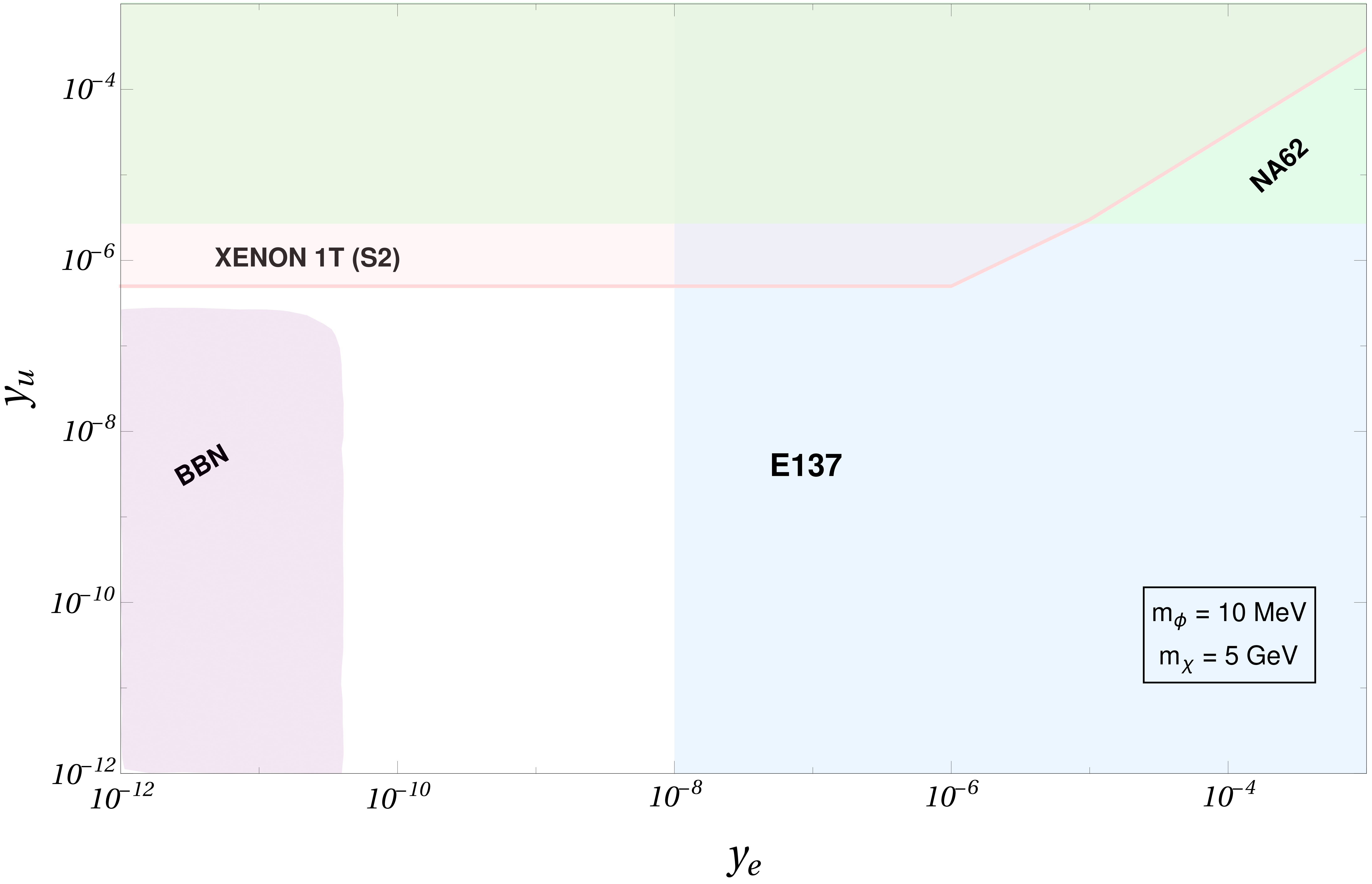
Probe for only leptophilic case



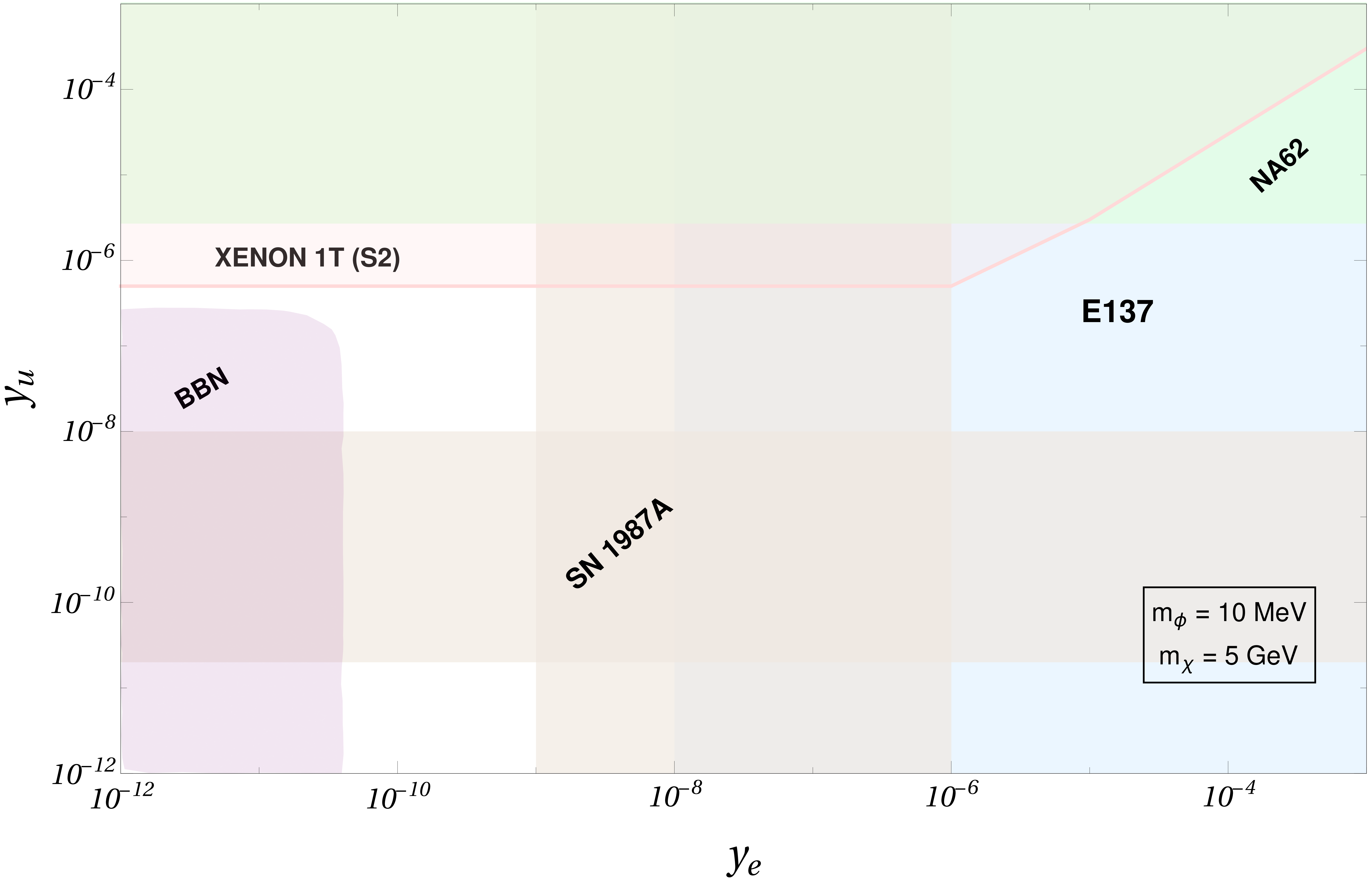
Probe for only leptophilic case



Modified limits



Modified limits



Take home

- Sequential freeze-in is a recently discovered DM production regime at work when $g_\chi \gg g_\phi$.
- Interestingly, values of coupling combinations much smaller than the standard freeze-in can still deliver good relic abundance.
- Direct detections, as well as beam-dump experiments, will be able to probe a large part of the parameter space.

Back ups

Thermal corrections

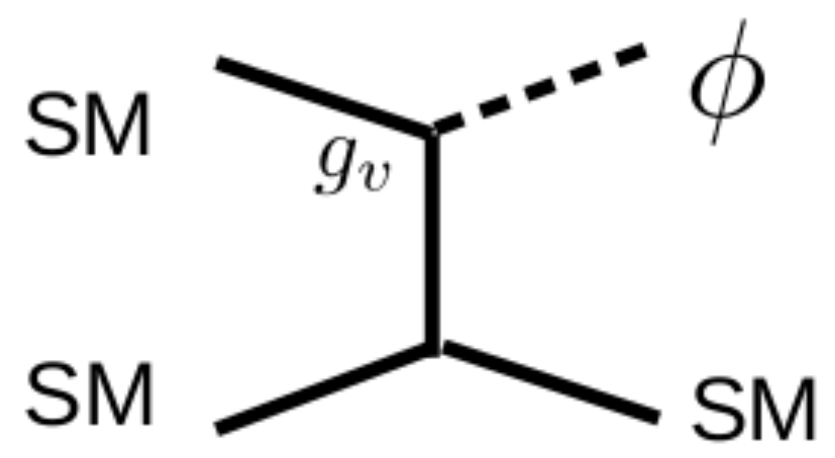
- Here thermal corrections are a priori relevant since DM production is out of equilibrium starting from very high temperatures.
- Thermal corrections are applicable to the collision term $C[f_\phi]$.

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

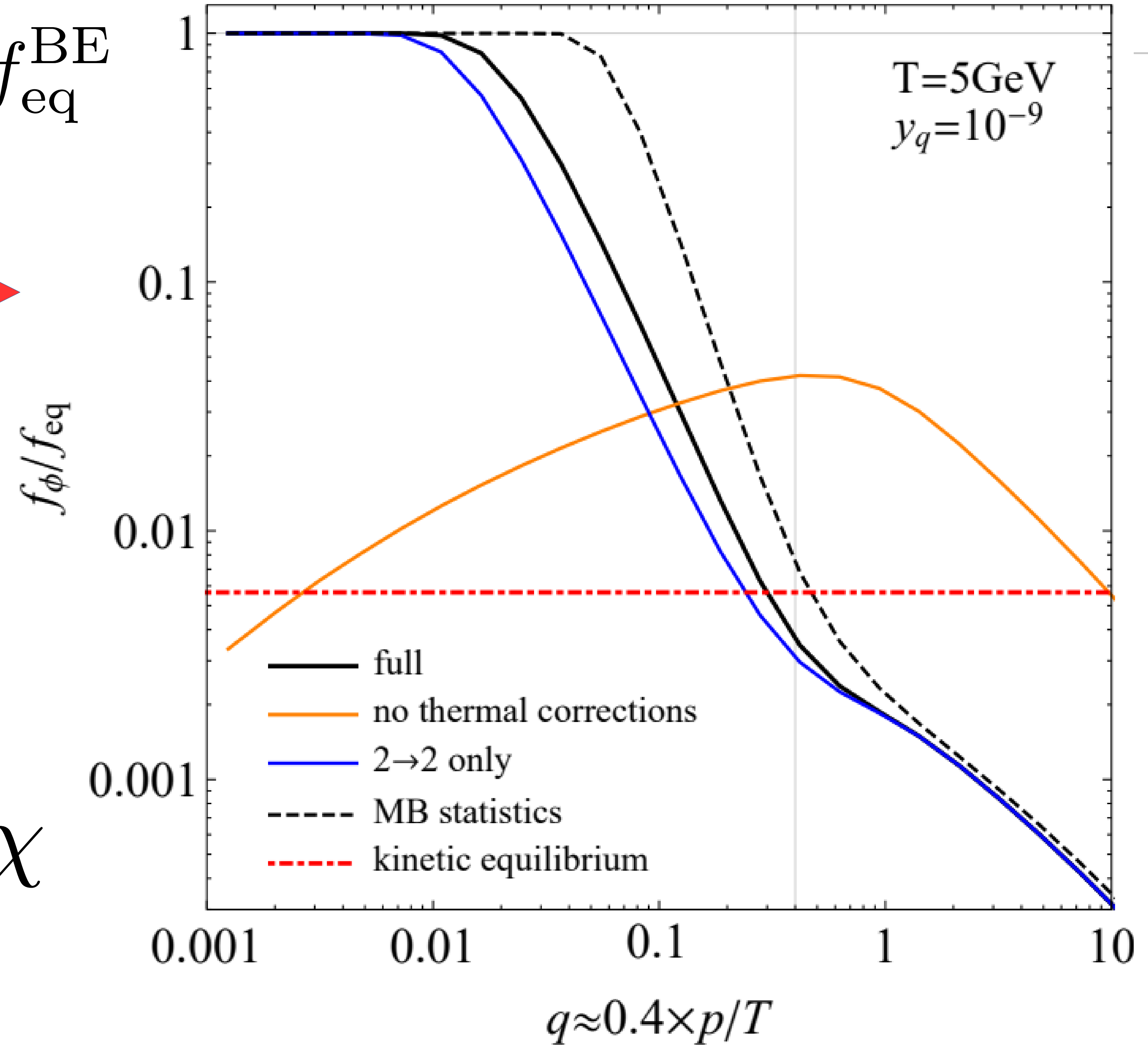


As for DM production is concerned:
O(1) change in the abundance, wrt not considering such corrections

Beyond kinetic equilibrium…

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 →

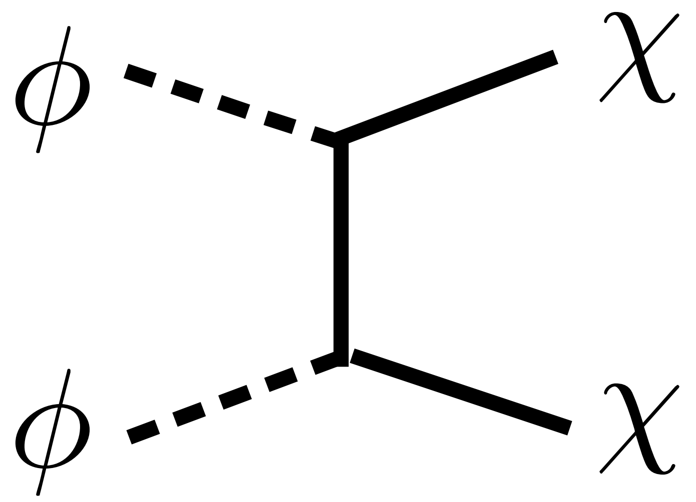


If assuming MB distrib. for the SM particles

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

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]