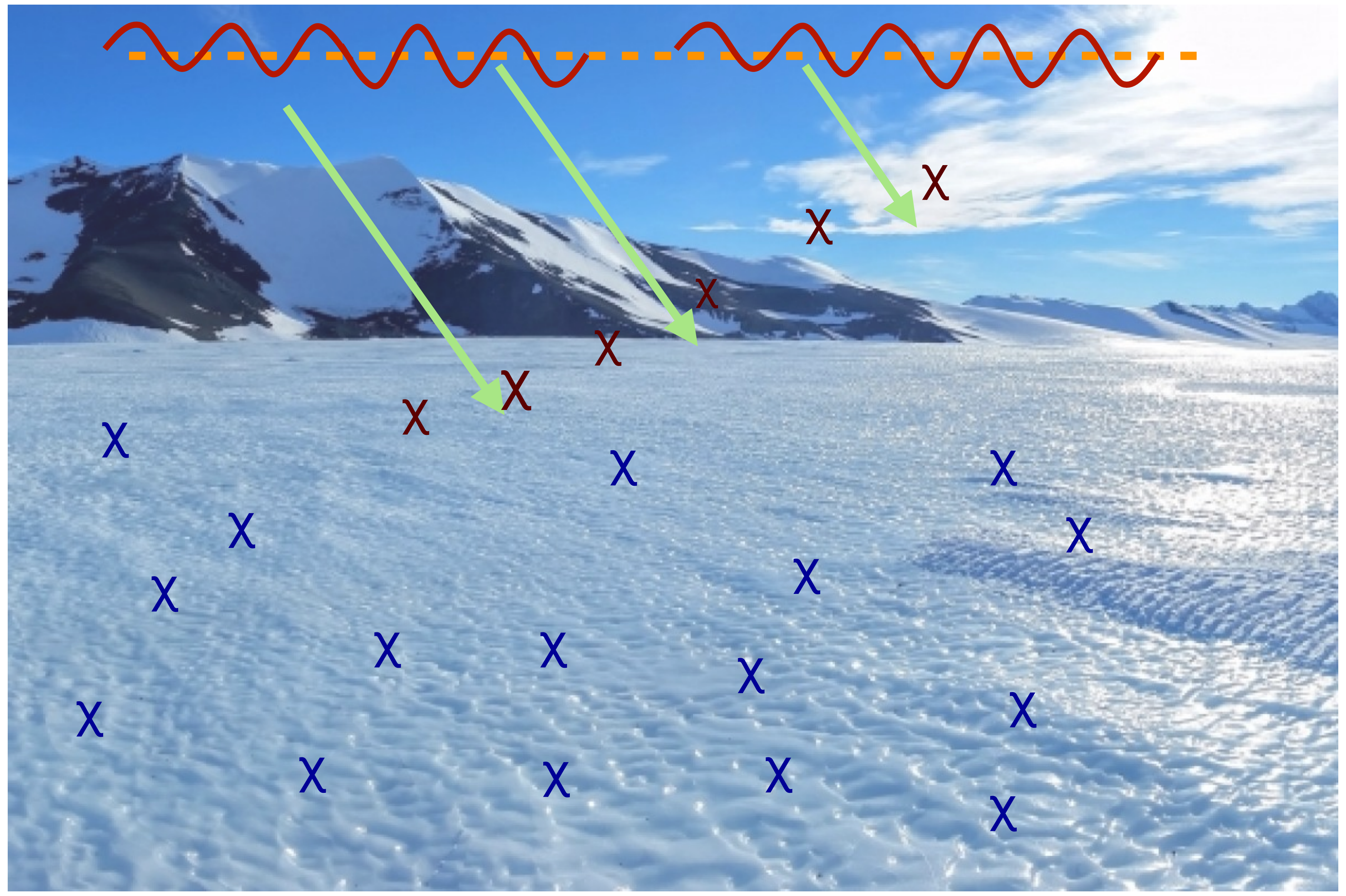
Freeze-in versus Glaciation: Freezing into a thermalized hidden sector

Nicolas Fernandez



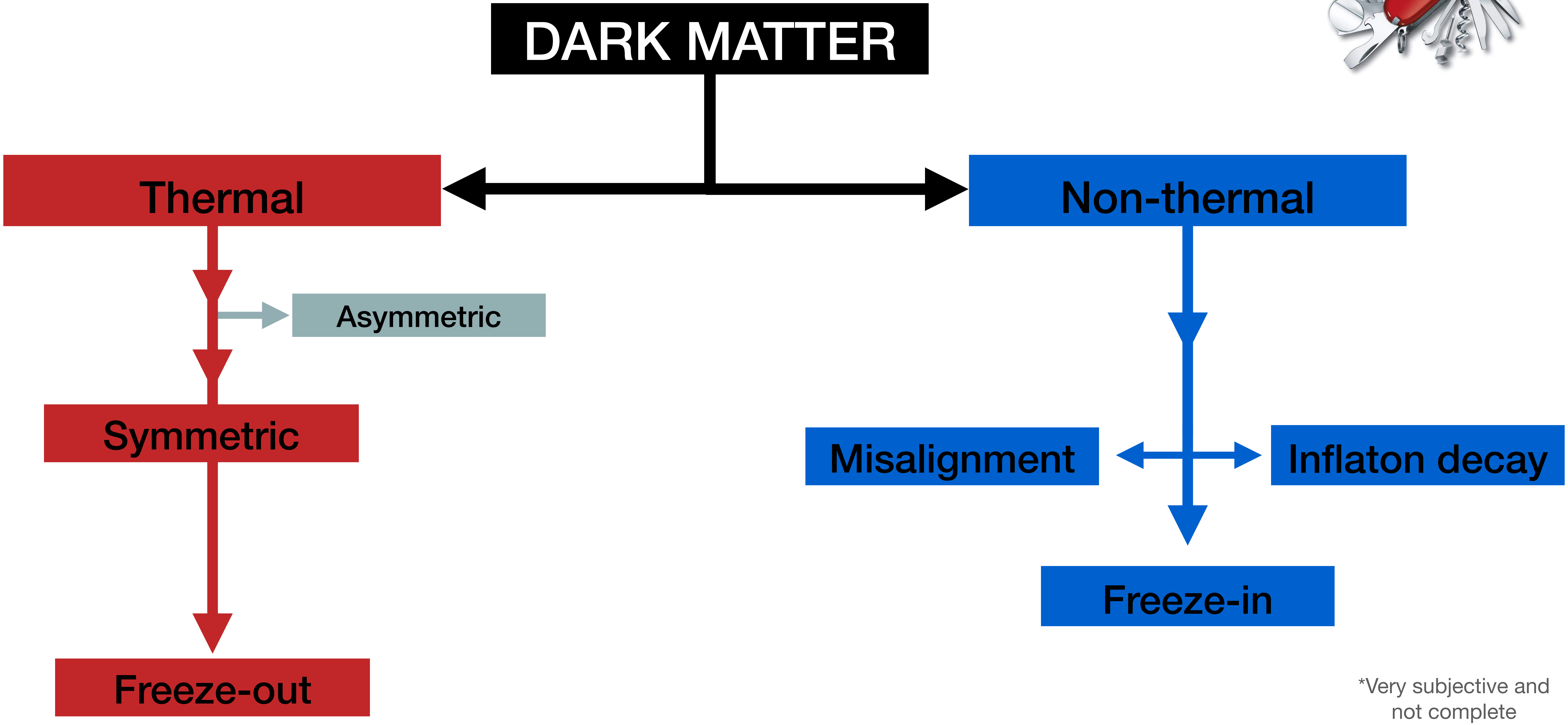
MOCa 2021

June 2021

ILLINOIS

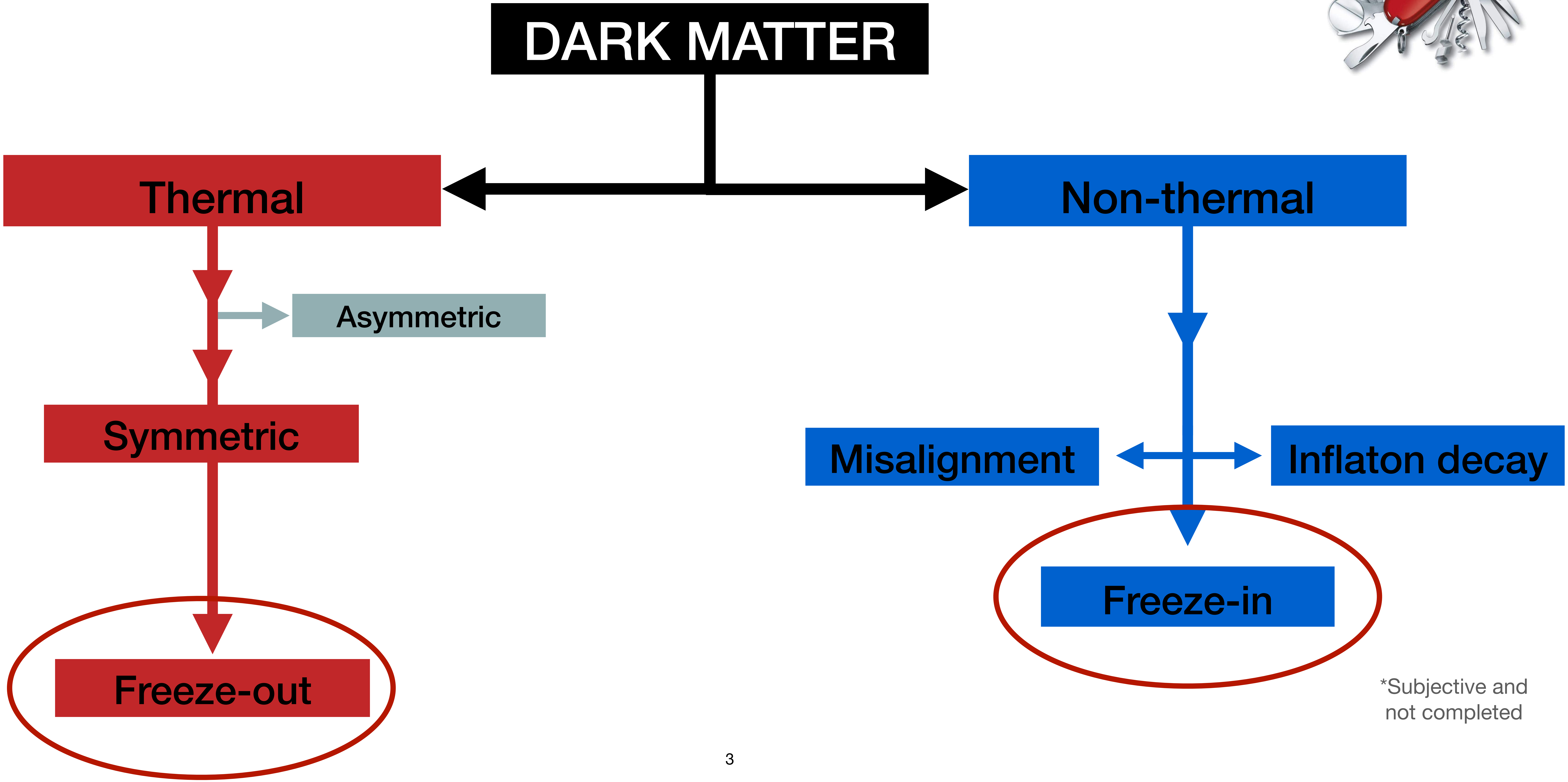
*Based on **NF,** Kahn and Shelton in prep.*

Dark Matter Production Flow*



*Very subjective and not complete

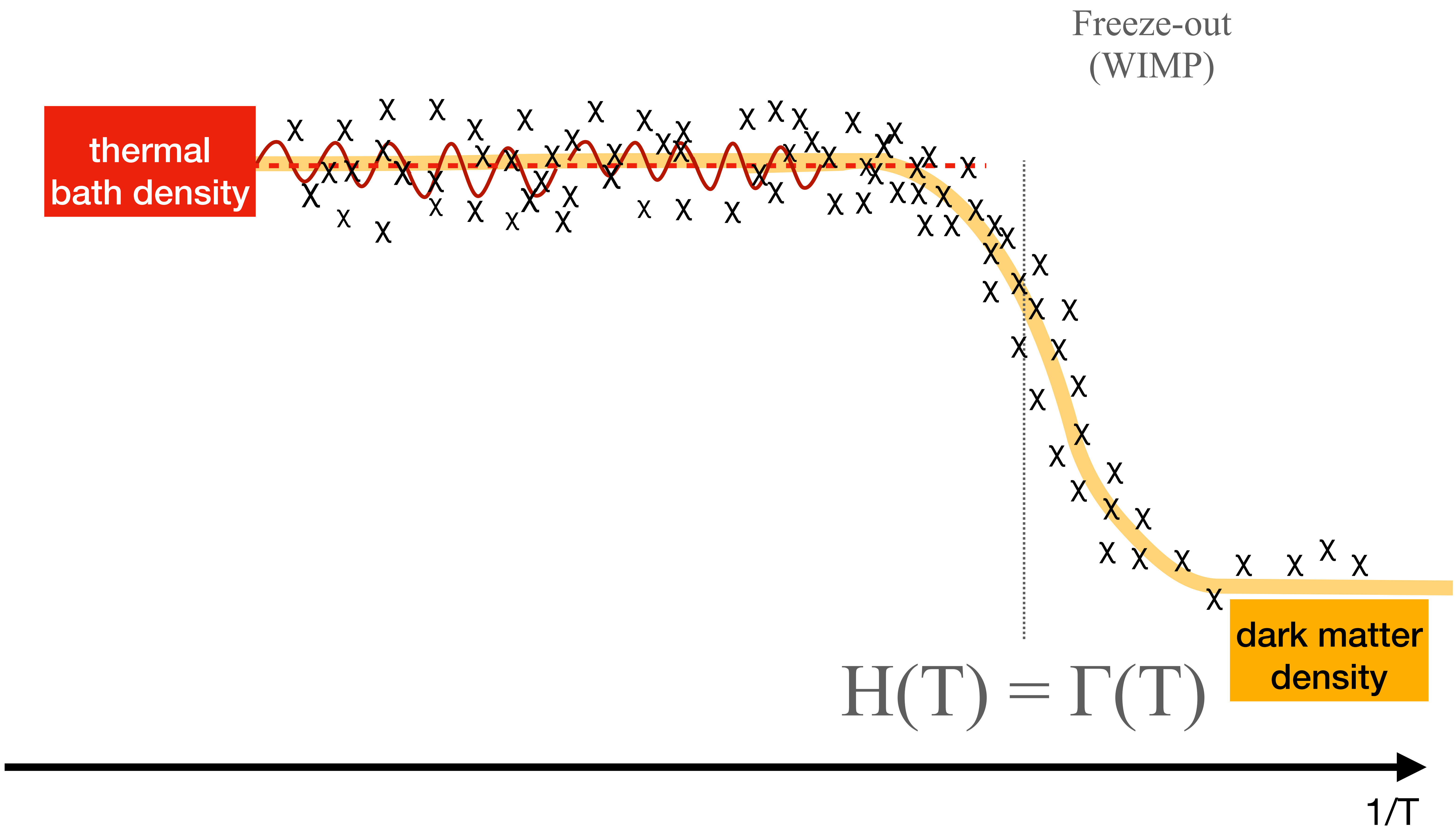
Dark Matter Production Flow*



*Subjective and not completed

Freeze-out

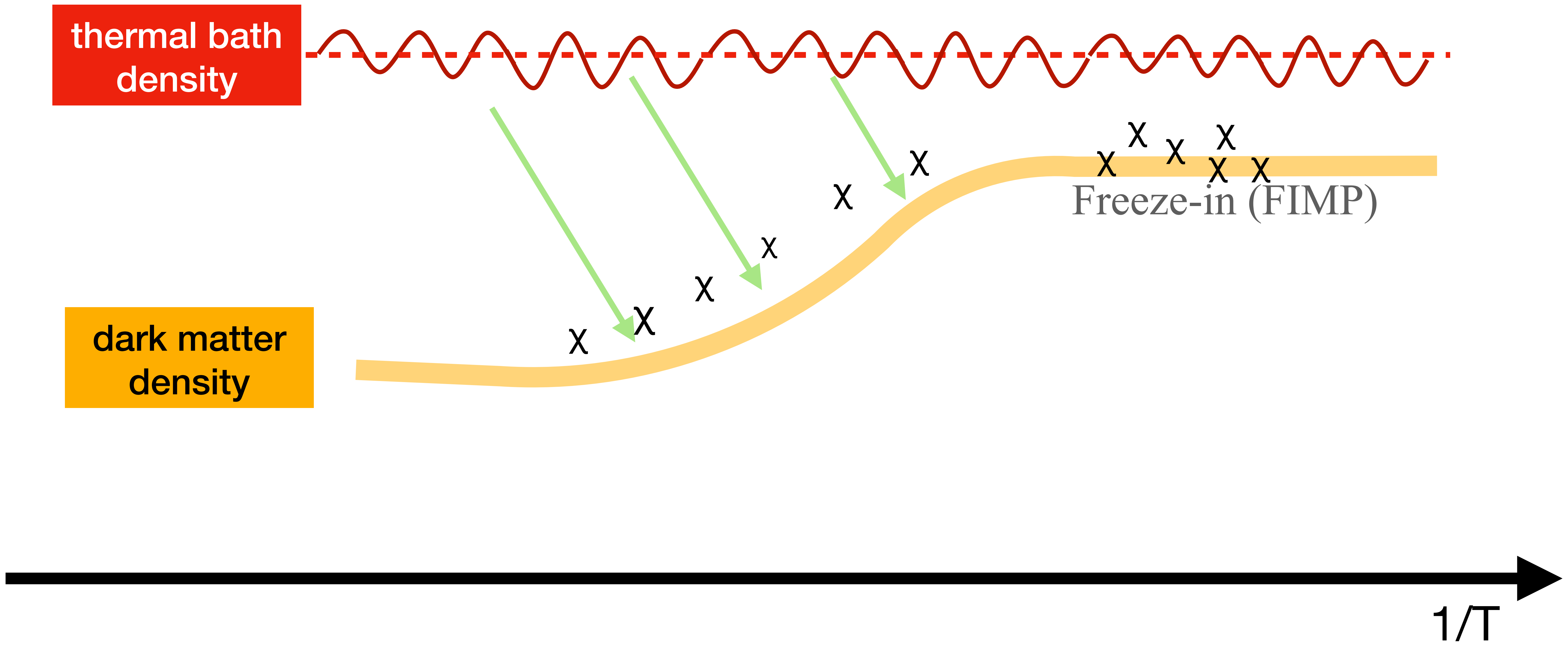
Or the art of getting rid of stuff



- Relic abundance is independent of initial conditions
- Fine with BBN (masses > few MeV)
- Experimentally testable. Past ~15 years

Freeze-in

Or the art of getting enough with less

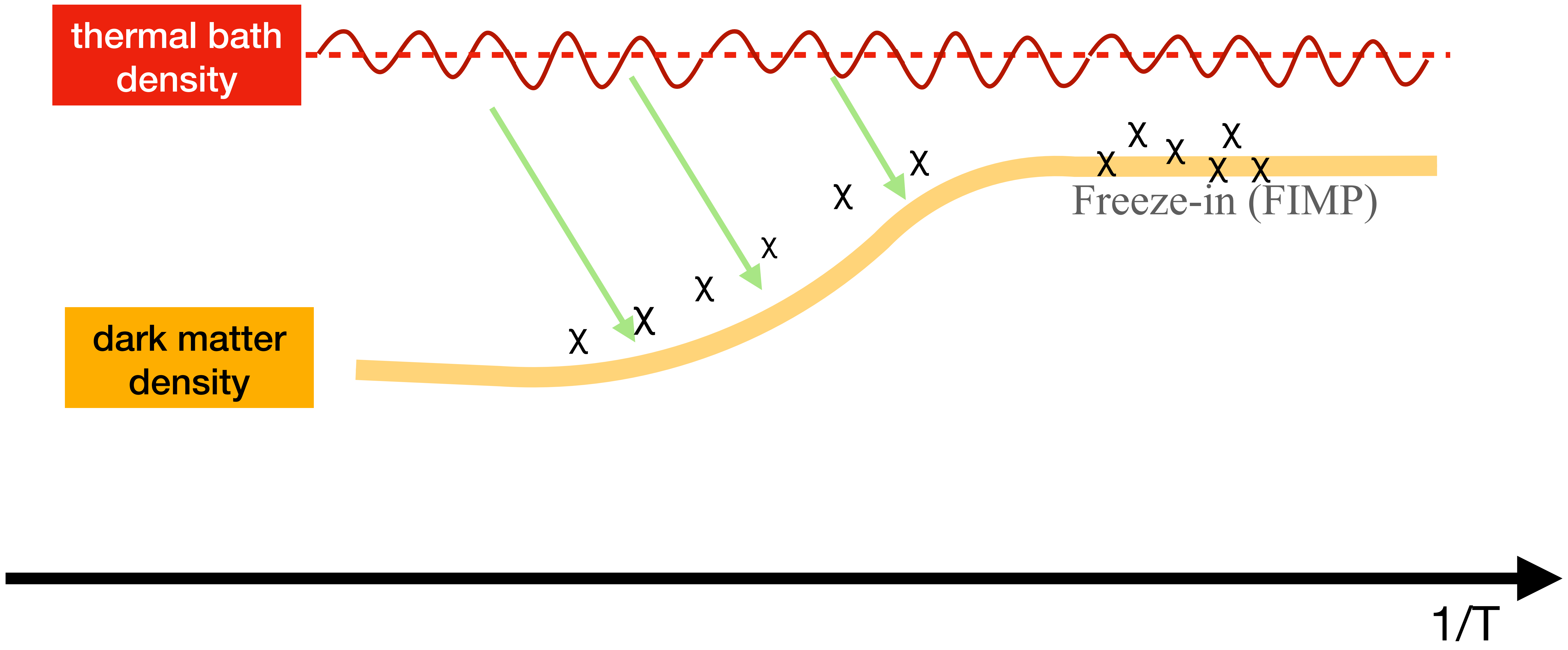


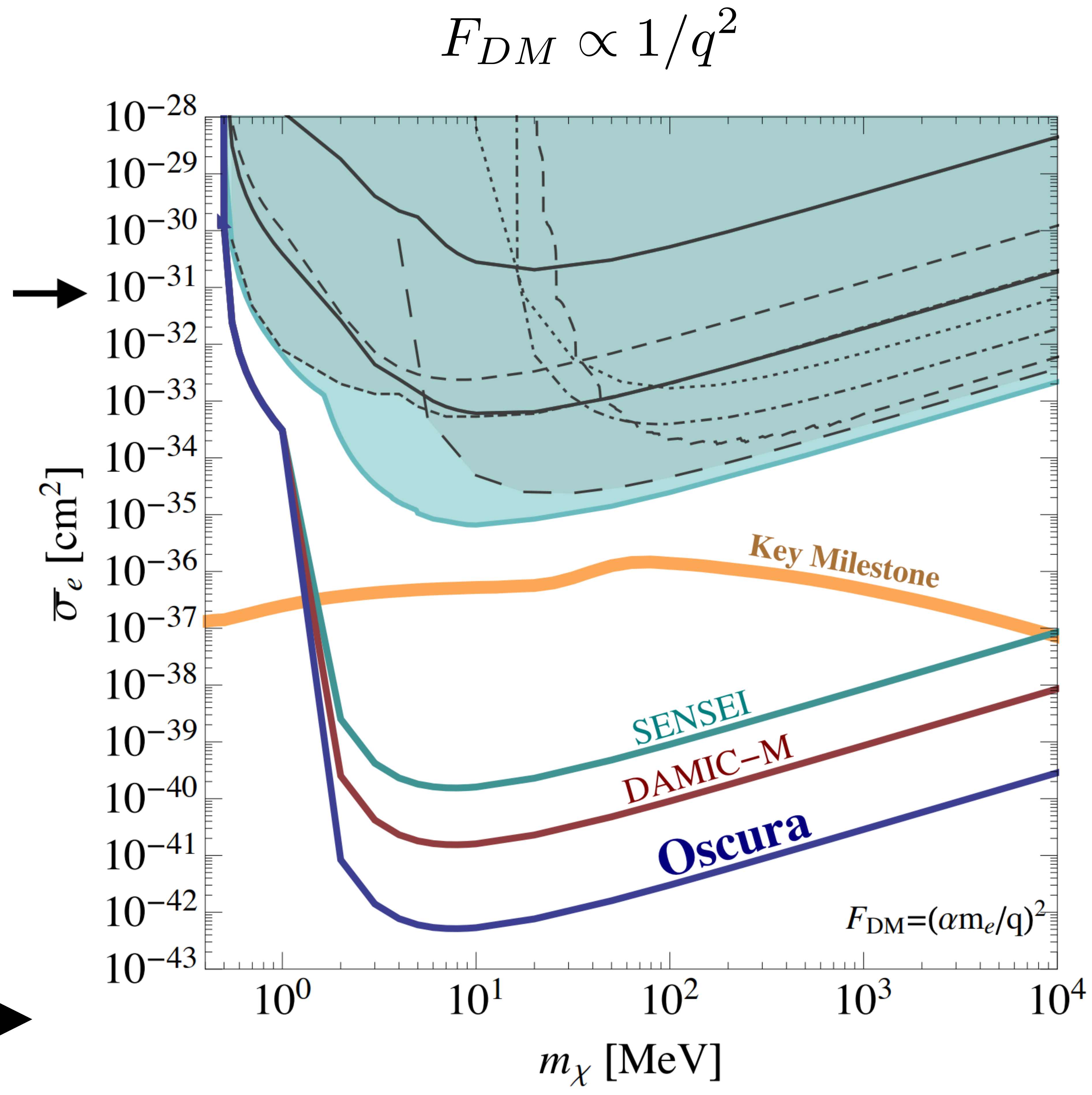
- Relic abundance is independent of initial conditions*
- Fine with BBN and Neff (masses > O(10) keV)
- Experimentally testable soon! Very exciting!

[Hall et al. 2009]

Freeze-in

Looking in to the future

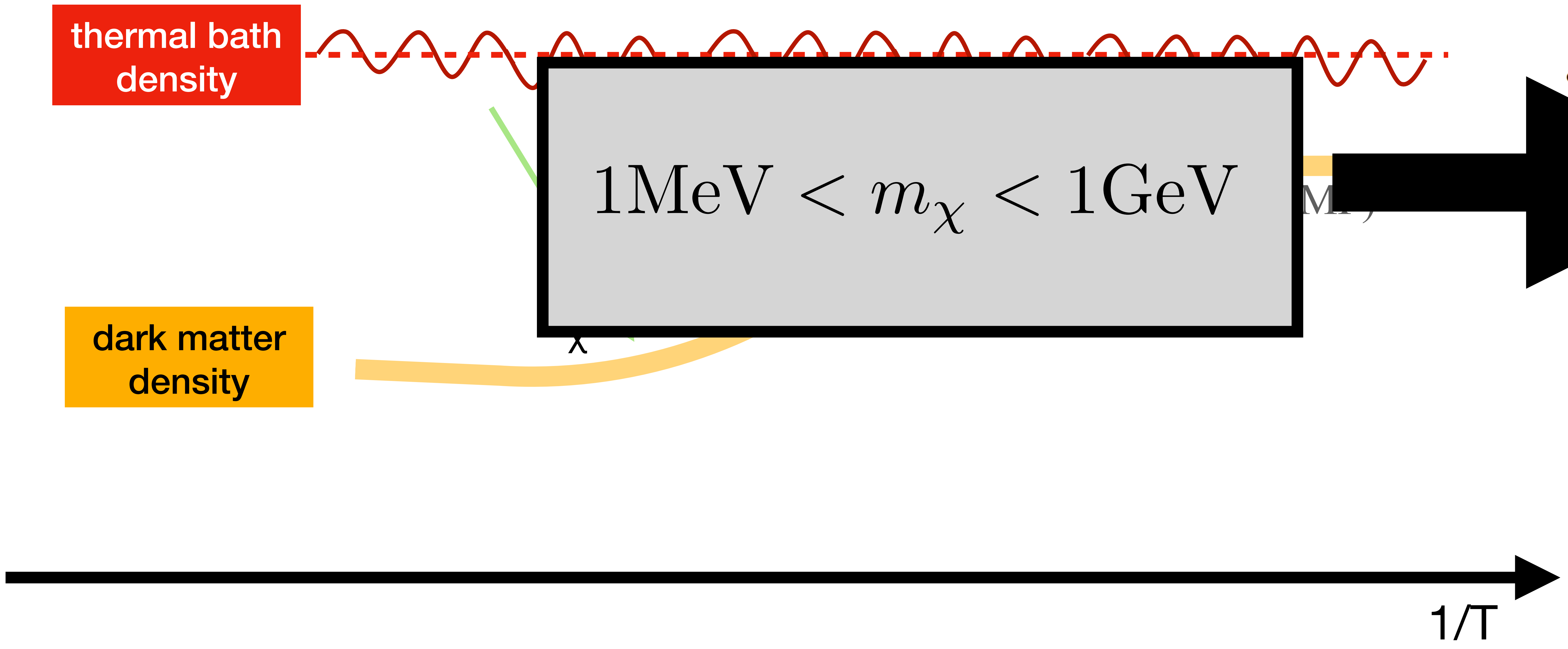


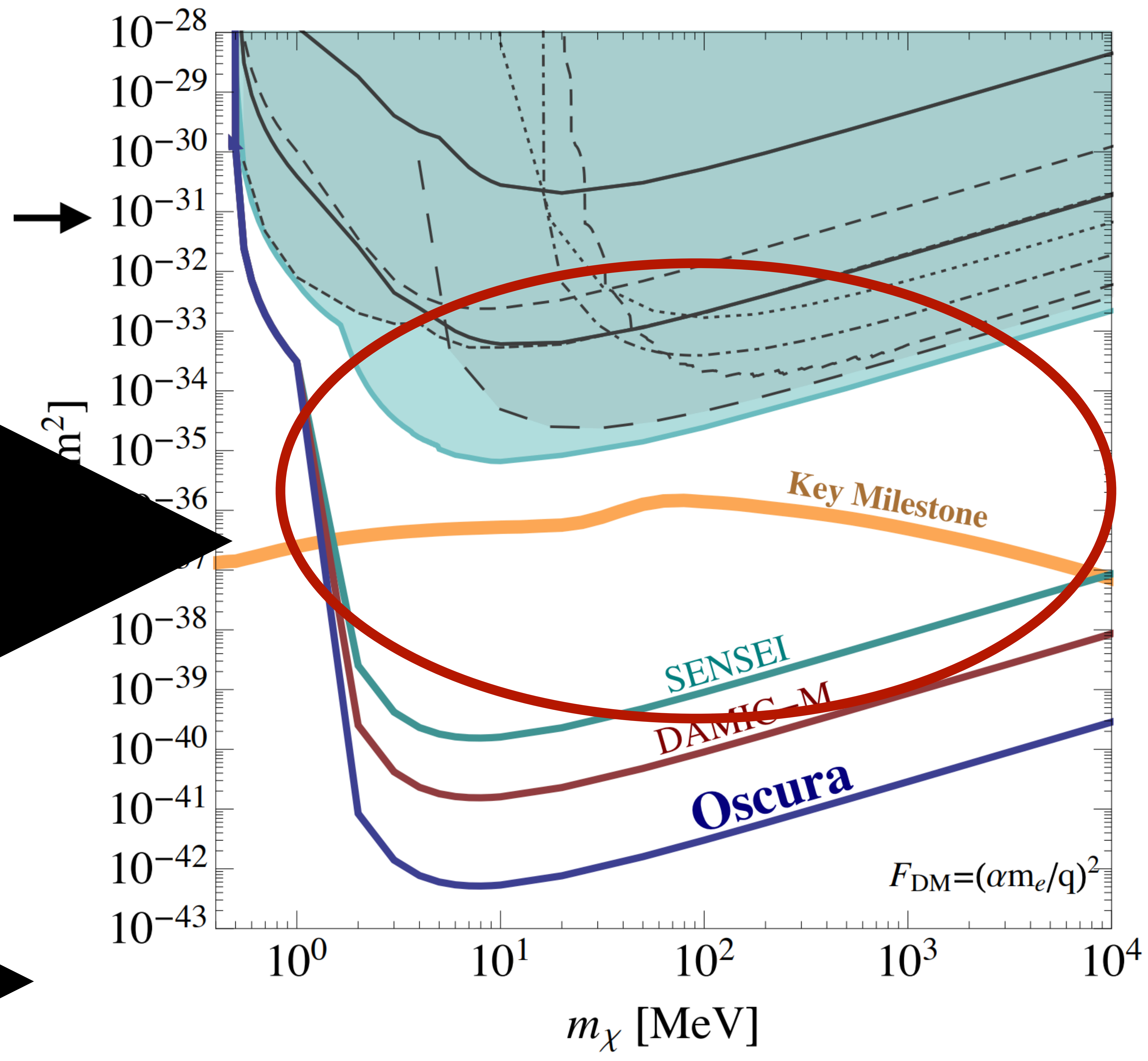


[Tien-Tien Yu: Snowmass CF1 2020]

Freeze-in

Looking in to the future

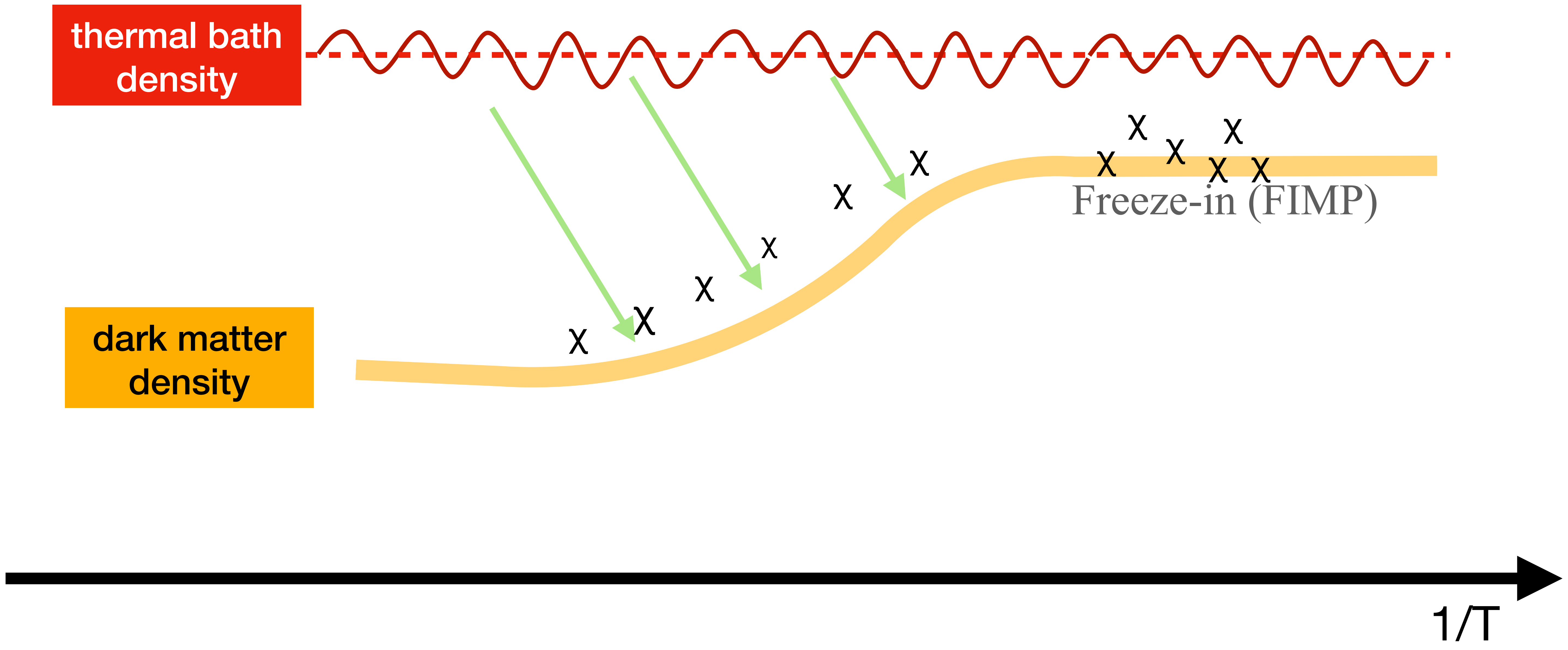




[Tien-Tien Yu: Snowmass CF1 2020]

Freeze-in

Trying to poke holes

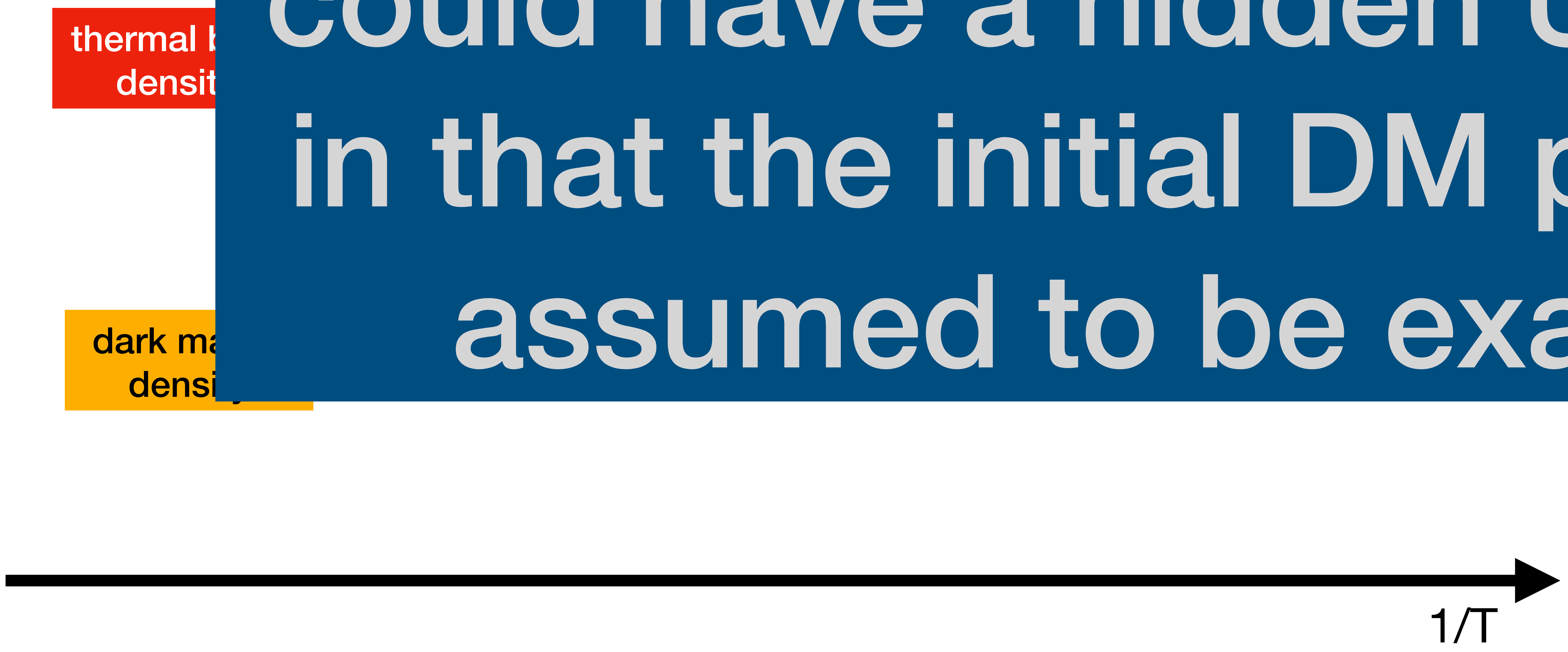


- Relic abundance is independent of initial conditions
- Fine with BBN and Neff (masses > O(10) keV)
- Experimentally testable soon! Very exciting!

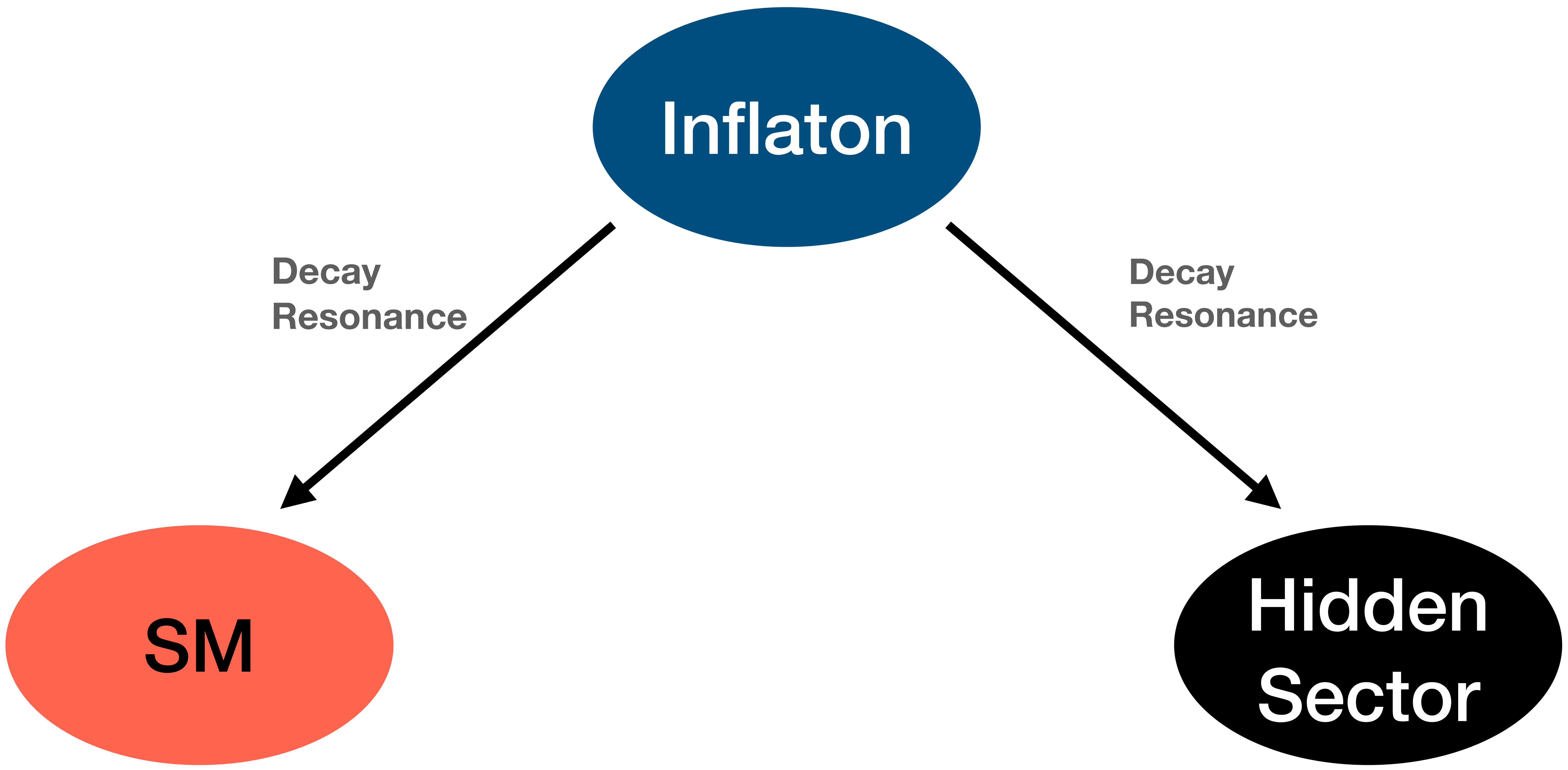
Freeze-in

Trying to poke holes

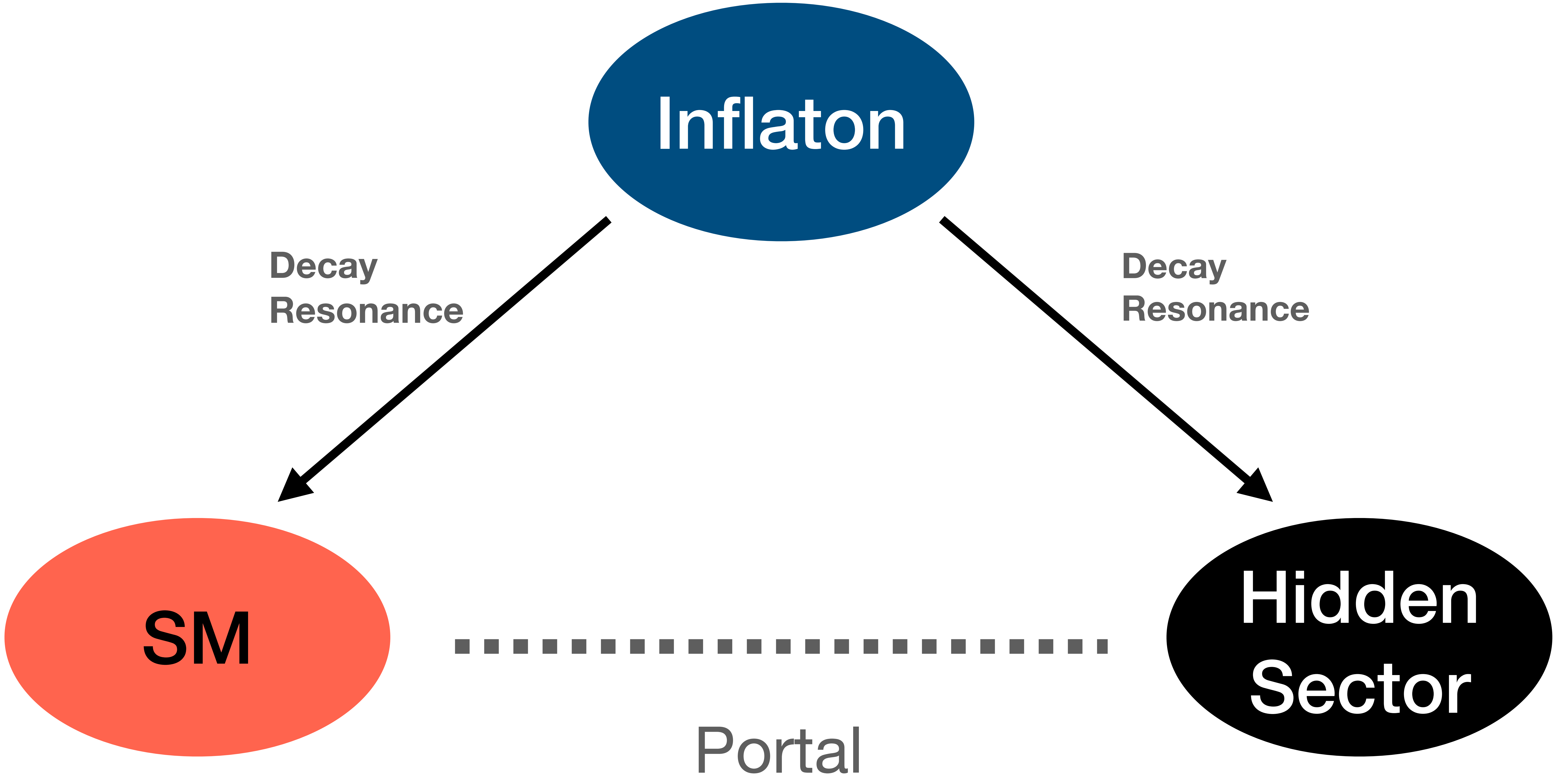
The standard freeze-in paradigm could have a hidden UV sensitivity in that the initial DM population is assumed to be exactly zero.



What if…

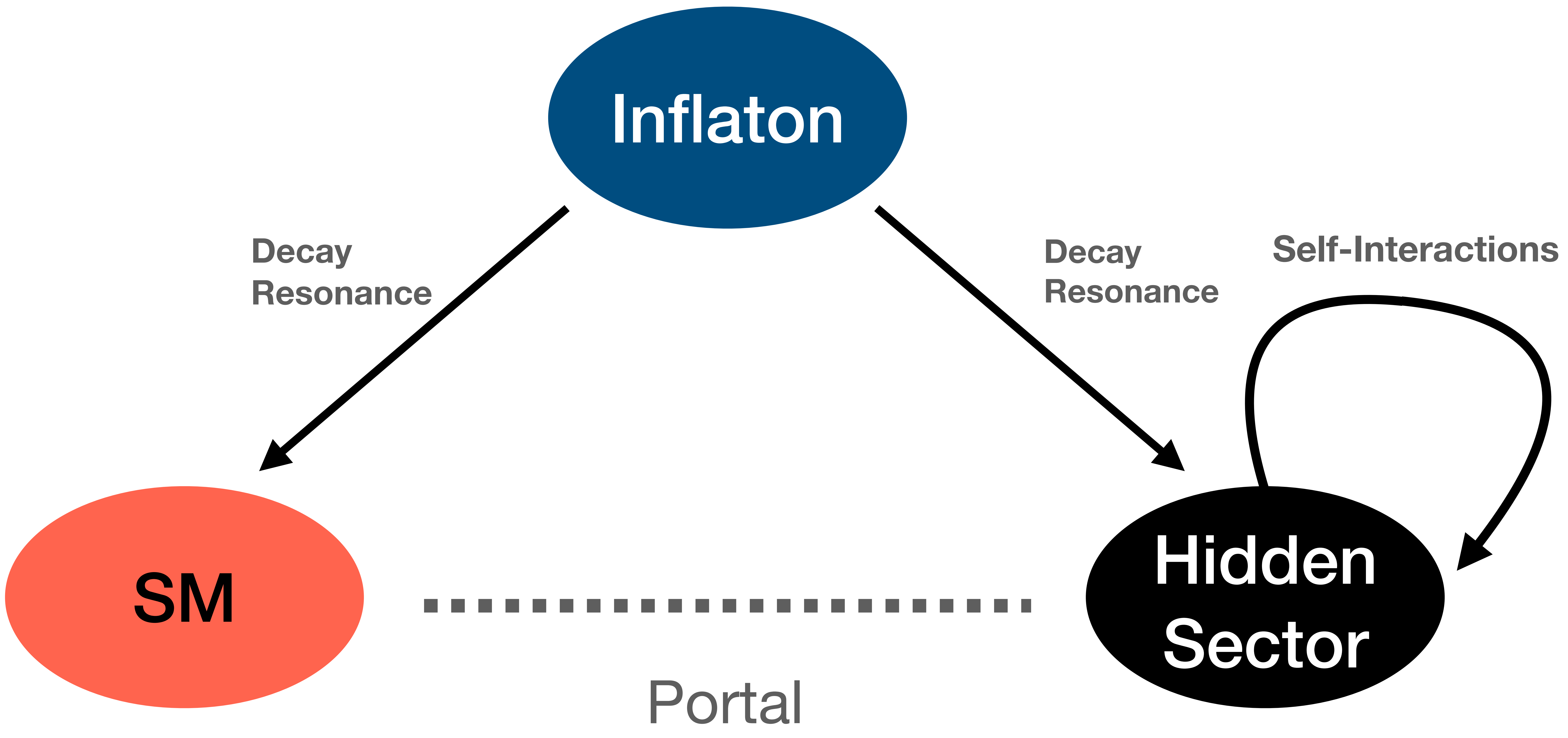

Inflaton
Decay
Resonance
Decay
Resonance
SM
Hidden
Sector

What if…



Inflaton
Decay
Resonance
Decay
Resonance
SM
Hidden
Sector
Portal

What if…


Inflaton
Decay
Resonance
Decay
Resonance
Self-Interactions
SM
Hidden
Sector
Portal

Let us explore an explicit model:

Kinetic mixing portal Dark photon

Explicit Model: Kinetic mixing portal
Dark photon

$$\mathcal{L} = -\frac{1}{4}\tilde{Z}'_{\mu\nu}\tilde{Z}'^{\mu\nu} - \frac{\epsilon}{2\cos\theta_W}\tilde{Z}'_{\mu\nu}\tilde{B}^{\mu\nu} - \frac{1}{2}m^2_{Z_D}\tilde{Z}_{D\mu}\tilde{Z}^{\mu}_{D} + g_\chi J^\mu_D \tilde{Z}_{D\mu} + \bar{\chi}\left(i\gamma^\mu\partial_\mu - m_\chi\right)\chi\,,$$

Rotating away the mixing term

Gauge boson mass eigenstates

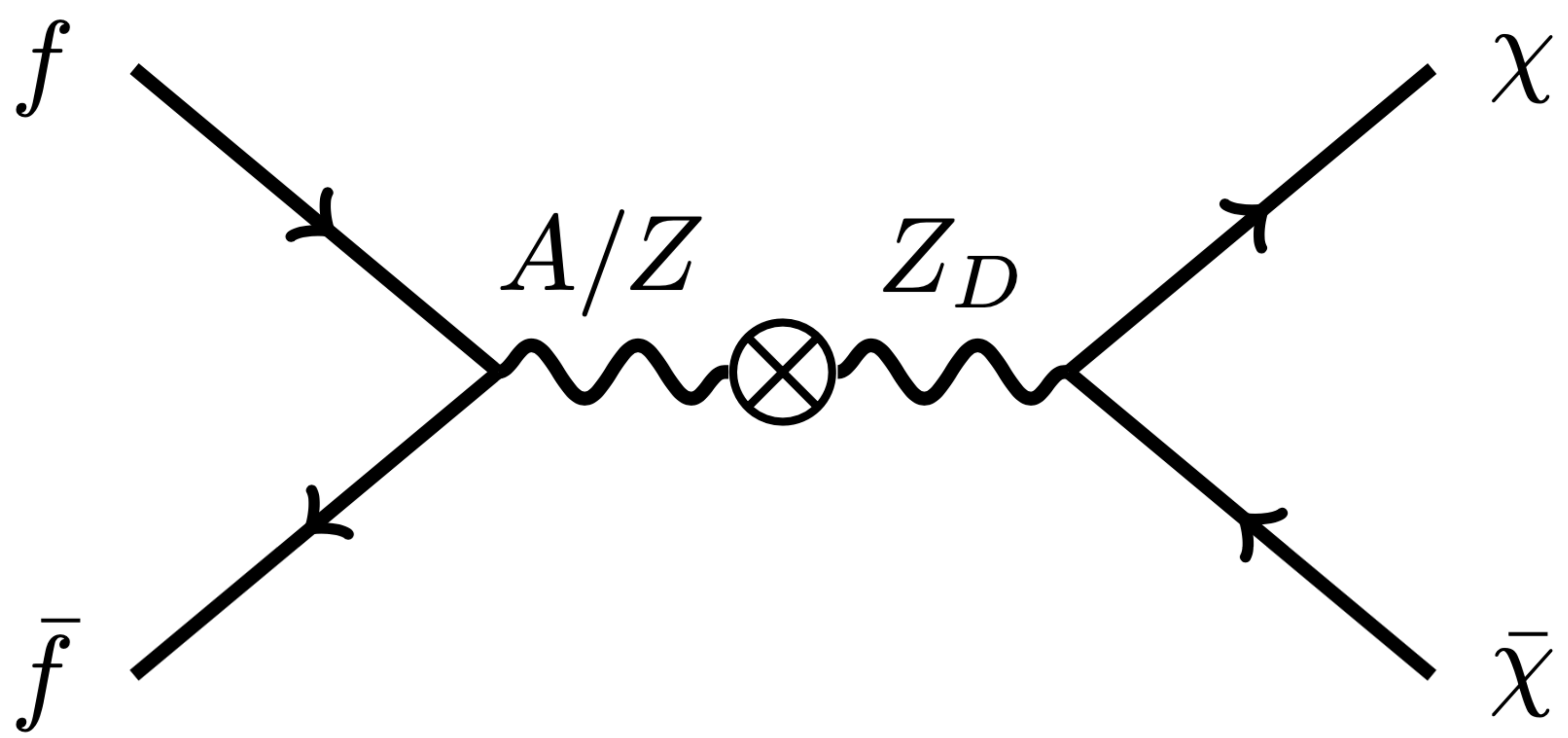
$m_{Z_D} \ll m_Z$ (ultra light mediator)

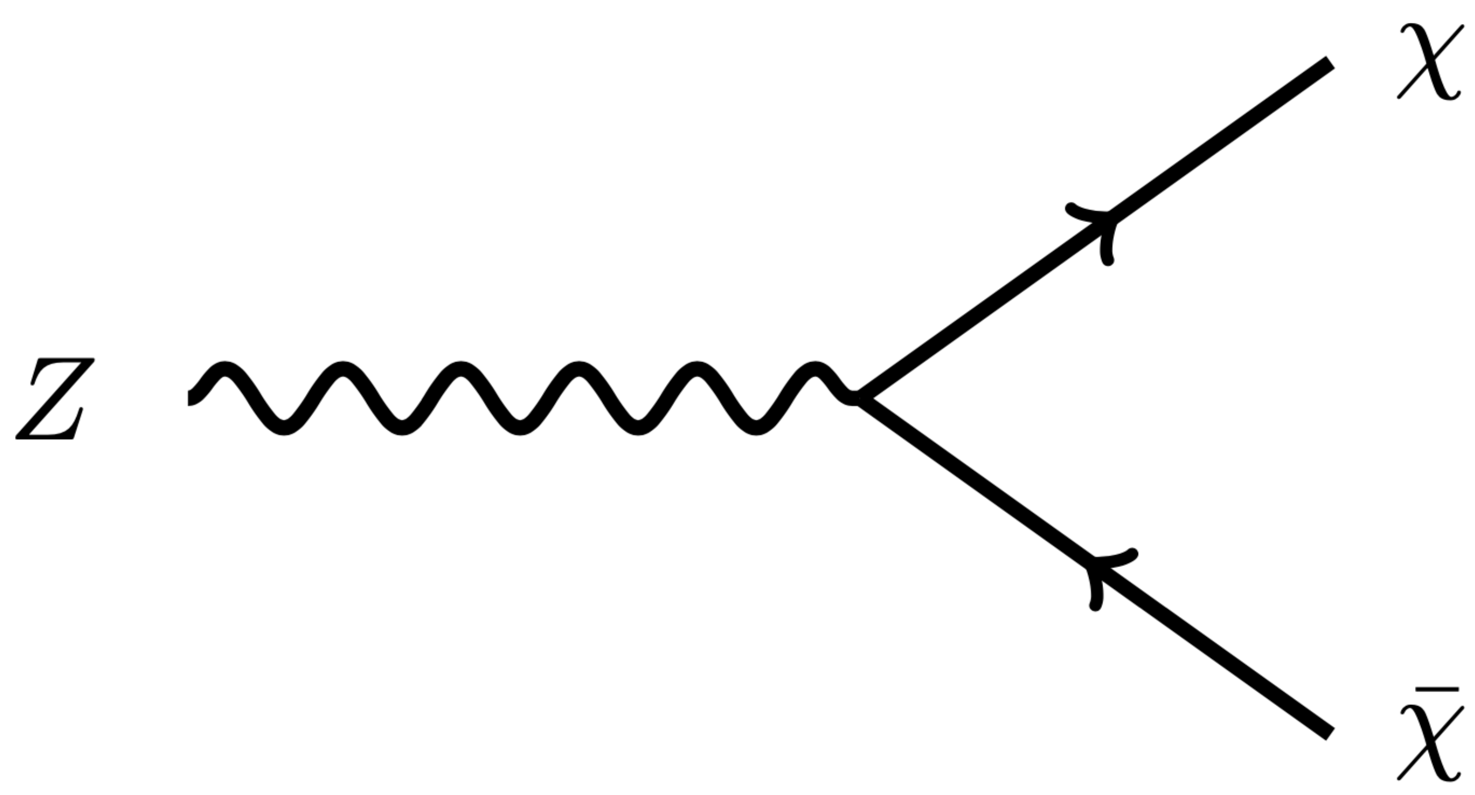
$$\mathcal{L} \supset -\epsilon e J^\mu_{\rm EM} Z_{D\mu} + \epsilon g_\chi \tan\theta_W J^\mu_D Z_\mu + g_\chi J^\mu_D Z_{D\mu}\,,$$

RELIC ABUNDANCE FROM FREEZE-IN

$$\mathcal{L} \supset -\epsilon e J^{\mu}_{\mathrm{EM}} Z_{D\mu} + \epsilon g_{\chi} \tan\theta_W J^{\mu}_{D} Z_{\mu} + g_{\chi} J^{\mu}_{D} Z_{D\mu} \,,$$

$1\mathrm{MeV} < m_{\chi} < 1\mathrm{GeV}$

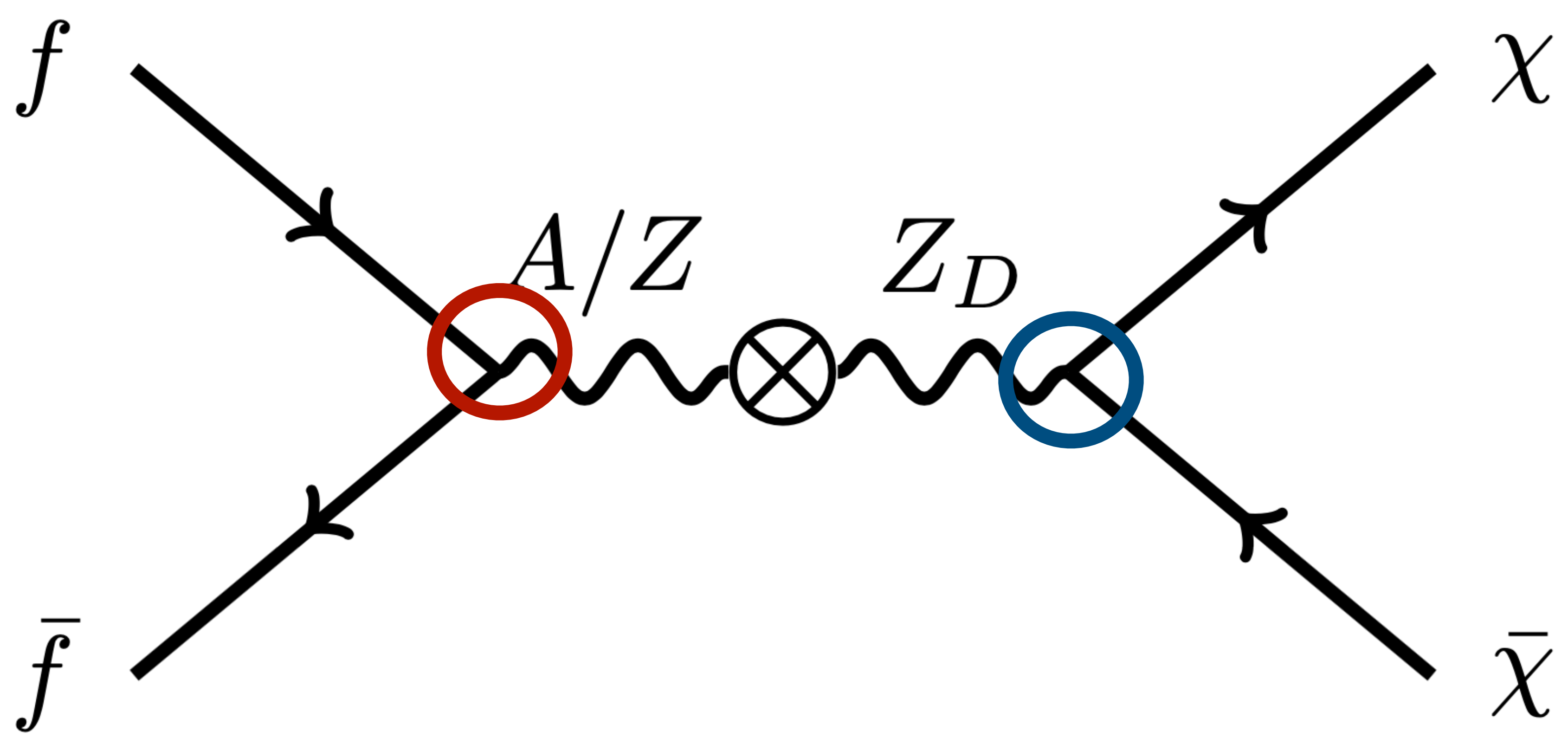


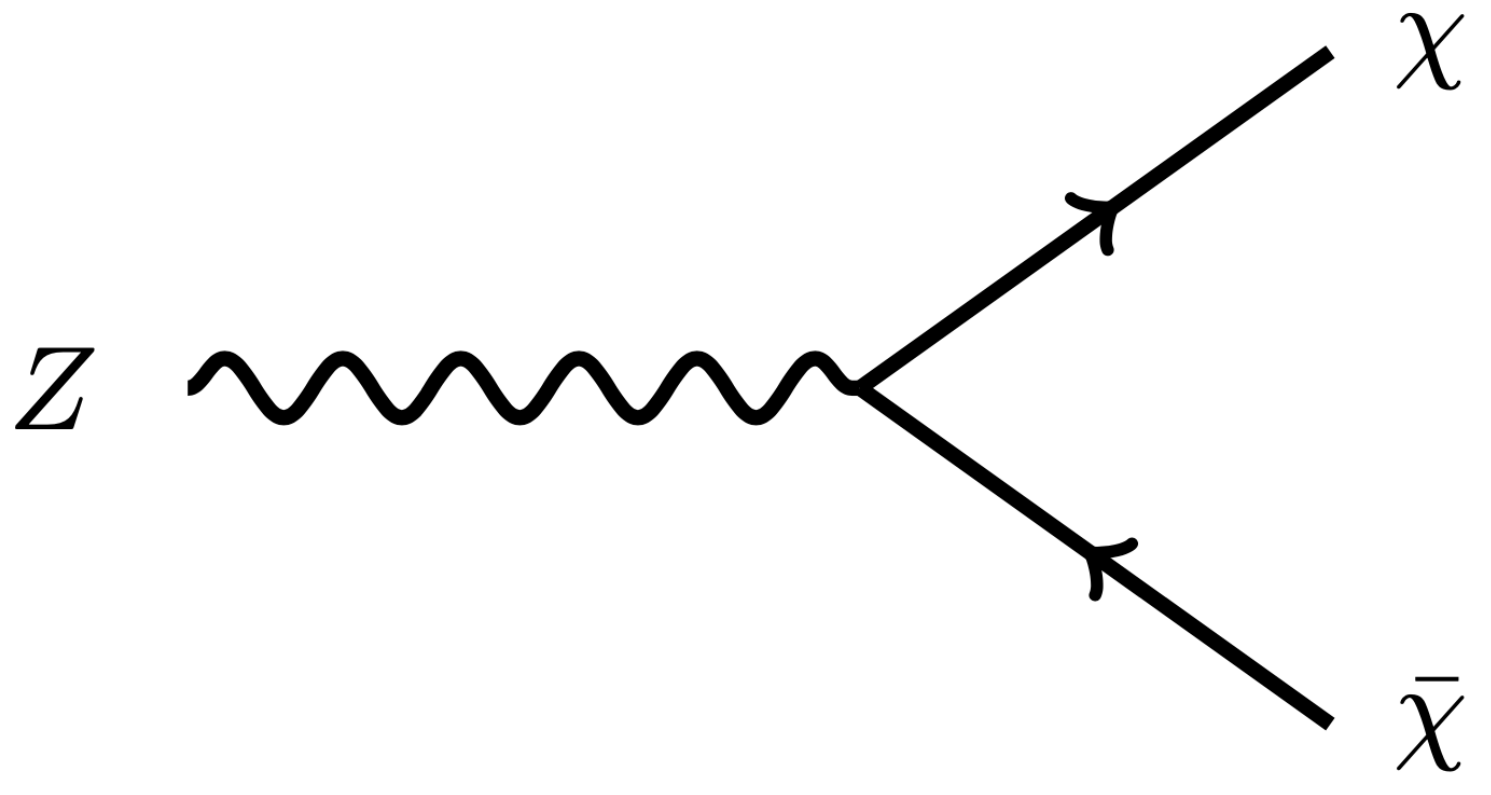


RELIC ABUNDANCE FROM FREEZE-IN

$$\mathcal{L} \supset -\epsilon e J^{\mu}_{\rm EM} Z_{D\mu} + \epsilon g_{\chi} \tan\theta_W J^{\mu}_D Z_{\mu} + g_{\chi} J^{\mu}_D Z_{D\mu} \,,$$

$$\alpha_D = \frac{g_\chi^2}{4\pi}$$

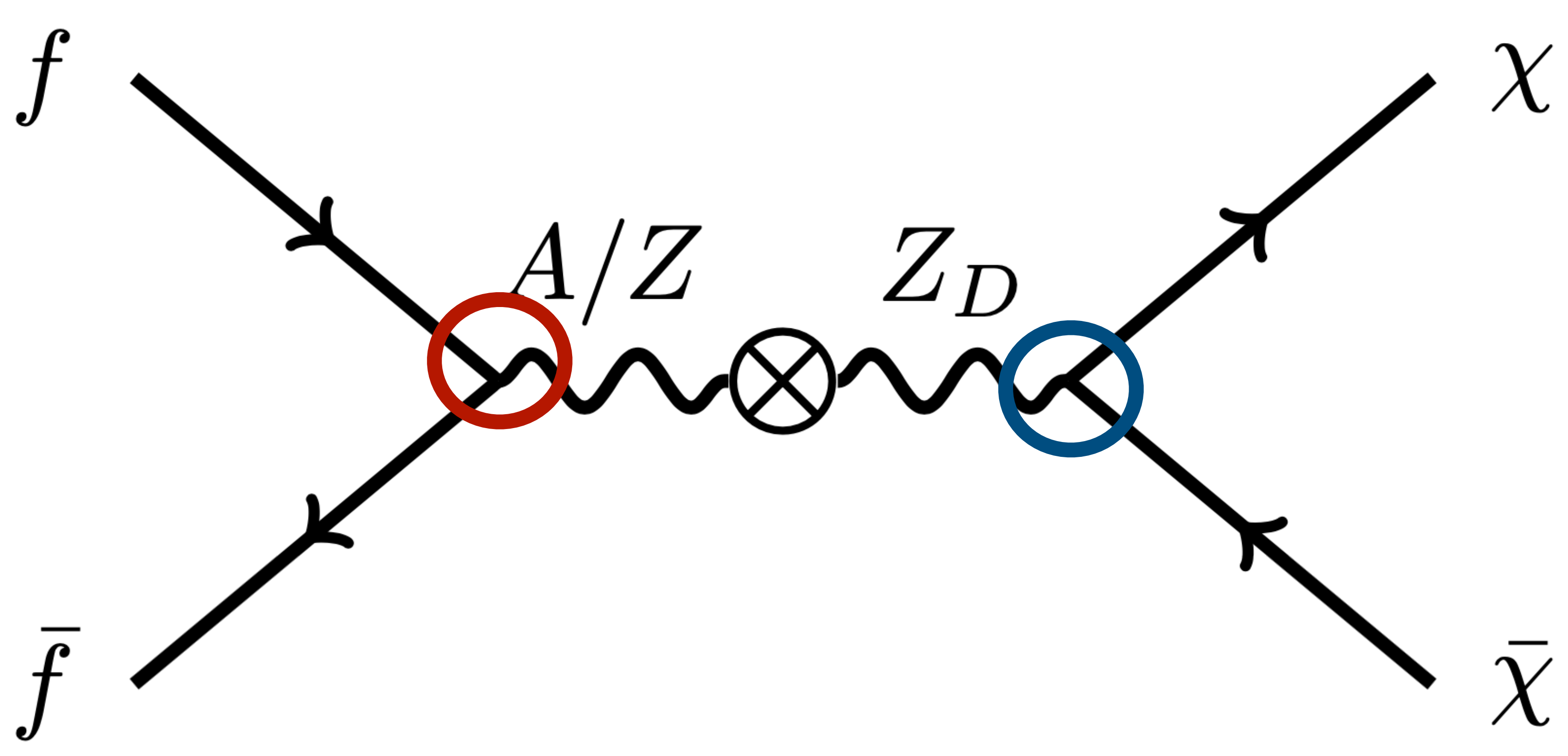


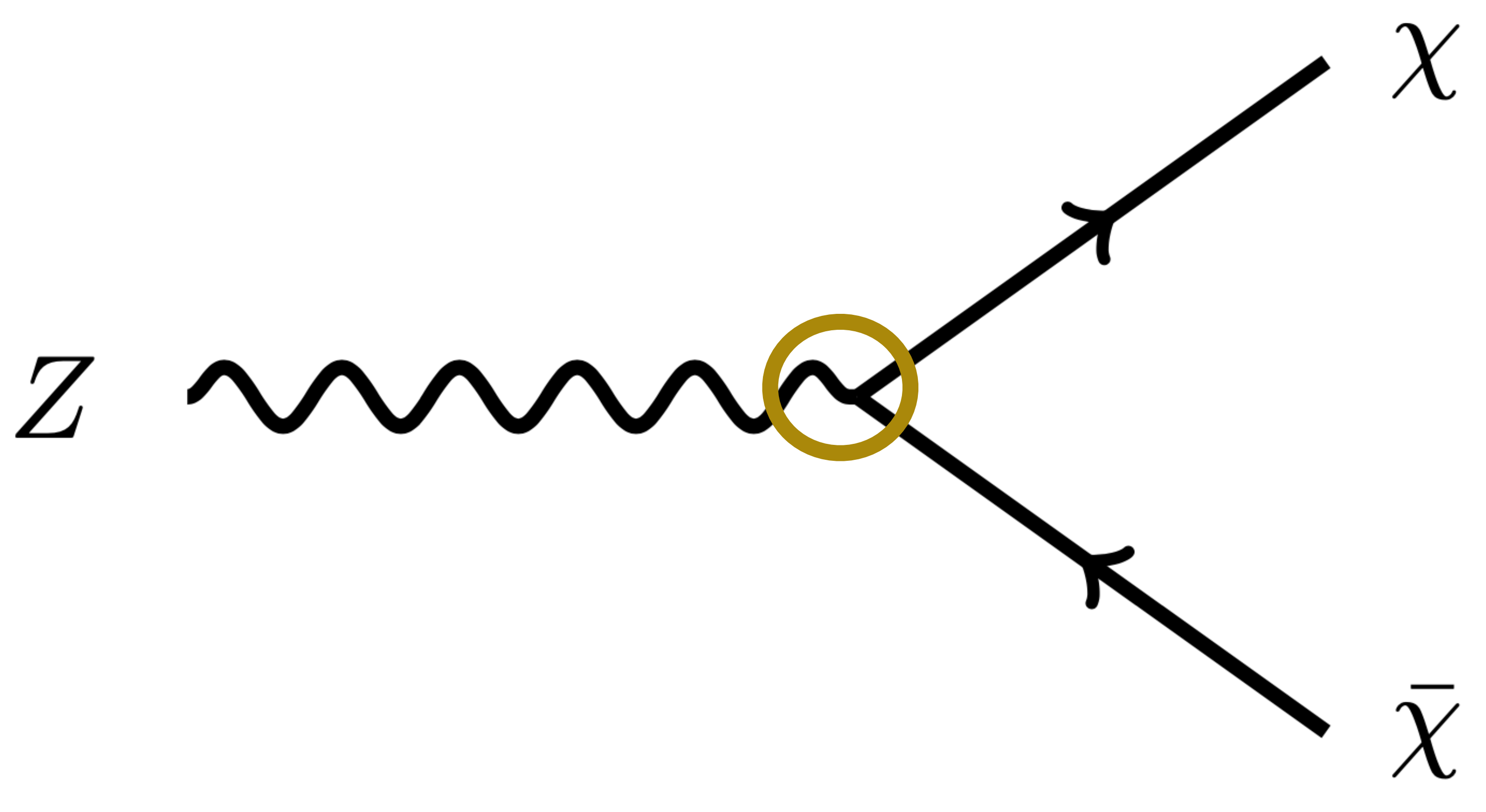


$$\langle \sigma v \rangle \propto \epsilon^2 \alpha_D$$

RELIC ABUNDANCE FROM FREEZE-IN

$$\mathcal{L} \supset -\epsilon e J^{\mu}_{\rm EM} Z_{D\mu} + \epsilon g_\chi \tan\theta_W J^{\mu}_D Z_\mu + g_\chi J^{\mu}_D Z_{D\mu} \,, \qquad \alpha_D = \frac{g_\chi^2}{4\pi}$$





$$\langle \sigma v \rangle \propto \epsilon^2 \alpha_D \qquad \langle \Gamma_{Z\to\chi\chi} \rangle \propto \epsilon^2 \alpha_D$$

$m_\chi > 1\text{GeV}$ ⟶ 10%

RELIC ABUNDANCE FROM FREEZE-IN

$$\mathcal{L} \supset -\epsilon e J^{\mu}_{\text{EM}} Z_{D\mu} + \epsilon g_{\chi} \tan\theta_W J^{\mu}_{D} Z_{\mu} + g_{\chi} J^{\mu}_{D} Z_{D\mu} \,,$$

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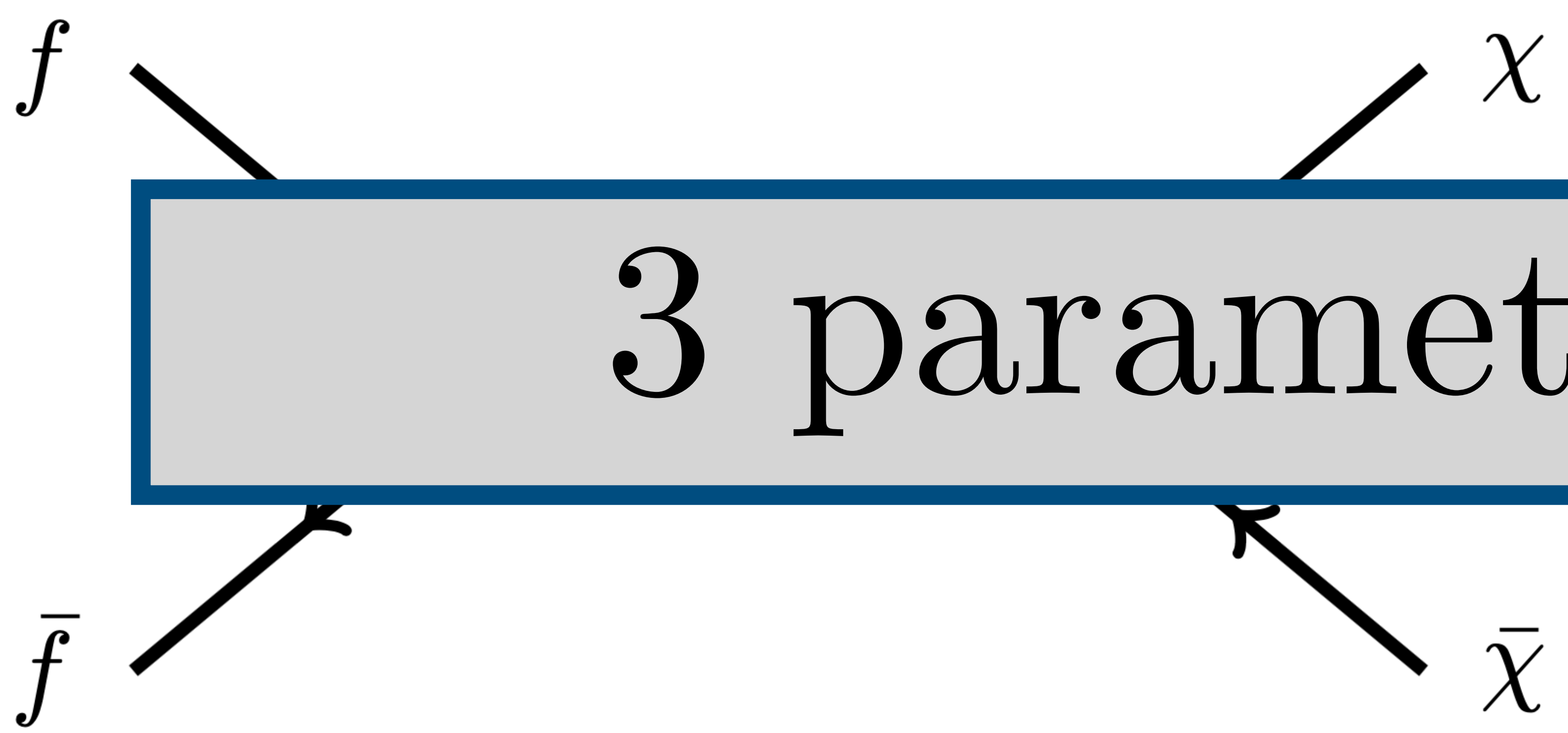
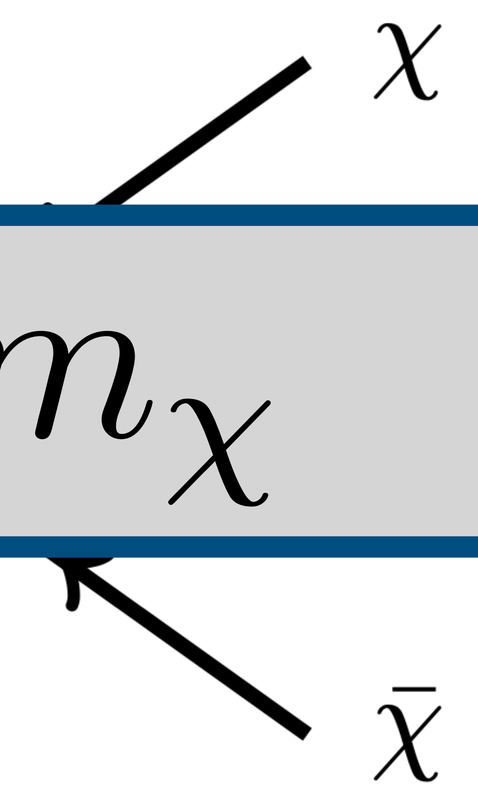




3 parameters: ϵ, α_D and m_χ

$$\langle \sigma v \rangle \propto \epsilon^2 \alpha_D$$

$$\langle \Gamma_{Z \to \chi\chi} \rangle \propto \epsilon^2 \alpha_D$$

$m_\chi > 1\text{GeV}$ ⟶ 10%

RELIC ABUNDANCE FROM FREEZE-IN

$$\mathcal{L} \supset -\epsilon e J^\mu_{\rm EM} Z_{D\mu} + \epsilon g_\chi \tan\theta_W J^\mu_D Z_\mu + g_\chi J^\mu_D Z_{D\mu}\,,$$

$$\alpha_D = \frac{g_\chi^2}{4\pi}$$

f

$\bar{f}$

The relic abundance is given by the combination

$$\epsilon^2 \alpha_D$$

$$\langle \sigma v \rangle \propto \epsilon^2 \alpha_D$$

$$\langle \Gamma_{Z \to \chi\chi} \rangle \propto \epsilon^2 \alpha_D$$

Boltzmann Equation

Number density of DM:

$$\dot{n}_\chi + 3Hn_\chi = -\langle \sigma v \rangle_{fo}^{\tilde{T}} (n_\chi^2 - n_{eq}^2(\tilde{T})) + \langle \sigma v \rangle_{fi}^{T} n_{eq}^2$$

Energy density of the HS:

$$\dot{\rho}_{HS} + 3H(\rho_{HS} + P_{HS}) = \langle \sigma v E \rangle_{fi}^{T} n_{eq}^2(T)$$

Boltzmann Equation

Number density of DM:

$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle^{\tilde{T}}_{fo}(n_\chi^2 - n_{eq}^2(\tilde{T})) + \langle\sigma v\rangle^{T}_{fi} n_{eq}^2$$

→ μ_χ

Energy density of the HS:

$$\dot{\rho}_{HS} + 3H(\rho_{HS} + P_{HS}) = \langle\sigma v E\rangle^{T}_{fi} n_{eq}^2(T)$$

→ $\tilde{T}$

- Instantaneous kinetic equilibration assumed

Boltzmann Equation

$$\chi\chi \leftrightarrow Z_D Z_D$$

Number density of DM:

$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle_{fo}^{\tilde{T}}(n_\chi^2 - n_{eq}^2(\tilde{T})) + \langle\sigma v\rangle_{fi}^{T} n_{eq}^2$$

$$f\bar{f} \to \chi\chi$$

Energy density of the HS:

$$\dot{\rho}_{HS} + 3H(\rho_{HS} + P_{HS}) = \langle\sigma v E\rangle_{fi}^{T} n_{eq}^2(T)$$

- Instantaneous kinetic equilibration assumed

Competing terms

Energy injection:

$Z \to \chi\bar{\chi}$

$f\bar{f} \to \chi\bar{\chi}$

$\epsilon^2 \alpha_D$

vs

Kinetic thermalization:

$\chi\chi \to \chi\chi \qquad \chi\bar{\chi} \to \chi\bar{\chi}$

$\chi Z_D \to \chi Z_D \qquad \chi\bar{\chi} \to Z_D Z_D$

α_D^2

$\epsilon \qquad \alpha_D$

Competing terms

Energy injection:

$$Z \to \chi\bar{\chi}$$

$$f\bar{f} \to \chi\bar{\chi}$$

$$\epsilon^2 \alpha_D \downarrow\downarrow\uparrow$$

$$\epsilon \downarrow \quad \alpha_D \uparrow$$

Maira Dutra's talk for Z'

VS

Kinetic thermalization:

$$\chi\chi \to \chi\chi \qquad \chi\bar{\chi} \to \chi\bar{\chi}$$

$$\chi Z_D \to \chi Z_D \qquad \chi\bar{\chi} \to Z_D Z_D$$

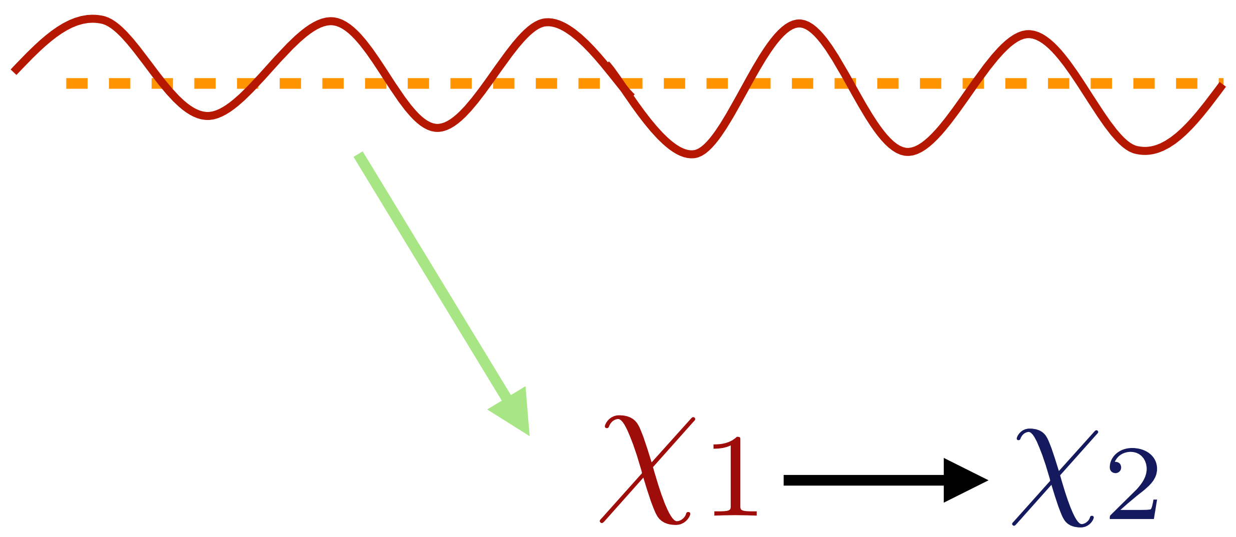
$$\alpha_D^2 \uparrow\uparrow$$

Self-interactions could be important

Let us check two things:

- **Instantaneous kinetic equilibration assumption**
- **Initial conditions**

Instantaneous kinetic equilibration of DM



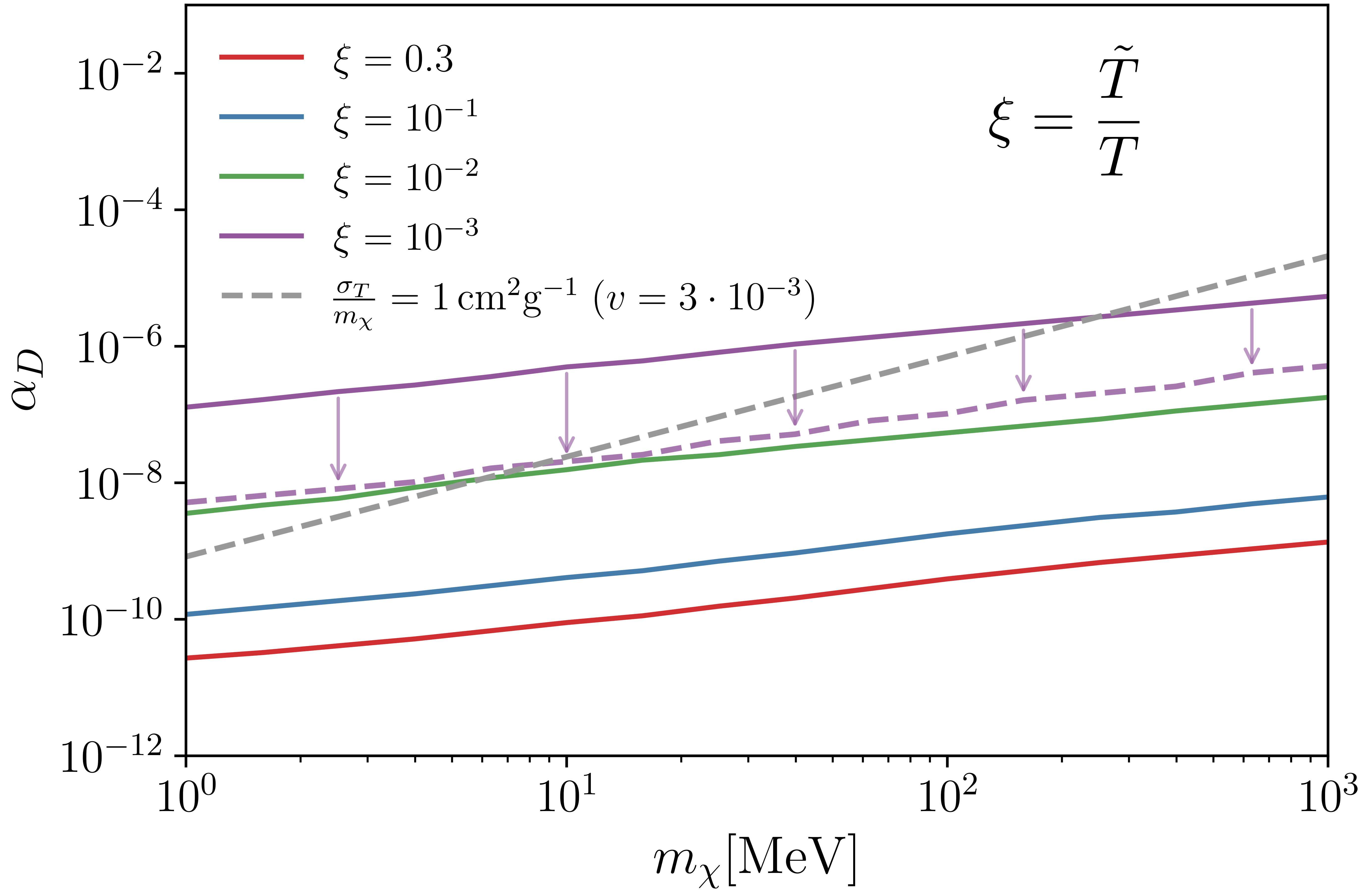
$$T_1 \neq T_2$$

- Two different temperatures in the initial state
- Relativistic

Thermally averaged momentum loss:

$$\Gamma_{p\,\mathrm{loss}} \approx \langle \frac{dp}{dt} \rangle \frac{1}{\langle p \rangle} = \frac{n_{2\mathrm{eq}}(\tilde{T}) \langle \sigma_T v p \rangle}{\langle p \rangle} \gtrsim H$$

Instantaneous kinetic equilibration of DM
Vs
DM self-interaction constraints



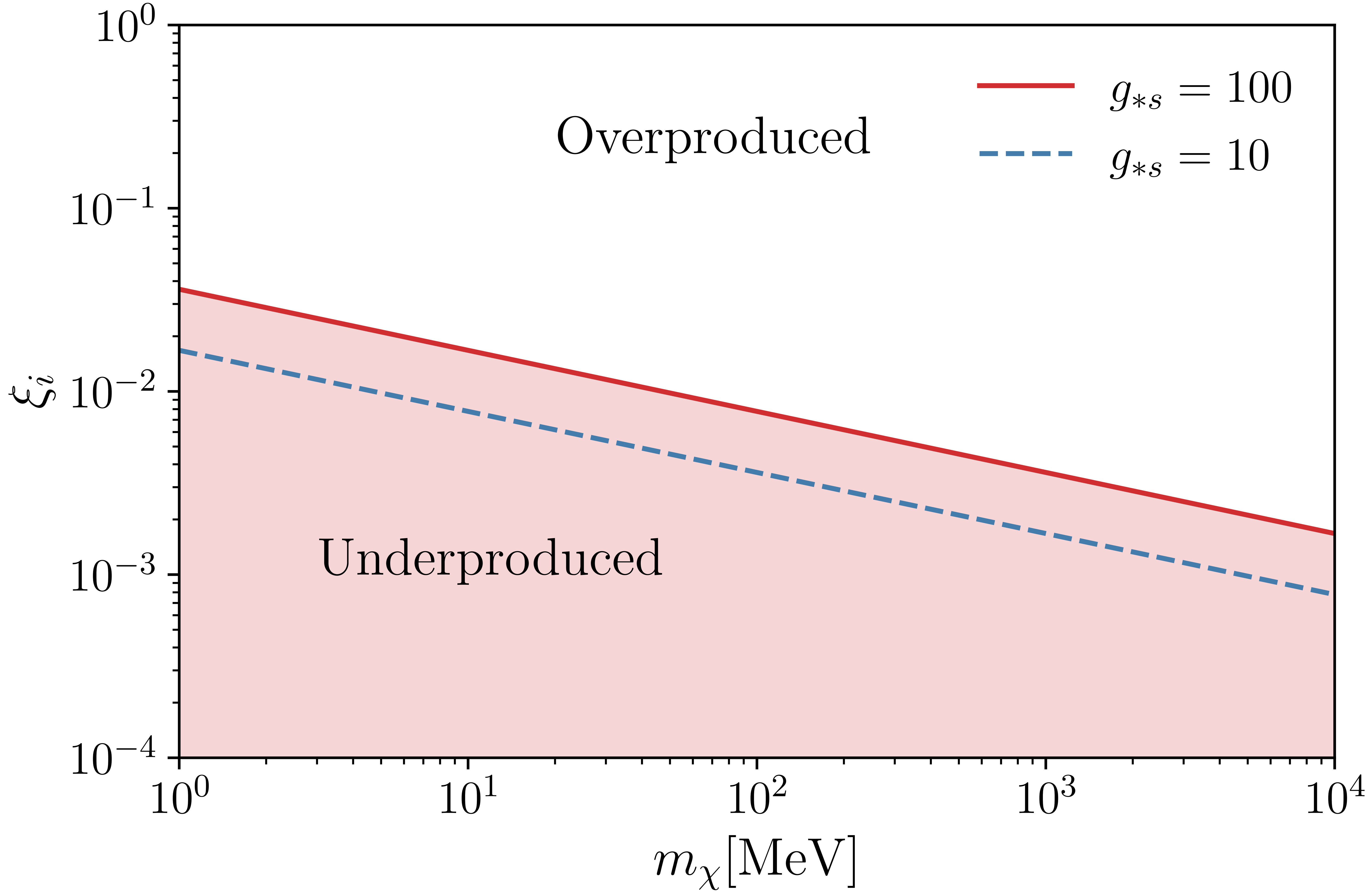
$$\chi_1\chi_2 \to \chi_1\chi_2$$

$$\chi_1\bar{\chi}_2 \to \chi_1\bar{\chi}_2$$

$$\chi_1 Z_D \to \chi_1 Z_D$$

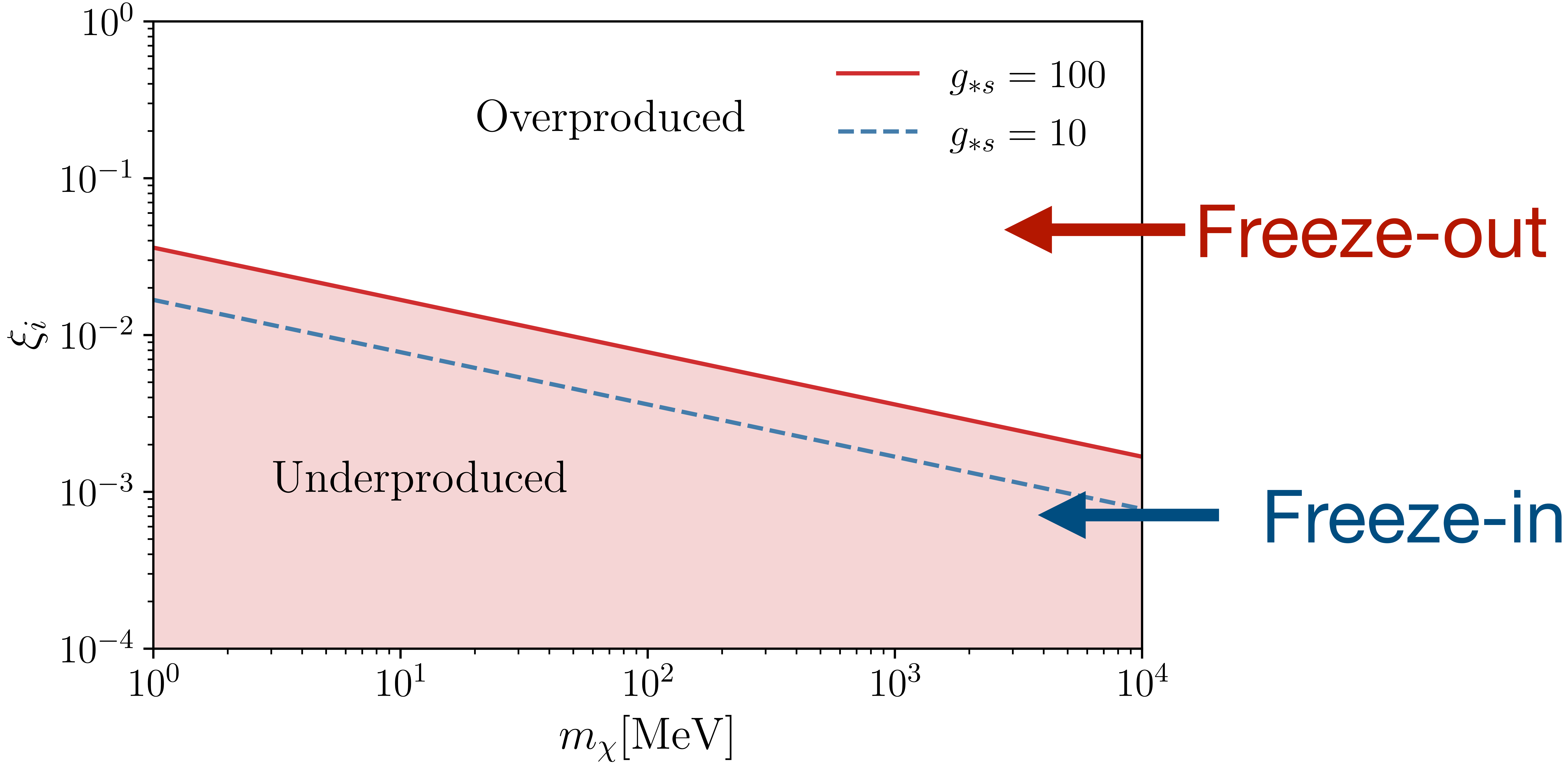
NF, *Kahn and Shelton in prep.*

Initial condition DM



***NF,** Kahn and Shelton in prep.*

Freeze-in or freeze-out?

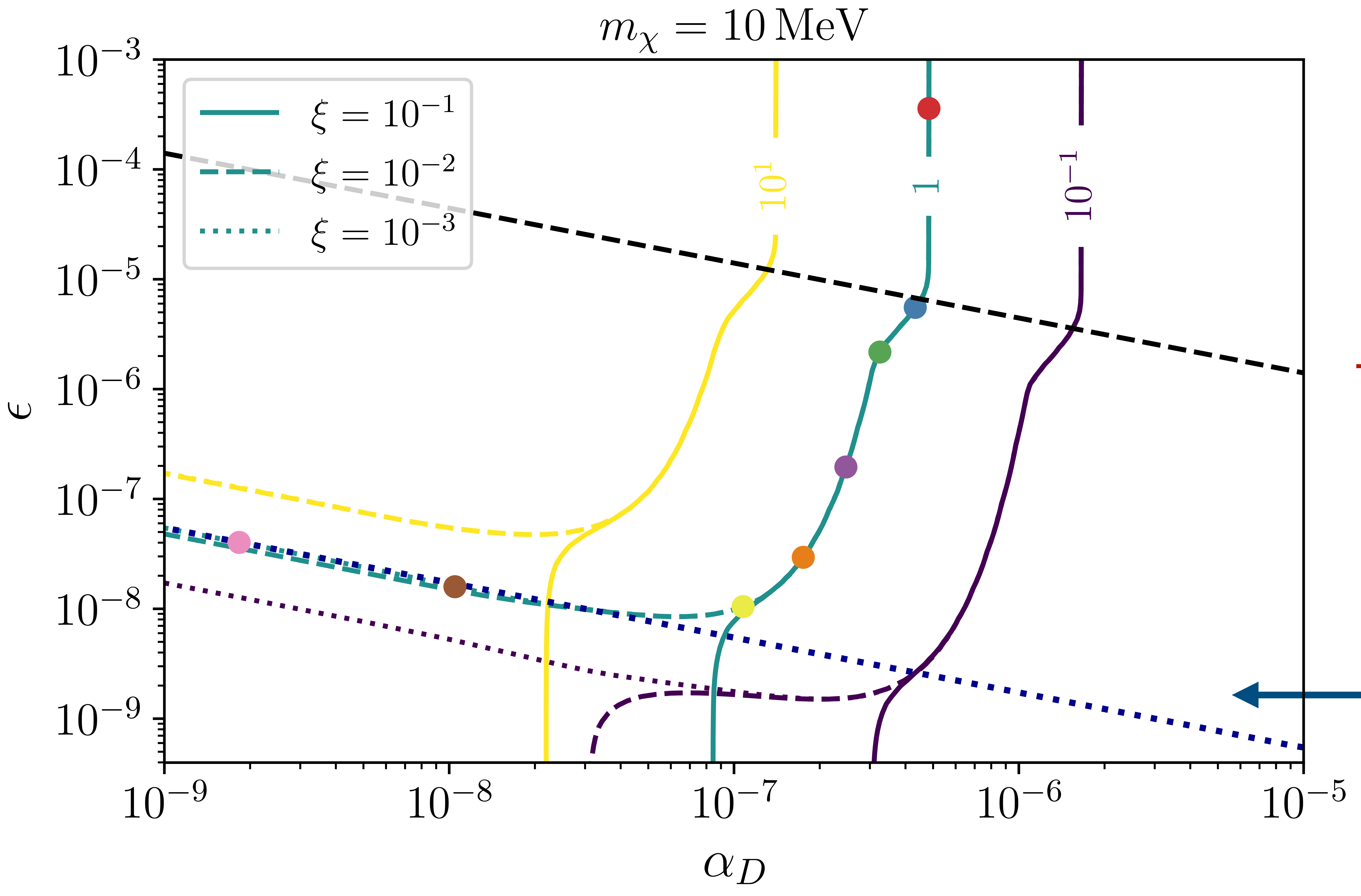


***NF,** Kahn and Shelton in prep.*

Parameter space and DM relic abundance

***NF,** Kahn and Shelton in prep.*

DM relic abundance

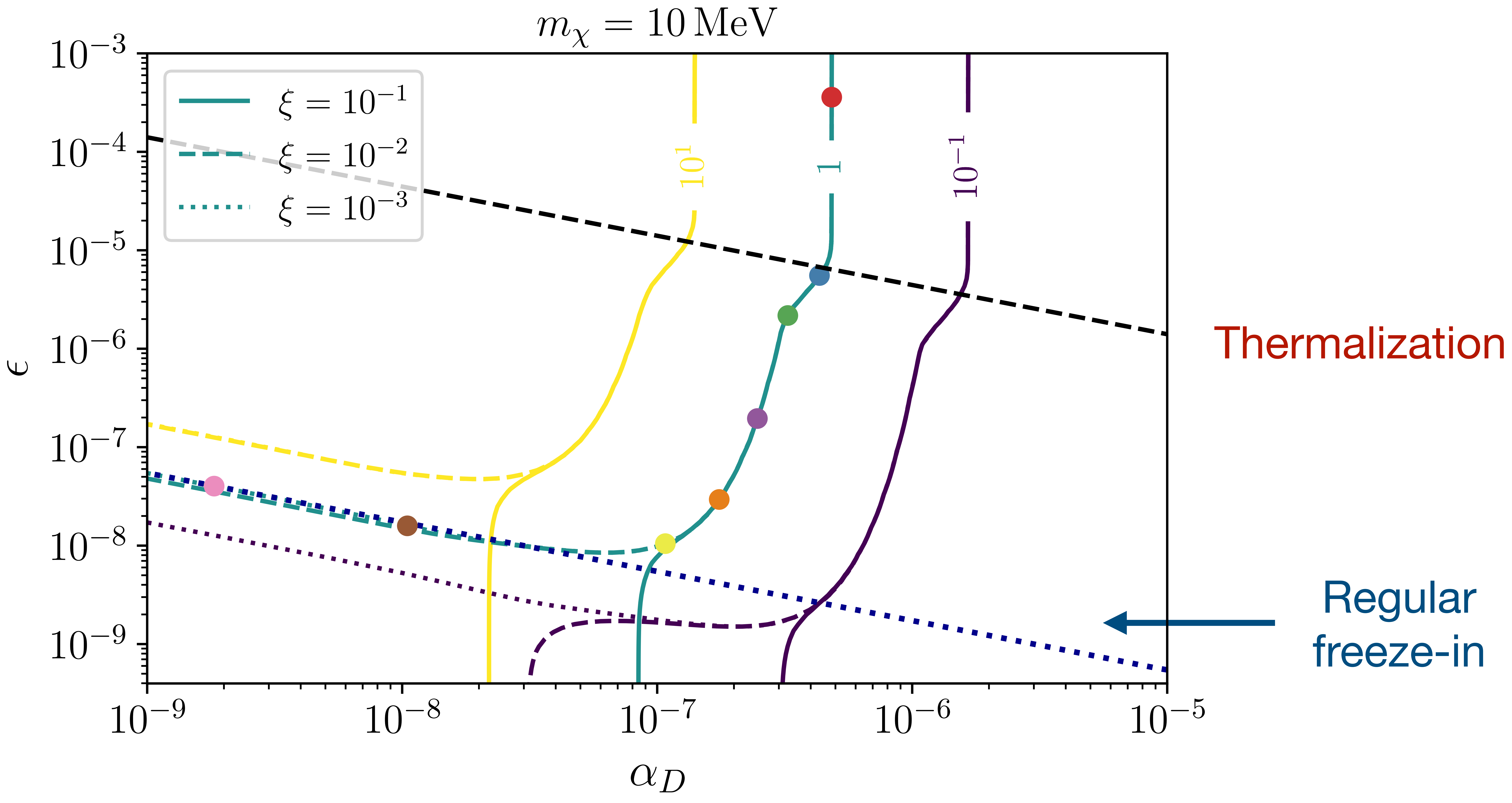


Thermalization

Regular freeze-in

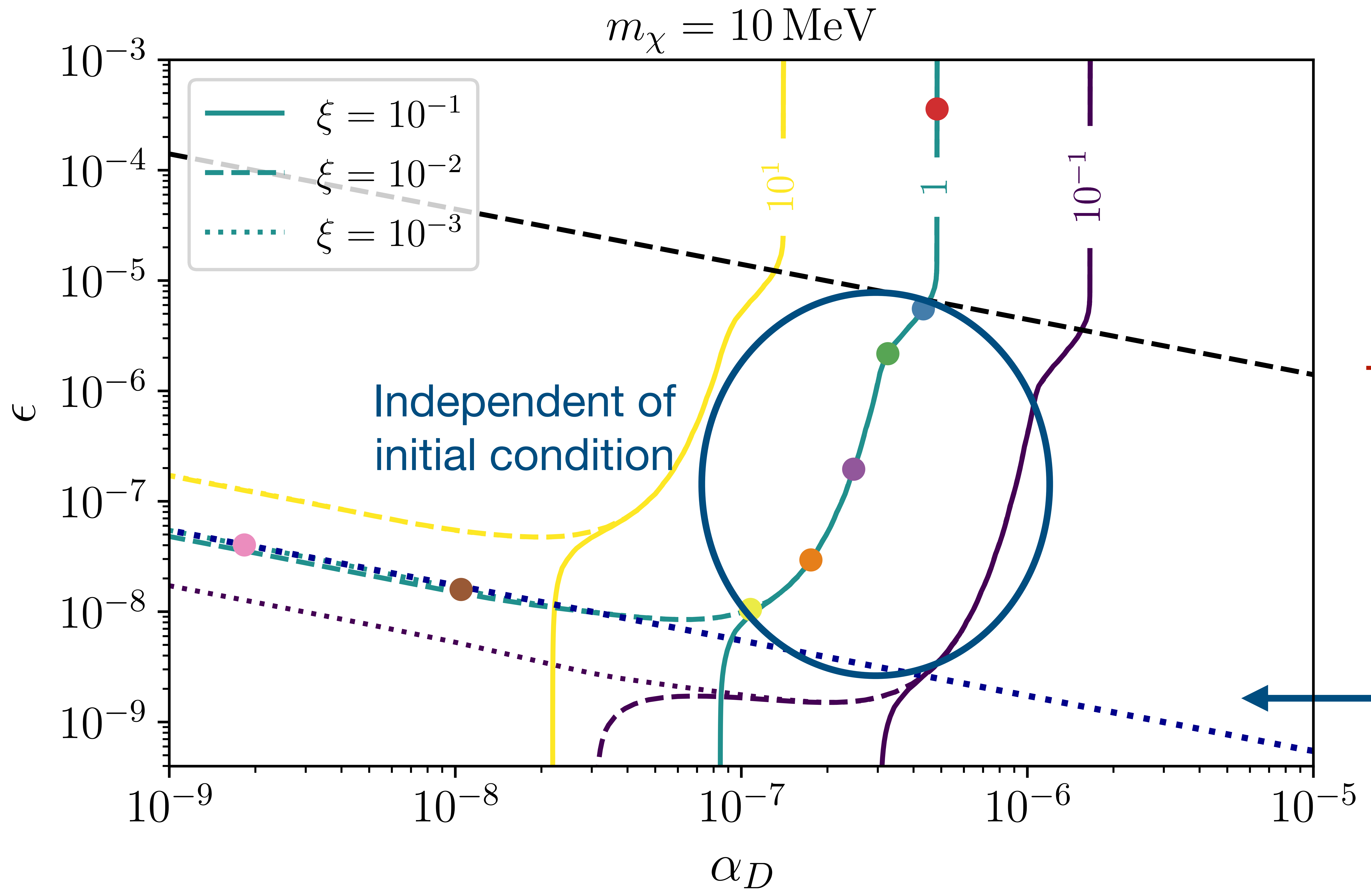
NF, *Kahn and Shelton in prep.*

DM relic abundance



NF, *Kahn and Shelton in prep.*

DM relic abundance



Thermalization

Regular freeze-in

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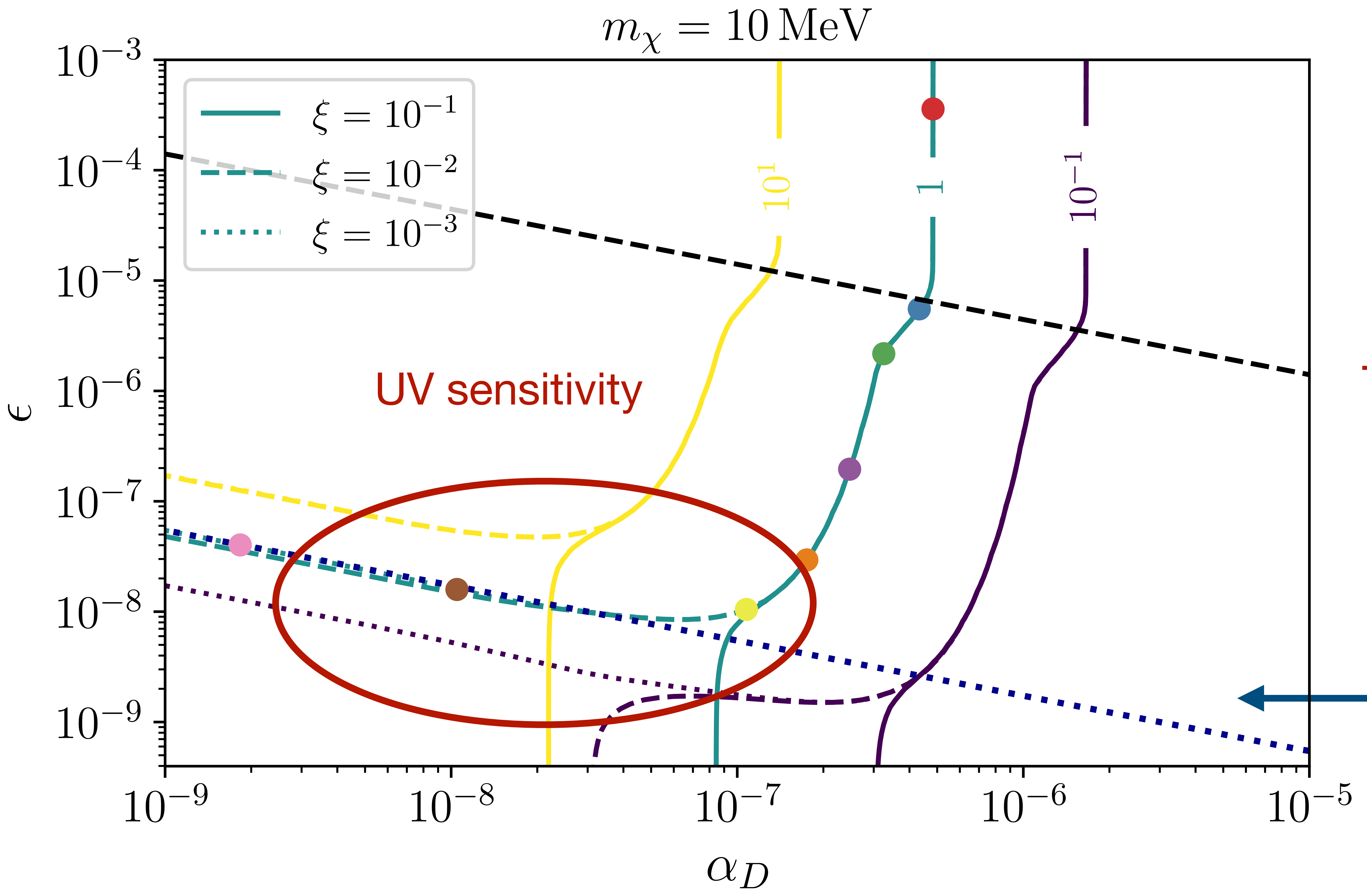
DM relic abundance



Thermalization

Regular freeze-in

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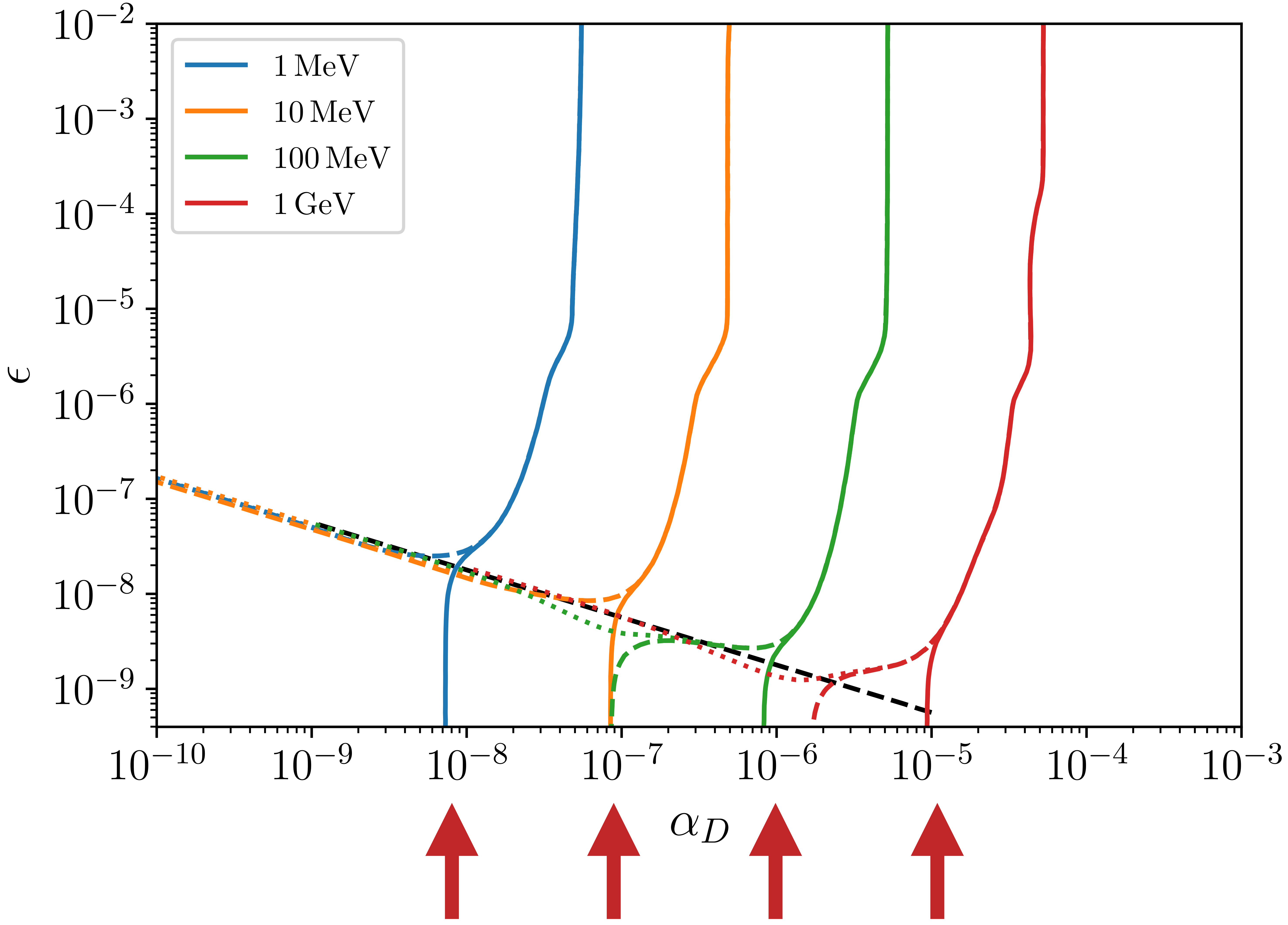
DM relic abundance and parameter space

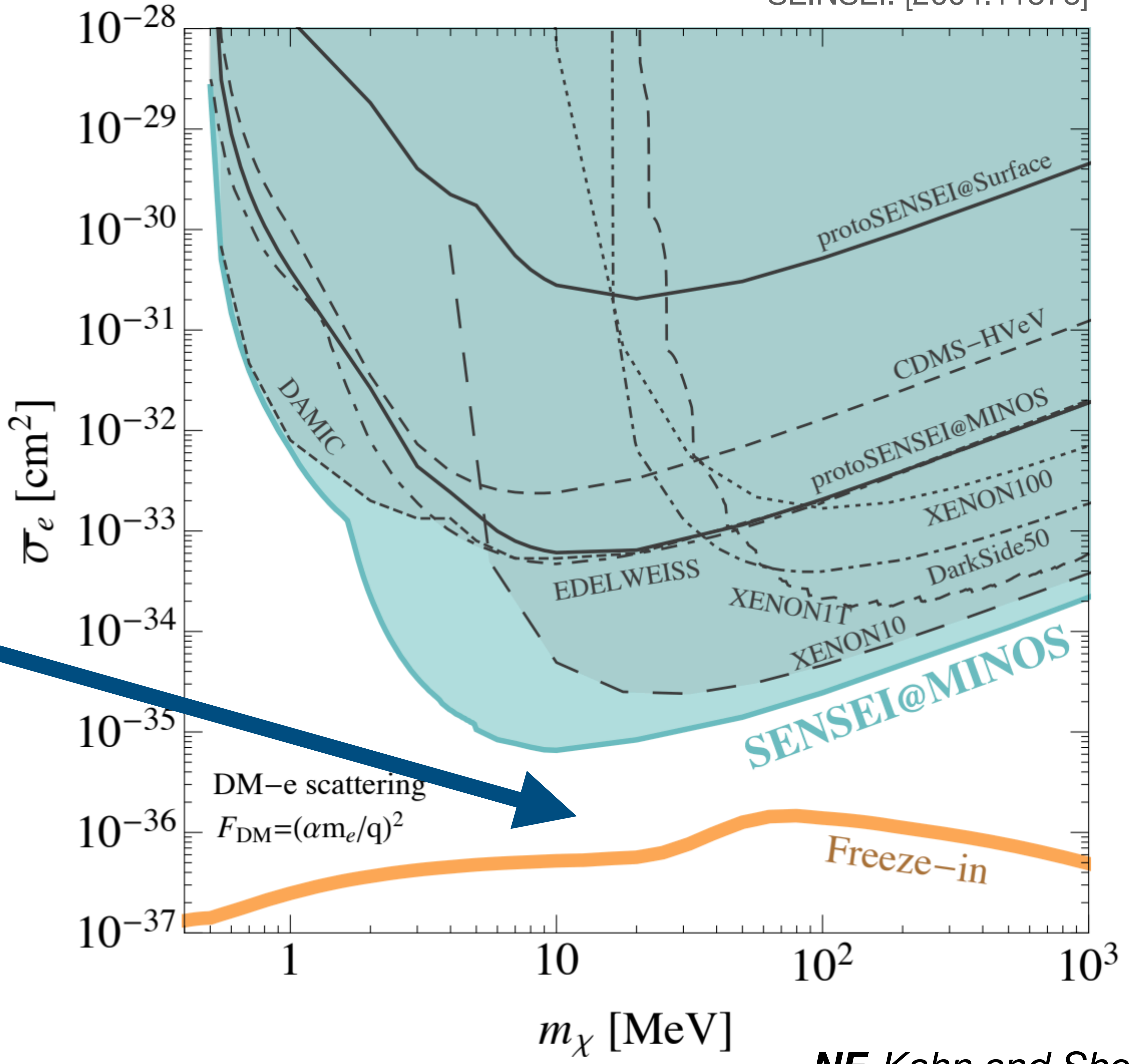


Self-interactions are important

NF, *Kahn and Shelton in prep.*

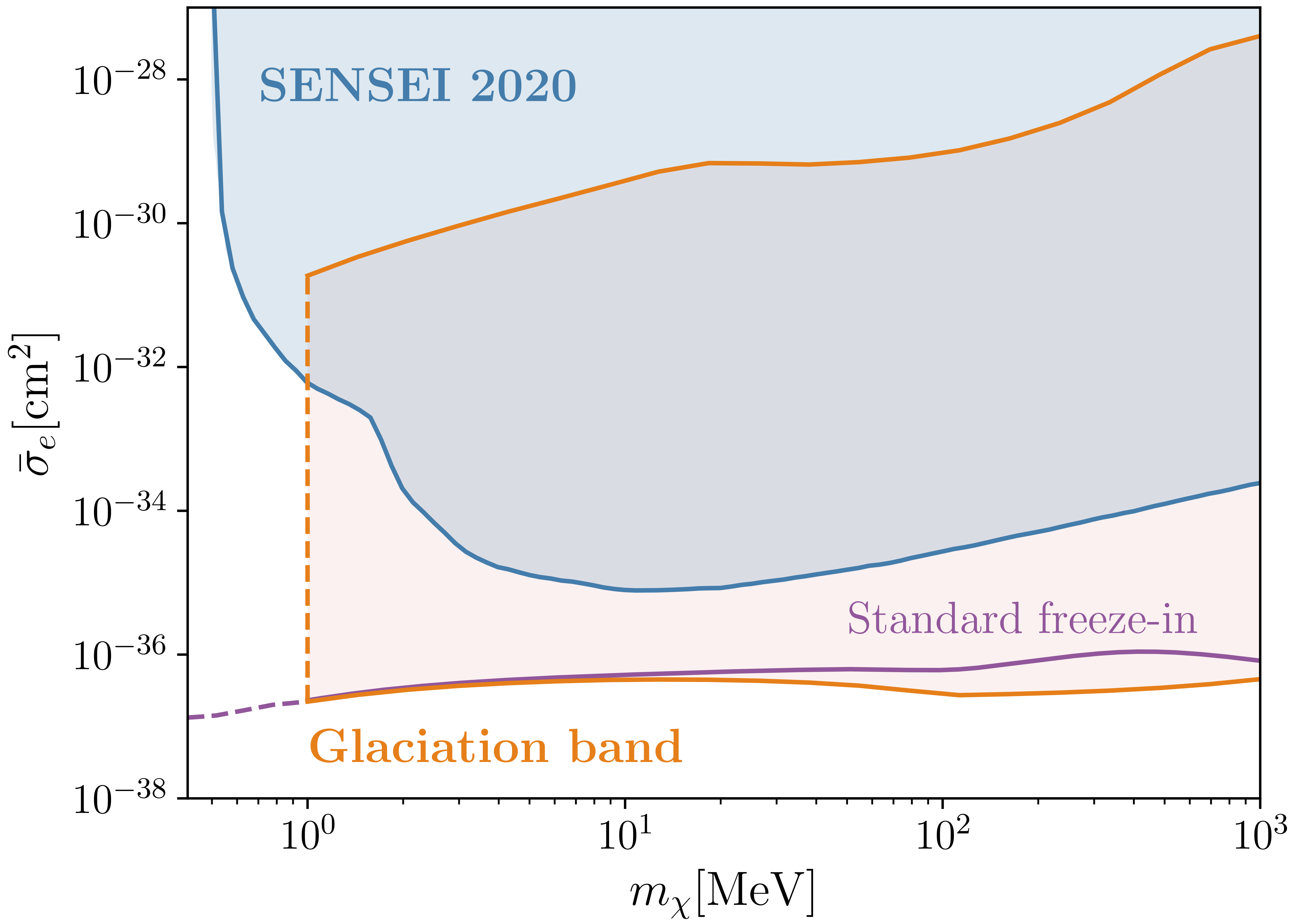
SENSEI 2020

- How the the freeze-in line is affected?



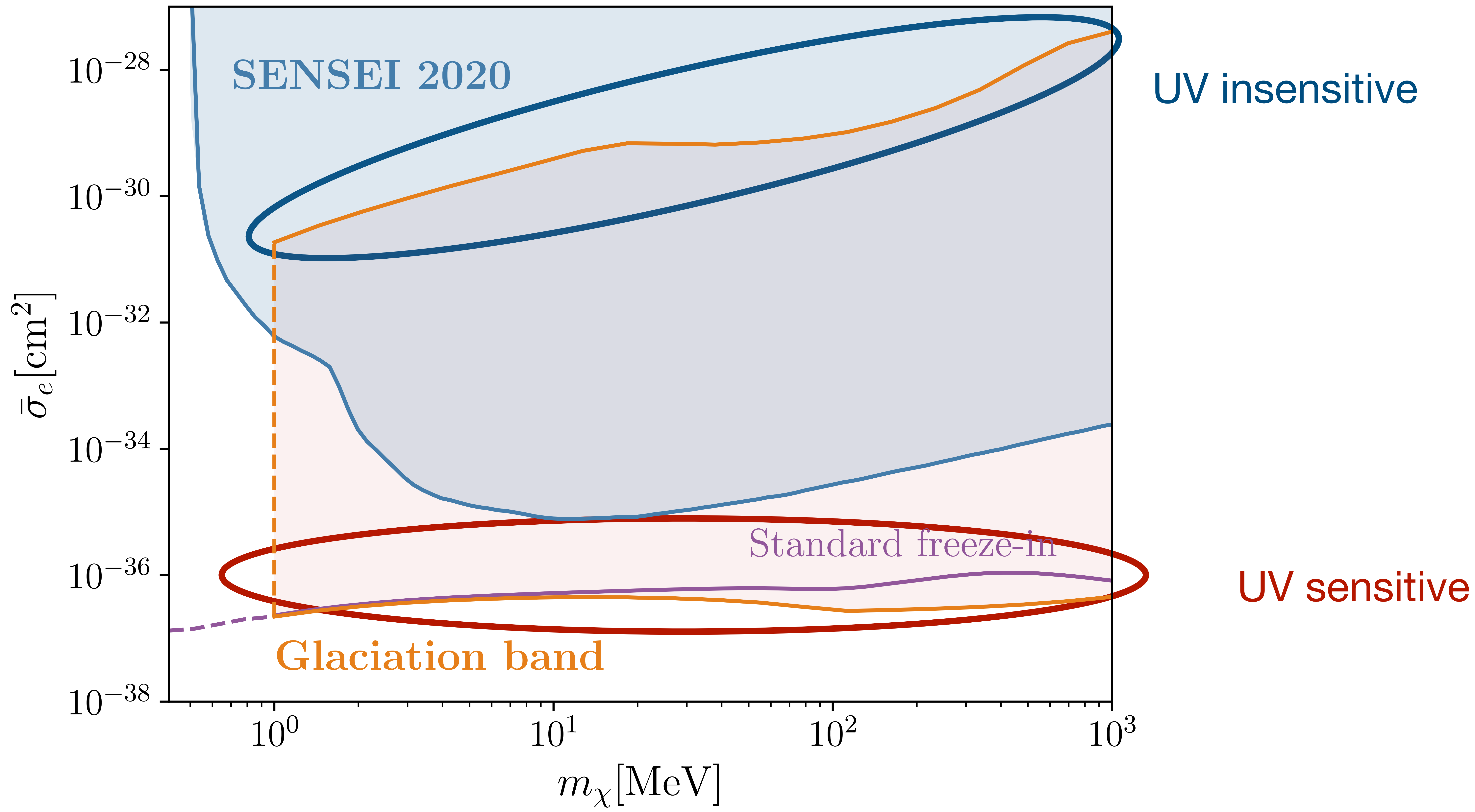
NF, *Kahn and Shelton in prep.*

Current Experiments



***NF,** Kahn and Shelton in prep.*

Current Experiments are testing this parameter space



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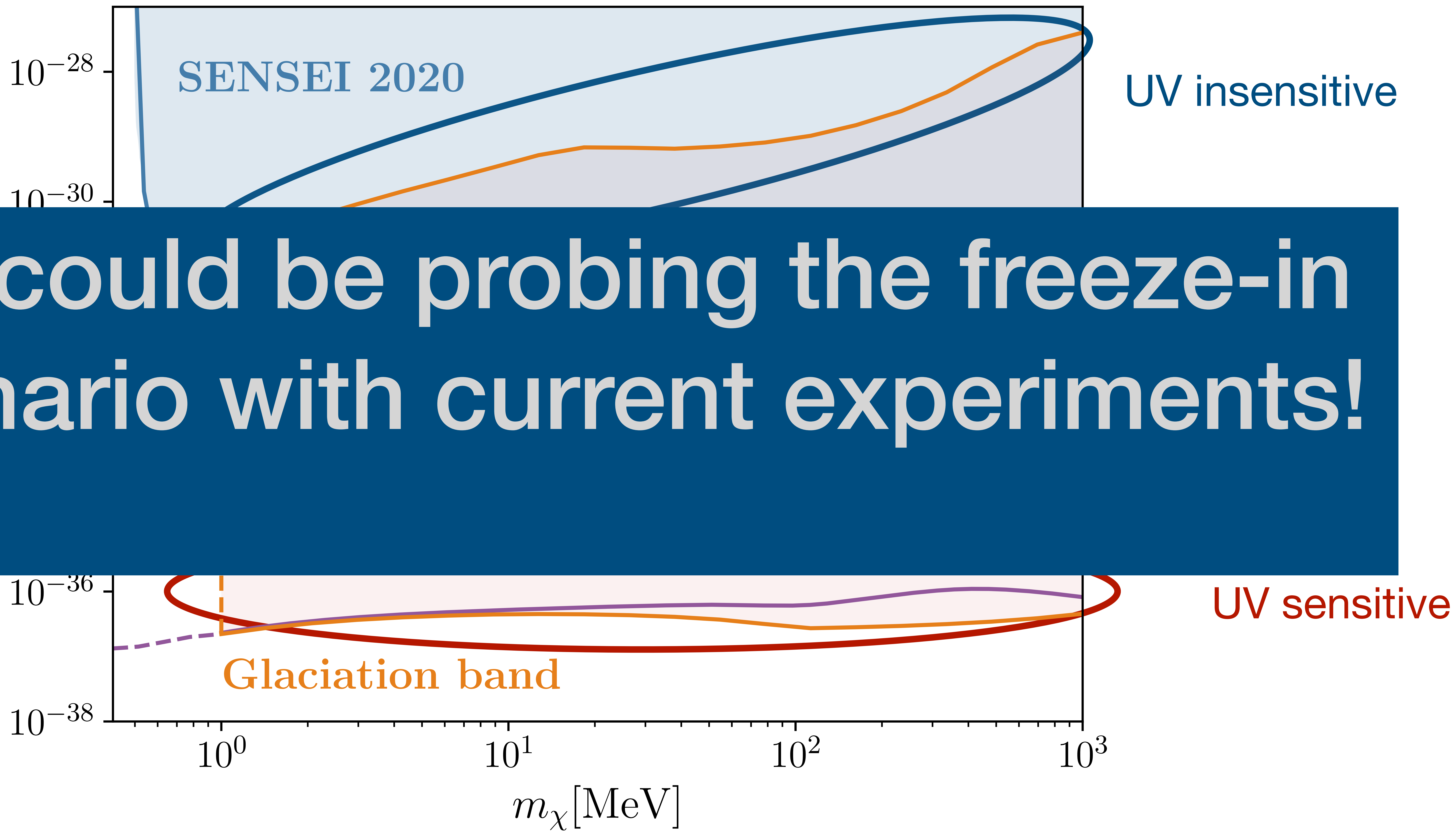
Current Experiments are testing this parameter space



We could be probing the freeze-in scenario with current experiments!

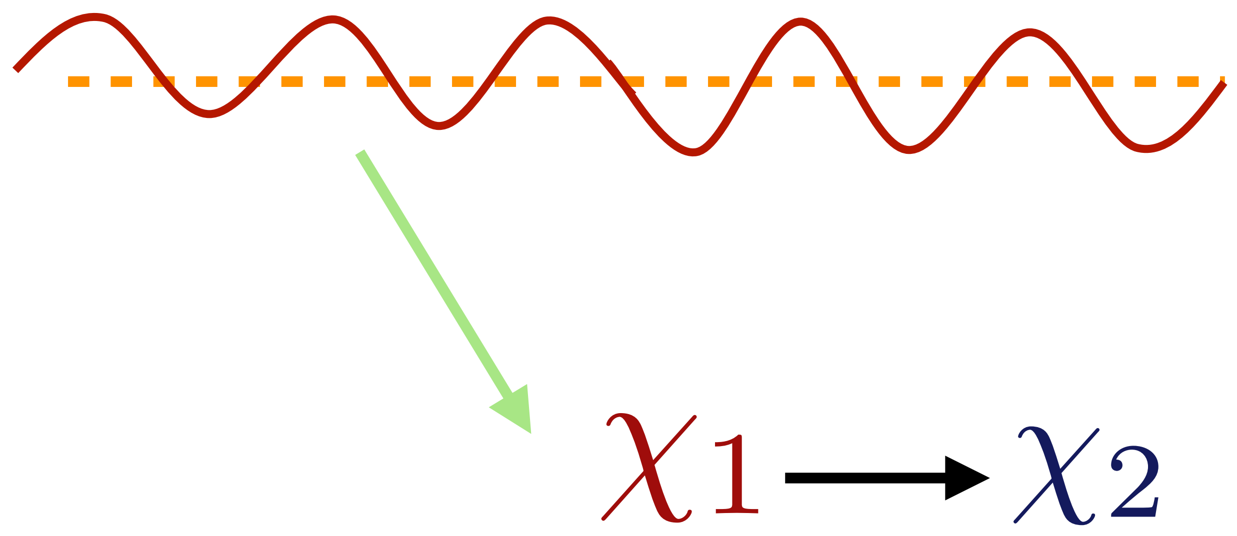
NF,* *Kahn and Shelton in prep.

Conclusion

The standard freeze-in paradigm, this same combination of couplings appears in the annihilation cross section, leading to a 1-to-1 relation between thermal history parameter space and direct detection parameter space. As soon as one allows for an initial thermalized population in the dark sector or sizable self-interactions, this “freeze-in line” expands to a “glaciation band” because there are multiple points in the $\epsilon - \alpha_D$ plane which achieve the correct relic abundance.

Gracias

Instantaneous kinetic equilibration of DM



$$T_1 \neq T_2$$

$$x_i = \frac{m_i}{T_i}$$

Momentum transferred:

$$\mathcal{C}^{p}_{1\,2\to3\,4}(T,\tilde{T}) = n_1^{\rm eq}(T)n_2^{\rm eq}(\tilde{T})\langle\sigma v p\rangle$$

$$= -\frac{g_1 g_2 T^4 \tilde{T}^3}{32\pi^4}\int_{\tilde{s}_{\rm min}}^{\infty} d\tilde{s}\,\frac{\lambda^{\frac{1}{2}}(\tilde{s}^2,x_1,x_2)}{\tilde{s}}\sigma(s)\left(\lambda(\tilde{s}^2,x_1,x_2)K_2(\tilde{s})+4\tilde{s}x_1^2K_1(\tilde{s})\right)$$

$$s = \tilde{s}^2 T\tilde{T} + (T-\tilde{T})(Tx_1^2 - \tilde{T}x_2^2)\,, \qquad \tilde{s}_{\rm min} = x_1 + x_2$$

- Two different temperatures in the initial state
- Relativistic
- One Integration variable left