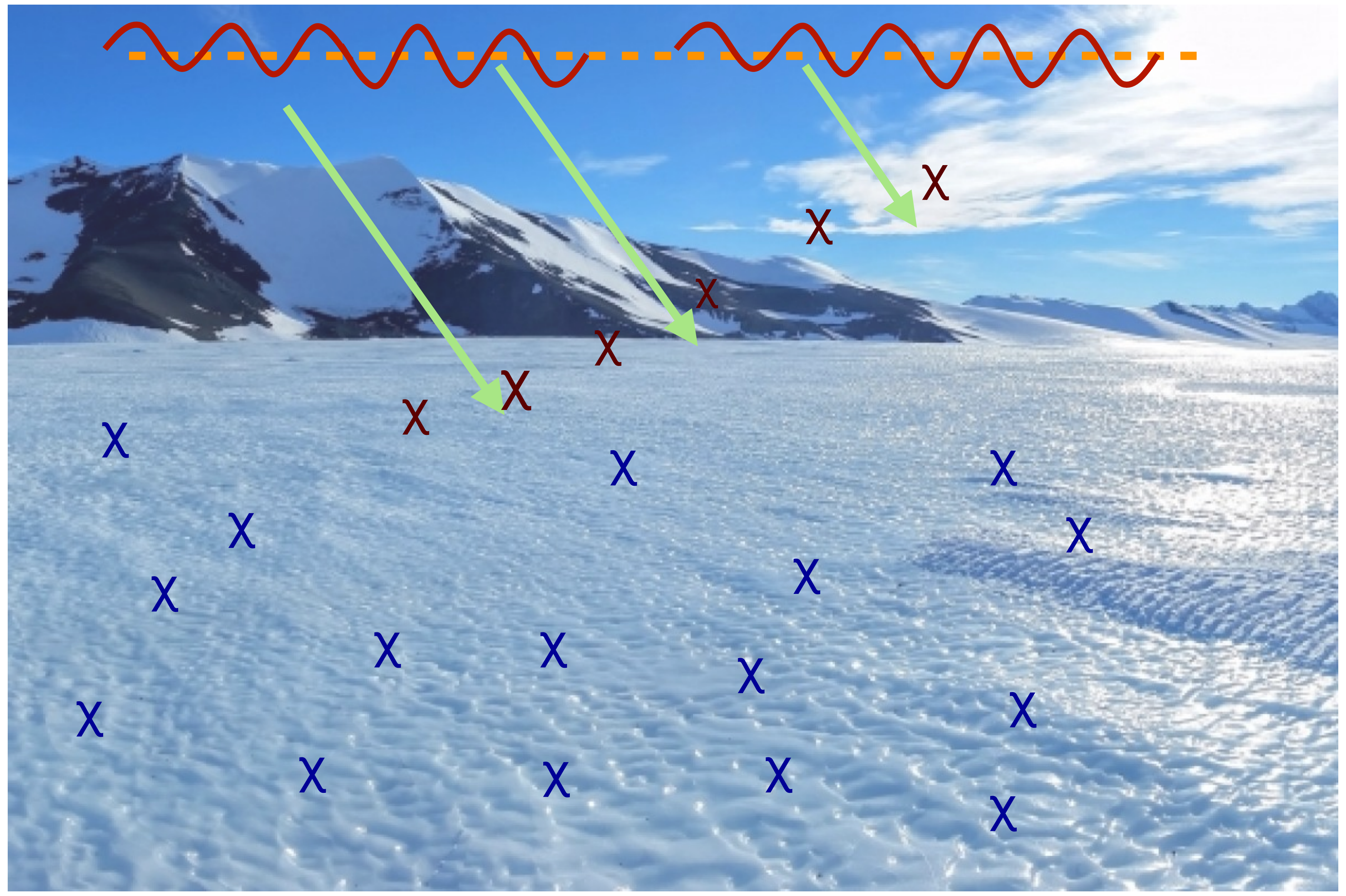
Freeze-in versus Glaciation: Freezing into a thermalized hidden sector

Nicolas Fernandez



University of Michigan

"Brown bag" seminar

March 2021

ILLINOIS

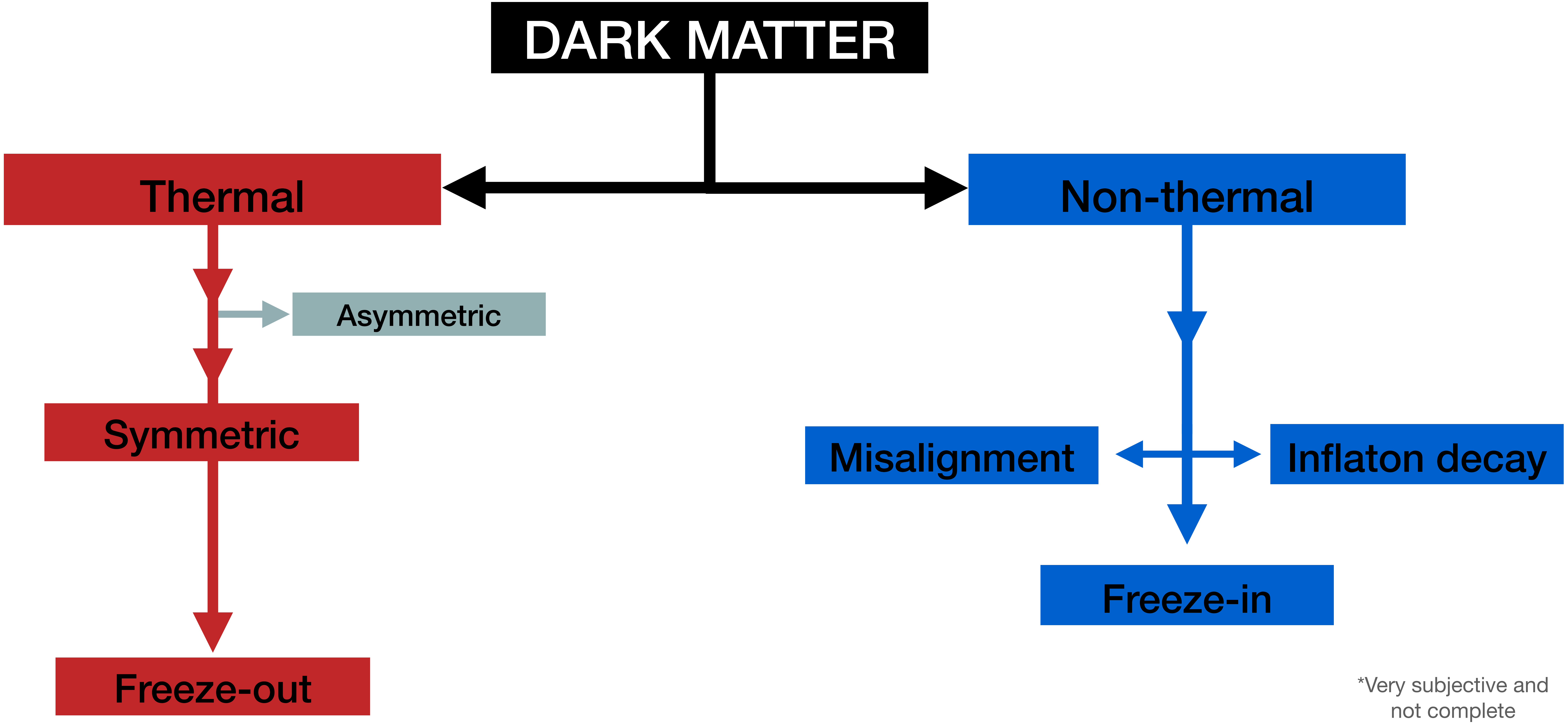
*Based on **NF,** Kahn and Shelton in prep.*

Dark Matter also have feelings

Take home massage

As soon as one allows for an initial thermalized population in the dark sector, the freeze-in standard story line expands to a “glaciation band” which is currently being proved by direct-detection experiments

Dark Matter Production Flow*



*Very subjective and not complete

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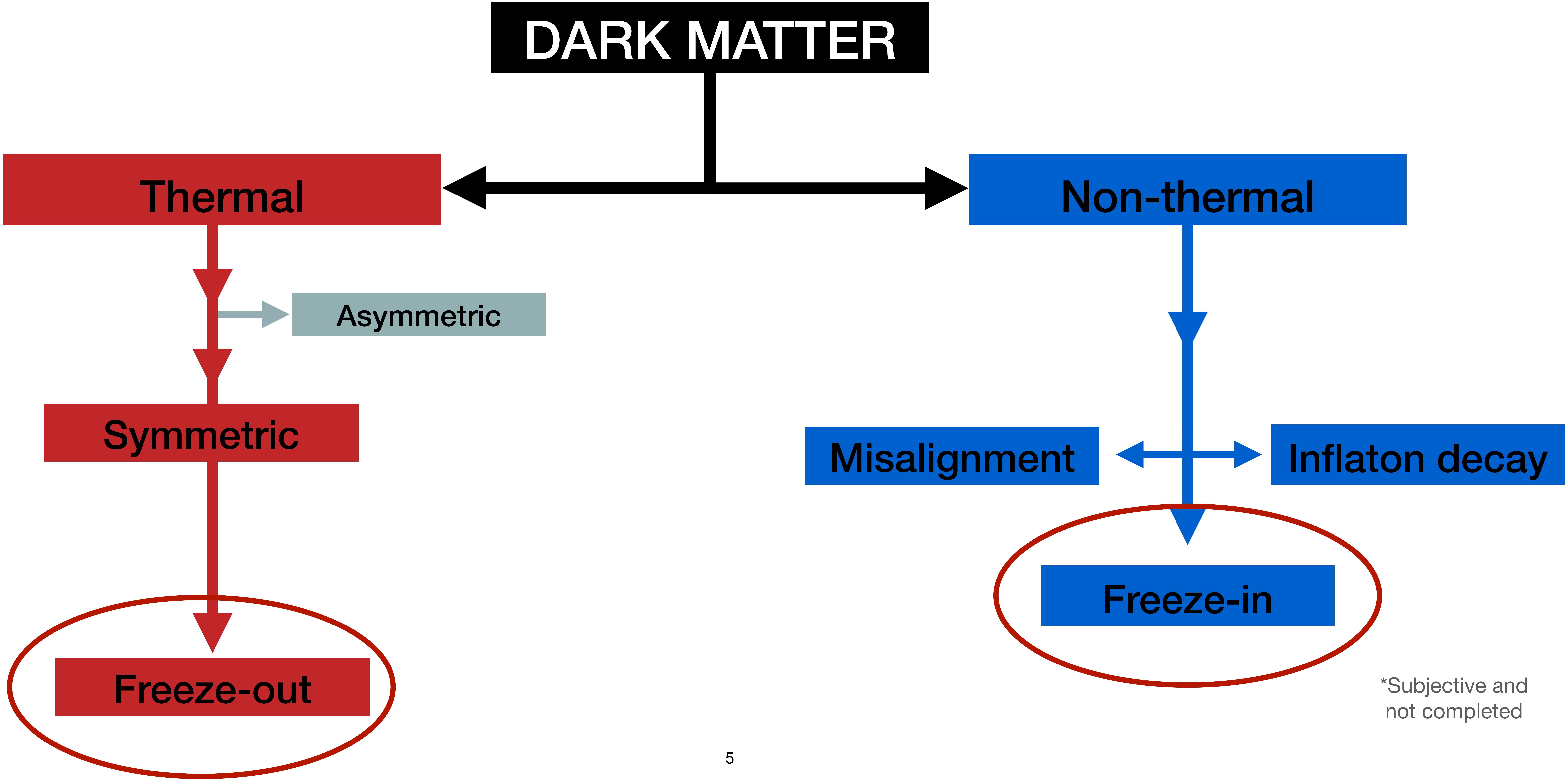

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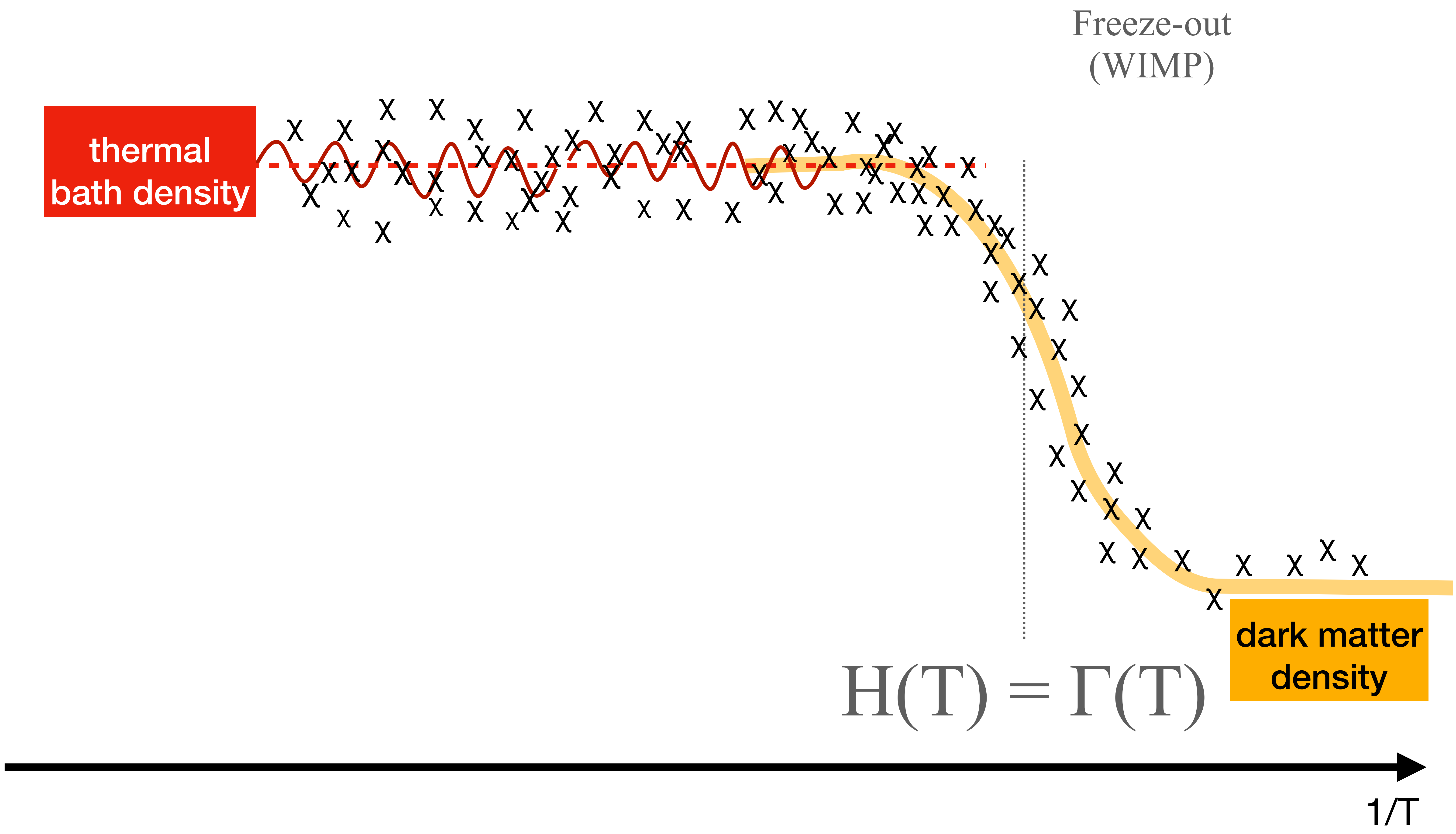
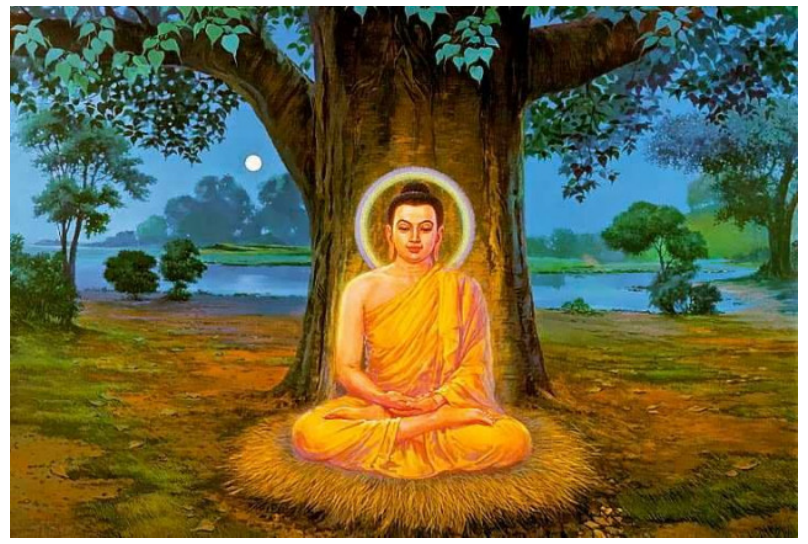
Freeze-out

Or the art of getting rid of stuff

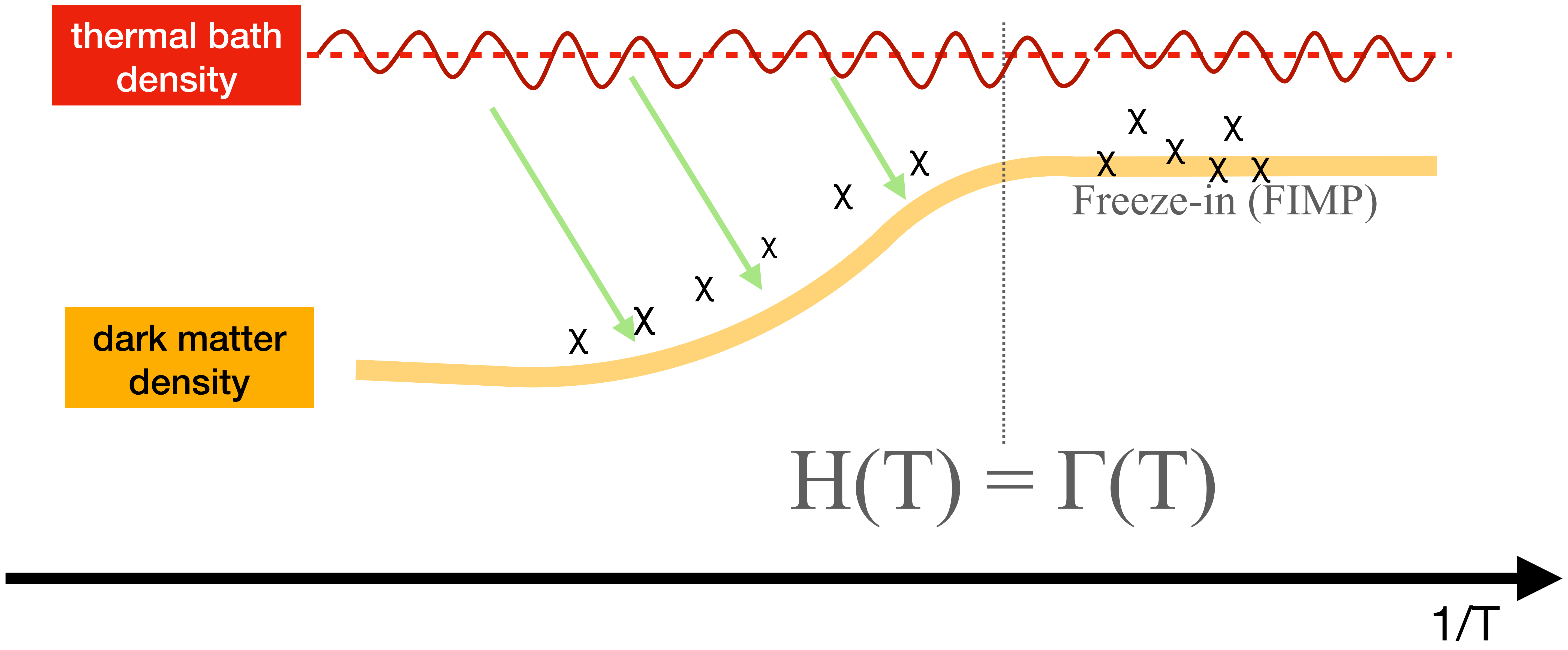


- Relic abundance is independent of initial conditions
- Fine with BBN (masses > few MeV)
- Experimentally testable. Past ~15 years

Freeze-in



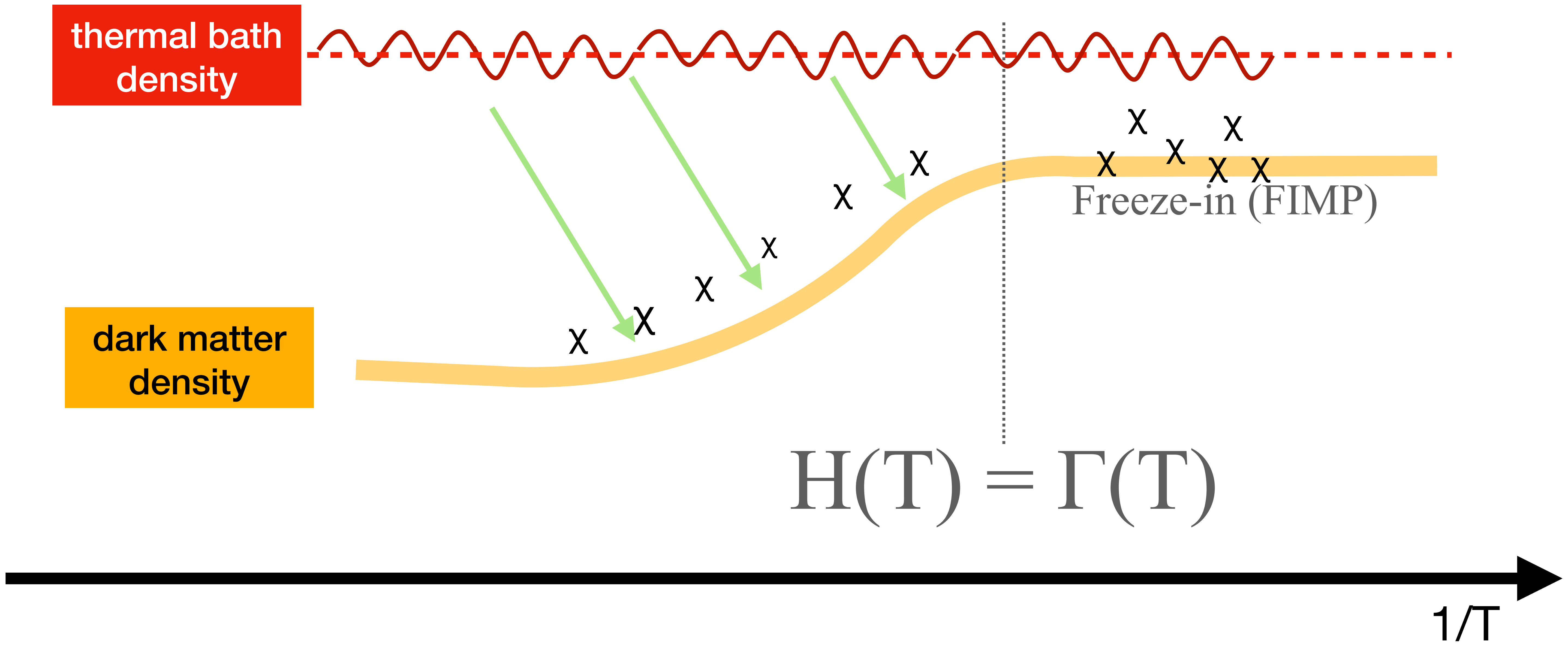
Or the art of getting enough with less

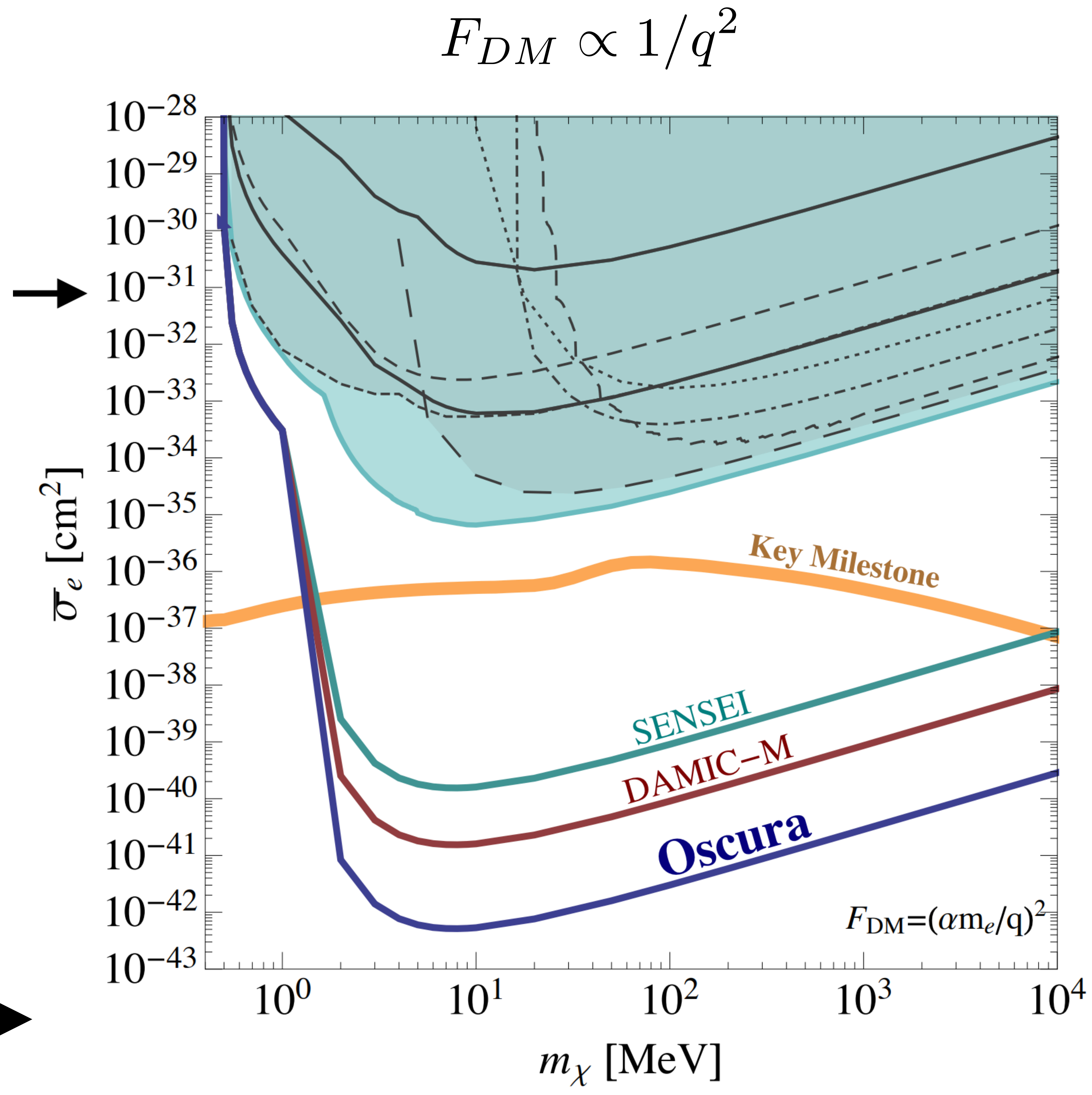


- Relic abundance is independent of initial conditions*
- Fine with BBN and Neff (masses > keV)
- Experimentally testable soon! Very exciting!

Freeze-in

Or the art of getting less and just enough

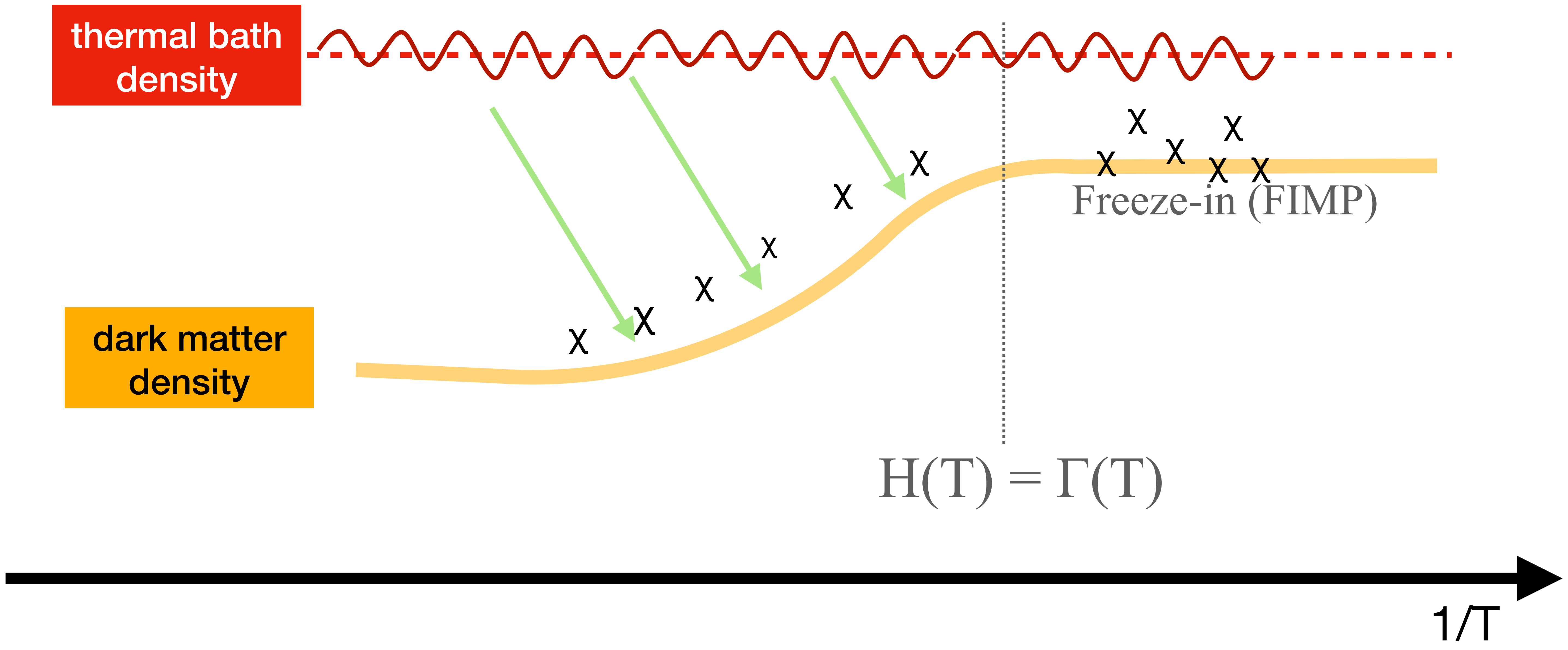




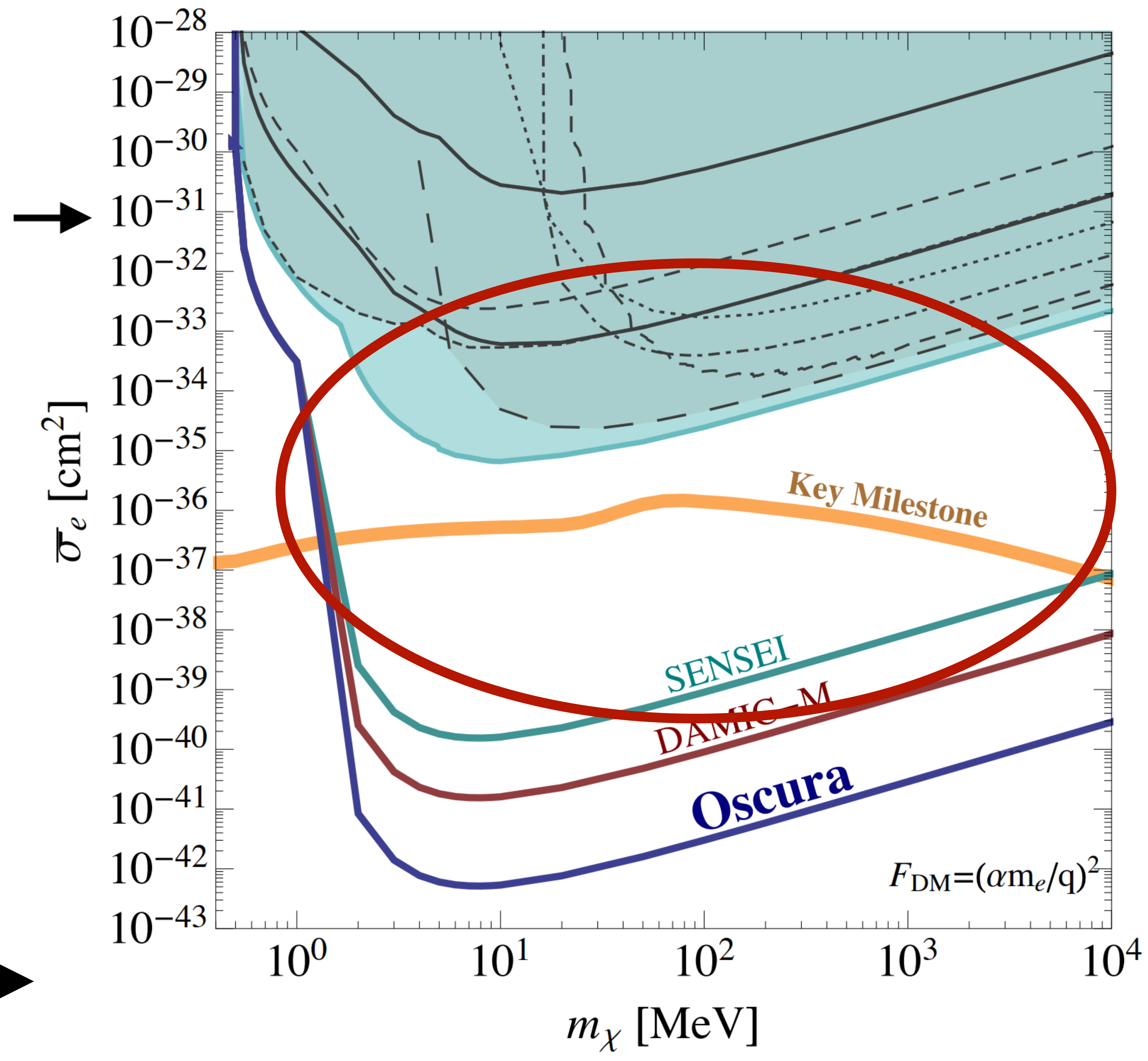
[Tien-Tien Yu: Snowmass CF1 2020]

Freeze-in

Or the art of getting less and just enough



$F_{DM} \propto 1/q^2$



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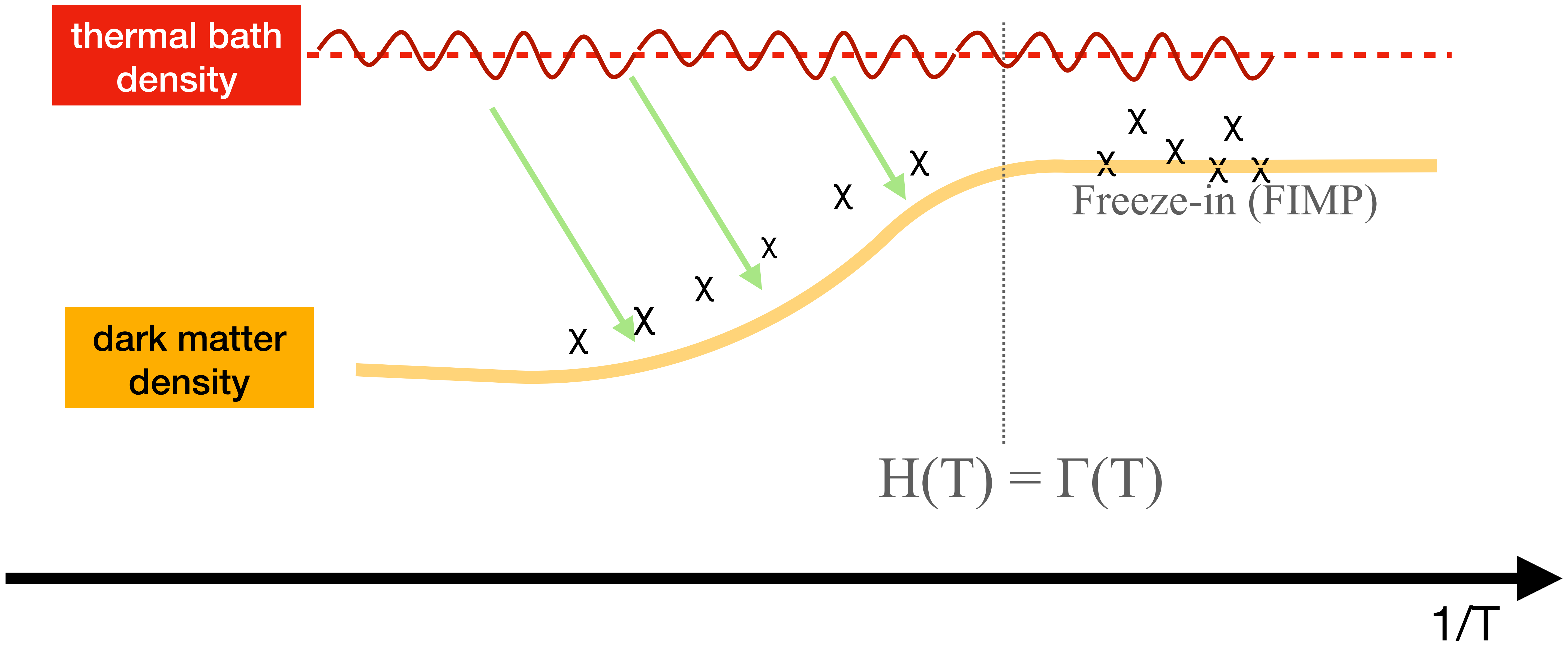

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Freeze-in

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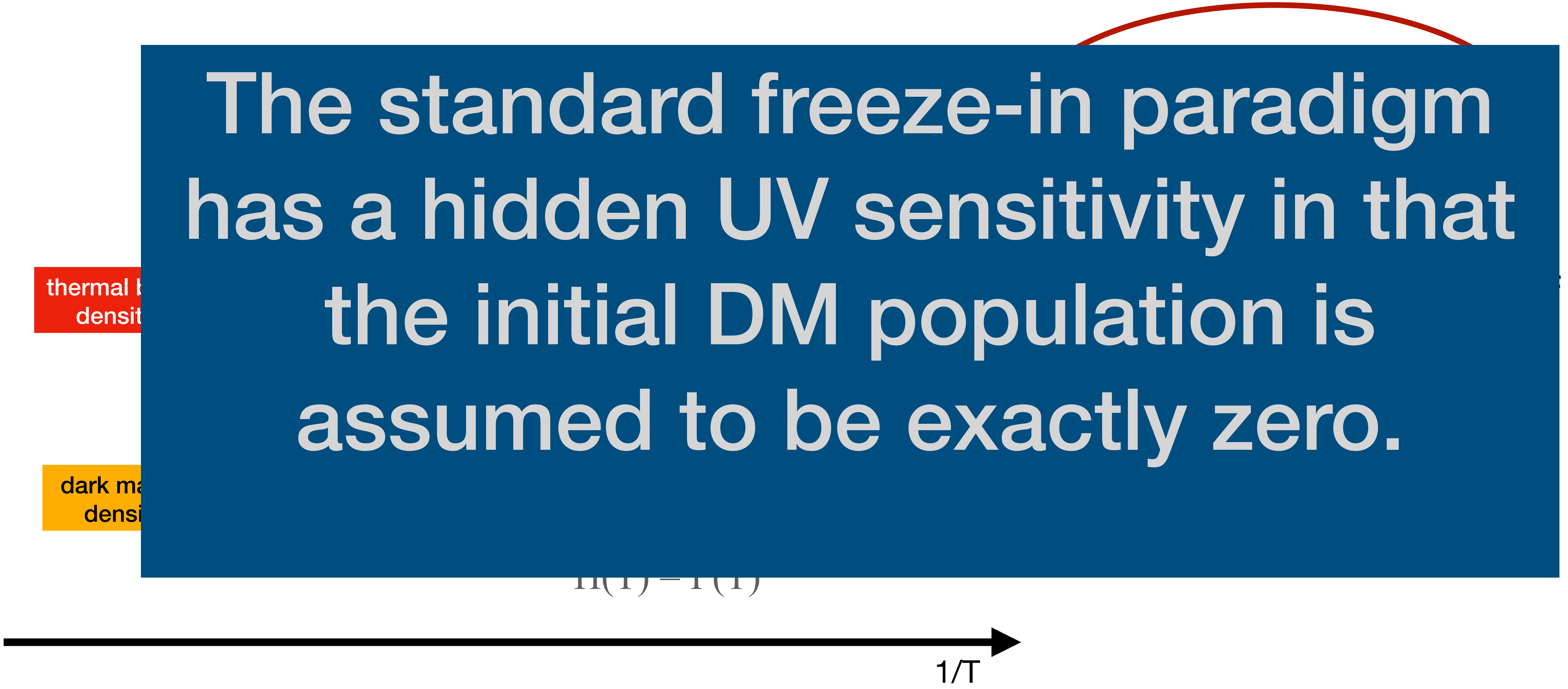
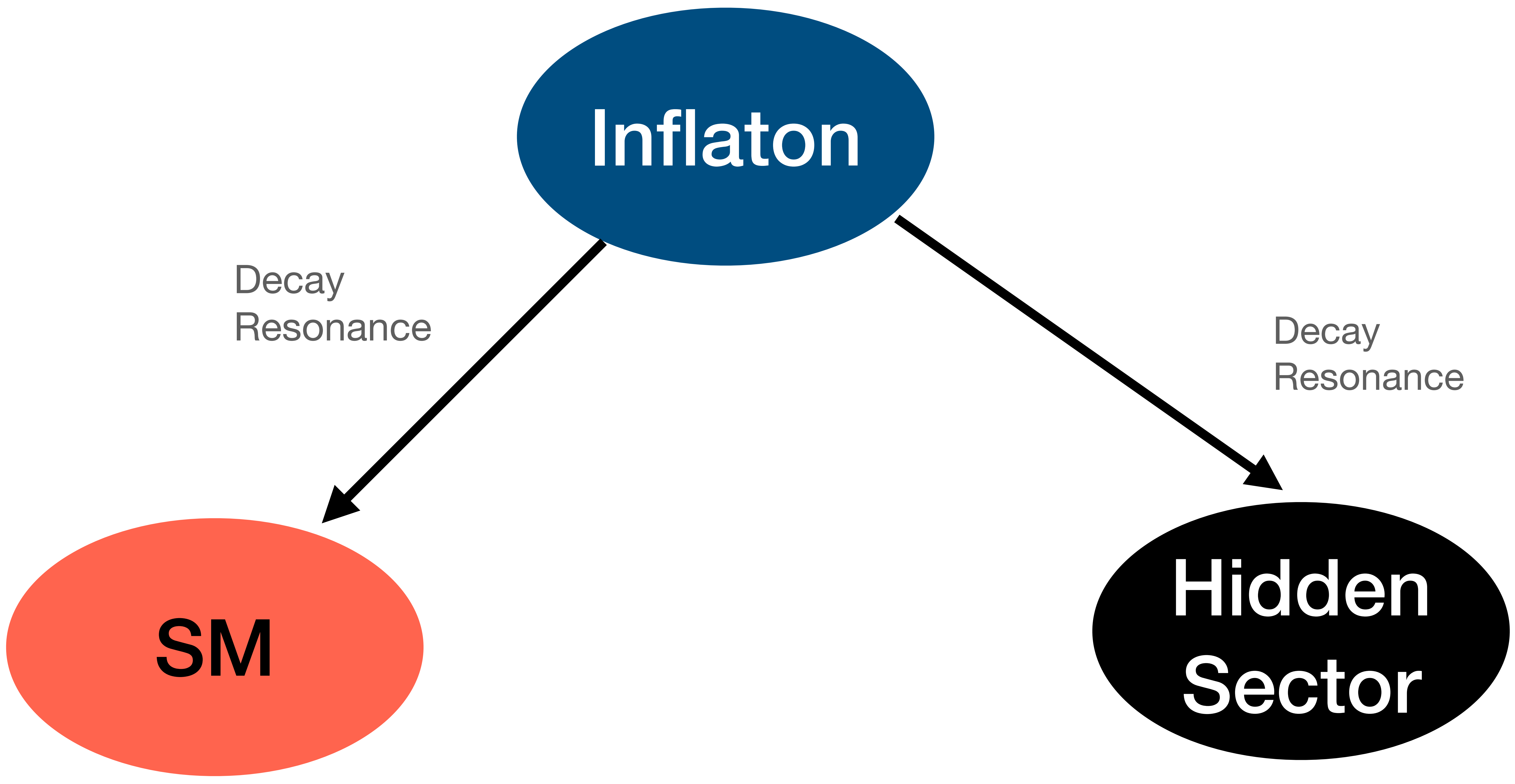


The standard freeze-in paradigm has a hidden UV sensitivity in that the initial DM population is assumed to be exactly zero.

What if…


Inflaton
Decay
Resonance
Decay
Resonance
SM
Hidden
Sector

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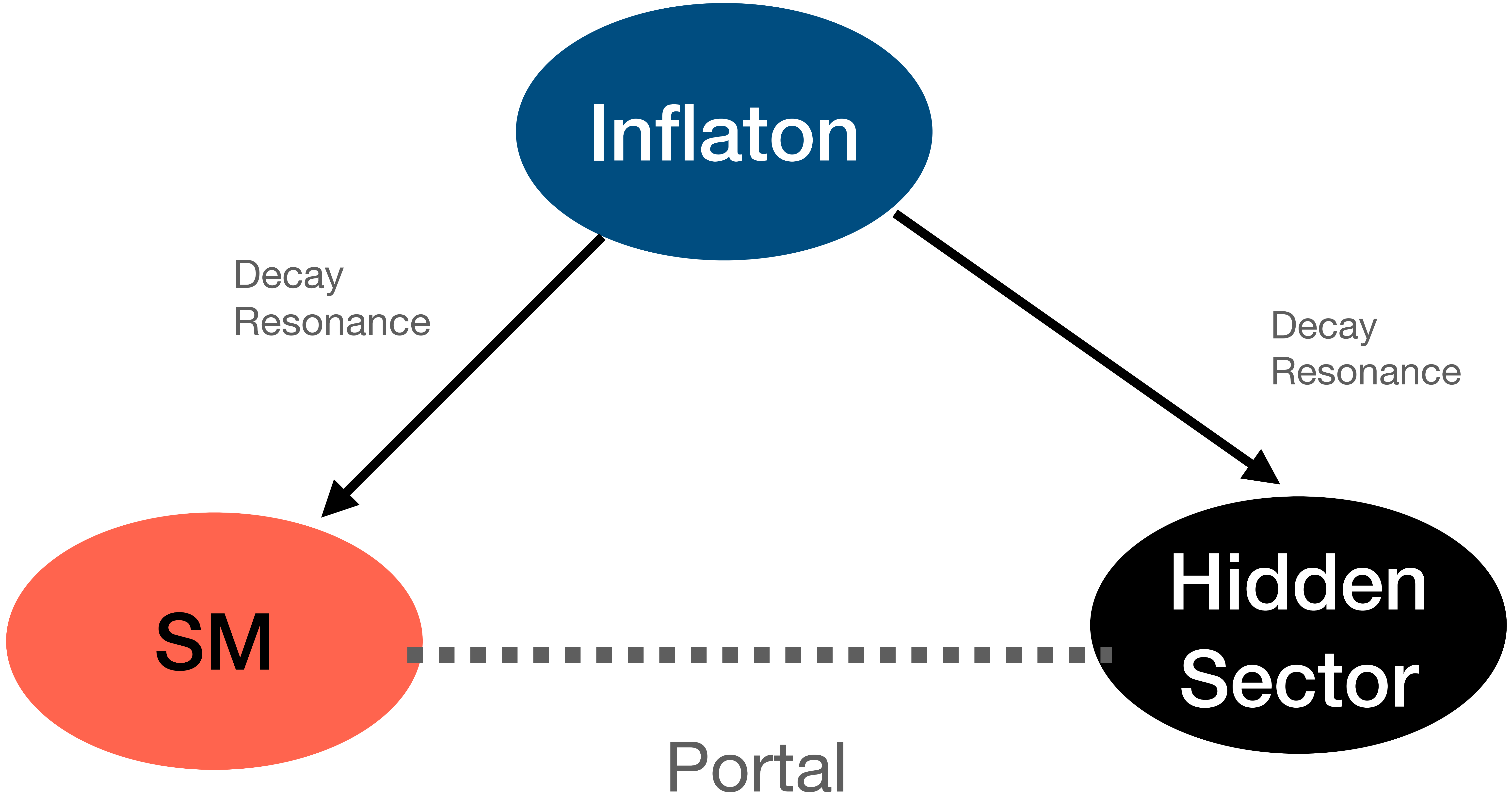
Inflaton
Decay
Resonance
Decay
Resonance
SM
Hidden
Sector
Portal

Explicit Model: Kinetic mixing portal
Dark photon

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

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

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

[X. Chu,T.H., M.Tytgat ‘11]

Explicit Model: Kinetic mixing portal Dark photon

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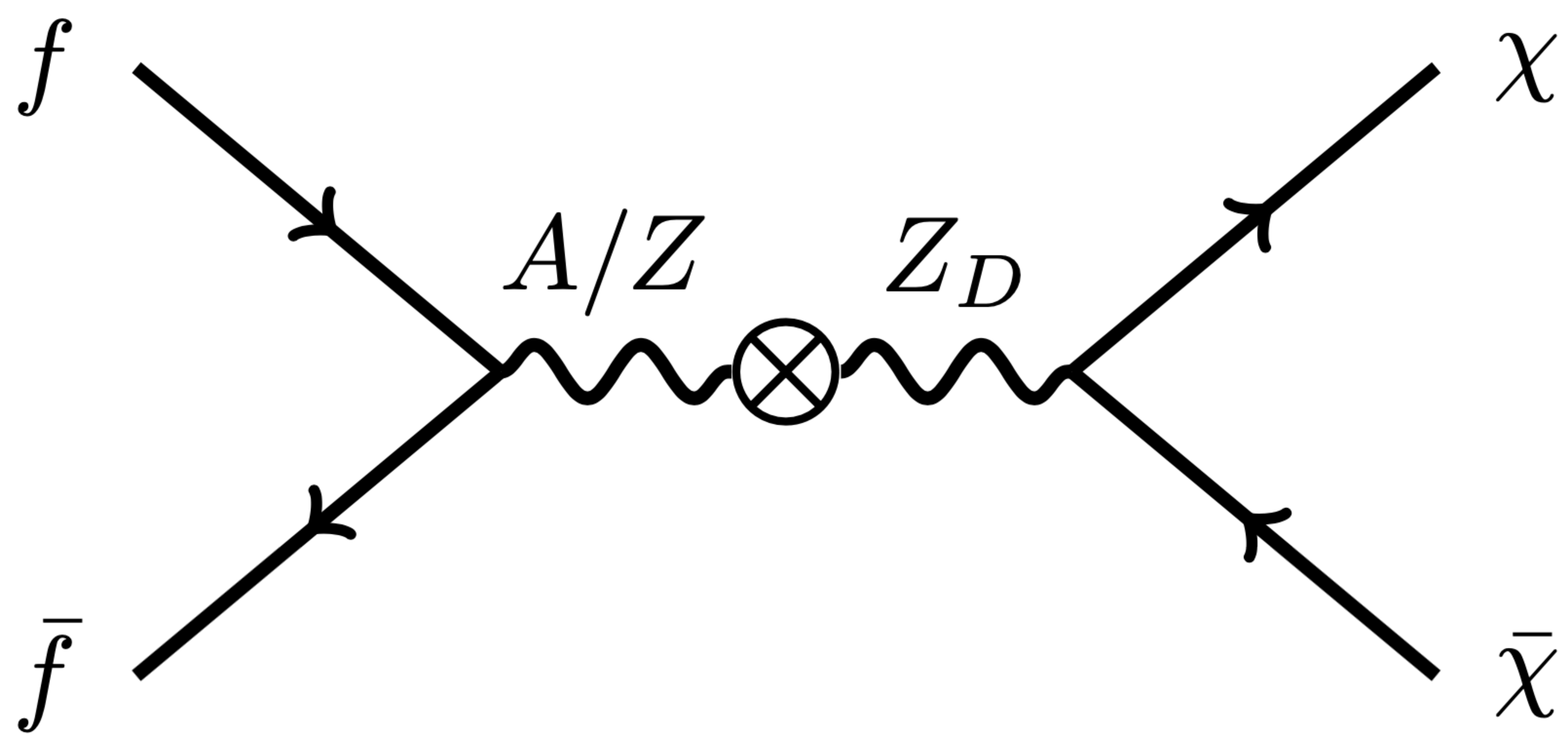
$$1\mathrm{MeV} < m_{\chi} < 1\mathrm{GeV}$$



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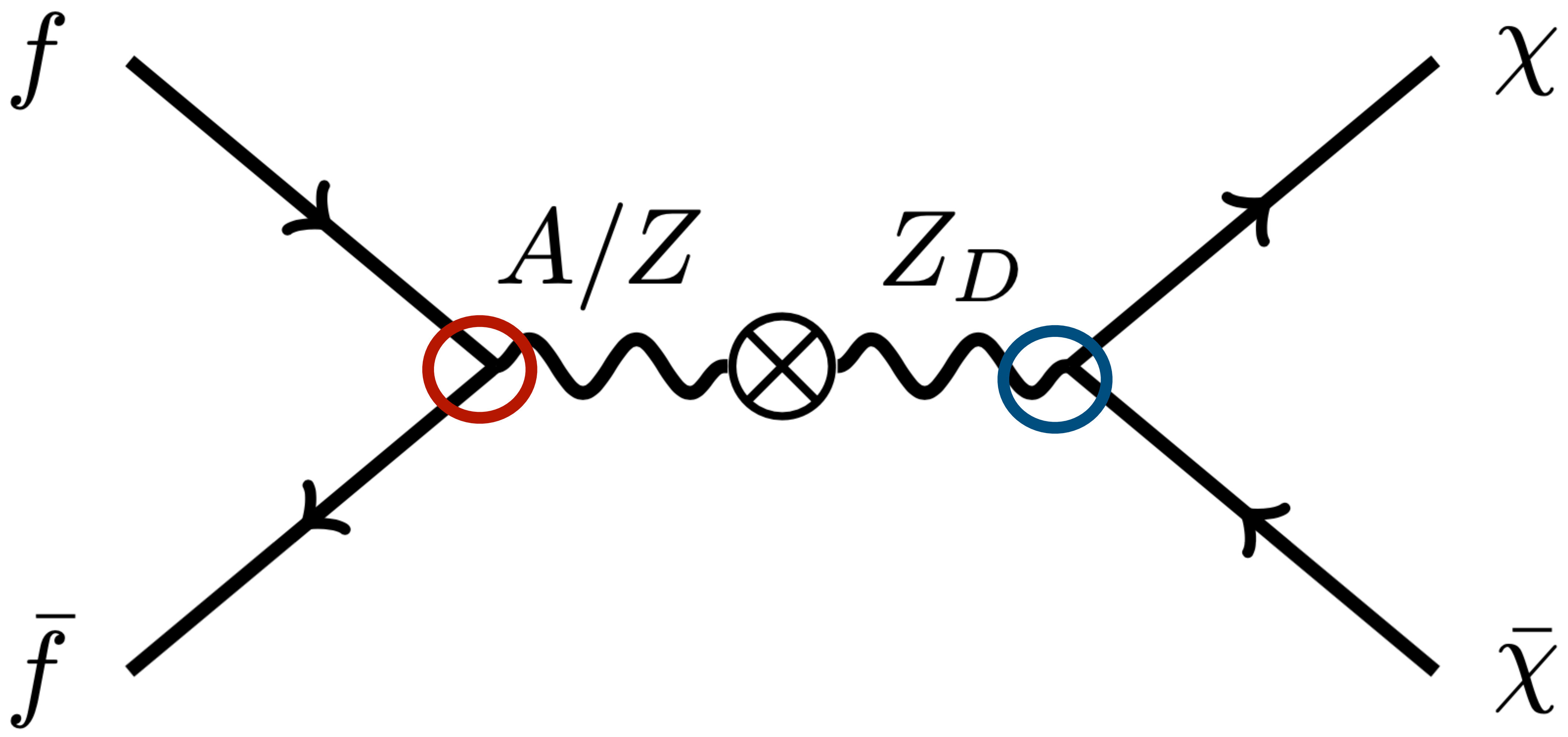

$$\langle \sigma v \rangle \propto \epsilon^2 \alpha_D$$

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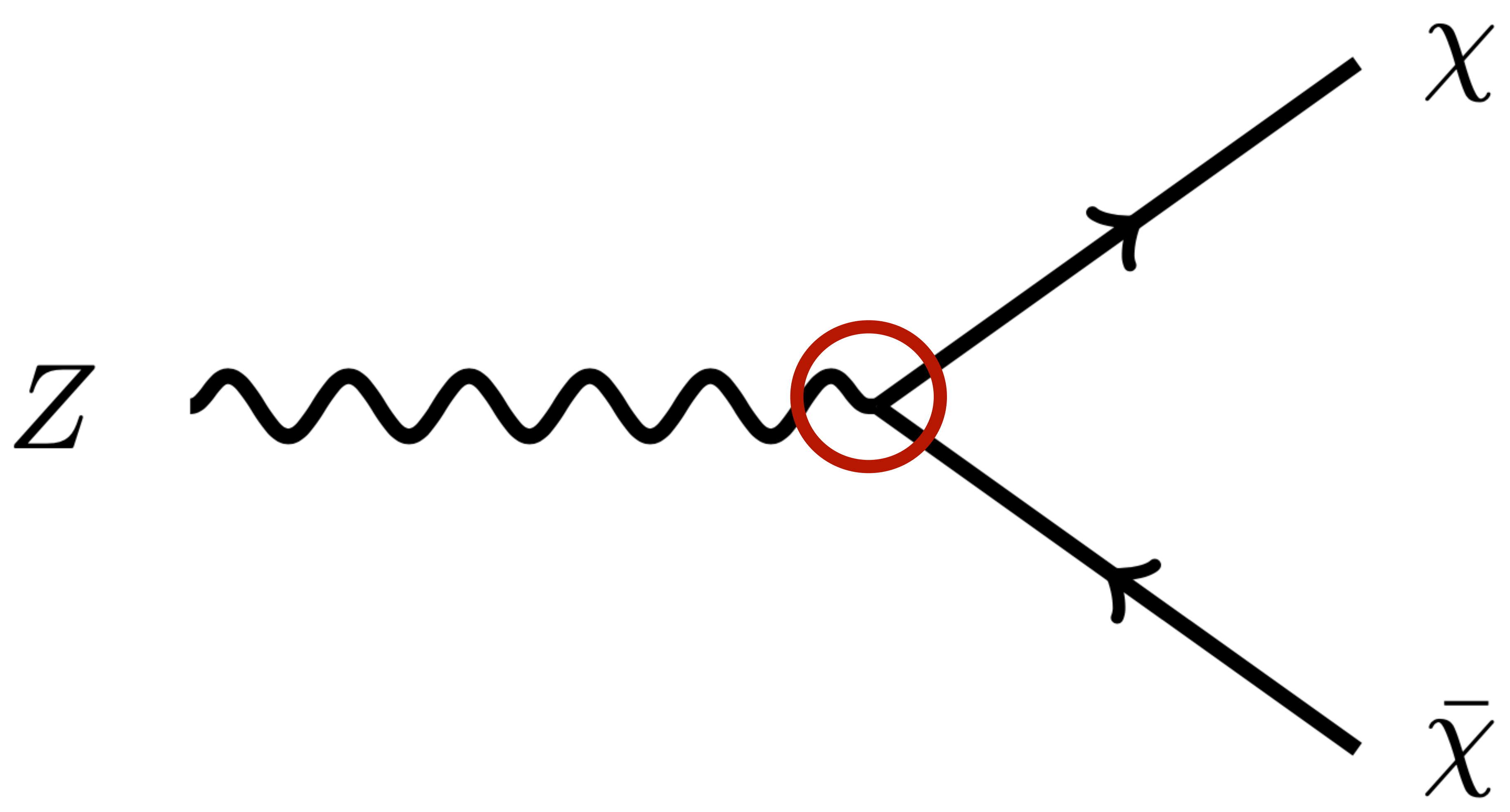

$$\langle \Gamma_{Z\to\chi\chi} \rangle \propto \epsilon^2 \alpha_D$$

$m_{\chi} > 1\text{GeV}$ → 10%

Scenario

- We explore how a pre-existing population of DM, either alone or as part of a thermalized dark sector, affects the dynamics of freeze-in.
- For a kinetically mixed dark photon, the dominant source of energy injection into the hidden sector is through DM pair production (thermal corrections).
- Elastic processes are fast enough for instantaneous kinetic equilibrium.

Boltzmann Equation

Number density of DM:

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

Energy density of the HS:

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

Boltzmann Equation

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$\rightarrow \mu_\chi$

Energy density of the HS:

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

$\rightarrow \tilde{T}$

Boltzmann Equation

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

Number density of DM:

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

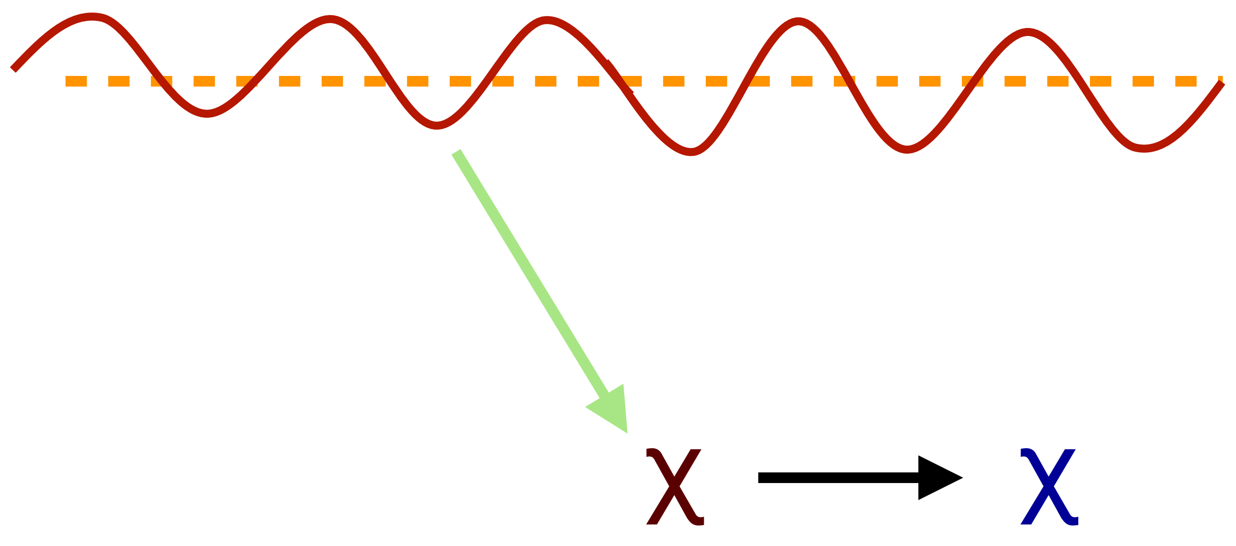
$$f\bar{f} \to \chi\chi$$

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 correct? Parameter space?
- Initial condition

Instantaneous kinetic equilibration of DM



$$\chi\bar{\chi} \to \chi\bar{\chi} \qquad (1\,2 \to 3\,4)$$

$$T_1 \neq T_2$$

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

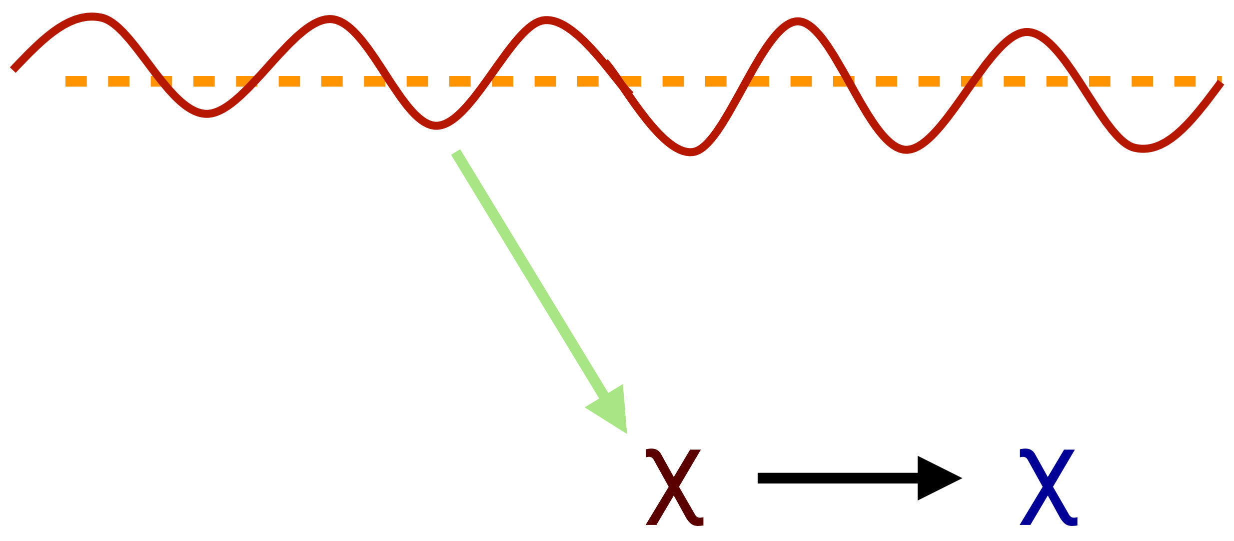
Momentum transferred:

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

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

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

Instantaneous kinetic equilibration of DM



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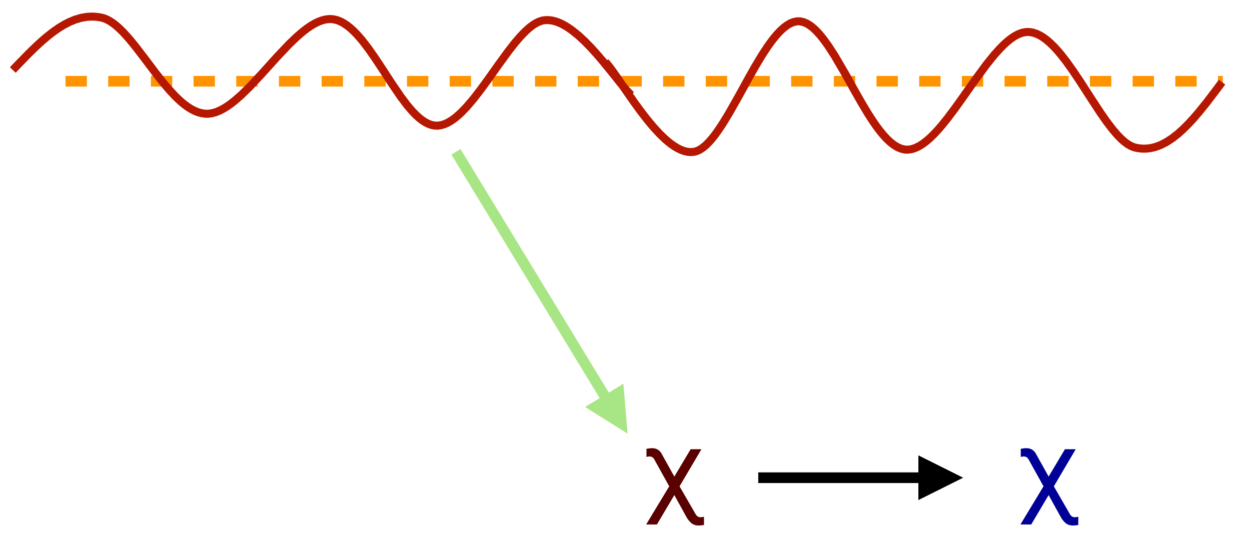
Have you seen this formula?

- Two different temperatures
- One Integration variable left

Instantaneous kinetic equilibration of DM

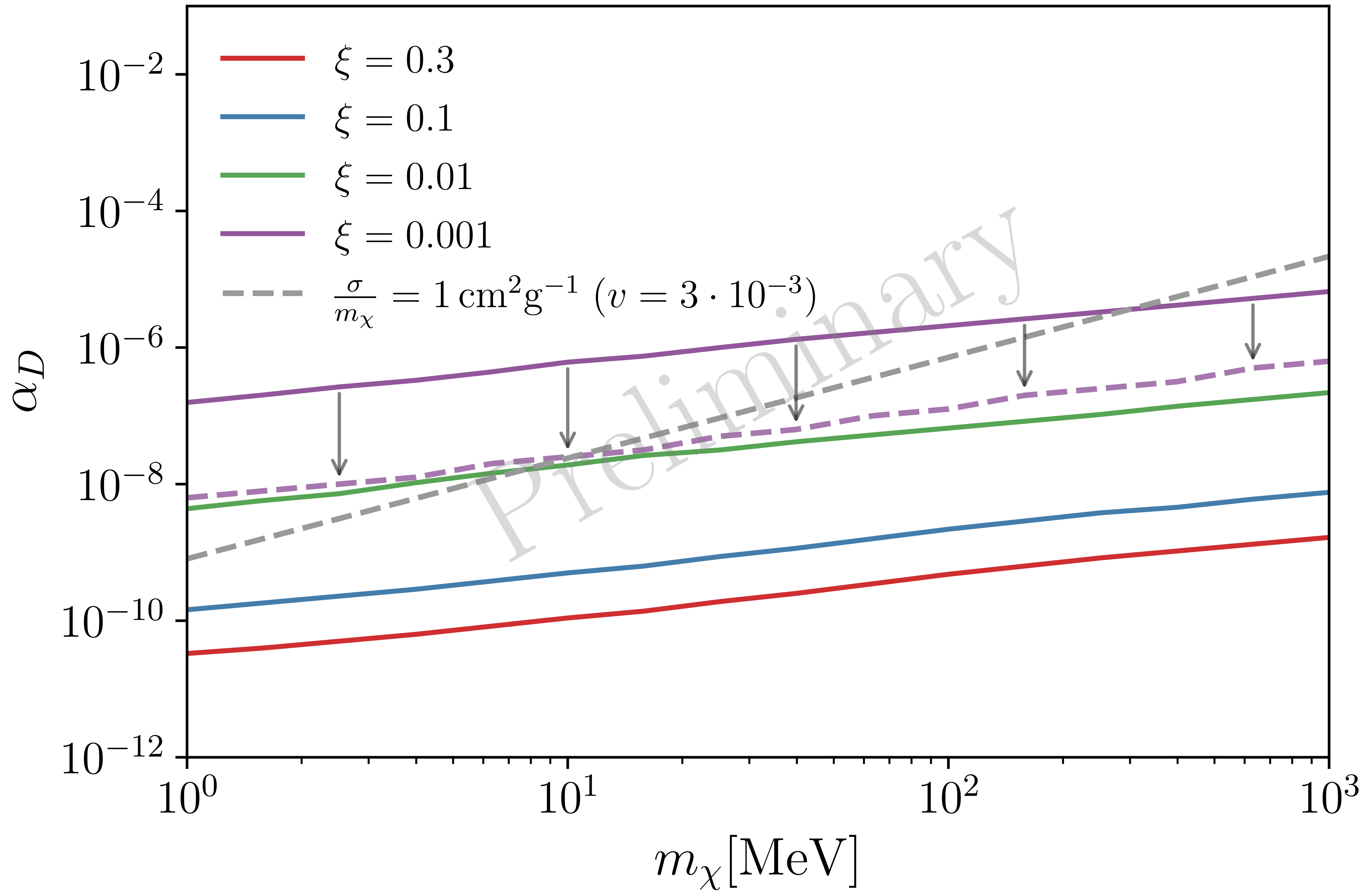


$$\chi\bar{\chi} \to \chi\bar{\chi} \qquad (1\,2 \to 3\,4) \qquad T_1 \neq T_2$$

Thermally averaged momentum loss:

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

Instantaneous kinetic equilibration of DM
Vs
DM self-interaction constraints



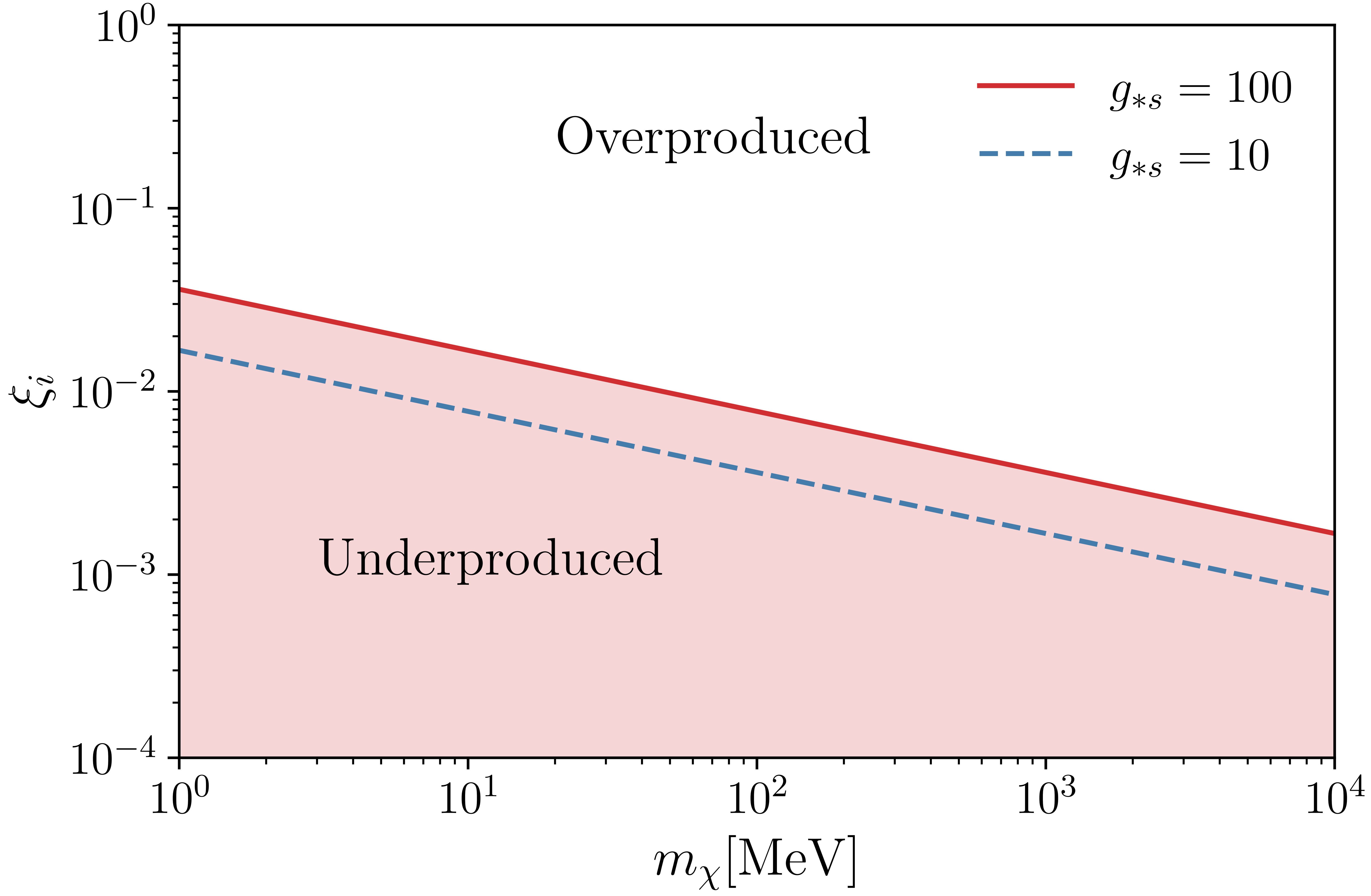
$$\chi_1 \chi_2 \to \chi_1 \chi_2$$

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

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

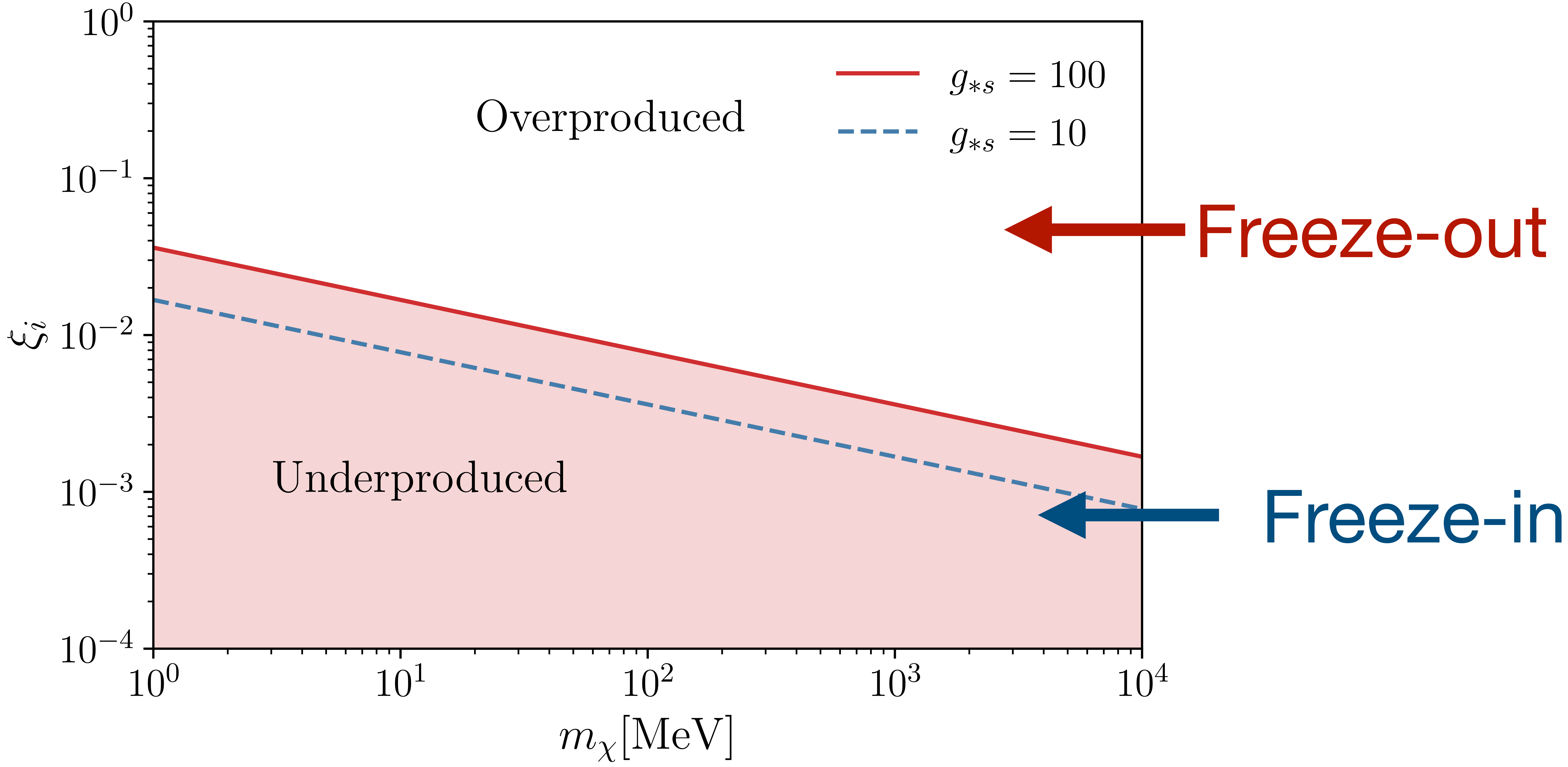
NF, *Kahn and Shelton in prep.*

Initial condition DM



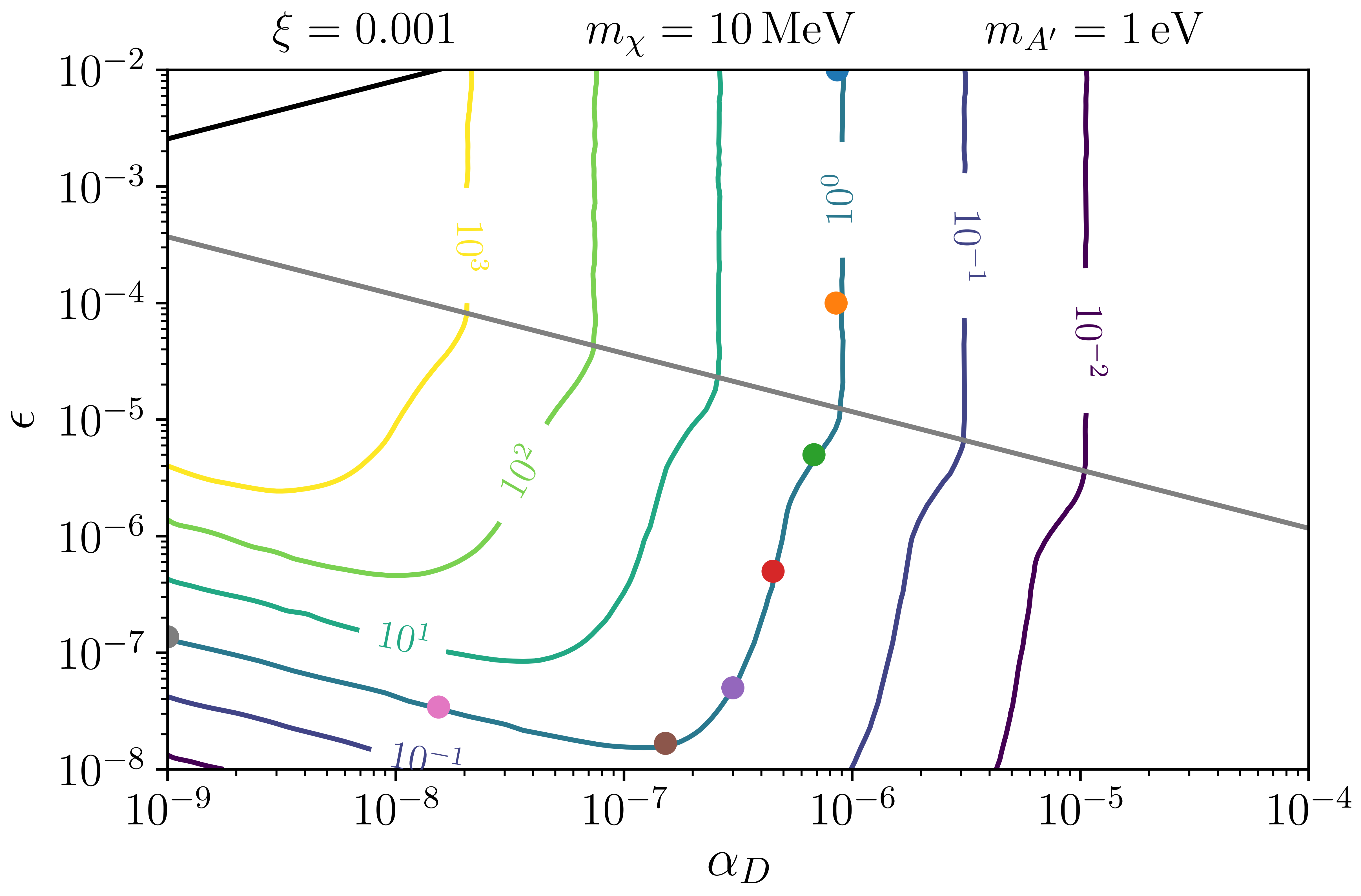
NF, *Kahn and Shelton in prep.*

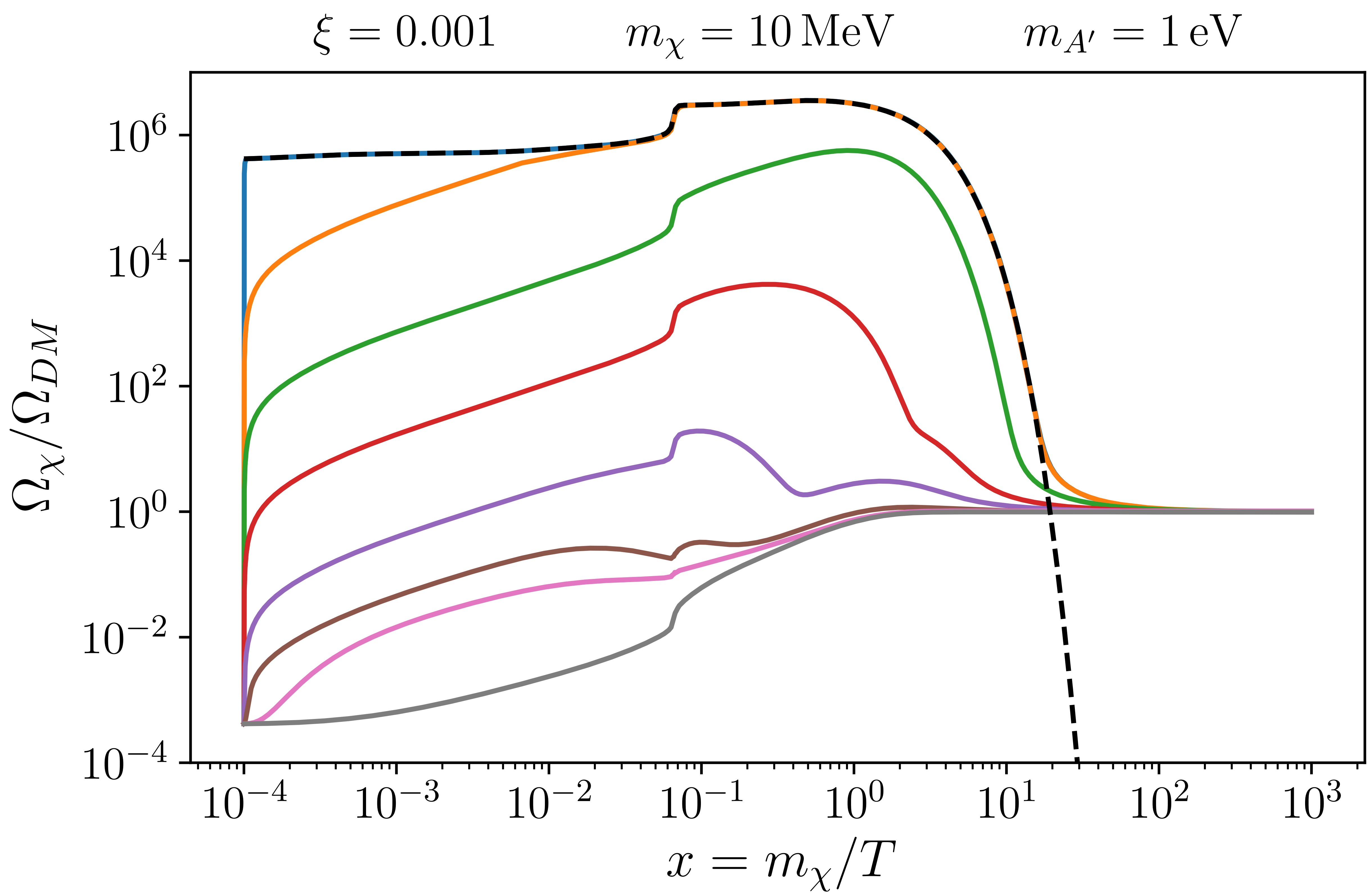
Freeze-in or freeze-out?



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

Parameter space and DM relic abundance

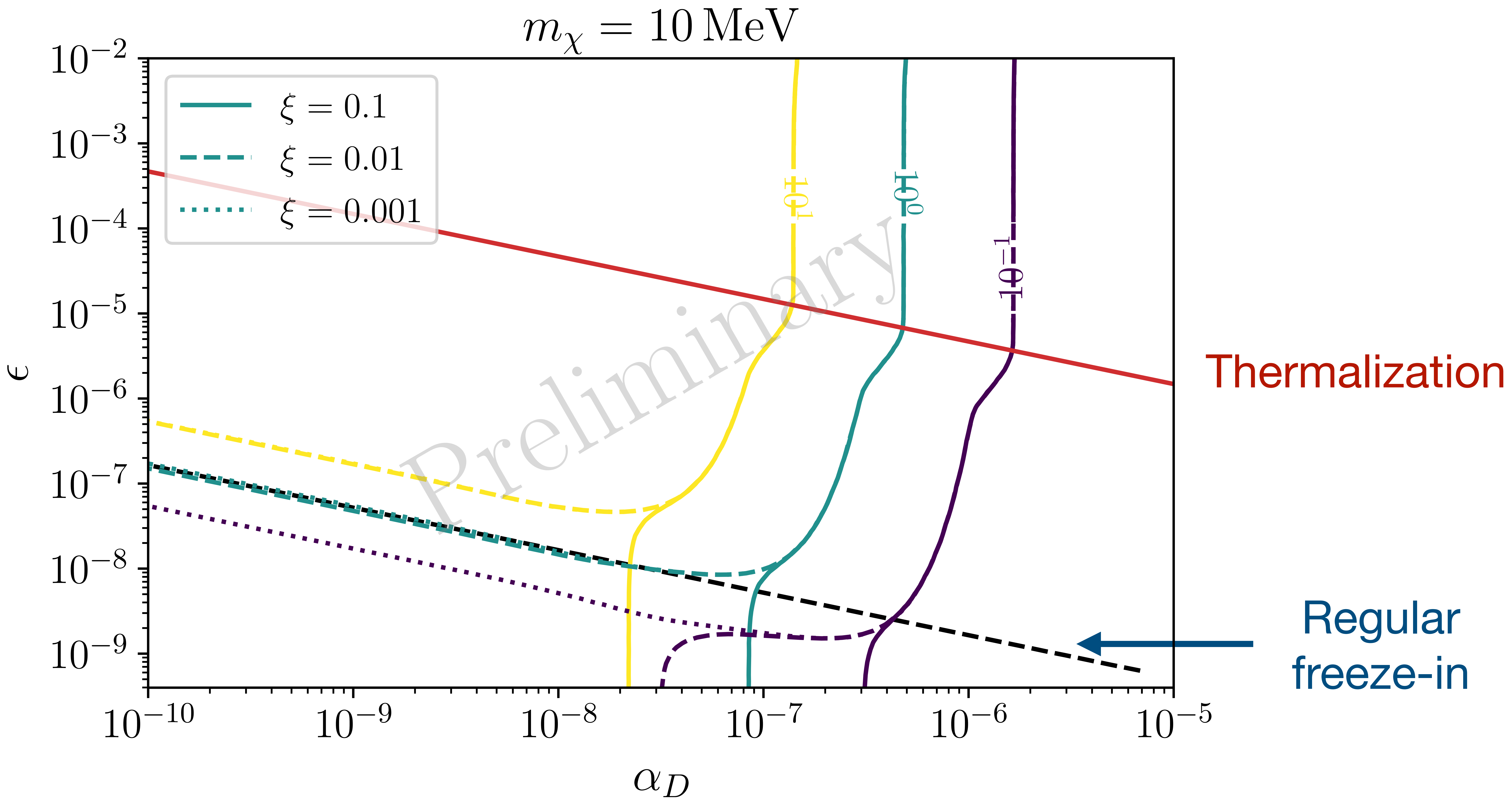




*Not update values

NF, *Kahn and Shelton in prep.*

DM relic abundance



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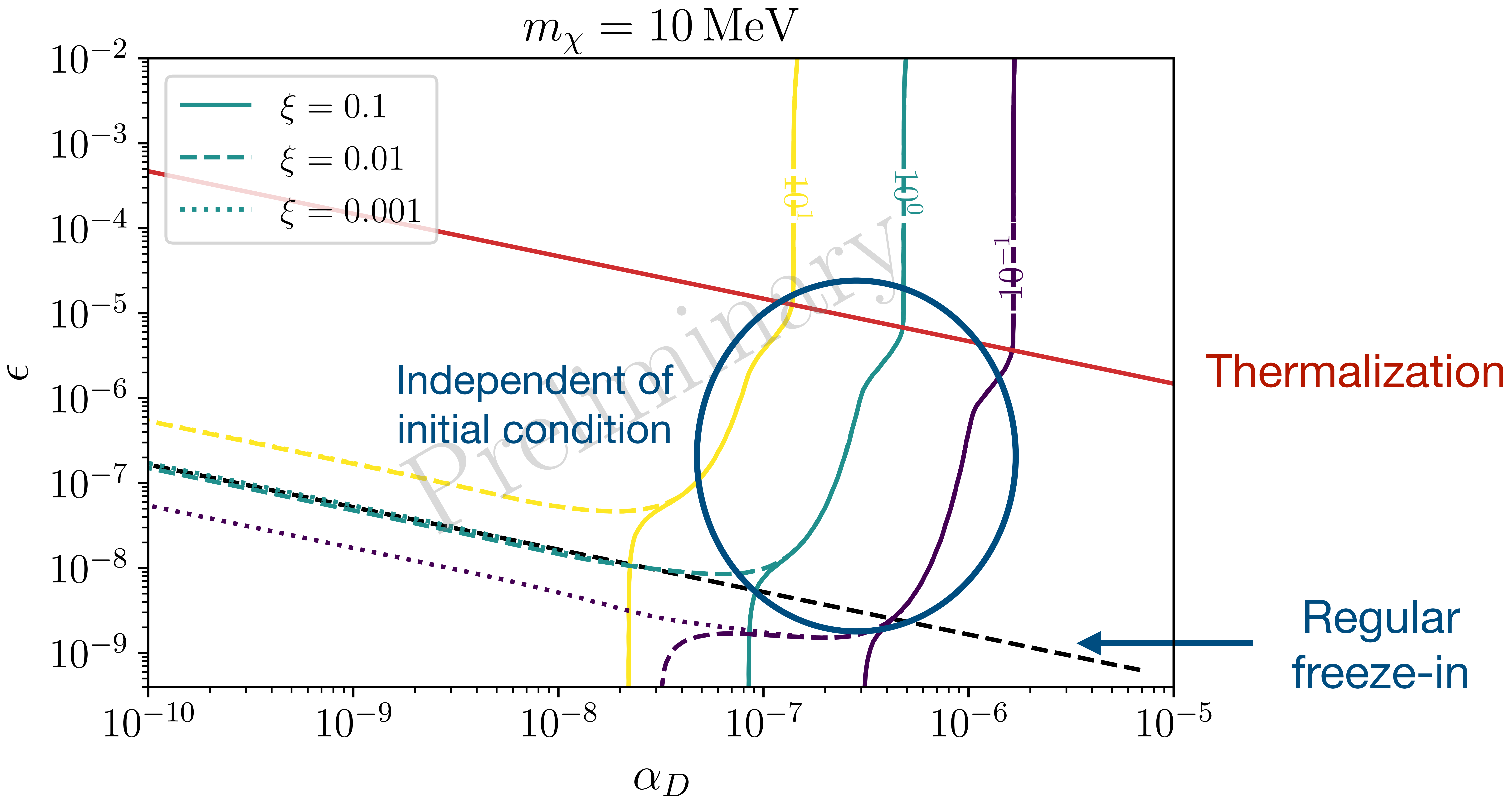
DM relic abundance



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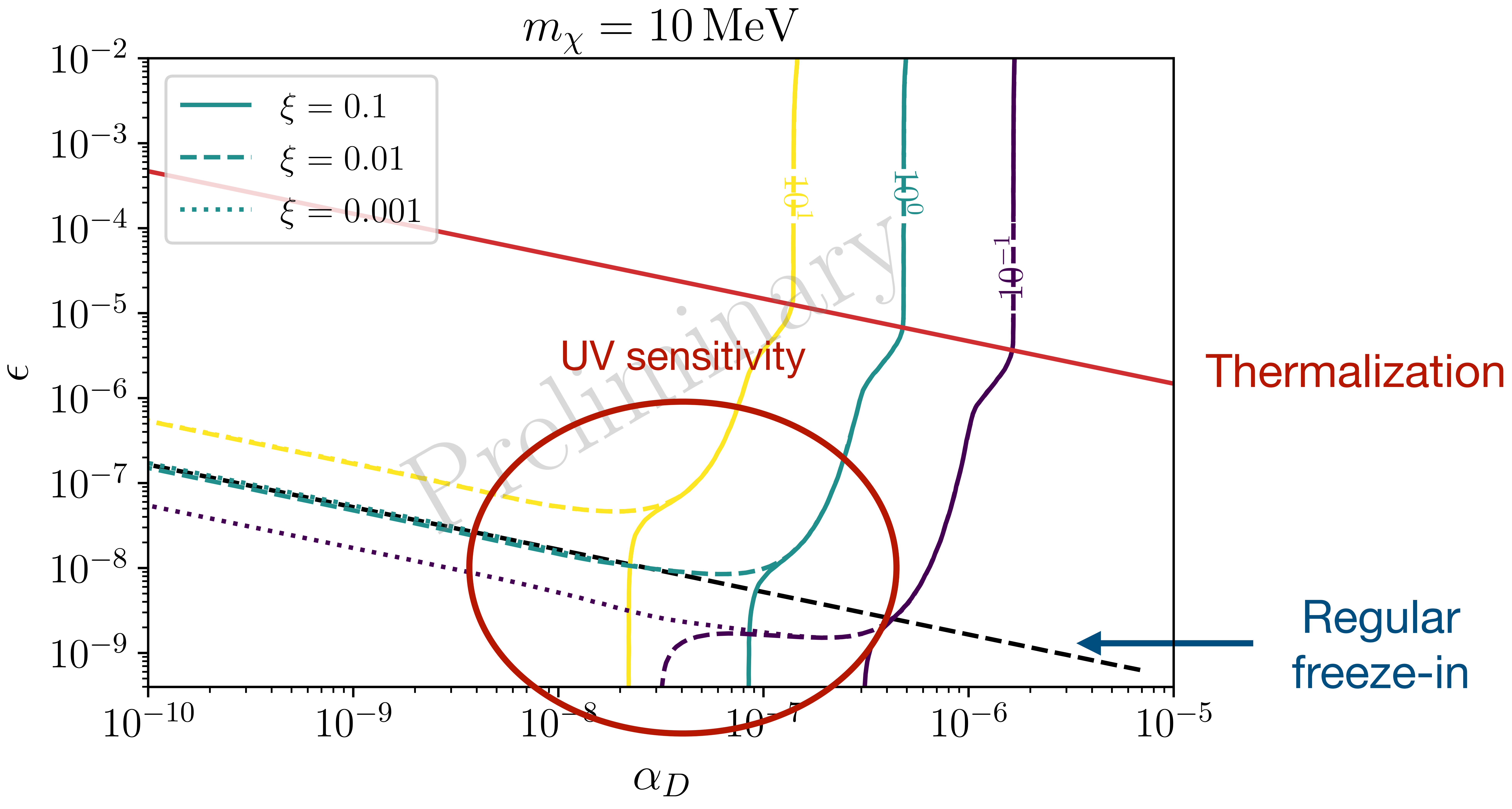
DM relic abundance



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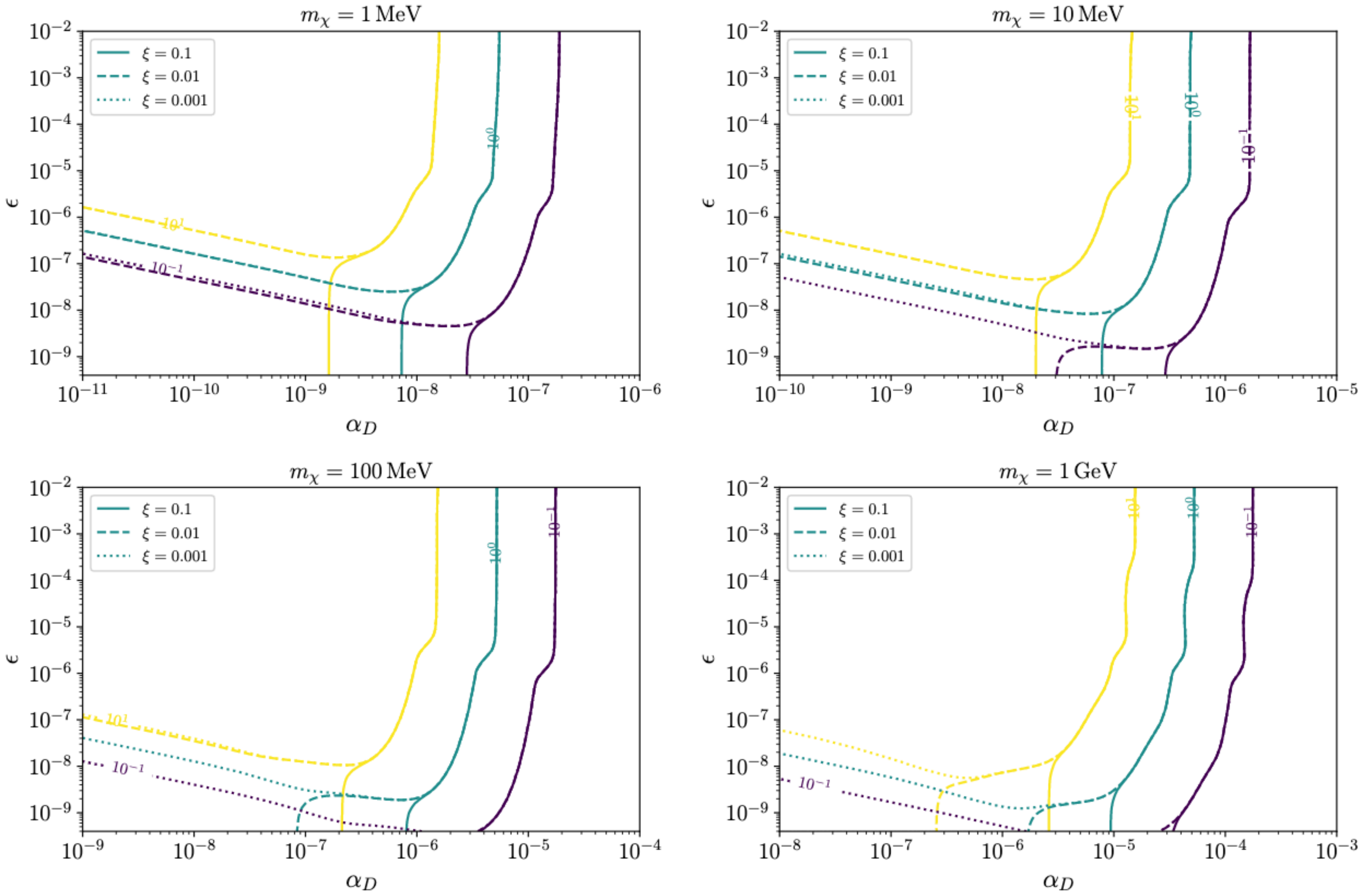
DM relic abundance

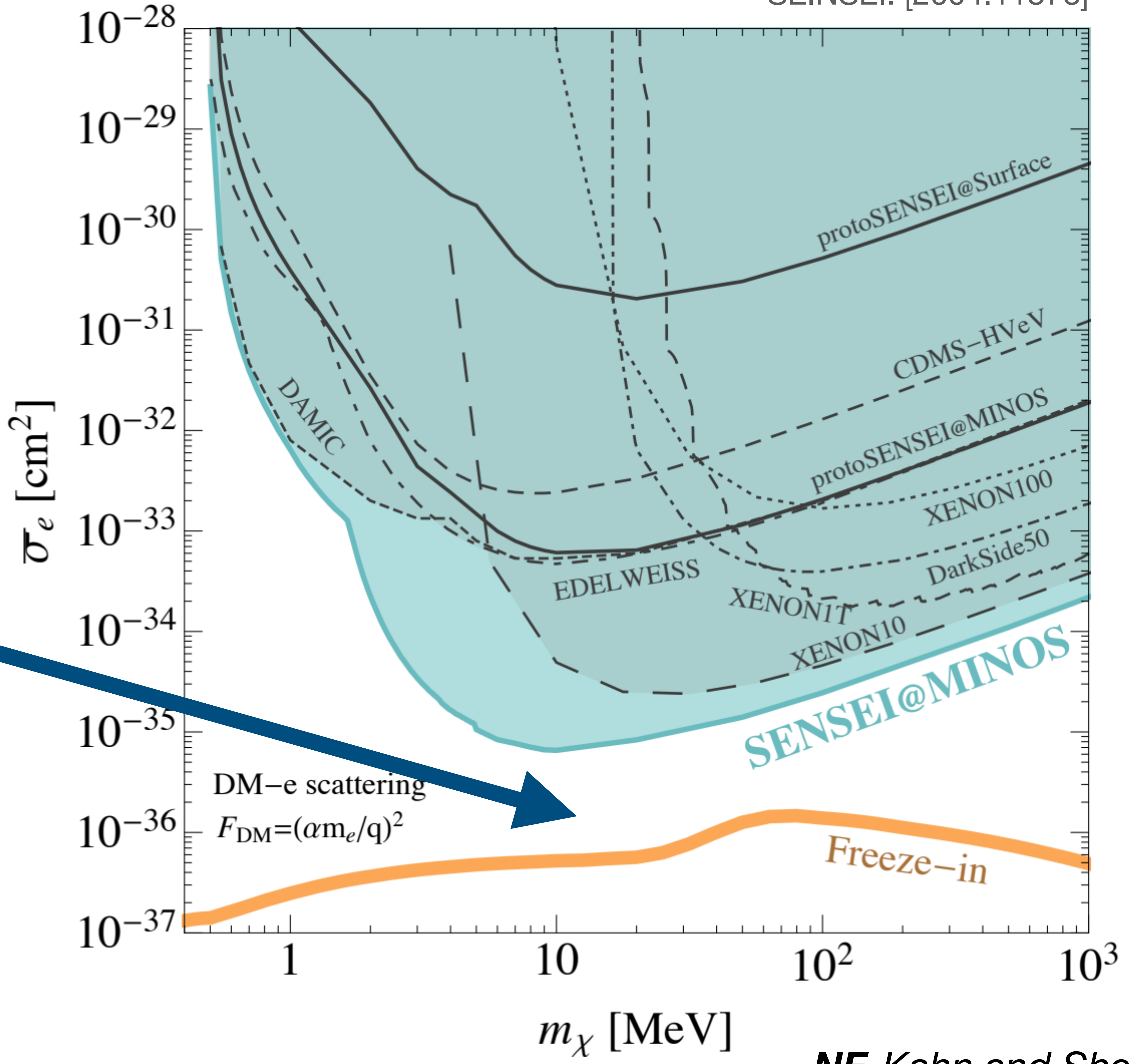


NF, Kahn and Shelton in prep.

SENSEI 2020

- How the the freeze-in line is affected?

SEINSEI: [2004.11378]



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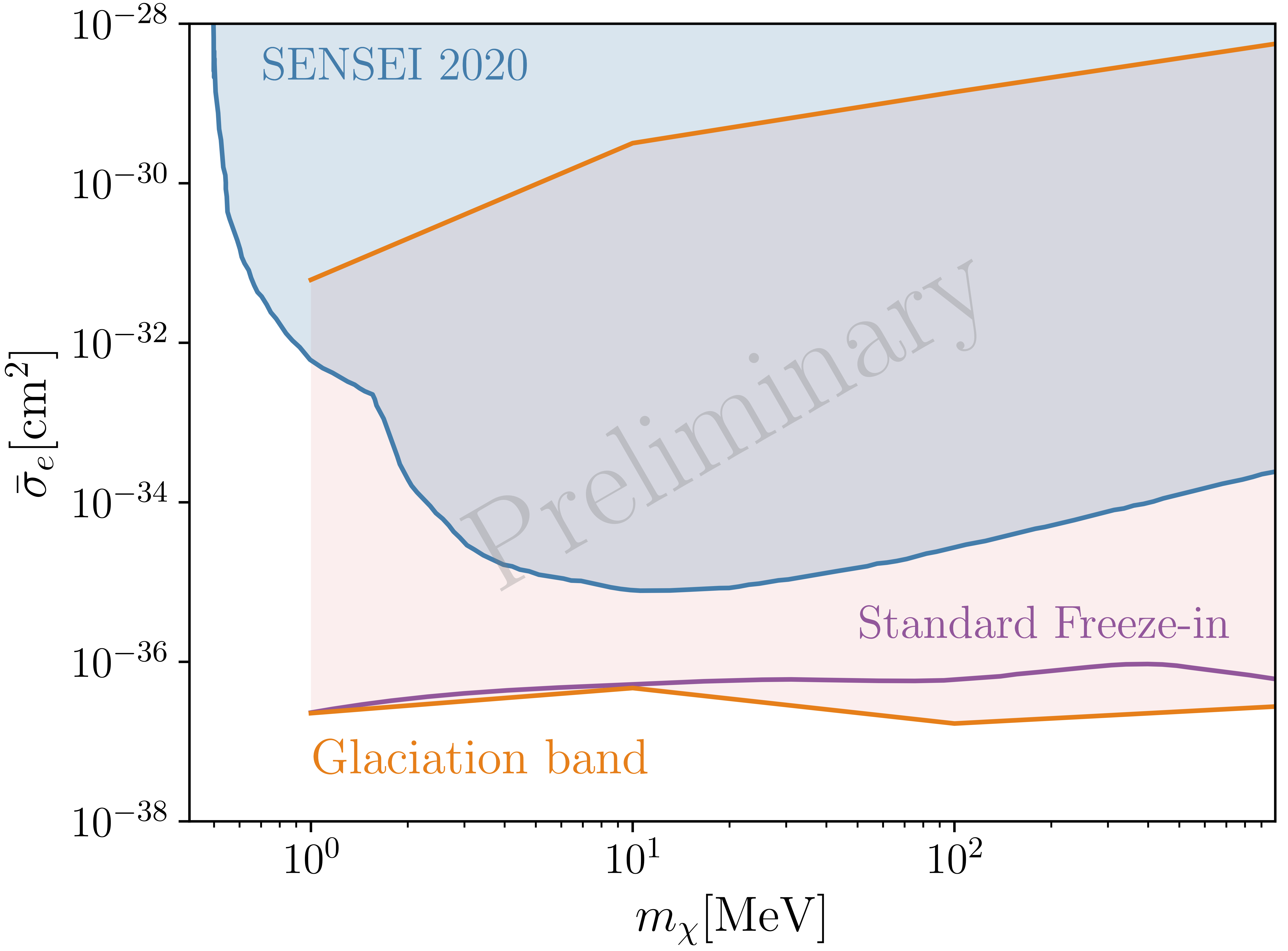
Current Experiments



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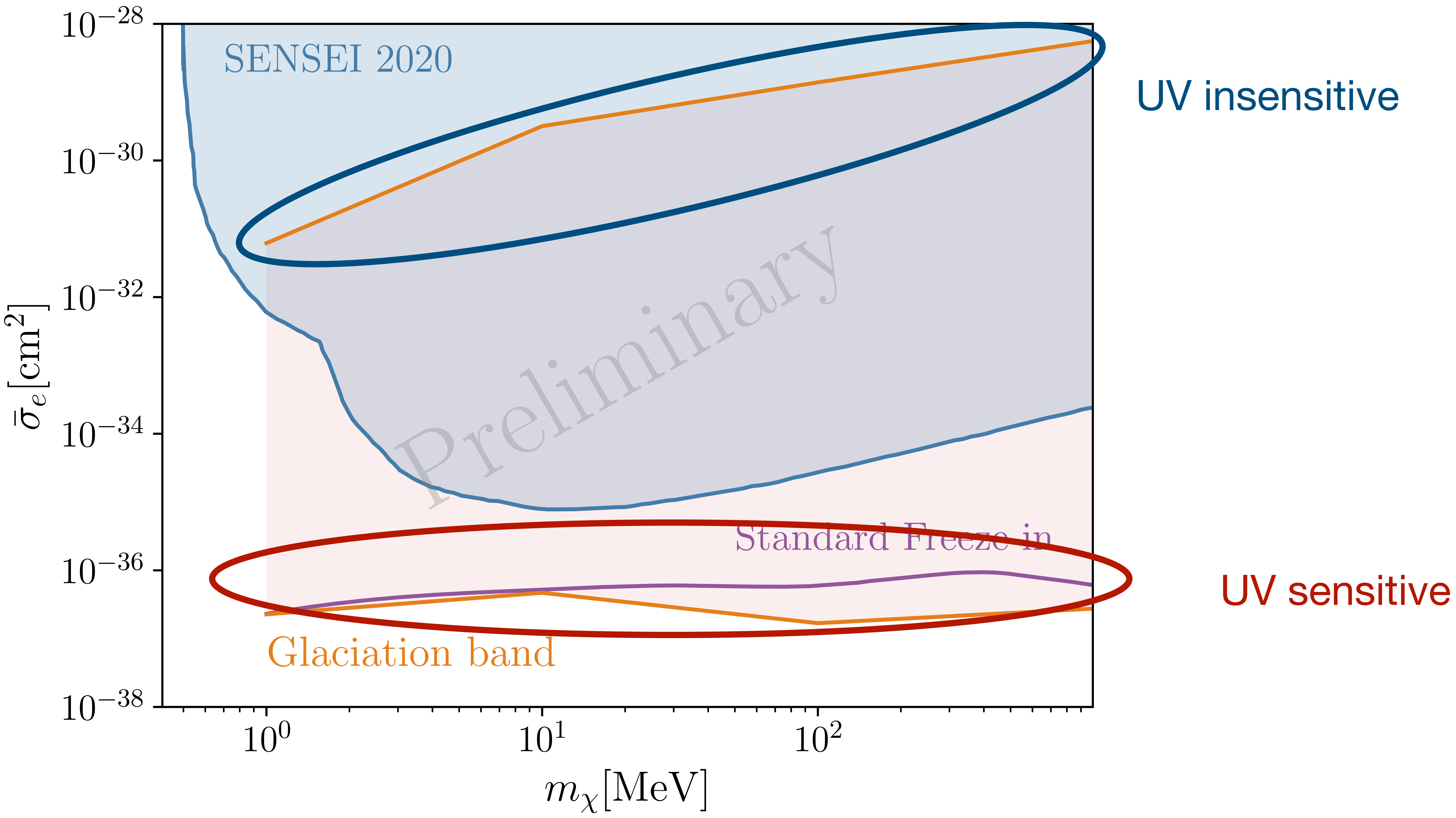
Current Experiments are testing this parameter space



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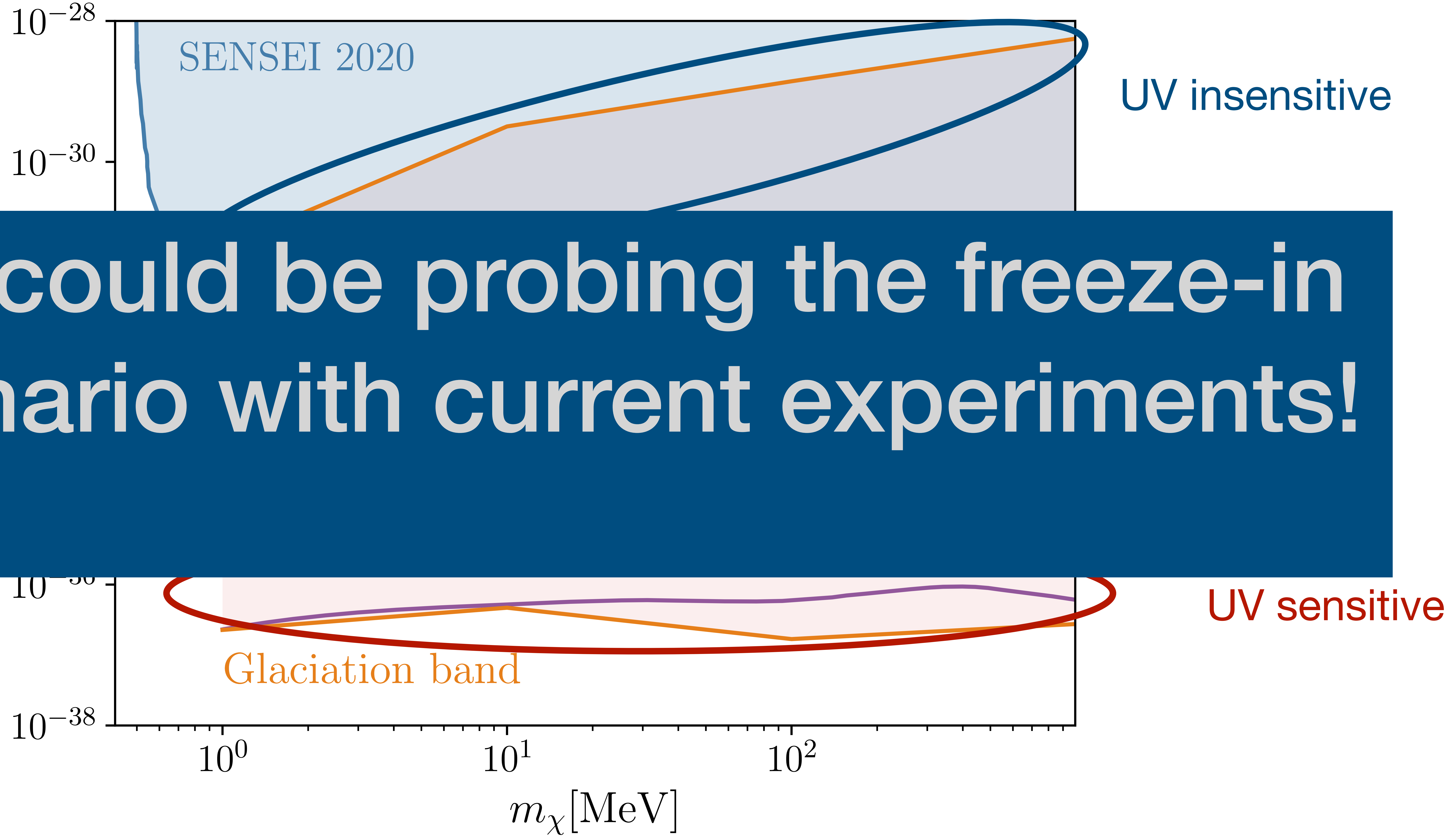

We could be probing the freeze-in scenario with current experiments!

***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, this “freeze-in line” expands to a “glaciation band” because there are multiple points in the $\varepsilon - \alpha_D$ plane which achieve the correct relic abundance.

Thanks!