

# COSMOLOGICAL CONSIDERATIONS FOR DARK SECTORS WITH LIGHT MEDIATORS

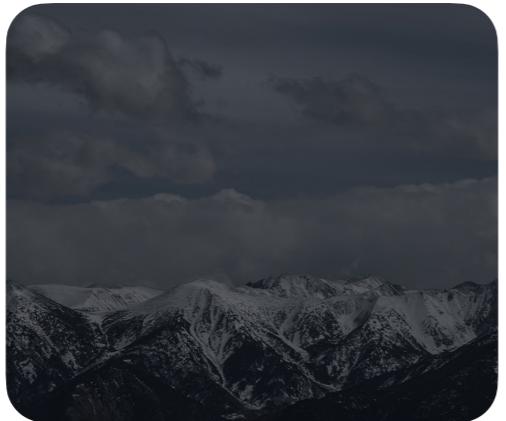
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Jessie Shelton  
UIUC

*Aspen Winter Conference, March 30, 2023*

# DARK SECTORS

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SM

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# DARK SECTORS WITH LIGHT MEDIATORS

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—  $\chi$  — *may be all or part of DM*

—  $\phi$  — *may be stable or unstable*

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- Important targets for sub-GeV dark matter direct detection
- Theoretical motivations:
  - mirror sectors (neutral naturalness, Nnaturalness, ...)
  - decoupled dark sectors

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- Important targets for **sub-GeV dark matter direct detection**
- Theoretical motivations:
  - mirror sectors (neutral naturalness, Nnaturalness, ...)
  - decoupled dark sectors
- Cosmological history: need to track abundance of  $\phi$

# THREE POINTS FOR TODAY

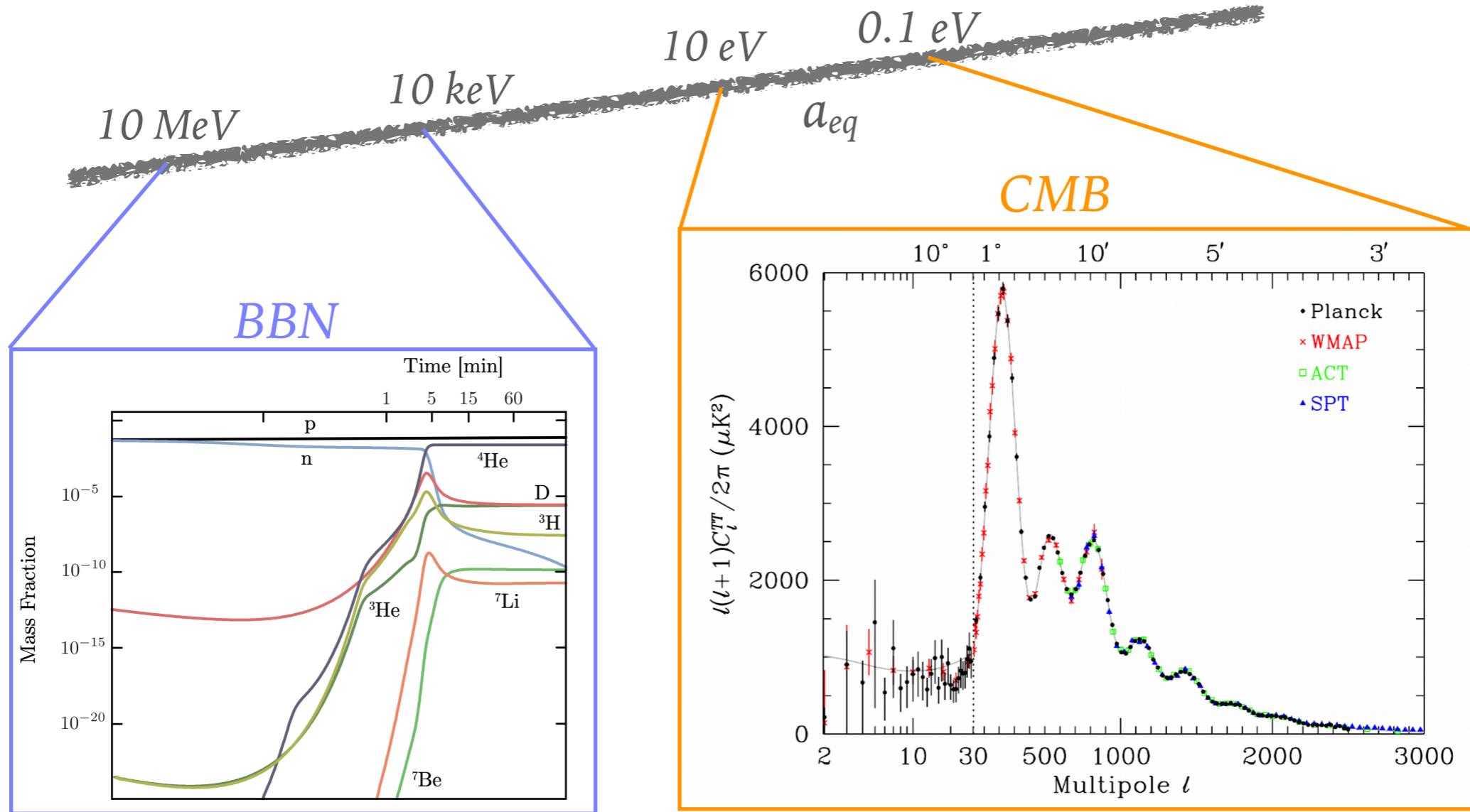
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- Cosmological constraints on stable dark mediators:  $N_{\text{eff}}$
- $N_{\text{eff}}$  constraints on out-of-equilibrium low-mass dark sectors
- terrestrial searches for out-of-equilibrium low-mass dark sectors

# DARK RADIATION

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- Early universe measurements have sensitivity to **relativistic relics**:  $N_{\text{eff}}$

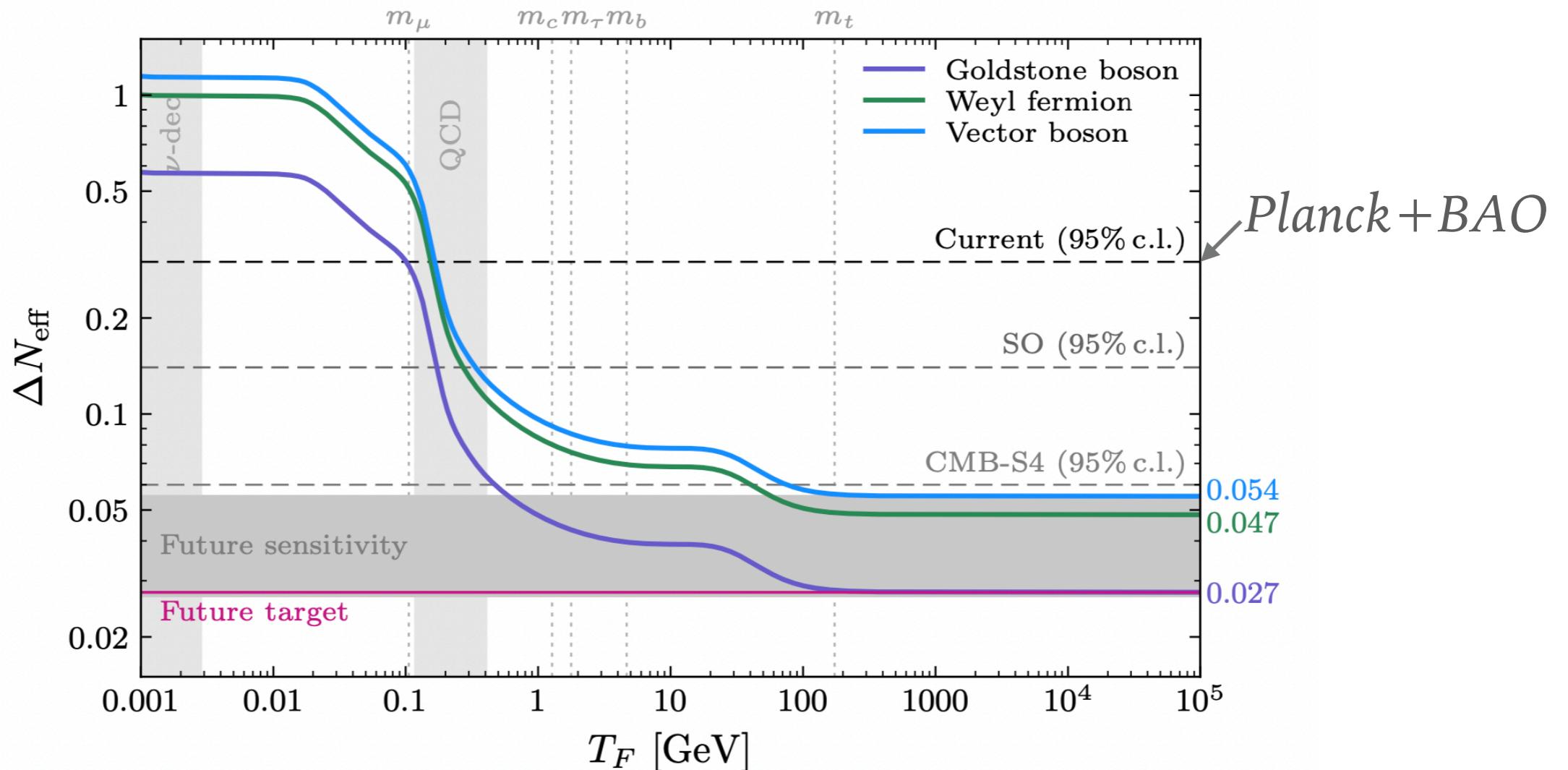


- Concordance of BBN, CMB with SM+ $\Lambda$ CDM: stringent constraints, especially dark sectors that equilibrate with SM

# CURRENT AND FUTURE MEASUREMENTS OF $N_{\text{eff}}$

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- Improved sensitivity to  $N_{\text{eff}}$  is a major target of next-generation CMB experiments:

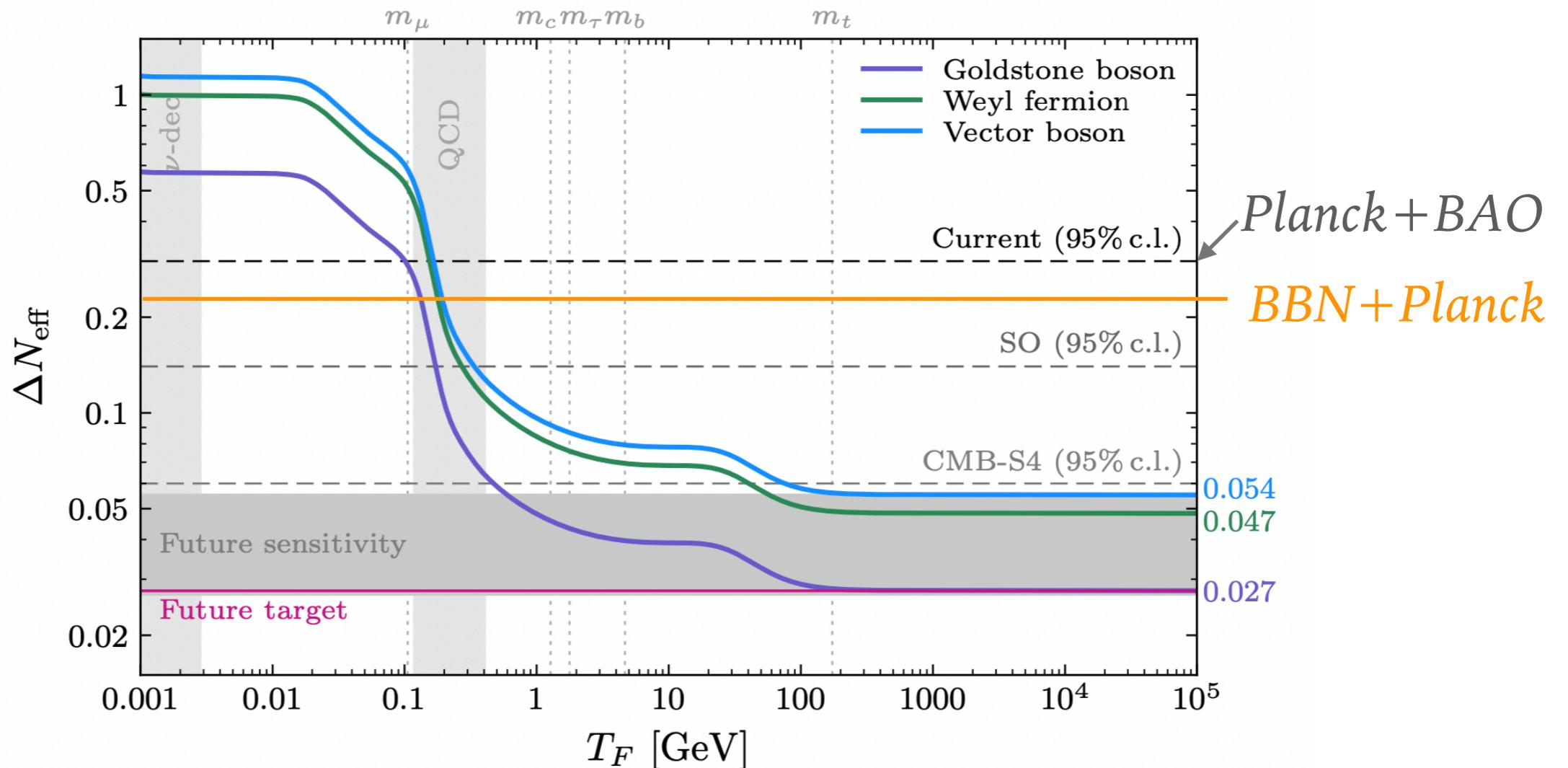


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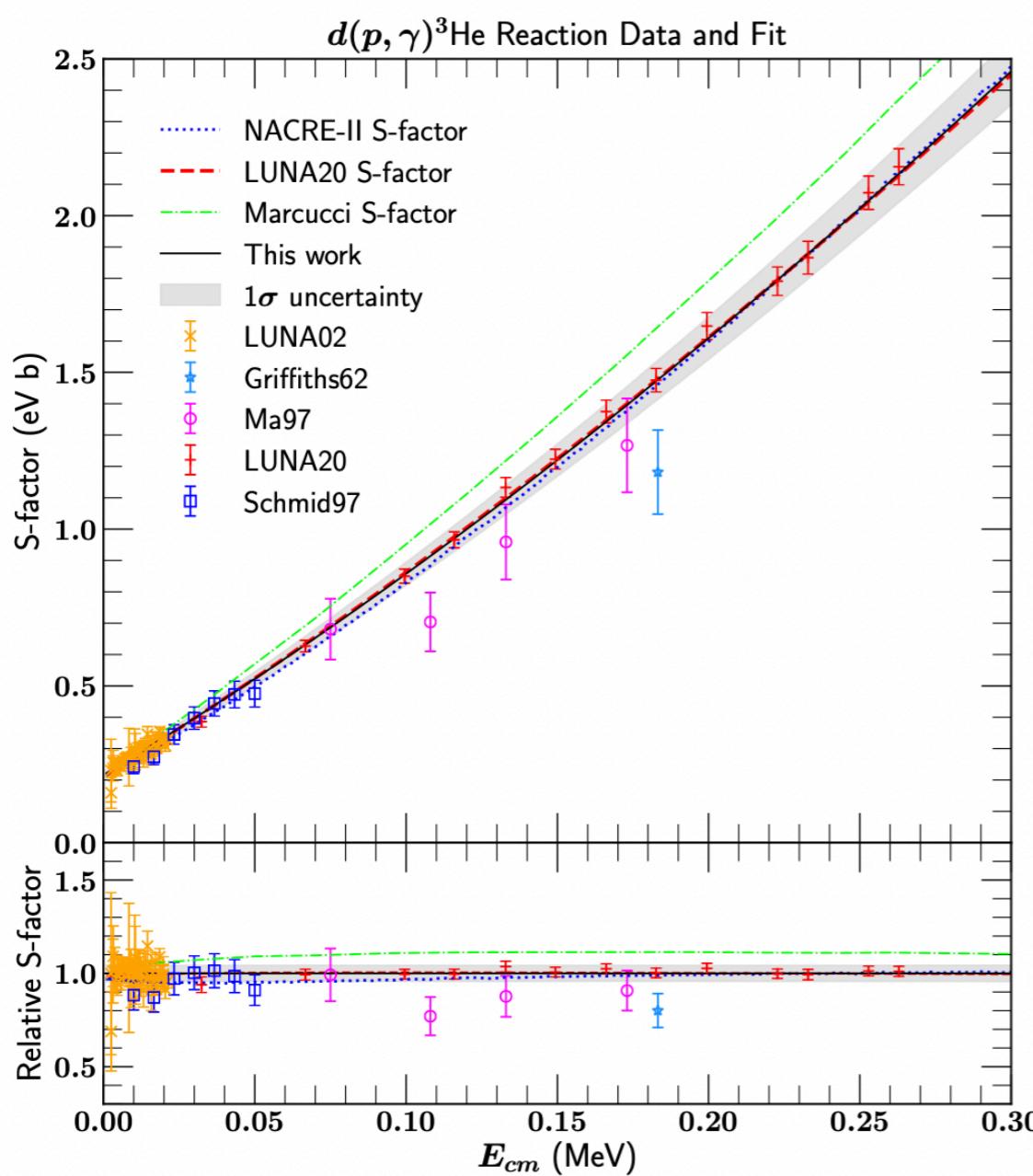


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# NEW DEUTERIUM BURNING RATES

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- 2020: LUNA collaboration measures  $pd \rightarrow \gamma^3\text{He}$  cross-section at BBN energies



[Yeh, Fields, Olive]

- This rate dominated theoretical uncertainties on BBN predictions
- New BBN + Planck constraint on  $N_{\text{eff}}$ :
  - $\Delta N_{\text{eff}} < 0.226$
  - updated treatment of other deuterium rates
  - ignoring Lithium, EMPRESS He

[Yeh, JS, Olive, Fields]

# COMPARING BBN AND CMB

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- Constraints on  $N_{\text{eff}}$ , baryon-to-photon ratio  $\eta$ :

Constraints Used	mean $\eta_{10}$	peak $\eta_{10}$	mean $N_\nu$	peak $N_\nu$	$\delta N_\nu$
CMB-only	$6.090 \pm 0.061$	$6.090^{+0.061}_{-0.062}$	$2.800 \pm 0.294$	$2.764^{+0.308}_{-0.282}$	0.513
BBN+ $Y_p$ +D	$5.986 \pm 0.161$	$5.980^{+0.163}_{-0.159}$	$2.889 \pm 0.229$	$2.878^{+0.232}_{-0.226}$	0.407
CMB+BBN	$6.087 \pm 0.061$	$6.088^{+0.061}_{-0.062}$	$2.848 \pm 0.190$	$2.843^{+0.192}_{-0.189}$	0.296
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One-sided upper  
limit on  $(N_{\text{eff}} - N_{\text{eff}}^{\text{SM}})$

# APPLICATION TO DARK SECTORS

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- $N_{\text{eff}}$  constraints on dark radiation:

$$\gg \Delta N_\nu = \frac{4}{7} g_{*\text{HS}}^{\text{IR}} \left( \frac{T_{\text{DR}}}{T_\nu} \right)^4 = 2.2 g_{*\text{HS}}^{\text{IR}} \left( \frac{T_{\text{DR}}}{T_\gamma} \right)^4$$

SM

HS

$T_\gamma$

$T_{\text{DR}}$

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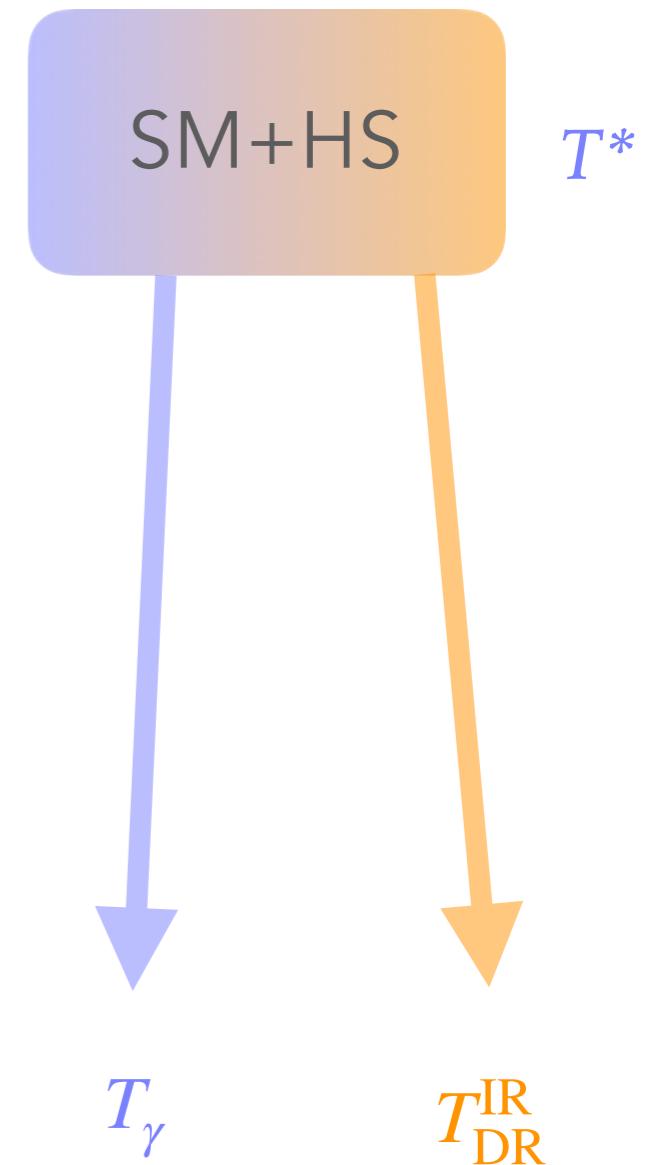
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- Given equilibrium at a common temperature  $T^*$ :

- $\Delta N_{\nu} = 2.2 g_{*HS}^{\text{IR}} \left( \frac{43/4}{g_{*S,\text{SM}}(T_*)} \right)^{4/3} \left( \frac{g_{*S,\text{HS}}(T_*)}{g_{*S,\text{HS}}(T_{\text{DR}}^{\text{IR}})} \right)^{4/3}$

- $\delta N_{\nu} < 0.226$  : at most two degrees of freedom in HS

- no evolution within HS after decoupling



# APPLICATION TO DARK SECTORS

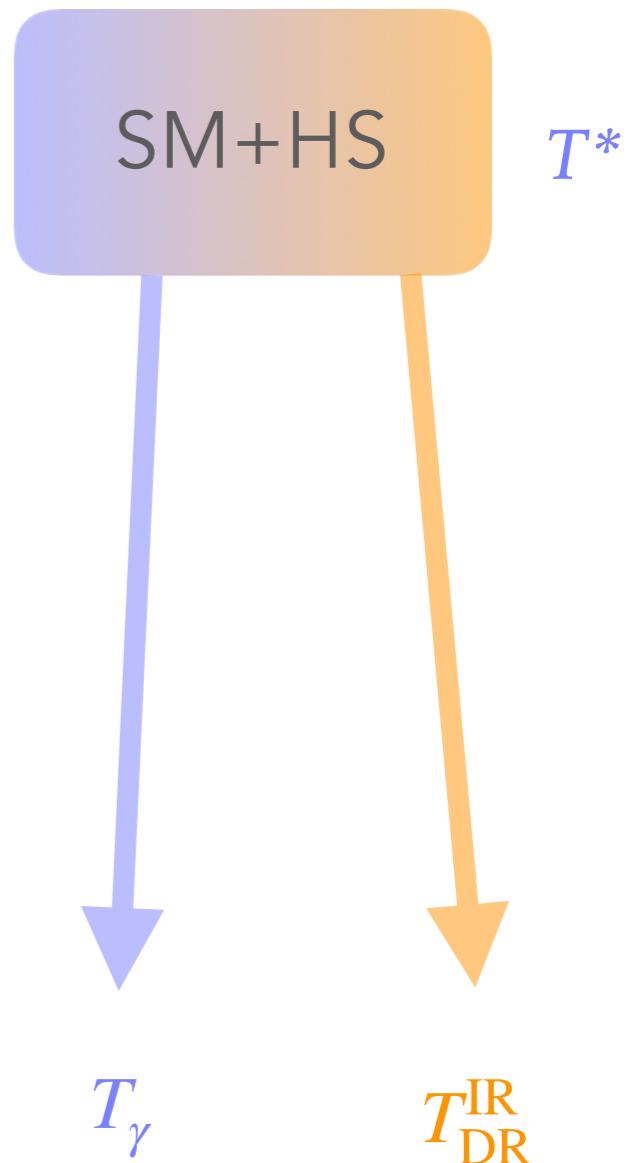
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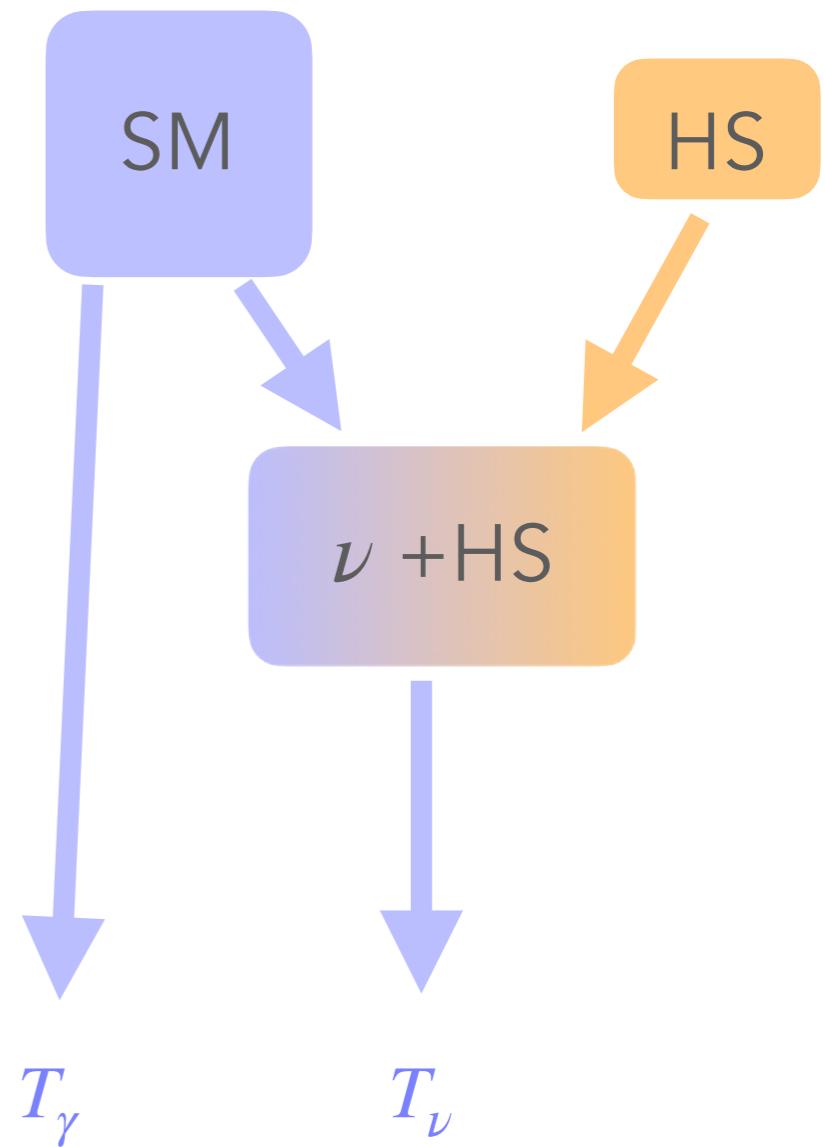
# APPLICATION TO DARK SECTORS

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- Limiting variation of  $N_{\text{eff}}$  between BBN, CMB
- Late-time equilibration with neutrinos:

$$\Delta N_\nu \approx 3 \left( 1 + \frac{g^*_{HS}}{g^*_\nu} \right)^{1/3} \left( 1 + \frac{g^*_{HS}}{g^*_\nu} \left( \frac{T_{HS}}{T_\nu} \right)^4 \right) - 1$$

- no more than one degree of freedom
- initial temperature ratio  $< 0.6$



[Berlin, Blinov; Berlin, Blinov, Li]

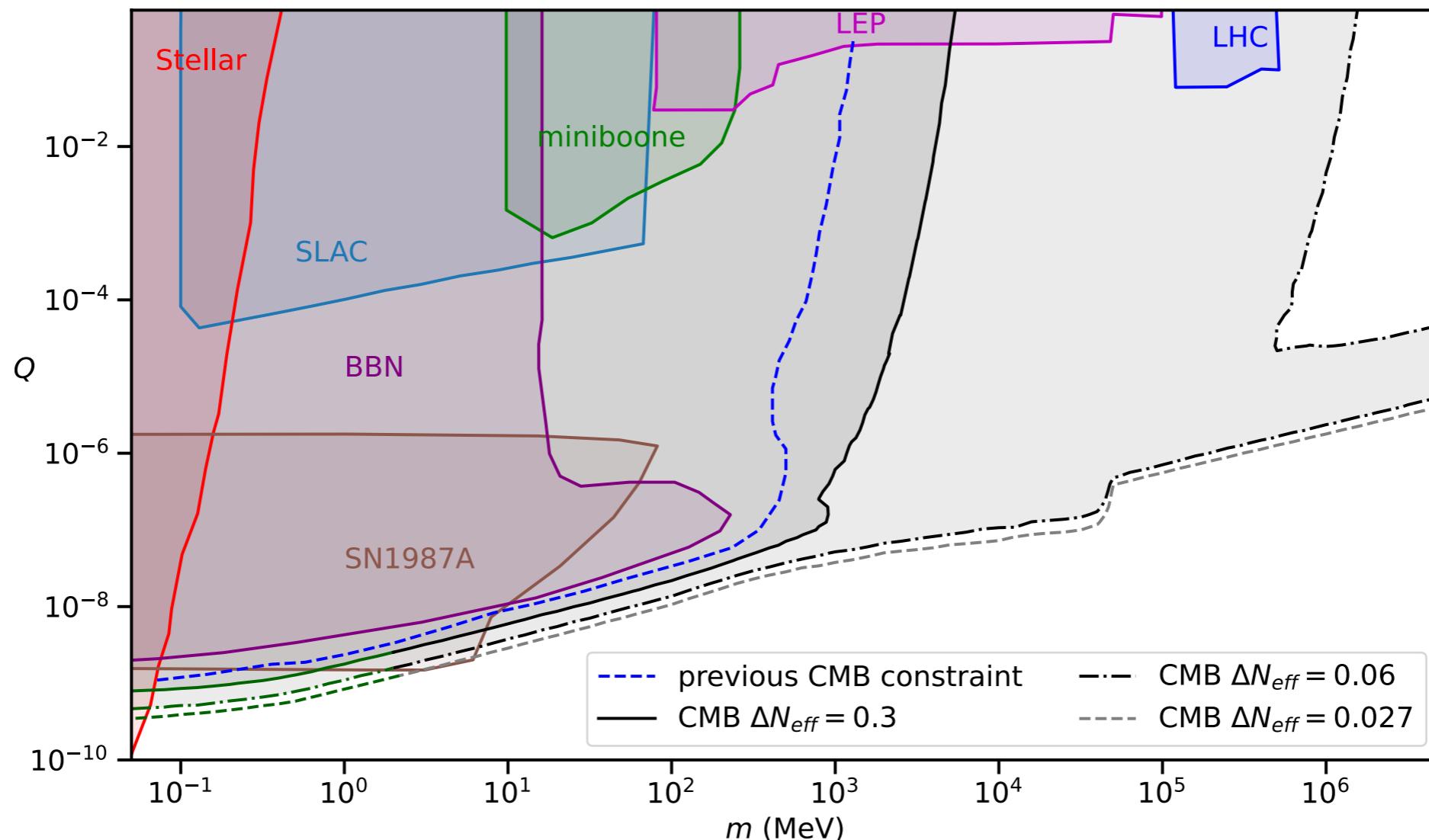
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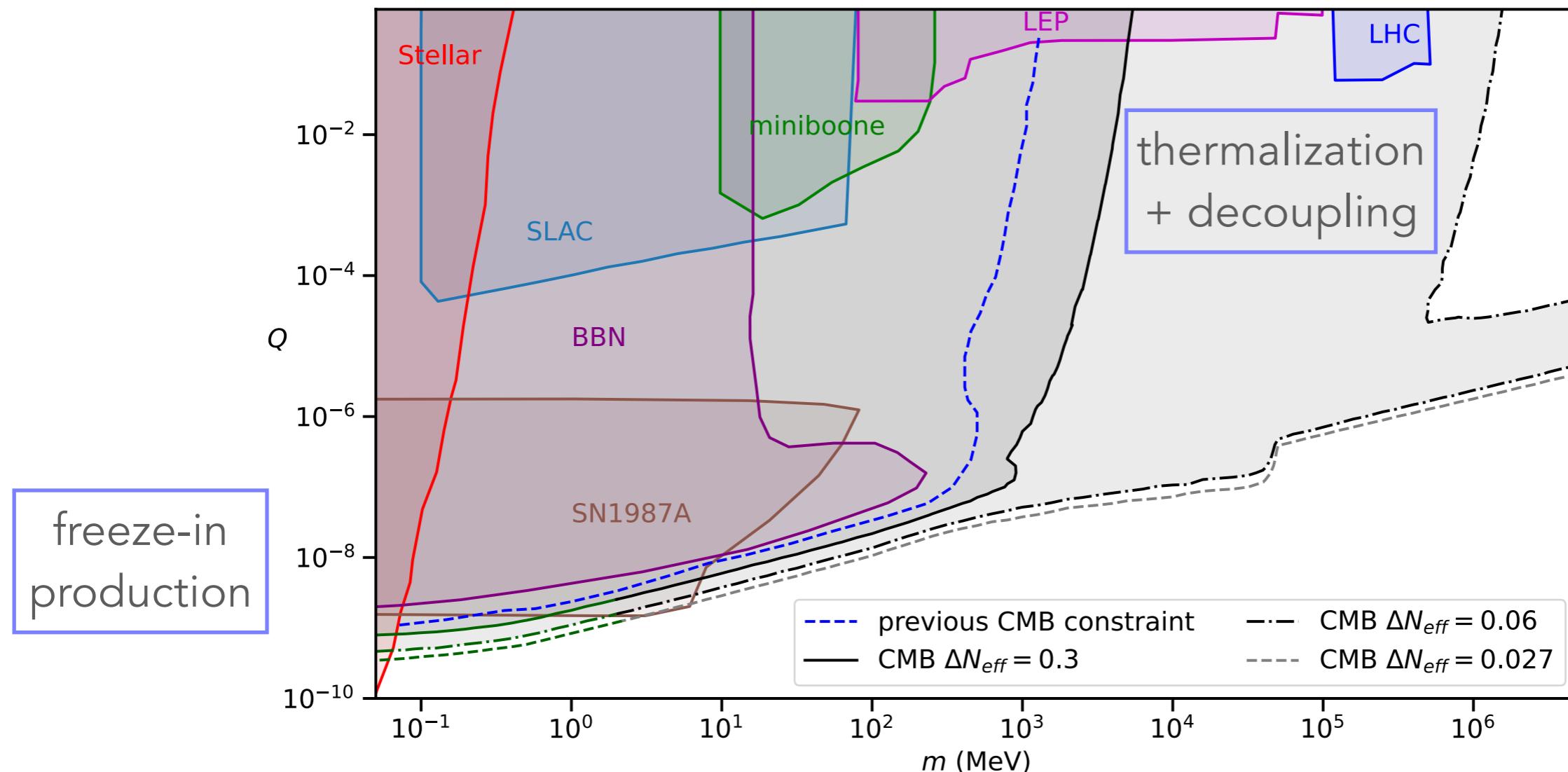
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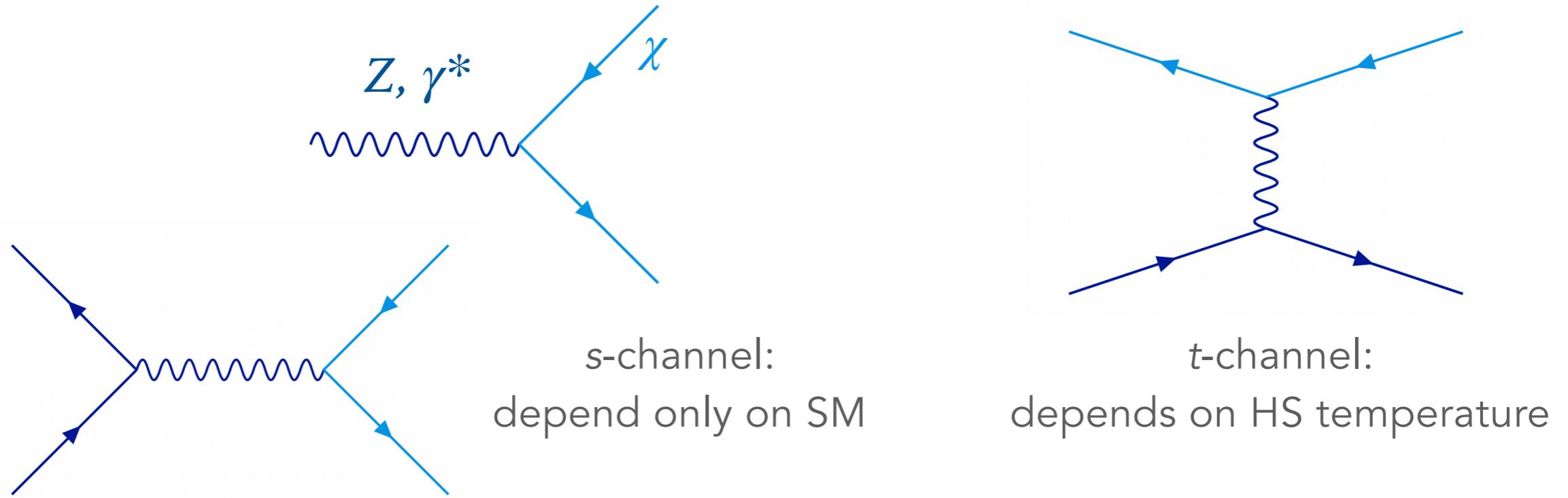
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# $N_{\text{eff}}$ FOR OUT-OF-EQUILIBRIUM DARK SECTORS

- Evaluating energy evolution in out-of-equilibrium dark sectors can be technically involved
- Dominant energy transfer processes for millicharged particle:



- Energy transferred to  $\chi$  is efficiently deposited into dark photons in region where  $N_{\text{eff}}$  is constraining

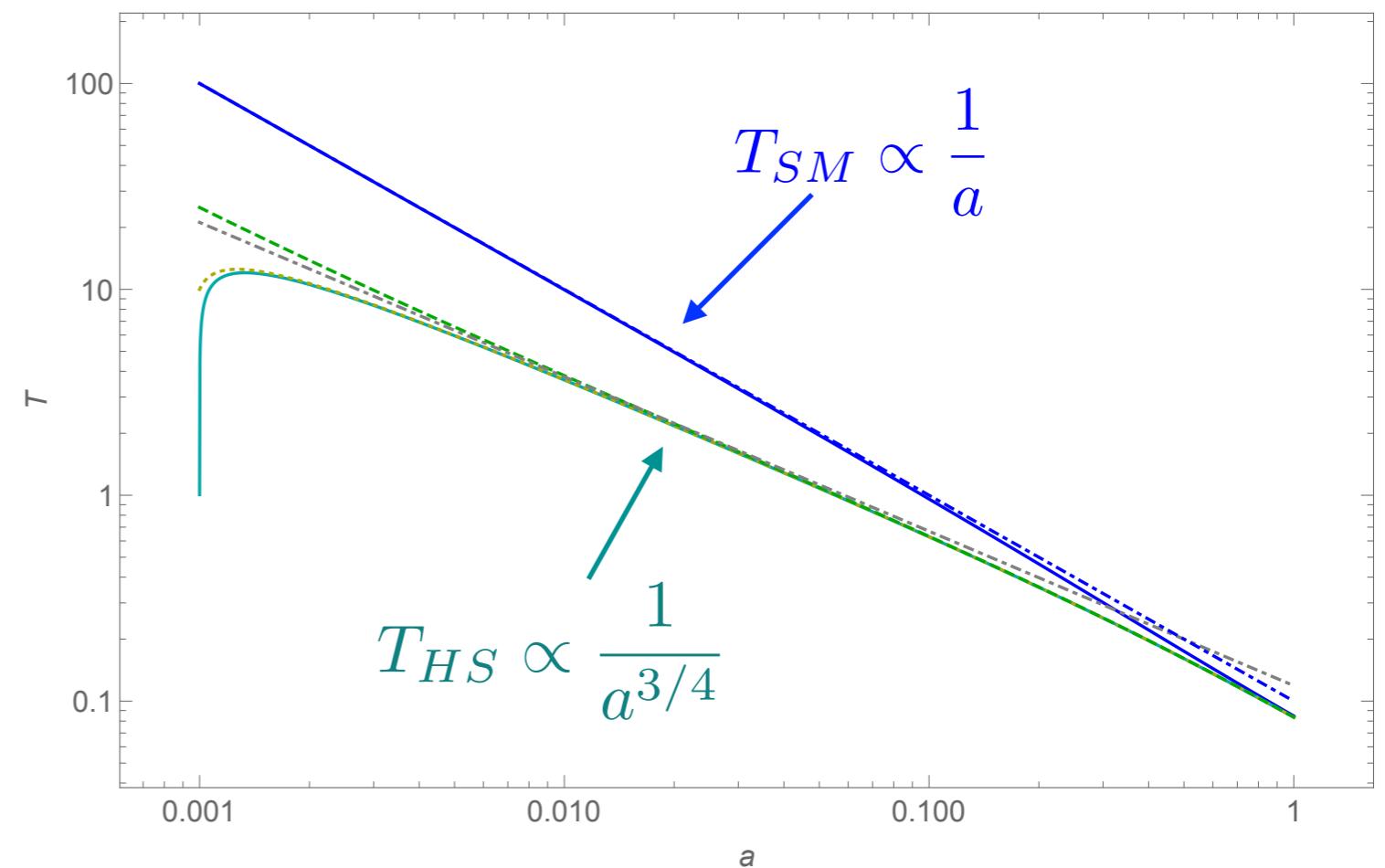
# ALGORITHM TO OBTAIN SIMPLE CONSERVATIVE LIMIT

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- Neglect  $t$ -channel processes: lower bound on energy transfer
- For renormalizable interactions: resulting HS energy density has an **attractor solution**

$$\dot{\rho}_{SM} + 4H\rho_{SM} \approx 0$$

$$\dot{\rho}_{HS} + 4H\rho_{HS} = \mathcal{C}(T_{SM})$$

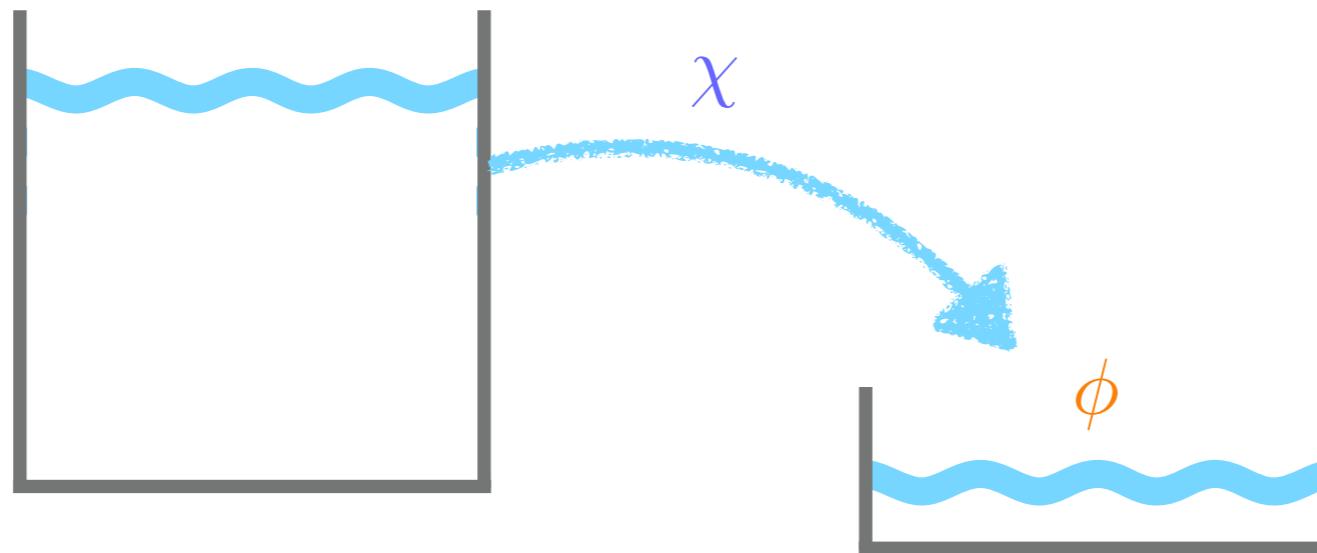


- final energy density can be evaluated algebraically from collision term, given a scale where energy transfer stops

# CONSERVATIVE BOUND AND APPLICATIONS

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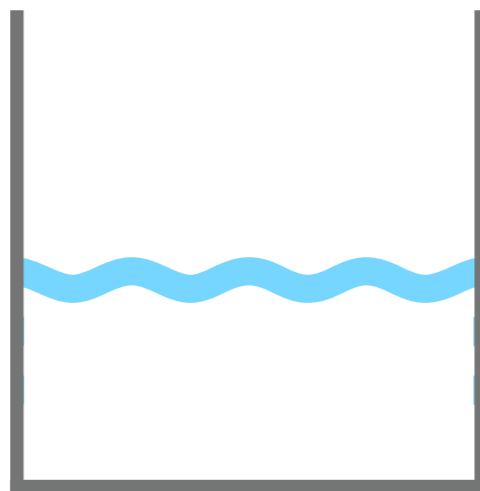
- Under these conditions, simple visualization:



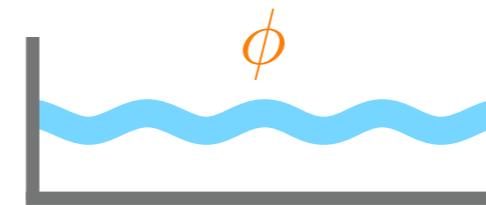
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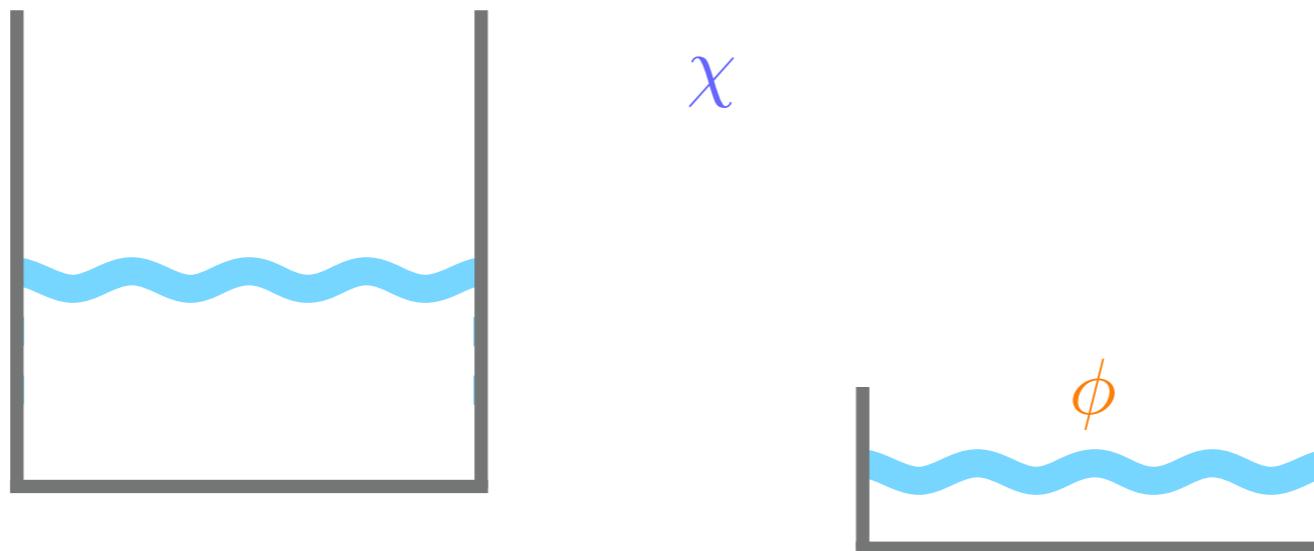
$\chi$



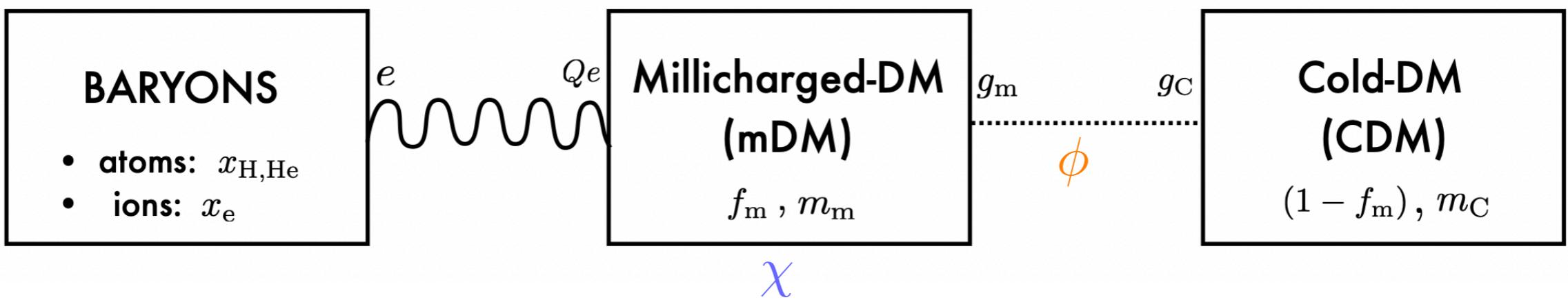
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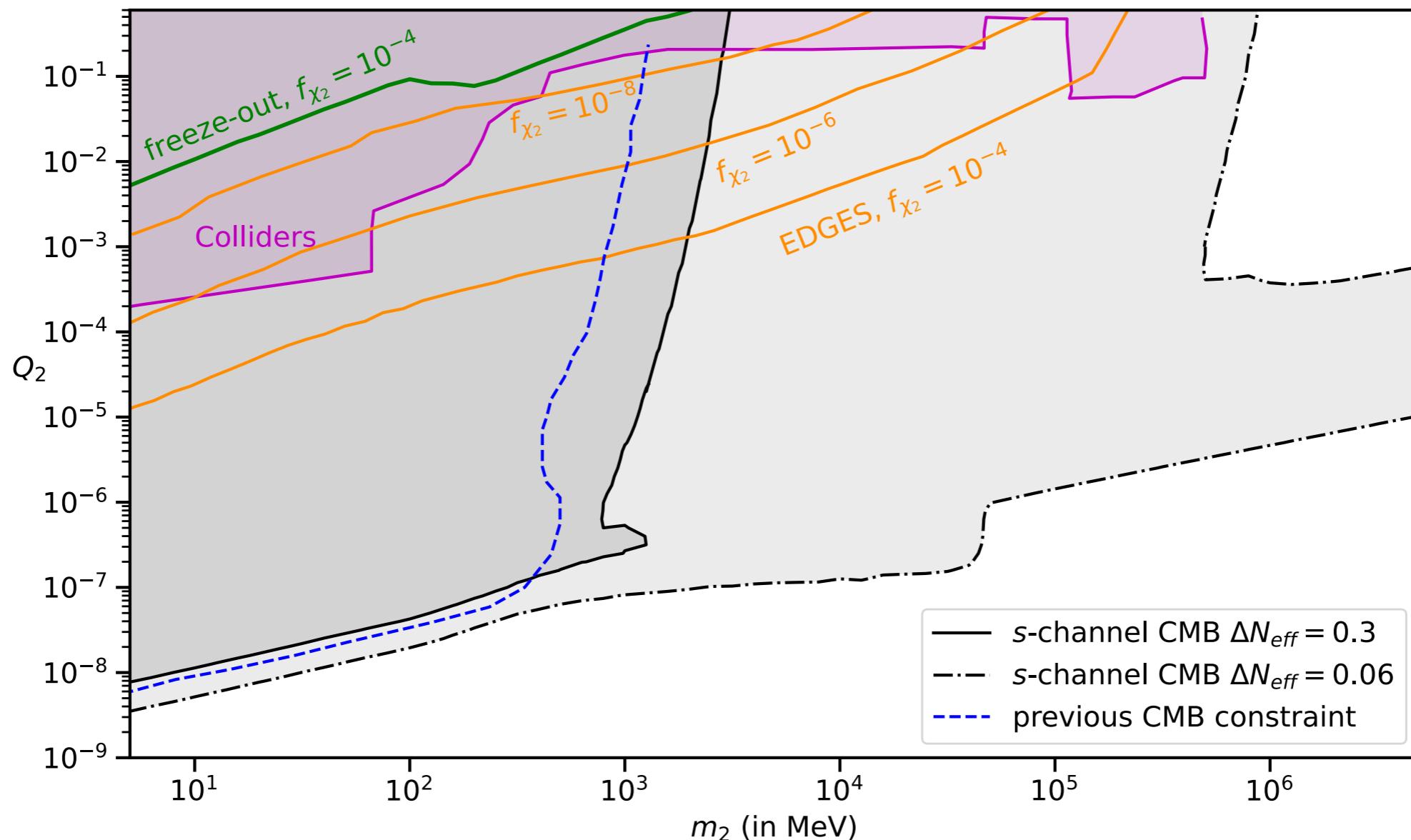


- For example: proposal for extra chilling of baryons in “dark ages”: [Liu, Outmezguine, Redigolo, Volansky]



# MODEL-INSENSITIVE: APPLY TO MORE COMPLICATED MODELS

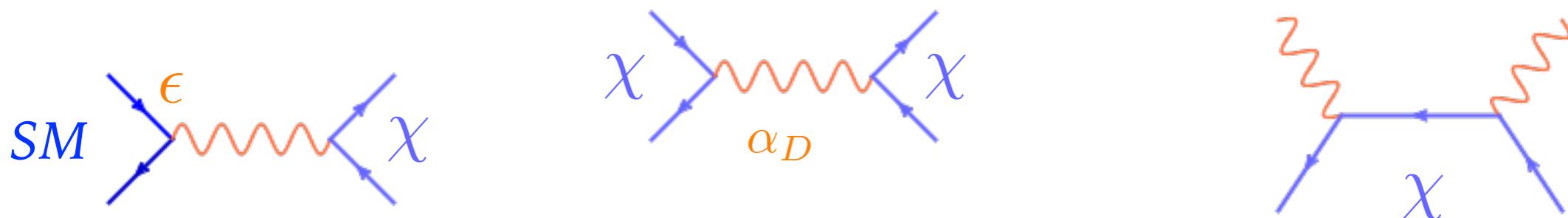
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# DARK PHOTON ABUNDANCE AND FREEZE-IN DM

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- Cosmological histories of out-of-equilibrium dark sectors can be important for understanding terrestrial observables
- Freeze-in production of sub-GeV DM: important benchmarks for low-mass direct detection program
- Standard benchmark model for low-mass direct detection: Dirac fermion DM, interacting with light dark photon



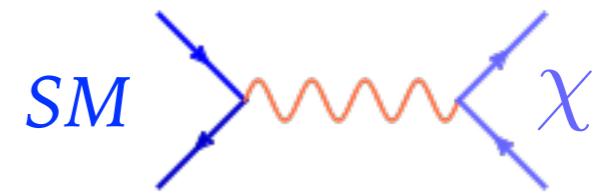
# FREEZE-IN DARK MATTER

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- Freeze-in through renormalizable interactions is IR-dominated and therefore **UV-insensitive**:

$$\dot{n}_\chi + 3Hn_\chi = 2\langle\sigma v\rangle n_f^2$$

- SM source term shuts off at  $T \sim m_\chi$
- Residual UV sensitivity: initial condition on  $n_\chi$ 
  - (small) constant offset in final abundance
- Have implicitly assumed DM **does not interact** after it is produced

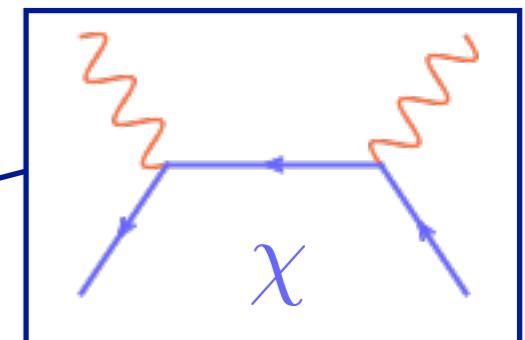


# FREEZE-IN, FREEZE-OUT

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- However in models with a light mediator, subsequent interactions among the dark particles can be **very important**
- Assuming dark sector is in kinetic equilibrium:

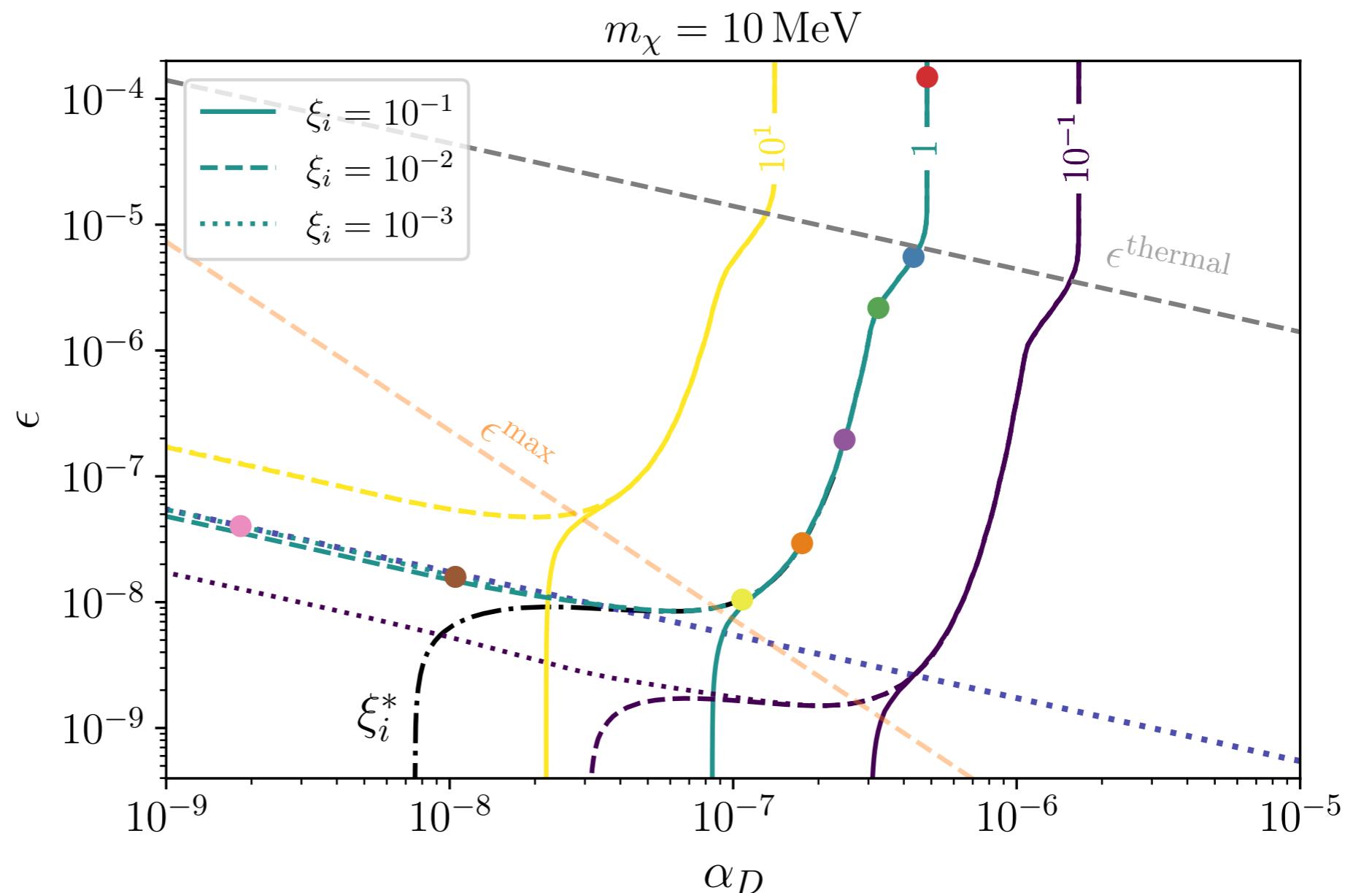
$$\dot{n}_{\text{DM}} + 3Hn_{\text{DM}} = -\frac{1}{2}\langle\sigma v\rangle_{\text{fo}}(n_{\text{DM}}^2 - n_{\text{eq}}^2(\tilde{T}))$$



$$\begin{aligned} \text{SM} &\rightarrow \chi \rightarrow +2 \sum_f \langle\sigma v\rangle_{\text{fi}} n_f^2(T) + 2\langle\Gamma\rangle_Z n_Z(T) \\ \dot{\rho}_{\text{HS}} + 3H(\rho_{\text{HS}} + P_{\text{HS}}) &= \sum_f \langle\sigma v E\rangle_{\text{fi}} n_f^2(T) + \langle\Gamma E\rangle_Z n_Z(T) \end{aligned}$$

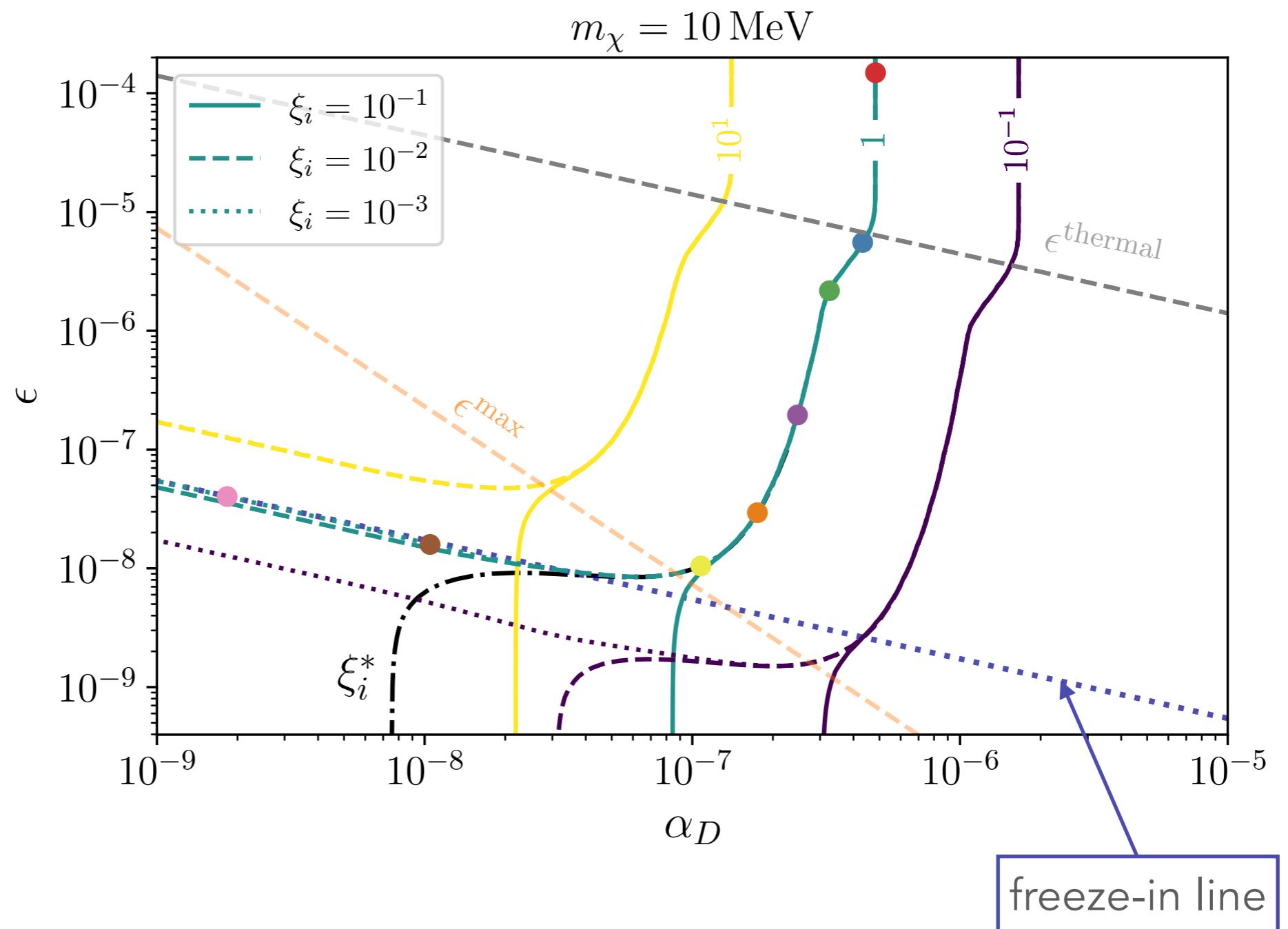
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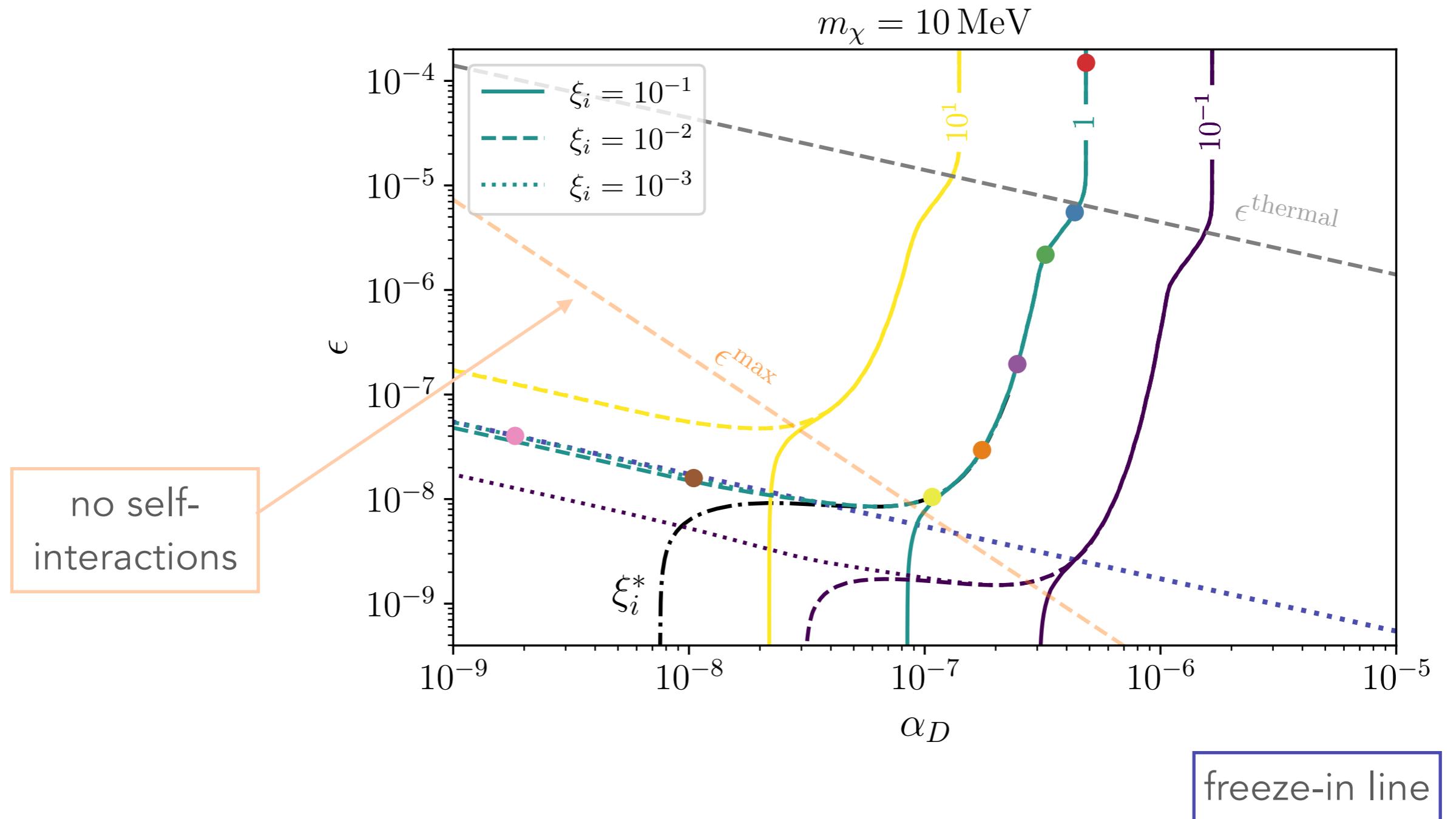
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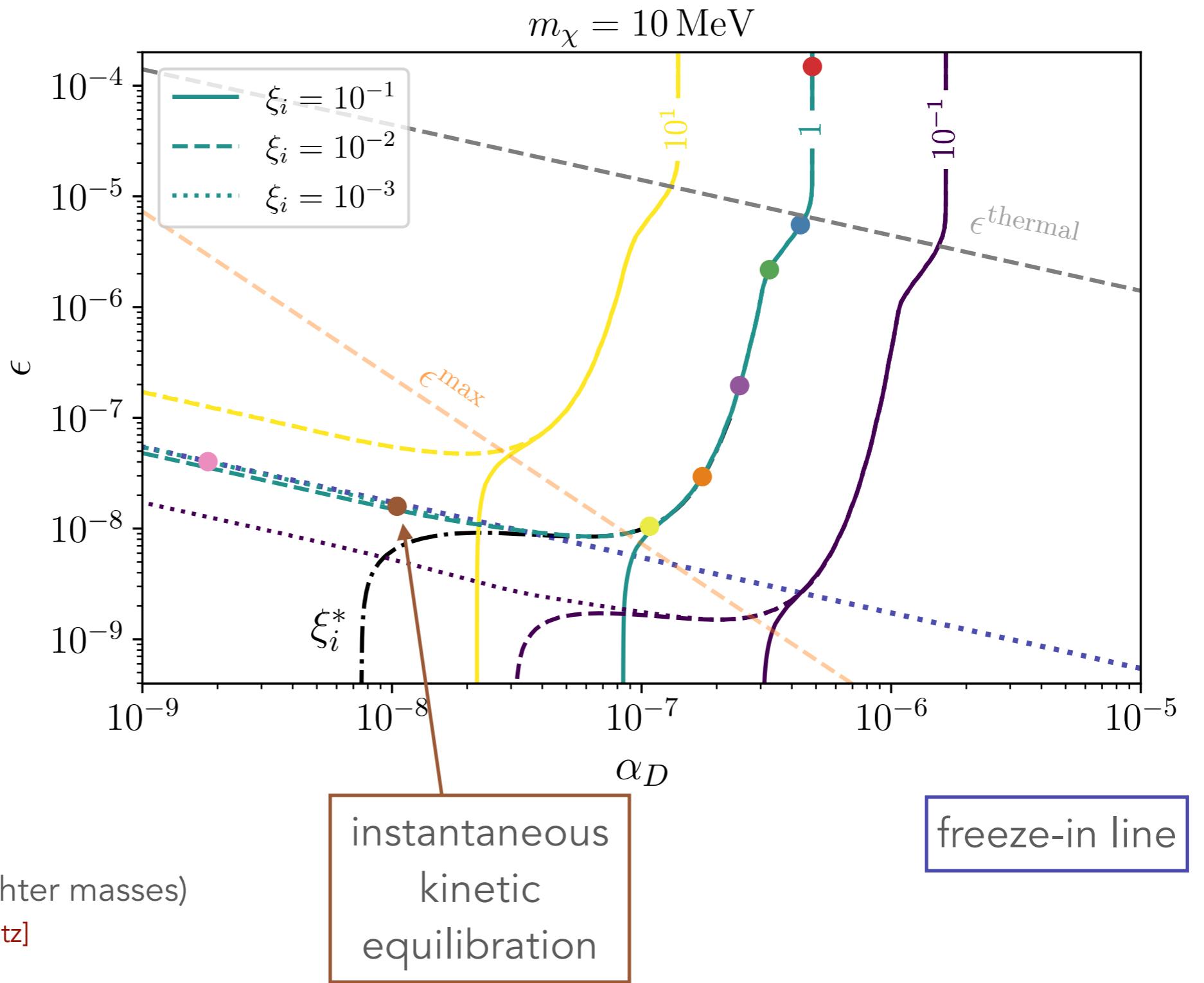


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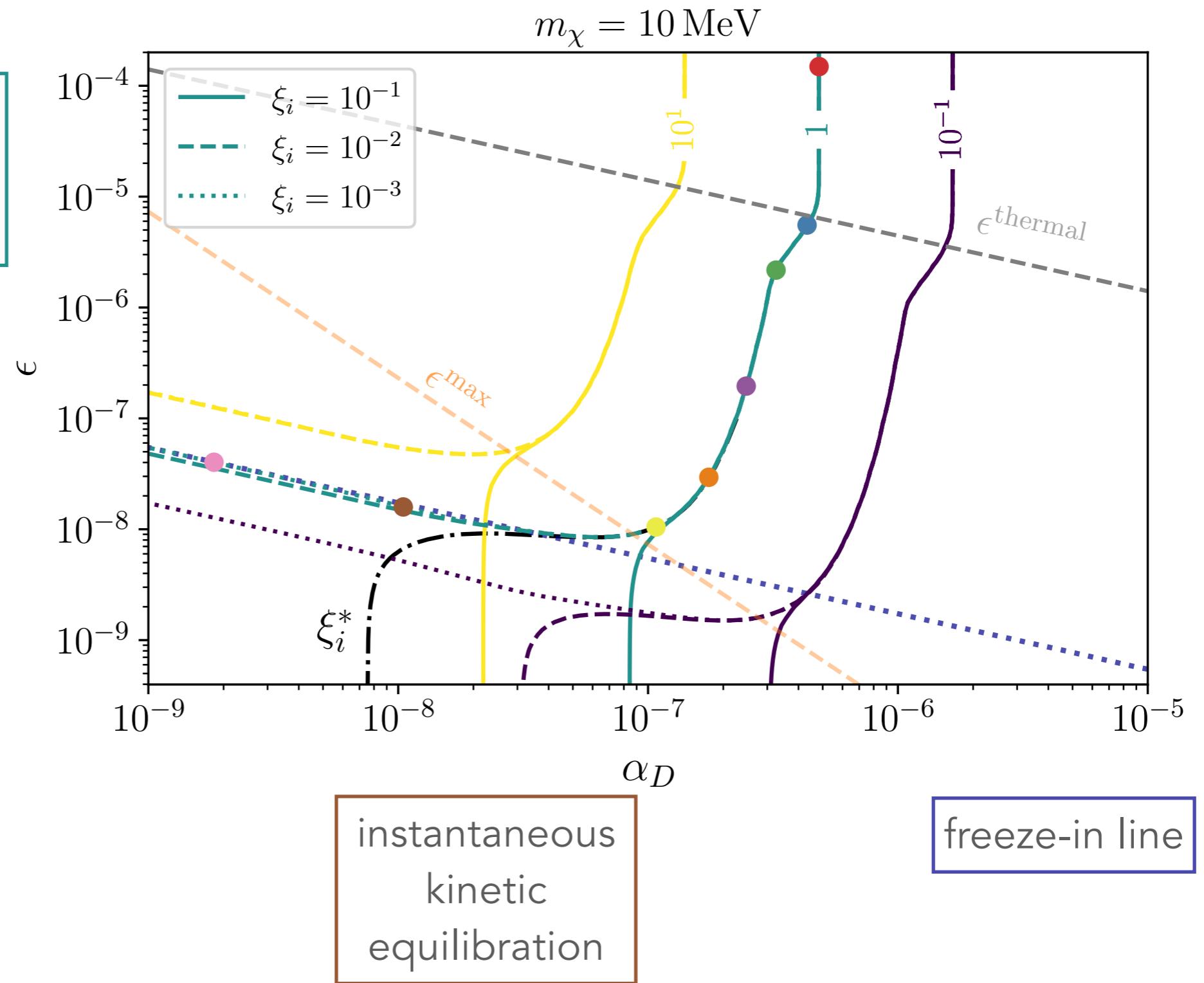
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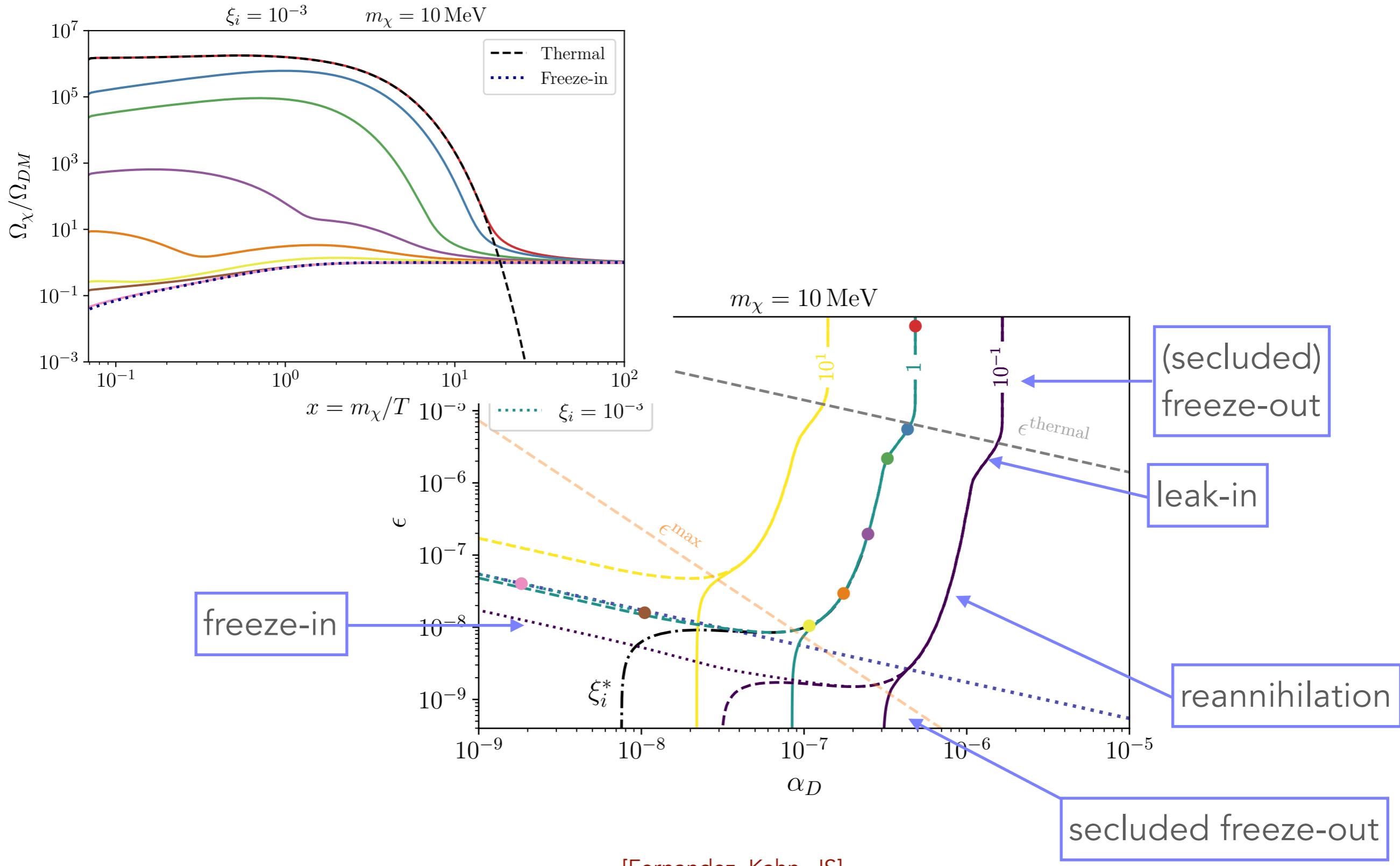
# PHASES OF BEHAVIOR

initial  
temperature ratio  
 $\xi_i = T(a_i)/T_{SM}(a_i)$

no self-  
interactions

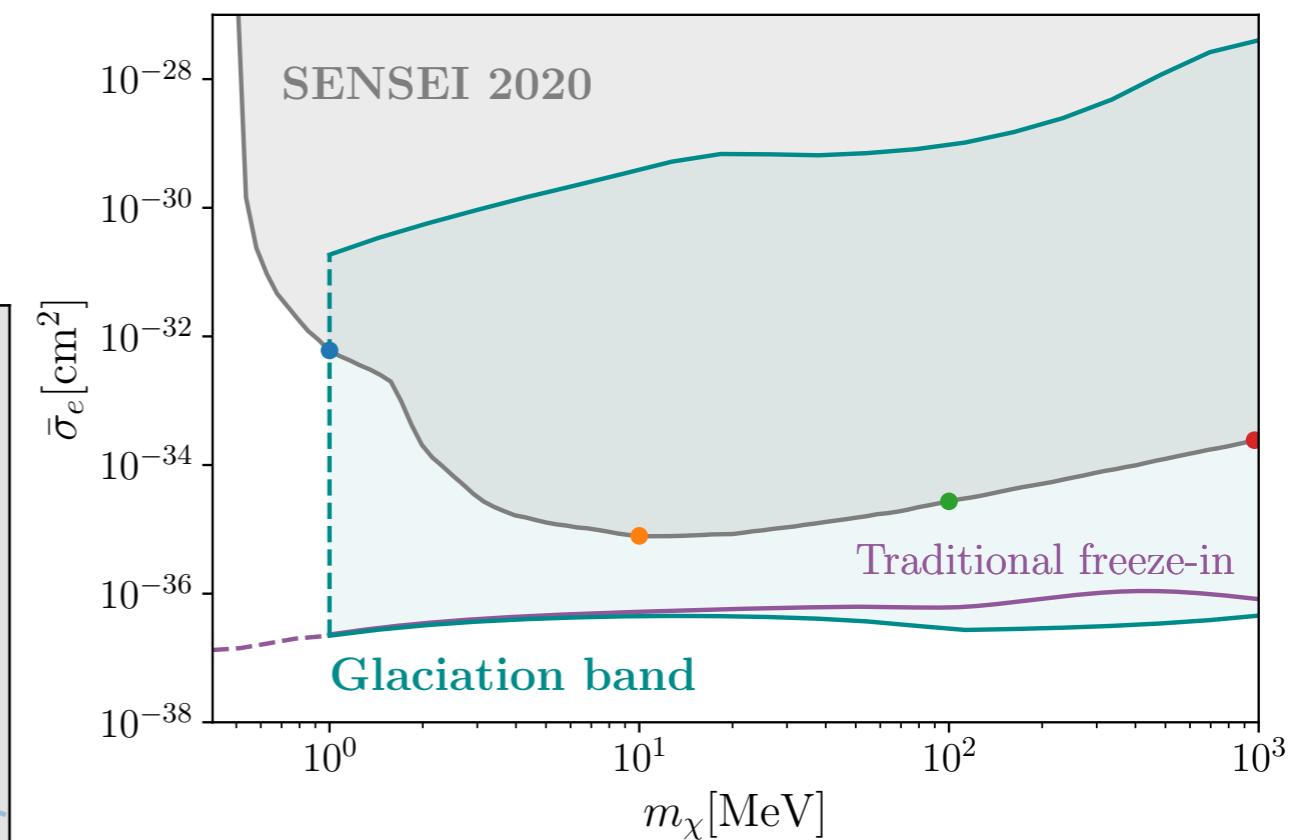
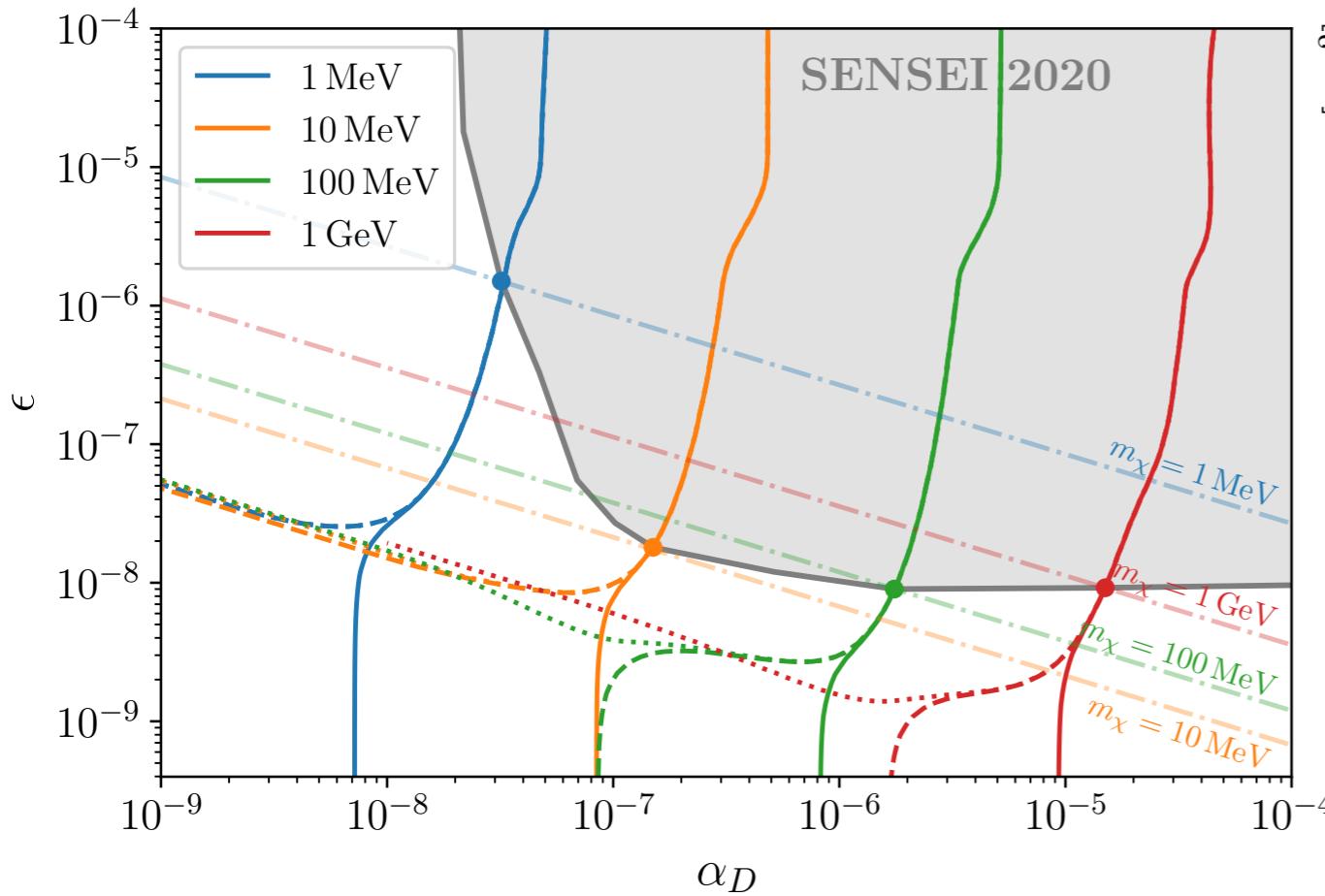


# PHASES OF BEHAVIOR



# INITIAL CONDITION DEPENDENCE FOR DIRECT DETECTION

- ▶ currently direct detection is probing UV-insensitive regions, but near the 'freeze-in' target predictions diverge depending on initial conditions



# SUMMARY

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- BBN and the CMB are powerful probes of dark sectors
  - New BBN constraints on  $N_{\text{eff}}$  further restrict scope for relativistic relics
  - Future CMB observations will be a major leap in sensitivity
- MeV-scale dark sectors interacting with SM: out-of-equilibrium
  - IR-dominance can help simplify many calculations
  - but sometimes it doesn't!