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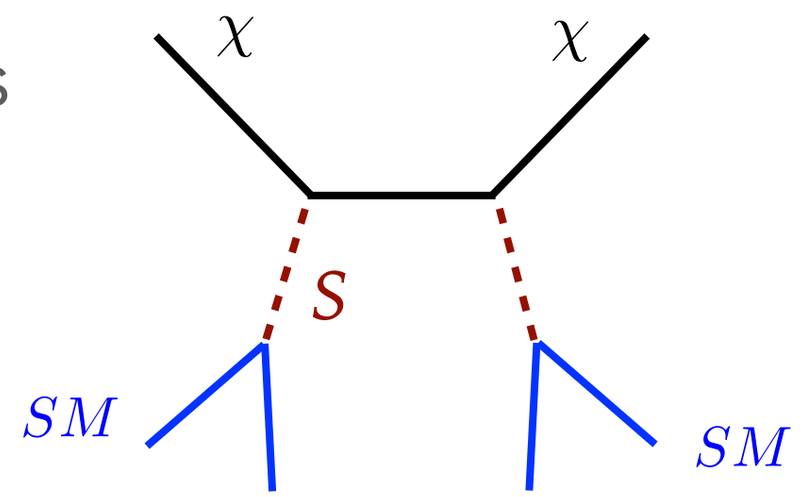
PROBING COSMIC HISTORIES IN THE LAB

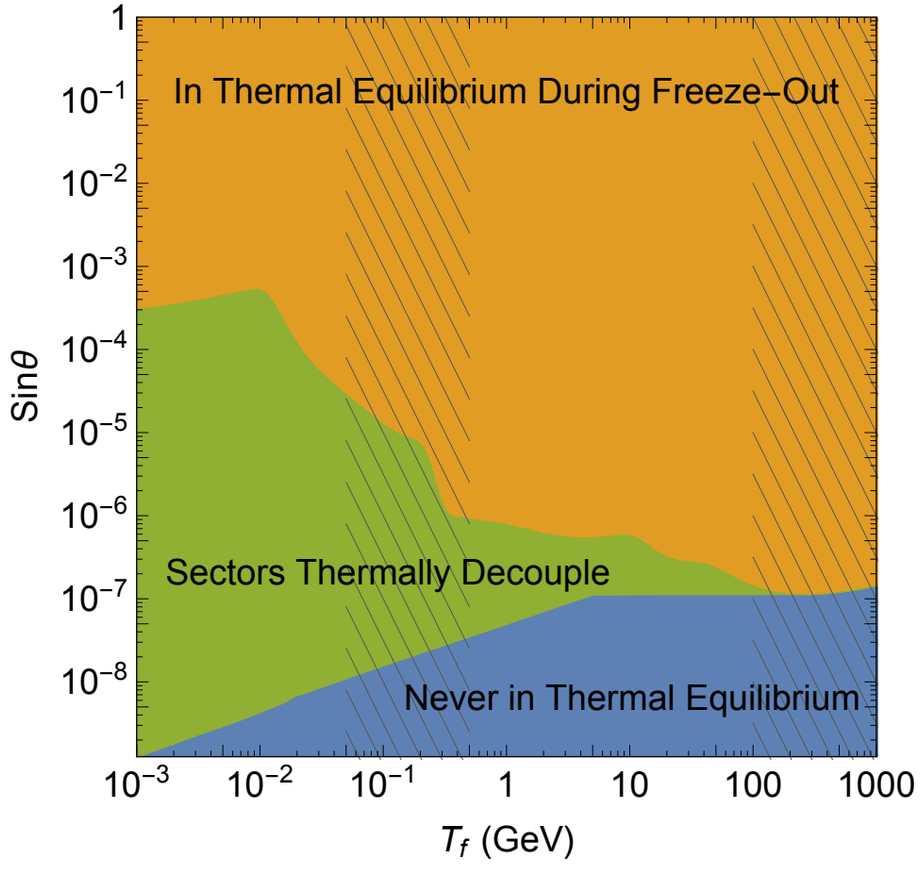
DIRECT DETECTION AND DARK SECTORS

- Direct detection experiments are now so sensitive that searches for dark sectors must make assumptions about the thermal history of dark matter

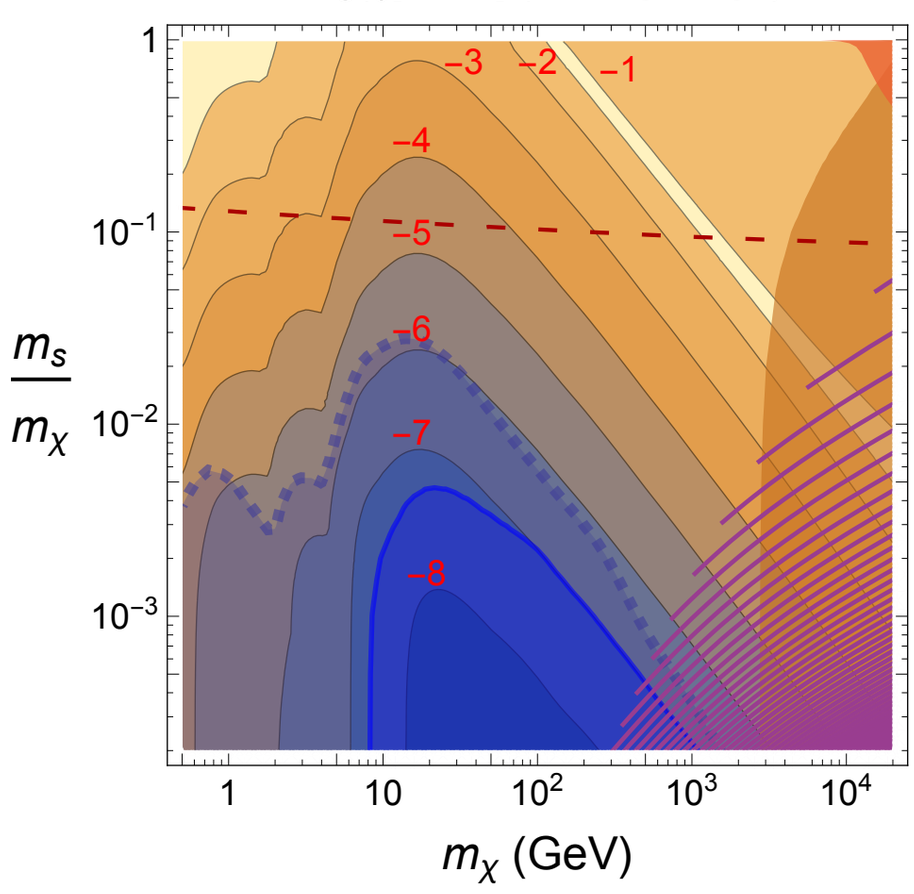
DIRECT DETECTION AND DARK SECTORS

- Generically true for models with dark forces
- Higgs-portal mediator example:





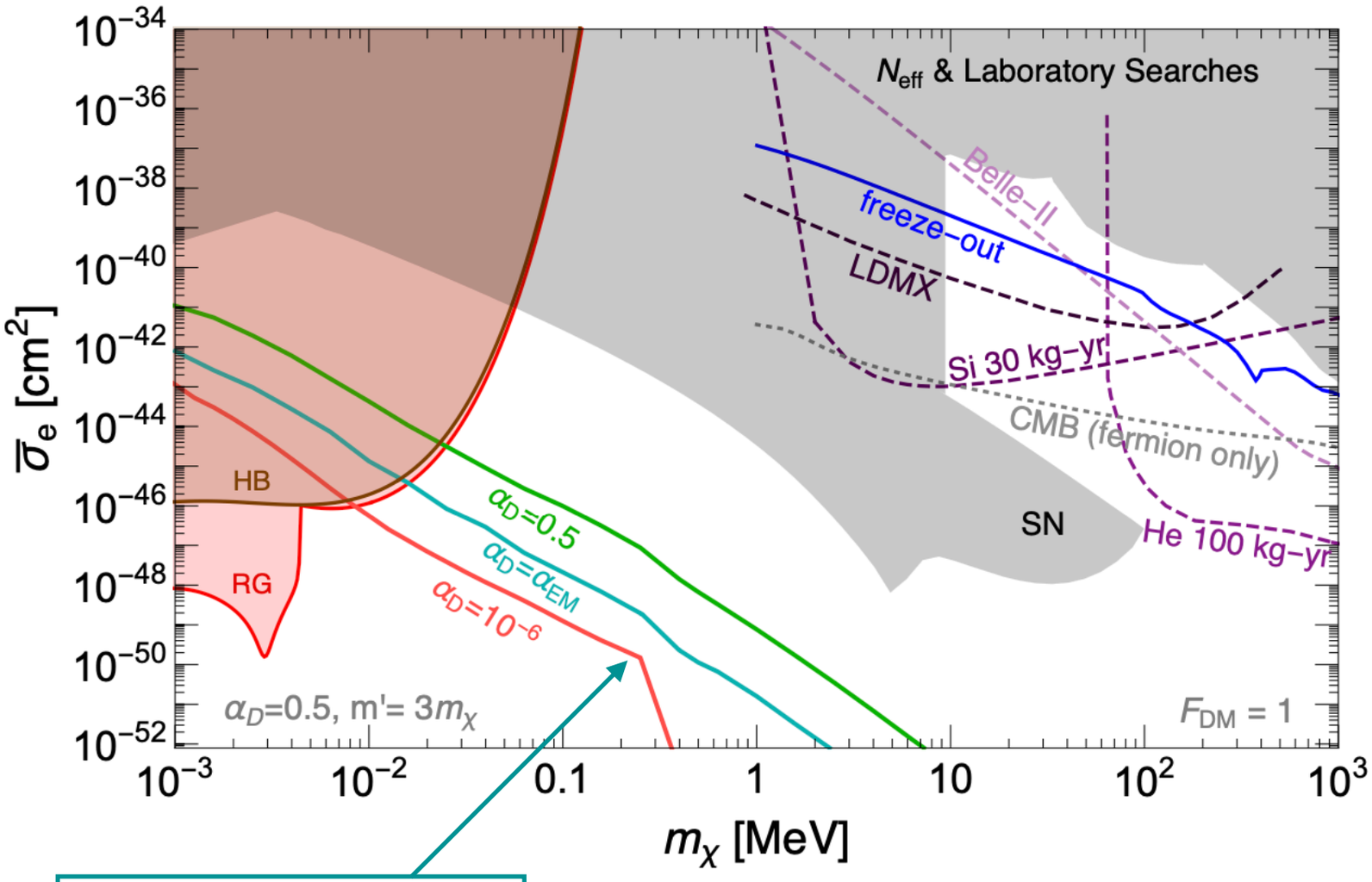
$\mathrm{Log}_{10}[\mathrm{Sin}\,\theta]$ (for $T_{HS} = T_{SM}$)



[Evans, Gori, JS]

DIRECT DETECTION AND FREEZE-IN

- For sub-GeV dark matter, freeze-in models are key targets



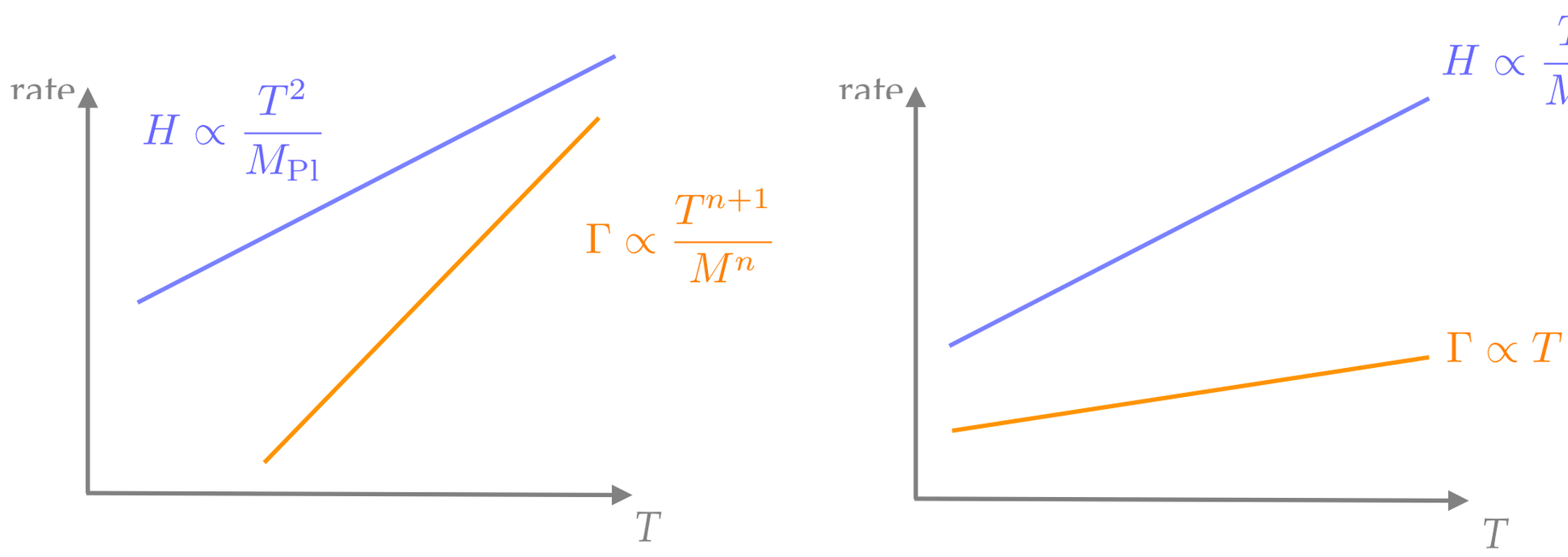
[Chang, Essig, Reinert]

DIRECT DETECTION AND FREEZE-IN

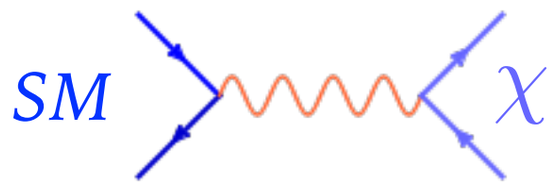
- Setting out to test out-of-equilibrium models requires more careful thought than testing WIMPy models
- Thermal equilibrium is a profound simplifier
  - Simpler calculations: easier to translate model into prediction
  - Erases dependence on initial conditions

FREEZE-IN

- freeze-in with light mediators is UV-insensitive: production rate falls off more slowly than Hubble



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

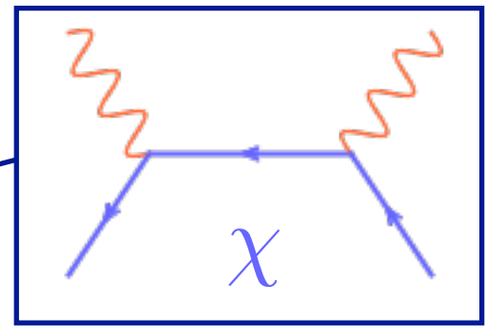


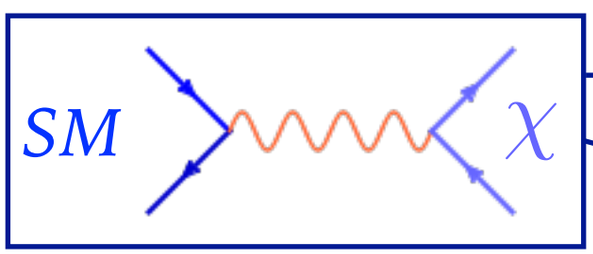
- SM source term shuts off at $T \sim m_\chi$
- Residual UV sensitivity: initial condition on n_χ
  - (very very small) constant off-set in relic abundance

FREEZE-IN, FREEZE-OUT

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

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





$$+2\sum_f \langle\sigma v\rangle_{\rm fi} n^2_f(T) + 2\langle\Gamma\rangle_Z n_Z(T)$$

$$\dot{\rho}_{\rm HS} + 3H\left(\rho_{\rm HS} + P_{\rm HS}\right) = \sum_f \langle\sigma v E\rangle_{\rm fi}\, n^2_f(T) + \langle\Gamma E\rangle_Z n_Z(T)$$

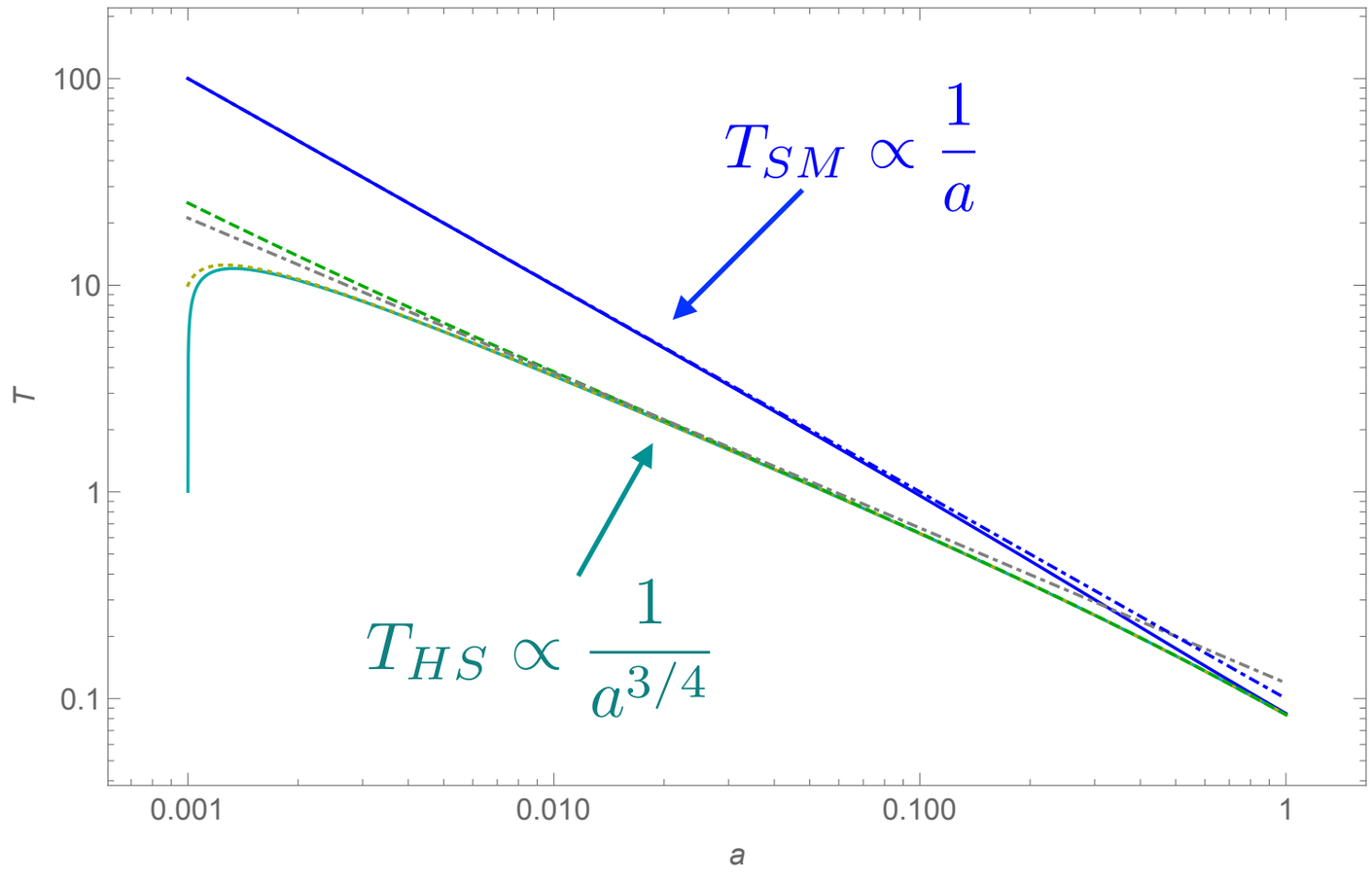
[Chu, Hambye, Tytgat; Krnjaic; Berger et al; Evans, Gaidau, JS; Hambye et al; …]

FREEZE-IN, FREEZE-OUT

- Initial conditions also for dark photon: parameterize as initial temperature ratio $\xi_i = T(a_i)/T_{SM}(a_i)$
  - An assumption: internal kinetic equilibrium
  - How does DM abundance depend on this initial condition?
  - What aspects remain UV-insensitive?

TEMPERATURE EVOLUTION: LEAK-IN

- Energy injection into hidden radiation bath makes it evolve non-adiabatically:

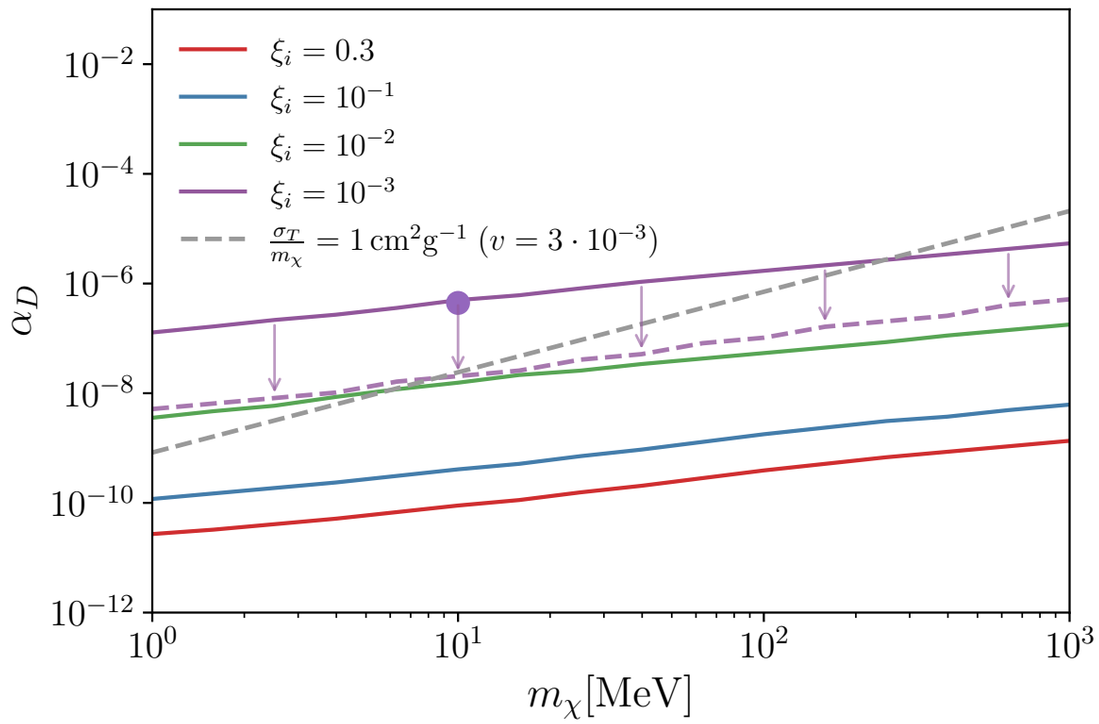


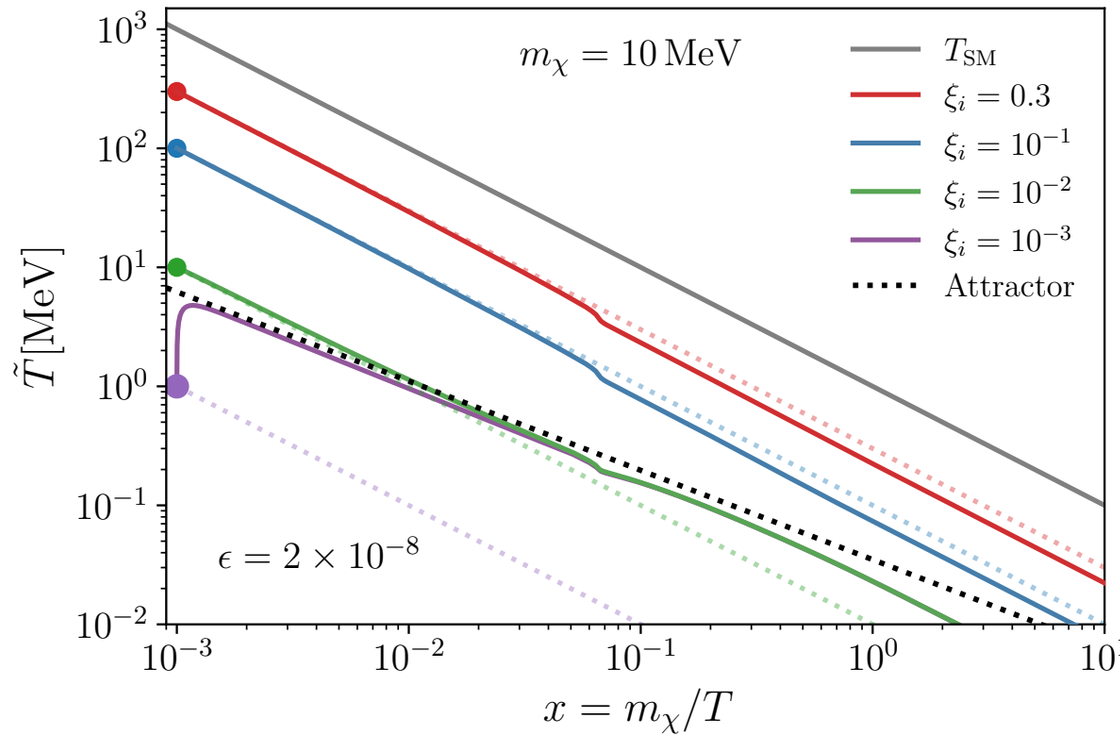
- UV-insensitive quasi-static equilibrium phase: leak-in
  - attractor solution: $\propto \epsilon^2 \alpha_D$

[Chu, Hambye, Tytgat; Evans, Gaidau, JS]

KINETIC EQUILIBRATION

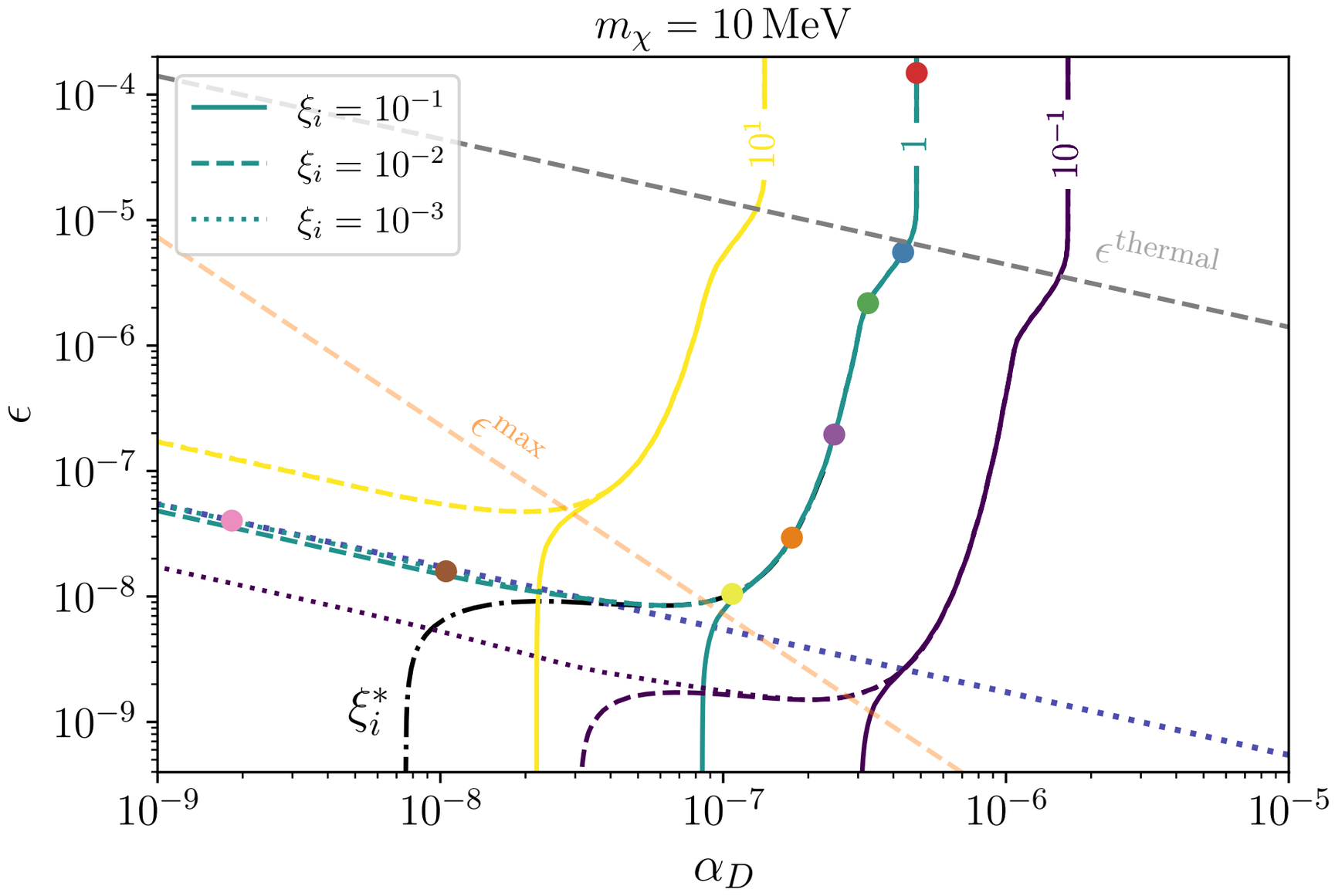
- this attractor solution helps extend region where instantaneous kinetic equilibration is a good approximation:





[Fernandez, Kahn, JS]

PHASES OF BEHAVIOR



[Fernandez, Kahn, JS]

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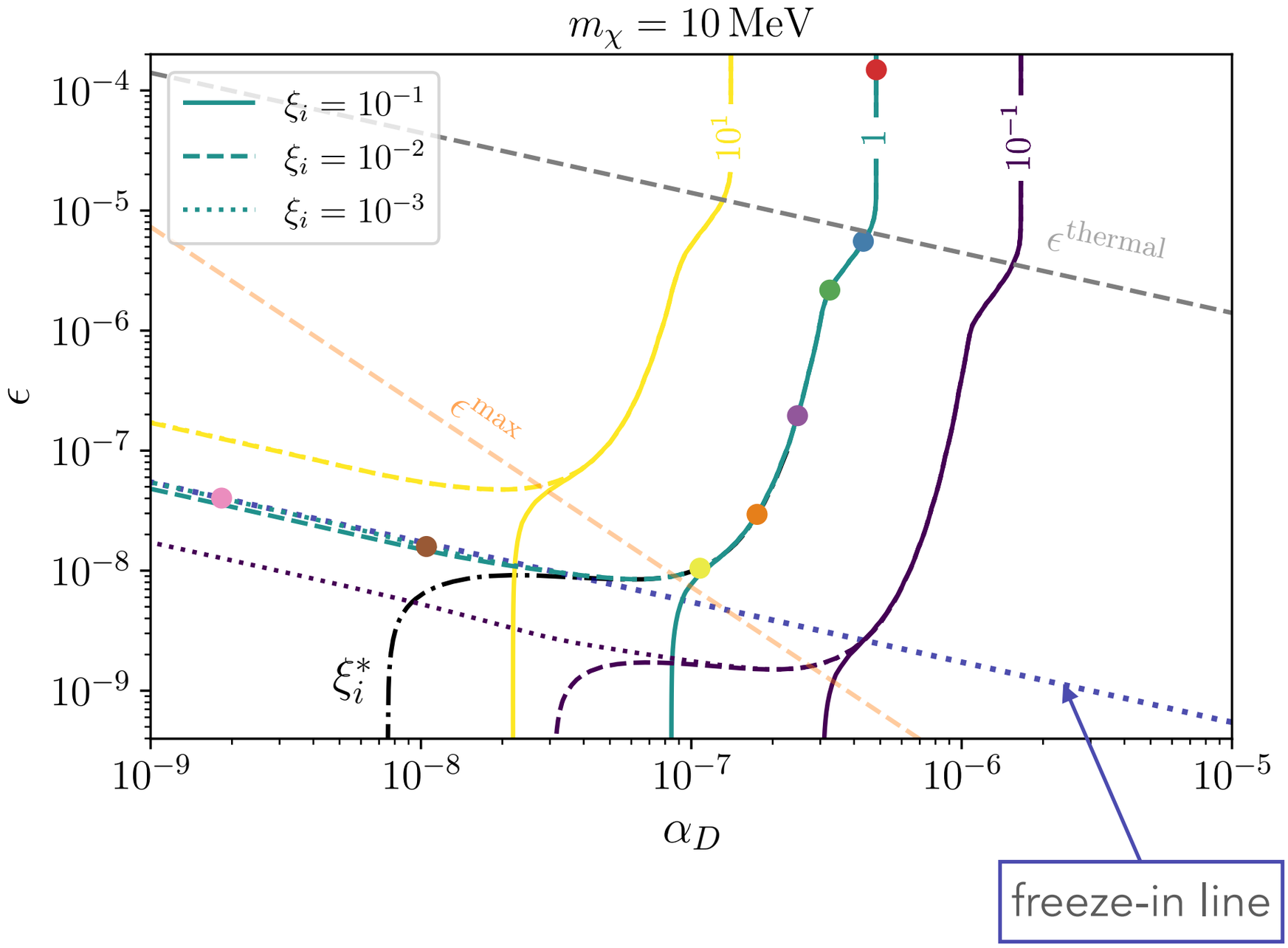

[Fernandez, Kahn, JS]

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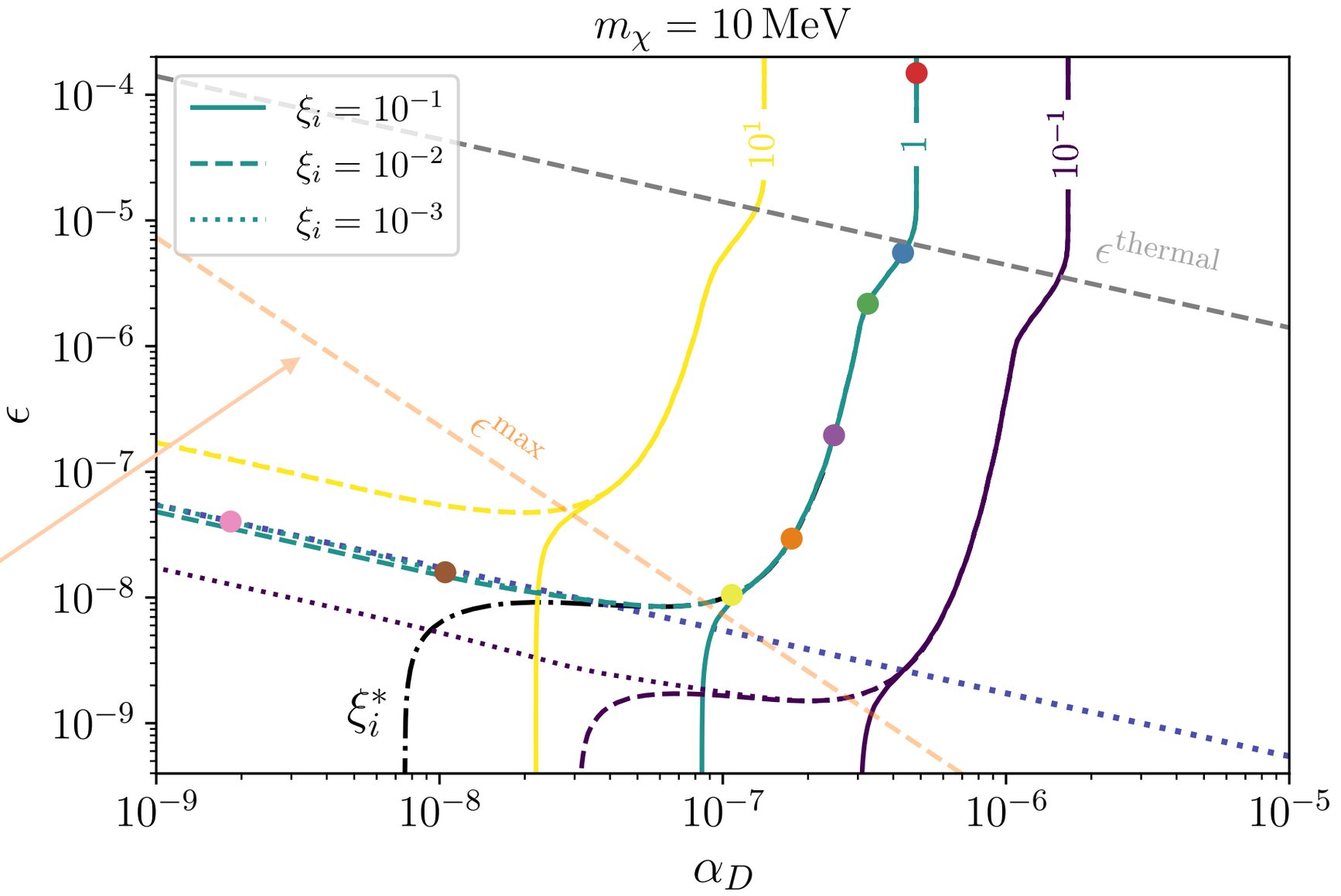
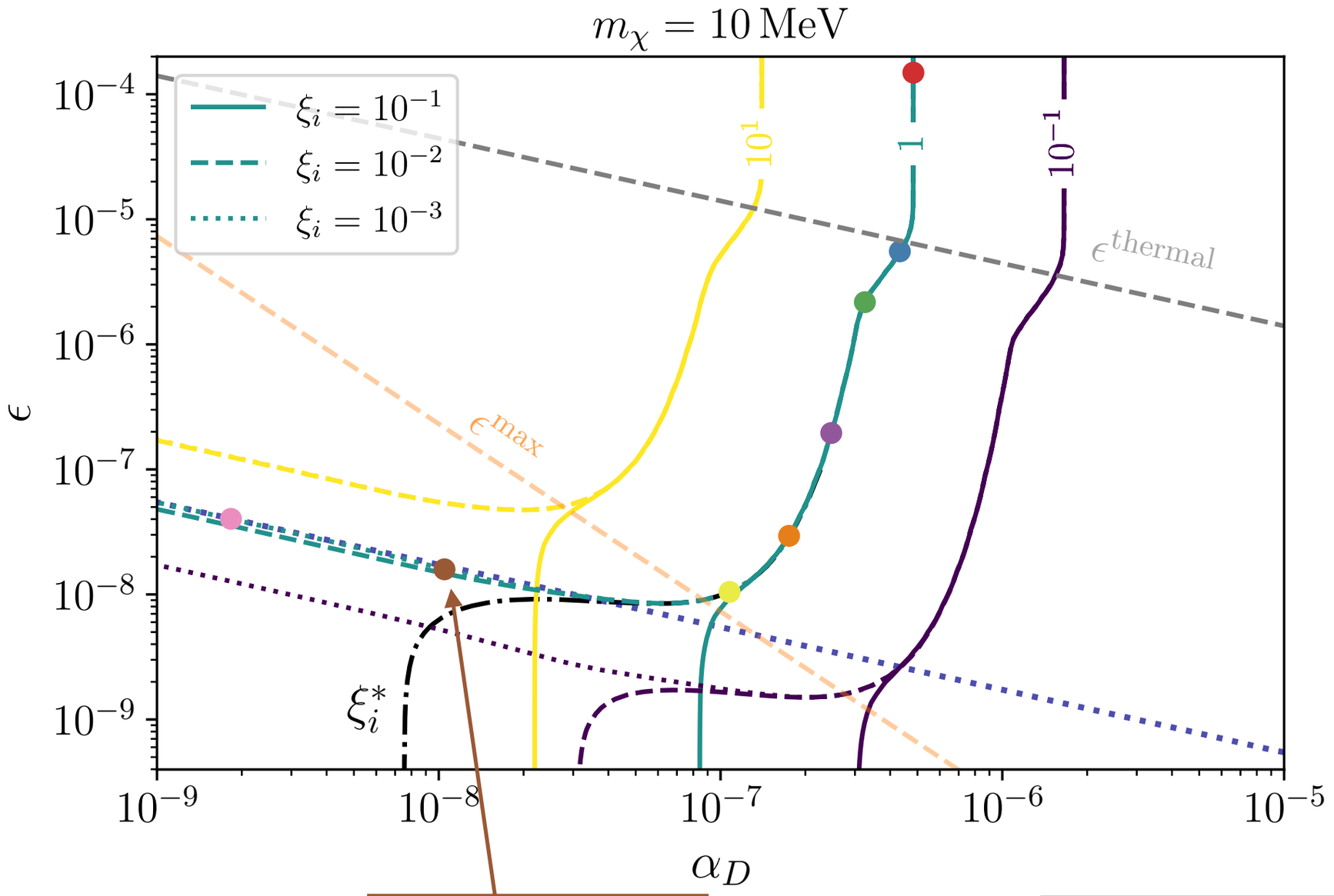


no self-interactions

freeze-in line

[Fernandez, Kahn, JS]

PHASES OF BEHAVIOR



no self-interactions

→structure formation (lighter masses)

[Dvorkin, Lin, Schutz]

instantaneous kinetic equilibration

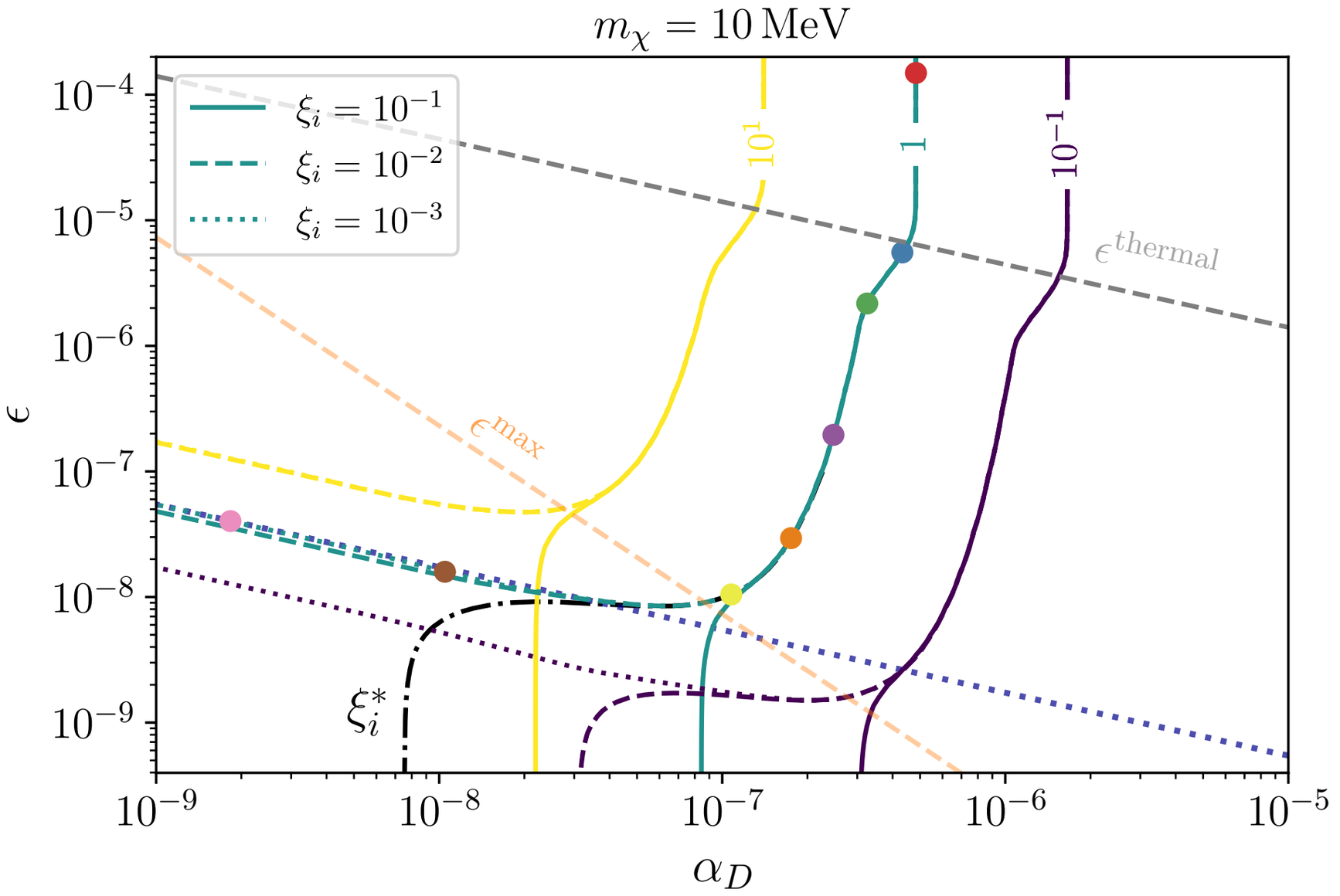
[Fernandez, Kahn, JS]

freeze-in line

PHASES OF BEHAVIOR

initial temperature ratio

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



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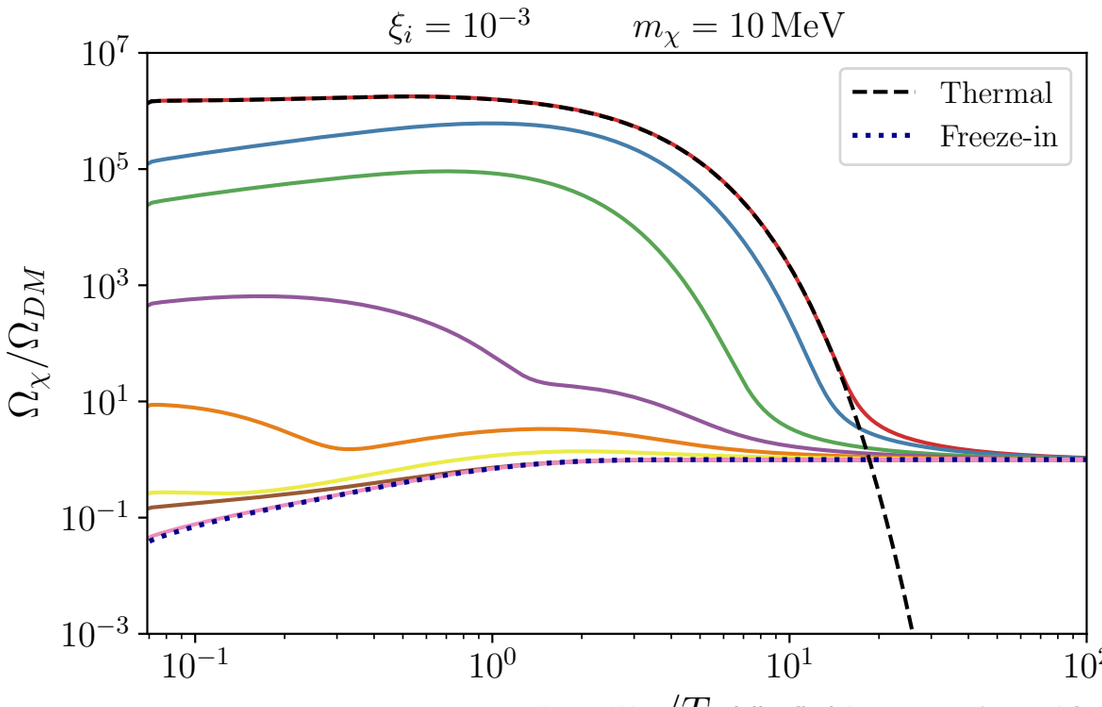
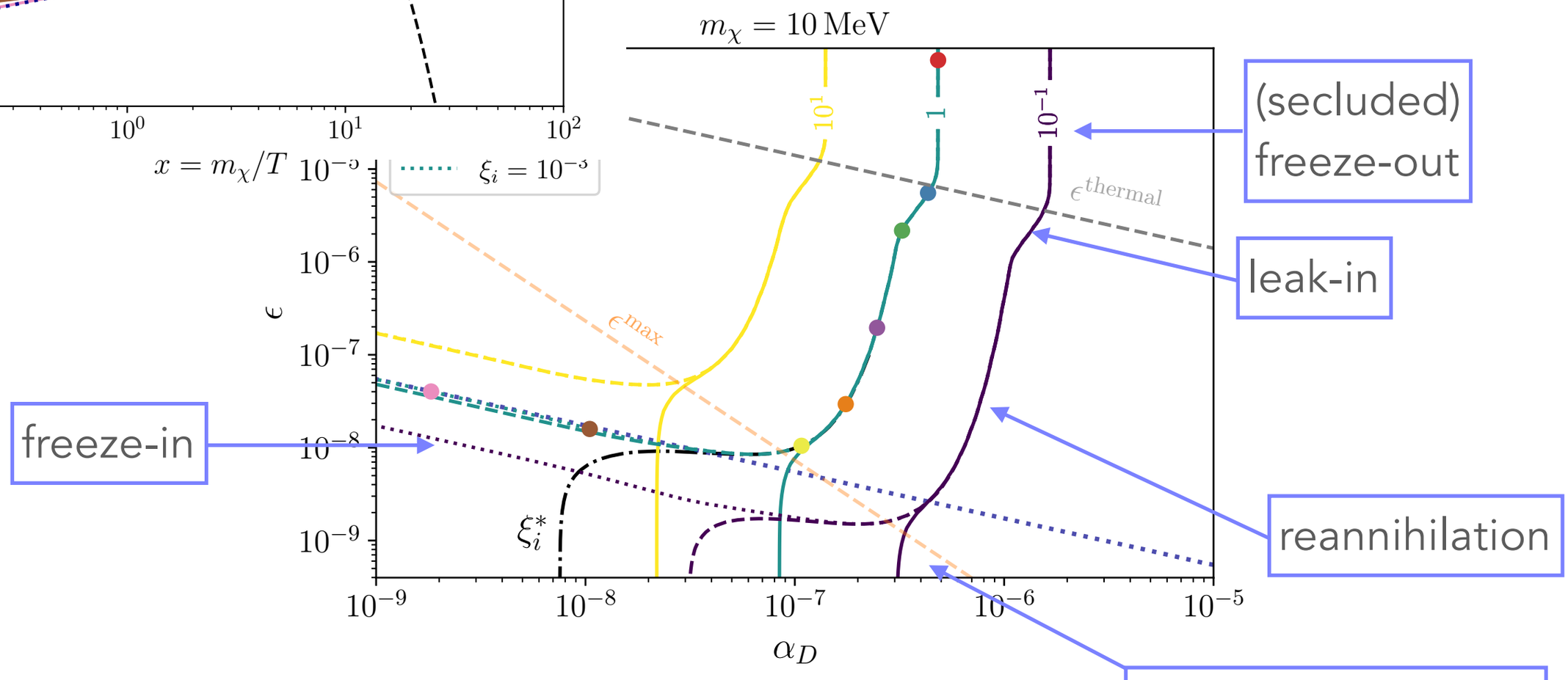
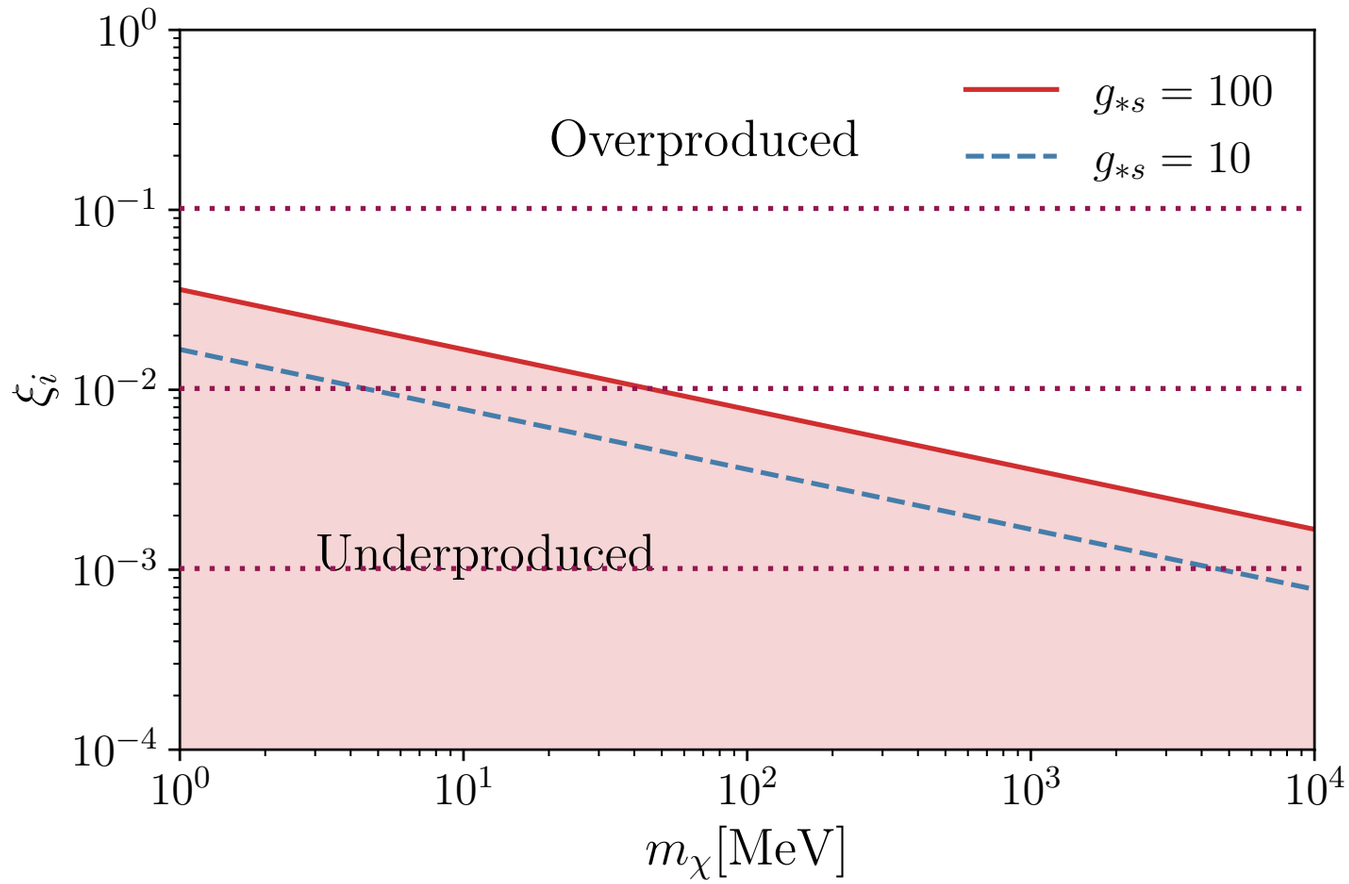




[Fernandez, Kahn, JS]

INITIAL CONDITION DEPENDENCE

- postdictions: boundary between initially over/under abundant DM is robust against attractor solution for (α_D, ϵ) near end of FI line



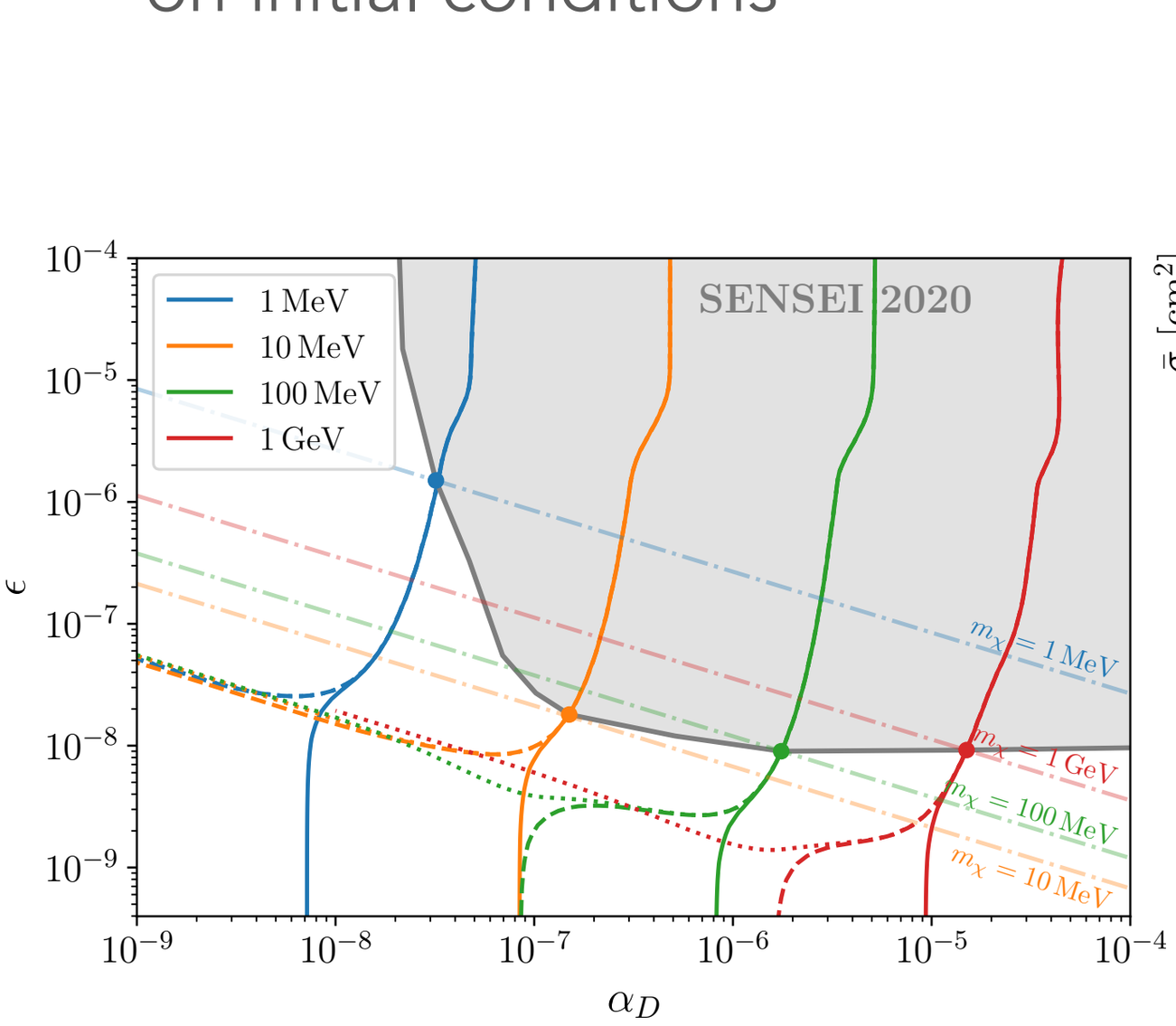
$n_\chi(\tilde{T}_i) > n_{obs}$

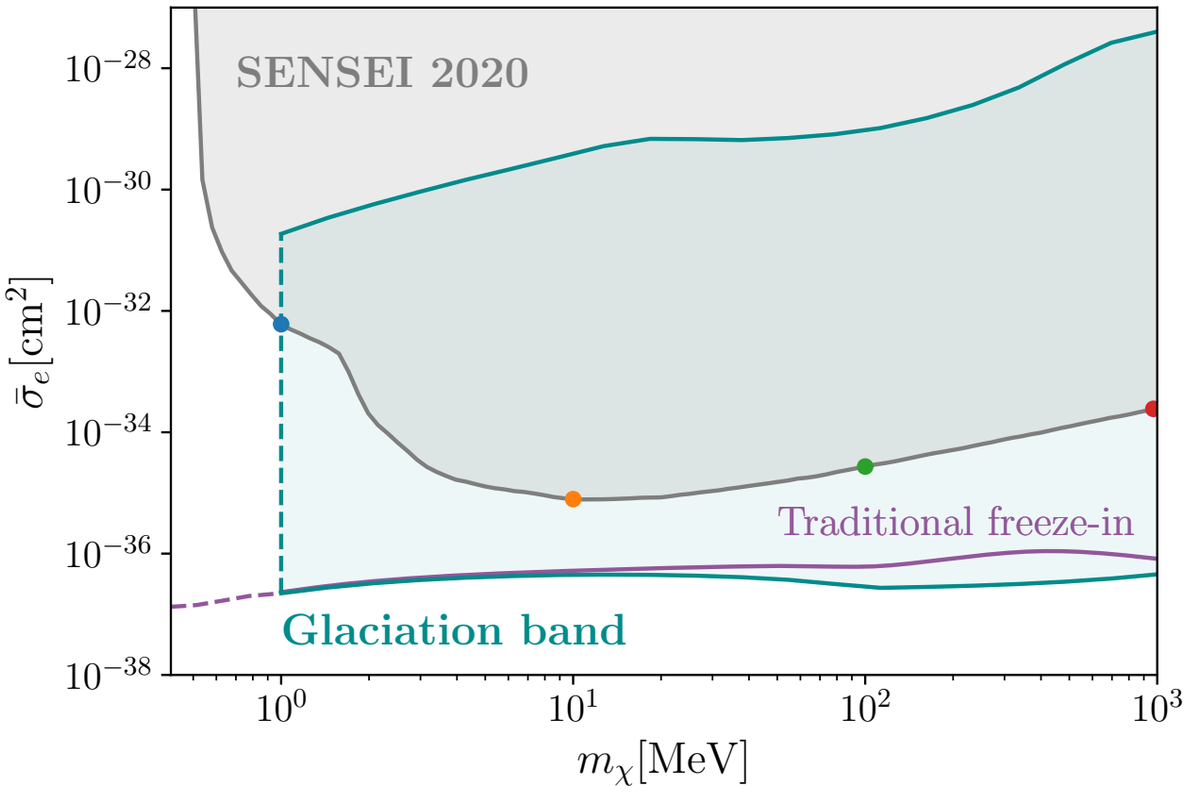
$n_\chi(\tilde{T}_i) < n_{obs}$

[Fernandez, Kahn, JS]

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

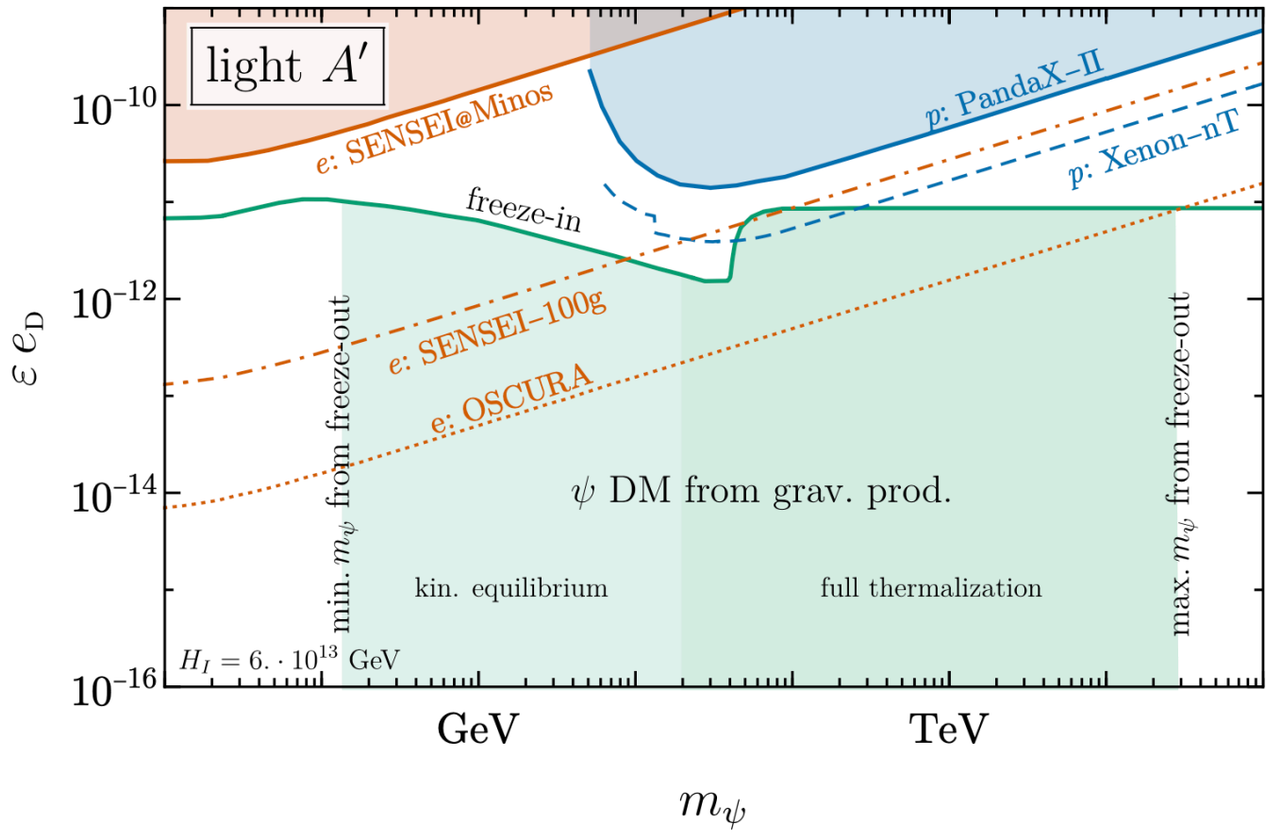




[Fernandez, Kahn, JS]

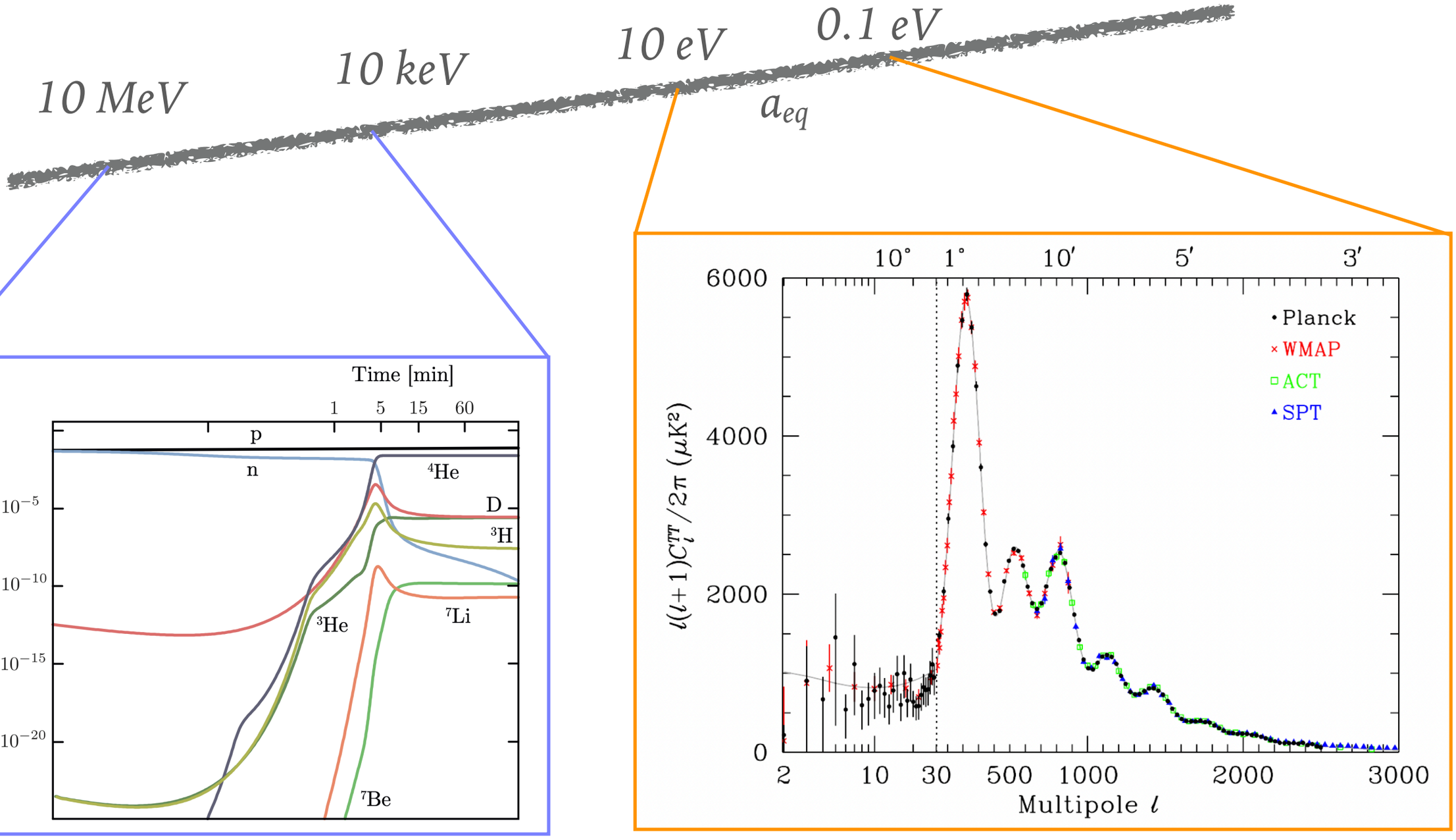
INITIAL CONDITIONS?

- Dark sectors with light mediators will have some initial population from inflationary dynamics:
  - inflationary production:
  - excitement during reheating [Ema, Jinno, Mukaida, Nakayama; …; Brandenberger, Kamali, Ramos]
- This population is initially highly nonthermal and details of thermalization can unfortunately matter



[Arvanitaki, Dimopoulos, Galanis, Racco, Simon, Thompson]

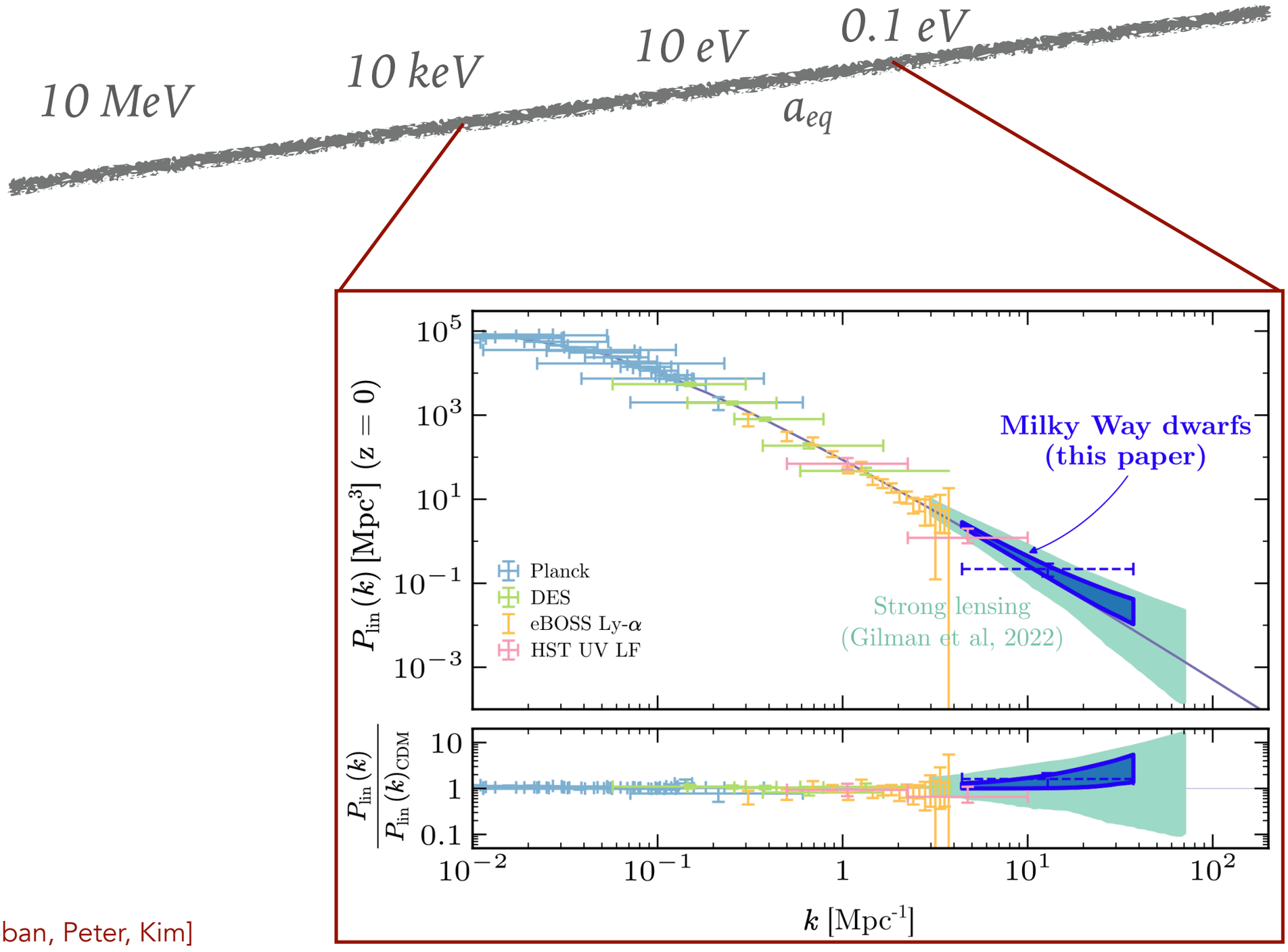
THE LATE EARLY UNIVERSE



PROBES OF THE HOMOGENEOUS UNIVERSE

- Excellent agreement between BBN, CMB can stringently constrain departures from LCDM
  - N_{eff}, both constant and time-varying, Y_p: constraints on low-mass dark sectors [e.g.: Hufnagel, Schmidt-Hoberg, Wild; An, Gluscevic, Calabrese, Hill; …]
  - BBN as well as CMB constraints are tightening or will soon
    - CMB: upcoming S4 experiment
    - BBN: measurements from LUNA collaboration on key deuterium rates reduces uncertainty on predictions, tightens constraints on (e.g.) N_{eff} [Yeh, Olive, Fields; Yeh, JS, Olive, Fields]

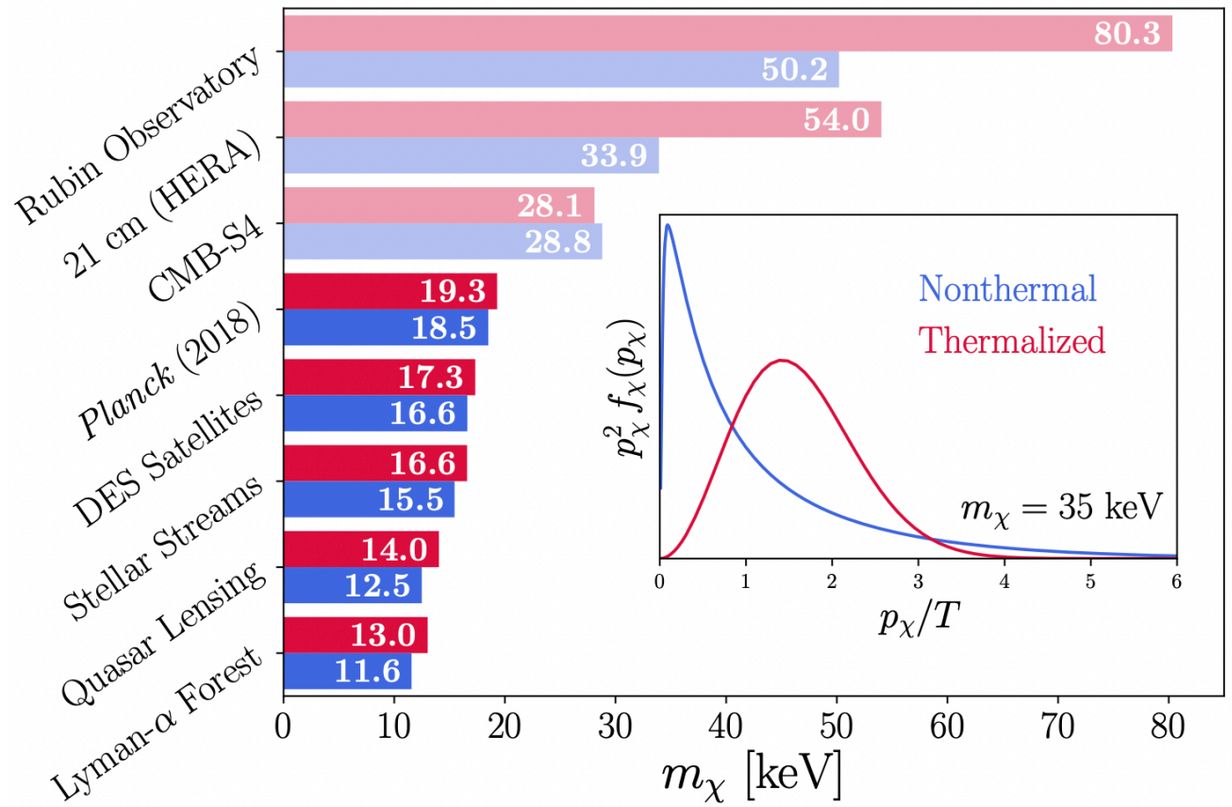
THE LATE EARLY UNIVERSE



[Esteban, Peter, Kim]

PROBES OF THE INHOMOGENEOUS UNIVERSE

- Structure formation is a key probe of low-mass particle DM, especially low-mass DM born out of equilibrium
  - Not just sterile neutrinos!
  - Can also be sensitive to DM-baryon interactions
- New probes of the small-scale matter power spectrum soon from:
  - galaxy surveys (Euclid, Roman)
  - 21-cm measurements (HERA)



[Dvorkin, Lin, Schutz]

SUMMARY AND CONCLUSIONS

- Direct detection experiments are now probing dark sectors that were out-of-equilibrium with the SM in the early universe
- For models with light mediators, the freeze-in line is mass, coupling, and initial-condition dependent and not always well-defined
  - however it is still an interesting and well-motivated experimental target
    - interpreting results can become quite involved: multiple temperatures, initial condition dependence
    - (un)fortunately there are interesting models that sit below the freeze-in line
- Models of sub-GeV DM evolve through epochs of our universe where we have observational probes
  - Most of those probes will advance in sensitivity soon: synergy with direct detection program