# DARK SECTORS IN AND OUT OF THERMAL EQUILIBRIUM

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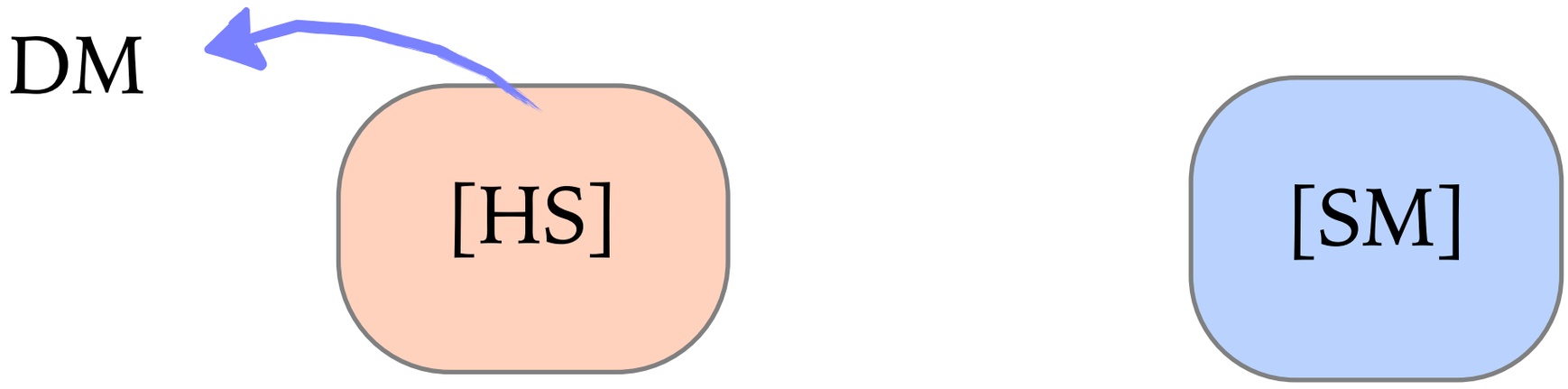
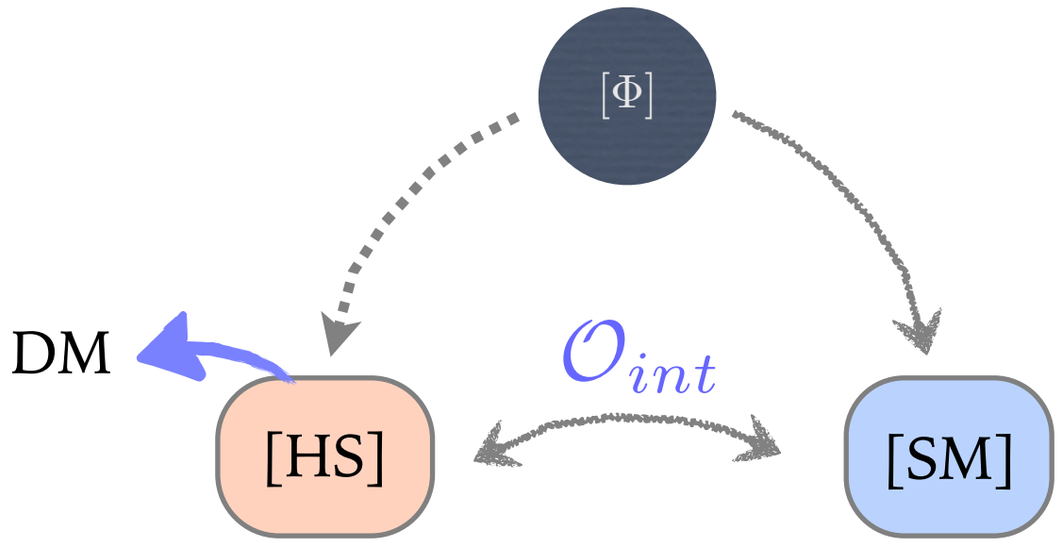
*Snowmass Rare and Precision Frontier meeting, Dec. 4, 2020*

# DARK SECTORS




- Dark matter is part of a multi-particle hidden sector with its own interactions
- Here: focus on regime where couplings internal to the dark sector are important for determining final abundance
- Focus for simplicity on minimal models:
  - two states (DM, mediator)
  - mphi << mchi

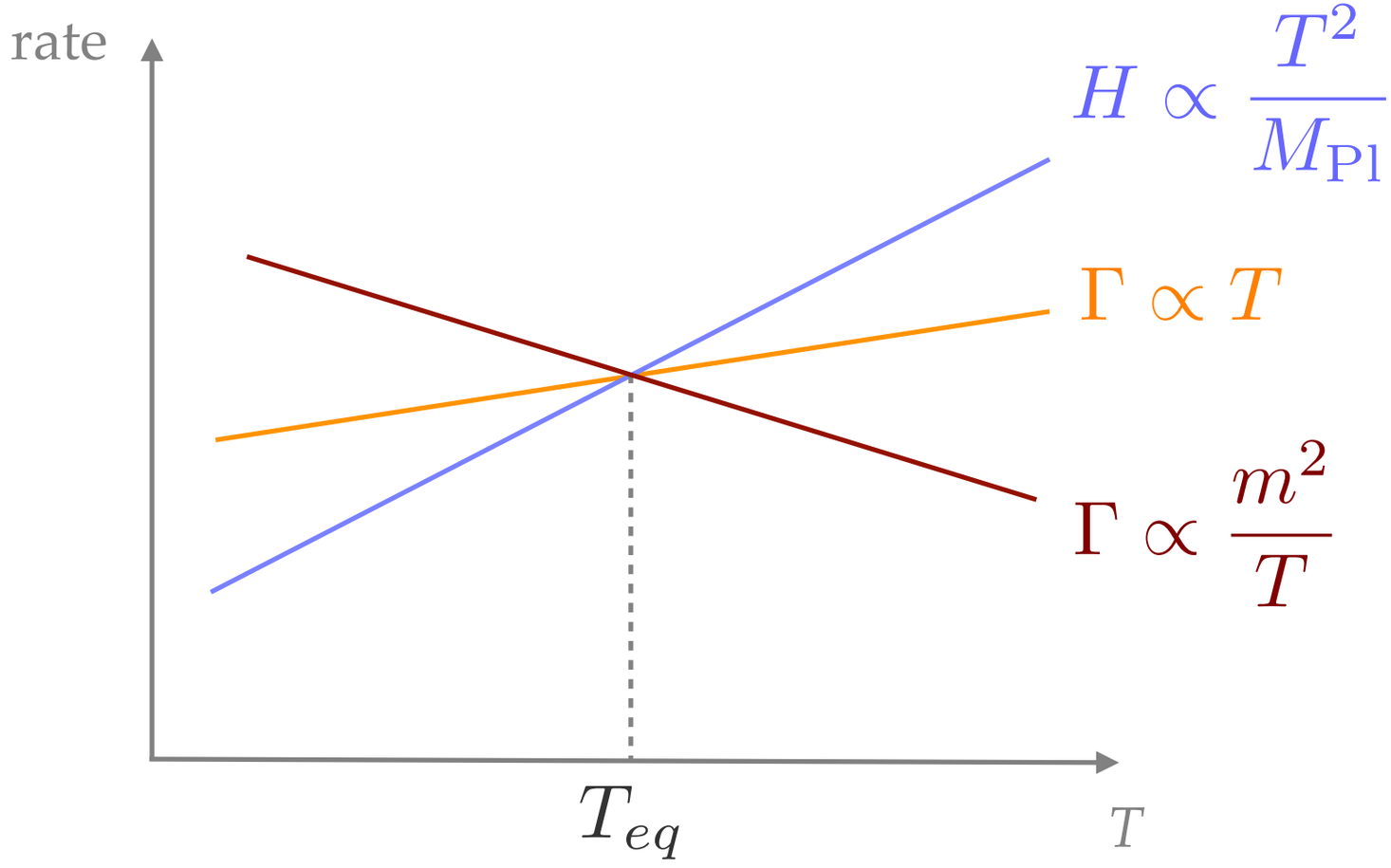
# COSMOLOGICAL POPULATION OF DARK SECTORS




- For terrestrial detection prospects: most interesting scenarios are where SM interactions are important for cosmic population
  - scale of connecting interactions determines temperature dependence
  - renormalizeable interactions: increasingly important at low temperatures

# POPULATION FROM SM

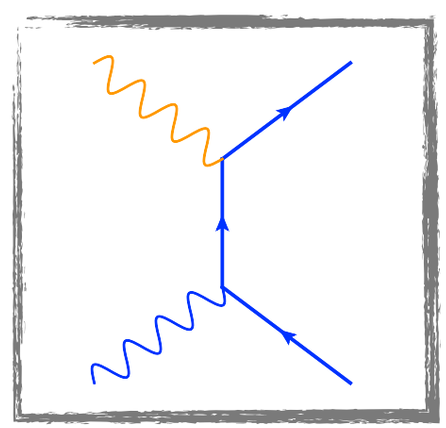
- Renormalizeable interactions:




- IR-dominated: insensitive to unknown physics in UV
- handful of possible choices for structure of interactions

# ASIDE ON PRODUCTION RATES AND KINETIC THEORY

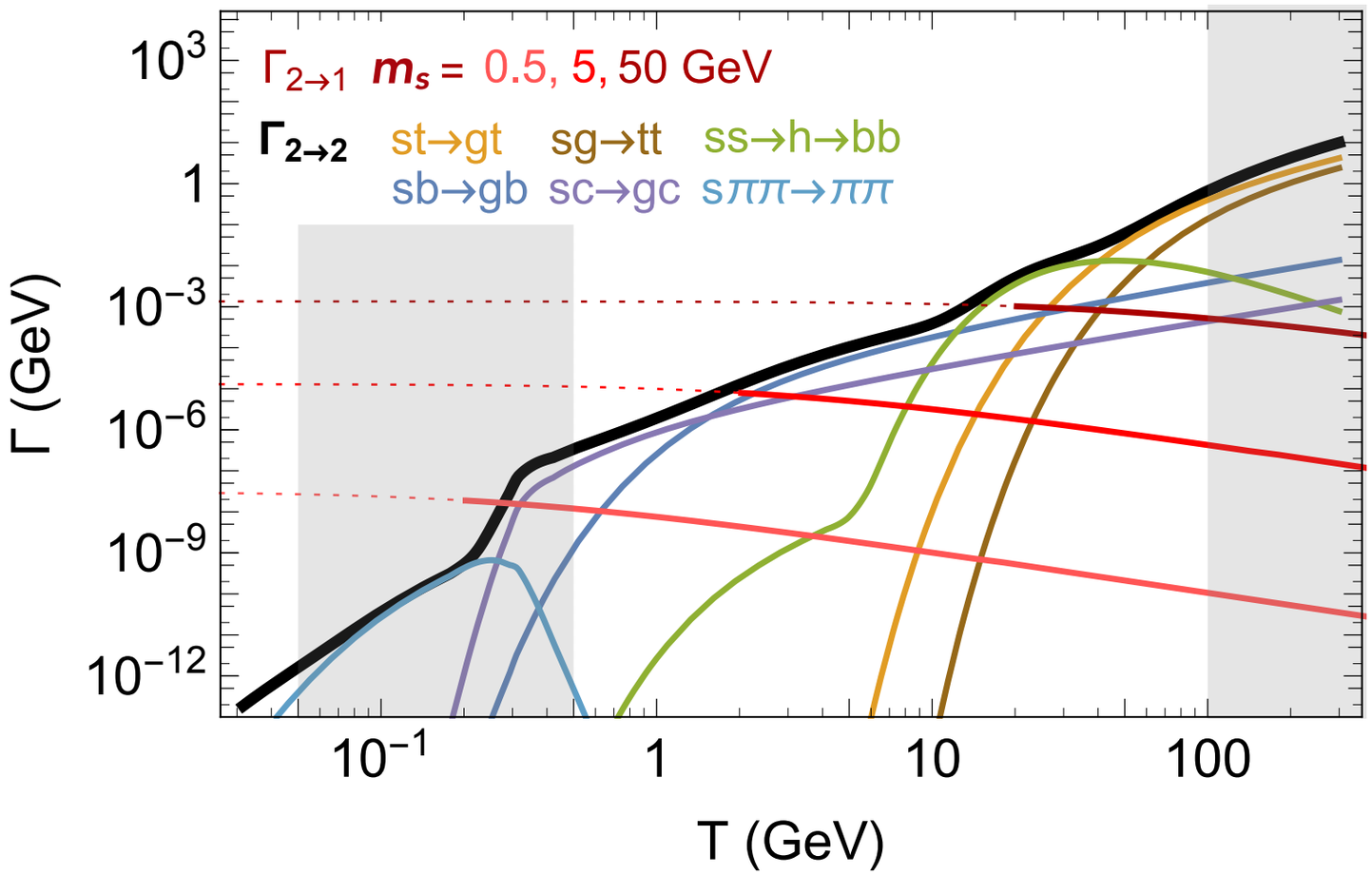
- Kinetic theory: $2 \to 2$ scatterings, $\Gamma \propto T$
- In-medium corrections can parametrically alter this scaling
- Distinguish two cases:
  - new species $X$ inherits all its couplings to SM bath via mixing
    - e.g.: dark photon
  - $X$ has distinct structure of interactions with SM particles
    - e.g.: Higgs portal scalar, $B$-$L$ boson
- For simplicity, here study interactions where kinetic theory is a good guide: trust results to $\sim O(1)$



[Redondo, Postma; An, Pospelov, Pradler; Hardy, Lasenby]

# THERMAL MEDIATOR PRODUCTION (HIGGS PORTAL)

➤ SM has lots of mass threshholds:

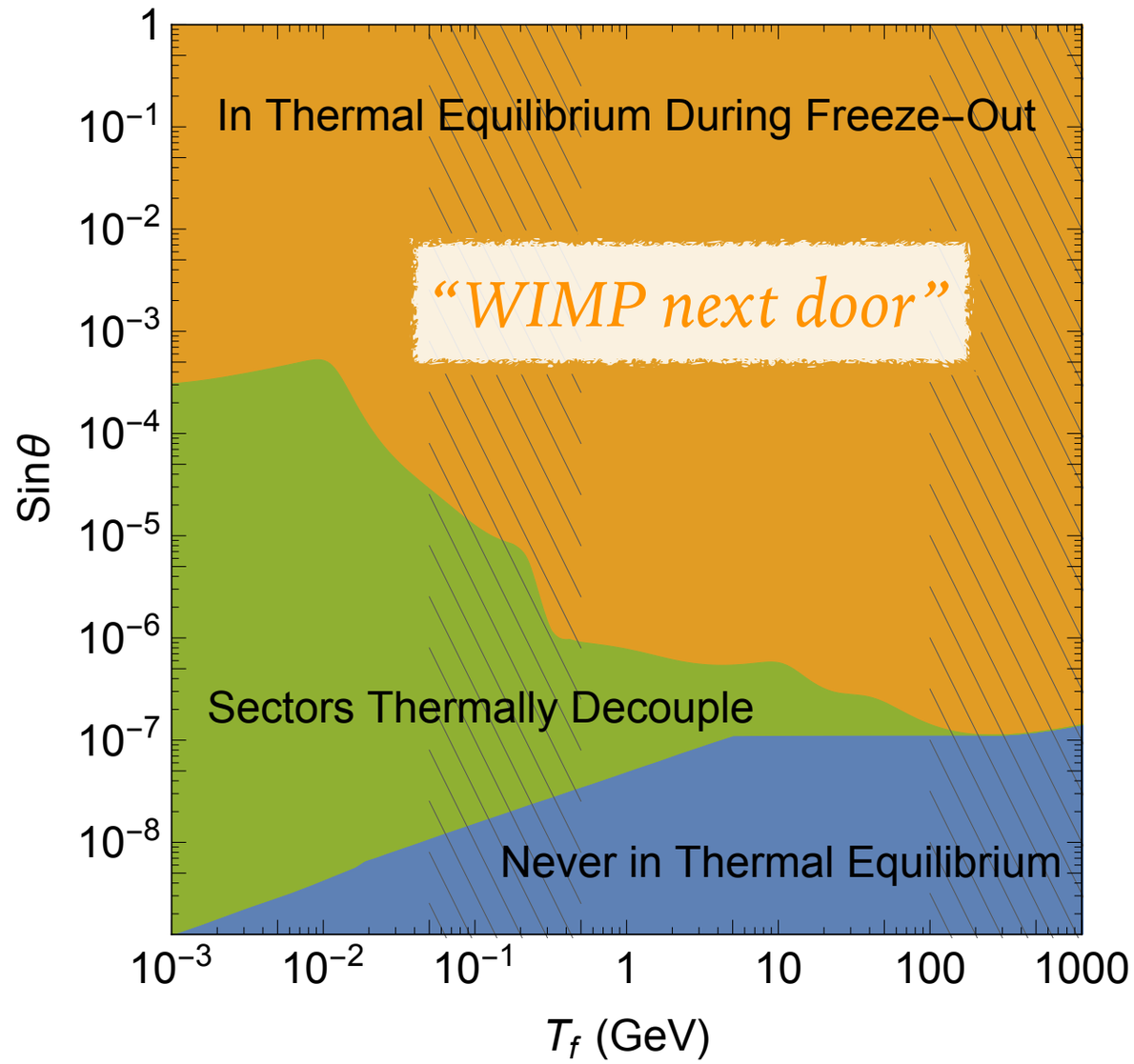



scalar portal

[Evans, Gori, JS]

# HIGGS PORTAL WIMP NEXT DOOR

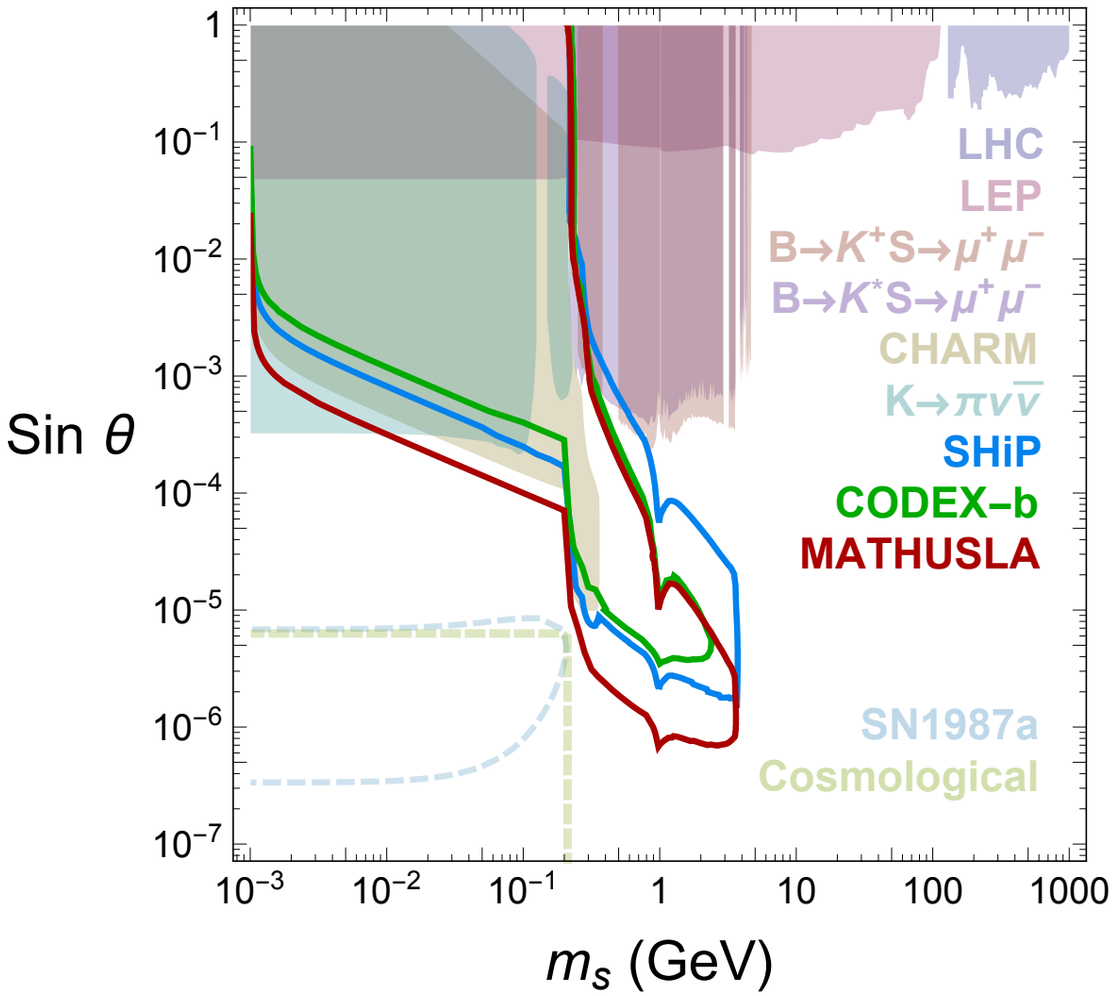
- Thermalization:

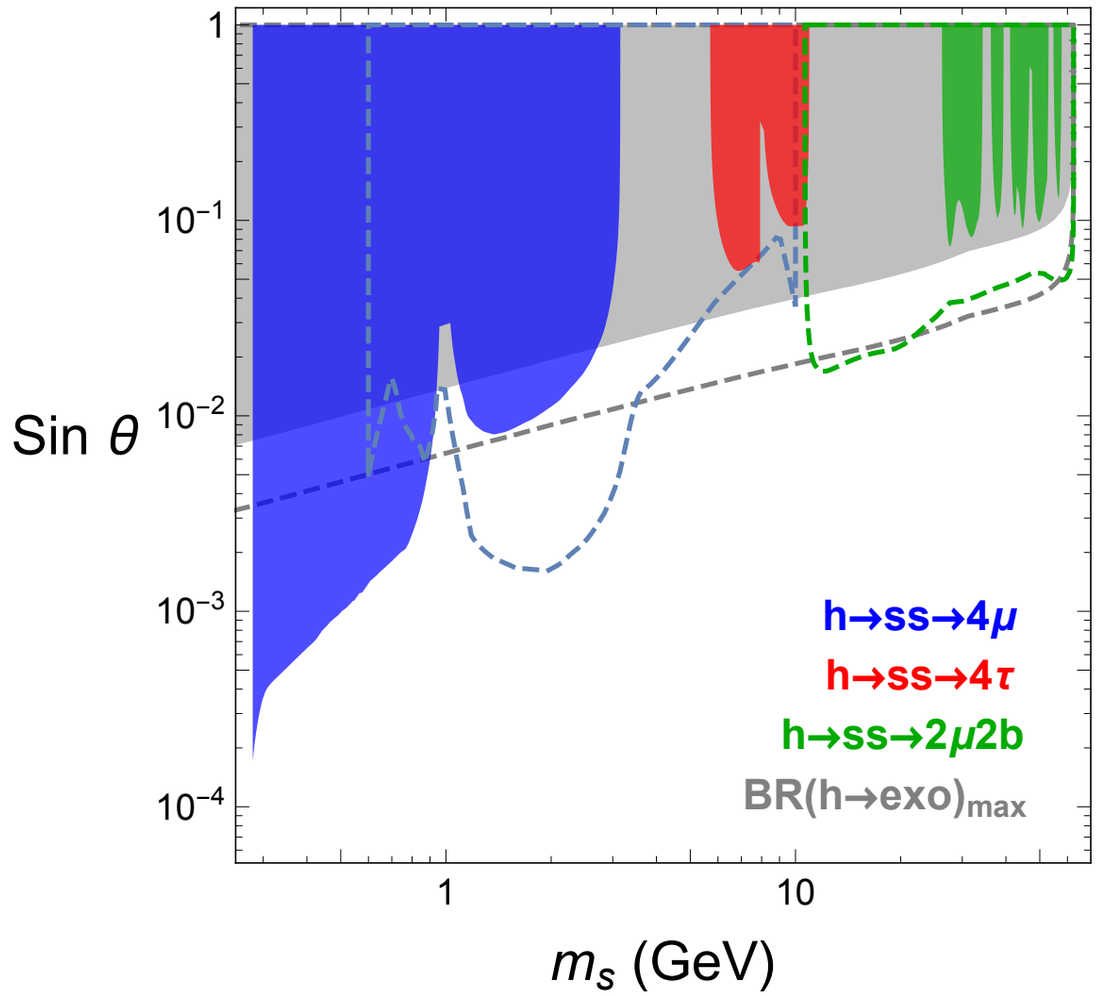



[Evans, Gori, JS]

# HIGGS PORTAL SCALARS IN EXPERIMENT

- Terrestrial experiments are generally probing dark particles that were in thermal equilibrium in early universe*

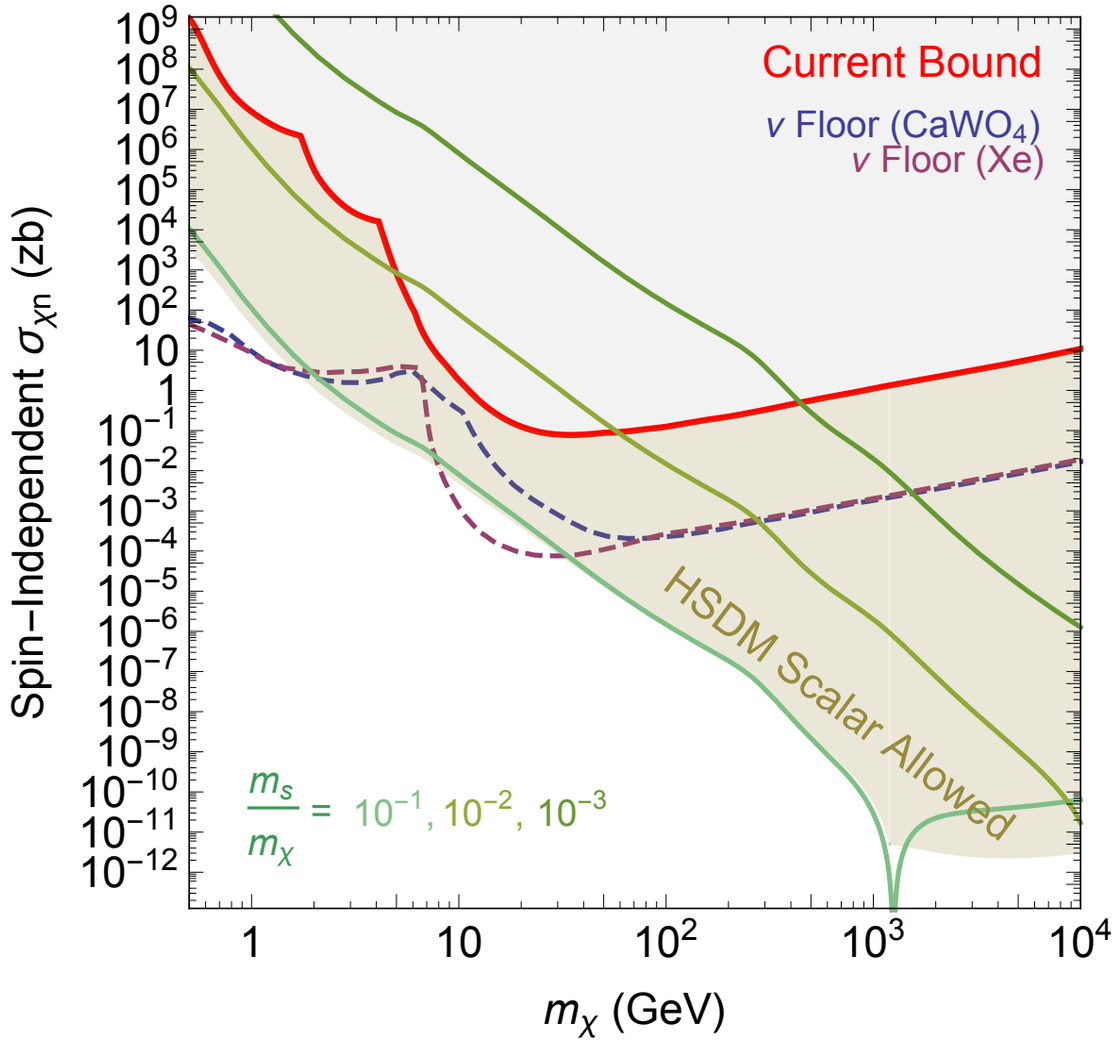


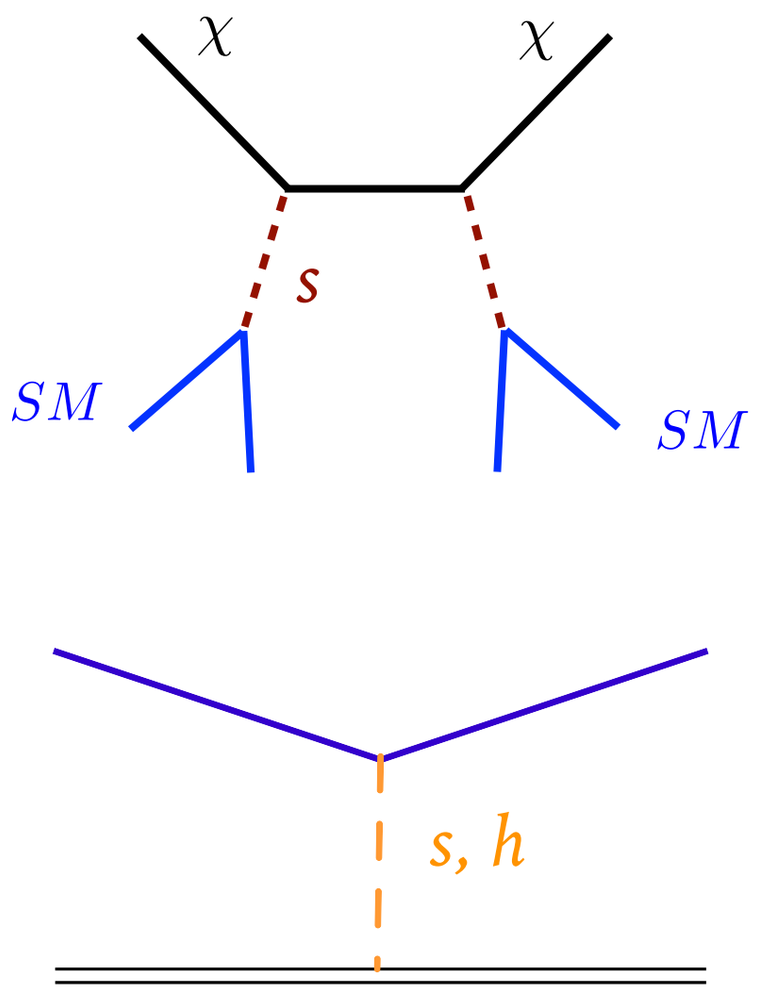




[Evans, Gori, JS; Kahlhoefer]

# HIGGS PORTAL WIMP NEXT DOOR

- however direct detection has some ability to test this cosmology




[Evans, Gori, JS; see also Krnjaic; Hambye, Tytgat, Vandecasteele, Vanderheyden; Hooper, Leane, Tsai, Wegsman, Witte]

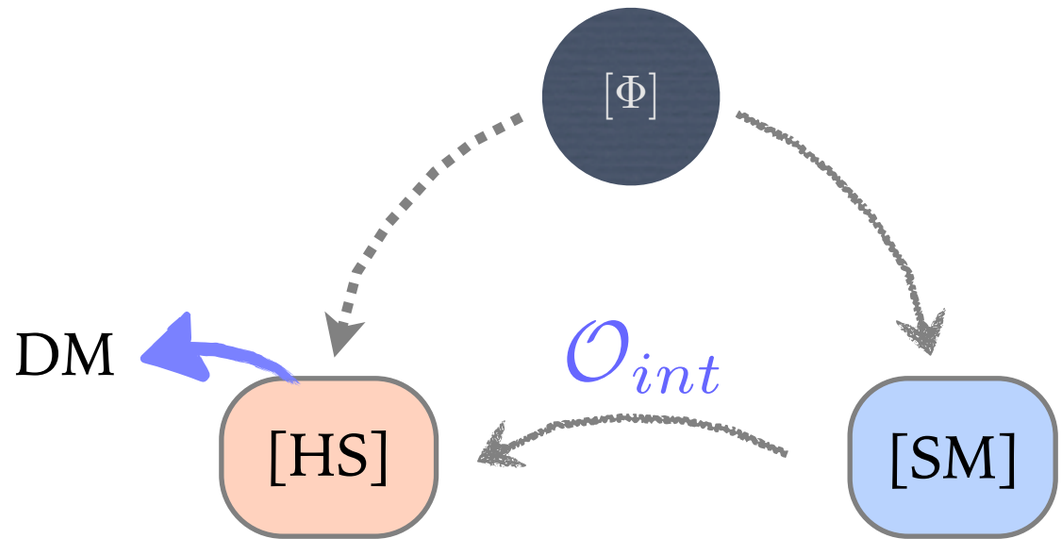
# THE EQUILIBRATION FLOOR

- Given a renormalizeable mediator interaction, the equilibration floor is an important experimental target
  - fundamental information about possible cosmic histories of our universe
  - understanding the floor is critical for comparing to results of direct detection experiments
- in minimal models of hidden-sector freezeout ("WIMPs next door") the equilibration floor can provide challenging but well-defined benchmarks
- Below the equilibration floor, the cosmic history of even minimal DM models gets a lot more involved

[Evans, Gori, JS; see also Krnjaic; Hambye, Tytgat, Vandecasteele, Vanderheyden; Hooper, Leane, Tsai, Wegsman, Witte]

# BELOW THE EQUILIBRATION FLOOR

- What happens when leading interaction never reaches equilibrium?

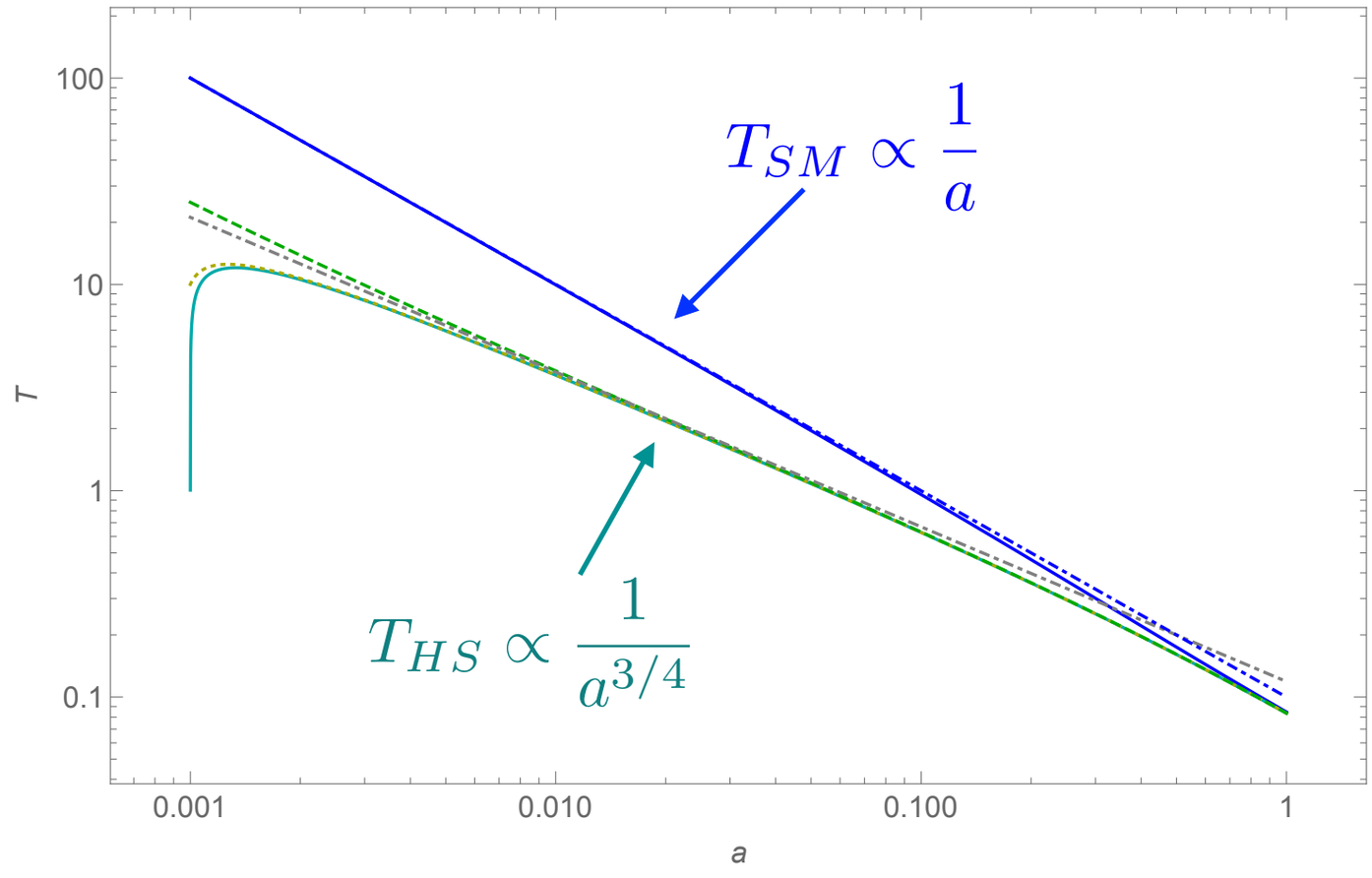



- continuous leak of energy from SM: non-adiabatic evolution

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

# FREEZING IN A DARK SECTOR IS DIFFERENT: LEAK-IN

- A radiation bath fed by out-of-equilibrium $2 \to 2$ renormalizeble interactions redshifts like matter:




- UV-insensitive quasi-static equilibrium phase
  - What happens to DM freezing out of such a bath?

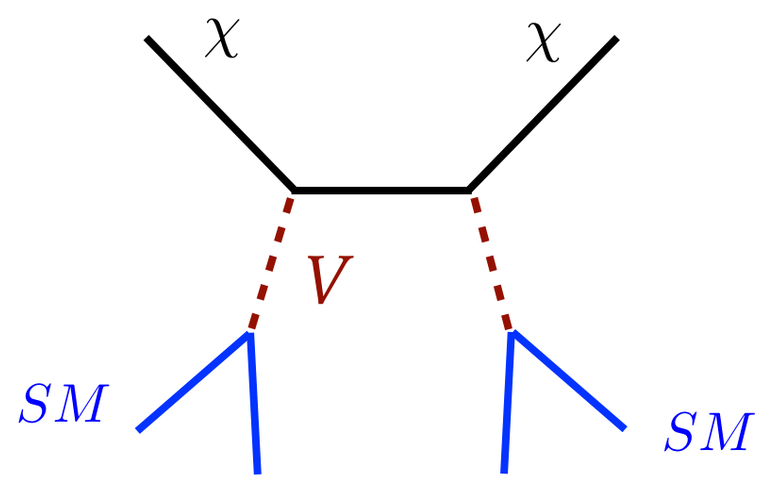
[Chu, Hambye, Tytgat; Evans, Gaidau, JS]

# LEAK-IN, FREEZE-OUT

- Annihilation cross-section is suppressed:

$$\frac{\langle \sigma v \rangle_{\rm LI}}{\langle \sigma v \rangle_{\rm WIMP}} = b \left( \frac{\tilde{T}_f}{m} \right)^{1/3}$$

parametrizes effective coldness of HS, $\propto \left( \frac{M_{pl}}{m} \right)^{1/3} \epsilon^{2/3}$

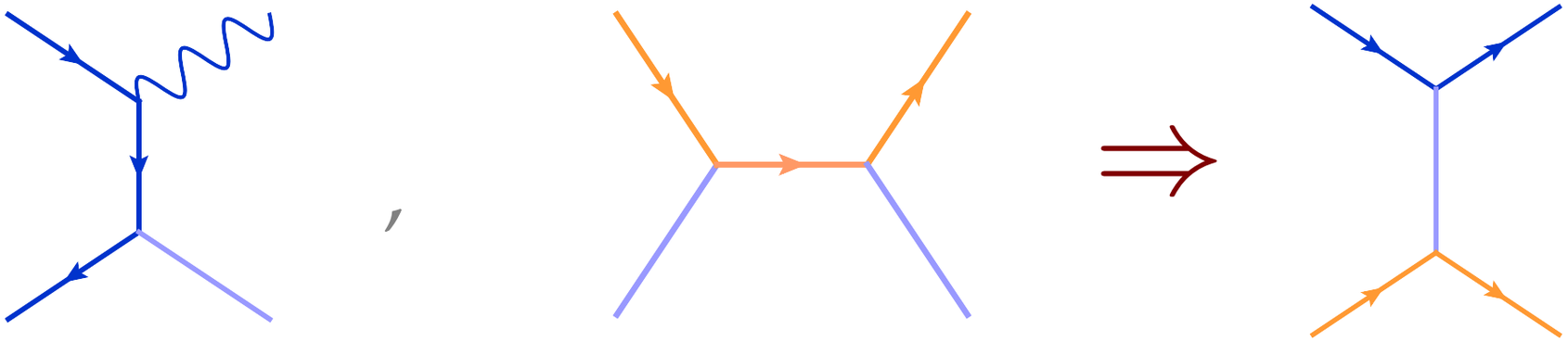


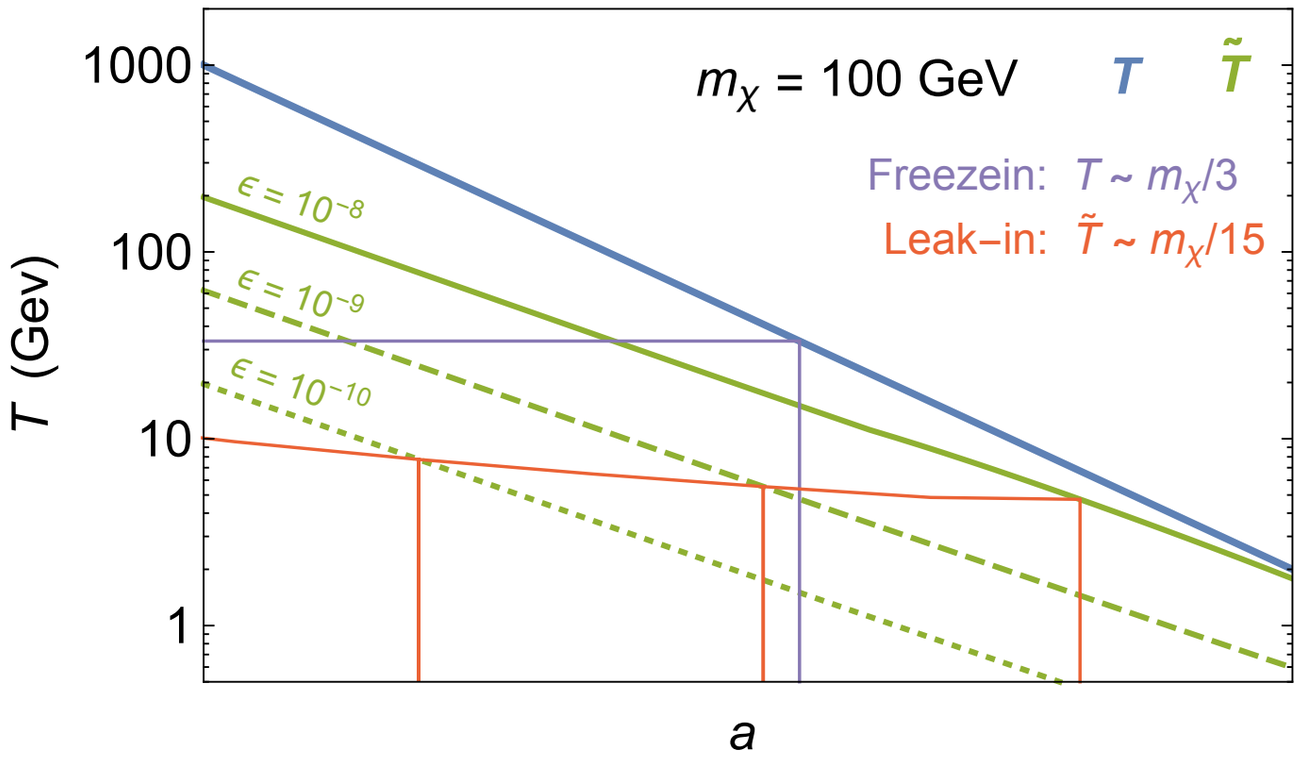

- lower bound on $\epsilon$ : $T_{HS}$ never large enough to populate sufficient DM for any cross-section
- For concrete illustration, minimal *B*-*L* model

[Evans, Gaidau, JS]

# LEAK-IN, FREEZE-OUT

- direct freeze-in production of DM is also generically present





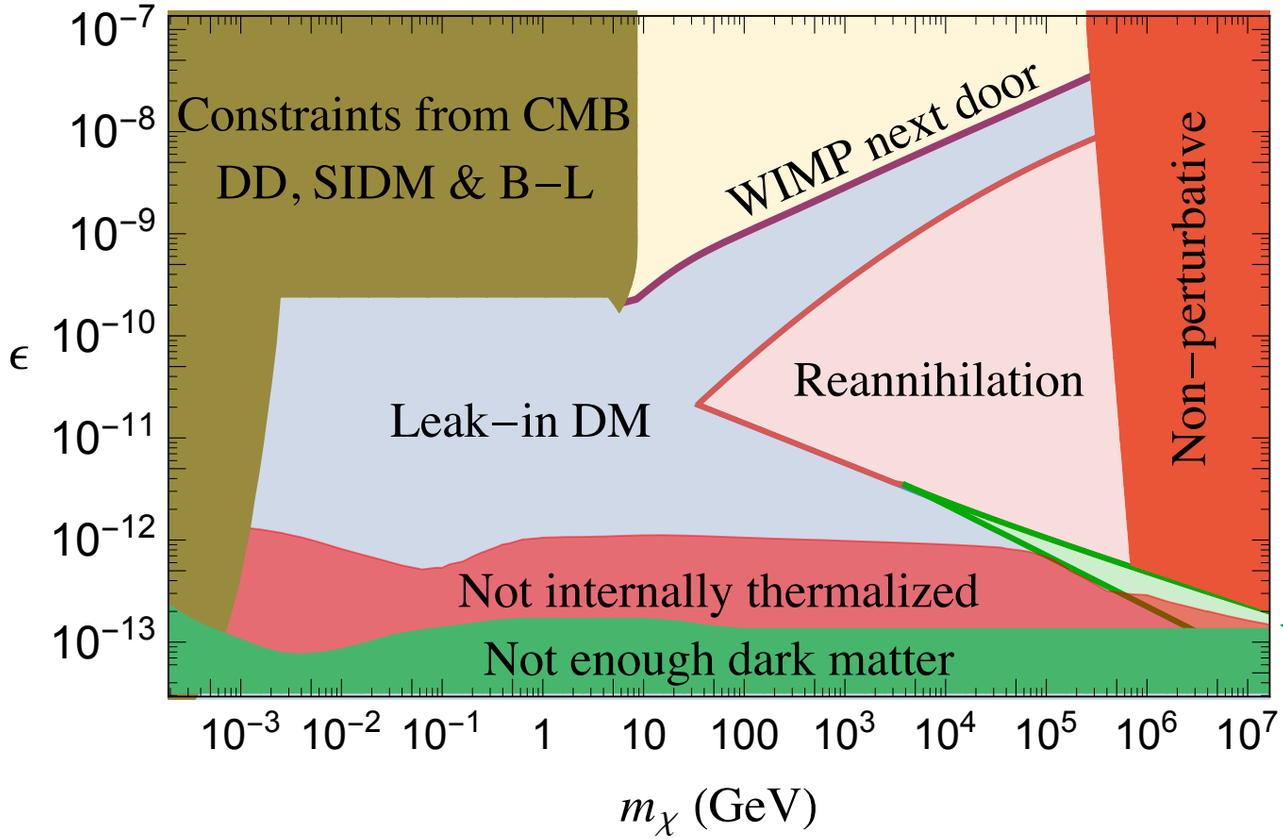

leak-in dominates:

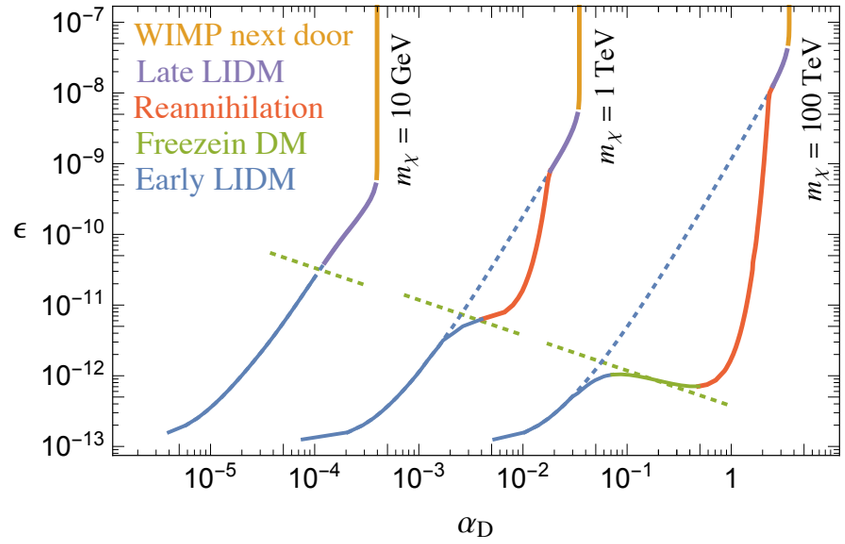
- near floor
- at low masses (freeze-in contribution is tiny)

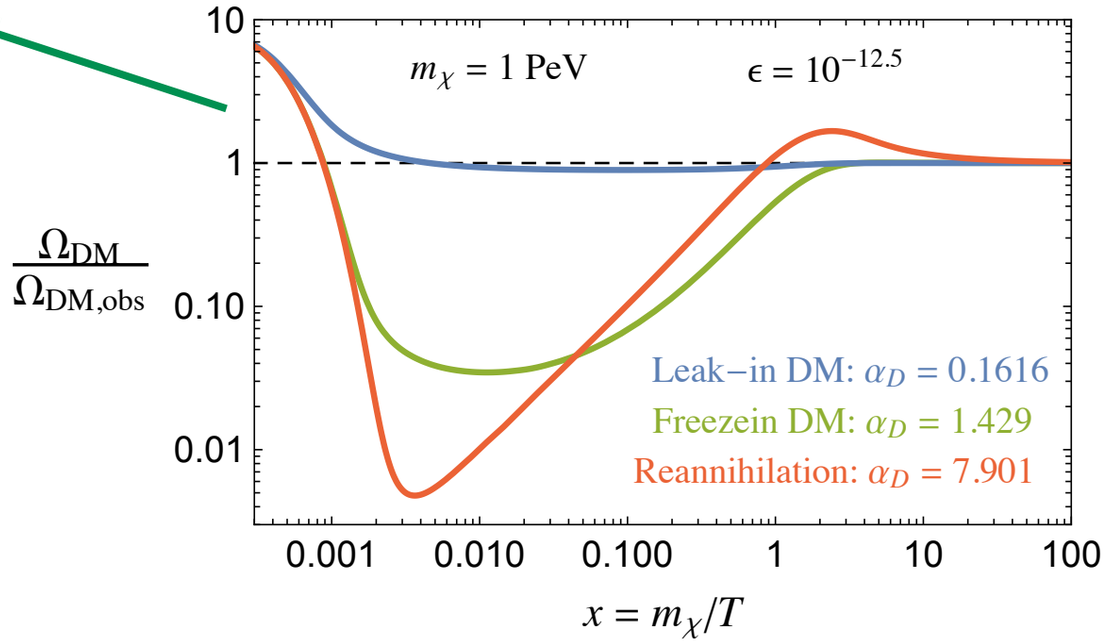
[Chu, Hambye, Tytgat; Krnjaic; Evans, Gaidau, JS; see also Berger, Croon, El Hedri, Jedamzik, Perko]

# POPULATION FROM SM

- Bounded parameter space with distinct phases:



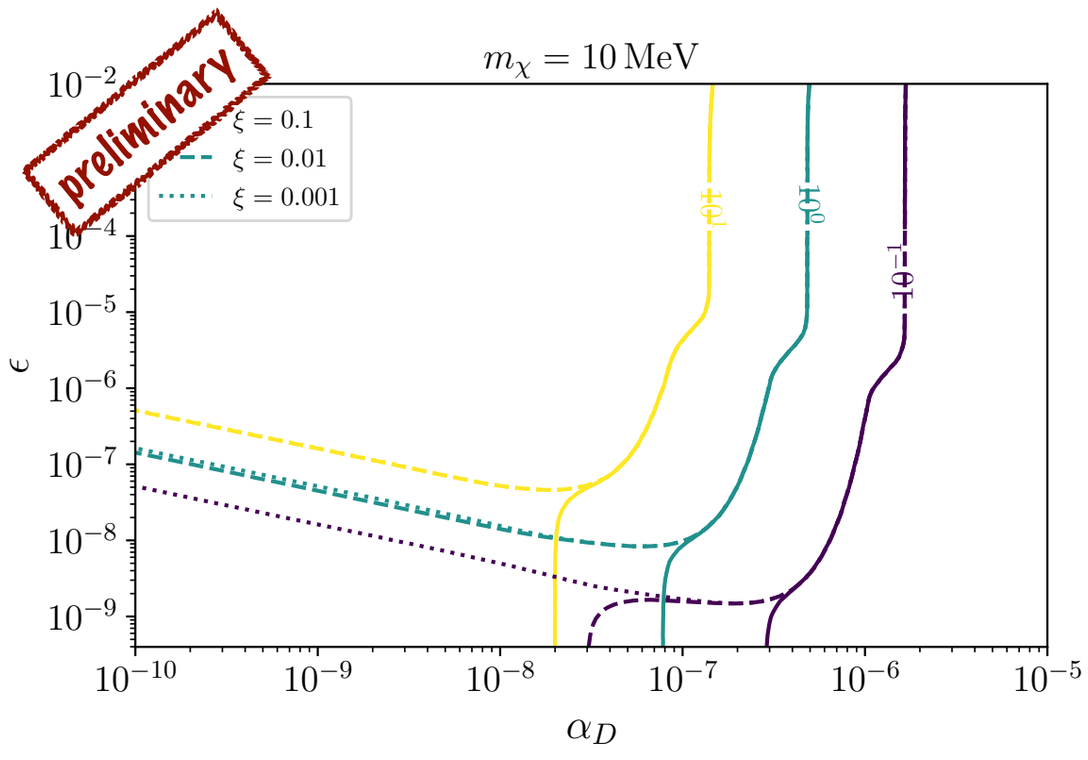




[Evans, Gaidau, JS]

# FREEZING IN A DARK SECTOR IS DIFFERENT: GLACIATION

- When the dark sector has relevant self interactions, changes initial condition dependence for freeze-in
  - glaciation: freeze-in injection of DM into pre-existing dark thermal bath
  - Rapid kinetic equilibration changes distribution of injected energy




dark photon mediator

[Fernandez, Kahn, JS (to appear)]

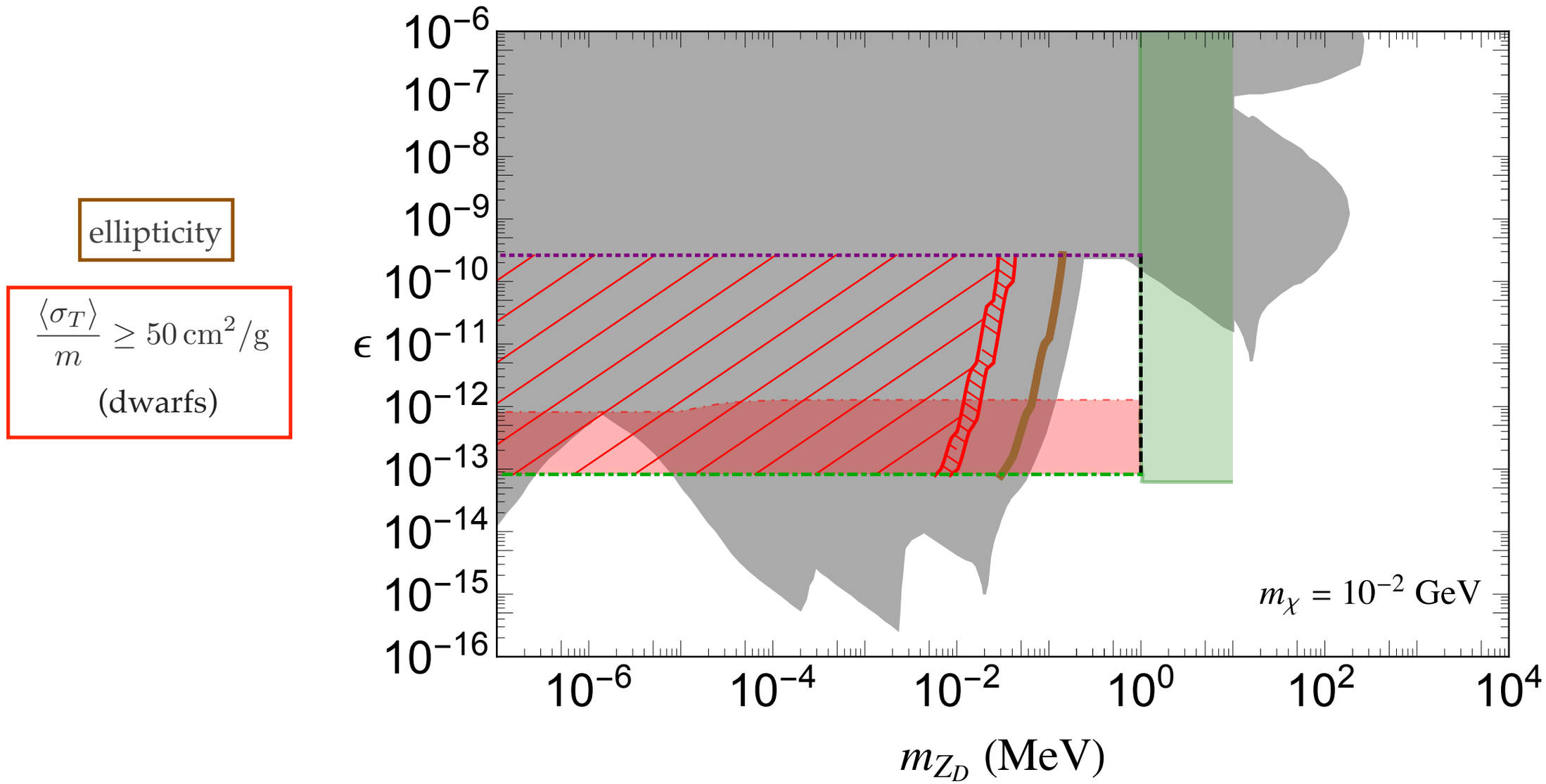
# SUMMARY AND CONCLUSIONS

- The interplay of SM and HS interactions in thermal dark sector models can be very rich
- Thermalization of the two sectors keeps things simple
- The equilibration floor is a challenging but interesting target
  - Calculable for a given renormalizeable portal interaction, as a function of earliest thermalization temperature
  - Directly testable in parts of parameter space, particularly low masses, Higgs portal
  - Must be understood to compare with direct detection results
  - See also: astrophysical bounds from cooling of compact objects

# BACKUP

# B-L LEAK-IN PARAMETER SPACE

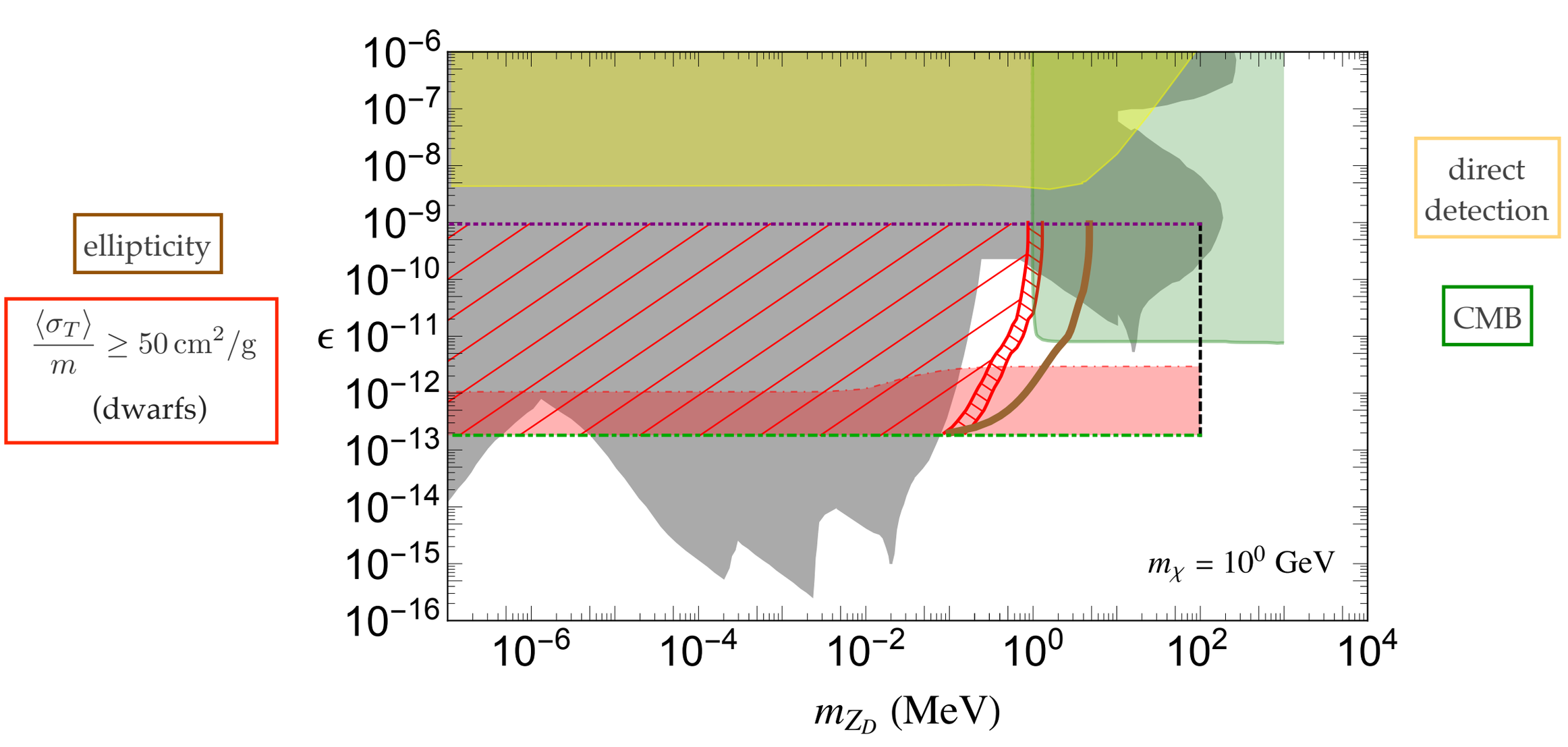
- Stringent constraints on low-mass B-L boson dominate low mass boundary of parameter space:




[Evans, Gaidau, JS]

# B-L LEAK-IN PARAMETER SPACE

- CMB constraints are powerful once visible decays are allowed



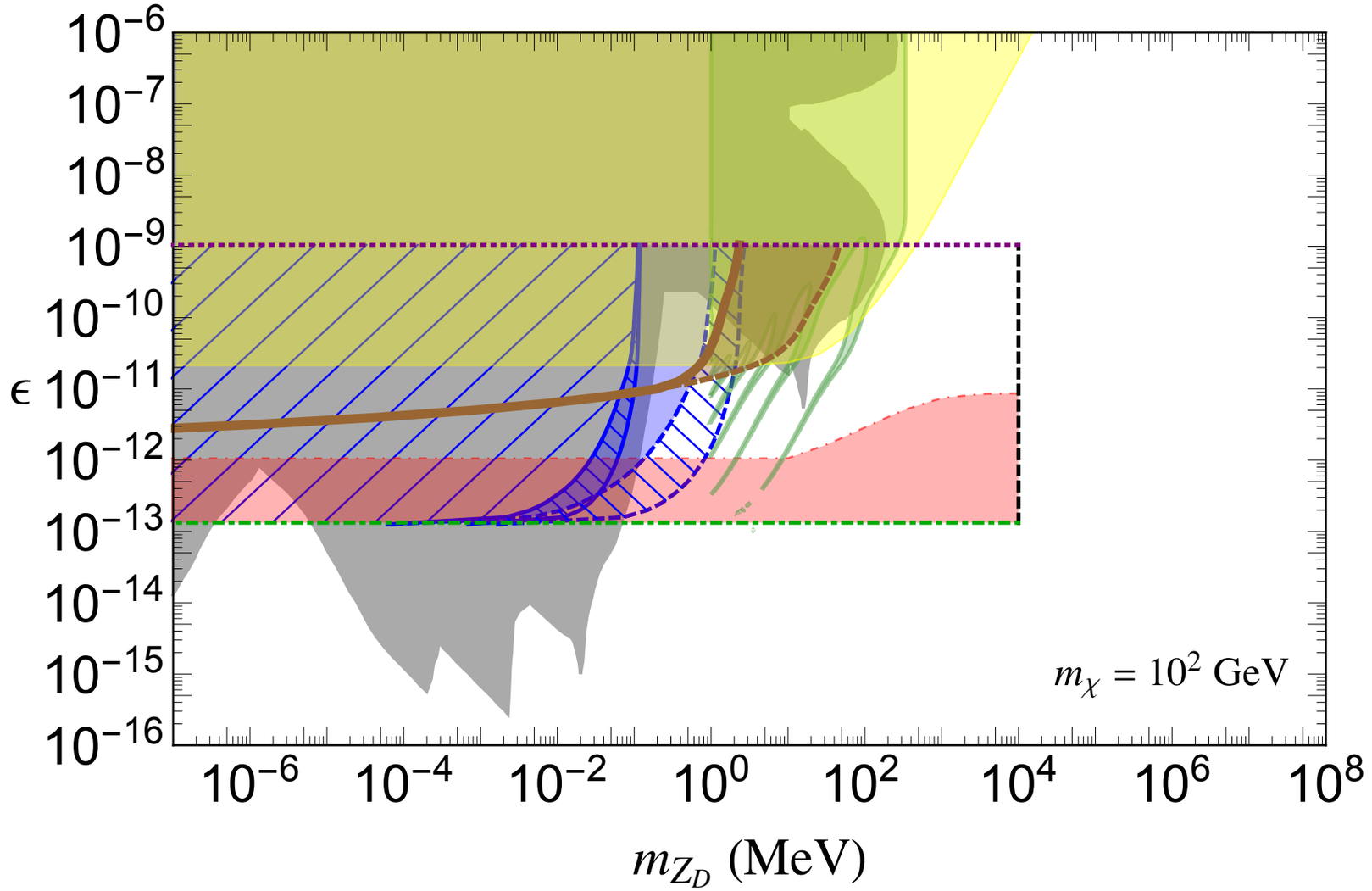

[Evans, Gaidau, JS]

# B-L LEAK-IN PARAMETER SPACE

- Sommerfeld-enhanced annihilations become increasingly powerful at higher mass; (in)visible SIDM

$\frac{\langle \sigma_T \rangle}{m} \geq 50\,\mathrm{cm}^2/\mathrm{g}$ (dwarfs)

ellipticity




CMB

direct detection

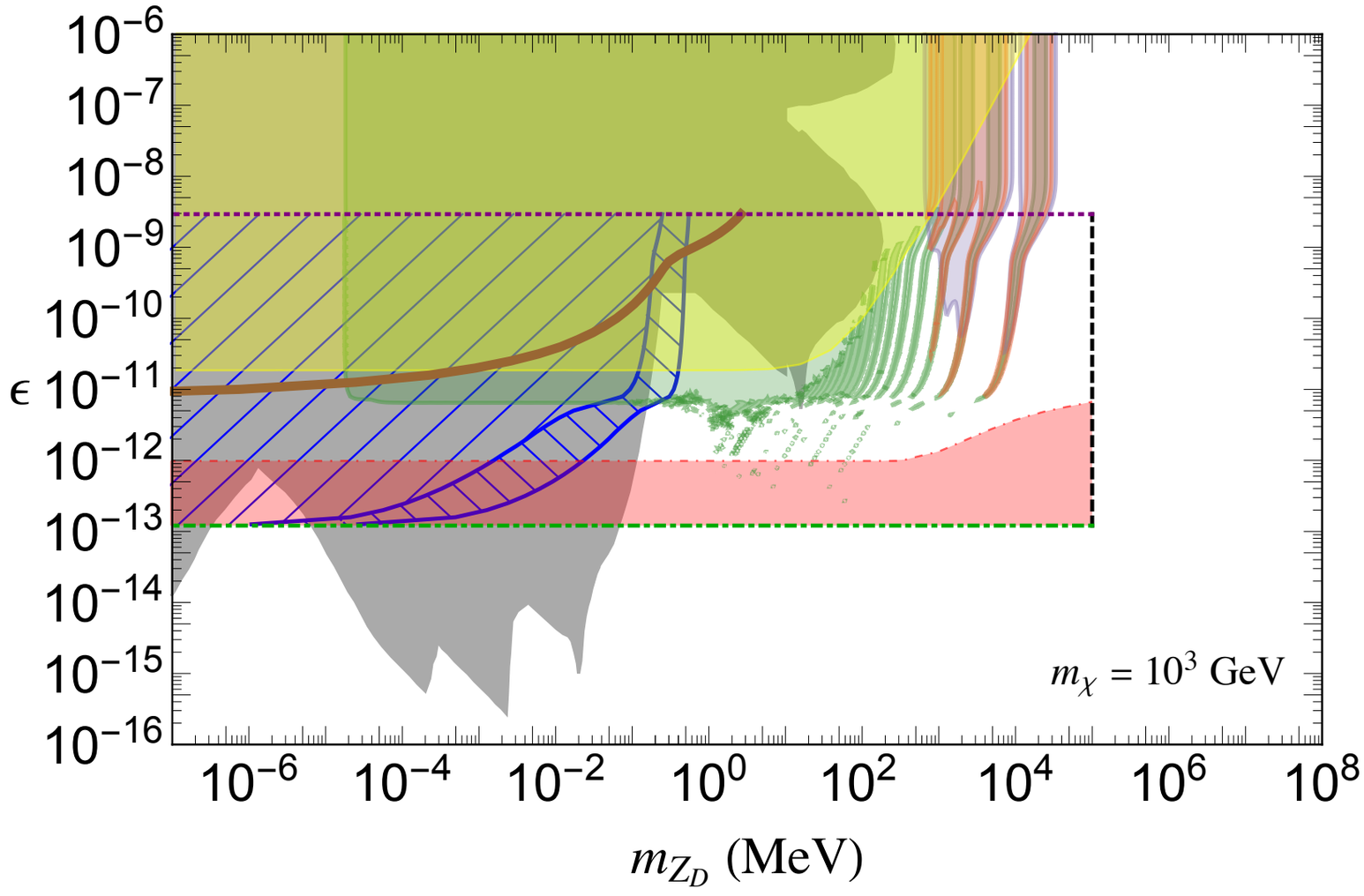
[Evans, Gaidau, JS]

# B-L LEAK-IN PARAMETER SPACE

- Sommerfeld resonances increasingly cover visible parameter space (reannihilation)

$\frac{\langle \sigma_T \rangle}{m} \geq 50\,\mathrm{cm}^2/\mathrm{g}$ (dwarfs)

ellipticity




CMB

direct detection

Fermi / Hess

[Evans, Gaidau, JS]