



A complex, dark-toned visualization of a cosmic web, showing a dense network of thin, glowing filaments and nodes against a black background. The filaments form a chaotic, interconnected pattern of lines and loops, with some brighter spots indicating clusters or galaxies.

DARK THERMAL HISTORIES

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UIUC

New directions in the search for light dark matter particles, Fermilab

June 4, 2019

WHAT WE KNOW ABOUT THE UNIVERSE

DM

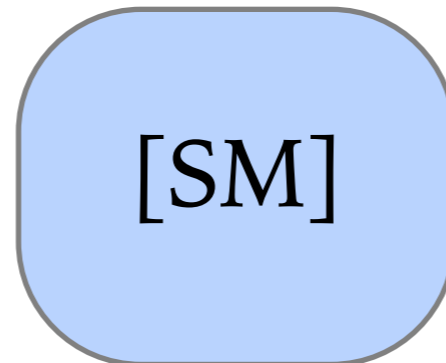
[SM]

Thermal SM radiation bath:
CMB ($T \sim eV$),
Big Bang Nucleosynthesis
($T \sim MeV$)

WHAT WE KNOW ABOUT THE UNIVERSE



DM



CMB, large-scale structure:

- ▶ new
- ▶ cold
- ▶ limited interactions

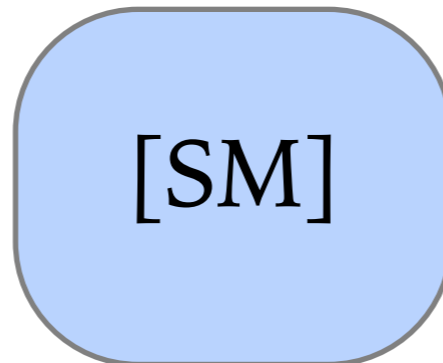
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WHAT WE KNOW ABOUT THE UNIVERSE



post-inflationary **reheating**
requires non-gravitational
interactions to successfully
populate matter fields

DM

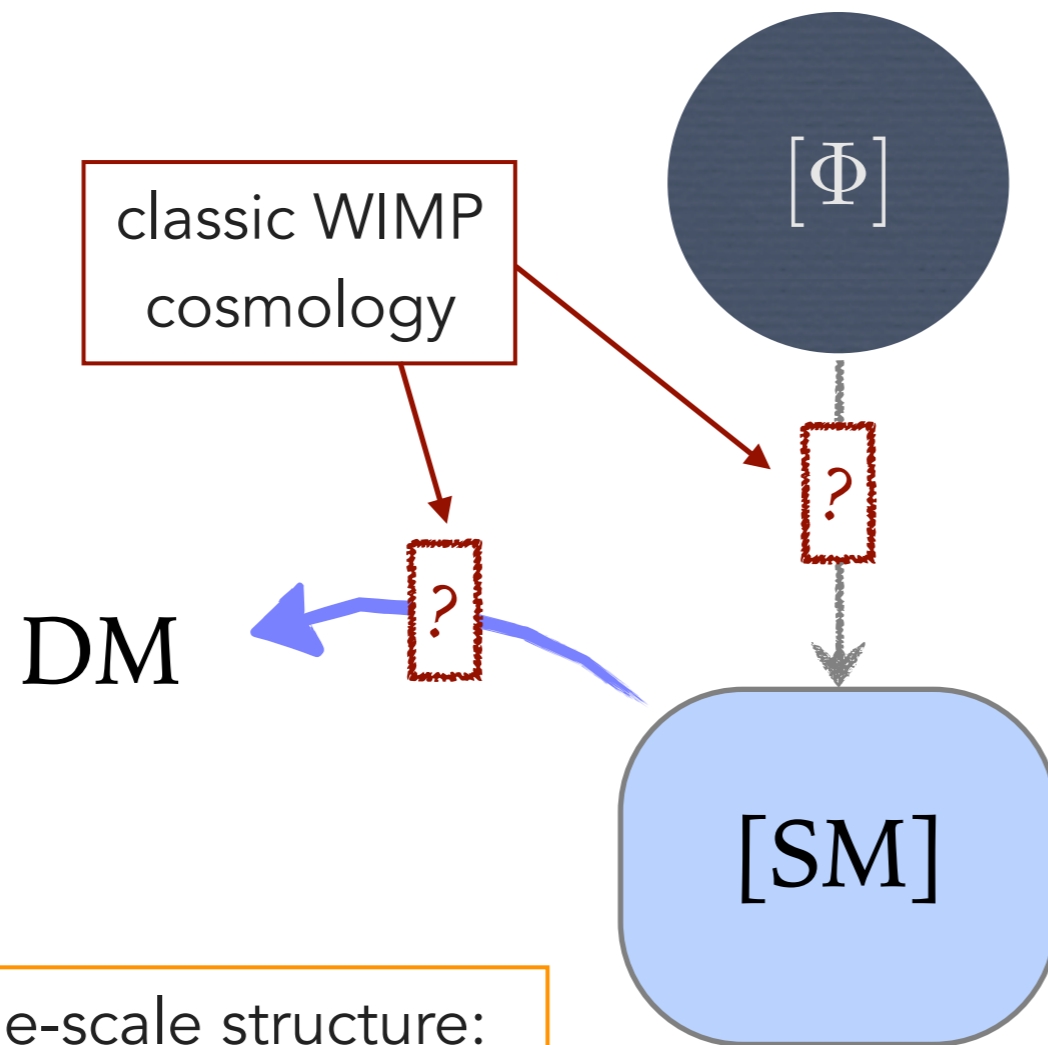


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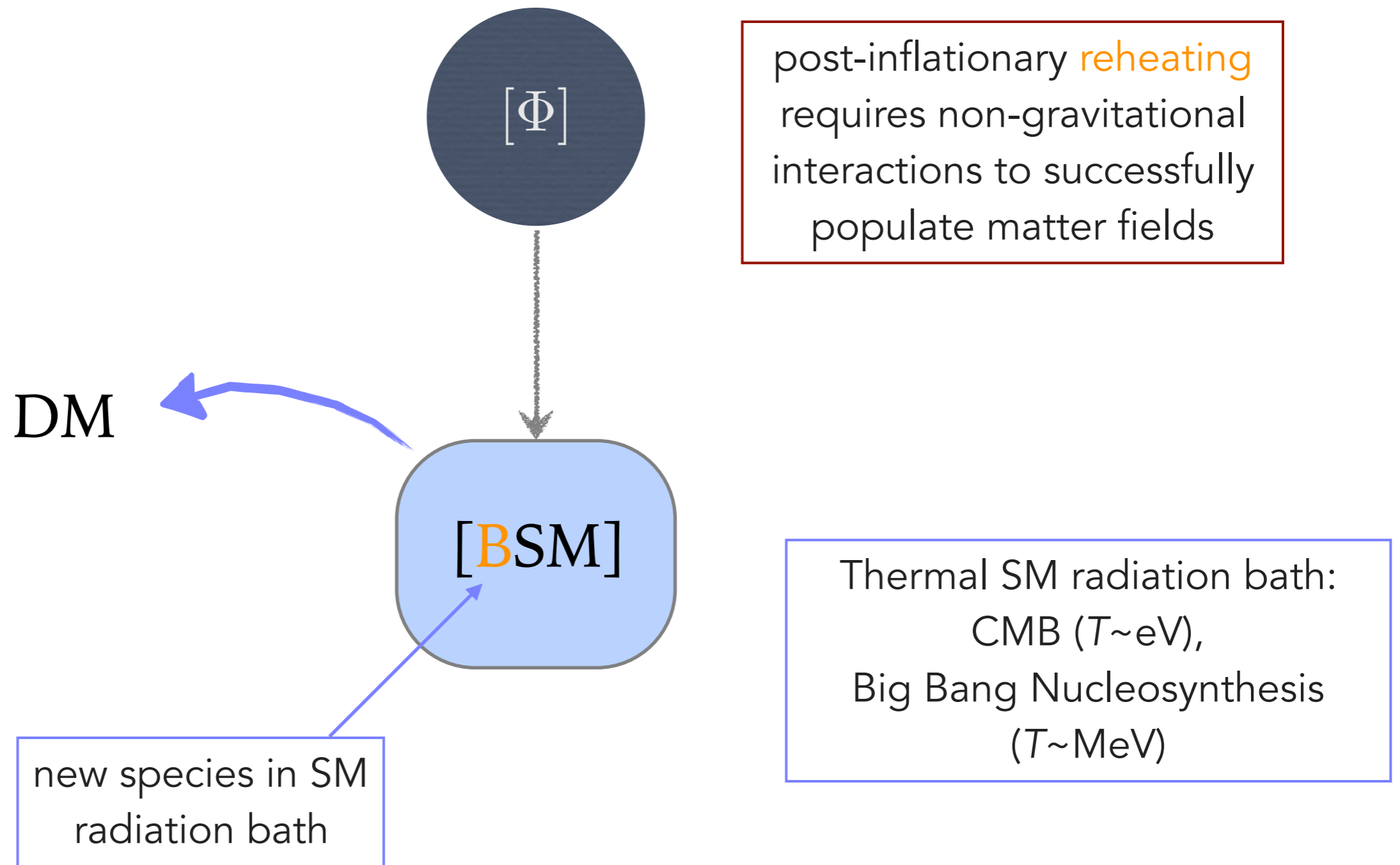
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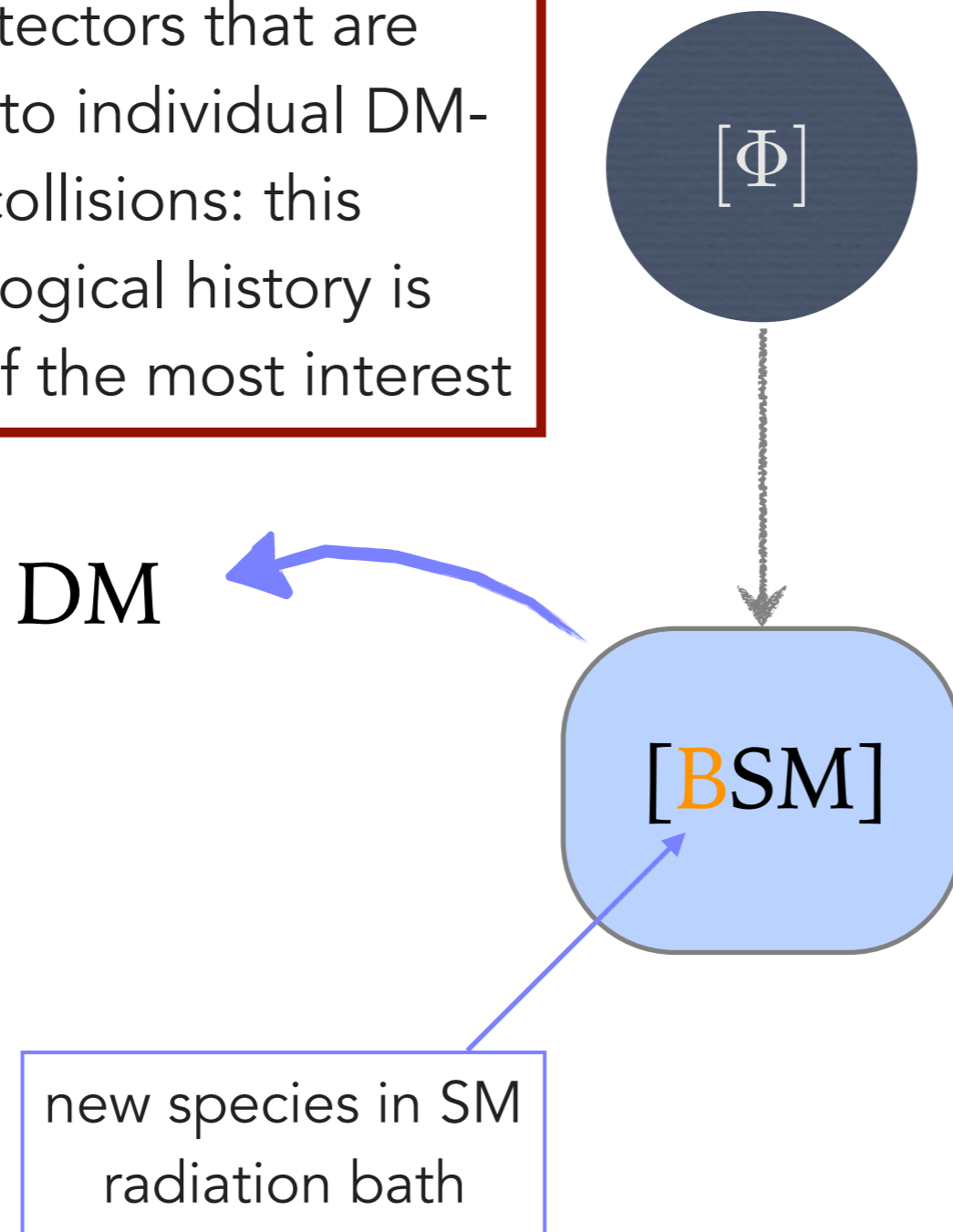
- ▶ new
- ▶ cold
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“WIMP-Y” COSMOLOGIES



“WIMP-Y” COSMOLOGIES

For detectors that are sensitive to individual DM-SM collisions: this cosmological history is typically of the most interest



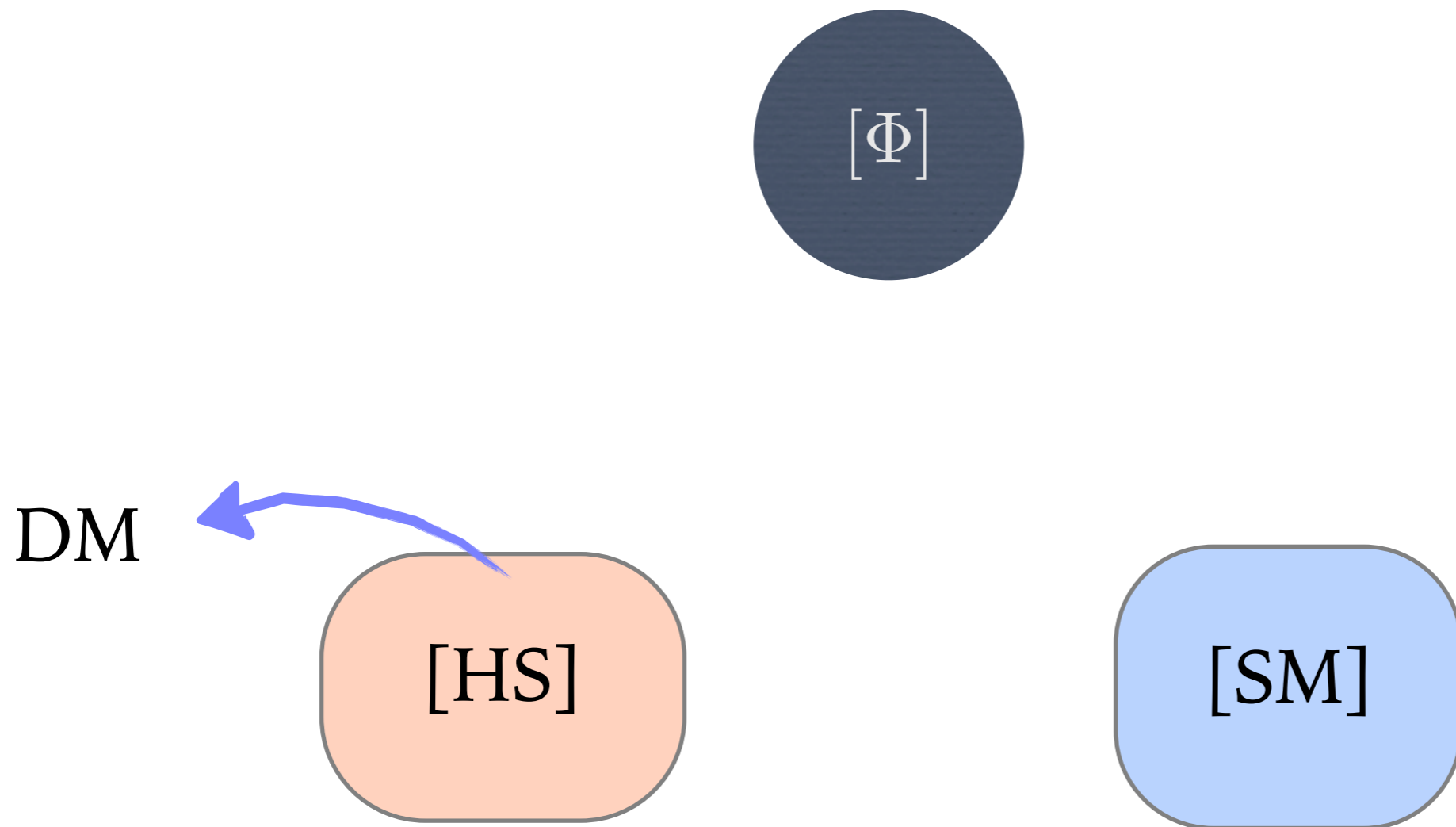
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DARK SECTORS

- Dark sector: **DM + other SM-singlet particle(s)**
 - WIMP-y cosmology: DM is born out of an augmented SM radiation bath
 - Equally minimal but less terrestrially optimistic, **hidden sector DM**: DM may be born out of a dark radiation bath (may/not be in equilibrium with the SM)
 - broad, generic class of theories
 - many many many mechanisms to get DM out of an internally thermalized radiation bath
 - in general **no particular reason to expect SM couplings to be directly involved**

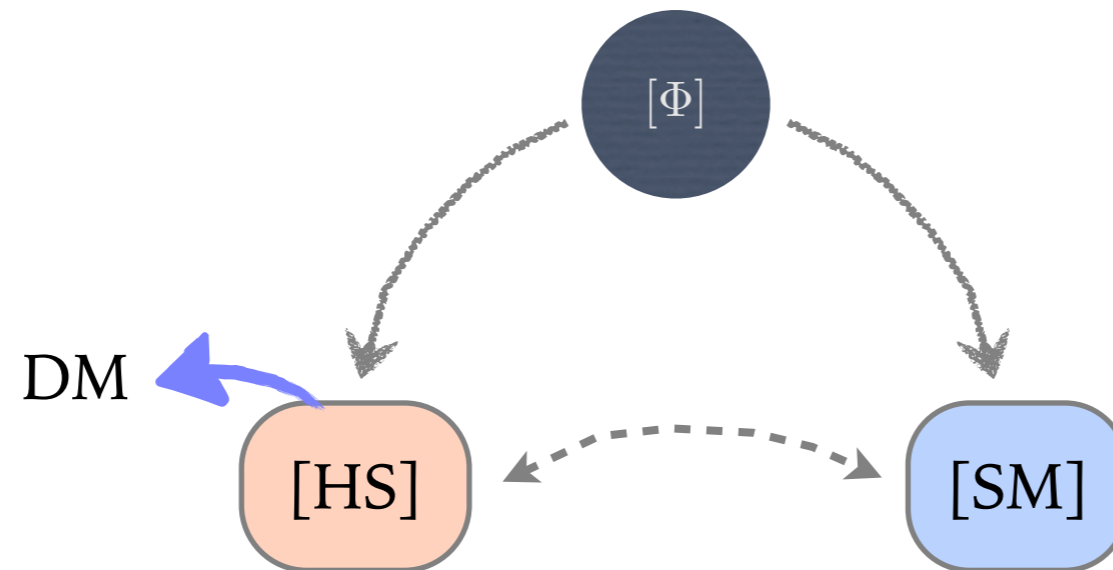
DARK SECTORS



- Minimal cosmological histories for dark radiation baths?

MINIMAL COSMOLOGY I: ASYMMETRIC REHEATING

- reheating populates HS, SM directly

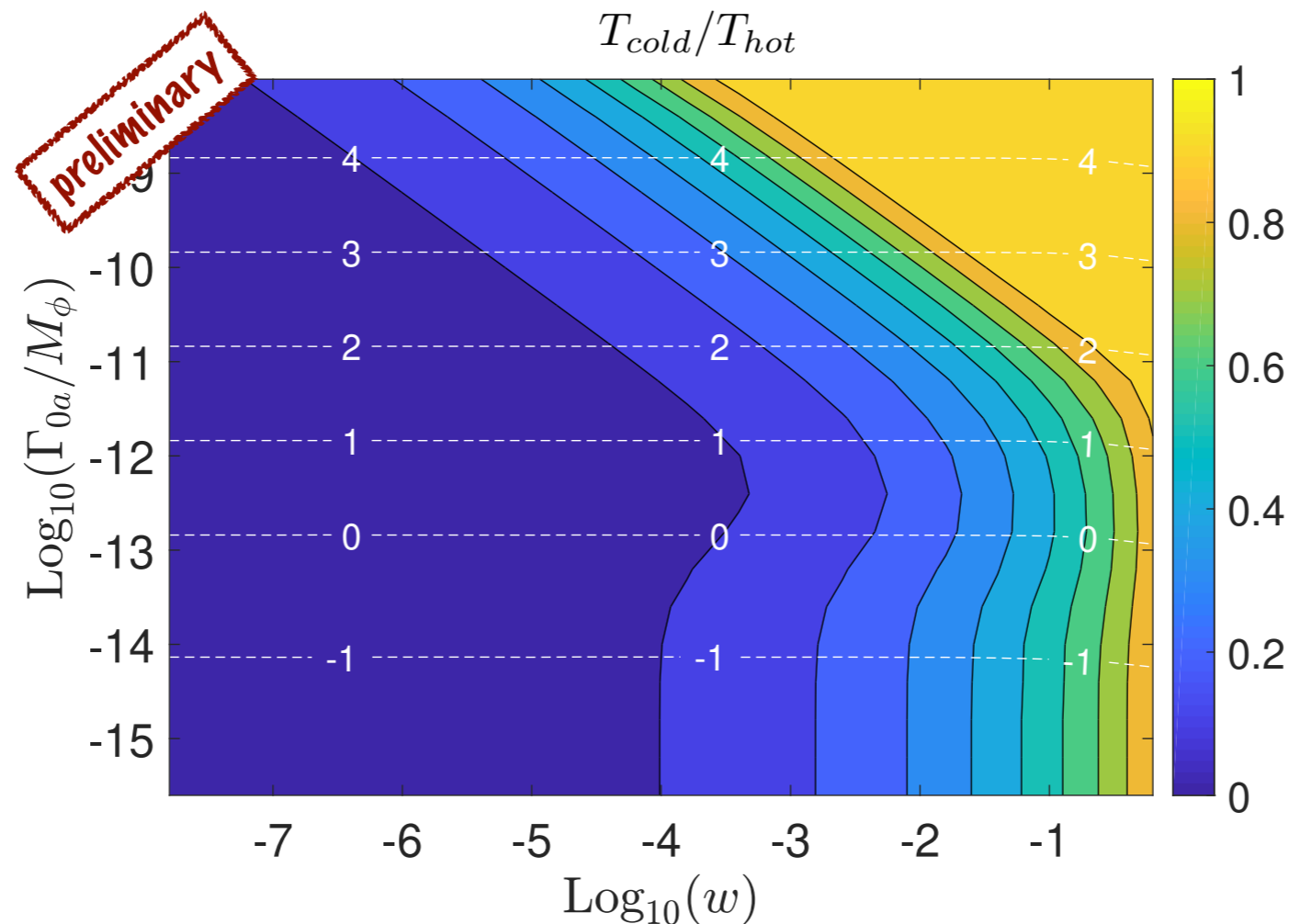


coupling sectors to same physics in UV necessarily implies interactions

- single-field inflation: all fluctuations are adiabatic
- generally $T_{HS} \neq T_{SM}$
- how important is scattering? Depends on whether m_ϕ is light compared to T_{RH}

ASYMMETRIC REHEATING

- ▶ for large T_{RH} , the colder sector is dominantly populated by energy leaking out of the hotter sector



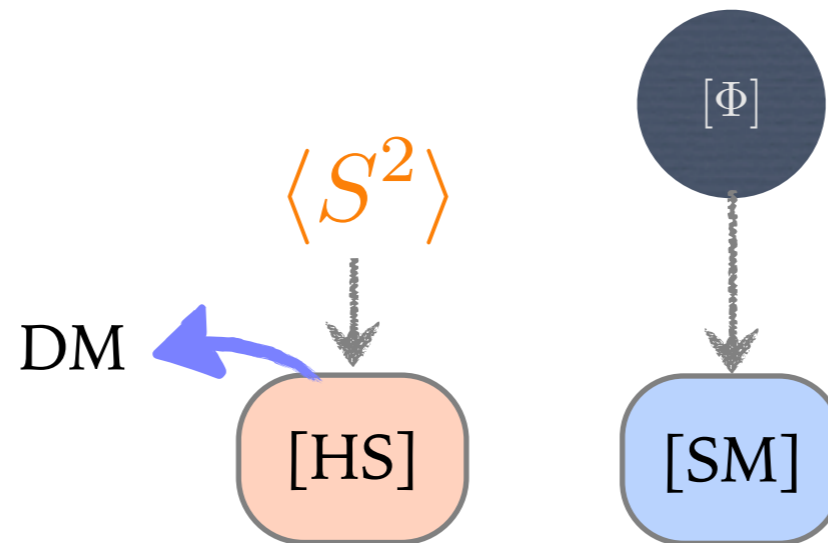
- ▶ for small T_{RH} , the two sectors are for all intents and purposes decoupled

ASYMMETRIC REHEATING

- A few opinions:
 - the question of what couplings to matter an inflaton should have is really a question for inflationary model builders
 - large reheating-era temps are a fun playground for non-equilibrium phenomena but in majority of hep-ph's favorite explicit inflationary models, $T_{RH} \ll m_\phi$
 - it naively seems hard to square "large" couplings to matter with slow-roll requirement of extremely flat potential
 - explicit stringy model building shows it is not hard to obtain highly asymmetric inflaton couplings [Halverson, Long, Nelson, Salinas]
- personal bottom line: appears straightforward to obtain highly decoupled dark sectors with any desired temperature ratio

MINIMAL SCENARIO II: STOCHASTIC POPULATION

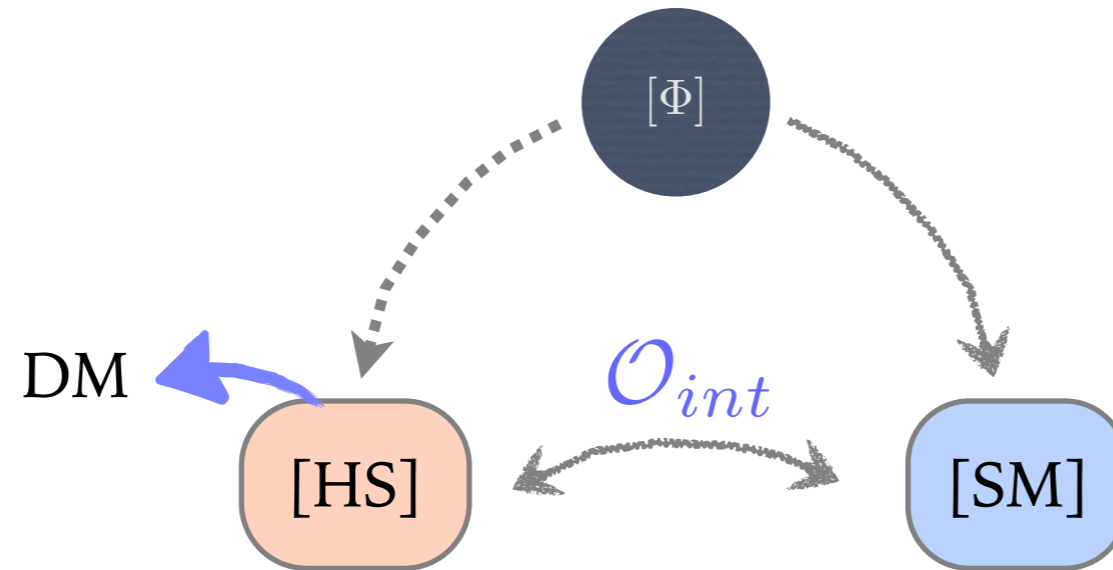
- a light ($m < H_I$) scalar field will random-walk during inflation:



- ρ_{HS} subdominant to ρ_ϕ at start of reheating \rightarrow not easy to get large HS temperatures
- isocurvature perturbations
- see also: coherent (non-thermal) bosonic DM

MINIMAL COSMOLOGY III: POPULATE FROM SM

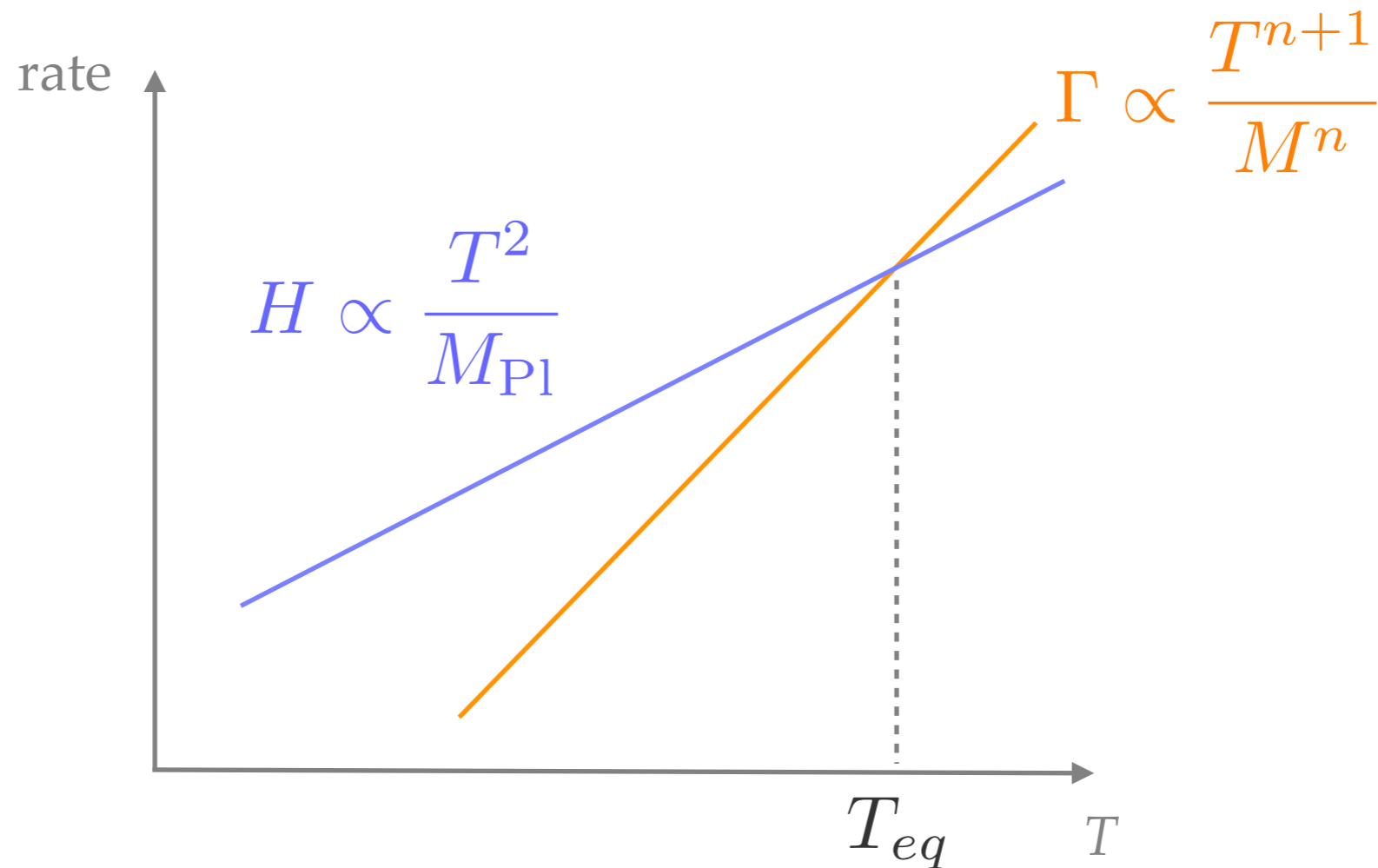
- the HS has interestingly strong interactions with SM



- most important choice for cosmology: **scale** of connecting interactions
 - new UV physics connecting sectors?
 - rely on renormalizeable interactions?

POPULATION FROM SM

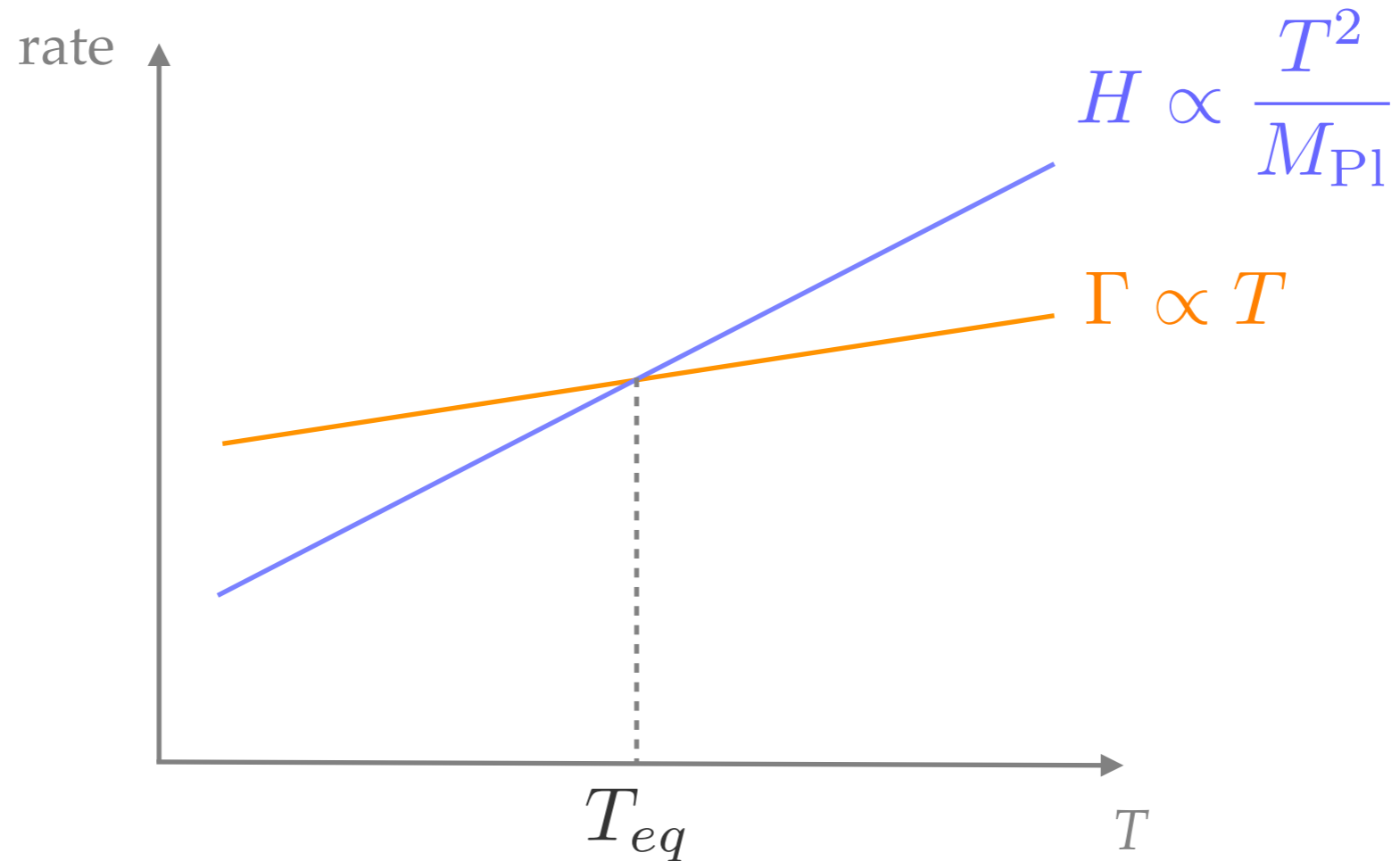
- Non-renormalizable interactions:



- population of HS dominantly at T_{eq} : decoupled afterward
- UV sensitive

POPULATION FROM SM

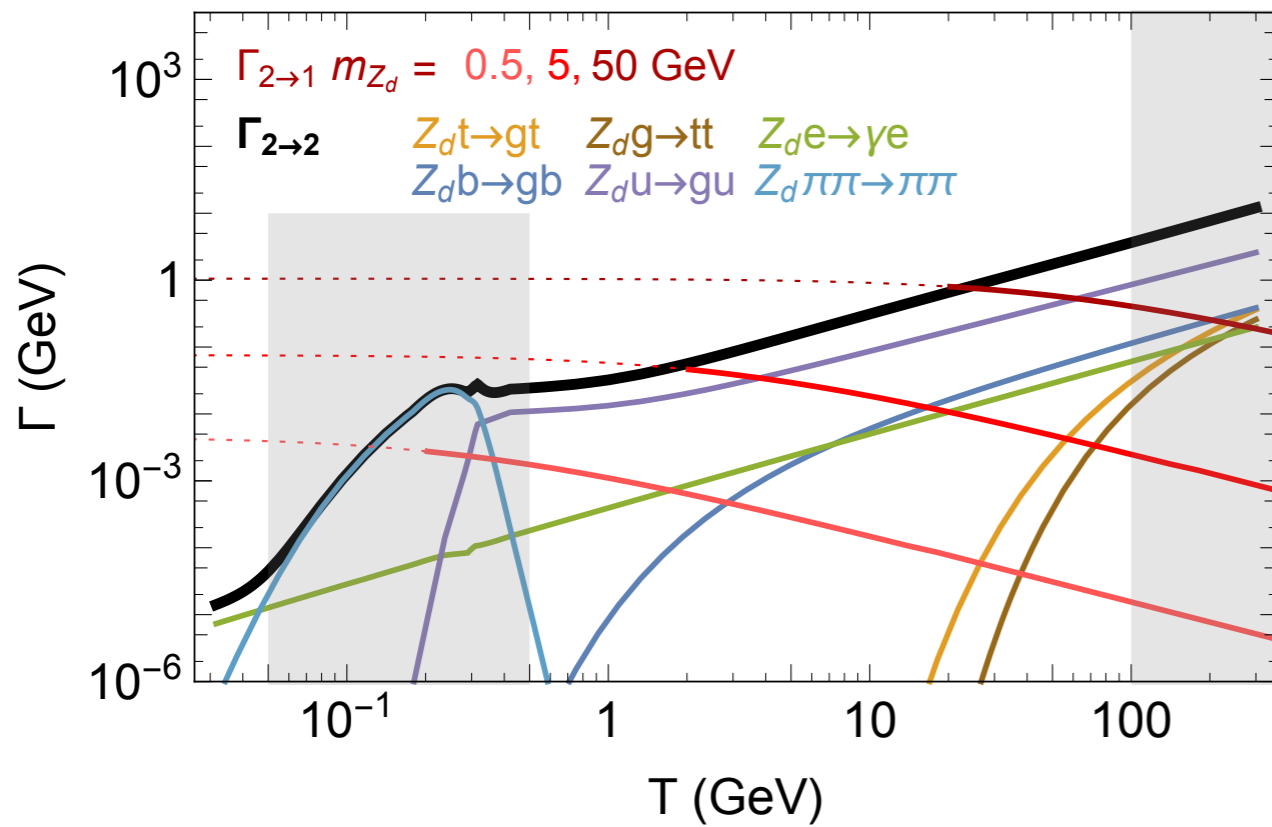
- Renormalizable interactions:



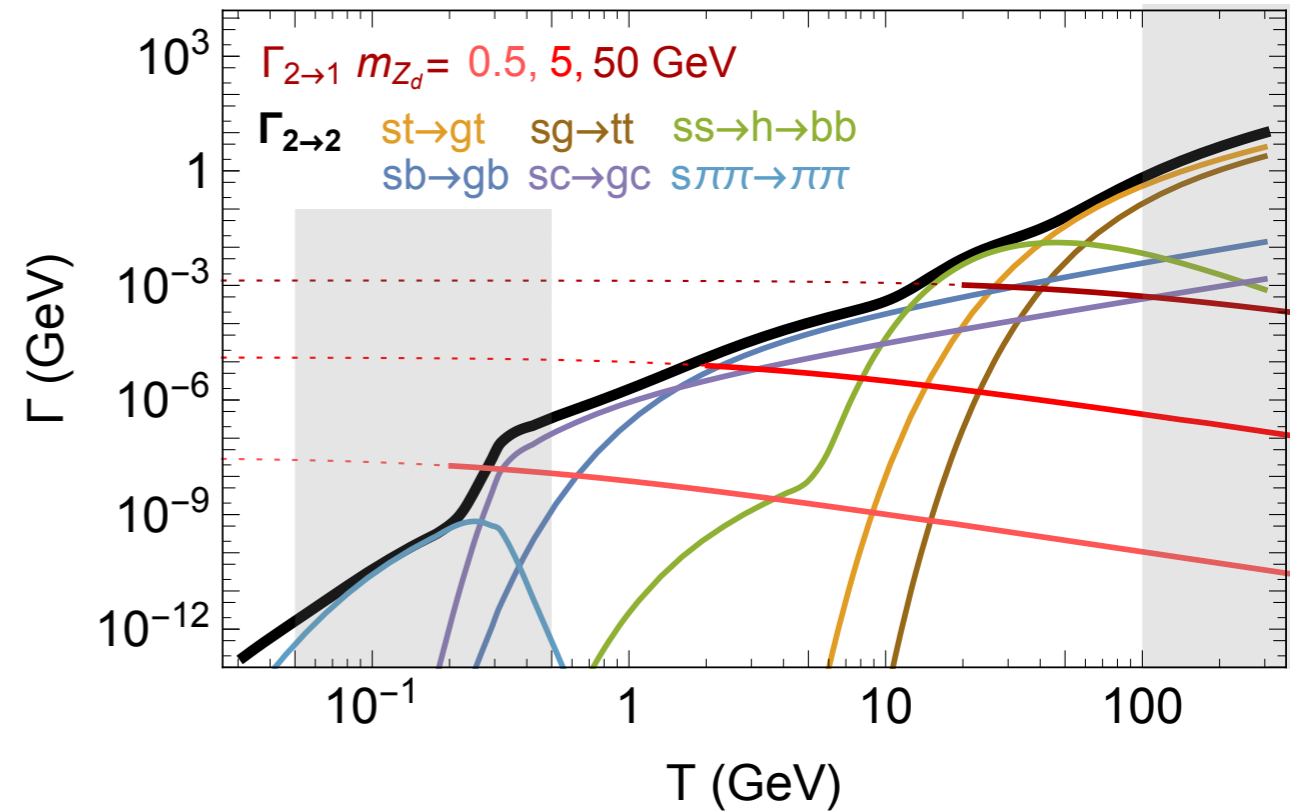
- **IR-dominated**: insensitive to unknown physics in UV
- handful of possible choices for structure of interactions

POPULATION FROM SM

- SM has lots of mass thresholds:



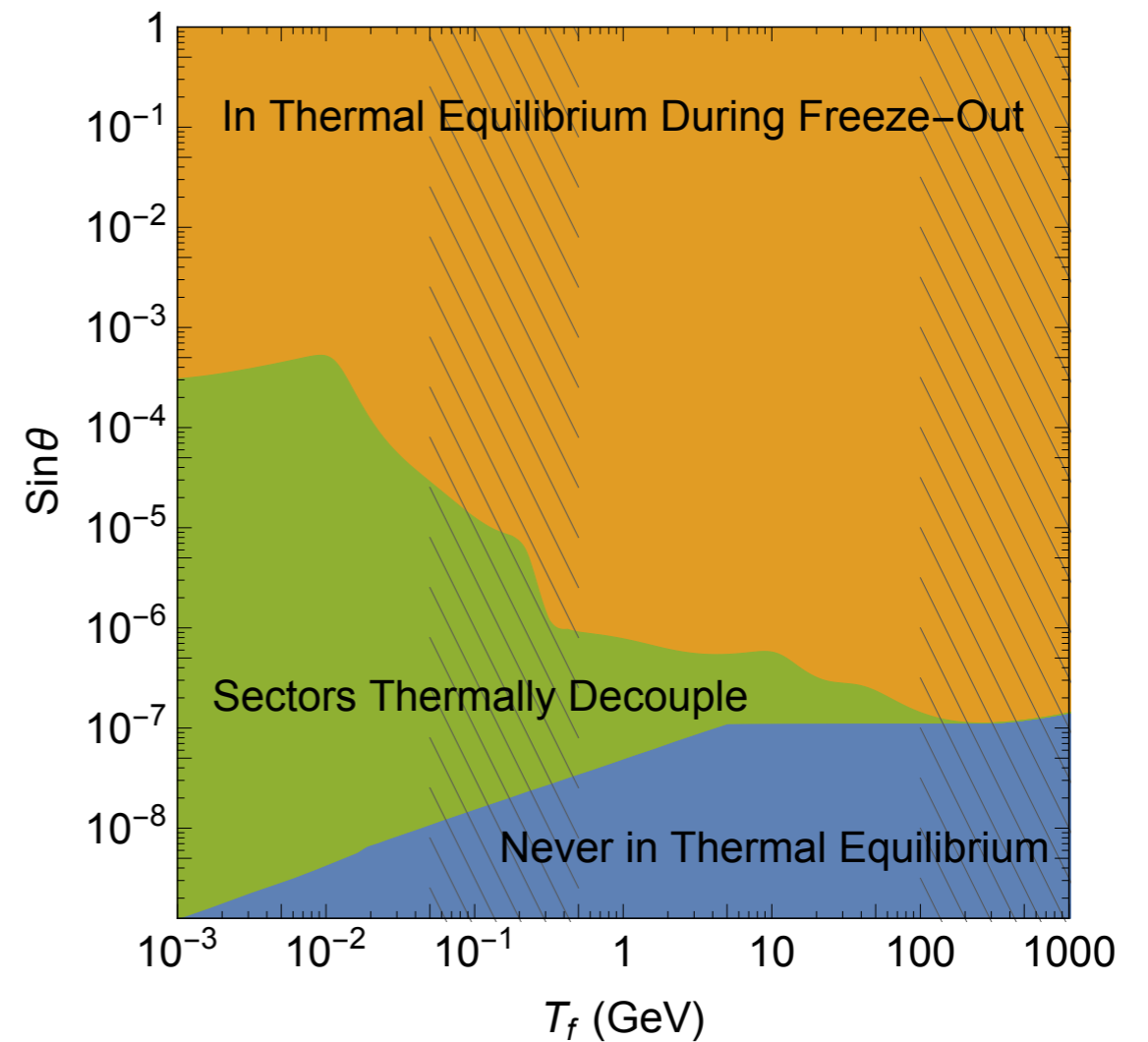
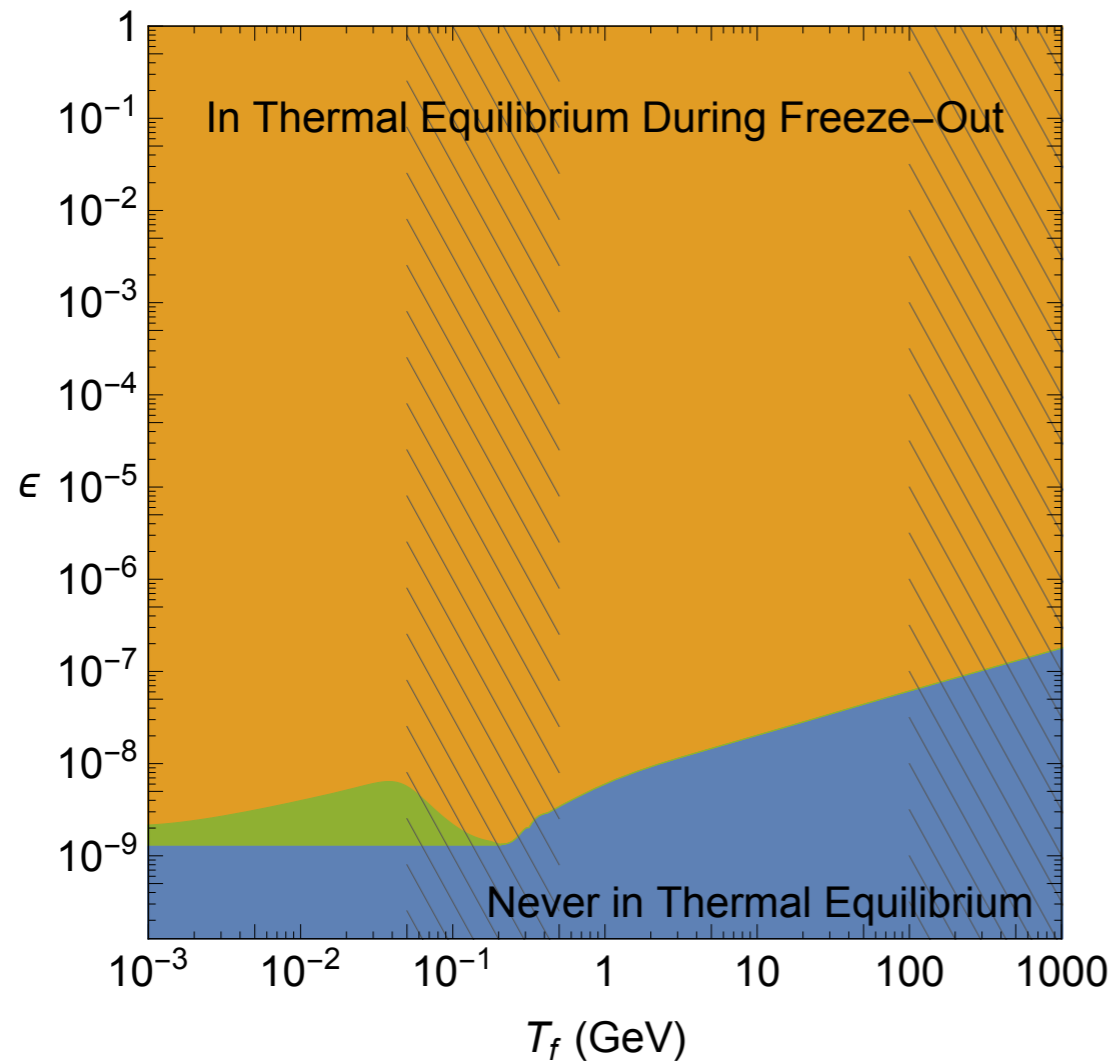
vector portal



scalar portal

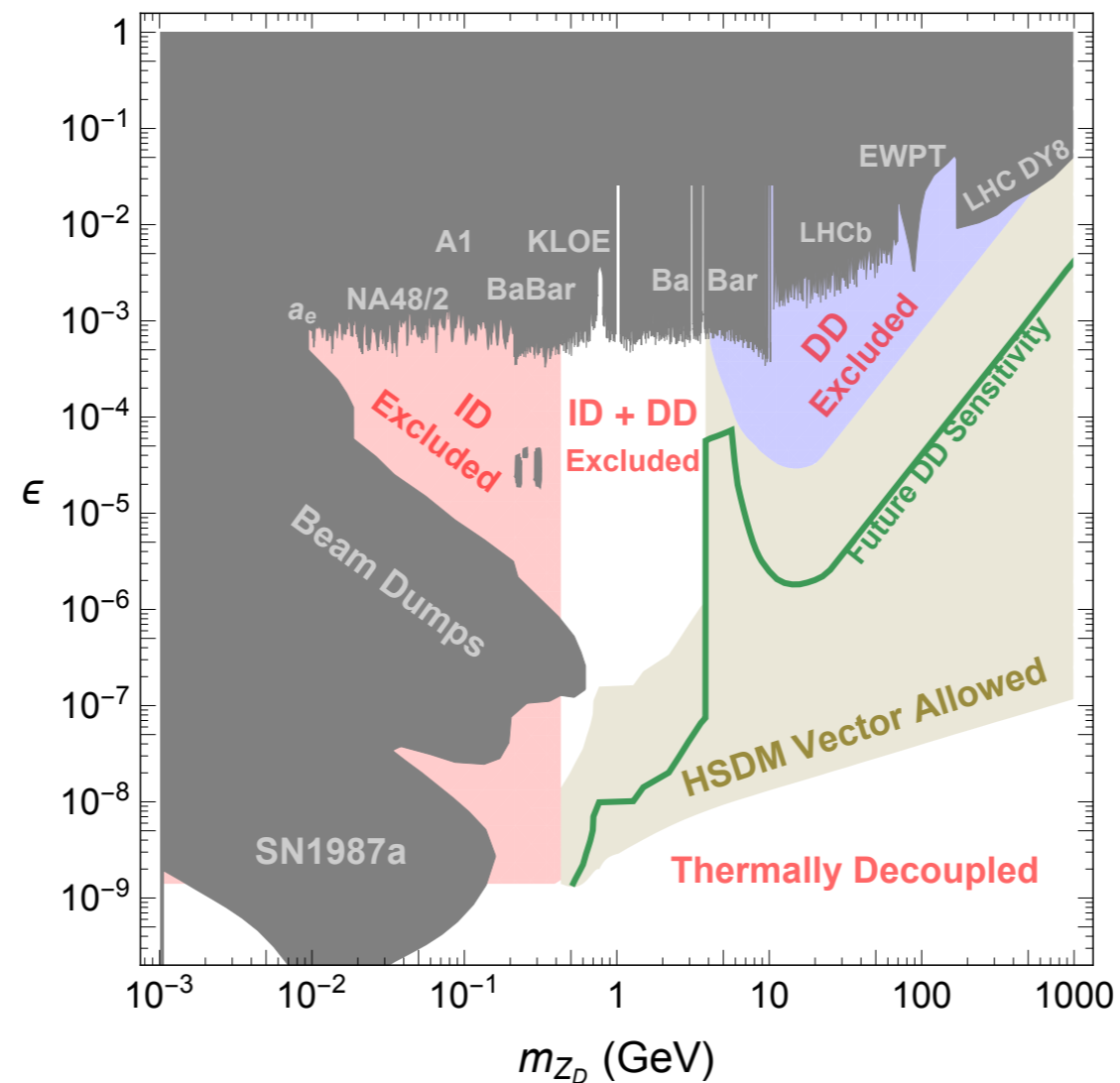
POPULATION FROM SM

► Thermalization:



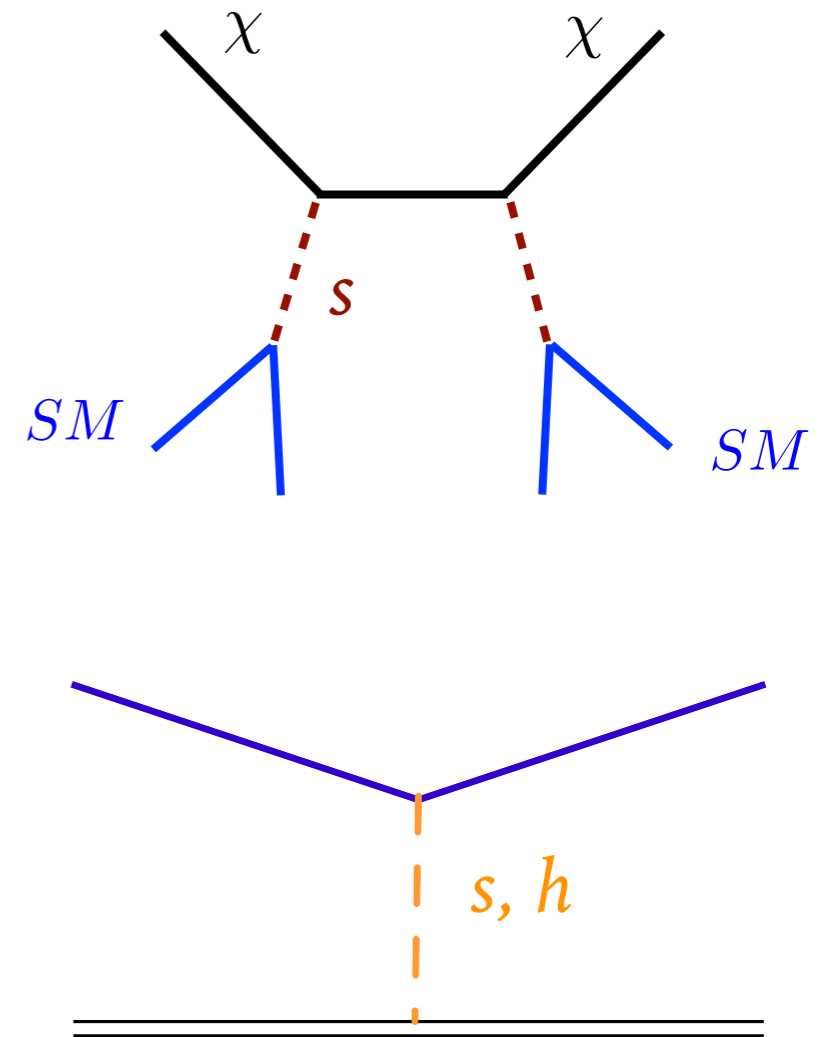
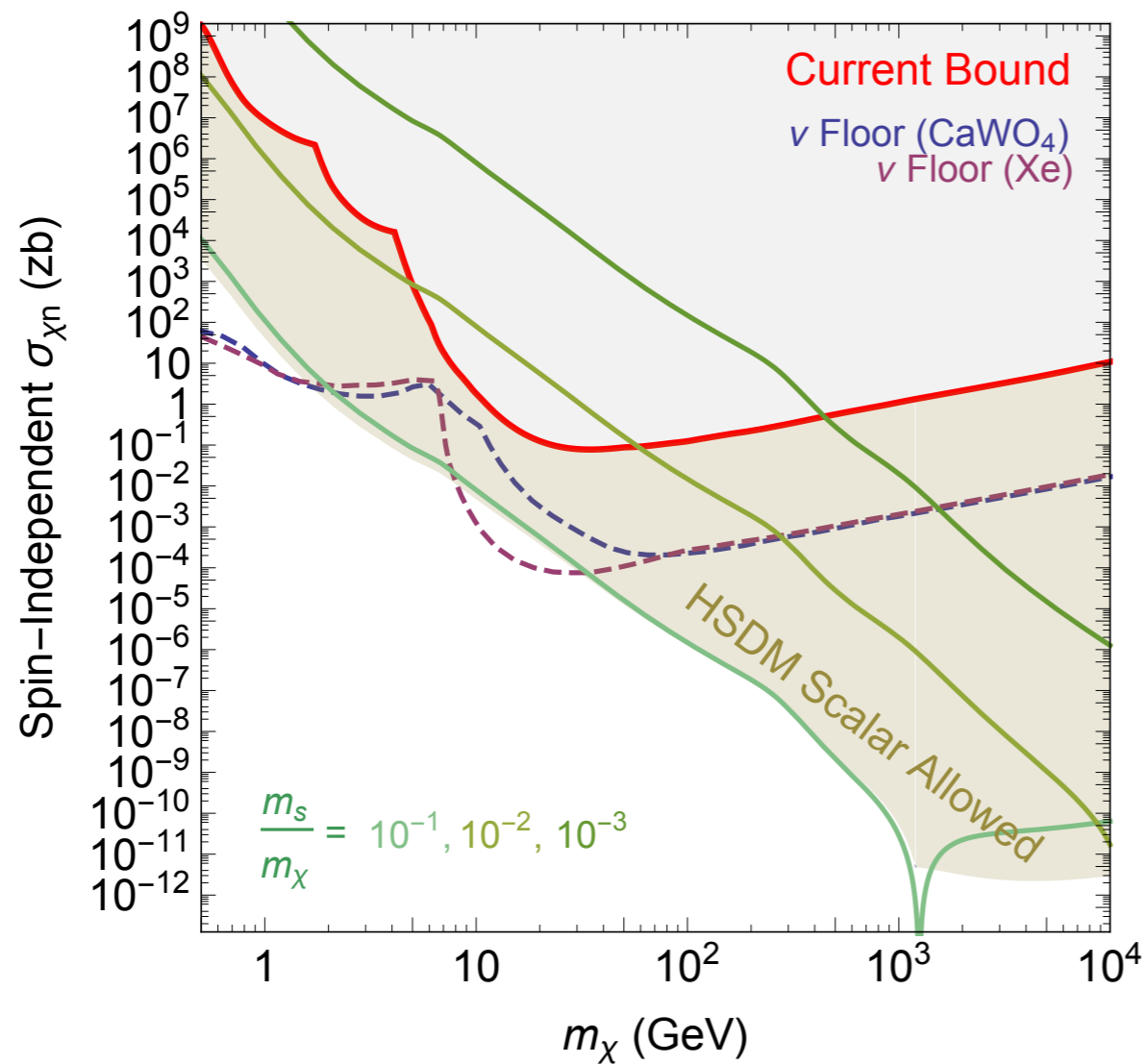
POPULATION FROM SM

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



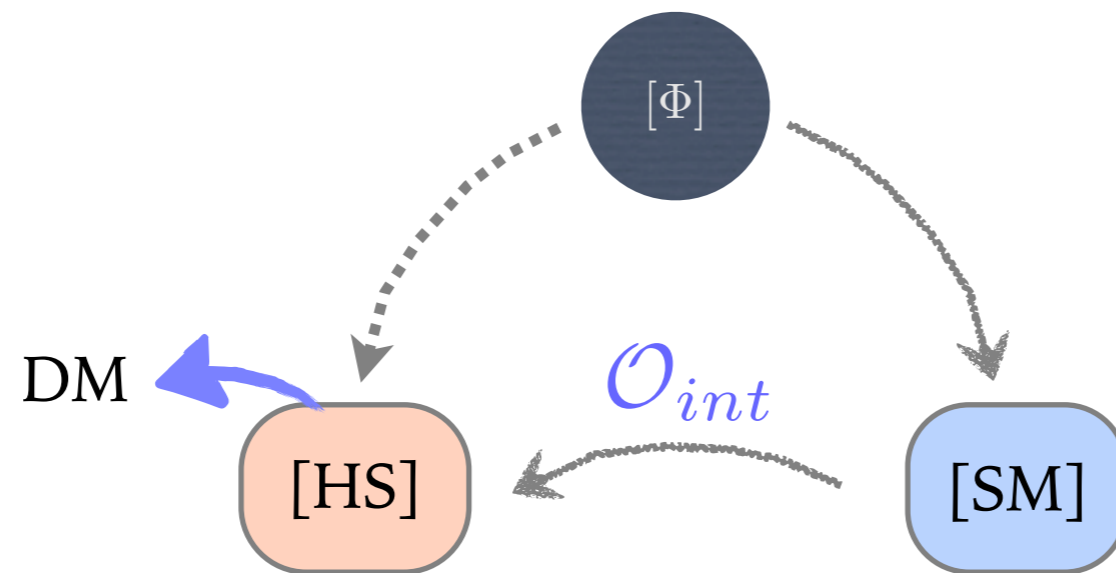
POPULATION FROM SM

- ▶ however direct detection has some ability to test this cosmology



POPULATION FROM SM

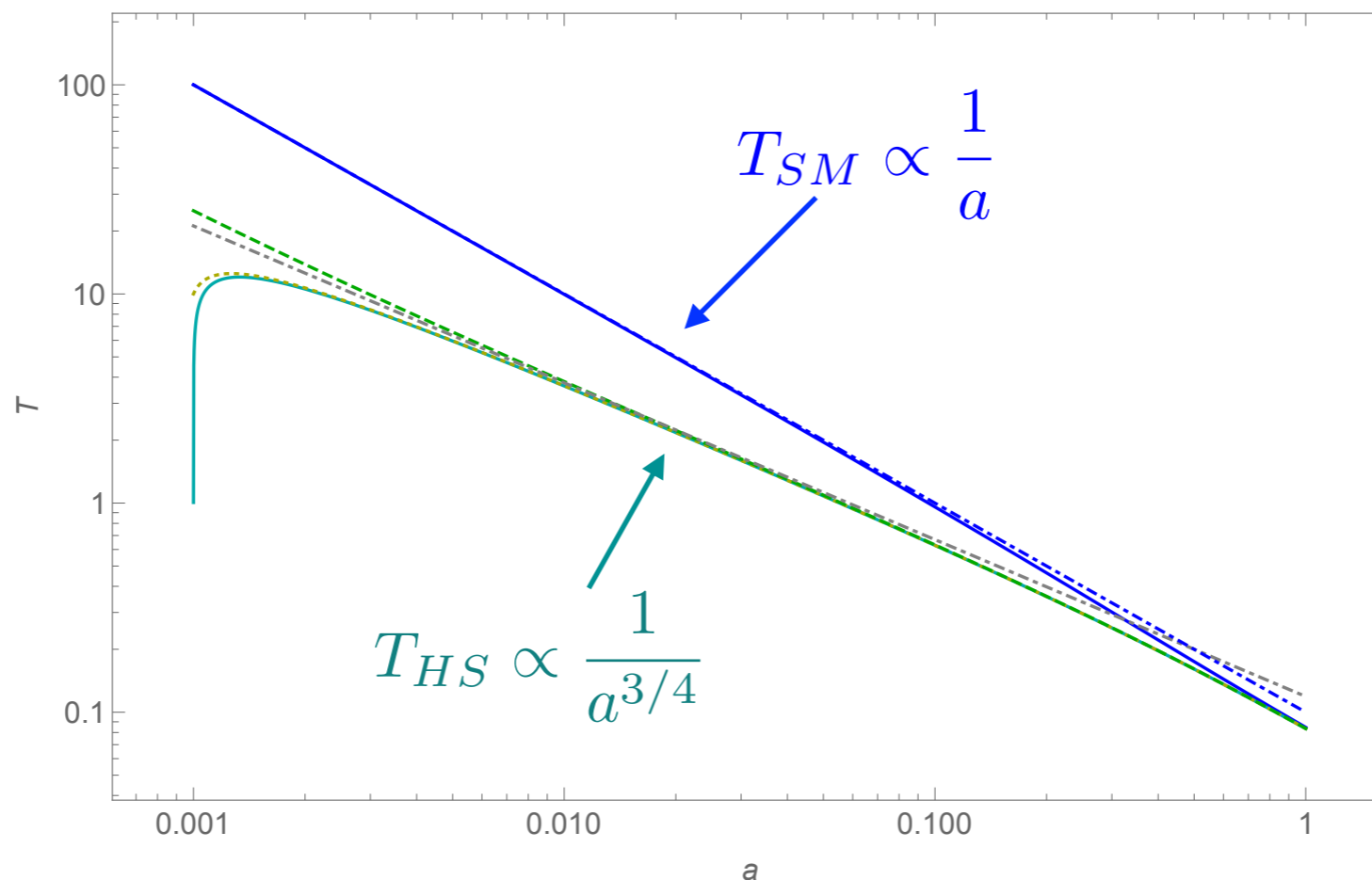
- ▶ BBN stops us from having very light DM in this cosmology. Consider out-of-equilibrium population: “leak-in”



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

POPULATION FROM SM

- A radiation bath fed by out-of-equilibrium renormalizable interactions redshifts like matter:



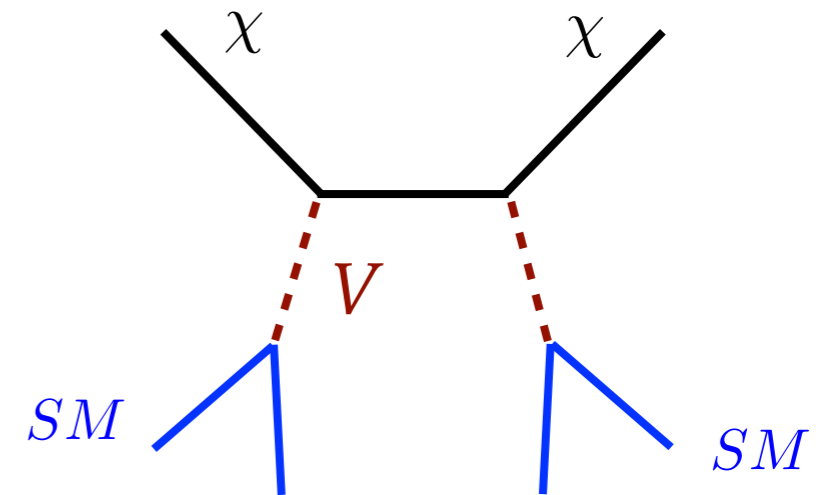
- UV-insensitive quasi-static equilibrium phase
 - What happens to DM freezing out of such a bath?

POPULATION FROM SM

- Annihilation cross-section is suppressed:

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

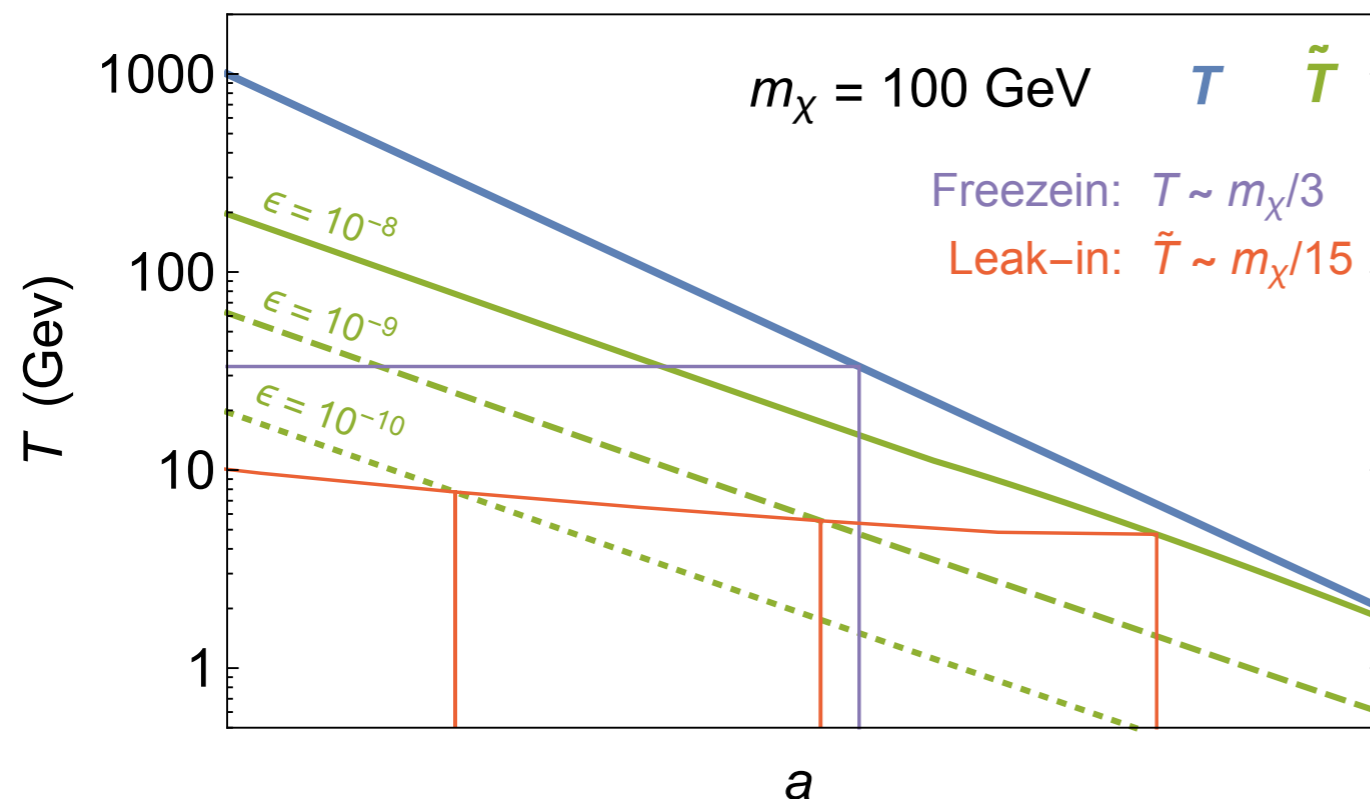
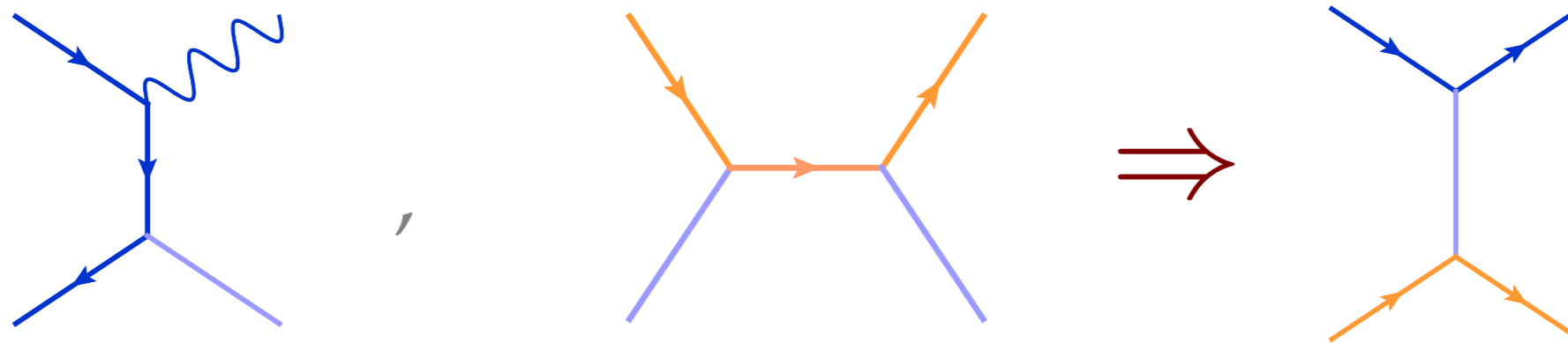
parametrizes effective coldness
of HS, $\propto \left(\frac{M_{pl}}{m}\right)^{1/3} \epsilon^{2/3}$



- lower bound on ϵ : T_{HS} never large enough to populate sufficient DM for any cross-section
- For concrete illustration, minimal vector portal model

POPULATION FROM SM

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

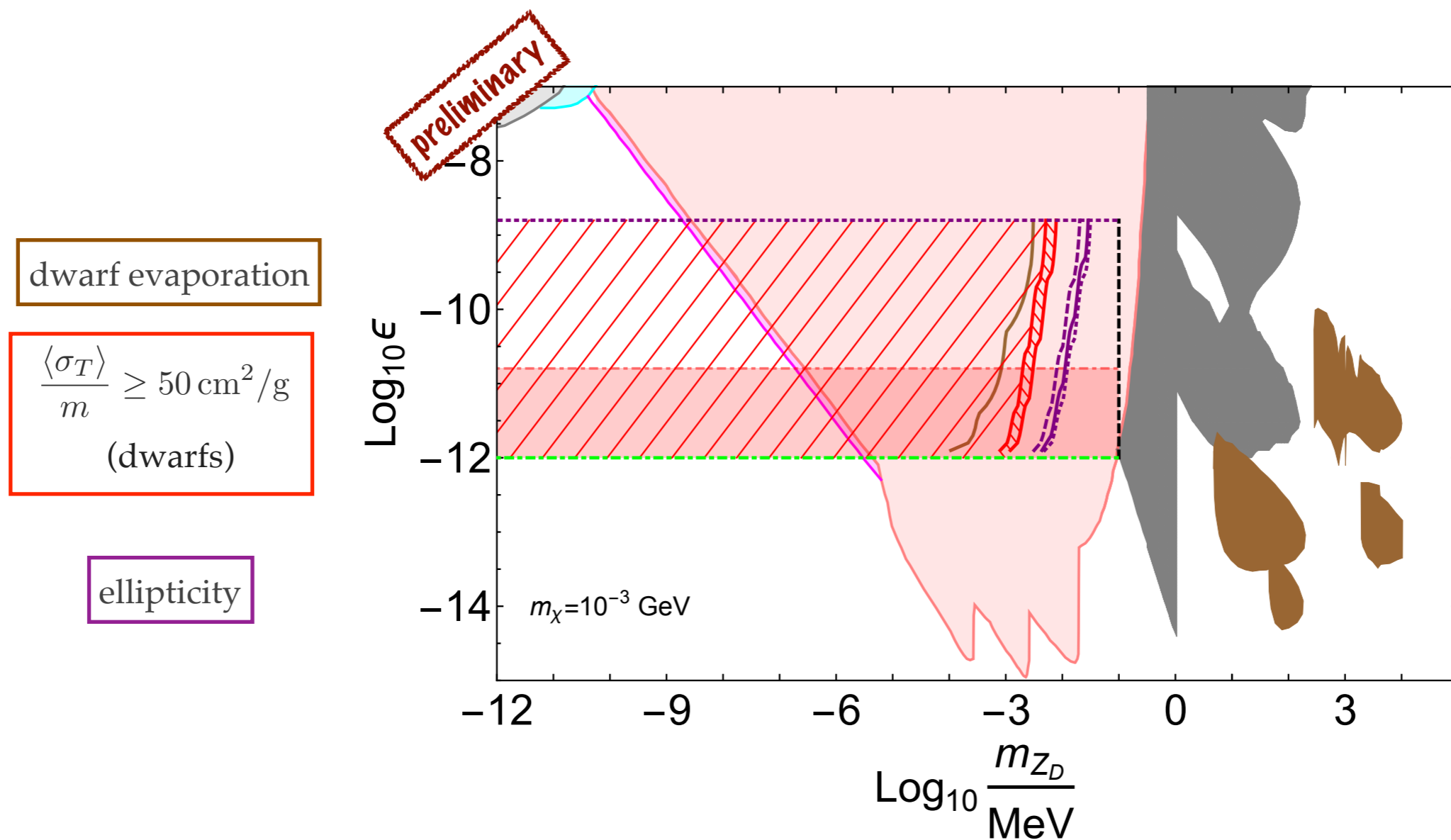


leak-in dominates:

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

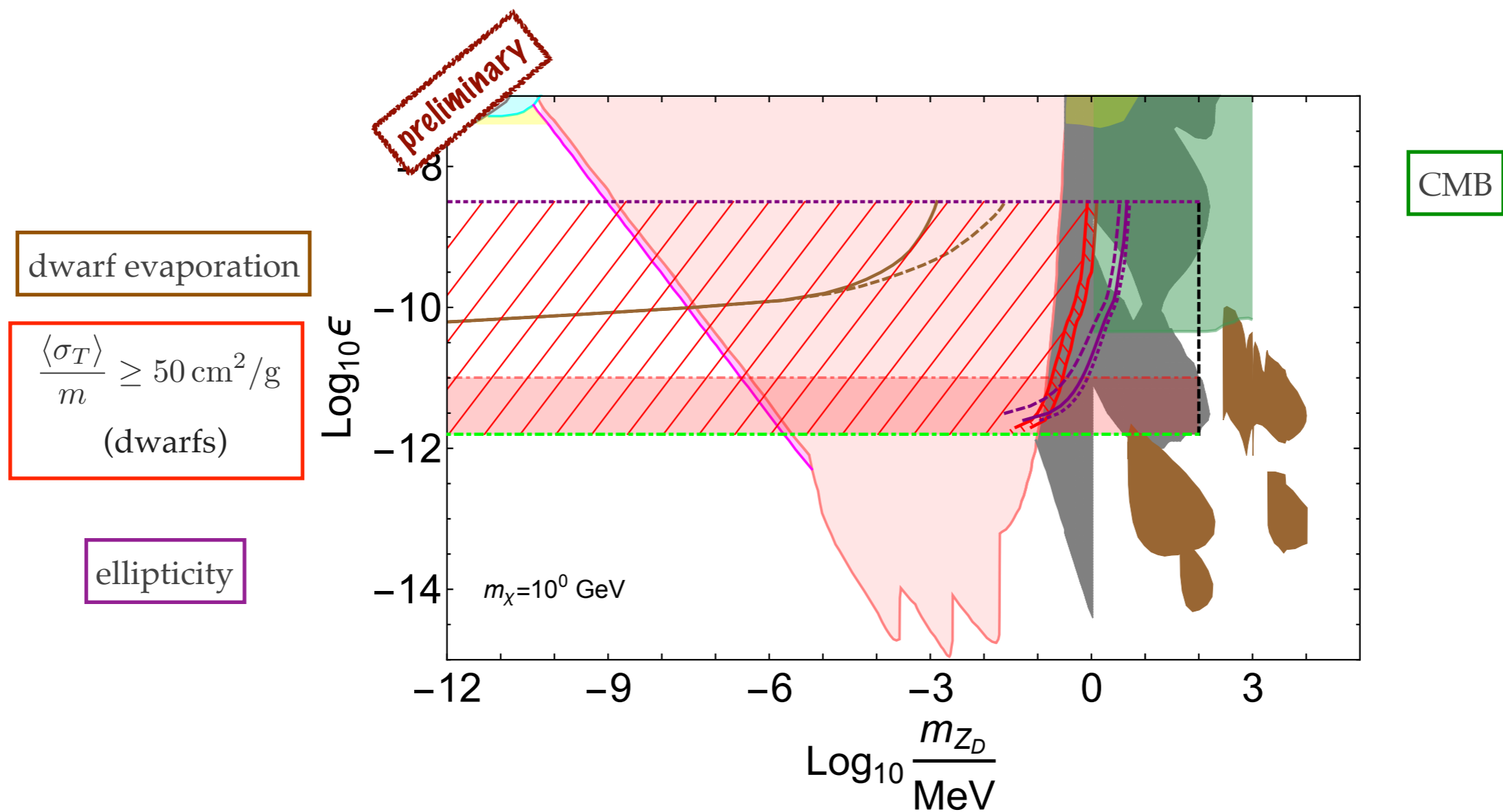
POPULATION FROM SM

- Dark photons below the electron threshold are hard to accomodate:



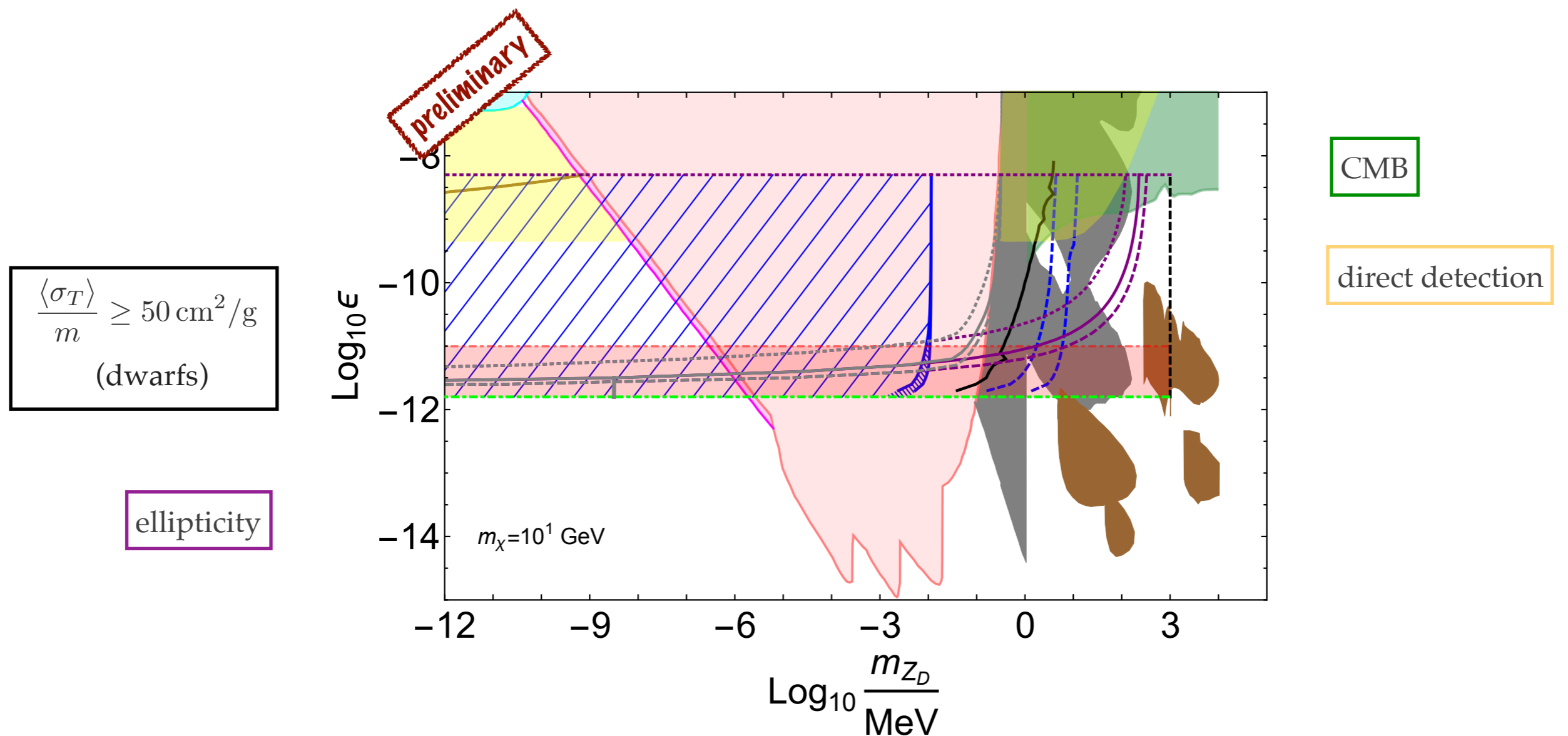
POPULATION FROM SM

- Dark photons below the electron threshold are hard to accommodate:



POPULATION FROM SM

- ▶ Viable parameter space with visible annihilations at higher masses



SOME FINAL THOUGHTS AND OPINIONS

- Many possible dark thermal histories
 - most of them do **not** predict terrestrially relevant interaction rates with SM particles
 - look instead to **astrophysics/cosmology** for signals
 - Simple hidden sector cosmologies readily yield **~100 MeV DM** with potentially interesting DD cross-sections
 - ...but **nuclear scattering** is easier to realize than electronic (CMB)
 - self-interactions + stellar cooling constraints are a powerful combination
- Thermal cosmologies that do allow sub-MeV DM are few and highly constrained: **motivated, highly predictive, testable**