Simplified SIDM models in an era of Low Reheating Temperatures

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in a collaboration with
Nicolás Bernal, Marta Losada
(arXiv:2406.17039)
Nicolás Bernal, Esau Cervantes, Andrzej Hryczuk
(arXiv:2506.09155)

SIDM Workshop, Valencia

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- Thermal DM candidates: WIMPs, SIMPs, ELDERs and Cannibals.
  - For a given mass (m), depends on two key temperatures:
    - Temperature at Chemical Freezeout ($T_{\rm fo}$, $T'_{\rm fo}$)
    - Temperature at Kinetic Decoupling ($T_{\rm k}$).
- Non-thermal DM production (FIMPs)
  - IR FIMPs:
    - Production through portal couplings between SM and DM sector.

Enriched phenomenology in presence of Self interactions

- Behavior in Non-Standard Cosmologies... **with low reheating temperatures**

WIMPs (Weakly Interacting Massive Particles): $m > T_{fo} > T_k$

$$\langle \sigma v \rangle \equiv \frac{\epsilon_{\rm eff}^2}{m^2}$$

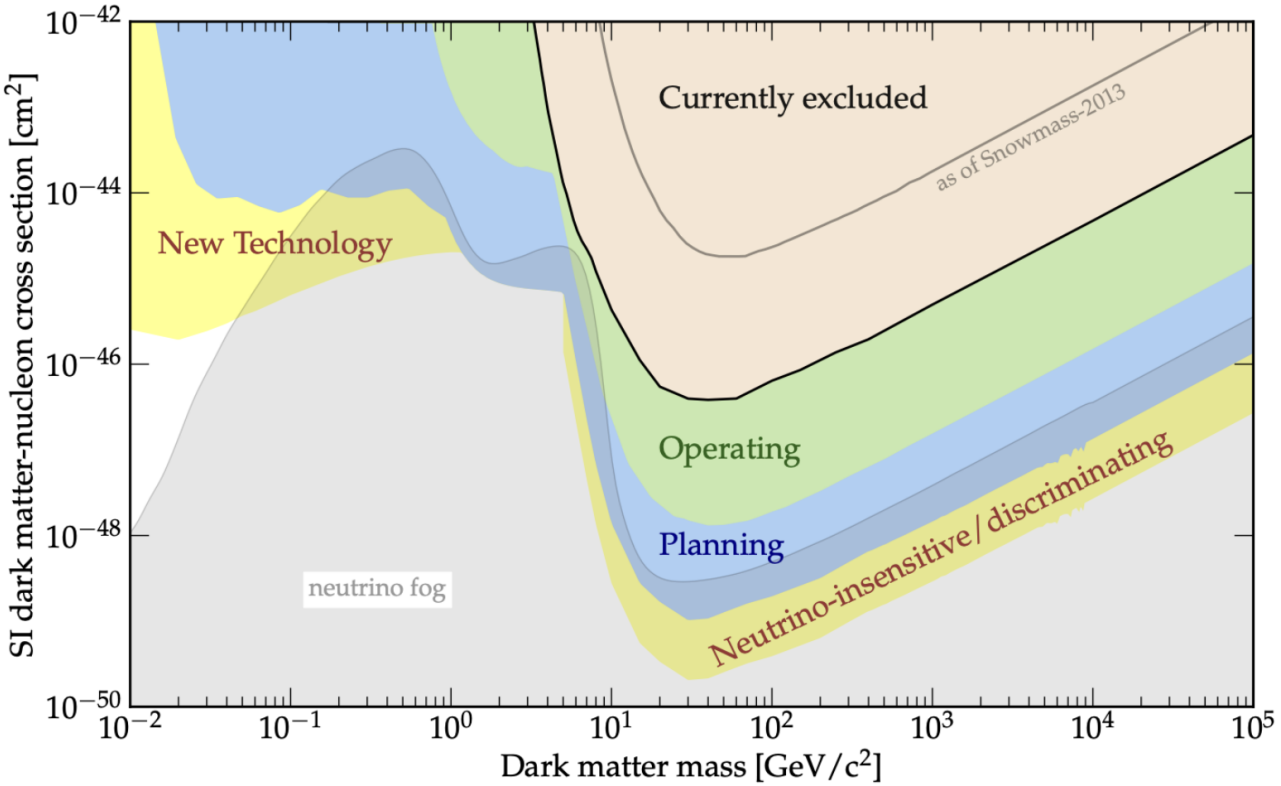
$$\mathcal{L}_{\rm int} = \frac{m_f}{\Lambda^2}\chi^\dagger\chi\bar{f}f \quad \epsilon_{\rm eff} \simeq \mathcal{O}(m_f m_{\rm DM}/\Lambda^2) \qquad \mathcal{L}_{\rm int} = \frac{\alpha_{\rm EM}}{4\pi\Lambda^2}\chi^\dagger\chi F_{\mu\nu}F^{\mu\nu} \quad \epsilon_{\rm eff} \simeq \mathcal{O}(\alpha_{\rm EM} m_{\rm DM}^2/4\pi\Lambda^2)$$

$$n_\chi(T_{fo}) \sim \frac{T_{\rm eql}\, m^2}{x_{fo}^3} \qquad T_{\rm eql} \sim 0.8 \text{ eV}$$

$$\Gamma_{2\to 2} = n_\chi(T_{fo}) \cdot \frac{\epsilon_{\rm eff}^2}{m^2} \sim H \sim \frac{T_{fo}^2}{M_{\rm Pl}} \sim \frac{m^2}{x_{fo}^2 M_{\rm Pl}}.$$

$$\boxed{m \sim \epsilon_{\rm eff}\sqrt{T_{\rm eql} M_{\rm Pl}} \sim \epsilon_{\rm eff} \times (30 \text{ TeV}).}$$

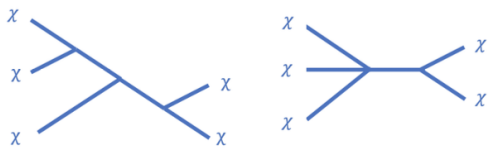
WIMP MIRACLE!!!

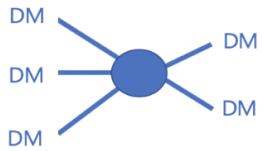

Currently excluded
as of Snowmass-2013
New Technology
Operating
Planning
Neutrino-insensitive/discriminating
neutrino fog
SI dark matter-nucleon cross section [cm^2]
Dark matter mass [GeV/c^2]
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{-50}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}

SIMPs (Strongly Interacting Massive Particles): $m > T_{\rm fo} > T_{\rm k}$

$$\mathcal{L}_{\rm DM} = |\partial\chi|^2 - m^2\,|\chi|^2 - \frac{\kappa}{6}\chi^3 - \frac{\kappa^\dagger}{6}\chi^{\dagger 3} - \frac{\lambda}{4}|\chi|^4 .$$

$$\Gamma_{3\to 2} \sim n_\chi^2 \langle\sigma v^2\rangle_{3\to 2} . \qquad \langle\sigma v^2\rangle_{3\to 2} \equiv \frac{y_{\rm eff}^3}{m^5}$$

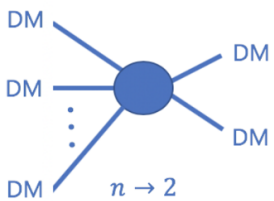




$$m \sim y_{\rm eff}\left(T_{\rm eql}^2 M_{\rm Pl}\right)^{1/3} \sim y_{\rm eff}\cdot(100\ {\rm MeV}) .$$

FOR $\alpha_{\rm eff} \sim \mathcal{O}(1)$ ⟹ Strong Scale Emerges

SIMP MIRACLE!!!



$$\Gamma_{n\to 2} \sim n_\chi^{n-1}\langle\sigma v^{n-1}\rangle_{n\to 2} \sim H \quad ; \qquad \langle\sigma v^{n-1}\rangle_{n\to 2} \equiv \frac{\alpha^n}{m^{3n-4}} .$$

$$m \sim y_{\rm eff}\left(T_{\rm eql}^{n-1} M_{\rm Pl}\right)^{1/n} ,$$

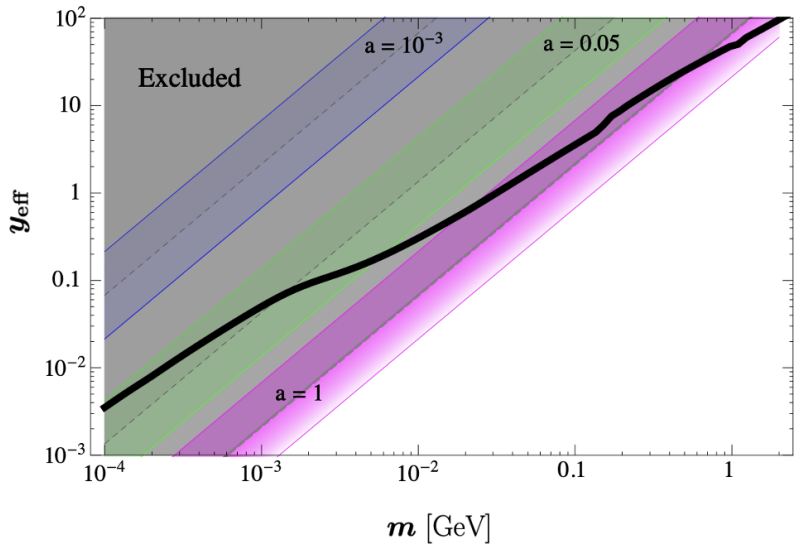
SIMPs (Strongly Interacting Massive Particles): $m > T_{fo} > T_k$

$$\frac{\sigma_{\rm scatter}}{m} = \frac{a y_{\rm eff}^2}{m^3}$$

$$\left(\frac{\sigma_{\rm scatter}}{m}\right)_{\rm obs} = (0.1 - 10)\ {\rm cm}^2/{\rm g}$$

$$\frac{\sigma_{\rm scatter}}{m} \lesssim 1\ {\rm cm}^2/{\rm g}$$

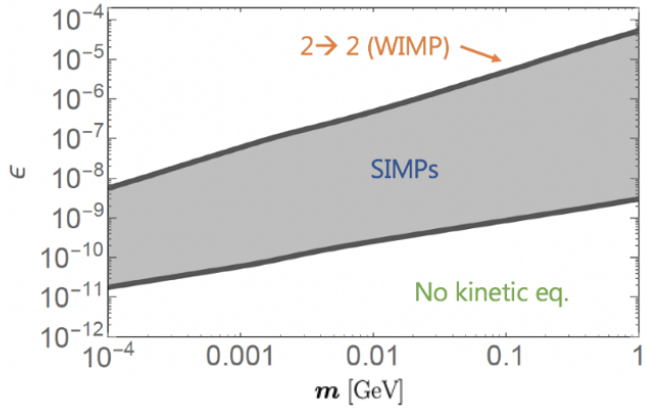
[arXiv:1402.5143 [hep-ph]]

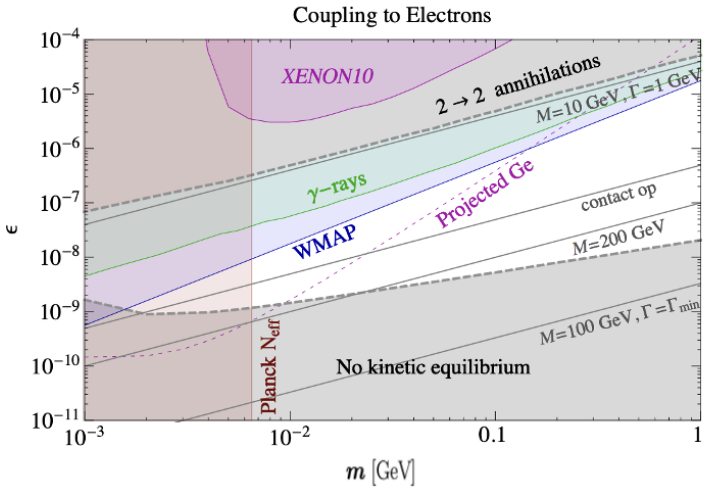


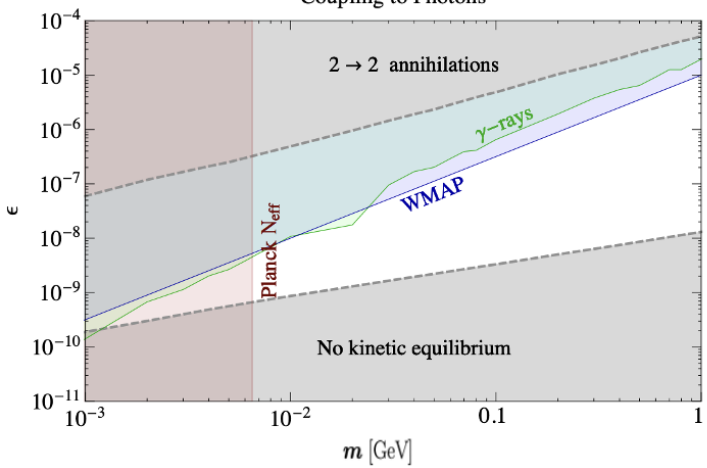
SIMPs (Strongly Interacting Massive Particles): $m > T_{fo} > T_k$

$$\Gamma_{\rm cool} \sim n_{\rm SM} \langle \sigma v \rangle , \qquad \Gamma_{\rm ann} \sim n_{\chi} \langle \sigma v \rangle .$$

$$\left. \frac{\Gamma_{\rm cool}}{\Gamma_{3\to 2}} \right|_{T_{fo}} \gtrsim 1 , \qquad \left. \frac{\Gamma_{\rm ann}}{\Gamma_{3\to 2}} \right|_{T_{fo}} \lesssim 1 .$$

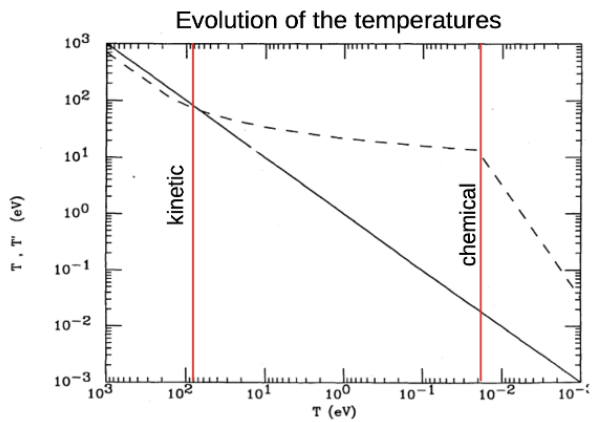


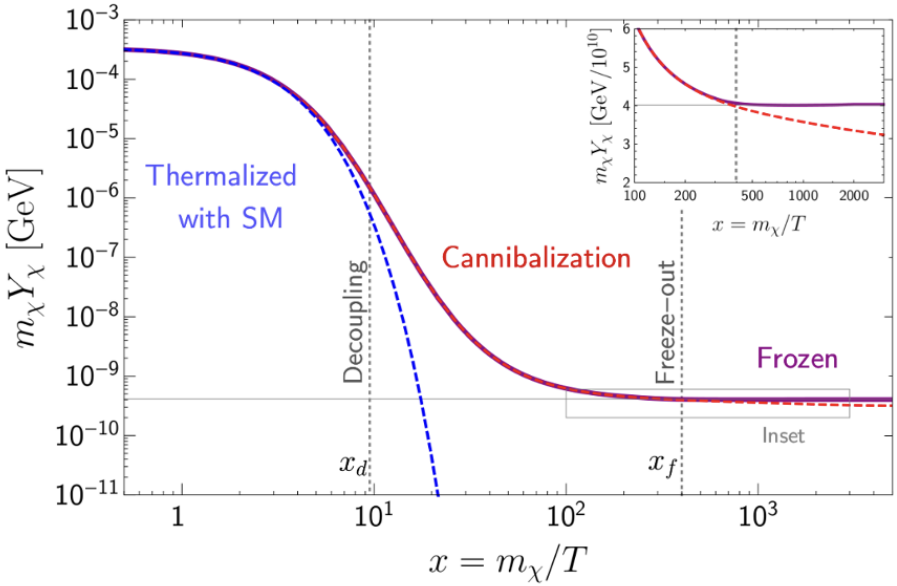




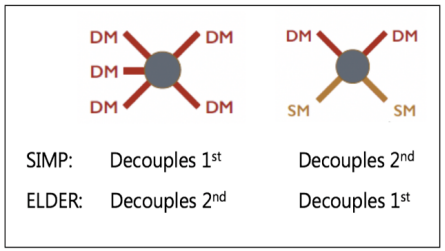
Early kinetic decoupling: $T_k > T_{fo}$

Entropies of the SM and DM separately conserved after *kinetic* decoupling

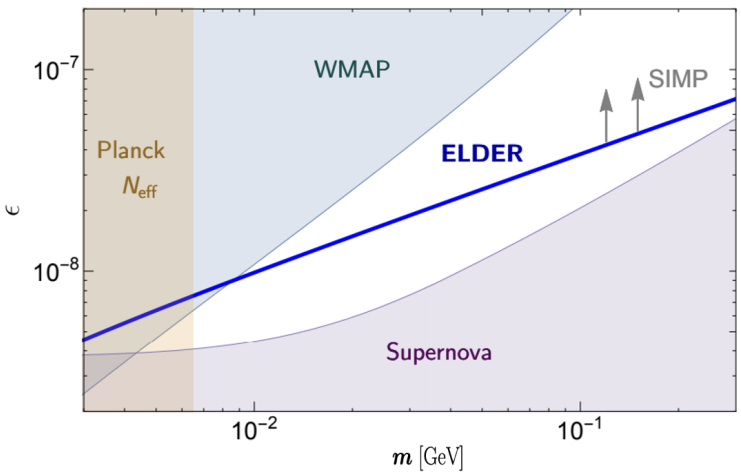




ELDERs (ELastically DEcoupled Relics): $m > T_k > T_{fo}$



[arXiv:1512.04545 [hep-ph]]



Cannibals: $T_k > m > T_{fo}$

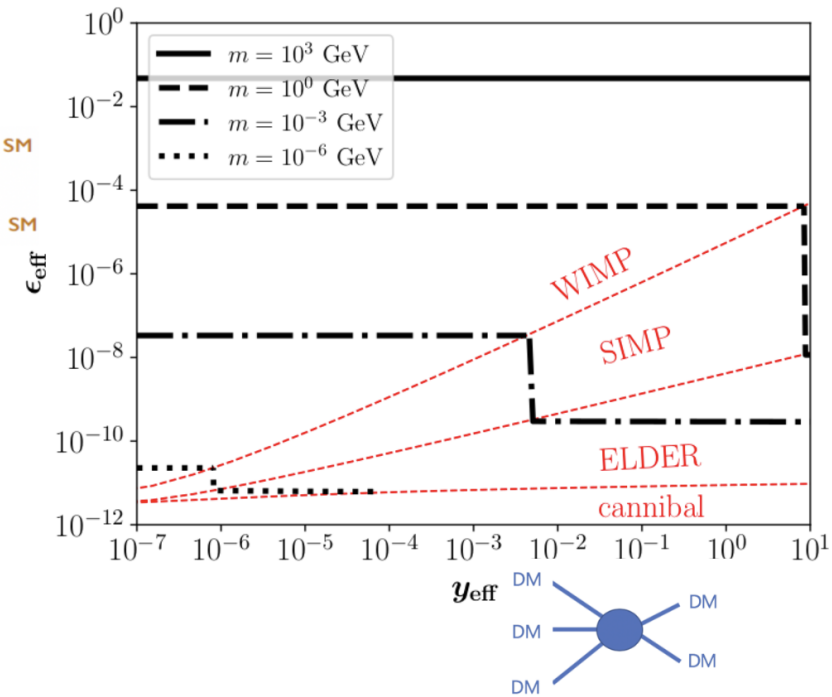
$$\Gamma_{el}(x_k) = H(x_k)$$

$$\downarrow$$

$$x_k \geq x_k^{min} \simeq 1.8$$

Cannibal Solutions not possible

Parameter space after reheating



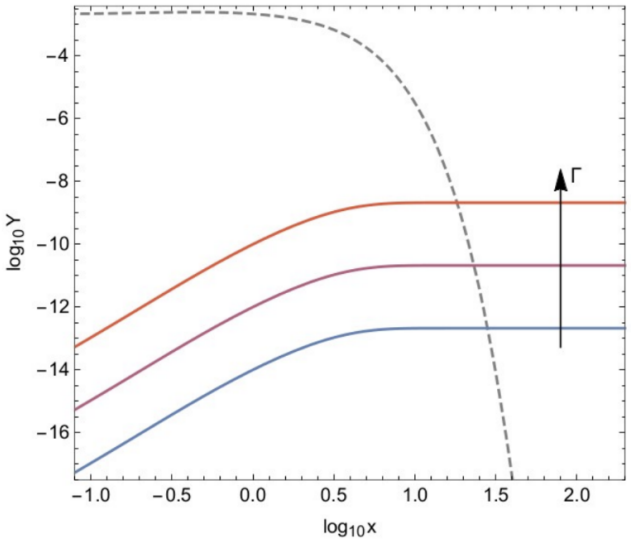
FIMP Dark Matter

$$\frac{dn_\chi}{dt} + 3\,H\,n_\chi = -\langle v\sigma_\chi\rangle\,\left[\cancel{n_\chi^2} - (n_\chi^{\rm eq})^2\right]$$

FIMP DM typically requires:

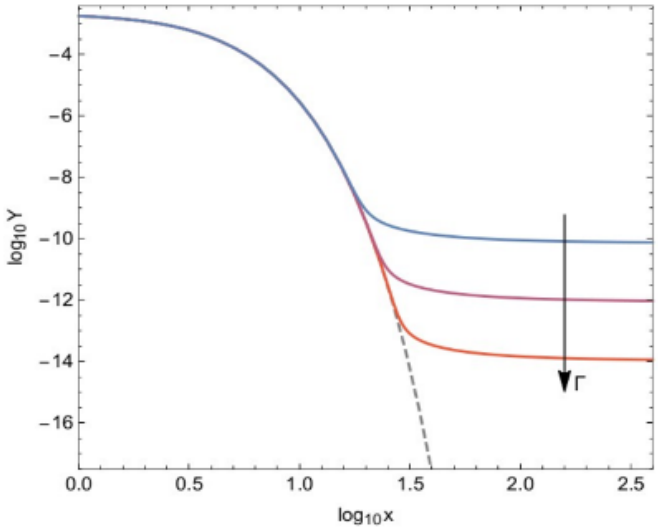
* Very suppressed DM-SM interaction rates
  to avoid thermalization between
  the dark and the visible sectors
* masses > keV (!)
* Usually *assumed* a dark sector
  with a negligible initial population

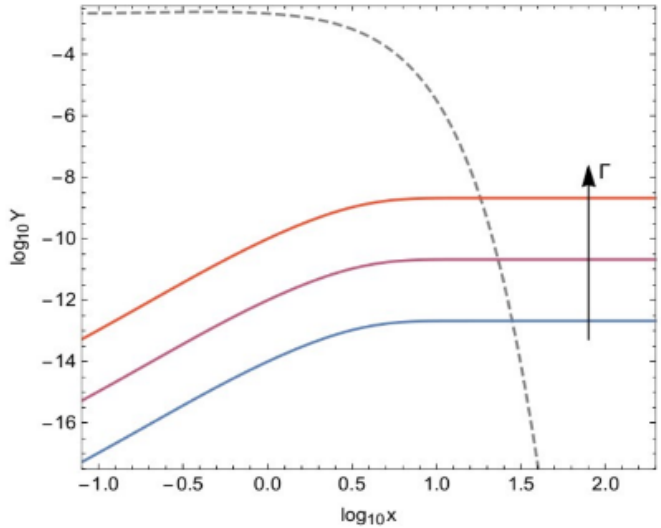
→ Dependent of initial conditions!

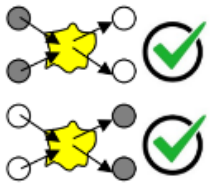


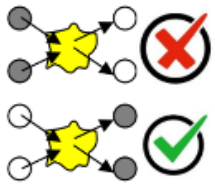
WIMP vs FIMP Dark Matter

$$\frac{dn_\chi}{dt} + 3\,H\,n_\chi = -\langle v\sigma_\chi\rangle\left[n_\chi^2 - (n_\chi^{\rm eq})^2\right]$$

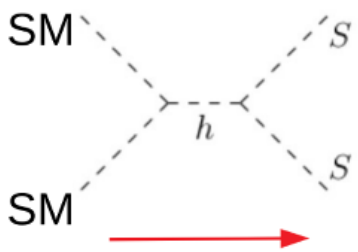


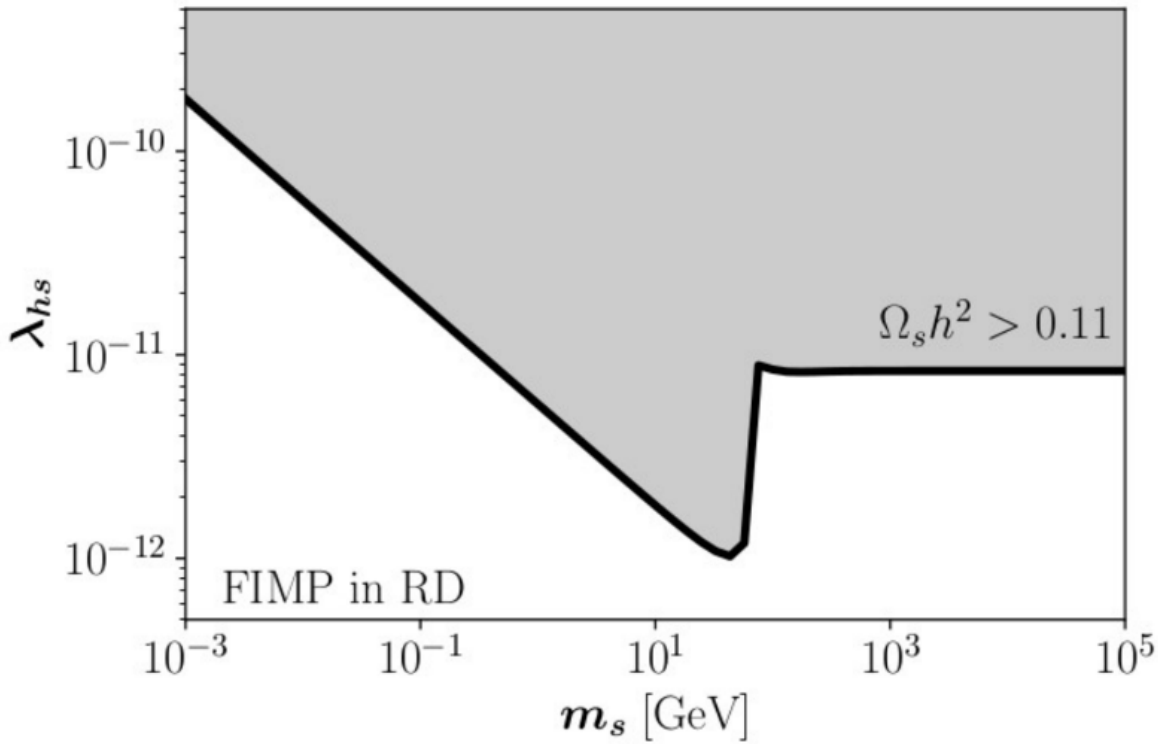






Singlet Scalar DM - FIMP

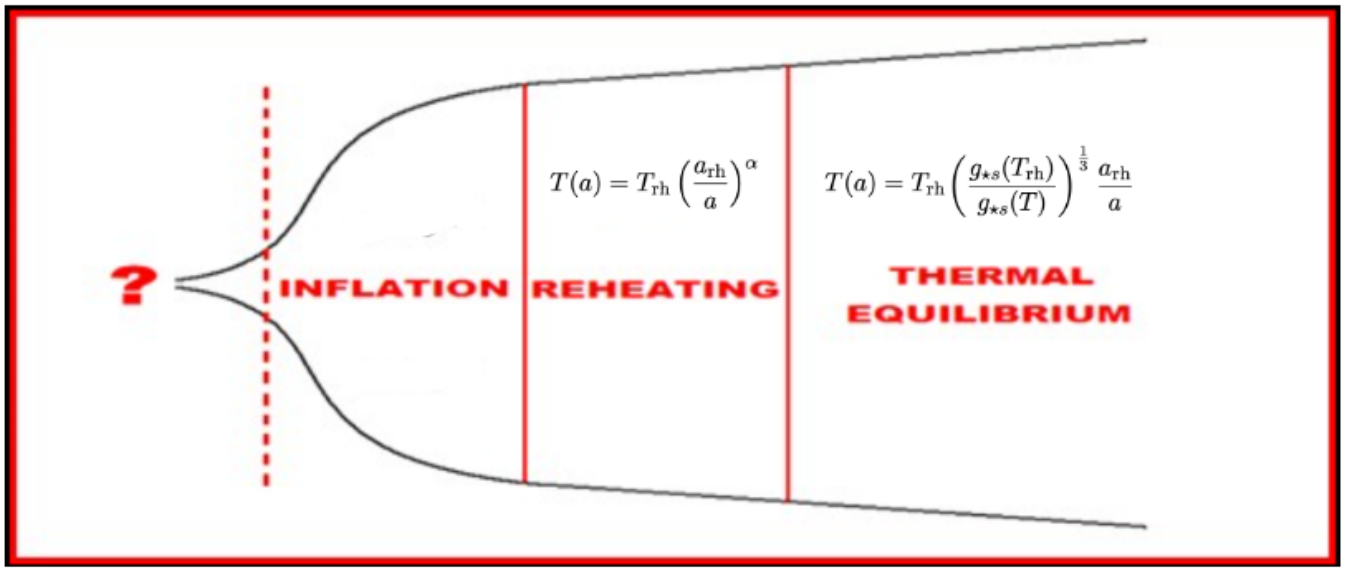


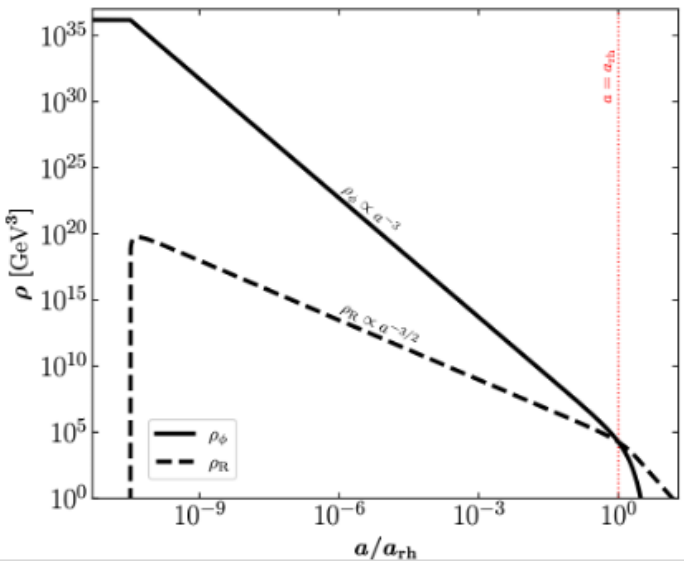


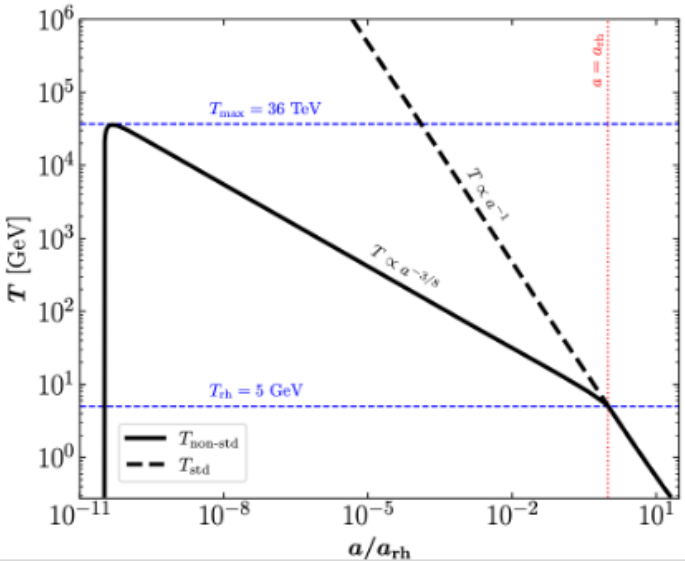
Standard Cosmology

* We know that at BBN, $T \sim O(\text{MeV})$, the universe was dominated by SM radiation

* Standard cosmology
  → **extrapolation** up to the reheating epoch $T \sim 10^{10}$ GeV (?)
  → SM entropy conserved
  → early universe dominated by SM radiation
  → instantaneous reheating at a very high temperature


?
INFLATION
REHEATING
THERMAL EQUILIBRIUM
$T(a) = T_{\rm rh}\left(\frac{a_{\rm rh}}{a}\right)^{\alpha}$
$T(a) = T_{\rm rh}\left(\frac{g_{\star s}(T_{\rm rh})}{g_{\star s}(T)}\right)^{\frac{1}{3}}\frac{a_{\rm rh}}{a}$


ρ [GeV^3]
$a/a_{\rm rh}$
$a = a_{\rm rh}$
$\rho_\phi \propto a^{-3}$
$\rho_{\rm R} \propto a^{-3/2}$
ρ_ϕ
$\rho_{\rm R}$


T [GeV]
$a/a_{\rm rh}$
$a = a_{\rm rh}$
$T_{\rm max} = 36$ TeV
$T_{\rm rh} = 5$ GeV
$T \propto a^{-1}$
$T \propto a^{-3/8}$
$T_{\rm non\text{-}std}$
$T_{\rm std}$

Low Temperature Reheating

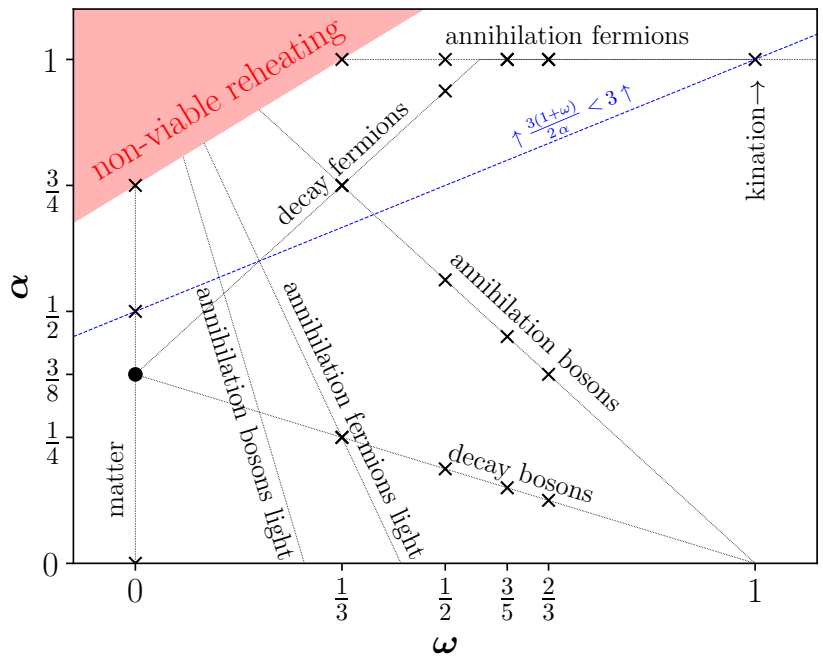
Cosmic **reheating**
→ Transition from an inflaton-dominated to a SM radiation-dominated era
→ End of reheating at T_{rh}
→ $T_{rh} > T_{bbn} \sim 4$ MeV

Inflaton Energy Density:

$$\rho_\phi(a) \propto a^{-3(1+\omega)}$$

Scaling of SM temperature:

$$T(a) = T_{\rm rh} \left(\frac{a_{\rm rh}}{a}\right)^{\alpha}$$

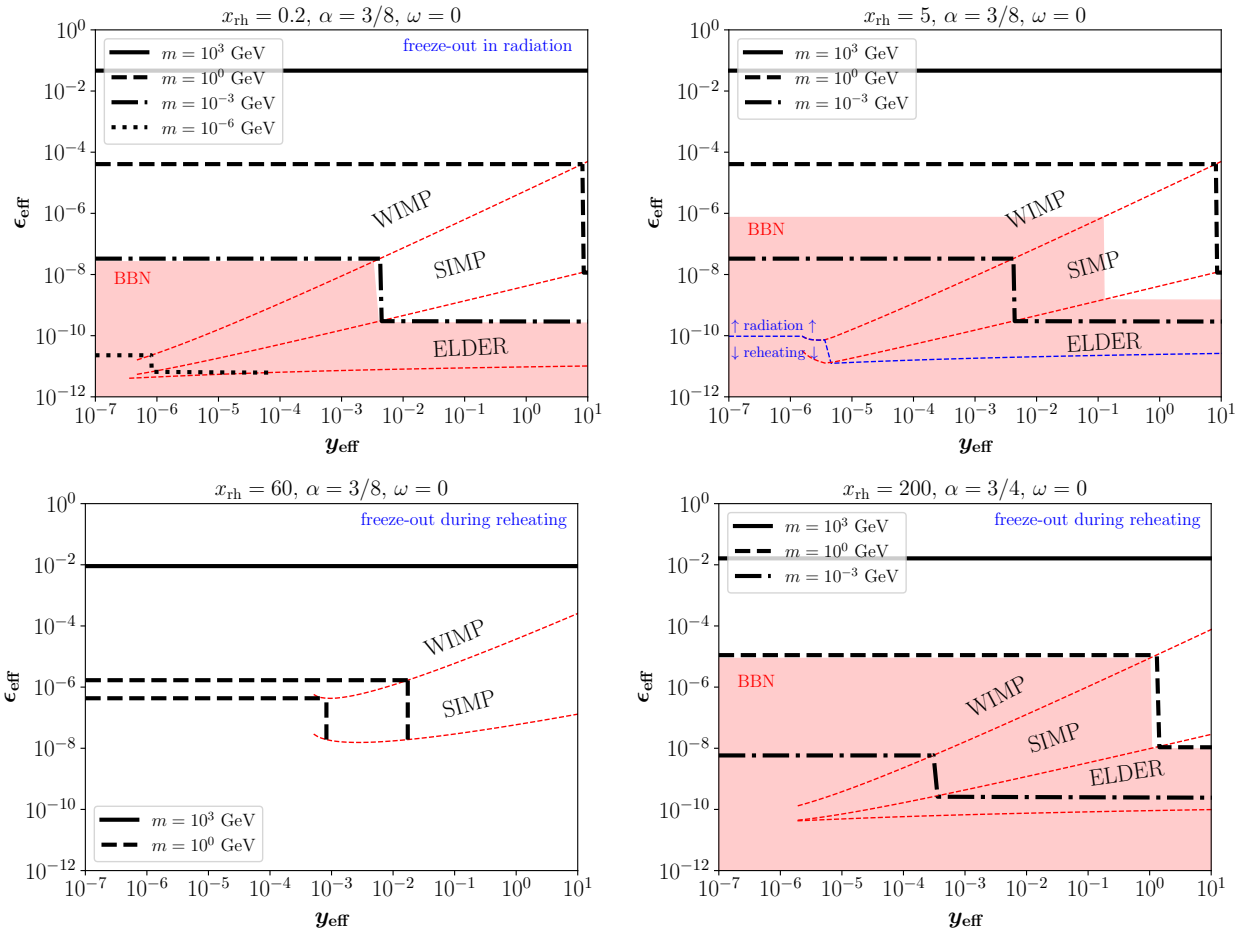


Hubble Scaling: $H(T) \simeq H(T_{\rm rh}) \times \left(\frac{T}{T_{\rm rh}}\right)^{\frac{3(1+\omega)}{2\alpha}}$ for $T \geq T_{\rm rh}$

Parameter space during reheating

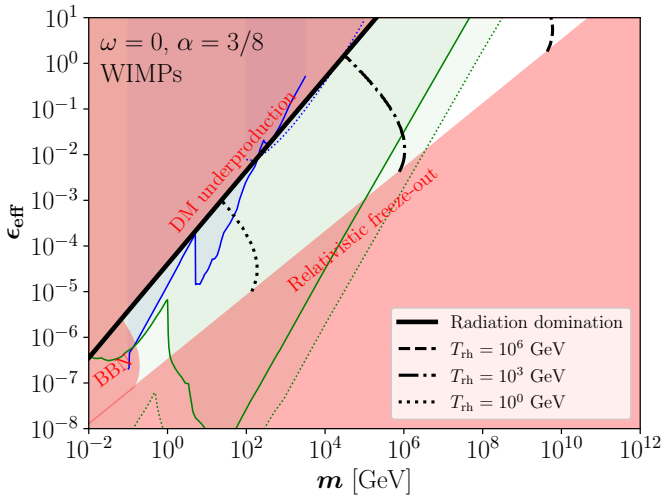
Cannibal Solutions still not possible!!

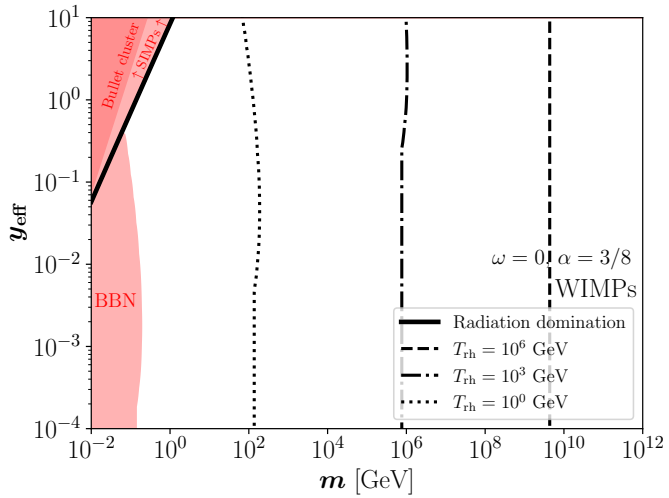
ELDER Solutions during reheating possible for $2 \leq \frac{3(1+\omega)}{2\alpha} < 3$.

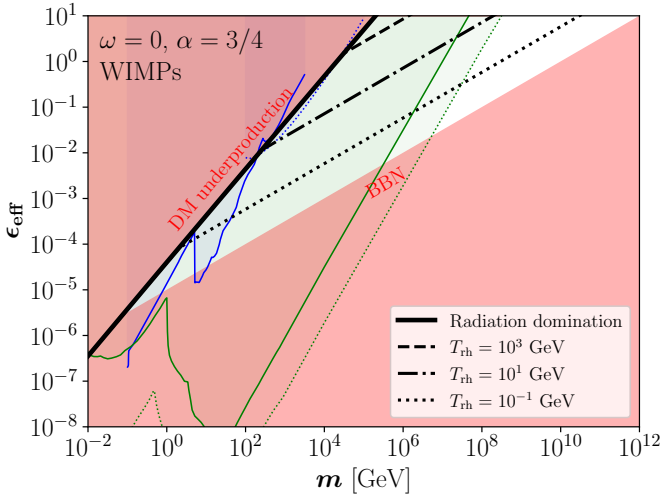


Parameter Regions

Direct and indirect detection constraints: WIMPs

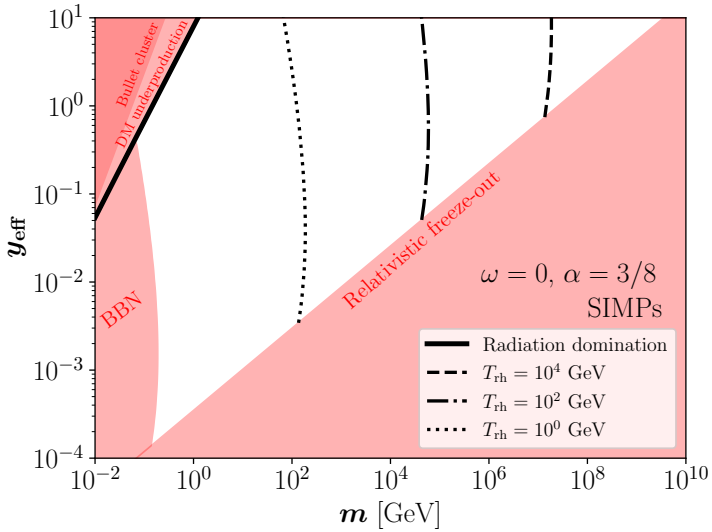


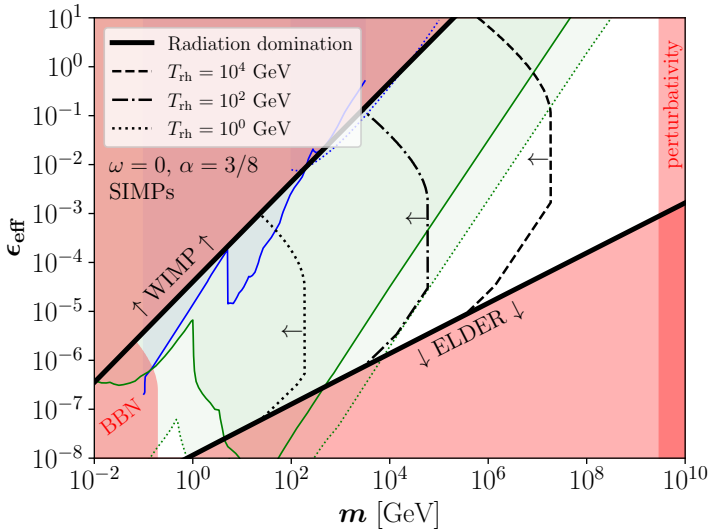




Parameter Regions

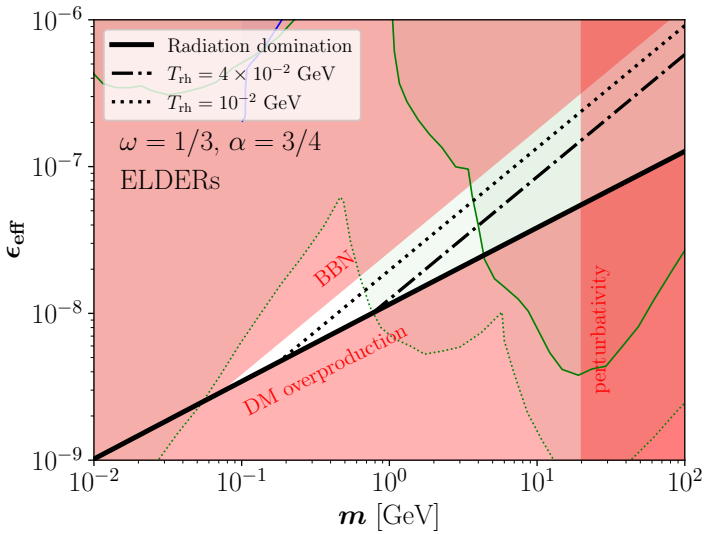
Direct and indirect detection constraints: SIMPs

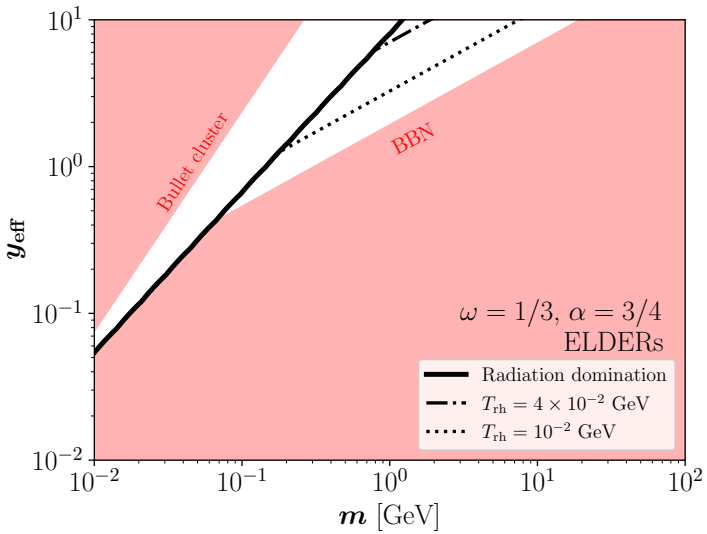




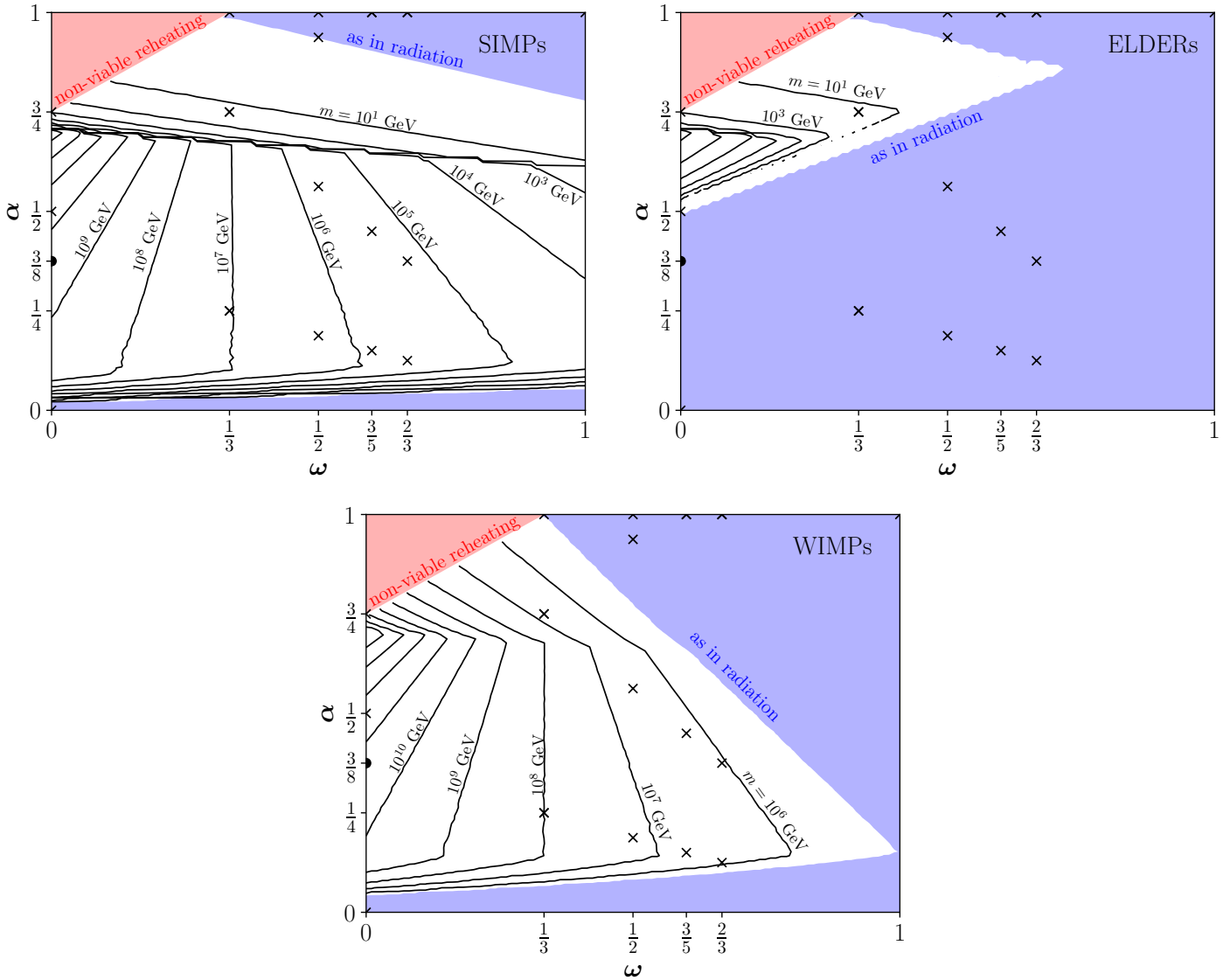
Parameter Regions

Direct and indirect detection constraints: ELDERs





Maximum masses attainable for different cosmologies

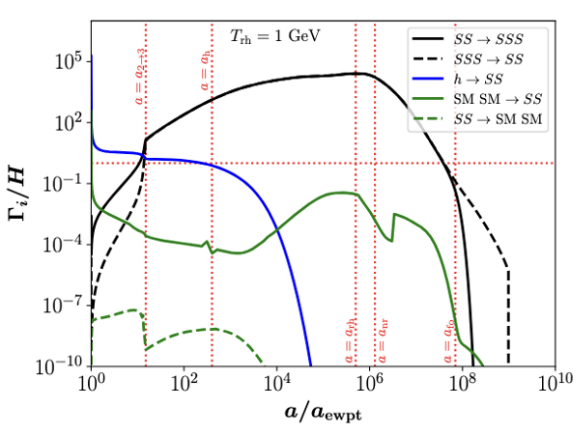


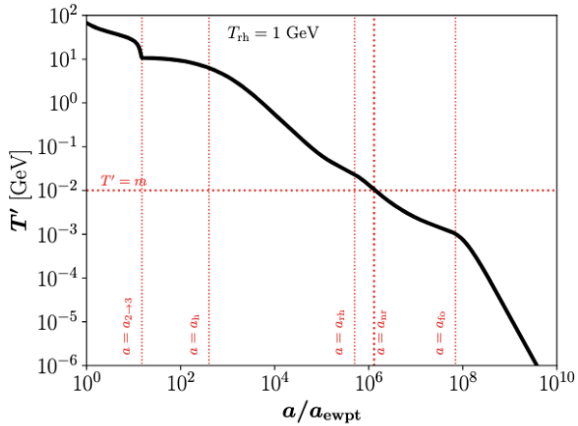
Let's freeze-in the Cannibals with low reheating temperatures...

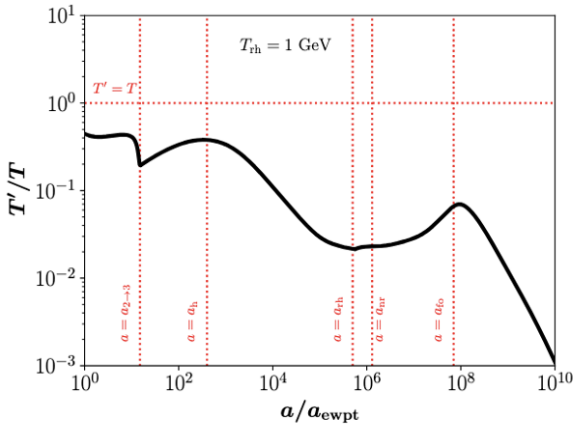
IR-FIMP: Z3 scalar DM with self-interactions during reheating

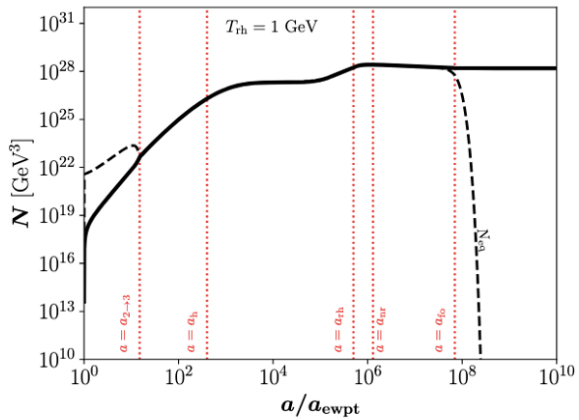
$$V_{\rm HP}(\widetilde{H}, S) = \lambda_{hs} \, |\widetilde{H}|^2 \, |S|^2$$

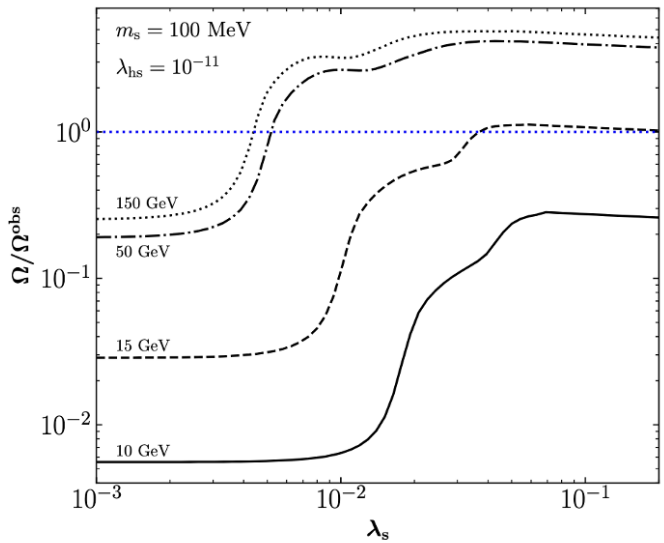
$$V_s(S) = \mu_s^2 \, |S|^2 + \frac{g_s}{3!} \left(S^3 + (S^*)^3\right) + \frac{\lambda_s}{4} \, |S|^4$$

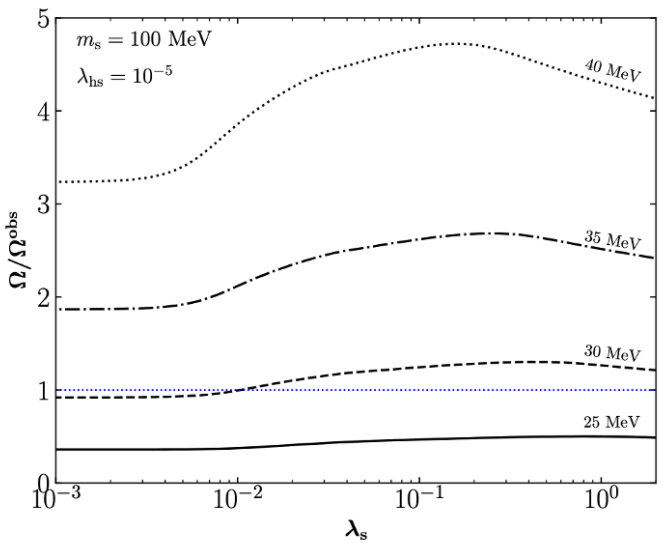


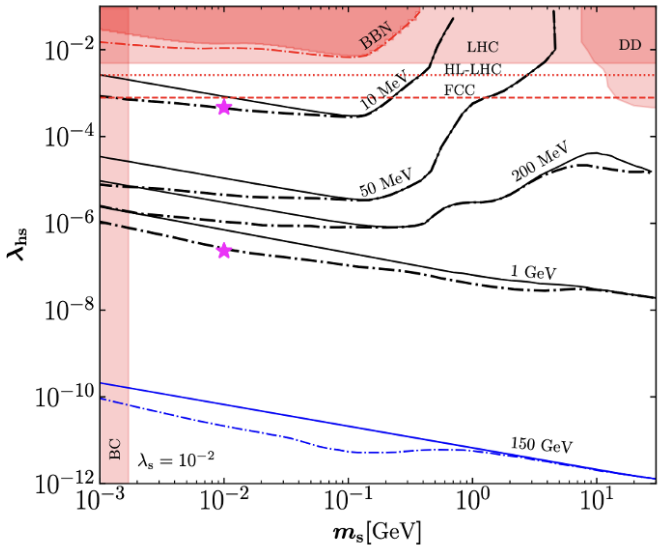


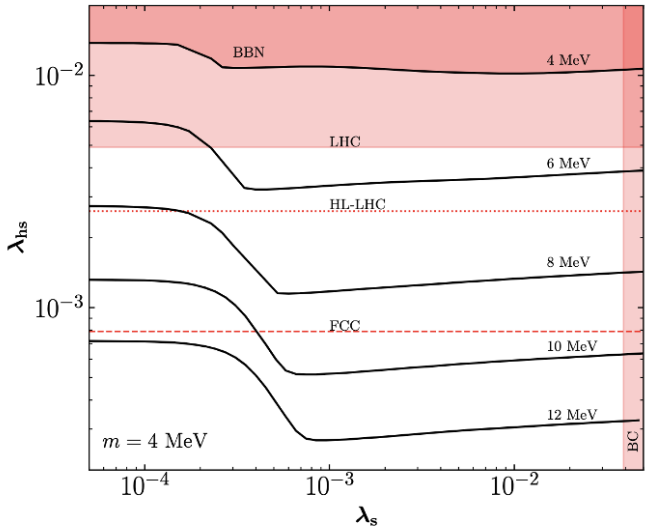












Please attend Esau's talk next Thursday at 11:22 am for more details on Z3 SIMPs during reheating...

Summary

- Dark Matter exists
- The nature of Dark Matter is still unknown
- Understanding Dark Matter is one of the major problems in particle physics & cosmology
- WIMP paradigm is by far the favorite scenario ← huge prejudice!
- Various other alternatives exist:
  SIDMs discussed here: ***SIMPs***, ***ELDERs***, ***FIMPs***
- Dark Matter could be produced during cosmic reheating
  Cosmology: ***non-standard cosmologies*** & ***low-reheating temperatures.***
- Parameter space is greatly enlarged, enriching the phenomenology.
- Dark Matter production during reheating (and inflation!) has to be studied more!

Cosmological history of the Universe important for DM genesis.