Dark Matter Genesis in the Reheating Era

Kuldeep Deka

in a collaboration with
Nicolás Bernal, Marta Losada

Esau Cervantes, Andrzej Hryczuk
(arXiv:2406.17039, arXiv:2501.04774, arXiv:2506.09155)

Seminar
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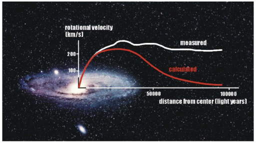
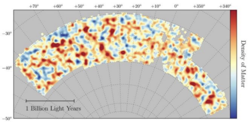
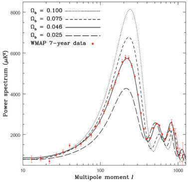
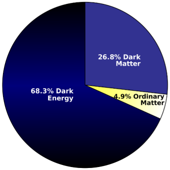
July 9, 2025

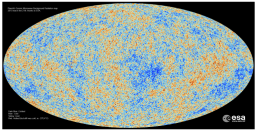
Dark Matter exists.......











Credits:
HST, Chandra, DE Survey, WMAP, Planck

Dark Matter is there! :-)
But what is it? :-/

* Neutral (electric and color)
* Massive (non relativistic @ structure formation)
* 'Weak' interactions with the SM
* Stable or long-lived

NEEDS BSM PHYSICS

- 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
  - UV FIMPs
    - Non-renormalizable operators.
- Behavior in Non-Standard Cosmologies... **with low reheating temperatures**

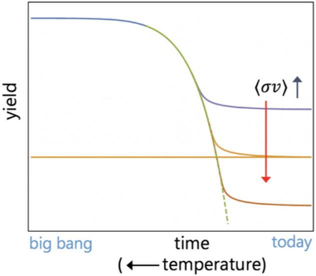
WIMPs (Weakly Interacting Massive Particles): $m > T_{\rm fo} > T_{\rm k}$

$$Y_0 \simeq Y_{\rm fo} = \frac{n_{\rm eq}(T_{\rm fo})}{s(T_{\rm fo})} \simeq \frac{45}{2^{5/2}\,\pi^{7/2}}\,\frac{g}{g_{\star s}(T_{\rm fo})}\,x_{\rm fo}^{3/2}\,e^{-x_{\rm fo}},$$

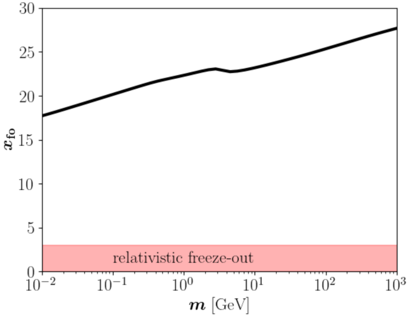
$$\Gamma_{2\to 2} = n_\chi \langle \sigma v \rangle \sim H \sim \frac{T^2}{M_{\rm Pl}}.$$

$$m\,Y_0 = \frac{\Omega h^2\,\rho_c}{s_0\,h^2} \simeq 4.3 \times 10^{-10}\ {\rm GeV},$$

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



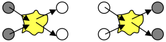
WIMPs (Weakly Interacting Massive Particles): $m > T_{\text{fo}} > T_{\text{k}}$



* **Chemical** freeze-out

→ *inelastic* interactions

@ x_{fo} ~ 20



* **Kinetic** freeze-out

→ *elastic* interactions

→ $T_\gamma = T_{dm}$

@ x_k ~ 10^2 - 10^5

Mass-Coupling relation

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

$$\mathcal{L}_{\text{int}} = \frac{m_f}{\Lambda^2}\chi^\dagger\chi\bar{f}f \quad \epsilon_{\text{eff}} \simeq \mathcal{O}(m_f m_{\text{DM}}/\Lambda^2)$$

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

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

$$\Gamma_{2\to2} = n_\chi(T_{fo}) \cdot \frac{\epsilon_{\text{eff}}^2}{m^2} \sim H \sim \frac{T_{fo}^2}{M_{\text{Pl}}} \sim \frac{m^2}{x_{fo}^2 M_{\text{Pl}}}.$$

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

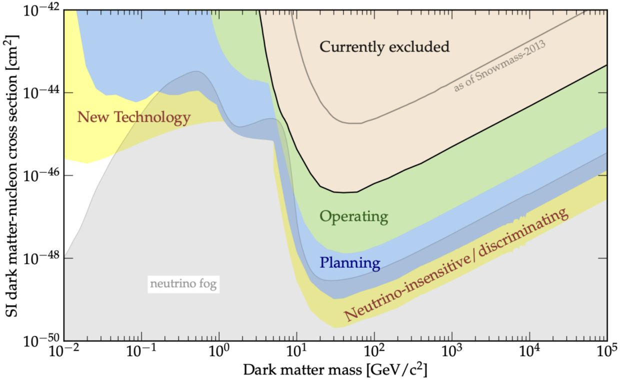
WIMP MIRACLE!!!

WIMP DM typically requires:
<σv> ~ few 10^{-26} cm³/s

* GeV to TeV masses
* $O(1)$ couplings DM-SM

→ Independent on initial conditions!

* reheating temperature
* coupling to the inflaton
* DM density after reheating
* cosmological evolution before freeze-out

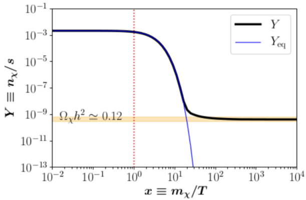

Currently excluded
as of Snowmass-2013
New Technology
Operating
Planning
Neutrino-insensitive / discriminating
neutrino fog
SI dark matter-nucleon cross section [cm^2]
Dark matter mass [GeV/c^2]
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{-50}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}

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

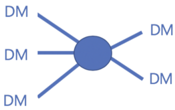
$$n_{\rm eq}(T) = \frac{g}{2\pi^2} m^2 T K_2\left(\frac{m}{T}\right) \qquad s(T) \equiv \frac{2\pi^2}{45} g_{\star s}(T) T^3$$

$$Y_0 \simeq Y_{\rm fo} = \frac{n_{\rm eq}(T_{\rm fo})}{s(T_{\rm fo})} \simeq \frac{45}{2^{5/2}\pi^{7/2}} \frac{g}{g_{\star s}(T_{\rm fo})} x_{\rm fo}^{3/2} e^{-x_{\rm fo}}$$

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

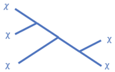


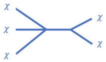
Freezeout within the Dark sector



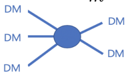
SIMPs (Strongly Interacting Massive Particles): $m > T_{\rm fo} > T_{\rm k}$

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





$$\langle\sigma v^2\rangle_{3\to2} \equiv \frac{y_{\rm eff}^3}{m^5}$$



$$\Gamma_{3\to2} \sim n_\chi^2 \langle\sigma v^2\rangle_{3\to2}$$

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

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

SIMP MIRACLE!!!

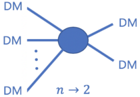
SIMPs = *Freeze-out within the dark sector*

SIMP DM typically requires:

* MeV masses
* *O*(1) couplings DM-DM
* very suppressed couplings DM-SM

→ Independent on initial conditions!

* reheating temperature
* coupling to the inflaton
* DM density after reheating
* cosmological evolution before freeze-out



$$\Gamma_{n\to2} \sim n_\chi^{n-1}\langle\sigma v^{n-1}\rangle_{n\to2} \sim H$$

$$\langle\sigma v^{n-1}\rangle_{n\to2} \equiv \frac{\alpha^n}{m^{3n-4}}.$$

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

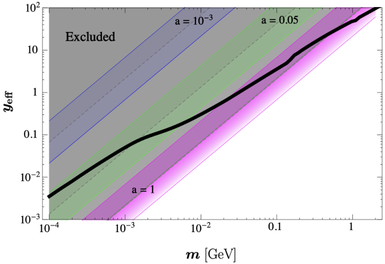
SIMPs (Strongly Interacting Massive Particles): $m > T_{\rm fo} > T_{\rm k}$

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

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

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

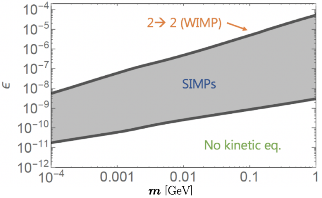
[arXiv:1402.5143 [hep-ph]]

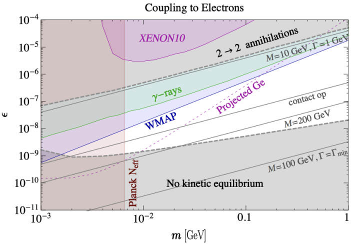


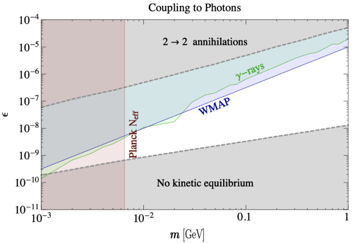
SIMPs (Strongly Interacting Massive Particles): $m > T_{\rm fo} > T_{\rm k}$

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

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







Early kinetic decoupling: $T_{\mathrm{k}} > T_{\mathrm{fo}}$

$$Y_{\rm fo} = \frac{n_{\rm eq}(T'_{\rm fo})}{s(T_{\rm fo})} = \frac{n_{\rm eq}(T'_{\rm fo})}{s(T_{\rm k})}\,\frac{s'(T_{\rm k})}{s'(T'_{\rm fo})} \qquad s'(T') = \frac{\rho'(T') + p'(T')}{T'} = \frac{g}{2\pi^2}\, m^3\, K_3\left(\frac{m}{T'}\right)$$

$$\rho'(T') = \frac{g}{2\pi^2}\, m^3\, T' \left[K_1\left(\frac{m}{T'}\right) + 3\,\frac{T'}{m}\, K_2\left(\frac{m}{T'}\right)\right],$$
$$p'(T') = \frac{g}{2\pi^2}\, m^2\, T'^2\, K_2\left(\frac{m}{T'}\right),$$

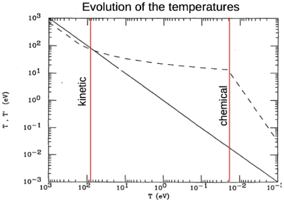
$$Y_0 \simeq Y_{\rm fo} = \frac{45}{4\pi^4}\,\frac{g}{g_{\star s}(T_{\rm k})}\,\frac{x_{\rm k}^3}{x'_{\rm fo}}\,\frac{K_2(x'_{\rm fo})\,K_3(x_{\rm k})}{K_3(x'_{\rm fo})}$$

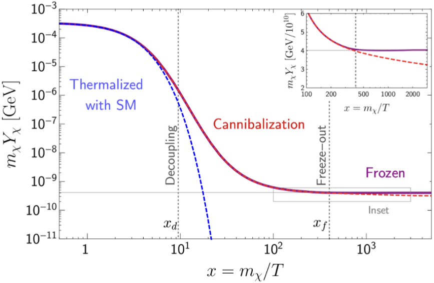
$$x_{\rm fo} \equiv \frac{m}{T_{\rm fo}} = x_{\rm k}\left[\frac{g_{\star s}(T_{\rm fo})}{g_{\star s}(T_{\rm k})}\,\frac{K_3(x_{\rm k})}{K_3(x'_{\rm fo})}\right]^{1/3}$$

SIMP:	Decouples 1st	Decouples 2nd
ELDER:	Decouples 2nd	Decouples 1st

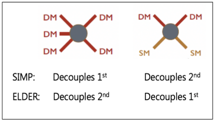
Early kinetic decoupling: $T_\mathrm{k} > T_\mathrm{fo}$

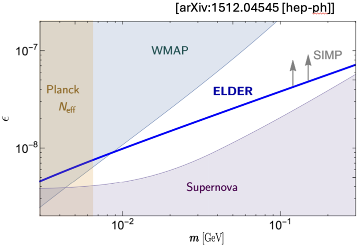
Entropies of the SM and DM
separately conserved
after *kinetic* decoupling





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





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

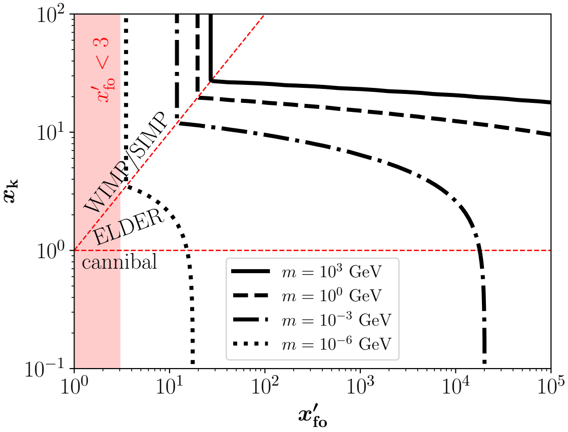
$$\Gamma_{el}(x_k) = H(x_k)$$

$$\Downarrow$$

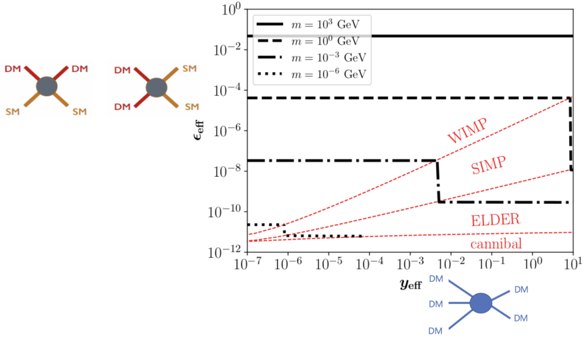
$$x_k \geq x_k^{min} \simeq 1.8$$

Cannibal Solutions not possible

Parameter space in $x'_{\rm fo}$ and $x_{\rm k}$



Parameter space during radiation



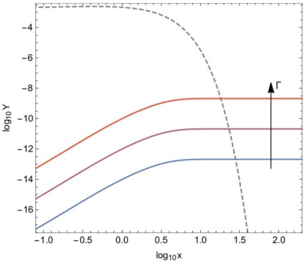
FIMP Dark Matter

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

FIMP DM typically requires:

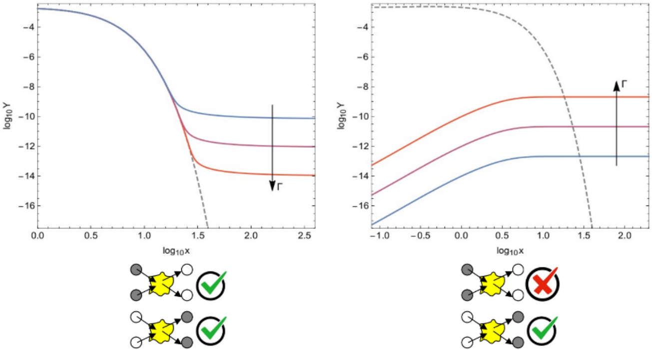
* Very suppressed DM-SM interaction rates to avoid thermalization between the dark and the visible sectors
* masses > keV (!)
* Usually *assumed* a dark sector with a negligible initial population

→ Dependent of initial conditions!

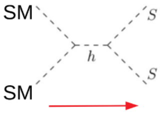


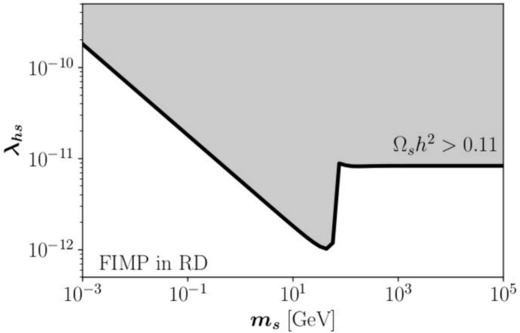
WIMP vs FIMP Dark Matter

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



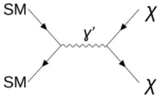
Singlet Scalar DM - FIMP

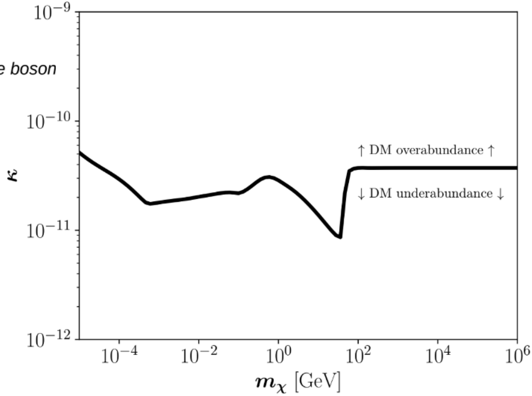




Dark Photon and Dirac Fermion DM Freeze-In

* Additional gauged *U(1)$_D$*
* *Mediator: Massless gauge boson*
* DM: Dirac fermion



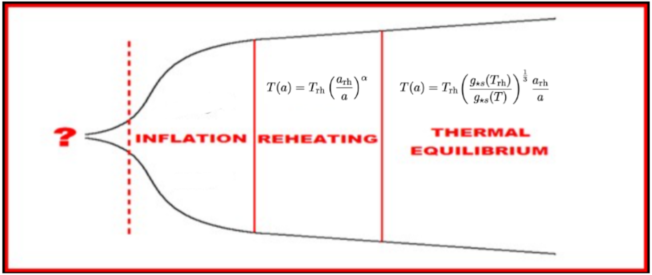


Standard Cosmology

* We know that at BBN, $T \sim O$(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

Non-instantaneous Reheating



Low Temperature Reheating

Cosmic **reheating**

→ Transition from an inflaton-dominated to a SM radiation-dominated era

→ End of reheating at T_{rh}

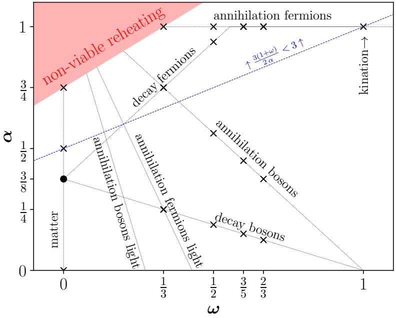
→ $T_{rh} > T_{bbn} \sim 4$ MeV

Inflaton Energy Density:

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

Scaling of SM temperature:

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

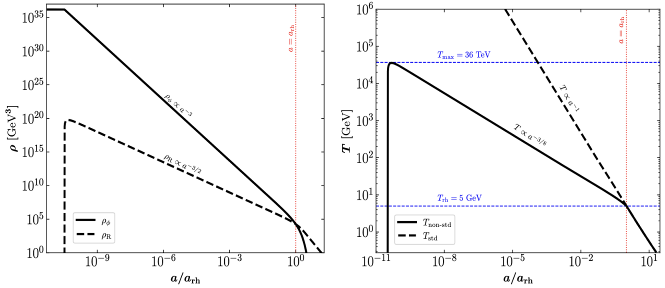


Hubble Scaling: $H(T) \simeq H(T_{\rm rh}) \times \left(\frac{T}{T_{\rm rh}}\right)^{\frac{3\,(1+\omega)}{2\,\alpha}}$ for $T \geq T_{\rm rh}$

Early Matter Domination: $\omega = 0$, $\alpha = \frac{3}{8}$

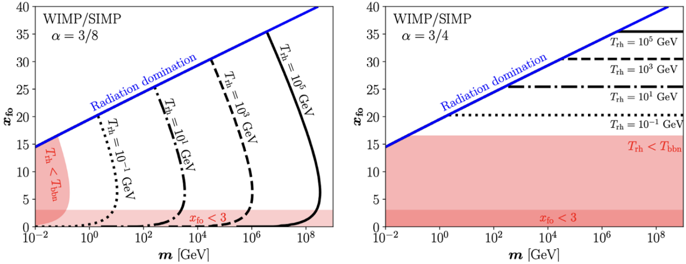
$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = -\Gamma\rho_\phi$$

$$\frac{d\rho_R}{dt} + 4H\rho_R = +\Gamma\rho_\phi$$



Differences w.r.t. Radiation: WIMP/SIMP

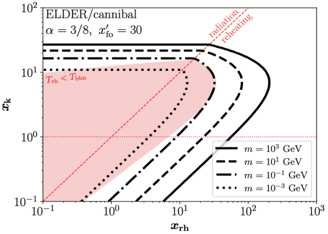
$$Y_0 \simeq Y_{\rm rh} = Y_{\rm fo}\,\frac{S(T_{\rm fo})}{S(T_{\rm rh})} = \frac{45}{4\pi^4}\,\frac{g}{g_{\star s}(T_{\rm rh})}\,x_{\rm fo}^2\,K_2(x_{\rm fo})\left(\frac{x_{\rm fo}}{x_{\rm rh}}\right)^{\frac{3\,(1-\alpha)}{\alpha}}$$

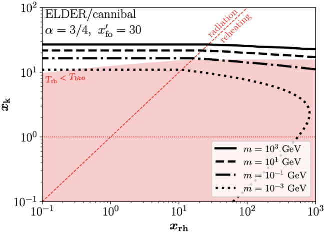


Differences w.r.t. Radiation: ELDER/Cannibal

$$Y_0 \simeq Y_{\rm rh} = \frac{45}{4\pi^4} \frac{g}{g_{\star s}(T_{\rm rh})} \frac{x_{\rm rh}^3}{x'_{\rm fo}} \left(\frac{x_{\rm k}}{x_{\rm rh}}\right)^{\frac{3}{\alpha}} \frac{K_2(x'_{\rm fo})\, K_3(x_{\rm k})}{K_3(x'_{\rm fo})}$$

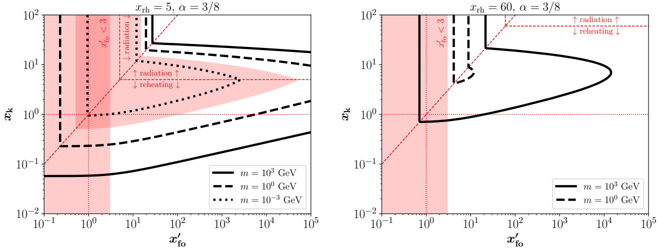
ELDERS: $Y_0 \simeq \frac{45}{2^{5/2}\,\pi^{7/2}} \frac{g}{g_{\star s}(T_{\rm rh})} \frac{x_{\rm k}^{5/2}\, e^{-x_{\rm k}}}{x'_{\rm fo}} \left(\frac{x_{\rm k}}{x_{\rm rh}}\right)^{\frac{3(1-\alpha)}{\alpha}}$ **Cannibal:** $Y_0 \simeq \frac{90}{\pi^4} \frac{g}{g_{\star s}(T_{\rm rh})} \frac{1}{x'_{\rm fo}} \left(\frac{x_{\rm k}}{x_{\rm rh}}\right)^{\frac{3(1-\alpha)}{\alpha}}$





DM production during reheating allows for larger $T_{\rm fo}$ and $T_{\rm k}$.

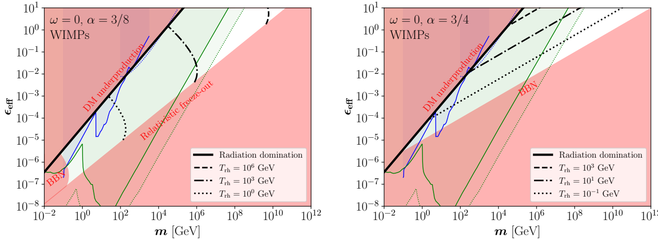
Parameter space in $x'_{\rm fo}$ and $x_{\rm k}$ with fixed $x_{\rm rh}$



For a given mass (m), upto two DM solutions are viable.

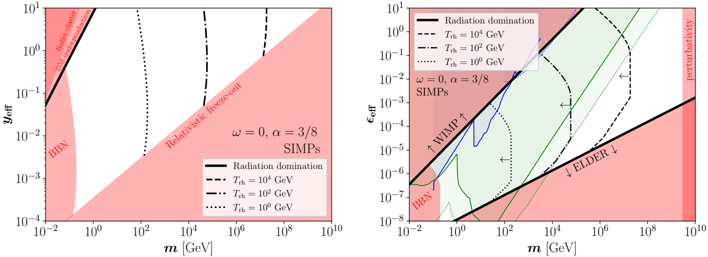
Parameter Regions

Direct and indirect detection constraints: WIMPs



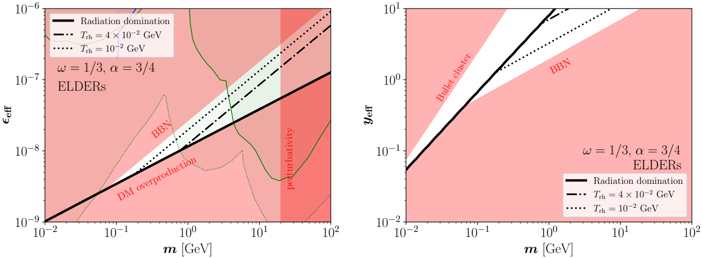
Parameter Regions

Direct and indirect detection constraints: SIMPs

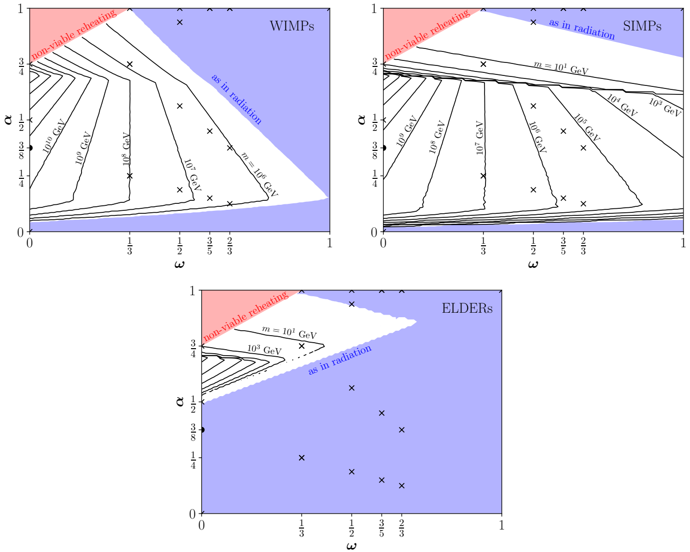


Parameter Regions

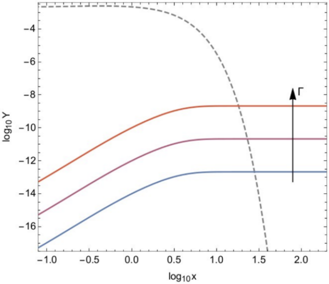
Direct and indirect detection constraints: ELDERs



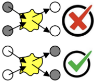
Maximum masses attainable for different cosmologies



IR FIMP paradigm



$$\frac{dn}{dt} + 3\,H\,n = -\langle\sigma v\rangle\,\left(\cancel{n^2} - n_{\rm eq}^2\right)$$

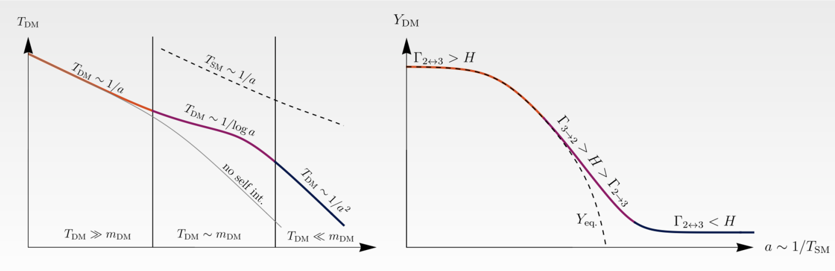


* chemical equilibrium never reached
* **renormalizable** operators
* masses: keV to $\sim M_P$
* $\lambda_{\text{DM-SM}} \sim 10^{-11}$ ← "Unnaturally" small… but could be *technically natural*!
* $T_{fi} \sim m$

→ (mild) dependence from initial conditions

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

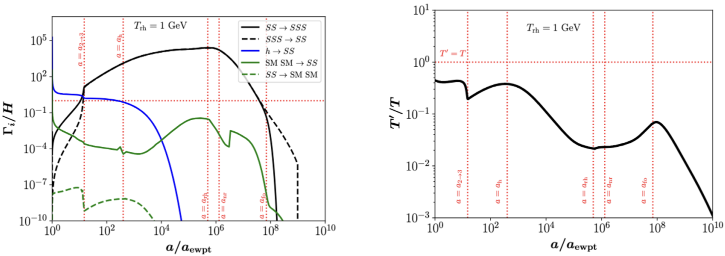
$$V_{\rm HP}(\widetilde{H}, S) = \lambda_{hs}\,|\widetilde{H}|^2\,|S|^2 \qquad V_s(S) = \mu_s^2\,|S|^2 + \frac{g_s}{3!}\left(S^3 + (S^*)^3\right) + \frac{\lambda_s}{4}\,|S|^4$$

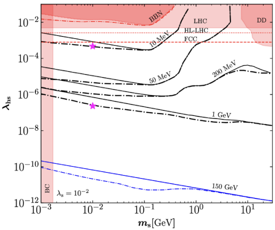


Let's freeze-in the Cannibals with low reheating temperatures...

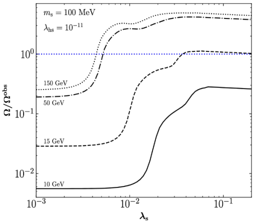
IR-FIMP: Z3 scalar DM with self-interactions during reheating ($\omega = 0, \alpha = \frac{3}{8}$)

$$V_{\rm HP}(\widetilde{H}, S) = \lambda_{hs}\,|\widetilde{H}|^2\,|S|^2 \qquad V_s(S) = \mu_s^2\,|S|^2 + \frac{g_s}{3!}\left(S^3 + (S^*)^3\right) + \frac{\lambda_s}{4}\,|S|^4$$

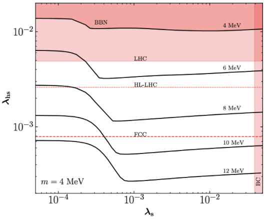




BBN
LHC
HL-LHC
FCC
DD
10 MeV
50 MeV
200 MeV
1 GeV
150 GeV
BC
$\lambda_s = 10^{-2}$
λ_{hs}
m_s[GeV]



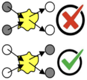
$m_s = 100$ MeV
$\lambda_{hs} = 10^{-11}$
150 GeV
50 GeV
15 GeV
10 GeV
Ω/Ω^{obs}
λ_s



BBN
4 MeV
LHC
6 MeV
HL-LHC
8 MeV
FCC
10 MeV
12 MeV
$m = 4$ MeV
BC
λ_{hs}
λ_s

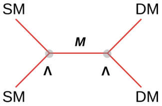
UV-FIMP paradigm

$$\frac{dn}{dt} + 3\,H\,n = -\langle\sigma v\rangle\,(\cancel{n^2} - n_{\rm eq}^2)$$



* chemical equilibrium never reached
* ***non*-renormalizable** operators
* masses: keV to ~M_P
* $\Lambda > T_{rh}$
* $T_{fi} \sim T_{rh}$

→ (strong) dependence from initial conditions



$$\langle\sigma v\rangle = \frac{T^n}{\Lambda^{2+n}}$$

- **Heavy mediator** ($M >> T_{rh}$)

$$\langle\sigma v\rangle \propto g^4 \frac{T^2}{M^4}$$

- **Suppressed couplings** ($\Lambda >> T_{rh}$)

$$\langle\sigma v\rangle \propto \frac{T^2}{\Lambda^4}$$

- **Heavy mediator + suppressed couplings** ($M, \Lambda >> T_{rh}$)

$$\langle\sigma v\rangle \propto \frac{T^6}{\Lambda^4\,M^4}$$

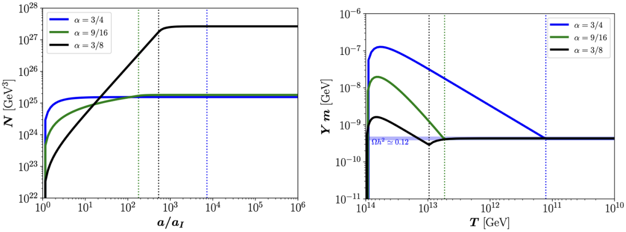
UV-FIMP paradigm

$$\frac{dN}{da} = \frac{a^2}{H}\gamma$$

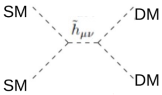
$$\gamma = \gamma_a + \gamma_d \, .$$

$$\gamma_a(T) = \frac{T^k}{\Lambda^{k-4}}$$

k = 8

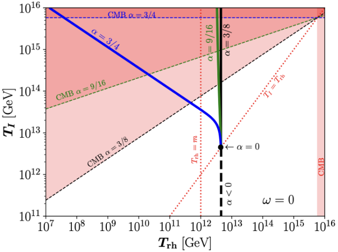


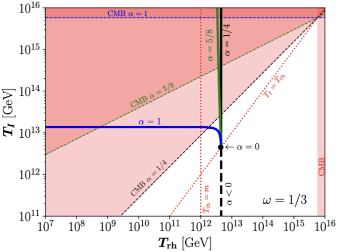
UV-FIMP: Gravitational annihilations of SM



$$\langle \sigma v \rangle = \alpha_{\rm DM} \frac{T^2}{M_P^4}$$

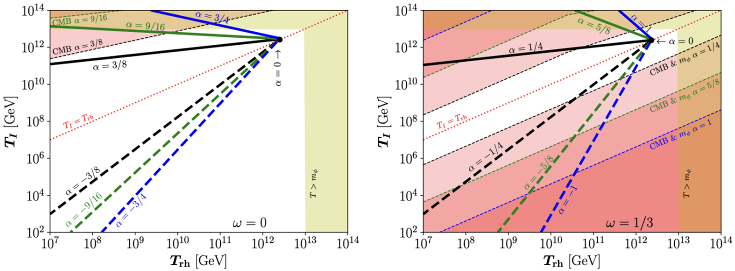
$$\gamma_a \simeq \mathcal{C}_g \frac{T^8}{M_P^4}$$





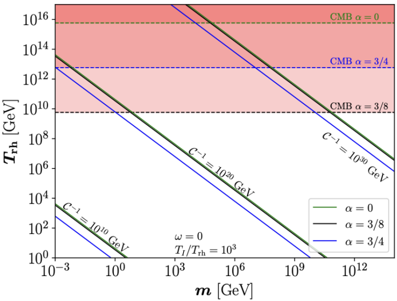
UV-FIMP: Gravitational annihilations of Inflatons

$$\gamma \simeq \frac{\rho_\phi^2}{m_\phi^2}\frac{m^2}{64\pi M_P^4} \simeq \frac{9}{64\pi}\frac{m^2 H_{\rm rh}^4}{m_\phi^{\rm rh\,2}}\left(\frac{T}{T_{\rm rh}}\right)^{\frac{6}{\alpha}}$$



UV-FIMP paradigm: Decays of Inflaton

$$\gamma_d = 12\,(1-\alpha)\,\mathcal{C}\,M_P^2\,H_{\rm rh}^3\left(\frac{a_{\rm rh}}{a}\right)^{\frac{8\alpha+3(1-\omega)}{2}} \qquad \mathcal{C} \equiv \frac{x\,{\rm Br}}{m_\phi^{\rm rh}}.$$

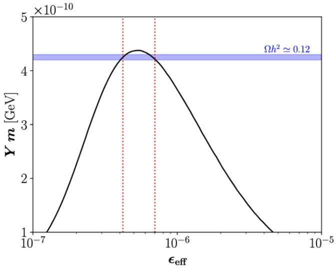


Summary

- 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:
  Discussed here: SIMPs, ELDERs, FIMPs
- Dark Matter could be produced during cosmic reheating
  Cosmology: non-standard cosmologies & low-temperature reheating
- Parameter space is greatly enlarged
- Dark Matter production during reheating (and inflation!) has to be studied more!

Cosmological history of the Universe important for DM genesis.

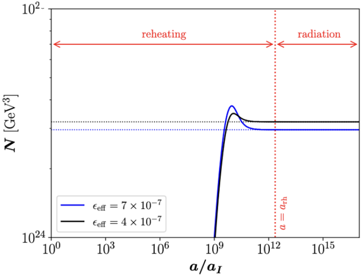
Numerical Validation

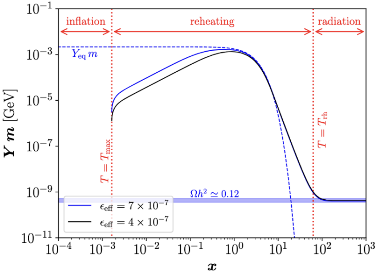


$$\frac{d\rho_\phi}{dt} + 3\,H\,\rho_\phi = -\Gamma\,\rho_\phi\,,$$

$$\frac{d\rho_R}{dt} + 4\,H\,\rho_R = +\Gamma\,\rho_\phi\,,$$

$$\frac{dn}{dt} + 3\,H\,n = -\langle\sigma v\rangle_{2\to 2}\left[n^2 - n_{\rm eq}^2\right]$$





Coupled Boltzmann equations

From the fBE we can obtain a 'temperature' Boltzmann equation:

We define $T' := \frac{g_{dm}}{3n} \int \frac{d^3p}{(2\pi)^3} \frac{p^2}{E} f(p)$;

we integrate $g(2\pi)^{-3} \int d^3p \, \frac{p^2}{E} (\partial_t - H\vec{p} \cdot \vec{\nabla}_p) f = g(2\pi)^{-3} \int d^3p \, \frac{p^2}{E} C[f] =: C_2$;

to obtain $\frac{dT'}{da} = -\frac{2\,T'}{a} + \frac{1}{3\,a} \left\langle \frac{p^4}{E^3} \right\rangle + \frac{a^2}{3\,H\,N} C_2 - \frac{a^2\,T'}{H\,N} C_0$;

along with the usual nBE: $\frac{dN}{da} = \frac{a^2}{H} g \int \frac{d^3p}{(2\pi)^3} C[f] =: \frac{a^2}{H} C_0 \,, N = na^3$;

we close the system by assuming $f(E, T') = \frac{n}{n_{\rm eq}} \exp\left[-\frac{E}{T'}\right]$.