Self-interacting Dark Matter with Low-Temperature Reheating

Based on
NB, Kuldeep Deka & Marta Losada 2406.17039
NB, Esaú Cervantes, Kuldeep Deka & Andrzej Hryczuk 2506.09155

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Valencia workshop on the small-scale structure of the universe and self-interacting dark matter
June 13th, 2025

1. Why do we even care about cosmic reheating?

Why do we care about reheating?

To have a reliable estimation of the DM relic abundance one has to have under control

* particle physics model
* cosmological background

e.g. DM is typically produced when $\Gamma \sim H$

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

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  → SM entropy conserved
  → early universe dominated by SM radiation
  → instantaneous reheating

* But, reheating is not instantaneous,
  early matter domination, early PBH domination, kination...

Cosmic Reheating

* Cosmic Inflation
  → Exponentially fast expansion of the universe
  → Gives rise to an empty Universe

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

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

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

  → *Unknown* scaling of the temperature

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

Cosmic Reheating

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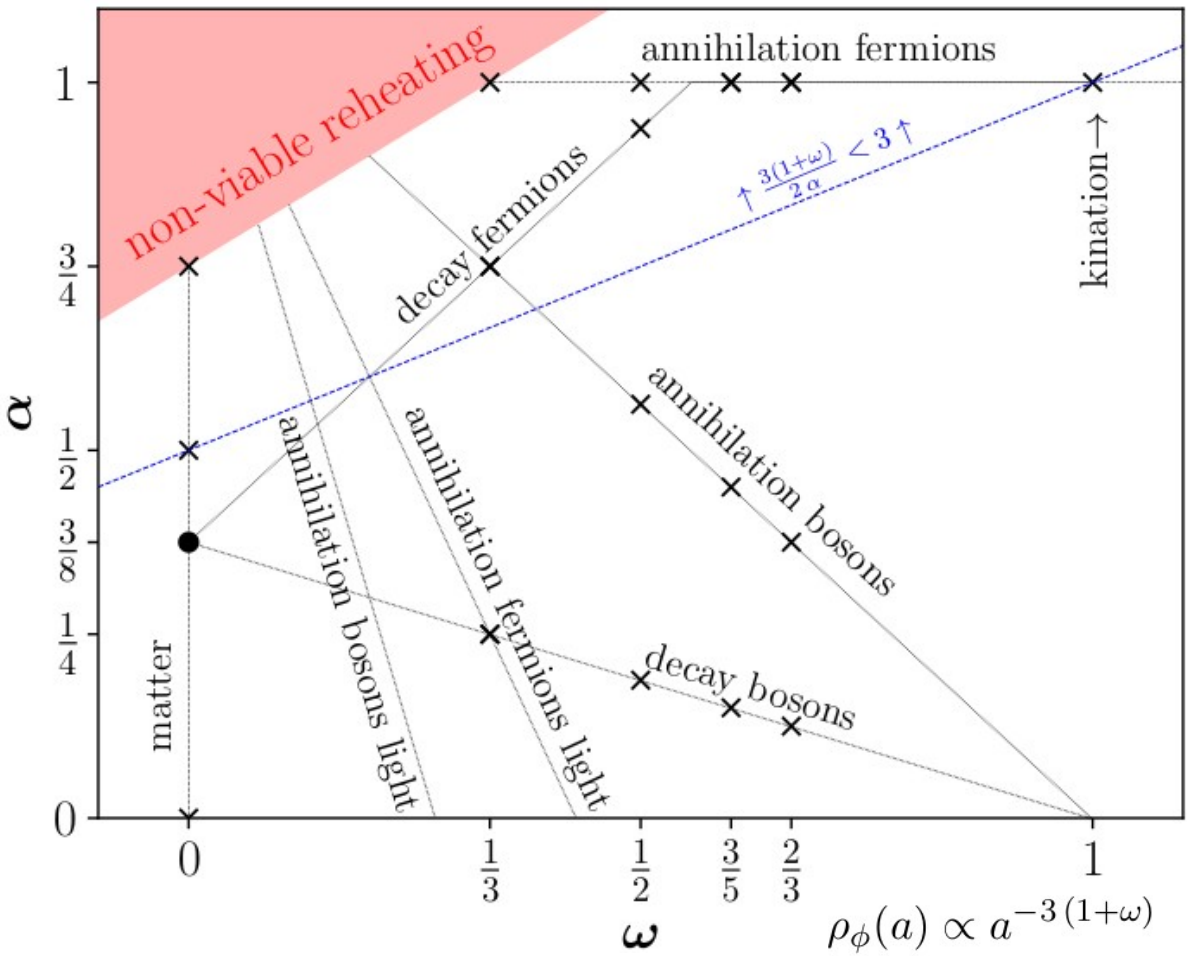
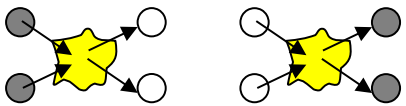


2. Self-interacting Dark Matter

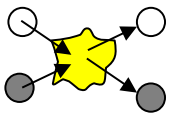
Self-interacting Dark Matter

Self-interactions → DM in thermal (chemical + kinetic) equilibrium

* **Chemical** freeze-out
→ *inelastic* interactions



* **Kinetic** freeze-out
→ *elastic* interactions
→ $T_\gamma = T_{dm}$



Chemical and Kinetic freeze-out
→ *Classify* different DM production mechanisms

WIMPs (Weakly Interacting Massive Particles)

$m > T_{fo} > T_k$

SIMPs (Strongly Interacting Massive Particles)

$m > T_{fo} > T_k$

ELDERs (ELastically DEcoupled Relics)

$m > T_k > T_{fo}$

Cannibal Dark Matter

$T_k > m > T_{fo}$

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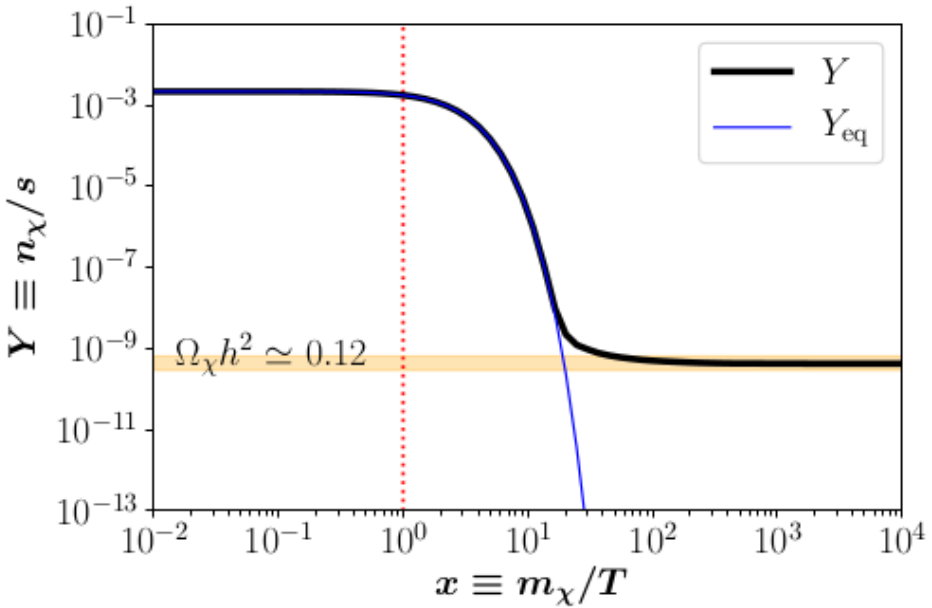
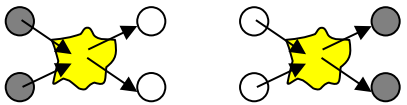
WIMP Dark Matter

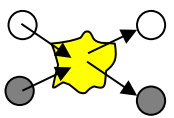
$$\frac{dn_\chi}{dt} + 3\,H\,n_\chi = -\langle v\sigma_\chi\rangle\left[n_\chi^2 - (n_\chi^{\rm eq})^2\right]$$



* **Chemical** freeze-out
→ *inelastic* interactions
@ $x_{fo} \sim 20$



* **Kinetic** freeze-out
→ *elastic* interactions
→ $T_\chi = T_{dm}$
@ $x_k \sim 10^2$ - 10^5



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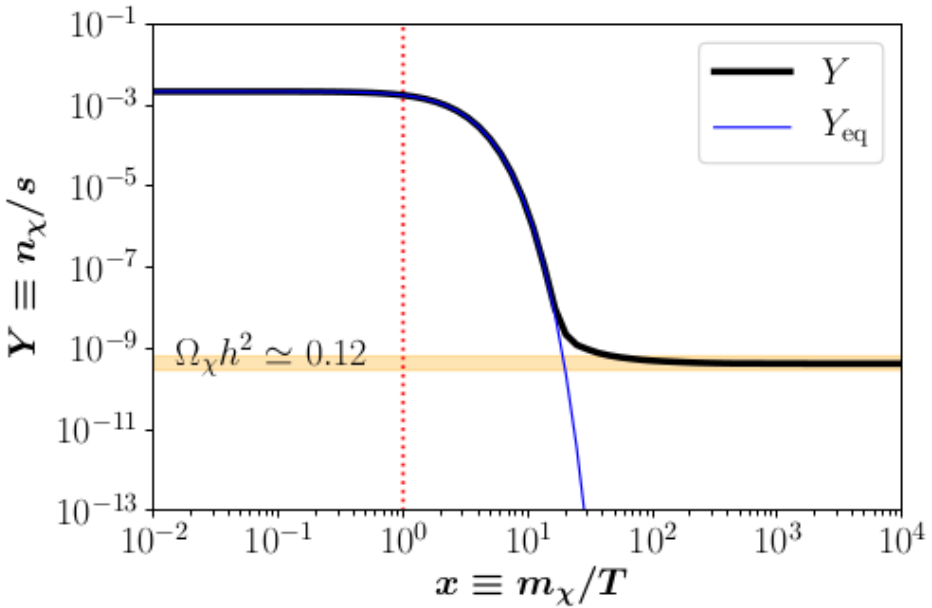

WIMP DM typically requires:
$\langle\sigma v\rangle$ ~ few 10^{-26} cm^3/s

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

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

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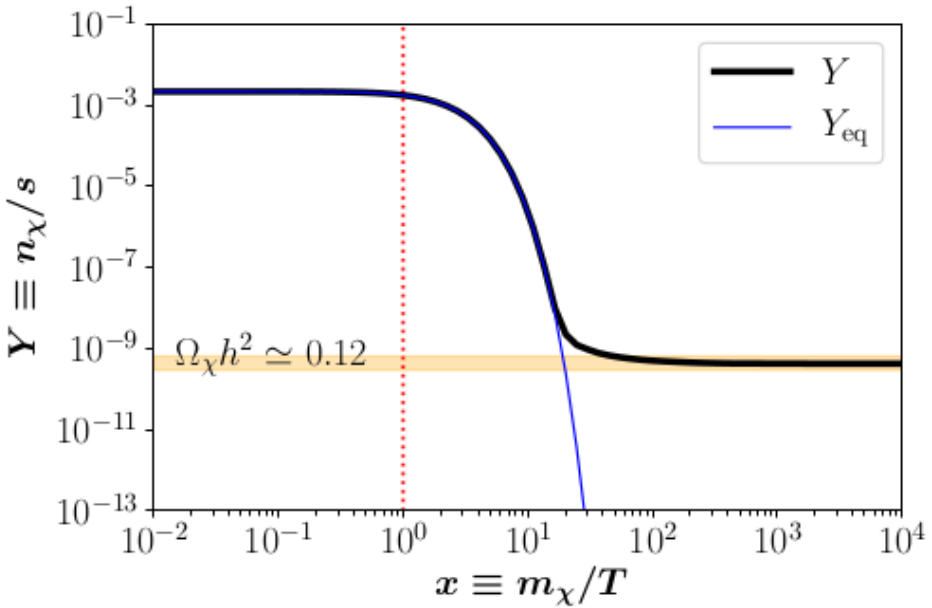
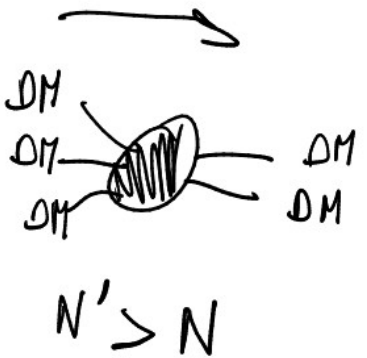
SIMP Dark Matter

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



SIMPs = *Freeze-out within the dark sector*



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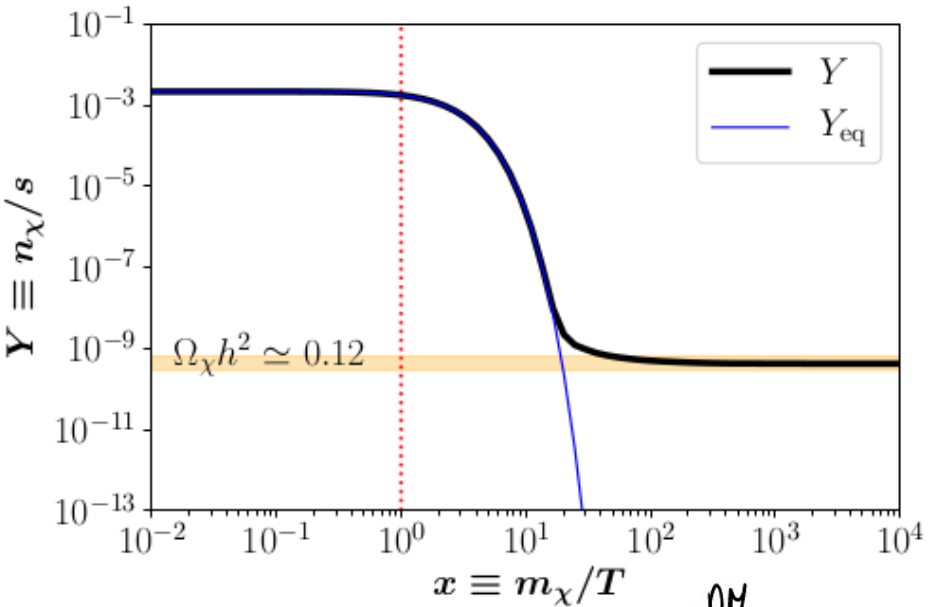

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SIMP DM typically requires:

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

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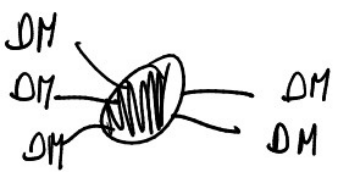

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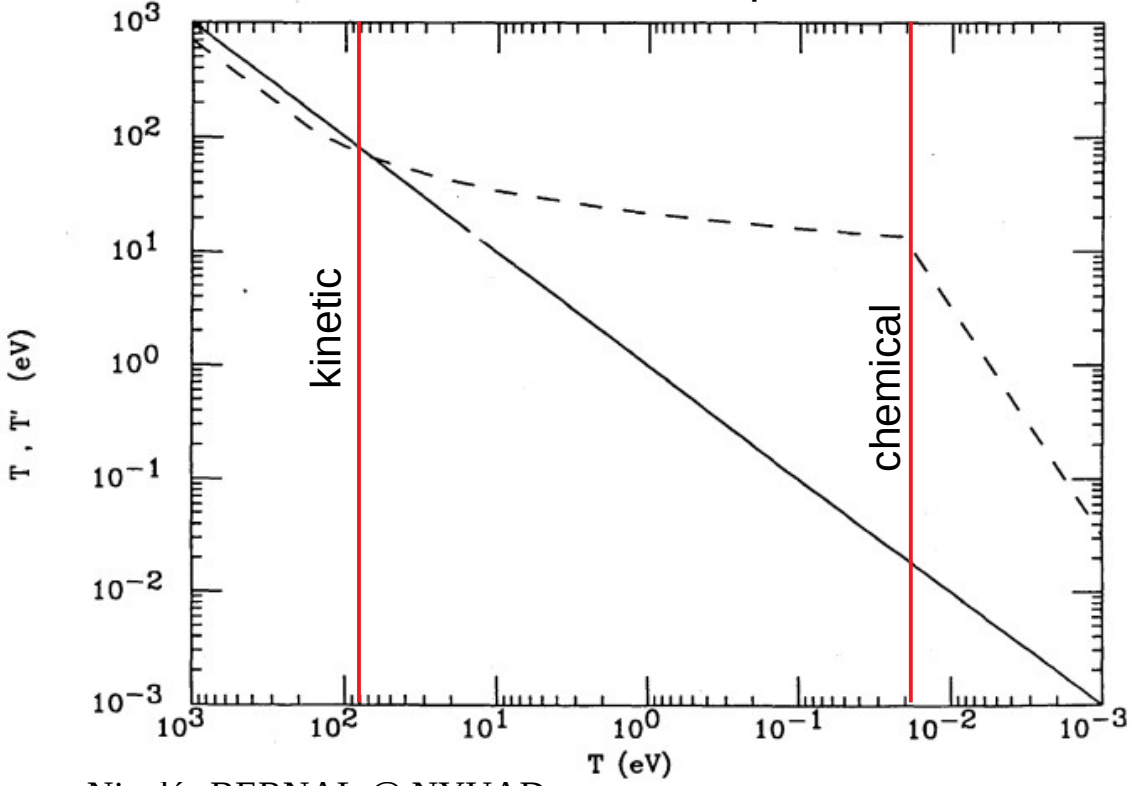
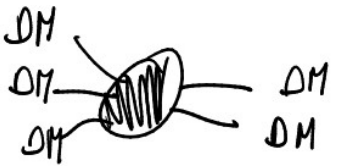
ELDER Dark Matter

Evolution of the temperatures



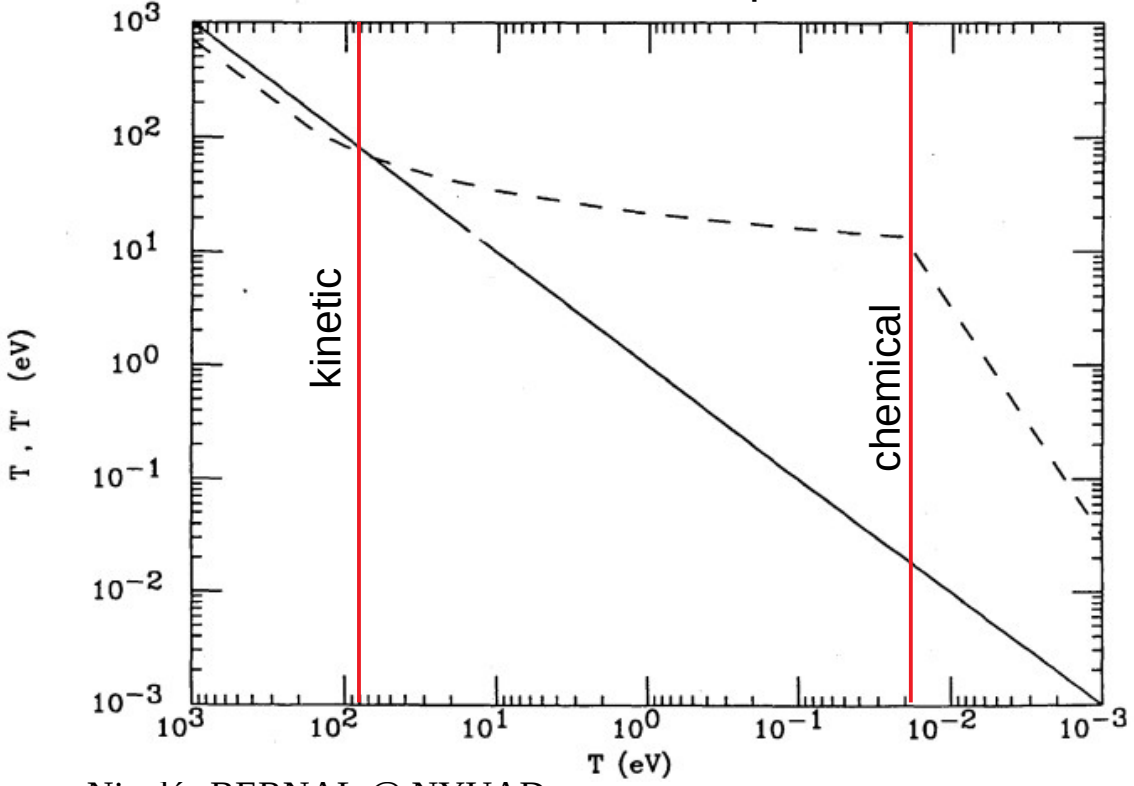


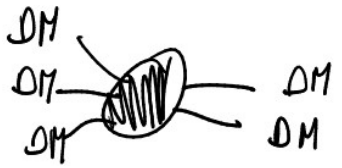
Entropies of the SM and DM separately conserved after *kinetic* decoupling

→ kinetic decoupling occurs when DM is **non-relativistic**

ELDER Dark Matter

Evolution of the temperatures





$$Y_0 \simeq \frac{45}{2^{5/2}\,\pi^{7/2}}\,\frac{g}{g_{\star s}(T_{\rm k})}\,\frac{x_{\rm k}^{5/2}\,e^{-x_{\rm k}}}{x'_{\rm fo}}$$

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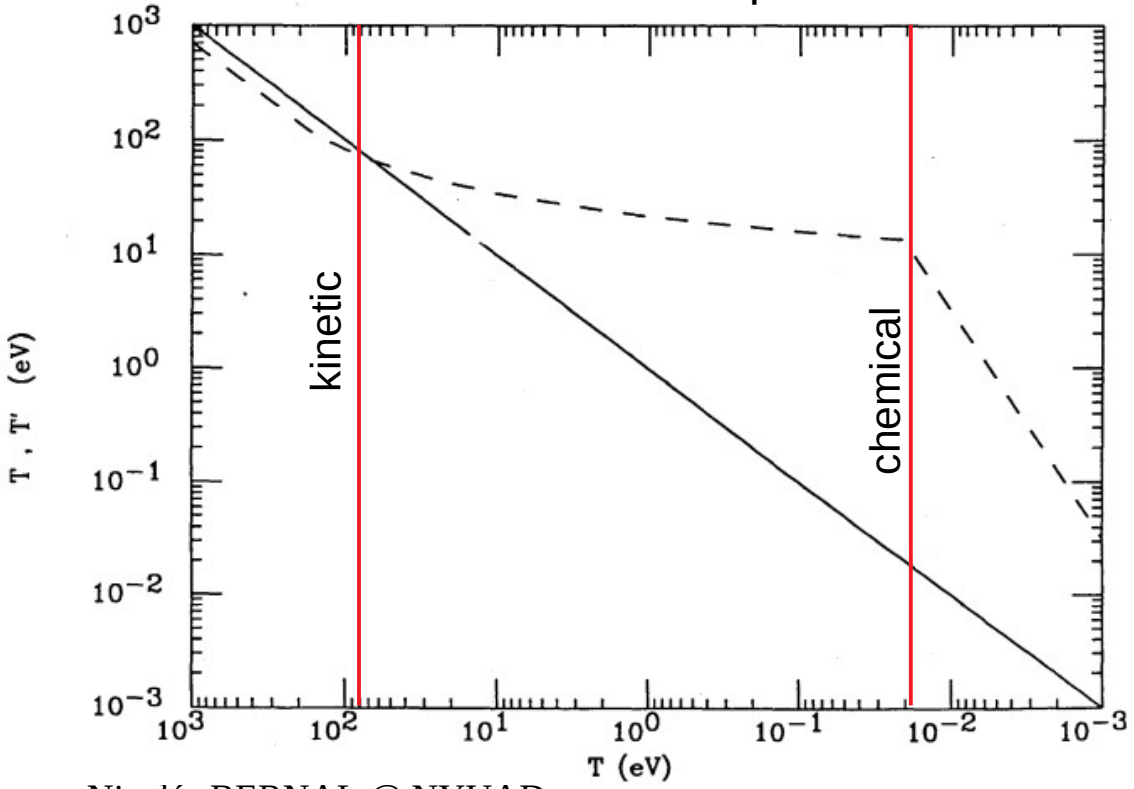

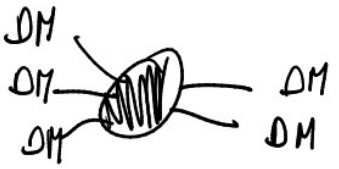

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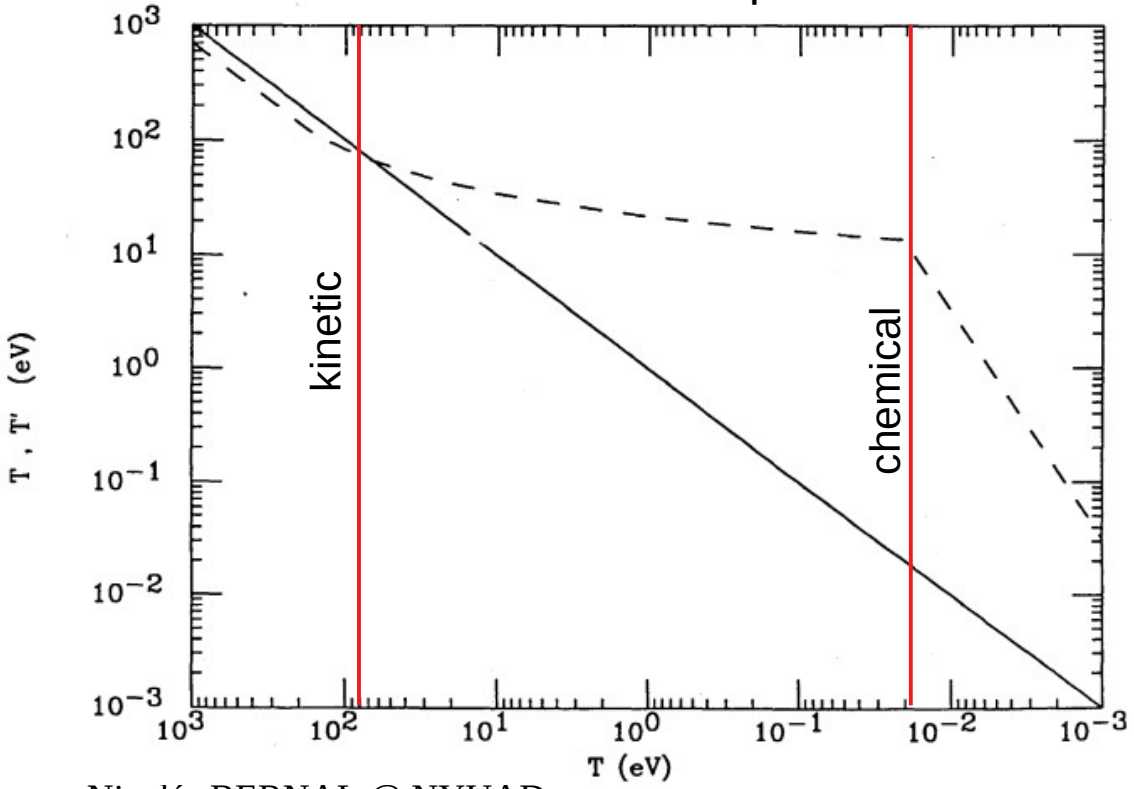
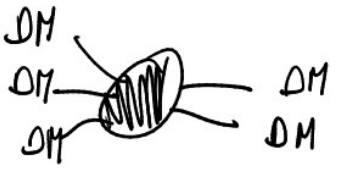
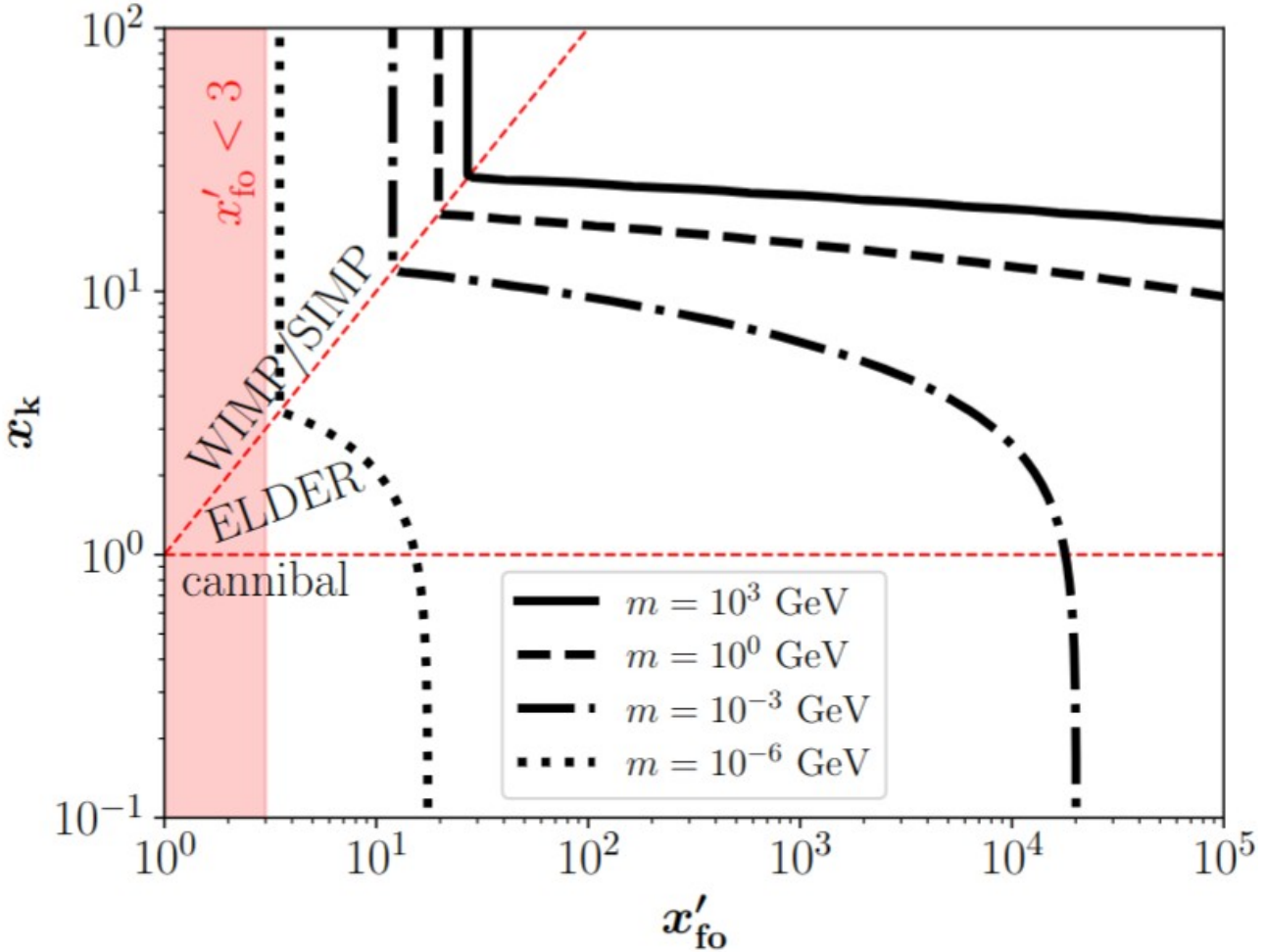




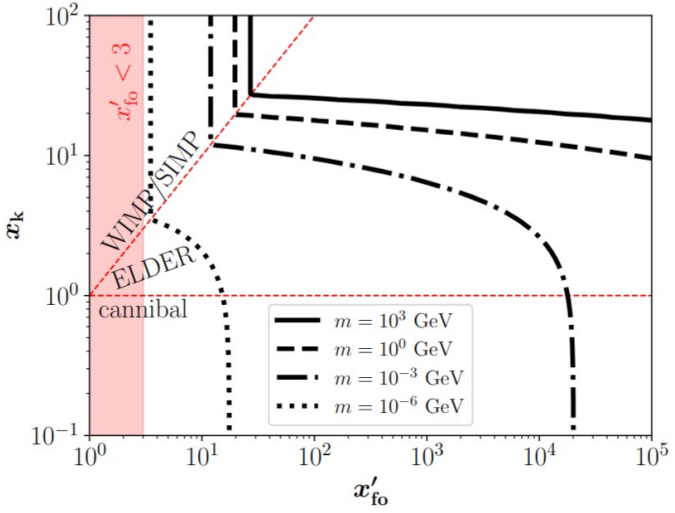
$$Y_0 \simeq \frac{90}{\pi^4} \frac{g}{g_{\star s}(T_{\rm k})} \frac{1}{x'_{\rm fo}}$$

SIDM in Standard Cosmology



3. Self-interacting DM with Low Reheating Temperature

SIDM *after* Reheating



SIDM *after* or *during* Reheating

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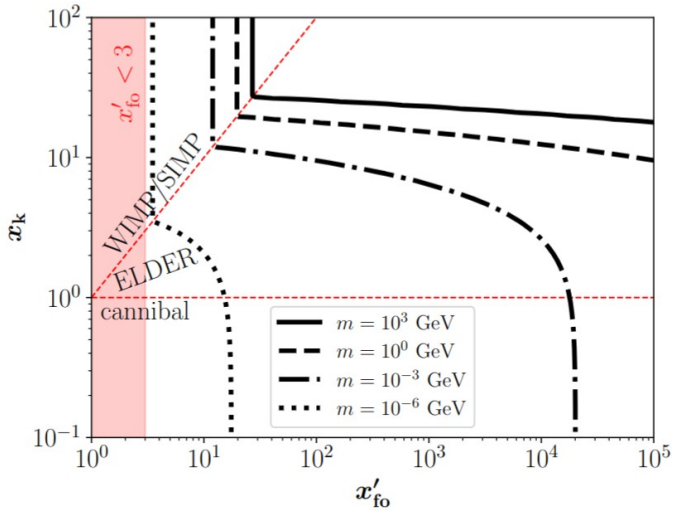
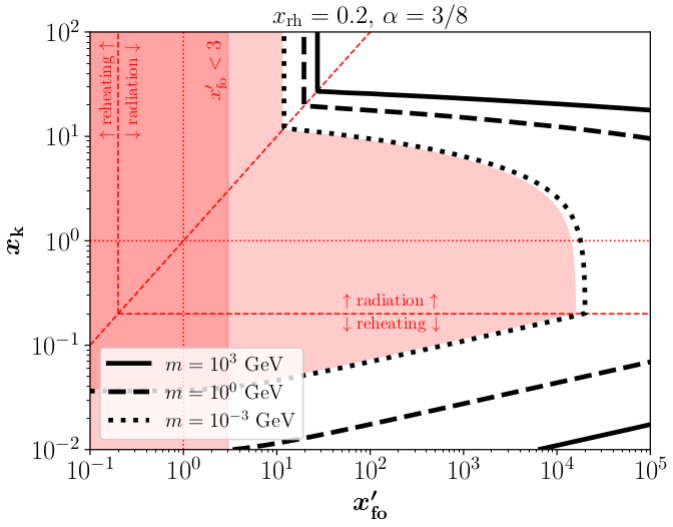
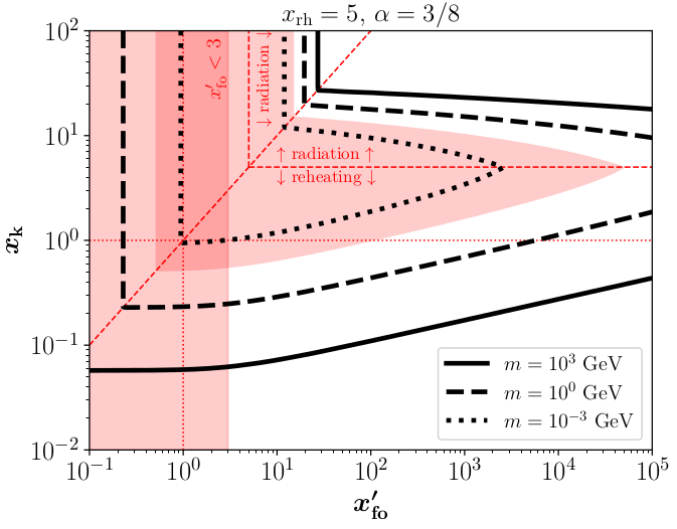
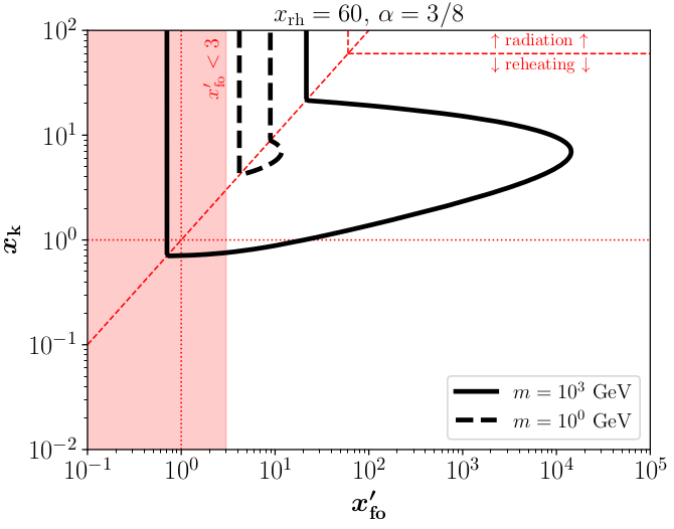






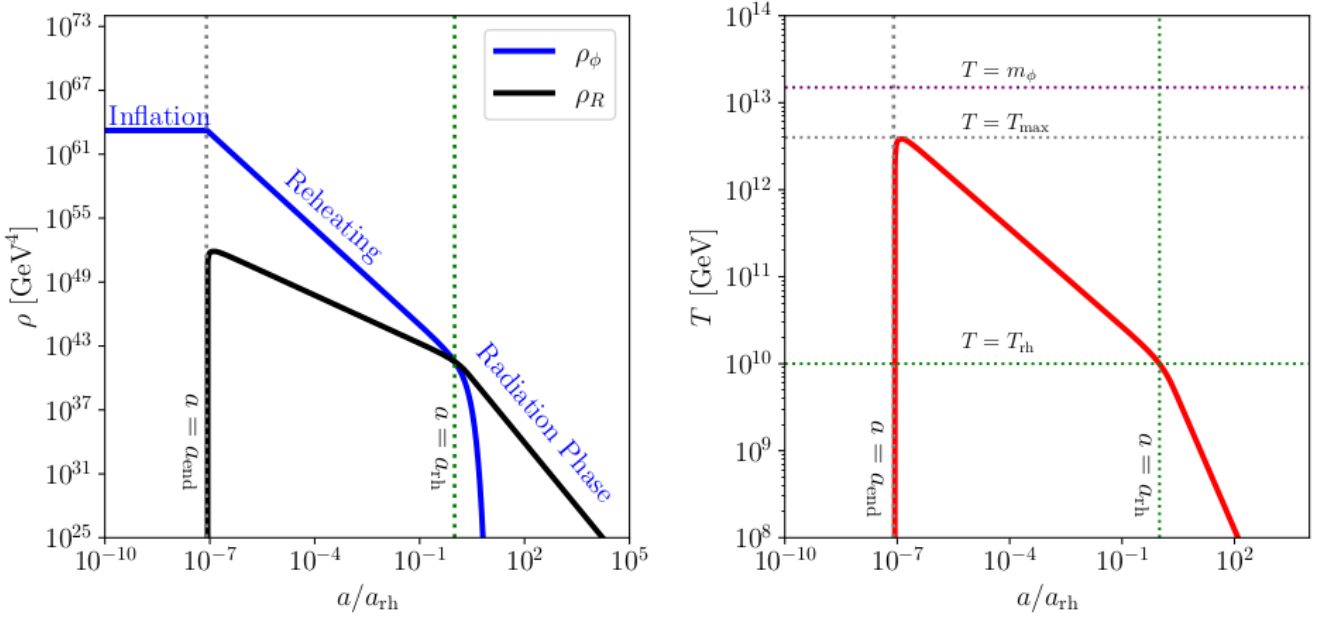


Conclusions

- Unknown history of the Early Universe
- Dark Matter could have been produced during **Cosmic Reheating**
  → Large uncertainties (T_{rh}, equation of state, scaling of SM temperature)
- Self-interactions play a fundamental role in DM genesis:
  → SIMPs, ELDERs and Cannibals
- **Model-independent approach**: Chemical vs. kinetic equilibrium
- Non-standard cosmological scenarios
  → drastically change the standard picture
  → smooth transition between different thermal and non-thermal DM
  → relax strong experimental constraints on thermal DM
  → increase detection chances of non-thermal DM
- For specific realizations
  → Kuldeep Deka
  → Esaú Cervantes

Gracias!

Non-instantaneous Reheating



Decay or annihilation of inflatons into SM radiation is a *continuous process*

$$\frac{d\rho_\phi}{dt} + 3(1+\omega)\,H\,\rho_\phi = -\Gamma_\phi\,\rho_\phi$$

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