Thermal DM with low temperature reheating

Kuldeep Deka

in a collaboration with

Nicolás Bernal and Marta Losada
(arXiv:2406.17039)

Light Dark World 2024
KAIST, Daejeon

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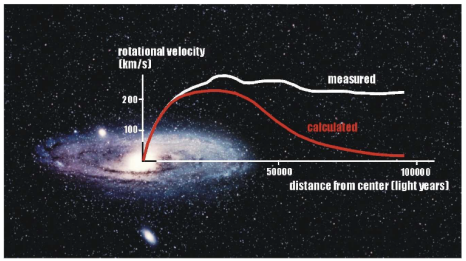
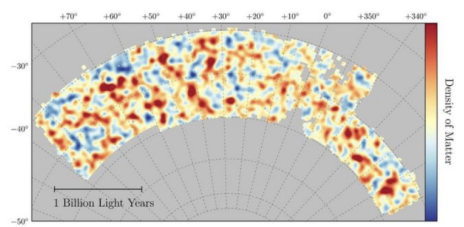
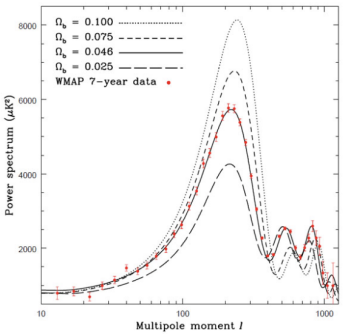
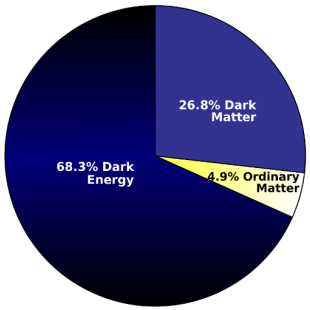
جامعة نيويورك أبوظبي
NYU ABU DHABI

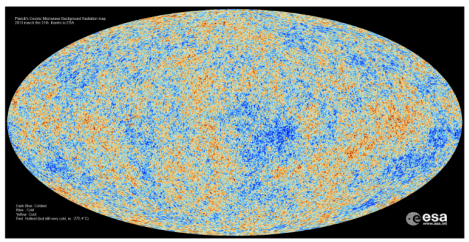
Dark Matter exists.....









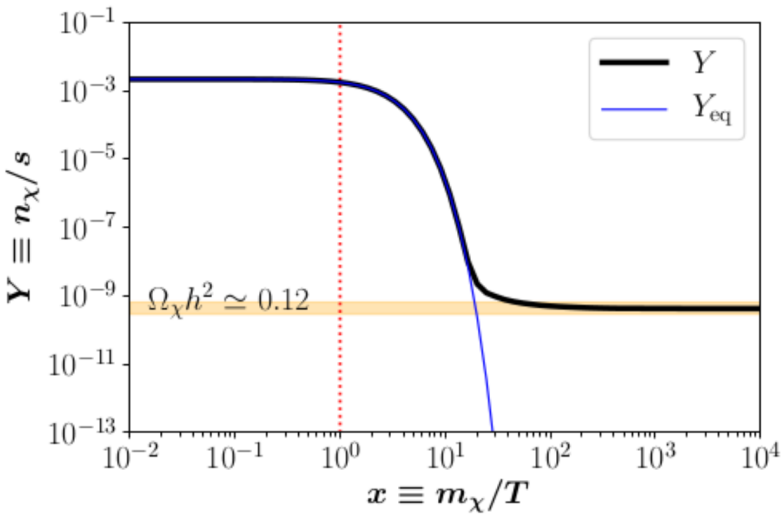


Credits:
HST, Chandra, DE Survey, WMAP, Planck

- 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 ($T_{\rm k}$).

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

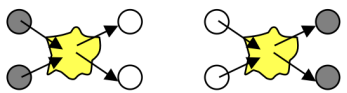
$$\frac{dn_\chi}{dt} + 3\,H\,n_\chi = -\langle v\sigma_\chi\rangle\left[n_\chi^2 - (n_\chi^{eq})^2\right]$$



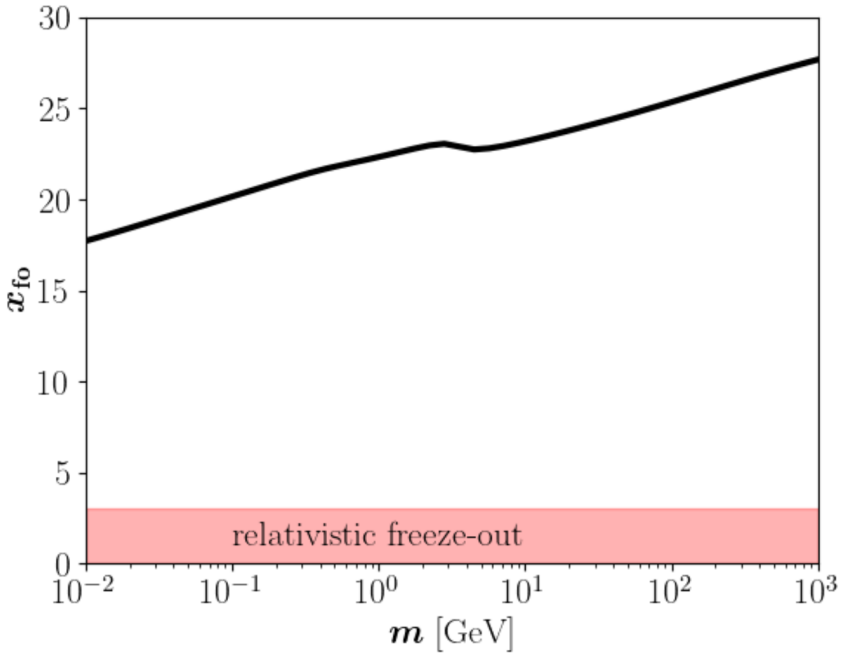
WIMP DM typically requires:
$\langle\sigma v\rangle$ ~ few 10^{-26} cm^3/s

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

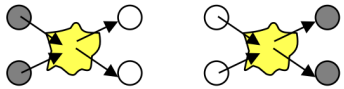
→ Independent on initial conditions!
* reheating temperature
* coupling to the inflaton
* DM density after reheating
* cosmological evolution before freeze-out



WIMP Dark Matter



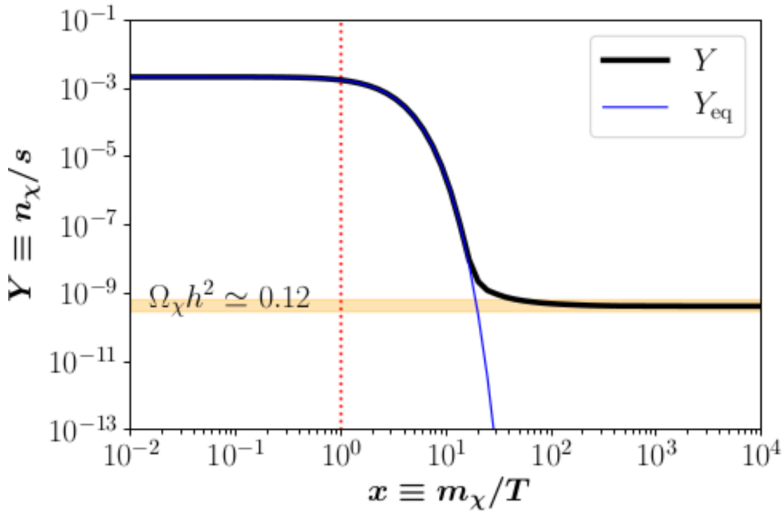
* **Chemical** freeze-out
  → *inelastic* interactions
  @ $x_{fo} \sim 20$



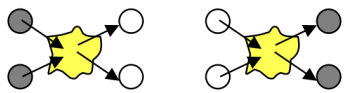
* **Kinetic** freeze-out
  → *elastic* interactions
  → $T_\gamma = T_{dm}$
  @ $x_k \sim 10^2$ - 10^5

WIMP Dark Matter

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

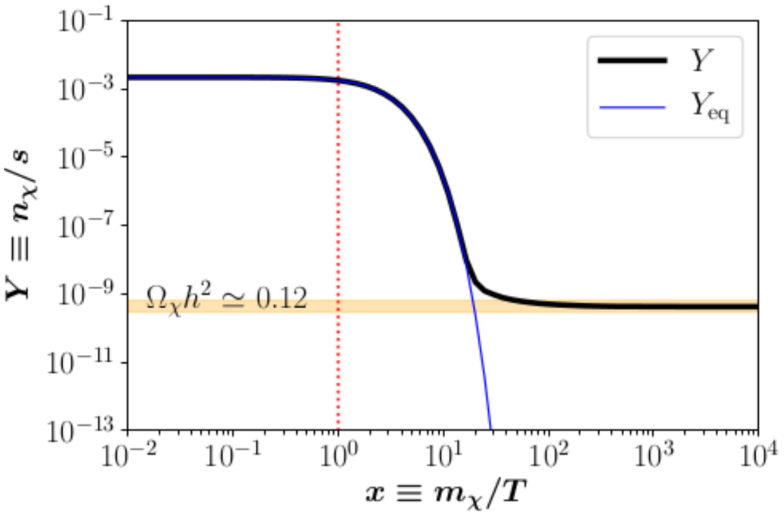


$$Y_0 \simeq Y_{\rm fo} = \frac{n_{\rm eq}(T_{\rm fo})}{s(T_{\rm fo})} \simeq \frac{45}{2^{5/2}\,\pi^{7/2}}\,\frac{g}{g_{\star s}(T_{\rm fo})}\,x_{\rm fo}^{3/2}\,e^{-x_{\rm fo}}$$

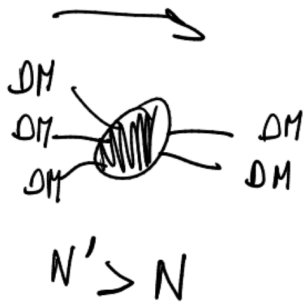


SIMPs (Strongly Interacting Massive Particles): $m > T_{fo} > T_k$

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

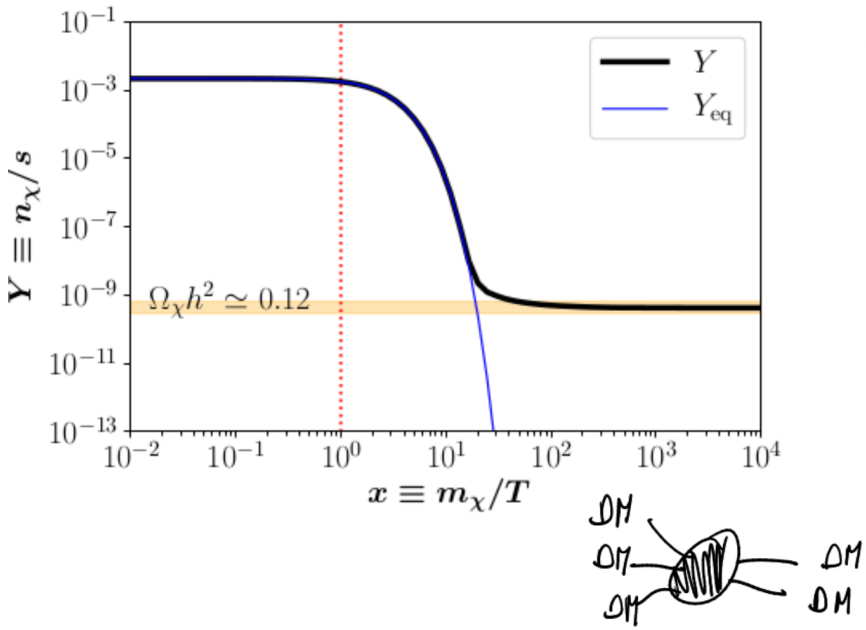


SIMPs = *Freeze-out within the dark sector*



SIMP Dark Matter

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



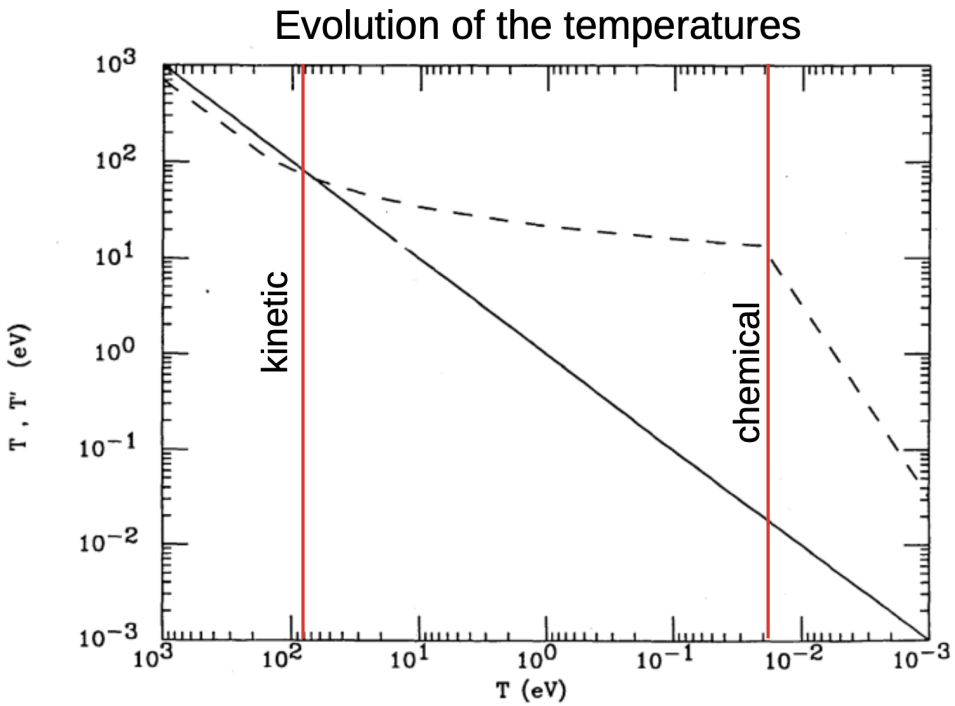
SIMPs = *Freeze-out within the dark sector*

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

ELDERs (ELastically DEcoupled Relics): $m > T_{\rm k} > T_{\rm fo}$

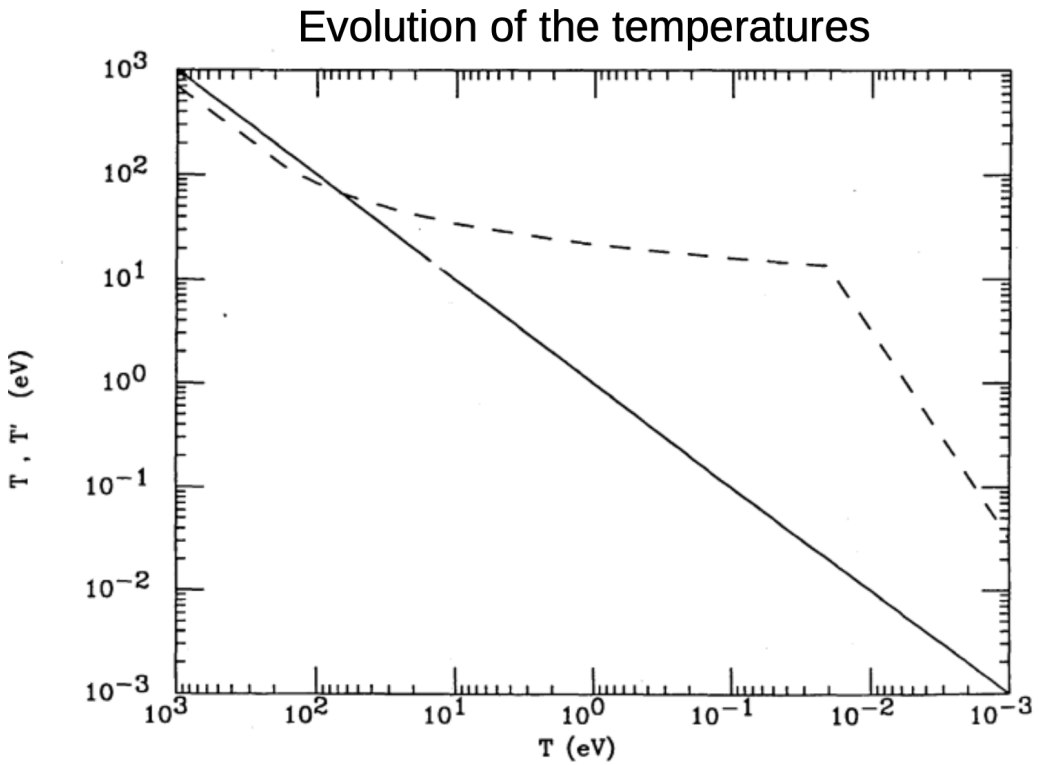


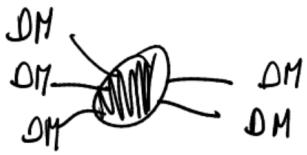
Entropies of the SM and DM separately conserved after *kinetic* decoupling

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

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

Cannibal: $T_{\rm k} > m > T_{\rm fo}$



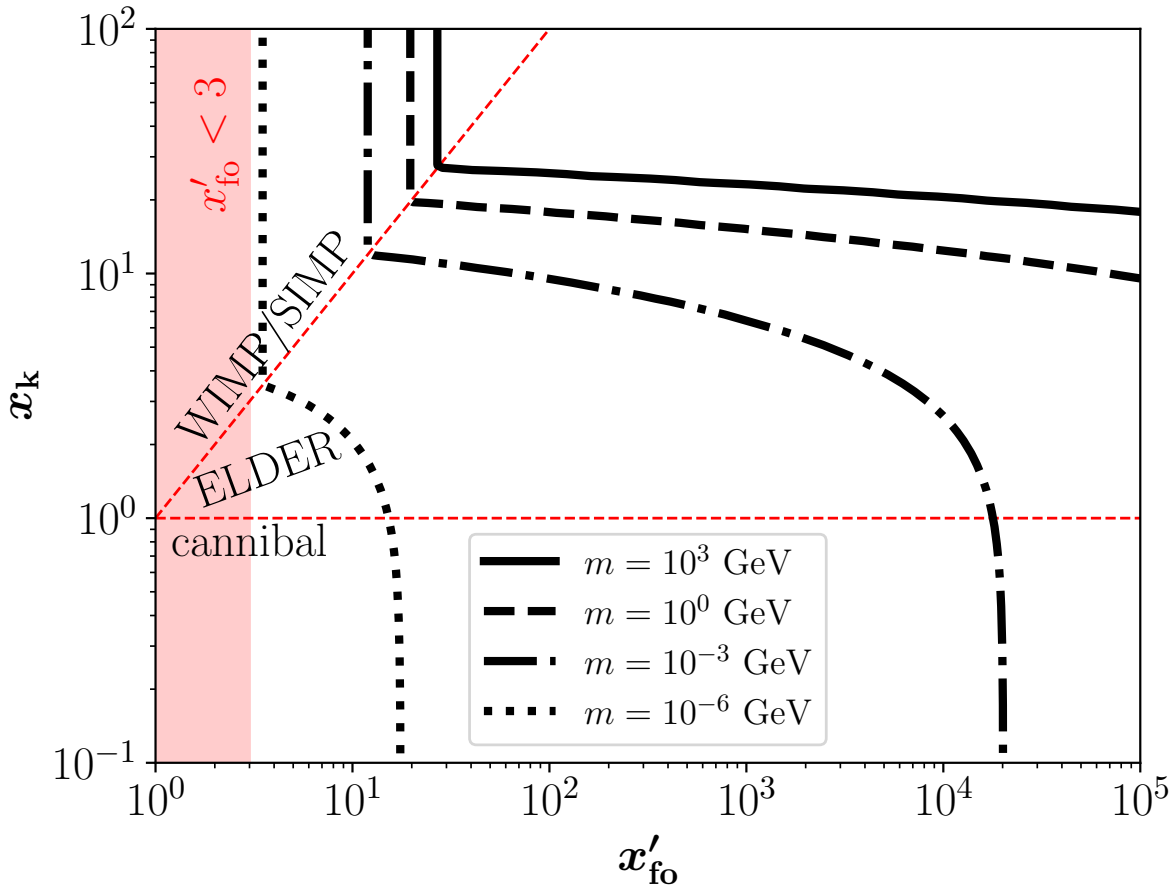


Entropies of the SM and DM separately conserved after *kinetic* decoupling

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

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

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



Low Temperature Reheating

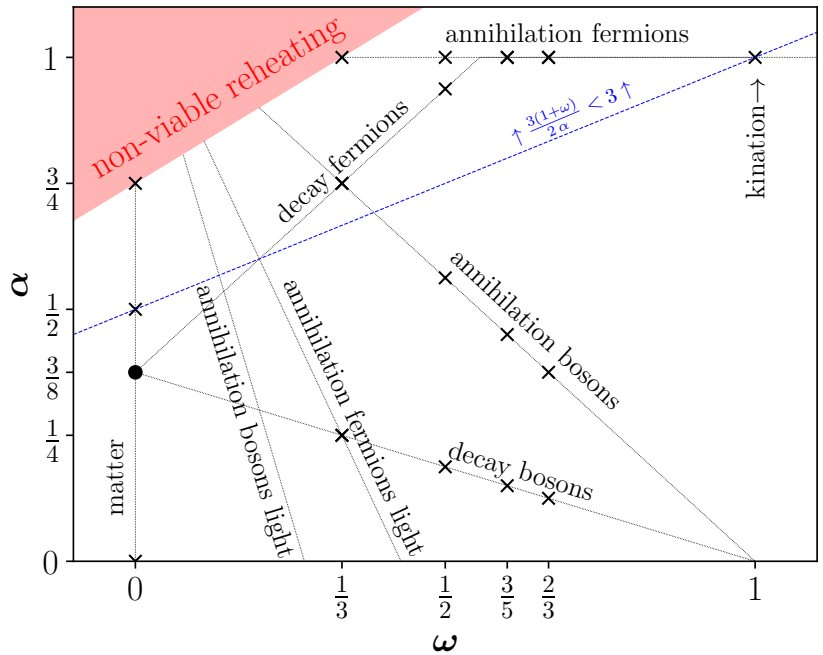
Cosmic **reheating**
→ Transition from an inflaton-dominated to a SM radiation-dominated era
→ End of reheating at T_{rh}
→ $T_{rh} > T_{bbn} \sim 4$ MeV

Inflaton Energy Density:

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

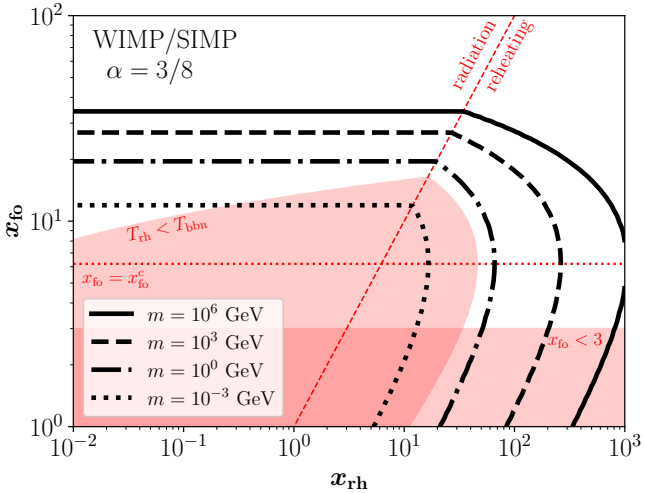
Scaling of SM temperature:

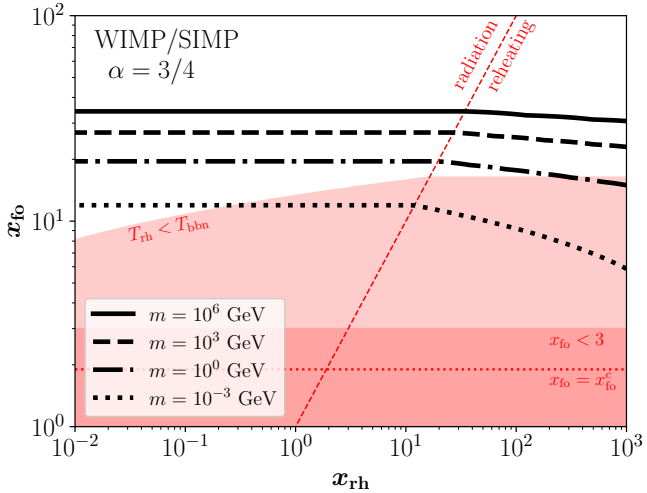
$$T(a) = T_{\rm rh} \left(\frac{a_{\rm rh}}{a}\right)^{\alpha}$$

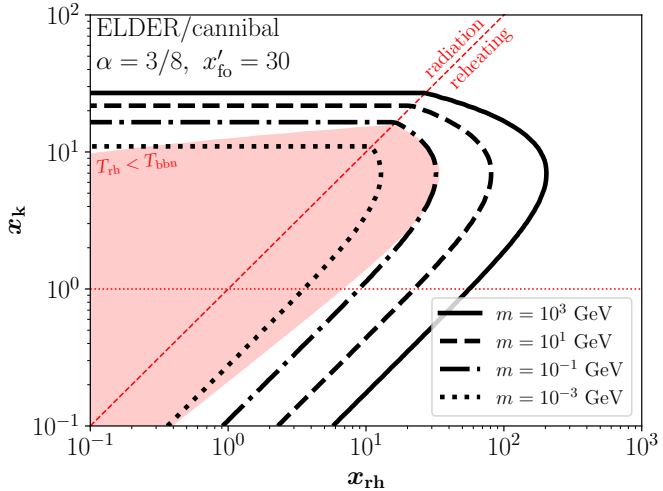


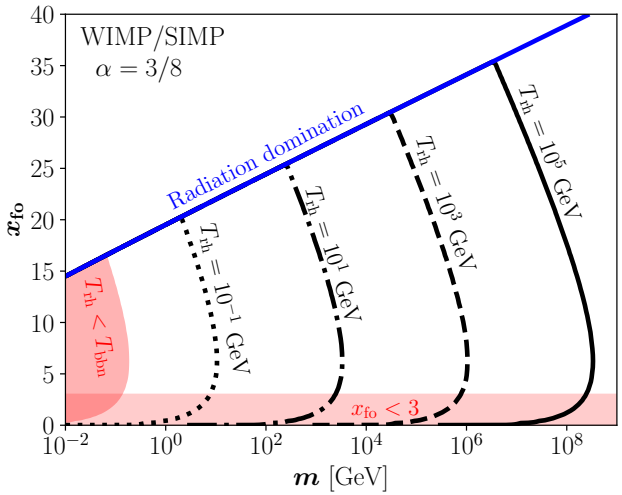
Hubble Scaling: $H(T) \simeq H(T_{\rm rh}) \times \left(\frac{T}{T_{\rm rh}}\right)^{\frac{3(1+\omega)}{2\alpha}}$ for $T \geq T_{\rm rh}$

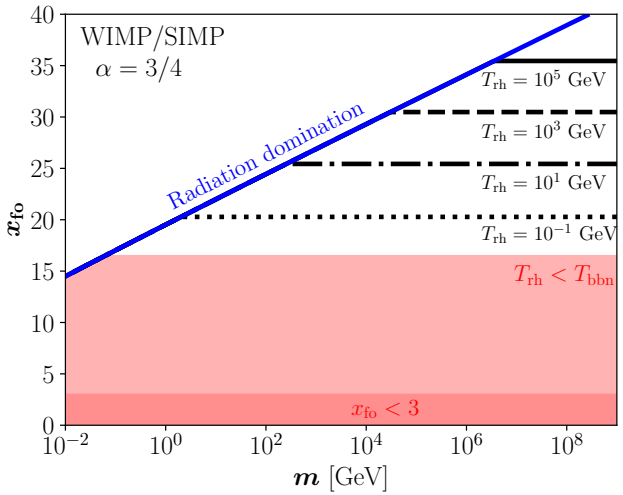
Differences w.r.t. Radiation

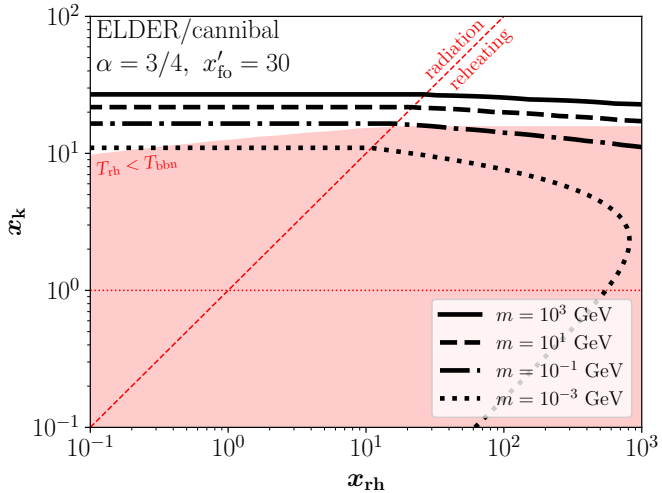






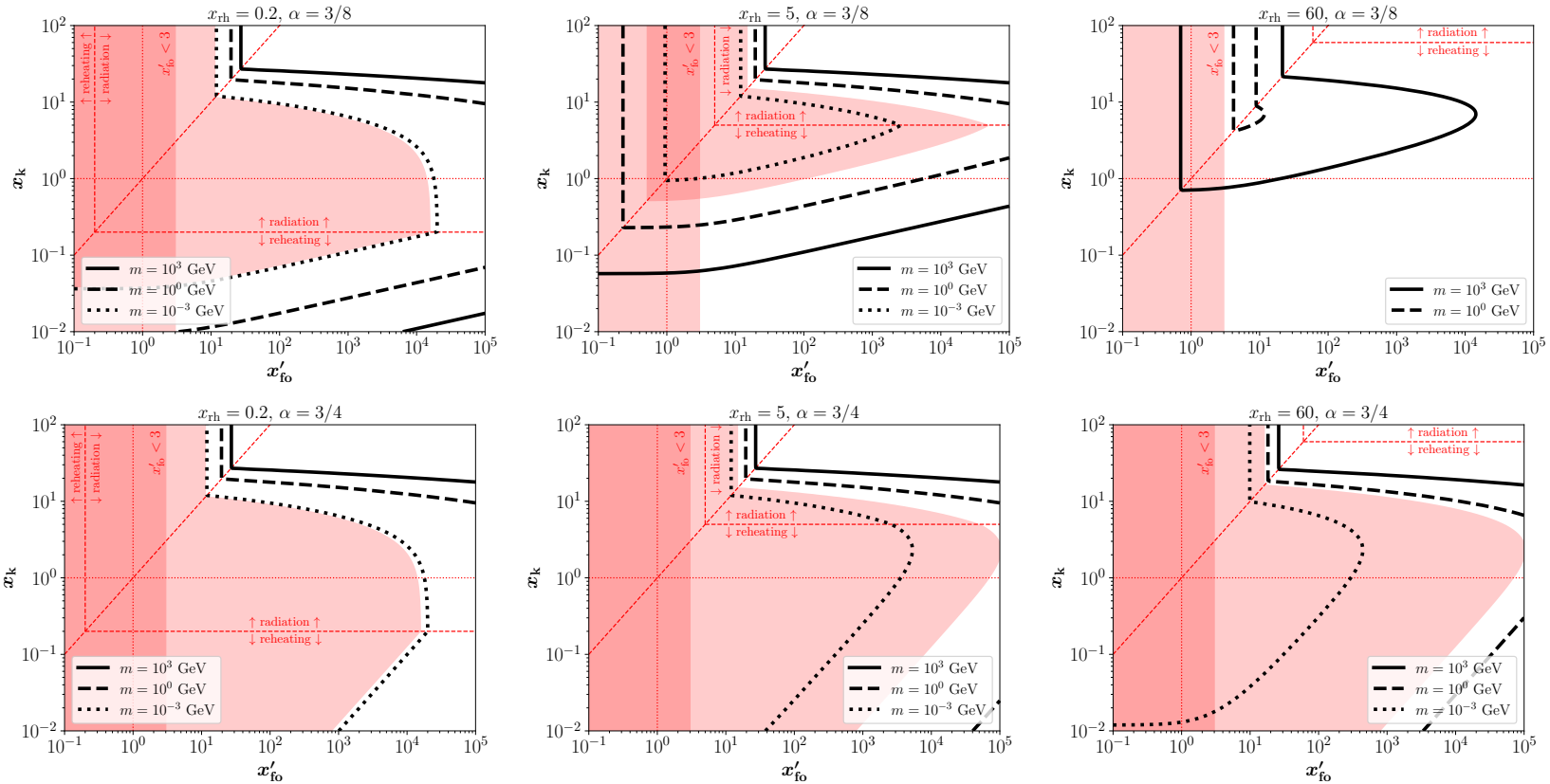






DM production during reheating allows for larger $T_{\rm fo}$ and $T_{\rm k}$.

Parameter space in x'_{fo} and x_k with fixed x_{rh}

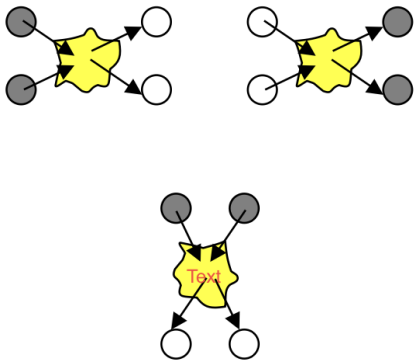


For a given mass (m), upto two DM solutions are viable.

Simple particle physics realisation

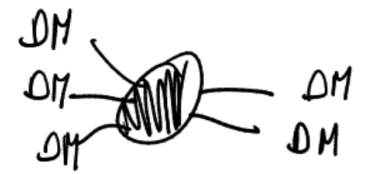
$2 \to 2$ DM-SM interaction:

$$\langle \sigma v \rangle_{\text{el},2\to 2} \sim \left[\frac{\epsilon_{\text{eff}}}{m} \frac{K_1(x)}{K_2(x)} \right]^2$$

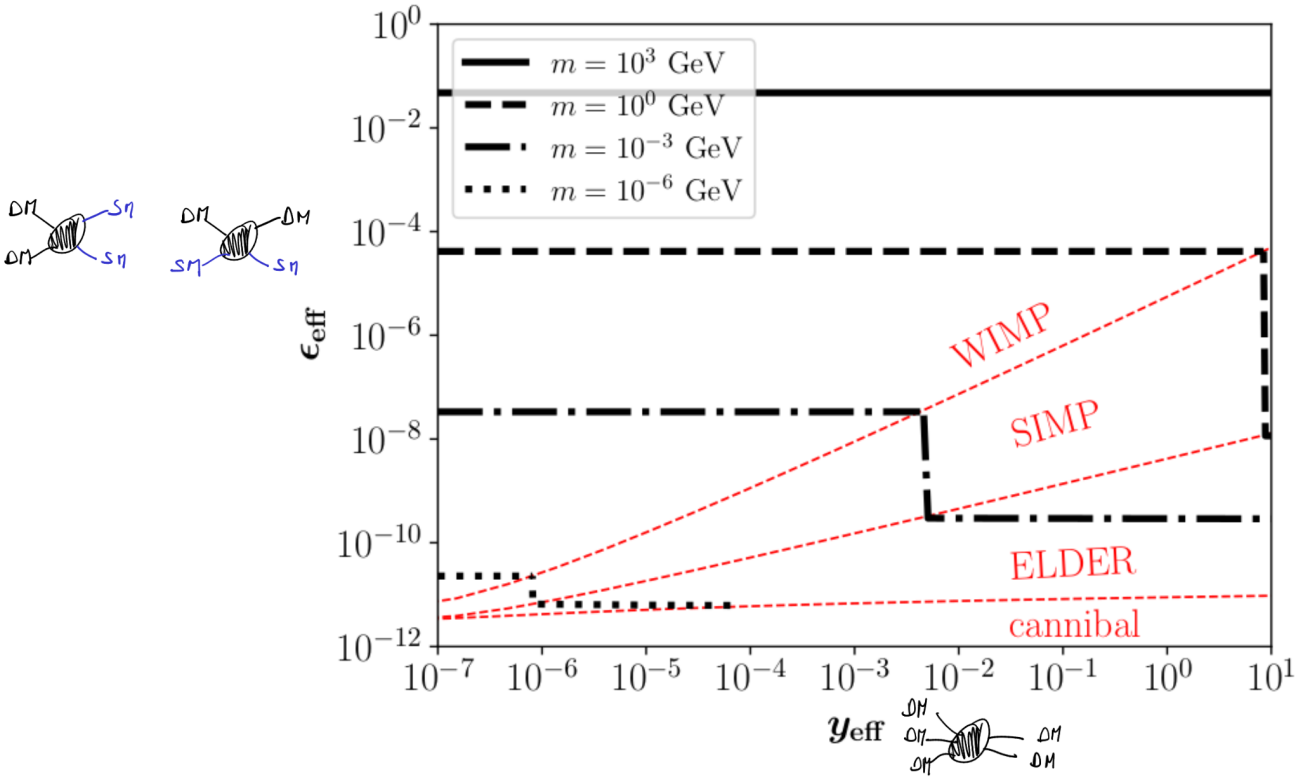


$3 \to 2$ DM self-annihilation :

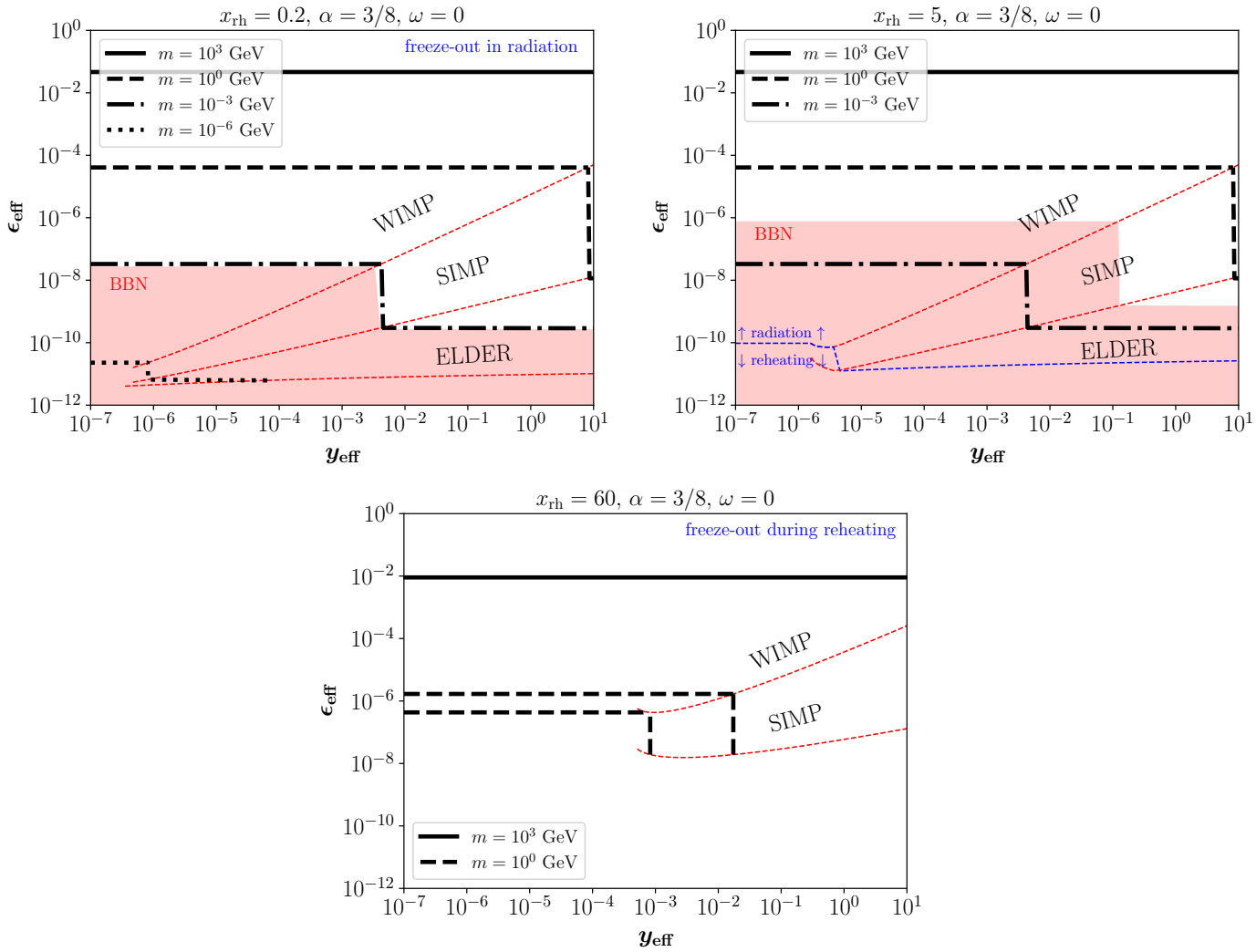
$$\langle \sigma v^2 \rangle_{3\to 2} \sim \frac{y_{\text{eff}}^3}{m^5}$$



Parameter space during radiation

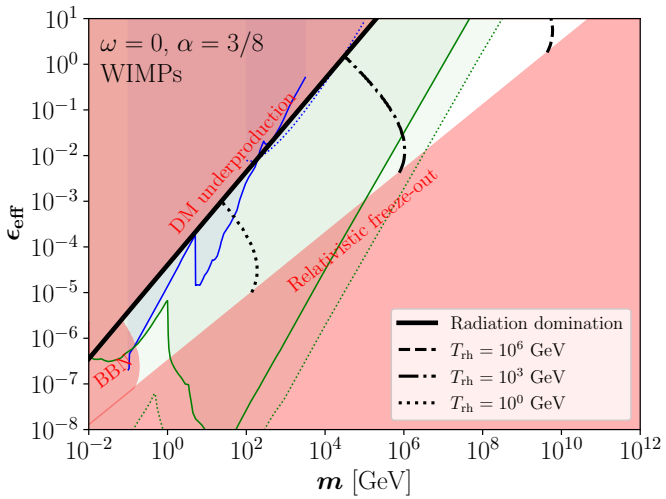


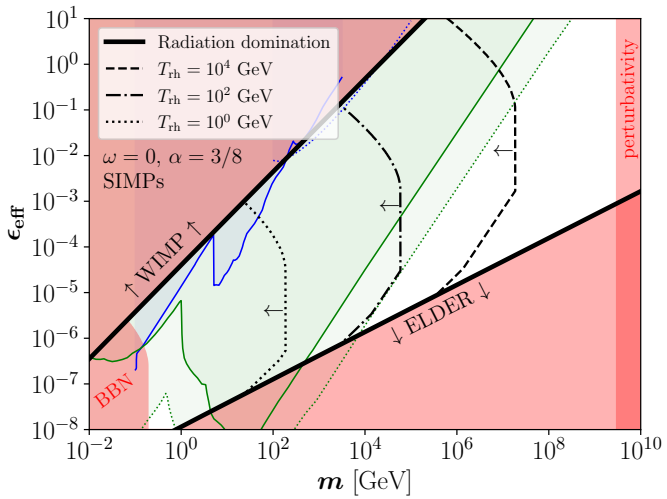
Parameter space during reheating

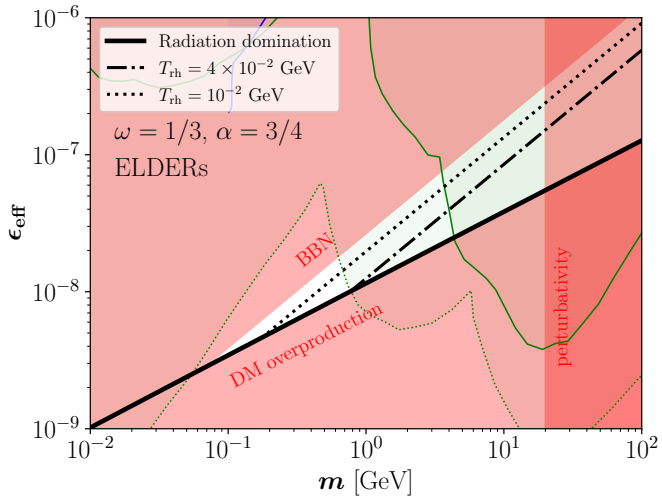


Parameter Regions

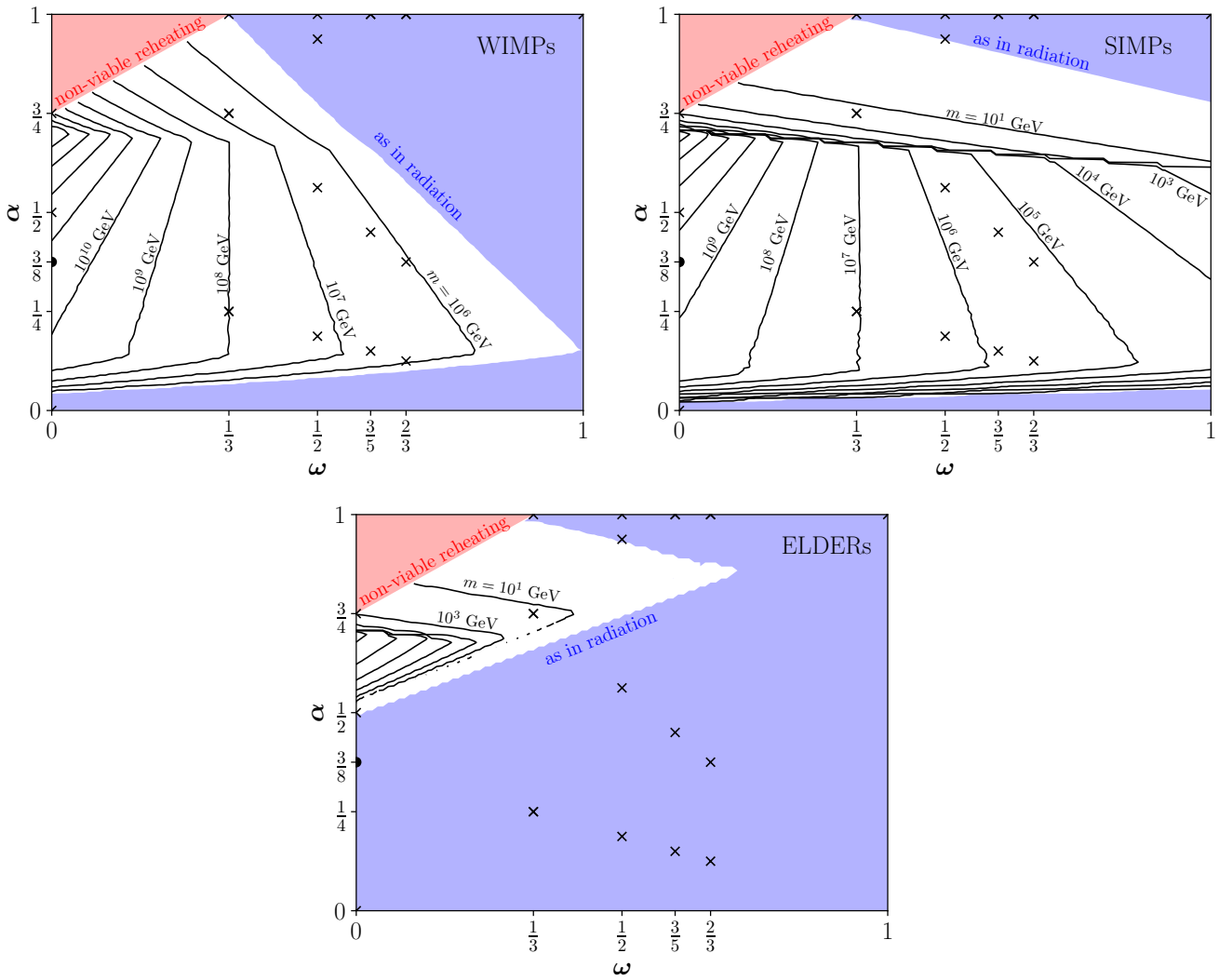
Direct and indirect detection constraints







Maximum masses attainable for different cosmologies



Summary

Cosmological history of the Universe important for DM genesis.

- **Thermal Dark Matter**: WIMPs, SIMPs, ELDERs and Cannibals
- **Model-independent approach**: Chemical vs. kinetic equilibrium
- Dark Matter could have been produced during **Cosmic Reheating**
  → Large uncertainties (T_{rh}, equation of state, scaling of SM temperature)
- Parameter space greatly enlarged
  → $m < 10^{13}$ GeV
  → smaller DM-SM couplings, but *within the range of future detectors*
- Dark Matter production during reheating (and inflation!) has to be studied!