Ultra-relativistic freeze-out (UFO) during reheating

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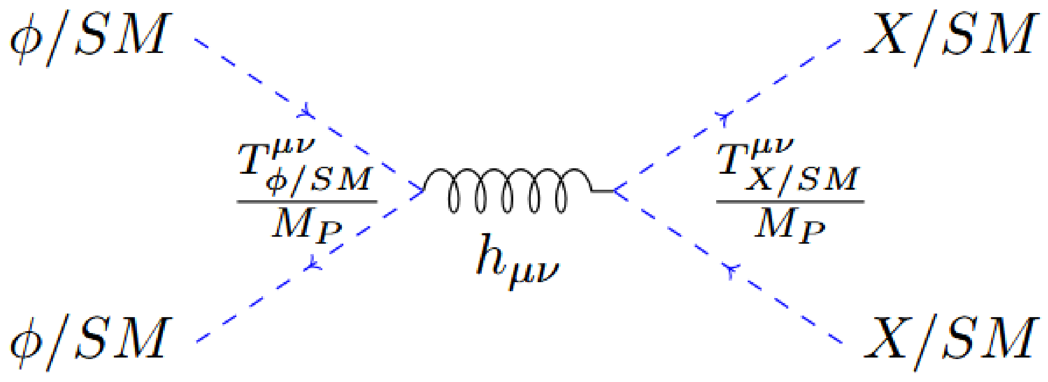
Based on : arXiv:2505.04703v1 (Published in *Phys.Rev.D*)
In collaboration with: Stephen E. Henrich, Yann Mambrini and Keith A. Olive

Outline

- Standard dark-matter production scenarios
- Reheating
- Freeze-out during reheating
- Conclusion

Freeze-in in a nutshell (FIMPS)



Dark matter never reach thermal equilibrium

$$\frac{dn_\chi}{dt} + 3Hn_\chi = R(T)$$

$$\dot{n}_\chi + 3Hn_\chi = \frac{T}{128\pi^6}\int \frac{ds}{\sqrt{s}}\, p^{\rm CM}_{\chi\chi}\, p^{\rm CM}_{ab}\, \tilde{K}_1(s,T)\, |\mathcal{M}|^2\, d\Omega$$

Need to integrate over time $\Rightarrow$ Strongly depend on initial condition and cosmological history

Small coupling $\Rightarrow$ Difficult to probe

Non-relativistic freeze-out (WIMPS)

We will assume: $\langle \sigma v \rangle \sim \frac{T^n}{\Lambda^{n+2}}$

$$n_{eq} \simeq g \left(\frac{m_\chi T}{2\pi}\right)^{\frac{3}{2}} e^{-\frac{m_\chi}{T}}$$

$$\frac{dn_\chi}{dt} + 3Hn_\chi = \langle \sigma v \rangle (n_{eq}^2 - n_\chi^2)$$

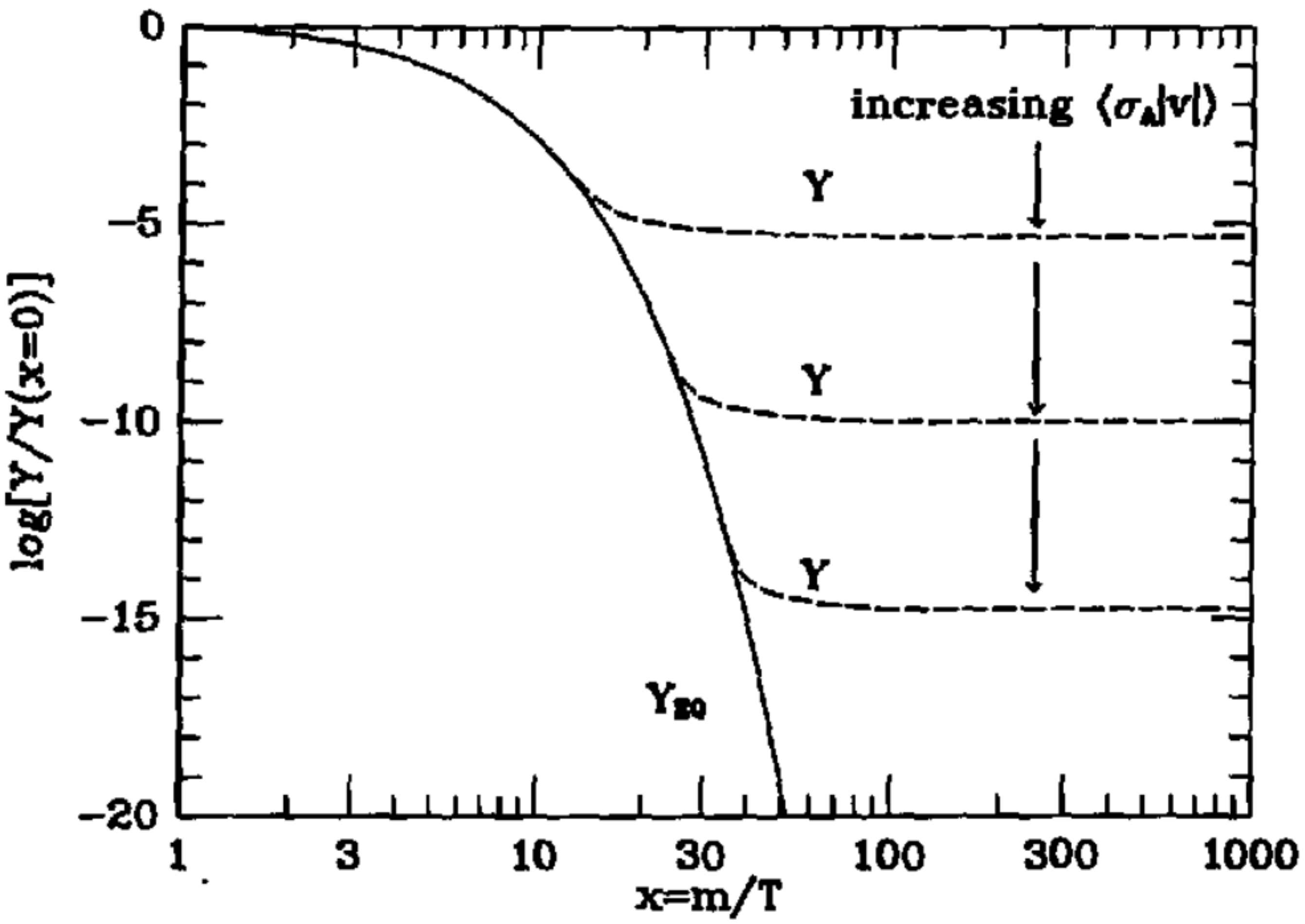
$$\Leftrightarrow \frac{da^3 n_\chi}{da} = \frac{\langle \sigma v \rangle a^2}{H}(n_{eq}^2 - n_\chi^2)$$

Follow thermal equilibrium until:

$$\Gamma(t_{fo}) = n_{eq}\langle \sigma v \rangle \sim H(t_{fo})$$

$$\underset{n=0}{\Rightarrow} \frac{m_\chi}{T_{fo}} = -\frac{1}{2}\mathcal{W}_{-1}\left[-\frac{8\pi^5}{45}\frac{g_*}{g^2}\frac{\Lambda^4}{M_P^2 m_\chi^2}\right]$$

Kolb and Turner, **The Early Universe** Front.Phys. 69 (1990), 1-547



Relativistic freeze-out

We will assume: $\langle\sigma v\rangle \sim \frac{T^n}{\Lambda^{n+2}}$

$$n_{eq} = \frac{g\zeta(3)}{\pi^2}T^3$$

$$\frac{dn_\chi}{dt} + 3Hn_\chi = \langle\sigma v\rangle(n_{eq}^2 - n_\chi^2)$$

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Follow thermal equilibrium until:

$$\Gamma(t_{fo}) = n_{eq}\langle\sigma v\rangle \sim H(t_{fo})$$

$$\Rightarrow T_{fo} = \Lambda\left(\frac{\Lambda}{M_P}\frac{2\pi^2}{g\zeta(3)}\sqrt{\frac{\alpha}{3}}\right)^{\frac{1}{n+1}}$$

However due to entropy conservation: $n_{eq}a^3 = cst$

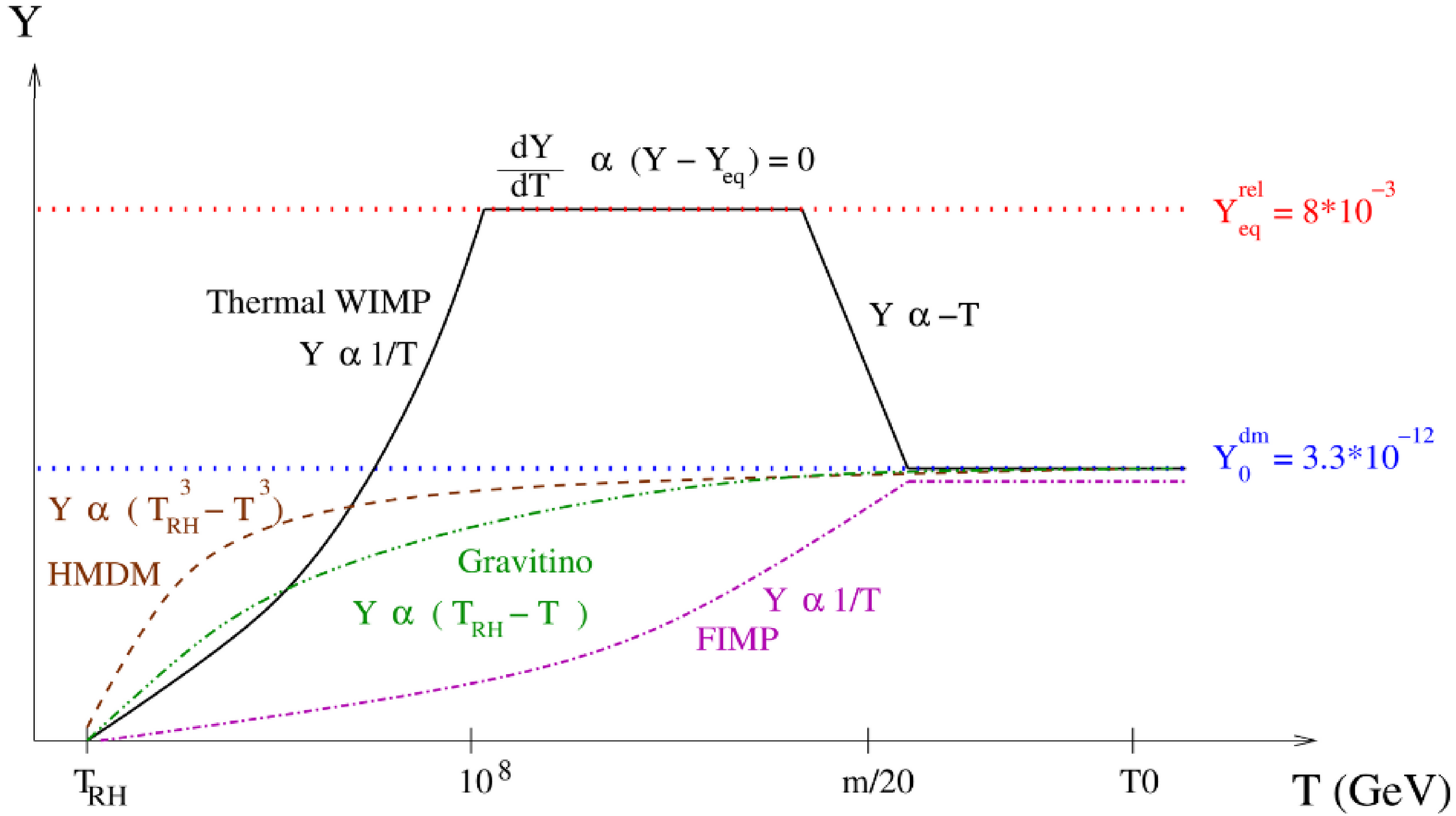
$$\frac{\Omega_\chi h^2}{0.12} \simeq g\left(\frac{106.75}{g_{fo}}\right)\left(\frac{m_\chi}{170\,\mathrm{eV}}\right)$$

$$17\,\mathrm{eV} \lesssim m_\chi \lesssim 170\,\mathrm{eV} \quad \text{(real scalar)}$$

$$11\,\mathrm{eV} \lesssim m_\chi \lesssim 110\,\mathrm{eV} \quad \text{(Majorana fermion)}$$

No dependance on the coupling!

Sumary of standard dark matter production

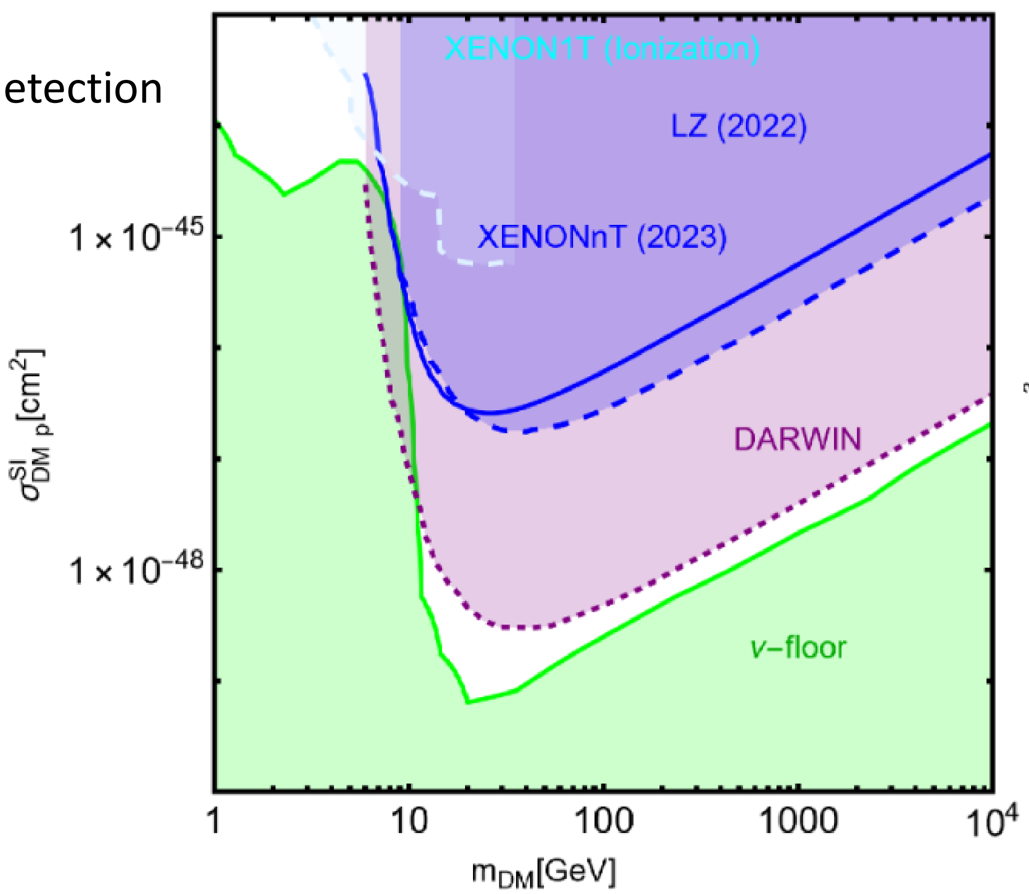


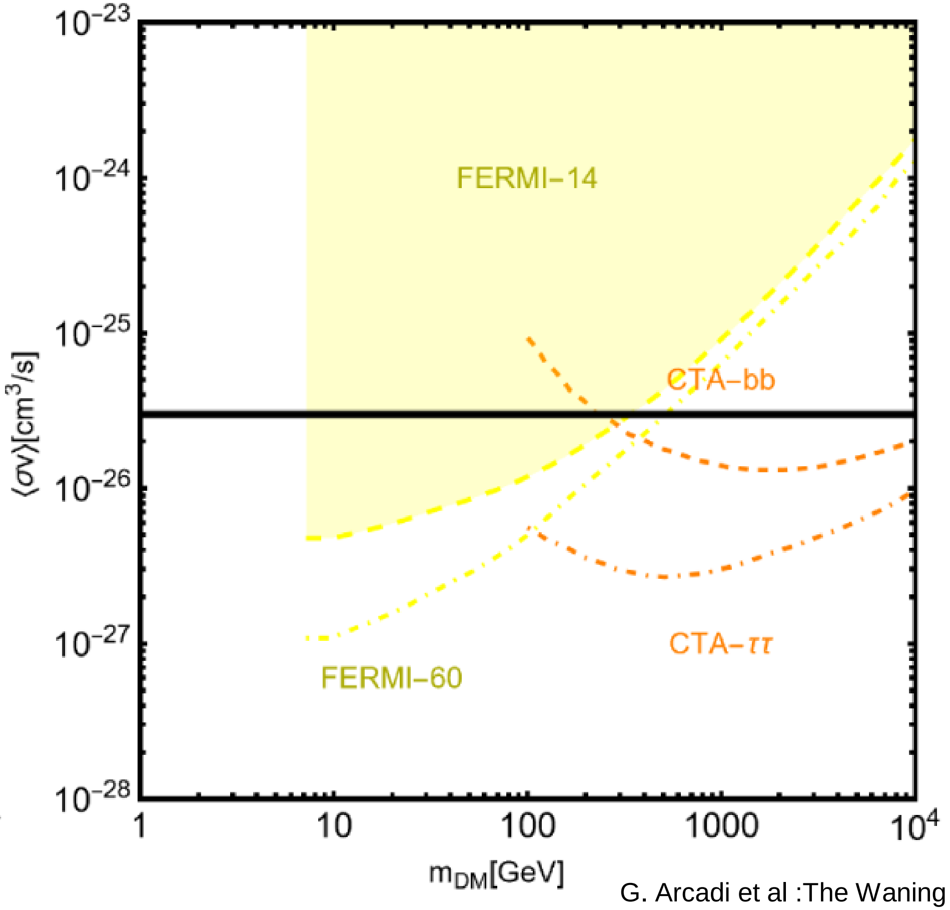
Yann Mambrini Particles in the dark universe

Thermal equilibrium erase memory !

A small problem of measurements

Direct detection





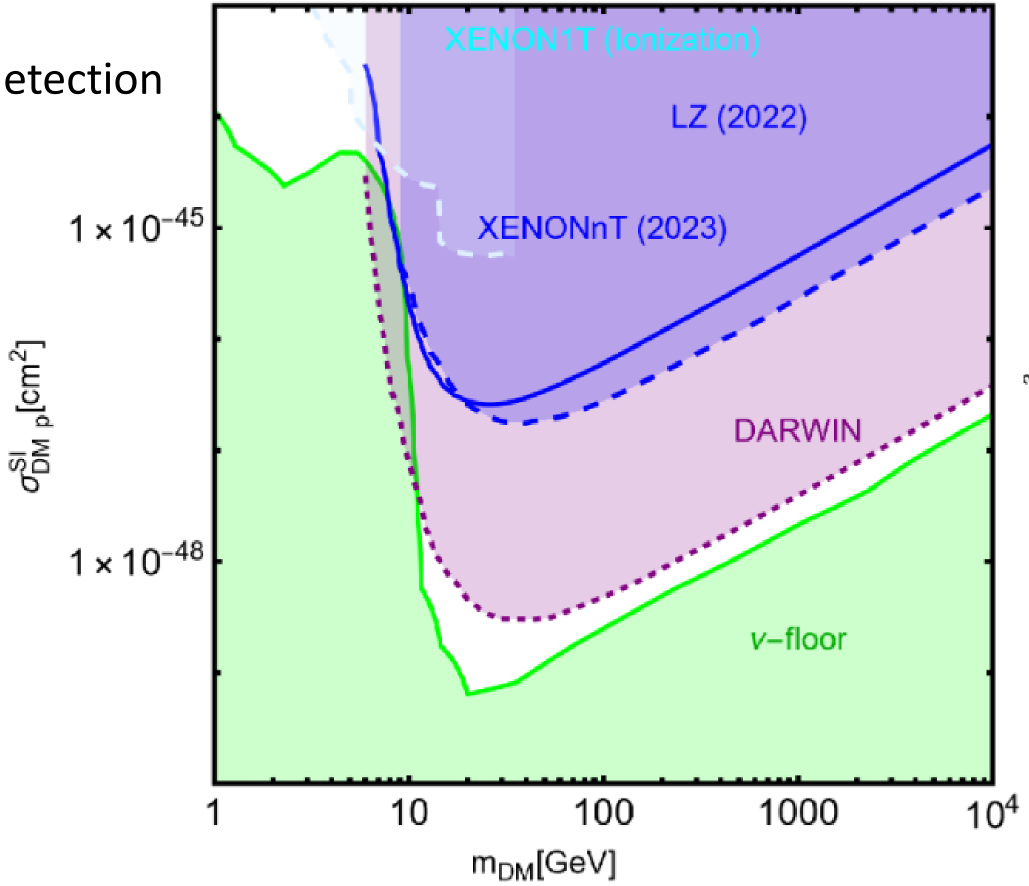
indirect detection

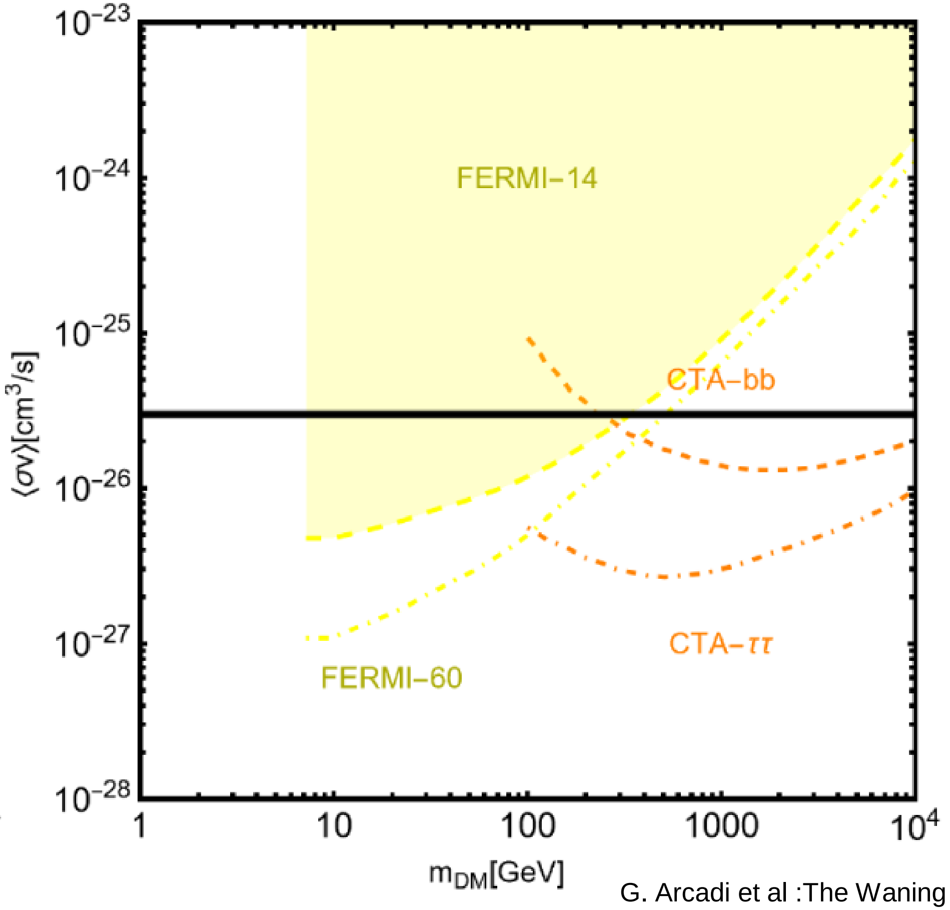
G. Arcadi et al :The Waning of the WIMP: Endgame?

We need to look for caveats if we want to keep thermal equilibrium!

A small problem of measurements

Direct detection





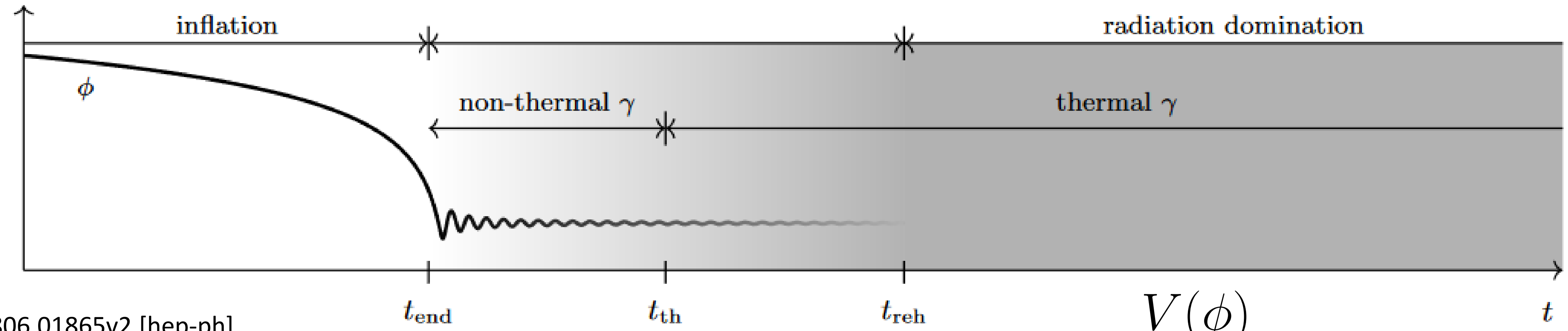
indirect detection

G. Arcadi et al :The Waning of the WIMP: Endgame?

We need to look for caveats if we want to keep thermal equilibrium!

- Higher masses?
- Non standard cosmological evolution?
- …

Reheating after inflation

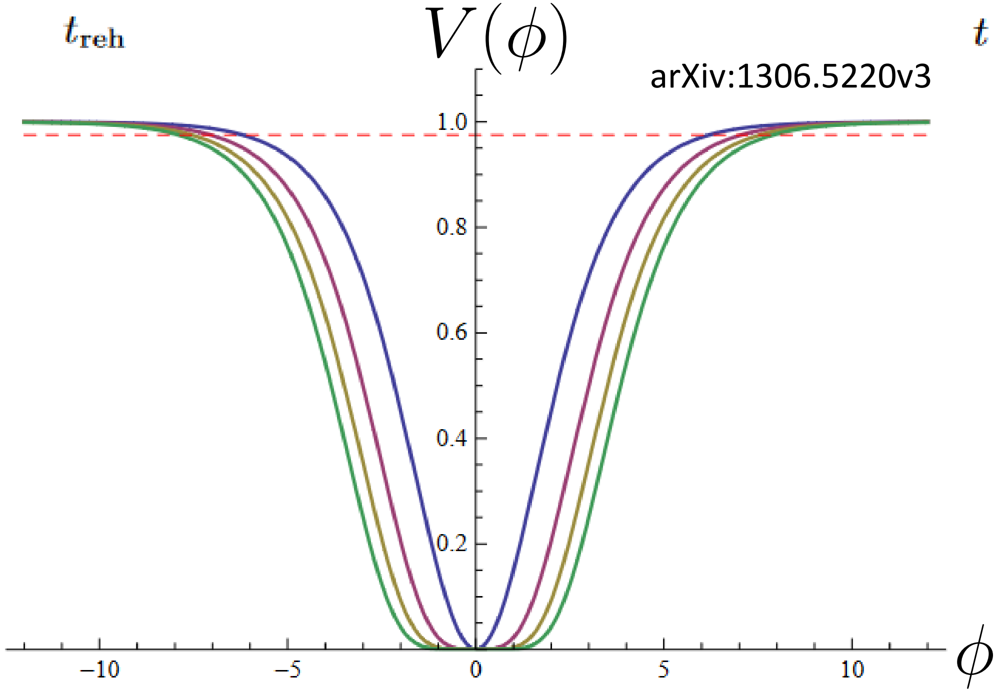


arXiv:1806.01865v2 [hep-ph]

$$S = \int d^4x \sqrt{-g} \left(\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right)$$

$$V(\phi) = \lambda M_P^4 \left[\sqrt{6} \tanh \left(\frac{\phi}{\sqrt{6} M_P} \right) \right]^k$$

$$\Rightarrow w_\phi = \frac{k-2}{k+2}$$



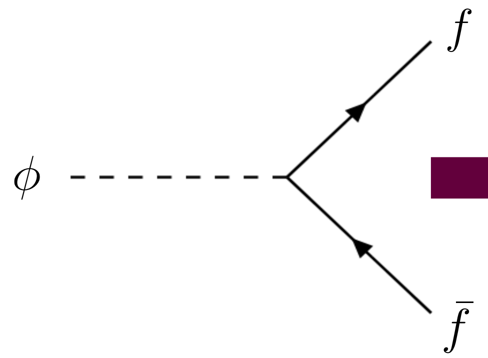
arXiv:1306.5220v3

Reheating after inflation

We use the boltzmann equations :

$$\dot{\rho}_\phi + 3H(1 + w_\phi)\rho_\phi = -(1 + w_\phi)\Gamma_\phi \rho_\phi$$
$$\dot{\rho}_{\mathrm{R}} + 4H\rho_{\mathrm{R}} = (1 + w_\phi)\Gamma_\phi \rho_\phi$$

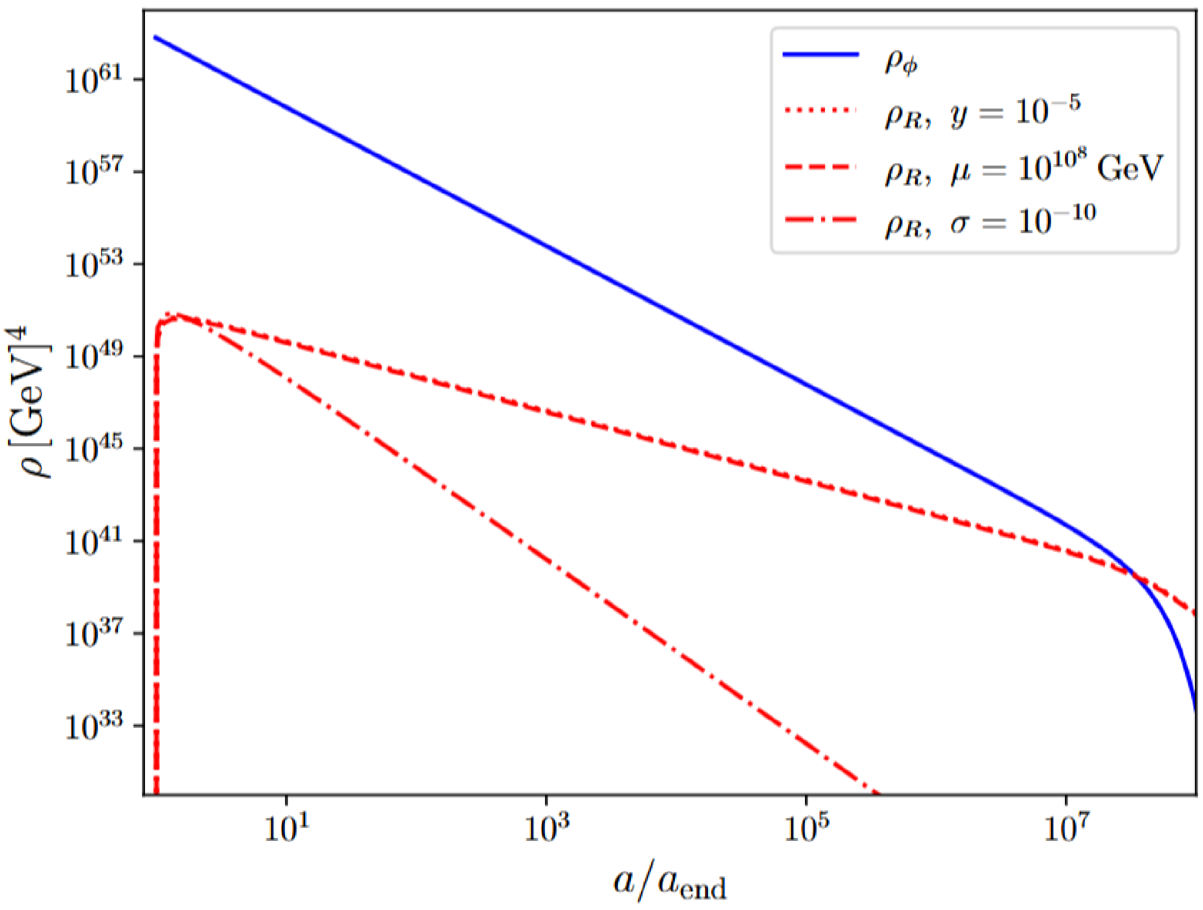
During this talk we will assume :



$$\mathcal{L}_{int} \sim y\phi f \bar{f}$$

$$T \sim a^{-\frac{3k-3}{2k+4}}$$

$k = 2$



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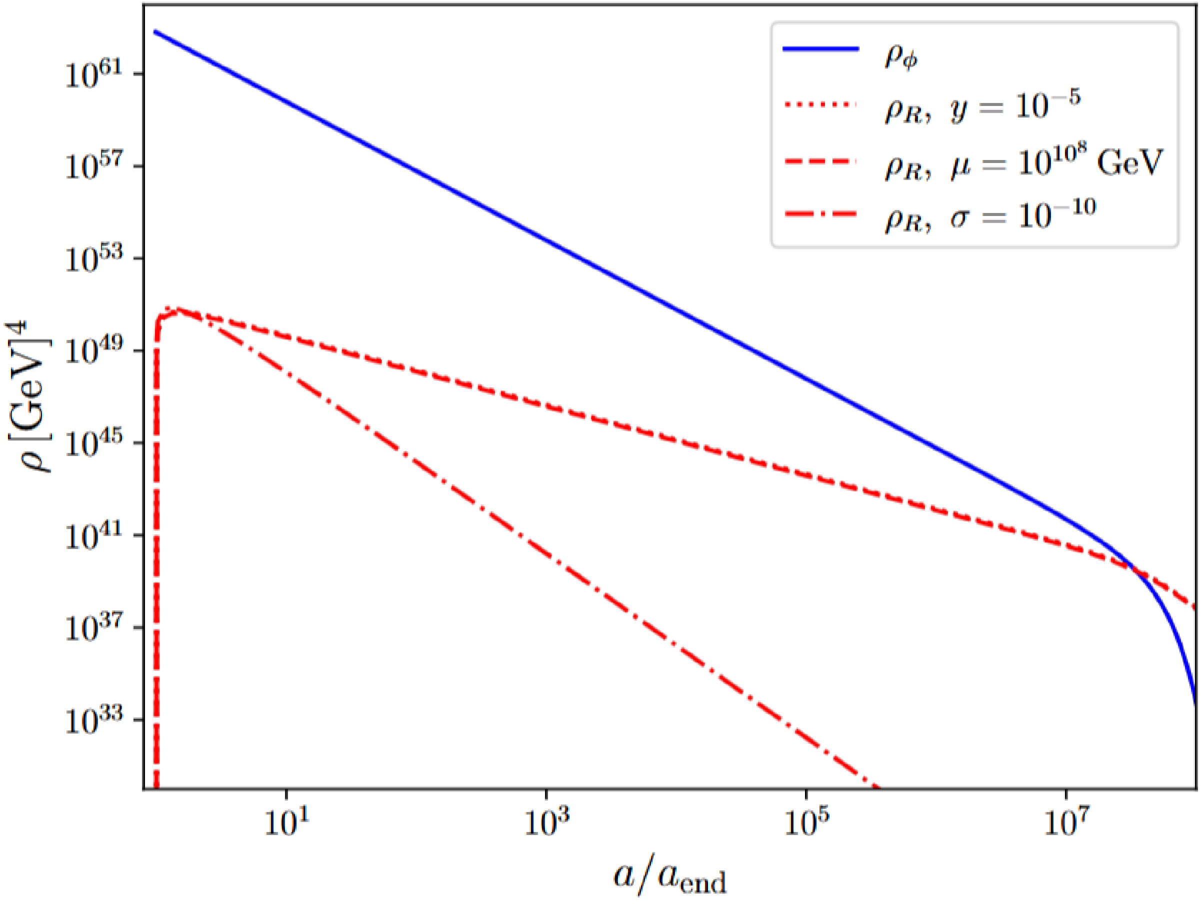
$$\Gamma_{\phi\to f\bar{f}} = \frac{y_{eff}^2}{8\pi} m_\phi$$

$$\rho_\phi \propto \left(\frac{a_\mathrm{end}}{a}\right)^{-3(1+w_\phi)}$$

$$\rho_\mathrm{R} = \frac{1+w_\phi}{a^4}\int dln(a)\frac{\Gamma_\phi\rho_\phi a^4}{H}$$



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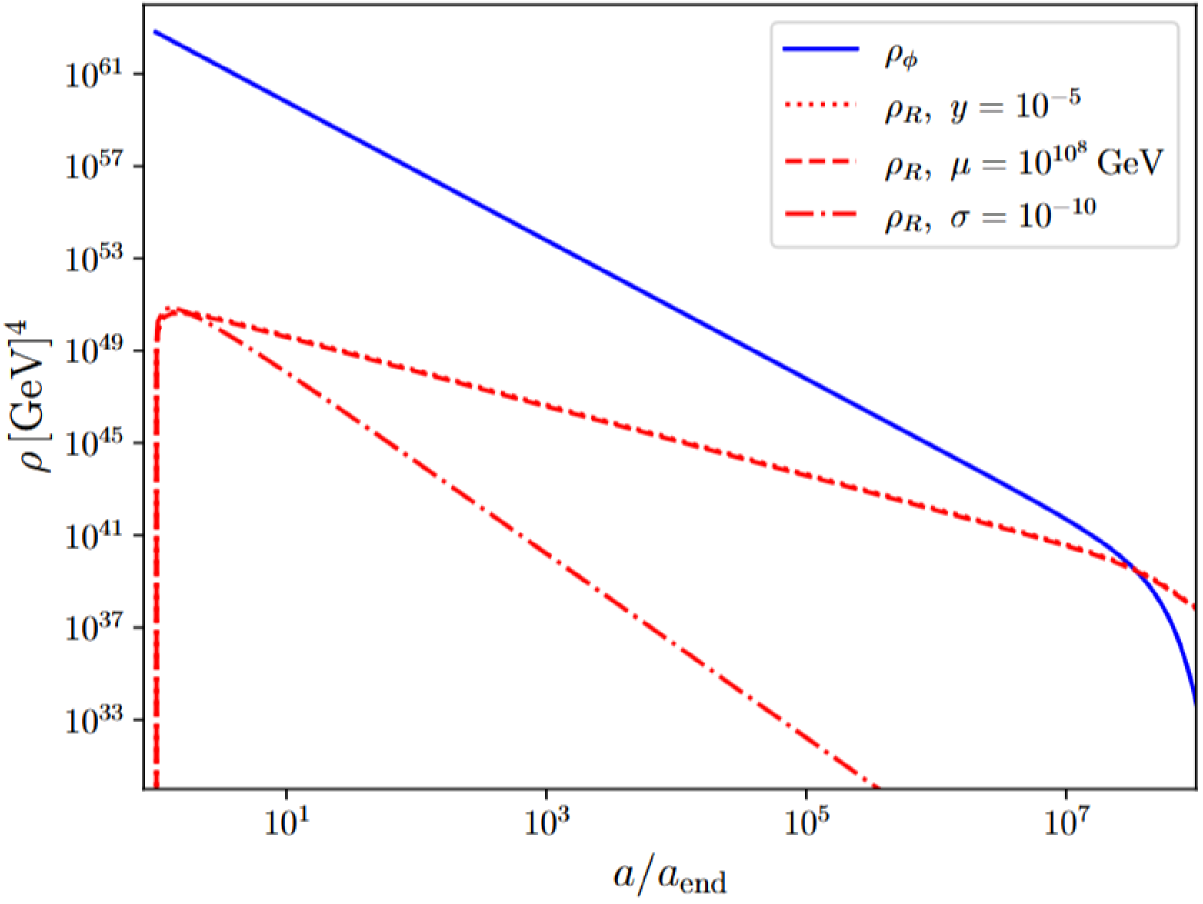
Entropy injection dilutes dark matter!



Non-relativistic freeze-out during reheating

We will assume: $\langle \sigma v \rangle \sim \frac{T^n}{\Lambda^{n+2}}$

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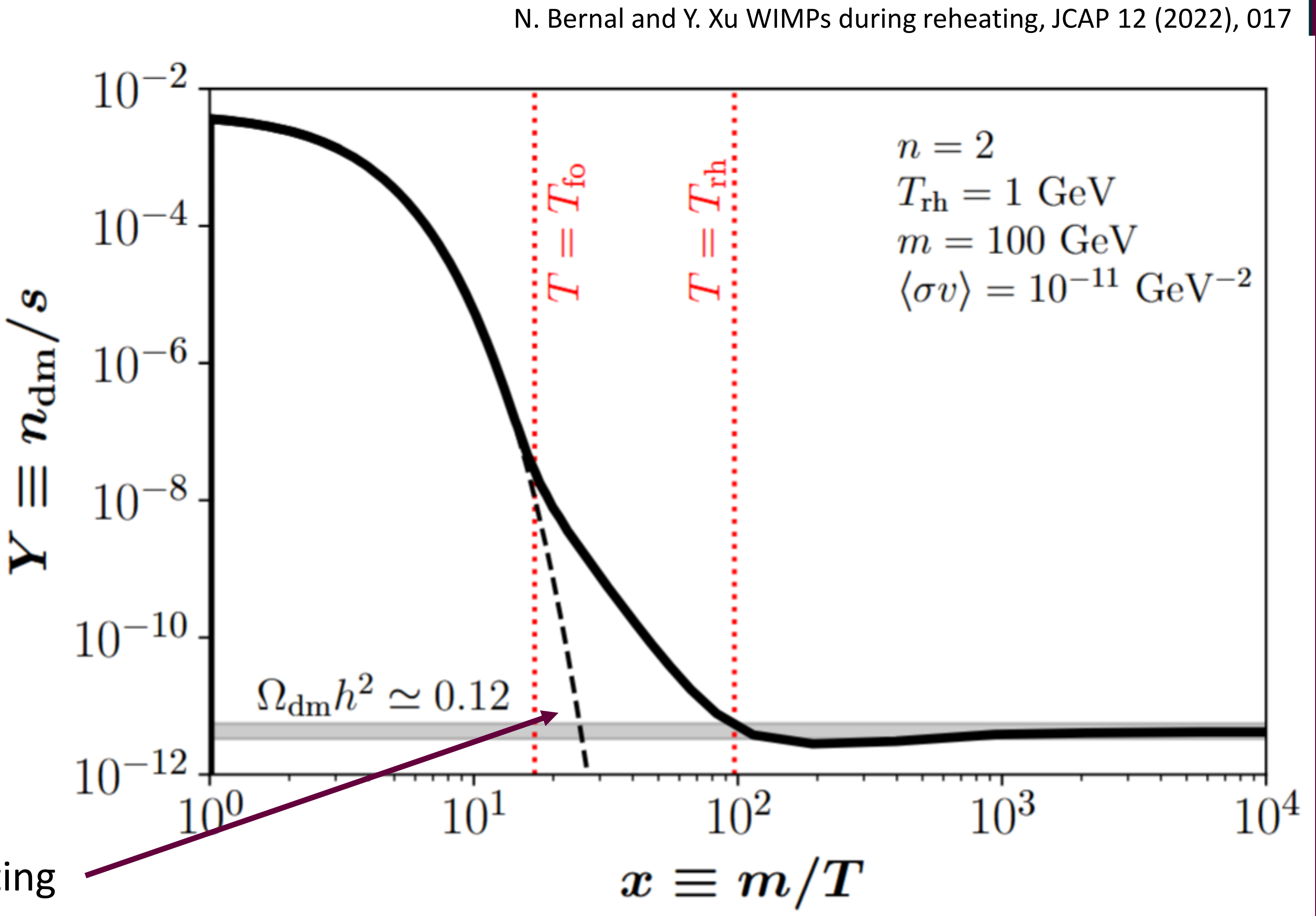

Extra dilution due to entropy injection during reheating

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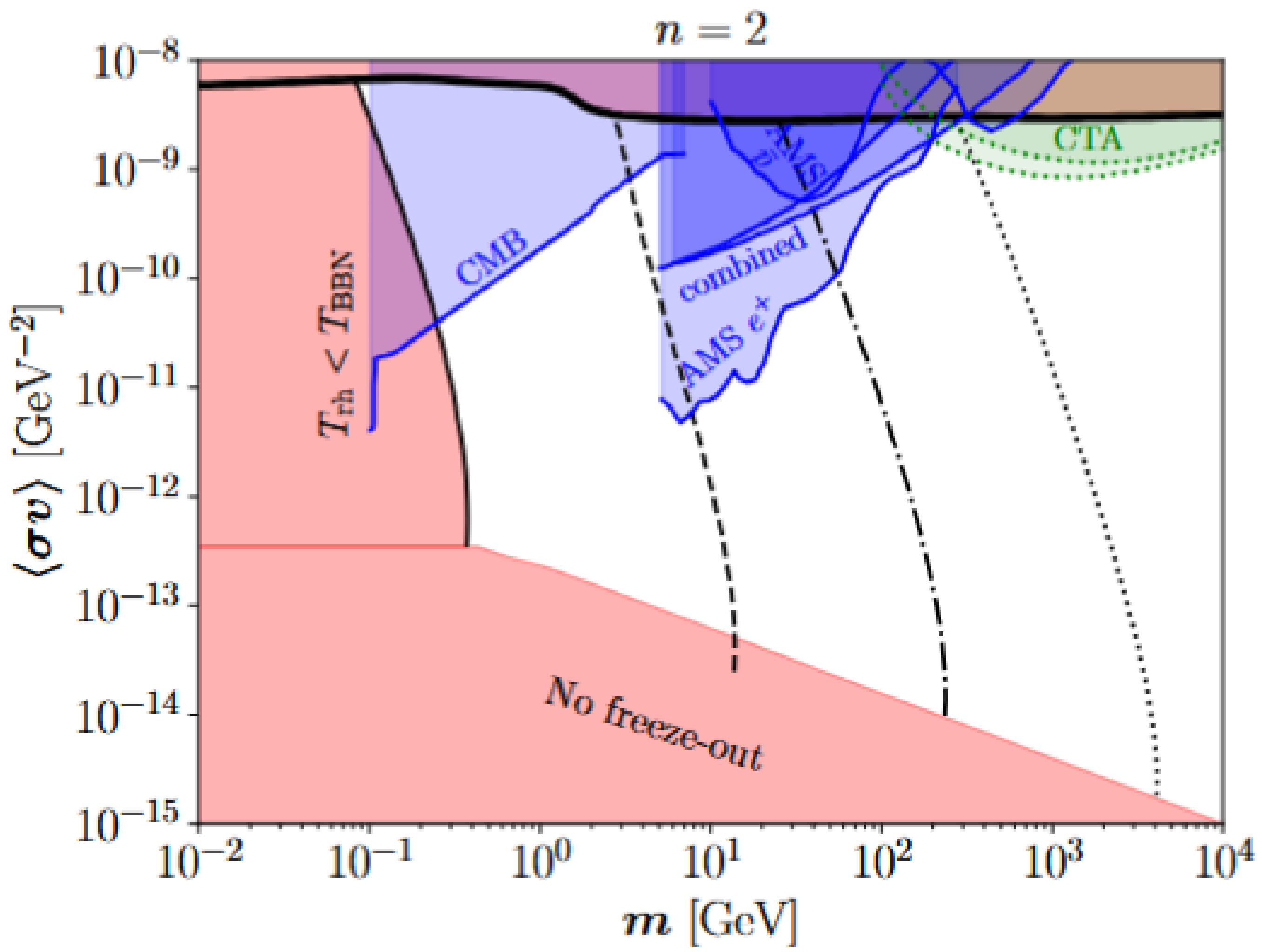
N. Bernal and Y. Xu WIMPs during reheating, JCAP 12 (2022), 017



Relativistic freeze-out during reheating

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$$\Rightarrow T_{fo} = \Lambda \left(\frac{\Lambda}{M_P} \frac{2\pi^2}{g\zeta(3)} \sqrt{\frac{\alpha}{3}} \right)^{\frac{1}{n+1}}$$

$$\frac{\Omega_\chi h^2}{0.12} \simeq g \left(\frac{106.75}{g_{fo}} \right) \left(\frac{m_\chi}{170\,\mathrm{eV}} \right)$$

Overproduce dark matter if $m_\chi \gtrsim O(10^2)\,\mathrm{eV}$

Reheating can save the day!

Relativistic freeze-out during reheating

$$\Gamma(t_{fo}) = n_{eq}\langle\sigma v\rangle \sim H(t_{fo})$$

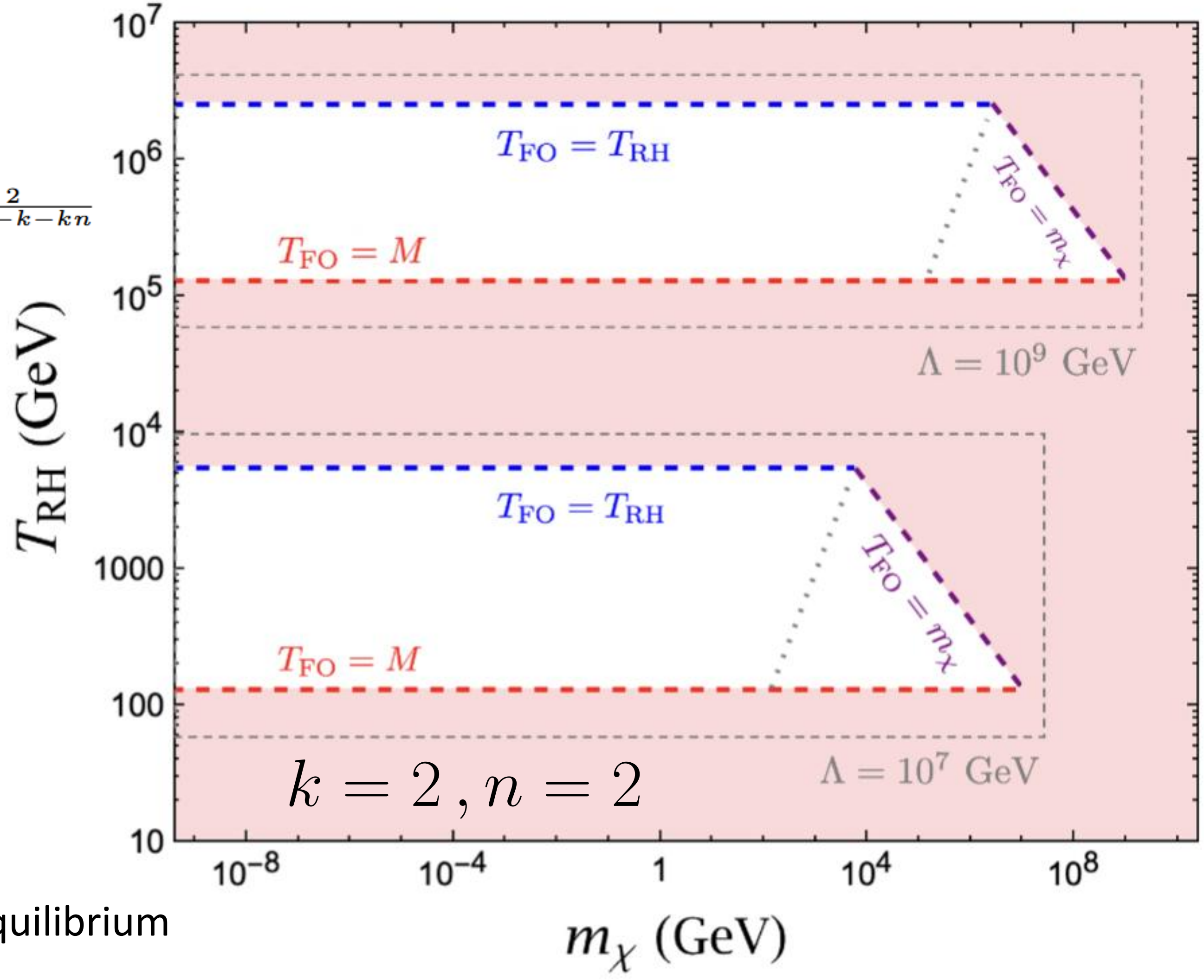
$$T_{\rm FO}^{k<7} = \left(\frac{3k}{k+2}\frac{\pi^2}{g_\chi\zeta(3)}\sqrt{\frac{\alpha}{3}}\frac{\Lambda^{n+2}}{M_P}\right)^{\frac{k-1}{k+nk-n-3}} T_{\rm RH}^{\frac{2}{n+3-k-kn}}$$

UFO has 3 requirement:

$T_{fo} > T_{RH}$ Happens during reheating

$T_{fo} > m_\chi$ Relativistic

$T_{fo} < M \sim \Lambda$ Can enter then exit thermal quilibrium



Relativistic freeze-out during reheating

The boltzmann equations gives: $\Gamma \sim T^{n+3} \quad H \sim T^{\frac{2k}{k-1}}$

$$\frac{dY_\chi}{da} \propto a^{\frac{3n+26-8k-3kn}{2k+4}}$$

⇒ Freeze-in period after decoupling depending on how fast is the transition

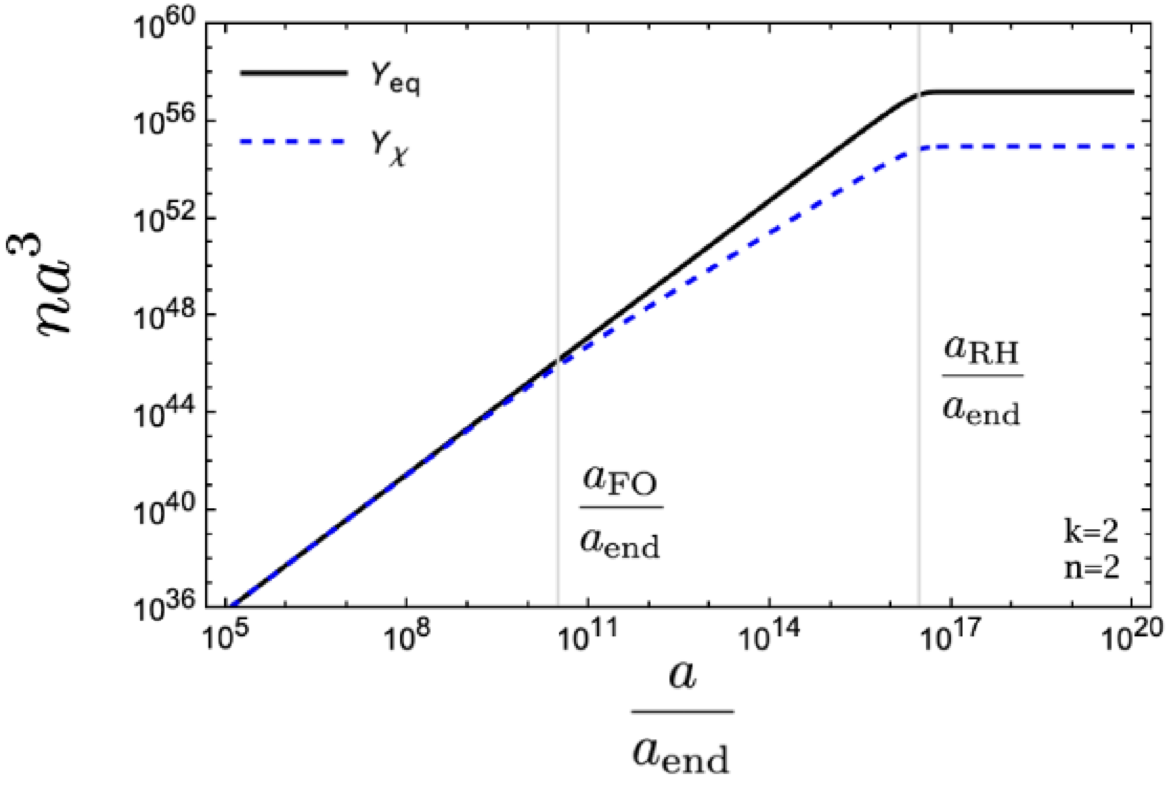
$$Y_\chi(a) = Y_{\rm FO} + \frac{g_\chi^2\,\zeta(3)^2}{\pi^4}\sqrt{\frac{3}{\alpha}}\frac{T_{\rm RH}^{n+4}M_P}{\Lambda^{n+2}}a_{\rm RH}^{\frac{(3k-3)(n+6)-6k}{2k+4}}\left(\frac{2k+4}{3n-3nk-6k+30}\right)\times\left[a^{\frac{(3-3k)(n+6)+12k+12}{2k+4}} - a_{\rm FO}^{\frac{(3-3k)(n+6)+12k+12}{2k+4}}\right]$$

$$\Rightarrow Y_\chi(a_{RH}) = Y_{FO} + Y_{UV} + Y_{IR}$$

Relativistic freeze-out during reheating $m_\chi < T_{RH}$

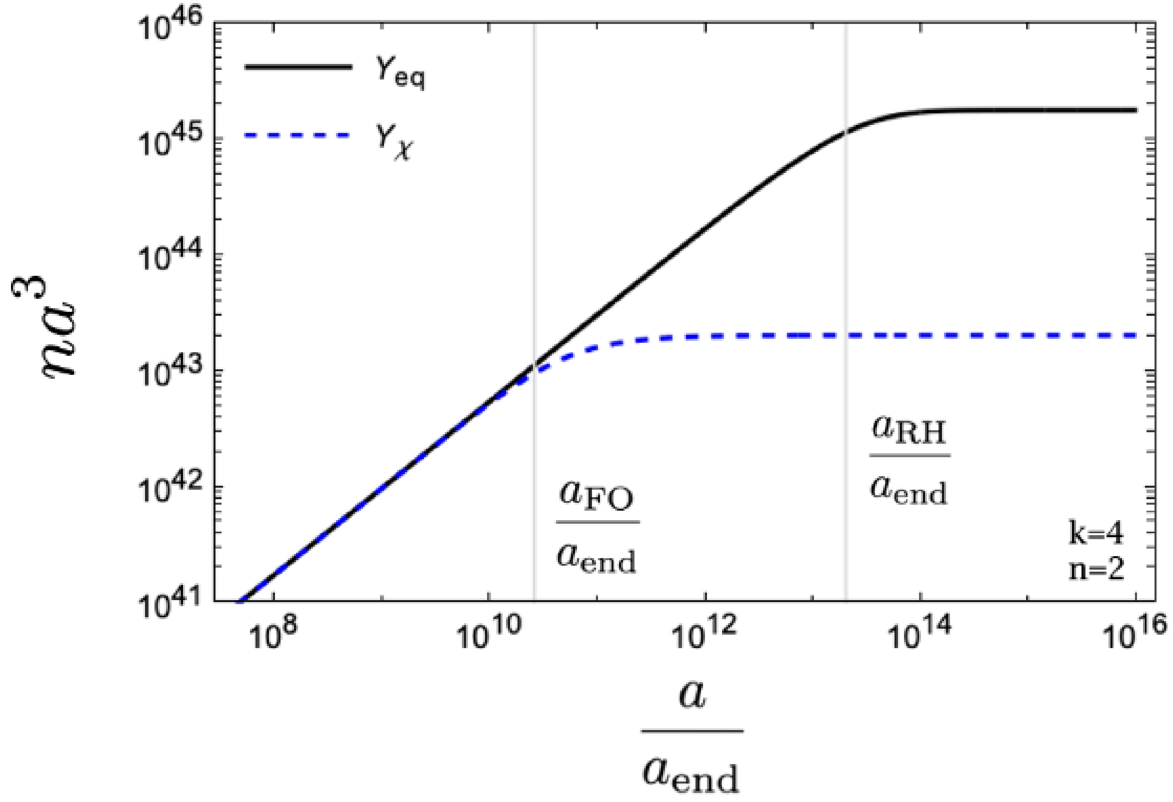
$$Y_\chi(a_{RH}) = Y_{FO} + Y_{UV} + Y_{IR}$$

IR dominated UFO



$$Y_\chi(a_{RH}) \approx 3Y_{fo}$$

UV dominated UFO



Relativistic freeze-out during reheating

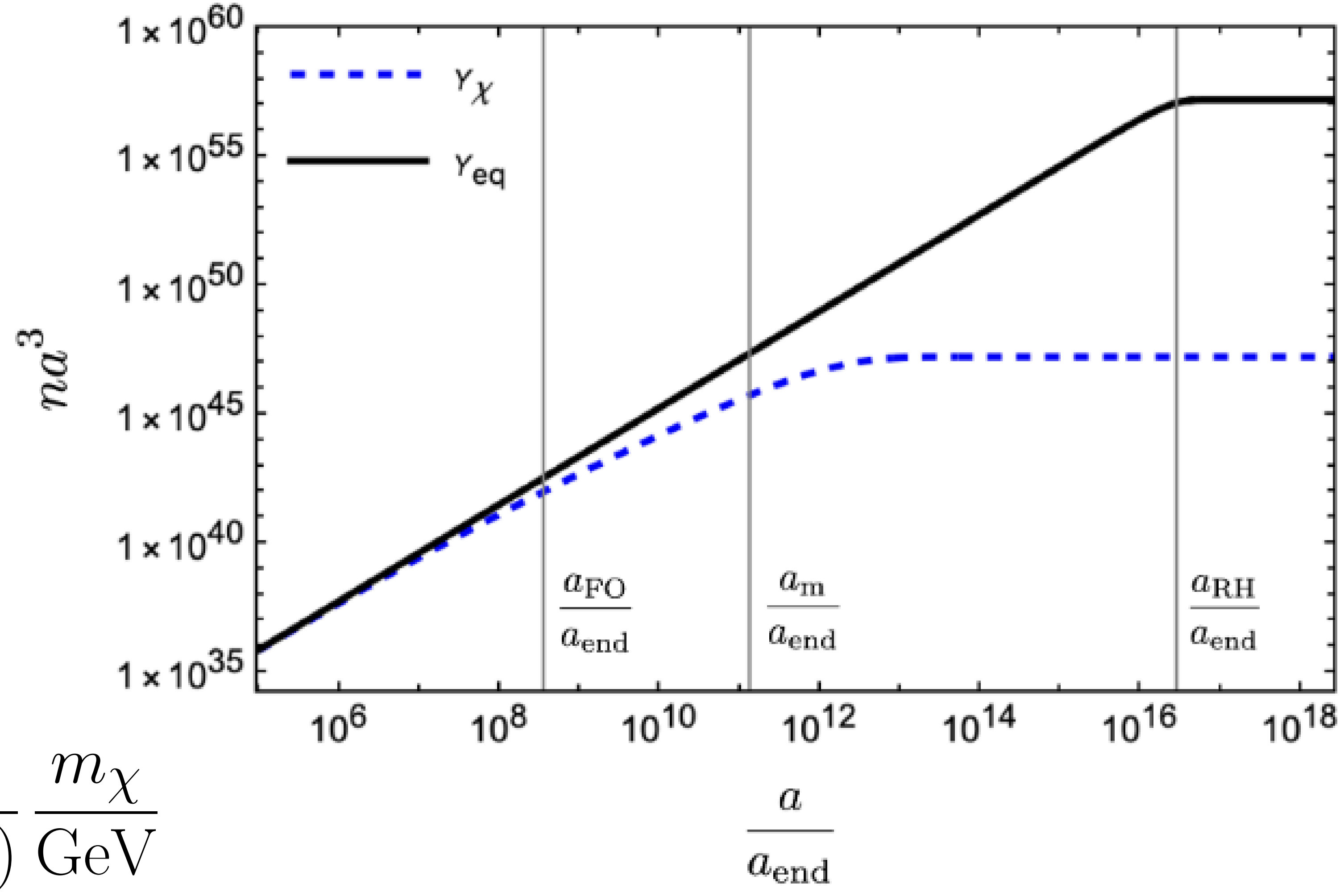
$m_\chi > T_{RH}$

$$\frac{dY_\chi}{da} \propto a^{\frac{3n+26-8k-3kn}{2k+4}}$$

$$\Gamma \sim T^{n+3}$$

$$H \sim T^{\frac{2k}{k-1}}$$

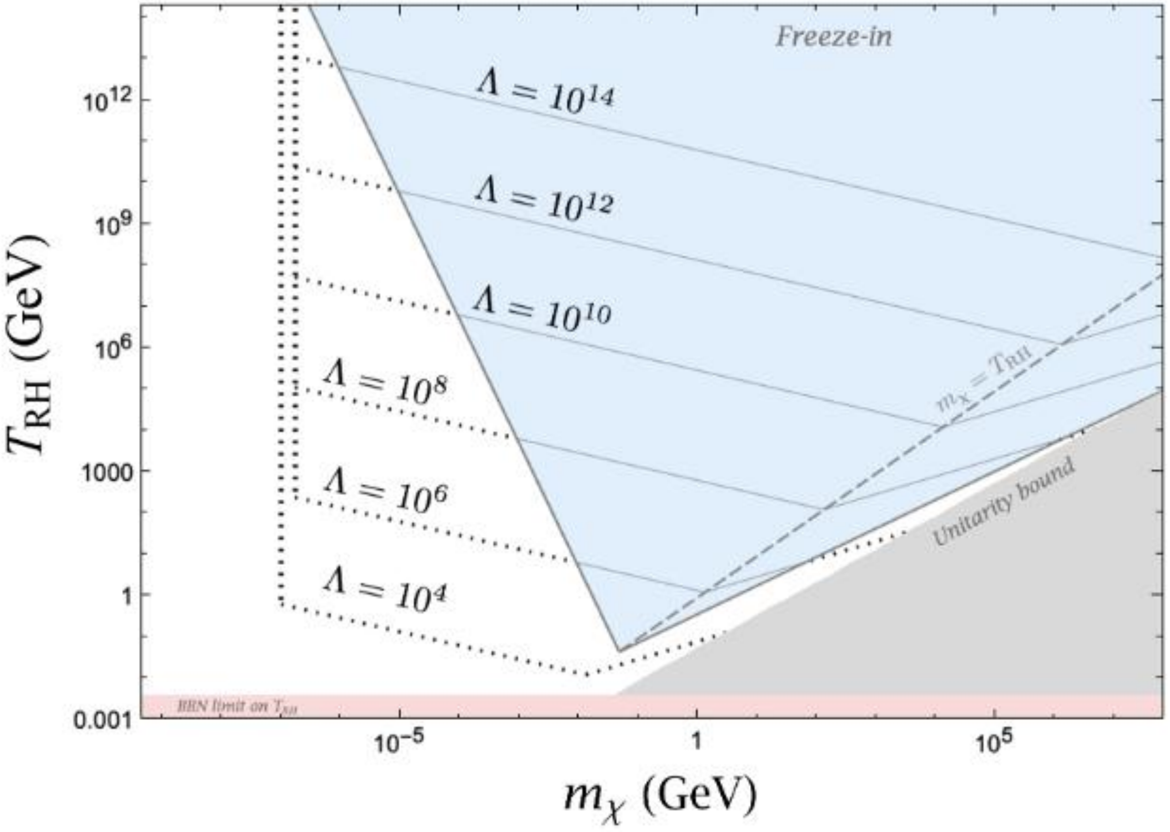
Freeze-in stop when $T \sim m_\chi$



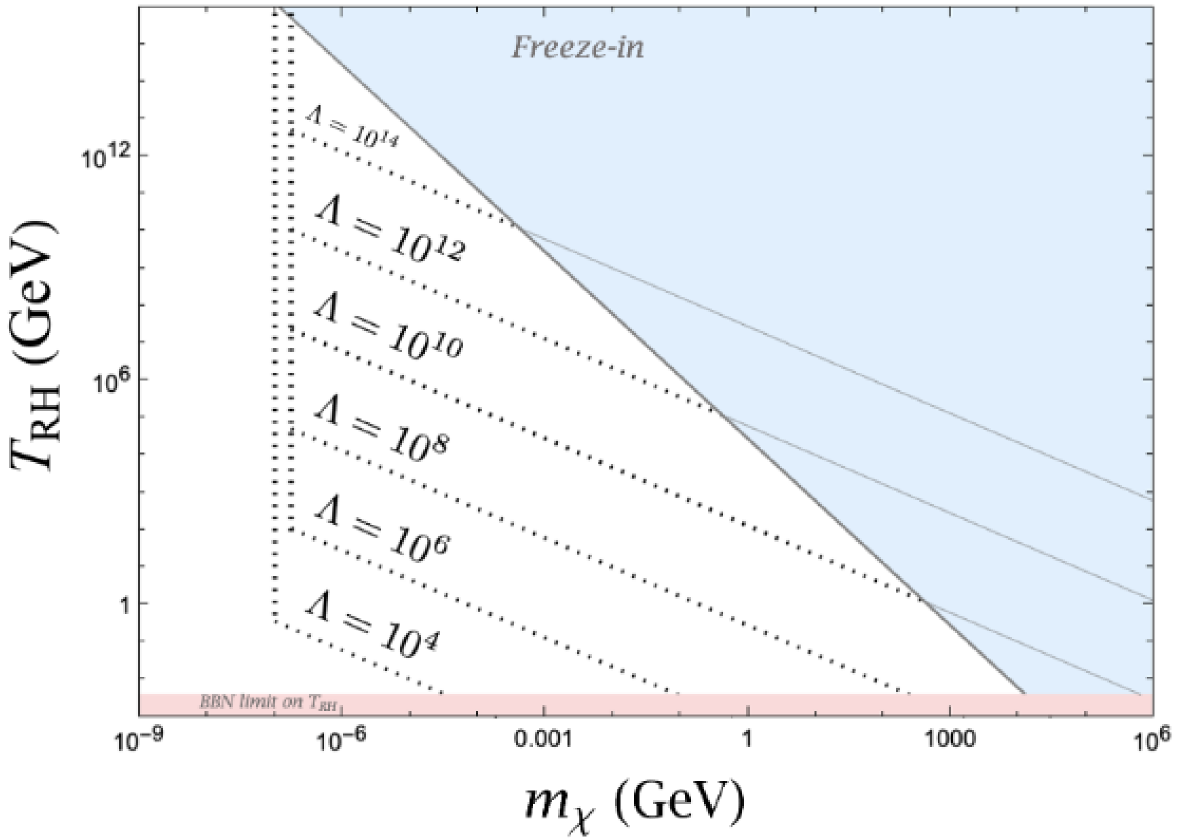
$$\frac{\Omega_\chi h^2}{0.12} = 6.0 \times 10^6 \, \frac{Y_{\rm RH}}{Y_{\rm eq}(a_{\rm RH})} \, \frac{m_\chi}{\rm GeV}$$

Producing the right relic abundance

$$k = 2\,, n = 2$$
$$V \sim \phi^2,\ \langle \sigma v \rangle \sim T^2$$



$$k = 4\,, n = 2$$
$$V \sim \phi^4,\ \langle \sigma v \rangle \sim T^2$$



A comment about cosmological constraints

Dark matter need to be compatible with relativistic degrees of freedom at CMB time: $\Delta N_{eff} < 0.18$

One can compute the DM temperature at BBN: $T'_{BBN} = T_{BBN} \left(\frac{T_{RH}}{T_{fo}}\right)^{\frac{7-k}{3k-3}} \left(\frac{g_{BBN}}{g_{RH}}\right)^{\frac{1}{3}} \left(\frac{g_{RH}}{g_{fo}}\right)^{\frac{k+2}{6k-6}}$

$\Rightarrow$ $T_{RH} \leq 1.3 T_{fo}$ Always satisfied!

DM need to be cold at the time of structure formation: $m_\chi > 5\text{keV} \left(\frac{T_{RH}}{T_{fo}}\right)^{\frac{7-k}{3k-3}}$

Conclusion

- Relativistic freeze-out can be done during reheating.
- It offers a compeling alternative in between the usual WIMP and FIMP paradigm.
- Drawback: Small reheating temperature for higher masses.

Thank you!