February 7th 2024

Workshop on Particle Production and Thermal effects in Inflation

Virtual @ King's College London

Dark Matter production from Warm Inflation via Freeze-In

Gabriele Montefalcone

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Based on work with Katherine Freese & Barmak Shams Es Haghi (arXiv:2401.17371)

KING'S College LONDON

TEXAS The University of Texas at Austin

Outline of the Talk

- **Dark Matter:**

  What we know about it

  Production mechanisms from a thermal bath (Freeze-out & Freeze-in)

- **Warm Inflation:**

  What it is and the basics of how it works

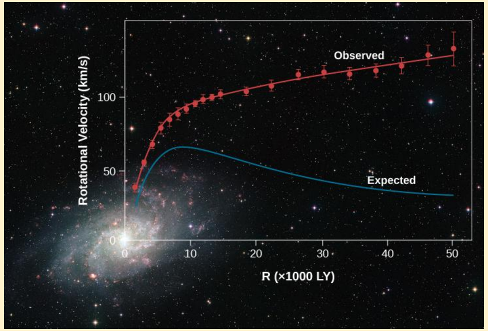
- **WIFI Framework:**

  General features and a representative example

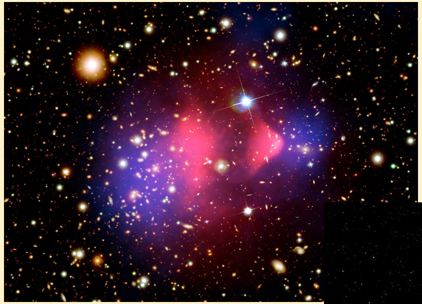
Evidence for Dark Matter (DM)

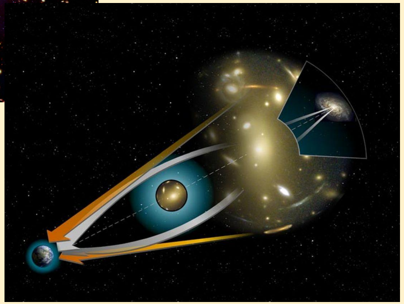
Huge amount of evidence from all scales
(only from gravitational interaction)

Galactic scales

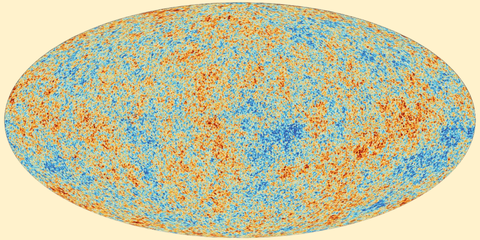


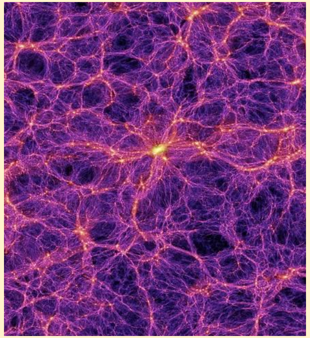
Cluster scales





Cosmological scales





What we know about DM

- Cold and Massive
- Stable/long lived
- No/weak interactions with the SM
- No/weak SM charge (electric and color)
- Abundance: DM corresponds to **%25** of the energy budget in the universe today (**~5x** the amount of ordinary matter)

What we know about DM

- Cold and Massive
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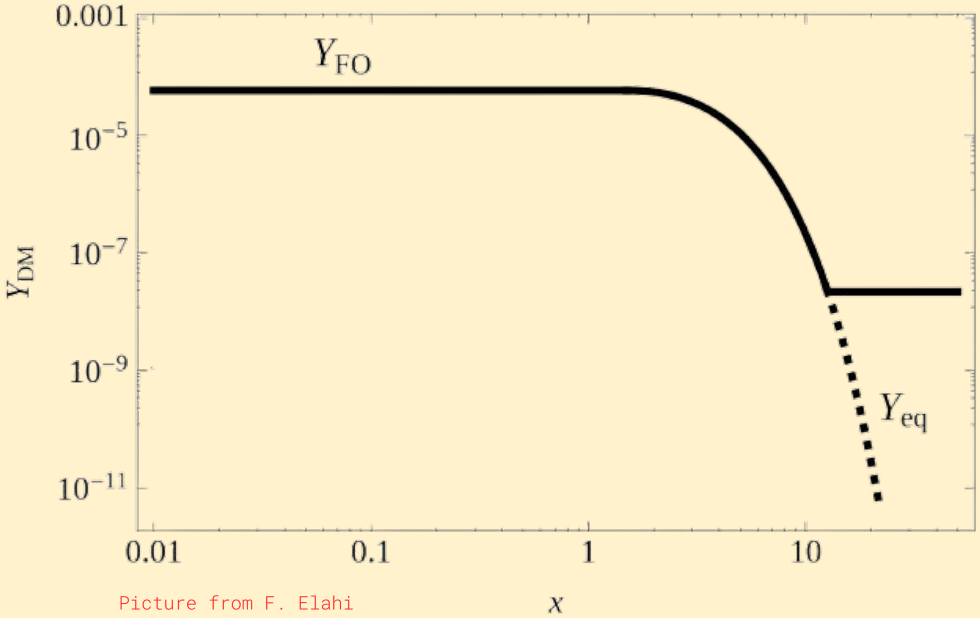
- Abundance: DM corresponds to **%25** of the energy budget in the universe today (**~5x** the amount of ordinary matter)

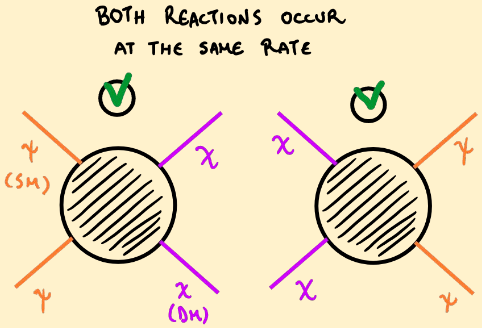
How was DM produced in the early universe?

The Canonical Freeze-out story

- DM is in thermal equilibrium with SM when $T \gg m_{DM}$
- DM freezes out at $T \,\square\, m_{DM}/20$



Picture from F. Elahi



$$Y_{\rm DM} \equiv \frac{n_{\rm DM}}{s}$$

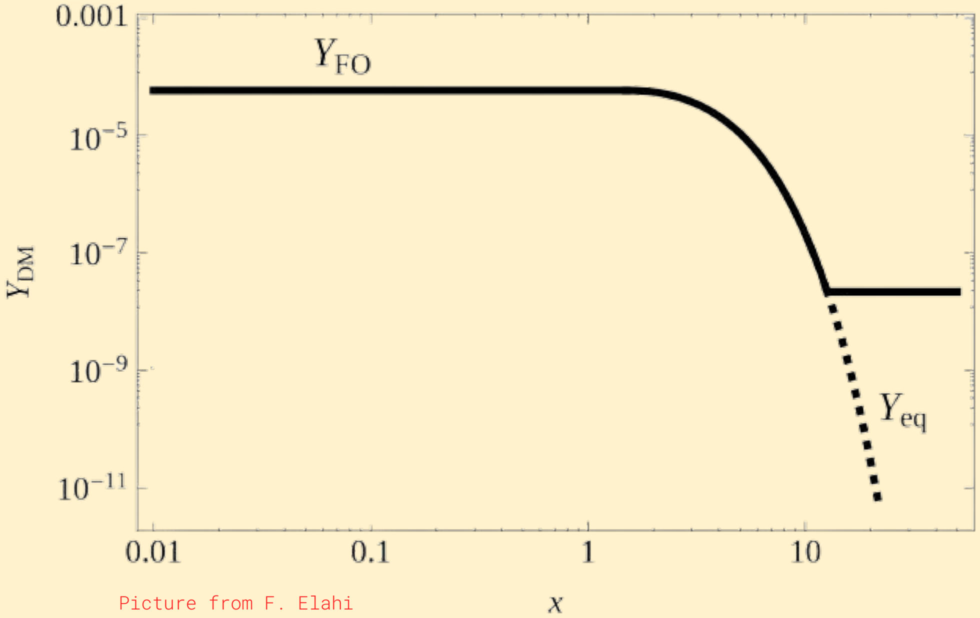
$$x \equiv \frac{m_{\rm DM}}{T}$$

The Canonical Freeze-out story

- **The WIMP miracle**

  $m_{DM} \sim m_W$ and $\sigma_{DM} \sim \alpha_W^2/m_W^2$ roughly reproduces the observed DM abundance

  ($\alpha_W \sim 10^{-2}$ $m_W \sim 100$ GeV)



Picture from F. Elahi

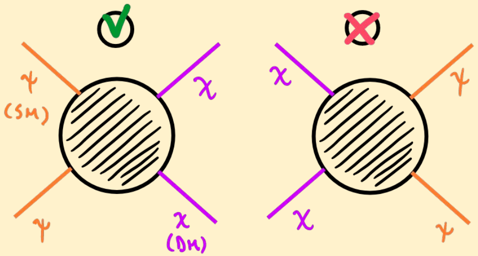
$$Y_{DM} \equiv \frac{n_{DM}}{s}$$

$$x \equiv \frac{m_{DM}}{T}$$

An alternative Scenario: Freeze-in

L. J. Hall, K. Jedamzik, J. March-Russell, & S. M. West, JHEP 03, 080 (2010)

- **Feeble** interaction between DM and the SM so that DM is never in thermal equilibrium with the SM bath
- Initial DM abundance is negligible (i.e. inflaton reheats primarily the SM)
- The DM abundance is built up gradually (no inverse process!)



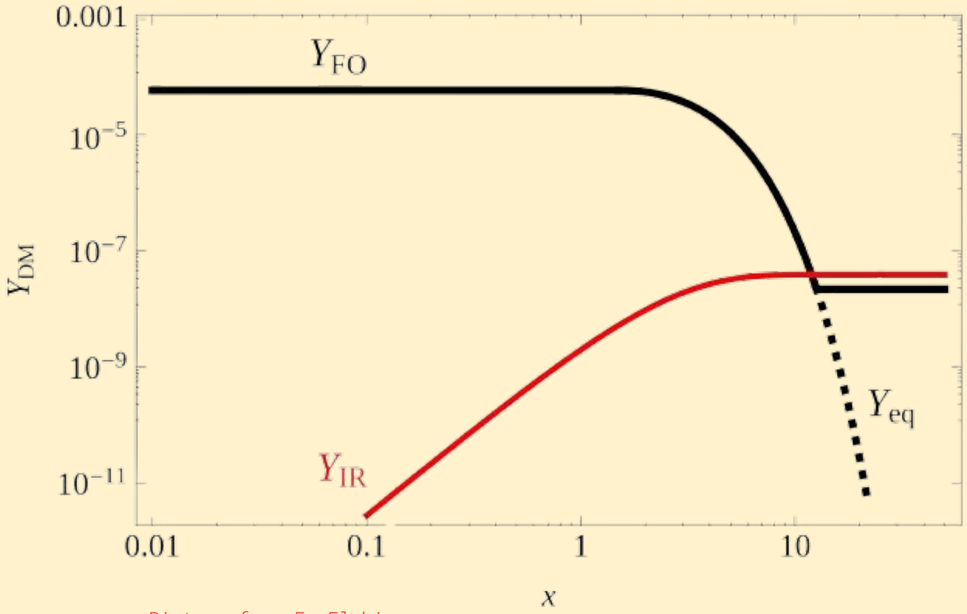
The evolution of the DM abundance is sensitive to the nature of the suppressed interaction between DM and SM

IR Freeze-in

Interaction through Renormalizable operator

L. J. Hall, K. Jedamzik, J. March-Russell, & S. M. West, JHEP 03, 080 (2010)

- DM couples to SM through a renormalizable interaction with a very small coupling constant (**$\lambda_{DM\text{-}SM}$~10^{-11}**)



Picture from F. Elahi

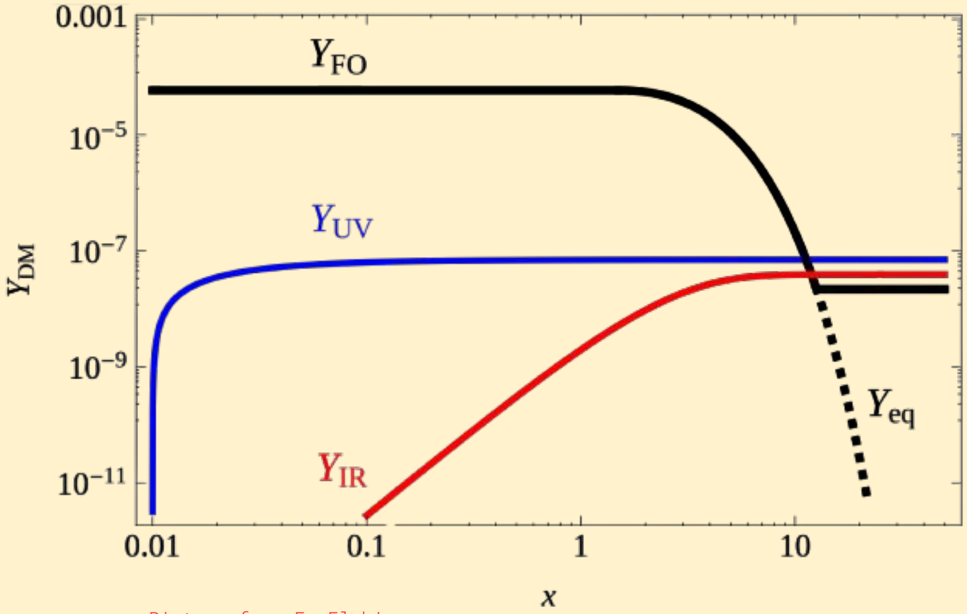
DM abundance is set by lowest T, i.e. **T□m_{DM}**

UV Freeze-in

F. Elahi, C. Kolda, and J. Unwin, JHEP 03, 048 (2015)

Interaction through Non-Renormalizable operator

- DM couples to SM through a non-renormalizable interaction with a heavy mass scale **Λ**



Picture from F. Elahi

DM abundance is set by highest temperature, i.e. T_{rh}

UV Freeze-in

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Interaction through Non-Renormalizable operator

$$\mathcal{L} \supset \mathcal{O}_{n+4}/\Lambda^n$$

$$\dot{n}_\chi + 3Hn_\chi = T^{2n+4}/\Lambda^{2n}$$

$$Y_\chi \equiv \frac{n_\chi}{\underbrace{s}_{\text{Bath entropy density}}}$$

$s = (2\pi^2/45)g_{\star,S}(T)T^3$

- Assumptions:
  - Instantaneous Reheating (rh) to radiation-dominated (RD) epoch
  - Vanishing initial DM abundance

$$\boxed{Y_{\chi,\infty}^{\mathrm{RD}} \simeq \frac{1}{\sqrt{2}}\left(\frac{45}{\pi^2 \underbrace{g_\star}_{\text{(the effective number of relativistic degrees of freedom)}}}\right)^{3/2} \frac{1}{2n-1}\frac{M_{\mathrm{Pl}}T_{\mathrm{rh}}^{2n-1}}{\Lambda^{2n}}.}$$

UV Freeze-in

F. Elahi, C. Kolda, and J. Unwin, JHEP 03, 048 (2015)

Interaction through Non-Renormalizable operator

$$\mathcal{L} \supset \mathcal{O}_{n+4}/\Lambda^n$$

- Natural small coupling for heavy mass scale **Λ**
- Wide range of **m_{DM}** reproduces observed DM abundance
  - Connection to UV physics via correlation between **m_{DM}**, **T_{rh}** and **Λ**

UV Freeze-in

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What if we go beyond the instantaneous reheating approximation in the context UV freeze-in?

UV Freeze-in
Beyond Instantaneous Reheating

- Careful consideration of reheating has shown that the DM yield can be enhanced compared to the case of instantaneous reheating
    - Matter-dominated Universe M.A.G. Garcia, Y. Mambrini, K.A. Olive,M. Peloso Phys.Rev.D 96,103510 S.-L. Chen, Z. Kang, JCAP 05, 036 (2018)
    - Non-standard cosmologies N. Bernal, F. Elahi, C. Maldonado, J. Unwin, JCAP 11, 026 (2019) B. Barman, N. Bernal, Y. Xu, O. Zapata, JCAP 07, 019 (2022)
- The enhancement becomes relevant for **$n \gtrsim 4$**

UV Freeze-in
Interaction through Non-Renormalizable operator

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- The enhancement becomes relevant for **$n \gtrsim 4$**

Can inflation play a role in the DM production via UV freeze-in?

Warm Inflation (WI)
The Basics (T>H)

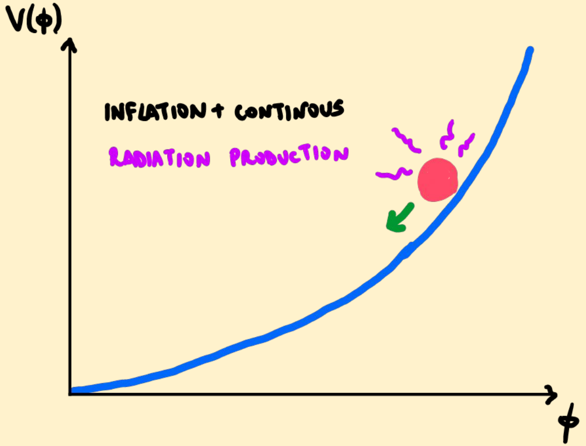
A. Berera, Phys. Rev. Lett. 75 (1995) 3218

$$\ddot{\phi} + (3H + \overbrace{\Upsilon}^{\text{(Dissipation Rate)}})\dot{\phi} + V_\phi = 0, \qquad \dot{\rho}_r + 4H\rho_r = \Upsilon\dot{\phi}^2,$$

$$H^2 = (\rho_\phi + \rho_r) / \left(3M_{\rm pl}^2\right),$$

inflaton energy density: $\rho_\phi = V(\phi) + \dot{\phi}^2/2$

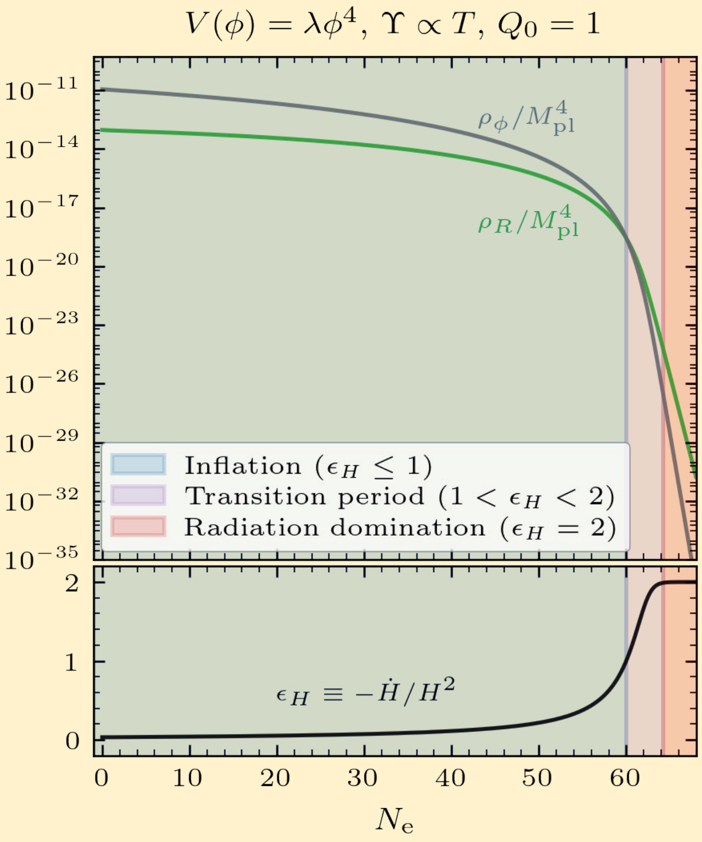
radiation energy density: $\rho_r = (\pi^2/30)g_\star(T)T^4$



- **V(ϕ)** dominates the energy density of the universe
- Via dissipative interactions, inflaton continually sources the production of radiation.
  - We cannot neglect **ϒ**!
  - **Q=ϒ/(3H)** defines the strength of the dissipation

Warm Inflation (WI)
Main features

- Allows smooth transition to the RD phase
- Can avoid **$\Delta\phi > M_{pl}$** due to thermal friction.
- Distinct observables due to thermal nature of perturbations
  - Tensor-to-scalar ratio **r** generically suppressed



Example motivated by Warm Little Inflaton

Warm Inflation (WI)
Main features

- Allows smooth transition to the RD phase
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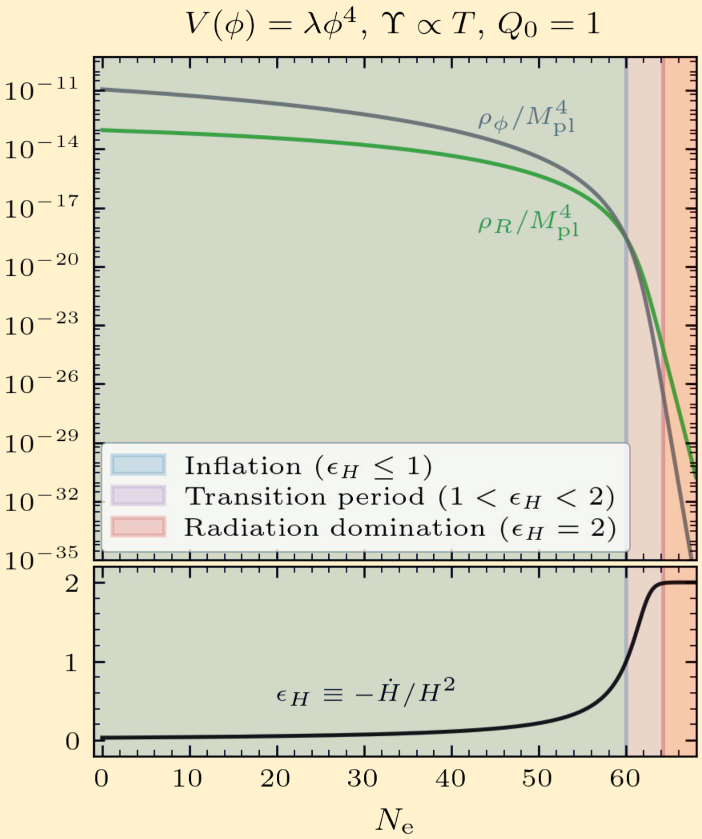
Recent development of minimal set-ups for a concrete particle physics realization of WI

- Warm Little Inflaton — M. Bastero-Gil, A. Berera, R. O. Ramos, & J. G. Rosa, Phys. Rev. Lett. 117, 151301 (2016), Phys.Lett.B 813 (2021) 136055
- Minimal Warm Inflation — Kim V. Berghaus, Peter W. Graham, David E. Kaplan, JCAP 03 (2020) 034



Example motivated by Warm Little Inflaton

DM production during WI via UV Freeze-In

The WIFI framework

Can the persistent thermal bath, sustained by dissipative interactions with the inflaton, source a sizable DM abundance via the non-renormalizable interaction characteristic of UV-freeze in?

DM production during WI via UV Freeze-In
The WIFI framework

- Vanishing DM abundance deep into the inflationary phase
- No interaction between DM and the inflaton field
- Canonical assumptions of UV freeze in:
  - DM never reaches thermal eq. with the bath
  - $\Lambda > T$ (EFT requirement)
  - $m_{DM} < T$ (to avoid additional Boltzmann suppression)
- The suppressed interaction between the DM and the bath makes DM a harmless addition to the WI framework.

DM production during WI via UV Freeze-In

The WIFI framework

$$\dot{n}_\chi + 3Hn_\chi = T^{2n+4}/\Lambda^{2n} \longrightarrow \underbrace{Y_\chi(N_e)}_{\substack{\text{Number of e-folds} \\ dN_e = Hdt}} = \frac{45}{2\pi^2 g_\star} \frac{e^{-3N_e}}{T^3(N_e)} \int_{\underbrace{N_{e,0}}_{Y_\chi(N_{e,0})=0}}^{N_e} \mathcal{I}_\chi(N_e') dN_e',$$

- DM production mostly occurs at the peak of $\mathcal{I}_\chi$ which represents the rate of change of the comoving DM number density $N_\chi \equiv e^{3N_e} n_\chi$

- In WIFI: **T** and **H** from WI dynamics

$$\boxed{\mathcal{I}_\chi(N_e) = \frac{dN_\chi}{dN_e} \equiv e^{3N_e} \frac{T^{2n+4}(N_e)}{\Lambda^{2n} H(N_e)}}$$

DM production during WI via UV Freeze-In
The WIFI framework

- **In WIFI $\mathcal{I}_\chi$ is sharply peaked** at some e-fold N_e^{peak}

$$3 + (2n+4)\frac{d\ln T(N_e)}{dN_e} - \frac{d\ln H(N_e)}{dN_e} = 0$$

  - Deep in WI: $T, H \sim \text{const.} : \mathcal{I}_\chi \sim e^{3N_e}$
  - In RD: $T \sim e^{-N_e}, H \sim T^2 : \mathcal{I}_\chi \sim e^{-(2n-1)N_e}$

$$\boxed{\mathcal{I}_\chi(N_e) = \frac{dN_\chi}{dN_e} \equiv e^{3N_e}\frac{T^{2n+4}(N_e)}{\Lambda^{2n}H(N_e)}}$$

DM production during WI via UV Freeze-In
The WIFI framework

- **In WIFI** $\mathcal{I}_\chi$ **is sharply peaked** at some e-fold N_e^{peak}

$$3 + (2n+4)\frac{d\ln T(N_e)}{dN_e} - \frac{d\ln H(N_e)}{dN_e} = 0$$

$$Y_\chi(N_e) \simeq \frac{45}{2\pi^2 g_\star} \frac{e^{3\left(N_e^{\rm peak} - N_e\right)}}{\Lambda^{2n} T^3(N_e)} \underbrace{\Delta N_e^{\rm peak}}_{\text{full width at half maximum}} \times \frac{T^{2n+4}(N_e^{\rm peak})}{H(N_e^{\rm peak})}, \qquad (N_e > N_e^{\rm peak})$$

Key distinction from RD UV-freeze in:
In WIFI, the relic DM yield is <u>not set</u> by the highest temperature of the bath, but rather in a short time interval around N_e^{peak}

DM production during WI via UV Freeze-In

WIFI vs RD UV-freeze in

The Enhancement Ratio:

$$\boxed{\begin{aligned} R_\chi^{(n)} &\equiv Y_{\chi,\infty}/Y_{\chi,\infty}^{\mathrm{RD}}(T_{\mathrm{rh}}) \\ &\simeq (2n-1)\frac{\mathcal{I}_\chi(N_e^{\mathrm{peak}})}{\mathcal{I}_\chi(N_e^{\mathrm{RD}})}\Delta N_e^{\mathrm{peak}} \end{aligned}}$$

RD condition:

$$T_{\mathrm{rh}} \equiv T(\epsilon_H = 2)$$
$$N_e^{\mathrm{RD}} \equiv N_e(\epsilon_H = 2)$$
$$T(N_e^{\mathrm{RD}}) = T_{\mathrm{rh}}$$

The resulting DM yield in WIFI is always enhanced compared to the (conventional) RD UV freeze-in scenario for the same reheat temperature

DM production during WI via UV Freeze-In

WIFI vs RD UV-freeze in

$$R_\chi^{(n)} \simeq (2n-1)\frac{\mathcal{I}_\chi(N_e^{\rm peak})}{\mathcal{I}_\chi(N_e^{\rm RD})}\Delta N_e^{\rm peak}$$

$\gg 1$

the most significant factor

- The enhancement ratio increases noticeably with increasing **n**
  - faster decay of $\mathcal{I}_\chi$ after its peak
  - Peak occurs at earlier time
- Specific WI dynamics also impact the enhancement ratio via $\mathcal{I}_\chi$

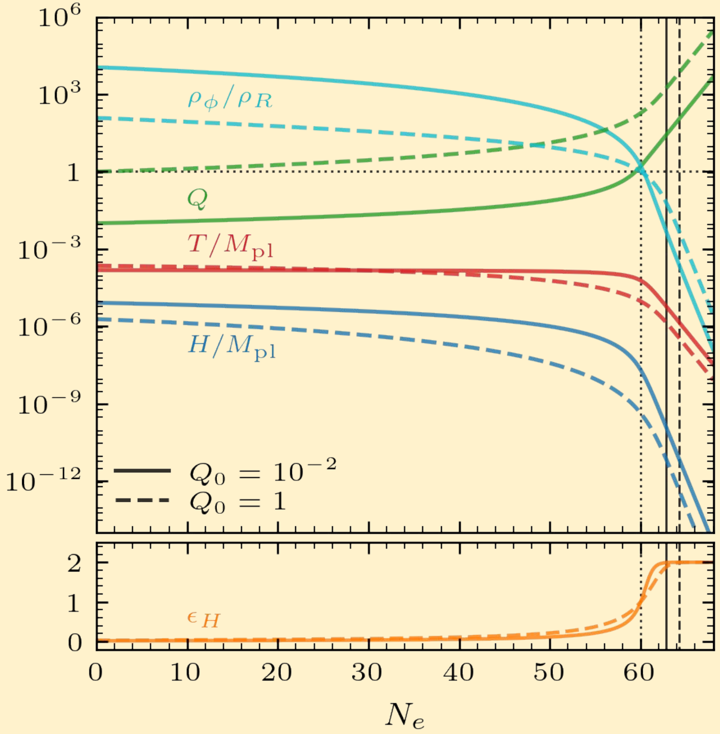
$$\mathcal{I}_\chi(N_e) \equiv e^{3N_e}\frac{T^{2n+4}(N_e)}{\Lambda^{2n}H(N_e)}$$

An example of DM production in WIFI
WI dynamics

- We consider two scenarios: $V(\phi)=\lambda\phi^4$, $\Upsilon \propto T$ with $Q_0=10^{-2}$ and $Q_0=1$.
    - motivated by Warm Little Inflaton

M. Bastero-Gil, A. Berera, R. O. Ramos, & J. G. Rosa,

- parameters of the inflaton potential set to enforce 60 e-folds and produce cosmological observables consistent with CMB data



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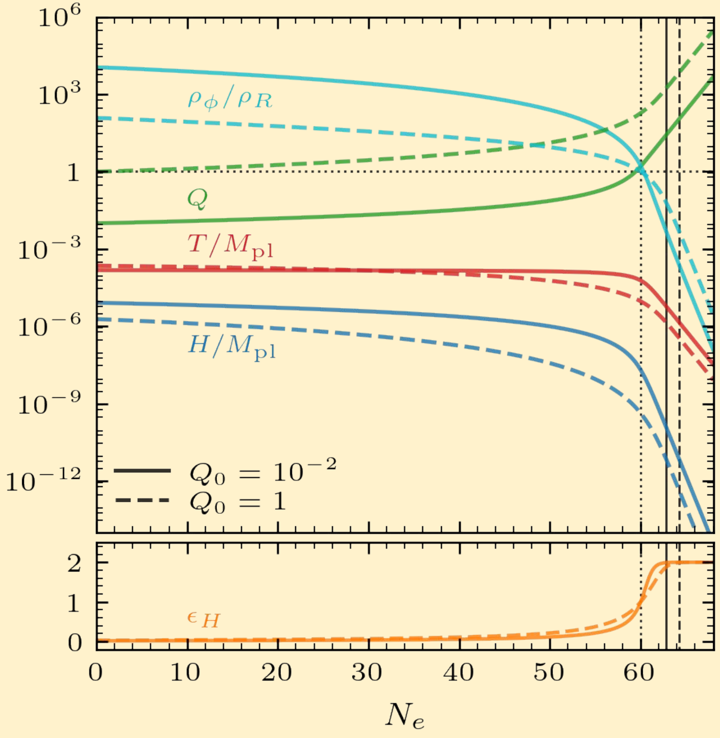
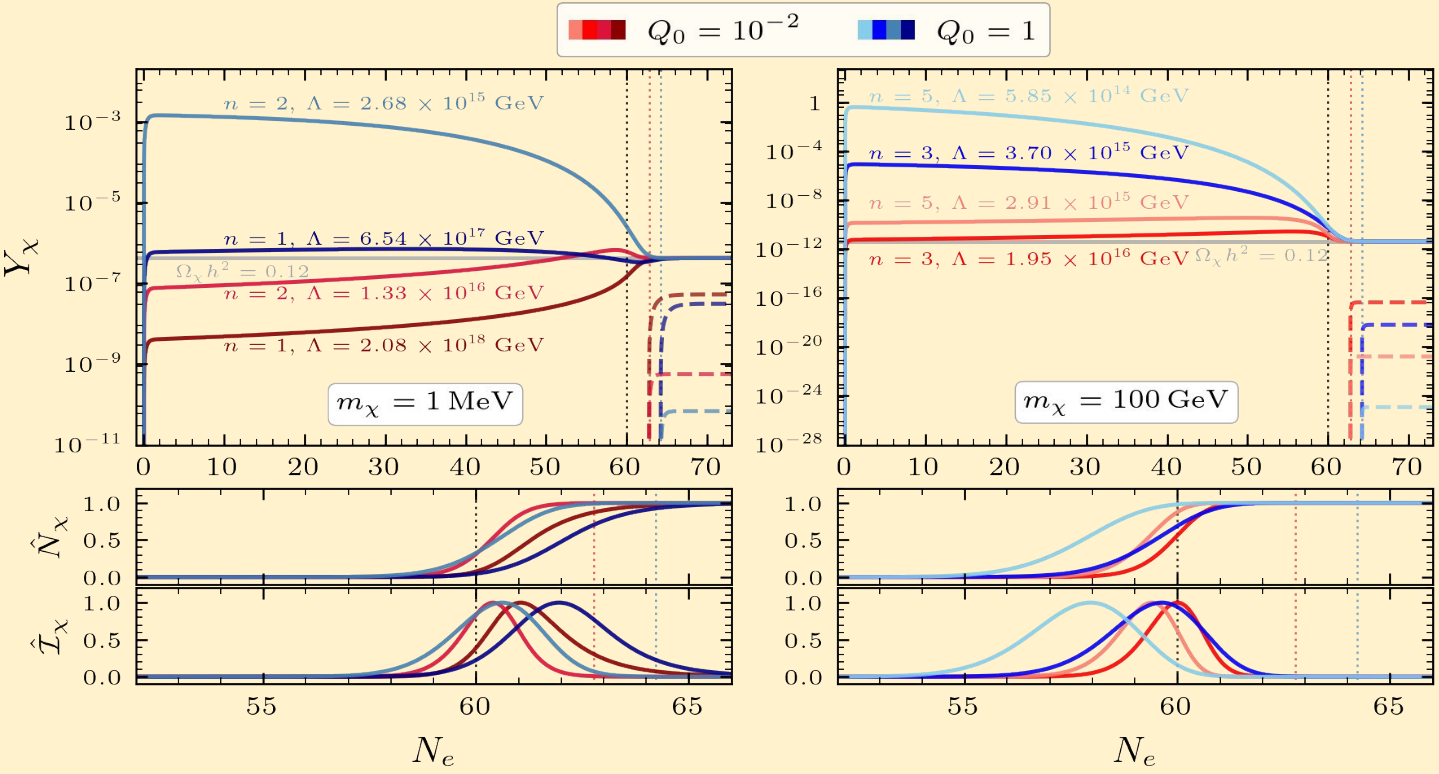


Dynamics computed with **WarmSPy!**
github.com/GabrieleMonte/WarmSPy
(arXiv:2306.16190)
GM, V. Aragam, L. Visinelli, K. Freese

An example of DM production in WIFI
The DM yield evolution



$$N_\chi = e^{3N_e} n_\chi$$

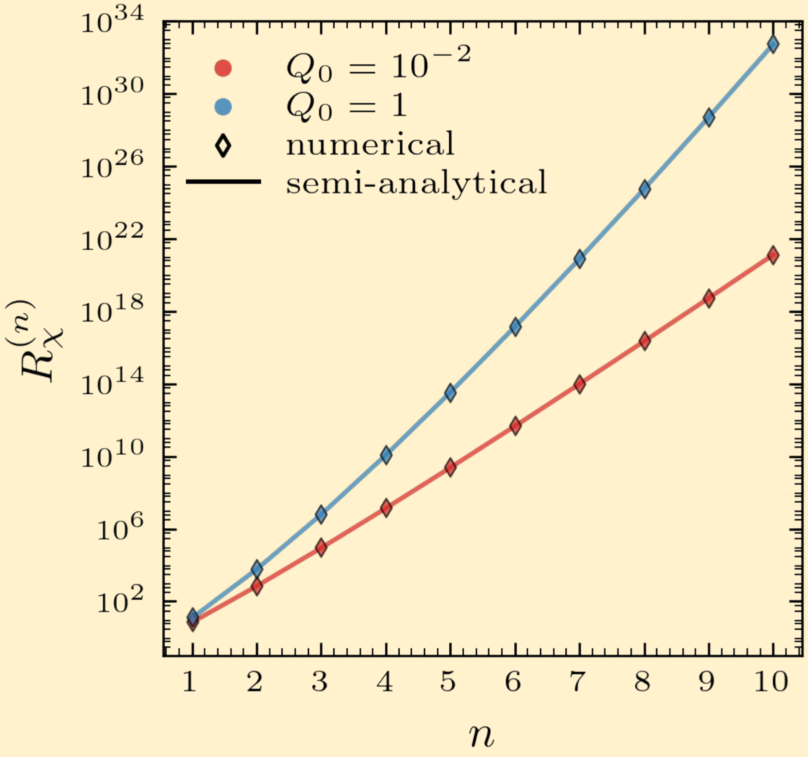
$$\mathcal{I}_\chi \equiv e^{3N_e} \frac{T^{2n+4}}{H \Lambda^{2n}} = \frac{dN_\chi}{dN_e}$$

An example of DM production in WIFI

The enhancement ratio

$$R_\chi^{(n)} \simeq (2n-1)\frac{\mathcal{I}_\chi(N_e^{\mathrm{peak}})}{\mathcal{I}_\chi(N_e^{\mathrm{RD}})}\Delta N_e^{\mathrm{peak}}$$

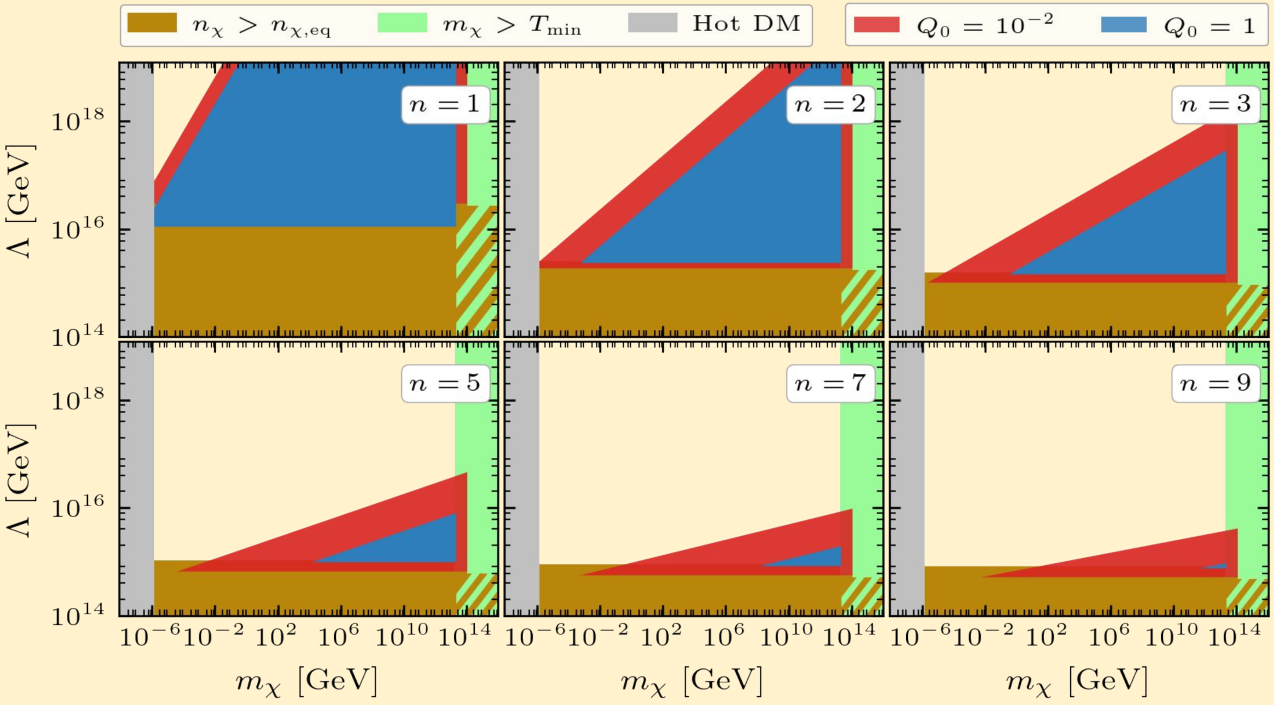
- The enhancement ratio increases exponentially with **n**
  - **$\gg 10^3$** for **$n \geq 3$**
  - As large as **$\sim 10^{30}$**
- For sufficiently large **n**, the DM abundance can be fully determined during the inflationary phase
- WI dynamics has a significant effect on the overall enhancement, e.g. enhancement for **$Q_0=1$** always greater than **$Q_0=10^{-2}$**



An example of DM production in WIFI

Constraints on Λ and m_χ

$$m_\chi \cdot Y_{\chi,\infty}(\Lambda, n) = \left(\frac{\Omega_\chi h^2}{0.12}\right)\left(\frac{\rho_c}{1.0537\times10^{-5}\,h^2\,\mathrm{GeV\,cm^{-3}}}\right)\left(\frac{2891.2\,\mathrm{cm^{-3}}}{s_0}\right)$$



Conclusions

1. In a **WI** setting, the persistent thermal bath can source a **sizable DM abundance** via **UV freeze-in!**

2. The DM yield in **WIFI** is **always enhanced** compared to the **RD UV freeze-in** scenario for the **same reheat** temperature

   - The **larger** the value of **n**, the **greater** the **enhancement**
   - The specific **WI dynamics** has a **significant** impact on the **overall enhancement**

3. For **sufficiently large** values of **n**, the DM relic abundance is **entirely** created during the **inflationary phase**

4. **Wide range** of allowed m_χ, whose value is strongly **correlated** to Λ, **n** and underlying **WI dynamics**.

Grazie per l'attenzione

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Based on work with Katherine Freese & Barmak Shams Es Haghi (arXiv:2401.17371)

BACK-UP SLIDES

UV Freeze-In
A Concrete Example

- Extension of SM by a **U(1)**, broken at a high scale **Λ**
  - Both DM and SM fermions are charged under this new **U(1)’** group

$$\mathcal{L} \supset i\bar{Q}\not{D}Q + i\bar{u}\not{D}u + i\bar{\chi}\not{D}\chi + \dots \qquad \not{D} = \not{\partial} + \underbrace{iq'\not{Z}'}_{} + \dots$$

Z’ and **q’** are respectively the mediator and the charge of the **U(1)’**

  - For scales $\ll \Lambda \sim M_{Z'}$, **Z’** is integrated out:

$$\mathcal{L}_{\text{eff}} \supset \frac{1}{\Lambda^2}\bar{Q}\gamma_\mu Q\bar{\chi}\gamma^\mu\chi + \frac{1}{\Lambda^2}\bar{u}^c\gamma_\mu u^c\bar{\chi}\gamma^\mu\chi + \dots$$

UV Freeze-In

DM number density evolution

- Consider a dimension (n+4) operator $\frac{1}{\Lambda^n}\underbrace{\phi_1\phi_2\cdots\phi_{n+3}}_{\text{SM fields}}\underbrace{\varphi}_{\text{DM}}$ $\quad(\phi_1\phi_2 \to \phi_3\cdots\phi_{n+3}\varphi)$

$$\dot{n}_\varphi + 3Hn_\varphi = \int \mathrm{d}\Pi_1\ \mathrm{d}\Pi_2 f_1 f_2 |\mathcal{M}|^2_{(n)}\ \mathrm{DLIPS}_{(n+2)}$$

$$\simeq \frac{2T}{(4\pi)^5\Lambda^{2n}}\left[\frac{1}{4\pi^2}\right]^n \int_0^\infty \mathrm{d}s\, s^{(2n+1)/2} K_1(\sqrt{s}/T)$$

$$\mathrm{DLIPS}_{(n+2)} \sim \left[\frac{s}{4\pi^2}\right]^n \mathrm{DLIPS}_{(2)}$$

$$|\mathcal{M}|^2_{(n)} \sim \left(\frac{1}{\Lambda^2}\right)^n$$

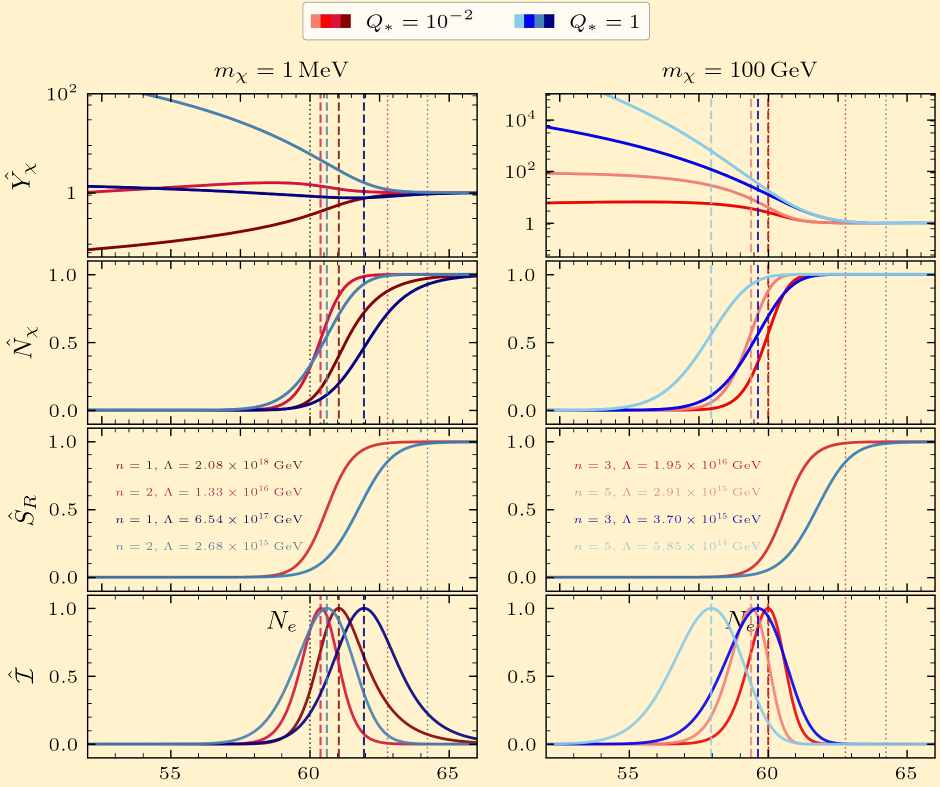
$$\boxed{\dot{n}_\varphi + 3Hn_\varphi \simeq \underbrace{\frac{1}{(2\pi)^7}\left(\frac{n!(n+1)!}{\pi^{2n-2}}\right)}_{\substack{\text{Numerical prefactor} \\ \text{set to 1 in our work}}}\frac{T^{2n+4}}{\Lambda^{2n}}}$$

Warm Inflation
Computing Cosmological Observables

- We use **WarmSPy** to compute the background dynamics.
    - We fix the initial dissipation strength Q_0 (60 e-folds before the end of inflation)
    - We use an iterative algorithm to get the initial field value to ensure 60 e-folds of inflation, i.e. $\varepsilon_H(N_e=60)=1$
    - We fix the height of the potential (in our case λ), to match the amplitude of the primordial power spectrum at the CMB pivot scale $k_*=0.05\ \mathrm{Mpc}^{-1}$
    - We compute r and n_s and ensure they are within the CMB bounds, otherwise we repeat the process for a different Q_0

An example of DM production in WIFI

More on the DM yield evolution



$$N_\chi = e^{3N_e} n_\chi$$

$$S_R = e^{3Ne} s_R$$

$$\mathcal{I}_\chi \equiv e^{3N_e}\frac{T^{2n+4}}{H\Lambda^{2n}} = \frac{dN_\chi}{dN_e}$$