March 27th 2024

The Future of High Energy Physics:
A new Generation, a New Vision
Aspen Center for Physics

WIFI
A novel framework for Dark Matter production

Gabriele Montefalcone

Weinberg Institute for Theoretical Physics, University of Texas at Austin

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

ASPEN CENTER FOR PHYSICS

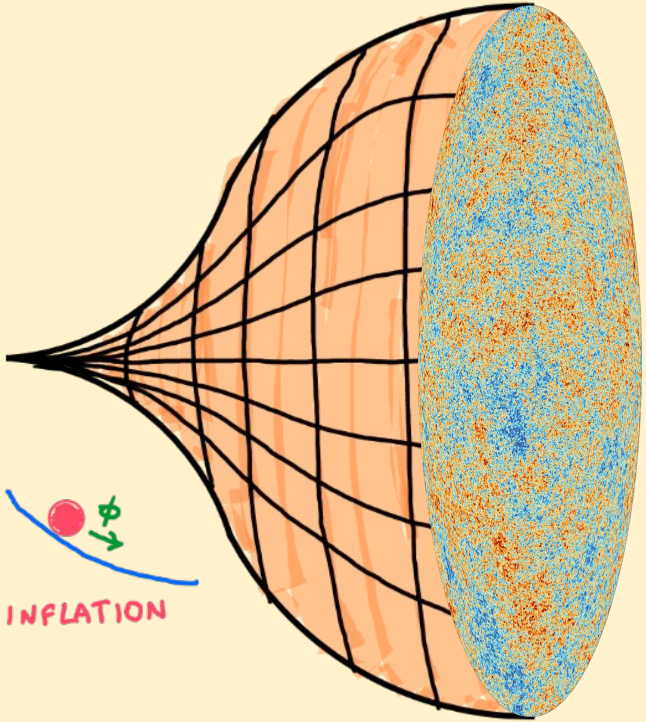
TEXAS
The University of Texas at Austin

INFLATION

Cosmic Inflation

Guth 1981

- A period of accelerated expansion in the early universe
- Explains the observed flatness, homogeneity, and the lack of relic monopoles
- Provides with a mechanism for generating the inhomogeneities observed in the Cosmic Microwave Background (CMB)



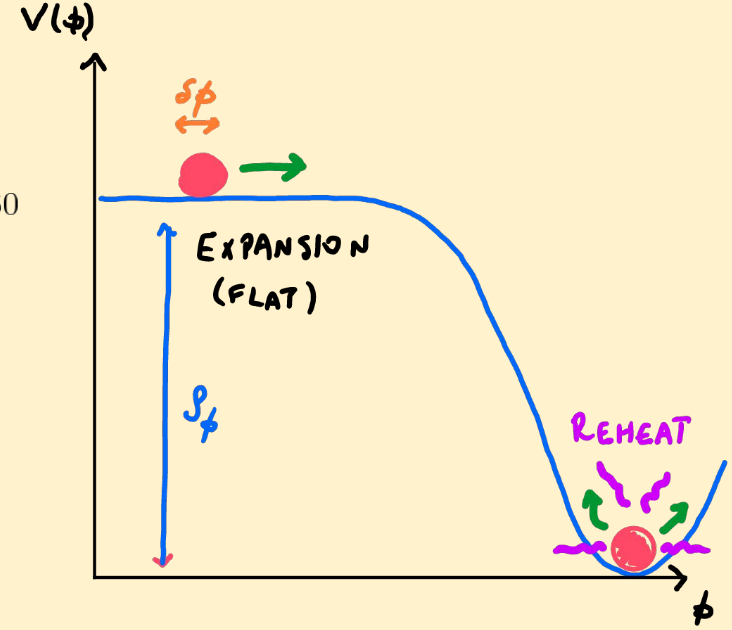
A simple mechanism for Inflation

Linde 1982; Albrecht, Steinhardt 1982

Single field - slow roll

$$\ddot{\phi} + (3H + \Gamma)\dot{\phi} + V_\phi = 0,$$

- The **Flat** region: $a(t) \sim e^{Ht}$
  - nearly constant **V(ϕ)**
  - ρ_ϕ dominates energy density of the universe
  - Typically $N_e \cong 60$ e-foldings: $a_f/a_i \simeq e^{60}$



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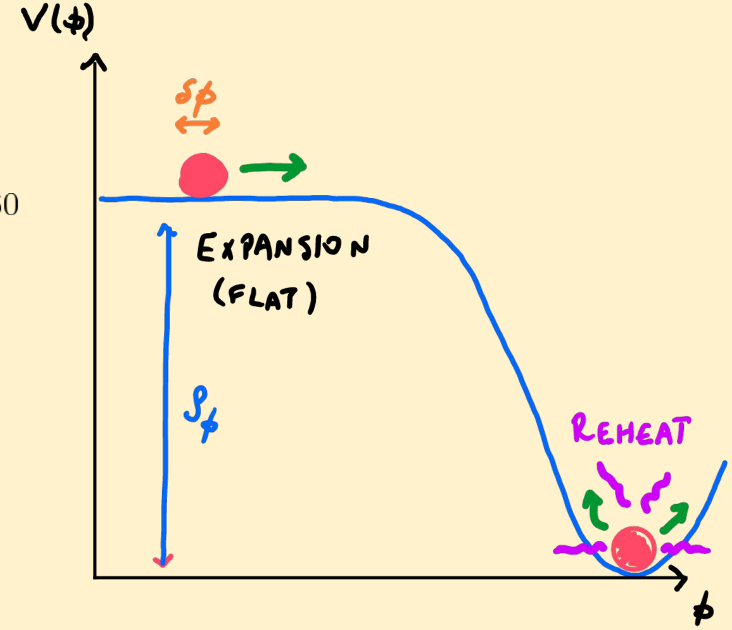
- **Reheating**:
    - Particle production via ϕ decay parametrized by Υ



Warm Inflation (WI)

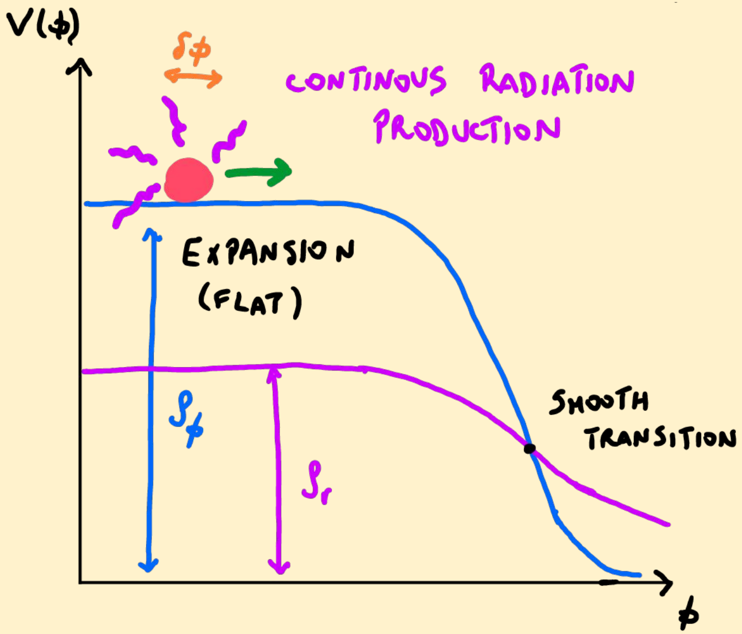
Berera 1995

Subdominant radiation bath from dissipation

T>H

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

- Subdominant radiation bath at **T>H** continuously sourced by dissipative interactions with $\boldsymbol{\phi}$.
- Dissipation rate Υ acts as additional thermal friction
  - This allows $\boldsymbol{\Delta\phi < M_{pl}}$
- Smooth transition to radiation dominated (RD) universe after inflation



Warm Inflation (WI)

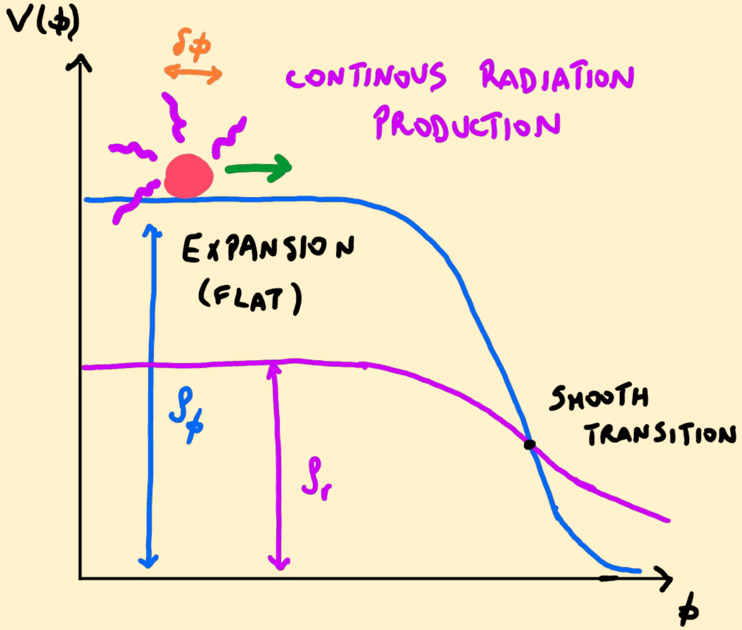
Main Features

Berera 1995

T>H

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

- Distinct observables due to thermal nature of perturbations
  - Tensor-to-scalar ratio **r** generically suppressed
  - Relatively large non-gaussianities

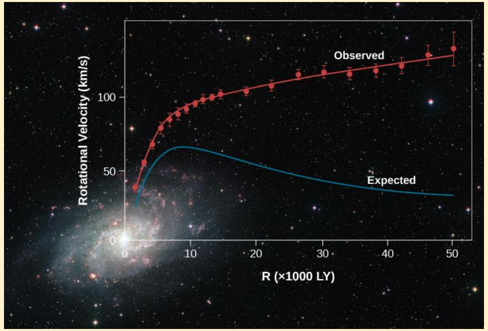


DARK MATTER

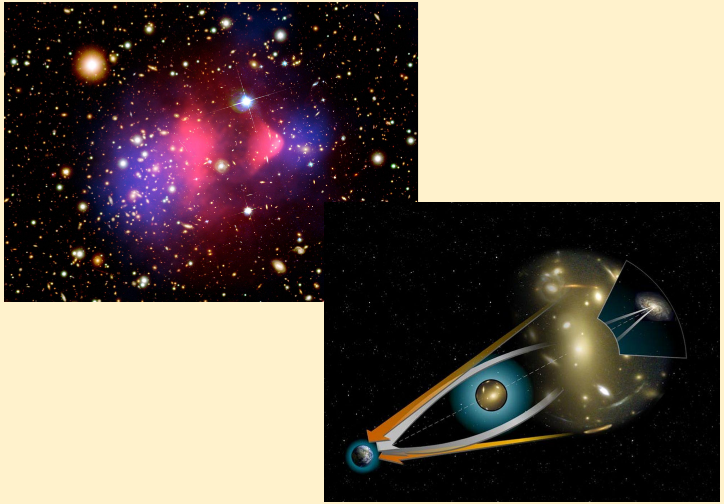
Evidence for Dark Matter (DM)

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

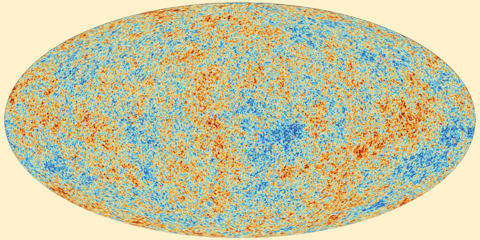
Galactic scales

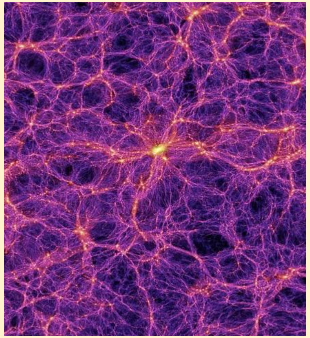


Cluster scales



Cosmological scales





What we know about DM

- Cold and Massive
- Stable/long lived
- No/weak interactions with the Standard Model (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)

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- Cold and Massive
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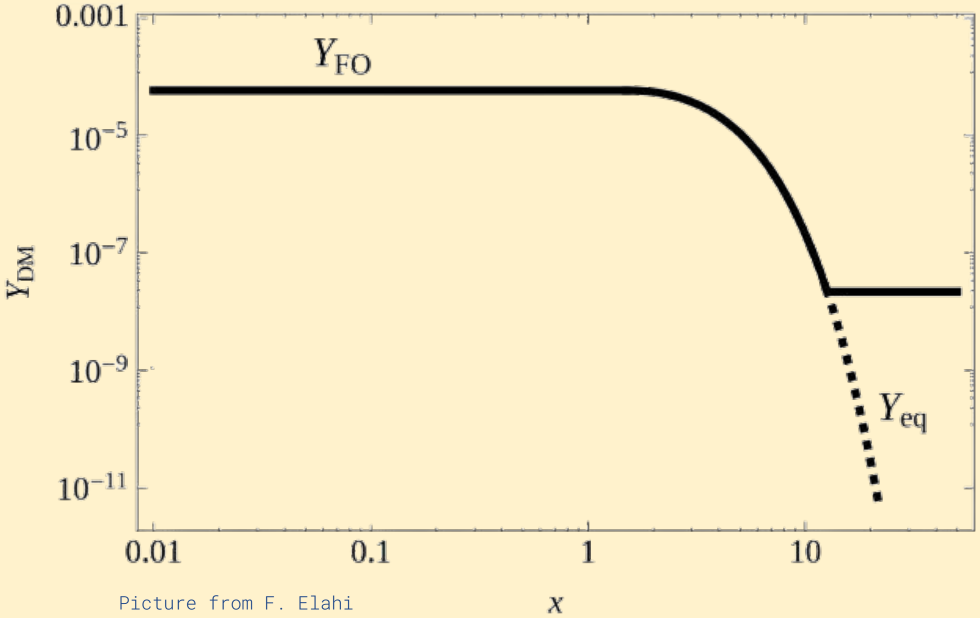
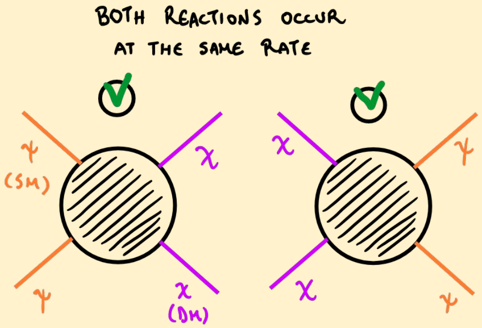
How was DM produced in the early universe?

The Canonical Freeze-out story

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



Picture from F. Elahi



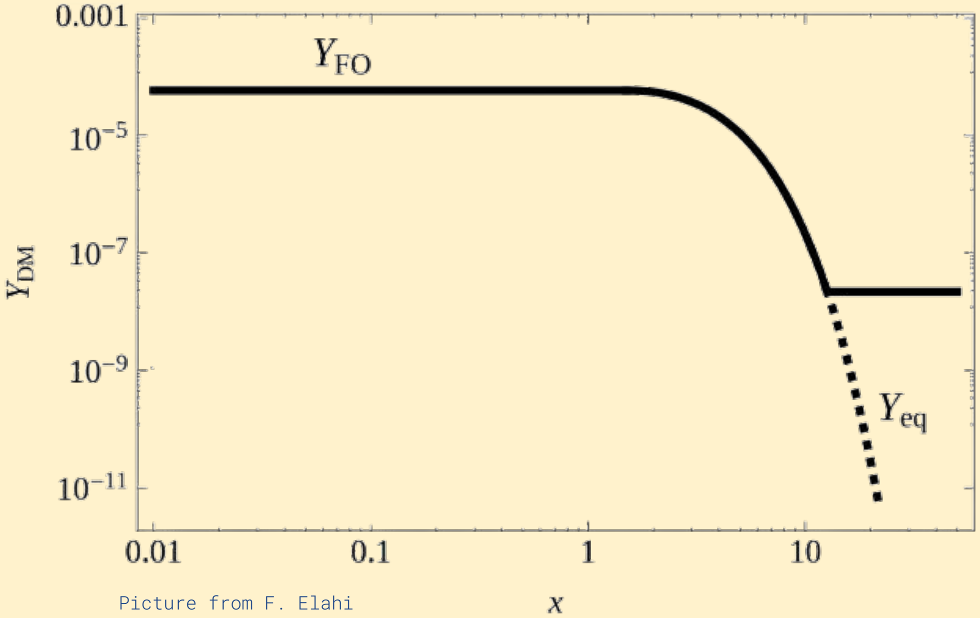
$$Y_{\rm DM} \equiv \frac{n_{\rm DM}}{s}$$

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

The Canonical Freeze-out story

The WIMP miracle!

$m_{DM} \sim m_W$ and $\sigma_{DM} \sim \alpha_W^2/m_W^2$ reproduces the observed DM abundance ($\alpha_W \sim 10^{-2}$ $m_W \sim 100$ GeV)



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

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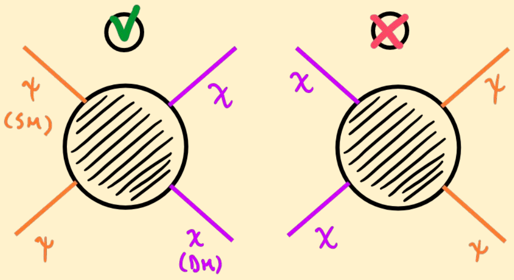
An alternative Scenario: Freeze-in

Hall, Jedamzik, March-Russell, West 2010

DM from a feeble interaction with SM

- **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!)



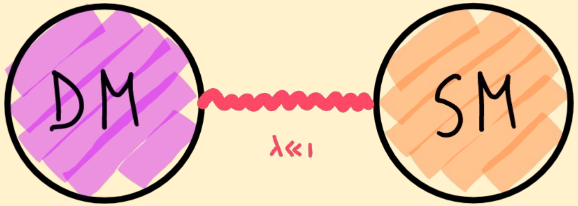
An alternative Scenario: Freeze-in

DM from a feeble interaction with SM

The suppressed interaction with SM can arise from:

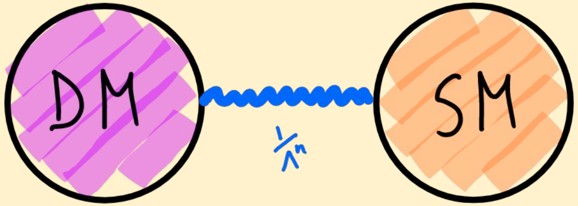
- **A very small** dimensionless coupling λ_{DM-SM}
  - renormalizable interaction

    Hall, Jedamzik, March-Russell, West 2010



- Dimensionful coupling suppressed by a **heavy mass scale Λ**
  - non-renormalizable interaction of dimension **n+4**
  - Known as **UV freeze-in**

    Elahi, Kolda, Unwin 2015



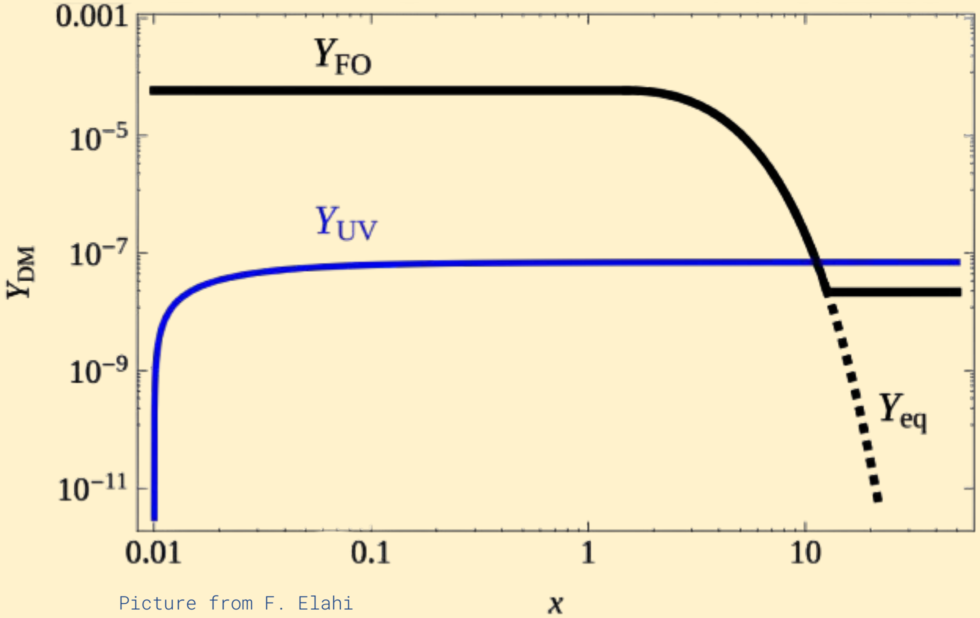
UV Freeze-in

Evolution of DM abundance

Elahi, Kolda, Unwin 2015

The DM abundance freezes-in quickly and depends on the highest temperature, i.e. T_{rh}

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



Picture from F. Elahi

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

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

$$Y_{UV,\infty} \sim \frac{M_{pl} T_{rh}^{2n-1}}{\Lambda^{2n}}$$

UV Freeze-in

Beyond instantaneous reheating

So far we assumed instantaneous reheating to SM

→ What if we go beyond the instantaneous reheating approximation?

UV Freeze-in

Beyond instantaneous reheating

So far we assumed instantaneous reheating to SM

What if we go beyond the instantaneous reheating approximation?

Finite reheating can **enhance** final DM abundance ✅

Garcia, Mambrini, Olive, Peloso 2017; Chen, Kang 2018; Bernal, Elahi, Maldonado, Unwin 2019; Barman, Bernal, Xu, Zapata 2022

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What if we consider the production during inflation?

UV Freeze-in
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➡ **What if we consider the production during inflation?**

The WIFI framework **Freese, GM, Shams 2024** ✅

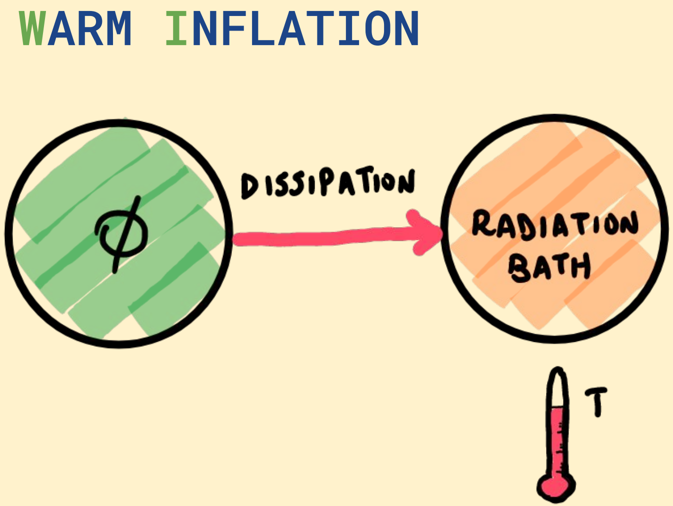
We show, for the first time, that inflation, specifically in a warm setting, can lead to substantial DM production via freeze-in.

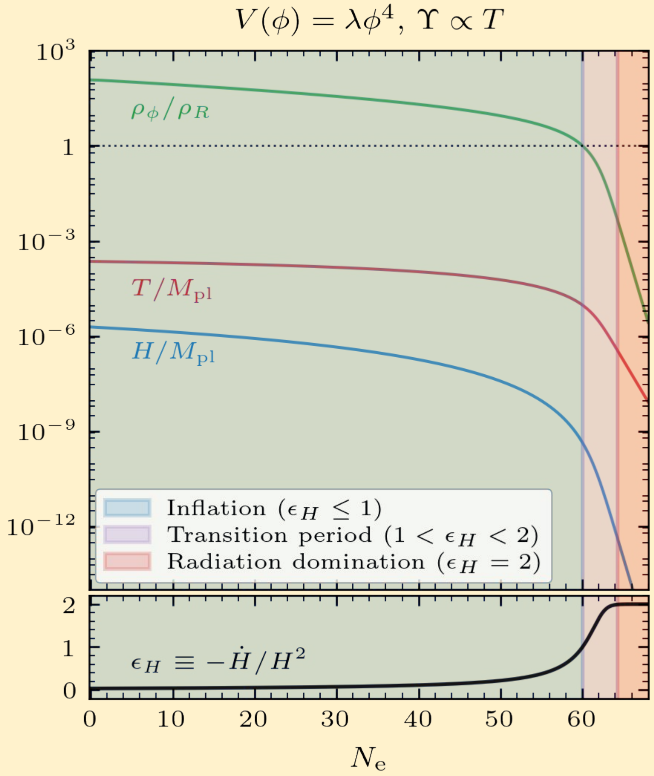
In fact, all of the DM in our universe can be produced during inflation via this mechanism.

DM from Warm Inflation via UV Freeze-In

The WIFI framework

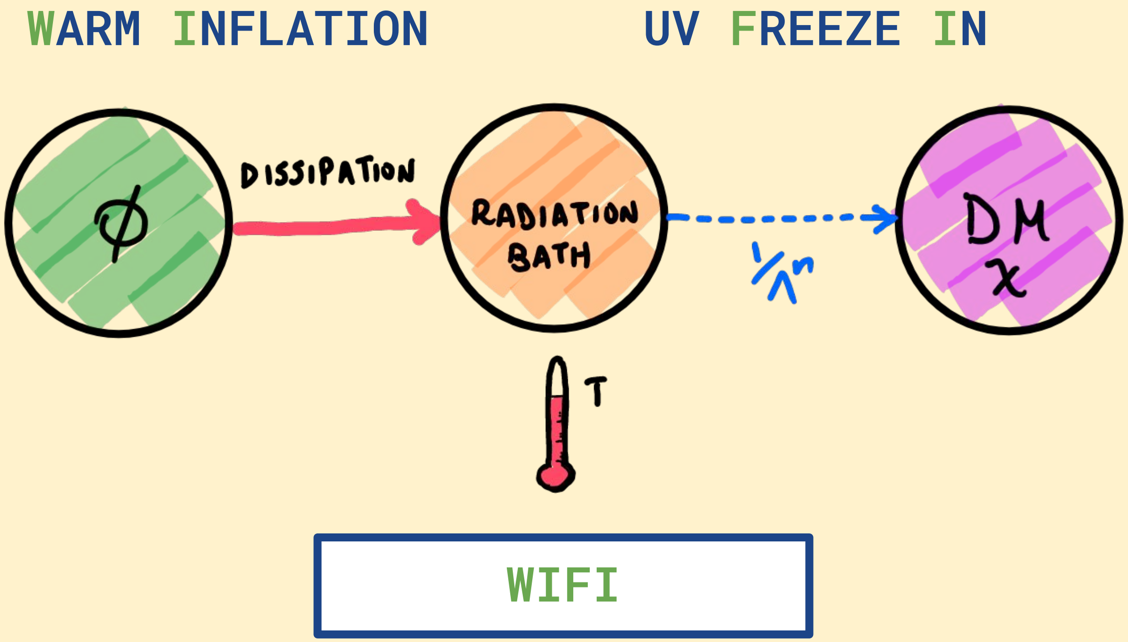
DM production during WI via UV Freeze-In
The WIFI framework





DM production during WI via UV Freeze-In

The WIFI framework



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

DM production mostly occurs when the rate of change of the comoving DM number density $N_\chi \equiv e^{3N_e} n_\chi$ is peaked

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

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

Number of e-folds
$dN_e = Hdt$

NOTATION REMINDER: Hereafter, we refer to DM by the greek letter χ

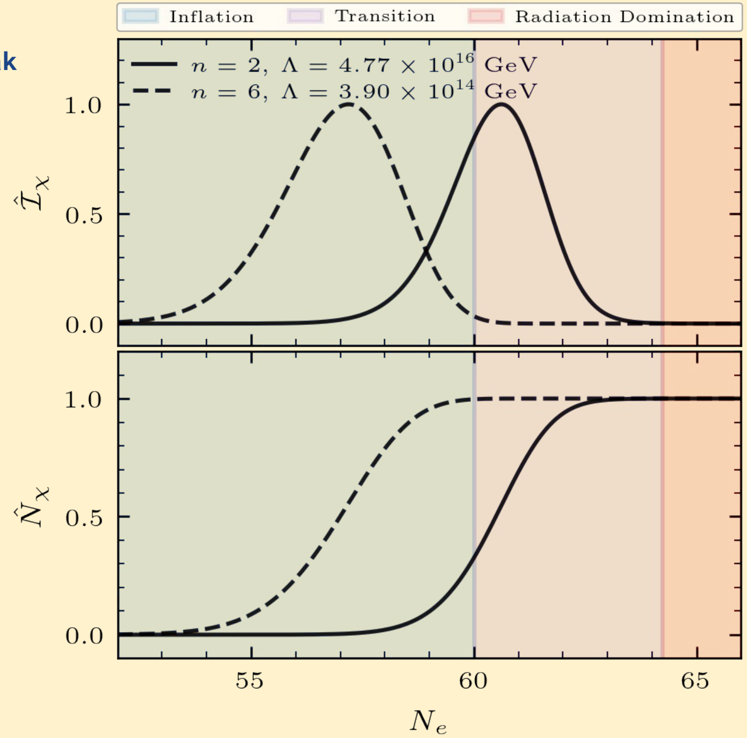
DM production during WI via UV Freeze-In
The WIFI framework

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: $T \sim e^{-N_e}, H \sim T^2 : \ \mathcal{I}_\chi \sim e^{-(2n-1)N_e}$

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



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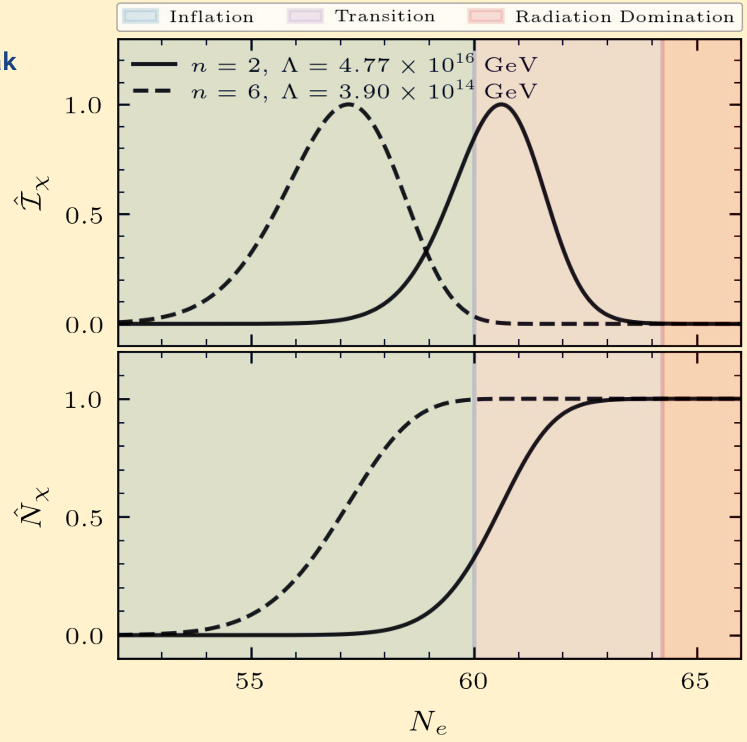
Key distinction from (standard) radiation-dominated UV freeze-in:

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
The WIFI framework

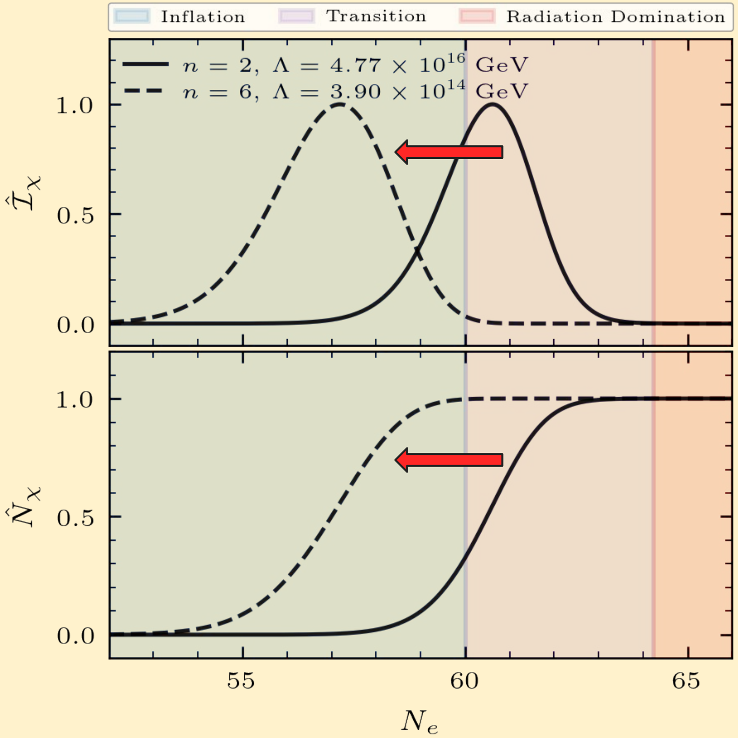
For increasing value of **n**

- Peak occurs at earlier time
- Faster decay of $\mathcal{I}_\chi$ after its peak

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

Recall:

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



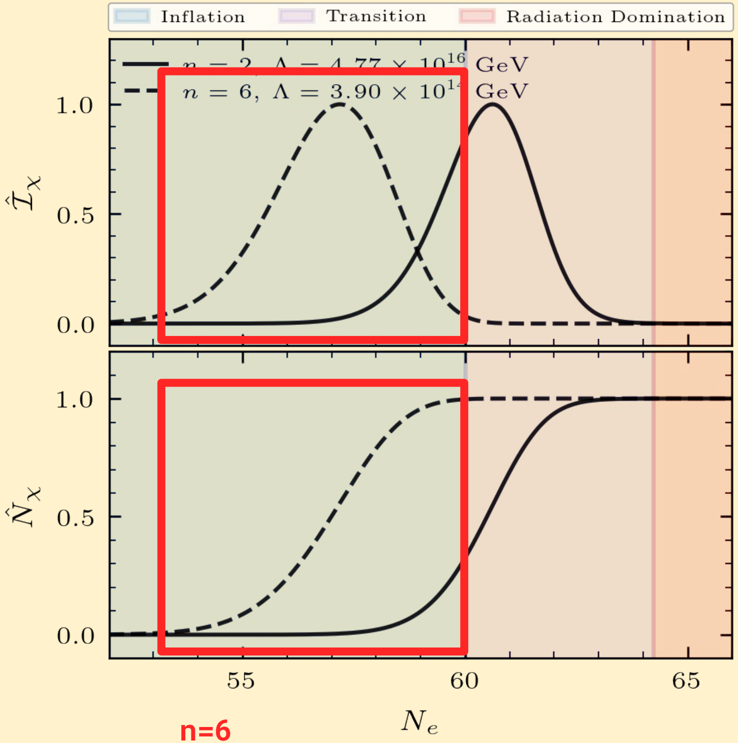
DM production during WI via UV Freeze-In

The WIFI framework

For increasing value of n

- Peak occurs at earlier time
- Faster decay of $\mathcal{I}_\chi$ after its peak

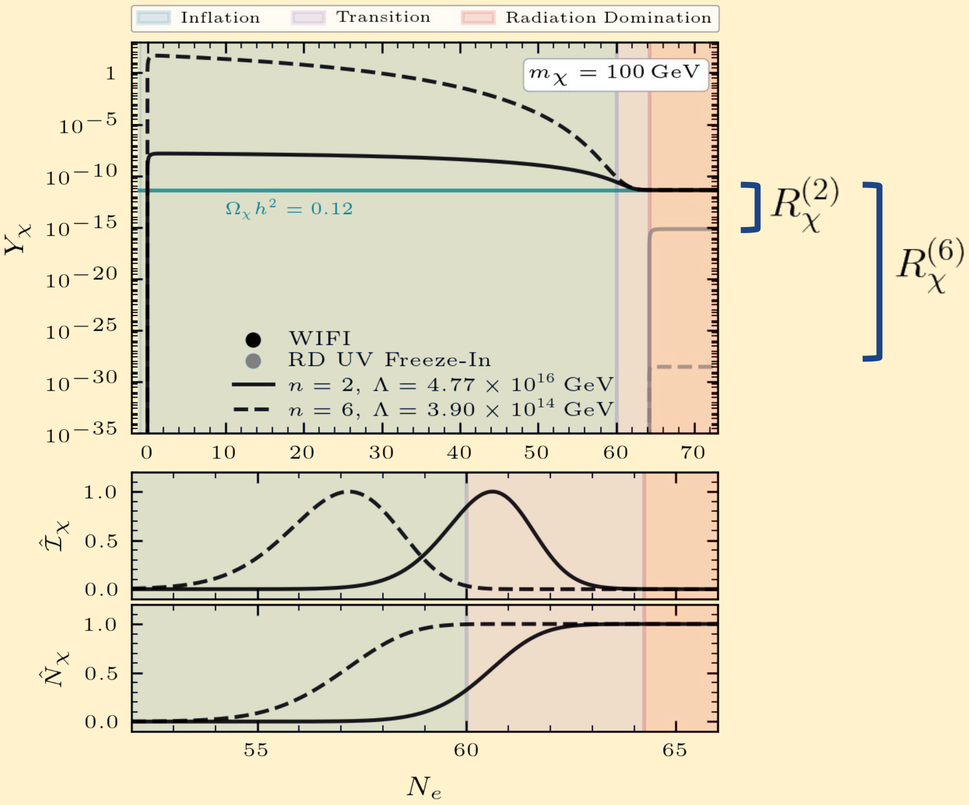
For sufficiently large values of n, the DM relic abundance is entirely created during the inflationary phase



n=6
$\Lambda = 3.9\times10^{14}$ GeV

An example of DM production in WIFI

Evolution of DM abundance



The Enhancement Ratio:

$$R_\chi^{(n)} \equiv Y_{\chi,\infty}^{\mathrm{WIFI}} / Y_{\chi,\infty}^{\mathrm{UV}}$$

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

RD condition:

$$\epsilon_H \equiv -\dot{H}/H^2$$

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

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

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

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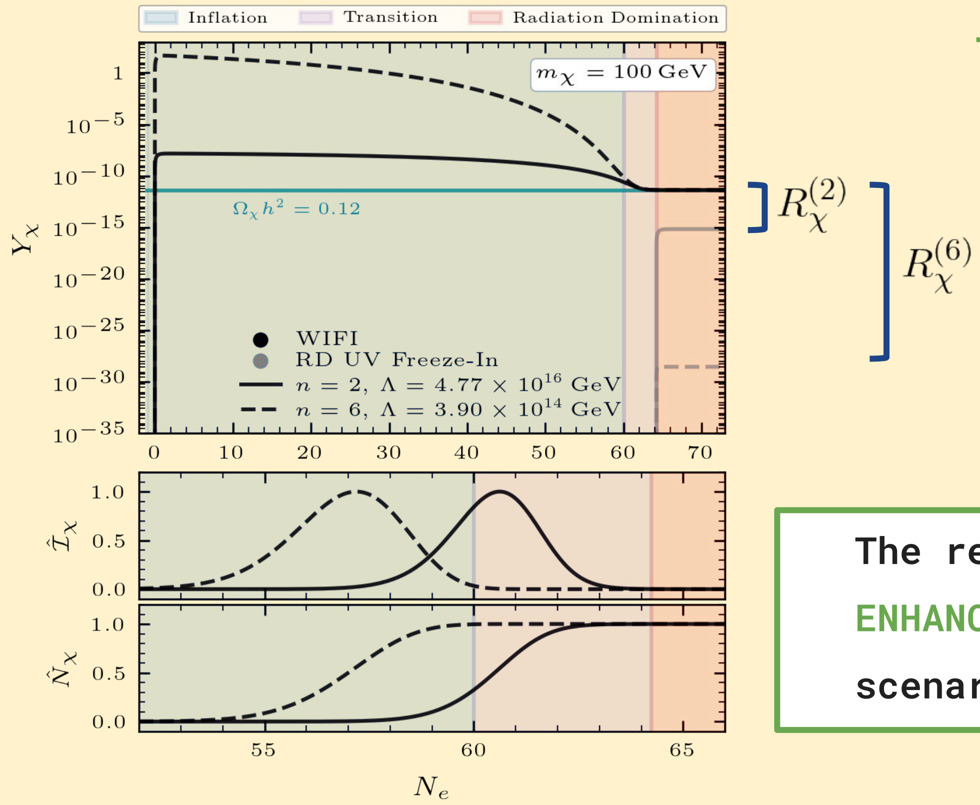

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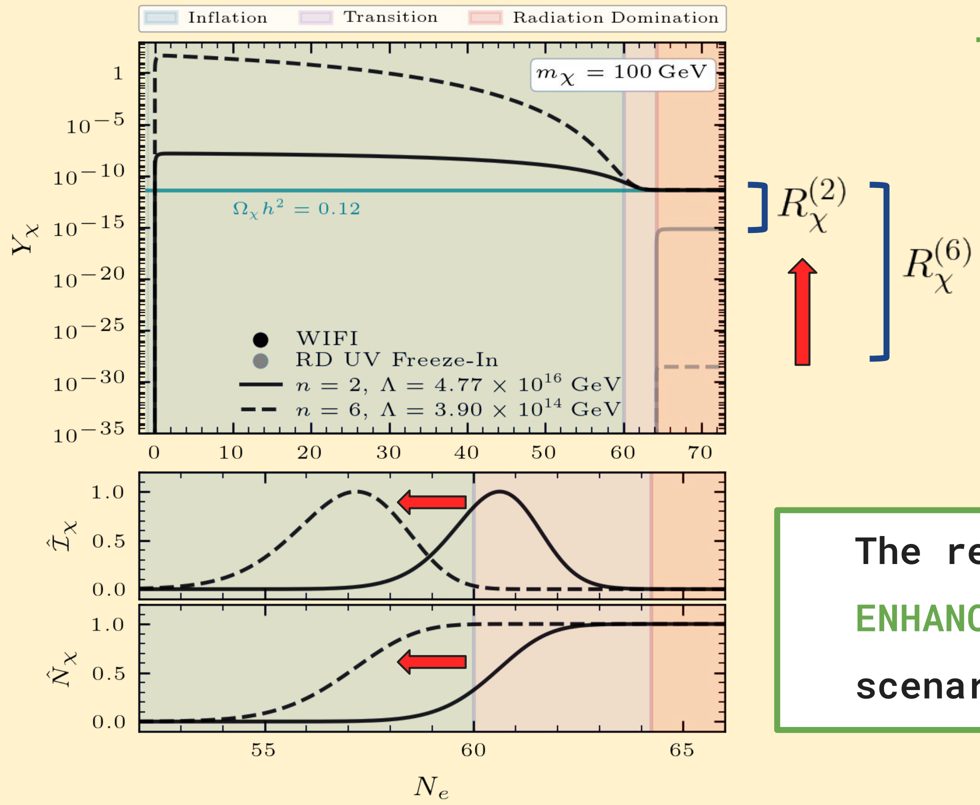
$\gg 1$

The resulting DM yield in WIFI is ALWAYS ENHANCED compared to the RD UV freeze-in scenario for the same reheat temperature

An example of DM production in WIFI

Evolution of DM abundance



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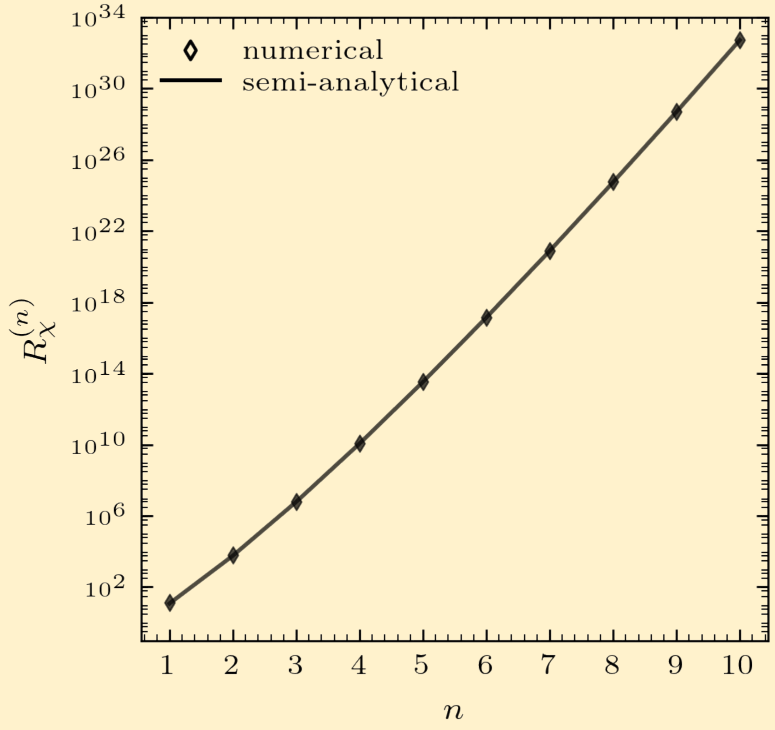
An example of DM production in **WIFI**

The Enhancement Ratio

- The enhancement ratio increases **exponentially** with **n**
  - **≫10^3** for **n≥3**
  - As large as **~10^{30}**

- For **sufficiently large n**, the DM abundance is fully determined during the **inflationary phase**, leading also to the **greatest enhancement in DM yield**.

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



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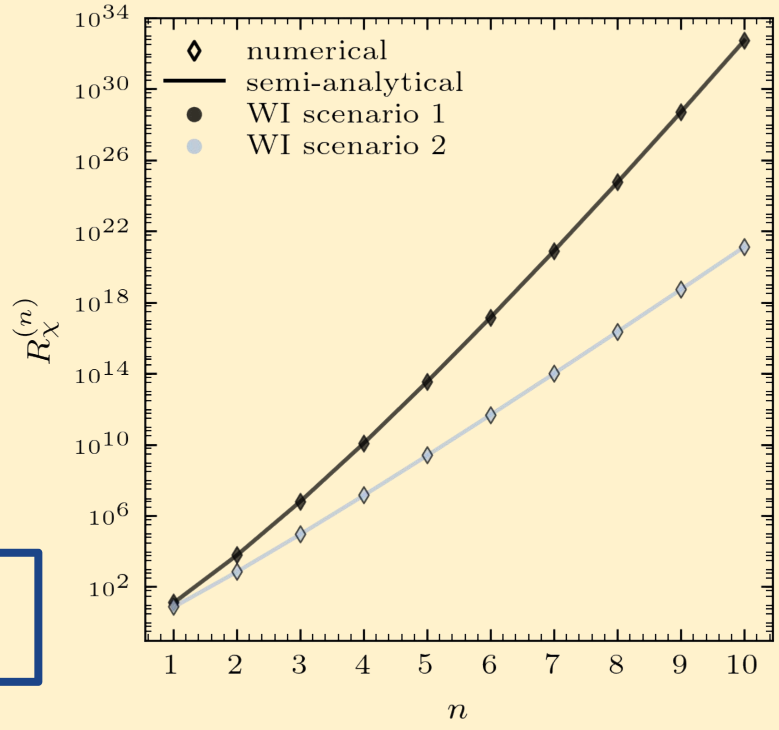
- For **sufficiently large n**, the DM abundance is fully determined during the **inflationary phase**, leading also to the **greatest enhancement in DM yield**.

NOTE: The specific WI dynamics has a significant effect on the overall enhancement

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



Conclusions

1. We showed, for the first time, that inflation, specifically in a **warm setting**, can lead to **substantial DM production** via **freeze-in**.

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

3. **All of the DM in our universe** can be produced during **inflation** via the **WIFI** mechanism.

Outlook and Future Work

1. Tight link between inflationary dynamics and DM production
    - **Rich phenomenology** to be further explored
    - Possible **inprint in the phase-space distribution** of relic DM particles.
2. The WIFI framework can be also used to **produce other cosmological relics**, which could potentially play a significant role in the early Universe evolution.

Grazie per l’attenzione

Gabriele Montefalcone

Weinberg Institute for Theoretical Physics, University of Texas at Austin

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

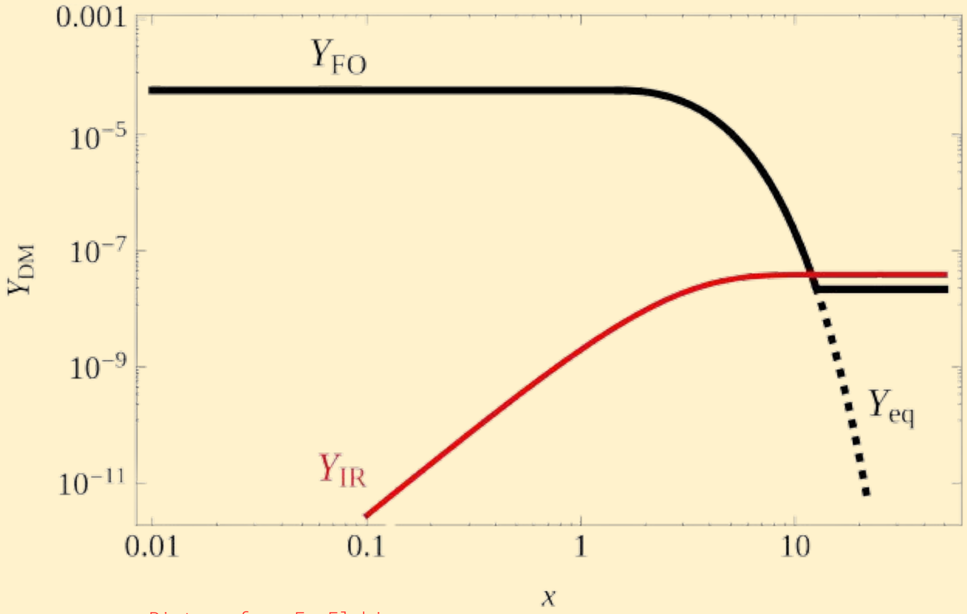
BACK-UP SLIDES

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 (**λ_{DM-SM}~10^{-11}**)



Picture from F. Elahi

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

UV Freeze-In
DM number density evolution

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

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

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

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

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

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

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 **≪ Λ ~ $M_{Z'}$**, **Z'** is integrated out:

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

UV Freeze-in

Main Features

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

- Natural small coupling from 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

$$\Omega_{\mathrm{DM}} \propto \frac{m_{\mathrm{DM}} T_{\mathrm{rh}}^{2n-1}}{\Lambda^{2n}}$$

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 **$n \gtrsim 4$**

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

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

Warm Inflation

- Subdominant radiation bath at **T>H** continuously sourced by dissipative interactions with inflaton ϕ.
- No separate reheating: smooth transition to radiation dominated (RD) universe

UV Freeze-In

- Feeble coupling between DM and the bath from heavy scale Λ
- No interaction between DM and the inflaton ϕ

WIFI

- Vanishing DM abundance deep into the inflationary phase
- **Background evolution of ϕ is unaffected by DM-radiation interaction.**

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)

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

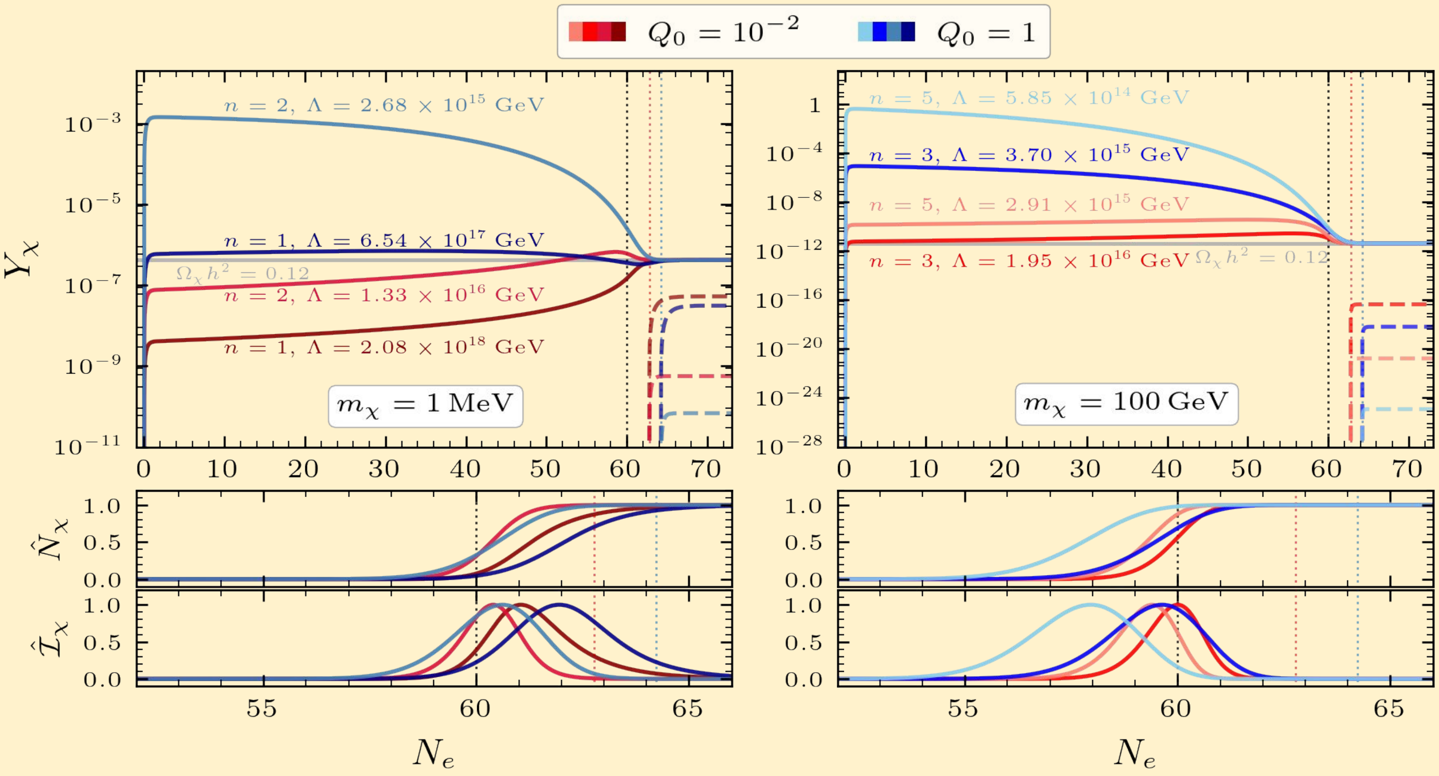
In WIFI $\mathcal{I}_\chi$ **is sharply peaked** at some e-fold N_e^{peak}

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

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

An example of DM production in WIFI

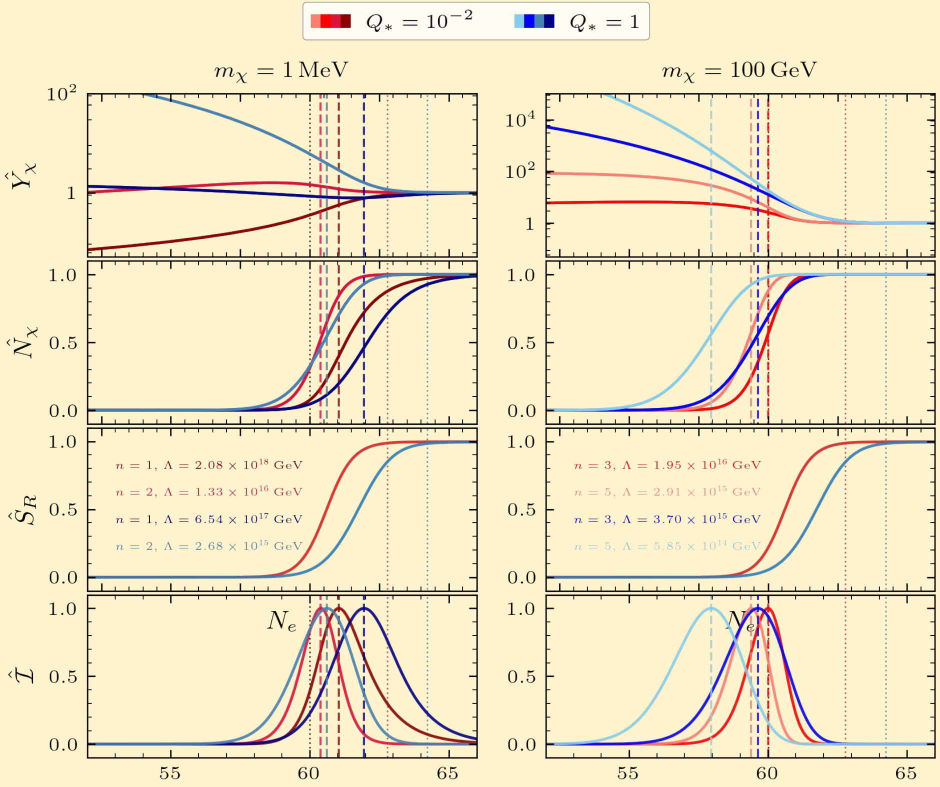
More on the DM yield evolution



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

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

An example of DM production in WIFI
More on the DM yield evolution



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

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

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

An example of DM production in WIFI

Constraints on Λ and m_χ

$$m_\chi \cdot Y_{\chi,\infty}(\Lambda, n) = \left(\frac{\Omega_\chi h^2}{0.12}\right)\left(\frac{\rho_c}{1.0537 \times 10^{-5}\, h^2\, \mathrm{GeV\,cm^{-3}}}\right)\left(\frac{2891.2\,\mathrm{cm^{-3}}}{s_0}\right)$$