July 5th 2024

Quantum Aspects of Inflationary Cosmology

Munich Institute of Astro-,Particle & BioPhysics

WIFI
A novel framework for Dark Matter production

Gabriele Montefalcone

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

MIAPbP

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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:

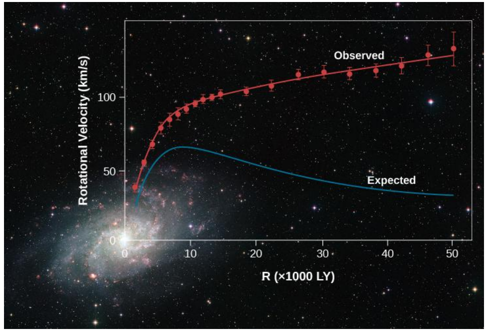
  General features and a representative example

DARK MATTER

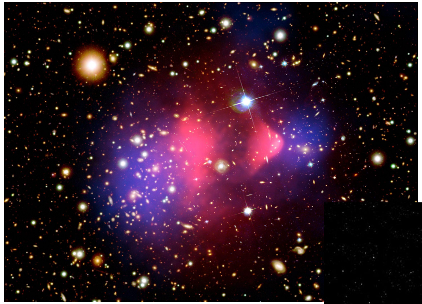
Evidence for Dark Matter (DM)

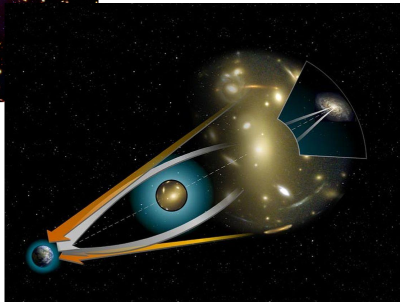
Huge amount of evidence from all scales (only from gravitational interaction)

Galactic scales

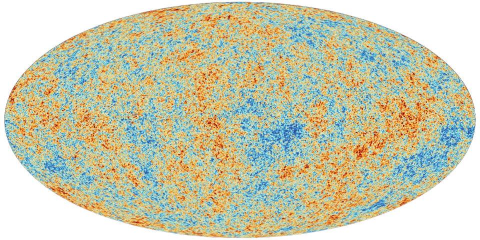


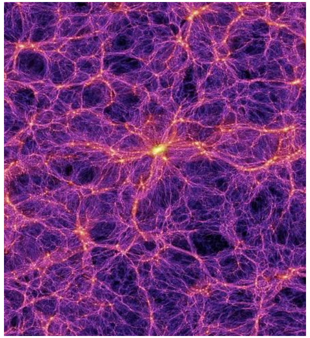
Cluster scales





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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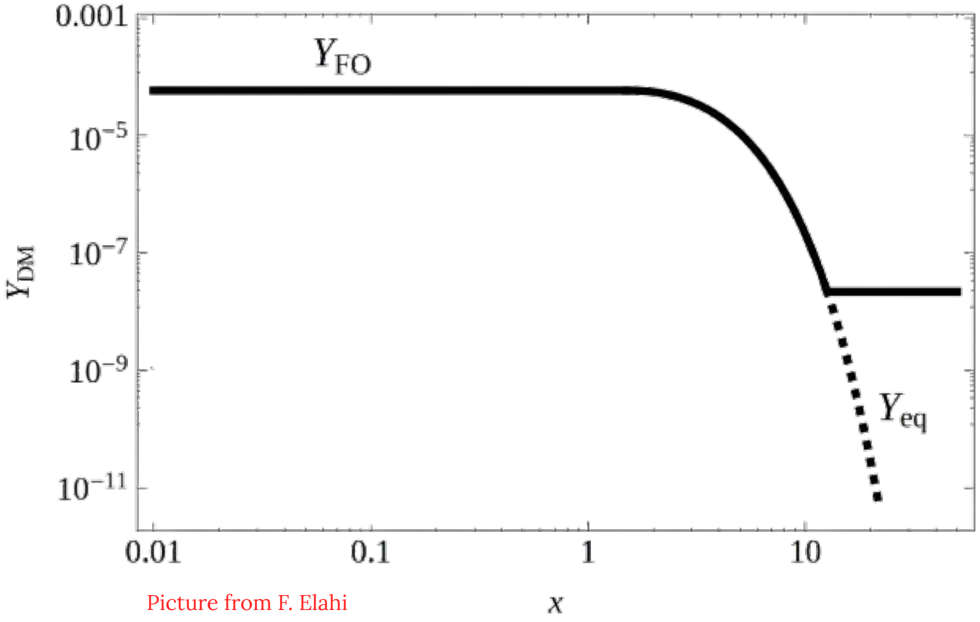
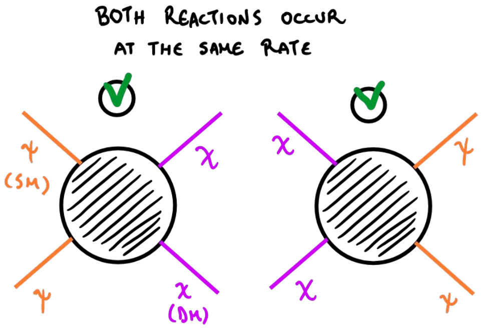
How was DM produced in the early universe?

The Canonical Freeze-out story

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



Picture from F. Elahi



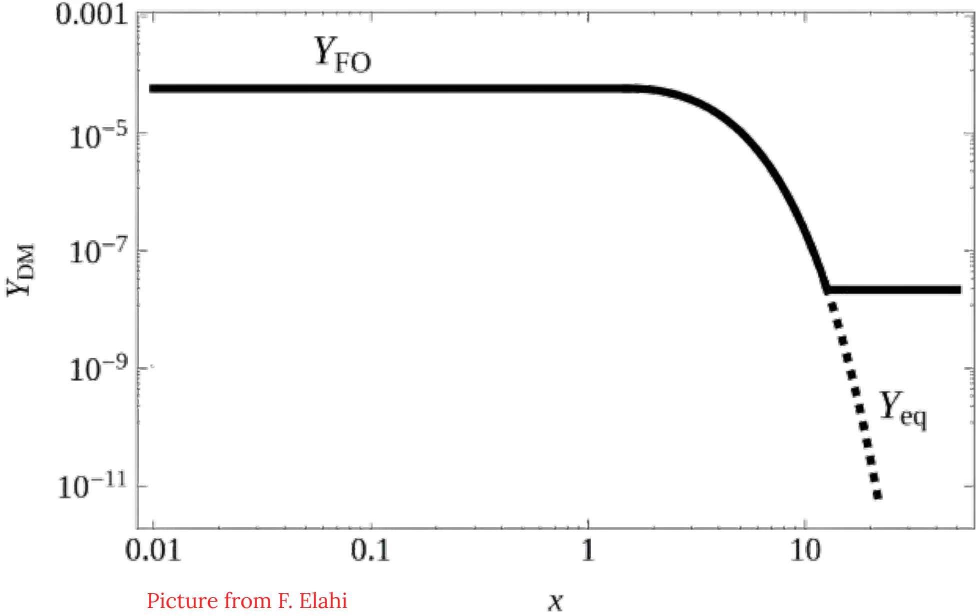
$$Y_{\rm DM} \equiv \frac{n_{\rm DM}}{s}$$

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

The Canonical Freeze-out story

The WIMP miracle!

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



Picture from F. Elahi

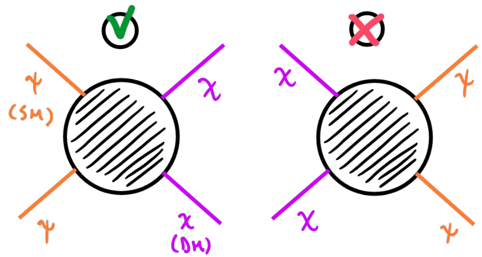
$$Y_{\rm DM} \equiv \frac{n_{\rm DM}}{s}$$

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

An alternative Scenario: Freeze-in

Hall, Jedamzik, March-Russell, West 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!)



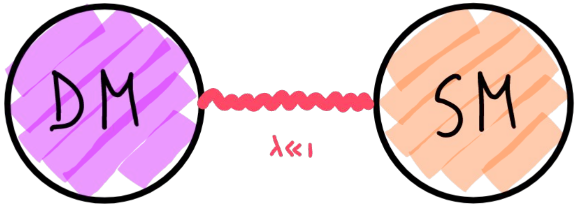
An alternative Scenario: Freeze-in

DM from a feeble interaction with SM

The suppressed interaction with SM can arise from:

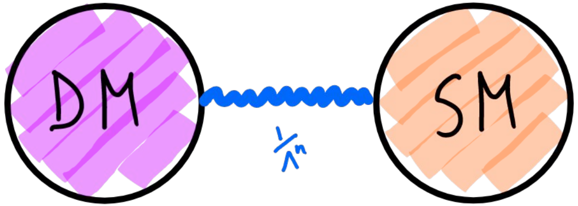
- **A very small** dimensionless coupling $\lambda_{\text{DM-SM}}$
  - renormalizable interaction

    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

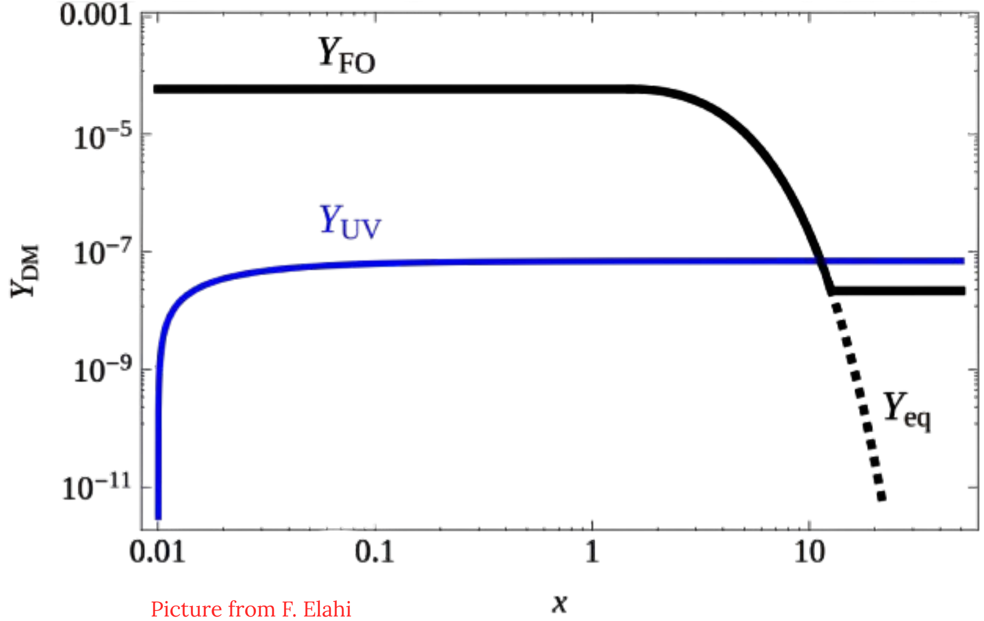


UV Freeze-in
Interaction through Non-Renormalizable operator

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

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

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

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

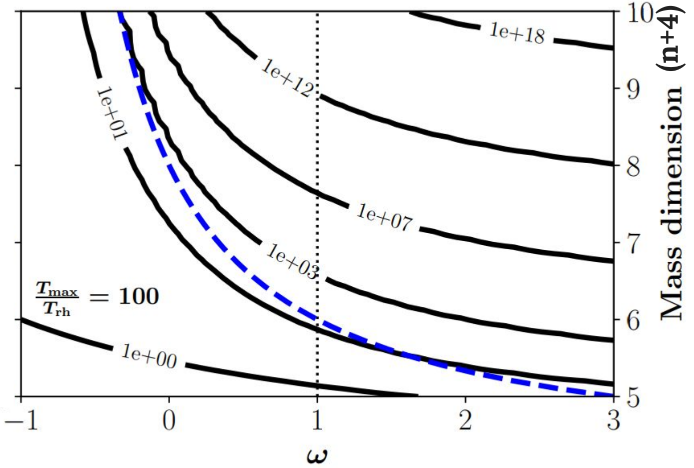
What if we go beyond the instantaneous reheating approximation?

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

- When $\mathbf{T_{max} >> T_{rh}}$ Chung, Kolb, Riotto, 1998; Giudice, Kolb, Riotto, 2000; Kolb, Notari, Riotto, 2003
- The enhancement becomes relevant for **n≳3**

$$Y_{\chi,\infty}/Y^{\rm RD}_{\chi,\infty}(T_{\rm rh}) \sim \left(\frac{T_{\rm max}}{T_{\rm rh}}\right)^{n-n_c}, \quad n > n_c$$



Bernal, Elahi ,Maldonado, Unwin 2019

UV Freeze-in

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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?

Requires a thermal bath within the inflationary phase, i.e. **Warm 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.*

WARM INFLATION

Berera 1995

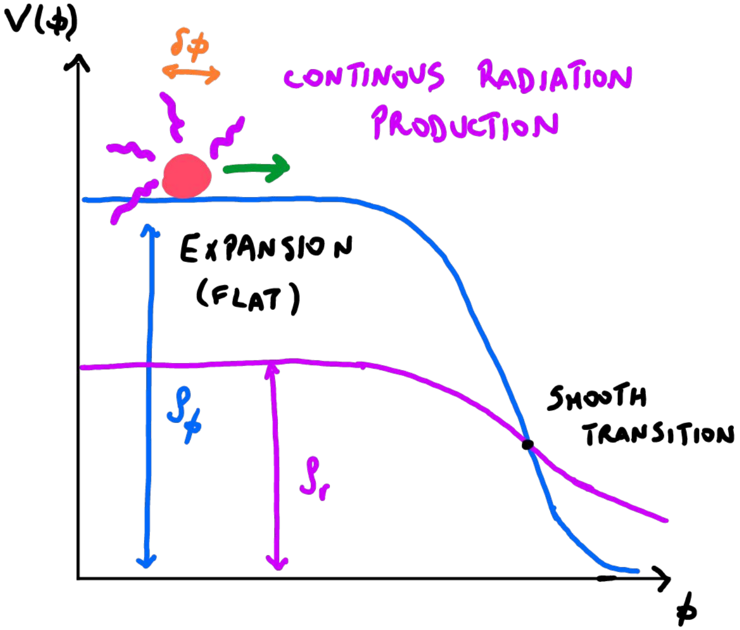
Warm Inflation (WI)

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 ϕ.
- Dissipation rate Υ acts as additional thermal friction
  - This allows $\Delta\phi < M_{pl}$
- Smooth transition to radiation dominated (RD) universe after inflation



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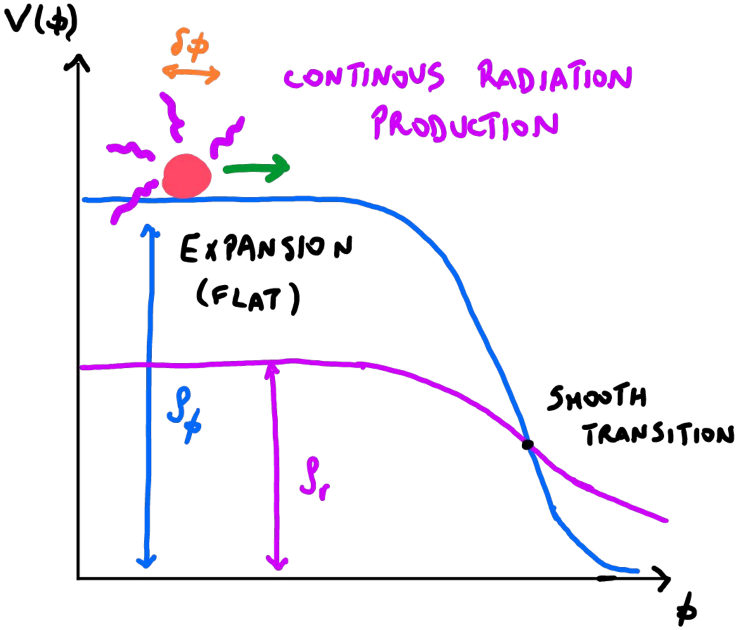
    - Tensor-to-scalar ratio **r** generically suppressed
    - Relatively large non-gaussianities



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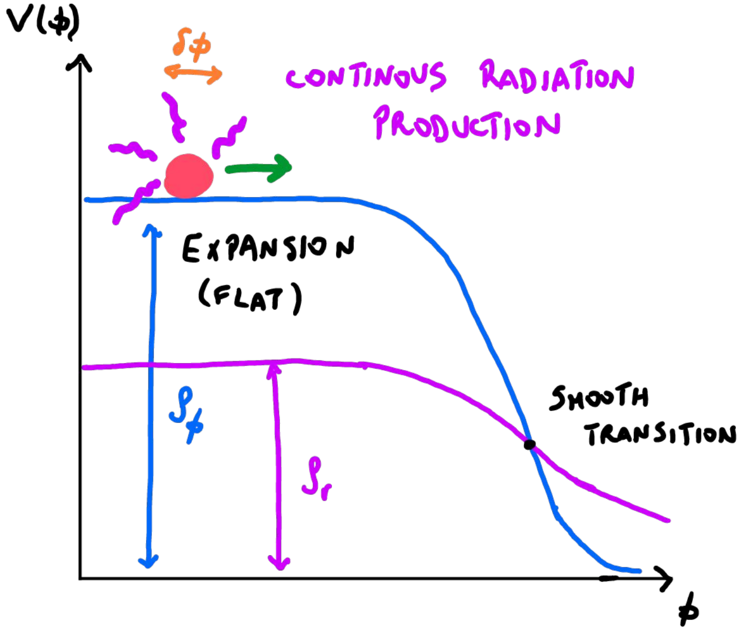


Recent development of minimal set-ups for a concrete particle physics realization of WI

- Warm Little Inflaton Bastero-Gil, Berera, Ramos, Rosa 2016
- Minimal Warm Inflation Berghaus, Graham, Kaplan 2019

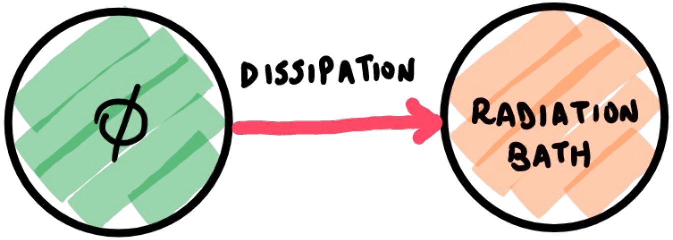
DM from Warm Inflation via UV Freeze-In

The WIFI framework

DM production during WI via UV Freeze-In

The WIFI framework

WARM INFLATION



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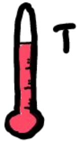
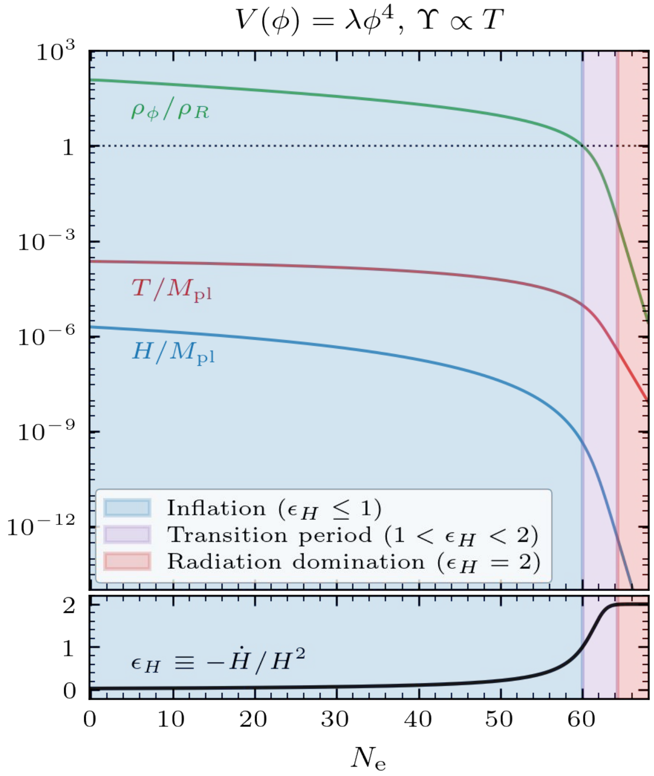




Example motivated by Warm Little Inflaton

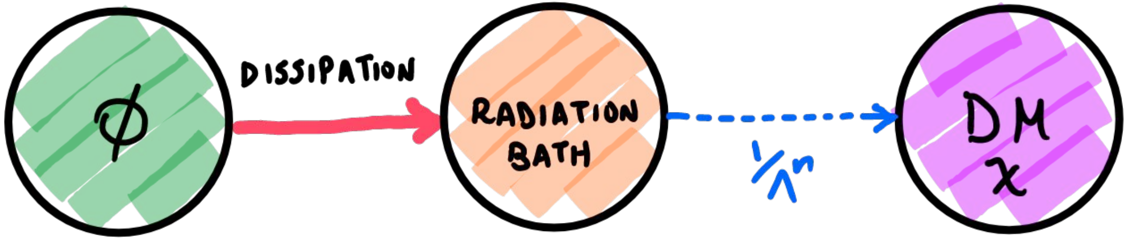
Bastero-Gil, Berera, Ramos, Rosa 2016

DM production during WI via UV Freeze-In

The WIFI framework

WARM INFLATION

UV FREEZE IN



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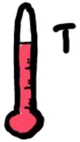

$$\dot{n}_\chi + 3Hn_\chi = T^{2n+4}/\Lambda^{2n}$$

WIFI

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

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

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

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 $\mathbf{N_e^{peak}}$

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

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

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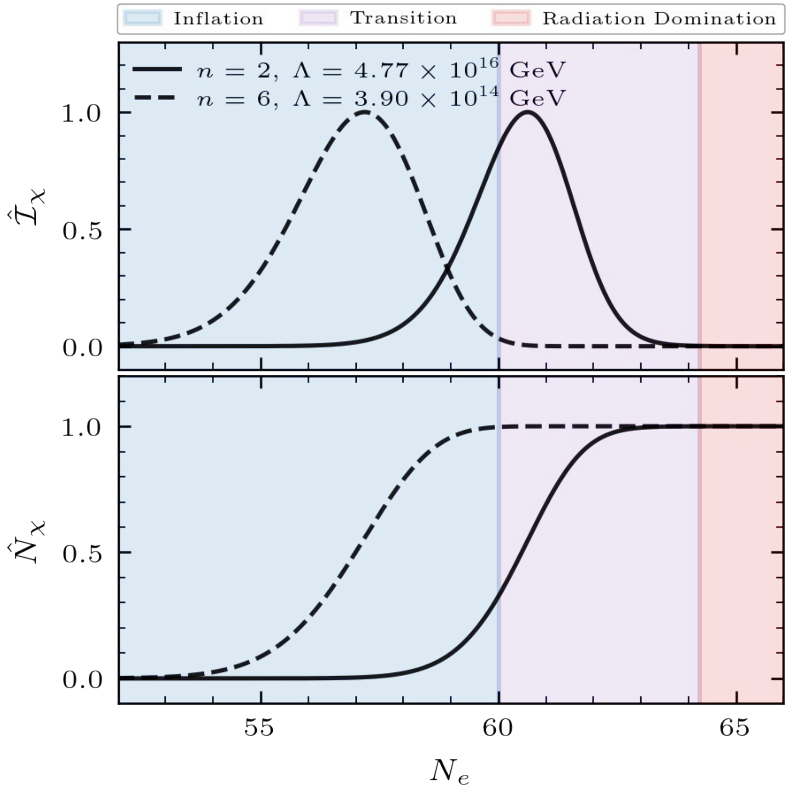

DM production during WI via UV Freeze-In

The WIFI framework

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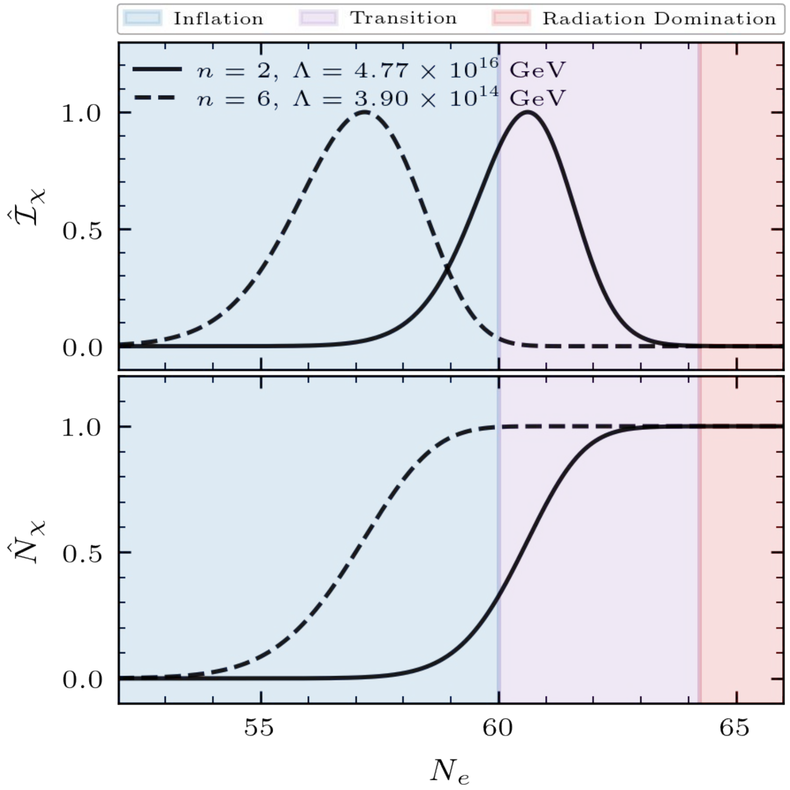


Key distinction from (standard) radiation-dominated UV freeze-in:

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

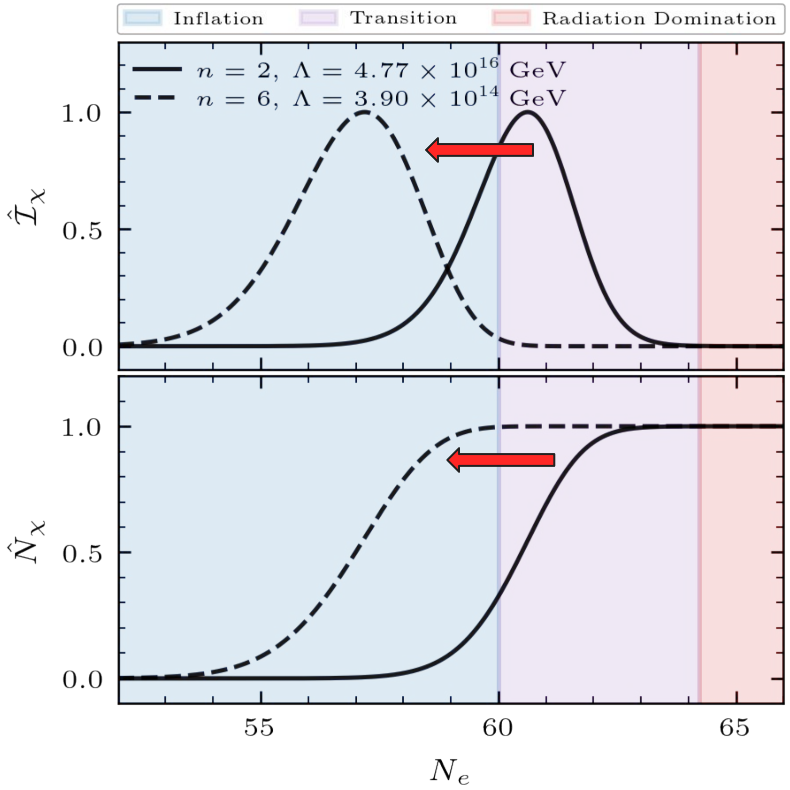
The WIFI framework

For increasing value of **n**, the peak of $\mathcal{I}_\chi$ moves to earlier times

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

Recall:

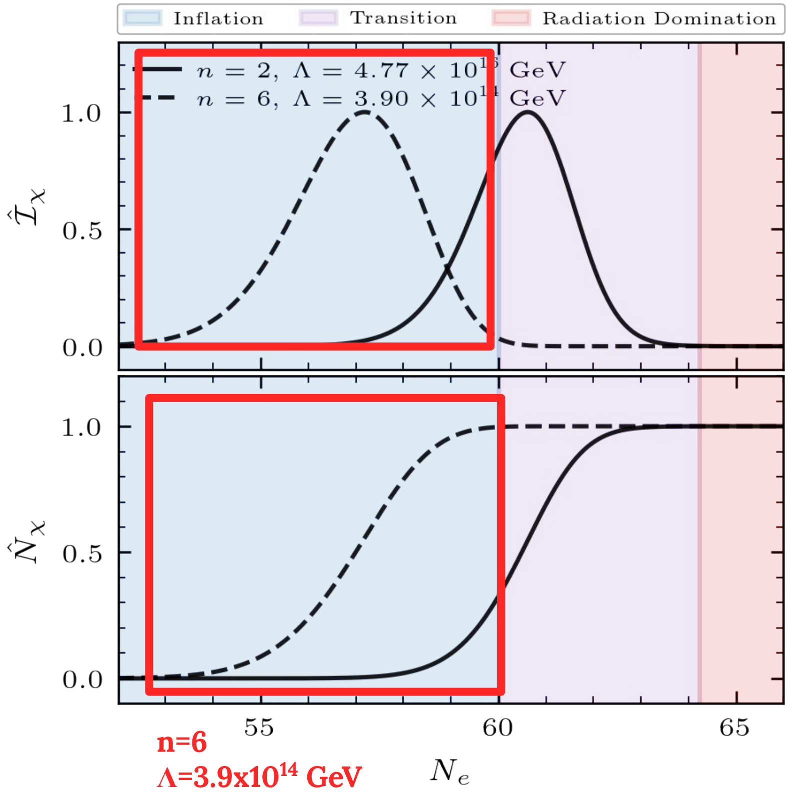
- Deep in WI: $\mathcal{I}_\chi \sim e^{3N_e}$
- In RD: $\mathcal{I}_\chi \sim e^{-(2n-1)N_e}$



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

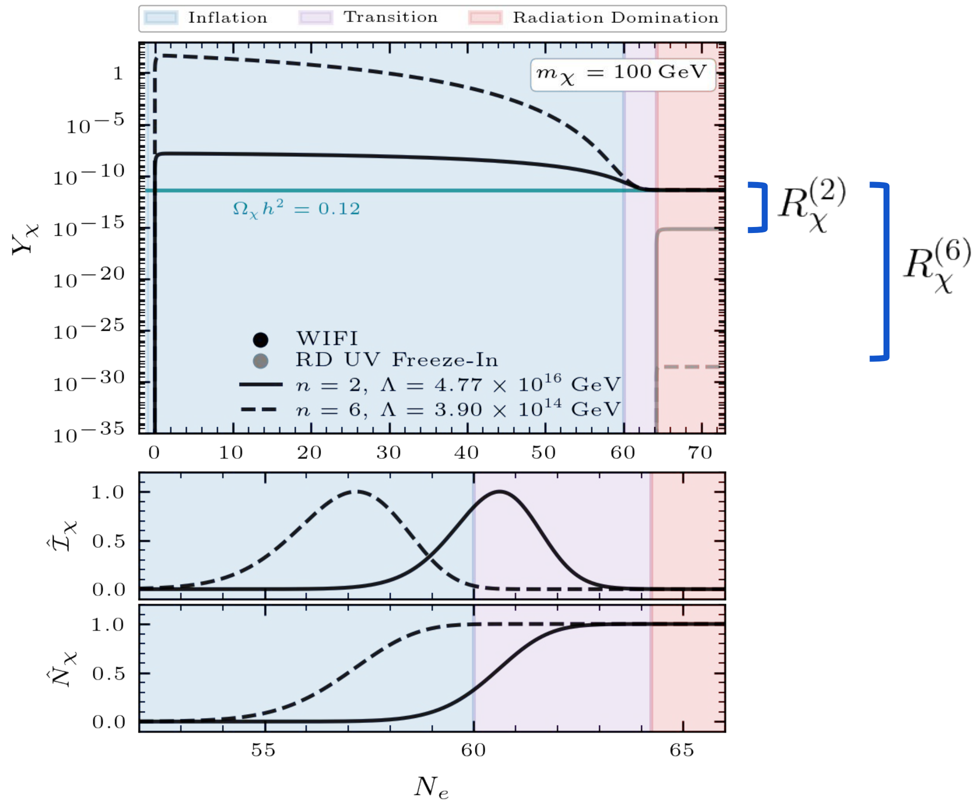
For increasing value of **n**, the peak of $\mathcal{I}_\chi$ moves to earlier times

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



An example of DM production in WIFI

Evolution of DM abundance



The Enhancement Ratio:

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

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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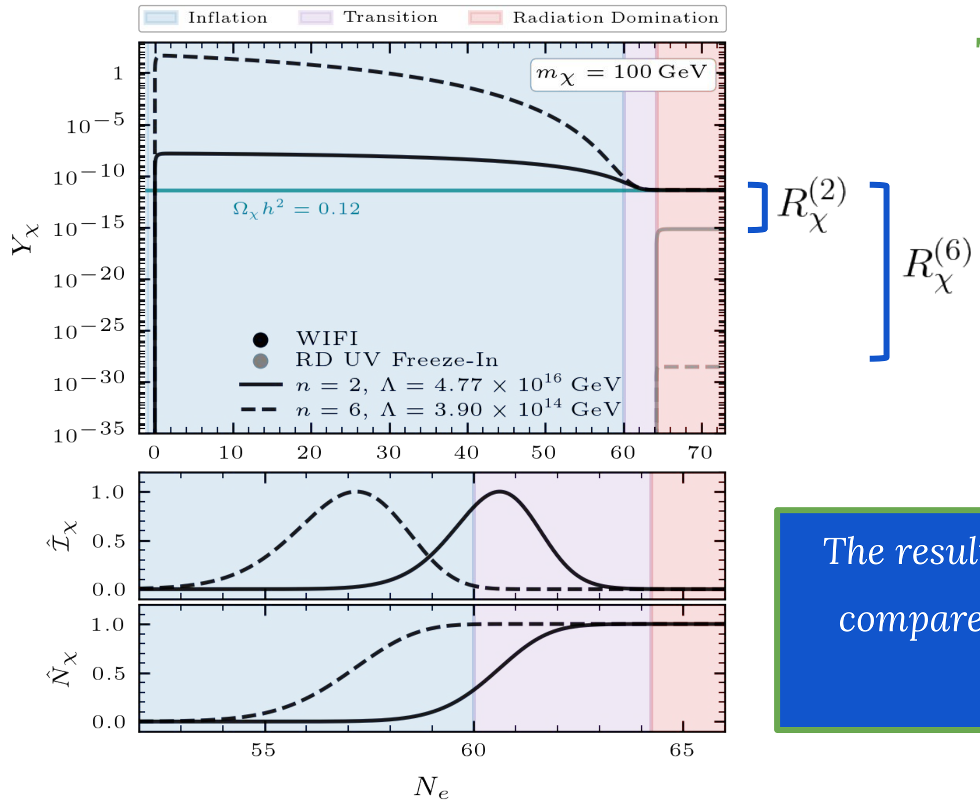

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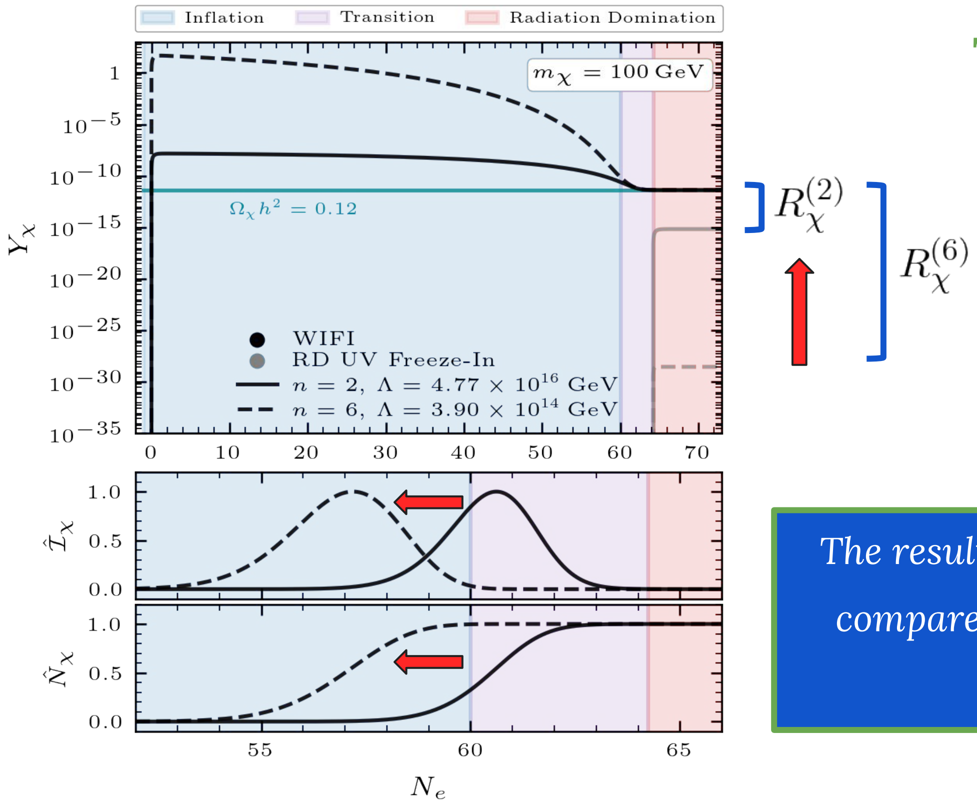
$\gg 1$

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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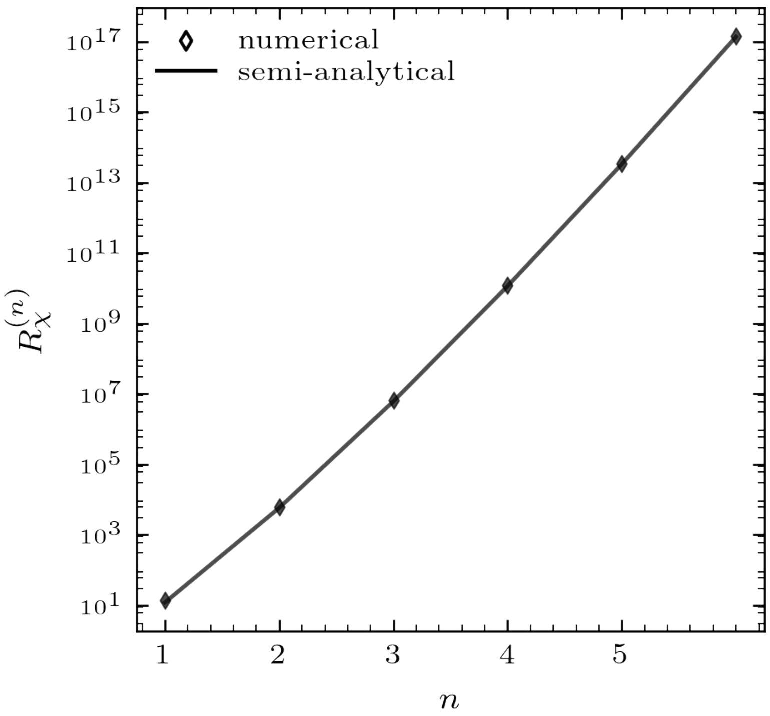
The Enhancement Ratio

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

- The enhancement ratio increases **exponentially** with **n**
  - **~10** already for **n=1**
  - **≫10^3** for **n≥3**

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



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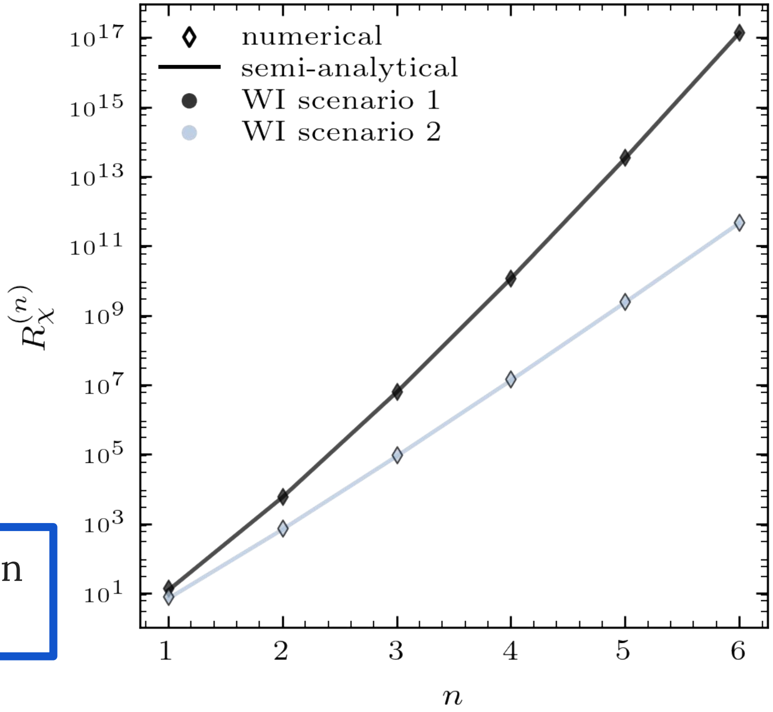


NOTE: The specific WI dynamics has a significant effect on the size of overall enhancement

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)

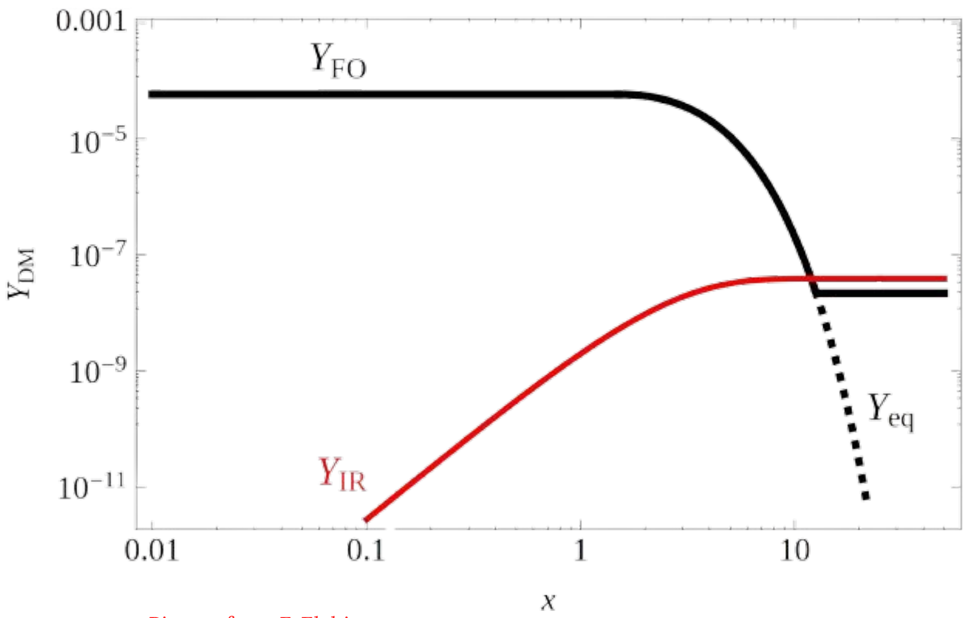
BACK-UP SLIDES

IR Freeze-in

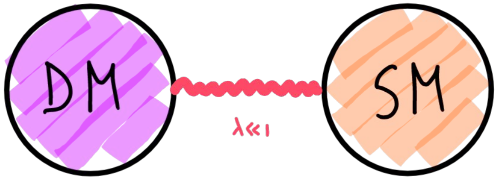
Hall, Jedamzik, March-Russell, West 2010

Interaction through Renormalizable operator

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



Picture from F. Elahi



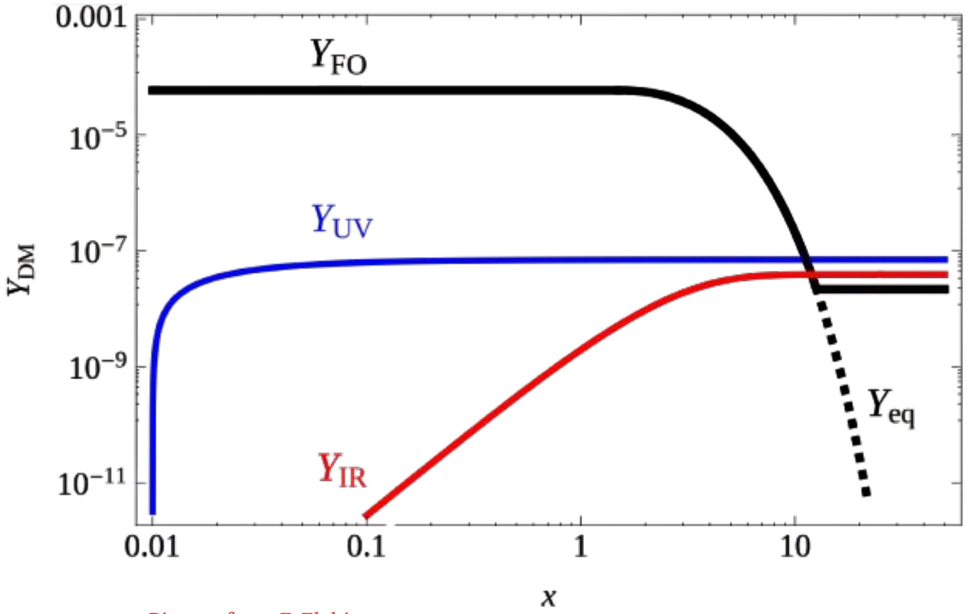
DM freezes-in **gradually** and depends on the **lowest T**, i.e. $T \square m_{DM}$

UV Freeze-in

Elahi, Kolda, Unwin 2015

Interaction through Non-Renormalizable operator

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



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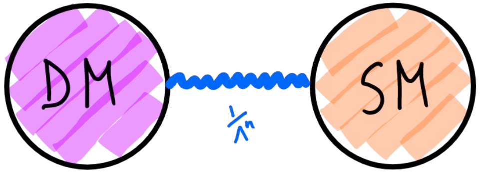


DM freezes-in **quickly** and depends on the **highest T**, i.e. $\mathbf{T_{rh}}$

UV Freeze-in

Elahi, Kolda, Unwin 2015

Interaction through Non-Renormalizable operator

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

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

$$Y_\chi \equiv \frac{n_\chi}{\underbrace{s}}$$

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

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

(the effective number of relativistic degrees of freedom)

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

$$\frac{1}{\Lambda^n}\underbrace{\phi_1\phi_2\cdots\phi_{n+3}}_{\text{SM fields}}\underbrace{\varphi}_{\text{DM}} \qquad (\phi_1\phi_2 \to \phi_3\cdots\phi_{n+3}\varphi)$$

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

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

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

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

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

Warm Inflation Model Building

The Challenge

Inflaton couples to light fields

↓

To have a sustained radiation bath, interaction cannot be too small

↓

light fields gain large masses

↓

Leads to large quantum and thermal corrections
to inflaton mass, that spoil dynamics

J. Yokoyama, A. Linde, 1998

Warm Inflation Model Building

Early Attempts

- Make theory supersymmetric to control quantum corrections

  Berera, Gleiser, Ramos, 1999

- Avoid directly coupling inflaton to radiation fields: only indirectly through heavy mediators so that thermal corrections are Boltzmann suppressed

  Berera, Ramos 2001 - 2003; Moss, Xiong 2006; Bastero-Gil, Berera, Ramos 2011; Bastero-Gil, Berera, Ramos, Rosa 2014 - 2015

$$\mathcal{L} = V(\phi) - g^2\phi^2\chi^2 - h\phi\bar{\psi}_\chi\psi_\chi - f\chi\bar{\psi}_\sigma\psi_\sigma + g'^2\chi^2\sigma^2 + \cdots$$

Heavy mediators

$m_\chi = g\phi \gg H, T$

Light Fermions

$m_\sigma \ll T$

  - Need large number (**~10^6**) of mediator fields though

Warm Inflation Model Building

Recent Developments

Warm Little Inflaton

Bastero-Gil, Berera, Ramos, Rosa 2016

$$-\mathcal{L} \supset V(\phi) + gM\cos(\phi/M)\bar{\psi}_1\psi_1 + gM\sin(\phi/M)\bar{\psi}_2\psi_2 + h\sigma\left(\bar{\psi}_j\chi + \bar{\chi}\psi_j\right)$$

- Inflaton is a PNGB coupled to a pair of light fermions
- Symmetry structure enforces (1) bounded fermion masses; (2) no thermal corrections

Minimal Warm Inflation

Berghaus, Graham, Kaplan 2019

$$\mathcal{L} \supset -V(\phi) + \frac{\phi}{f}\tilde{F}^{a\mu\nu}F^{a}_{\mu\nu}$$

- Inflaton is an axion-like particle protected by its shift symmetry
- Dissipation from sphaleron heating via coupling to Yang-Mills Fields

$\longrightarrow$ In this models, WI is almost inevitable DeRocco, Graham, Kalia 2021

Warm Inflation
Perturbation Spectra

Bastero-Gil, Berera, Ramos 2011
Graham, Moss 2009

- The scalar power spectrum is enhanced by thermal effects;
- The tensor power spectrum is unaltered;
- G(Q) accounts for the direct coupling of the inflaton and radiation fluctuations due to a temperature dependent dissipative rate $\Upsilon \propto T^c$
    - Approximated to a polynomial in Q
    - If c>0 : spectrum is further enhanced;
    - If c<0 : spectrum is suppressed;

$$\Delta_s^2 = \left(\frac{H^2}{2\pi\dot{\phi}}\right)^2 \left[\underbrace{1 + 2n_{BE}}_{\Delta_s^{2\,(\text{vac, warm})}} + \underbrace{\frac{2\sqrt{3}\pi Q}{\sqrt{3+4\pi Q}}\left(\frac{T}{H}\right)}_{\Delta_s^{2\,(\text{diss})}}\right] G(Q)$$

$$\Delta_s^{2\,(\text{vac, cold})} = \left(\frac{H^2}{2\pi\dot{\phi}}\right)^2$$

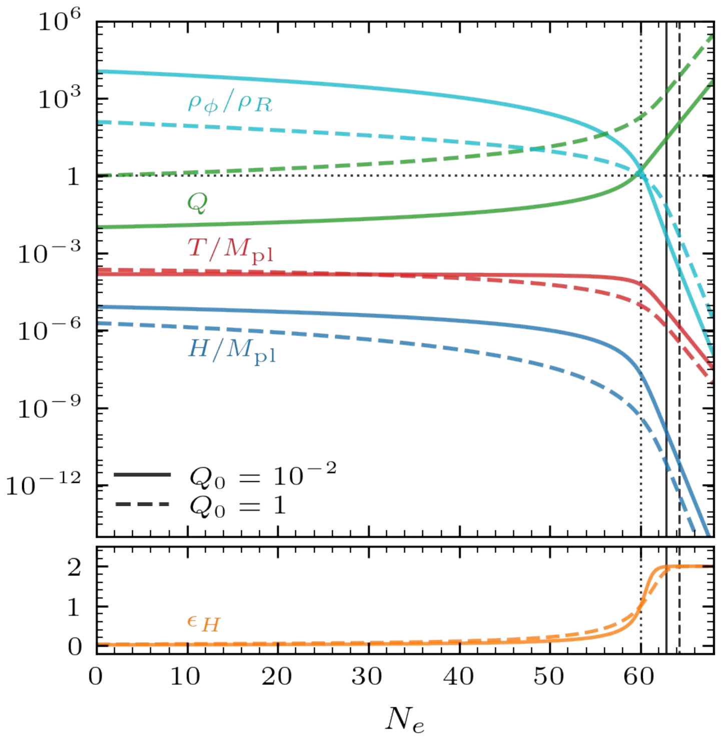
$$n_{\text{BE}} = 1/[\exp(H/T) - 1]$$

Warm Inflation
Computing Cosmological Observables

- We use **WarmSPy** to compute the background dynamics. GM, V. Aragam, L. Visinelli, K. Freese 2023
  - We fix the initial dissipation strength $\mathbf{Q_0}$ (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. $\boldsymbol{\varepsilon_H(N_e=60)=1}$
  - We fix the height of the potential (in our case $\boldsymbol{\lambda}$), to match the amplitude of the primordial power spectrum at the CMB pivot scale $\mathbf{k_*=0.05\ Mpc^{-1}}$
  - We compute $\mathbf{r}$ and $\mathbf{n_s}$ and ensure they are within the CMB bounds, otherwise we repeat the process for a different $\mathbf{Q_0}$

An example of DM production in WIFI
WI dynamics

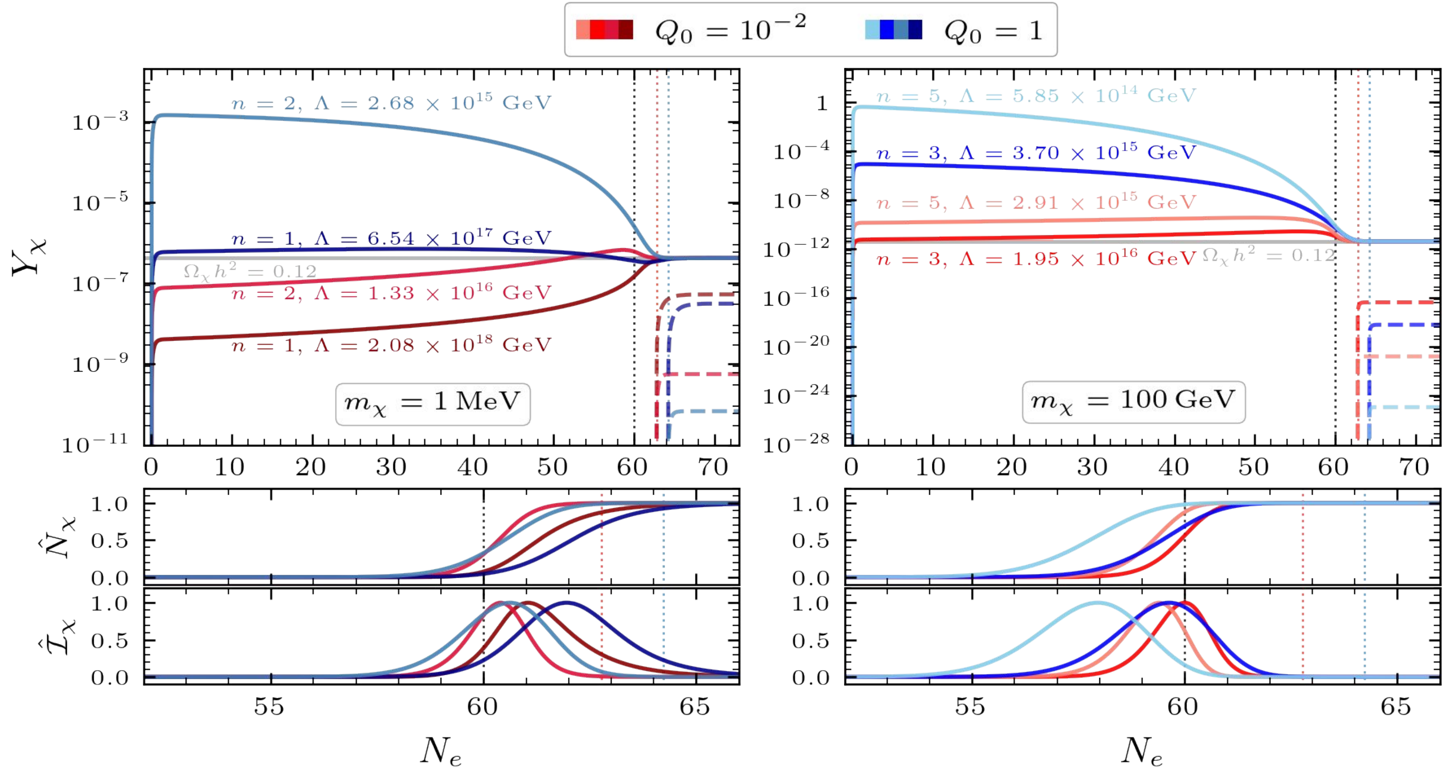
- We consider two scenarios: **$V(\phi)=\lambda\phi^4, \Upsilon \propto T$** with **$Q_0=10^{-2}$** and **$Q_0=1$**.
  - Note **$Q=\Upsilon/(3H)$** defines the strength of the dissipation
- parameters of the inflaton potential set to enforce 60 e-folds and produce cosmological observables consistent with CMB data



Dynamics computed with **WarmSPy!**
github.com/GabrieleMonte/WarmSPy

GM, V. Aragam, L. Visinelli, K. Freese 2023

An example of DM production in WIFI
The DM Yield Evolution



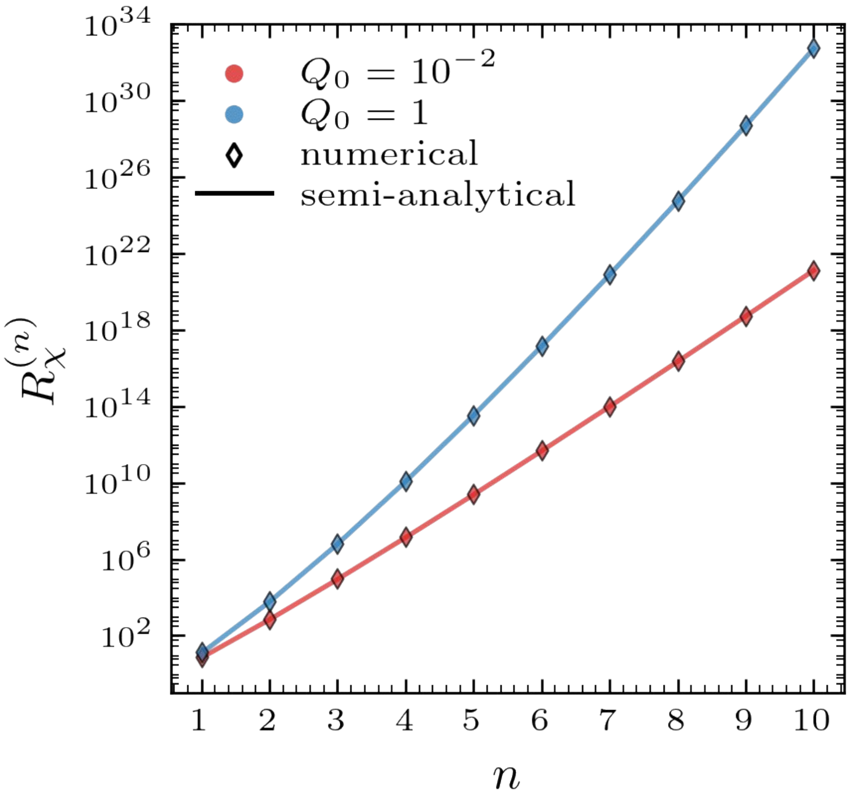
$$N_\chi = e^{3N_e} n_\chi$$

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

An example of DM production in WIFI

The Enhancement Ratio

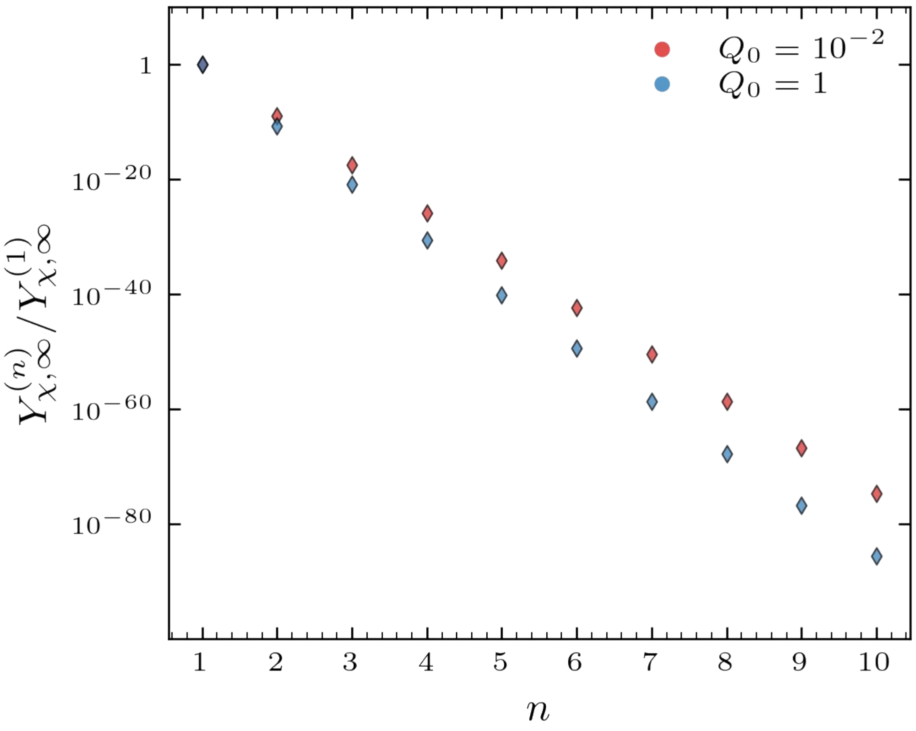
$$R_\chi^{(n)} \simeq (2n-1)\frac{\mathcal{I}_\chi(N_e^{\rm peak})}{\mathcal{I}_\chi(N_e^{\rm RD})}\Delta N_e^{\rm peak}$$



An example of DM production in WIFI

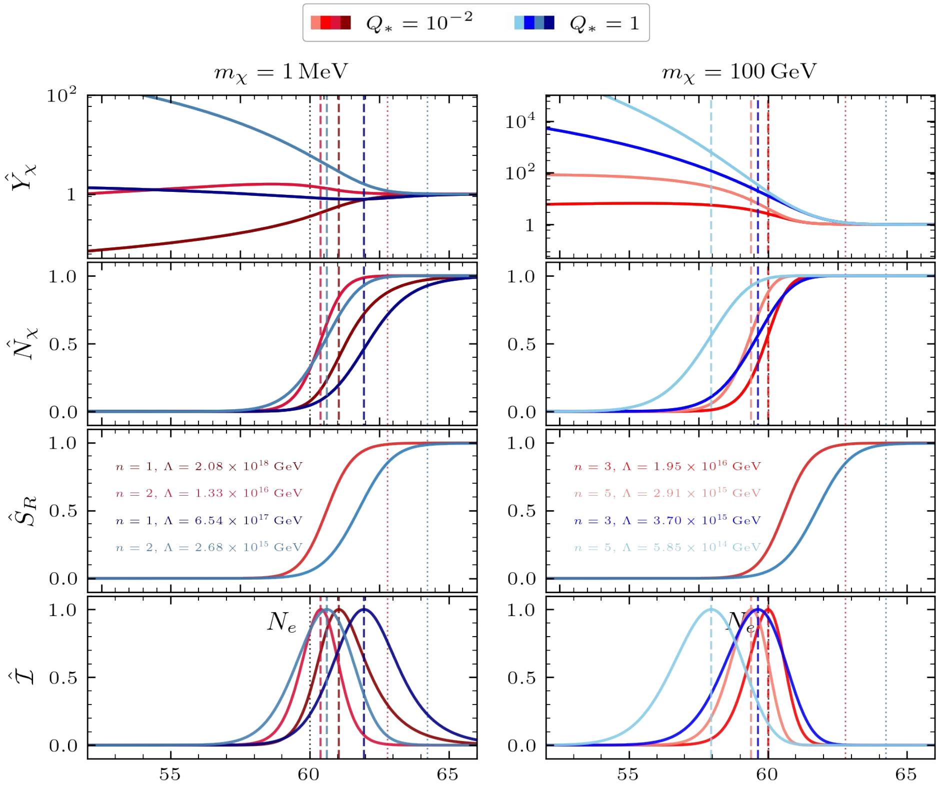
Comparison of DM yield for different n values

As expected for a fixed value of Λ*,*
the relic DM yield is exponentially suppressed
at large values of n



An example of DM production in WIFI

More on the 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

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