Dark Matter Production During Warm Inflation via Freeze-In

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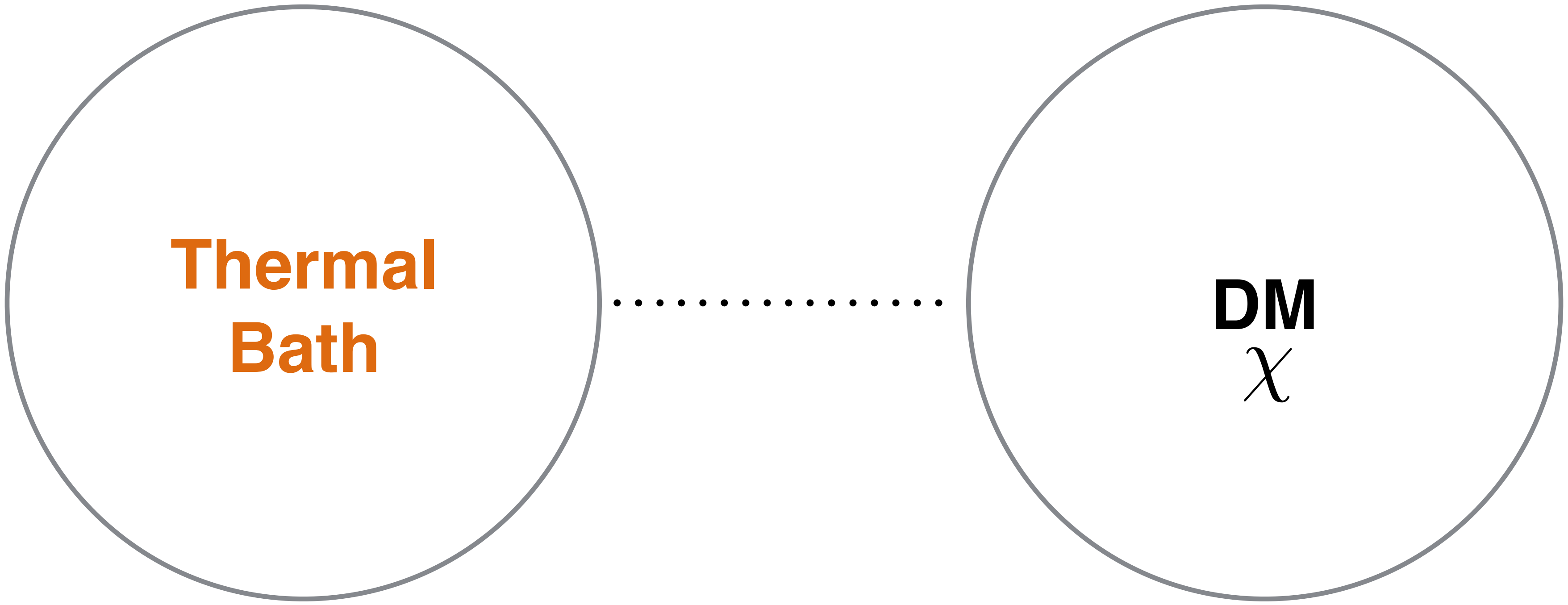
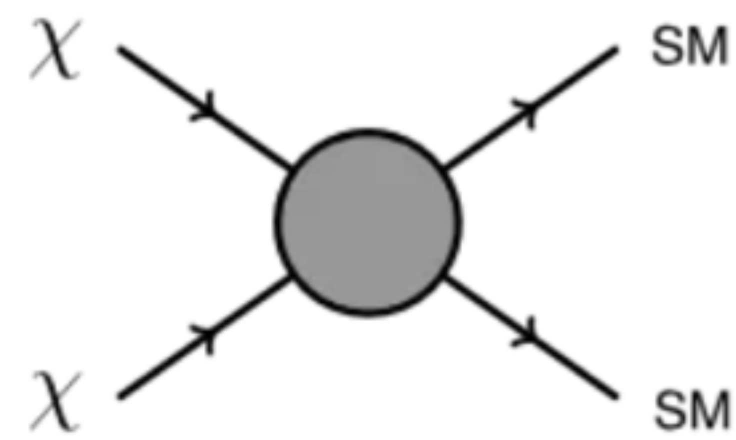
An intriguing mechanism to produce DM:
through interaction with a **thermal bath.**

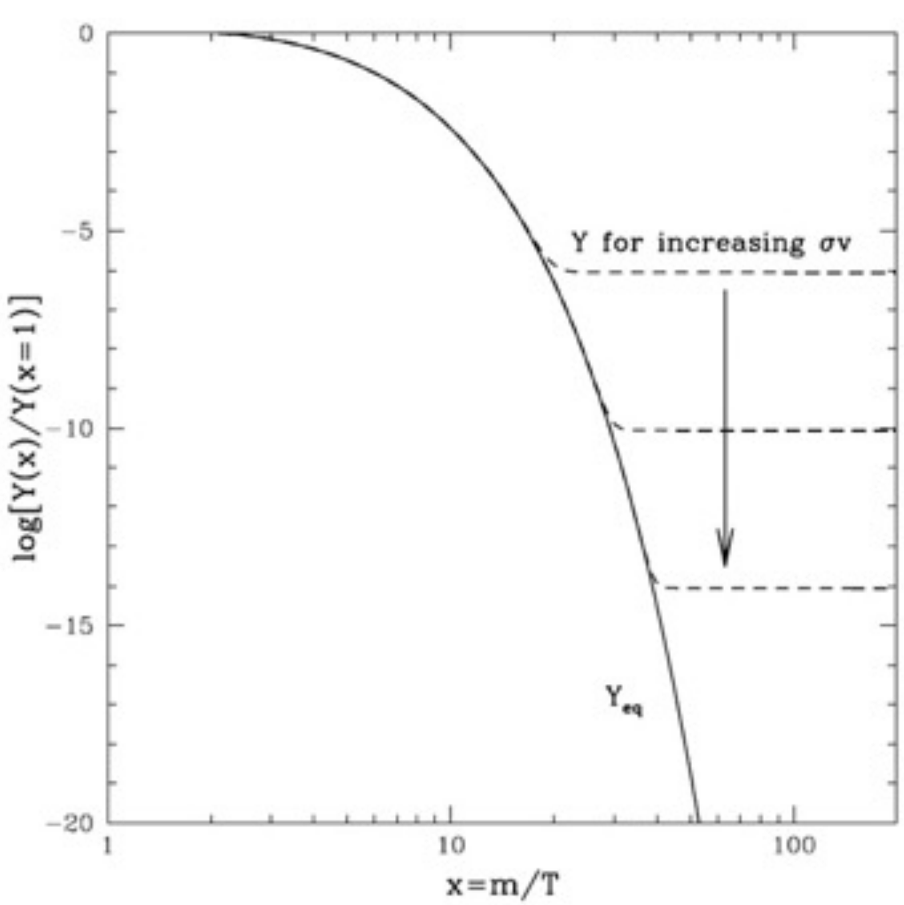


depending on the interaction:
DM abundance is mainly established by
freeze-out or **freeze-in** mechanisms.

Freeze-out:

$$\dot{n}_\chi + 3Hn_\chi = -\langle \sigma v \rangle \left(n_\chi^2 - n_{\chi,\mathrm{eq}}^2 \right)$$



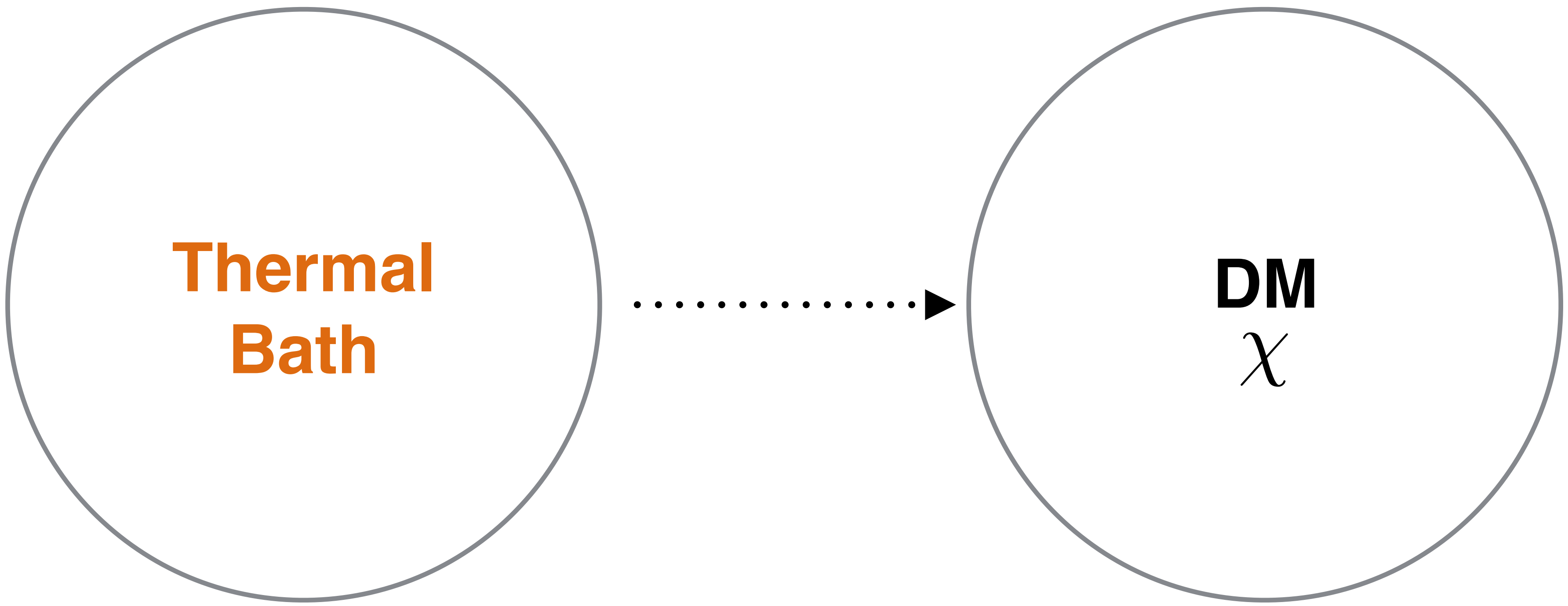


Freeze-in:

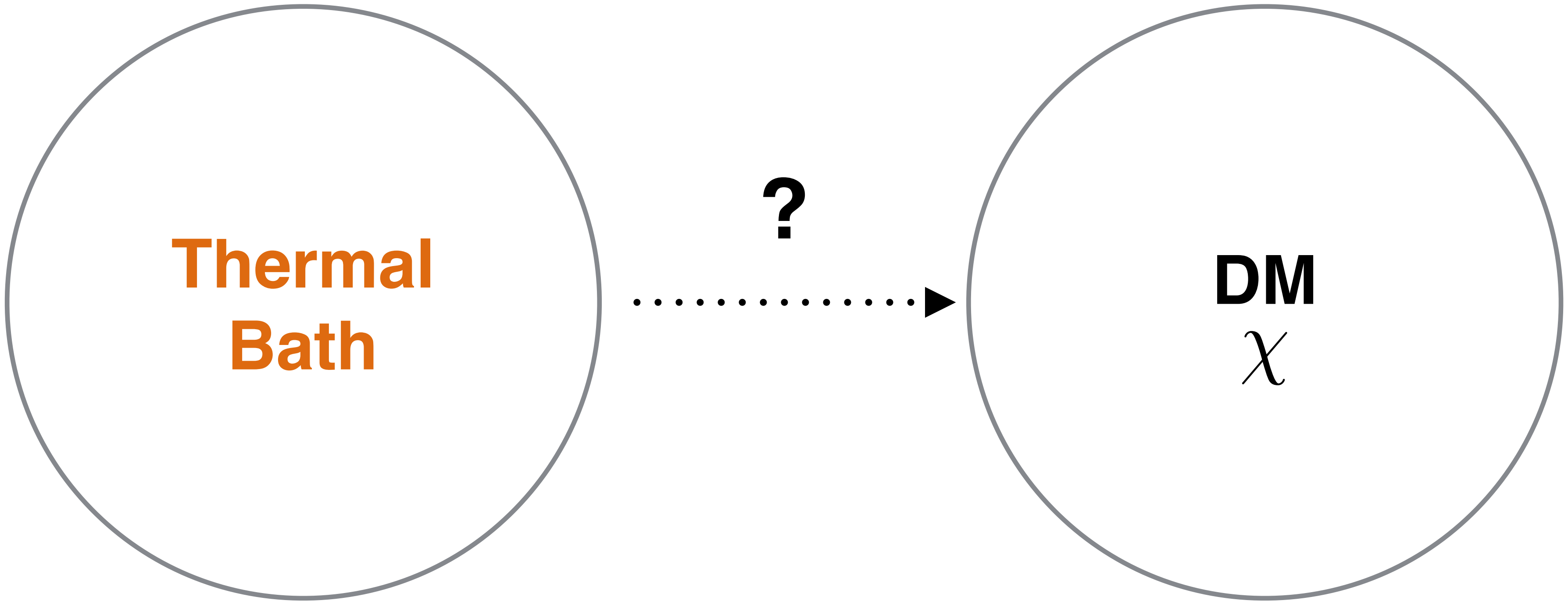
$$\dot{n}_\chi + 3Hn_\chi = -\langle \sigma v \rangle \left(n_\chi^2 - n_{\chi,\mathrm{eq}}^2 \right)$$

the DM final abundance is built up gradually over time

L. J. Hall, K. Jedamzik, J. March-Russell, S. M. West, 2009



How can we suppress the production rate?



renormaizblae operators
and **very small coupling**

$$\lambda \ll 1 \qquad Y_\chi \sim \lambda^2 \frac{m_{\rm Pl}}{T} \sim \lambda^2 \frac{m_{\rm Pl}}{m_\chi}$$

L. J. Hall, K. Jedamzik, J. March-Russell, S. M. West, 2009

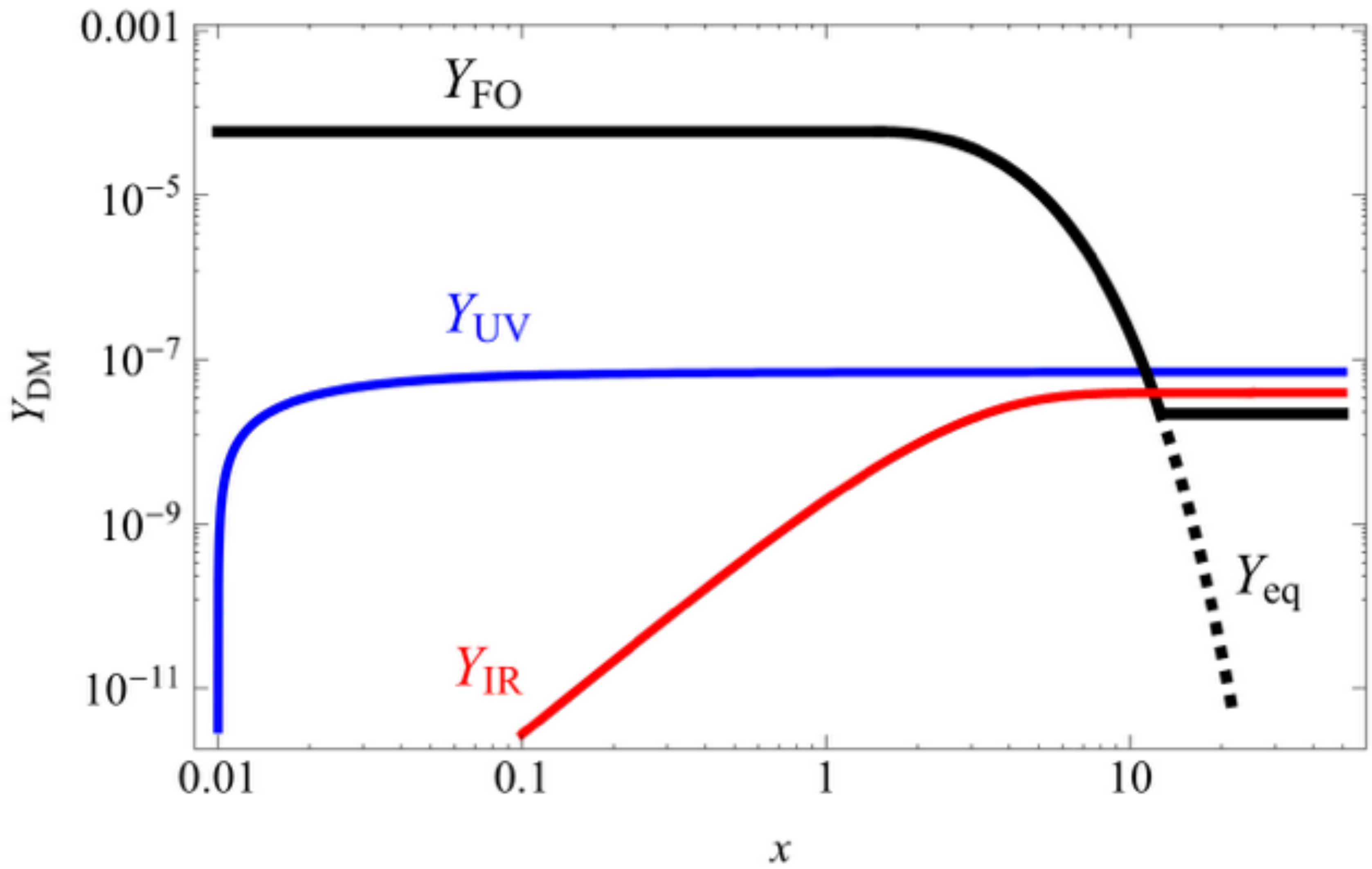
IR freeze-in

non-renormaizblae operators
(a heavy scale)

$$\frac{1}{\Lambda^n} \qquad Y_\chi \sim \frac{m_{\rm Pl} T^{2n-1}}{\Lambda^{2n}}$$

F. Elahi, C. Kolda, J. Unwin, 2014

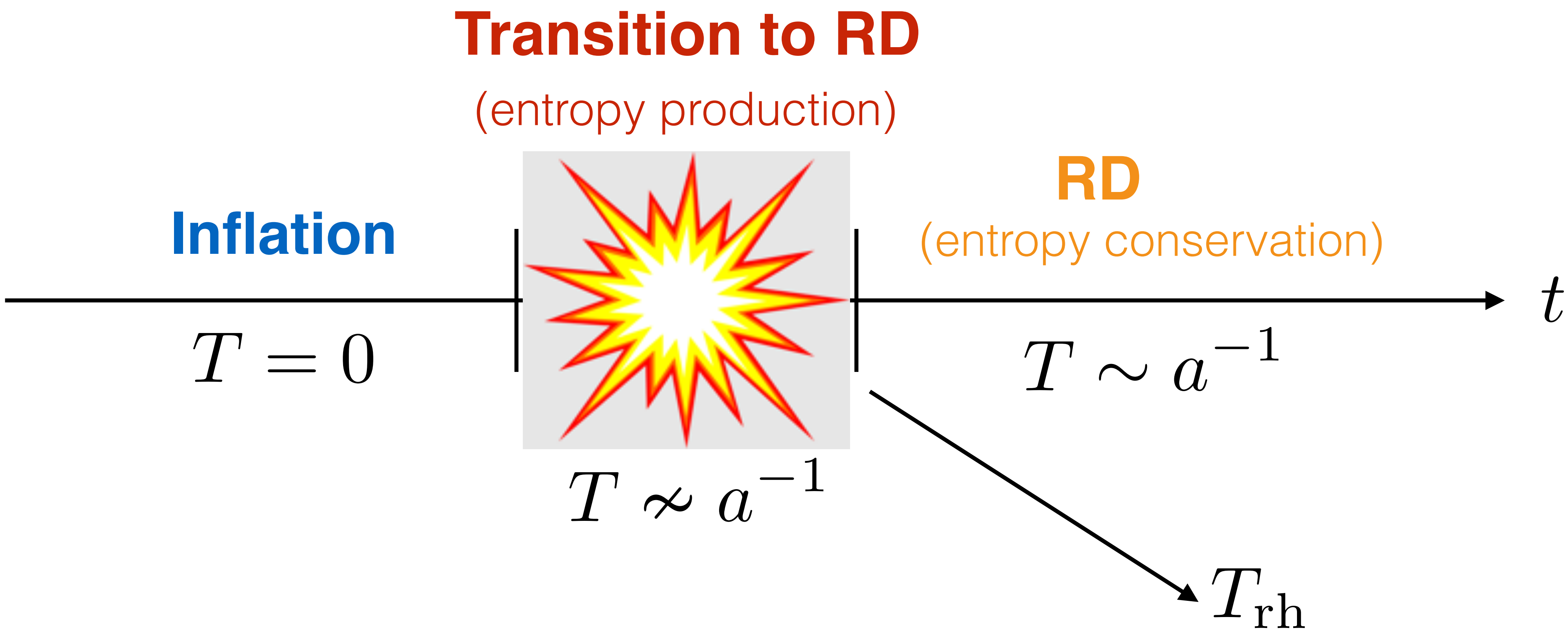
UV freeze-in



F. Elahi, C. Kolda, J. Unwin, 2014

UV freeze-in is sensitive to the highest temperature.

What is the highest temperature of the bath?



$$T_{\rm max} \gg T_{\rm rh} \qquad \frac{T_{\rm max}}{T_{\rm rh}} \sim \left(\frac{H_I m_{\rm Pl}}{T_{\rm rh}^2}\right)^{1/4} \gtrsim 10^3$$

D.J. H. Chung, E. W. Kolb, A. Riotto, 1998

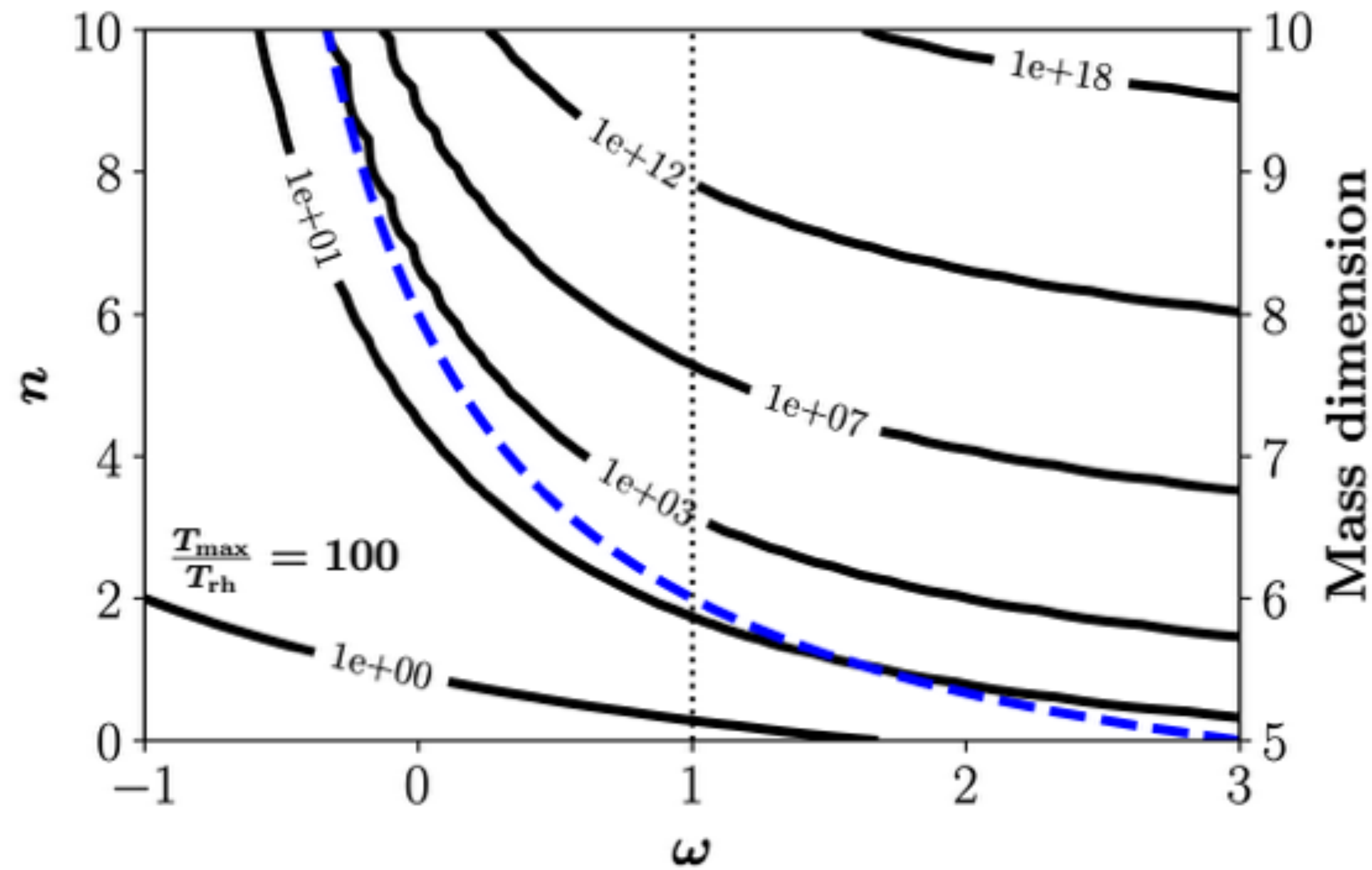
G. F. Giudice, E. W. Kolb, A. Riotto, 2000

E. W. Kolb, A. Notari, A. Riotto, 2003

UV freeze-in during reheating prior to RD :

Enhancement of DM yield from UV freeze-in compared to instantaneous reheating case

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



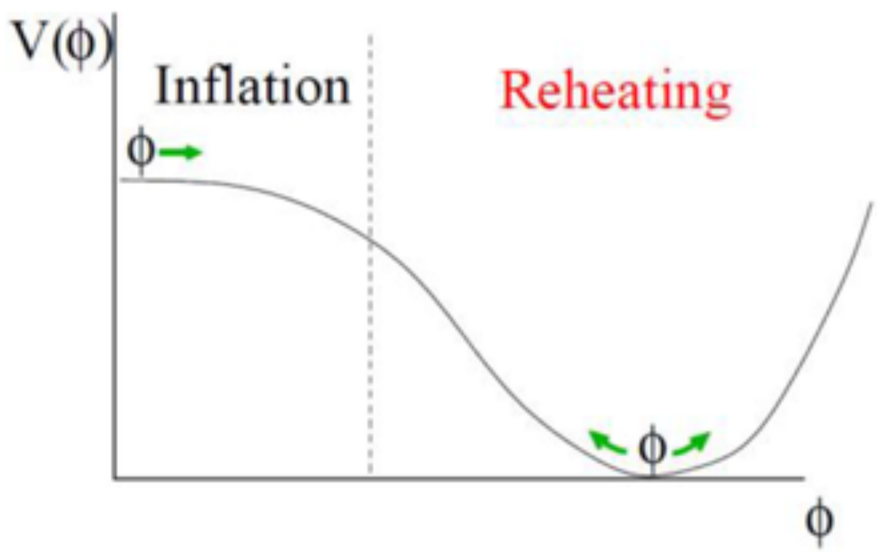
N. Bernal, F. Elahi, C. Maldonado, J. Unwin, 2019

UV freeze-in during reheating ✓

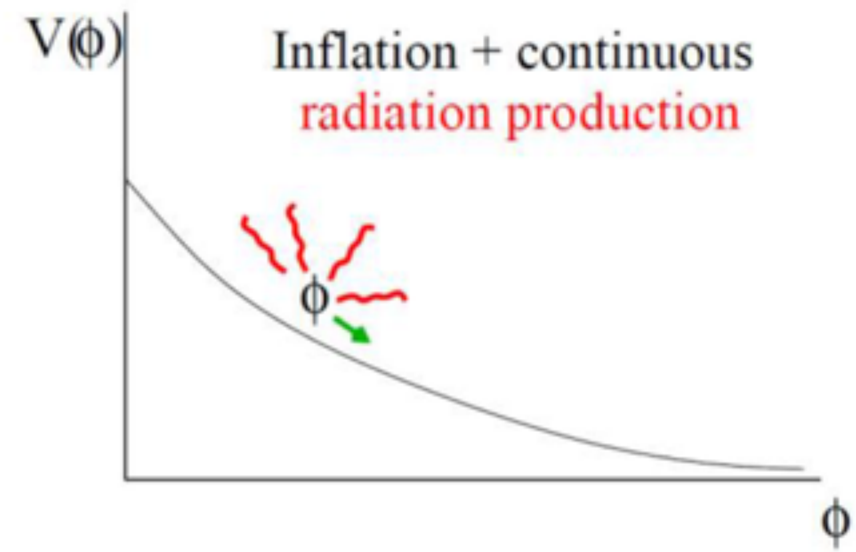
How about UV freeze-in during inflation?

Requires a thermal bath within the inflationary phase:
warming up cold inflation!

Cold Inflation



Warm Inflation



Berera, 1995

$$\ddot{\phi} + (3H + \Upsilon)\dot{\phi} + dV(\phi)/d\phi = 0$$

$$\dot{\rho}_r + 4H\rho_r = \Upsilon\dot{\phi}^2$$

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

the inhomogeneities sourced by thermal fluctuations

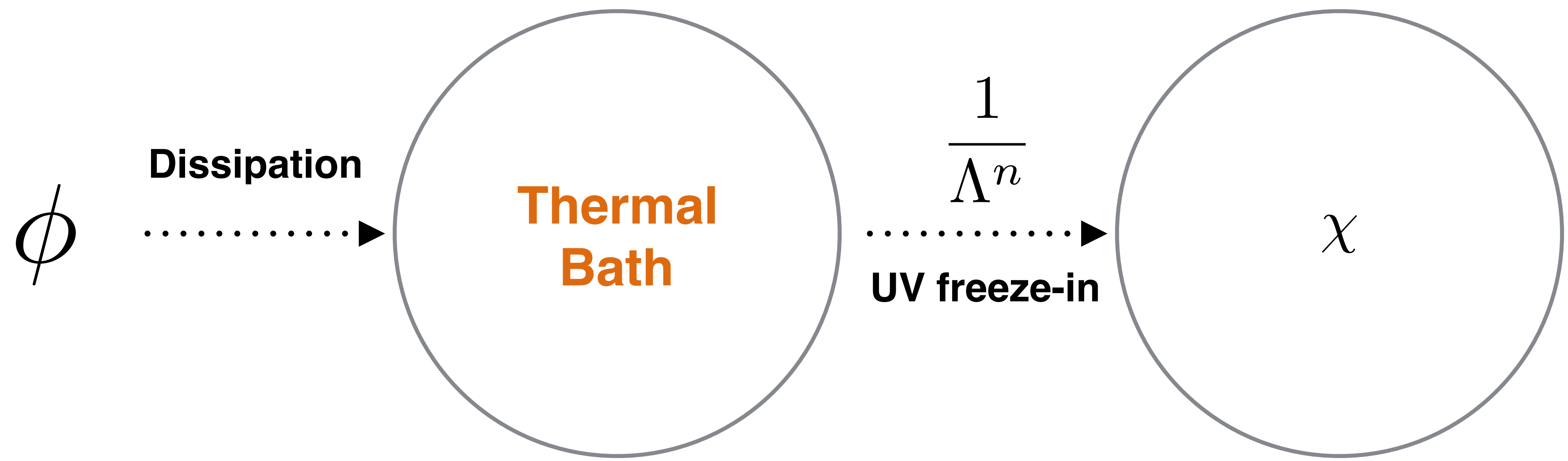
$\rho_\phi > \rho_r$ inflation

$\Upsilon \gtrsim 3H$

$\max\{\Upsilon, H\} > m_\phi$ slow-roll regime

$T > H$ Thermal fluctuations dominate over quantum ones

DM production during Warm Inflation via ultraviolet Freeze-In (WIFI)



Cosmology:

$$\ddot{\phi} + (3H + \Upsilon)\dot{\phi} + dV(\phi)/d\phi = 0$$

$$\dot{\rho}_r + 4H\rho_r = \Upsilon\dot{\phi}^2$$

$$\Upsilon = \Upsilon(\phi, T)$$

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

DM production via UV freeze-in:

$$\mathcal{L} \supset \mathcal{O}_{n+4}/\Lambda^n \qquad 2 \to n+2$$

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

Evolution of DM yield:

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

T **and** ***H*** are outputs of warm inflation model

$$Y_\chi(N_e) = \frac{45}{2\pi^2 g_\star}\frac{e^{-3N_e}}{T^3(N_e)}\int_{N_{e,0}}^{N_e}\mathcal{I}_\chi(N_e')dN_e'$$

$$N_e \equiv \ln a$$

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

rate of change of comoving DM number density

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

deep in warm inflation: $\mathcal{I}_\chi(N_e) \sim e^{3N_e}$

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

it has to peak somewhere between

Maximum contribution to the yield:

comoving production rate is sharply peaked at N_e^{peak}

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

Key distinction from UV freeze-in during reheating:

In WIFI, DM abundance is not set by the highest temperature of the bath, but rather in a short time around N_e^{peak}

Warm Little Inflaton

M. Bastero-Gil, A. Berera, R. O. Ramos, J. G. Rosa , 2016

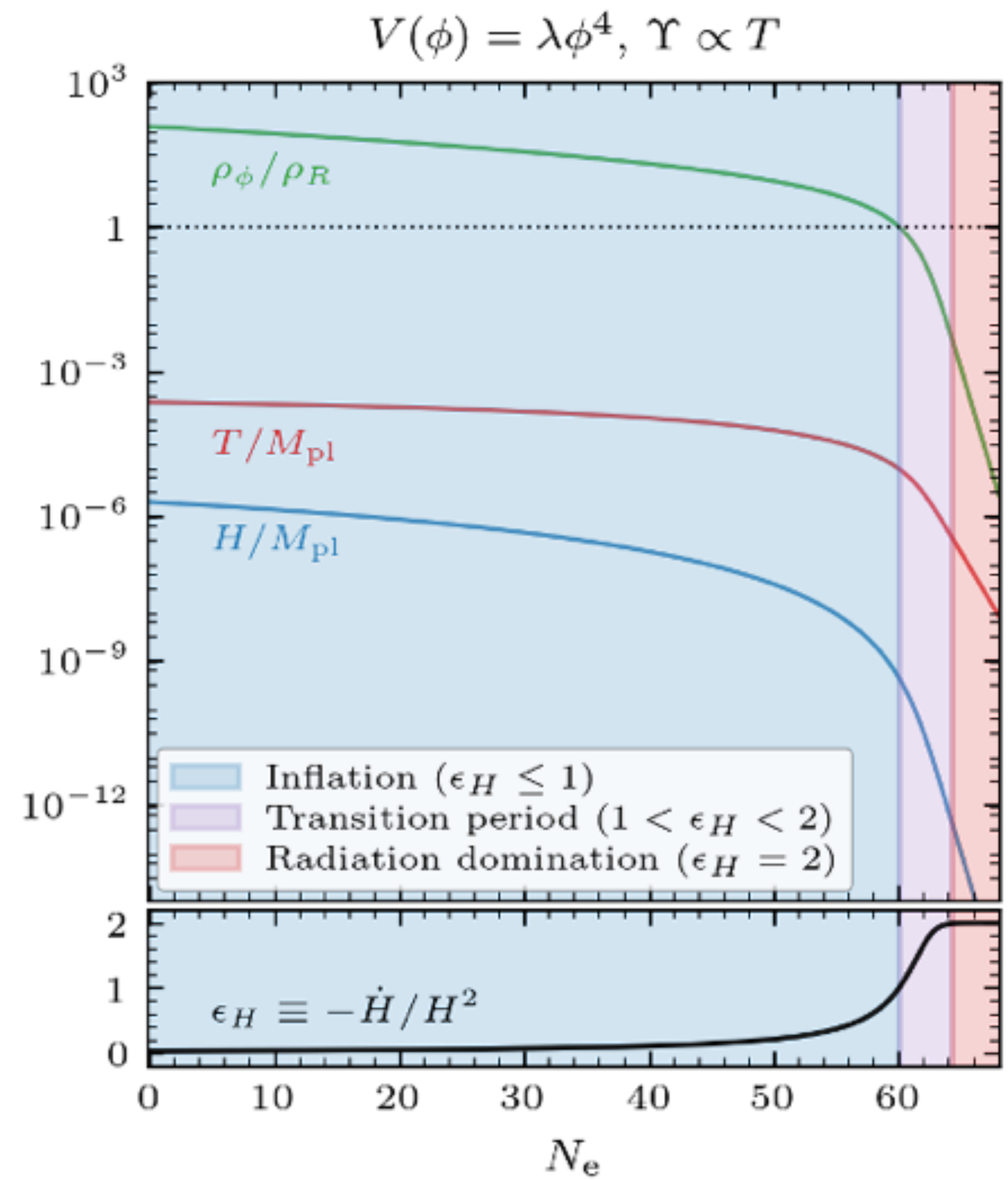
$$-\mathcal{L} \supset V(\phi) + gM\cos(\phi/M)\bar{\psi}_1\psi_1 + gM\sin(\phi/M)\bar{\psi}_2\psi_2 + h\sigma(\bar{\psi}_j\chi + \bar{\chi}\psi_j)$$

Example:

$$V(\phi) = \lambda\phi^4$$

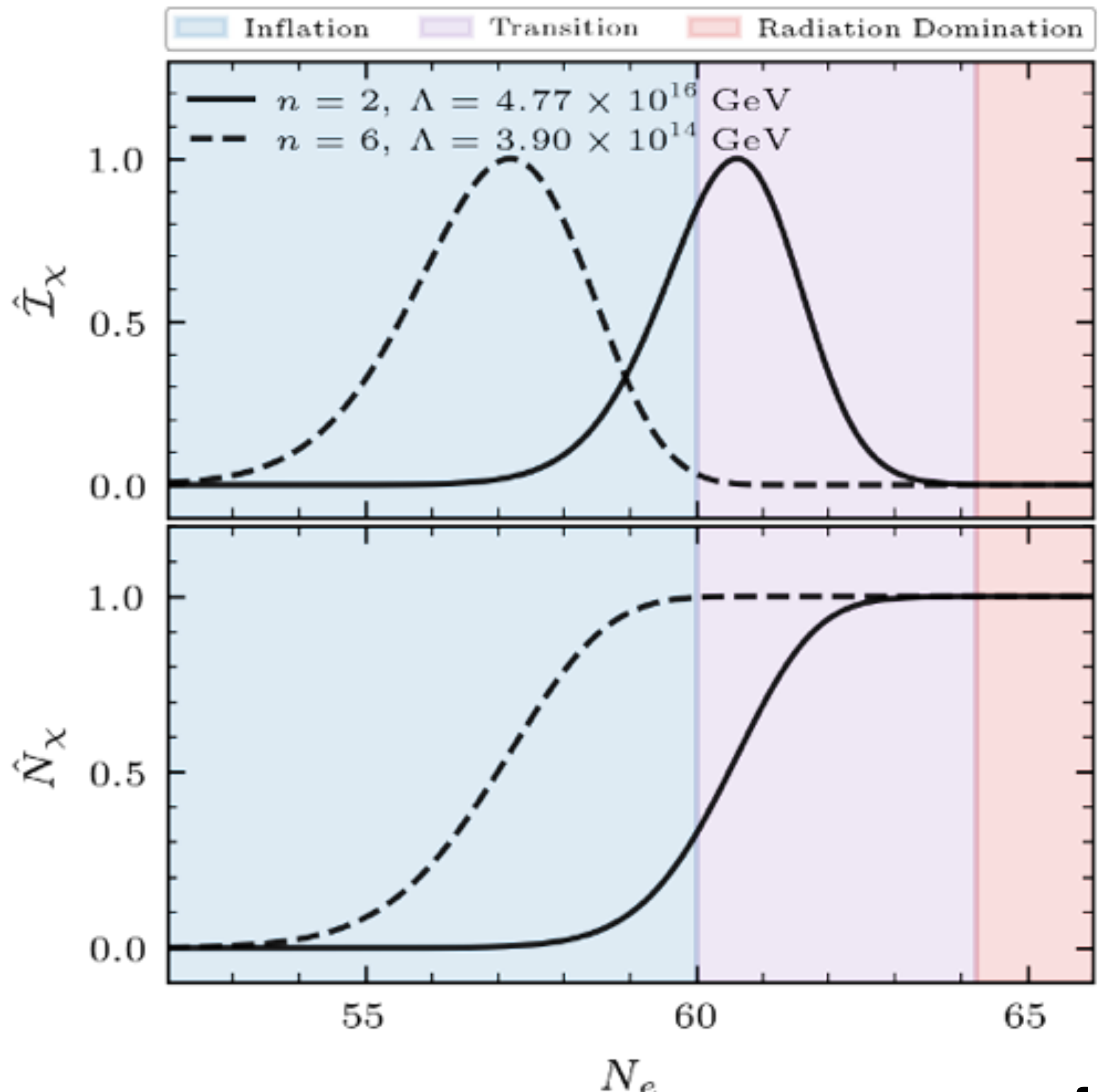
$$\Upsilon \sim T$$

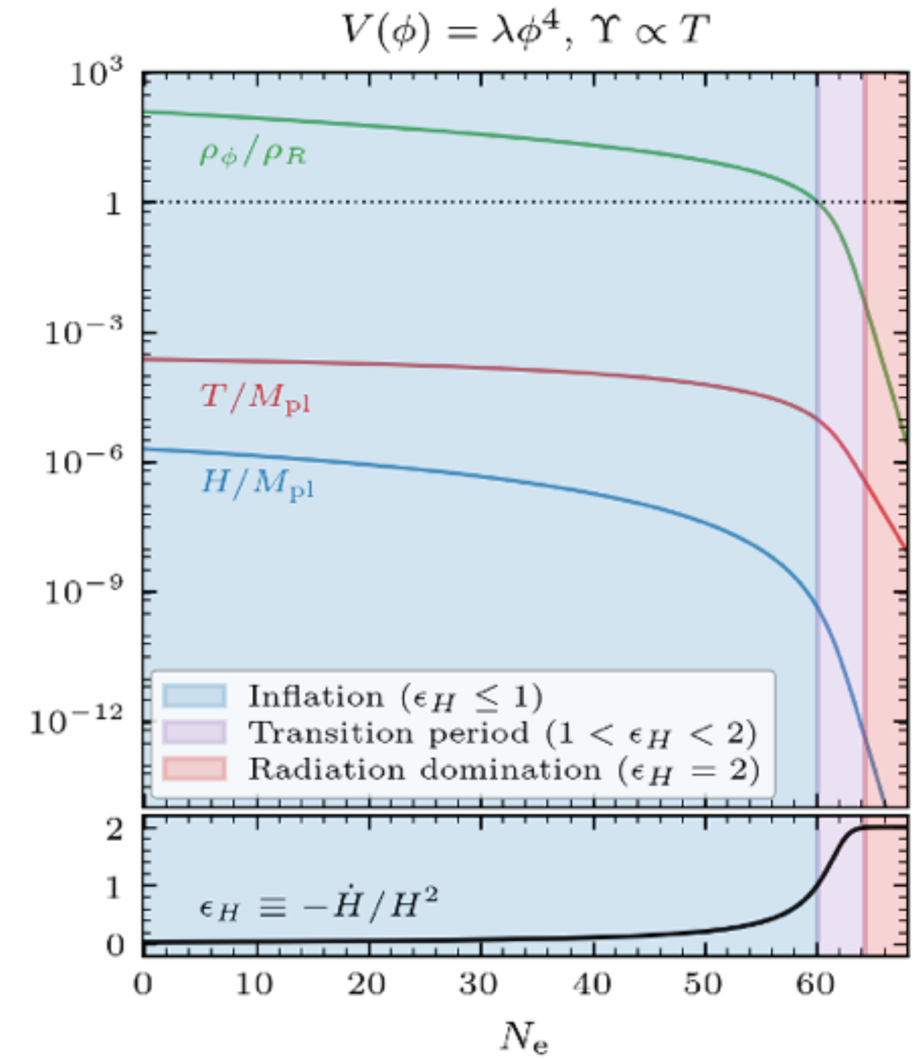
$$\ddot{\phi} + (3H + \Upsilon)\dot{\phi} + dV(\phi)/d\phi = 0$$



Pick a model to evaluate ***T*** and ***H***: **Warm Little Inflaton**

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





by increasing ***n***:
peak occurs at earlier times.

for sufficiently large value of *n*:
the whole DM abundance is produced entirely during the inflationary phase!

Comparison with conventional Uv freeze-in during RD:

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

always enhancement

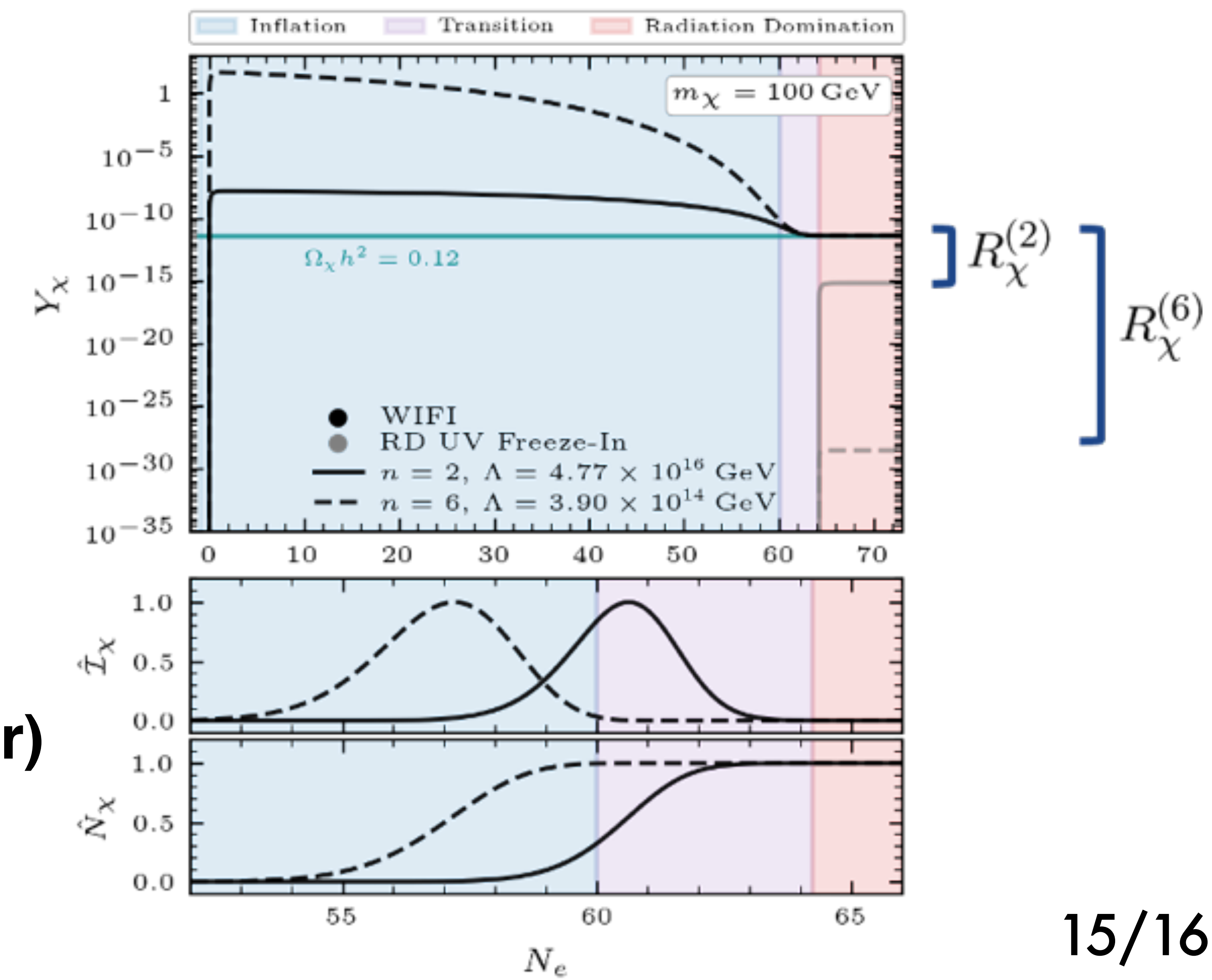
examples:

onset of RD:

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

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

even for *n*=1 (dim. 5 operator) enhancement can be >10



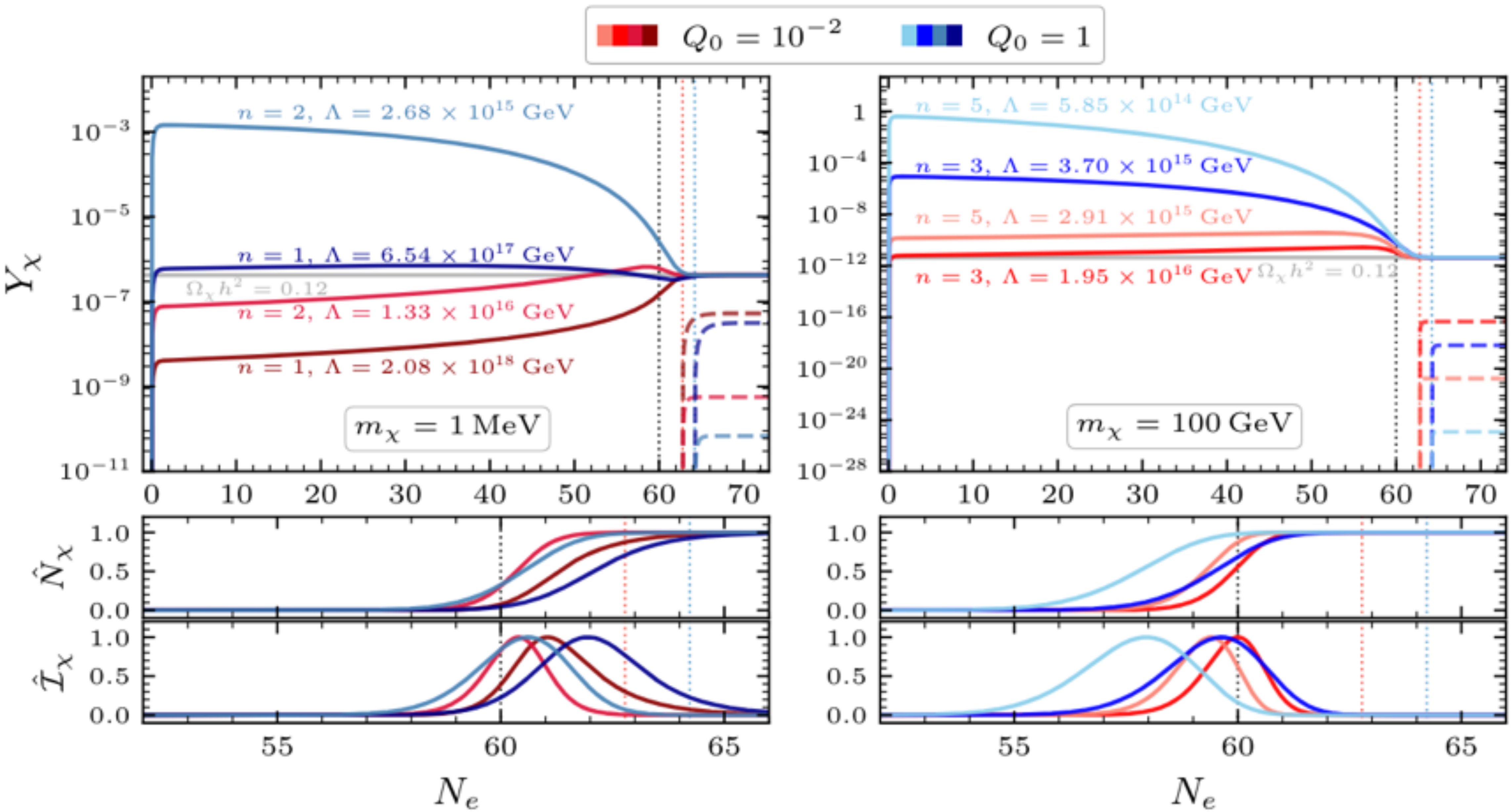
Conclusion:

A novel perspective on the role of inflation in the production of DM:
DM production during Warm Inflation via ultraviolet Freeze-In

UV freeze-in from warm inflation also provides new ways for reheating into the Standard Model.

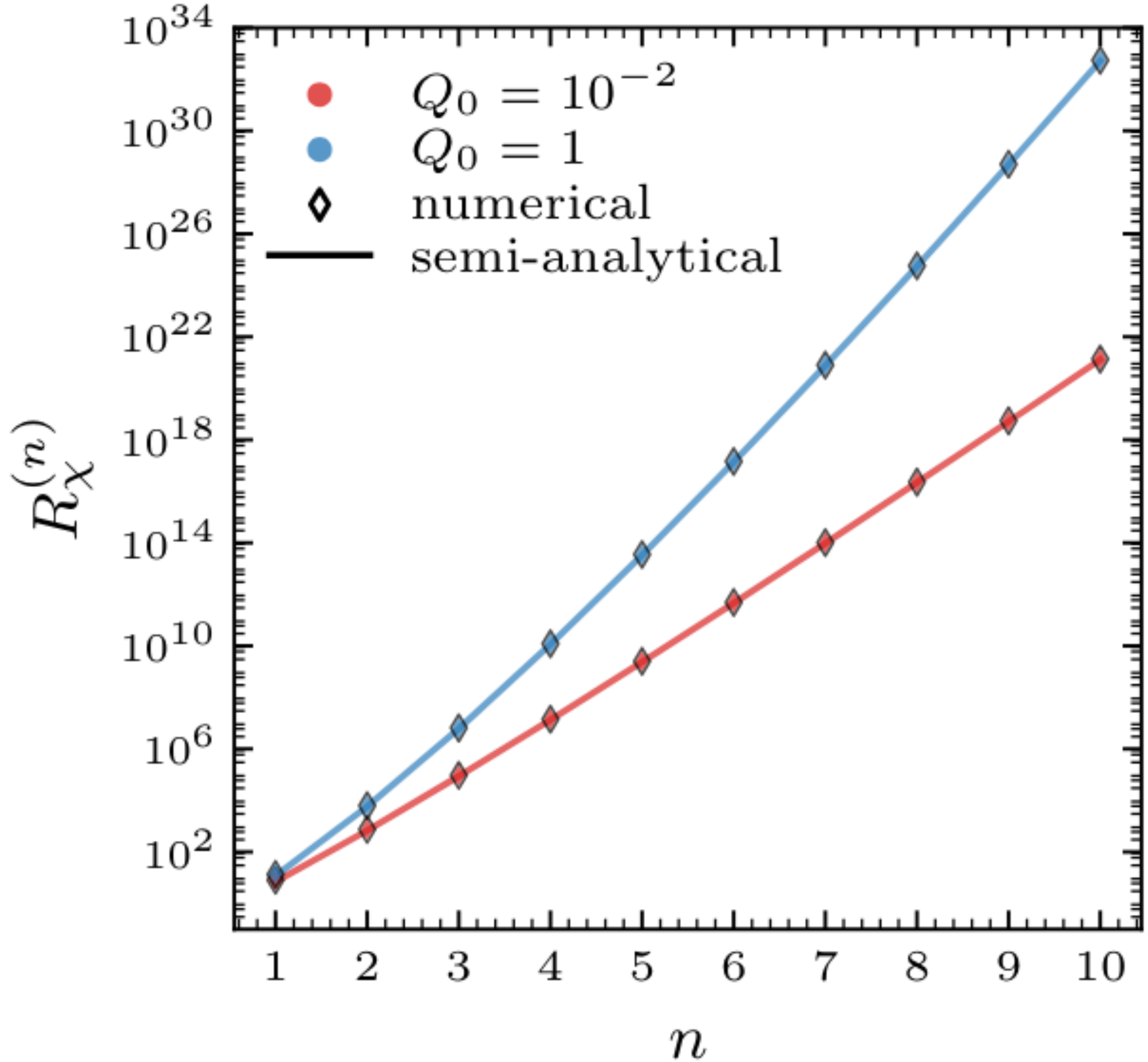
The persistent thermal bath during warm inflation provides an intriguing cosmological set-up for phenomenologists!

more examples:



Exponential enhancement!

$$R_\chi^{(n)} \equiv Y_{\chi,\infty}/Y_{\chi,\infty}^{\rm RD}(T_{\rm rh})$$



Model-building is challenging!

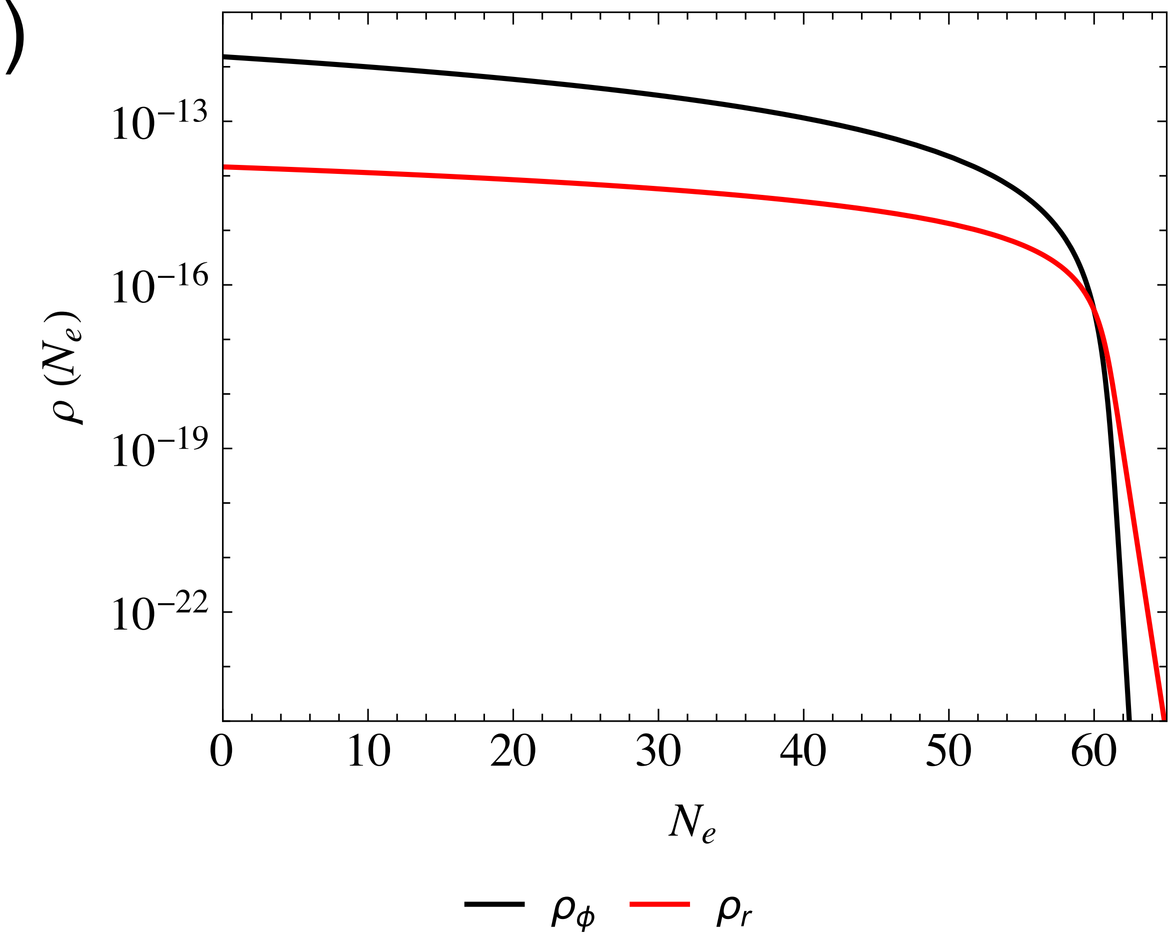
inflaton couples to light fields:
To have a sustained radiation bath, interaction cannot be too small:
light fields gaining large masses,
large quantum and thermal corrections to inflaton mass.

Is Warm Inflation Possible? J. Yokoyama, A. Linde, 1998

Consequences of Warm Inflation:

Dissipation rate: additional thermal friction
allows sub-Planckian field excursion even for very steep potentials.

smooth transition to RD, no need of a separate reheating phase:
even potentials without a minimum can also
be embedded into warm inflation)



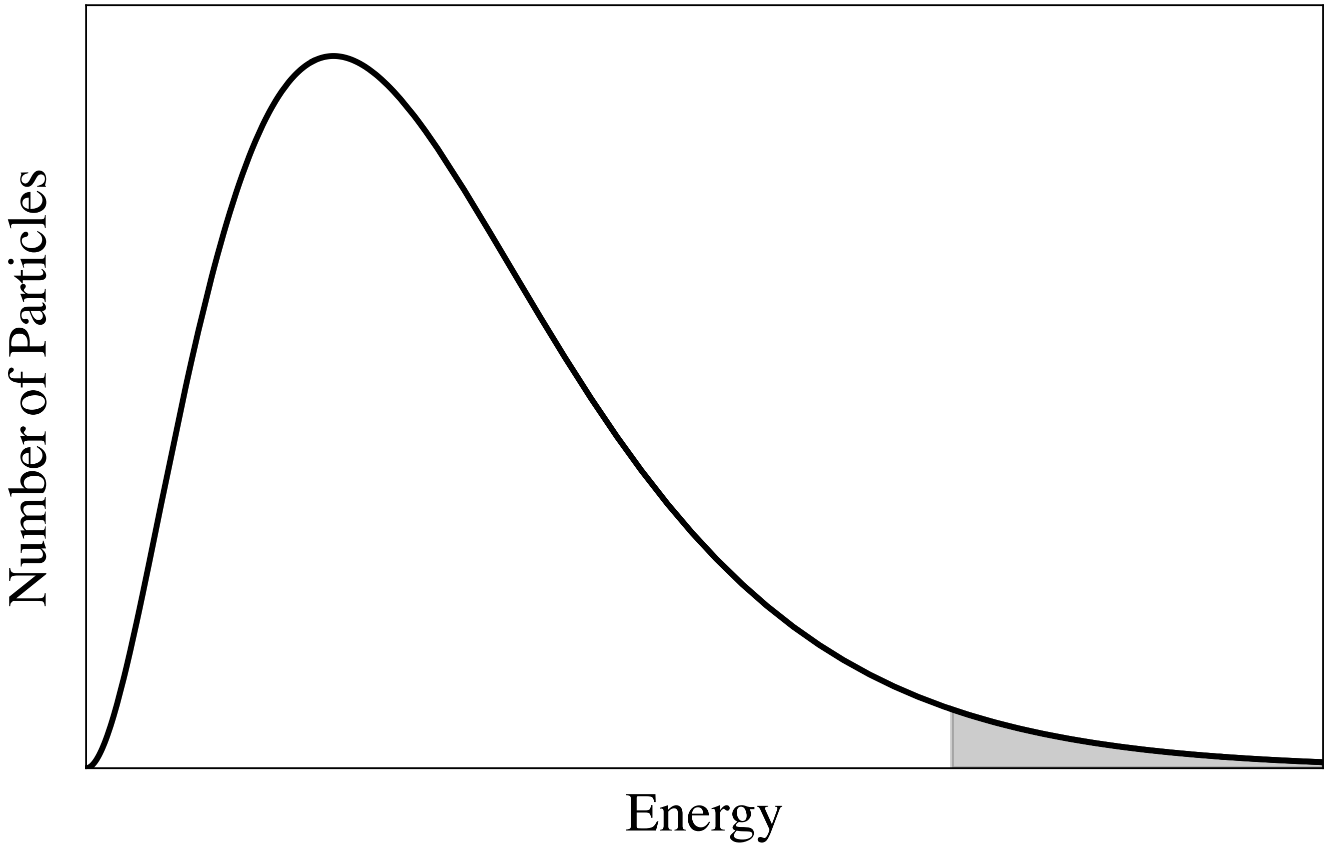
Generally, Suppressed tensor-to-scalar ratio, r, and relatively large non-gaussianities.

Kinematics: Boltzmann suppression

Standard cosmology: RD
with some initial temperature, $T_i \ll m_\chi$

$$\Gamma_{\text{production}} \sim e^{-2m_\chi/T}$$

V. A. Kuzmin, V. A. Rubakov, 1998
C. Cosme, F. Costa, O. Lebedev, 2023
K. Boddy, K. Freese, G. Montefalcone, BSE, 2024



Warm Inflation Models:

Distributed Mass Model

A. Berera, M. Gleiser, R. O. Ramos, 1999

$$\mathcal{L} \supset -V(\phi) + g(\phi - M_j)^2\chi^2 + h(\phi - M_j)\bar{\psi}_j\psi_j$$

controlling corrections by making the theory supersymmetric

Warm Little Inflaton

M. Bastero-Gil, A. Berera, R. O. Ramos, J. G. Rosa , 2016

inflaton: pseudo-Nambu-Goldstone boson (PNGB)

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

Recent progress:

Minimal Warm Inflation:

K. V. Berghaus, P. W. Graham and D. E. Kaplan, 2019

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

inflaton: axion-like particle interacting with Yang -Mills fields,

protected by shift symmetry

In these models, a warm inflation phase is almost inevitable.

W. DeRocco, P. W. Graham, S. Kalia, 2021