Dark Matter and Graviton Freeze-in from Warm Inflation

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Outline:

Producing Dark Matter (DM) from a thermal bath:

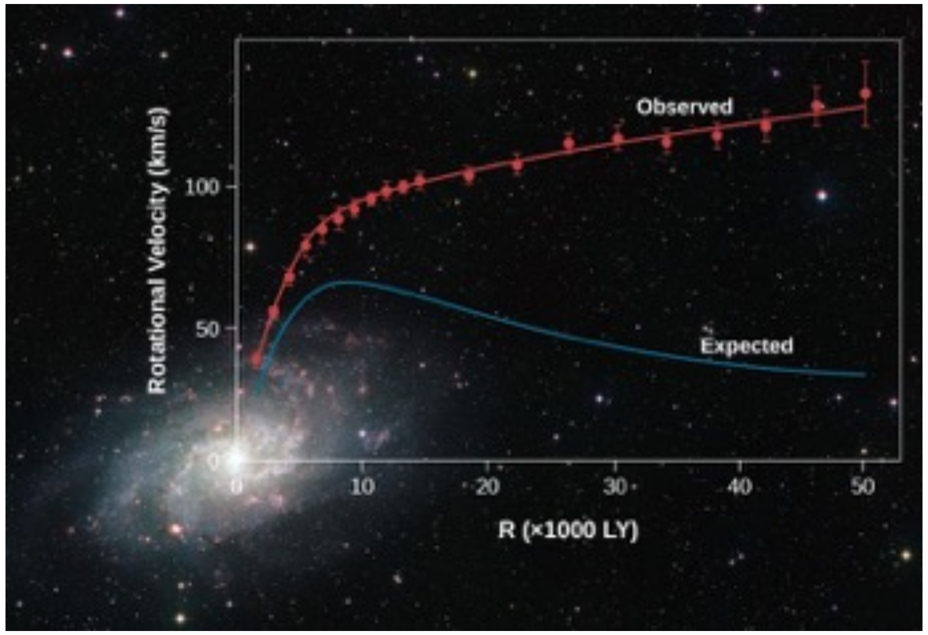
freeze-out
freeze-in

sensitivity of DM abundance to initial condition of the bath

Possibility of a thermal bath during inflation: **warm inflation**
(interesting ***non-standard*** cosmology)
producing DM during warm inflation

High frequency gravitons from warm inflation

Evidence for Dark Matter from different scales (All from Gravitational Interaction)

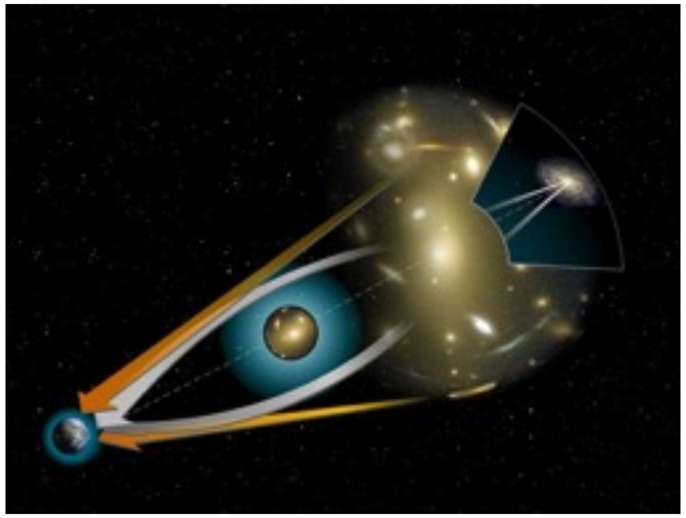


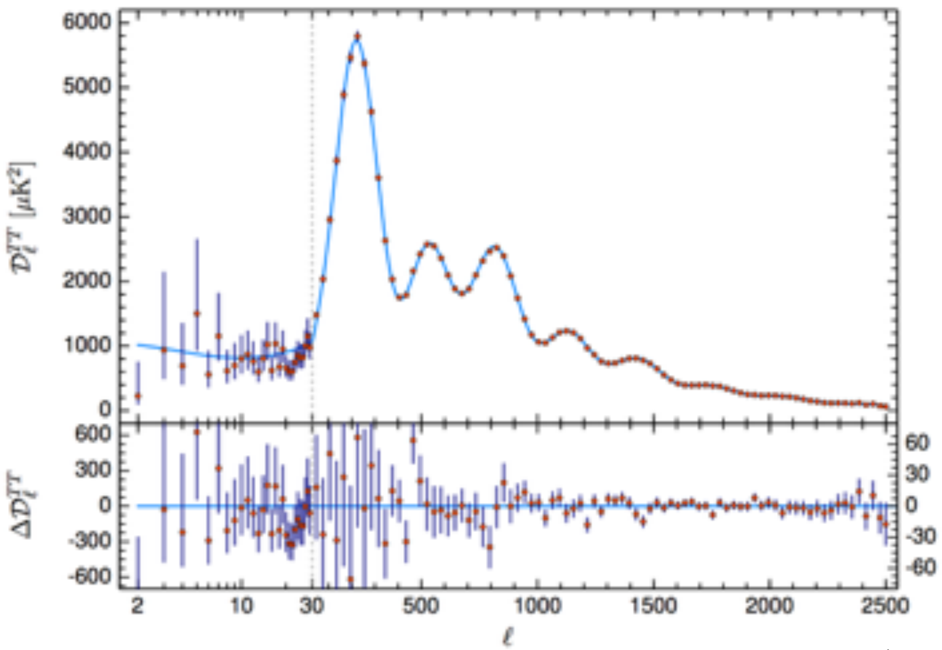
Rotation Curves of Galaxies

Structure Formation

Gravitational Lensing

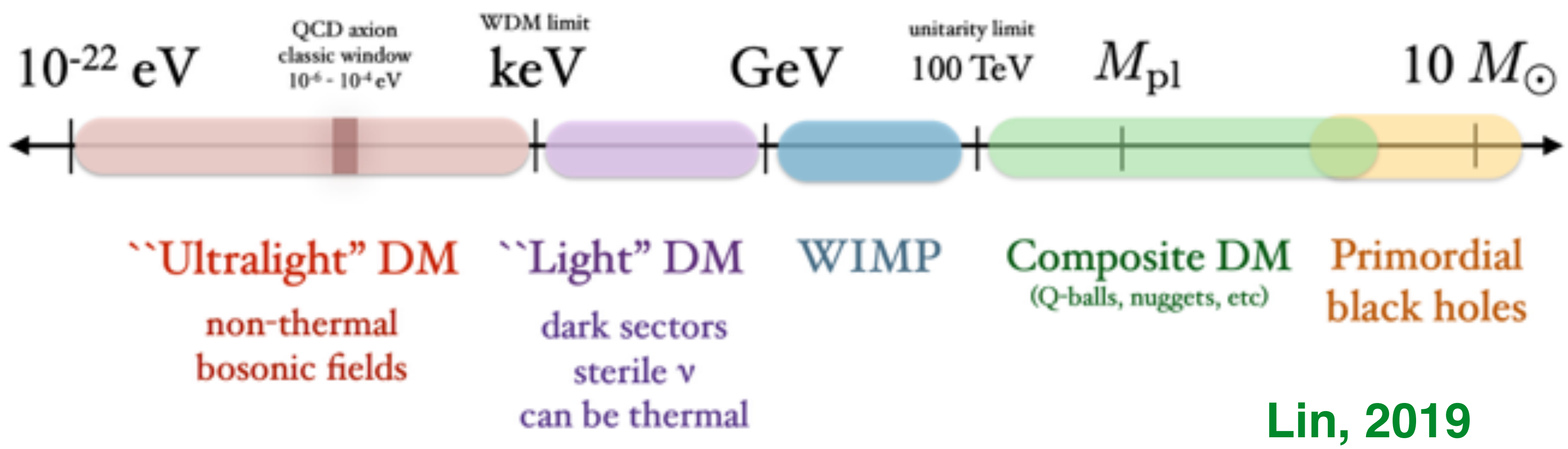
Cosmic Microwave Background (CMB)





Nature of Dark Matter?

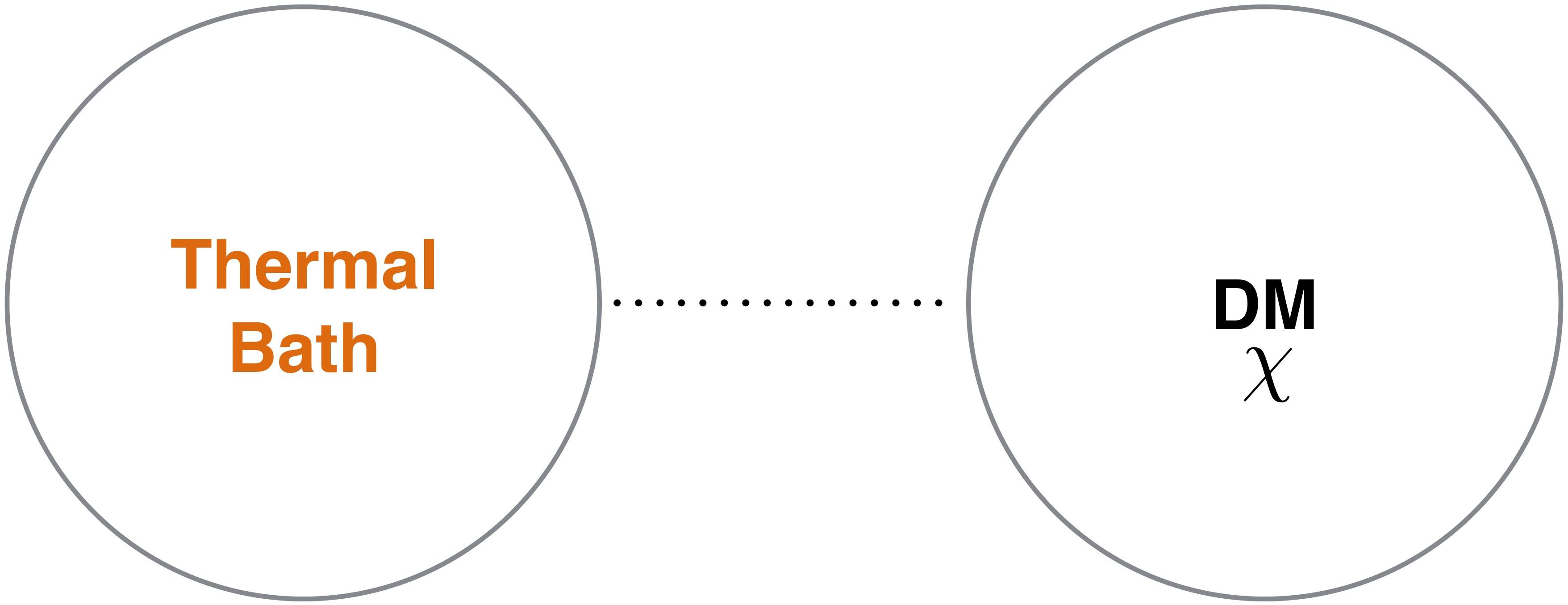
our knowledge is limited:
DM: candidates with a mass range spanning over 90 orders of magnitude.
each model can only be partially constrained.



Lin, 2019

nature of DM and the prospects for its detection:
closely related to production mechanism

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

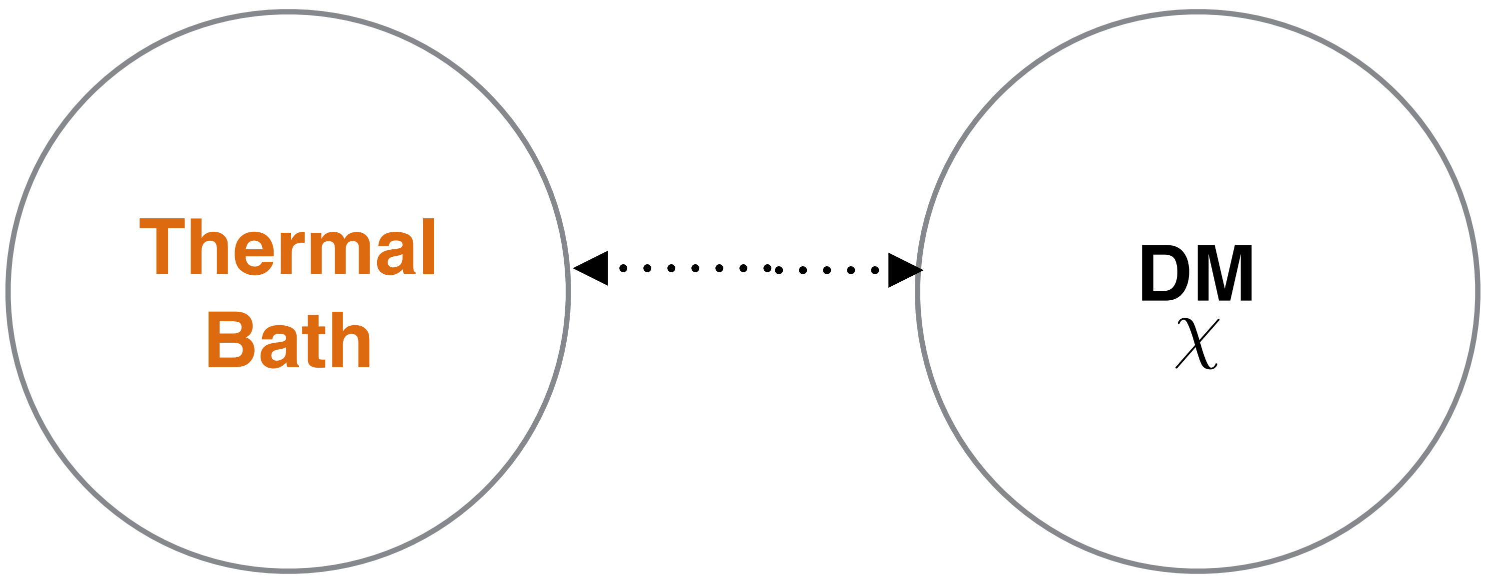


non-gravitational interactions between DM and the bath establish DM abundance mainly by: **freeze-out** or **freeze-in** mechanisms.

(gravitational DM freeze-in is possible)

Freeze-out:

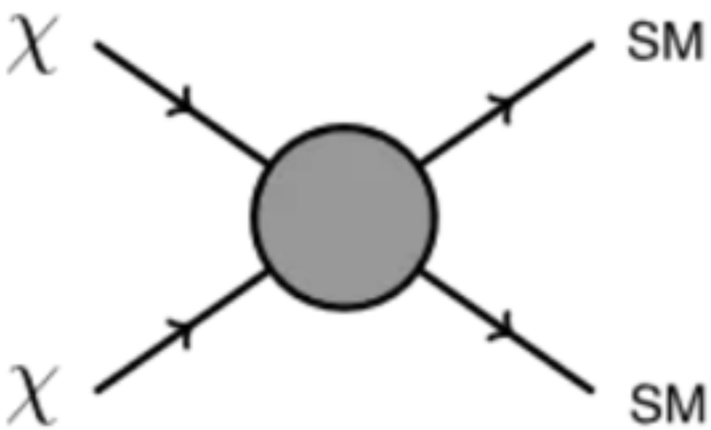
Standard Cosmology: Radiation Dominated (RD),
with some initial temperature, above the mass of DM

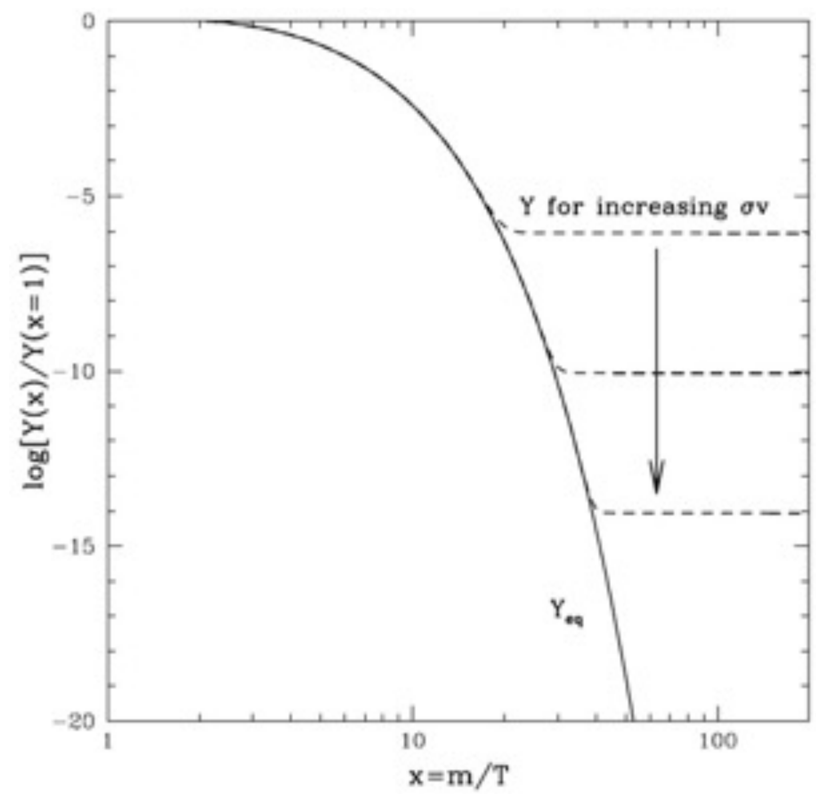


Interaction is strong enough to keep DM in **chemical equilibrium** with the bath at early times.

Departure from chemical equilibrium:
sets the final DM abundance.

Weakly Interacting Massive Particles (WIMPs):





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

$$Y_\chi \equiv n_\chi / s$$

$$Y_\chi \sim \frac{1}{M_{\mathrm{Pl}} m_\chi \langle\sigma v\rangle}$$

$$\langle\sigma v\rangle \sim 10^{-9}\,\mathrm{GeV}^{-2} \sim 10^{-26}\,\mathrm{cm}^3/\mathrm{s} \sim \frac{(0.01)^2}{(100\,\mathrm{GeV})^2}$$

weak-scale couplings, weak scale mass

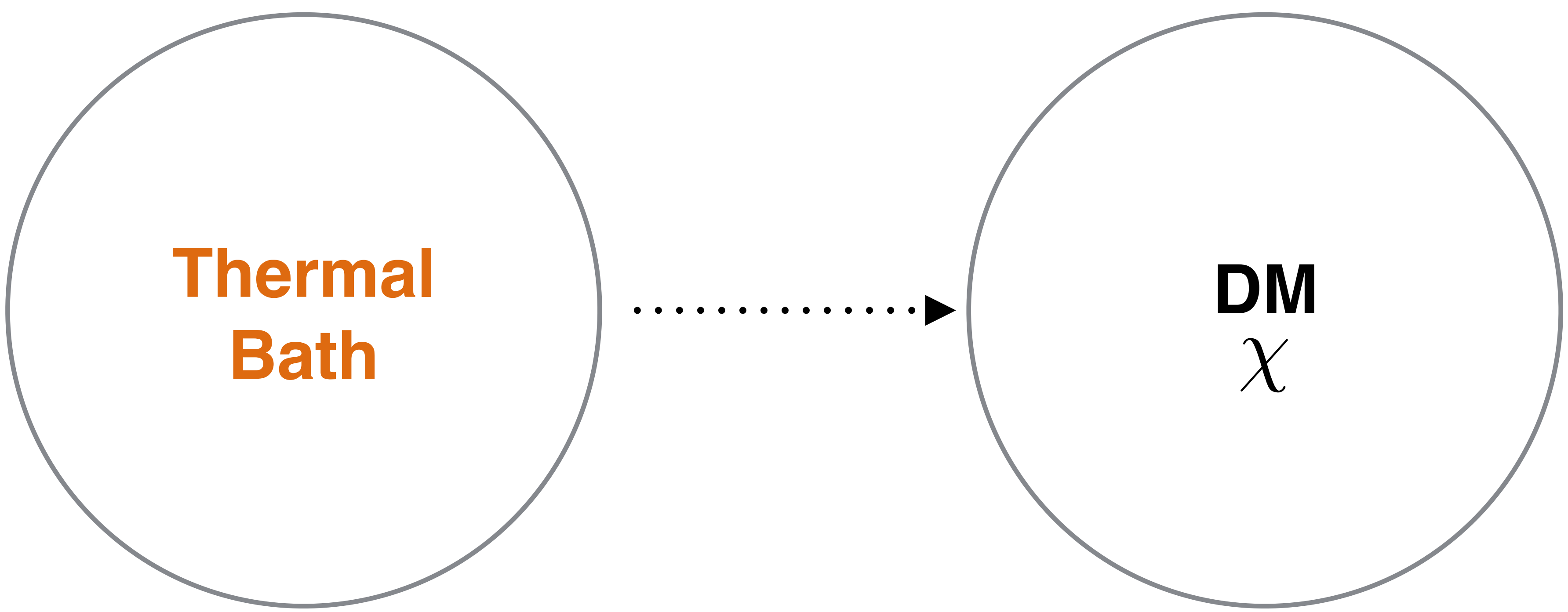
advantage:
Due to thermalization, no dependence on the initial temperature of the bath

Freeze-in:
negligible initial number density
no equilibrium/no annihilation
small production rate

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

the DM final abundance is built up gradually over time

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



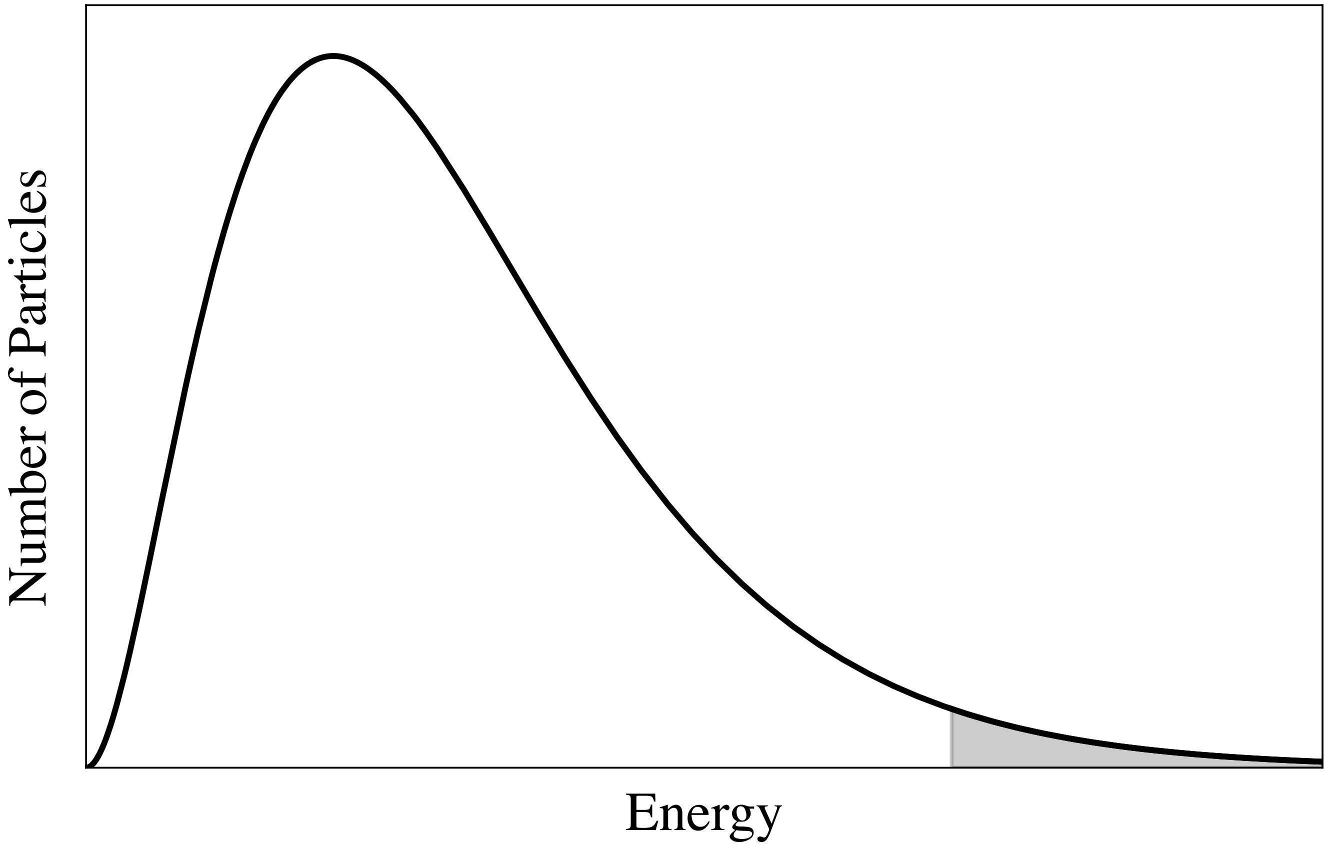
How can we suppress the production rate?

Kinematics: Boltzmann suppression

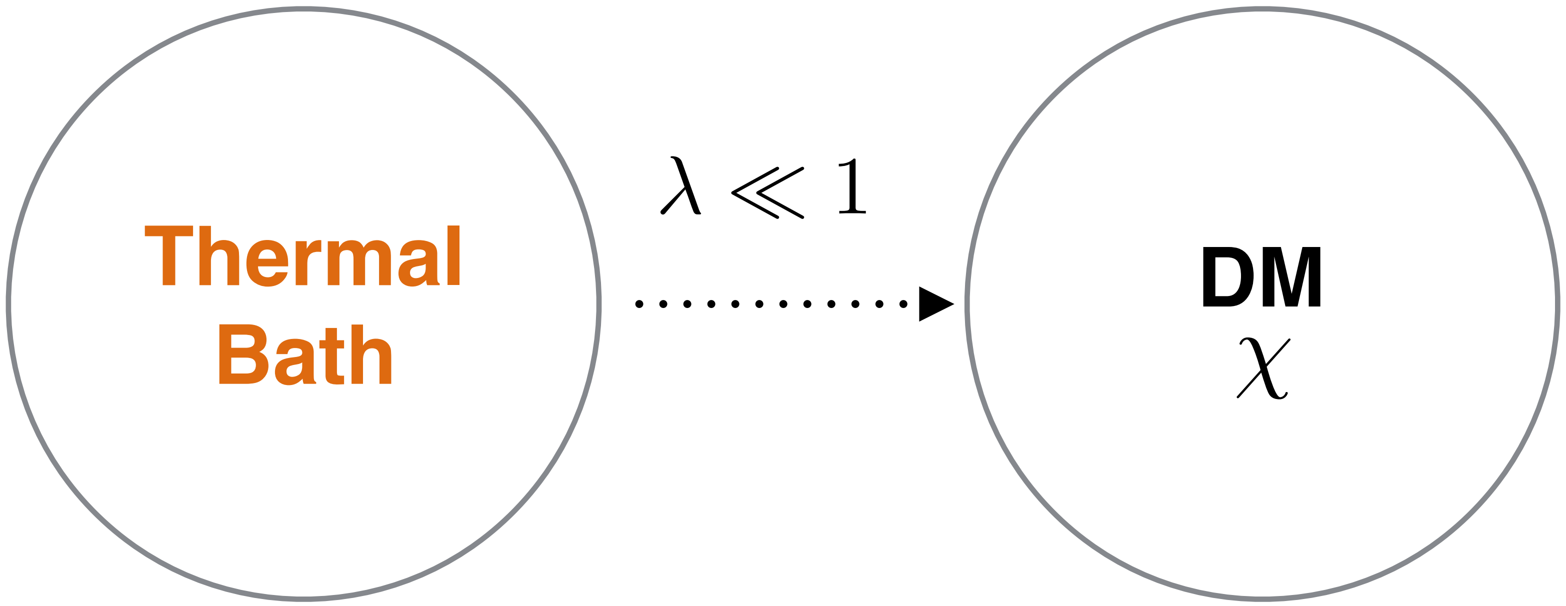
Standard cosmology: RD
with some initial temperature, $T_i \ll m_\chi$

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

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



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

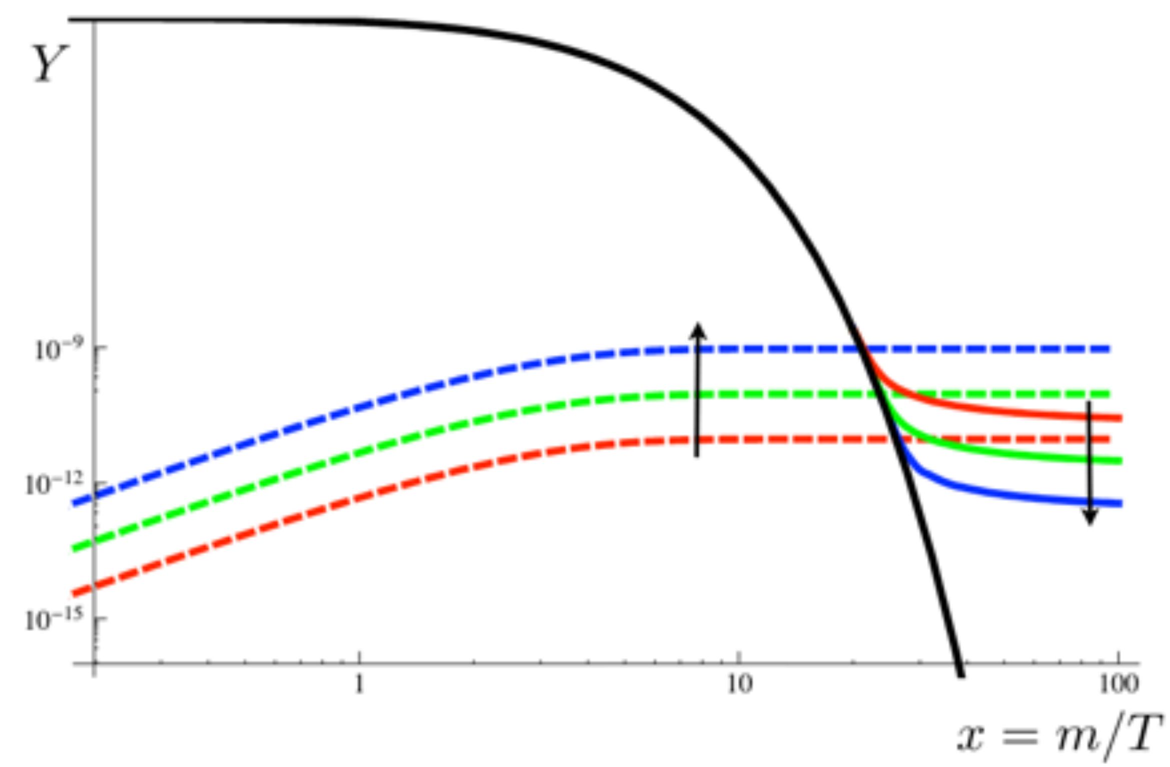


renormaizblae operators
and **very small coupling**

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

$$\lambda \lesssim 10^{-7}$$

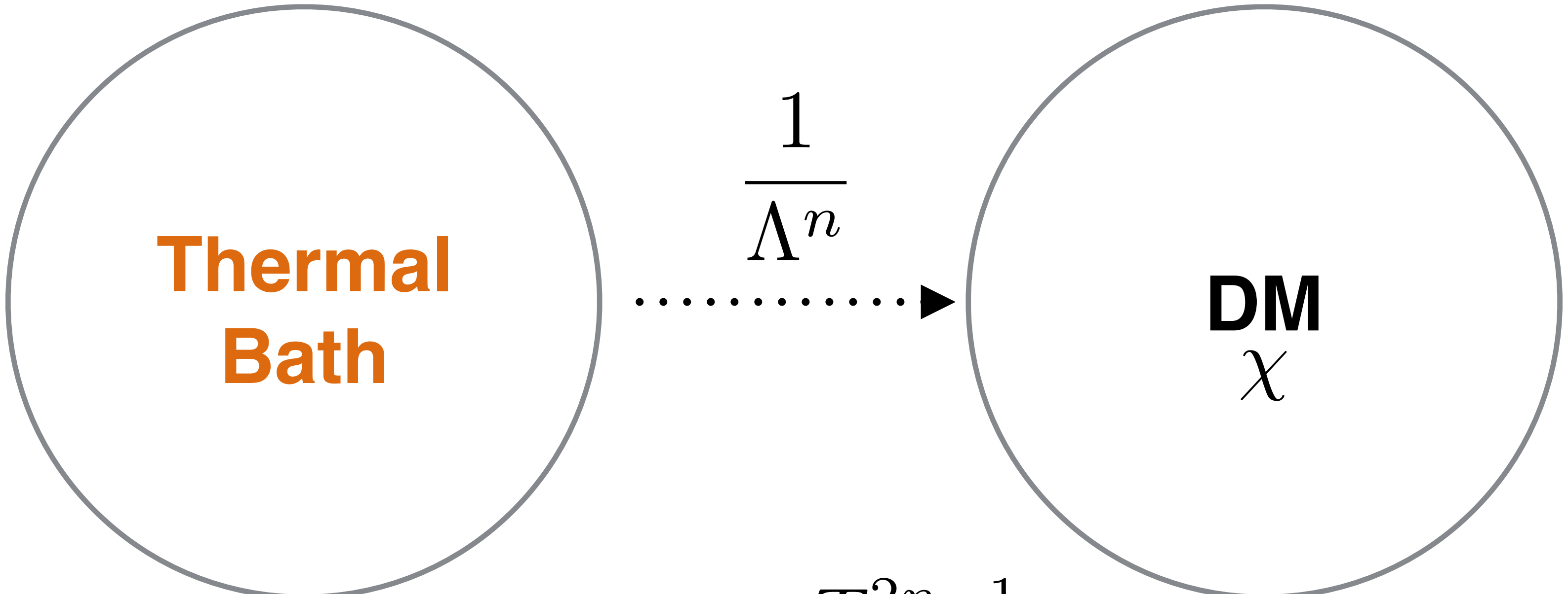
L. J. Hall, K. Jedamzik, J. March-Russell, S. M. West, 2009



IR dominated:
independent of initial temperature,
most of the DM produced when $T \sim m_\chi$

IR freeze-in

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

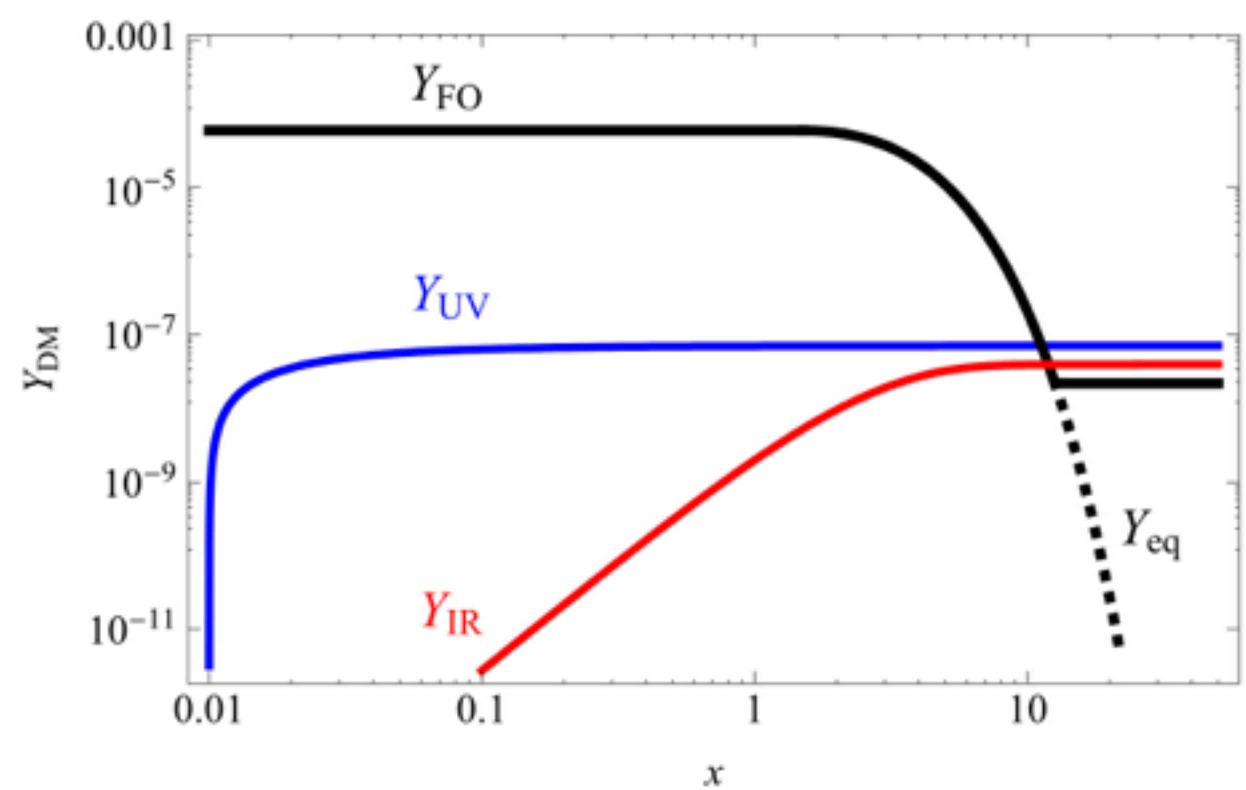


non-renormaizblae operators (a heavy scale)

$$\Lambda \gg T_i$$

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

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



UV dominated:
sensitive to highest temperature,
most of the DM produced at the beginning

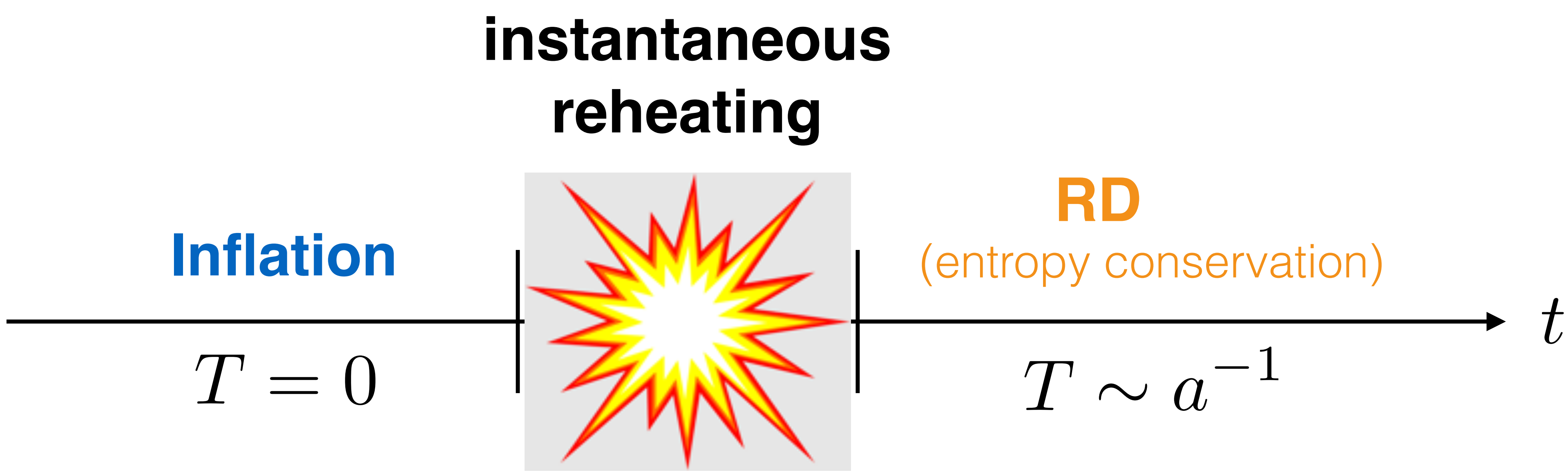
UV freeze-in

UV freeze-in is sensitive to the highest temperature:

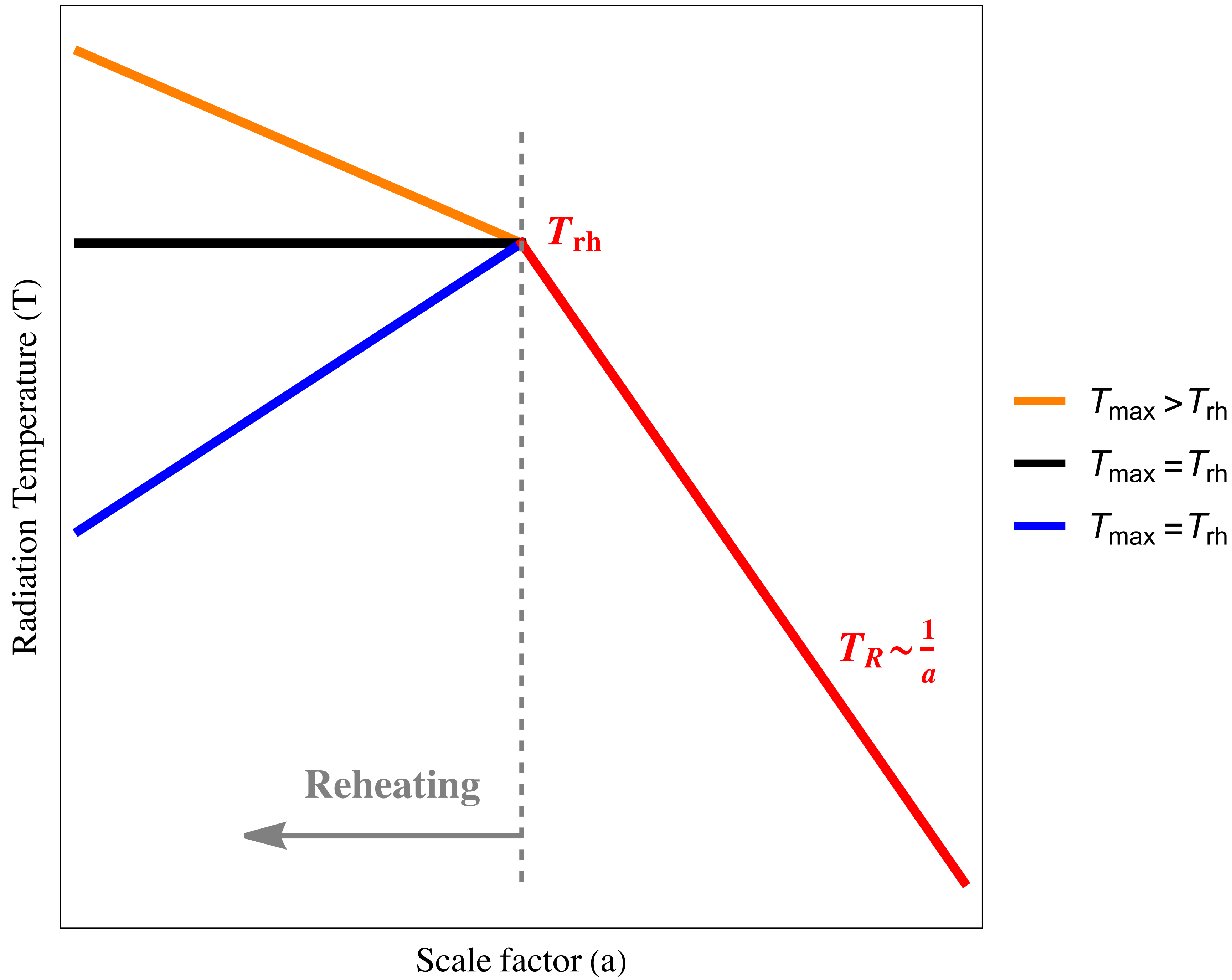
What is the highest temperature of the bath?

reheating temperature:
temperature at the onset of RD T_{rh}

instantaneous reheating: $T_{\mathrm{max}} = T_{\mathrm{rh}}$



Maximum temperature vs. reheating temperature:

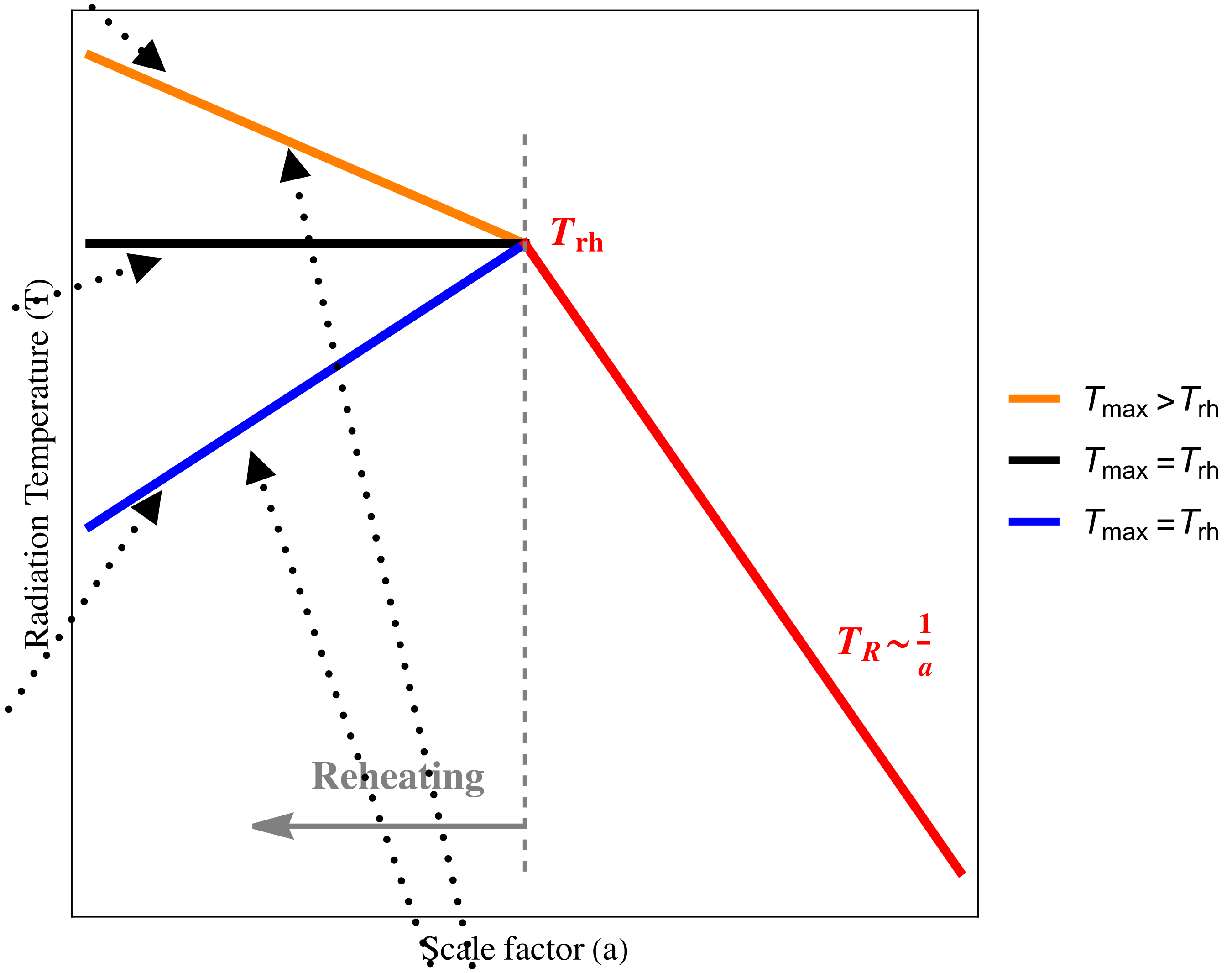


inflaton decays to radiation directly

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



inflaton decays to an unstable particle which then decays to radiation

C. Cosme, F. Costa, O. Lebedev, 2024

inflaton has generic dissipation rate dependent on temperature and scale factor

R. T. Co, E. Gonzalez, K. Harigaya, 2021

Resonant reheating: s-channel inflaton annihilation

B. Barman, N. Bernal, Y. Xu, 2024

Non-Standard Cosmologies after inflation, prior to RD phase: reheating

Inflation	Transition to RD (entropy production)	RD (entropy conservation)
$T = 0$	$T \not\sim a^{-1}$	$T \sim a^{-1}$

$\rightarrow t$

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

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

employed in the context of **freeze-out**: overcome Boltzmann suppression when

$$T_{\rm rh} \ll m_\chi$$

UV freeze-in during reheating and prior to RD :

UV freeze-in during matter domination prior to RD

M. A. G. Garcia, Y. Mambrini, K. A. Olive, M. Peloso, 2017

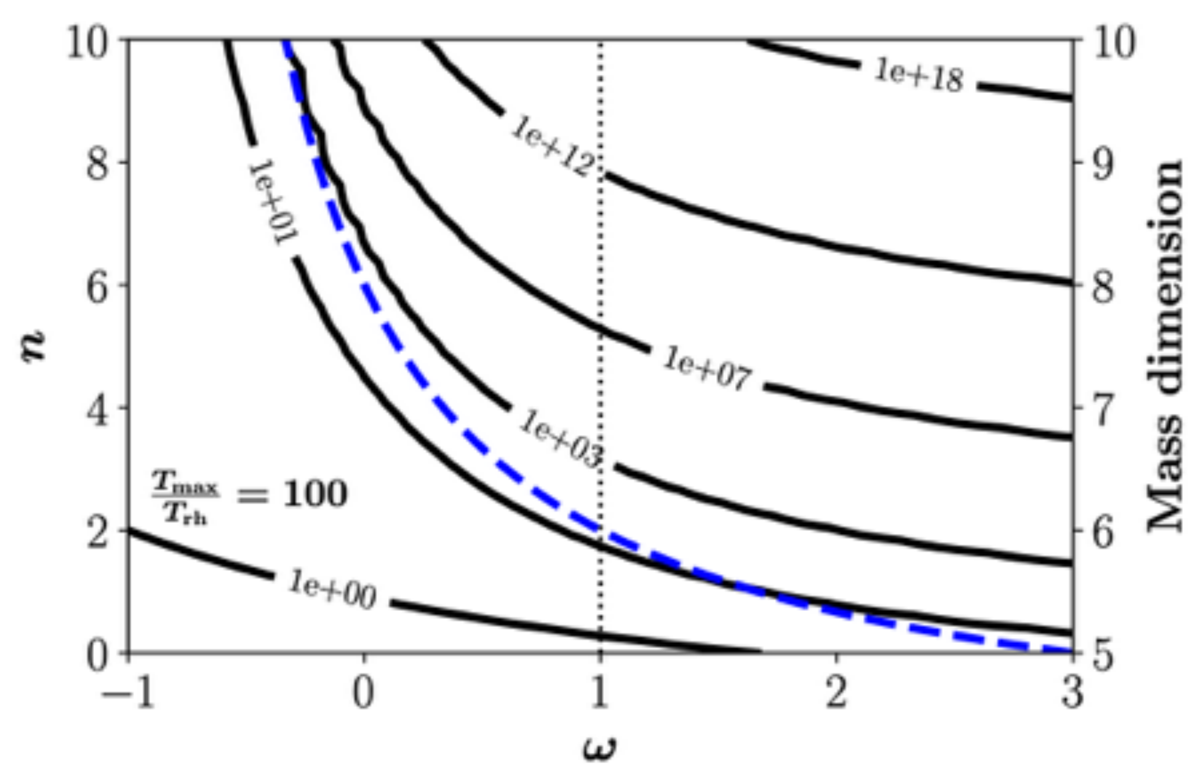
S. Chen, Z. Kang, 2017

UV freeze-in during other non-standard cosmologies before RD

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

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

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



Note: for dim. 5 operator enhancement is NOT noticeable

UV freeze-in during reheating ✓

How about UV freeze-in during inflation?

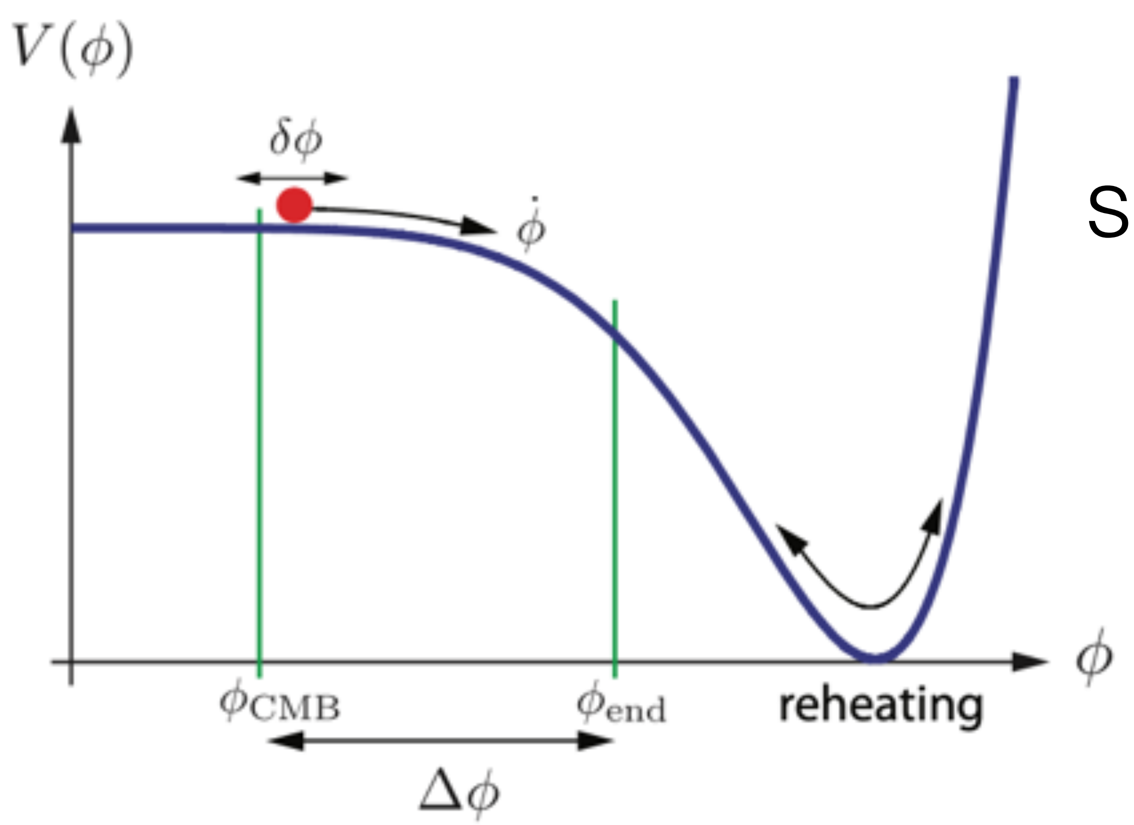
Requires a thermal bath within the inflationary phase: warming up cold inflation!

(Cold) Inflation

an early period of accelerated expansion to drive
the primordial universe towards homogeneity, isotropy and flatness.

Quantum fluctuations:
generate the inhomogeneities observed in the CMB

Linde 1982
Albrecht, Steinhardt 1982



D.Baumann , 2012

slow-roll: $\ddot{\phi} + (3H + \cancel{\Upsilon})\dot{\phi} + dV(\phi)/d\phi = 0$

$$\epsilon_V = \frac{M_{\rm Pl}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1$$

$$|\eta_V| = \left| M_{\rm Pl}^2 \left(\frac{V''}{V}\right)\right| \ll 1$$

reheating: $\ddot{\phi} + (3H + \Upsilon)\dot{\phi} + dV(\phi)/d\phi = 0$
particle production via decay

Warm inflation

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

A. Berera, 1995

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

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

the inhomogeneities sourced by thermal fluctuations

Phenomenology:

$\rho_\phi > \rho_r$ inflation

$\Upsilon \gtrsim 3H$ (in contrast to cold inflation where dissipation is negligible)

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

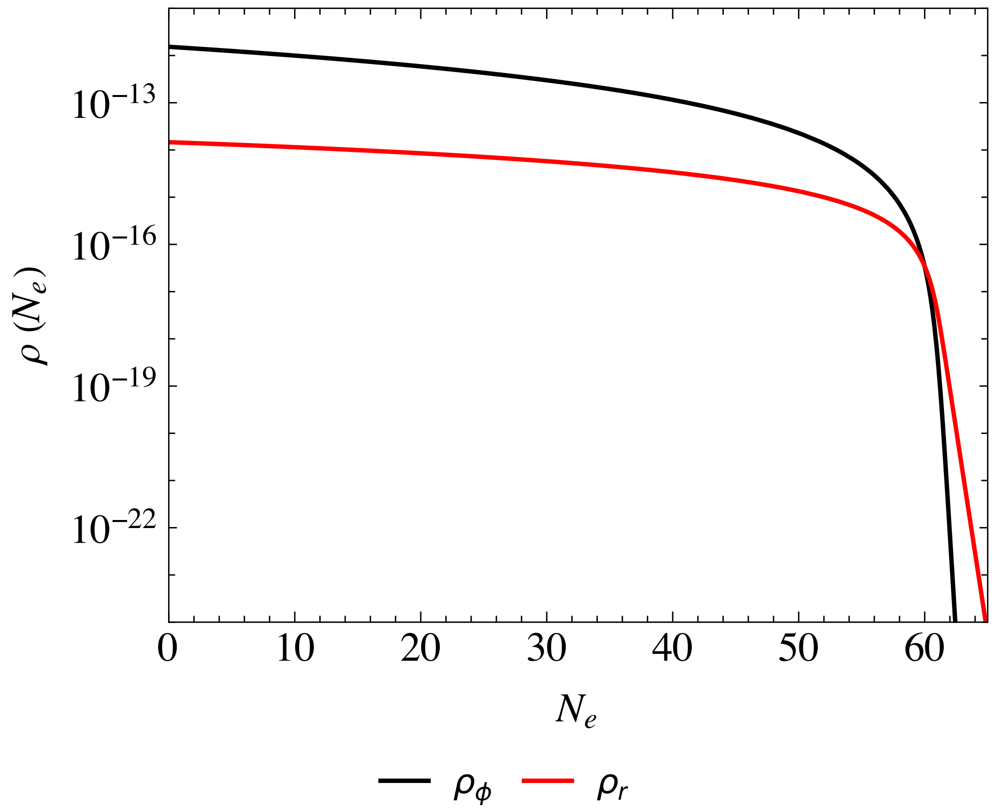
$T > H$ Thermal fluctuations dominate over quantum ones

Consequences of Warm Inflation:

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

$$\epsilon_V\,,|\eta_V| < 1 + \frac{\Upsilon}{3H}$$

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.

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**

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.

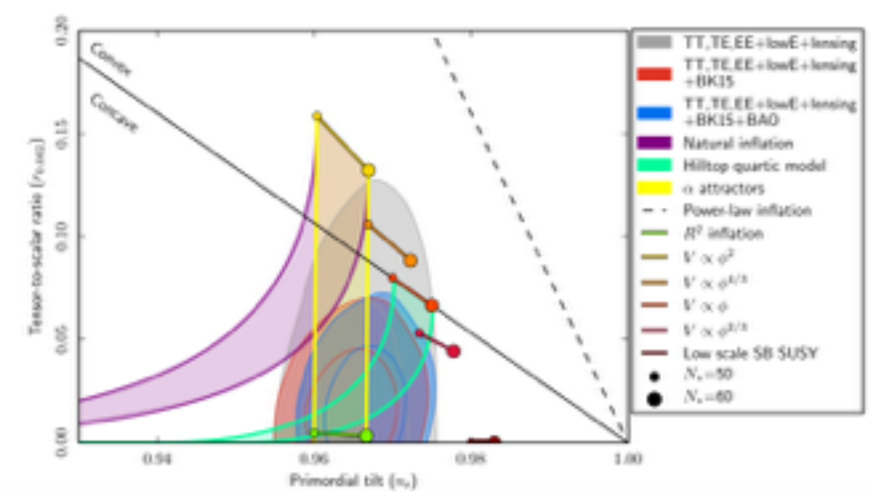
W. DeRocco, P. W. Graham, S. Kalia, 2021

Warm Inflation set-up:

Model: $$\mathcal{L} = \mathcal{L}(\phi) + \mathcal{L}(X) + \mathcal{L}(\phi, X)$$

Calculate dissipation coefficient from first principles: $$\Upsilon = \Upsilon(\phi, T)$$

Confront with the observation r, n_s



Phenomenological approach:

(no concrete model)

$$V(\phi)$$

$$\Upsilon = \Upsilon(T) \sim T^n$$

Warm Little Inflaton

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

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

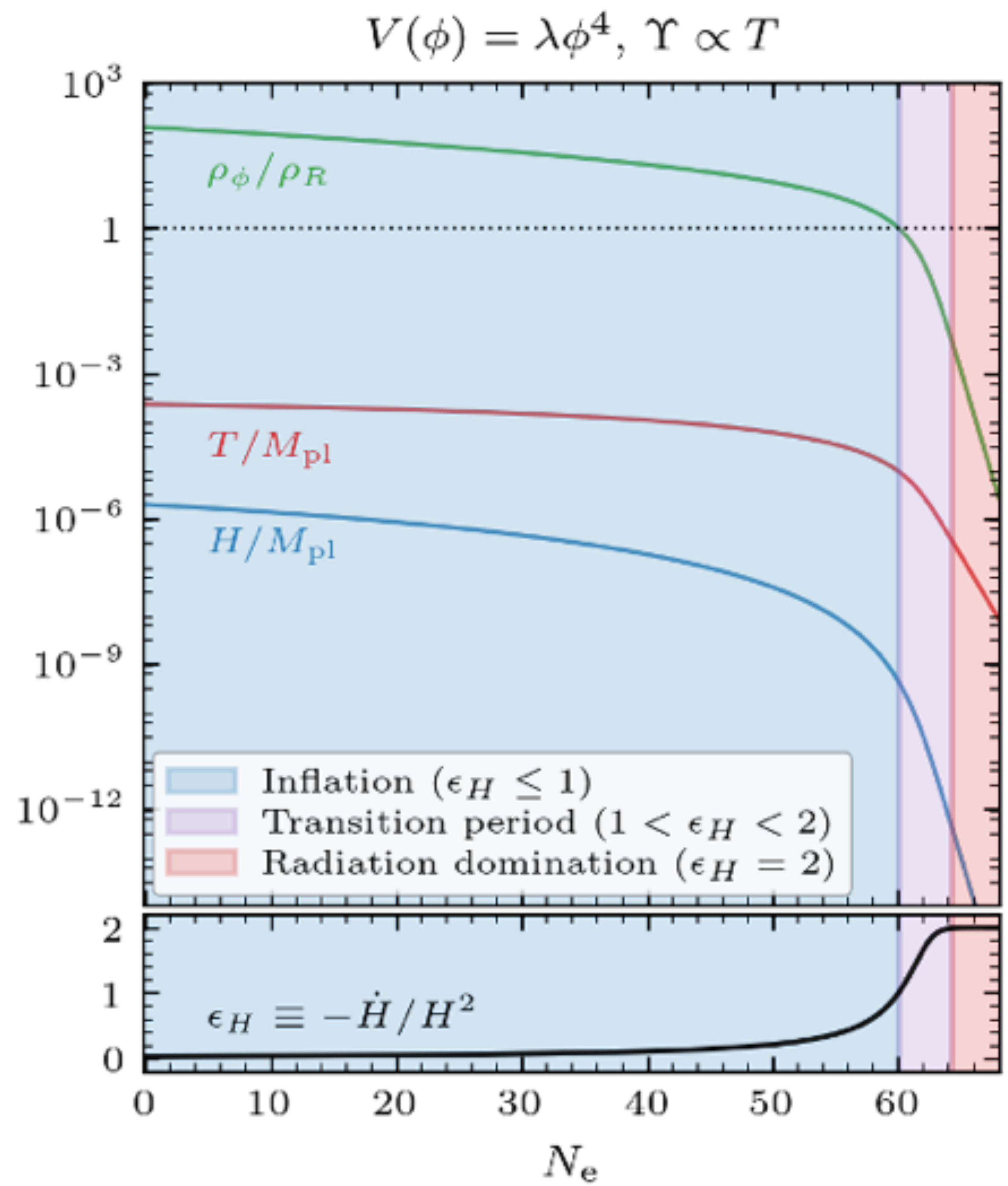
Cosmology:

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

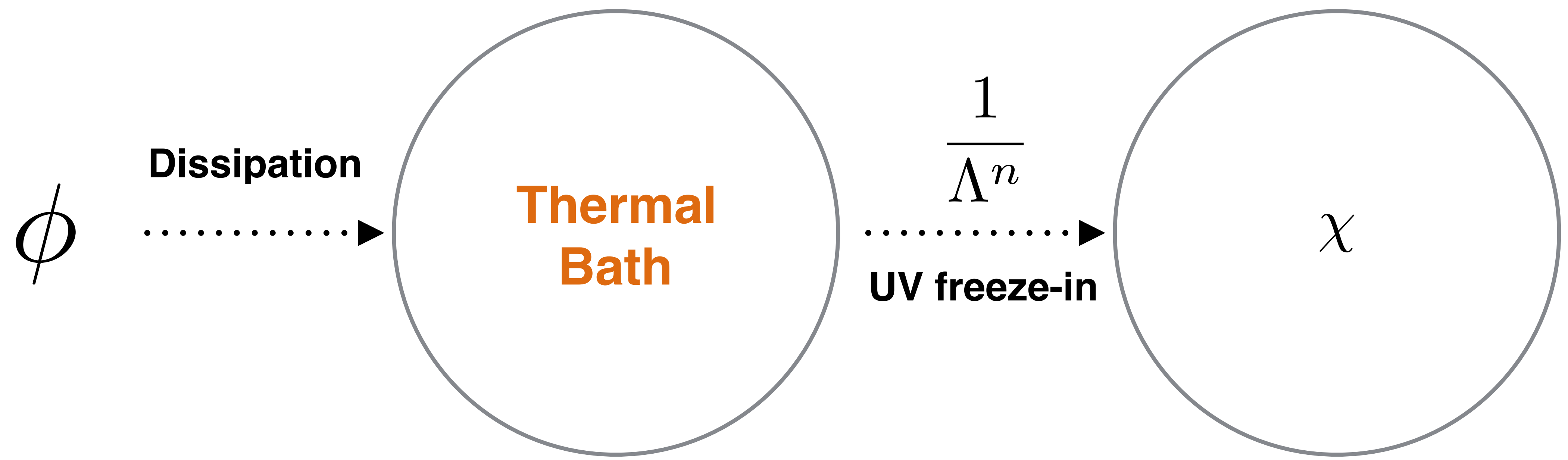
$$\dot{\rho}_r + 4H\rho_r = \Upsilon\dot{\phi}^2$$

$$\Upsilon \sim T$$

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



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:

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

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

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 $N_e^{\rm peak}$

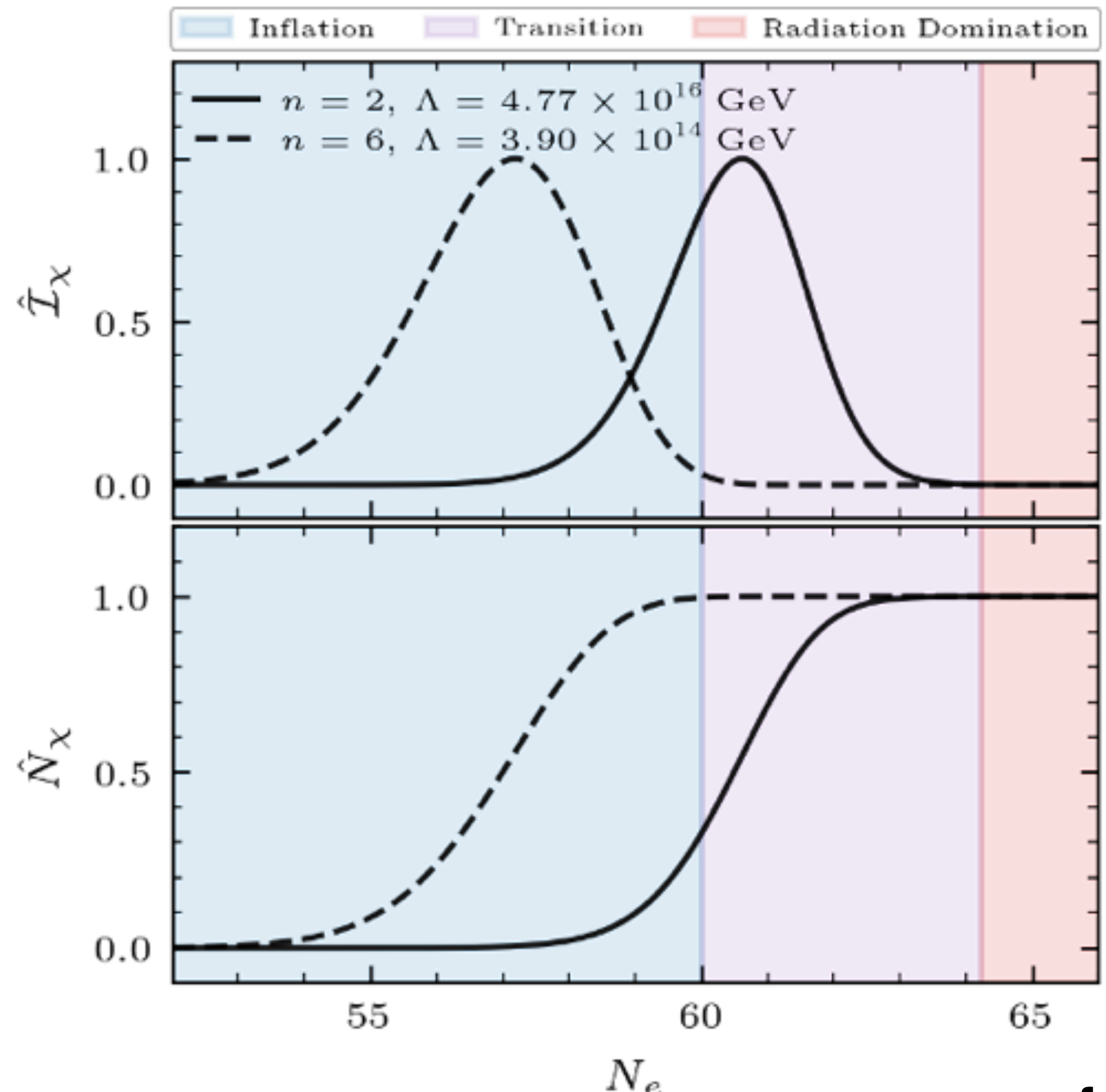
$$3 + (2n+4)\frac{d\ln T(N_e)}{dN_e} - \frac{d\ln H(N_e)}{dN_e} = 0$$

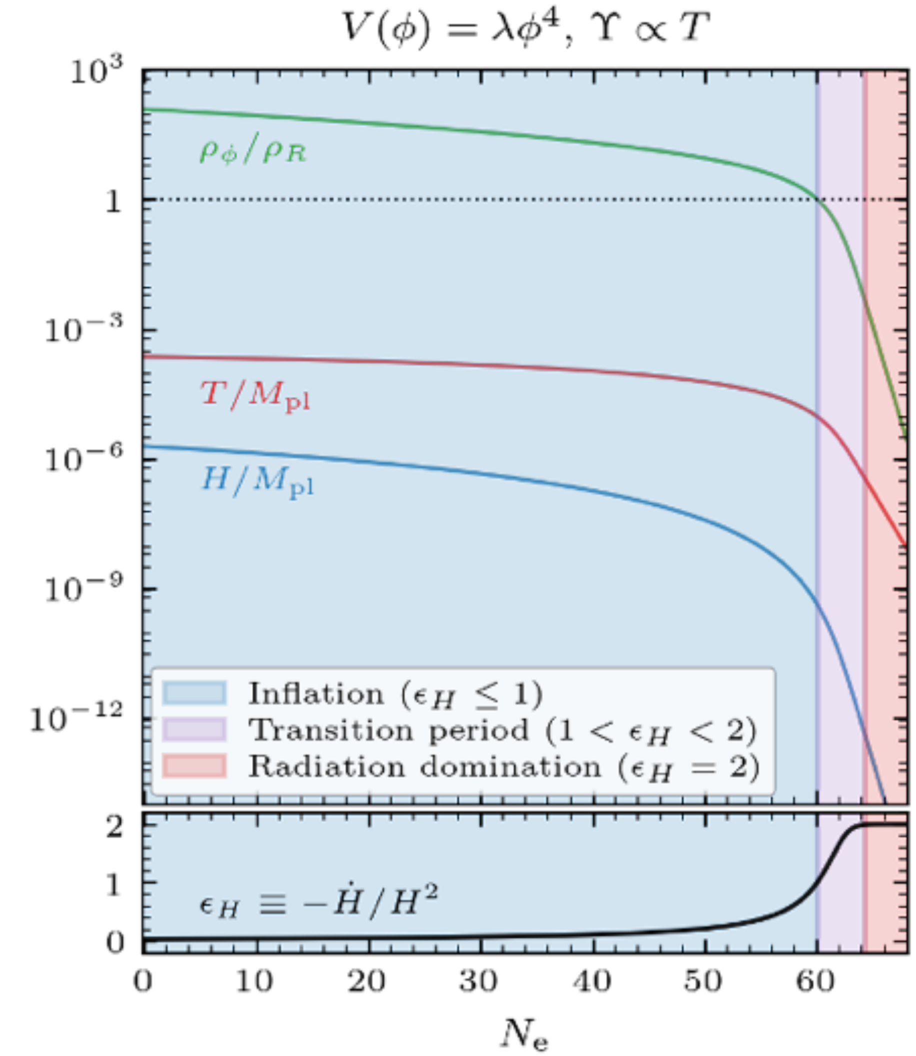
Key distinction from (standard) RD UV freeze-in:

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

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

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





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

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:

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

always enhancement

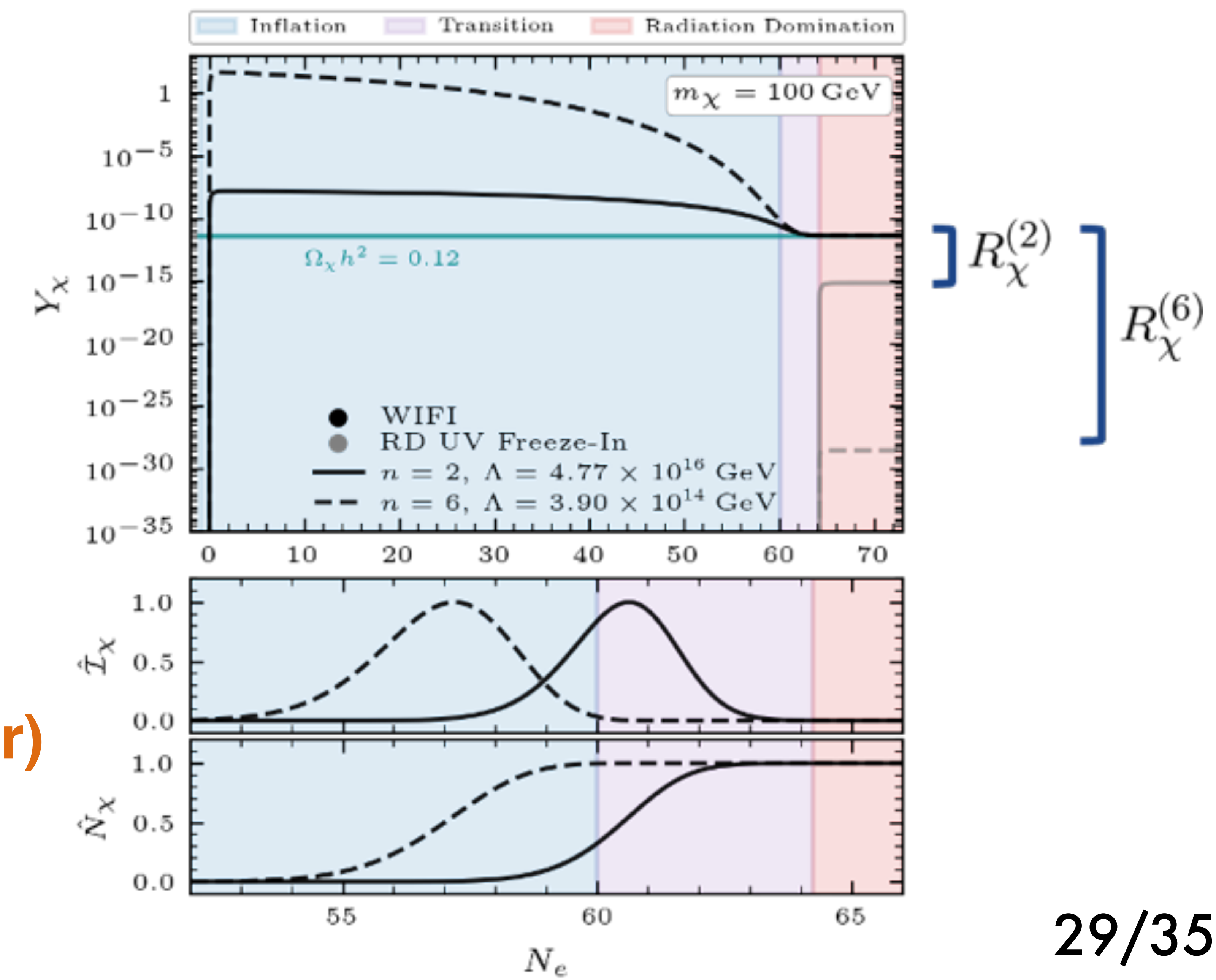
examples:

onset of RD:

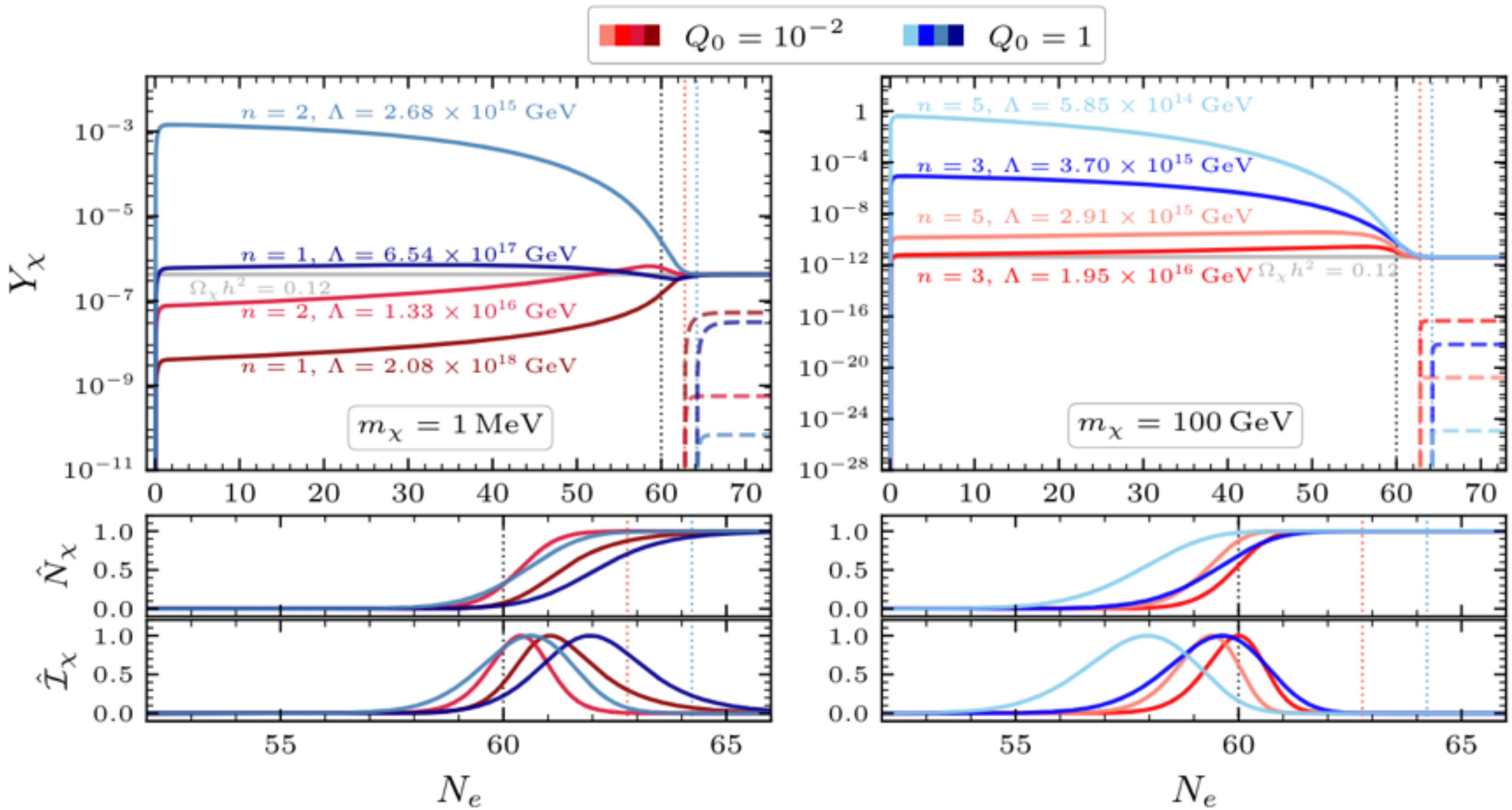
$$\epsilon_H \equiv -\dot{H}/H^2$$

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

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

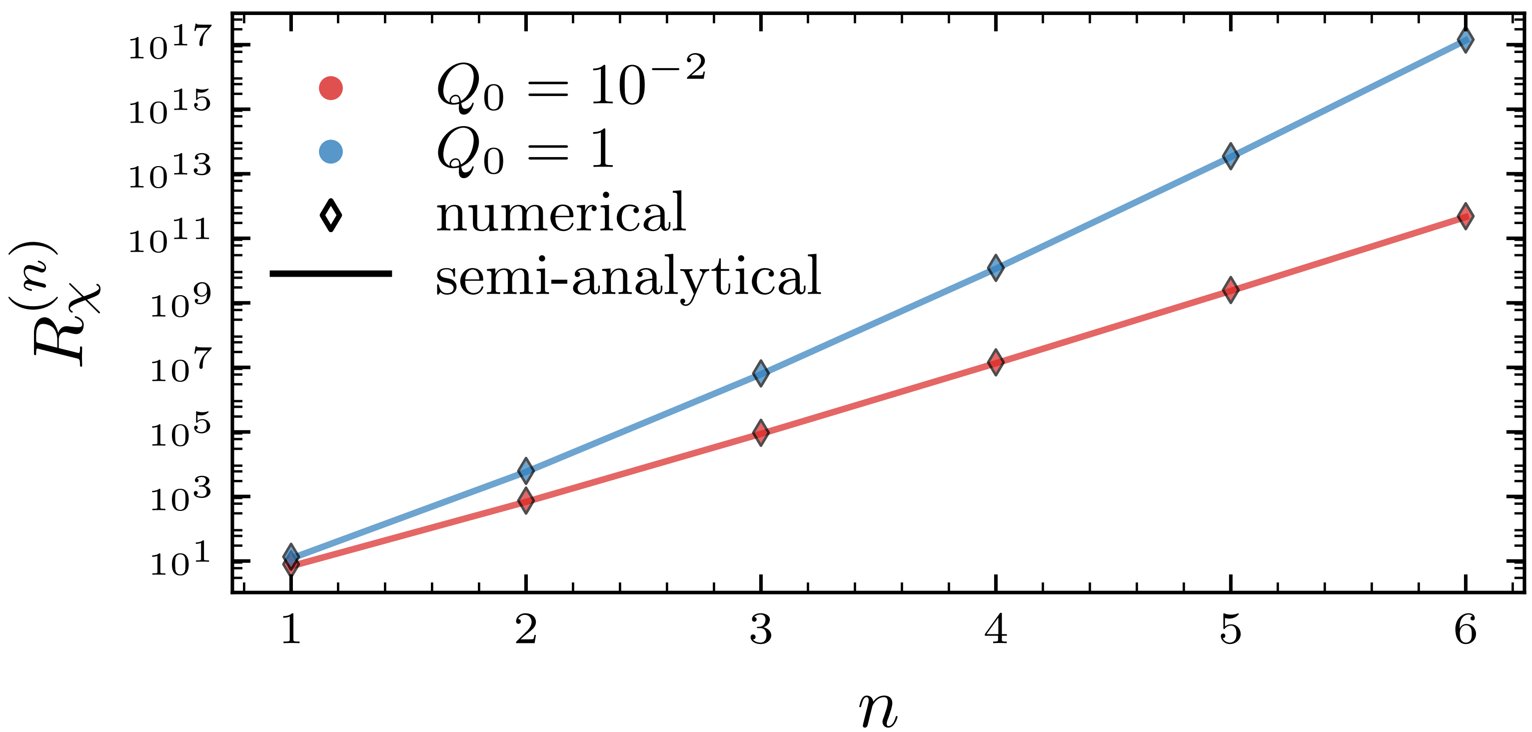


more examples:



Exponential enhancement!

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



Take-home message:

Harmless relic:
UV freeze-in yield too low?
Switch to a non-standard cosmology (prior to RD)!
Better yet, kick things off from the beginning of (warm) inflation!

Dangerous relic:
UV freeze-in yield too low?
Be careful if you want to Switch to a non-standard cosmologies!

Hot Gravitons from Warm Inflation

Work in progress with: **Gabriele Montefalcone, and Tao Xu**

S. Winberg, 1972

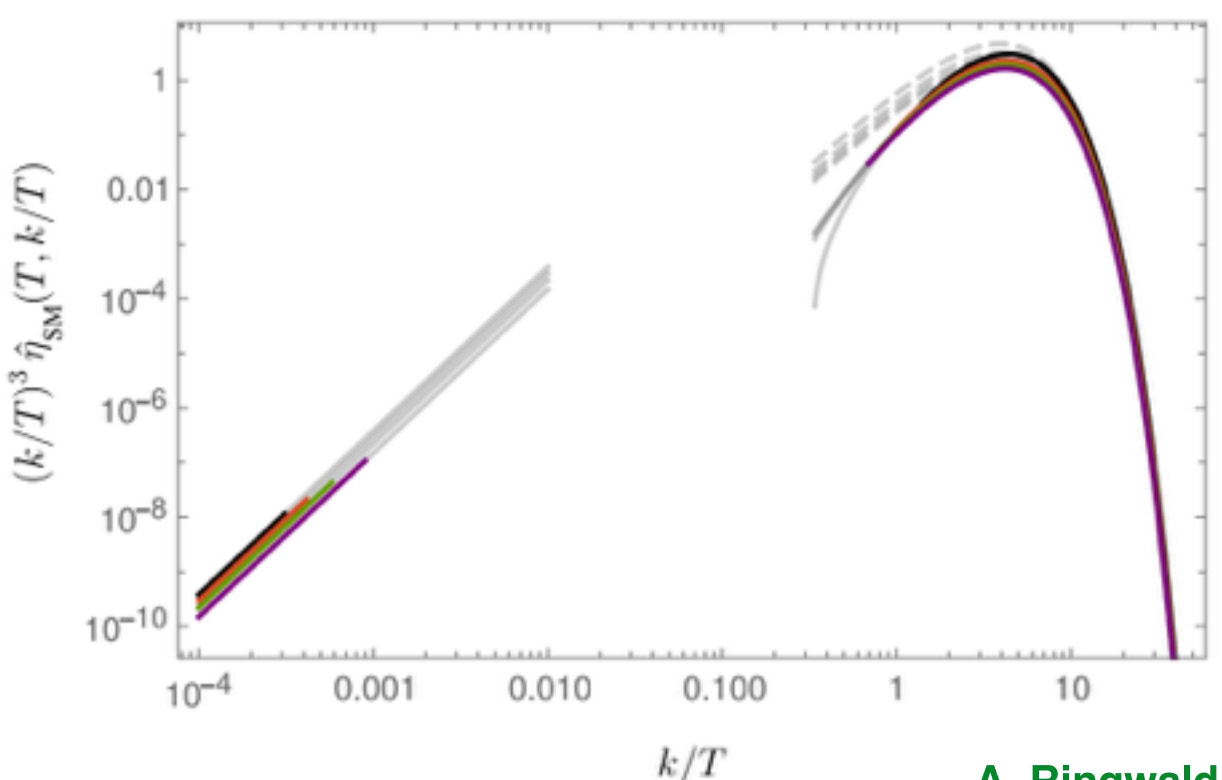
J. Ghiglieri, M. Laine, 2015

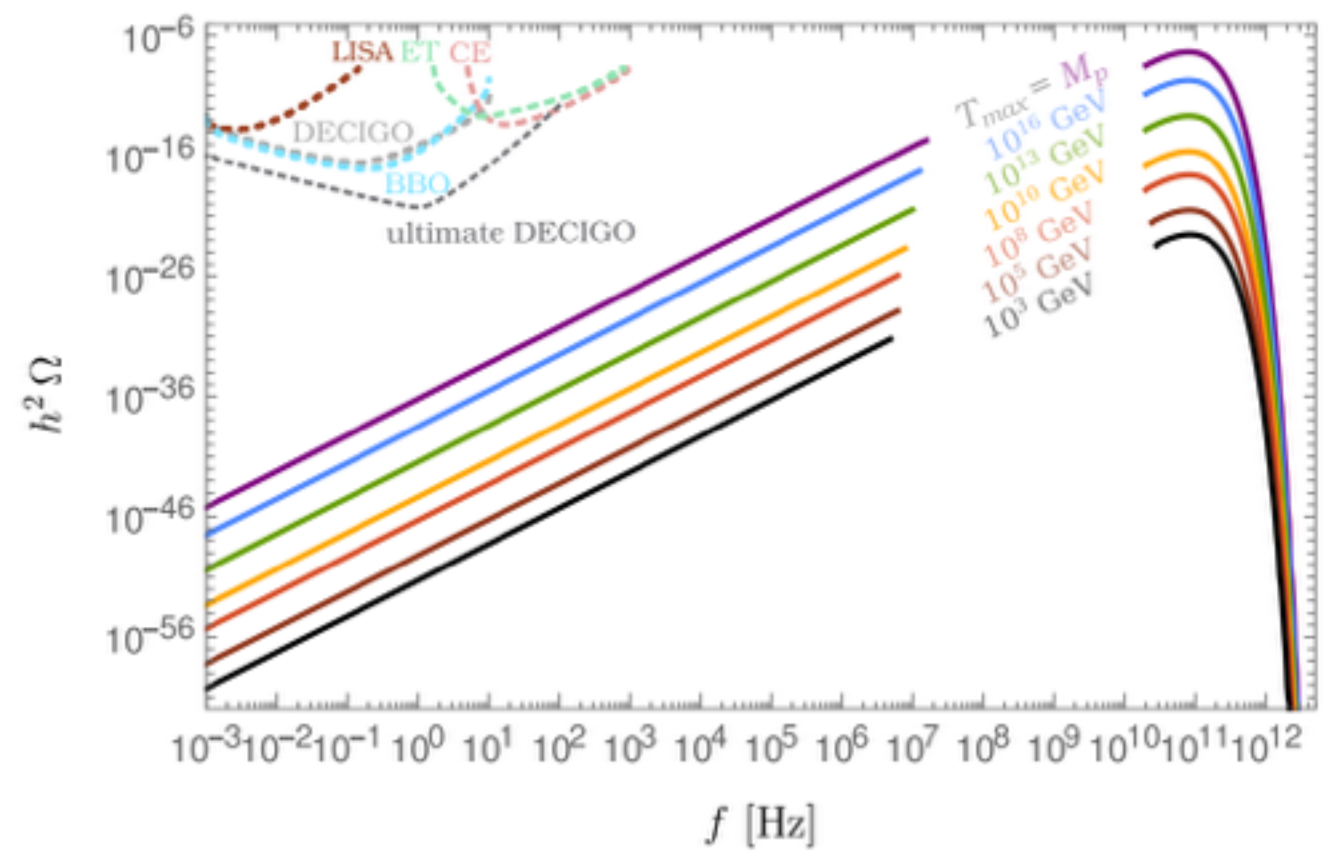
J. Ghiglieri, G. Jackson, M. Laine, Y. Zhu, 2020

A. Ringwald, J. Schutte-Engel, C. Tamarit, 2020

In a thermal bath particles scatter off each other, experience acceleration, emit GWs

$$\dot{\rho}_{\rm GW} + 4H\rho_{\rm GW} = \frac{T^4}{M_{\rm Pl}^2}\int \frac{d^3k}{(2\pi)^3}\hat{\eta}(T,k/T)$$





A. Ringwald, J. Schutte-Engel, C. Tamarit, 2020

$$\dot{\rho}_{\mathrm{GW}} + 4H\rho_{\mathrm{GW}} = \frac{T^4}{M_{\mathrm{Pl}}^2}\int \frac{d^3k}{(2\pi)^3}\hat{\eta}(T, k/T)$$

high-frequency gravitons:

$$\frac{\mathrm{d}\rho_{\mathrm{GW}}}{\mathrm{d}N_e} + 4\rho_{\mathrm{GW}} = \frac{T^7}{M_{\mathrm{Pl}}^2\, H}$$

gravitons can contribute to dark radiation:
impact the Hubble expansion rate.

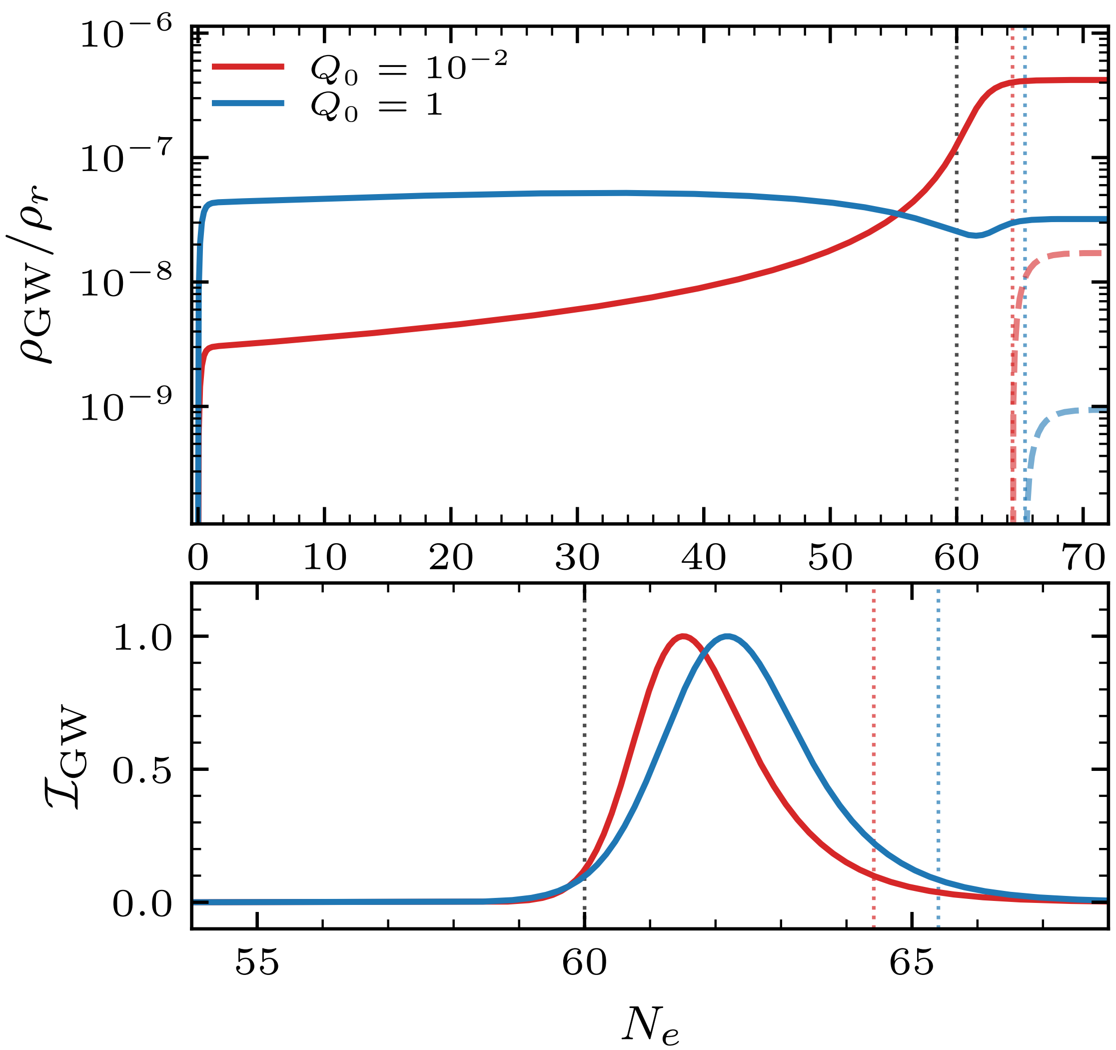
$$\rho_{\mathrm{rad}}(T_{\Delta N_{\mathrm{eff}}}) = \rho_\gamma + \rho_\nu + \rho_{\mathrm{GW}} = \left[1 + \frac{7}{8}\left(\frac{T_\nu}{T_\gamma}\right)^4 N_{\mathrm{eff}}\right]\rho_\gamma(T_{\Delta N_{\mathrm{eff}}})$$

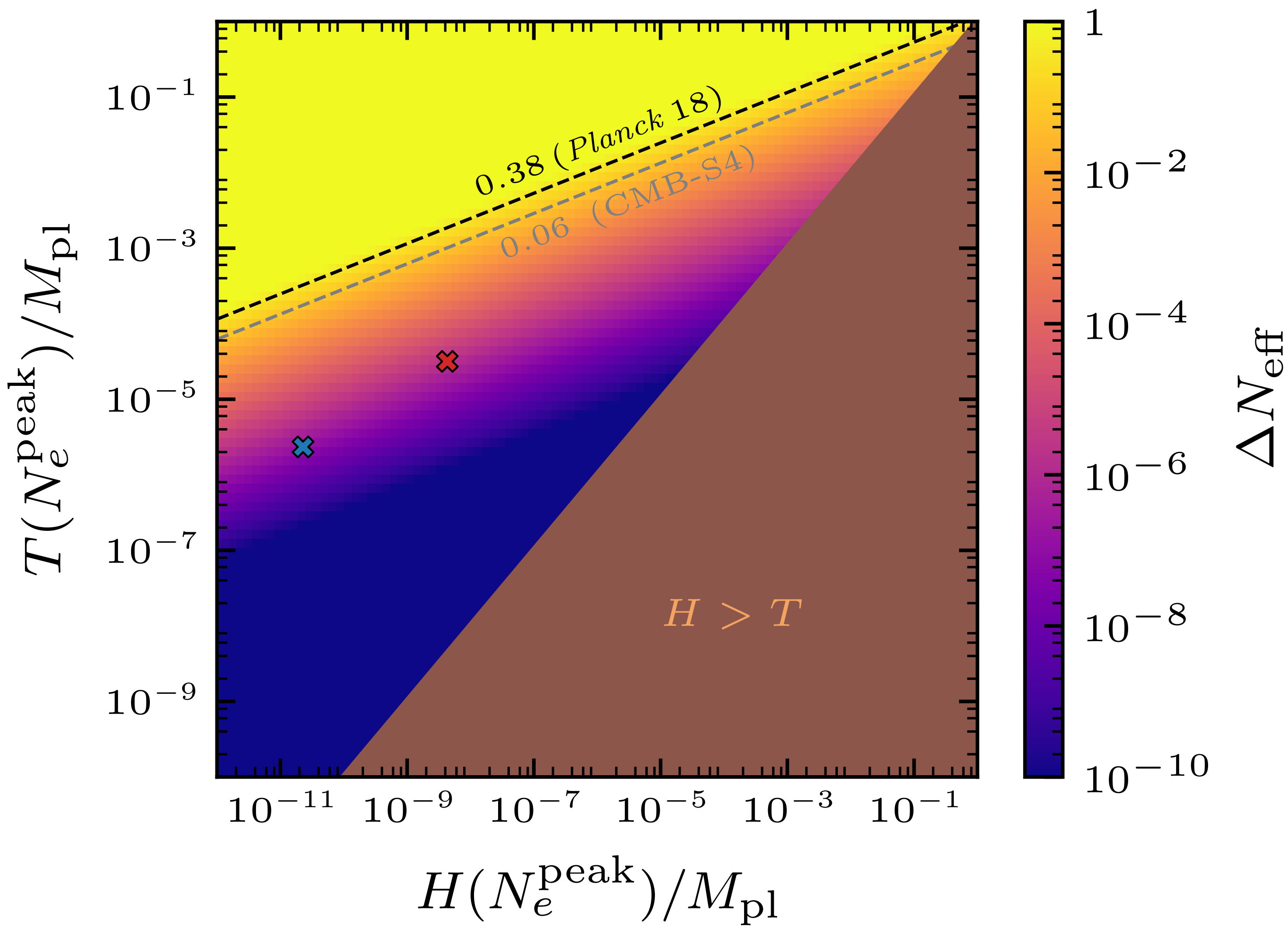
$$\Delta N_{\mathrm{eff}} \equiv N_{\mathrm{eff}} - N_{\mathrm{eff}}^{\mathrm{SM}} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{\rho_{\mathrm{GW}}(T_{\Delta N_{\mathrm{eff}}})}{\rho_\gamma(T_{\Delta N_{\mathrm{eff}}})}$$

$$T_{\mathrm{BBN}} \sim 0.1\ \mathrm{MeV}$$

$$T_{\mathrm{CMB}} \sim 0.3\ \mathrm{eV}$$

Hot Gravitons from Warm Inflation





Simple, single-field warm inflation models do not appear to be constrained.

GW spectrum: could still be interesting …

Conclusion:

A novel perspective on the role of inflation in the production of DM:
DM production during Warm Inflation via Freeze-In (WIFI).

The first complete picture of DM production via freeze-in
from the onset of inflation to today.

WIFI provides new ways for reheating of warm inflation into the SM
(production and decay of heavy meta-stable particles).

The persistent and out-of-equilibrium thermal bath during warm inflation
provides an intriguing cosmological setup for phenomenologists!
(e.g. regarding baryogenesis)

Freeze-out during warm inflation? more challenging …