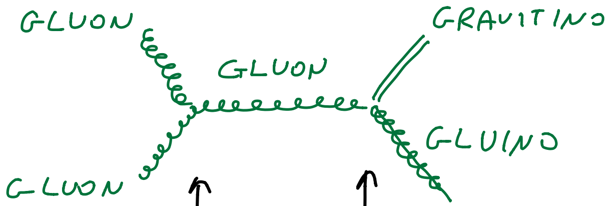
MARCO PELOSO LECTURE 3

INFLATION - ICTP 2022

• GRAVITINO PRODUCTION



DOMINANT PRODUCTION PROCESS

STRONG INTERACTION $g \sim 1$

GRAVITATIONAL INTERACTION $g \sim \frac{1}{M_P}$

$\Rightarrow \quad \sigma \sim \frac{1}{M_P^2}$

$\Rightarrow \Gamma \sim \frac{T^3}{M_P^2}$ FROM A THERMAL BATH

Γ HAS MASS DIMENSION +1

$$\frac{\Gamma}{H} \sim \frac{T^3}{M_P^2} \frac{M_P}{T^2} = \frac{T}{M_P}$$, MAXIMUM PRODUCTION WHEN $T \sim T_{RH}$

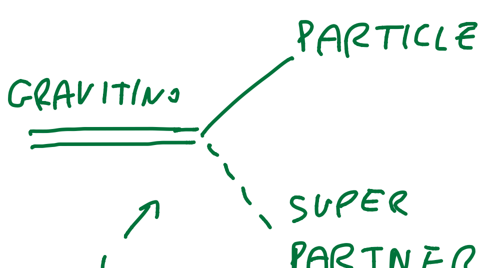
ONE GRAVITINO PER PROCESS $\Rightarrow$ $\boxed{n_{3/2} \sim \frac{T_{RH}}{M_P} n_\gamma}$

NANOPOULOS
OLIVE
SREDNICKI '83

INVERSE PROCESS NEGLIGIBLE FOR $T_{RH} \ll M_P$

GRAVITINO DECAY AND DISRUPTION OF BBN PREDICTIONS

IF UNSTABLE, GRAVITINOS DECAY THROUGH



$g \sim \frac{1}{M_P}$

$$\Gamma \propto \frac{1}{M_P^2} \Rightarrow \Gamma \simeq \frac{m_{3/2}^3}{M_P^2}$$

TEMPERATURE OF THERMAL BATH WHEN GRAVITINO DECAYS

$$\Gamma = H \Rightarrow \frac{m_{3/2}^3}{M_p^2} = \frac{T^2}{M_p}$$

NO PROBLEM IF DECAY BEFORE BBN, NAMELY IF $T > \mathrm{MeV}$

$$\Rightarrow m_{3/2} \simeq \left(T^2 M_p\right)^{1/3} \simeq \left(10^{-6}\,\mathrm{GeV}^2\, 10^{18}\,\mathrm{GeV}\right)^{1/3} \simeq 10^4\,\mathrm{GeV}$$
$$= 10\,\mathrm{TeV}$$

IF $m_{3/2} < 10\,\mathrm{TeV}$, WE MUST REQUIRE THAT $n_{3/2} \simeq T_{RH}/M_p\, n_\gamma$ IS SUFFICIENTLY SMALL

$\Rightarrow$ UPPER LIMIT ON REHEATING TEMPERATURE

SLIDE 3

IS REHEATING REALLY INSTANTANEOUS ?

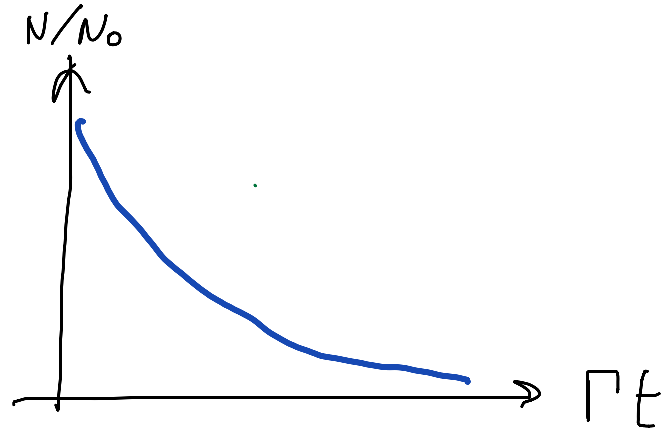
RECALL $H \sim \frac{\rho^{1/2}}{M_P} \sim \frac{1}{t} \Rightarrow \frac{t_{RH}}{t_{END}} \sim \frac{\rho_{END}^{1/2}}{\rho_{RH}^{1/2}} \sim \frac{\rho_{INF}^{1/2}}{T_{RH}^2} \sim \frac{10^{33}\,\text{GeV}^2\, r^{1/2}}{T_{RH}^2}$

FOR $T_{RH} = 10^5\,\text{GeV}$, $\boxed{t_{RH} \sim 10^{23}\, r^{1/2}\, t_{END}}$

FROM $N(t) = N_0\, e^{-\Gamma t}$

WE NOTE THAT

$$\left|\frac{dN}{dt}\right| = N_0 \Gamma e^{-\Gamma t}$$



IS GREATER AT THE INITIAL TIME, SO WE EXPECT THE FORMATION OF A THERMAL BATH AT TIMES $t \ll \Gamma^{-1}$

(ASSUMPTION OF THERMALIZATION OF THE DECAY PRODUCTS FAR FROM TRIVIAL. IT APPEARS TO BE A REASONABLE ASSUMPTION IN PRESENCE OF GAUGE INTERACTIONS

DAVIDSON, SARKAR '00; HARIGAYA, MUKAIDA '13)

ASSUMING NON-INSTANTANEOUS DECAY, BUT INSTANTANEOUS THERMALIZATION OF THE DECAY PRODUCTS, HOW DOES THE TEMPERATURE EVOLVE?

AND HOW DOES THE GRAVITINO ABUNDANCE?

THE EVOLUTION OF THE INFLATON + RADIATION ENERGY DENSITY IS GOVERNED BY

$$\begin{cases} \dot{\rho}_\phi + (3H+\Gamma)\,\rho_\phi = 0 \\ \dot{\rho}_\gamma + 4H\rho_\gamma = \Gamma\rho_\phi \\ \rho_\phi + \rho_\gamma = 3M_p^2H^2 \end{cases}$$

THE INFLATON DECAY, WITH RATE Γ, DECREASES ρ_ϕ & INCREASES ρ_γ

- IF $\Gamma = 0 \Rightarrow \dot{\rho}_\phi + 3\frac{\dot{a}}{a}\rho_\phi = 0 \Rightarrow \rho_\phi \propto a^{-3}$ AS WE SAW

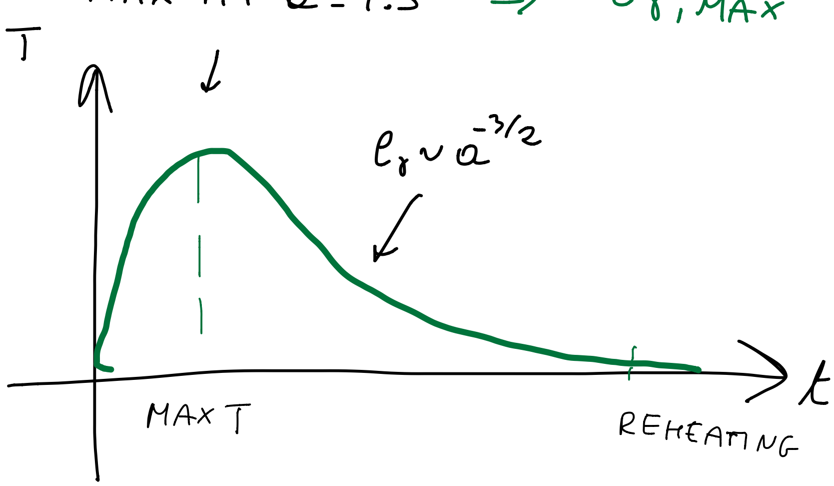
- WE CAN SOLVE THE SYSTEM ANALYTICALLY AT EARLY TIMES, UNDER ASSUMPTION $\rho_\gamma << \rho_\phi \rightarrow a \propto t^{2/3}$

HOMEWORK $\rightarrow$

$$\boxed{\rho_\gamma = \frac{6}{5} M_p^2 H_{END}\, \Gamma\, \frac{a^{5/2}-1}{a^4}}$$

($a_{END} = 1$ AT END OF INFLATION

MAX AT $a \simeq 1.5 \Rightarrow \rho_{\gamma,MAX} \simeq 0.4\, M_p^2 H_{END}\, \Gamma$



→ IF WE INSTEAD ASSUME INSTANTANEOUS REHEATING WHEN $\Gamma \simeq H$, WE HAVE $\rho_{\gamma,inst} = 3 M_P^2 H^2 = 3 M_P^2 \Gamma^2$

⇒ THE RATIO BETWEEN THE MAXIMUM ENERGY DENSITY, AND THE ENERGY DENSITY OBTAINED UNDER THE ASSUMPTION OF INSTANTANEOUS DECAY IS

$$\frac{\rho_{\gamma,MAX}}{\rho_{\gamma,inst}} \simeq 0.1 \frac{H_{END}}{\Gamma}$$

THIS RATIO CAN BE $\gg 1$ BY MANY ORDERS OF MAGNITUDES!

HOW RELEVANT IS THIS?

- $T_{MAX} \gg T_{REH}$ REACHED RIGHT AFTER INFLATION WHILE INFLATON IS STILL DOMINATING
- QUANTA OF PARTICLES X PRODUCED IN MUCH GREATER NUMBER DUE TO $T \gg T_{REH}$; HOWEVER DILUTED BY CONTINUOUS DECAY OF ϕ

WHETHER THIS IS IMPORTANT OR NOT DEPENDS ON HOW SENSITIVE THE PRODUCTION OF X IS TO THE TEMPERATURE

INFLATON ϕ $\longrightarrow$ THERMAL BATH $\longrightarrow$ PARTICLE X

ASSUME PARTICLE X PRODUCED FROM THERMAL SCATTERINGS BY $\gamma\gamma \to XX$ WITH CROSS SECTION $\sigma \propto T^n$

HOMEWORK

- IF $n \geq 6$ PRODUCTION AT VERY EARLY TIMES DOMINATES, AND $\rho_{X,\,\text{TRUE}} \gg \rho_{X,\,\text{INSTANTANEOUS DECAY APPROX}}$

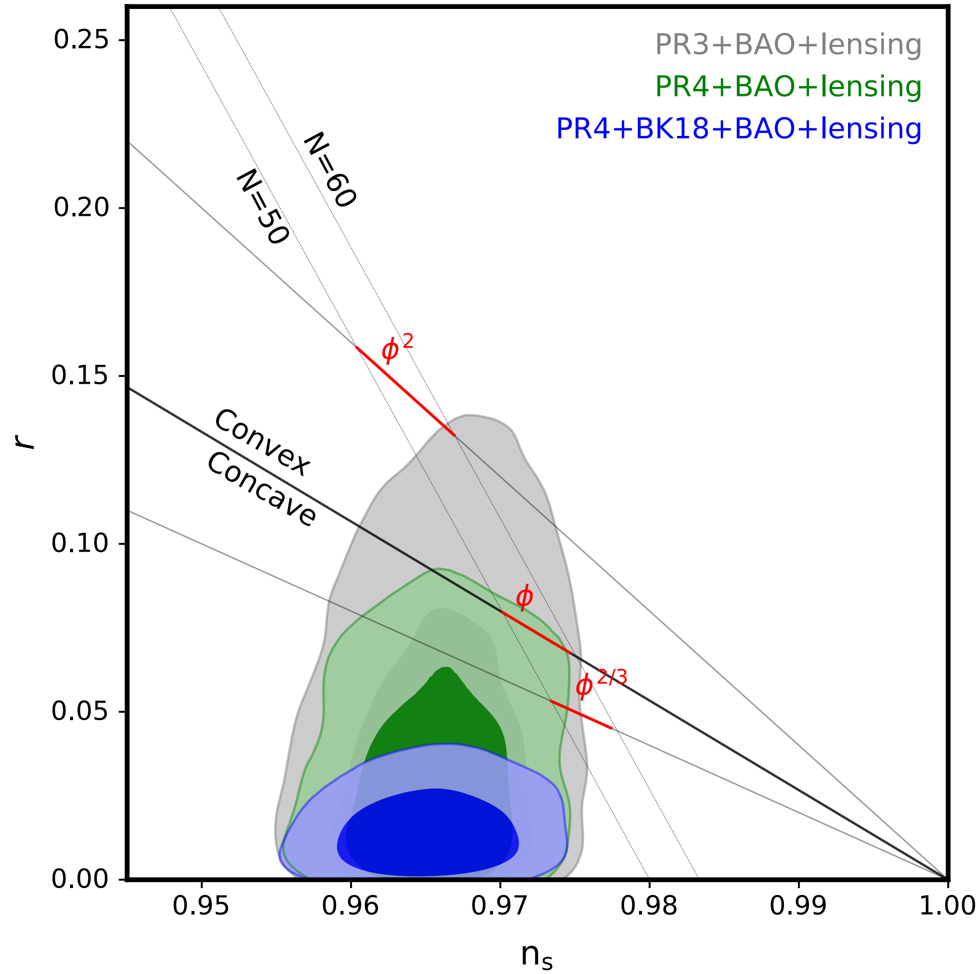
- IF $n < 6$ EFFECT OF DILUTION IS MORE IMPORTANT, AND INSTANTANEOUS ϕ-DECAY APPROX GIVES EXCELLENT RESULTS

SLIDE 4

Tristram et al '21

$$P_\zeta \propto \lambda^{1-n_s} \qquad n_s - 1 = 6\epsilon - 2\eta$$

$$r \equiv \frac{P_{\rm GW}}{P_\zeta} \qquad r = 16\epsilon$$



$$\begin{cases} P_\zeta = \frac{H^2}{8\pi^2 M_p^2 \epsilon} & = 2.2 \cdot 10^{-9} \\ P_{\rm GW} = \frac{2H^2}{\pi^2 M_p^2} & \equiv r\, P_\zeta \end{cases}$$

We measured the combination H^2/ϵ. Measuring GW ($\equiv$ knowing r)

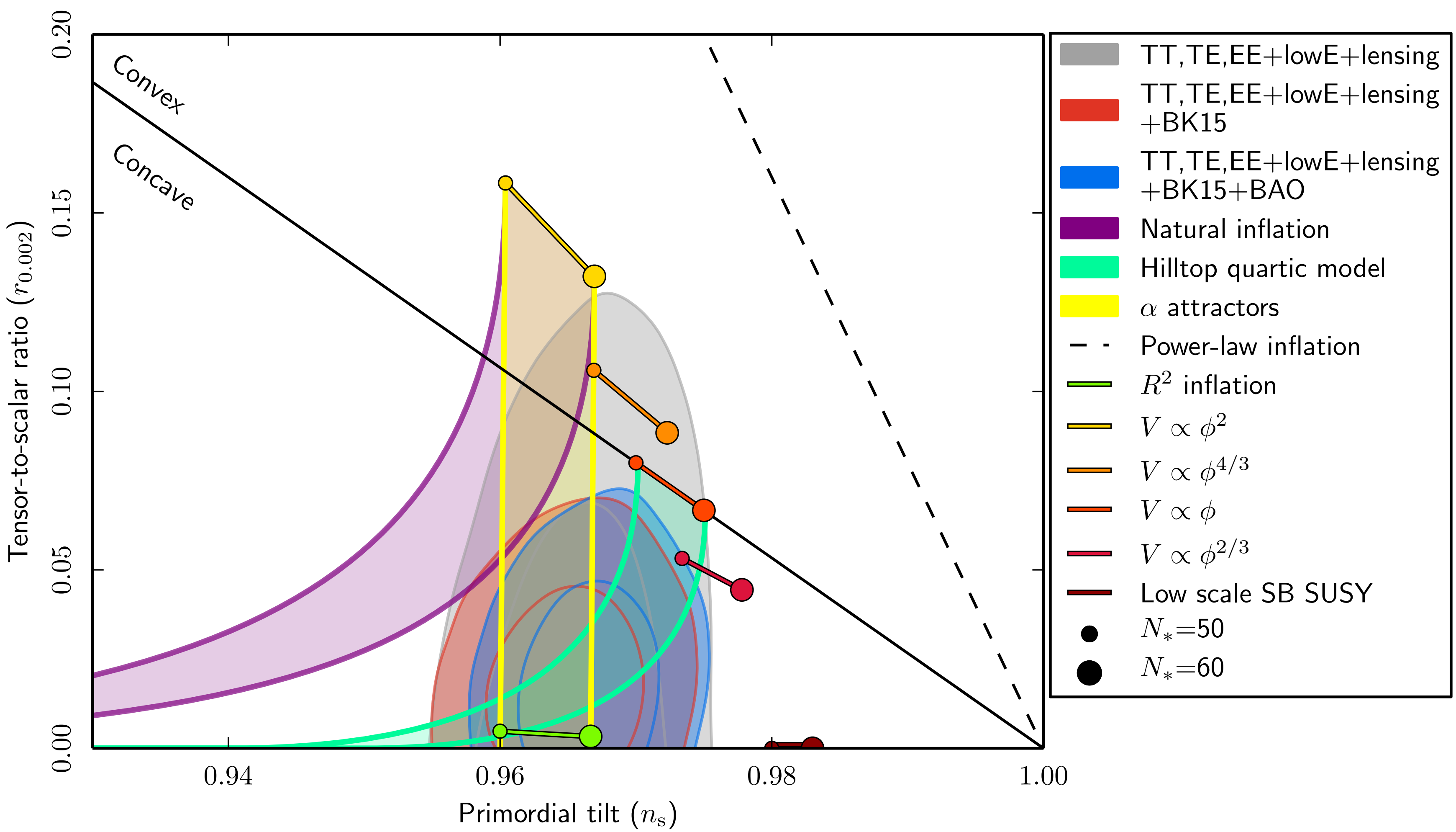
$\rightarrow$ scale of inflation

$$H \simeq 4.5 \cdot 10^{13}\,\text{GeV} \sqrt{\frac{r}{0.032}} \qquad \rho^{1/4} \simeq 1.4 \cdot 10^{16}\,\text{GeV} \left(\frac{r}{0.032}\right)^{1/4}$$

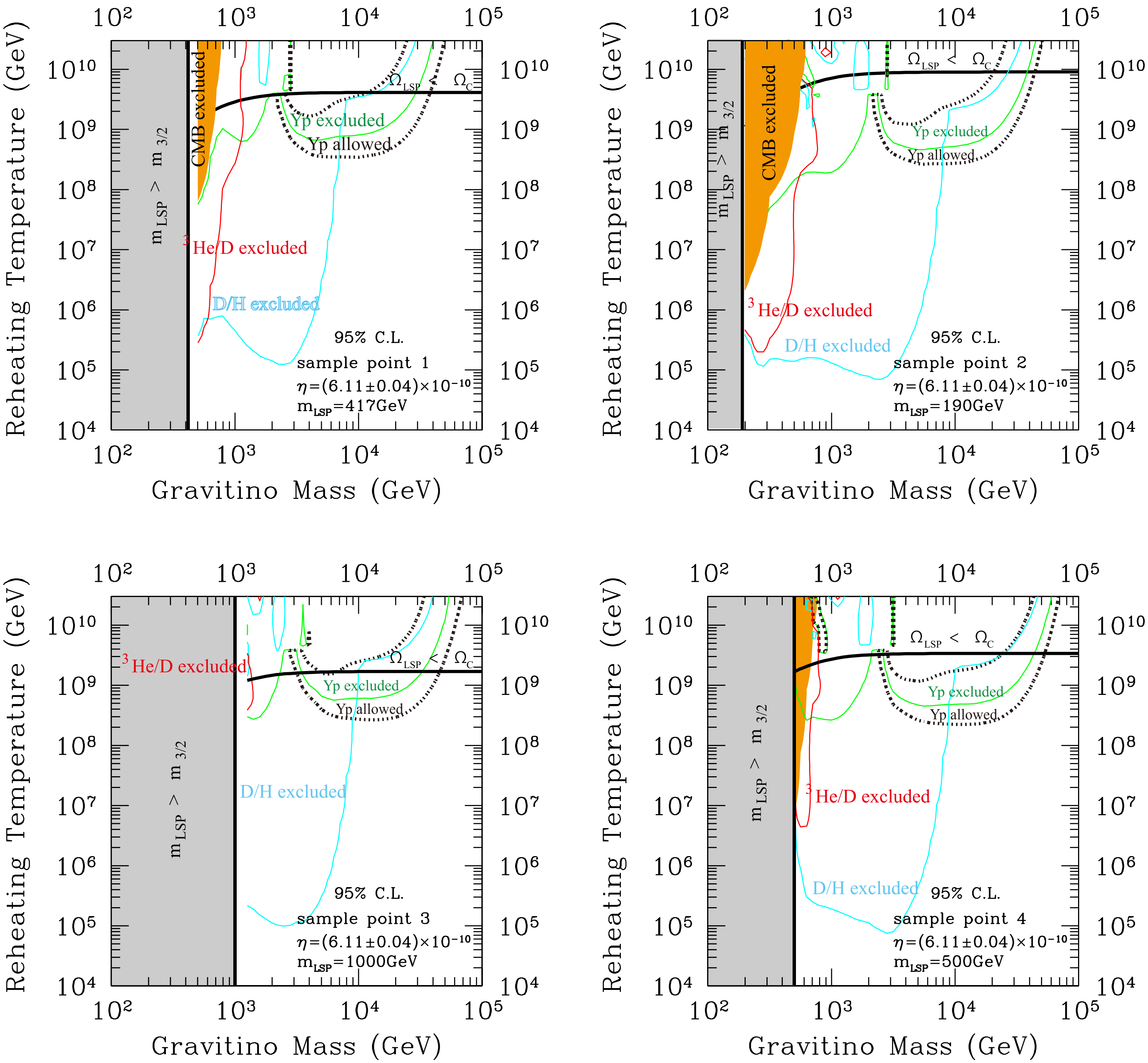
$$N \simeq 55.6 + 2\ln\frac{V_k^{1/4}}{10^{16}\,\mathrm{GeV}} + \ln\frac{10^{16}\,\mathrm{GeV}}{\rho_{\mathrm{end}}^{1/4}} + \frac{1-3w}{12\,(1+w)}\ln\frac{\rho_{\mathrm{reh}}}{\rho_{\mathrm{end}}}$$

(i) instantaneous reheating after inflation $\longrightarrow$ $\Delta N = 0$

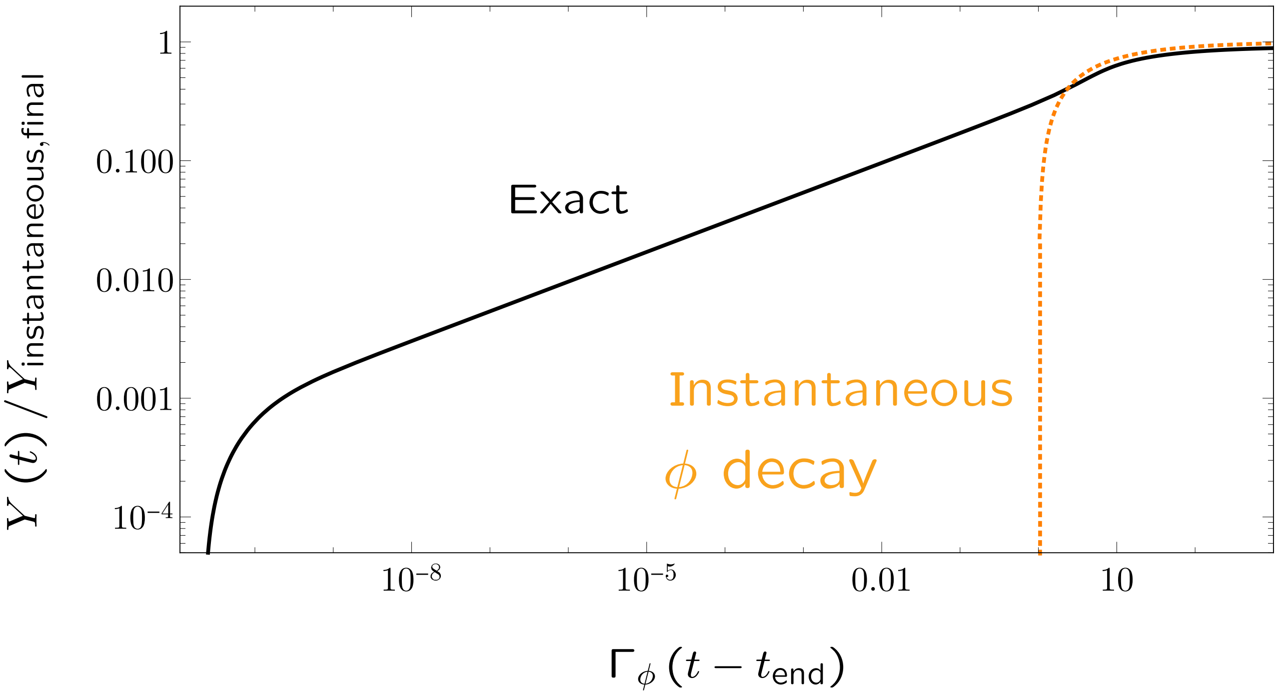
(ii) slowest possible decay $T_{\mathrm{reh}} \sim$ MeV $\longrightarrow$ $\Delta N \sim -15$



Limits in Minimal Supersymmetric Standard Model for ≠ benchmark scenarios (≠ superparticle masses)



Kawasaki, Kohri, Moroi, Takaesu '17

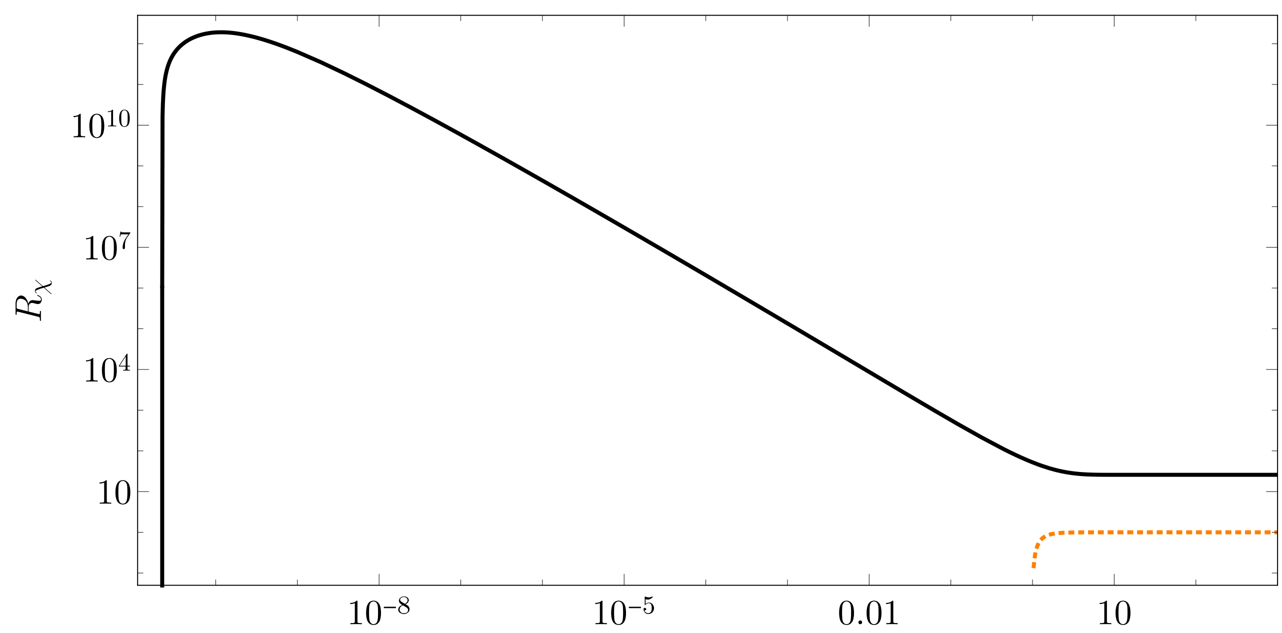


Example: gravitinos,

$$\sigma \simeq \frac{1}{M_p^2} \quad \rightarrow \quad n = 0$$

Massive spin 2

$$\sigma \propto \frac{1}{\Lambda^4 M^4} T^6$$



See for instance 1709.01549 and 1803.01866

Nonperturbative reheating

- In computing Γ_ϕ we treat ϕ as collection of independent quanta
- Coherent oscillations $\phi(t) \rightarrow$ faster decay, at sufficiently large couplings

Shtanov, Taschen, Brandenberger '94

Kofman, Linde, Starobinsky '94; '97

Example: massive inflaton ϕ, oscillating about minimum of potential,

with quartic coupling with another scalar field χ

$$V = \frac{1}{2} m^2 \phi^2 + \frac{g^2}{2} \phi^2 \chi^2$$

- Next slide: Result of lattice simulation (Latticeeasy: Felder, Tkachev).

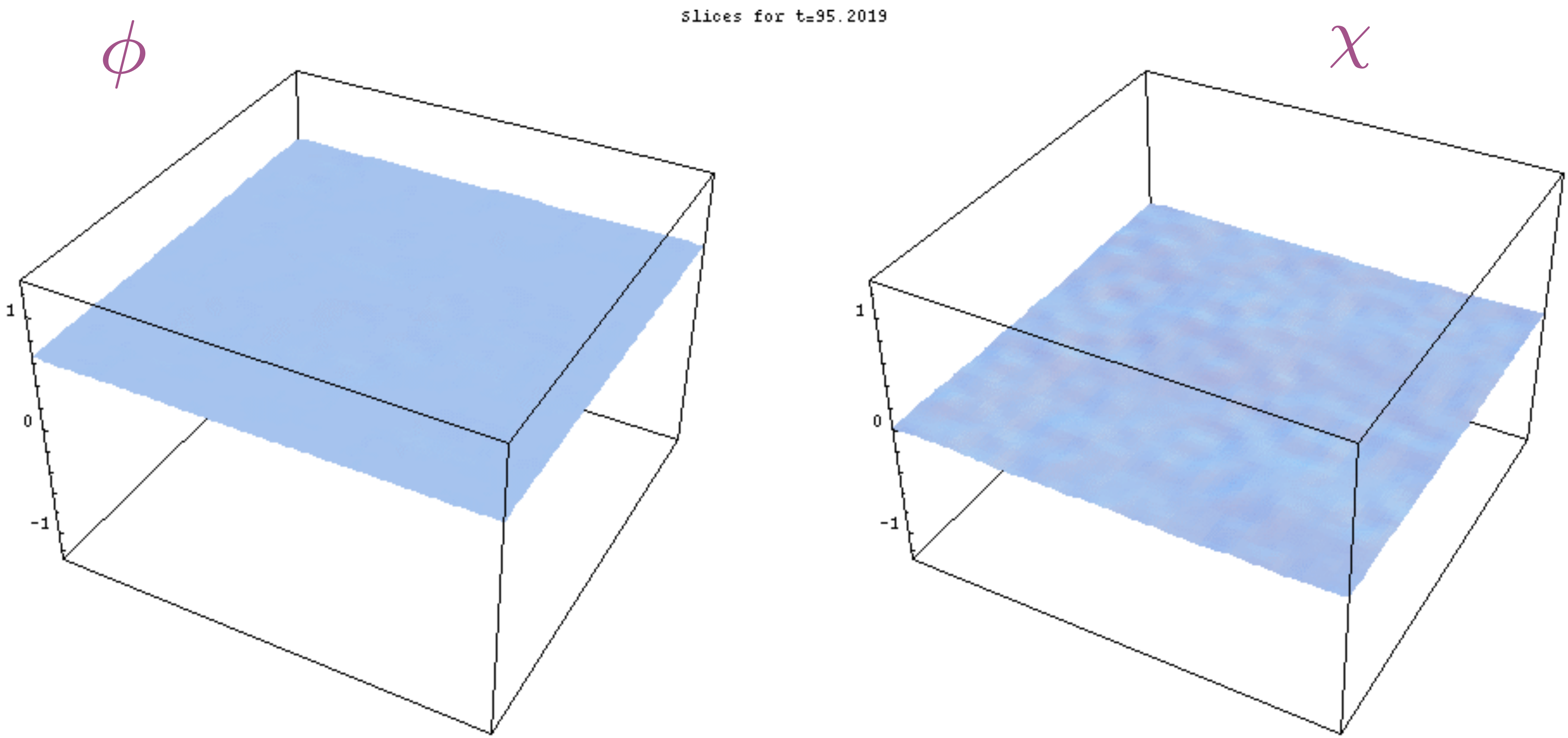
Three phases:

(1) Coherent inflaton oscillations

(2) χ excitations

(3) ϕ excitations

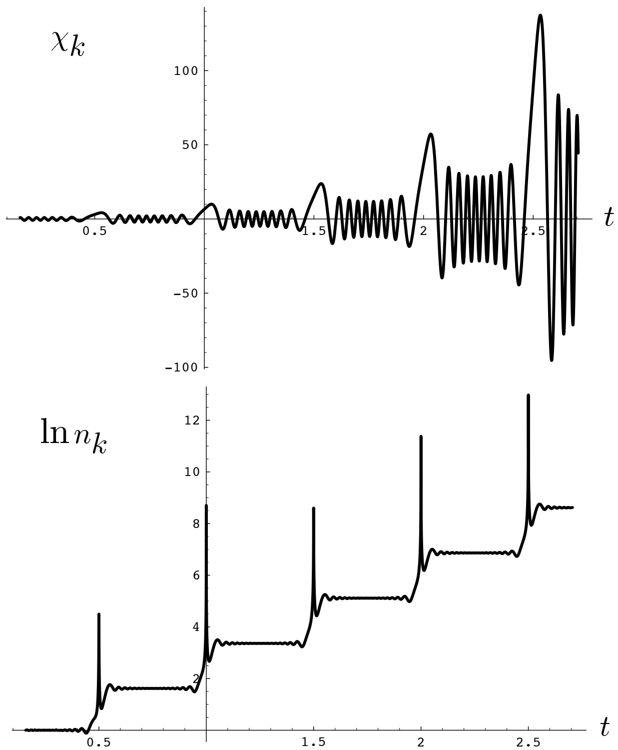
$$V = \frac{1}{2}m^2\phi^2 + \frac{g^2}{2}\phi^2\chi^2$$



G. Felder, I. Tkachev

$$V = \frac{1}{2}m^2\phi^2 + \frac{g^2}{2}\phi^2\chi^2$$

While lattice simulations required for the full dynamics, the early stages, and initial excitations of χ, can be obtained analytically



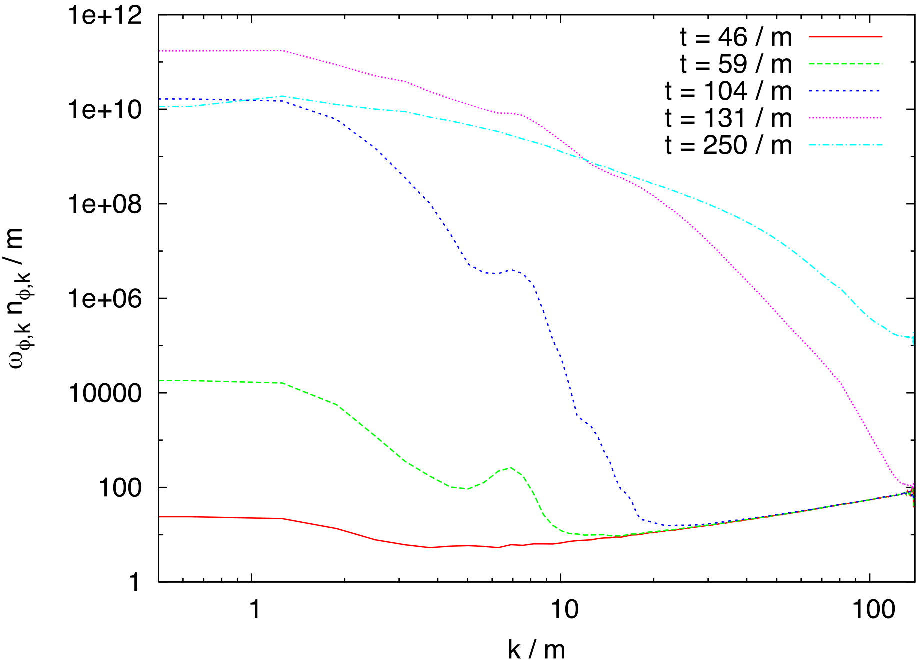
In this example, $m^2_{\chi,\text{effective}} = g^2\,\phi^2\,(t)$

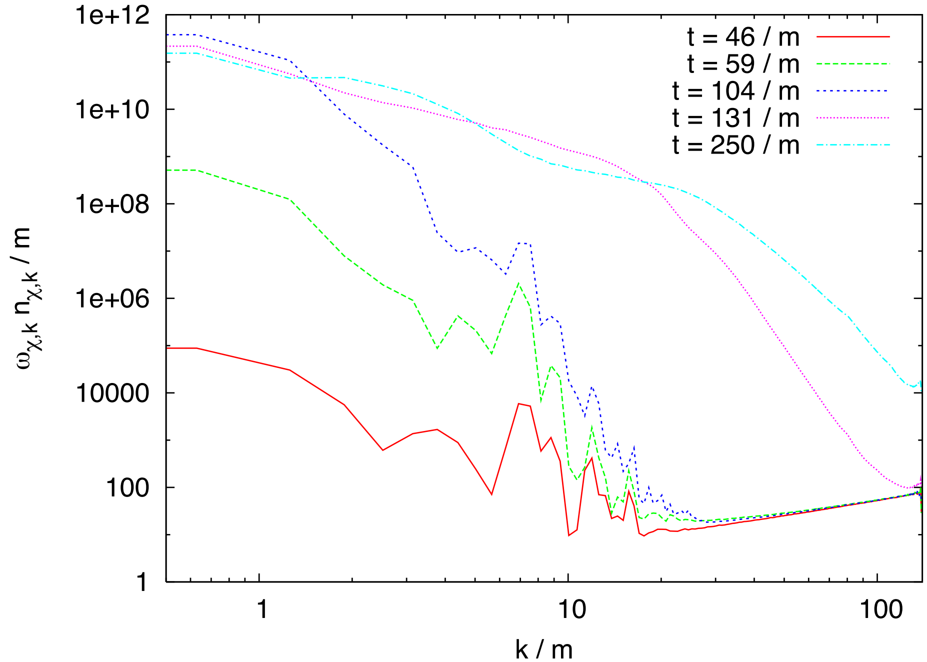
with $\phi\,(t) \simeq \Phi_0 \sin\,(mt)$

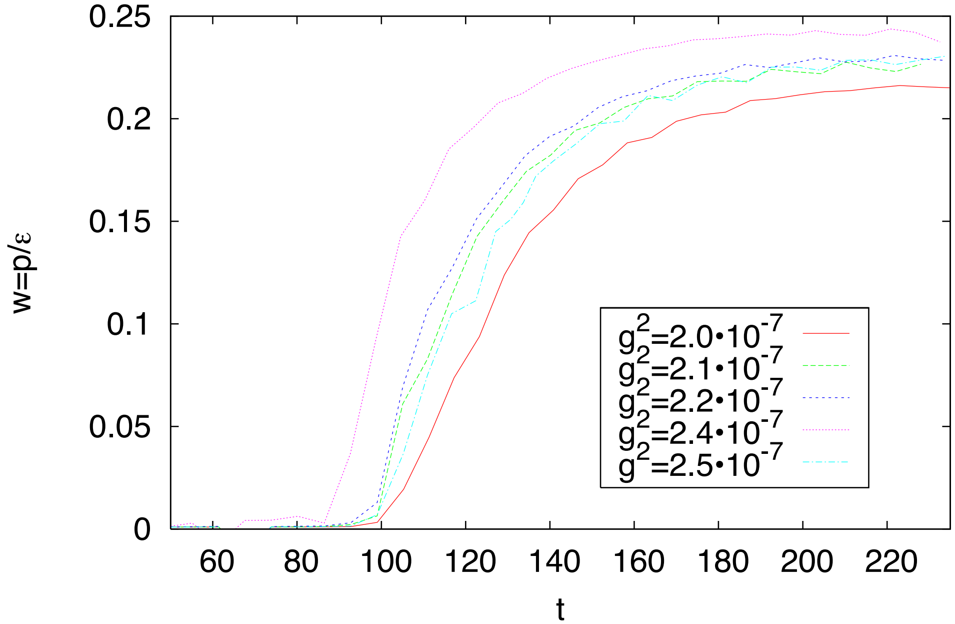
$$\Rightarrow \quad \omega = \sqrt{k^2 + g^2\,\Phi_0^2 \sin^2(mt)}$$

- $\dot{\omega}/\omega^2$ maximum whenever $\phi = 0$
- Oscillator with periodically changing frequency $\rightarrow$ Resonance

Spectra from lattice simulations show initial growth, then saturation, then slow propagation towards UV. Still very far from thermal equilibrium







Intermediate equation of state

between matter and radiation

Thermalization timescale well

beyond the reach of the lattice