Title: Reheating and Thermalization after inflation

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Abstract:

Reheating and thermalization after inflation

Marco Peloso, Minnesota

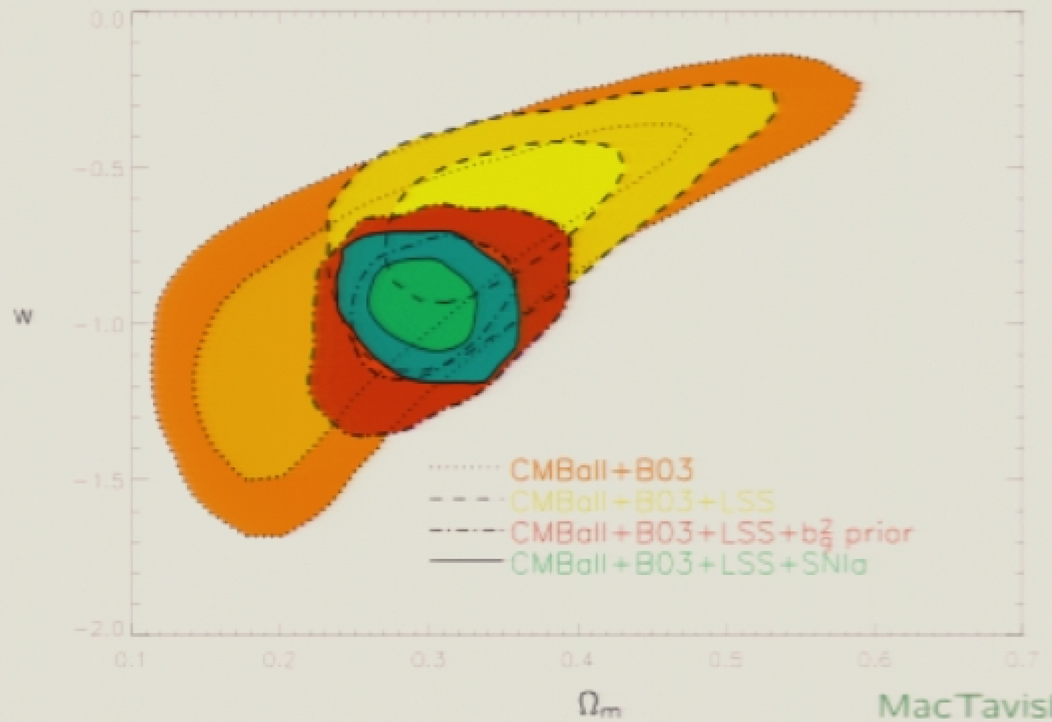
- Overview
- Intermediate equation of state
- Trilinear interactions

Podolsky, Felder, Kofman, M.P., '05

Dufaux, Felder, Kofman, M.P., Podolsky

History of the Universe

Clear knowledge from BBN on



MacTavish et al. '05

$$\Omega_Q \simeq 2/3 \quad , \quad \Omega_m \simeq 1/3 \quad , \quad T_\gamma \simeq 2.7\,\mathrm{K}$$

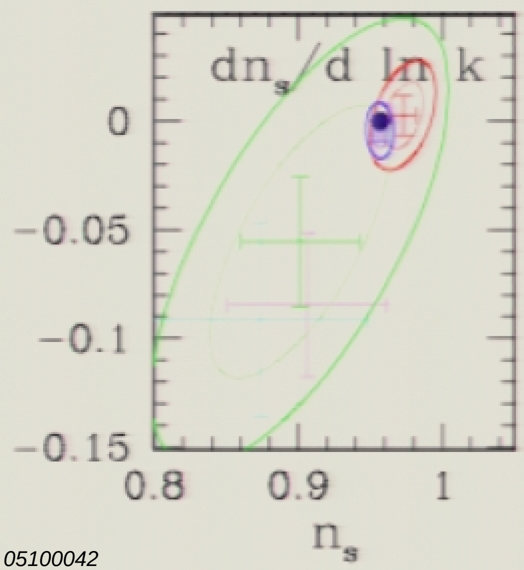
$$\Rightarrow \quad \begin{array}{llll} w_Q & \lesssim & -0.7 & z \in [0\,,\,0.25] \\ w_m & = & 0 & z \in \left[0.25\,,\,10^4\right] \\ w_r & = & 1/3 & z \in \left[10^4\,,\,?\right] \end{array}$$

$z_{\mathrm{BBN}} \simeq 10^{10}$

Good theoretical control & data for inflation

Slow Roll : $\epsilon = \frac{M_p^2}{16\pi}\left(\frac{V'}{V}\right)^2 \quad , \quad \eta = \frac{M_p^2}{8\pi}\frac{V''}{V} \, , \, \ldots$

- COBE normalization $\left(\frac{V}{\epsilon}\right)^{1/4} = 6.7 \cdot 10^{16}\,\mathrm{GeV}$
- Spectral index $n_s - 1 = -6\epsilon + 2\eta$
- Tensor mode $P_T(k) = \frac{2}{M_p^2}\left(\frac{H_k}{2\pi}\right)^2$



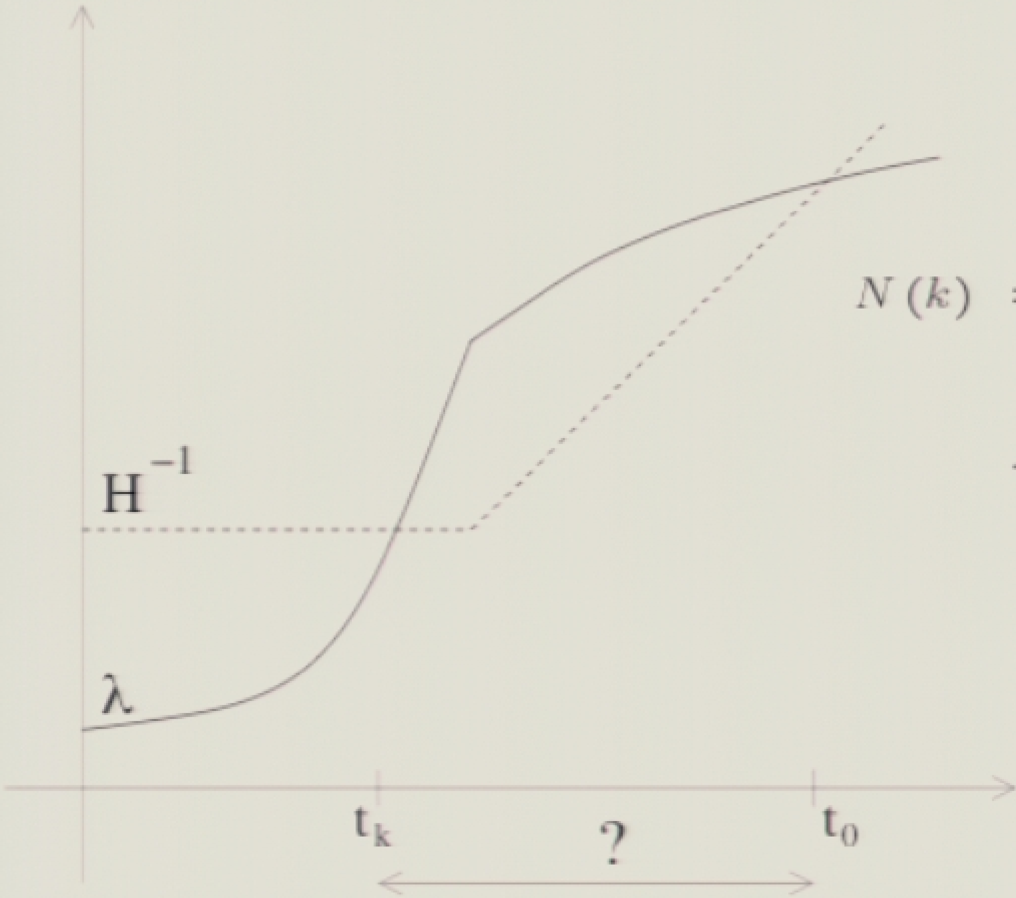
WMAP4

WMAP4 + ground based polarization telescopes

Planck

Bond, Contaldi, Lewis, Pogosyan '04

Present scale $\leftrightarrow$ horizon exit during inflation ?



$$N(k) = 62 - \ln \frac{k}{6.96 \times 10^{-5}\,\mathrm{Mpc}^{-1}} - \ln \frac{10^{16}\,\mathrm{GeV}}{V_k^{1/4}} + \frac{1}{4}\ln\frac{V_k}{V_\mathrm{end}} - \frac{1}{4}\ln\frac{V_\mathrm{end}^{1/3}}{\rho_\mathrm{reh}^{1/3}}$$

Liddle, Lyth

$$-\frac{1}{4}\ln\frac{a_\mathrm{reh}}{a_\mathrm{end}}$$

assumption of MD

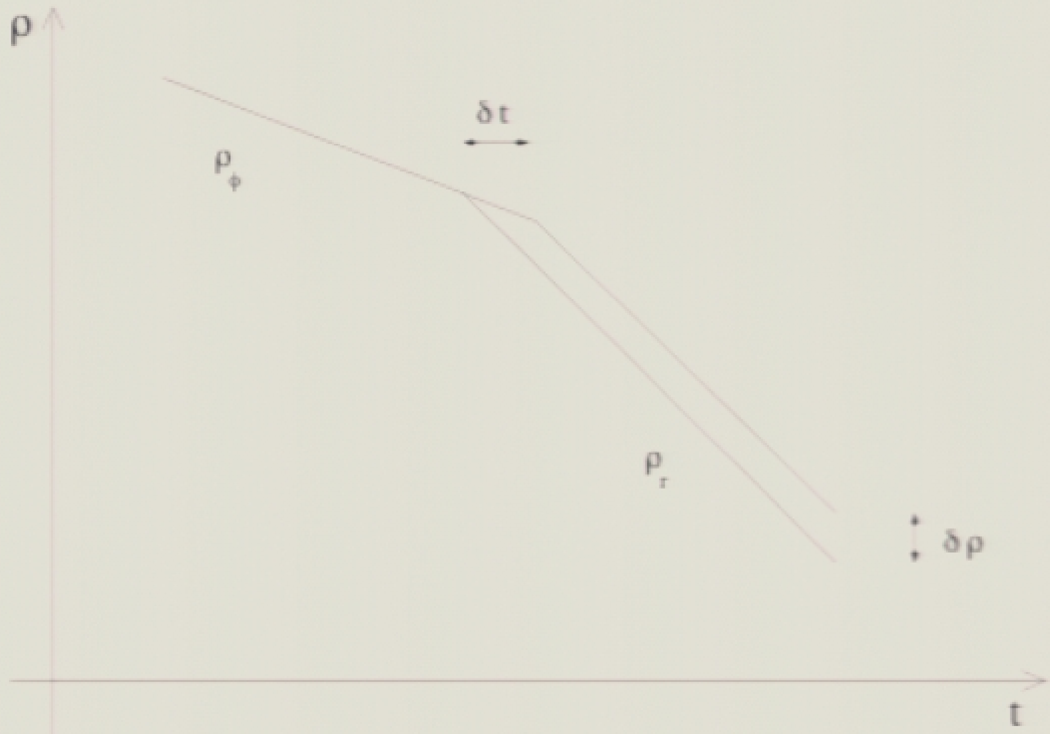
- MD between $H_\mathrm{inf} = 10^{13}\,\mathrm{GeV}$ and $T_\mathrm{rh} = 10^{9}\,\mathrm{GeV}$ $\Rightarrow -\frac{1}{4}\ln 10^{8} \simeq -4.6$
- Immediate inflaton decay at preheating $\Rightarrow -\frac{1}{4}\ln 20 \simeq -0.75$

Modulated fluctuations

Kofman '03

Dvali, Gruzinov, Zaldarriaga '03

- $V = g^2\phi^2\chi^2$. Fluctuations of the coupling give rise to density perturbations



$$g^2 = g^2(z)\ ,\ \ \delta g^2 = \frac{dg^2}{dz}\delta z$$

$\delta\rho$ due to $\omega_\phi \neq \omega_r$

- To make predictions, need to know details of the transition inflaton → radiation

Nonperturbative inflaton decay

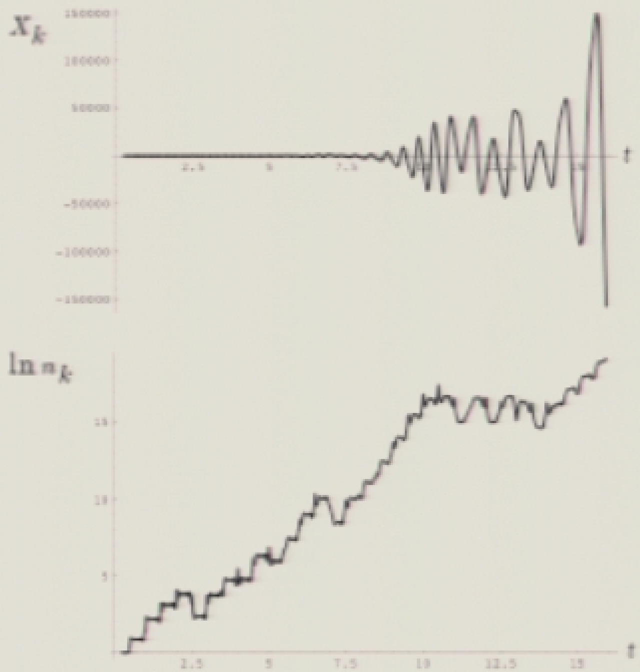
- Traschen, Brandenberger '90; Shtanov, Traschen, Brandenberger '94
- Preheating: Kofman, Linde, Starobinsky '94; '97

Resonant particle production due to coherent inflaton oscillations

$$V = \frac{1}{2} m^2 \phi^2 + \frac{g^2}{2} \phi^2 \chi^2 \quad \Rightarrow \quad \omega_\chi^2 = (k/a)^2 + g^2 \phi(t)^2$$

- Excitation when $\dot{\omega}_\chi > \omega_\chi^2$
- Periodic "driving force" $\rightarrow$ resonant instability bands

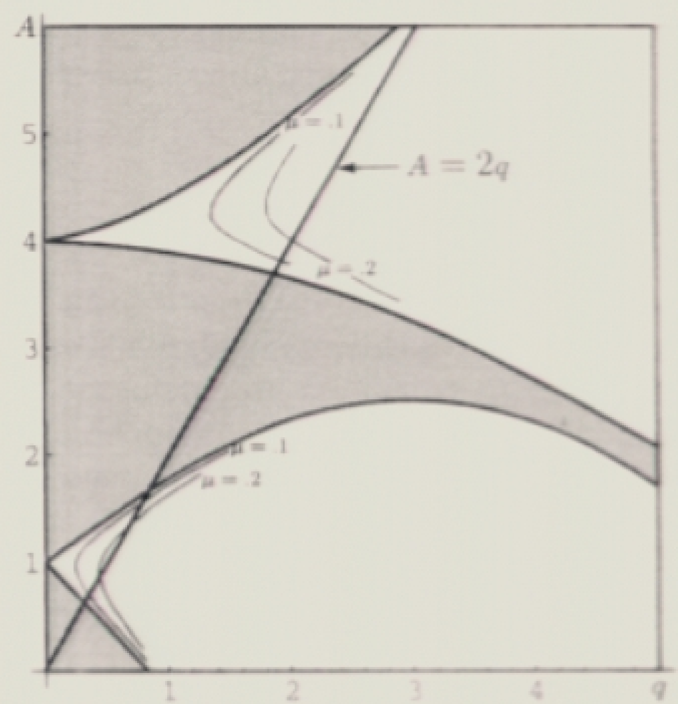
$$\omega^2 \sim m^2 + g^2 \phi^2 \ \Rightarrow \ g^2 \gtrsim \frac{m^2}{\phi^2} \sim 10^{-10}$$



- Stimulated particle production
- Redshift of physical momenta:

modes cross stability/instability bands

Stability / Instability chart



$$q \equiv \frac{g^2\,\phi^2}{4\,m^2} \quad , \quad A \equiv \frac{k^2}{m^2\,a^2} + 2\,q$$

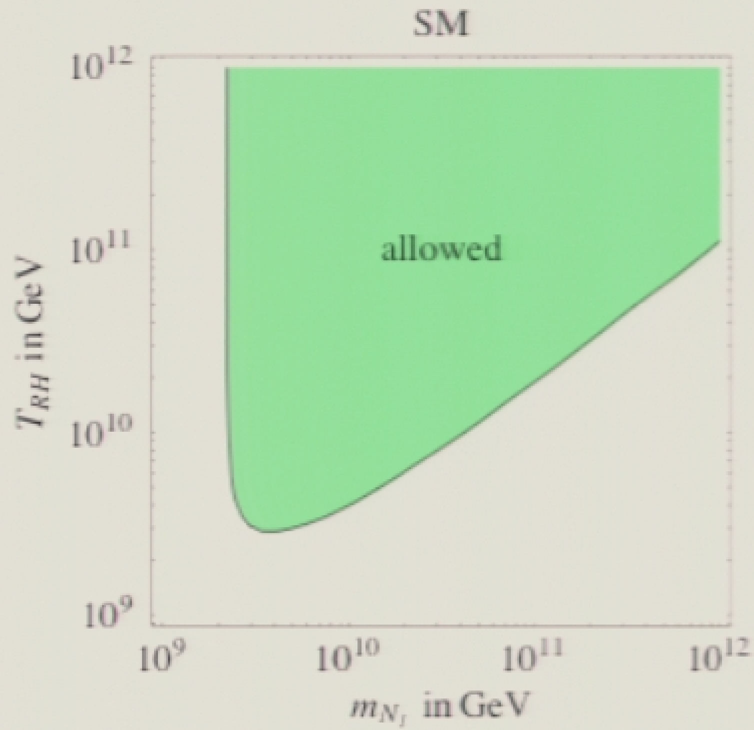
Production of super–heavy particles

- Many models of baryogenesis require heavy masses; thermal production can be in conflict with bounds on T_{rh} from gravitino problem

E.g. Thermal leptogenesis

from r.h. neutrinos

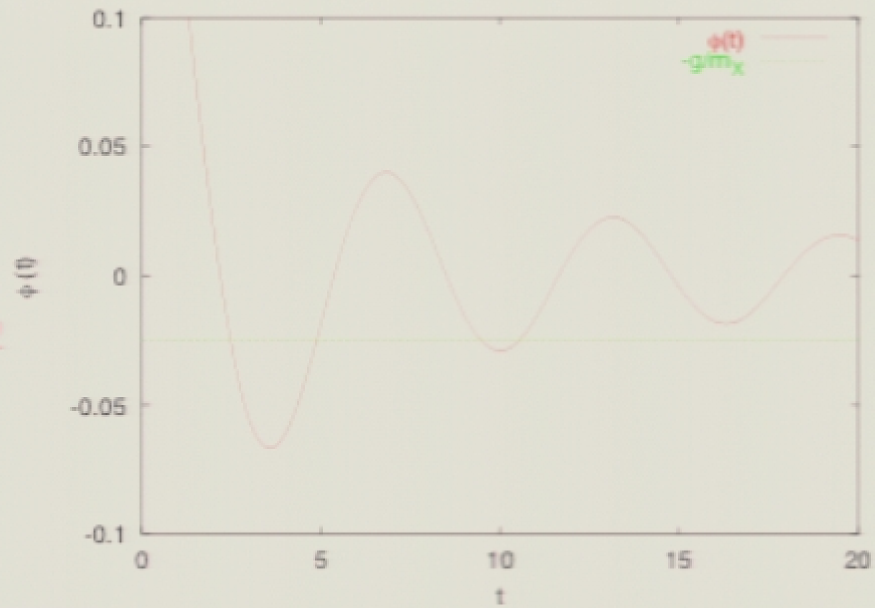
Giudice et al. '04



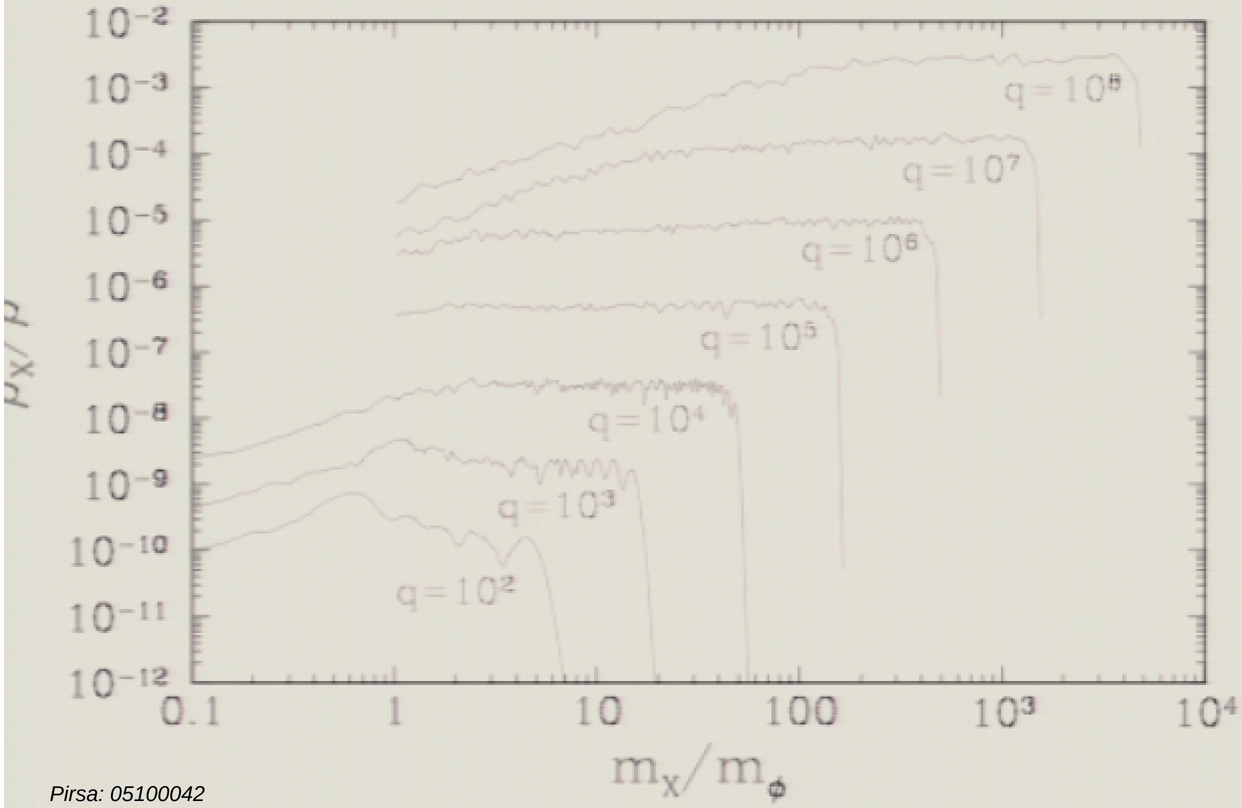
(main reason, $\delta_{\mathrm{CP}} \propto m_{N_1}$)

$$\mathcal{L}_{\phi X} = (m_X + g\,\phi)\,\bar{X}\,X$$

Preheating $\leftrightarrow \dot{\omega}_k \gtrsim \omega_k^2 \leftrightarrow \dot{m} \gtrsim m^2$



Giudice, M.P., Riotto, Tkachev, '99



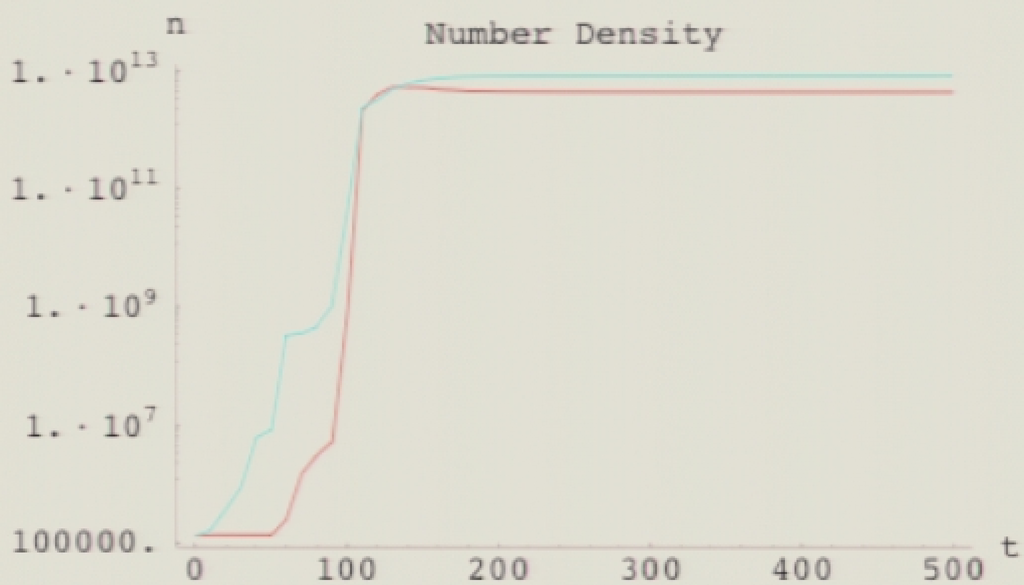
$$(m_X)_{\rm max} \sim q^2 = g\,\phi_0/2$$

$$\frac{\rho_X}{\rho_\phi} \propto q\,m_X^{1/2}\left[\log\frac{q^{1/2}}{m_X}\right]^{3/2}$$

M.P., Sorbo '00

Rescattering

- Parametric resonance ends at $t \sim 100/m$, when the decay products scatter off the zero mode of ϕ, destroying its coherence
- System cannot be studied analytically; perturbative approaches fail, due to the extremely high occupation numbers

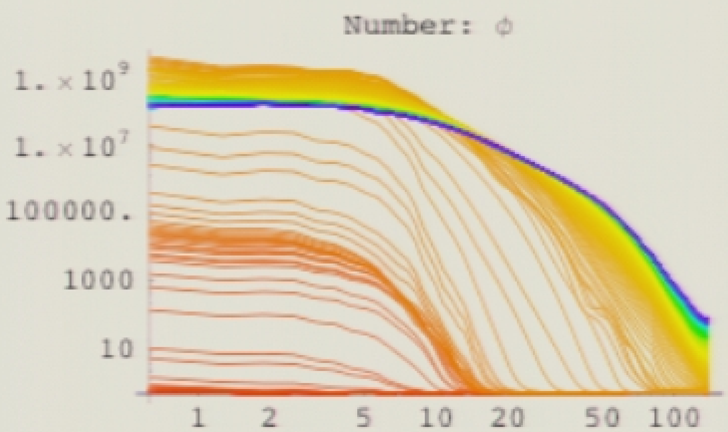


Classical lattice simulations

Khlebnikov, Tkachev '96

Prokopec, Ross '96

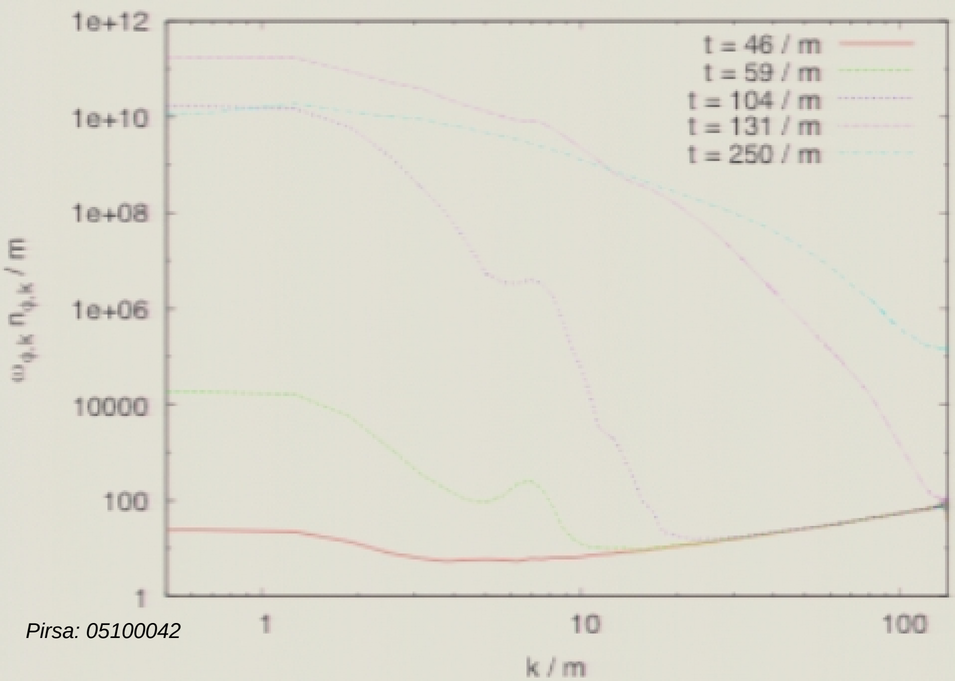
Felder, Tkachev '00



Distributions formed at rescattering much more populated in the IR than thermal distributions

$n_k \sim 1/g^2 \gg 1$

- Thermalization proceeds through particle fusion (slow motion towards UV)
- Excitations of fields not directly coupled to the inflaton, $\phi \leftrightarrow \chi \leftrightarrow \psi$



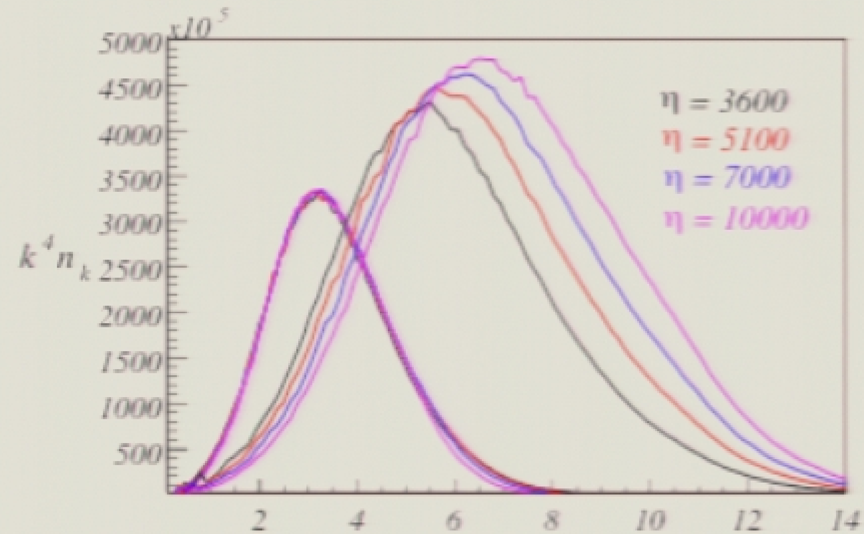
Saturated distribution, still very far from thermal

cf. Rayleigh–Jeans spectrum

$$n_k \approx \frac{T_{\text{eff}}}{\omega_k - \mu}$$

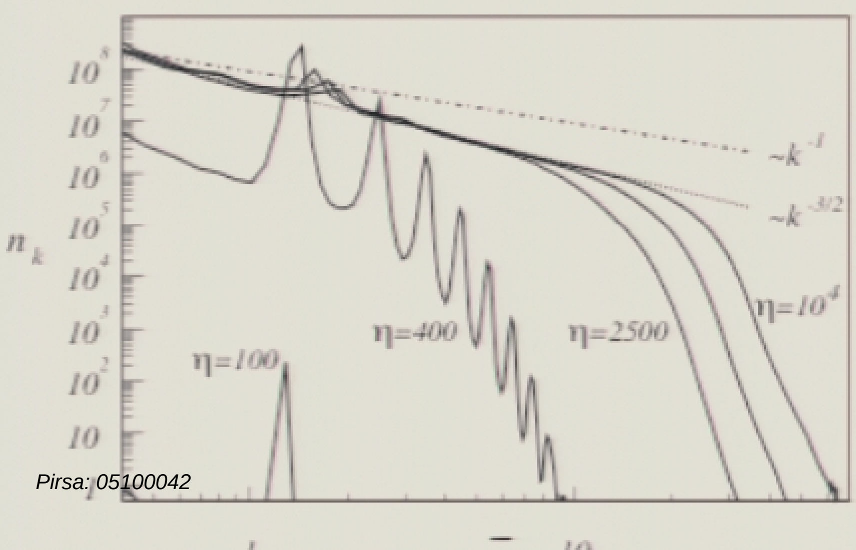
Thermalization occurs on a much longer timescale; lattice effective only for conformal cases, $\lambda\,\phi^4 + g^2\,\phi^2\,\chi^2$, or too much UV required

(Kolmogorov) Turbulence; distributions evolve self–similarly



$$n(k,\tau) = \tau^{-q} n_0(k\tau^{-p})\,.$$

$q = 3.5\,p$, $p = \dfrac{1}{2m-1}$, $m = 3$ $\quad (\delta\phi\,\phi_0 \leftrightarrow \delta\phi\,\delta\phi)$ Micha, Tkachev '04



$$n_k = k^{-3+m/(m-1)}$$

Kinetic equation

$$\dot{n}_k = \frac{\dot{\omega}_k}{\omega_k}\mathrm{Re}\,\sigma_k + \mathrm{Im}I_3(k) + \mathrm{Im}I_4(k)$$
$$i\dot{\sigma}_k = 2\omega_k\sigma_k + \frac{i}{2}\frac{\dot{\omega}_k}{\omega_k}n_k + I_3^*(k) + I_4^*(k)$$

$$\langle a^*_{\boldsymbol{k}} a_{\boldsymbol{q}} \rangle = n_k \delta^{(d)}(\boldsymbol{k}-\boldsymbol{q})$$
$$\langle a_{\boldsymbol{k}} a_{\boldsymbol{q}} \rangle = \sigma_k \delta^{(d)}(\boldsymbol{p}+\boldsymbol{q})$$ Anomalous correlators (phases)

Expanded around $\omega^2 = k^2 + 3\,\lambda\,\phi_0^2 + 3\,\lambda\,\langle\delta\phi^2\rangle$

$(1+n_1)\,(1+n_2)\,n_3\,n_4 - n_1\,n_2\,(1+n_3)\,(1+n_4)$ in the collisional integrals; usual dilute gas approximation, $n \ll 1$, does not apply !

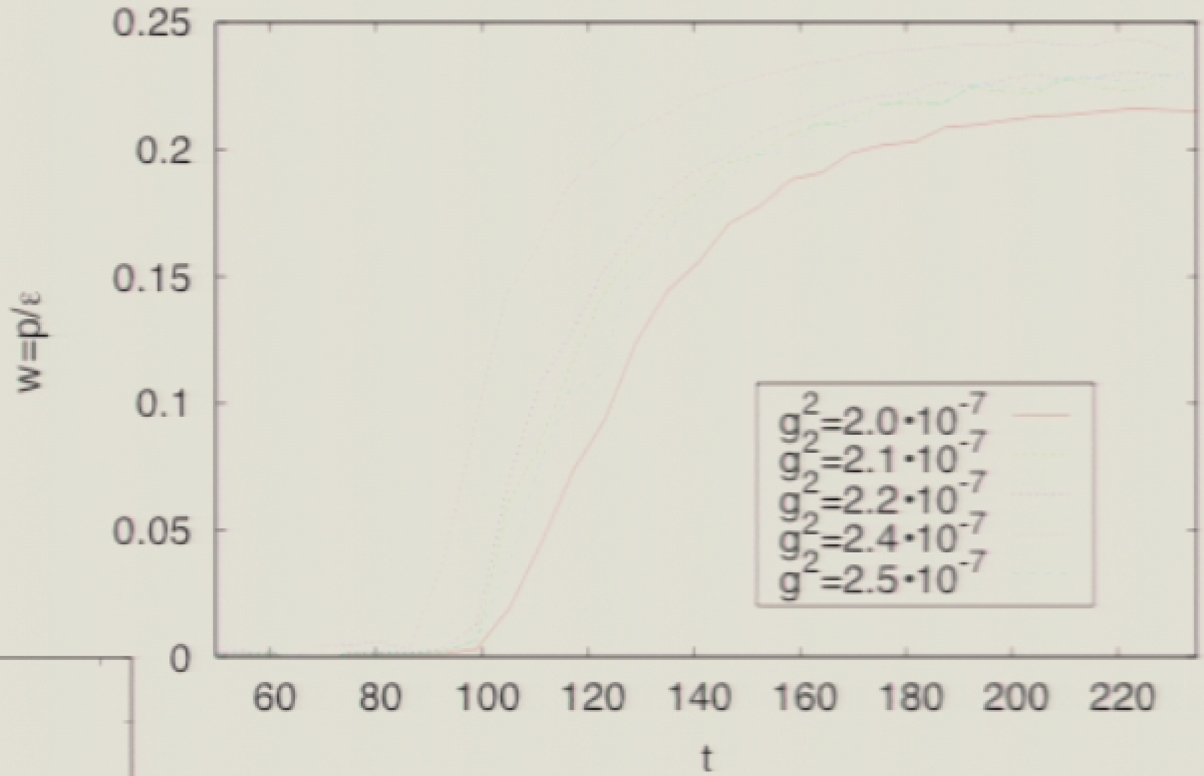
- Not clear speed up over the lattice; hoverer, more suitable approach for (i) fermions, (ii) quantum regime

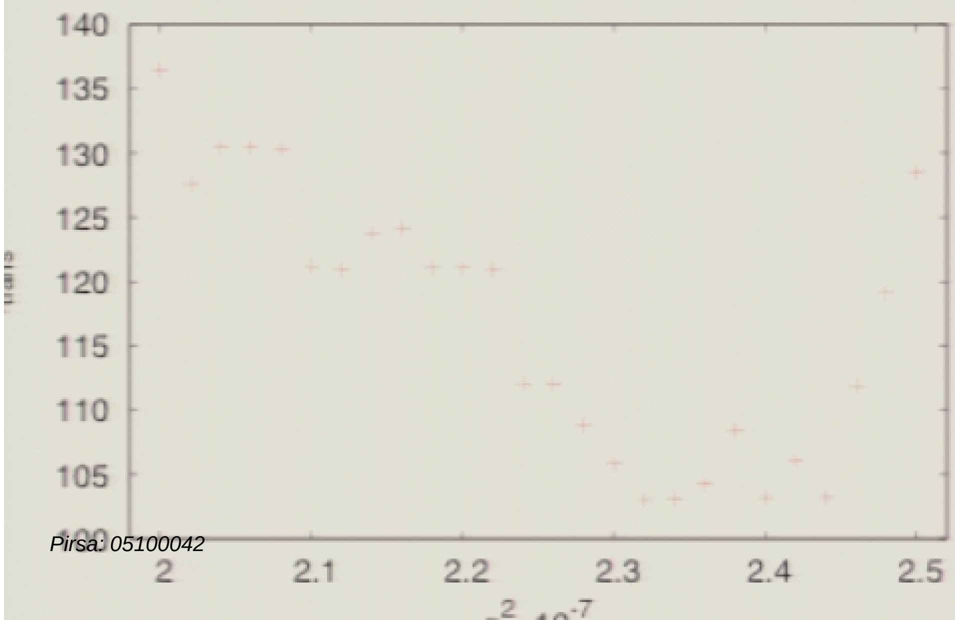
Intermediate equation of state

$\left(n_k \simeq 1/g^2 \right)$

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

At rescattering, EOS quickly "jumps" at an intermediate value between the ones of matter & radiation





Transition time ($w_{\text{trans}} = 0.15$)

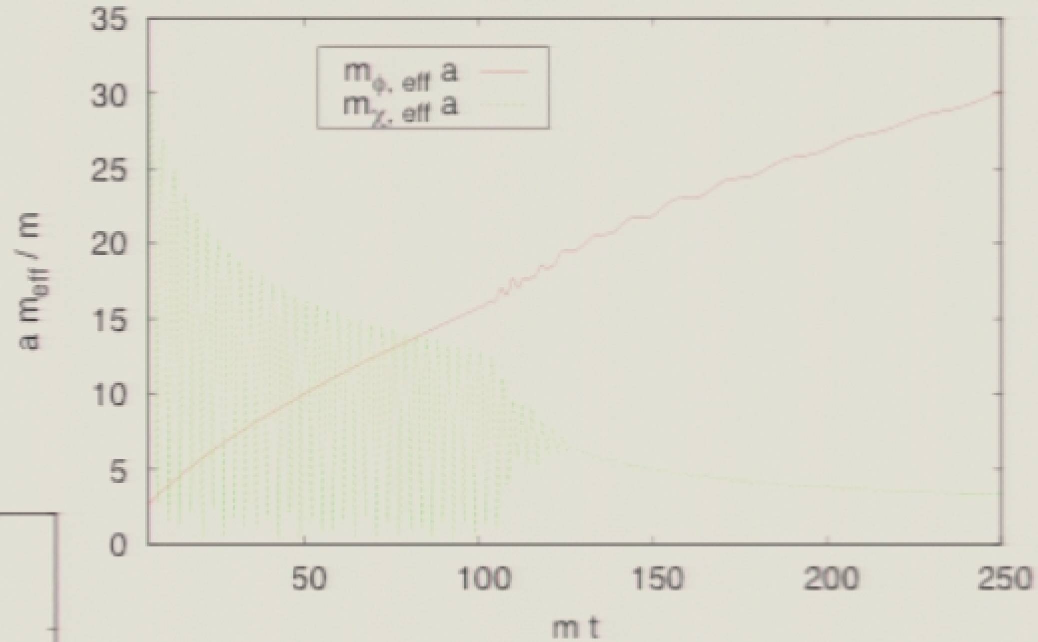
non monotonic function of g^2

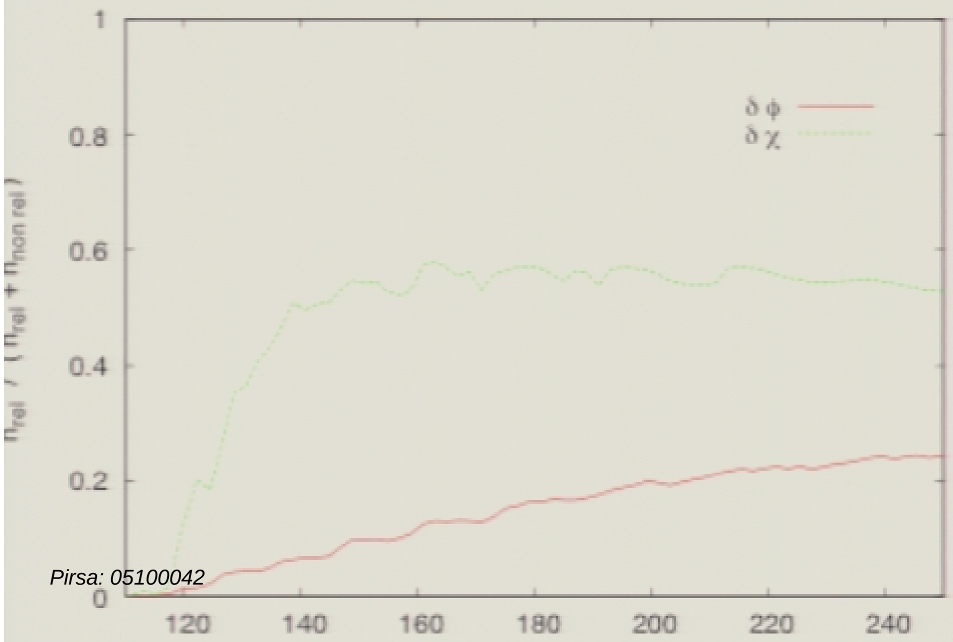
Effective masses

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

$$m_{\phi,\text{eff}} = m^2 + g^2\langle\chi^2\rangle$$
$$m_{\chi,\text{eff}} = g^2\langle\phi^2\rangle$$

$g^2 = 10^{-7}$





Fraction of relativistic quanta

$$k/a > m_{\text{eff}}$$

$$\Gamma\,(\phi\phi \to \chi\chi) \simeq \frac{g^4\,\Phi^2}{8\,\pi\,m} \propto a^{-3} \qquad \text{while } H \propto a^{-3/2}$$

Therefore, add trilinear term $\phi\,\chi^2$. Expected to speed up particle fusion, and thermalization

$$V = \frac{m^2}{2}\phi^2 + \frac{g^2}{2}\phi^2\,\chi^2 + \frac{\sigma}{2}\,\phi\,\chi^2 + \frac{\lambda}{4}\chi^4$$

New type of preheating. $m^2_{\text{eff},\chi} < 0$ at negative ϕ.

Quartic interaction contrast this effect, but:

- Preheating effects mainly at $\phi \simeq 0$, where the trilinear term dominates
- Expansion reduces amplitude of ϕ

See also Shuhmaher, Brandenberger '05, as a solution to moduli problem

Tachyonic resonance

$$\omega_k^2 = k^2 + \sigma\,\phi$$

WKB approx.

$$\chi_k^j(t) = \frac{\alpha_k^j}{\sqrt{2\omega_k(t)}}\exp\left(-i\int_{t_0}^{t}\omega_k(t')dt'\right) + \frac{\beta_k^j}{\sqrt{2\omega_k(t)}}\exp\left(i\int_{t_0}^{t}\omega_k(t')dt'\right) \quad , \ \omega_k^2 > 0$$

$$\chi_k(t) \simeq \frac{a_k^j}{\sqrt{2\Omega_k(t)}}\exp\left(-\int_{t_{k_j}^-}^{t}\Omega_k(t')dt'\right) + \frac{b_k^j}{\sqrt{2\Omega_k(t)}}\exp\left(\int_{t_{k_j}^-}^{t}\Omega_k(t')dt'\right) \quad , \ \Omega_k^2 = -\omega_k^2 > 0$$

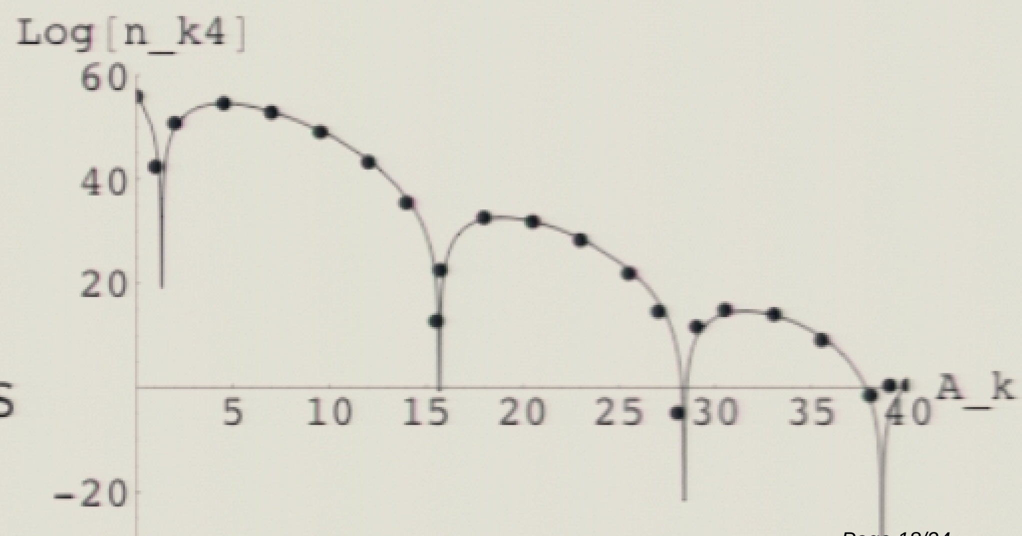
Parametric resonance: instability bands where $\phi\,(t)$ "resonate" with ω

Tachyonic resonance:

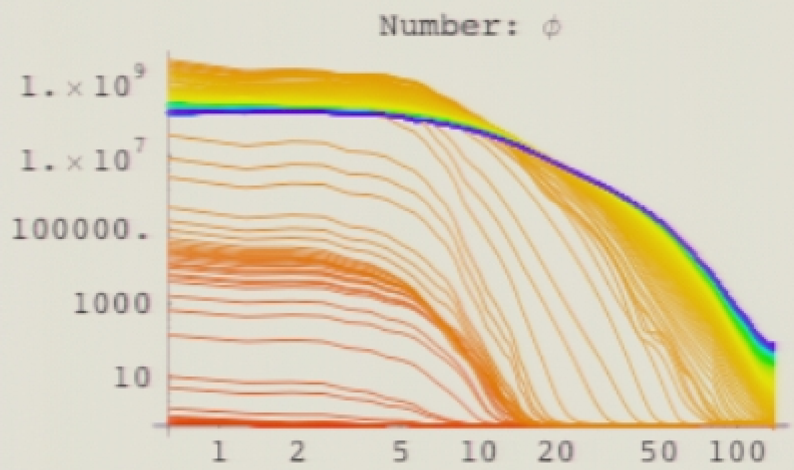
stability bands where

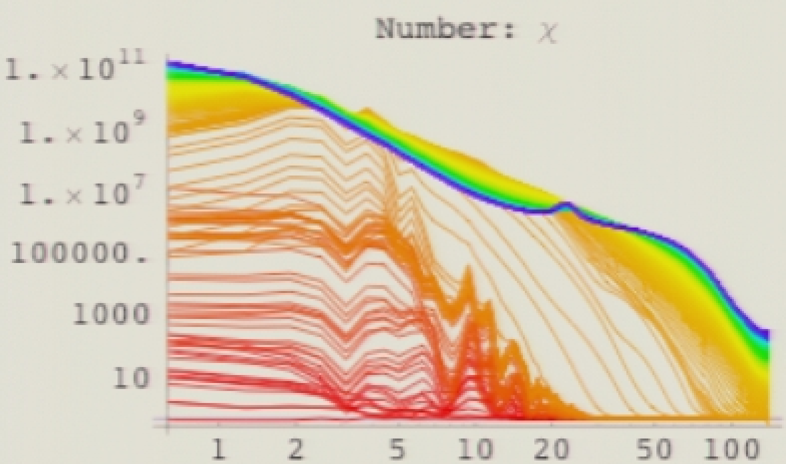
resonance counterbalances

the tachyonic instability

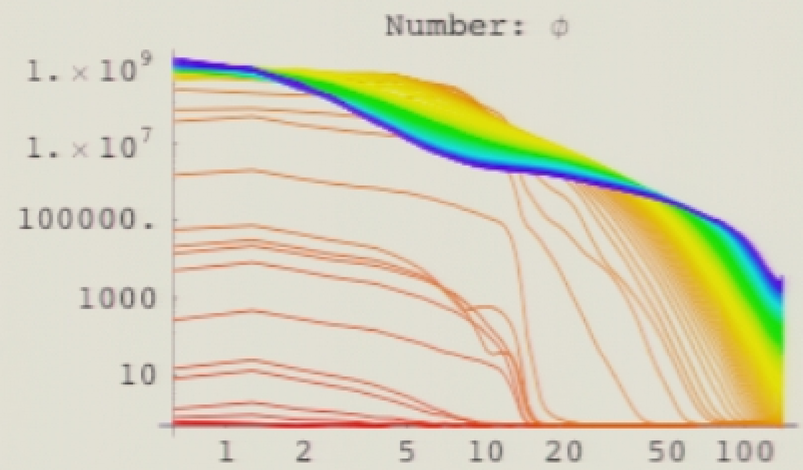


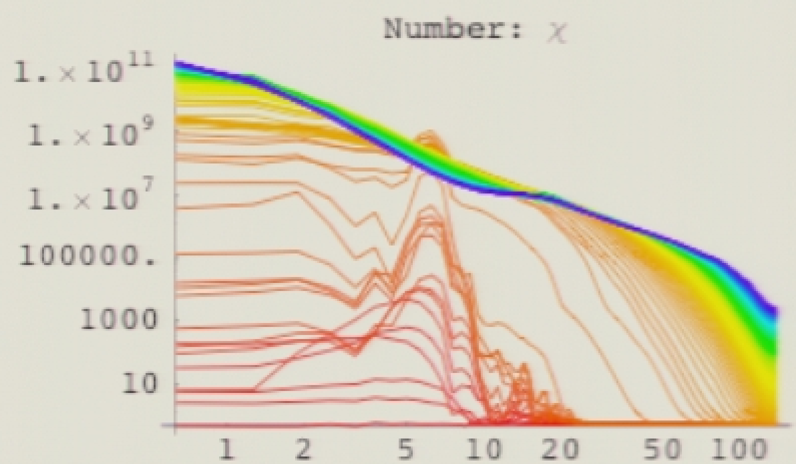
$$\frac{g^2}{2}\phi^2\chi^2$$



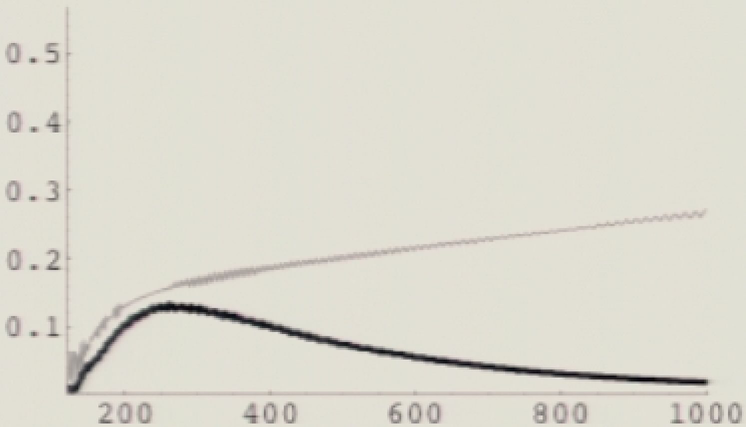


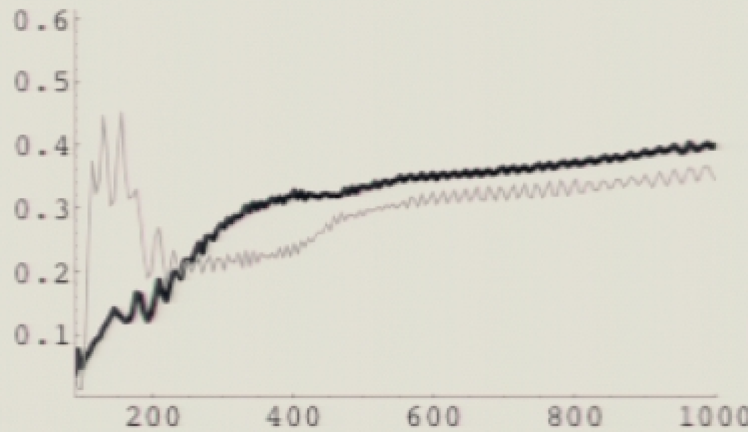
$$\frac{g^2}{2}\phi^2\chi^2 + \sigma\phi\chi^2$$



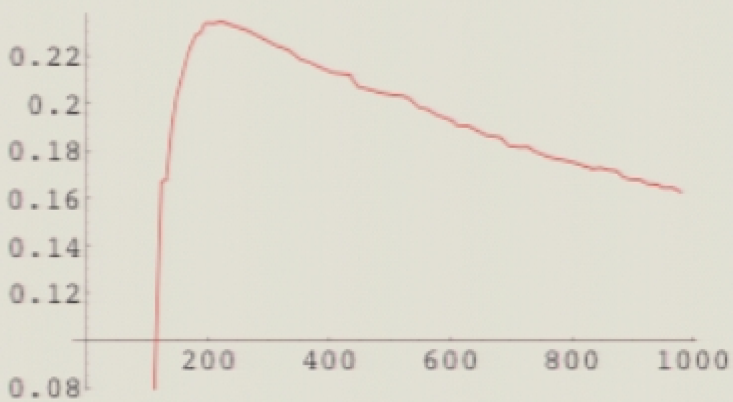


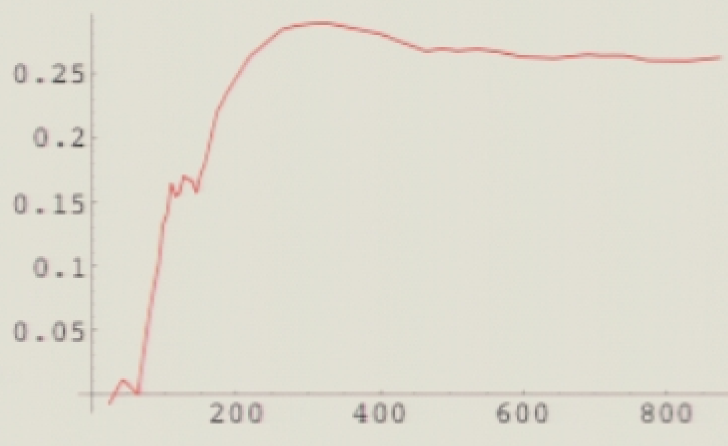
$$\frac{g^2}{2}\phi^2\chi^2 \qquad \frac{g^2}{2}\phi^2\chi^2+\sigma\phi\chi^2$$





Fraction of relativistic modes

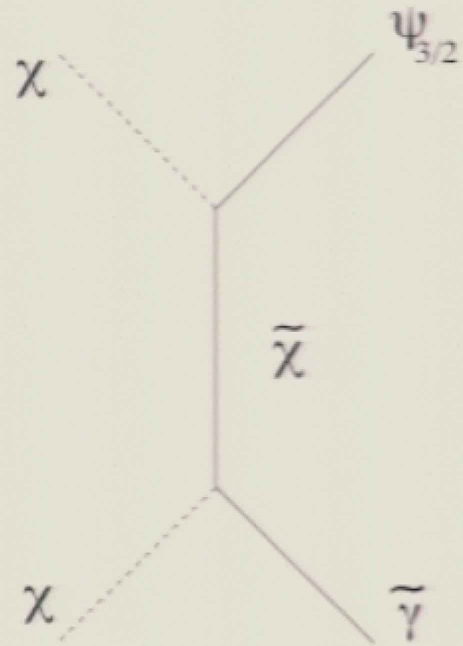




Equation of state

Gravitino thermal production

$$\frac{dn_{3/2}}{dt} + 3Hn_{3/2} = \langle \sigma \, |v| \rangle \, n_T^2$$



- $3Hn_{3/2}$ negligible
- $\sigma \simeq \frac{10^{-2}}{M_p^2}$, $n_T^2 \simeq T^6$

$$\Rightarrow \quad n_{3/2} \simeq \frac{10^{-2}\, T_{\rm rh}^6}{M_p^2} \times H_{\rm rh}^{-1} \simeq 10^{-2} \, \frac{T_{\rm rh}^4}{M_p} \, , \; Y_{3/2} = \frac{n_{3/2}}{s} \simeq 10^{-2} \frac{T_{\rm rh}}{M_p}$$

BBN bound $\; Y_{3/2} \lesssim 10^{-13} \left(100\,\text{GeV}/m_{3/2}\right) \;\Rightarrow\; T_{\rm rh} \lesssim 10^9\,\text{GeV}$

- Small $T_{\rm rh}$ $\equiv$ late inflaton decay; energy "frozen" in the coherent oscillations until diluted by expansion

- Rescattering $\rightarrow$ distributions far from thermal; but $\rho \gg \left(10^9\,\mathrm{GeV}\right)^4$. Compute gravitino production when they form, $t_* \simeq 120/m$.

$$V = \frac{1}{2} m^2 \phi^2 + \frac{g^2}{2} \phi^2 \chi^2 + h\,\chi\,\bar{\psi}\psi$$

Yukawa interaction as 2nd vertex

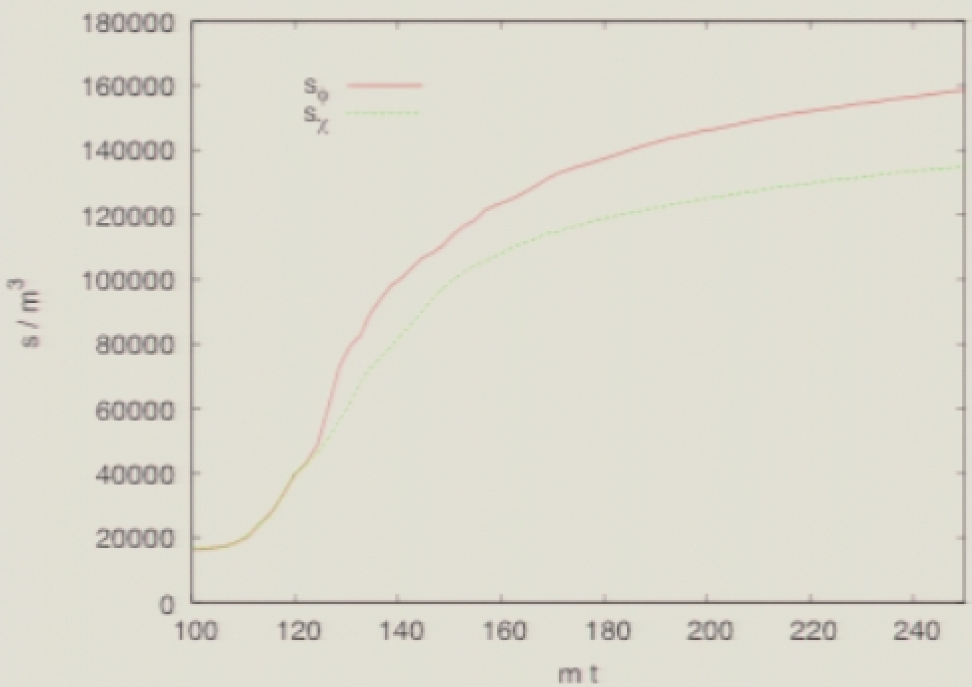
effective mass $\quad m_\psi = h\sqrt{\chi^2\,(t_*)} \simeq 5 \cdot 10^2\,h\,m$

Typical momenta χ quanta $\quad k/a\,(t_*) \simeq 0.5\,m$

$h \lesssim 10^{-3}$ effective production

$$n_{3/2}(t_*) \sim \frac{h^2}{M_p^2} N_\chi (t_*)^2 H(t_*)^{-1} \sim 10^7 h^2 m^3$$

Entropy $s = \int d^3k \, [(n_k + 1) \ln (n_k + 1) - n_n \ln (n_k)]$



$$s(t_*) \simeq 5 \cdot 10^4 m^3$$

increases during thermalization

$$s_{\text{th}} \equiv \rho^{3/4} \simeq 10^7 m^3$$

$$Y_{3/2} \gtrsim \frac{n_{3/2}}{\rho^{3/4}}\Big|_{t=t_*} \simeq h^2 \quad \Rightarrow \quad h \lesssim 10^{-7}$$

Conclusions

- Reheating belongs to the standard paradigm of cosmology. Yet, it is the most uncertain stage in the history of the universe, MeV $\lesssim T_{\mathrm{rh}} \lesssim 10^9\,$GeV
- Unsettled issues include generation of very massive particles, $M \lesssim T_{\mathrm{reh}}$, gravitational relics, connection $N_{\mathrm{infl}} \leftrightarrow \lambda_0$, modulated perturbations
- While basic formalism is known, major advance may require improvement of numerical techniques, or development of scaling solutions for more realistic cases