# Gravitational particle production after Reheating

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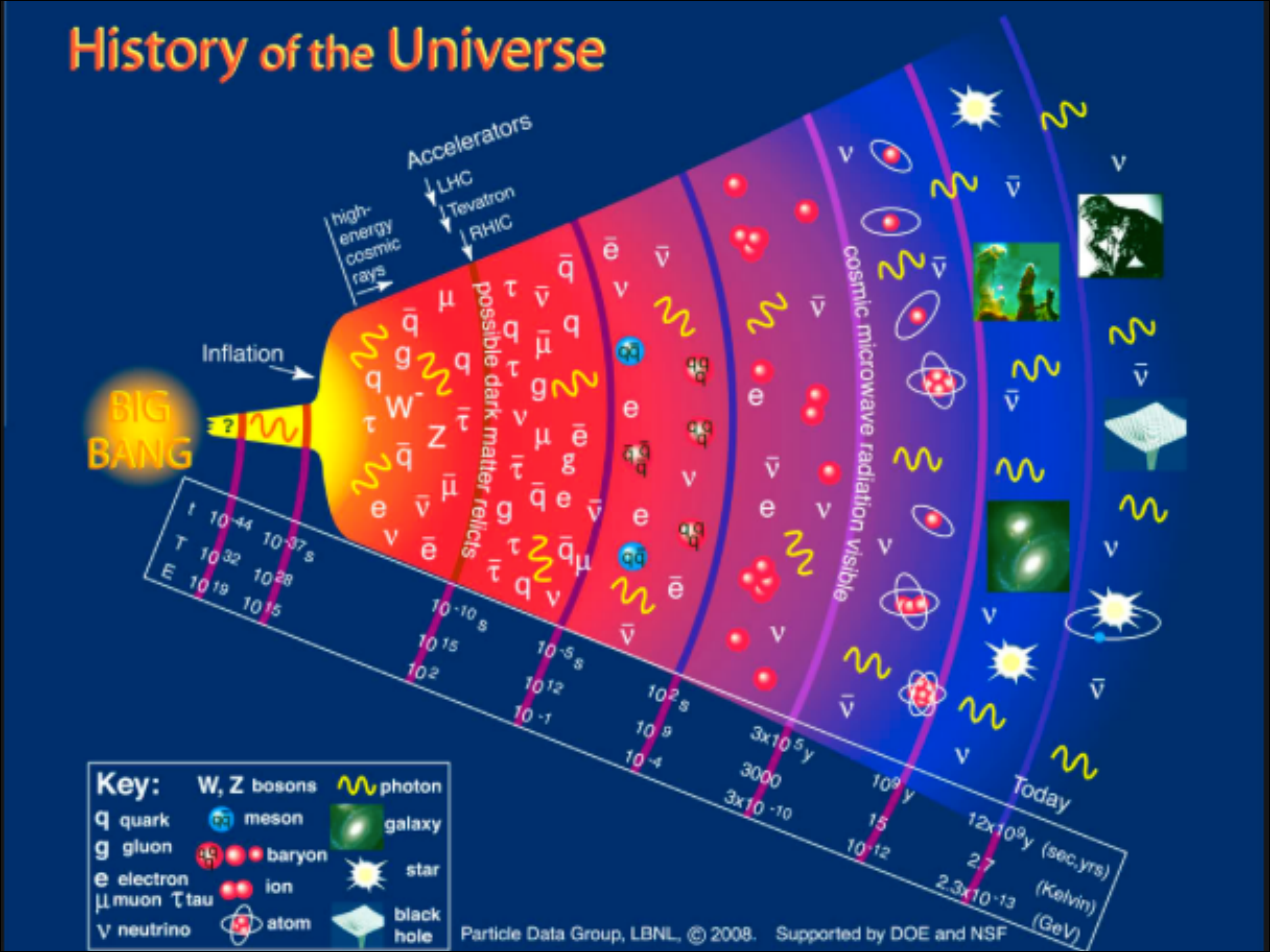
# Outline

- Introduction to Inflation and Reheating
- Quantization
- Particle production
- Conclusion


History of the Universe
BIG BANG
Inflation
high-energy cosmic rays
Accelerators
LHC
Tevatron
RHIC
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s 10-10 s 10-5 s 102 s 3x105 y 109 y 12x109 y (sec,yrs)
T 1032 1028 1015 1012 109 3000 15 2.7 (Kelvin)
E 1019 1015 102 10-1 10-4 3x10-10 10-12 2.3x10-13 (GeV)
Today
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

# Inflation

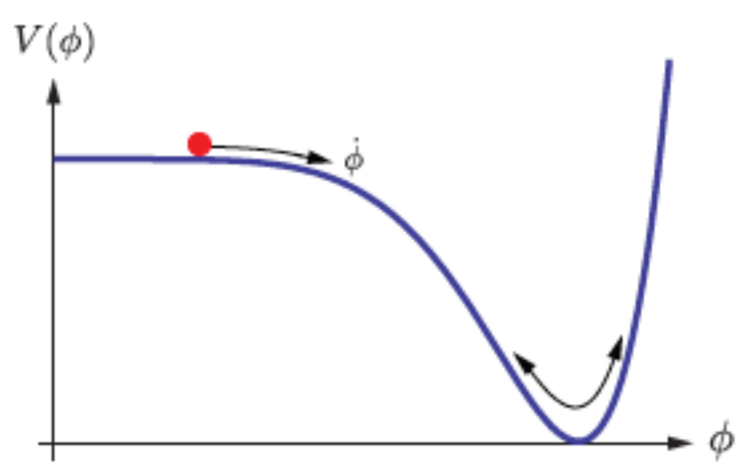
- Why do we need inflation?
  - Solves Flatness and Horizon problems
- It is a period of time where the Universe grows exponentially
  - De-Sitter-> Hubble constant

# Reheating

- At the end of Inflation, all the energy is stored in the Inflaton-> we need to transfer it to the SM particles

- The inflation oscillates around the minimum of the potential (suppose quadratic)

  - The universe evolves like matter dominated on average during these oscillations



# Scale factor

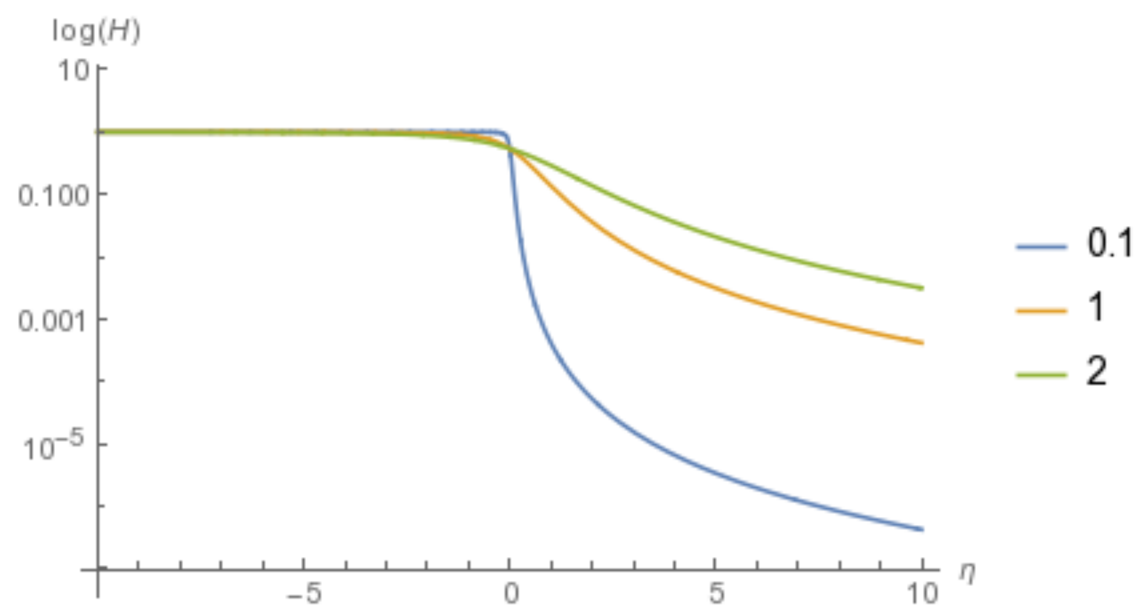
$$\frac{a^2}{6}R = \frac{a''}{a} = \frac{2}{\eta^2 + \eta_0^2}$$

Conformal time $dt = a(\eta)d\eta$

- Smooth transition from Inflation to Reheating

  Timescale $\eta_0$

$$H(\eta) = \frac{a'}{a^2}$$



# Set up calculation

$$\mathcal{L} = \frac{1}{2}\sqrt{|g|}(g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - m^2\phi^2 - \xi R\phi^2)$$

FRW metric-> Homogeneous and Isotropic

Decompose $$\phi(t,\mathbf{x}) = \sum_{\mathbf{k}}\left(A_{\mathbf{k}}\frac{\mathrm{e}^{i\mathbf{kx}}}{(2\pi)^{3/2}}\frac{y_k(\eta)}{a(\eta)} + \mathrm{H.c.}\right)$$

Equation of motion

$$y_k'' + \underbrace{\left(k^2 + a^2(\eta)\left(m^2 + \left(\xi - \frac{1}{6}\right)R(\eta)\right)\right)}_{\omega_k^2} y_k = 0$$

# Quantisation

Via Hamiltonian Diagonalisation

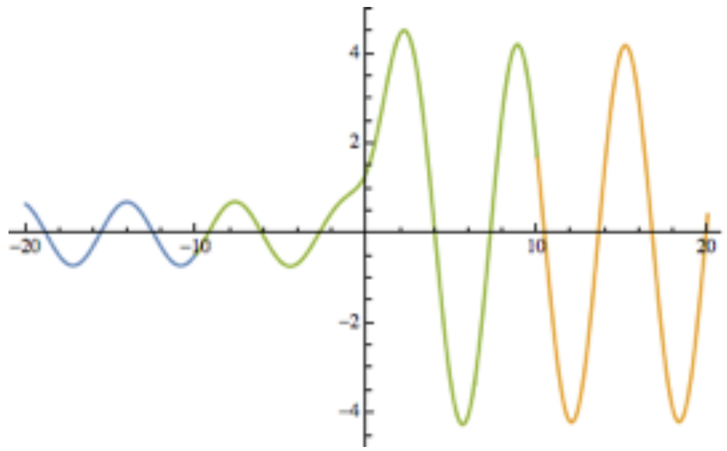
$$A_{\mathbf{k}}|0\rangle = 0 \quad \forall \mathbf{k}$$

Orthonormal base

$$\longrightarrow \quad |y_k|^2 = \frac{1}{2w_k} \quad y_k' = -iw_k y_k$$

As long as the frequency is constant and real-> No problem(?)

- If it isn't constant-> particle production
- It it isn't Real-> tachyonic particle production



# Particle production

$$\omega^2(\eta) = k^2 - \frac{2}{\eta^2 + \eta_0^2}$$

There is a dependence on time

Define 2 set of vacuum states

$$\phi = \sum_{\mathbf{k}} (a_{\mathbf{k}} f_{\mathbf{k}in} + \text{H.c.})$$

$$\phi = \sum_{\mathbf{k}} (b_{\mathbf{k}} f_{\mathbf{k}out} + \text{H.c.})$$

# Particle production

In modes

$$\langle N_{\mathbf{k}}\rangle_{\eta\to-\infty} =_{in} \langle 0|a^{+}_{\mathbf{k}} a_{\mathbf{k}}|0\rangle_{in} = 0 \quad \forall \mathbf{k} \qquad y_k^{in}(\eta) = \frac{1}{\sqrt{2k}} e^{-ik\eta}$$

Out modes

$$\langle N_{\mathbf{k}}\rangle_{\eta\to+\infty} =_{out} \langle 0|b^{+}_{\mathbf{k}} b_{\mathbf{k}}|0\rangle_{out} = 0 \quad \forall \mathbf{k}$$

$$y_k^{out}(\eta) = \frac{1}{\sqrt{2k}}(\alpha_k e^{-ik\eta} + \beta_k e^{+ik\eta}) = \alpha_k y_k^{in}(\eta) + \beta_k (y_k^{in}(\eta))^*$$

$$\boxed{\langle N_{\mathbf{k}}\rangle_{\eta\to+\infty} =_{in} \langle 0|b^{+}_{\mathbf{k}} b_{\mathbf{k}}|0\rangle_{in} = |\beta_k|^2}$$

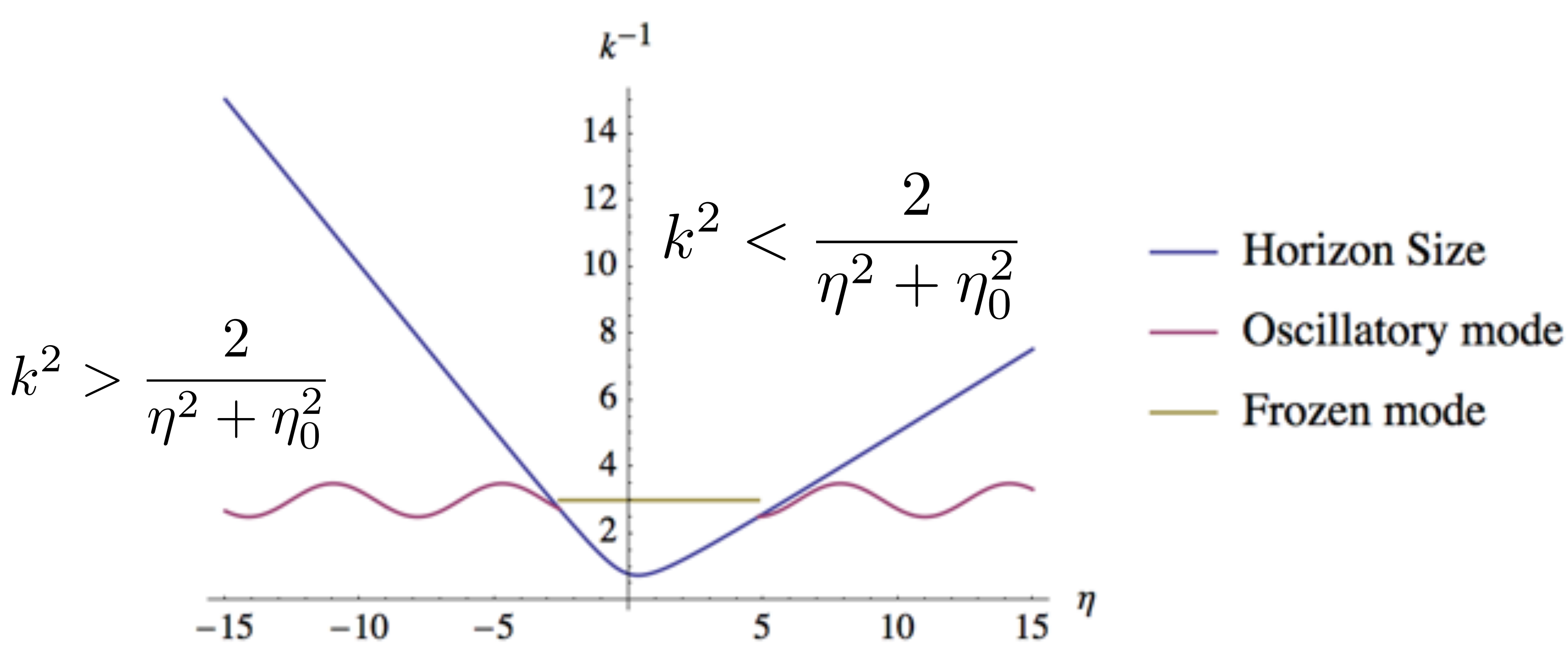
# Particle production

Number density $$n = \frac{1}{2\pi^2 a^3} \int_0^\infty dk \Big( k^2 |\beta_k|^2 \Big)$$

Energy density $$\rho = \frac{1}{2\pi^2 a^4} \int_0^\infty dk (k^3 |\beta_k|^2)$$

# Divergences

- Ultraviolet modes
  - They are going to be exponential suppress if the transition between eras is smooth $\longrightarrow \eta_0$
- Infrared modes
  - All the super horizon modes are frozen

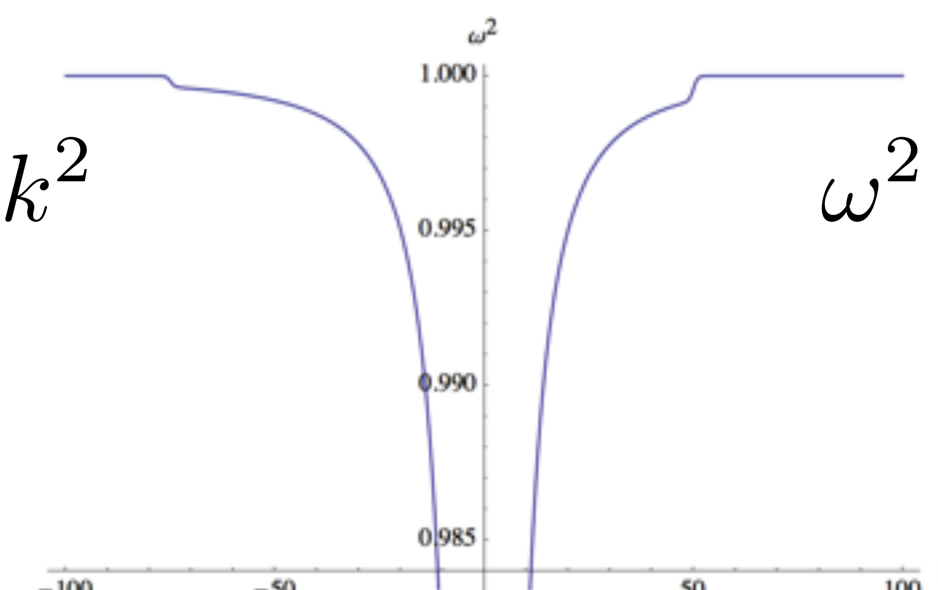


# Infrared divergence

- Limit duration Inflation and Reheating
  - Smooth step function

$$\omega_k^2 = k^2 - \frac{2}{\eta^2+1}\,\frac{1+\tanh(\eta+\eta_i)}{2}\,\frac{1-\tanh(\eta-\eta_m)}{2}$$

$$\omega^2 = k^2$$

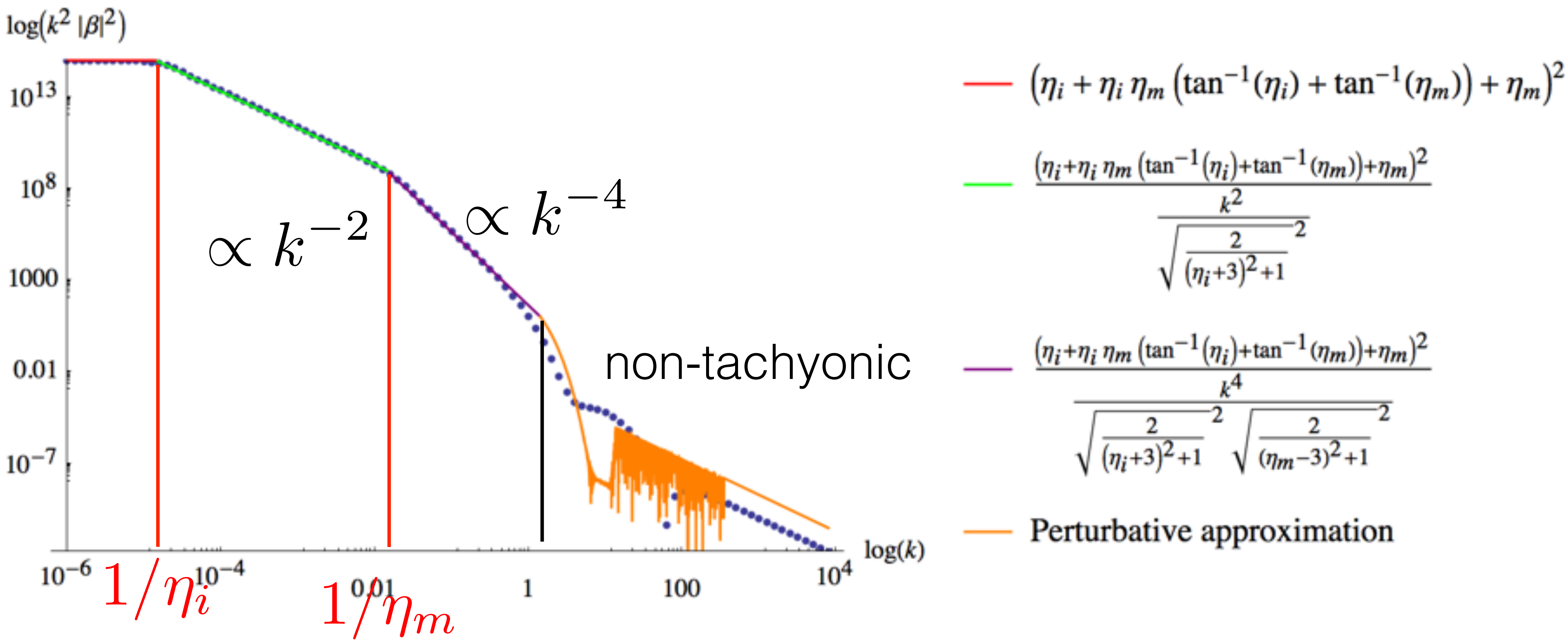



$$\omega^2 = k^2$$

$$\mathbf{k^2} - \left(\frac{2}{\eta^2+1}\,\frac{1+\mathrm{Tanh}[\eta+\eta_i]}{2}\,\frac{1-\mathrm{Tanh}[\eta-\eta_m]}{2}\right)$$

$$\omega^2 = k^2 - \frac{2}{\eta^2+1}$$

# Power spectrum




Neglect all super horizon modes at the end of reheating

$$k = 2/\eta_m$$

# Particle abundance

$$n = 2.4 \cdot 10^{-3} \frac{H_0^2 T_{reh}^2}{M_{pl}}$$

$$\rho = 6.5 \cdot 10^{-3} \left( \frac{H_0}{M_{pl}} \right)^2 T_{reh}^4$$

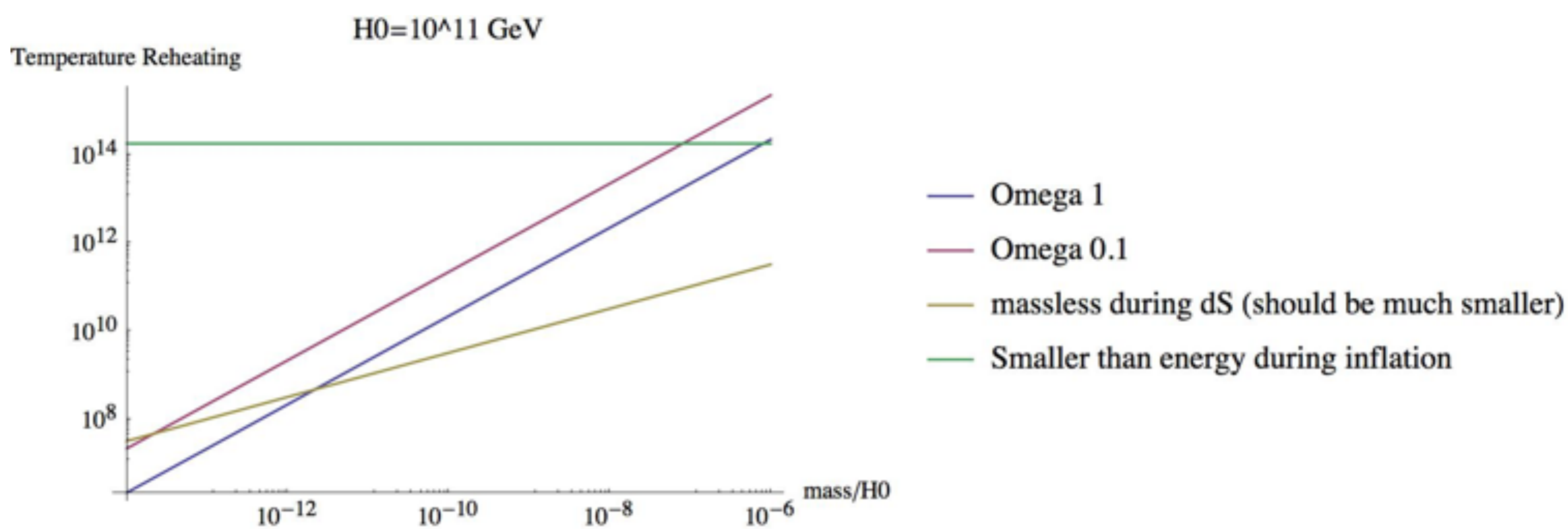
Adiabatic particle production

# Particle abundance today

massless during Inflation and Reheating

$$m \ll \frac{T_{reh}^2}{M_{pl}}$$

$$\Omega = 7.73 \cdot 10^{-5} \frac{g(T_{\rm today})}{\sqrt{g(T_{reh})}} \left(\frac{H_0}{H_{\rm today}}\right)^2 \left(\frac{T_{\rm today}}{M_{pl}}\right)^3 \frac{m}{T_{reh}}$$



# Conclusion

- Mechanism to produce adiabatic particles
- Problems with the definition of particle
    - Maybe another quantisation or modification of the set up can solve this IR divergence (coupling to other fields, quasi de-Sitter…)

Thank you