Nonequilibrium Goldstone Phenomenon in Tachyonic Preheating

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Outline

Continuum limit of classical field simulation ("renormalization")

Direct and indirect excitation of the Goldstone d.o.f.

Persistent nonthermal Goldstone gas

Earlier work in Minkowski metrics: Phys.Rev. D66 (2002) 025014
Recent paper in FRW geometry: Phys.Rev. D, 15 September.

Overview

Hybrid inflation: a popular scenario for studying

tachyonic preheating

Felder et al. 2001
Garcia -Bellido et. al 2002
Buchmüller et al 2002

topological defect formation

Copeland, Pascoli, Rajantie 2002
Hindmarsh, Rajantie 2001
Yamaguchi et. al. 1999

Cosmolgoical phase transitions with gauged symmetries

explosive excitation of gauge fields

Chern -Simons number changing phenomena

Rajantie, Suffin, Copeland, 2000
Skullerud, Smit, Tranberg 2003

Now we concentrate on global continuous symmetries:

the role of elementary angular exitations: the Goldstone modes

Garcia -Bellido et al 2003
Smit, Tranberg 2003

Model and Parameters

Hybrid Inflation

O(2) matter field (GUT) (Φ) → $M_h \sim 10^{15}\mathrm{GeV}$

Light Inflaton (Ψ) → $M_i \sim 10^{12}\mathrm{GeV}$

$$\mathcal{L} = \frac{1}{2}(\partial_\nu \psi(x))^2 - \frac{1}{2}m_\psi^2\psi^2 + \frac{1}{2}|\partial_\nu \Phi(x)|^2 - \frac{1}{2}m_\Phi^2|\Phi|^2 - \frac{\lambda}{24}|\Phi|^4 - \frac{1}{2}g^2\psi^2|\Phi|^2$$

in FRW metrics: *a(t)*

Radial O(2) component (ρ):
"Higgs"

Angular component (φ):
"to be Goldstone"

Initial conditions mimic zero temperature quantum noise.

Inflation: *50..100 e - folds*

Fluctuation: *COBE data*
at 5 e - folds before waterfall

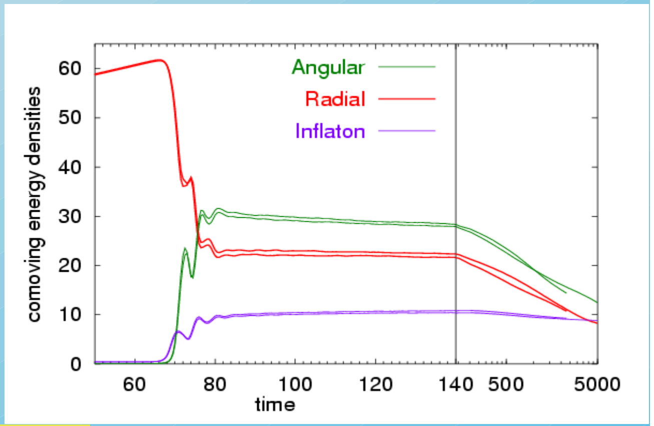
GUT coupling: $\lambda = 3g^2$
Motivated by SUSY

Inflaton coupling: $g \sim 0.1$

Nonequilibrium Classical Fields

- Divergencies at finite temperature
- Temperature dependent counterterms

Wang, Heinz 1996
Aarts, Smit 1997



How to regularize a classical state out of equilibrium?

Initial conditions:

For different lattice cut -off values (δ*x*)

- Fill modes with quantum noise only up to a certain fixed k_{max}
- Tune k_{max} so that the initial energy density is fixed
  (cut - off independent)

Smit et al, 2002, 2003

Continuum limit:

$$\delta x \to 0 \quad N\delta x \ \text{ fixed}$$

with fixed k_{max}

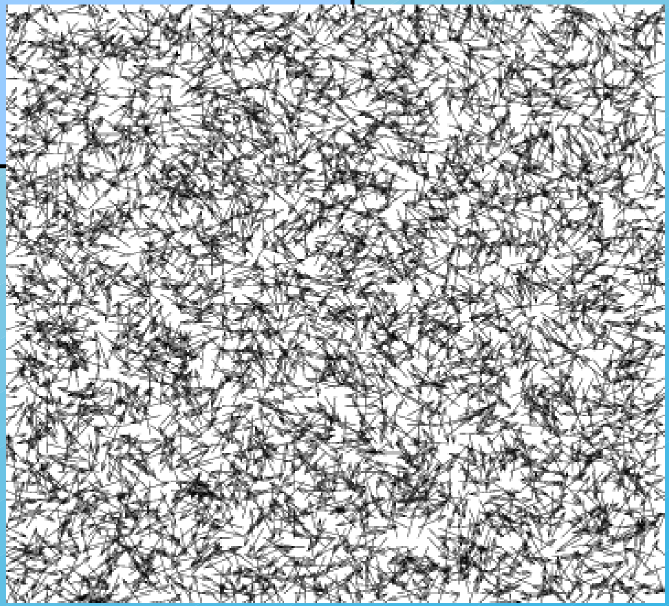
Thermodynamical limit:

$$N\delta x \to \infty$$

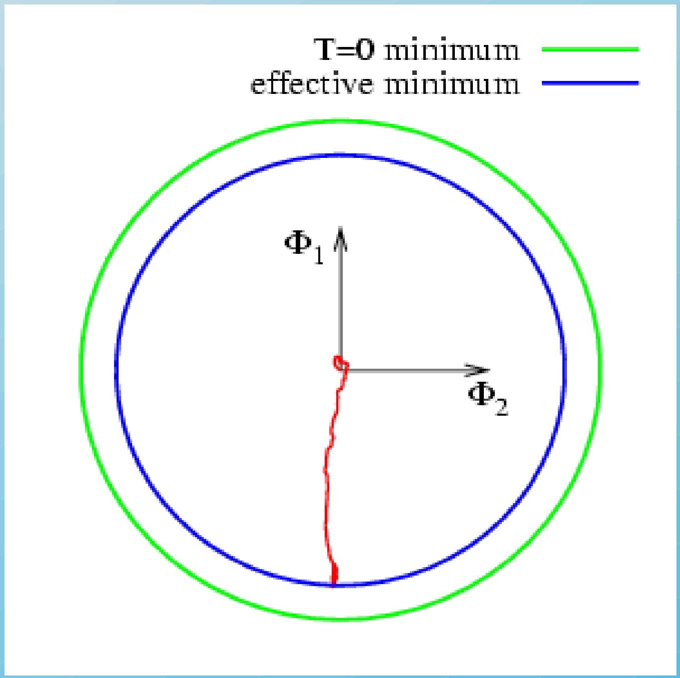
Results will *not* converge if
high *k* modes are active,
there is *no* physical cut - off (spinodal scale)
E.g. the fields thermalize (equipartition)

Instability & Symmetry Breaking

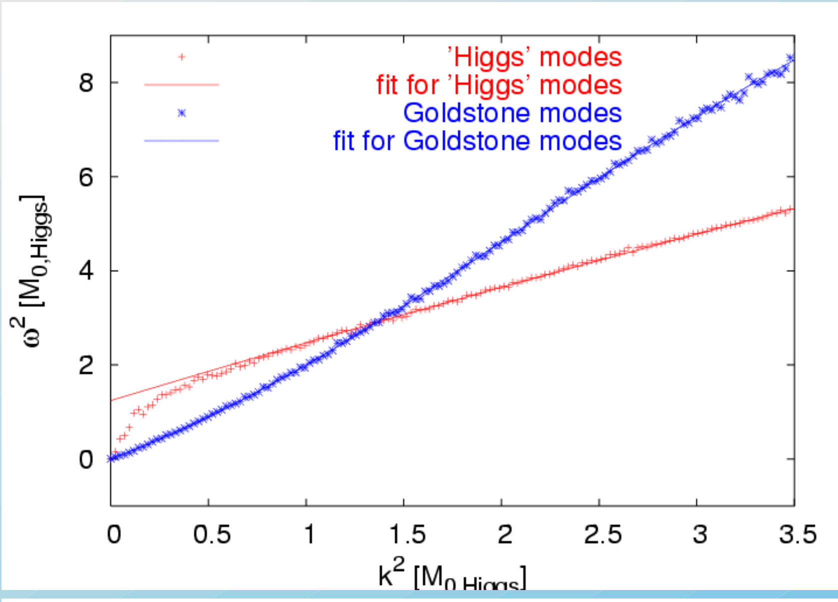
Microscopic dynamics:
2d slice of a 3d lattice, each arrow of unit length represents the phase of Φ_1,Φ_2.

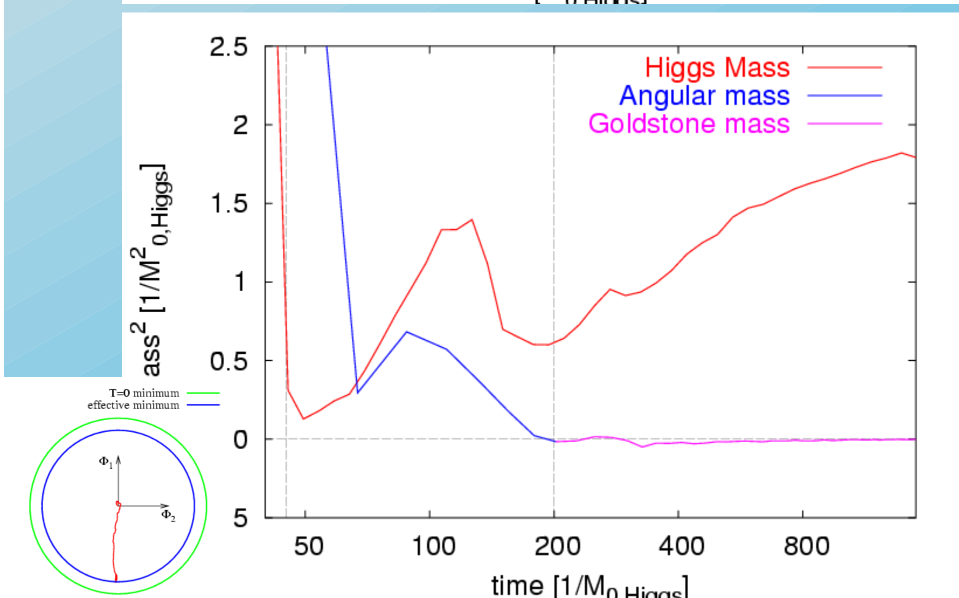


Order Parameter:



Onset of the Goldstone theorem





- *Dispersion relation is calculated at several time instants*

- *Polynomial fit* ⟶

Mass squared as a function of time

Mass of the angular field drops smoothly, it arrives at zero when SSB occurs.

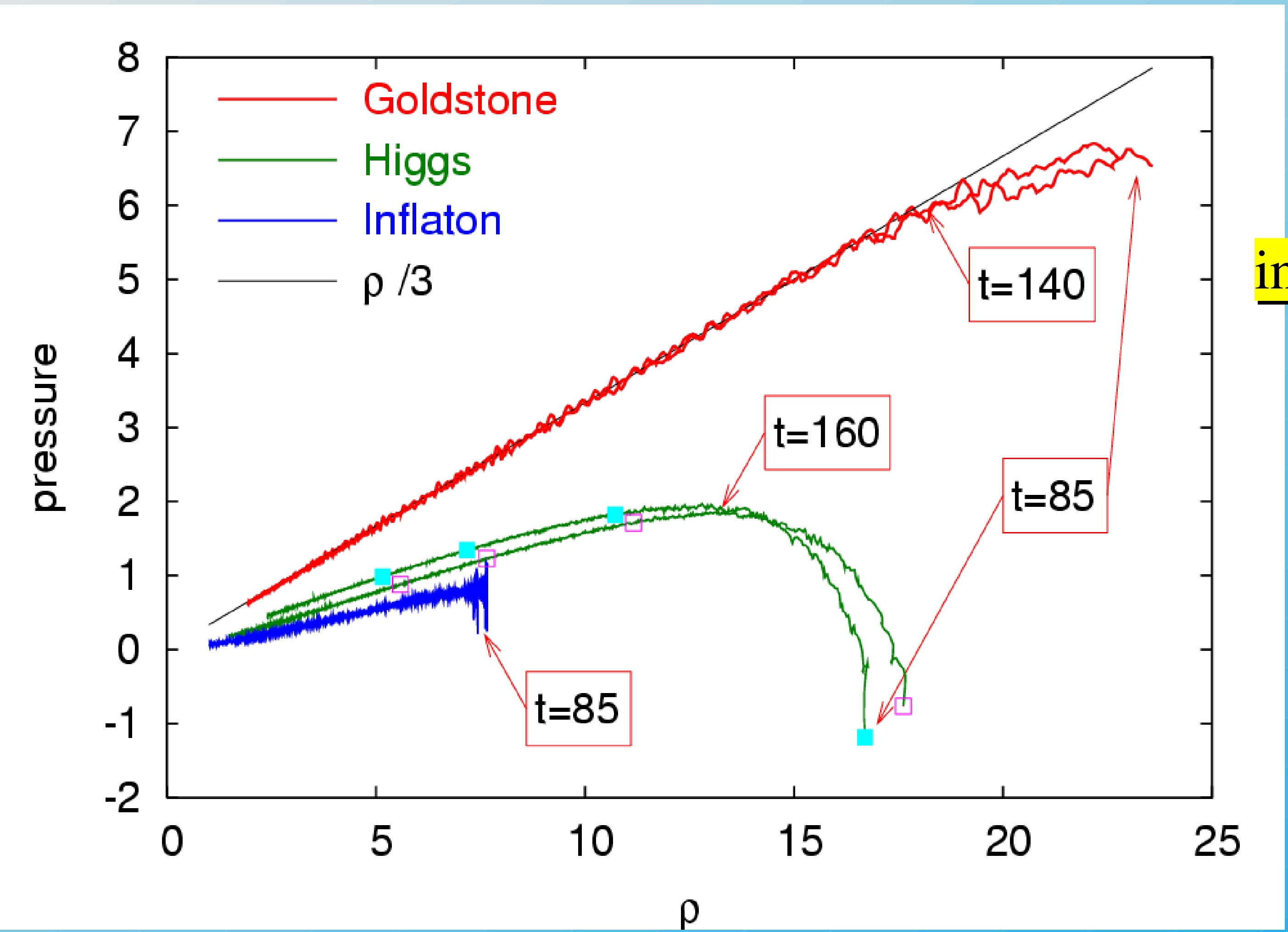
Angular ≠ Goldstone ✔

Zero - mass theorem ✔

Equation of State

$$\rho = K + G + V \qquad p = K - \frac{1}{3}G - V$$

K: kinetic energy
G: gradient energy
V: potential energy



instability t=70

The massless Goldstone field follows a perfect radiaton like equation of state .

Decomposition of the angular mixture

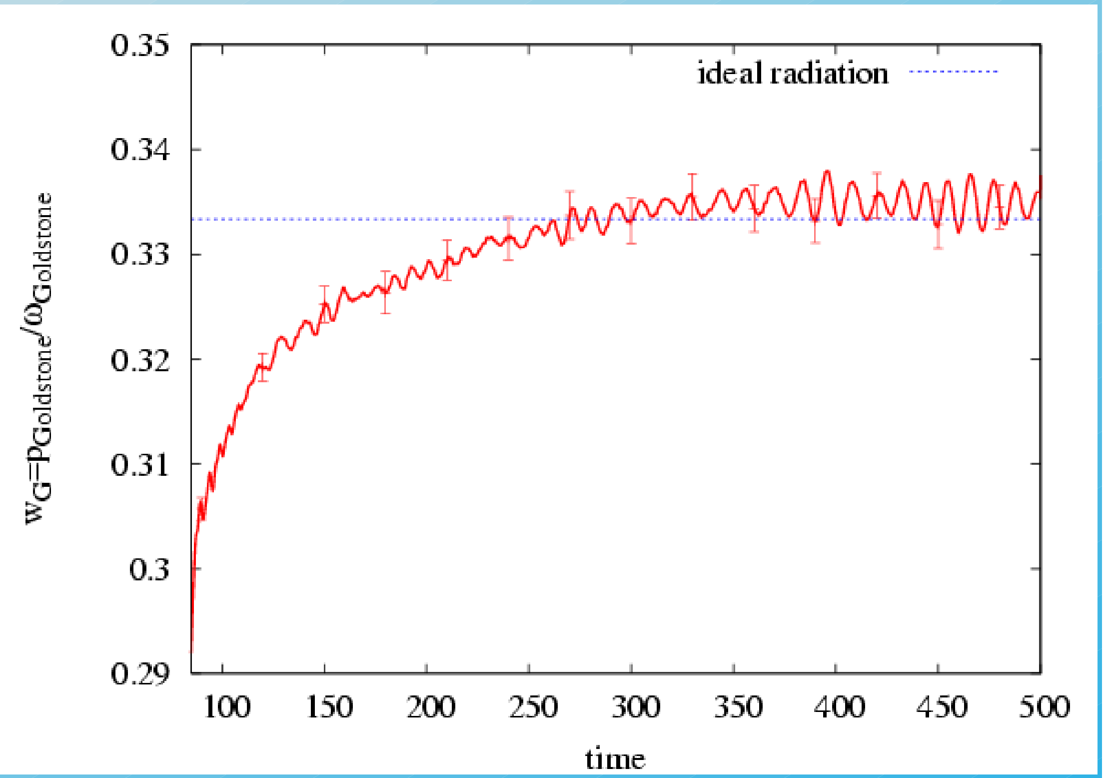
Equation of State:

(angular component)

$$p = w\rho$$

Assume two components:

heavy objects: $w = 0$
(strings, domain walls)
elementary excitations: w=1/3



Energy fraction:

$$\rho_{heavy}/\rho_{full} = 1 - 3w$$

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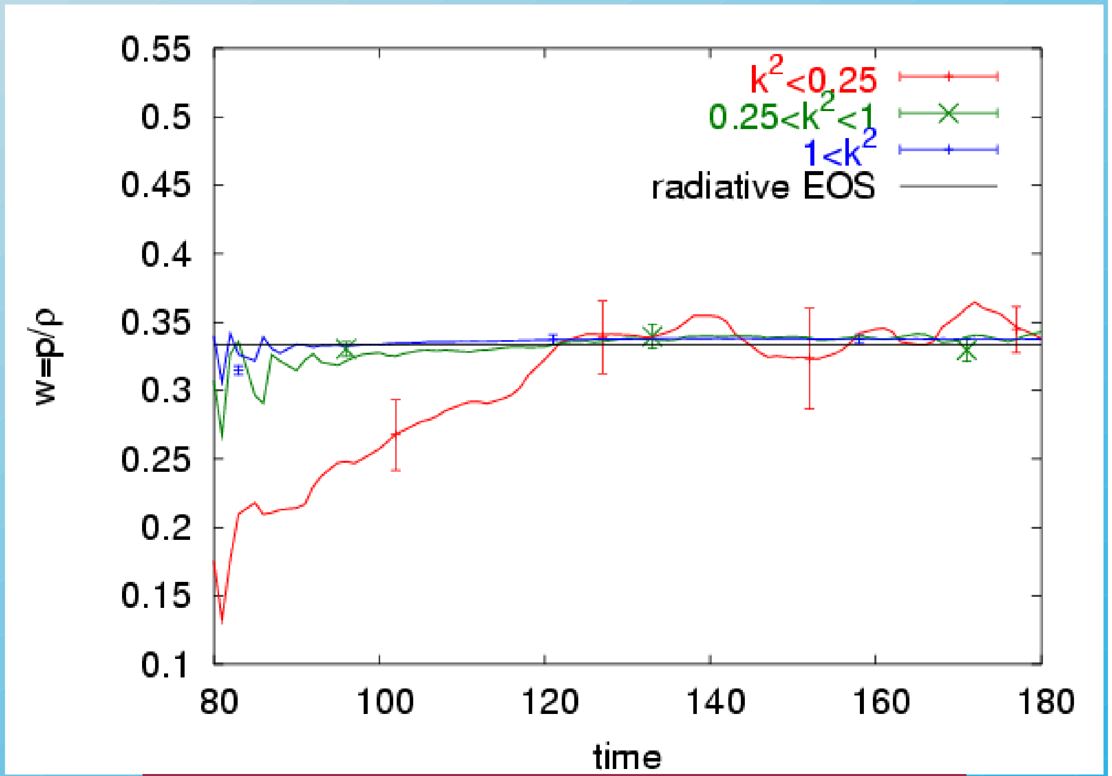


Spectral decomposition

Decomposition of the angular mixture

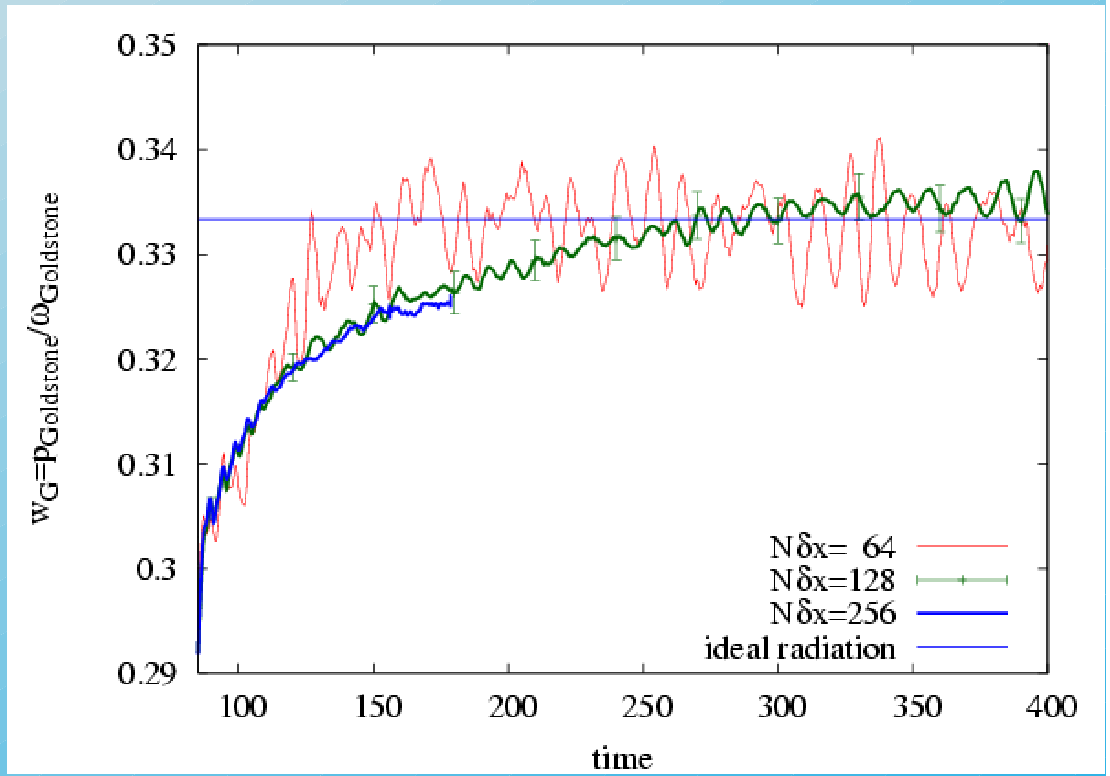
Equation of State:

(angular component)

$$p = w\rho$$

Assume two components:

heavy objects: $w = 0$
(strings, domain walls)
elementary excitations: $w = 1/3$



Energy fraction:

$$\rho_{\text{heavy}}/\rho_{full} = 1 - 3w$$

Energy fraction of elementary excitations

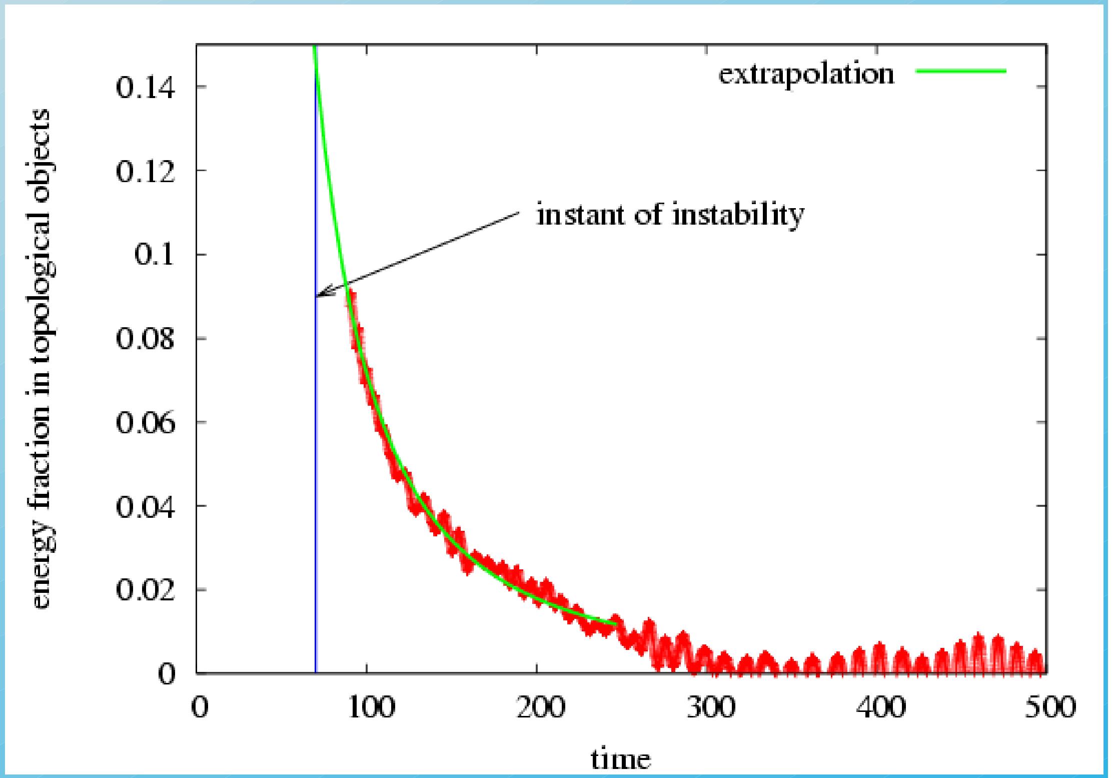
Equation of State:

(angular component)

$$p = w\rho$$

Assume two components:

heavy objects: $w = 0$
(strings, domain walls)
elementary excitations: w=1/3



Energy fraction:

$$\rho_{\text{heavy}}/\rho_{\textbf{\textit{full}}} = 1 - 3w$$

Extrapolation to the instant of instabilty:

$$\rho_{\text{heavy}}/\rho_{\textbf{\textit{full}}} \sim 0.15 \,..\, 0.5$$

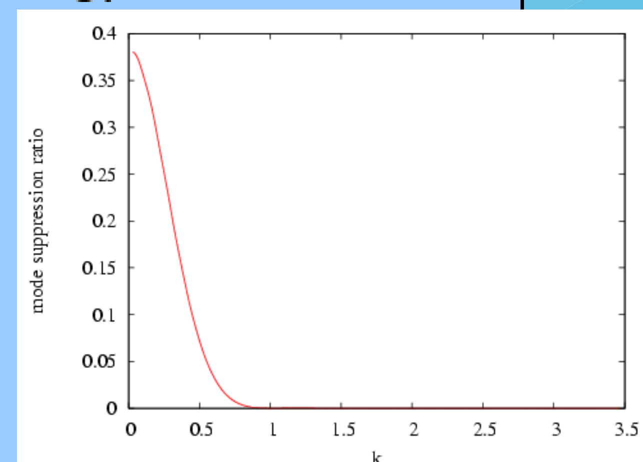
Mechanism of direct Goldstone production

$$\Phi_1(t,x) + i\Phi_2(t,x) = r(t,x)e^{i\phi(t,x)}$$

Effective equation:

Assume that the radial and angular modes are uncorrelated:

$$\ddot{\varphi}_{\mathbf{k}}(t) + 2\frac{d}{dt}\overline{\ln r(\mathbf{x},t)}^{V}\dot{\varphi}_{\mathbf{k}} + k^2\varphi_{\mathbf{k}} = 0.$$



Exponential r(x,t) ⟶ Linear $\overline{\ln r}^{V}$

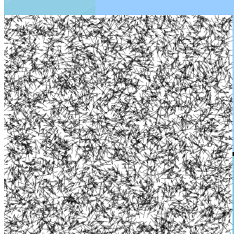
Damped harmonical oscillator for $\varphi_{\mathbf{k}}$

Vacuum:

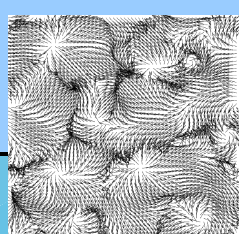
angular disorder, high fluctuations

Spinodal instability:

high-k modes are strongly damped, all modes loose kinetic energy excess in gradient energy



⟶



This mechanism gives an account for merely the 5 % of the observed energy density!

(Heavy objects, Interaction with inhomogeneous r(x,t))

Late Evolution

Cooling rate of field components:

$$3(1 + w_i(t)) = -\frac{d \ln \rho_i(t)}{d \ln a(t)}, \quad i = \text{Goldstone, Higgs, inflaton}$$

if the components are independent

	expect	observe
Goldstone:	$\rho \sim a^{-4}$	$\rho \sim a^{-3.6}$
Higgs:	$\rho \sim a^{-3}$	$\rho \sim a^{-3.6}$
Inflaton:	$\rho \sim a^{-3}$	$\rho \sim a^{-3}$

Higgs decay channel:

Higgs → Goldstone
Higgs → Goldstone

Only Goldstone modes above

$$k_{lim} > m_{Higgs} a(t)/2$$

are amplified.

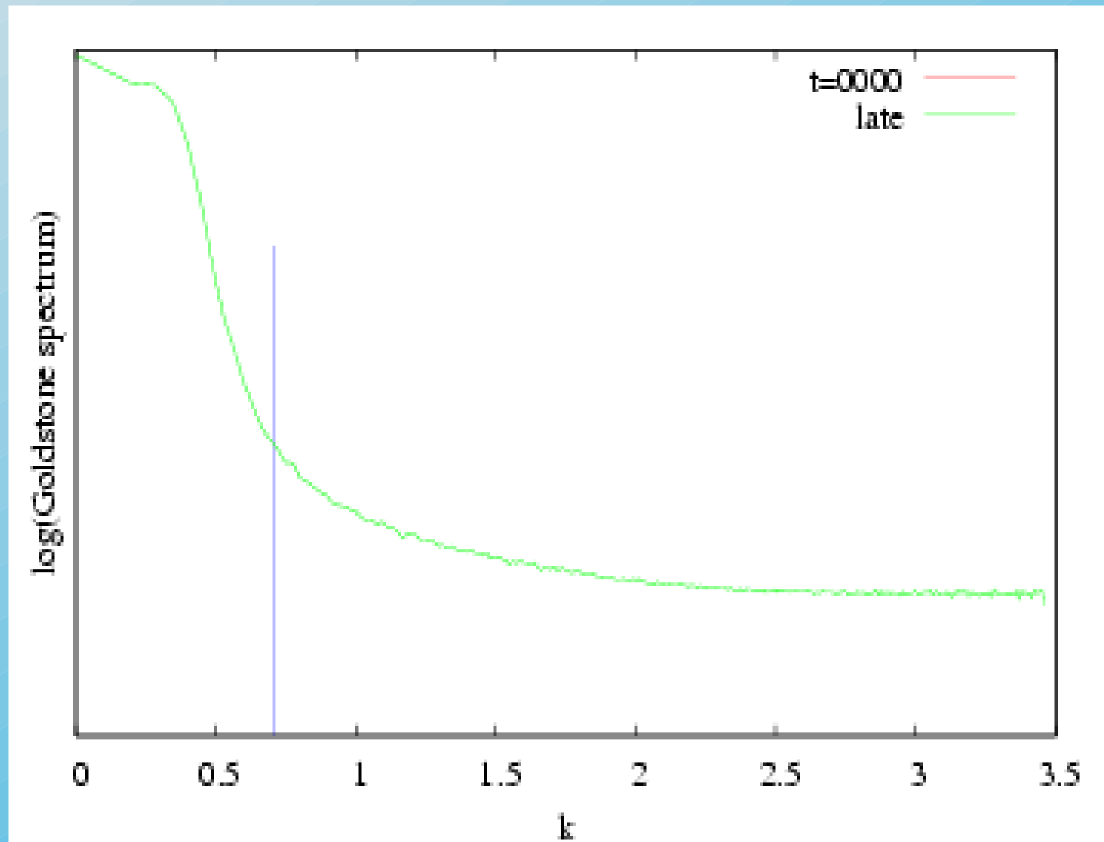
Persisting Goldstone waves

Kinetic momentum limit for Higgs decay is being shifted out of the spinodal range.

$$k_{lim} > m_{Higgs} a(t)/2$$

Hard modes are unoccupied
very slow decay
→ *<u>a highly nonequilibirum</u>* Goldstone spectrum is frozen out

$$\rho \sim a^{-4}$$



Conclusions

Classical field theory has been studied

close to the continuum limit

The initial conditions can be regularized so that the energy density is kept finite and fixed in the continuum limit.

Equation of State

testifies the presence of elementary goldstone excitations.

<u>directly and indirectly created Goldstone waves</u>

By the decay of heavy angular objects the goldstone degree of freedom acquires a radiation like equation of state.

Freeze -out of nonequilibrium Goldstone spectrum

Kinematic relations forbid the Goldstone creation

and suppress Goldstone decay