Curvaton and other spectators

Kari Enqvist

Helsinki University

and

Helsinki Institute of Physics

contents:

spectator dynamics

1. during

2. after

inflation

inflation

$$H_* \approx const.$$

dynamics unknown

slow rolling scalar(s)?

light scalar spectators exist

$$m << H_*$$

$$\rho_\sigma << \rho_{\inf}$$

example: the higgs

higgs as inflaton?

others?

during inflation → **spectators fluctuate**

mean field $\sqrt{\langle \sigma^2 \rangle}$

initial conditions for post-inflationary dynamics

field perturbations $\delta\sigma \approx H_*$

isocurvature perturbation

spectators

can play a dynamical role after inflation

1. because of their field perturbations

-modulated (p)reheating $\Gamma_{\text{inf}} = \Gamma(\sigma)$

-modulated end of inflation $t_{end} = t(\sigma)$

-conversion of isocurvature into adiabatic (curvaton)

2. because of their classical evolution

-flat directions & Affleck-Dine BG

-moduli problems

DURING INFLATION

massless scalars in an expanding background

⇨ stochastic treatment (cf. Starobinsky)

Langevin (simplified):

decompose field into UV and IR parts:

$$\Phi_{IR} \propto \int dk W(k,t)\phi_k(t)$$

$$W(k,t) = \theta\left(k - xaH\right)$$

$$\dot{\Phi}_{IR} = -\frac{\partial}{3H\partial\Phi}V\left(\Phi_{IR}\right) + s(x,\eta)$$

k<<aH

stochastic term, white noise correlators

$$\langle SS\rangle\left(dN\right) = \left(1 + x^3\right)\frac{H^2 dN}{4\pi^2}, \quad k = xa(N)H$$

inflationary fluctuations

massless field

$$\left\langle \phi^2 \right\rangle = \frac{1}{4\pi^2} H^2 N$$

N = # of efolds

evolution of pdf: Fokker-Planck

$$\frac{\partial P}{\partial t} = \frac{1}{3H} \frac{\partial}{\partial \phi} \left[V'(\phi) P \right] + \frac{H^3}{8\pi^2} \frac{\partial^2}{\partial \phi^2} P$$

equilibrium pdf:

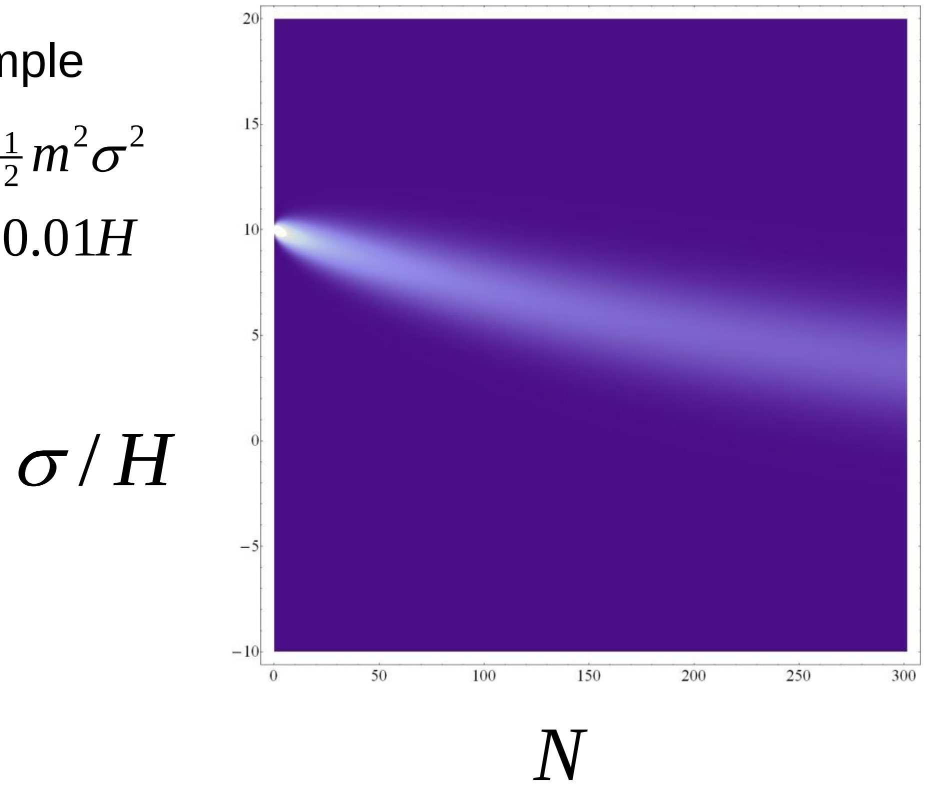
$$P \propto \exp(-8\pi^2 V / 3H^4)$$

example

$V = \frac{1}{2} m^2 \sigma^2$

$m = 0.01H$

KE, Lerner, Taanila, Tranberg

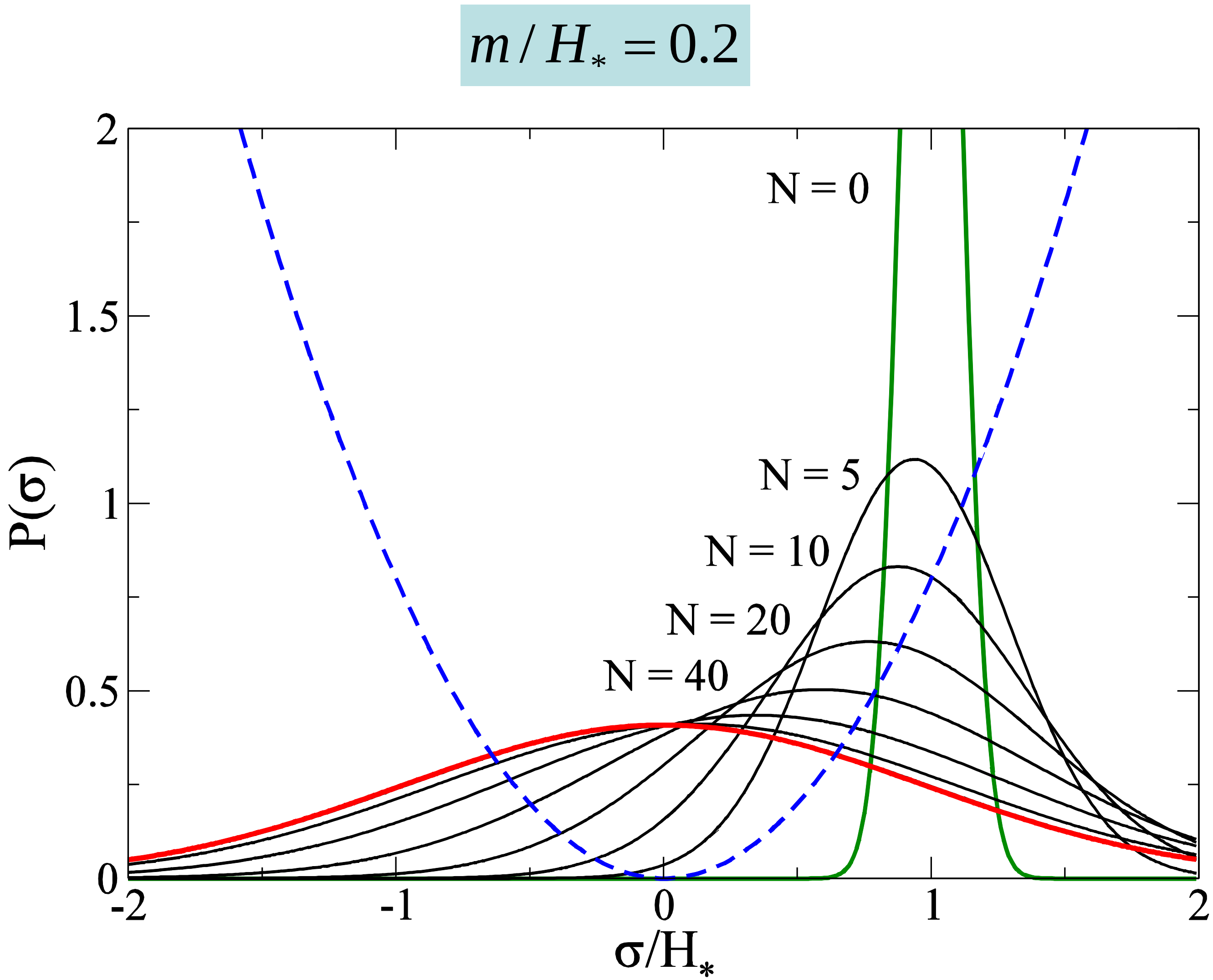


relaxation time

$$N_{rel} = \frac{3H_*^2}{m^2}$$

decoherence time

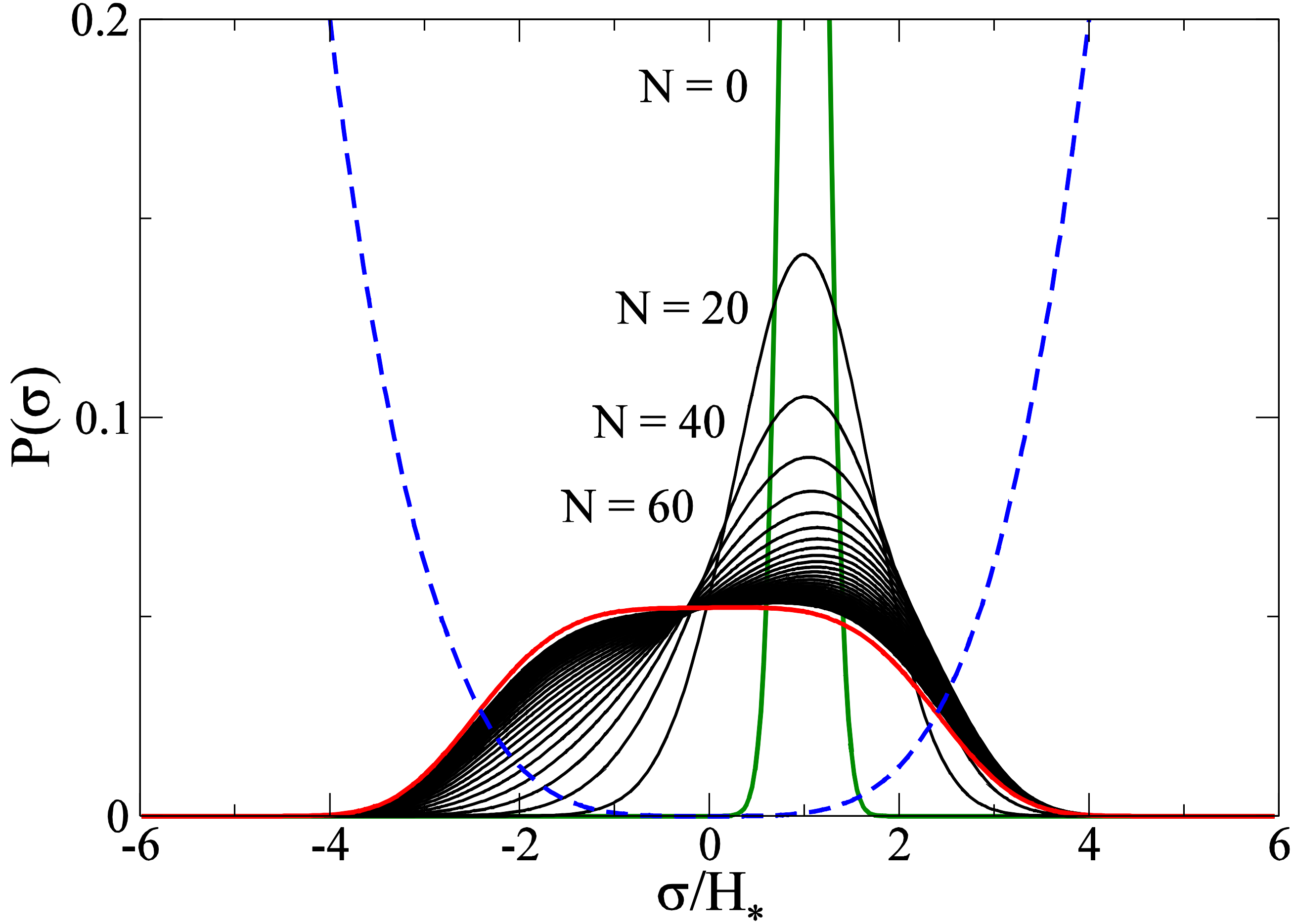
$$N_{dec} = \frac{3H_*^2}{2m^2}$$



$m / H_* = 0.2$
N = 0
N = 5
N = 10
N = 20
N = 40
P(σ)
σ/H*
2
1.5
1
0.5
0
-2
-1
0
1
2

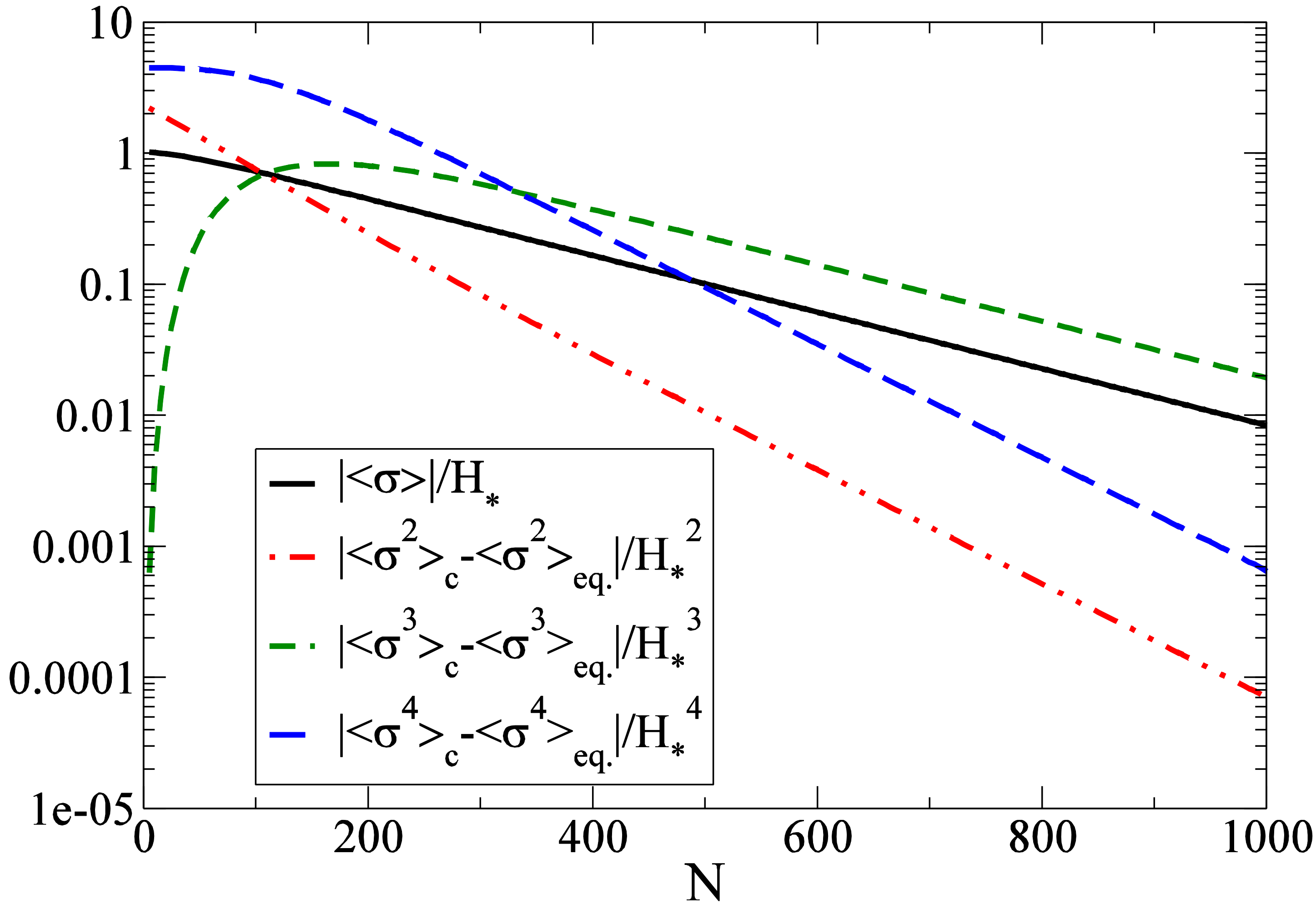
quartic potential $V = \frac{1}{4}\lambda\phi^4$

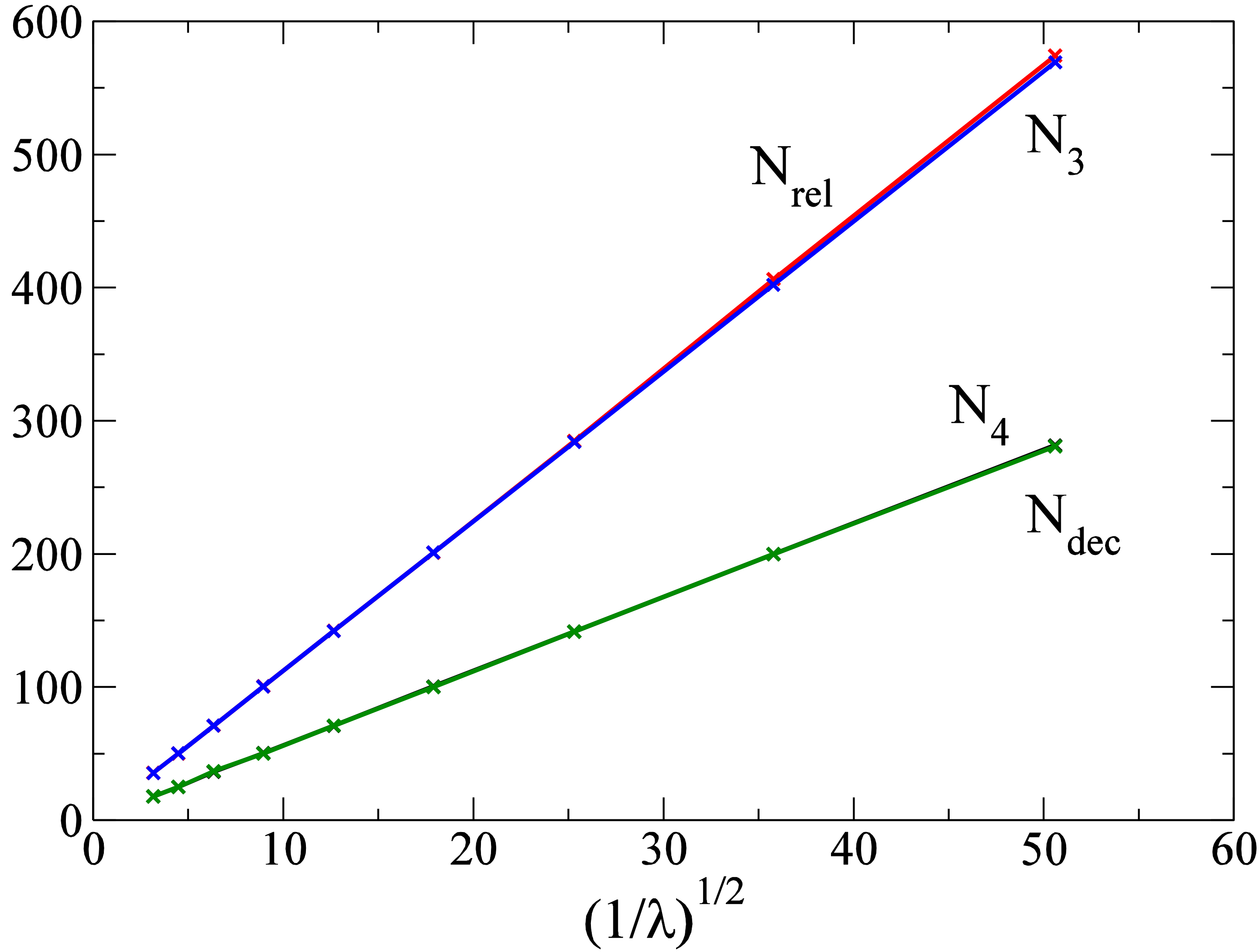
$\lambda = 0.003125$



quartic potential

$$V = \frac{1}{4}\lambda\phi^4$$





600
500
400
300
200
100
0
0
10
20
30
40
50
60
$(1/\lambda)^{1/2}$
N_{rel}
N_3
N_4
N_{dec}

relaxation time $N_{rel} \approx \frac{11.3}{\sqrt{\lambda}}$

decoherence time $N_{dec} \approx \frac{5.65}{\sqrt{\lambda}}$

Example: the higgs

$$V \approx \tfrac{1}{4} \lambda h^4$$

RGE → $\lambda \approx 0.01$ at inflationary scales

⇨ decoherence at ~ 60 efolds ⇨ mean field from equilibrium dist

⇨

$$h_* \approx 0.36 \lambda^{-1/4} H_* \approx 1.1 H_*$$

⇨ effective higgs mass $m_{h_*}^2 \approx V''(h_*) = 0.40 \lambda^{1/2} H_*^2 = 0.04 H_*^2$

mean field can matter:

flat directions

V=0 along a ray in field space; e.g. MSSM

fluctuations along flat directions → cosmological consequences when decay

baryogenesis a la Affleck-Dine
etc

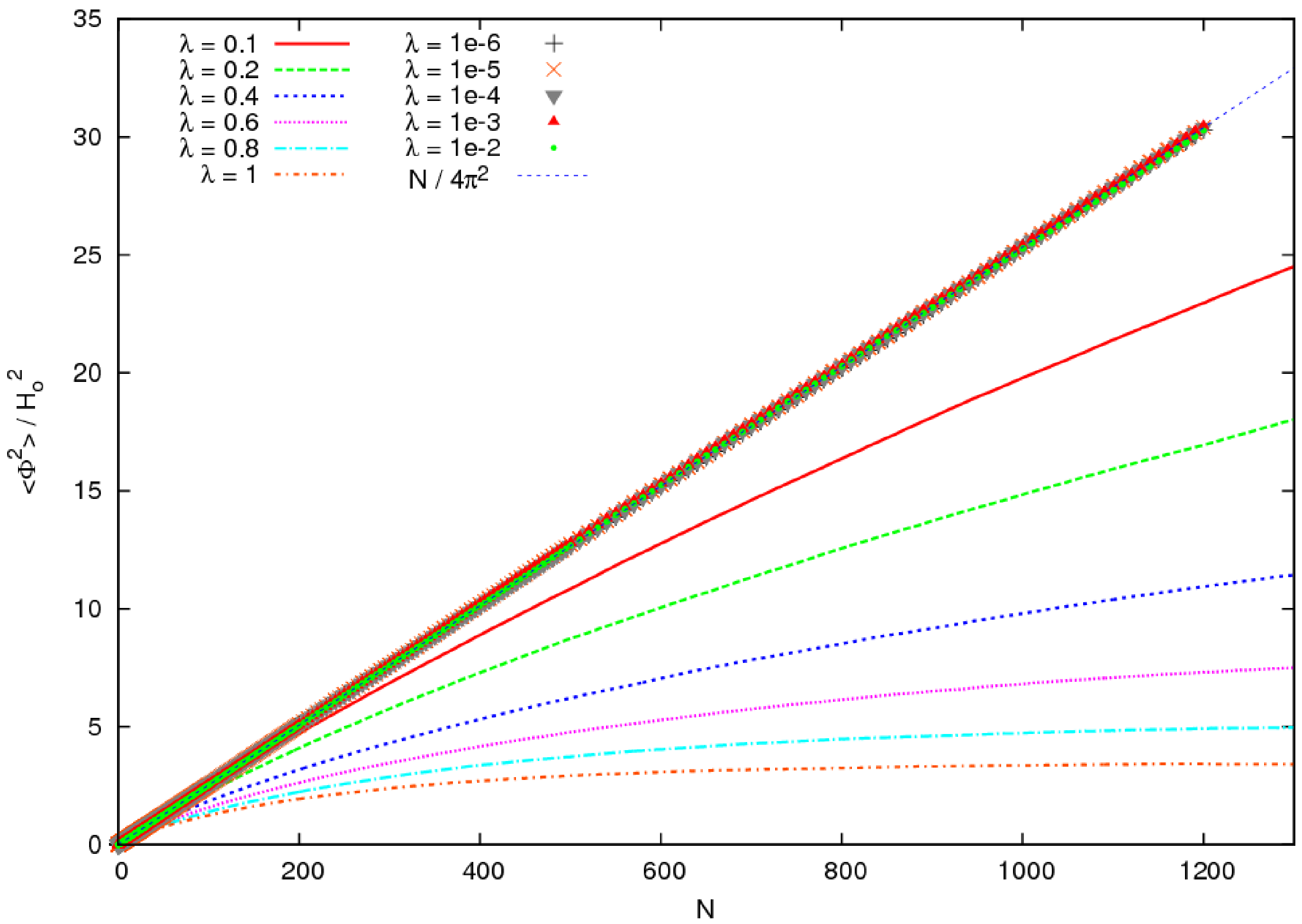
schematically

Figueroa, KE, Rigopoulos

$$V(\phi,\chi) \approx \lambda^2\phi^2\chi^2 + g^2\chi^4$$

Langevin eqs →

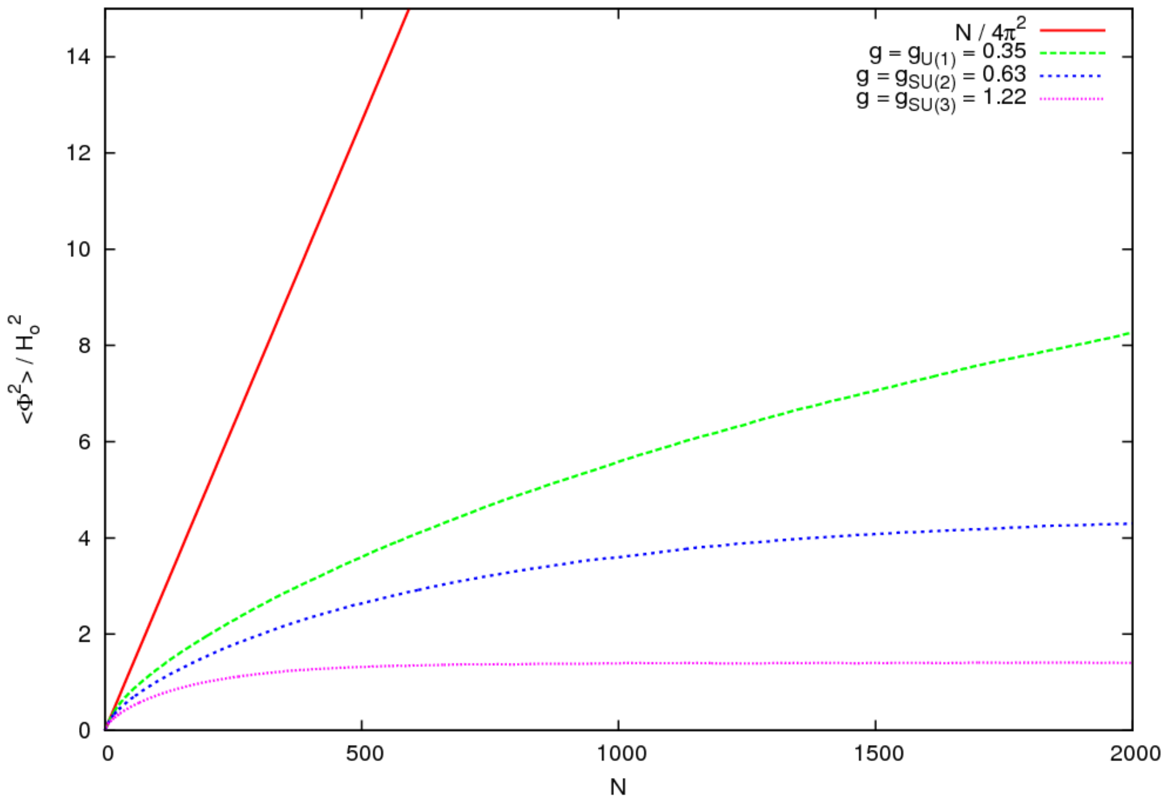
initial condition:
all fields at origin



consider MSSM D-term only with

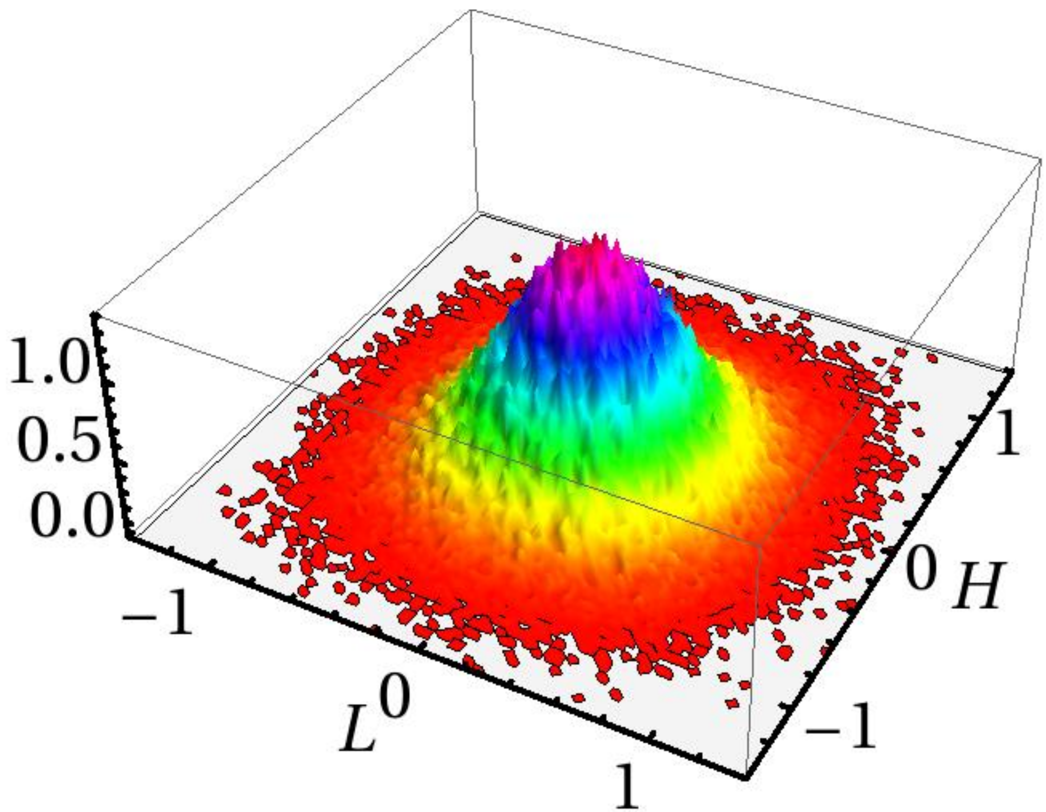
$$V(L,H) = \frac{g^2}{8}\left(L^2 - H^2\right)^2$$

all other = 0 but allow fluctuations to displace fields from the flat direction L = H

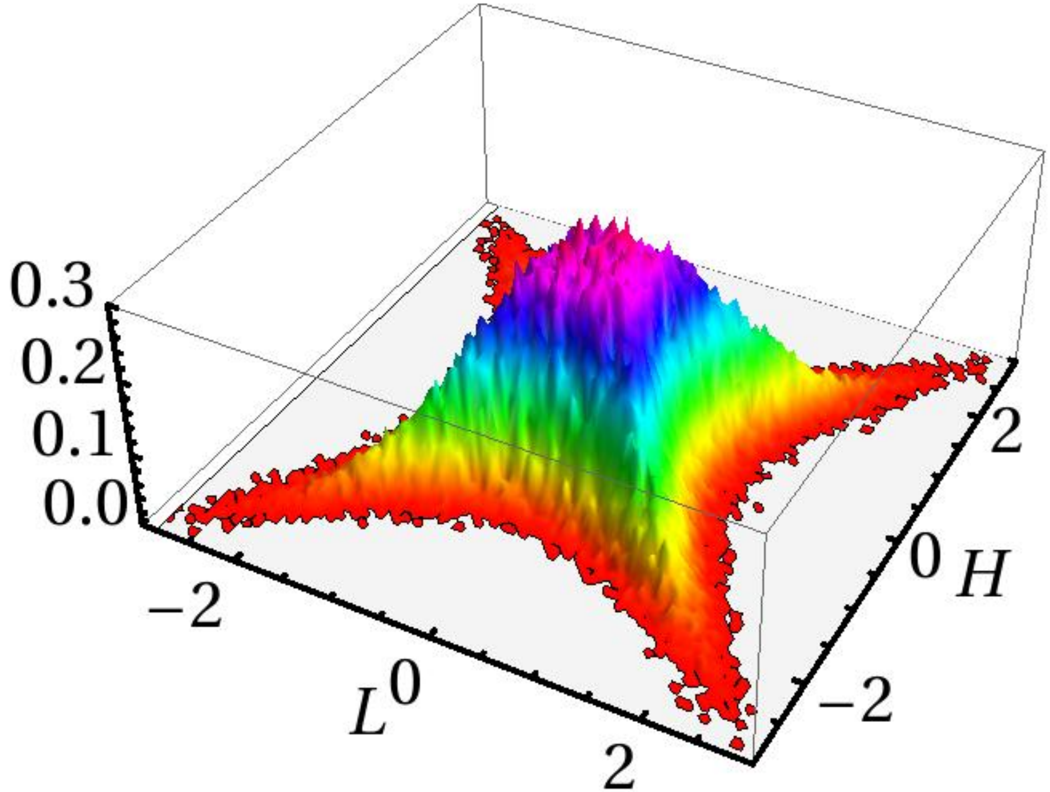


N = 5

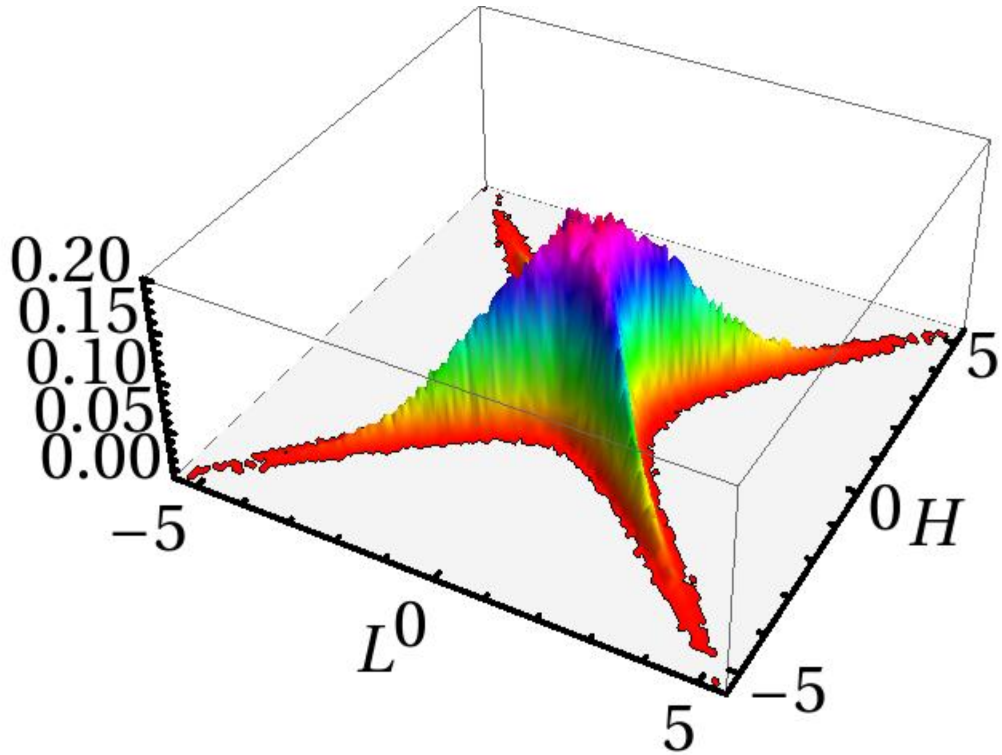
SU(2)



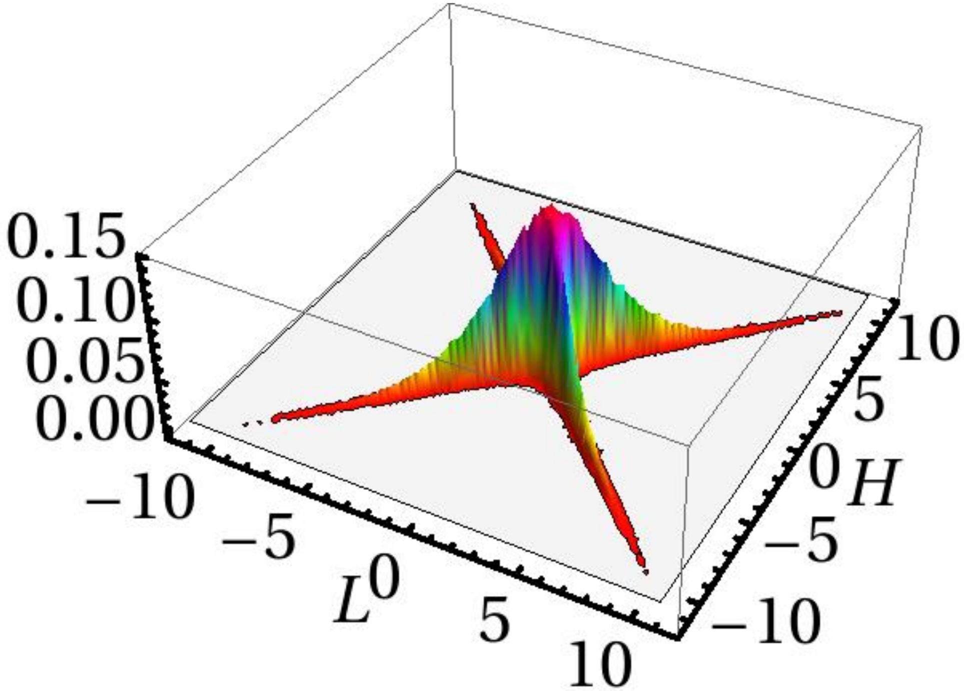
N = 40



N = 150



N = 1000



⇒

flat direction amplitude

blocked by fluctuations of non-flat directions

if fields initially at the origin

initially not at the origin? → techically complicated

KE, J. Bueno Sanchez

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

$$m_\phi^2=\frac{1}{2}g^2\chi^2$$ "light field"

$$m_\chi^2=\frac{1}{2}m^2\chi^2+\frac{1}{2}g^2\phi^2$$ "heavy field"

initially $\langle\phi\rangle=\phi_0 \Rightarrow m_\chi^2(0)=g^2\phi_0^2>>H^2$

dynamics depends on coarse graining scale

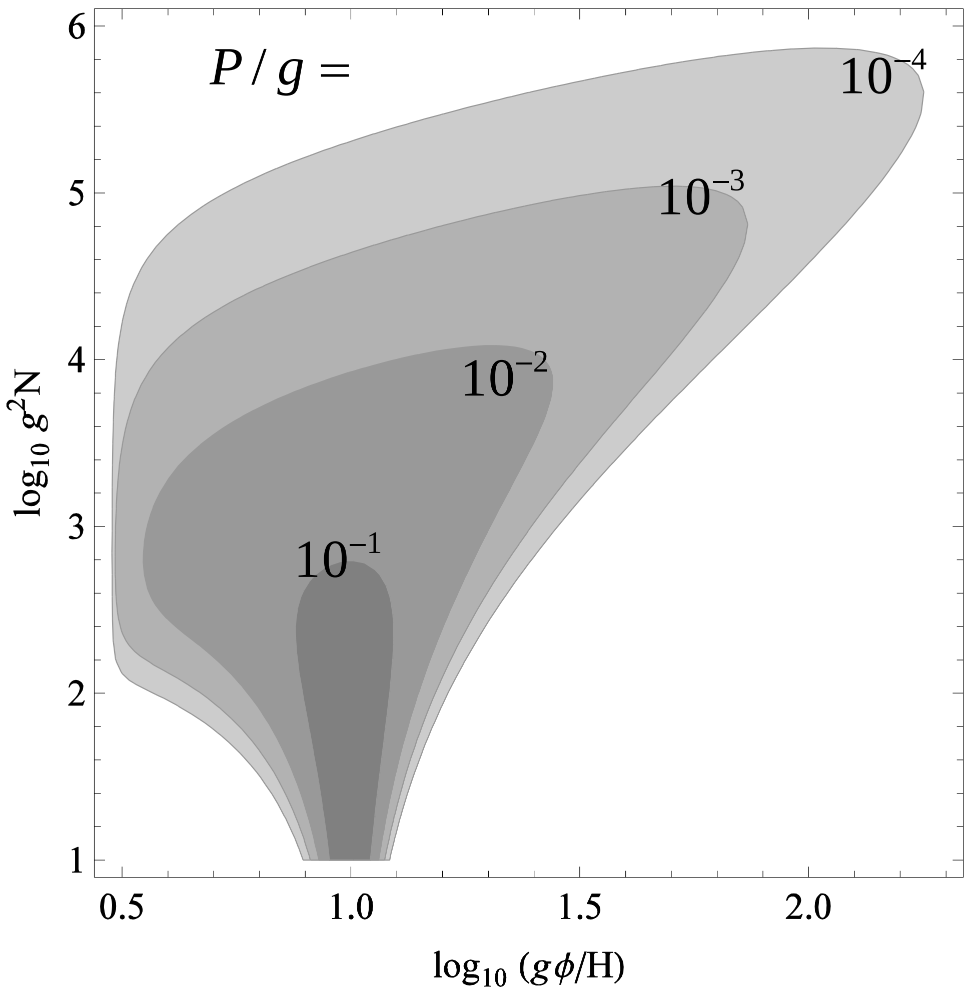
there is a cross-over scale below which both fields become light
as ϕ random walks → 0

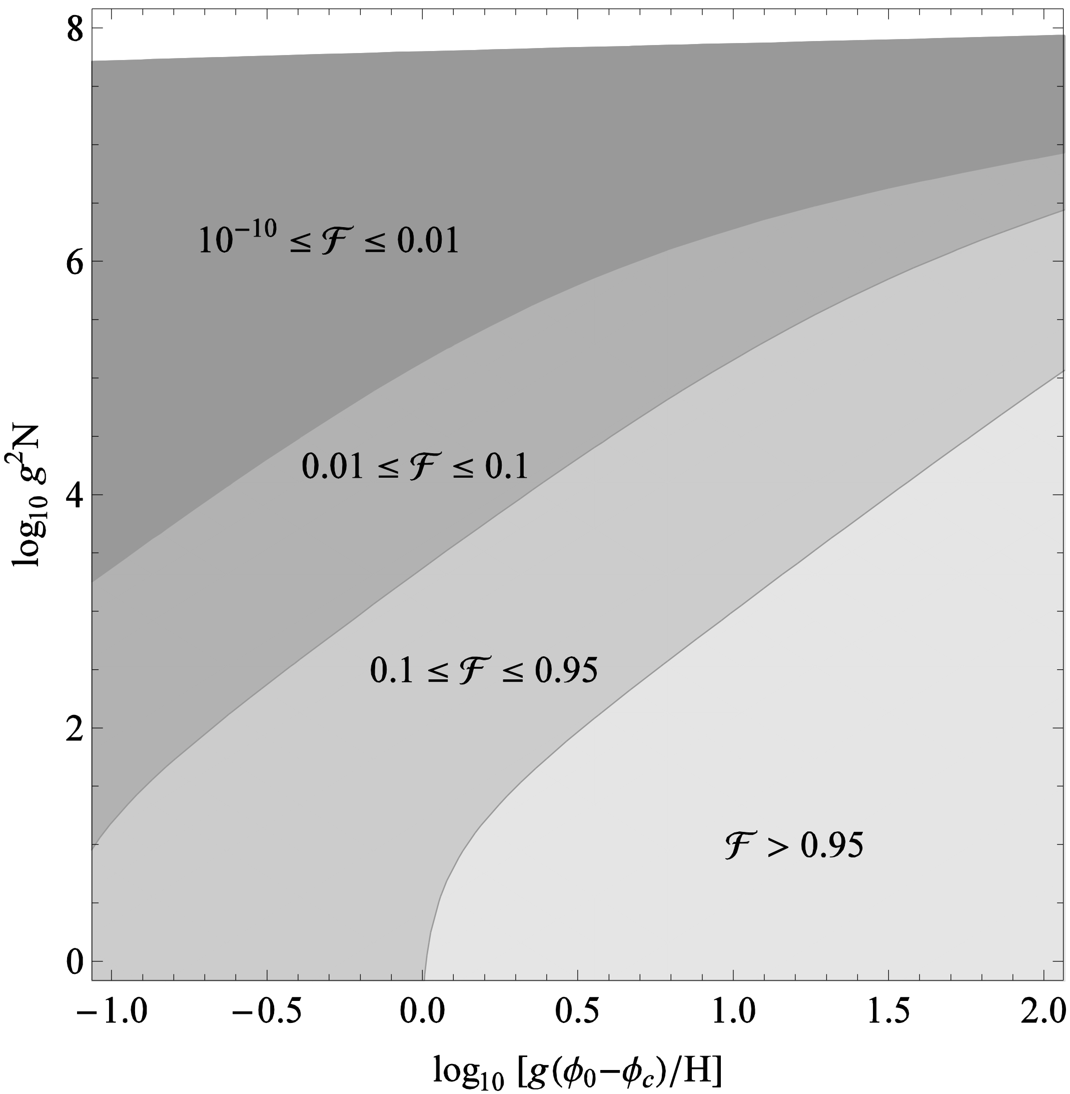
→ probability for trapping of fields around the origin cross-over scale at $\phi = \phi_c \approx few \times H / g$ difficult to compute

”absorbing barrier”

$$\phi_c = 3H / g$$

$$\phi_0 = 10H / g$$





$10^{-10} \leq \mathcal{F} \leq 0.01$
$0.01 \leq \mathcal{F} \leq 0.1$
$0.1 \leq \mathcal{F} \leq 0.95$
$\mathcal{F} > 0.95$
$\log_{10} g^2 N$
$\log_{10} [g(\phi_0 - \phi_c)/H]$
8
6
4
2
0
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0

if a spectator remains around for some time after inflaton decay, it can generate the observed curvature perturbation

the curvaton

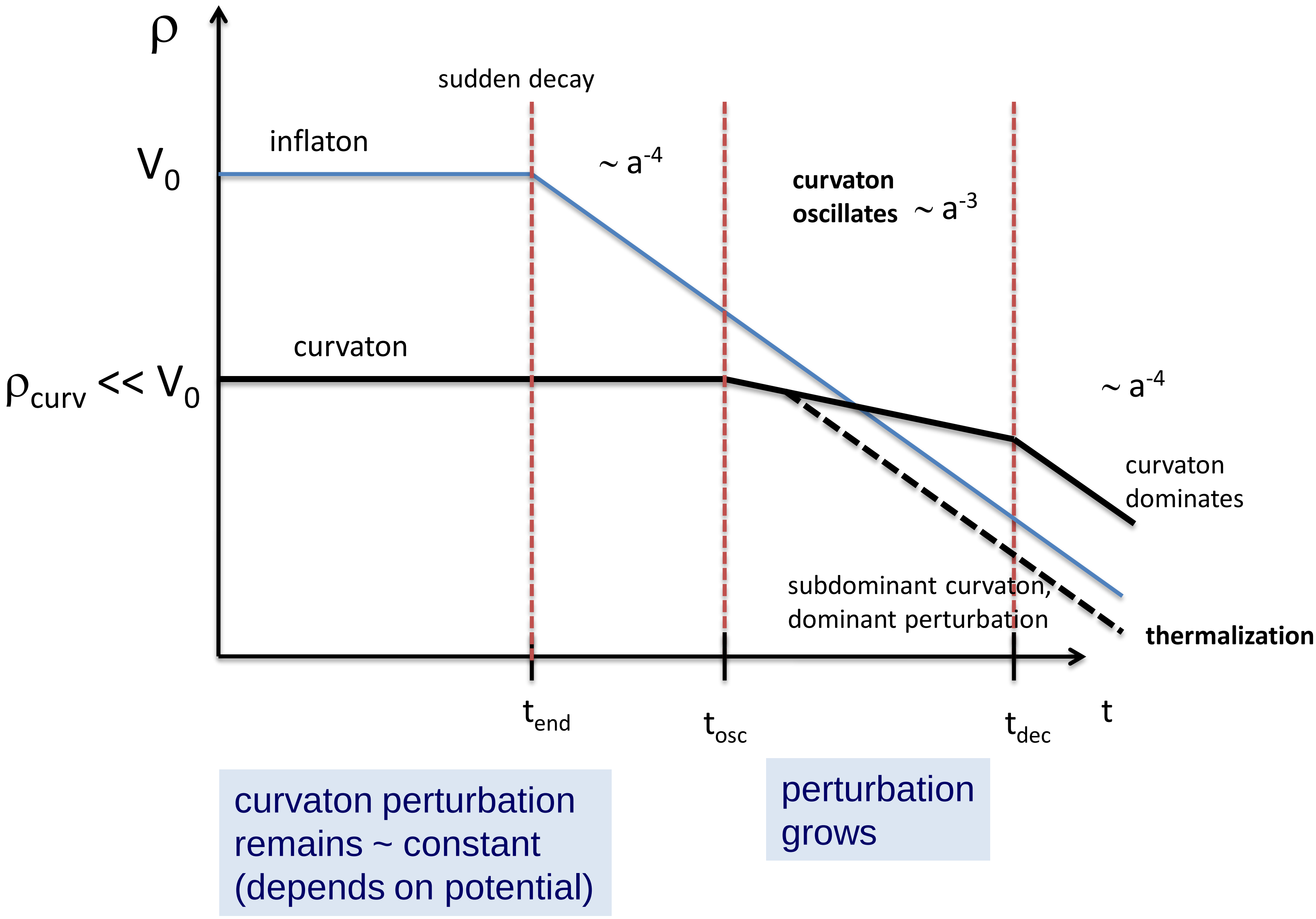
curvature perturbation generated after inflation

require

- curvaton decay products thermalize with radiation

⇒ initial curvaton isocurvature perturbation is transformed to an adiabatic perturbation

- $\varsigma_{\inf} << \varsigma_{\sigma} \approx 10^{-5}$



ρ
sudden decay
inflaton
V0
~ a-4
curvaton
oscillates ~ a-3
curvaton
ρcurv << V0
~ a-4
curvaton
dominates
subdominant curvaton,
dominant perturbation
thermalization
tend
tosc
tdec
t
curvaton perturbation
remains ~ constant
(depends on potential)
perturbation
grows

curvature perturbation

$$\varsigma = \frac{H_*}{3\pi\sigma_*} r_{eff} \approx 10^{-5}$$

$$r_{eff} \approx r_{dec} = \frac{3\rho_\sigma}{3\rho_r + 4\rho_\sigma}$$

simplest potential

$$V = \frac{1}{2} m^2 \sigma^2$$

$$f_{NL} \approx \frac{3}{8r}$$

large non-gaussianity = subdominant curvaton

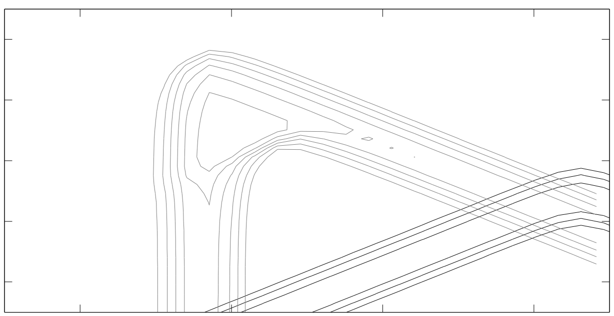
Initial condition for the curvaton field?

$$\varsigma = \frac{H_*}{3\pi\sigma_*} r_{eff} \Rightarrow r_{eff} = \frac{\sigma_*^2}{\sigma_*^2 + 4M_P^2(\Gamma/m)^{1/2}}$$

stochastic treatment ⇒ $P(10^{-6} \leq \zeta \leq 10^{-5}, N)$

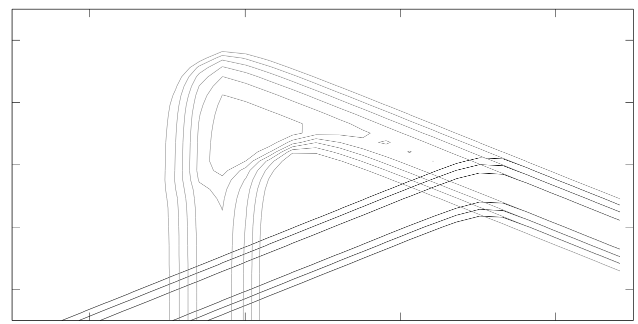
Lerner, Melville

Γ



m

Γ



m

contours $P = 0.1,\ldots,0.9$

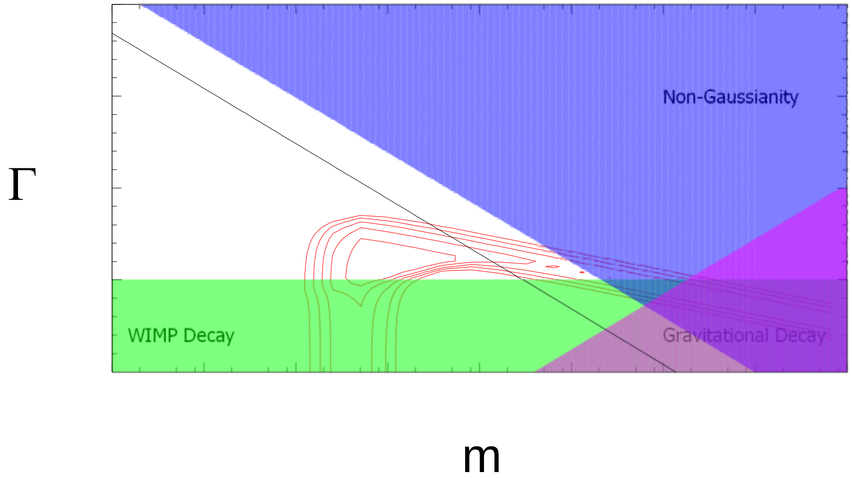
N=100

σ(0)=0

N=10^4

⇒ need a very large number of efolds

H = 10^{10} GeV



constraints on probable models

N.B.: interactions are important

- large field values $\rightarrow$ probe interaction terms

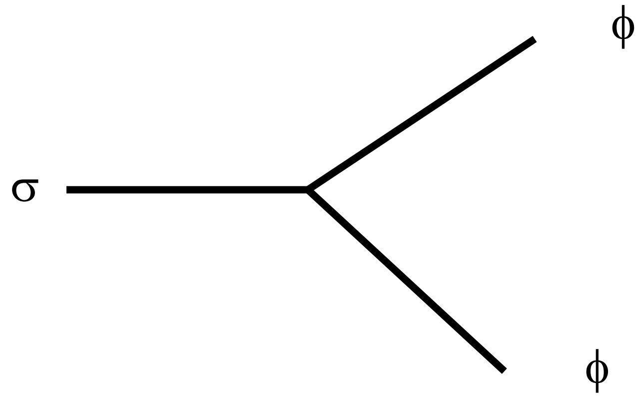
- interactions $\rightarrow$ non-linearities

non-linearities: sensitivity to the initial condition

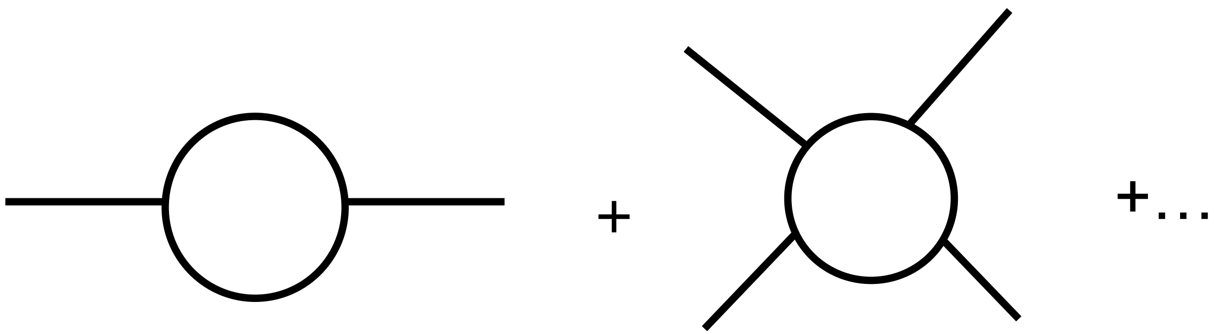
- in particular: non-gaussianity

$$f_{NL} \approx \frac{3}{8r} \rightarrow \frac{3}{8r} - g(n,\lambda)$$

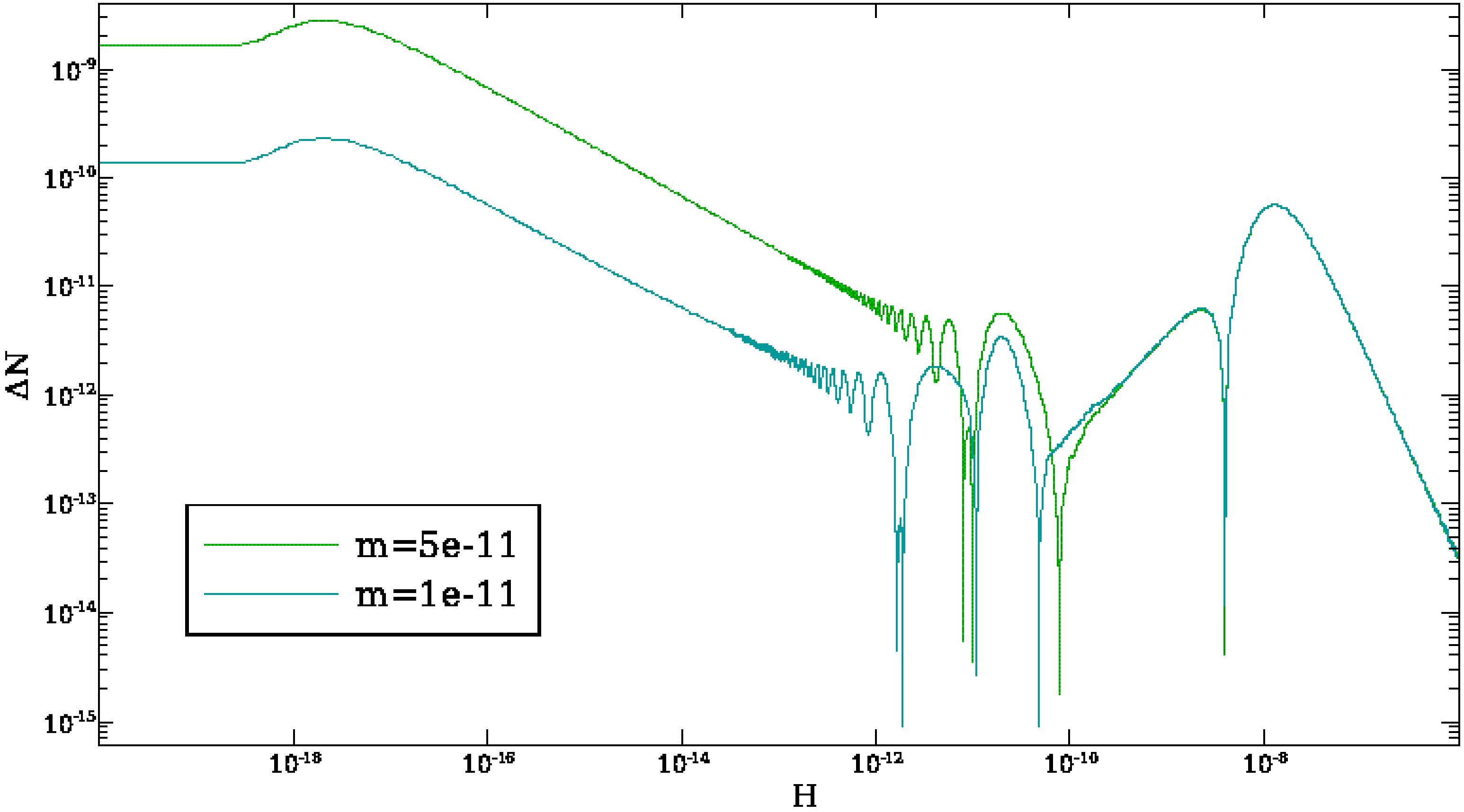
curvaton must decay:



higher order operators must exist:



perturbation sensitive to non-linearities:



$$V = \frac{1}{2} m^2 \sigma^2 + \lambda \sigma^6$$

KE, Nurmi, Taanila, Rigopoulos, Takahashi

CURVATON DECAY

the amplitude of the curvature perturbation depends on the time of decay of the curvaton

⇒ must account for the decay mechanism

OPTIONS

1. throw in a Γ

2. couple the curvaton to SM and compute

Higgs as the curvaton?

Choi & Huang
de Simone, Perrier, Riotto

NO: $V \approx \frac{1}{4}\lambda h^4$ → higgs oscillations behave as radiation

→ relative density does not grow

but could be a field modulating either a) end of inflation or b) inflaton decay rate

N:B:: need precise calculations – 2-loop RGE

$$\lambda(H_*) \approx 0.01,\ g(H_*) \approx 0.5$$

HIGGS MODULATED (P)REHEATING

KE, Meriniemi, Nurmi

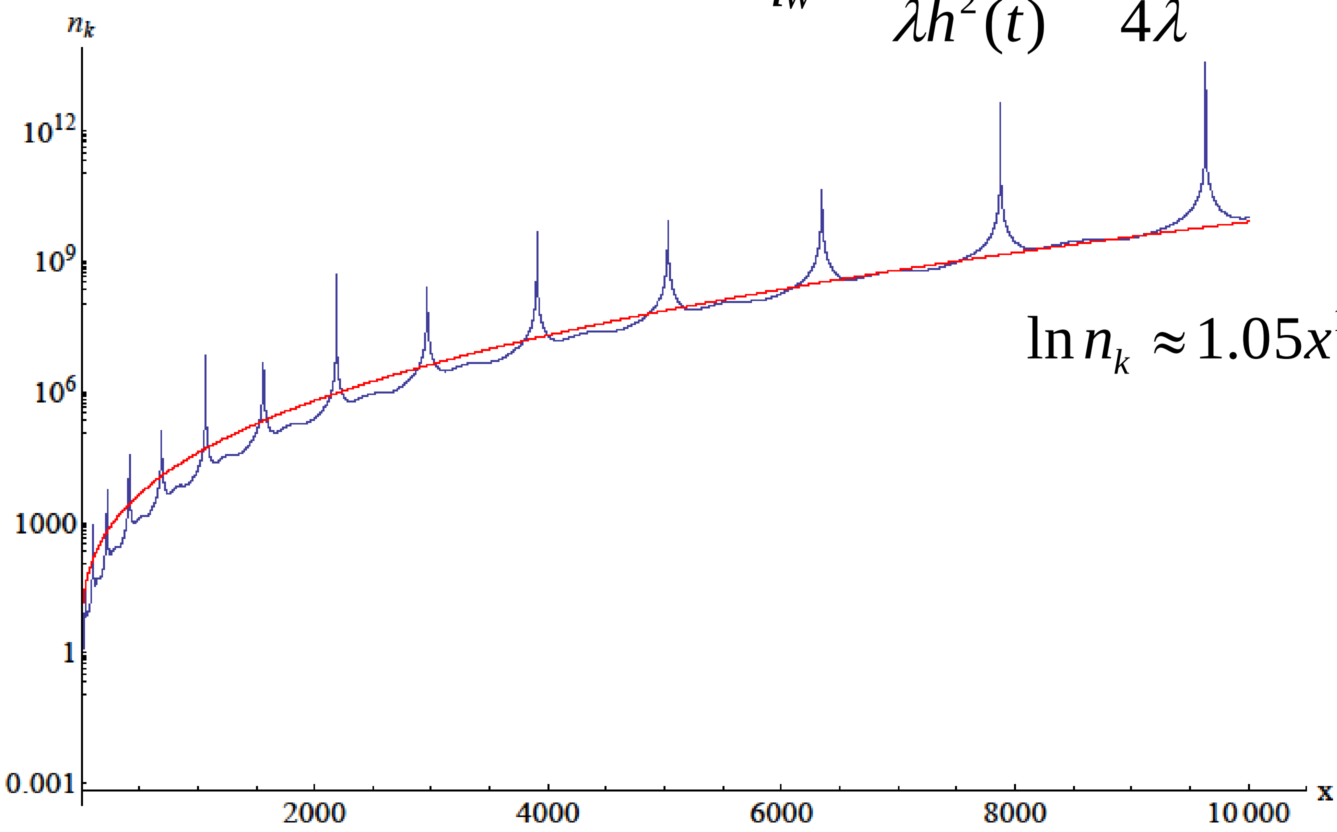
must require: higgs does not decay before the inflaton

- perturbative top- and W, Z channels blocked
- fastest perturbative channel is bb – very slow
- decay by resonant production of gauge bosons
- higgs self-decay at the edge of instability band - weak

non-perturbative decay of the higgs into gauge bosons

instability bands for k = 0 conformal model: $q = 1 \ldots 3; \quad 6 \ldots 10; \ldots$

$$q_W = \frac{m_W^2(t)}{\lambda h^2(t)} = \frac{g^2}{4\lambda}$$



$$\ln n_k \approx 1.05 x^{1/3}$$

$$x = \sqrt{\lambda h_{osc}^2}\left(t - t_{osc}\right)$$

Table 1: Numerical values for μ_k and approximations for $n_\phi^{\rm res}$ with different H_*.

H_*/GeV	λ	$(q_W\,,\,\mu_k)$	$(q_Z\,,\,\mu_k)$	$n_\phi^{\rm res}$
10^4	0.09	(1.1, 0.14)	(1.5, 0.23)	170
10^7	0.04	(2.3, 0.23)	(3.2, 0.00)	300
10^{10}	0.01	(8.1, 0.24)	(12.2, 0.00)	380

estimate the time $$\rho_W \approx \rho_h = \frac{\lambda}{4}\left(\frac{h}{a}\right)^4$$

→ # of inflaton oscillations before higgs decay

$$170 \ldots 380$$

$$H_* = 10^4 \ldots 10^{10}$$

assuming $m_\phi \approx H_*$

→ **curvature perturbation from higgs modulated (p)reheating implies rapid inflaton decay**

Curvaton coupled to SM higgs

Only renormalisable coupling to standard model:

$$V(\sigma,\Phi)=\frac{1}{2}m_\sigma^2\sigma^2+g^2\sigma^2\Phi^\dagger\Phi+\lambda\left(\Phi^\dagger\Phi-\frac{v^2}{2}\right)^2$$

curvaton
(real scalar)

SM higgs

KE, Figueroa, Lerner

Free parameters: g, m_σ, σ*, H*

- no perturbative decay (no three-point coupling)
- but expect non-perturbative decay, just like preheating
- there is a thermal background from inflaton decay
- higgs has a thermal mass $m^2(H)=g_T^2T^2,\ g_T^2\approx 0.1$

resonant production of higgs particles

oscillating curvaton with zero crossings

production takes place at resonant bands

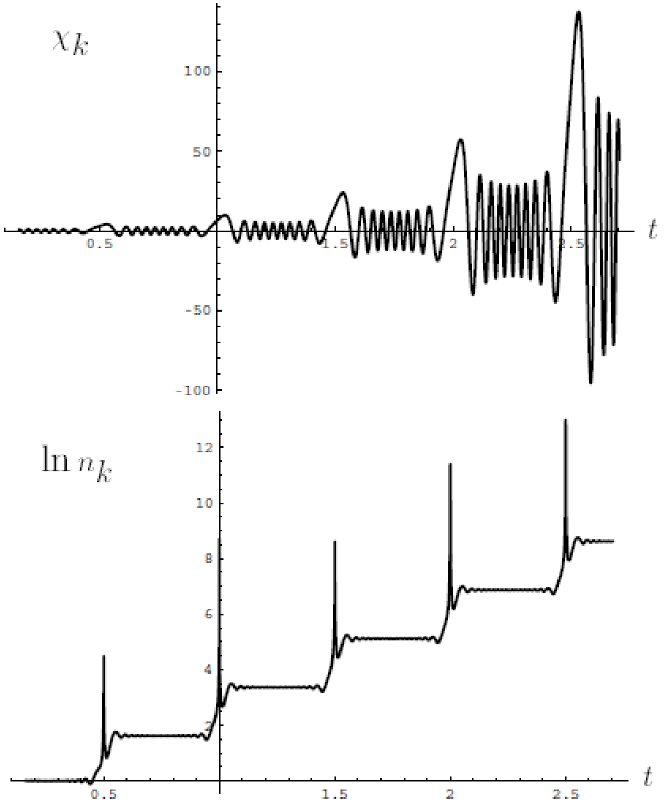
resonant parameter

$$q \equiv \frac{g^2\sigma^2}{4m_\sigma^2}$$

- broad resonance:
  q >> 1
- narrow resonance:
  q << 1

determined by the effective frequency of the higgs

broad resonance



Kofman, Linde, Starobinsky

- curvaton is oscillating
- higgs has mass gσ
- resonant production of higgs with momentum k
  - depends on the dispersion relation
  - requires non-adiabacity at zero crossing

(some differences between broad and narrow resonance)

corrected by thermal mass

(thermal background also induces mass for curvaton)

IR modes with k < k_{kcut}

$$K_{cut}(j) = \frac{k_{cut}(j)}{a} \approx j^{-3/8}\sqrt{gm\sigma_*}$$

jth zero crossing

need to consider

- as the curvaton is oscillating, the resonance parameter q also evolves
  - unblocking: broad or narrow resonance?
- as the curvaton is oscillating, its relative energy density is increasing
  - unblocking: radiation or matter (=curvaton oscillation) dominated

dispersion relation

- Higgs equation of motion:

j = time = # zero crossings

$$\frac{d^2\chi_\alpha}{dx^2} + \left(\kappa^2(j) + g_T^2 a^2(j)\frac{T^2(j)}{k_{cut}^2(j)} + x^2\right)\chi_\alpha = 0$$

- effective frequency:

$$\omega_k^2(j) = \kappa^2(j) + \frac{m_\sigma}{H_*} g_T^2 \frac{8}{14\pi}\left(\frac{T_*}{k_{cut}(j)}\right)^2 + x^2$$

$$\kappa^2(j) \approx \left(K / K_{cut}(j)\right)^2 \qquad x \equiv K_{cut}(j)t,$$

Adiabaticity violated if...

$$0 \leq k^2 \leq \underbrace{k^2_{cut}(j)}_{>0} - \underbrace{\frac{8 m_\sigma g_{\mathrm{T}}^2}{14\pi H_*} T_*^2}_{<0}$$

- RHS should be > 0
- Thermal mass of Higgs blocks resonance!
- Unblocked after **many** oscillations:

$$j \gtrsim j_{\mathrm{NP}}|_{RD} \equiv \frac{g_{\mathrm{T}}^8}{g^4 g_*^2}\left(\frac{M_P}{\sigma_*}\right)^4$$

it is not enough that the resonance becomes unblocked – energy must also be transferred to higgs particles

- if decay products do not thermalise:

$$\rho_H(j) \approx 0.028 f(q) q(j)^{1/4} \frac{(1+\frac{2}{e})^{\Delta j - 1}}{\left(\frac{1}{3} + \frac{(j_{\rm NP}+\Delta j)}{j_{\rm EQ}}\right)^2} \left(\frac{\sigma_*}{M_P}\right)^6 \frac{1}{\left(1 + \frac{\Delta j - 1}{(e/2+1)}\right)^{\frac{3}{2}}} \times (g m_\sigma \sigma_*)^2$$

where

$$f(q) \equiv 1 + \frac{2+e}{\exp\left(g_T\, q^{1/4} - 1\right)}$$

- if decay products thermalise ($m_\sigma \ll T(j_{\rm NP})$)

$$\rho_H(j_{\rm NP} + \Delta j) \approx \rho_H(j_{\rm NP}) \left[1 + \frac{1}{g_*} 0.01357\, \Delta j\right]$$

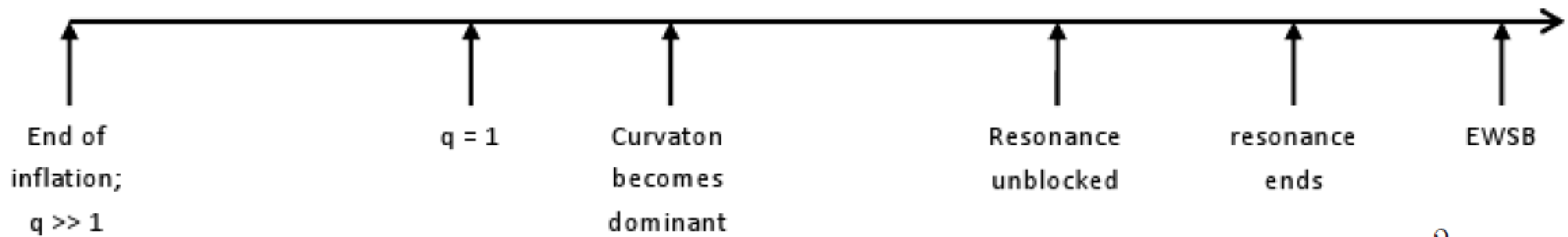
but: for a range in parameters, thermal blocking persists until electroweak symmetry breaking

don’t know what happens after that – assume that the curvaton decays

note: EWSB is not a phase transition but a smooth cross-over

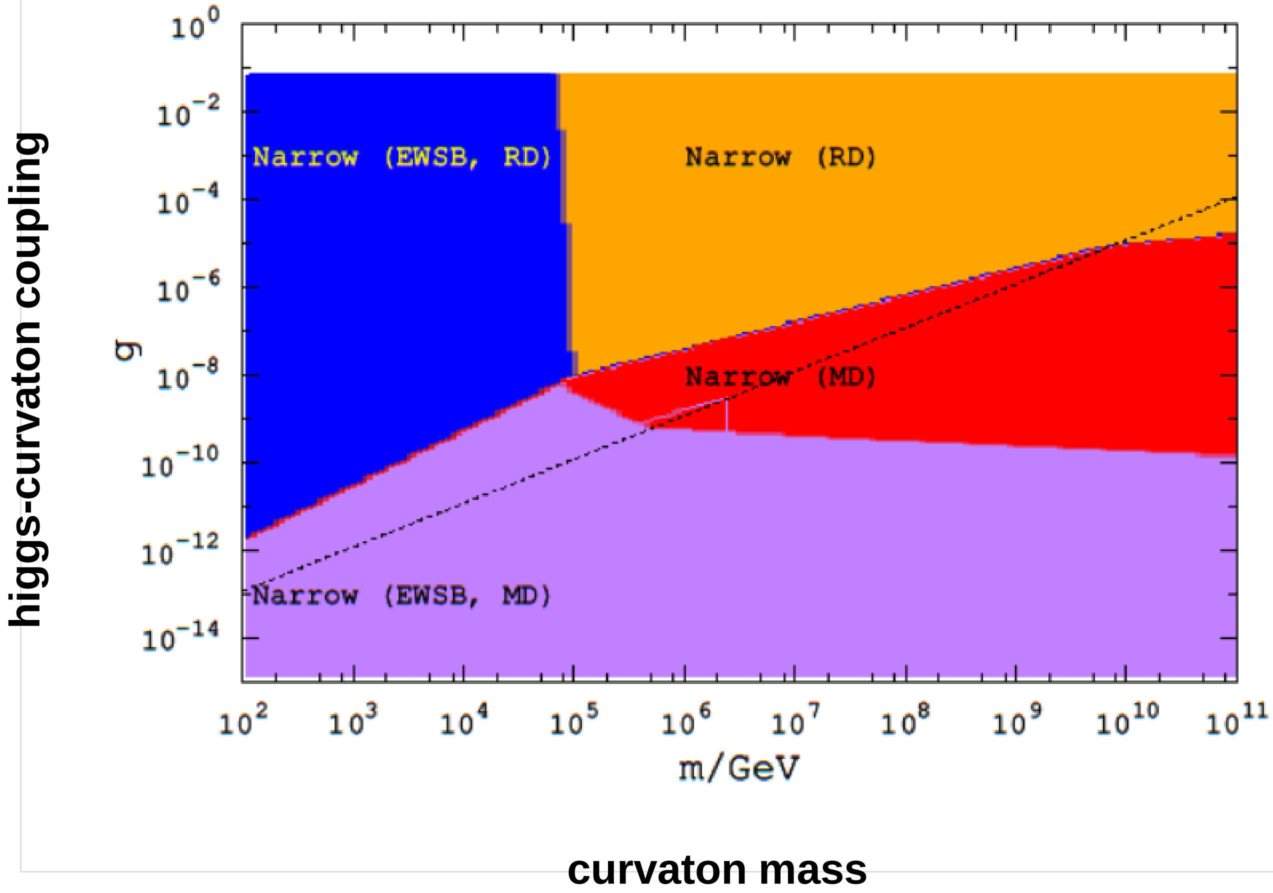
Possible timescales

- e.g. narrow resonance in matter-domination



- depends on resonance parameter $q \equiv \left(\frac{g\sigma(t)}{2m}\right)^2$
- q decreases with time
- narrow resonance: $T_{\rm NP} = \frac{m_\sigma(1+\mathcal{O}(q))}{g_T}$
- narrow resonance energy transfer:

$$\Delta j \simeq -\frac{\log(g^2\, q^{1/2}(j_{\rm NP}))}{\pi q(j_{\rm NP})}$$



higgs-curvaton coupling
g
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
Narrow (EWSB, RD)
Narrow (RD)
Narrow (MD)
Narrow (EWSB, MD)
10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11}
m/GeV
curvaton mass

MORE DETAILS ...

KE, Lerner, Rusak

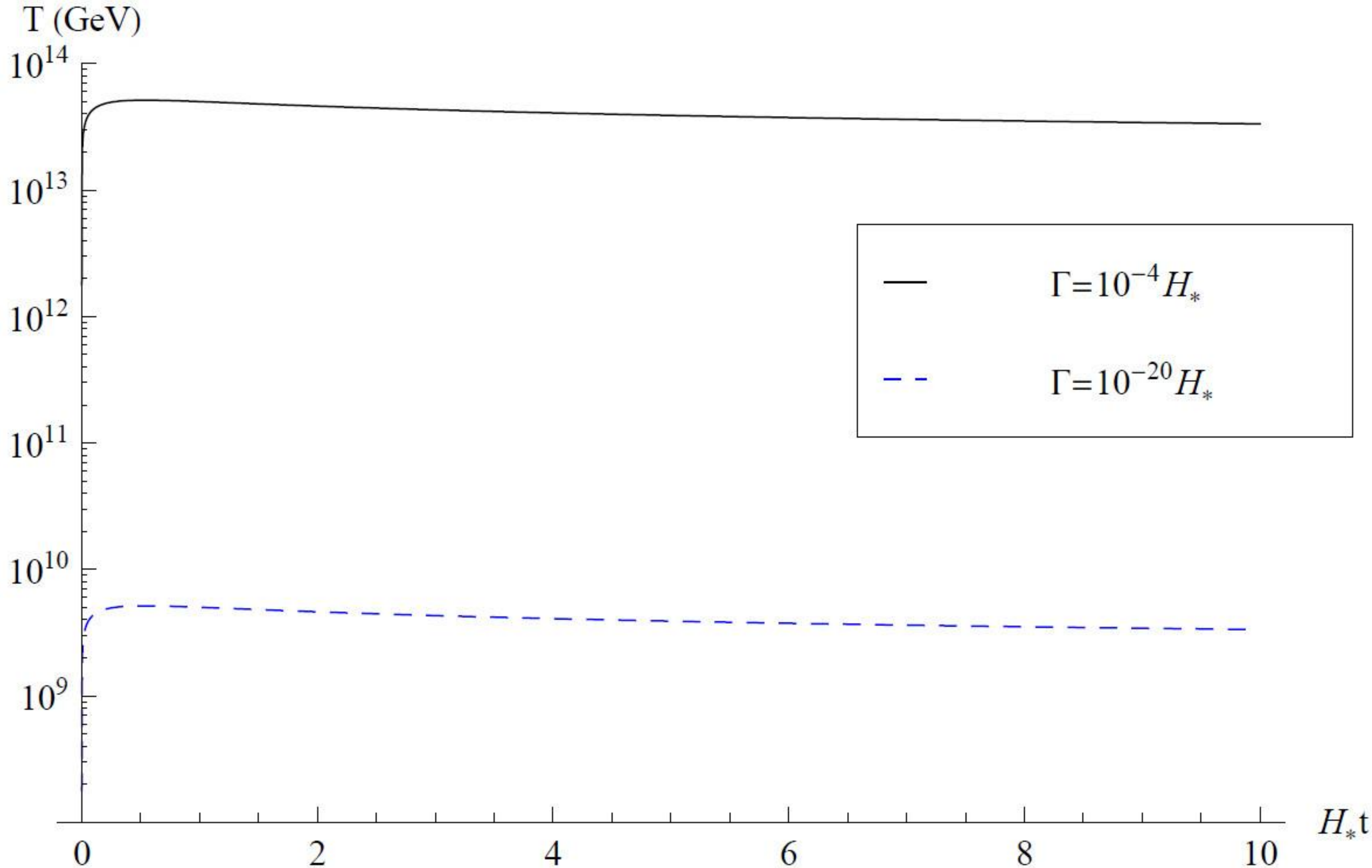
What actually happens at the onset of inflaton oscillation?

Inflaton decay not instantenous – radition background builds up

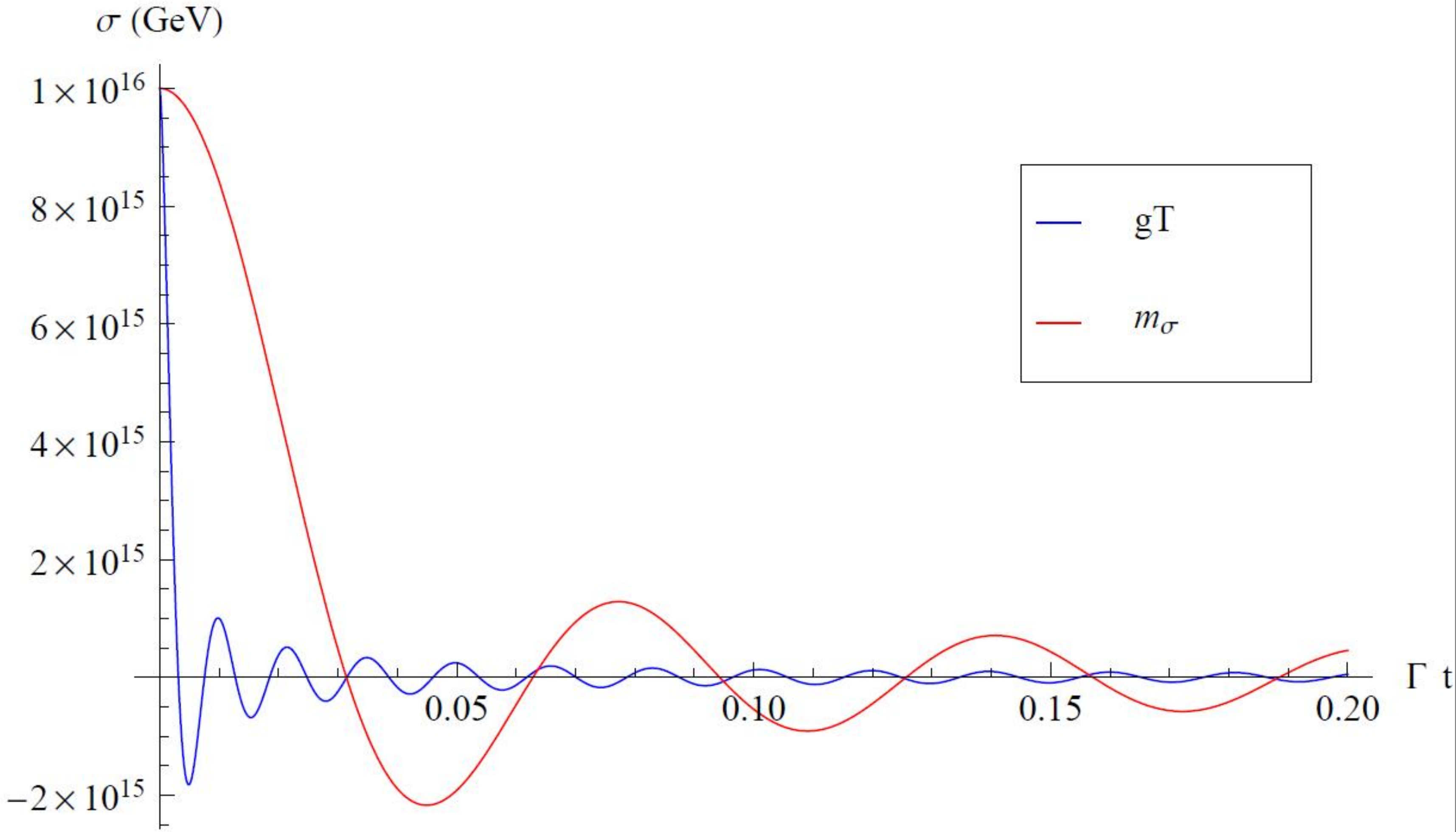
$$\rho_{\inf} = 3M_P^2 H_*^2 \left(\frac{a}{a_0}\right)^{-3} e^{-\Gamma t}$$

$$\rho_{SM} \approx \tfrac{6}{5} M_P^2 H_* \Gamma a^{-4} \left[a^{5/4} e^{-\Gamma t} - 1\right]$$

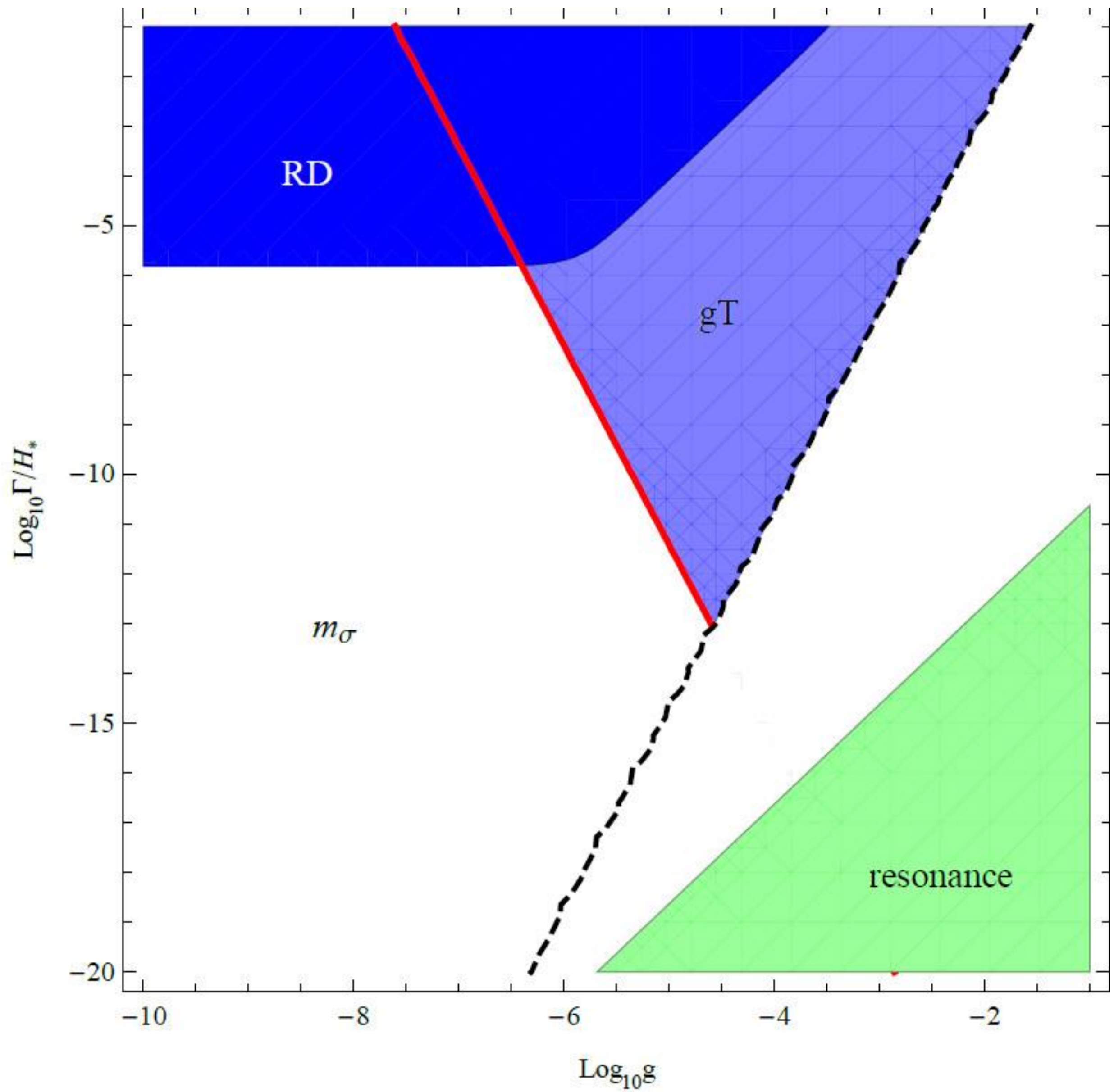
$$T_{\max,\, SM} \approx 0.330 \left(M_P^2 H_* \Gamma\right)^{1/4}$$



T (GeV)
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
$\Gamma=10^{-4}H_*$
$\Gamma=10^{-20}H_*$
0
2
4
6
8
10
H_*t



σ (GeV)
1 × 10^16
8 × 10^15
6 × 10^15
4 × 10^15
2 × 10^15
−2 × 10^15
0.05
0.10
0.15
0.20
Γ t
gT
m_σ



RD
gT
m_σ
resonance
$\mathrm{Log}_{10}\Gamma/H_*$
$\mathrm{Log}_{10}g$
−5
−10
−15
−20
−10
−8
−6
−4
−2