Decay of the Higgs and other spectators after inflation

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inflation

$$H_* \approx const.$$

dynamics unknown

slow rolling scalar(s)?

light scalar spectators exist

$$m << H_*$$

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

example: the higgs

others? – the curvaton

contents:

spectator dynamics

1. during
2. after

inflation

spectators

can play a dynamical role after inflation

1. because of their field perturbations

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

-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

-relaxation to (the correct) vacuum

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

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

N = # efoldings

inflationary fluctuations

massless field

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

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:

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

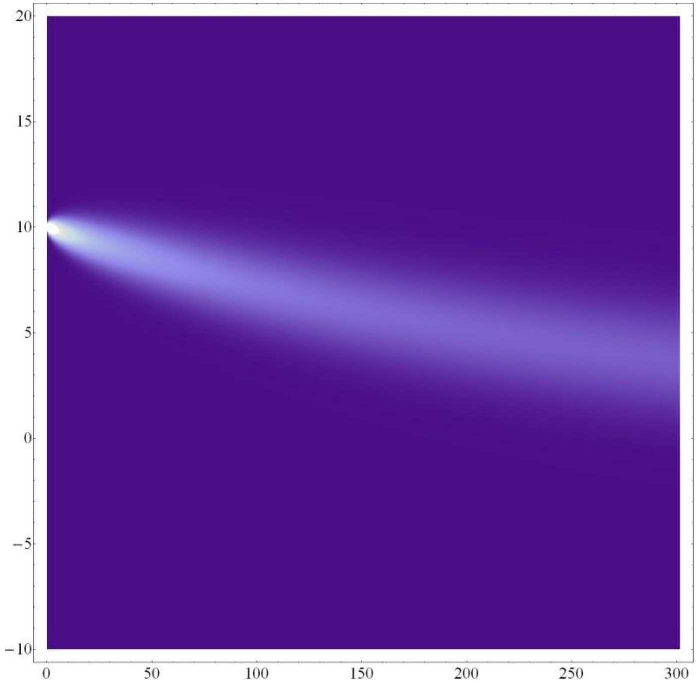
example

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

$m = 0.01H$

KE, Lerner, Taanila, Tranberg

σ / H



N

relaxation time

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

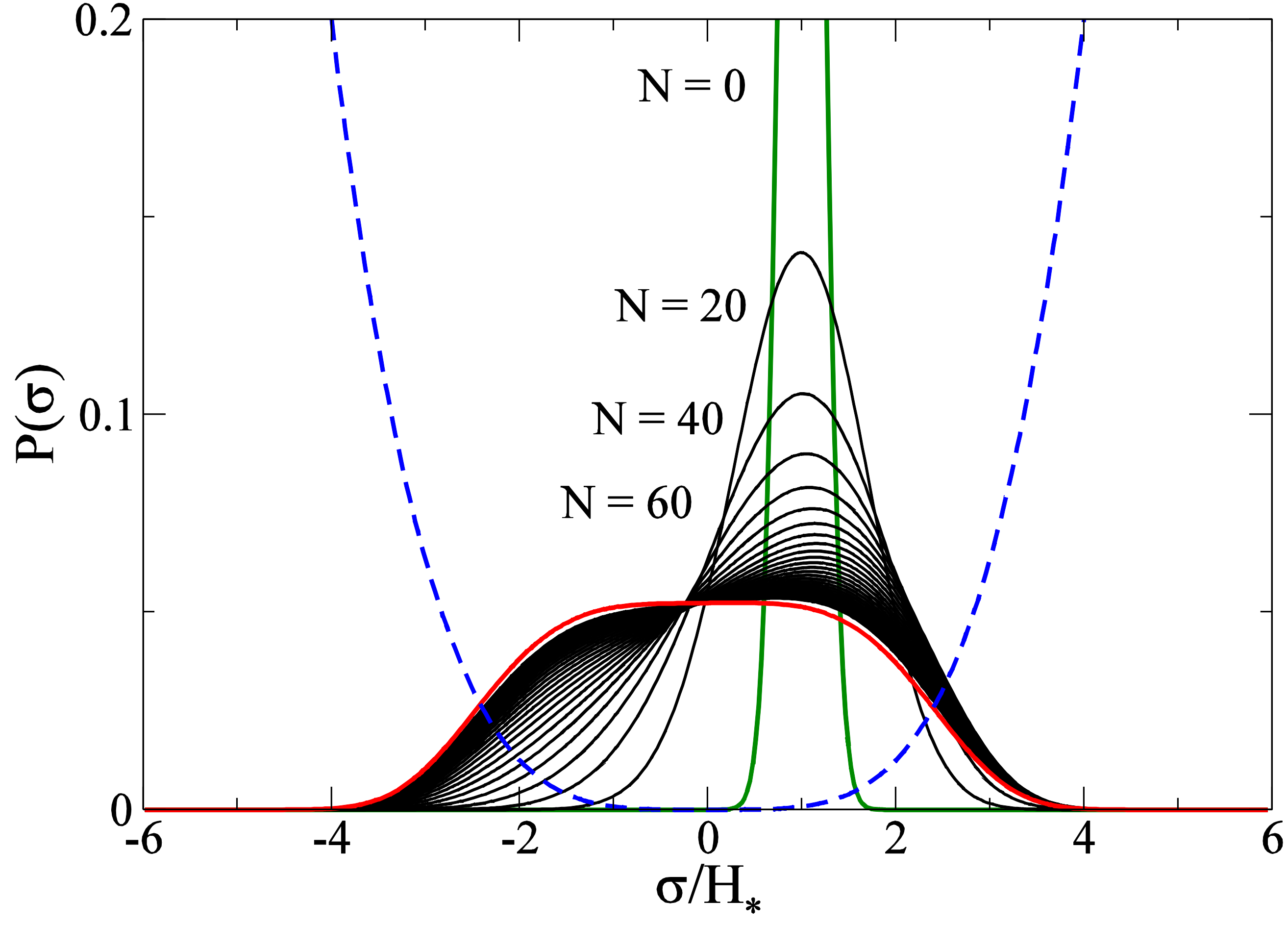
decoherence time

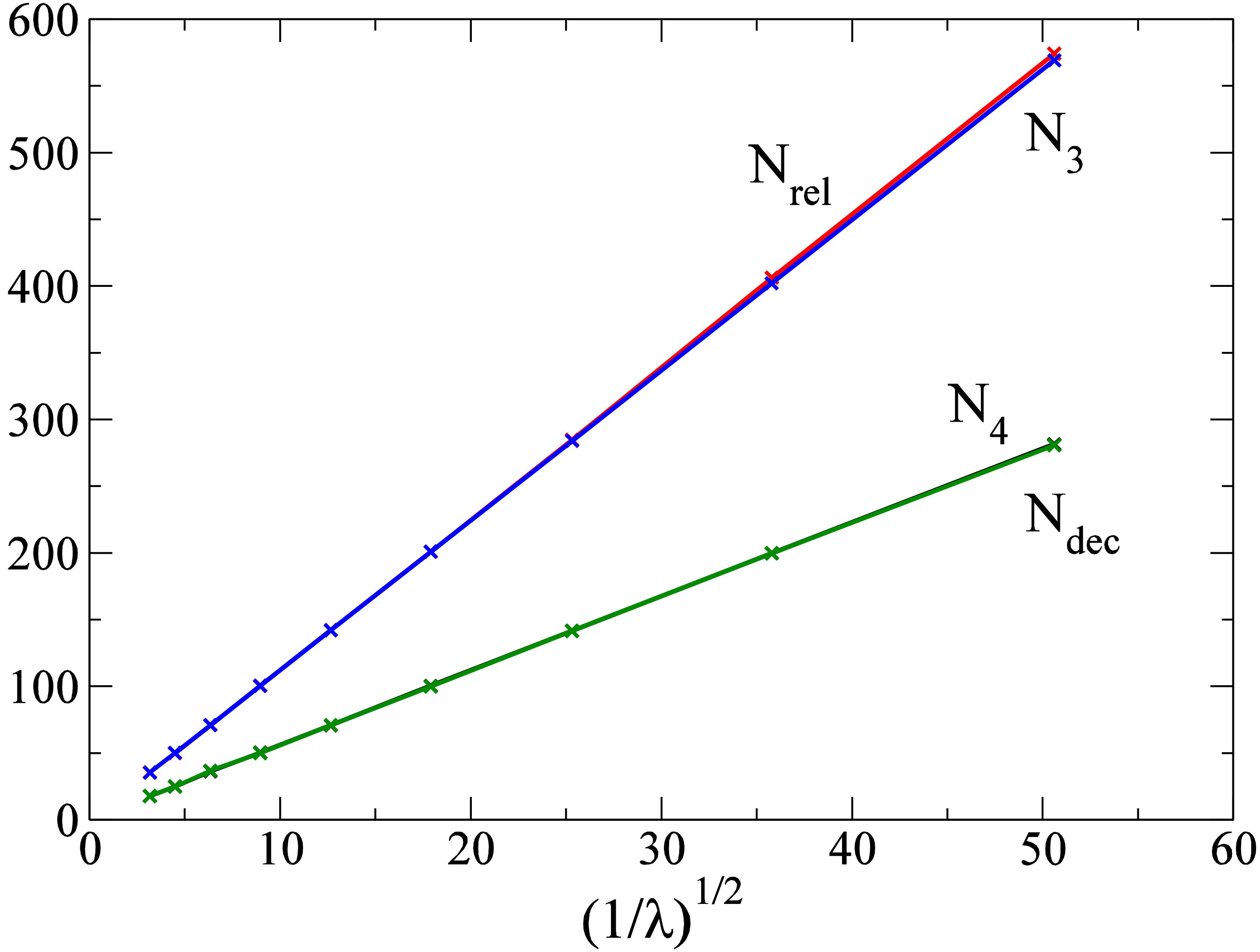
$$N_{dec} = \frac{3H_*^2}{2m^2}$$

quartic potential

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

$\lambda = 0.003125$





600
500
400
300
200
100
0
0
10
20
30
40
50
60
(1/λ)^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 $$m_{h_*}^2 \approx V''(h_*) = 0.40\lambda^{1/2} H_*^2 = 0.04 H_*^2$$

the Higgs condensate

at equilibrium after inflation: $h_* \approx 0.36\lambda^{-1/4} H_* \approx 1.1 H_*$

"typical value"

how does the condensate decay?

1. **inflaton decays first → thermal background (assuming thermalization)**

more complicated

2. **Higgs decays first (in matter dominated universe)**

if Higgs is to modulate inflaton decay, it can do so only while the condensate is still there

MATTER DOMINATION

KE, Meriniemi, Nurmi

after inflation

Higgs starts to move ... and becomes effectively massive at

$$\frac{H_{\rm osc}}{H_*} \sim \frac{1}{4}\lambda_*^{3/4}$$

⇨ oscillations $t_{\rm osc} \lesssim \mathcal{O}(10^2) H_*^{-1}$

decay rates depend on the value of the Higgs background field

m_h, m_f , m_G ~ h

perturbative decays

to gauge bosons: kinematically blocked until

$$t \sim \lambda(H_*)^{-3/8} \left(\frac{H_*}{10^2\mathrm{GeV}}\right)^{3/2} H_*^{-1}$$

not efficient unless $H_* \ll 10^5$ GeV.

perturbative decays (cont)

to fermions: top channel kinematically blocked, others ok

$$\Gamma(h \to bb) = \frac{3\sqrt{3\lambda}y_b^2 h_{\rm osc}}{16\pi}\left(1 - \frac{2y_b^2}{3\lambda}\right)^{3/2} \sim 10^{-6}\lambda_*^{3/4}H_*$$

takes >> 10^6 Hubble times

not efficient

others (to gluons, photons) even less efficient

non-perturbative decays

resonant production of gauge bosons

W's in the unitary gauge: (abelian approx.)

$$\ddot{\mathcal{W}}^{\pm}_{\mu}(z,k) + \omega_k^2 \mathcal{W}^{\pm}_{\mu}(z,k) = 0\,, \qquad \omega_k^2 = \frac{k^2}{a^2 \lambda h_{\rm osc}^2} + q_W \frac{h(z)^2}{h_{\rm osc}^2} + \Delta\,. \qquad q_W = \frac{m_W^2(t)}{\lambda h^2(t)} = \frac{g^2}{4\lambda}$$

$= 0$ for matter domination

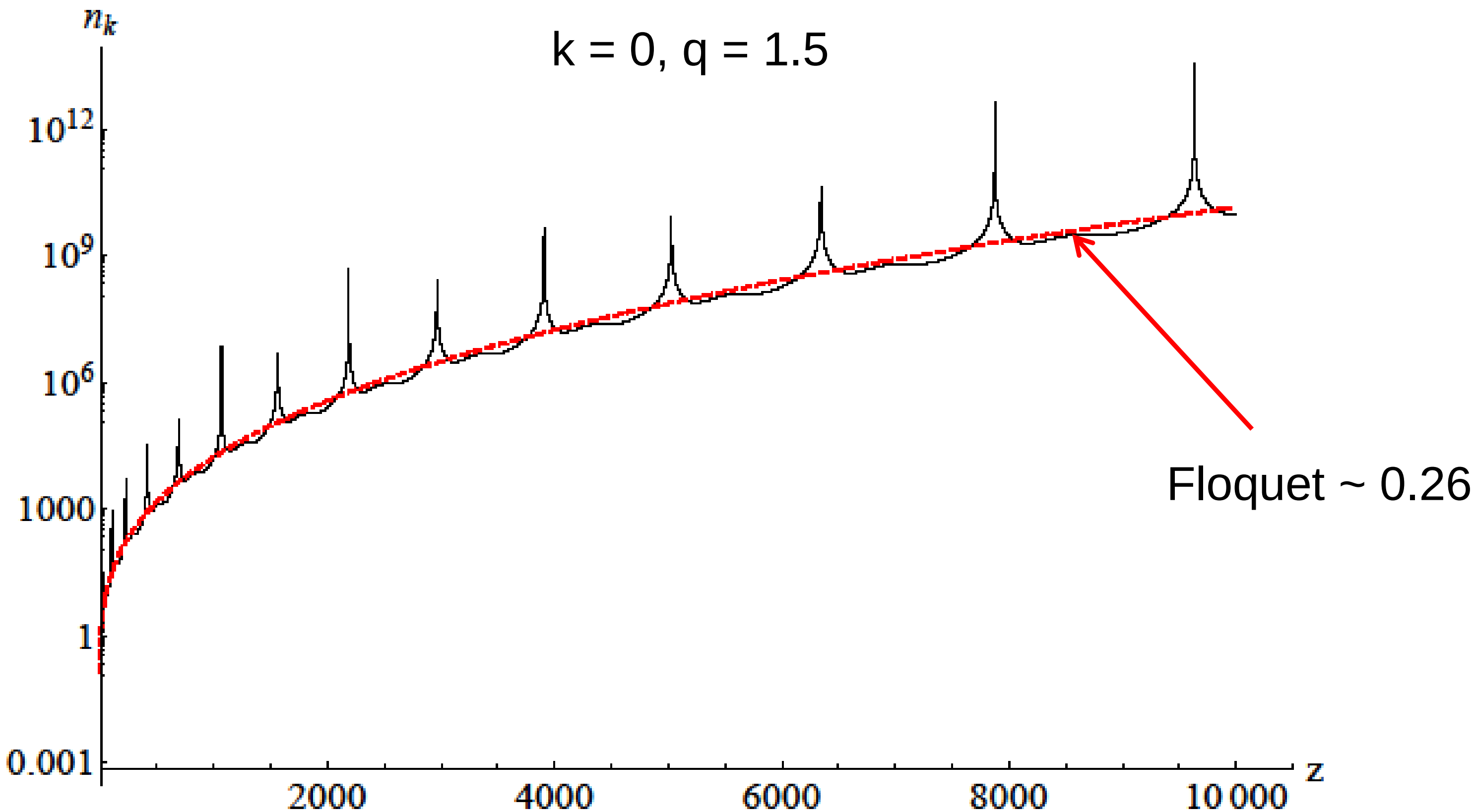
Higgs eq of motion

$$\frac{\ddot{h}}{h_{\rm osc}} + 3\frac{H}{\sqrt{\lambda} h_{\rm osc}} \frac{\dot{h}}{h_{\rm osc}} + \left(\frac{h}{h_{\rm osc}}\right)^3 = 0$$

Table 1: Numerical values of the characteristic exponent μ_k of $k = 0$ modes for a set of different values of H_*.

H_*/GeV	λ	$(q_W,\ \mu_k)$	$(q_Z,\ \mu_k)$
10^4	0.09	(1.1, 0.14)	(1.5, 0.26)
10^6	0.04	(2.3, 0.25)	(3.2, 0.00)
10^8	0.02	(4.4, 0.00)	(6.2, 0.14)
10^{10}	0.005	(16, 0.22)	(24, 0.00)

Example: resonant Z production



$$z = \sqrt{\lambda h_{\mathrm{osc}}^2}(t - t_{\mathrm{osc}})$$

no backreaction

resonant production of fermions, Higgses: inefficient

estimation of the end of decay time

effective Higgs mass generated by Ws starts to affect Higgs dynamics:

$$m^2_{h(W)} = 2q_W \lambda \left\langle W^{\mu+} W^-_\mu \right\rangle = 2q_W \lambda \left\langle W^2 \right\rangle$$

integrate up to a cut-off scale

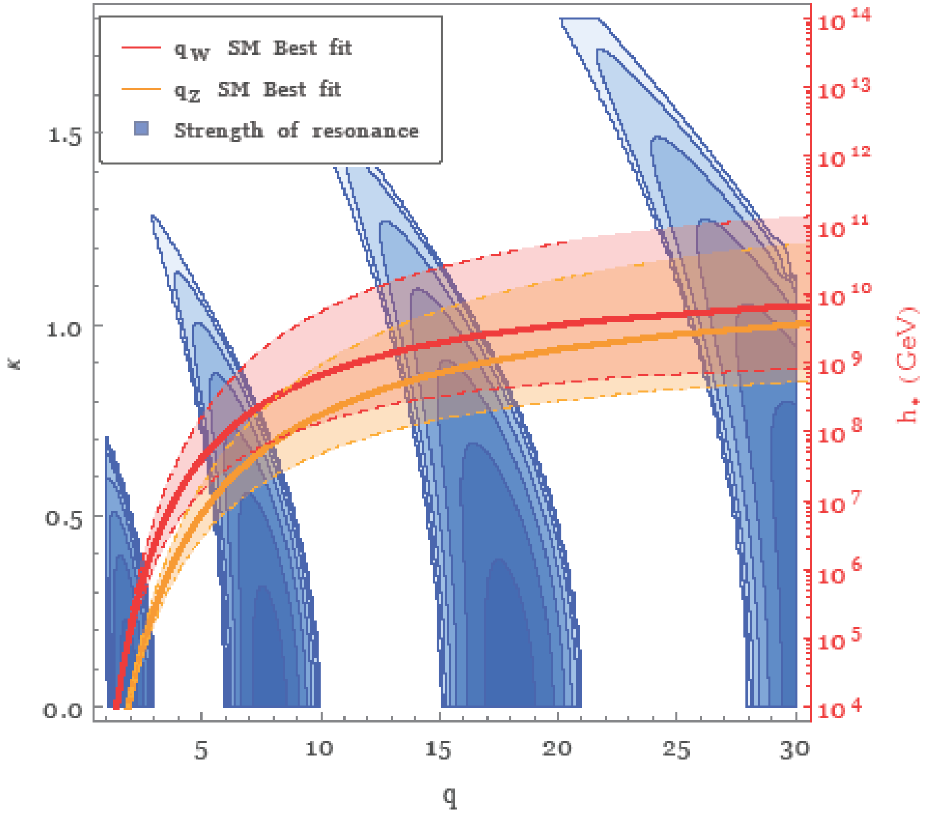
find when $m^2_{h(W)} \approx m^2_h$

H_*/GeV	λ	$H_{\mathrm{osc}}/H_{\mathrm{dec}}$	n_ϕ^{dec}
10^4	0.09	370	1 000
10^6	0.04	360	1 700
10^8	0.02	630	5 100
10^{10}	0.005	340	7 700

NB: resonant production cannot deplete the condensate completely

resonance structure

KE, Nurmi, Rusak



for SM, the resonance is broadish

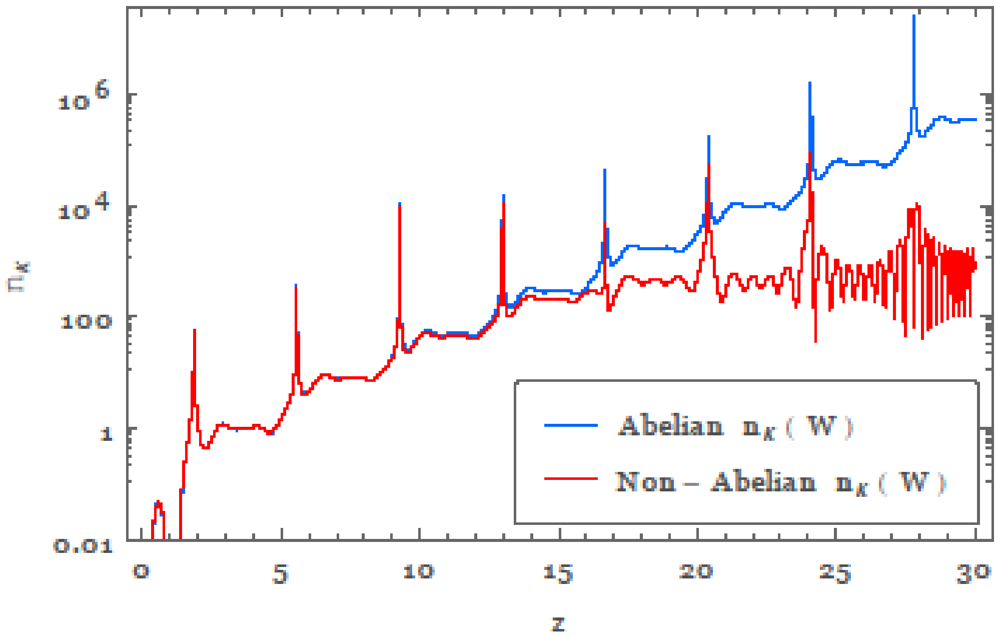
best fit SM: $q_W = 18$, $q_Z = 29$

role of non-abelian terms?

KE, Nurmi, Rusak

in the Hartree approximation

(non-linear terms → vevs of linear solutions)



$H = 10^{14}$ GeV

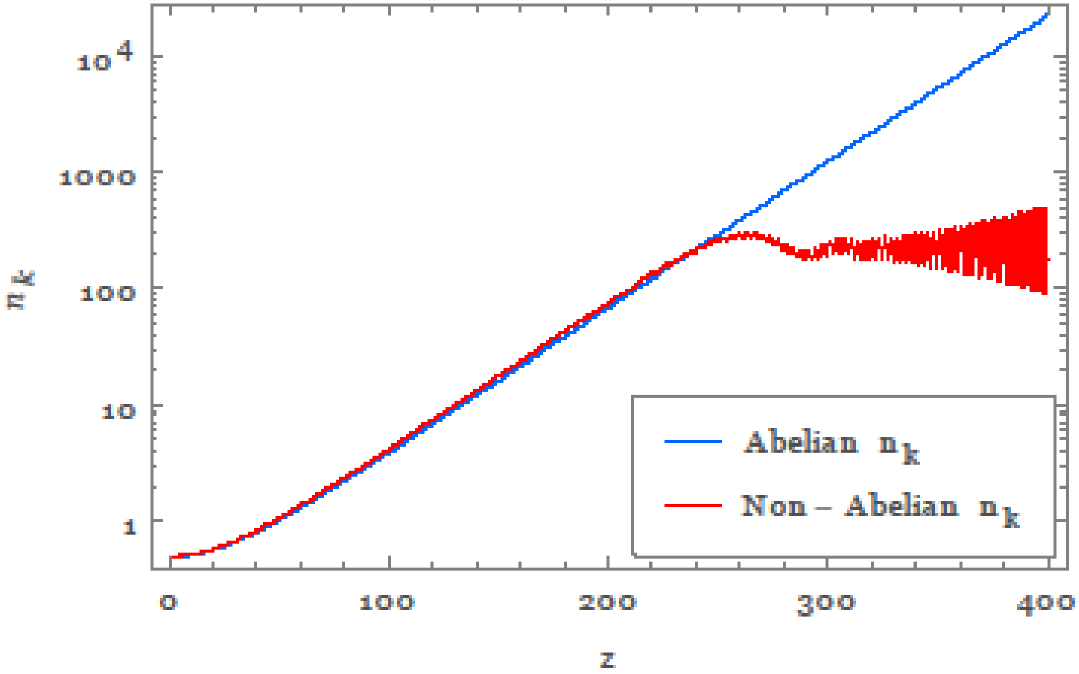
but: backreaction on Higgs mass kicks in earlier

abelian a good approximation at early stages

the opposite case:

narrow resonance (BSM)

example q = 0.1



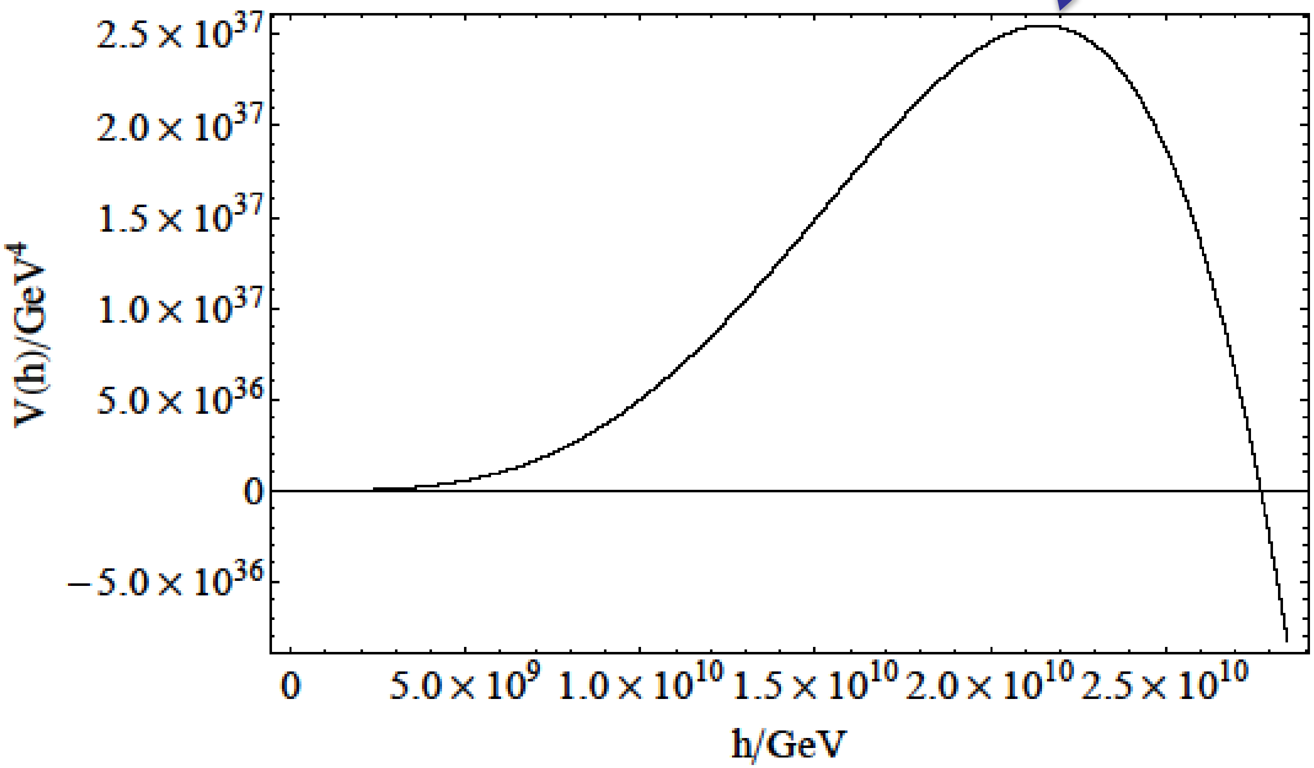
need lattice simulations

Higgs and large H

how to reach SM vacuum?

$$\lambda(h_{\max}) + \frac{\beta(h_{\max})}{4} = 0$$

very sensitive to RGE

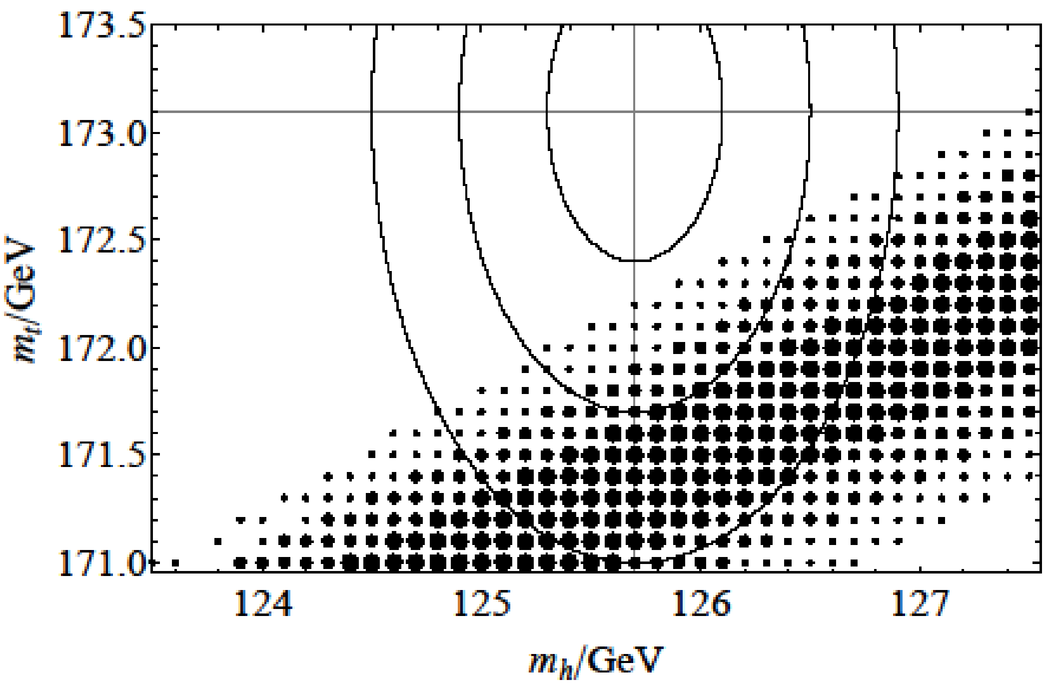


$$V_{\rm SM}^{1/4}(h) \ll \left(3M_P^2H^2\right)^{1/4} \simeq 1.6\times 10^{16}{\rm GeV}$$ ← BICEP2

Espinosa, Giudice,Riotto
Kobakhidze, Spencer-Smith
KE, Meriniemi, Nurmi

fluctuations in kinetic energy ~ H^4

wrong vacuum unless $V^{1/4}(h_{\rm max}) \gtrsim 10^{14}{\rm GeV}$



KE, Meriniemi, Nurmi

false vacuum during inflation?

tunneling to the top of V (= min ΔF)

1. stochastic epoch N < 20
2. classical drift N < 70
3. h → 0: quantum fluctuations dominate

mean field reaches equilibrium value if inflation lasts > O(100) efolds

$\xi R h^2$ → RGE? 1407.3142

so what?

Higgs exists, inflation (probably) took place

⇨ all of this actually happened

for other spectators exact decay time may matter much

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

KE, Sloth
Moroi, Takahashi
Lyth, Wands

the curvaton

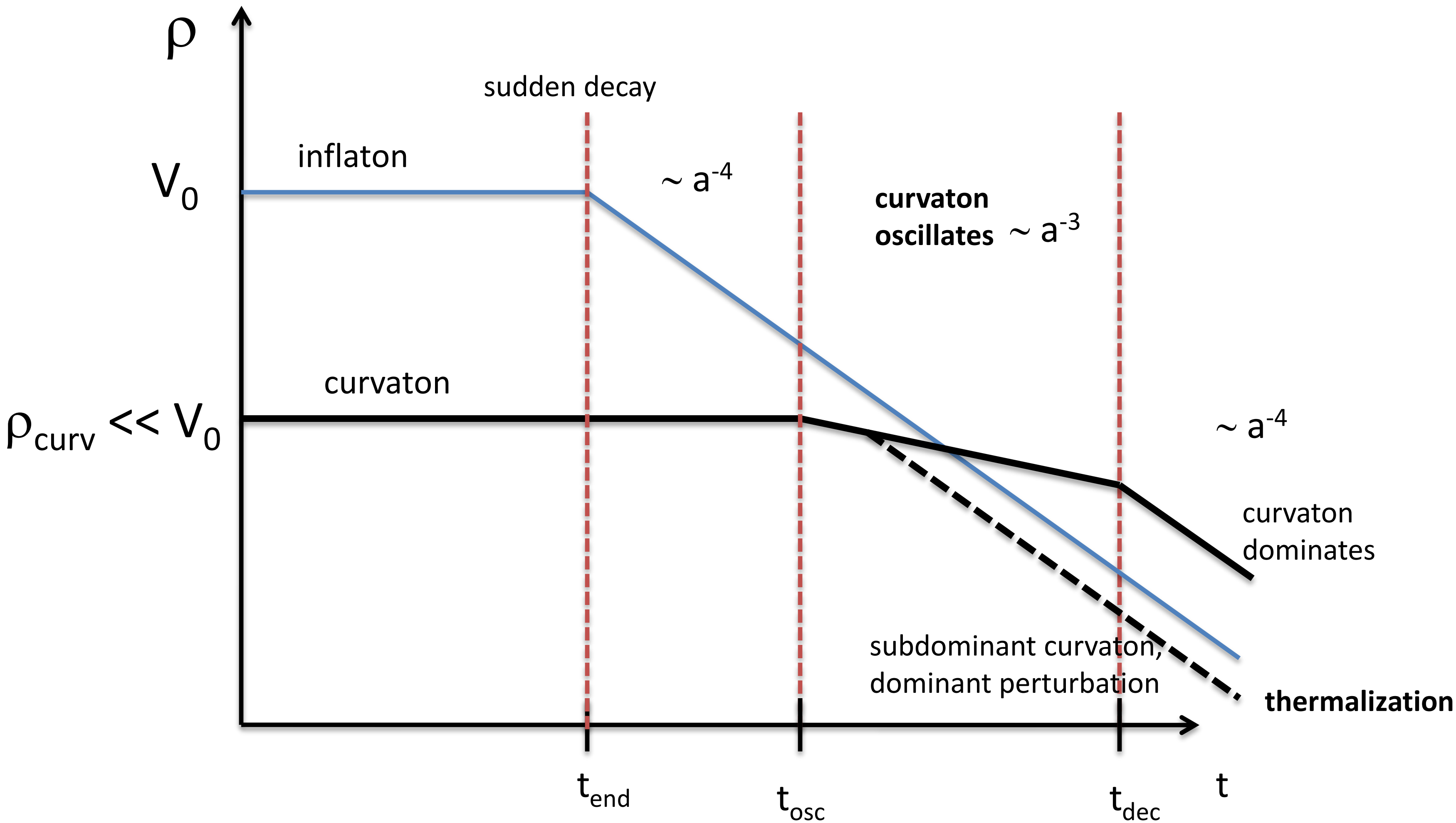
curvature perturbation generated after inflation

require

- curvaton decay products thermalize with radiation

⇨ initial curvaton isocurvature perturbation δσ(x) is converted to an adiabatic perturbation

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



curvaton perturbation remains ~ constant (depends on potential)

perturbation grows

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

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

initial value σ_* not fixed by mean field fluctuations (?)

Lerner, Melville 1402.3176

simplest potential

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

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

large non-gaussianity = subdominant curvaton

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

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 $m^2(H) = g_T^2 T^2,\ g_T^2 \approx 0.1$

resonant production of higgs particles

- 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)

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

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

dispersion relation

- Higgs equation of motion:

j = time = # zero crossings

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

- effective frequency:

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

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

Adiabaticity violated if...

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

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

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

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 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

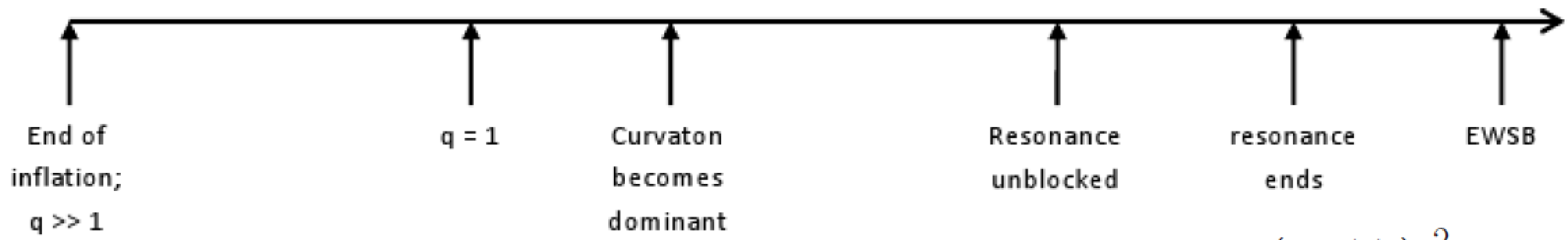
$$f(q) \equiv 1 + \frac{2+e}{\exp\left(g_T\, q^{1/4} - 1\right)}$$

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

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

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:

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

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

treatment of thermal effects: see also

Harigaya, Mukaida, JHEP 1405 (2014) 006
Mukaida, Nakayama, Takimoto, JCAP 1406 (2014) 013

Complete minimal curvaton-Higgs model

instant reheating

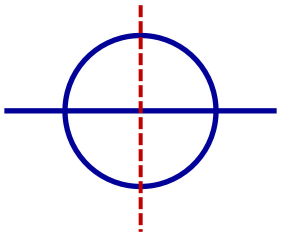
KE, Lerner, Takanashi

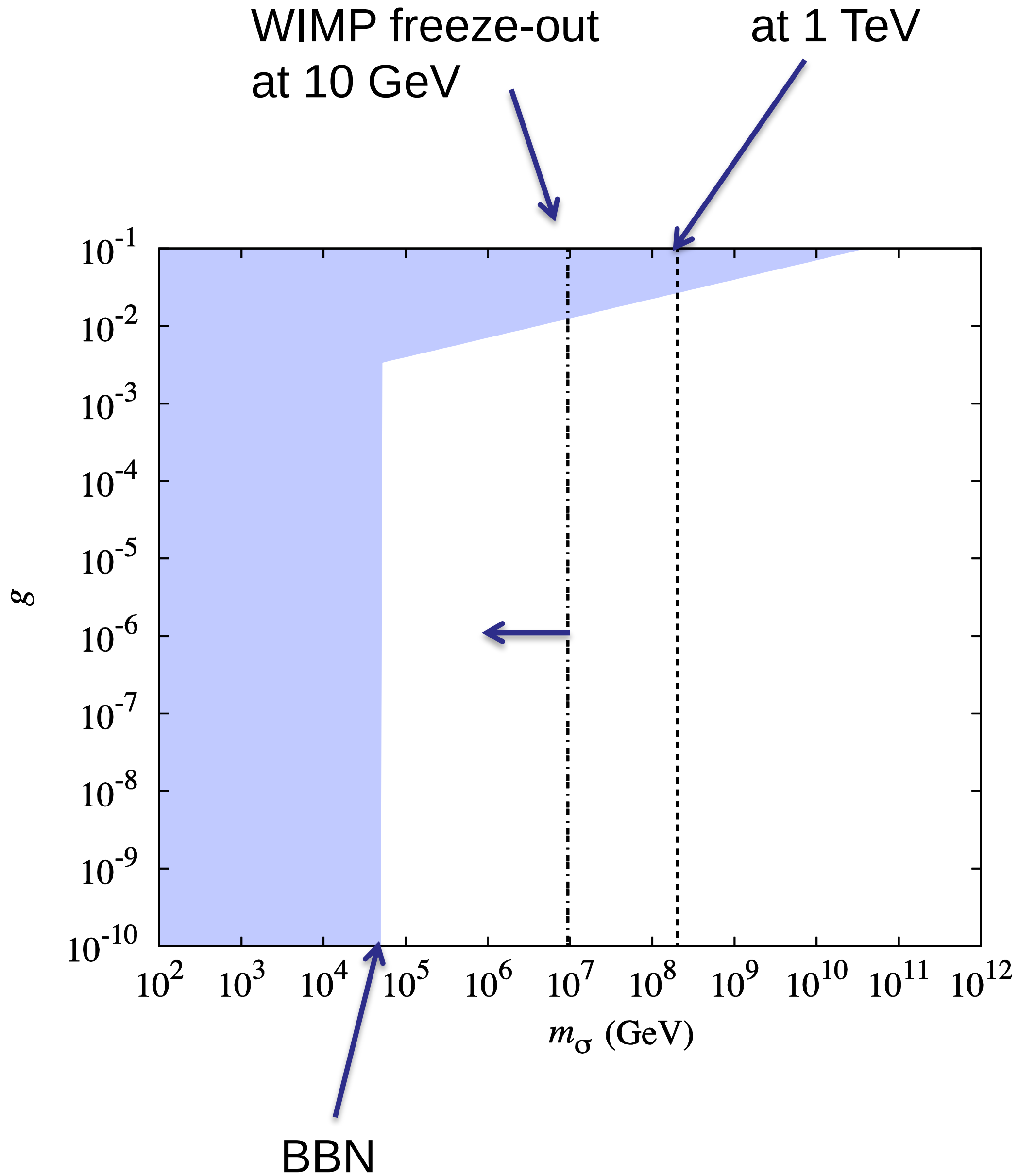
+ CW at 1 loop

+ dim 5 operators $\mathcal{L}_5 \propto \frac{1}{M_P} \sigma \bar{f} \Phi f \implies \Gamma_5 \approx \frac{m_\sigma^3}{M_P^2}$

responsible for completing the decay

+ evaporation by thermal scattering

Im 



WIMP freeze-out
at 10 GeV
at 1 TeV
BBN
g
m_σ (GeV)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12}

CONCLUSIONS:

-light spectators likely to exist (Higgs, curvatons, ...)

-how do they settle in their vacua?
thermal effects important

-dynamics depend on the inflationary Hubble scale

-High scale inflation: cosmology constrains particle physics?