Roadsigns for Cosmology

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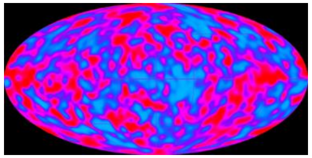
modern cosmology: prehistory

1. **Big Bang nucleosynthesis late 1970s**
2. **Guts & Guth: inflation 1980s** (Starobinsky R^2)

problems of the ’80s:

has there been a Big Bang? US astronomers in ’59: yes 33%
’80: yes 69%

COBE DMR ’91



the age crisis

$\Omega = 1 \rightarrow t = 9$ Gyrs

SN → DE ’97

Rapid Phase Transitions in Primordial Inflation With Flat Supergravity Potentials
K. Enqvist, Dimitri V. Nanopoulos (CERN). Mar 1984. Phys.Lett. 142B (1984) 349-354

1. - INTRODUCTION

The inflatory Universe[1),2)] appears to offer the only natural solution to the horizon and flatness problems of cosmology. By now, it is also evident that the early inflatory models based on grand unified theories (GUTs) with a Coleman-Weinberg-type symmetry breaking [3)] by radiative corrections have severe problems. In de Sitter space, quantum fluctuations cause density perturbations that are scale-invariant when they re-enter the Friedmann-Robertson-Walker horizon[4)]. This is a more than welcome feature, since this is just the Harrison-Zel'dovich[5)] spectrum of fluctuations needed for galaxy formation. Unfortunately, in inflation based on GUT phase tran-

blah blah ....

We feel that two-component inflation is a promising candidate for unifying all the successful features of GUTs and cosmological inflation. It can lead to a reheating high enough to be compatible with both the limits on proton stability and the generation of the cosmological baryon asymmetry by superheavy ($M_{H_3} > 10^{15}$ GeV) Higgs triplets. Indeed, in two-component inflation, one can accommodate GUTs, supersymmetry and early cosmological inflation in one single consistent picture.

inflation

progress, prospects?

Starobinsky
Dimopoulos
Järv

-(seemingly) acausal correlations

-spectral index $n < 1$

dynamical order parameter

-running of n, tensor modes, NG, CMB polarization,

μ distortion, structure formation, ...

future CMB: Delabrouille

model building

-(slow roll) inflaton

-something else

e.g. Starobinsky inflation, extended gravity

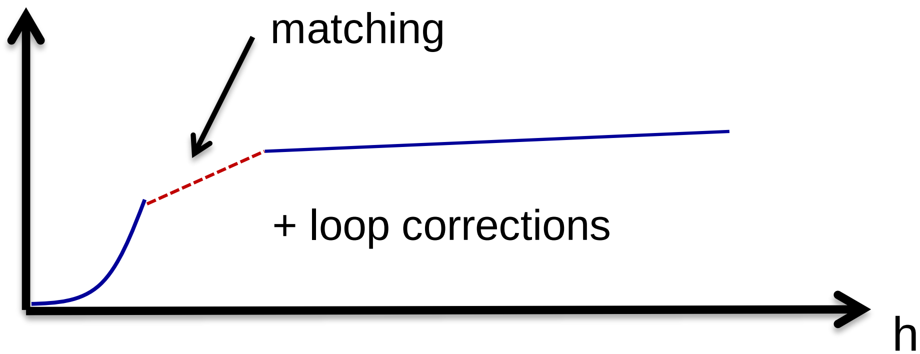
Inflation is for real

Higgs exists

large

$V \sim \lambda(h)h^4 + \xi h^2 R$

Higgs is the inflaton



metric/Palatini?
pert. unitarity?

RGE behaviour?

vacuum instability? very important for cosmology

Higgs is not the inflaton

$V \sim \lambda(h)h^4 + \xi h^2 R$

small

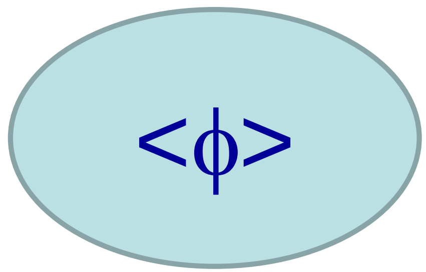
spectator during inflation

(near) massless scalars in an expanding background

⇒ stochastic treatment

(cf. Starobinsky)

1/H



ensemble of
Hubble patches

Perturbations: another story – e.g. curvatons

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

equilibrium pdf:

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

the Higgs

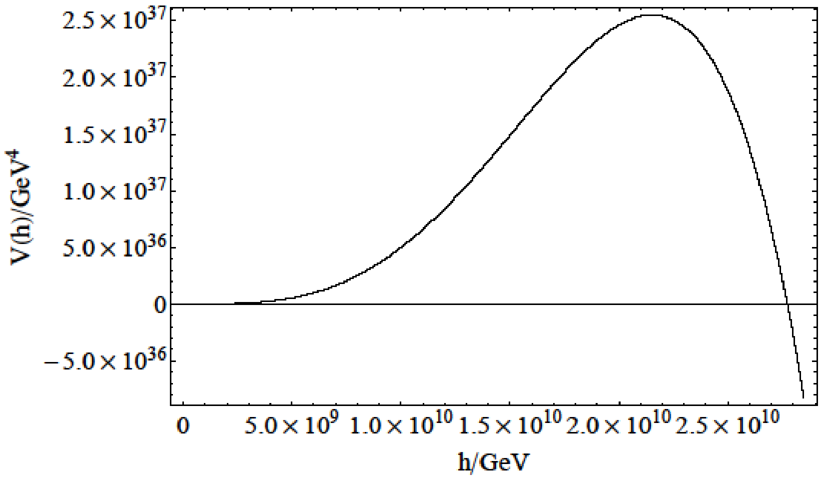
at equilibrium after inflation: $h_* \approx 0.36\lambda^{-1/4}H_* \approx 1.1H_*$

"typical value"

followed by condensate decay

very sensitive to RGE

vacuum instability?



fluctuate over the top

Grojean

-Higgs-inflaton mixing: over the top by via preheating – Lebedev
-Higgs portal models – fluctuations may help to determine the scale of inflation

Coupling the Higgs and the inflaton

KE, Lebedev, Karciauskas, Rusak, Zatta

$$L = L_{chaotic}(\phi) + L_{higgs}(h) - \tfrac{1}{4}\lambda_{h\phi}h^2\phi^2 - \tfrac{1}{2}\sigma_{h\phi}\phi h^2$$

preheating

tachyonic instability

$m = 1.3\times 10^{-6} M_{Pl}$

$V = \tfrac{1}{4}\lambda_h(h)h^4$

inflaton oscillates $\phi = \Phi(t)\cos(mt)$

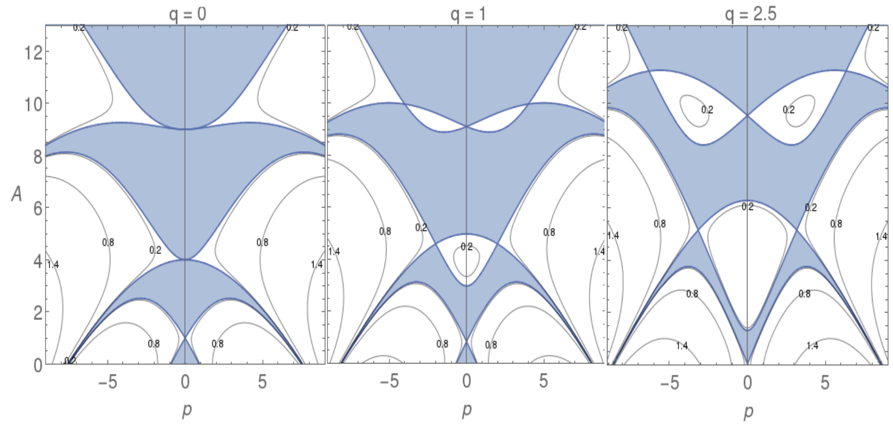
⇨ oscillating Higgs mass

$$\omega_k^2 = \frac{k^2}{a^2} + \sigma_{h\phi}\Phi\cos(mt) + \tfrac{1}{2}\lambda_{h\phi}\Phi^2\cos^2(mt) + 3\lambda_h a^{-3}\langle X^2\rangle$$

p q

$X_k = a^{3/2}h_k$

⇨ Whittaker-Hill
(= complicated Matthieu)



DARK MATTER

history: Bertone & Hooper, 1605.04909

XENON1T, Garbini; review Cirelli

Steigman & Turner ’84; Roszkowski et al 1707.06277

70s; Lee & Weinberg ’77

- WIMPs
- neutrinos
- inos
- axions
- gravitinos
- sterile neutrinos
- SIMPs
- FIMPs
- portals
- fuzzy
- wispy
- PBHs
- SIDM
- extra higgses
- Kaluza-Klein
- freeze-in
- freeze-out
- deep freeze, flash frozen, cryogenic, disney type frozen, ...

Bernal et al, 1706.07442

Garcia-Bellido, Dolgov

Tkatchev
Hambye
D’Amico
Jaeckel
Boiarskyi
Ibarra
Heikinheimo

NEED DIRECT OBSERVATION

DARK ENERGY

Euclid

Quintessence: Dimopoulos
beyond GR: Koivisto, Hassan, Frandsen

ΛCDM (with power law inflation)

deep stuff: Wetterich, quantum gravity

the smallest scales:

Frenk: grav lensing

Penarrubbia: grav field fluctuations

”missing satellites”: hydro

”too big to fail”: WDM? 2nd stage of inflation? DM-γ? PBHs?

Garcia-Bellido

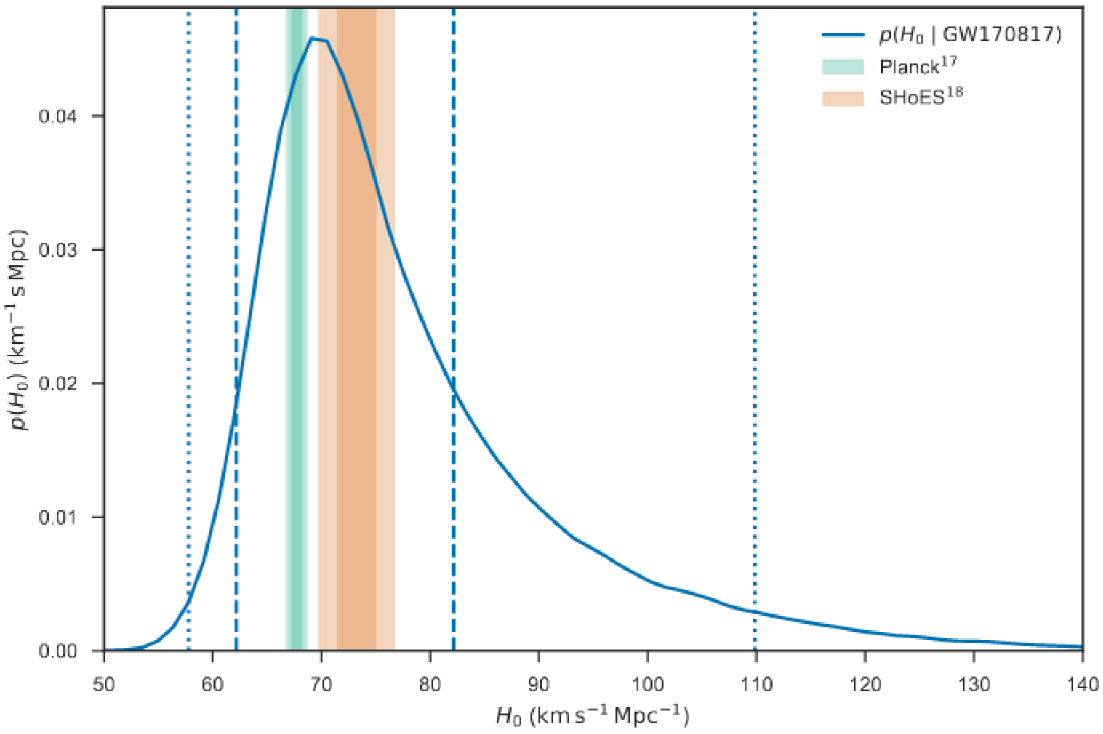
tension in σ_8?

exact isotropy, homogeneity? Tension in CMB dipole? Sarkar

tension in H_0?

Hubble rate

Abbott et al (LIGO) , arXiv:1710.05835 [astro-ph.CO]



”Standard sirens”

back reaction, new particle species, ...

GRAVITATIONAL WAVES

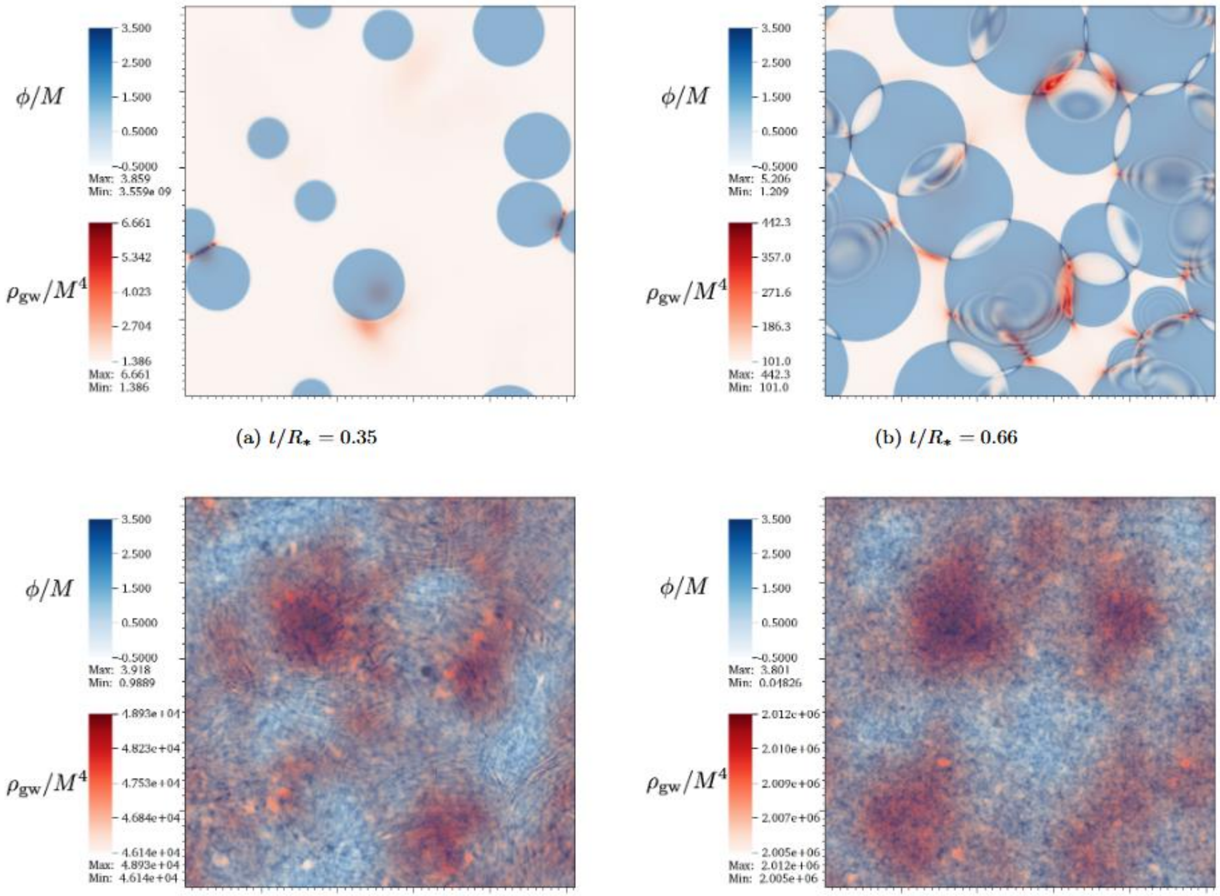
- preheating → inhomogeneous field configs → shear stresses → GW
- 1st order PT: colliding bubbles

Event	Time/s	Temp/GeV	f_0/Hz	
QCD phase transition	10^{-3}	0.1	10^{-8}	} cross-over
Higgs phase transition	10^{-11}	100	10^{-5}	
?	10^{-25}	10^{9}	100	LIGO
End of inflation	$\geq 10^{-36}$	$\leq 10^{16}$	$\leq 10^{8}$	

Inflation and topological defects: waves on all scales

Hindmarsh, Kubo, Rajantie

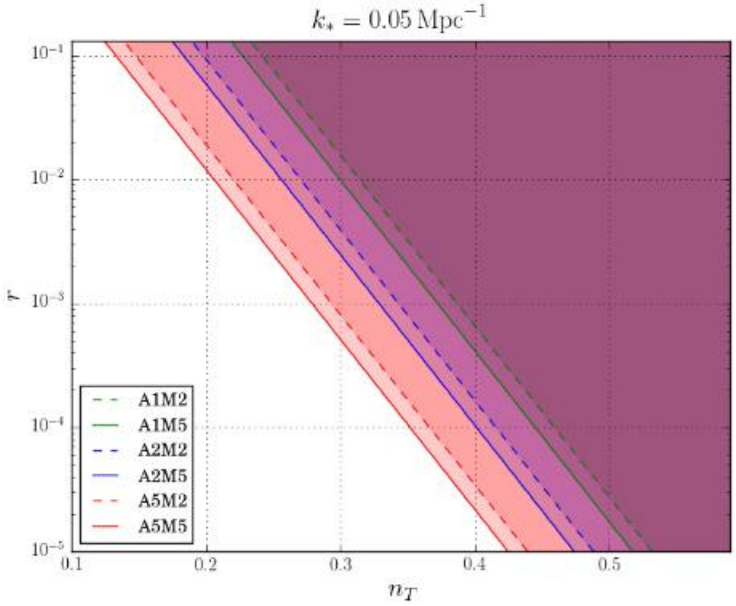
bubble collisions → gws



(a) $t/R_* = 0.35$ (b) $t/R_* = 0.66$

(c) $t/R_* = 2.50$ (d) $t/R_* = 7.8$

Cutting, Hindmarsh, Weir, 1802.05712

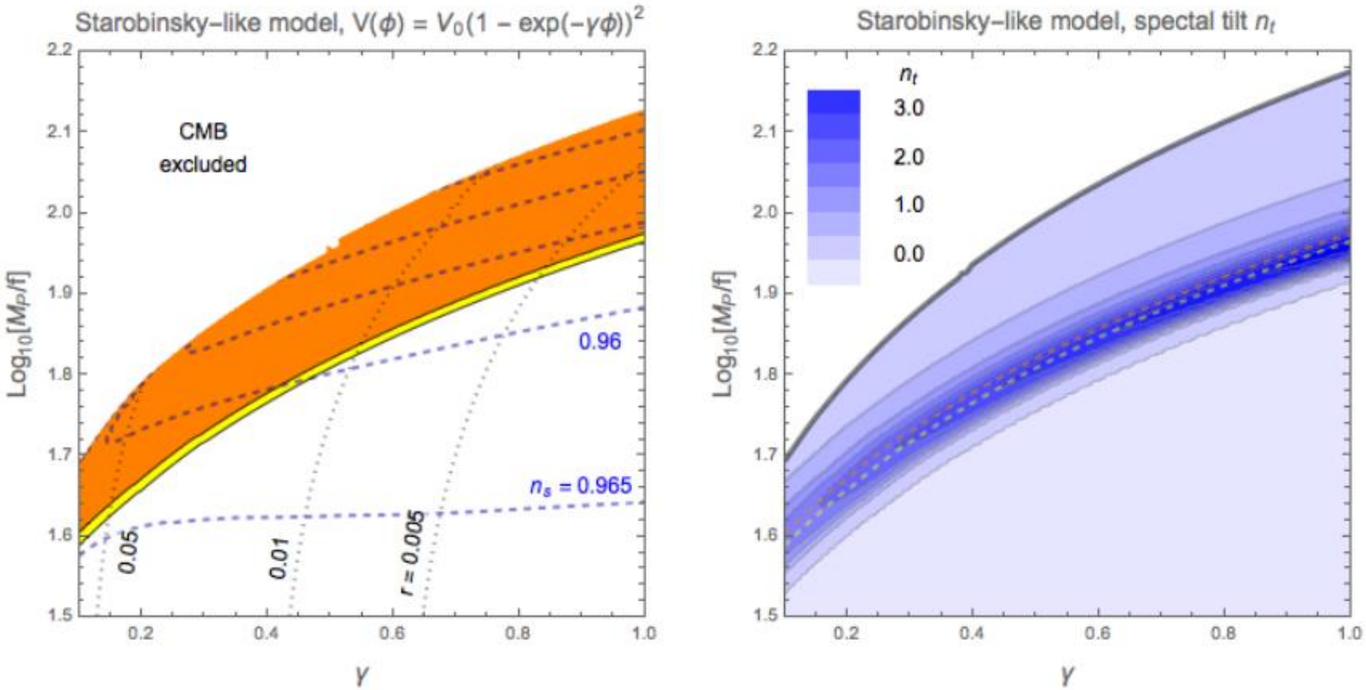


Bartolo et al, 1610.06481

-GW spectrum of PBHs formed at the end of inflation (e.g. hybrid model)

-GWs from spectator fields

-inflaton coupling to gauge fields (e.g. axion-like)



(a) CMB constraints and LISA sensitivity

(b) Spectral tilt

complementary between CMB and GW for n_s, f_{NL}, r, μ

Summary: Richard III