Imprints of the Early Universe dynamics in gravity wave spectrum

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Outline

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Initial singularity problem

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 = \frac{8\pi}{3} G\rho\,, \qquad p = w\rho\,, \;\; w > -\frac{1}{3}$$

dust: $p = 0$ — singular at $t = t_s$

$$\rho = \frac{\text{const}}{a^3}\,, \quad a(t) = const\cdot(t - t_s)^{2/3}\,, \quad \rho(t) = \frac{\text{const}}{(t-t_s)^2}$$

$$t_s = 0\,, \quad H(t) = \frac{\dot{a}}{a}(t) = \frac{2}{3t}\,, \quad \rho = \frac{3}{8\pi G}H^2 = \frac{1}{6\pi G}\frac{1}{t^2}$$

radiation: $p = \frac{1}{3}\rho$ — singular at $t = t_s$

$$\rho = \frac{\text{const}}{a^4}\,, \quad a(t) = const\cdot(t - t_s)^{1/2}\,, \quad \rho(t) = \frac{\text{const}}{(t-t_s)^2}$$

$$t_s = 0\,, \quad H(t) = \frac{\dot{a}}{a}(t) = \frac{1}{2t}\,, \quad \rho = \frac{3}{8\pi G}H^2 = \frac{3}{32\pi G}\frac{1}{t^2}$$

Entropy problem

$$\nabla_\mu T^{\mu 0} = 0 \;\longrightarrow\; \dot{\rho} + 3\frac{\dot{a}}{a}(\rho + p) = 0$$

for equation of state

$$p = p(\rho)$$

of the primordial plasma we obtain

$$-3d(\ln a) = \frac{d\rho}{p+\rho} = d(\ln s)$$

entropy is conserved in a comoving volume

$$sa^3 = \text{const}$$

For the visible part of the Universe: $S \sim s_{\gamma,0} \cdot l_H^3 \sim 10^{88}$

At the "Bang" for the Planck-size volume: $S_{BB} \sim s_{\gamma,0} \cdot l_{Pl}^3 \sim 100$

Horizon problem $l_H(t)$

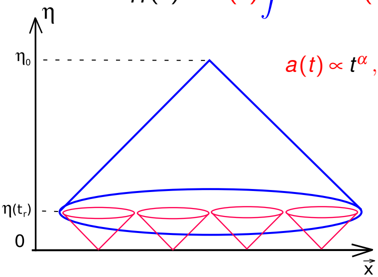
a distance covered by photon emitted at $t = 0$

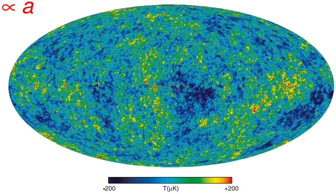
size of the causally connected part, that is the visible part of the Universe ("inside horison")

$$ds^2 = dt^2 - a^2(t)\,dx^2 = a^2(\eta)\left(d\eta^2 - dx^2\right) \qquad ds^2 = 0$$

$$l_H(t) = a(t)\int dx = a(t)\int d\eta = a(t)\int_0^t \frac{c\,dt'}{a(t')} \propto t \quad \propto 1/H(t)$$

$a(t) \propto t^\alpha$, $0 < \alpha < 1$, $L_{phys} \propto a$





$$l_{H_0}/l_{H,r}(t_0) \sim l_{H_0}/l_{H,r}(t_r)\,a(t_r)/a_0 \sim H_r/H_0\,a(t_r)/a_0 \sim \sqrt{1+z_r} \simeq 30$$

Flatness problem

- Take non-flat 3-dim manifold (general case)
- Curvature contribution to the total energy density behaves as $\rho_{curv}(t) \propto 1/a^2(t)$
- Then at present:

$$0.01 > \Omega_{curv} = \frac{\rho_{curv}(t_0)}{\rho_c} \sim 10^{-4} \times \frac{\rho_{curv}(t_0)}{\rho_{rad}(t_0)} = 10^{-4} \times \frac{a^2(t_0)}{a^2(t_*)} \frac{\rho_{curv}(t_*)}{\rho_{rad}(t_*)}$$
$$\sim 10^{-4} \times \frac{T_*^2}{T_0^2} \frac{\rho_{curv}(T_*)}{\rho_{tot}(T_*)}$$

- For hypothetical Planck epoch $T_* \sim M_{Pl} \sim 10^{19}$ GeV one gets

$$0.01 > \Omega_{curv} \sim 10^{60} \times \frac{\rho_{curv}(M_{Pl})}{\rho_{tot}(M_{Pl})}$$

Heavy relics problem (monopole problem)

- Let's introduce new stable particle X of mass M_X
- Imagine: at moment t_X they appear in the early Universe with small velocities (e.g. nonrelativistic) and small density $n_X(t_X) \ll n_{rad}(t_X)$
- Since $n_X \propto a^{-3} \propto n_{rad}$ then $n_X(t)/n_{rad}(t) \simeq \text{const}$

$$\frac{\rho_X(t)}{\rho_{rad}(t)} \sim \frac{M_X}{T(t)} \cdot \frac{n_X(t_X)}{n_{rad}(t_X)} \propto a(t)$$

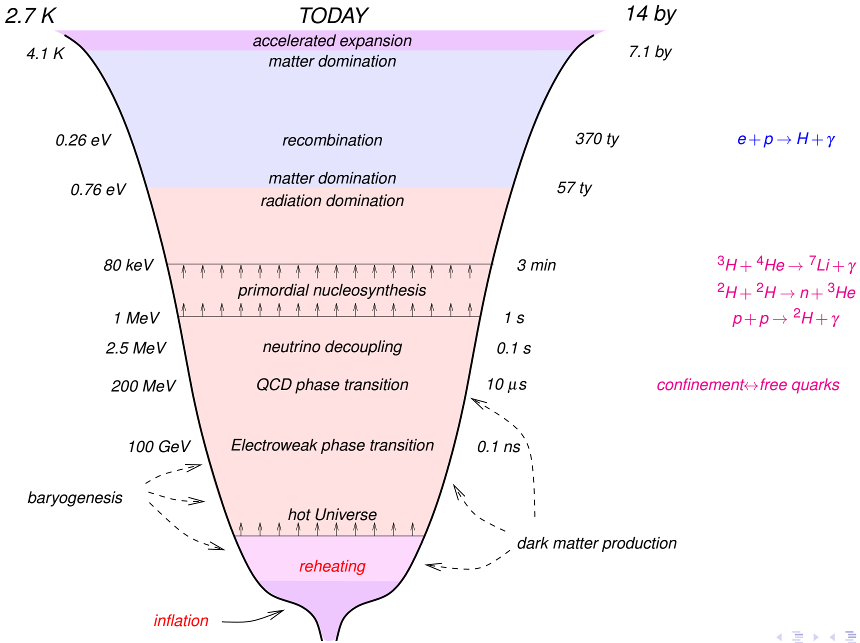
- Radiation dominates at least while $1\,\text{eV} \lesssim T \lesssim 3\,\text{MeV}$
- Therefore even for $M_X = 10\,\text{TeV}$ we must require $n_X(t_X)/n_{rad}(t_X) \ll 10^{-12}$!!!
- In some SM extensions it is difficult to avoid heavy relics production: gravitational production, $M_X \sim H$, phase transitions. . .

Example: monopoles, produced "one per horizon volume", $n_X(t_X) = 1/l_H^3(t_X) = H^3(t_X)$; Then for its present contribution:

$$\Omega_X = \frac{\rho_X}{\rho_c} \sim 10^{17} \times \frac{M_X}{10^{16}\,\text{GeV}} \left(\frac{T_X}{10^{16}\,\text{GeV}}\right)^3 \sqrt{\frac{g_*}{100}}$$

All the Hot Big Bang puzzles above

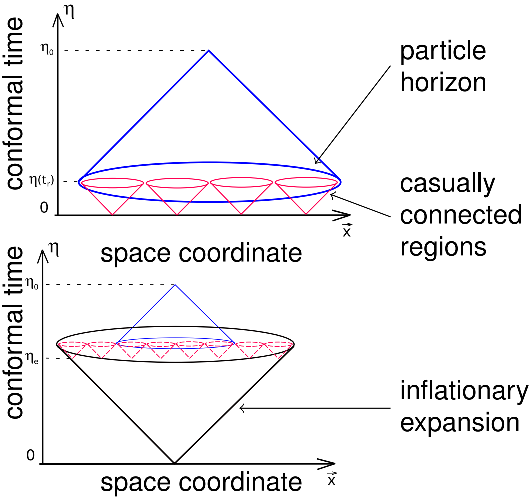
are problems of the initial state of our Universe


2.7 K
TODAY
14 by
accelerated expansion
4.1 K
matter domination
7.1 by
0.26 eV
recombination
370 ty
$e + p \to H + \gamma$
0.76 eV
matter domination
radiation domination
57 ty
80 keV
3 min
$^3H + {}^4He \to {}^7Li + \gamma$
primordial nucleosynthesis
$^2H + {}^2H \to n + {}^3He$
1 MeV
1 s
$p + p \to {}^2H + \gamma$
2.5 MeV
neutrino decoupling
0.1 s
200 MeV
QCD phase transition
10 μs
confinement↔free quarks
100 GeV
Electroweak phase transition
0.1 ns
baryogenesis
hot Universe
dark matter production
reheating
inflation

Outline

Inflationary solution of Hot Big Bang problems

- no initial singularity in dS space
- all scales grow exponentially, including the radius of the 3-sphere
  the Universe becomes exponentially flat
- any two particles are at exponentially large distances
  no heavy relics
  no traces of previous epochs!
- no particles in post-inflationary Universe
  to solve entropy problem we need post-inflationary reheating



Unexpected bonus: generation of perturbations

- Quantum fluctuations of wavelength λ of a free massless field φ have an amplitude of $\delta\varphi_\lambda \simeq 1/\lambda$
- In the expanding Universe: $\lambda \propto a$

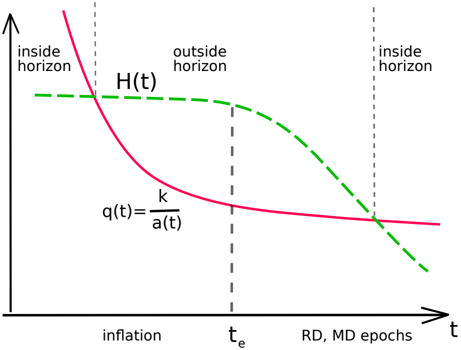
inflation: $l_H \sim 1/H = \text{const}$, so modes "exit horizon"
Ordinary stage: $l_H \sim 1/H \propto t$, $l_H/\lambda \nearrow$, modes "enter horizon"

Evolution at inflation

- inside horizon: $\lambda < l_H$
  $\lambda \propto a \Rightarrow \qquad \delta\varphi_\lambda \propto 1/\lambda \propto 1/a$

- outside horison: $\lambda > l_H$
  $\lambda \propto a \Rightarrow \qquad \delta\varphi_\lambda = \text{const} = H_{infl}$!!!

- got "classical" fluctuations:
  $\delta\varphi_\lambda = \delta\varphi_\lambda^{quantum} \times e^{N_e}$

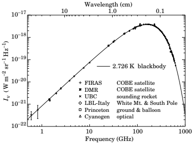


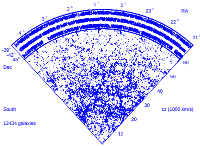
Key observable: matter (and tensor) perturbations

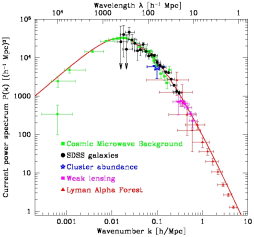
- CMB is isotropic, but "up to corrections, of course..."
  1. Earth movement with respect to CMB
     $$\frac{\Delta T_{\rm dipole}}{T} \sim 10^{-3}$$
  2. More complex anisotropy: $\frac{\Delta T}{T} \sim 10^{-4}$
- There were matter inhomogenities $\Delta\rho/\rho \sim \Delta T/T$ at the stage of recombination $(e+p \to \gamma + H^*)$ $\Longrightarrow$

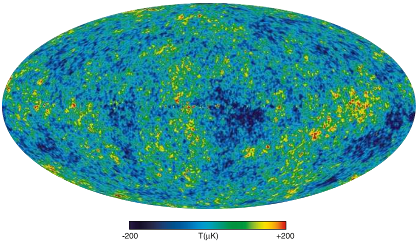
  Jeans instability in the system of gravitating particles at rest $\Longrightarrow$ $\Delta\rho/\rho \nearrow$ galaxies (CDM halos)
- There are neither sources no mechanisms to produce the initial inhomogeneities, if we the Universe is described by GR and SM

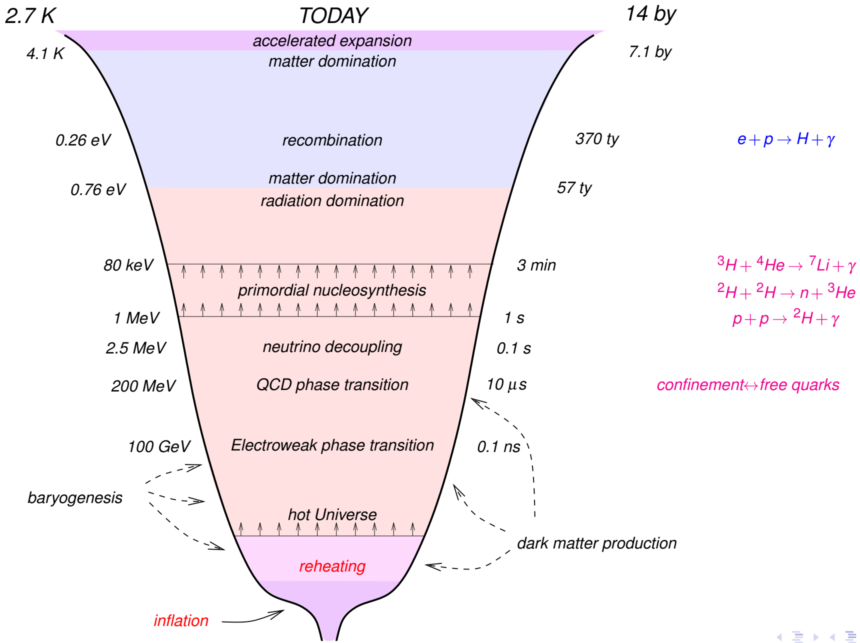
  we must modify the theory!







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baryogenesis
hot Universe
dark matter production
reheating
inflation

Role of reheating:

- Opens Hot Big Bang stage
- Helps to solve entropy problem

Reheating exploits interactions between inflaton and SM

- Either already existing
  gravity in R^2-model
  SM-interaction in the Higgs-inflation
- Or some new specially designed for this purpose
  Higgs-portal for any scalar inflaton: $H^\dagger H \phi^2$

Inflation & Reheating: simple realization with Higgs

$$\ddot{X} + 3H\dot{X} + V'(X) = 0$$

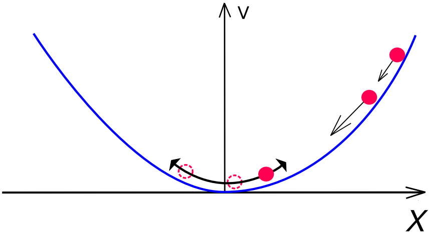
$X_e > M_{Pl}$

generation of scale-invariant scalar (and tensor) perturbations from exponentially stretched quantum fluctuations of X

$\delta\rho/\rho \sim 10^{-5}$ requires
e.g. for $V = \beta X^4$: $\beta \sim 10^{-13}$

reheating ? renormalizable?

the only choice: $\alpha H^\dagger H X^2$
"Higgs portal"



Chaotic inflation, A.Linde (1983)

larger α larger T_{reh}

quantum corrections $\propto \alpha^2 \lesssim \beta$

No scale, no problem

Studying the reheating stage can help to

- Explore the mechanism of SM particles production operating in the early Universe
- Distinguish between otherwise similar inflationary models
  e.g.: Higgs-inflation vs. R^2-inflation
- Understand late-times cosmology
  e.g.: Dark matter production at reheating
  Baryogenesis via Affleck–Dine mechanism
- Probe other new physics
  e.g.: in R^2-inflation T_{reh} counts the number of scalars lighter than 10^{13} GeV

What do we know about reheating?

- From observation (BBN) we know that $T_{reh} > 1\,\text{MeV}$
  Most probably, (BAU) $T_{reh} > 100\,\text{GeV}$
- In a particular inflationary model

$$\rho_{rad} = \frac{\pi^2}{30} g_* T^4 < V_{inf} = 3 H_{inf}^2 M_P^2$$

- Upper limits on H_{inf} from searches for GW:
  contribution to expansion rate at BBN

$$\Delta N_\nu \lesssim 0.5 \Rightarrow \rho_{GW}(BBN) < \rho_{total}(BBN)$$

CMB limits on tensor modes

$$r < 0.15 \Rightarrow \frac{H_{inf}}{M_P} < 4 \times 10^{-4}$$

Hence one obtains

$$T_{reh} \lesssim 4 \times 10^{16}\,\text{GeV}$$

Details of reheating (GW can reflect!)

Instant or Continious?

$\rho_{\rm rad} + \rho_{\rm inf}$: change the Universe expansion rate

often the effect can be absorbed by a shift in $T_{\rm reh}$

Homogeneous or not (e.g. structured)

spatial size $l \lesssim l_H \sim M_P / T_{\rm reh}^2$

inhomogeneities in matter of present size

$$l_0 \sim l_H \cdot \frac{a_0}{a_{\rm reh}} \sim 0.01\,{\rm pc} \times \left(\frac{10^2\,{\rm GeV}}{T_{\rm reh}}\right)$$

are unobservable…

GW can help

Instant or Continious?

Homogeneous or not?

Gravity waves freely propagate

Its spectrum saves all information about their production and later Universe expansion

However, in practice it works only for specific classes of models

Outline

General test of reheating

Accurate fit to the power spectrum of scalar (also tensor) perturbations

- In fact, spectra are a bit tilted, as H_{infl} slightly evolves

$$\mathcal{P}_{\mathcal{R}}(k) = A_{\mathcal{R}} \left(\frac{k}{k_*}\right)^{n_s - 1} , \qquad \mathcal{P}_T(k) = A_T \left(\frac{k}{k_*}\right)^{n_T} .$$

- CMB anisotropy measurement determines $A_{\mathcal{R}}$ at present scales $q = k_*/a_0 \simeq 0.002/\text{Mpc}$, which fixes the number of e-foldings left N_e
- For tensor perturbations one introduces $r \equiv \frac{A_T}{A_{\mathcal{R}}}$

Works for any inflationary model !

However, the sensitivity to T_{reh} is logarithmic only !

The power spectra of primordial perturbations

The same potential, the same ϕ at the end of inflation

e.g. F.Bezrukov, D.G., M.Shaposhnikov (2008)

$$n_s \simeq 1 - \frac{8(4N+9)}{(4N+3)^2}\,, \qquad r \simeq \frac{192}{(4N+3)^2}$$

But WMAP observes different N in the two models:
$k/a_0 = 0.002/\text{Mpc}$ exits horizon at different moments

$$N = \frac{1}{3}\log\left(\frac{\pi^2}{30\sqrt{27}}\right) - \log\frac{(k/a_0)}{T_0 g_0^{1/3}} + \log\frac{V_*^{1/2}}{V_e^{1/4} M_P} - \frac{1}{3}\log\frac{V_e^{1/4}}{10^{13}\,\text{GeV}} - \frac{1}{3}\log\frac{10^{13}\,\text{GeV}}{T_{reh}}$$

The difference is

F.Bezrukov, D.G. (2011)

$$N_* \approx 57 - \frac{1}{3}\log\frac{10^{13}\,\text{GeV}}{T_{reh}}\,, \quad N_{R^2} = 54.37, \quad N_H = 57.66$$

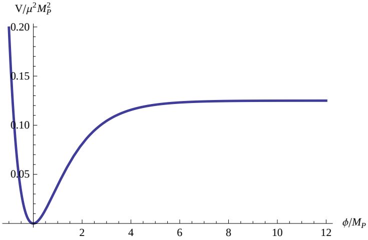
R^2-inflation: $n_s = 0.964$, $r = 0.0036$,

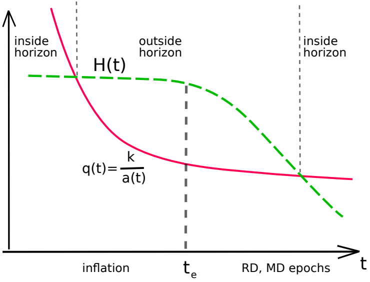
Higgs-inflation: $n_s = 0.966$, $r = 0.0032$.

Planck(?), CMBPol(1-2σ)

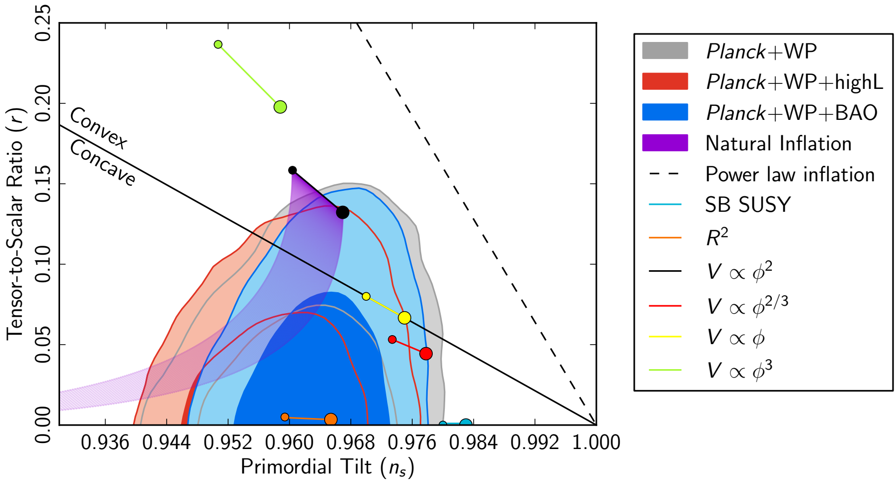
NLO is needed

D.G., A.Tokareva (2013)





Recent analysis (Planck) of cosmlogical data



1303.5062

$N_e = 50 - 60$

Break in spectrum of primordial GW

Notice that for postinflationary stage with $p = w\rho$

at w $< 1/3$: $\rho_{GW}/\rho_U \propto 1/a^{\varepsilon}$, at RD : $\rho_{GW}/\rho_U \propto \text{const}$

One expects a break ("knee") in inflationary GW spectrum at $\nu\,(T_{reh})$

Likewise one expects grows of perturbations!

which may enter nonlinear regime and starts to form halos made of inflaton

Gravity waves from inflation and inflaton clumps

Notice that

$$\text{at MD}: \quad \rho_{GW}/\rho_U \propto 1/a\,, \qquad \text{at RD}: \quad \rho_{GW}/\rho_U \propto \text{const}$$

One expects a break ("knee") in inflationary GW spectrum at $\nu(T_{reh})$

$$\text{at MD}: \quad \delta\rho/\rho \propto a$$

F.Bezrukov, D.G. (2011)

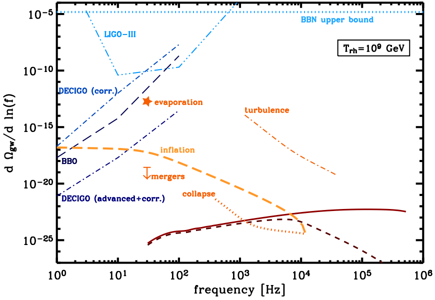
$$\text{e.g.,}R^2-\text{inflation}: \quad \frac{a_{reh}}{a_{inf}} \sim 10^7$$

scalar perturbations enter nonlinear regime

GW from:

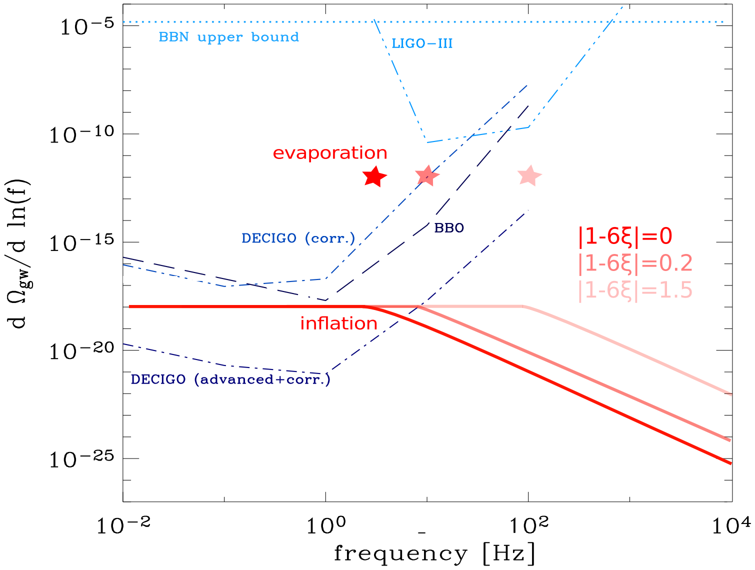
- collapses at formation of clumps
- merging of clumps
- evaporation of clumps (inflaton decays)

Since $\rho_{GW}/\rho_U \propto 1/a$, the strongest signal in present GW spectrum is expected at $\nu(T_{reh})$



K.Jedamzik, M.Lemoine, J.Martin (2010)

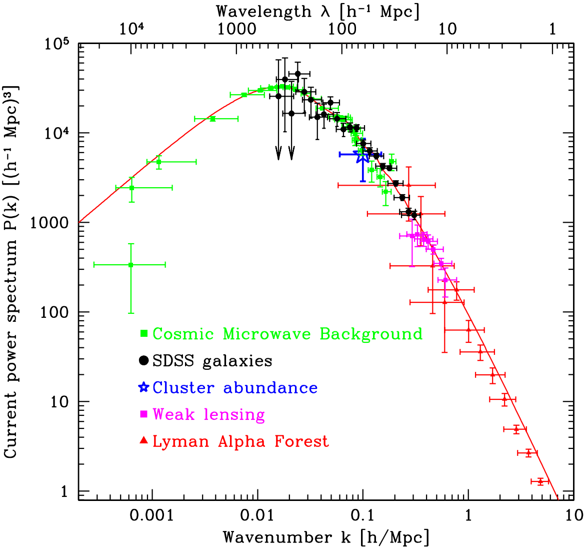
Help in distinguishing the models: R^2 with $\xi H^\dagger HR$



D.G., A.Tokareva

(2013)

Actually we observe rather narrow range



Observable range:

$$\frac{k_{max}}{k_{min}} \sim 10^5$$

$$\Delta N_e \simeq 10$$

We can't describe small scales:
for a long time they are in nonlinear regime

With GW we can probe perturbations at other scales!
(important for exotic models of inflation)

Exotic models: production at preheating

Preheating: very effective production of ultrarelativistic, firestly noninteracting particles (bose enhancement, coherence, etc)

Ultrarelativistic noninteracting particles sources GW

J.-F.Dufaux, A.Bergman, G.Felder, L.Kofman and J.-Ph.Uzan (2007)

Conclusion

Study of GW signal allows to

- probe primordial spectrum at small scales
  (for scalar modes it is obscured by structure formation)
- test the postinflating physics, including the reheating mechanism
  (distinguish between quite similar inflationary models,
  e.g. R^2 and Higgs-inflation)

We badly need new experiments (space missions) to detect GW !!!

Presently achieved sensitivities in cosmic photons (γ, X-rays, radio wave bands), cosmic neutrinos (e.g. ICECUBE), cosmic rays (e.g. CASCADE GRANDE, AUGER) to the flux from logarithmic scale range are at similar level of erg/cm^2/s,

while for GW the sensitivities achieved (e.g. LIGO, VIRGO) are about TEN orders worse

Backup slides

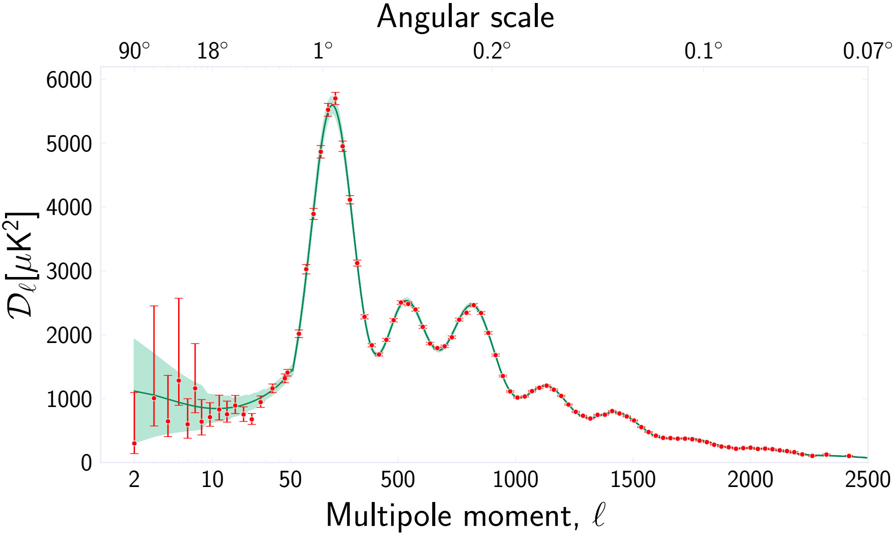
Mode evolution

- Amplitude remains constant, while superhorizon, e.g. $k/a < H$
- Subhorizon Inhomogeneities of DM start to grow at MD-stage, $\delta\rho_{CDM}/\rho_{CDM} \propto a$ from $T \approx 0.8\,\text{eV}$
  Smaller objects (first stars, dwarf galaxies) are first to form
- Subhorizon Inhomogeneities of baryons join those of DM only after recombination, $\delta\rho_{CDM}/\rho_{CDM} \propto a$ from $T_{rec} \approx 0.25\,\text{eV}$
- at recombination $\delta\rho_B/\rho_B \sim \delta T/T \sim 10^{-4}$ and would grow only by a factor $T_{rec}/T_0 \sim 10^3$ without DM
- Subhorizon Inhomogeneities of photons $\delta\rho_\gamma/\rho_\gamma$ oscillate with constant amplitude at RD and with decreasing amplitude at MD, thus we can measure $T_{RD/MD}/T_{rec}$
- Phase of oscillations decoupled after recombination depends on the wave-length, recombination time and sound speed

$$\delta\rho_\gamma/\rho_\gamma \propto \cos\left(k\int_0^{t_r}\frac{v_s\,dt}{a(t)}\right) = cos(kl_{sound})$$

- $$\delta T(\theta,\varphi) = \sum a_{lm}Y_{lm}(\theta,\varphi)\,, \qquad \langle a^*_{lm}a_{lm}\rangle = C_l \equiv 2\pi\mathscr{D}_l/(l(l+1))$$

CMB measurements (Planck) $H_0, \Omega_{DM}, \Omega_B, \Omega_\Lambda, \Delta_{\mathscr{R}}, n_s$



Power spectrum of perturbations

In the Minkowski space-time:

- fluctuations of a free quantum field φ are gaussian its power spectrum is defined as

$$\int_0^\infty \frac{dq}{q}\,\mathscr{P}_\varphi(q) \equiv \langle \varphi^2(x) \rangle = \int_0^\infty \frac{dq}{q}\,\frac{q^2}{(2\pi)^2}$$

  We define amplitude as $\delta\varphi(q) \equiv \sqrt{\mathscr{P}_\varphi} = q/(2\pi)$
- In the expanding Universe momenta $q = k/a$ gets redshifted
- Cast the solution in terms $\phi(\mathbf{x},t) = \phi_c(t) + \varphi(\mathbf{x},t)\,, \quad \varphi(\mathbf{x},t) \propto \mathrm{e}^{\pm i\mathbf{kx}}\,\varphi(\mathbf{k},t)$
  φ solves the equation

$$\ddot{\varphi} + 3H\dot{\varphi} + \frac{k^2}{a^2}\varphi + V''(\phi_c)\varphi = 0$$

- $q = k/a \gg H \;\Rightarrow$ as in Minkowski space-time
- $q = k/a \ll H \;\Rightarrow$ for inflaton $\varphi = \mathrm{const}$
- Matching at t_k: $q(t_k) = k/a(t_k) = H(t_k) \equiv H_k$ gives

$$\delta\varphi(q) = \frac{H_k}{2\pi} \;\Rightarrow\; \mathscr{P}_\varphi(q) = \frac{H_k^2}{(2\pi)^2}$$

amplification $H_k/q = \mathrm{e}^{N_e(k)}$!!!

$H_k \approx \mathrm{const} = H_{infl}$ hence (almost) flat spectrum

Transfer to matter perturbations: simple models

Illustration: Local delay(advance)δt in evolution due to impact of $\delta\phi$ of all modes with $\lambda > H$:

$$\delta\phi = \dot{\phi}_c \delta t \,, \quad \delta\rho \sim \dot{\rho}\, \delta t$$

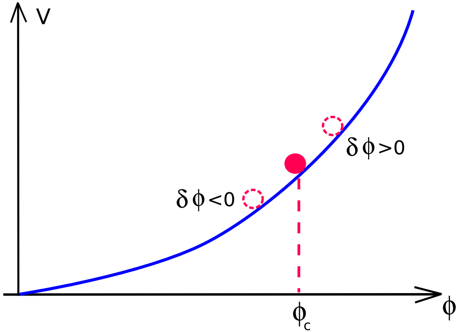
at the end of inflation $\dot{\rho} \sim -H\rho$, then

$$\frac{\delta\rho}{\rho} \sim \frac{H}{\dot{\phi}_c} \delta\phi$$

Hence, $\delta\rho/\rho$ is also gaussian.
Power spectrum of scalar perturbations

$$\mathcal{P}_{\mathcal{R}}(k) = \left(\frac{H^2}{2\pi\,\dot{\phi}_c}\right)^2 \,,$$

calculated at $t = t_k : H = k/a \equiv H_k$



Analogously for the tensor perturbations: each of the two polarizations of the gravity waves solves the free scalar field equation!

$$\mathcal{P}_T(k) = \frac{16}{\pi} \frac{H_k^2}{M_{Pl}^2}$$

To the leading order no k-dependence: both spectra are “flat” (scale-invariant)!

Light inflaton nonminimally coupled to gravity

$$S_{XSM} = \int \sqrt{-g}\, d^4x \left(\mathscr{L}_{SM} + \mathscr{L}_{XH} + \mathscr{L}_{ext} + \mathscr{L}_{grav} \right),$$

$$\mathscr{L}_{XH} = \frac{1}{2}\partial_\mu X \partial^\mu X + \frac{1}{2} m_X^2 X^2 - \frac{\beta}{4} X^4 - \lambda \left(H^\dagger H - \frac{\alpha}{\lambda} X^2 \right)^2,$$

$$\mathscr{L}_{grav} = -\frac{M_P^2 + \xi X^2}{2} R,$$

$$g_{\mu\nu} \to \tilde{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}, \qquad \Omega^2 = 1 + \xi X^2/M_P^2,$$

$$U(X) = \frac{\beta X^4}{4\Omega^4} \to \text{const} = \frac{\beta}{\xi^2} M_P^4 \quad \text{at} \quad X \to \infty.$$

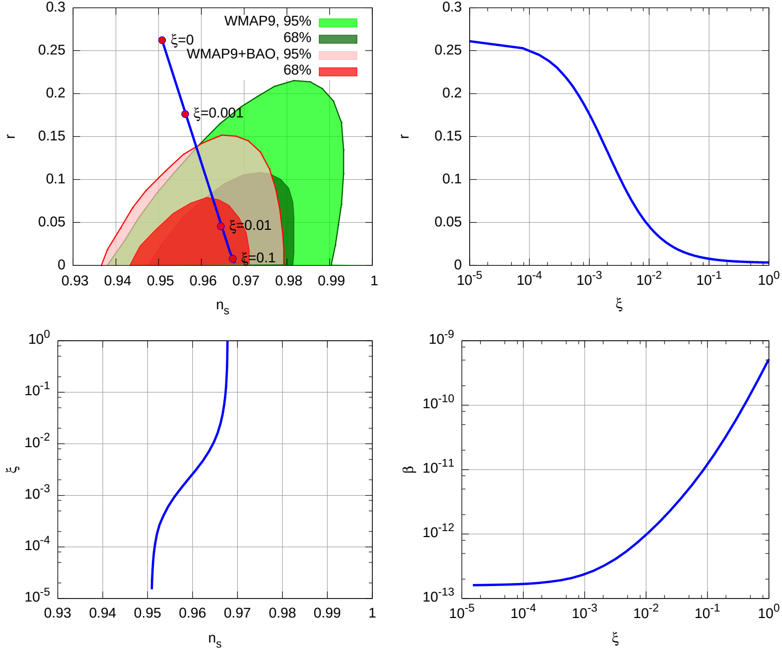
$$X \to \mathscr{X}: \quad \frac{d\mathscr{X}}{dX} = \sqrt{\frac{\Omega^2 + 6\xi^2 X^2/M_P^2}{\Omega^4}}$$

$$m_\chi = m_h \sqrt{\frac{\beta}{2\alpha}} = \sqrt{\frac{\beta}{\lambda\theta^2}}.$$

$$\theta^2 = \frac{2\beta v^2}{m_\chi^2} = \frac{2\alpha}{\lambda}.$$

Outcome: easier to test!

$$\beta \nearrow \implies \tau_\chi \searrow, \ \mathrm{Br}(B \to \chi) \nearrow$$


WMAP9, 95%
68%
WMAP9+BAO, 95%
68%
ξ=0
ξ=0.001
ξ=0.01
ξ=0.1
r
n_s
ξ
β

Higgs-inflation

F.Bezrukov, M.Shaposhnikov (2007)

$$S = \int d^4x\sqrt{-g}\left(-\frac{M_P^2}{2}R - \xi H^\dagger H R + \mathscr{L}_{SM}\right)$$

In a unitary gauge $H^T = \left(0\,,(h+v)/\sqrt{2}\right)$ (and neglecting $v = 246\,\text{GeV}$)

$$S = \int d^4x\sqrt{-g}\left(-\frac{M_P^2 + \xi\,h^2}{2}R + \frac{(\partial_\mu\,h)^2}{2} - \frac{\lambda\,h^4}{4}\right)$$

slow roll behavior due to modified kinetic term even for $\lambda \sim 1$

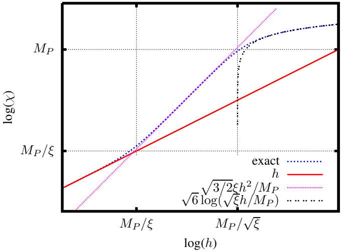
Go to the Einstein frame: $(M_P^2 + \xi\,h^2)\,R \to M_P^2\,\tilde{R}$

$$g_{\mu\nu} = \Omega^{-2}\tilde{g}_{\mu\nu}\,, \qquad \Omega^2 = 1 + \frac{\xi\,h^2}{M_P^2}$$

with canonically normalized χ:

$$\frac{d\chi}{dh} = \frac{M_P\sqrt{M_P^2 + (6\xi+1)\xi\,h^2}}{M_P^2 + \xi\,h^2}\,,\quad U(\chi) = \frac{\lambda\,M_P^4\,h^4(\chi)}{4(M_P^2 + \xi\,h^2(\chi))^2}\,.$$

we have a flat potential at large fields: $U(\chi) \to \text{const}$ @ $h \gg M_P/\sqrt{\xi}$



Reheating by Higgs field

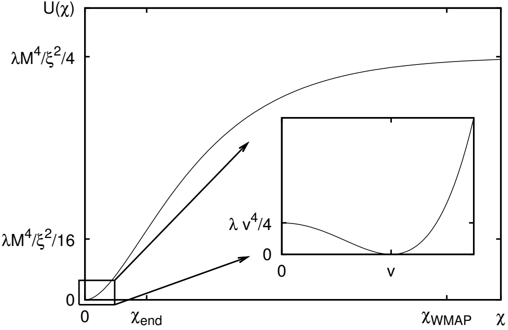
after inflation: $M_P/\xi < h < M_P/\sqrt{\xi}$

effective dynamics : $h^2 \to \chi$

$$\mathscr{L} = \frac{1}{2}\partial_\mu \chi \partial^\mu \chi - \frac{\lambda}{6}\frac{M_P^2}{\xi^2}\chi^2$$

Advantage: NO NEW interactions to reheat the Universe

inflaton couples to all SM fields!



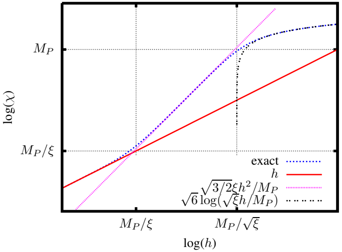
exponentially flat potential! @ $h \gg M_P/\sqrt{\xi}$:

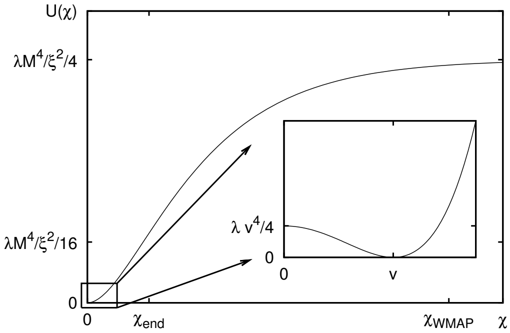
$$U(\chi) = \frac{\lambda M_P^4}{4\xi^2}\left(1 - \exp\left(-\frac{\sqrt{2}\chi}{\sqrt{3}M_P}\right)\right)^2$$

NO NEW d.o.f. 0812.3622, 1111.4397

Different reheating temperature. . .

from WMAP-normalization: $\xi \approx 47000 \times \sqrt{\lambda}$





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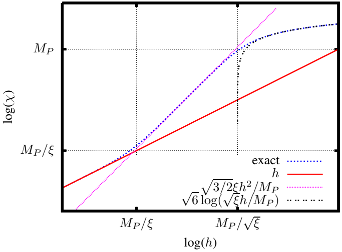

$$m_W^2(\chi) = \frac{g^2}{2\sqrt{6}}\frac{M_P|\chi(t)|}{\xi}$$

$$m_t(\chi) = y_t\sqrt{\frac{M_P|\chi(t)|}{\sqrt{6}\xi}}\,\text{sign}\,\chi(t)$$

reheating via W^+W^-, ZZ production at zero crossings

then nonrelativistic gauge bosons scatter to light fermions

$$\chi \to W^+W^- \to f\bar{f}$$

Reheating by Higgs field

after inflation: $M_P/\xi < h < M_P/\sqrt{\xi}$

Hot stage starts almost from $T = M_P/\xi \sim 10^{14}$ GeV:

effective dynamics : $h^2 \to \chi$

$$\mathscr{L} = \frac{1}{2}\partial_\mu\chi\partial^\mu\chi - \frac{\lambda}{6}\frac{M_P^2}{\xi^2}\chi^2$$

$$3.4\times10^{13}\,\text{GeV} < T_r < 9.2\times10^{13}\left(\frac{\lambda}{0.125}\right)^{1/4}\text{GeV}$$

Advantage: NO NEW interactions
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inflaton couples to all SM fields!

$n_s = 0.967$, $r = 0.0032$ F.Bezrukov, D.G.,