What could we learn about high energy particle physics from cosmological observations at largest spatial scales?

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The main message

- Physics at the highest energy scales may be probed with observations at the largest spatial scales (just somewhat smaller than the size of the visible Universe)

- However, we are not (yet) ready to make the tests realistic (theory)
Universe is expanding

\[ \lambda_{\text{abs.}} / \lambda_{\text{em.}} \equiv 1 + z \]

Doppler redshift \( Z \) of light

\[ L \propto a(t) \]

Hubble parameter

\[ H(t) = \frac{\dot{a}(t)}{a(t)} \]
Universe is homogeneous and isotropic

2dF Galaxy Redshift Survey

106688 Galaxies
Universe is occupied by “thermal” photons

the spectrum (shape and normalization!) is thermal

\[ T_0 = 2.726 \text{ K} \]

\[ n_\gamma = 411 \text{ cm}^{-3} \]
Conclusions from observations

The Universe is homogeneous, isotropic, hot and expanding...

- Interval between events gets modified

\[ \Delta s^2 = c^2 \Delta t^2 - a^2(t) \Delta x^2 \]

- In GR expansion is described by the Friedmann equation

\[ \left( \frac{\dot{a}}{a} \right)^2 = H^2(t) = \frac{8\pi}{3} G \rho_{\text{energy}} \]

\[ \rho_{\text{density}} = \rho_{\text{matter}} + \rho_{\text{radiation}} + \ldots \]

- \( \rho_{\text{matter}} \propto 1/a^3(t) \), \( \rho_{\text{radiation}} \propto 1/a^4(t) \), \( \rho_{\text{curvature}} \propto 1/a^2(t) \)

- In the past, the matter density was higher, our Universe was “hotter”, and was filled with electromagnetic plasma
Present knowledge about the past: back to 2-3 MeV

past stages
- deceleration/acceleration: $\ddot{a} = 0$
- reionization
- recombination
- RD/MD equality
- nucleosynthesis
- neutrino decoupling

observables
- SN Ia, CMB, clusters
- CMB, quasars, stars
- CMB, BAO
- cold gas clouds

$H^2 \propto \rho_\gamma + \rho_\nu$
New Physics in Cosmology: any energy scales...

Cosmology constrains the time-scale, rather than energy-scale

$$\Gamma \sim H \propto T^2 / M_{Pl}$$

- Dark matter (if particles) be produced by $T \gg 1$ eV
- Dark energy be present by $T \gg 5$ K
- Baryon asymmetry be generated by $T \gg 1$ MeV
Inhomogeneous Universe

Large Scale Structure

CMB anisotropy
These inhomogeneities (matter perturbations) originate from the initial matter density (scalar) perturbations 

\[ \frac{\delta \rho}{\rho} \sim \frac{\delta T}{T} \sim 10^{-4}, \text{ which are} \]

adiabatic 

\[ \delta \left( \frac{n_B}{s} \right) = \delta \left( \frac{n_{DM}}{s} \right) = \delta \left( \frac{n_L}{s} \right) \]

Gaussian 

\[ \langle \frac{\delta \rho}{\rho} (\mathbf{k}) \frac{\delta \rho}{\rho} (\mathbf{k'}) \rangle \propto \left( \frac{\delta \rho}{\rho} (\mathbf{k}) \right)^2 \times \delta(\mathbf{k} + \mathbf{k'}) \]

flat spectrum 

\[ \langle \left( \frac{\delta \rho}{\rho} (\mathbf{x}) \right)^2 \rangle = \int_0^{\infty} \frac{dk}{k} \mathcal{P}_S(k) \quad \mathcal{P}_S(k) \approx \text{const} \]

LSS and CMB 

\[ \mathcal{P}_S \equiv A_S \times \left( \frac{k}{k_*} \right)^{n_s-1} \quad A_S \approx 2.5 \times 10^{-9}, \quad n_s \approx 0.97 \]
General facts and key observables

TODAY

- 2.7 K
- 4.4 K
- 0.26 eV
- 0.8 eV
- 50 keV
- 1 MeV
- 2.5 MeV
- 200 MeV
- 100 GeV
- Electroweak phase transition
- Baryogenesis
- Hot Universe
- Reheating
- Inflation

14 by

- 7.7 by
- 370 ty
- 50 ty
- 5 min
- 1 s
- 0.1 s
- 10 μs
- 0.1 ns

1.7 K

- Dark matter production
- Confinement ↔ free quarks

Accelerated expansion
Matter domination
Radiation domination
Primordial nucleosynthesis
Neutrino decoupling
QCD transition

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High energy physics from cosmology
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Quantum fluctuations of wavelength $\lambda$ of a free massless field $\varphi$ have 3-momenta $q \sim 1/\lambda$ and an amplitudes of $\delta \varphi_\lambda \sim q$ (inflaton and gravitons !!)

Evolution at inflation

- **inside horizon:** $q > H$
  $q \propto 1/a \Rightarrow \delta \varphi_\lambda \propto q \propto 1/a$

- **outside horizon:** $q < H$
  $q \propto a \Rightarrow \delta \varphi_\lambda = \text{const} = H_{\text{infl}}/2\pi$ !!

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

scalar modes $\delta \phi_\lambda \sim H_{\text{infl}}$
tensor modes $\delta g_{\mu\nu} \sim h \sim H_{\text{infl}}/M_{Pl}$

Later at normal stage

$H \propto 1/t$, $q/H \nearrow$, modes “enter horizon”
All bosons fluctuate including the SM Higgs $\phi \sim H/2\pi$

Thus we either constrain inflation, $H \lesssim \ldots 10^{10}$ GeV $\ldots$ and hence GW, that is $r$ or ask for NP at a lower scale
Probing the matter power spectrum

\[ \delta \phi \rightarrow \frac{\delta \rho}{\rho} \sim \frac{H^2}{\dot{\phi}} \propto \frac{V^{3/2}}{V'}, \quad h \sim \frac{H}{M_{Pl}} \propto V^{1/2} \]

upper limit on the inflation scale
from the absence of tensor modes (relic Gravity Waves)

\[ V^{1/4} \lesssim 10^{16} \text{ GeV} \]
Probing the inflaton dynamics

\[ A_S \rightarrow \frac{V^{3/2}}{V'}, \quad n_S \rightarrow \frac{V''}{V}, \left( \frac{V'}{V} \right)^2, \quad r \equiv \frac{A_T}{A_S} \rightarrow \left( \frac{V'}{V} \right)^2 \]
Planck 2015 favors flat inflaton potentials

$$r = \frac{A_T}{A_S} \propto \frac{\dot{\phi}^2}{H^2 M_{Pl}^2} \propto \left( \frac{V'}{V} \right)^2 \ll 1$$
Inflationary models and quantum corrections

perturbations $\delta T/T \sim 10^{-4}$ fix $\mu \approx 10^{13}$ GeV

$R^2$-inflation by A. Starobinsky (1980)

$$V(\phi) = \frac{3\mu^2 M_P^2}{4} \left(1 - \exp\left(-\sqrt{2/3}\phi/M_P\right)\right)^2,$$

- large fields:
  - exponentially flat
  - protected by the shift invariance
    $$\phi \rightarrow \phi + \text{const}$$

- small fields:
  - polynomial potential
  - protected by the renormalizability
    $$\phi^2 + \phi^4$$

- no way to match them at
  $$\phi \sim M_P$$
Inflationary models and quantum corrections

- Inflationary predictions are robust
- But we cannot test them with low energy particle physics experiment
- Including physics at reheating
- Similar observation for many other models: Higgs-flation, $\alpha$-attractor, etc

- Large fields:
  - Exponentially flat
  - Protected by the shift invariance
  - $\phi \rightarrow \phi + \text{const}$

- Small fields:
  - Polynomial potential
  - Protected by the renormalizability
  - $\phi^2 + \phi^4$

- No way to match them at $\phi \sim M_P$

\[
V/\mu^2M_P^2 = \frac{3M_P^2\mu^2}{4} \left( 1 - e^{-\#\phi/M_P} \right)
\]

\[
\mu^2\phi^2/2
\]
Summary

- The Universe was as hot as 2-3 MeV and most probably (much) hotter
- DM and BAU imply New Physics
  - but cosmology does not point at a particular scale
- Inflation must save the EW vacuum,
  - which can suggest New Physics
  - (it is difficult to prove, because a new collider is needed to pin down $m_t$ and $m_h$)
- Inhomogeneities of the largest sizes
  - can allow us to probe physics at the highest energies.
  - However, (most) models are nonrenormalizable,
  - hence no direct connection between low- and high-energy model parameters
Quantum corrections to $R^2$...

\[ S^{JF} = -\frac{M^2_P}{2} \int \sqrt{-g} d^4x \left( R - \frac{R^2}{6 \mu^2} \right) + \ldots \xi R^2 \log R , \]

Jordan Frame $\rightarrow$ Einstein Frame [scale invariance $\rightarrow$ shift invariance] \hspace{1cm} A. Starobinsky (1980)

\[ g_{\mu\nu} \rightarrow \tilde{g}_{\mu\nu} = \chi g_{\mu\nu} , \quad \chi = \exp \left( \sqrt{2/3} \phi / M_P \right) . \]

\[ S^{EF} = \int \sqrt{-\tilde{g}} d^4x \left[ -\frac{M^2_P}{2} \tilde{R} + \frac{1}{2} \tilde{g}^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - \frac{3 \mu^2 M^2_P}{4} \left( 1 - \frac{1}{\chi(\phi)} \right)^2 \right] + S_{\text{matter}} , \]

generation of perturbations $\sim 10^{-5}$

\[ \frac{1}{2} \dot{\phi}^2 \sim \frac{1}{2} (\partial_i \phi)^2 \sim M^4_P \gg V(\phi) \]

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Quantum corrections to the Higgs-inflation


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

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

\[ (M_P^2 + \xi h^2) R \rightarrow M_P^2 \tilde{R} \]

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

with canonically normalized \( \chi \):

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

we have a flat potential at large fields: \( U(\chi) \rightarrow \text{const} \quad @ \quad h \gg M_P / \sqrt{\xi} \)
Dark Matter Properties

(If) particles:
1. stable on cosmological time-scale
2. nonrelativistic long before RD/MD-transition (either Cold or Warm, $v_{RD/MD} \lesssim 10^{-3}$)
3. (almost) collisionless
4. (almost) electrically neutral

If were in thermal equilibrium: $M_X \gtrsim 1 \text{ keV}$

If not: for bosons

$$\lambda = \frac{2\pi}{(M_X v_X)}$$

in a galaxy $v_X \sim 0.5 \cdot 10^{-3}$ \quad $M_X \gtrsim 3 \cdot 10^{-22} \text{ eV}$

for fermions $M_X \gtrsim 750 \text{ eV}$

Pauli blocking:

$$f(p, x) = \frac{\rho_X(x)}{M_X} \cdot \frac{1}{\left(\sqrt{2\pi} M_X v_X\right)^3} \cdot e^{-\frac{p^2}{2M_X^2v_X^2}} \bigg|_{p=0} \leq \frac{g_X}{(2\pi)^3}$$

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Astrophysical and cosmological data are in agreement

\[
\left( \frac{\dot{a}}{a} \right)^2 = H^2(t) = \frac{8\pi}{3} G \rho_{\text{density}}
\]

\[
\rho_{\text{density}} = \rho_{\text{radiation}} + \rho_{\text{ordinary matter}} + \rho_{\text{dark matter}} + \rho_{\Lambda}
\]

\[
\rho_{\text{radiation}} \propto 1/a^4(t) \propto T^4(t), \quad \rho_{\text{matter}} \propto 1/a^3(t)
\]

\[
\rho_{\Lambda} = \text{const}
\]

\[
\frac{3H_0^2}{8\pi G} = \frac{\rho_{\text{energy}}(t_0)}{\rho_c} \equiv \rho_c \approx 0.53 \times 10^{-5} \text{ GeV} / \text{cm}^3
\]

- **radiation:** \( \Omega_\gamma \equiv \frac{\rho_\gamma}{\rho_c} = 0.5 \times 10^{-4} \)
- **Baryons (H, He):** \( \Omega_B \equiv \frac{\rho_B}{\rho_c} = 0.05 \)
- **Neutrino:** \( \Omega_\nu \equiv \frac{\sum \rho_\nu}{\rho_c} < 0.01 \)
- **Dark matter:** \( \Omega_{\text{DM}} \equiv \frac{\rho_{\text{DM}}}{\rho_c} = 0.27 \)
- **Dark energy:** \( \Omega_\Lambda \equiv \frac{\rho_\Lambda}{\rho_c} = 0.68 \)
Expansion: redshift $z$

$$\lambda_{\text{abs.}}/\lambda_{\text{em.}} \equiv 1 + z$$

$z \ll 1$ Hubble law: $z = H_0 r$

$$H_0 = h \cdot 100 \frac{\text{km}}{\text{s} \cdot \text{Mpc}}, \quad h \approx 0.68$$

Hubble Diagram for Cepheids (flow-corrected) standard candles