Cosmology : theory

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From the point of view of cosmology,

two compelling events in recent years:

2012: discovery of the Higgs particle at LHC

2013: release of Planck data

Why? In the early 1980s, the high energy community developed a model of the Primordial Universe based on the Standard Model and its extensions (in particular Grand Unification)
This Model led to a common framework for explaining:

- the matter-antimatter asymmetry through fundamental interactions

- the flatness, horizon (and monopole) problems through the scenario of inflation

Einstein eqns: $T_{\mu\nu} \sim \rho_0 \ g_{\mu\nu} \implies H^2 = 8\pi G_N \rho_0 /3 = \text{cst} \ H_{\text{vac}}^2 \implies \text{de Sitter solution} \ a(t) \sim \exp (H_{\text{vac}} t)$

energy stored typically $\rho_0 \sim M_U^4 \sim (10^{16} \text{ GeV})^4$

potential at high $T$

A. Linde A. Guth
This Model led to a common framework for explaining:

- the matter-antimatter asymmetry through fundamental interactions
- the flatness, horizon (and monopole) problems through the scenario of inflation
- the rotation curves of galaxies, and more recent manifestations of dark matter
- more recently, the acceleration of the expansion of the Universe, through a new component, dark energy
In all this, « fundamental » scalar fields play a central role.

**Why?**

Scalar fields easily provide a diffuse background

Speed of sound $c_s^2 = (\frac{\delta p}{\delta \rho})_{\text{adiabatic}}$

In most models, $c_s^2 \sim 1$, i.e. the pressure of the scalar field resists gravitational clustering:

Unless in specific cases, scalar fields tend not to cluster.
Hence the discovery of the Higgs has provided the first « fundamental » scalar field.

If there is one, why not many?

Indeed, triviality argument

\[
\lambda \phi^4
\]

\[
\Lambda
\]

\[
\text{abelian gauge}
\]

\[
\text{nonabelian gauge}
\]
Planck results: what comforted the inflation paradigm?

Pre-Planck: spacetime is spatially flat $\Omega = 1$ or $\rho = \rho_c$

Planck: $n_s = 0.968 \pm 0.006$

$n_s = 1$, inflation for ever (de Sitter)

$n_s < 1$, built-in instability

Reheating: inflaton decay into particles slows down oscillations and repopulates the Universe
Basic questions which cosmology may have to address:

• What is the exact mechanism for inflation? Is eternal inflation a valid option?

• How to explain the matter-antimatter asymmetry?
Basic questions which cosmology may have to address:

- What is the cause of the (recent) acceleration of the expansion of the Universe?
- What is the exact mechanism for inflation? Is eternal inflation a valid option?
- How to explain the matter-antimatter asymmetry?
- How to compute the energy of the vacuum?
- How to reconcile gravity with the other forces described by the SM?
Basic questions which cosmology may have to address:

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• What is the cause of the (recent) acceleration of the expansion of the Universe?

• How to compute the energy of the vacuum?

• How to reconcile gravity with the other forces described by the SM?

• Why is the Higgs mass stable under radiative corrections?

• Why is the Higgs mass so close to the instability frontier?
Potential clues for future theories:

- Confirmation of the basic principles of inflation
- Acceleration of the expansion of the Universe

Why is it that vacuum energy seems to dominate at the beginning and at the end of our history?
Potential clues for future theories:

- Confirmation of the basic principles of inflation
- Higgs close to instability?
- Acceleration of the expansion of the Universe

Does it mean anything?

Big Bang

History of the Universe

Now
Regarding inflation and/or dark energy, we have an infinite range of possibilities but, on the other hand, no sign of new physics.

\[\Rightarrow\] a trend in the theory studies of the last two years has been to follow the road of minimality.

Rely on the Higgs (+ possibly the QCD axion field) to address the issues.
Higgs inflation

**Higgs h of the original SM cannot be the inflaton**

Condition to avoid quantum gravity regime during slowroll: quartic coupling $\lambda \ll 10^{-2}$

(wheras $\lambda \sim 10^{-1}$)

*Need to couple it to spacetime curvature $R$*

\[
S = \int d^4x \sqrt{-g} \left\{ -\frac{M_p^2}{2} \left( 1 + \xi \frac{h^2}{M_p^2} \right) R + \frac{1}{2} \partial^\mu h \partial_\mu h - \frac{\lambda}{4} (h^2 - v^2)^2 \right\}
\]

Berzukov, Shaposhnikov
0710.3755 [hep-th]...

\[
S = \int d^4x \sqrt{-g} \left\{ -\frac{M_p^2}{2} R - \frac{1}{2} \left[ g^{\mu\nu} - \frac{M_p^2}{2} (R^{\mu\nu} - R g^{\mu\nu} / 2 ) \right] \partial_\mu h \partial_\nu h - \frac{\lambda}{4} (h^2 - v^2)^2 \right\}
\]

Germani, Kehagias
1003.2635 [hep-ph]...
Note: problem with unitarity at scale $M_p/\xi$; app. shift symmetry helps at scale $\gg M_p/\xi$ (inflation)

Bezrukov, Magnin, Shaposhnikov, Sibiryakov 1008.5157
Ferrara, Kallosh, Linde, Marrani, Van Proeyen 1008.2942

Burgess, Lee, Trott 0902.4465,1002.2730
George, Mooij, Postma, 1310.2157
What happens if the Higgs field is in the instability region?

In the general case, this might require Higgs-inflaton coupling:
Is it dependent on the type of field and on the details of the low-energy potential?

No!

\[ S = \int d^4x \sqrt{-g} \left\{ -\frac{M_p^2}{2} \left( 1 + \frac{\xi}{\xi^2} \right) R + \frac{1}{2} \partial_{\mu} h \partial_{\mu} h - \frac{\lambda}{4} (h^2 - v^2)^2 \right\} \]

generalize

\[ S = \int d^4x \sqrt{-g} \left\{ -\frac{M_p^2}{2} \left( 1 + \xi f(\phi) \right) R + \frac{1}{2} \partial_{\mu} h \partial_{\mu} h - \lambda f(\phi)^2 \right\} \]

In the limit \( \xi \) large, one obtains the predictions of Higgs inflation

Kallosh, Linde, Roest 1310.3950
$\alpha$-attractors

Kallosh, Linde, Roest 1310.3950
We have to understand two severe fine tuning problems:

\[ \frac{M_p^4}{\Lambda} \sim 10^{120} \]

\[ \frac{M_p}{m} \sim 10^{16} \quad \text{m Higgs mass} \]

Dirac large number hypothesis (1937)

\textit{Large mass scale ratios are a consequence of the age of the Universe, i.e. are the result of the cosmological evolution.}

Dirac concluded that \( G \propto 1/t \) which is not observed.

But could we apply similar arguments to fine tuning ratios?

Abbott 1985, Dvali and Vilenkin hep-th/0404043, Dvali hep-th/0410286
Simplest model: SM + QCD axion $\phi$

\[ \mathcal{L} \supset (\mathcal{L} + g\phi)|h|^2 + gM^2\phi + g^2\phi^2 + \cdots + \Lambda^4 \cos \frac{\phi}{f} \]

Large mass scale $M$

$\Lambda^4 \sim f_\pi m_\pi^2 \propto (\lambda_u + \lambda_d) <h>$
Simplest model: SM + QCD axion $\phi$

$$\mathcal{L} \supset (-M^2 + g\phi)|h|^2 + gM^2\phi + g^2\phi^2 + \cdots + \Lambda^4 \cos \frac{\phi}{f}$$

In the limit $g \to 0$,
shift symmetry: $\phi \to \phi + 2\pi f$
(from continuous symmetry
(in the absence of strong interactions)
$\phi \to \phi + \text{cst}$
g naturally small
• QCD axion

\[ M < 3 \times 10^8 \text{ GeV} \]

• Variations: i) drop the slope

\[
\mathcal{L} \supset (-M^2 + g \phi)|h|^2 + \kappa \sigma^2 \phi + g M^2 \phi + \cdots + \Lambda^4 \cos \frac{\phi}{f}
\]

inflaton - drops at end of inflation

\[
M < 1000 \text{ TeV} \left( \frac{\theta}{10^{-10}} \right)^{\frac{1}{4}}
\]

ii) Use a different strong group and couple \( \phi \) to \( G''_{\mu \nu} \tilde{C}'_{\mu \nu} \)
Thus interesting class of models which require further investigation:

- the g parameter is very small (e.g. $10^{-31}$ GeV): this is natural in a technical sense but why?
- the model requires a long inflation period; connection $\phi$ field $\leftrightarrow$ inflaton
- reheating
- can the $\phi$ field provide dark matter

see also Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant 1506.09217
Back to general models of inflation:
• how to use cosmological data to identify the dynamics of inflation?
• can we understand why different models give the same predictions?

Indeed, and this might be due to a very fundamental reasons

In fact, one may identify characteristic classes of models (in a sense very similar to the characteristic classes of critical phenomena in condensed matter physics)
In an inflation scenario, one first have to solve the classical equation of motion of the inflaton field in its potential.

Suppose that we are in an expanding Universe with cosmic scale factor $a(t)$

\[ H(t) \equiv \frac{\dot{a}(t)}{a(t)} \equiv \frac{d}{dt} \]

Equation of evolution of the field $\phi$

\[ \dot{\phi} + 3 H \phi = -\frac{dV}{d\phi} \]

Energy density

\[ \rho_\phi = \frac{\dot{\phi}^2}{2} + V(\phi) \]

Pressure

\[ p_\phi = \frac{\dot{\phi}^2}{2} - V(\phi) \]
There is a simple way of extracting a first integral of motion

Bond and Salopek, 1990

Write \( H(t) = \dot{a}/a(t) \equiv -W(\phi)/2 \)

Then [...] the equation of motion becomes simply

\[
\dot{\phi} = W_\phi
\]

\[
V(\phi) = 3W^2/4 - W_\phi^2/2
\]

\( W(\phi) \) superpotential

But

\[
\frac{d\phi}{d\ln a} = \frac{d\phi}{dt} \quad \frac{dt}{d\ln a} = \frac{\phi}{H} = \frac{1}{H} \quad \frac{dW}{d\phi} = -2 \frac{W_\phi}{W}
\]

\( W_\phi \frac{dW}{d\phi} \)
evolution of $\phi$

\[
\frac{d\phi}{d\ln a} = -2 \frac{W_\phi}{W}
\]
The evolution of the field $\phi$ is described by the equation:

$$\frac{d\phi}{d\ln a} = -2 \frac{W_\phi}{W} \equiv \beta(\phi)$$

The renormalisation group equation in QFT or statistical physics is given by:

$$\frac{dg}{d\ln \mu} = \beta(g)$$

- Field $\phi$
- Gauge coupling $g$
- Cosmic scale factor $a$
- Renormalisation scale $\mu$
Where does this come from? Understandable in the context of AdS/CFT.

Gravity theory in anti de Sitter

Conformally invariant QFT (typically gauge theory w/ $\beta(g)=0$)

Inflation

Gravity theory in de Sitter

McFadden, Skenderis, E. Kiritsis 1307.5873
Where does this come from? Understandable in the context of AdS/CFT

Gravity theory in almost anti de Sitter

Conformally invariant QFT (typically gauge theory) + operators $\beta(g) \neq 0$

$V \leftrightarrow -V$

$M_P^2 \leftrightarrow -M_P^2$

INFLATION gravity theory in almost deSitter $\beta(\phi) \neq 0$

Mcfadden, Skenderis

Mcfadden, Skenderis  E. Kiritsis 1307.5873
evolution of $\phi$

\[
\frac{d\phi}{d \ln a} = -2 \frac{W\phi}{W} \equiv \beta(\phi)
\]

renormalisation group equation in QFT or statistical physics

\[
\frac{dg}{d \ln \mu} = \beta(g)
\]

field $\phi$

cosmic scale factor $a$

gauge coupling $g$

renormalisation scale $\mu$

Note: $\beta(\phi) = \left[ 3(p_\phi + \rho_\phi)/\rho_\phi \right]^{1/2}$

Vacuum energy: $p = -\rho \Rightarrow \beta = 0$ fixed point

Inflation: vicinity of a fixed point

$n_s = 1$, inflation for ever

$n_s < 1$, built-in instability
Fixed point: zero of $\beta$

$\beta(\phi_0) = 0$

$\phi_0$ inflation

$\phi_0'$ inflation (dark energy?)
Solutions classified into universality classes:

Class Ia: \( \beta(\phi) = \beta_q (\phi - \phi_0)^q \)

\[ V(\phi) \sim A[1 - B(\phi - \phi_0)^{q+1} + \ldots] \]

Class II: \( \beta(\phi) = -\beta \exp[-\gamma \phi] \)

Ex: Higgs inflation, Starobinsky \( R^2 \) inflation
P.B., Kiritsis, Mabillard, Pietroni 1407.0820
The simultaneous discovery of the Higgs and confirmation of (some of) the basic features of inflation has opened a new era in the common understanding of cosmology and particle physics.

Even to understand the basic problems faced by high energy physics today, it might be important to recall that we leave in an expanding hence dynamical Universe.

The cosmological dynamics may help us to find clues for some of the most fundamental problems that we face and maybe pave the way for a reconciliation of gravity (described by general relativity) with the quantum theory (Standard Model).