The LHC & the universe

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The connection between the micro & macro cosmos is one of the most astounding achievements of modern physics.

Nature’s fundamental laws become apparent only at small distances.
simplicity

complexity

small
distances

large
distances
The micro/macro connection is not just a qualitative feature

Best example: 
inflation

Quantum fluctuation of a primordial field

CMB anisotropy

Large scale structures
LHC: timeline

21 Mar 1984
First LHC studies

16 Dec 1994
LHC approved

10 Sep 2008
LHC starts

19 Sep 2008
LHC incident

20 Nov 2009
LHC restarts

30 Mar 2010
First collisions at 7 TeV

30 Oct 2011
End of $pp$ run (5 fb$^{-1}$)

5 Apr 2012
First collisions at 8 TeV

4 Jul 2012
Higgs discovery

19 Jan 2013
End of $pp$ run (20 fb$^{-1}$)

03 Jun 2015
First collisions at 13 TeV

04 Nov 2015
End of $pp$ run (4 fb$^{-1}$)
The last brick of the SM building,
... but a special brick...
The success of the SM rests on the gauge principle

- elegant
- robust
- predictive

Higgs interactions: first known example of non-gauge fundamental forces?

The origin of all SM problems
\[ L = \left( h_{ij} \overline{\psi}_i \psi_j H + \text{h.c.} \right) - \lambda |H|^4 + \mu^2 |H|^2 - \Lambda_{\text{CC}}^4 \]

- Flavor puzzle
- Stability of the potential
- Hierarchy problem
- Cosmological constant problem
Is the Higgs a fundamental scalar with non-gauge interactions?

The Higgs is SM-like at the level of 20-40% accuracy
Δ = \frac{v^2}{f^2} \quad \Rightarrow \quad \text{compositeness scale} \quad 4\pi f > \sqrt{\frac{20\%}{\Delta}} \quad 7 \text{ TeV}

Does new dynamics reinstate the gauge principle?
Is the Higgs truly fundamental? \quad \Rightarrow \text{experiments!}

If so, fuel for inflationary model-building
Scalar fields no longer tools for toy models

Extreme case: the Higgs as inflaton
Simplest example: Higgs-curvature term

\[ \delta S_{NM} = \int d^4x \sqrt{-g} \left[ -\xi \Phi^\dagger \Phi R \right] U(\chi) \]

Bezrukov-Shaposhnikov

needs large-field modification
\[ \xi \approx 47000 \sqrt{\lambda} \]

\[ n_s \approx 1 - \frac{4N + 9}{(4N + 3)^2} \approx 0.967, \]

\[ N \approx 57.7 \]

\[ r \approx \frac{192}{(4N + 3)^2} \approx 0.0031, \]

**Predictions of inflationary models:**

- **Higgs inflation**
- R\(^2\) inflation
- \(\lambda\phi^4 + \xi\phi^2R/2\)
- Non-minimal derivative coupling
Perturbative unitarity violated at $M_P / \xi$

New physics must appear at that scale
(we cannot trust the potential above the cutoff)

**Next-to-simplest example: Higgs + 1 scalar**

Giudice-Lee
Barbon-Casas-Elias-Espinosa

**General lessons from UV-completed models**

- Higgs may play a role in inflation, but it is unlikely to be the dominant source
- Inflationary predictions are fairly robust
- Except for special cases, observation of $r$ can rule out the models
If SM + Higgs is the full story, new implications for cosmology

- Higgs mass
- Top quark mass

\[ \frac{16\pi^2}{3} \mu \frac{d\lambda}{d\mu} = -2y_t^4 + 4y_t^2\lambda + 8\lambda^2 + \]

\[ M_h = 125.66 \text{ GeV} \]
\[ 3\sigma \text{ bands in} \]
\[ M_t = 173.36 \pm 0.66 \text{ GeV} \]
\[ \alpha_s(M_Z) = 0.1184 \pm 0.0007 \]

\[ M_t = 171.4 \text{ GeV} \]
\[ \alpha_s(M_Z) \approx 0.1205 \]
\[ \alpha_s(M_Z) = 0.1163 \]
\[ M_t = 175.3 \text{ GeV} \]
Critical sensitivity on SM parameters

Degrassi et al.
What does metastability imply for the early universe?

1) How did we end up here?

- Initial condition from pre-inflationary thermal phase
- Large $Rh^2 \approx H^2 h^2$ stabilizing the origin
- Small coupling to inflaton (negligible Higgs contribution to energy density)

$$10^{-10} \leq \lambda_{h\phi} \leq 10^{-6}$$

Lebedev-Westphal
2) Why wasn’t the vacuum destabilized by thermal effects?
2) Why wasn’t the vacuum destabilized during inflation?

Espinosa-Giudice-Riotto

\[ H << h_{\text{max}} \quad \text{and} \quad H >> h_{\text{max}} \]
• Vacuum stability implies a constraint on Hubble during inflation
• Important if tensor modes are detected
  \[ H \approx 8 \times 10^{13} \text{ GeV} \left( \frac{r}{0.1} \right)^{1/2} \]
Is there a message in Higgs near-criticality?

- Coincidence?
- Dynamical attractor? Self-organized criticality?
- Statistical explanation in the multiverse?
- Cosmological evolution of fundamental parameters?
Higgs naturalness as a “criticality” condition

\[ V(H) = -m_H^2 |H|^2 + \lambda |H|^4 \]

- Why is nature so close to the critical line?
  - Is \( m_H^2 \approx 0 \) special because of symmetry? (supersymmetry, Goldstone symmetry)
  - Is \( m_H^2 \approx 0 \) special because of SOC?
An example of Higgs naturalness explained by SOC

Graham-Kaplan-Rajendran

- The relaxion rolls down a shift-breaking potential
- The Higgs mass is scanned during the cosmological evolution
- Back-reaction from EW breaking
We are facing a fundamental issue that will influence the future strategy of particle physics and early cosmology.

The SM is an EFT emerging from a more fundamental theory at the TeV scale.

Higgs naturalness and the CC indicate a breakdown of EFT intuition (SOC, multiverse, cosmological selection of parameters, ...).
LHC: the future

From Apr 2016 to Nov 2018 $\rightarrow 100 \text{ fb}^{-1}$ @ 13 TeV
LS2 until 2021
HL-LHC $\rightarrow 3000 \text{ fb}^{-1}$

A lot to be learned for cosmology:
- Nature of the Higgs boson
- Higgs naturalness
- EW phase transition
- New physics?
- Dark matter?
DM at the LHC

The standard lore...

direct detection

thermal freeze-out (early Univ.)
indirect detection (now)

production at colliders
DM at the LHC

The standard lore...

... is misleading

- Main signal comes from DM mediators
- EFT have limited use
- Searches are very model dependent
Conclusions

- Particle physics gives the tools for developing cosmology
- This is why the LHC is a formidable source of information for cosmology
- Lessons from Higgs: near-criticality, EW phase transition
- Naturalness has been challenged by LHC8. The answers from LHC13 will be critical for the strategy to go BSM, hence for cosmology
- The discovery of new physics can revolutionize our understanding of the microworld
- New information on the nature of dark matter