Higher Energy Physics and Cosmology

Current Status and Future Prospects

M.M. Sheikh-Jabbari

IPM, Tehran

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Introduction

- Physics is the science of *uncovering laws of Nature*.

- Implicit concepts and philosophical stands:
  - There exists a Nature (Realistic viewpoint).
  - Nature has Laws. It works upon pregiven/preassigned laws.
  - We, the humans, have the potential to uncover these laws.
  - These laws are describable through mathematical equations and formulations, i.e.

- Our mental abilities/(mathematical) logic have the potential to *model the Nature*.

- In the end, this is the Nature, i.e. experiment or observation, which decides whether our modeling is the right one.

- Laws of Nature generically describe the dynamics, how the systems evolve,

- systems of all possible scales, from the smallest to the largest we have been able to observe/detect.

- As time goes by this range is expanding.....

- In this talk I will focus on scales which are relevant to particle physics and early Universe cosmology.

Plan of the talk

- The five "types" of research works.
- Status of the field in particle physics and early universe cosmology.
- The main standing questions, with the emphasis on **fundamental aspects**.

Disclaimers:

- *Each of the above topics is a tall tale I will only be able to sketch through.*
- *This is my take and viewpoint andnot necessarily shared by all physicists.*

Work distribution among physicists

- Job division basis among physicists:
  - Subjectwise,
  - Theory vs. experiment
- Theory vs. experiment *(applicable to all empirical sciences)*
  - Preparing the theory (framework)
  - Model building
  - Phenomenology
  - Data analysis
  - Experiment/Observation

Philosophical/Fundamental aspects are in the theory part.

Work distribution among physicists

- Subject classification is based on:
  - *Decoupling of scales, physics at different energy or length scales are decoupled* which is among the most fundamental and intuitive ideas in physics, and
  - the degree of freedom under study.
- This classification icludes

  astrophysics, cosmology, particle physics, high energy physics.

Current Status in early universe cosmology and particle physics:

- Theory/Framework: Relativistic Quantum Field Theory and General Relativity.

- Models: Standard model of cosmology and Standard model of particle physics.

- Phenomenology: Extract out all possible observables of these standard models.

- Data analysis/Experiments: "Combined analyses" of all relevant data; "Big data" issues.

Tensions and theory/model shortcomings in the Current Status:

- **Tensions**
  - are classified by their *statistical significance*:
  - in "vanilla model" of cosmology we have tensions on H_0.
  - in SM particle physics we have established tensions on μ-magnetic dipole moment.
  - No notable significant tension in other data regarding particle physics.

Model and phenomenological (our analysis power) questions or shortcomings:

- A general question: **Why parameters of the Standard models have the values they have?**

- In cosmology:

  - Inflationary sector is under-determined by data.

  - End of inflation–recombination era ("first three minutes") is under-determined by current data sources.

  - Dark sectors of the vanilla model.

  - The need for nonlinear analysis for the structure formation.

  - Baryon asymmetry of the universe; baryongenesis.

Model and phenomenological (our analysis power) shortcomings:

- In SM of particle physics:
  - Dark matter candidates.
  - Neutrino sector.
  - Confinement, hadron and nuclei spectrum; phases of QCD; the need for nonperturbative, strongly coupled QFT methods.
  - Higgs and stability of its potential, hierarchy problem.
  - Elementary particles? Are quarks, leptons or Higgs composites?
  - Sources of CP violation?!
  - Too many parameters.

Theory shortcomings:

- In cosmology/astrophysics:
  - Is inflation natural/inevitable?
  - Multiverse?!
  - Singularity problem.
  - What Banged?!
  - Cosmological constant problem.
  - Issues in **black hole physics**, classical, semiclassical and quantum.
  - General Relativity-Quantum Theory reconciliation.
  - Beyond Einstein GR?!

Theory shortcomings:

- Current framework of particle physics, **the QFT**, works extremely well. Nonetheless:
  - Nonperturbative methods in QFT.
  - Beyond QFT: String theory or others?!
  - Is spacetime/gravity **emergent**?! Quantum spacetime?!
  - Arrow of time?
  - Lorentz symmetry violation in UV?
  - Questions regarding measurement in quantum theory.

Theory shortcomings, cont'd

- Lack of a guiding principle (decoupling of scales?!, reductionist viewpoint/perturbation theory?, symmetries?!, naturalness?!, simplicity vs universality or wide coverage?!)

- Expectations from a "physics theory/framework"? Is mathematical consistency enough or there is more?!

- Quantum vs Classical world, where is the border? Quantum coherence?

- Fate of the universe in the accelerated expansion phase?

You are cordially invited to take part in this endeavor.

Thank You
For Your Attention