Séminaire Thématique: “Physique de l’Inflation et Énergie Noir”
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Open questions in cosmic inflation physics

Elias Kiritsis

APC, Paris

Introduction

• Inflation is a paradigm: since it was proposed in 1980 (Kazanas, Guth), it has become one of the pillars of the modern cosmological framework.

• It was proposed to explain conceptual problems with observations: the horizon and curvature problems.

• Its major breakthrough was the prediction that (almost scale invariant and almost Gaussian) quantum fluctuations during inflation are responsible for the observable structure of the universe today.

Chibisov+Mukhanov

• The enormous progress in observations has made this idea more than plausible: it is considered today as the benchmark explanation for the structure of the universe.

The goal of the present short presentation will be to summarize several proposals of the French scientific community on the theory of the inflationary topic, with a focus on the following two questions:

- What kind of issues we do not understand in theory? What kind of theoretical questions we can ask? And whether we can propose to observers what to observe.

- There are also related questions on the observational side: What can the observers obseve, that might lead the theorists to "explain" the data.

A survey of theoretical problems

• The paradigm of inflation can be realized by literally thousands of different models.

• Even in the case of a single scalar field, you can imagine many different potentials that can do the job (and agree with data constraints).

• But there are many more realizations that utilize more than one scalar or completely different mechanisms.

• Examples are Hořava-Lifshitz gravity, brane universe inflation, mirage inflation, etc.

• In ALL cases, to have inflation we must fine-tune theory!

• This is one of the many fine-tunings we think we have in physics:

♠ The cosmological constant (today).

♠ The electroweak scale.

• In particular, the cosmological constant problem is not only acute but of direct relevance:

• QFT predicts today vacuum energies of order the characteristic scales of particle physics.

• These are 10^{60} or more times bigger than what we measure (indirectly).

• Obviously, there must be something that alleviates this discrepancy.

• Inflation is usually driven by vacuum energy.

• Therefore, its occurrence and dynamics must be also affected by what fixes the cosmological constant discrepancy.

• Inflation happens early in the history of the universe while the cosmological constant discrepancy is an acute late time problem. Is there something that decouples the two?

• How do we classify and categorize models of inflation?

• How do we embed inflation in a fundamental theory that contains both gravity and the Standard Model and is fully quantum mechanical?

• How inflation started?. Can we ask questions that pertain to before inflation started?

It should be remembered that what we always called the "big bang" in inflationary theory corresponds to the end of inflation and the reheating of the universe.

• Can we control, even perturbatively, QFT in a inflationary background beyond the Gaussian approximation?

• It may come as a surprise to many of you that for almost all cases the answer to the above is NO, today.

• Can we observe the gravitational power spectrum of inflation?

• Are there other observables beyond non-Gaussianity? Or, what are good correlator-related data that can be measured and interpreted?

• How is reheating done, and whether the mechanism can be indirectly observed? In other words: Can we observe the workings of the "big bang"?

• Is CP-asymmetry present in the inflationary sector and is it imprinted in the aftermath?

• Can we observe the cosmic neutrino background and what can we learn from it?

• Is the QCD axion related in any way to inflationary dynamics?

• Are primordial magnetic fields seeded during or because of inflationary dynamics?

• Can inflation or one of its avatars produce primordial black holes?

• Can we prove experimentally that what we observe as classical structure today, was once quantum fluctuations? Is there an analogue of Bell's inequalities in this case?

The three contributions

IN2P3 Prospectives 2020

GT05 Physique de l'inflation et énergie noire

Cosmic Inflation - Theory

Porteur: Vincent Vennin

Dominic Beck,[a] Josquin Errard,[a] Ken Ganga,[a] Yannick Giraud-Héraud,[a] Jean-Christophe Hamilton,[a] Sophie Henrot-Versillé,[b] Elias Kiritsis,[a] David Langlois,[a] Thibaut Louis,[b] Ludovic Montier,[c] Baptiste Mot,[c] Francesco Nitti,[a] Michel Piat,[a] Julien Serreau,[a] Dani Steer,[a] Radek Stompor,[a] Matthieu Tristram,[b] Bartjan van Tent,[d] Vincent Vennin[a]

[a]APC (UMR 7164)
[b]LAL (UMR 8607)
[c]IRAP (UMR 5277)
[d]LPT (UMR 8627)

Contribution Prospectives IN2P3 2020

Predictive Physics of Inflation and Grand Unification *for and from* the CMB observations

Principal Author:

Name: Norma G. SANCHEZ

Institution: CNRS LERMA OP-PSL SU

IN2P3 Prospects 2020

GT05, Physique de l'inflation et énergie noire

SUSY Cosmic Inflation
or when cosmology meets particle physics

Porteur: G. Moultaka

on behalf of: Laurent Duflot[b], Sophie Henrot-Versillé[b], Nikola Makovec[b], Ludovic Montier[c], Baptiste Mot[c], Matthieu Tristam[b], Vincent Vennin[a], and Dirk Zerwas[b]

[a]APC
[b]LAL
[c]IRAP
[d]L2C

Embedding inflation in a fundamental theory

• For a complete cosmology we need:

1. A theory of gravity (preferably quantum)

2. A theory of matter (The SM and its extensions)

3. An inflaton that couples both to 1 and 2 (and may be part of either).

4. The total theory must make sense quantum mechanically, at least up to the scale of inflation.

• We know only an invariant part of 1: the graviton and its low energy interactions.

• We know also a substantial part of 2: the SM

• We know that both 1+2 must have more ingredients for many theoretical reasons: UV completeness, theory of neutrino masses, CP-violations and many other less solid motivations.

• There are many attempts at quantizing gravity, and extending the standard model.

• There is only one that can give at the same time semiclassical gravity in some controllable regimes: string theory.

• There is a current very lively debate in string theory:

a) Does the theory provide a huge number (10^{500}) of possible ground states that are inflating at early times?

Kachru+Kallosh+Linde+Trivedi

b) Or the theory has NO ground states that inflate.

Ooguri+Vafa

• The claim in the second case is that one can only obtain quintessence-like behavior, with roll parameters that are severely constrained.

• Moreover, we have very strong constraints from the AdS/CFT correspondence that say (among others) that it is impossible to have pure quantum gravity.

Witten,Benjamin+Ooguri+Shao+Wang

The cosmological Constant vs Cosmology

- They are three approaches to the cosmological constant problem:

- The "just so" approach: the cosmological constant is measured in the IR and is what it is. This is usually in the same ball park as the anthropic explanation.

Weinberg

- The anthropic explanation needs a theory that has many possible values of the CC, and it must choose its value dynamically (string theory maybe able to do this).

- Transitions to universes with a different CC involve quantum tunneling effects but these are not very well controllable.

- A different approach is to modify gravity in the IR, so that it screens the CC. Massive gravity is one such possibility. There are many models but none that is fully viable.

Pauli+Fierz+thousands of papers, including from groups in APC, Paris and the rest of France

• A third approach involves the "self-tuning idea": The theory dynamically adjusts itself so that it screens the CC. This idea is old and to work one must have extra dimensions. However, until very recently it could not be made to work.

• Two years ago, a successful implementation was proposed in the context of brane theories. The theory on the brane has massive gravity with a hierarchically small graviton mass.

Charmousis+Kiritsis+Nitti

• Moreover in this context one can have an early phase of inflation.

Amariti+Charmousis+Forcela+Kiritsis+Nitti

• There are however a lot more to be done to construct models that reproduce the observable numbers and investigate further predictions.

• Overall, we are in need of experimental probes of the three mechanisms that affect the cosmological constant and how it enters cosmology.

Classification and testing of Inflationary models

• Until recently we had a proliferation of inflationary models.

• It was realized that as in QFT, one can use the symmetry of de Sitter space O(1,5) which involves among other things scale invariance to classify inflationary models as Wilson did in QFT.

Kiritsis, Binetruy+Kiritsis+Mabillard+Pieroni+Rosset

• They are classified using the β-functions, as in QFT.

• Models in the same class give the same leading observables:

♠ The scalar spectral index and the spectral tilt.

♠ The tensor spectral index and power ratio and the tensor tilt.

♠ Non-Gaussianity: a lot of the details of the inflationary model are hidden here.

♠ The spectrum and spectral distortions.

Reheating

• Although the general idea looks simple, reheating is a set of processes that are poorly understood even in the absence of gravity, and are difficult to be made quantitative.

• What we observe today depends crucially on reheating.

• In most cases the scales today that have been affected by it are rather small and are therefore fully in the non-linear regime.

Martin+Ringeval+Vennin

• We need smart experimental ideas on how to measure effects related to reheating, that are still visible in the universe.

Quantum Corrections to Inflation

• In most cases the semiclassical approach (free-field-theory) is used, as the theory is to leading order Gaussian.

• When quantum effects were computed, there were surprises:

• For light enough particles, the inflaton, the graviton etc, standard perturbation theory is breaks down even at weak-coupling.

Mottola+Mazur, Iliopoulos+Tomaras+Tsamis,Tsamis+Woodard, Weinberg, Starobinsky, Senatore+Zaldarianga

• Several scientists speculated that QFT does not exist on de Sitter, or the QFT backreaction destroys deSitter.

Mottola, Tsamis+Woodard, Polyakov

• Starobinsky developed a stochastic framework to improve the QFT behavior.

Staronbinsky, Senatore+Gorbenko

• The problem remains open for many QFTs and experts do not agree. No complete+controlable calculation exists so far (!!!).

• The exact truncated RG was used to bypass perturbation theory problems and calculate the backreaction to the inflationary background.

Moreau+Serreau

• Holography and the Ads/CFT correspondence has been also used to calculate the backreaction to de Sitter.

Gosh+Kiritsis+Nitti+Witkowski

• These hold promise that the problem will be eventually settled.

Other related questions

- Can inflation produce primordial black holes?

- How did Inflation start?

- Are the cosmological perturbations quantum?

Starobinsky, Martin+Vennin

Sanchez' contribution

Predictive Physics of Inflation and GUT *for and from* the CMB observations

Norma G. SANCHEZ CNRS-OP-PSL SU Paris

Objectives: *To focus on realistic and timely situations of inflation in connection with the* CMB, dark energy, gravitational and particle physics, in the Standard model of the Universe, *adding inter-disciplinarity and unification values,* within a strongly predictive physical approach.

The formulation of inflation in the Ginsburg-Landau approach clarifies and places inflation in the setting of the succesful effective field theories of particle physics, phase transitions and superconductivity: Recall: O(4) sigma model (for microscopic QCD), Landau-Wilson-Kadanoff (& for microscopic BCS)...

Powerful Approach: RESULTS

- ***Universal*** **form** for the slow-roll inflaton potential **encodes the essential physics of the problem**:
- $V(\varphi) = N M^4 w(\chi)$. N = number of efolds, **M = scale of inflation**,
- $w(\chi)$ = dimensionless = order 1.
- **Slow-roll expansion** becomes a **explicit and *systematic* 1/N expansion**. **Couplings become *naturally* small:** suppression factors arising as powers of the ratio $(M/M_{Pl})^2$, $(M/M_{Pl})^4$,...., $(M/M_{Pl})^n$ **(no fine tuning).**
- **Scalar Adiabatic fluctuations:**

$|\Delta^R_k \text{ ad}| = N (M/M_{Pl})^2$ implies using the **CMB data $\Delta T/T$**:

- **M = 0.54 10^{16} GeV = GUT SCALE**

(besides the direct determination of M from tensor ratio r when detected)

- **Inflaton mass $m = M^2/M_{PL}$**

m = 1.21 x10^{13}GeV *see-saw type*

- **Small running of the scalar index:**

$-4 \times 10^{-4} \leq dns/d\ln k \leq -2 \times 10^{-4}$

- **Small Non-gaussianity:**

$f_{NL} \sim (1 / N) \sim 0.02$

- **Lower and upper Tensor r bounds**

$0.021 \leq r \leq 0.59$

- **$r \sim 0.04$, ns = 0.9608**
- **Universal (ns, r) banane surface**
- **Departure of scale invariance:**

$\Delta = (½) (ns - 1) + r/8.$

Negative concavity of the potentia

$V''(\chi) < 0$ →→Symmetry breaking: double well : new inflation:

Binomial or trinomial potential

- Fast-roll stage generically precedes the Slow-roll stage and explains the low CMB multipoles: TT, TE, EE spectra and *the* ***quadrupole supression***: Upper bound on the **Total number of inflation efolds:** Ntotal < 82 . Favoured value: Ntotal ≃ 66.
- Transfert Function of Generic Initial Conditions computed: D(k) on the Power Spectra
- Quantum loop corrections to Inflation computed: small and controlled by powers of $(H/M_{Pl})^2 \sim 10^{-9}$: Validates Ginsburg-Landau Effective Theory of Inflation.
- Phases Before Inflation: planckian and trans-planckian phase: **Implications for Dark energy, H_0 and CMB.**
- **Gravitational Entropy = Vacuum Energy of the Universe. Results: Evolution : Dark Energy Action, LSS, ESA Voyage 2050…**

OUTLOOK AND CONCLUSIONS

- **Robust predictive physical approach** well prepared and timely: allow to extract relevant physics from the CMB+LSS data. **Paves the way with a strategy of discoveries, namely : B-mode detection, the probe of Grand Unification scale and the hint of supersymmetry breaking .**
- **Predicted r = 0.04 , (r, ns) banane**

B mode detection : LiteBIRD, and other future CMB observations.

- **Grand Unification Physics Scale = Scale of Inflation = Scale of Semiclassical Gravity (Semiclassical Vacuum and Connection with Hawking Temperature)**
- **GUT scale appears in: (1) Scale of particle physics coupling unification. (2) Scale in the See-saw mass neutrino oscillations .(3) Scale in the See-saw mass of the inflaton and hints to the SUSY breaking scale …A suivre . THANK YOU !!!**

Multaka's contribution

IN2P3 Prospects 2020
GT05, Physique de l'inflation et énergie noire
GT01, Physique des particules

SUSY Cosmic Inflation
or when cosmology meets particle physics

Porteur: G. Moultaka[d]

L. Duflot[a], S. Henrot-Versillé[a], N. Makovec[a], L. Montier[b], B. Mot[b], M. Tristam[a], V. Vennin[c], D. Zerwas[a]

[a]LAL, [b]IRAP, [c]APC, [d]L2C

Motivation

- The LHC discovery of the Higgs ...and nothing beyond (sofar)...BUT we still need BSM for many reasons
- The Planck results supporting strongly the inflation hypothesis...BUT we still need an embedding theory

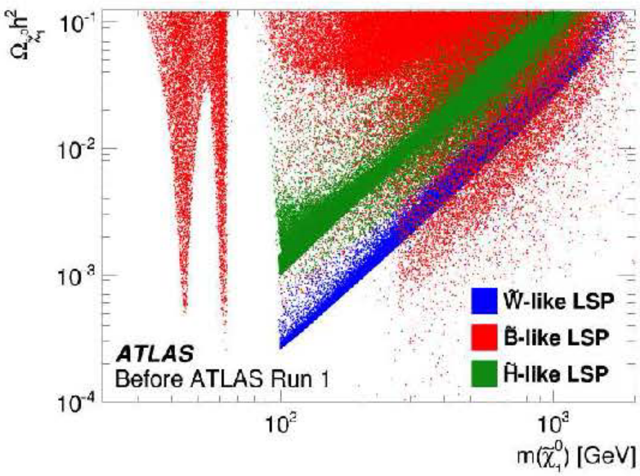
Is there a common message?

→ Heavy or difficult SUSY scenarios @LHC
→ SUSY Flat directions inflation
→ SUSY Higgs-inflation → e.g. SUGRA-NMSSM

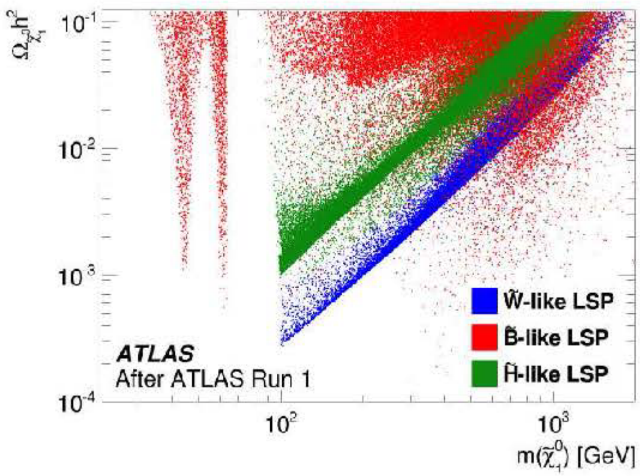
The proposal:

Put together experimental and theoretical expertise on SUSY searches & parameter exploration, CMB analyses and cosmo parameter exploration, to constrain/improve SUSY-inflation models from present and future experimental data.

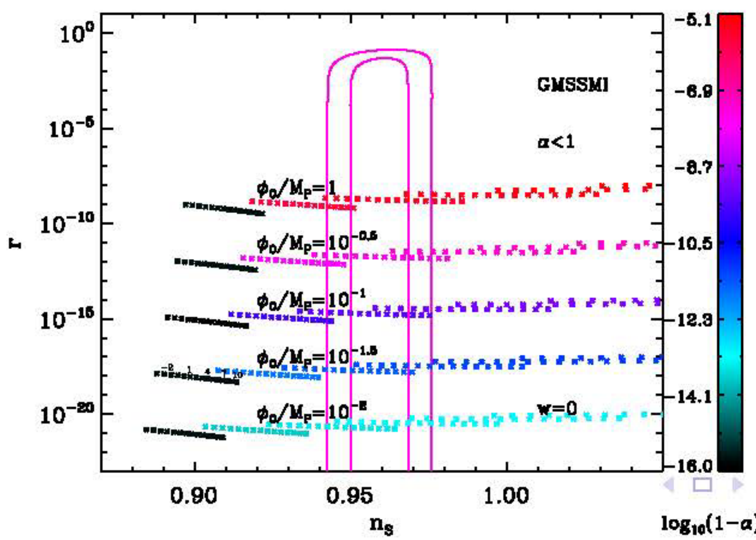
Participants: members of collaborations (LHC, Planck,..), or theoreticians (Inflation, SUSY), and (co)authors of analysis codes: ASPIC, SFitter, SuSpect.



(a) Before ATLAS Run 1



(b) After ATLAS Run 1



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Interface SFitter/SuSpect with ASPIC

$\downarrow$

relate high- scale (cosmo) and low-scale (PP) features of a SUSY-inflation model

compare predictions with cosmo & PP data (CMB, spectral index, tensor-to-scalar ratio, limits on SUSY searches, Dark Matter relic, (in)direct detection, low energy observables,...)

$\downarrow$

constraints!

- first (on-going) application: inflection-point-MSSM-inflation; *LLe*, *udd* flat directions lifted by non-renormalizable operators. Implementation of RG-flow relating the inflation scale to the LHC scale; soft SUSY scalar masses $\rightarrow$ inflaton mass; other soft breaking SUGRA-mediated scenarios $\rightarrow$ effective inflation potential. In principle fully calculable.

Comments

- Theory is in much worse shape than people think: There are many open problems of conceptual (CC, embedding) or technical (QFT In de Sitter, reheating) nature.

- Such problems will be addressed in the near future and this is global trend.

- There are many things to measure in the CMB, almost all challenging.

- We need, however to look also elsewhere at non-linear regimes and to try to extract information. This is non-trivial, but it is a good bet if you are going after the Nobel prize!

- Dark energy shares many similarities with inflation. The experimental process has not asked all possible questions.

- We need to cross-correlate different regimes in cosmology.

THANK YOU!

Detailed plan of the presentation

- Title page 0 minutes
- Introduction 2 minutes
- A survey at theoretical problems 8 minutes
- The three contributions 9 minutes
- Embedding Inflation In the fundamental theory 11 minutes
- The cosmological constant vs Cosmology 13 minutes
- Classification and Testing of Cosmological Models 14 minutes
- Reheating 15 minutes
- Quantum Corrections to Inflation 17 minutes
- Other related questions 18 minutes
- Sanchez' Contribution 21 minutes
- Multaka' Contribution 24 minutes
- Outlook 25 minutes