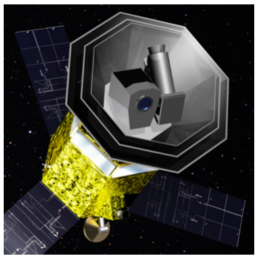

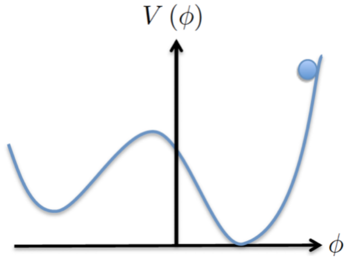


# IN2P3 Prospects 2020

GT05, Physique de l'inflation et énergie noire

GT01, Physique des particules

## ***SUSY Cosmic Inflation***
## **or when cosmology meets particle physics**

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# 1 Introduction

Slow-roll inflation models are often simply defined by theoretically motivated inflationary potentials, described by some parameters, associated to one or several scalar fields, allowing to estimate whether a model is favored or not based on inflationary observables. This is a very important topic to dig into in the coming years, and is addressed in another proposal to the IN2P3 prospective, namely Cosmic Inflation I: Theory, that we fully support. Still such models explorations do not provide a coherent description of the physics from the high energy scale of inflation and beyond to the lower energy scales.

In that prospect, the still-alive supersymmetric models (MSSM, NMSSM...) are very attractive as they provide a theoretical framework that allows to describe both the inflation era (as it naturally encompasses flat directions that provide a way for inflation to occur), and the physics at the LHC. Such a theory can predict multiple observables (from both cosmology and high-energy physics - HEP) that can then be compared to measurements to further assess the favored/disfavored area in the parameters space within a coherent description of our universe.

To derive the theory, to interface the various software tools, to study the shrink of the parameters space with respect to such and such observable, and eventually make forecasts, we need to reinforce the link between theoreticians and experimentalists, and between the HEP and cosmology communities. For this purpose we would highly benefit from a long term forum (as part of a GDR for instance) in which we could gather together.

# 2 Goals

Tackling the understanding of the physics of inflation is the next challenge of Cosmic Microwave Background (CMB) experiments. The observation of large scale polarization B-modes of the CMB offers a unique probe of fundamental physics at energies far beyond the reach of CERN's Large Hadron Collider, opening a new window toward primordial cosmology.

A key feature of this period of nearly exponential expansion of the Universe called inflation is that it stretches quantum fluctuations to cosmological scales. This phenomenon not only generates density perturbations, but in addition creates primordial gravitational waves. These gravitational waves persist and become imprinted in the CMB temperature and polarization anisotropies that CMB experiments, such as LiteBIRD and SO-SAT, aim at observing. It is needless to write at this point that we enthousiastically support, in parallel, the two related papers to the IN2P3 prospective.

The results of the Planck satellite strongly supports the hypothesis of inflation. The scalar spectral index of the primordial scalar power spectrum has been measured precisely, and is in agreement with slow-roll inflationary models: the potential of the inflaton should remain sufficiently flat at the energy scale of inflation so that slow-roll inflation can take place and generate the observed temperature and polarization anisotropies in the CMB we observe today. In parallel, the discovery of Higgs boson at the LHC adds more confidence in the role of scalar fields in fundamental physics. It also opens the door to the study of models in which inflation is generated by the Standard Model Higgs. Still the Standard Model (SM) of high energy physics does not give a clue on a particle dark matter (DM) candidate. Such DM candidates naturally emerge in supersymmetric (SUSY) theories, through the Lightest Supersymmetric Particles (LSP). In addition, such models (MSSM or NMSSM like) can provide natural candidates for the inflaton.

The goal of this work is to study the SUSY parameters that can successfully predict inflationary related observables in agreement with today's measurement/upper limits: the tensor to scalar ratio and $n_s$, the dark matter energy density, the Higgs mass, and rare B decays branching ratios but also masses of sparticles for which exclusion limits are measured at the LHC and WIMP-nucleons cross-sections accessible through dark matter direct searches. For this we rely on the fact that fixed running of the SUSY parameters connects masses and couplings during inflation with their values at the TeV scale. This connection, together with SUSY breaking and mediation asumptions, allows us to constrain our model simultaneously by CMB measurements as well as LHC and direct detection limits on the SUSY model space. Therefore we can answer the key questions what are the properties of a model that can accommodate all observed limits while reproducing the conditions for inflation, the measured relic density and the Higgs mass. Such a global analysis will offer insights into the dynamics of physics beyond the standard model. It will also give hints toward which plausible scenarios are in reach of collider searches that could eventually be explored by the High luminosity LHC run starting in 2021 and by the future LiteBIRD mission. One of the big challenge, from the theory side, is to be able to describe the physics from the Planck scale down to the LHC energy scale. To be able to perform such a study, we need to gather together experts of Supersymmetry, HEP and cosmological data analysis, and experts of inflationary physics from the theoretical, phenomenological and experimental points of view.

# 3 Scientific context

This project is the convergence of the SUSY parameter space exploration done either within the ATLAS collaboration (L. Duflot, S. Henrot-Versillé, N. Makovec, D. Zerwas) and/or with the SFitter tool(S. Henrot-Versillé, D. Zerwas), and the inflationary parameter space explored using ASPIC for which V. Vennin is an expert. It is further

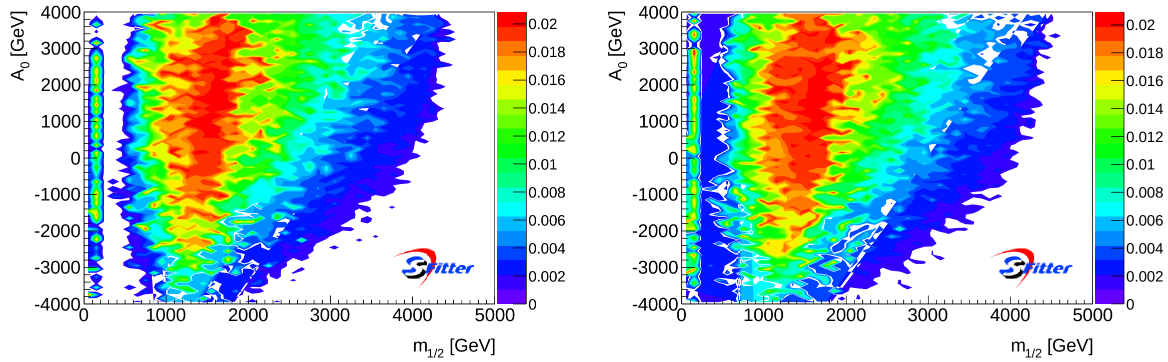



Figure 1: Profile likelihood projection onto the $(m_{1/2}, A_0)$ plane using the Planck (left) and WMAP (right) measurements (extracted from (4)).

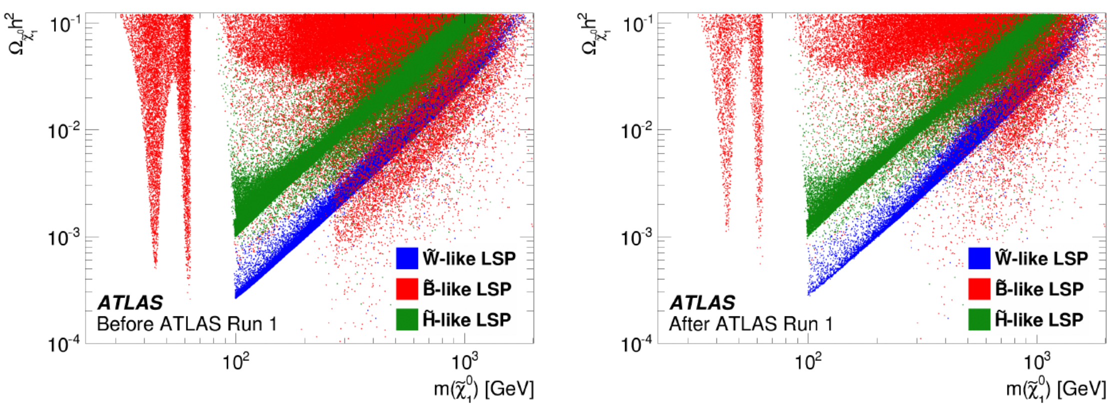
complemented by the expertise on CMB data analysis and cosmological parameters explorations (S. Henrot-Versillé, L. Montier, M. Tristram see for instance (1), (2), (3)), and by experts on SUSY observables predictions (G. Moultaka, D. Zerwas).

Examples of SUSY parameter space explorations encompassing most of the HEP measurements combined with the cold dark matter energy density are examplified in Fig.1 extracted from (4) for the mSUGRA and MSSM SUSY models. In this figure are compared the exclusion area of the $(m_{1/2}, A_0)$ parameter space of the mSUGRA model using Planck and WMAP $\Omega_{\mathrm{cdm}} h^2$. An exploration of the NMSSM parameter space has also been performed in (5).

This is further completed by the ATLAS exhaustive analysis of run I data in which most of us were involved (6) for which, among others thorough results, different types of LSP dark matter candidates were explored as illustrated by Fig. 2.

An example of inflationary parameter space exploration is shown in Fig.3. The predictions for the CMB spectral index and tensor-to-scalar ratio given by the generalised MSSM inflation model are compared with observational constraints from the Planck satellite mission. The $\alpha$ parameter shown here in the color bar is linked to SUSY microphysical parameters that can be further constrained by lower scale HEP processes observations.

Another important aspect of the inflationary scenario is the reheating epoch, during which the energy contained in the fields driving inflation decay into the other degrees of freedom of the standard model, and ordinary matter is created. This mechanism is driven by the coupling between the inflaton and the standard model. Most models of inflation remain elusive about these couplings, which explains why little is known about reheating. However, the dynamics of reheating plays an important role in determining the inflationary predictions since it sets the location of the observational window along the inflationary potential. If inflation is embedded in SUSY, couplings between the inflaton and the other fields can be made explicit, which offers the possibility to investigate reheating in more detail.




(a) Before ATLAS Run 1 (b) After ATLAS Run 1

Figure 2: The density of pMSSM points projected onto the plane of dark matter relic density versus LSP mass, before and after the constraints from the search analyses from (6).

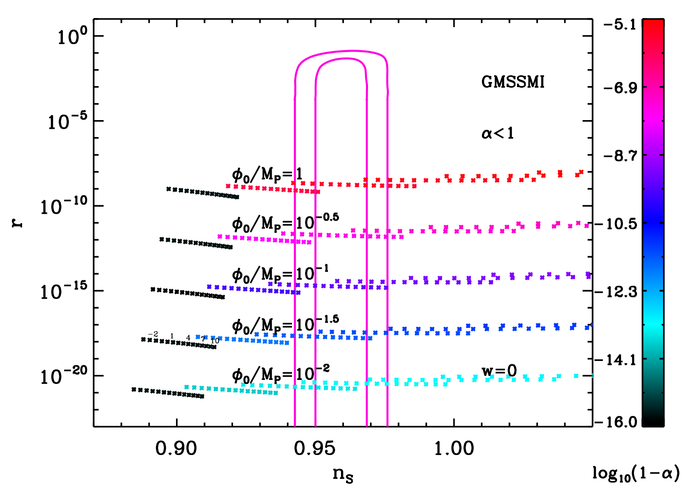



Figure 3: CMB spectral index $n_s$ and tensor-to-scalar ratio $r$ predicted by the generalised MSSM inflation model, for different values of $\phi_0$ and $\alpha$, that characterise the inflationary potential in this setup. The magenta lines are the one- and two-sigma contours of the Planck data (extracted from (7)).

# 4 Software Tools

SFitter (8) is an elaborate fitting tool that combines technical expertise with a high flexibility with respect to physics topics. The sophisticated treatment of statistical, systematic and theoretical uncertainties including their correlation lies at the heart of the fitting procedure. For an efficient analysis of the large SUSY parameter space we use a combination of fitting algorithms including cooling Markov Chains, Migrad and Minuit. The results are visualised in terms of one- and two-dimensional representations of the obtained limits in order to highlight correlations between model parameters. Finally the results are interpreted in a frequentist and a bayesian way which allows us to obtain a better handle on the uncertainties of the obtained limits.

To perform the calculation of superymmetric spectra, the spectrum calculator SuSpect will be used (9). SuSpect has been developed over the last 20 years by Gilbert Moultaka (L2C), Jean-Loic Kneur (L2C) and Abdelhak Djouadi (LAPP Annecy) to provide precise predictions for minimal supersymmetric extensions of the Standard Model such as the MSSM (low scale and high scale), anomaly mediated supersymmetry breaking (AMSB), gauge mediated supersymmetry breaking (GMSB) as well as mSUGRA (minimal supergravity). Dirk Zerwas has worked with Jean-Loic Kneur and Gilbert Moultaka on SuSpect3.

For the prediction of cosmological observable quantities we will use ASPIC developped by V. Vennin. Aspic provides Hubble flow functions, up to second order in the slow-roll approximation, which are in direct correspondence with the spectral index, the tensor-to-scalar ratio and the running of the primordial power spectrum. The API for communication with the spectrum calculator is the main technical challenge.

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