Minimal Inflation

Work in progress with C. Gómez and Raúl Jiménez

Inflation is over 30 years old

Originally Inflation was related to the horizon, flatness and relic problems

Nowadays, its major claim to fame is seeds of structure. There is more and more evidence that the general philosophy has some elements of truth, and it is remarkably robust…

Many of the features that agree with observation are rather model independent

Lately Planck and WMAP9 have provided interesting measurements on Non-Gaussianity

Origins of Inflation

The number of models trying to generate inflation is (very) large. Frequently they are not very compelling and with large fine tunings.

Different UV completions of the SM provide alternative scenarios for cosmology, and it makes sense to explore their cosmic consequences. Hence any such theories lead to some variations on Cosmology and/or inflation.

Basic properties

Enough slow-roll to generate the necessary number of e-foldings and the necessary seeds for structure.

A (not so-) graceful exit from inflation, otherwise we are left with nothing.

A way of converting "CC" into useful energy: reheating.

Everyone tries to find "natural" mechanisms within its favourite theory.

Supersymmetry is our choice

In the standard treatment of global supersymmetry the order parameter of supersymmetry breaking is associated with the vacuum energy density. More precisely, in local Susy, the gravitino mass is the true order parameter.

Having a vacuum energy density will also break scale and conformal invariance.

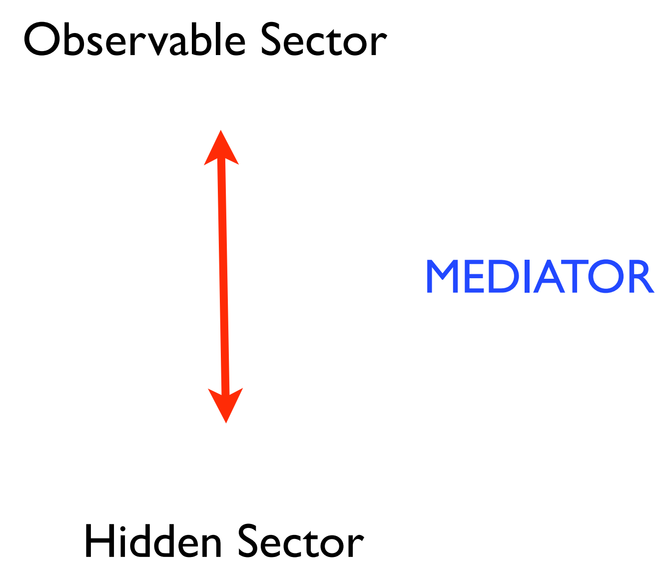
When supergravity is included the breaking mechanism is more subtle, and the scalar potential far more complicated.

Needless to say, all this assumes that supersymmetry exists in Nature

An important remark: We use supersymmetry breaking itself to generate inflation. Not include inflation in a supersymmetric field theory and then break supersymmetry independently. This gives highly non-trivial constraints if one takes into account that the current cosmological constant is nearly zero

It provides naturally an inflaton and a graceful exit

SSB Scenarios



It is normally assumed that SSB takes places at scales well below the Planck scale. The universal prediction is then the existence of a massless goldstino that is eaten by the gravitino. However in the scenario considered, the low-energy gravitino couplings are dominated by its goldstino component and can be analyzed also in the global limit.

This often goes under the name of the Akulov-Volkov lagrangian, or the non-linear realization of SUSY

$$m_{3/2} = \frac{f}{M_p} = \frac{\mu^2}{M_p} \qquad \begin{array}{ccc} \mu & \to & \infty \\ M & \to & \infty \end{array} \qquad m_{3/2} \text{ fixed}$$

Flat directions

One reason to use SUSY in inflationary theories is the abundance of flat directions. Once SUSY breaks most flat directions are lifted, sometime by non-perturbative effects. However, the slopes in the potential can be maintained reasonably gentle without excessive fine-tuning. The symmetries of the superpotential become complexified:

$$G \to G^c$$

For flat Kahler potentials, and F-term breaking, there is always a complex flat direction in the potential. A general way of getting PSGB, the key to most susy models. The property below holds for any W breaking SUSY.

Most models of supersymmetric inflation are hybrid models (multi-field models, chaotic, waterfall...)

$$\begin{aligned} F &= -\partial W(\phi) \\ V &= \partial W(\phi)\,\overline{\partial W(\phi)} \end{aligned}$$

$$V(\phi + z\langle F\rangle) = V(\phi)$$

R-symmetry explicitly broken

$$\Phi(x,\theta) \to e^{iq\,\alpha}\,\Phi(x, e^{i\alpha}\,\theta)$$

The R-symmetry is explicitly broken to a discrete subgroup

An explicit R-symmetry does not allow a soft mass for the gluinos

If it is spontaneously broken, the light axion field generated has generically unacceptable couplings.

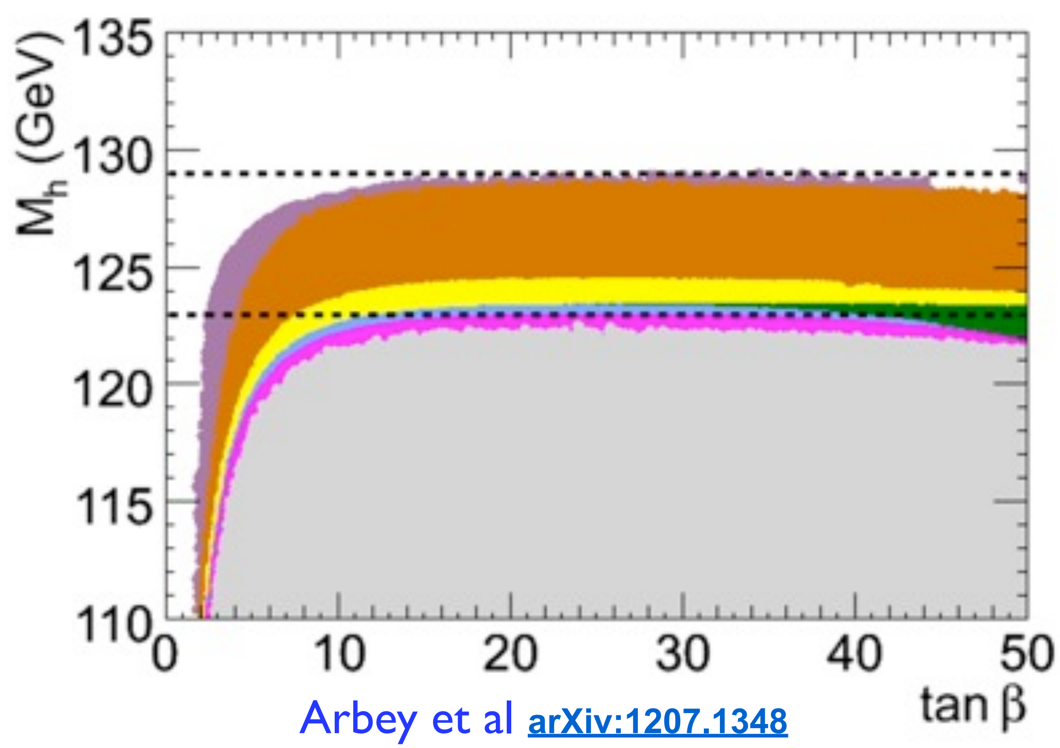
Furthermore, since we need to include (super)gravity, it is a necessary condition to solve the η-problem that plagues many of these theories

News from SUSY

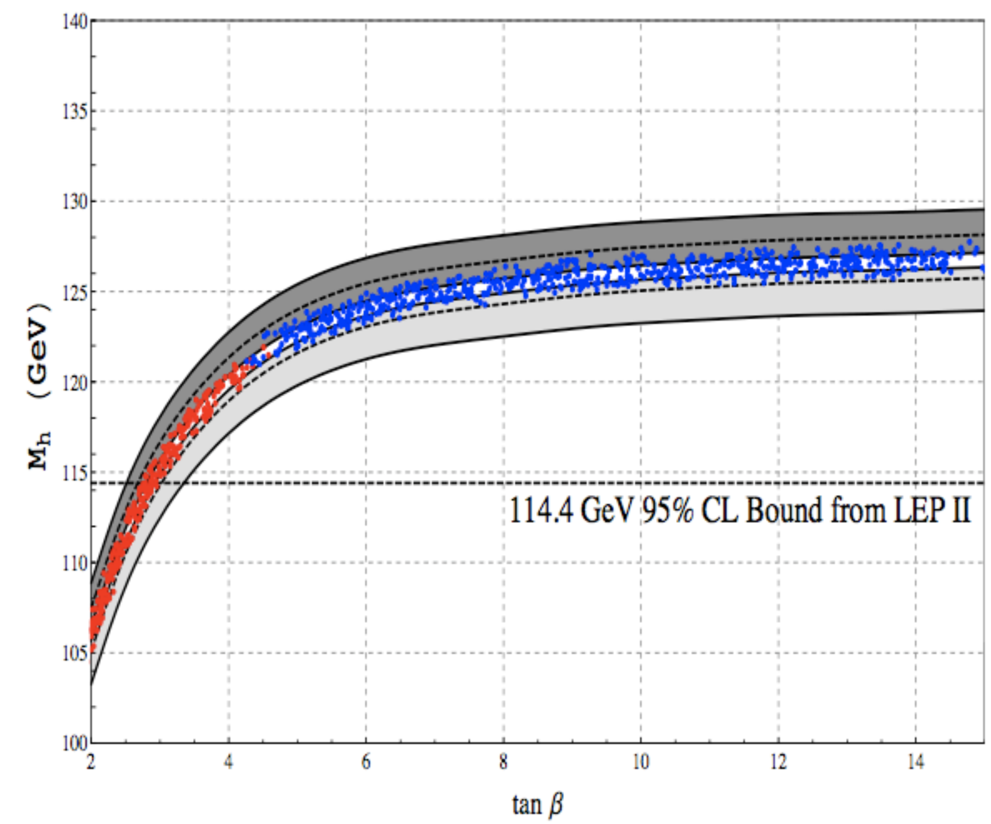
Not very good so far. No experiment has yet given any positive evidence. Many superpartners have their masses pushed about the ½ TeV scale.

Can we read off the supersymmetry breaking scale from the sky?

This is the purpose of our scenario



Arbey et al arXiv:1207.1348



Acharya, Kane & Kumar: arXiv:1204.2795

Important properties of SSB

The starting point of their analysis is the Ferrara-Zumino (FZ) multiplet of currents that contains the energy-momentum tensor, the supercurrent and the R-symmetry current (we follow the presentation of Komargodski and Seiberg)

$$J_\mu = j_\mu + \theta^\alpha S_{\mu\alpha} + \overline{\theta}_{\dot\alpha} \overline{S}_\mu^{\dot\alpha} + (\theta\sigma^\nu\overline{\theta})\, 2T_{\nu\mu} + \dots$$

$$X = x(y) + \sqrt{2}\theta\psi(y) + \theta^2 F(y)$$

$$\psi_\alpha = \frac{\sqrt{2}}{3}\sigma^\mu_{\alpha\dot\alpha}\overline{S}^{\dot\alpha}_\mu, \qquad F = \frac{2}{3}T + i\partial_\mu j^\mu$$

$$\overline{D}^{\dot\alpha} J_{\alpha\dot\alpha} = D_\alpha X$$

General Local Lagrangian

$$S=\int d^4\theta K(\Phi^i,\bar{\Phi}^{\bar{i}}) + \int d^2\theta W(\Phi^i) + \int d^2\bar{\theta}\bar{W}(\bar{\Phi}^{\bar{i}})$$

$$J_{\alpha\dot{\alpha}} = 2g_i(D_\alpha\Phi^i)(\bar{D}_{\dot{\alpha}}\bar{\Phi}) - \tfrac{2}{3}[D_\alpha,\bar{D}_{\dot{\alpha}}]K + i\partial_\alpha(Y(\Phi) - \bar{Y}(\bar{\Phi}))$$

$$X = 4W - \frac{1}{3}\overline{D}^2 K - \frac{1}{2}\overline{D}^2 Y(\Phi)$$

X is a chiral superfield, microscopically it contains the conformal anomaly (the anomaly multiplet), hence it contains the order parameter for SUSY breaking as well as the goldstino field. It may be elementary in the UV, but composite in the IR. Generically its scalar component is a PSGB in the UV. This is our inflaton. The difficulty with this approach is that WE WANT TO BREAK SUSY ONLY ONCE! unlike other scenarios in the literature, and cancelling the cosmological constant today yields very strong constraints on the inflationary parameters. This is why we call this scenario minimal inflation.

The key observation is: X is essentially unique, and:

$$X \to X_{NL} \qquad X_{NL}^2 = 0$$

$$UV \to IR$$

$$SPoincare/Poincare$$

Some IR consequences

$$L = \int d^4\theta\, X_{NL}\overline{X}_{NL} + \int d^2\theta\, f\, X_{NL} + c.c.$$

$$X_{NL} = \frac{G^2}{2F} + \sqrt{2}\theta G + \theta^2 F$$

This is precisely the Akulov-Volkov Lagrangian

Coupling goldstinos to other fields: reheating

We can have two regimes of interest. Recall that a useful way to express SUSY breaking effects in Lagrangians is the use of spurion fields. The gluino mass can also be included...

$$m_{soft} << E << \Lambda$$

The goldstino superfield is the spurion

$$\int d^4\theta \left|\frac{X_{NL}}{f}\right| m^2\, Qe^V\overline{Q} + \int d^2\theta \frac{X_{NL}}{f}(B\,Q\,Q + AQ\,Q\,Q\,) + c.c.$$

$$E << m_{soft}$$

Integrate out the massive superpartners adding extra non-linear constraints

$$X_{NL}^2 = 0, \qquad X_{NL}\,Q_{NL} = 0$$

For light fermions, and similar conditions for scalars, gauge fields,...

Reheating depends very much on the details of the model, as does CP violation, baryogenesis...

Some details

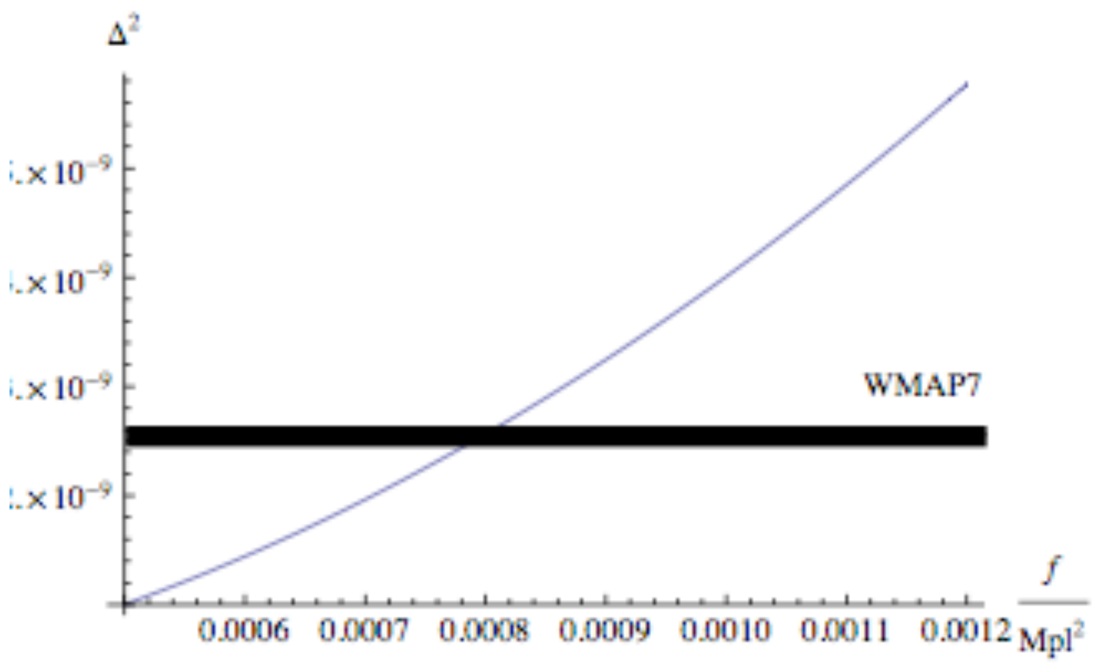
An important part of our analysis is the fact that the graceful exit is provided by the Fermi pressure in the Landau liquid in which the state of the X-field converts once we reach the NL-regime. This is a little crazy, but very minimal however...

$$K(X,\bar{X}) \;=\; X\bar{X}\left(1+\frac{a(X+\bar{X})}{2M}-\frac{bX\bar{X}}{6M^2}-\frac{c\left(X^2+\bar{X}^2\right)}{9M^2}+\dots\right)-2M^2\log\left(\frac{X+\bar{X}}{M}+1\right)$$

$$W(X) \;=\; f_0 \,+\, f\,X$$

$$V = e^{\frac{K}{M^2}}(K^{-1}_{X,\bar{X}}DW\bar{D}W-\frac{3}{M^2}|W|^2) \qquad DW \;=\; \partial_X W \,+\, \frac{1}{M^2}\partial_X K\,W$$

Primordial density fluctuations



$$\sqrt{f} \sim 10^{11-13}\,\mathrm{GeV}$$

$$\epsilon = \frac{M_{pl}^2}{2}\left(\frac{V'}{V}\right)^2, \qquad \eta = M_{pl}^2 \frac{V''}{V};$$

$$\begin{aligned} n_S &= 1 - 6\epsilon + 2\eta, \\ r &= 16\epsilon \\ n_t &= -2\epsilon, \\ \Delta_R^2 &= \frac{V M_{pl}^4}{24\pi^2\epsilon}. \end{aligned}$$

Choosing useful variables

$$z = M(\alpha + i\beta)/\sqrt{2}$$

$$ds^2 = 2g_{z\bar{z}} ds d\bar{z} = \partial_z \partial_{\bar{z}} K(\alpha, \beta) M^2 (d\alpha^2 + d\beta^2)$$

$$S = L^3 \int dt a^3 \left(\frac{1}{2} g(\alpha, \beta) M^2 (\dot{\alpha}^2 + \dot{\beta}^2) - f^2 V(\alpha, \beta) \right)$$

$$t = \tau M/f \qquad S = L^3 f^2 m_{3/2}^{-1} \int d\tau a^3 \left(\frac{1}{2} g(\alpha, \beta)(\alpha'^2 + \beta'^2) - V(\alpha, \beta) \right)$$

Cosmological equations

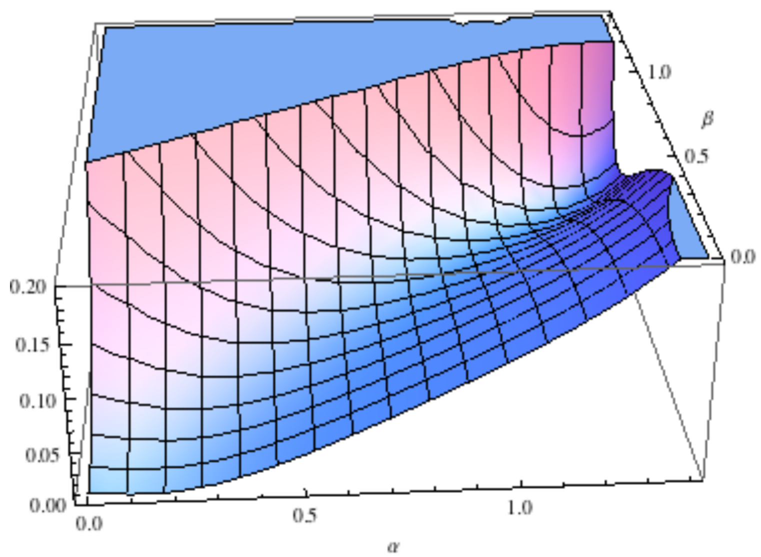
The full equations of motion, without fermions

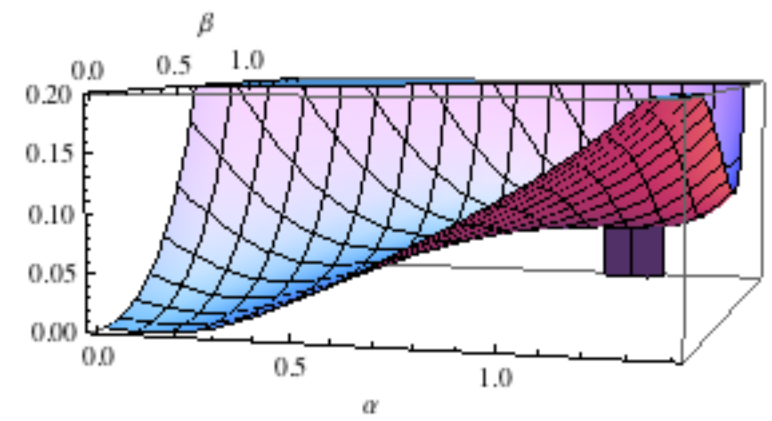
$$\begin{aligned}
\alpha'' + 3\frac{a'}{a}\alpha' + \frac{1}{2}\partial_\alpha \log g(\alpha'^2 - \beta'^2) + \partial_\beta \log g\alpha'\beta' + g^{-1}V'_\alpha &= 0 \\
\beta'' + 3\frac{a'}{a}\beta' + \frac{1}{2}\partial_\beta \log g(\beta'^2 - \alpha'^2) + \partial_\alpha \log g\alpha'\beta' + g^{-1}V'_\beta &= 0 \\
\frac{a'}{a} = \frac{H}{M_{3/2}} = \frac{1}{\sqrt{3}}\left(\frac{1}{2}g(\alpha'^2 + \beta'^2) + V(\alpha,\beta)\right)
\end{aligned}$$

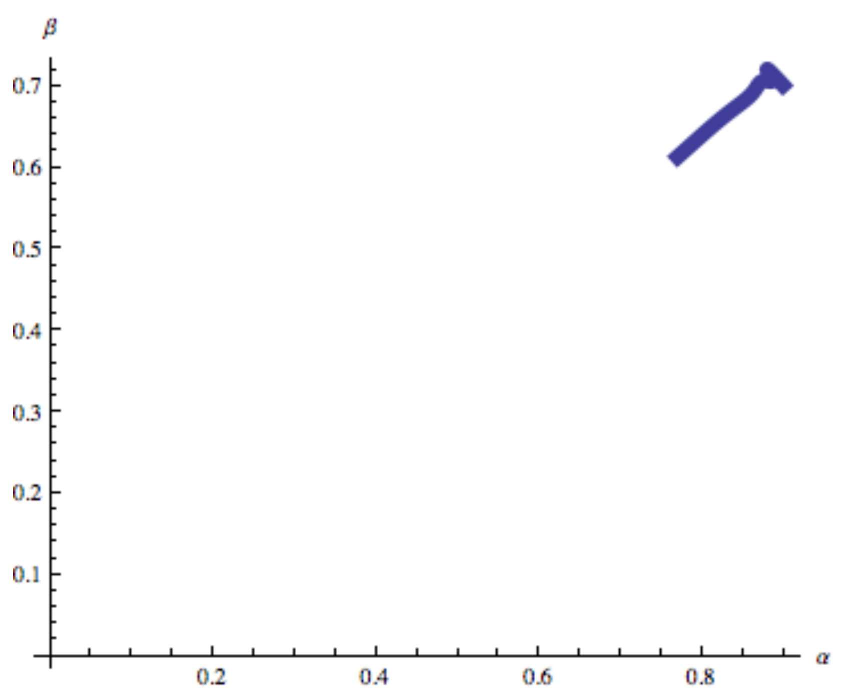
Looking for the attractor and slow roll implies that the geodesic equation on the target manifold is satisfied for a particular set of initial conditions. This determines the attractor trajectories in general for any model of hybrid inflation. Numerical integration shows how it works. We have not tried to prove "theorems' but there should be general ways of showing how the attractor is obtained this way

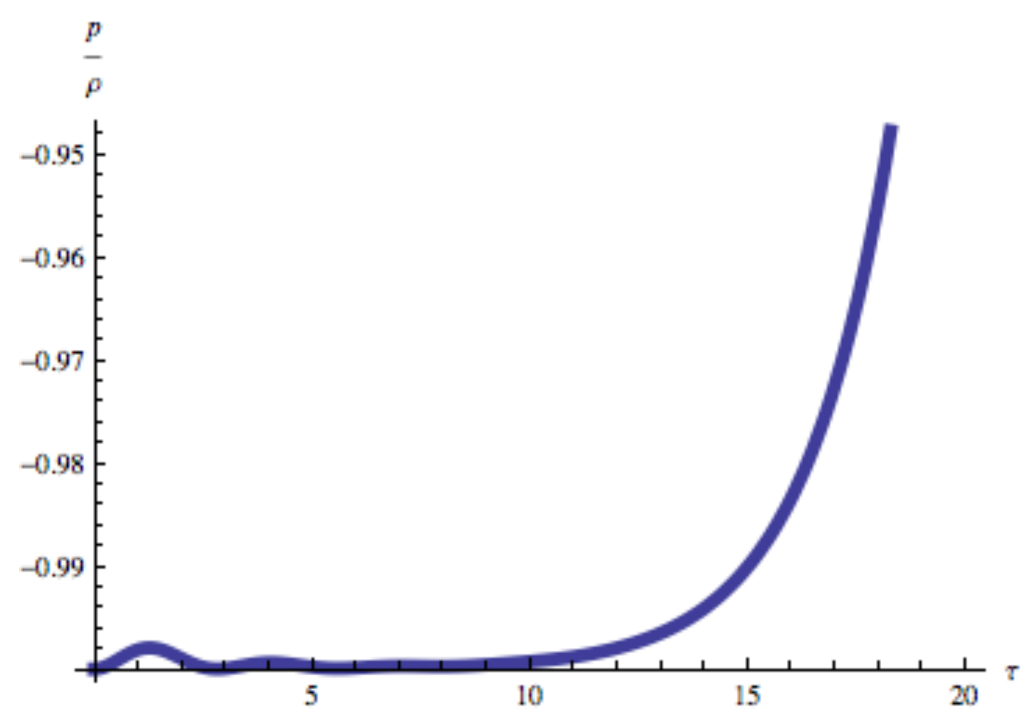
$$D\dot{\Phi}^i/dt \sim 0 \qquad\qquad H = \sqrt{\frac{1}{18}}\left(3V + \sqrt{6V' + 9V^2}\right)$$

Trajectories with more than the observed 12 e-folding a=0, b=1, c=-1.5

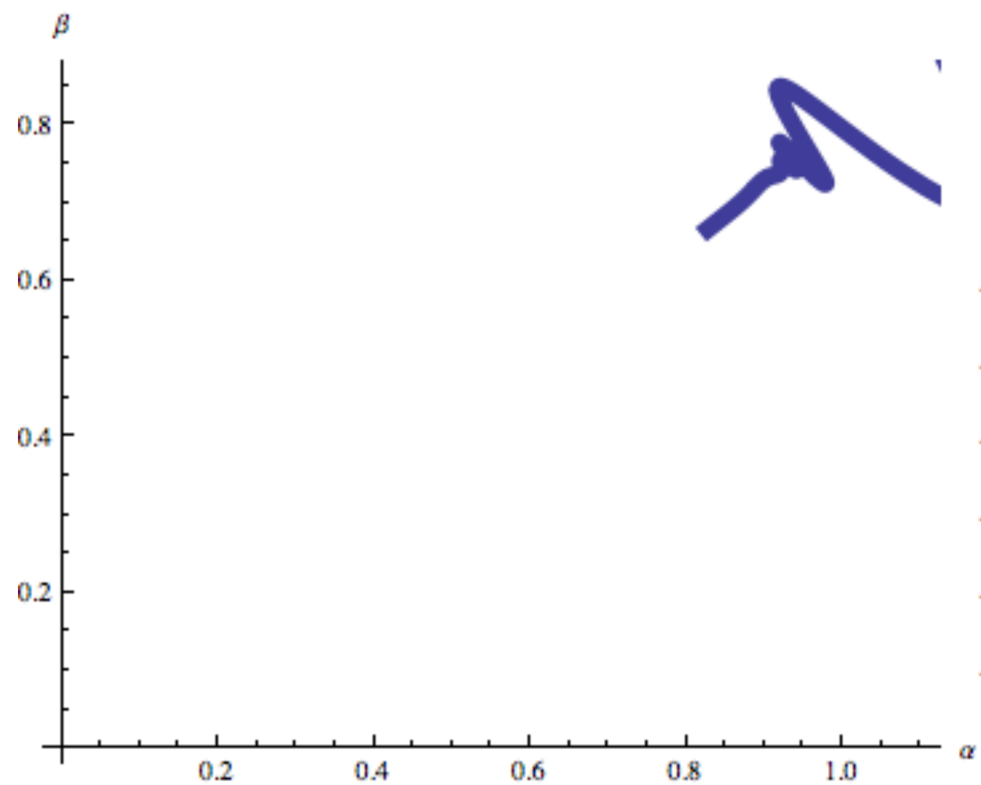


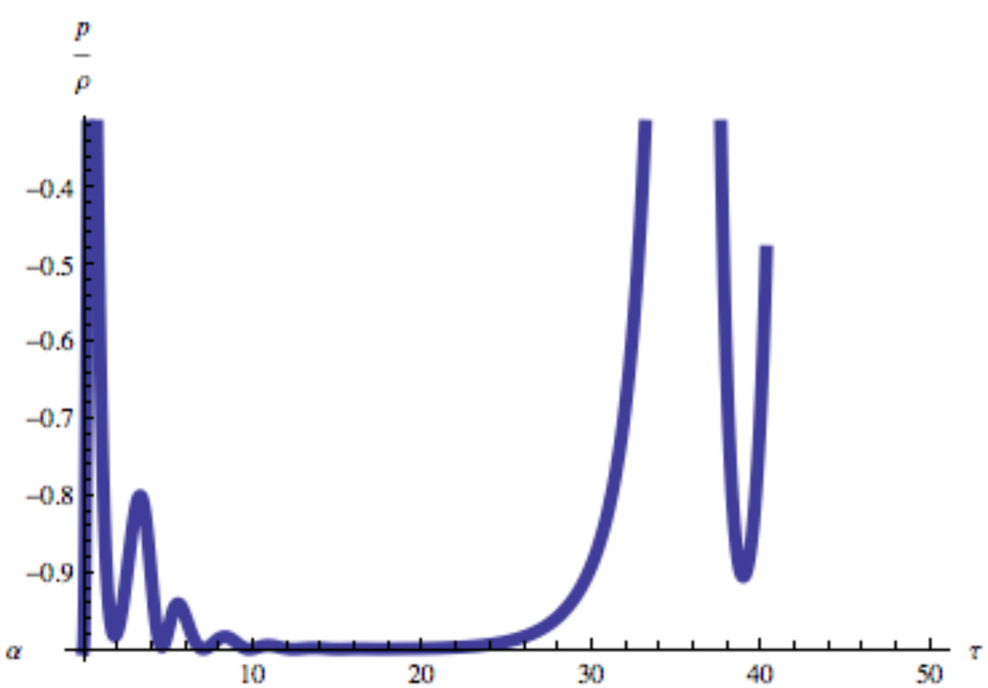




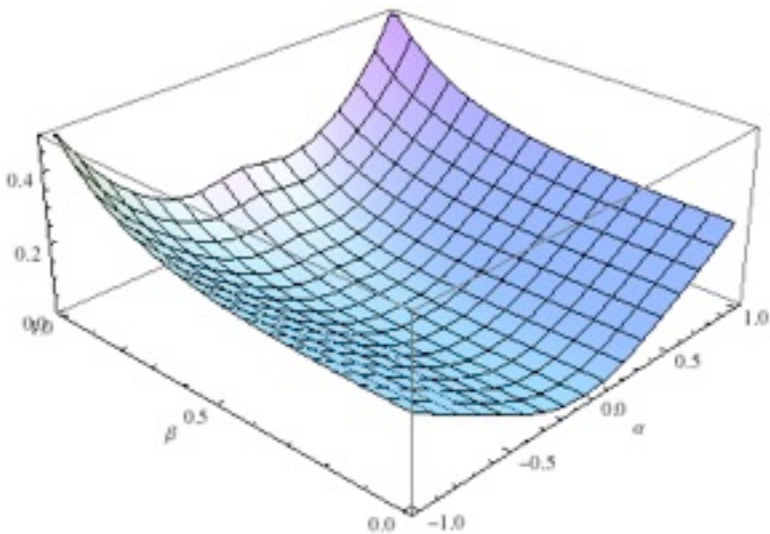


One more example

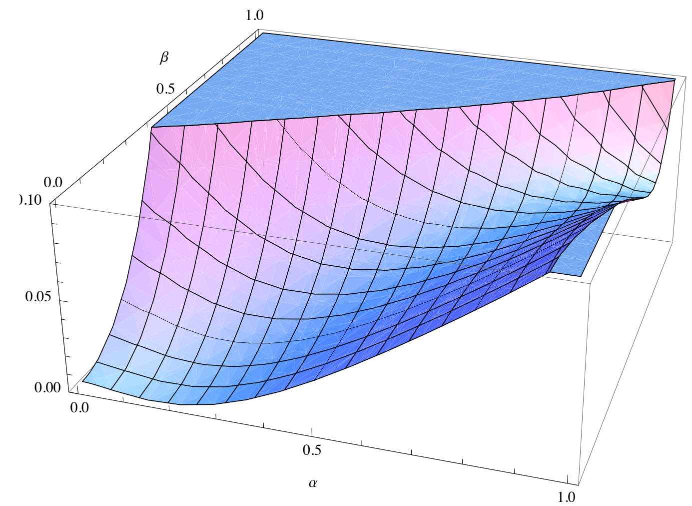




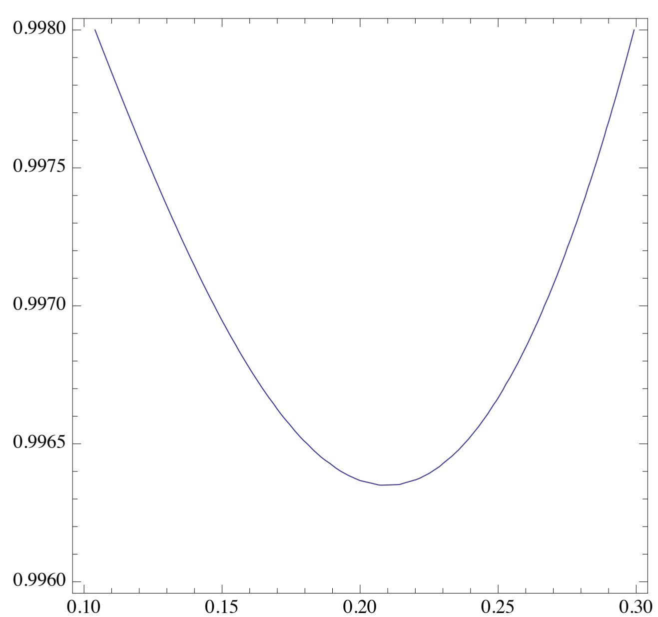
The scalar potential

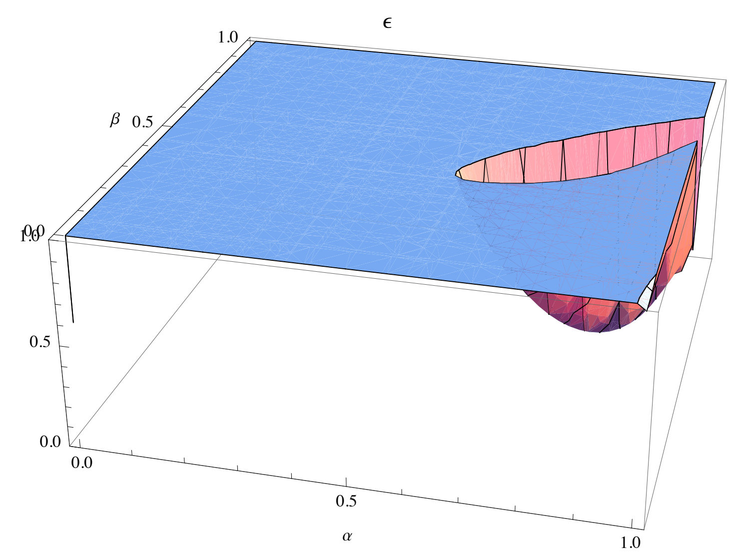


a=0, b=1, c=0



a=0, b=1, c=-1.7



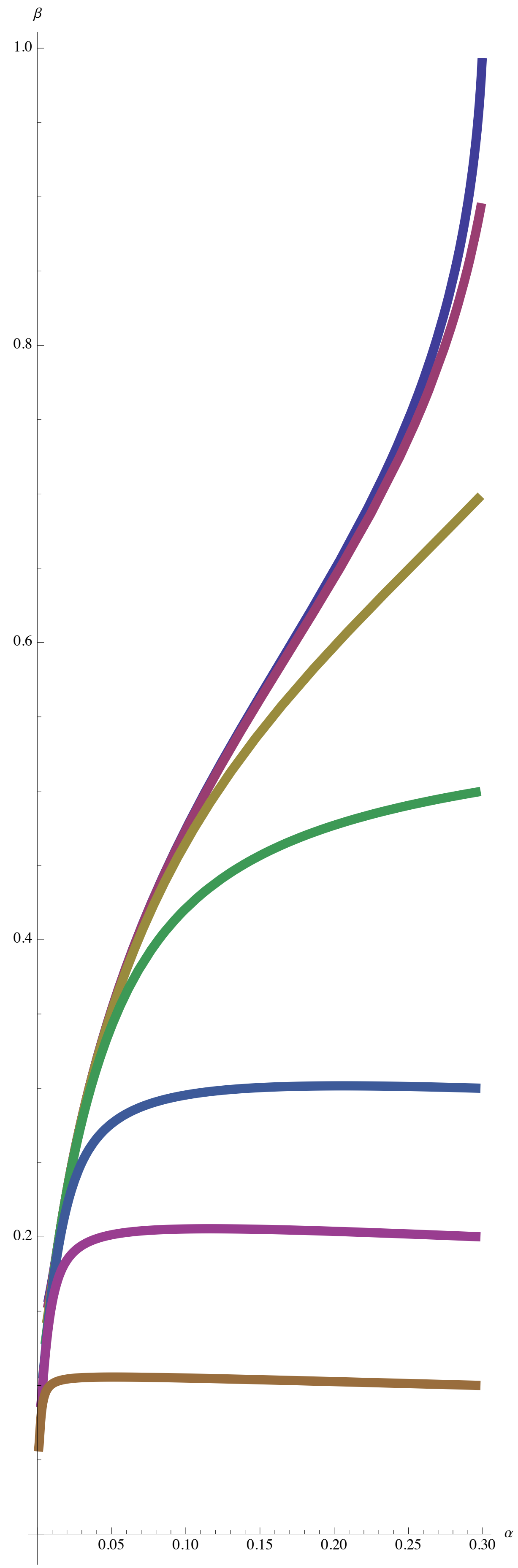


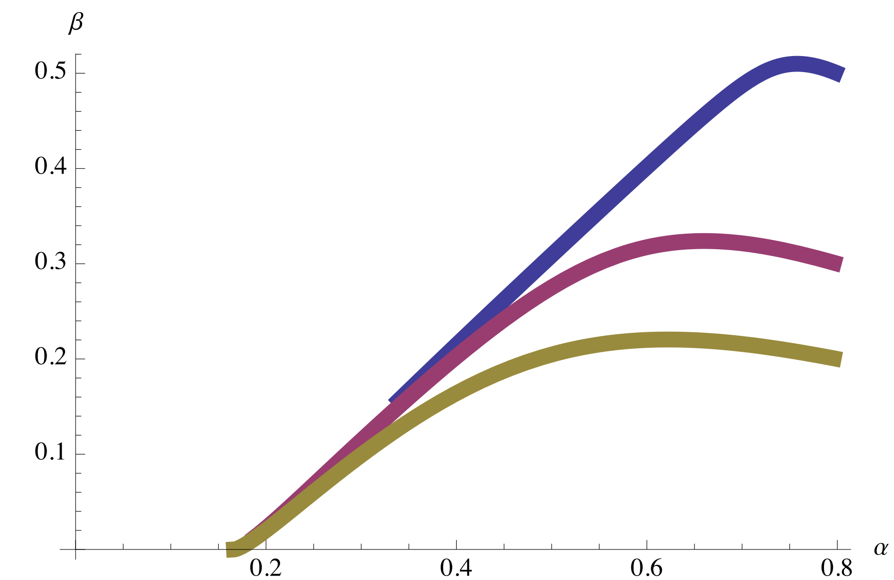
$$
\begin{aligned}
H^2 &= \frac{8\,\pi\,G}{3}\left(\frac{1}{2}G_{ij}\dot{X}^i\,\dot{X}^j + V(X)\right) \\
\frac{D\dot{X}^i}{dt} &+ 3\,H\,\dot{X}^i + G^{ij}\,\partial_j\,V = 0,
\end{aligned}
$$

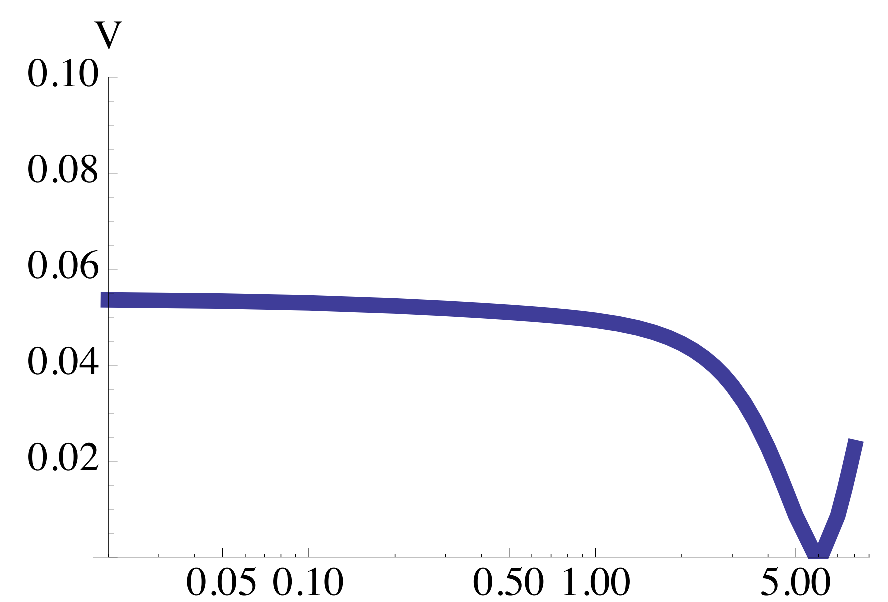
$$
\ddot{z} + \partial_z \log G\,\dot{z}^2 + 3\,H\,\dot{z} + G^{-1}\,\partial_{\bar{z}}\,V = 0.
$$

$$
\frac{d\,E[X]}{dt} = -3\,H\,G(\rho,\theta)\,(\dot{\rho}^2 + \rho^2\,\dot{\theta}^2), \qquad z = \rho\,e^{i\,\theta}
$$

Attractor and inflationary trajectories







Nearly a textbook example of inflationary potential

Decoupling and the Fermi sphere

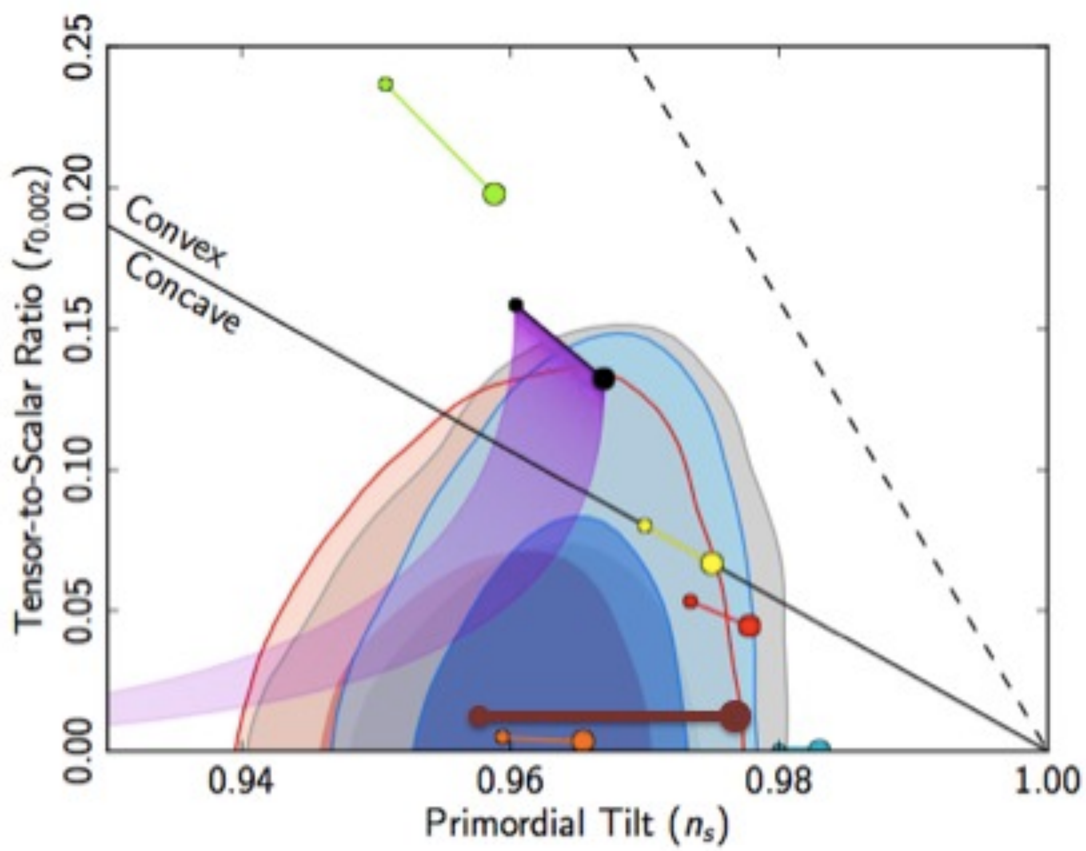
$$\eta = (\frac{m_{\rm INF}}{m_{3/2}})^2$$

The energy density in the universe (f^2) contained in the coherent X-field quickly transforms into a Fermi sea whose level is not difficult to compute, we match the high energy theory dominated by the X-field and the Goldstino Fock vacuum into a theory where effectively the scalar has disappeared and we get a Fermi sea, whose Fermi momentum is

$$q_F = \sqrt{\frac{f}{\eta}}$$

To produce the observed number of particles in the universe leads to gravitino masses in the 10-100 TeV region.

Our models in the Planck plot

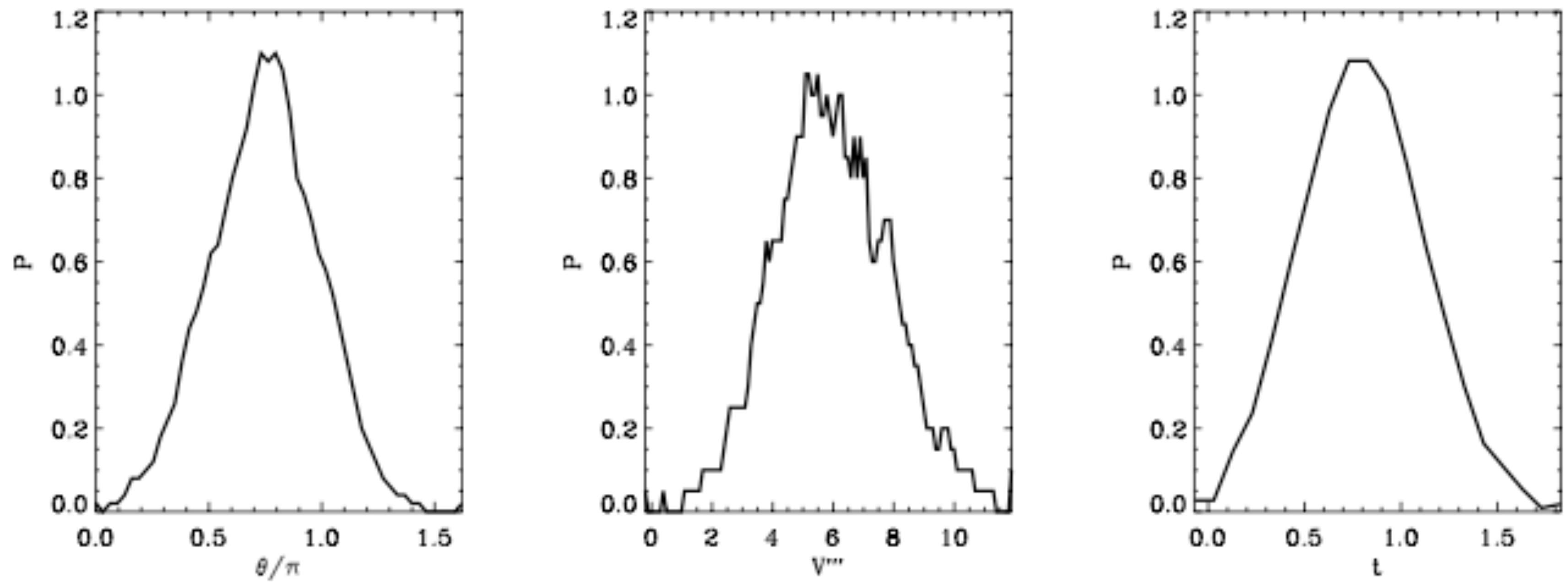


Non-Gaussianities

In our theory we naturally have two fields, and before we enter the inflationary regime, there is some slashing back and forth. Regarless of the initial velocity (within limits) the nonlinear friction slows down the field rapidly, entering into an effective single field regime. From Chen (2006):

$$f_{NL}^{\rm int} = \alpha(\nu)\frac{1}{P_\zeta^{1/2}}\left(\frac{-V'''}{H}\right)\left(\frac{\dot{\theta}_0}{H}\right)^3$$

Parameter distributions



For most trajectories which can generate 40-50 efoldings. Nongaussianities are generated at large scales, comparable to the horizon scale today, and scales of the size of dwarf galaxies. This is the typical behaviour for most trajectories.

$$\sqrt{f} = \frac{\sqrt{f_{\rm NL}}}{10^5} M$$

Once again we get relatively high values for supersymmetry breaking but below 10^{14} GeV

Summary of our scenario

We take as the basic object the X field containing the Goldstino. Its scalar component above SSB behaves like a PSGB and drives inflation

Its non-linear conversion into a Landau liquid in the NL regime provides an original graceful exit, in our case the conversion is not complete and we get a dark universe with goldstinos and inflatons. The conversion is not complete because the mass relations are such that the inflaton is not much heavier than the goldstinos. We get a hybrid universe populated by dark objects. The next step would be to work out some simple scenario for reheating.

Reheating can be obtained through the usual Goldstino coupling to low energy matter

In the simplest of all possible such scenarios, the Susy breaking scale is fitted to be of the order of 10^{13-14} GeV, m of the order of 10-100 TeV (the plot from Kane et al).

It is interesting that for a range of parameters, the conclusions we draw from NG agree with the fit to fluctuations.

We believe that our ideas show that the general properties of supersymmetry breaking in a supergravity context provide a natural description of inflation in terms of a hybrid field that avoid the standard no-go theorems on non-gaussianity. It seems a robust scenario as required by inflation.

Thank you