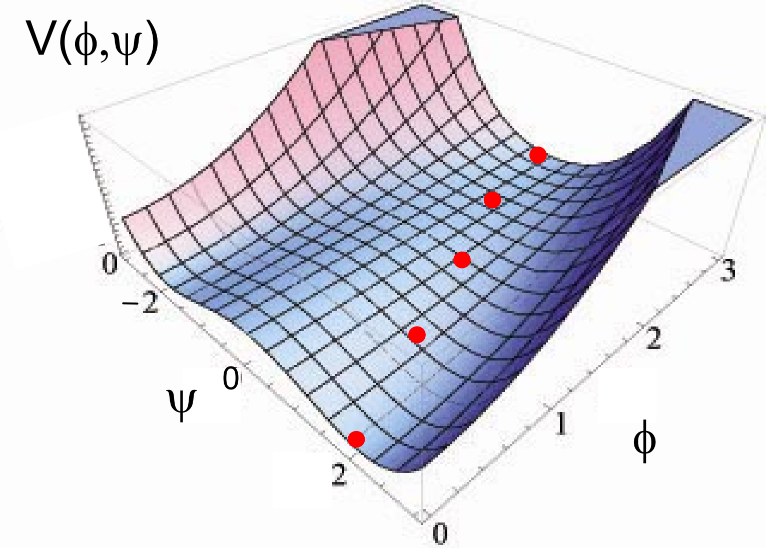
J. Stefan Institute, Ljubjana, May 28th 2009

Challenges for hybrid inflation : SUSY GUTs, n_s & initial conditions



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Jeannerot, J.R., Sakellariadou PRD 03;

J.R., M. Sakellariadou JCAP 05;

S. Clesse, J.R., PRD 09

(+ S. Clesse, Ringeval, J.R. in prep;
Bajc, Mazumdar, J.R., in prep)

Outline

Introduction : From the CMB to hybrid inflation

Part A : Embedding hybrid inflation in SUSY GUTs

1. Embedding the fields and superpotential ?
2. Genericity of cosmic strings formation in SUSY GUTs
3. Constraints from the CMB

Part B : Non-SUSY model : is there a spectral index problem ?

Part C : Two-field dynamics and initial conditions

1. Exact dynamics of 2-field inflation
2. Grids of initial conditions and trajectories in the field space
3. Effects of the potential parameters
4. SUSY/SUGRA effects ? Non-renormalizable terms ?

Conclusions and open questions

Intro : From CMB to inflation

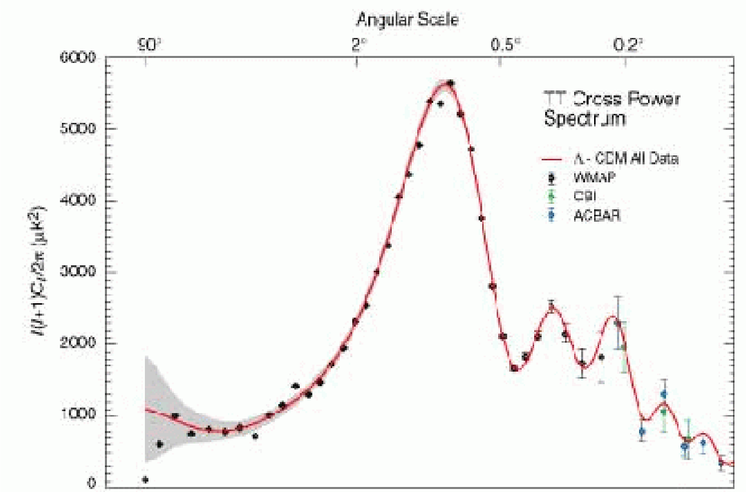
WMAP observed of CMB anisotropies with highest resolution :

Image of the power-spectrum of primordial fluctuations : mostly gaussian, adiabatic

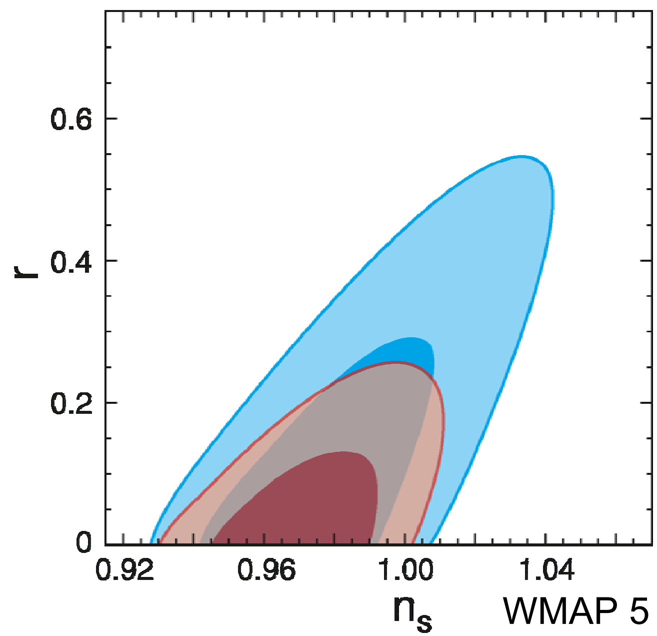
$P_s(k) = A_s\ (k/k_0)^{ns-1}$

$P_T(k) = A_T\ (k/k_0)^{nT}$

$r = A_T/A_S$



WMAP



WMAP 5

Inflation = easiest way to explain scale invariant power-spectrum + resolution to horizon problem, monopole problem.

3 main classes of models :

Power-law $V(\phi)\ \alpha\ \phi^p$: $n_s < 1$, $r >>$

Exponential $V(\phi)\ \alpha\ Exp(\phi/\mu)$: $n_s < 1$, $r >>$

Hybrid $V(\phi)\ \alpha\ 1+ (\phi/\mu)^p$: $n_s > 1$, $r <<$

[J. Martin 03]

Hybrid models of inflation

- Introduced to account for CMB normalization without fine-tuning (chaotic inflation requires $\lambda \sim 10^{-14}$)

Original version $$V(\phi,\psi) = \frac{1}{2}m^2\phi^2 + \frac{\lambda'}{2}\phi^2\psi^2 + \frac{\lambda}{4}\left(\psi^2 - M^2\right)^2$$

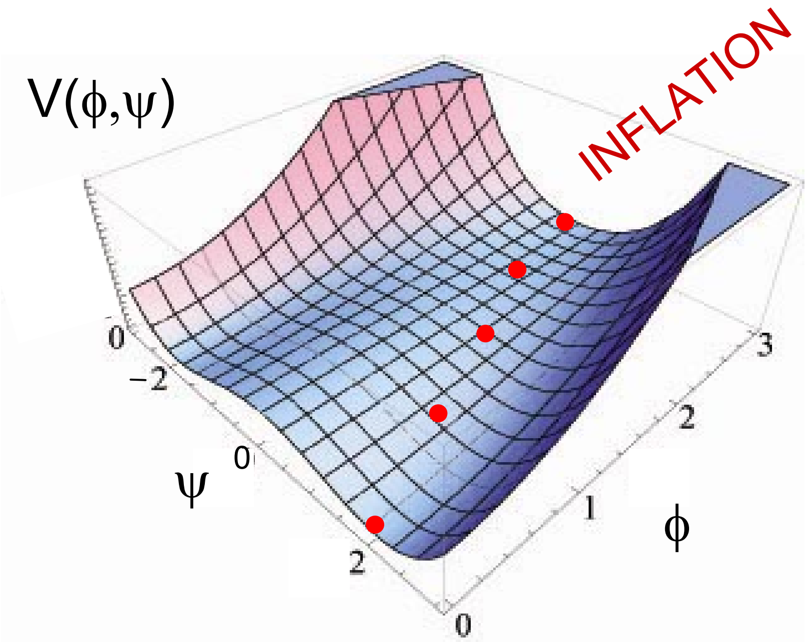
[Linde 93, Copeland et al 94]

SUSY version : “F-term” $$W^F = \kappa S(\Sigma\overline{\Sigma} - M^2)$$

[Dvali, Shafi, Schaefer 94]

- Motivations : High Energy/Particle Physics :
  - Models to study coupling inflaton / other scalar fields (Higgs field(s) of SM or GUT, sfermions of SUSY, moduli of string theory, …)
  - “Easily” embedded in (SUSY) GUT [Jeannerot 97, Jeannerot, J.R., Sakellariadou 03]
  - A F-term and D-term version exist in SUSY/SUGRA. Stable against radiative corrections, SUGRA corrections, SUGRA from SCFT [Copeland et al 94, Dvali et al 94, Dvali et al 04, J. R. & Sakellariadou 06]
  - P-term in extended (N=2) SUGRA [Kallosh & Linde 03]
  - In string theory, brane inflation ~ hybrid D-term model [Dvali & Tye 02]

- Properties :
  - Power law model coupled to a Higgs field
  - Standard dynamics : inflation realized @ large ϕ with $<\psi>=0$. At ϕ_{crit}, ψ becomes tachyonic and $<\psi>=M$.
  - Inflation ends by an SSB.



- Is there a topological defect problem ?
  - Yes if formation of monopole
  - Generic formation of cosmic (super)strings at the end of (brane) SUSY version. How generic? Consequences ?

  $\Rightarrow$ Part A

- Is there a spectral index problem ?

$\Rightarrow$Part B

- Is there an initial conditions problem ?

$\Rightarrow$ Part C

Part A : Embedding in SUSY GUT

1. Embedding the fields and the superpotential

Embedding F-term hybrid inflation in minimal SUSY SO(10) ?

$$W^F = \kappa S(\Sigma\overline{\Sigma} - M^2)$$

Σ and $\overline{\Sigma}$ generically break B-L symmetry, Σ=**126**, $\overline{\Sigma}$=**$\overline{126}$**, (see next slide).

Embedding F-term hybrid inflation in minimal SUSY SO(10) ? [Bajc, et al 2004]

Most general superpotential :

$$W^{SO(10)} = f(\Phi_{210}, \Sigma_{126}, \overline{\Sigma}_{\overline{126}}, H_{10})$$
$$= \eta\Phi\Sigma\overline{\Sigma} + m\Phi^2 + \lambda\Phi^3 + m_\Sigma\Sigma\overline{\Sigma} + m_H H^2 + \Phi H(\alpha\Sigma + \overline{\alpha}\overline{\Sigma})$$

Φ= candidate for the inflaton ? W contains the coupling with $126.\overline{126}$

- But impossible to write a gauge invariant term $M^2\Phi$. S = additional GUT singlet ?
- But only way to prevent "dangerous" terms = additional global U(1) with precise charge assignment : Q(S) ≠ 0. For Q(Φ), Q(H) impossible !

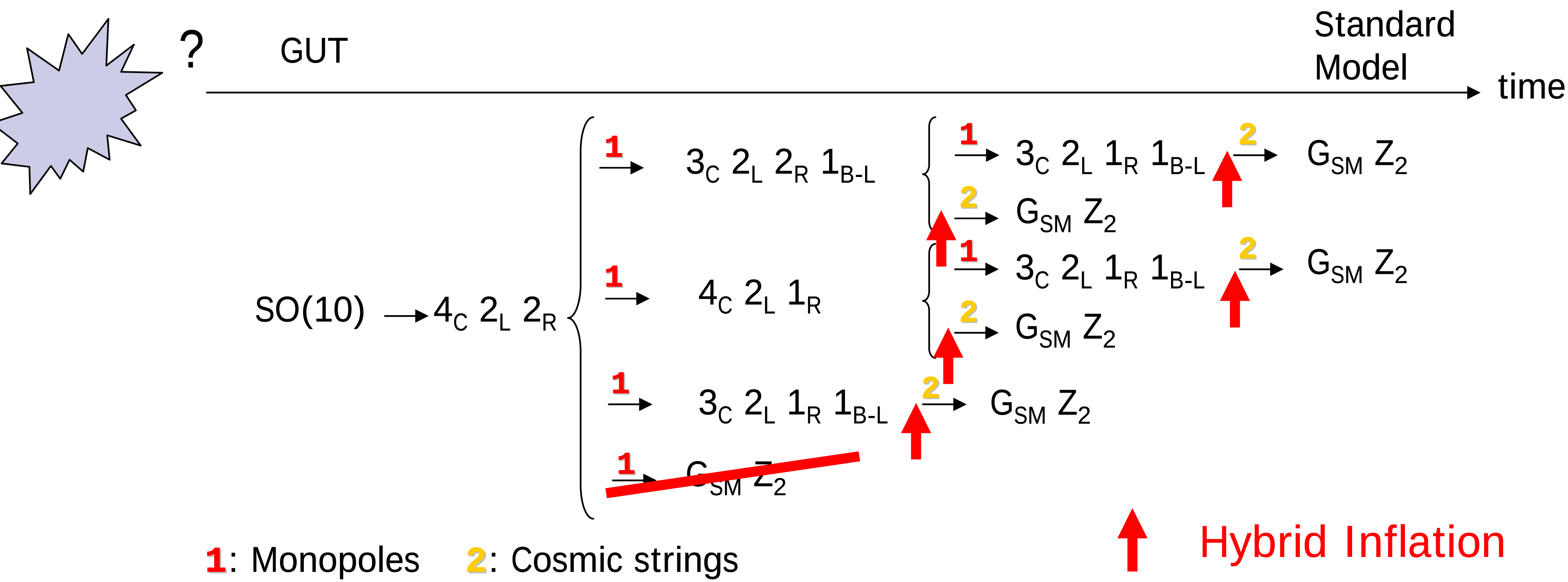
Hybrid inflation not fully embedded in SUSY GUTs, only coupled ?
Inflation at lower energy/symmetry than G_{GUT} could give effective W^F ?

2. How generic is the cosmic strings formation in SUSY GUTs ?

SUSY GUTs models considered :

- Models based on SU(n), SO(10), E_6.
- \+ most standard phenomenological ingredients :
- Proton life-time measurements (Super-Kamiokande) $\tau_P(p \to e^+\pi^0) > 6\times10^{33}$ yr
  Motivates :
  - Supersymmetry (M_{GUT} sufficiently high)
  - Z_2 of R-parity unbroken at low energy (Bonus = dark matter)
- Oscillations of solar and atmospheric neutrinos [Super-K, 98], …
  Requires mass to neutrinos (via See-saw)
  Requires B-L in G_{GUT} and broken at high energy (Bonus = leptogenesis)
- To explain the CMB data, solve the monopole problem, …, a phase of inflation (hybrid)

Ex. Let's assume $G_{GUT} = SO(10)$



Conclusion : for all possible scheme of all GUT group studied, cosmic strings generically form at the end of hybrid inflation $\mu \approx M_{infl}^2$

[Jeannerot, J.R., Sakellariadou PRD 2003]

Higgs fields responsible break B-L in SO(10) => link with neutrino & leptogenesis

Inflaton ? List the singlets at lower energy/symmetry [Bajc, Mazumdar, J.R. in prep]

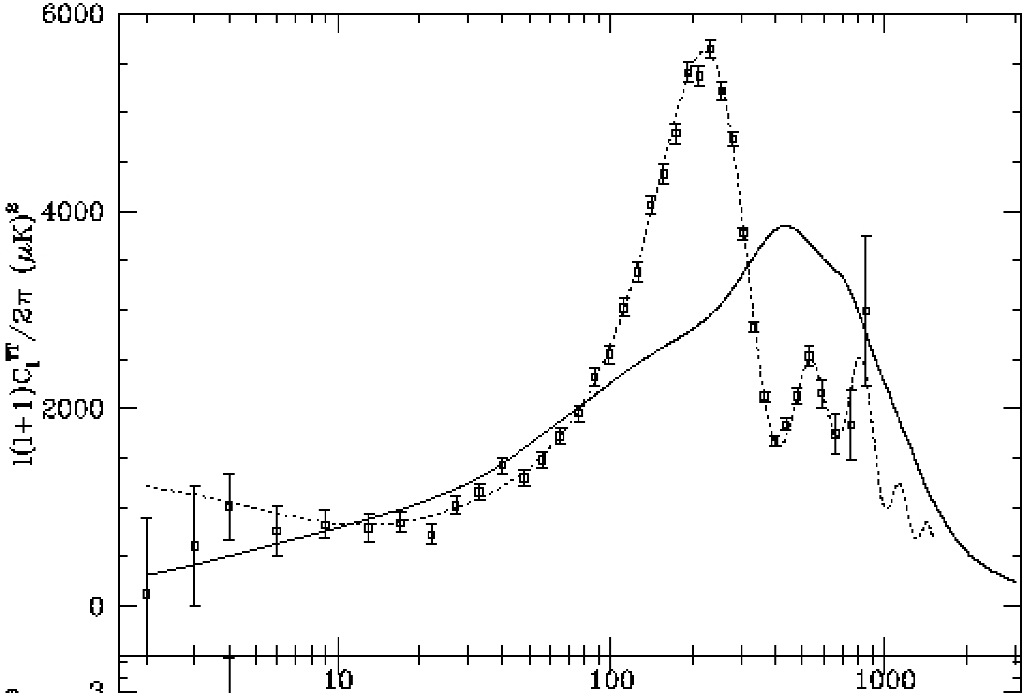
3. Observations in the CMB and parameter constraints

However cosmic strings are not observed in universe :

WMAP data very well fit by inflation only.

If fit data with 1 additional parameter α :

$$C_l^{tot} = \alpha\, C_l^{\text{strings}} + (1-\alpha) C_l^{\text{inflation}}$$



[Wyman et al. (2005)]

- WMAP + SDSS : Monte-Carlo analysis with 6+2 parameters

  α < 14% (95% CL), [Wyman et al. (2005)].

+ best fit with α = 4% but compatible with α = 0% [Fraisse (2005)].

- WMAP 3 : α < 11% (95% CL), [Bevis (2007)].

What constraint on inflationary parameters ?

$$W^F = \kappa S(\Sigma\overline{\Sigma} - M^2)$$

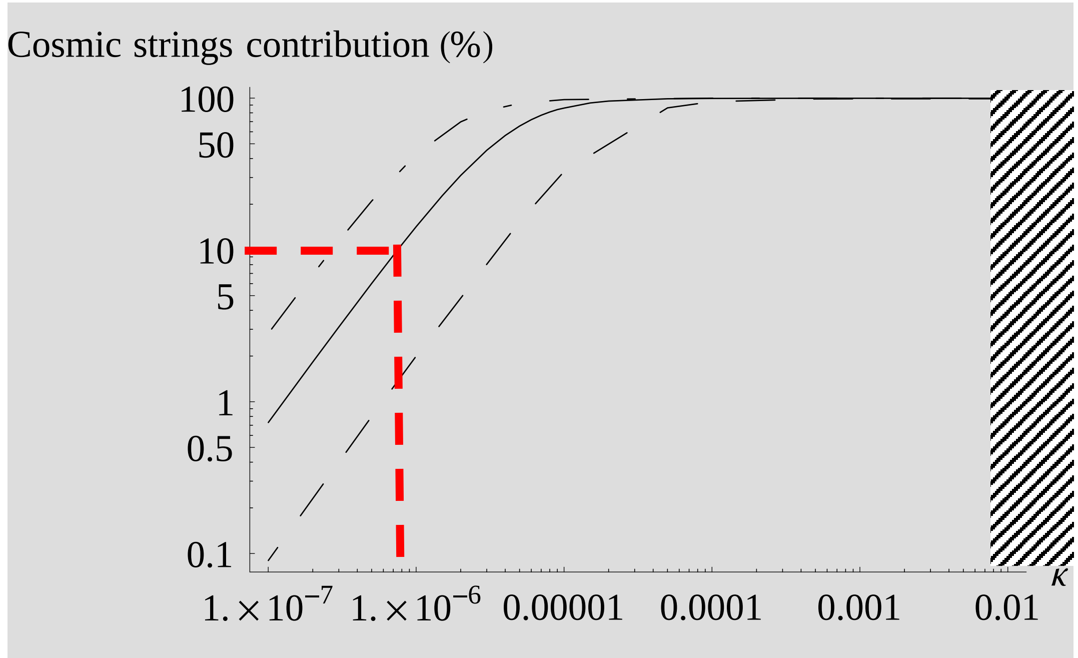
We impose :

- Normalization to CMB

$$\left.\frac{\delta T}{T}\right|_{Q-\text{infl}} = f(M,\kappa,\phi_Q)$$

$$\left.\frac{\delta T}{T}\right|_{Q-\text{strings}} = f(M)$$

- Resolution of the horizon problem : N_Q=60



- Coupling to see-saw mechanism, gravitino overproduction imposes $\kappa < 10^{-2}$.

- WMAP3 : A_{CS} < 11% (95% CL). [Bevis et al. (2007)]

For SO(10) : $\kappa < 7x10^{-7}$ << 1 (fine tuning ?)

or $M < 2x\ 10^{15}$ GeV

[J.R., Sakellariadou JCAP 2005]

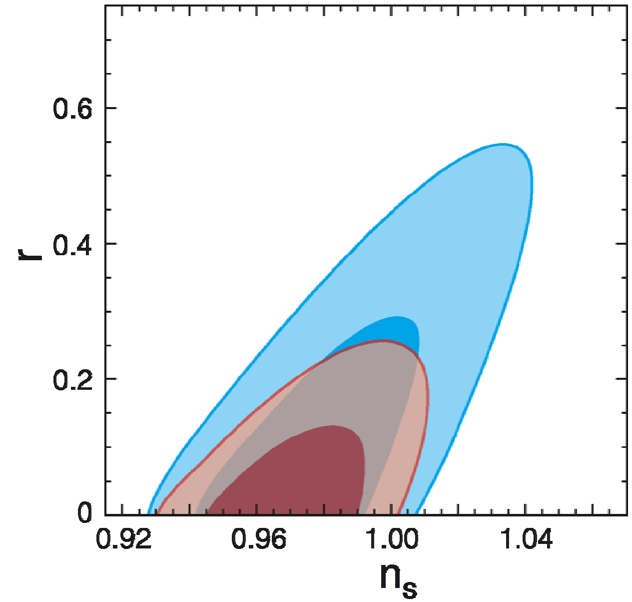
Similar results for other G_{GUT}, D-term inflation in (min and non-min) SUGRA, SCFT.

Conclusion: the coupling inflaton/Higgs is much smaller than expected.

Part B : Is hybrid inflation ruled out by WMAP 5 ?

Effective one field model :

$$V(\phi,\psi) \longrightarrow V(\phi) \approx \Lambda\left(1+\frac{\phi^2}{\mu^2}\right) \quad \& \quad \phi_{crit}$$



WMAP 5 : n_S=0.96 ± 0.013 (1σ)
but generic prediction > 1 !

Hubble flow parameters

$$\varepsilon_1 = -\dot{H}/H^2$$

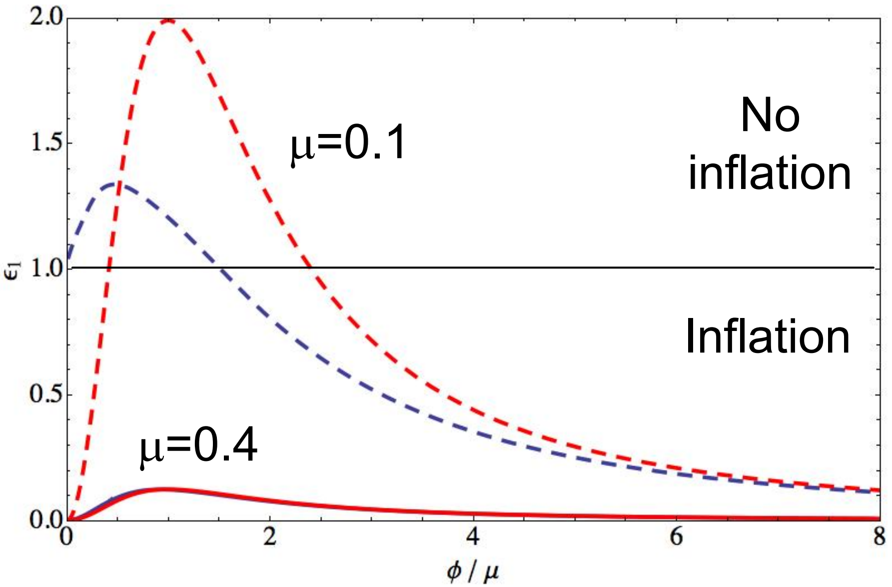
$$\varepsilon_{n+1} = \mathrm{d}\ln\varepsilon_n/\mathrm{d}N$$ [Schwarz et al 01, 04]

Inflation if $\varepsilon_1 < 1$, slow roll if $\varepsilon_n \ll 1$

For 1-field hybrid model in SR :

$$\varepsilon_1 = \frac{1}{4\pi}\left(\frac{m_{pl}}{\mu}\right)^2 \frac{(\phi/\mu)^2}{[1+(\phi/\mu)^2]^2}$$

$$\varepsilon_2 = \frac{1}{2\pi}\left(\frac{m_{pl}}{\mu}\right)^2 \frac{(\phi/\mu)^2-1}{[1+(\phi/\mu)^2]^2}$$



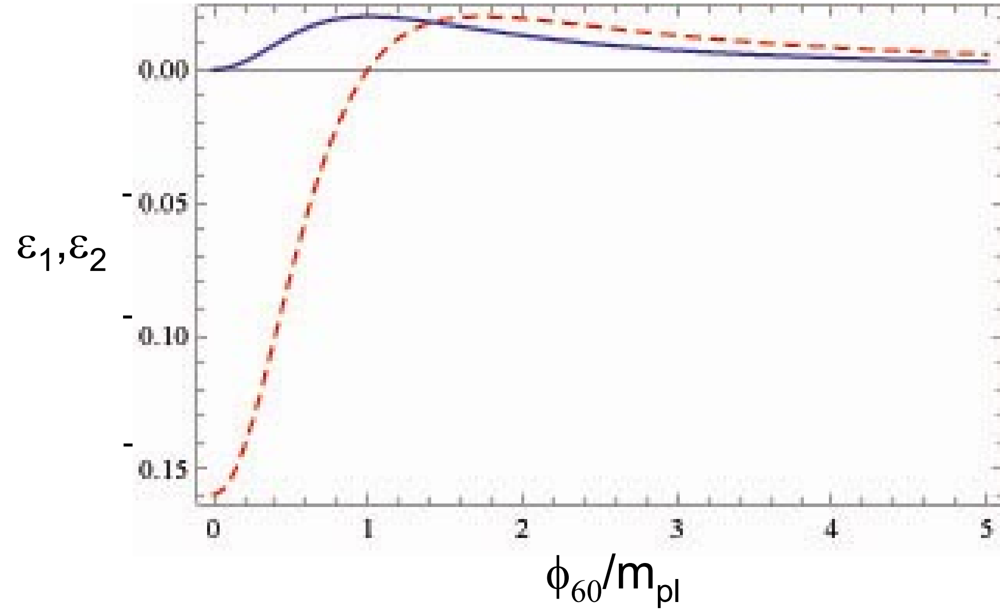
Numerically exact calculation in blue.

In slow roll : $n_S = 1 - 2\varepsilon_1(\phi_{60}) - \varepsilon_2(\phi_{60})$

We computed $\varepsilon_1(\phi)$ NOT in slow roll

- ϕ_{SSB} can be large to prevent the second phase of inflation

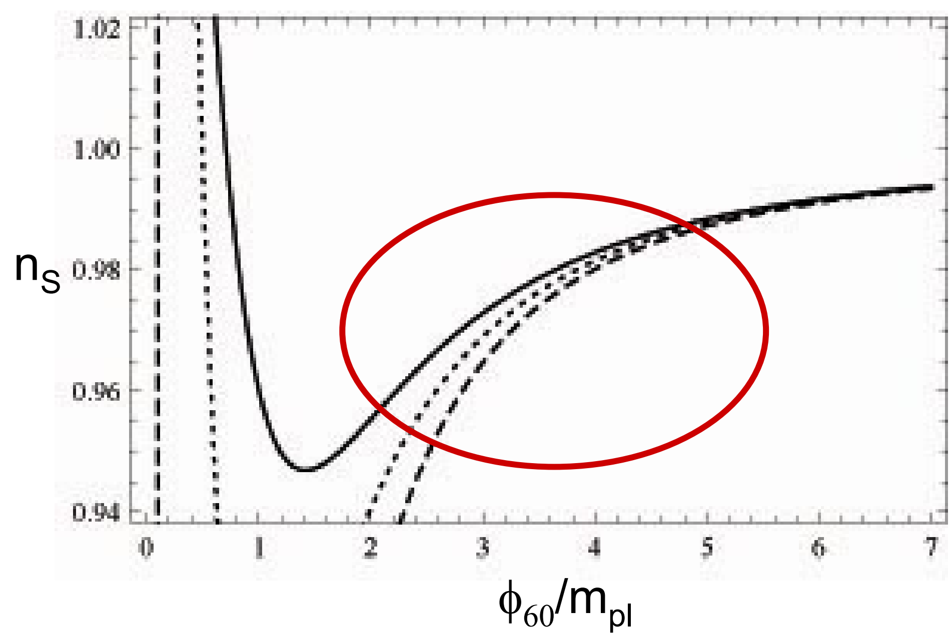
- If $\mu < \mu_{crit}$ NO second phase of inflation. (NEW !)



Conclusions :

- $n_S < 1$ if small μ or large ϕ_{crit}.
- But both suggest a large field regime !

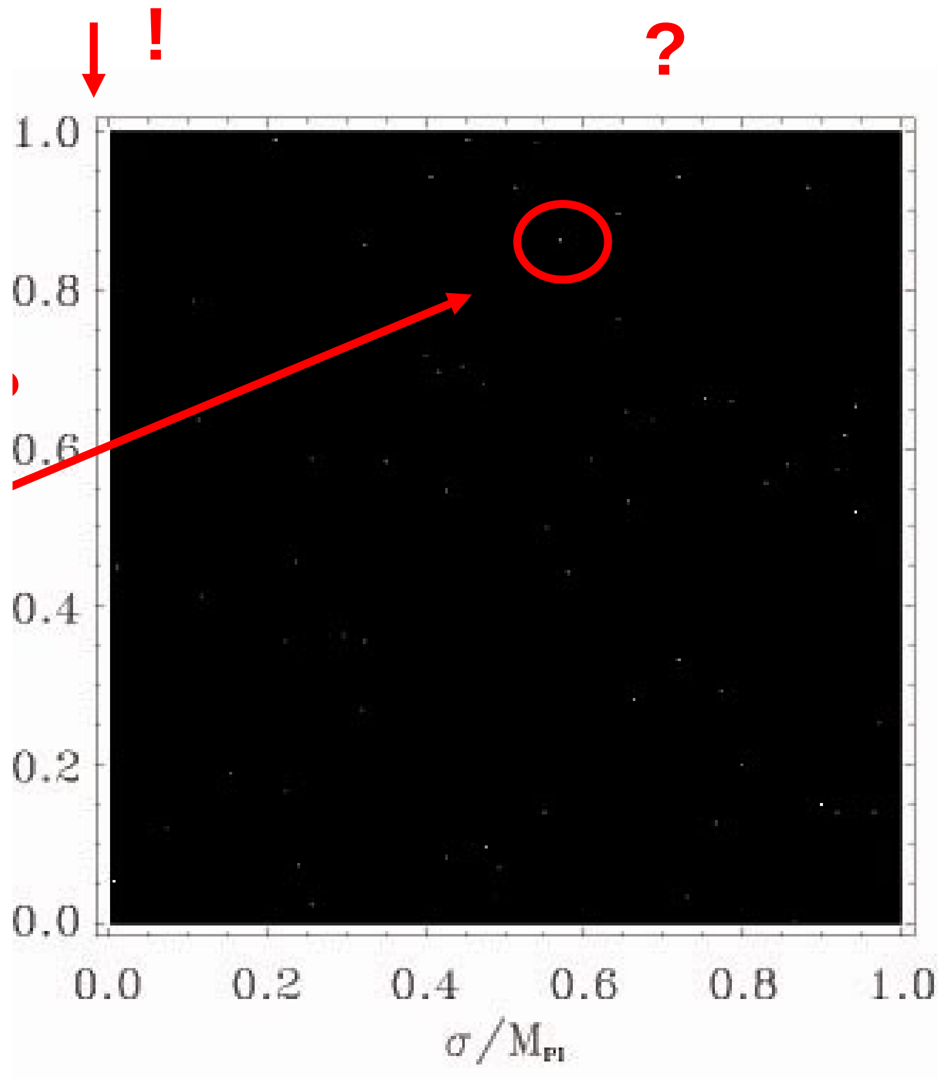
Clesse & J.R. PRD 2009



Part C : Fine tuning of initial conditions for hybrid inflation ?

- Successful = thin (ψ=0) band + isolated points. Problem ?

- Are the isolated points of null measure ? Are there some patterns ?
- Can they make sense ? Why is successful IC not continuous ?
- What is the proportion of successful values ? Can we talk about fine tuning ?
- How to avoid fine tuning ?



[Mendes & Liddle 2000]

2-field dynamics of hybrid inflation

Numerical integration of 2-field EoM (background):

$$H^2 = \kappa\left[\frac{1}{2}\left(\dot\phi^2 + \dot\psi^2\right) + V(\phi,\psi)\right] \qquad \ddot\phi + 3H\dot\phi + \frac{\partial V}{\partial \phi} = 0$$

$$\frac{\ddot a}{a} = \kappa\left[-\dot\phi^2 - \dot\psi^2 + V(\phi,\psi)\right] \qquad \ddot\psi + 3H\dot\psi + \frac{\partial V}{\partial \psi} = 0$$

S.R.

• Slow roll NOT assumed (because can be transiently violated !).

• Assume all initial values (ϕ_i, ψ_i) and vanishing initial velocities. Allow for transplanckian values.

• Integration stopped when $E_{system} < E_{barrier} = \lambda M^4$.

• For each initial value, we compute $\phi(t)$, $\psi(t)$, N(t), N_{end} and generate 2D grids of $N_{end}(\phi_i,\psi_i)$.

• Successful inflation is defined by $N \geq 60$. Correct normalization requires a rescaling that doesn't affect the dynamics + normalization dependent on initial point.

❑ Successful initial conditions :

- Recover "isolated points" in the unsuccessful region
- At larger fields, inflation always successful

❑ Fit of unsuccessful zone :

- Width of narrow band by comparison of the ϕ and ψ oscillation times

$$\psi_w \propto M\sqrt{\lambda / \lambda'}$$

- Limit A : gradient of potential. Strongly depend on λ'.
- Limit B : ε_1 isocurve

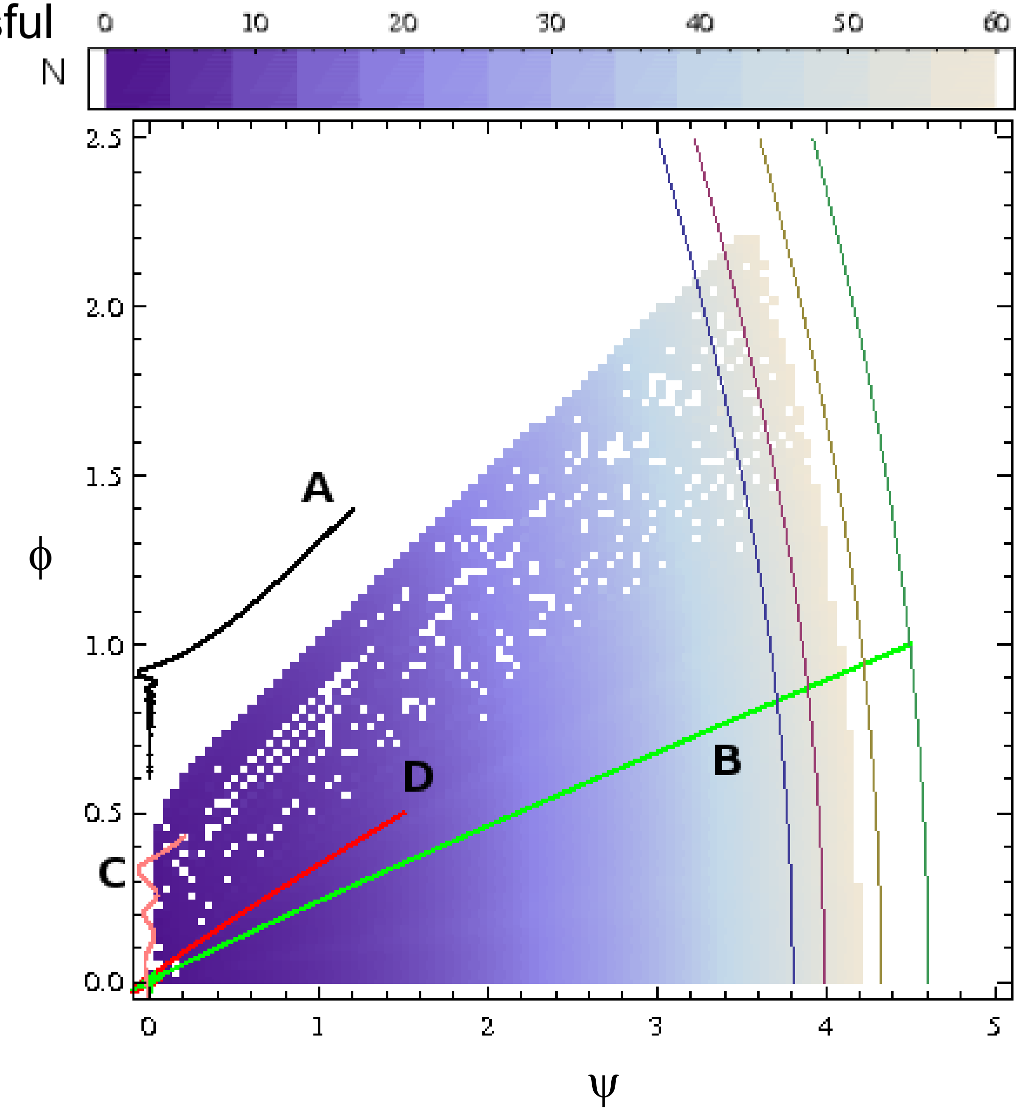
❑ 3 types of successful trajectories :

A = Standard (equiv. to 1 field)

B = Radial (purely 2 field)

C = "miraculous"

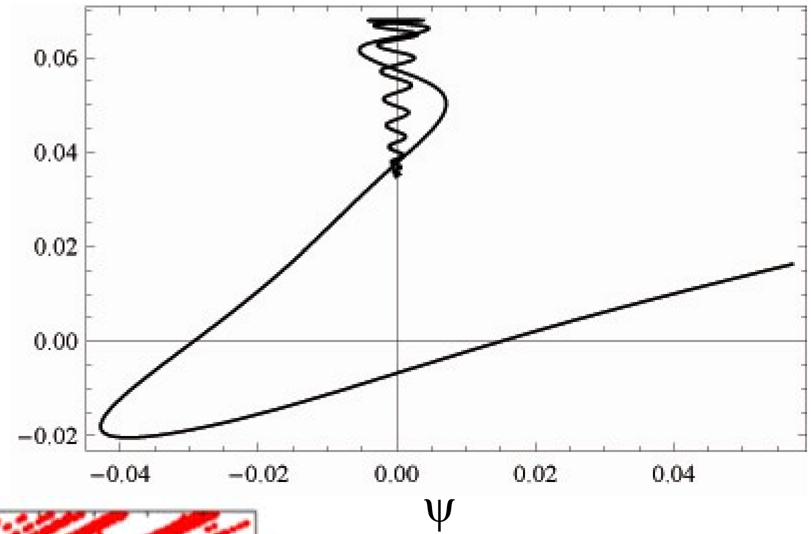
\+ D = typical failed trajectory

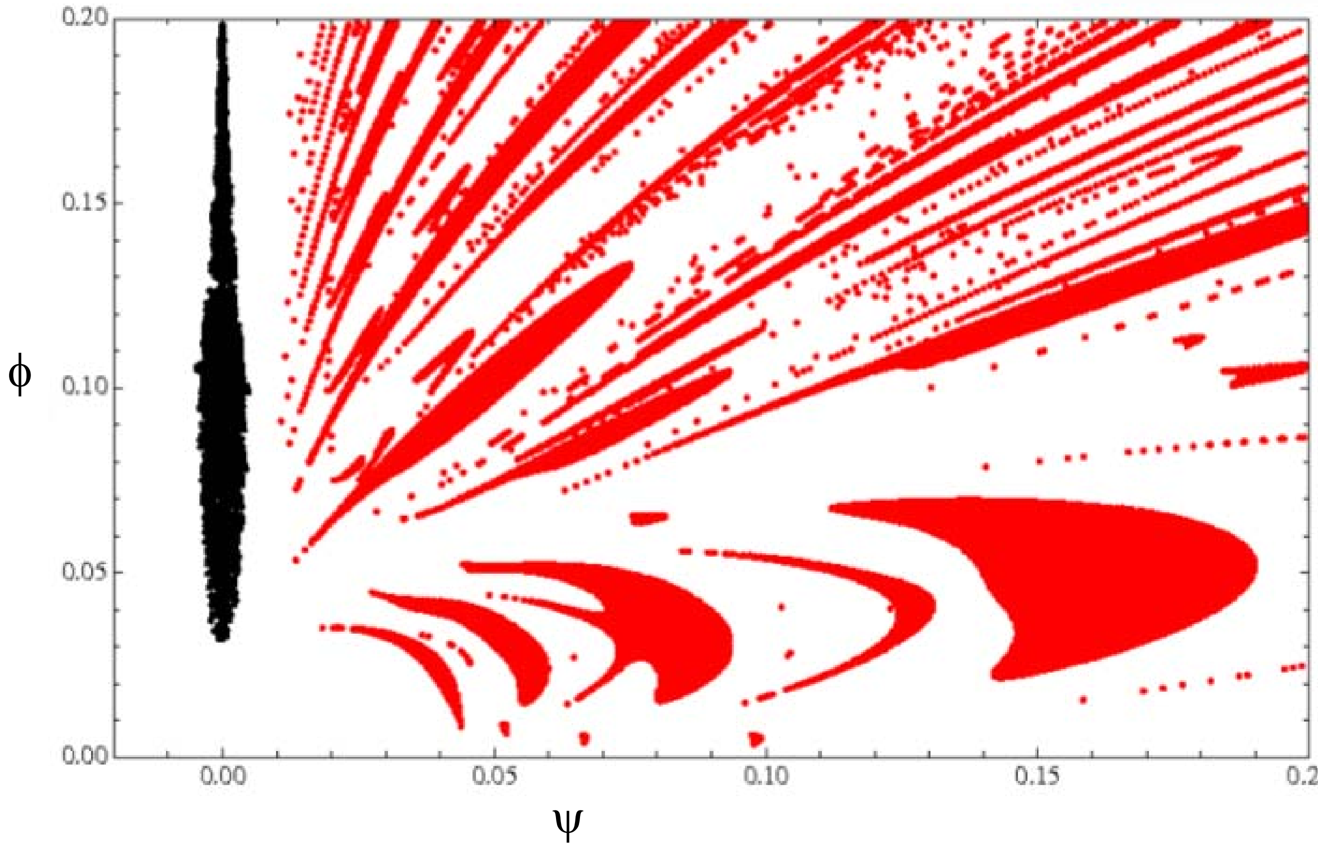


Conclusion : “miraculous” points have the right velocity to climb up the valley to become type A trajectories !

Structure :
Composed of continuous regions. Each corresponds to a unique number of crossing of the $\phi=0$ axis.

C





Quantification :

In a square of length M_{pl} 17% of IC successful, 15% in the points !

Clesse, J.R. PRD 2009

Stat. properties :

- Fractal : d=1.2
- When zoom in, new succ. regions appear.

Clesse, Ringeval, J.R. in prep

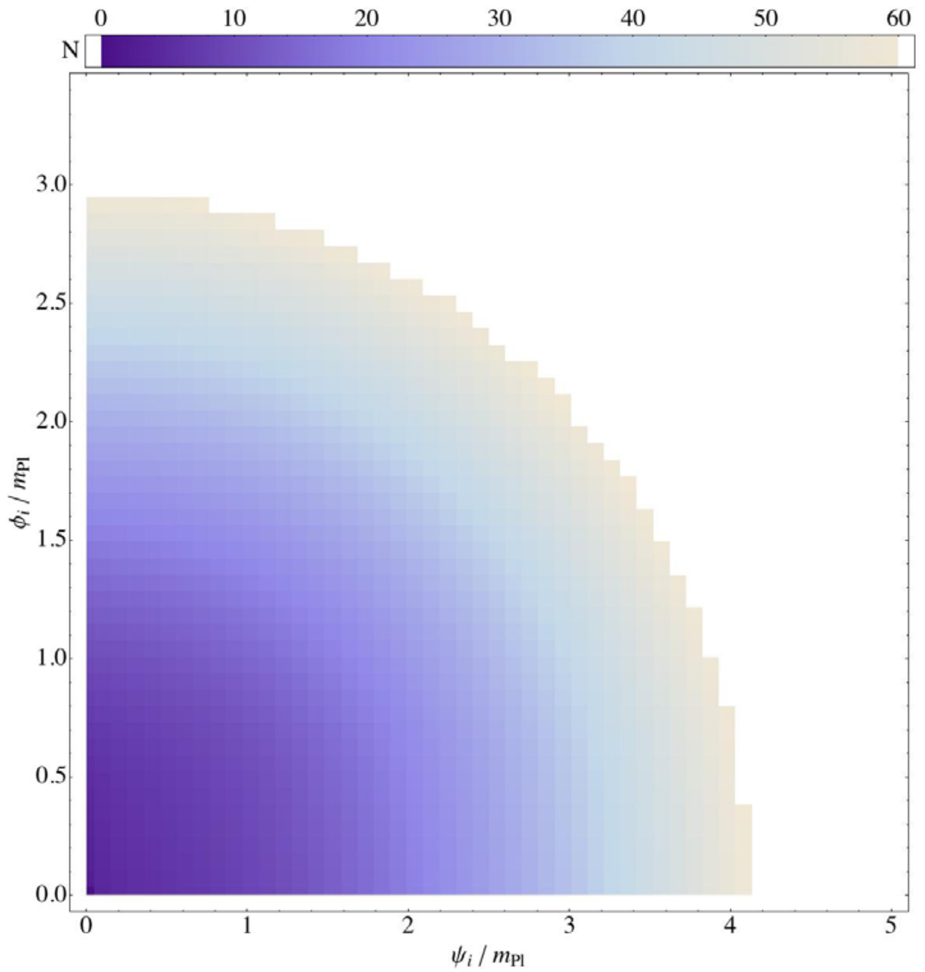
Different set of parameters to have red spectrum in inflationary valley …

Conclusions :

• miraculous points disappeared : amount of success depends on pot. parameters.

• large field regime required in both directions.

More work required to confront to CMB fully in the two field plane.



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Robustness : Non-renormalizable and SUGRA effects

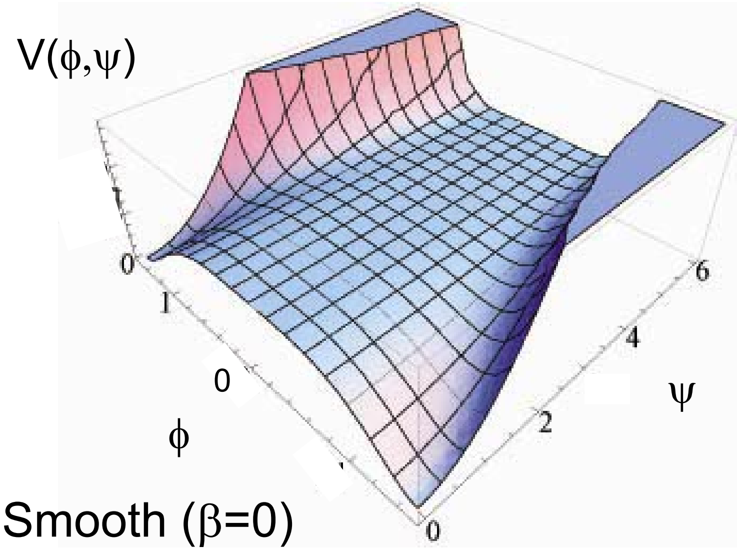
Effects of non-renorm terms => others models studied

- Smooth hybrid inflation
- Shifted hybrid inflation

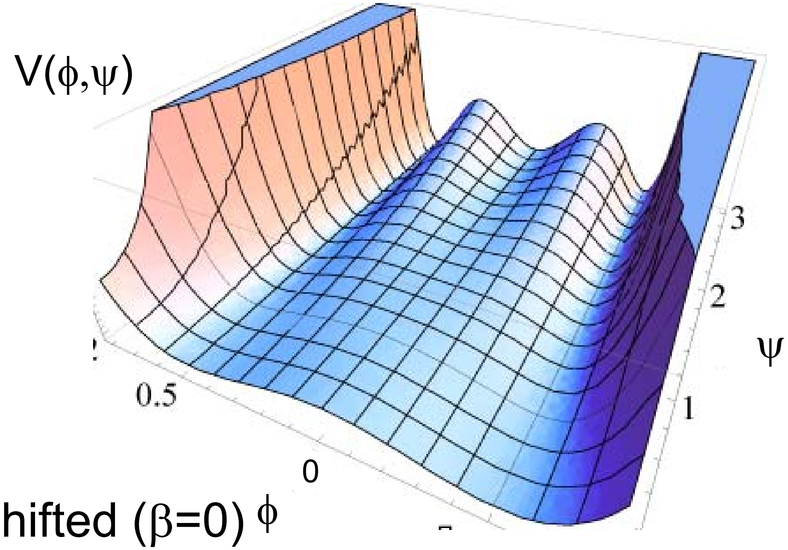
} Extended SUSY hybrid models with shifted valleys to avoid topological defects [Lazarides & Panagiotakopoulos 95, Jeannerot et al 00]

+ study (minimal) SUGRA effects

$$V(\phi,\psi) = \kappa^2 \left(\frac{\psi^p}{M_{\rm pl}^{p-2}} - M^2 - \beta \frac{\psi^4}{M_{\rm pl}^2} \right)^2 + \kappa^2 \phi^2 \frac{\psi^q}{M_{\rm pl}^{q-2}} \left(1 - \beta \frac{\psi^2}{M_{\rm pl}^2} \right)^2 + V_{SUGRA}$$



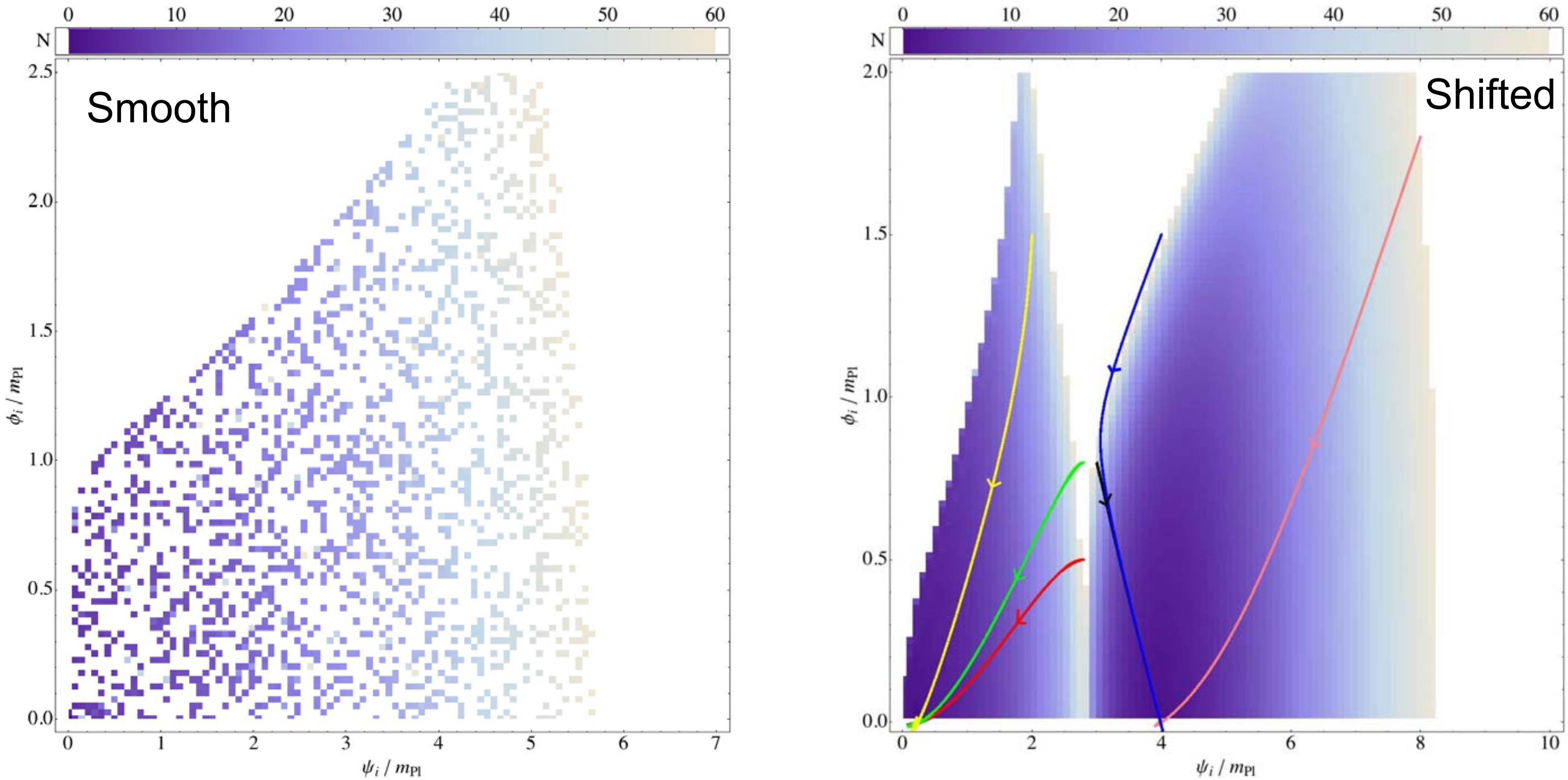
Smooth (β=0)



Shifted (β=0)

Some results :

- Smooth inflation have up to 80%
- Shifted inflation always below 10%.
- Large IC: still automatic if SUSY. If SUGRA, this disappears but not miraculous IC.



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Conclusions

Embedding in SUSY GUTs

- If written at the GUT level, hybrid inflation requires a singlet outside of SUSY GUTs + some tuning compared to general W.
- Cosmic strings generically for at the end. CMB imposes a small coupling 10^{-6}.

Space of initial conditions

- Space better understood. 3 types of trajectories. Isolated IC not isolated but in patterns => fine tuning ?
- If restrict to subplanckian IC, 17% of IC successful. fine tuning ?
- If we allow superplanckian IC, successful inflation generic. Exist new type of trajectories outside usual valley.

Confrontation to CMB

- Possible to have red spectral index.
- But this pushes original hybrid in large field regime
- More being done in 2-field space, + all parameters …

Jeannerot, J.R. Sakellariadou 03
J.R. Sakellariadou 05
Clesse, J.R. ArXiv 0809.4355,
Clesse, Ringeval, J.R. in prep
Bajc, Mazumdar, J.R., in prep

Open questions and work in progress

SUSY GUTs and orthogonal constraints

Bajc, Mazumdar, J.R., in prep

- Indentifying all possibilities for the inflaton in fields present (in progress).
- See-saw constraint on energy scale/coupling of hybrid inflation ? (Too) many param ?
- Gauge coupling unification constraint on energy scale of hybrid inflation ?

Generic nature of Cosmic Strings in GUT

- Study presence of currents in strings : requires full GUT lagrangian and coupling S to other field.

Peter, J.R., Sakellariadou, in prep

- Cosmological consequences of realistic strings.

Two-field confrontation to CMB

- Effects of initial velocities
- Statistical properties of the IC space
- Predictions of n_s and r in all plane.

Clesse, Ringeval, J.R. in prep

- MCMC to confront to the data. Gives a measure in the space of initial conditions.