Introduction to Inflation in SUSY GUTs

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For further details, see arxiv:1003.3233

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Outline

Part 1

- Problems of the Standard Big Bang Model (SBBM)
- Basics of Inflation & Hybrid Inflation

Part 2

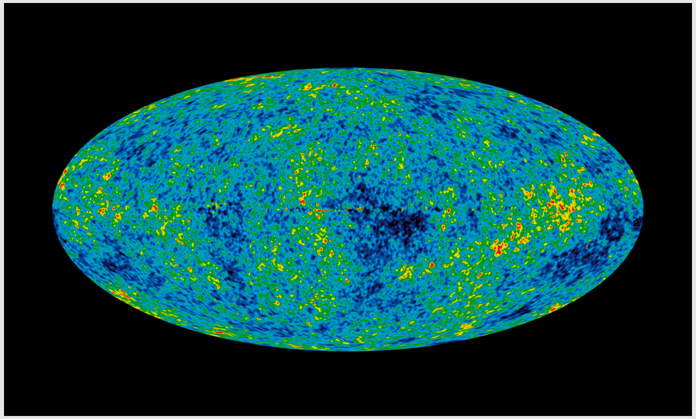
- Inflation in SUSY GUTs

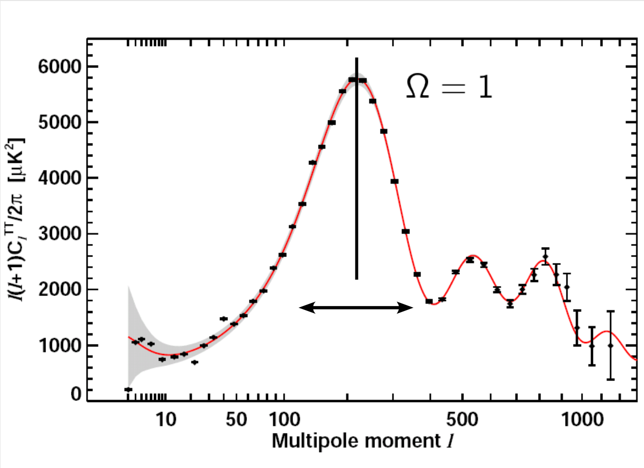
Part 3

- Summary

Part 1

Why Inflation ?





$$\Delta T / T \leqslant 10^{-4}$$

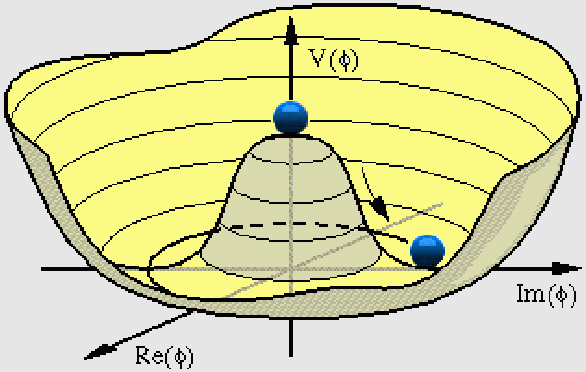
Horizon Problem

$$|\Omega_{BBN} - 1| \leqslant 10^{-12}$$

Flatness Problem

[WMAP Science Team]

Why Inflation ?



Origin of small scale structure ?

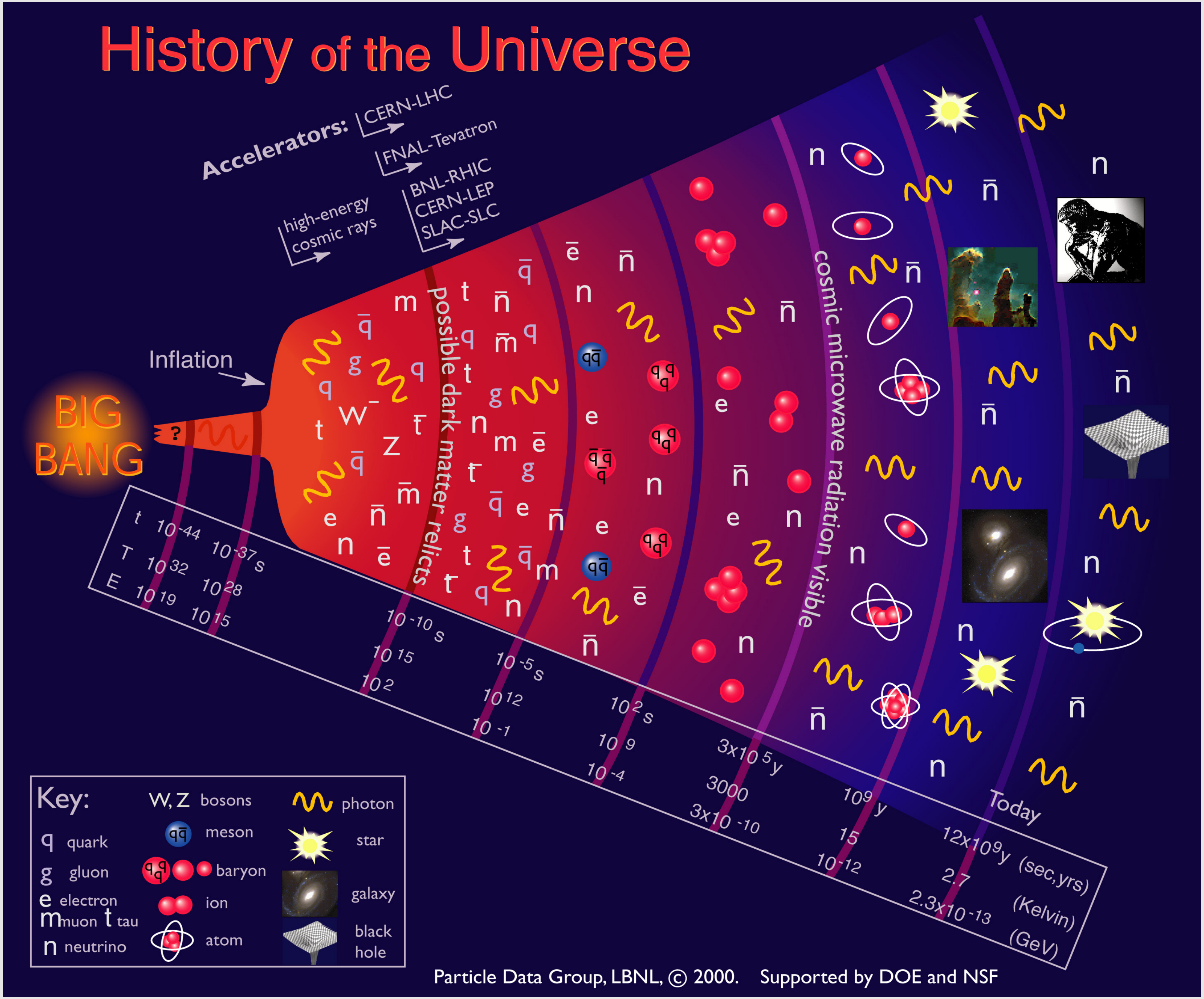
Monopole Problem

Why Inflation ?

- Inflation is a stage of accelerated expansion of the Universe

$$\ddot{a} > 0 \quad \longleftrightarrow \quad \rho + 3p < 0$$

- Solves all 4 Problems **simultaneously** !
  - ✗ Inflates an initially tiny causal patch to a hugh size
  - ✗ Drives the Universe towards flatness
  - ✗ Quantum fluctuations get stretched and become classical
  - ✗ Monopoles get diluted


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
Today
12x109 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Scalar Field as Inflaton

- We need an equation of state $p = \omega \rho$ with $\omega < -1/3$ for accelerated expansion !
- Consider a slowly rolling Scalar Field in a FRW Background

$$\mathcal{L}_\phi = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \, \partial_\nu \phi - V(\phi)$$

$$\rho = \frac{1}{2} \dot{\phi}^2 + V(\phi)$$

$$p = \frac{1}{2} \dot{\phi}^2 - V(\phi)$$

$$\ddot{\phi} + 3\mathrm{H} \dot{\phi} + V'(\phi) = 0$$

Scalar Field as Inflaton

$$\rho = \cancel{\frac{1}{2}\dot{\phi}^2} + V(\phi)$$
$$p = \cancel{\frac{1}{2}\dot{\phi}^2} - V(\phi)$$

$$\cancel{\ddot{\phi}} + 3\mathrm{H}\dot{\phi} + V'(\phi) = 0$$

$$\epsilon = \frac{1}{16\pi G}\left(\frac{V'}{V}\right)^2 < 1$$

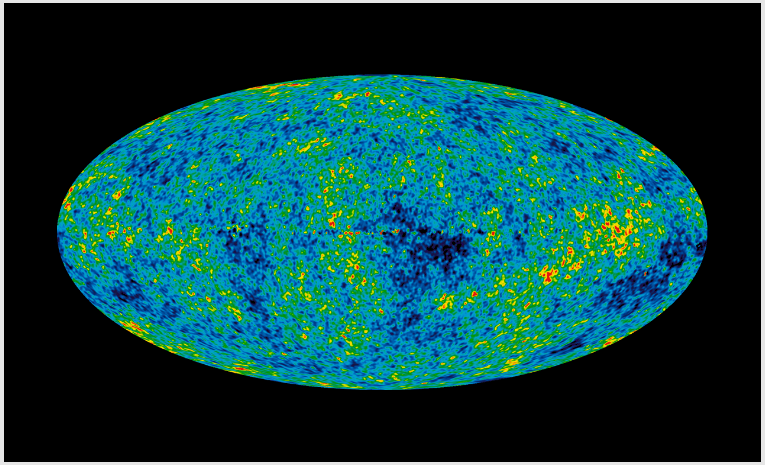
Slow Roll

$$|\eta| = \left|\frac{1}{8\pi G}\left(\frac{V''}{V}\right)\right| < 1$$

$$p = -\rho$$
$$a \sim \mathrm{e}^{Ht}$$

$$H^2 \simeq \frac{8\pi G}{3} V(\phi)$$
$$3\mathrm{H}\dot{\phi} + V' \simeq 0$$

Connection to Experiments



$$\langle 0|(\mathcal{R}(\mathbf{x},t))^2|0\rangle \equiv \int \frac{dk}{k} \mathcal{P}_{\mathcal{R}}(k)$$

$$n-1 \equiv \frac{1}{d\ln(k)} d\mathcal{P}_{\mathcal{R}}(k)$$

$$r = \Delta_h^2 / \Delta_{\mathcal{R}}^2$$

$$n = 0.963 \pm 0.012 \,(68\% CL)$$
$$r < 0.24 \,(95\% CL)$$

[Komatsu et al., astro-ph:1001.4538]

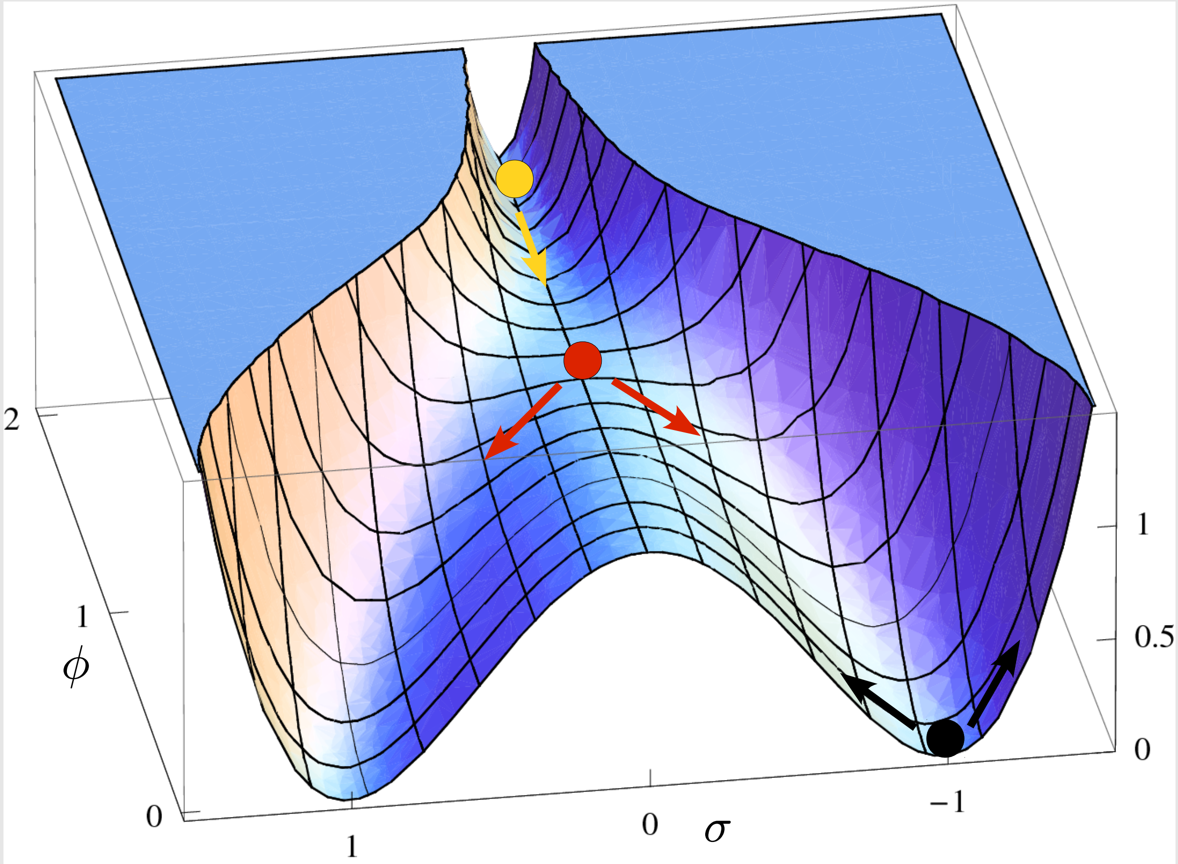
Model of Inflation

$$V(\phi,\ldots) = \ldots$$
$$\epsilon, \eta = \ldots$$

$$n-1 = 2\eta - 6\epsilon$$
$$r = 16\epsilon$$

Hybrid Inflation

$$V(\sigma,\phi)=\kappa(M^2-\sigma^2)^2+\frac{m^2}{2}\phi^2+\frac{g^2}{2}\phi^2\sigma^2$$ [Linde, Phys.Rev.D 49]



- Inflation
- Violation of slow-roll, Phase transition
- Reheating

Linde-Model : $n>1$

Simple SUSY Model: $n=0.98$

[Dvali et al., Phys.Rev.Lett 73]

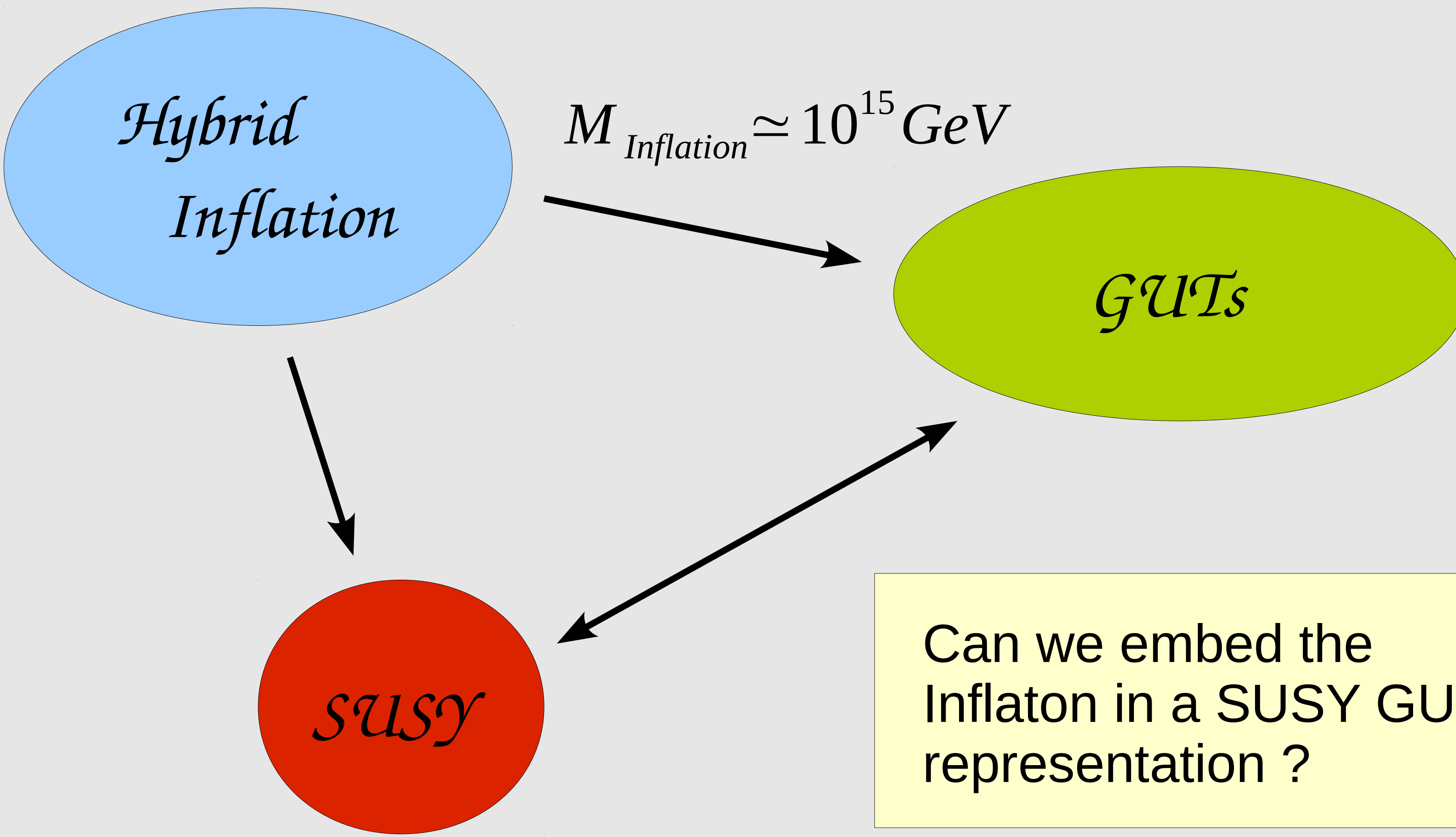
Part 2

Connection to Particle Physics

- SUSY Hybrid Inflation is an attractive scenario

But who are those fields?

Connection to Particle Physics



Can we embed the Inflaton in a SUSY GUT representation ?

Gauge Non-Singlet (GNS) Inflaton ?

- We want to identify the Inflaton with the scalar superpartner of some „matter field“

- Then the Inflaton is a gauge non-singlet

- Several new problems arise
  - ✗ The Inflaton potential might receive large D-term contributions

    ➟ Violates slow-roll

  - ✗ Two loop mass corrections might drive the Inflaton mass above the Hubble scale

    ➟ $m^2 > H, |\eta| > 1$ [Dvali, Phys.Lett.B 355]

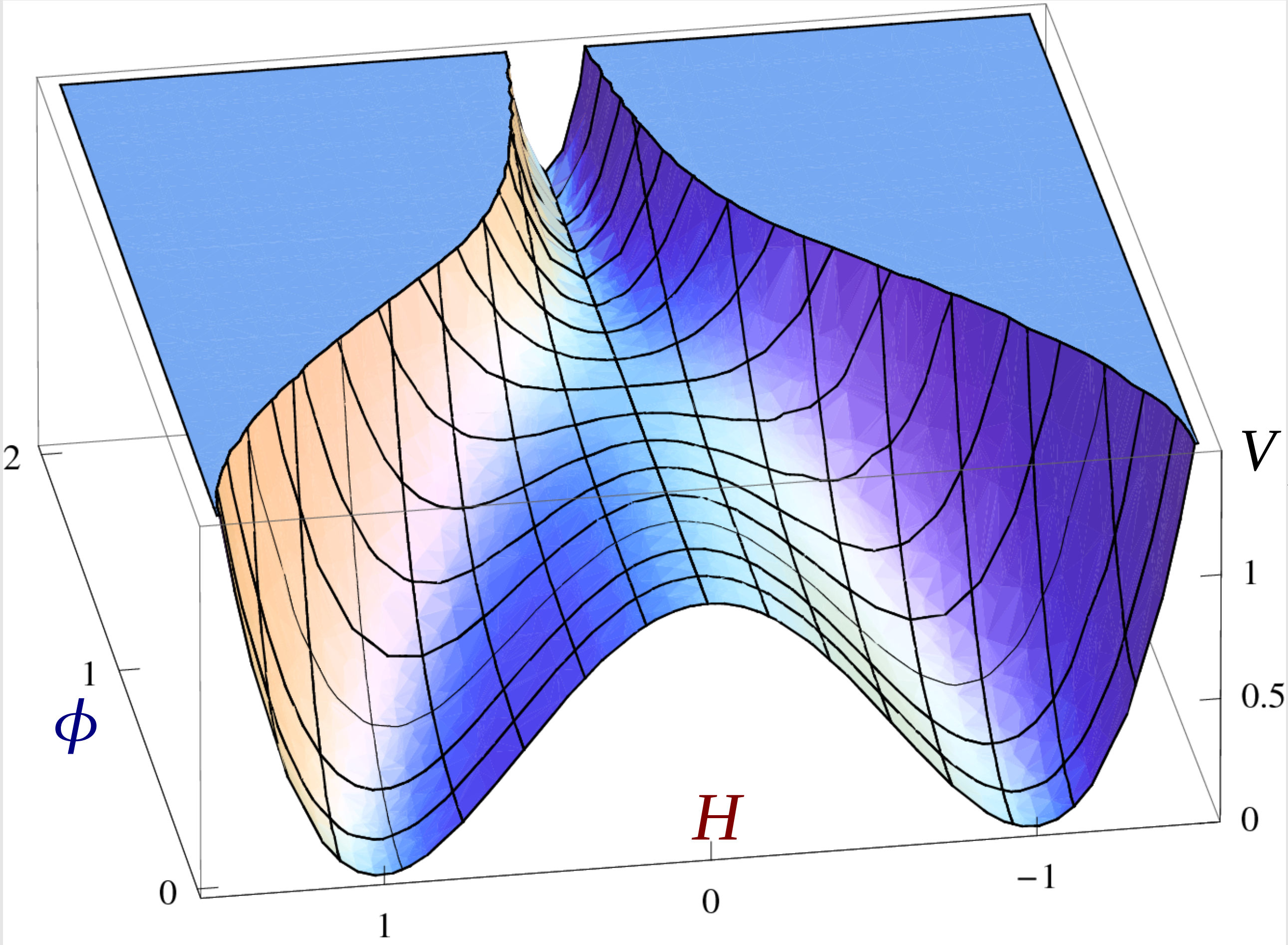
  - ✗ The production of stable topological defects has to be avoided

Inflaton charged under U(1)

$$W = \kappa S(H\bar{H} - M^2) + \frac{\xi}{\Lambda}(H\bar{H})(\phi\bar{\phi}) + \ldots$$

- S is kept at 0 during and after Inflation and provides the vacuum energy by its F-term
- The waterfall fields H and $\bar{H}$ remain at 0 during Inflation and end Inflation by acquiring a vev in a 2nd order phase transition
- ϕ and $\bar{\phi}$ act as Inflatons

For $\langle\bar{\phi}\rangle^* = \langle\phi\rangle$ and $\langle\bar{H}\rangle = \langle H\rangle = \langle S\rangle = 0$ Inflation proceeds along a D-flat valley. On this trajectory the Inflaton potential is tree-level flat !



$$V_F = \sum_i \left| \frac{\partial W}{\partial \Phi_i} \right|^2 \qquad V_D = \frac{1}{2} \sum_a g_a^2 (\Phi^* T^a \Phi)^2$$

Sneutrino Inflation in Pati-Salam

$G_{PS} = SU(4)_C \times SU(2)_L \times SU(2)_R$
[Pati,Salam, Phys.Rev.D 10]

Minimalistic field content:

$$R_i^c = (\bar{4}, 1, \bar{2}) = \begin{pmatrix} u_i^c & u_i^c & u_i^c & \nu_i^c \\ d_i^c & d_i^c & d_i^c & e_i^c \end{pmatrix} \qquad \bar{R}^c = (4,1,2) = \begin{pmatrix} \bar{u}^c & \bar{u}^c & \bar{u}^c & \bar{\nu}^c \\ \bar{d}^c & \bar{d}^c & \bar{d}^c & \bar{e}^c \end{pmatrix}$$

$$H^c = (\bar{4}, 1, \bar{2}) = \begin{pmatrix} u_H^c & u_H^c & u_H^c & \nu_H^c \\ d_H^c & d_H^c & d_H^c & e_H^c \end{pmatrix} \qquad \bar{H}^c = (4,1,2) = \begin{pmatrix} \bar{u}_H^c & \bar{u}_H^c & \bar{u}_H^c & \bar{\nu}_H^c \\ \bar{d}_H^c & \bar{d}_H^c & \bar{d}_H^c & \bar{e}_H^c \end{pmatrix}$$

$$X, S = (1,1,1)$$

i = 4 (four generations) ►3 light generations after Inflation

Superpotential:

$$W = \kappa S \left(\frac{\langle X \rangle}{\Lambda} H^c \bar{H}^c - M^2 \right)$$
$$+ \frac{\lambda_{ij}}{\Lambda} (R_i^c \bar{H}^c)(R_j^c \bar{H}^c) + \frac{\gamma}{\Lambda} (\bar{R}^c H^c)(\bar{R}^c H^c) + \frac{\zeta_i}{\Lambda} (R_i^c \bar{R}^c)(H^c \bar{H}^c) + \frac{\xi_i}{\Lambda} (R_i^c \bar{H}^c)(\bar{R}^c H^c) + \ldots$$

Sneutrino Trajectory

Consider a special trajectory in field space: Sneutrino Inflation !

$$\langle R_1^c \rangle = \begin{pmatrix} 0 & 0 & 0 & \langle \nu^c \rangle \\ 0 & 0 & 0 & 0 \end{pmatrix} \qquad \langle \bar{R}^c \rangle = \begin{pmatrix} 0 & 0 & 0 & \langle \bar{\nu}^c \rangle \\ 0 & 0 & 0 & 0 \end{pmatrix} \qquad \langle R^c_{i\neq 1} \rangle = 0$$

- D-flatness
  - ➟ $V_D = 0$
  - ➟ $|\langle \nu^c \rangle| = |\langle \bar{\nu}^c \rangle| \equiv \nu/\sqrt{2} \in \mathbb{R}$
- $\langle H^c \rangle = \langle \bar{H}^c \rangle = 0$ during Inflation due to large masses from the F-term potential
- At some critical value ν_{crit} one or more component fields of $H^c, \bar{H}^c$ become tachyonic and end Inflation by acquiring a vev („waterfall")

$$\nu_{crit} = \sqrt{\frac{2|\kappa| M}{|\zeta|}} \quad for \quad u_H^c, d_H^c, e_H^c, \ldots$$

$$\nu_{crit} = \sqrt{\frac{2|\kappa| M}{|\zeta + \xi \pm 2\gamma|}} \quad for \quad \Re, \Im(\nu_H^{\bar{c}} - \nu_H^c)$$

→

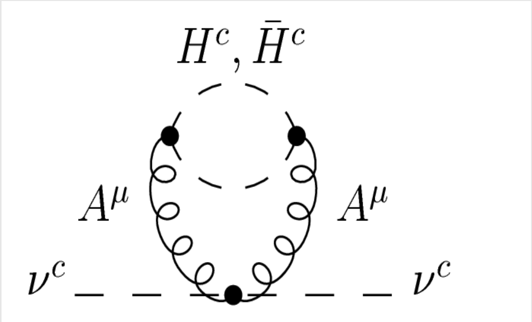
Preferred direction

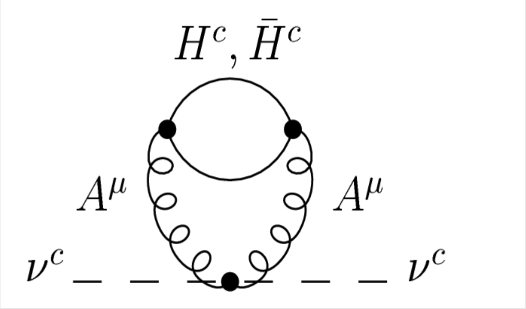
➟ No monopoles !

GNS Inflaton ?

- D-term contributions → D flat valley ✓
- Monopoles → Preferred direction ✓

- Two loop contributions to the Inflaton mass, e.g.





- Typical problem: 2-loop mass contribution for non-singlets

$$\delta m^2 \sim \frac{g^4}{(4\pi)^2} \frac{|W_S|^2}{m_F^2} > H^2$$ [Dvali '95]

- However in our class of models: Gauge symmetry broken in the Inflaton direction

$$\delta m^2 \sim \frac{g^4}{(4\pi)^2} \frac{\mu^4}{M_G^2} \ll H^2$$

Summary

- Inflation solves a number of problems of the SBBM simultaneously
- Inflation is a stage of accelerated expansion of the Universe, for example driven by the vacuum energy of a slowly rolling scalar field
- Models of Inflation yield predictions that can be compared to experiments (scalar index n_s, tensor-to-scalar ratio r ...)
- The connection between Particle Physics and Inflation is still unclear
- We established a possible connection by embedding the Inflaton into a matter representation of a SUSY GUT
- Inflaton gauge interactions and D-term contributions lead to challenges for realizing slow-roll Inflation which are resolved in our model