Neutrinos, GUTs, and the Early Universe

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“What is nu ... ?”, Invisibles 12, Smirnov Fest
GGI, Florence

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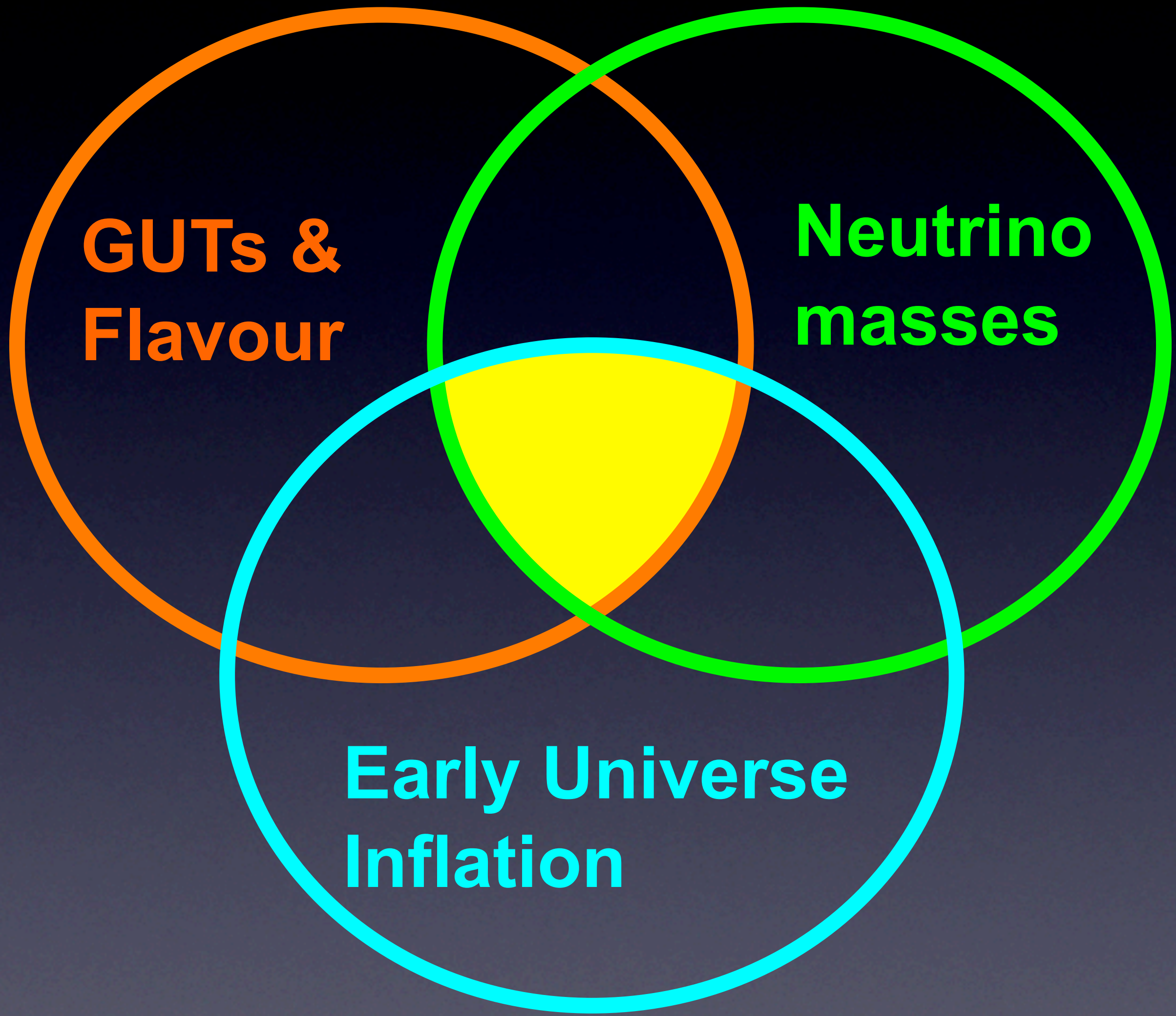
Three challenges …



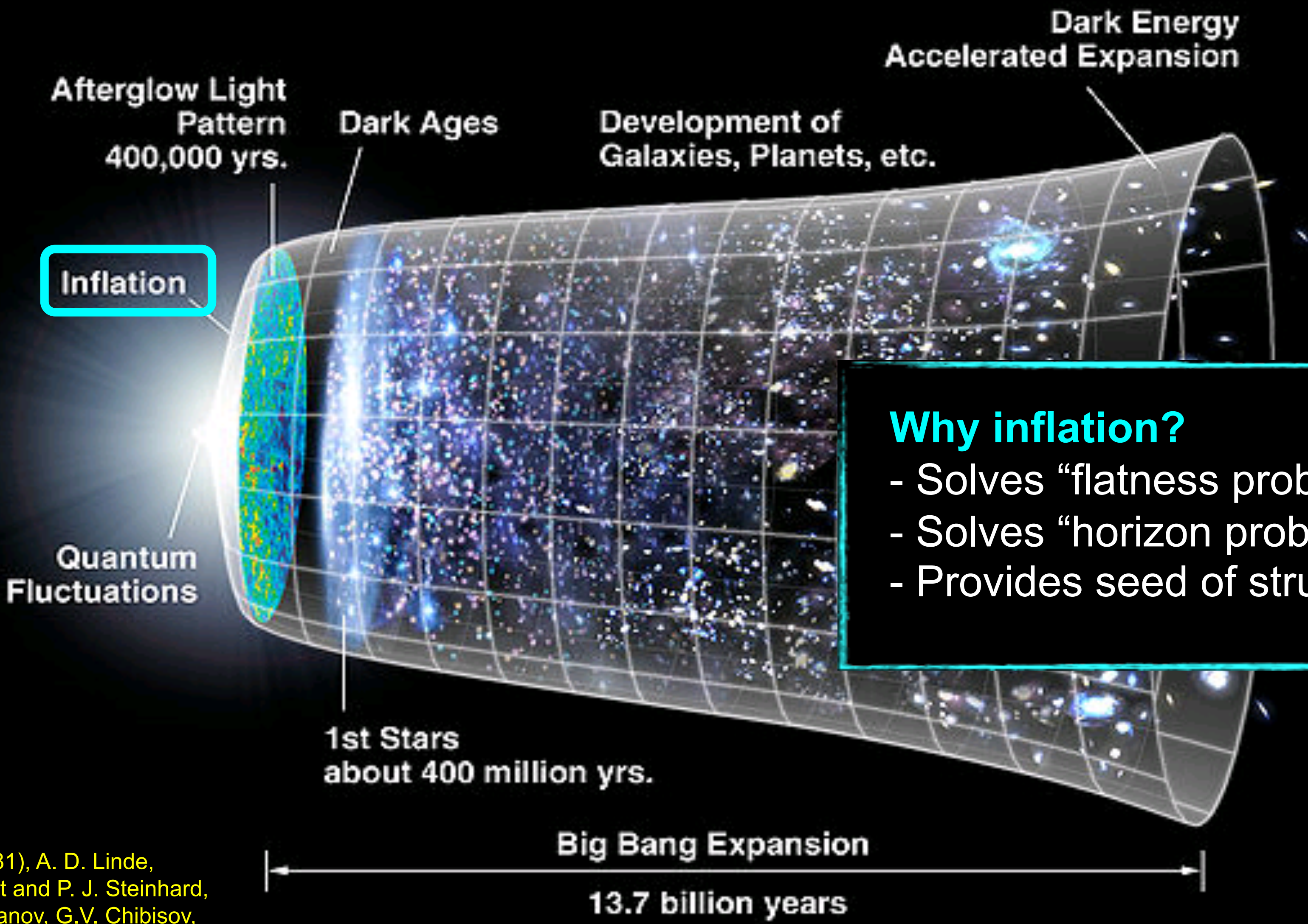
Overview: Two topics

- Part 1: Neutrinos and inflation
- Part 2: Is there a footprint of GUTs in U_{PMNS}?

First part of my talk:

Neutrinos and inflation

Inflation = Era of accelerated expansion in the very early universe



Why inflation?
- Solves “flatness problem”
- Solves “horizon problem”
- Provides seed of structure

A. Guth ('81), A. D. Linde,
A. Albrecht and P. J. Steinhard,
V.F. Mukhanov, G.V. Chibisov,
A.H. Guth and S.Y. Pi,
A.A. Starobinsky, S.W. Hawking

picture from WMAP website

How can inflation be realised?

- Simple and attractive possibility: Slowly rolling scalar field ϕ (minimally coupled to gravity)

$$T_{\mu\nu} = \partial_\mu \phi \partial_\nu \phi - g_{\mu\nu} \left(\frac{1}{2} \partial_\rho \phi \partial_\rho \phi + V(\phi) \right)$$

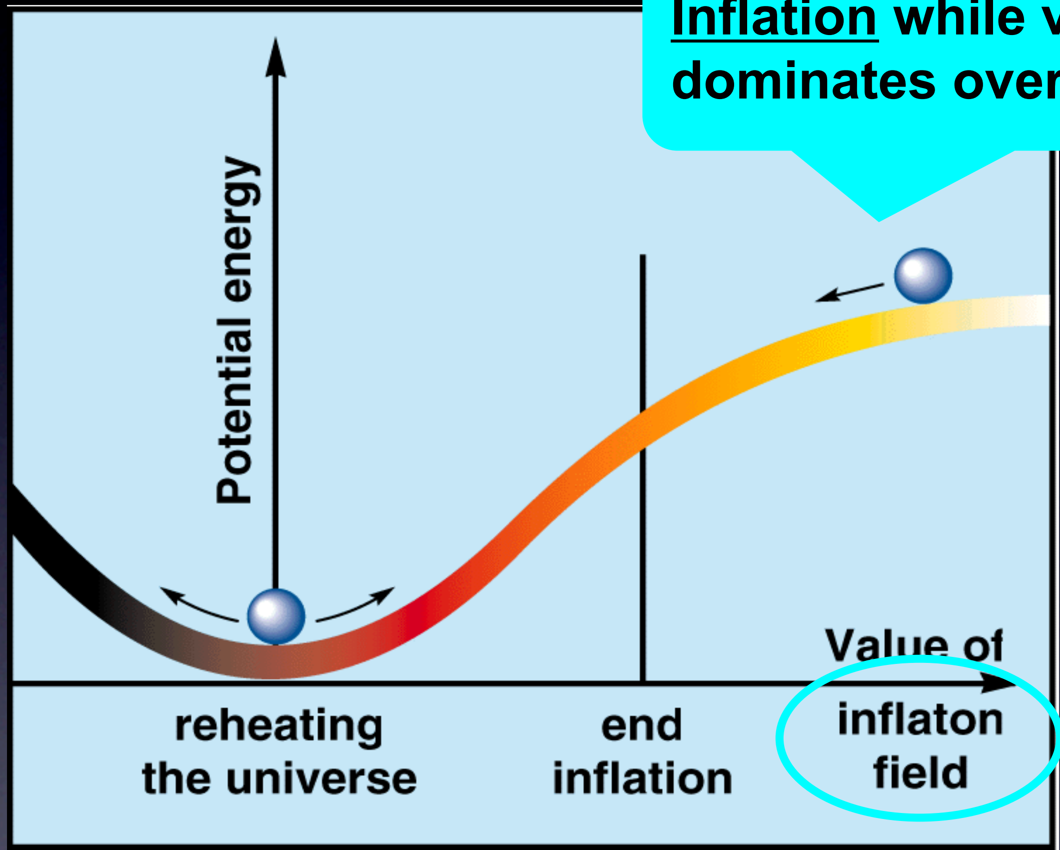
If the vacuum energy V(ϕ) dominates:

$$\Rightarrow \quad a(t) = \exp\left(\sqrt{\frac{8\pi G_N V(\phi)}{3}} t \right)$$

and the universe "inflates"!

Important: The field ϕ is dynamical
⇒ inflation can end!

Dynamics during and after inflation

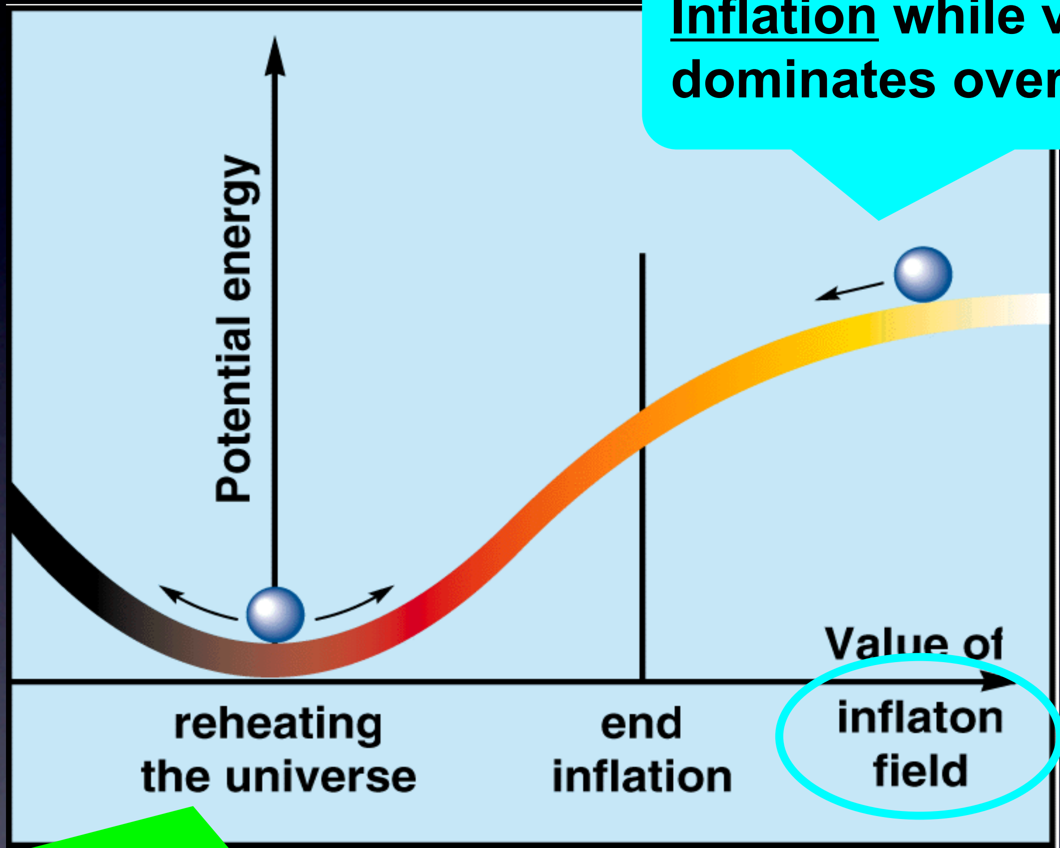


<u>Inflation</u> while vacuum energy dominates over kinetic energy

V_0

Vacuum energy during inflation:
$(V_0)^{1/4} \sim 10^{16}$ GeV $\sim M_{GUT}$

Dynamics during and after inflation



Inflation while vacuum energy dominates over kinetic energy

V_0

Decays of the inflaton:
→ matter & antimatter, and possibly their asymmetry get produced!

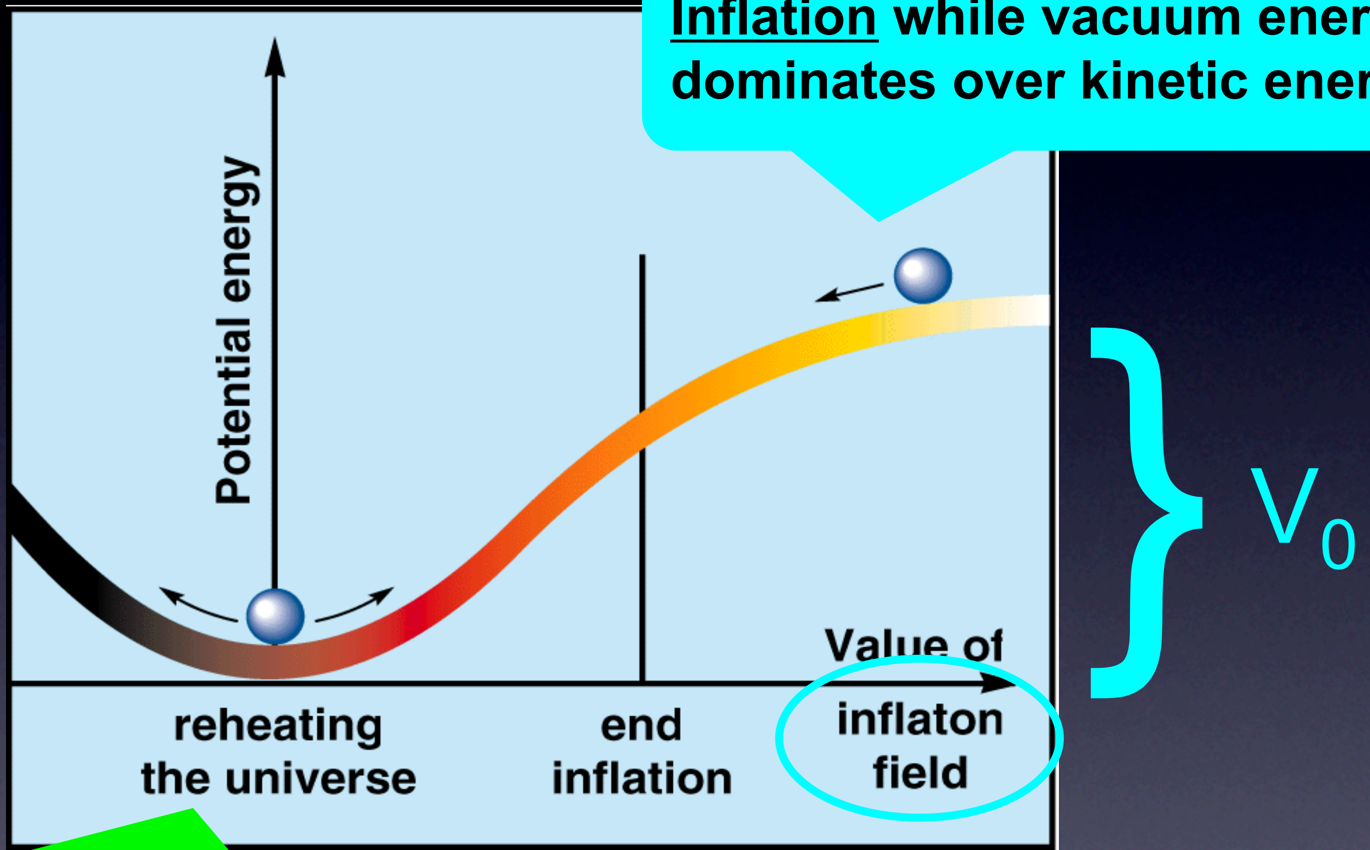
Vacuum energy during inflation:
$(V_0)^{1/4} \sim 10^{16}$ GeV $\sim M_{GUT}$

Dynamics during and after inflation

Requirements:
• more than ~ 60 e-foldings of inflation
• consistency with CMB observables
• viable reheating

→ beyond the SM
(or change gravity)

Inflation while vacuum energy dominates over kinetic energy



Decays of the inflaton:
→ matter & antimatter, and possibly their asymmetry get produced!

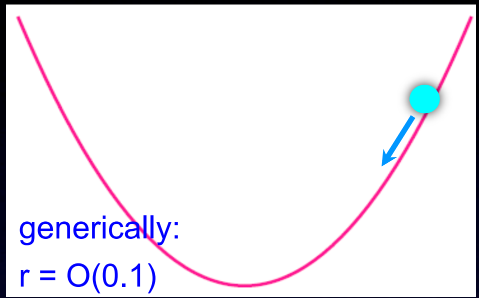
Vacuum energy during inflation:
$(V_0)^{1/4} \sim 10^{16}$ GeV $\sim M_{GUT}$

Two major questions:

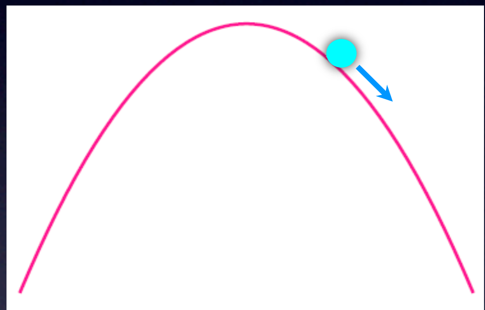
Which particle physics scenario can give rise to successful inflation?

And finally: Who is the inflaton particle?

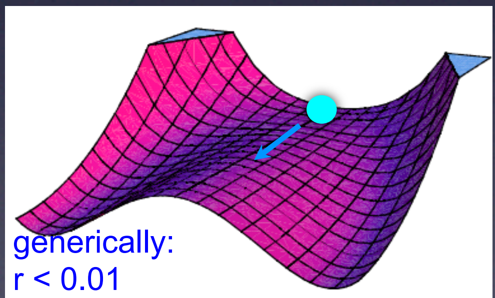
Bottom-up considerations …



'Large field' (chaotic) inflation



'Small field' (new) inflation



'Hybrid-type' inflation models

Various considerations & viewpoints:

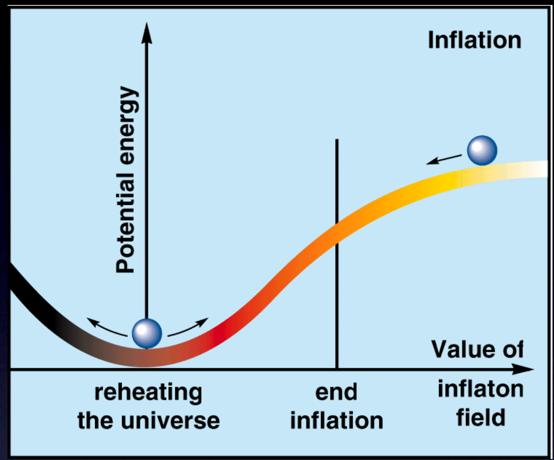
- Basic classes of inflation models
- Often: One just adds a singlet scalar field plus potential without connection to the rest of the theory …
- Take SM particle (e.g. Higgs) and modify gravity (e.g. introduce non-minimal coupling to gravity …)
- Look for candiates in extensions of the SM …

Top-down viewpoints ...

Various top-down possibilities:

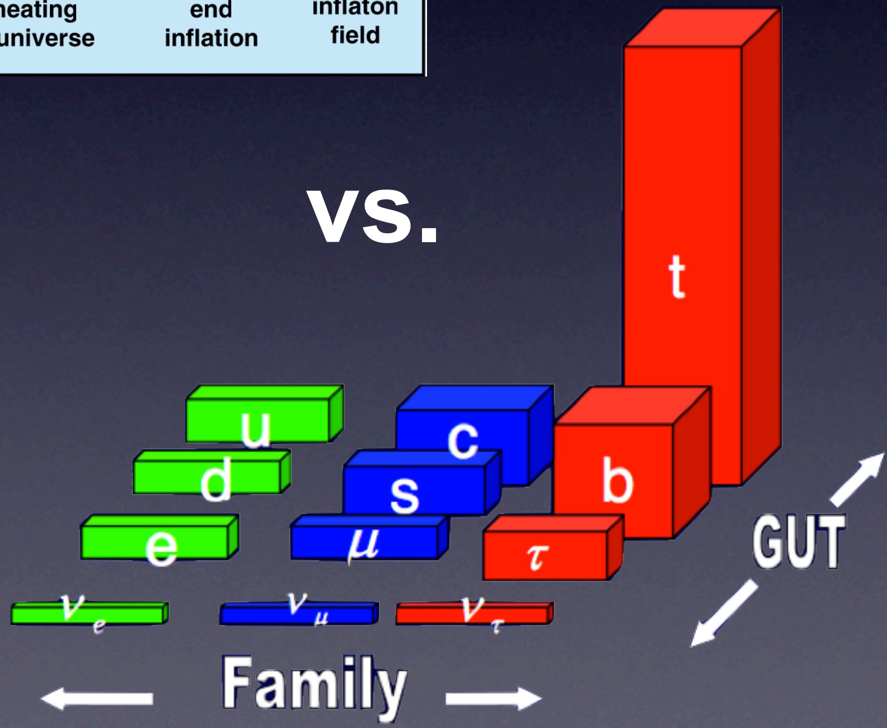
- Grand Unified Theories (GUTs)?
- Family symmetries?
- Supersymmetry/Supergravity
- Seesaw mechanism for ν-masses
- String theory, extra dimensions …

↔



$\} V_0 \sim M_{GUT}$

vs.



How does inflation fit into a more fundamental theory … ?

Various top-down possibilities:

- Grand Unified Theories (GUTs)?
- Family symmetries?
- Supersymmetry/Supergravity
- Seesaw mechanism for ν-masses
- String theory, extra dimensions …

⟷

Various considerations & viewpoints:

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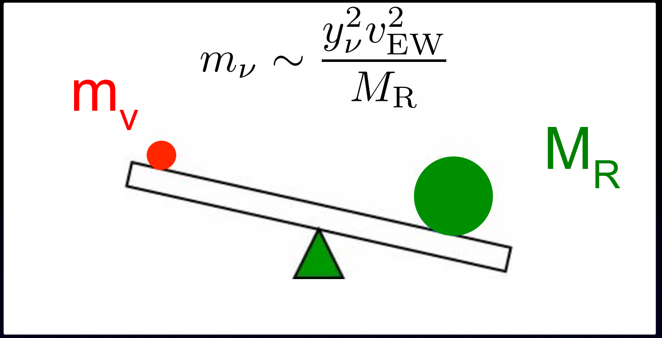
- Take SM particle (e.g. Higgs) and modify gravity (e.g. introduce non-minimal coupling to gravity …)
- Look for candiates in extensions of the SM …

Seesaw + SUSY $\to$ *The RH sneutrino as the inflaton*

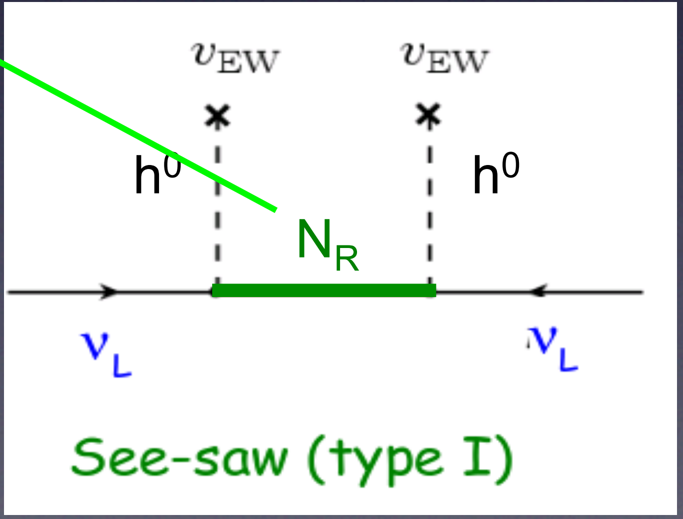


The right-handed neutrino superfield:

$$\nu_{\rm R} = \widetilde{N}_{\rm R} + \sqrt{2}\theta N_{\rm R} + \theta\theta F_{N_{\rm R}}$$

P. Minkowski ('77), Mohapatra, Senjanovic, Yanagida, Gell-Mann, Ramond, Slansky, Schechter, Valle, ...

The right-handed sneutrinos, i.e. the scalar superpartners of the RH neutrinos $\to$ excellent candidates for acting as the inflaton field!



Framework: local supersymmetry = supergravity

Two possibilities for the origin of the large RH neutrino masses $\leftrightarrow$ two options for realising inflation with RH sneutrinos

Origin of right-handed neutrino masses

I) Direct mass terms:

$$\boxed{\mathcal{W}_{M_\mathrm{R}} = M_\mathrm{R}\nu_\mathrm{R}\nu_\mathrm{R}}$$

II) Mass terms from spontaneous symmetry breaking

$$\boxed{\mathcal{W}_{M_\mathrm{R}} = \frac{\lambda}{M_\mathrm{Pl}}\nu_\mathrm{R}\nu_\mathrm{R}HH}$$

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For example:

In SO(10) GUTs:

$$\frac{1}{\Lambda}16_i 16_j H_{\overline{16}} H_{\overline{16}}$$

In some A_4 flavour models (with $\theta^{(i)}$ flavons in 3 of A_4):

$$\frac{1}{\Lambda}\nu_{\mathrm{R}i}\nu_{\mathrm{R}j}\theta^{(i)}\theta^{(j)}$$

Chaotic Sneutrino Inflation

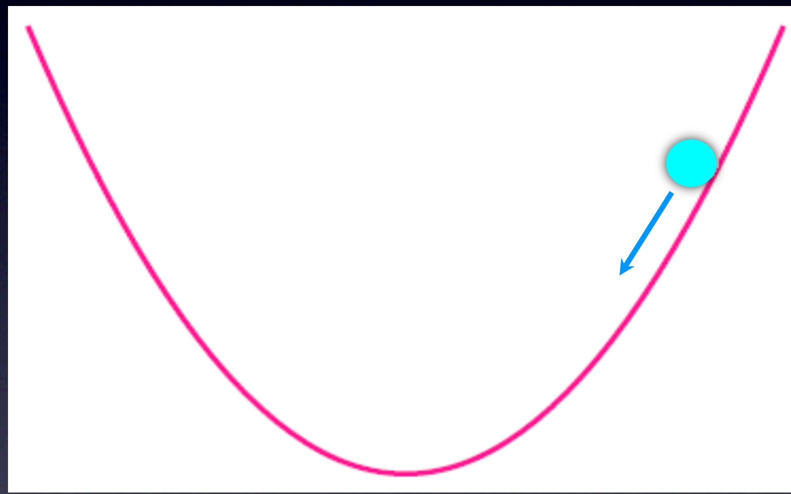
I) Direct mass terms:

Murayama, Suziki, Yanagida, Yokoyama (‘93)

$$\boxed{\mathcal{W}_{M_\mathrm{R}} = M_\mathrm{R} \nu_\mathrm{R} \nu_\mathrm{R}}$$

Inflaton potential from:

$$|F_{\nu_R}|^2 = \left|\frac{\partial W}{\partial \nu_R}\right|_{\theta=0} = |M_R \tilde{N}_R|^2$$



'Large field' (chaotic) sneutrino inflation

Predictions for CMB observables:
$n_s \approx 0.96$, $r \approx 0.16$

Predictions for neutrino physics:
$M_R \sim 10^{13}$ GeV

Note: ν_R has to be a total singlet!

In supergravity:
W+ suitable Kähler potential K

Sneutrino Hybrid Inflation

II) Mass term from spontaneous symmetry breaking (SSB)

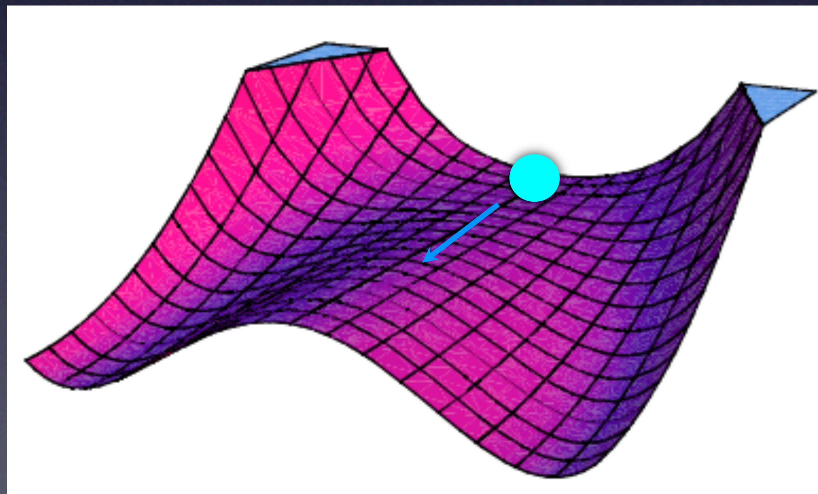
$$\boxed{\mathcal{W} = \kappa S(H^2 - M^2) + \frac{\lambda}{M_{\mathrm{Pl}}}\nu_{\mathrm{R}}\nu_{\mathrm{R}}HH}$$

S.A., Bastero-Gil, King, Shafi ('04)

i) $<\tilde{N}_R> \neq 0$ can stabilise H at $<H> = 0$ and leads to large vacuum energy $V_0 \sim M$
ii) Large masses for the RH (s)neutrinos when H gets a vev after inflation

Additional term in W is just a SUSY version of a SSB potential

$|F_S|^2 \Rightarrow$

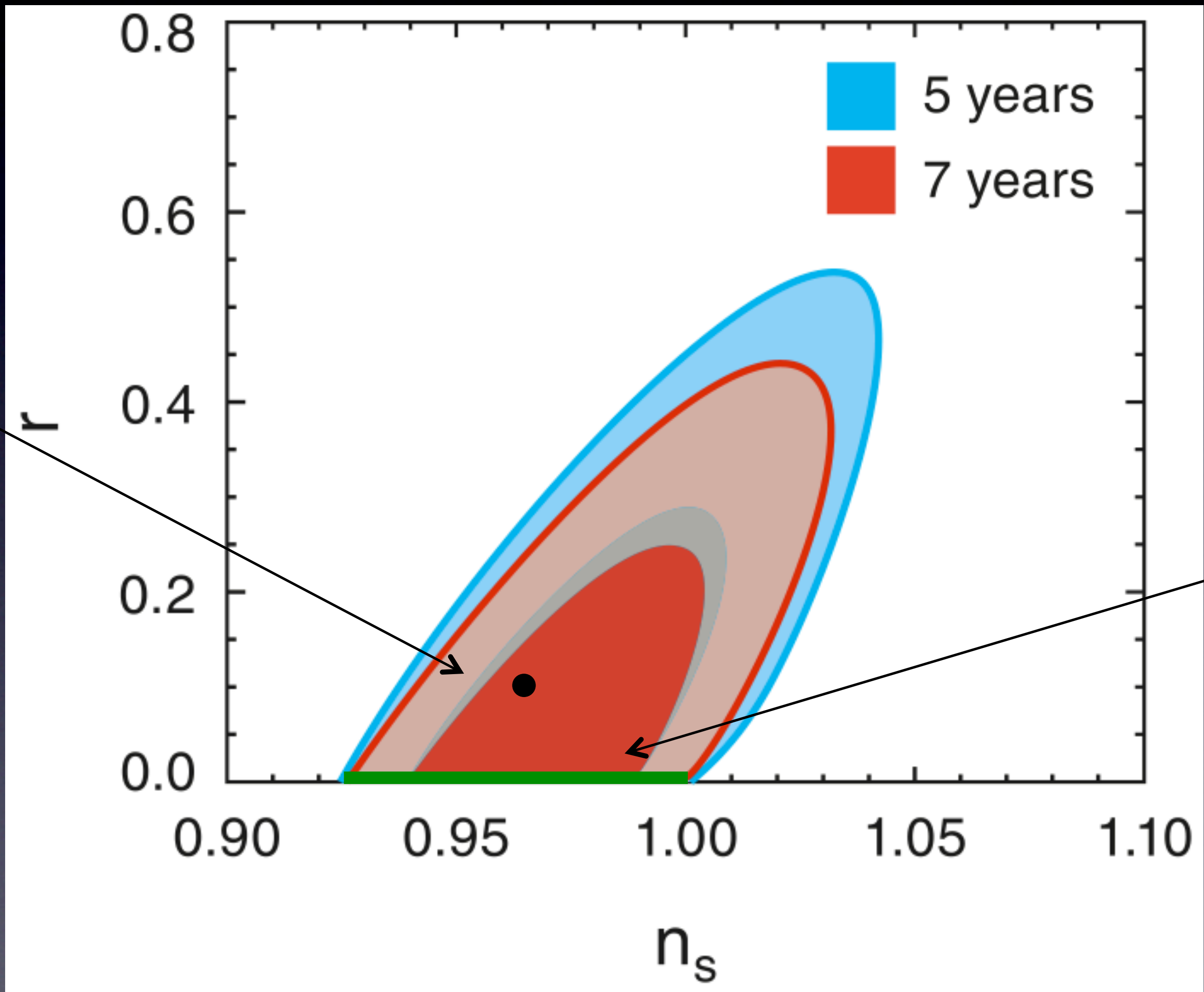


'Hybrid-type' sneutrino inflation

Chaotic ↔ Hybrid models can be distinguished by the results of the Planck satellite

Prediction of
Chaotic Sneutrino Inflation

Murayama, Suziki, Yanagida, Yokoyama ('93)



Prediction of
Sneutrino Hybrid Inflation

S.A., Bastero-Gil, King, Shafi ('04)

(WMAP '10, WMAP '08)

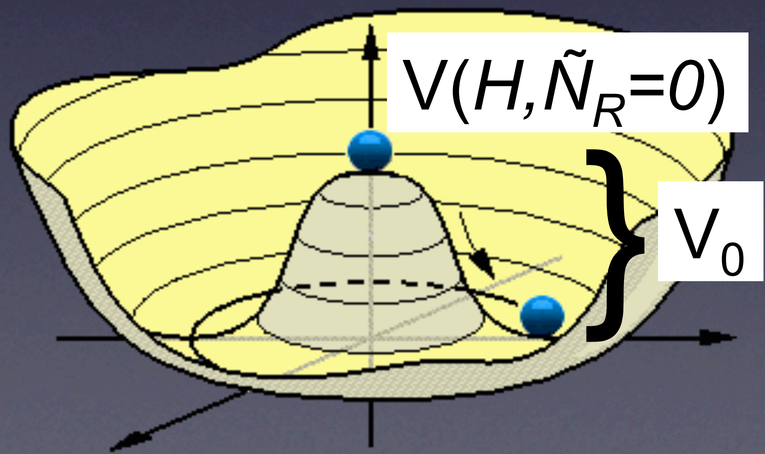
Sneutrino Hybrid Inflation

$$\mathcal{W} = \kappa S (H^2 - M^2) + \frac{\lambda}{M_{\rm Pl}} \nu_{\rm R} \nu_{\rm R} H H$$

Driving superfield
(its F-term generates the potential for H and provides the vacuum energy V_0; During and after inflation: <S> = 0.)

Waterfall superfield
(contains the “waterfall field” (e.g. GUT- or Flavour-Higgs field) that ends inflation by a 2nd order phase transition)

$|F_S|^2 \Rightarrow$



In supergravity:
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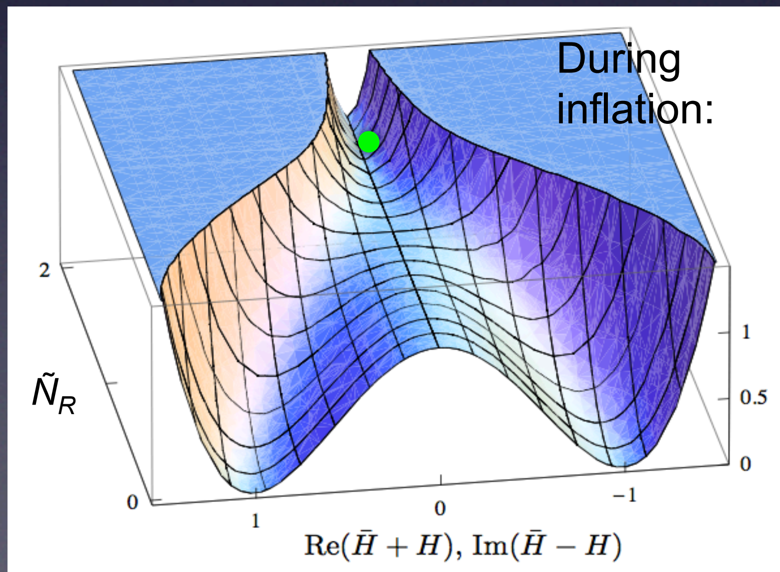
Sneutrino Hybrid Inflation

$$\mathcal{W} = \kappa S(H^2 - M^2) + \frac{\lambda}{M_{\rm Pl}} \nu_{\rm R} \nu_{\rm R} H H$$

$|F_S|^2 \Rightarrow$

22

$\langle\tilde{N}_R\rangle > \tilde{N}_{R,crit}$



Inflaton superfield

(ν_R contains the inflaton field $\tilde{N}_R$ as scalar component; For $\langle\tilde{N}_R\rangle > \tilde{N}_{R,crit}$ it stabilises H at $\langle H\rangle = 0$)

Sneutrino Hybrid Inflation

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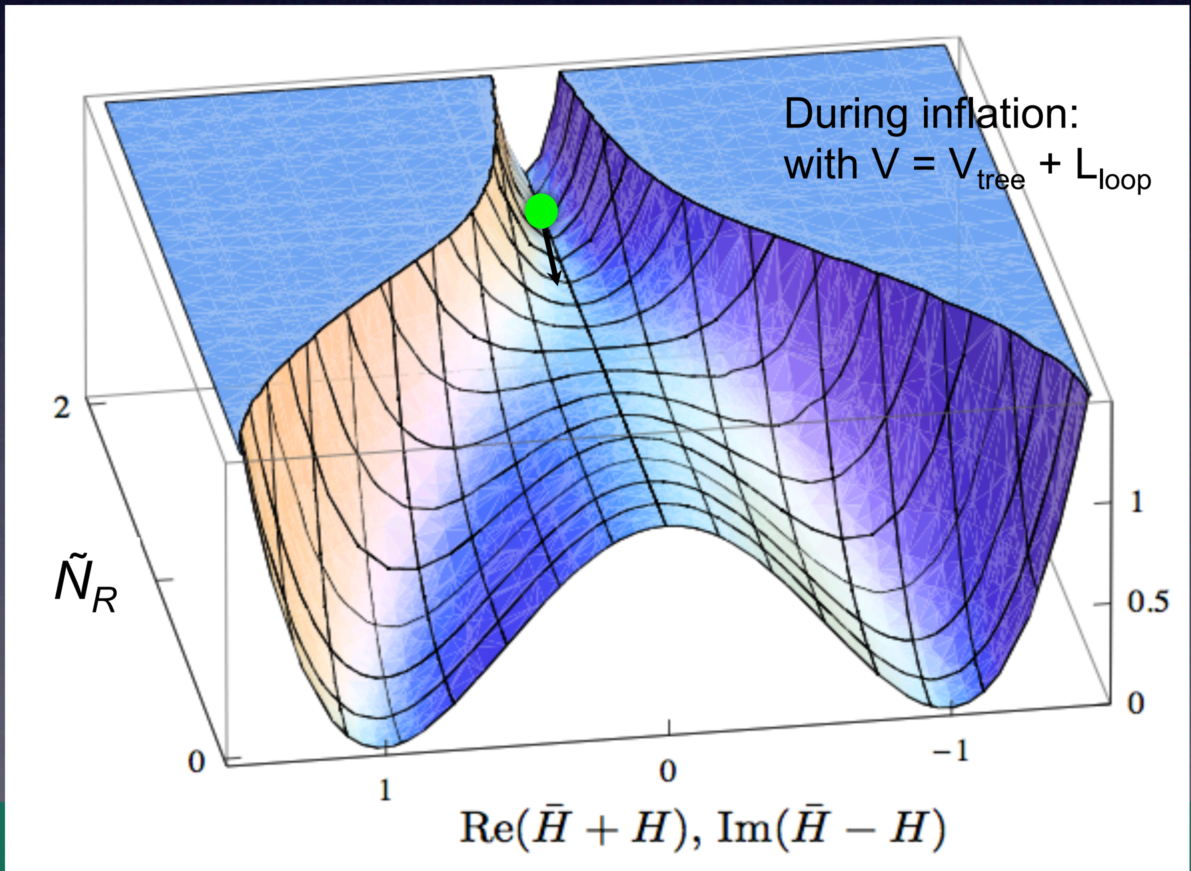

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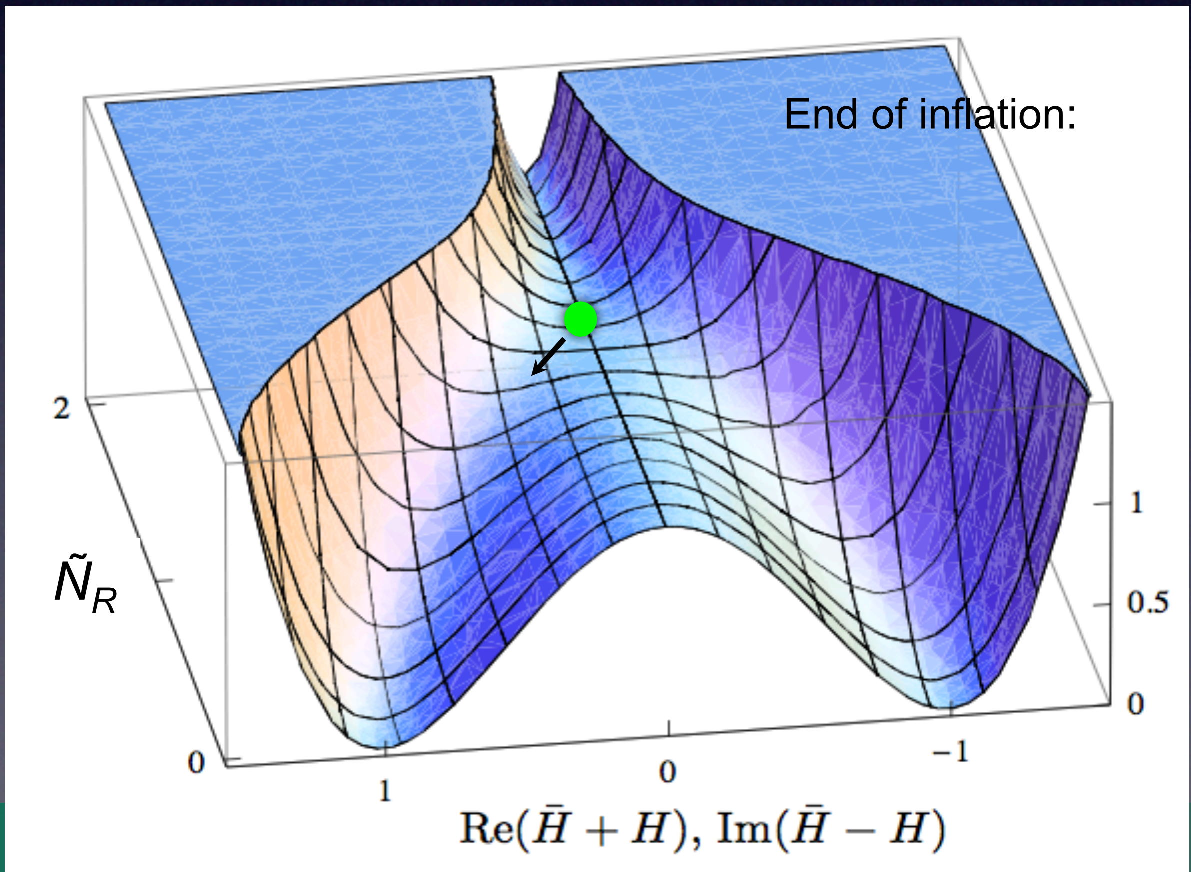

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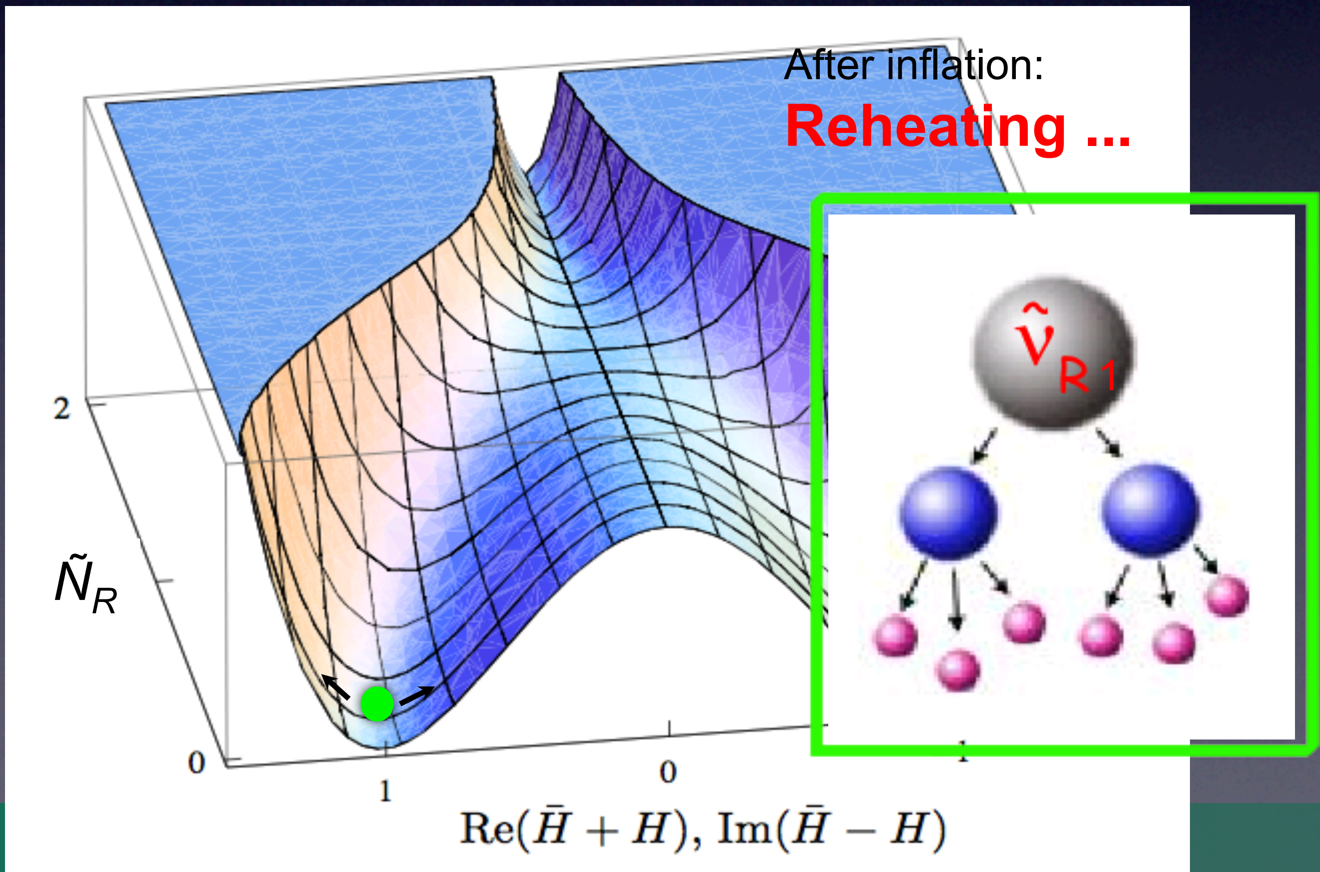
Sneutrino Hybrid Inflation

$$\mathcal{W} = \kappa S(H^2 - M^2) + \frac{\lambda}{M_{\mathrm{Pl}}}\nu_{\mathrm{R}i}\nu_{\mathrm{R}i}HH + (y_\nu)_{ij}\nu_{\mathrm{R}i}hL_j$$

Neutrino Yukawa couplings



Sneutrino Hybrid Inflation

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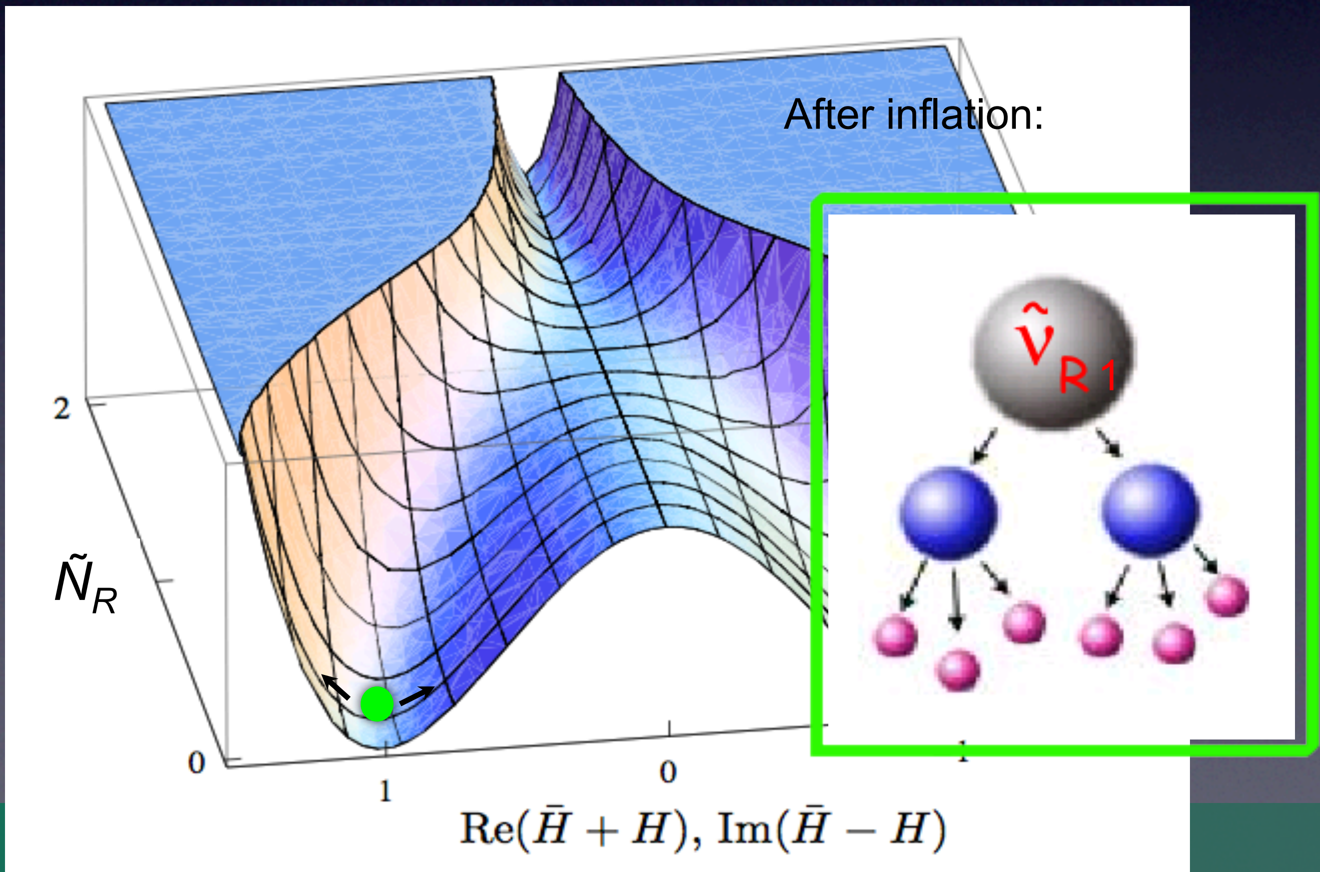
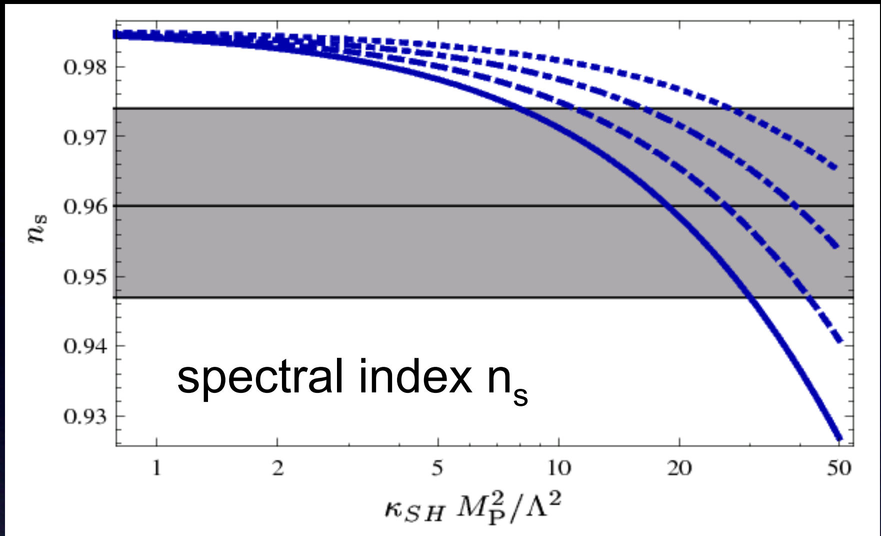
Neutrino Yukawa couplings

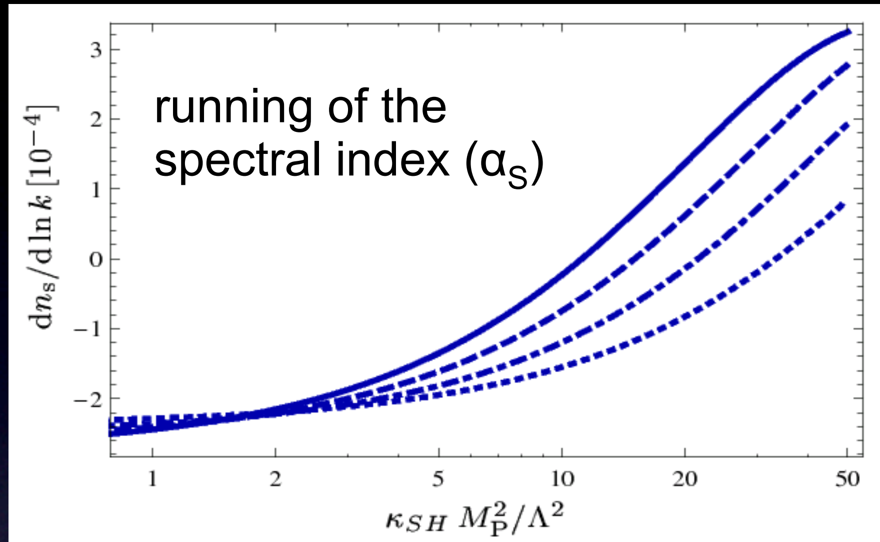


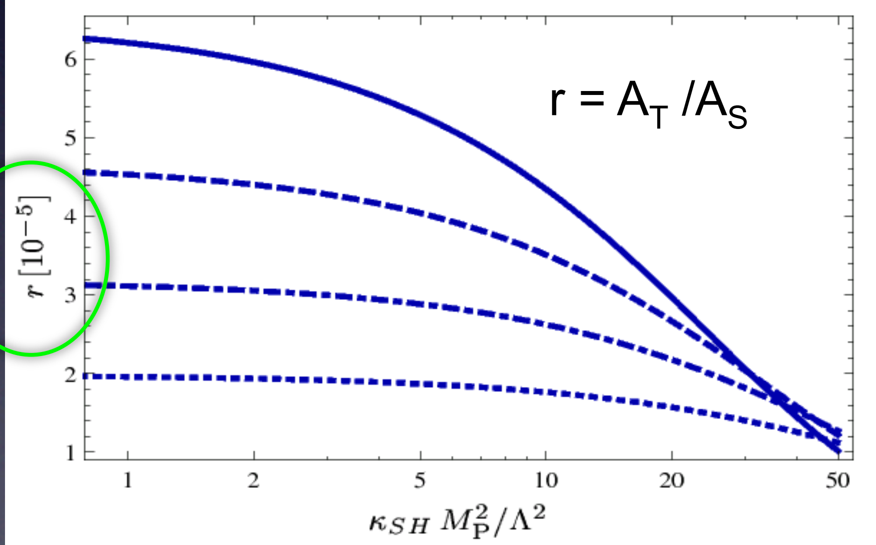
Non-thermal leptogenesis after sneutrino inflation: very efficient way of generating the observed baryon asymmetry!

In Sneutrino Hybrid Inflation:
S.A., Baumann, Domcke, Kostka ('10)

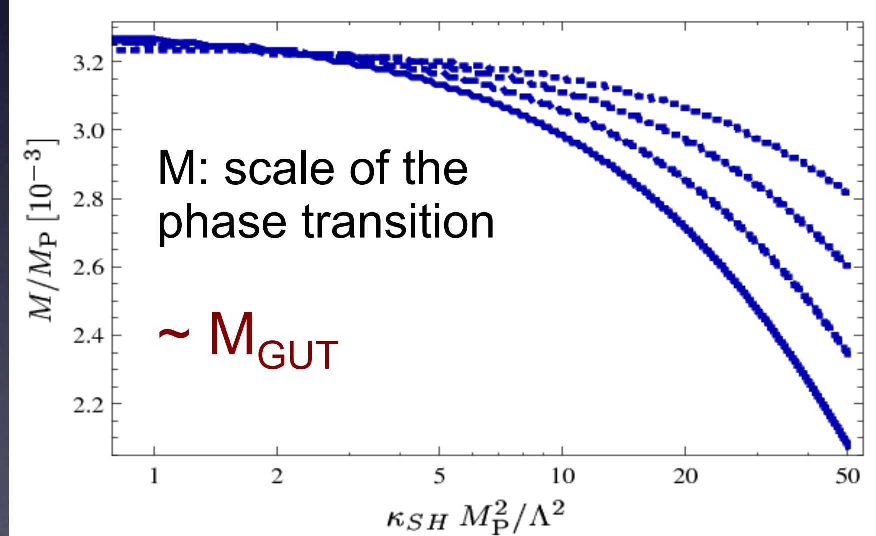
CMB observables







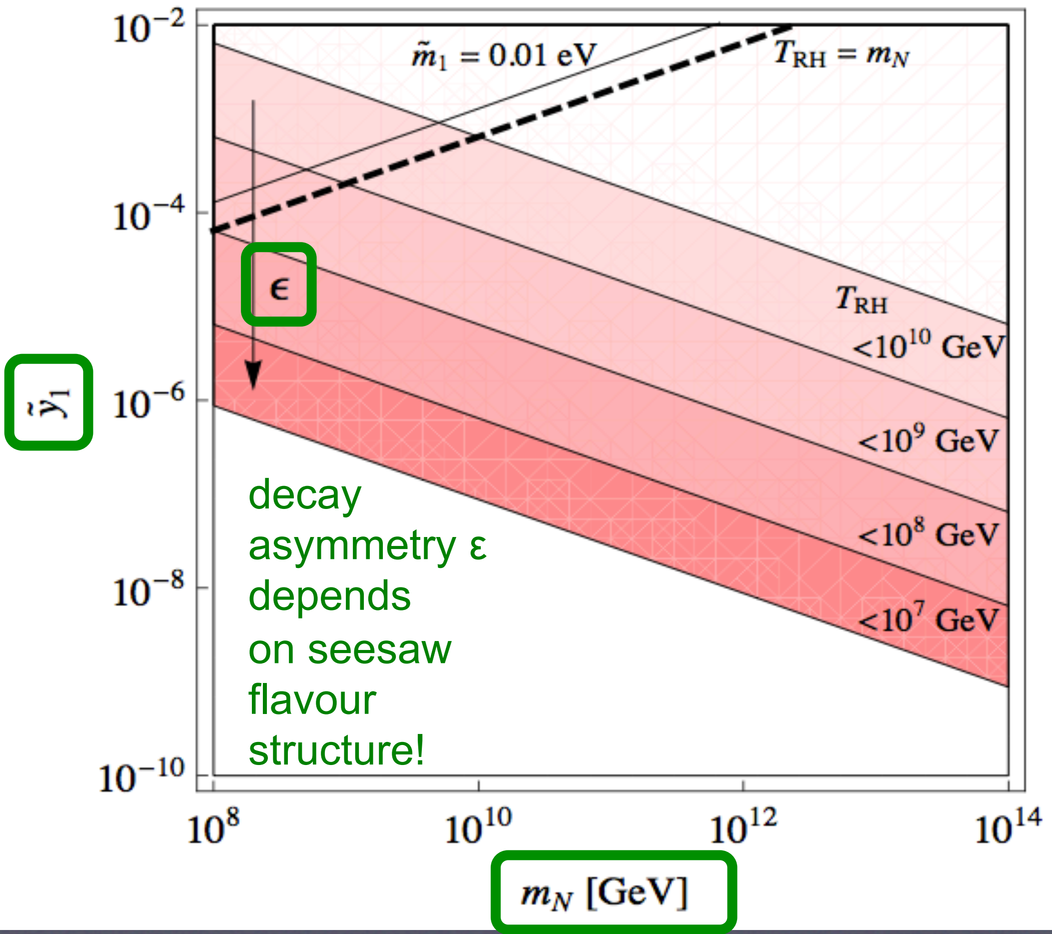
very small
(as typical for Hybrid-type models)



Example: Predictions in a toy model ...

S.A., K. Dutta, P. M. Kostka ('09)

Sneutrino hybrid inflation and non-thermal leptogenesis



- Reheating + Leptogenesis

$\tilde{N}_{R1} \leftrightarrow$ inflaton

$$\tilde{y}_1 \equiv \sqrt{(y_\nu y_\nu^\dagger)_{11}}$$

$$m_N = \text{(s)neutrino mass}$$

$$\tilde{m}_1 = \tilde{y}_1^2 \langle v \rangle^2 / m_N$$

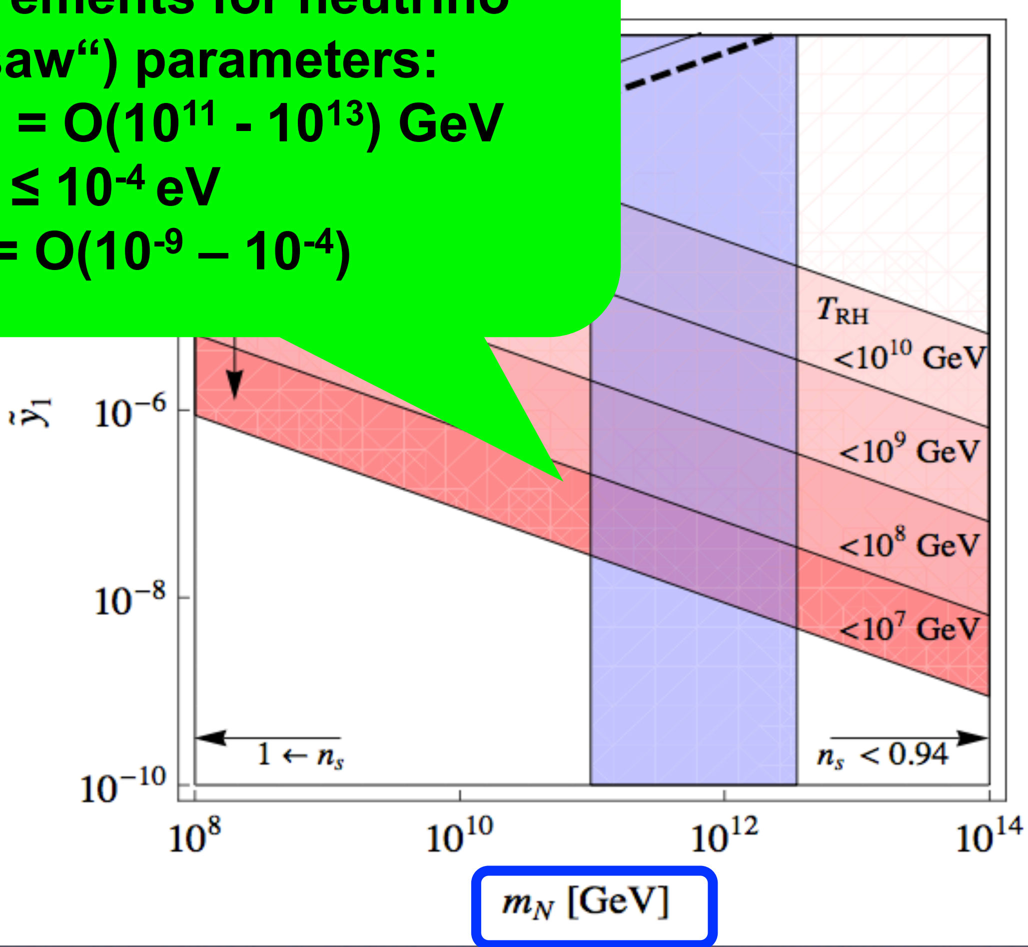
$$\epsilon < \frac{3}{8\pi} \frac{\sqrt{\Delta m^2_{atm}} m_N}{\langle v \rangle^2}$$

[S. Davidson, A. Ibarra '02]

S.A., Baumann, Domcke, Kostka ('10)

Sneutrino hybrid inflation and non-thermal leptogenesis

Requirements for neutrino ("seesaw") parameters:
→ $m_{N1} = O(10^{11} - 10^{13})$ GeV
→ $m_{\nu 1} \lesssim 10^{-4}$ eV
→ $y_{\nu 1} = O(10^{-9} – 10^{-4})$



- Reheating + Leptogenesis
- Inflation

$\tilde{N}_{R1} \leftrightarrow$ inflaton

$$\tilde{y}_1 \equiv \sqrt{(y_\nu y_\nu^\dagger)_{11}}$$
$$m_N = \text{(s)neutrino mass}$$
$$\tilde{m}_1 = \tilde{y}_1^2 \langle v \rangle^2 / m_N$$
$$\epsilon < \frac{3}{8\pi} \frac{\sqrt{\Delta m^2_{atm}} m_N}{\langle v \rangle^2}$$

[S. Davidson, A. Ibarra '02]

in a simple example model of Sneutrino Hybrid Inflation ... S.A., Baumann, Domcke, Kostka ('10)

Sneutrino Hybrid Inflation belongs to a more general class of models: Matter Inflation

$$\mathcal{W} = \kappa S (f(H) - M^2) + g(\phi, H)$$

Driving superfield

Waterfall superfield

Inflaton superfield (resides in the matter sector)

- Also referred to as "Tribrid Inflation", because three fields play some role in the superpotential of the models …

S.A., M. Bastero-Gil, K. Dutta, S. F. King, P. M. Kostka ('08)

Further developments & possibilities in Matter Inflation

- Inflaton does not have to be a gauge singlet. It can also be a gauge non-singlet (e.g. a D-flat direction of GUT representations)

S.A., Bastero-Gil, Baumann, Dutta, King, Kostka ('10)

- The (2^{nd} order) phase transition at the end of inflation can be …
  - ✓ ... a GUT phase transition

Dvali, Shafi, Schaefer ('94)

  - ✓ ... the breaking of a family symmetry (e.g. A_4, …)

S. A., King, Malinsky, Velasco-Sevilla, Zavala ('07)

- Possibilites for realising Matter Inflation in Heterotic String Theory ...

S. A., Halter, Erdmenger ('11)

Further developments & possibilities in Matter Inflation

- No monopoles are generated at the end of inflation ...
  - ✓ ... if the inflaton is a gauge non-singlet (→ group broken during inflation)
    S.A., Bastero-Gil, Baumann, Dutta, King, Kostka (‘10)
  - ✓ ... if a family symmetry is broken at the end of inflation (as in “flavon inflation”)
    S. A., King, Malinsky, Velasco-Sevilla, Zavala (‘07)
  - ✓ ... in “pseudosmooth” versions of tribrid inflation
    S.A., Nolde, Ur Rehman (‘12)

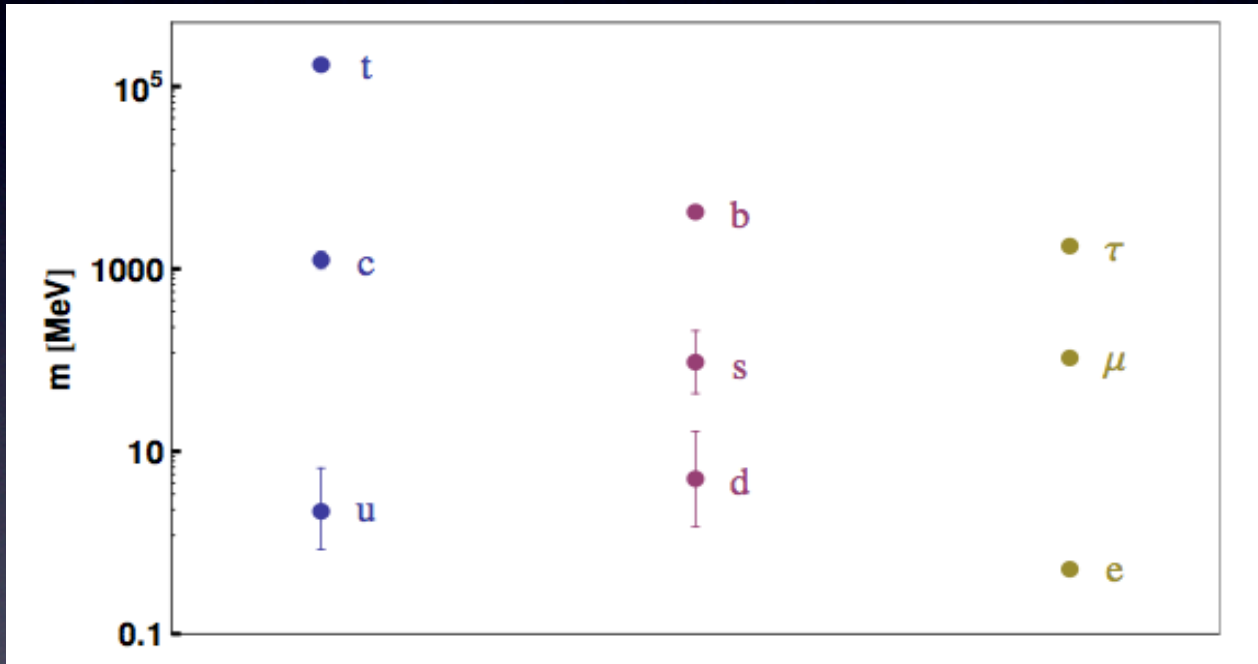
✓ The η-problem (→ “flatness problem” of the inflaton potential) can be solved in SUGRA by symmetry (e.g. by a Heisenberg or shift symmetry in the Kähler potential)

S.A., M. Bastero-Gil, K. Dutta, S. F. King, P. M. Kostka (‘08)
S.A., K. Dutta, P. M. Kostka ('09)

Second part of my talk:

Are there GUT-footprints in fermion masses and mixings?

- One motivation: Why are the observed masses of down-type quarks and charged leptons "similar" (but not equal)?



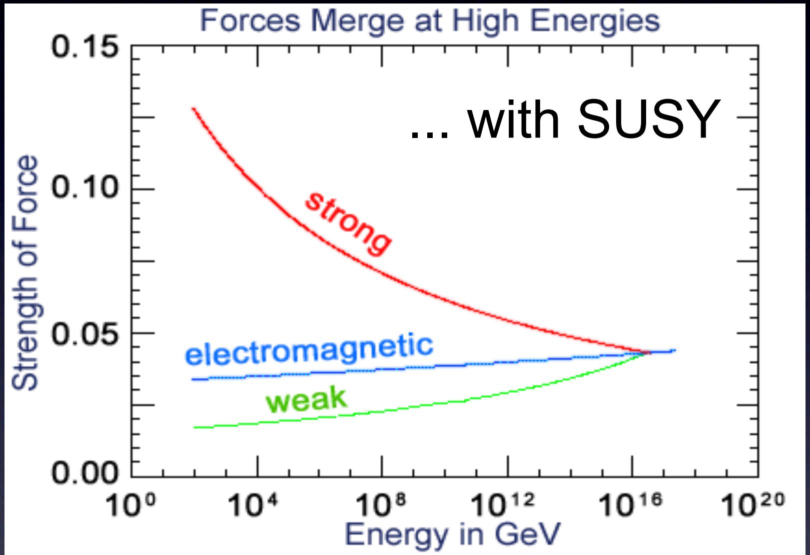
$m_b \leftrightarrow m_\tau$?

$m_s \leftrightarrow m_\mu$?

(running masses at the top-mass scale; errors are 3 times the 1σ errors ...)

GUTs: Unification of forces and of matter particles

i) Unification of forces at $M_{GUT} \sim 10^{16}$ GeV



ii) Unification of matter particles in joint representations of the GUT group

E.g. in SU(5) GUTs:

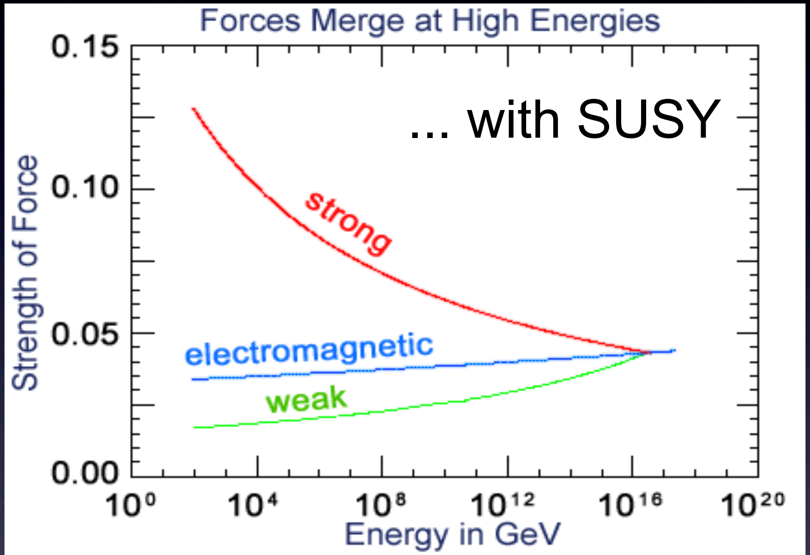
$$\boxed{\bar{5}_i = \begin{pmatrix} d_R^{cR} & d_R^{cB} & d_R^{cG} & e_L & -\nu_L \end{pmatrix}_i}$$

$$\boxed{\mathbf{10}_i = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & -u_R^{cG} & u_R^{cB} & -u_L^R & -d_L^R \\ u_R^{cG} & 0 & -u_R^{cR} & -u_L^B & -d_L^B \\ -u_R^{cB} & u_R^{cR} & 0 & -u_L^G & -d_L^G \\ u_L^R & u_L^B & u_L^G & 0 & -e_R^c \\ d_L^R & d_L^B & d_L^G & e_R^c & 0 \end{pmatrix}_i}$$

In SO(10) GUTs: $\bar{5}_i + 10_i + \nu_{Ri}$ in 16_i

GUTs: Unification of forces and of matter particles

i) Unification of forces at $M_{GUT} \sim 10^{16}$ GeV



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In SO(10) GUTs: $\bar{5}_i + 10_i + \nu_{Ri}$ in 16_i

One consequence:
Elements of the matrices M_d and M_e can be generated by one single operator
$\longrightarrow$ they differ only by group theoretical Clebsch factors

➢ This leads to GUT relations between the masses of down-type quarks and charged leptons (e.g. in SU(5) GUTs):

- Relations from fundamental operators:

$$\bar{\mathbf{5}}_3 \mathbf{10}_3 \langle \bar{H}_5 \rangle \Rightarrow \boxed{\frac{m_\tau}{m_b}\Big|_{M_{\mathrm{GUT}}} = 1}$$

"bottom-tau unification"

$$\bar{\mathbf{5}}_2 \mathbf{10}_2 \langle \bar{H}_{45} \rangle \Rightarrow \boxed{\frac{m_\mu}{m_s}\Big|_{M_{\mathrm{GUT}}} = 3}$$

Georgi, Jarlskog ('79)

SM Higgs particle in GUT representation H_{45}

Remark:
In models aiming at explaining the fermion mass hierarchies, the masses << m_t are typically generated by effective operators!
Froggatt, Nielsen ('79)

→ With effective operators new interesting GUT predictions for m_τ / m_b and m_μ / m_s can arise!

S. A., Spinrath ('09)

- This leads to GUT relations between the masses of down-type quarks and charged leptons (e.g. in SU(5) GUTs):

  - Relations from effective operators, e.g.:

S. A., Spinrath ('09)

$$\overline{\mathbf{5}}_3 \frac{\langle H_{24} \rangle}{\Lambda} \mathbf{10}_3 \langle \bar{H}_5 \rangle \quad \Rightarrow \quad \boxed{\frac{m_\tau}{m_b}\Big|_{M_{\mathrm{GUT}}} = \frac{3}{2}}$$

$$\overline{\mathbf{5}}_2 \frac{\langle H_{24} \rangle}{\Lambda} \mathbf{10}_2 \langle \bar{H}_{45} \rangle \quad \Rightarrow \quad \frac{m_\mu}{m_s}\Big|_{M_{\mathrm{GUT}}} = \frac{9}{2}$$

$$\overline{\mathbf{5}}_2 \langle \bar{H}_5 \rangle \mathbf{10}_2 \frac{\langle H_{24} \rangle}{\Lambda} \quad \Rightarrow \quad \frac{m_\mu}{m_s}\Big|_{M_{\mathrm{GUT}}} = 6$$

Their viablity depends on RG running and threshold corrections (in SUSY)!

i) The "GUT Higgs" H_{24} breaks the GUT symmetry to the SM
ii) The effective operators can explain the hierarchy of masses

$M_u \longleftrightarrow M_d$

$U_{CKM} = U^{u\dagger} U^d$

GUT relations

$m_\nu \longleftrightarrow M_e$

$U_{PMNS} = U^{e\dagger} U^\nu$

Mass relations @ M_{GUT}, e.g.:

$$\boxed{\frac{m_\tau}{m_b} = c_{33} = 1, \frac{3}{2}}$$

$$\boxed{\frac{m_\mu}{m_s} = c_{22} = 3, \frac{9}{2}, 6}$$

(c_{ij}: group theory Clebsch factors)

Clebsch factors ∈ {1,3} in GUTs: Georgi, Jarlskog ('79)
New possible Clebsch factors ∈ {3/2,3,9/2,6,...}: S.A., Spinrath ('09)

In addition to GUT relations for the mass eigenvalues, there are also relations for the mixing angles ...

$M_u \longleftrightarrow M_d$

$U_{CKM} = U^{u\dagger}\, U^{d}$

Mixing angle relations @ M_{GUT}, e.g.:

$\updownarrow$ GUT relations

$m_\nu \longleftrightarrow M_e$

$U_{PMNS} = U^{e\dagger}\, U^{\nu}$

$$\boxed{\theta^{\mathrm{e}}_{12} = \frac{c_{12}}{c_{22}}\, \theta^{\mathrm{d}}_{12}}$$

Such GUT relations for the mixings can leave footprints in the observable leptonic (PMNS) mixing parameters ...

Possible new combinations of Clebsches leading to large θ_{13}^{PMNS}: S.A., Maurer ('11) Mazocca, Petcov, Romanino, Spinrath ('11)

$$M_u \longleftrightarrow M_d$$

$$U_{CKM} = U^{u\dagger} U^d$$

Let us consider ...

Specific mixing pattern in m_ν, e.g.:

$$m_\nu \longleftrightarrow M_e$$

$$U_{PMNS} = U^{e\dagger} U^\nu$$

$$\left.\begin{array}{l} \bullet \text{ Tri-bimaximal mixing: } U^\nu = U_{TB} \\ \bullet \text{ Bimaximal mixing: } U^\nu = U_{Bimax} \end{array}\right\} \boxed{\text{with } \theta_{13}^\nu \approx 0}$$

More hierarchical masses in M_u than in M_d $\Rightarrow$ $\theta_{ij}^u << \theta_{ij}^d$ $\Rightarrow$ typically $\boxed{\theta_{12}^d \cong \theta_C}$

and θ_{13}^d, $\theta_{23}^d << \theta_C$

$$M_u \longleftrightarrow M_d$$

$$\boxed{U_{CKM} = U^{u\dagger} U^d}$$

Let us consider U^ν with:

$$\boxed{\theta_{13}^\nu \approx 0}$$

$$m_\nu \longleftrightarrow M_e$$

$$U_{PMNS} = U^{e\dagger} U^\nu$$

$\theta_{12}^d \cong \theta_C$

M_u ⟷ M_d

$U_{CKM} = U^{u\dagger} U^d$

GUT relations

$$\theta_{12}^e = \frac{c_{12}}{c_{22}} \theta_{12}^d = \frac{c_{12}}{c_{22}} \theta_C$$

and $\theta_{13}^e, \theta_{23}^e << \theta_C$

Let us consider U^ν with:

$\theta_{13}^\nu \approx 0$

m_ν ⟷ M_e

$U_{PMNS} = U^{e\dagger} U^\nu$

$\theta_{12}^{d} \cong \theta_C$

$M_u \longleftrightarrow M_d$

$U_{CKM} = U^{u\dagger} U^{d}$

GUT relations

$$\theta_{12}^{e} = \frac{c_{12}}{c_{22}}\,\theta_{12}^{d} = \frac{c_{12}}{c_{22}}\,\theta_C$$

and θ_{13}^{e}, $\theta_{23}^{e} \ll \theta_C$

Let us consider U^{ν} with:

$\theta_{13}^{\nu} \approx 0$

$m_\nu \longleftrightarrow M_e$

$U_{PMNS} = U^{e\dagger} U^{\nu}$

The PMNS mixing parameters result from U^{ν} and charged lepton mixing effects ($U^{e\dagger}$)

⇒ Two main effects

Charged lepton mixing effects:
works by many authors ...

$\theta_{12}^{d} \cong \theta_C$

$M_u \longleftrightarrow M_d$

$U_{CKM} = U^{u\dagger} U^{d}$

GUT relations

$m_\nu \longleftrightarrow M_e$

$$\theta_{12}^{e} = \frac{c_{12}}{c_{22}}\,\theta_{12}^{d} = \frac{c_{12}}{c_{22}}\,\theta_C$$

and $\theta_{13}^{e}, \theta_{23}^{e} \ll \theta_C$

Let us consider U^ν with:

$\theta_{13}^{\nu} \approx 0$

$U_{PMNS} = U^{e\dagger} U^{\nu}$

1) Prediction for θ_{13}^{PMNS}:

under simple conditions in GUTs

$$\theta_{13}^{PMNS} = \frac{\theta_{12}^{e}}{\sqrt{2}} = \frac{\theta_C}{\sqrt{2}}\frac{c_{12}}{c_{22}}$$

e.g.: $$\theta_{13}^{PMNS} = \frac{\theta_C}{\sqrt{2}}$$

S.A., Maurer ('11); Mazocca, Petcov, Romanino, Spinrath ('11); King ('12); S.A., Gross, Maurer, Sluka ('12)

Remark: $\theta_{13}^{PMNS} = \theta_C/\sqrt{2}$ also appears, e.g., in a variant of Quark-Lepton-Complementarity: Minakata, Smirnov ('04)

$\theta_{12}^d \cong \theta_C$

$M_u \longleftrightarrow M_d$

$U_{CKM} = U^{u\dagger} U^d$

GUT relations

Let us consider U^ν with:

$\theta_{13}^\nu \approx 0$

$m_\nu \longleftrightarrow M_e$

$$\theta_{12}^{e} = \frac{c_{12}}{c_{22}}\,\theta_{12}^{d} = \frac{c_{12}}{c_{22}}\,\theta_{C}$$

and $\theta_{13}^e, \theta_{23}^e \ll \theta_C$

$U_{PMNS} = U^{e\dagger} U^\nu$

2) "Lepton Mixing Sum Rule":

$$\theta_{12}^{PMNS} = \theta_{12}^{\nu} + \theta_{13}^{PMNS}\cos(\delta^{PMNS})$$

King ('05); Masina ('05); S.A., King ('05)

Reconstructing θ_{12}^{ν} using the lepton mixing sum rule

$$\theta_{12}^{\mathrm{PMNS}} = \theta_{12}^{\nu} + \theta_{13}^{\mathrm{PMNS}} \cos(\delta^{\mathrm{PMNS}})$$

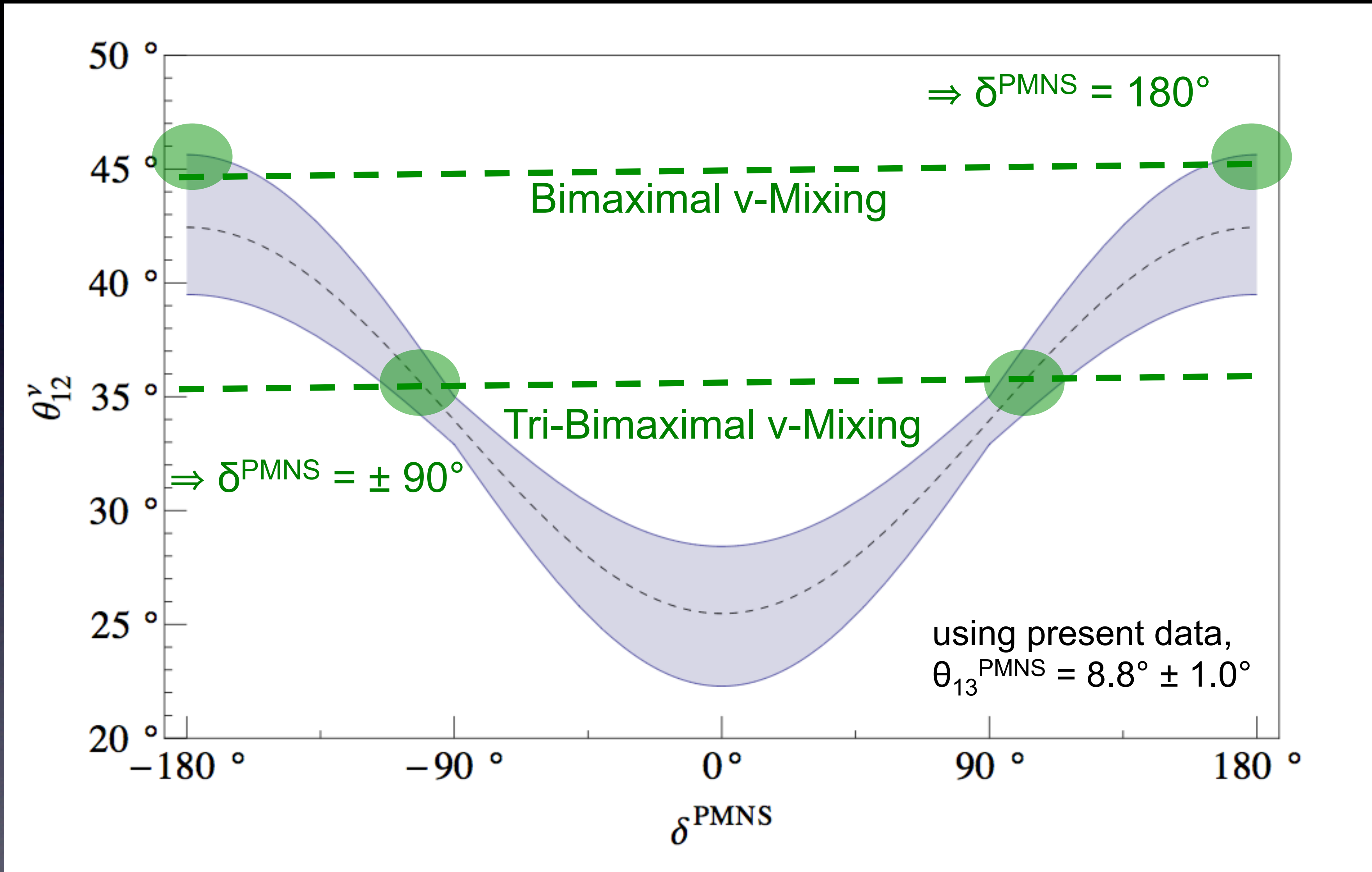


figure from S.A., Gross, Maurer, Sluka ('12)

Note: Predictions emerge at high energies → RG running required

RGEs for the leptonic mixing angles (in LO in θ_{13}; in the MSSM):

$$\dot{\theta}_{12} \approx -\frac{y_\tau^2}{32\pi^2} \sin 2\theta_{12}\, s_{23}^2 \frac{|m_1\, e^{i\varphi_1} + m_2\, e^{i\varphi_2}|^2}{\Delta m_{\text{sol}}^2} + \mathscr{O}(\theta_{13})$$

$$\dot{\theta}_{13} \approx \frac{y_\tau^2}{32\pi^2} \sin 2\theta_{12} \sin 2\theta_{23} \frac{m_3}{\Delta m_{\text{atm}}^2} \left[m_1 \cos(\varphi_1 - \delta) - m_2 \cos(\varphi_2 - \delta)\right] + \mathscr{O}(\theta_{13})$$

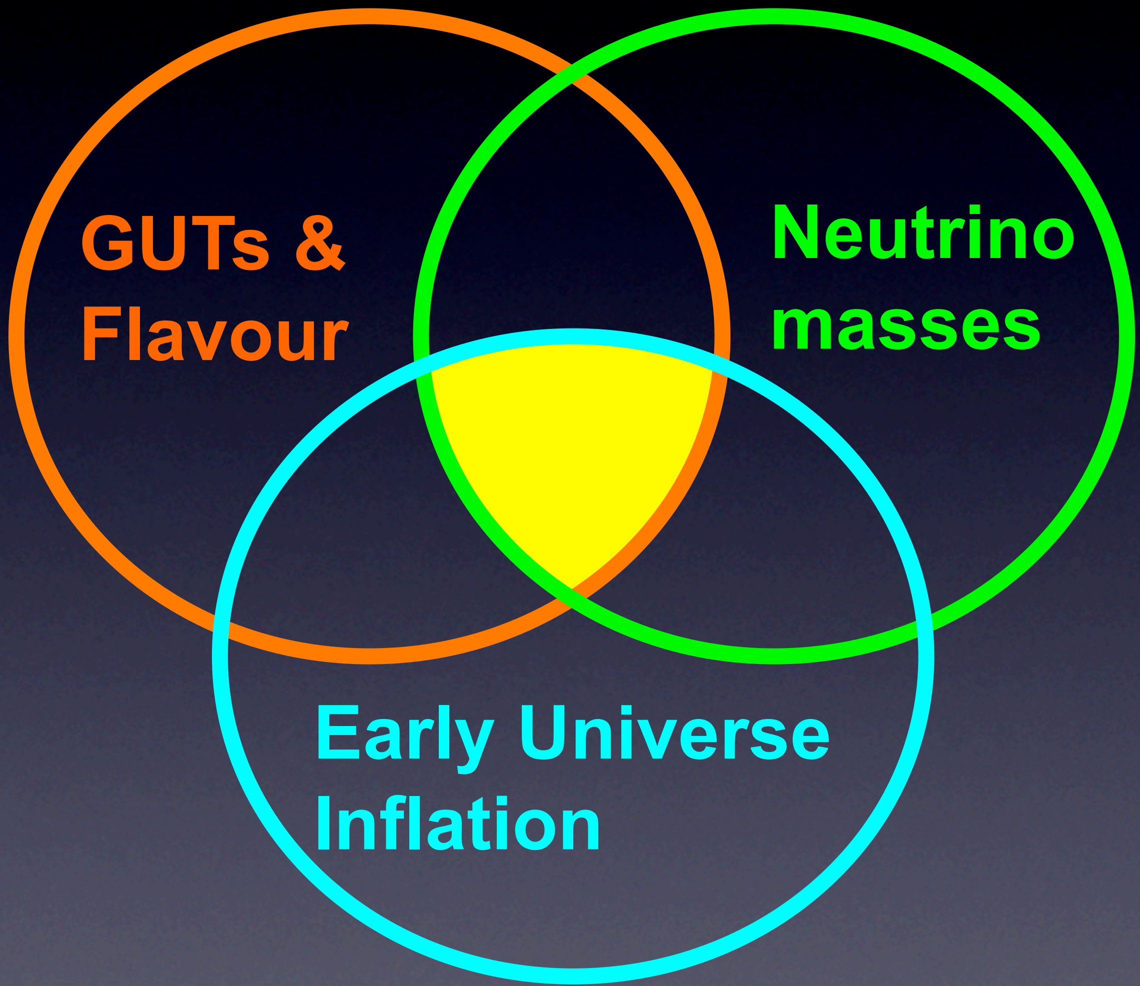
$$\dot{\theta}_{23} \approx -\frac{y_\tau^2}{32\pi^2} \sin 2\theta_{23} \frac{1}{\Delta m_{\text{atm}}^2} \left[c_{12}^2\, |m_2\, e^{i\varphi_2} + m_3|^2 + s_{12}^2\, |m_1\, e^{i\varphi_1} + m_3|^2\right] + \mathscr{O}(\theta_{13})$$

S.A., Kersten, Lindner, Ratz ('03)

(RGEs in the SM: above equations times -3/2)

Including RG effects from Y_ν (analytical formulae + software REAP):
S.A., Kersten, Lindner, Ratz, Schmidt ('05)

Summary and conclusions



- The RH sneutrino is an attractive candidate for the Inflation: Chaotic vs Hybrid-like (= "Tribrid")

- In Sneutrino "Tribrid" Inflation: The end of inflation can be associated with GUT or family symmetry breaking

- $\theta_{13}^{PMNS} \approx \theta_C / \sqrt{2}$ can emerge under simple conditions from GUTs

- Predictions @ high energies (M_{GUT}): careful model analysis including RG running required ... !