Unified Matter Inflation

Stefan Antusch

Max Planck Research Group:
"Beyond the Standard Model"

Project Review 2010

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

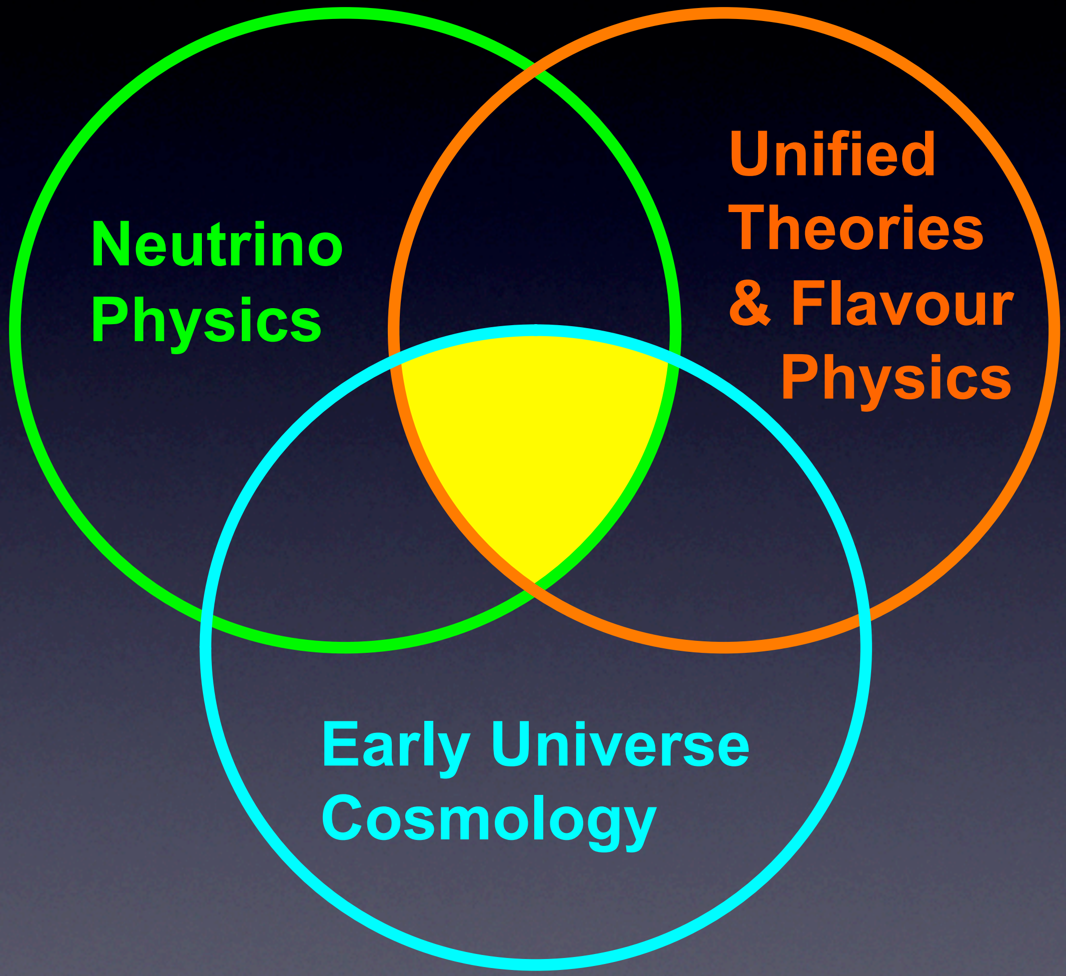
Max Planck Research Group: Beyond the Standard Model

Members:

- Group leader: **Stefan Antusch**
- Postdocs:
  - **Lorenzo Calibbi**
  - **Yu Min Kim** (arrived 10/10)
  - **Toshihiko Ota**
  - **Enrique Fernandez-Martinez** (since 10/10 → CERN)
  - **Koushik Dutta** (since 10/10 → DESY)
- Phd students:
  - **Jochen Baumann**
  - **Sebastian Halter**
  - **Philipp Kostka** (defended his thesis 12/10)
  - **David de Sousa Seixas**
  - **Martin Spinrath** (since 10/10 → SISSA)
- Diploma students:
  - **Valerie Domcke** (thesis handed in 11/10)
  - **Vinzenz Maurer**

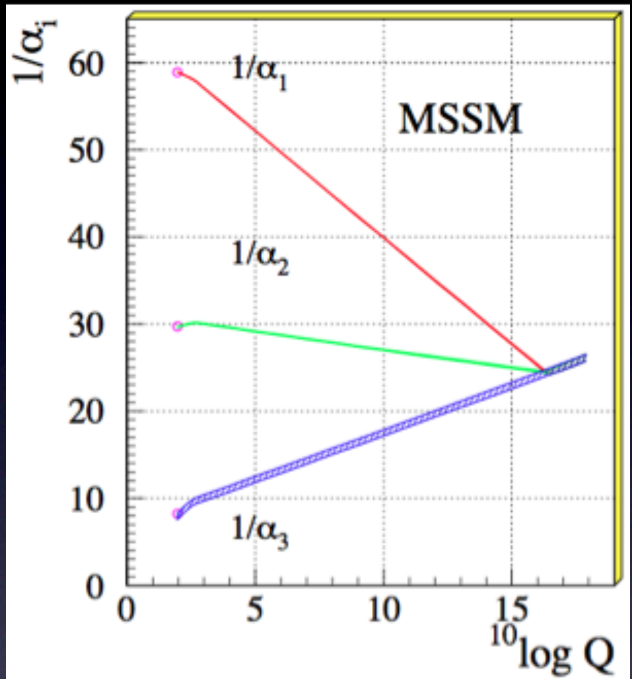
Max Planck Research Group: Beyond the Standard Model

Research:



Grand Unified Theories: 'Unification of forces and Matter'

@ energies ~ 10^{16} GeV



(assuming supersymmetry)

Quarks:	u	c	t
	d	s	b
Leptons:	e	μ	τ
	ν_e	ν_μ	ν_τ
	↓	↓	↓
SO(10) GUTs:	16_1	16_2	16_3

Forces unified:

$SU(3)_C \times SU(2)_L \times U(1)_Y \subset G_{GUT}$.
Examples: $G_{GUT} = SU(5)$, $G_{GUT} = SO(10)$

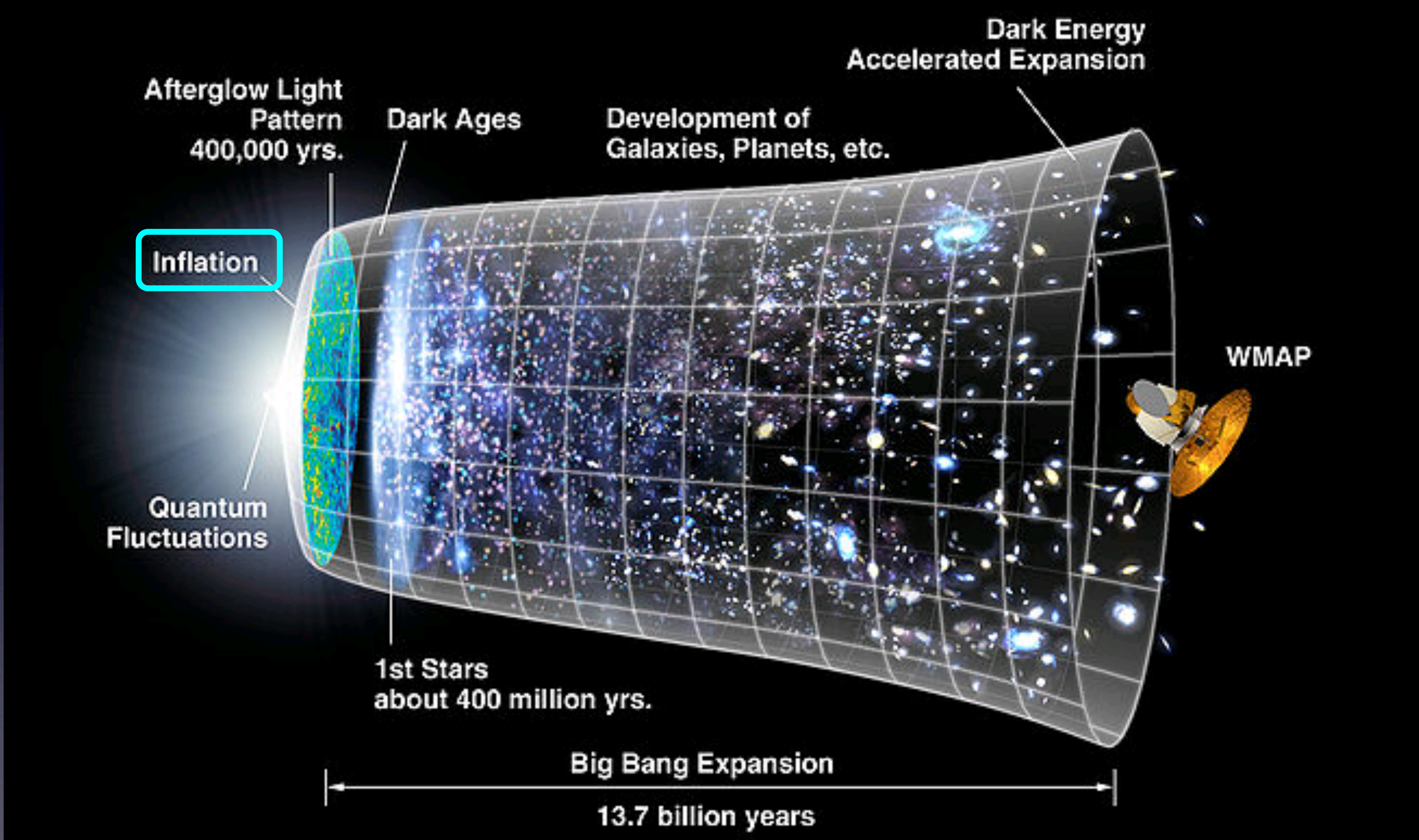
Matter particles unified:

All known matter particles of one family plus one RH neutrino are in

$$\mathbf{16}_i = \left(q_L \quad u^c_R \quad e^c_R \quad d^c_R \quad \ell_L \quad \nu^c_R\right)_i$$

Inflation = Era of accelerated expansion in the very early universe

picture from WMAP website



vacuum energy for inflation: typically ~ 10^{16} GeV (→ Grand Unified Theories)

Outline

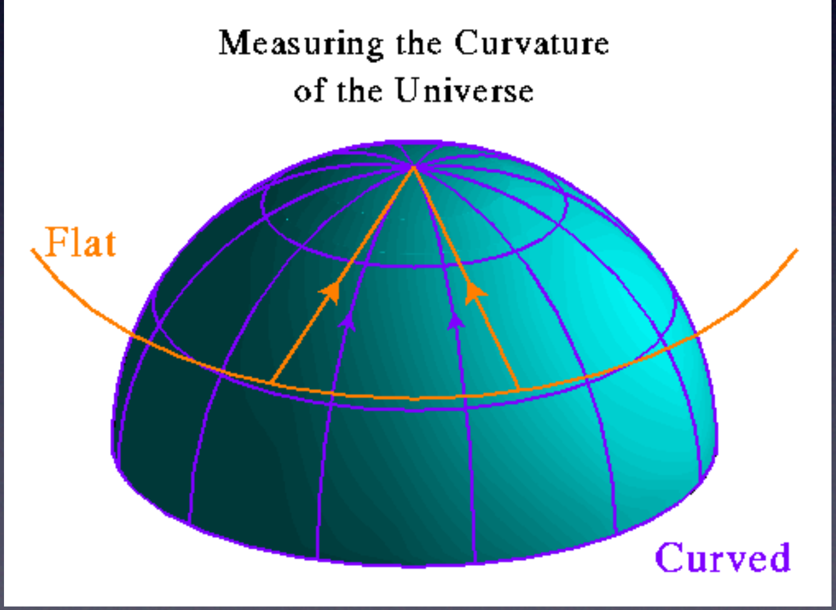
- ➡ Cosmic inflation: A successul paradigm for the early universe

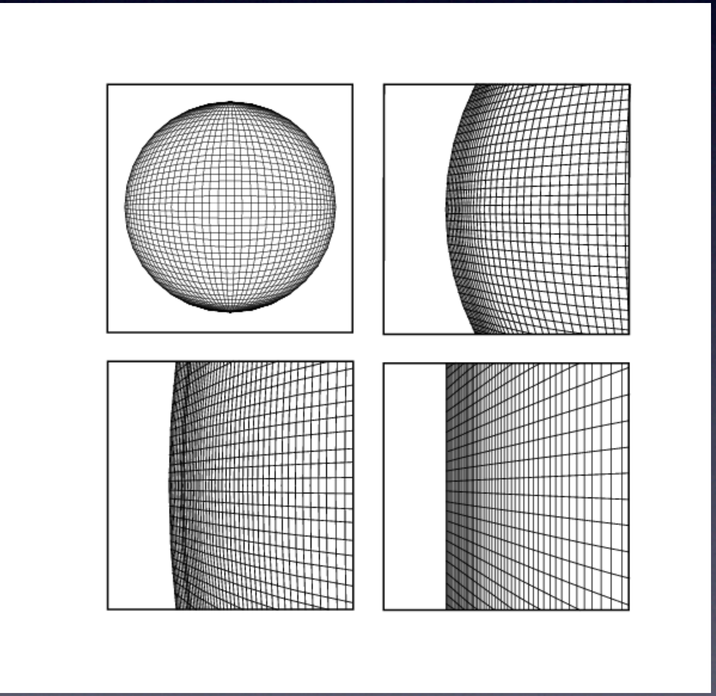
- ➡ How can inflation be realised in particle physics?
  - Framework: Local supersymmetry (= supergravity)
  - Challenge: The η-problem; Possible solution: Symmetries
  - New class of models: ‘Tribrid inflation’ + Symmetries
  - Promising inflaton candidate: The ‘Unified Matter Superparticle’

Why inflation?

- The “Flatness Problem“: Why is the universe so flat?

Exponential expansion:
”flattens“ the universe



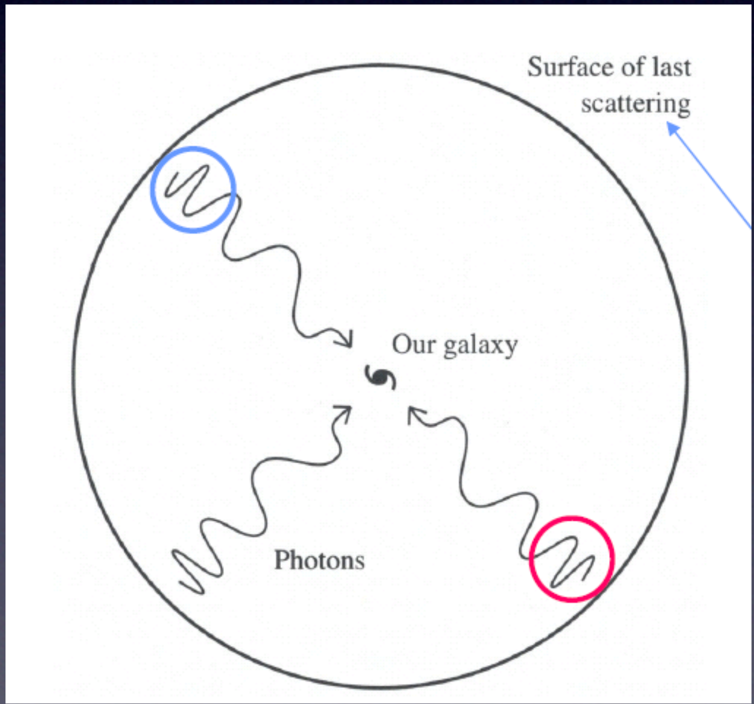


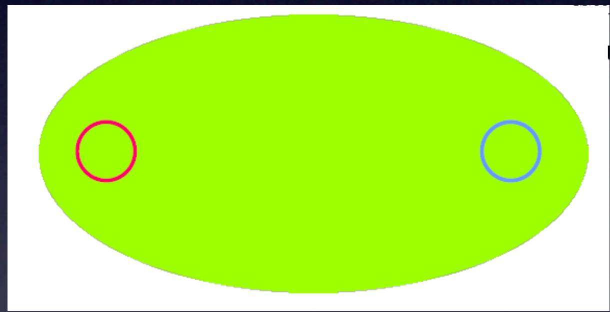
Today: $\Omega_k < 0.01$; Planck times: $\Omega_k < 10^{-60}$

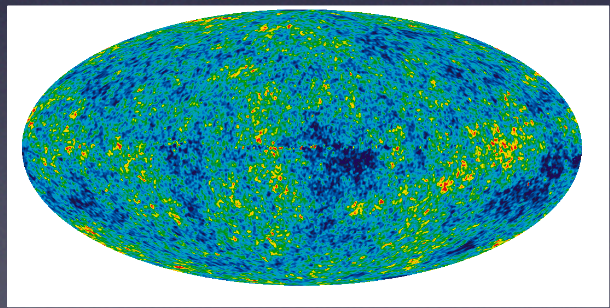
Why inflation?

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

- The “Flatness Problem“: Why is the universe so flat? → Solved!
- The “Horizon Problem“: Why is the universe so homogenous. In particular, why is the CMBR so uniform (isotropic on large scales)?







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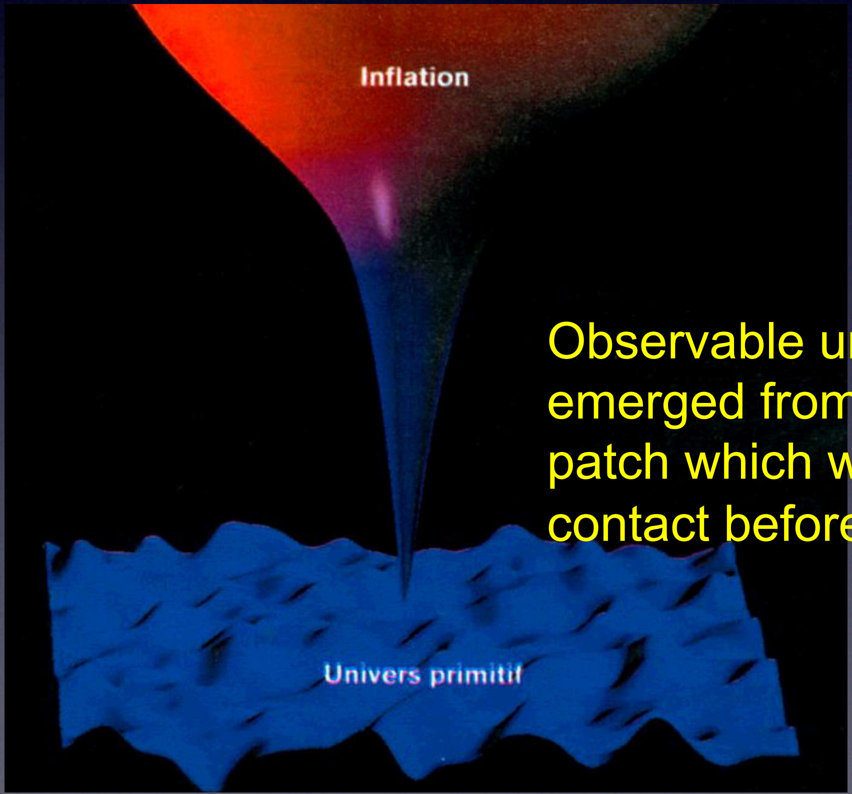
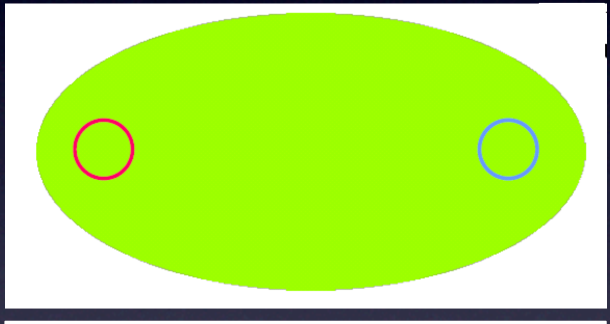
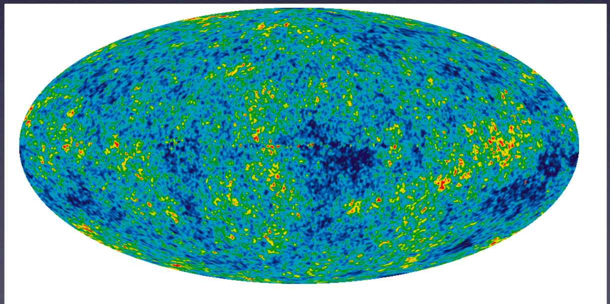


Observable universe emerged from a small patch which was in causal contact before inflation





✓ Plus: Quantum fluctuations of the inflaton field can be seed of structure ...

How can inflation be realised?

- Basic formula: Einstein's equations of General Relativity

Λ: Cosmological constant

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = 8\pi G_N T_{\mu\nu}$$

Metric $g_{\mu\nu}$: Gravity ↔ geometry of space-time

Energy mementum tensor: represents particle theory & content of the universe

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:

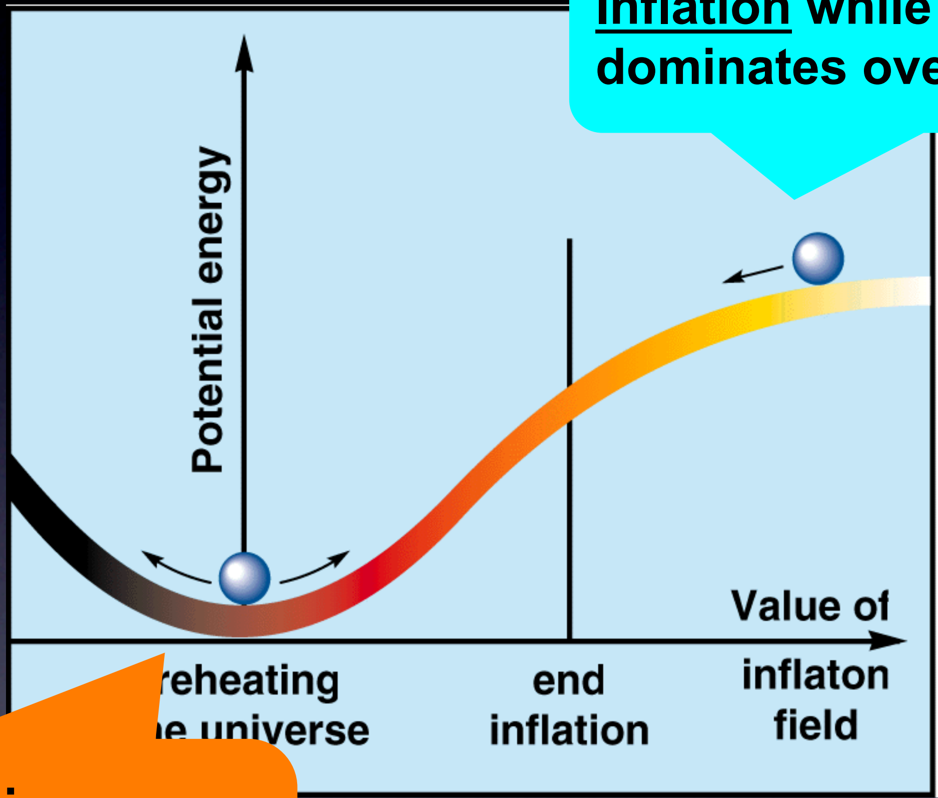
$$\Rightarrow \quad a(t) = \exp\left(\sqrt{\frac{8\pi G_N V(\phi)}{3}} t \right)$$

and the universe "inflates"!

Important: The field ϕ is dynamical $\Rightarrow$ inflation can end!

Dynamics during and after inflation

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



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

Requirements for realising inflation

- "Slow roll" inflation: Vacuum energy has to dominate over kinetic energy!
  - "Slow roll parameters" small: ε, $|\eta|$, ξ << 1, V ~ V_0 dominates

$$\epsilon = \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2 , \quad \eta = M_P^2 \left(\frac{V''}{V}\right) , \quad \xi = M_P^4 \left(\frac{V' V'''}{V^2}\right)$$

"slope of V" "inflaton mass"

The η-problem

- Challenge for realising inflation: Flat enough potential, $m_\phi << \mathcal{H}$

$$\mathcal{H} = \frac{\sqrt{V}}{\sqrt{3}M_P}$$

  - Generic (effective field theory)

$$V \subset V_0 \frac{\phi^\dagger \phi}{M_P^2} \Rightarrow m_\phi \sim \mathcal{H} \leftrightarrow \eta \sim 1$$

  - In supergravity (with K = $\phi^*\phi$ and V_0 from F-term)

$$V_F = \mathrm{e}^{K/M_P^2} \left(K^{i\bar{j}} D_i W \, D_{\bar{j}} W^* - \frac{3|W|^2}{M_P^2} \right)$$

$$V_F \sim \left(1 + \frac{\phi^\dagger \phi}{M_P^2} + \ldots \right) V_0$$

with $D_i W := W_i + K_i W$

E.J Copeland, A.R. Liddle, D.H. Lyth, E.D. Stewart, D. Wands ('94)

Approaches to solve the η-problem: 3 strategies in supergravity

- Expansion of K in fields/M_P:

requires tuning of parameters! (at 1%-level)

$$K = |\phi|^2 + \frac{\lambda_\phi}{M_P^2}|\phi|^4 + \frac{\lambda_{\phi i}}{M_P^2}|\phi|^2|X_i|^2 + \ldots$$

- 'Shift' symmetry:

$$\phi \to \phi + i\alpha$$

$$K = f(\phi + \phi^*)$$

protects Im[ϕ] from obtaining a SUGRA mass by symmetry!

(used in many works ...)

- Heisenberg symmetry:

solves the η-problem for |ϕ| by symmetry!

$$T \to T + \mathrm{i}\,\beta\,, \quad T \to T + \alpha^*\,\phi + |\alpha|^2/2\,, \quad \phi \to \phi + \alpha$$

$$K = f(\rho)\,, \ \text{with} \quad \rho = T + T^* - |\phi|^2$$

T: 'modulus field' → has to be stabilised

Binetruy, Gaillard ('87),
Gaillard, Murayama, Olive ('95),
S.A., Bastero-Gil, Dutta, King, Kostka ('08,'09)

Approaches to solve the η-problem: 3 strategies in supergravity

- Expansion of K in fields/M_P:

- 'Shift' symmetry:

- Heisenberg symmetry:

Remark:
Symmetries have to be broken to allow for slope of $V(\phi)$!
→ approximate symmetries

Can the inflaton field be a Gauge Non-Singlet in SUGRA inflation?

Note: ... incomplete table!

*) problems pointed out by Brax et al ('06), Davis, Postma ('08)

	K expansion + tuning	Shift symmetry	Heisenberg symmetry	Non-singlet Inflaton
Singlet inflaton in 'Hybrid Inflation'	(yes) Copeland et al; Dvali, Shafi, Schaefer ('94)	X*	X	X
H is the inflaton in 'New Inflation'	(yes) Shafi, Senoguz ('04)	X (?)	X (?)	yes
Matter field inflaton in 'Tribrid Inflation'	(yes) S.A., Bastero-Gil, King, Shafi ('04)	yes S.A., Dutta, Kostka ('09) Postma, Mooij ('10)	yes S.A., Bastero-Gil, Dutta, King, Kostka ('08)	yes S.A., Bastero-Gil, Baumann Dutta, King, Kostka ('10)
Singlet large field 'Chaotic Inflation'	X	yes Kawasaki et al ('00)	yes S.A., Bastero-Gil, Dutta, King, Kostka ('09)	X

Unified Matter Inflation in SUSY GUTs

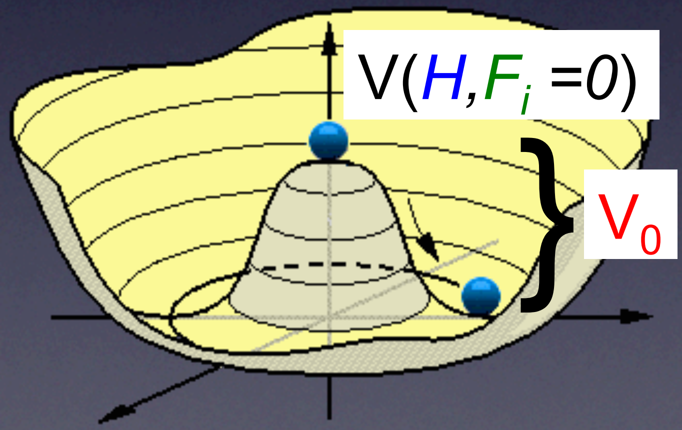
- New class of models: 'Tribrid Inflation'

$$W = S(\bar{H}H - M^2) + \frac{1}{\Lambda}(\bar{F}F_i)(\bar{H}H)$$

Driving field
(its F-term provides the vacuum energy)

Waterfall fields
(= Higgs fields that give mass to the matter fields)

Inflaton field(s)
(are here gauge non-singlets)



S.A., M. Bastero-Gil, J. Baumann, K. Dutta, S. F. King, P. M. Kostka ('10)

Unified Matter Inflation in SUSY GUTs

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Driving field
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The Unified Matter Superparticle:

$$\mathbf{16}_i = (q_L \quad u_R^c \quad e_R^c \quad d_R^c \quad \ell_L \quad \nu_R^c)_i$$

Right-handed neutrinos: Get their large masses after inflation and induce small masses of light ν's

Example: SO(10) GUTs

F_i in representation 16 of SO(10)
$\bar{F}$ in representation $\overline{16}$ of SO(10)

i = (1,...,4)

S.A., M. Bastero-Gil, J. Baumann, K. Dutta, S. F. King, P. M. Kostka ('10)

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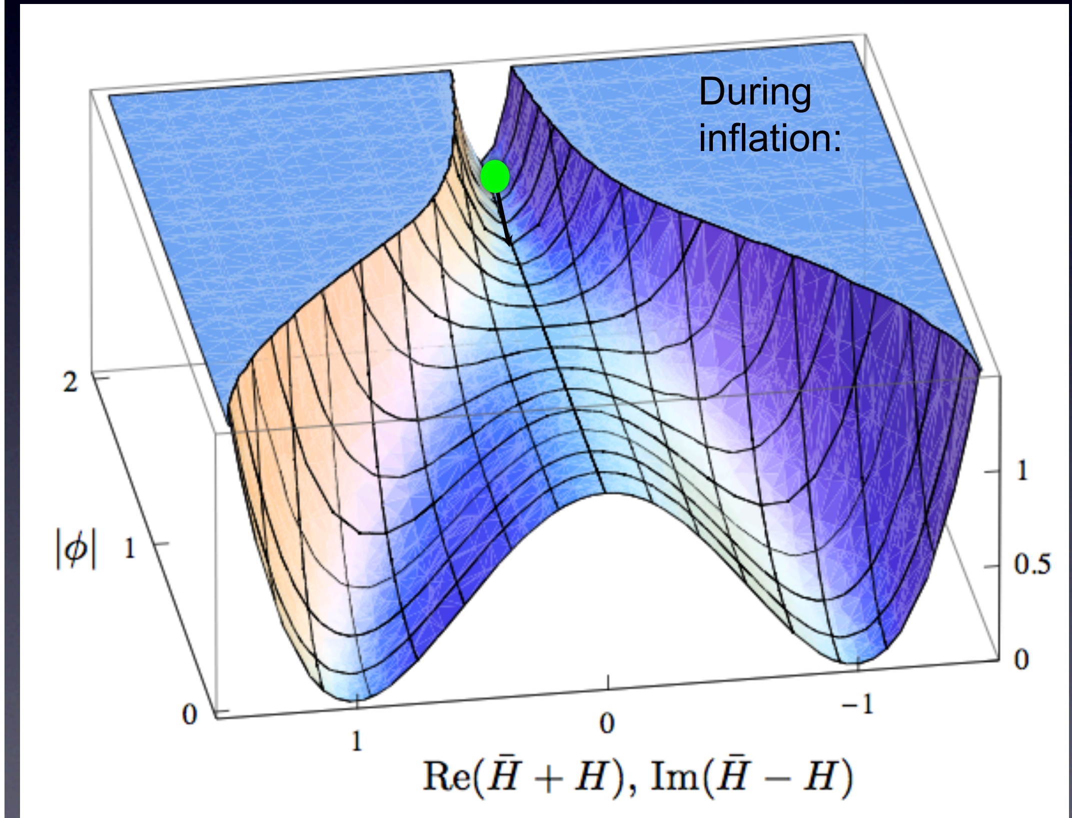

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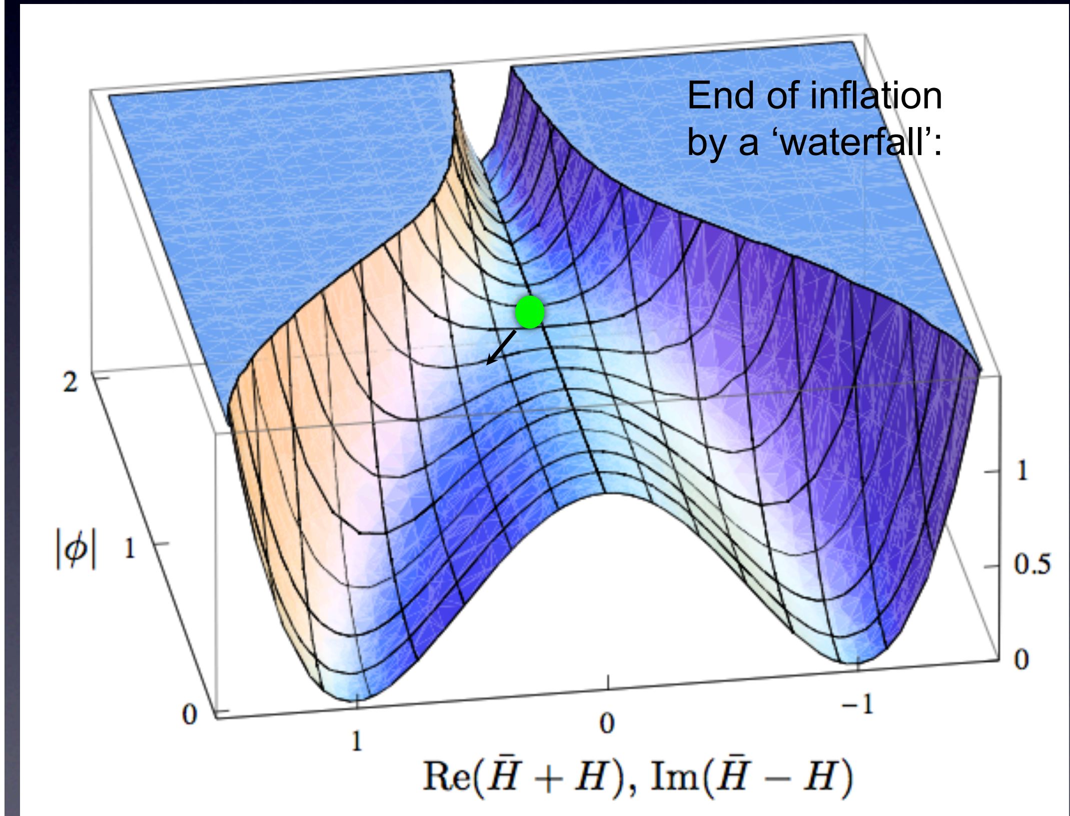
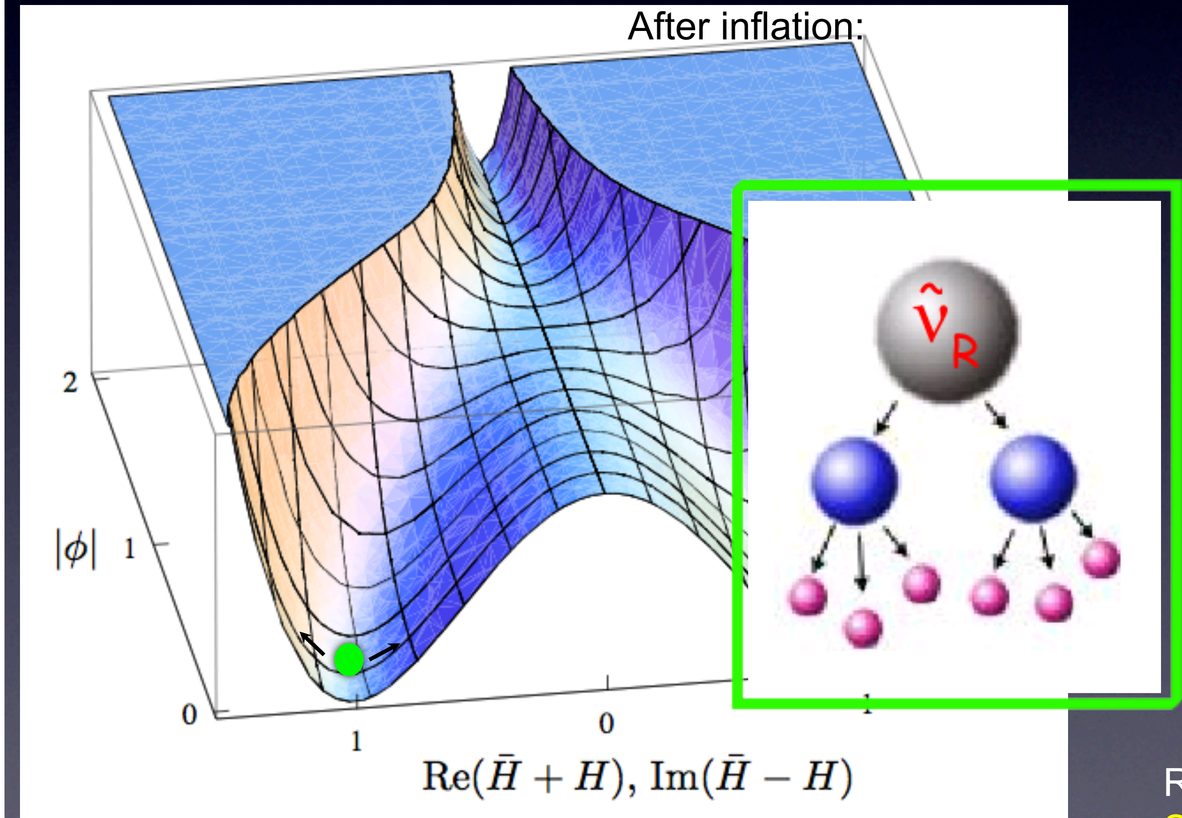


Non-thermal Leptogenesis after Inflation

When the $\tilde{\nu}_R$ component dominates the universe after inflation ...

$$\mathbf{16}_i = (q_L \quad u_R^c \quad e_R^c \quad d_R^c \quad \ell_L \quad \nu_R^c)_i$$



⇒ The matter-antimatter asymmetry of the universe can be generated very efficiently via the (non-thermal) leptogenesis mechanism!

Recent study in 'Tribrid (sneutrino) inflation':
S.A., Baumann, Domcke, Kostka ('10)

Unified Matter Inflation in SUSY GUTs

- Various challenges for such ’Gauge Non-Singlet‘ (GNS) inflation models ... all resolved:

  ✓ SUGRA η-problem can be solved by Heisenberg symmetry:

  ✓ ‘2-loop gauge η-problem’ (Dvali ’95) solved

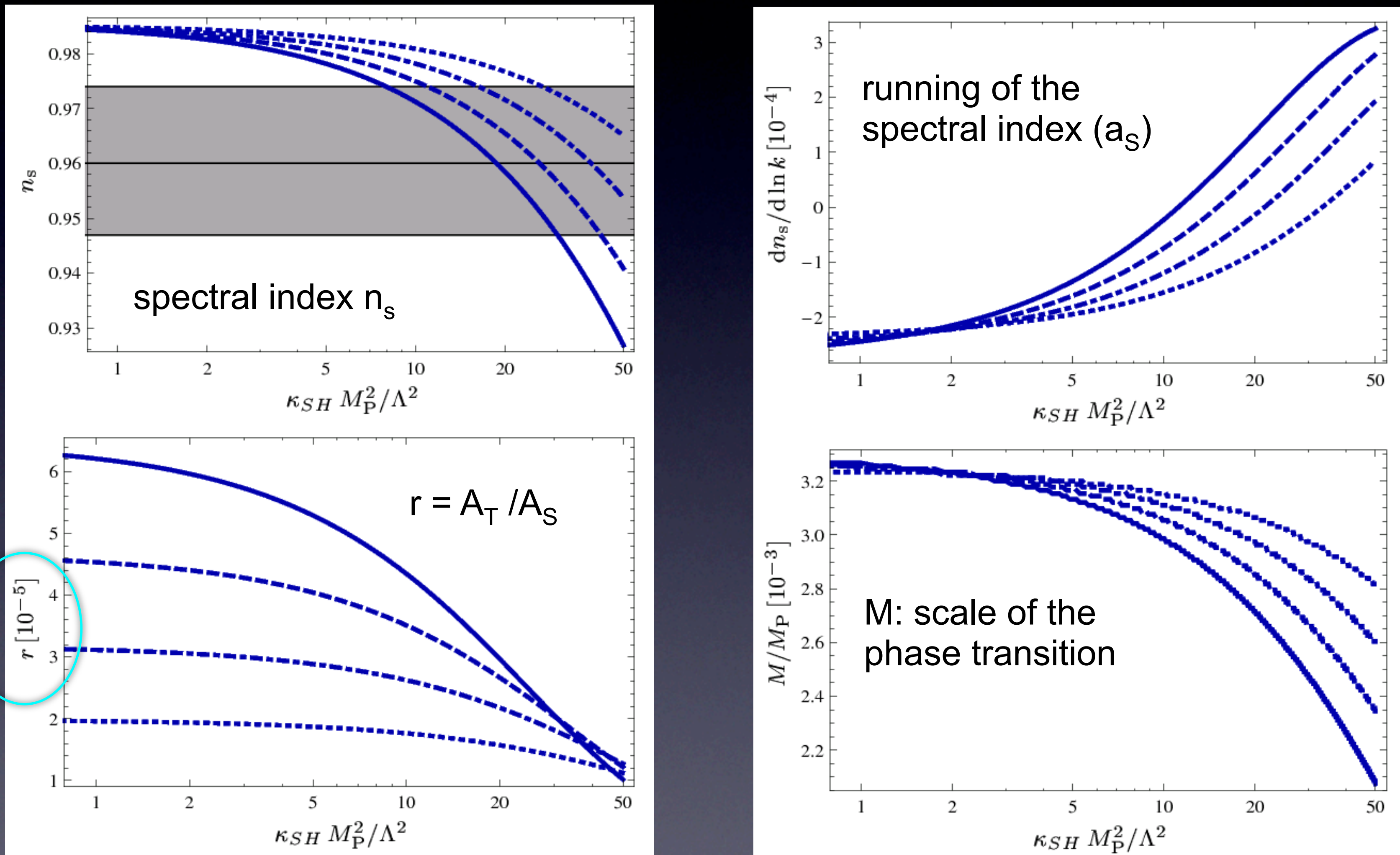
  ✓ Monopole problem can be solved

  ✓ Modulus ρ stabilized by large vacuum energy V_0 during inflation

S.A., M. Bastero-Gil, J. Baumann, K. Dutta, S. F. King, P. M. Kostka (’10)

In an explicit model: calculation of the predictions for CMB observables ...

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



very small (as typical for Hybrid models)

Example: predictions in toy model of "Tribrid inflation"

Conclusions and Outlook

- Cosmic inflation: A successul paradigm for the early universe
  - Challenge: The η-problem
  - Big open question: How connected to particle physics?
- New class of inflation models in supergravity: ‘Tribrid Inflation’
  - The η-problem can be solved, e.g., by a Heisenberg symmetry
  - The inflaton can reside in the matter sector of the theory
- Attractive inflaton candidate: The ‘Unified Matter Superparticle’
- Outlook: Generalisation of this scenario may also open up new ways to realise inflation in string theory ...

S.A., Dutta, Erdmenger, Halter (in preparation)