Title: Flavon Inflation

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Abstract: A new class of particle physics models of inflation is presented which is based on the phase transition associated with the spontaneous breaking of family symmetry responsible for the generation of the effective quark and lepton Yukawa couplings. We show

Flavon Inflation

Talk at Pascos08, Perimeter Institute, Waterloo, Canada, June 6th, 2008

based on arXiv:0805.0325
in collaboration with
S.F. King, M. Malinsky, L. Velasco-Sevilla, I. Zavala

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Idea: Inflation connected to family symmetry breaking

'Flavons' = Higgs fields of family symmetry breaking

Inflation ⟷ Flavour (Family Symmetry Breaking)

ntroduced to solve flatness and horizon
blems (A.H. Guth ('81), A.D. Linde ('82),
lbrecht, P.J. Steinhardt ('82), ...)

... family symmetries introduced towards explaining the observed fermion masses and mixings (Froggatt, Nielsen ('79), ...)

... spontaneous family symmetry breaking: responsible for the generation of the effective quark and lepton Yukawa couplings

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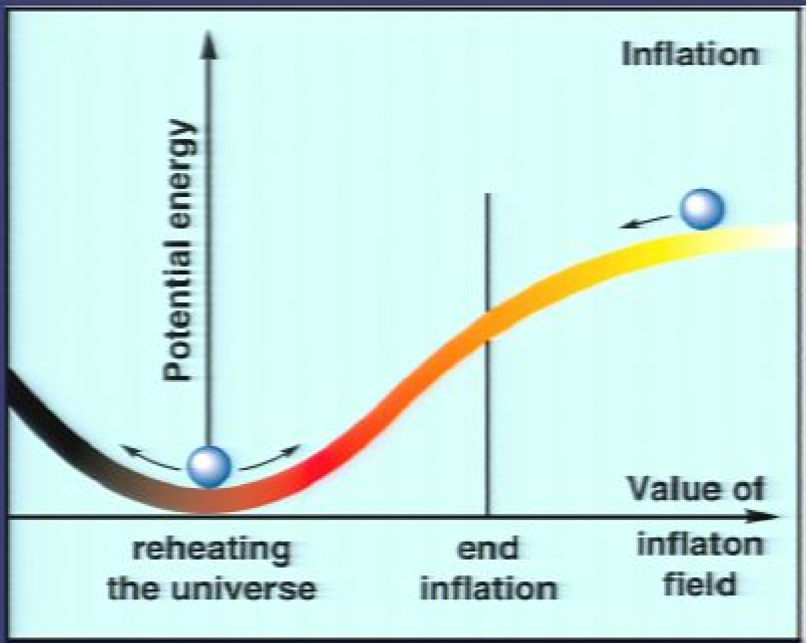
Motivation

New answer to open question: How is inflation connected to particle physics? (Other approaches: GUT inflation, ...)

Family symmetry breaking phase transition particularly suitable for driving inflation':

- Family symmetry is completely* broken → no monopoles produced!
- With family symmetry breaking below the GUT scale (as often predicted): → unwanted relics (monopoles) from earlier GUT phase transition can be inflated away



ventually: discrete symmetries remaining; typically broken by
her dimensional operators → domain wall networks effectively

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Outline

- Idea and motivation (previous slides)
- Short introduction to family symmetries
- Explicit examples how 'Flavon Inflation' can be realised
  - Example 1: Flavons (= Flavour Higgs fields) as inflatons in a model of new inflation based on A_4 family symmetry
  - Example 2: 'Driving fields' as inflatons, flavons as 'waterfall fields' in hybrid inflation
- Summary, Outlook and Conclusions

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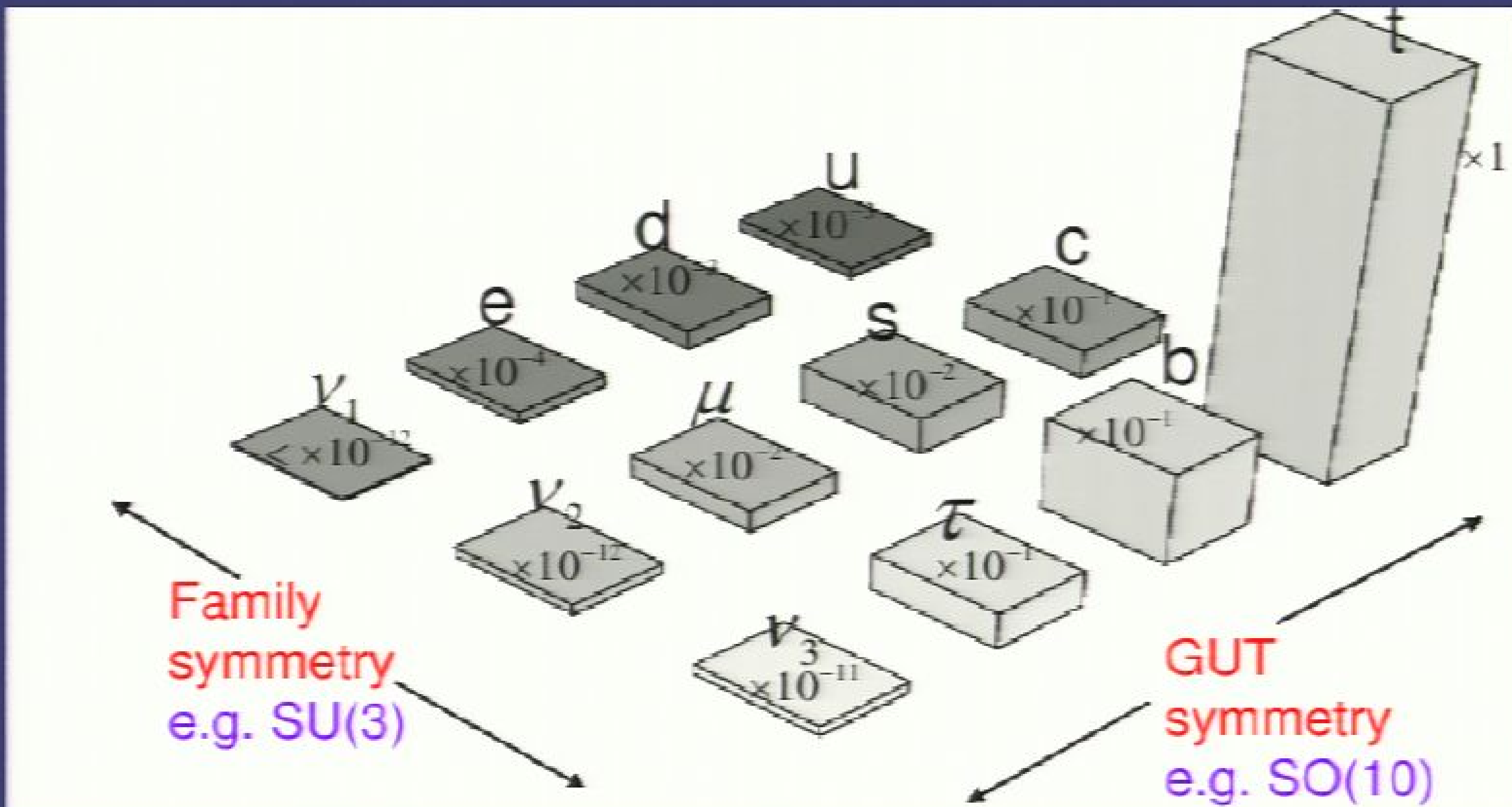
Family Symmetries



- Family symmetries act horizontally: different families unified in represenations of family symmetry group G_F

(many possibilities: Abelian or non-Abelian, continous or discrete, global or local, ...)

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Flavour Structure from Family Symmetry Breaking

- Assume family symmetry G_F (e.g. SU(3), with 3 families of SM fermions ψ_i, ψ^c_i in fundamental representation)

- Yukawa couplings arise from non-renormalisable operators, e.g.:

$(\phi/M)^n \psi\psi^c H$ (where ψ, ψ^c are SM fermion fields and H is a SM Higgs field)

- Whan the family symmetry gets spontaneously broken by the flavons ϕ acquiring vacuum expectation values (vevs)
$\rightarrow$ Yukawa couplings are generated

$\varepsilon^n \psi\psi^c H$ where $\varepsilon = \langle\phi\rangle / M$

higher powers of ε: can explain hierarchies in the fermion masses Froggatt, Nielsen ('79)

- In this sense: Breaking of family symmetry is responsible for the generation of fermion masses and mixing (after EW breaking)

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Flavon Inflation: 2 Example Models

- Example1: Flavons as inflaton fields
- Example 2: 'Driving fields' as inflatons, flavons as 'waterfall fields'

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Example 1: Flavon(s) as Inflaton(s)

- Example 'toy model': ($G_F = A_4$, 'new inflation' type of inflation model)

$$W = \kappa S \left[\frac{(\phi_1 \phi_2 \phi_3)^n}{M_*^{3n-2}} - \mu^2 \right]$$

μ: inflation scale ($V_0 \sim \mu^4$)

(without loss of generality: $\kappa = 1$)

$$K = |S|^2 + |\phi|^2 + \kappa_2 \frac{|S|^2 |\phi|^2}{M_P^2} + \kappa_1 \frac{|\phi|^4}{4M_{Pl}^2} + \kappa_3 \frac{|S|^4}{4M_{Pl}^2} + \ldots$$

ϕ: flavon (in anti-triplet represenation of A_4)

- Inflationary trajectory where the flavon fields ϕ moves from small values to its true minimum

- Scale of family symmetry breaking (= flavon vev) equal to:

$$M = M_* \left(\frac{\mu}{M_*} \right)^{2/3n}$$

Remark:
This type of inflation models have been considered in the literature (see e.g. Senoguz, Shafi ('04)) however new types of potantials are possible when the standard invariants are replaced by family symmetry invariant combination of fields, e.g. the A_4 or Δ_{27} invariant $\phi^3 = \phi_1 \phi_2 \phi_3$

Example 1: Flavon(s) as Inflaton(s)

- Analysis of the model:
  - Simplest inflationary trajectory $|\phi_i| \equiv \varphi/\sqrt{2}$
  - Case where S is heavy (> Hubble scale H → S = 0): $\kappa_3 < -1/3$
  - Scalar potential:

$$V = e^{K/M_{Pl}^2}\left[K^{i\bar{j}} D_i W D_{\bar{j}} \overline{W} - 3\frac{|W|^2}{M_{Pl}^2}\right]$$

$$D_i W = \partial_i W + \frac{W}{M_{Pl}^2}\partial_i K$$

$$K^{i\bar{j}} = (\partial_i \partial_{\bar{j}} K)^{-1}$$

  - Leading order form:

$$V \simeq \mu^4\left[1 - \frac{\beta}{2}\frac{\varphi^2}{M_{Pl}^2} + \frac{\lambda}{4}\frac{\varphi^4}{M_{Pl}^4} - \gamma\frac{\varphi^{3n}}{M^{3n}} + \cdots\right]$$

where:

$$\gamma = 2/(6)^{3n/2} \lesssim 0.14$$

$$\beta = (\kappa_2 - 1),\ \lambda = (\beta(\beta+1) + 1/2 + \kappa_1/12)$$

see also e.g.: Ross, Sarkar ('01), Senoguz, Shafi ('04), Kohri, Lin, Lyth ('07)

  - We focuse on the case where: $|\gamma \frac{\varphi^{3n}}{M^{3n}}| \gg |\frac{\lambda}{4}\frac{\varphi^4}{M_{Pl}^4}|$
  - We use the observed amplitude of density perturbations $\delta_H = 1.9 \times 10^{-5}$ as constraint

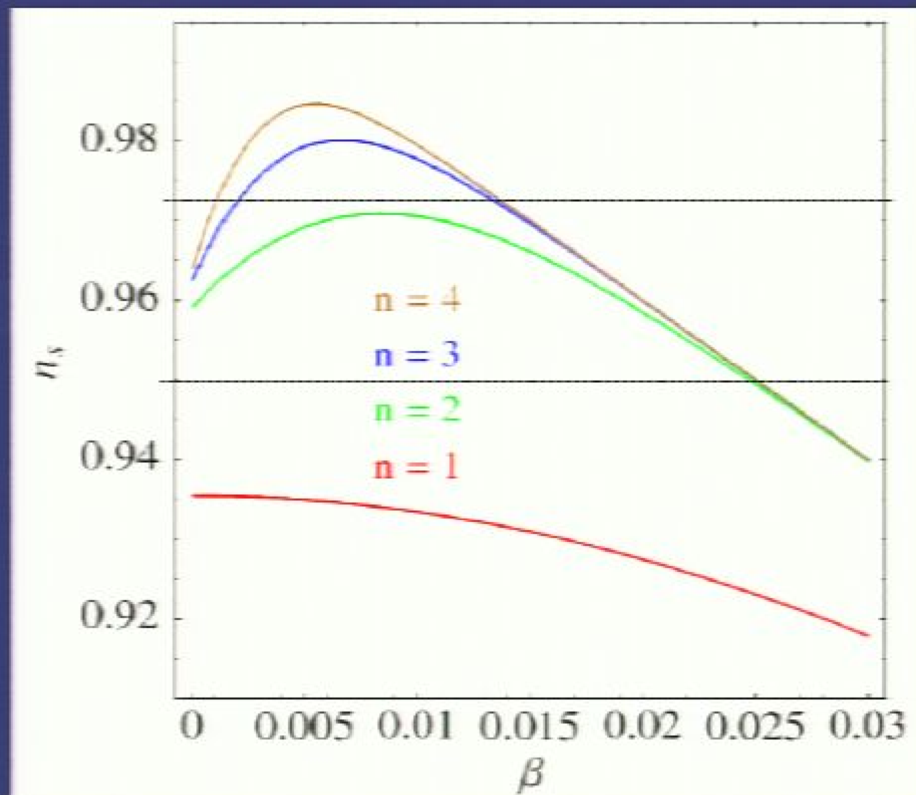
Example 1: Flavon(s) as Inflaton(s)

- Numerical results

WMAP 5-year data:

$$n_s = 0.96 \pm 0.014$$

$$W = \kappa S \left[\frac{(\phi_1 \phi_2 \phi_3)^n}{M_*^{3n-2}} - \mu^2 \right]$$



analytically:

$$n_s \approx 1 - 2\beta \left[1 + \frac{(3n-1)(1-\beta)}{[(3n-2)\beta + 1] e^{\beta(3n-2)N} + \beta - 1} \right] \quad \text{for } \beta \neq 0$$

$$n_s \approx 1 - \frac{6n-2}{(3n-2)N + (3n-1)} \quad \text{for } \beta = 0$$

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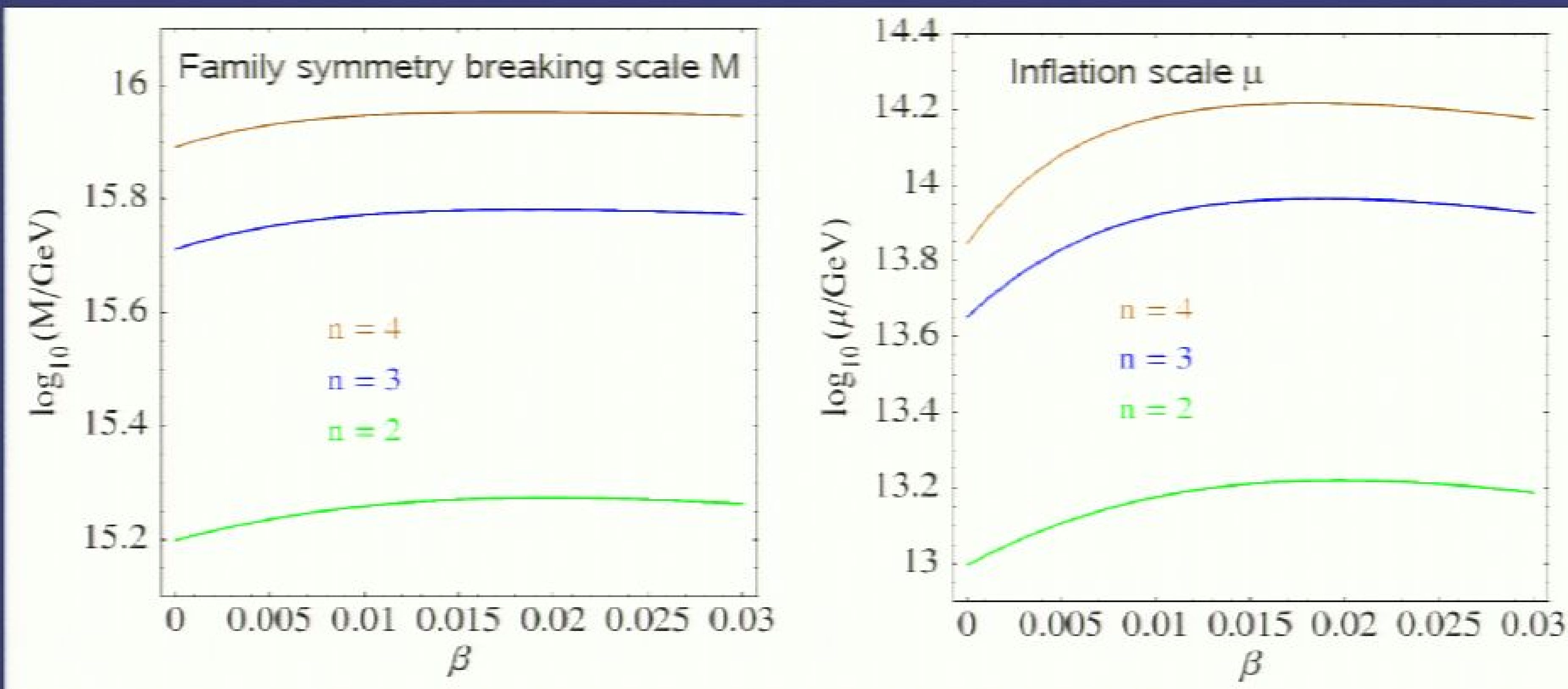
Example 1: Flavon(s) as Inflaton(s)

Remark: case n = 1 special; much lower μ and M possible!

- Numerical results: (for $M_* = M_{GUT}$)



$$M = M_* \left(\frac{\mu}{M_*}\right)^{2/3n}$$

Predicted inflation scale and family symmetry breaking scale can be below the GUT scale ...

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Example 2: Driving field(s) as Inflaton(s) in existing SU(3) model

- Definition of 'driving superfield': If $|F_S|^2$ 'drives' the potential (and finally the vev) of a flavon field ϕ, then S is called a 'driving superfield' ...
- Example: existing flavour model with SU(3) family symmetry from the literature (I. de Medeiros-Varzielas, G.G. Ross ('05)).
  The relevant part of the superpotential is given by:

$$W = \kappa S(\bar{\phi}_{123}\phi_{123} - M^2) + \kappa' Y_{123}\bar{\phi}_{23}\phi_{123} + \kappa'' Z_{123}\bar{\phi}_{123}\Sigma\phi_{123} + \ldots$$

... at the final stage of family symmetry breaking, the flavons Σ and ϕ_{23} are already in their true minima; in addition, we consider a non-minimal Kähler potential

$$\langle\Sigma\rangle = \mathrm{diag}(a, a, -2a)$$

$$\langle\phi_{23}\rangle \propto (0, 1, 1)^T$$

$$K = |S|^2 + |\phi_{123}|^2 + |\bar{\phi}_{123}|^2 + |Y_{123}|^2 + |\bar{\phi}_{23}|^2 + |\phi_{23}|^2 + |Z_{123}|^2 + |\Sigma_{123}|^2 + \kappa_S \frac{|S|^4}{4M_{Pl}^2} + \kappa_{SZ}\frac{|S|^2|Z_{123}|^2}{4M_{Pl}^2} + \ldots\,.$$

S, Y_{123} and Z_{123} are 'driving superfields' (govern potential for ϕ_{123})

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Example 2: Driving field(s) as Inflaton(s) in existing SU(3) model

'Hybrid model' of inflation

$$W = \kappa S(\bar{\phi}_{123}\phi_{123} - M^2) + \kappa' Y_{123}\bar{\phi}_{23}\phi_{123} + \kappa'' Z_{123}\bar{\phi}_{123}\Sigma\phi_{123} + \ldots$$

(Hybrid inflation: Linde ('90,'91), Copeland, Liddle, Lyth, Stewart, Wands ('94), Lyth ('96), Linde, Riotto ('97))

- Scalar components of driving superfields can act as inflatons

- Flavon ϕ_{123} acts as so-called 'waterfall field' of hybrid inflation; the 'waterfall' (= rapid movement of ϕ_{123} to its true minimum) ends inflation!

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Example 2: Driving field(s) as Inflaton(s) in existing SU(3) model

- Analysis of the model:
  - 'Last stage of family symmetry breaking': ϕ_{123} not yet in true minimum
  - Y_{123} heavy from superpotential $\quad Y_{123} = \phi_{123} = \bar{\phi}_{123} = 0$
  - Two inflaton candidates: S and Z_{123}
  - We define $|S| = \sigma/\sqrt{2},\ |Z_{123}| = \xi/\sqrt{2}$ and $\gamma = \kappa_{SZ} - 1$
  - Leading order (tree-level) scalar potential:

$$V_{\text{tree}} = \kappa^2 M^4 \left[1 - \gamma \frac{\xi^2}{2M_{Pl}^2} - 2\kappa_S \frac{\sigma^2}{2M_{Pl}^4} + \ldots\right]$$

Remark: Inclusion of V_{loop} is important for obtaining consistent spectral index n_s

$n_s = 0.96 \pm 0.014$ WMAP ('05)

- Numerically (for $\gamma < -1/3$ such that ξ is heavier than H and we have single field inflation) $M \approx 10^{15}$ GeV ... from δ_H; family symmetry breaking scale below M_{GUT}

$\kappa_S \approx 0.01$ ... to obtain observed n_s

...udied in detail in ...isting literature ... !

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Summary, Conclusions and Outlook

- We have proposed a new class of particle physics models of inflation: 'Flavon Inflation' based on the phase transition of spontaneous family symmetry breaking
- Higgs fields of family symmetry breaking (= flavons) are natrual candidates for
  (i) the inflaton field in 'new inflation' or
  (ii) the waterfall field in hybrid inflation
- Attractive features: no monopole problem, monopoles from earlier GUT phase transition can be inflated away
- Additional interesting consequences for particle physics and for cosmology (due to family symmetry breaking scale below GUT scale; inflaton potentials and decay properties connected to physics of flavour)

... to be explored in more detail (work in progress)

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