(IN)VALIDITY OF EFT TREATMENT FOR HIGH SCALE INFLATION

Anupam Mazumdar

LANCASTER UNIVERSITY

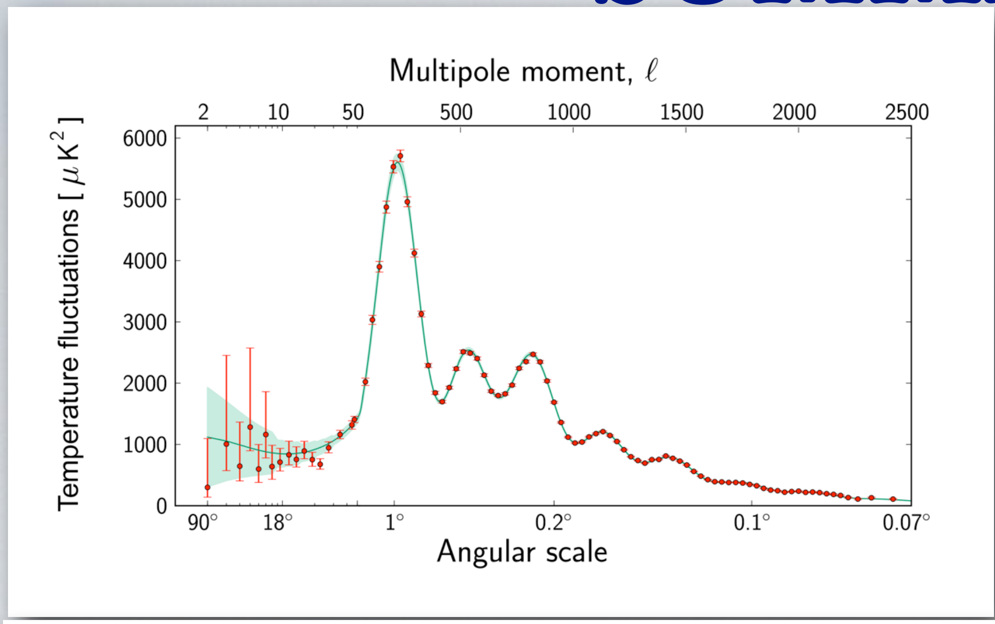
CFP

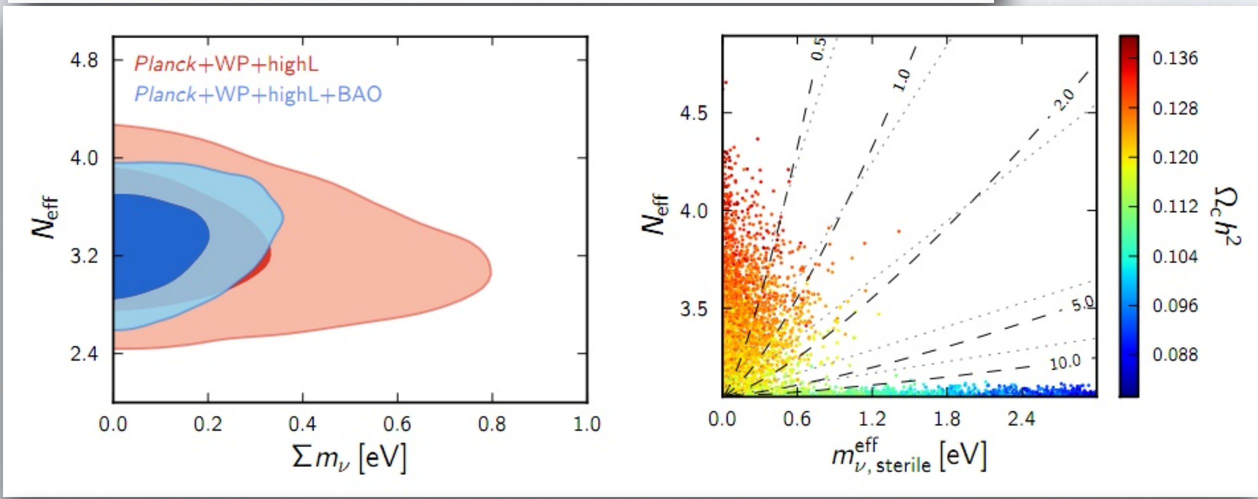
SUSY-2014
Manchester

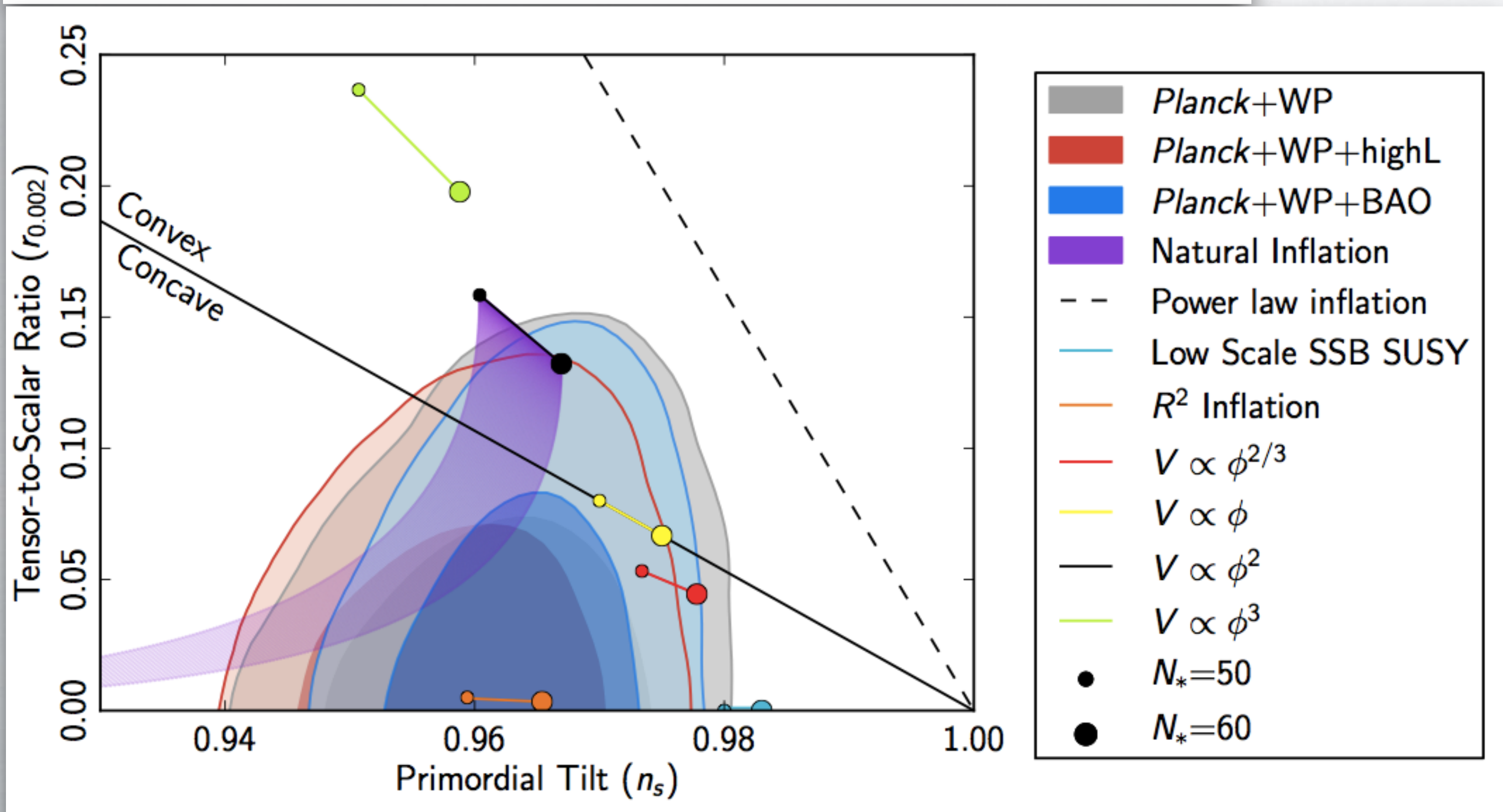
Fundamental problems of inflation

* Initial condition & slow roll Abuse
* Quantum corrections: Potential + Kinetic
* EFT treatment and high scale inflation

SUMMARISING PLANCK DATA

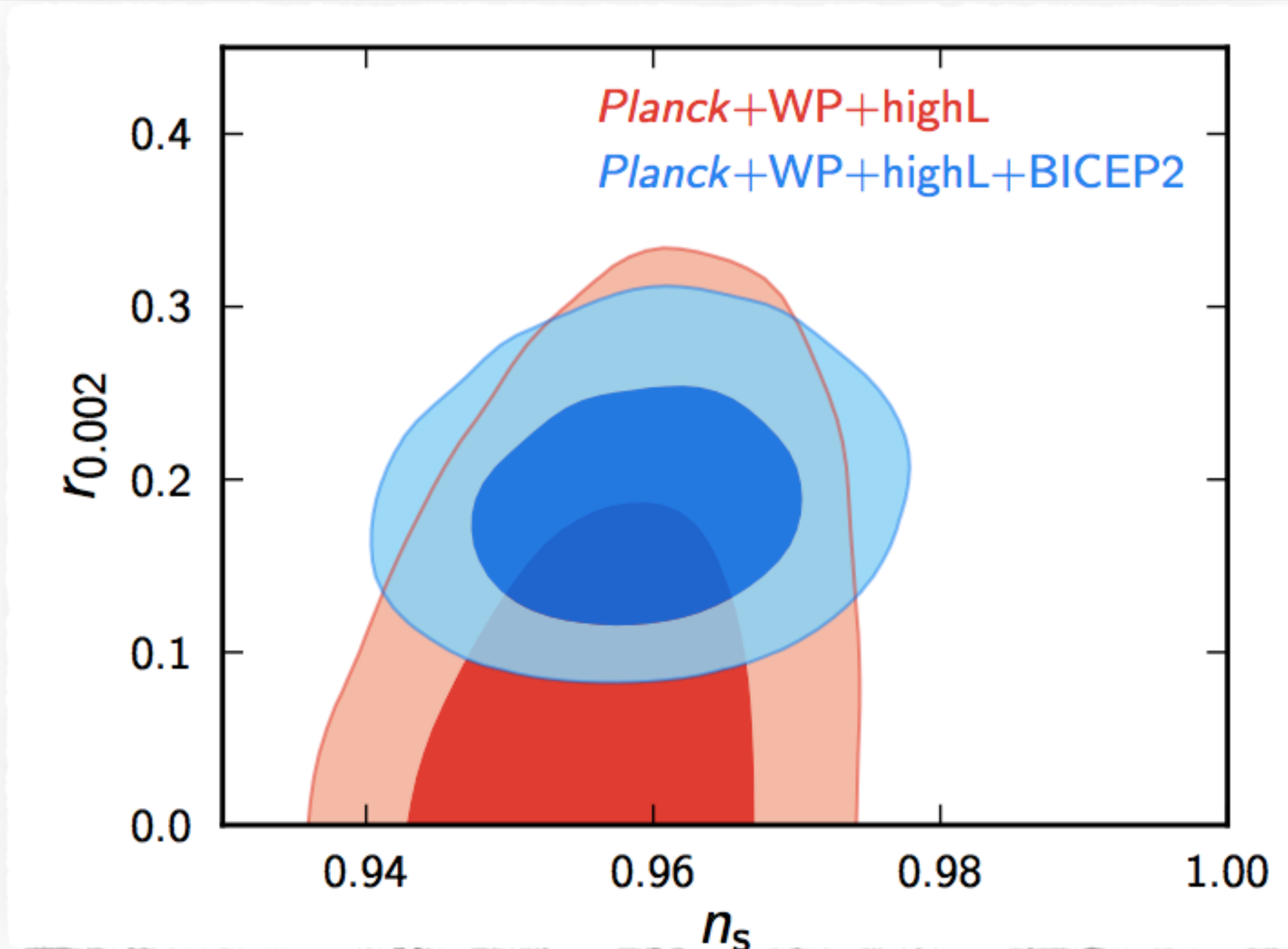






- **Almost Gaussian Perturbations**
- **No Evidence of Non-Gaussianity**
- **Virtually no Iso-curvature Perturbations**
- **No evidence of Extra Relativistic Species other than the Standard Model**
- **No Evidence of Tensor Perturbations**

BICEP & the Challenges



Conundrum with Large field value inflation

$$\Delta\phi > M_f$$

What are the challenges of large field value inflation ?

Caution: BICEP data may go away by October 2014...

Inflation Requires prior Homogeneity & Isotropy

Do we have a fundamental theory to explain this ?
NO, we assume so, how good it is?

Conjecture: If gravity becomes weak in UV (Emerging gravity in IR) , there is a possibility to explain homogeneity & isotropy, see: **BGKM gravity**. Ghost free and singularity free gravity, PRL (2011)

Irrespective of large or small field value inflation

Chaotic Inflation & Anthropic arguments

$$\ddot{\varphi} + 3H\dot{\varphi} + V_{,\varphi} = 0 \qquad H^2 = \frac{8\pi}{3}\left(\frac{1}{2}\dot{\varphi}^2 + V(\varphi)\right) \qquad V = \frac{1}{2}m^2\phi^2$$

Natural Expectation:

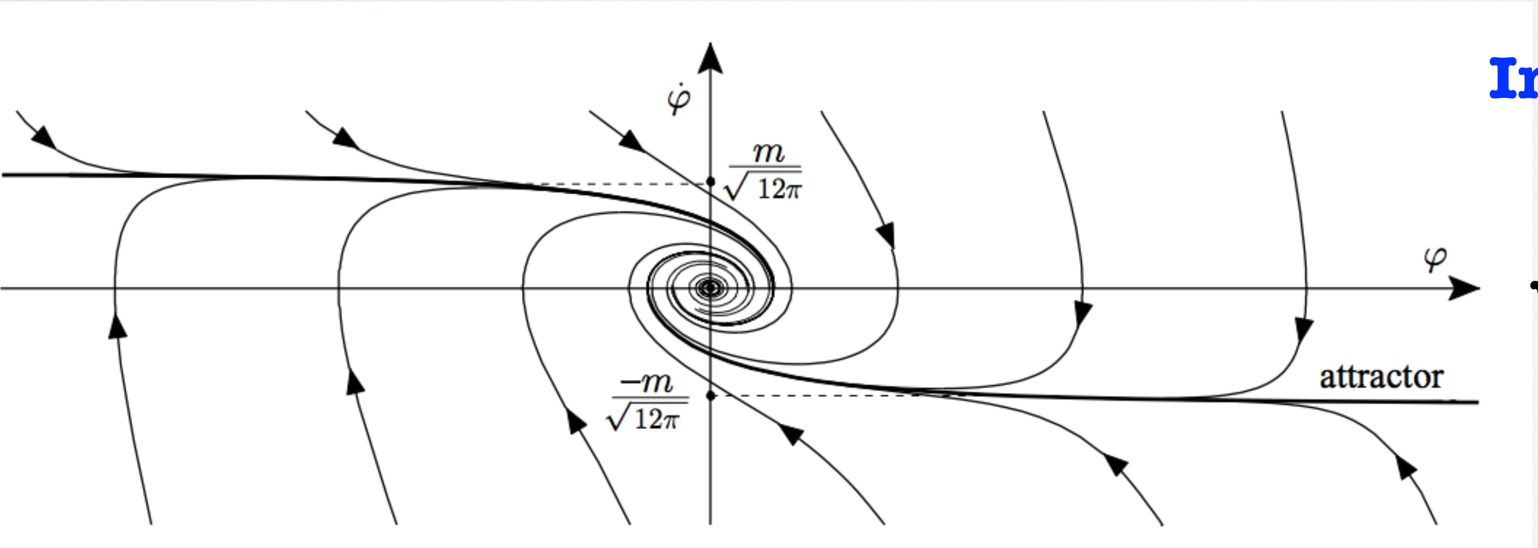
$$\frac{1}{2}\dot{\phi}^2 \sim \frac{1}{2}(\partial_i\phi)^2 \sim V(\phi) \sim M_p^4$$

Initial condition at the Planck epoch

$$\Downarrow$$

Inflation Requires:

$$\frac{1}{2}\dot{\phi}^2 + \frac{1}{2}(\partial_i\phi)^2 \leq V(\phi) \leq M_p^4$$



In order to seek inflation/attractor, we neglect the gradient term, why?

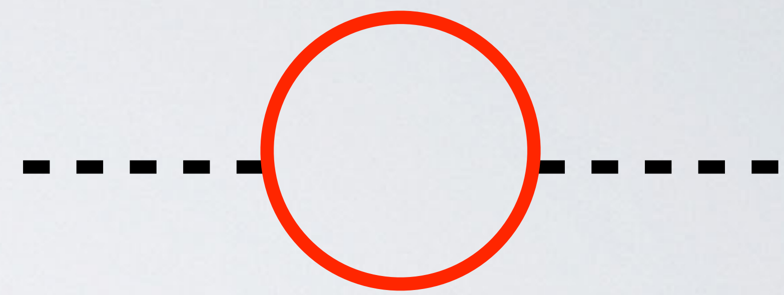
Whether this assumption is correct?

Linde, Mukhanov

Anthropic argument - there must exist a patch which could inflate !

Caveats behind EFT treatment for Super-Planckian inflation ?

* **Although:** $\rho_\phi \ll M_p^4$

* **But Momentum transfer is large :** 

$$V \sim \sum_i^N g_i \phi \bar{\psi}_i \psi_i \,, \qquad V \sim \sum_i^N g_i' \phi F^i_{\mu\nu} F^{i\ \mu\nu}$$

$$g_i,\ g_i' \sim \mathcal{O}(1), \quad \langle\phi\rangle \sim \mathcal{O}(1-10) M_p$$

Super-Planckian massive fermion/ photon during inflation

Inflaton must couple to matter

$$m_{\psi,\ A_\mu} \sim g\langle\phi\rangle \sim 10 g M_p$$

* **EFT treatment becomes invalid !**

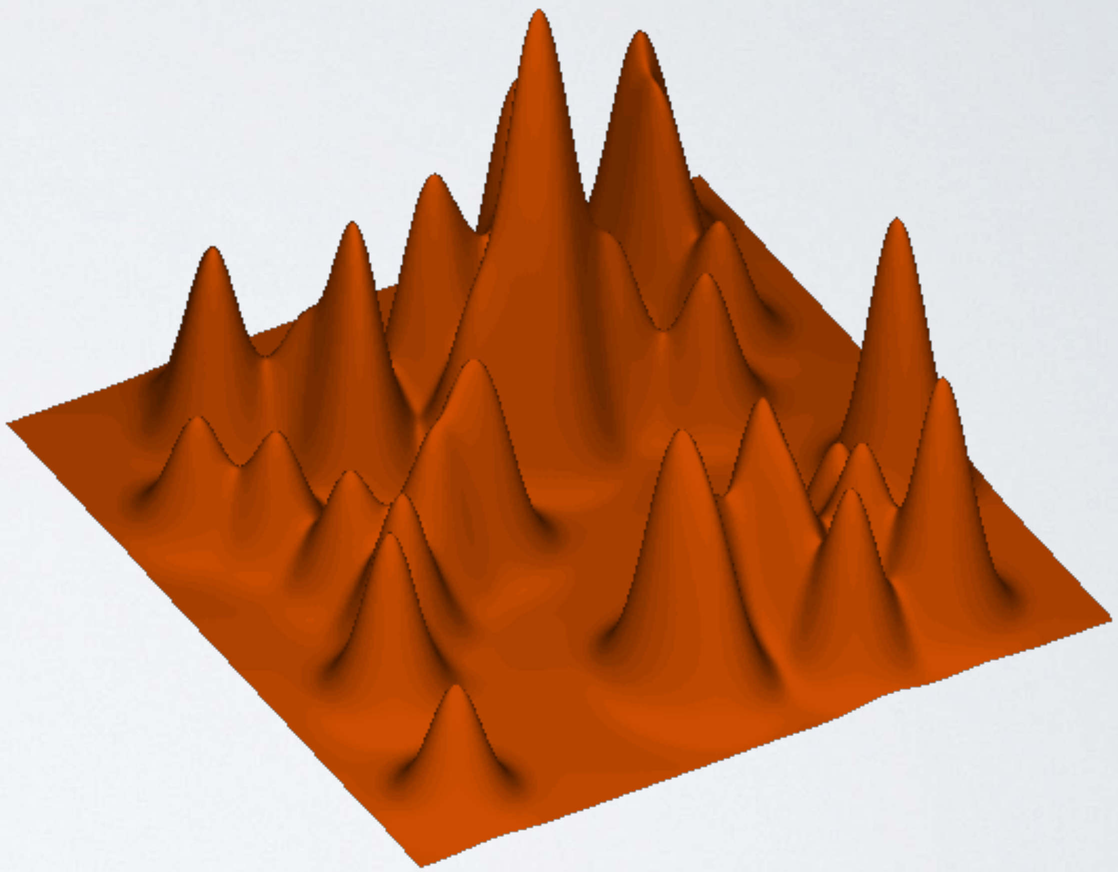
QUANTUM CORRECTIONS: SEA OF BLACK HOLES!

$$(N \times m_{\psi, A_\mu})^4 \sim (g \times N \times \langle\phi\rangle)^4 \leq \rho_\phi \sim 10^{64}\ (\mathbf{GeV})^4$$

Back reaction

energy density of the coupled field should be less than that of the inflaton

$$Ng \leq 10^{-3}$$



Diego Chialva+Mazumdar (2014)

Any inflationary model must satisfy this constraint:
Does string theory provide any constraints: NO

QUESTION: HOW GOOD IS THIS EXPECTATION FROM THEORY?

$$\frac{1}{2}\dot{\phi}^2 + \frac{1}{2}(\partial_i \phi)^2 \leq V(\phi) \leq M_p^4$$

Assumption: There is only One Scale - Planck Scale

Nature does not have ONE unique scale, but there are many many scales possibly close to the UV

$$M_s \leq M_c \leq M_p \; (\; in \; 4 \; d)$$

String theory: at least 3 scales in 4 d

QUANTUM CORRECTIONS

CORRECTIONS TO THE POTENTIAL

$$\mathcal{L} \sim \sum_n \lambda_n \frac{\phi^n}{M_f^{n-4}}$$

Inflaton coupling to graviton and matter

CORRECTIONS TO THE K.E.

(α' CORRECTIONS)

$$\mathcal{L} \sim \sum_{n,m} d_m \left(\frac{(\nabla \phi)^2}{M_f^4} \right)^m \frac{\phi^n}{M_f^{n-4}}$$

Potentially dangerous corrections

Diego Chialva+Mazumdar (2014)

QUANTUM CORRECTIONS

$$\mathcal{L} \sim \sum_{n,m} d_m \left(\frac{(\nabla \phi)^2}{M_f^4} \right)^m \frac{\phi^n}{M_f^{n-4}}$$

Although these terms are suppressed by a scale, one would argue the effect is small, but this assumes :

$$\frac{1}{2}\dot{\phi}^2 + \frac{1}{2}(\partial_i \phi)^2 \leq V(\phi) \leq M_p^4$$

There is no reason why the derivatives will be small at the very onset of inflation : there is NO apriori attractor solution

How do we know that slow roll is a Good Assumption?

FURTHER CONCEPTUAL ISSUE : BEYOND 2-DERIVATIVES...

$$S = \int d^4x \, [\phi \Gamma(\Box)\phi - V_{int}(\phi)], \qquad \Box = g^{\mu\nu}\nabla_\mu \nabla_\nu$$

$$\Gamma(-p^2) \sim (p^2 + m_1^2)(p^2 + m_2^2)\dots(p^2 + m_n^2)$$

$$\frac{1}{(p^2 + m_1^2)(p^2 + m_2^2)} \sim \frac{1}{p^2 + m_1^2} - \frac{1}{p^2 + m_2^2}$$

Ghosts, vacuum becomes unstable, one cannot make predictions

Order by order ghosts cannot be tamed, one needs higher derivatives to infinite order: This will modify the propagator

ENTIRE FUNCTIONS

$$\Gamma(-p^2) \sim (p^2 + m_1^2)(p^2 + m_2^2)\dots(p^2 + m_n^2)$$

Propagator e.g. :

$$\Gamma(-p^2) \sim e^{-p^2/M_f^2}$$

Entire functions : do not introduce any new states, no new poles, only essential singularities at the boundary

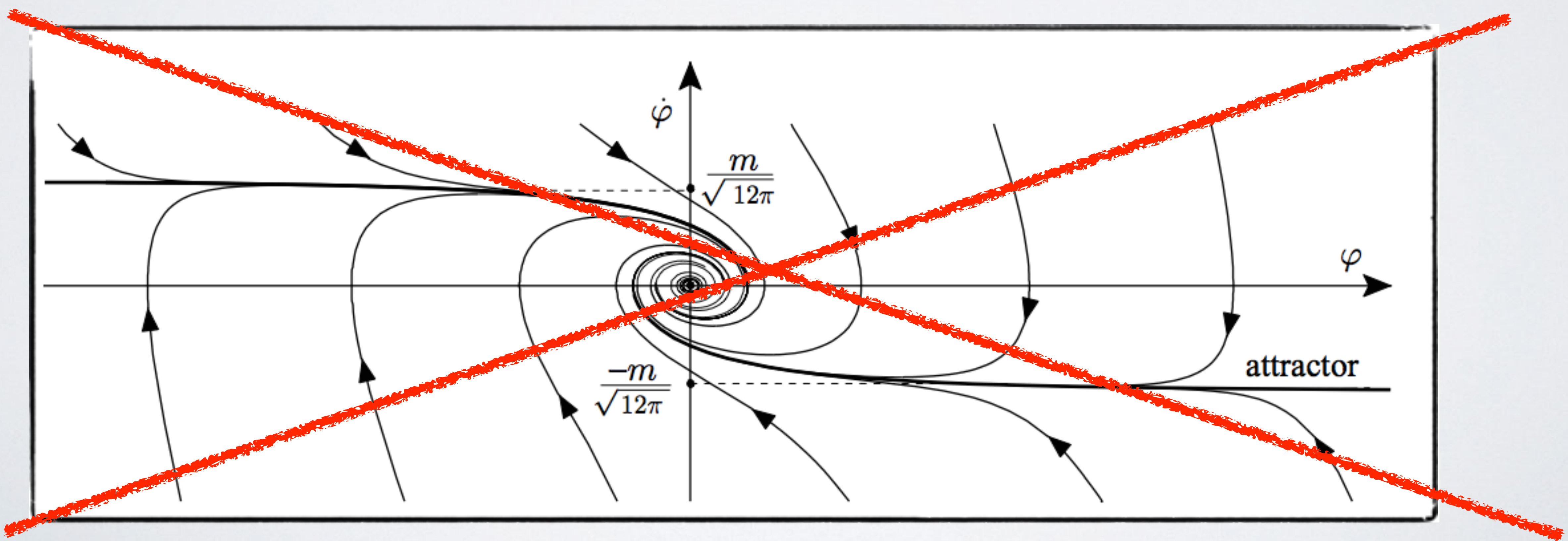
"Wiestrass Theorem"

AN EXAMPLE: P-ADIC STRINGS

$$\mathcal{L} \sim \frac{M_s^4}{g_p^2}\left[-\frac{1}{2}\phi e^{-\frac{\Box}{m_p^2}}\phi + \frac{\phi^{p+1}}{p+1}\right]$$

$$g_p^{-2} = g_s^{-2}(p^2/p-1) \text{ and } m_p^2 = 2M_s^2/\ln p.$$

We will not get the attractor solution at all! :-)
Need not be any homogeneous patch!



GRAVITY

BGKM Formulation of Ghost Free & Asymptotically Free Gravity

$$\mathcal{L}_{\rm gr} \sim \frac{R}{2} + R\mathcal{F}_1\left(\frac{\Box}{M_f^2}\right)R + R_{\mu\nu}\mathcal{F}_2\left(\frac{\Box}{M_f^2}\right)R^{\mu\nu} + R_{\mu\nu\lambda\sigma}\mathcal{F}_3\left(\frac{\Box}{M_f^2}\right)R^{\mu\nu\lambda\sigma} + \ldots .$$

where,

$$\mathcal{F}_i(\Box/M_f^2) = \sum_{n\geq 0}^{\infty} f_{i,\ n}\Box^n\ , \quad \Box = g^{\mu\nu}\nabla_\mu\nabla_\nu .$$

Biswas, Gerwick, Koivisto, AM, PRL (2011)

At the lowest order correction, one would expect infinite derivatives, these are known as alpha' correction in string theory

Infinite derivatives, NON-Locality, is an essence of string theory

WHY EFT FOR INFLATION BREAKS DOWN ?

a) **The VEV of inflaton is comparable to the cut-off**

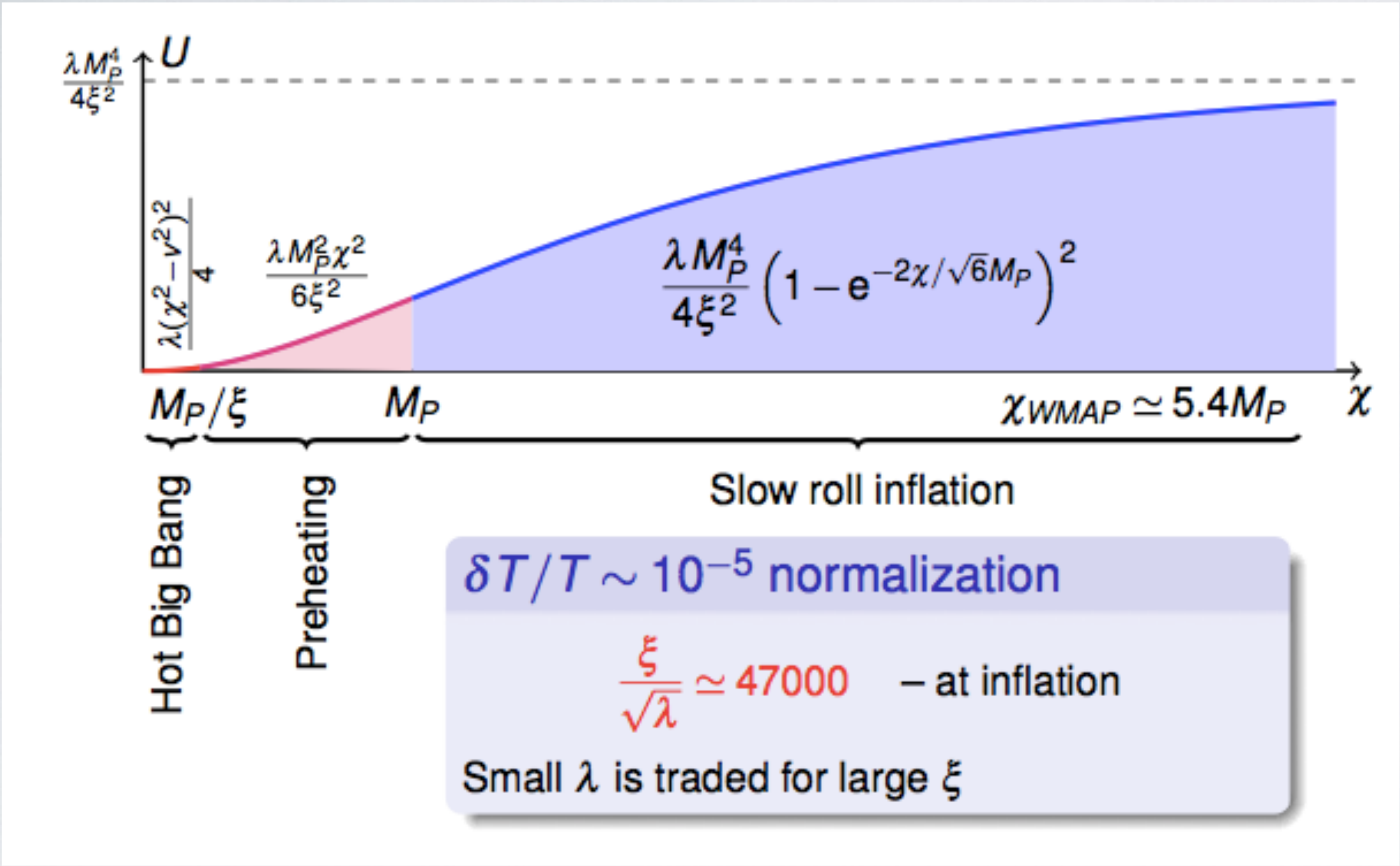
b) **The kinetic term is comparable to the cut-off**

c) **The inflaton vacuum gets modified due to quantum corrections, which may not lead to adiabatic evolution**

In UV we do not know how good our assumptions are for adiabatic and slow roll hypothesis !

SOME EXAMPLES OF INFLATION WHERE

EFT BREAKS DOWN EXPLICITLY



*Higgs Inflation

Berzukov+Shaposhnikov

Super Planckian inflation, Authors do not take KE corrections

*Monodromy Inflation

Silverstein, et.al.

$$\phi \to \phi + ia$$

Super Planckian inflation + Axion decay constant is above String scale

$$K.E. \sim \phi\Gamma(\Box)\phi\ (also\ respects\ Shift\ Symmetry)$$

SOME EXAMPLES OF INFLATION WHERE
EFT BREAKS DOWN EXPLICITLY

*** Staronbinsky Inflation:**

Finite Number of Higher Derivatives

$$\mathcal{L} \sim R + c_1 R^2 \implies Ghosts$$

We usually fix "c" from CMB, but at higher loops one obtain Ghosts, i.e. higher derivative theory contains Ghosts

$$\mathcal{L} \sim R + c_1 R^2 + c_2 R_{\mu\nu} R^{\mu\nu} + c_3 R_{\mu\nu\alpha\beta} R^{\mu\nu\alpha\beta} \implies Ghosts$$

Stelle's Gravity: Renormalizable but contains Ghosts …

WHAT ARE THE SOLUTIONS?

Q: Is there a dynamical mechanism to Slow down the inflaton ? NO

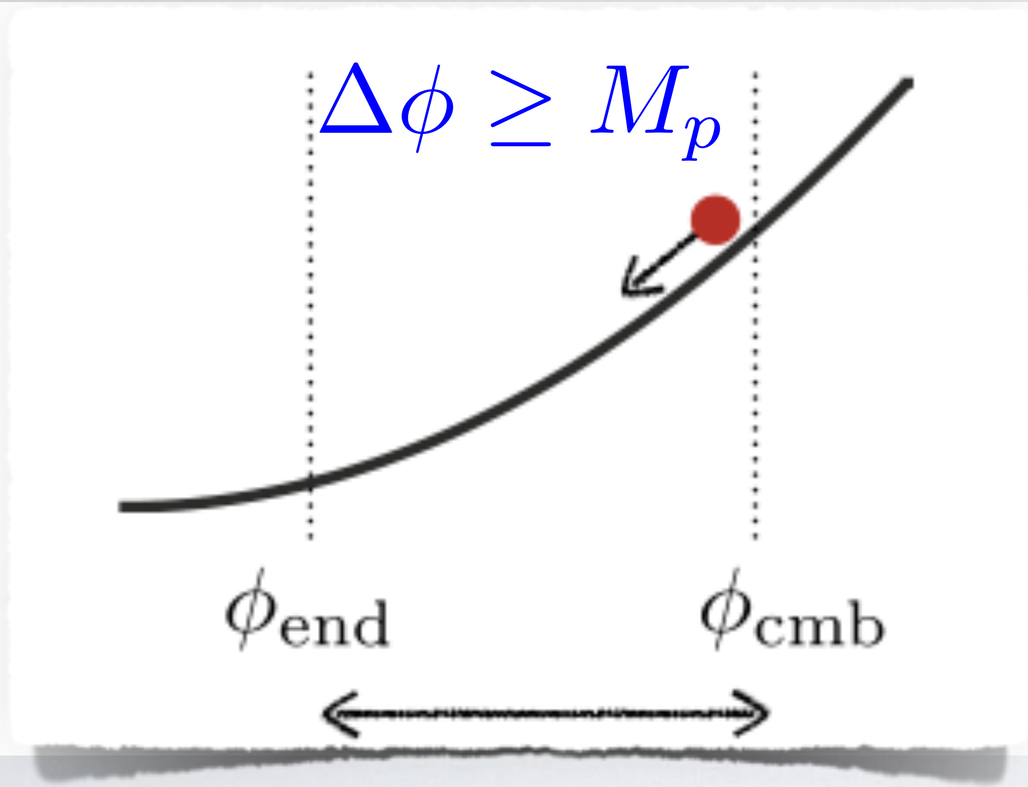
Q: Anthropically : YES

$$-\Box \approx 3H_{inf}\partial_t$$

BICEP data is wrong and tensor to scalar ratio is negligible ==> EFT, Slow Roll are all good approximations

$$(\langle\phi\rangle,\ H) < M_f, \qquad \rho_\phi \ll M_p^4$$

Super-Planckian excursions with Monotonically evolving potentials



$$V \sim \lambda \frac{\phi^n}{M_p^{n-4}}$$

$$n_s = 1 - \frac{2+n}{2N}$$

$$r = \frac{3.1n}{N}$$

$$r \equiv \frac{\Delta_t^2}{\Delta_s^2} = \frac{8}{M_{\rm pl}^2}\left(\frac{\dot\phi}{H}\right)^2 = \frac{8}{M_{\rm pl}^2}\left(\frac{d\phi}{dN}\right)^2$$

$$r \lesssim 0.003 \left(\frac{50}{N}\right)^2 \left(\frac{\Delta\phi}{M_{\rm P}}\right)^2$$

We can generate large "r" of order 0.1, 0.2, etc.

Lyth Bound : ϵ Evolves Monotonically

Assisted Inflation/ n-flation: N copies

Liddle-Mazumdar-Shunck (1998), Dimopoulos, Kachru, (2004)

$$V = \sum_{i=1}^{N_f} \lambda_i \phi_i^\alpha \qquad N \simeq -\frac{1}{M_{\rm Pl}^2} \sum_i \int_{\phi_i}^{\phi_i^{\rm end}} \frac{V_i}{V_i'} d\phi_i \simeq \frac{\sum_i \phi_i^2}{2\alpha M_{\rm Pl}^2} \approx \frac{N_f \phi_0^2}{M_{\rm Pl}^2}$$

$$r \simeq \frac{8M_{\rm Pl}^2}{\sum_i (V_i/V_i')^2} \simeq \frac{4\alpha}{N}$$

sub-Planckian Inflation

$$N = 100, \;\; \phi_0 = 0.1 M_{\rm Pl} \Rightarrow N_f = 10^4$$

$$r \approx \frac{4 \times 2}{100} \sim 0.8$$

$$r \approx \frac{4 \times 4}{100} \sim 0.16$$

$$n_s = 1 - \frac{4}{N} \sim 0.96$$

N-COPIES OF INFLATON to make EFT work

CONCLUIONS & DISCUSSIONS

a) **High scale inflation cannot be described by EFT, there are many scales which can bring new physics and corrections.**

b) **If BICEP data holds : -) an excellent opportunity to press upon understanding UV completeness of inflation and gravity**

c) **Important progress has been made in the paper by BGKM construction of Gravity in UV**

All of them are good signs for science !!

Many many models of inflation...

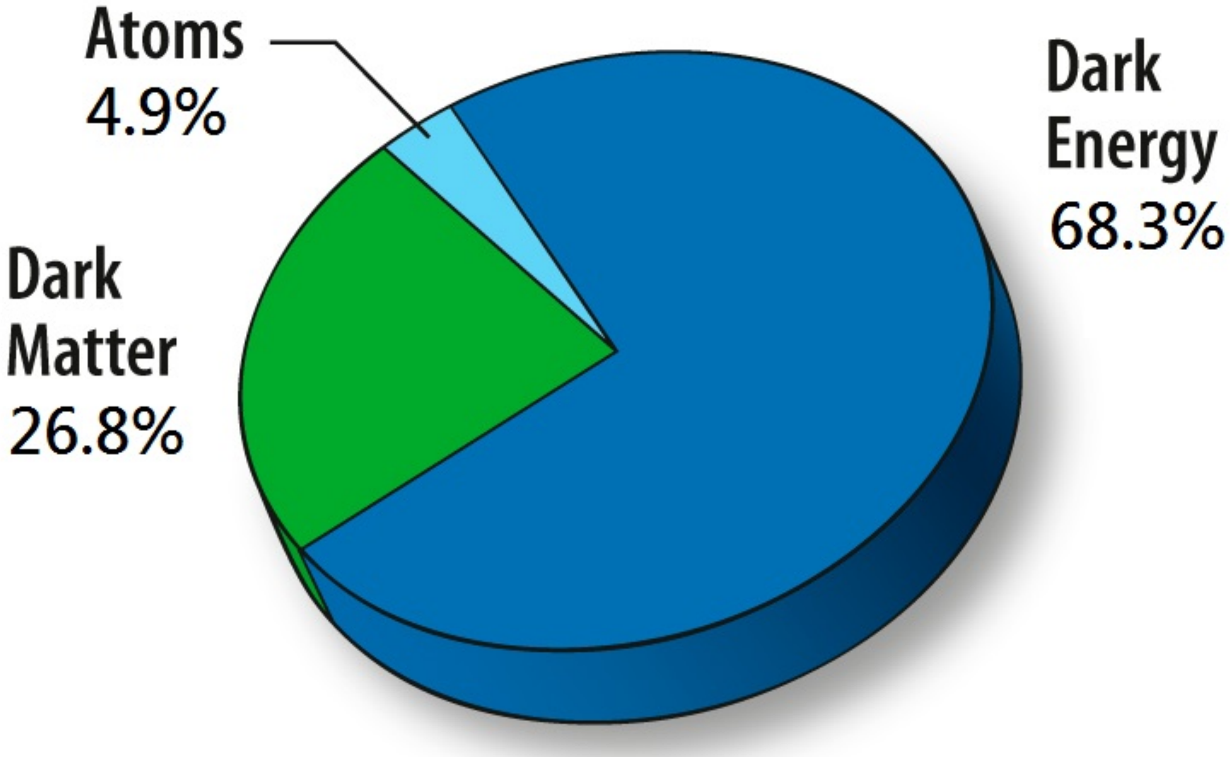
How many can really yield the Universe we see?

assisted brane inflation
anomaly-induced inflation
assisted inflation
assisted chaotic inflation
B-inflation
boundary inflation
brane inflation
brane-assisted inflation
brane gas inflation
brane-antibrane inflation
braneworld inflation
Brans-Dicke chaotic inflation
Brans-Dicke inflation
bulky brane inflation
chaotic inflation
chaotic hybrid inflation
chaotic new inflation
Chromo-Natural Inflation
D-brane inflation
D-term inflation
dilaton-driven inflation
dilaton-driven brane inflation
double inflation
double D-term inflation
dual inflation
dynamical inflation
dynamical SUSY inflation
S-dimensional assisted inflation
eternal inflation
extended inflation
extended open inflation
extended warm inflation
extra dimensional inflation

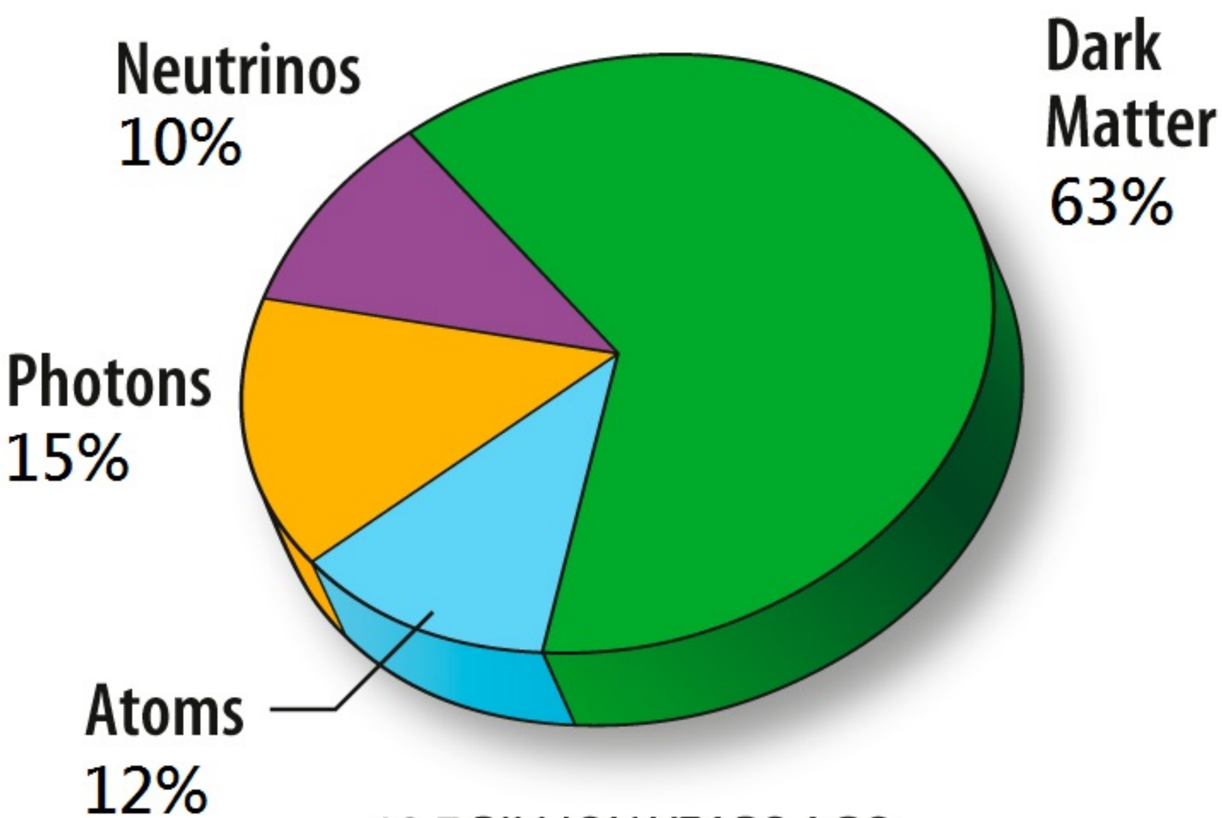
Roulette inflation
curvature inflation
Natural inflation
Warm natural inflation
Super inflation
Super natural inflation
Thermal inflation
Discrete inflation
Polarcap inflation
Open inflation
Topological inflation
Multiple inflation
Warm inflation
Stochastic inflation
Generalised assisted inflation
Self-sustained inflation
Graduated inflation
Local inflation
Singular inflation
Slinky inflation
Locked inflation
Elastic inflation
Mixed inflation
Phantom inflation
Non-commutative inflation
Tachyonic inflation
Tsunami inflation
Lambda inflation
Steep inflation
Oscillating inflation
Mutated hybrid inflation
Inhomogeneous inflation

higher-curvature inflation
hybrid inflation
Hyper-extended inflation
induced gravity inflation
intermediate inflation
inverted hybrid inflation
Power-law inflation
K-inflation
Super symmetric inflation
F-term inflation
F-term hybrid inflation
false-vacuum inflation
false-vacuum chaotic inflation
fast-roll inflation
first-order inflation
gauged inflation
Ghost inflation
Hagedorn inflation

perhaps,
NONE!



TODAY



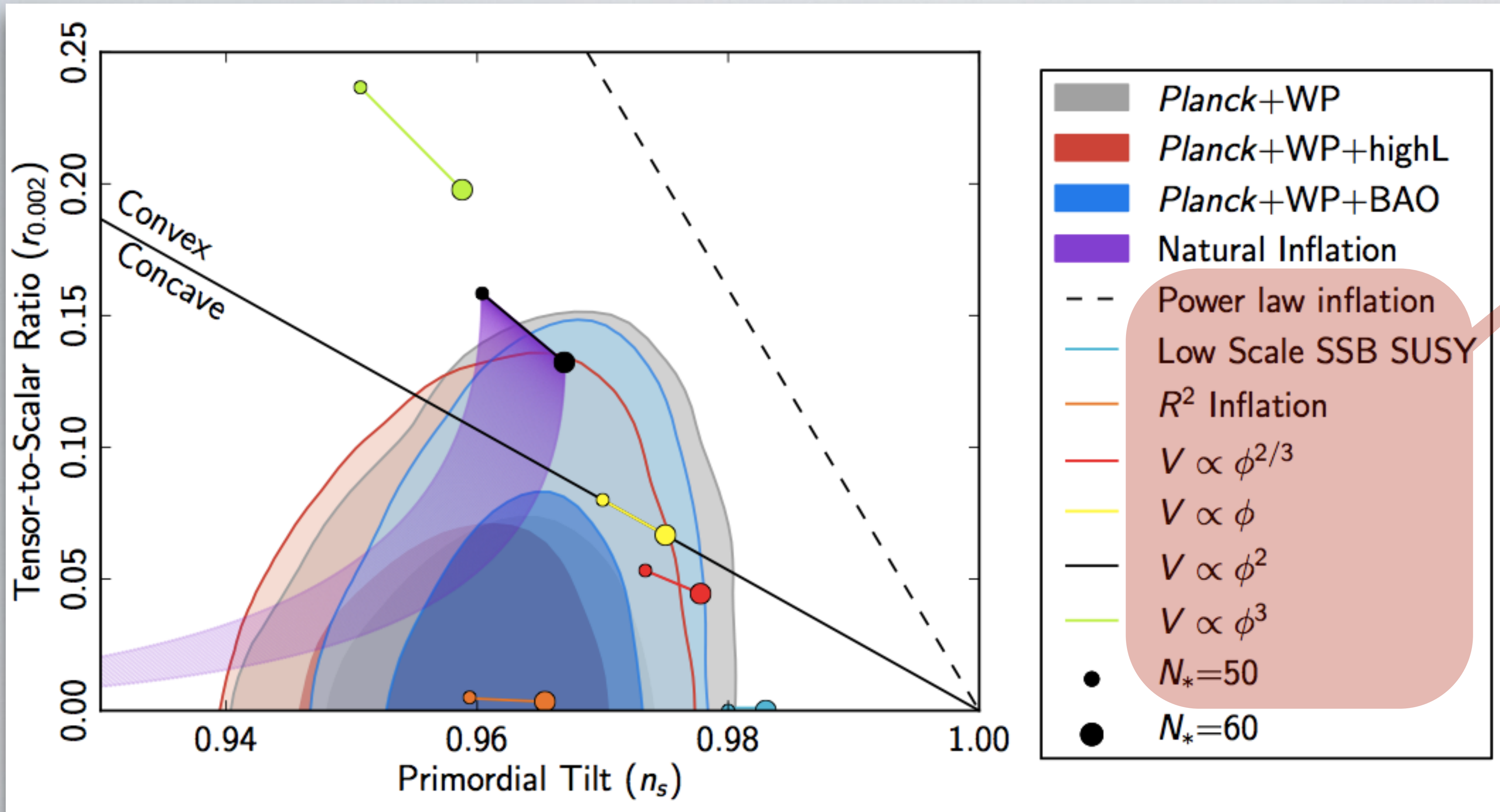
13.7 BILLION YEARS AGO
(Universe 380,000 years old)

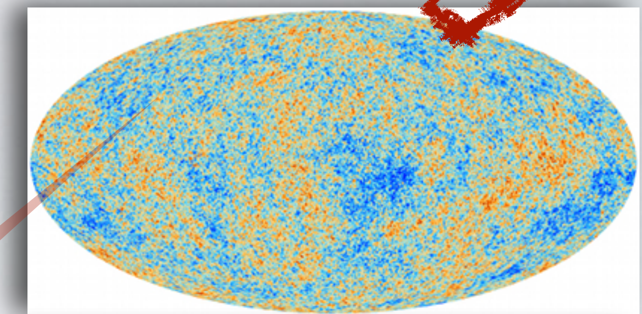
Success of BBN

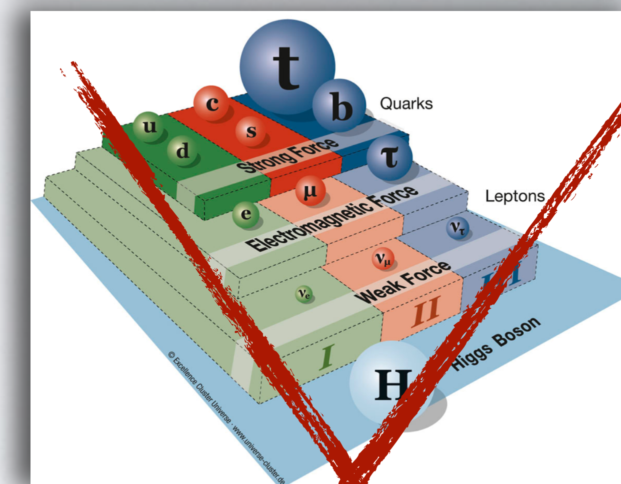
Successful creation of matter-anti-matter asymmetry

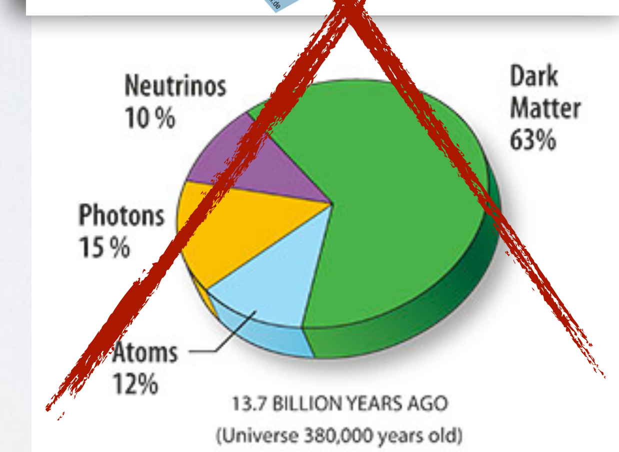
Therefore pinning down the scale of inflation is so important, i.e. tensor to scalar ratio

Vacuum where Inflation Ends ?









Inflaton is not embedded in any Particle Theory, they are moduli or Gauge Singlets arising from String Theory

Higgs Inflation

EFT breaks down!

Vacuum is well defined

MSSM Inflation

EFT is good but no large “r”

In all other models Inflaton is introduced like an ad-hoc Singlet Field

MSSM Flat Directions

	B−L	Always lifted by W_{renorm}?
$\mathrm{LH_u}$	−1	
$\mathrm{H_uH_d}$	0	
udd	−1	
LLe	−1	
QdL	−1	
$\mathrm{QuH_u}$	0	√
$\mathrm{QdH_d}$	0	√
$\mathrm{LH_de}$	0	√
QQQL	0	
QuQd	0	
QuLe	0	
uude	0	
$\mathrm{QQQH_d}$	1	√
$\mathrm{QuH_de}$	1	√
dddLL	−3	
uuuee	1	
QuQue	1	
QQQQu	1	
$\mathrm{dddLH_d}$	−2	√
$\mathrm{uudQdH_u}$	−1	√
$\mathrm{(QQQ)_4LLH_u}$	−1	√
$\mathrm{(QQQ)_4LH_uH_d}$	0	√
$\mathrm{(QQQ)_4H_uH_dH_d}$	1	√
$\mathrm{(QQQ)_4LLLe}$	−1	
uudQdQd	−1	
$\mathrm{(QQQ)_4LLH_de}$	0	√
$\mathrm{(QQQ)_4LH_dH_de}$	1	√
$\mathrm{(QQQ)_4H_dH_dH_de}$	2	√

$$SU(3) \times SU(2)_l \times U(1)_Y$$

$$u_1 d_2 d_3 \qquad d_2^\beta = \frac{1}{\sqrt{3}}\phi \qquad u_1^\alpha = \frac{1}{\sqrt{3}}\phi \qquad d_3^\gamma = \frac{1}{\sqrt{3}}\phi$$

$$L_1 L_2 e_3 \qquad L_1^a = \frac{1}{\sqrt{3}}\begin{pmatrix}0\\ \phi\end{pmatrix} \qquad L_2^b = \frac{1}{\sqrt{3}}\begin{pmatrix}\phi\\ 0\end{pmatrix} \qquad e_3 = \frac{1}{\sqrt{3}}\phi$$

$$H_u H_d \qquad H_u = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi\\ 0\end{pmatrix} \qquad H_d = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ \phi\end{pmatrix}$$

$$SU(3) \times SU(2)_l \times U(1)_Y \times U(1)_{B-L}$$

$$N H_u L \qquad N = \frac{1}{\sqrt{3}}\phi \qquad H_u = \frac{1}{\sqrt{3}}\begin{pmatrix}0\\ \phi\end{pmatrix} \qquad L = \frac{1}{\sqrt{3}}\begin{pmatrix}\phi\\ 0\end{pmatrix}$$

Allahverdi, Enqvist, Bellido, AM, (PRL, 2006), (JCAP, 2007), Allahverdi, Kusenko, AM, JCAP (2007)

UV COMPLETION

Matter/Inflaton

Shift symmetry, Anthropic arguments can still save the day

Gravity

There is no escape

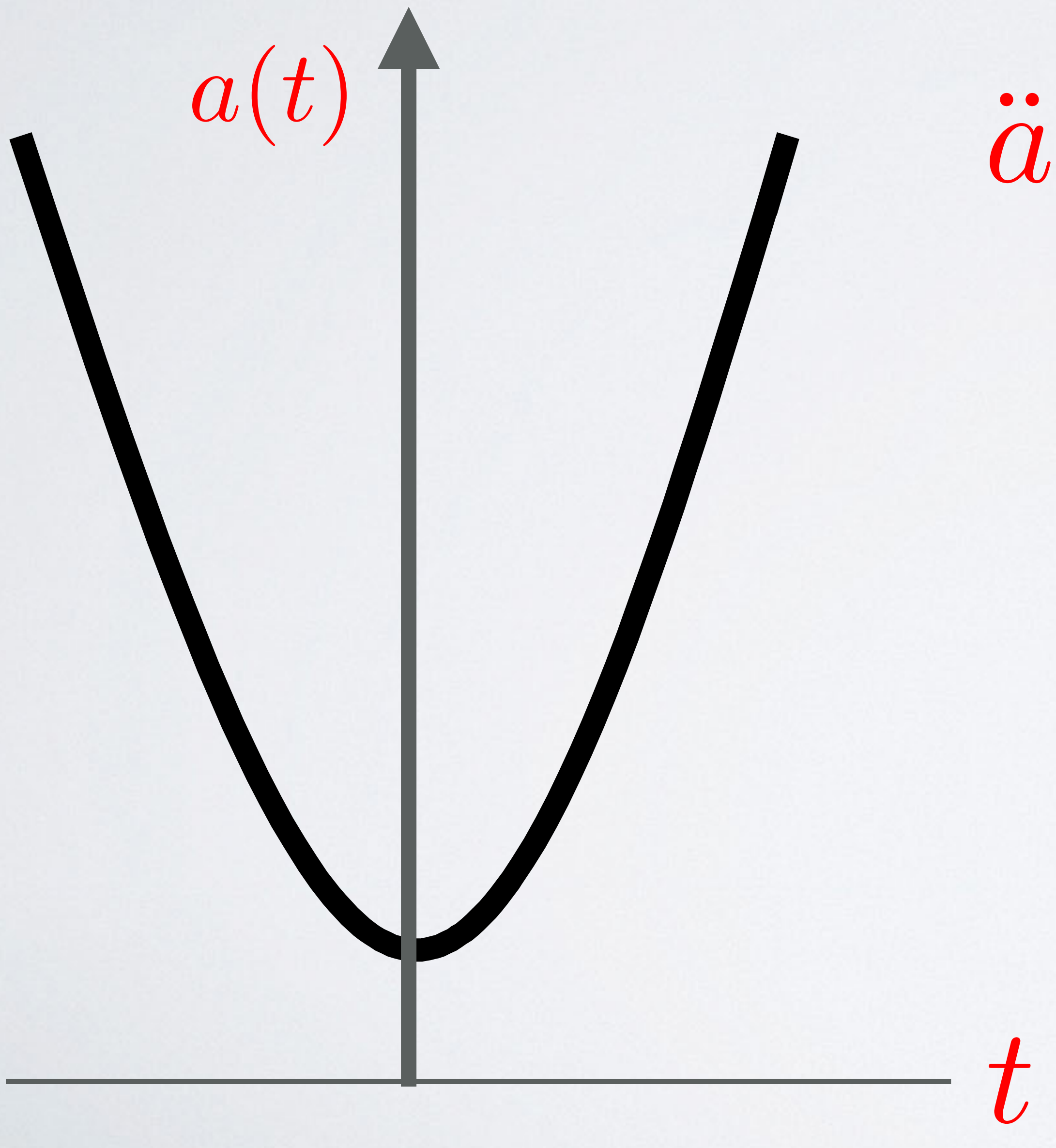
CAN WE AMELIORATE GRAVITY IN THE UV ?

a) At high energies gravity can be **weakened** at early times and short distances

b) Space time inhomogeneities can be **smoothened**: Good for inflationary initial conditions

WHAT IF UNIVERSE HAD THE PLANCKIAN ENERGY ?

$$\frac{1}{2}\dot{\phi}^2 \sim \frac{1}{2}(\partial_i\phi)^2 \sim V(\phi) \sim M_p^4$$



$$\ddot{a}(t) > 0 \ :-) \ Inflation$$

A Non-Singular Bouncing Universe

Full UV understanding of gravity: —) perhaps String theory can help us

SHIFT SYMMETRY

$$\phi \to \phi + C \quad (C \ : \ real\ constant),$$

$$S \to S\frac{\phi}{\phi + C}$$

$$\phi S = \text{const.}$$

$$\langle S \rangle = m \neq 0 \qquad m \to 0 \ Shift\ Symmetry\ restored$$

$$V \sim m^2\phi^2 + \cdots$$

$$K.E. \sim \phi\Gamma(\Box)\phi \ (also\ respects\ Shift\ Symmetry)$$