Recent developments on the application of discrete symmetries

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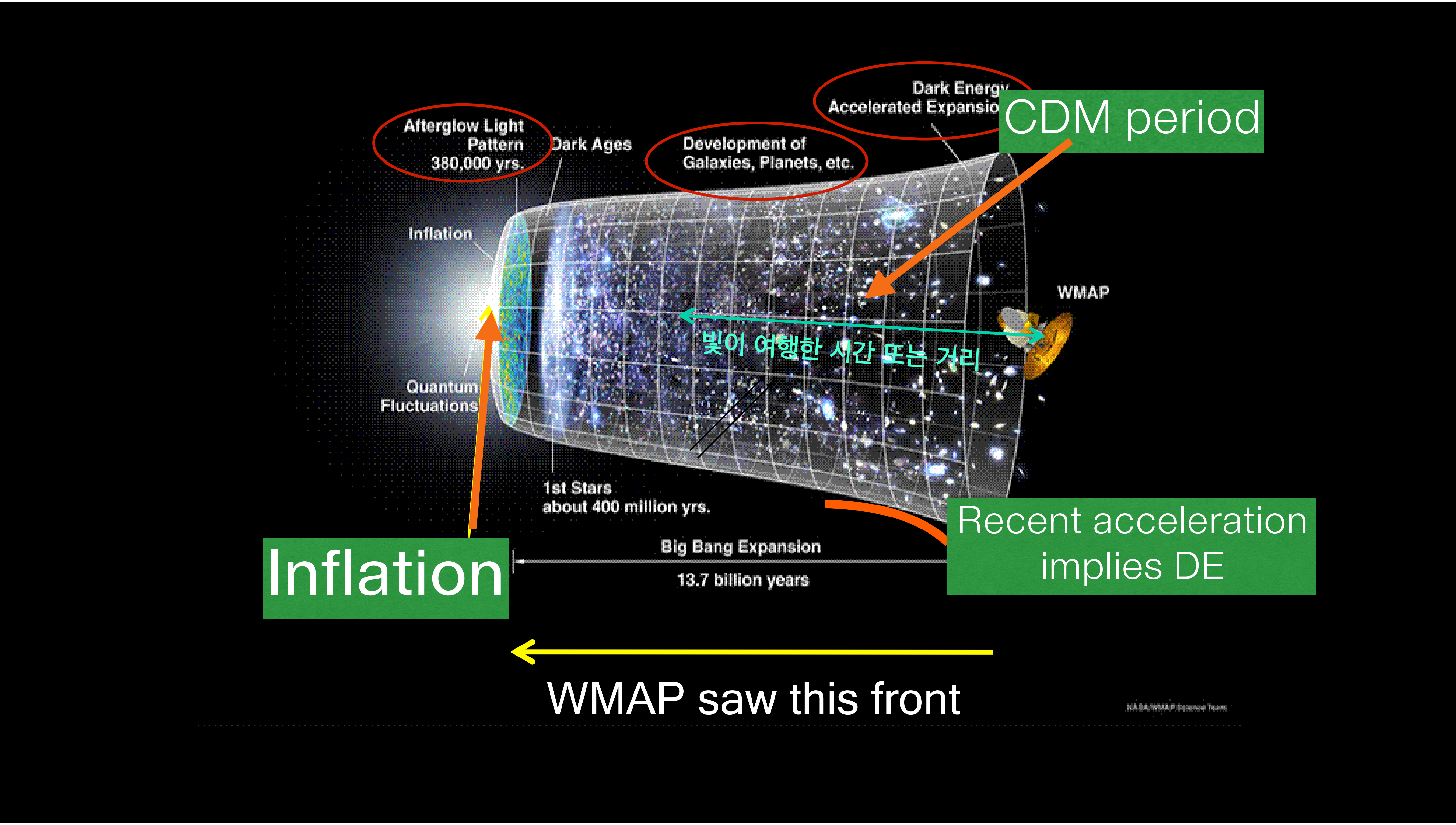
4th Joint Winter Conference on Particle Physics, String and Cosmology

Influentials lately

D K Hong Aug 2008

평화의 전당 ICHEP 2018

S Nam, Apr. 2013



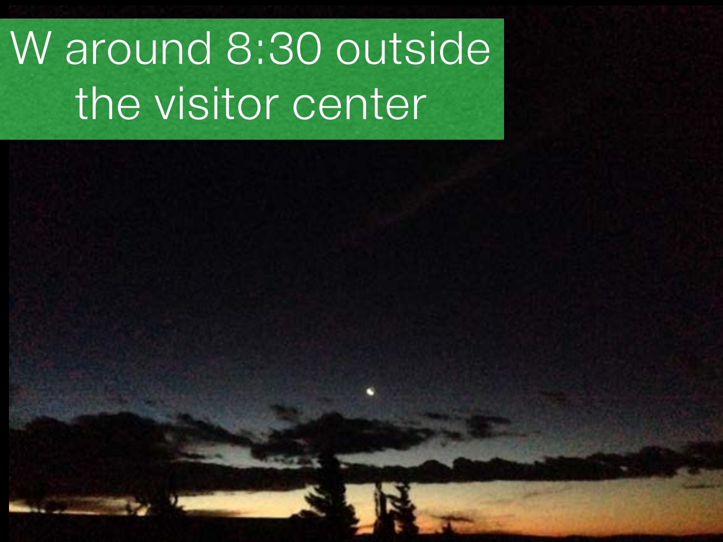
Dark Energy
Accelerated Expansio
CDM period
Afterglow Light Pattern 380,000 yrs.
Dark Ages
Development of Galaxies, Planets, etc.
Inflation
WMAP
빛이 여행한 시간 또는 거리
Quantum Fluctuations
1st Stars about 400 million yrs.
Recent acceleration implies DE
Inflation
Big Bang Expansion
13.7 billion years
WMAP saw this front

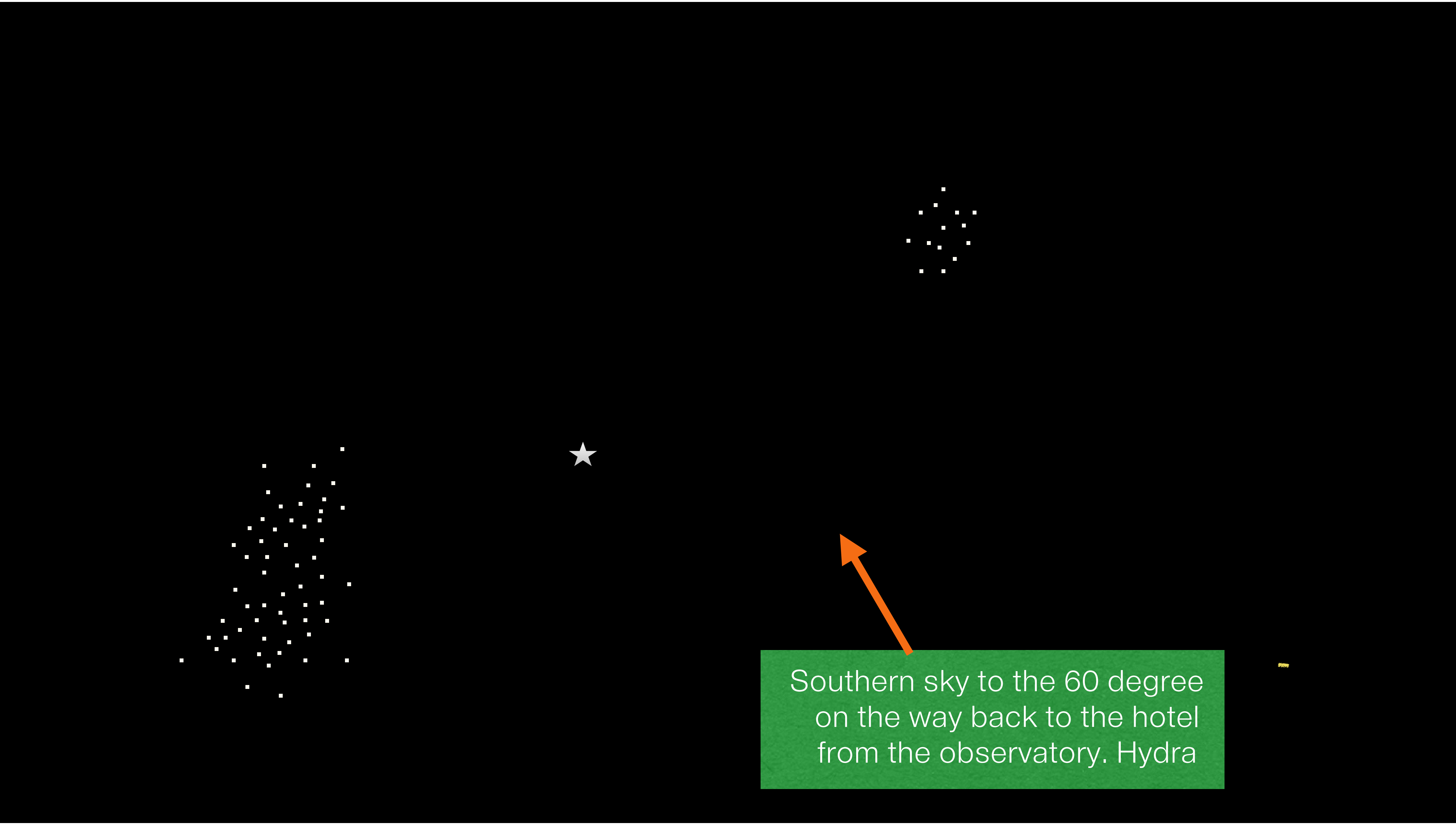
E right after sunset

W around 7:30pm at
Sutherland dorm area

Southern sky to the 60 degree
on the way back to the hotel
from the observatory

W around 8:30 outside
the visitor center




Southern sky to the 60 degree on the way back to the hotel from the observatory. Hydra

Southern sky to the 60 degree on the way back to the hotel from the observatory. Hydra

1. BCM can do many: Discrete symmetry is the key.
   With discrete symmetry

2. DE by QCD axion.
   With BCM includes QCD axion.

3. The strong CP prob. is solved and the very light axion provides some CDM component and even a lighter one for DE.

Applied to high scale inflation

4. High scale inflation needs NDW=1
5. Possible in string comp. with anomalous U(1)
6. CAPP may get an answer to axion in the micro- to milli-eV range, even with 10% of CDM

- Introduction
- Axions and the strong CP problem
- Discrete symmetry on the bottom of global symmetries
- Dark energy from $U(1)_{DE}$
- Gravity waves with large r
- PQ symmetry breaking below H_I

1. Introduction

DE as BCM review
Kim-Semertzidis-Tsujikawa,
1409.2497 [hep-ph]

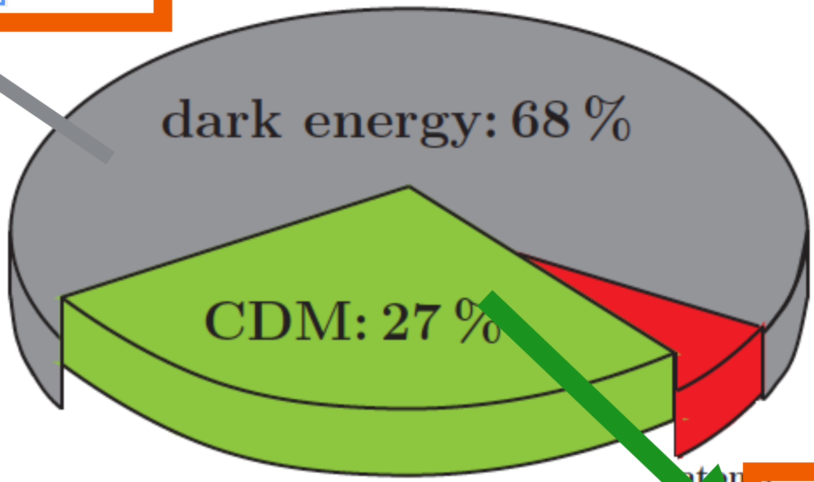


Figure 1.1: Cosmic energy pie

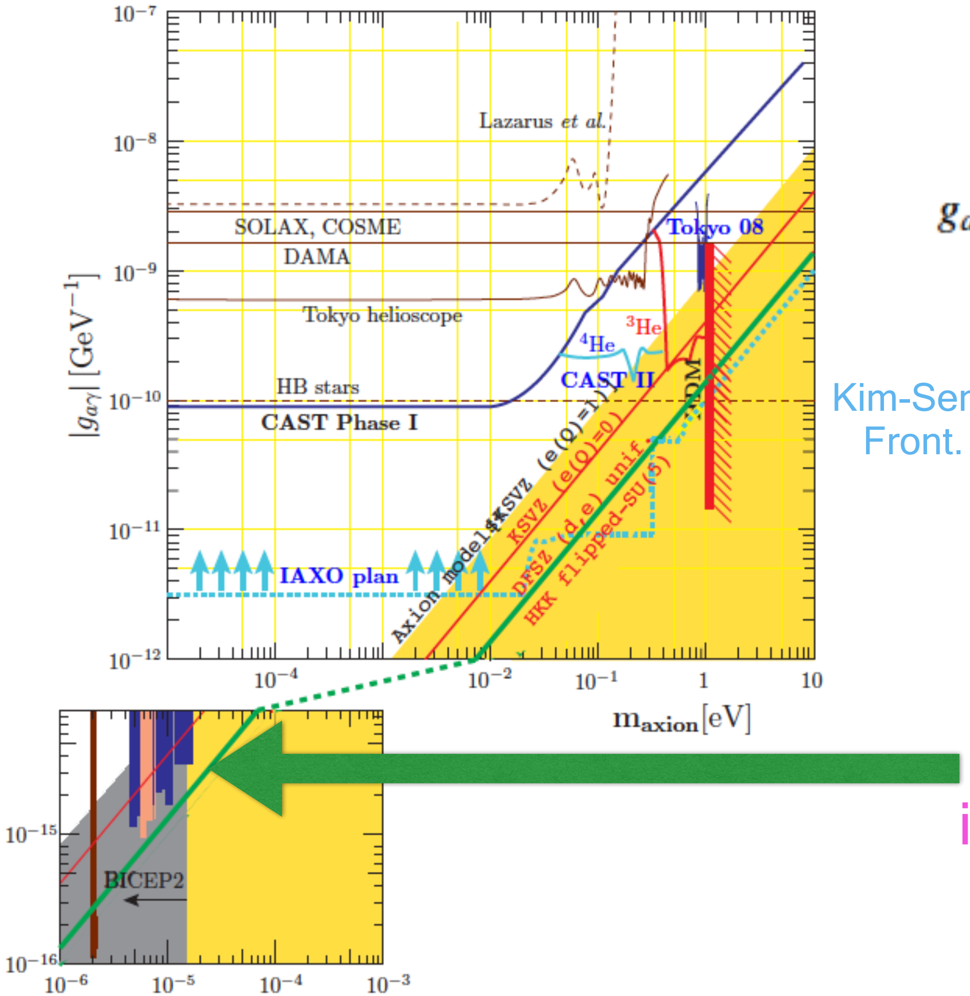
Yes

2 ethers?

No

Non-thermal DM review,
Baer et al. Phys. Rep. 555 (2015) 1
doi:10.1016/j.physrep.2014.10.002

BCM review
Kim-Semertzidis-Tsujikawa,
Front. Phys. 2 (2014) 60
1409.2497

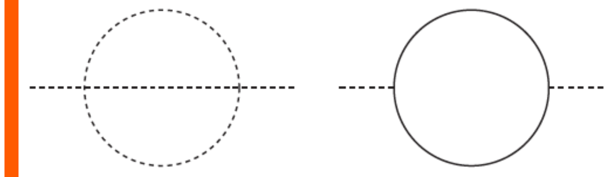


$g_{a\gamma}(= 1.57 \times 10^{-10} c_{a\gamma\gamma})$ vs. m_a plot

Kim-Semertzidis-Tsujikawa,
Front. Phys. 2 (2014) 60

Kim, PLB 735 (2014) 95,
Corrigenda
[in HKK model with
SU(5)xSU(5)'
in Z(12-I) orb. comp. (2009)]
c(a-photon-photon)=8/3.

Ideas	Description [scalar S or pseudoscalar P]	Discr. sym.?	Fine-tuning?	Model from string
MOND [a]	Change Newtonian gravity. [No boson]	Irrelevant	Yes	Not yet
Anthropic principle	Out of many possible vacua, only those suitable for age $> t_{\rm U}$ survived. [S or P]	Irrelevant	Irrelevant	Not yet [b]
Quintessence	With a runaway $V \propto 1/\phi^n$ $(n>0)$. [S]	No	Yes [c]	Not yet
Dilaton	P-Gold. boson from dilaton sym. [S]	No	Yes [d]	Not yet
$\rm U(1)_{DE}$ Gold. boson	P-Gold. boson from $\rm U(1)_{DE}$ sym. [P]	Yes	No	Yes [e]



If each vertex satisfies U(1), the whole diagram also!!!

Kim-Semertzidis-Tsujikawa (2014): Bosonic coherent motion review

Kim-Semertzidis-Tsujikawa, Front. Phys. 2, 60 (2014):
Bosonic coherent motion review
[Review in research topic BCM,
New one: Frontiers in Physics,
HE & astroparticle physics]

BCM:

BCM1 → Axion
BCM2 → Inflaton

CCtmp:

→ Dark energy

2. Axions and the strong CP problem

- Because of instanton solutions of QCD, there exists an effective interaction term G G-dual. It is the flavor singlet and the source of solving the U(1) problem of QCD: ’t Hooft, Phys. Rep. (1986).

- This term is physical, but leads to

- The strong CP problem, “Why is the nEDM so small?”

- The remaining ‘natural solution’ is “very light axion”.

- The gluon interaction.

$$\mathcal{L} = \bar{\theta}\{G\tilde{G}\} \equiv \frac{\bar{\theta}}{64\pi^2}\epsilon^{\mu\nu\rho\sigma}G^a_{\mu\nu}G^a_{\rho\sigma},$$

- The neutron mass term.

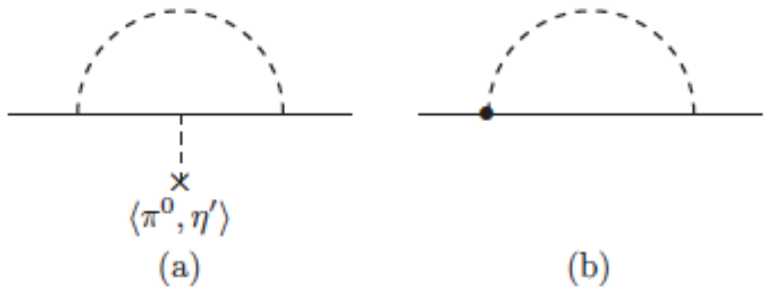
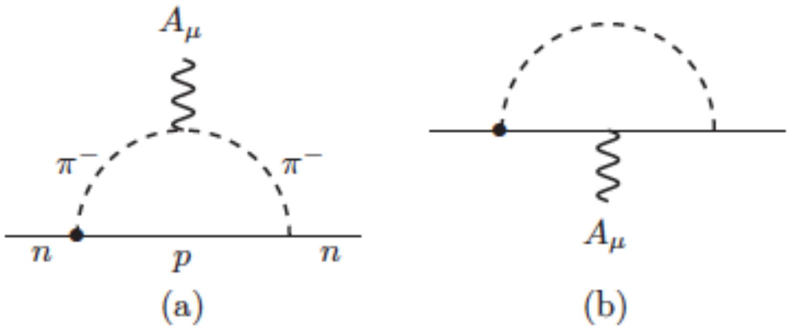


FIG. 4. Loop corrections for $\bar{n}n$-meson coupling. Insertion of the CP violation effect by VEVs of π^0 and η' in (a). They can be transferred to one vertex shown as a bullet in (b). With this bullet, CP violation is present because of a mismatch between the CP-conserving RHS vertex and CP-violating LHS vertex.

- The neutron EDM term.



$$\frac{d_n}{e} = \frac{g_{\pi NN}\overline{g_{\pi NN}}}{4\pi^2 m_N}\ln\left(\frac{m_N}{m_\pi}\right),$$

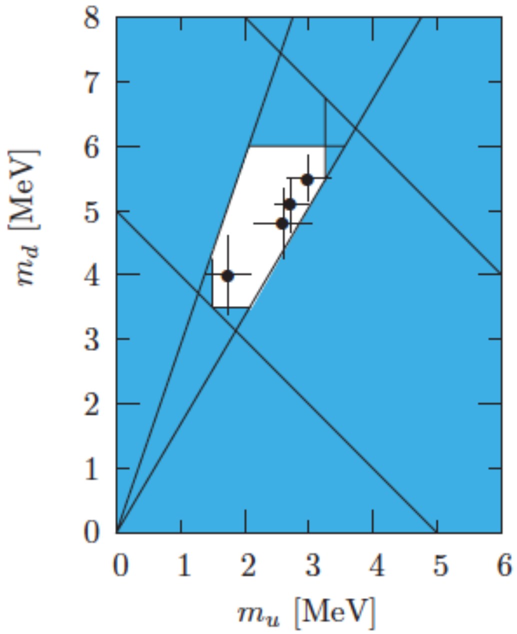
FIG. 5. Diagrams contributing to the NEDM with the bullet representing the CP violation effect. (a) is the physically observable contribution.

Pion VEV (CP violating) in the meson L can give

$$\overline{g_{\pi NN}} = -\bar{\theta}\frac{Z}{(1+Z)} \simeq -\frac{\bar{\theta}}{3}.$$

Massles up quark:

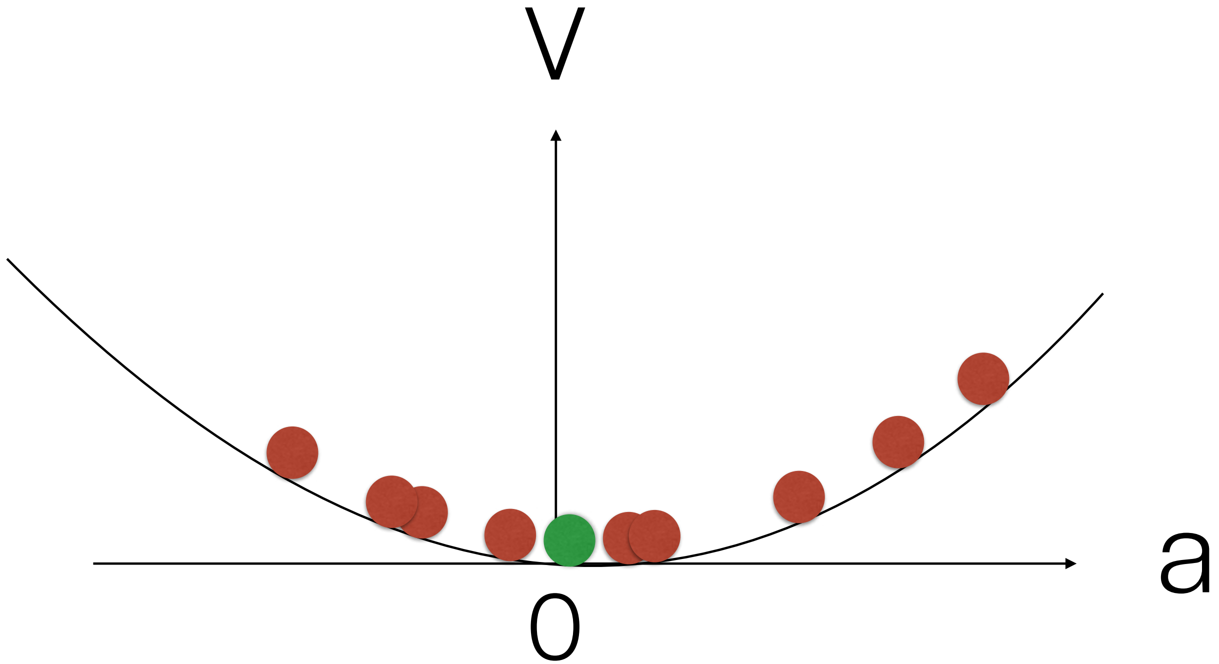
PDG book,
Manohar-Sachrajda

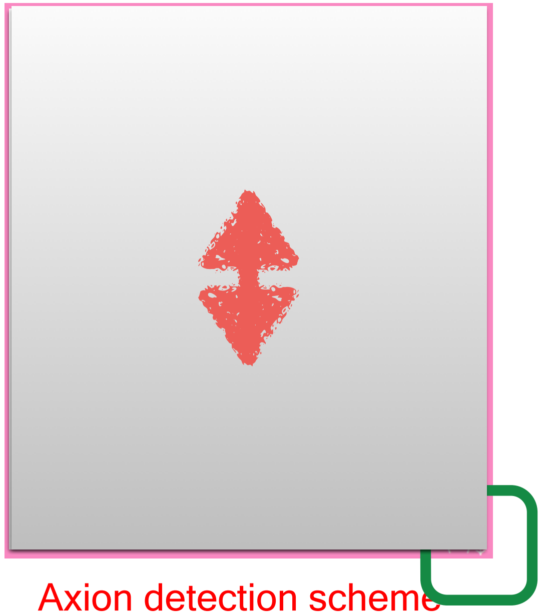


Symmetry solution (natural solution, calculable solution):

Beg-Tsao, Georgi, MS, ···, Nelson, Barr:
But no compelling model with very small theta-bar

Axion solution = cosmological solution

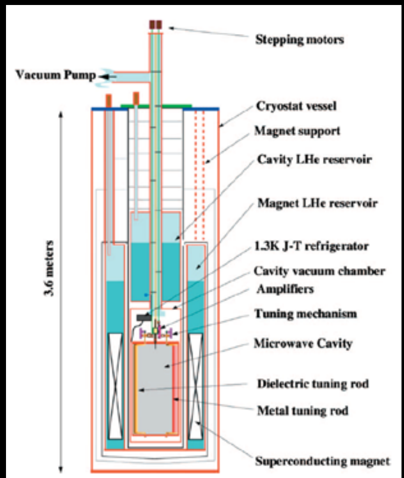




Axion detection scheme

Constant B field
E field follows the axion oscillation

Very light axion : 1979
CDM candidate



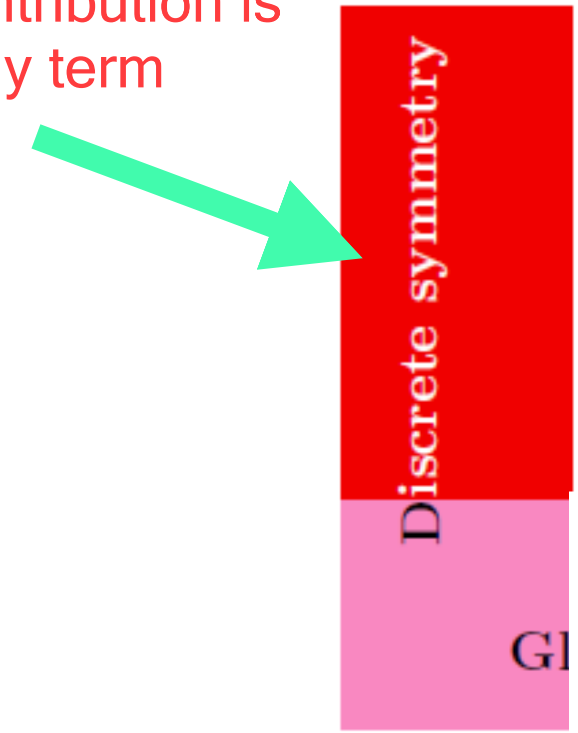
PQ symmetry : 1977
Detection suggested : 1983
CAPP started : 2013

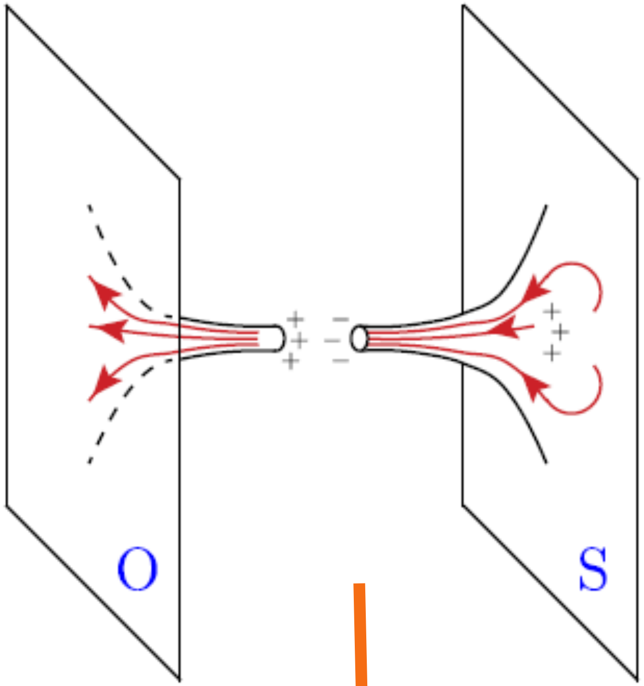
ADMX

CAPP: ???

3. Discrete symmetries on the bottom of global symmetries

The dominant contribution is
QCD anomaly term





Wormholes:
Gidding-Strominger,
Coleman, Cline

For PQ,
Barr-Seckel,
Kamionkowski-MarchRussel,
Holdom et al.
Exclude terms up to dim 8.

The example of acc symm.

Discrete gauge symmetry:
Ibanez-Ross,
Krauss-Wilczek

★ We can think of two possibilities of discrete symmetries realized from string compactification, below M_P:

(i) The discrete symmetry arises as a par t of a gauge symmetry.
[Krauss-Wilczek, PRL 62 (1989) 1211]

We choose this.

(ii) The string selection rules directly give the discrete symmetry.
[JEK, PRL 111 (2013) 031801]

- All global symmetries are NOT exact!!!
- Question is "What is the explicit breaking terms?"
- If it is spontaneously broken by VEVs of scalar fields, then there is "decay constant f."
- So we have two scales: Lambda and f.
- Anomaly breaking is, probably numerically, the dominant piece.

Axion-photon-photon coupling

1. KSVZ and DFSZ are not the cases from string compactification.
2. Several couplings are ← from Kim (1998)

TABLE I. $c_{a\gamma\gamma}$ in several field theoretic models. The left block is for the KSVZ and the right block is for the DFSZ. (m,n) in the KSVZ block denotes m copies of $Q_{\rm em}=\frac{2}{3}$ and n copies of $Q_{\rm em}=-\frac{1}{3}$ heavy quarks with the same PQ charge. In the DHSZ block $x=\tan\beta=v_u/v_d$.

$Q_{\rm em}$	$c_{a\gamma\gamma}$	x	one Higgs couples to	$c_{a\gamma\gamma}$
0	–1.95	any x	(d^c,e)	0.72
$\pm\frac{1}{3}$	–1.28	any x	(u^c,e)	–1.28
$\pm\frac{2}{3}$	0.72			
± 1	4.05			
(m,m)	–0.28			

Approximate PQ symmetry:

K S Choi-I W Kim-JEK, JHEP 0703 (2007) 116, Z(12-I) orb. comp.;
Choi-Nilles-RamoSanches-Vaudrevange , PLB675 (2009) 381, Z(6-II)

When we use the anomalous U(1), the PQ symmetry is not the accidental one.

Strategy: Findout compactifications with anomalous U(1).
If it is a GUT, it is calculable since there are relatively a small number of representations.

It is done only with a flipped SU(5)
[JEK, PLB735, 95. arXiv:1405.6175].
It gives an exact U(1)PQ, but spontaneously broken.

SU(5)-flip xSU(5)'xSU(2)'   x six U(1)s

$$Q_{\rm anom} = 84Q_1 + 147Q_2 - 42Q_3 - 63Q_5 - 9Q_6.$$

$$Q_1 = (0^5; 12\,0\,0)(0^8)', \qquad \tilde{Q}_1 = \frac{1}{12}Q_1,$$
$$Q_2 = (0^5; 0\,12\,0)(0^8)', \qquad \tilde{Q}_2 = \frac{1}{12}Q_2,$$
$$Q_3 = (0^5; 0\,0\,12)(0^8)', \qquad \tilde{Q}_3 = \frac{1}{12}Q_3,$$
$$Q_4 = (0^8)(0^4, 0; 12\ -12\ 0)', \qquad \tilde{Q}_4 = \frac{1}{12\sqrt{2}}Q_4,$$
$$Q_5 = (0^8)(0^5; -6\ -6\ 12)', \qquad \tilde{Q}_5 = \frac{1}{6\sqrt{6}}Q_5,$$
$$Q_6 = (0^8)(-6\ -6\ -6\ -6\ 18; 0\,0\,6)',$$

SM sector in flip-SU(5): $\sum_i Q(q_i)n(q_i) =$ −16 −28 +8 0 +18 +6 **-6984** = −17058

Sect.	Colored states	$SU(5)_X$	Multiplicity	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_{anom}	Label	$Q_a^{\gamma\gamma}$
U	$(\underline{+++--};--+)(0^8)'$	$\overline{\mathbf{10}}_{-1}$								−1638	$3C_2$	−3276

SU(5)' sector: $\sum_i Q(q'_i)n(q'_i) =$ −16 −28 +8 0 +18 +6 **-6984** −1960

The SU(5)' representations. Notations are the same as in Table 1.

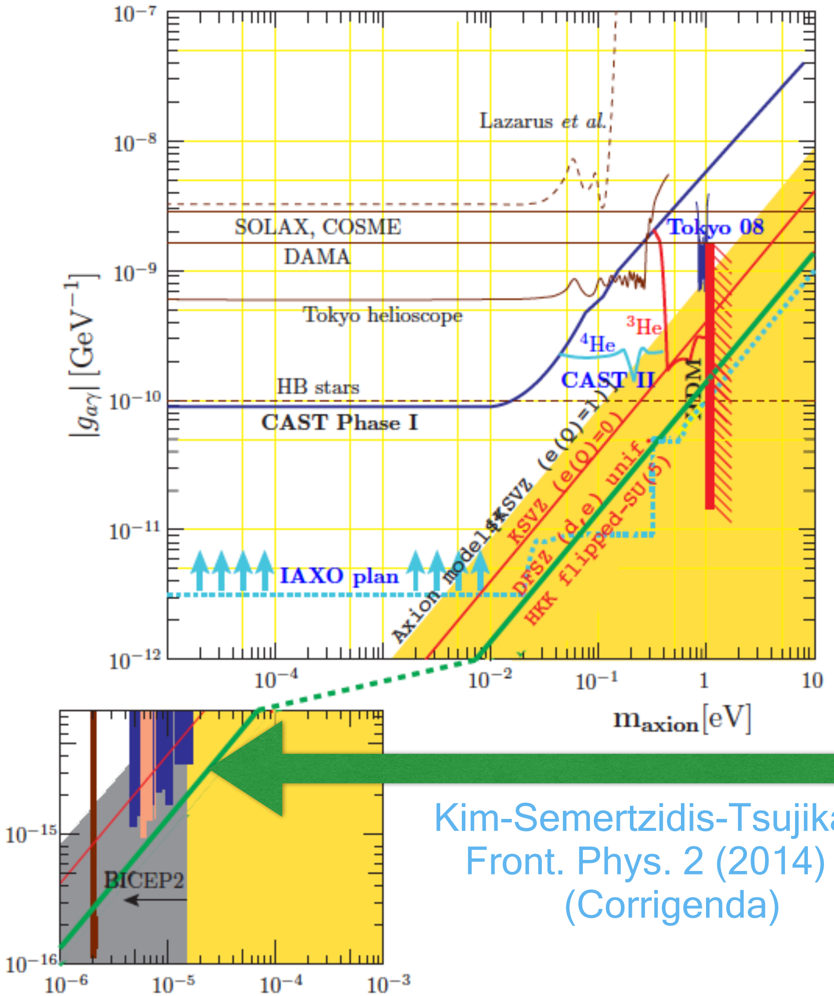
SU(2)' sector: $\sum_i Q(2'_i)n(2'_i) =$ −16 −28 +8 0 +18 +6 **-6984** −736

extra U(1)s:

Sect.	States	SU(5)'	Multiplicity	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_{anom}	Label	$Q_a^{\gamma\gamma}$
T_1^0	$(10000;\frac{-1}{6}\frac{-1}{6}\frac{-1}{6})(\underline{-10000};\frac{1}{4}\frac{1}{4}\frac{1}{2})'$ $(10000;\frac{-1}{6}\frac{-1}{6}\frac{-1}{6})(\underline{\frac{1}{2}\frac{1}{2}\frac{-1}{2}\frac{-1}{2}}\frac{1}{2};\frac{-1}{4}\frac{-1}{4}0)'$	$\mathbf{10}'_0$	1	−2	−2	−2	0	[illegible]	[illegible]	−648	$3T'_1$	0
T_1^0	$(00000;\frac{-1}{6}\frac{-1}{6}\frac{-1}{6})(\underline{10000};\frac{1}{4}\frac{1}{4}\frac{1}{2})'$ $(00000;\frac{-1}{6}\frac{-1}{6}\frac{-1}{6})(00000;\frac{-3}{4}\frac{-3}{4}\frac{-1}{2})'$ $(00000;\frac{-1}{6}\frac{-1}{6}\frac{-1}{6})(\underline{\frac{1}{2}\frac{-1}{2}\frac{-1}{2}\frac{-1}{2}}\frac{-1}{2};\frac{-1}{4}\frac{-1}{4}0)'$ $(00000;\frac{-1}{6}\frac{-1}{6}\frac{-1}{6})(\frac{1}{2}\frac{1}{2}\frac{1}{2}\frac{1}{2}\frac{-1}{2};\frac{-1}{4}\frac{-1}{4}0)'$	$(\mathbf{5}',\mathbf{2}')_0$	1	−2	−2	−2	0	+3	−3	−540	$2F'_1$	0
T_1^0	$(00000;\frac{-1}{6}\frac{-1}{6}\frac{-1}{6})(\underline{\frac{-1}{2}\frac{1}{2}\frac{1}{2}\frac{1}{2}}\frac{-1}{2};\frac{-1}{4}\frac{-1}{4}0)'$ $(00000;\frac{-1}{6}\frac{-1}{6}\frac{-1}{6})(0000-1;\frac{1}{4}\frac{1}{4}\frac{1}{2})'$	$\overline{\mathbf{5}}'_0$	1	−2	−2	−2	0	+3	−15	−432	F'_2	0
T_1^+	$(\frac{1}{6}\frac{1}{6}\frac{1}{6}\frac{1}{6}\frac{1}{6};\frac{1}{3}\frac{-1}{3}0)(\underline{\frac{-5}{6}\frac{1}{6}\frac{1}{6}\frac{1}{6}}\frac{1}{2};\frac{1}{12}\frac{-1}{4}0)'$ [illegible]	$\overline{\mathbf{5}}'_{-5/3}$	1	+4	−4	0	+4	+1	+11	−414	F'_3	−230
T_4^+	$(\frac{1}{6}\frac{1}{6}\frac{1}{6}\frac{1}{6}\frac{1}{6};\frac{-1}{6}\frac{1}{6}\frac{1}{2})(\underline{\frac{2}{3}\frac{-1}{3}\frac{-1}{3}\frac{-1}{3}}0;\frac{1}{3}00)'$ $(\frac{1}{6}\frac{1}{6}\frac{1}{6}\frac{1}{6}\frac{1}{6};\frac{-1}{6}\frac{1}{6}\frac{1}{2})(\frac{1}{6}\frac{1}{6}\frac{1}{6}\frac{1}{6}\frac{1}{2};\frac{-1}{6}\frac{-1}{2}\frac{-1}{2})'$	$\mathbf{5}'_{-5/3}$	3	−2	+2	+6	+4	−2	+2	[illegible]	$3F'_4$	[illegible]
T_4^-	$(\frac{-1}{6}\frac{-1}{6}\frac{-1}{6}\frac{-1}{6}\frac{-1}{6};\frac{-1}{6}\frac{-1}{2}\frac{1}{6})(\underline{\frac{-2}{3}\frac{1}{3}\frac{1}{3}\frac{1}{3}}0;\frac{-1}{3}00)'$ $(\frac{-1}{6}\frac{-1}{6}\frac{-1}{6}\frac{-1}{6}\frac{-1}{6};\frac{-1}{6}\frac{-1}{2}\frac{1}{6})(\frac{-1}{6}\frac{-1}{6}\frac{-1}{6}\frac{-1}{6}\frac{-1}{2};\frac{1}{6}\frac{1}{2}\frac{1}{2})'$	$\overline{\mathbf{5}}'_{5/3}$	3	−2	−6	+2	−4	+2	−2	−1242	$3F'_5$	[illegible]
T_7^-	$(\frac{-1}{6}\frac{-1}{6}\frac{-1}{6}\frac{-1}{6}\frac{-1}{6};\frac{1}{3}0\frac{-1}{3})(\underline{\frac{5}{6}\frac{-1}{6}\frac{-1}{6}\frac{-1}{6}}\frac{-1}{2};\frac{-1}{12}\frac{1}{4}0)'$ $(\frac{-1}{6}\frac{-1}{6}\frac{-1}{6}\frac{-1}{6}\frac{-1}{6};\frac{1}{3}0\frac{-1}{3})(\frac{1}{3}\frac{1}{3}\frac{1}{3}\frac{1}{3}0;\frac{-7}{12}\frac{-1}{4}\frac{-1}{2})'$	$\mathbf{5}'_{-5/3}$	1	+4	0	−4	−4	−1	−11	+666	F'_6	+370
		$\sum_i Q(q'_i)n(q'_i) =$		−16	−28	+8	0	+18	+6	−6984	$\sum_i =$	−1960

extra U(1) charges of all: $\sum_i Q(\mathbf{1}_i)n(\mathbf{1}_i) =$ −16 −28 +8 0 +18 +4 −7632 $\sum_i =$ −460

$Q_a^{\gamma\gamma}$
−3276
−294
−882
−756
+1008
+1008
0
0
−1188
+1188
−1296
−1296
−17058



Kim-Semertzidis-Tsujikawa, Front. Phys. 2 (2014) 60 (Corrigenda)

$g_{a\gamma}(= 1.57\times 10^{-10}\, c_{a\gamma\gamma})$ vs. m_a plot

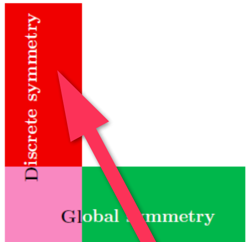
c(axion-photon-photon) =8/3 - 1.98

Kim, PLB 735 (2014) 95, Corrigenda [in HKK model with SU(5)xSU(5)' in Z(12-I) orb. comp. (2009)] c(a-photon-photon)=8/3.

4. Dark energy from $U(1)_{DE}$

For DE, the potential is extremely flat; still the DE vacuum looks like contributing to cosmological constant.

Anomaly-free is a small part.



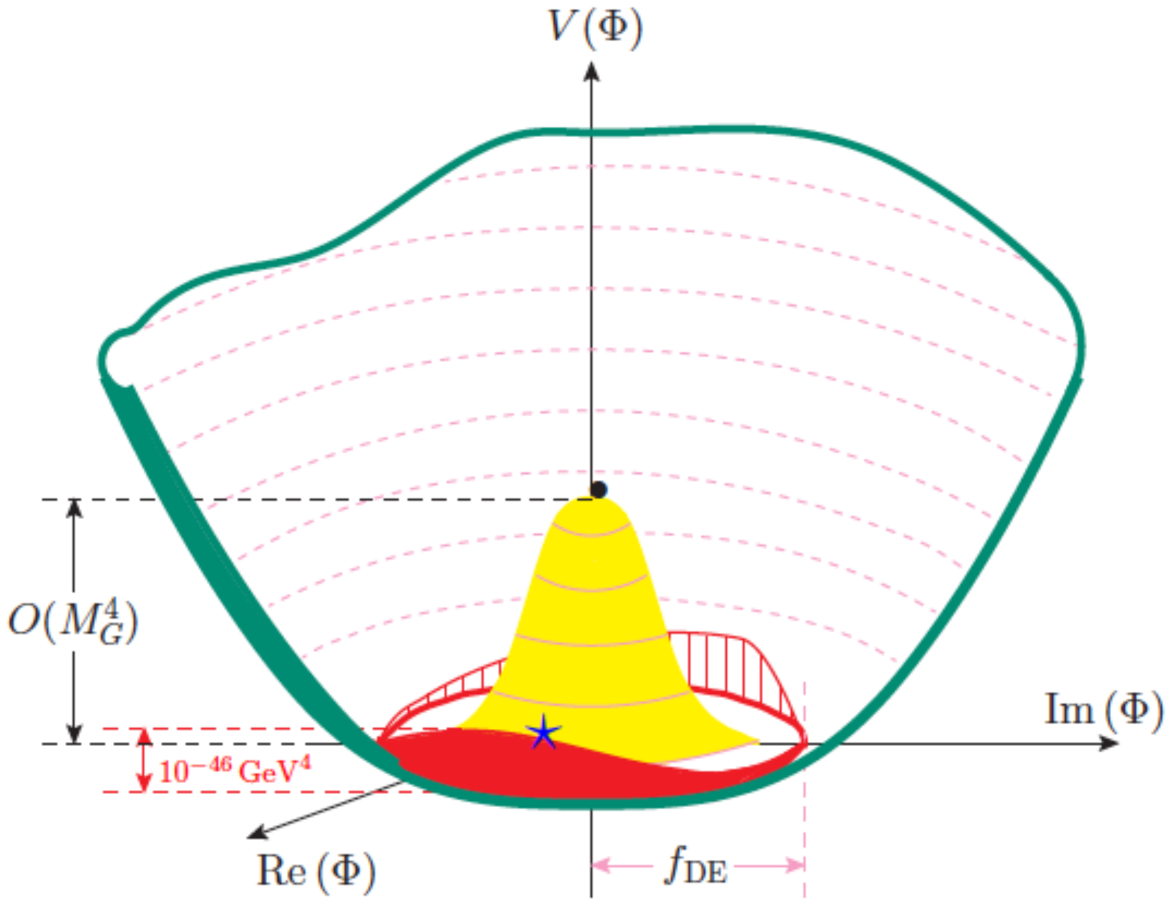
axion, the vaucuum already started bosonic motion(BCM) at $T_1 \approx 1$ GeV.

Anomaly is a large part.

How can one very flat and the oth so flat?

By the red part!!!

To solve DE, we necessarily introduce QCD axion for it to carry QCD anomaly.



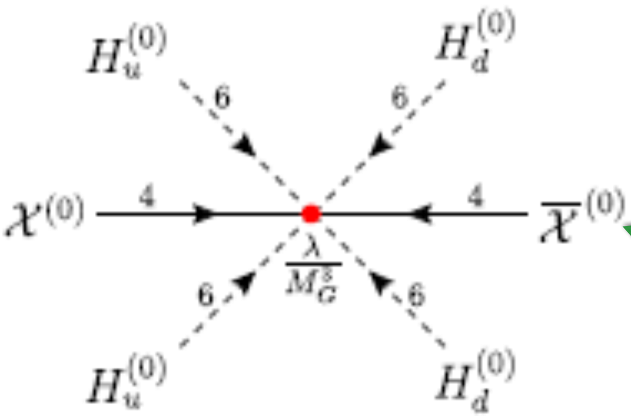
$V(\Phi)$
$O(M_G^4)$
$10^{-46}\,\mathrm{GeV}^4$
$\mathrm{Im}\,(\Phi)$
$\mathrm{Re}\,(\Phi)$
$f_{\rm DE}$

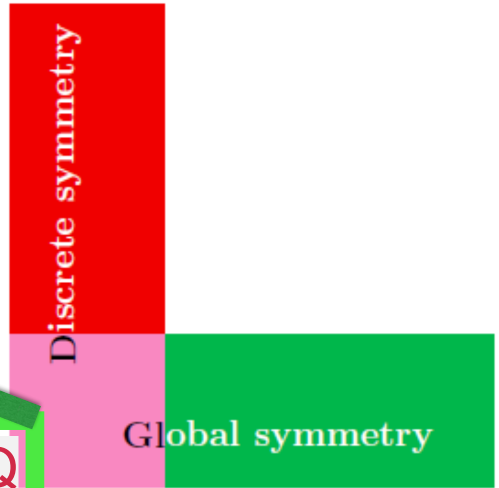
- Z(12-I) is the simplest orbifold on 2-torus since there are only 3 fixed points. [Huh-K-Kyae, PRD 80, 115012 (2009)] Higgs with two units of discrete charge. 2 families from T4 and 1 family from U. The gauge group is flipped-SU(5)xSU(5)' with extra (mostly) U(1) groups.

  - EM neutral singlets contain for example,

Sectors	Singlet states	χ	$(N^L)_j$	$\mathcal{P}(f_0)$	Label	P	Z_4	Z_8	Z_{10}	Z_{12}
T_3	$(0\,0\,0\,0\,0;\frac{-1}{2}\,\frac{-1}{2}\,\frac{-1}{2})(0\,0\,0\,0\,0\,\frac{3}{4}\,\frac{-1}{4}\,\frac{-1}{2})'$	L	0	1	S_9	-3	-4	-8	-10	-12
T_9	$(0\,0\,0\,0\,0;\frac{1}{2}\,\frac{1}{2}\,\frac{1}{2})(0\,0\,0\,0\,0\,\frac{-3}{4}\,\frac{1}{4}\,\frac{1}{2})'$	L	0	1	S_{13}	$+3$	$+4$	$+8$	$+10$	$+12$

  - Z(10)R is quite large to forbid many terms in W.

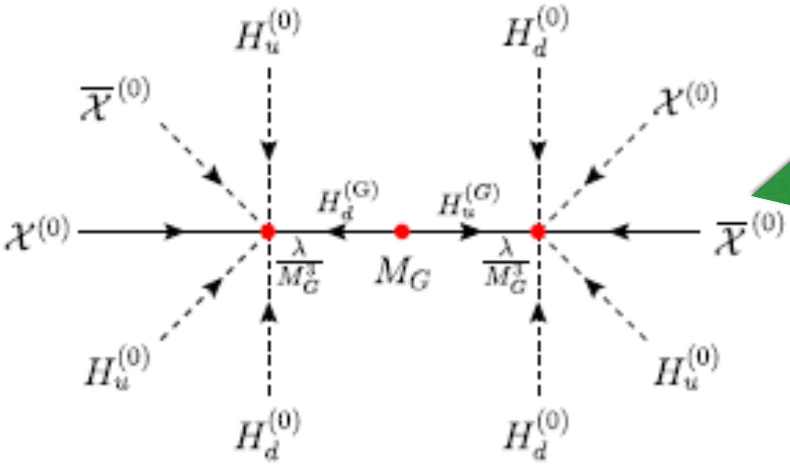


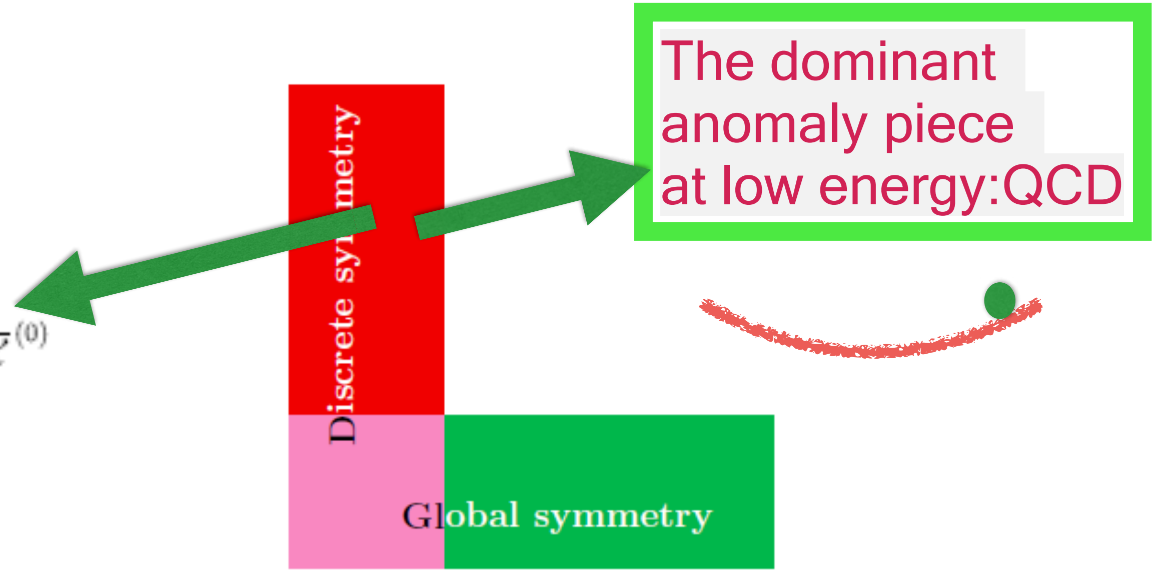


Define PQ

Constructed so that there is no QCD anomaly

- Higgs portal to high energy physics.
- This discrete symmetry charges are from the mother gauge U(1) charges.



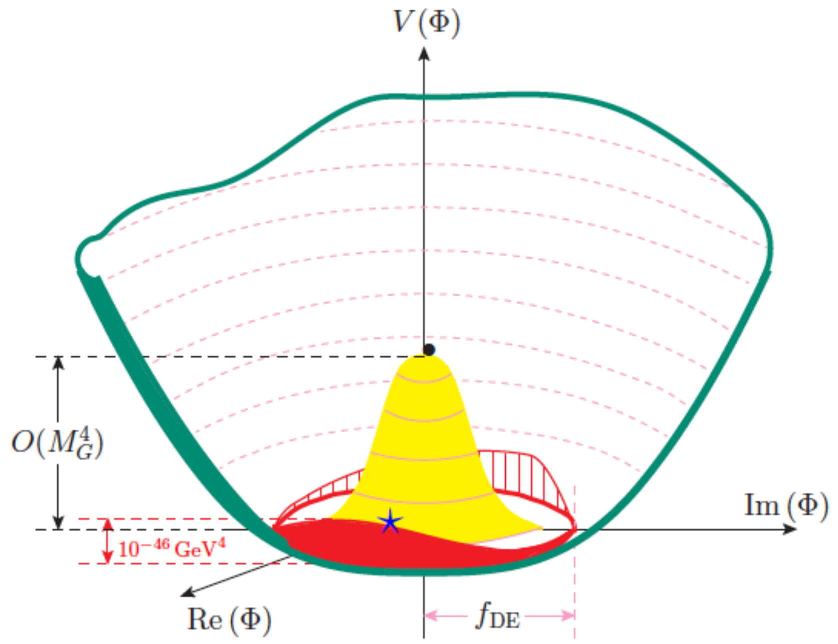


★ The height of the potential is highly suppressed and we can obtain 10^{-47} GeV^4 from discrete symmetry Z_{10R}, without the gravity spoil of the global symmetry breaking term.

5. Inflation with trans-Planckian inflaton

The DE potential had the form of the potential with a GUT scale vacuum energy.

It predicts a hilltop inflation.

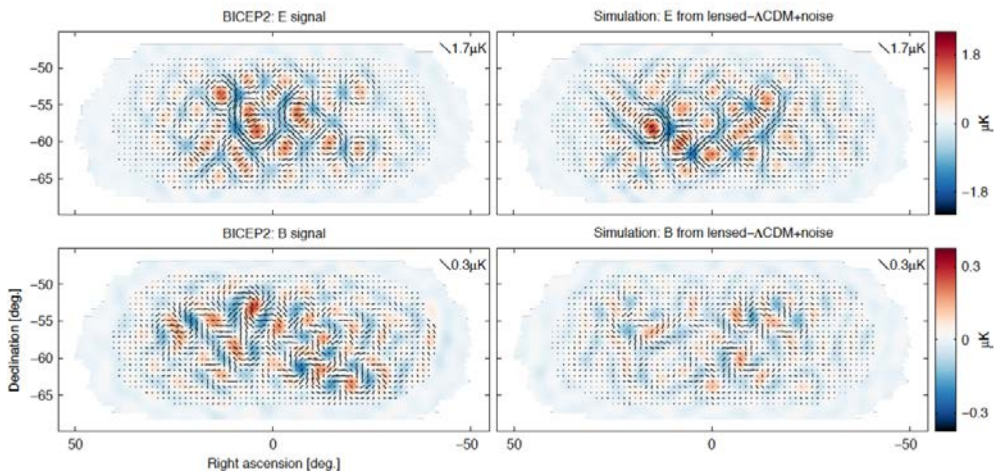


But there was the r and ns values given by BICEP2. Is the hilltop consistent?

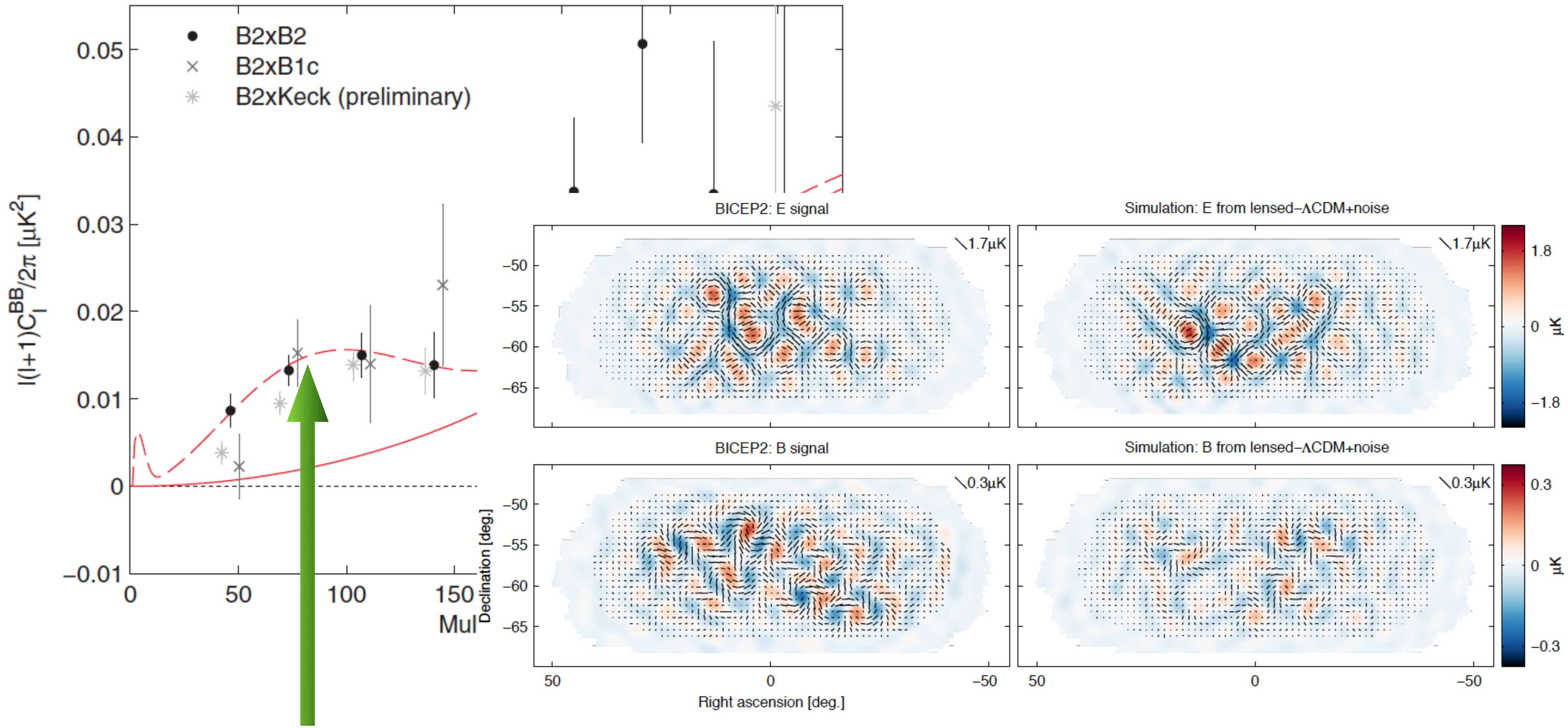
∇ x E = div B (Faraday)

∇ x B= …….. (Ampere-Maxwell)

For large scales,
Gravity can give a
curl type as B has
a curl with current.



r = tensor:scalar ratio



For small l, r is measured.

★ We obtain

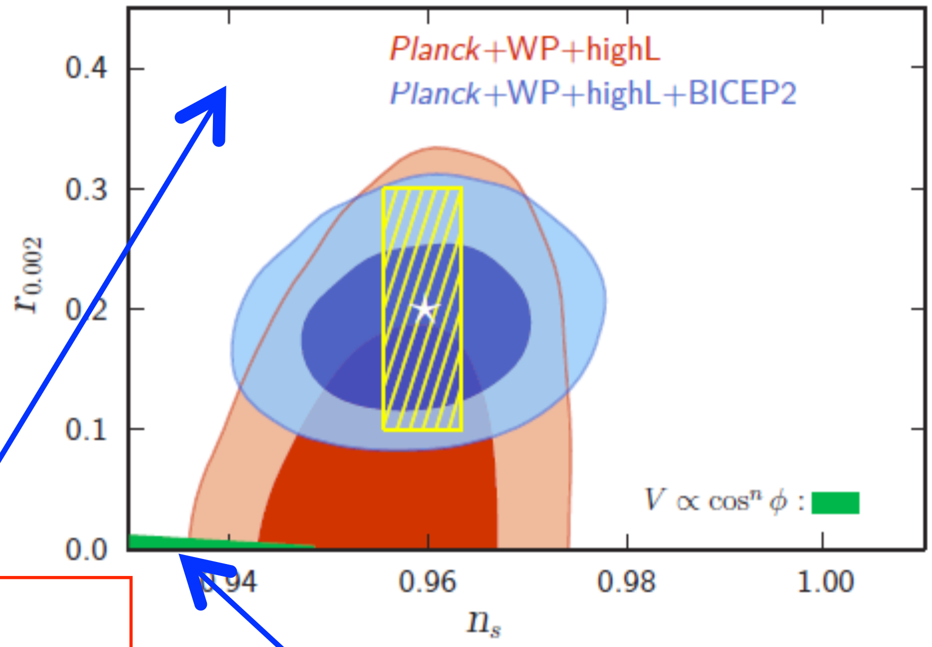
$$n_s = 1 + \Delta n_s = 1 - \left[\frac{r}{8} + \frac{1}{20s} + 2s\right] \le 1 - \left[\frac{r}{8} + \sqrt{\frac{r}{2}}\right]$$

[0.96, 0.008]♪

$$V = \Lambda^4 \cos^s\phi + \Delta V$$

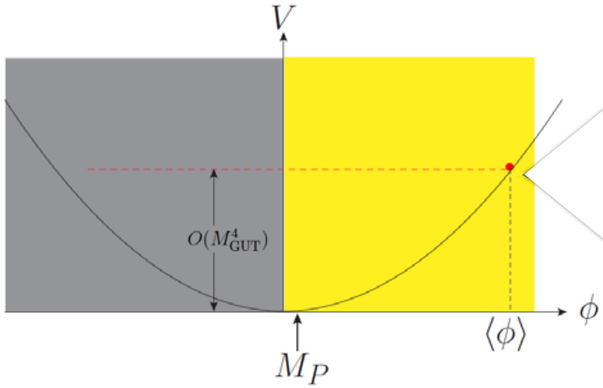
$$\text{with } (\Delta V)'' > 0$$

New type (chaoton) hybrid inflation



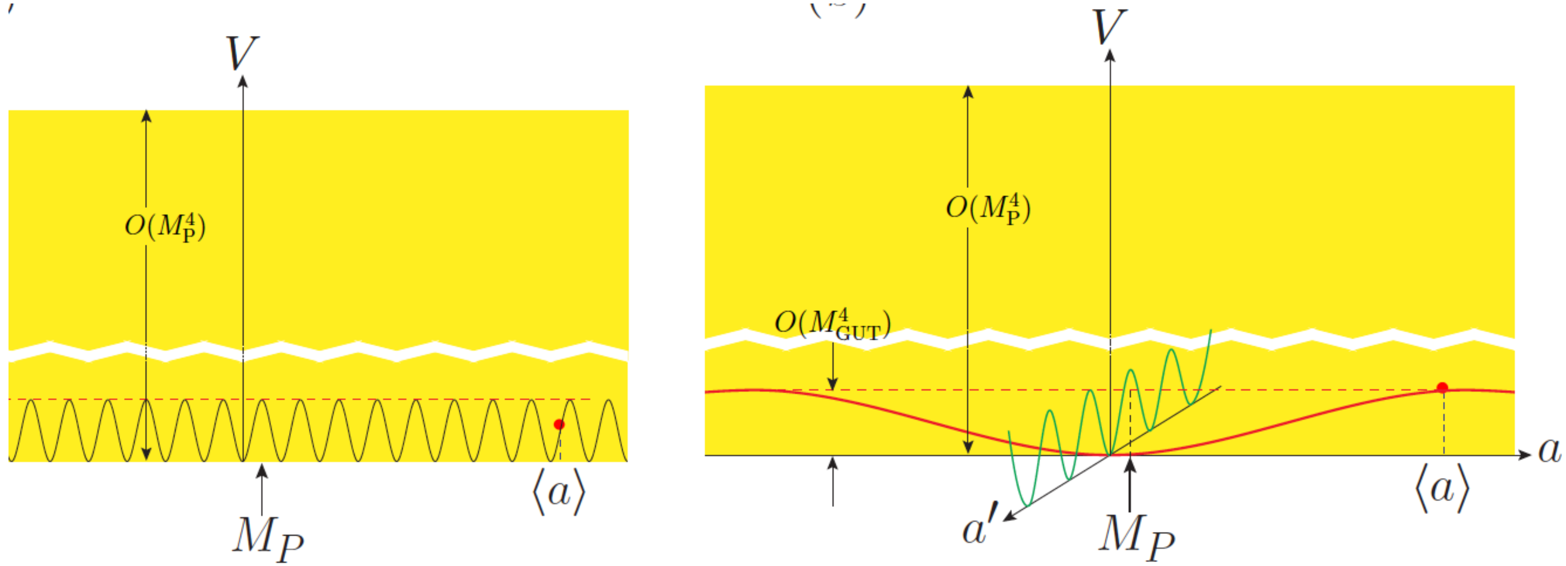
Natural inflation starting at π is here. Freese-Kinney: 1403.5277.

Natural inflation starting at 0 is here.



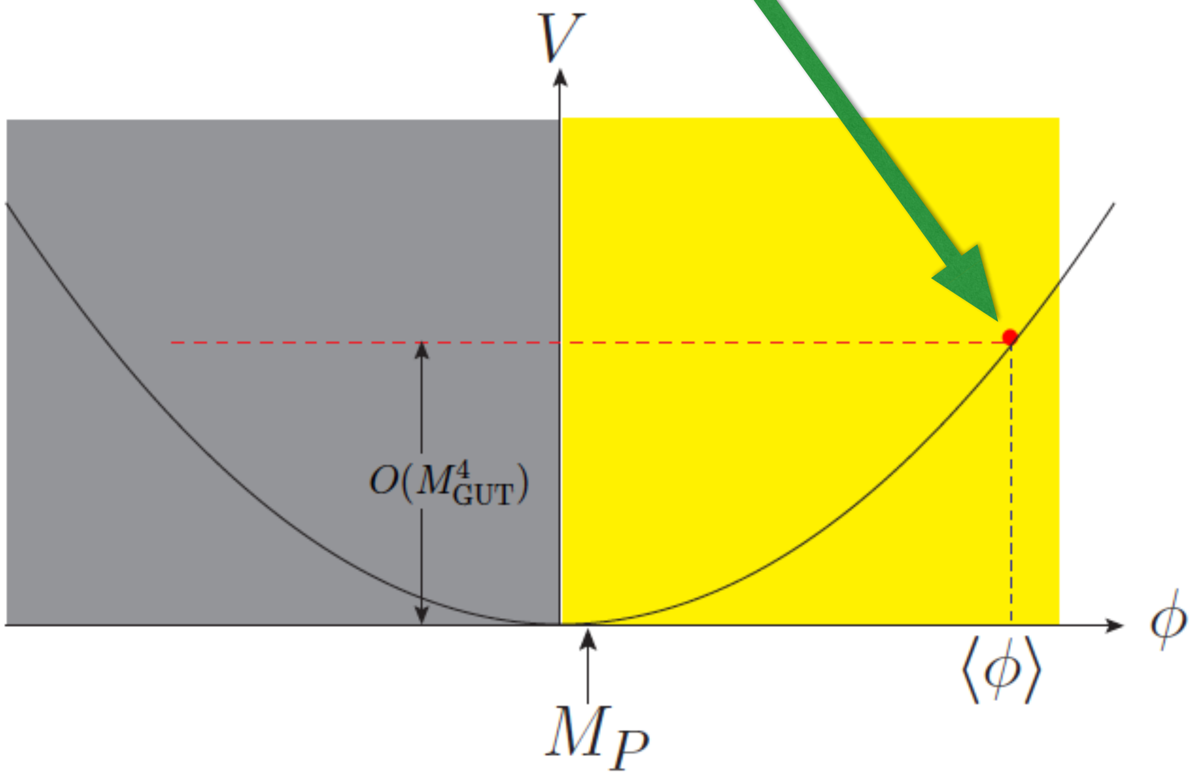
chaotic inflation with $m^2\phi^2$ [140].

What happens here for higher order terms?



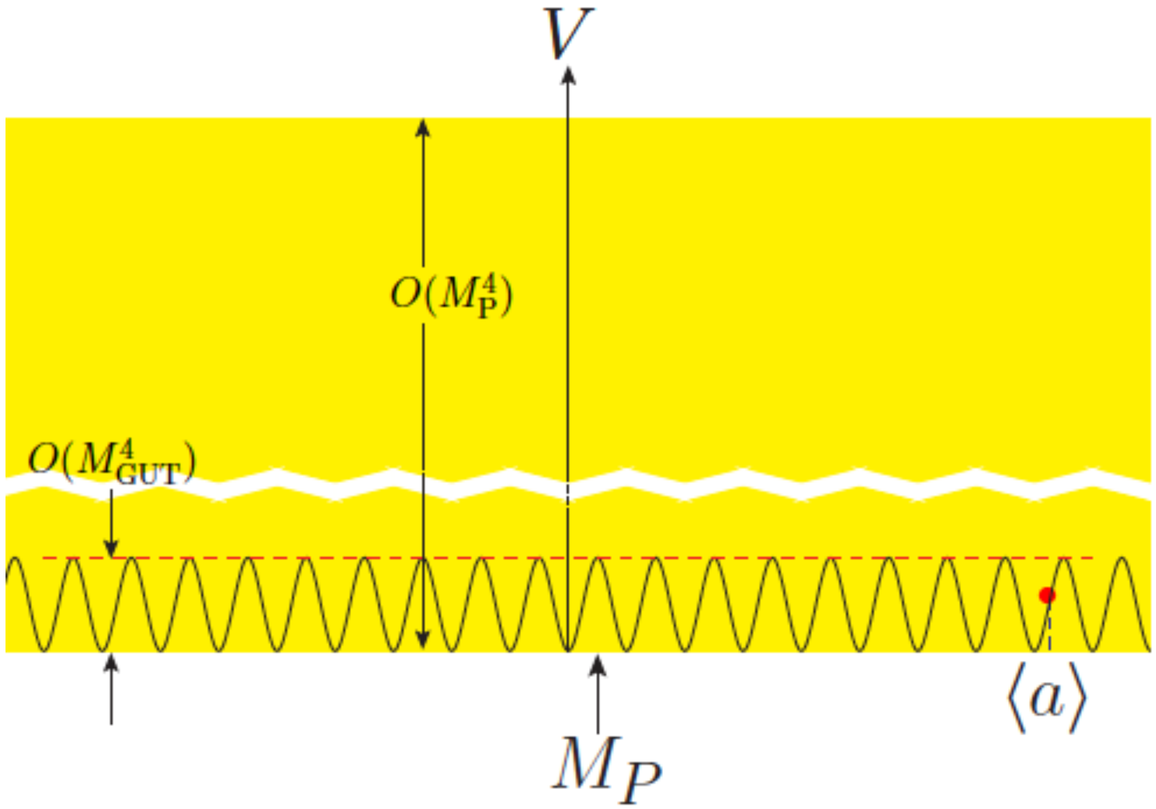
The natural inflation of [148]; (b) The KNP inflation [149].

Linde's chaotic inflation
needs a large field value
Lyth bound: > 15 M_P



Natural inflation suggested:

[Freese-Frieman-Orlino]



$$V = \Lambda_{GUT}^4 \left(1 - \cos\frac{a_N}{f_N}\right).$$

Freese-Frieman-Orlinto (1990)

Decay constant f can be determined by radial component

$$V = \frac{1}{4}\lambda(|\phi|^2 - f^2)^2.$$

10^{-6} for trans-Planckian

Then, it is the hill top inflation.

So, the radial field must roll down the hill quickly: not inflaton

If we stick to a single field inflation, the hilltop inflation is almost ruled out.

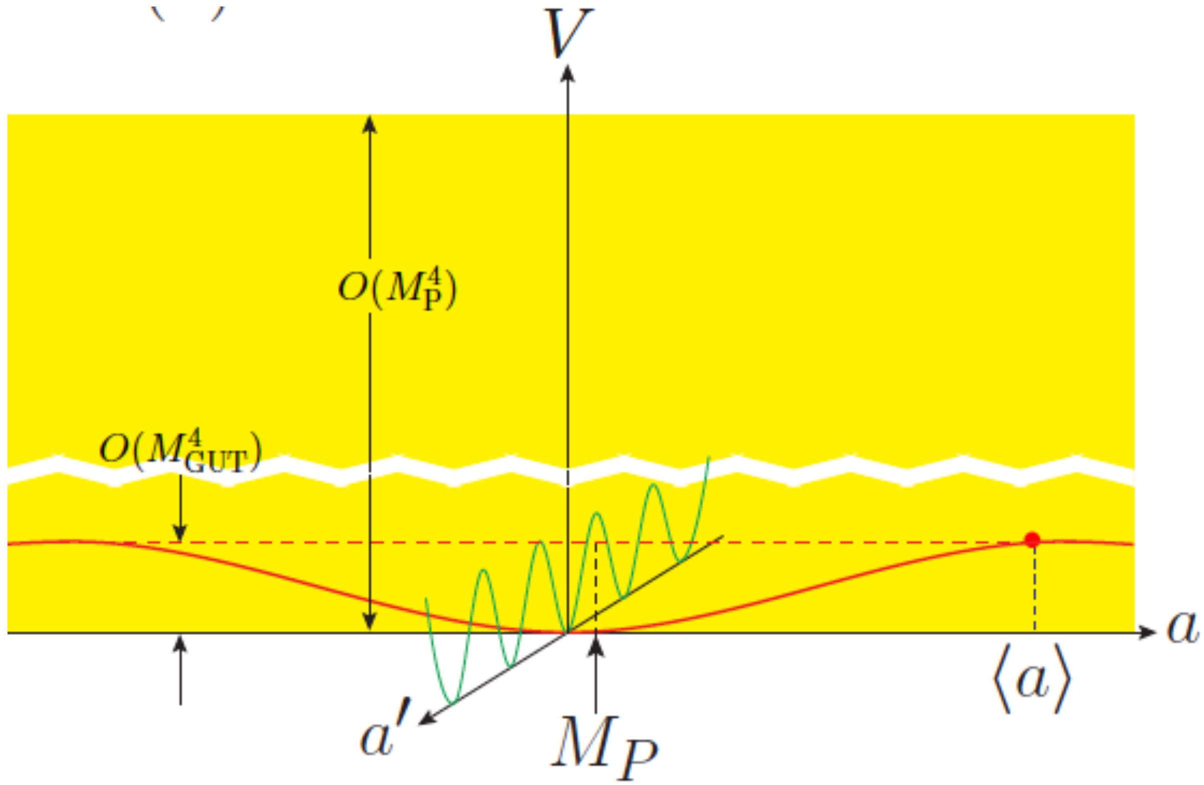
$$V(\phi) = \ell^4 \times \begin{cases} \left(\phi^2 - f_{\mathrm{DE}}^2\right) - m^4 \\ \cos^s\phi \qquad s = \mathrm{even} \end{cases}$$

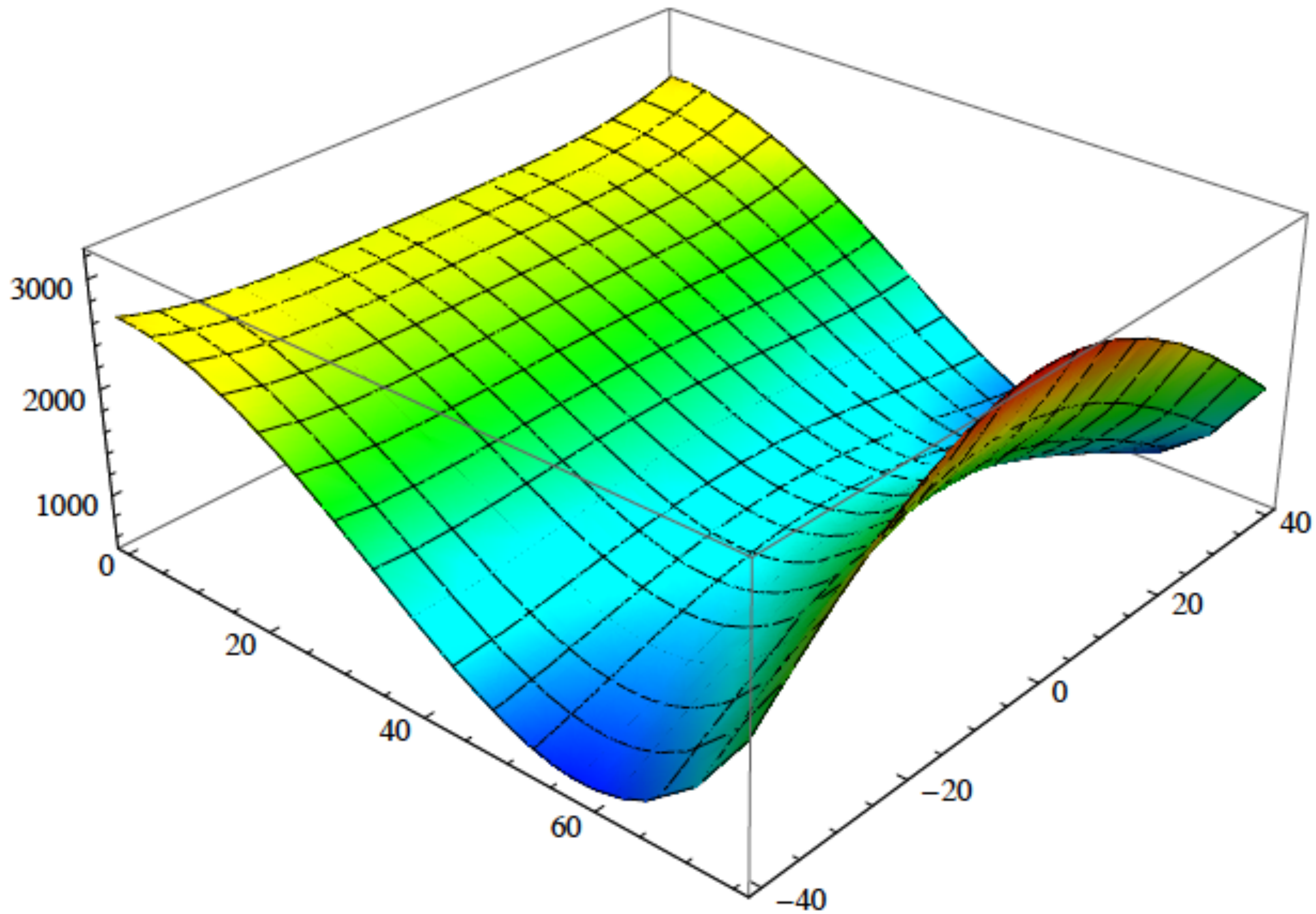
$$n_s = 1 + \Delta n_s = 1 - \left[\frac{r}{8} + \frac{1}{20s} + 2s\right] \le 1 - \left[\frac{r}{8} + \sqrt{\frac{r}{2}}\right]$$

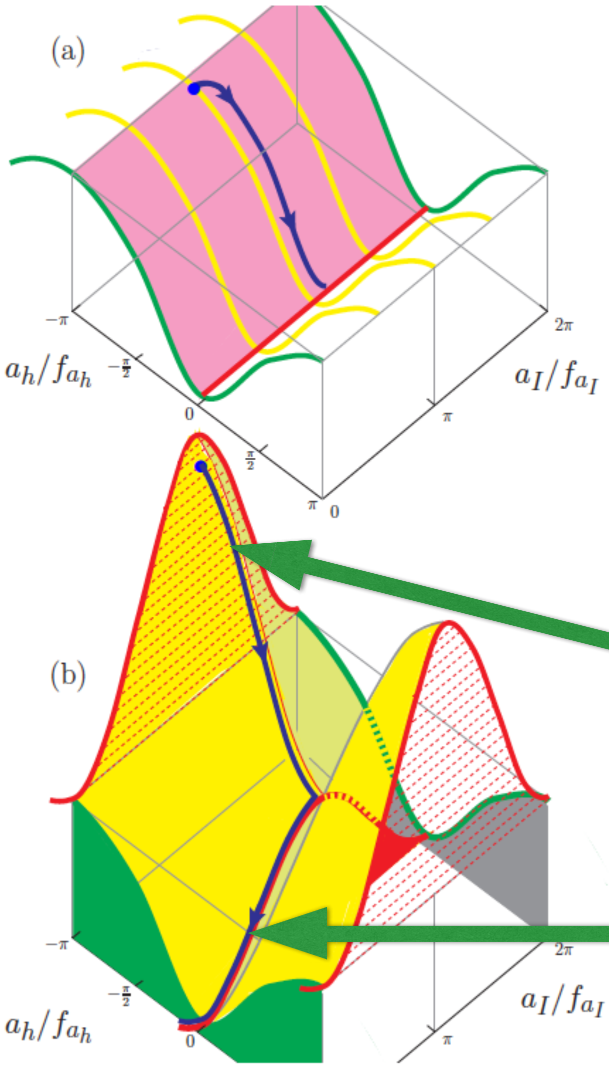
→ [0.96, 0.008]♪

2-flation suggested:

[Kim-Nilles-Peloso]



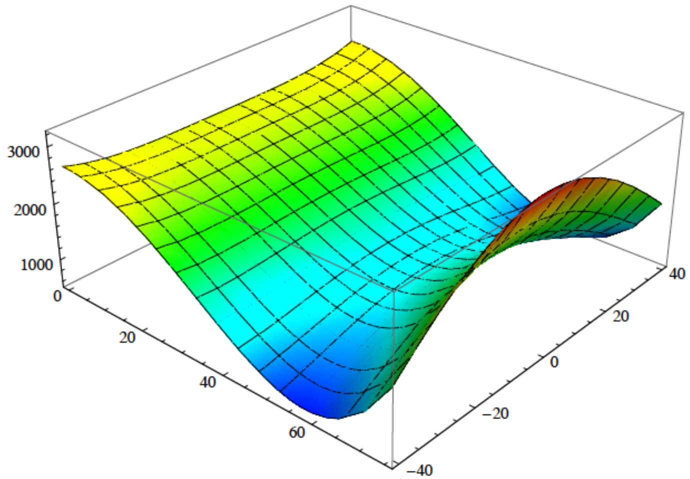

3000
2000
1000
0
20
40
60
40
20
0
−20
−40



So, the radial field must roll down the hill quickly: not inflaton

Then inflatons are angle fields: pseudoscalars

Two angle 2-flation with 2 confining forces: K-Nilles-Peloso (2005)

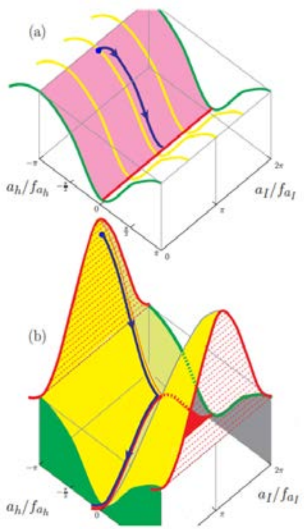


ickly.

wly:

What is the number of confining groups?

Rank: 16-4=12, 4+4+4
So, N-flation not likely.



What is the 2-flation condition?

$$V = \Lambda_1^4 \left(1 - \cos\left[\alpha \frac{a_1}{f_1} + \beta \frac{a_2}{f_2})\right]\right) + \Lambda_2^4 \left(1 - \cos\left[\gamma \frac{a_1}{f_1} + \delta \frac{a_2}{f_2})\right]\right).$$

$$M^2 = \begin{pmatrix} \frac{1}{f_1^2}\left(\alpha^2\Lambda_1^4 + \gamma^2\Lambda_2^4\right), & \frac{1}{f_1 f_2}(\alpha\beta\Lambda_1^4 + \gamma\delta\Lambda_2^4) \\ \frac{1}{f_1 f_2}(\alpha\beta\Lambda_1^4 + \gamma\delta\Lambda_2^4), & \frac{1}{f_2^2}(\beta^2\Lambda_1^4 + \delta^2\Lambda_2^4) \end{pmatrix}.$$

$$M^2 = \begin{pmatrix} \frac{1}{f_1^2}\left(\alpha^2\Lambda_1^4 + \gamma^2\Lambda_2^4\right), & \frac{1}{f_1 f_2}(\alpha\beta\Lambda_1^4 + \gamma\delta\Lambda_2^4) \\ \frac{1}{f_1 f_2}(\alpha\beta\Lambda_1^4 + \gamma\delta\Lambda_2^4), & \frac{1}{f_2^2}(\beta^2\Lambda_1^4 + \delta^2\Lambda_2^4) \end{pmatrix}.$$

$$m_h^2 = \frac{1}{2}(A+B),$$
$$m_l^2 = \frac{1}{2}(A-B),$$

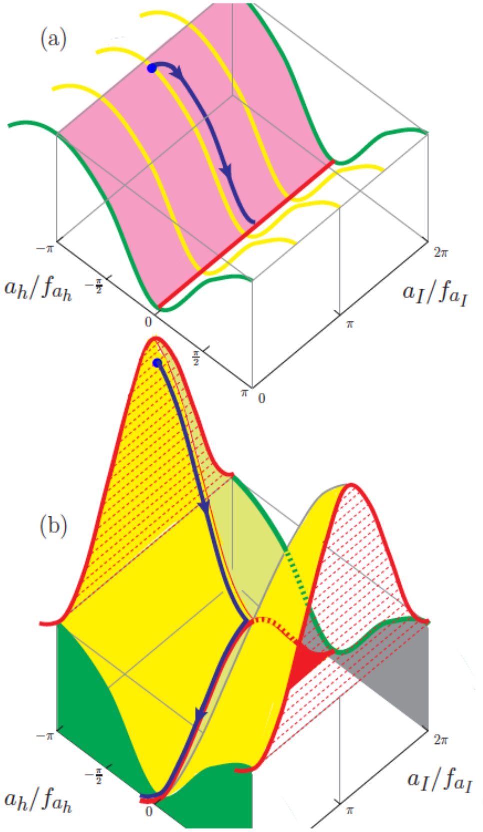
$$A = \left(\frac{\alpha^2\Lambda_1^4 + \gamma^2\Lambda_2^4}{f_1^2} + \frac{\beta^2\Lambda_1^4 + \delta^2\Lambda_2^4}{f_2^2}\right),$$

for $\alpha\delta = \beta\gamma + \Delta$

$$B = \sqrt{\left(\frac{\alpha^2\Lambda_1^4 + \gamma^2\Lambda_2^4}{f_1^2} + \frac{\beta^2\Lambda_1^4 + \delta^2\Lambda_2^4}{f_2^2}\right)^2 - 4(\alpha\delta - \beta\gamma)^2\frac{\Lambda_1^4\Lambda_2^4}{f_1^2 f_2^2}}.$$

$$m_{a_h}^2 \simeq (\alpha^2 + \beta^2 + \gamma^2 + \delta^2)\frac{\Lambda^4}{f^2},$$
$$m_{a_l}^2 \simeq \frac{\Lambda^4}{(\alpha^2 + \beta^2 + \gamma^2 + \delta^2) f^2/\Delta^2}.$$

← Very large decay constant possible.



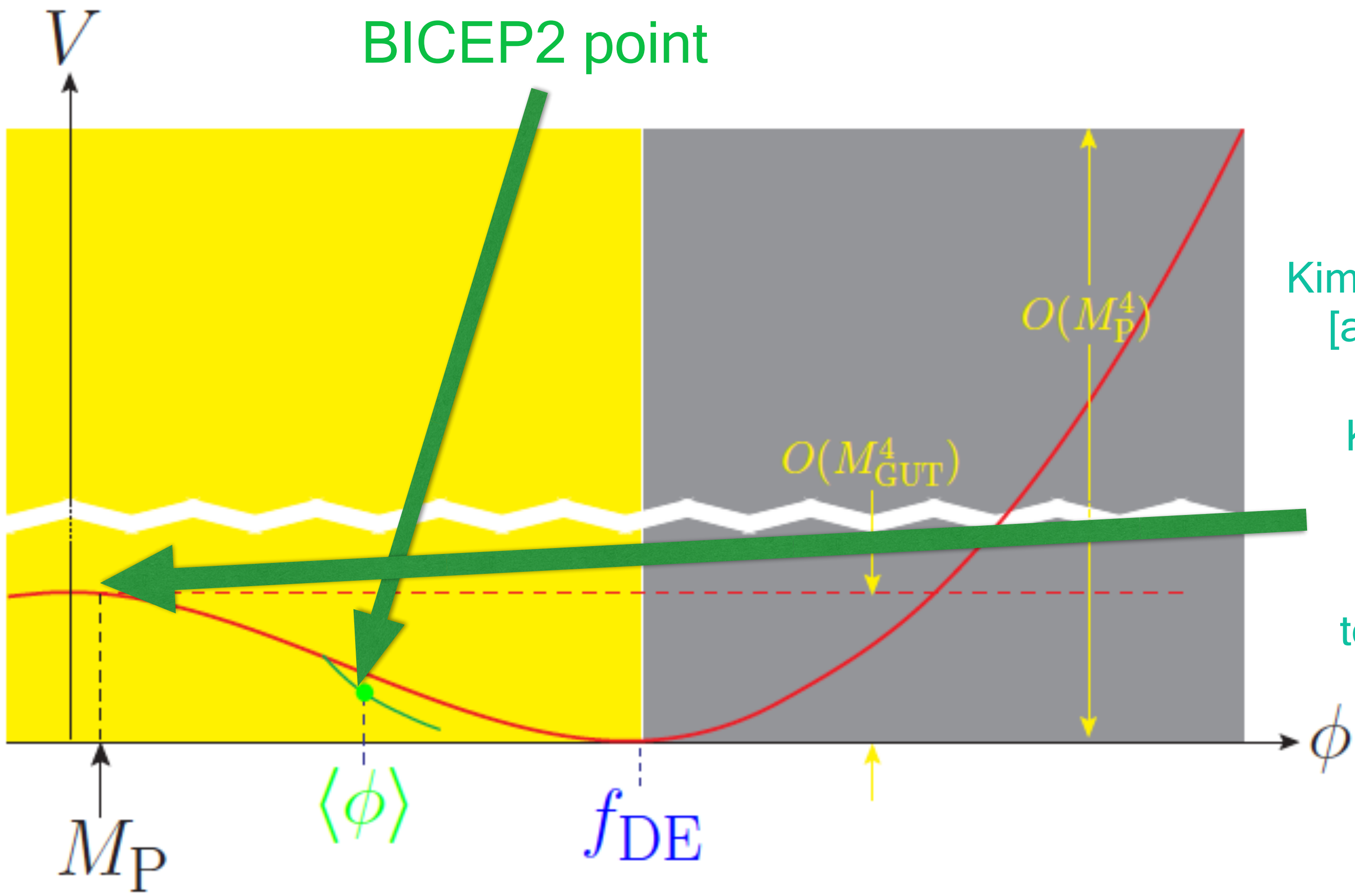
PQ quantum numbers
Delta=1
alpha=50

Prob.=1/2500?

[Choi-Kim-Kyae, front. phys. 2 (2015) 83 [1410.1762]]

$$f_{a_I} = \frac{\sqrt{\alpha^2+\beta^2+\gamma^2+\delta^2} f}{\Delta}.$$

- Let us go back to the hilltop inflation.



Kim, PLB737 (2014) 1
[arXiv:1404.4022]

Kim-Mo, computer search, starting from the hilltop to BICEP2, and to the inflation end.

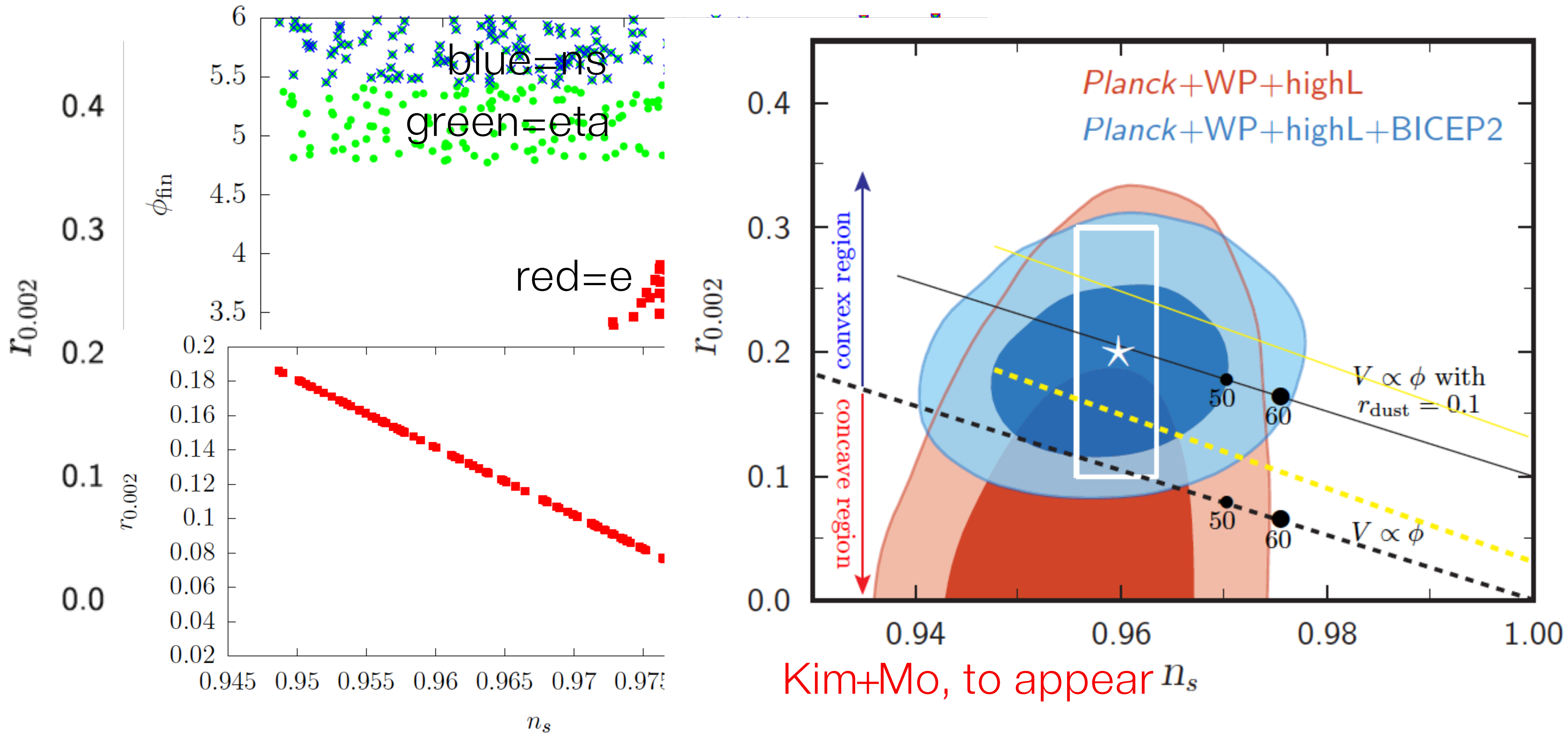
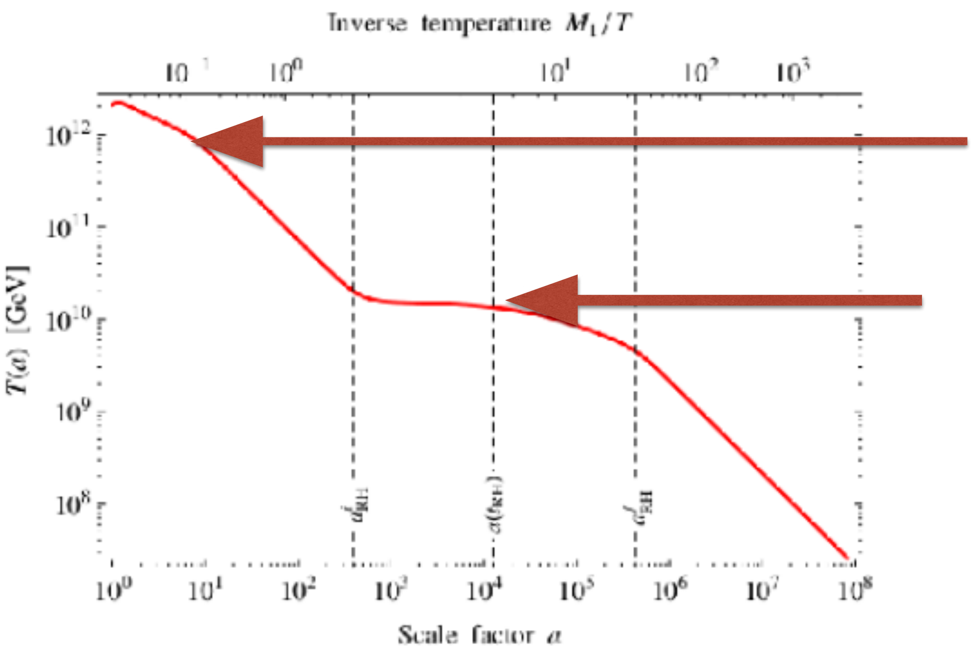


FIG. 4: The yellow curves for the e-fold numbers between 50–60 with parameters of Eq. (1) from data points of Fig. 3. Th

6. PQ symmetry breaking below H_I

With the GUT scale energy density for inflation, the reheat temperature after inflation is most likely, no more less than 1/100 times the hubble parameter.



W. Buchmueller et al., 1309.7788

$$H_I \simeq 10^{14}\ \text{GeV}$$

$$T_{\text{rh}} \simeq\simeq 10^{12}\ \text{GeV}$$

Probably, this is the most significant implication of BICEP2 result on axion physics, with DW number 1:

Vissineli-Gondolo, 1403.4594.
Marsh et al, 1403.4216. 71 micro-eV???

But, it needs a calculation of axions from the system of string-domain walls.

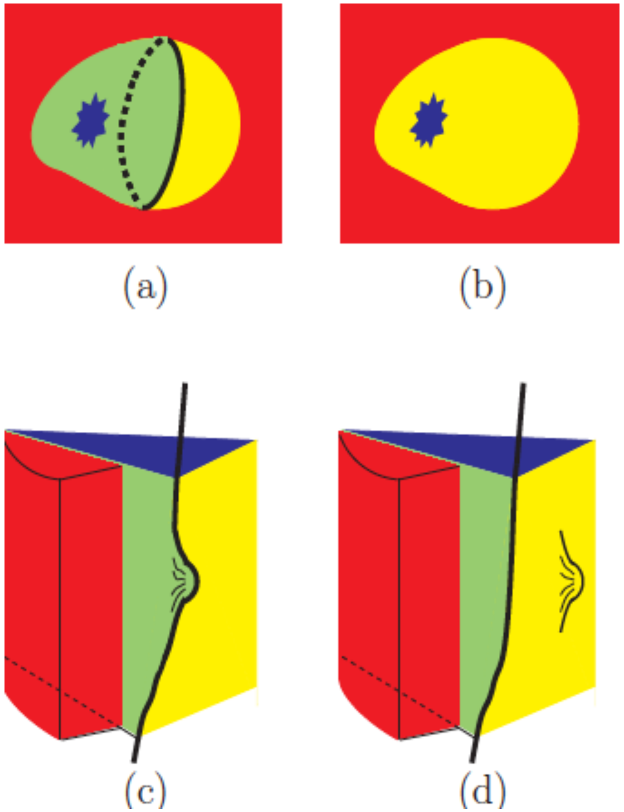
Florida group: 1
Cambridge group: O(100-1000)

Tokyo group: 25 ← This number is used

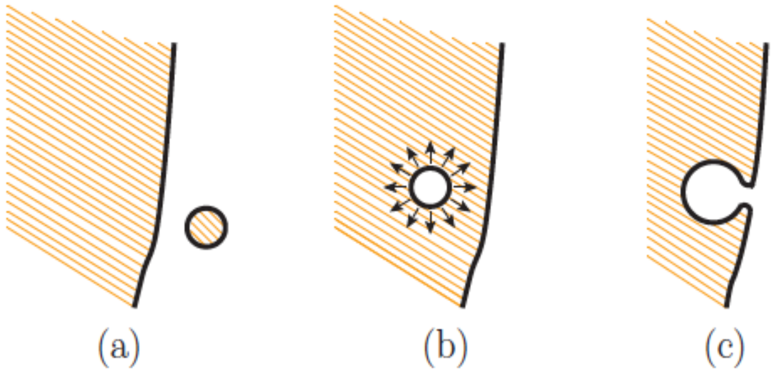
Small string-DW are not problematic.

The horizon scale string-DW
system is problematic.

Barr-Kim, to appear in PRL.



Sikivie (1982)



Vilenkin-Everett (1982);
Barr-Choi-Kim (1987)

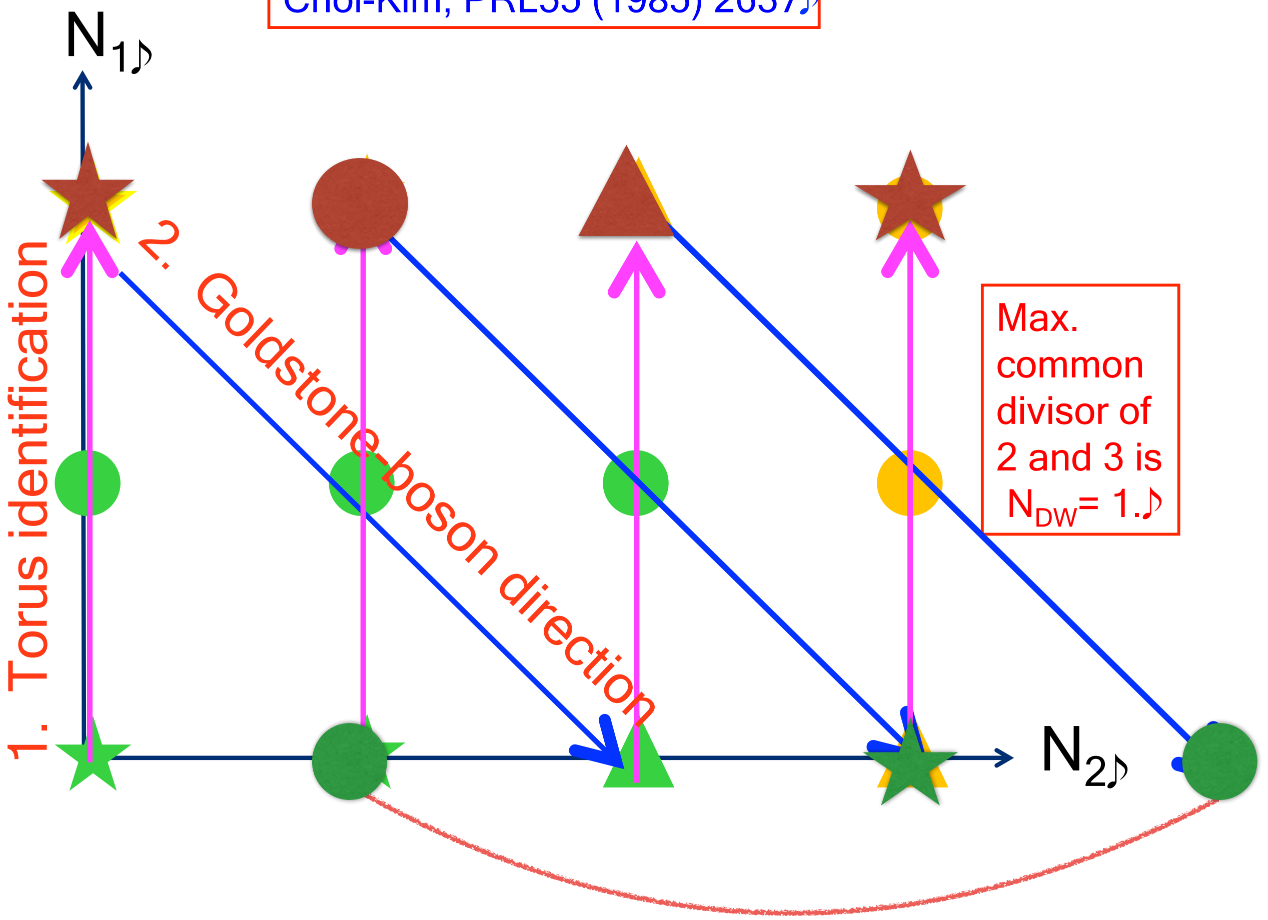
Top-down approach, using string compactification

1. Anomalous U(1) gauge symmetry.
2. Anomalous U(1) becomes global U(1) below the GUT scale.
3. The global U(1) is broken at the axion window.
4. DW number here. By giving a VEV to NPQ=1 field, we obtain NDW=1.
5. Choi-Kim mechanism.

For this we need a Goldstone boson direction

Choi-Kim mechanism

Choi-Kim, PRL55 (1985) 2637



8. Conclusion

1. With discrete symmetry. / BCM: Discrete symmetry is the key.

2. DE by QCD axion. / With BCM includes QCD axion.

3. The strong CP problem is solved and the very light axion provides some CDM component.

Applied to high scale inflation

4. High scale inflation needs NDW=1

5. Possible in string comp. with anomalous U(1)

6. CAPP may get an answer to axion in the micro- to milli-eV range. in string comp. even with 10% of CDM