Inflation from a supersymmetric axion model

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COSMO/CosPA2010 2010/9/27@University of Tokyo

M.Kawasaki, N.Kitajima, KN, arXiv:1008.5013

Problems in the SM

- Hierarchy Problem

  Why is the Higgs so light ? $m_h \sim O(100)\mathrm{GeV}$

- Strong CP Problem $\mathcal{L}_\theta = \frac{\theta g_s^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{\mu\nu a}$

  Why does QCD conserve CP? $\theta < 10^{-9}$

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→ Supersymmetric axion model

SUSY axion model also explains inflation and dark matter in the Universe

Strong CP problem & PQ mechanism

Nonperturbative effect in QCD

$$\mathcal{L}_\theta = \frac{\theta g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{\mu\nu a}$$

CP violating term

contribute to neutron Electric Dipole Moment

→ Experimental bound : $\theta < 10^{-9}$

Strong CP problem

Solution : Anomalous U(1)symmetry (PQ symmetry)

Peccei, Quinn (77)

PQ symmetry breaking scale F_a

Pseudo-Nambu-Goldstone boson a : Axion

$$\rightarrow \mathcal{L}_\theta = \frac{g_s^2}{32\pi^2}\left(\underbrace{\theta - \frac{a}{F_a}}_{\to 0}\right) G^a_{\mu\nu} \tilde{G}^{\mu\nu a}$$

Dynamical Cancellation

SUSY axion model

- Superpotential

$$\boxed{W = \kappa S(\Psi\bar{\Psi} - f_a^2)}$$

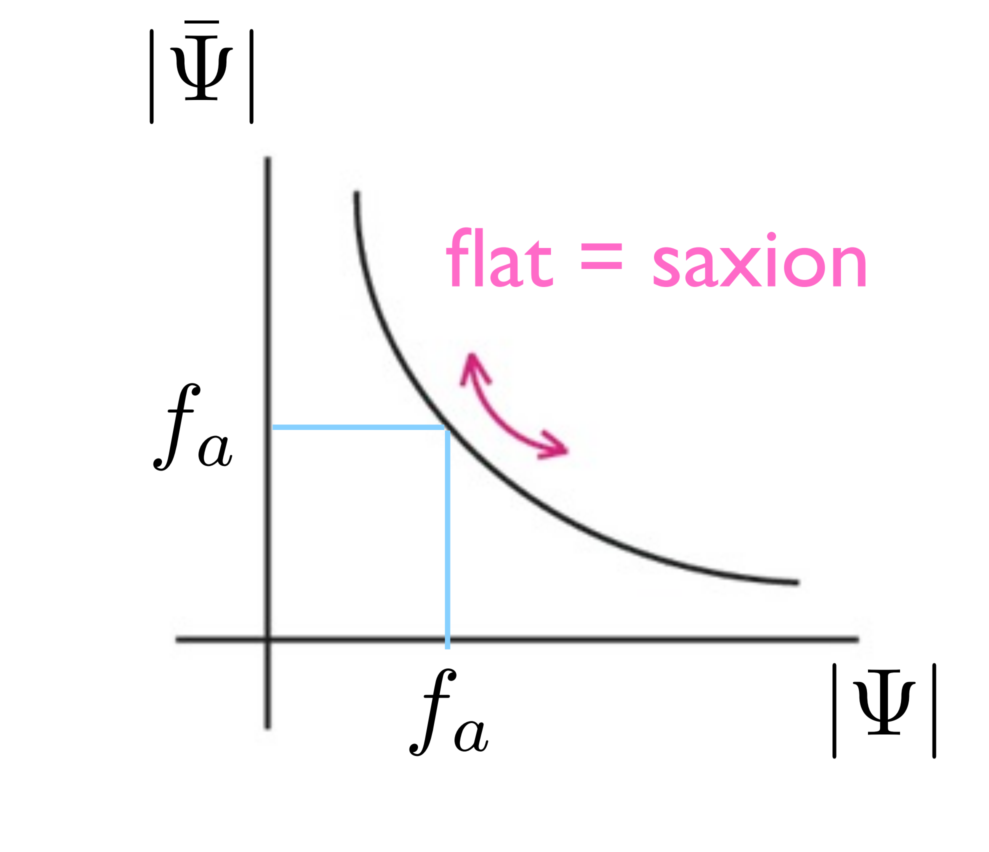
$$\mathrm{PQ} \ : \ \Psi(1), \bar{\Psi}(-1), S(0)$$

$$V = m_{3/2}^2 \left(c|S|^2 + c_1|\Psi|^2 + c_2|\bar{\Psi}|^2\right)$$
$$+|\kappa|^2 \left\{|\Psi\bar{\Psi} - f_a^2|^2 + |S|^2 \left(|\Psi|^2 + |\bar{\Psi}|^2\right)\right\}$$

$\longrightarrow$ Saxion direction : $\Psi\bar{\Psi} = f_a^2$

Saxion mass : $m_s \sim m_{3/2}$

Minimum at $|\Psi| \sim |\bar{\Psi}| \sim f_a$



Break PQ $\longrightarrow$ Solve strong CP

SUSY axion model

- Superpotential

$$\boxed{W = \kappa S(\Psi\bar{\Psi} - f_a^2)}$$

PQ : $\Psi(1), \bar{\Psi}(-1), S(0)$

This is same as hybrid inflation form!

Copeland et al. (1994),
G.R.Dvali, Q.Shafi, R.K.Schaefer (1994)

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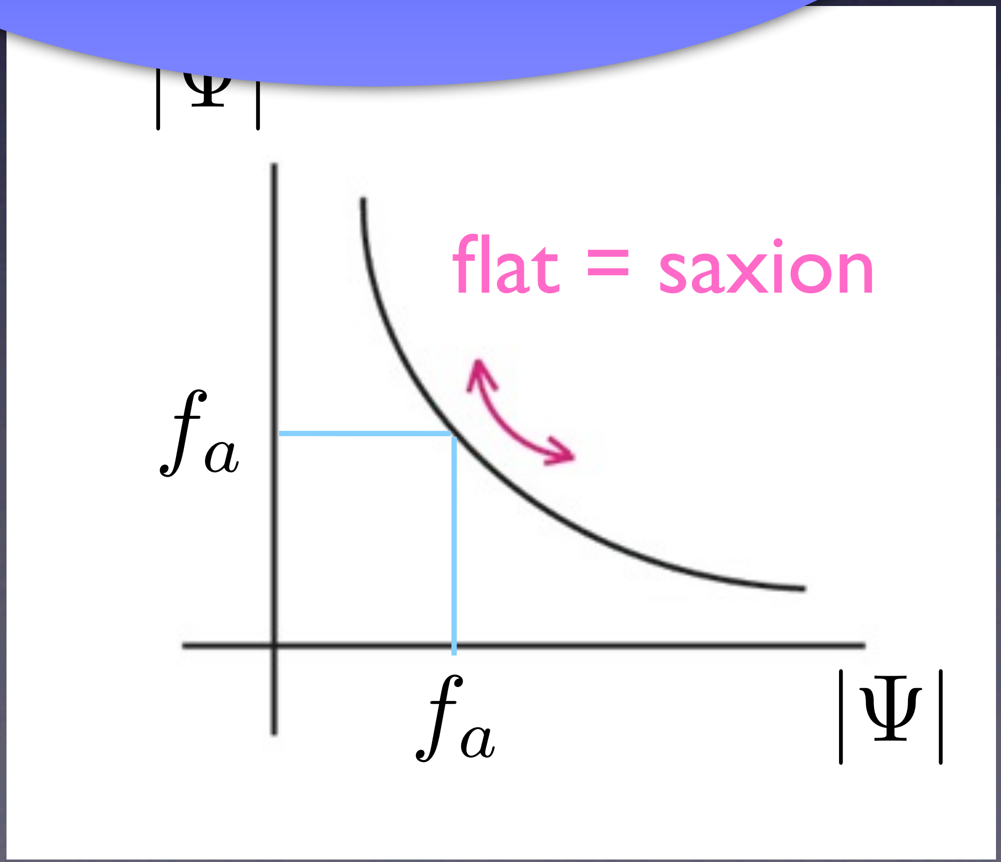


Break PQ $\longrightarrow$ Solve strong CP

Hybrid inflation from SUSY axion

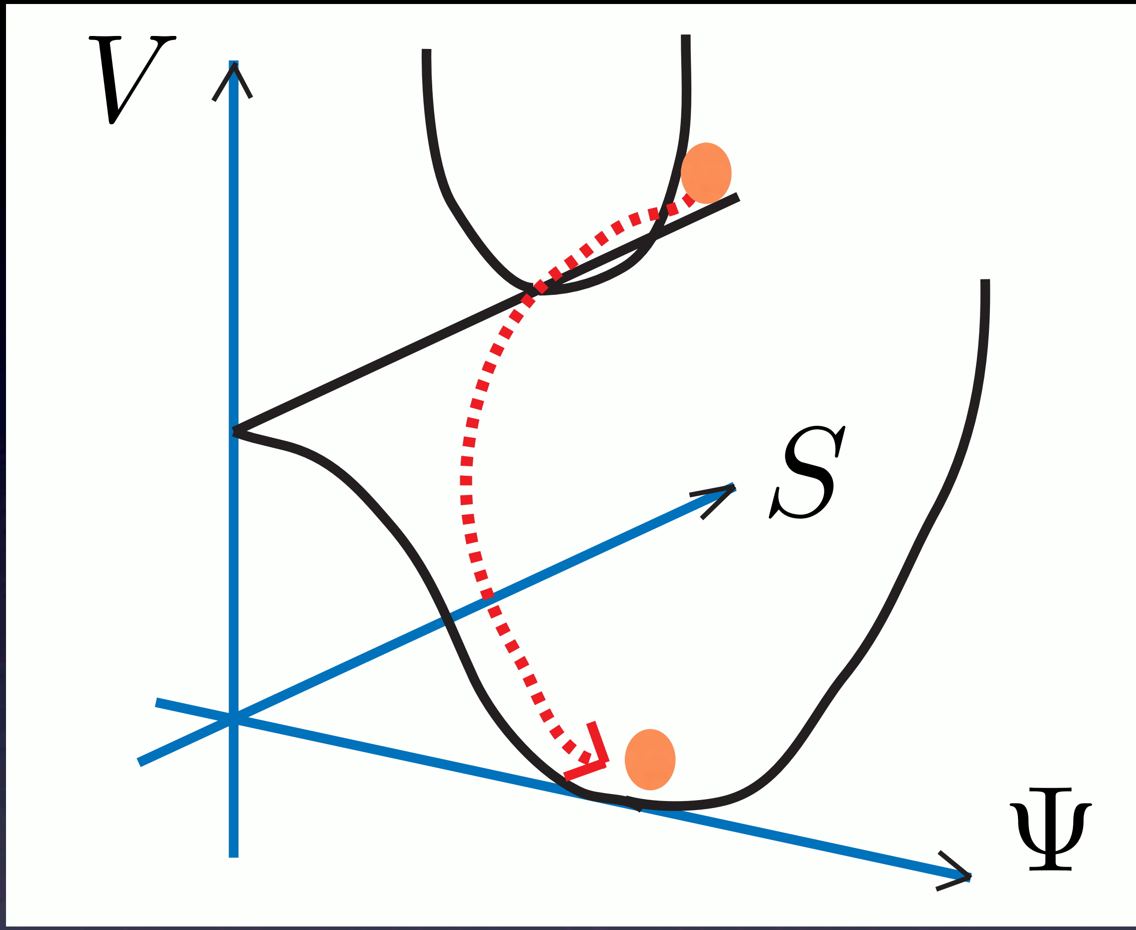
M.Kawasaki, N.Kitajima, KN, arXiv:1008.5013

- Superpotential

$$W = \kappa S(\Psi\bar{\Psi} - f_a^2)$$

S : inflaton

Ψ : water fall field



- Scalar potential

$$V = \kappa^2|\Psi\bar{\Psi} - f_a^2|^2 + \kappa^2|S|^2(|\Psi|^2 + |\bar{\Psi}|^2)$$

$S > f_a$: flat potential $\longrightarrow$ inflation

$S < f_a$: waterfall $\longrightarrow$ inflation ends

SUSY axion model naturally induces inflation !

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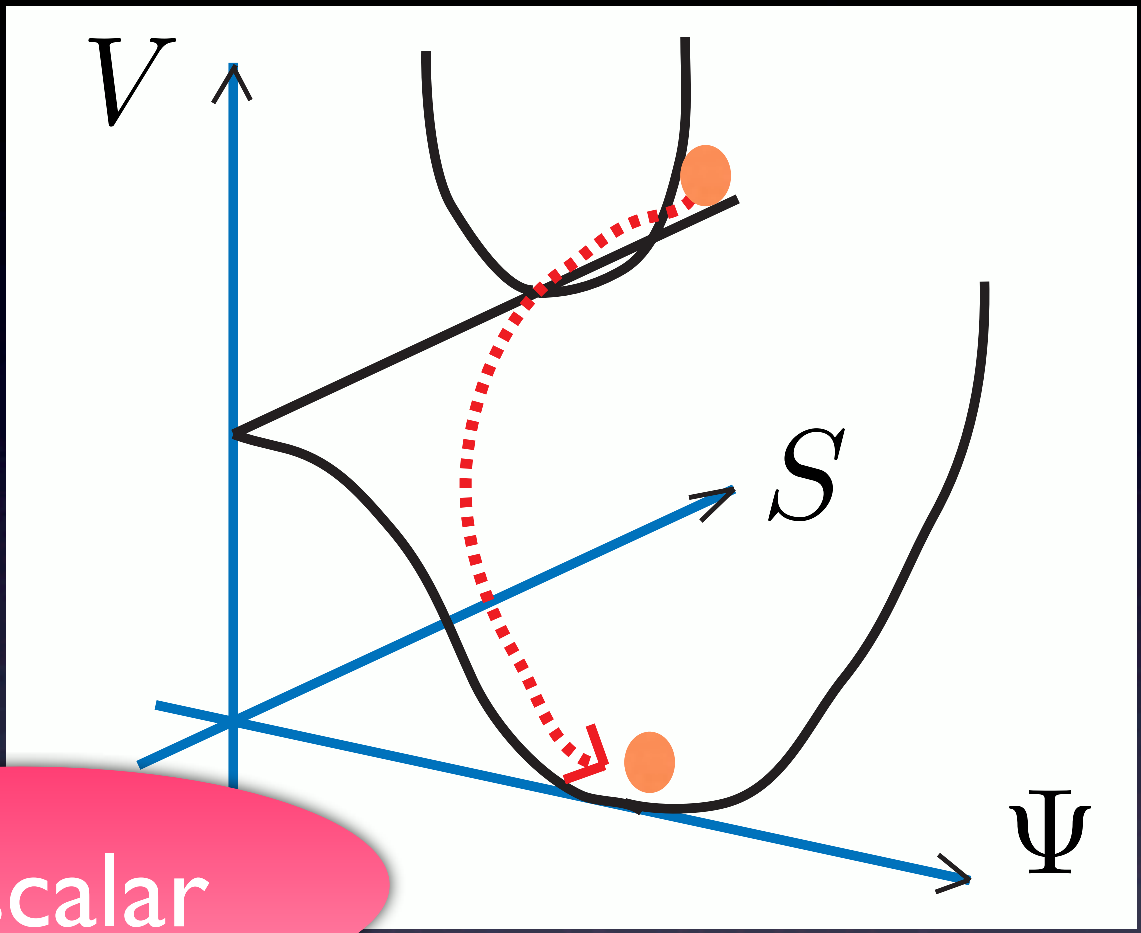

PQ scalar

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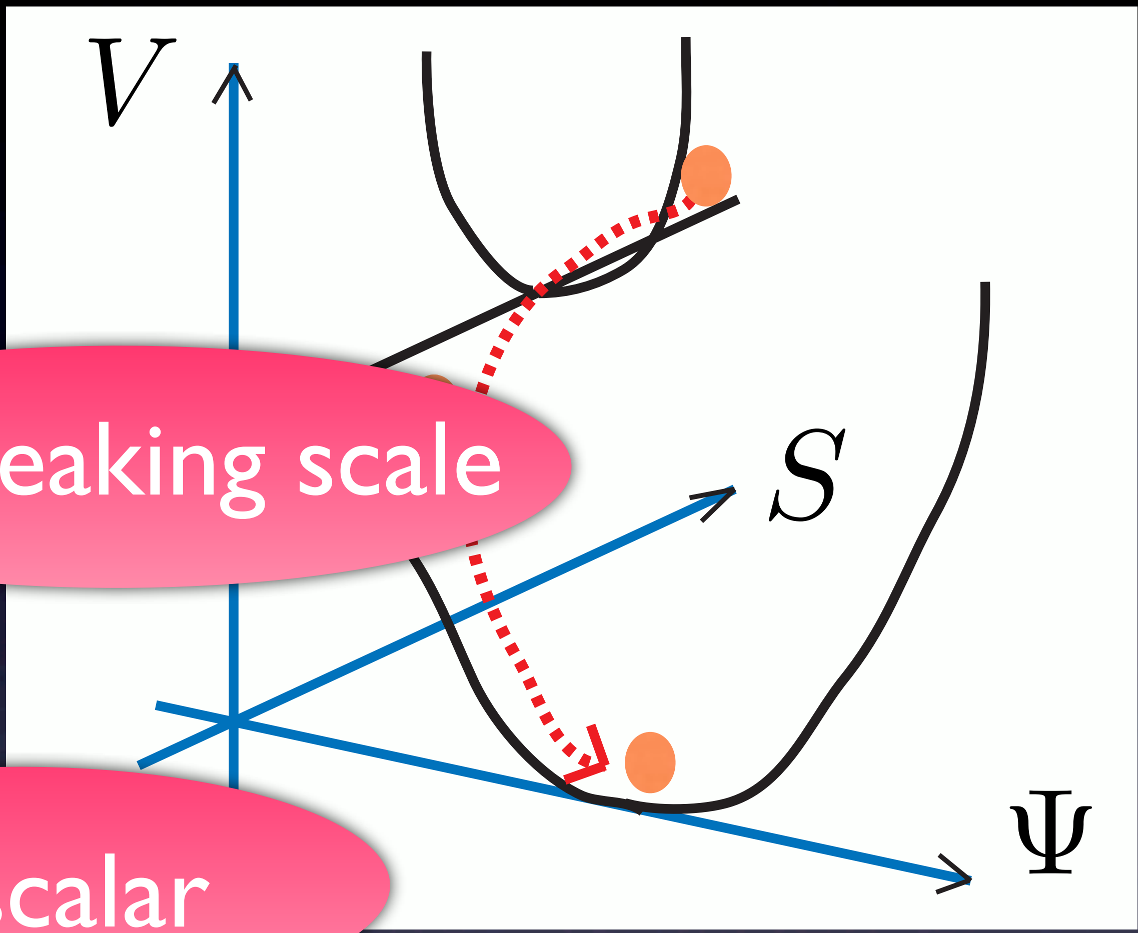
PQ breaking scale

S : inflaton

$\boxed{\Psi \ : \ \text{water fall field}}$

PQ scalar



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Kahler & super potential

constant term to make c.c. zero

$$K = |S|^2 + k_1 \frac{|S|^4}{2M_P^2} \qquad W = \kappa S(\Psi\bar{\Psi} - f_a^2) + W_0$$

Scalar potential in supergravity

$$W_0 = m_{3/2} M_P^2$$

$$V_{\rm SUGRA} \simeq \kappa^2 f_a^4 \left[1 - k_1 \frac{|S|^2}{2M_P^2} + \frac{|S|^4}{8M_P^4}\right], +2\kappa m_{3/2} f_a^2 (S + S^*)$$

Coleman-Weinberg potential

fermion : $M_\Psi^2 = \kappa^2 |S|^2$

boson : $M_{\tilde{\Psi}}^2 = \kappa^2 |S|^2 \pm \kappa^2 f_a^2$

$$\rightarrow \quad V_{\rm CW} \simeq \frac{\kappa^4 f_a^4}{16\pi^2} \log \frac{|S|^2}{\Lambda^2}$$

WMAP normalization : $f_a \sim 10^{15} \mathrm{GeV} \quad \kappa \sim 10^{-3}$

Too large PQ scale ?

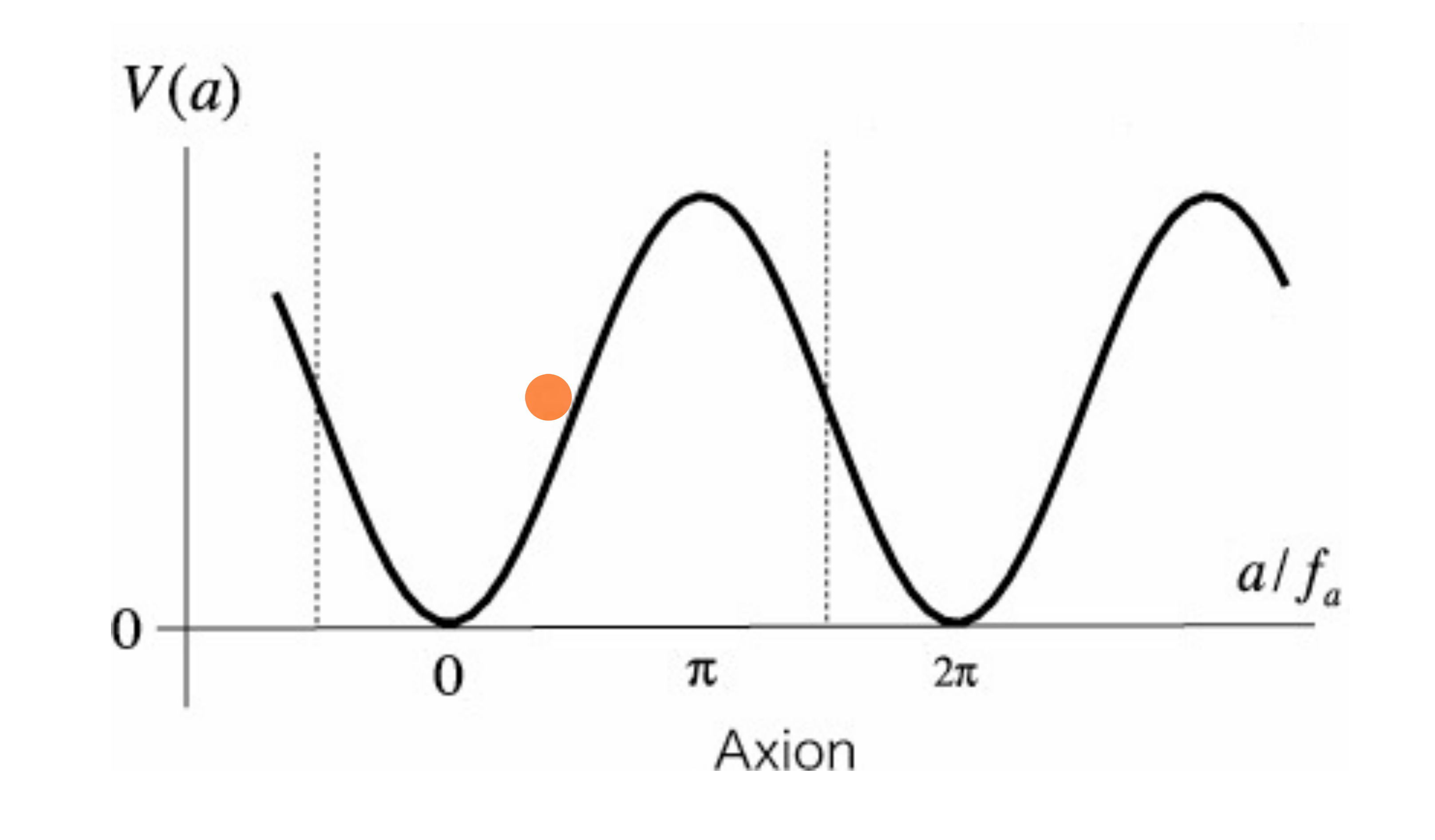
- WMAP normalization of density perturbation

$$\longrightarrow \quad f_a \sim 10^{15}\mathrm{GeV}$$

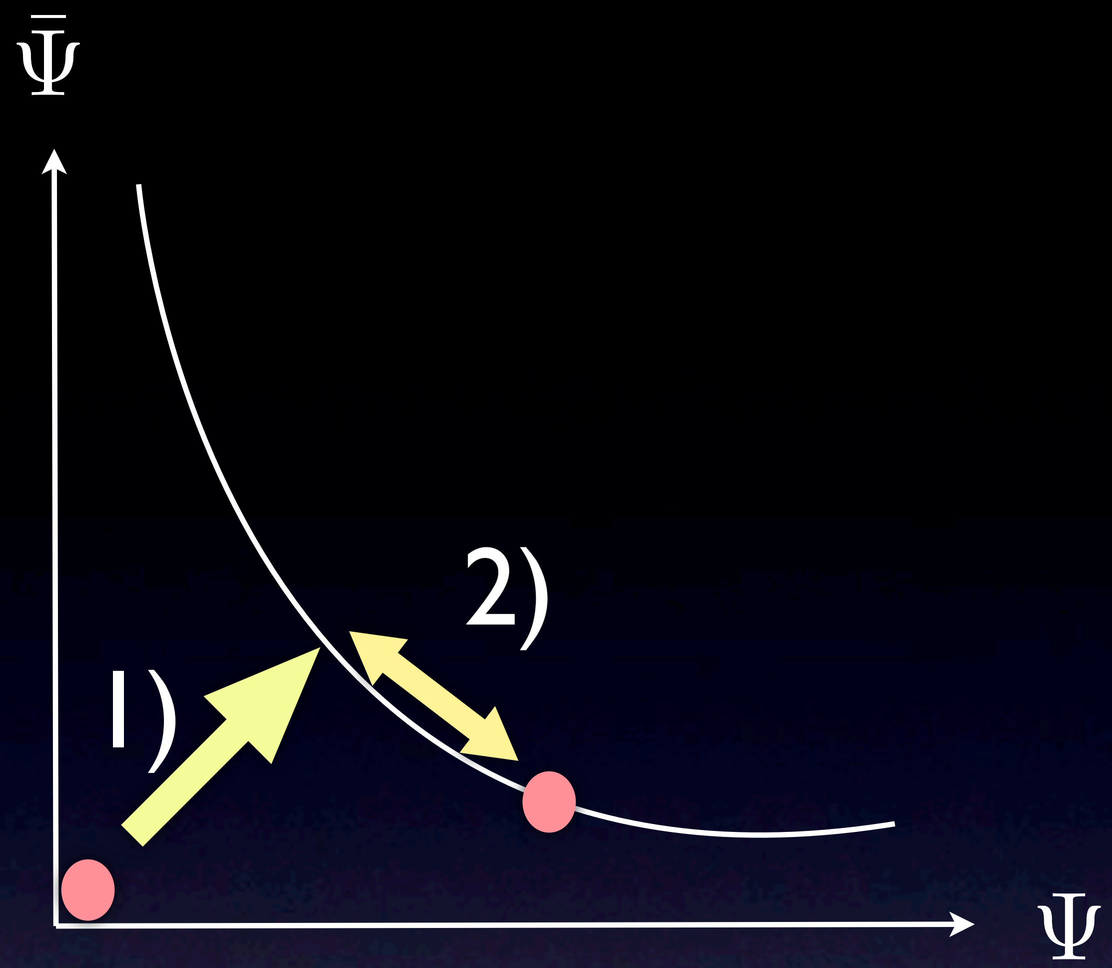
- After QCD phase transition, the axion begins to oscillate

The axion abundance : $\Omega_a h^2 \sim 0.2 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}} \right)^{1.18}$

$$\longrightarrow \quad f_a \lesssim 10^{12}\mathrm{GeV}$$



However, entropy production necessarily occurs and the axion is diluted



1) After inflation, massive modes oscillate and decay rapidly.

2) Well after that, flat direction (saxion) begins to oscillate and dominates the Universe.

3) Saxion decays and produces huge amount of entropy.

$$\Gamma(\sigma \to 2g) \sim \frac{\alpha_s^2}{32\pi^3}\frac{m_\sigma^3}{f_a^2}$$

$\Rightarrow$ $T_\sigma \sim 1\mathrm{MeV}\ \text{for}\ f_a = 10^{15}\mathrm{GeV}$

$$\Gamma(\sigma \to 2h) \sim \frac{1}{8\pi}\frac{m_\sigma^3}{f_a^2}$$

Axion is diluted and becomes DM.

$\Rightarrow$ Axion DM

$$\boxed{\Omega_a h^2 \sim 0.05 \left(\frac{T_\sigma}{1\mathrm{MeV}}\right)\left(\frac{f_a}{10^{15}\mathrm{GeV}}\right)^2}$$

Gravitino Problem

Gravitino decay after BBN and detroy light elements

→ Constraint on the gravitino abundance

(Khlopov, Linde (84), Ellis, Kim, Nanopoulos (84), Moroi, Murayama, Yamaguchi (93), Bolz, et al. (01))

- Thermal production

Scattering of particles in thermal bath

$$\frac{n_{3/2}}{s} \sim 2 \times 10^{-12} \left(1 + \frac{m_{\tilde{g}}^2}{3m_{3/2}^2}\right) \left(\frac{T_R}{10^{10}\mathrm{GeV}}\right).$$

- Nonthermal production

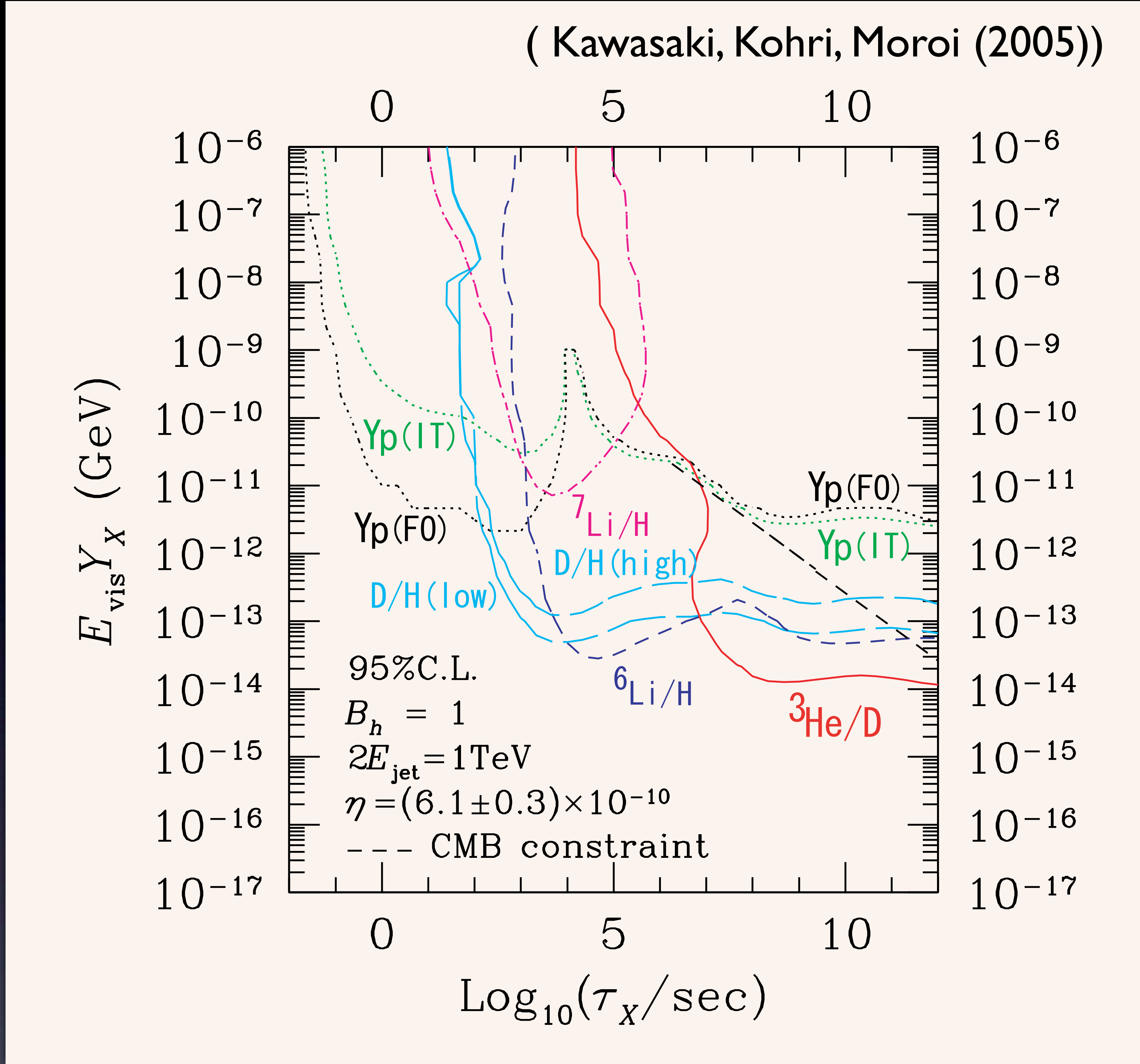
(Kawasaki, F. Takahashi, T. Yanagida (2006) Endo, F. Takahashi, Yanagida (2006))

Inflaton decay

$$\frac{n_{3/2}}{s} \sim 10^{-14} \left(\frac{T_\mathrm{R}}{10^{10}\mathrm{GeV}}\right)^{-1} \left(\frac{m_\phi}{10^{12}\mathrm{GeV}}\right)^2 \left(\frac{\langle\phi\rangle}{10^{15}\mathrm{GeV}}\right)^2,$$

Stringent constraint on the gravitino abundance from BBN

Gravitino problem



In this model, however, the saxion decay dilutes the gravitino

Dilution factor $\Delta \sim (T_R/T_\sigma) \sim 10^{10}$

→ Gravitino problem is automatically solved !

Comments

- Domain wall problem does not exist in the KSVZ axion model
- Cosmic strings disappear at QCD phase transition
- Axions from strings may be comparable to DM
- Scalar spectral index is around 0.96-0.98, well consistent with WMAP
- Tensor scalar ratio is small : $r \lesssim 10^{-10}$

Conclusion

- Supersymmetric axion model is well motivated from theoretical viewpoint.
- SUSY axion model naturally cause inflation
- PQ scale is determined $f_a \sim 10^{15}\mathrm{GeV}$
- It can explain dark matter (axion)
- Gravitino problem is solved
- (Almost) no free parameter

All of these are solved !

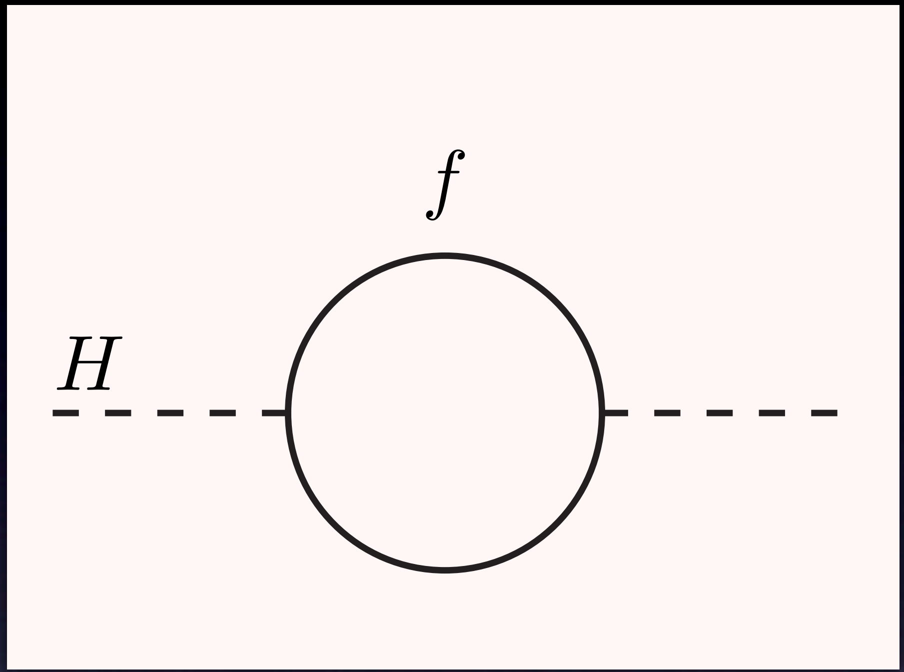
Strong CP problem, Hierarchy problem, Inflation,
Dark matter problem, Gravitino problem

Backup slides

Hierarchy problem

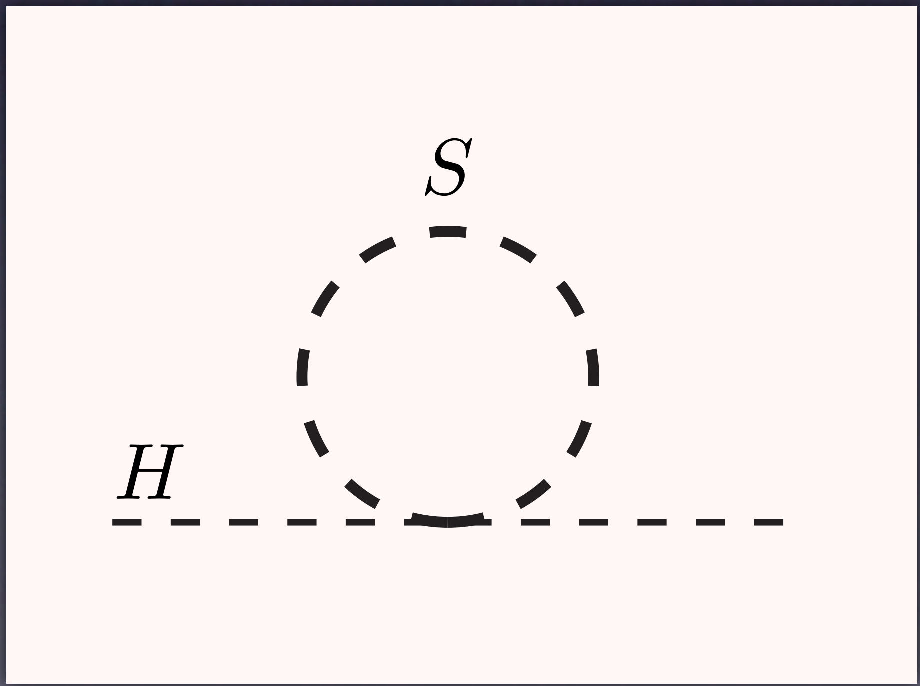
- Higgs boson mass $m_h \sim O(100)\mathrm{GeV}$
- Radiative correction :

$$m_h \sim \Lambda_{\mathrm{cut}} \sim 10^{16}\mathrm{GeV?}$$



Hierarchy problem

→ **Supersymmetry**



Dangerous radiative correction cancels out due to SUSY.

Strong CP problem

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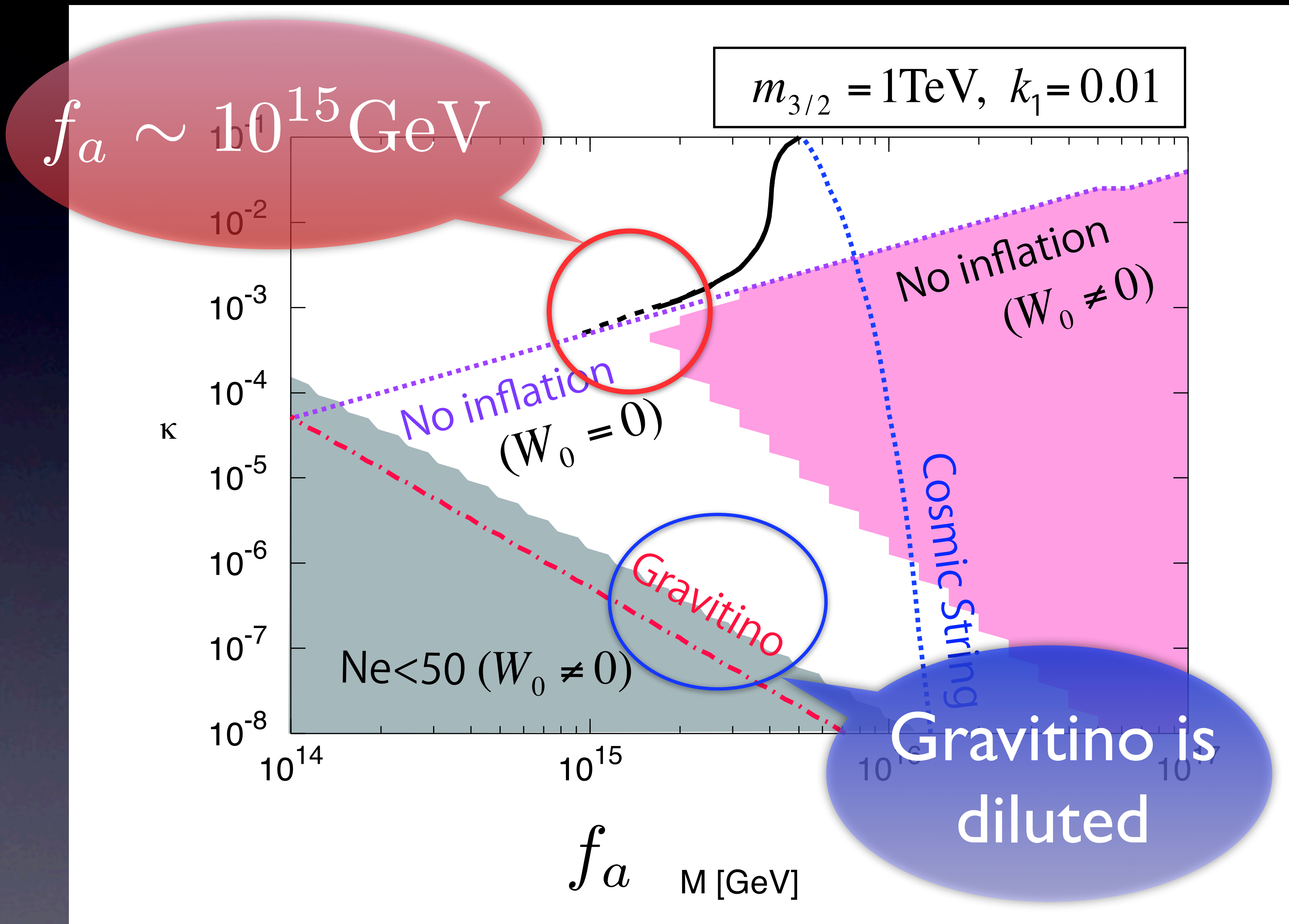
Dynamical Cancellation

2010年9月27日月曜日

Density perturbation



KN, F.Takahashi, T.Yanagida, 1007.5152

KSVZ vs DFSZ

- KSVZ axion $W = \kappa S(\Psi\bar{\Psi} - f_a^2) + \lambda\Psi Q\bar{Q}$

  J.E.Kim (79), Shifman, Vainshtein, Zakharov (80)

  No domain wall problem.

  Saxion decay $\sigma \to 2a$ must be suppressed.

- DFSZ axion $W = \kappa S(\Psi\bar{\Psi} - f_a^2) + \lambda\Psi H_u H_d$

  Dine, Fischler, Srednicki (81), Zhitnitski (80)

  Additional matters must be introduced for solving domain wall problem.

  Saxion decays into Higgses.

Inflaton decay & mu-term

- KSVZ axion $W = \kappa S(\Psi\bar{\Psi} - f_a^2) + \lambda\Psi Q\bar{Q} + \boxed{kSH_uH_d}$

PQ charge : $\Psi(+1),\ \bar{\Psi}(-1),\ Q(-1/2), \bar{Q}(-1/2)$

$$\Gamma(S \to H_uH_d) \simeq \frac{k^2}{8\pi} m_S \Rightarrow \boxed{T_R \sim 10^{11}\mathrm{GeV}}$$

(Note : $k \gtrsim \kappa$ for correct vacuum)

- A-term : $V_A \sim m_{3/2}\kappa f_a^2 S \longrightarrow \langle S \rangle \sim m_{3/2}/\kappa$

$\Rightarrow \boxed{\mu \sim m_{3/2} \sim 1\ \mathrm{TeV}}$ Solve mu problem!

Dvali, Lazarides, Shafi (1998)

Finite-temperature effect

- KSVZ axion $W = \kappa S(\Psi\bar{\Psi} - f_a^2) + \lambda \Psi Q\bar{Q}$

PQ scalar couples to heavy quarks, which couples to gluons.

→ **Two-loop effects induce thermal potential**

$$V_T \sim \alpha_s^2 T^4 \log(\Psi)$$

Anisimov, Dine (2001)

The saxion oscillation may be induced by this effect.

But the final result (axion & gravitino abundance) is not much affected by this effect.