TOHOKU
UNIVERSITY

Cosmological implications for SUSY and its breaking

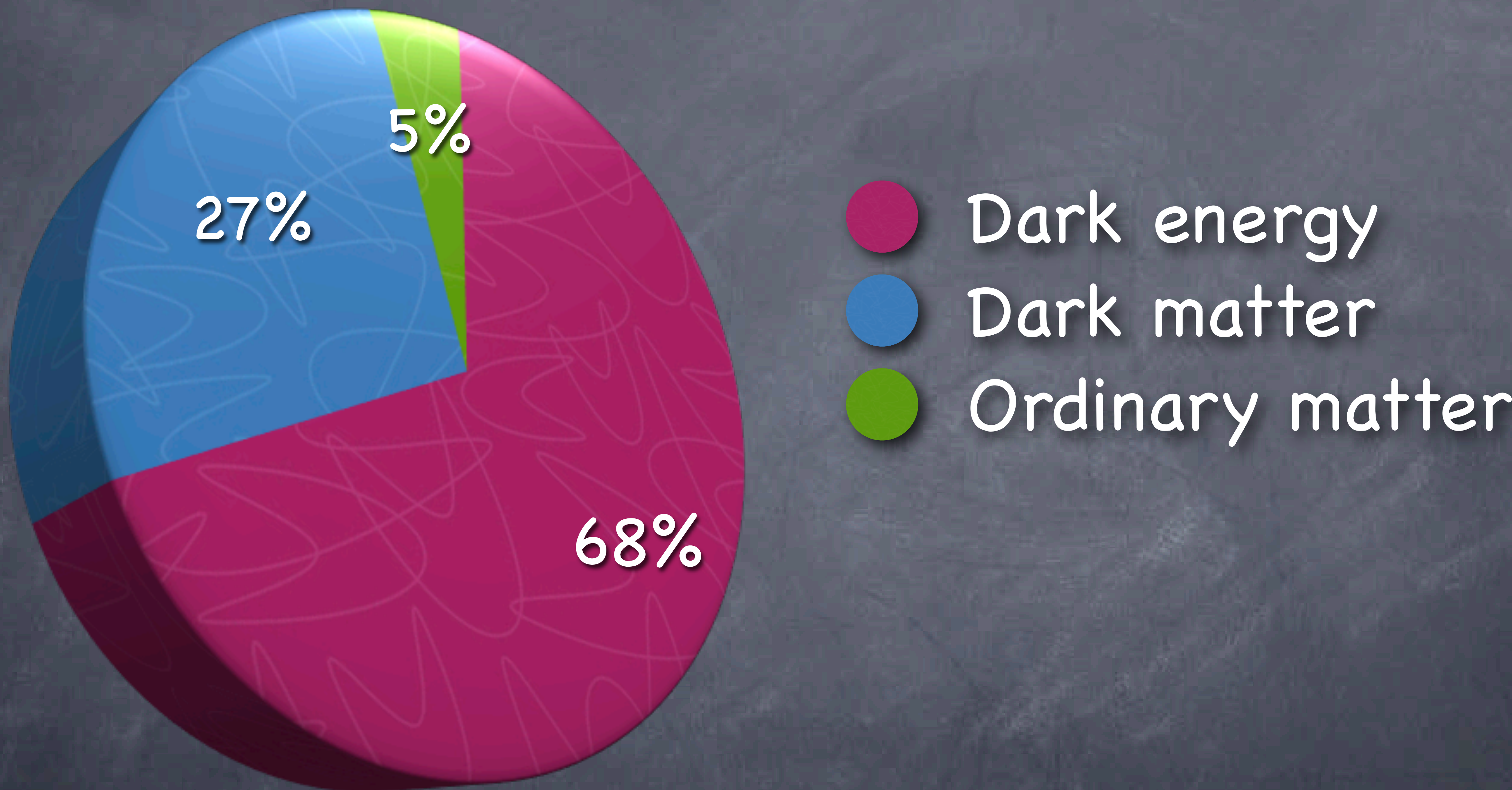
2-4 December 2013

``SUSY: Model-building and Phenomenology" at IPMU

Fumi Takahashi
(Tohoku University)

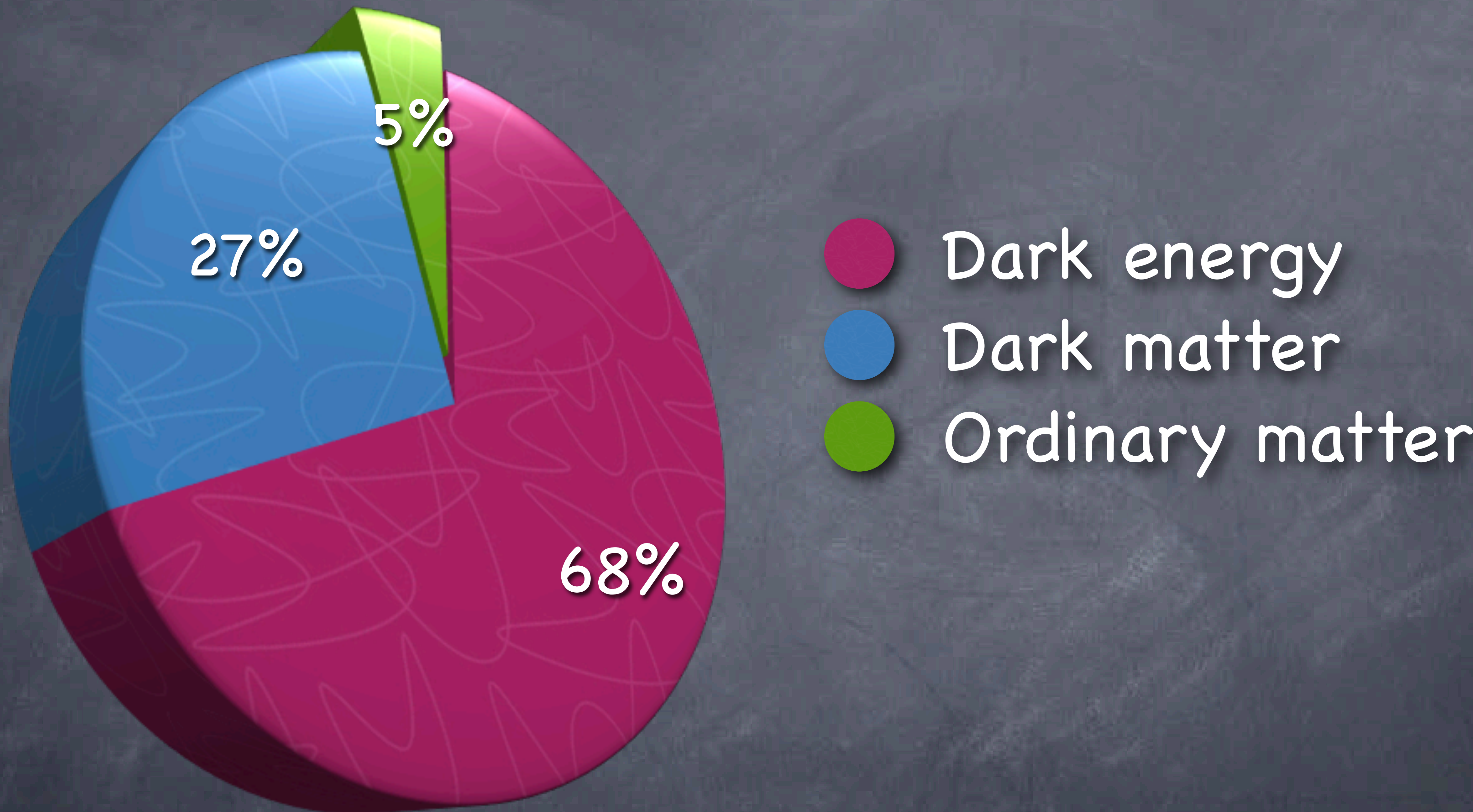
Cosmology

Dark sector



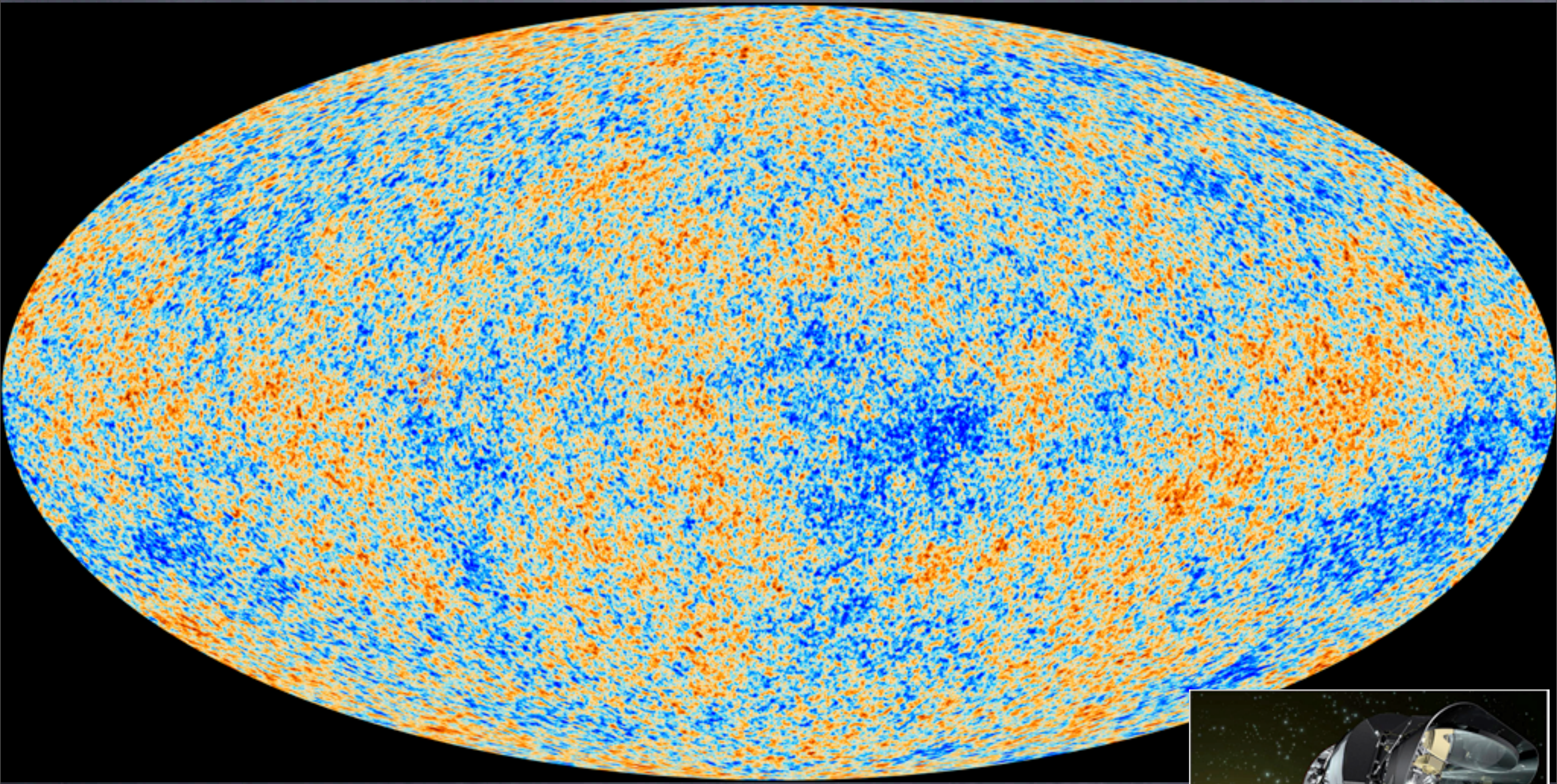
Dark matter and dark energy clearly call for new physics beyond standard model.

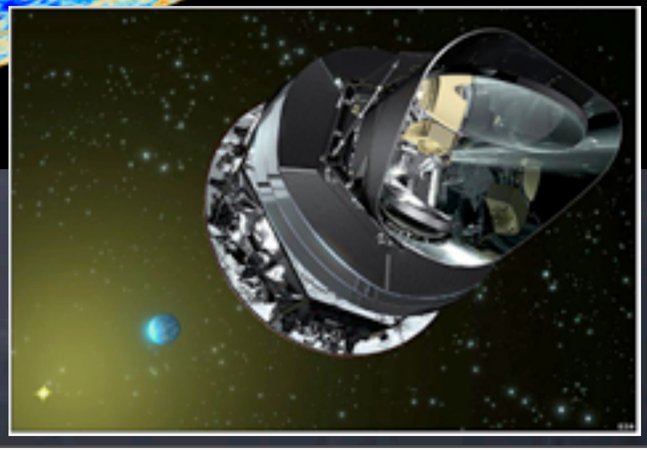
Visible sector



The origin of matter-antimatter asymmetry is not known.

CMB





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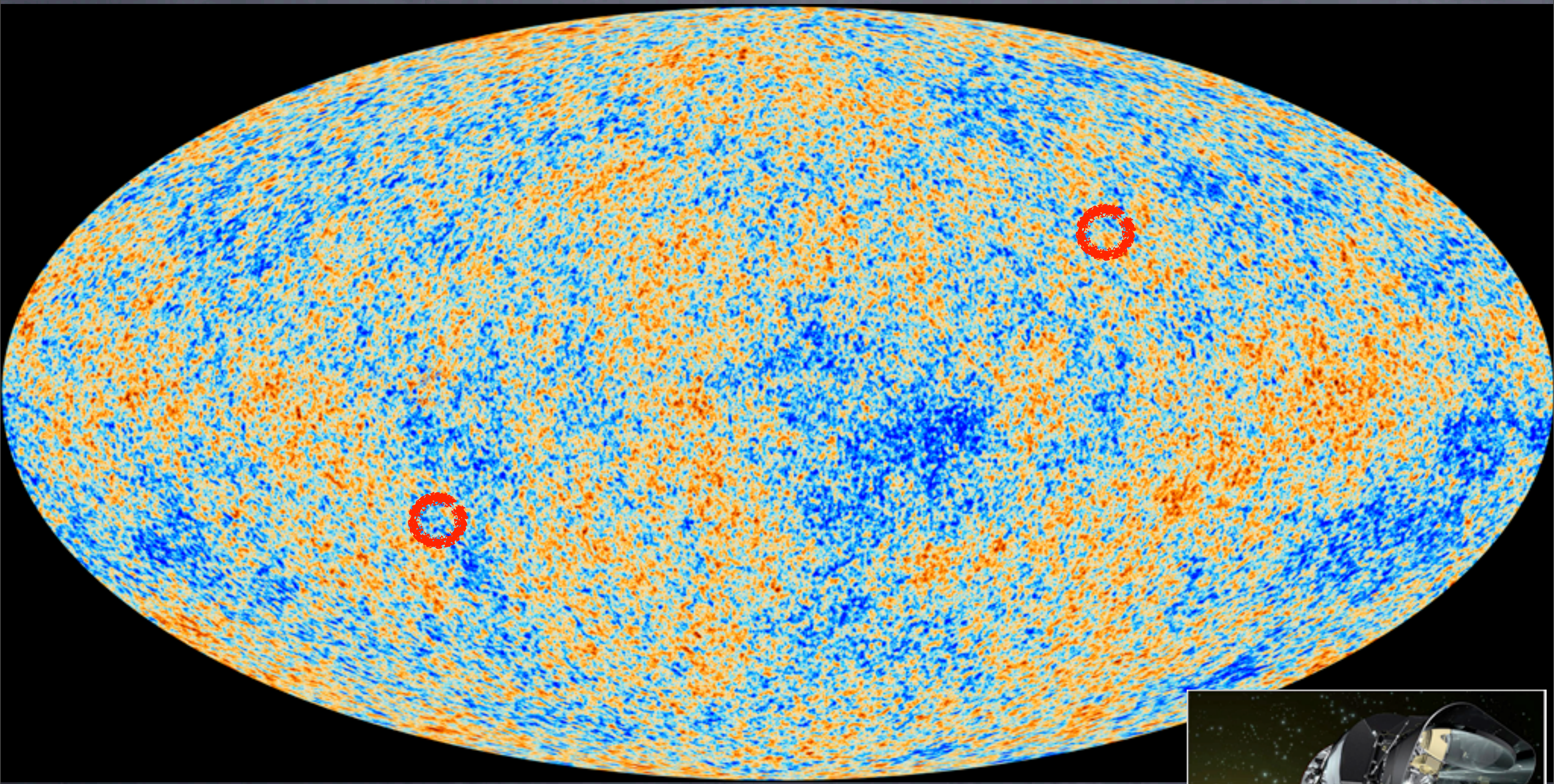
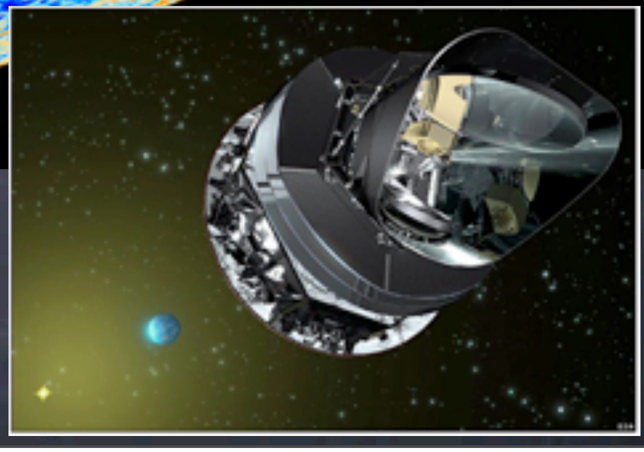
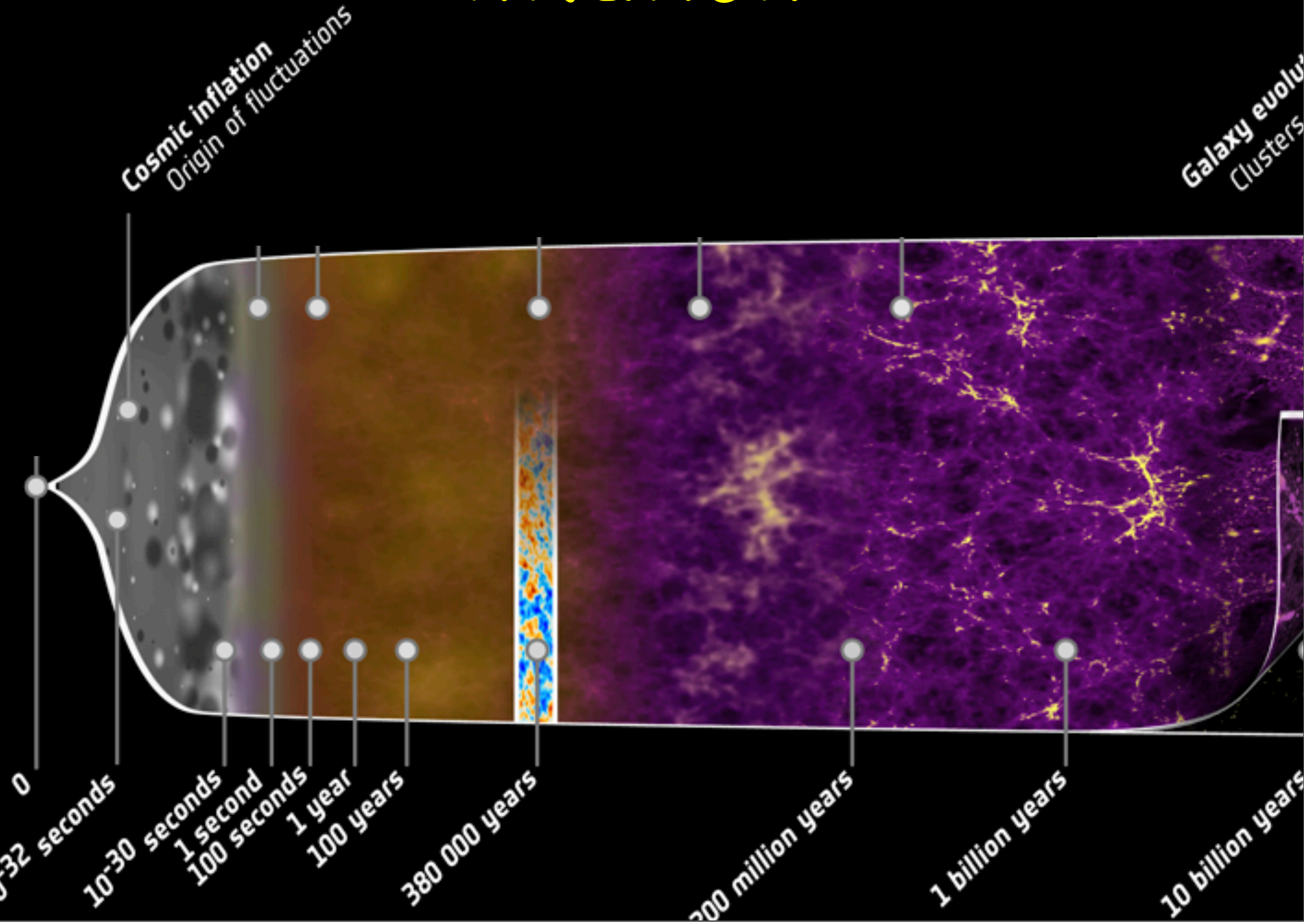




Inflation

Inflation



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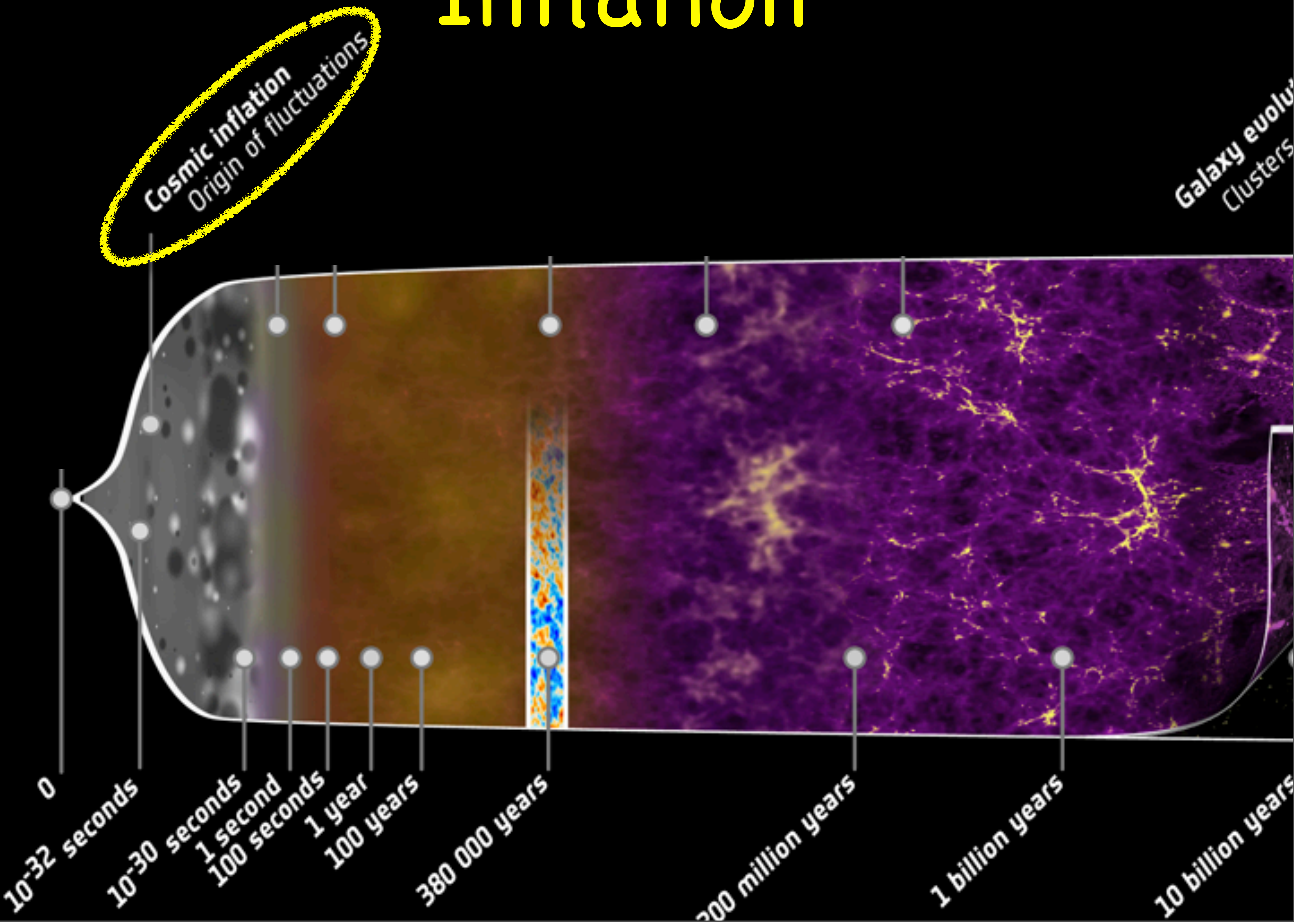
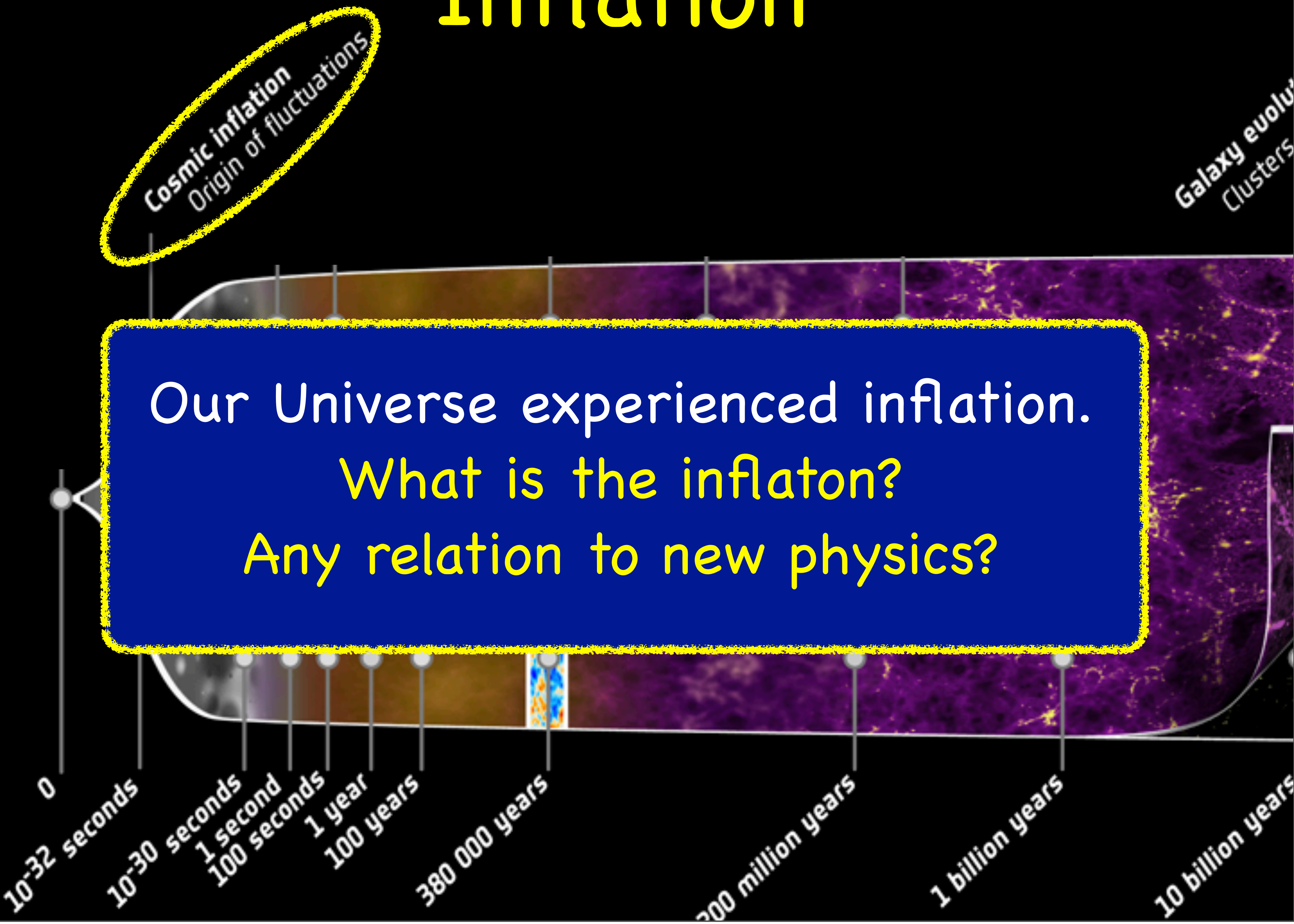
Inflation



Cosmic inflation
Origin of fluctuations
Galaxy evolu
Clusters
0
10^{-32} seconds
10^{-30} seconds
1 second
100 seconds
1 year
100 years
380 000 years
00 million years
1 billion years
10 billion years

Inflation



Our Universe experienced inflation.

What is the inflaton?

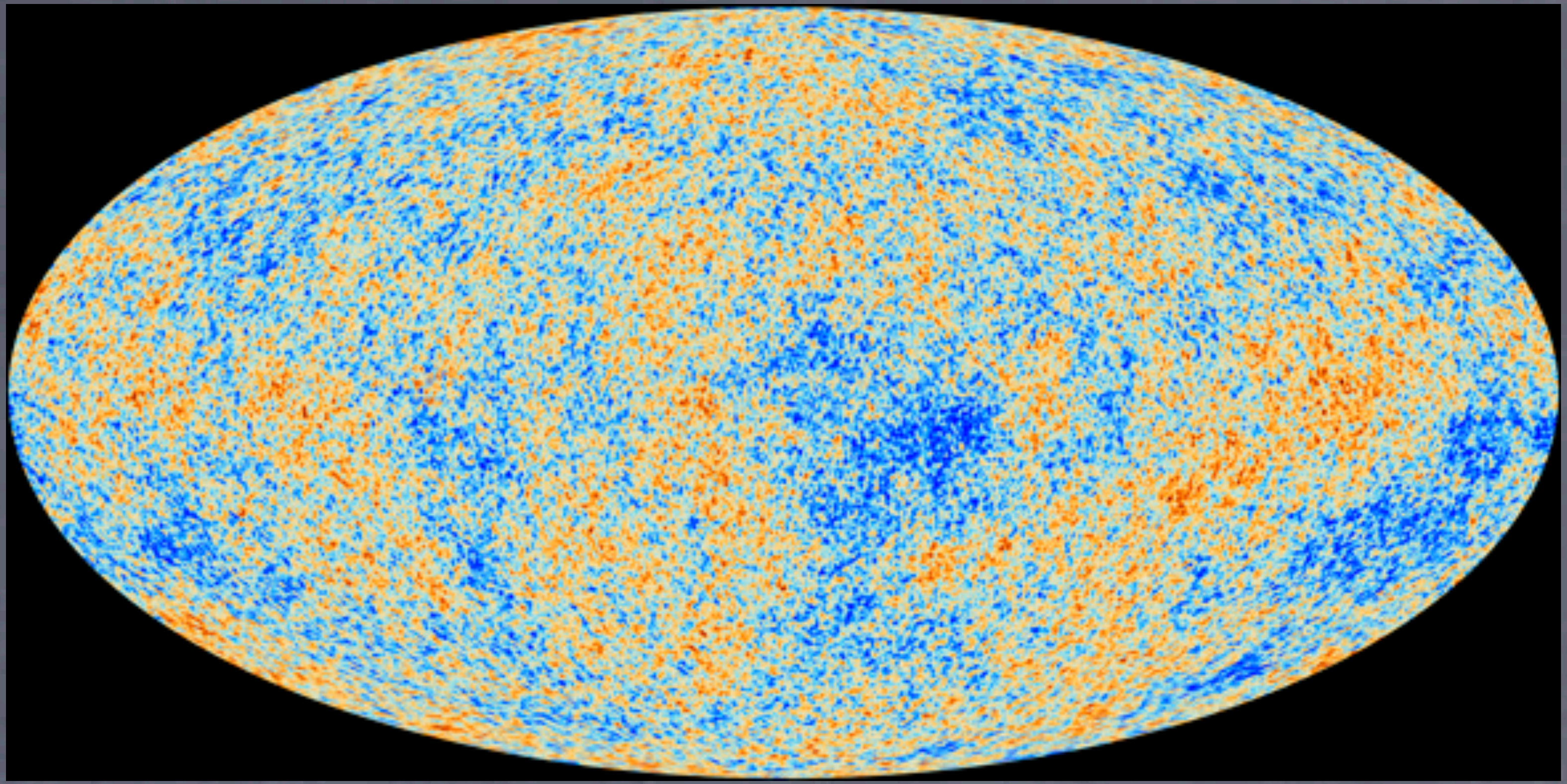
Any relation to new physics?

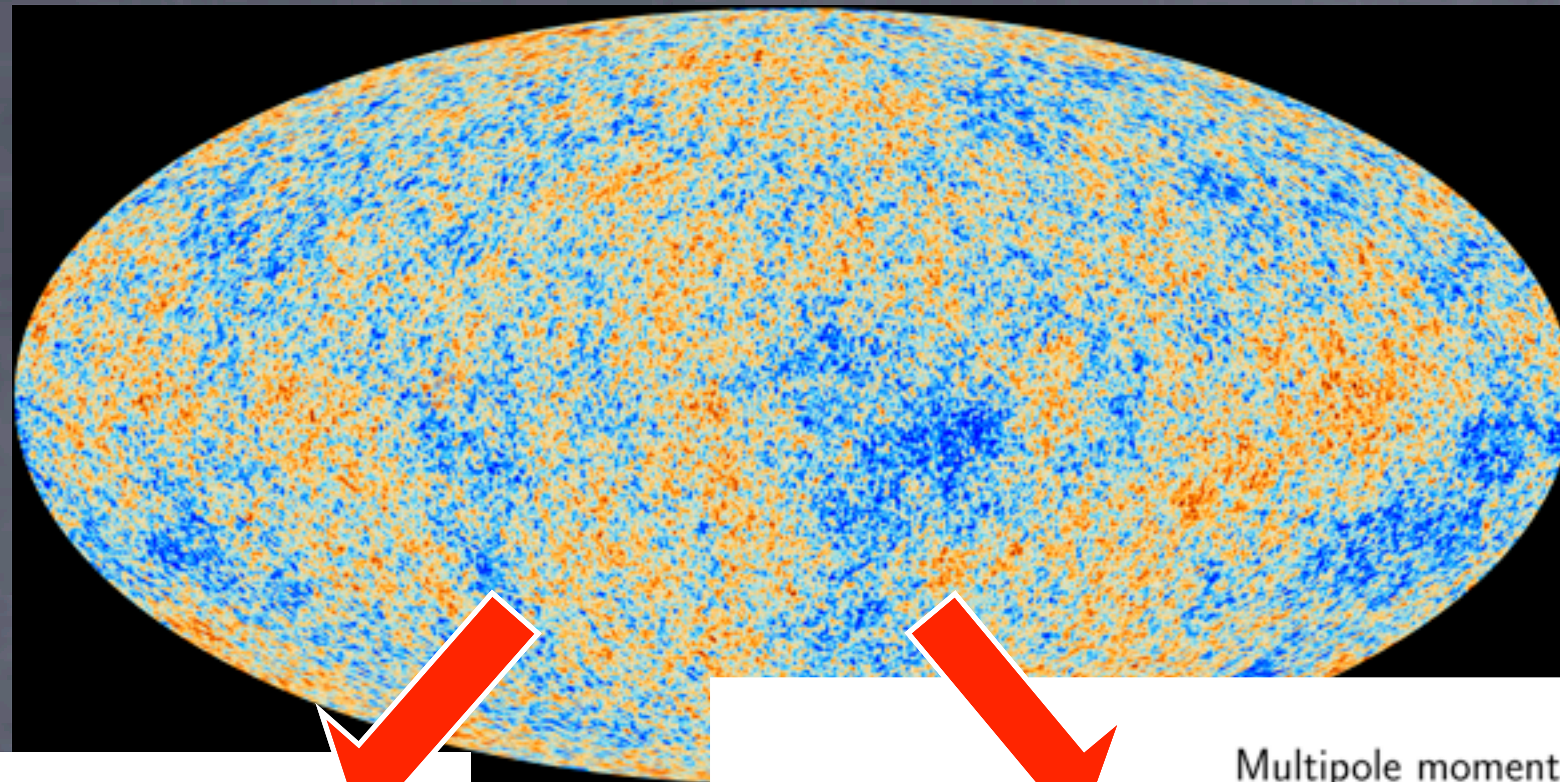
Cosmology

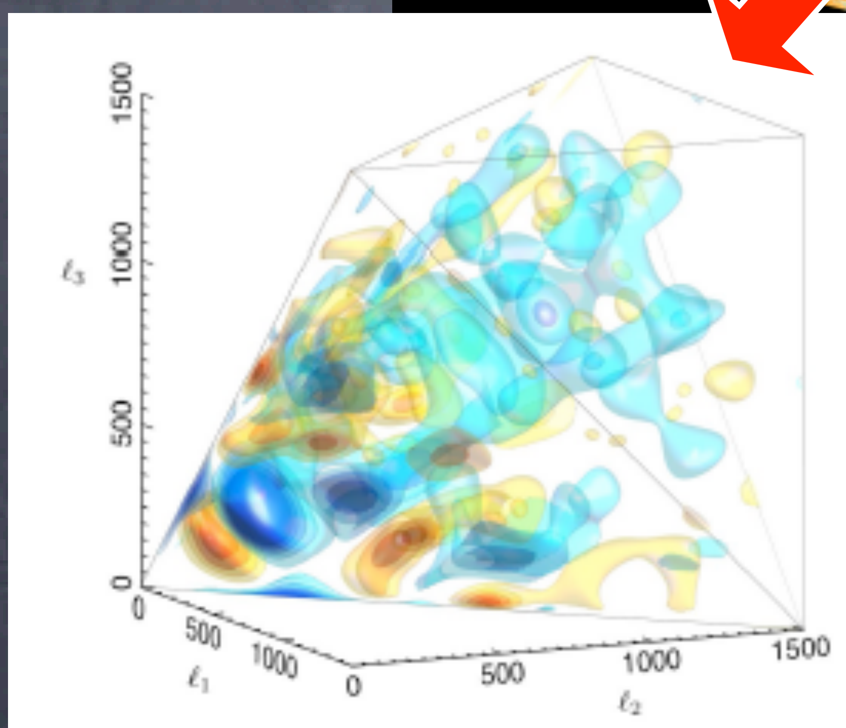
I discuss the cosmological implication for SUSY and its breaking, focusing on the following two topics.

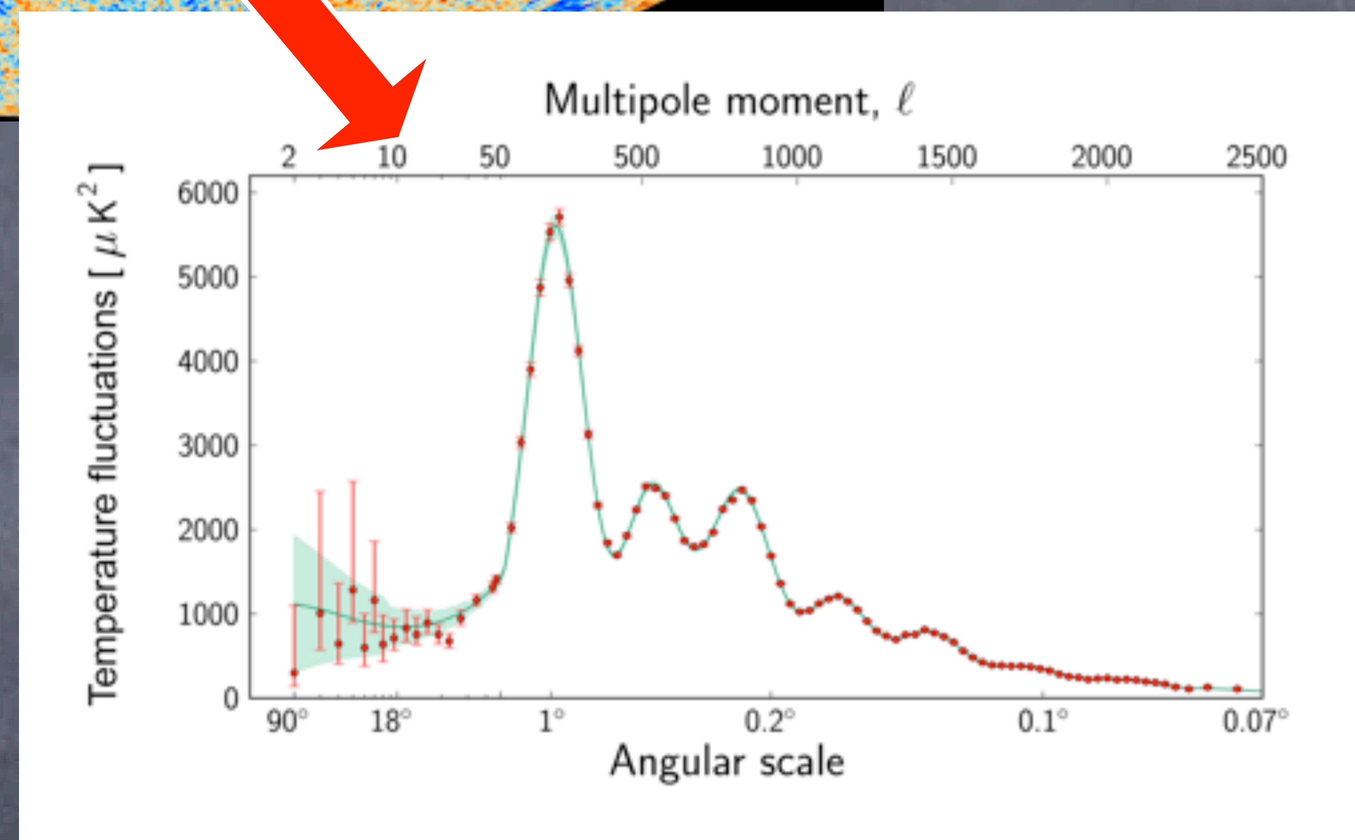
- ✓Inflation dynamics and SUSY breaking
- ✓Reheating and baryogenesis

2. Inflation









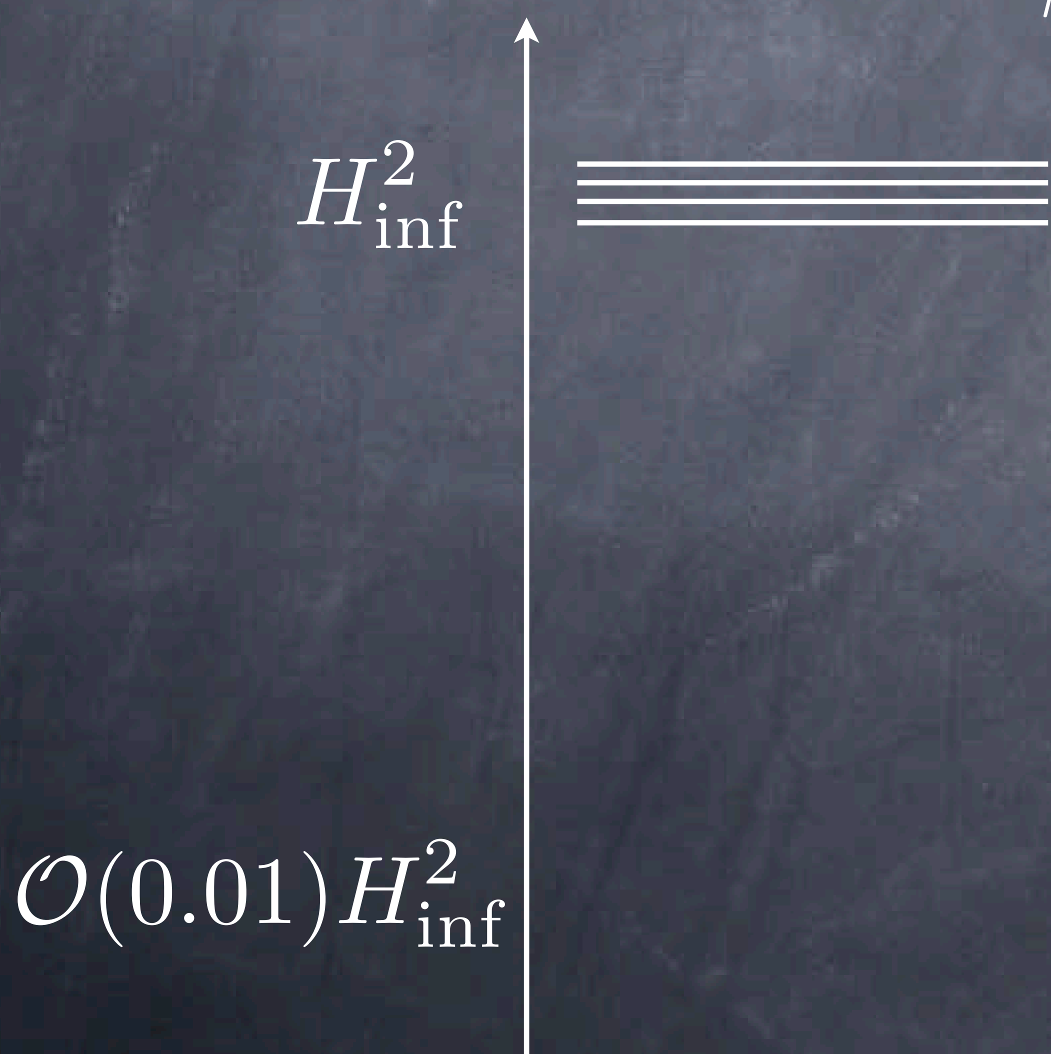
Adiabatic and gaussian density perturbations (w/o isocurvature and running) at super-horizon scales support for canonical single-field inflation.

Minimality and fine-tuning

In supergravity, scalars generically acquire a mass of order H_{inf}.

exception: axions

$$m_{\phi i}^2 \sim H_{\rm inf}^2$$



For successful inflation, the inflaton mass must be much lighter.

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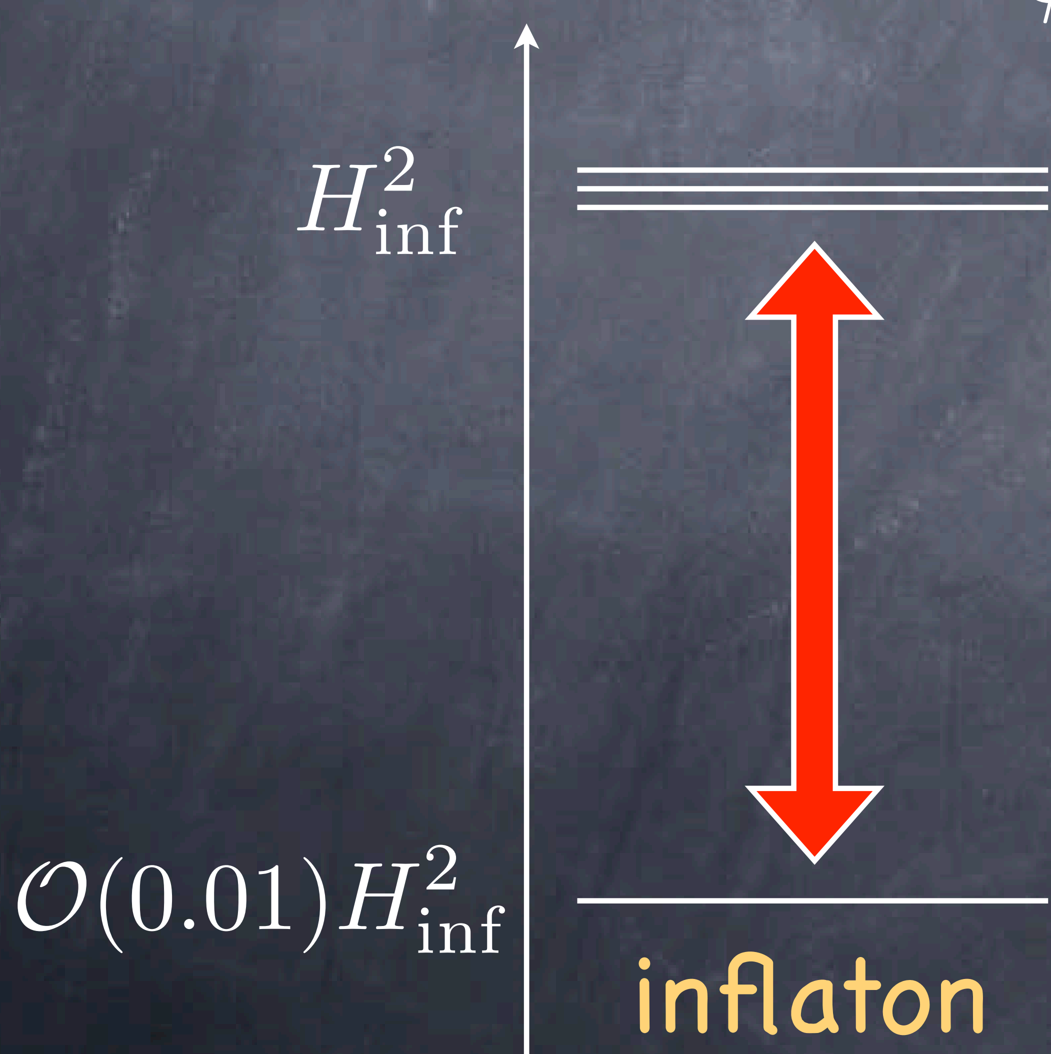

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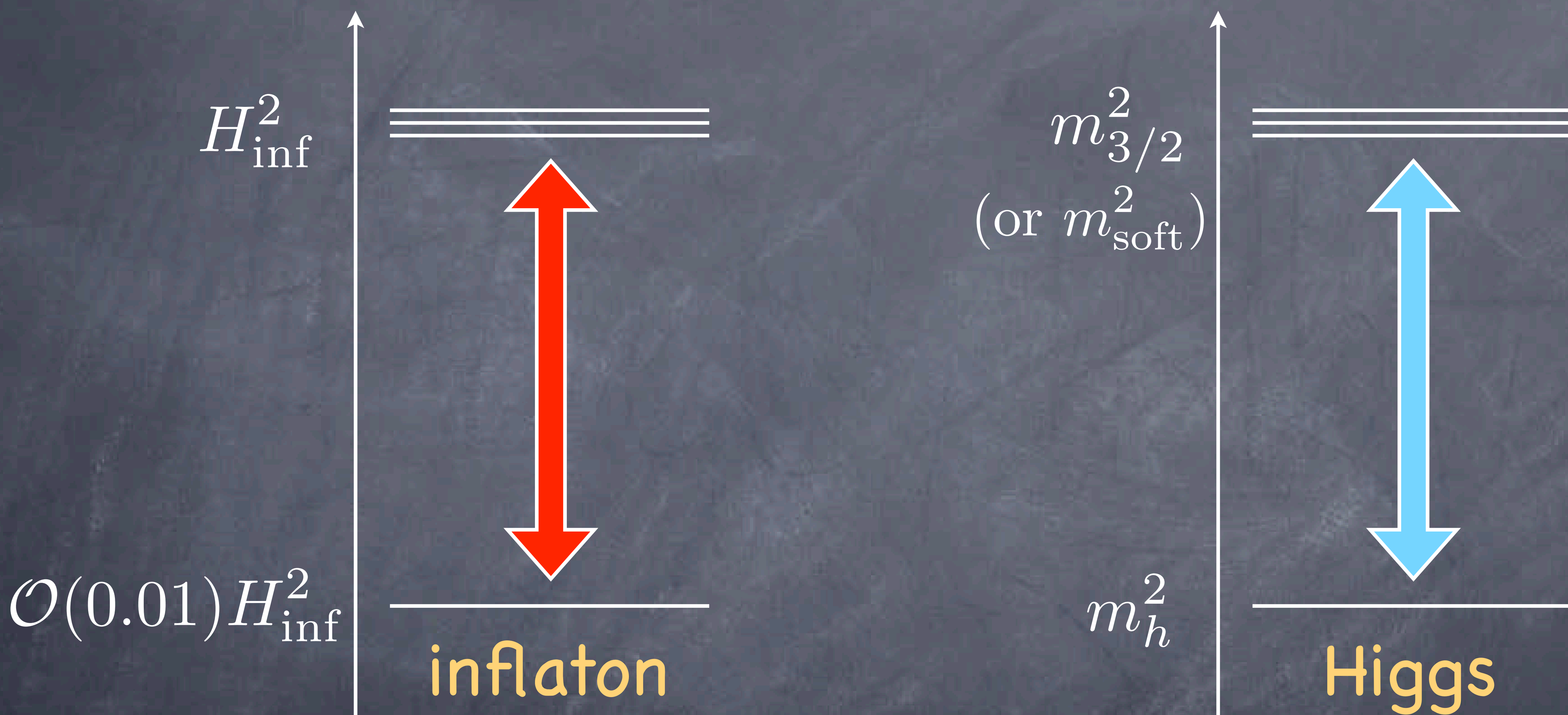
The eta-problem

Minimality and fine-tuning



The apparent minimality may be due to the fine-tuning in the landscape.

Inflation and SUSY

- SUSY helps inflation to occur because it controls radiative corrections and there are flat directions.

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- SUSY helps inflation to occur because it controls radiative corrections and there are flat directions.
- I consider the following effects on the inflaton dynamics by SUSY breaking.

✓ Inflaton tadpole

✓ Radiative corrections

Inflaton tadpole problem

Nakayama, FT, Yanagida, `10

The $U(1)_R$ symmetry can keep the flatness of the inflaton potential in a class of inflation models.

However, $U(1)_R$ is only approximate and explicitly broken by W_0, leading to the inflaton tadpole.

$$\mathrm{m}_{3/2} = \langle e^{K/2} W \rangle \simeq W_0$$

⇒ Inflaton dynamics can constrain the SUSY breaking scale.

Inflaton tadpole problem

- Consider F-term inflation with

$$\mathrm{W} = \mu^2\phi \quad \Rightarrow \quad V(\phi) = \left|\frac{\partial W}{\partial \phi}\right|^2 = \mu^4$$

ϕ : inflaton flat direction

Inflaton tadpole problem

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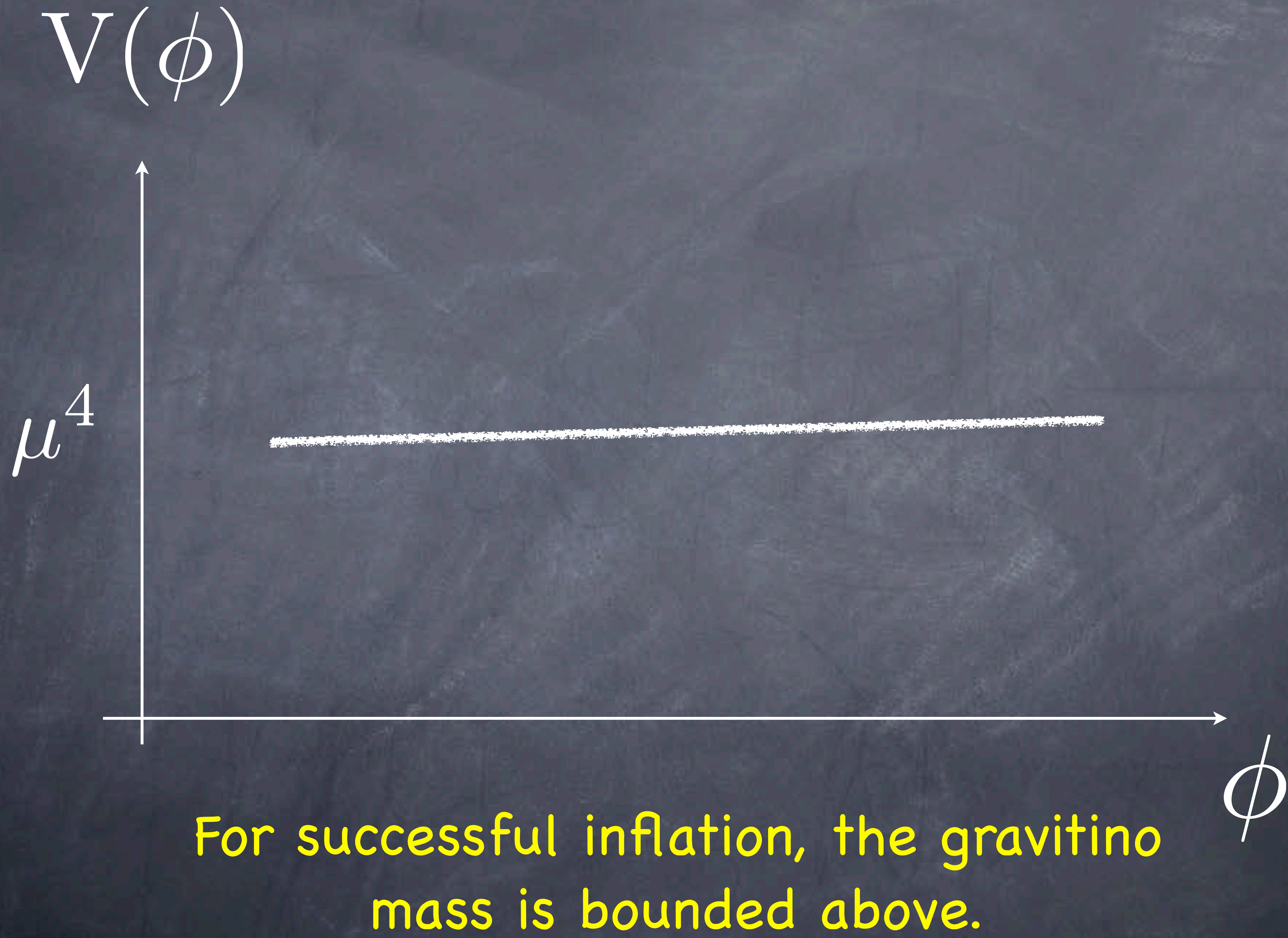
ϕ : inflaton flat direction

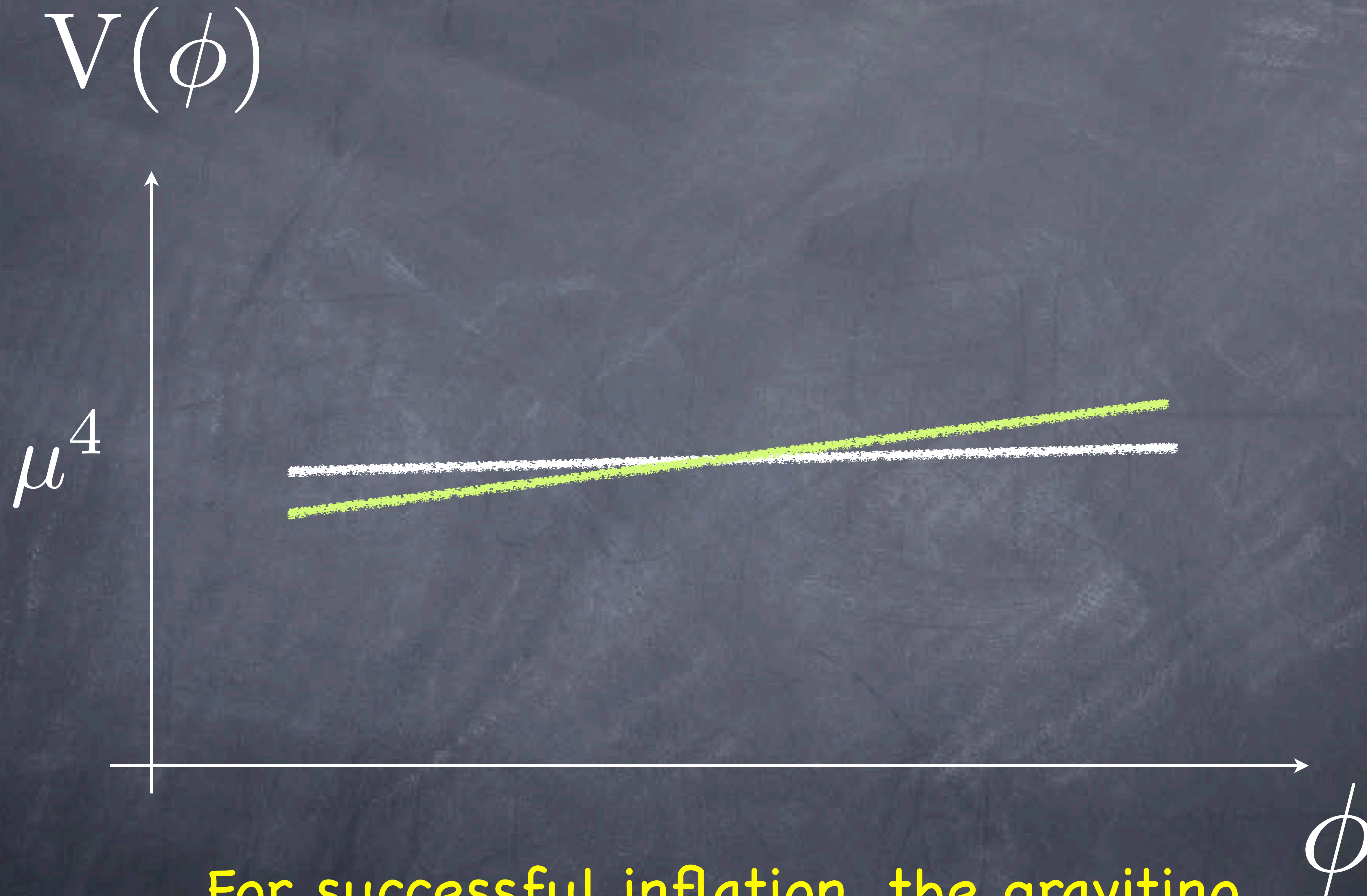
In supergravity, there must be a constant W_0 to realize the vanishingly small cosmological constant.

$$W = \mu^2\phi + W_0 \qquad W_0 \simeq m_{3/2}$$

$$\Rightarrow \quad V(\phi) = e^K(D_i W g^{ij^*} D_{j^*} W^* - 3|W|^2)$$

$$\supset \mu^4 + m_{3/2}\mu^2\phi + \text{h.c.}$$


$V(\phi)$
μ^4
ϕ
For successful inflation, the gravitino mass is bounded above.



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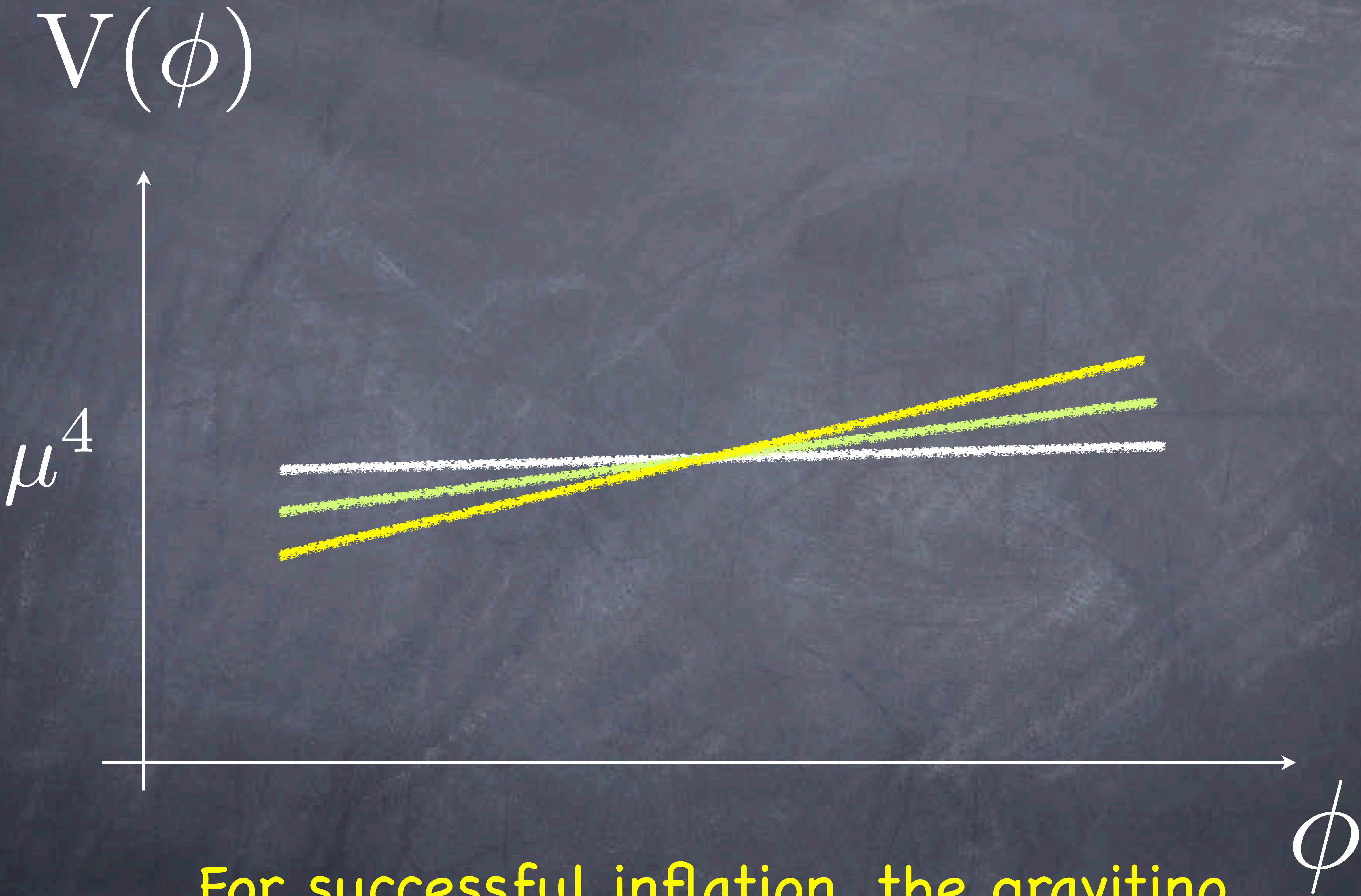

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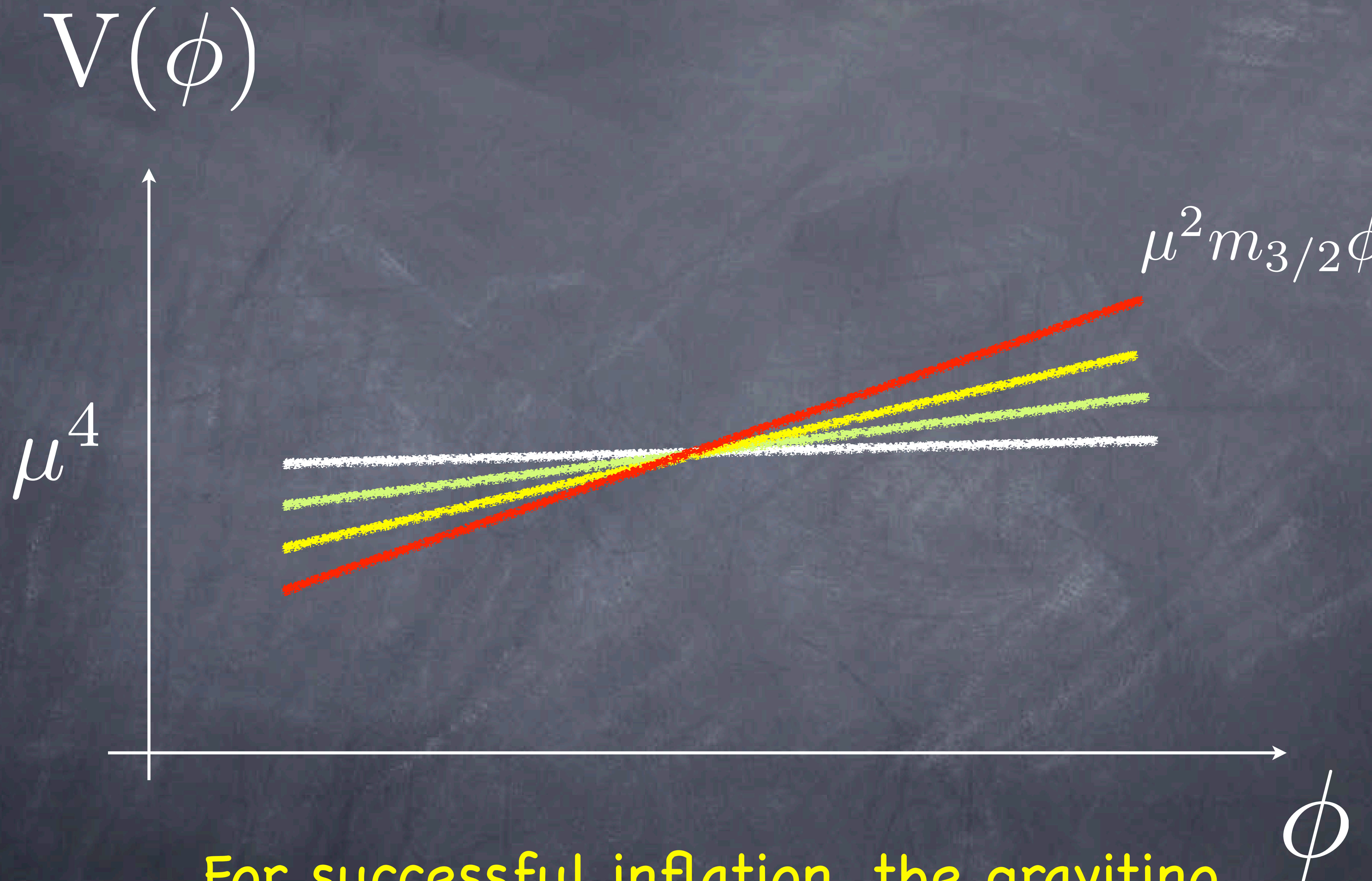


For successful inflation, the gravitino mass is bounded above.

1. Hybrid inflation

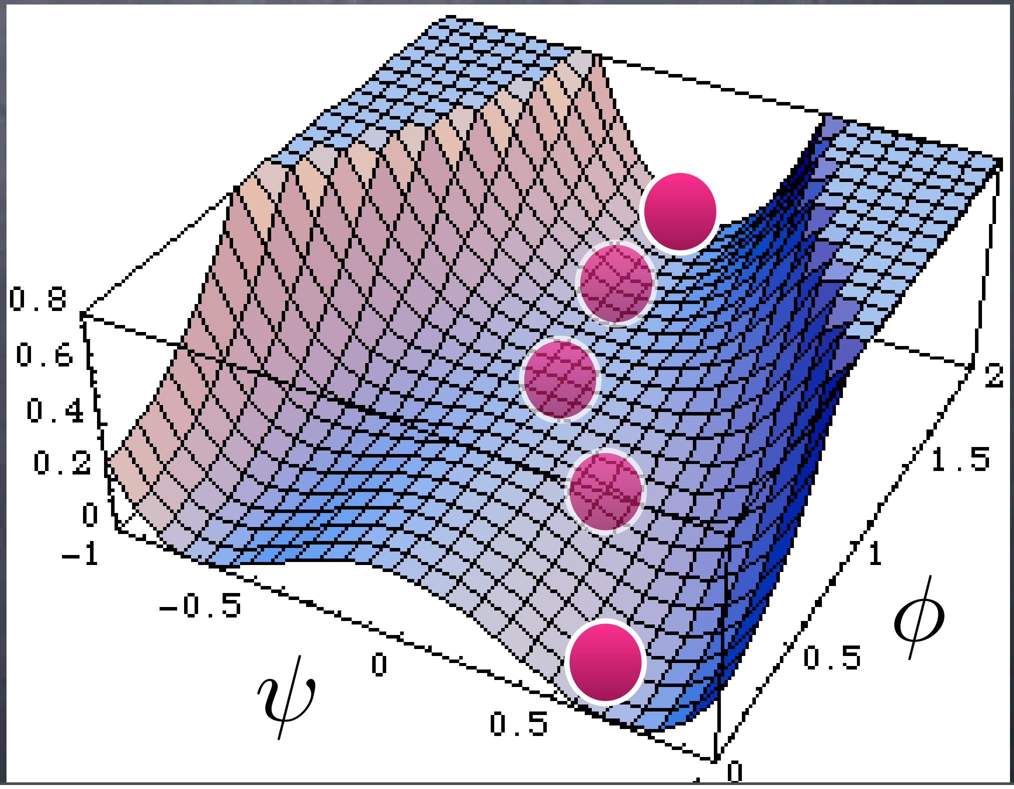
$$K = |\phi|^2 + |\psi|^2 + |\bar{\psi}|^2$$
$$W = \kappa\phi\left(\psi\bar{\psi} - M^2\right) + W_0$$

Copeland et al `94
Dvali, Shafi, Schaefer `94
Linde, Riotto, `97

Buchmuller, Covi, Delepine `01
Nakayama, FT, Yanagida, `10

At large values of ϕ, $\psi = \bar{\psi} = 0$ is the minimum.
Then we can identify ϕ with the inflaton.

$$W = -\kappa M^2 \phi + W_0$$



Thus, the inflaton acquires linear potential.

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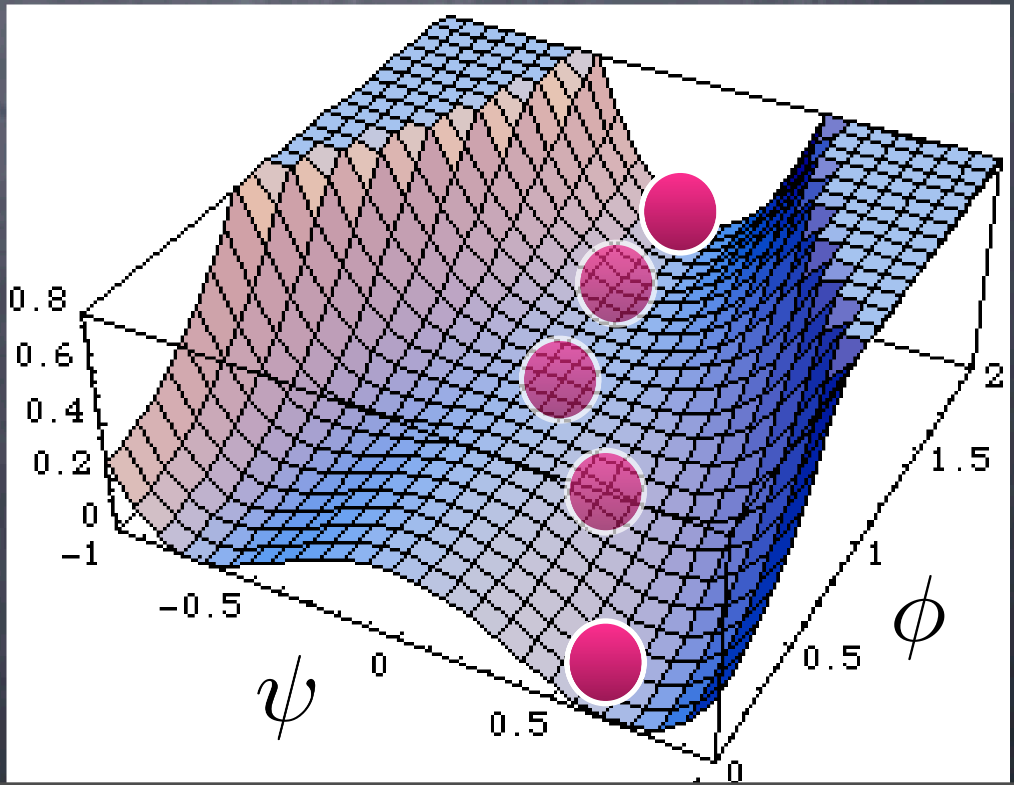
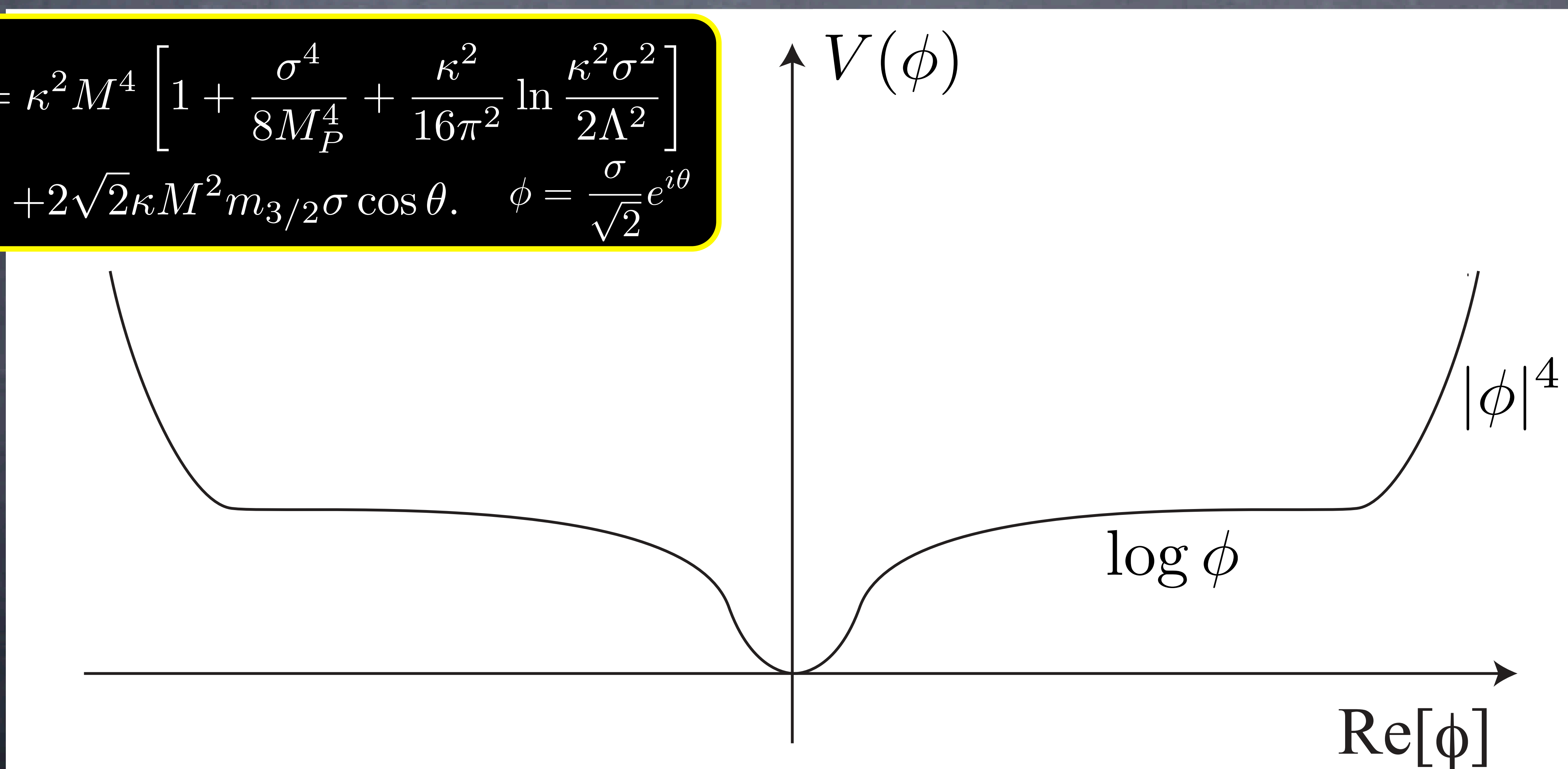


Inflaton potential with tadpole

- The initial condition must be fine-tuned in order not to be trapped at the unwanted minimum generated by the tadpole.

$$V = \kappa^2 M^4 \left[1 + \frac{\sigma^4}{8M_P^4} + \frac{\kappa^2}{16\pi^2} \ln \frac{\kappa^2 \sigma^2}{2\Lambda^2} \right]$$
$$+ 2\sqrt{2}\kappa M^2 m_{3/2} \sigma \cos\theta. \qquad \phi = \frac{\sigma}{\sqrt{2}} e^{i\theta}$$



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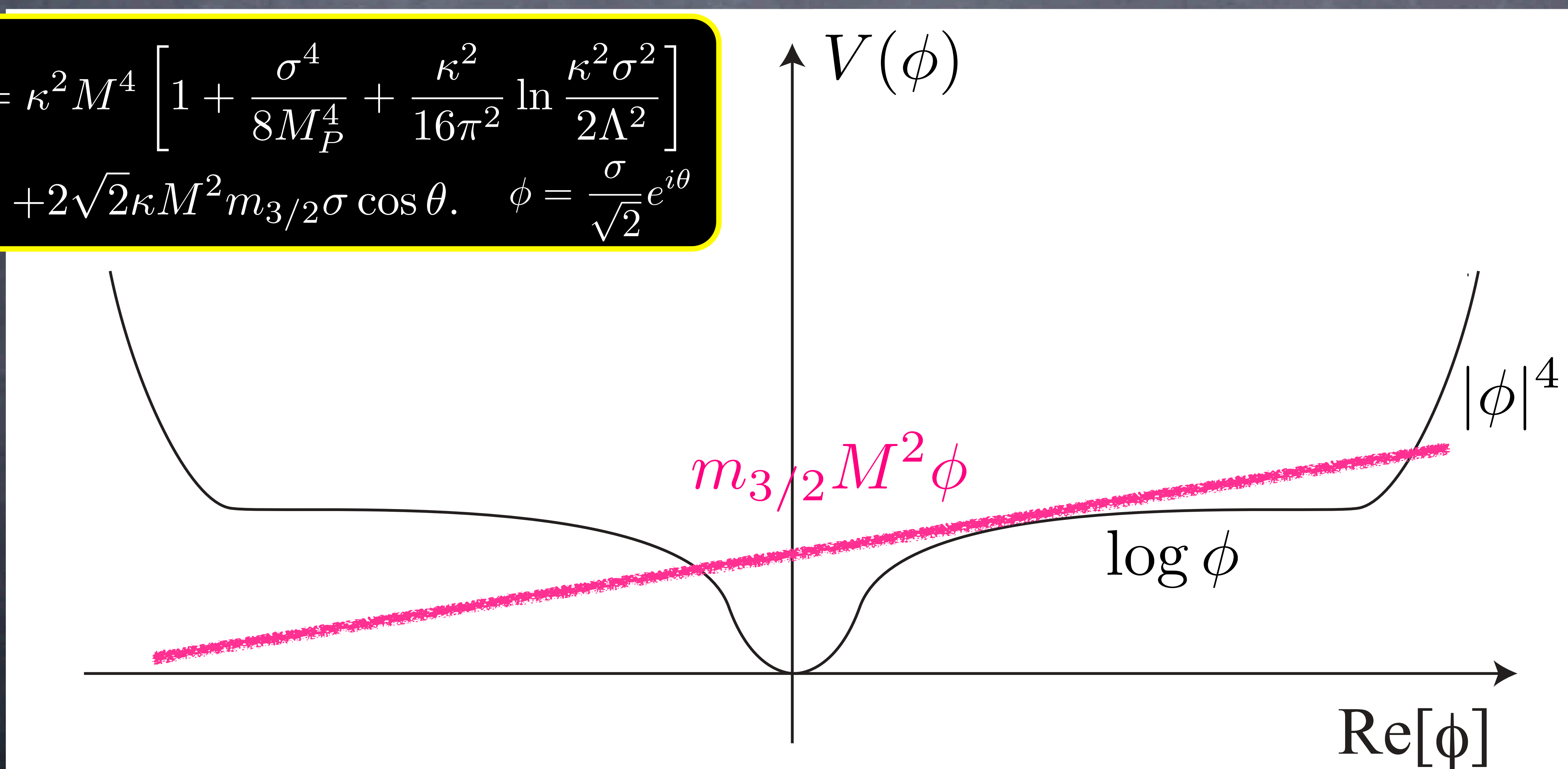

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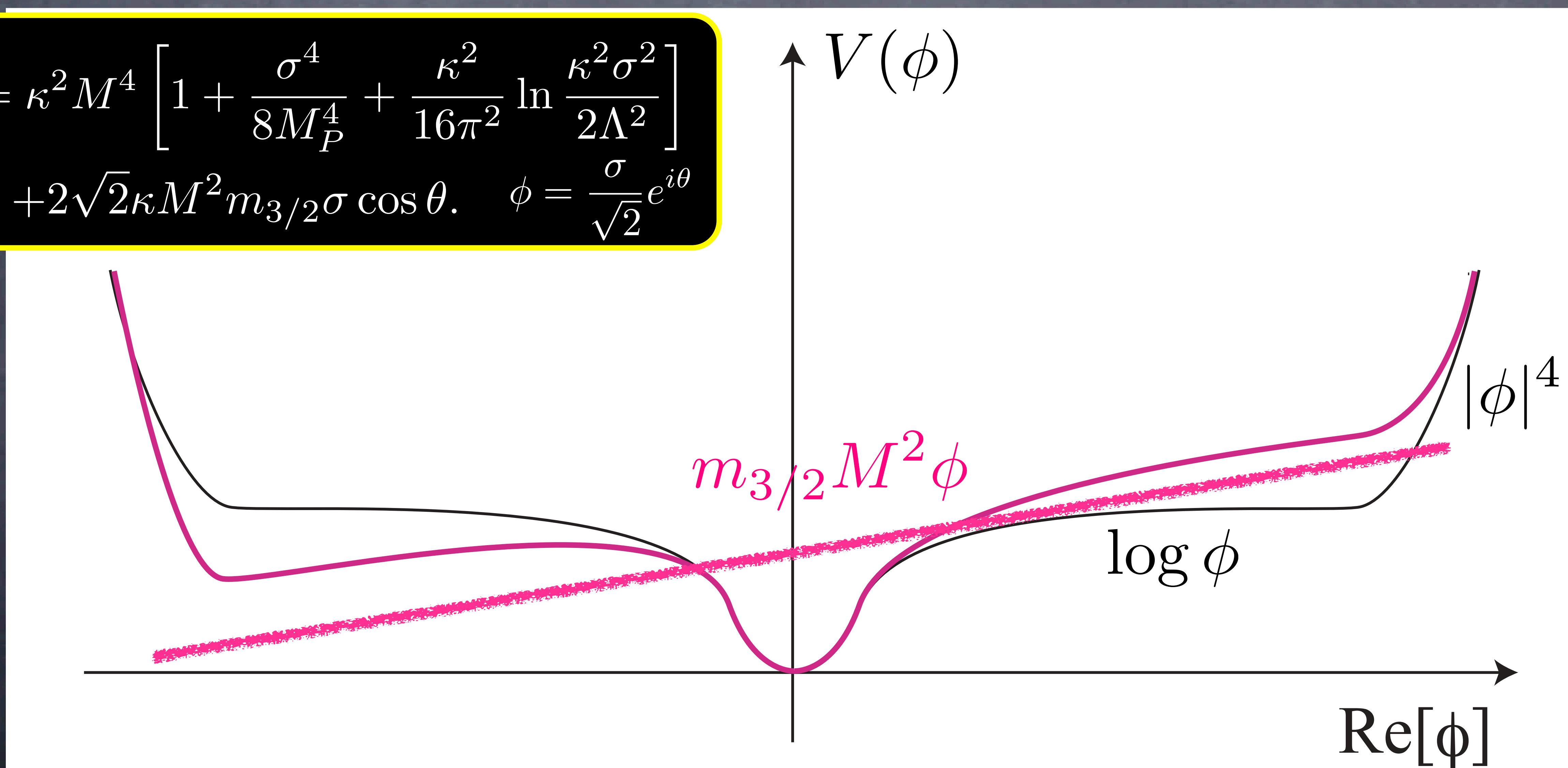
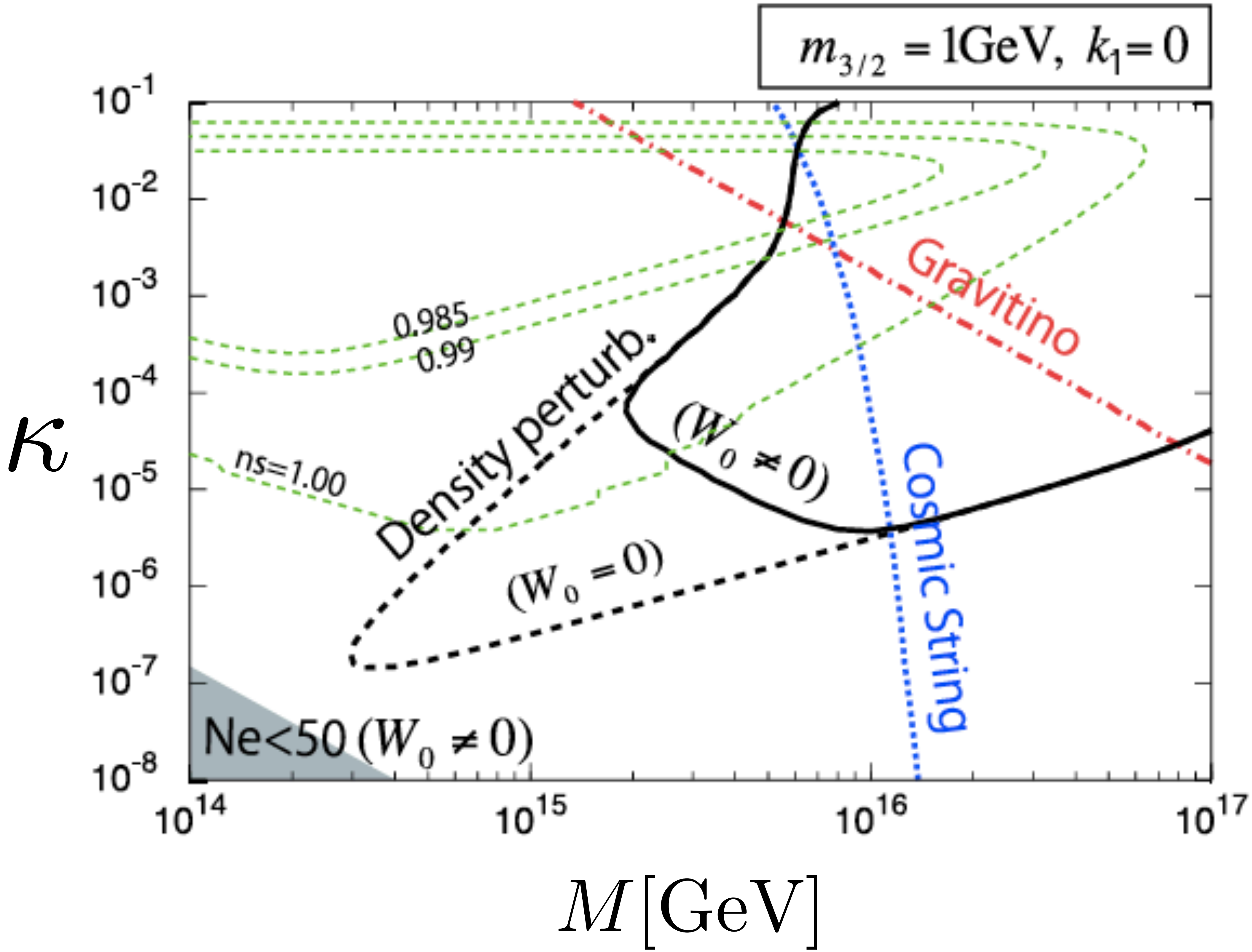
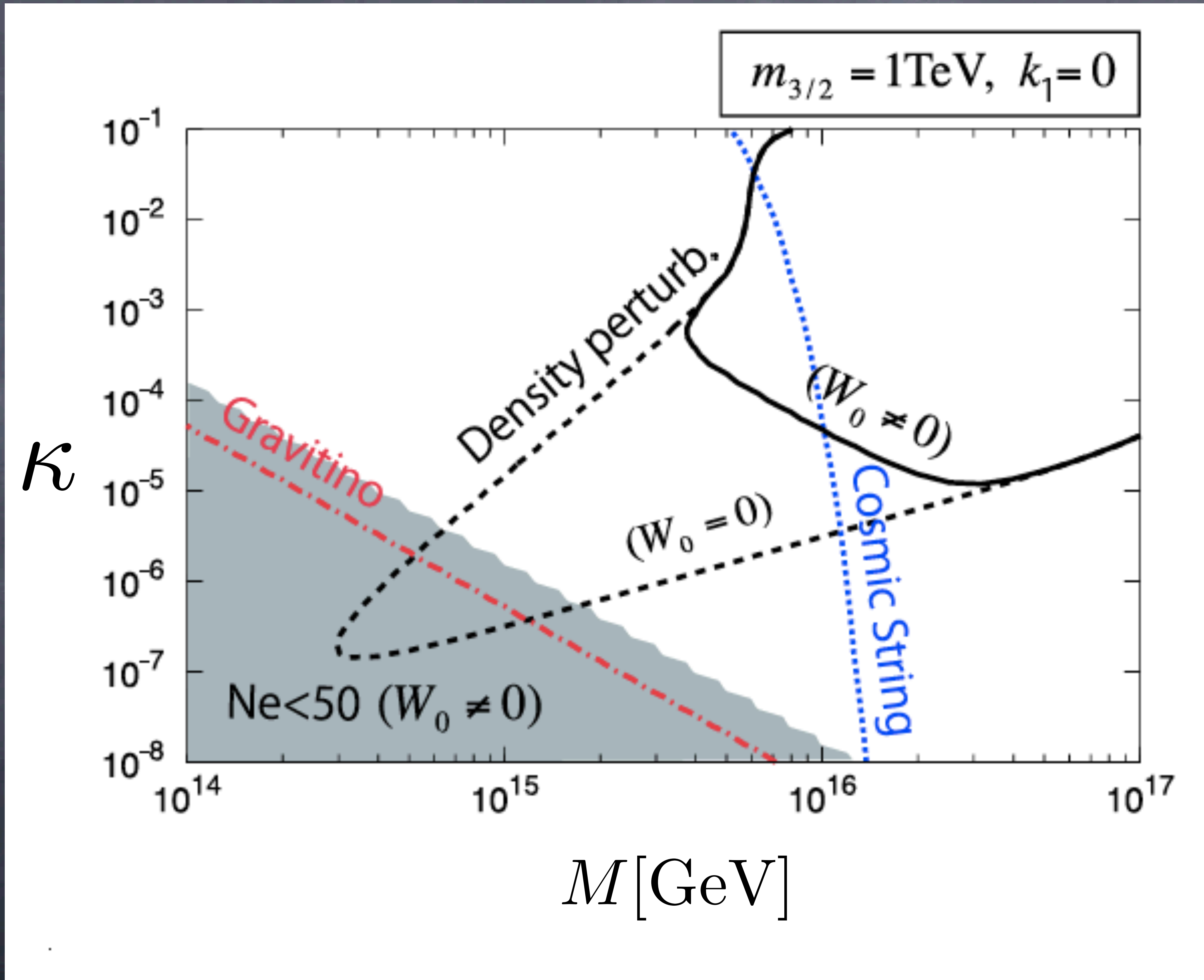




$m_{3/2} = 1\text{GeV},\ k_1 = 0$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
κ
0.985
0.99
ns=1.00
Density perturb.
$(W_0 \neq 0)$
$(W_0 = 0)$
Gravitino
Cosmic String
Ne<50 $(W_0 \neq 0)$
10^{14}
10^{15}
10^{16}
10^{17}
$M\,[\text{GeV}]$


$m_{3/2}$ = 1TeV, k_1= 0
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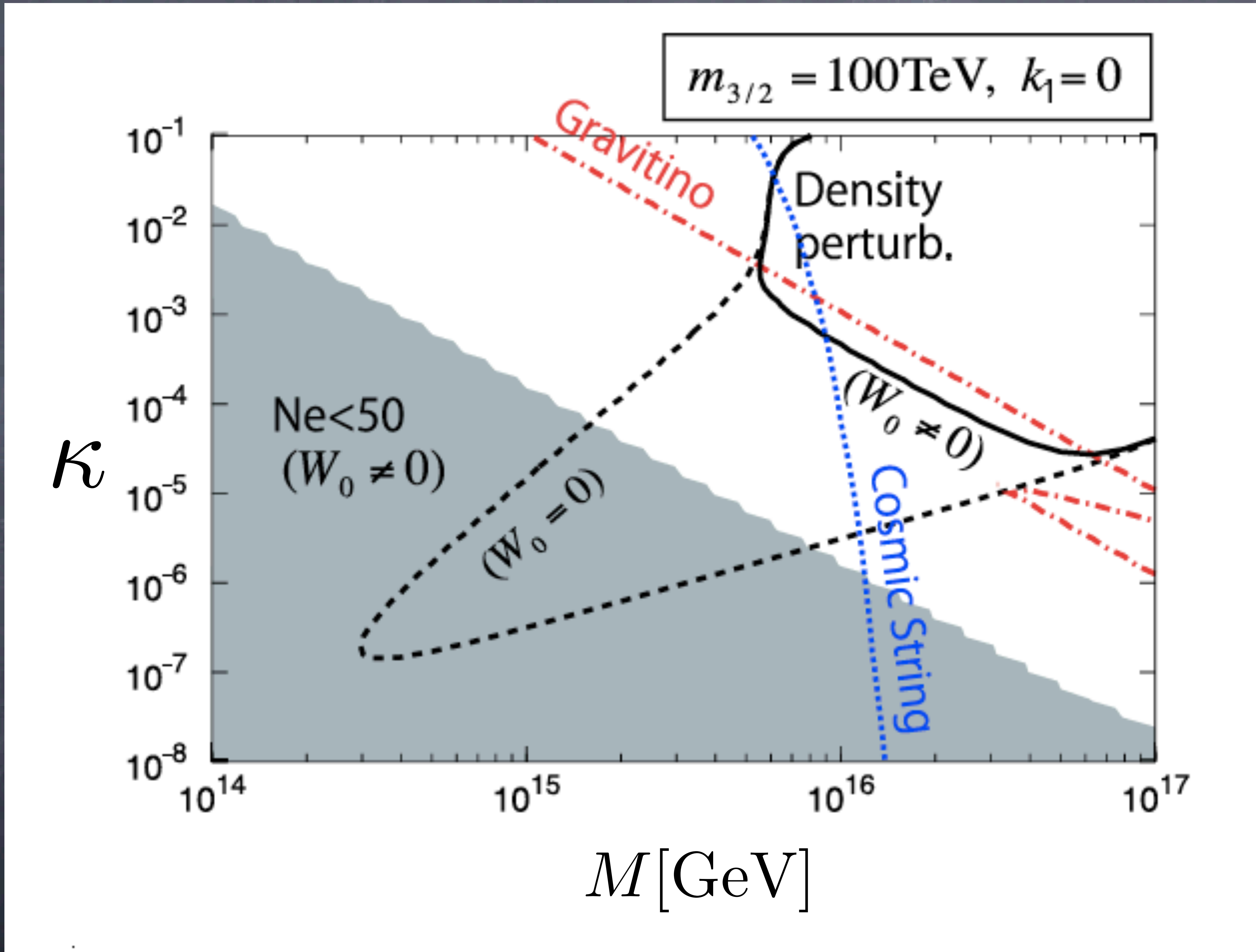
M[GeV]



$m_{3/2} = 100\mathrm{TeV},\ k_1 = 0$
Gravitino
Density perturb.
Ne<50
$(W_0 \neq 0)$
$(W_0 = 0)$
$(W_0 \neq 0)$
Cosmic String
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
κ
10^{14}
10^{15}
10^{16}
10^{17}
$M[\mathrm{GeV}]$

- Hybrid inflation -

- The inflaton tadpole generically affects the inflaton dynamics.

- The gravitino mass should be smaller than O(100)TeV for successful inflation.

Solutions to the inflaton tadpole problem

Solutions to the inflaton tadpole problem

1. Hybrid inflation in no-scale supergravity

Higaki, Jeong, FT, 1211.0994

The tadpole is canceled for the no-scale Kahler:

$$K = -3\ln\left(T + T^\dagger - \frac{1}{3}\sum_i |\phi_i|^2\right)$$

Solutions to the inflaton tadpole problem

1. Hybrid inflation in no-scale supergravity

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The tadpole is canceled for the no-scale Kahler:

$$K = -3 \ln \left(T + T^\dagger - \frac{1}{3} \sum_i |\phi_i|^2 \right)$$

The modulus T must be stabilized, while suppressing the inflaton tadpole. Also axion DR produced by the modulus decay relaxes a tension between the observed and predicted values of n_s.

2. The constant term in W may be small during inflation, but appear after inflation.

e.g.) Single-field new inflation

Kumekawa, Moroi, Yanagida `94
Izawa, Yanagida `96

$$W = \mu^2 \phi - \frac{g}{n+1}\phi^{n+1} + c$$

$$m_{3/2} \simeq \langle W(\phi) \rangle$$

FT `13
Harigaya, Ibe, Yanagida, `13
See Talk by Harigaya

e.g.2) Hybrid-new double inflation

Kawasaki, Nakajima, Nakayama, Yanagida, `13

3. The inflaton has no sizable F-term.

$$W = X f(\phi) \qquad \langle f(\phi) \rangle \neq 0$$

X has a non-zero F-term, but it is ϕ that slow-rolls.

e.g.) Two-field new inflation, Smooth hybrid inflation, etc.

2. Single-field New inflation

Kumekawa, Moroi, Yanagida `94

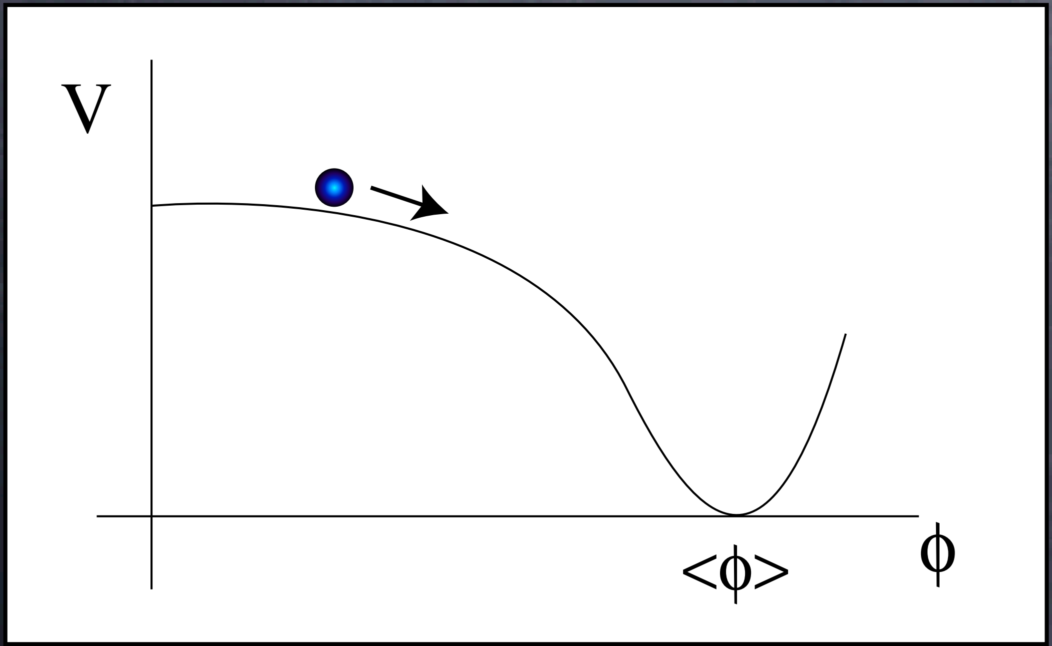
Izawa, Yanagida `96

$$K(\phi,\phi^\dagger) = |\phi|^2 + \frac{k}{4}|\phi|^4 + \cdots$$
$$W(\phi) = v^2\phi - \frac{g}{n+1}\phi^{n+1}$$

No constant term

where $R[\phi]=2$ and a discrete $Z_{2n\mathrm{R}}$ is assumed.

$$V(\varphi) \simeq v^4 - \frac{k}{2}v^4\varphi^2 - \frac{g}{2^{\frac{n}{2}-1}}v^2\varphi^n + \frac{g^2}{2^n}\varphi^{2n}$$



After inflation, the inflaton acquires a vev, $\langle\phi\rangle = (v^2/g)^{\frac{1}{n}}$

$$m_{3/2} = \left\langle e^{K/2}W \right\rangle \simeq \frac{nv^2}{n+1}\langle\phi\rangle$$

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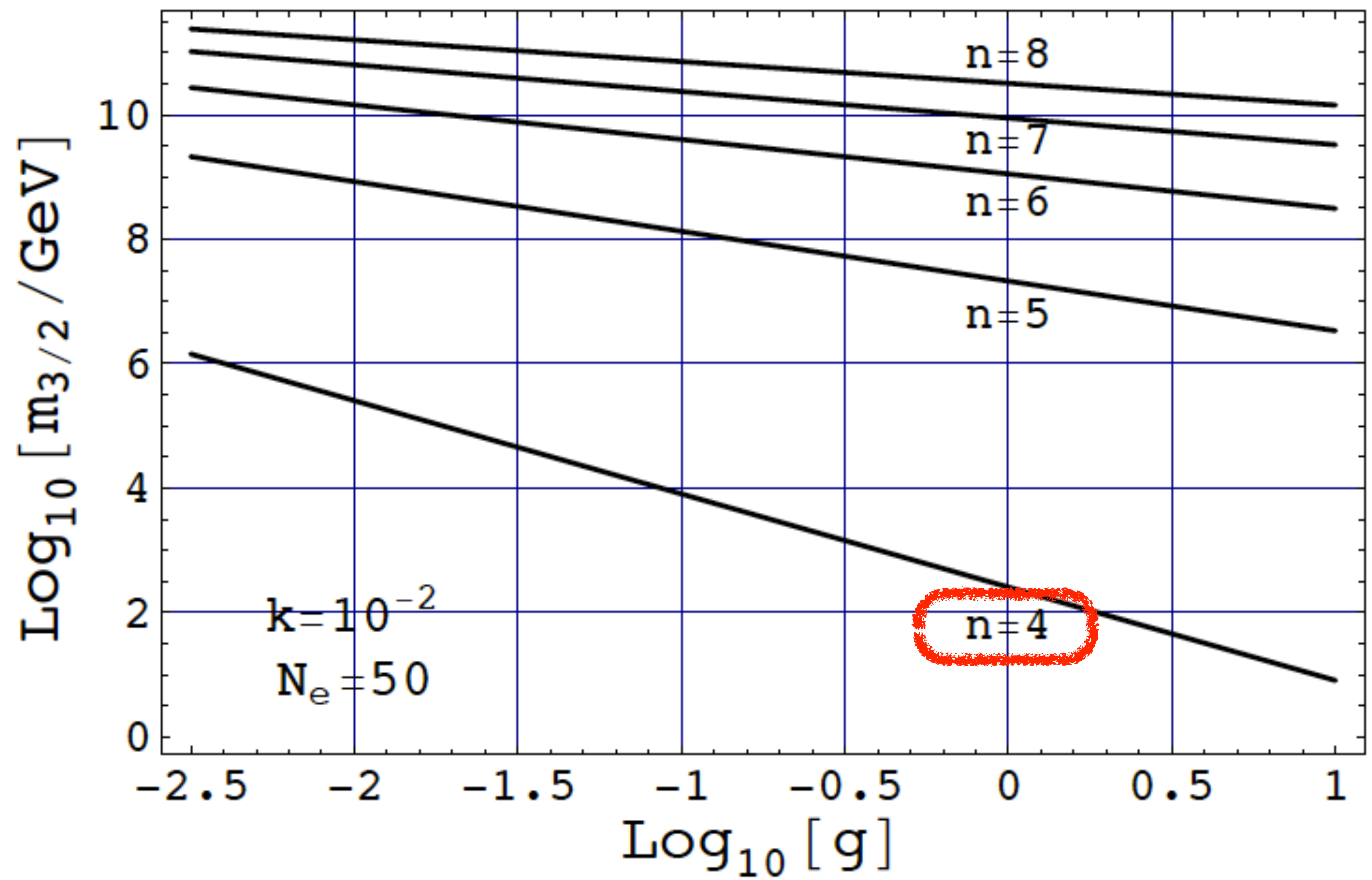
The gravitino mass

n=4 leads to $m_{3/2}$ = 100GeV-100TeV for g = O(0.01-1).



Ibe, Shinbara, Yanagida, hep-ph/0608127

See also Harigaya, Ibe, Yanagida 1311.1898

The gravitino mass

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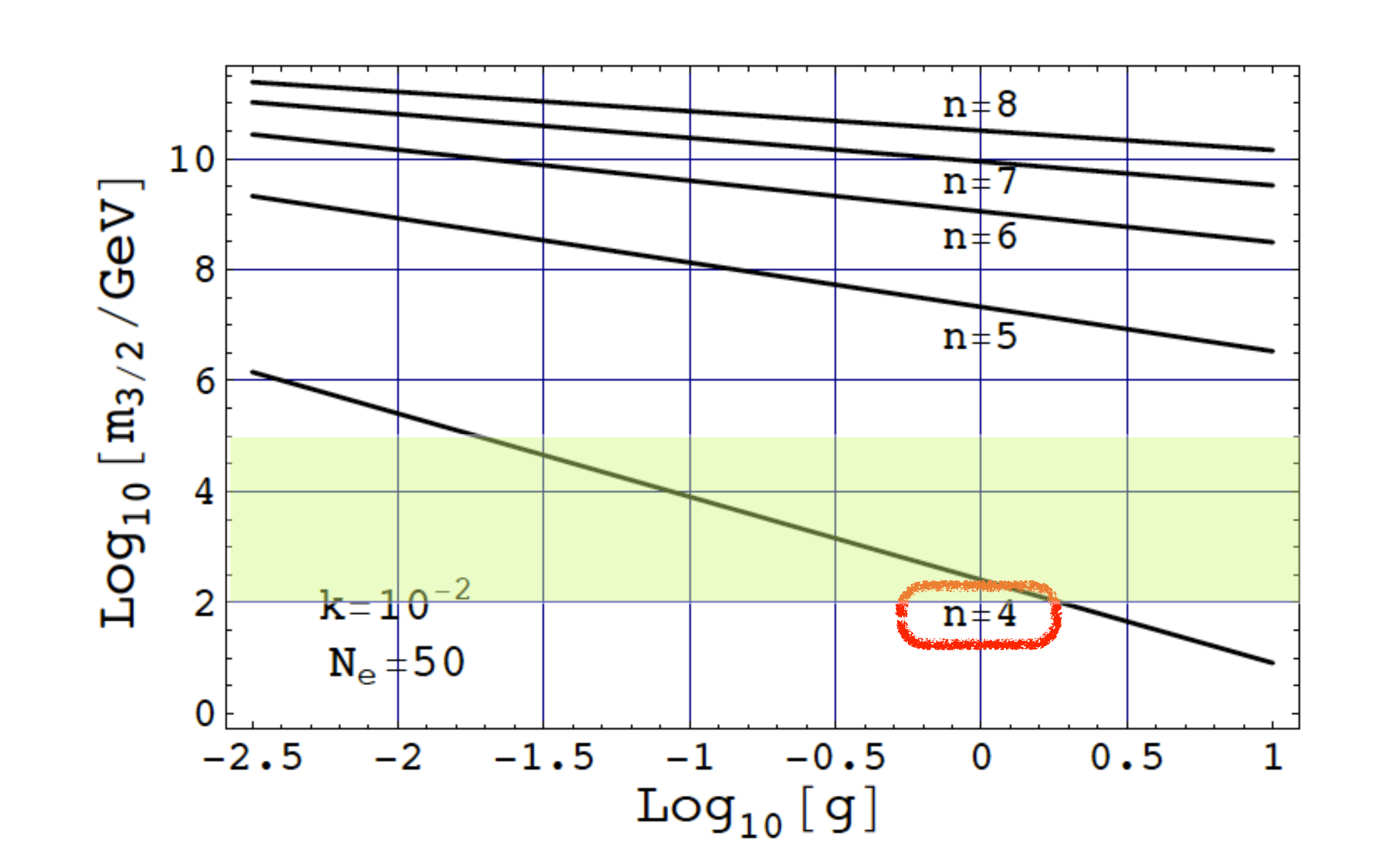

Ibe, Shinbara, Yanagida, hep-ph/0608127

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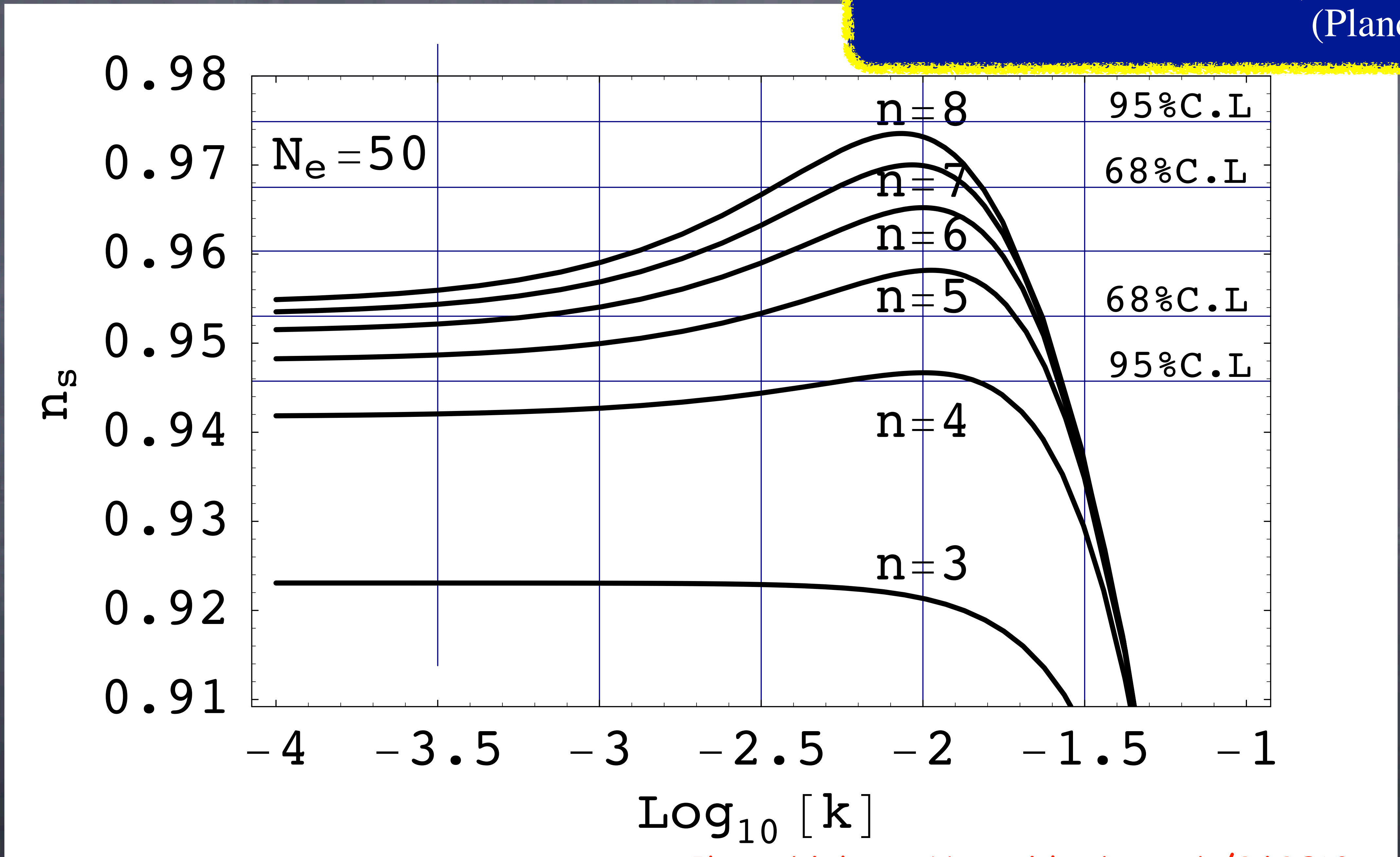
Spectral index

$$n_s = 0.9603 \pm 0.0073 \ (68\%\text{C.L.})$$
(Planck)



Ibe, Shinbara, Yanagida, hep-ph/0608127

However, n_s tends to be too low for n=4.

So far the constant in W was set to be zero. However, a tiny tadpole, if exists, will have a significant impact on the inflaton dynamics.

$$K(\phi, \phi^\dagger) = |\phi|^2 + \frac{k}{4}|\phi|^4 + \cdots$$

$$W = \mu^2\phi - \frac{g}{n+1}\phi^{n+1} + c$$

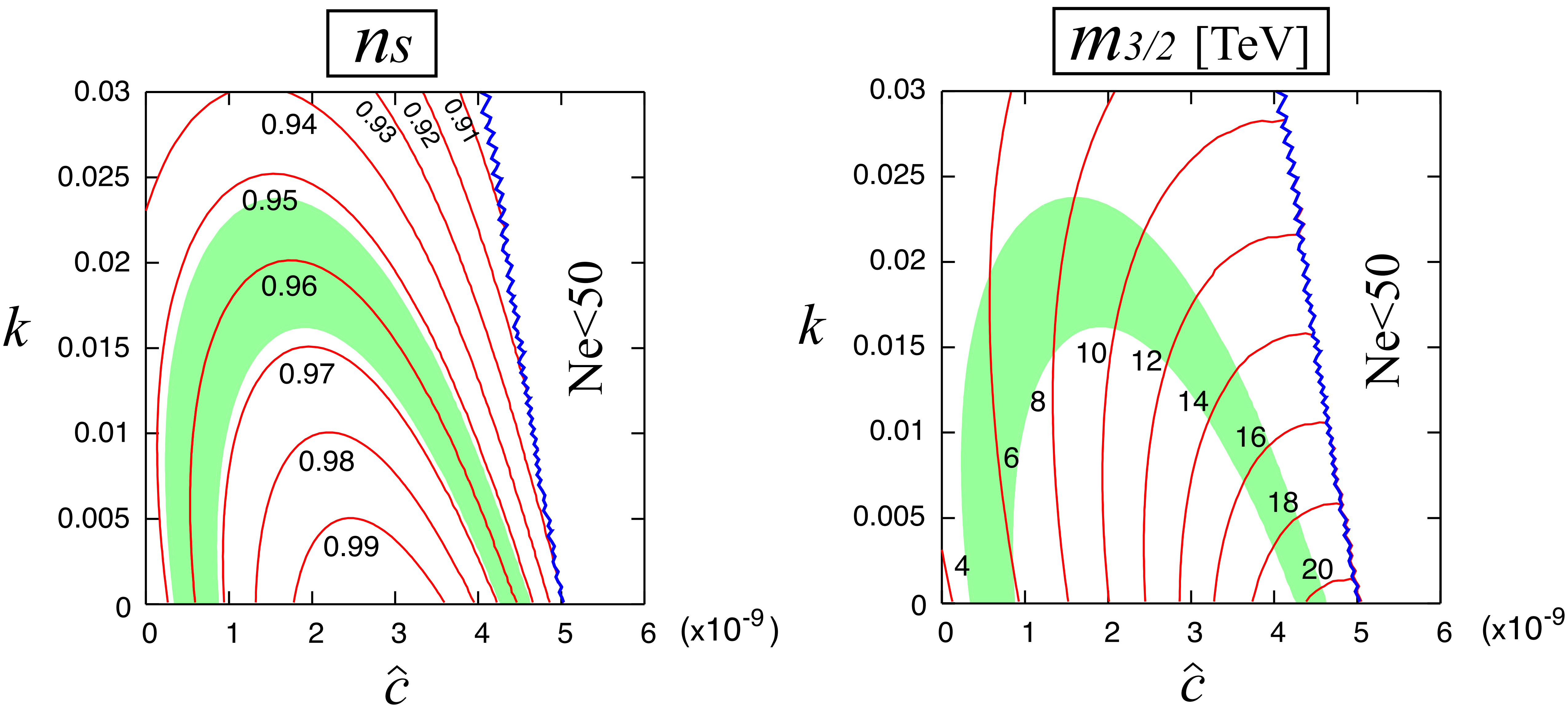
$c \ll m_{3/2}$

- In fact, the spectral index can be increased.

FT, 1308.4212

$$\langle \phi \rangle = 3 \times 10^{15}\,\mathrm{GeV}$$

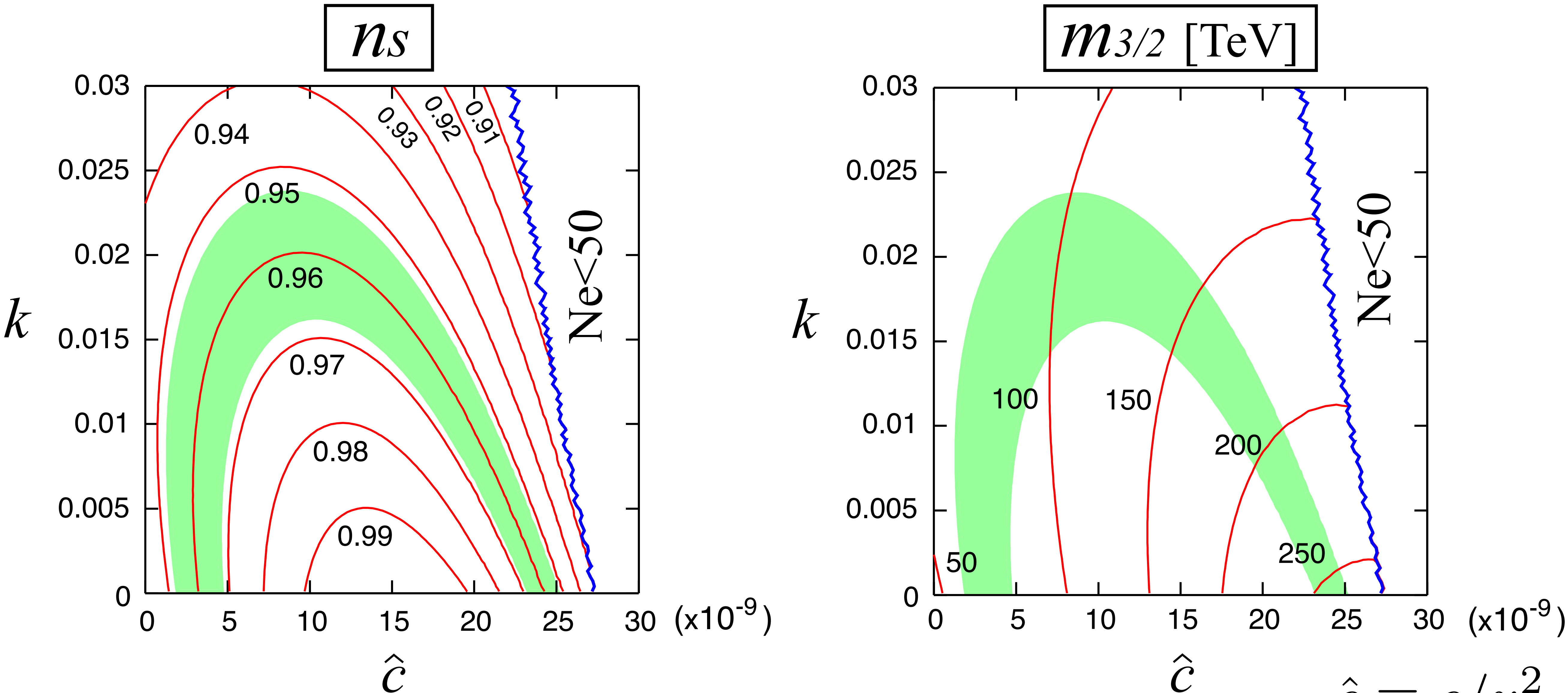
FT, 1308.4212



$$\hat{c} \equiv c/v^2$$

$\langle \phi \rangle = 7 \times 10^{15}\,\mathrm{GeV}$

FT, 1308.4212

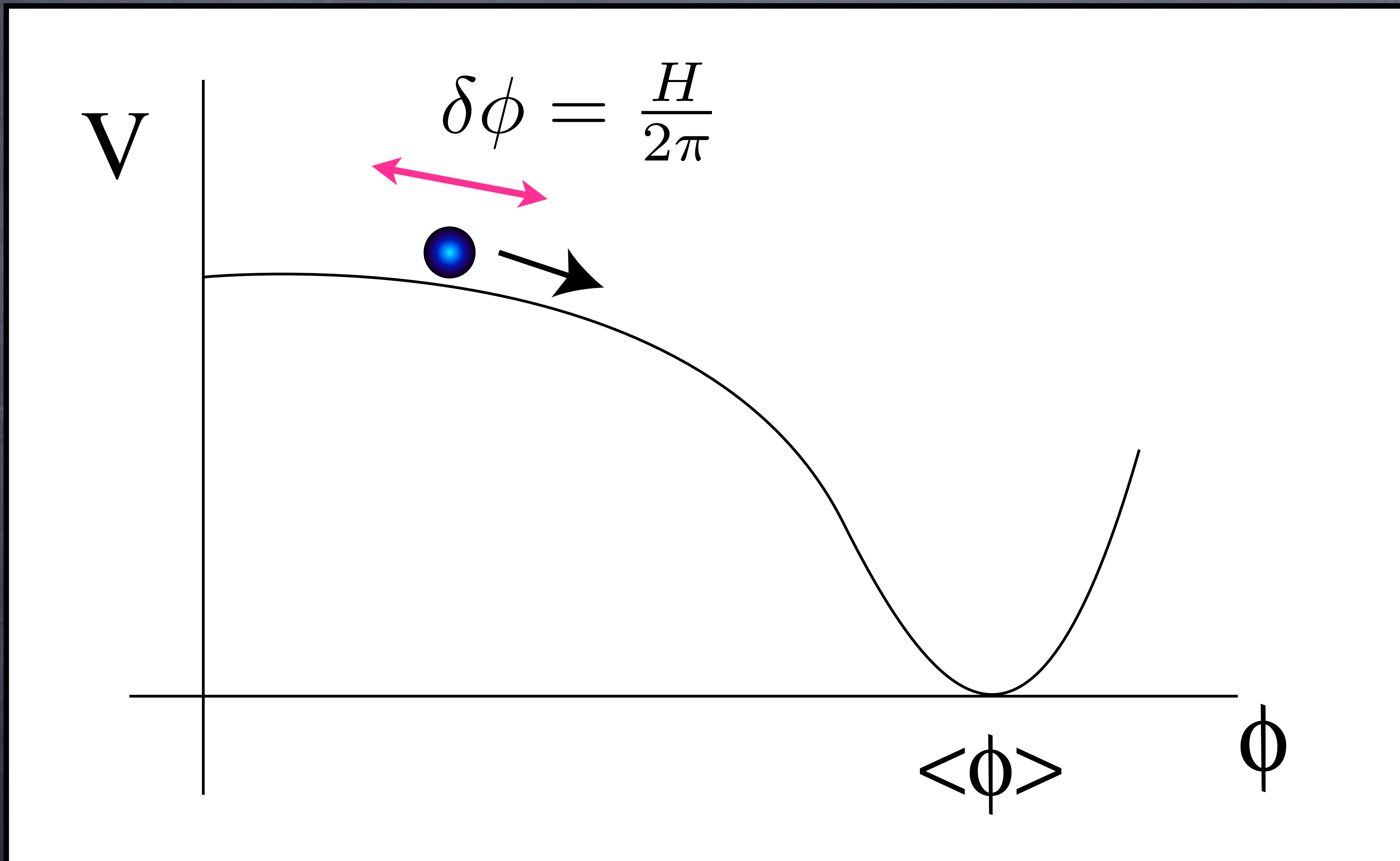


$\hat{c} \equiv c/v^2$

- New inflation -

- The inflaton tadpole problem is avoided if W_0 is absent during inflation.
- $m_{3/2}$ is fixed by the inflaton vev, and O(1-100)TeV gravitino is realized for the case of n=4.
- Still, the tiny tadpole can have a significant impact on the inflaton dynamics, and n_s = 0.96 can be realized in the case of n=4.

3. B-L Higgs New inflation



Let us consider an extension of SM,

SM + RH neutrinos + U(1)B-L

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SM + RH neutrinos + U(1)B-L

The seesaw mechanism

$$m_\nu \sim \frac{\langle h \rangle^2}{M_R}$$

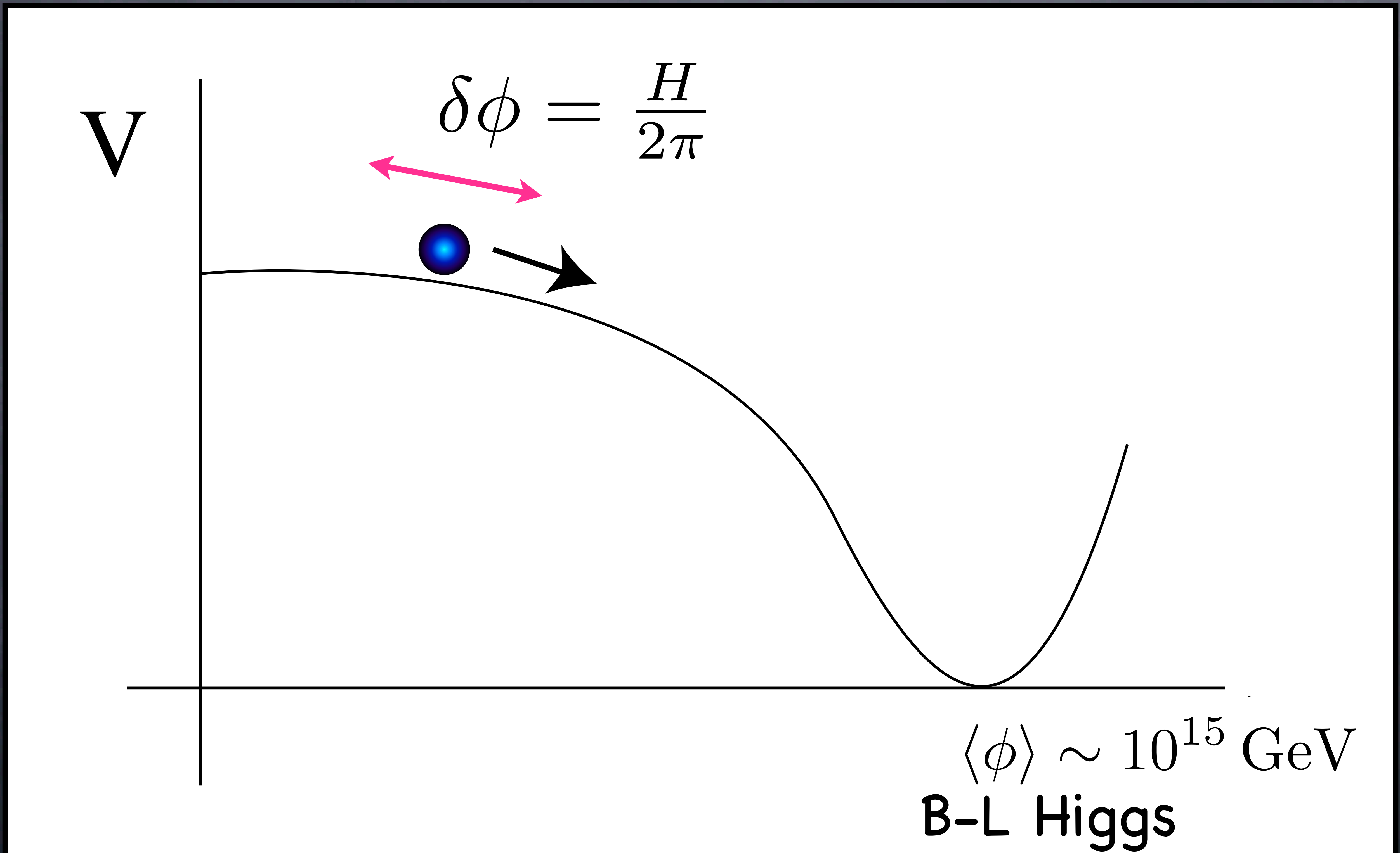
GUT & Charge quantization

T. Yanagida `79, M.Gell-Mann, P.Ramond and R.Slansky `79, Minkowski, `77

$$\mathcal{L} = -\frac{y_N}{2}\phi\,\bar{\nu}_R^c \nu_R + \text{h.c.}.$$

$$M_R \sim \langle \phi \rangle \sim 10^{15}\,\text{GeV}$$

B-L new inflation model



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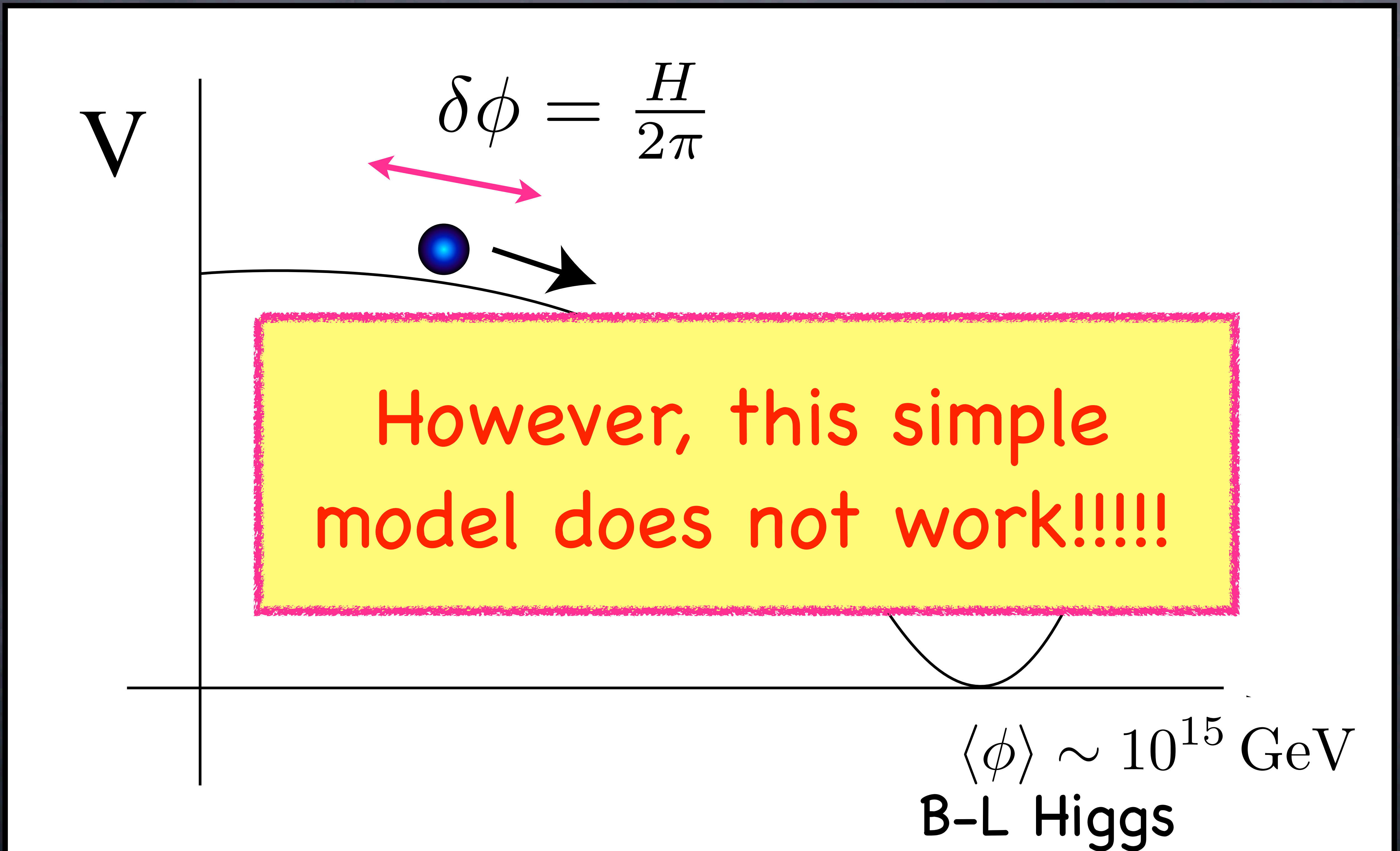

Radiative Correction

$$V_{\rm CW} = \frac{1}{64\pi^2}\sum(-1)^s(2s+1)\,m(\varphi)^4\left(\ln\frac{m(\varphi)^2}{\mu^2} - C\right)$$

The B-L Higgs boson is coupled to the B-L gauge boson, leading to

$$\frac{3}{64\pi^2}g_{\rm B-L}^4 q_\varphi^4 \sigma^4\left(\ln\frac{g_{\rm B-L}^2 q_\varphi^2 \sigma^2}{\mu^2} - \frac{5}{6}\right),$$

$$\sigma \equiv \sqrt{2}|\varphi|$$

The potential is so steep that the density perturbation becomes too large!!

Hawking `82, Starobinsky `82, Guth and Pi `82.

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Solutions

1. Gauge singlet inflaton.

2. SUSY

Hawking, `82

Ellis, Nanopoulos, Olive and Tamvakis `83

Let us introduce SUSY and derive the upper bound on the SUSY breaking for the B-L Higgs inflation to work.

In SUSY, two Higgs are required for anomaly cancellation.

$$\Phi(+2), \quad \bar{\Phi}(-2)$$

We identify the inflaton with the D-flat direction

$$|\Phi| = |\bar{\Phi}| = |\varphi|/\sqrt{2}$$

Bosons

✓ B-L gauge boson

$$m_B^2 = g_{\mathrm{B-L}}^2 q_\varphi^2 \sigma^2$$

Fermions

✓ B-L gaugino

$$m_F = g_{\mathrm{B-L}} q_\varphi \sigma \pm \frac{1}{2} M_\lambda$$

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$$|\Phi| = |\bar{\Phi}| = |\varphi|/\sqrt{2}$$

Bosons

✓ B-L gauge boson

$$m_B^2 = g_{\mathrm{B-L}}^2 q_\varphi^2 \sigma^2$$

Fermions

✓ B-L gaugino

$$m_F = g_{\mathrm{B-L}} q_\varphi \sigma \pm \frac{1}{2} M_\lambda$$

soft SUSY breaking mass

Then the CW potential is partially cancelled,

$$V^{\rm susy}_{\rm CW,gauge}(\sigma) \simeq \frac{g_{\rm B-L}^2}{8\pi^2}\left(\frac{q_\varphi}{2}\right)^2 M_\lambda^2\sigma^2\left(1-3\ln\frac{g_{\rm B-L}^2 q_\varphi^2\sigma^2}{\mu^2}\right).$$

Requiring that the curvature of the potential be smaller than the Hubble parameter, we obtain

$$M_\lambda \lesssim O(0.1) H_{\rm inf}$$

Nakayama and FT 1108.0070, 1203.0323

Similar bound on the soft breaking mass of the RH sneutrino: $m_{\tilde{N},3} \lesssim O(0.1) H_{\rm inf}$

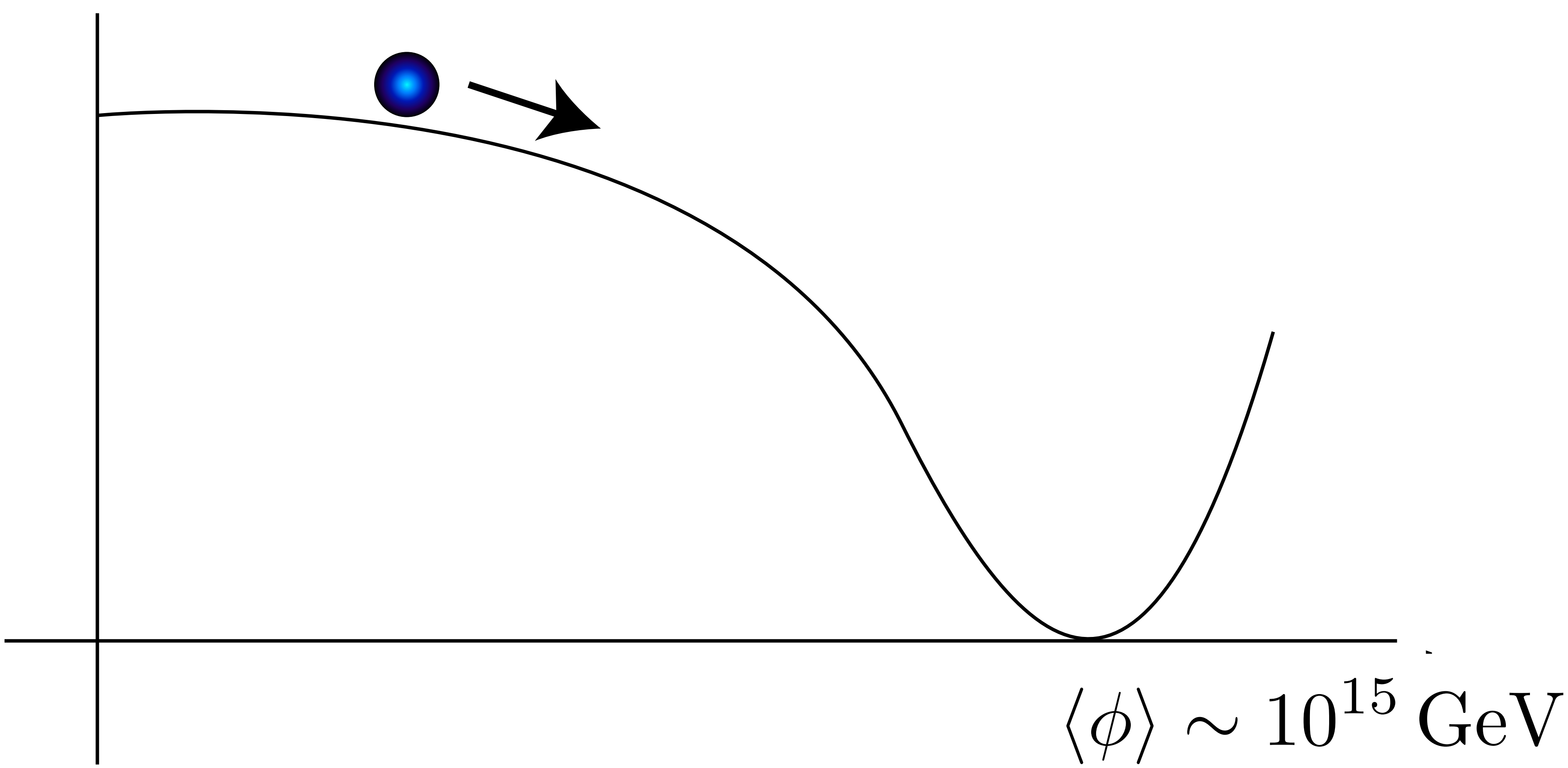
B-L Higgs new inflation model

$$K = |\phi|^2 + |S|^2 + \frac{\kappa_1}{4}|\phi|^4 + \kappa_2|\phi|^2|S|^2 + \frac{\kappa_3}{4}|S|^4,$$

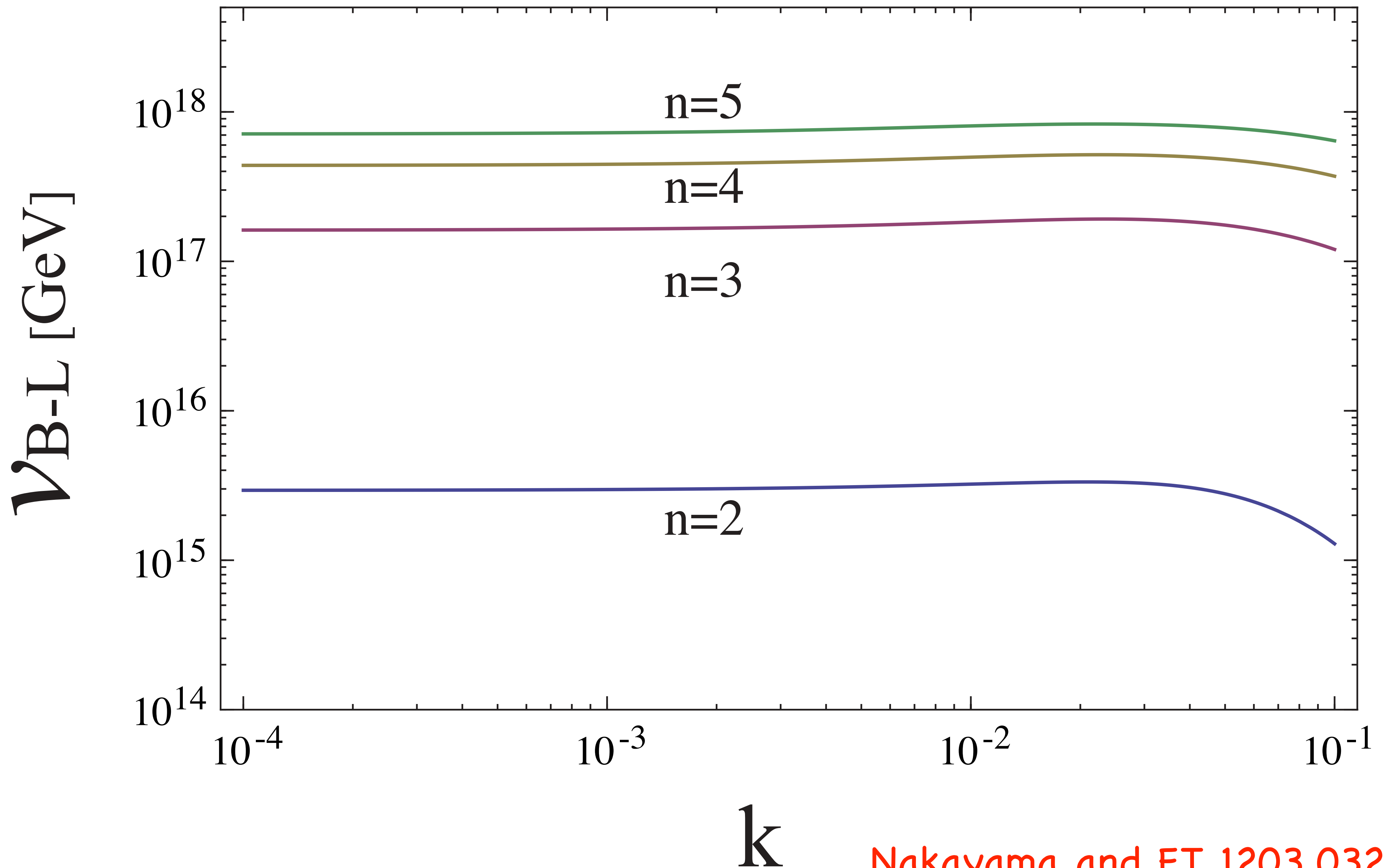
$$W = S\left(v^2 - k\phi^{2n}\right), \qquad \phi^2 \equiv \Phi\bar{\Phi}$$

Asaka et al `99
Senoguz and Shafi, `04

$$V(\phi) \simeq v^4 - m_0^2|\phi|^2 - kv^2(\phi^{2n} + \phi^{*2n}) + k^2|\phi|^{4n}$$



B-L breaking scale (inflaton VEV) is fixed by the COBE normalization.



Nakayama and FT 1203.0323

n=2 is special because $v_{B\text{-}L}$ is close to the see-saw scale.

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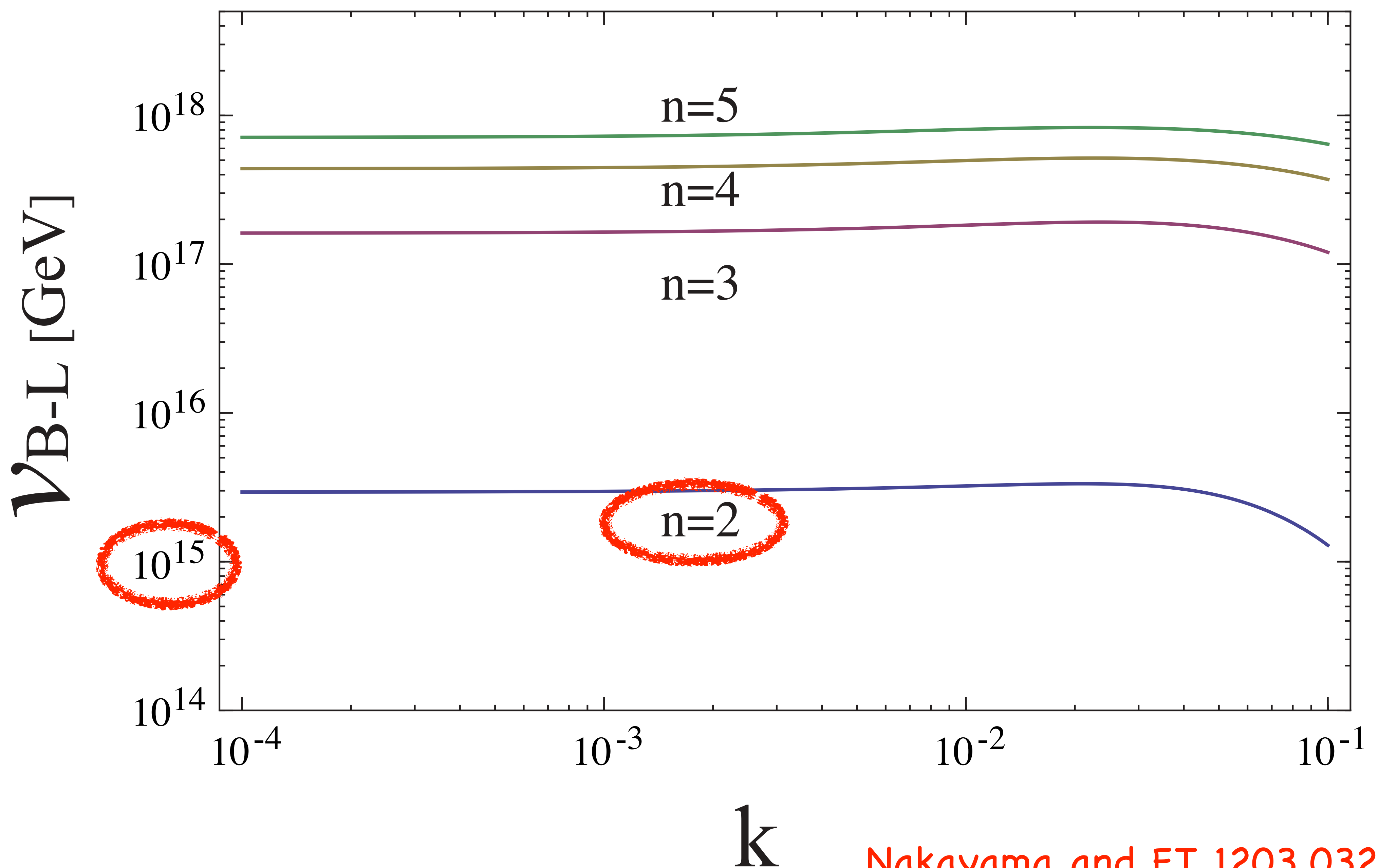

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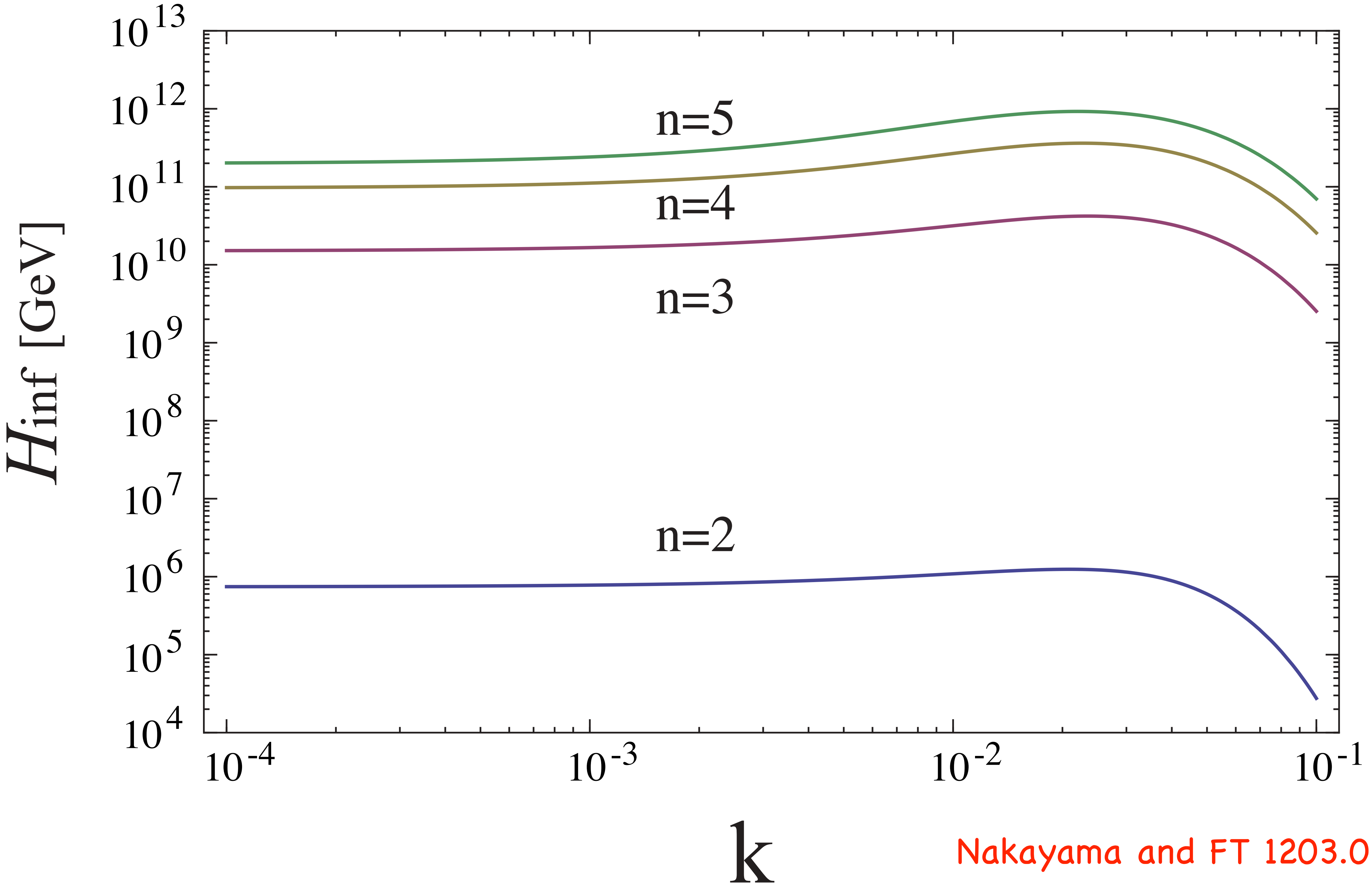
Inflation scale



Nakayama and FT 1203.0323

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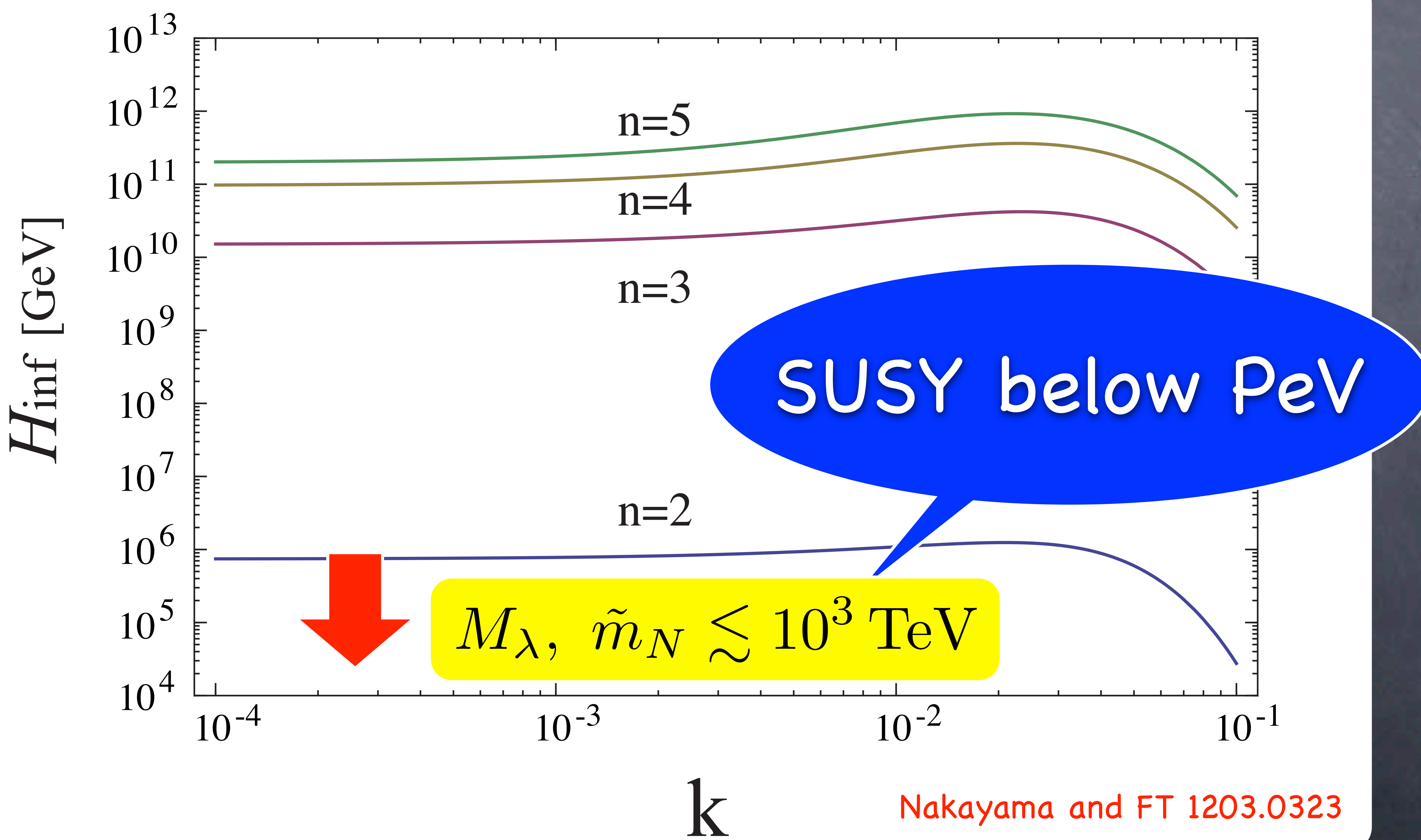


- B-L Higgs inflation -

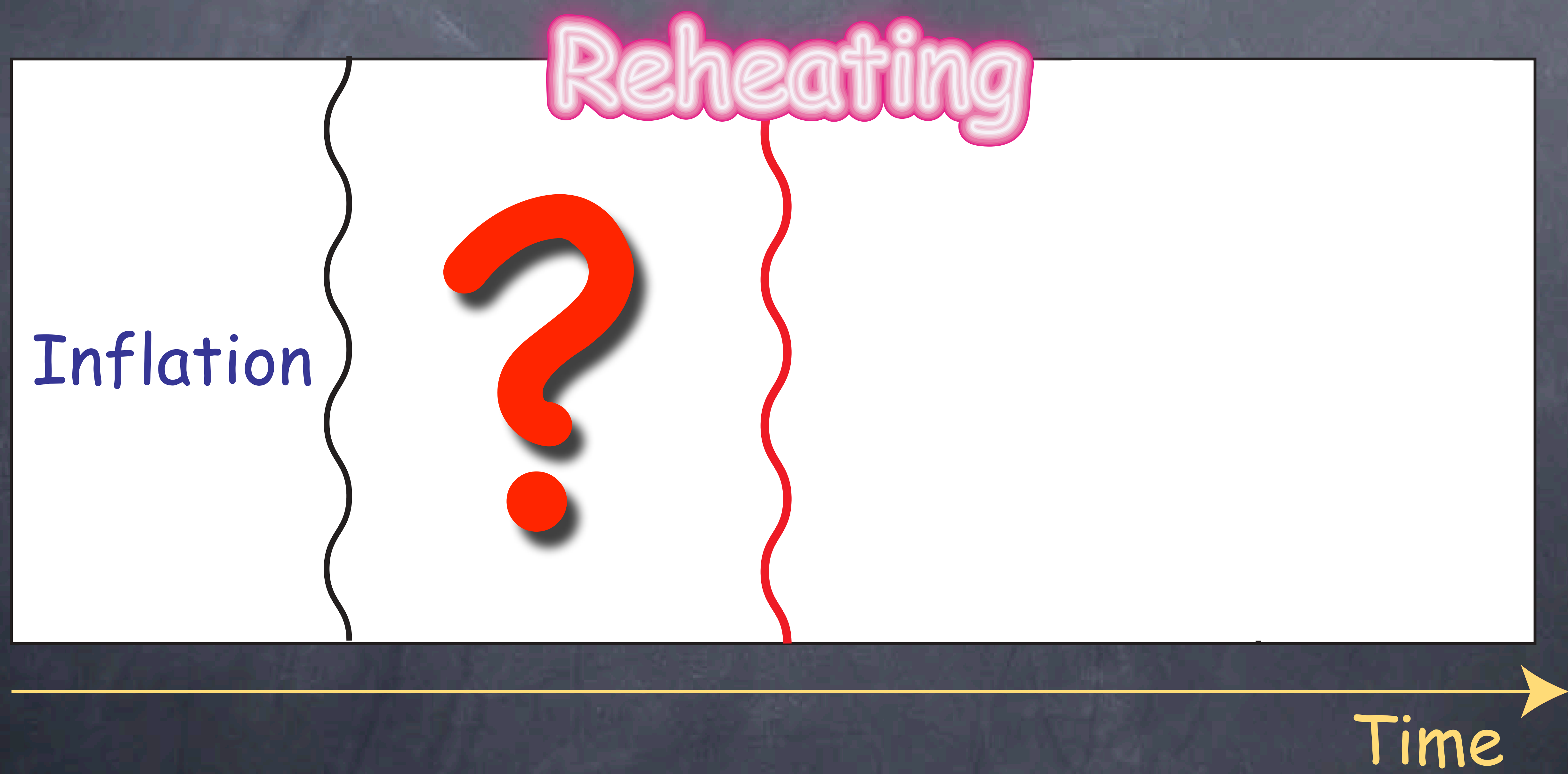
- The sot SUSY breaking mass should be below PeV to suppress the radiative corrections.

- The B-L breaking scale is fixed to be of order 10^{15}GeV by COBE normalization.

- Non-thermal leptogenesis is possible.

3. Reheating

Reheating



Reheating

2013年12月4日水曜日

How to reheat our Universe?

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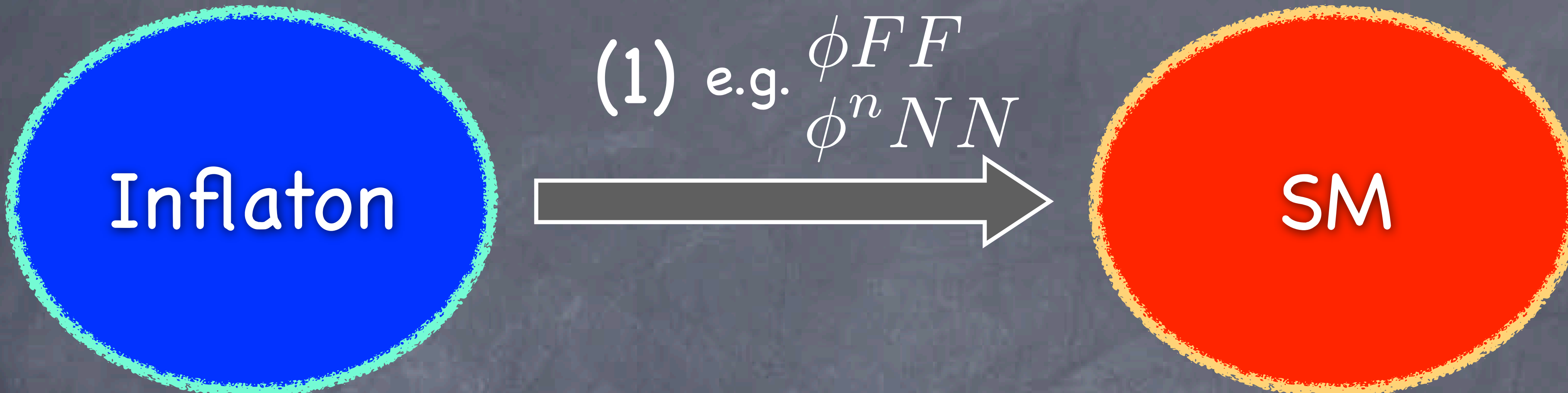
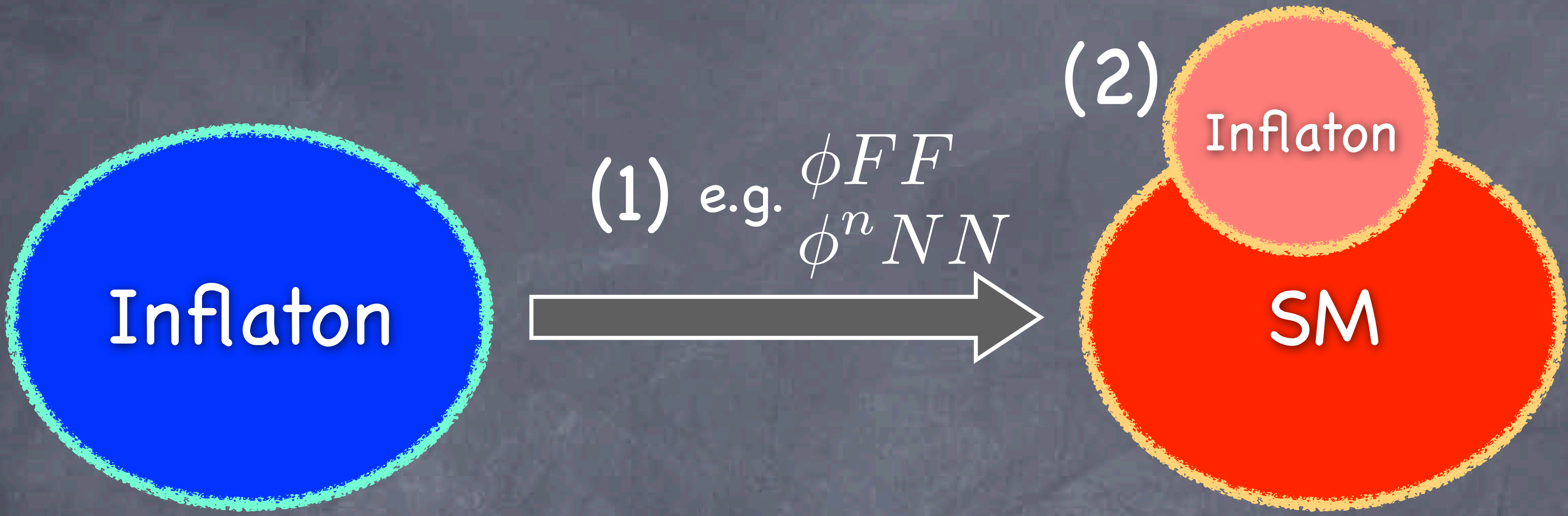


(1) Add couplings by hand.

How to reheat our Universe?



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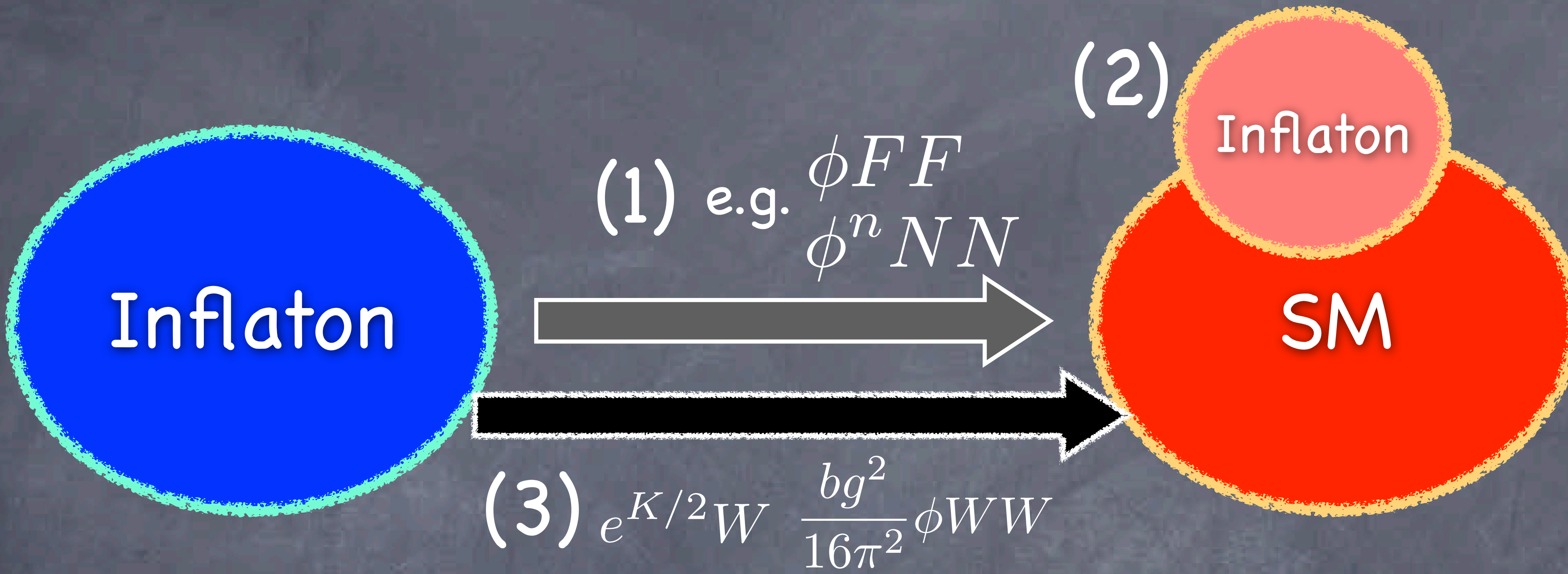

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(3) Through supergravity effects if $\langle K_{\bar{\phi}} \rangle \sim \langle \phi \rangle \neq 0$

Endo, Kawasaki, FT, Yanagida `06
Endo, FT, Yanagida `07

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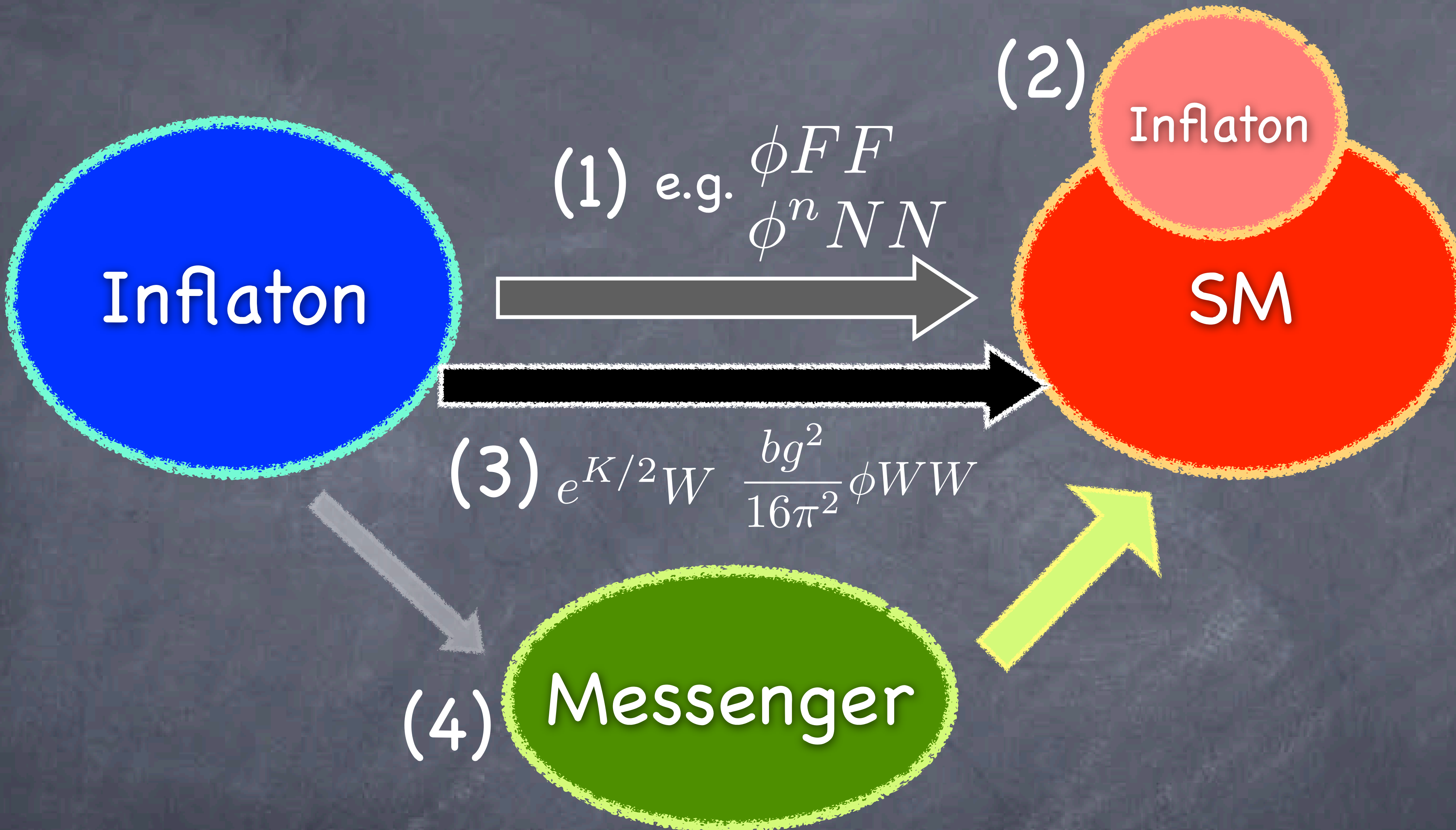


(1) Add couplings by hand.

(2) Inflation in SM or its extension.

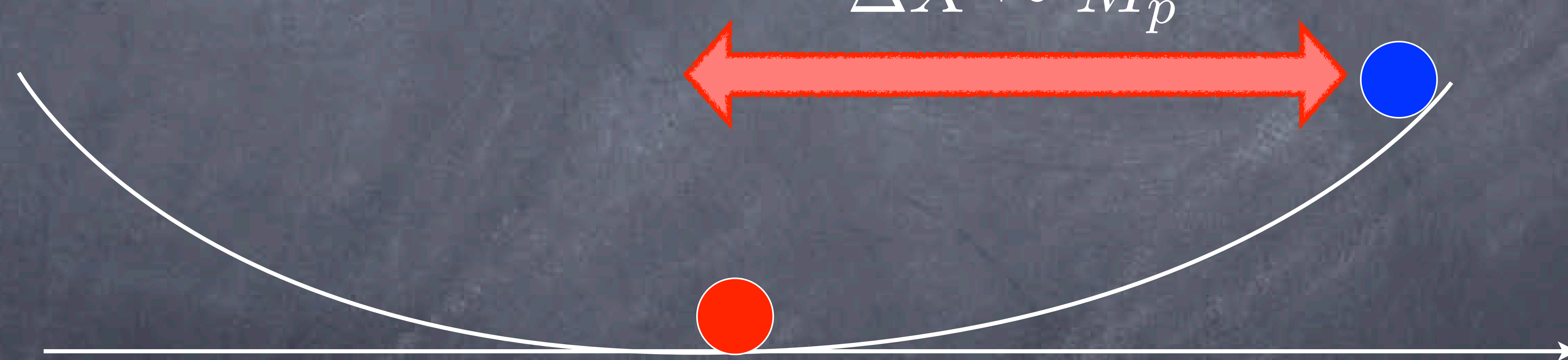
(3) Through supergravity effects if $\langle K_{\bar{\phi}} \rangle \sim \langle \phi \rangle \neq 0$

(4) Reheating messengers: gravitinos, moduli, and saxions.

Endo, Kawasaki, FT, Yanagida `06
Endo, FT, Yanagida `07

Moduli

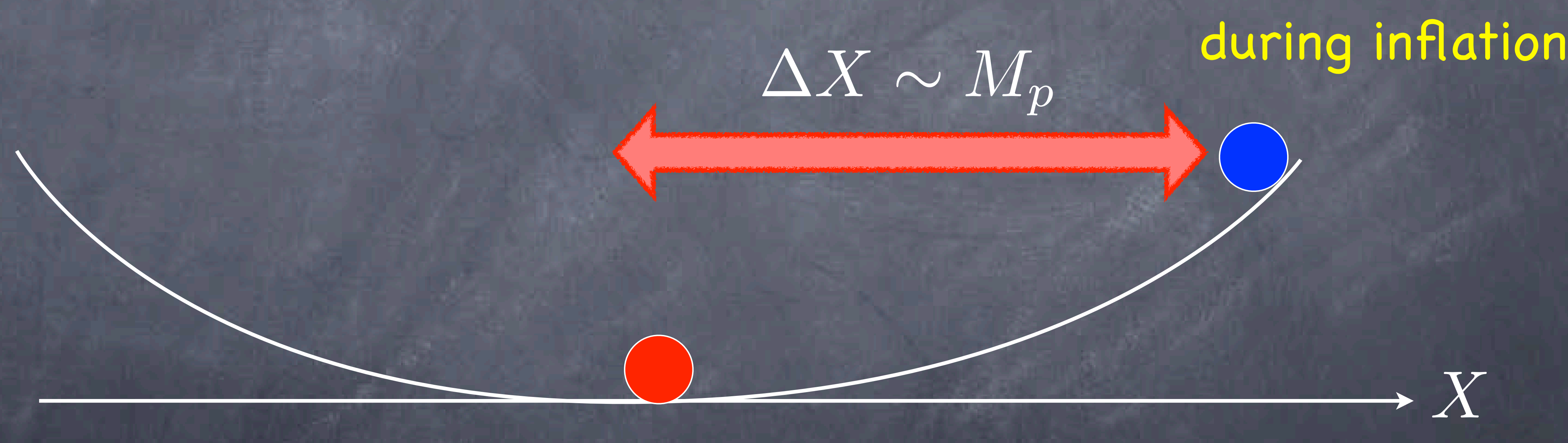
- Ubiquitous in the supergravity/string theory.
- QCD saxion could be one of such moduli.



The moduli dominate the Universe and decay after BBN unless they are very heavier than O(10)TeV.

Moduli

- Ubiquitous in the supergravity/string theory.
- QCD saxion is one of non-SUSY moduli.



The heavy moduli decay before BBN, but dilute any pre-existing baryon asymmetry.

Baryogenesis in modular cosmology

1. Efficient baryogenesis before the modulus decay

e.g. Affleck-Dine mechanism

2. Low-scale baryogenesis after modulus decay

Moduli-induced baryogenesis

Ishiwata, Jeong, FT 1312.????

- The Sakharov conditions for baryogenesis

1. Baryon number violation

2. C and CP violation

3. Departure from thermal equilibrium

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SUSY particles are produced non-thermally by modulus decay

$$\Gamma_X \sim \frac{m_X^3}{M_p^2} \qquad T_d \sim \sqrt{\Gamma_X M_p} \sim m_X \left(\frac{m_X}{M_p}\right)^{\frac{1}{2}} \ll m_{\rm soft}$$

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No helicity suppression for XWW

Endo Hamaguchi FT `06
Nakamura Yamaguchi `06
Endo FT `06

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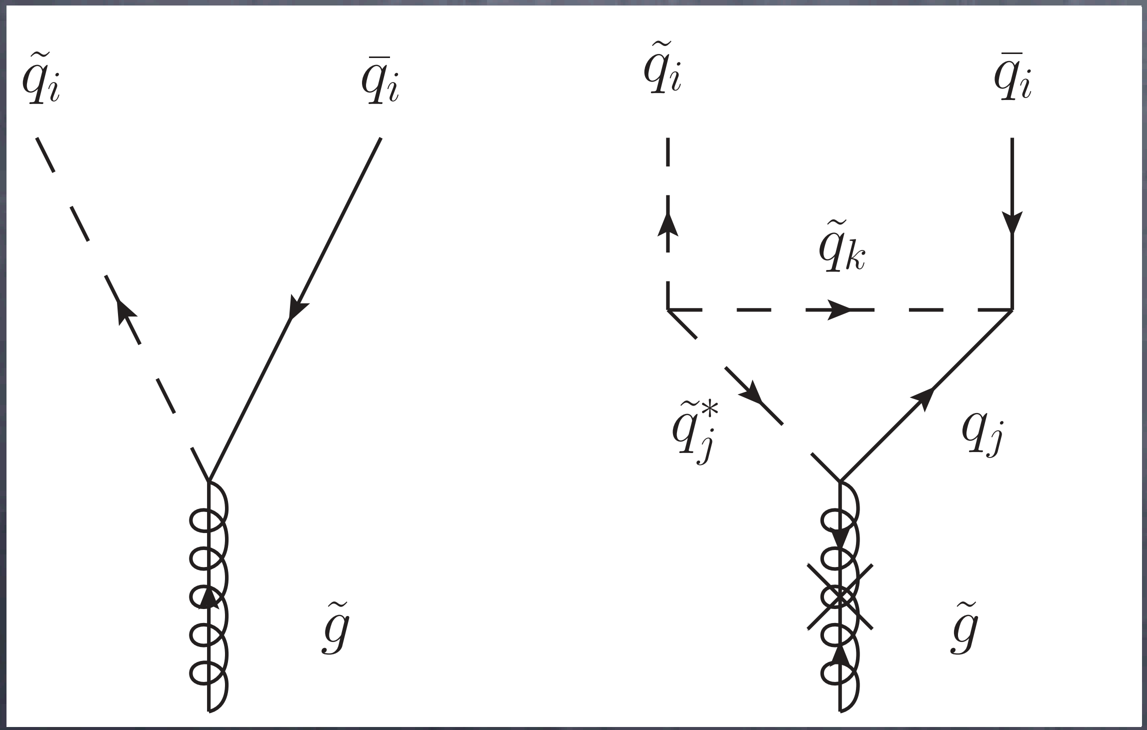
Moduli-induced baryogenesis

Ishiwata, Jeong, FT 1312.????

cf. Cline, Raby `90
Mollerach, Roulet, `91
Krauss et al `13

- Modulus X decays into gluinos.
- The gluinos decay into quarks and squarks, generating CP asymmetry.



$$\Delta\Gamma_{\tilde{g}\to\tilde{q}_i\bar{q}_i} \equiv \Gamma_{\tilde{g}\to\tilde{q}_{Ri}\bar{q}_{Ri}} - \Gamma_{\tilde{g}\to\tilde{q}^*_{Ri}q_{Ri}}$$

$$\frac{\Delta\Gamma_{\tilde{g}}}{\Gamma_{\tilde{g}}} \simeq \frac{|\lambda_{332}|^2}{12\pi}\frac{\mathrm{Im}(A_{332}M^*_{\tilde{g}})}{|M_{\tilde{g}}|^2}.$$

- B-number violating squark decay.

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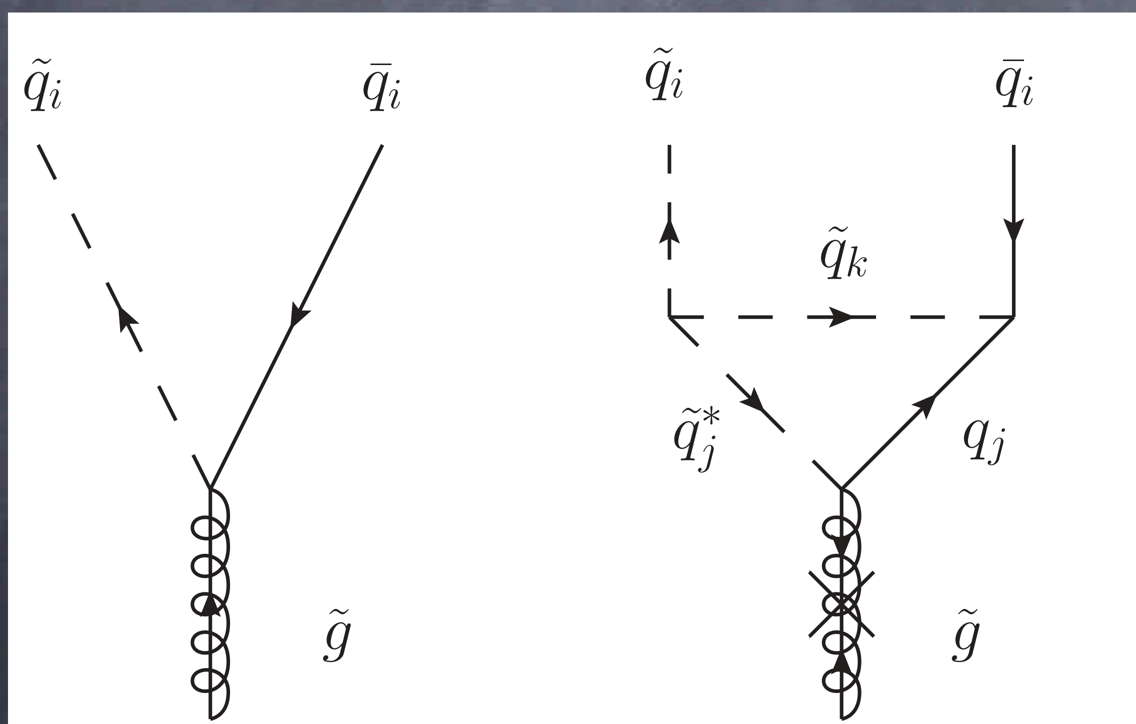

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2013年12月4日水曜日

KKLT moduli stabilization

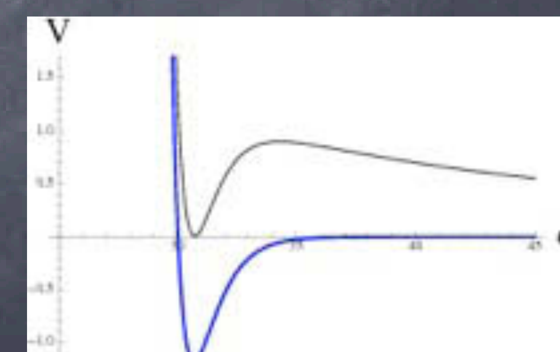
- We consider a mixed modulus-anomaly mediation in KKLT mechanism.

Choi et al, `04 and `05
Endo, Yamaguchi, Yoshioka `05

$$K_0 = -3\ln(X + X^\dagger)$$
$$W_0 = \omega_0 + W_{\rm np}(X)$$

- The moduli stabilized at a SUSY AdS min, and acquires a non-zero F-term due to the up-lift.

$$F^X \sim \frac{m_{3/2}^2}{m_X}$$



- Mass hierarchy:

$$\frac{m_{3/2}}{4\pi^2} \sim m_{\rm soft} \ll m_{3/2} \ll m_X \sim 8\pi^2 m_{3/2}$$

- Anomaly mediation generates CP conserving soft terms.

- In the original KKLT mechanism, the soft mass induced by the modulus F-term preserves CP phase due to $U(1)_R$ and the shift symmetry of X.

$$W_0 = \omega_0 - Ae^{-aX}$$

We can make ω_0 and A real by $U(1)_R$ and $U(1)_X$.

No CP phase!

- So we need at least two exponential terms:

$$W_0 = \omega_0 - Ae^{-aX} - Be^{-bX}$$

$$\omega_0, A \in \mathbf{R} \quad \mathrm{Im}[B] \neq 0$$

Then there is a nonzero CP phase between the modulus and anomaly mediation.

$$\arg(m_{3/2}\langle F^X \rangle) \approx \frac{b(b-a)}{a^2} \left(\frac{m_{3/2}}{M_P} \right)^{\frac{b-a}{a}} \frac{\mathrm{Im}(B)}{A},$$

Soft SUSY breaking terms

$$-\mathcal{L}_{\rm soft} = m_i^2|\phi_i|^2 + \left(A_{ijk} y_{ijk} \phi_i \phi_j \phi_k + \frac{1}{2} M_a \lambda_a \lambda_a + \text{h.c.} \right),$$

$$M_a(\Lambda) = \left\langle \frac{F^X}{X+X^*} \right\rangle + \frac{b_a g_a^2(\Lambda)}{16\pi^2} m_{3/2}^*,$$

$$f_a(\Lambda) = k_a X$$

$$A_{ijk}(\Lambda) = \sum n_i \left\langle \frac{F^X}{X+X^*} \right\rangle - \frac{\sum \gamma_i(\Lambda)}{16\pi^2} m_{3/2}^*;$$

cf. $\dfrac{\Delta\Gamma_{\tilde g}}{\Gamma_{\tilde g}} \simeq \dfrac{|\lambda_{332}|^2}{12\pi} \dfrac{\text{Im}(A_{332} M_{\tilde g}^*)}{|M_{\tilde g}|^2}.$

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Moduli mediation

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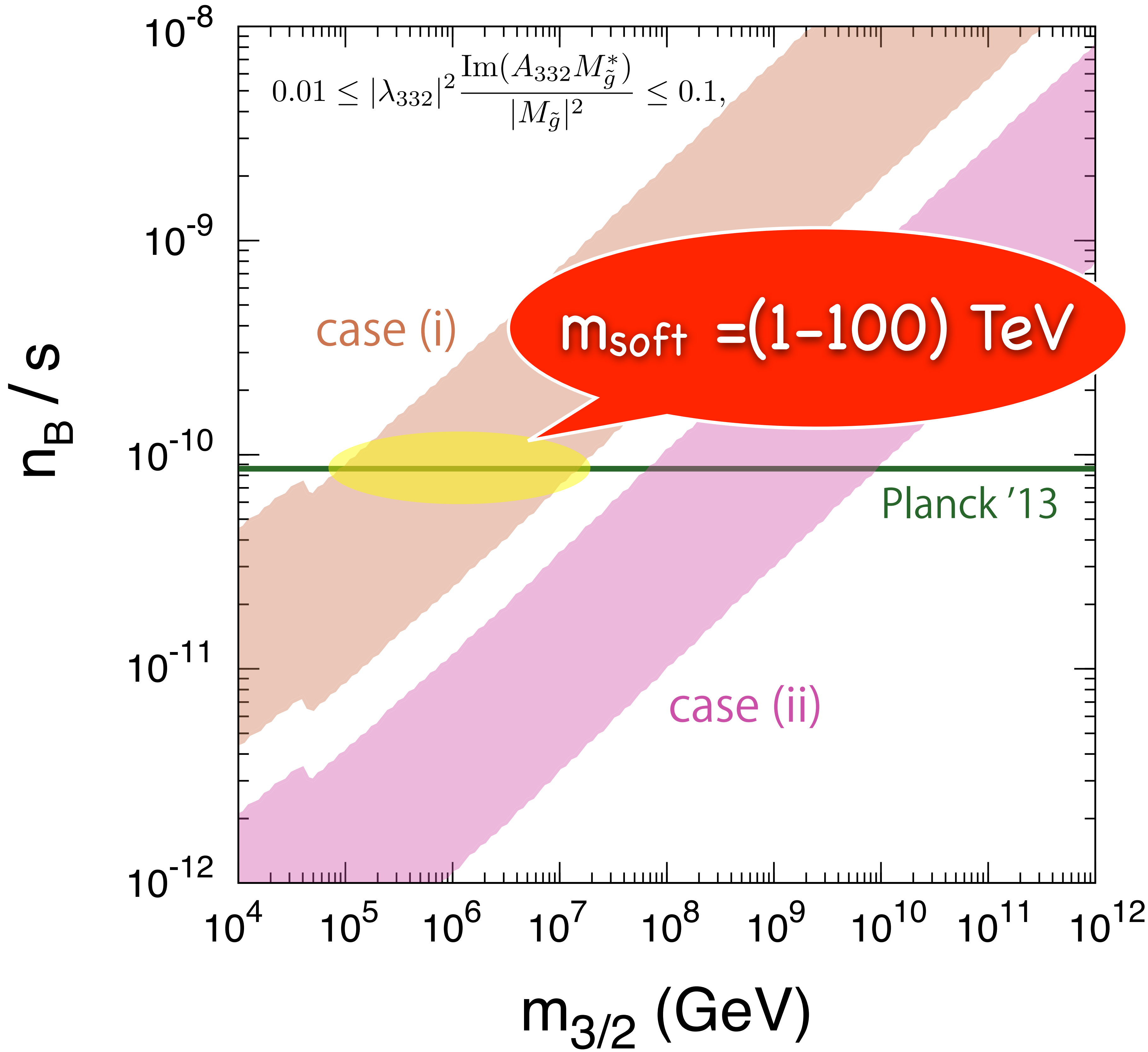

$$(i) M_{\tilde{g}} = 3m_{\rm soft}, \quad m_{\tilde{t},\,\tilde{b},\,\tilde{s}} = m_{\rm soft}, \quad m_{\tilde{q}\neq\tilde{t},\,\tilde{b},\,\tilde{s}} = 6m_{\rm soft}, \quad \mathrm{Br}^{\tilde{t},\,\tilde{b},\,\tilde{s}} = 0.5,$$

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Experimental bounds

- Neutron and electron EDM:

$$d_n \leq 2.9 \times 10^{-26} e \text{ cm} \quad (90\% \text{ C.L.}).$$
$$d_e \leq 8.7 \times 10^{-29} e \text{ cm} \quad (90\% \text{ C.L.}).$$

$$\Rightarrow \quad \frac{\mathrm{Im}(A_{ijk} M_{\tilde{g}}^*)}{|M_{\tilde{g}}|^2} \lesssim 0.1 \left(\frac{m_{\text{soft}}}{1 \text{ TeV}} \right)^2$$

- Dinucleon decay in ^{16}O

$$\tau(pp \to K^+ K^+) \geq 1.7 \times 10^{32} \text{ yr} \quad (90\% \text{ C.L.}).$$

$$\Rightarrow \quad |\lambda_{112}| \leq 3.2 \times 10^{-7} \left(\frac{m_{\text{soft}}}{1 \text{ TeV}} \right)^{5/2} \left(\frac{250 \text{ MeV}}{\tilde{\Lambda}} \right)^{5/2},$$

N.B. $\lambda_{112} = \mathcal{O}(10^{-7})$ is induced from $\lambda_{332} = 1$

Conclusions

- Inflation might have affected the low-energy observables, especially SUSY breaking scale.
  - In some inflation models, the SUSY breaking is bounded above, $m_{3/2} < O(100)$TeV, or fixed by the inflaton dynamics as $m_{3/2} = O(10\text{-}100)$TeV.
- The reheating is crucial for baryogenesis and dark matter production.
- Reheating messengers: moduli, saxion, gravitino.
  - Moduli-induced baryogenesis is possible for $m_{soft} = O(1\text{-}100)$TeV.