# Symmetry Breaking in supergravity inflation and the Early Universe

DESY theory seminar, 7.11.2011

Kohei Kamada (Tokyo -> DESY)

based on the work with K. Nakayama, J. Yokoyama
(and work in progress with Y. Miyamoto and J. Yokoyama)

# Self introduction: once more

Name: Kohei Kamada (鎌田耕平)

Research interest: Particle Cosmology

(Relation between the early Universe and high energy physics)

-Scalar field dynamics along the (MSSM) flat direction;

Affleck-Dine mechanism, thermal effects

-Symmetry breaking in the early Universe and Topological defects (1110.3904)

-Effect of SUSY breaking sector in the early Universe (1103.5097)

-Scalar field with higher order derivative coupling; G-inflation (1012.4238)

# Self introduction: once more

Name: Kohei Kamada (鎌田耕平)

Research interest: Particle Cosmology

(Relation between the early Universe and high energy physics)

-Scalar field dynamics along the (MSSM) flat direction;
Affleck-Dine mechanism, thermal effects

-Symmetry breaking in the early Universe and Topological defects (1110.3904)

-Effect of SUSY breaking sector in the early Universe (1103.5097)

-Scalar field with higher order derivative coupling; G-inflation (1012.4238)

# Contents

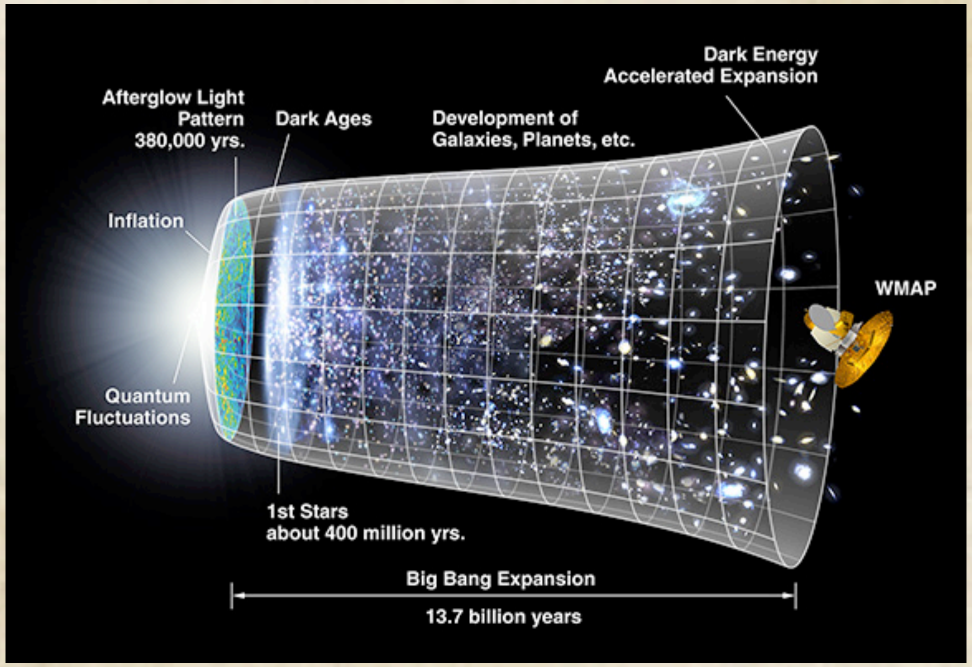
-Topological Defects

-Phase Transition in the Early Universe

-Constraint on the Symmetry Breaking Scale

(Early) Universe needs
physics beyond standard model (BSM)

- -Inflation
- -Baryogenesis
- -Dark matter
- -Dark energy




WMAP

Early Universe is a good laboratory
of the high energy physics/BSM

# Beyond the standard model?

- supersymmetry(SUSY)
  - hierarchy problem
  - dark matter candidate
- gauged $U(1)_{B-L}$
  - neutrino mass
- Grand Unified Thoeries (GUTs)

When are these symmetries, if ever, broken in the cosmic history?

# In this talk...

I will concentrate on the spontaneous breaking of GUTs and other intermediate symmetries based on the supersymmetric theories.

$$
\begin{aligned}
SU(5) &\to SU(3)_c \times SU(2)_L \times U(1)_Y \\
SO(10) &\to SU(4)_c \times SU(2)_R \times SU(2)_R \\
&\to SU(3)_c \times SU(2)_L \times U(1)_Y \\
SO(10) &\to SU(4)_c \times SU(2)_R \times SU(2)_R \\
&\to SU(3)_c \times SU(2)_L \times U(1)_R \times U(1)_{B-L} \\
&\to SU(3)_c \times SU(2)_L \times U(1)_Y \\
&\quad\vdots
\end{aligned}
$$

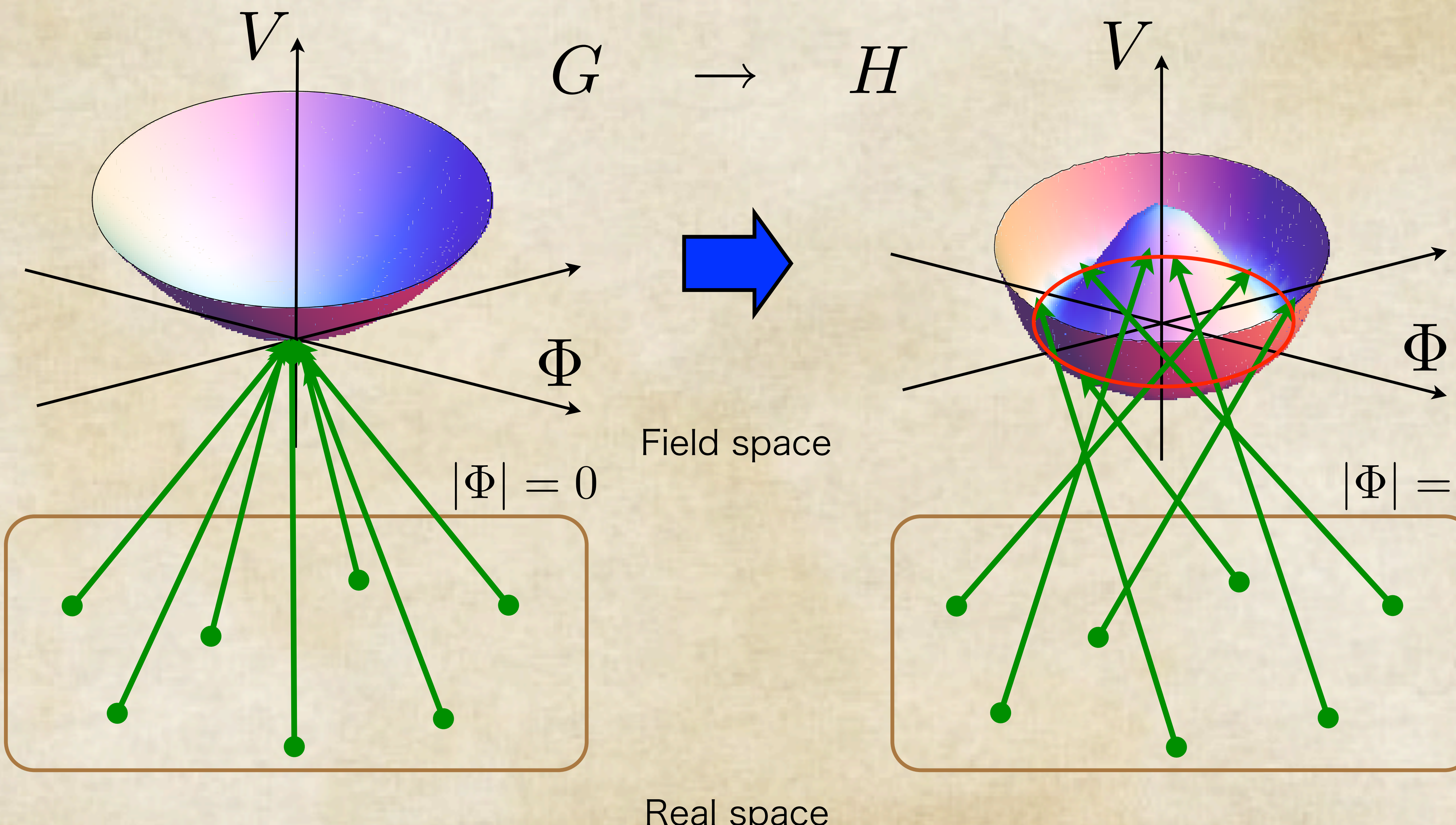
When a symmetry is broken, topological defects such as (magnetic) monopoles, cosmic strings, domain walls may be formed.

Kibble mechanism (Kibble '76)

When a symmetry is broken, topological defects such as (magnetic) monopoles, cosmic strings, domain walls may be formed.

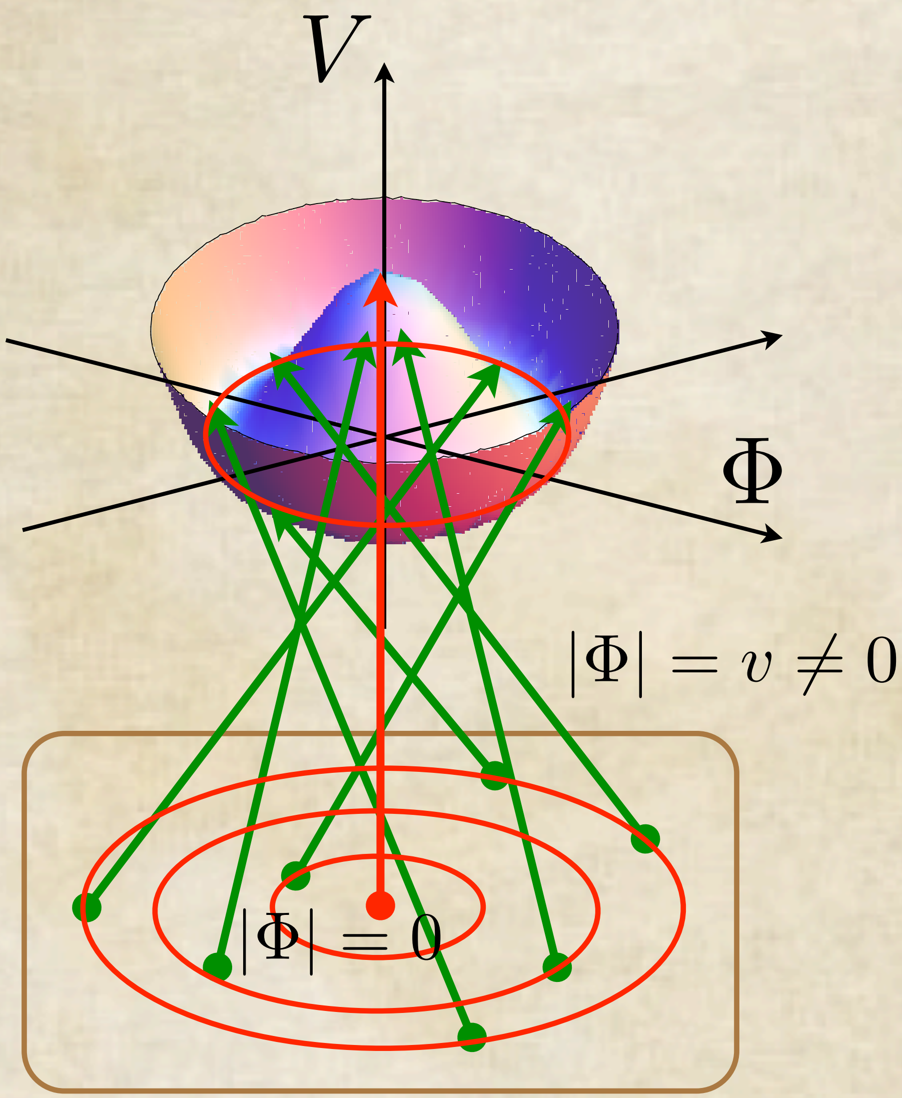
Kibble mechanism (Kibble '76)

Symmetry breaking



When a symmetry is broken, topological defects such as (magnetic) monopoles, cosmic strings, domain walls may be formed.

Kibble mechanism (Kibble '76)

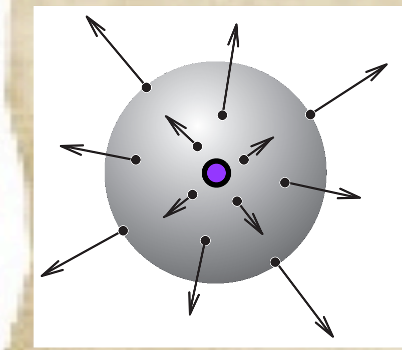



Higgs field in the vacuum manifold distributes randomly at the scale larger than the correlation scale.

There must be a point where Higgs field cannot fall down to the vacuum, $|\Phi| = 0$ , from the topological reason.
(At that point, the energy density remains high. )

Such field configuration is topologically stable and hence we call it "topological defects".

# There are several types of topological defects.

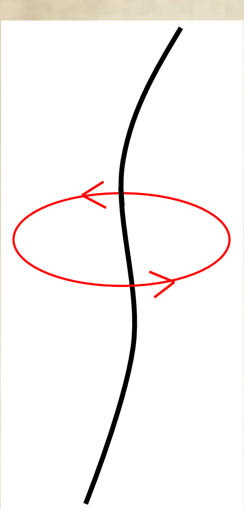


(magnetic) monopoles:

Point-like topological defect.

They are formed when the vacuum manifold is $S^2$ or $\pi_2(G/H) \neq 0$ .

Inevitable in the GUT breaking into $G_{\rm SM}$ because it contains $U(1)_Y$.



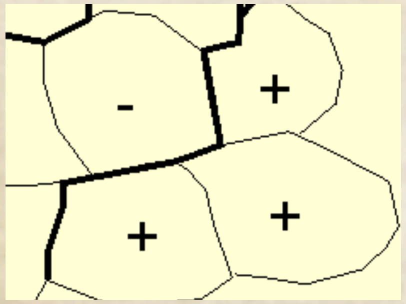
Cosmic strings:

String-like topological defect.

They are formed when the vacuum manifold is $S^1$ or $\pi_1(G/H) \neq 0$.

Produced at the breaking of $U(1)_{B-L}$ and other $U(1)$ symmetries.

Domain walls:




Sheet-like topological defect.

They are formed when the vacuum manifold is disconnect.

# What kind of topological defects are formed?

e.g.) R. Jeannerot+ ('03)

$$
4_{\rm C}\ 2_{\rm L}\ 2_{\rm R}
\begin{cases}
\xrightarrow{1} \ 3_{\rm C}\ 2_{\rm L}\ 2_{\rm R}\ 1_{\rm B-L}
\begin{cases}
\xrightarrow{1} \ 3_{\rm C}\ 2_{\rm L}\ 1_{\rm R}\ 1_{\rm B-L} \xrightarrow{2\ (2)} {\rm G}_{\rm SM}\ (Z_2) \\
\xrightarrow{2'\ (2)} \ {\rm G}_{\rm SM}\ (Z_2)
\end{cases} \\
\xrightarrow{1} \ 4_{\rm C}\ 2_{\rm L}\ 1_{\rm R}
\begin{cases}
\xrightarrow{1} \ 3_{\rm C}\ 2_{\rm L}\ 1_{\rm R}\ 1_{\rm B-L} \xrightarrow{2\ (2)} {\rm G}_{\rm SM}\ (Z_2) \\
\xrightarrow{2'\ (2)} \ {\rm G}_{\rm SM}\ (Z_2)
\end{cases} \\
\xrightarrow{1} \ 3_{\rm C}\ 2_{\rm L}\ 1_{\rm R}\ 1_{\rm B-L} \xrightarrow{2\ (2)} {\rm G}_{\rm SM}\ (Z_2) \\
\xrightarrow{1\ (1,2)} \ {\rm G}_{\rm SM}\ (Z_2)
\end{cases}
$$

1. monopoles
2. cosmic strings

# Effects of topological defects in cosmology

Magnetic monopoles:

Their formation would be a disaster since they may overclose the Universe. If some dilution mechanism takes place, they may be detected by future experiments. (One of the main motivations of inflation)

Cosmic strings:

They enter so-called “scaling regime” (Explain later!) and do not overclose the Universe. It may contribute to the Cosmic Microwave Background Radiation (CMB) and Gravitational Wave Background (GWB).

Domain walls:

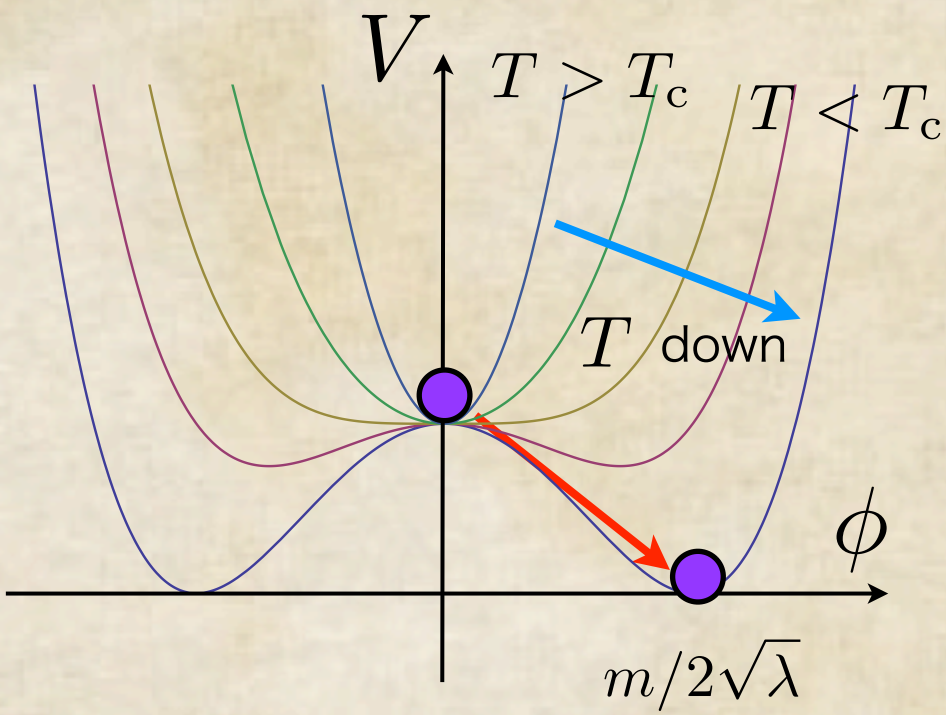
They may overclose the Universe and their formation is a disaster. Dilution mechanism is required, if ever.

# How topological defects are formed?

Thermal phase transition

Consider the Higgs potential including thermal correction
(Remember Mathias' workshop seminar!)

$$V_{\mathrm{eff}}(\phi, T) \sim \left( h^2 T^2 - \frac{1}{2} m^2 \right) \phi^2 + \lambda \phi^4$$




Phase transition takes place at $T \sim T_c \equiv m/\sqrt{2}h$.

Correlation length: $\xi \sim T^{-1}$

If the temperature of the Universe once high enough, this may be a disaster.
However, we can avoid this problem with inflation & low reheating temperature.

cf: $T_R < 10^{6-9}\mathrm{GeV}$ is required to avoid gravitino problem.

# Hubble induced mass driven phase transition

cf.)Shafi+('84), Vishniac+('87),Kofman+('87),Yokoyama('88,'89), Freese('96)

There is another possibly INEVITABLE phase transition in supersymmetric (supergravity) F-term inflation.

For definiteness, let us consider the following superpotential:

$$W = \kappa S(\Phi\bar{\Phi} - M^2) + W_{\rm inf}$$

This system has a global minimum at $\Phi\bar{\Phi} = M^2, \quad S = 0$ .

The effective potential during inflation reads,

$$V(\Phi, \bar{\Phi}) = \underline{3H^2(|\Phi|^2 + |\bar{\Phi}|^2)} + \kappa^2|\Phi\bar{\Phi} - M^2|^2 + \text{D-term}$$

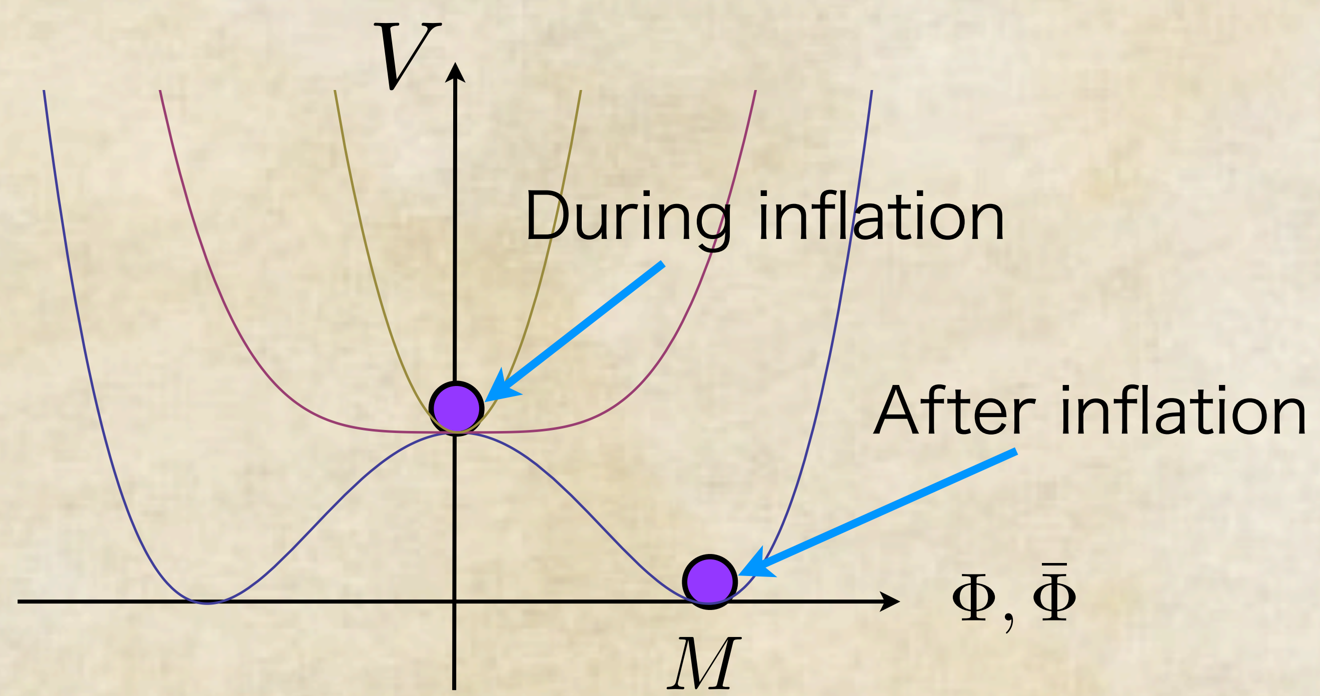
Hubble induced mass

The origin of Hubble induced mass :

$$V = e^K \left[ D_i W K^{i\bar{j}} D_{\bar{j}} W^* - \frac{3}{M_G^2}|W|^2 \right] \ni 3H^2 M_G^2 \exp\left(\frac{|\Phi|^2}{M_G^2}\right)$$

$$\simeq V_{\rm inf} = 3H^2 M_G^2$$

If the Hubble parameter during inflation is larger than the bare Higgs mass, $H_{\rm inf} > \kappa M$ , the symmetry is restored during inflation.



# General condition

$H_{\rm inf} \ll \kappa M$ : Symmetry is broken before inflation.
No significant effects on cosmology.

$H_{\rm inf} \gg \kappa M$ : Symmetry is broken after inflation.
Phase transition associated with monopole or domain wall production is ruled out.

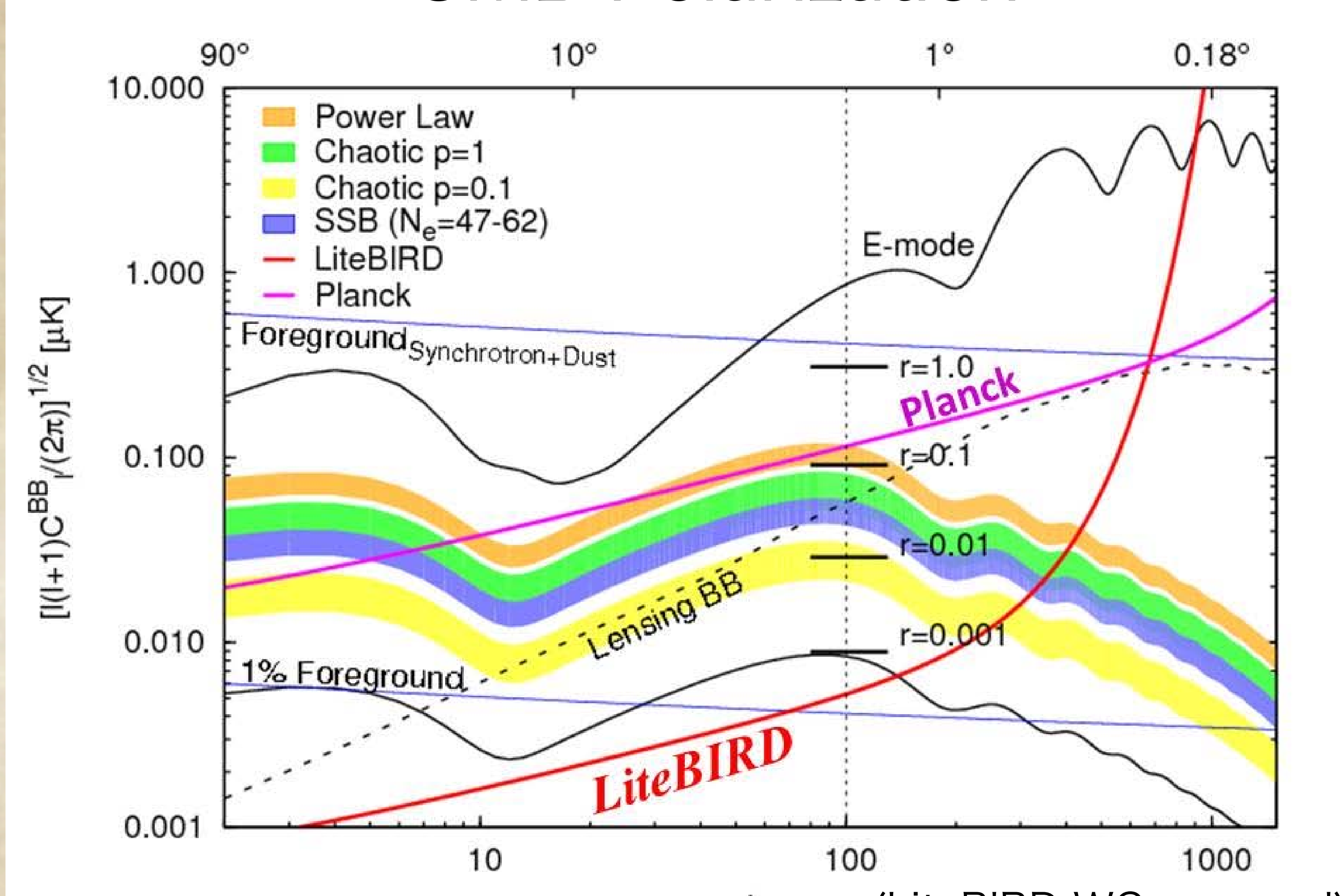
cf) Phase transition associated with cosmic string can be constrained by CMB and GWB (Explain later!)

$H_{\rm inf} \sim \kappa M$ : Symmetry braking can take place during inflation.
it is possible that topological defects are sufficiently diluted to be free from current constraints but still observable by planned experiments especially in inflation models in which the Hubble parameter changes rather considerably such as chaotic inflation.

$H_{\rm inf}$ is related to the tensor perturbation of primordial fluctuation:

$$\mathcal{P}_T = \frac{8}{M_G^2}\left(\frac{H}{2\pi}\right)^2\Bigg|_{H=k/a} \qquad r \equiv \frac{\mathcal{P}_T}{\mathcal{P}_S}$$

CMB Polarization




(LiteBIRD WG proposal)

$r \simeq 0.1 \leftrightarrow H_{\rm inf} \simeq 10^{13}{\rm GeV}$

$r \simeq 0.001 \leftrightarrow H_{\rm inf} \simeq 10^{12}{\rm GeV}$

The scale is a little small compared to usual GUT scale $\sim 10^{16}{\rm GeV}$, but other intermediate symmetry that predicts monopole production can be severely constrained.

# More precise treatment

-Concrete inflation model: (F-term) Chaotic inflation

(Linde ('83), Kawasaki, Yamaguchi & Yanagida ('00)

-Topological defect: (magnetic) monopole (& cosmic string)

Let us investigate how to pass the current constraint and prospects of future observation.

# Monopoles

KK, K.Nakayama & J. Yokoyama

# Status of monopole

Mass: $M_{\rm m} = \frac{4\pi M}{g_{\rm G}}$

Distribution and velocity: monopoles are accelerated by

$$\begin{cases} \text{galactic gravitational field: } v_{\rm m} \sim 10^{-3} c \\ \text{galactic magnetic field: } v_{\rm m} \sim 10^{-3} c (M_{\rm m}/10^{17}{\rm GeV})^{1/2} \end{cases}$$

$(B \sim 3 \times 10^{-6}{\rm Gauss})$

$$\begin{cases} M_{\rm m} > 10^{17}{\rm GeV} : \text{gravitational field is dominant; clumped to the galaxy} \\ \qquad \text{number density is enhanced by a factor of } c_{\rm en} \sim 10^5 \\ M_{\rm m} < 10^{17}{\rm GeV} : \text{magnetic field is dominant; uniform distribution} \end{cases}$$

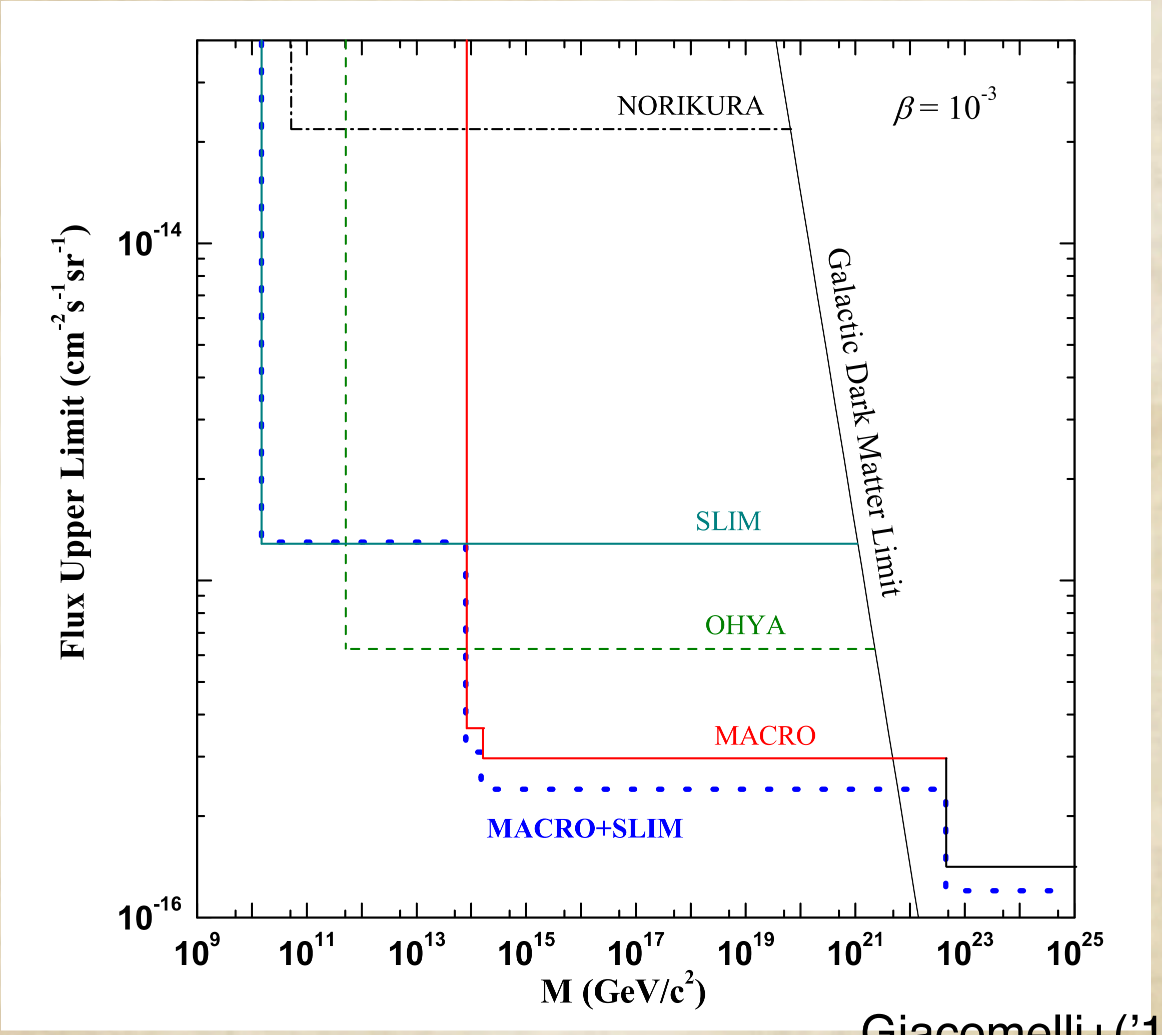
Flux on earth: $F = \frac{n_{\rm m} v_{\rm m}}{4\pi}$

# Current constraints

- Do not overclose the Universe: $\frac{\rho_{\rm m}}{s} = \frac{M_{\rm m} n_{\rm m}}{s} < 4 \times 10^{-10}{\rm GeV}$

- (Extended) Parker bound; Do not dissipate galactic magnetic field (at present and the beginning of the galaxy formation):

$$F < 1.2 \times 10^{-16} \left( \frac{M_{\rm m}}{10^{17}{\rm GeV}} \right) {\rm cm}^{-2}{\rm sr}^{-1}{\rm s}^{-1}$$




Giacomelli+('11)

- Several constraints from direct detection:

e.g.) MACRO experiment (catalyzed decay);

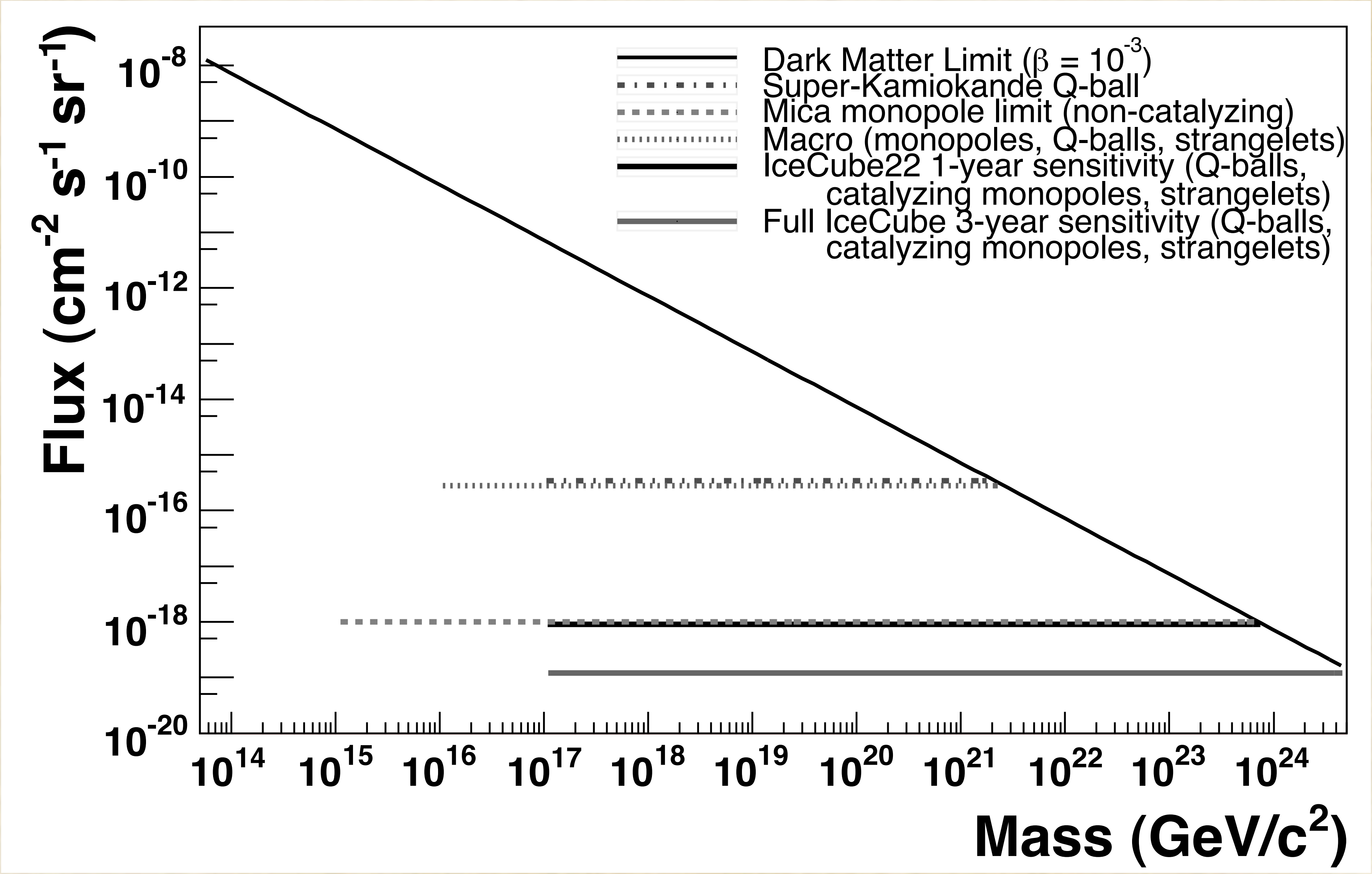
$$F < 3 \times 10^{-16}{\rm cm}^{-2}{\rm sr}^{-1}{\rm s}^{-1}$$

Extended Parker bound is severest around:

$$10^{15}{\rm GeV} \lesssim M_{\rm m} \lesssim 10^{17}{\rm GeV}$$

IceCube may constrain or detect monopoles up to

$$F \sim 10^{-19}\mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}$$




IceCube collaboration ('06)

Monopole production during chaotic inflation

$$K = \frac{1}{2}(\Phi + \Phi^\dagger)^2 + |X|^2 + |S|^2 + |\Sigma|^2,$$

$$W = mX\Phi + \kappa S\left(\mathrm{Tr}\Sigma^2 - M^2\right),$$

Inflation is driven by the imaginary part of $\Phi, \varphi \equiv \sqrt{2}\mathrm{Im}\Phi$.

$$V_{\mathrm{inf}}(\varphi) = \frac{1}{2}m^2\varphi^2 \simeq 3H^2M_G^2$$ ($m \simeq 10^{13}\mathrm{GeV}$ from CMB observation)

$$\mathcal{N}(\varphi) = \frac{1}{4M_G^2}(\varphi^2 - 2M_G^2) \qquad H(t) = H_0 - \frac{m^2 t}{3}$$

Potential for the mass eigenstate of Higgs field

$$V(\sigma_a) = \frac{3H^2(\varphi)}{2}\sum_a \sigma_a^2 + \frac{\kappa^2}{2}\left(\sum_a \sigma_a^2 - 2M^2\right)$$

$$m_\sigma(\varphi)^2 = 3H^2(\varphi) - \kappa^2 M^2$$

Phase transition takes place around

$$H(\varphi) \sim \kappa M$$

In order to estimate the present abundance of monopoles, we must clarify when the number of monopoles is determined.

Langevin equation for the long-wave mode of the Higgs field

$$\frac{d\sigma(\boldsymbol{x},\mathcal{N})}{d\mathcal{N}} = -\frac{V'(\sigma)}{3H^2(\mathcal{N})} + \frac{f(\boldsymbol{x},\mathcal{N})}{H(\mathcal{N})}, \ \langle f(\boldsymbol{x},\mathcal{N}_1) f(\boldsymbol{x},\mathcal{N}_2)\rangle = \frac{H^4(\mathcal{N}_1)}{4\pi^2}\delta(\mathcal{N}_1 - \mathcal{N}_2)$$

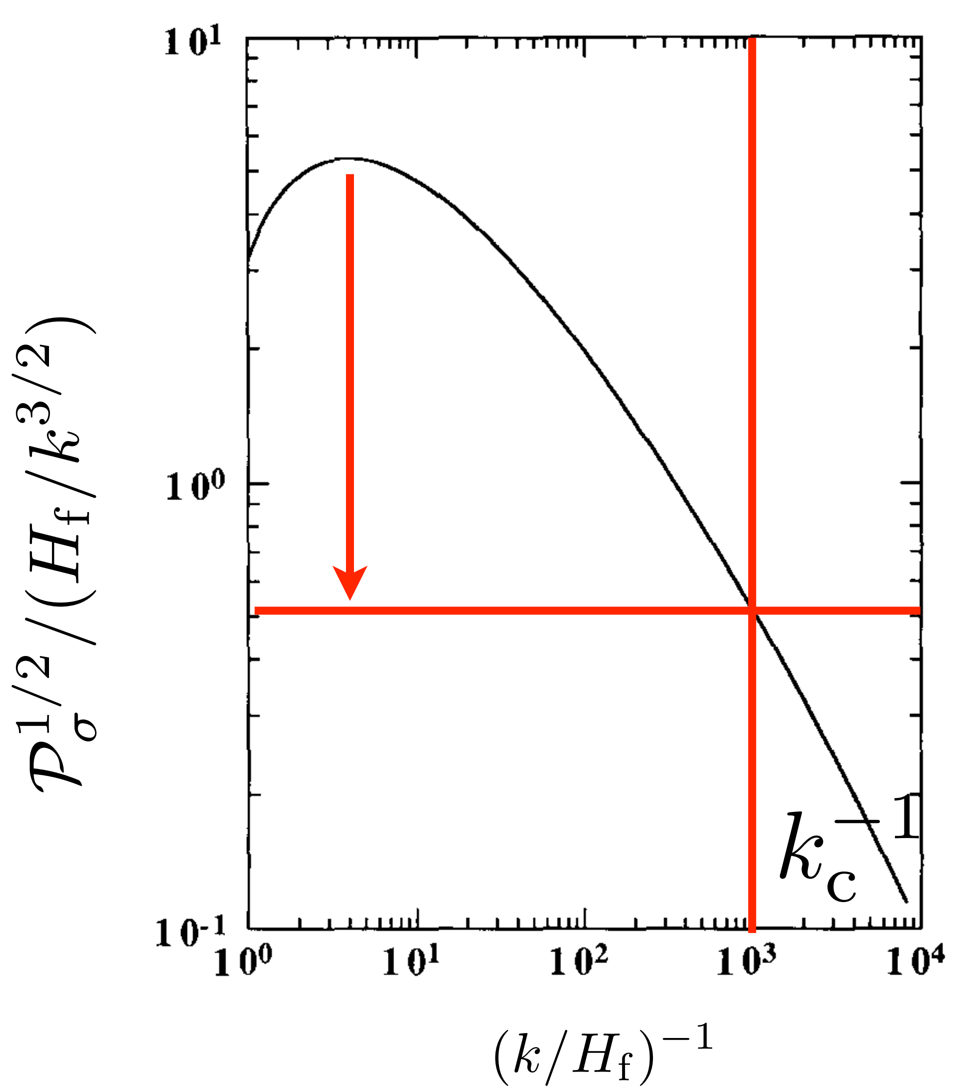
classical force      stochastic force

We conjectured that the number of monopoles are determined when classical force becomes stronger than stochastic force using the evaluation of $\langle \sigma^2(x,\mathcal{N})\rangle$

$$H_\mathrm{f} \equiv H(t_\mathrm{f}) \simeq \frac{m}{\sqrt{3}}\left(c - \sqrt{2c}\right)^{1/2}, \ c \equiv \kappa^2 M^2/m^2$$

Power spectrum of the Higgs field at $H = H_{\rm f}$ determines monopole abundance.

$$\mathcal{P}_\sigma = |\sigma_k|^2 \simeq \frac{H^2(t_k)}{2k^3}\left(\frac{S(t_k)}{S(t)}\right)\exp\left[-\frac{9}{2m^2}\left(H(t_k)-\frac{2m}{3}\sqrt{c-\frac{1}{2}}\right)^2+\frac{(2-\sqrt{3})^2 c}{4}\right].$$




Nagasawa & Yokoyama('92)

decays at scales larger than $k < k_{\rm c}$

monopole distributes at the scale:

$$k_{\rm c} < k < H_{\rm f}$$

$$n_{\rm m}(t_{\rm f}) \simeq \frac{3\log(H_{\rm f}a(t_{\rm f})/k_c)}{(k_{\rm c}/a(t_{\rm f}))^{-3} - H_{\rm f}^{-3}}$$

Even after monopole formation, inflation continues,

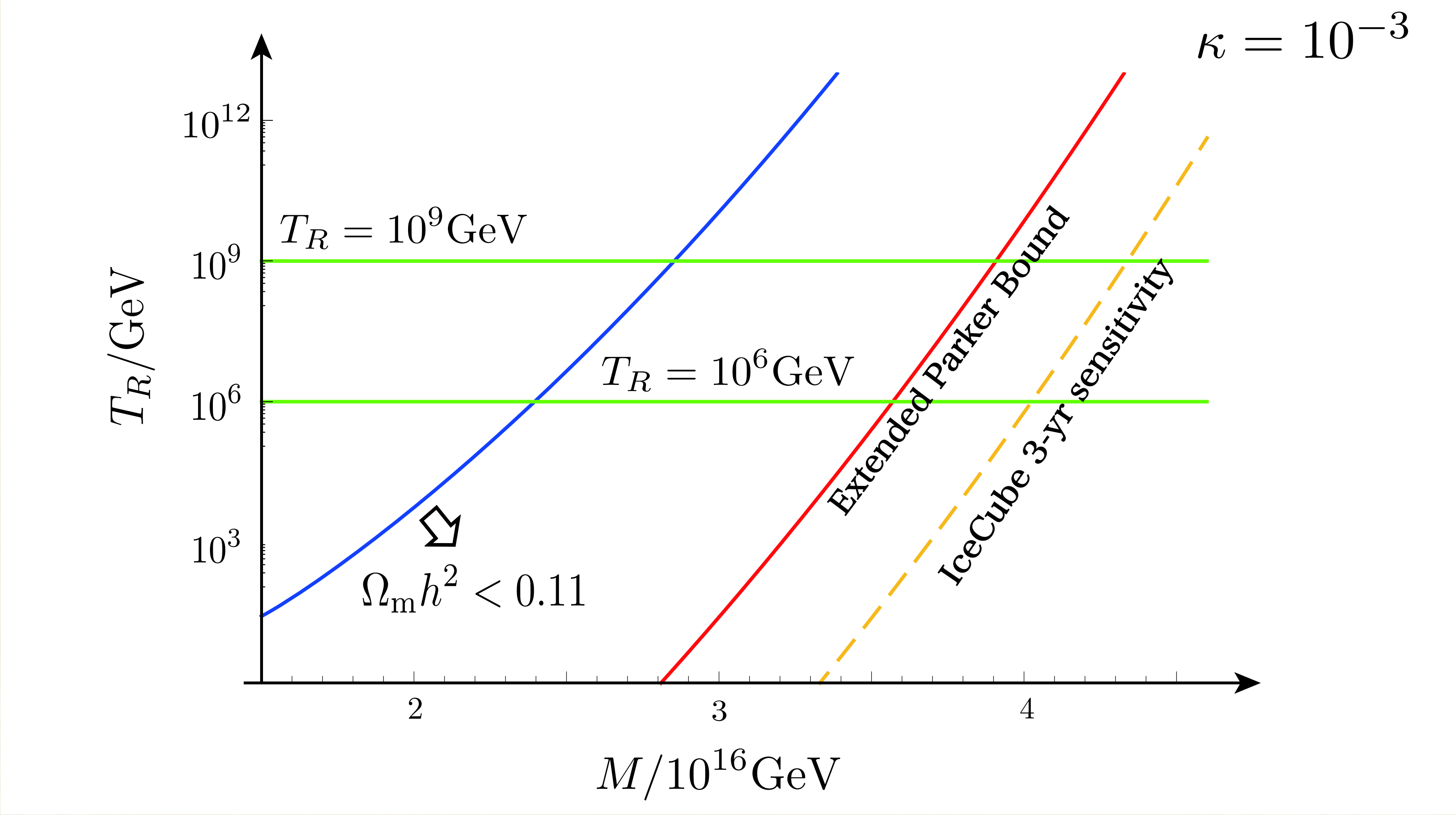
$$\Delta\mathcal{N} = \frac{3H_{\rm f}^2}{2m^2} - \frac{1}{2} \simeq \frac{1}{2}(c - \sqrt{2c} - 1).$$

Monopoles are diluted accordingly.

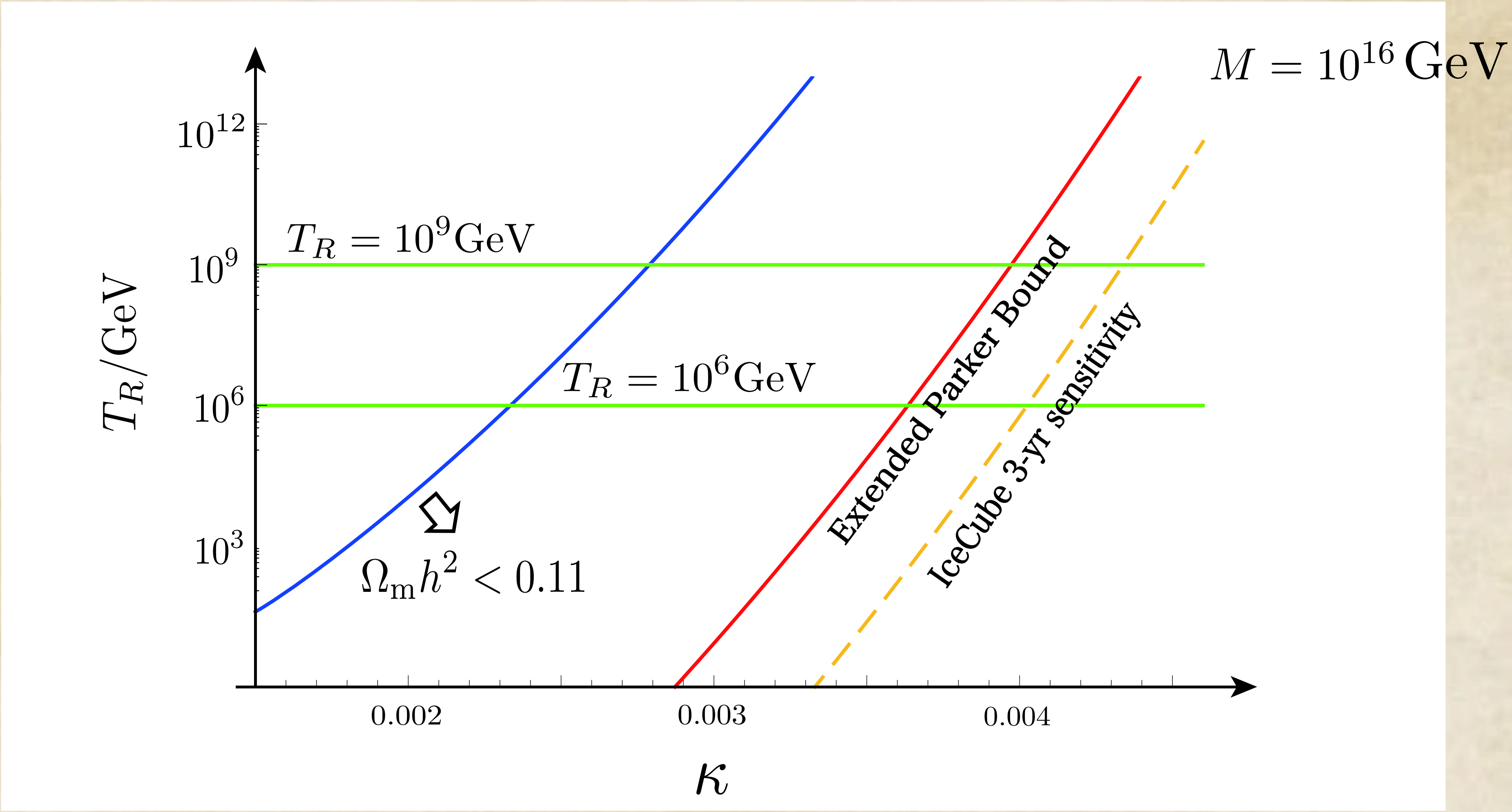
Taking into account the cosmic expansion after inflation, the present monopole abundance is evaluated as

$$\frac{\rho_{\rm m}}{s} = \frac{M_{\rm m} n_{\rm m}}{s} \simeq 3.2 \times 10^{-8} \left(\frac{M}{10^{15}{\rm GeV}}\right) \left(\frac{0.5}{g_{\rm G}}\right) \left(\frac{g_*}{g_{*s}}\right) \left(\frac{m}{10^{13}{\rm GeV}}\right) \left(\frac{n_{\rm m}(t_{\rm e})}{m^3}\right) T_R.$$

# Constraints



# Constraints



# Cosmic strings

KK, Y. Miyamoto & J.Yokoyama (Preliminary)

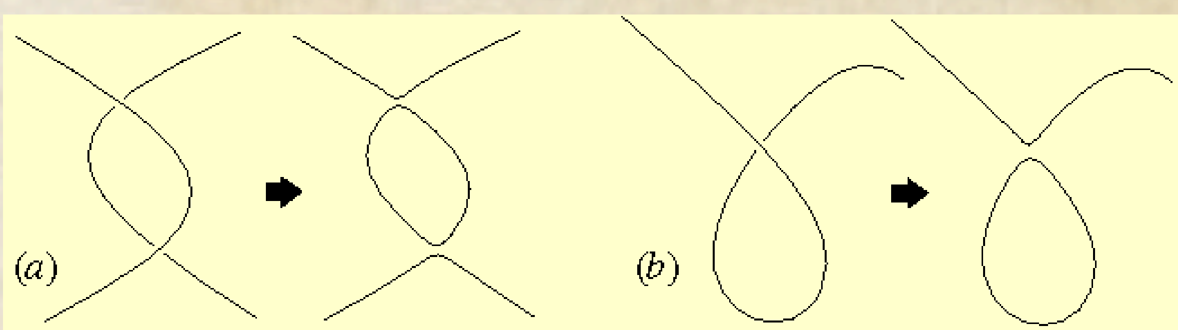
# Status of String

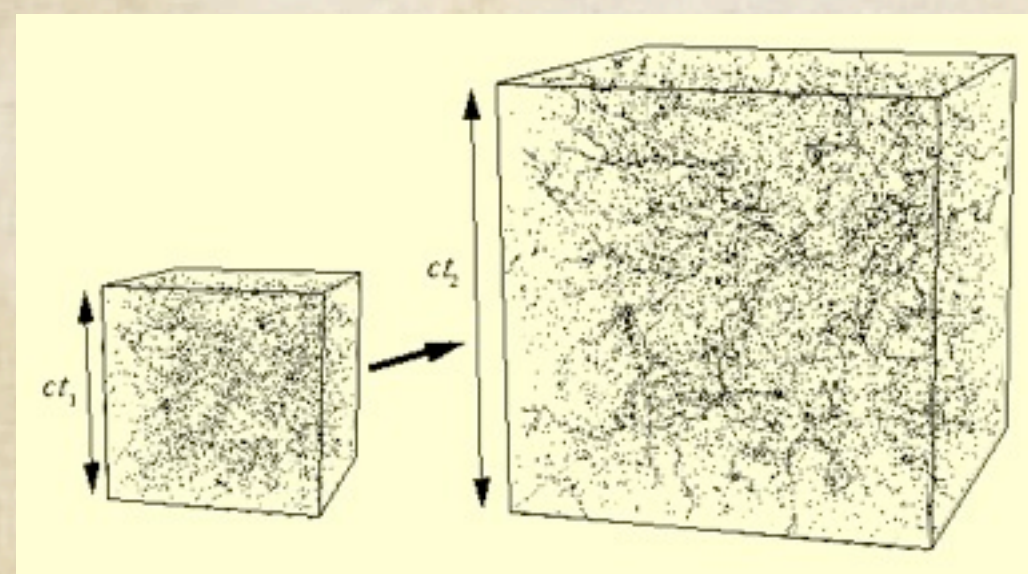
string tension: $\mu \simeq \pi M^2$

parameterized by only this parameter

Distribution: scaling distribution

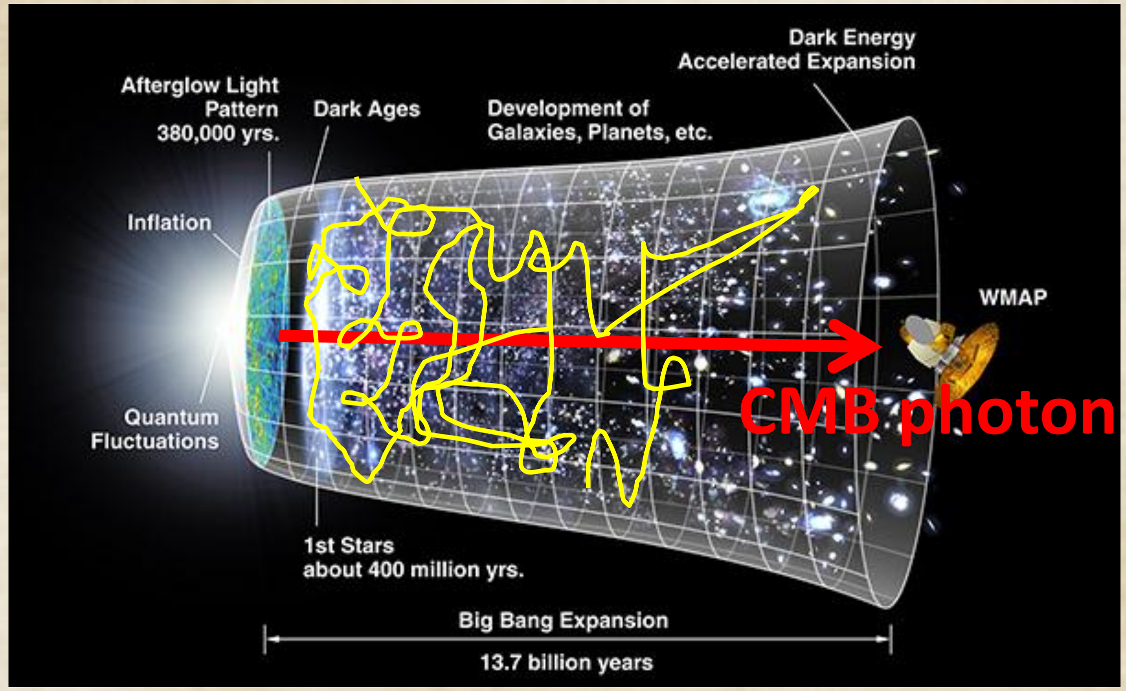
Strings in a Hubble volume intersect each other and generate loops. Loops shrinks emitting gravitational waves. As a result, there are always a few long strings and several loops, which we call “scaling distribution”.

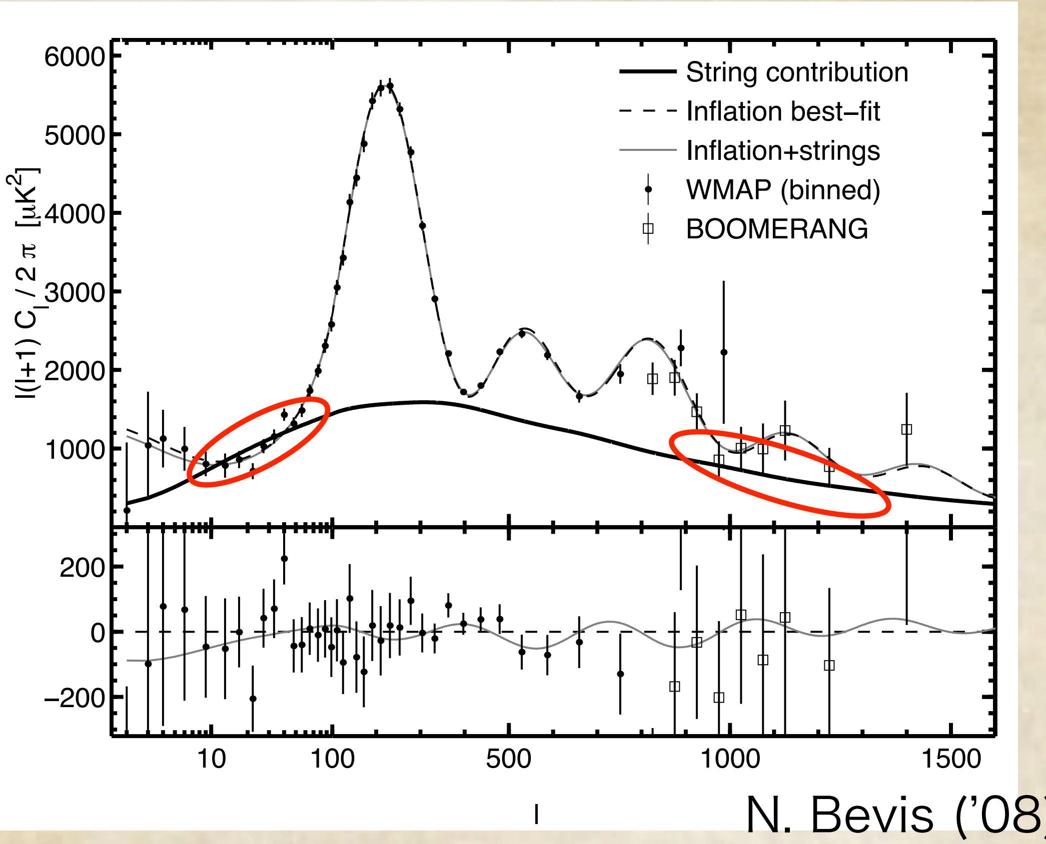


# Current constraints

(Do not) contribute to the CMB fluctuation:




N. Bevis ('08)

WMAP+SPT: $G\mu < 1.7 \times 10^{-7}$

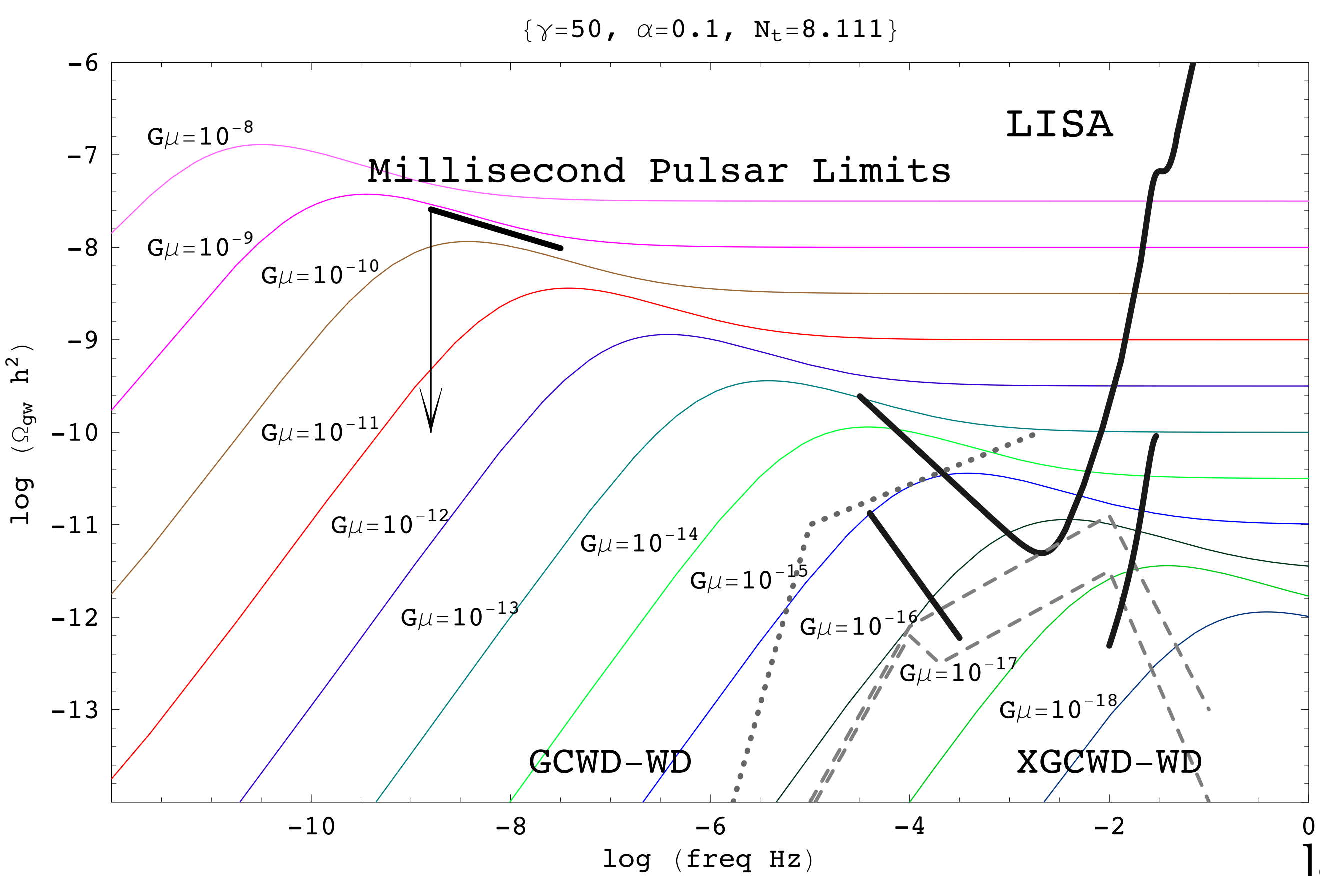
$\Leftrightarrow M < 2 \times 10^{15}\mathrm{GeV}$ Dvorkin ('11)

high l & B-mode in future observation are promising for detection.

# Current constraints

String loops generates gravitational waves consistently

$\Omega_{\rm GW}h^2$




$\log f[/\mathrm{Hz}]$

from loops formed
in matter dominated era

from loops formed
in radiation dominated era

M.R.DePies ('08)

Loops in radiation era:

$$\Omega_{\rm GW}h^2 = \mathrm{const}$$

Loops in matter era:

$$\Omega_{\rm GW}h^2 \propto f^{-1/3}$$

Pulsar timing array constraint:

$$G\mu < 4.0\times 10^{-9}$$

$$\Leftrightarrow M < 4\times 10^{14}\mathrm{GeV}$$

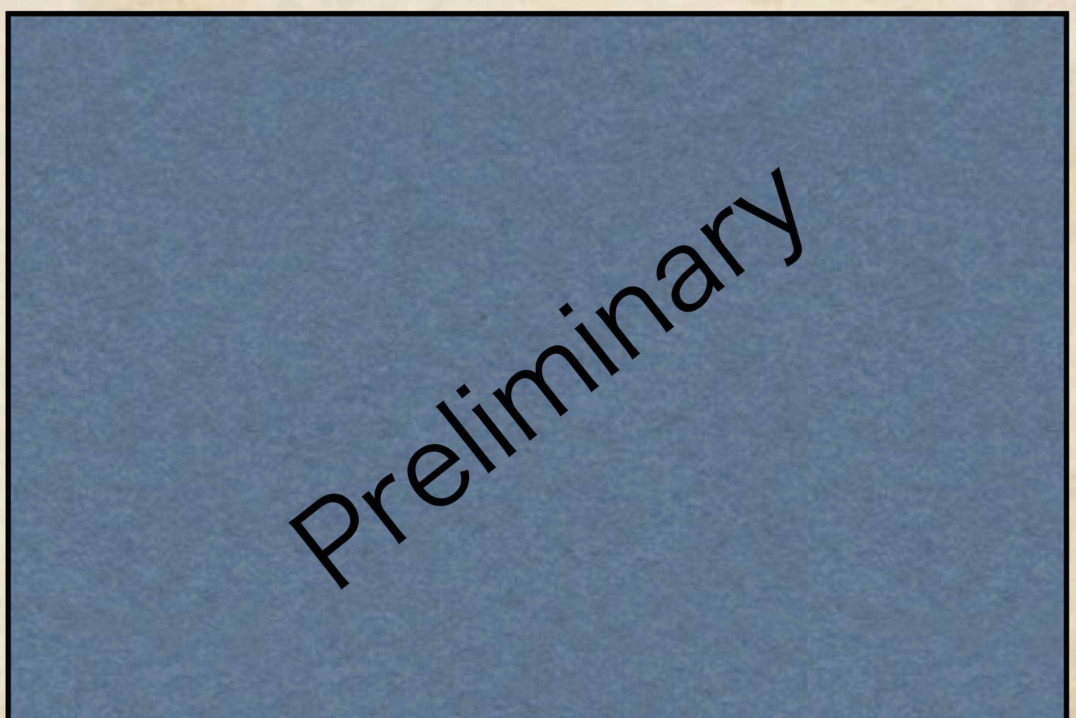
R. van Haasteren ('11)

Pulsar timing array constraint is much severer than that of CMB.

Is searching for their signatures in CMB hopeless?

## Our scenario can change the situation!

If loop formation starts recently due to the appropriate dilution during inflation, cosmic strings with $G\mu \simeq 10^{-7} - 10^{-8}$ can be detected in CMB while GWs are damped.




If Planck detect tensor perturbation, parameter region where

$$\kappa \simeq \mathcal{O}(0.1), \quad M \simeq 10^{14-15}\mathrm{GeV}$$

would be interesting!

# Summary

-Topological defects are good tool of exploring the early Universe and high energy physics.

-Hubble induced mass during F-term inflation can trigger the phase transition after/during inflation.

-We can constrain the symmetry breaking scale via CMB B-mode detection.

-Monopoles can be diluted enough but still observable future experiments such as IceCube.

-Cosmic Strings can be detected by CMB high l scale or B-mode observation.

-Interesting scale is around $\kappa M \simeq 10^{13}\mathrm{GeV}$.