Thermal history of the dark matter in the hidden gauge theory

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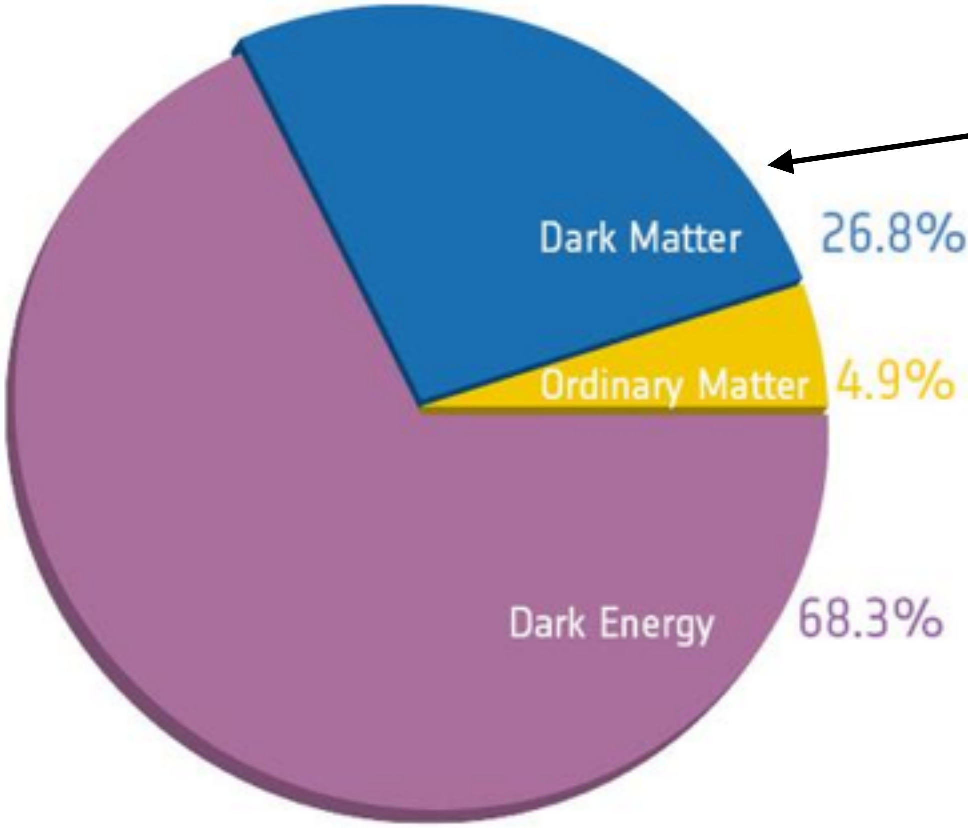
熱場の量子論
理研

Dark matter : 27% of the energy component of the Universe



Cosmic "makeup". Credit: ESA/Planck

Dark matter

Neutral, collisionless, nonrela, WIMP

Dark matter halo:

Our galaxy is surrounded
by a halo of dark matter

20kpc

DM density at the Earth: $0.3 \mathrm{GeV/cm^3}$

Suggested by:

- Galactic rotation curve
- N-body simulation
- Galactic bullet clusters
- Cosmic microwave background
- …

Need to explain dark matter in particle physics

Dark matter seems to be WIMP ⋯ Are there candidates in Standard model ?

→ No!

→ **We need to introduce some new physics beyond Standard model.**

What is a good candidate of new physics beyond standard model ?

- Not in conflict with phenomenology ← 当たり前ですね (´∀｀;)
- Naturalness

What is natural?

- Unified theories, effective theories (example : GUT)
- No fine-tuning, explain hierarchy problem

  (Massive parameters should have reasonable reasons)

Example of massive parameters :
Higgs mass, neutrino mass, QCD scale, cosmological constants,
dark matter mass, early inflation parameters, etc.

The idea is to introduce additional gauge theory(ies)

We consider SU(N_c) gauge theory very weakly coupled to Standard model (SM)

HGT and SM unifies near GUT scale

In hidden gauge theory, the dark matter is

- a pion if current (dark) quark mass < scale parameter
- a glue ball if current (dark) quark mass > scale parameter
- ~~a baryon if CP violation and quarks exists in HGT sector~~

(We do not consider this scenario today)

What is natural in HGT ?

- Mass scale controlled by the running coupling (input : N_c, N_f)
- Many gauge forces (4th, 5th, ⋯) unified at GUT scale

Object of study

As the HGT's exist since the GUT scale, particles in the HGT participate in the thermal evolution of the Universe.

How about the observational constraints?

Object of study:

- **Study HGT's thermal evolution and its phenomenological constraints.**
- **Propose a scenario for dark matter.**

We do not discuss the following topics:

- How gauge theories are unified at the GUT scale
- Supersymmetry

Dynamics of expanding Universe

Freedman equation (Einstein equation in homogeneous isotropic Universe)

$$\begin{cases} \dfrac{d\epsilon}{dt} + 2\sqrt{6\pi G}(\epsilon + p)\sqrt{\epsilon} = 0 \\ \dfrac{da}{dt} - \sqrt{\dfrac{8\pi G}{3}} a\sqrt{\epsilon} = 0 \end{cases}$$

ϵ : energy density
p : pressure
a : scale factor
G : Newton constant

Important cases of evolution:

- **Radiation dominant Universe**

$$\epsilon(T) \propto \frac{1}{T^4} \qquad a(T) \propto \frac{1}{T}$$

⇒ Temperature decreases as the Universe expands
⇒ Expansion decelerates in time

- **Matter dominant Universe**

$$\epsilon(T) \propto \frac{1}{T^3}$$

⇒ Slower decrease of energy density than radiation

- **de Sitter Universe (inflation)**

$$a(t) \propto e^{Kt}$$

⇒ Vacuum energy
⇒ Negative pressure induces exponentially <u>accelerating</u> expansion

Relic density of dark matter in HGT

We assume

- Entropy of the radiation is conserved: equilibrium in the comoving frame (adiabatic)
- DM Hadron mass = temperature of freeze-out
- DM QGP/hadron phase transition is a quasi-equilibrium process

Hadron number density at freeze-out temperature:

$$n^{(\mathrm{DM})}\left(T_{\mathrm{FO}}^{(\mathrm{DM})}\right) = g_{\mathrm{FO}}^{(\mathrm{DM})}\left(\frac{T_{\mathrm{FO}}^{(\mathrm{DM})} m_{\mathrm{DM}}}{2\pi}\right)^{\frac{3}{2}} e^{-\frac{m_{\mathrm{DM}}}{T_{\mathrm{FO}}^{(\mathrm{DM})}}} \simeq O(m_{\mathrm{DM}}^3)$$

Extrapolation from the current DM relic density:

$$n^{(\mathrm{DM})}\left(T_{\mathrm{FO}}^{(\mathrm{DM})}\right) = \frac{\rho_{\mathrm{m0}}}{m_{\mathrm{DM}}} \times \frac{1}{a_{\mathrm{FO}}^3} = \frac{\rho_{\mathrm{m0}}}{m_{\mathrm{DM}}} \times \frac{g_{\mathrm{FO}}^{(\mathrm{DM})}\left(T_{\mathrm{FO}}^{(\mathrm{SM})}\right)^3}{\underbrace{g_{\mathrm{eq}}^{(\mathrm{DM})}\left(T_{\mathrm{eq}}^{(\mathrm{SM})}\right)^3 a_{\mathrm{eq}}^3}_{\text{entropy conservation}}}$$

$$\rho_{\mathrm{m0}} \simeq 10^{-47}\mathrm{GeV}^4$$
$$a_{\mathrm{eq}} = 3 \times 10^{-4}$$
$$T_{\mathrm{eq}}^{(\mathrm{SM})} = 1 \times 10^4 \mathrm{K} \simeq 1\mathrm{eV}$$

If HGT and SM were not disturbed since the GUT time, $T_{\mathrm{FO}}^{(\mathrm{DM})} = T_{\mathrm{FO}}^{(\mathrm{SM})}$
(=entropy is conserved)

$$\Rightarrow \quad m_{\mathrm{DM}} \simeq 10^{-8}\mathrm{GeV}$$

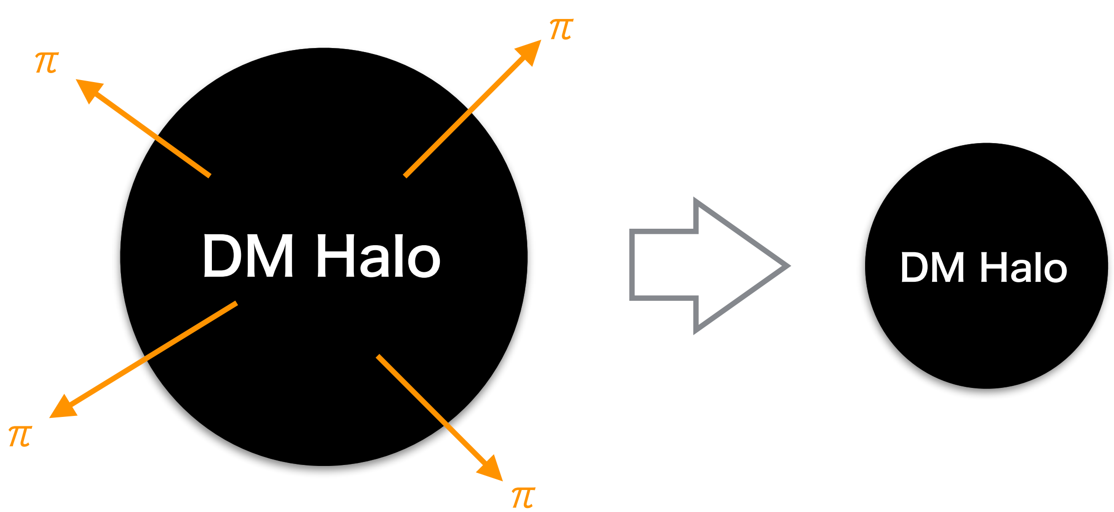
(´∀｀;) BBN ⋯

Constraint on DM mass from the stability of the DM halo

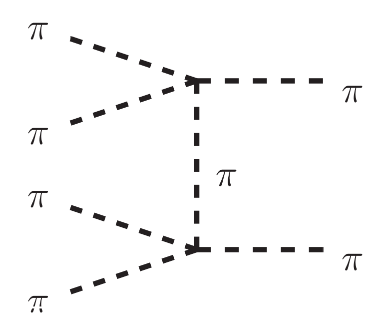
DM particle in the halo is nonrelativistic and bound by gravitational force

Annihilation processes can reduce the DM number

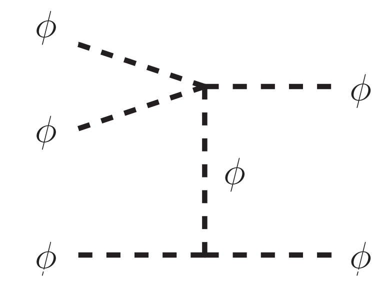
$\Rightarrow$ Relativistic products are ejected from the halo : decay of DM halo



Leading process:



Dark pion 4 → 2 process



Dark glueball 3 → 2 process

Current DM halo is stable $\Rightarrow$ Constraint on the mass scale of HGT

Simple dimensional analysis estimates

$$m_{DM} > 1 \text{ TeV}$$

(for pure Yang-Mills)

$$m_{DM} > 1 \text{ GeV}$$

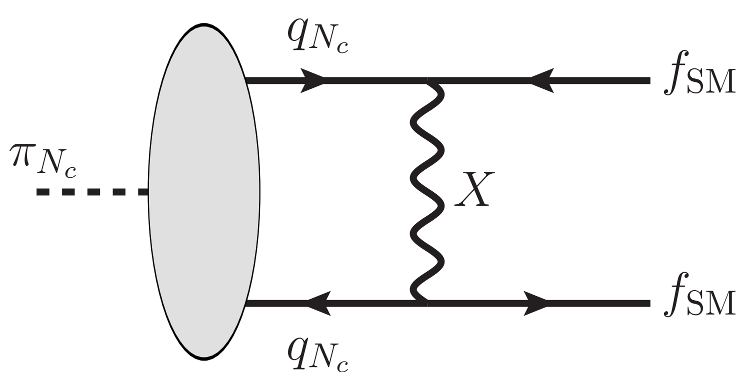
(with light quarks)

In conflict with previous naive evolution

We must decrease the dark sector temperature relative to SM sector

Constraint on the unification scale from high energy cosmic ray

DM particles can decay to SM particles via GUT force



Decay products can be observed as cosmic rays at Earth

⇒ Constraint on unification scale

We have used 2 probes:

- Electron/positron:

  Diffusion in the galaxy

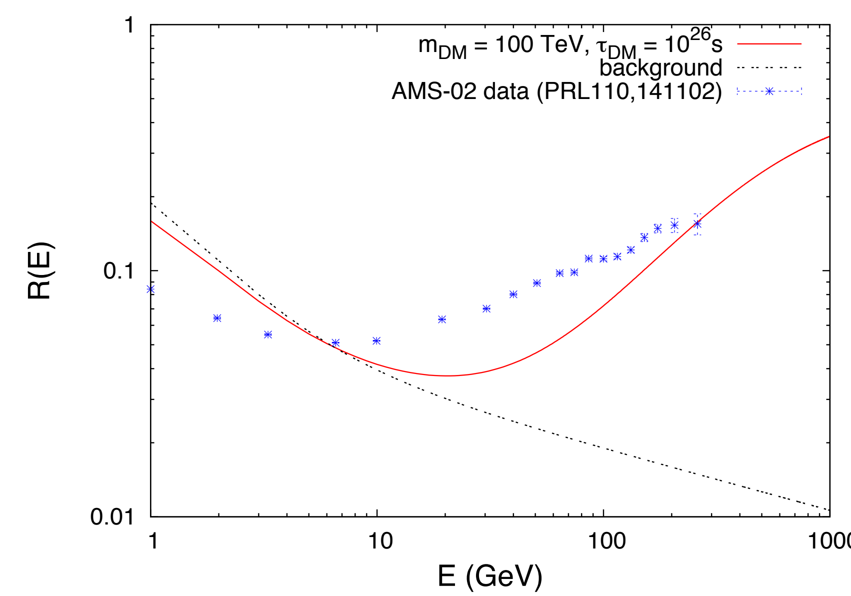
  Data from AMS-02.

  AMS-02 Collaboration, PRL 110, 141102 (2013).

- Neutrino:

  No diffusion, data from IceCube

  IceCube Collaboration, arXiv:1405.5303.



Positron fraction from DM decay

Constraint on GUT scale:

$$\Lambda_{\rm GUT} > 10^{-14}\ \mathrm{GeV}$$

(for m_{DM} ~ 1, 10 TeV, from AMS-02)

(for m_{DM} ~ 1 PeV, from Icecube)

- All couplings were set to 1
- DM decay only to electron/neutrino

How to resolve ?

DM relic density obtained by entropy conservation is in conflict
with the limit of halo stability

⇒ We must increase the entropy of SM sector by order of magnitude

By the way ··· Higgs sector is still unknown:

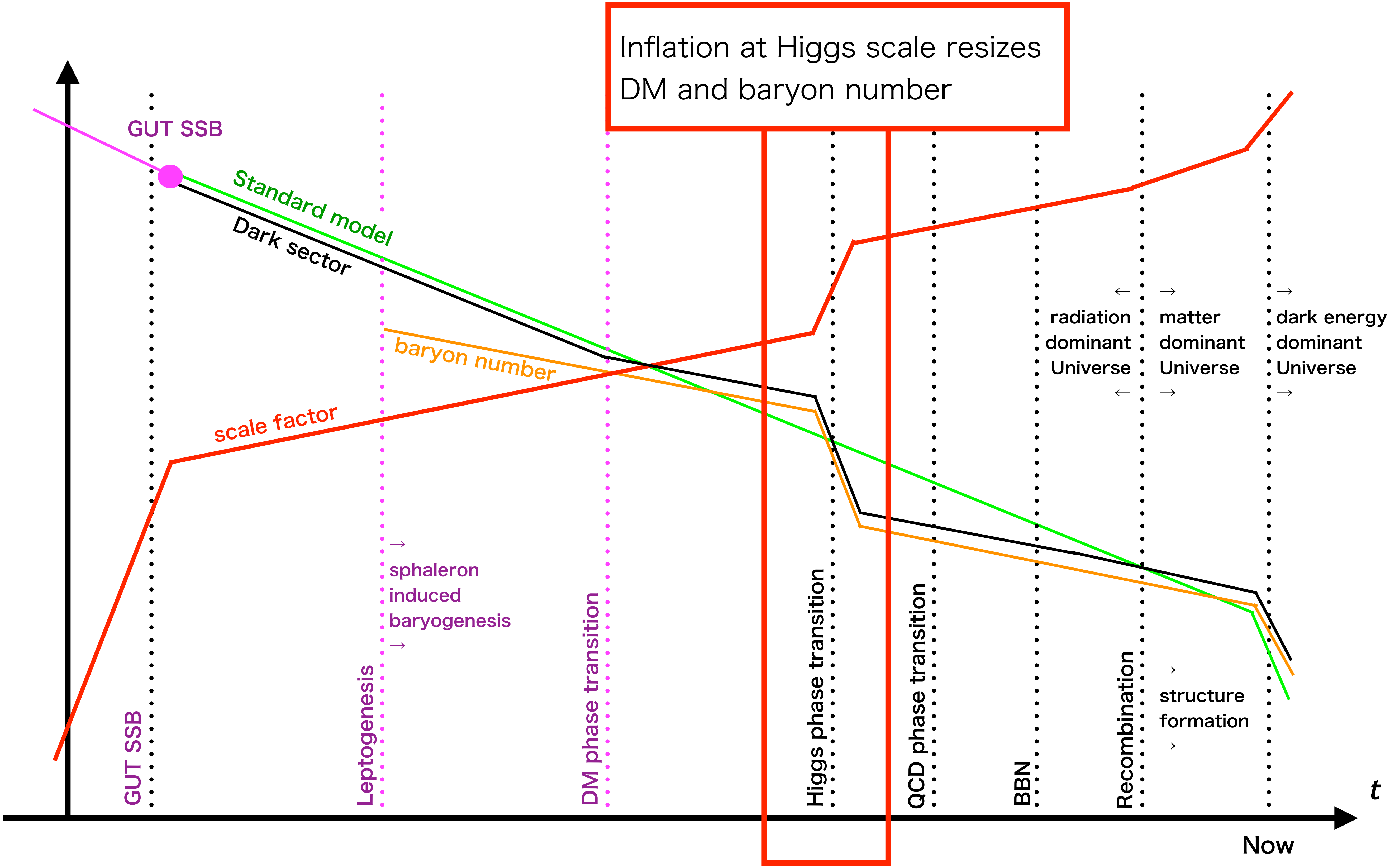
The Higgs effective potential may induce inflation and increase the entropy

Let us introduce a mini-inflation to the Higgs scale

By introducing a mini-inflation of $\Delta a = 10^3$, we expect

- Reduction of the DM density by $\sim 10^9$
- Reduction of baryon number density by 10^9 (current $n_B/s \sim 10^{-10}$!)
- No notable change of energy density in SM sector, due to reheating

Thermal history of the scenario we are proposing



Higgs scale mini-inflation ($\Delta a \sim 10^3$) is needed!

Prospective observations

- ## B-modes:

  Probe of Higgs mini-inflation (and other mini-inflation sources…)

  BICEP2, Planck.

- ## Gravitational wave backgrounds:

  Probe of 1st order phase transition (Higgs & DM)

  Y. Kikuta, K. Kohri, E. So, arXiv:1405.4166.

- ## Precision tests of Higgs sector:

  Probe the Higgs potential : Need precision test such as ILC!!

  ILC

- ## Decay of dark matter to SM particles:

  Probe the unification scale

  AMS-02, Icecube.

- ## Accurate knowledge of DM halo density profile

  Probe interactions among hadrons

  M. Rocha et al., Mon. Not. R. Astron. Soc. **430**, 81 (2013);
  A. H. G. Peter et al., Mon. Not. R. Astron. Soc. **430**, 105 (2013).

Summary:

- We have introduced the hidden gauge theory to explain dark matter.
- Phenomenology : thermal history, halo stability, cosmic rays.
- DM thermal history with entropy conservation contradicts with halo stability: need to increase SM sector entropy.
- We have proposed a new scenario with mini-inflation at the Higgs scale: consistent with the present baryon number.
- Many observational probes will be soon available
  $\Rightarrow$ Precise study of Higgs sector is needed $\Rightarrow$ ILC!!

Future prospects:

- Lattice study of thermal quantities in HGT.
- HGT with spontaneous symmetry breaking.
- HGT with SUSY.