Dark matter in the hidden gauge theory and Higgs mini-inflation

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arXiv:1411.2172 [hep-ph]

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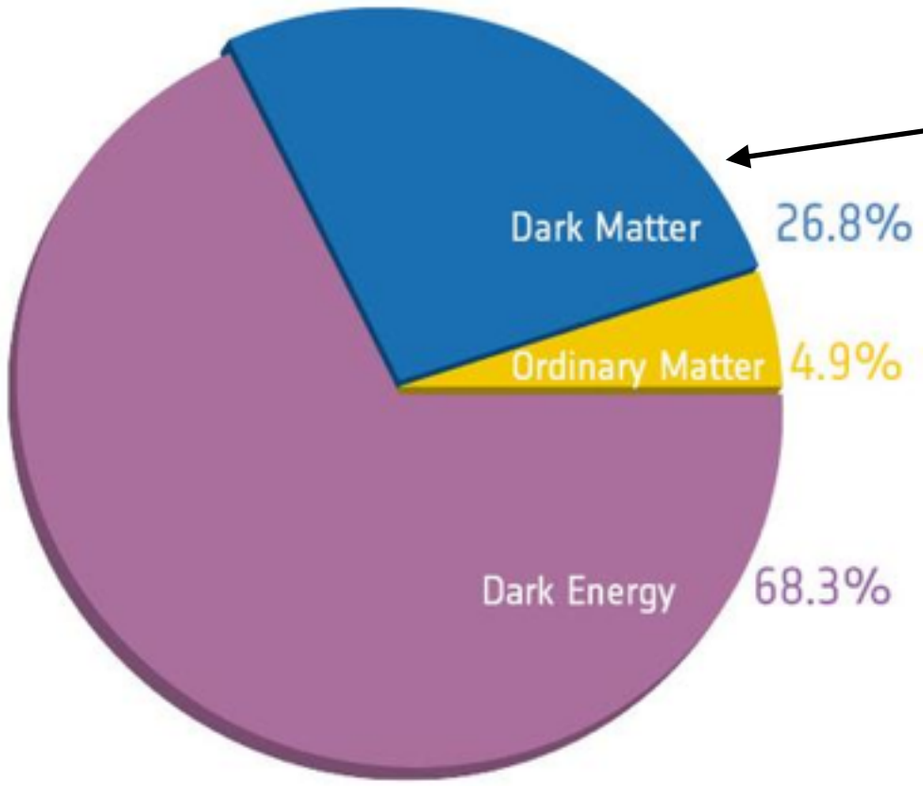
KEK

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

DM density at the Earth: 0.3GeV/cm^3

Suggested by:

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

Hidden gauge theory (HGT)

We need to introduce some
new physics beyond Standard model to explain dark matter

The idea is to introduce additional gauge theory(ies)

We consider SU(N_c) gauge theory decoupled with 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 glueball　　if current (dark) quark mass > scale parameter
- ~~a baryon　　if CP violation and quarks exists in HGT sector~~

We do not consider this scenario

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 HGTs exist since the GUT scale, particles in the HGT participate in the thermal evolution of the Universe.

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:

- CP and flavor violations in HGT
- How gauge theories are unified at the GUT scale
- Supersymmetry

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
- Entropies of SM and DM sector are same order at GUT (no sizable asymmetry at inflation)

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:

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

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

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

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

(´∀｀;) Hot DM, BBN …

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(=entropy is conserved)

$$m_{\mathrm{DM}} \simeq 10^{-8}\mathrm{GeV} \times \xi$$

(´∀｀;) Hot DM, BBN …

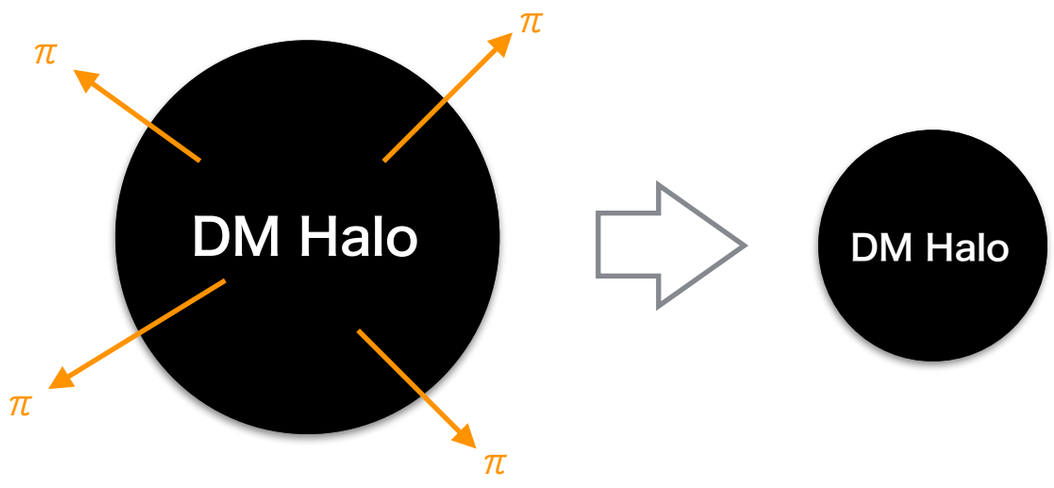
ξ = $s_{\mathrm{SM}}/s_{\mathrm{DM}}$

Constraint on DM mass from the stability of the DM halo

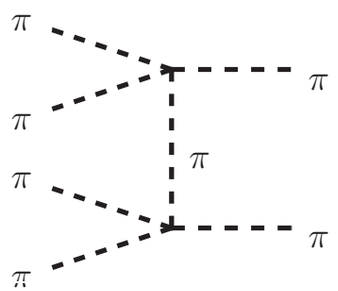
DM particle in the halo is nonrelativistic and bound by gravitational force

Annihilation processes can reduce the DM number

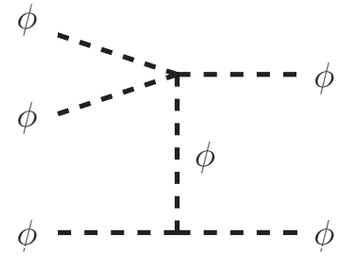
⇒ Relativistic products are ejected from the halo : decay of DM halo



Leading process:



Dark pion 4 → 2 process



Dark glueball 3 → 2 process

Current DM halo is stable ⇒ Constraint on the mass scale of HGT

Simple dimensional analysis estimates

$m_{DM} > 1$ TeV

(for pure Yang-Mills)

$m_{DM} > 1$ GeV

(with light quarks)

In conflict with previous naive evolution

We must decrease
the dark sector temperature
relative to SM sector

Self-interaction of the dark matter

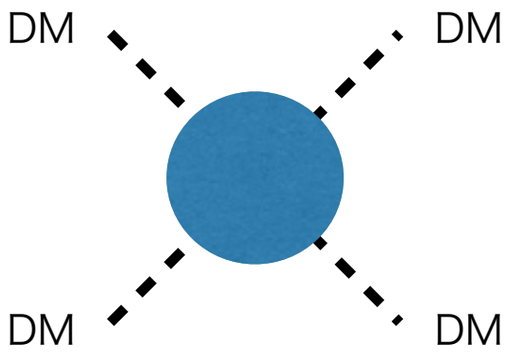
N-body simulation of Cold dark matter (with gravitation only):

Large scale structure ⇒ Yes !

Halo structure ⇒ No

Navarro, Frenk, White

Introducing dark matter self-interaction may resolve the problem



D. Spergel and P. Steinhardt, PRL 84, 3760 (2000).

Suggested scale of DM self-interaction by N-body simulation:

$$\sigma / m_{DM} \sim 0.6\ cm^2/g \quad \Rightarrow m_{DM} = \text{MeV} \sim \text{TeV}$$

J. Zavala et al., Monthly Notices of the Royal Astronomical Society: Letters 431 (2013) L20

OK!

How to increase visible sector entropy?

Naively, 3 ways:

- Asymmetry of entropy after GUT

- Transfer DM sector entropy to visible sector with mediator

- Increase visible (SM) sector entropy

How to increase visible sector entropy?

Naively, 3 ways:

- Asymmetry of entropy after GUT

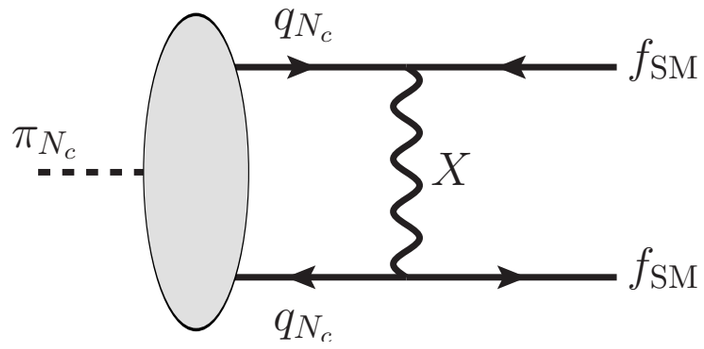
  ⇒ Not natural

- Transfer DM sector entropy to visible sector with mediator

- Increase visible (SM) sector entropy

Constraint on the unification scale from high energy cosmic ray

DM particles can decay to SM particles via GUT force or mediators



Decay products can be observed as cosmic rays at Earth

⇒ Constraint on mediator scale

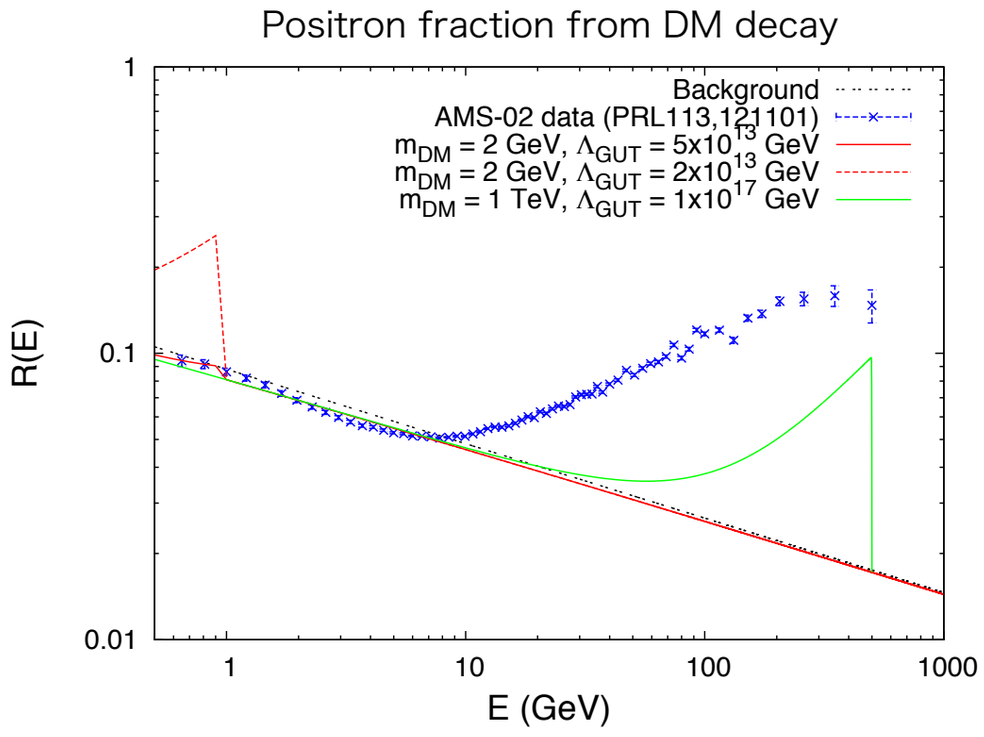
We have used positron fraction as probe:

Diffusion in the galaxy taken into account

E. A. Baltz and J. Edsjo, Phys. Rev. D 59, 023511 (1998).

Data from AMS-02.

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



Constraint on mediator (GUT) scale:

$\Lambda_{GUT} > 10^{14}$ GeV

(for m_{DM} ~ GeV)

Light mediator excluded!

- All couplings were set to 1
- DM decay only to e+e-

How to increase visible sector entropy?

Naively, 3 ways:

- Asymmetry of entropy after GUT

  ⇒ Not natural

- Transfer DM sector entropy to visible sector with mediator

  ⇒ No light mediator to cool DM during freeze-out

- Increase visible (SM) sector entropy

How to resolve ?

DM relic density obtained by entropy conservation is in conflict
with the phenomenology

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

By the way … the Higgs sector is still unknown:

The Higgs effective potential may induce inflation and increase the entropy

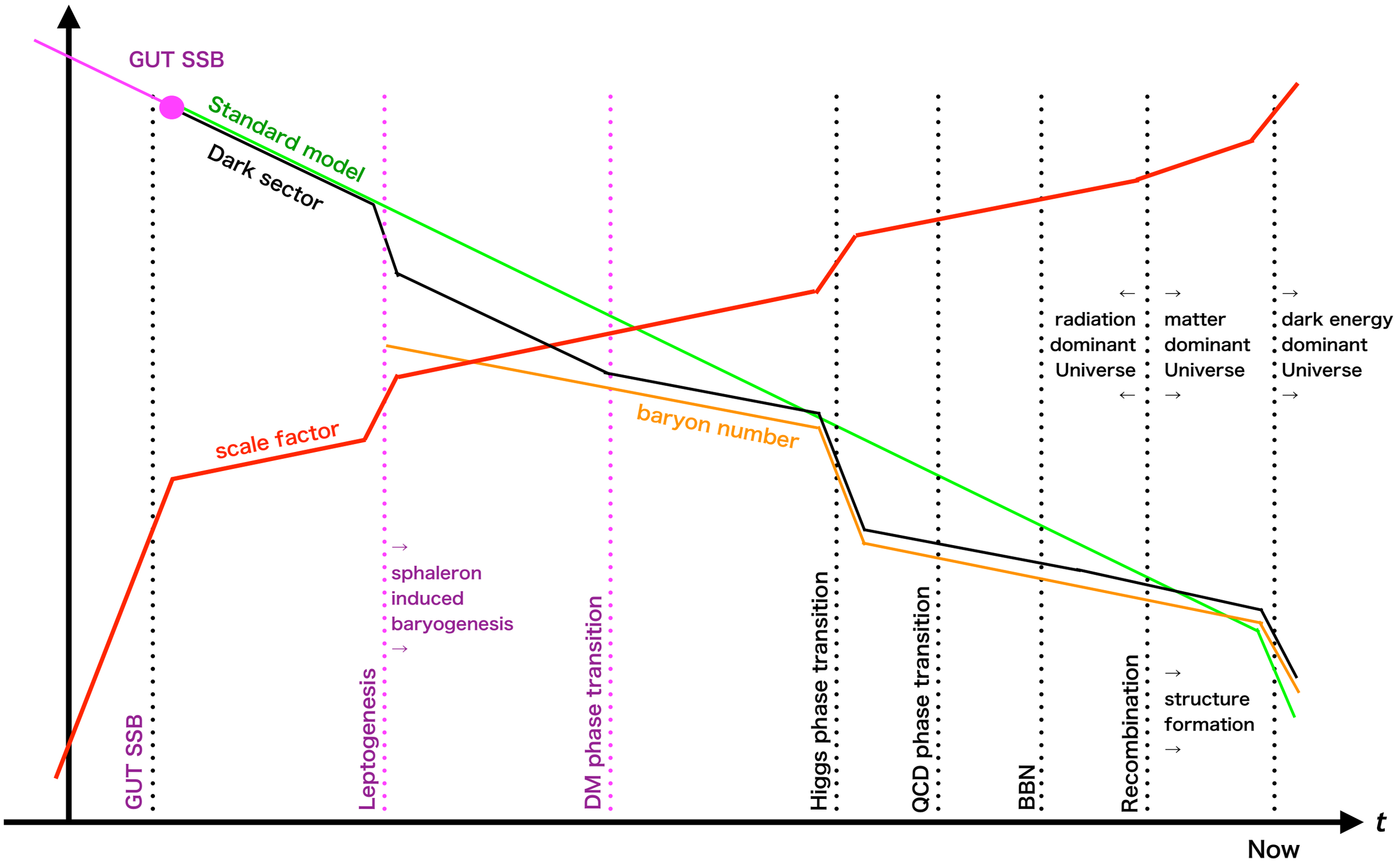
F. Bezrukov and M. Shaposhnikov, PLB 659, 703 (2008).

Mini-inflation to the Higgs scale resolves the problem!

By introducing a mini-inflation of $a_f/a_i = 10^3$ (e-folding nb ~ 7), we expect

- Reduction of the DM density by ~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



Thermal history of the scenario we are proposing

Inflation at Higgs scale resizes
DM and baryon number
⇒ HGT pion OK!

GUT SSB

Standard model

Dark sector

scale factor

baryon number

→ sphaleron induced baryogenesis →

← radiation dominant Universe ←

→ matter dominant Universe →

→ dark energy dominant Universe →

→ structure formation →

GUT SSB

Leptogenesis

DM phase transition

Higgs phase transition

QCD phase transition

BBN

Recombination

Now

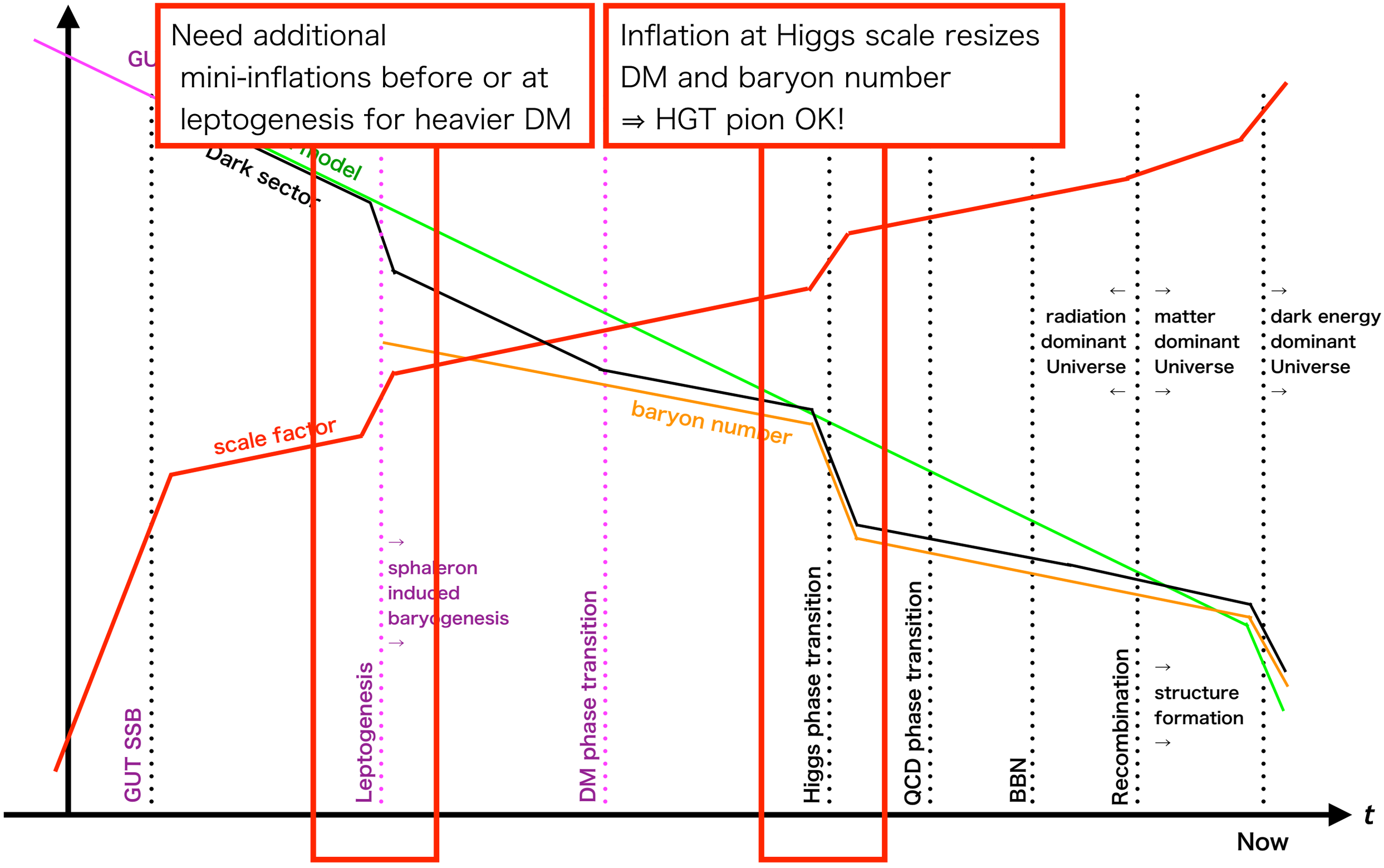
t

Higgs scale mini-inflation ($a_f/a_i \sim 10^3$) may shift entropy!

Thermal history of the scenario we are proposing

Need additional
mini-inflations before or at
leptogenesis for heavier DM

Inflation at Higgs scale resizes
DM and baryon number
⇒ HGT pion OK!



Higgs scale mini-inflation ($a_f/a_i \sim 10^3$) may shift entropy!

Prospective observations

- **Gravitational wave backgrounds:**

  Probe of 1st order phase transition (Higgs, before leptogenesis, HGT)

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

- **Precision tests of Higgs sector:**

  Probe the Higgs potential : Need precision test such as ILC

- **Decay of dark matter to SM particles:**

  Probe the unification scale

  AMS-02, IceCube, Fermi-LAT,…

- **Accurate knowledge of DM halo density profile**

  Probe interactions among HGT 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/structure, cosmic rays.
- Phenomenology requires the increase of SM sector entropy.
- We have proposed a new scenario with mini-inflation at the Higgs scale: consistent with the present baryon number for HGT pion DM.
- Many observational probes will be soon available
  ⇒ Precise study of Higgs sector is needed ⇒ ILC!!

Future prospects:

- To go further, quantitative analyses are absolutely required.
- Scenario with CP, flavor violations in HGT ⇒ with baryons

  ⇒ Nuclear physics !