Dark Matter, Inflation and Higgs Physics

Takehiro Nabeshima
University of Toyama

Higgs as a Probe of New Physics 2013, 13 Feb. 2013

1. Introduction

2. Dark matter

・Why we need dark matter?

・Dark matter models relate the Higgs sector .

3. Inflation

・Why we need inflation?

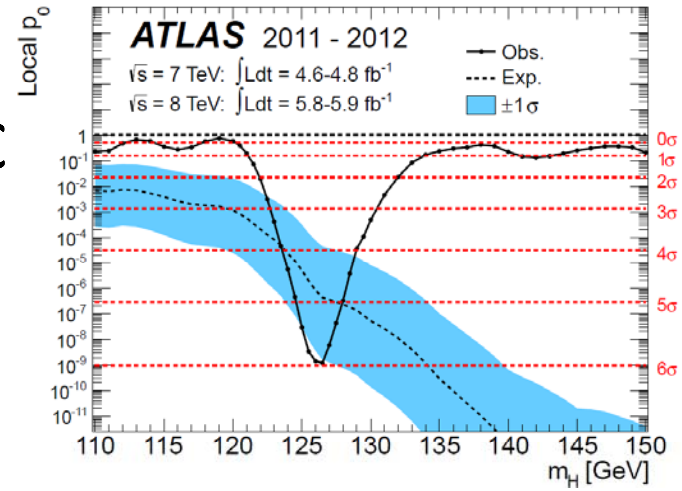
・Inflation models relate the Higgs sector.

4. Conclusion

1. Introduction

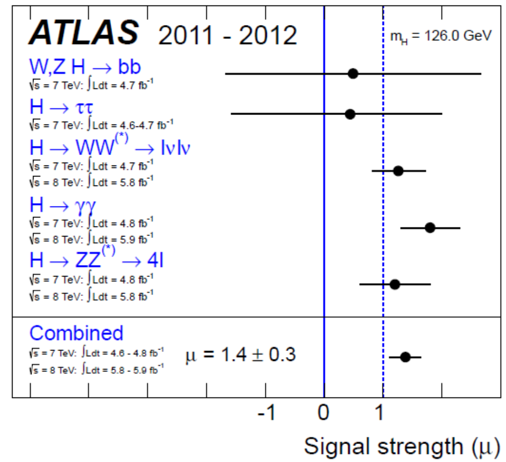
A Higgs-like boson was discovered

A new particle is discovered at the LHC



This new particle seems to be the Standard Model (SM) Higgs boson!

Existence of Higgs coupling constants to the massive particles are being confirmed at the LHC!

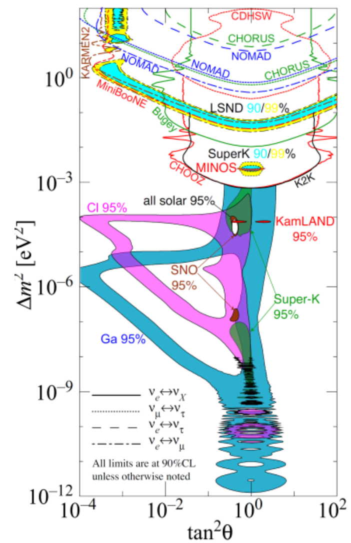


It does not mean the end of the story.
This discovery opens the door of the new physics!

1. Introduction

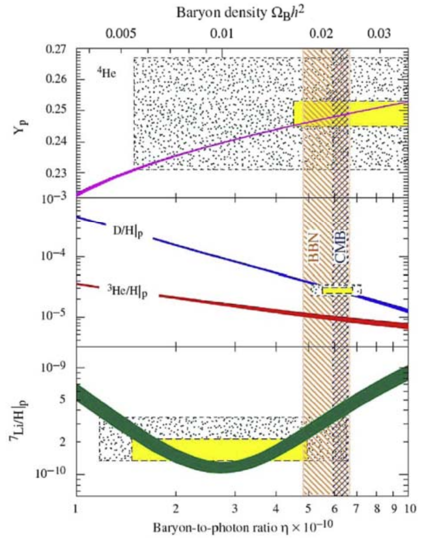
Beyond the SM phenomena

The SM must be extended.



・Neutrino flavor oscillation

This oscillation can be explained by masses of neutrinos.
However, neutrinos cannot have its masses in the minimal SM.



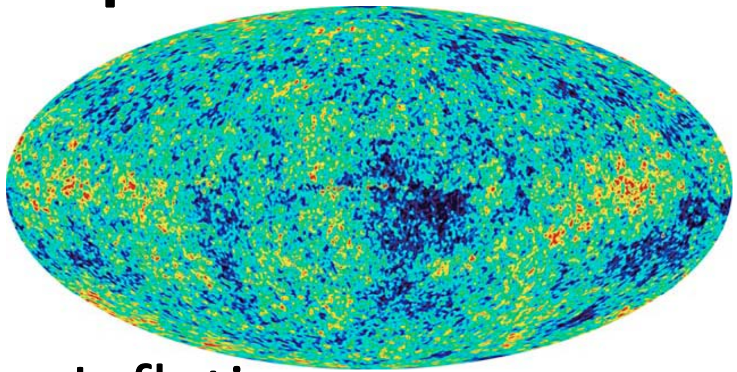
・Baryon asymmetry of the universe.

In our Universe, baryon number is finite value.
However, the SM cannot explain baryon number with out contradiction with current experimental data.

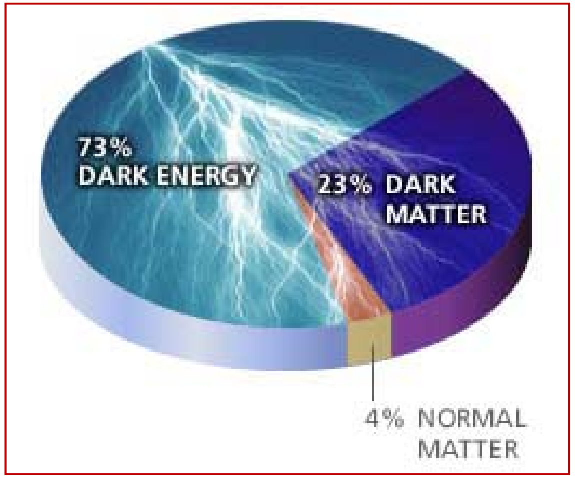
1. Introduction

Beyond the SM phenomena

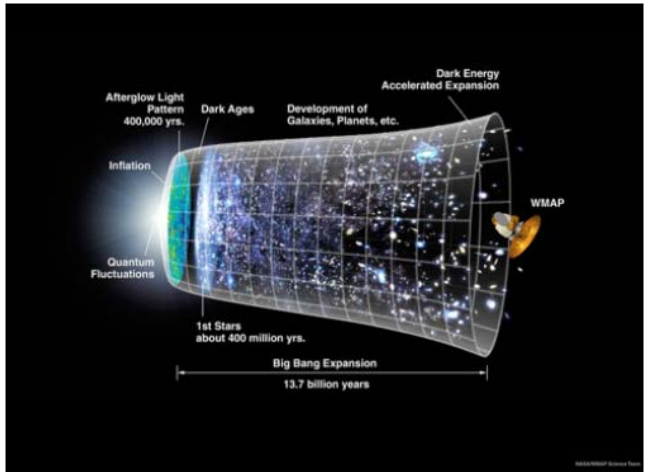
- Cosmic Microwave Background radiation(CMB)



Dark matter (DM)



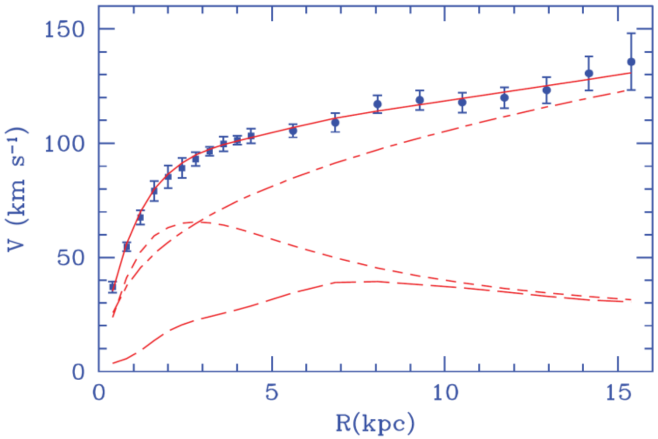
Inflation



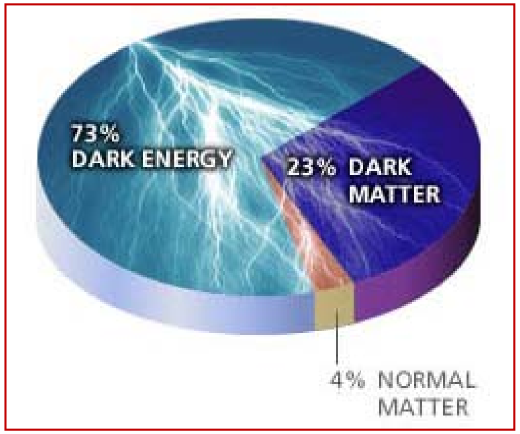
If these phenomena are related to the Higgs sector,
We can probe physics beyond the SM
by using data of the Higgs boson.

2. Dark matter

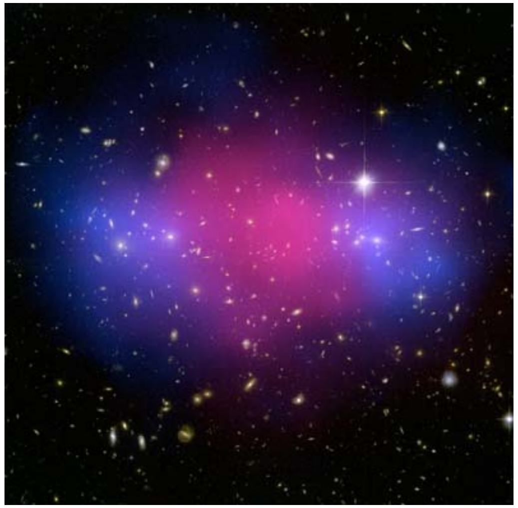
Why we need dark matter?



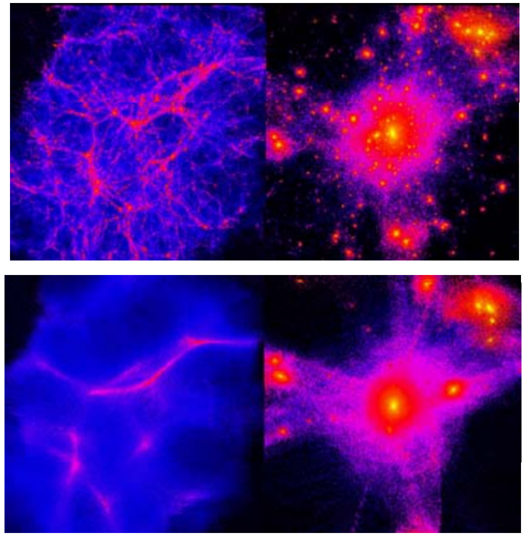
Rotation speed of galaxy



Abundance of dark matter



Collision of galaxies



Large-scale structure

2. Dark matter

Candidate of dark matter

Candidate	Mass scale
Axion	Very light
Warm DM	Less than 1 GeV
Asymmetric DM	O(1) GeV
WIMP	O(100) GeV

The mass scale of WIMP dark matter can be estimated around the electroweak scale.

⇩

The WIMP dark matter seems to relation with the Higgs boson!

We here concentrate on WIMP dark matter.

2. Dark matter

Case 1: The Higgs portal dark matter

Discussed in the second meeting.

The dark matter couples only to the Higgs boson!

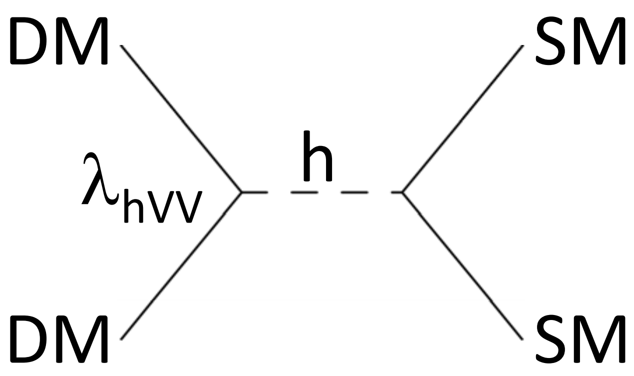
A. T. Abe, M. Kakizaki, S. Matsumoto and O. Seto(2012)
B. A. Djouadi, A. Falkowski,y Yann Mambrini and J. Quevillon(2012)
C. S. Kanemura, S. Matsumoto, T.N. and H. Taniguchi(2011)
D. S. Kanemura, S. Matsumoto, T.N. and N. Okada(2010)
E. M. Aoki, S. Kanemura and O. Seto(2010)
F. Y. G. Kim and S. Shin(2009)
G. K. Y. Lee, Y. G. Kim and S. Shin (2008)
H. K. Y. Lee, Y. G. Kim and S. Shin (2008)
I. K. Y. Lee and Y. G. Kim (2006)
J. S. Baek, P. Ko, W. Park and E. Senaha(2013)
K. S. Baek, P. Ko, W. Park and E. Senaha(2012)
L. S. Baek, P. Ko, W. Park and E. Senaha(2012)
M. S. Baek, P. Ko and W. Park(2012)
N. B. Swiezewska and M. Krawczyk(2012)
O. M. Krawczyk and D. Sokolowska (2011)
P. M. Krawczyk and D. Sokolowska (2009)
Q. R. Coimbra, M. O.P. Sampaio and R. Santos(2013)
R. H. Okada and T. Toma(2012)
S. And more.

2. Dark matter

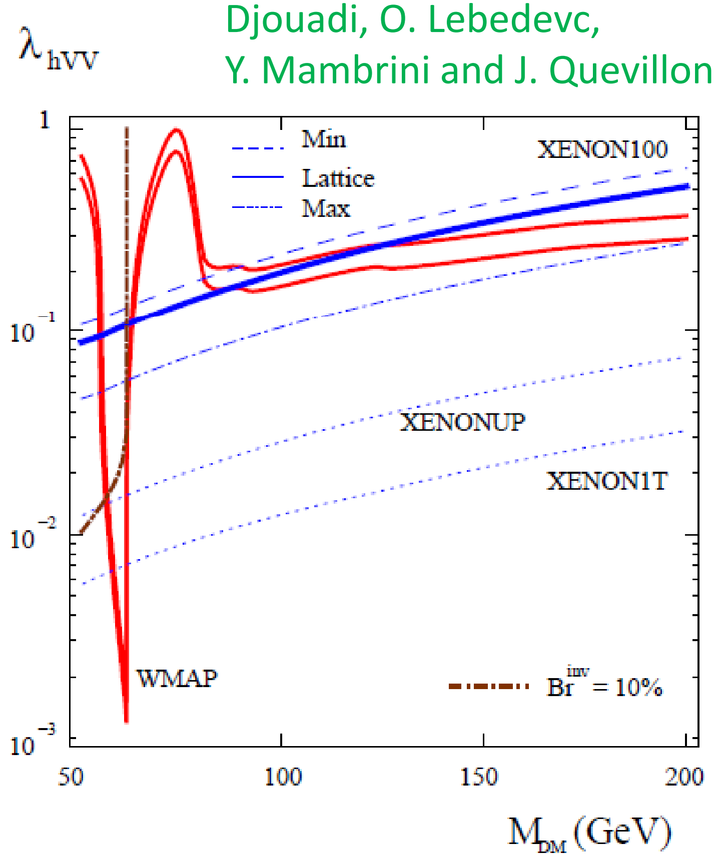
Case 1: The Higgs portal dark matter

Discussed in the second meeting.

The dark matter couples only to the Higgs boson!



Djouadi, O. Lebedevc,
Y. Mambrini and J. Quevillon (2012)

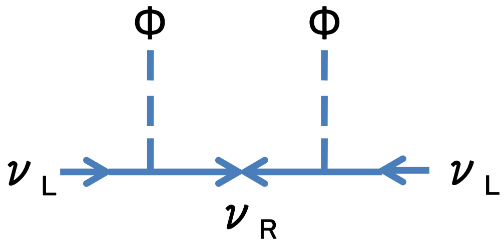


This dark matter model can be probed at direct detection experiment

2. Dark matter

The radiative seesaw model

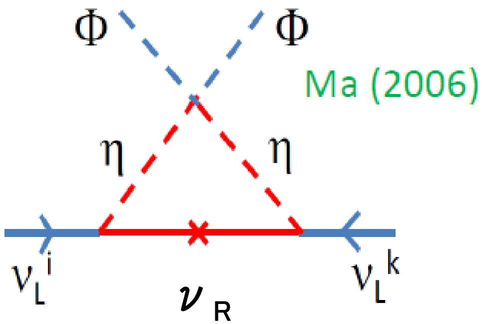
- Tree level



The seesaw mechanism is a very attractive candidate to give masses to neutrinos.

$M \sim O(10^{12})$ TeV → $c \sim O(1)$
$M \sim O(1)$ TeV → $c \sim O(10^{-6})$

- Loop level (radiative seesaw)



$M \sim O(1)$ TeV
→ $c \sim O(10^{-4})$

For M～O(1)TeV,

Coupling constants are sizable.

Dark matter candidate is naturally introduced.

2. Dark matter

The radiative seesaw model

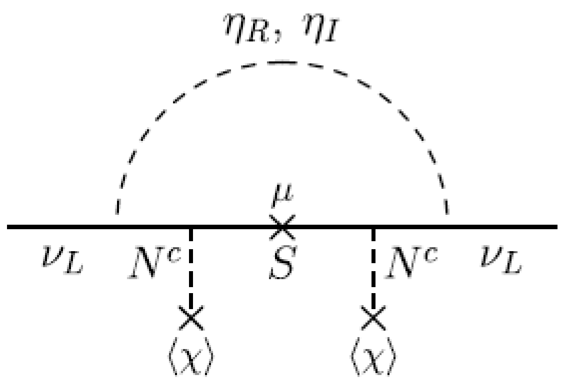
A. S. Kanemura and H. Sugiyama(2012)
B. S. Kanemura, T. N. and H. Sugiyama(2012)
C. S. Kanemura, T. N. and H. Sugiyama(2011)
D. S. Kanemura, O. Seto and T. Shimomura(2011)
E. M. Aoki, S. Kanemura and O. Seto(2009)
F. M. Aoki, S. Kanemura and O. Seto(2008)
G. S. Kashiwase and D. Suematsu(2013)
H. S. Kashiwase and D. Suematsu(2012)
I. J. Kubo and D. Suematsu(2006)
J. Y. Kajiyama, H. Okada and T. Toma(2012)
K. Y. Kajiyama, H. Okada and T. Toma(2011)
L. D. Suematsu and T. Toma(2011)
M. D. Suematsu, T. Toma and T. Yoshida(2010)
N. M. Aoki, S. Kanemura and K. Yagyu(2011)
O. And more.

2. Dark matter

Case 2:
Dark matter in the radiative seesaw model

- $U(1)_{B-L}$ gauge symmetry broken at the TeV scale.

- **Masses of neutrinos are given by 1-loop level diagram through the mixing between N and S.**

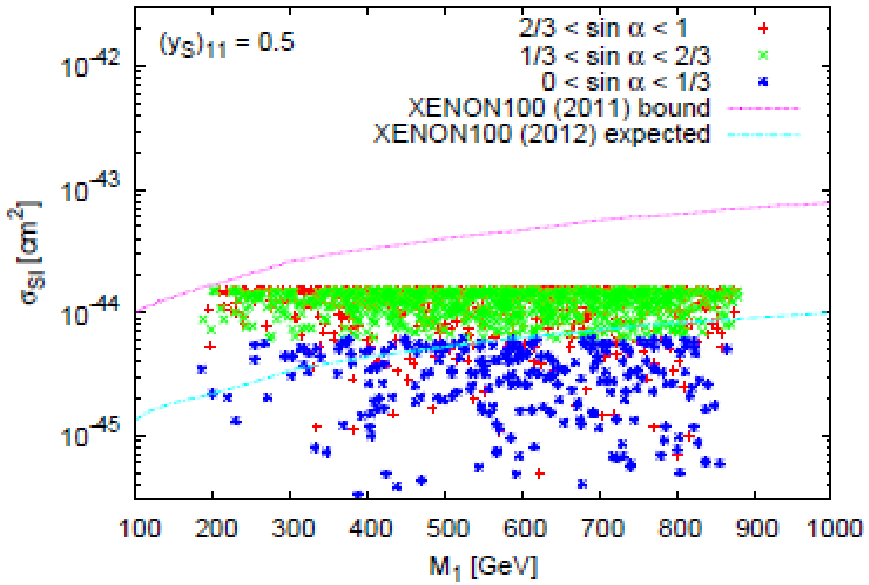


- **The Higgs mediated diagram is important for direct detection.**

Discussed in the second meeting.

	N^c	S	S'	η	χ
$SU(2)_L$	**1**	**1**	**1**	**2**	**1**
$U(1)_Y$	0	0	0	1/2	0
$U(1)_{B-L}$	1	$-3/4$	$3/4$	0	$-1/4$
$\mathbb{Z}_2$	-1	-1	$+1$	-1	$+1$

H. Okada and T. Toma (2012)

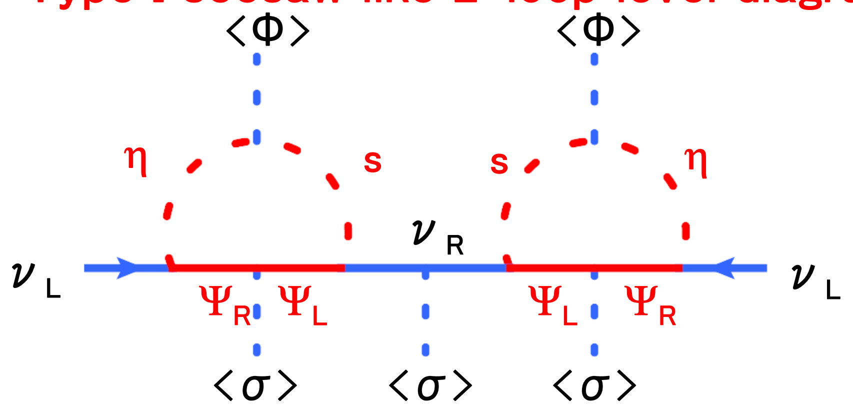


2. Dark matter

Case 3: Dark matter in the radiative seesaw model

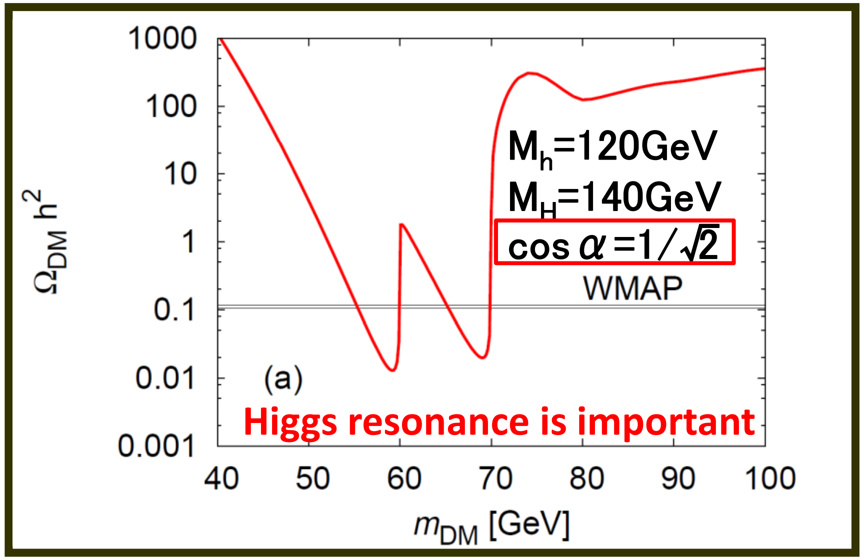
Discussed in the third meeting.

- $U(1)_{B-L}$ gauge symmetry broken at the TeV scale
- Dark matter(Ψ_1) mass: From y_{DM} Ψ Ψ σ coupling at tree level.
- Neutrino masses: Type I seesaw like 2-loop level diagram.



- Stability of dark matter: Global $U(1)_{DM}$ from $U(1)_{B-L}$ charge assignment.

	s	η	$(\Psi_R)_i$	$(\Psi_L)_i$	$(\nu_R)_i$	σ
$SU(2)_I$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$
$U(1)_Y$	0	1/2	0	0	0	0
$U(1)_{B-L}$	1/2	1/2	−1/2	3/2	1	2



S. Kanemura, T.N. and H. Sugiyama (2012)

Summary for the dark matter

We discussed some dark matter candidates which are related to the Higgs sector in the Higgs working group.

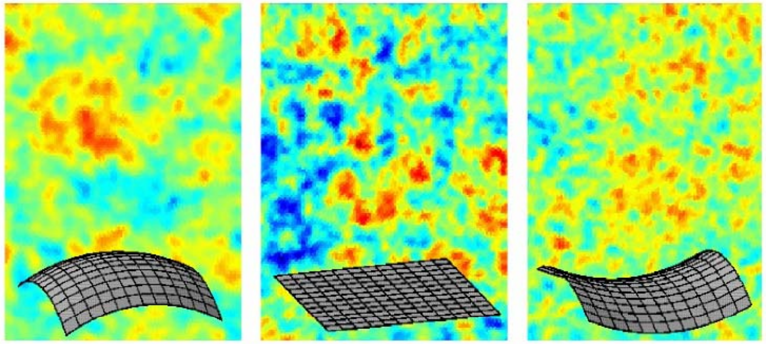
These dark matter candidates are constrained through the Higgs bosons properties.

The discovery of the Higgs boson is very important for the dark matter!

3. Inflation

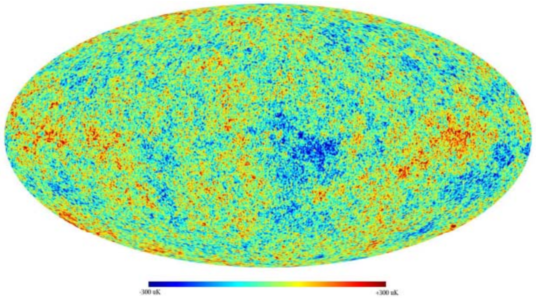
Why we need inflation?

・The flatness problem



The Universe is flat
but the standard cosmology
cannot explain this flatness.

・The horizon problem



The temperature of the CMB is
almost the same value but light
cone cover very small region.

These problems can be solved
by exponential expansion(inflation).

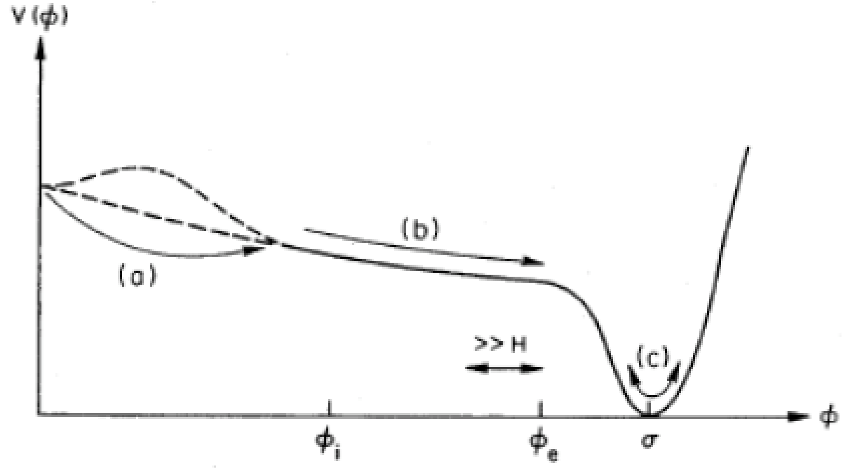
3. Inflation

How to explain inflation?

We introduce a real scalar ϕ

$$\mathscr{L} = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

$$H^2 = \frac{V}{3M_P^2} \qquad \left(H = \frac{\dot{a}}{a} \right)$$



If H is a constant, The Universe expands by exponential.

$$\varepsilon \equiv \frac{1}{2} M_P{}^2 (V'/V)^2 << 1 \qquad \eta \equiv M_P{}^2 V''/V << 1$$

Inflation can be explained by scalar particle(inflaton)

We here concentrate on the case which the Higgs boson act as the inflaton.

3. Inflation

Higgs inflation in the SM

Inflaton = Higgs

- **Higgs boson mass (m_h=126GeV)**
- **Slow-roll condition(ε, η)**
- **CMB temperature fluctuations (P_R)**

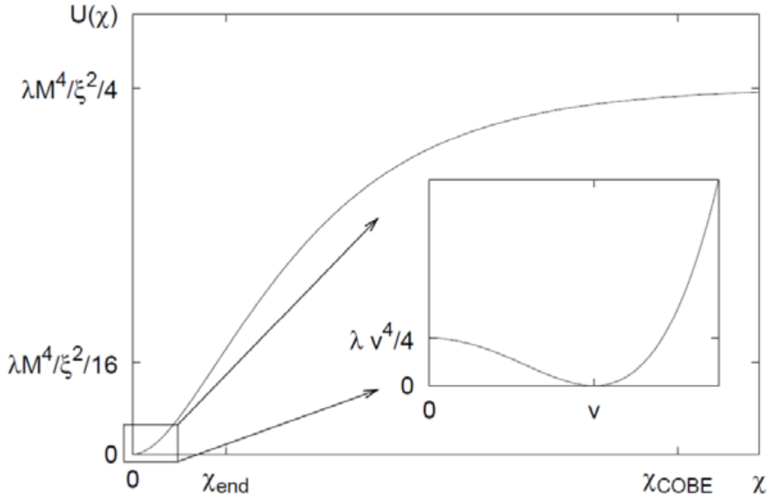
$$\varepsilon \equiv \frac{1}{2} M_P{}^2 (V'/V)^2 << 1$$

$$\eta \equiv M_P{}^2 V''/V << 1$$

$$L_{\rm tot} = L_{\rm SM} - \frac{M^2}{2} R - \xi H^\dagger H R$$

$$V(\chi) = \left(1 + \exp\left(-\frac{2\chi}{\sqrt{6} M_P}\right)\right)^{-2}$$

$$\left(\frac{d\chi}{dh} = \sqrt{\frac{\Omega^2 + 6\xi^2 h^2/M_P^2}{\Omega^4}}\right)$$



Bezrukov and Shaposhnikov (2008)

WMAP :

$$P_R = 2.430 \pm 0.091 \times 10^{-9}$$

$$\Rightarrow \quad \xi = 5 \times 10^4 \sqrt{\lambda}$$

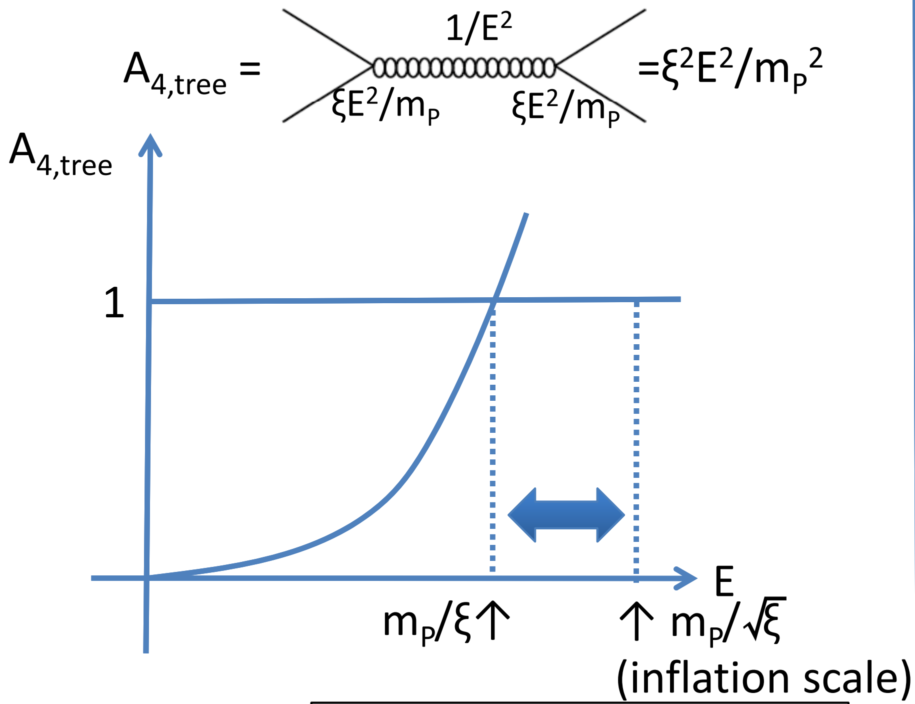
SM-Higgs satisfies ε, η and P_R !

3. Inflation

Problems in the simplest case

(Ⅰ)Unitarity

T. Han and S. Willenbtock, Phys. Lett. B 616, 215 (2005)

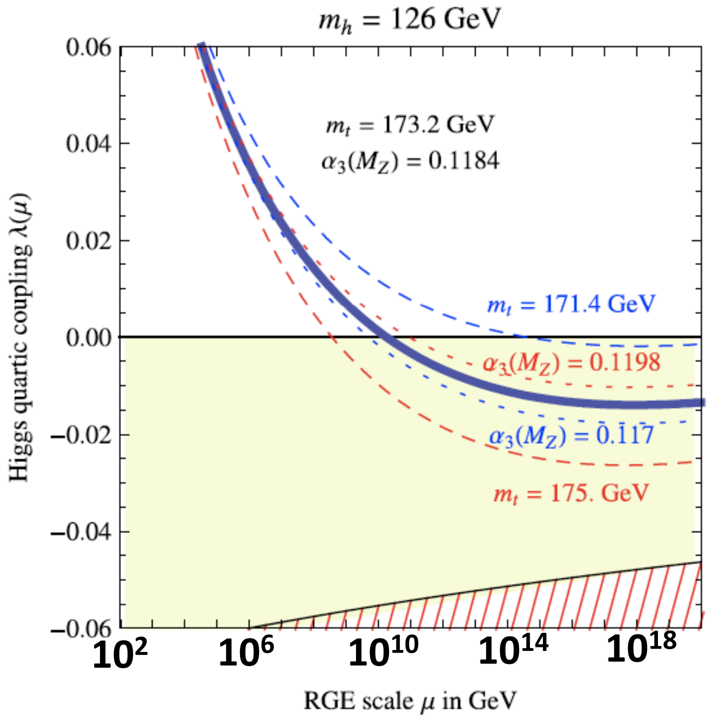


$\xi = O(10^4) \Rightarrow \Lambda \sim m_P/\xi$

Unitarity is broken at $O(10^{15})$ GeV

(Ⅱ)Vacuum stability

J.Elias-Miro et al, Phys. Lett. B 709, 222 (2012)



$m_h = 126\text{GeV} \Rightarrow \Lambda \sim 10^{10}\text{GeV}$

Vacuum cannot be stabilized at $O(10^{10})$ GeV

⇒Simplest Higgs inflation cannot reach to the inflation scale

3. Inflation

Solutions for the problems

(Ⅰ) Unitarity

G.F.Giudice, H.M.Lee, PLB694, 294(2011)

We add a heavy scalar particle to save unitarity.

(Ⅱ) Vacuum stability⇒ Extended Higgs sector.

・Renormalization group equations

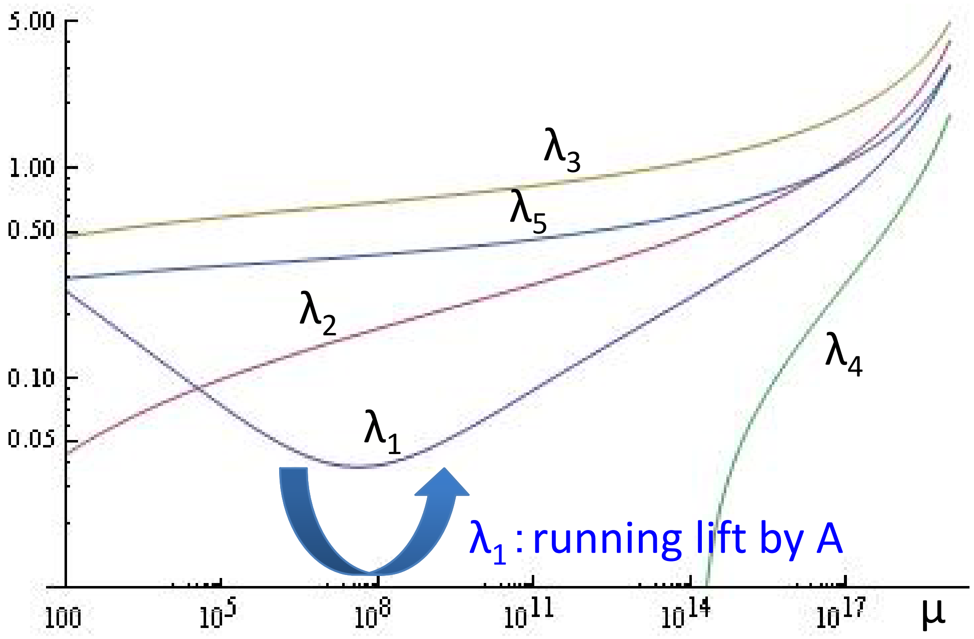
$$16\pi^2\mu\frac{d\lambda_1}{d\mu} \sim 12\lambda_1^2 - 12y_t^4 + A$$

The new bosonic loop cancel the y_t effect!

2HDM

$$A = 2\lambda_3^2 + 2(\lambda_3+\lambda_4)^2 + 2\lambda_5^2 > 0$$

S.Kanemura, T.Kasai, Y.Okada, Phys.Lett. B471 (1999)



m_h=126GeV, m_t=173.5GeV

3. Inflation

Higgs inflation in the two higgs doublet model

$$V = \frac{M_P R}{2} + (\xi_1|\Phi_1|^2 + \xi_2|\Phi_2|^2)R$$
$$+\mu_1^2|\Phi_1|^2 + \mu_2^2|\Phi_2|^2 + \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2$$
$$+\lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + [\frac{1}{2}\lambda_5((\Phi_1^\dagger\Phi_2)^2]$$

Gong, Lee and Kang (2012)

$$\Phi_1 = (\phi^+, \phi^0)$$
$$\Phi_2 = [H^+, (H^0 + iA^0)/\sqrt{2}]$$

Vacuum stability:

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 + \lambda_4 + \lambda_5 + \sqrt{\lambda_1\lambda_2} > 0$$

Inflaton condition:

$$\lambda_2\xi_1 - (\lambda_3 + \lambda_4)\xi_2 > 0$$
$$\lambda_1\xi_2 - (\lambda_3 + \lambda_4)\xi_1 > 0$$
$$\lambda_1\lambda_2 - (\lambda_3 + \lambda_4)^2 > 0$$

CMB temperature fluctuations: $a \equiv \xi_1/\xi_2$

$$\xi_2\sqrt{\frac{2(\lambda_1 + a^2\lambda_2 - 2a(\lambda_3 + \lambda_4))}{\lambda_1\lambda_2 - (\lambda_3 + \lambda_4)^2}} \simeq 5 \times 10^4$$
$$\frac{\lambda_5}{\xi_2}\frac{a\lambda_2 - (\lambda_3 + \lambda_4)}{\lambda_1 + a^2\lambda_2 - a(\lambda_3 + \lambda_4)} \leq 4 \times 10^{-12}$$

$$m_h^2 = \lambda_1 v^2$$
$$m_{H^\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2$$
$$m_H^2 = \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)v^2$$
$$m_A^2 = \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5)v^2$$

Inflation can be explained !

3. Inflation

Discussed at the forth meeting.

Higgs inflation in the two higgs doublet model

CMB temperature fluctuations: $a \equiv \xi_1/\xi_2$

$$\xi_2\sqrt{\frac{2(\lambda_1+a^2\lambda_2-2a(\lambda_3+\lambda_4))}{\lambda_1\lambda_2-(\lambda_3+\lambda_4)^2}} \simeq 5\times 10^4$$

$$\frac{\lambda_5}{\xi_2}\frac{a\lambda_2-(\lambda_3+\lambda_4)}{\lambda_1+a^2\lambda_2-a(\lambda_3+\lambda_4)} \leq 4\times 10^{-12}$$

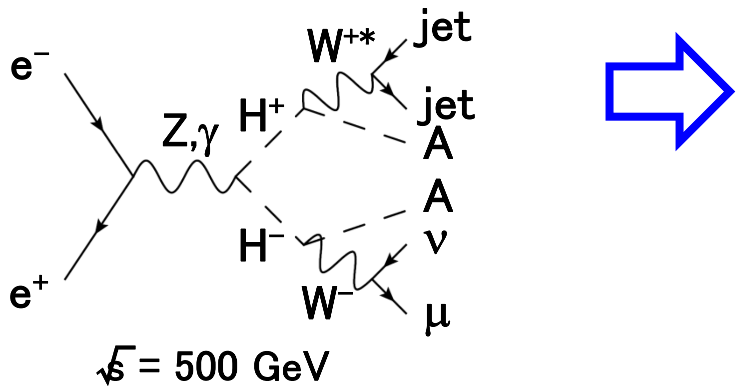
When relation $a\lambda_2-(\lambda_3+\lambda_4)\approx 0$ is satisfied at the inflation scale.

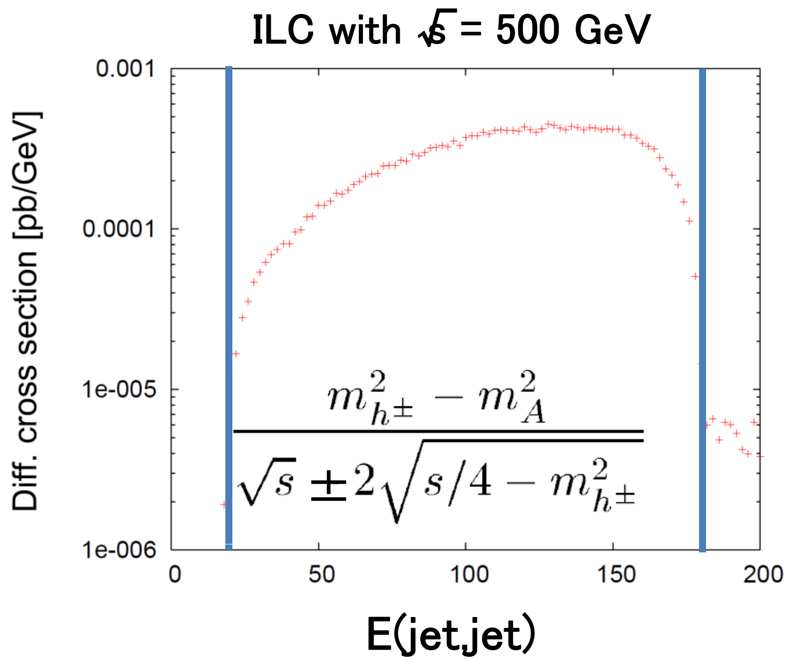
ILC could be tested characteristic mass spectrum!

m_h=126GeV

m_H=92.0GeV
$m_{H\pm}$=141GeV
m_A=65.0GeV

$m_A < m_H\ (\approx 90\text{GeV}) < m_h < m_{H\pm}\ (\approx 140\text{GeV})$





S. Kanemura, T.N. and T. Matsui (2012)

Summary for inflation

Usually, the scale of the Inflation is very high such as the Planck scale.
The Higgs inflation scenario has a potential to predict characteristic mass spectrum at the EW scale.

The mechanism of inflation could be tested through testing the Higgs properties at the EW scale!

Conclusion

The Higgs working group discussed models which explain the dark matter and inflation by using the physics of the Higgs sector.

In this case, cosmological observables are rerated to the Higgs properties.
Such models can be probed through the Higgs sector.

Discovery of the Higgs boson is very important for exploring new physics.

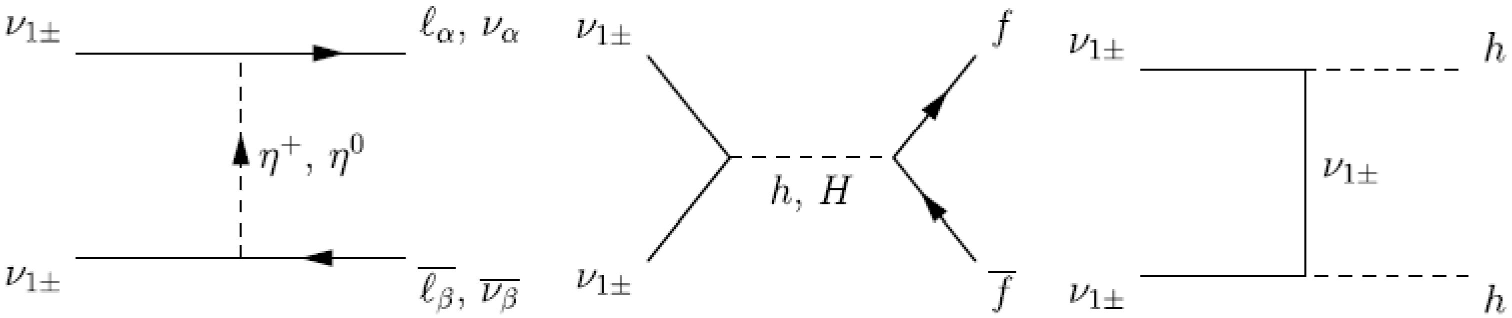
DMの残留密度

DM 候補: N^c, S, η_R (η_I)

N^c, S (ゲージ固有状態) $\to \nu_\pm$ (質量固有状態)
DM を $\nu_{1\pm}$ とする.

$$m_{i\pm} = \sqrt{M_i^2 + \frac{\mu_i^2}{4}} \pm \frac{\mu_i}{2} \qquad \text{質量差：} \quad \mu \ll M$$

- ν_{1-} と ν_{1+} の coannihilation
- 3 つの対消滅プロセス



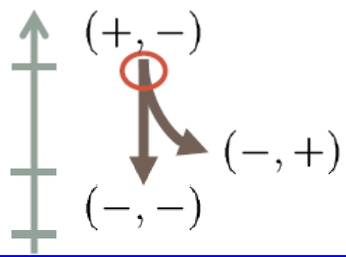
2. Dark matter

Multi component dark matter

M. Aoki, J. Kubo, T. Okawa and H. Takano(2012)
R. Coimbra, M. O.P. Sampaio and R. Santos(2013)
S. Khalil, H. Okada and T. Toma(2011)
H. Fukuoka, D. Suematsu and T. Toma(2011) and more.

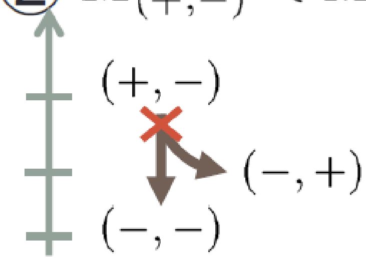
When two symmetries, Z_2 and Z_2', exist, several dark matter candidates co-exist by the kinematical situation.

① $M_{(+,-)} > M_{(-,+)} + M_{(-,-)}$



When one of the dark matter candidates can decay into another candidate,
dark matter is composed of two particles.

② $M_{(+,-)} < M_{(-,+)} + M_{(-,-)}$

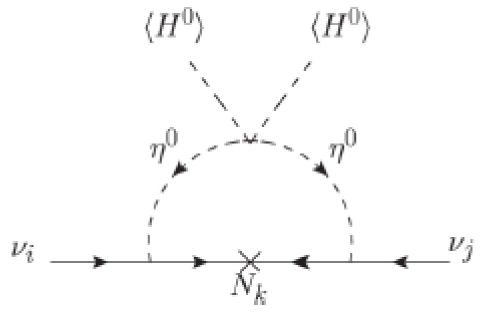


When one of the dark matter candidate cannot decay into another candidate,
dark matter is composed of three particles.

2. Dark matter

Case 4: Multi component dark matter

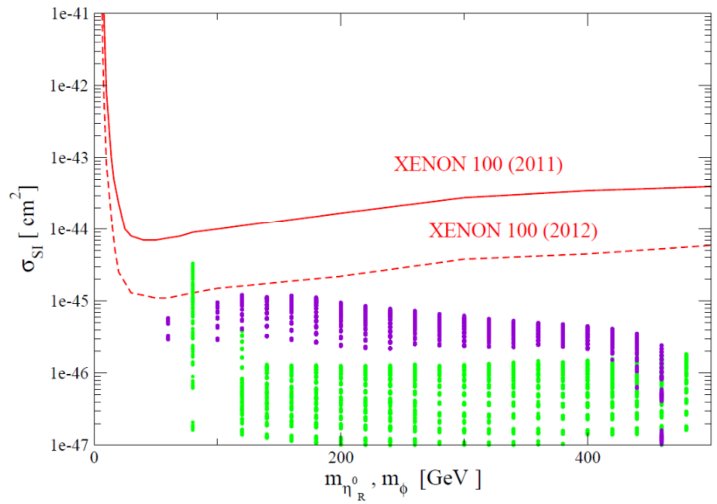
Discussed in the third meeting.



- extended Ma model with new Z_2' symmetry.

field	$SU(2)_L$	$U(1)_Y$	Z_2	Z_2'
(ν_{Li}, l_i)	2	$-1/2$	+	+
l_i^c	1	1	+	+
N_i^c	1	0	−	+
$H = (H^+, H^0)$	2	1/2	+	+
$\eta = (\eta^+, \eta^0)$	2	1/2	−	+
χ	1	0	+	−
ϕ	1	0	−	−

- If dark matter is composed of some particles, direct detection bound can be relaxed.



M. Aoki, J. Kubo and H. Takano (2012)