Vacuum stability, neutrinos, and dark matter

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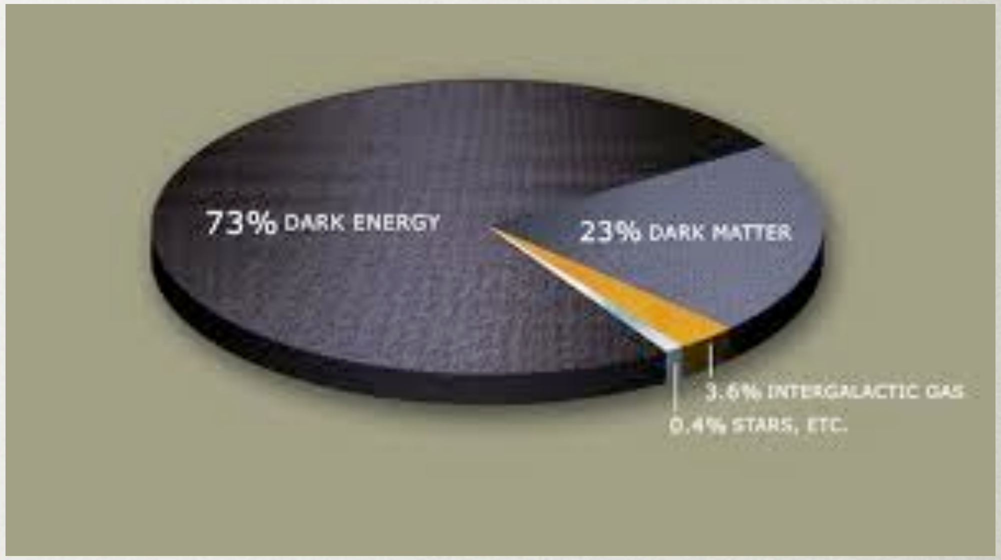
with Yong Tang

OUTLINE

- Introduction
- The frameworks
- Vacuum stability within SM + ν/DM
- Conclusion

INTRODUCTION

- Standard model successfully describe most phenomena but is incomplete.
- Neutrino oscillations indicate neutrinos have non-zero and tiny masses.
- There is only matter around us.
- The Universe is dark.
- At least three copies of fundamental fermions.



One of the main goal of large hadron collider is to find the last piece of Standard Model particle - Higgs boson.

12年5月8日星期二

- Neutrinos are regarded as massless, left-handed, and charge neutral fundamental fermions in Standard Model.
- Neutrino oscillations can be described by the mixings between weak eigenstates and mass eigenstates.

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\nu_i$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\alpha} \\ 0 & 1 & 0 \\ -s_{13}e^{i\alpha} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\phi_1} & 0 \\ 0 & 0 & e^{i\phi_2} \end{pmatrix}$$

U : PMNS mixing matrix
Pontecorvo , Sov. Phys. JETP**6**,429(1958) , **33**, 549(1967)
Z. Maki,M. Nakagawa, S. Sakata, Prog.Theor. Phys. **28**,870(1962)

$$P(\nu_{\alpha\rightarrow\nu_\beta}) = \delta_{\alpha\beta} - 4\sum_{i=1}^{3}\sum_{j=i+1}^{3} U_{\alpha i}U_{\beta i}U_{\alpha j}U_{\beta j}\sin^2(\frac{\Delta m_{ij}^2 L}{2E_\nu})$$

- Neutrinos are regarded as massless, left-handed, and charge neutral fundamental fermions in Standard Model.
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parameter	best fit $\pm 1\sigma$	2σ	3σ
$\Delta m^2_{21}\ [10^{-5}\mathrm{eV}^2]$	$7.59^{+0.20}_{-0.18}$	7.24–7.99	7.09–8.19
$\Delta m^2_{31}\ [10^{-3}\mathrm{eV}^2]$	$2.50^{+0.09}_{-0.16}$ $-(2.40^{+0.08}_{-0.09})$	$2.25-2.68$ $-(2.23-2.58)$	$2.14-2.76$ $-(2.13-2.67)$
$\sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$	0.28–0.35	0.27–0.36
$\sin^2\theta_{23}$	$0.52^{+0.06}_{-0.07}$ 0.52 ± 0.06	0.41–0.61 0.42–0.61	0.39–0.64
$\sin^2\theta_{13}$	$0.013^{+0.007}_{-0.005}$ $0.016^{+0.008}_{-0.006}$	0.004–0.028 0.005–0.031	0.001–0.035 0.001–0.039
δ	$\left(-0.61^{+0.75}_{-0.65}\right)\pi$ $\left(-0.41^{+0.65}_{-0.70}\right)\pi$	$0-2\pi$	$0-2\pi$

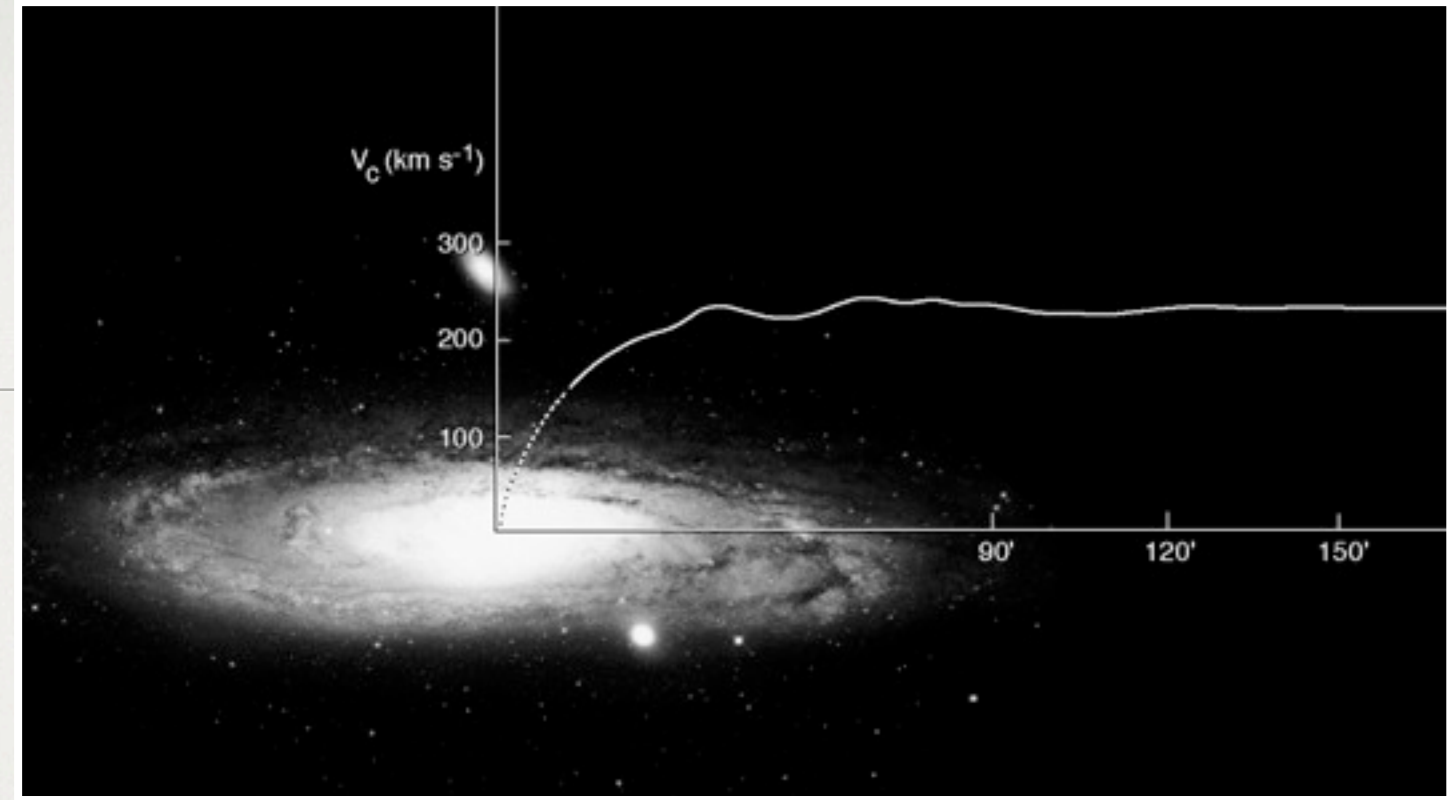
$U = \Big(\ \ldots \ \begin{matrix} 0 \\ 0 \\ e^{i\phi_2} \end{matrix} \Big)$

$P(\nu_{\alpha\to\nu_\beta}) = \delta_{\alpha\beta} - 4\sum_{i=1}\sum_{j=i+1} U_{\alpha i}U_{\beta i}U_{\alpha j}U_{\beta j}\sin(\ldots\frac{\ldots m^2_{ij}L}{2E_\nu})$

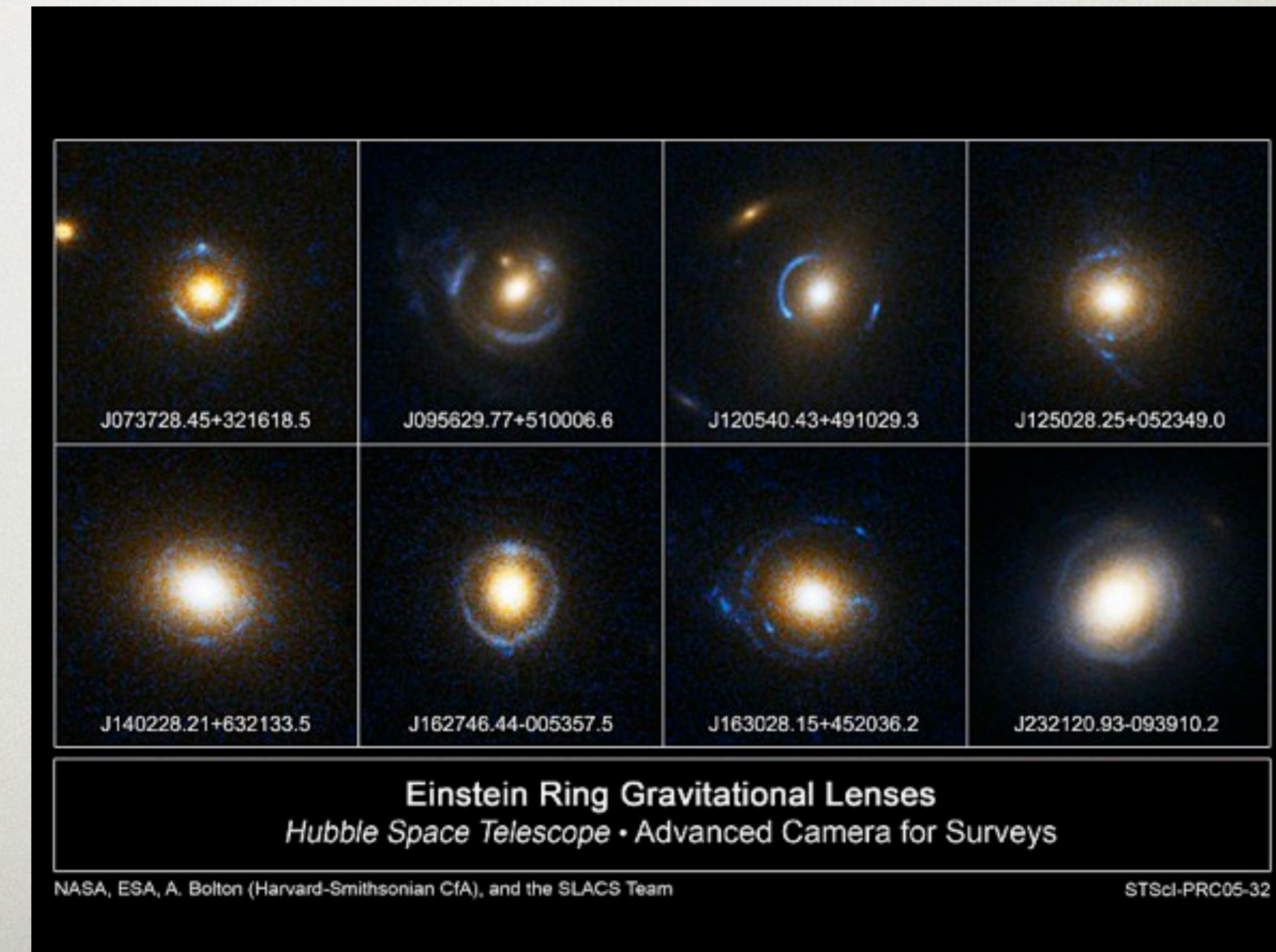
T. Schwetz, et al, 2011

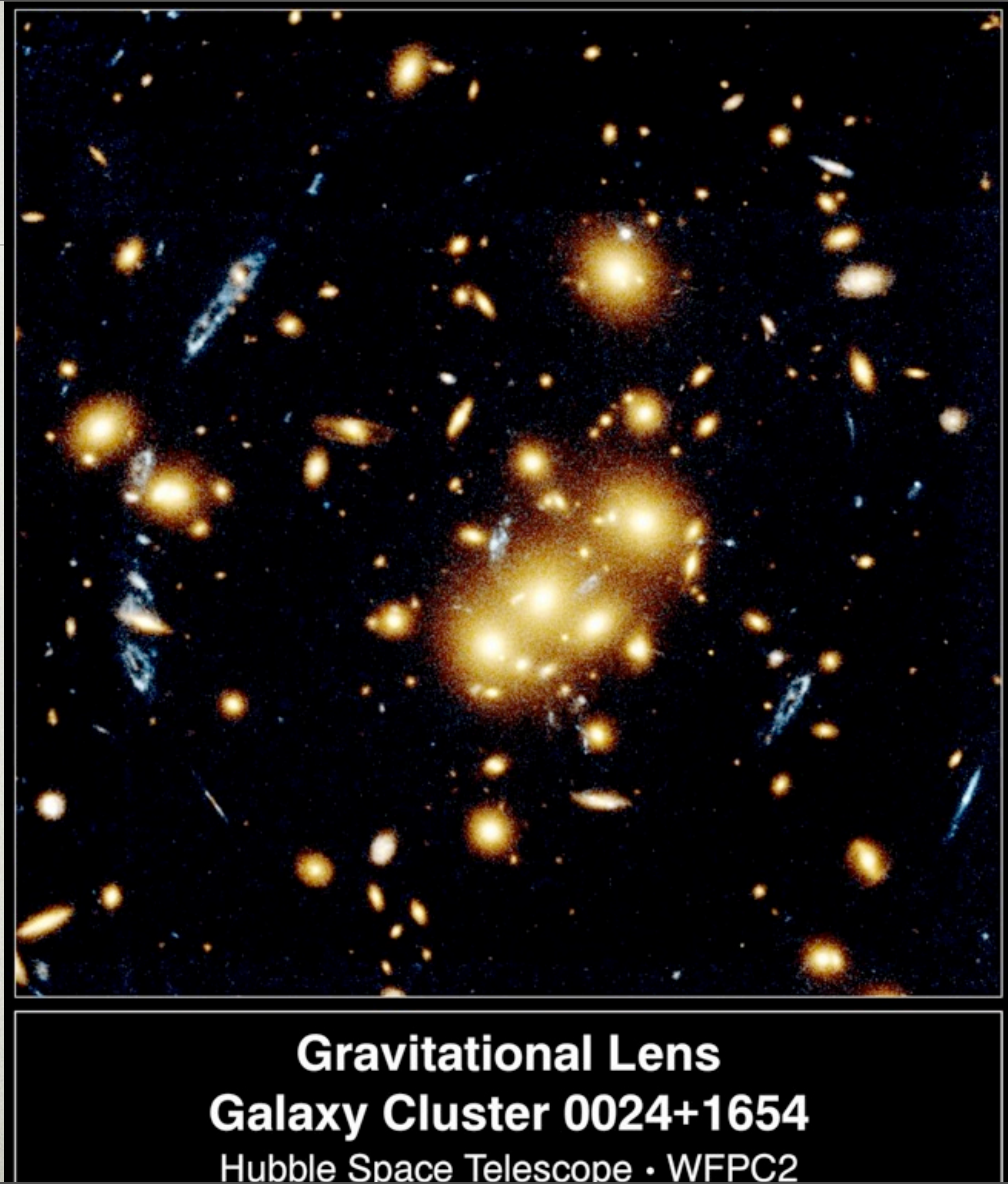
U : PMNS m...
Pontecorvo , Sov. Phys...
549(1967)
Z. Maki, M. Nakagawa, S. Sakata, Prog. Theor. Phys. **28**, 870(1962)

Cluster Dark matter



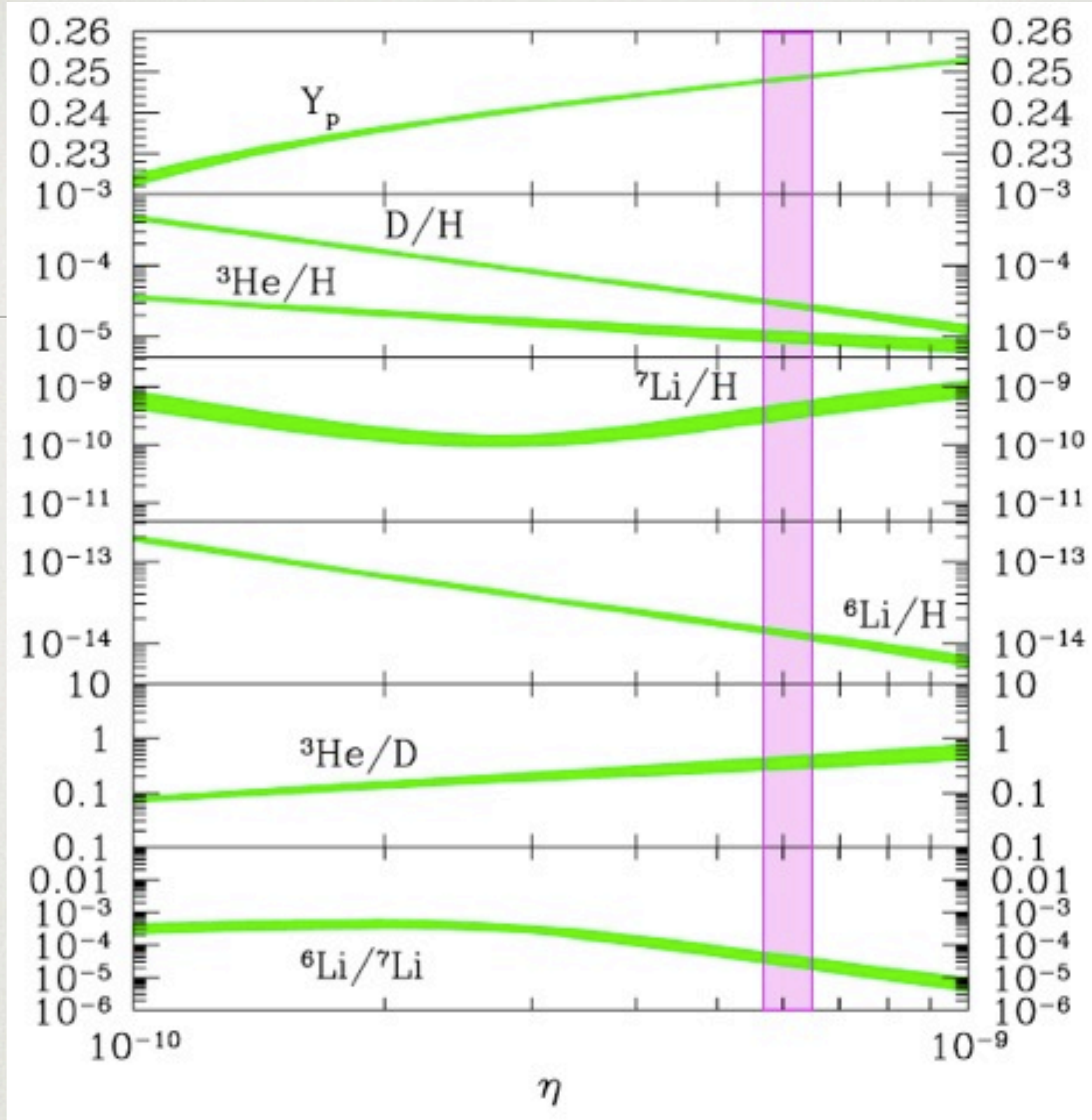
Dark matter and gravitational lensing




Gravitational Lens
Galaxy Cluster 0024+1654
Hubble Space Telescope • WFPC2

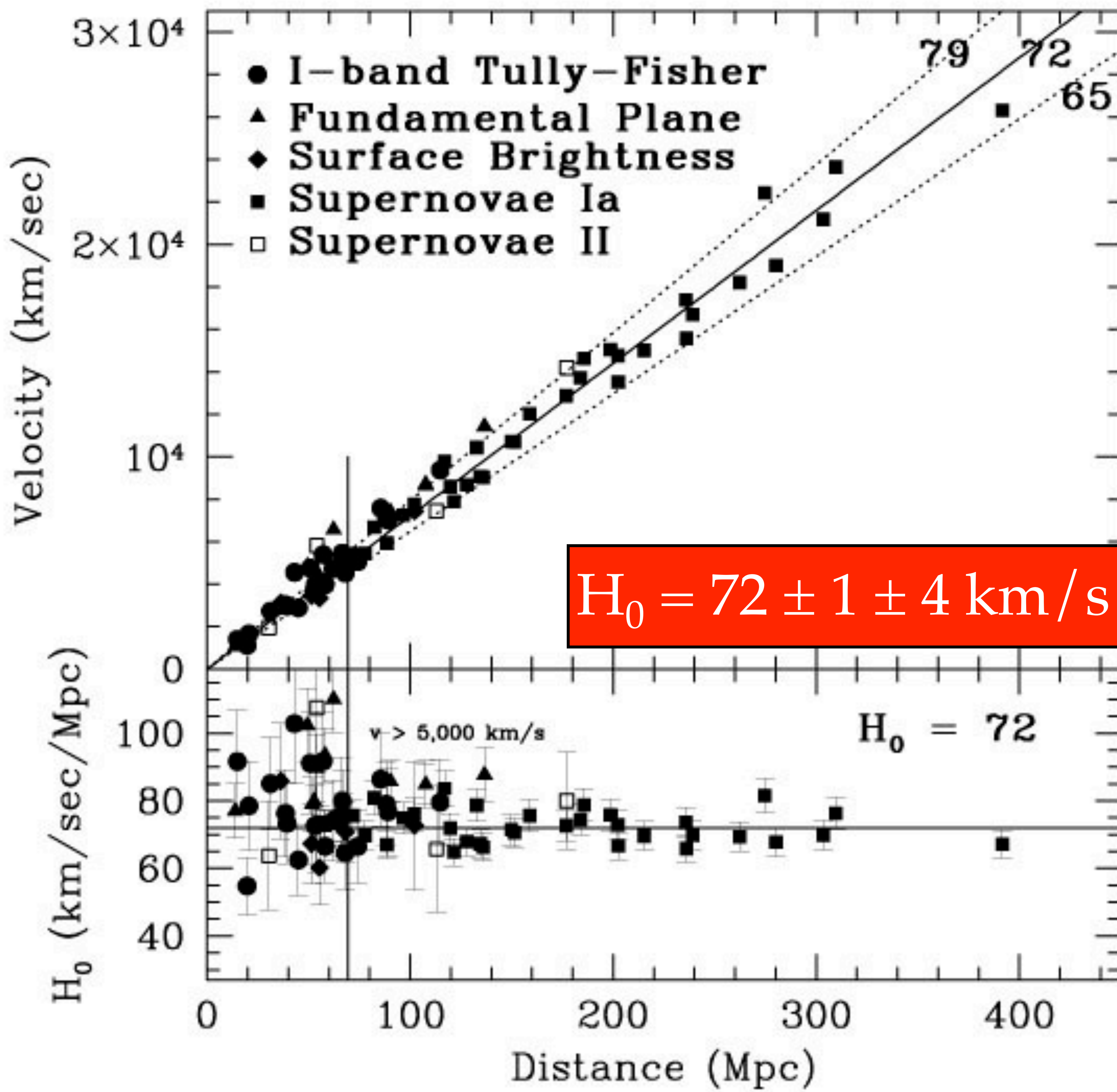
Gravitationally Lensed Quasar in Galaxy Cluster SDSS J1004+4112
Hubble Space Telescope • ACS/WFC

NASA, ESA, K. Sharon (Tel Aviv University), and E. Ofek (Caltech) STScI-PRC06-23

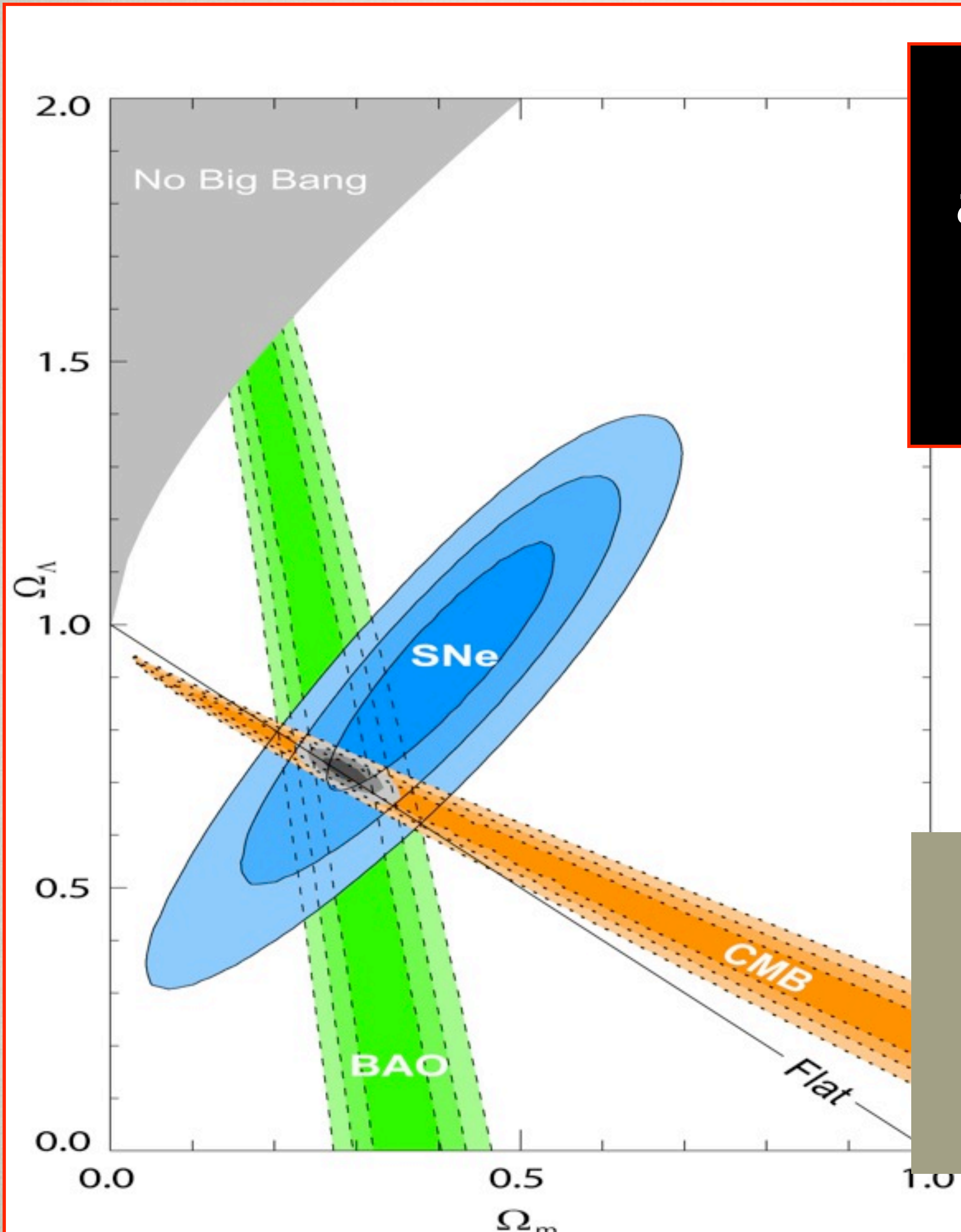


Depends on

- Neutron lifetime
- Number of massless neutrino species
- Baryon-to-photon ratio η

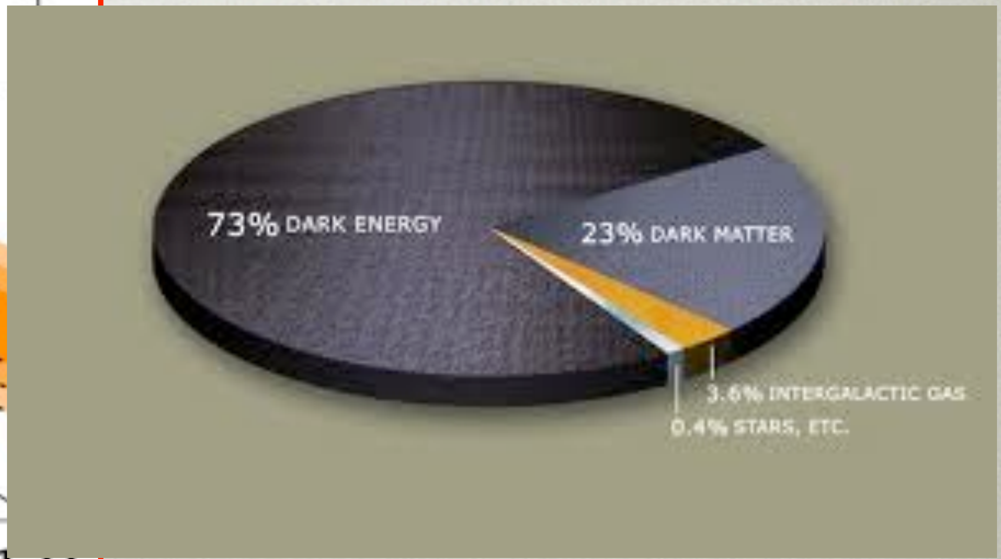


$H_0 = 72 \pm 1 \pm 4$ km/s/Mpc



Consistent with all observations:

$\Omega_\Lambda = 0.71 \pm 0.02$

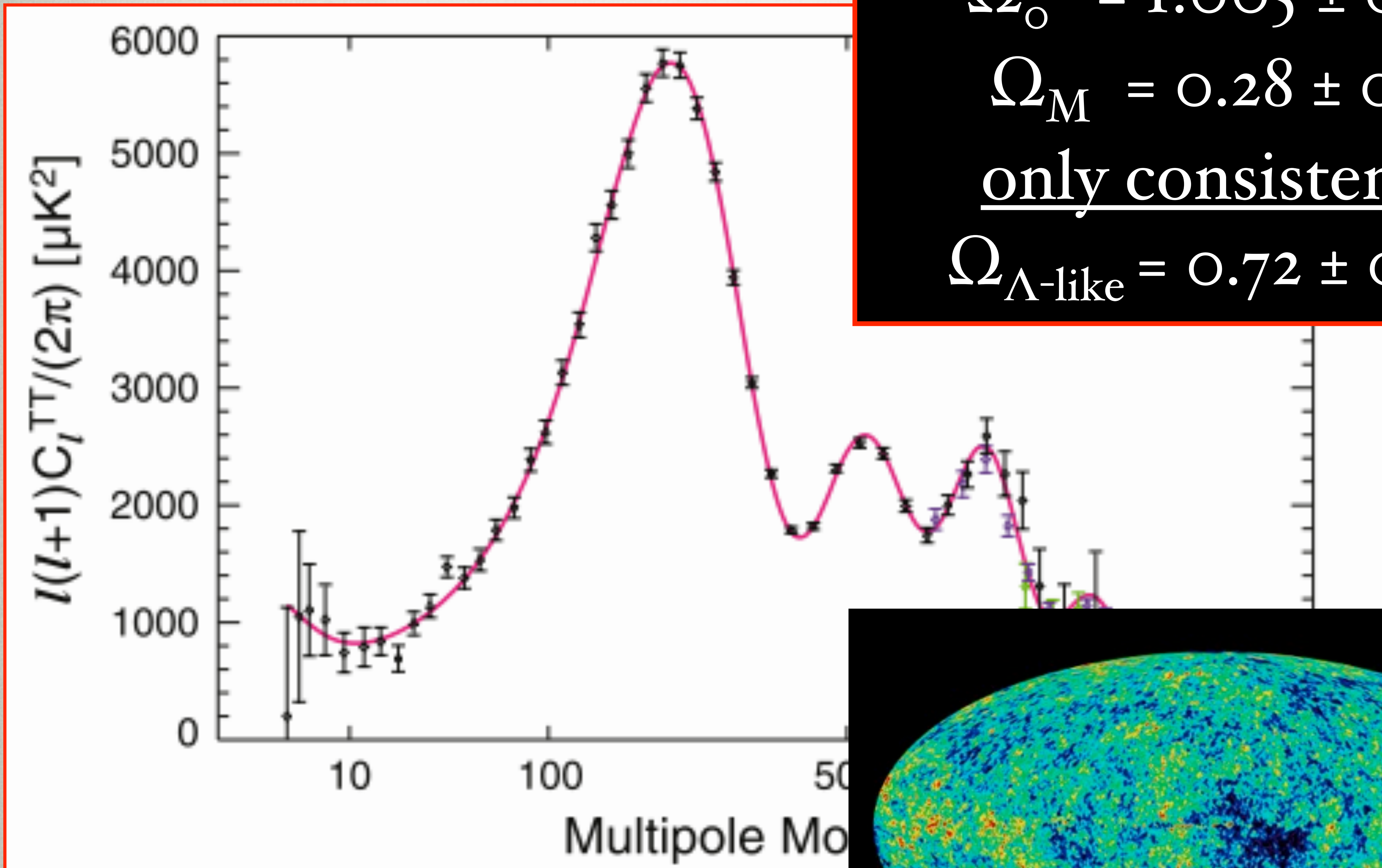


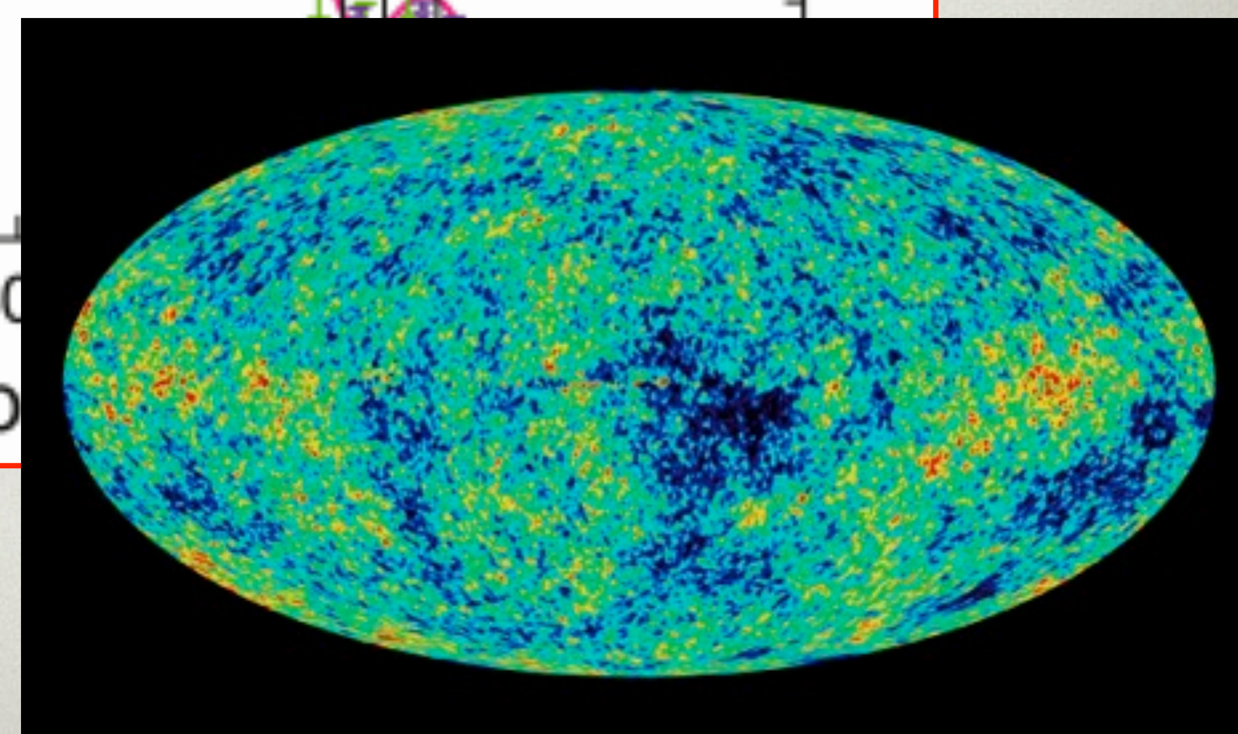
Ω_0 = 1.005 ± 0.006

Ω_M = 0.28 ± 0.015

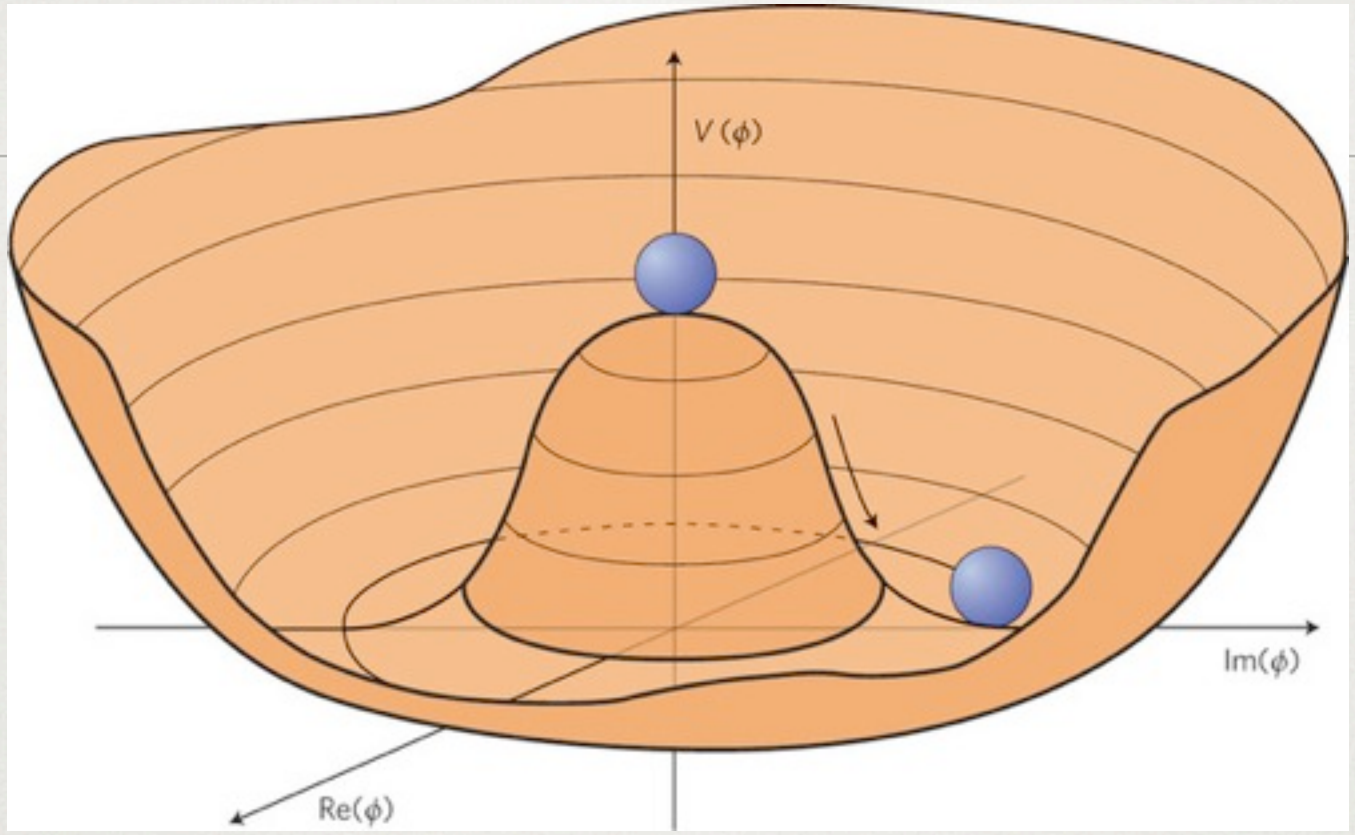
<u>only consistent if</u>

$\Omega_{\Lambda\text{-like}}$ = 0.72 ± 0.015





- Electroweak vacuum



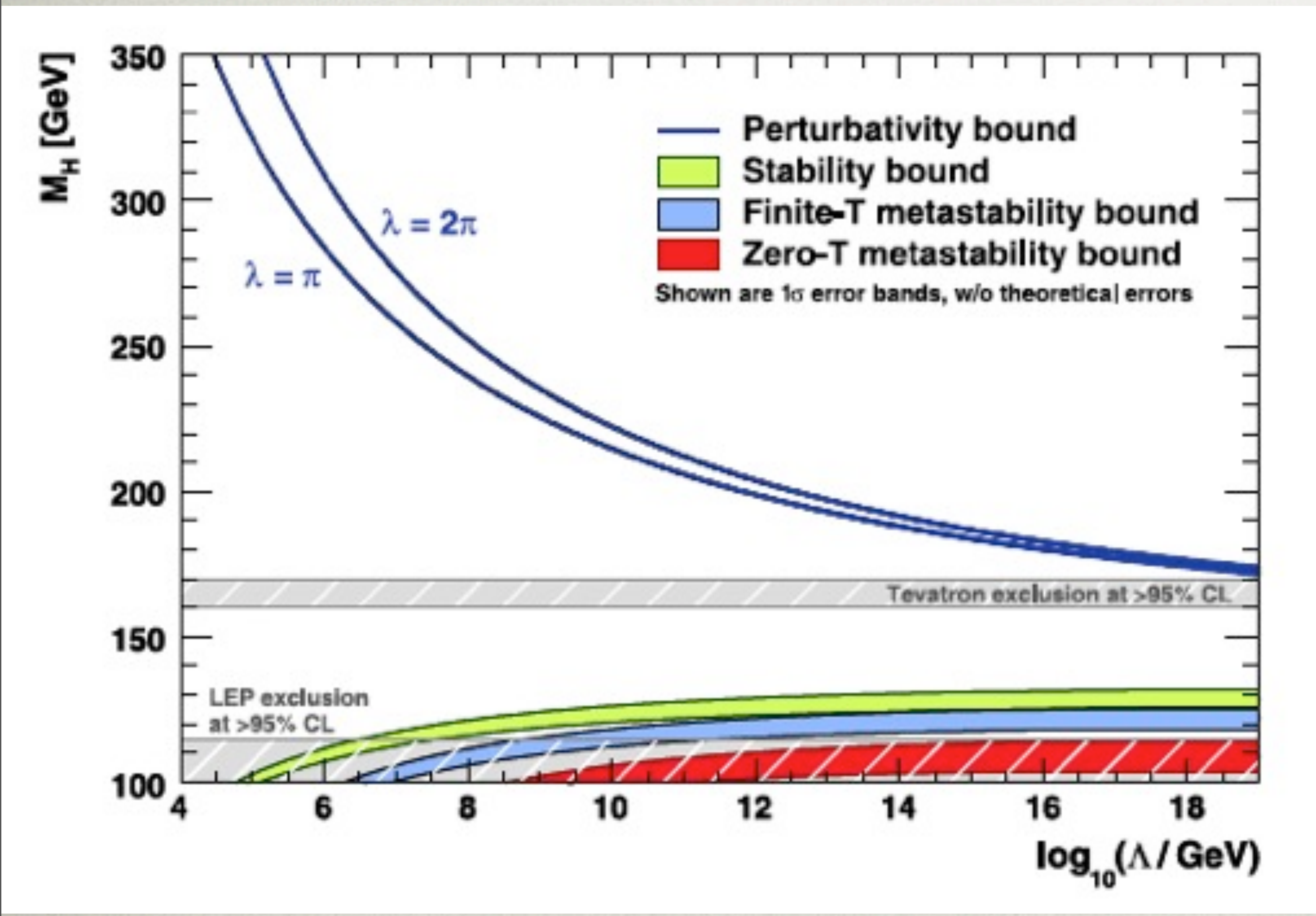
- Higgs potential

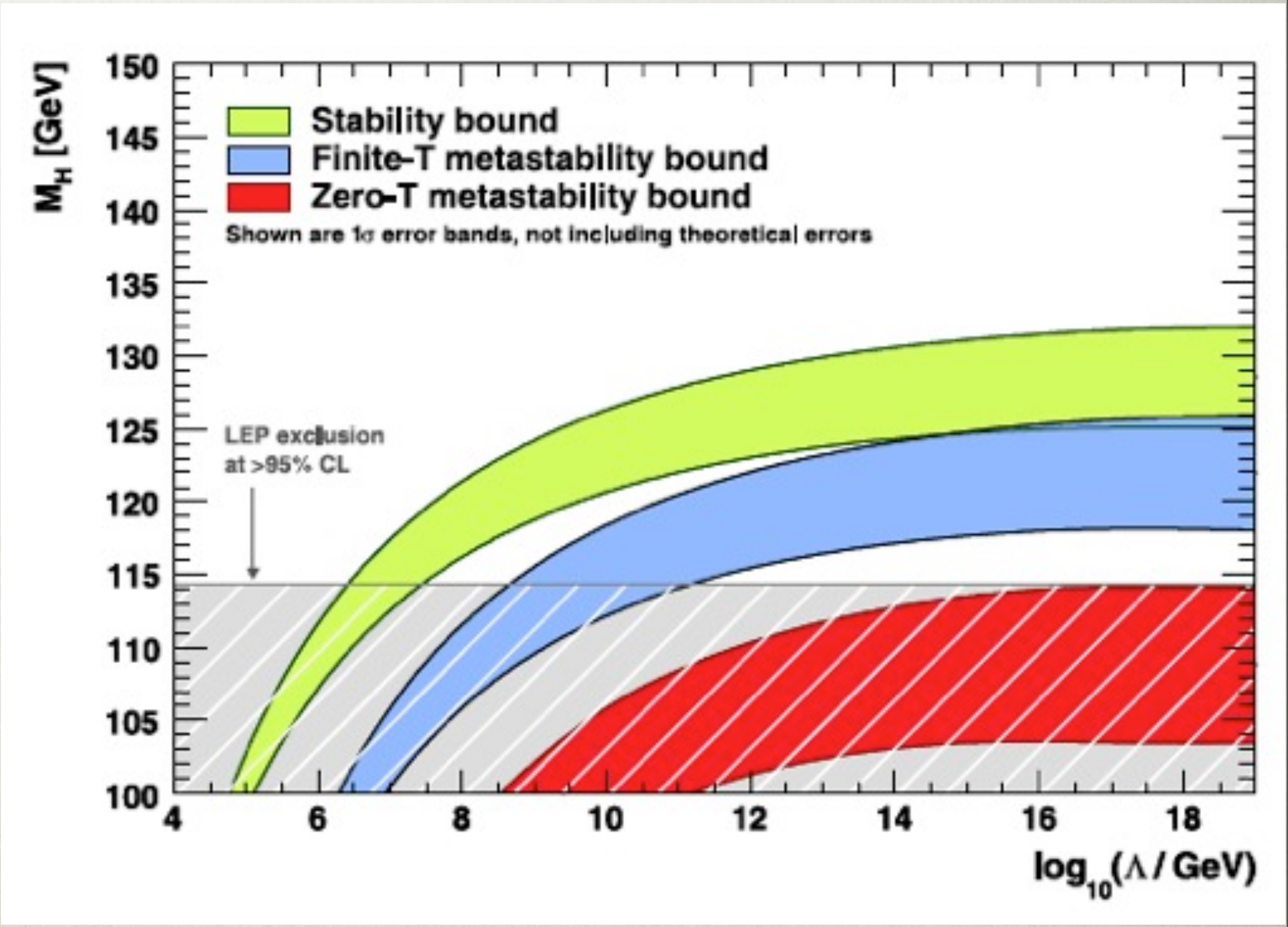
$$V_0 = -\frac{1}{2}m(\mu)^2 h^2(\mu) + \frac{1}{4}\lambda(\mu) h^4(\mu),$$

Some conceptual issues for Higgs : hierarchy problem and vacuum stability

- Perturbativity and instability bounds on Higgs

$$\lambda_{obs} = \frac{\lambda_0}{1+\beta\lambda_o \ln \Lambda/m} \quad \Rightarrow \quad \lambda_0 = \frac{\lambda_{obs}}{1-\beta\lambda_{obs} \ln \Lambda/m} \qquad \frac{d\lambda}{d\ln\mu} = \beta(\lambda)$$





$$\beta_\lambda = \frac{1}{(4\pi)^2}\left[24\lambda^2 - 6y_t^4 + \frac{3}{8}\left(2g^4 + \left(g^2+g'^2\right)^2\right) + \left(-9g^2 - 3g'^2 + 12y_t^2\right)\lambda\right]$$

$$+ \frac{1}{(4\pi)^4}\left[\frac{1}{48}\left(915g^6 - 289g^4g'^2 - 559g^2g'^4 - 379g'^6\right) + 30y_t^6 - y_t^4\left(\frac{8g'^2}{3} + 32g_s^2 + 3\lambda\right)\right.$$

$$+ \lambda\left(-\frac{73}{8}g^4 + \frac{39}{4}g^2g'^2 + \frac{629}{24}g'^4 + 108g^2\lambda + 36g'^2\lambda - 312\lambda^2\right)$$

$$\left. + y_t^2\left(-\frac{9}{4}g^4 + \frac{21}{2}g^2g'^2 - \frac{19}{4}g'^4 + \lambda\left(\frac{45}{2}g^2 + \frac{85}{6}g'^2 + 80g_s^2 - 144\lambda\right)\right)\right].$$

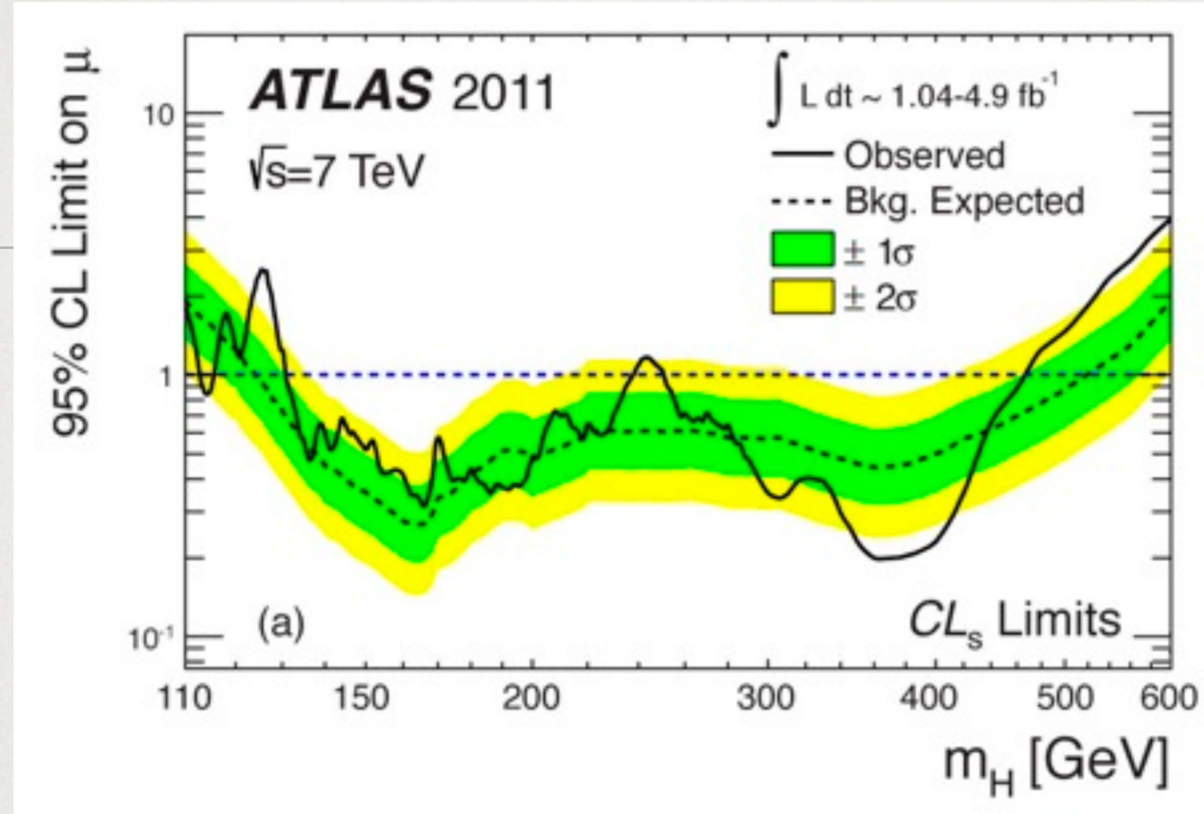
$$\beta_{y_t} = \frac{y_t}{(4\pi)^2}\left[\frac{9}{2}y_t^2 - \frac{9}{4}g^2 - \frac{17}{12}g'^2 - 8g_s^2\right] + \frac{y_t}{(4\pi)^4}\left[-\frac{23}{4}g^4 - \frac{3}{4}g^2g'^2 + \frac{1187}{216}g'^4 + 9g^2g_s^2\right.$$

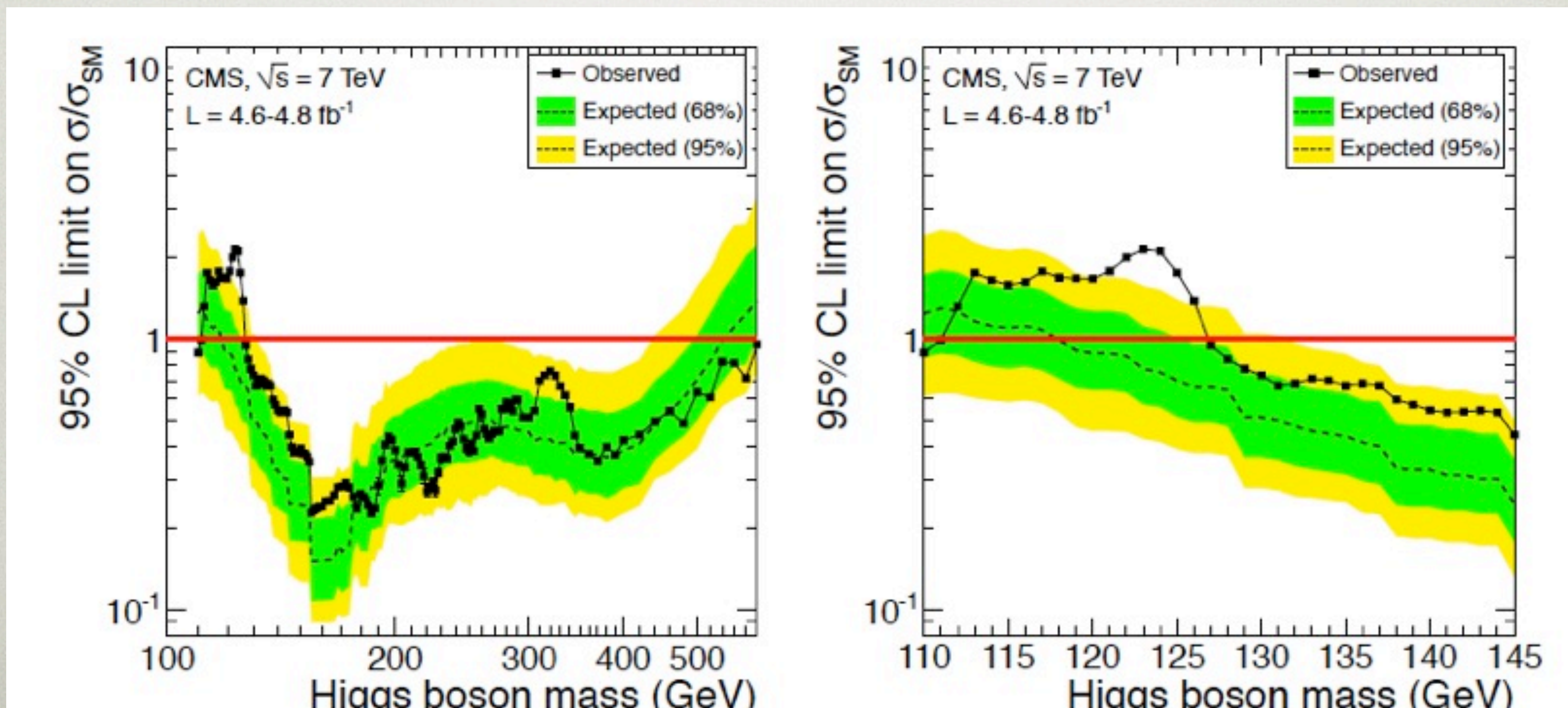
$$\left. + \frac{19}{9}g'^2g_s^2 - 108g_s^4 + \left(\frac{225}{16}g^2 + \frac{131}{16}g'^2 + 36g_s^2\right)y_t^2 + 6\left(-2y_t^4 - 2y_t^2\lambda + \lambda^2\right)\right].$$

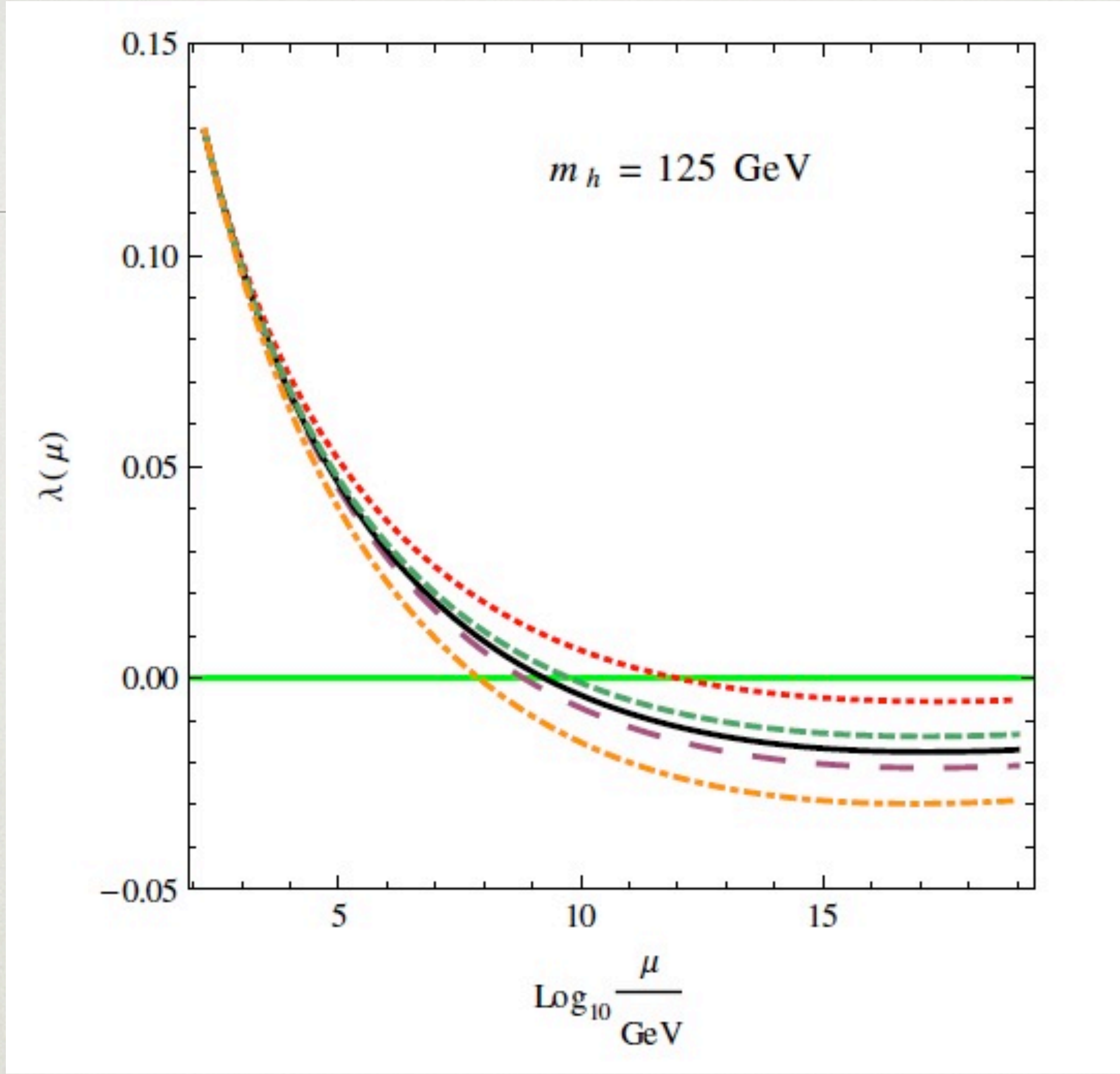
$$\beta_{g_i} = \frac{1}{(4\pi)^2}g_i^3 b_i + \frac{1}{(4\pi)^4}g_i^3\left[\sum_{j=1}^{3} c_{ij}g_j^2 - d_i y_t^2\right]$$

$$b = (41/6, -19/6, -7), \quad c = \begin{pmatrix} 199/18 & 9/2 & 44/3 \\ 3/2 & 35/6 & 12 \\ 11/6 & 9/2 & -26 \end{pmatrix}, \quad d = (17/6, 3/2, 2).$$

- Current results at LHC

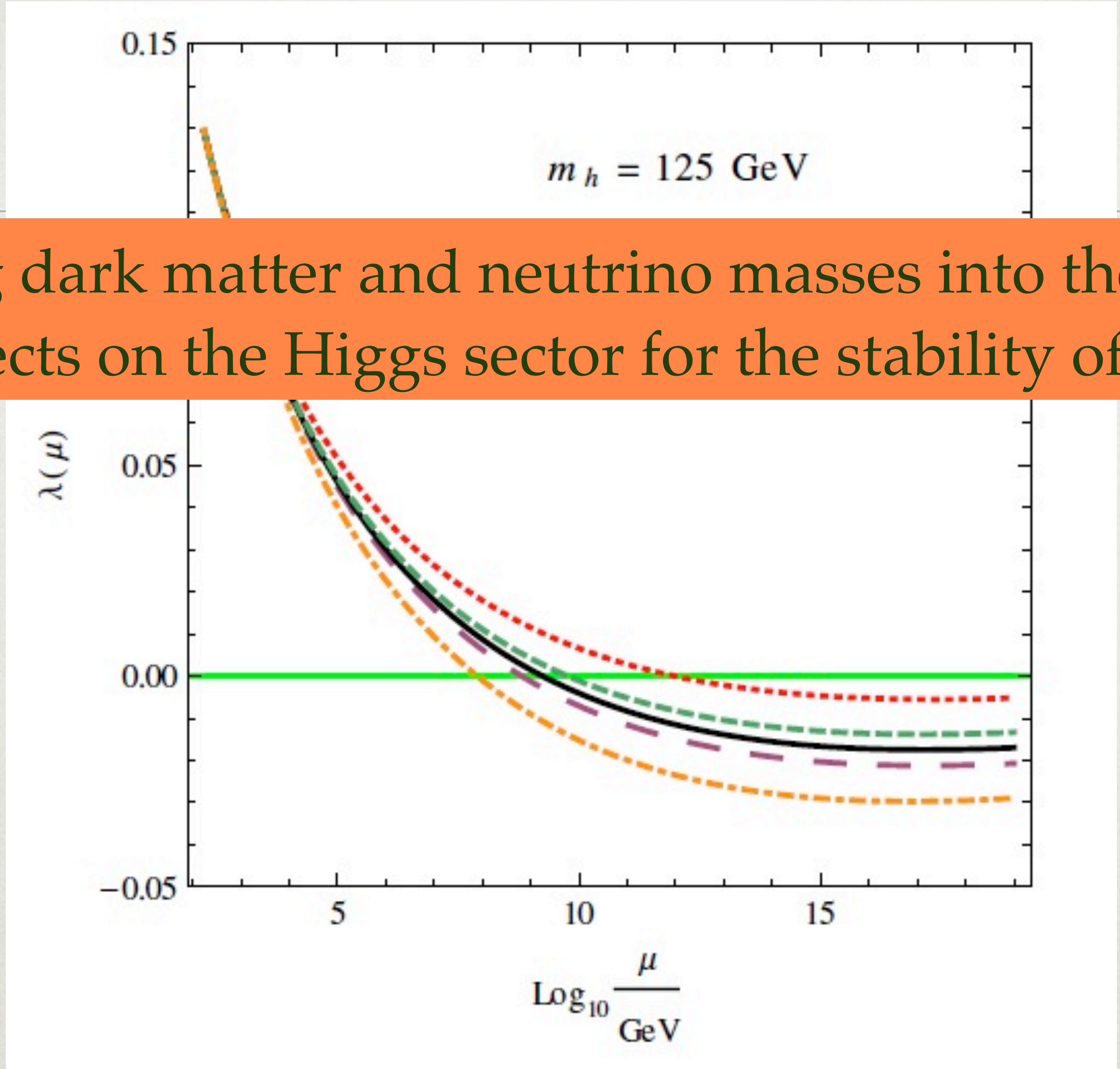






$$m_h = 125\ \mathrm{GeV},\ m_t = 173.2 \pm 0.9\ \mathrm{GeV},\ M_Z = 91.188\ \mathrm{GeV},$$

$$\alpha_s(M_Z) = 0.1184 \pm 0.0007,\ \alpha(M_Z) = 1/127.926,\ \sin^2\theta(M_Z) = 0.2312.$$



Enclosing dark matter and neutrino masses into the SM may have effects on the Higgs sector for the stability of vacuum

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$$\alpha_s(M_Z) = 0.1184 \pm 0.0007,\ \alpha(M_Z) = 1/127.926,\ \sin^2\theta(M_Z) = 0.2312.$$

Neutrino and Seesaw mechanisms

- The famous idea to realize the tiny neutrino masses is the "**seesaw mechanism**"

In the See-Saw picture, the Majorana mass is much larger than the Dirac mass, so the splitting is very large as well.

Which scale?

$\mathcal{M}_{LNV} \simeq M_{GUT}$

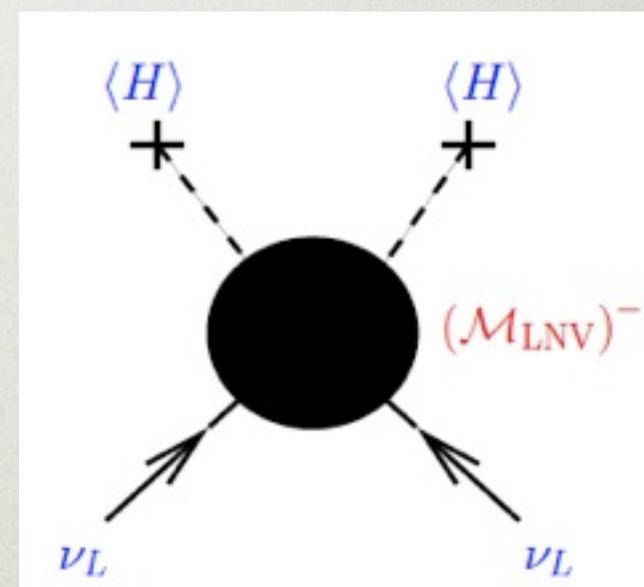
or

$\mathcal{M}_{LNV} \simeq M_{EW}$

Field theory description :

Weinberg, 1979

$$m_\nu = \frac{1}{\mathcal{M}_{LNV}}(LH)(LH)$$



✳ Seesaw mechanism (Type I,III seesaw)

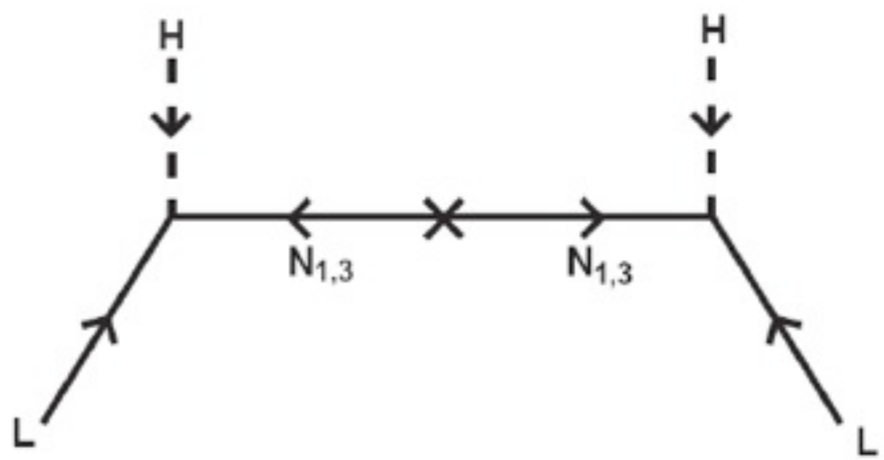
In the basis of (ν_L,ν_R) with mass matrix

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M_M \end{pmatrix}$$

If $m_D \ll M_M$:

$$m_{1/2} \simeq (-\frac{m_D^2}{M_M}, M_M)$$

Type (I,III) seesaw



$N_1 : (1, 1, 0)$

$N_3 : (1, 3, 0)$

Type-I: SM + 3 right-handed Majorana ν's
(Minkowski 77; Yanagida 79; Glashow 79; Gell-Mann, Ramond, Slanski 79; Mohapatra, Senjanovic 79)

Type-III:SM + 3 triplet fermions (Foot,Lew,He,Joshi 89)

- Type-I seesaw :

$$\mathcal{L}_\nu = Y_{\nu_{\alpha i}} \bar{l}_\alpha \tilde{H} \nu_{R_i} + \frac{1}{2} M_{R_i} \overline{(\nu_R)^c}_i \nu_{R_i} + \text{h.c.},$$

- Type-III seesaw :

$$\mathcal{L}_\Sigma = Tr[\bar{\Sigma} i \not{D} \Sigma] - \frac{1}{2} Tr[\bar{\Sigma} M_\Sigma \Sigma] - \overline{l_{L\alpha}} \sqrt{2} Y^\dagger_{\Sigma_{\alpha i}} \Sigma_i \tilde{H} - H^T \epsilon^T \bar{\Sigma}_i \sqrt{2} Y_{\Sigma_{\alpha i}} l_{L_\alpha},$$

$$\Sigma_R = \begin{pmatrix} \Sigma_R^0/\sqrt{2} & \Sigma_R^+ \\ \Sigma_R^- & -\Sigma_R^0/\sqrt{2} \end{pmatrix}$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M_M \end{pmatrix}$$

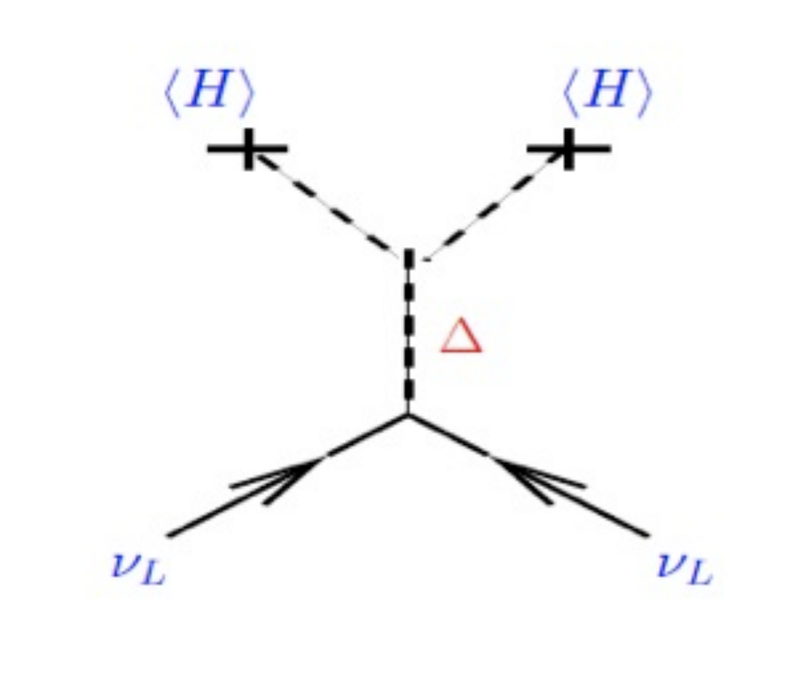
$m_D = vY_\nu/2\sqrt{2}$ $\quad M_M = M_R$ $\quad$ For Type-I

$= vY_\Sigma/2\sqrt{2}$ $\quad = M_\Sigma$ $\quad$ For Type-III

- Seesaw mechanism (Type II seesaw)

Schechter & Valle, 1980, 1982
Cheng & Li, 1980
Mohapatra, Senjanovic, 1981
...

$\Delta : (1,3,2)$



$$\mathcal{V} = -\mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2 + \frac{1}{2} M_\Delta^2 \mathrm{Tr}\left(\Delta^\dagger \Delta\right) - \left[\lambda_\Delta M_\Delta H^T i\sigma_2 \Delta H + \mathrm{h.c.}\right]$$

$$m_M \simeq Y^\nu \langle \Delta_L^0 \rangle$$

$$Y_\Delta v_\Delta \approx \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta}$$

$$\mathcal{M}_\nu = \begin{pmatrix} m_M & 0 \\ 0 & 0 \end{pmatrix}$$

Dark matter candidates

- We choose two models of dark matter which minimally change the SM Higgs potential.

1. Darkon - a real singlet scalar (A.Zee et al,1985)

$$\mathcal{L}_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{m_0^2}{2}S^2 - \frac{\lambda_S}{4}S^4 - \lambda_{SH}S^2 H^\dagger H.$$

2. Minimal dark matter - a fermion quintuplet with zero hypercharge

(A.Strumia et al,1985)

No free parameters: mass = 9.6 TeV, direct detection cross section = 10^{-44} cm^2

Vacuum stability within SM + Type-I(III) seesaw/ darkon(minimal dark matter)

- SM + Type-I / Type-III seesaw :

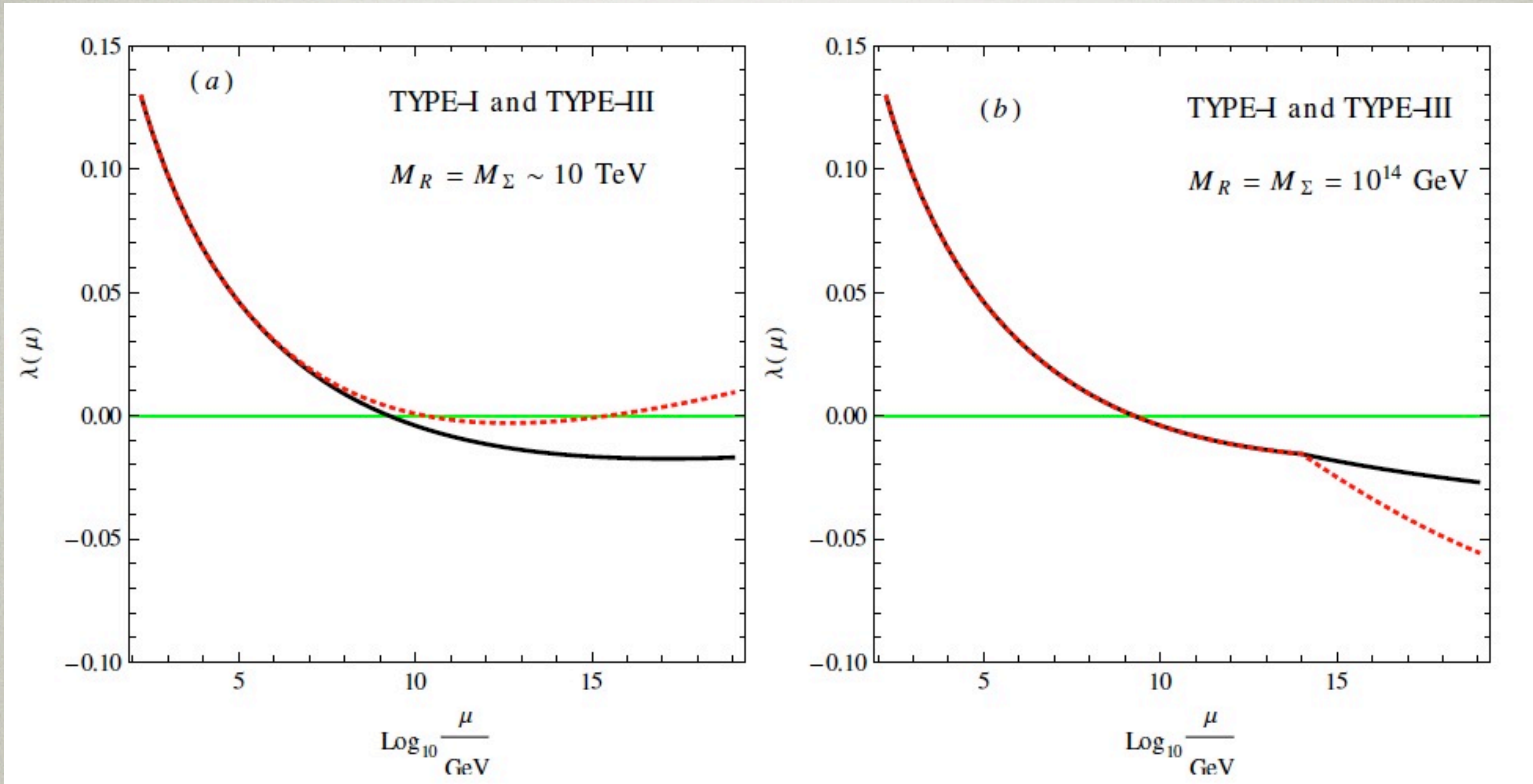
  The new Yukawa interactions $Y_{\nu_{\alpha i}} \bar{l}_\alpha \tilde{H} \nu_{R_i}$ and $H^T \epsilon^T \bar{\Sigma}_i \sqrt{2} Y_{\Sigma_{\alpha i}} l_{L_\alpha}$ bring the additional corrections to the β function of λ

$$\Delta\beta_{\lambda_{\rm I}} = \frac{1}{(4\pi)^2}\left[-4\ {\rm Tr}Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger + 4\lambda\ {\rm Tr}Y_\nu Y_\nu^\dagger\right]$$

For Type-I

$$\Delta\beta_{\lambda_{\rm III}} = \frac{1}{(4\pi)^2}\left[-20\ {\rm Tr}Y_\Sigma Y_\Sigma^\dagger Y_\Sigma Y_\Sigma^\dagger + 12\lambda\ {\rm Tr}Y_\Sigma Y_\Sigma^\dagger\right]$$

For Type-III



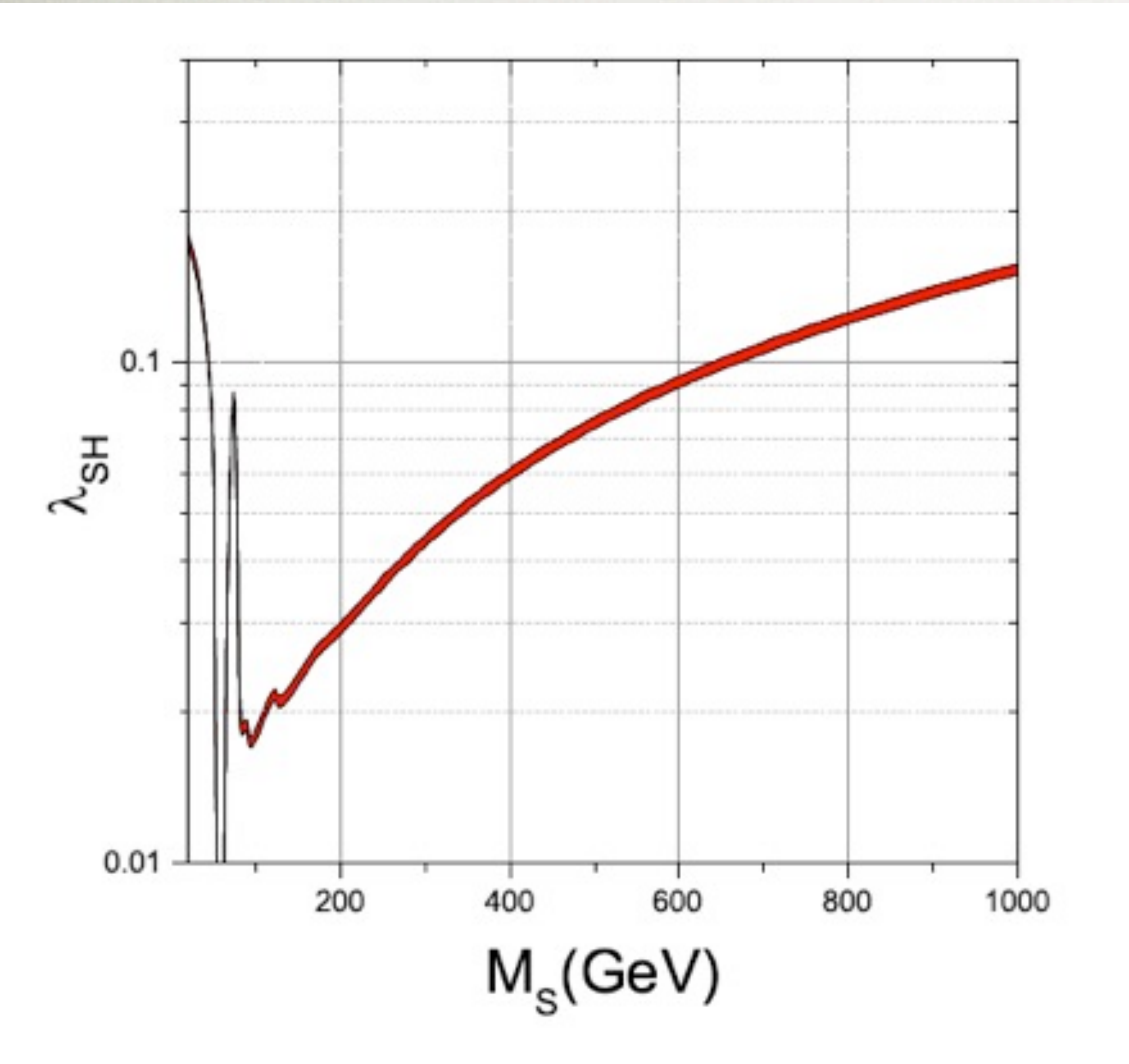
The triplet fermions in Type-III seesaw will change the $SU(2)_L$ gauge coupling RG running with the modification

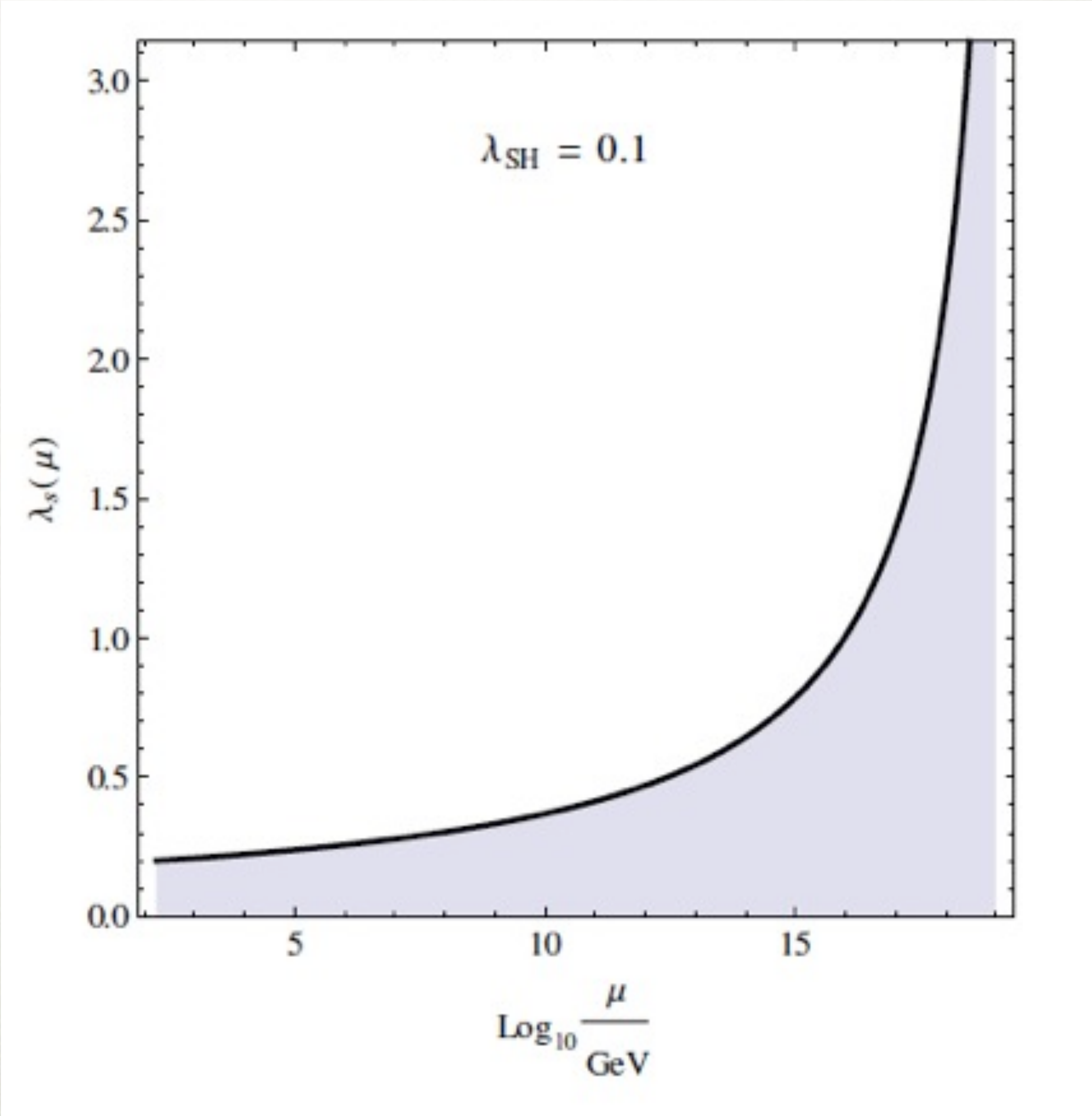
$$\Delta\beta_{g_{2_{\mathrm{III}}}} = \frac{1}{(4\pi)^2}\frac{4n}{3}$$

- SM + darkon/minimal dark matter :

For darkon, we first scan the parameter space.

Relic abundance: perturbativity:





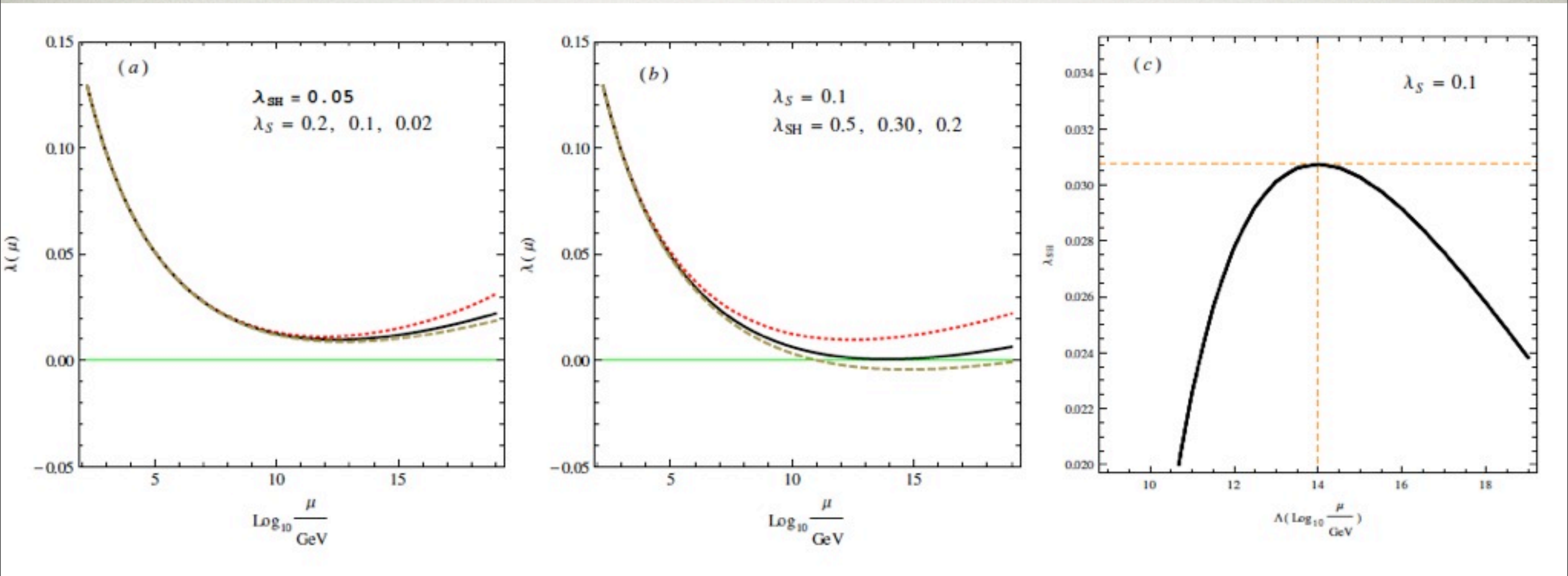
$$0 < \lambda_S < 0.2$$

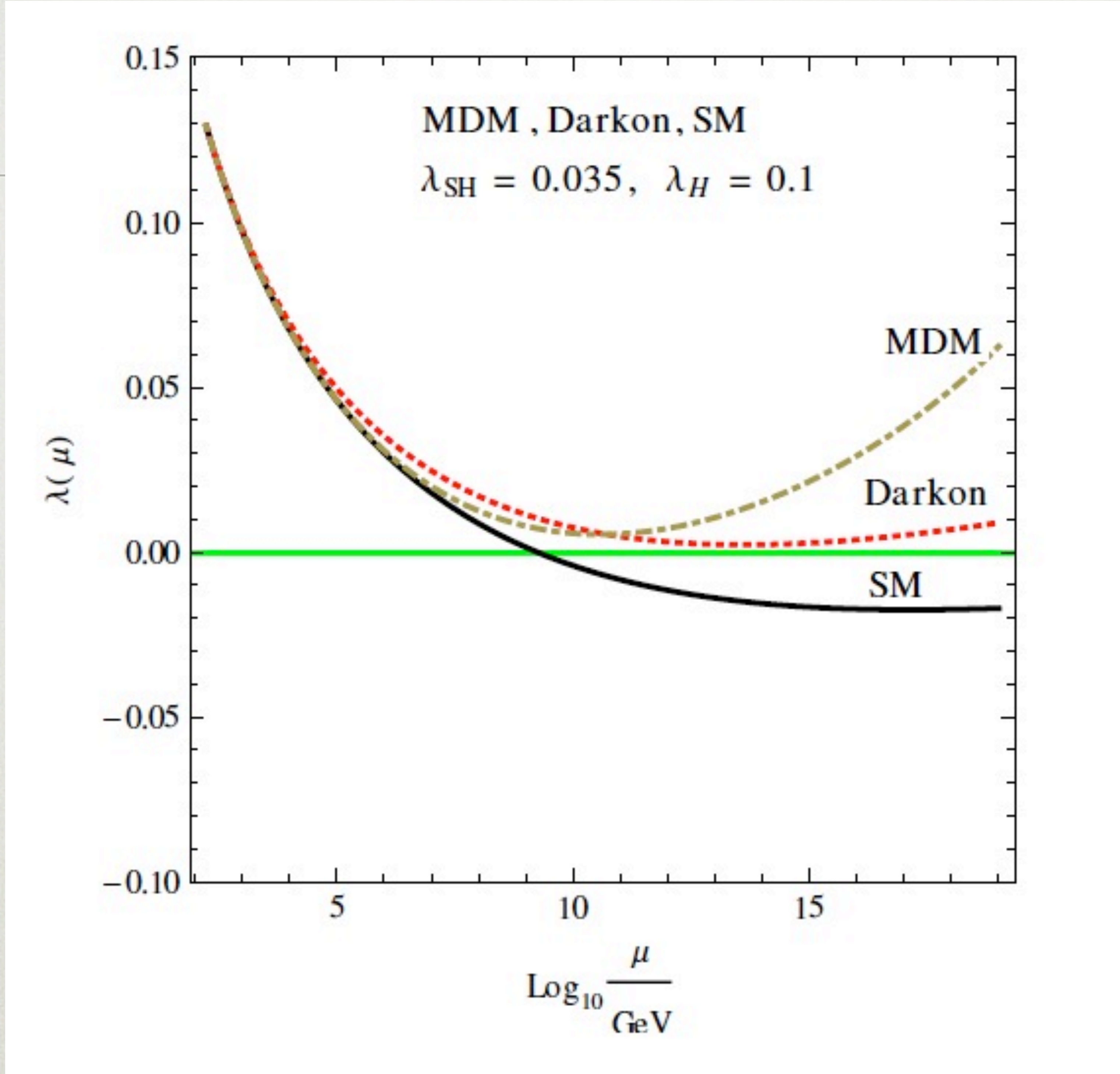
The β function of λ is modified by $\Delta\beta_{\lambda_{\rm darkon}} = \frac{1}{(4\pi)^2} 2\lambda_{SH}^2$

For minimal dark matter, there is no interactions with the SM fields except the gauge interaction. The $SU(2)_L$ gauge coupling RG is changed by

$$\Delta\beta_{g2_{\rm MDM}} = \frac{1}{(4\pi)^2}\frac{20}{3},$$

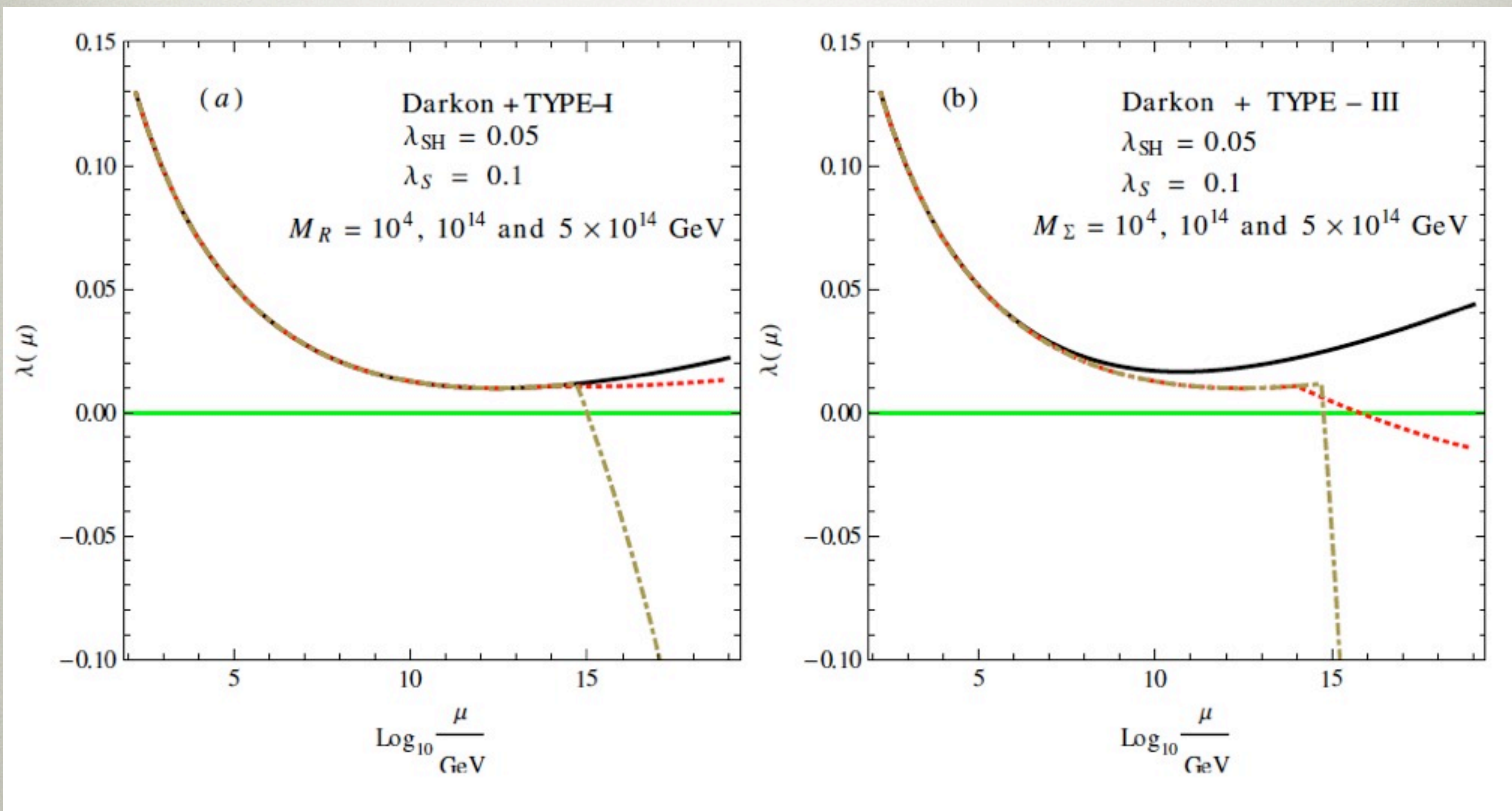
darkon





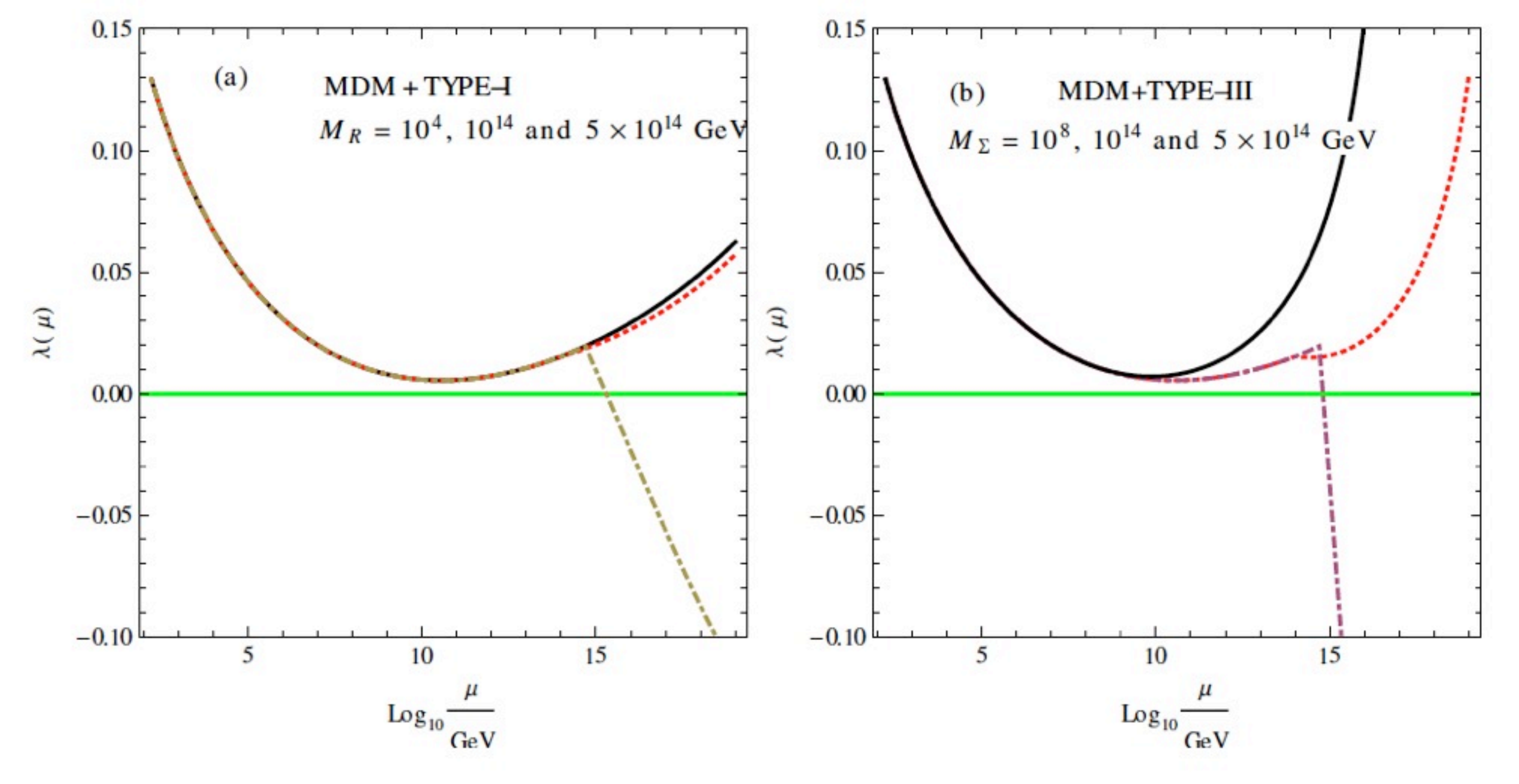
Unlike the darkon case, in minimal dark matter extension there is no free parameter after the mass is fixed by relic density and λ(μ) is positive up to Planck scale.

SM + Type-I/Type-III + darkon

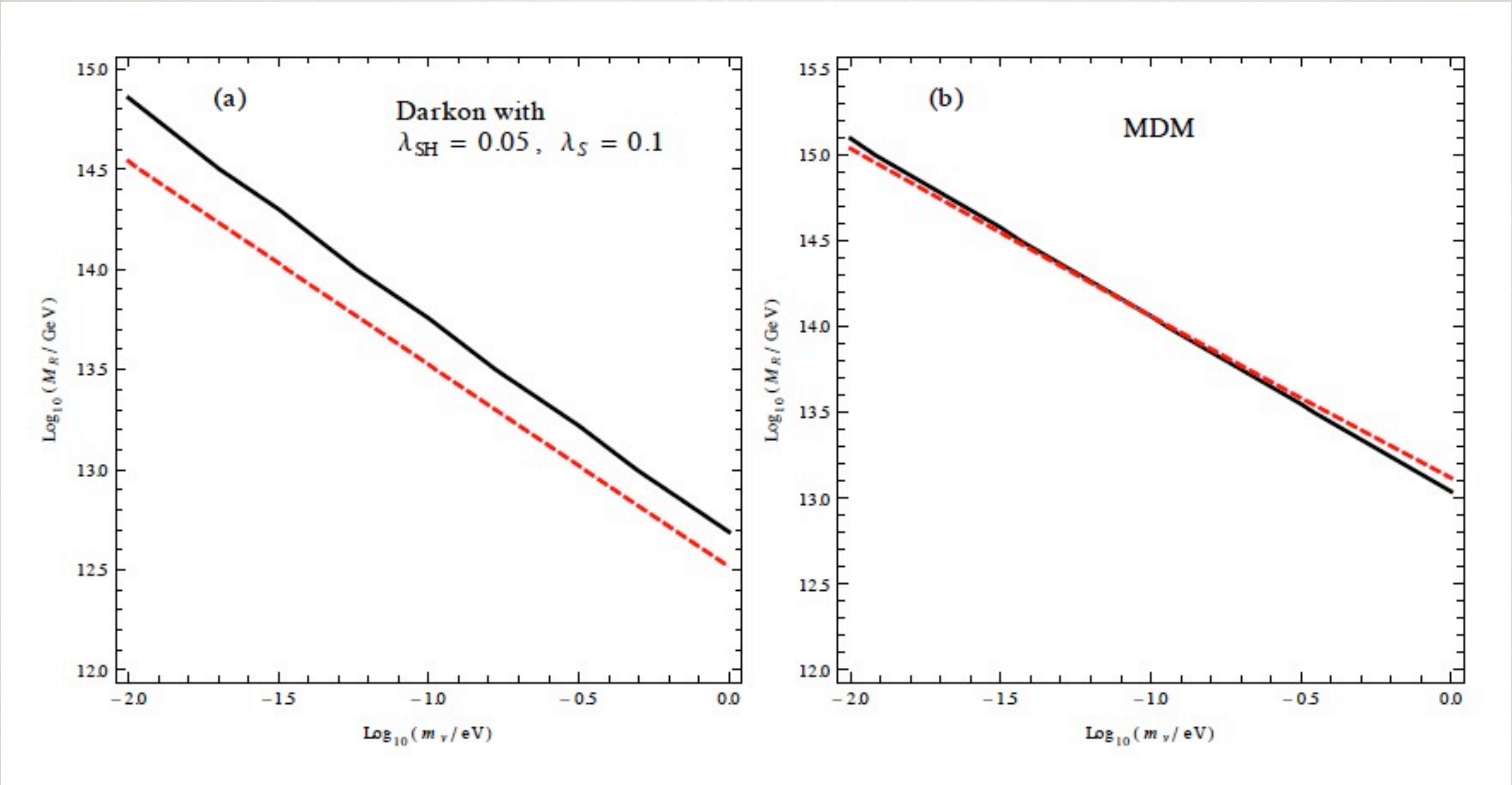


Instability is sensitive to Yukawa couplings

SM + Type-I/Type-III + MDM



The raise of $\lambda(\mu)$ via the growth of gauge coupling would compensate for the negative contributions from Yukawa couplings and avoid the instability at high scale



- Quartic coupling $\lambda(M_P) > 0$, bounds on neutrino sector parameters.

Conclusion

- We study the impact of the possible discovery of SM Higgs boson at 125 GeV on the electroweak vacuum stability.
- Confronting the neutrino masses and dark matter puzzles in particle physics, we extend the SM in these two directions with the minimal change of Higgs potential as the guidance.
- Type-I/Type-III seesaw and darkon/minimal dark matter are the extension frameworks we investigate.