Scalegenesis and fermionic dark matters in the flatland scenario

Yu Hamada (Kyoto Univ.)

Based on [arXiv:2002.03666]

Collaborators:
Koji Tsumura (Kyushu U.),
Masatoshi Yamada (Heidelberg U.)

Asymptotic safety seminar (23 Mar. 2020)

Out line

- Introduction (6p.)
- Asymptotic safety and Flatland scenario (7p.)
- Fermionic dark matter in flatland scenario (6p.)
- Summary

Introduction

Motivation

After the Higgs boson's discovery, the Standard Model is established.

https://www.theguardian.com/science/blog/2012/jul/04/higgs-boson-discovered-live-coverage-cern

Motivation

But there are still many problems unanswered by the SM.

Gauge hierarchy

Dark matter

Neutrino mass

Baryon asymmetry

etc.

Motivation

But there are still many problems unanswered by the SM.

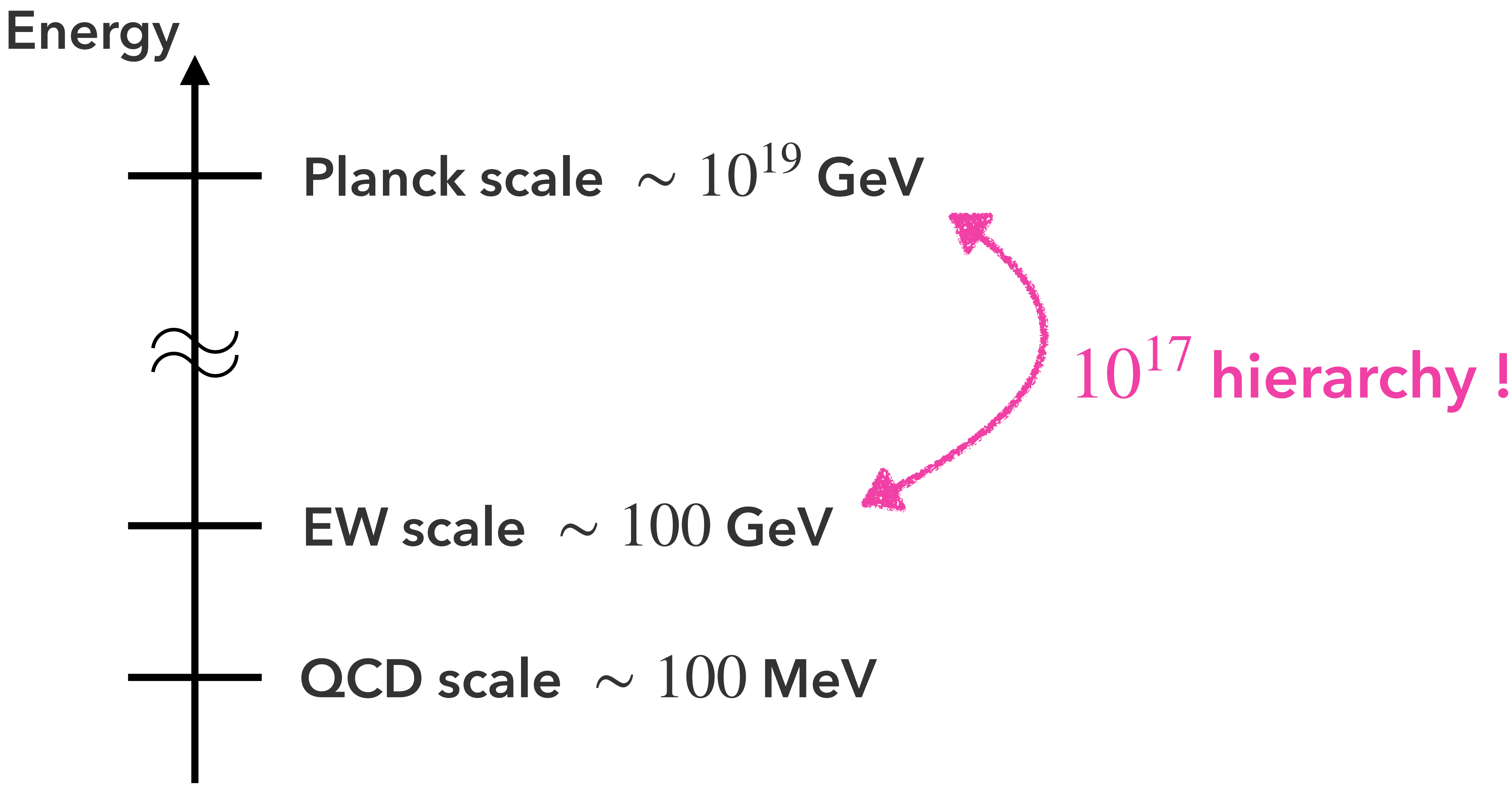
Gauge hierarchy Dark matter

Neutrino mass Baryon asymmetry

etc.

We tackle these two problems in this talk.

Gauge Hierarchy

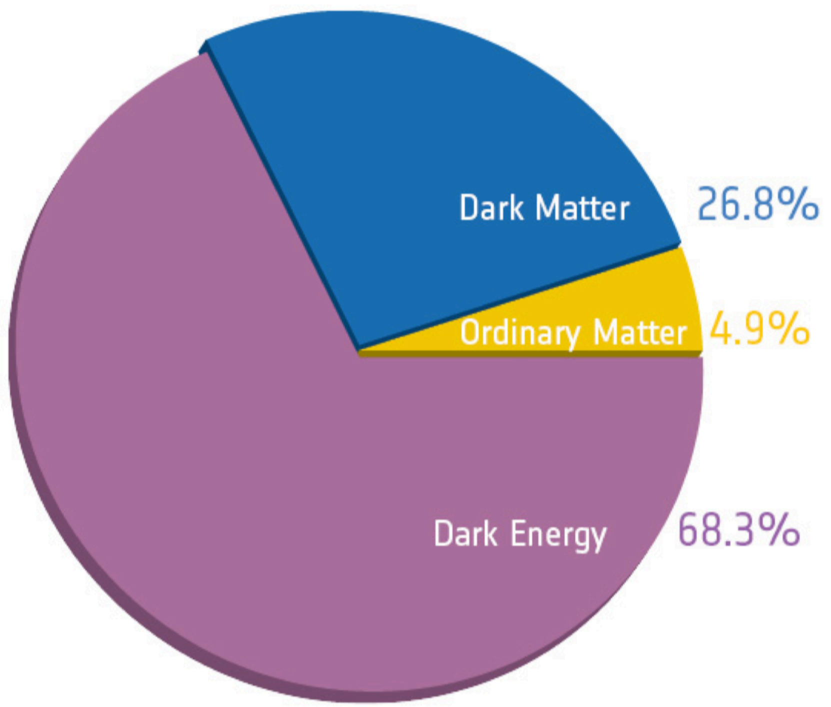


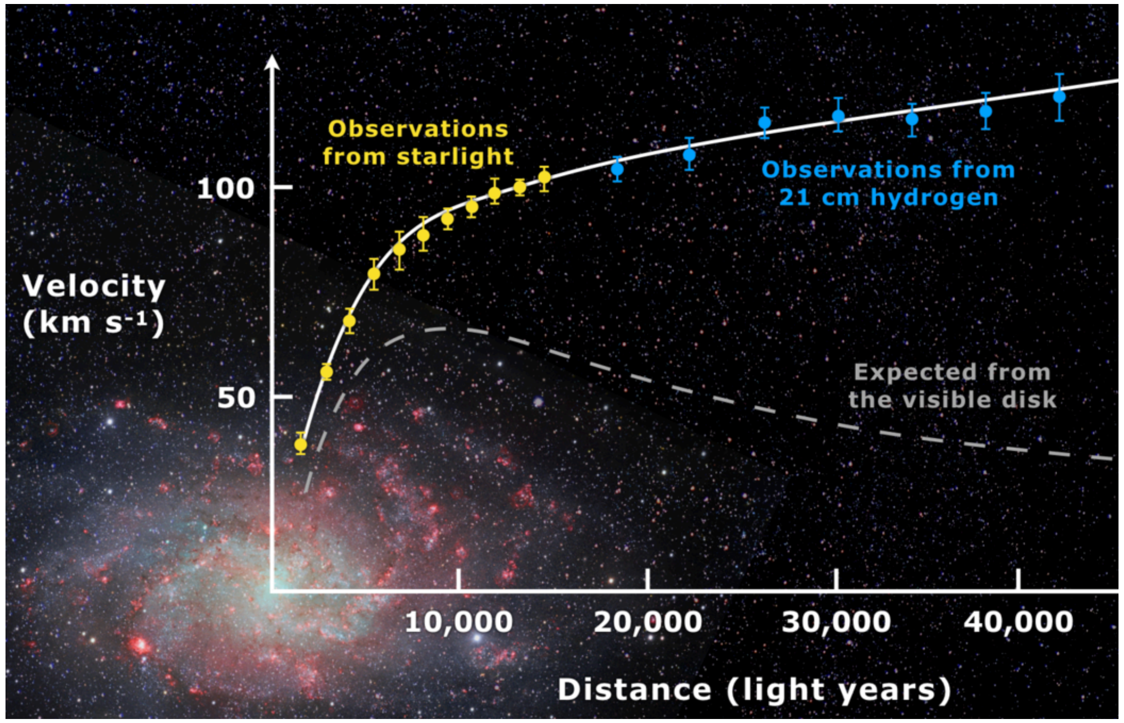
- How can we naturally explain this hierarchy?

= **What is the origin of EW scale?**

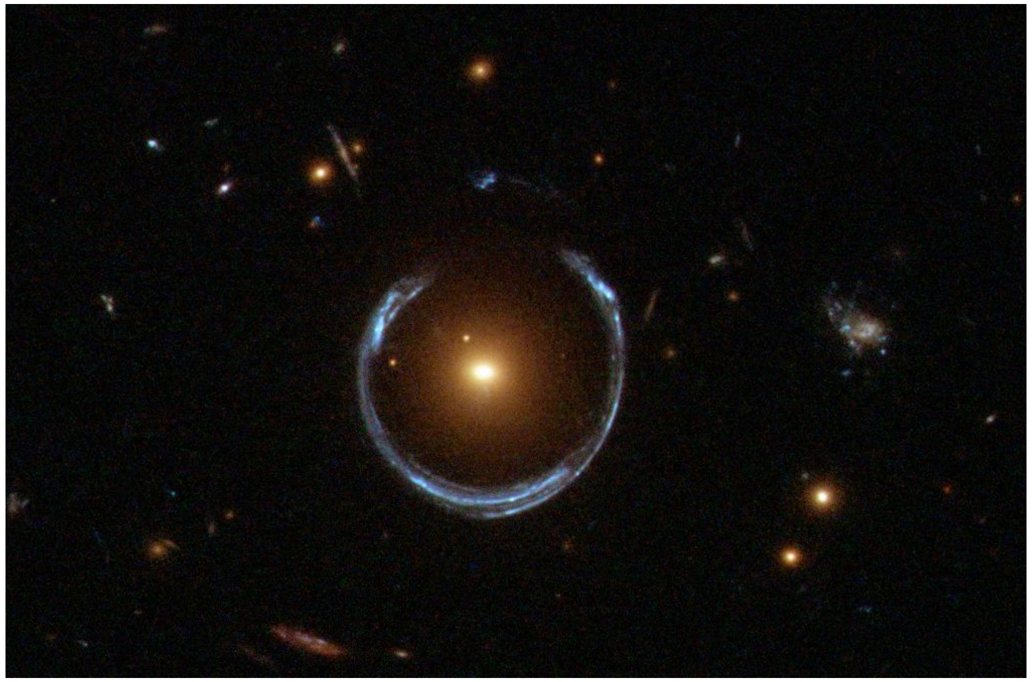
Dark Matter

- There are many evidences for dark matter





Galaxy rotation curve (from Wiki)



Gravitational lens (from Wiki)

Our model

- Inspired by **asymptotic safety scenario of quantum gravity**, we propose a $U(1)_X$ **extended model** beyond the SM.

$G_{SM} \times$ $U(1)_X$ **gauge sym.**

$$\boxed{\begin{aligned}\mathscr{L} = \mathscr{L}_{SM}|_{m_H \to 0} + |D_\mu S|^2 - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} + \bar{\chi}_R \not{D} \chi_R + \bar{\chi}_L \not{D} \chi_L \\ + \epsilon X_{\mu\nu} B^{\mu\nu} + y_R S \bar{\chi}_R^c \chi_R + y_L S \bar{\chi}_L^c \chi_L + V(H,S) + \mathrm{h.c.}\end{aligned}} \quad (1)$$

	$U(1)_X$ charge
χ_R χ_L	$+1$
S	-2

Both are SM singlet

Our model

- Inspired by **asymptotic safety scenario of quantum gravity**, we propose a $U(1)_X$ **extended model** beyond the SM.

$G_{SM} \times$ $U(1)_X$ **gauge sym.**

$$\boxed{\begin{aligned}\mathscr{L} = \mathscr{L}_{SM}\big|_{m_H \to 0} + |D_\mu S|^2 - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \bar{\chi}_R \not{D}\chi_R + \bar{\chi}_L \not{D}\chi_L \\ + \epsilon X_{\mu\nu}B^{\mu\nu} + y_R S \bar{\chi}^c_R \chi_R + y_L S \bar{\chi}^c_L \chi_L + V(H,S) + \mathrm{h.c.}\end{aligned}} \qquad (1)$$

	$U(1)_X$ charge
χ_R χ_L	$+1$
S	-2

DM candidates ← χ_R χ_L

$\langle S \rangle \neq 0$ triggers EWSB ← S

Both are SM singlet

Today's Message

- Asymptotically safe gravity gives severe constraints on this model.

- This model has only one free parameter.

$\longrightarrow$ strong predictability!

Today's Message

- Asymptotically safe gravity gives severe constraints on this model.

- This model has only one free parameter.

$\longrightarrow$ strong predictability!

Phenomenology of asymptotically safe gravity is interesting!!

Out line

- Introduction (6p.)
- Asymptotic safety and Flatland scenario (7p.)
- Fermionic dark matter in flatland scenario (6p.)
- Summary

Asymptotic safety and Flatland scenario

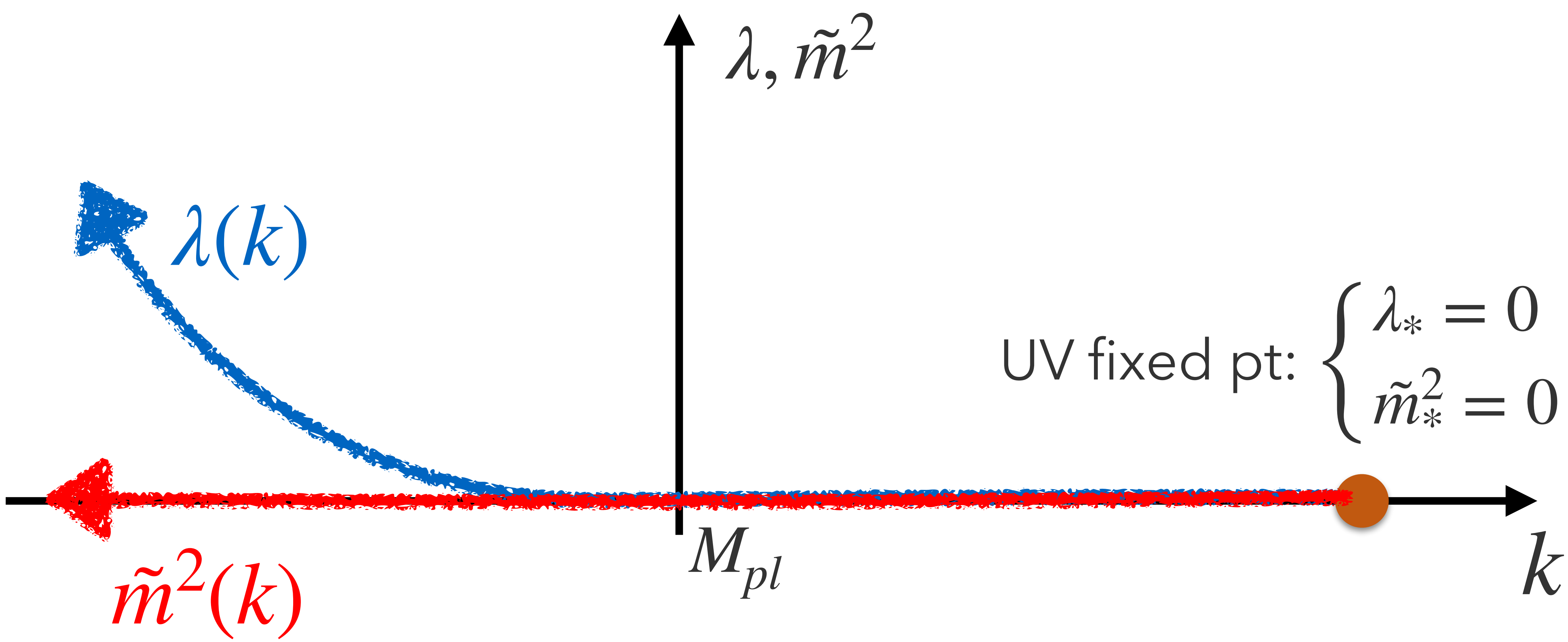
Gravity effect on scalar potential

['17 Eichhorn, Hamada, Lumma, Yamada]

Ex.) single scalar

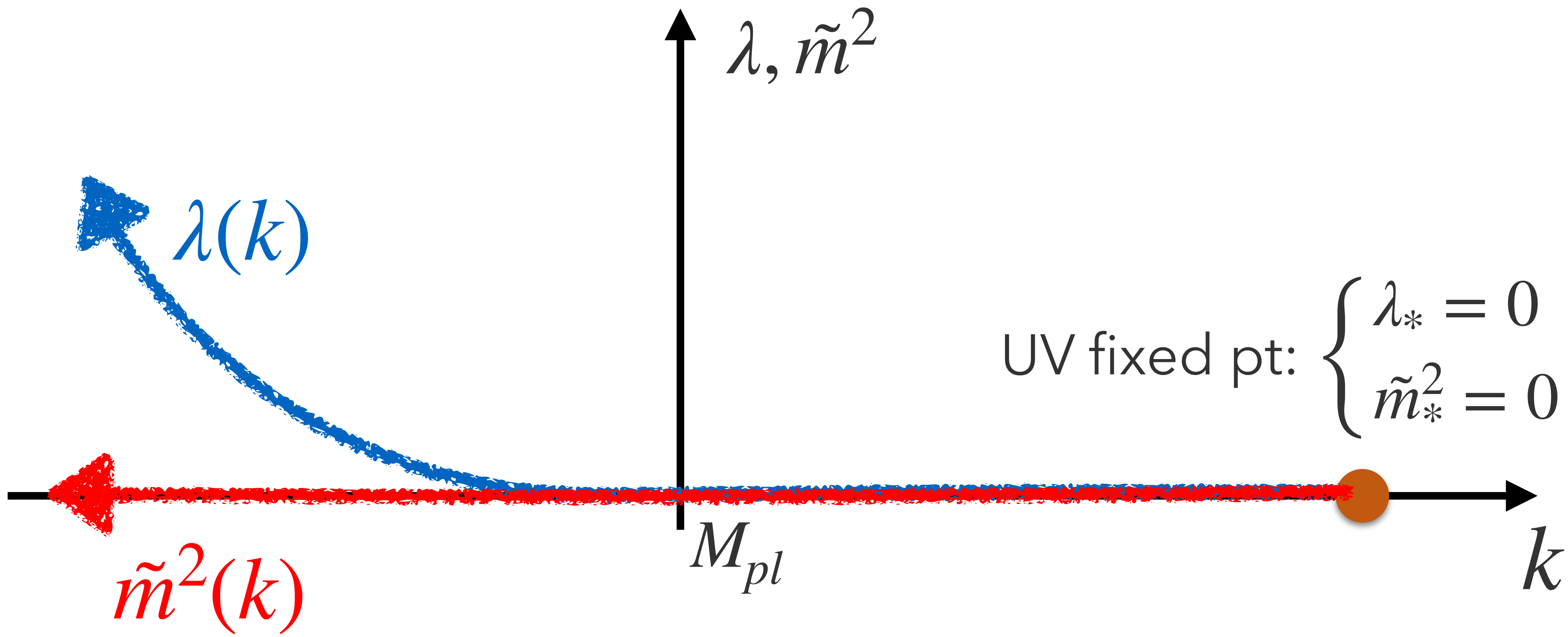
$$V(\phi) = \frac{m^2}{2}\phi^2 + \frac{\lambda}{4!}\phi^4$$

- $\theta_m, \theta_\lambda < 0$ above M_{pl} due to graviton fluctuation
- In order to make the potential UV-complete, they must run as



Flatland scenario

['13, '14 Hashimoto, Iso, Orikasa]
['13 Chun, Jung, Lee]



boundary conditions: $\boxed{\lambda(M_{pl}) = \tilde{m}^2(M_{pl}) = 0}$ **flat potential**

- Impose these conditions on **all scalar masses and couplings**

$$V(H,S) = \cancel{M_S^2|S|^2 + M_H^2|H|^2} + \boxed{\lambda_S}|S|^4 + \boxed{\lambda_H}|H|^4 + \boxed{\lambda_{HS}}|H|^2|S|^2 \quad (2)$$

0 at M_{pl}

Coleman-Weinberg mechanism ['73 Coleman, Weinberg]

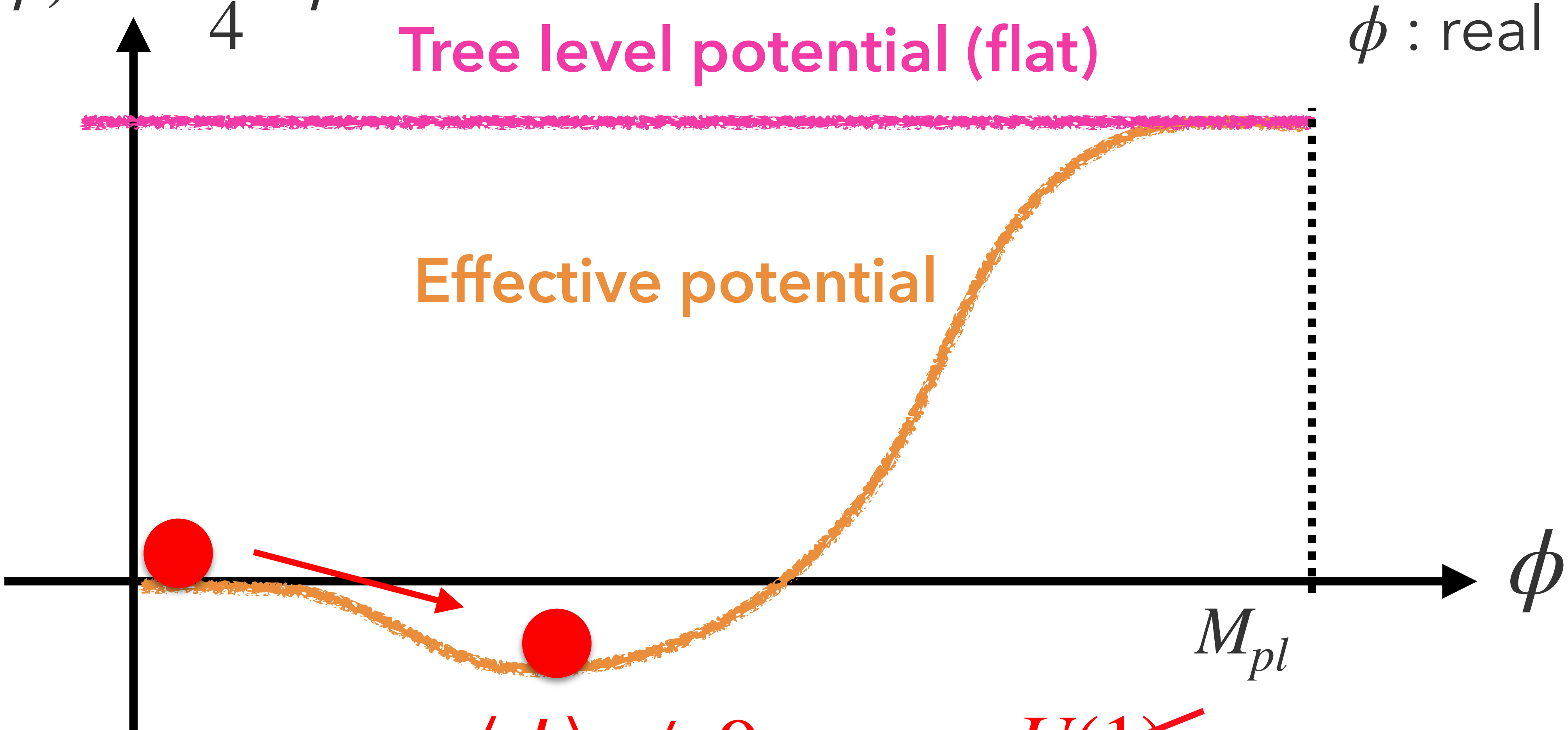
- We have no scale (besides M_{pl}) at the classical level. How can we generate the EW scale?

➡ SSB takes place by **radiative corrections**

$$V(\phi) = \frac{\lambda(\phi)}{4}\phi^4$$

$S = \phi/\sqrt{2}$ (unitary gauge)

ϕ : real



$$\langle \phi \rangle \neq 0 \longrightarrow \cancel{U(1)_X}$$

Trigger of EW symmetry breaking

- **SSB of $U(1)_X$ triggers EW symmetry breaking**

$$V(H,S) = \lambda_S |S|^4 + \lambda_H |H|^4 + \lambda_{HS} |S|^2 |H|^2 \tag{3}$$

$$\langle S \rangle = v_S/\sqrt{2}$$

$$V(H,S) = \frac{\lambda_S v_S^4}{4} + \lambda_H |H|^4 + \frac{\lambda_{HS} v_s^2}{2} |H|^2 \tag{4}$$

Trigger of EW symmetry breaking

- **SSB of $U(1)_X$ triggers EW symmetry breaking**

$$V(H,S) = \lambda_S |S|^4 + \lambda_H |H|^4 + \lambda_{HS} |S|^2 |H|^2 \tag{3}$$

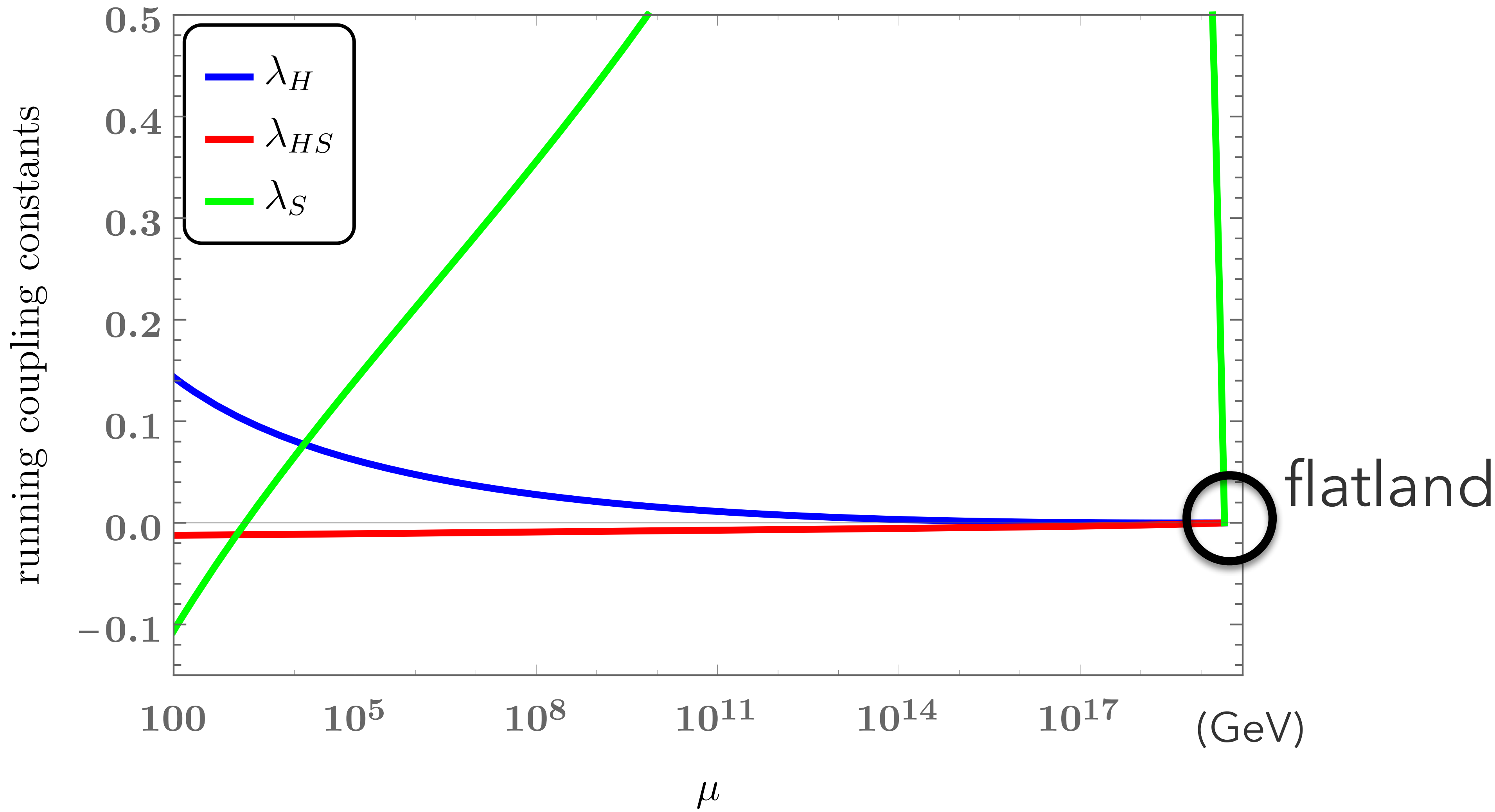
$$\langle S \rangle = v_S/\sqrt{2}$$

$$V(H,S) = \frac{\lambda_S v_S^4}{4} + \lambda_H |H|^4 + \frac{\lambda_{HS} v_s^2}{2} |H|^2 \tag{4}$$

If $\lambda_{HS} < 0$, this is negative mass term for Higgs

$\longrightarrow$ **Electroweak symmetry breaking occurs!**

Typical running of the scalar couplings

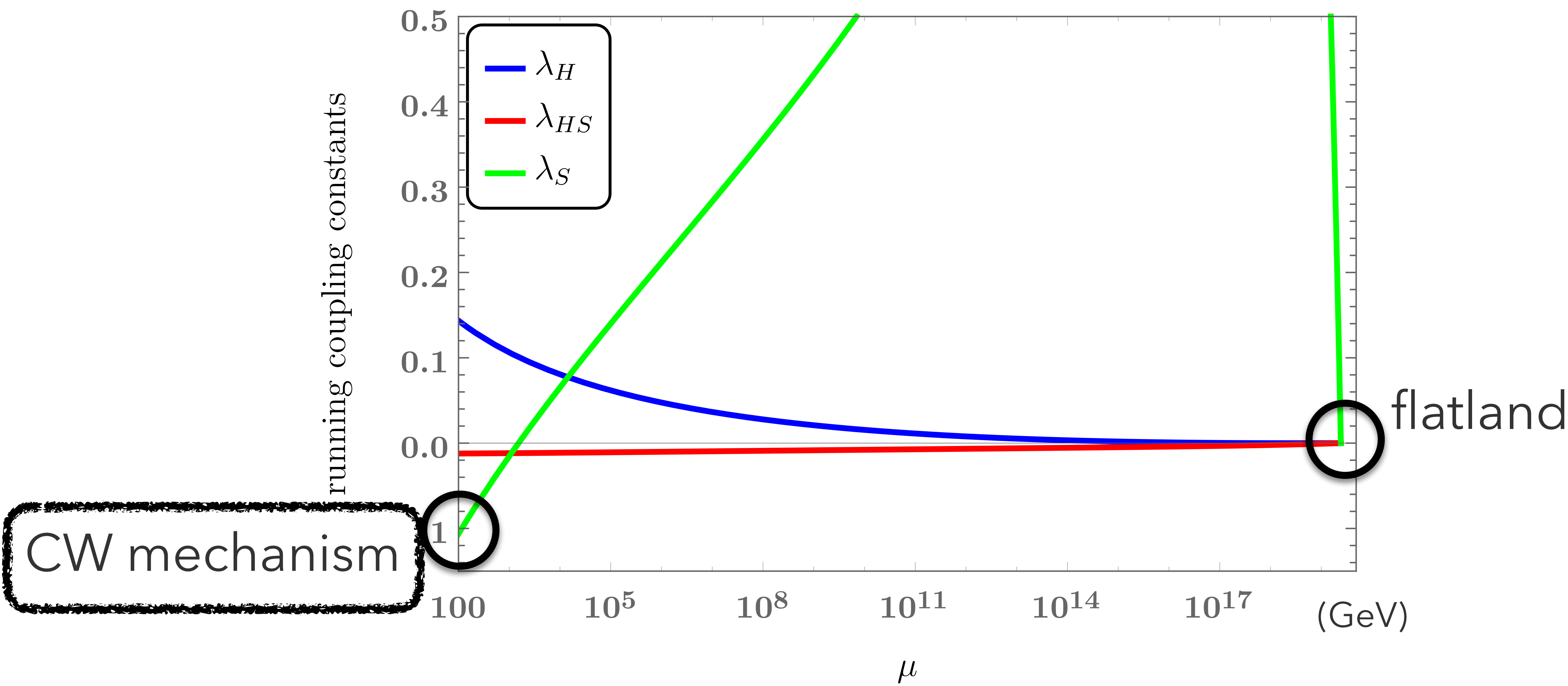


$$\beta_{\lambda_S} = \frac{1}{16\pi^2}\left[\#_1(\text{bosons}) - \#_2(\text{fermions})\right] \qquad (5)$$

$$\boxed{X_\mu} \qquad \boxed{\chi_R \quad \chi_L}$$

Both of boson and fermions are essential !

Typical running of the scalar couplings

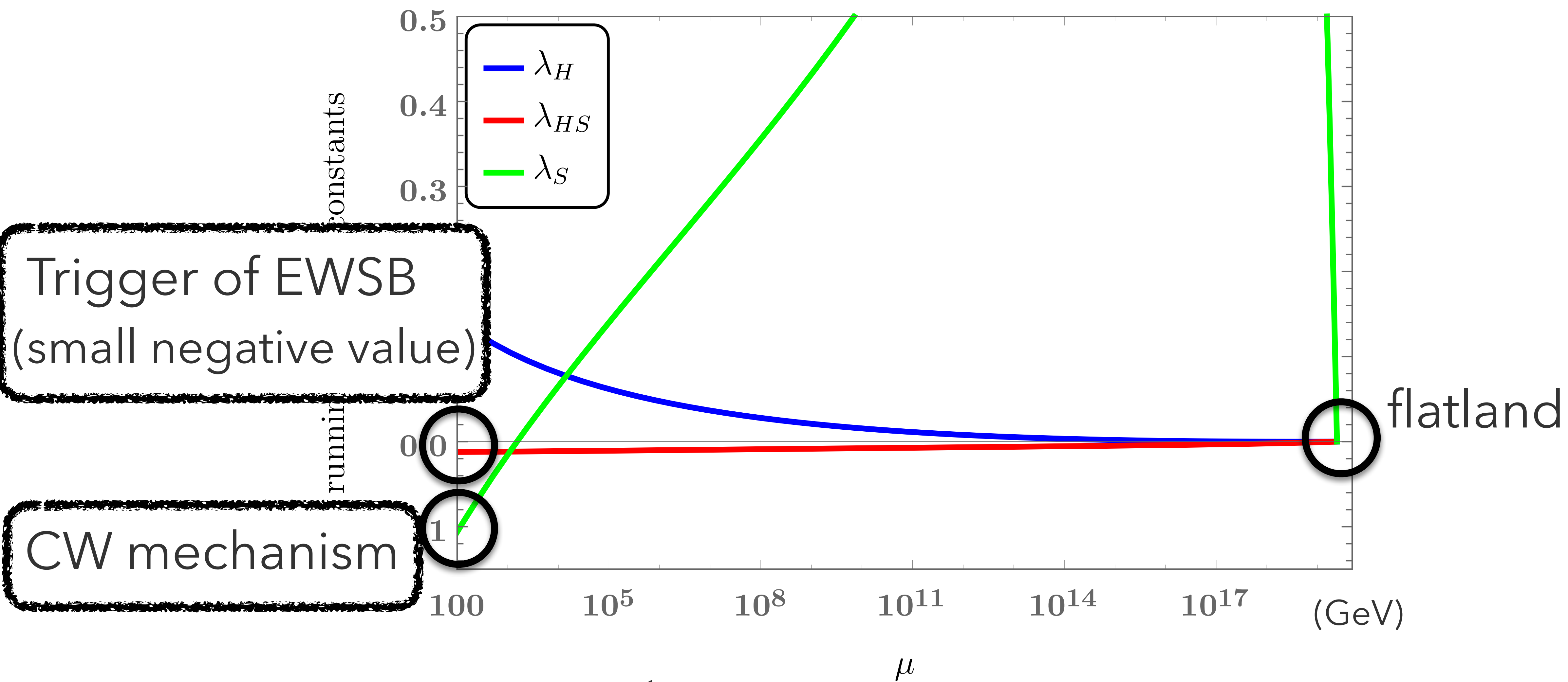


$$\beta_{\lambda_S} = \frac{1}{16\pi^2}\left[\#_1(\text{bosons}) - \#_2(\text{fermions})\right] \qquad (5)$$

X_μ $\qquad$ $\chi_R \quad \chi_L$

Both of boson and fermions are essential !

Typical running of the scalar couplings



$$\beta_{\lambda_{HS}} = \frac{1}{16\pi^2}\left[\underbrace{\#_3\lambda_{HS}}_{\sim 0} + \underline{\#_4\epsilon g_X g_Y}\right] \tag{6}$$

- The running of λ_{HS} is dominated by 2nd part
- ϵ : mixing parameter between $U(1)_X$ and SM $U(1)_Y$

$$\mathscr{L} \supset \epsilon B_{\mu\nu}X^{\mu\nu}$$

Free parameters in the model

- Originally we have 7 parameters in the model.

$$\boxed{\epsilon \quad g_X \quad y_L \quad \xi \quad \lambda_S \quad \lambda_{HS} \quad \lambda_H}$$

$(\xi \equiv y_R/y_L < 1)$

- λ's are determined by the flat conditions:

$$\lambda_S(M_{pl}) = \lambda_{HS}(M_{pl}) = \lambda_H(M_{pl}) = 0$$

- y_L and the mixing ϵ are determined s.t. CW mechanism works,

i.e., reproduce the observed EW parameters: $\begin{cases} \langle h \rangle = 246 \text{ GeV} \\ m_h = 125 \text{ GeV} \end{cases}$

We have only 2 free parameters : ξ and g_X !

Out line

- Introduction (6p.)
- Asymptotic safety and Flatland scenario (7p.)
- Fermionic dark matter in flatland scenario (6p.)
- Summary

Fermionic dark matter in flatland scenario

Majorana fermions

- After the scalegenesis,

$$\boxed{\mathscr{L} \supset y_R S \bar{\chi}_R^c \chi_R + y_L S \bar{\chi}_L^c \chi_L + \mathrm{h.c.}} \tag{7}$$

$$\Downarrow \quad \langle S \rangle = v_S/\sqrt{2}$$

$$\boxed{\mathscr{L} \supset \frac{M_R}{2} \bar{\chi}_R^c \chi_R + \frac{M_L}{2} \bar{\chi}_L^c \chi_L + \mathrm{h.c.}} \tag{8}$$

$$M_{R(L)} \equiv \sqrt{2} y_{R(L)} v_S$$

- **Can these Majorana fermions be dark matter?**

Majorana fermions

- After the scalegenesis,

$$\boxed{\mathscr{L} \supset y_R S \bar{\chi}_R^c \chi_R + y_L S \bar{\chi}_L^c \chi_L + \mathrm{h.c.}} \tag{7}$$

$$\Downarrow \quad \langle S \rangle = v_S/\sqrt{2}$$

$$\boxed{\mathscr{L} \supset \frac{M_R}{2} \bar{\chi}_R^c \chi_R + \frac{M_L}{2} \bar{\chi}_L^c \chi_L + \mathrm{h.c.}} \tag{8}$$

$$M_{R(L)} \equiv \sqrt{2} y_{R(L)} v_S$$

- **Can these Majorana fermions be dark matter?**

Yes !

Freeze out mechanism

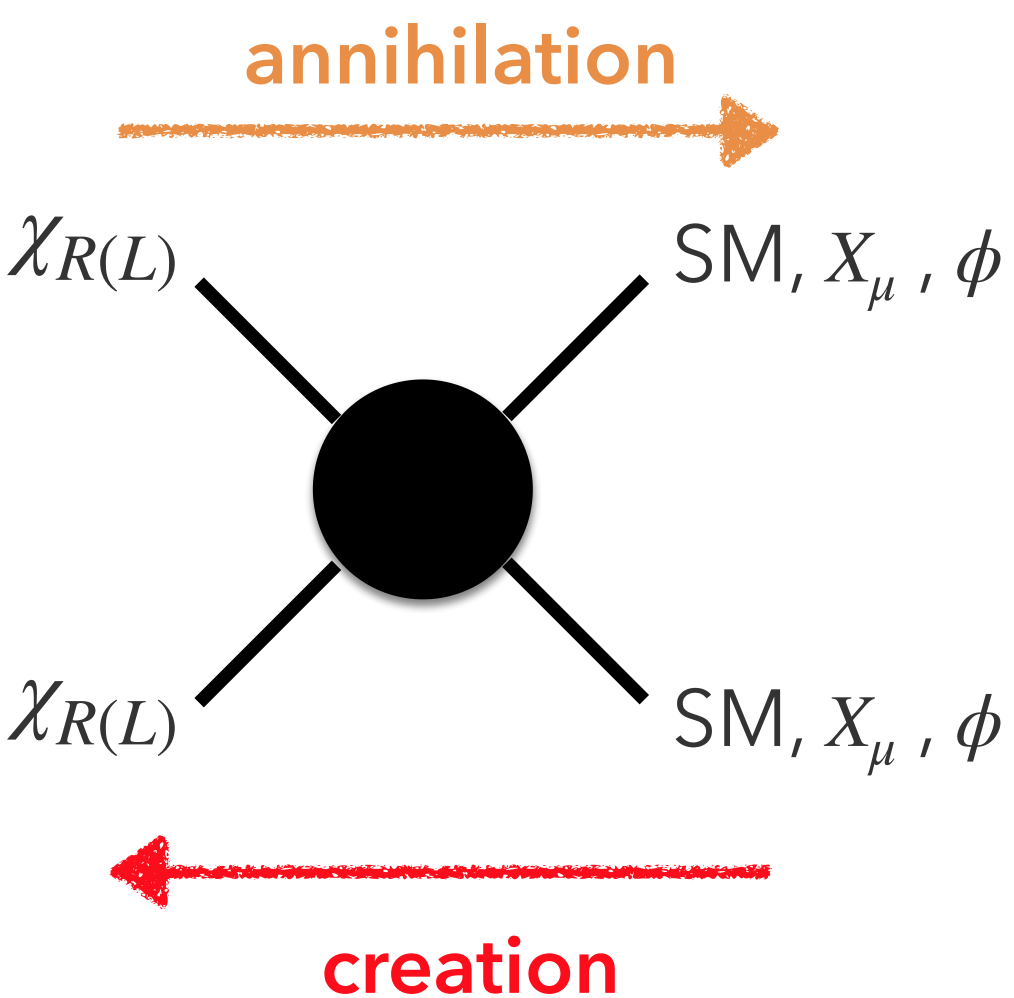
- The relic abundance of $\chi_{R(L)}$ in the early universe is determined by Boltzman equation:

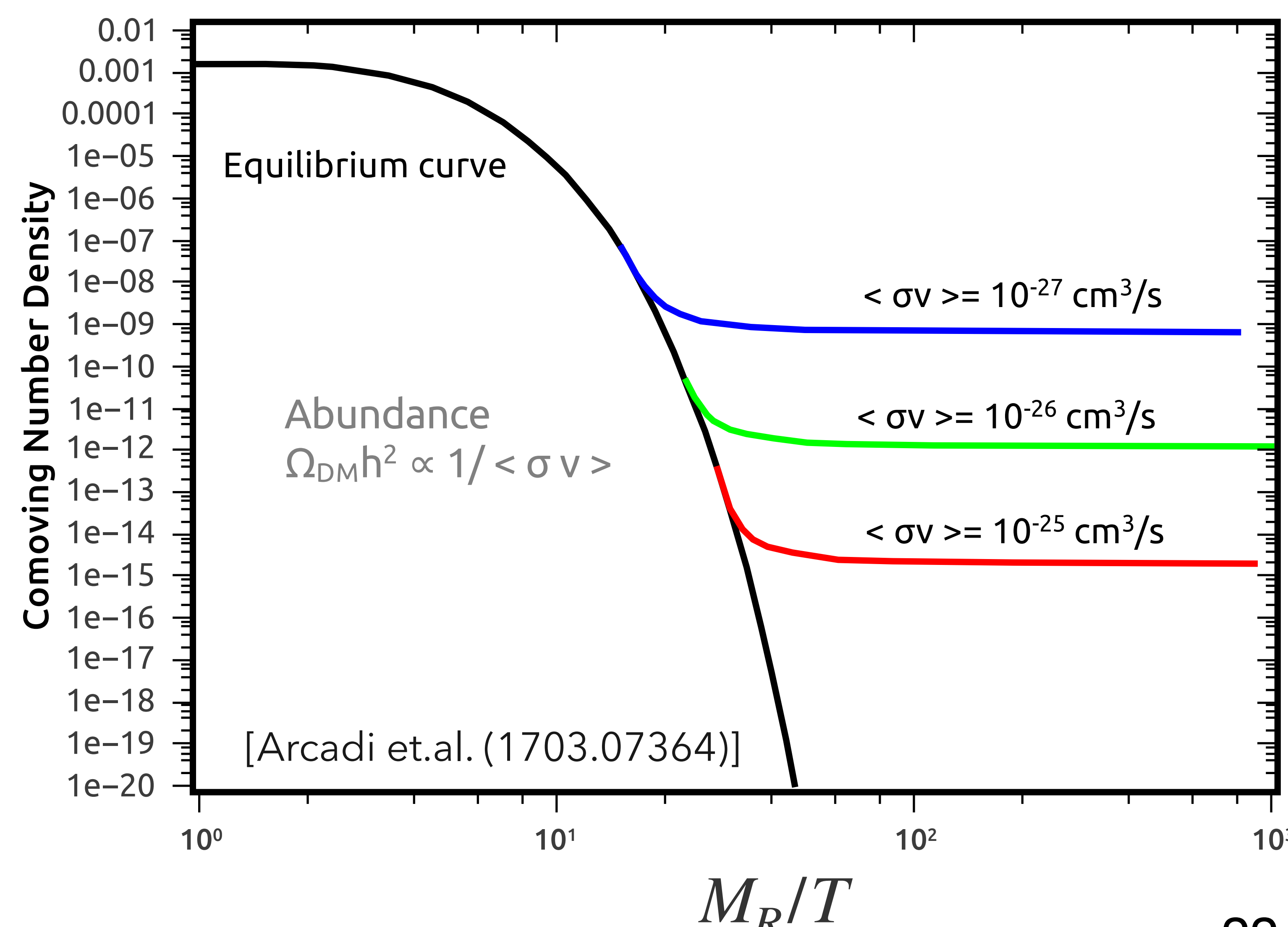
$$\frac{dn_R}{dt} + 3Hn_R = -\langle \sigma v \rangle (n_R^2 - n_{R,eq.}^2) \qquad (9)$$

n_R : number density

H: Hubble constant

σ: cross section





Dark matter relic abundance

- Dark matter relic abundance is given by

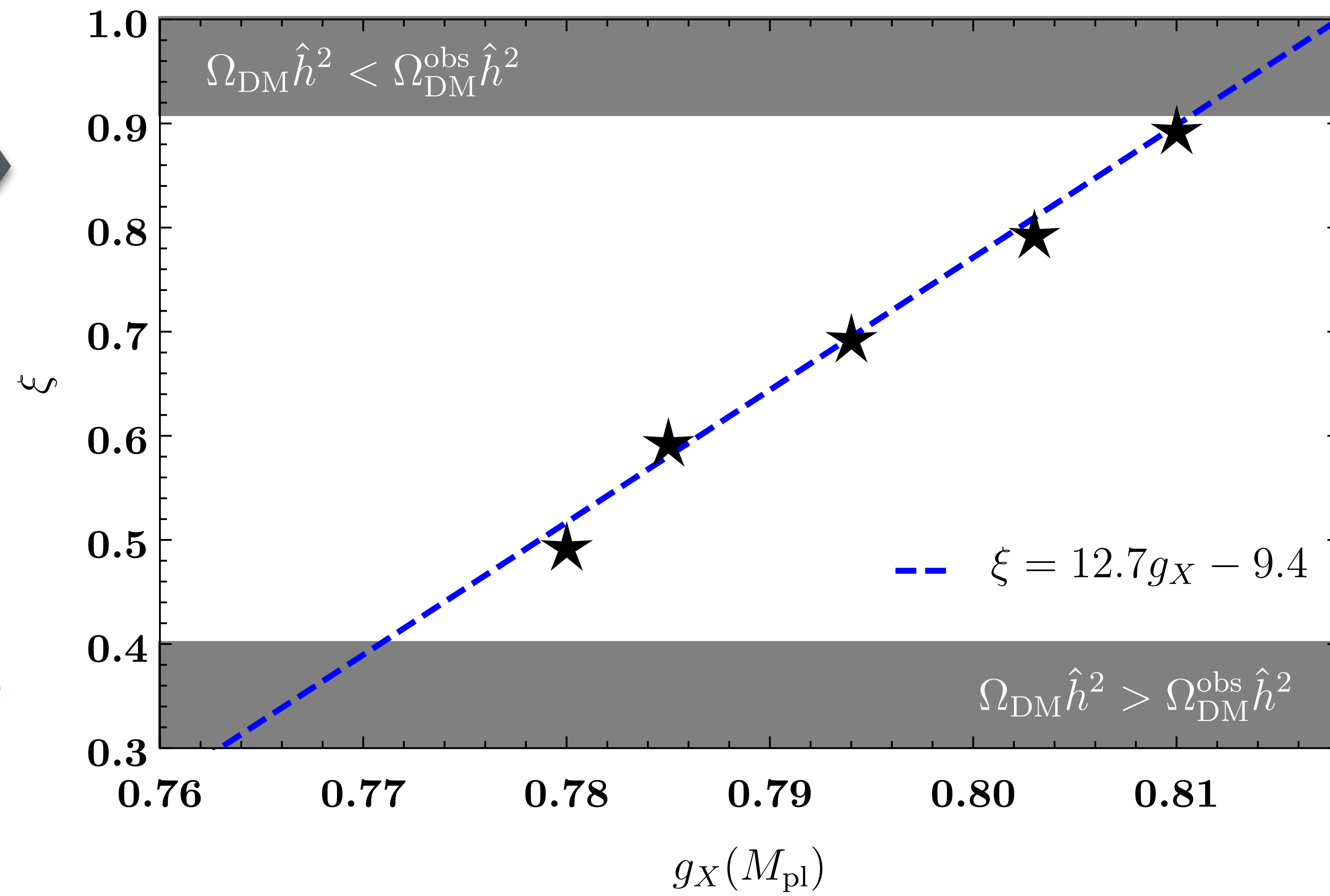
$$\Omega_{DM}h^2 = \frac{h^2}{\rho_c}\left(M_R n_R(\infty) + M_L n_L(\infty)\right) \qquad (10)$$

h: dimensionless Hubble const. ρ_c : critical energy density

- To explain the observed dark matter relic abundance,

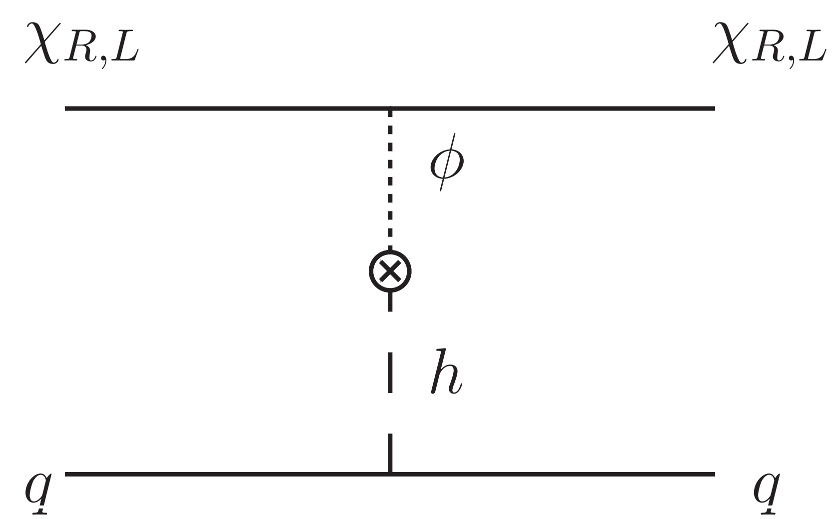
$$\Omega_{DM}h^2 = \Omega^{obs.}_{DM}h^2 \simeq 0.1193$$

$$(\xi \equiv y_R/y_L < 1)$$



Only one free parameter g_X !

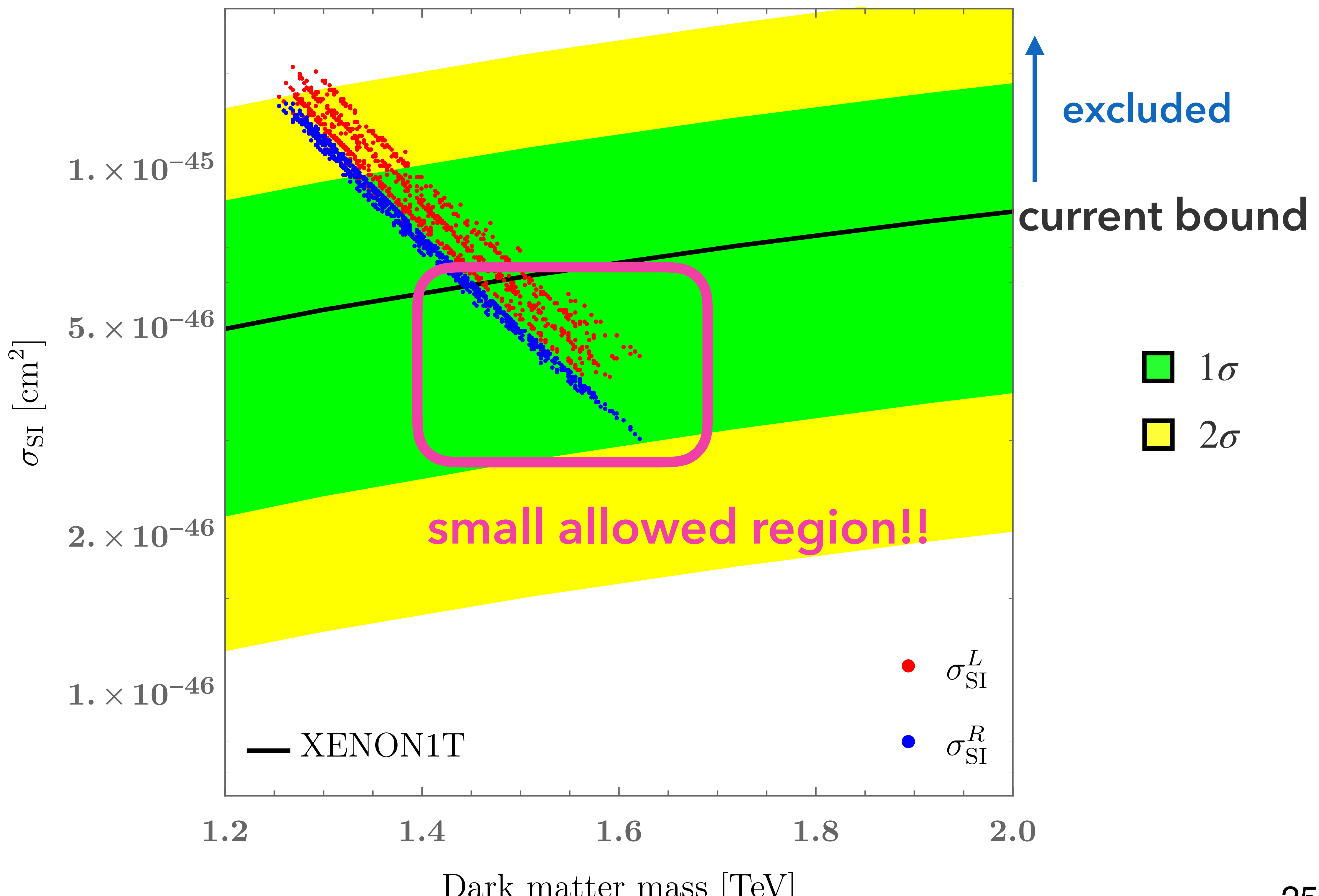
Dark matter direct detection



- The dark matter candidates χ_R, χ_L can be observed by **a spin-independent elastic scattering between χ_R, χ_L and nucleons.**

- We calculate the spin-independent cross section $\sigma_{SI}^L, \sigma_{SI}^R$, and **compare the current experimental bound (XENON1T)** .

Dark matter direct detection



Dark matter direct detection

- Our model has small allowed region

$\longrightarrow$ will be soon **detected or excluded** by future experiment ! (XENONnT)

- If DM is detected and the mass is observed , **the only free parameter g_X will be determined**

$\longrightarrow$ All parameters in our model are determined !

super strong predictability !!

Summary

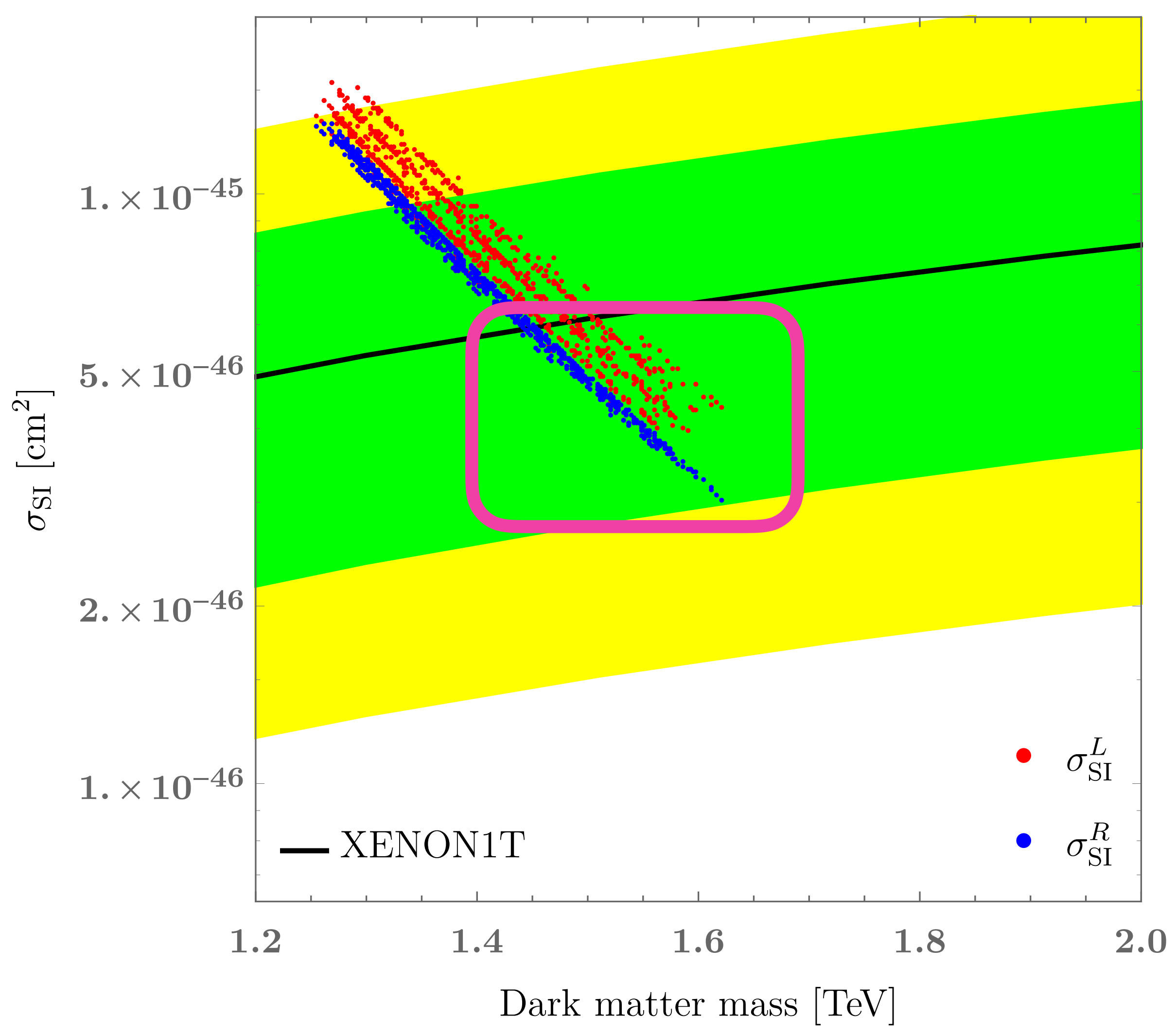
- **Asymptotic safety scenario for quantum gravity provides natural conditions, called as flatland scenario.**

- $U(1)_X$ is spontaneously broken by **CW mechanism, which triggers EW symmetry breaking.**

- Two fermions χ_R, χ_L can be DM candidates.

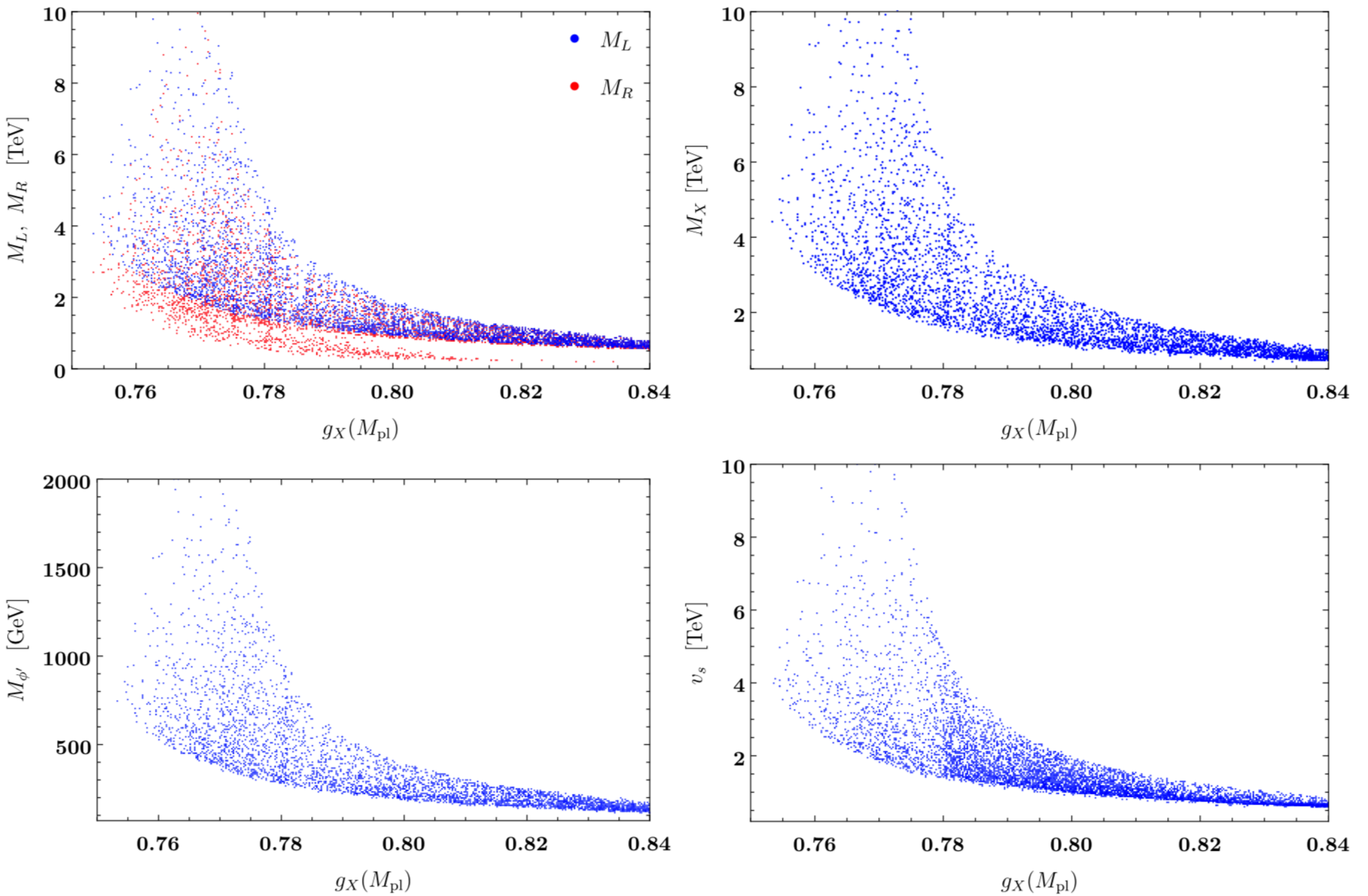
- If DM mass is observed, **all parameters are determined!**

super strong predictability !!

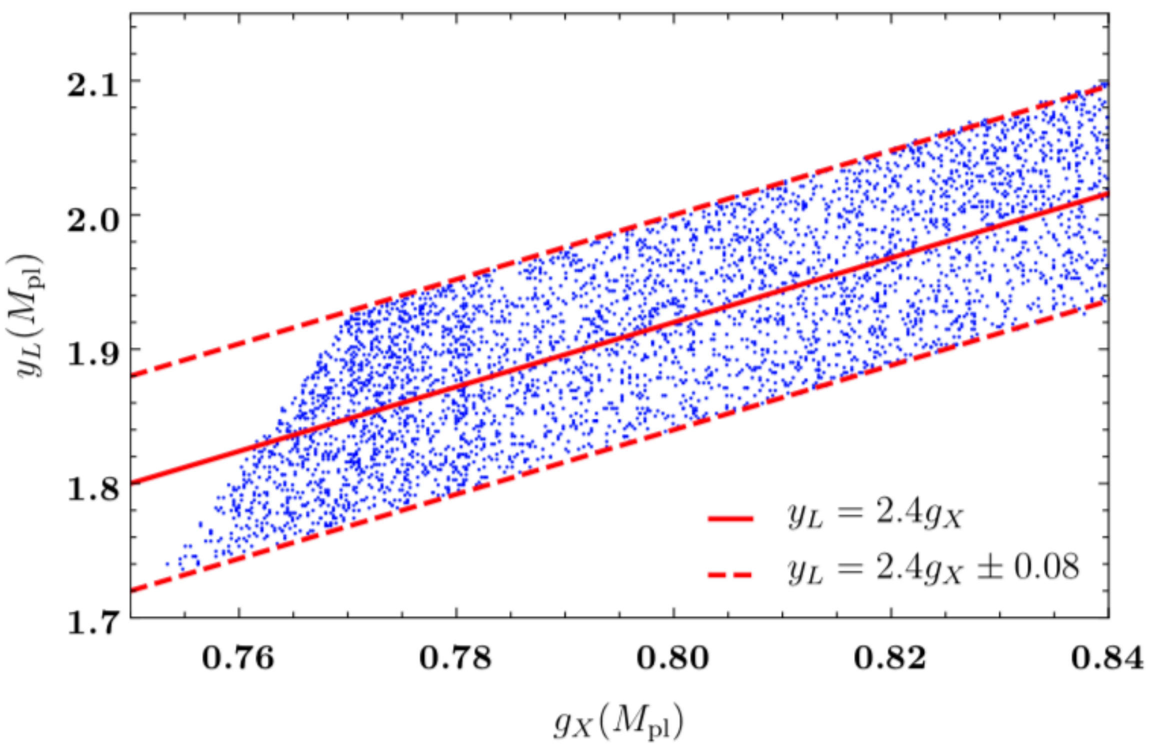


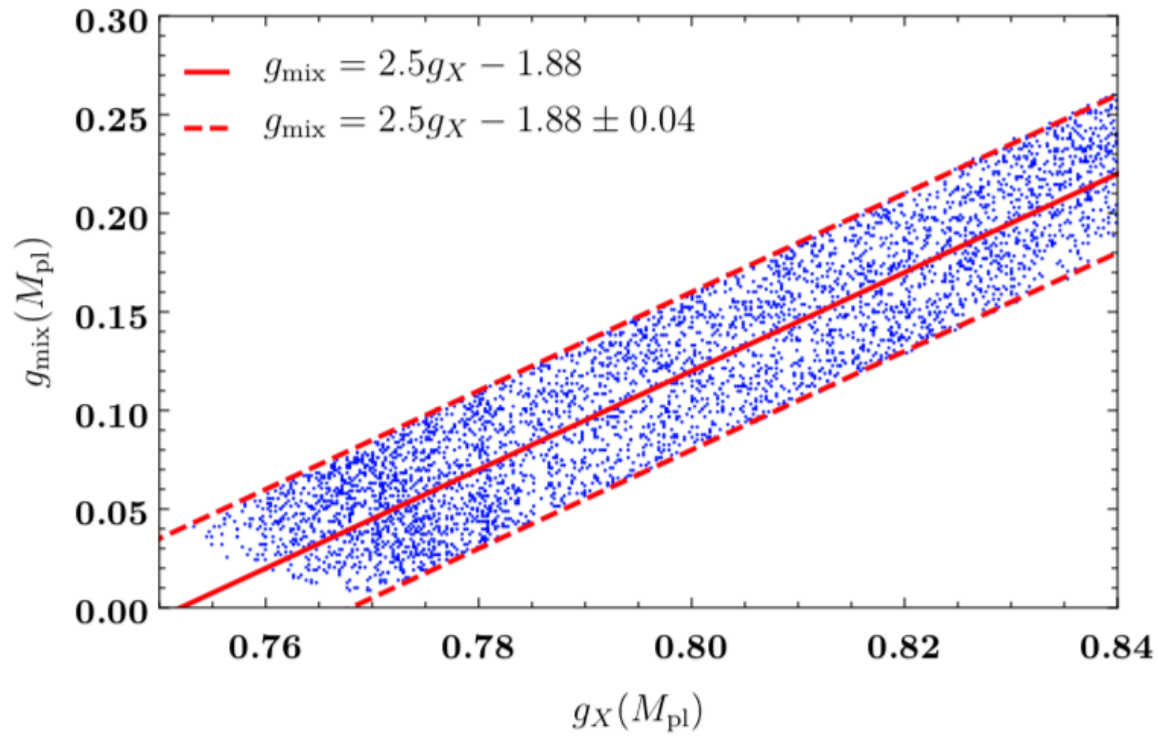
Back up

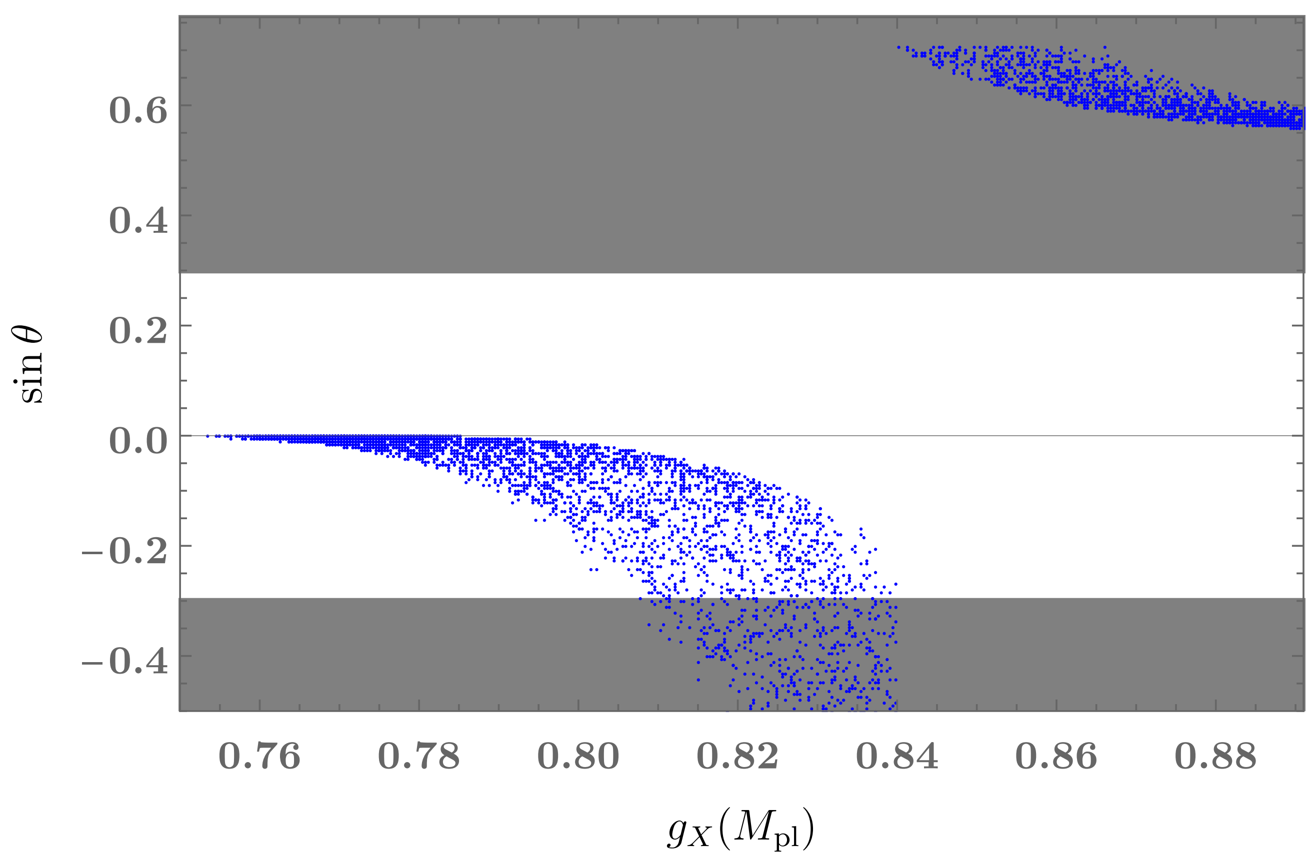
Allowed region for scalegenesis



Allowed region for scalegenesis







Benchmark values

- Input parameters at M_{pl} as

$$y_L(M_{pl}) = 1.842 \qquad y_R(M_{pl}) = 1.354$$

$$g_X(M_{pl}) = 0.794 \qquad g_{mix}(M_{pl}) = -\frac{\epsilon}{\sqrt{1-\epsilon^2}} g_Y = 0.134$$

$$v_S = 1756.2 \text{ GeV} \qquad M_L = 1114.3 \text{ GeV} \qquad M_R = 1042.5 \text{ GeV}$$

$$M_X = 1380.8 \text{ GeV} \qquad M_\phi = 227.9 \text{ GeV}$$