False Vacuum in Supersymmetric Mass Varying Neutrinos

Focus week : Neutrino Mass
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Reference
RT, M. Tanimoto, (PRD77 045015 2008)

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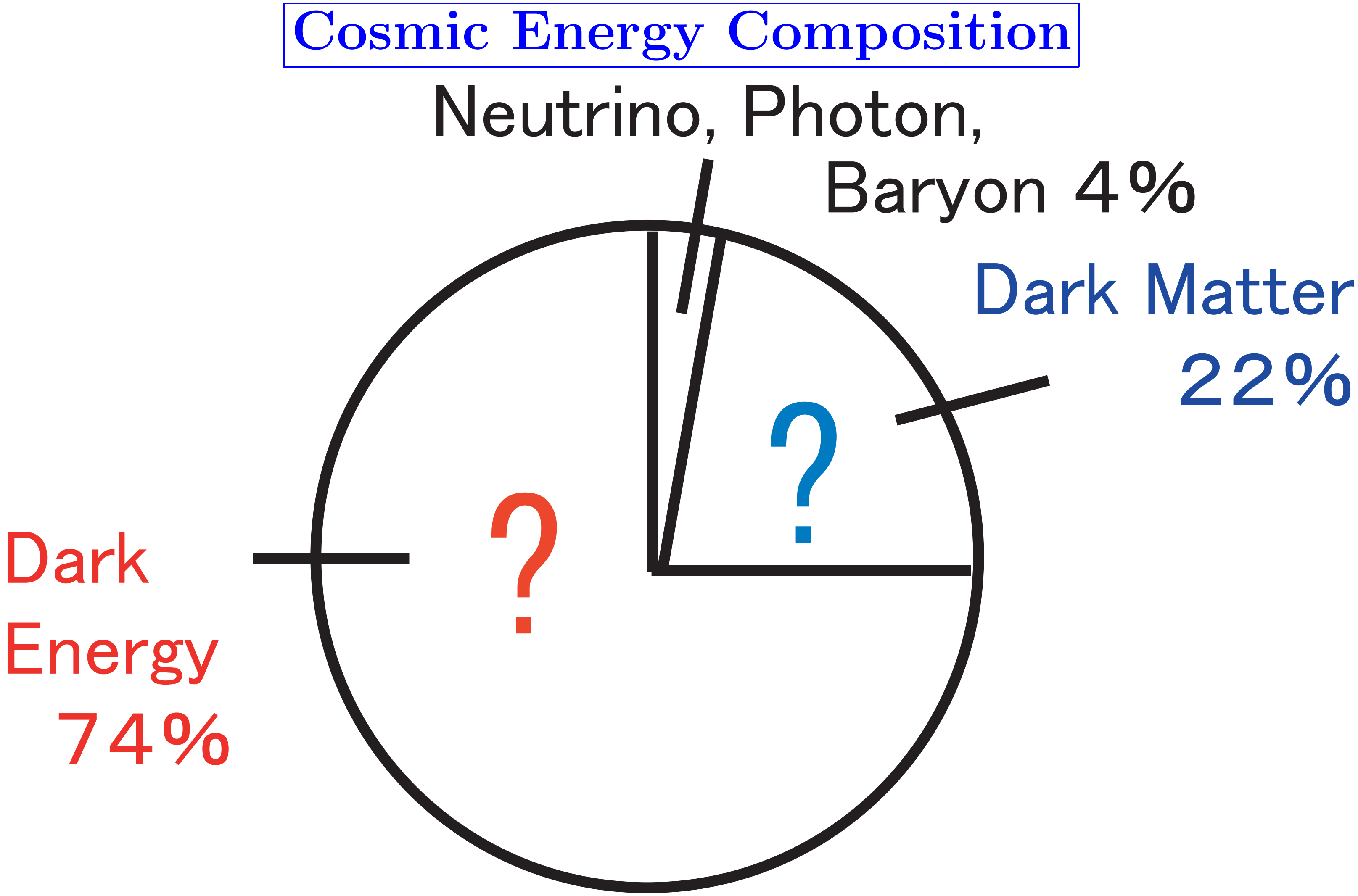
1. Introduction



Properties of the Dark Energy

Positive energy density, Negative pressure

Fluid having negative pressure ⇒ Cosmic acceleration

Important Parameter

Equation of state parameter :

$$w = \frac{p_{\rm DE}}{\rho_{\rm DE}} = \begin{cases} -0.97^{+0.07}_{-0.09} & \text{(Flat, WMAP-3+SNLS)} \\ -1.06^{+0.13}_{-0.08} & \text{(WMAP-3+LSS \& SN)} \end{cases}$$

Candidates for Dark Energy

$w = -1$

- Cosmological Constant

$w > -1$

- Quintessence (scalar field : $m_\phi \sim 10^{-33}$eV)
- Mass Varying Neutrinos
  $\Rightarrow$ scalar field interacts with CνB

⋮

$w < -1$

- Phantom Energy

⋮

2. Mass Varying Neutrinos (MaVaNs) Scenario

Variable Neutrino Mass

- Neutrino Dark Matter

Kawasaki, Murayama, Yanagida (1992)

- Relation between neutrino and dark energy

Gu, Wang, Zhang, PRD 68(2003)087301

Fardon, Nelson, Weiner, JCAP 10(2004)005

$\Rightarrow$ Mass Varying Neutrinos (MaVaNs)

Motivation of MaVaNs

- The mass scale of the neutrino is close to the dark energy scale.

Neutrino mass scale

$$\Delta m^2_{\rm sol} \sim 7.6 \times 10^{-5}\ {\rm eV}^2\ ,\quad \Delta m^2_{\rm atm} \sim 2.4 \times 10^{-3}\ {\rm eV}^2$$

Dark energy scale

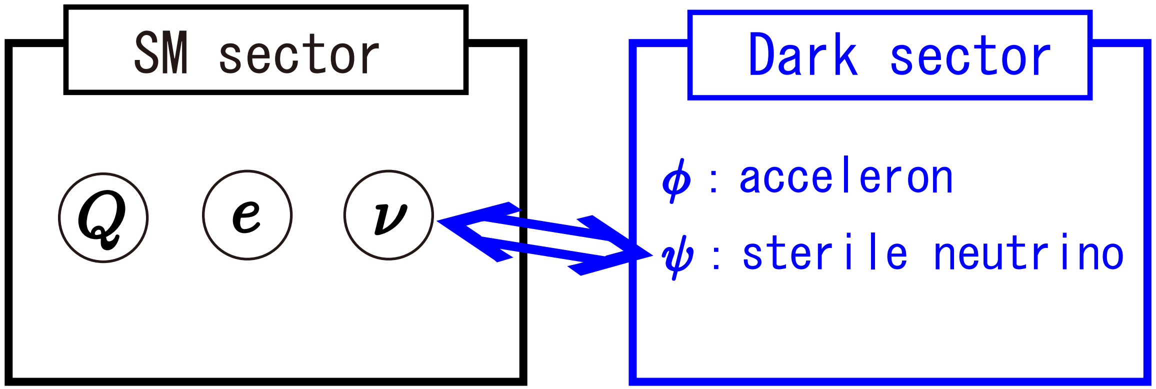
$$\Lambda_{\rm DE} \sim 2 \times 10^{-3}\ {\rm eV}$$

Minimal Matter Contents

"Dark Sector" (=unknown particles with no SM charges)

- ▷ Scalar field ("acceleron") ϕ
- ▷ Fermion field ("sterile neutrino") ψ
- ▷ Yukawa interaction $\lambda\phi\psi\psi$
- ▷ Scalar potential $V(\phi)$

Simple Model



$$-\mathcal{L}_{\text{MaVaNs}} = y\tilde{\Phi}l\psi + \lambda\phi\psi\psi + h.c. \Rightarrow m_D \nu_L \psi + \lambda\phi\psi\psi + h.c.$$

$$\Downarrow$$

$$m_\nu = m_\nu(\phi) = \frac{m_D^2}{\lambda\phi}$$

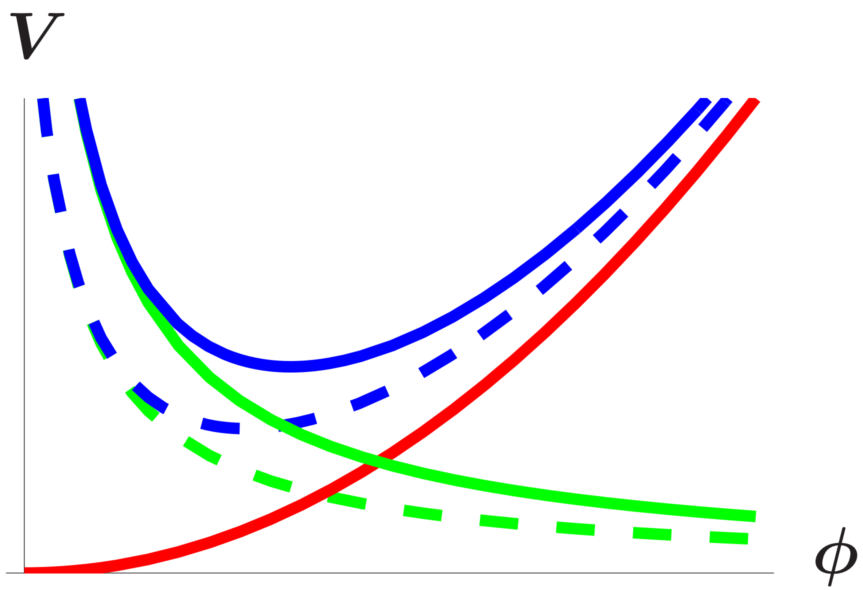
Stationary Condition

$$\frac{\partial}{\partial \phi}[V(\phi) + \rho_\nu(m_\nu(\phi))] = 0$$

$$\Updownarrow$$

$$\frac{\partial}{\partial m_\nu}[V(\phi) + \rho_\nu(m_\nu(\phi))] = 0 \qquad \left(\frac{\partial m_\nu}{\partial \phi} \neq 0\right)$$

Consequences



$\Rightarrow \langle\phi\rangle$ & $\rho_{\rm DE}$ vary on cosmological time scale.

$\Rightarrow m_\nu(\phi)$ also varies.

For non-relativistic neutrinos

$$\begin{aligned}\rho_{\rm DE} &= V(\phi) + \rho_\nu(m_\nu(\phi)) \\ &= V(\phi) + m_\nu(\phi) n_\nu \\ &= V(\phi) + \frac{m_D^2}{\lambda\phi} n_\nu\end{aligned}$$

As the universe expands, n_ν decreases:

— $\rho_{\rm DE}$ $\Rightarrow$ - - $\rho'_{\rm DE}$

— ρ_ν - - ρ'_ν

—$V(\phi)$

1 generation model

R. D. Peccei, Phys. Rev. D71 (2005) 023527

Energy density of neutrinos

$$\rho_\nu = T^4 F(\xi) \qquad \text{(For non-relativistic neutrinos : } \rho_\nu = m_\nu n_\nu)$$

$$\xi = m_\nu / T$$

$$F(\xi) = \frac{1}{\pi^2}\int_0^\infty \frac{dy y^2 \sqrt{y^2+\xi^2}}{e^y+1}$$

Equation of state for the dark energy

- Energy conservation law : $\dot{\rho}_{\rm DE} = -3H(\rho_{\rm DE} + p_{\rm DE})$
- Stationary condition : $\frac{\partial \rho_{\rm DE}}{\partial m_\nu} = \frac{\partial \rho_\nu}{\partial m_\nu} + \frac{\partial V(\phi(m_\nu))}{\partial m_\nu} = 0$

$$w + 1 = \frac{4 - h(\xi)}{3\left[1 + \frac{V(\phi(m_\nu))}{T^4 F(\xi)}\right]} \Longrightarrow \frac{m_\nu n_\nu}{V(\phi) + m_\nu n_\nu} \quad \text{(Non-rel. limit)}$$

$$h(\xi) \equiv \frac{\xi(\partial F(\xi)/\partial \xi)}{F(\xi)}$$

Evolution of the equation of state

When neutrinos become non-relativistic,

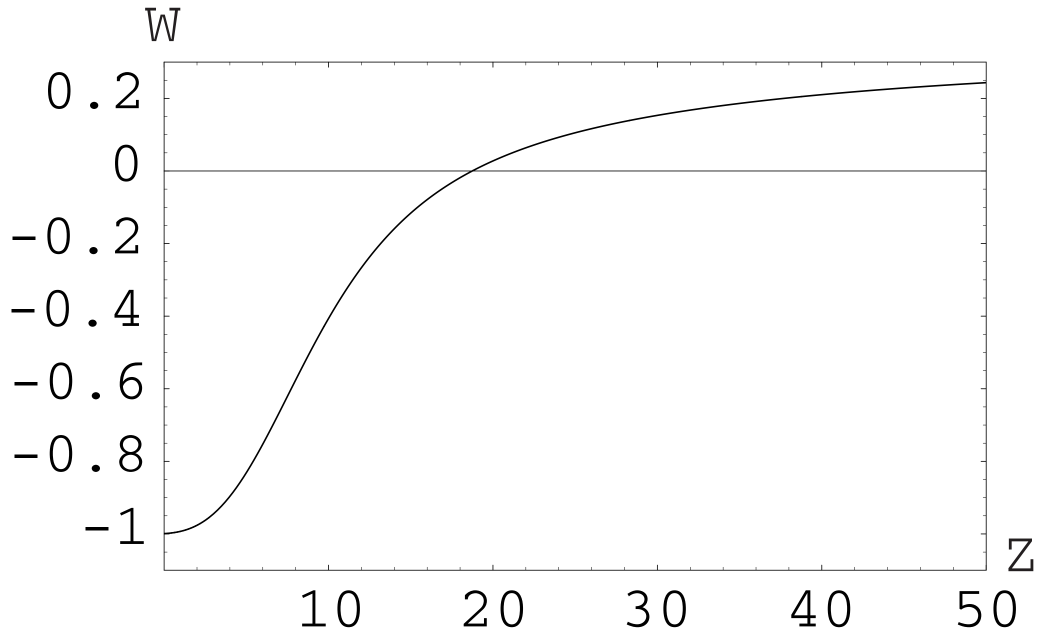
$$w + 1 = \frac{m_\nu n_\nu}{V(\phi) + m_\nu n_\nu}.$$

$$w = \begin{cases} -0.97^{+0.07}_{-0.09} & (\text{Flat, WMAP-3+SNLS}) \\ -1.06^{+0.13}_{-0.08} & (\text{WMAP-3+LSS \& SN}) \end{cases} \Rightarrow m_\nu n_\nu \ll V(\phi)$$

Dark Energy

$$\rho_{\rm DE} = V(\phi) + \rho_\nu$$

Past ↓ **Radiation**
↓
↓ **Matter**
↓
Now ↓ **≃ Cosmological Constant**
↓
Future ↓



Stationary condition

$$\frac{\partial \rho_{\rm DE}}{\partial m_\nu} = \frac{\partial \rho_\nu}{\partial m_\nu} + \frac{\partial V(\phi(m_\nu))}{\partial m_\nu} = 0$$

$$= T^3 \frac{\partial F}{\partial \xi} + \frac{\partial V(\phi(m_\nu))}{\partial m_\nu} = 0$$

Constraints on scalar potential

(i) Observations : $\Omega_{\rm DE,0} = \rho_{\rm DE,0}/\rho_c \simeq 0.74$

$$\Rightarrow V(\phi(m_{\nu,0})) = 0.74\rho_c - \rho_{\nu,0} \simeq 2.96 \times 10^{-11}\,\mathrm{eV}^4$$

(ii) Stationary condition (@ the present) :

$$\Rightarrow \left.\frac{\partial V(\phi(m_\nu))}{\partial m_\nu}\right|_{m_\nu = m_{\nu,0}} = -T^3 \left.\frac{\partial F}{\partial \xi}\right|_{m_\nu = m_{\nu,0},\, T = T_0} \simeq -n_{\nu,0} \simeq -8.82 \times 10^{-13}\,\mathrm{eV}^3$$

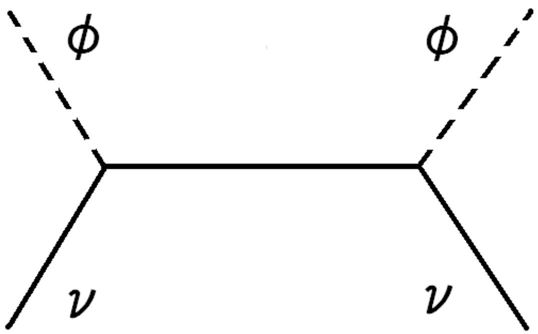
- The present value of a scalar potential must be small, and its gradient must be flat.

Limits on acceleron production from supernovae

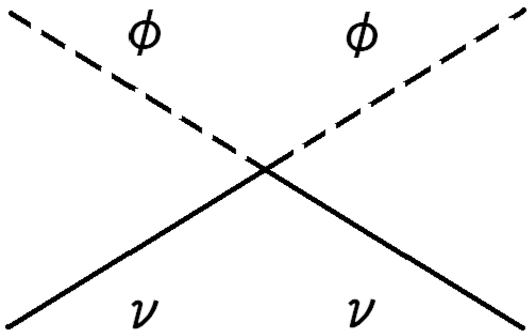
- ϕ production must not cool a protoneutron star too quickly to alter the observed spectrum of ν emitted in the first 10 seconds:

$$\Gamma_\phi < \frac{1}{10\ \text{sec.}}.$$

$$\Downarrow$$



$$: \left(\frac{\partial m_\nu}{\partial \phi}\right)^4 \lesssim 10^{-23}$$



$$: \left(\frac{\partial^2 m_\nu}{\partial \phi^2}\right)^2 \lesssim 10^{-37}\text{eV}^{-2}$$

Summary of MaVaNs scenario

- "Dark Sector" (=unknown particles with no SM charges)
  - ▷ Scalar field ("acceleron") ϕ
  - ▷ Fermion field ("sterile neutrino") ψ
  - ▷ Yukawa interaction $\lambda\phi\psi\psi, \quad y\tilde{\Phi}l\psi$
  - ▷ Scalar potential $V(\phi)$

$$V(\phi(m_{\nu,0})) \sim \mathcal{O}(10^{-11}) \text{ eV}^4$$

$$\left.\frac{\partial V}{\partial m_\nu}\right|_{m_\nu = m_{\nu,0}} \sim -\mathcal{O}(10^{-13}) \text{ eV}^3$$

- Limits on acceleron production from supernovae

$$\left(\frac{\partial m_\nu}{\partial \phi}\right)^2 \lesssim 10^{-12}, \quad \left(\frac{\partial^2 m_\nu}{\partial \phi^2}\right)^2 \lesssim 10^{-37}\text{eV}^{-2}$$

3. Supersymmetric Mass Varying Neutrinos Model

- **Chiral superfields are assumed in a dark sector.**

Two chiral superfields model

- ▷ Scalar field ("acceleron") $\phi \Rightarrow A$
- ▷ Fermion field ("sterile neutrino") $\psi \Rightarrow N$

- $W = \lambda ANN + m_D LN + m'_D LA + M_D LR + M_R RR$

RT, M. Tanimoto, PLB633 (2006) 675

- $W = \lambda_{ij} AN_i N_j + m_i L_i N_i + \lambda_{ijk} N_i N_j N_k$

Fardon, Nelson, Weiner, JHEP 0603 (2006) 042

One chiral superfield model

- ▷ Scalar field ("acceleron") ϕ
- ▷ Fermion field ("sterile neutrino") ψ

$\left.\begin{matrix}\phi \\ \psi\end{matrix}\right\} A$

- $W = \frac{\lambda_1}{6} A^3 + m_D LA + M_D LR + \frac{\lambda_2}{2} A^2 R + \frac{M_A}{2} A^2 + \frac{M_R}{2} R^2$

RT, M. Tanimoto, PRD 74 (2006) 055002

RT, M. Tanimoto, PRD 77 (2008) 045015

$$\bullet W = \frac{\lambda_1}{6}A^3 + m_D LA + M_D LR + \frac{\lambda_2}{2}A^2 R + \frac{M_A}{2}A^2 + \frac{M_R}{2}R^2$$

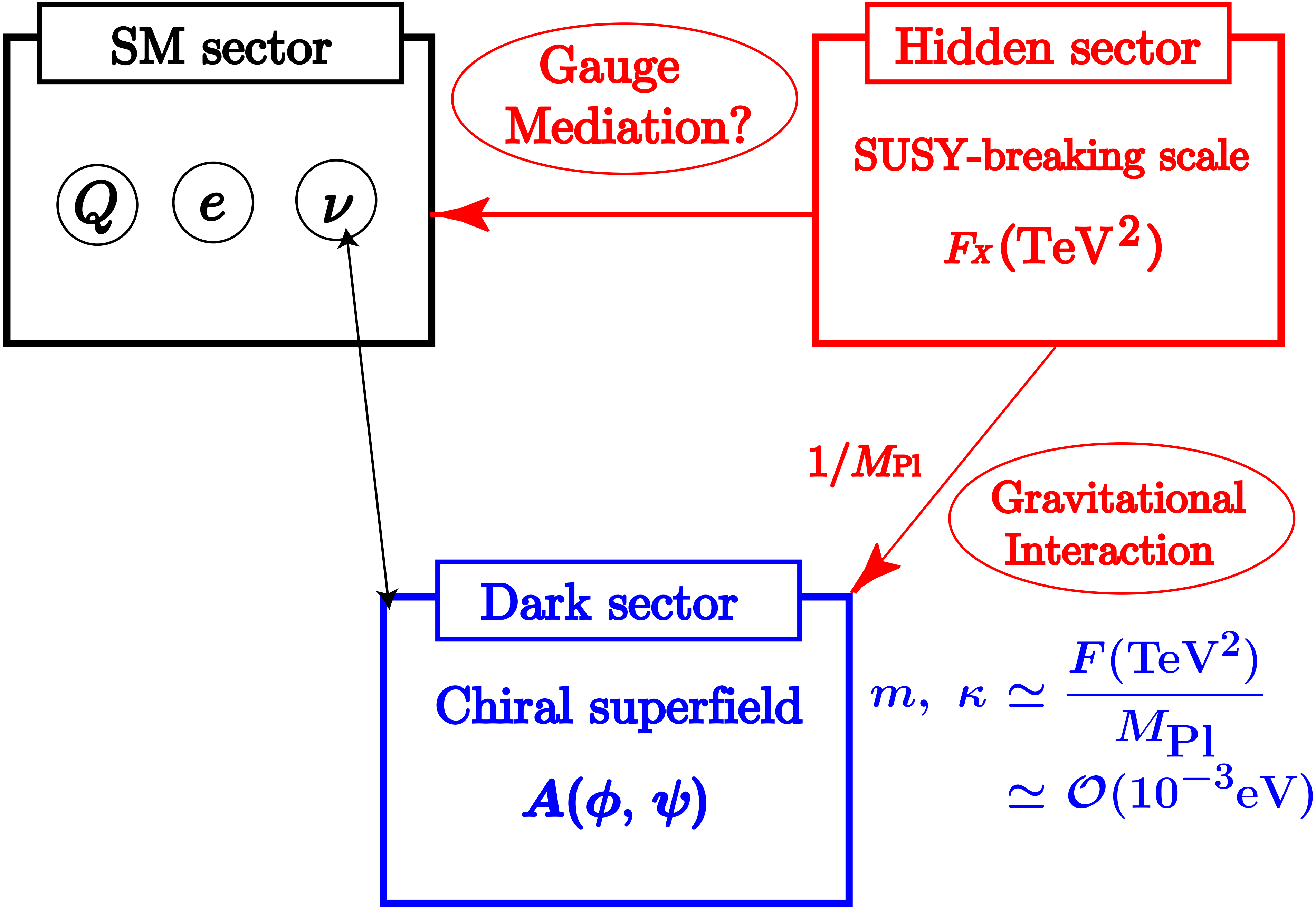
$$\Rightarrow V(\phi) = \frac{\lambda_1^2 + \lambda_2^2}{4}|\phi|^4 + (M_A^2 + m_D^2 - m^2)|\phi|^2 + \left(\frac{\lambda_1}{2}M_A|\phi|^2\phi - \frac{\kappa}{3}\phi^3 + h.c.\right) + V$$

$$(\langle\tilde{\nu}_{L,R}\rangle = 0)$$

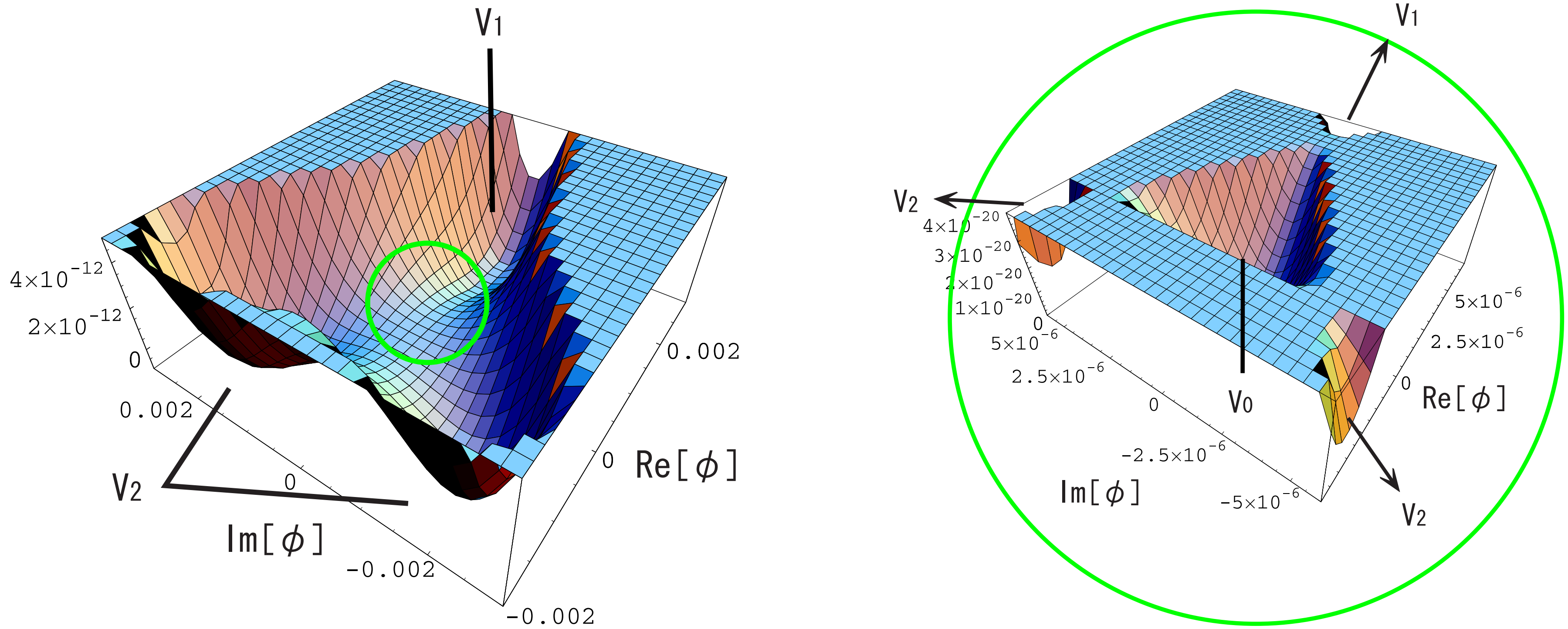
Numerical analysis

$$\begin{cases} \lambda_1 \lesssim 4\times 10^{-9} & : \text{constrained by data of supernovae} \\ \lambda_2 = 1 & \\ m_D \lesssim 10^{-3}\text{eV} & \\ M_A \lesssim 10^{-1}\text{eV} & \\ M_D \ll M_R & : \text{seesaw mechanism} \\ m,\ \kappa \simeq \mathcal{O}(10^{-3}\text{eV}) & : F(\text{TeV}^2)/M_{\text{Pl}} \Rightarrow \boxed{\text{Dark Sector}} \\ V & : V(\phi) = 0 \text{ @True minimum} \\ \langle\phi\rangle_0 \simeq 0 & \end{cases}$$

Supersymmetry breaking



Vacuum structure of the scalar potential



- MaVaNs scenario is realized near the origin ($\langle\phi\rangle_0 \simeq 0$)
- Dark energy is identified with the false vacuum energy

$$\triangleright \quad V = |V_2| \simeq \frac{(\lambda_1 M_A + 4\kappa)^6}{3 \cdot 32^2 \kappa^2 (\lambda_1^2 + \lambda_2^2)} \sim \mathcal{O}(\kappa^4) \sim \rho_{\mathrm{DE},0}$$

$$\triangleright \quad \kappa \sim \frac{\langle F(\mathrm{TeV})^2 \rangle}{M_{\mathrm{Pl}}} \sim 10^{-3}\mathrm{eV}$$

4. Summary and Perspective

Summary of MaVaNs scenario

- "Dark Sector" (=unknown particles with no SM charges)
  - ▷ Scalar field ("acceleron") ϕ
  - ▷ Fermion field ("sterile neutrino") ψ
  - ▷ Yukawa interactions $\lambda\phi\psi\psi$, $y\tilde{\Phi}l\psi$
  - ▷ Scalar potential $V(\phi)$

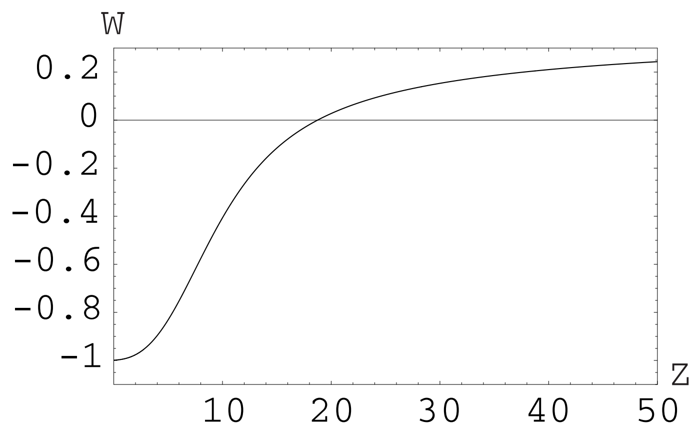
    $V(\phi(m_{\nu,0})) \sim \mathcal{O}(10^{-11})\ \mathrm{eV}^4$

    $\partial V/\partial m_\nu|_{m_\nu=m_{\nu,0}} \sim -\mathcal{O}(10^{-13})\ \mathrm{eV}^3$
- Limits on acceleron production from supernovae

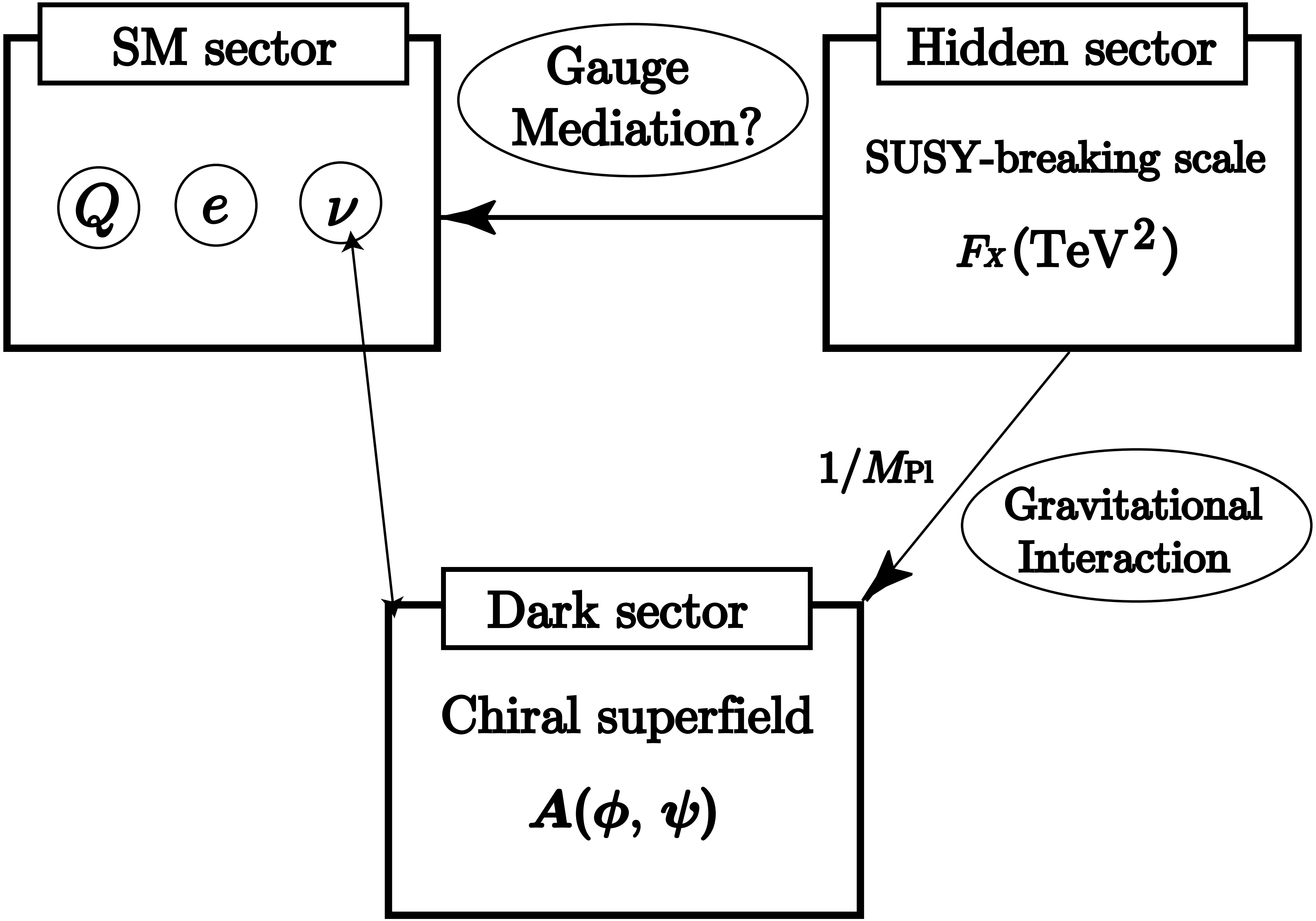
  $(\partial m_\nu/\partial\phi)^2 \lesssim 10^{-12}$, $(\partial^2 m_\nu/\partial\phi^2)^2 \lesssim 10^{-37}\mathrm{eV}^{-2}$
- Phenomenological consequences
  - ▷ $\rho_{\mathrm{DE}}(\phi)$, $m_\nu(\phi)$, $w(z)$: Variable
  - ▷ DE : Radiation ⇒ Matter

    ⇒≃Cosmological Constant

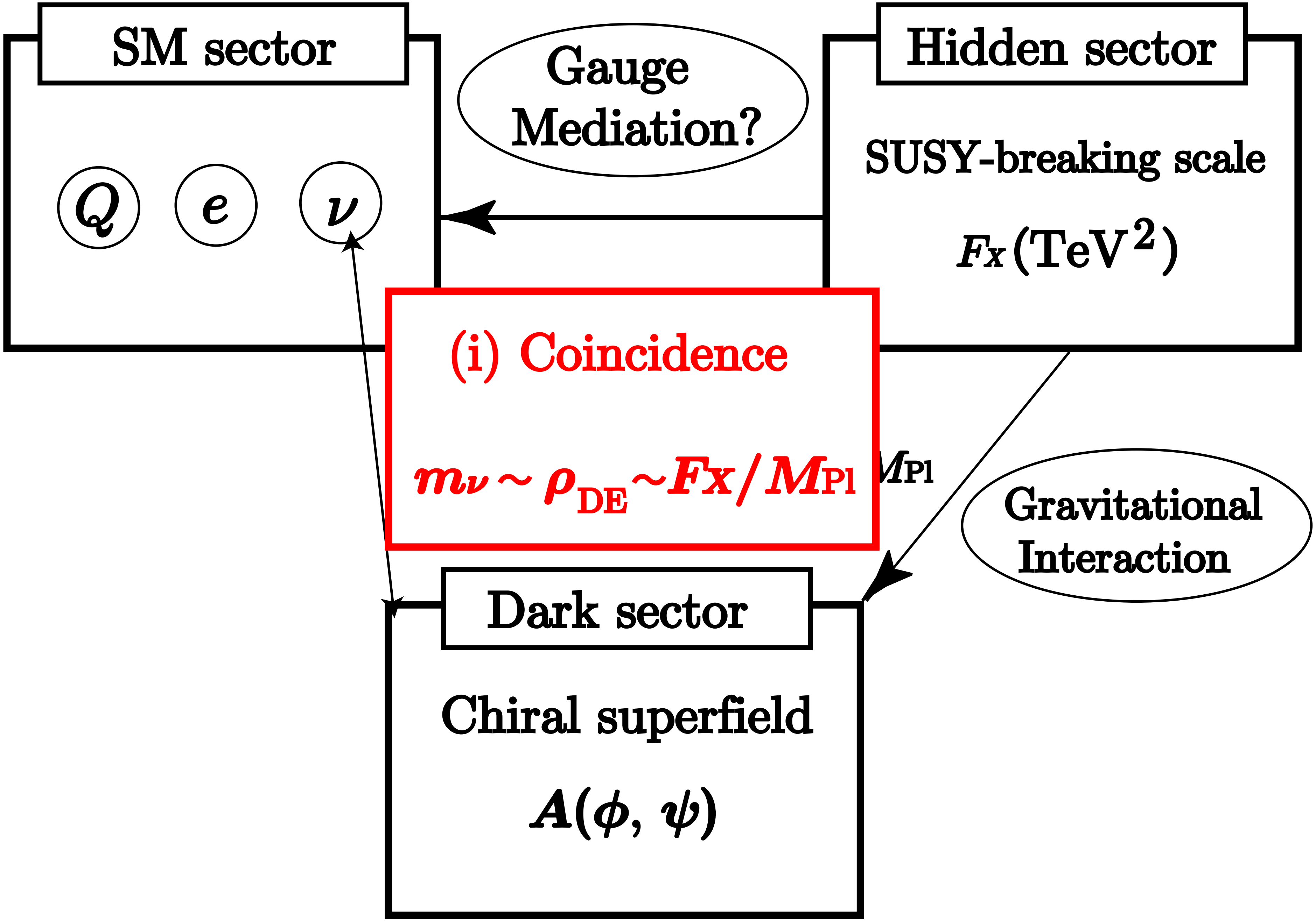
    $(-1 < w)$



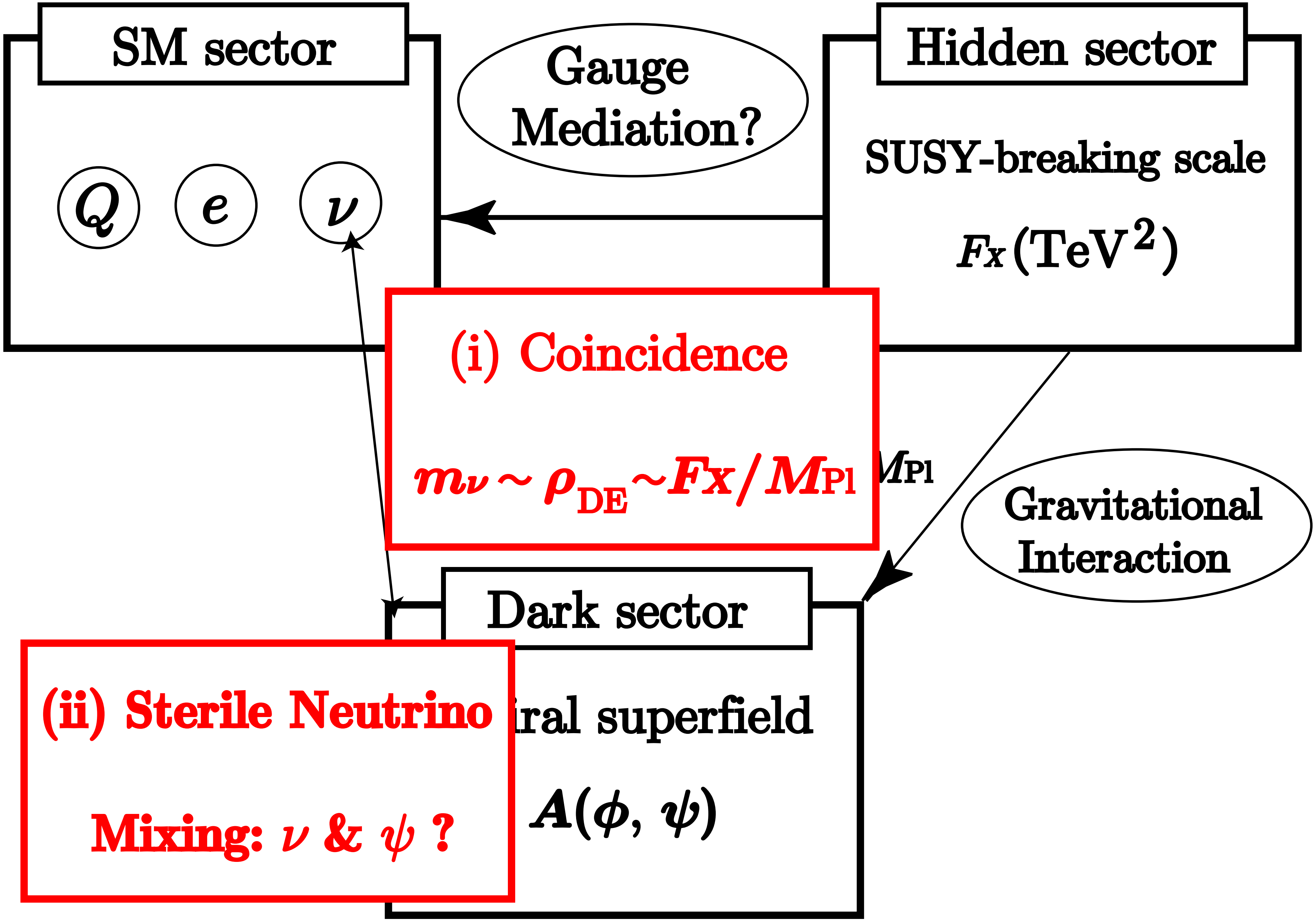
Perspective



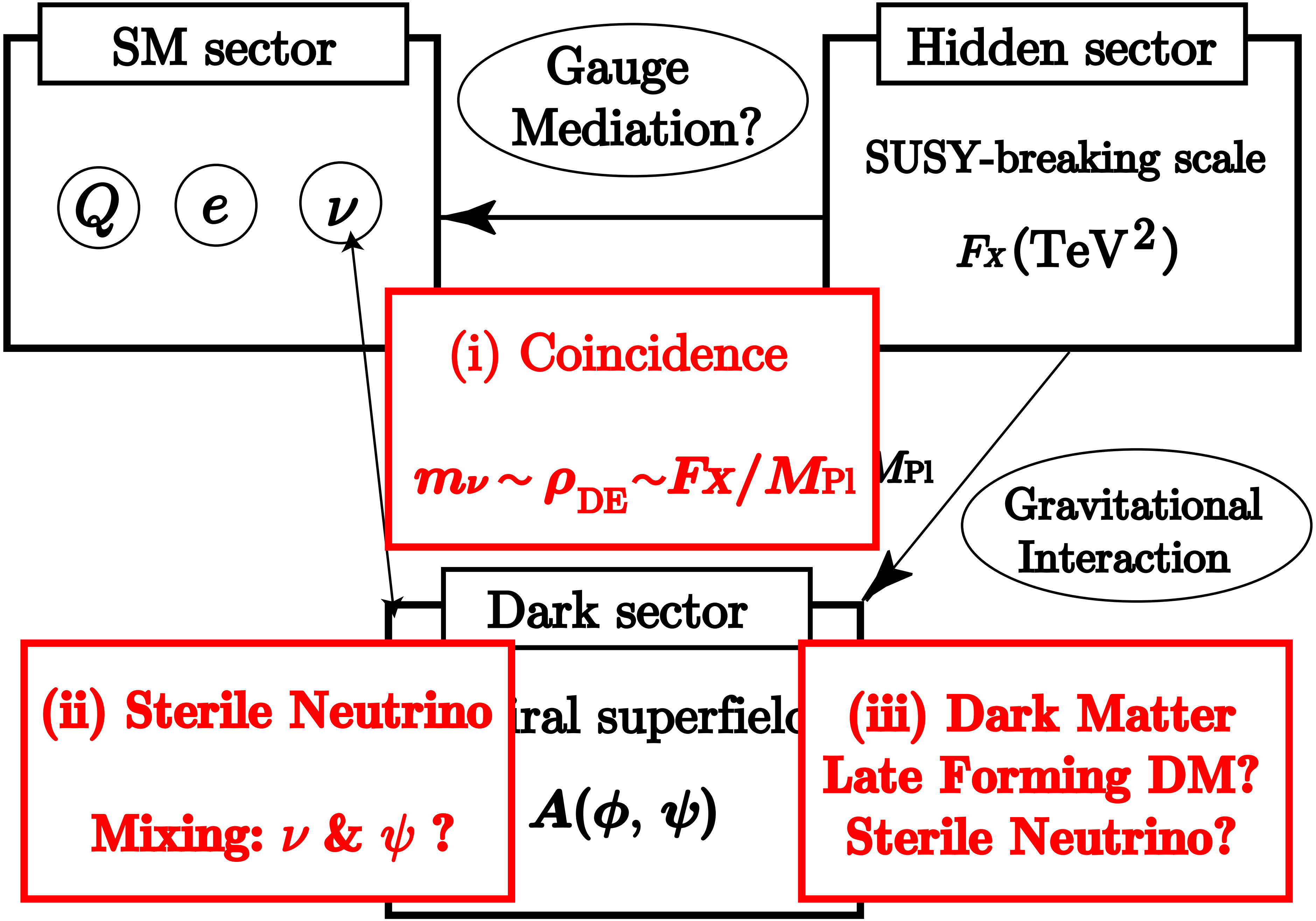
Perspective



Perspective



Perspective



Late Forming Dark Matter

Das and Weiner, [astro-ph/0611353]

- A scalar field converts the energy of a metastable point to dark matter at times late in the history of the universe, near the era of matter-radiation equality.
  - Metastable point : Hybrid MaVaNs (Hybrid potential)
  - Scalar field : Sterile sneutrino (Waterfall field)

Sterile Neutrino Dark Matter (νMSM)

Asaka, Blanchet and Shaposhnikov, [hep-ph/0503065]

- The lightest right-handed (sterile) neutrino can be a candidate for dark matter.

$$M_1 \sim \text{ keV } (y \simeq 6 \times 10^{-13}) \qquad \Rightarrow \text{DM}$$
$$M_2 \sim 10 \text{ GeV } (y \simeq 5 \times 10^{-8})$$
$$M_3 \sim 10 \text{ GeV } (y \simeq 1 \times 10^{-7})$$