TOWARDS DARK MATTER DISCOVERY

WORKSHOP
APRIL 11-13, 2018
CHICAGO

Fuzzy Dark Matter and Non-Standard Neutrino Interactions

Xiao-Ping Wang

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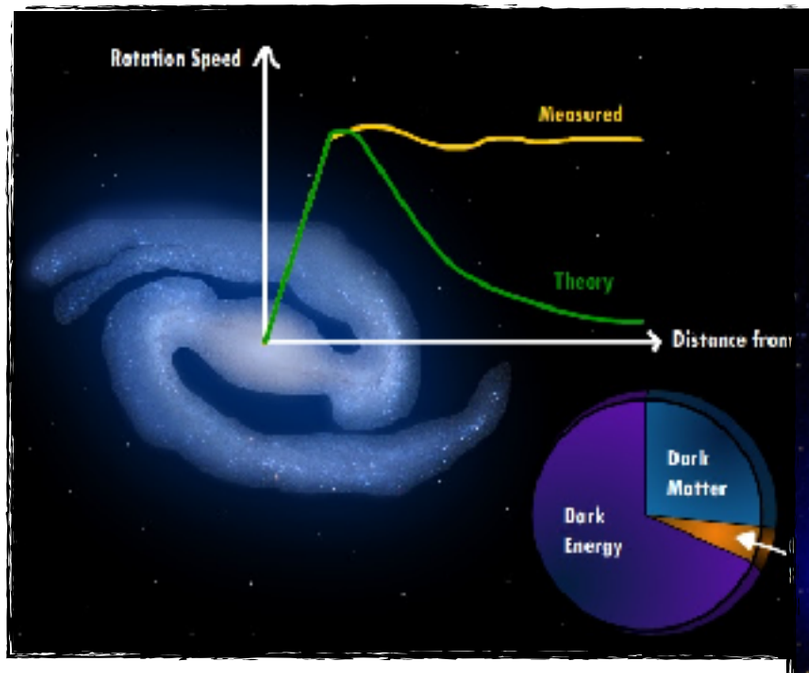
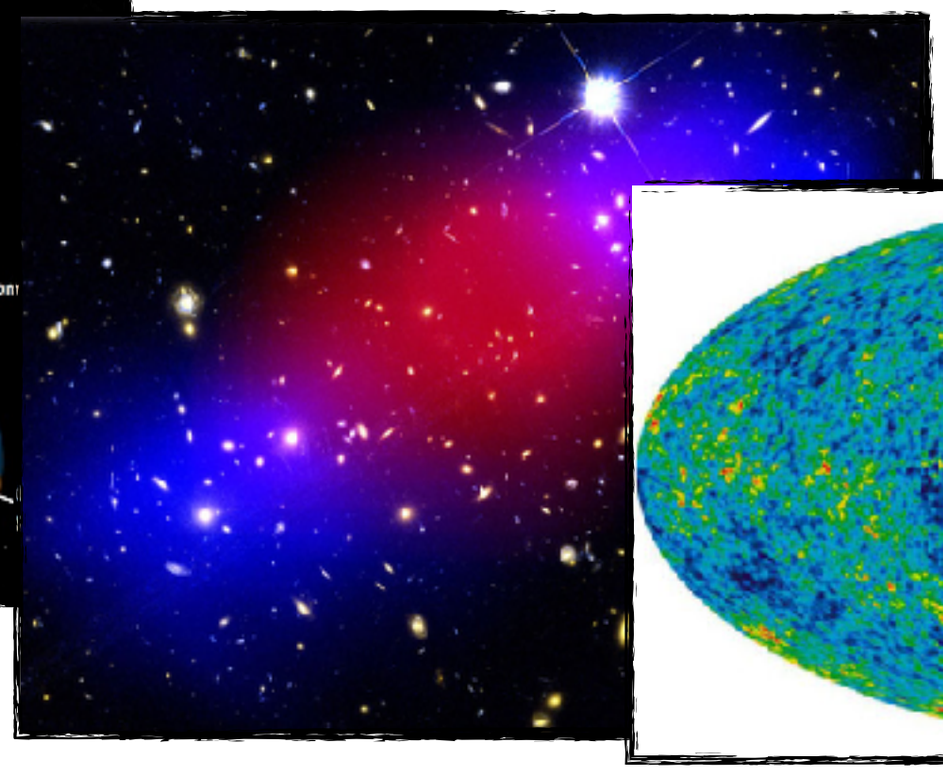
Collaborated with Vedran Brdar, Joachim Kopp, Jia Liu and Pascal Prass

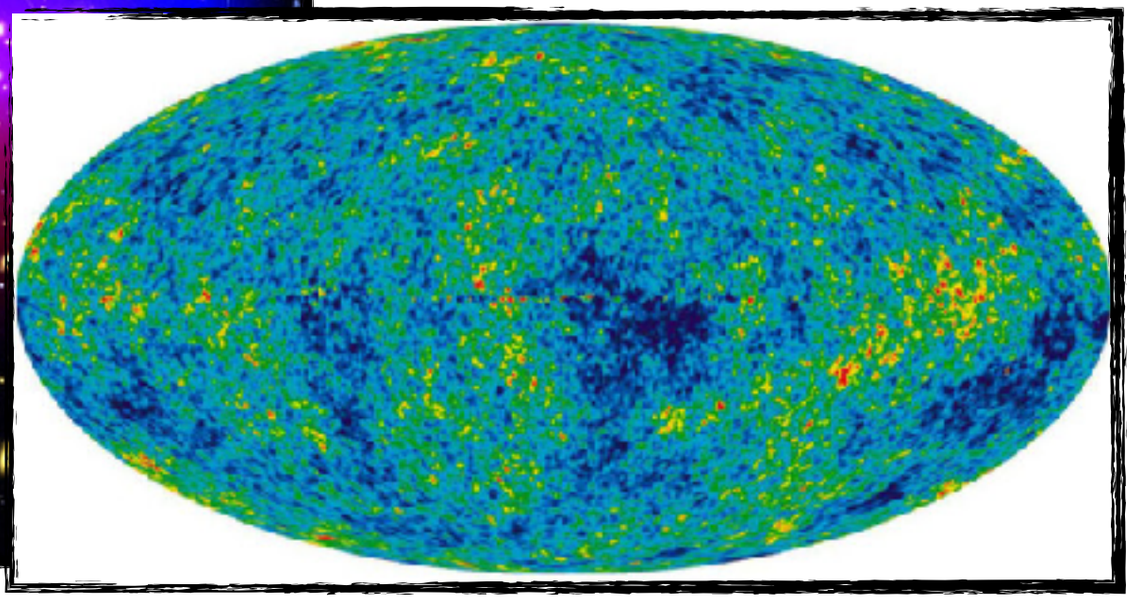
Dark Matter Introduction

✤ **Evidence from different scale**

Galaxy Cluster Universe







Dark Matter Introduction

✤Dark Matter characters

✓Strong gravitational force

✓(very) Weak interaction with other particles

✓Uncharged

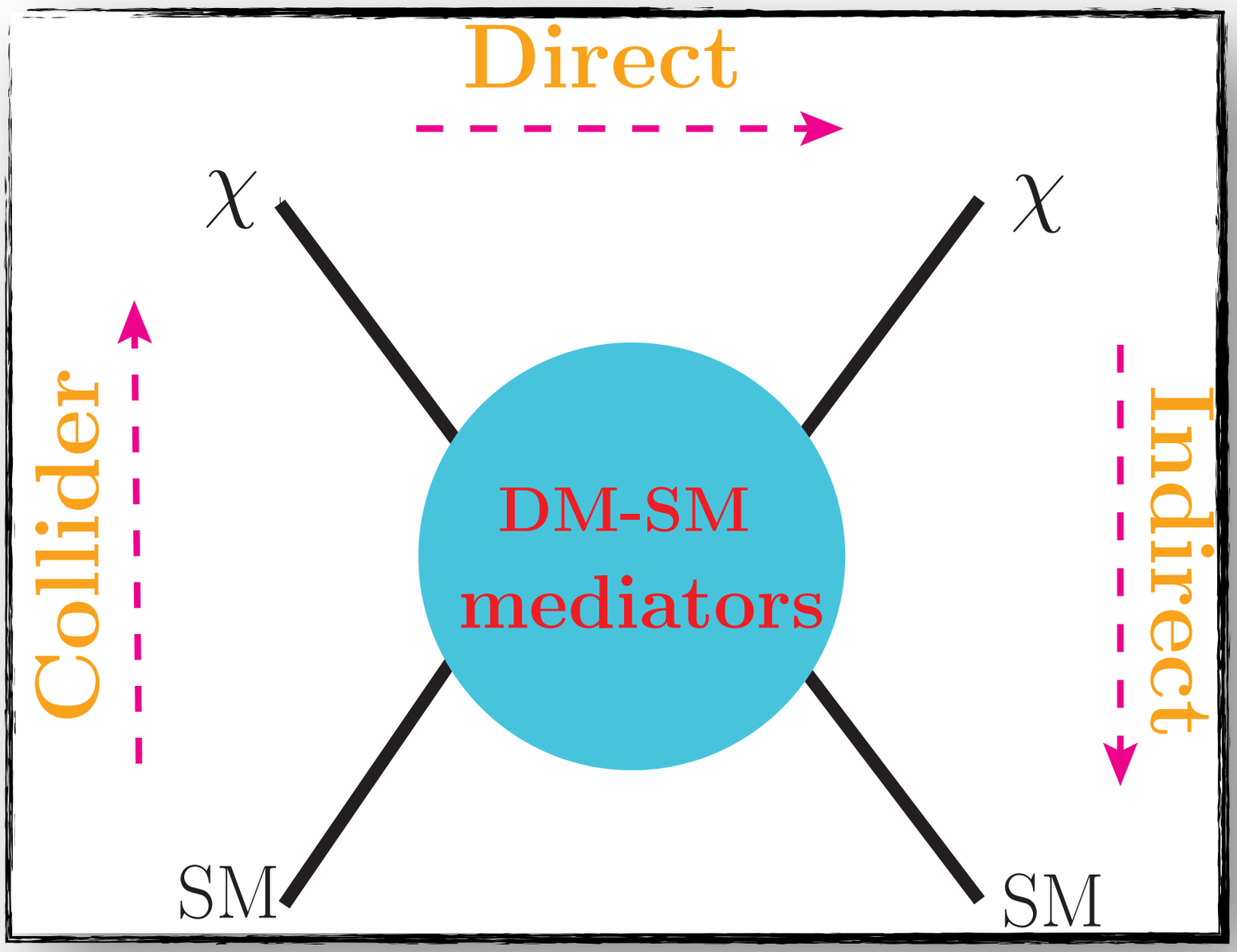
✓Color Force does not appear

✓Massive

✓Stable

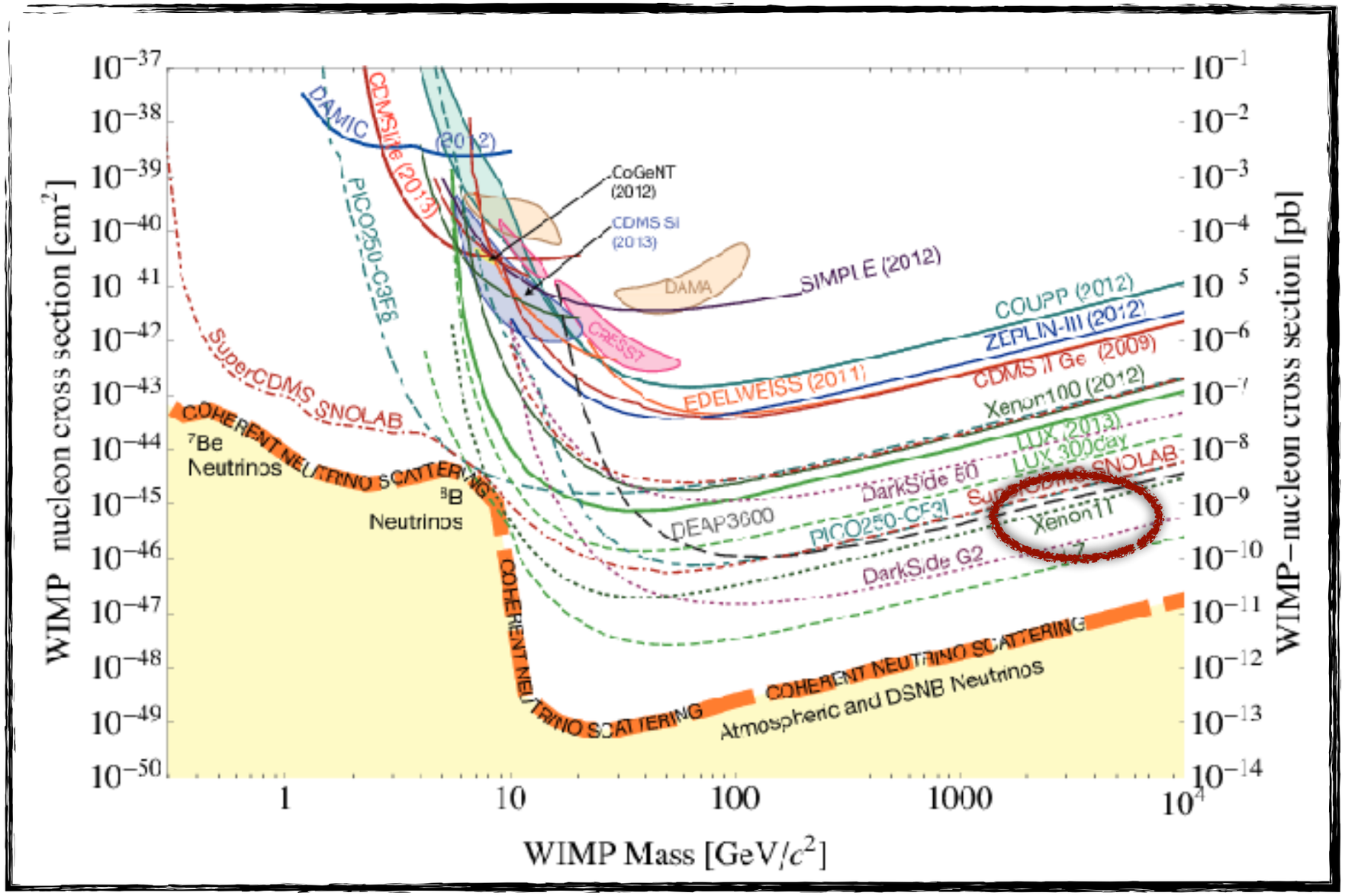
Dark Matter Introduction

✤Detection Methods



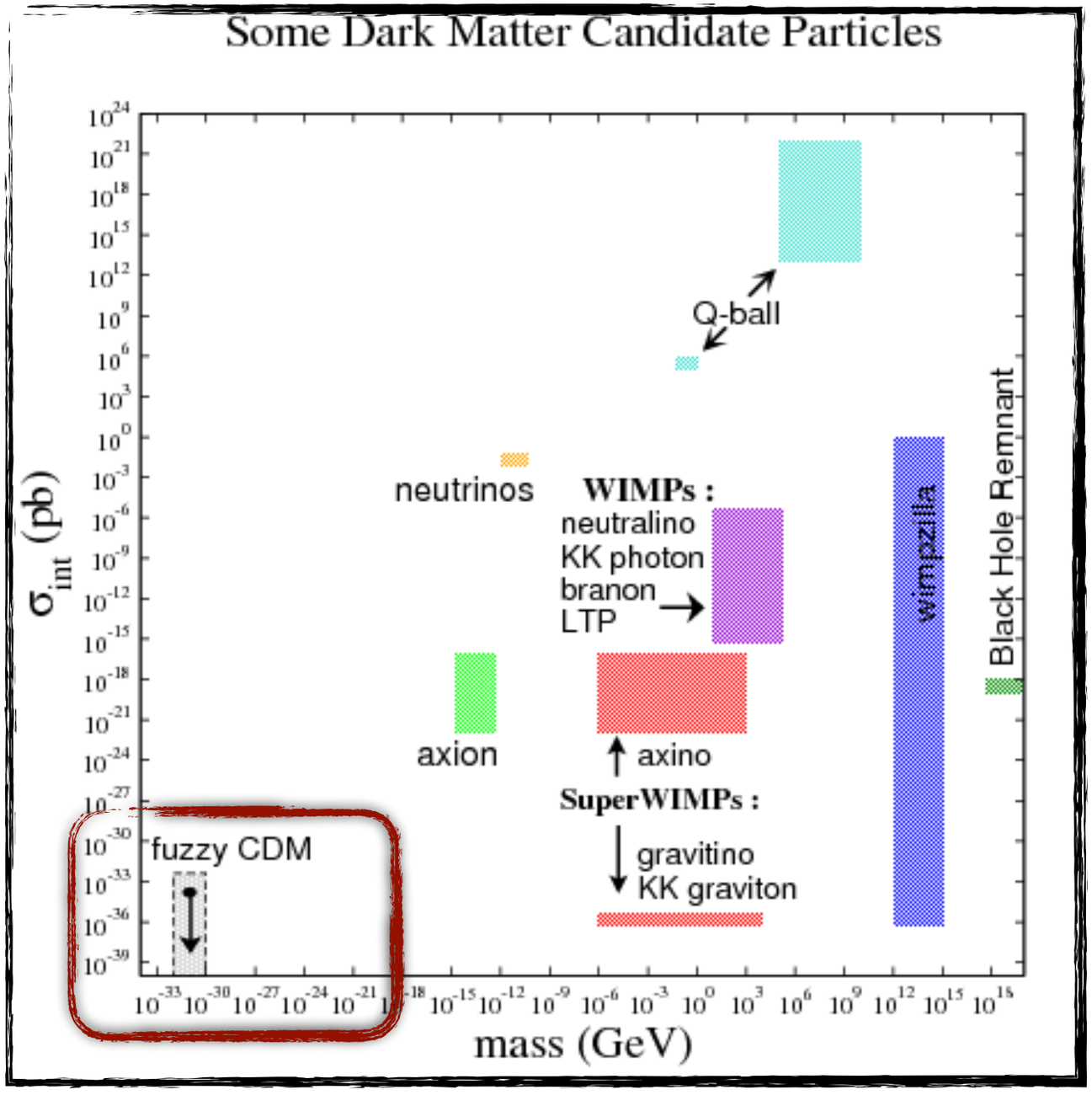
Dark Matter Introduction

✤Detection Results



Dark Matter Introduction

✤Other possibility of Dark Matter Candidate



Fuzzy Dark Matter

✤Cusp vs Core problem

✓Parameterize density profile as $\rho(r) \propto r^{-\alpha}$. Observation shows $\alpha \sim 0$, but simulation predict $1 \leq \alpha \leq 1.5$

✤Missing satellites problem

✓Milky Way seems to have fewer satellite galaxies (23) than expected in CDM simulations (~100-1000)

✤Too big to fail problem

✓Predict more subhalos (5-40) with vmax > 25 km/s than observed (~0).

Dark matter search

Dark Portal:

★ Vector Portal: $B_{\mu\nu}Z'^{\mu\nu}$

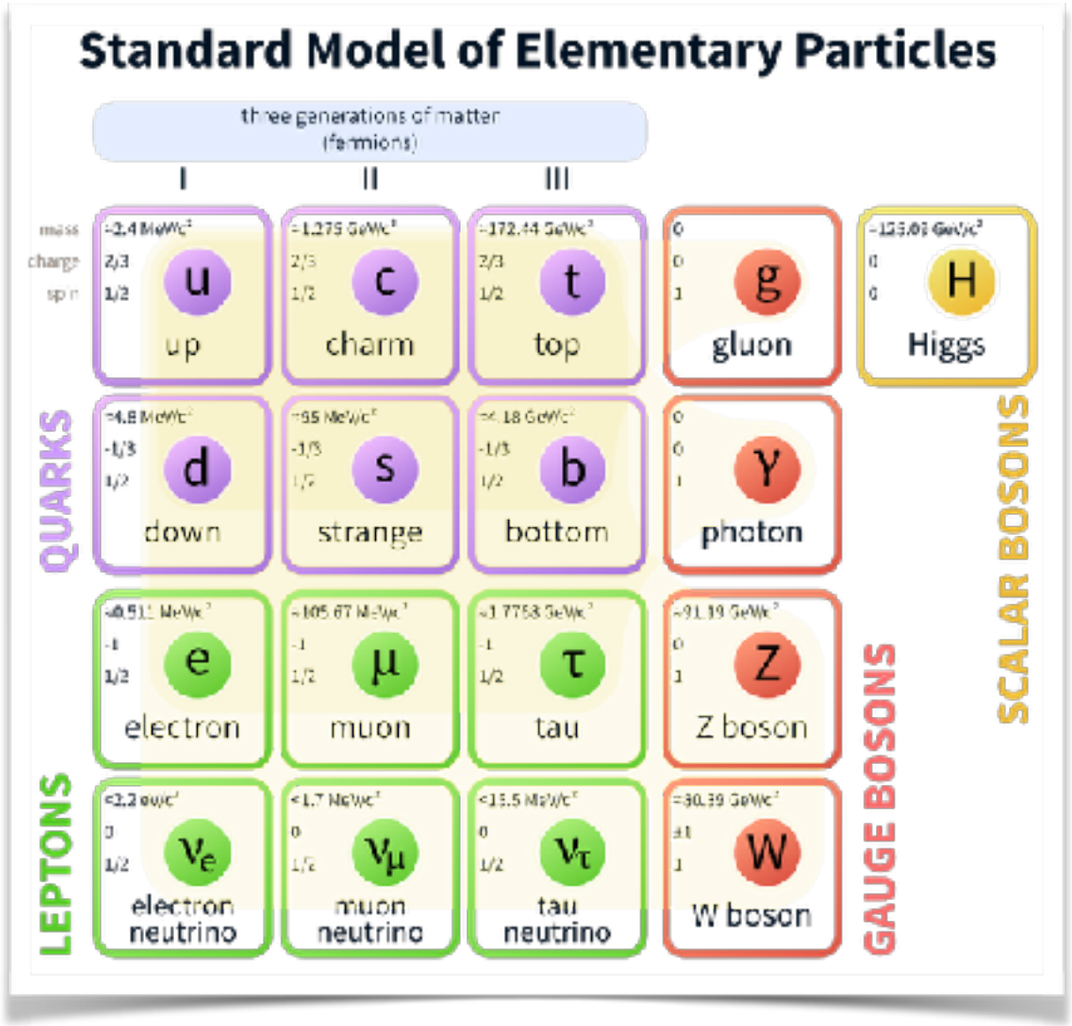
★ Higgs Portal: $S^2 H^\dagger H$

★ Axion portal: $\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$

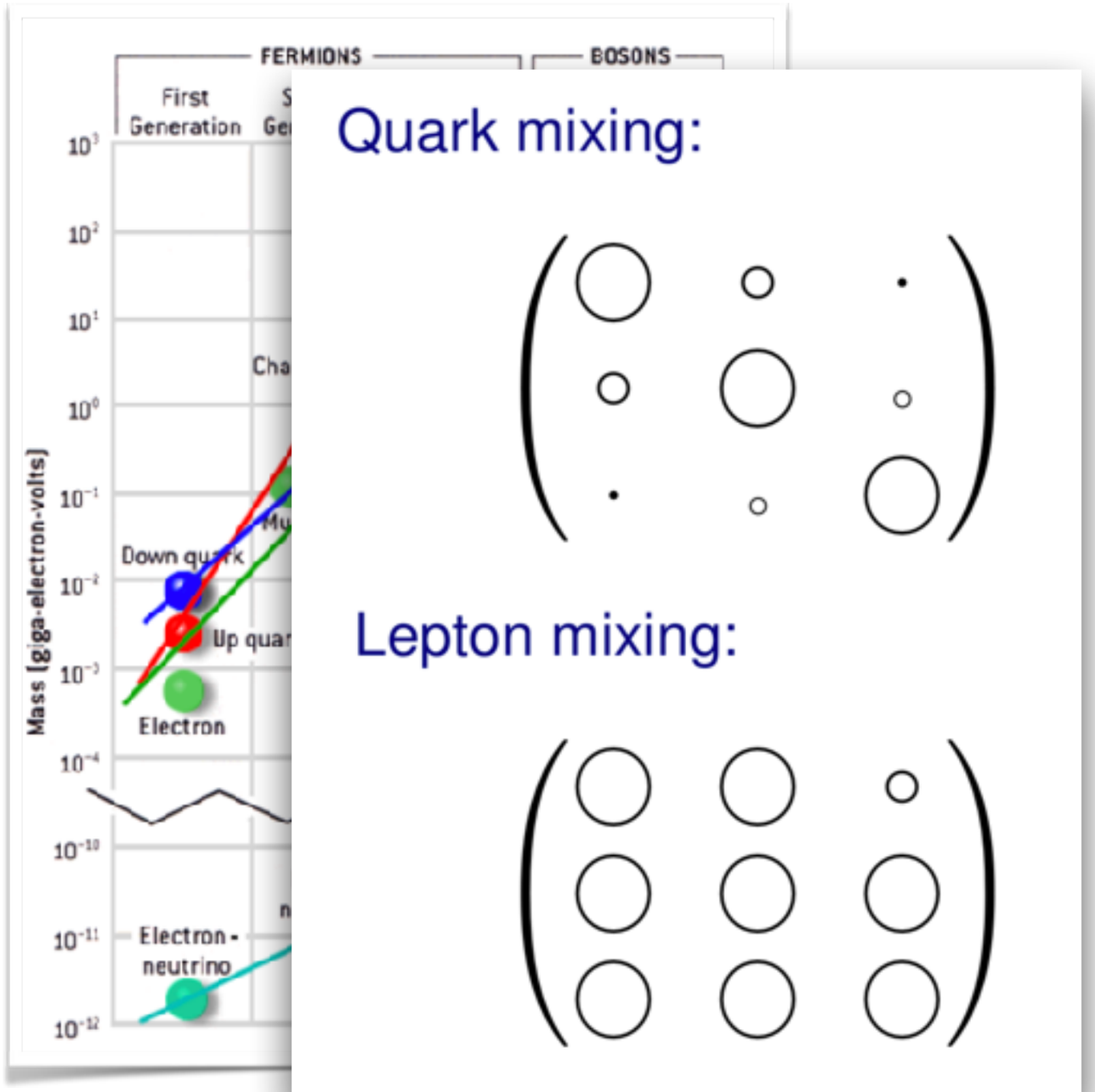
★ Neutrino Portal: LHN

Neutrino Introduction

✤ Look at SM, there are lots of unexplained structure:



Courtesy from Joachim Kopp



Neutrino Introduction

✤ Neutrino Mass

$$\mathcal{L}_{\text{seesaw}} = \lambda_i \bar{L} H N_R + m_M \bar{N}_R^c N_R$$

✓Mass Matrix: $M = \begin{pmatrix} 0 & m_D \\ m_D & m_M \end{pmatrix}$ $m_D = \lambda_i v$

✓Mass Eigenstates: $\begin{pmatrix} \nu_L \\ N_R^c \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \tilde{\nu}_L \\ \tilde{N}_R^c \end{pmatrix}$ $\sin\theta \simeq \frac{m_D}{m_M}$

✓Interesting neutrino mass: $m_1 \simeq \frac{m_D^2}{m_M}$

✓Effective Lagrangian:

$$\mathcal{L}_{\text{seesaw}} = \lambda_i \sin\theta\cos\theta \bar{\tilde{\nu}}_L^{c,i} h \tilde{\nu}_L^i - \lambda_i \sin\theta\cos\theta \bar{\tilde{N}}_R^c h \tilde{N}_R + m_{\tilde{\nu}_L} \bar{\tilde{\nu}}_L^c \tilde{\nu}_L + m_{\tilde{N}_R^c} \bar{\tilde{N}}_R^c \tilde{N}_R$$

Neutrino Introduction

✤ Neutrino Oscillation in vacuum

✓Mass eigenstates to flavor eigenstates: $|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} \, |\nu_j\rangle$

✓Wave function at L and T: $|\nu_\alpha(T,L)\rangle = \sum_j U^*_{\alpha j} e^{-iE_jT+ip_jL} \, |\nu_j\rangle$

✓The Amplitude: $\langle\nu_\beta|\nu_\alpha(T,L)\rangle = \sum_j U^*_{\alpha j} U_{\beta j} e^{-iE_jT+ip_jL}$

✓Oscillation Probability: $P_{\alpha\beta}(T,L) = |\langle\nu_\beta|\nu_\alpha(T,L)\rangle|^2$

✓In a typical experiment:

$$P_{\alpha\beta}(L) = \frac{1}{N}\int dT P_{\alpha\beta}(T,L) \simeq \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \exp\left[-i\frac{\Delta m^2_{jk} L}{2E}\right]$$

Neutrino Introduction

$$P_{\alpha\beta}(L) = \simeq \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \exp \left| -i \frac{\Delta m^2_{jk} L}{2E} \right.$$

✤ Neutrino Oscillation for two flavor case:

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \quad \Rightarrow \quad P_{2-\text{flavor}}(L) = \sin^2 2\theta \sin^2 \left[\frac{\Delta m^2 L}{4E} \right]$$

✓Massless neutrinos lead to $P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta}$

✓Flavor change has no relationship to matter effect

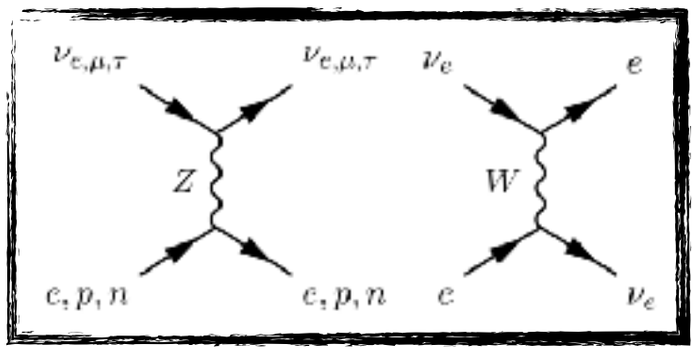
✓If there is no mixing, then $P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta}$

✓Oscillations depends on square mass splitting

Neutrino Introduction

✤ Neutrino Oscillation in matter

$$\mathcal{H} \supset -\sum_{\alpha=e,\mu,\tau}\left[\frac{g}{\sqrt{2}}\left(\overline{\nu_{\alpha,L}}\gamma^{\mu}e_{\alpha,L}W_{\mu}^{+}+h.c.\right)+\frac{g}{2\cos\theta_{w}}\overline{\nu_{\alpha,L}}\gamma^{\mu}\nu_{\alpha,L}Z_{\mu}\right]$$



$$\mathcal{H}_{\text{eff}} \supset \frac{g^2}{2M_W^2}\left[\overline{\nu_{e,L}}\gamma^{\mu}e_L\right]\left[\overline{e_L}\gamma^{\mu}\nu_{e,L}\right] = \frac{G_F}{\sqrt{2}}\left[\overline{e}\gamma^{\mu}(1-\gamma^5)e\right]\left[\overline{\nu_e}\gamma^{\mu}(1-\gamma^5)\nu_e\right]$$

$$\supset \frac{G_F}{\sqrt{2}}\left\langle\overline{e}\gamma^{\mu}(1-\gamma^5)e\right\rangle\left[\overline{\nu_e}\gamma^{\mu}(1-\gamma^5)\nu_e\right] = \underbrace{\sqrt{2}G_F n_e}_{\equiv V_{CC}}\,\overline{\nu_{eL}}\gamma^0\nu_{eL}$$

$$V_W = \sqrt{2}G_F n_e \qquad V_Z = -\frac{\sqrt{2}}{2}G_F n_{(n,p,e)}$$

Neutrino Introduction

$$V_W = \sqrt{2} G_F n_e \qquad V_Z = -\frac{\sqrt{2}}{2} G_F n_{(n,p,e)}$$

✤ Matter effect on neutrino oscillation

$$\mathcal{H}_M = \frac{\Delta m^2}{4E} \begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} + (V_W + V_Z) I_{2\times 2} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \frac{V_W}{2} & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta - \frac{V_W}{2} \end{pmatrix}$$

$$= \frac{\Delta m^2_M}{4E} \begin{pmatrix} -\cos 2\theta_M & \sin 2\theta_M \\ \sin 2\theta_M & \cos 2\theta_M \end{pmatrix}$$

✤The oscillation probability

$$P^M_{\alpha\to\beta} = \sin^2 2\theta_M \sin^2 \left[\Delta m^2_M \frac{L}{4E}\right]$$

Experiments

✓Long Baseline:

Past | Current | Future

K2K
KEK to Kamioka
250 km, 5 kW

~10GeV

~GeV

MINOS (+)
FNAL to Soudan
734 km, 400 kW

CNGS
CERN to LNGS
730 km, 400 kW

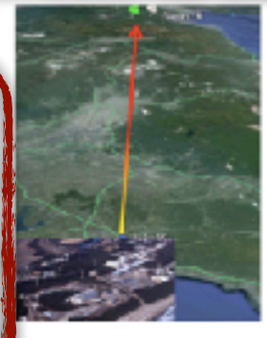
~20GeV

NOνA
FNAL to Ash River
810 km, 700 kW

T2K
J-PARC to Kamioka
295 km, 380-750 kW

~0.6GeV

LBNF/DUNE ~GeV
FNAL to Homestake
1300 km, 1.2 MW (➔2.3 MW)



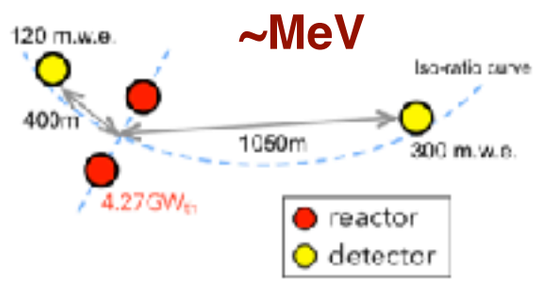
Hyper-K
J-PARC to Kamioka
295 km, 750 kW
(➔..)

~0.01GeV

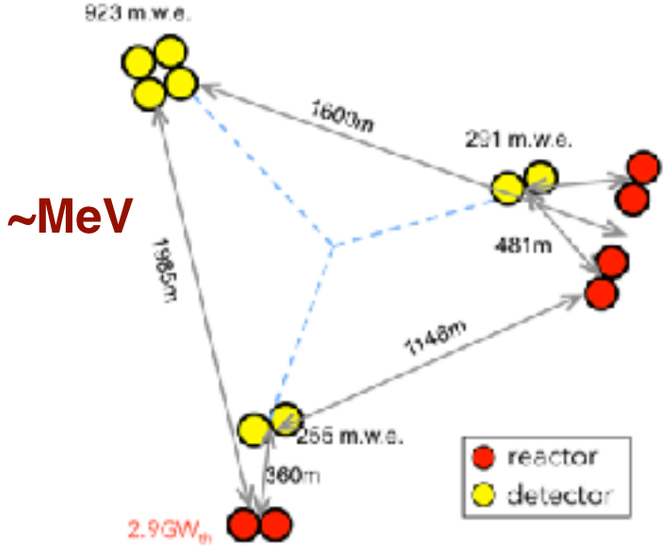
Experiments

✓Reactor & Short Baseline:

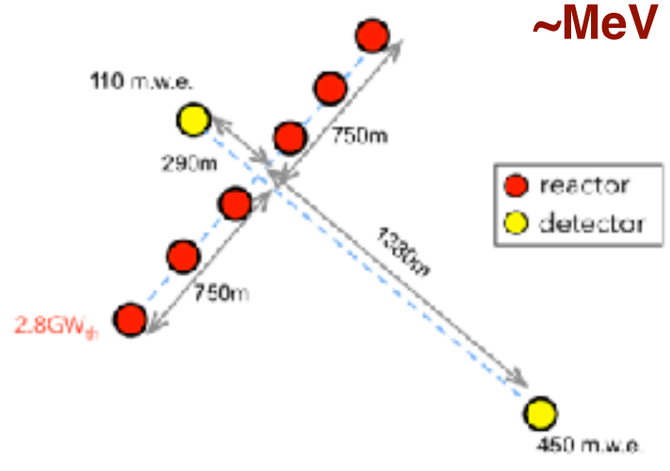
Double Chooz (France)



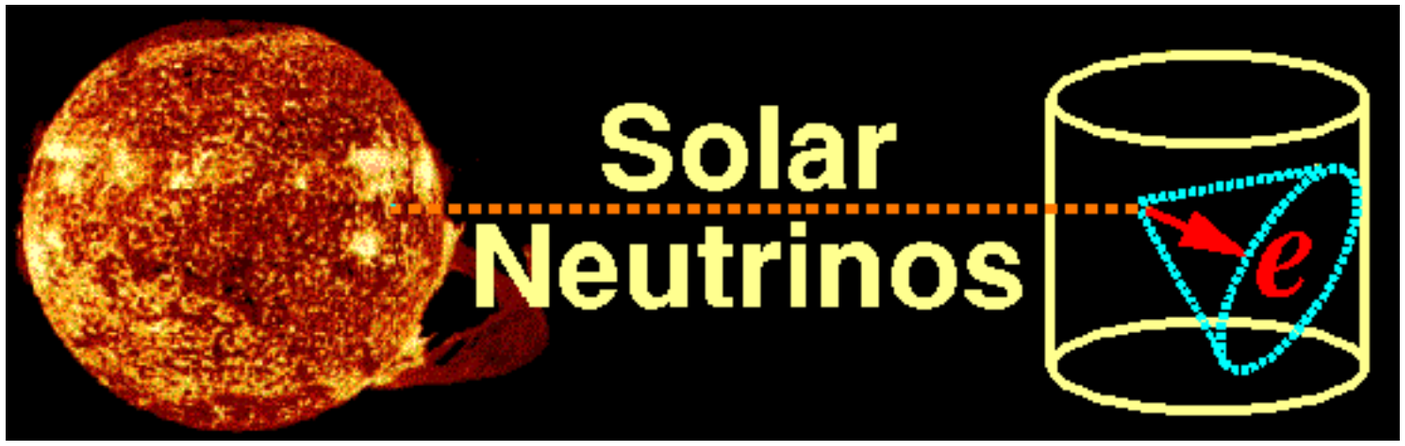
Daya Bay (China)

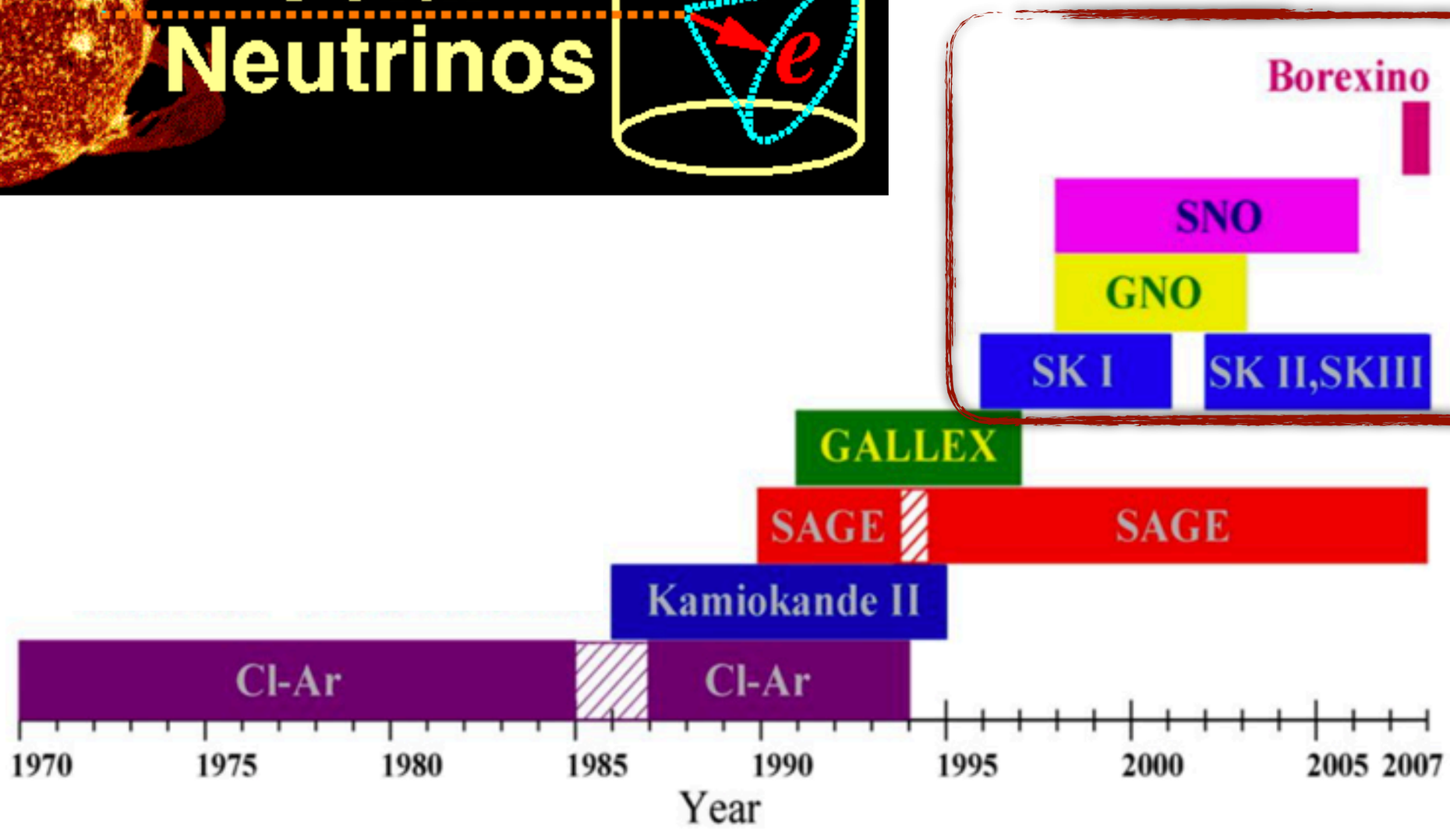


RENO (Korea)

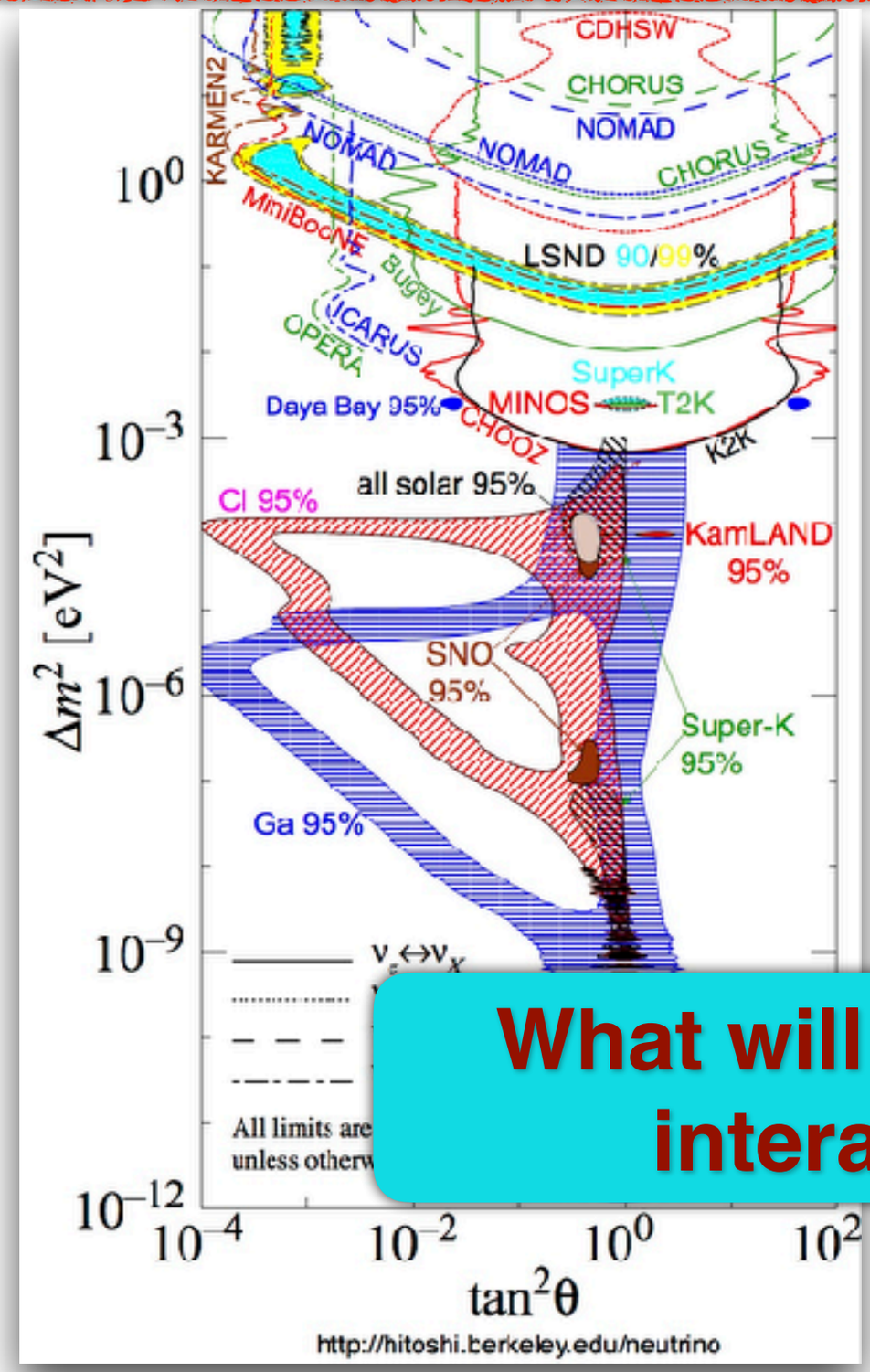


Experiments





Experiment Situation



"Atmospheric Oscillations"

- ✓ $\nu_\mu \to \nu_\tau$ Oscillations .
- ✓ $\Delta m^2_{23} = \left(2.50^{+0.09}_{-0.16}\right) \times 10^{-3}\mathrm{eV}^2$.
- ✓ $\sin^2\theta_{23} \simeq 0.52^{+0.06}_{-0.07}$.
- ✓ Observed in Super-K, K2K, Minos,T2K,.....

"Solar Oscillations"

- ✓ $\nu_e \to \nu_\mu, \nu_\tau$ Oscillations .
- ✓ $\Delta m^2_{21} = \left(7.59^{+0.20}_{-0.18}\right) \times 10^{-5}\mathrm{eV}^2$.
- ✓ $\sin^2\theta_{12} = 0.312^{+0.017}$

mLAND

What will happen if dark matter also interact with neutrino as W?

Review of recent works

✤ Asher Berlin; arXiv:1609.02555 [Phys.Rev.Lett. 117 (2016)]

$$-\mathcal{L} \supset \frac{1}{2}\, m_\phi^2\, \phi^2 + \frac{1}{2}\, m_i\, \bar{\nu}_i\, \nu_i + g_\phi\, \phi\, \bar{\nu}_1\, \nu_2 + \cdots$$

$$\sin\theta_{12}(t) \simeq \sin\theta_{12} + \frac{\cos\theta_{12}}{\Delta m_{12}}\, \frac{g_\phi \sqrt{2\,\rho_{\rm DM}}}{m_\phi}\, \cos m_\phi\, t$$

$$\Phi_{\rm eff} \equiv \Phi\left(P_{\nu_e}^{\odot} + \left(1 - P_{\nu_e}^{\odot}\right) \frac{\sigma_{\mu,\tau}}{\sigma_e}\right) = \Phi^{(0)} + \Phi^{(1)} \cos m_\phi t$$

✤Gordan Krnjaic, Pedro A. N. Machado, Lina Necib; arXiv:1705.06740

$$\mathscr{L}_{\rm eff} = -m_\nu \left(1 + y\frac{\phi}{\Lambda}\right) \nu\nu + h.c.$$

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

✤Jiajun Liao, Danny Marfatia, Kerry Whisnant; arXiv: 1803.01773

✤.....

✓Mark B. Wise, Yue Zhang; arXiv: 1803.00591 $\dfrac{V_{\rm eff}}{\sqrt{2} G_F n_e}$

Ultralight Bosonic Dark Matter

✤ Scalar DM model

$$\mathcal{L}_{\rm scalar} = \bar{\nu}_L^\alpha i\gamma^\rho \partial \nu_L^\alpha - \tfrac{1}{2} m_\nu^{\alpha\beta} \overline{(\nu_L^c)^\alpha} \nu_L^\beta - \tfrac{1}{2} y^{\alpha\beta} \phi \, \overline{(\nu_L^c)^\alpha} \nu_L^\beta$$

✤ Vector DM model

$$\mathcal{L}_{\rm vector} = \bar{\nu}_L^\alpha i\gamma^\rho \partial \nu_L^\alpha - \tfrac{1}{2} m_\nu^{\alpha\beta} \overline{(\nu_L^c)^\alpha} \nu_L^\beta + g Q^{\alpha\beta} \phi^\mu \bar{\nu}_L^\alpha \gamma_\mu \nu_L^\beta$$

Scalar Dark Matter

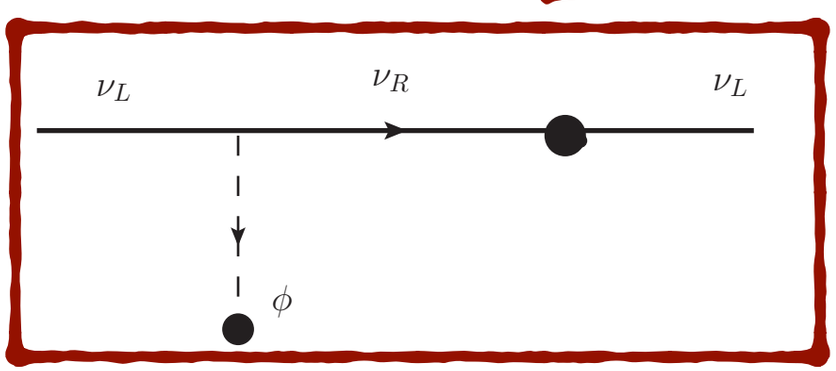
$$\mathcal{L}_{\rm scalar} = \bar{\nu}_L^\alpha i\gamma^\rho \partial \nu_L^\alpha - \tfrac{1}{2} m_\nu^{\alpha\beta} \overline{(\nu_L^c)^\alpha} \nu_L^\beta - \tfrac{1}{2} y^{\alpha\beta} \phi \, \overline{(\nu_L^c)^\alpha} \nu_L^\beta$$

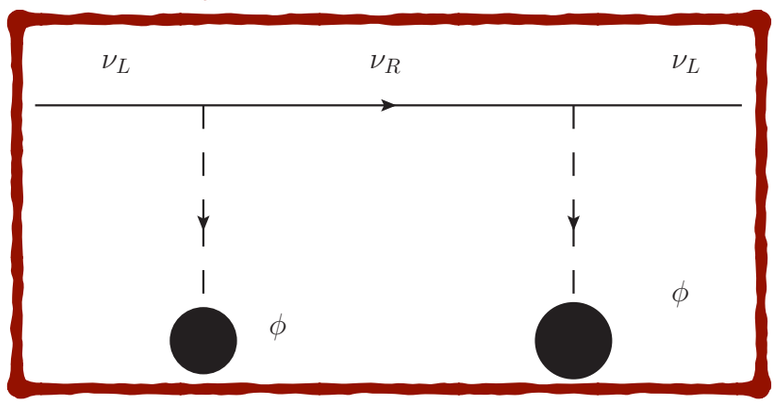
✓ **Dispersion relation**

$$(E_\nu - V_{\rm eff})^2 = \vec{p}_\nu^{\,2} + m_\nu^2$$

$$m_\nu^2 \sim y \phi m_\nu$$

$$V_{\rm eff} = \frac{1}{2E_\nu}\Big(\phi\,(y\,m_\nu + m_\nu\,y) + \phi^2 y^2\Big)$$





Scalar Dark Matter

$$V_{\rm eff} = \frac{1}{2E_\nu}\Big(\phi\,(y\,m_\nu + m_\nu\,y) + \phi^2 y^2\Big)$$

✓ Dark Matter Production - misalignment

$$\partial_t\partial_t\phi + 3H\partial_t\phi + m^2\phi^2 = 0$$

$$\phi = \phi_0\cos(m_\phi t)$$

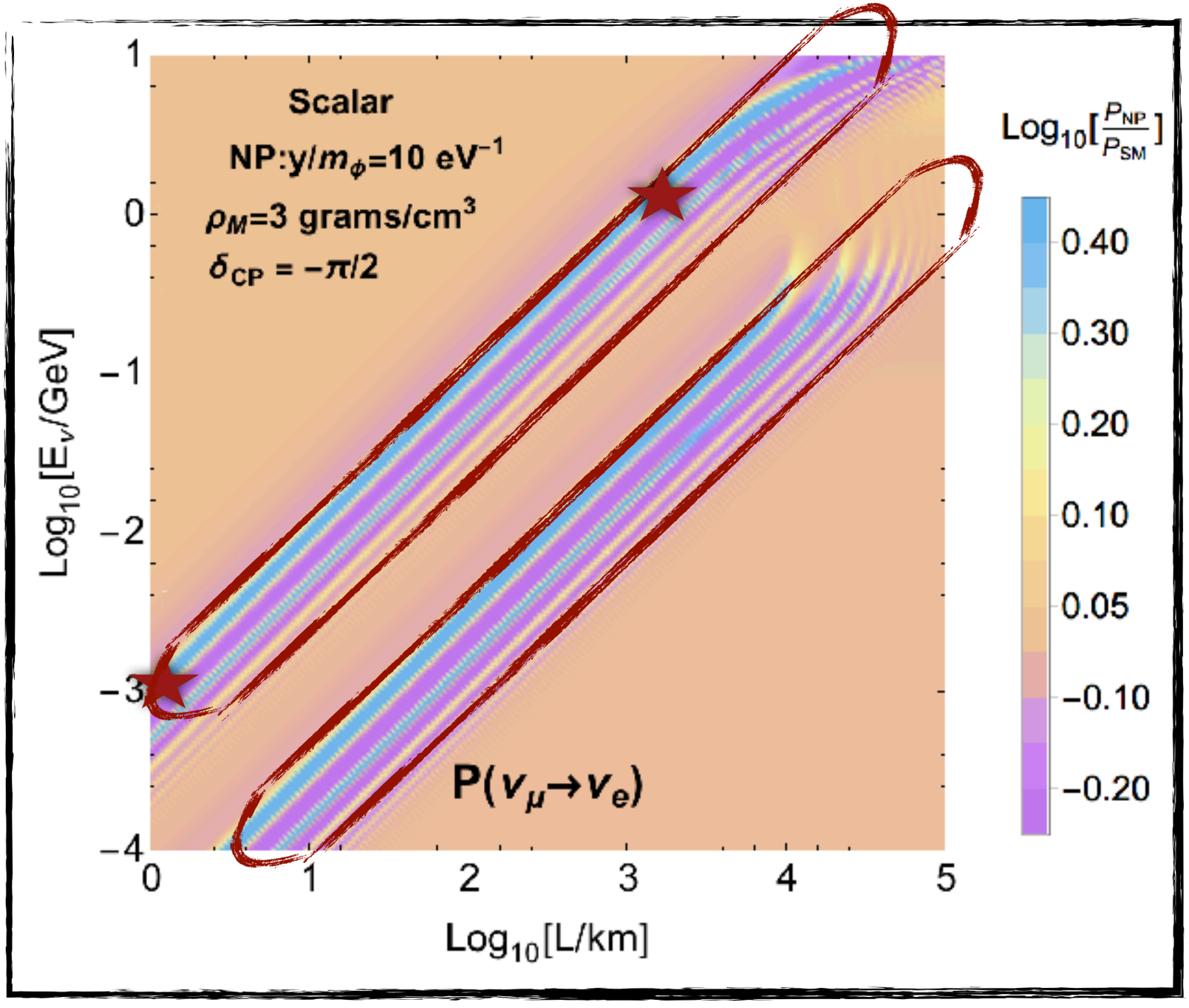
✓Local density 0.3 GeV/cm^3

$$\rho_\phi = \frac{1}{2}m_\phi^2\phi_0^2 \qquad \xrightarrow{\quad m_\nu^2 \sim y\phi m_\nu \quad} \qquad \frac{y}{m_\phi} \sim \frac{m_\nu}{\sqrt{2\rho_\phi}} \sim 10\ \mathrm{eV}^{-1}$$

✓ Expansion on probability

$$P_{\alpha\beta} = P_0 + P_1\cos(m_\phi t) + P_2\cos^2(m_\phi t)$$

Oscillation of Scalar Dark Matter



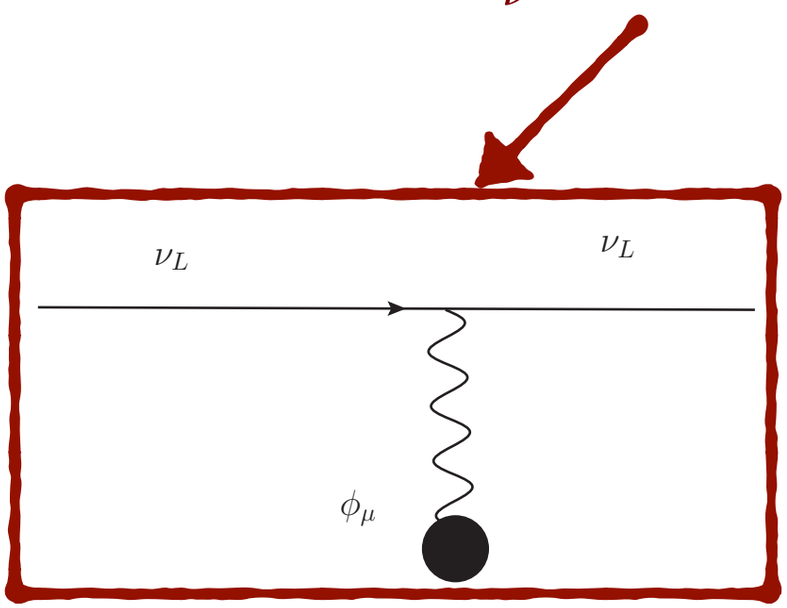
Vector Dark Matter

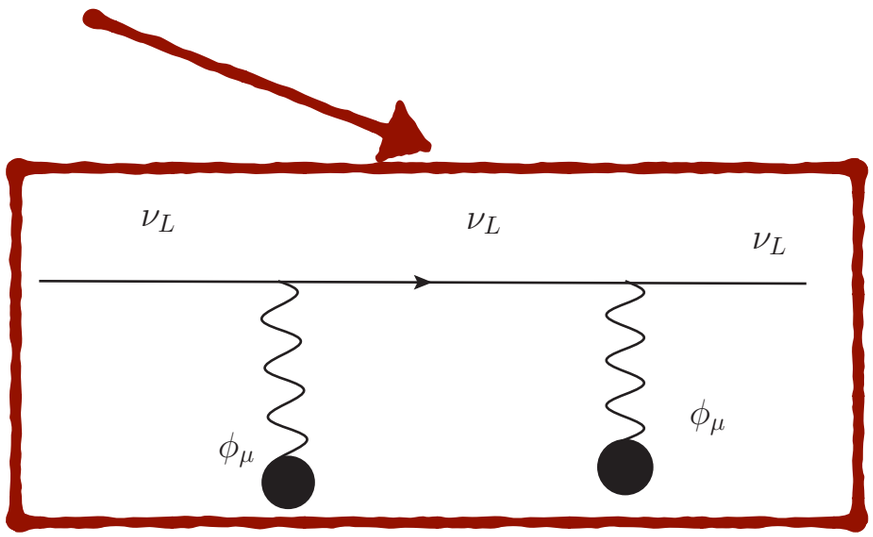
$$\mathcal{L}_{\rm vector} = \bar{\nu}_L^\alpha i\gamma^\rho \partial \nu_L^\alpha - \tfrac{1}{2} m_\nu^{\alpha\beta} \overline{(\nu_L^c)^\alpha} \nu_L^\beta + gQ^{\alpha\beta}\phi^\mu \bar{\nu}_L^\alpha \gamma_\mu \nu_L^\beta$$

✓ **Dispersion relation**

$$(E_\nu - V_{\rm eff})^2 = \vec{p}_\nu^{\,2} + m_\nu^2$$

$$V_{\rm eff} = -\frac{1}{2E_\nu}\Big(2(p_\nu \cdot \phi) gQ + g^2 Q^2 \phi^2\Big)$$





Vector Dark Matter

$$V_{\rm eff} = -\frac{1}{2E_\nu}\Big(2(p_\nu \cdot \phi)gQ + g^2Q^2\phi^2\Big) \qquad \sim \frac{m_\nu^2}{E_\nu}$$

✓ Dark Matter Production-quantum fluctuations during inflation(Longitudinal)

$$\phi^\mu = \phi_0 \xi^\mu \cos(m_\phi t)$$

✓Local density 0.3 GeV/cm^3

$$\rho_\phi = \frac{1}{2} m_\phi^2 \phi_0^2$$

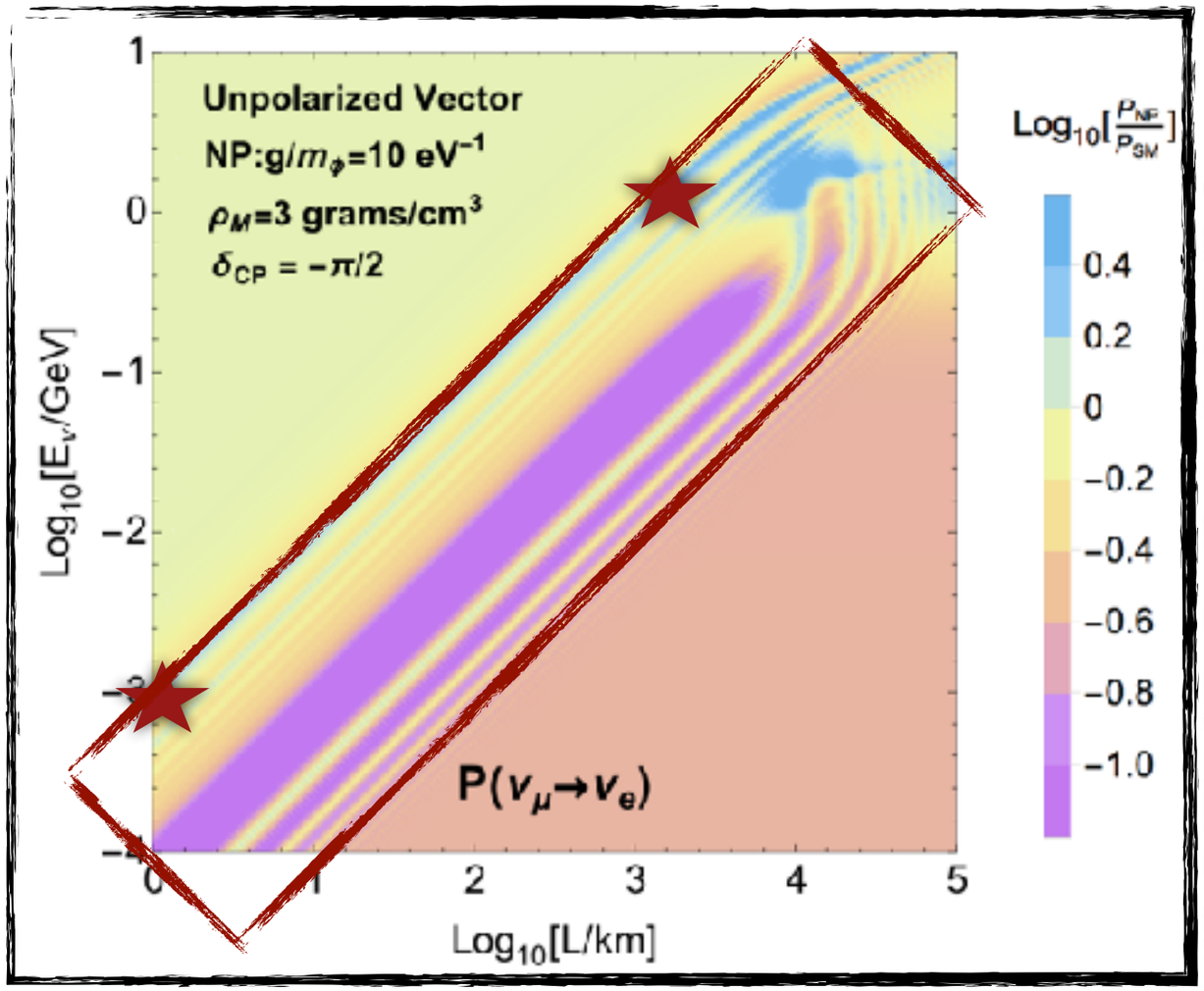
$E_\nu \phi g \sim m_\nu^2$ → $\frac{g}{m_\phi} \simeq \frac{10}{E_\nu}$

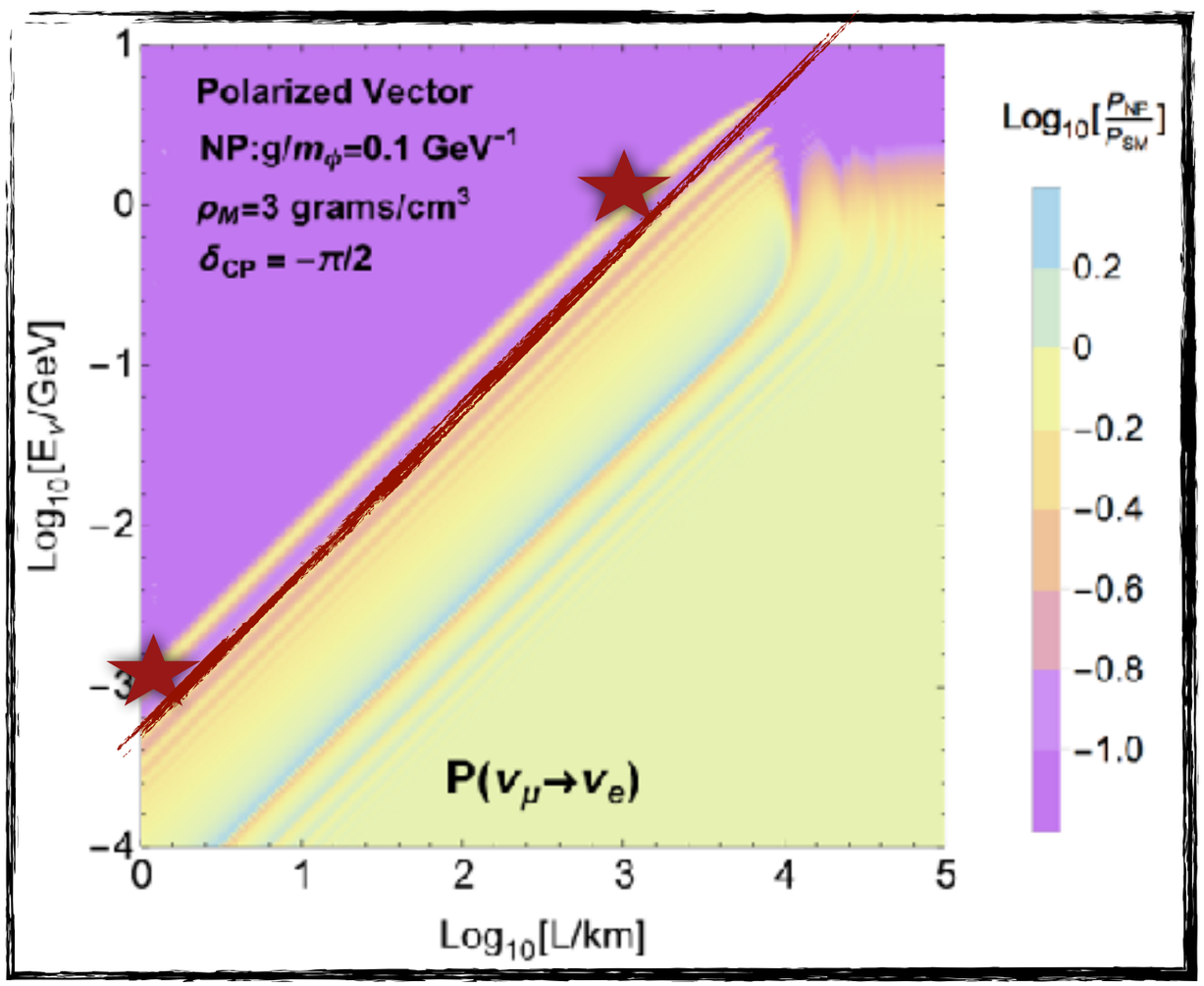
$g^2\phi^2 \sim m_\nu^2$ → $\frac{g}{m_\phi} \simeq 10\ \mathrm{eV}^{-1}$

✓ Expansion on probability

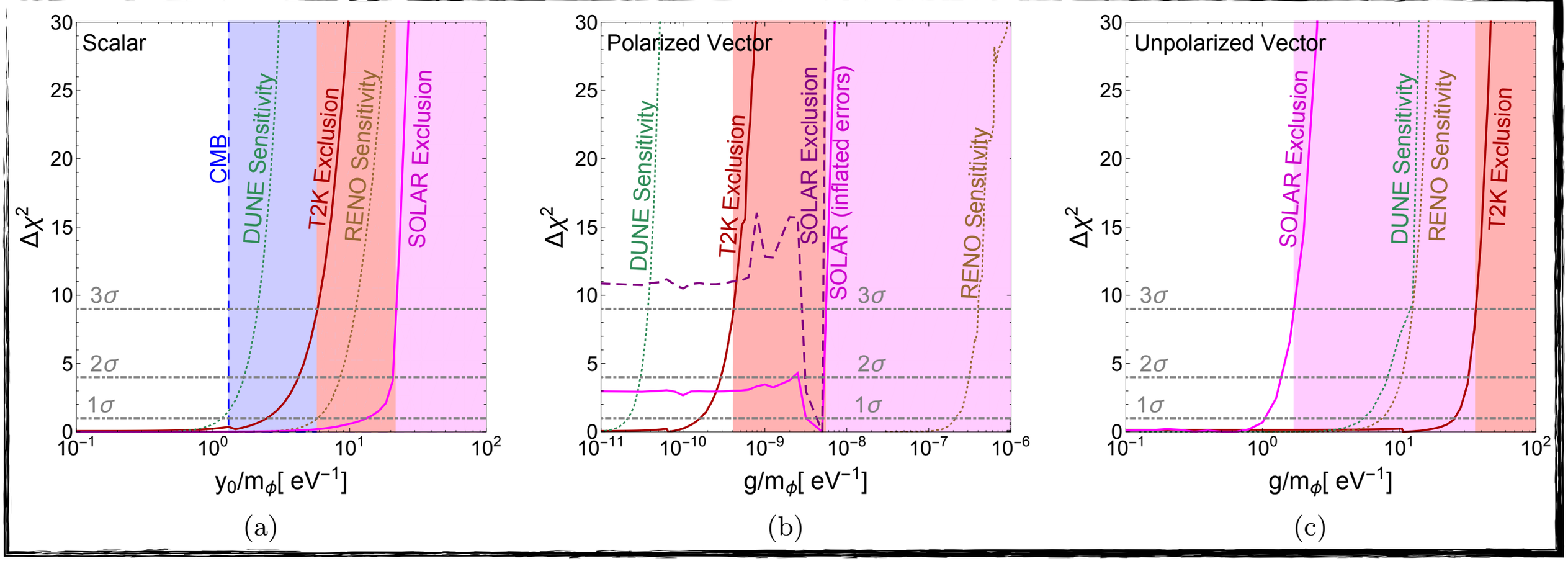
$$P_{\alpha\beta} = P_0 + P_1 \cos(m_\phi t) + P_2 \cos^2(m_\phi t)$$

Oscillation of Vector Dark Matter





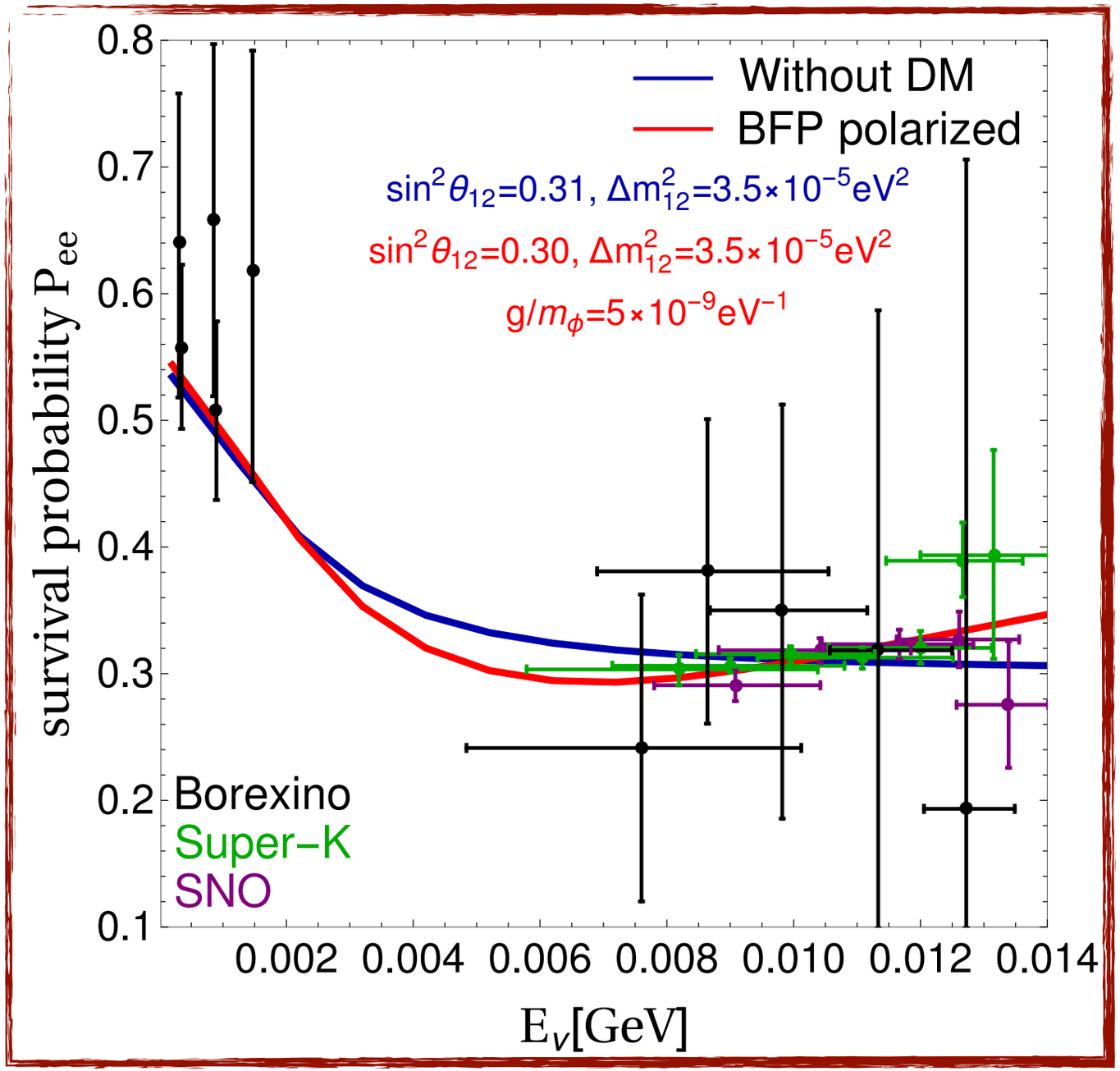
Results from Simulation



(a) (b) (c)

Solar Neutrino Results

✓Survival probability $P_{ee}(E_\nu) = \sum_i |U_{ei}^{\odot}|^2 \, |U_{ei}^{\oplus}|^2$



Other Constraints

✓Cosmological Constraints (CMB)

$$\sum m_\nu \leq 0.1eV$$

$$y\phi_0(1+z)^3 \sim m_\nu$$

$$\phi_0 = \frac{\sqrt{2\rho_c\Omega}}{m_\phi}$$

$$\Rightarrow \quad \frac{y}{m_\phi} \sim 1.3\ \mathrm{eV}^{-1}$$

✓Astrophysical Neutrinos: $\tau_\nu(E_\nu) = \sigma_{\nu\phi}(E_\nu) X_\phi m_\phi^{-1} < 1$

$$\frac{y}{m_\phi} < 1.3 \cdot 10^{11}\,\mathrm{eV}^{-1} \left(\frac{m_\nu}{0.1\,\mathrm{eV}}\right)^{\frac{1}{2}} \left(\frac{10^{-22}\,\mathrm{eV}}{m_\phi}\right)^{\frac{3}{4}} \qquad \text{(Scalar DM)}$$

$$\frac{g}{m_\phi} < 3 \cdot 10^{8}\,\mathrm{eV}^{-1} \left(\frac{E_\nu}{\mathrm{PeV}}\right)^{\frac{1}{2}} \left(\frac{0.1\,\mathrm{eV}}{m_\nu}\right)^{\frac{1}{2}} \left(\frac{10^{-22}\,\mathrm{eV}}{m_\phi}\right)^{\frac{1}{4}} \qquad \text{(Vector DM)}$$

Summary

- We introduce ultralight bosonic DM and non-standard interaction with neutrinos

- Stringent constraints from oscillation:

  - ✓ Scalar, unpolarized Vector: y/m <~ eV^-1

  - ✓ Polarized Vector: y/m<~10^-10 eV^-1

- Linear term apply when classic field description holds, #>>1 (m<10^-16 eV, if neutrino coherent length L ~ 10^-10m)

- Quadratic term always applies (QFT forward scattering), valid for any DM mass

Any Questions?