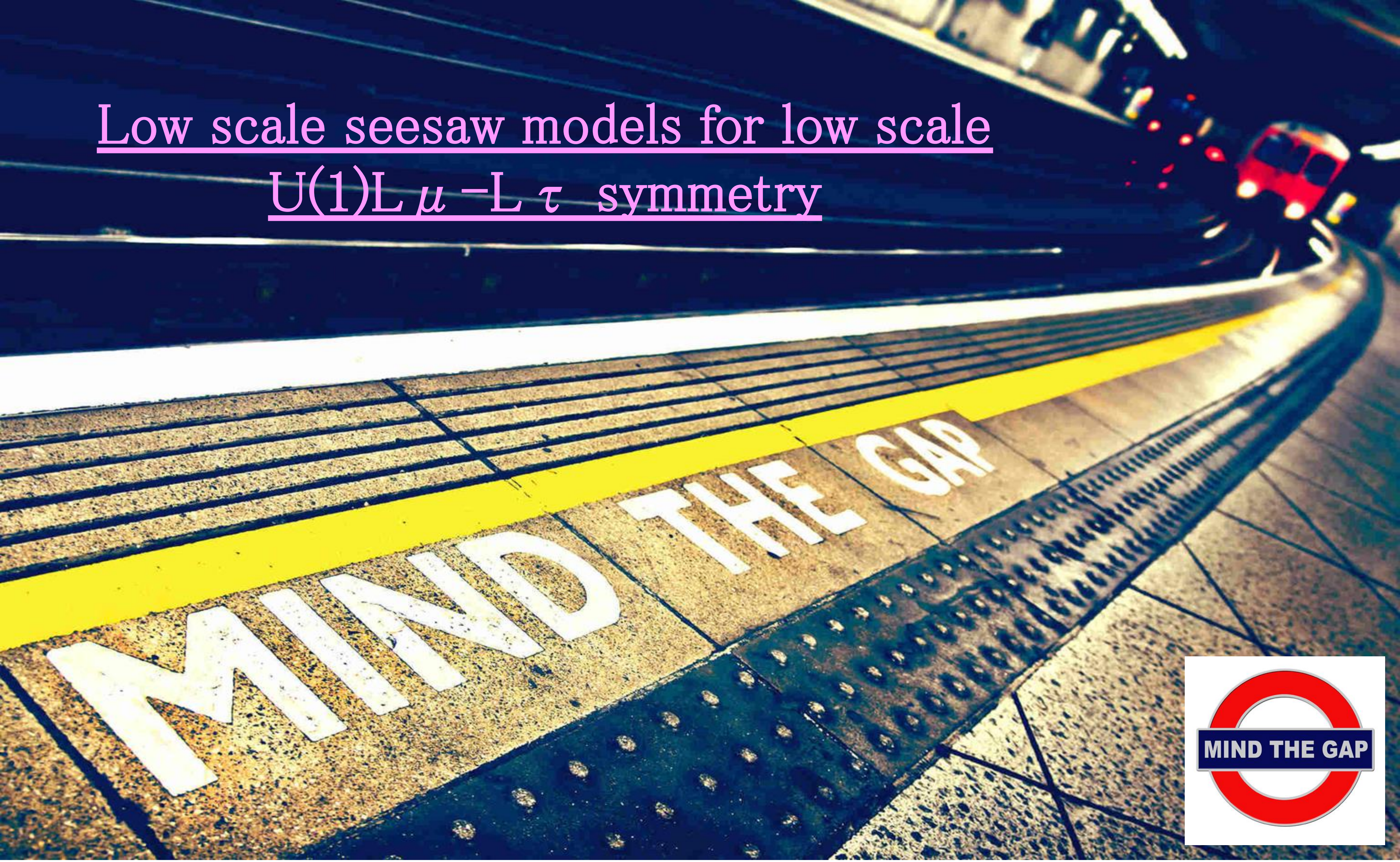
Low scale seesaw models for low scale U(1)$L_\mu - L_\tau$ symmetry



Joe Sato (Saitama U.)

Based on PRD91, 037301 and PRD93, 013014、PRD100, 095012.

Collaboration with T. Araki, K.Asai, F. Kaneko, Y. Konishi, T. Ota, T. Shimomura.

Outline

- Introduction
- IceCube Gap and U(1)$L_\mu - L_\tau$ model

  PRD 91 & 93
- UV completion of U(1)$L_\mu - L_\tau$

  PRD 100
- Summary

Introduction

Motivations of $U(1)_{L\mu - L\tau}$

New U(1) force acting on only μ and τ flavor leptons.

	e, ν_e	μ, ν_μ	τ, ν_τ	others
$U(1)_{L\mu - L\tau}$	0	+1	−1	0

Motivated by

Muon g−2 problem,
Energy spectrum of cosmic neutrinos (IceCube),
Flavor puzzles in the lepton sector,
etc.

Muon g−2

Longstanding discrepancy between experiments and theory:

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = 26.1(8.0) \times 10^{-10}$$

3.3 σ

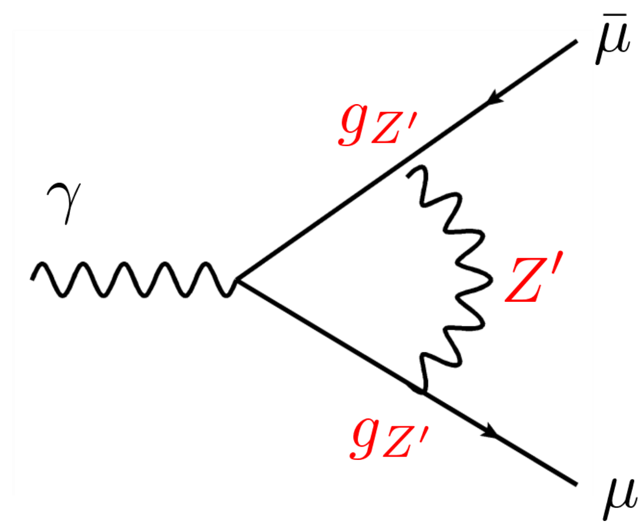
[Hagiwara, Liao, Martin, Nomura, Teubner, JPG38, 085003 (2011)]

In the $U(1)_{L_\mu - L_\tau}$ model, we have an additional contribution:

$$a_\mu^{\rm EXP} - (a_\mu^{\rm SM} + \underline{a_\mu^{Z'}})$$

$$a_\mu^{Z'} = \frac{g_{Z'}^2}{8\pi^2} \int_0^1 \frac{2m_\mu^2 x^2 (1-x)}{x^2 m_\mu^2 + (1-x) m_{Z'}^2} dx$$

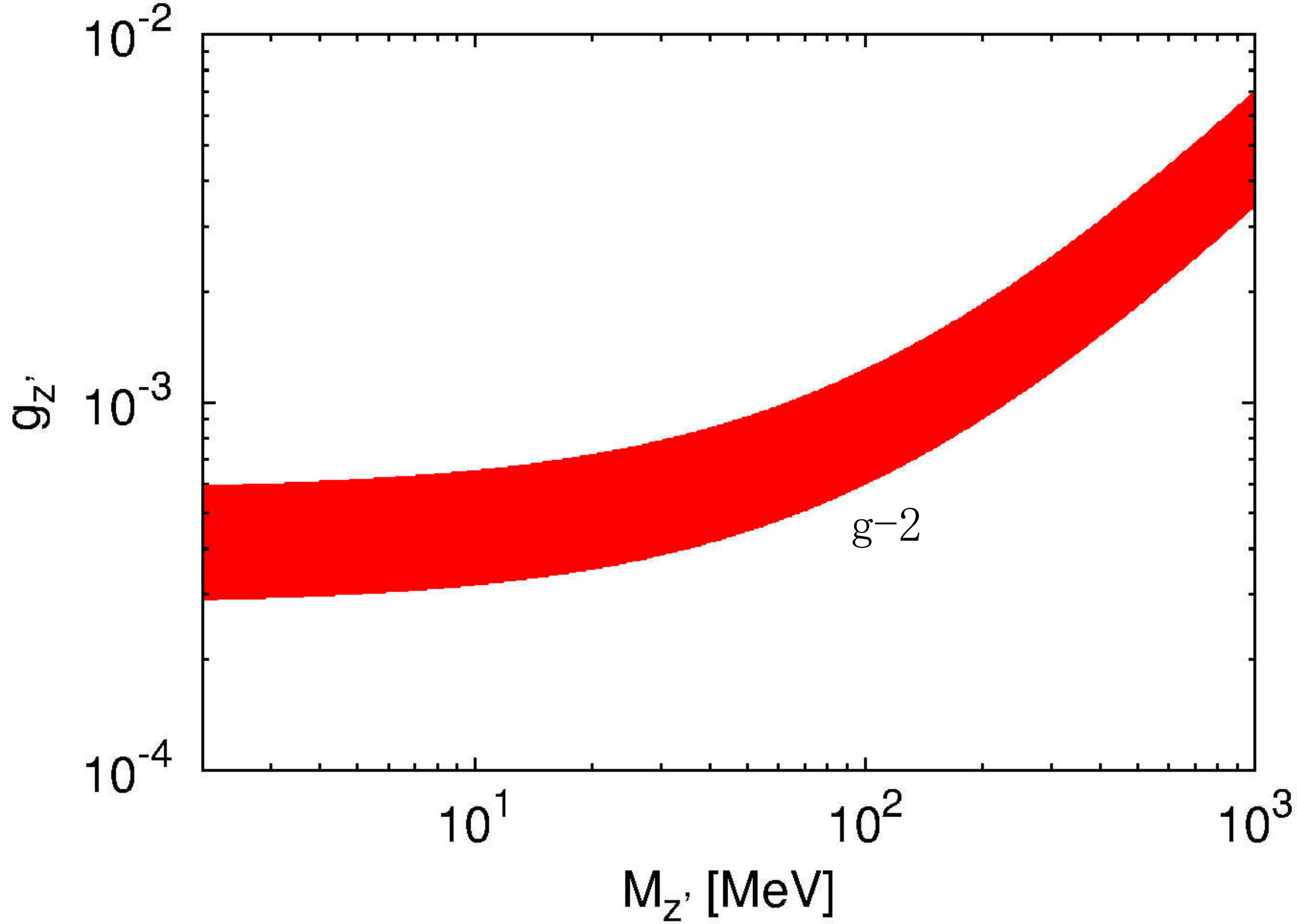
$$\left(a_\mu = \frac{g_\mu - 2}{2} \right)$$



$(\, g_{Z'} \, \bar{\mu}\gamma^\rho \mu Z'_\rho \,)$

Muon g−2

The red band is consistent with g−2 within 2σ



Motivations of $U(1)_{L\mu - L\tau}$

New U(1) force acting on only μ and τ flavor leptons.

	e, ν_e	μ, ν_μ	τ, ν_τ	others
$U(1)_{L\mu - L\tau}$	0	+1	−1	0

Motivated by

- Muon g−2 problem,
- Energy spectrum of cosmic neutrinos (IceCube),
- Flavor puzzles in the lepton sector,
- etc.

IceCube Gap

PRD91&93

High energy cosmic neutrinos

Our target: neutrinos produced in cosmic-ray interactions with gas (p) or radiation (γ), followed by pion decays.

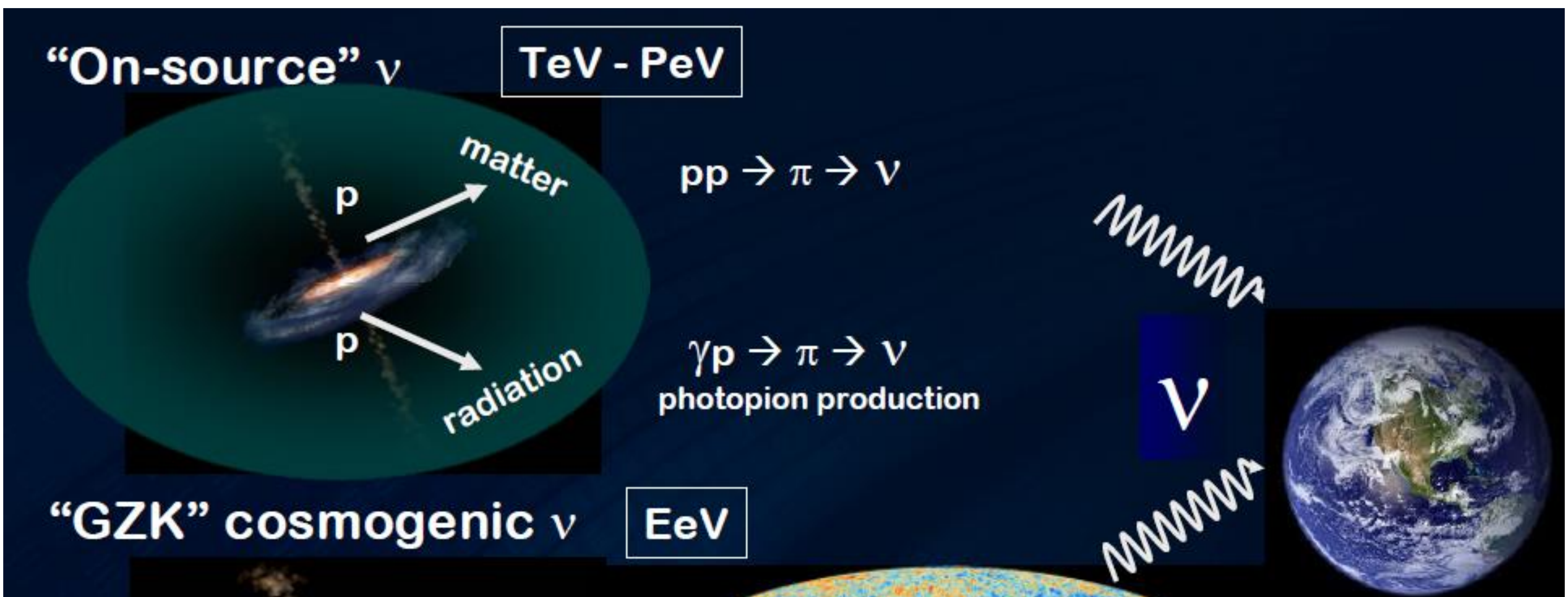
@ Source

$$\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$$

oscillation →

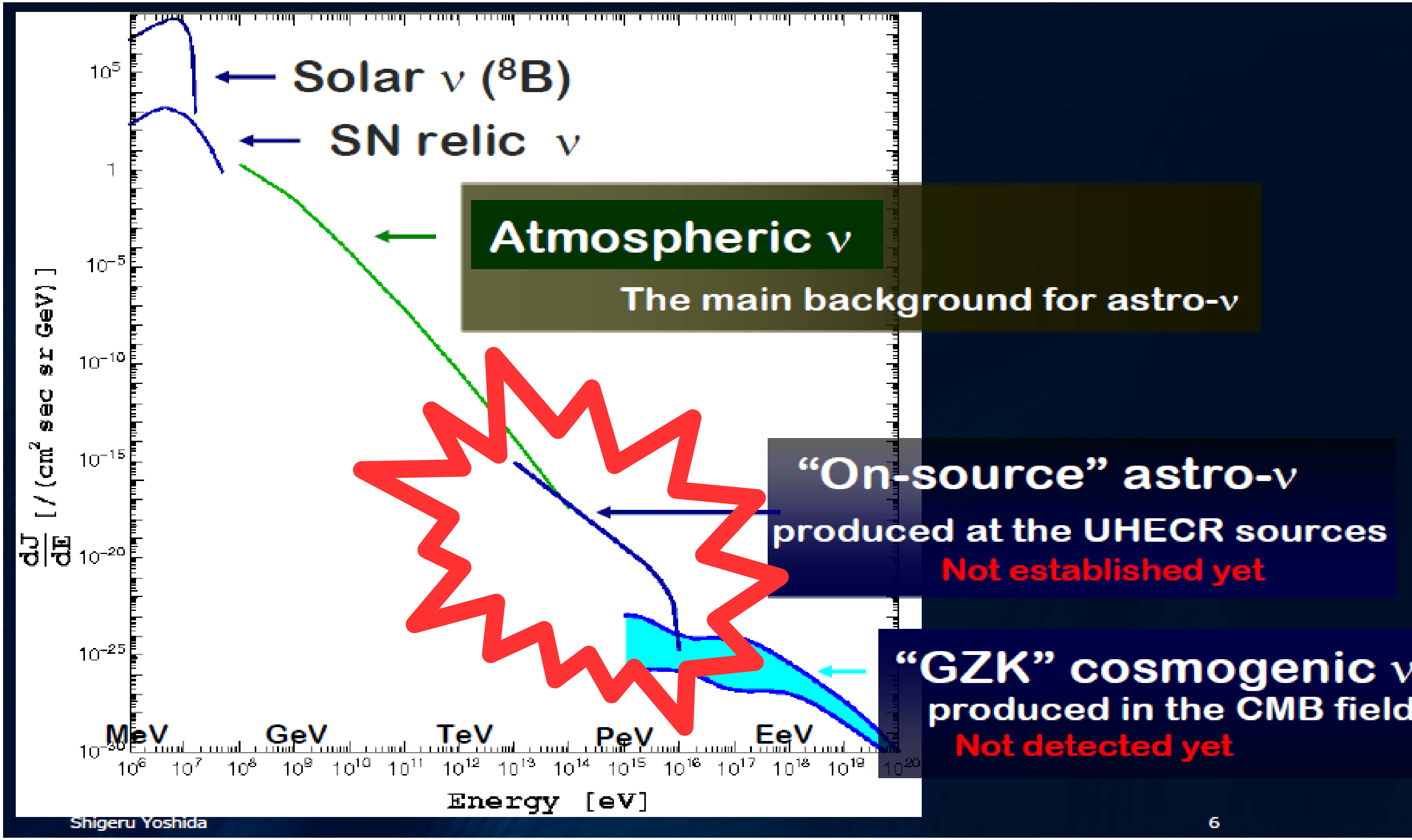
@ Earth

$$\simeq 1 : 1 : 1$$



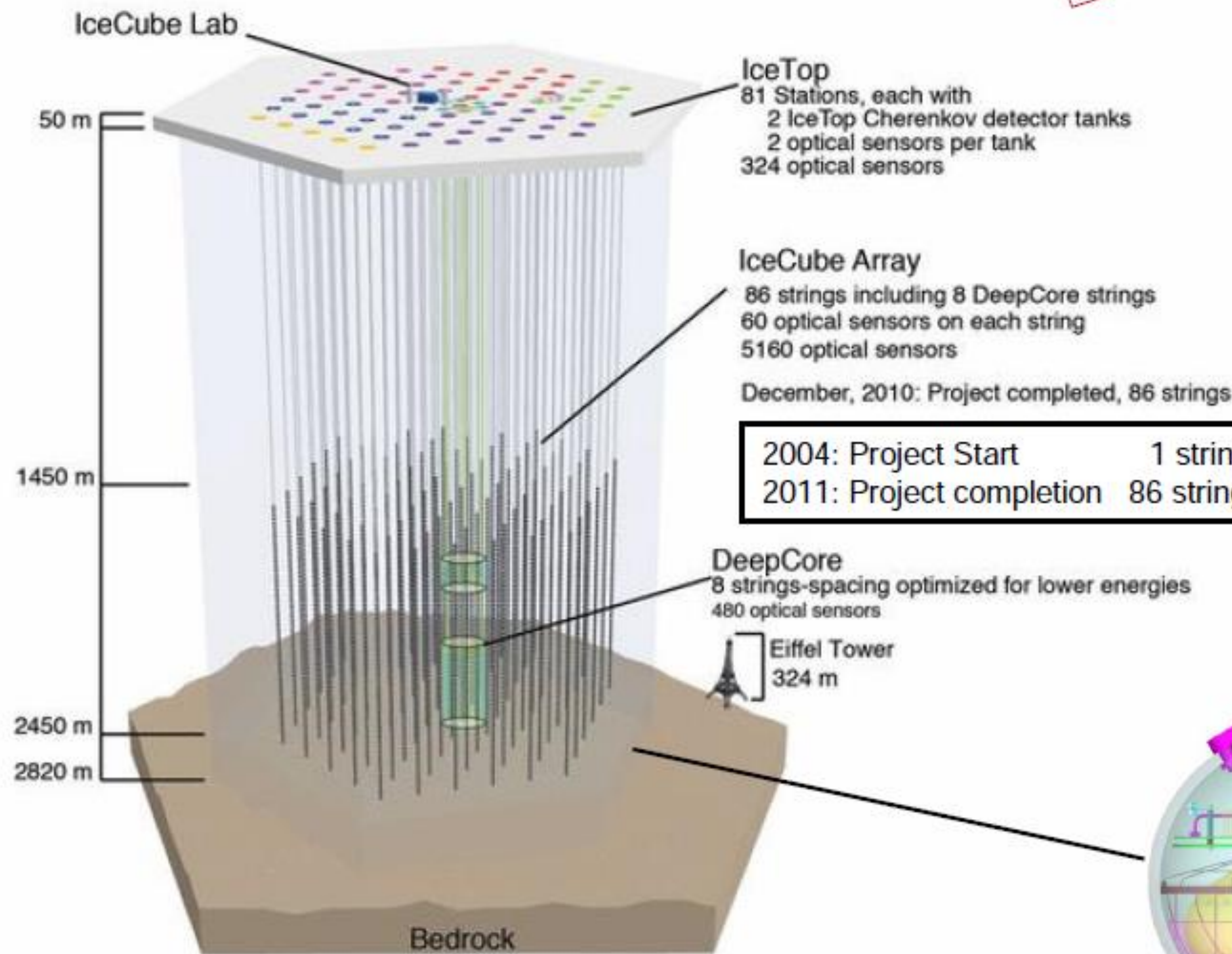
High energy cosmic neutrinos

Our target: neutrinos having energies of O(TeV - PeV) .



The IceCube Neutrino Observatory

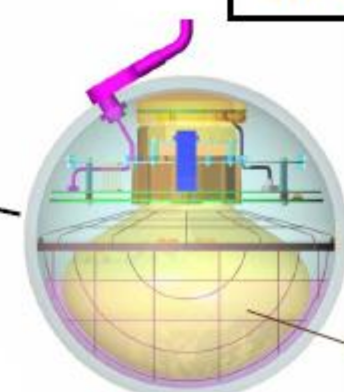
Completed: Dec 2010



2004: Project Start	1 string
2011: Project completion	86 strings

Configuration chronology

2006: IC9
2007: IC22
2008: IC40
2009: IC59
2010: IC79
2011: IC86



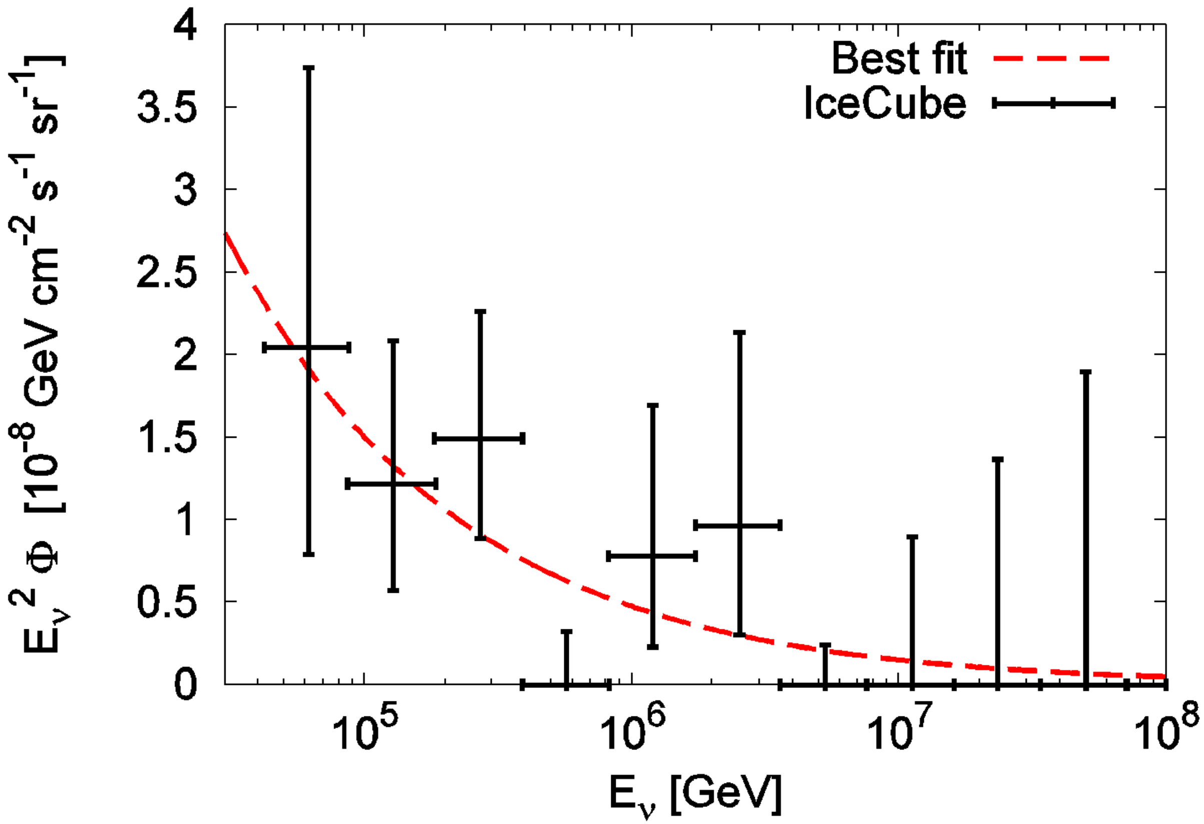
Digital Optical Module (DOM)

Full operation with all strings since May 2011

Three−year data

Neutrino flux ($\nu + \bar{\nu}$) as a function of its energy.

[PRL 113 (2014), 101101]



1. It rejects a purely atmospheric explanation at 5.7 sigma.
2. The data are consistent with equal (1:1:1) flavor ratios and isotropic arrival directions.
3. The best−fit power low is

$$\Phi(E) = \phi \left[\frac{E_\nu}{100\mathrm{TeV}} \right]^{-2.5}$$

※ Combined analysis:
[Astrophys. J. 809 (2015) 1, 98]

Impacts of IceCube

The IceCube data have a great impact on

not only astrophysics

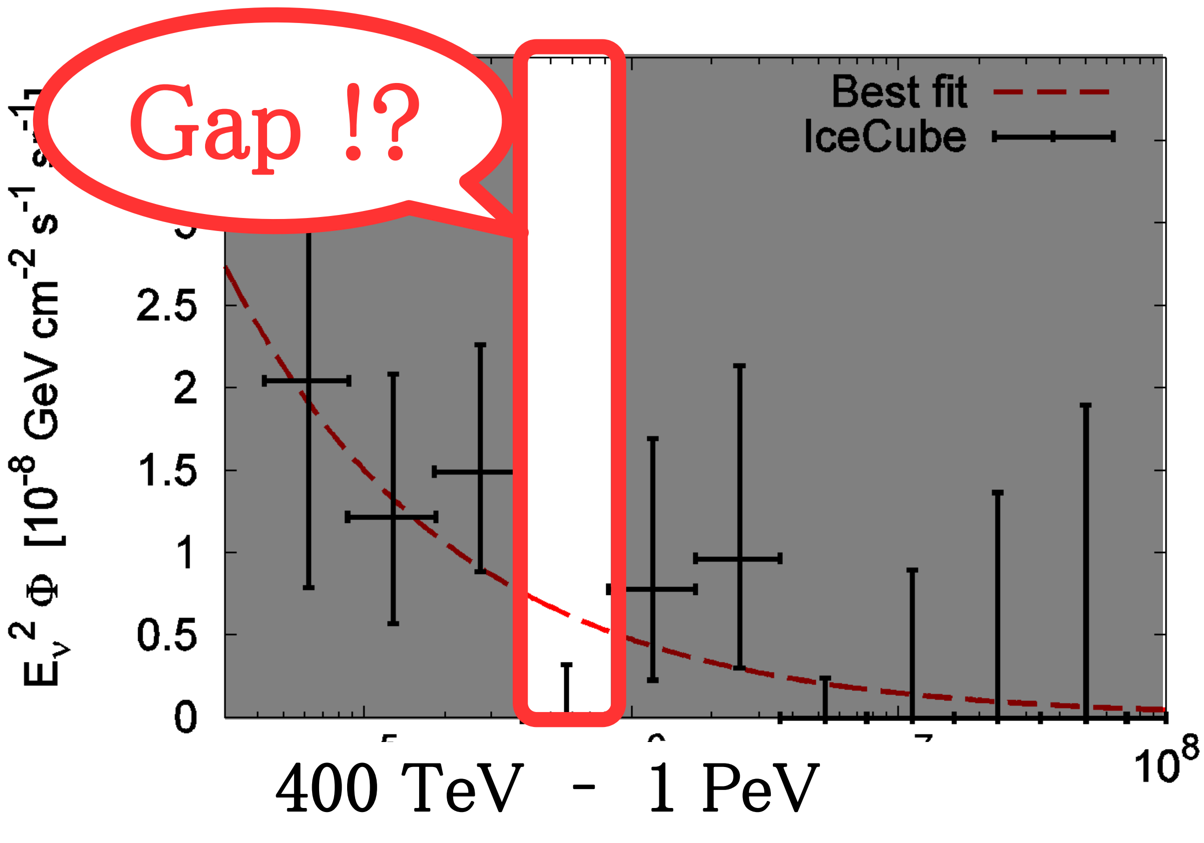
the origin of high energy cosmic neutrinos,
an acceleration mechanism of cosmic rays

but also **particle physics**.

Gap or fluctuation?

Neutrino flux ($\nu + \bar{\nu}$) as a function of its energy.

[PRL 113 (2014), 101101]



1. It rejects a purely atmospheric explanation at 5.7 sigma.
2. The data are consistent with equal (1:1:1) flavor ratios and isotropic arrival directions.
3. The best−fit power low is

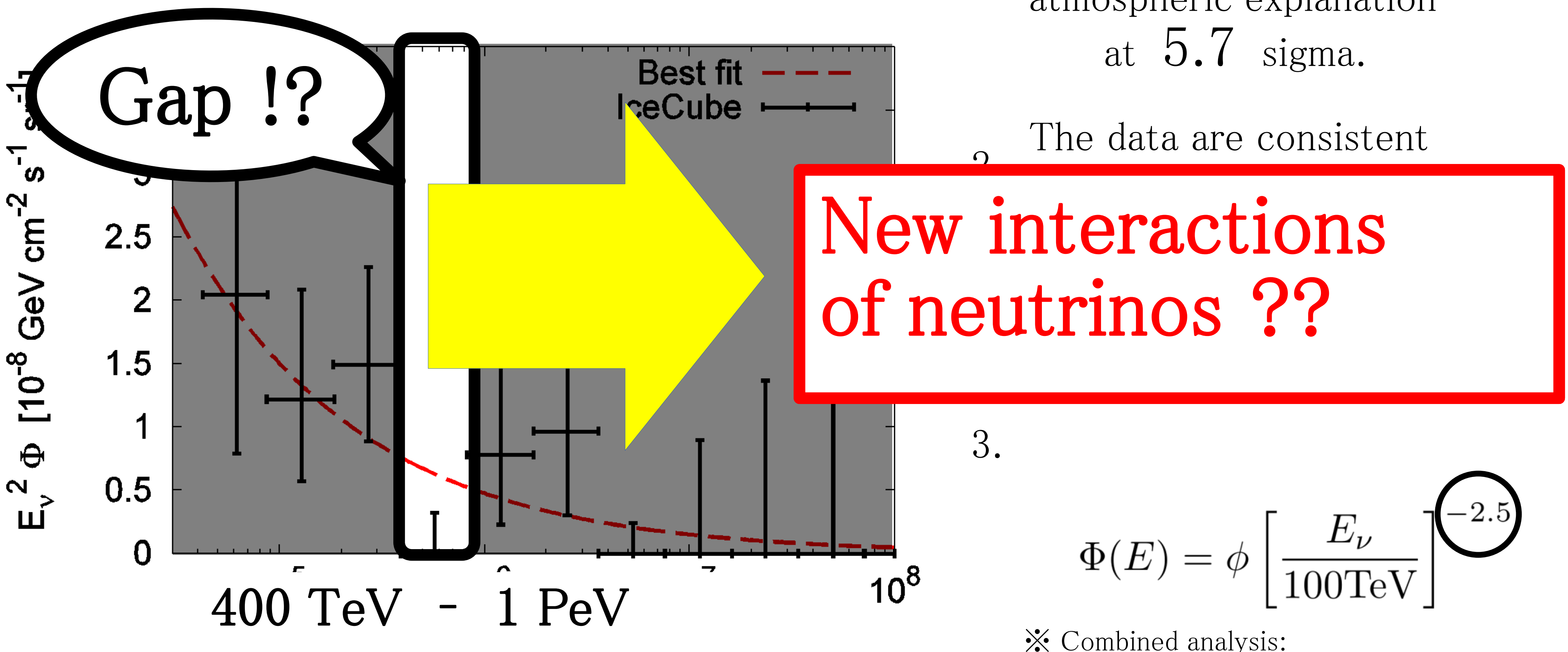
$$\Phi(E) = \phi\left[\frac{E_\nu}{100\text{TeV}}\right]^{-2.5}$$

※ Combined analysis:
[Astrophys. J. 809 (2015) 1, 98]

Gap or fluctuation?

Neutrino flux ($\nu + \bar{\nu}$) as a function of its energy.

[PRL 113 (2014), 101101]



1. It rejects a purely atmospheric explanation at 5.7 sigma.
2. The data are consistent
3.

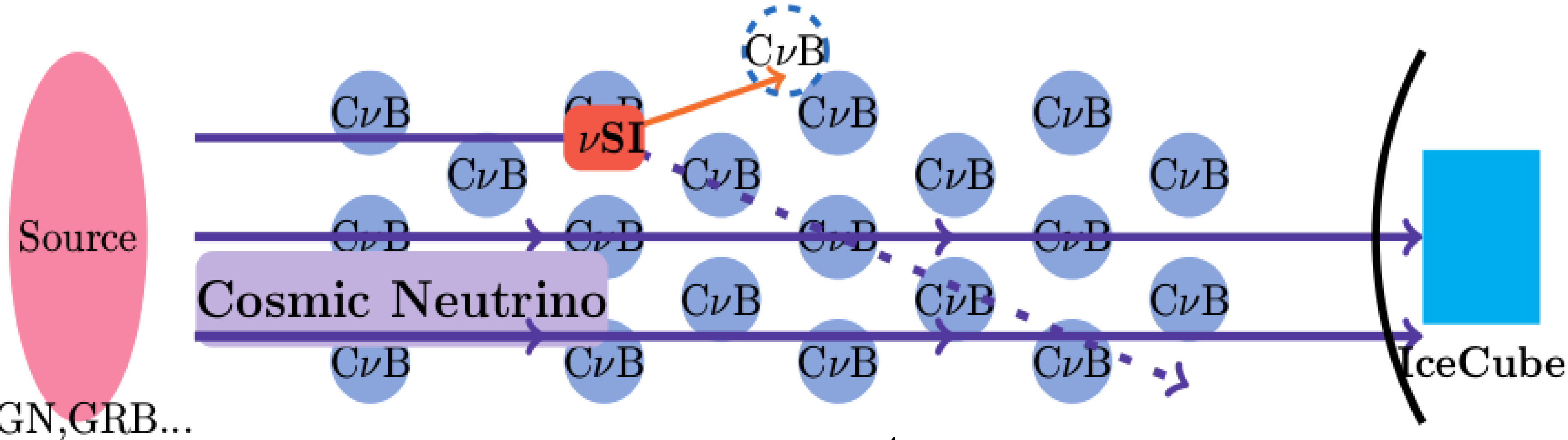
$$\Phi(E) = \phi \left[\frac{E_\nu}{100\text{TeV}} \right]^{-2.5}$$

※ Combined analysis:
[Astrophys. J. 809 (2015) 1, 98]

Ioka, Murase, PTEP2014, 061E01
Ng, Beacom, PRD90, 065035 (201
Ibe, Kaneta, PRD90, 053011 (201

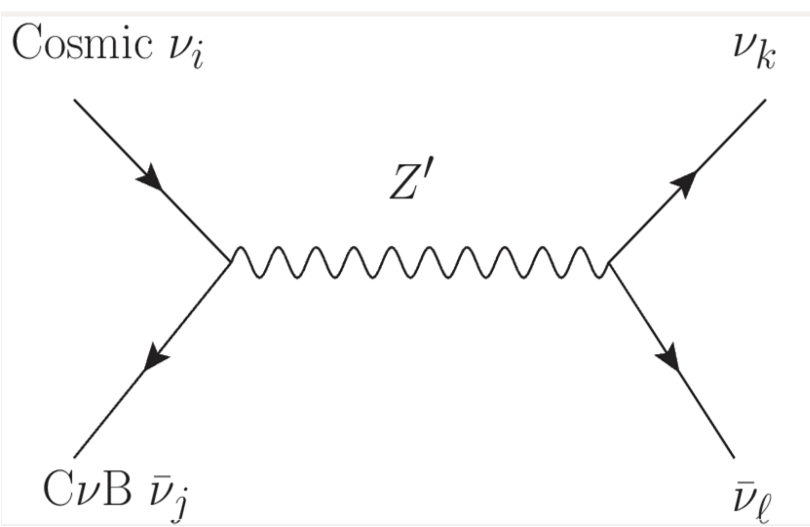
Secret neutrino interaction

The Gap may indicate *Secret Neutrino Interaction (ν SI)*.



$$\sigma = \frac{g_Z^4}{3\pi} \frac{s}{(s - M_{Z'}^2)^2 + M_{Z'}^2 \Gamma_{Z'}^2}$$

Cross section is enhanced as $\sqrt{s} \simeq M_{Z'}$



$$\sqrt{s} = \sqrt{(p_{\text{Cosmic}} + p_{\text{C}\nu\text{B}})^2}$$
$$\simeq \sqrt{2E_{\text{Cosmic}} m_\nu} \simeq \textbf{MeV}$$

500 TeV

10^{-3} eV

$\sqrt{s}$: center of mass energy

Secret neutrino interaction

Rough estimation of the mass of X and its coupling.

ν

$\bar{\nu}$

New physics at the MeV scale
is a possible candidate
for the IceCube gap!!

$m_{\mathrm{C}\nu\mathrm{B}} \simeq (0.01 - 0.1)\ \mathrm{eV} \quad E_\nu \simeq 1\ \mathrm{PeV}$

(2) To attenuate sufficient amount of cosmic neutrino:

$$\sigma > 10^{-30}\ \mathrm{cm}^2 \quad \Rightarrow \quad g > 10^{-4}.$$

Explanation by $U(1)_{L_\mu - L_\tau}$.

A new gauged U(1): mu – tau

We introduce a new U(1) gauge symmetry associated with

the muon number minus tau number: $U(1)_{L_\mu - L_\tau}$.

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} Z'_{\rho\sigma} Z'^{\rho\sigma} - \frac{\epsilon}{4} Z'_{\rho\sigma} B^{\rho\sigma} + + m_{Z'} Z'_{\rho} Z'^{\rho}$$

$$+ g_{Z'} (\bar{\nu}_\mu \gamma^\rho P_L \nu_\mu - \bar{\nu}_\tau \gamma^\rho P_L \nu_\tau + \bar{\mu}\gamma^\rho \mu - \bar{\tau}\gamma^\rho \tau) Z'_\rho$$

$L_\mu - L_\tau$

New gauge coupling

New gauge boson

1. No quantum gauge anomalies.
2. No LFV couplings.
3. Large atm. and small reactor mixing: $\theta_{23} = 45^\circ,\ \theta_{13} = 0^\circ$.
4. A possible solution for muon anomalous magnetic moment.

Kinetic mixing is forbidden in $m_\mu = m_\tau$ limit

$$\mathcal{L}_{\rm int} = g_{Z'}(+\bar{\nu}_\mu\gamma^\rho P_L\nu_\mu - \bar{\nu}_\tau\gamma^\rho P_L\nu_\tau + \bar{\mu}\gamma^\rho\mu - \bar{\tau}\gamma^\rho\tau)Z'_\rho$$

In $m_\mu = m_\tau$ limit, we cannot distinguish between μ and τ.
Then, a discrete symmetry appears.

$$\mu \longleftrightarrow \tau$$
$$B_\rho \longrightarrow B_\rho$$
$$Z'_\rho \longrightarrow -Z'_\rho$$

$$Z'_{\rho\sigma} = \partial_\rho Z'_\sigma - \partial_\sigma Z'_\rho$$

Therefore, $-\frac{\epsilon}{4}Z'_{\rho\sigma}B^{\rho\sigma}$ is forbidden in $L_\mu - L_\tau$ model.

A new gauged U(1): mu – tau

We introduce a new U(1) gauge symmetry associated with

the muon number minus tau number: $U(1)_{L_\mu - L_\tau}$.

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} Z'_{\rho\sigma} Z'^{\rho\sigma} - \frac{\epsilon}{4} Z'_{\rho\sigma} B^{\rho\sigma} + + m_{Z'} Z'_\rho Z'^\rho$$

$$+ g_{Z'} \underbrace{(\bar{\nu}_\mu \gamma^\rho P_L \nu_\mu - \bar{\nu}_\tau \gamma^\rho P_L \nu_\tau + \bar{\mu} \gamma^\rho \mu - \bar{\tau} \gamma^\rho \tau)}_{L_\mu - L_\tau} Z'_\rho$$

New gauge coupling

New gauge boson

1. No quantum gauge anomalies.
2. No LFV couplings.
3. Large atm. and small reactor mixing: $\theta_{23} = 45^\circ,\ \theta_{13} = 0^\circ$.
4. A possible solution for muon anomalous magnetic moment.

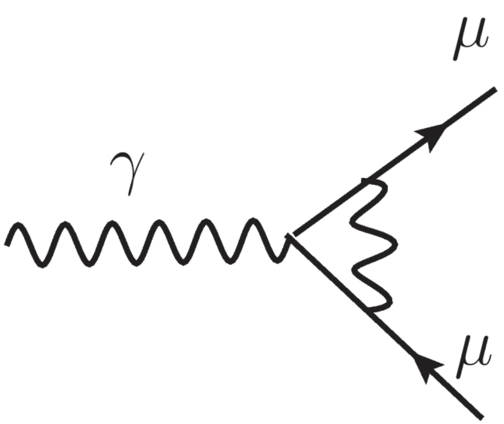
Muon g−2

The interaction between the electron/muon spin and magnetic field,

$$H_{int} = -\boldsymbol{\mu} \cdot \boldsymbol{B}$$

Magnetic moment, $$\boldsymbol{\mu} = -g\frac{e}{2m}\boldsymbol{s}$$

g−factor



The prediction of Dirac equation, $g = 2$.

Due to the field theory, a small difference with Dirac value appers.

$$a = \frac{g-2}{2}$$

Consistent with SM

$$\Delta a_e = a_e^{\mathrm{exp}} - a_e^{\mathrm{SM}} = -1.04(82) \times 10^{-12}$$

K. Hagiwara et al., J. Phys. G 38, 0850003 (2011). Marc Knecht, arXiv:1412.1228

Muon g−2

Longstanding discrepancy between experiments and theory:

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = 26.1(8.0)\times 10^{-10}$$

3.3 σ

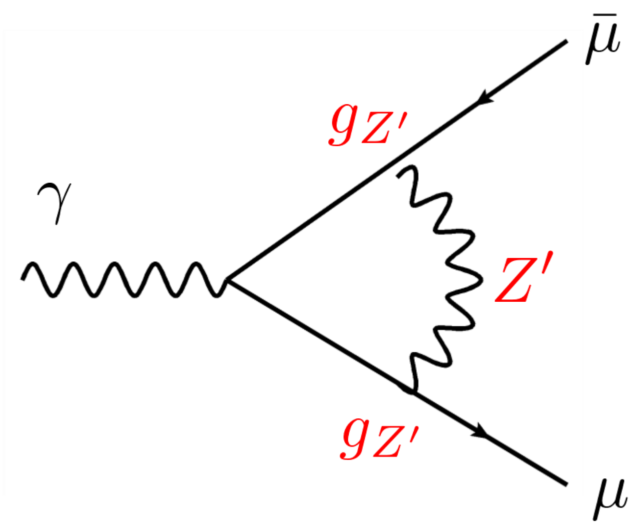
[Hagiwara, Liao, Martin, Nomura, Teubner, JPG38, 085003 (2011)]

In the $U(1)_{L_\mu - L_\tau}$ model, we have an additional contribution:

$$a_\mu^{\rm EXP} - (a_\mu^{\rm SM} + \underline{a_\mu^{Z'}})$$

$$a_\mu^{Z'} = \frac{g_{Z'}^2}{8\pi^2}\int_0^1 \frac{2m_\mu^2 x^2(1-x)}{x^2 m_\mu^2 + (1-x)m_{Z'}^2}dx$$

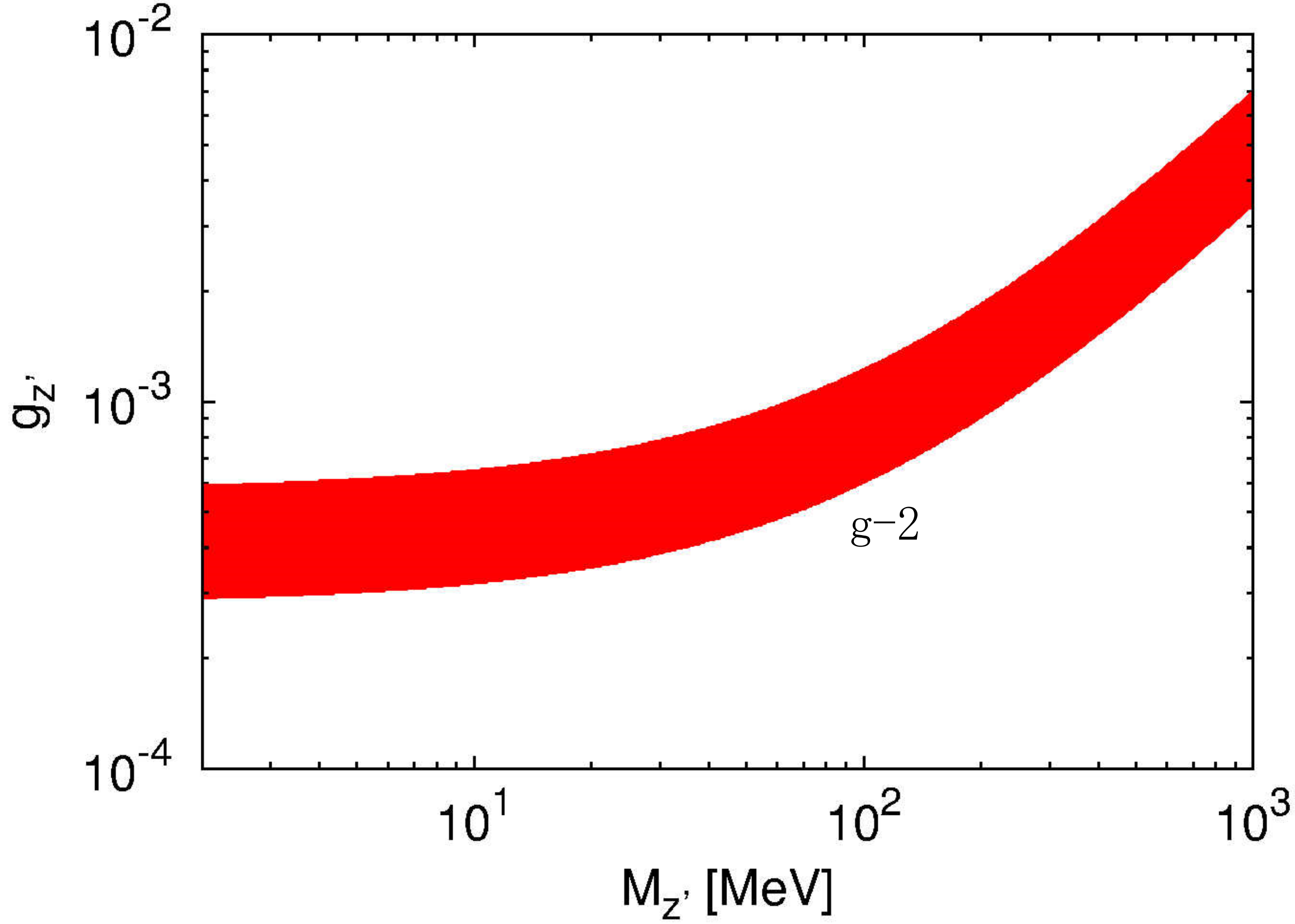
$$\left(a_\mu = \frac{g_\mu - 2}{2}\right)$$



$(\ g_{Z'} \ \bar\mu\gamma^\rho\mu Z'_\rho \ )$

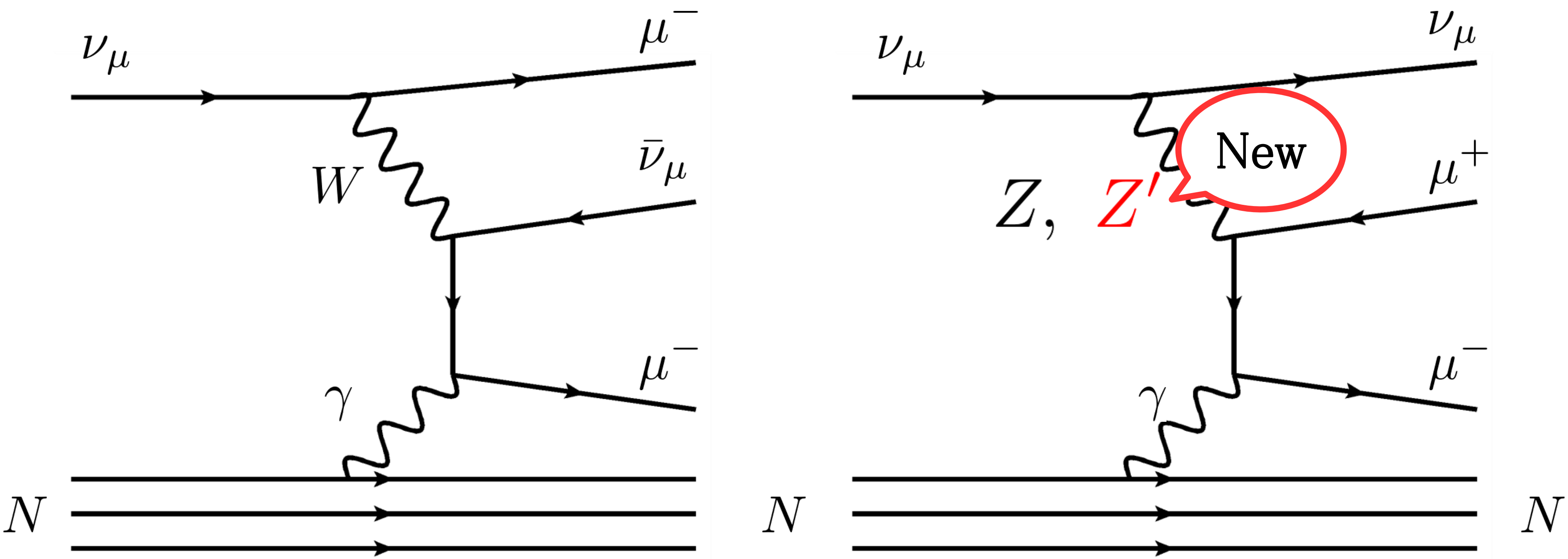
Muon g−2

The red band is consistent with g−2 within . 2σ



Neutrino trident production

The model is constrained by the neutrino trident production.



$$\frac{\sigma^{\mathrm{EXP}}}{\sigma^{\mathrm{SM}}} = 0.82 \pm 0.28$$

in good agreement with SM

[CCFR collaboration, PRL66, 3117 (1991)]

(This confirmed the destructive interference of W–Z, and thus SM.)

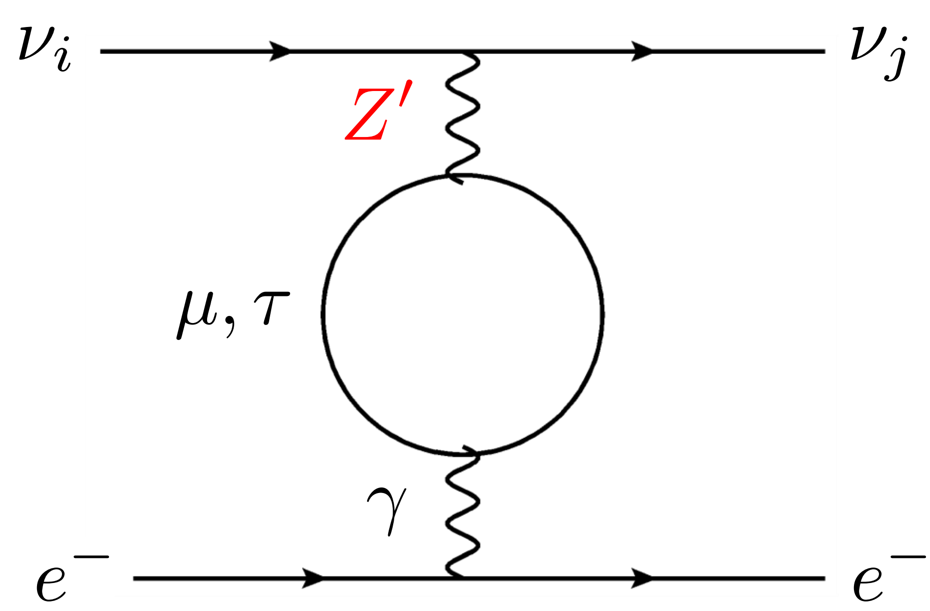
Other constraints

$Z' - \gamma$ one–loop mixing

It contributes to $\nu e \to \nu e$:

$$|\varepsilon_{\mathrm{loop}}| = \frac{8}{3}\frac{e g_{Z'}}{(4\pi)^2} \ln \frac{m_\tau}{m_\mu}$$

$$\left(\mathcal{M}(\nu e \to \nu e) \propto \varepsilon_{\mathrm{loop}} \frac{e g_{Z'}}{q^2 - M_{Z'}^2} \right).$$



The model is constrained by Borexino.

[Harnik, Kopp, Machado, JCAP 1207, 026 (2012)]

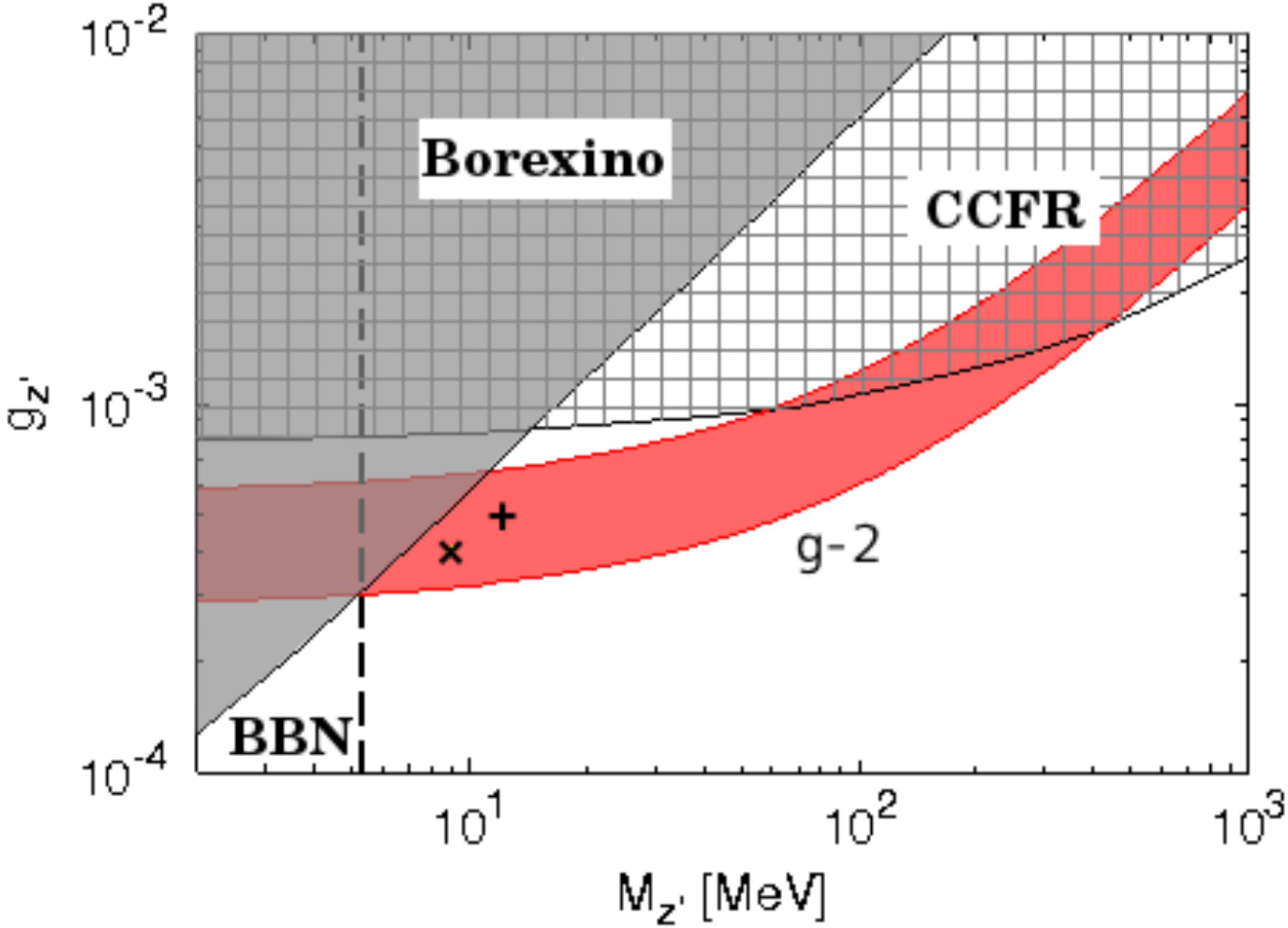
BBN

Such a light Z' increases the effective numbe N_{eff} .

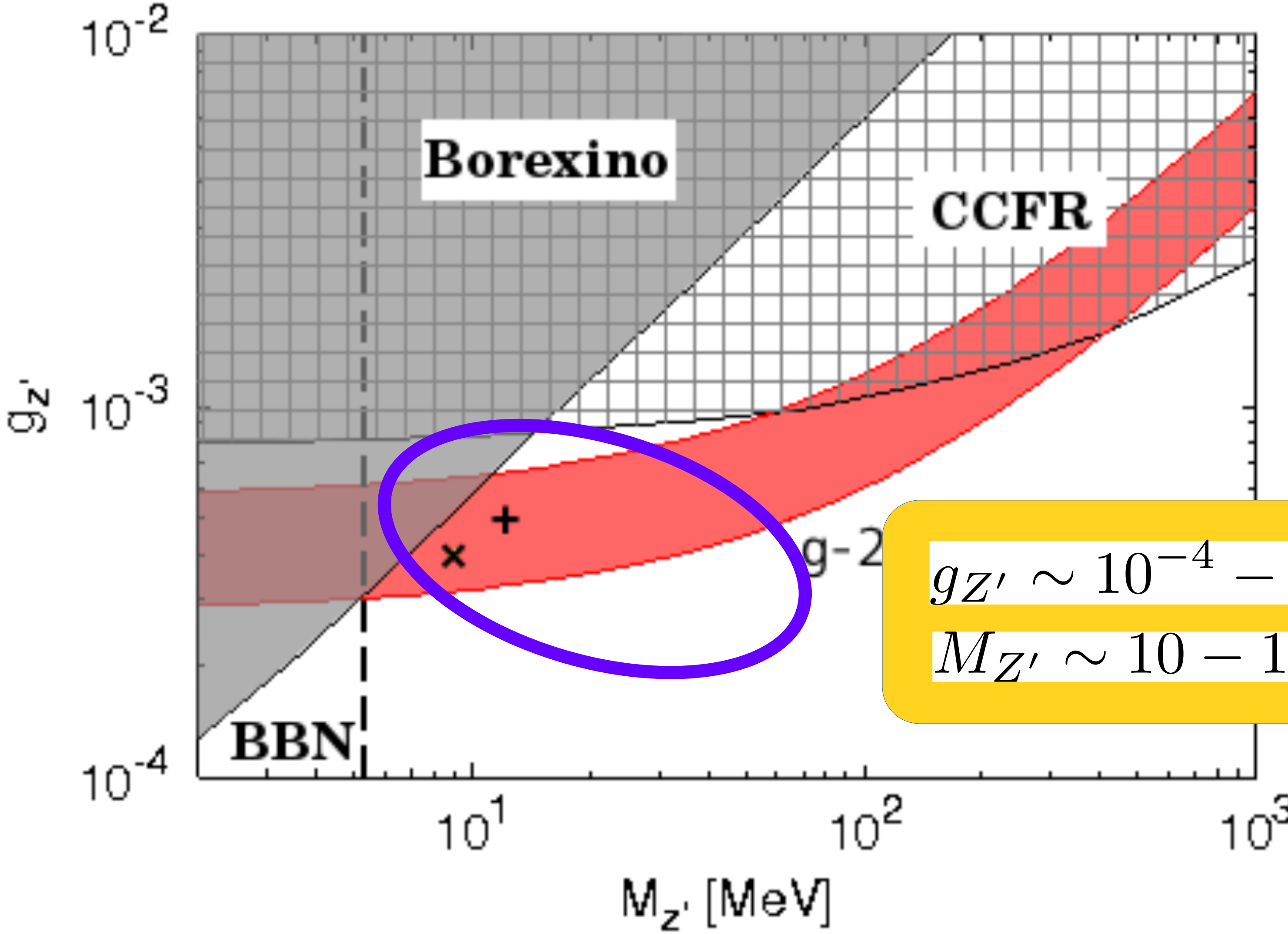
- Directly $\Rightarrow$ $M_{Z'} > 1$ MeV
- Indirectly $\Rightarrow$ $M_{Z'} > 5$ MeV

[Kamada, Yu, 1594.00711]

Parameter region



Parameter region



$g_{Z'} \sim 10^{-4} - 10^{-3}$

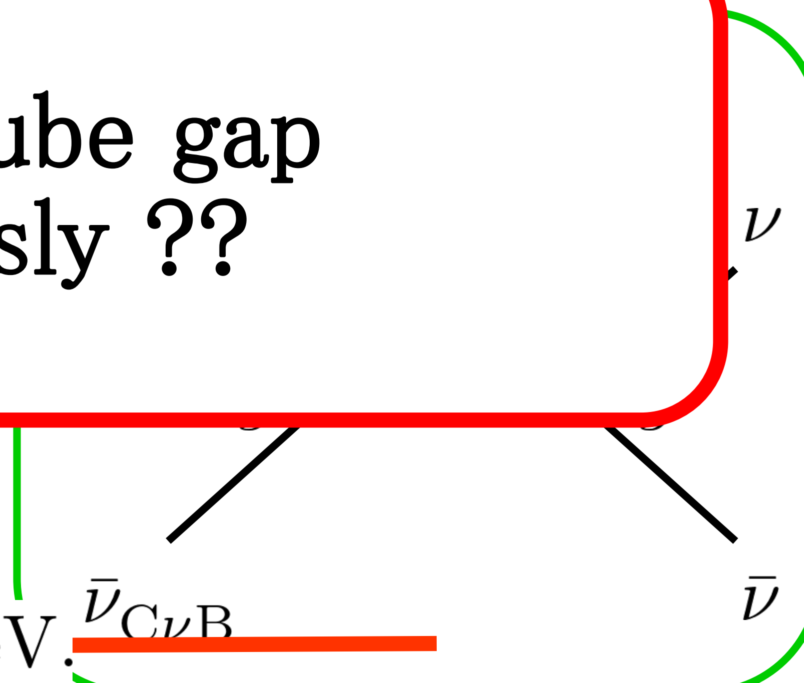
$M_{Z'} \sim 10 - 100$ MeV

Secret neutrino interaction

Roug

Challenge

g–2 and IceCube gap simultaneously ??



(1) Resonant condition requires:

$$M_X \simeq \sqrt{2E_\nu^{\rm res} m_{C\nu B}} \sim 1 - 10 \text{ MeV}.$$

$$m_{C\nu B} \simeq (0.01 - 0.1) \text{ eV} \quad E_\nu \simeq 1 \text{ PeV}$$

(2) To attenuate sufficient amount of cosmic neutrino:

$$\sigma > 10^{-30} \text{ cm}^2 \quad \Rightarrow \quad g > 10^{-4}.$$

Calculation of neutrino flux and model parameter

Propagation of neutrinos

A propagation equation for cosmic neutrino:

$$\frac{\partial \tilde{n}_i}{\partial t} = \frac{\partial}{\partial E_i} b \tilde{n}_i + \mathcal{L}_i - c n_{\mathrm{C}\nu\mathrm{B}} \tilde{n}_i \sum_j \sigma(\nu_i \overline{\nu}_j^{\mathrm{C}\nu\mathrm{B}} \to \nu\overline{\nu})$$

$$+ c n_{\mathrm{C}\nu\mathrm{B}} \sum_{j,k} \int_{E_i}^{\infty} dE_k \tilde{n}_k \frac{d\sigma(\nu_k \overline{\nu}_j^{\mathrm{C}\nu\mathrm{B}} \to \nu_i \overline{\nu})}{dE_k}$$

$$\tilde{n}_i(E_i, z) = \frac{dn_i}{dE_i}$$

c: speed of light

z: redshift parameter

$n_{\mathrm{C}\nu\mathrm{B}}$: number density of CnB

Propagation of neutrinos

A propagation equation for cosmic neutrino:

$$\frac{\partial \tilde{n}_i}{\partial t} = \frac{\partial}{\partial E_i} b \tilde{n}_i + \mathcal{L}_i - c n_{\mathrm{C}\nu\mathrm{B}} \tilde{n}_i \sum_j \sigma(\nu_i \overline{\nu}_j^{\mathrm{C}\nu\mathrm{B}} \to \nu \overline{\nu})$$

$$+ c n_{\mathrm{C}\nu\mathrm{B}} \sum_{j,k} \int_{E_i}^{\infty} dE_k \tilde{n}_k \frac{d\sigma(\nu_k \overline{\nu}_j^{\mathrm{C}\nu\mathrm{B}} \to \nu_i \overline{\nu})}{dE_k}$$

1. Energy loss via redshift

$$b = H(z) E$$

Propagation of neutrinos

A propagation equation for cosmic neutrino:

$$\frac{\partial \tilde{n}_i}{\partial t} = \frac{\partial}{\partial E_i} b\tilde{n}_i + \mathcal{L}_i - c n_{\mathrm{C}\nu\mathrm{B}} \tilde{n}_i \sum_j \sigma(\nu_i \overline{\nu}_j^{\mathrm{C}\nu\mathrm{B}} \to \nu\overline{\nu})$$

$$+ c n_{\mathrm{C}\nu\mathrm{B}} \sum_{j,k} \int_{E_i}^{\infty} dE_k \tilde{n}_k \frac{d\sigma(\nu_k \overline{\nu}_j^{\mathrm{C}\nu\mathrm{B}} \to \nu_i \overline{\nu})}{dE_k}$$

2. Source term

$$\mathcal{L}_i = \mathcal{W}(z)\mathcal{L}_0(E_i)$$

$$\mathcal{L}_0 = \mathcal{Q}_0 E_i^{-s_\nu} \exp\left[\frac{E_i}{E_{\mathrm{cut}}}\right]$$

$$\mathcal{W}(z) = \begin{cases} (1+z)^{3.4} & 0 \le z < 1, \\ (1+z)^{-0.3} & 1 \le z \le 4. \end{cases}$$

Star formation rate

$\mathcal{Q}_0$: normalization of flux

S_ν : spectral index

E_{cut} : cut-off energy

Propagation of neutrinos

A propagation equation for cosmic neutrino:

$$\frac{\partial \tilde{n}_i}{\partial t} = \frac{\partial}{\partial E_i} b\tilde{n}_i + \mathcal{L}_i - c n_{\mathrm{C\nu B}} \tilde{n}_i \sum_j \sigma(\nu_i \overline{\nu}_j^{\mathrm{C\nu B}} \to \nu\overline{\nu})$$

$$+ c n_{\mathrm{C\nu B}} \sum_{j,k} \int_{E_i}^{\infty} dE_k \tilde{n}_k \frac{d\sigma(\nu_k \overline{\nu}_j^{\mathrm{C\nu B}} \to \nu_i \overline{\nu})}{dE_k}$$

3. Scattering with CnB

$$\sigma(\nu_i \bar{\nu}_j^{\mathrm{C\nu B}} \to \nu\bar{\nu}) = \frac{|g'_{ji}|^2 g_{Z'}^2}{6\pi} \frac{s}{(s - M_{Z'}^2)^2 + M_{Z'}^2 \Gamma_{Z'}^2}$$

$$\Gamma_{Z'} = \frac{g_{Z'}^2 M_{Z'}}{12\pi}$$

$\sqrt{s}$ ‡ center-of-mass energy

$$g'_{ij} = g_{Z'} U_{\mathrm{MNS}}^{\dagger} \mathrm{diag}(0, 1, -1) U_{\mathrm{MNS}}$$

Propagation of neutrinos

A propagation equation for cosmic neutrino:

$$\frac{\partial \tilde{n}_i}{\partial t} = \frac{\partial}{\partial E_i} b\tilde{n}_i + \mathcal{L}_i - c n_{\mathrm{C\nu B}} \tilde{n}_i \sum_j \sigma(\nu_i \overline{\nu}_j^{\mathrm{C\nu B}} \to \nu\overline{\nu})$$

$$+ c n_{\mathrm{C\nu B}} \sum_{j,k} \int_{E_i}^{\infty} dE_k \tilde{n}_k \frac{d\sigma(\nu_k \overline{\nu}_j^{\mathrm{C\nu B}} \to \nu_i \overline{\nu})}{dE_k}$$

4. Regeneration term

$$\frac{\mathrm{d}\sigma(\nu_k \bar{\nu}_j^{\mathrm{C\nu B}} \to \nu_i \bar{\nu})}{\mathrm{d}E_{\nu_i}} = \frac{|g'_{jk}|^2 \sum_l |g'_{il}|^2}{2\pi} \frac{m_{\nu_j} E_{\nu_i}^2}{E_{\nu_k}^2} \times \frac{1}{(s - M_{Z'}^2)^2 + M_{Z'}^2 \Gamma_{Z'}^2}$$

Parameter setting

Neutrino mixing

[Forero, Tortola, Valle, PRD90, 093006 (2014)]

We use best-fit values for the normal (inverted) mass hierarchy:

$$\sin^2\theta_{12} = 0.323 \quad \sin^2\theta_{23} = 0.567\ (0.573)$$

$$\sin^2\theta_{13} = 0.0234\ (0.0240)$$

$$\Delta m_{12}^2 = 7.60 \times 10^{-5}\ \ \mathrm{eV}^2$$

$$|\Delta m_{23}^2| = 2.48\ (2.38) \times 10^{-3}\ \ \mathrm{eV}^2$$

and $\delta_{\mathrm{CP}} = 0$

Propagation equation

Q_0 : normalization of flux

E_{cut} : cut-off energy

⇒ Adjust to fit the IceCube data.

We calculate diffuse neutrino flux for several values of

$M_{Z'}$, $g_{Z'}$, m_{lightest}, S_ν for NH and IH.

Gap: Spectral index

Diffuse neutrino flux for several spectral indices.

Normal hierarchy

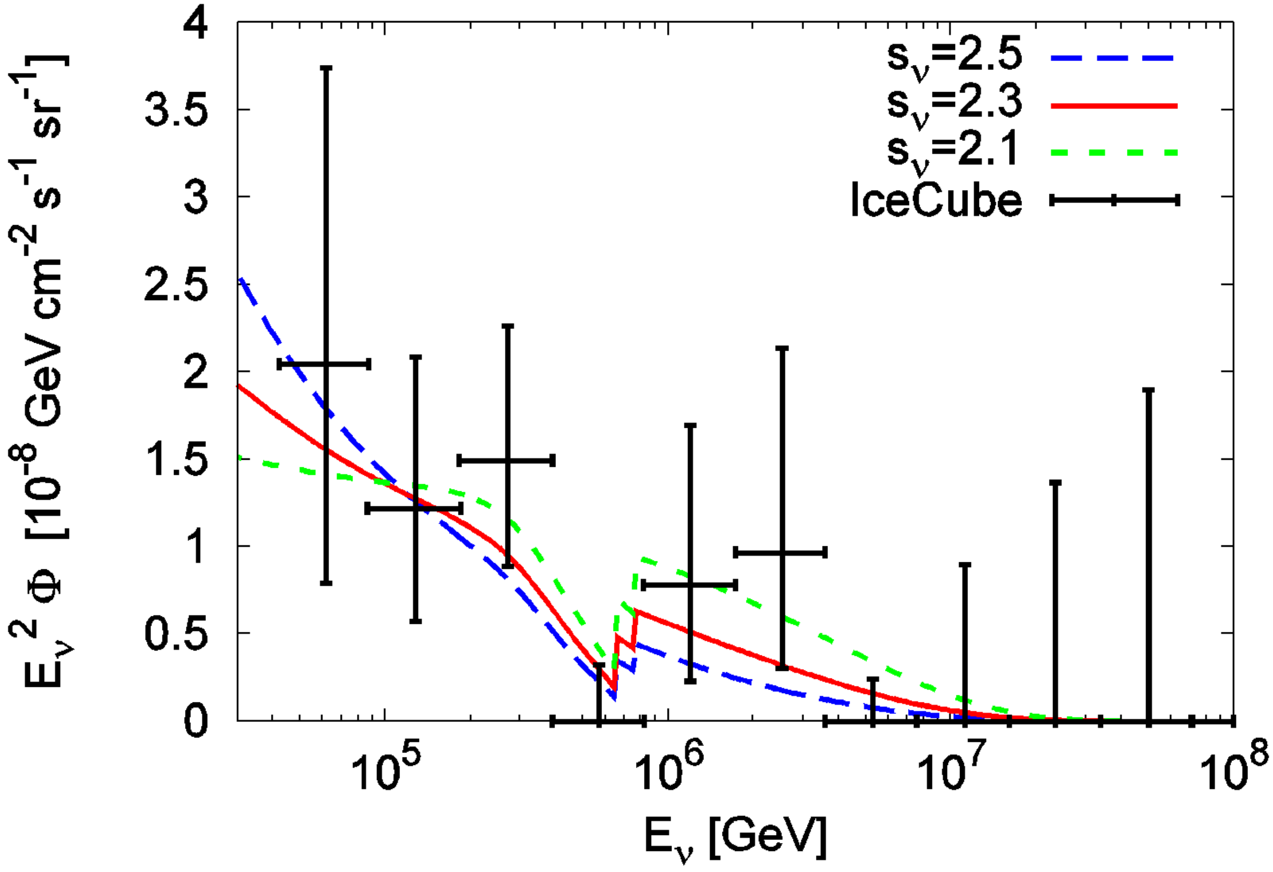
$$m_1 = 0.08 \text{ eV}$$

(quasi-degenerate)

$$M_{Z'} = 11 \text{ MeV}$$

$$g_{Z'} = 5 \times 10^{-4}$$

($E_{\text{cut}} = 10^7$ GeV)



The gap can **successfully be reproduced**, but not completely.

Some events are expected in IceCube in the future. Indeed now appearing !

Gap: Source distribution

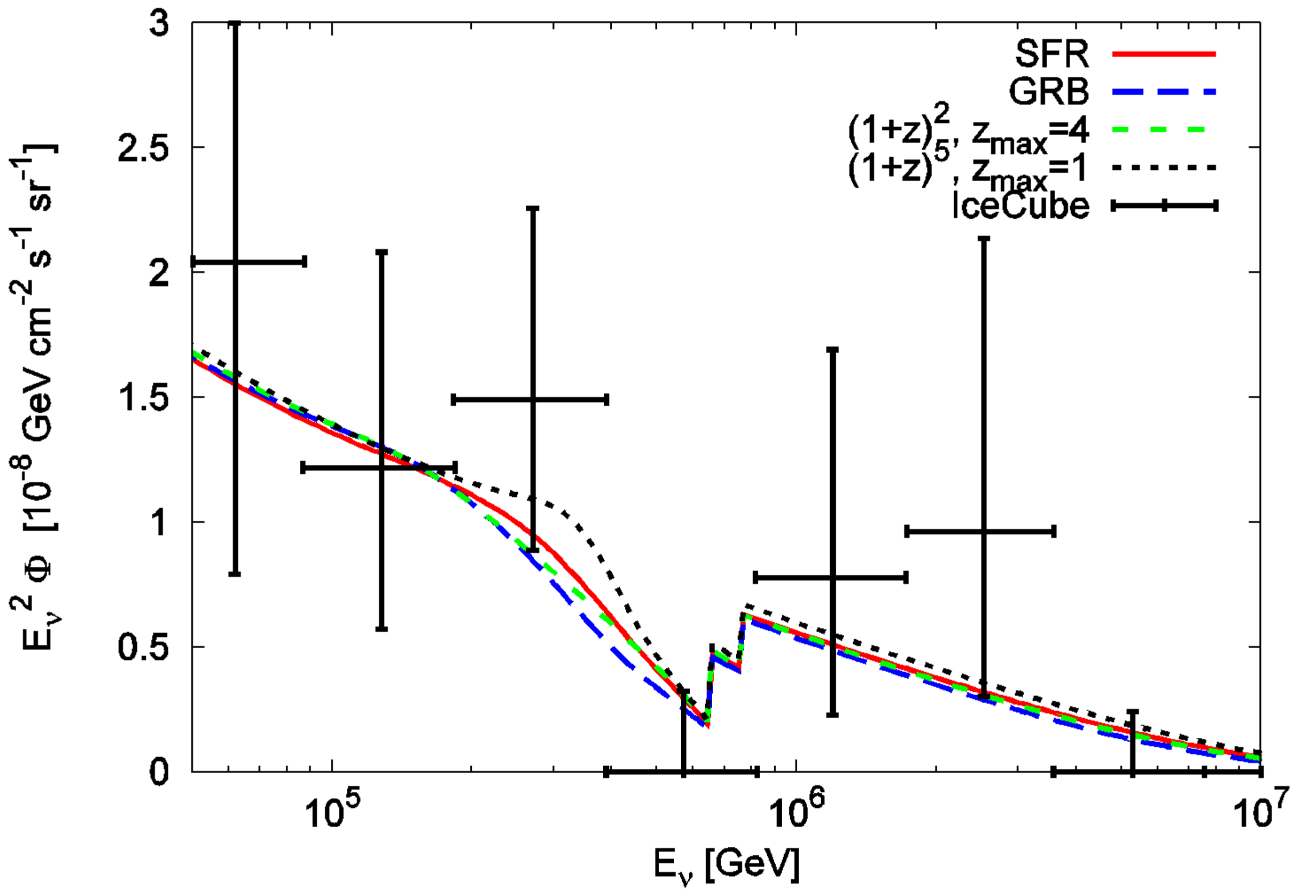
Diffuse neutrino flux for several types of source distribution.

Normal hierarchy

$m_1 = 0.08$ eV
(quasi−degenerate)

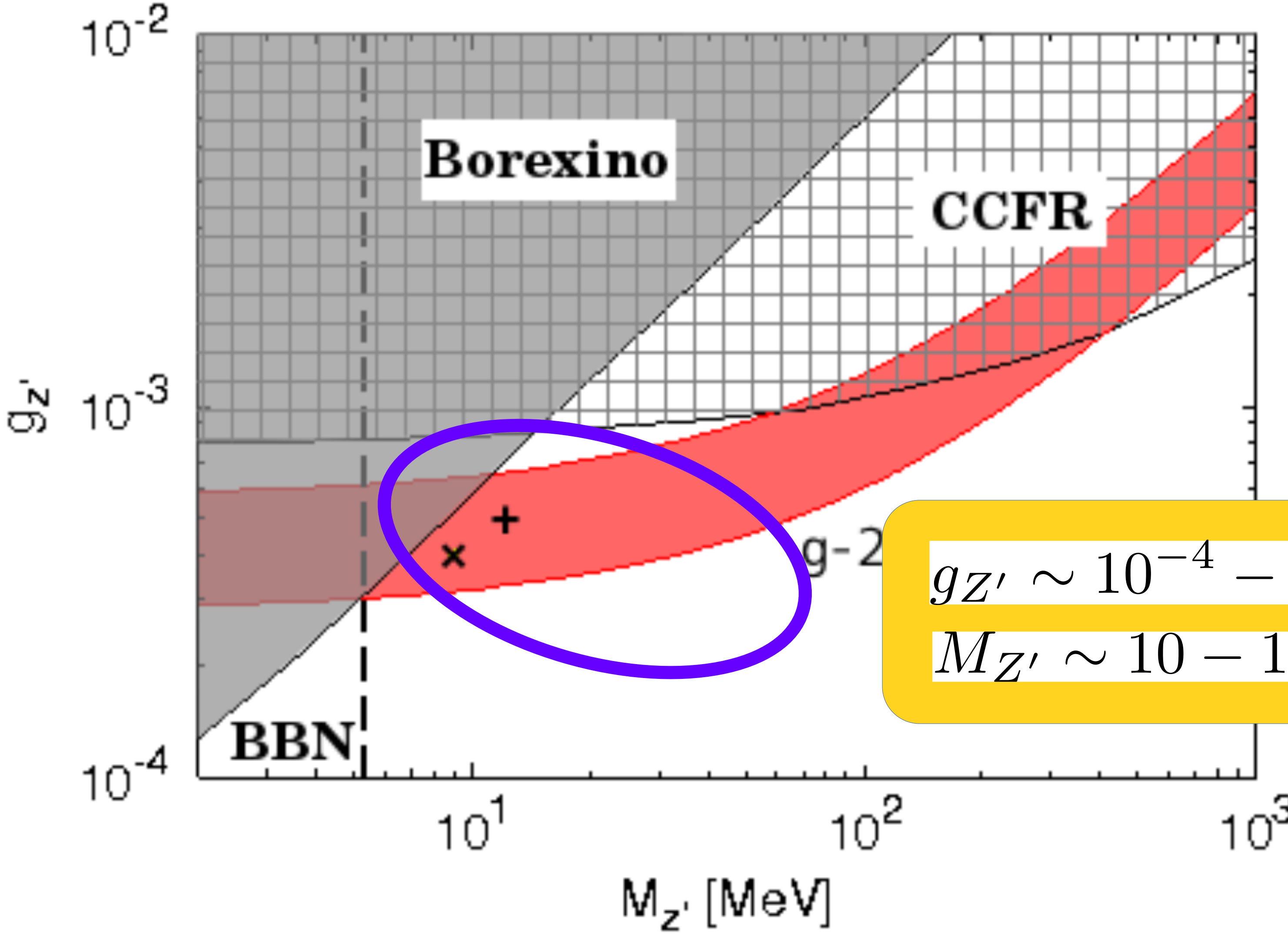
$M_{Z'} = 11$ MeV

$g_{Z'} = 5 \times 10^{-4}$
($E_{\rm cut} = 10^7$ GeV)



Source distributions have **a small impact** on the flux.

Parameter region



$$g_{Z'} \sim 10^{-4} - 10^{-3}$$
$$M_{Z'} \sim 10 - 100 \text{ MeV}$$

A Concrete Model

PRD100

Motivation

Extra U(1) models are often studied as an effective theory

- Really it exists ?

Including scalar potentials ? Say, extra matter(s) in low energy ?

Predictive or just parameter physics ?

For example,

In cosmic neutrino attenuation,

if there were more light particles , prediction would have differed,

Neutrino masses and lepton mixings are predictive?

For latter zero texture is a key.

Zero textures

Zeros in neutrino mass matrix gives constraint = prediction

$$M_\nu = V \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix} V^T$$

$$V_{\mathrm{MNS}} = U \cdot \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

One zero yields two conditions.

- Zero textures

$$(M_\nu)_{ab} = 0$$

$$\Rightarrow (m_1 e^{2i\alpha_1}) U_{a1} U_{b1} + (m_2 e^{2i\alpha_2}) U_{a2} U_{b2} + (m_3) U_{a3} U_{b3} = 0$$

- Zero−minor textures

$$(M_\nu^{-1})_{ab} = 0$$

$$\Rightarrow \frac{1}{m_1 e^{2i\alpha_1}} U_{a1} U_{b1} + \frac{1}{m_2 e^{2i\alpha_2}} U_{a2} U_{b2} + \frac{1}{m_3} U_{a3} U_{b3} = 0$$

One can check the consistency of the conditions.

Testable !

Mass matrix in $U(1)_{L\mu - L\tau}$

$U(1)_{L\mu - L\tau}$ charges of a Dirac mass matrix.

$$Q_{L_\mu - L_\tau}(M_{\rm Dirac}) = \begin{pmatrix} 0 & 1 & -1 \\ -1 & 0 & -2 \\ 1 & 2 & 0 \end{pmatrix}$$

$U(1)_{L\mu - L\tau}$ symmetric, allowed.

Not $U(1)_{L\mu - L\tau}$ symmetric, forbidden.

Thus, the mass matrix is given by

(ex.) $\bar{\Psi}_L \Psi_R \phi_1$

$$M_{\rm Dirac} = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix} \xrightarrow{\ \not{U(1)}_{L\mu - L\tau}\ } M_{\rm Dirac} = \begin{pmatrix} \times & 0 & \times \\ \times & \times & 0 \\ 0 & 0 & \times \end{pmatrix}$$

Mass matrix in $U(1)_{L\mu - L\tau}$

$U(1)_{L\mu - L\tau}$ charges of a Majorana mass matrix.

$$Q_{L_\mu - L_\tau}(M_{\rm Majorana}) = \begin{pmatrix} 0 & 1 & -1 \\ 1 & 2 & 0 \\ -1 & 0 & -2 \end{pmatrix}$$

Thus, the mass matrix is given by

$$M_{\rm Majorana} = \begin{pmatrix} \times & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & 0 \end{pmatrix}$$

$\cancel{U(1)_{L\mu - L\tau}}$ ⇒

(ex.) $\overline{\Psi^c_R}\Psi_R\phi_1$

$$M_{\rm Majorana} = \begin{pmatrix} \times & 0 & \times \\ 0 & 0 & \times \\ \times & \times & 0 \end{pmatrix}$$

Neutrino masses & mixing in $U(1)_{L\mu - L\tau}$

(Majorana) neutrino masses and mixing in $U(1)_{L\mu - L\tau}$.

$$M_\ell = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix} \qquad M_\nu = \begin{pmatrix} \times & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & 0 \end{pmatrix}$$

predictions

$$m_2 = m_3 \qquad m_2^{\text{exp.}} \neq m_3^{\text{exp.}}$$

$$\theta_{12} = 0^\circ \qquad \theta_{12}^{\text{exp.}} \simeq 33.8^\circ$$

VS exps.

$$\theta_{13} = 0^\circ \qquad \theta_{13}^{\text{exp.}} \simeq 8.5^\circ$$

$$\theta_{23} = 45^\circ \qquad \theta_{23}^{\text{exp.}} \simeq 49.6^\circ$$

$U(1)_{L\mu - L\tau}$ must be broken.

From the first , though
the symmetry must be broken, since there is no massless gauge other than photon.
How to break ?

Breaking of U(1)$_{L\mu - L\tau}$

U(1)$_{L\mu - L\tau}$ symmetry must be broken in the neutrino sector.

·With U(1)$_{L\mu - L\tau}$ charge 1 scalars.

$$\frac{y}{\Lambda} LLHH \qquad \frac{y}{\Lambda^2} LLHH\phi_1 \qquad \frac{y}{\Lambda^3} LLHH\phi_1\phi_1$$

$$M_\nu = \begin{pmatrix} \times & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & 0 \end{pmatrix} + \begin{pmatrix} 0 & \times & \times \\ \times & \times & 0 \\ \times & 0 & \times \end{pmatrix}$$

Many possibilities,
we will focus on this.

·With U(1)$_{L\mu - L\tau}$ charge 2 scalars.

$$\frac{y}{\Lambda} LLHH \qquad \frac{y}{\Lambda^2} LLHH\phi_2$$

$$M_\nu = \begin{pmatrix} \times & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & 0 \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix}$$

θ_{12} and θ_{13} remain
vanishing, unrealistic.

Zero textures

Zero textures

One zero yields two conditions.

$$M_\nu = V \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix} V^T$$

$$V_{\mathrm{MNS}} = U \cdot \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

- Zero textures

$$(M_\nu)_{ab} = 0$$

$$\Rightarrow (m_1 e^{2i\alpha_1}) U_{a1} U_{b1} + (m_2 e^{2i\alpha_2}) U_{a2} U_{b2} + (m_3) U_{a3} U_{b3} = 0$$

- Zero-minor textures

$$(M_\nu^{-1})_{ab} = 0$$

$$\Rightarrow \frac{1}{m_1 e^{2i\alpha_1}} U_{a1} U_{b1} + \frac{1}{m_2 e^{2i\alpha_2}} U_{a2} U_{b2} + \frac{1}{m_3} U_{a3} U_{b3} = 0$$

One can check the consistency of the conditions.

Testable !

Two-zero textures

Simple models give often two zeros

The number of parameters in two-zero textures.

$$9 - 4 = 5 \text{ parameters}$$

Three masses, three angles three CP phases.

Two zeros yield four conditions (four constraints).

One can predict 4 observables with 5 input parameters.

(ex.) $\sum m \quad \delta \quad \alpha_1 \quad \alpha_2 \qquad \Delta m_{12}^2 \quad \Delta m_{23}^2 \quad \theta_{12} \quad \theta_{13} \quad \theta_{23}$

Too predictive ⋯

Possible two-zero textures before Planck

- Two-zero textures

[S. Zhou, Chin. Phys. C40 (2016)]

$$M_\nu = \begin{pmatrix} \times & \times & \times \\ \times & 0 & \times \\ \times & \times & 0 \end{pmatrix} \quad \begin{pmatrix} \times & \times & 0 \\ \times & 0 & \times \\ 0 & \times & \times \end{pmatrix} \quad \begin{pmatrix} \times & 0 & \times \\ 0 & \times & \times \\ \times & \times & 0 \end{pmatrix}$$

$$\begin{pmatrix} 0 & \times & 0 \\ \times & \times & \times \\ 0 & \times & \times \end{pmatrix} \quad \begin{pmatrix} 0 & 0 & \times \\ 0 & \times & \times \\ \times & \times & \times \end{pmatrix} \quad \begin{pmatrix} \times & \times & 0 \\ \times & \times & \times \\ 0 & \times & 0 \end{pmatrix} \quad \begin{pmatrix} \times & 0 & \times \\ 0 & 0 & \times \\ \times & \times & \times \end{pmatrix}$$

Equivalent

- Two-zero-minor textures

$$(M_\nu)^{-1} = \begin{pmatrix} \times & \times & \times \\ \times & 0 & 0 \\ \times & 0 & \times \end{pmatrix} \quad \begin{pmatrix} \times & \times & \times \\ \times & \times & 0 \\ \times & 0 & 0 \end{pmatrix} \quad \begin{pmatrix} \times & 0 & \times \\ 0 & 0 & \times \\ \times & \times & \times \end{pmatrix} \quad \begin{pmatrix} \times & \times & 0 \\ \times & \times & \times \\ 0 & \times & 0 \end{pmatrix}$$

$$\begin{pmatrix} \times & \times & 0 \\ \times & 0 & \times \\ 0 & \times & \times \end{pmatrix} \quad \begin{pmatrix} \times & 0 & \times \\ 0 & \times & \times \\ \times & \times & 0 \end{pmatrix} \quad \begin{pmatrix} \times & \times & \times \\ \times & 0 & \times \\ \times & \times & 0 \end{pmatrix}$$

Checking the consistency of two-zero textures

Two-zero textures vs Planck

Input parameters; within 3 σ errors for NO(IO).

$$\sin^2\theta_{12} = 0.275 - 0.350 \quad (0.275 - 0.350),$$

$$\sin^2\theta_{13} = 0.02045 - 0.02439 \quad (0.02068 - 0.02463),$$

$$\Delta m^2_{31}/10^{-3} = 2.427 - 2.625 \quad (\Delta m^2_{23}/10^{-3} = 2.412 - 2.611),$$

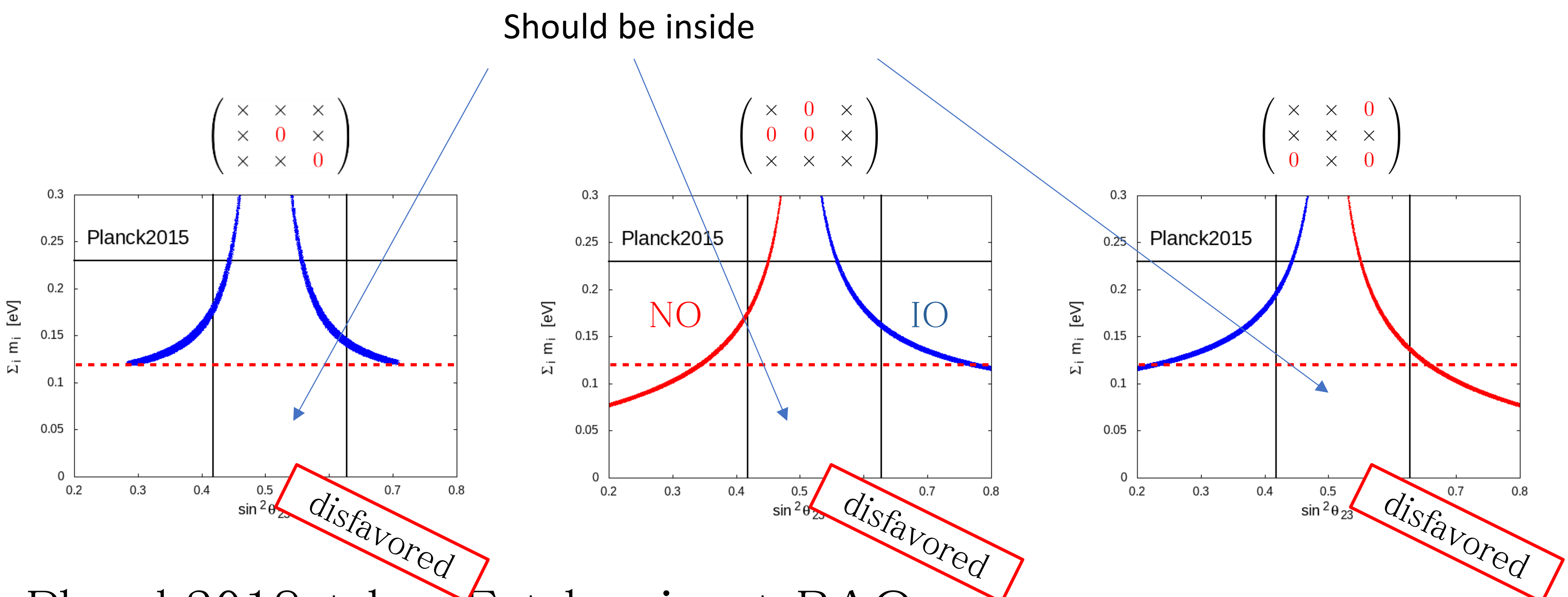
$$\Delta m^2_{21}/10^{-5} = 6.79 - 8.01 \quad (6.79 - 8.01),$$

$$\delta = 125^\circ - 392^\circ \quad (196^\circ - 360^\circ)$$

[I. Esteban, et al, JHEP01, 106 (2019).]

Outputs: $\sin^2\theta_{23}$ and Σm .

Two-zero textures vs Planck



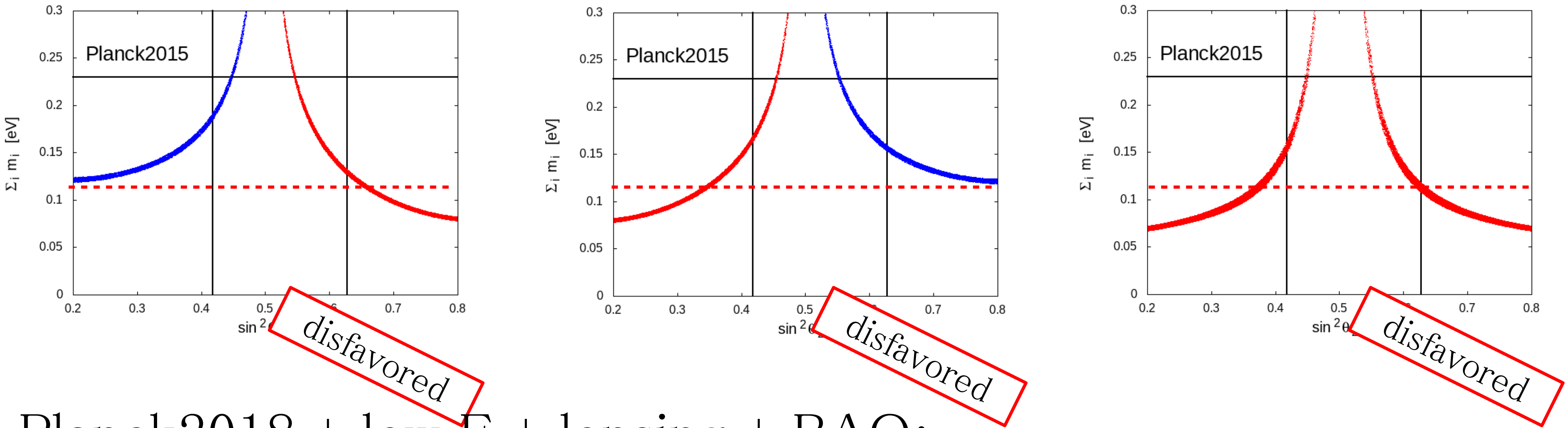
Planck2018 + low E + lensing + BAO:

$\Sigma\ m < 0.12$ eV (95% C.L.)

[Planck Callaboration, arXiv1807.06209]

Two-zero-minors vs Planck

$$\begin{pmatrix} \times & \times & 0 \\ \times & 0 & \times \\ 0 & \times & \times \end{pmatrix} \quad \begin{pmatrix} \times & 0 & \times \\ 0 & \times & \times \\ \times & \times & 0 \end{pmatrix} \quad \begin{pmatrix} \times & \times & \times \\ \times & 0 & \times \\ \times & \times & 0 \end{pmatrix}$$



Planck2018 + low E + lensing + BAO:

$$\Sigma\ m < 0.12\ \mathrm{eV}\ (95\%\ \mathrm{C.L.})$$

[Planck Callaboration, arXiv1807.06209]

New model

Our model

Particle contents

2 generations ($N_{R_e}, N_{R_{\mu(\tau)}}$ and $N_{L_e}, N_{L_{\mu(\tau)}}$)

~~$U(1)_L$~~ (Φ, S_L) $U(1)_{L_\mu - L_\tau}$ ($S_{\mu\tau}$)

	$\ell_{L_e}, \ell_{L_\mu}, \ell_{L_\tau}$	$\ell_{R_e}, \ell_{R_\mu}, \ell_{R_\tau}$	$N_{R_e}, N_{R_{\mu(\tau)}}$	$N_{L_e}, N_{L_{\mu(\tau)}}$	H	Φ	S_L	$S_{\mu\tau}$
$U(1)_{L_\mu - L_\tau}$	$0, 1, -1$	$0, 1, -1$	$0, 1(-1)$	$0, 1(-1)$	0	0	0	1
$U(1)_L$	1	1	1	1	0	-2	-2	0
$SU(2)_L$	2	1	1	1	2	2	1	1

- Model - A : $(N_{Re}, N_{R\mu}) = (0, 1)$ $(N_{Le}, N_{L\mu}) = (0, 1)$
- Model - B : $(N_{Re}, N_{R\tau}) = (0, -1)$ $(N_{Le}, N_{L\tau}) = (0, -1)$

Our model

The 7 by 7 effective neutrino mass matrix is obtained, after the scalars develop VEVs.

$$\mathcal{M}_\nu^{7\times 7} = \begin{pmatrix} 0 & M_D & M_N \\ M_D^T & M_R & M_S \\ M_N^T & M_S^T & M_L \end{pmatrix}$$

⟨Φ⟩, it triggers Linear seesaw.

$$\begin{pmatrix} 0 & M_D & M_N \\ M_D^T & 0 & M_S \\ M_N^T & M_S^T & 0 \end{pmatrix}$$

~~U(1)~~$_{L_\mu - L_\tau}$ by $\langle S_{\mu\tau} \rangle$.

$\langle S_L \rangle$, it triggers Inverse seesaw.

$$\begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M_S \\ 0 & M_S^T & M_L \end{pmatrix}$$

Our model

$$m_D = \begin{pmatrix} m_d^{ee} & 0 \\ 0 & m_d^{\mu\mu} \\ 0 & 0 \end{pmatrix}, \quad m_N = \begin{pmatrix} m_n^{ee} & 0 \\ 0 & 0 \\ 0 & m_n^{\tau\mu} \end{pmatrix}, \quad m_S = \begin{pmatrix} m_s^{ee} & m_s^{e\mu} \\ m_s^{\mu e} & m_s^{\mu\mu} \end{pmatrix},$$

$$m_{LL} = \begin{pmatrix} m_L & 0 \\ 0 & 0 \end{pmatrix}, \quad m_{RR} = \begin{pmatrix} m_R & 0 \\ 0 & 0 \end{pmatrix},$$

Model A

$$m_D = \begin{pmatrix} m_d^{ee} & 0 \\ 0 & 0 \\ 0 & m_d^{\tau\tau} \end{pmatrix}, \quad m_N = \begin{pmatrix} m_n^{ee} & 0 \\ 0 & m_n^{\mu\tau} \\ 0 & 0 \end{pmatrix}, \quad m_S = \begin{pmatrix} m_s^{ee} & m_s^{e\tau} \\ m_s^{\tau e} & m_s^{\tau\tau} \end{pmatrix},$$

$$m_{LL} = \begin{pmatrix} m_L & 0 \\ 0 & 0 \end{pmatrix}, \quad m_{RR} = \begin{pmatrix} m_R & 0 \\ 0 & 0 \end{pmatrix},$$

Model B

Our model

The 7 by 7 effective neutrino mass matrix is obtained, after the scalars develop VEVs.

$$\mathcal{M}_\nu^{7\times 7} = \begin{pmatrix} 0 & M_D & M_N \\ M_D^T & M_R & M_S \\ M_N^T & M_S^T & M_L \end{pmatrix}$$

⟨Φ⟩, it triggers Linear seesaw.

$$\begin{pmatrix} 0 & M_D & M_N \\ M_D^T & 0 & M_S \\ M_N^T & M_S^T & 0 \end{pmatrix}$$

~~U(1)~~$_{L\mu-L\tau}$ by ⟨$S_{\mu\tau}$⟩.

⟨S_L⟩, it triggers Inverse seesaw.

$$\begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M_S \\ 0 & M_S^T & M_L \end{pmatrix}$$

Our model

After block diagonalization, the active neutrino mass matrix is obtained.

Linear

$$M_\nu = -M_D(M_S^T)^{-1}M_N^T - M_N(M_S)^{-1}M_D^T$$

$\mathcal{O}(10^{-27})$ GeV

Inverse

$$+M_D(M_S^T)^{-1}M_L(M_S)^{-1}M_D^T + M_N(M_S)^{-1}M_R(M_S^T)^{-1}M_N^T$$

Tiny neutrino masses can be realized.

$M_N \sim \mathcal{O}(10^{-8})$ GeV $\quad M_S \sim \mathcal{O}(10^2)$ GeV

$M_L \sim \mathcal{O}(10^{-7})$ GeV $\quad M_D \sim \mathcal{O}(1)$ GeV

Small $\cancel{U(1)}_L$

$$\Rightarrow M_\nu \sim \mathcal{O}(10^{-11} - 10^{-10})\text{GeV}$$

Our model

One−zero textures are obtains.

·Model - A :　(N_{Re}, $N_{R\mu}$)=(0, 1)　(N_{Le}, $N_{L\mu}$)=(0, 1)

Linear　　Inverse

$$M_\nu = \begin{pmatrix} \times & \times & \times \\ \times & 0 & \times \\ \times & \times & 0 \end{pmatrix} + \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{pmatrix} = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & 0 \end{pmatrix}$$

·Model - B :　(N_{Re}, $N_{R\tau}$)=(0, −1)　(N_{Le}, $N_{L\tau}$)=(0, −1)

$$M_\nu = \begin{pmatrix} \times & \times & \times \\ \times & 0 & \times \\ \times & \times & 0 \end{pmatrix} + \begin{pmatrix} \times & 0 & \times \\ 0 & 0 & 0 \\ \times & 0 & \times \end{pmatrix} = \begin{pmatrix} \times & \times & \times \\ \times & 0 & \times \\ \times & \times & \times \end{pmatrix}$$

One zero

One–zero textures

The number of parameters in two–zero textures.

$$9 - 2 = 7 \text{ parameters}$$

Three masses,
three angles
three CP phases.

One zero yields
two conditions
(two constraints).

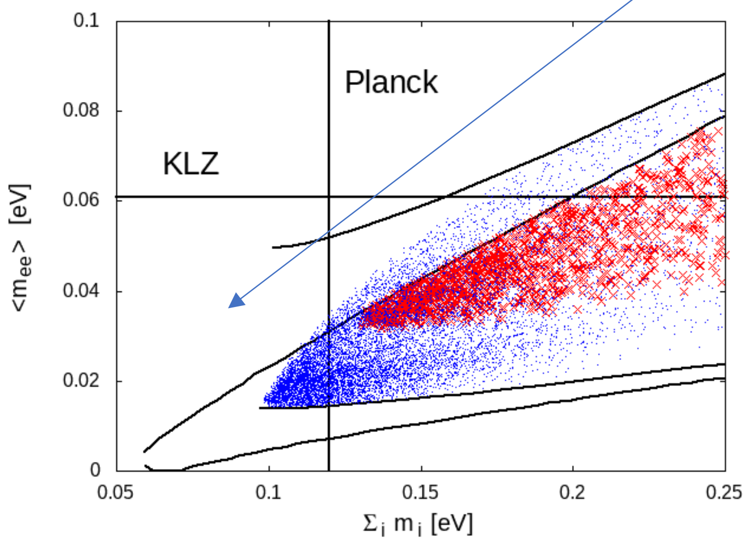
One can predict 2 observables with 7 input parameters.

$\sum m \quad < m_{ee} >$

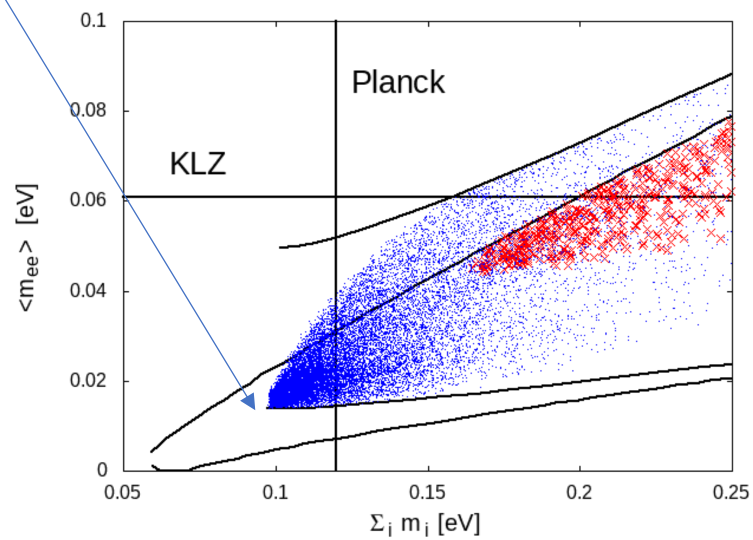
$\Delta m_{12}^2 \quad \Delta m_{23}^2 \quad \theta_{12} \quad \theta_{13} \quad \theta_{23}$
$\delta \quad \alpha_{1(2)}$

One-zero textures

$$\text{Model}-\text{A}\begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & 0 \end{pmatrix}$$



$$\text{Model}-\text{B}\begin{pmatrix} \times & \times & \times \\ \times & 0 & \times \\ \times & \times & \times \end{pmatrix}$$

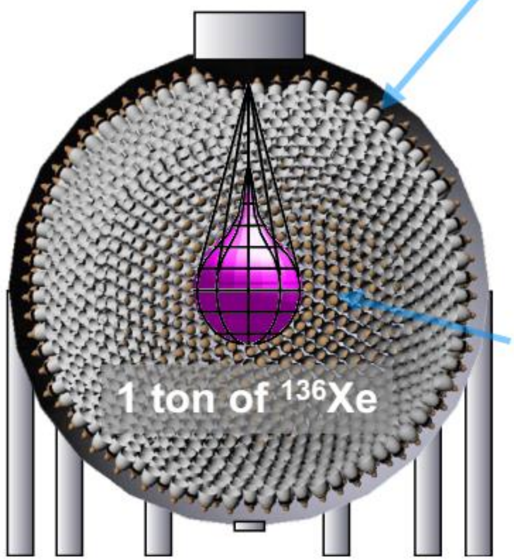


Normal ordering (NO) is disfavored,

inverted ordering (IO) is allowed.

KamLAND2-Zen KamLAND → KamLAND2

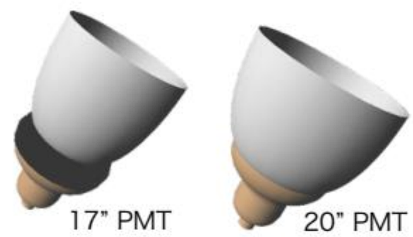
- Enlarge opening
- General use: accommodate various devices such as $CdWO_4$, NaI, CaF_2 detectors



R&D to improve the energy resolution

Winstone cone & High QE PMT

Improve light collection efficiency and photo coverage **×1.9**

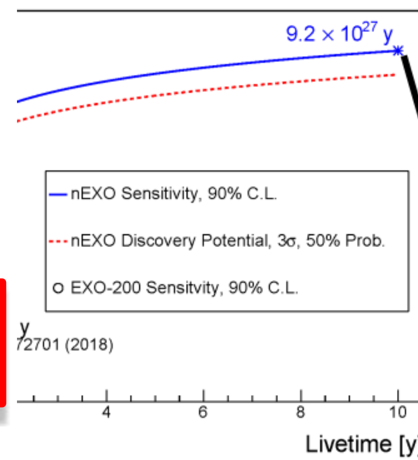


Brighter LS **×1.4**

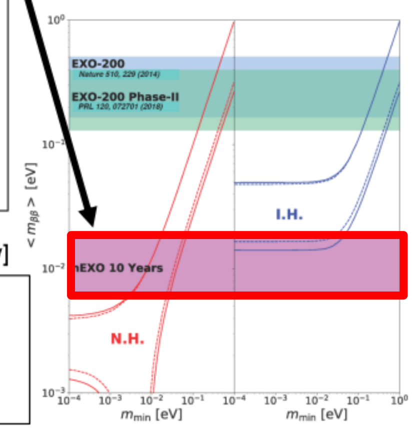
Current LS ~8,000 photon/MeV
LAB based new LS ~12,000 photon/MeV

σ(2.6MeV)=4% → < 2.5%
Target ⟨$m_{\beta\beta}$⟩ ~20meV in 5 yrs

ivity as a function of time for the baseline design



nEXO



- $g_A = g_A^{free}$=-1.2723
- Band is the envelope of NME:
  - EDF: T.R. Rodríguez and G. Martínez-Pinedo, PRL 105, 252503 (2010)
  - ISM: J. Menendez et al., Nucl Phys A 818, 139 (2009)
  - IBM-2: J. Barea, J. Kotila, and F. Iachello, PRC 91, 034304 (2015)
  - QRPA: F. Šimkovic et al., PRC 87 045501 (2013)
  - SkyrmeQRPA: M.T. Mustonen and J. Engel PRC 87 064302 (2013)

Scalar potential

The scalar potential is given by

$$V = m_H^2|H|^2 + m_\Phi^2|\Phi|^2 + m_L^2|S_L|^2 + m_{\mu\tau}^2|S_{\mu\tau}|^2$$
$$+ \mu[H^\dagger \Phi S_L^\dagger + h.c.]$$
$$+ \lambda_1|H|^4 + \lambda_2|\Phi|^4 + \lambda_3|H|^2|\Phi|^2 + \lambda_4(H^\dagger\Phi)(\Phi^\dagger H)$$
$$+ \lambda_5|S_{\mu\tau}|^4 + \lambda_6|H|^2|S_{\mu\tau}|^2 + \lambda_7|\Phi|^2|S_{\mu\tau}|^2$$
$$+ \lambda_8|S_L|^4 + \lambda_9|H|^2|S_L|^2 + \lambda_{10}|\Phi|^2|S_L|^2 + \lambda_{11}|S_L|^2|S_{\mu\tau}|^2$$

The $U(1)_L$ term is necessary. Small $U(1)_L$ → Small VEVs

$$V_{\not L} = B^2[H^\dagger\Phi + h.c.]$$

[E. Ma, PRL86, 2502 (2001)]

$$v_\Phi \simeq -\frac{B^2 v_{\rm ew}}{m_\Phi^2 - \frac{\mu^2}{2}\frac{v_{\rm ew}^2}{m_L^2}} \qquad v_L \simeq -\frac{\mu}{\sqrt{2}}\frac{v_{\rm ew}}{m_L^2}v_\Phi$$

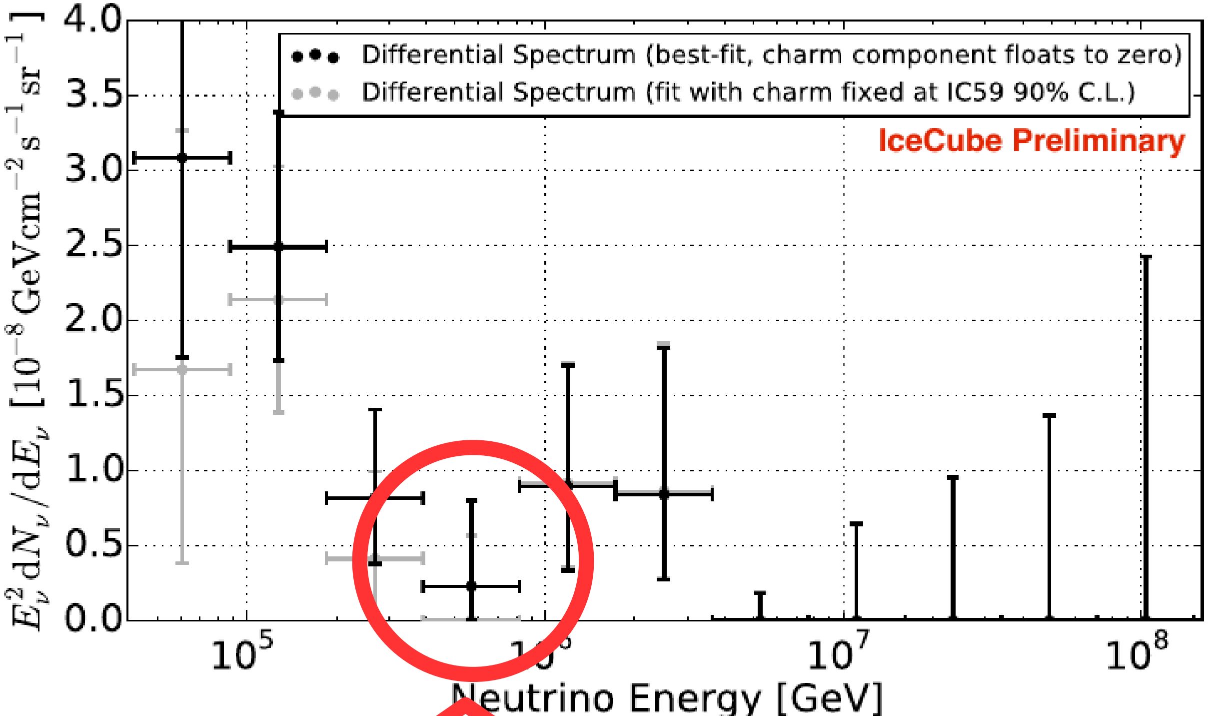
Light Scalar(s)? “Majoron” and …

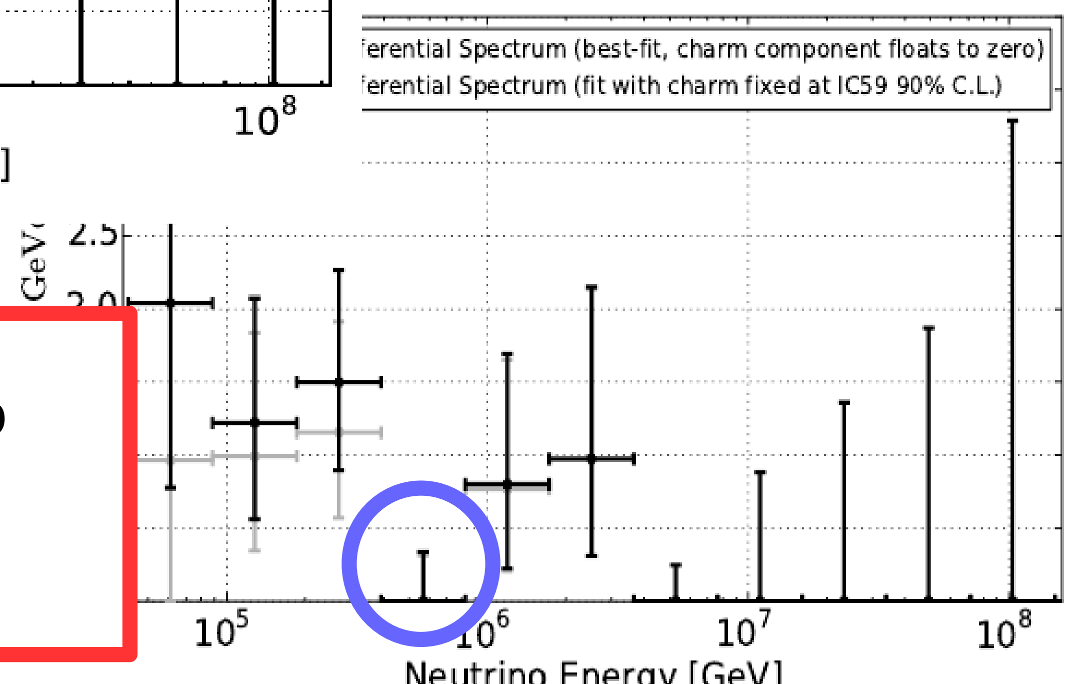
Summary

- Extension of SM with U(1)$L_\mu - L_\tau$ gauge is very attractive.
- Not only g−2, here we show
- It explains the gap observed at IceCube around 500 TeV.
- We also construct a UV completion of such model which explains neutrino physics with predictions.

Backup

Three–years vs four–years

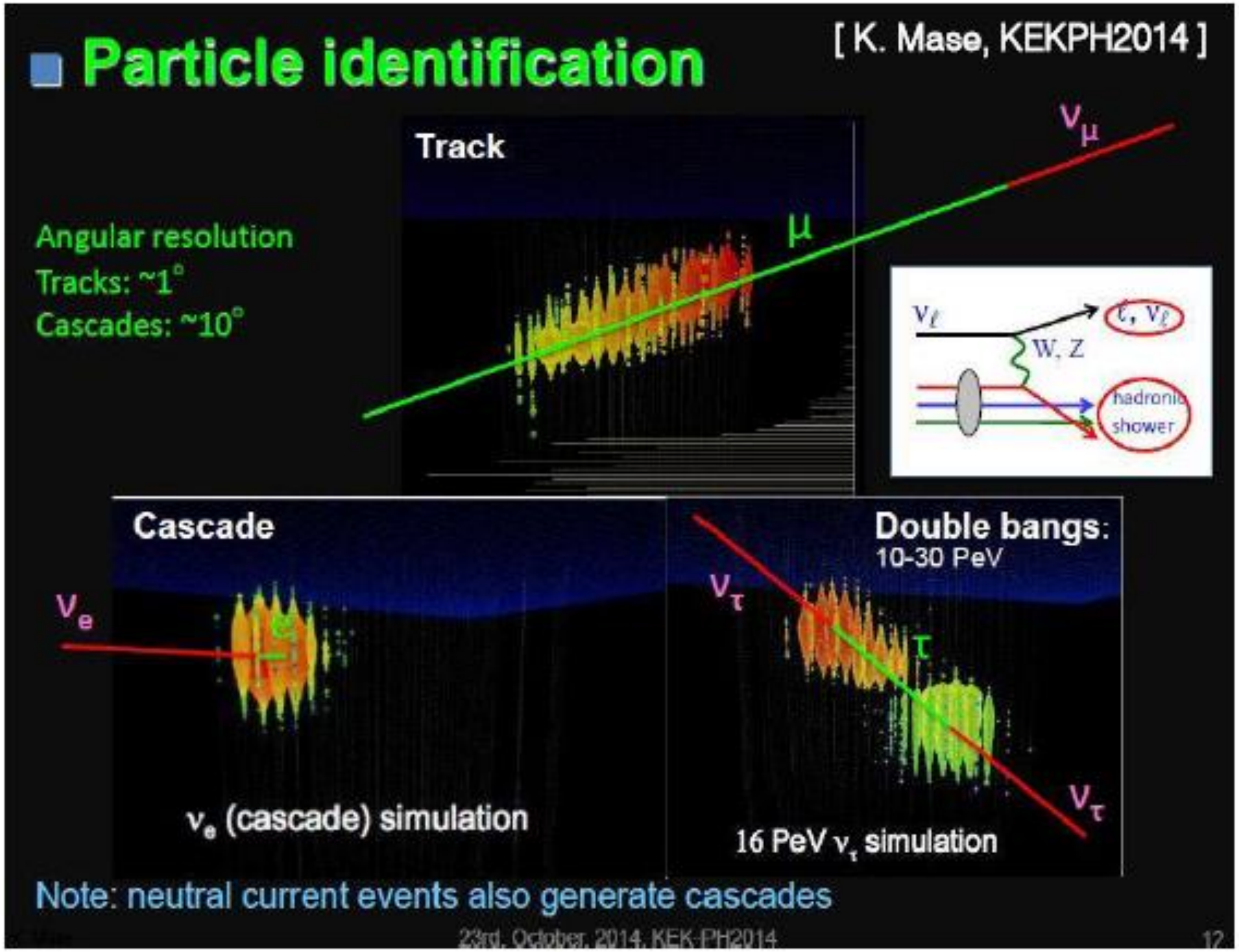




In four–years data, the gap has been somewhat filled, but there still exists a dip.

Event topology (flavors)

IceCube can distinguish flavors by observing event topology.



[K. Mase, KEK-PH2014]

Charged Current (CC)

- electrons → shower
- muons → track
- taus → shower, track, double-bang

Neutral Current (NC)

hadronic shower for all flavors

Energy cut-off

Diffuse neutrino flux for several spectral indices.

Inverted hierarchy

$m_3 = 0.001$ eV

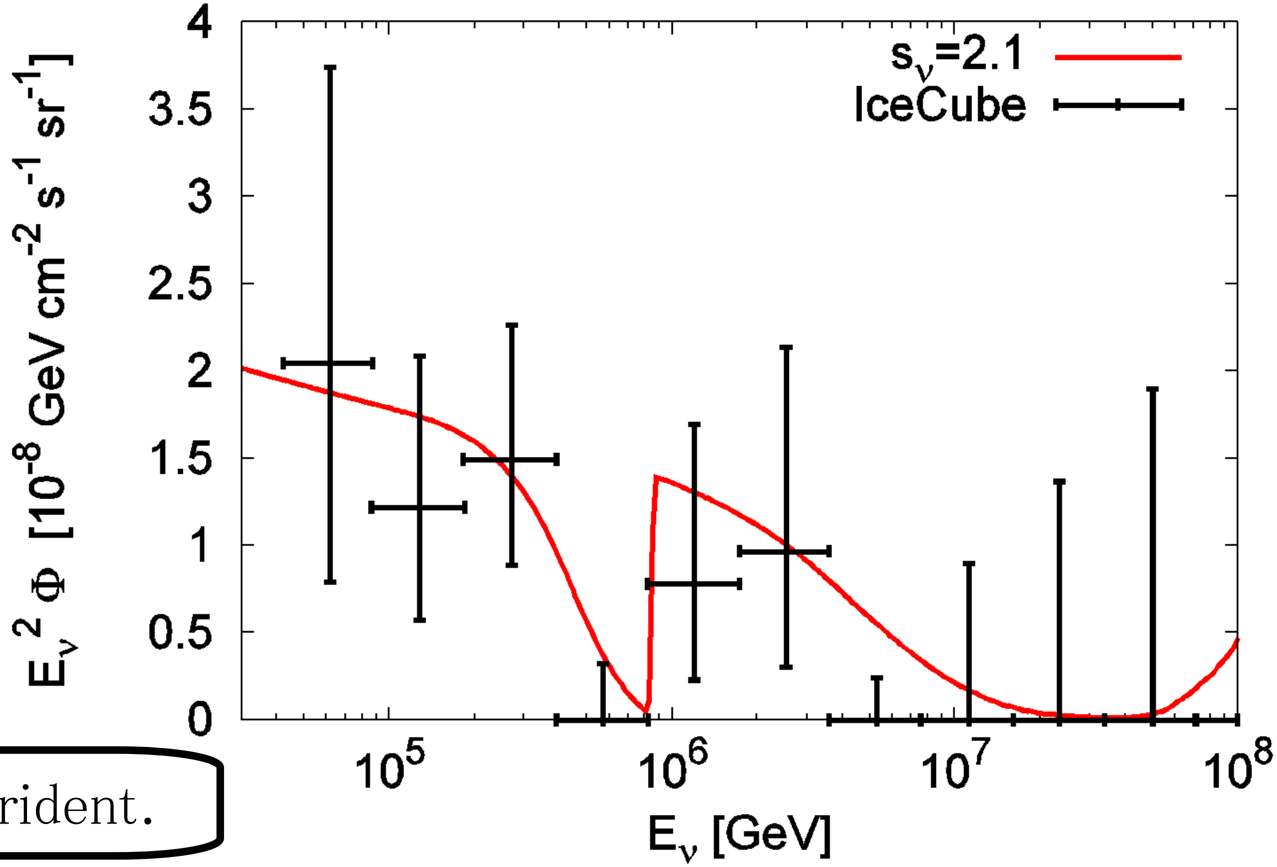
(hierarchical)

Without setting $E_{\rm cut}$

$M_{Z'} = 9$ MeV

$g_{Z'} = 5 \times 10^{-3}$

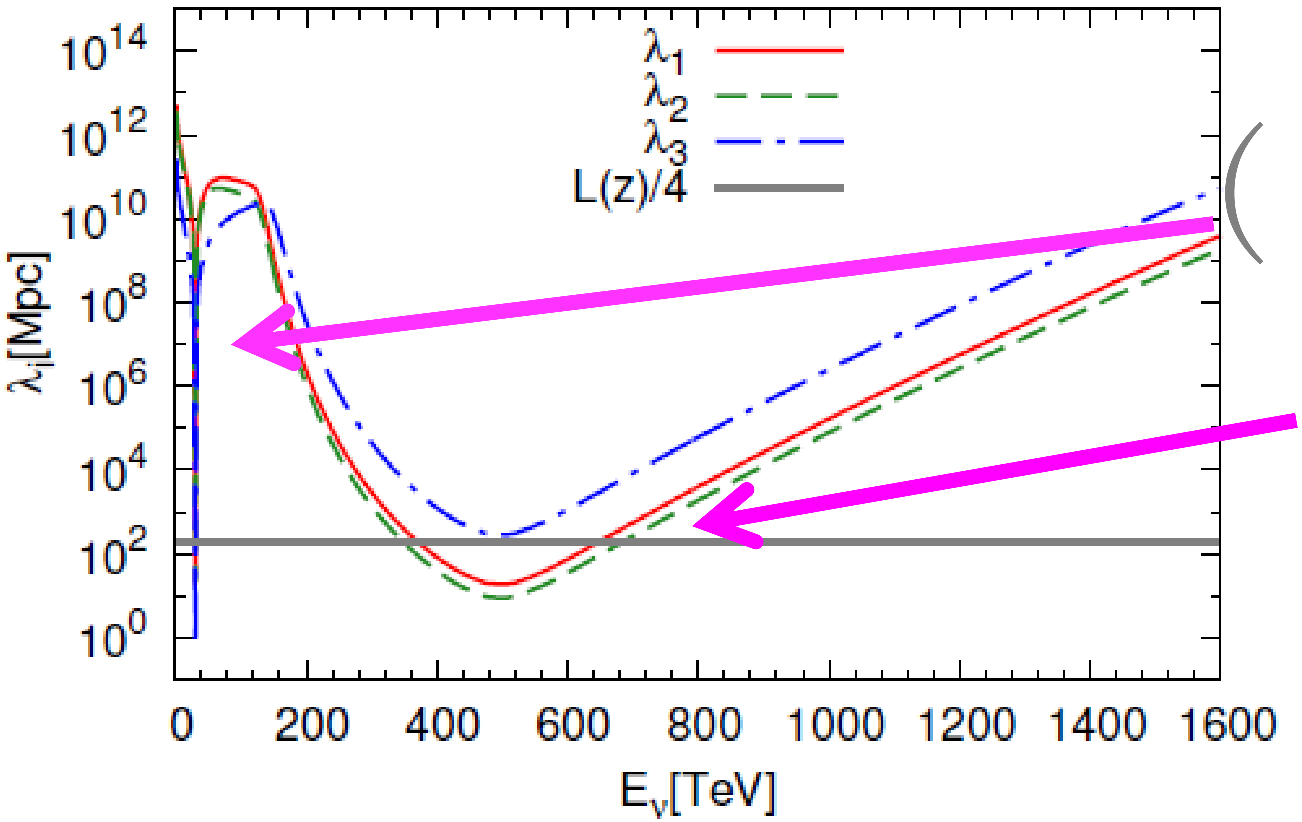
Excluded by trident.



We need $g_{Z'} = \mathcal{O}(10^{-3})$nd the CnuB momentum effects.

($m_{\rm lightest} \ll T_\nu$)

Calculation of mean free path



$m_{\nu_1} = 4.89 \times 10^{-4}$ eV

$m_{\nu_2} = 4.96 \times 10^{-4}$ eV

$m_{\nu_3} = 3 \times 10^{-3}$ eV

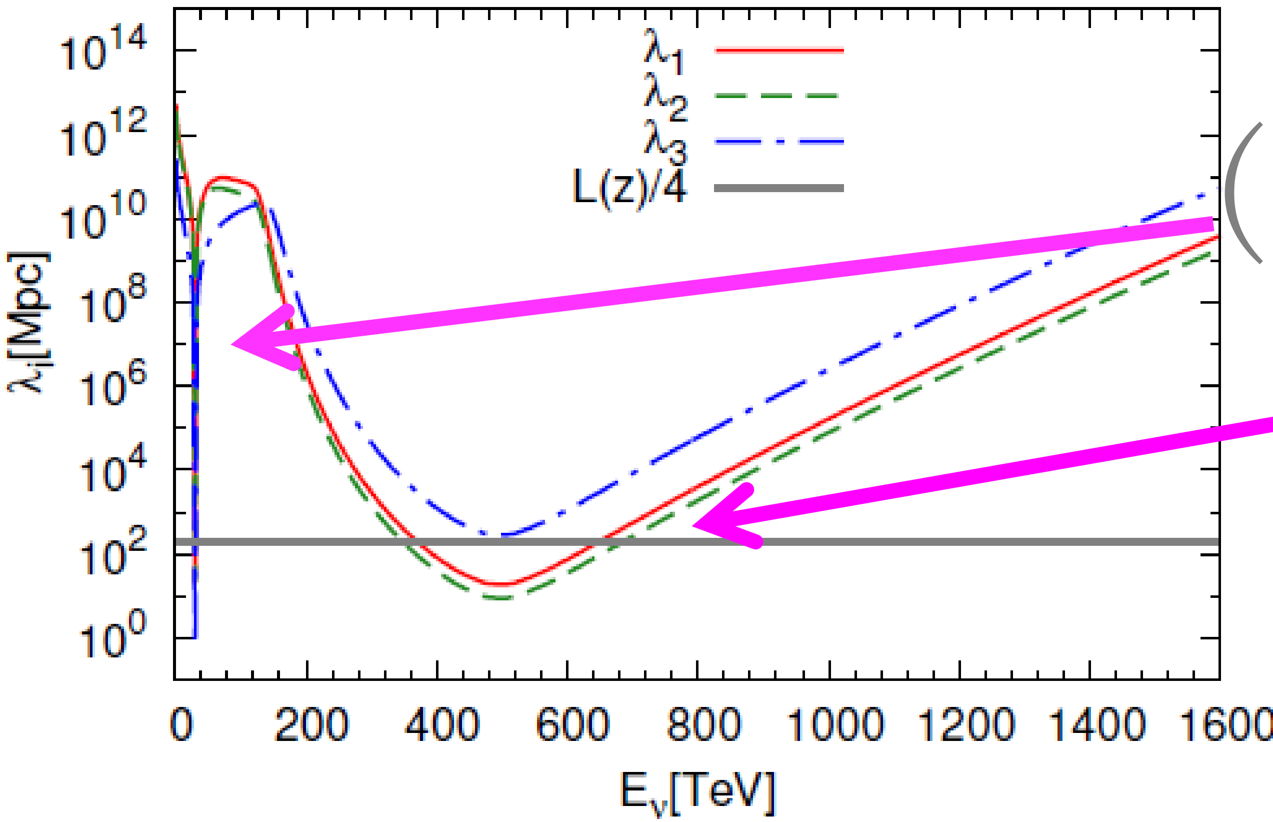
(Inverted hierarchy)

(1) Positions of the gaps.

$$m_{Z'} \simeq \sqrt{2 E^{\rm res}_{\nu_i} {}_\nu m_{\rm C\nu B}}$$

$$E^{\rm res}_{\nu_i} = \begin{cases} \frac{1}{1+z} \frac{m^2_{Z'}}{2 m_{\nu_{1(2)}}} \simeq 30 \text{ TeV}, \\ \frac{1}{1+z} \frac{m^2_{Z'}}{2 m_{\nu_3}} \simeq 500 \text{ TeV} . \end{cases}$$

Calculation of mean free path



$m_{\nu_1} = 4.89 \times 10^{-2}$ eV

$m_{\nu_2} = 4.96 \times 10^{-2}$ eV

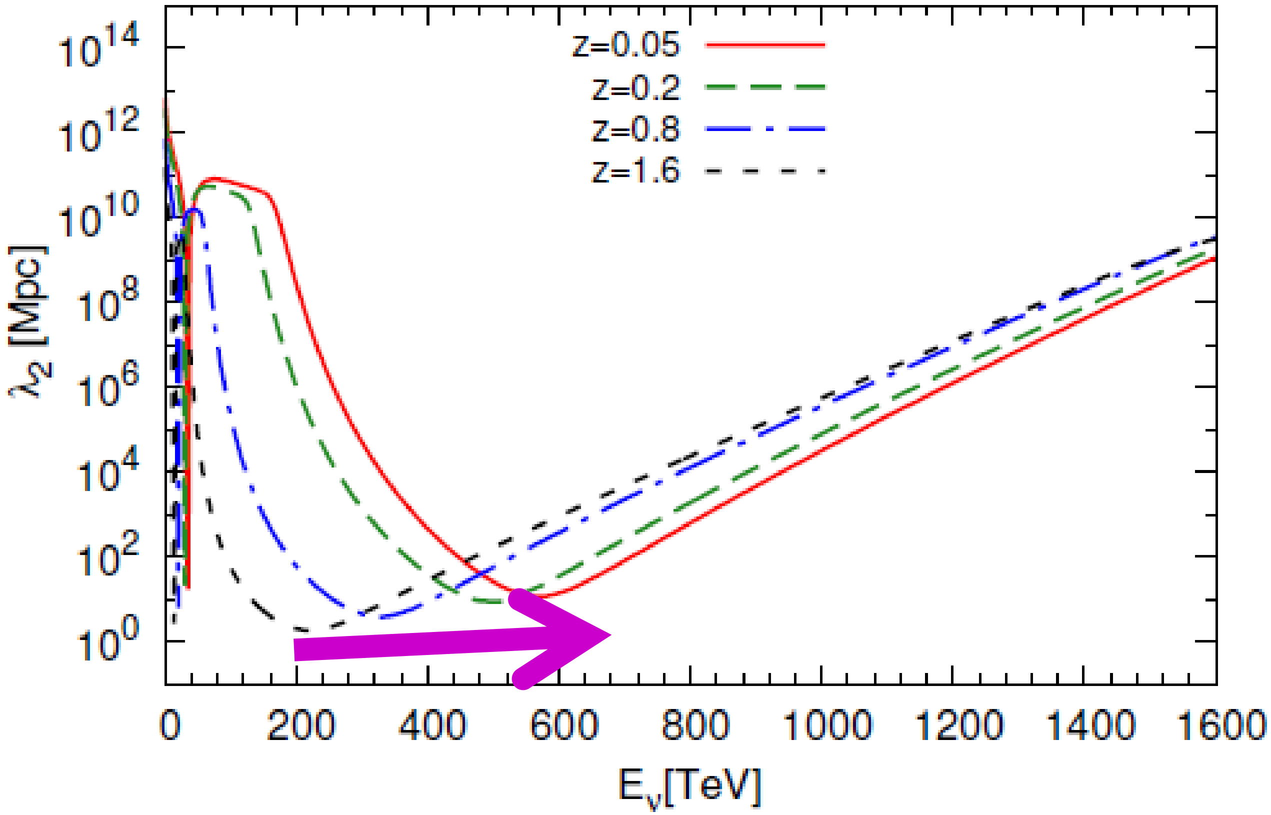
$m_{\nu_3} = 3 \times 10^{-3}$ eV

(Inverted hierarchy)

(2) Smaller CnuB mass → Broader gap

$$M_{Z'}^2 \simeq 2E_{\rm res}(1+z)\left[\sqrt{|\mathbf{p}|^2 + m_{\rm C\nu B}^2} - |\mathbf{p}|\cos\theta\right]$$

Calculation of mean free path



$m_{\nu_1} = 4.89 \times 10^{-2}$ eV

$m_{\nu_2} = 4.96 \times 10^{-2}$ eV

$m_{\nu_3} = 3 \times 10^{-3}$ eV

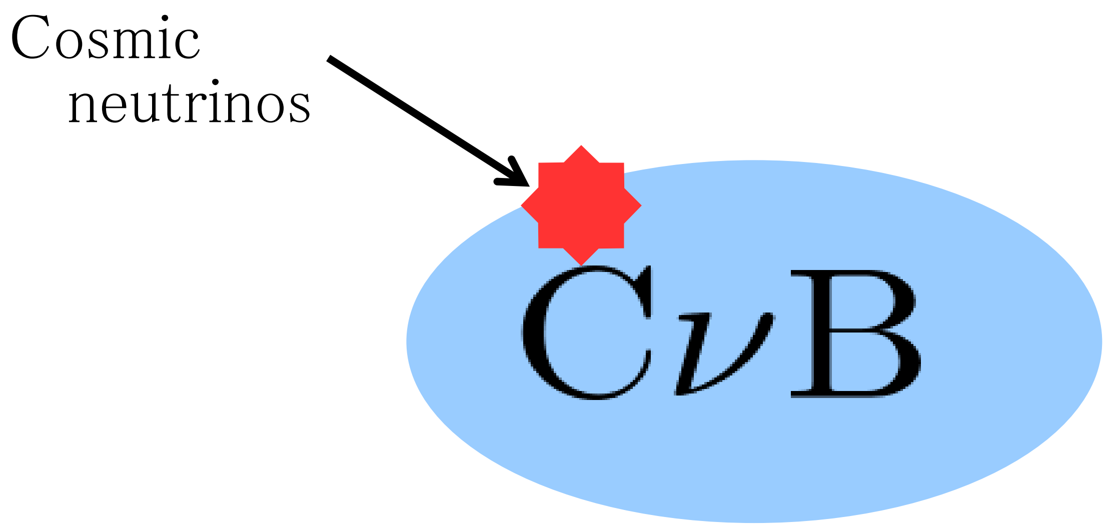
(Inverted hierarchy)

(3) Larger red-shift → Broader gap

$$M_{Z'}^2 \simeq 2E_{\rm res}(1+z)\left[\sqrt{|\mathbf{p}|^2 + m_{\rm C\nu B}^2} - |\mathbf{p}|\cos\theta\right]$$

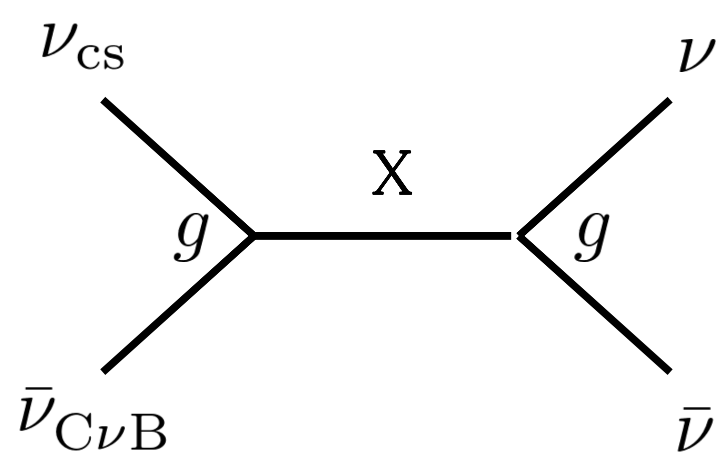
Secret neutrino interaction

The gap may indicate ***Secret Neutrino Interaction.***



Cosmic Neutrino Background ($C\nu B$)

$$\mathcal{L}_{S\nu I} = g\bar{\nu}\nu X + h.c.$$



A gap at a particular energy could be realized by a resonant interaction mediated by a new particle X.

[Ioka, Murase, PTEP2014, 061E01]
[Ng, Beacom, PRD90, 065035 (2014)]
[Ibe, Kaneta, PRD90, 053011 (2014)]

$U(1)_{L_\mu - L_\tau}$ Breaking in Seesaw mechanisms

Breaking of $U(1)_{L\mu - L\tau}$

(ex.) Type−I seesaw

$$\mathcal{M} = \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix}$$

- Without symmetry breaking.

$$M_D = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix} \qquad M_R = \begin{pmatrix} \times & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & 0 \end{pmatrix}$$

$$\Rightarrow \quad M_\nu = -M_D (M_R)^{-1} M_D^T = \begin{pmatrix} \times & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & 0 \end{pmatrix}$$

- A SM singlet scalar having $U(1)_{L\mu - L\tau}$ charge 1 or −1.

$$M_D = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix} \quad M_R = \begin{pmatrix} \times & \times & \times \\ \times & 0 & \times \\ \times & \times & 0 \end{pmatrix} \quad \Rightarrow \quad M_\nu = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{pmatrix}$$

Two zero minors.

$$(M_\nu^{-1})_{\mu\mu} = (M_\nu^{-1})_{\tau\tau} = 0$$

Breaking of $U(1)_{L\mu - L\tau}$

(ex.) Type−I seesaw

- An SU(2) doublet scalar having $U(1)_{L\mu - L\tau}$ charge 1.

$$M_D = \begin{pmatrix} \times & \times & 0 \\ 0 & \times & 0 \\ \times & 0 & \times \end{pmatrix} \quad M_R = \begin{pmatrix} \times & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & 0 \end{pmatrix} \Rightarrow M_\nu = \begin{pmatrix} \times & 0 & \times \\ 0 & 0 & \times \\ \times & \times & \times \end{pmatrix}$$

- An SU(2) doublet scalar having $U(1)_{L\mu - L\tau}$ charge −1.

$$M_D = \begin{pmatrix} \times & 0 & \times \\ \times & \times & 0 \\ 0 & 0 & \times \end{pmatrix} \quad M_R = \begin{pmatrix} \times & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & 0 \end{pmatrix} \Rightarrow M_\nu = \begin{pmatrix} \times & \times & 0 \\ \times & \times & \times \\ 0 & \times & 0 \end{pmatrix}$$

→ Two−zero textures are obtained.

Breaking of U(1)$_{L\mu - L\tau}$

(ex.) Inverse seesaw

$$\mathcal{M} = \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M_S \\ 0 & M_S^T & M_L \end{pmatrix}$$

- Without symmetry breaking.

$$M_D = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix} \quad M_S = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix} \quad M_L = \begin{pmatrix} \times & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & 0 \end{pmatrix}$$

$$\Rightarrow \quad M_\nu = -M_D (M_S^T)^{-1} M_L (M_S)^{-1} M_D^T = \begin{pmatrix} \times & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & 0 \end{pmatrix}$$

Breaking of U(1)$_{L\mu - L\tau}$

(ex.) Inverse seesaw

- A SM singlet scalar having U(1)$_{L\mu - L\tau}$ charge 1.

$$M_D = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix} \quad M_S = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix} \quad M_L = \begin{pmatrix} \times & \times & \times \\ \times & 0 & \times \\ \times & \times & 0 \end{pmatrix} \Rightarrow M_\nu = \begin{pmatrix} \times & \times & \times \\ \times & 0 & \times \\ \times & \times & 0 \end{pmatrix}$$

- An SU(2) doublet scalar having U(1)$_{L\mu - L\tau}$ charge 1or −1.

$$M_D = \begin{pmatrix} \times & 0 & \times \\ \times & \times & 0 \\ 0 & 0 & \times \end{pmatrix} \quad M_S = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix} \quad M_L = \begin{pmatrix} \times & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & 0 \end{pmatrix} \Rightarrow M_\nu = \begin{pmatrix} \times & \times & 0 \\ \times & \times & \times \\ 0 & \times & 0 \end{pmatrix}$$

$$M_D = \begin{pmatrix} \times & \times & 0 \\ 0 & \times & 0 \\ \times & 0 & \times \end{pmatrix} \quad M_S = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix} \quad M_L = \begin{pmatrix} \times & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & 0 \end{pmatrix} \Rightarrow M_\nu = \begin{pmatrix} \times & 0 & \times \\ 0 & 0 & \times \\ \times & \times & \times \end{pmatrix}$$

Breaking of U(1)$_{L\mu - L\tau}$

(ex.) Linear seesaw

$$\mathcal{M} = \begin{pmatrix} 0 & M_D & M_N \\ M_D^T & 0 & M_S \\ M_N^T & M_S^T & 0 \end{pmatrix}$$

- Without symmetry breaking.

$$M_D = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix} \quad M_S = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix} \quad M_N = \begin{pmatrix} \times & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & 0 \end{pmatrix}$$

$$\Rightarrow \quad M_\nu = -M_N (M_S)^{-1} M_D^T - M_D (M_S^T)^{-1} M_N^T = \begin{pmatrix} \times & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & 0 \end{pmatrix}$$

Breaking of $U(1)_{L\mu - L\tau}$

(ex.) Linear seesaw

- An SU(2) doublet scalar having $U(1)_{L\mu - L\tau}$ charge 1 or −1.

$$M_D = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix} \quad M_S = \begin{pmatrix} \times & \times & 0 \\ 0 & \times & 0 \\ \times & 0 & \times \end{pmatrix} \quad M_N = \begin{pmatrix} \times & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & 0 \end{pmatrix} \Rightarrow M_\nu = \begin{pmatrix} \times & \times & 0 \\ \times & \times & \times \\ 0 & \times & 0 \end{pmatrix}$$

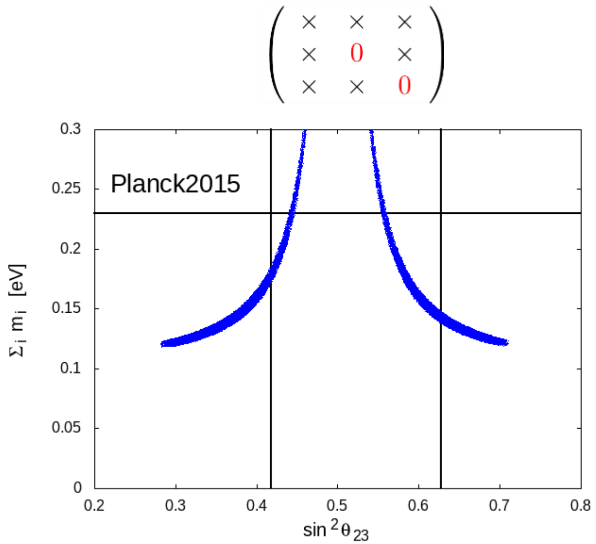
$$M_D = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix} \quad M_S = \begin{pmatrix} \times & 0 & \times \\ \times & \times & 0 \\ 0 & 0 & \times \end{pmatrix} \quad M_N = \begin{pmatrix} \times & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & 0 \end{pmatrix} \Rightarrow M_\nu = \begin{pmatrix} \times & 0 & \times \\ 0 & 0 & \times \\ \times & \times & \times \end{pmatrix}$$

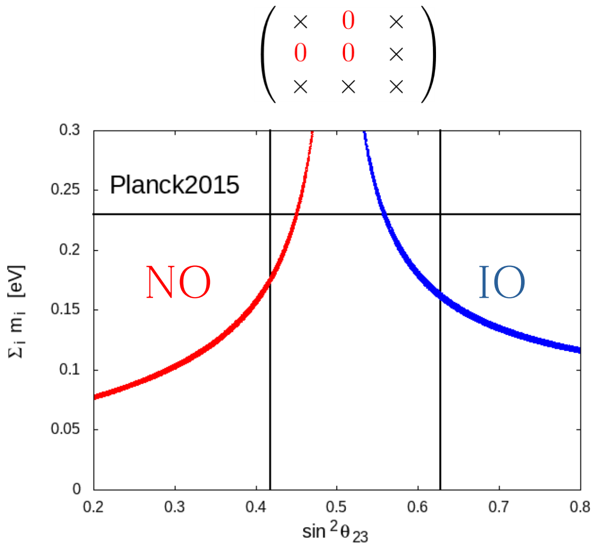
- Two SU(2) doublet scalar having $U(1)_{L\mu - L\tau}$ charge 1, −1.

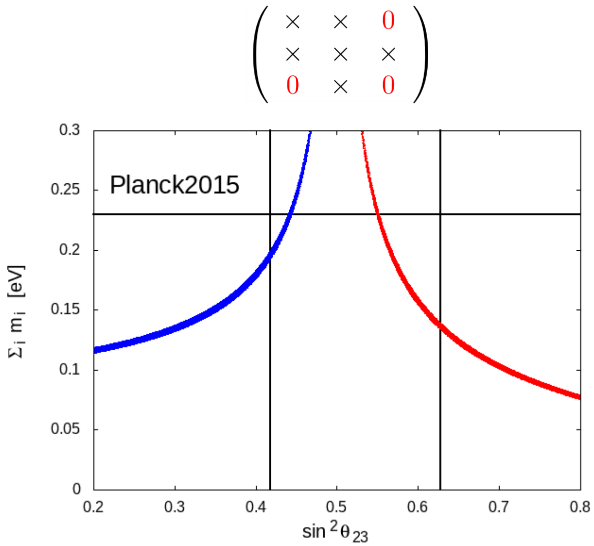
$$M_D = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix} \quad M_S = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix} \quad M_N = \begin{pmatrix} \times & \times & \times \\ \times & 0 & \times \\ \times & \times & 0 \end{pmatrix} \Rightarrow M_\nu = \begin{pmatrix} \times & \times & \times \\ \times & 0 & \times \\ \times & \times & 0 \end{pmatrix}$$

$$M_D = \begin{pmatrix} \times & \times & \times \\ \times & \times & 0 \\ \times & 0 & \times \end{pmatrix} \quad M_S = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix} \quad M_N = \begin{pmatrix} \times & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & 0 \end{pmatrix} \Rightarrow M_\nu = \begin{pmatrix} \times & \times & \times \\ \times & 0 & \times \\ \times & \times & 0 \end{pmatrix}$$

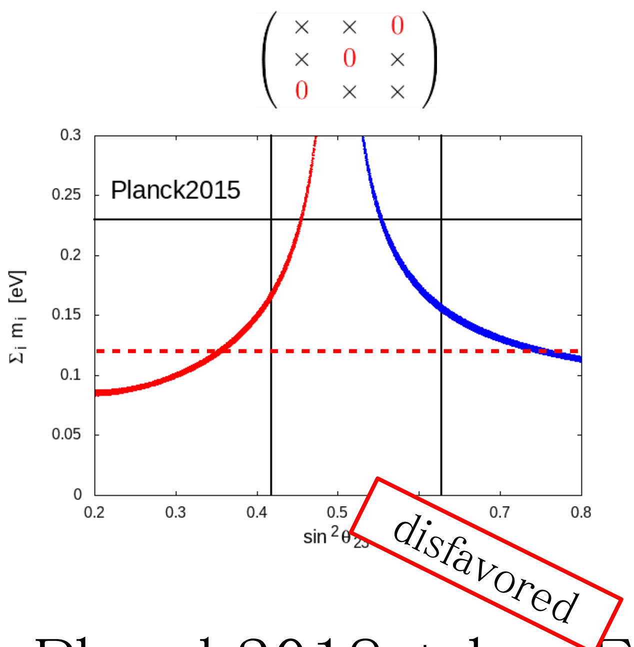
Two–zero textures vs Planck

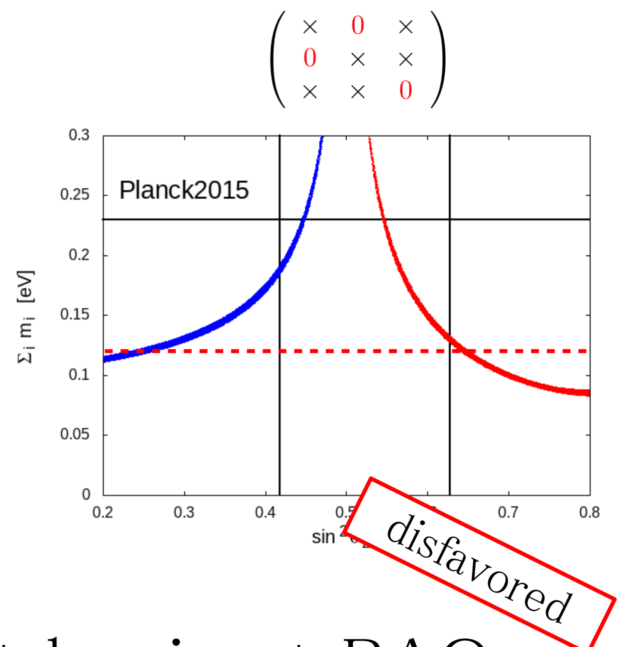


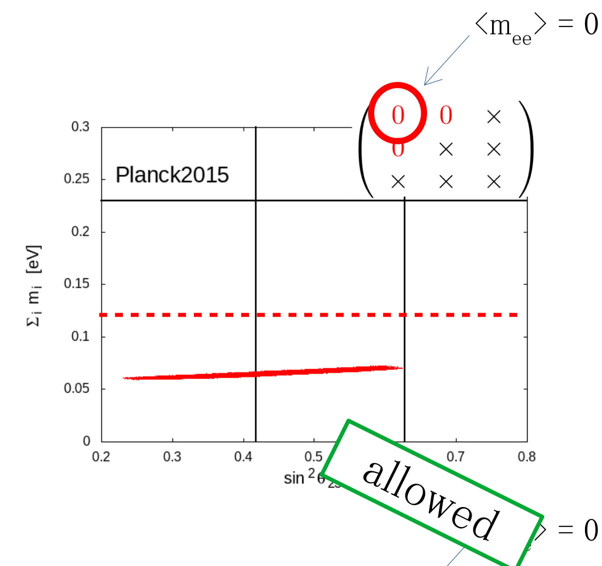


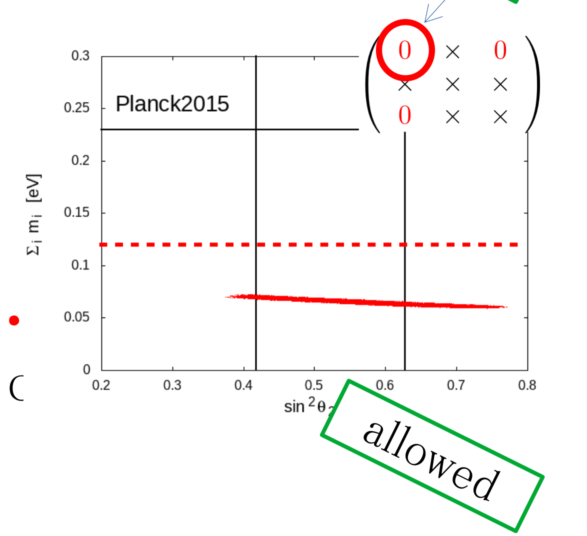


Two-zero textures vs Planck









Planck2018 + low E + lensing + BAO:

$\Sigma\ m < 0.12$ eV (95% C.

[Planck (