MeV scale leptonic force for cosmic neutrino spectrum and muon anomalous

Joe Sato (Saitama U.)

Based on arXiv: 1409.4180, 1508.07471 [hep-ph],
collaboration with T. Araki, F. Kaneko, Y. Konishi, T. Ota and T. Shimomura

Outline

- Introduction

  ~Cosmic neutrino & IceCube~

- Previous works
- Our approach
- Calculation of neutrino flux
- Summary

Introduction

High energy cosmic neutrino

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

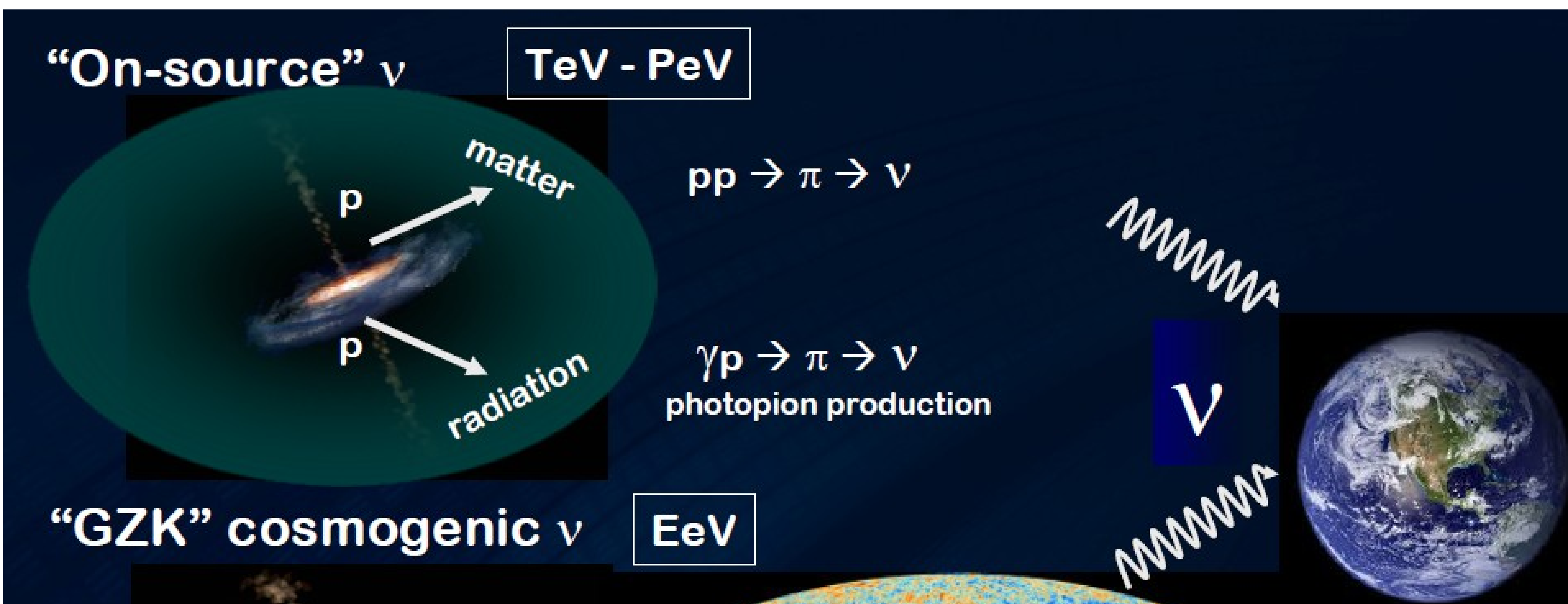
@ Source

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

oscillation →

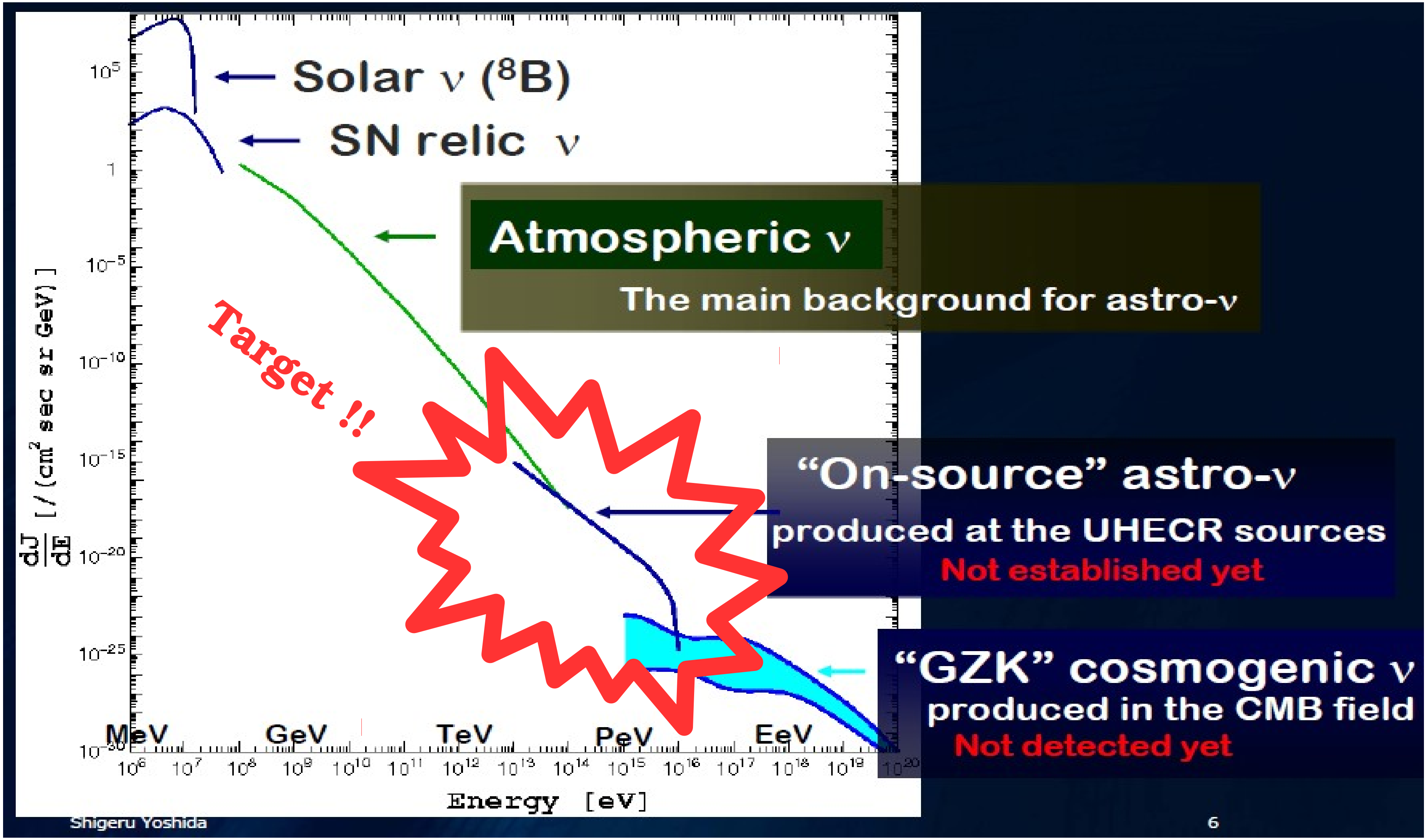
@ Earth

$$\simeq 1 : 1 : 1$$



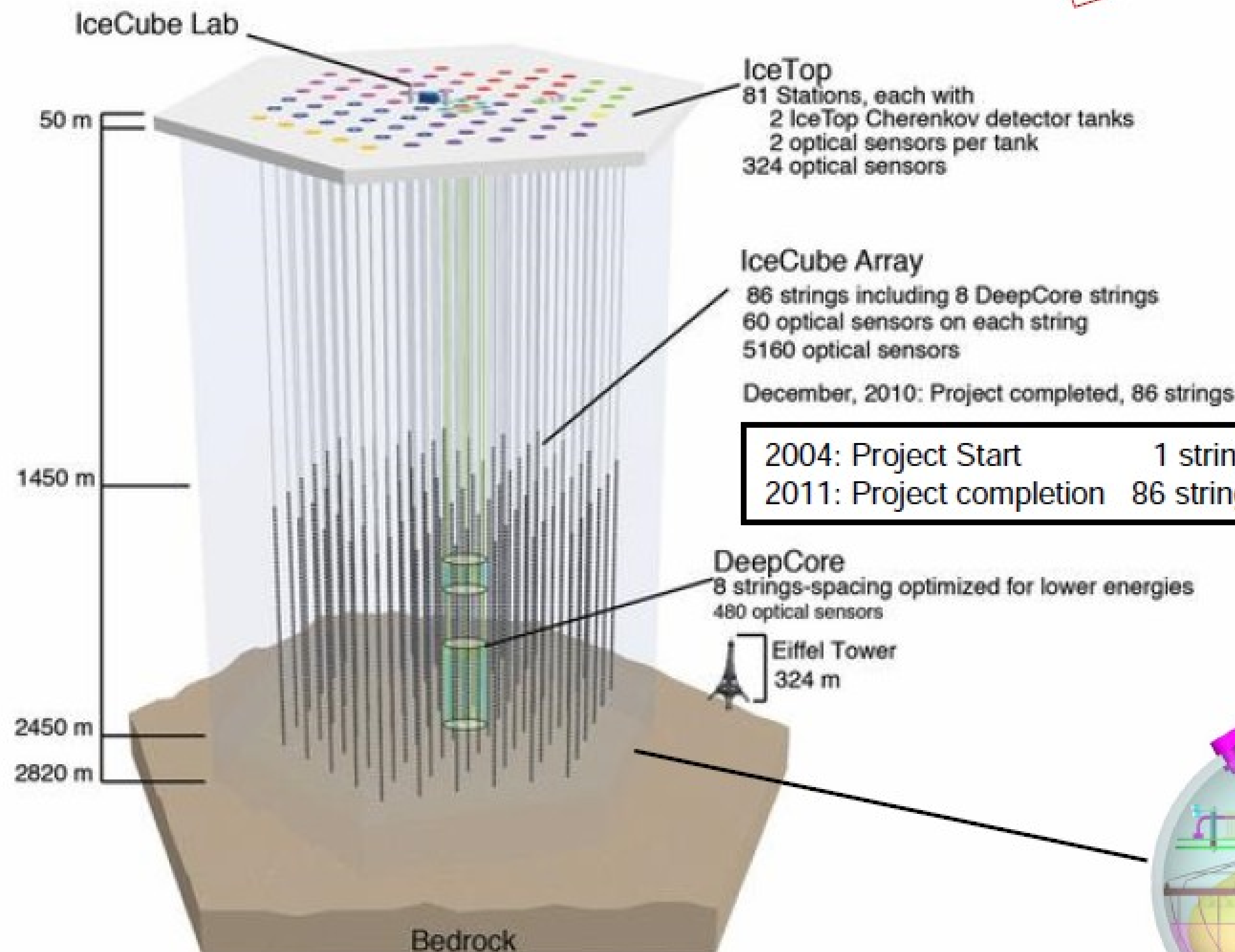
High energy cosmic neutrino

Target: Neutrinos having energies of O(TeV – PeV) .



The IceCube Neutrino Observatory

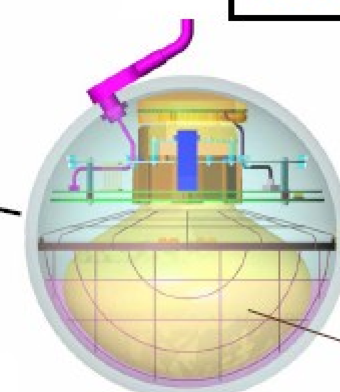
Completed: Dec 2010



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

Configuration chronology

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



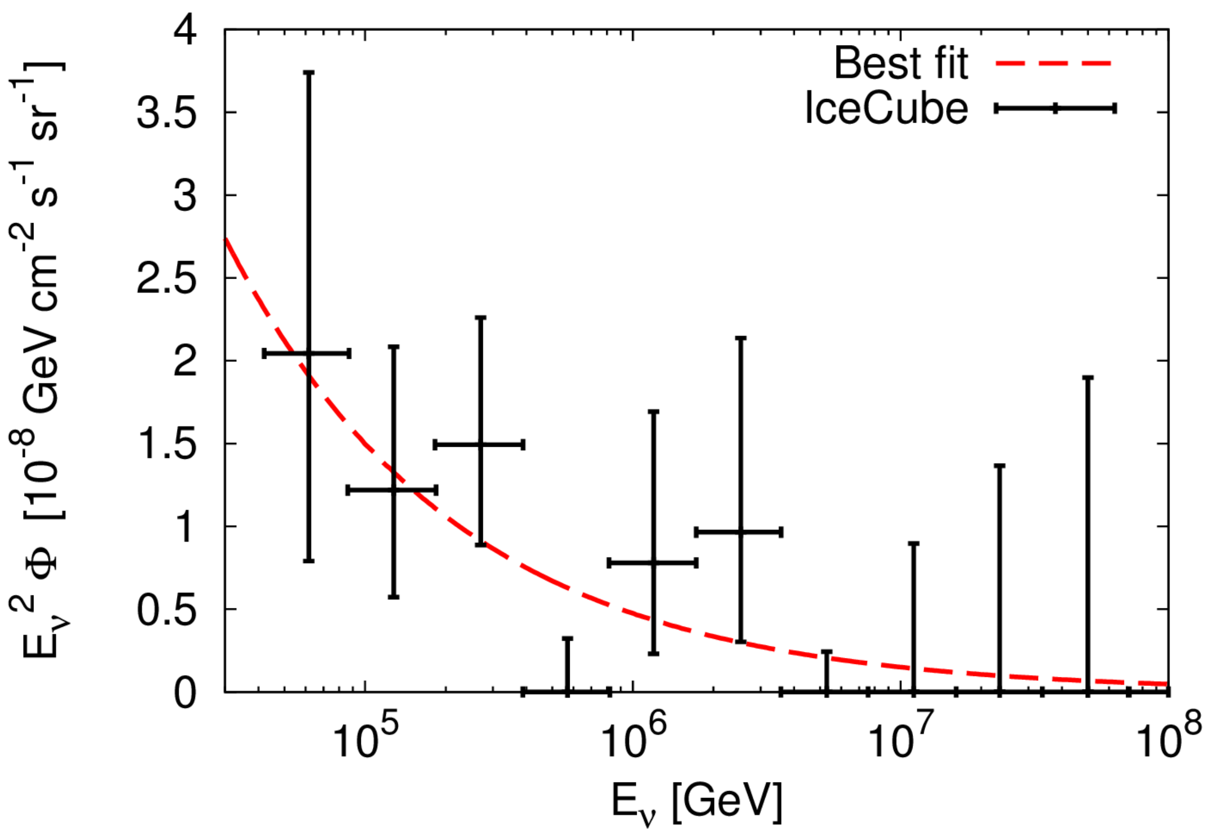
Digital Optical Module (DOM)

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

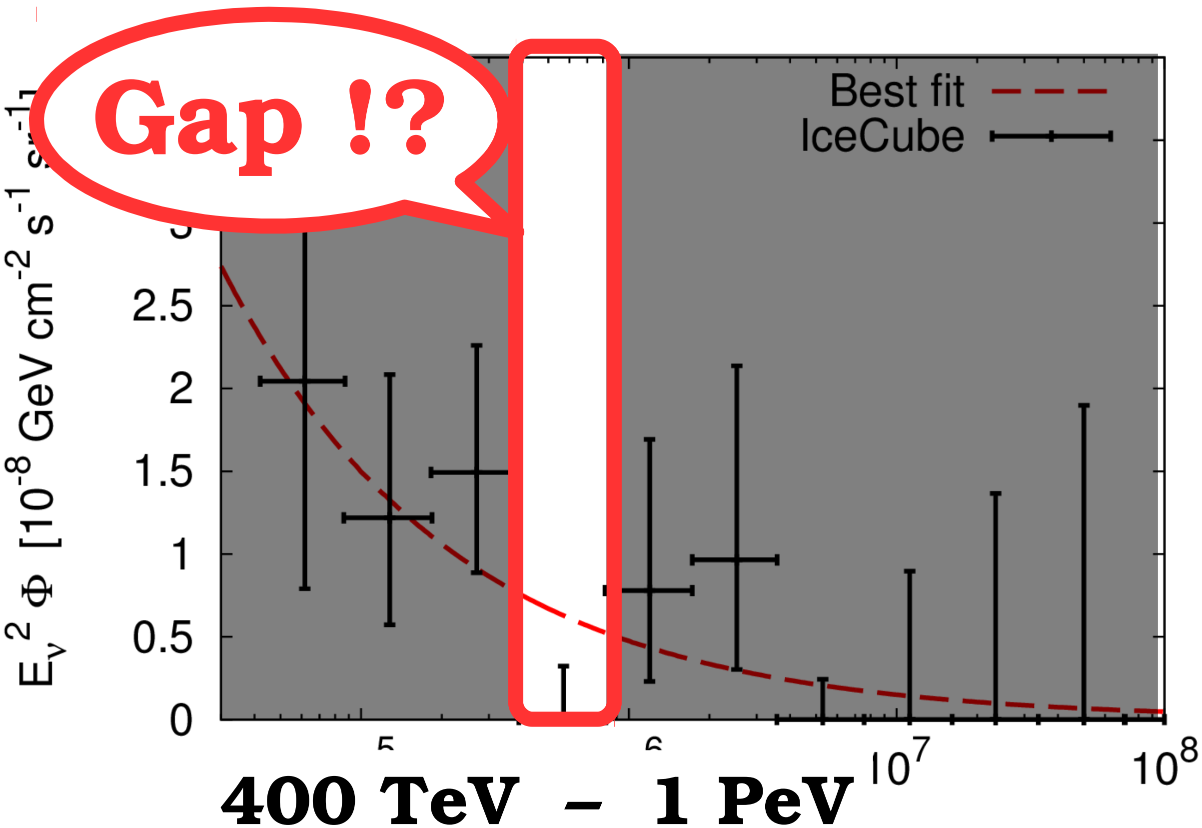
the origin of high energy cosmic neutrinos,
an acceleration mechanism of cosmic rays

but also **particle physics**.

Gap or fluctuation?

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

[PRL 113 (2014), 101101]



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Gap or fluctuation?

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

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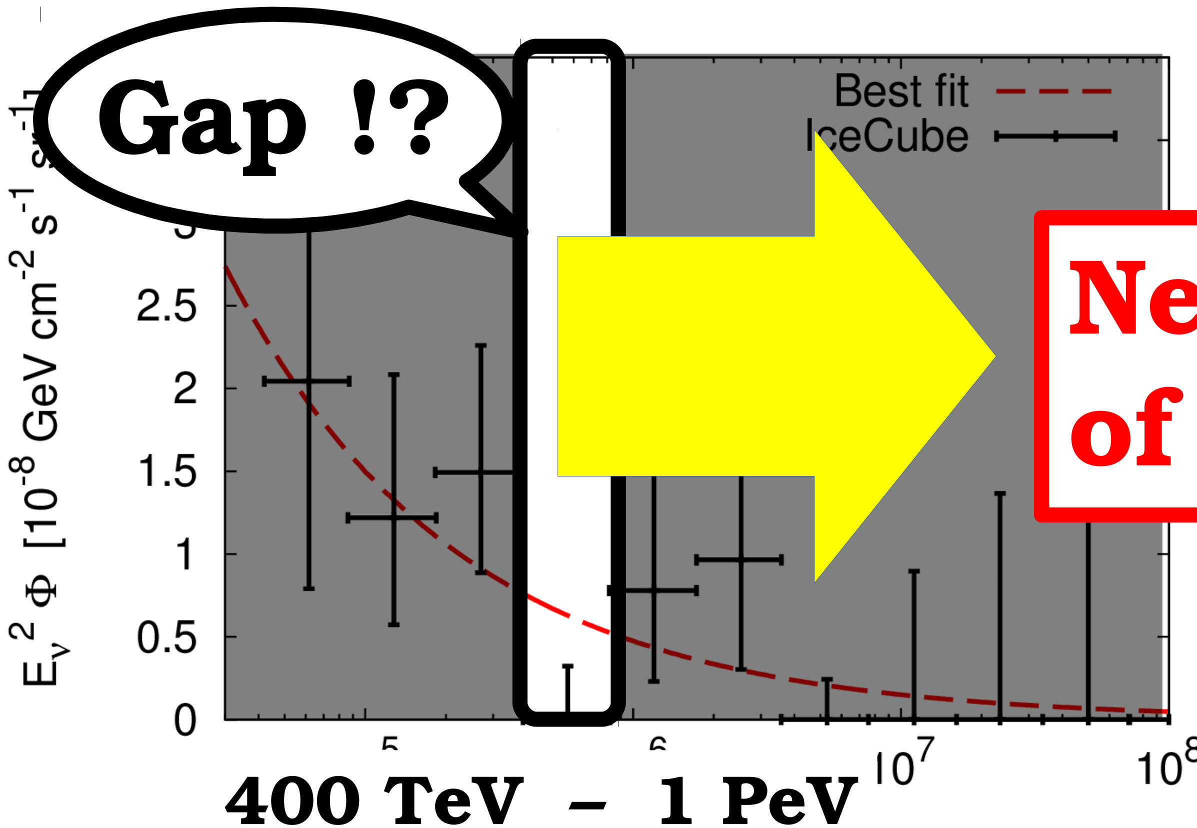


1. It rejects a purely atmospheric explanation at 5.7 sigma.
2. The data are consistent

New interactions of neutrinos ??

3. The best-fit power low is

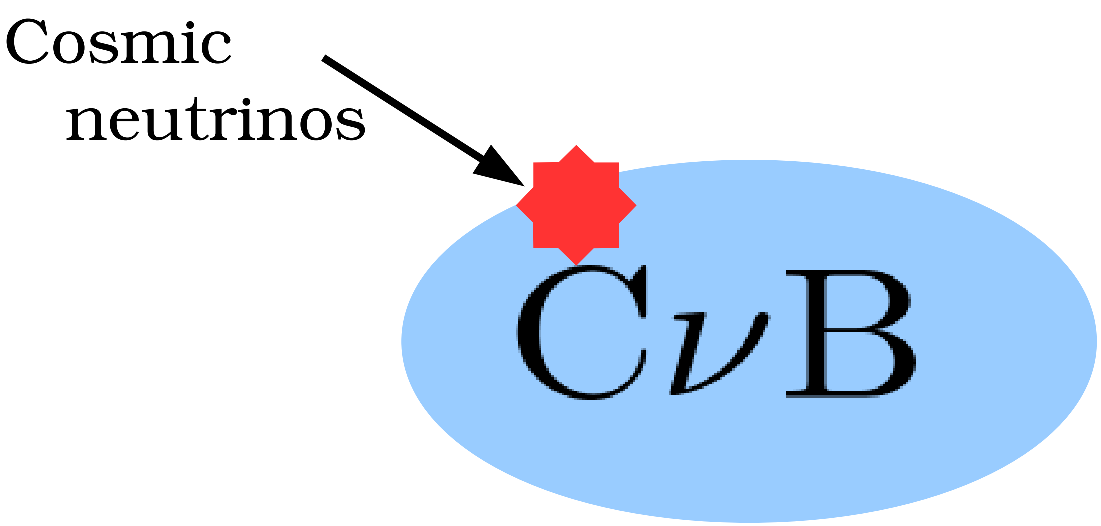
$$\Phi(E) = \phi \left[\frac{E_\nu}{100\text{TeV}} \right]^{-2.5}$$

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

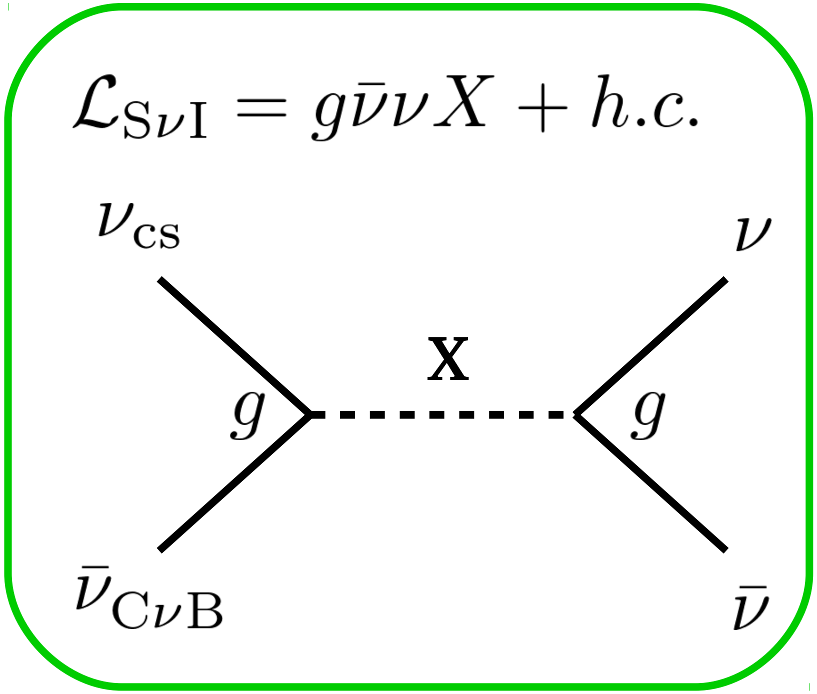
Previous works

Secret neutrino interaction

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



Cosmic Neutrino Background (CνB)



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)]

Secret neutrino interaction

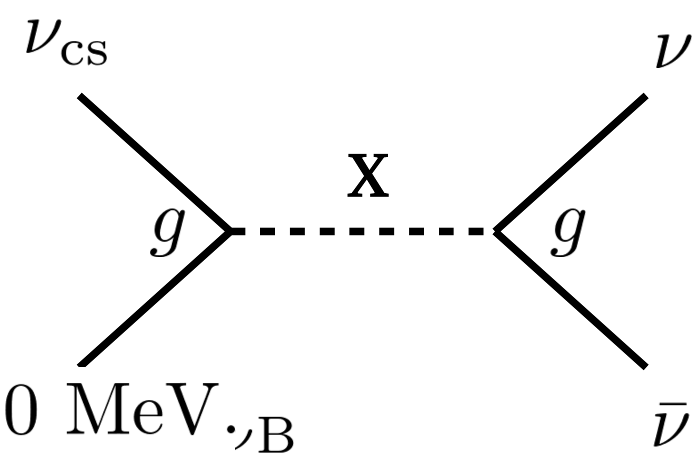
Rough estimation of the mass of X and its coupling.

$$\sigma = \frac{2\pi g^2}{M_X^2}\,\delta\left(1 - \frac{M_X^2}{s}\right)$$

$\sqrt{s}$ ‡ center-of-mass energy

M_X ‡ mass of X

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



(1) Resonant condition requires:

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

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

(2) To attenuate sufficient amount of cosmic neutrino:

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

Secret neutrino interaction

Rough estimation of the mass of X and its coupling.

New physics at the MeV scale

is a possible solution

for the IceCube gap!!

(1) R

(2) To attenuate sufficient amount of cosmic neutrino:

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

Our approach

A new gauged U(1): mu - tau

We introduce a new U(1) gauge symmetry associated with
the muon number minus tau number: $U(1)_{L_\mu - L_\tau}$.

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

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

New gauge coupling ($g_{Z'}$)

New gauge boson (Z'_ρ)

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

Longstanding discrepancy between experiments and theory:

$$a_\mu^{\rm EXP} - a_\mu^{\rm SM} = (26.1 \pm 8.0). \quad \Rightarrow \quad 3.3\ \sigma$$

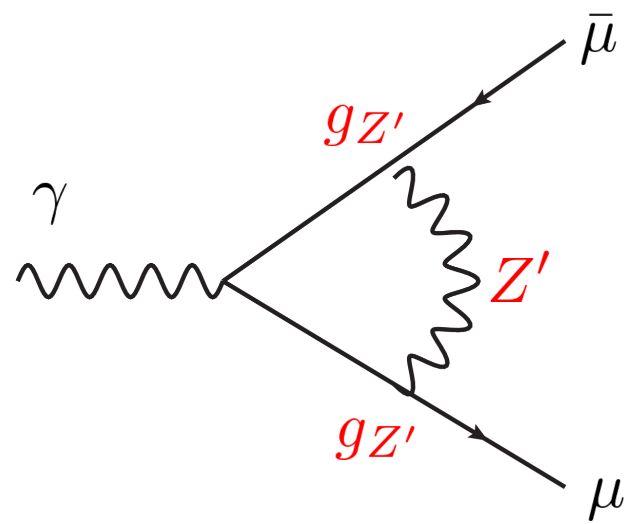
[Hagiwara, Liao, Martin, Nomura, Teubner, JPG38, 085003 (2011)]

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

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

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

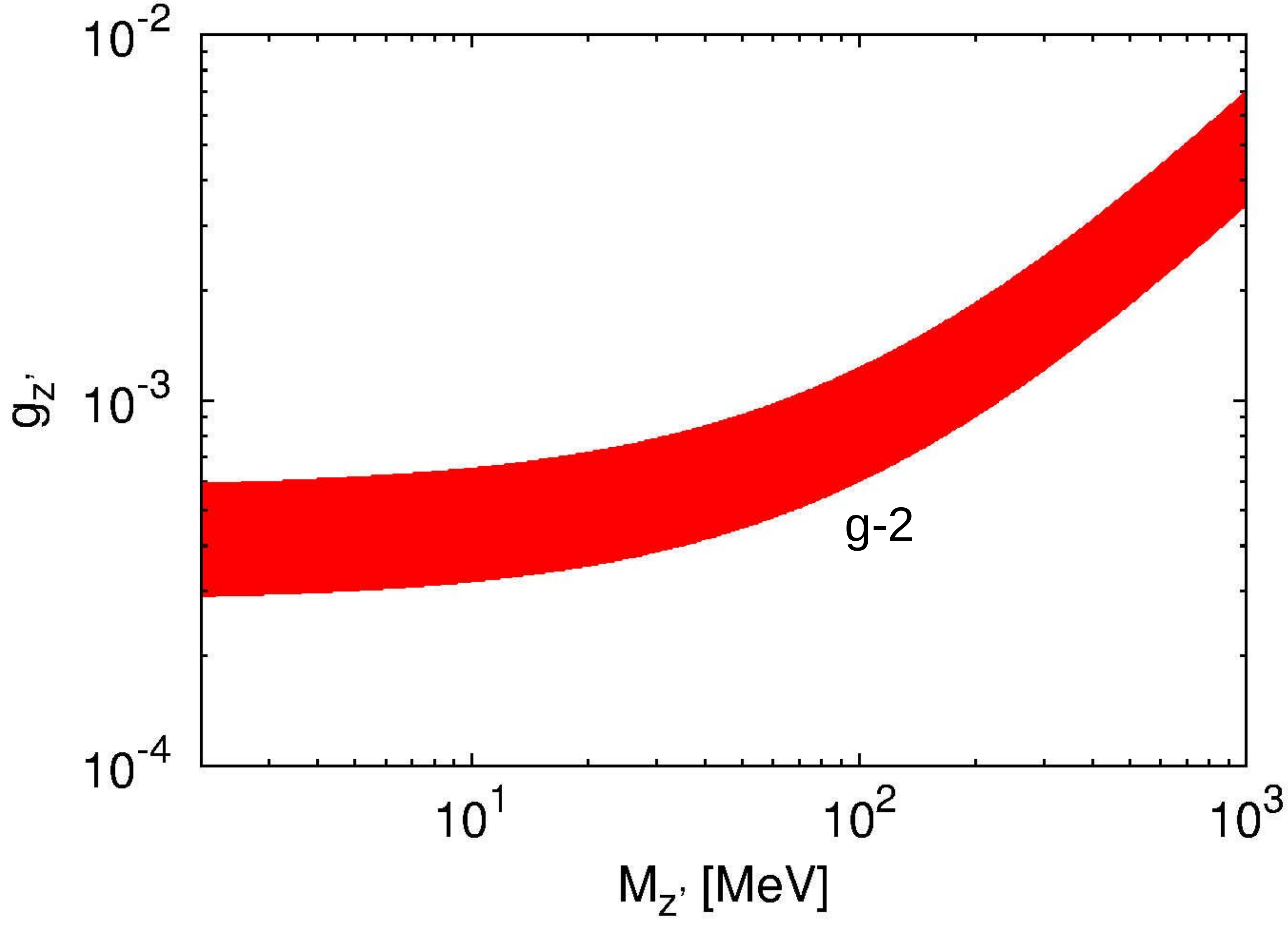
$$\left(a_\mu = \frac{g_\mu - 2}{2} \right)$$



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

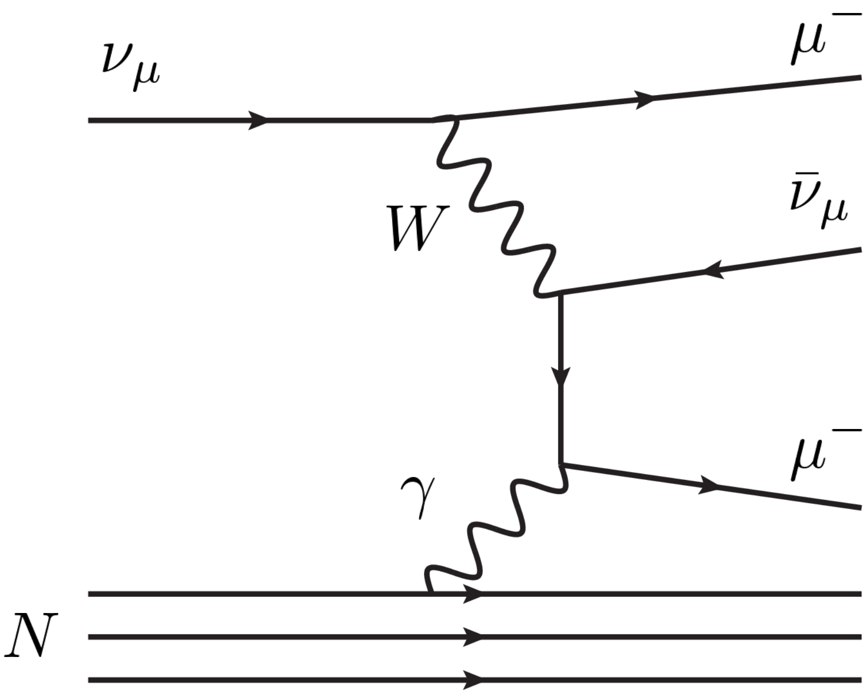
Muon g-2

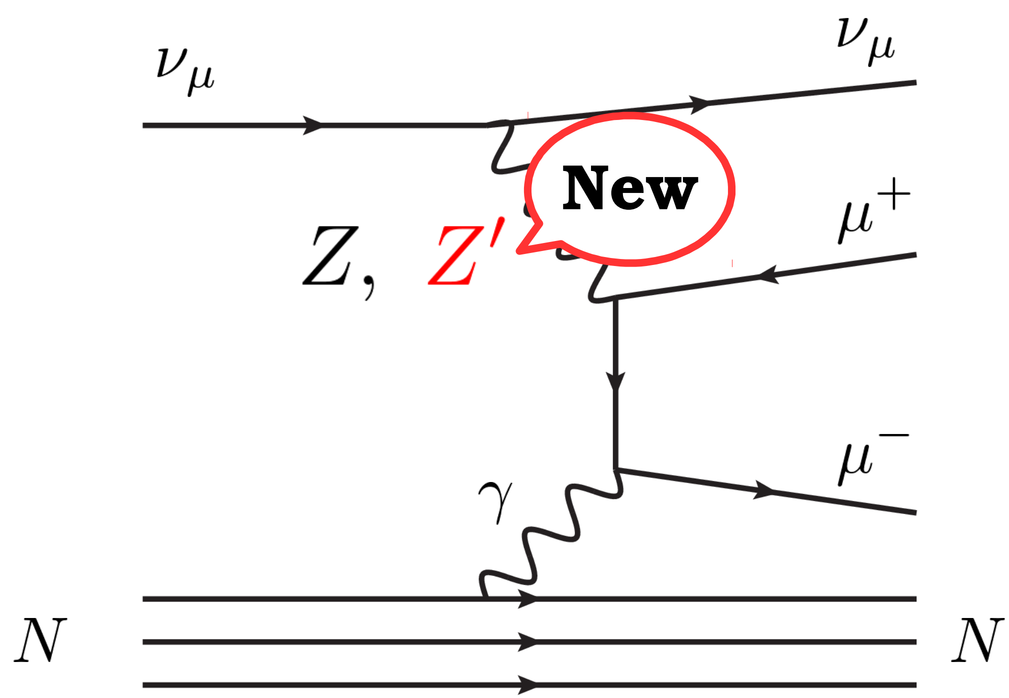
The red band is consistent with g-2 within 2σ.



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.)

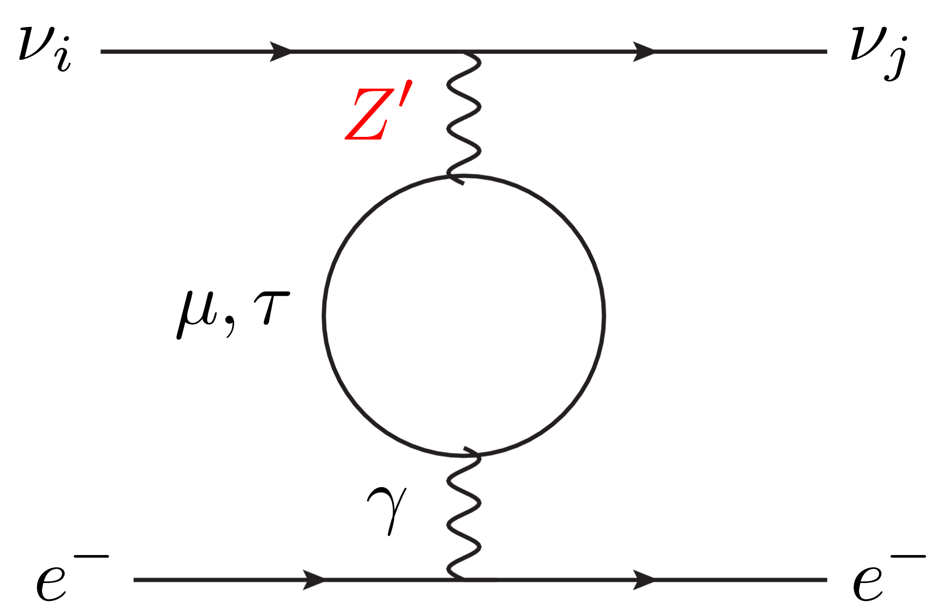
Other constraints

$Z' - \gamma$ one-loop mixing

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

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

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



The model is constrained by Borexino.

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

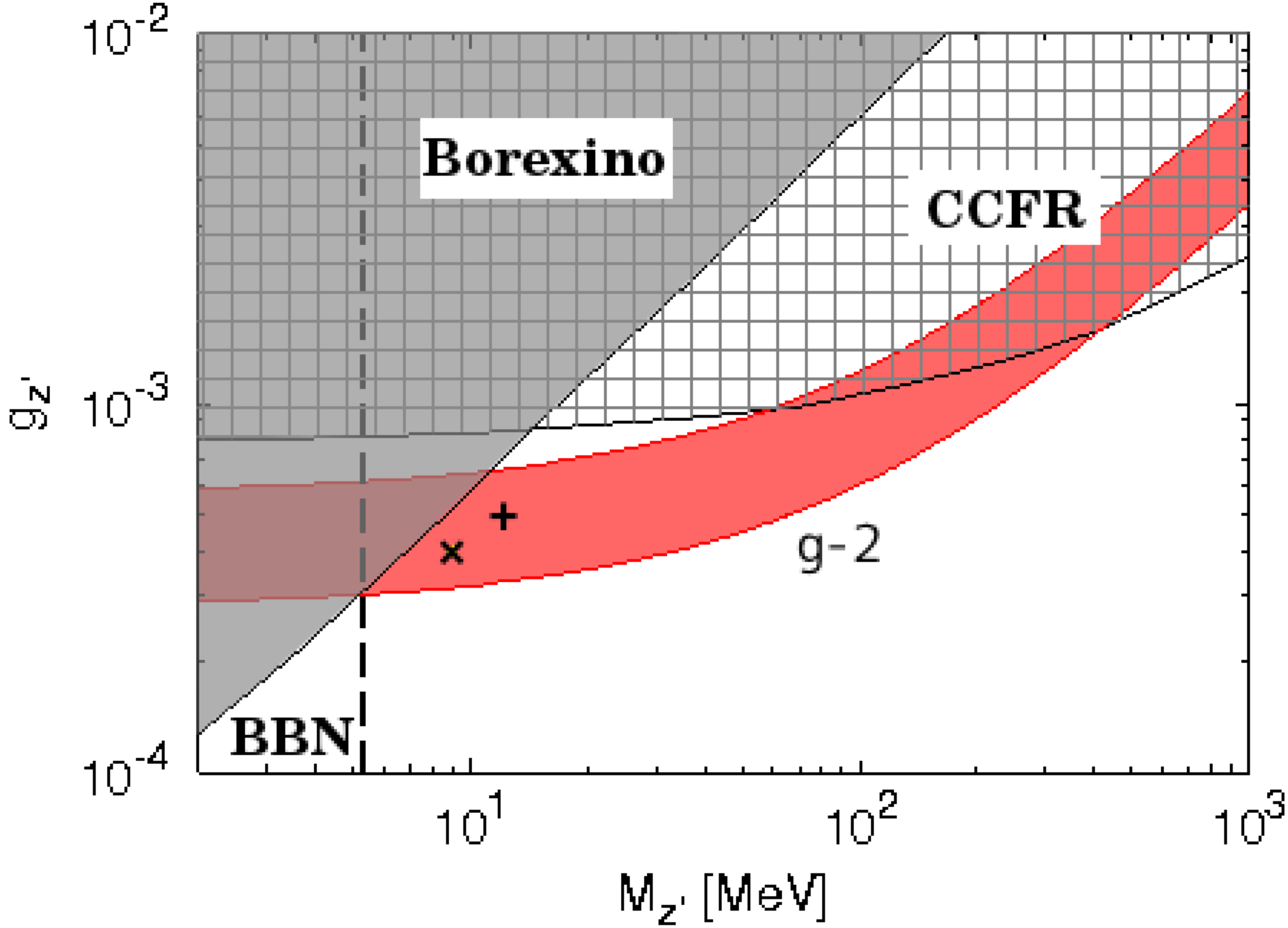
BBN

Such a light Z' increases the effective number $N_{\rm eff}$.

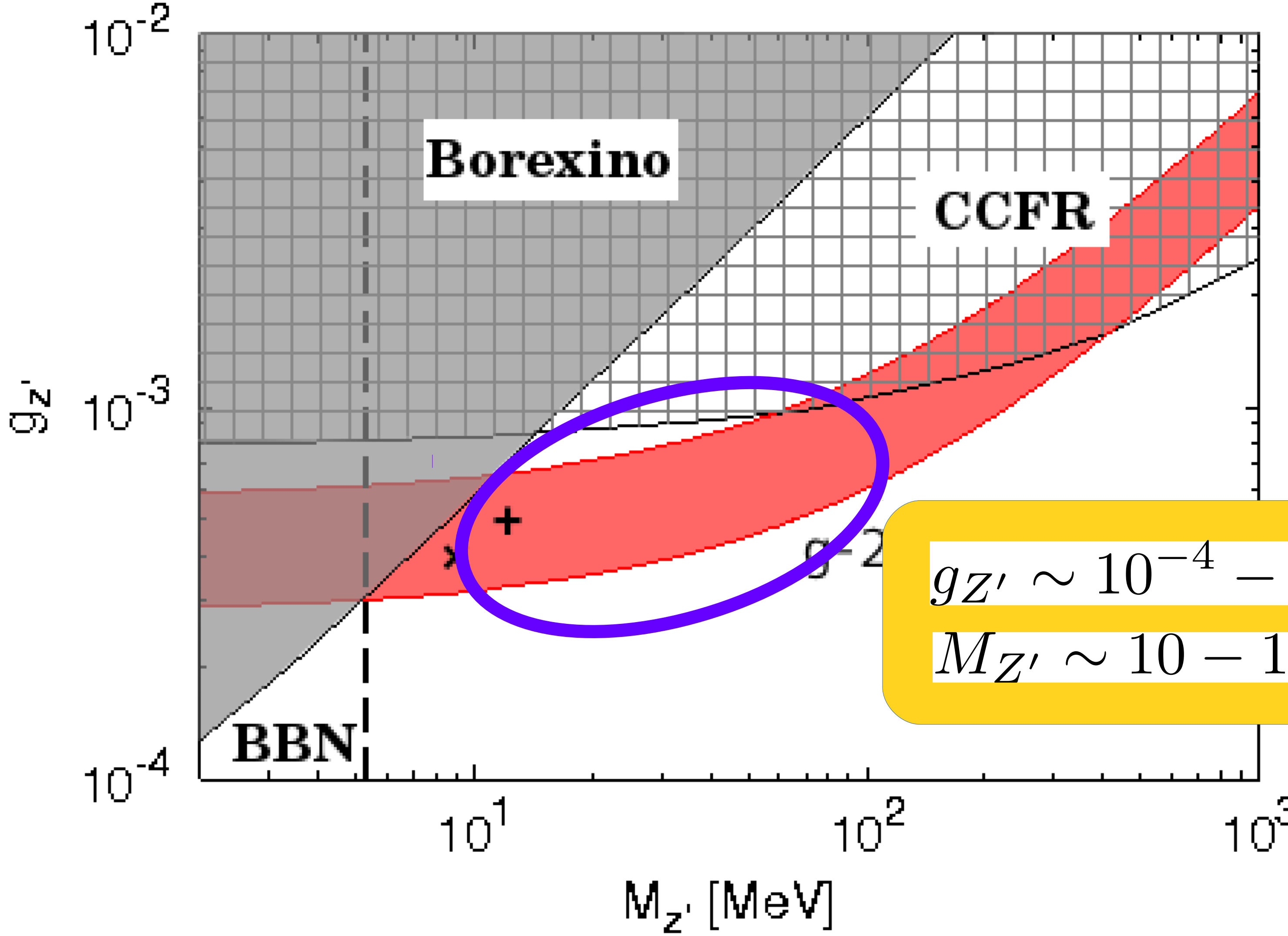
- Directly $\quad M_{Z'} > 1$ MeV
- Indirectly $\quad M_{Z'} > 5$ MeV

[Kamada, Yu, 1594.00711]

Parameter region



Parameter region



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

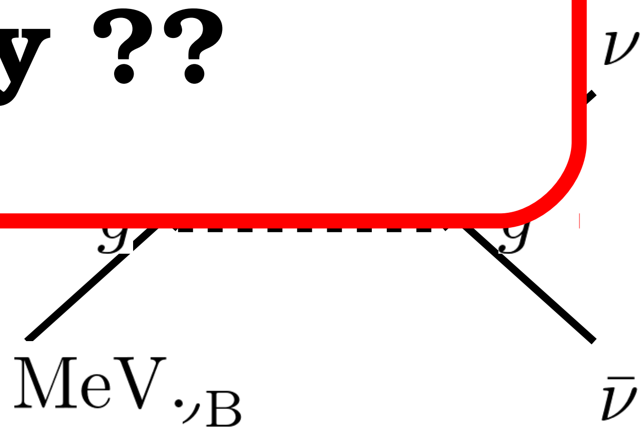
$M_{Z'} \sim 10 - 100 \text{ MeV}$

Secret neutrino interaction

Roug[…]he mass of X and the coupling of SnI.

Challenge

g-2 and IceCube gap simultaneously ??



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

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

(2) To attenuate sufficient amount of cosmic neutrinos:

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

Calculation of neutrino flux

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

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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:

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

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

3. Scattering with CnB

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

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

$\sqrt{s}$ ‡ 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:

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

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

4. Regeneration term

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

Results

Parameter setting

Neutrino mixing

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

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

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

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

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

$$|\Delta m_{23}^2| = 2.48\ (2.38) \times 10^{-3}\ \ \mathrm{eV}^2 \quad \text{and} \quad \delta_{\mathrm{CP}} = 0$$

Propagation equation

$\mathcal{Q}_0$: 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

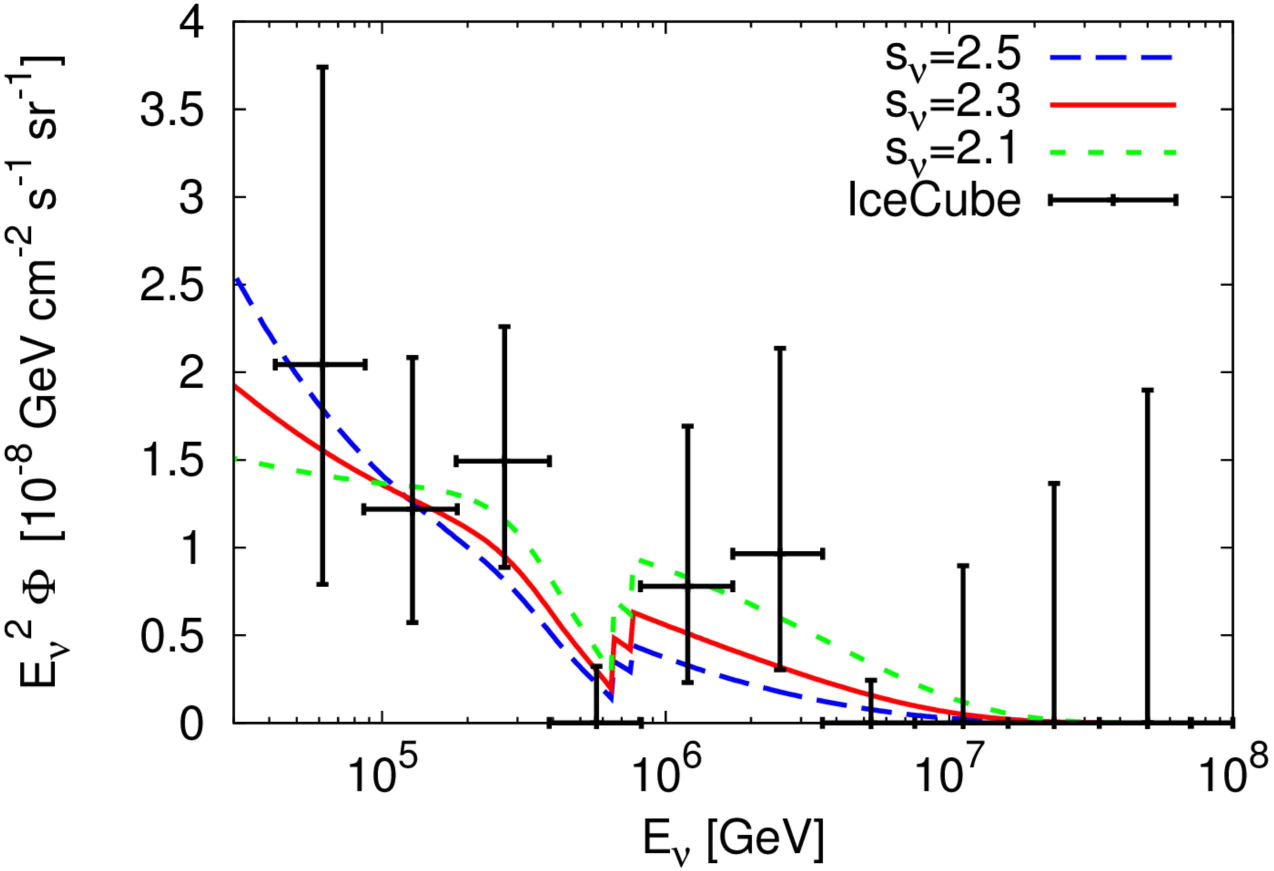
$m_1 = 0.08$ eV

(quasi-degenerate)

$M_{Z'} = 11$ MeV

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

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



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

Some events are expected in IceCube in the future.

Gap: Source distribution

Diffuse neutrino flux for several types of source distribution.

Normal hierarchy

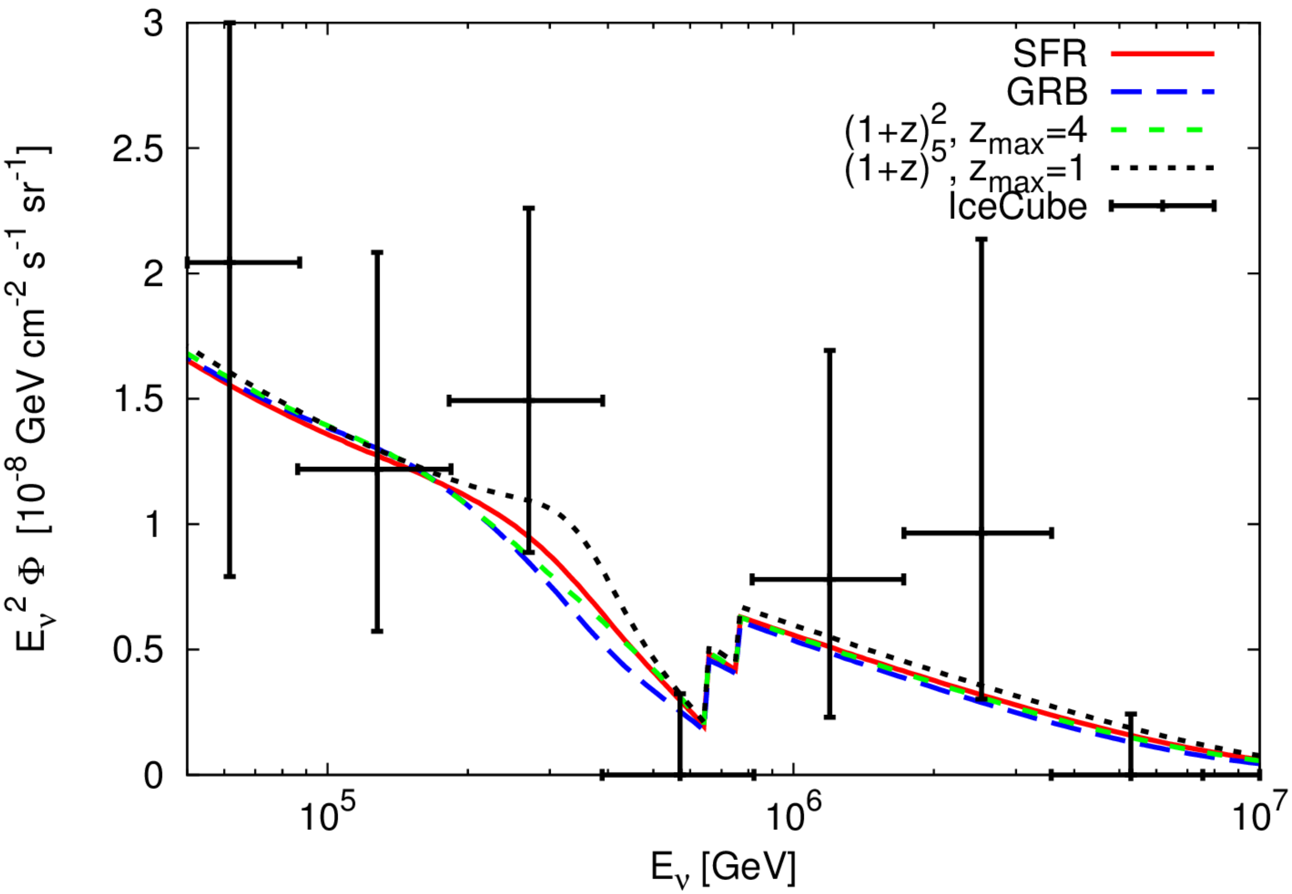
$m_1 = 0.08$ eV

(quasi-degenerate)

$M_{Z'} = 11$ MeV

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

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



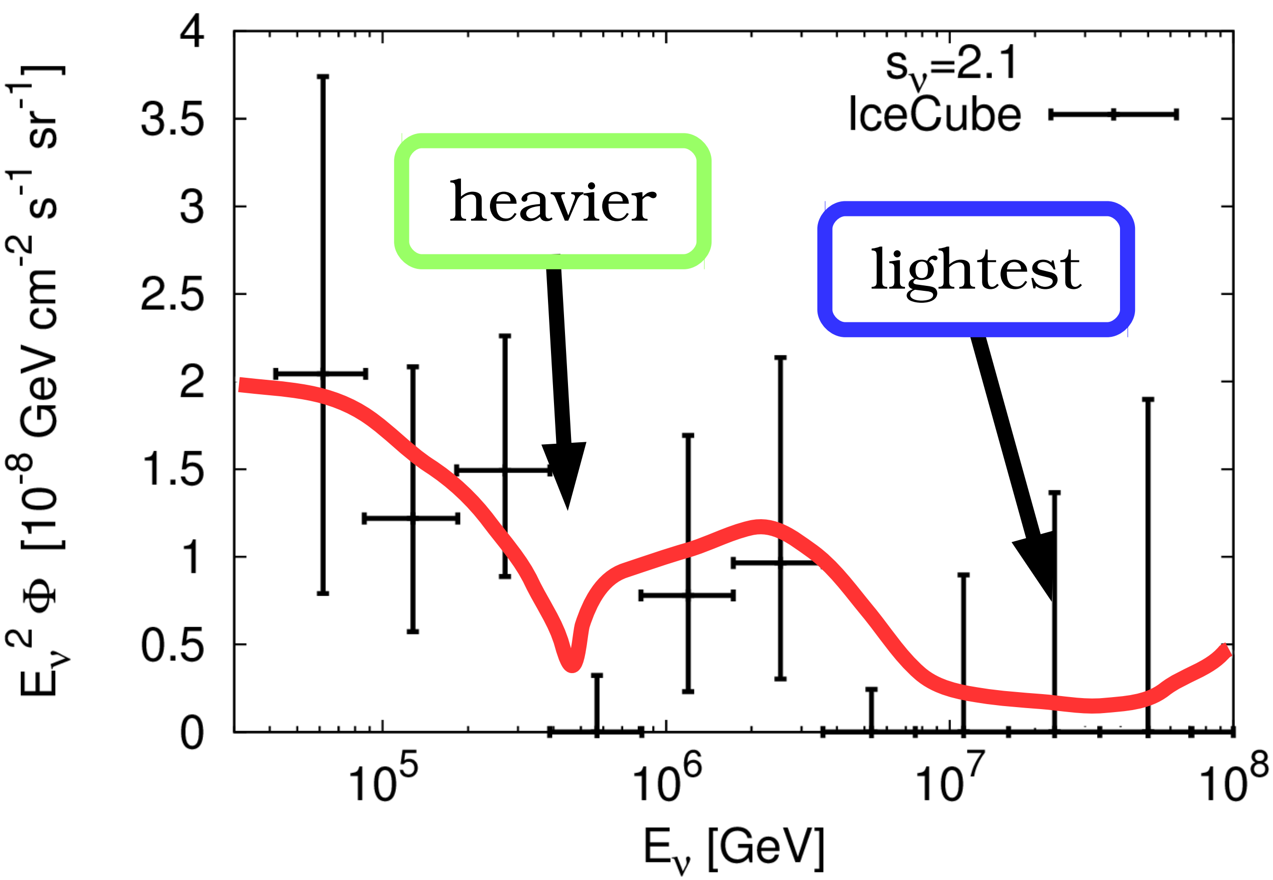
Source distributions have **a small impact** on the flux.

Energy cut-off

Can we realize the cut-off by $L_\mu - L_\tau$ with a lower spectral index ?

preferred for the case of pp production

[Tamborra, Ando, Murase, JCAP1409, 043 (2014)]



We have 3 neutrinos

(lightest + heaviers).

We have 3 resonances

(higher + lowers).

$$\left(E_{\rm res} \simeq \frac{M_{Z'}}{2m_\nu} \right)$$

Energy cut-off

Diffuse neutrino flux for several spectral indices.

Inverted hierarchy

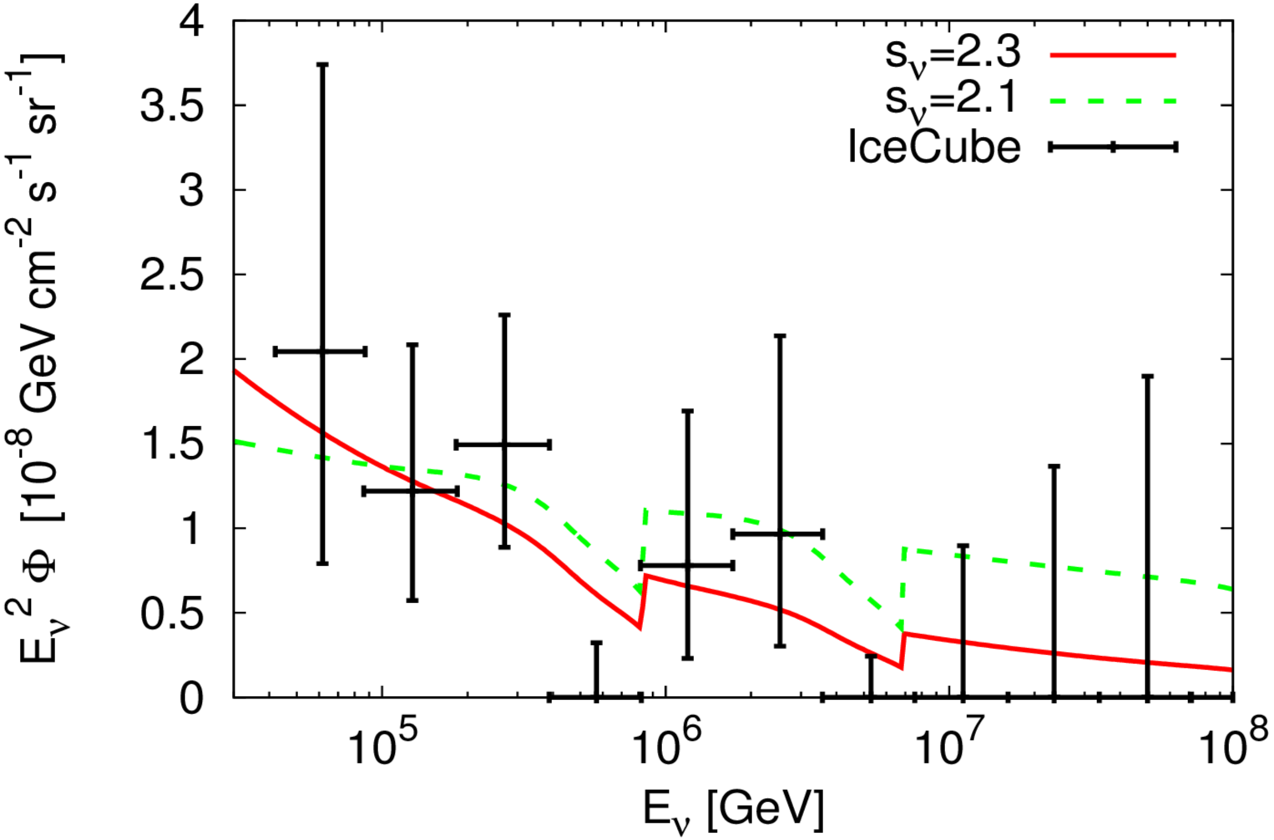
$m_3 = 0.006$ eV

(hierarchical)

$M_{Z'} = 9$ MeV

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

Without setting $E_{\rm cut}$



Unfortunately, too **narrow** and **shallow**...

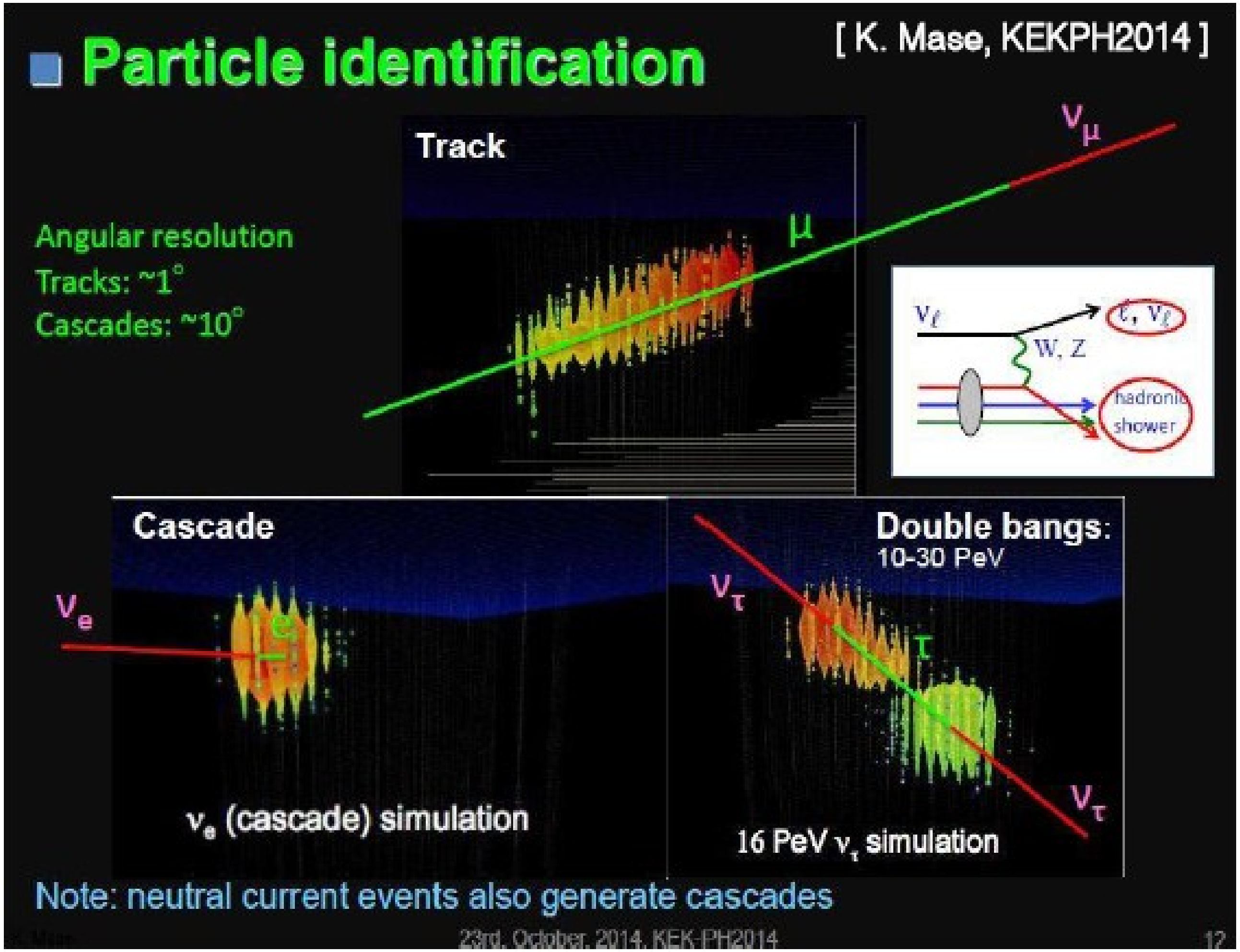
Summary

- At present, the IceCube data are compatible with the standard astrophysical scenario.
- But, there is a gap in the energy spectrum between 400 GeV – 1 PeV.
- We have introduce a new gauge interaction and succeeded in simultaneously explaining the gap and the muon g-2 problem.
- Unfortunately, the Z' coupling is too small to realize the energy cut-off as well as the gap.

Backup

Event topology (flavors)

IceCube can distinguish flavors by observing event topology.



Charged Current (CC)

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

Neutral Current (NC)

hadronic shower
for
all flavors

[K. Mase, KEK-PH2014]

Energy cut-off

Diffuse neutrino flux for several spectral indices.

Inverted hierarchy

$m_3 = 0.001$ eV

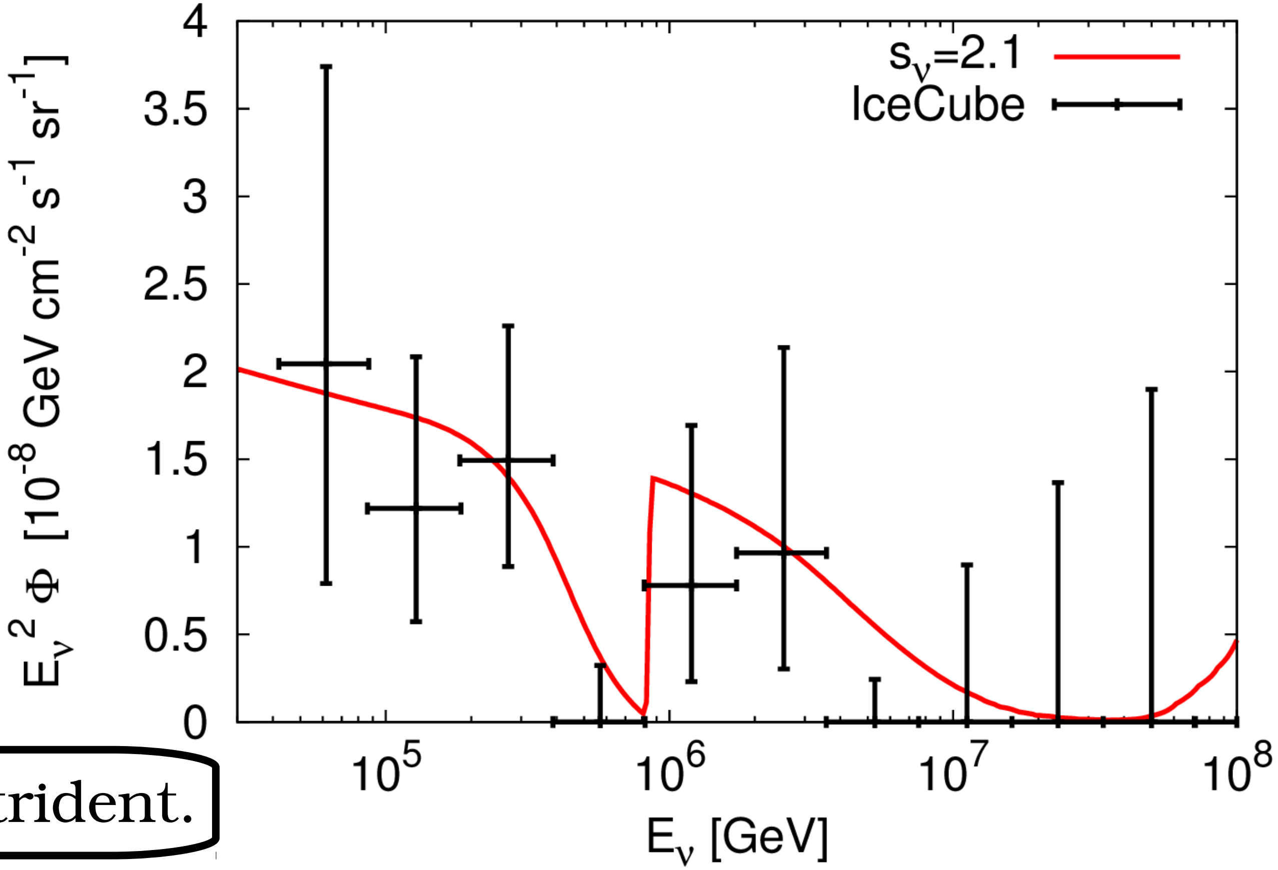
(hierarchical)

Without setting $E_{\rm cut}$

$M_{Z'} = 9$ MeV

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

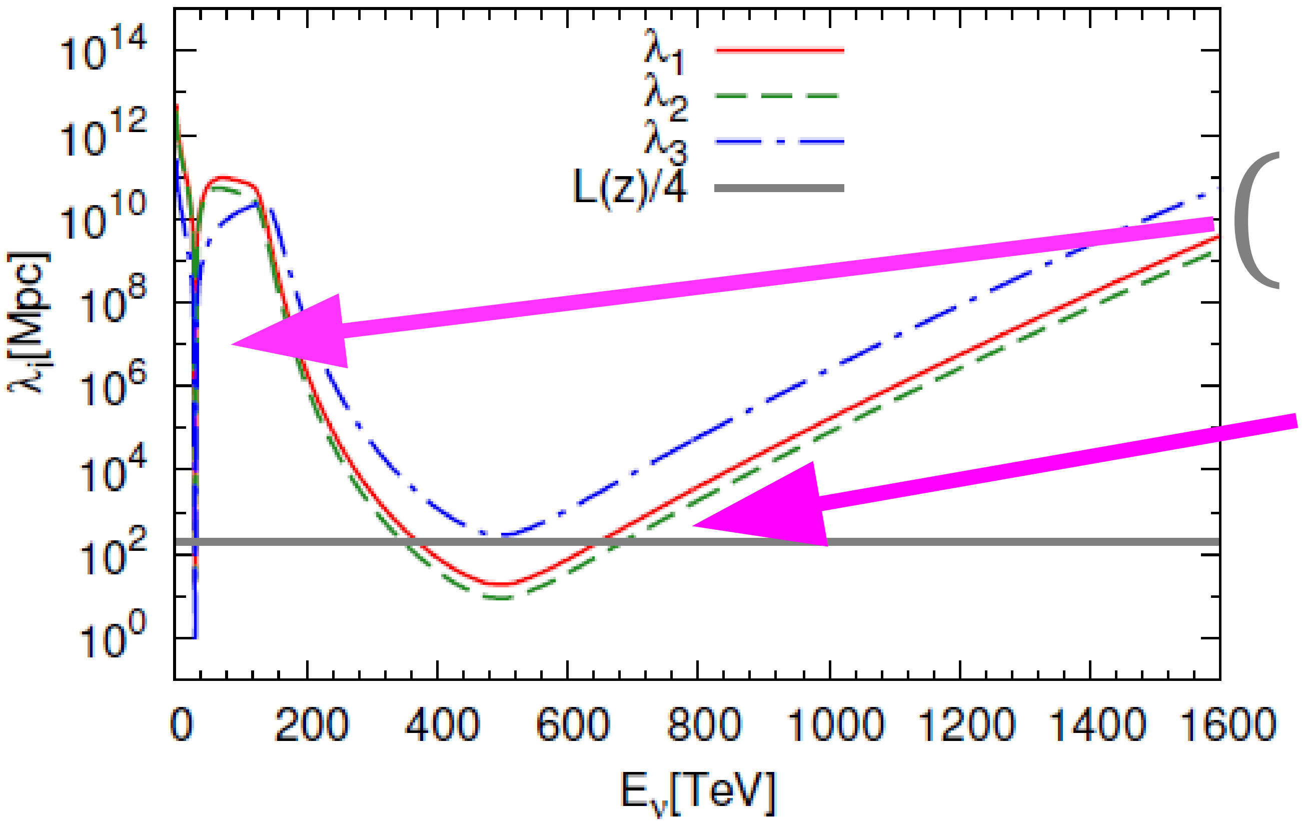
Excluded by trident.



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

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

Calculation of mean free path



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

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

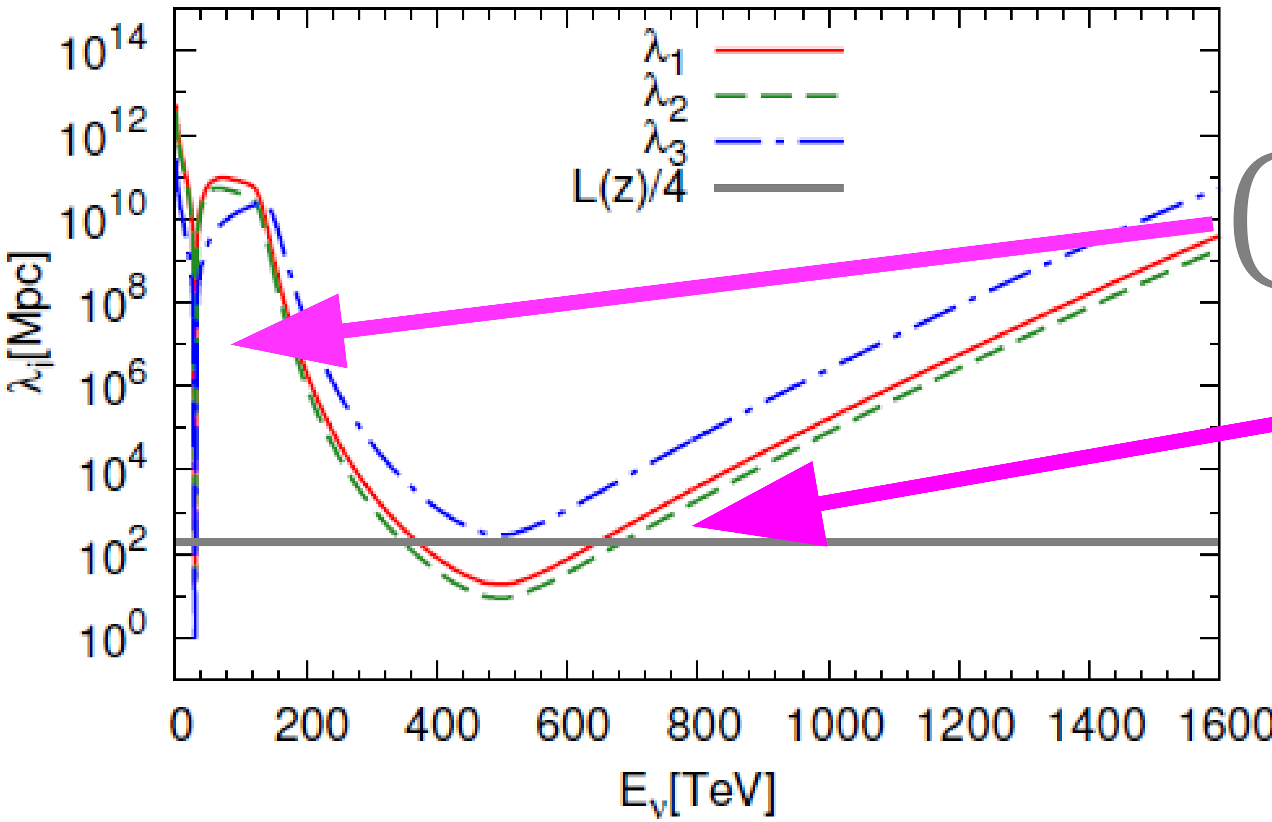
$$m_{\nu_3} = 3 \times 10^{-3}\ \text{eV}$$

(Inverted hierarchy)

(1) Positions of the gaps.

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

Calculation of mean free path



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

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

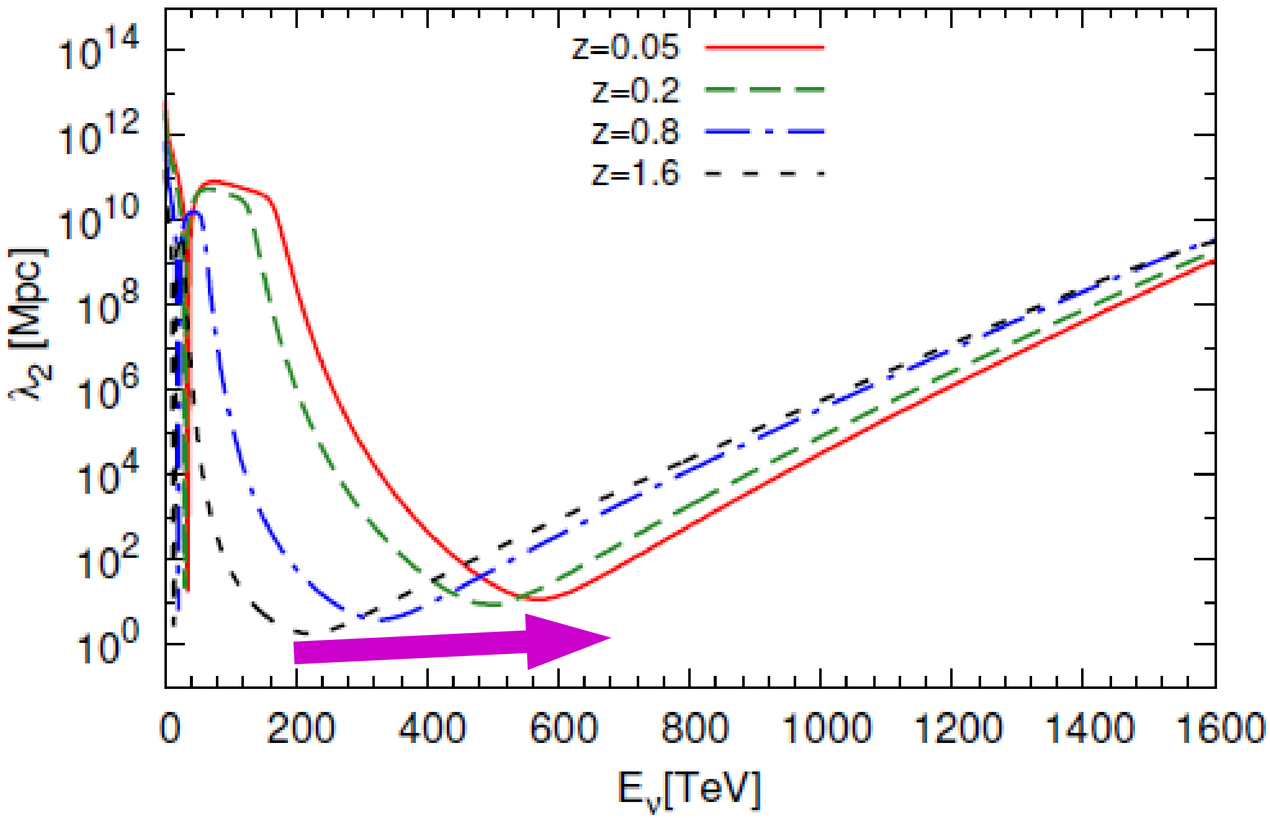
$m_{\nu_3} = 3 \times 10^{-3}$ eV

(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



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

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

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

(Inverted hierarchy)

(3) Larger red-shift → Broader gap

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