Saitama University 埼玉大学

Mind the Gap on IceCube

Cosmic neutrino spectrum and muon anomalous magnetic moment

Toshihiko Ota

Saitama University 埼玉大学

based on

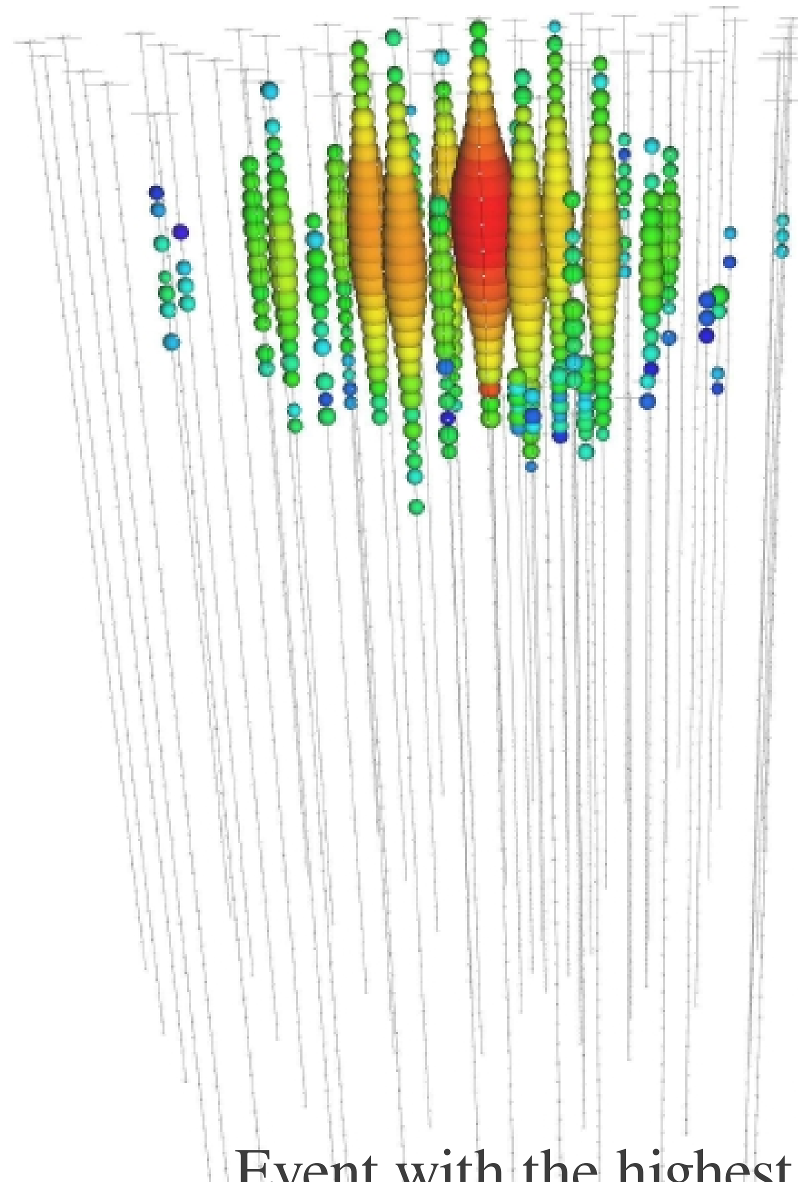
T.Araki, Y.Konishi, F.Kaneko, TO, J.Sato, T.Shimomura

ArXiv.1409.4180v2

Physical Review **D91** (2015) 037301

Preface

- PeV cosmic neutrino spectrum
  IceCube collaboration PRL **113** (2014) 101101



Event with the highest deposit energy~2 PeV

PeV cosmic neutrino spectrum

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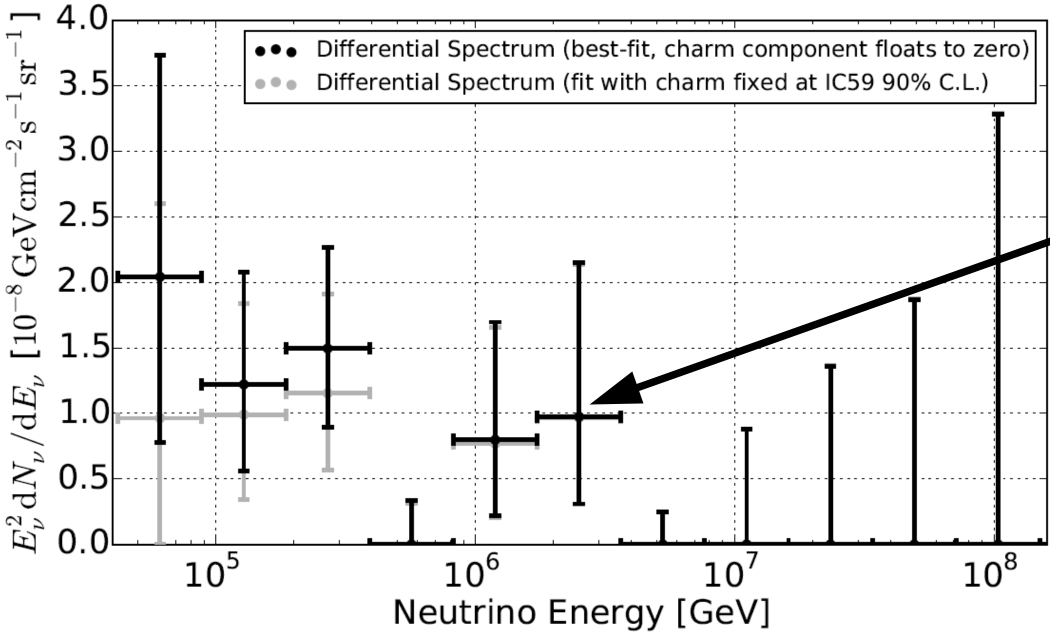
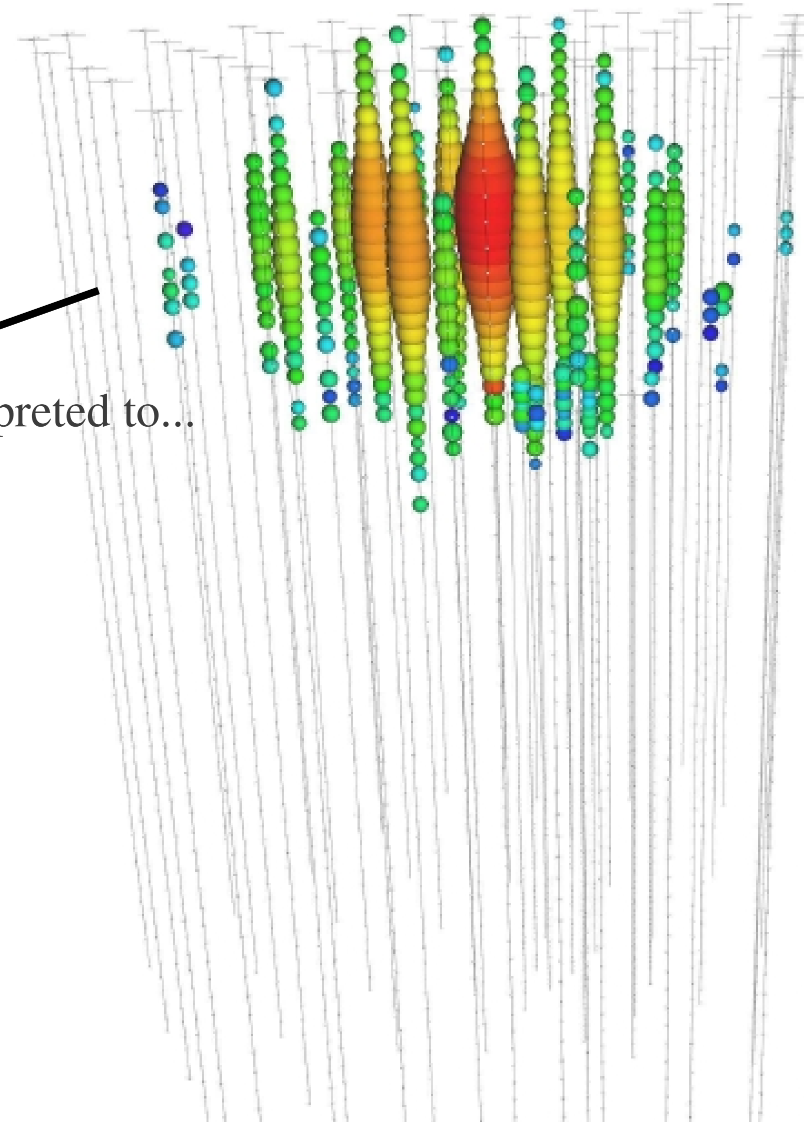


Interpreted to...



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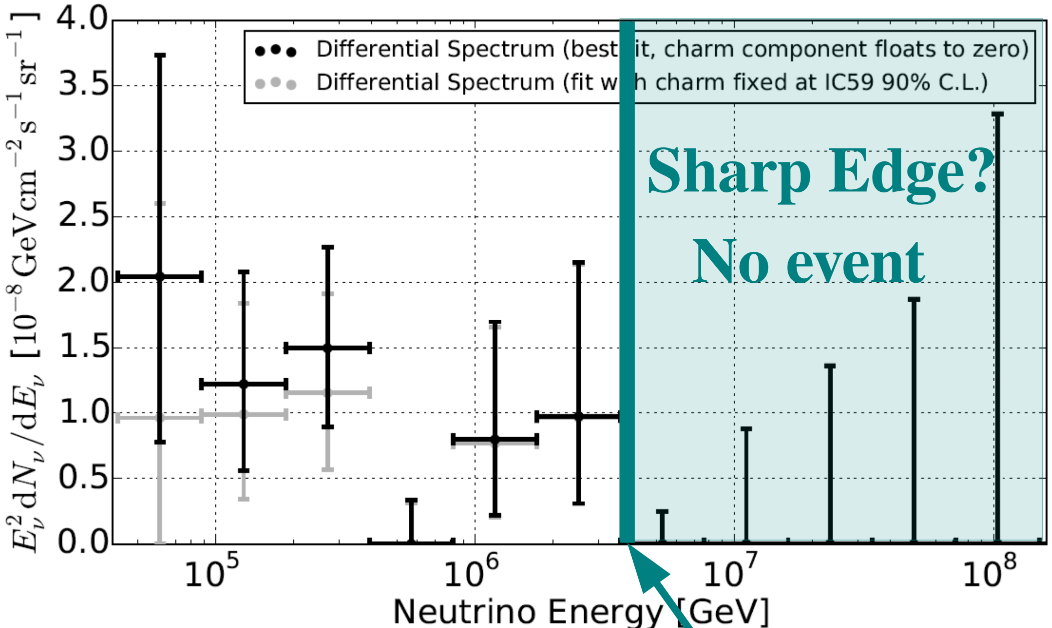
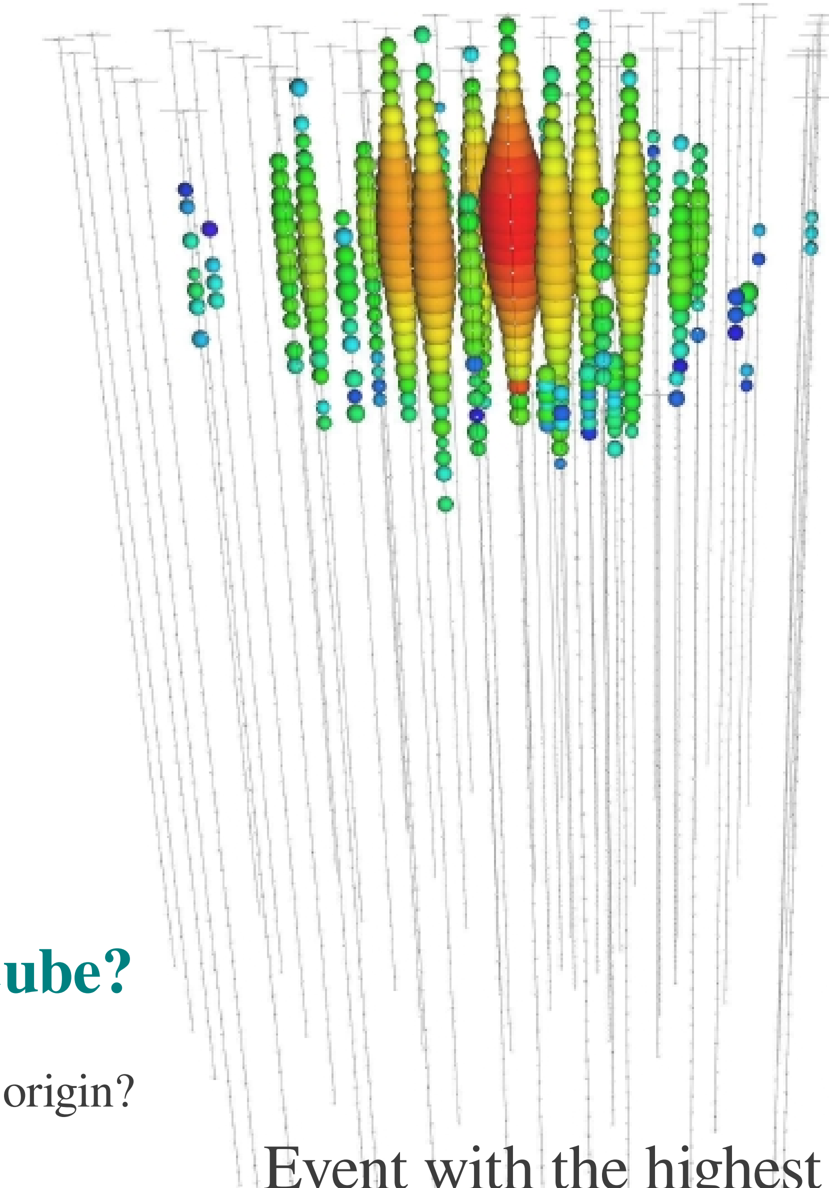


Edge of IceCube?
at 3 PeV
may be astrophysical origin?



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ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

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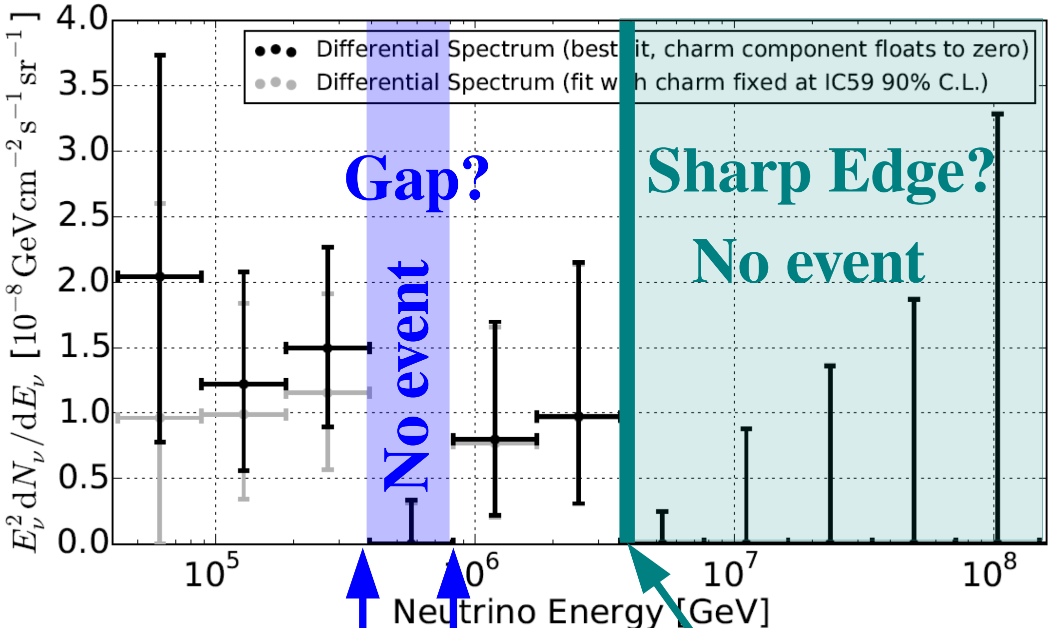

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No event at 0.4-1 PeV

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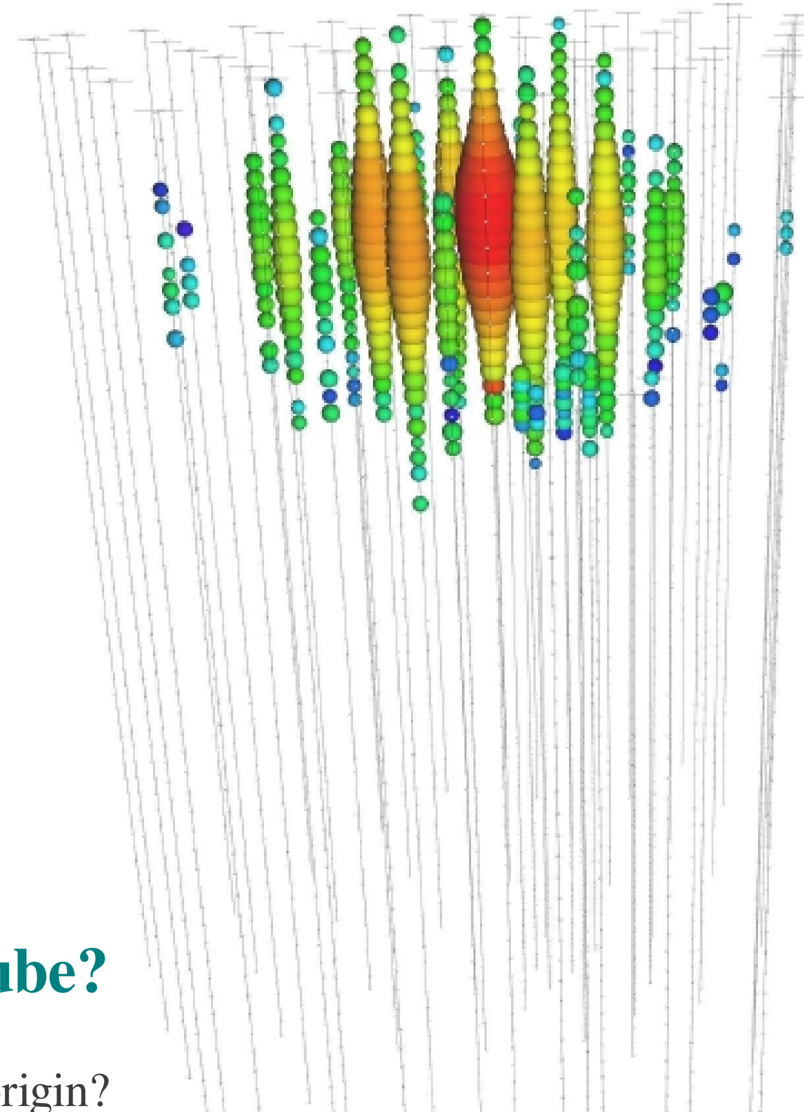

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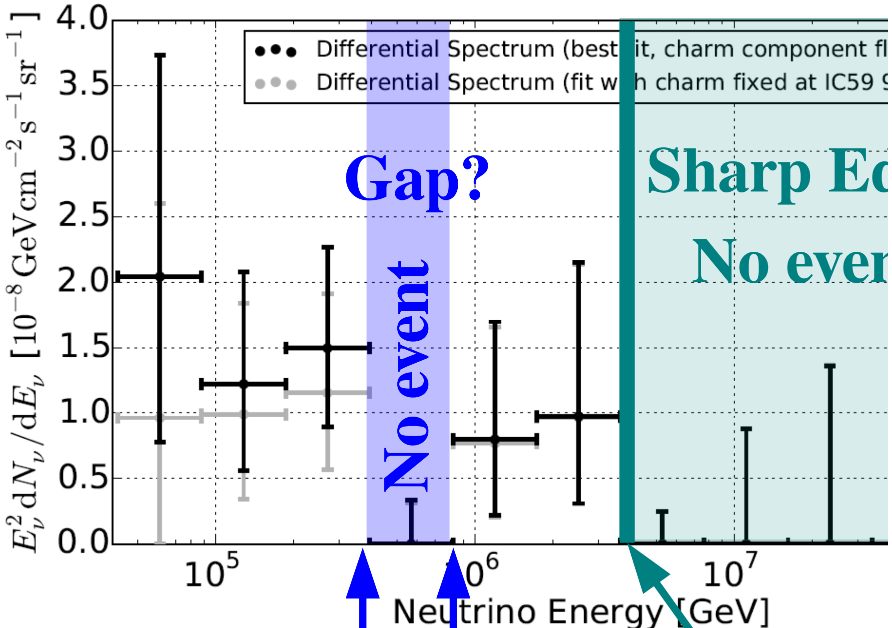
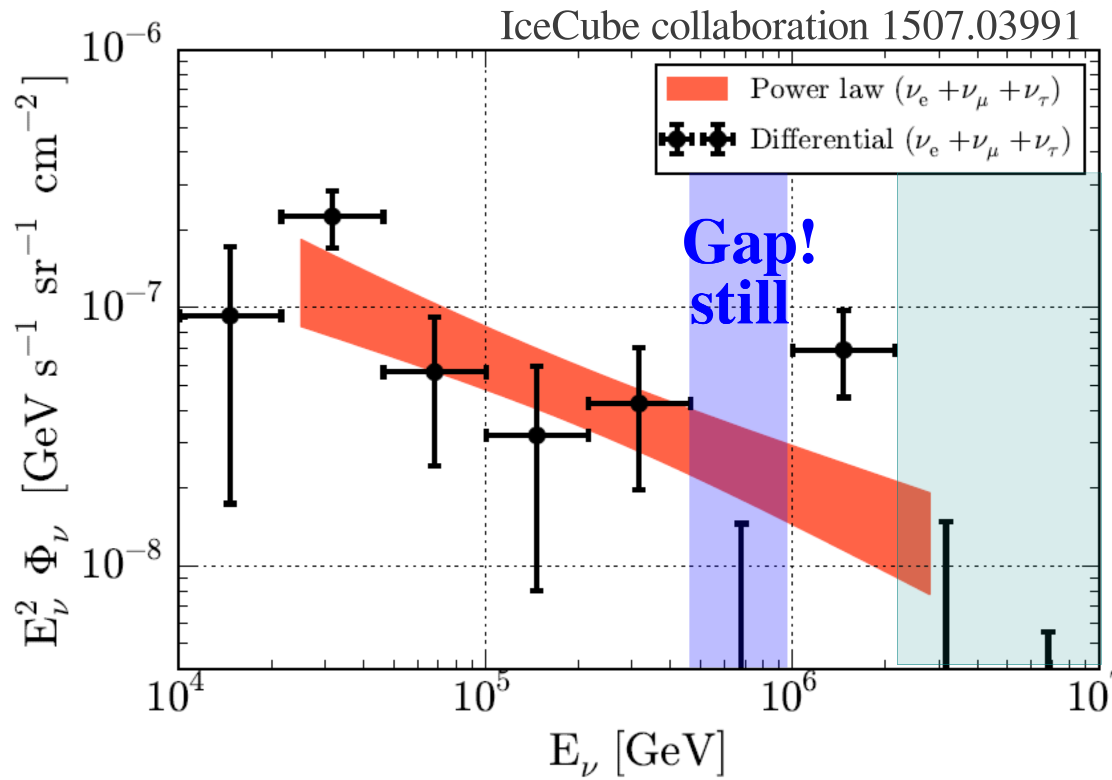


IceCube collaboration 1507.03991



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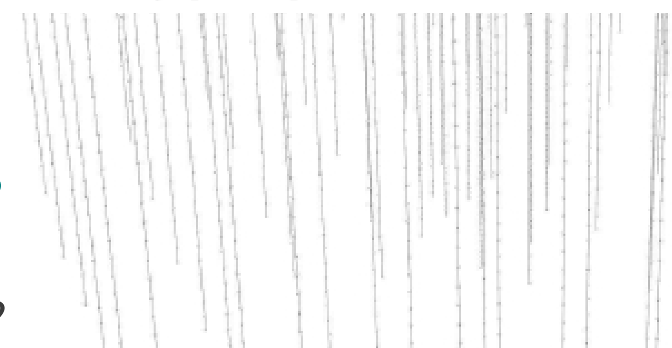

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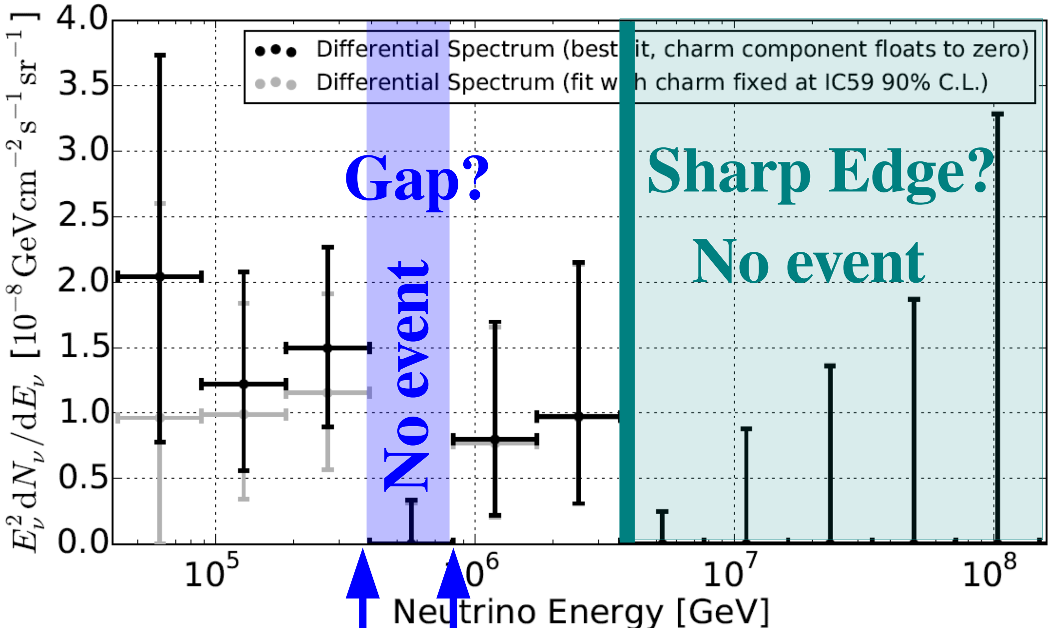
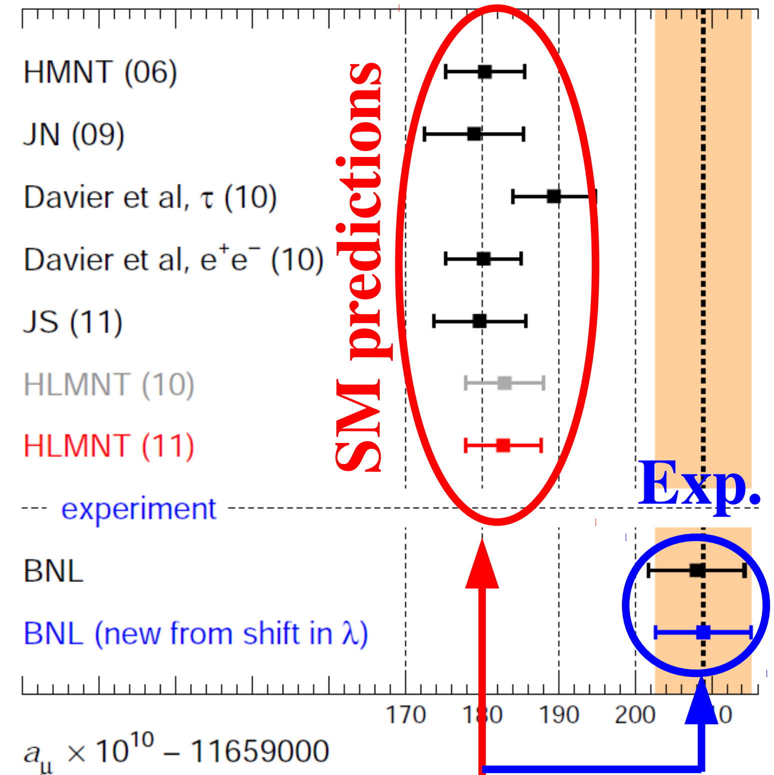


- Muon g-2
  Hagiwara et al., J.Phys. **G38** (2011) 085003



IceCube Gap

No event at 0.4-1 PeV

$g_\mu - 2$ Gap

$a_\mu^{\rm Exp} - a_\mu^{\rm SM} = (26.1 \pm 8.0) \cdot 10^{-10}$ (3.3σ)

New physics at the MeV scale

may explain both the gaps

Outline

1 IceCube gap

- Attenuation of cosmic neutrino by secret neutrino interaction
- Gauged leptonic force $L_\mu - L_\tau$ as the secret interaction

2 Muon anomalous magnetic moment

- Gauged leptonic force as a contribution to muon g-2
- Constraints from colliders and neutrino trident process

3 A solution to the gaps

- Reproduction of the IceCube gap → distance to the neutrino source
  → neutrino mass spectrum

1 IceCube gap

If the **IceCube Gap** is explained by some **New Physics (NP)**...

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- **NP at Source: PeV Dark matter decay**

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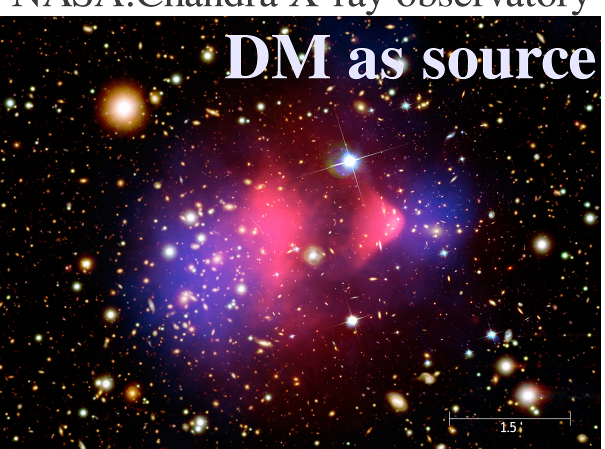
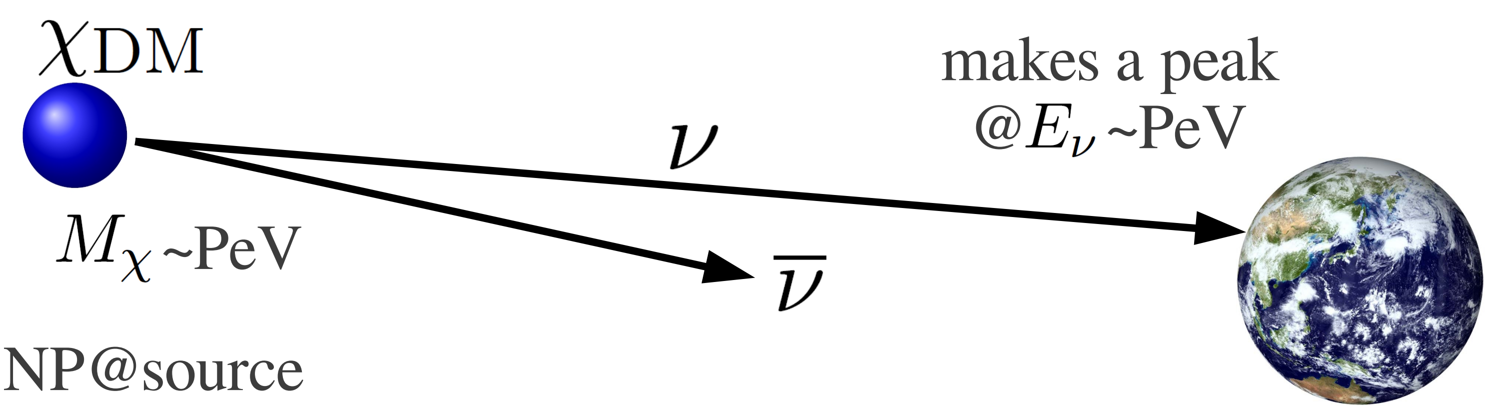
  Higaki Kitano Sato JHEP **1407**(2014) 044. Fong Minakata Panes Zukanovich-Funchal JHEP **1502** (2015) 189
  Shadow DM: Berezhiani talk at NOW 2014, 1506.09040.

  and more

NASA:Chandra X-ray observatory





NP@source

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- **NP in Propagation: Scattering with CNB with a MeV mediator**

  As an effective int.: Ng Beacom PR**D90** (2014) 065035, Ioka Murase PTEP **6** (2014) 061E01
  With neutrino mass model: Ibe Kaneta PR**D90** (2014) 053011, Blum Hook Murase 1408.3799
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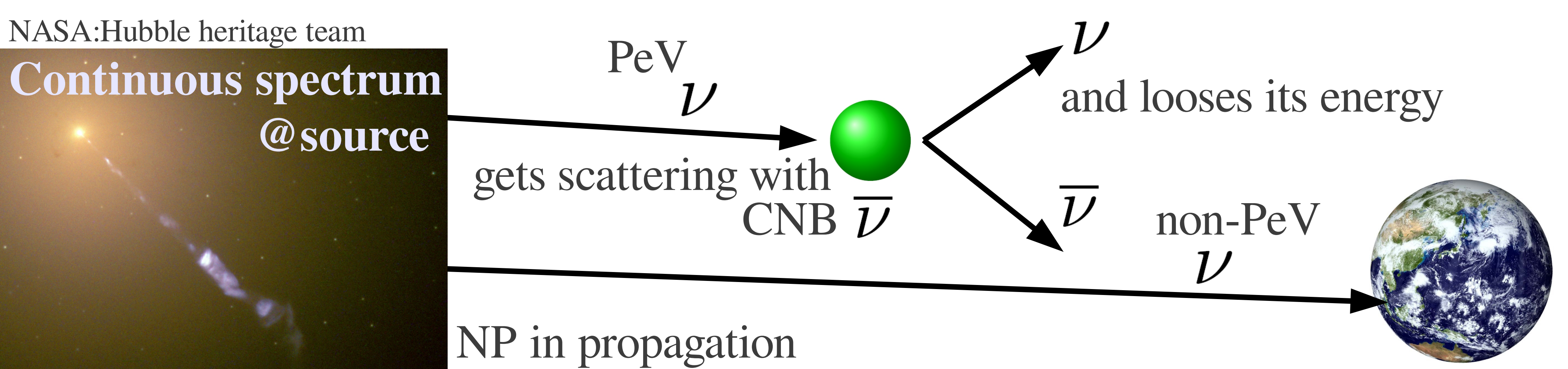
NASA:Hubble heritage team



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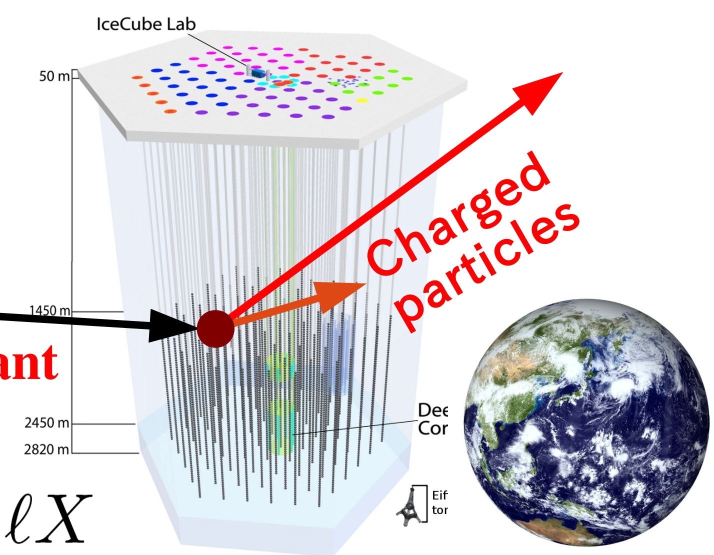
- **NP at Detection: CC int. mediated by a new TeV field**

  Barger Keung PL**B727** (2013) 190…

NASA:Hubble heritage team

PeV ν



New resonant CC int.

NP@detection $\nu N \xrightarrow{\phi_{\rm NP}} \ell X$

- In this talk, we pursue the possibility of

  ➡ **NP in propagation**, namely **Resonant scattering with CNB**

- We set **3 assumptions** for cosmic neutrino sources

① IceCube gap

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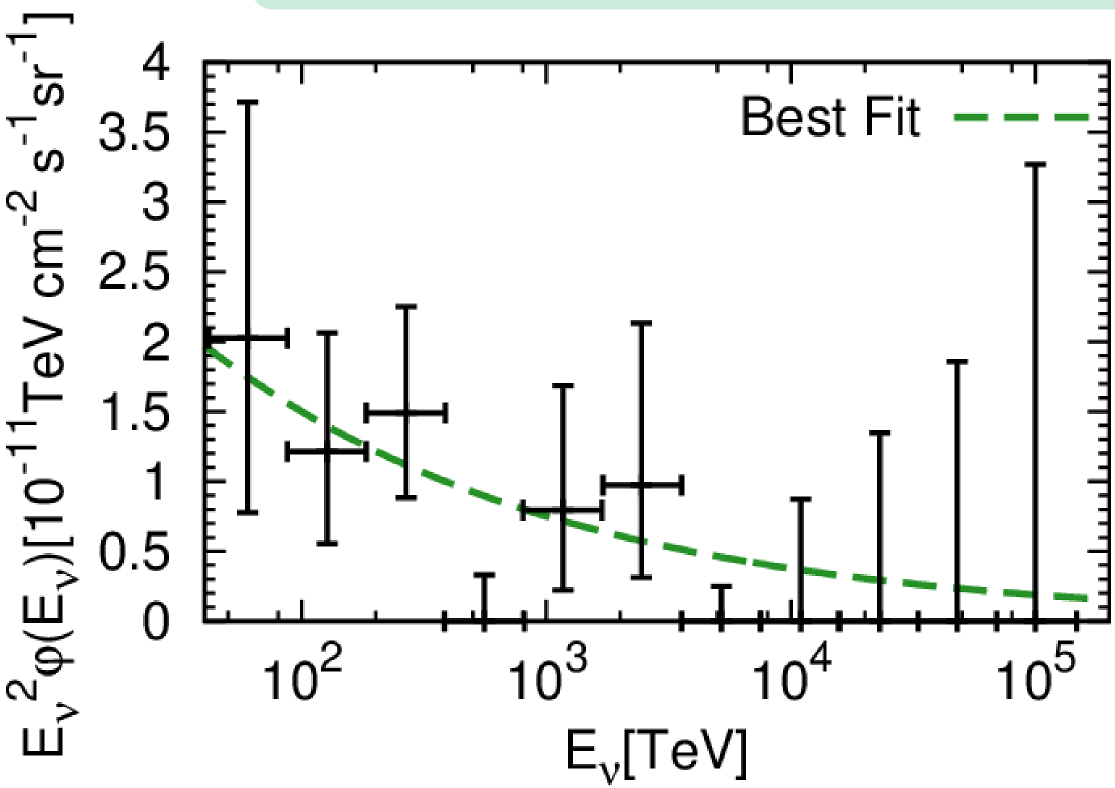
① Continuous (power-law) spectrum



① The spectrum shown with the **green curve** is reproduced, **if there is no NP**.

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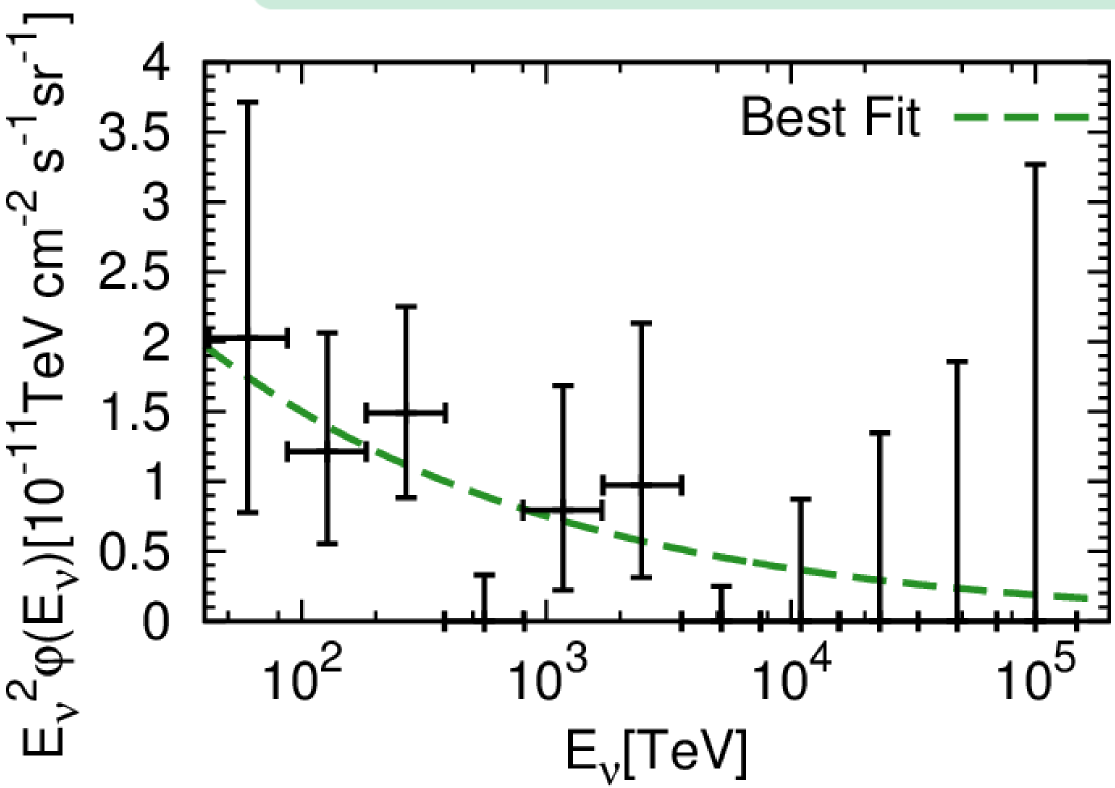
② Flavour ratio ~1:1:1 after leaving sources



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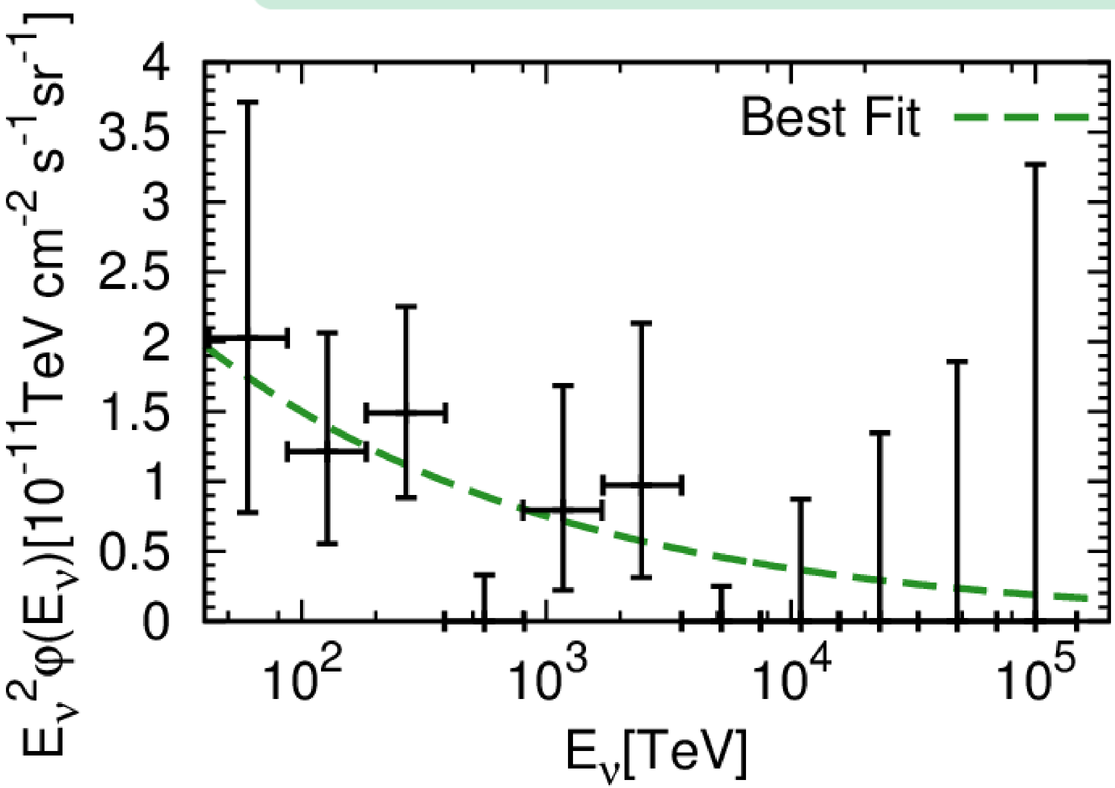
  ① Continuous (power-law) spectrum

  ② Flavour ratio ~1:1:1 after leaving sources

  ③ Sources distribute around a particular redshift $z_{\rm source}$



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③ for simplicity.

→ z-dependence of source distribution

e.g., The star-formation rate has a peak at z =1~2.

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"A narrow gap" → "Cosmic neutrino with a particular energy is scattered off"

The key idea is..."Resonant interaction with Cosmic Neutrino Background (CNB)"

New Physics in propagation

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a la. Ng-Beacom, Ioka-Murase

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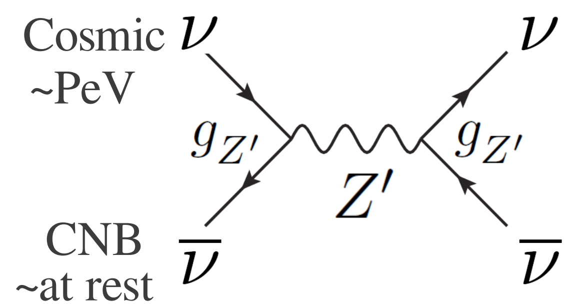

Why CNB? → $n_{\text{CNB}} \gg n_{\text{Baryon}}$

$n_{\text{CNB}} = 56.8$ [/cm^3] for each dof

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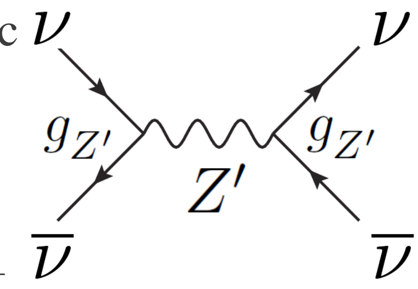
~sub-PeV ~0.1eV



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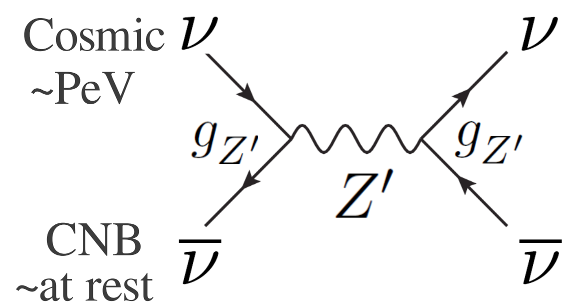
NP @MeV scale



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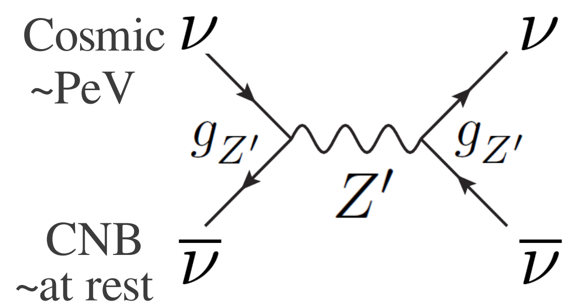

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$$\lambda \simeq 1/n_{\rm CNB}\sigma_{\rm @Res.}$$

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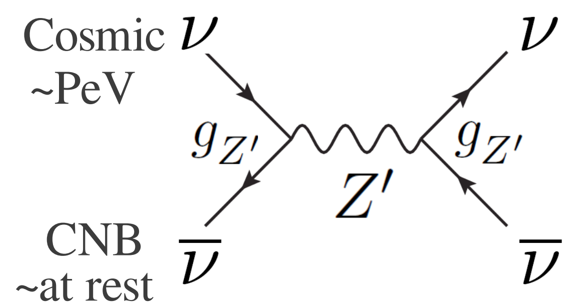

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Extra galactic source

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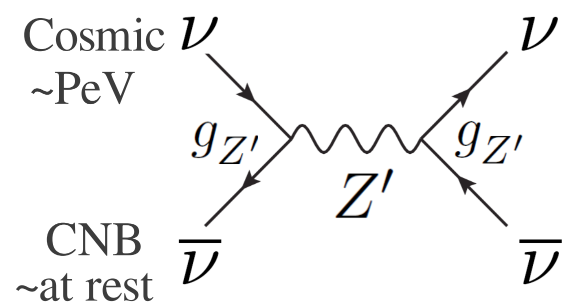

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$$\rightarrow \sigma_{\text{@Res.}} \simeq 10^{-30}\ [\text{cm}^2]$$

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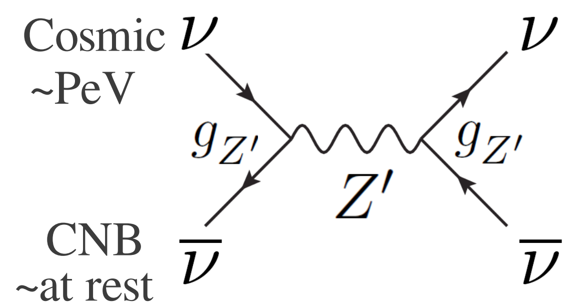

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IceCube Gap requires

$M_{Z'} \sim$ MeV, $\sigma_{@\text{Res.}} \gtrsim 10^{-30}$ [cm^2].

Let us calculate the cross-section in a particular model...

Model

- Gauged $U(1)\,L_\mu - L_\tau$ force as **a benchmark model**

Charge assignments $Y(L_\mu) = +1, Y(L_\tau) = -1,$
$Y(\mu_R) = +1, Y(\tau_R) = -1, Y(\text{others}) = 0.$

$$\mathscr{L}_{L_\mu - L_\tau} = g_{Z'}\overline{L}_\mu \gamma^\rho L_\mu Z'_\rho - g_{Z'}\overline{L}_\tau \gamma^\rho L_\tau Z'_\rho + g_{Z'}\overline{\mu_R}\gamma^\rho \mu_R Z'_\rho - g_{Z'}\overline{\tau_R}\gamma^\rho \tau_R Z'_\rho$$

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New neutrino int.

Constrained! but...
Contribute to muon *g-2*

We discuss it in **Sec.** 2

Coupling in mass eigenbasis
$$g_{ij} = g_{Z'}(U^\dagger_{\mathrm{PMNS}})_{i\alpha}\mathrm{diag}(0,1,-1)_{\alpha\beta}(U_{\mathrm{PMNS}})_{\beta j}$$

* Cosmic neutrino is produced as a flavour eigenstate= a coherent sum of mass eigenstates.
But the coherence might be lost in its travel. cf. Farzan Smirnov Nucl. Phys. **B805** (2008) 356.

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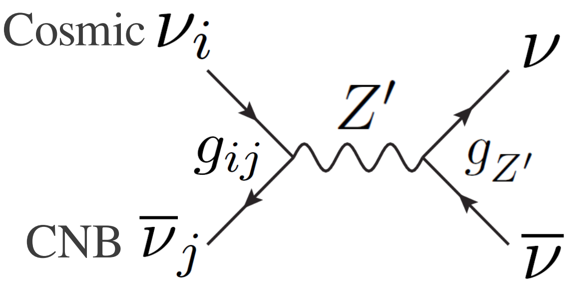
- **Motivated from...**
  - Gauge anomaly free Foot Mod.Phys.**A6** (1991) 527, He et al., PR**D43** (1990) R22
  - (almost) Maximal mixing Choubey Rodejohann Eur.Phys.J **C40** (2005) 259
  - Phenomenologies... Heeck Rodejohann (2010), Crivellin D'Anbrosio Heeck (2015) etc...
- In this talk, we do not go into the details of the spontaneous breaking of the $L_\mu - L_\tau$ sym. →

Model parameters
$g_{Z'}$ and $M_{Z'}$

Cross-section of the neutrino scattering proc.

$$\sigma(\nu_i \overline{\nu}_j \to \nu \overline{\nu}) = \frac{|g_{ij}|^2 g_{Z'}^2}{6\pi} \frac{s}{(s - M_{Z'}^2)^2 + M_{Z'}^2 \Gamma_{Z'}^2}$$



Decay rate

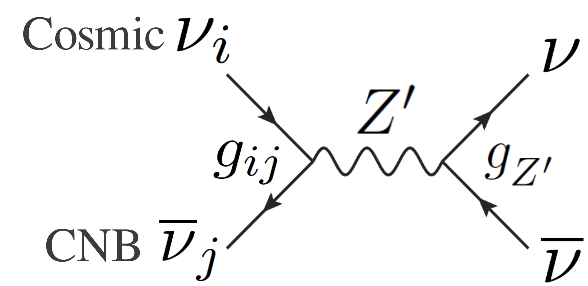
$$\Gamma_{Z'} = \frac{g_{Z'}^2 M_{Z'}}{12\pi}$$

Cross-section@Resonance

$$\sigma_{\text{@Res.}} = \frac{4\pi |g_{ij}|^2}{M_{Z'}^2} \delta \left(1 - \frac{M_{Z'}^2}{s}\right)$$

Cross-section of the neutrino scattering proc.

$$\sigma(\nu_i \overline{\nu}_j \to \nu\overline{\nu}) = \frac{|g_{ij}|^2 g_{Z'}^2}{6\pi} \frac{s}{(s - M_{Z'}^2)^2 + M_{Z'}^2 \Gamma_{Z'}^2}$$



Decay rate

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

Cross-section@Resonance

For IceCube Gap

$$\sigma_{\text{@Res.}} = \frac{4\pi |g_{ij}|^2}{M_{Z'}^2} \delta\left(1 - \frac{M_{Z'}^2}{s}\right) \stackrel{!}{=} 10^{-30}\ [\text{cm}^2]$$

$M_{Z'} \sim$MeV

Model ① IceCube gap

Cross-section of the neutrino scattering proc.

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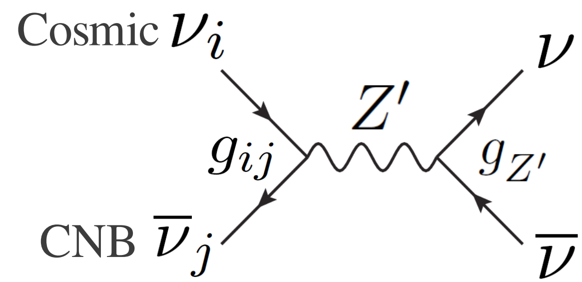

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Cross-section@Resonance

For IceCube Gap

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$M_{Z'} \sim$MeV $\to g_{Z'} \simeq$ several$\times 10^{-4}$

① IceCube gap

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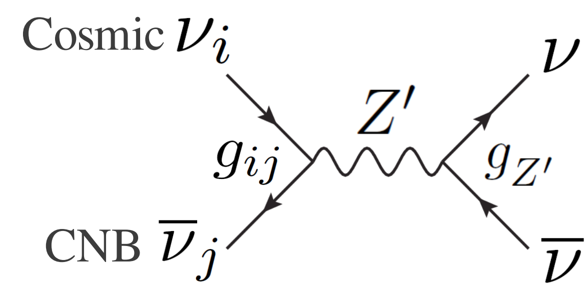

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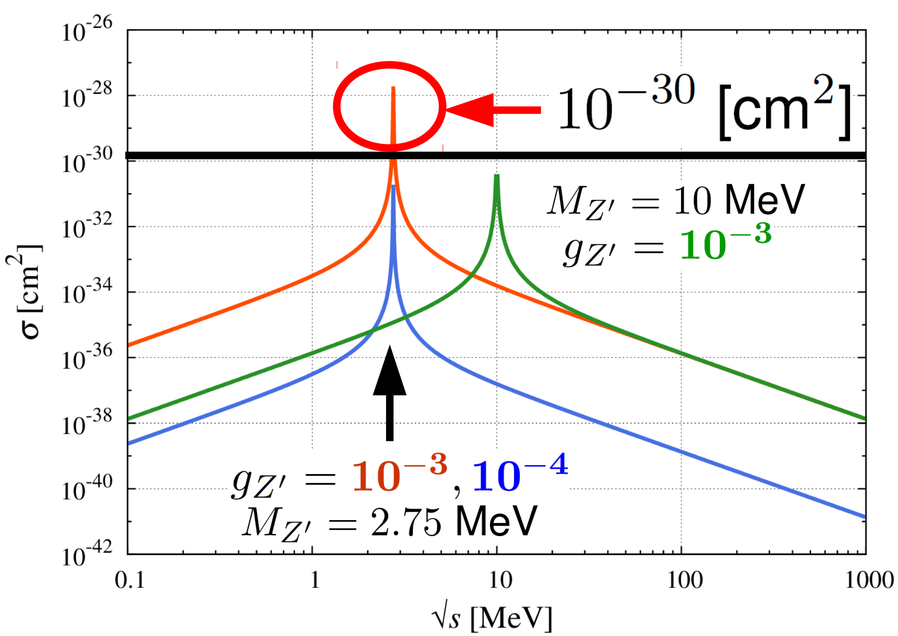


IceCube Gap requires

$M_{Z'} \sim$MeV, $\quad g_{Z'} \gtrsim 10^{-4}$.

- The width might be **too narrow** for the **IceCube Gap** (**0.4-1PeV**).
- We can ask the help to m_ν and z → **Sec. ③**

Before going into the details of the cosmic neutrino spectrum, let's check muon g-2.

Outline

1 IceCube gap

- Attenuation of cosmic neutrino by secret neutrino interaction
- Gauged leptonic force $L_\mu - L_\tau$ as the secret interaction

2 Muon anomalous magnetic moment

- Gauged leptonic force as a contribution to muon g-2
- Constraints from colliders and neutrino trident process

3 A solution to the gaps

- Reproduction of the IceCube gap $\rightarrow$ distance to the neutrino source
  $\rightarrow$ neutrino mass spectrum

Z' contribution to $g_\mu - 2$

$$\mathscr{L}_{L_\mu - L_\tau} = \underbrace{g_{ij}\overline{\nu}_i\gamma^\rho \mathrm{P}_L \nu_j Z'_\rho}_{\text{New neutrino int.}} + \underbrace{g_{Z'}\mathsf{diag}(0,1,-1)_{\alpha\beta}\overline{\ell}_\alpha\gamma^\rho\ell_\beta Z'_\rho}_{\text{Contribute to muon } g\text{-}2}$$

New neutrino int.

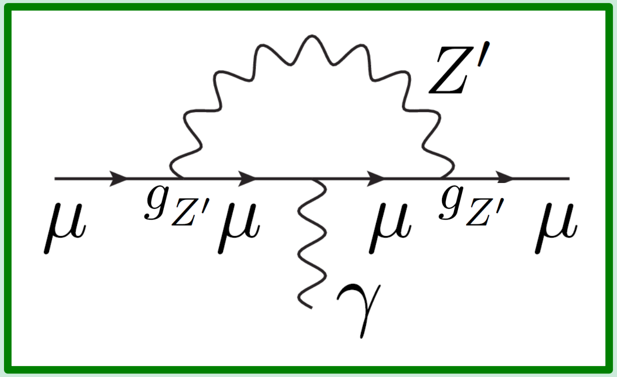
Contribute to muon *g-2*

Z' contribution to $g_\mu - 2$

See e.g., Baek Deshpande He Ko PRD64 (2001) 055006

$$\mathscr{L}_{L_\mu - L_\tau} = g_{ij}\overline{\nu}_i \gamma^\rho \mathrm{P}_L \nu_j Z'_\rho + \underline{g_{Z'}\mathrm{diag}(0,1,-1)_{\alpha\beta}\overline{\ell}_\alpha \gamma^\rho \ell_\beta Z'_\rho}$$

- $M_{Z'} \gg m_\mu \rightarrow \Delta a_\mu^{Z'} = \frac{g_{Z'}^2}{12\pi^2}\frac{m_\mu^2}{M_{Z'}^2}$
- $M_{Z'} \ll m_\mu \rightarrow \Delta a_\mu^{Z'} = \frac{g_{Z'}^2}{8\pi^2}$



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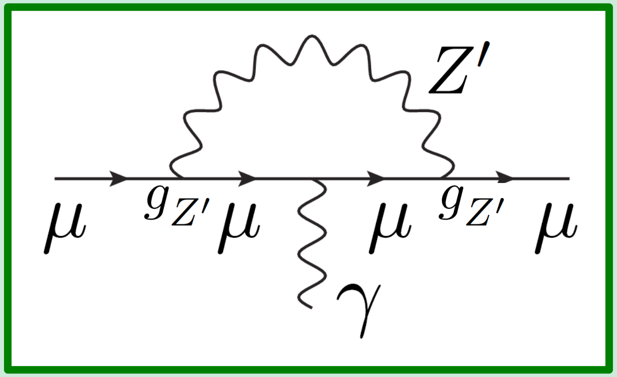
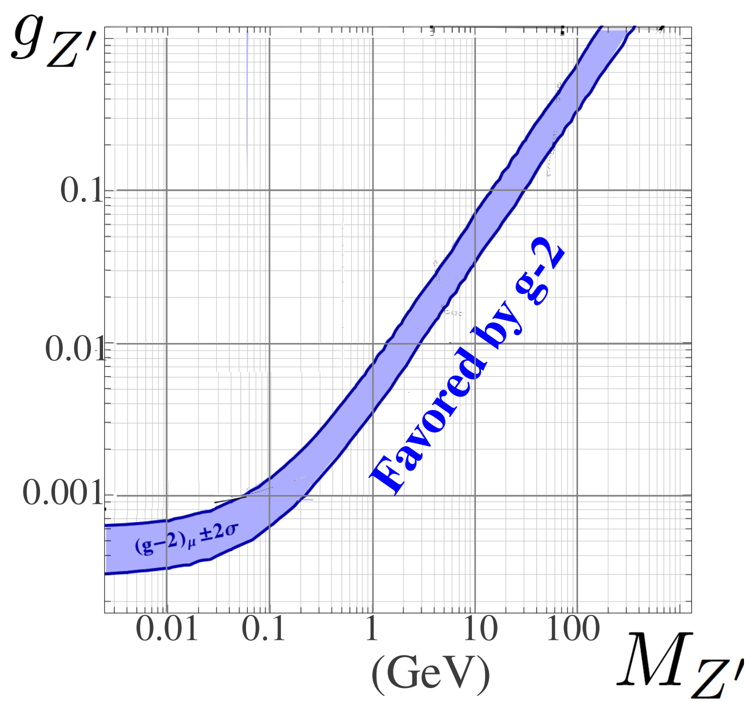


$g_\mu - 2$ Gap

$$a_\mu^{\text{Exp}} - a_\mu^{\text{SM}} = (26.1 \pm 8.0)\cdot 10^{-10}\ (3.3\sigma)$$

$\rightarrow$ We need $\Delta a_\mu^{\text{NP}} \simeq (20\text{-}30)\cdot 10^{-10}$



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$$\mathscr{L}_{L_\mu - L_\tau} = g_{ij}\overline{\nu}_i \gamma^\rho P_L \nu_j Z'_\rho + \underline{g_{Z'} \mathrm{diag}(0,1,-1)_{\alpha\beta} \overline{\ell}_\alpha \gamma^\rho \ell_\beta Z'_\rho}$$

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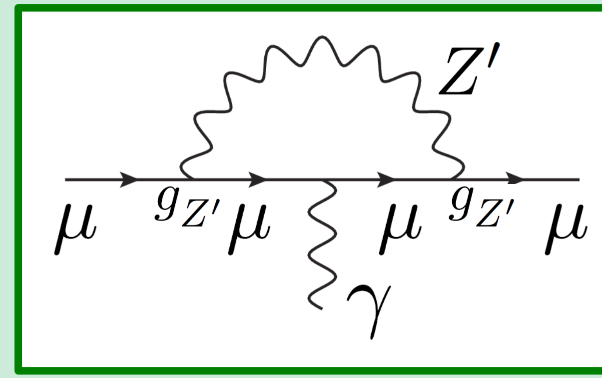

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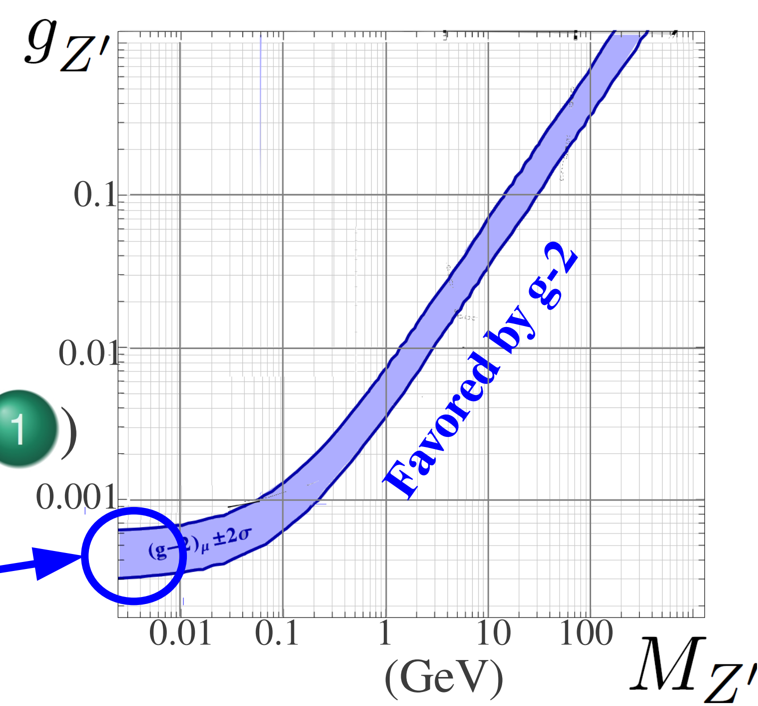
- Let me remind (back-of-the envelope calc. in **Sec. 1**)

IceCube Gap requires

$M_{Z'} \sim$ MeV, $\quad g_{Z'} \gtrsim 10^{-4}$.



Collider bounds

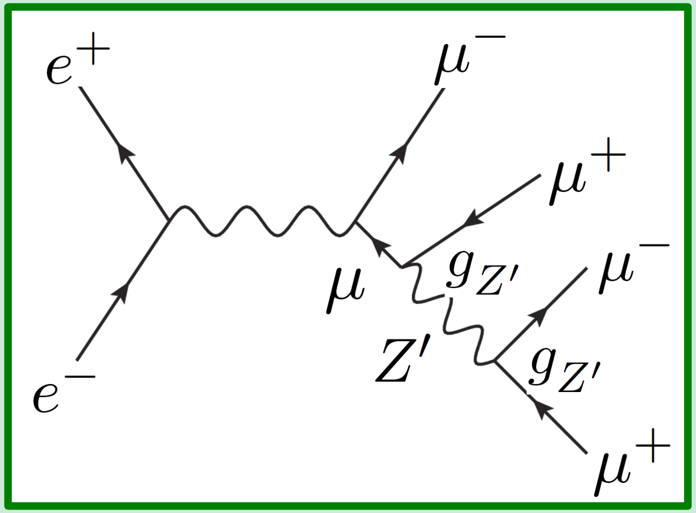
Harigaya et al., JHEP **1403** (2014) 105.

- Process: $e^+e^- \to 4\mu$

  $PP(P\bar{P}) \to 4\mu/2\mu2\tau$

  only constrain relatively heavy Z'

  $\to$ LEP, LHC: $g_{Z'} \lesssim 0.1$ at $M_{Z'} \simeq \mathcal{O}(10)$ GeV



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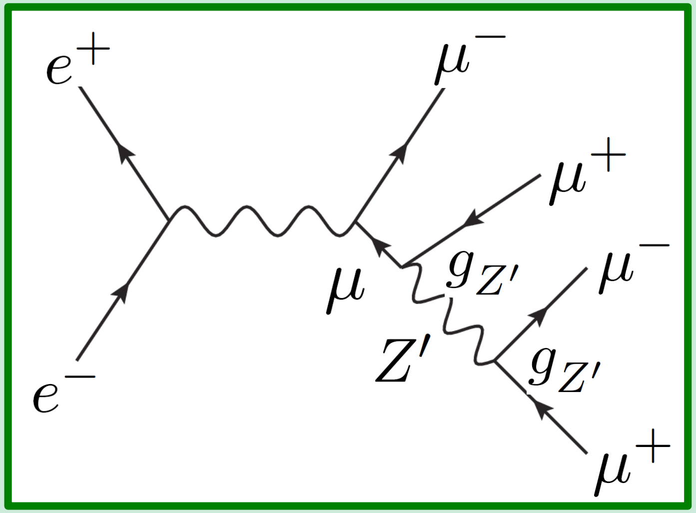

Rare meson decays

Lessa and Peres, PRD**75** (2007) 094001

- Process: $\pi^+/K^+ \to \mu^+\nu_\mu Z'$

  Bound from Kaon decay $\to g_{Z'} \lesssim 0.01$ at $M_{Z'}$ ~MeV

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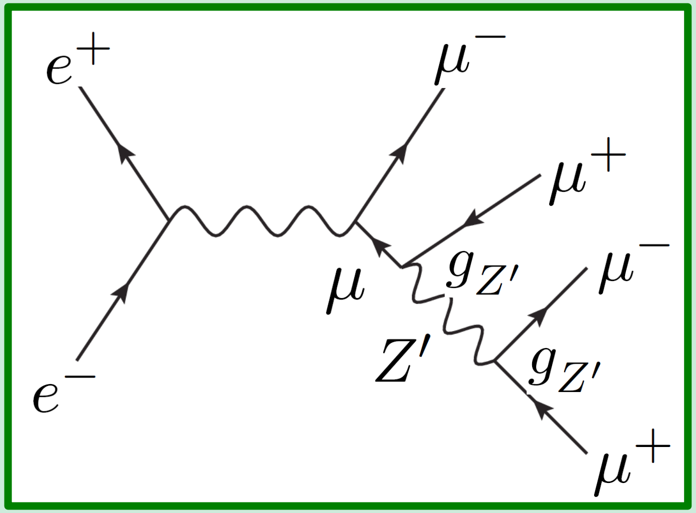

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- The most relevant bound from lab. experiments is

  Neutrino trident process in neutrino-nucleon scattering

  Altmannshofer Gori Pospelov Yavin, PRL **113** (2014) 091801

- Bounds from CMB, BBN, and also from SN1987A $\to$ References in Ng Beacom

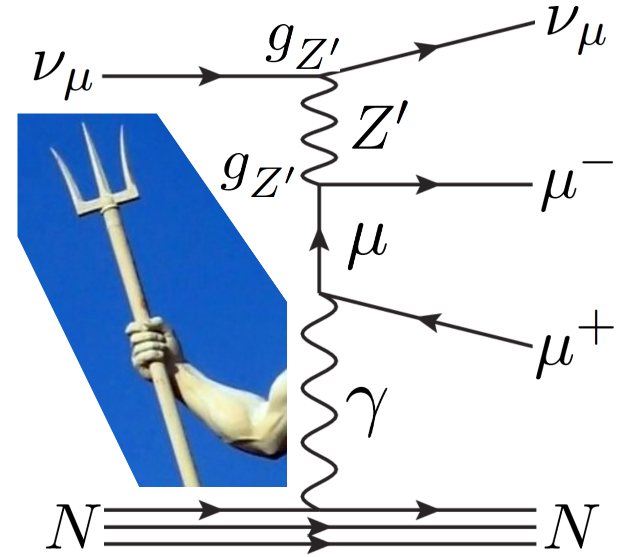
Constraints: Neutrino Trident Process

- **Neutrino trident process**
  in neutrino-nucleon scattering events

  - Available **data** reported by CCFR in 1991!

    37 events (±12.4)

    CCFR collaboration, PRL **66** (1991) 3117
    excavated recently (only cited ~20 times)



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  - Expected **SM contribution** mediated by Z and W

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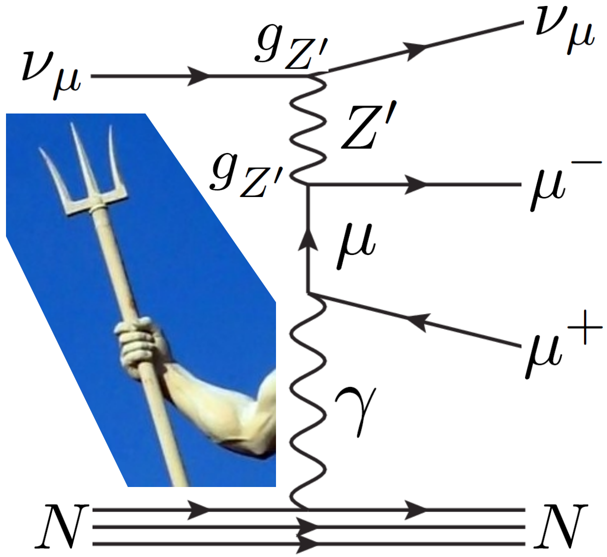
  → **Consistent** → constrains $g_{Z'}$ and $M_{Z'}$



Altmannshofer et al., PRL **113** (2014) 091801

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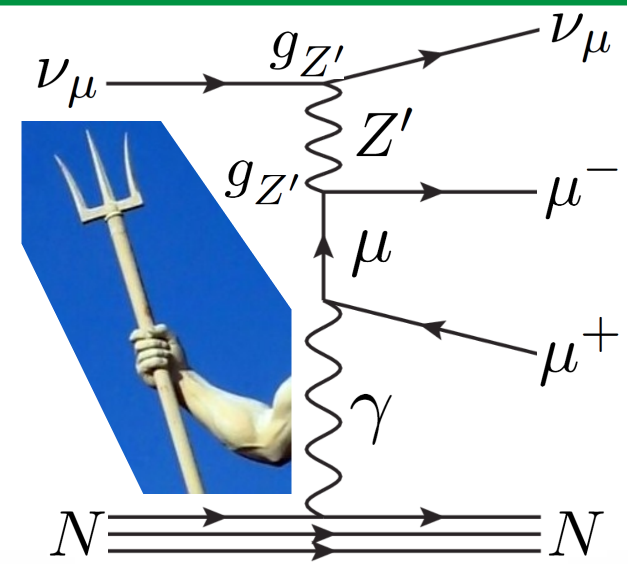

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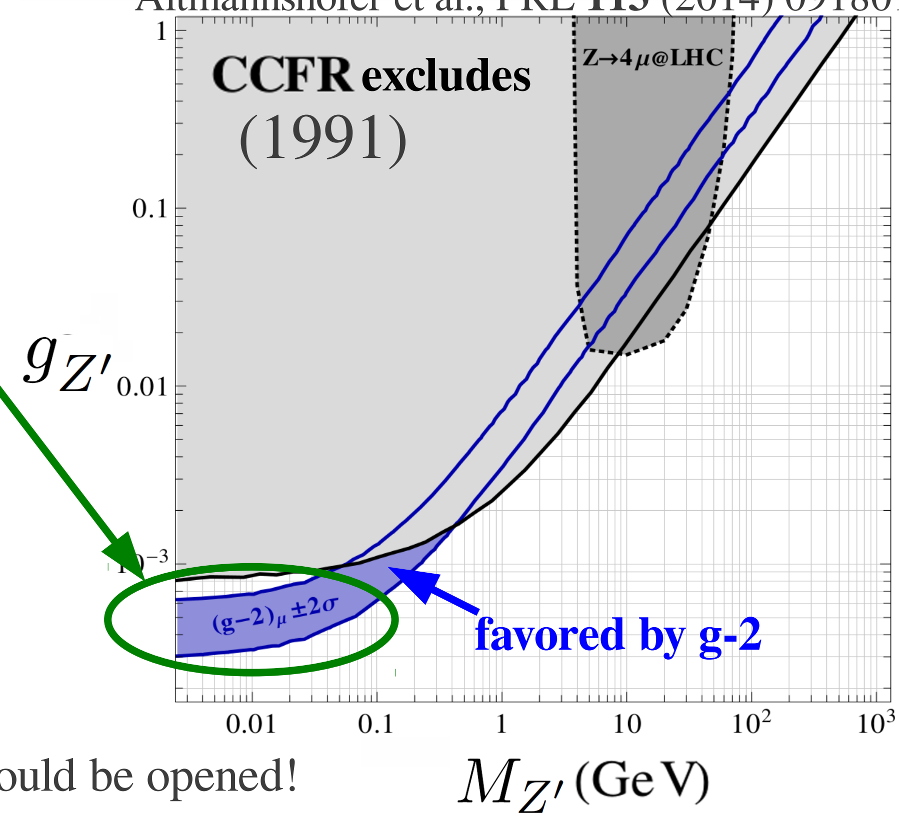

$g_\mu - 2$ favored - Trident excl.

$M_{Z'} \lesssim 100$ MeV, $\quad g_{Z'} \simeq$ several $\cdot\, 10^{-4}$.

*The trident process must be recorded on the hard disks of the near detectors in modern oscillation experiments. They should be opened!

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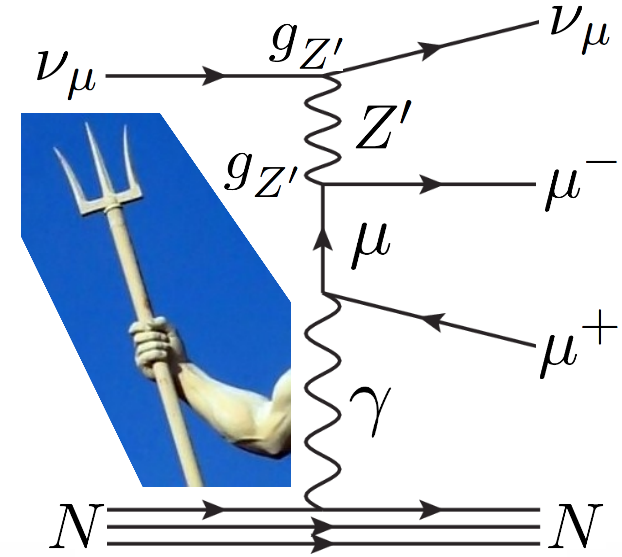

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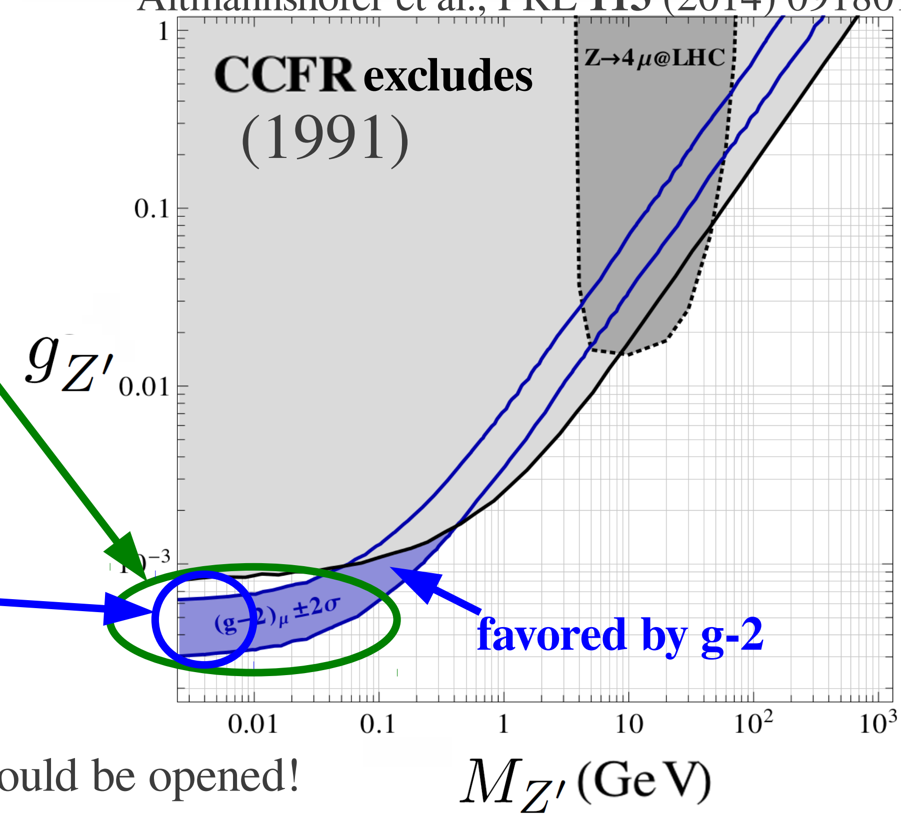

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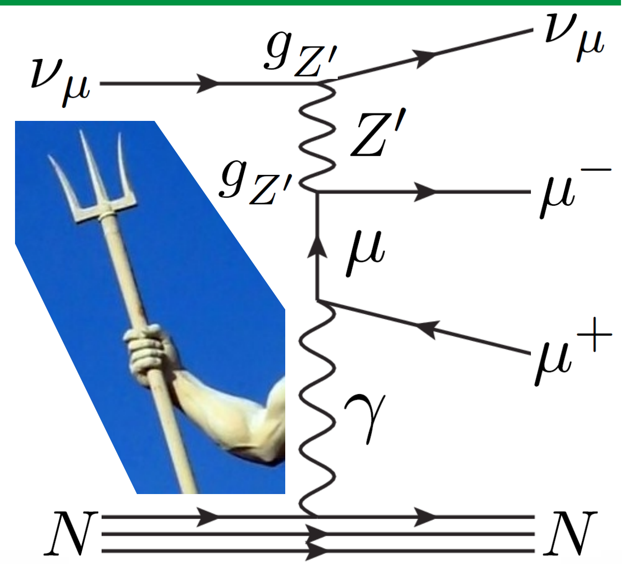

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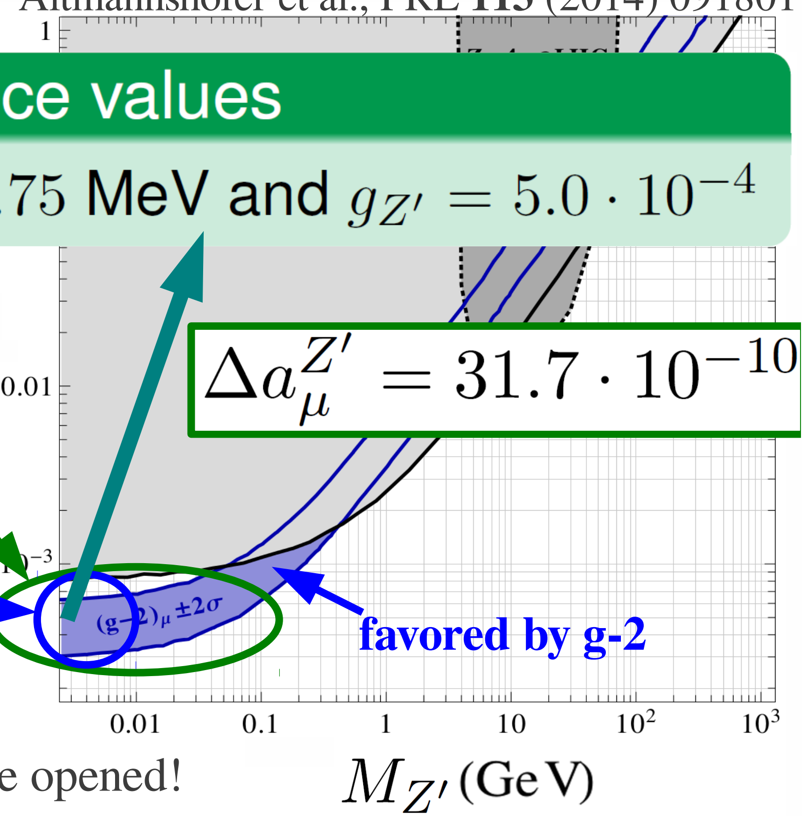

Reference values

$M_{Z'} = 2.75$ MeV and $g_{Z'} = 5.0 \cdot 10^{-4}$

$\Delta a_\mu^{Z'} = 31.7 \cdot 10^{-10}$

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$M_{Z'} \lesssim 100$ MeV, $g_{Z'} \simeq$ several $\cdot 10^{-4}$.

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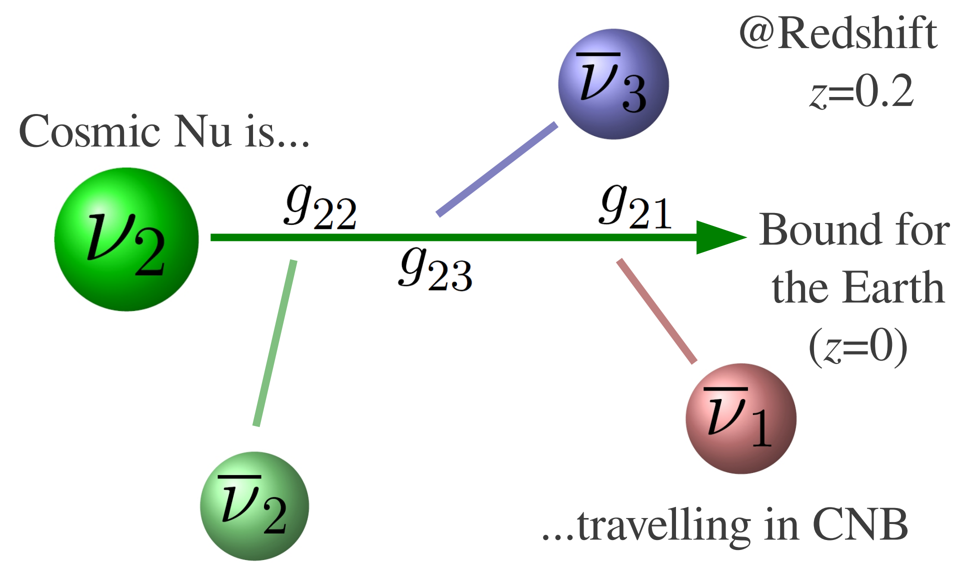
3 Cosmic neutrino spectrum

- $M_{Z'} = 2.75\ \text{MeV}, g_{Z'} = 5.0 \cdot 10^{-4}$ → Favored by ***g-2*** and allowed by **Trident**
- We fix $m_{\nu_{\text{lightest}}} = 3.0 \cdot 10^{-3}\ \text{eV}$ and take IH $m_{\nu_3} \ll m_{\nu_1} < m_{\nu_2}$
- Let us calculate the **mean free path** (for 2nd neutrino) at z=0.2.



Working example ③ Cosmic neutrino spectrum

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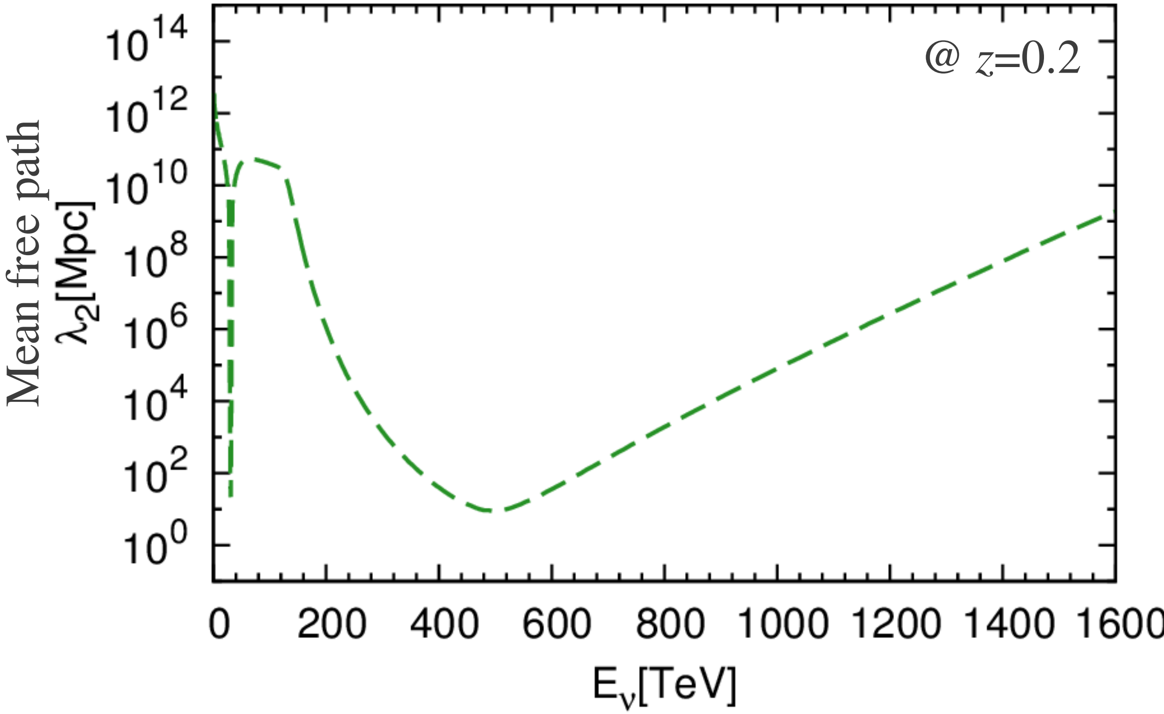
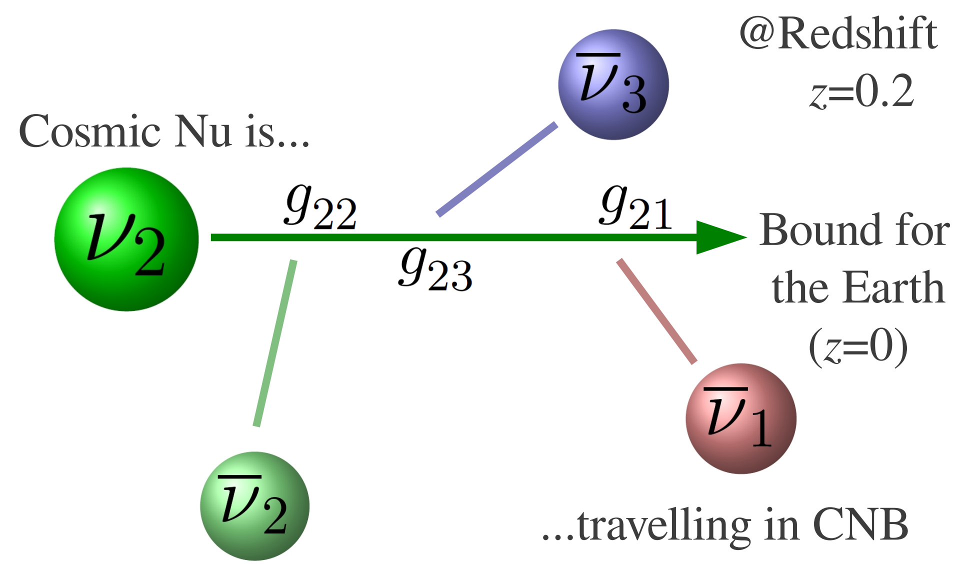


Neutrino energy observed at IceCube



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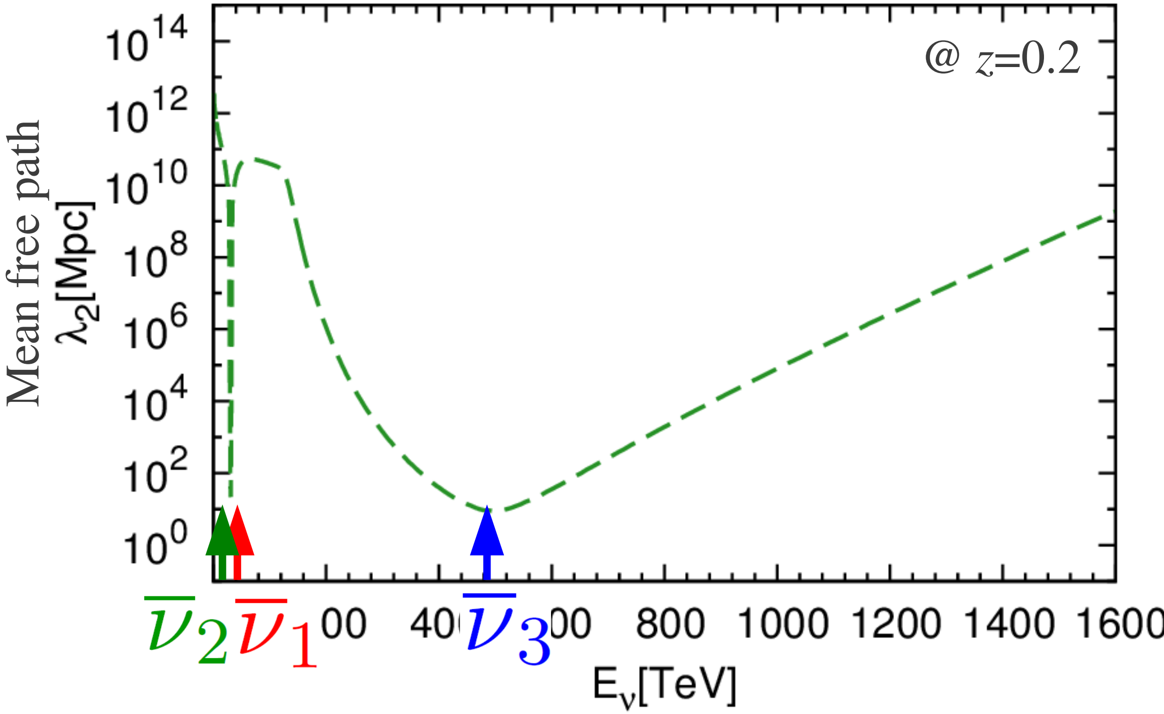

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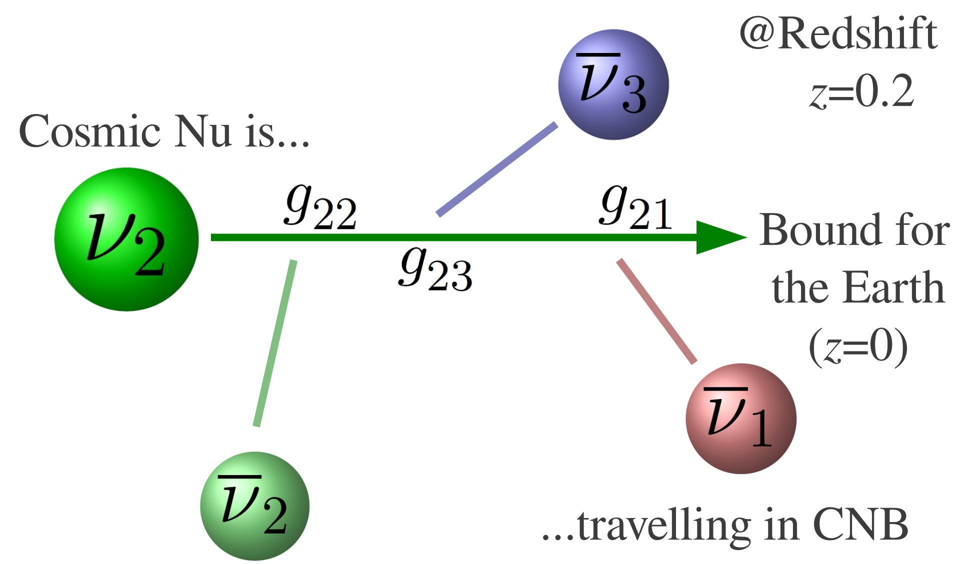

- **Resonant condition w. CNB distribution**

$$s \simeq 2E_{\nu_{i=2}}(1+z)\left[\sqrt{|\boldsymbol{p}|^2 + m_{\nu_j}^2} - |\boldsymbol{p}|\cos\theta\right] \overset{!}{=} M_{Z'}^2$$

Neutrino energy @z

$|\boldsymbol{p}|$: **CNB momentum** follows Fermi-Dirac dist. $\lesssim (1+z)T_{\nu 0} \sim 2.0 \cdot 10^{-4}$ [eV] @$z = 0.2$

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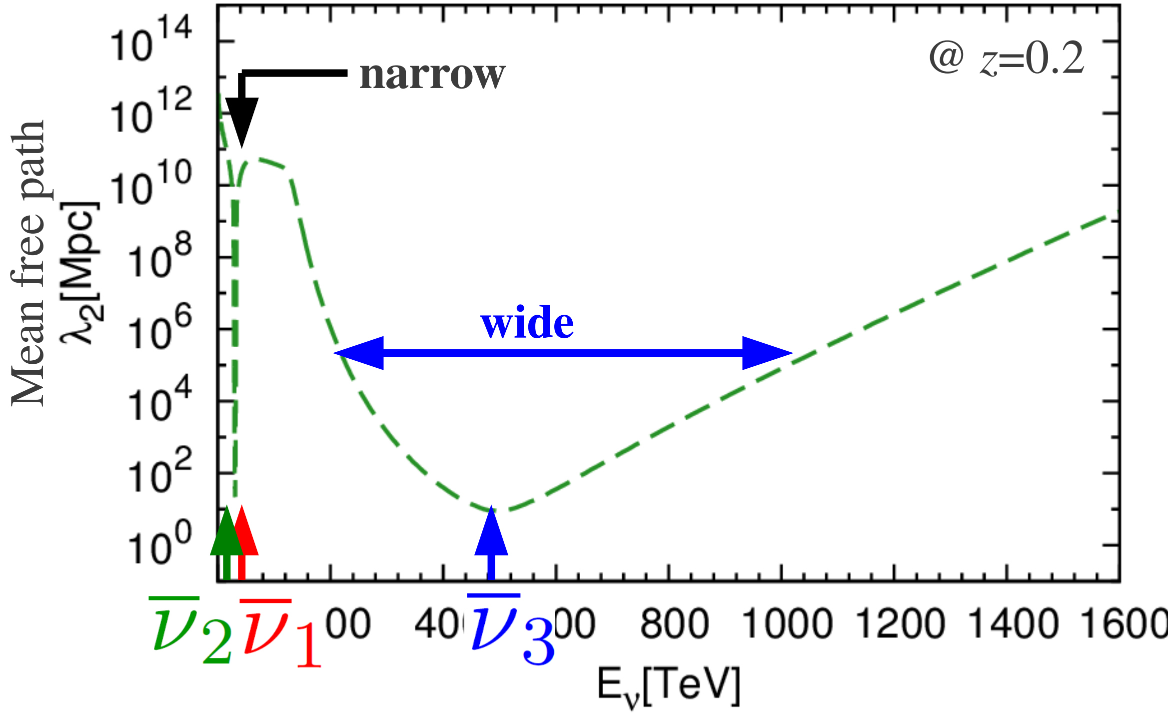

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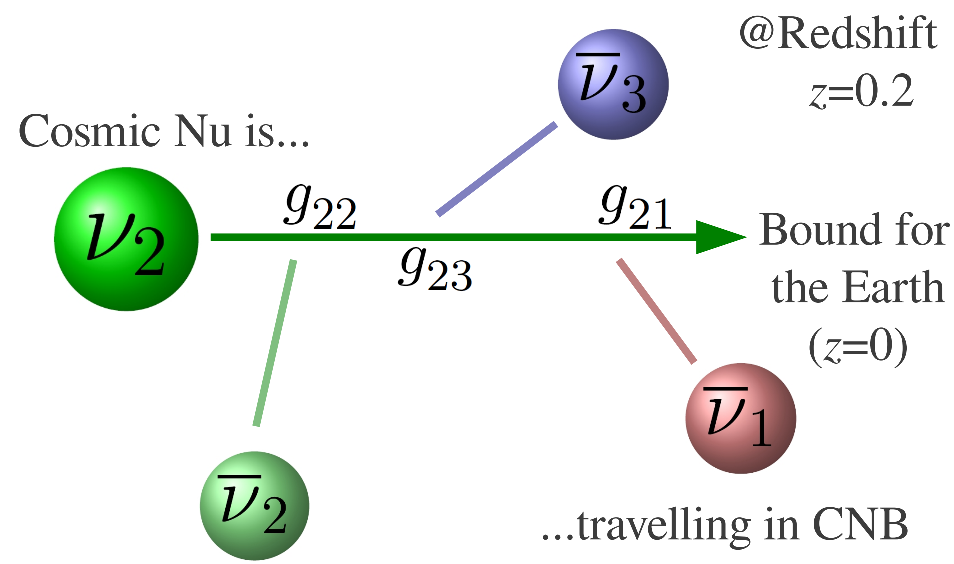

$$m_{\nu_3} \sim |\boldsymbol{p}|$$
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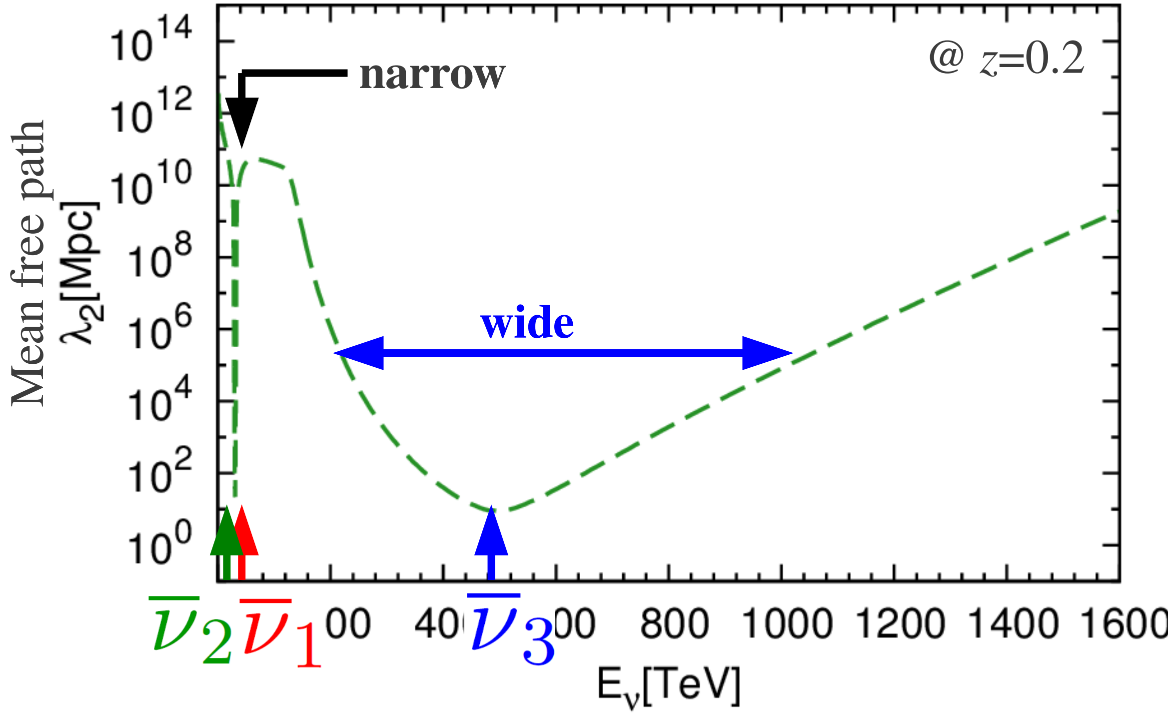

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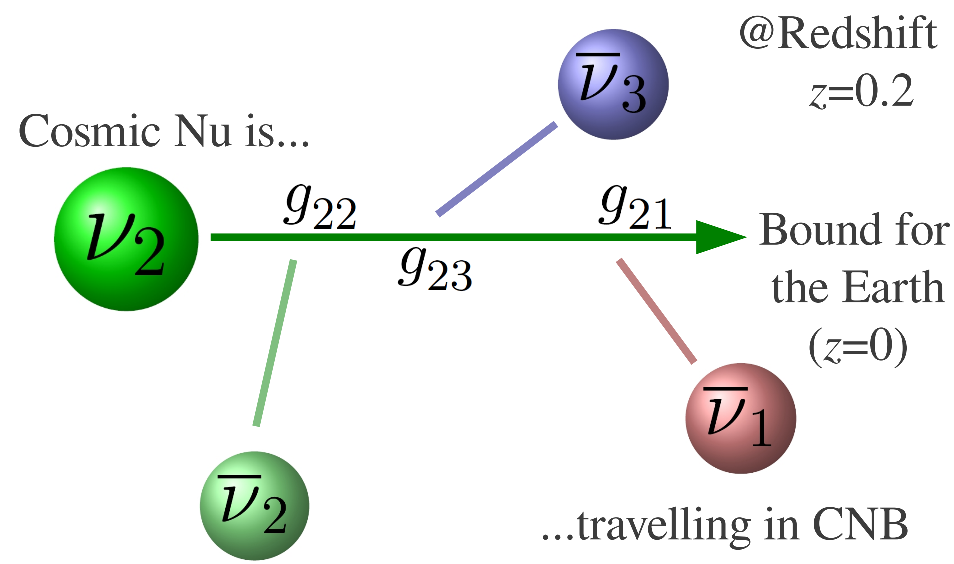

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Neutrino energy @z

z shifts resonant E
Small mNu→ wide width
Large z → wide width

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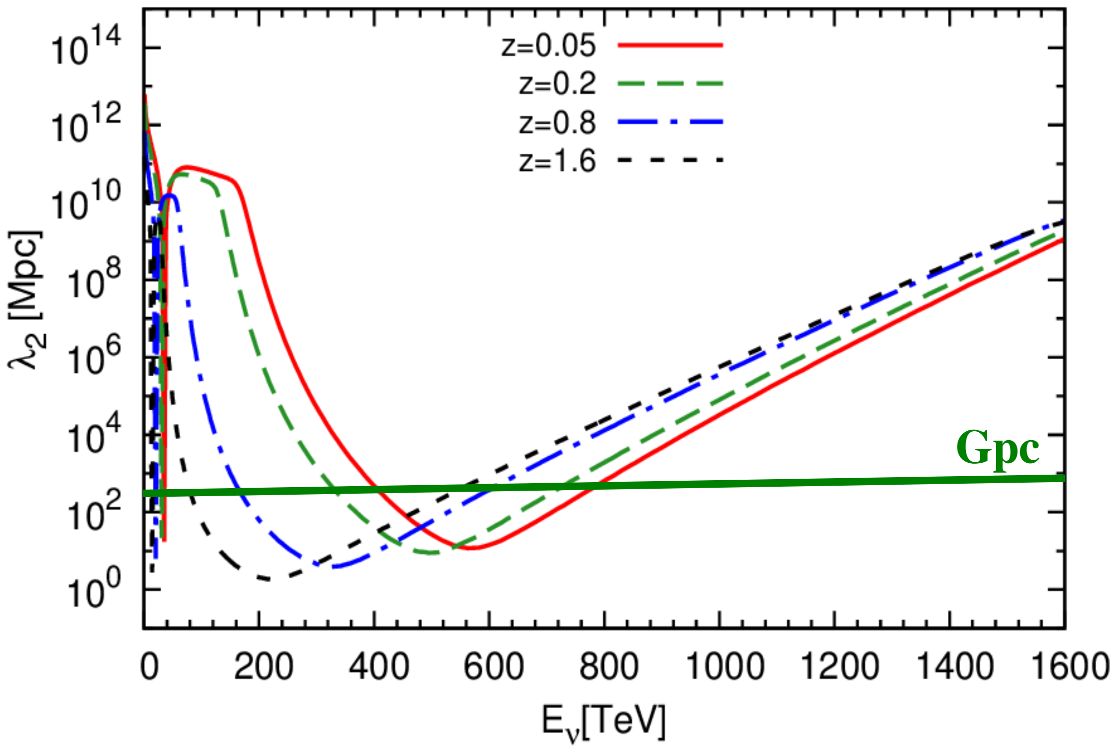

Saitama University 埼玉大学 Working example

③ Cosmic neutrino spectrum

- $M_{Z'} = 2.75$ MeV, $g_{Z'} = 5.0 \cdot 10^{-4}$
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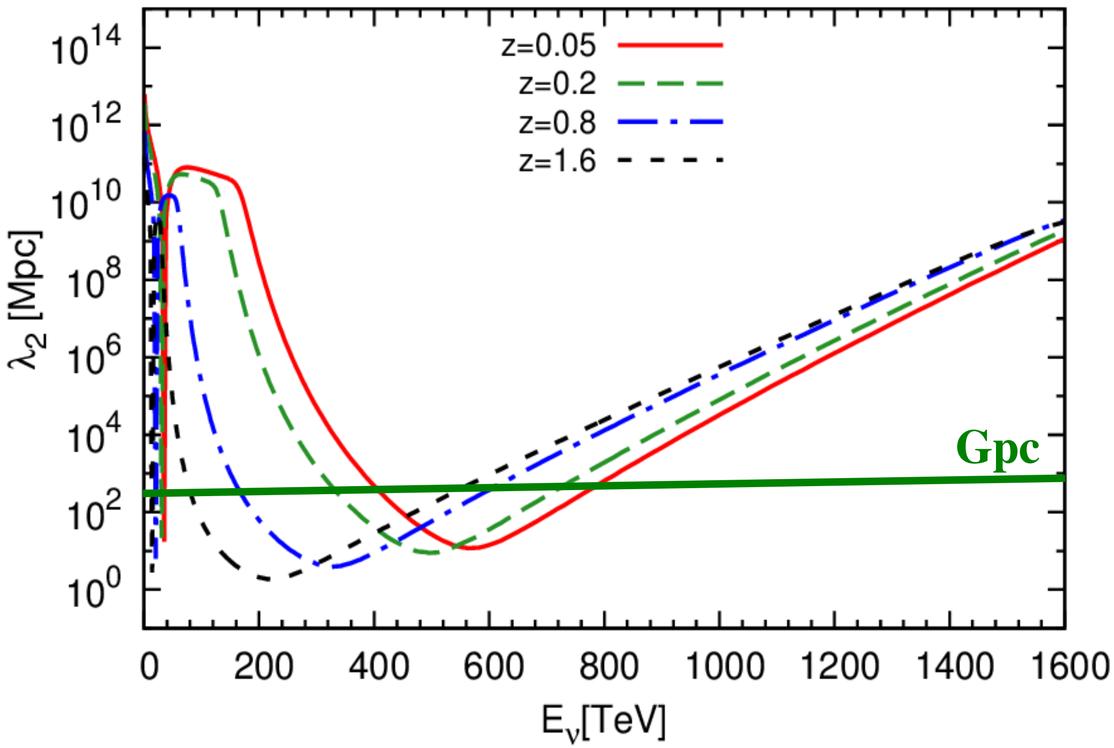

- Cosmic neutrinos travel from z_{source} to $z = 0$ (Earth)

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- The resonance energy shifts along the travel path.

To keep the width of the gap appropriate, the source should not be so distant from the Earth.

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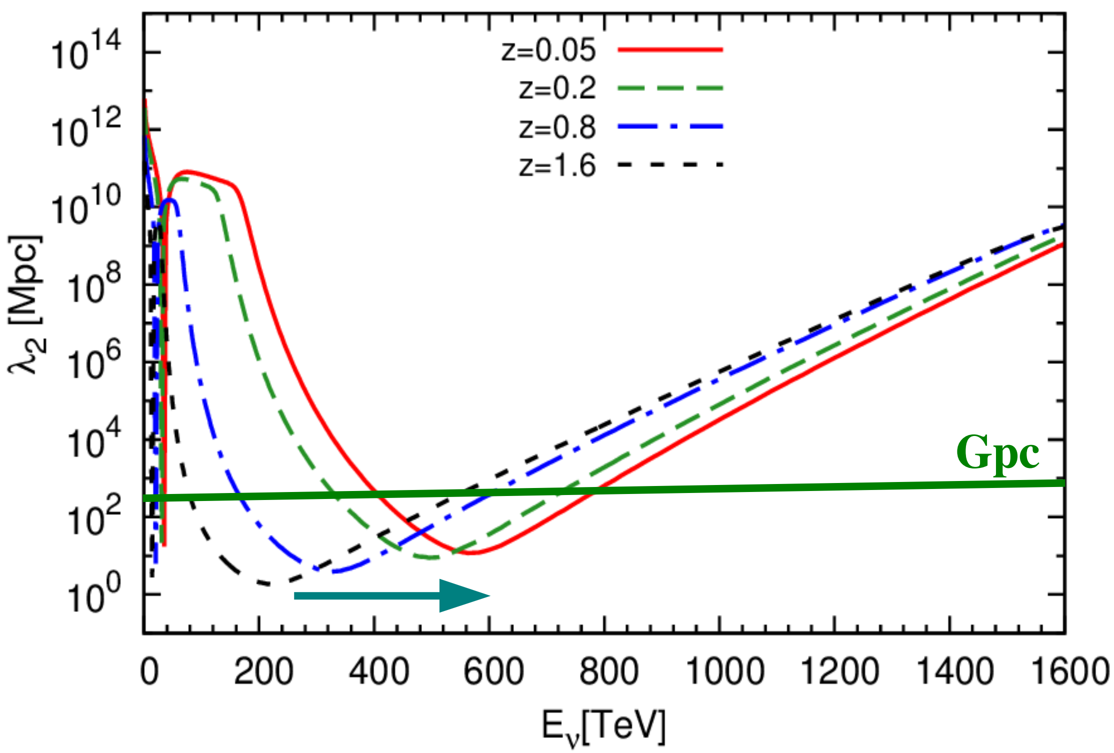

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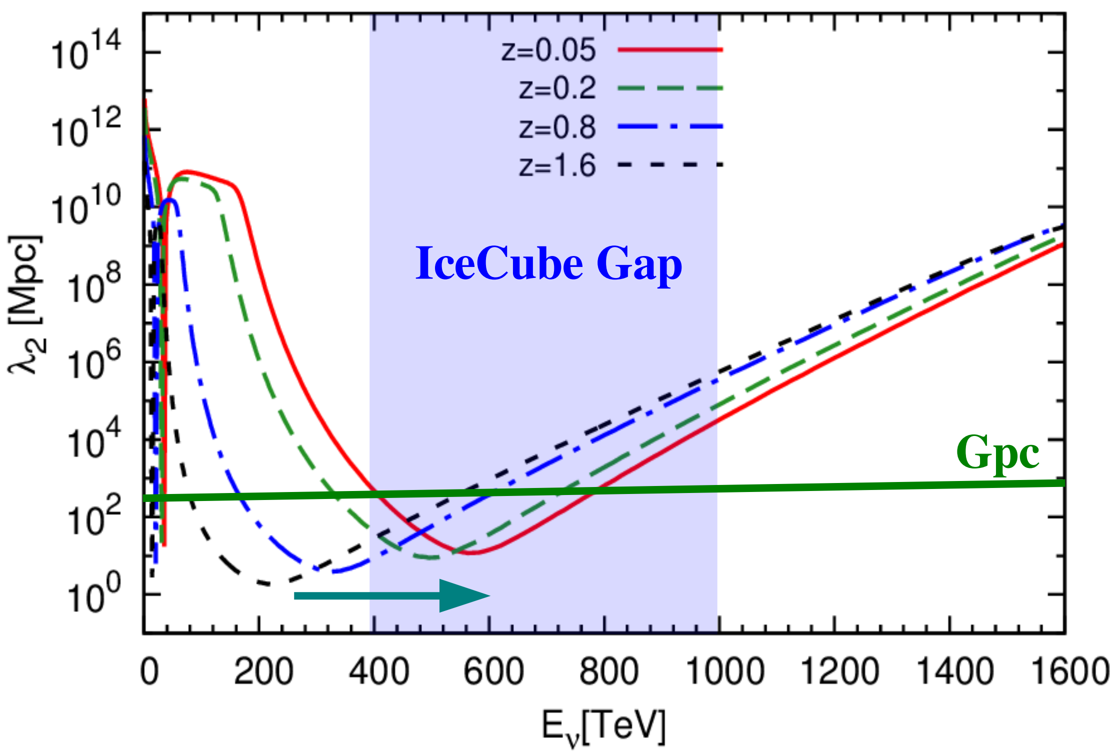

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- We set z_{source}=0.2 so that the IceCube Gap is reproduced.

In reality, sources of cosmic neutrinos are distributed following some distribution function (e.g., the star formation rate)

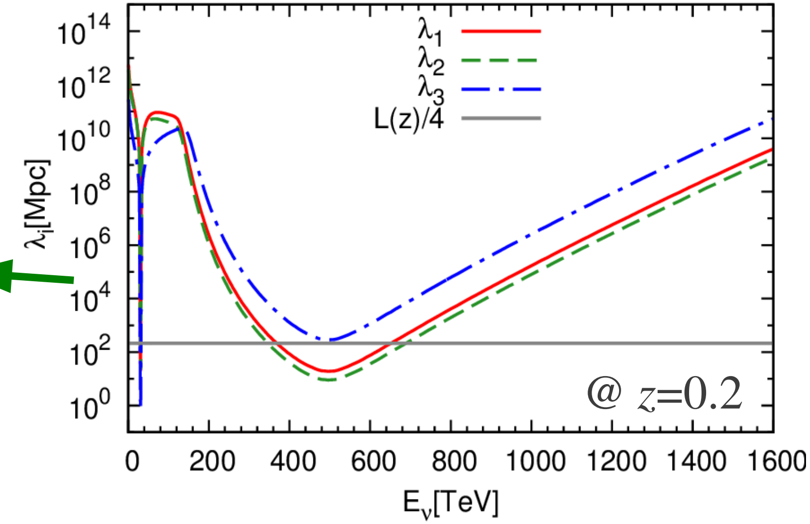
Mean free path → Spectrum

Following the approximation adopted in Ibe Kaneta PRD...

$$\varphi_i(E_\nu) = \varphi_i^{\text{original}}(E_\nu)\exp\left[-\int_0^{z_{\text{source}}} \frac{1}{\lambda_i(E_\nu)}\frac{\mathrm{d}L}{\mathrm{d}z}\mathrm{d}z\right]$$

MFP

Same for 3 cosmic Nu's...



The resulting gap does not depends on the initial flavour composition.

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Resulting spectrum

MFP

Continuous (power-law) spectrum

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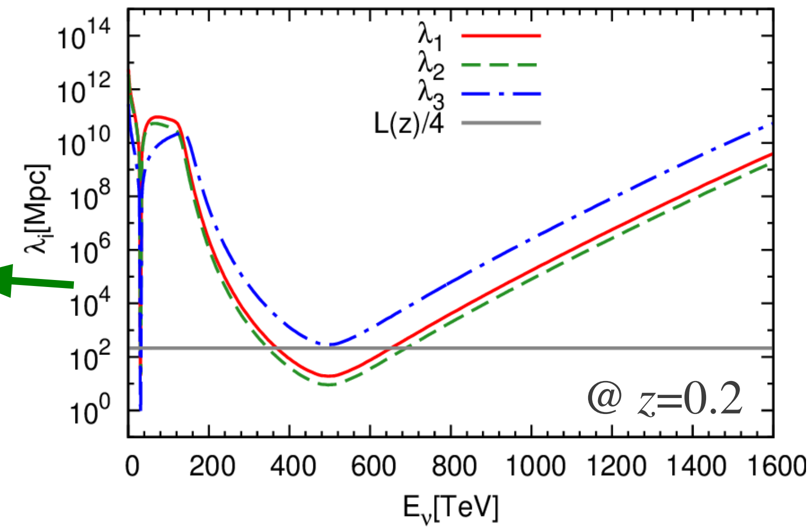

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Mean free path → Spectrum

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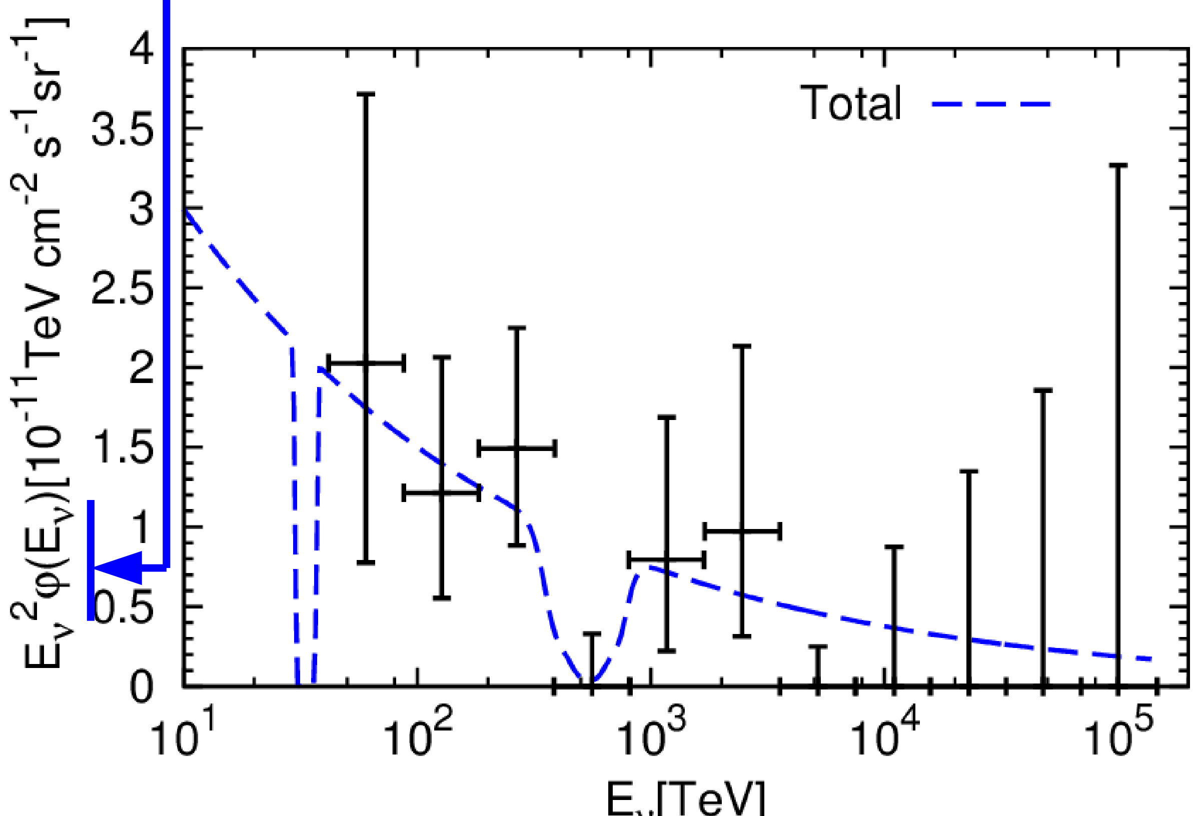
$$\varphi_i(E_\nu) = \varphi_i^{\text{original}}(E_\nu) \exp\left[- \int_0^{z_{\text{source}}} \frac{1}{\lambda_i(E_\nu)} \frac{\mathrm{d}L}{\mathrm{d}z} \mathrm{d}z \right]$$

Resulting spectrum

$$\varphi(E_\nu) = \sum_i \varphi_i(E_\nu)$$

assuming flavour universal $\varphi_i^{\text{original}}(E_\nu)$



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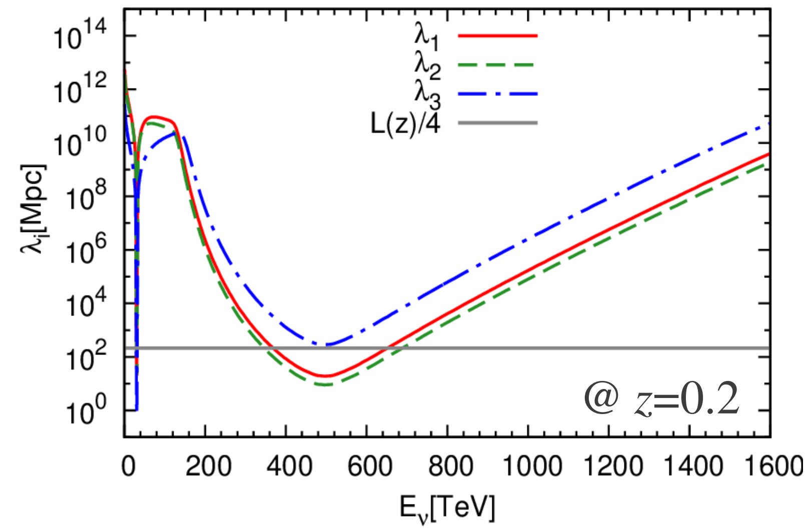

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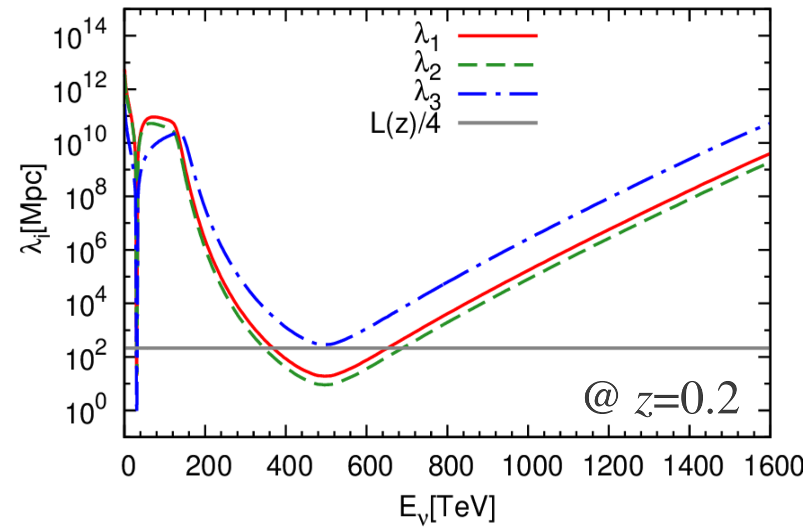

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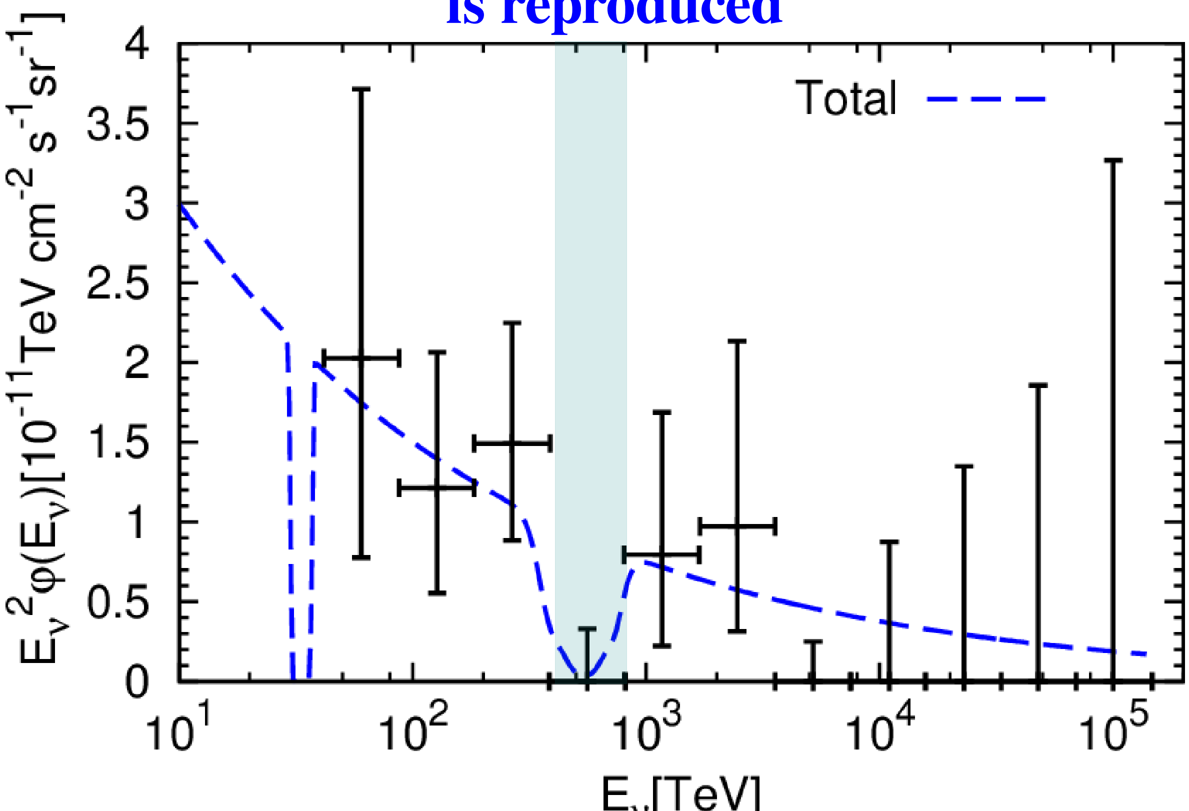

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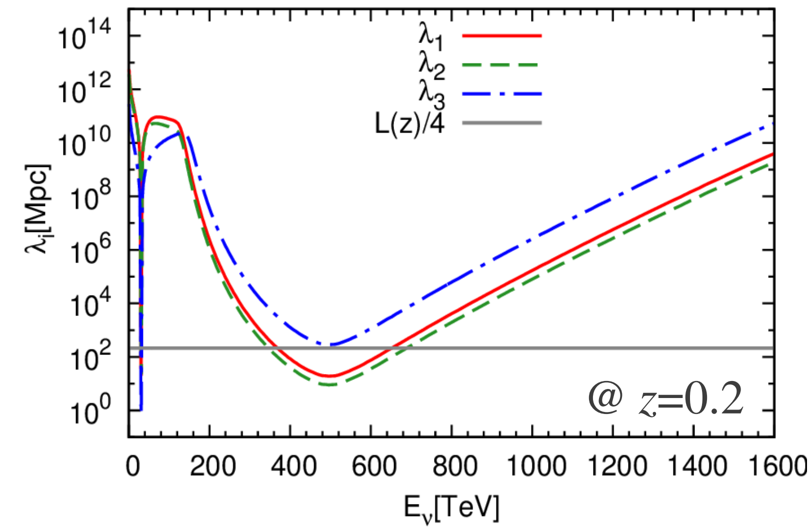

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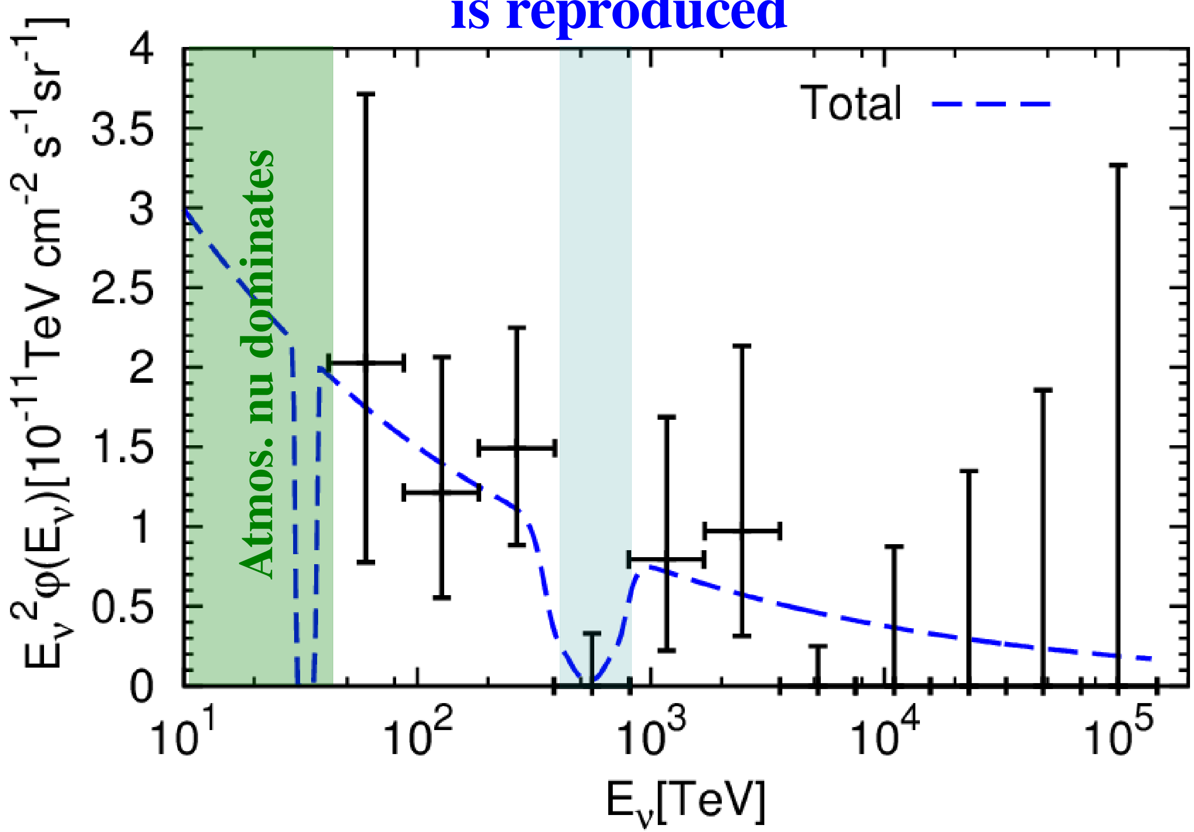

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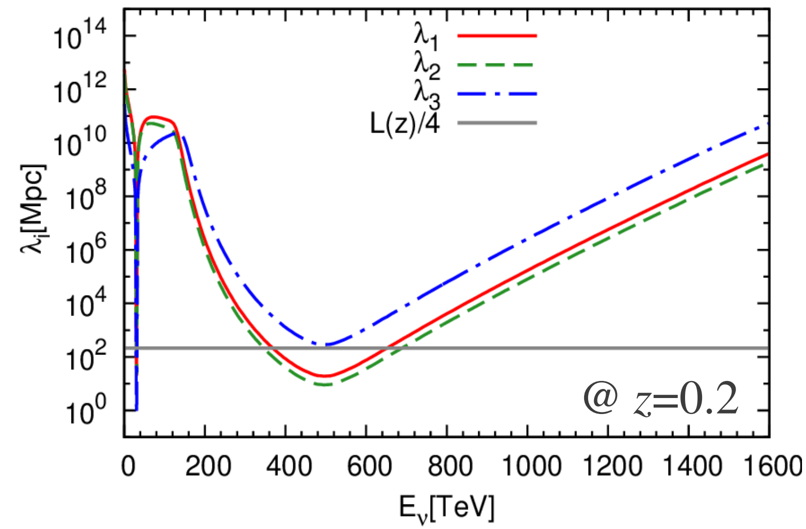

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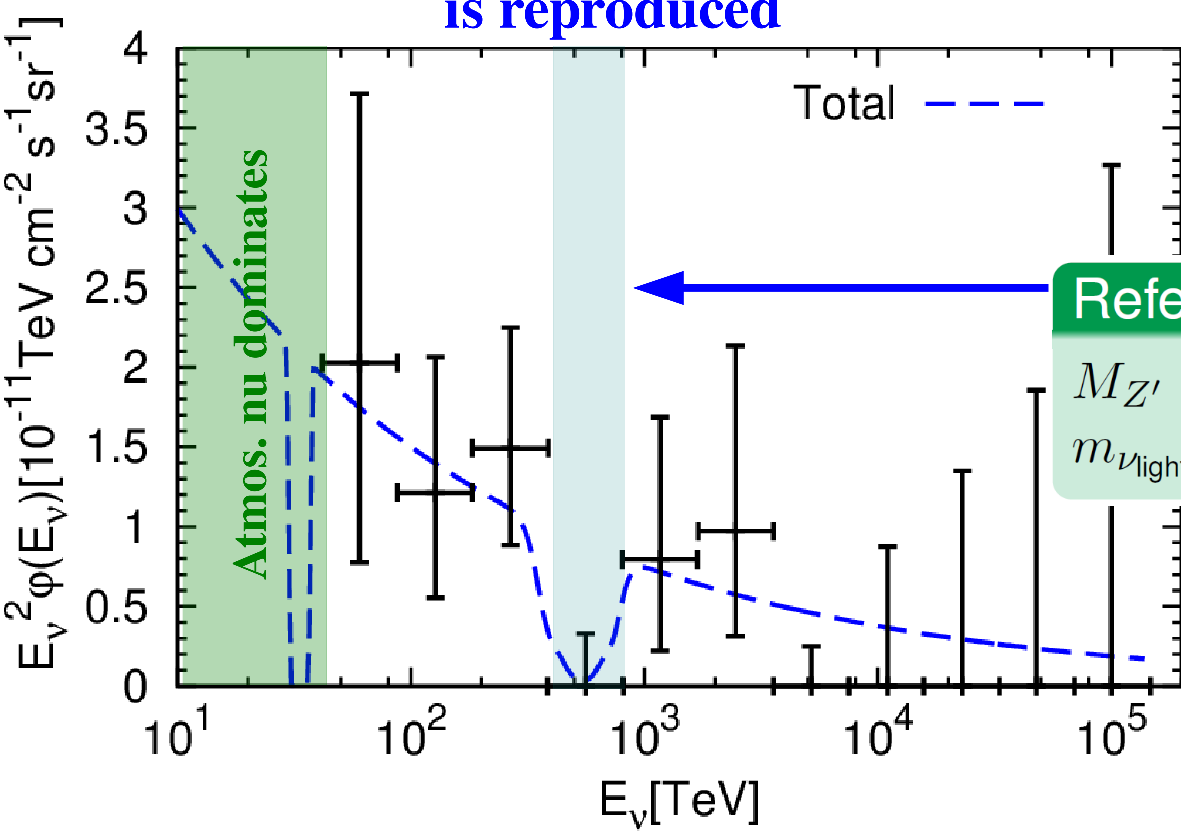

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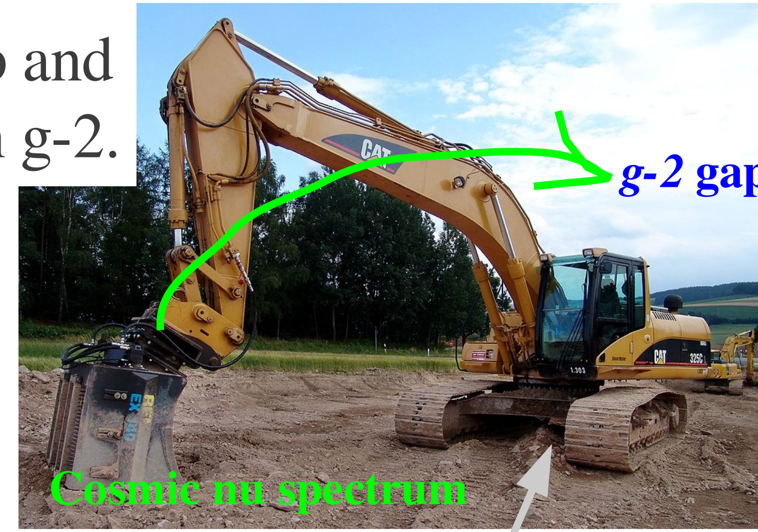
Z' contribution to muon g-2

$$\Delta a_\mu^{Z'} = 31.7 \cdot 10^{-10}$$

***g-2* Gap is filled**

Summary and future prospects

We dig the cosmic neutrino spectrum to make a gap and swing around the surplus soil to fill the gap in muon g-2.



This tool is called as "*U(1)* leptonic force Lmu-Ltau"

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- ...take distribution of neutrino source into account.
- ...count the secondary neutrino effect.
- ...discuss details of the model.
- ...consider the constraint from the neutrino-electron scattering in Borexino

Harnik Kopp Machado JCAP **1207** (2012) 026

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More precise, detailed, and sophisticated study may be worth to be done.

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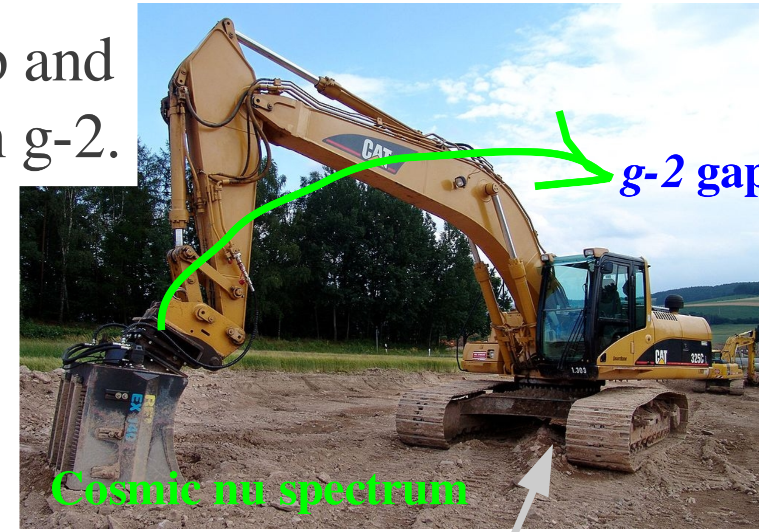

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Now we are doing

Saitama University 埼玉大学

Improvements

ArXiv.1508.*****

Improved calc.

- To take account of distribution of neutrino sources... Ng Beacom (2014), DiFranzo Hooper (2015)

Outflow by scattering

Influx from source

$$\frac{\partial \tilde{n}_{\nu_i}}{\partial t} = \frac{\partial}{\partial E_{\nu_i}} b \tilde{n}_{\nu_i} + \mathcal{L} - c n_{\mathrm{C}\nu\mathrm{B}} \tilde{n}_{\nu_i} \sum_j \sigma(\nu_i \bar{\nu}_j^{\mathrm{C}\nu\mathrm{B}} \to \nu\bar{\nu})$$
$$+ c n_{\mathrm{C}\nu\mathrm{B}} \sum_{j,k} \int_{E_{\nu_i}}^{\infty} \mathrm{d}E_{\nu_k} \tilde{n}_{\nu_k} \frac{\mathrm{d}\sigma(\nu_k \bar{\nu}_j^{\mathrm{C}\nu\mathrm{B}} \to \nu_i \bar{\nu})}{\mathrm{d}E_{\nu_i}}$$
$$+ c n_{\mathrm{C}\nu\mathrm{B}} \sum_{j,k} \int_{E_{\nu_i}}^{\infty} \mathrm{d}E_{\bar{\nu}_k} \tilde{n}_{\bar{\nu}_k} \frac{\mathrm{d}\sigma(\bar{\nu}_k \nu_j^{\mathrm{C}\nu\mathrm{B}} \to \nu_i \bar{\nu})}{\mathrm{d}E_{\nu_i}},$$

z development
$z = zmax \to z = 0$

Energy loss
by redshift

Influx after scattering (aka regeneration)

* A step back: We do not take the CNB temperature effect into account.

- After solving the diff. equations, we can obtain the number densities at z=0,

$$\tilde{n}_{\nu_i}(E_{\nu_i}, z = 0)$$

which is proportional to the flux, $\phi_{\nu_i}(E_{\nu_i})$, observed at IceCube.

Improved calc.

Safe from the Borexino bound

$E_{\rm cut} = 10^7$ GeV, $g_{Z'} = 6 \times 10^{-4}$, $M_{Z'} = 12$ MeV, $m_\nu^{\rm lightest} = 0.09$ eV.

No CnB thermal effect