(c) Transport for London

Mind the Gap on IceCube

Cosmic neutrino spectrum and muon anomalous magnetic moment

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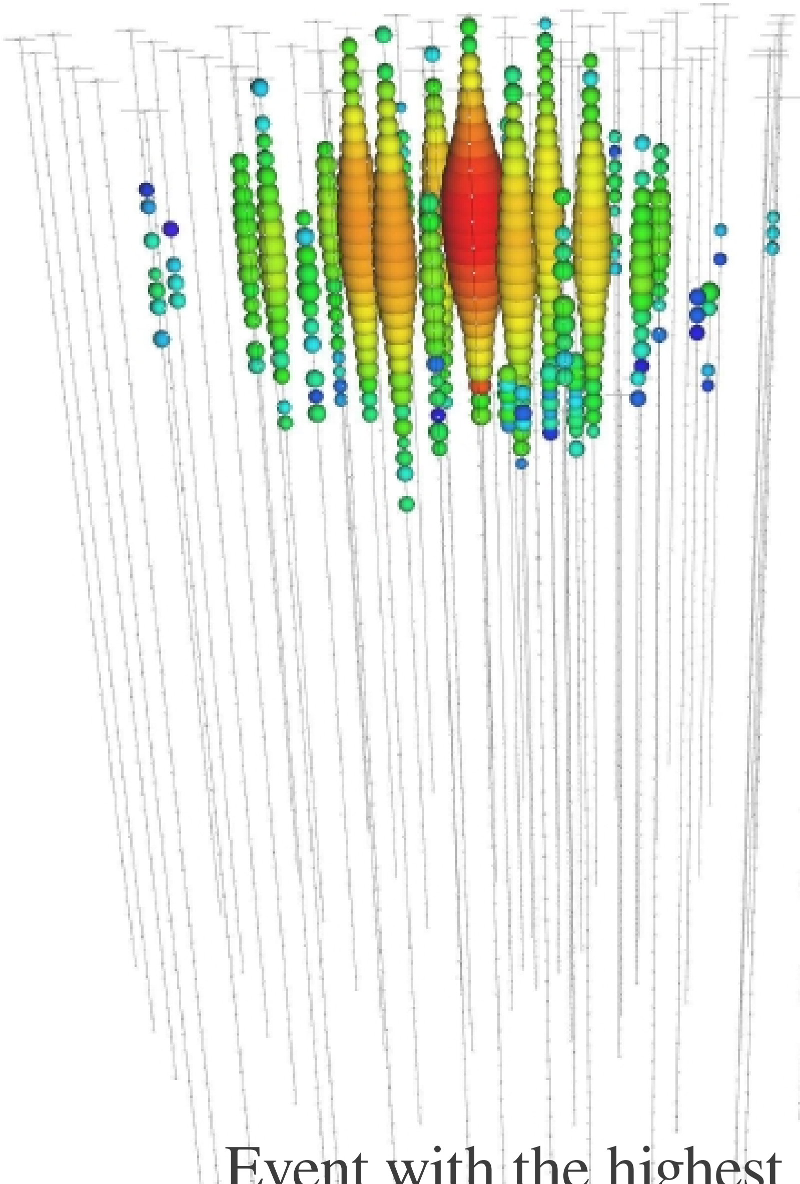
based on
T.Araki, Y.Konishi, F.Kaneko, TO, J.Sato, T.Shimomura

ArXiv.1409.4180v2
will be published in PRD

Preface

- PeV cosmic neutrino spectrum

  IceCube collaboration PRL **113** (2014) 101101



Event with the highest deposit energy~2 PeV

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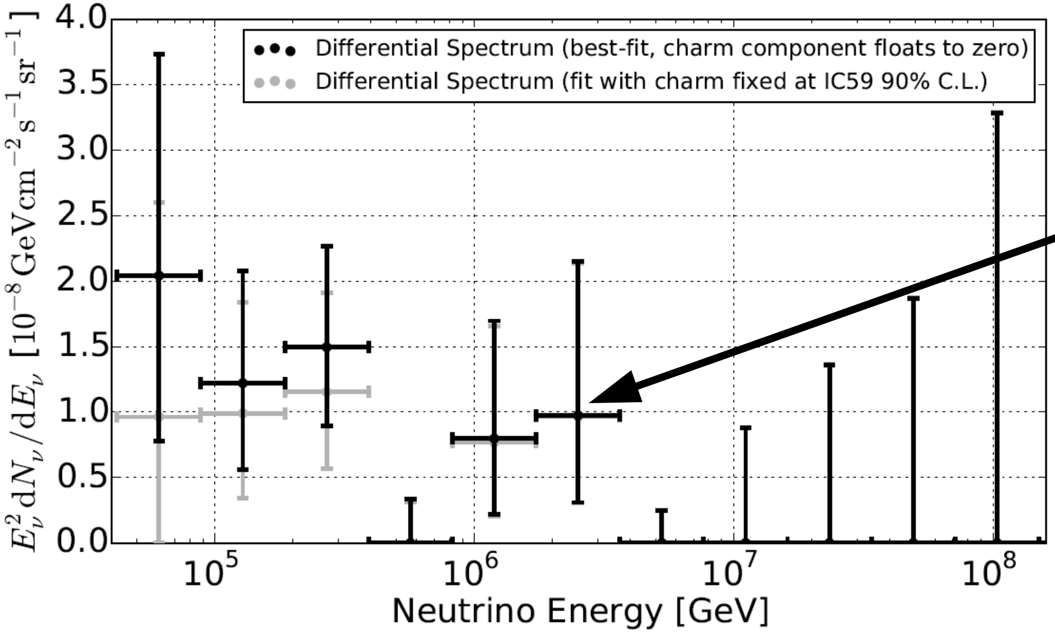
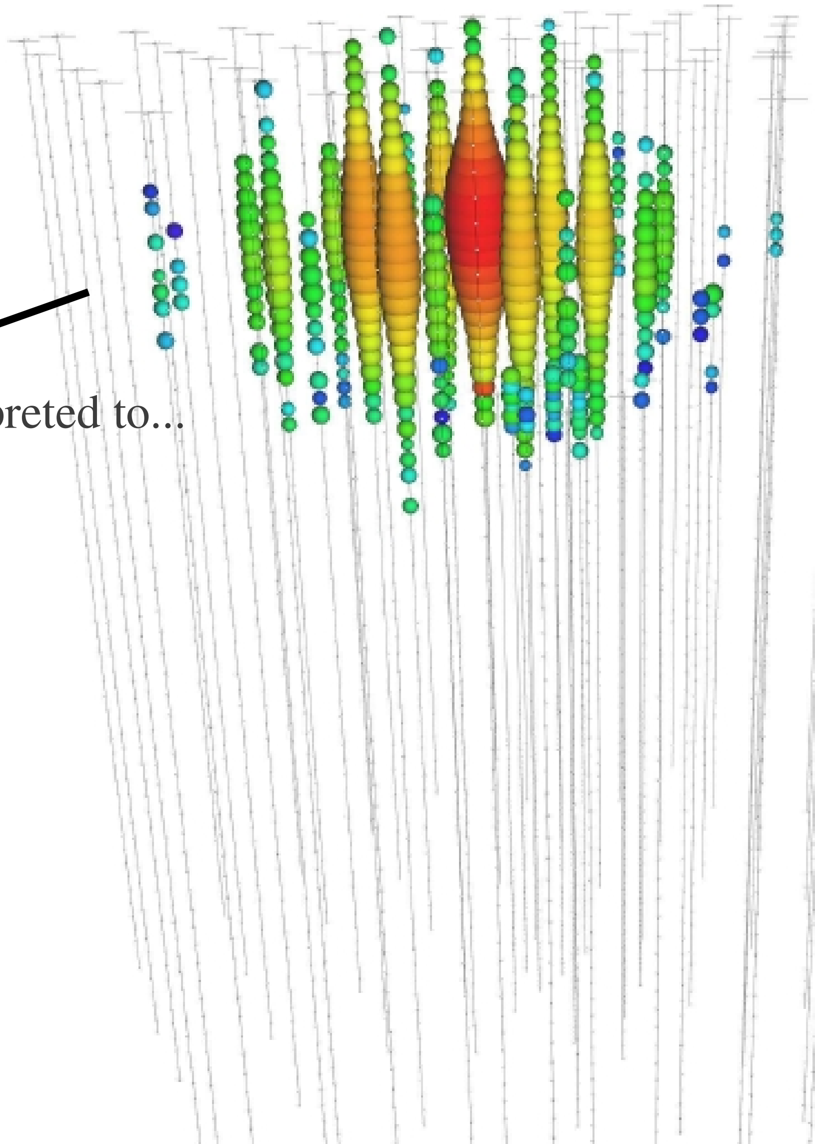


Interpreted to...



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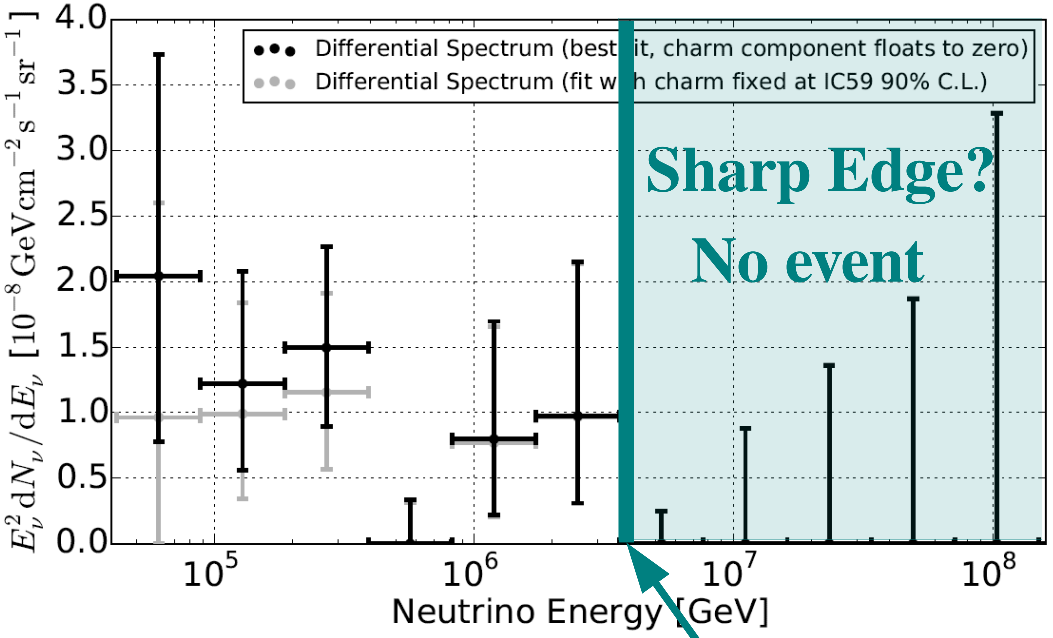
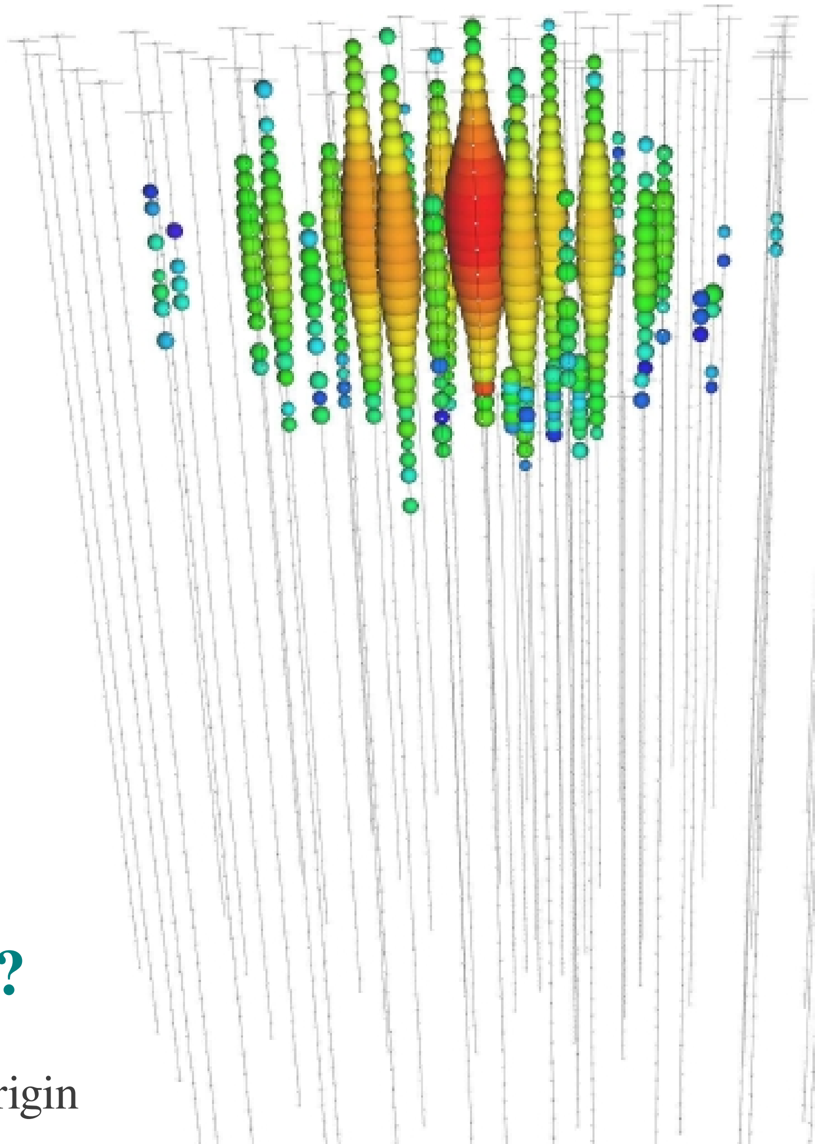


IceCube Edge?

at 3 PeV

may be astrophysical origin



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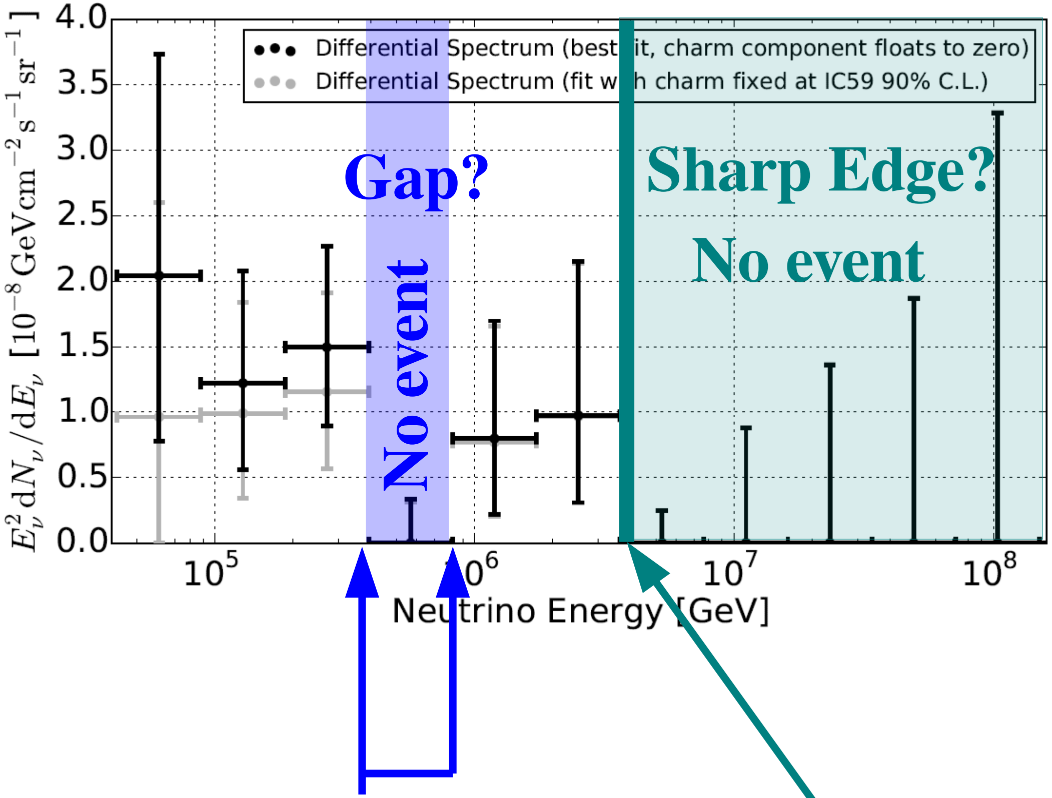

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No event at 0.4-1 PeV

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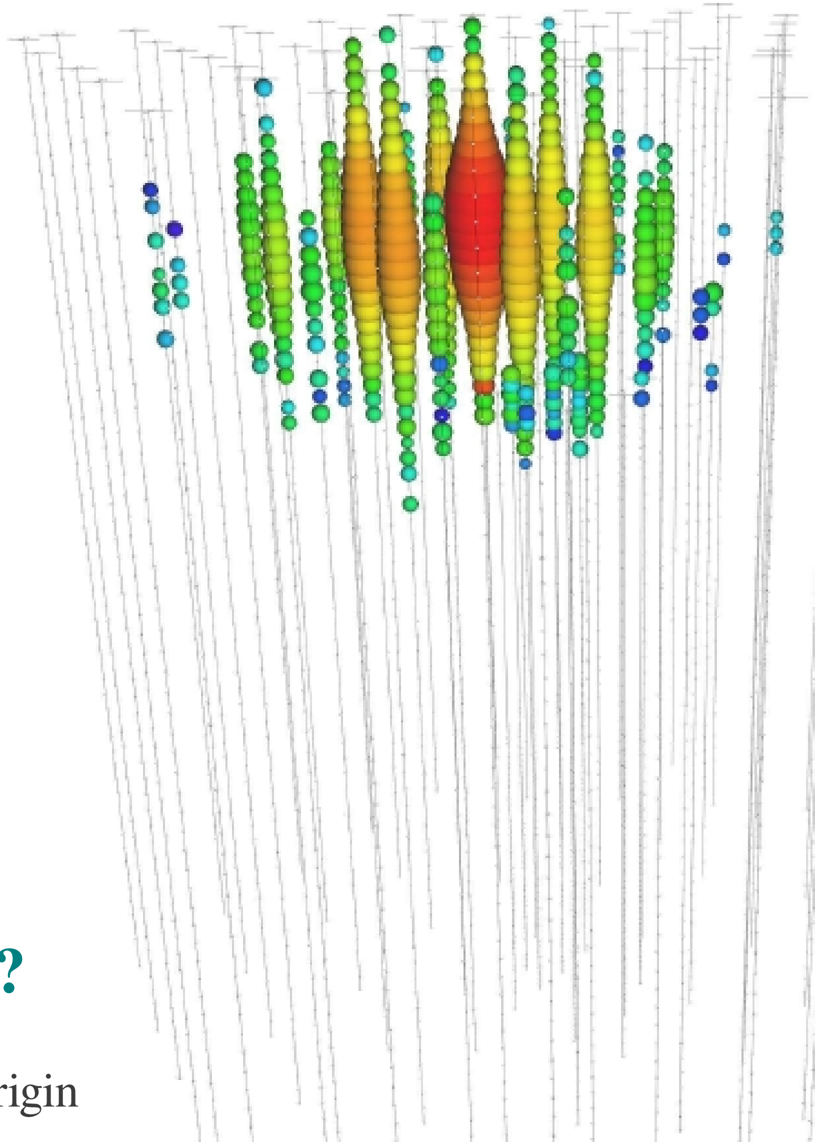

Event with the highest deposit energy~2 PeV

ICECUBE

SOUTH POLE NEUTRINO OBSERVATORY

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- PeV cosmic neutrino spectrum

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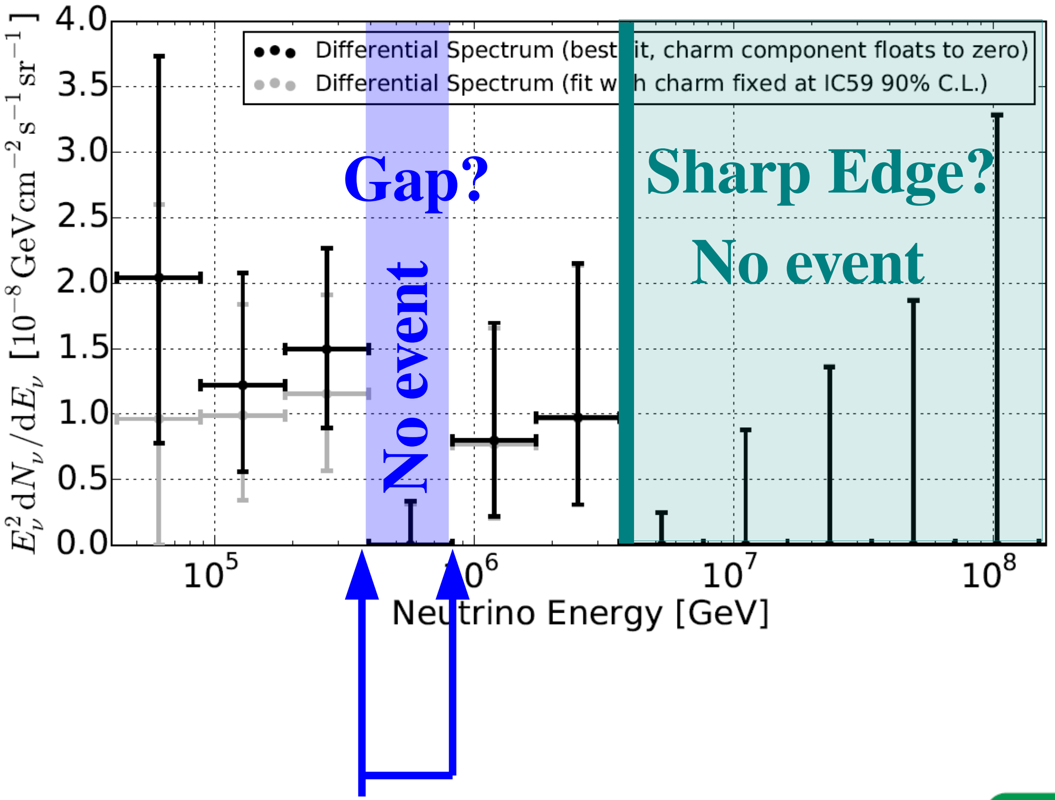
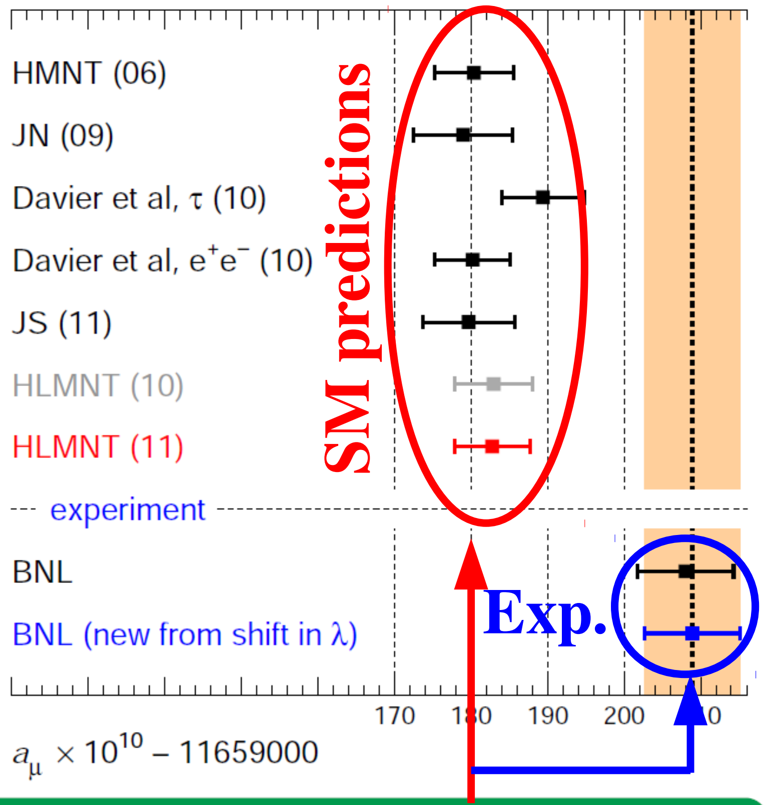


IceCube Gap

No event at 0.4-1 PeV

- Muon g-2

Hagiwara et al., J.Phys. **G38** (2011) 085003



$g_\mu - 2$ Gap

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

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 secret interaction

2 Muon anomalous magnetic moment

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

3 A solution to the gaps

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

① IceCube gap

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

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

  Feldstein Kusenko Matsumoto Yanagida, PR**D88** (2013) 015004. Zabala PR**D89** (2014) 123514.
  Ibarra Tran Weniger Int.J.Mod.Phys. **A28** (2013) 1330040.
  Esmaili Serpico JCAP **1311** (2013) 054, Esmaili Kang Serpico, 1410.5979.
  Ema Jinno Moroi PL**B733**(2014) 120, JHEP **1410** (2014) 150. Rott Kohri Park 1408.3799.
  Higaki Kitano Sato JHEP **1407**(2014) 044. Fong Minakata Panes Zukanovich-Funchal 1411.5318.

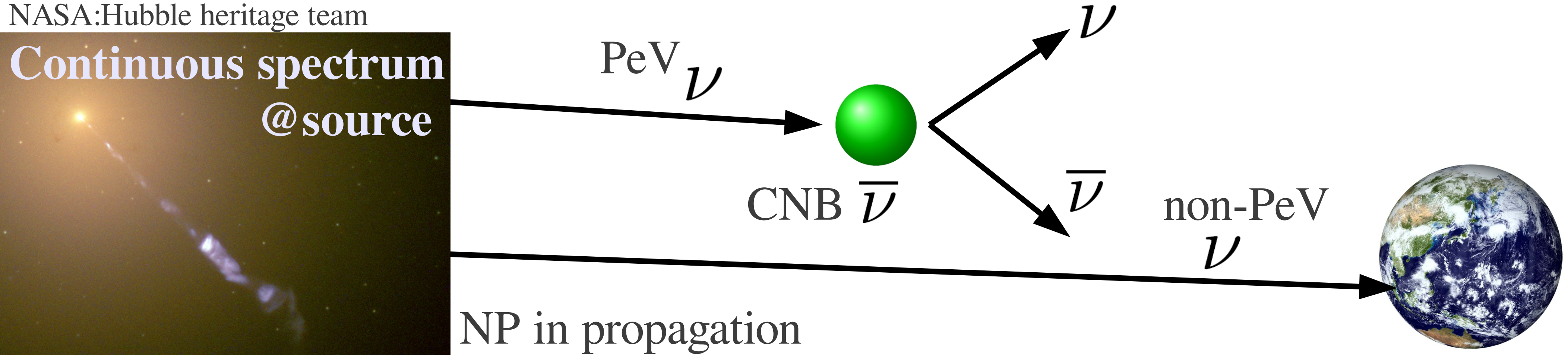
- ➡ **NP in Propagation: Scattering with CNB with a MeV mediator**

  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

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

  Barger Keung PL**B727** (2013) 190…

NASA:Hubble heritage team



New Physics in propagation

- In this talk, we pursue the possibility of

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

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

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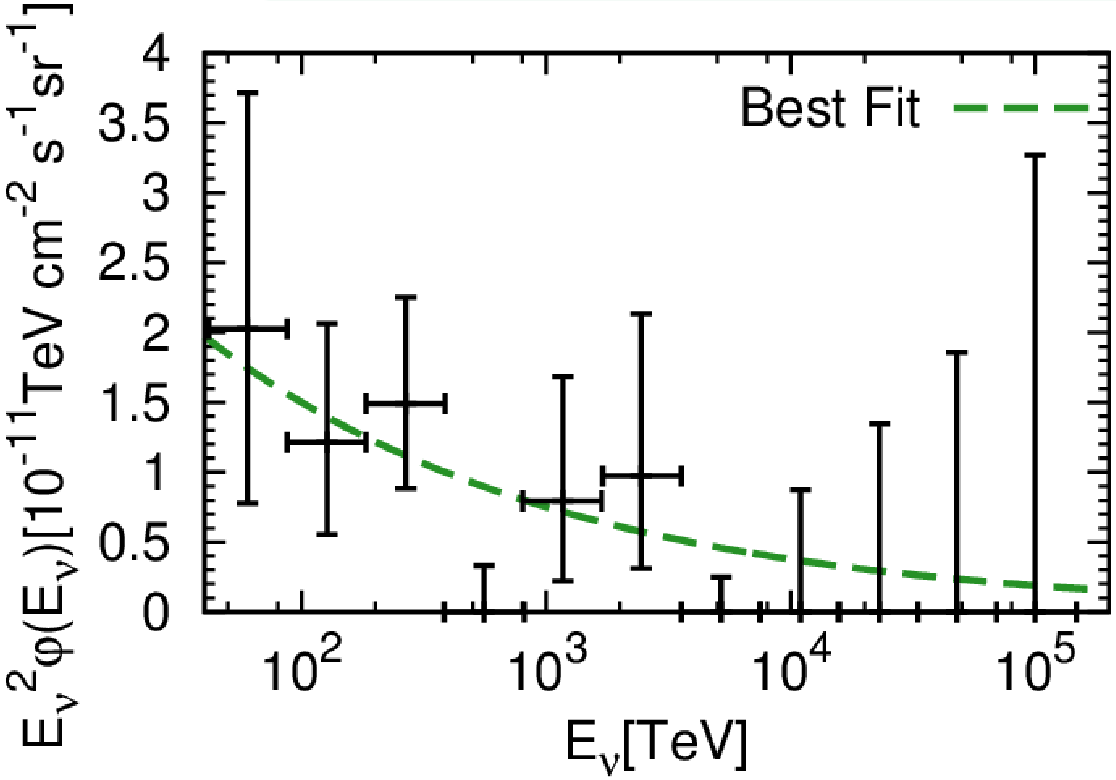
① Continuous (power-law) spectrum



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

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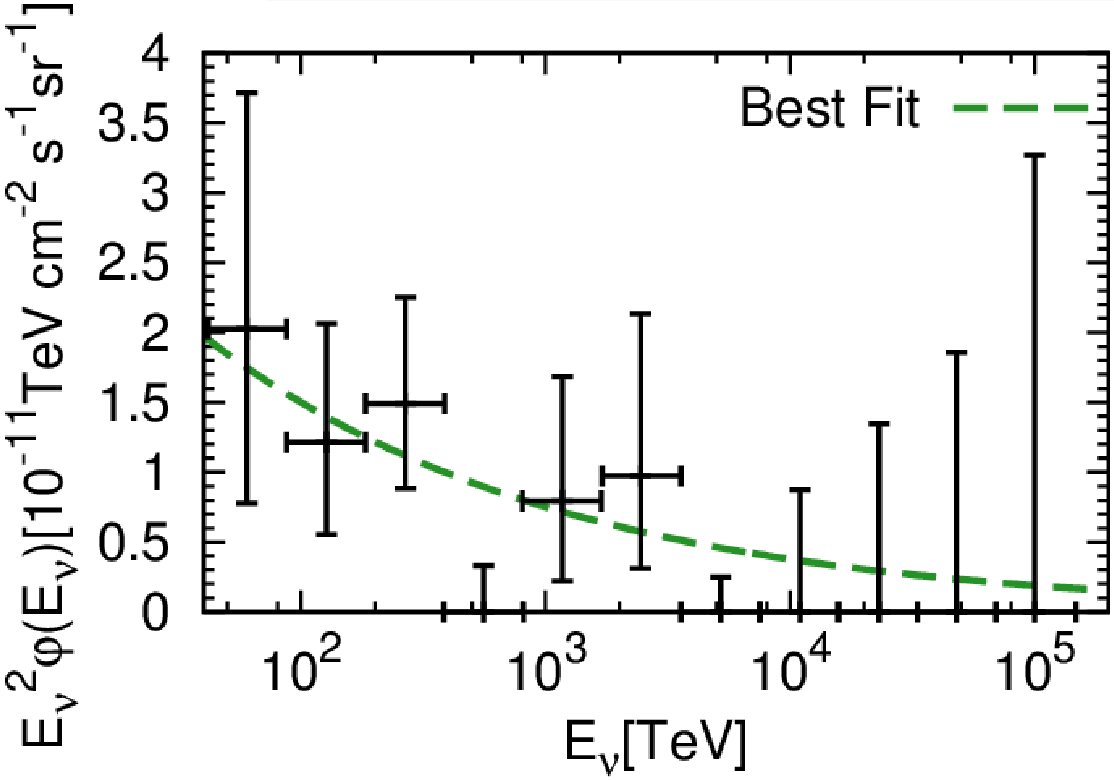

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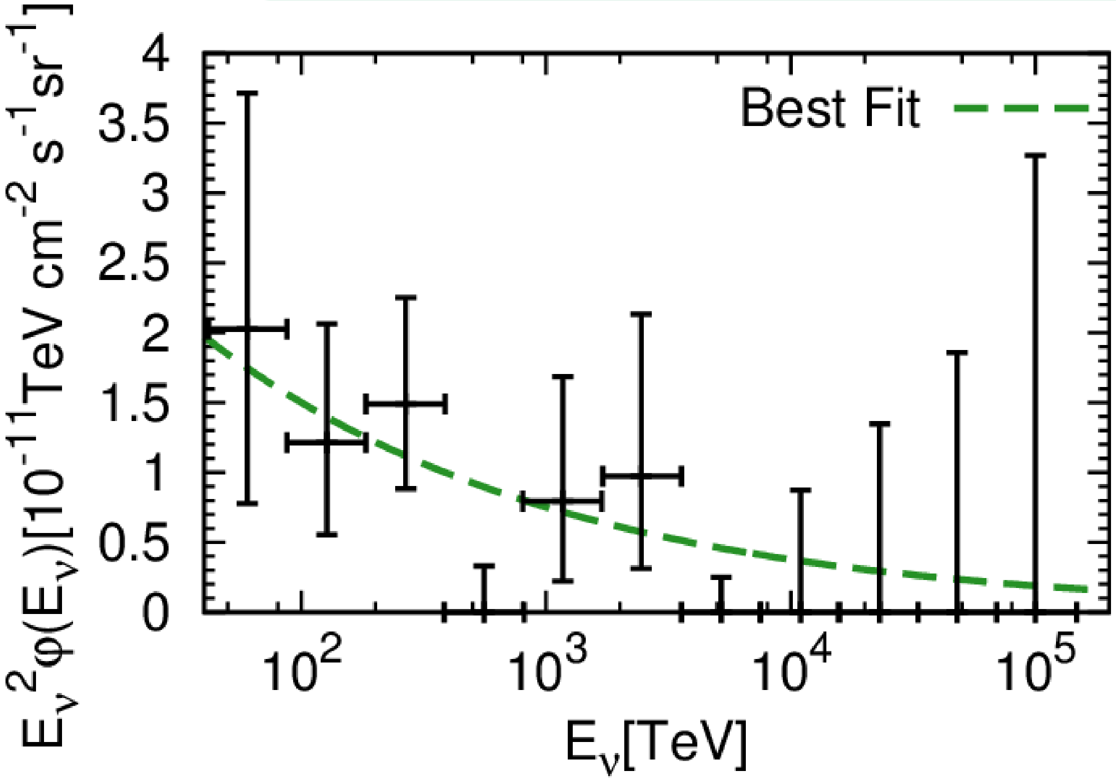
② Flavour ratio ~1:1:1 after leaving sources

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.

New Physics in propagation

① IceCube gap

“A sharp gap” → “Cosmic neutrino with a particular energy is scattered off”

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

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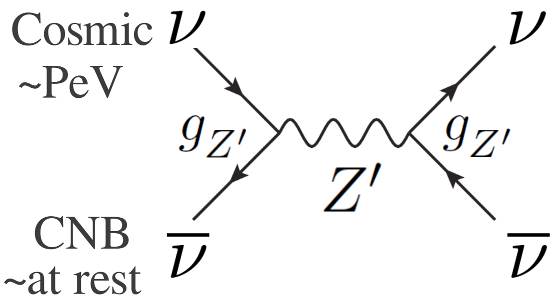
$$s \simeq 2E_{\nu_{\text{Cosmic}}} m_{\nu_{\text{CNB}}} \overset{!}{=} M_{Z'}^2$$



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

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

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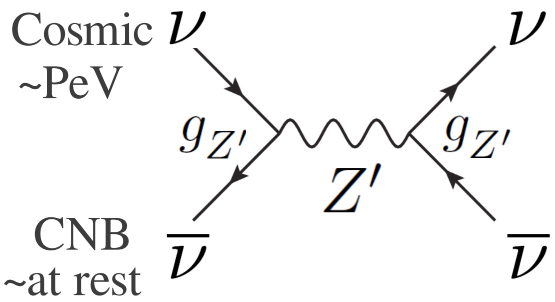

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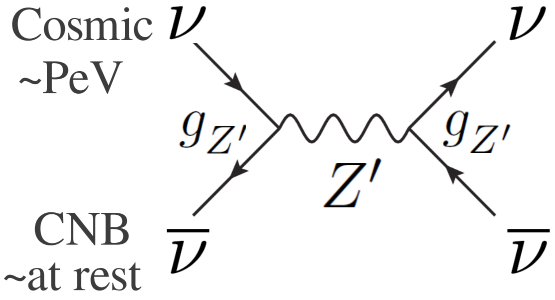
~sub-PeV ~0.1eV

$$\to M_{Z'} \sim \text{MeV}$$

NP @MeV scale



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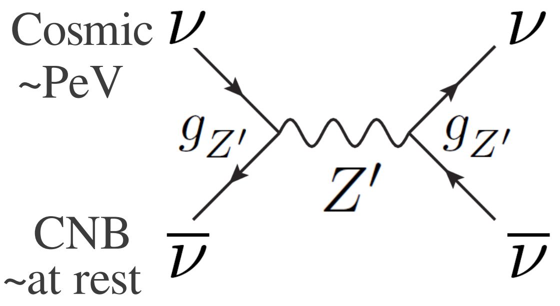

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$$\lambda \simeq 1/n_{\text{CNB}}\sigma_{\text{@Res.}}$$

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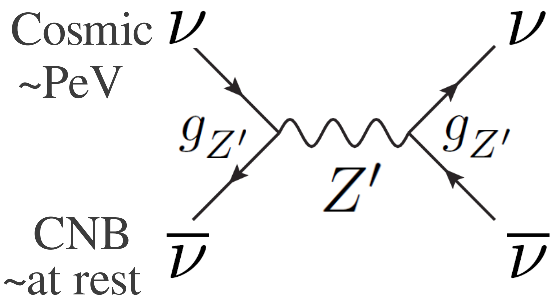

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Extra galactic source

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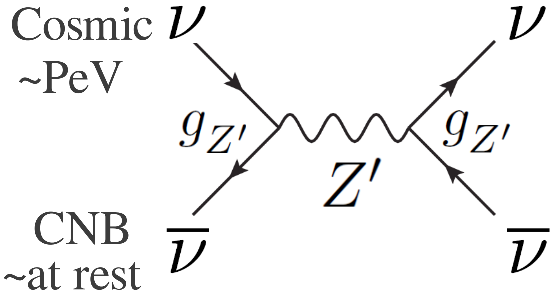

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Extra galactic source

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

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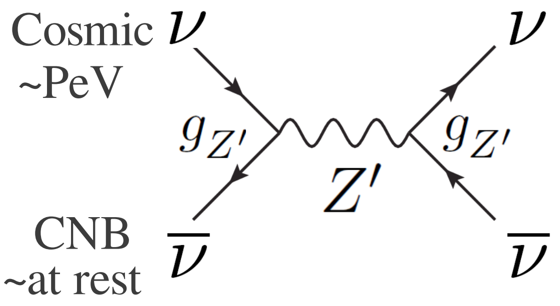

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IceCube Gap requires

$M_{Z'} \sim$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 $Y(L_\mu) = +1, Y(L_\tau) = -1,$
$Y(\mu_R) = +1, Y(\tau_R) = -1, Y(\text{others}) = 0.$

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

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Model

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&= \underline{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}
\end{aligned}
$$

Neutrino secret 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 is lost in its travel.

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But the coherence is lost in its travel.

- **Motivated from...**
  - (almost) Maximal mixing Choubey Rodejohann Eur.Phys.J C40 (2005) 259
  - Gauge anomaly free Foot Mod.Phys.A6 (1991) 527, He et al., PRD43 (1990) R22

- In this talk, we do not go into the details of the spontaneous breaking of the $L_\mu - L_\tau$ sym. →

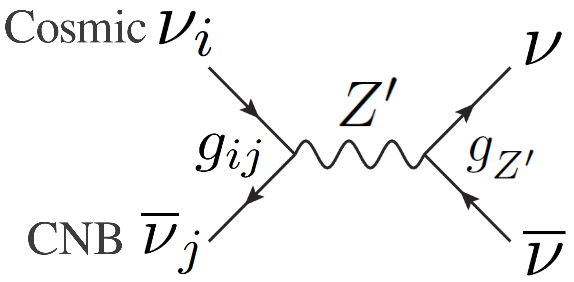
Model parameters

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

① IceCube gap

- **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**

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

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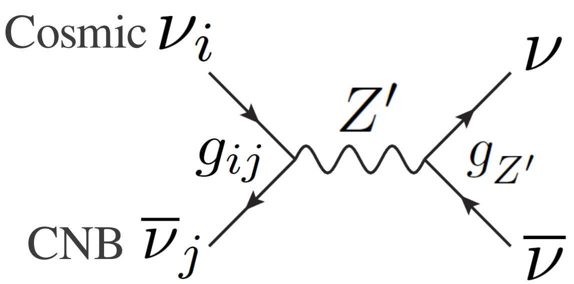

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For IceCube Gap

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$M_{Z'}$ ~MeV

Model

① IceCube gap

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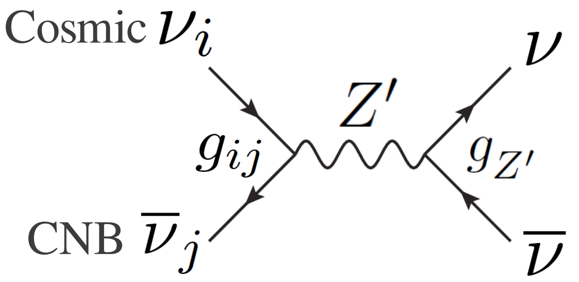

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$M_{Z'}$ ~MeV $\to g_{Z'} \simeq 10^{-3}$

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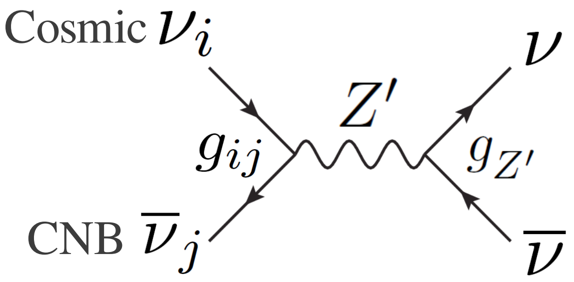

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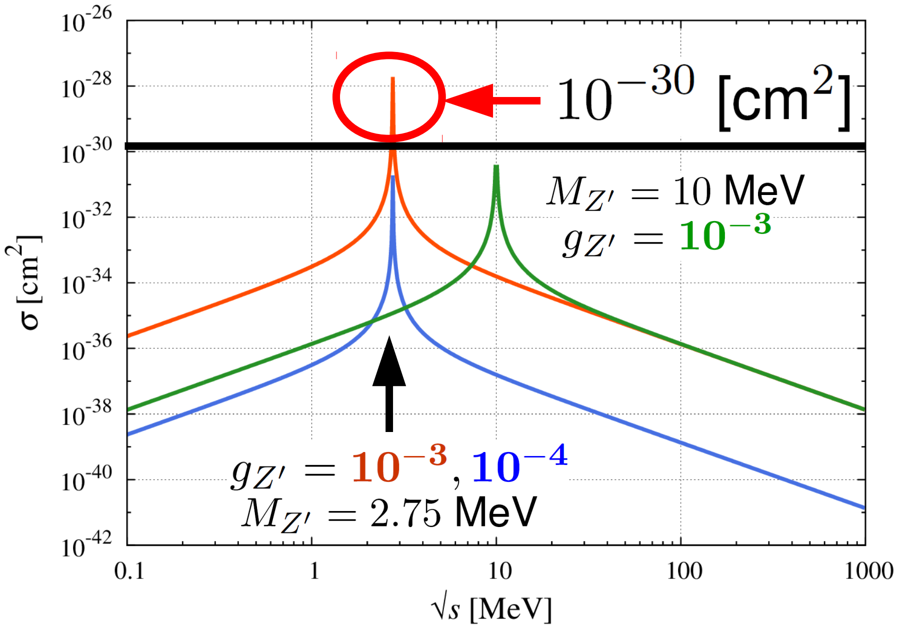
$M_{Z'} \sim$MeV $\to g_{Z'} \simeq 10^{-3}$



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 secret interaction

2 Muon anomalous magnetic moment

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

3 A solution to the gaps

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

Z' contribution to $g_\mu - 2$

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

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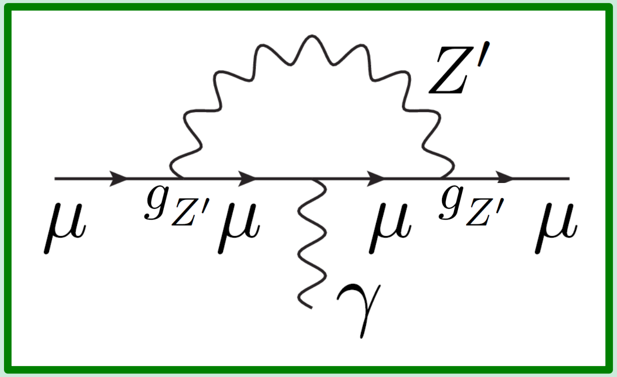
- $M_{Z'} \gg m_\mu \;\rightarrow \Delta a_\mu^{Z'} = \frac{g_{Z'}^2}{12\pi^2}\frac{m_\mu^2}{M_{Z'}^2}$
- $M_{Z'} \ll m_\mu \;\rightarrow \Delta a_\mu^{Z'} = \frac{g_{Z'}^2}{8\pi^2}$



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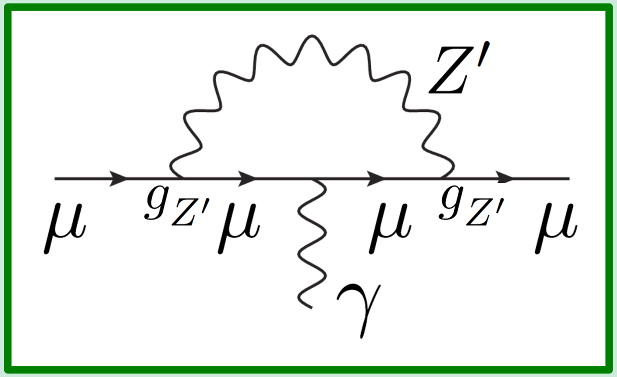
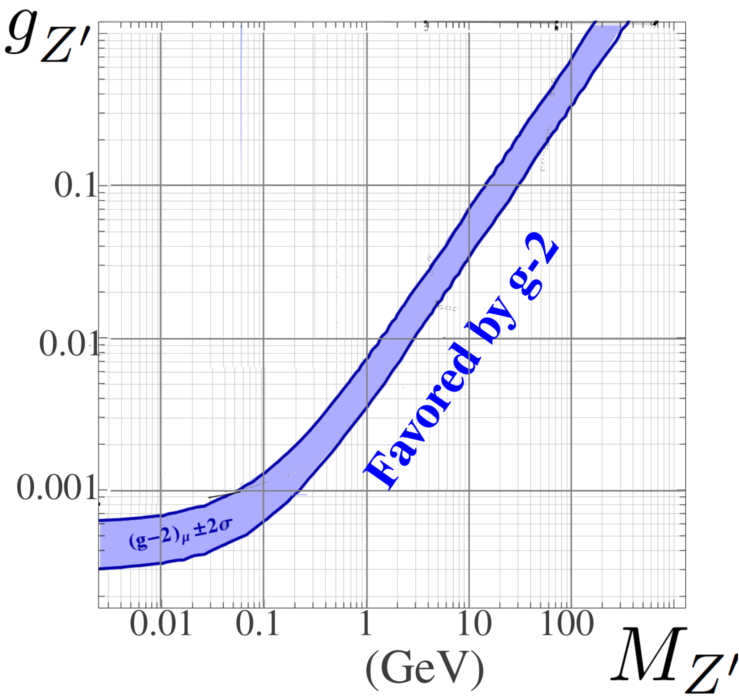


$g_\mu - 2$ Gap

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

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



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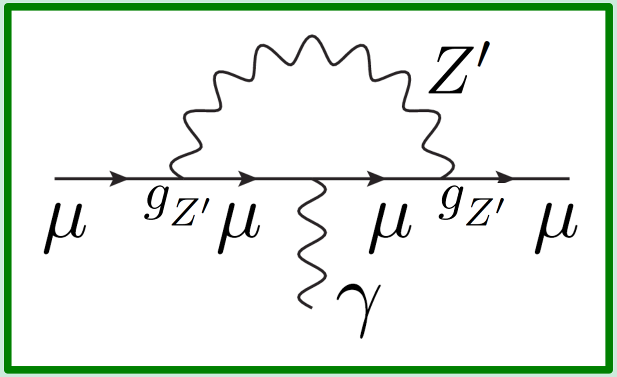

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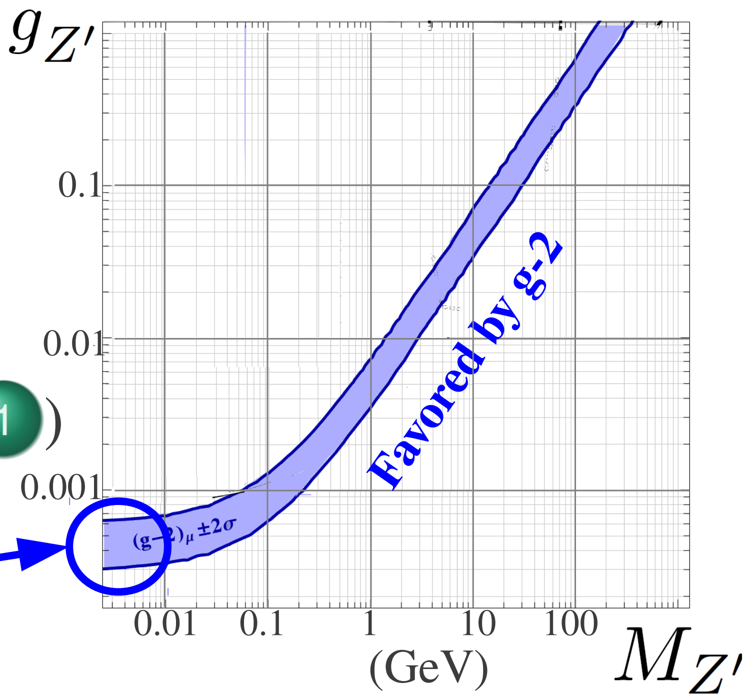
- Let me remind (back-of-the envelope calc. in **Sec.** ①)

IceCube Gap requires

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



Constraints

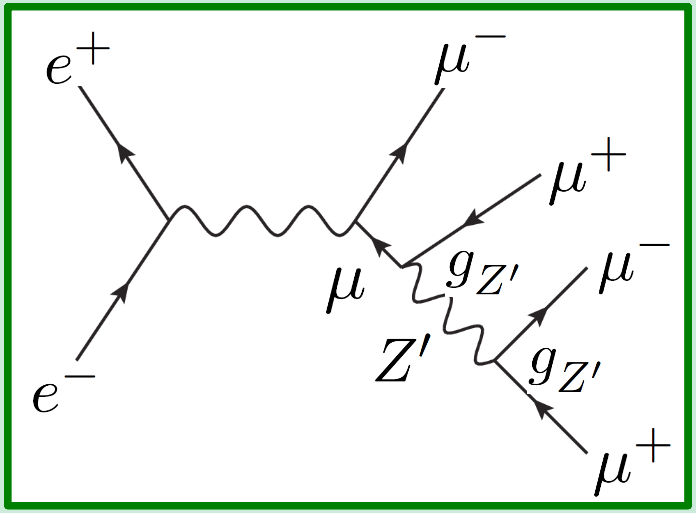
Collider bounds

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

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

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

  only constrain relatively heavy Z'



→ LEP, LHC: $g_{Z'} \lesssim 0.1$ at $M_{Z'} \simeq 100$ GeV

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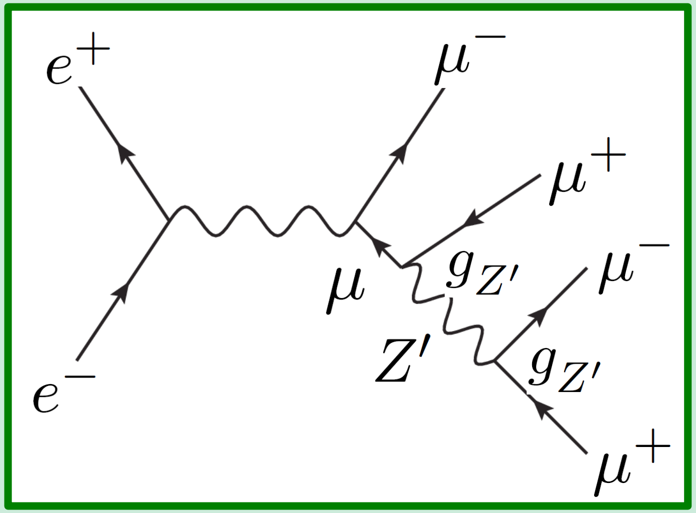

Rare meson decays

Lessa and Peres, PR**D75** (2007) 094001

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

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

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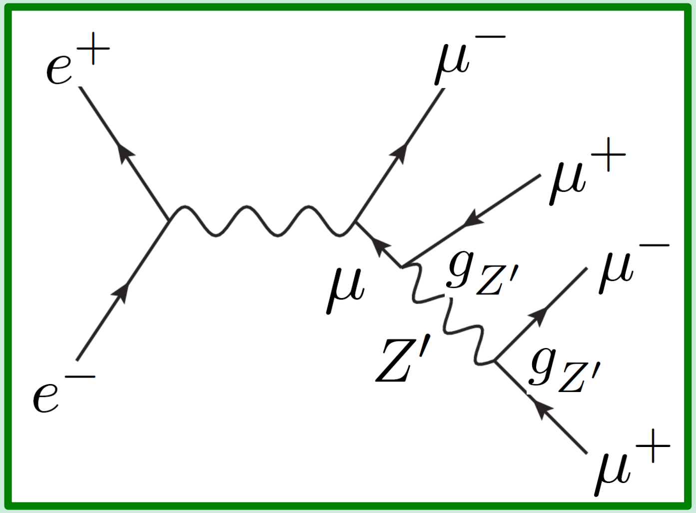

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- Process: $\pi^+/K^+ \to \mu^+\nu_\mu Z'$

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

- The most relevant bound from lab. experiments is

  Neutrino trident process in neutrino-nucleon scattering

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

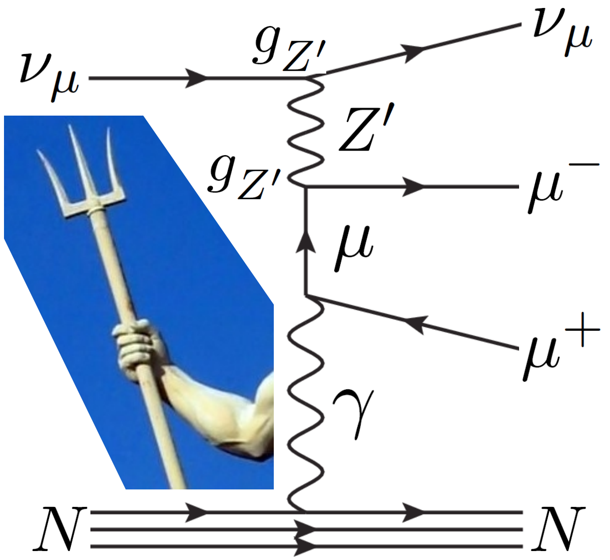
- Bounds from CMB, BBN, and also from SN1987A → References in Ng Beacom

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 18 times)*



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

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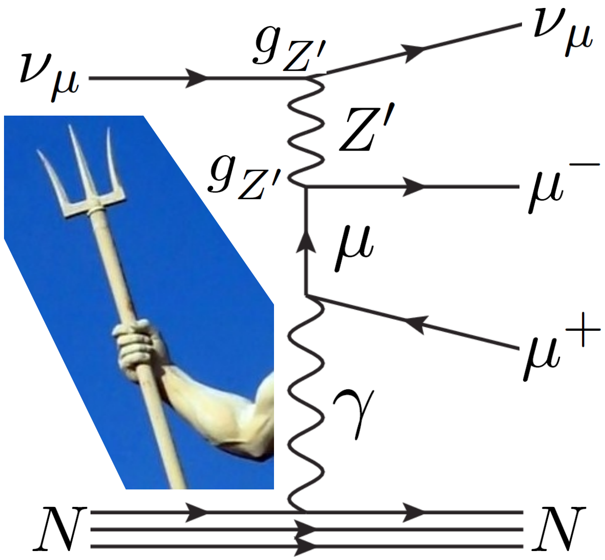
Consistent → constrains $g_{Z'}$ and $M_{Z'}$



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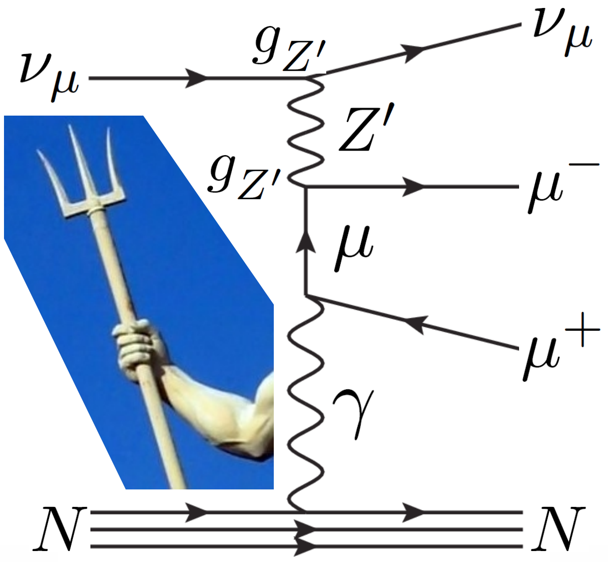

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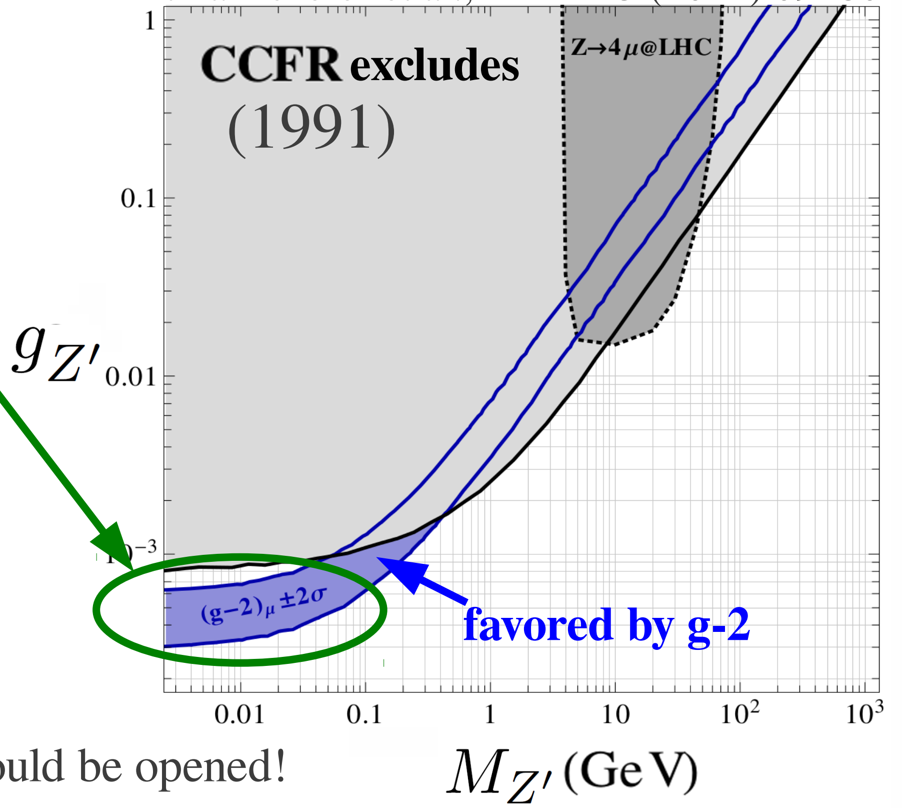
$g_\mu - 2$ favored - Trident excl.

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

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



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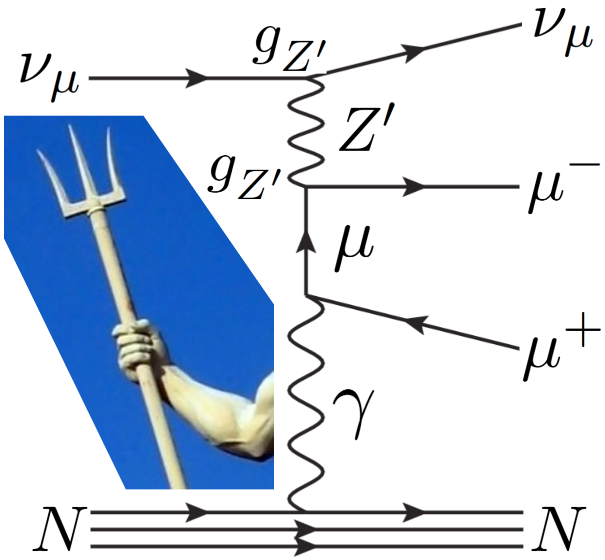

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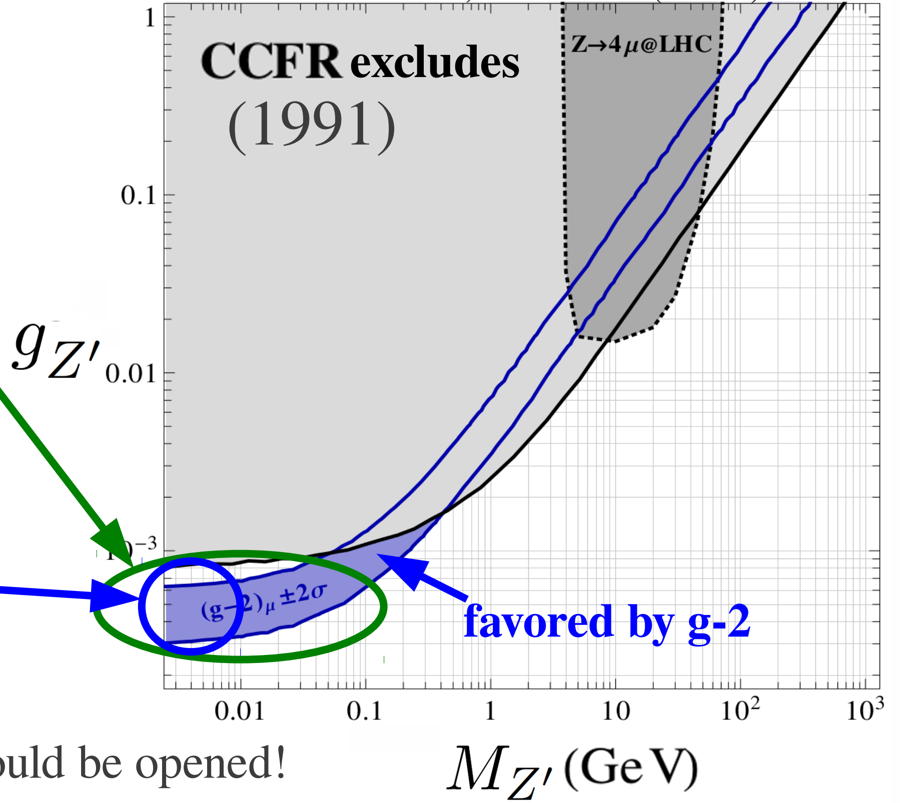

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↕ **Coincide!**

IceCube Gap requires

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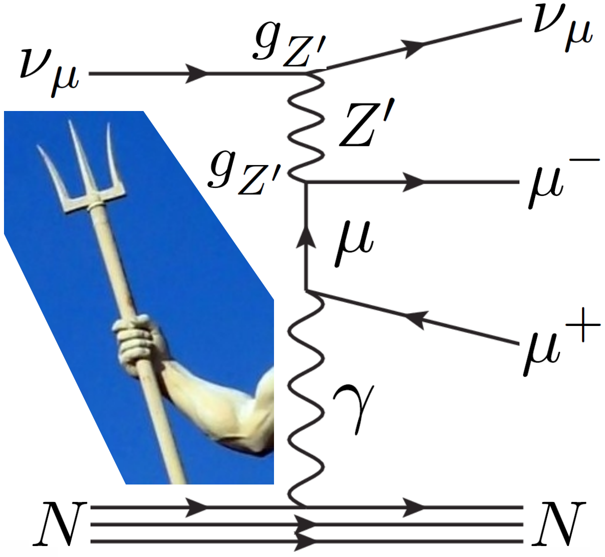

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Consistent → constrains $g_{Z'}$ and $M_{Z'}$

Reference values

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

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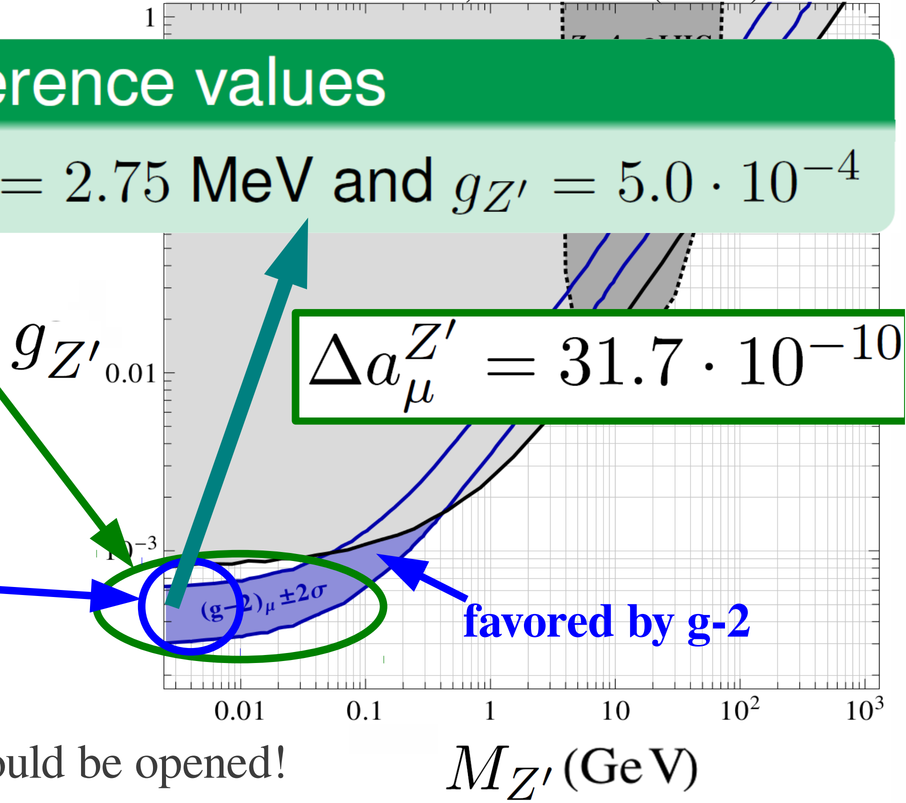

$$\Delta a_\mu^{Z'} = 31.7 \cdot 10^{-10}$$

favored by g-2

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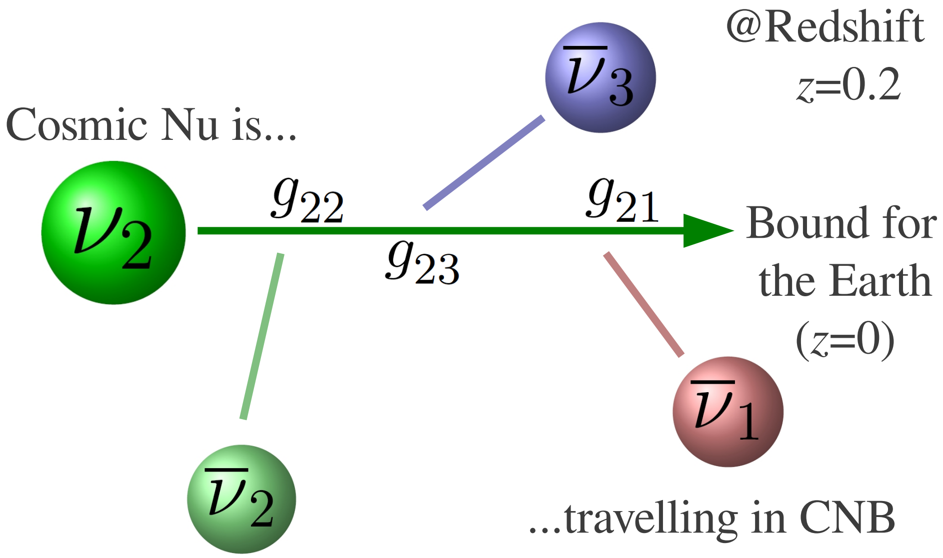
- We fix $m_{\nu_{\text{lightest}}} = 3.0 \cdot 10^{-3}\ \text{eV}$ and take IH $m_{\nu_3} \ll m_{\nu_1} < m_{\nu_2}$
- Let us calculate the mean free path (for 2nd neutrino) at *z*=0.2.



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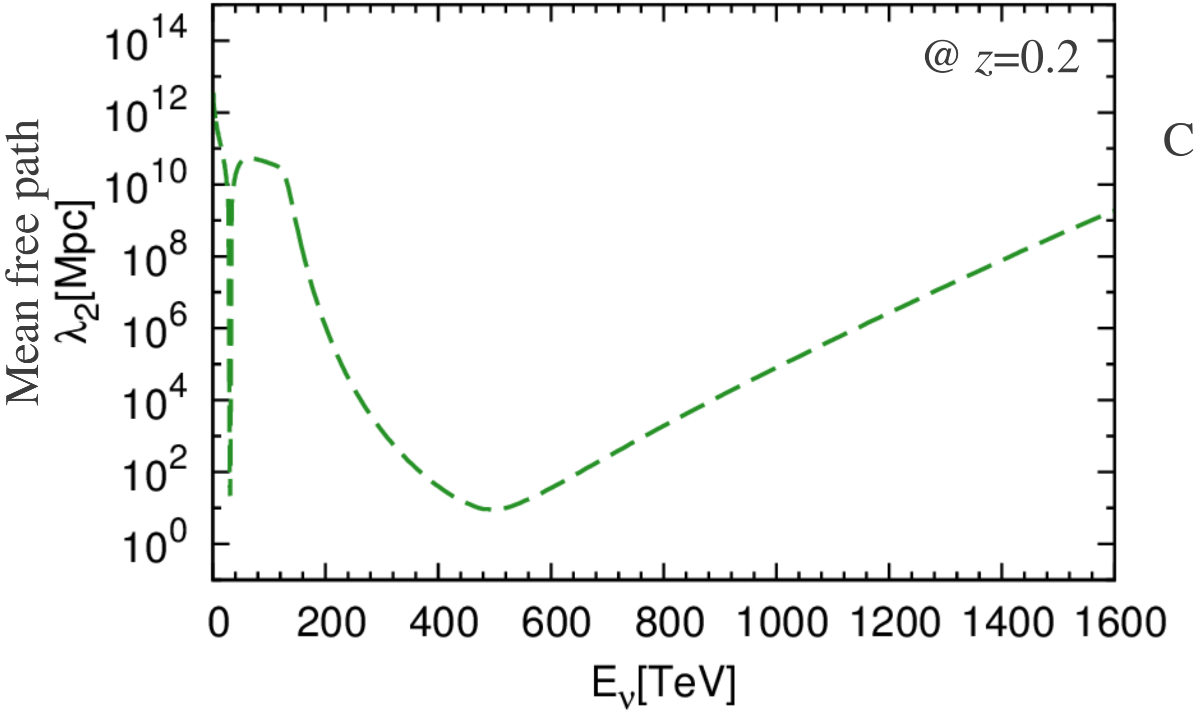
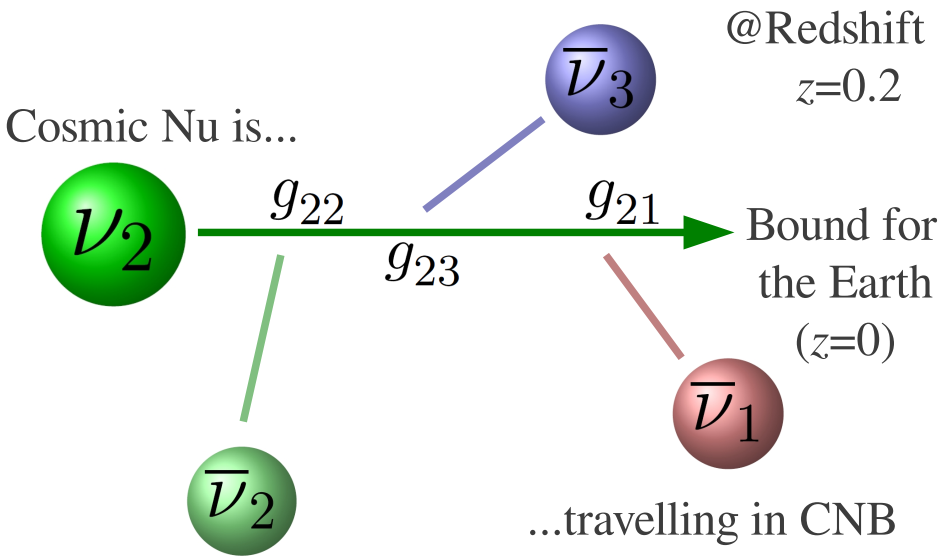


Neutrino energy observed at IceCube



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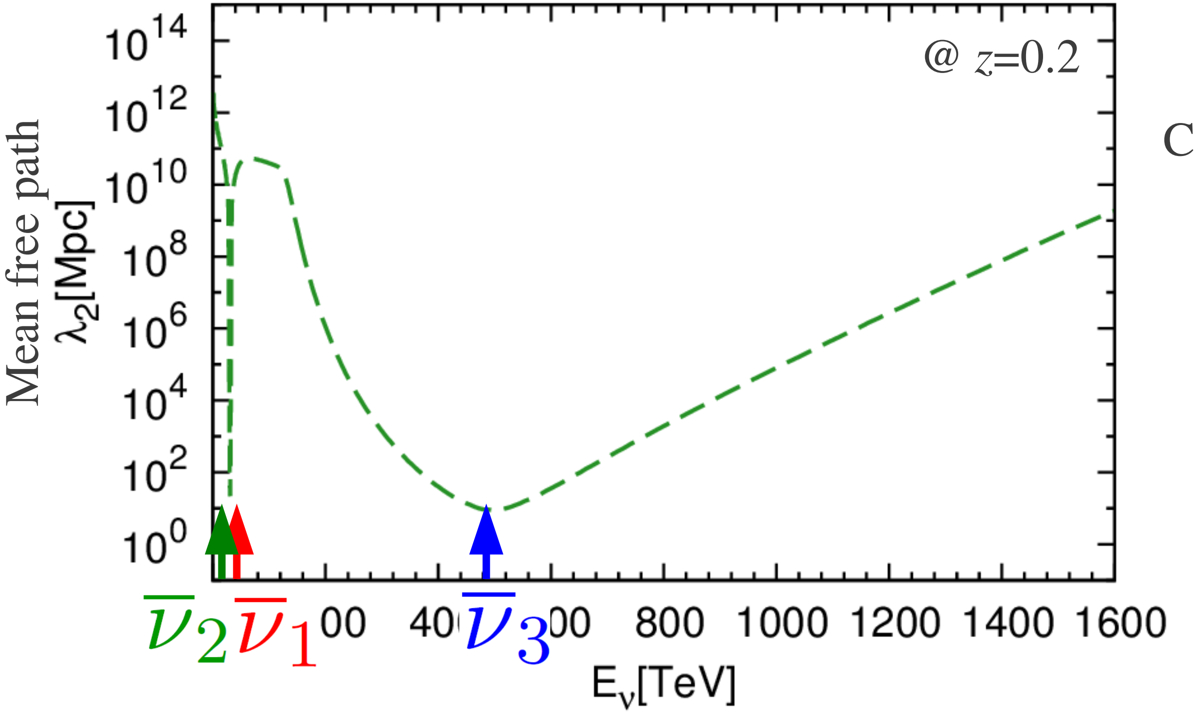

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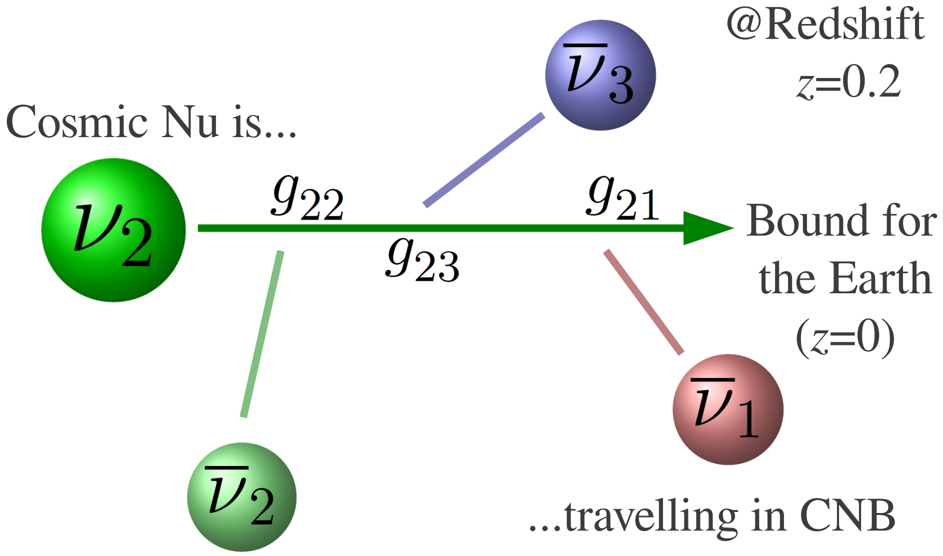

- **Resonant condition w. CNB distribution**

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

$|\boldsymbol{p}|$: **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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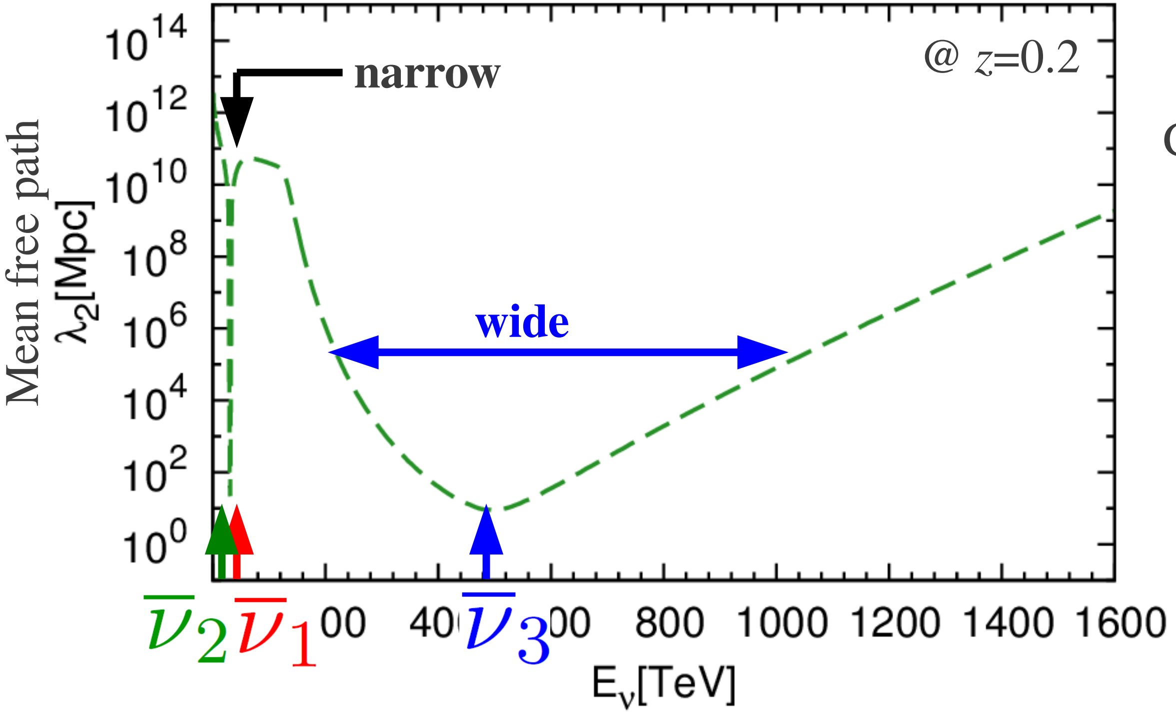

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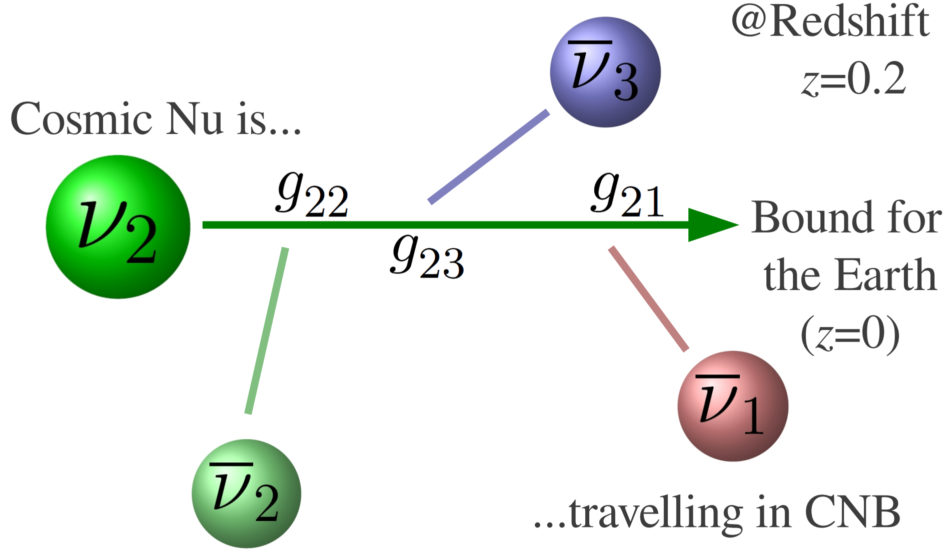

$$\boxed{\begin{array}{l} m_{\nu_3} \sim |\boldsymbol{p}| \\ m_{\nu_{1,2}} \gg |\boldsymbol{p}| \end{array}}$$

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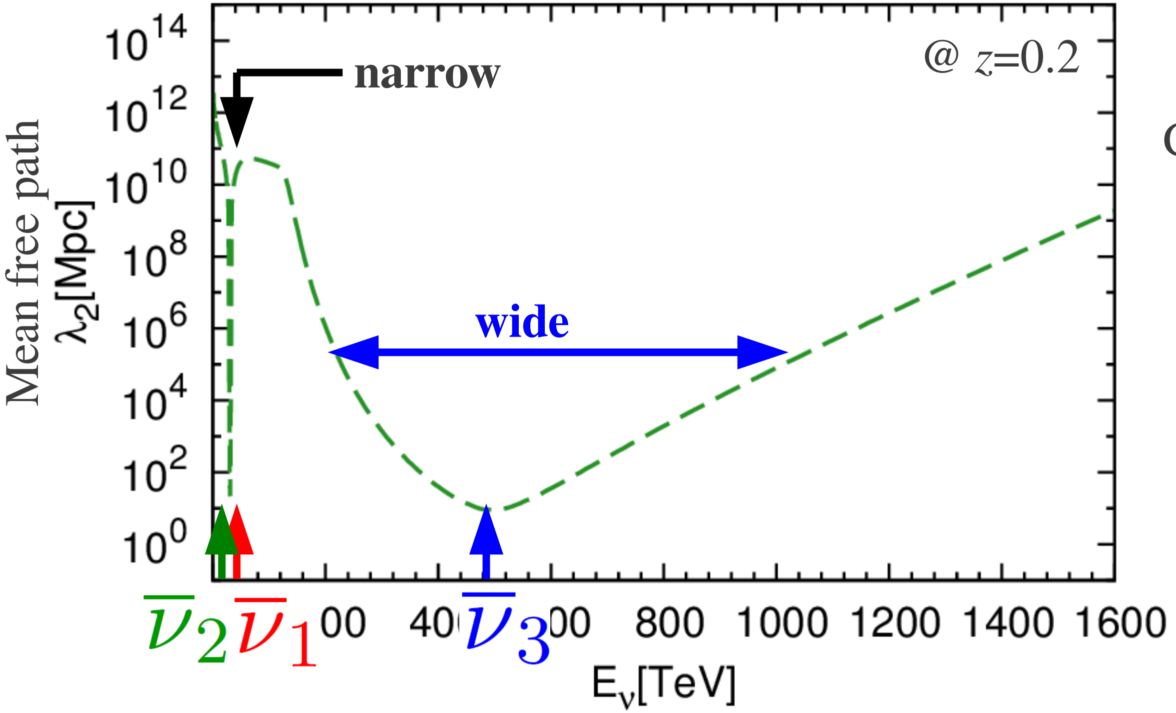

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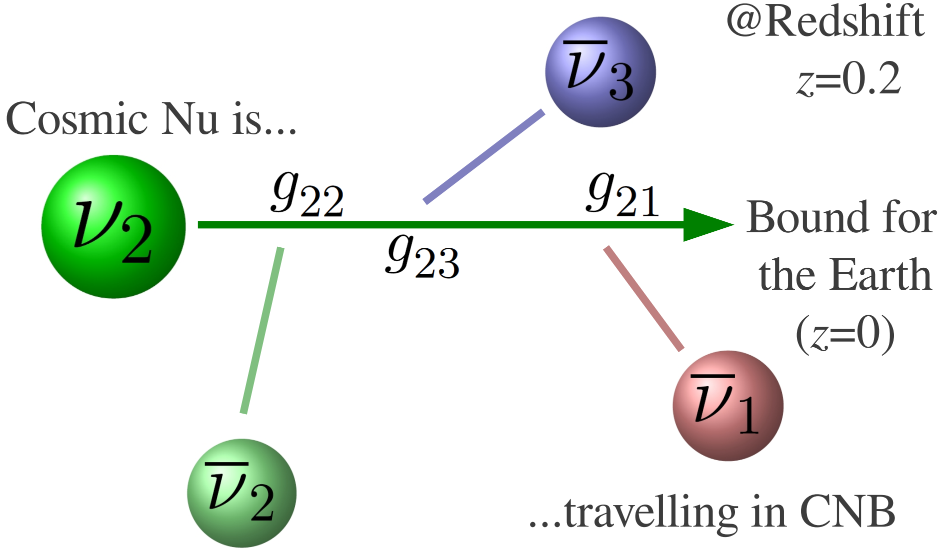

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z shifts resonant E

Small *mNu*→ wide width

Large *z* → wide width

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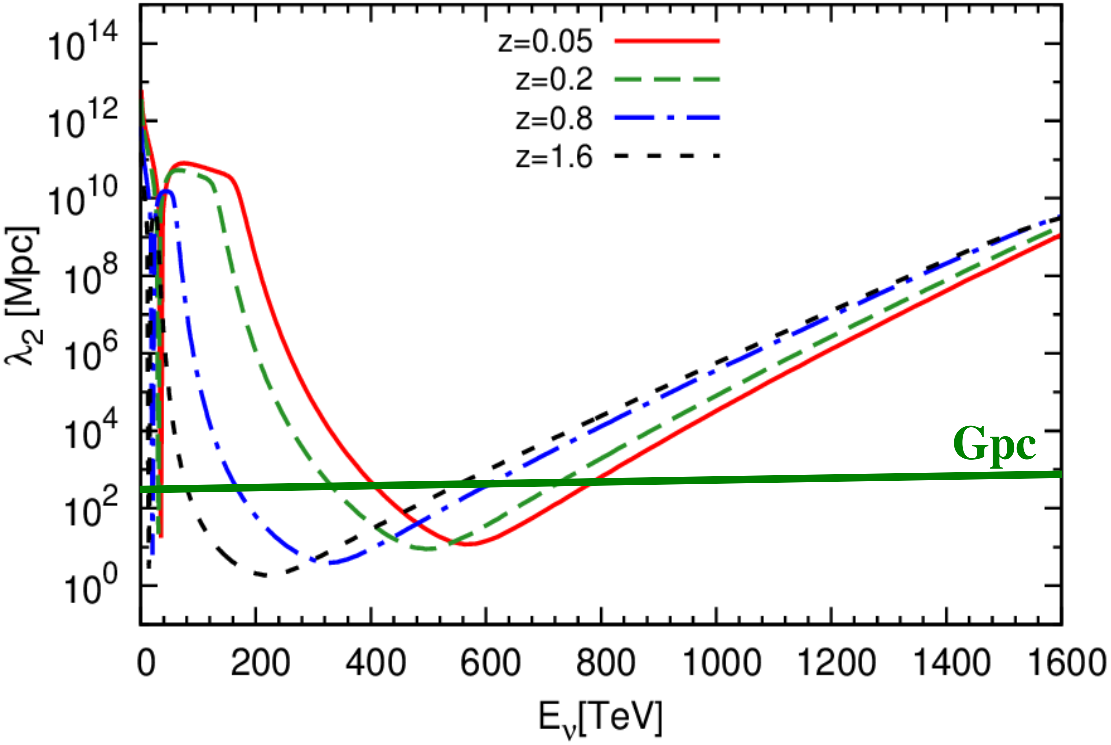

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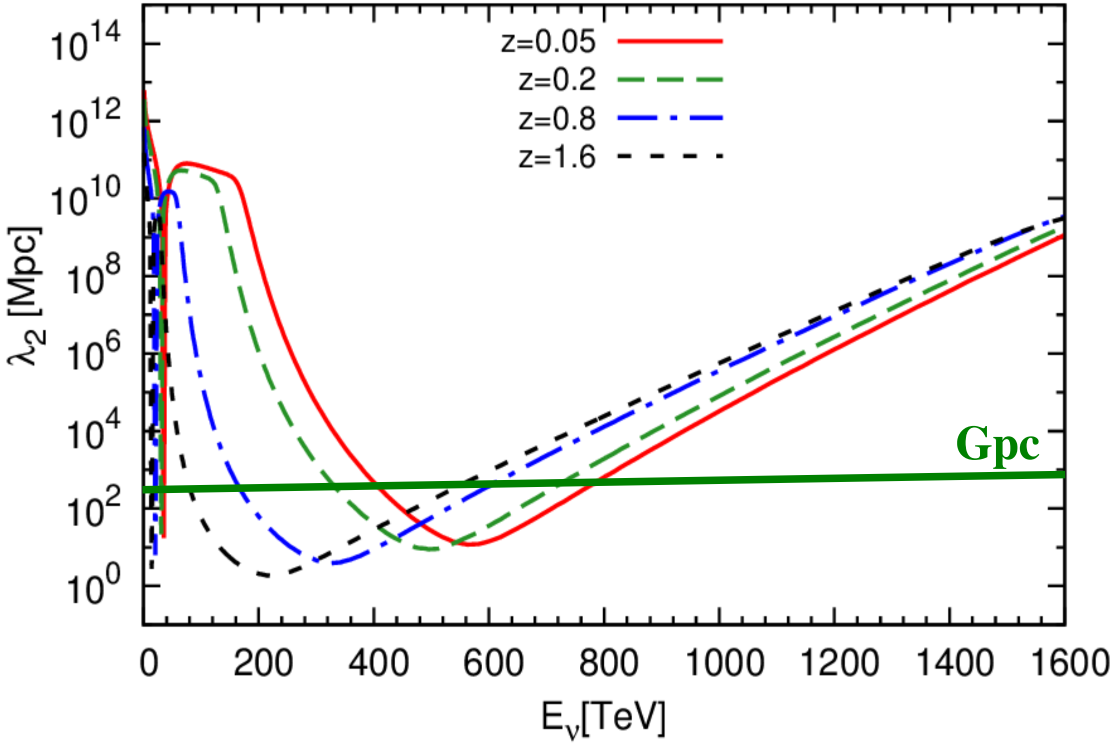

- Cosmic neutrinos travel from z_{source} to $z = 0$ (Earth)

↓

- 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.

3 Cosmic neutrino spectrum

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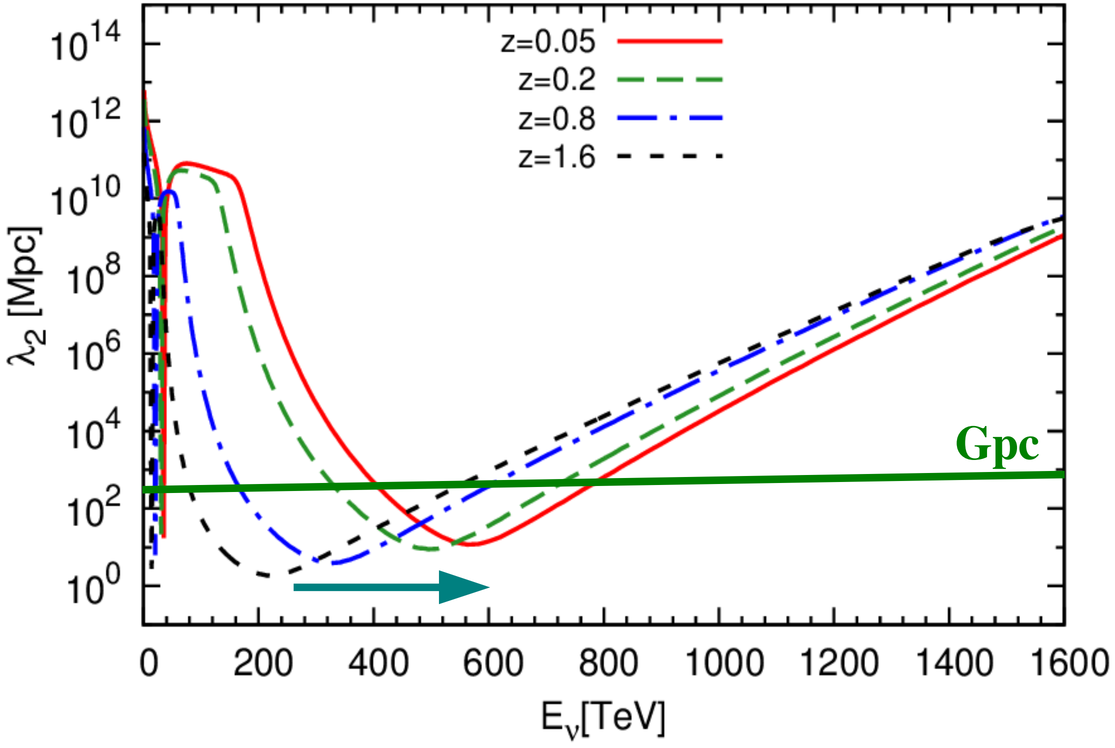

Peak position moves

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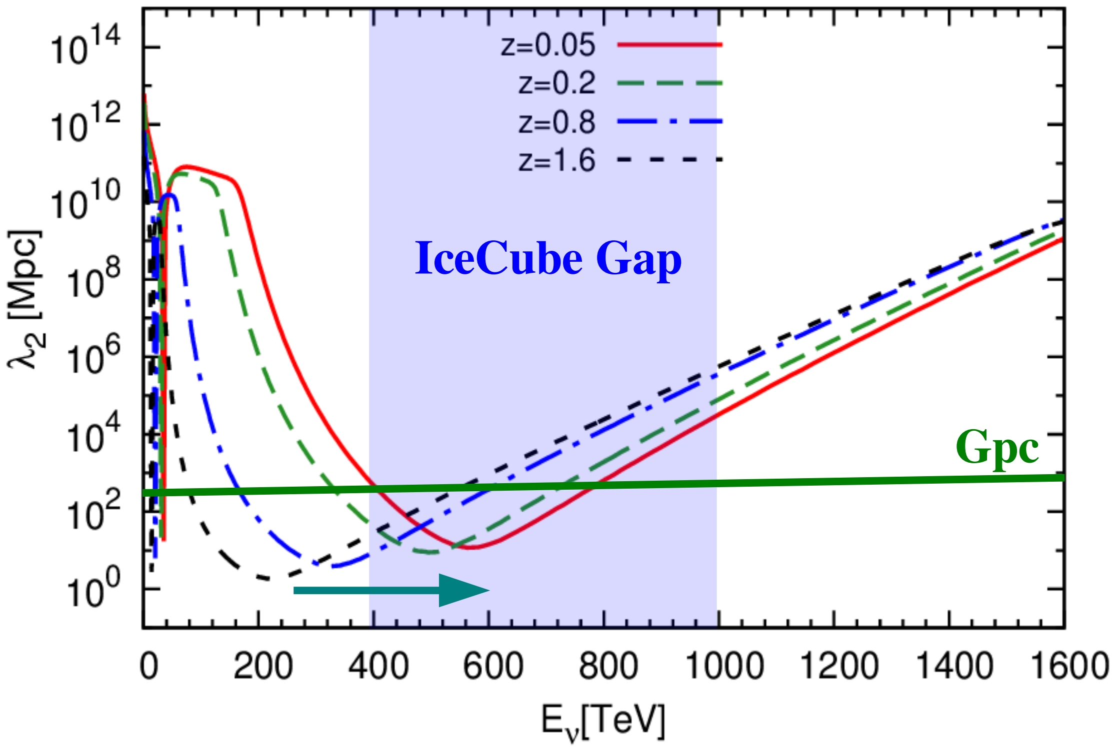

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To keep the width of the gap appropriate, the source should not be so distant from the Earth.

- 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)

Working example ③ Cosmic neutrino spectrum

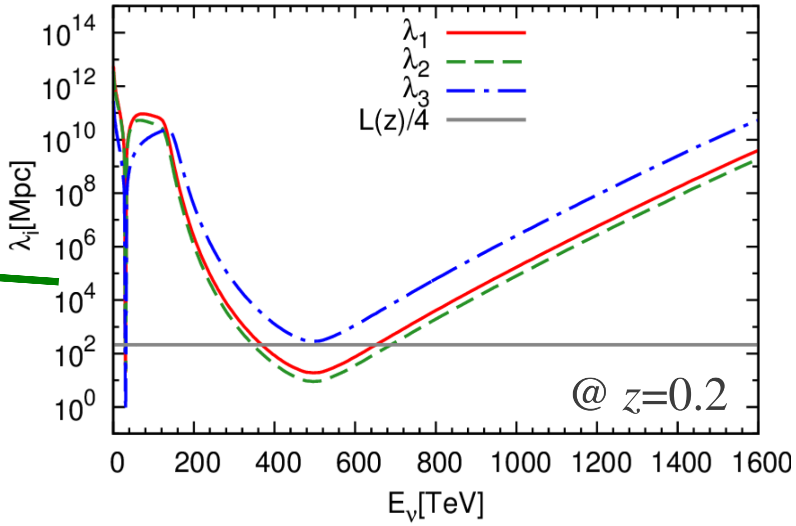
- **Mean free path → Spectrum**

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.

③ Cosmic neutrino spectrum

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Resulting spectrum

Continuous (power-law) spectrum

MFP

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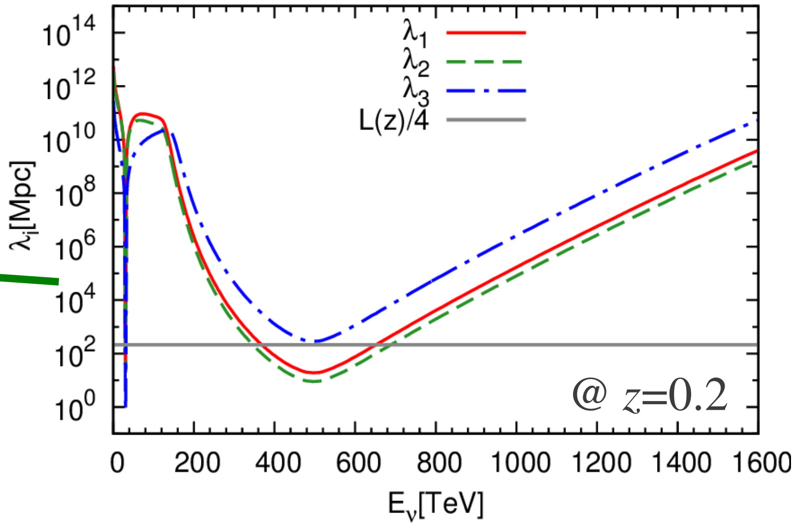

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Saitama University 埼玉大学 Working example

③ Cosmic neutrino spectrum

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Resulting spectrum

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

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

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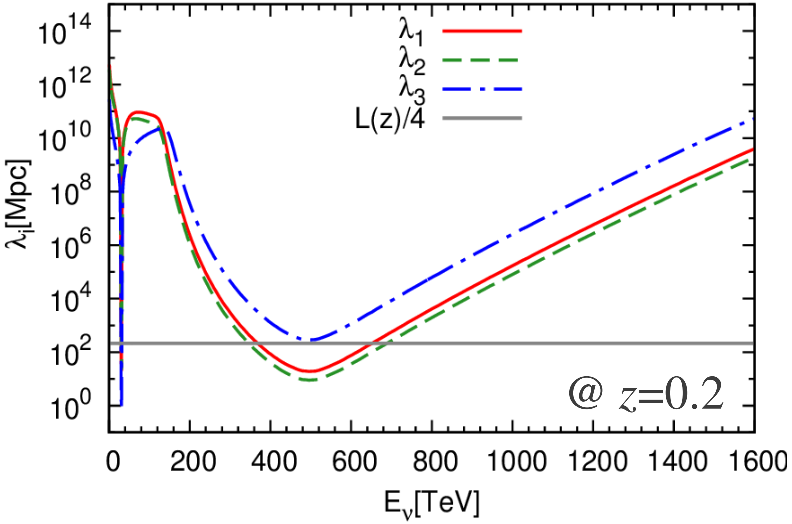

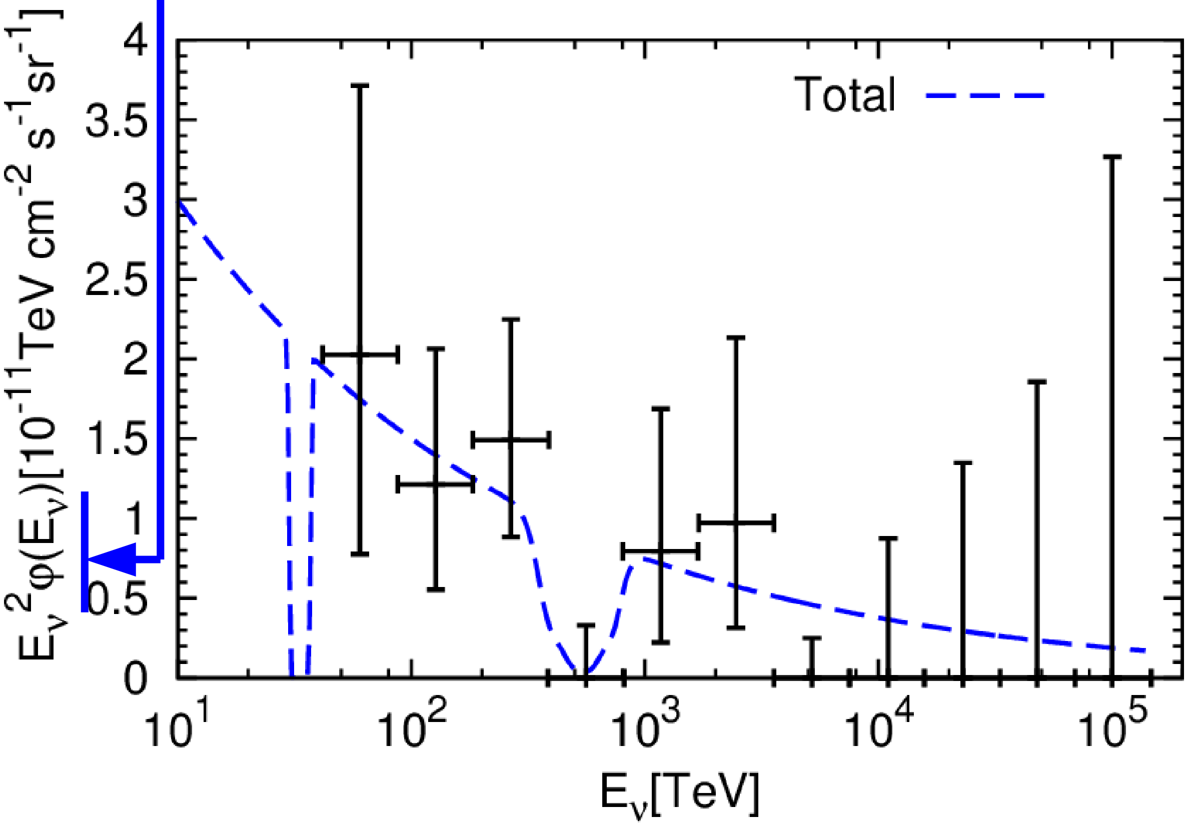

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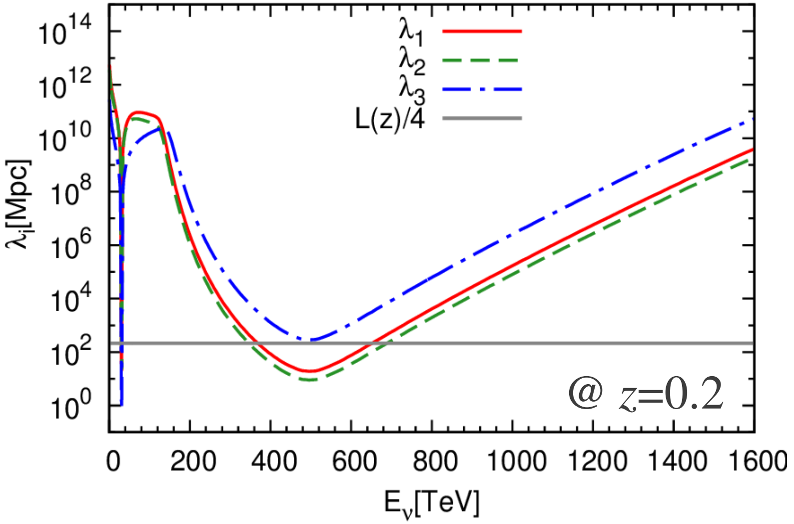

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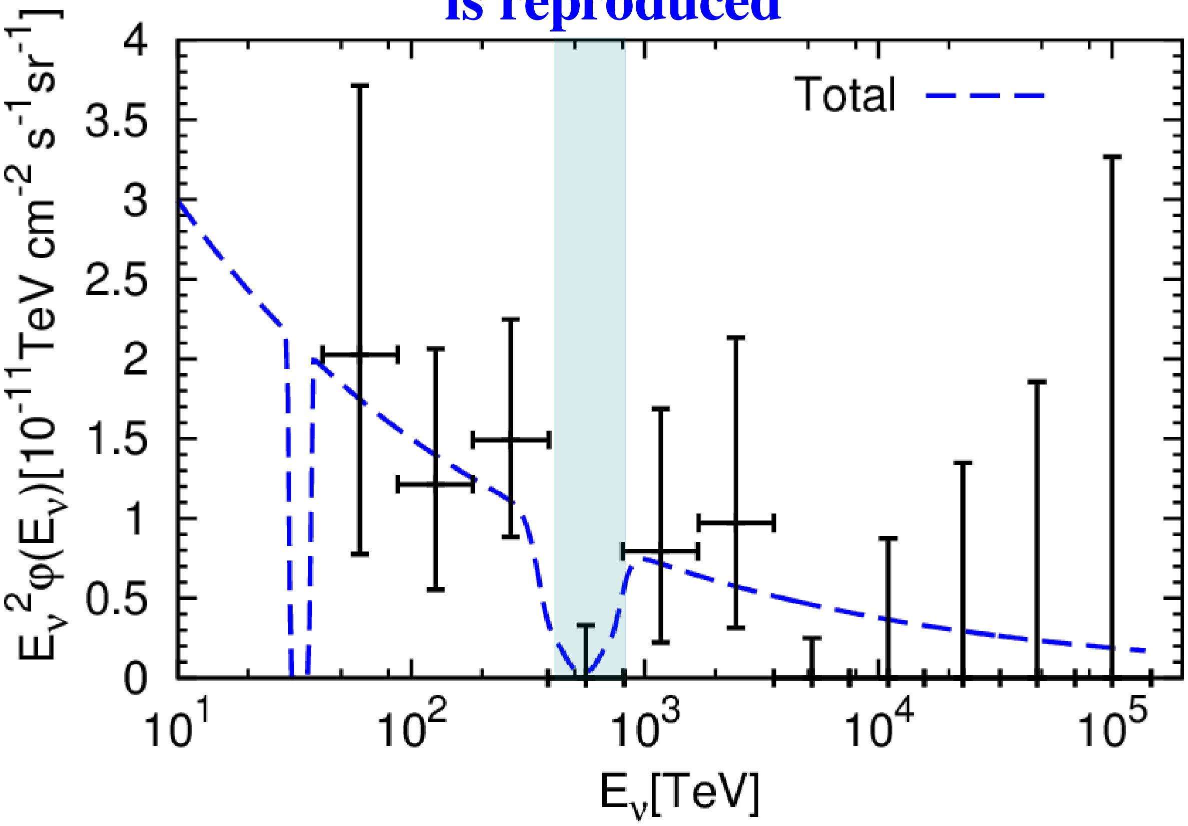
IceCube Gap is reproduced



③ Cosmic neutrino spectrum

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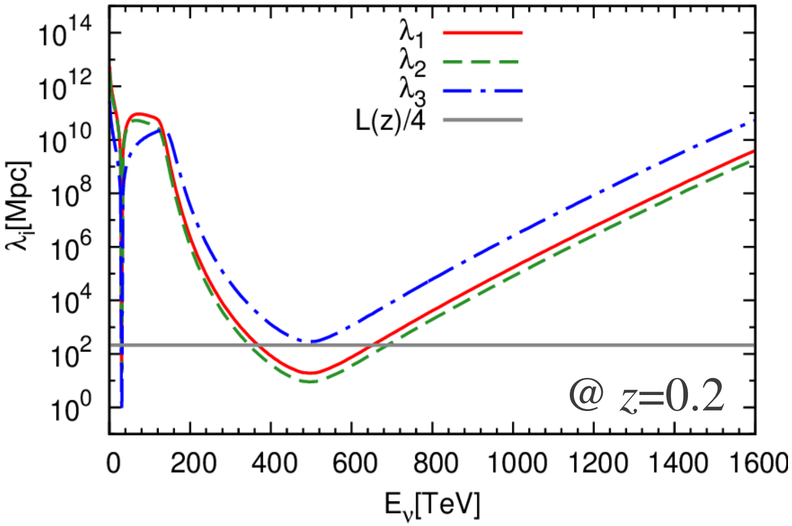

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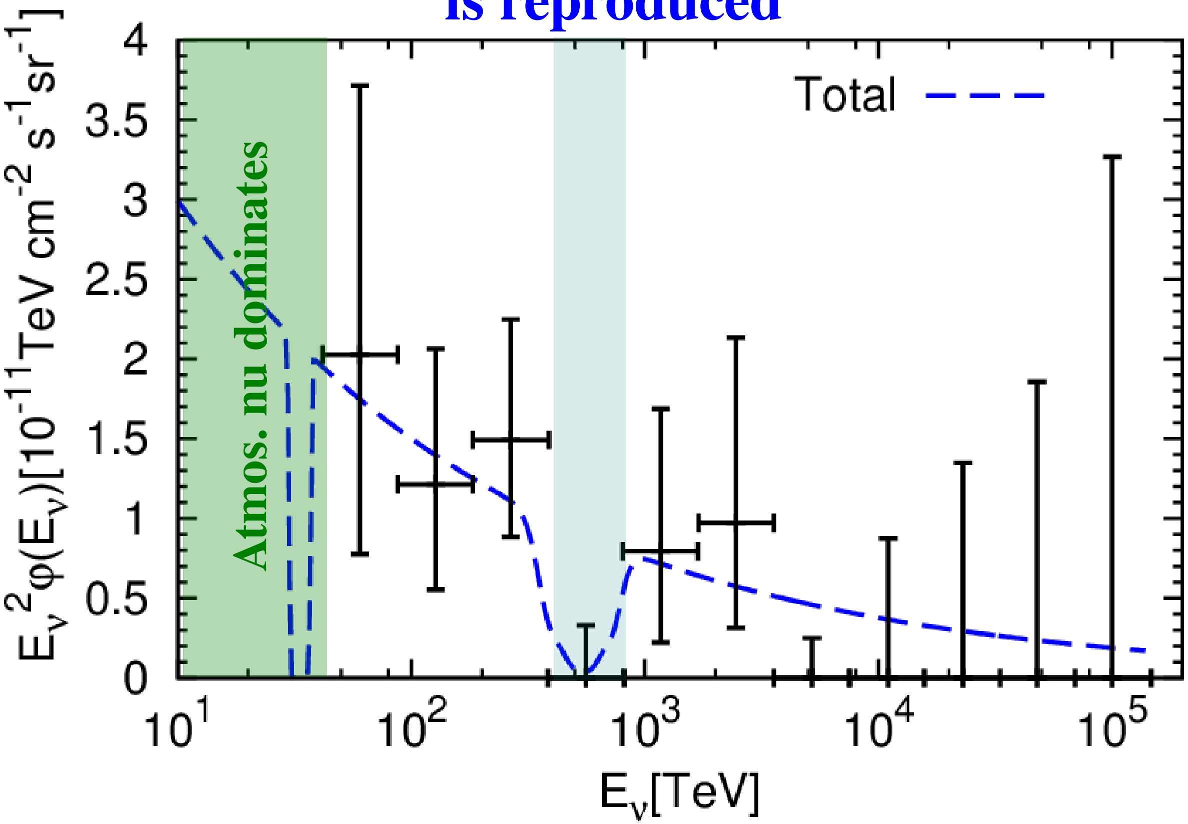

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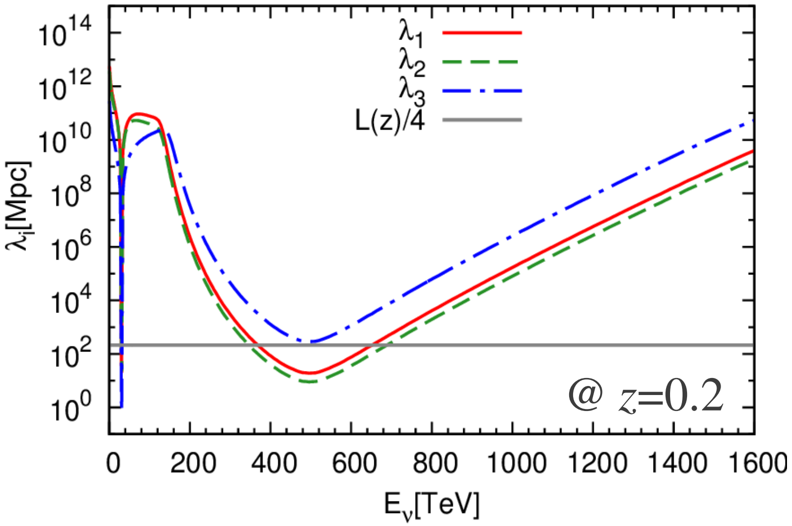

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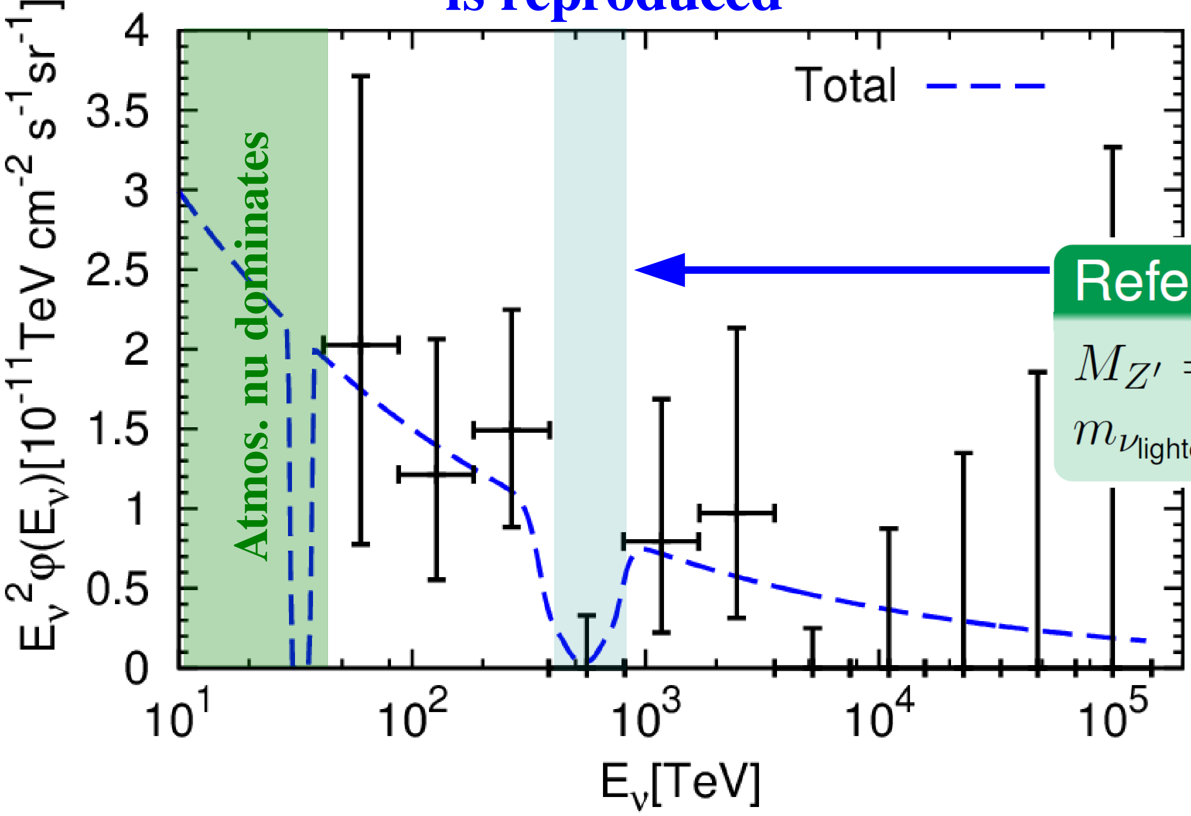


The resulting gap does not depends on the initial flavour composition.

Reference values

$M_{Z'} = 2.75$ MeV, $g_{Z'} = 5.0\cdot 10^{-4}$,
$m_{\nu_{\text{lightest}}} = 3.0\cdot 10^{-3}$ eV (IH) and $z_{\text{source}} = 0.2$.

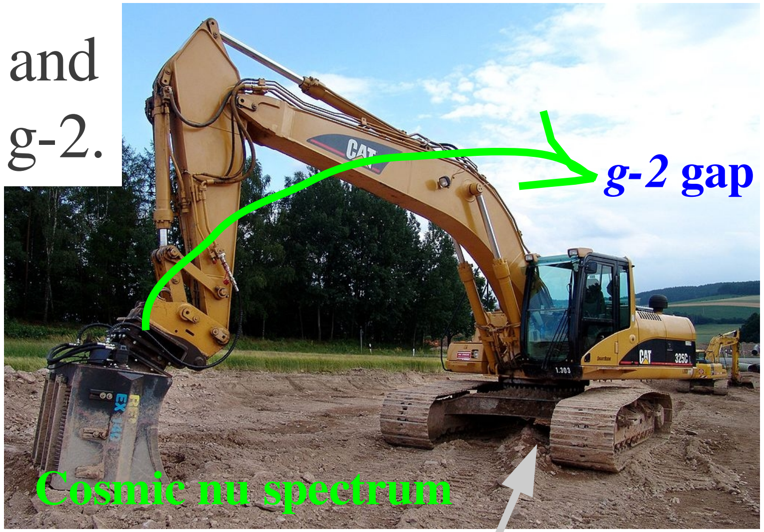
Z' contribution to muon g-2

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

***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"

Reference values

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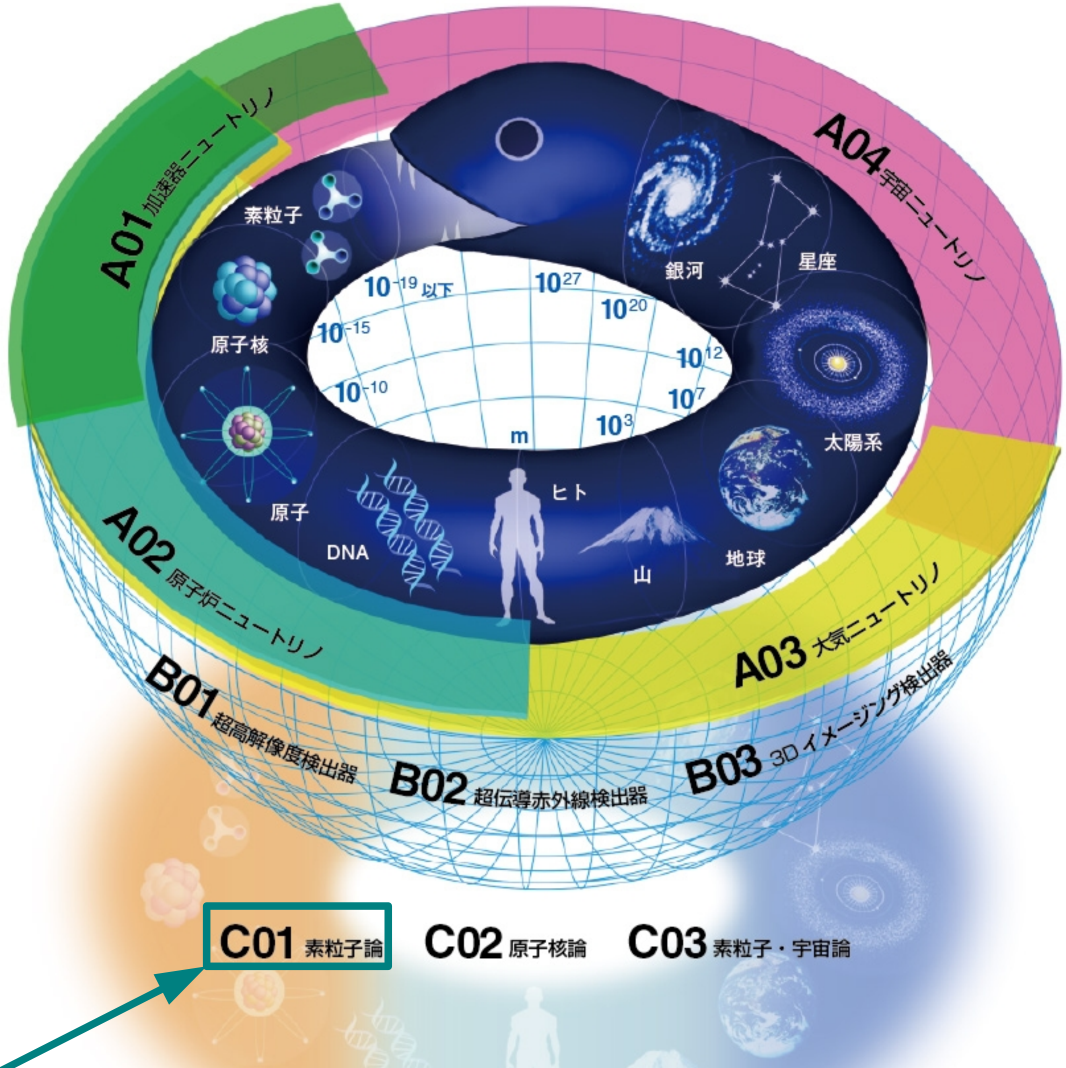
- IceCube Gap is reproduced.
- $\Delta a_\mu^{Z'} = 31.7 \cdot 10^{-10}$

But we did not...

- ...take into account distribution of neutrino sources.
- ...also take into account secondary neutrino effect.
- ...discuss details of the model.

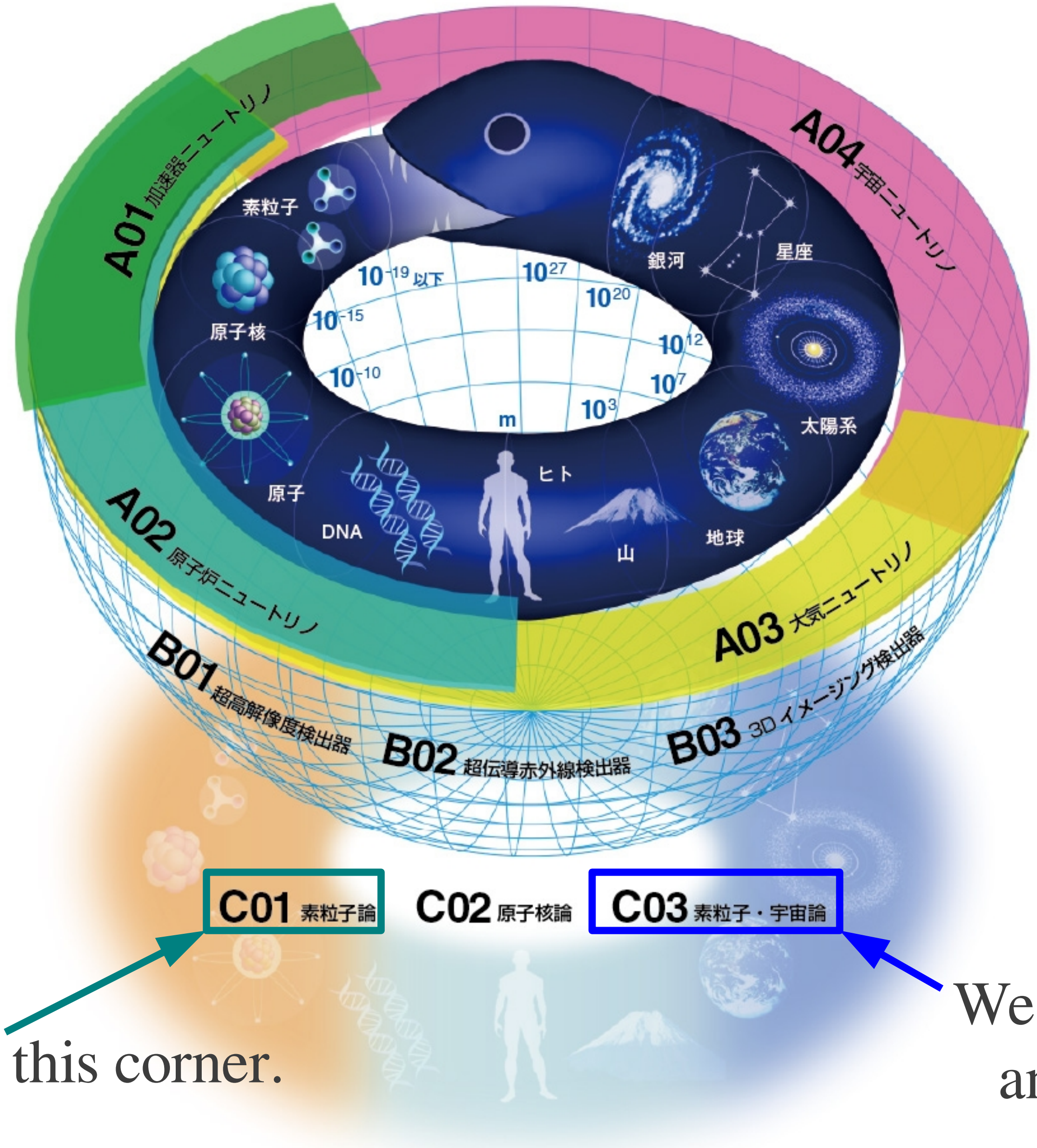
This small try shows that the idea works!
More precise, detailed, and sophisticated study may be worth to be done.

Relation to Neutrino Frontier



I belong to this corner.

Relation to Neutrino Frontier



I belong to this corner.

We share interest
and ideas with...

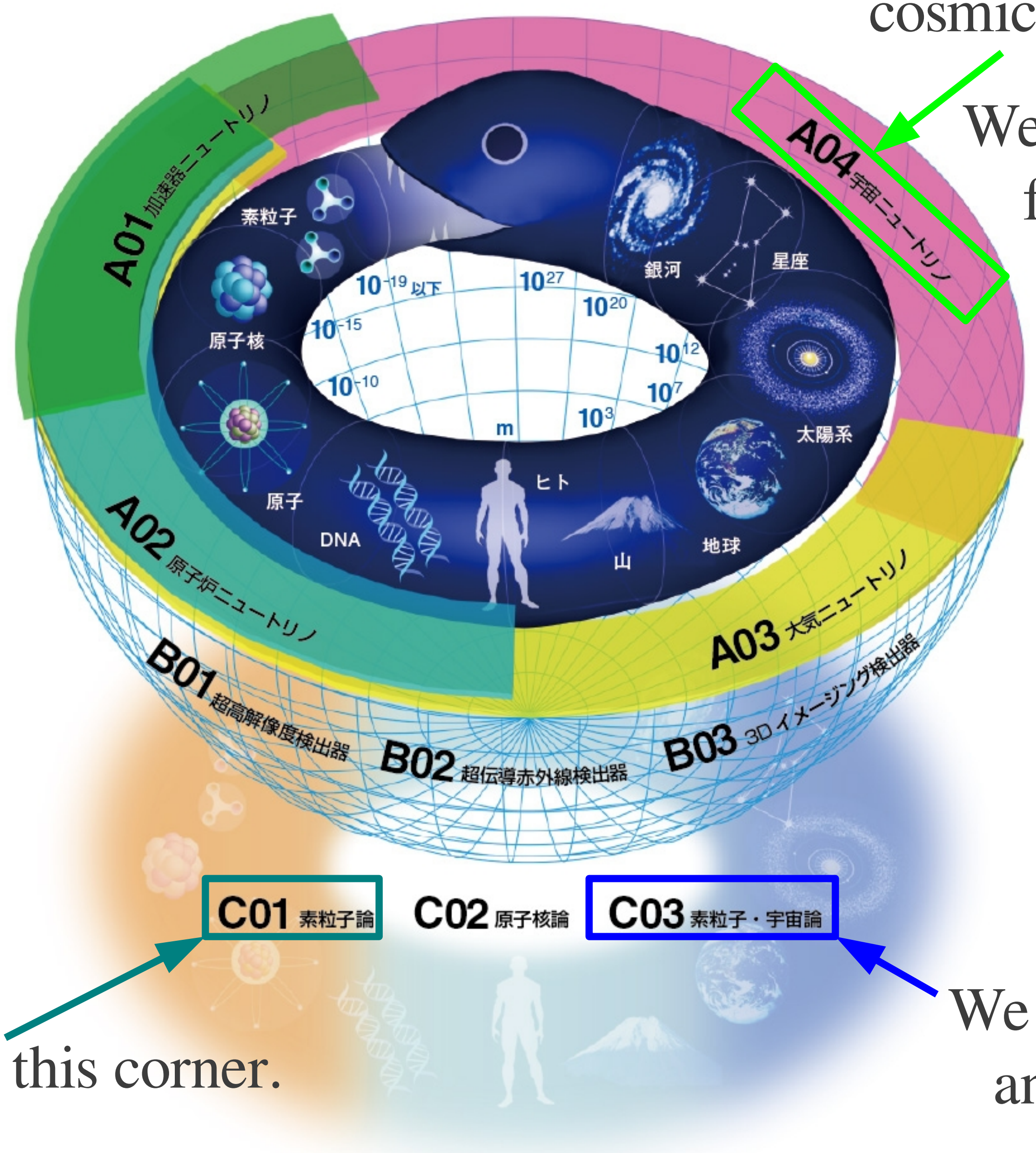
Relation to Neutrino Frontier

Special thanks to Yoshida-san

We **mind the gap** on cosmic neutrino spectrum

We are also motivated from **muon *g-2***

Charged Lepton



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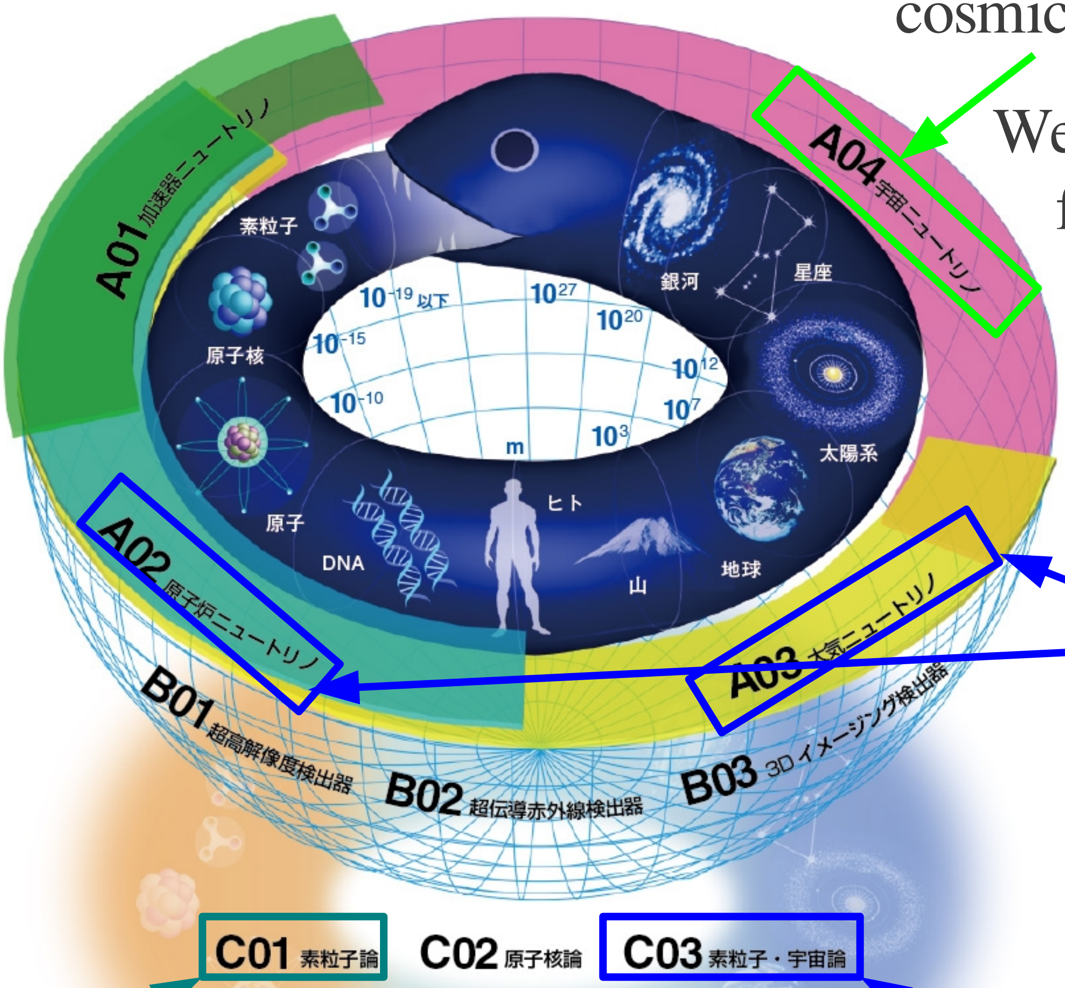

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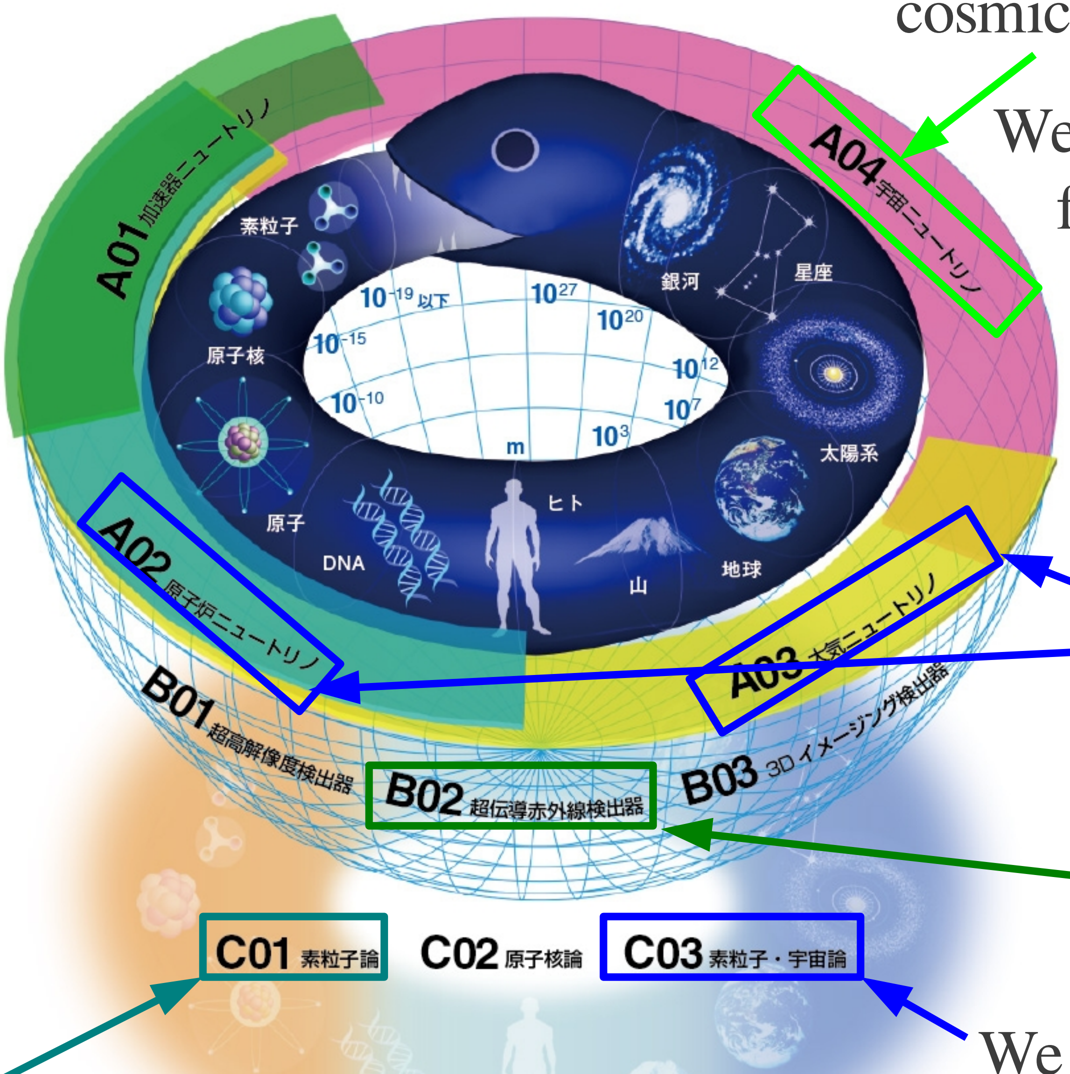

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CNB int.

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Precision measurement of neutrino int.

The most relevant bound
is **neutrino trident proc.**

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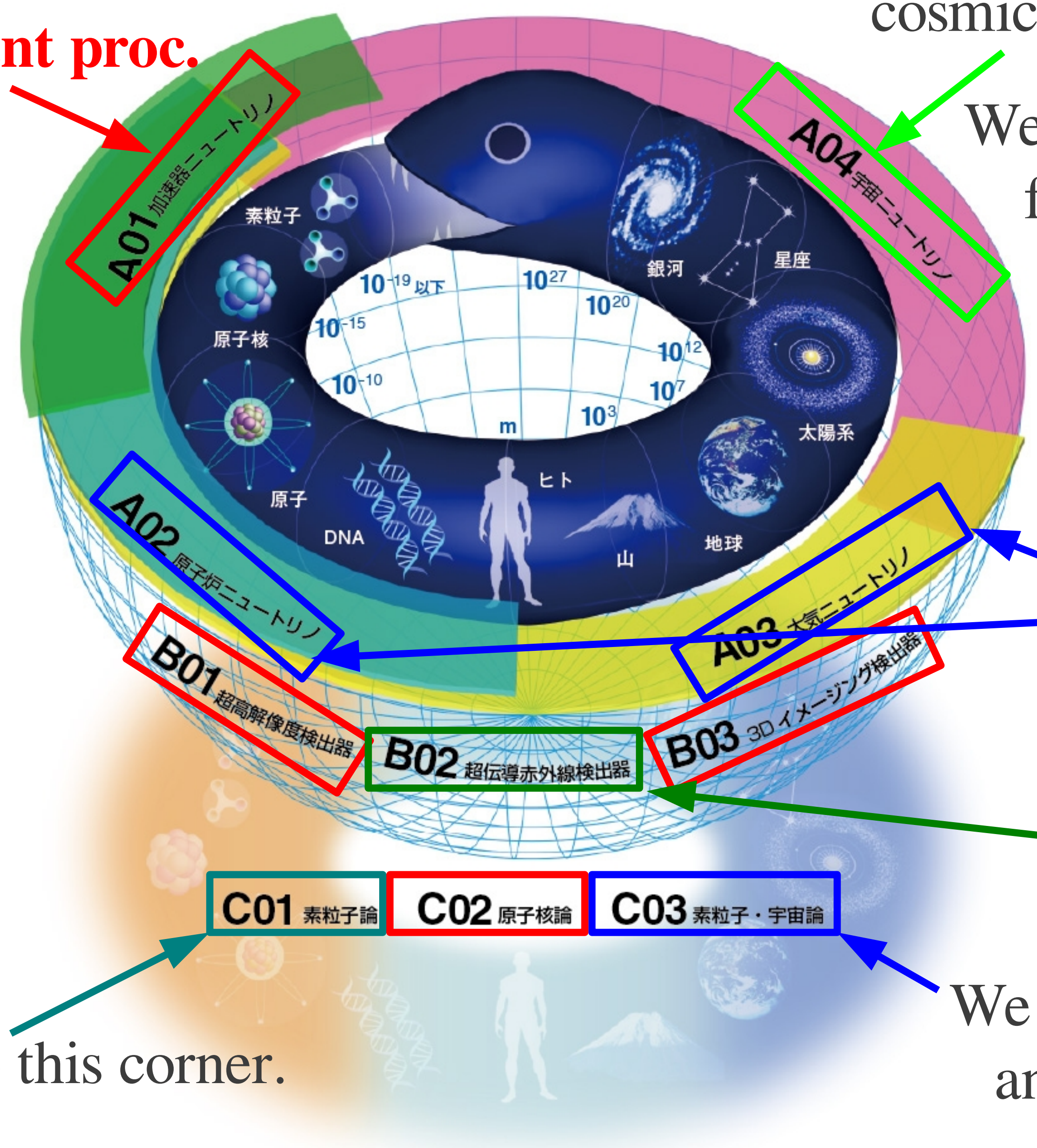

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Ask a favor (or two) to experimentalists

- Please provide new data (to feed theorists)
- Please check the **trident proc**. in your HDs.

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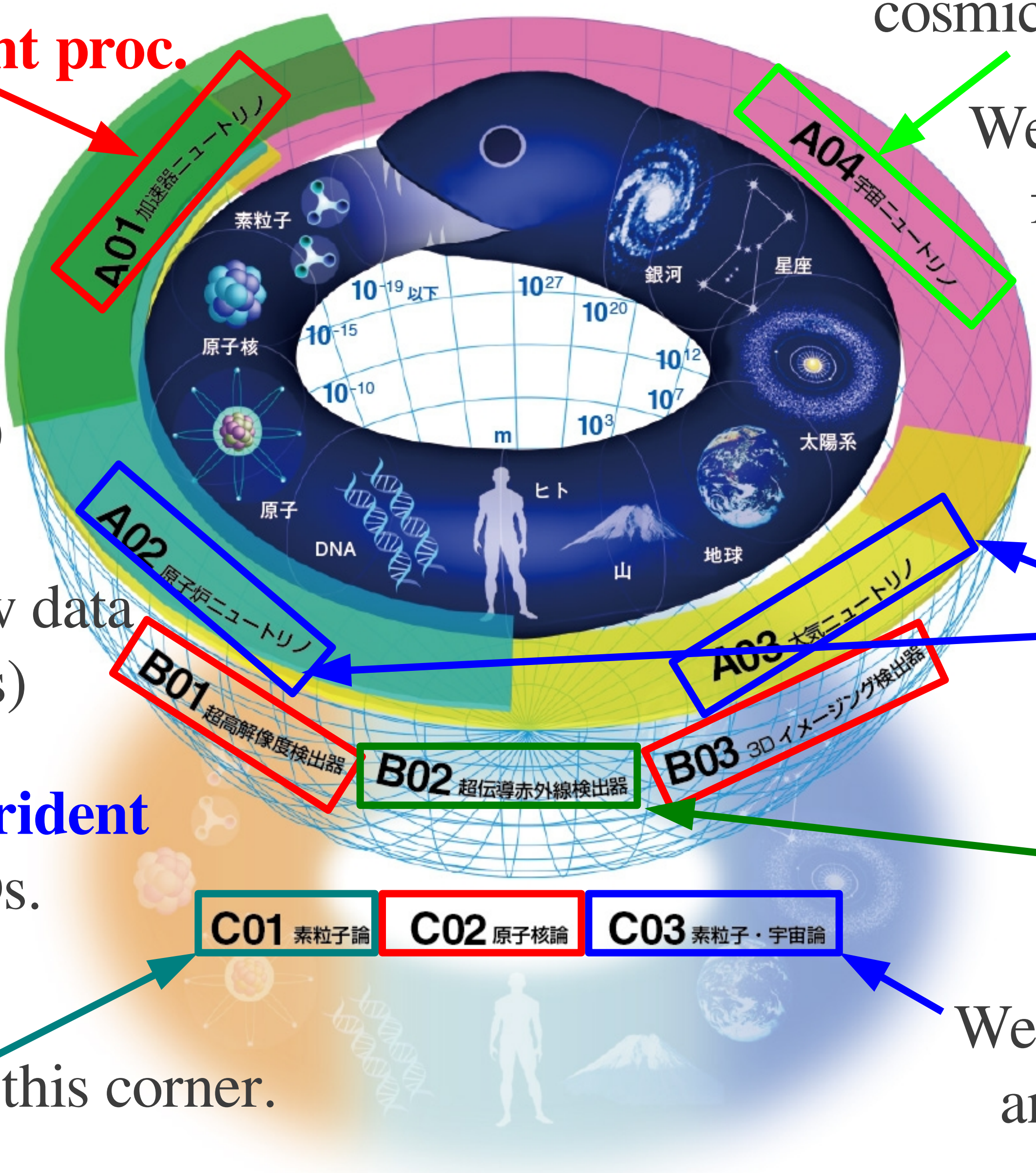

Back up slides