Mind the Gap on IceCube

Cosmic neutrino spectrum and muon anomalous magnetic moment

Toshihiko Ota
Saitama University

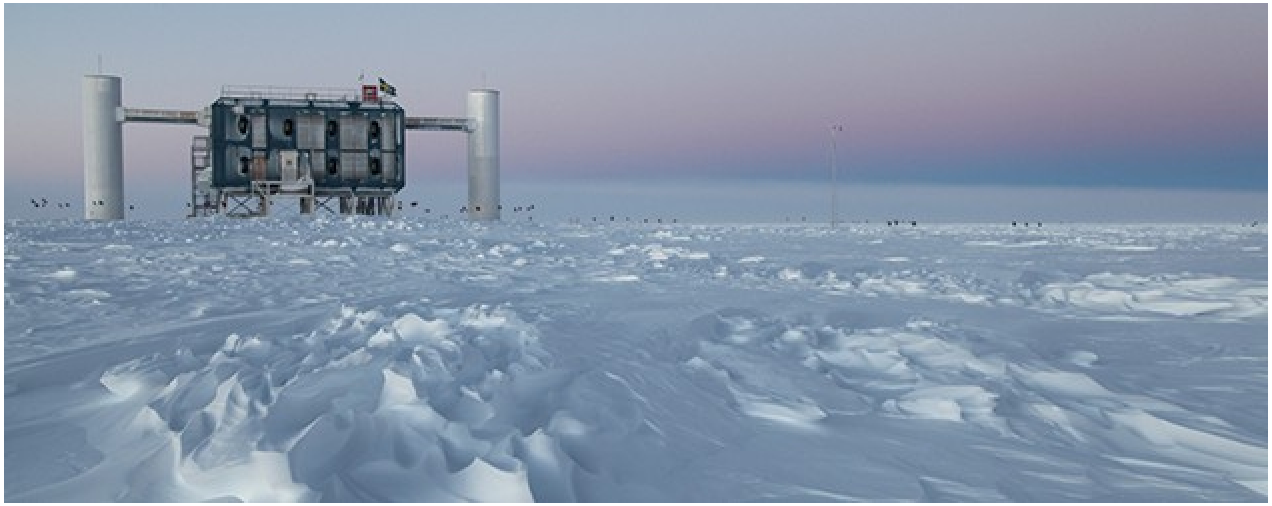
based on the collaboration works with

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

PR**D91** (2015) 037301 and PR**D93** (2016) 013014

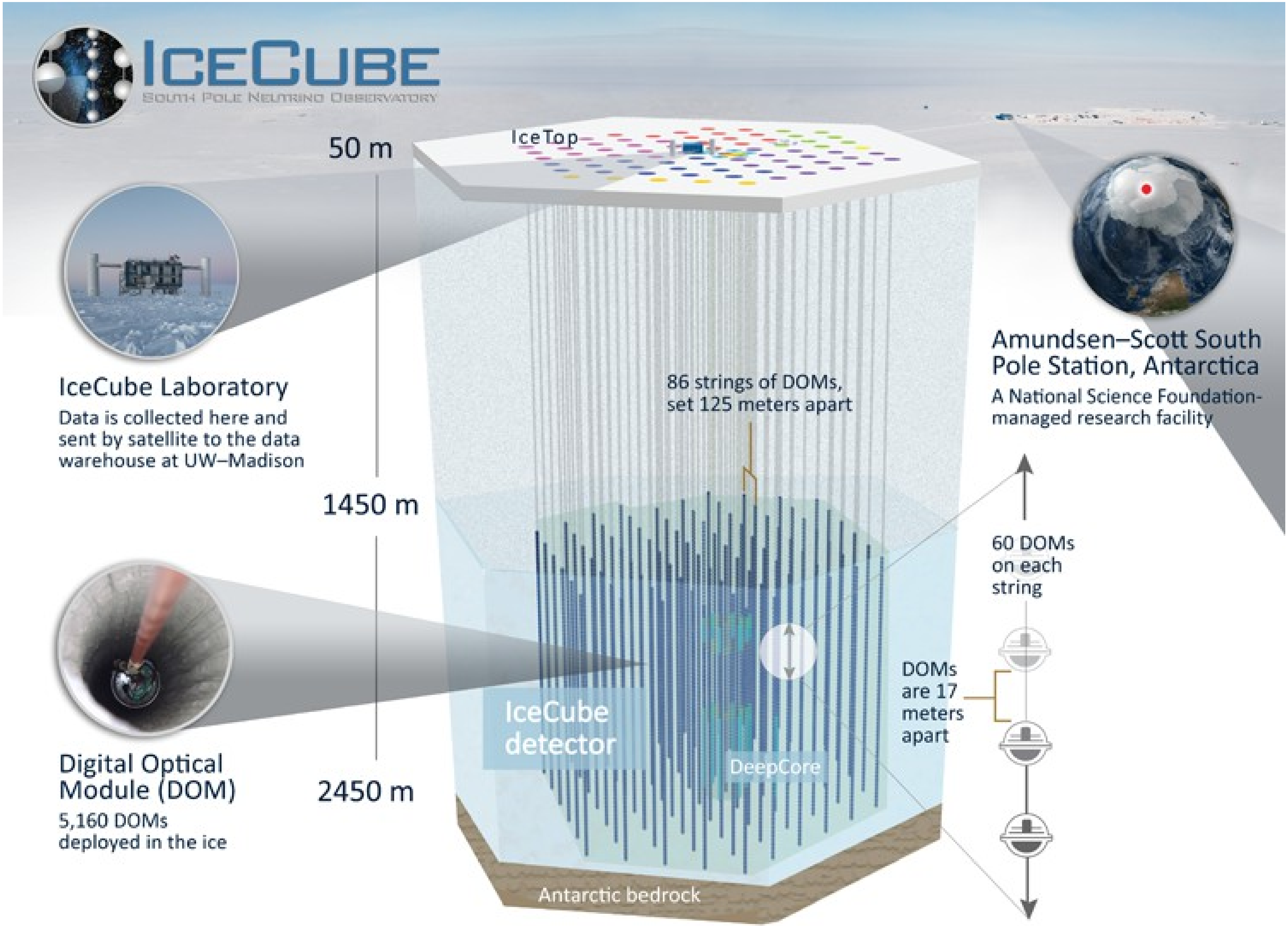
Abstract

- In 2013, IceCube discovered two high-energy neutrino events…



IceCube collaboration

■ Abstract


ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
50 m
IceTop
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
IceCube detector
DeepCore
Antarctic bedrock

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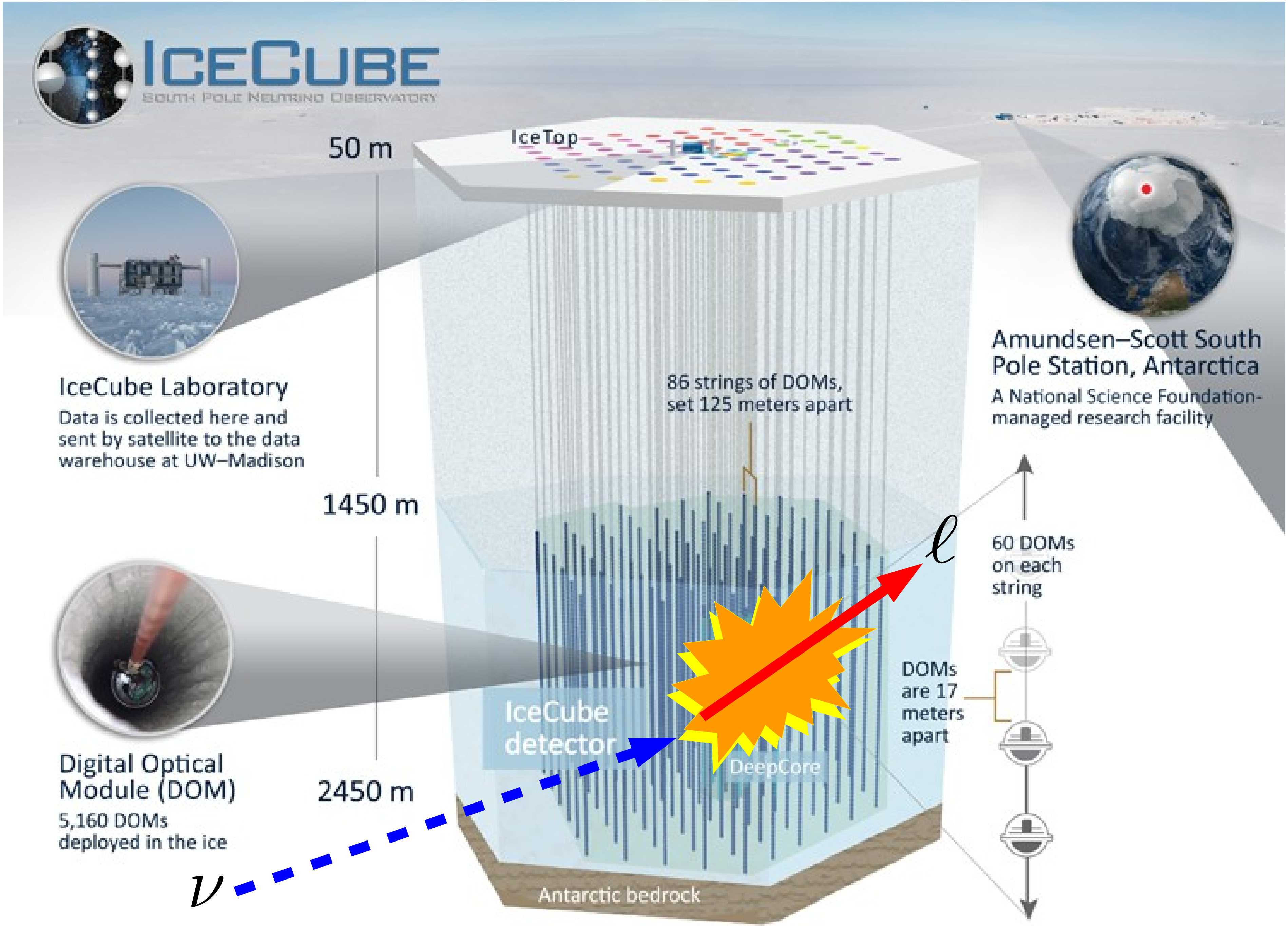
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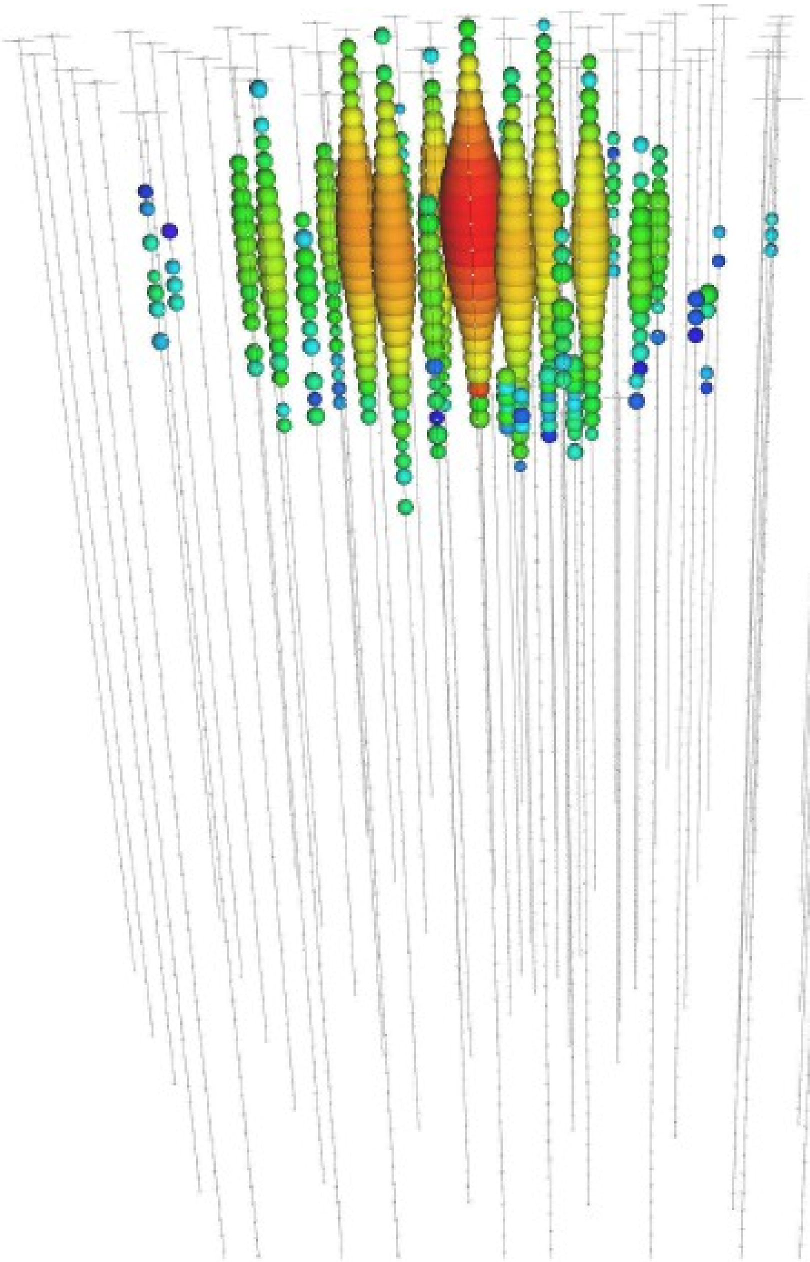
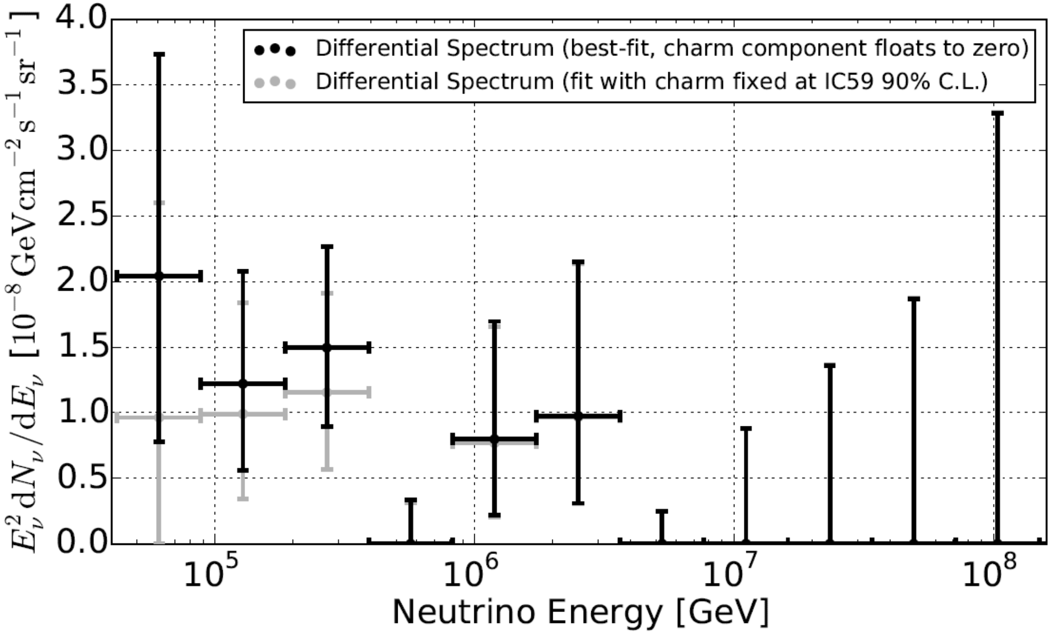
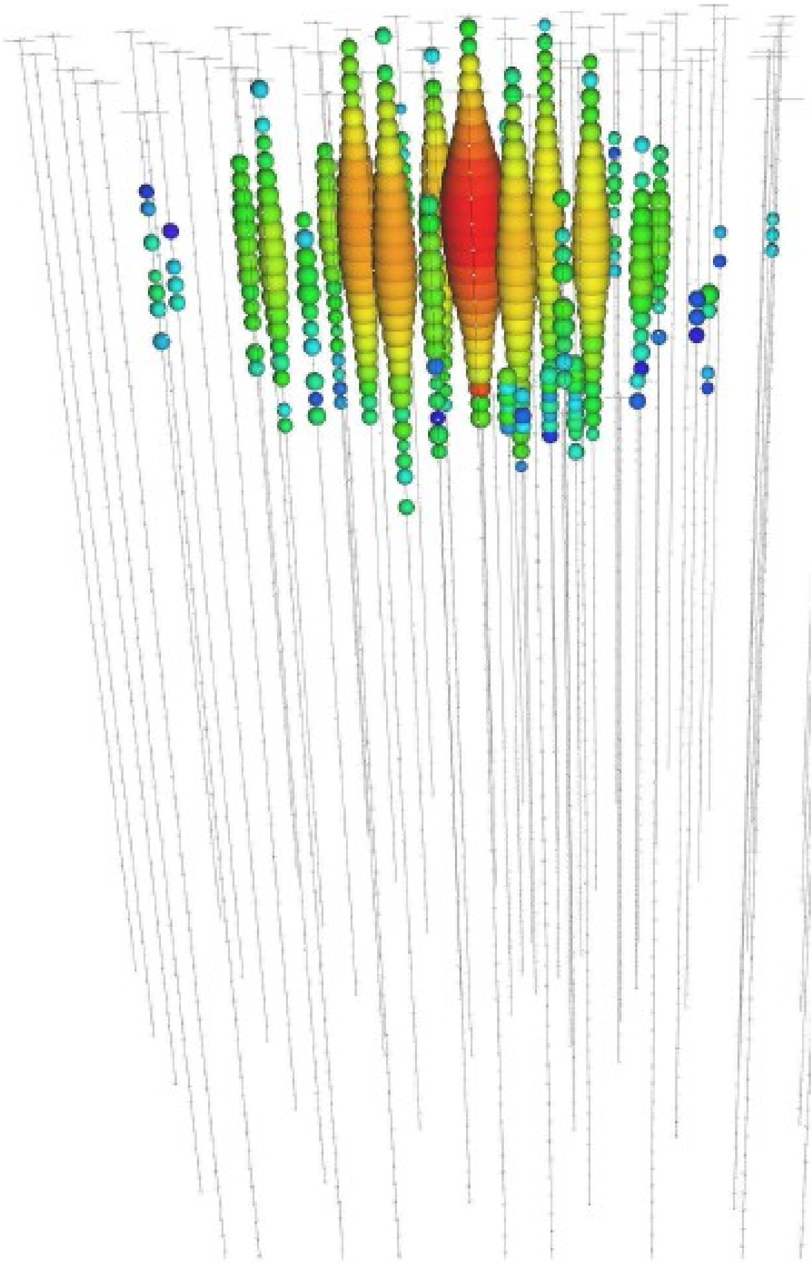


■ PeV cosmic neutrino spectrum

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





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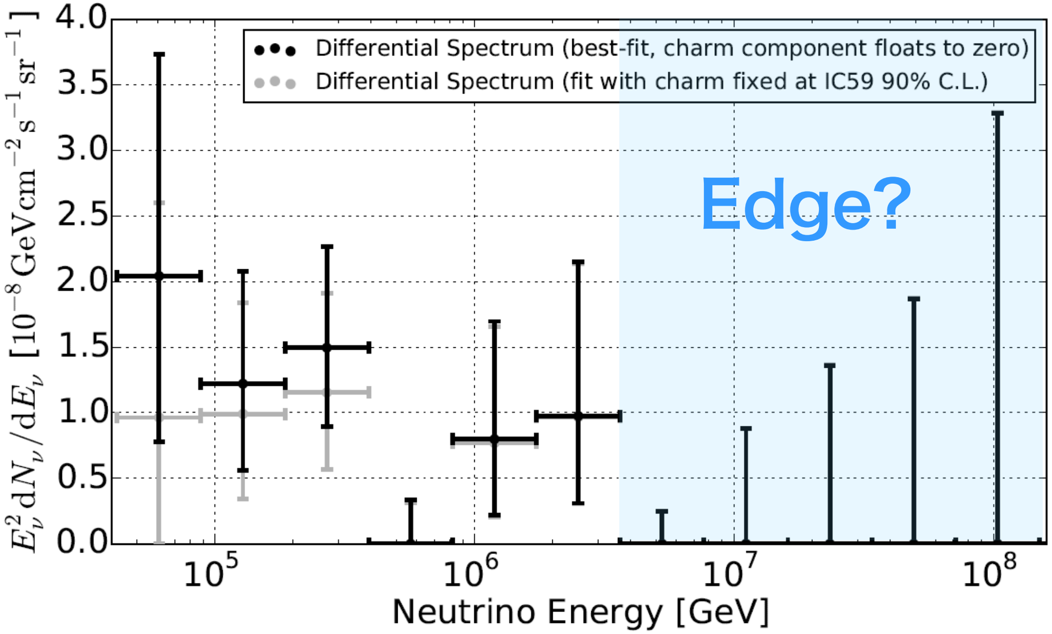
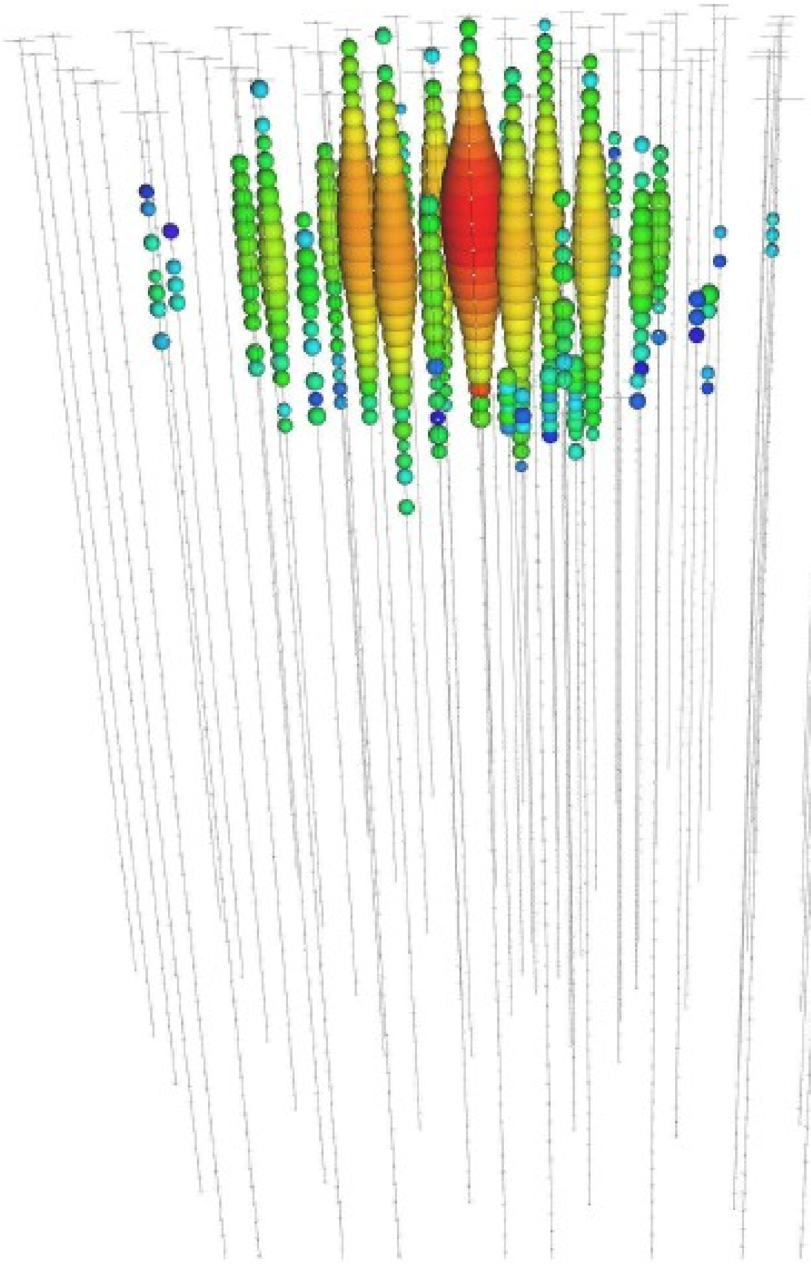
IceCube collaboration PRL **113** (2014) 101101





ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

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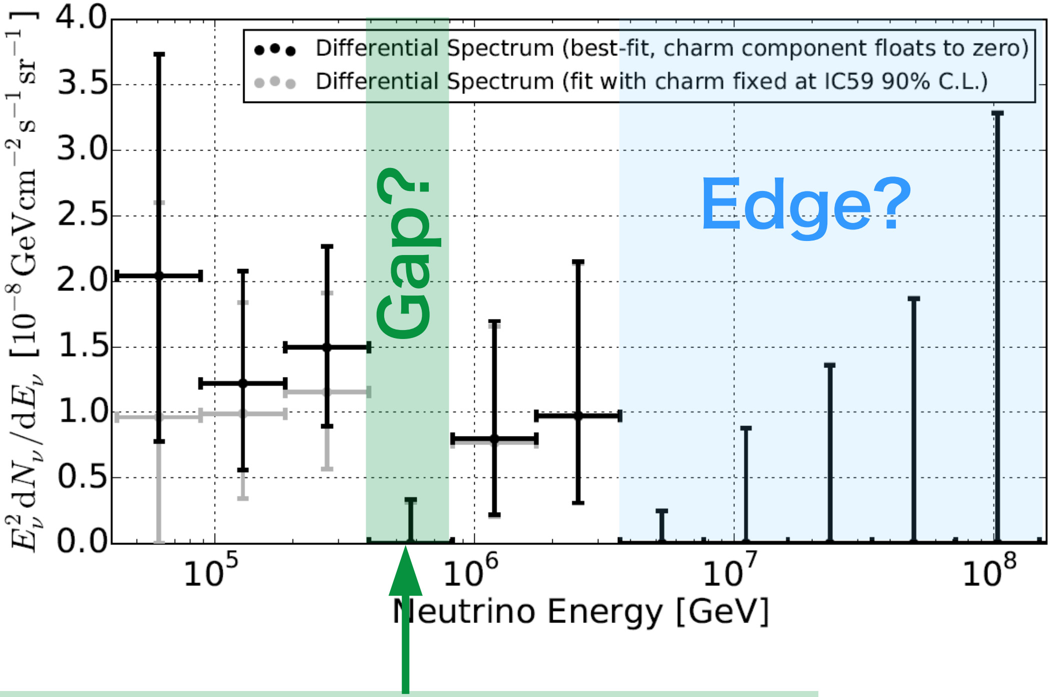

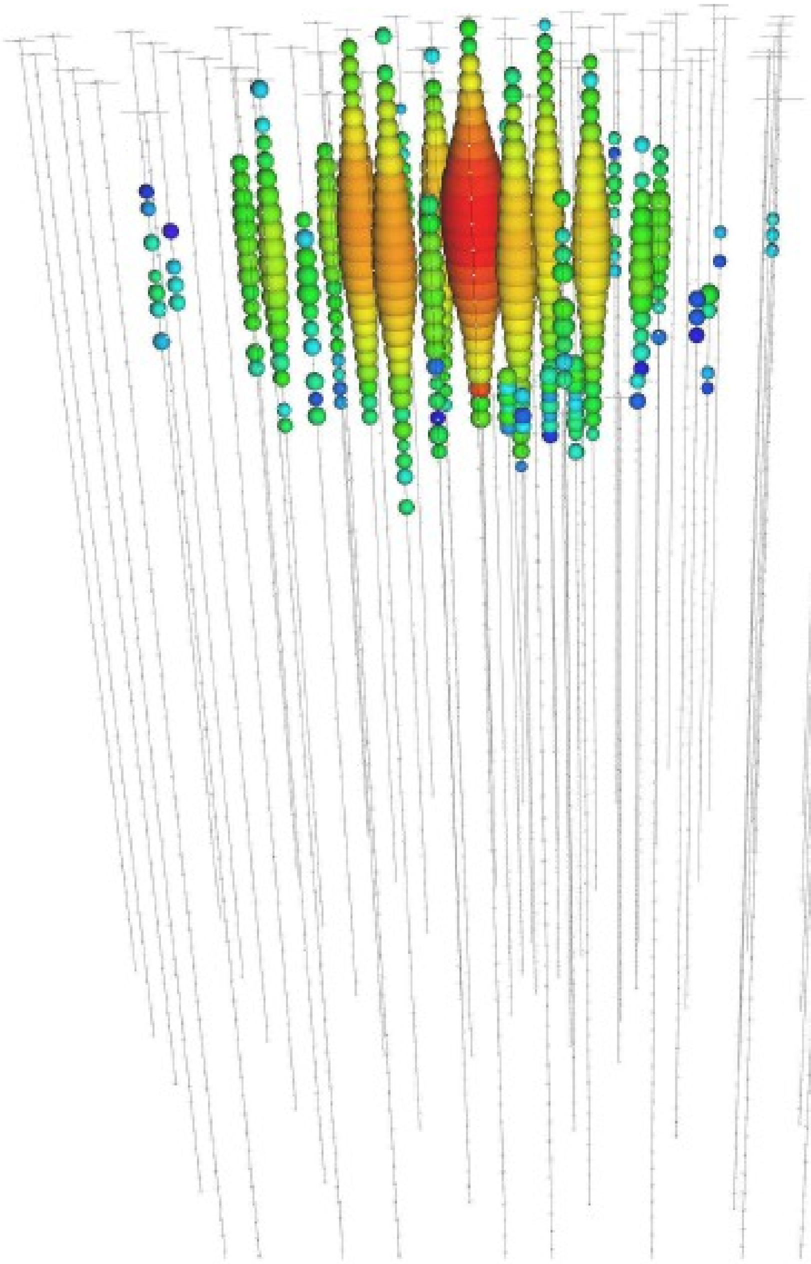

■ Gap in the spectrum?

No event at 0.4-1PeV

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SOUTH POLE NEUTRINO OBSERVATORY

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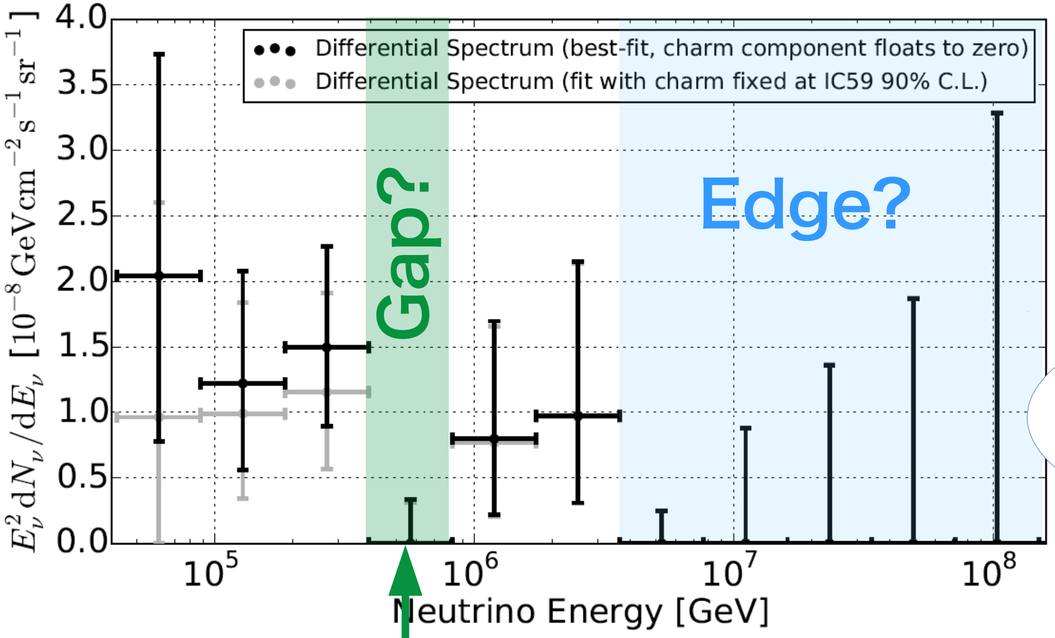
IceCube collaboration PRL **113** (2014) 101101



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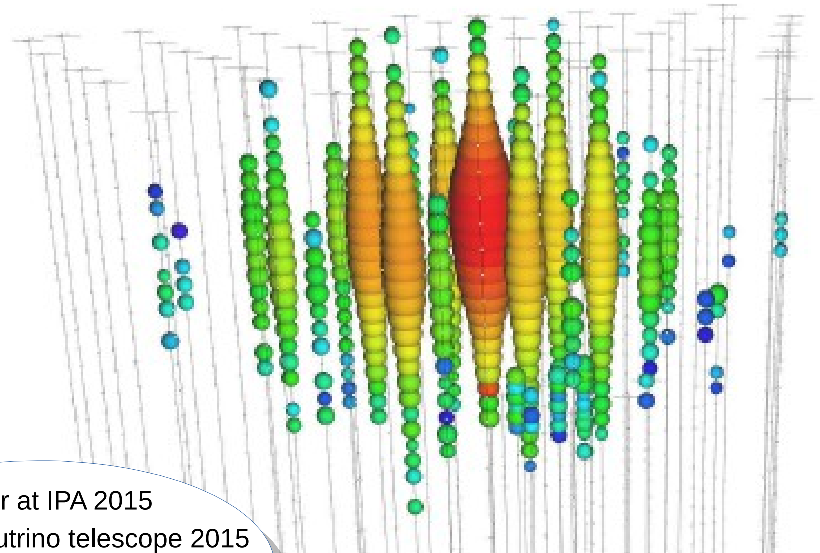
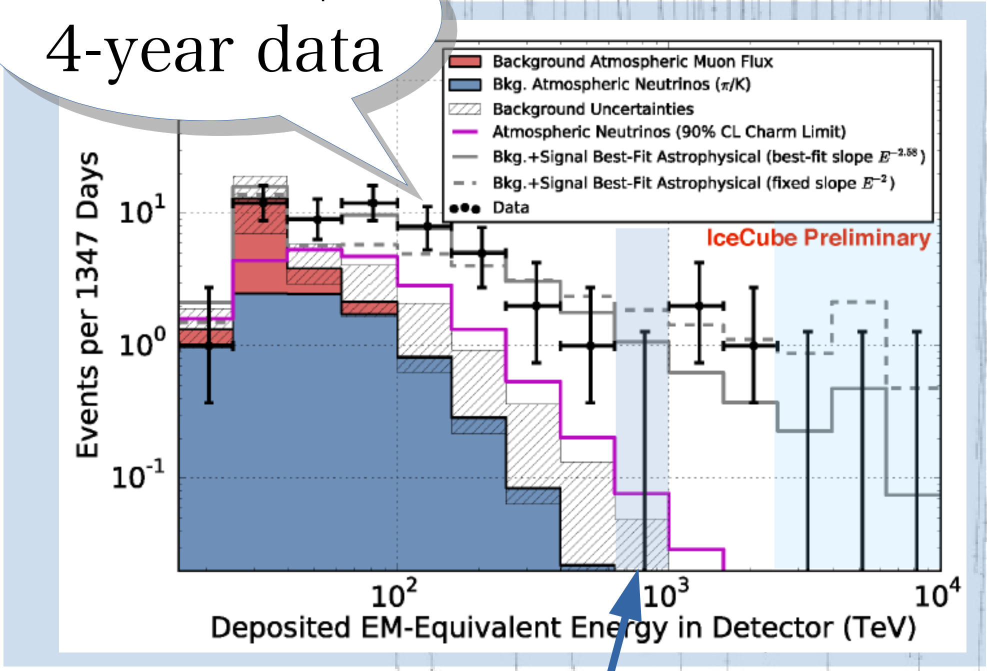


Botner at IPA 2015
Halzen at Neutrino telescope 2015

4-year data



Gap???

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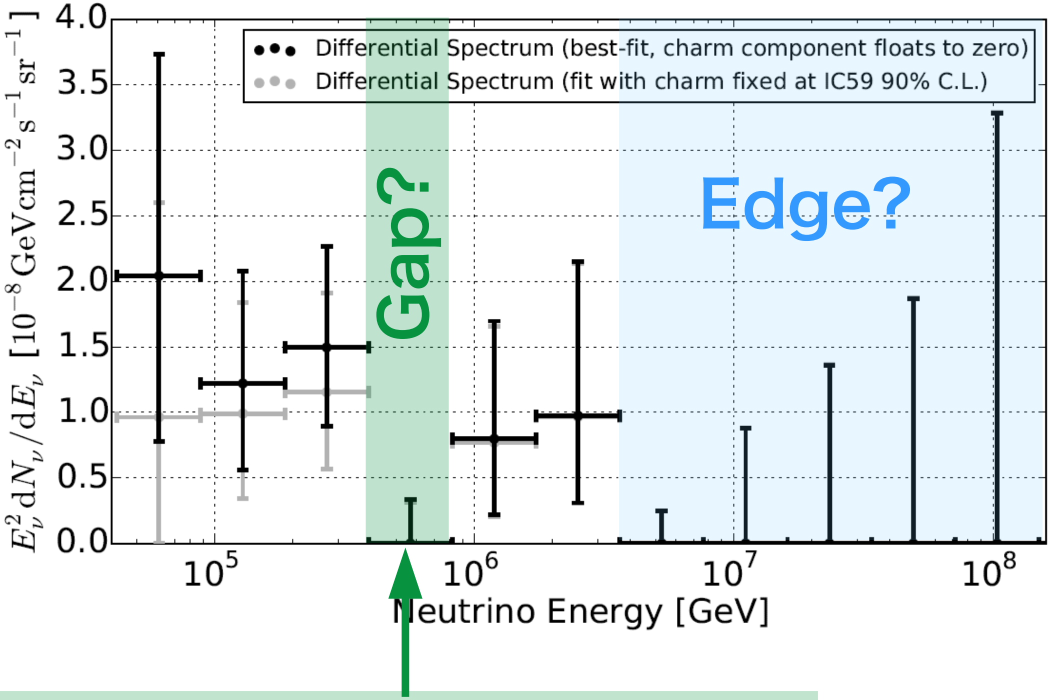

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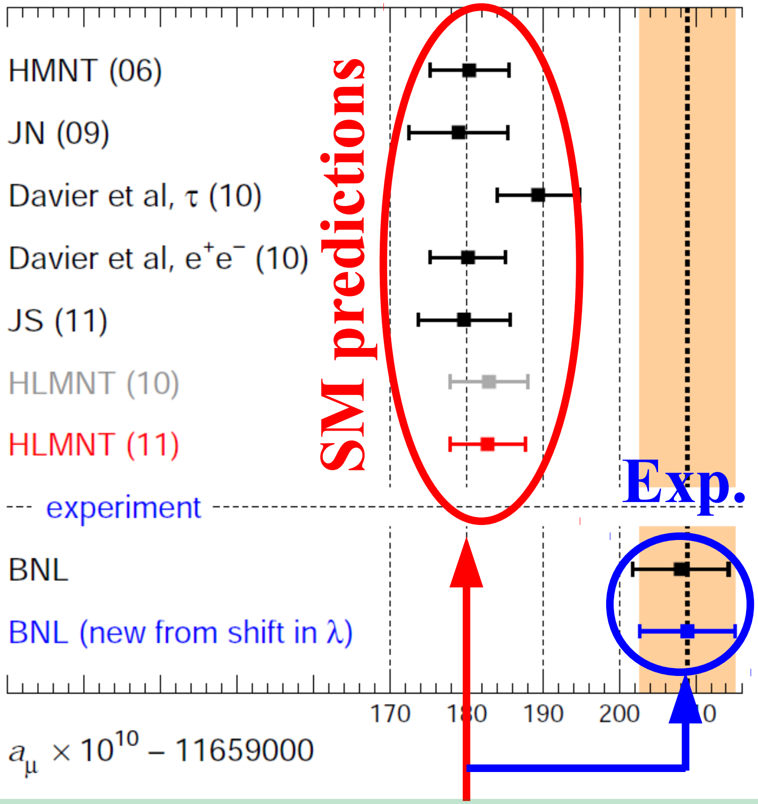
■ Muon g-2

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



■ Gap in muon g-2

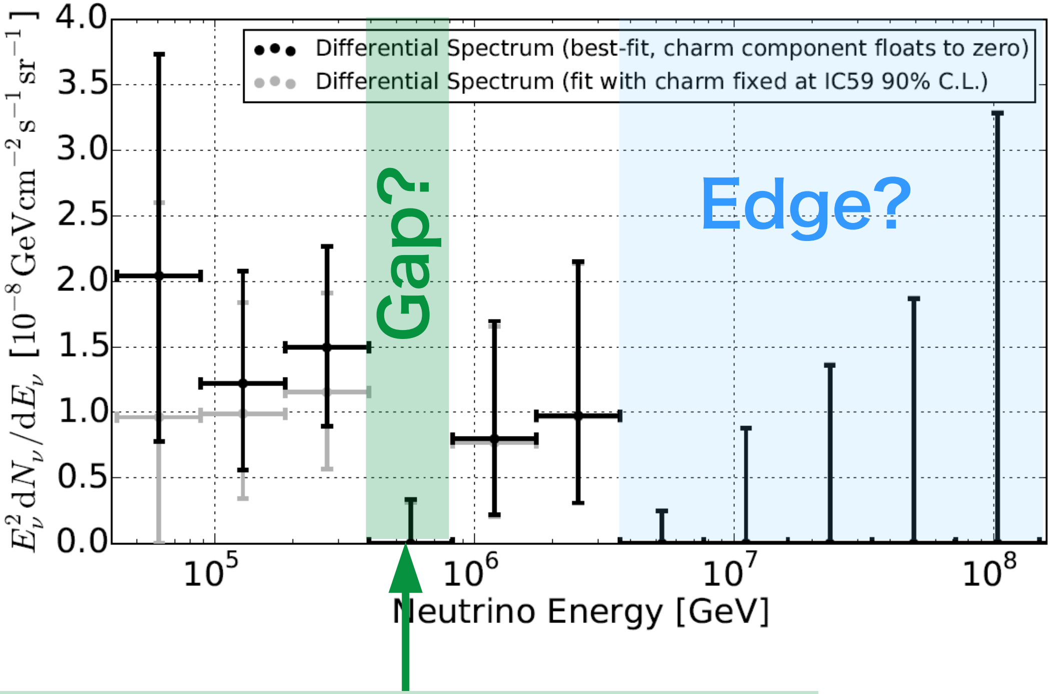
SM predictions vs exp.

$$a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}} = (26.1 \pm 8.0) \cdot 10^{-10}$$

■ Abstract

■ PeV cosmic neutrino spectrum

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



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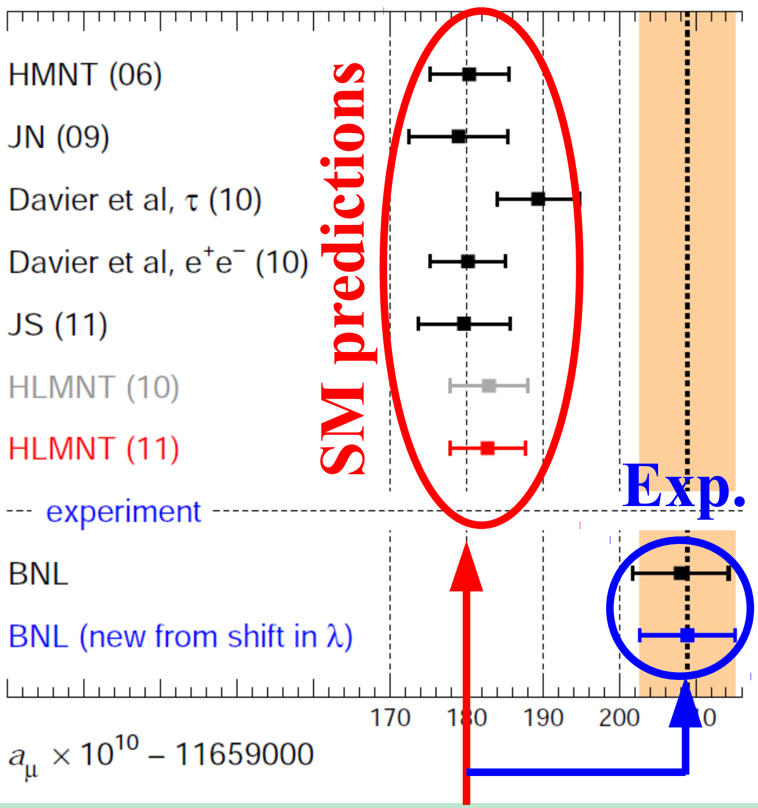

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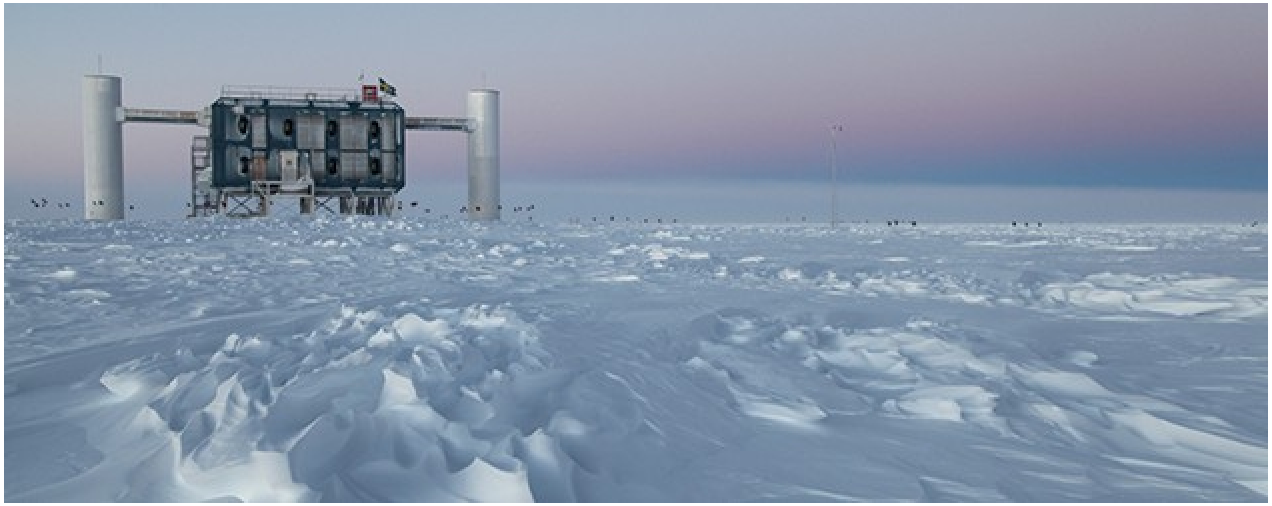
(c) Transport in London

MeV leptonic force

may be responsible to both the gaps

- What does he tell us?

- IceCube has opened the door to the new era of neutrino astronomy

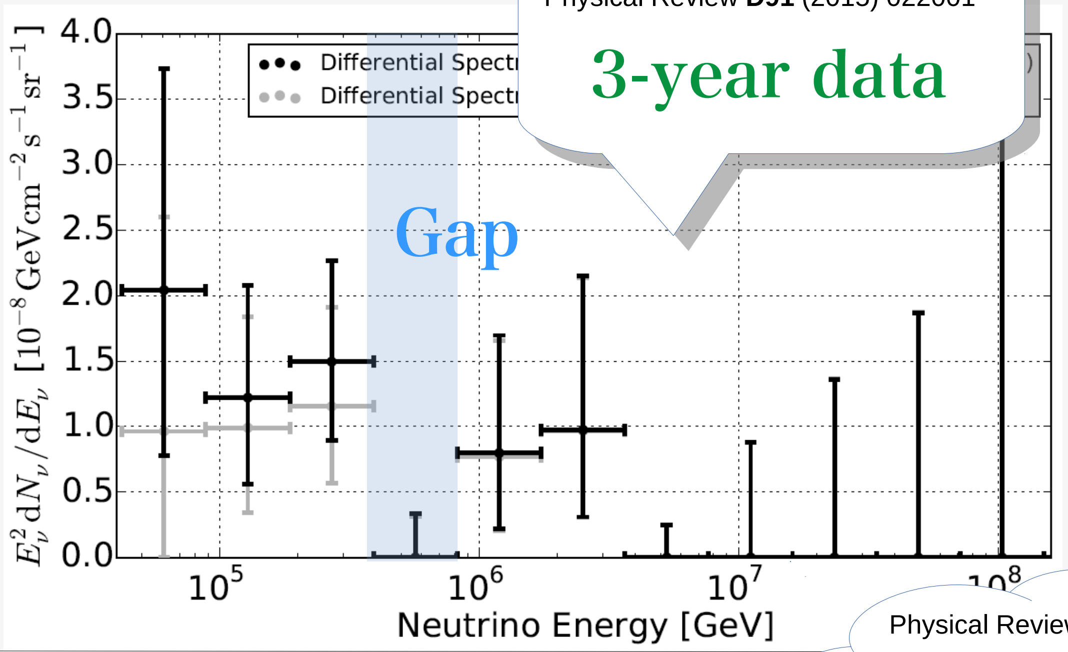


IceCube collaboration

■Spectrum of high energy cosmic neutrino

Physical Review **D91** (2015) 022001

3-year data



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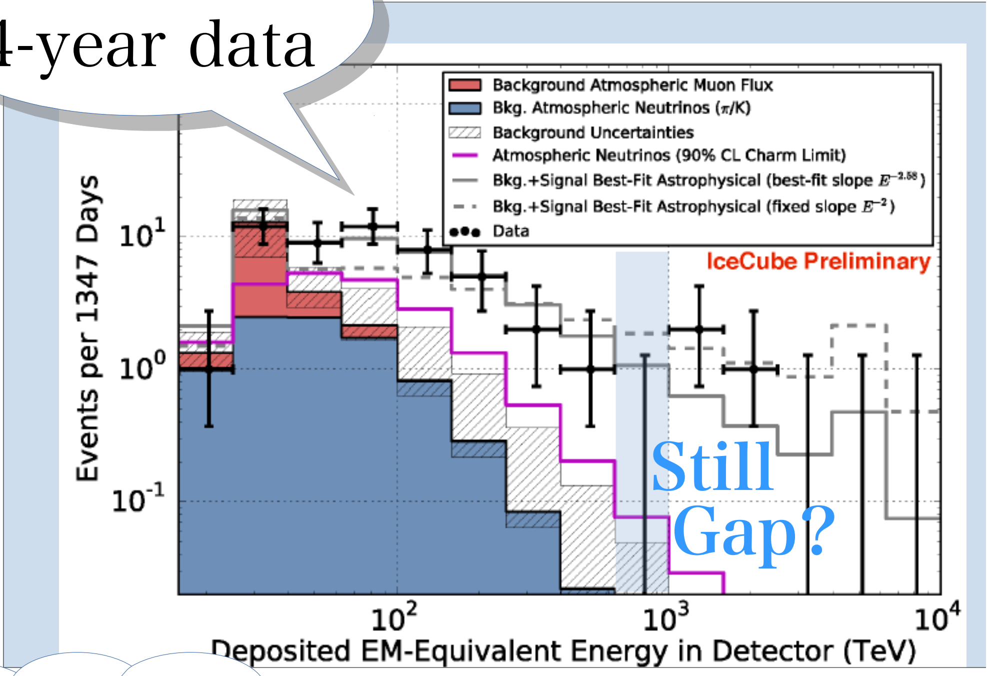
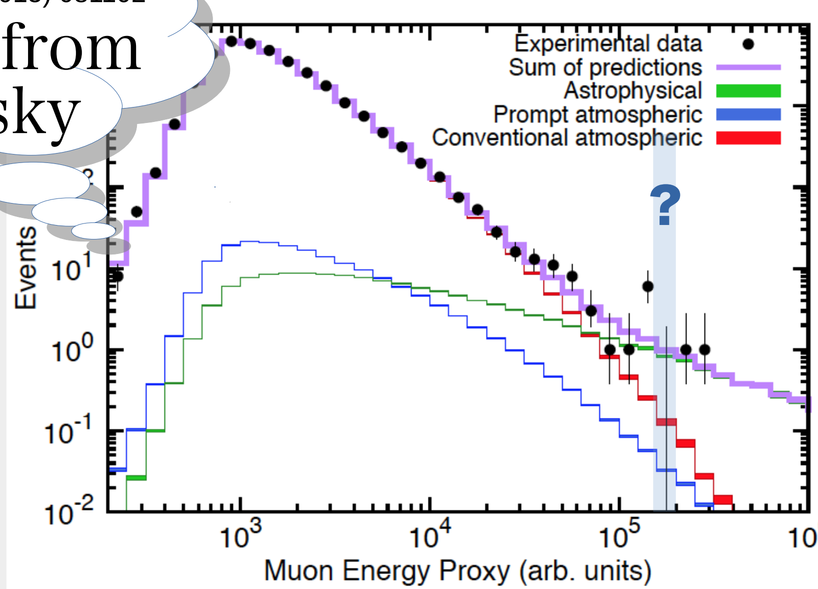


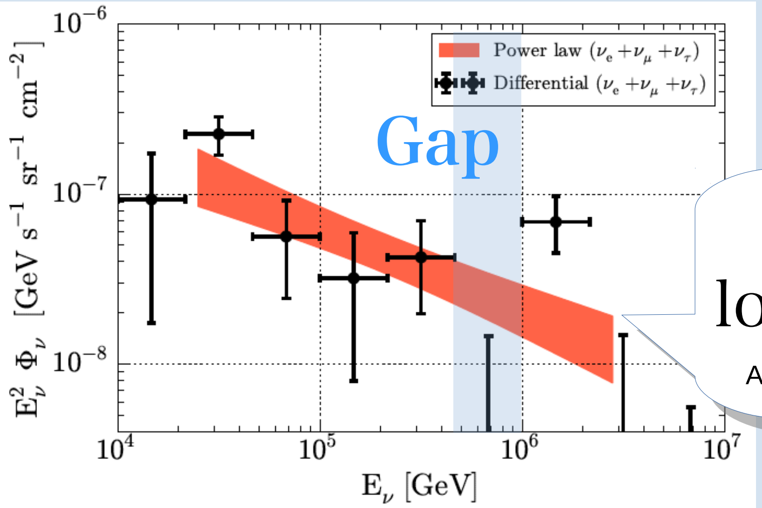
Physical Review Letters **115** (2015) 081102

Muon events from northern sky



2-year low E threshold

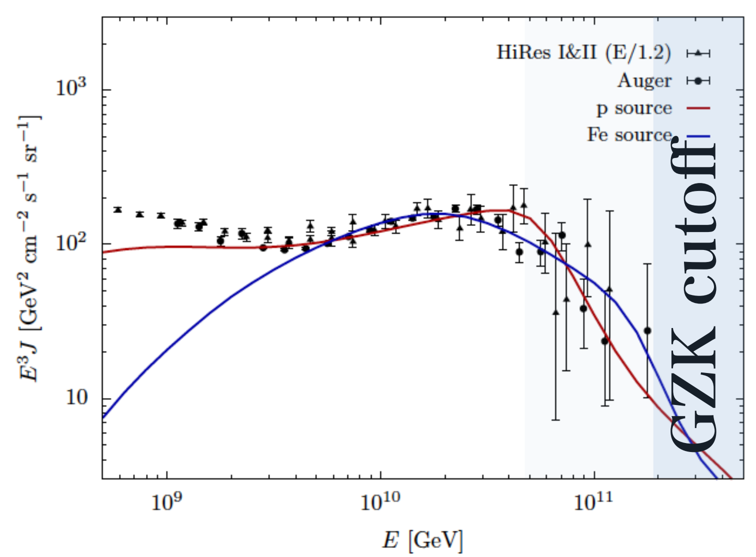
Astrophysical Journal **809** (2015) 98



GZK neutrino (aka Cosmogenic neutrino)?

The GZK cut-off in CR spectrum guarantees resulting neutrinos.

$p\gamma_{\mathrm{CMB}} \xrightarrow{\Delta^+} \pi^+ n$ and π^+ produce GZK neutrinos.



Observed CR flux

What are they? Where do they come from?

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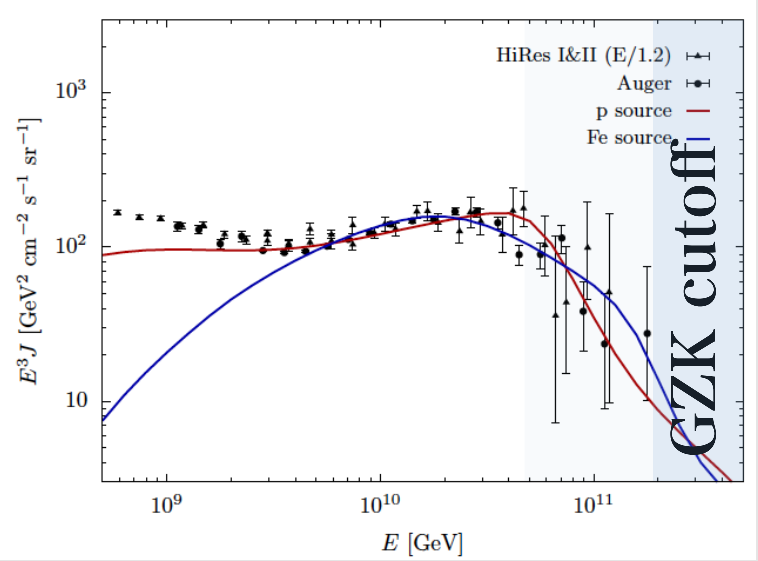
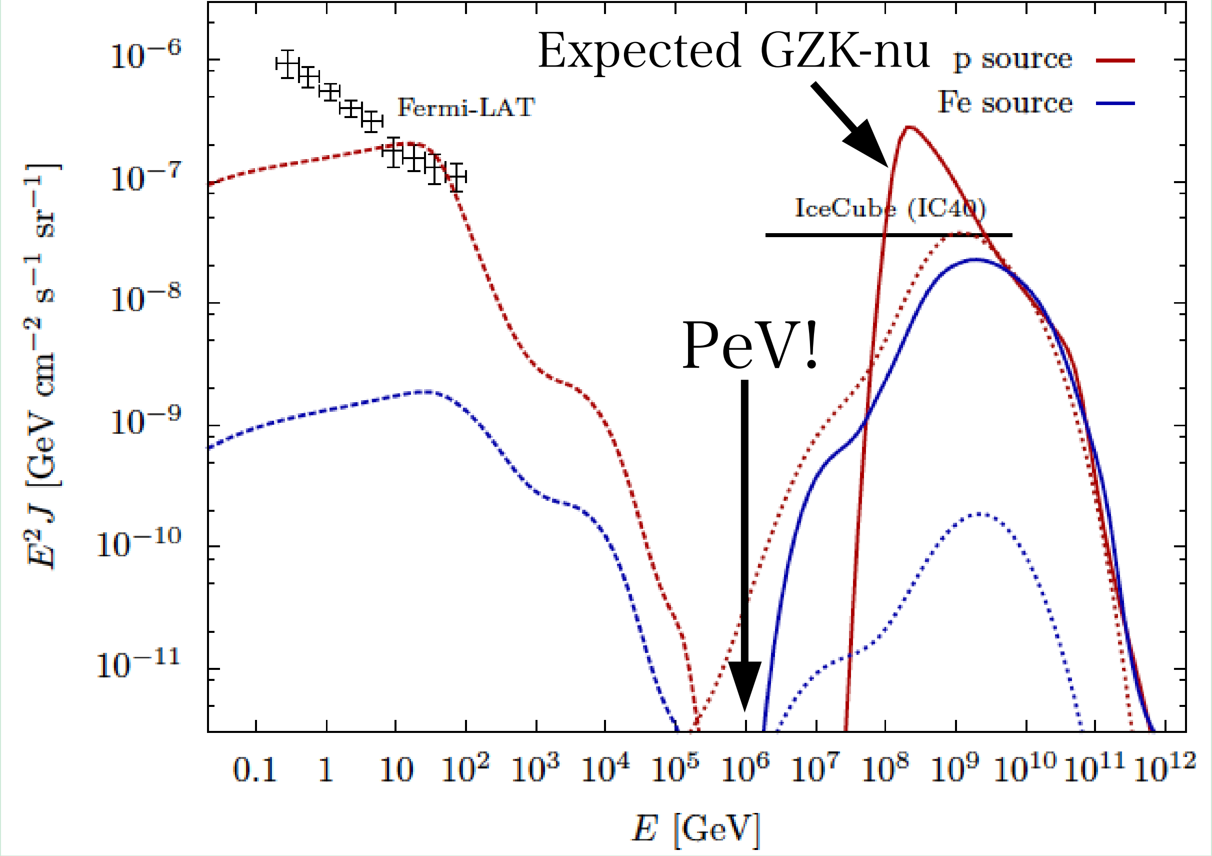


Observed CR flux

Expected GZK-nu and gamma fluxes

Ahlers and Halzen, Phys.Rev. D86 (2012) 083010.



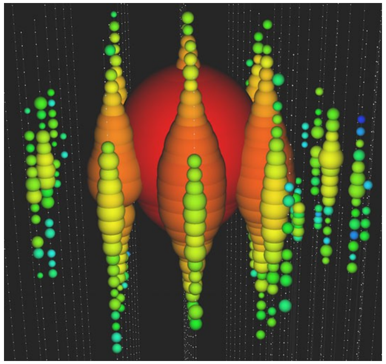
Typical energy range is EeV. PeV may be too low.

■ Where do they come from?

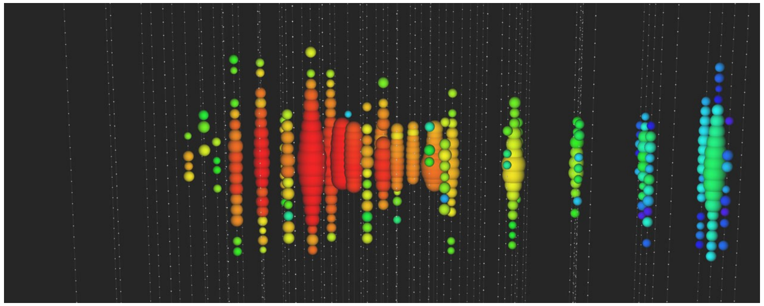
■ Event distribution in the sky

No significant local excess.

+ Cascade events



× Muon tracks



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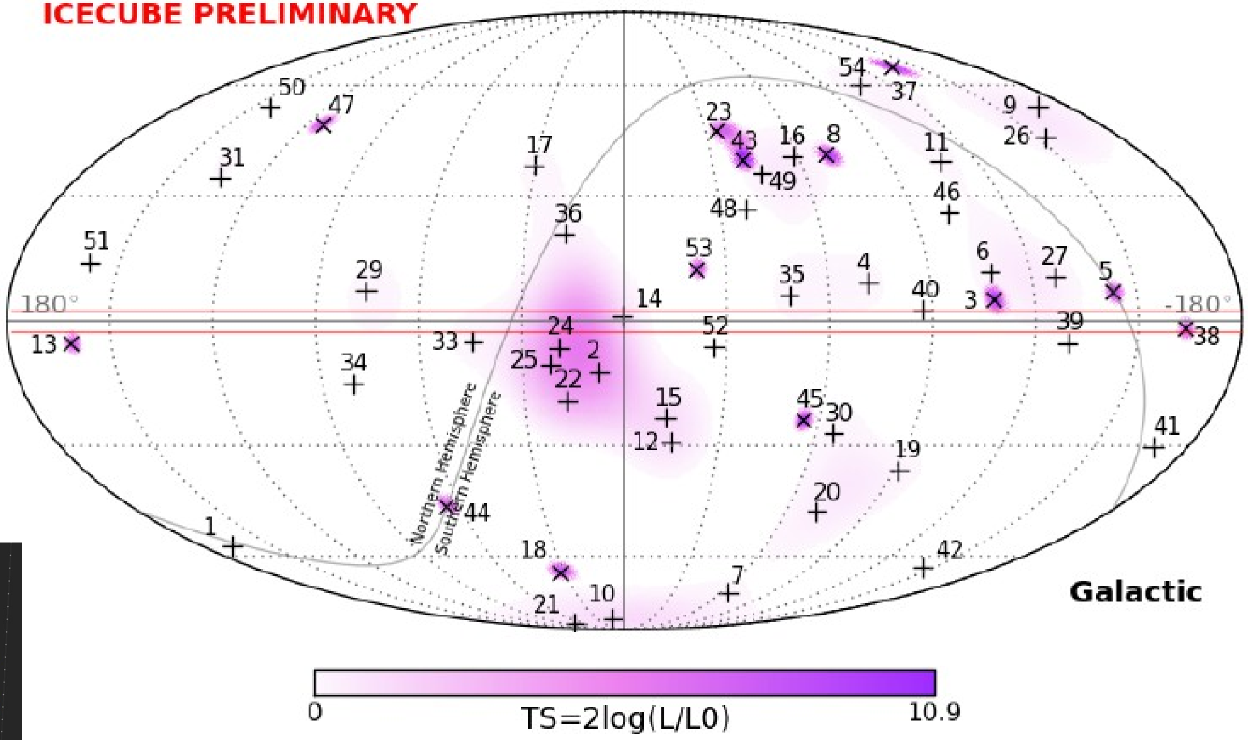
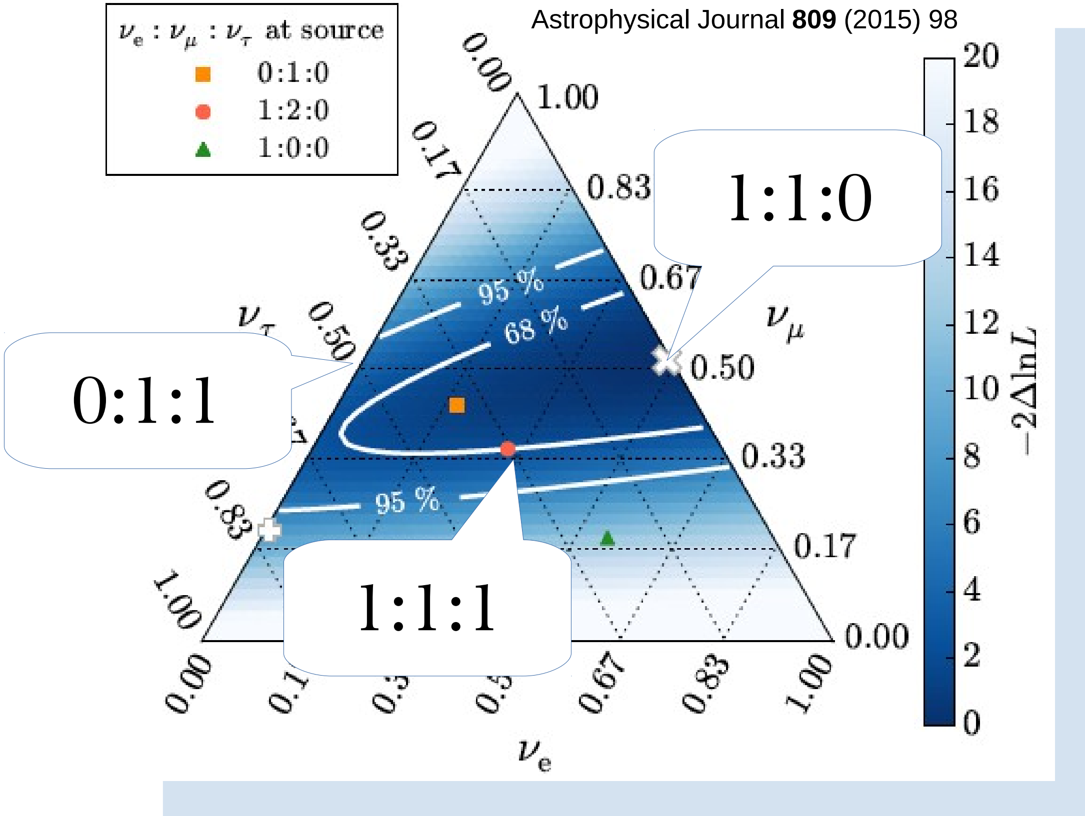


So far, we do not find a close tie between the PeV neutrino source and known astrophysical objects.

Diffuse flux from unknown sources?

Flavour composition of the events



Astrophysical Journal **809** (2015) 98

1:1:0

0:1:1

1:1:1

Observed flavour ratio

$$(\nu_e + \bar{\nu}_e) : (\nu_\mu + \bar{\nu}_\mu) : (\nu_\tau + \bar{\nu}_\tau)$$

@IceCube

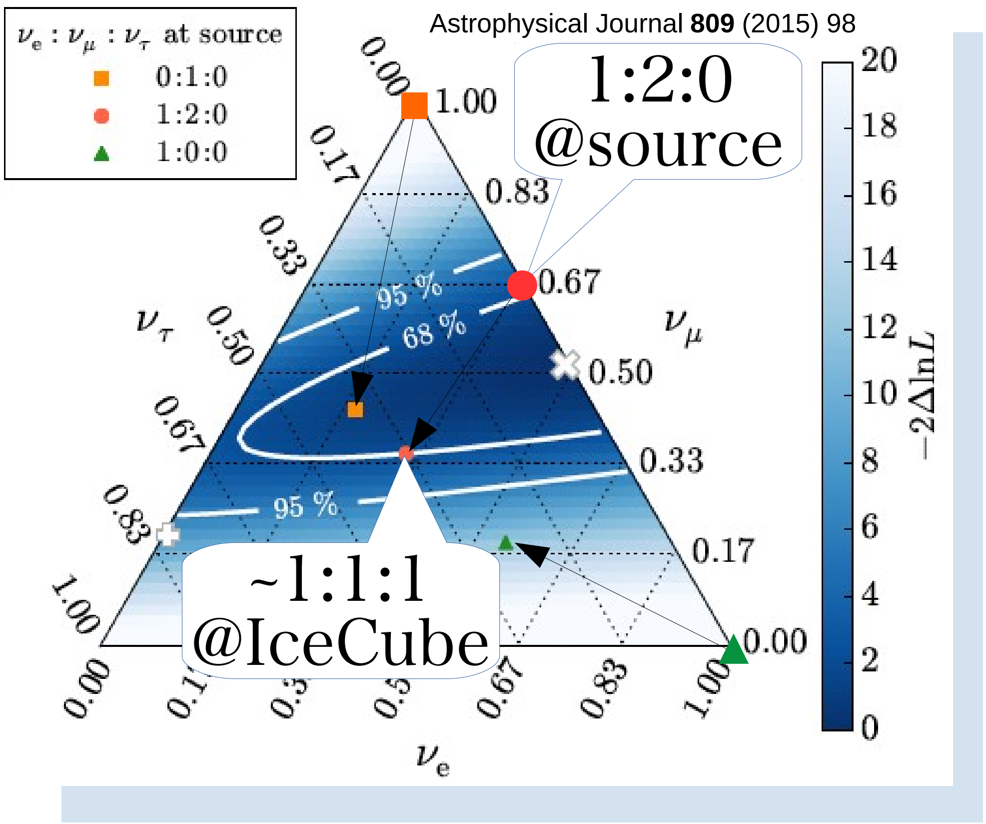
- Many “Showers (e, tau)”, but also “Tracks (mu)”.
- “Double bang=high E tau neutrino” has not been discovered yet.

Physical Review **D93** (2016) 022001

- Flavour ratio is consistent with 1:1:1 → hadronuclear source

■ Flavour composition of the events

Astrophysical Journal **809** (2015) 98



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@IceCube

$$\phi^{\text{@IceCube}}_{\nu_\beta} = \sum_{i,\alpha} |U_{\beta i}|^2 |U_{\alpha i}|^2 \phi^{\text{@source}}_{\nu_\alpha}$$

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Physical Review **D93** (2016) 022001

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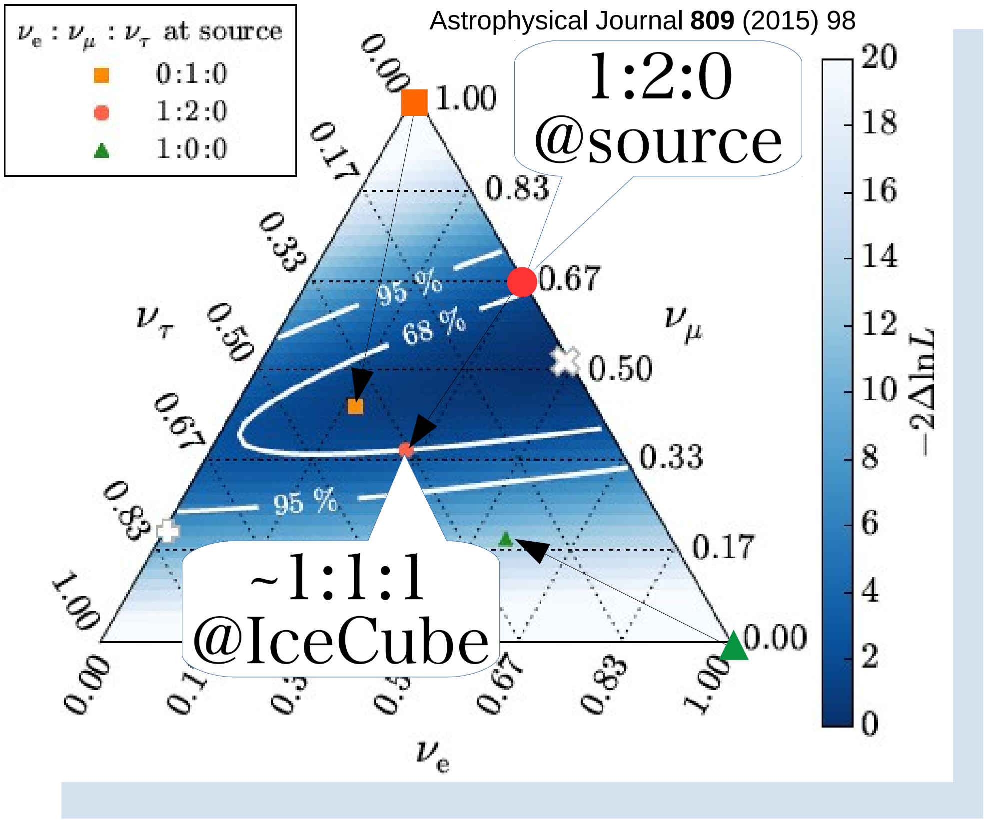
Flavour composition of the events

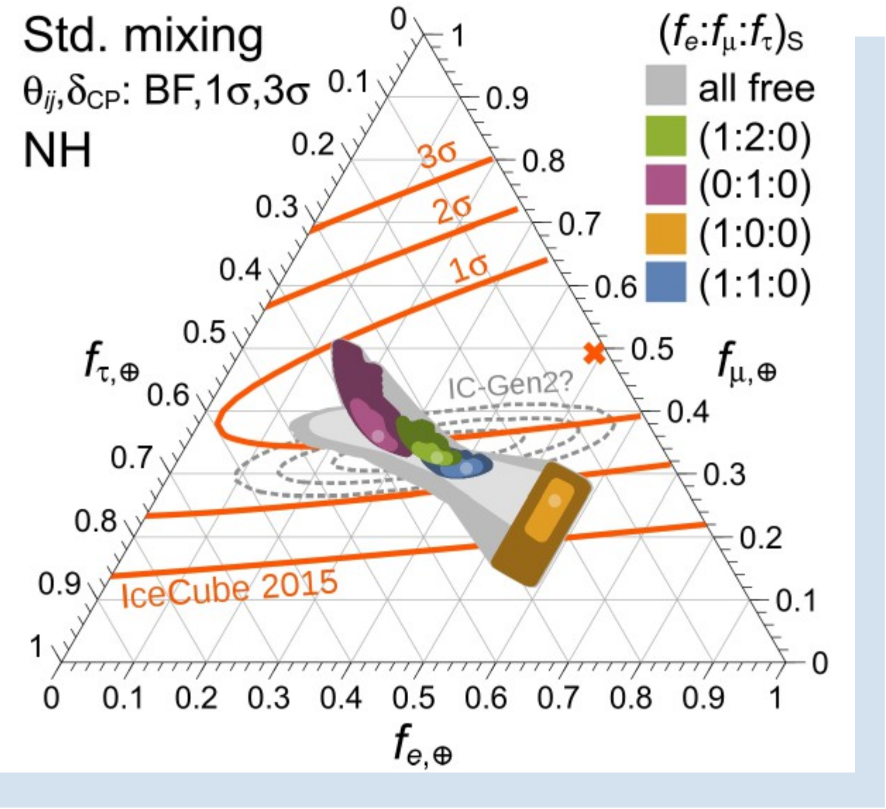
Bustamante Beacom Winter
Phys.Rev.Lett. **115** (2015) 16, 161302



Astrophysical Journal **809** (2015) 98

1:2:0
@source

~1:1:1
@IceCube



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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 neutrino trident and neutrino-electron scattering

③ A solution to the gaps

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

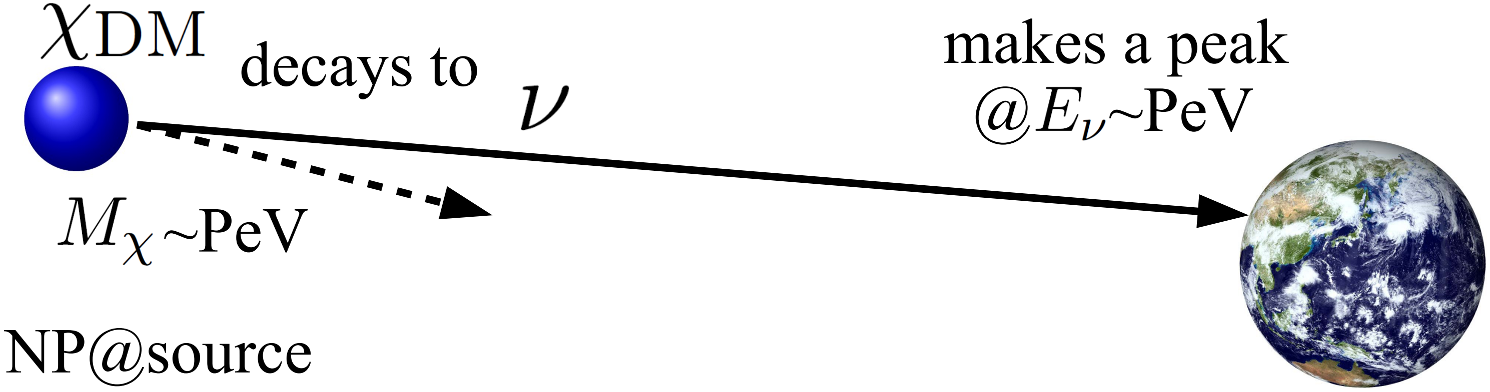
■If the Gap is explained by New Physics…

■ 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, JCAP **1412** (2014) 054.
Ema Jinno Moroi PL**B733**(2014) 120, JHEP **1410** (2014) 150. Rott Kohri Park PR**D92** (2015) 023529.
Higaki Kitano Sato JHEP **1407**(2014) 044. Fong Minakata Panes Zukanovich-Funchal JHEP **1502** (2015) 189
Murase Laha Ando Ahlers Phys.Rev.Lett. **115** (2015) 7, 071301
Berezhiani talk at NOW 2014, 1506.09040.

and more

NASA:Chandra X-ray observatory



χDM

decays to ν

makes a peak
@E_ν~PeV

M_χ~PeV

NP@source

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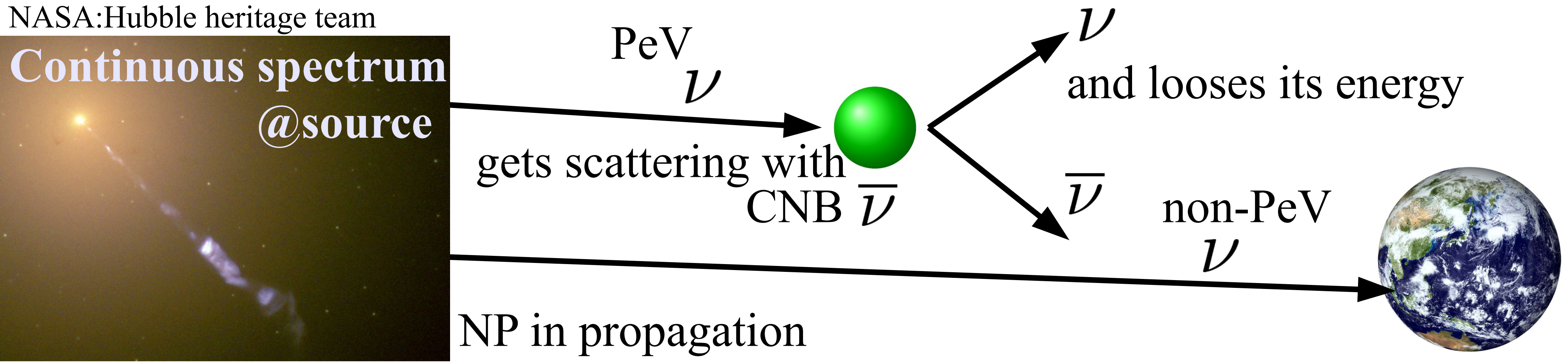
and more

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
Lmu-Ltau model: Kamada Yu Phys.Rev. **D92** (2015) 113004, DiFranzo Hooper Phys.Rev. **D92** (2015) 095007
Sterile Nu: Shoemaker Murase 1512.07228

NASA:Hubble heritage team



Continuous spectrum
@source

PeV ν

gets scattering with
CNB $\bar{\nu}$

ν
and looses its energy

$\bar{\nu}$

non-PeV
ν

NP in propagation

■If the Gap is explained by New Physics…

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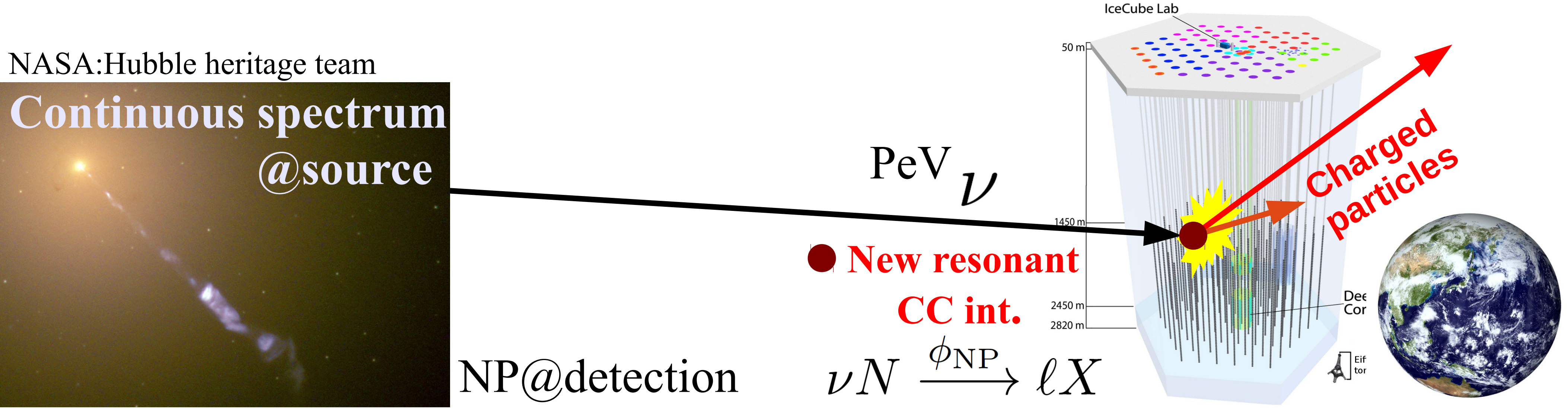
Sterile Nu: Shoemaker Murase 1512.07228

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

Barger Keung PL**B727** (2013) 190…

NASA:Hubble heritage team



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

■ FermiLAT and IceCube may see the common source

Hadronuclear (pp) source $pp \rightarrow \pi^{\pm} \rightarrow \nu$ IceCube PeV neutrino

*typically, Galaxy clusters containing AGN $\rightarrow \pi^{0} \rightarrow \gamma$ FermiLAT GeV gamma

Multi-messenger approach

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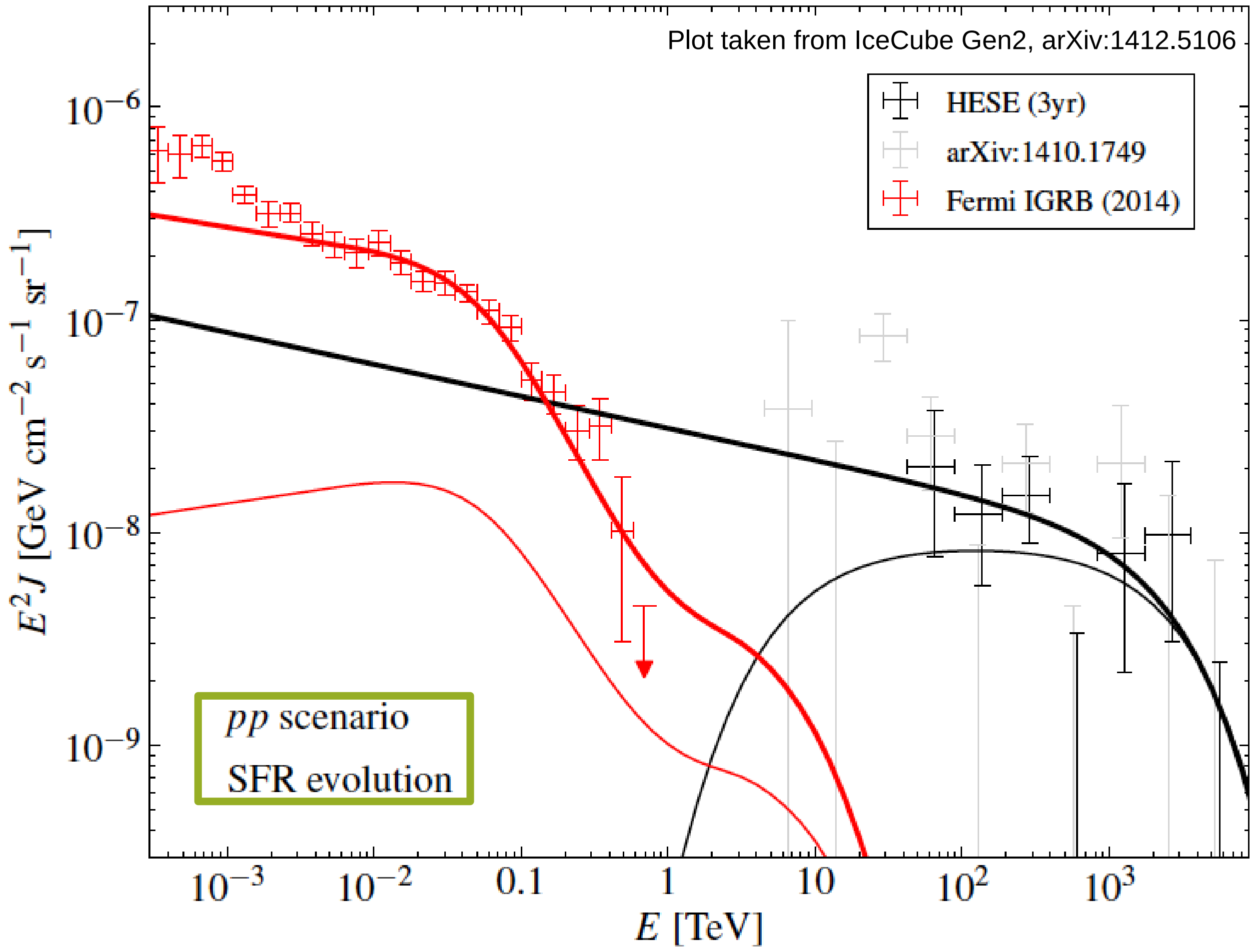
Diffuse fluxes of Gamma and Nu from common sources

K. Murase, arXiv:1410.3680

K. Murase, M. Ahlers, and B. C. Lacki, Phys.Rev. **D88**, 121301 (2013)



Plot taken from IceCube Gen2, arXiv:1412.5106

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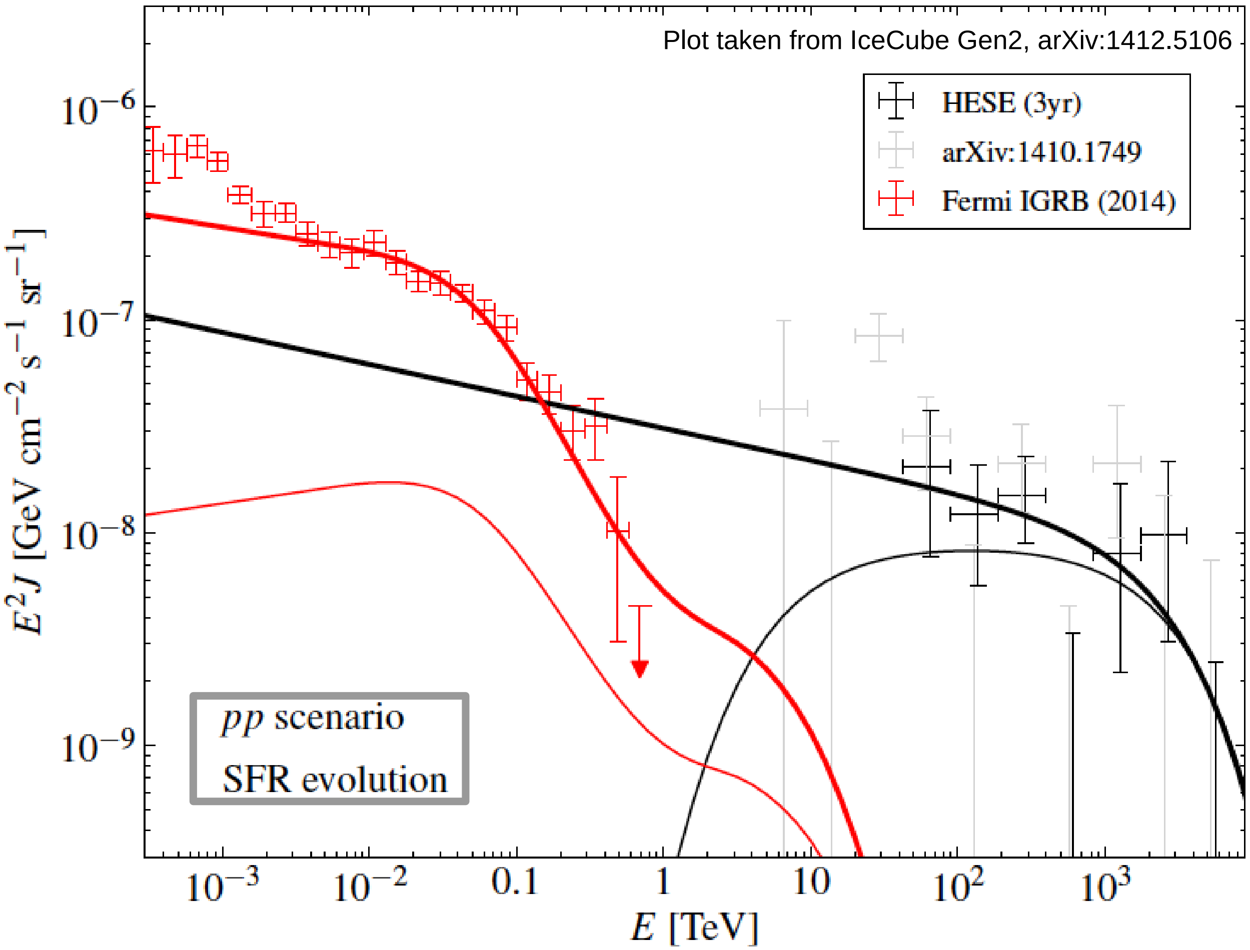
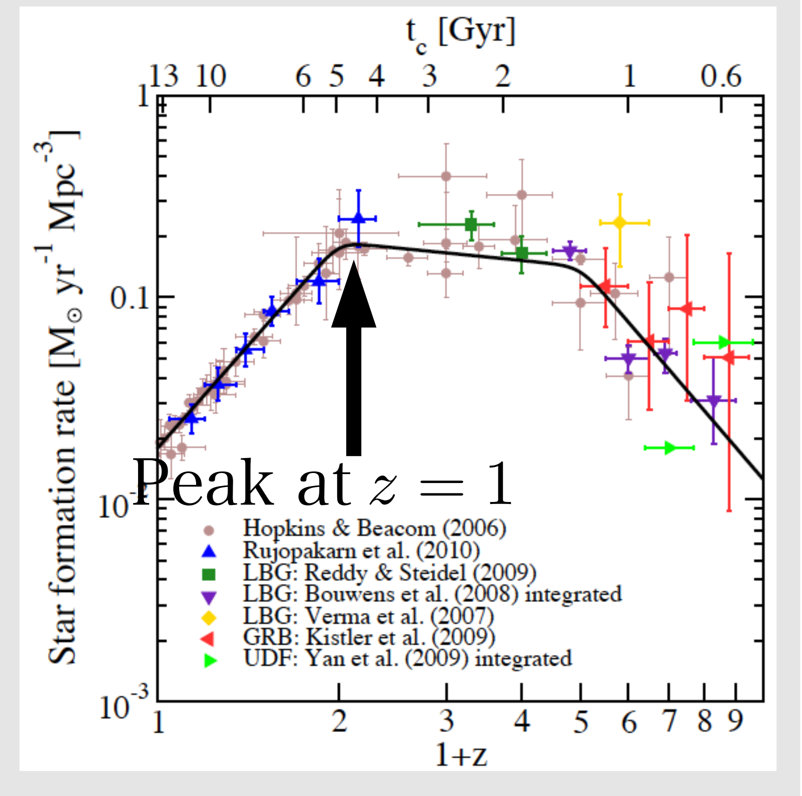


taken from Horiuchi Beacom
Astrophys. J. **723** (2010) 329-341

Star Formation Rate



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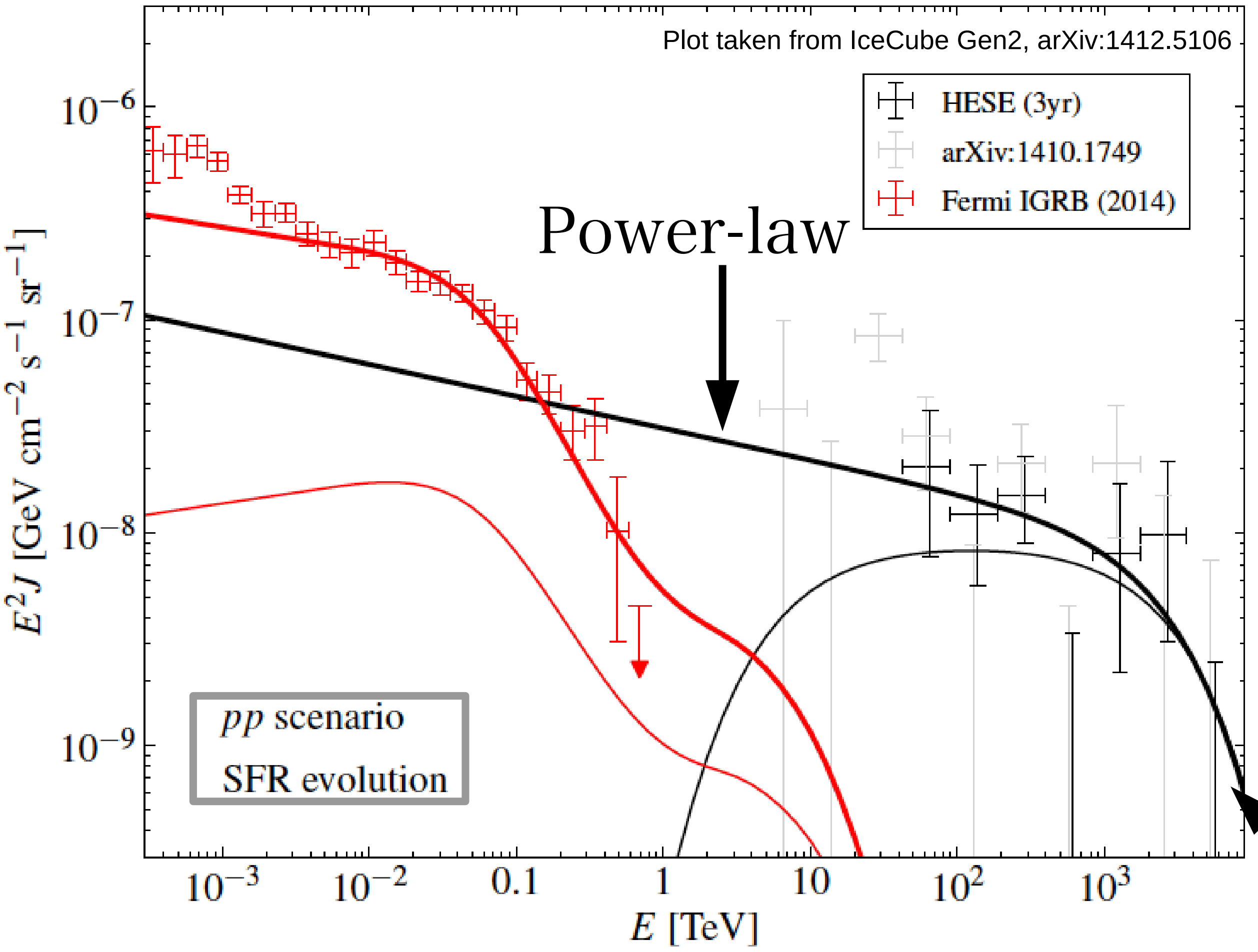

Plot taken from IceCube Gen2, arXiv:1412.5106

Power-law

Cut-off

taken from Horiuchi Beacom
Astrophys. J. **723** (2010) 329-341

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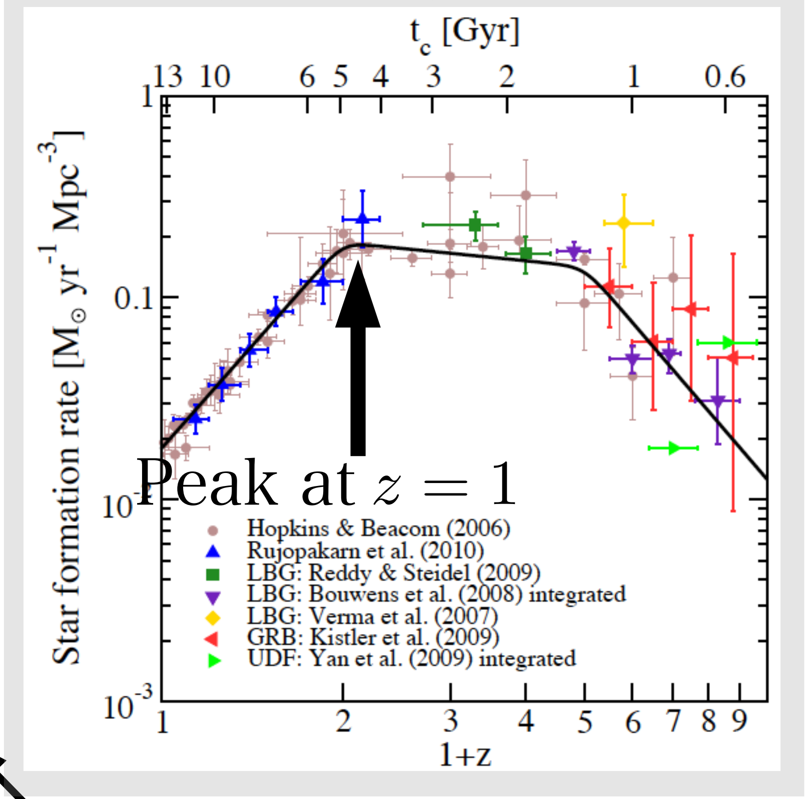

Peak at $z = 1$

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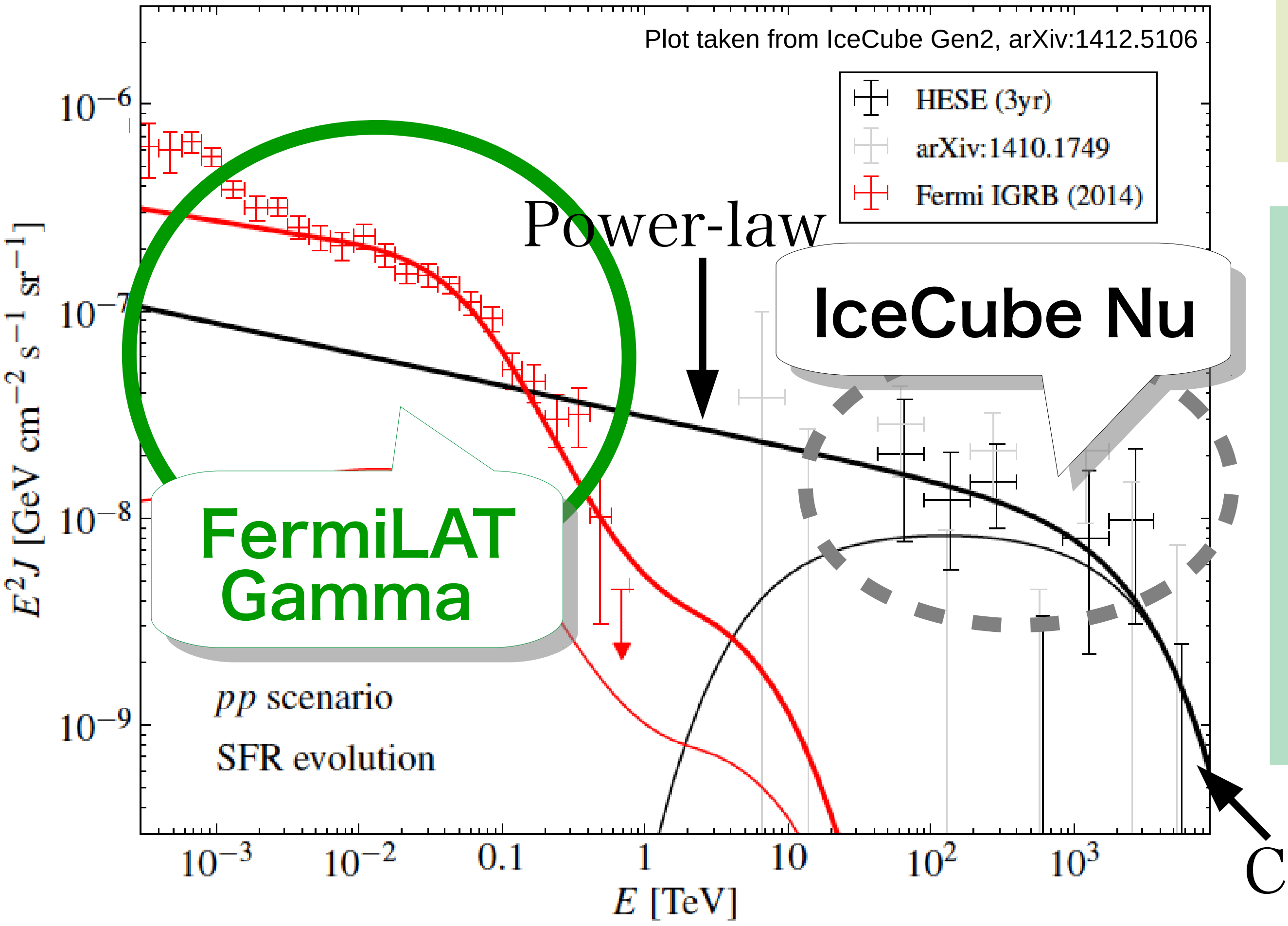
*typically, Galaxy clusters containing AGN $\to \pi^{0} \to \gamma$ FermiLAT GeV gamma

Diffuse fluxes of Gamma and Nu from common sources

K. Murase, arXiv:1410.3680

K. Murase, M. Ahlers, and B. C. Lacki, Phys.Rev. **D88**, 121301 (2013)


Plot taken from IceCube Gen2, arXiv:1412.5106

Cut-off

We are led by these impressive agreements

Benchmark flux

Diffuse flux of pp sources

SFR for z-dependence
of the sources

Power-law + cut-off
spectral index~2.1-2.2

■Back-of-the-envelope estimation for the Gap

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

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

cf. Ng-Beacom, Ioka-Murase, Ibe-Kaneta, ...

Early works on secret neutrino interactions

Bardin Bilenky Pontecorvo, Pakvasa, Kolb Turner, ⋯

Early works on resonant scattering with CNB

Z-burst: Weiler, Phys. Rev. Lett. **49**, 234 (1982), Astrophys. J. 285, **495** (1984).
Roulet, Phys. Rev. **D47**, 5247 (1993).
Yoshida, Astropart. Phys. **2**, 187 (1994).
Yoshida, Dai, Jui, Sommers, Astrophys. J. **479**, 547 (1997).
Weiler, Astropart. Phys. **11**, 303 (1999).
Sigl, Lee, Bhattacharjee, Yoshida, Phys. Rev. **D59**, 043504 (1999).
Fodor, Katz, Ringwald, Phys. Rev. Lett. **88**, 171101 (2002), JHEP **06**, 046.
Kalashev, Kuzmin, Semikoz, Sigl, Phys. Rev. **D66**, 063004 (2002).
Eberle, Ringwald, Song, Weiler, Phys. Rev. **D70**, 023007 (2004).
Barenboim, Mena Requejo, Quigg, Phys. Rev. **D71**, 083002 (2005).

mini-Z-burst: Kolb Turner, Phys. Rev. **D36**, 2895 (1987).
Keranen, Phys.Lett. **B417**, 320 (1998).
Goldberg, Perez, Sarcevic, JHEP **0611**, 023 (2006).
Baker, Goldberg, Perez, Sarcevic, Phys. Rev. **D76**, 063004 (2007).
Hooper, Phys. Rev. **D75**, 123001 (2007).

and more and more...

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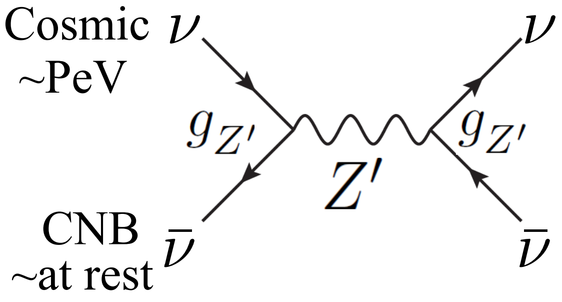
- **Resonance condition**



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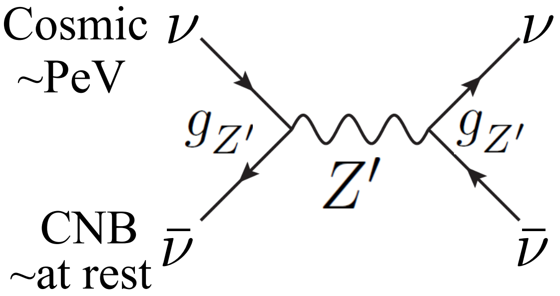

Why CNB? → $n_{\mathsf{CNB}} \gg n_{\mathsf{Baryon}}$

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

Saitama University 埼玉大学

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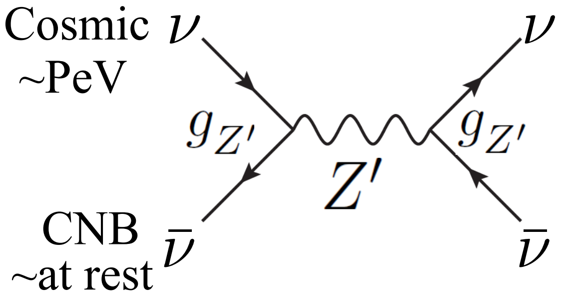

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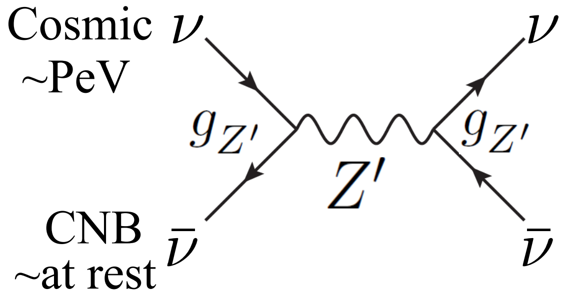
NP @MeV scale



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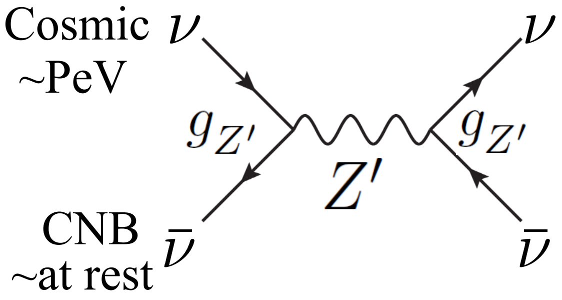

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- **How far can cosmic neutrinos travel in CNB?** → Mean free path λ

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

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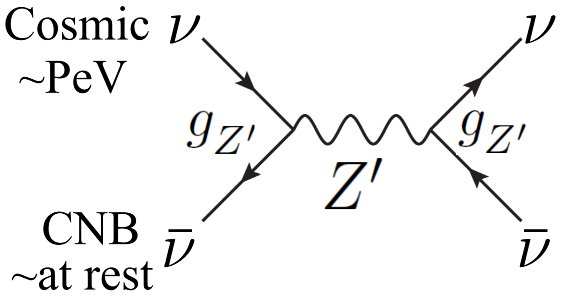

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From extra galactic source

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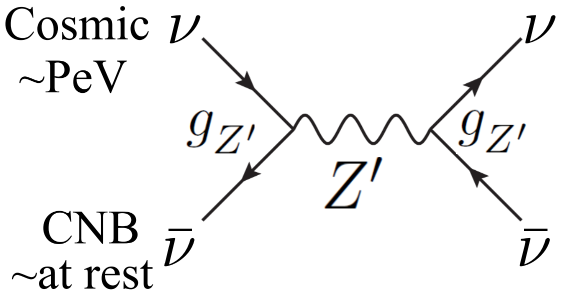

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From extra galactic source

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

IceCube Gap requires

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

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

A benchmark model for the Gap

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

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

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Model

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

New neutrino int.

Constrained! but...

Contribute to muon *g-2*

We discuss it in **Sec.**②

Coupling in mass eigenbasis

$$g_{ij} = g_{Z'}(U^\dagger_{\text{PMNS}})_{i\alpha}\mathsf{diag}(0,1,-1)_{\alpha\beta}(U_{\text{PMNS}})_{\beta j}$$

* 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 e.g., Petcov Rodejohann Phys.Rev.**D71** (2005) 073002, Choubey Rodejohann Eur.Phys.J **C40** (2005) 259...
- Phenomenologies... Heeck Rodejohann (2010), Crivellin D'Anbrosio Heeck (2015) etc...

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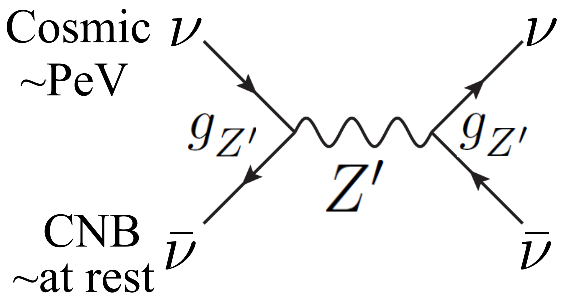
Model parameters

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

■ From the model to the 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

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

~MeV

For significant scattering effect

From the model to the Gap

Cross-section of the neutrino scattering proc.

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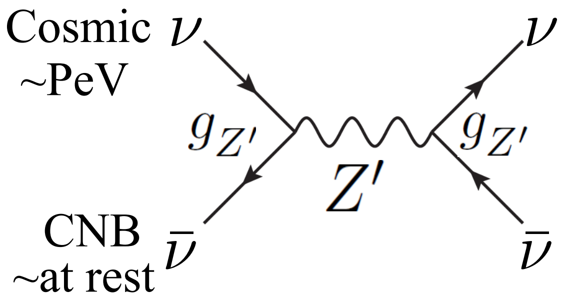

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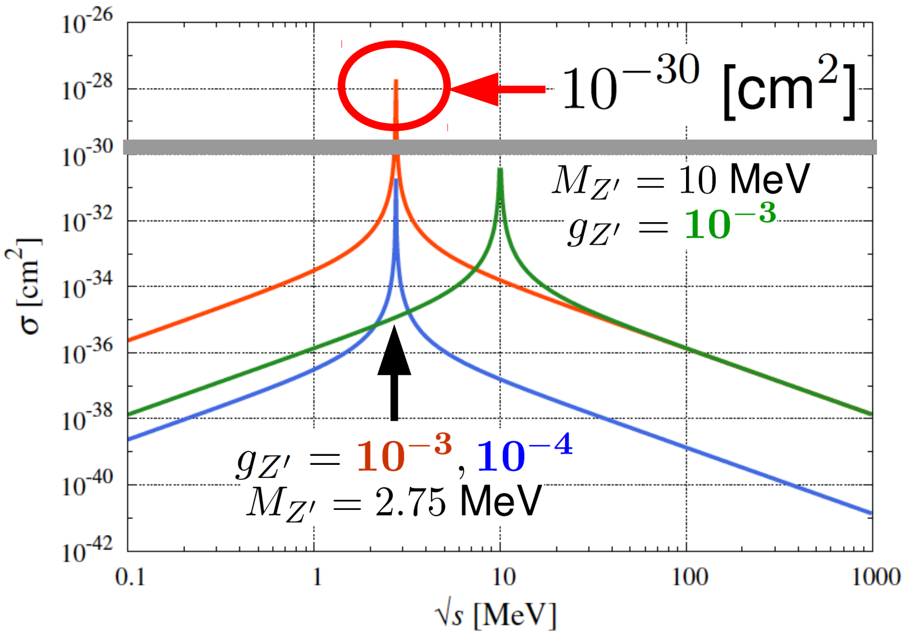
$g_{Z'} \simeq$ several $\times 10^{-4}$



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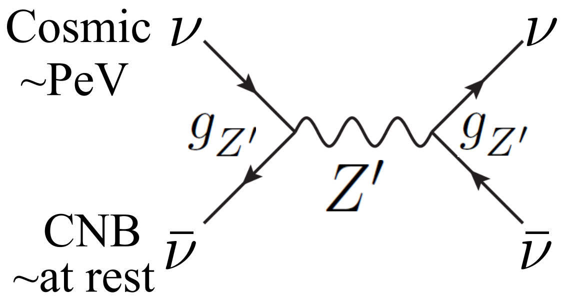

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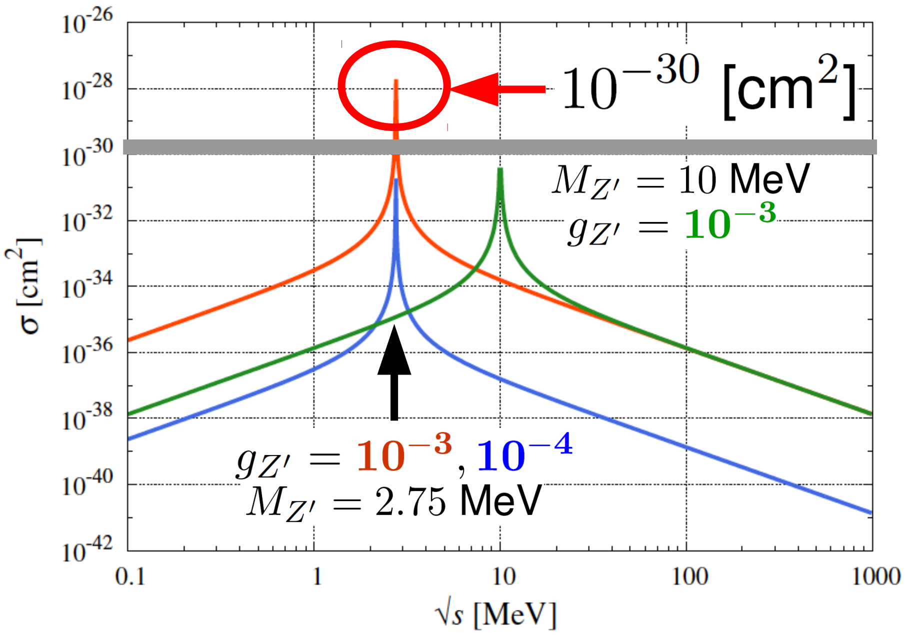

IceCube Gap requires

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

- The width might be **too narrow** for the **IceCube Gap** **(0.4-1PeV)**.
- We can ask the help to the sources of cosmic neutrinos → Sec. ③

Before going to numerics, let's check muon g-2...

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 neutrino trident and neutrino-electron scattering

3 A solution to the gaps

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

■ Muon g-2 in gauged leptonic force

■ Gauged leptonic force

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■ New contribution to muon g-2

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

$$\Delta a_\mu^{Z'} = \frac{g_{Z'}^2}{12\pi^2}\frac{m_\mu^2}{M_{Z'}^2} \qquad M_{Z'} \gg m_\mu$$

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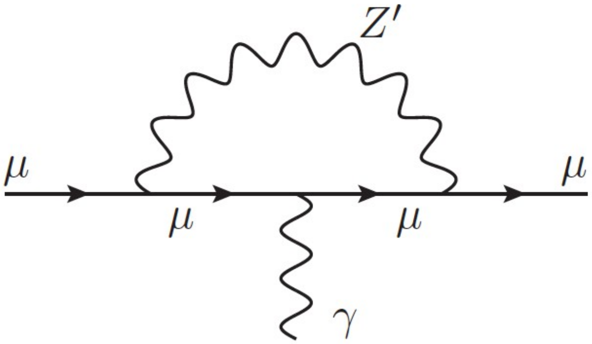

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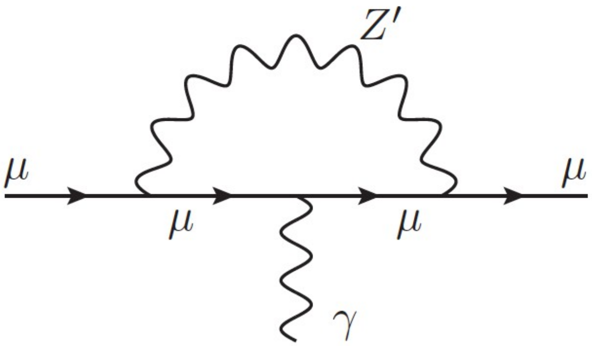

■ Gap in muon g-2

$$a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}} = (26.1 \pm 8.0) \cdot 10^{-10}$$

■ To fill the gap, we need

$$\Delta a_\mu^{Z'} \simeq 20\text{-}30 \cdot 10^{-10}$$

which corresponds to...

Muon g-2 in gauged leptonic force

Gauged leptonic force

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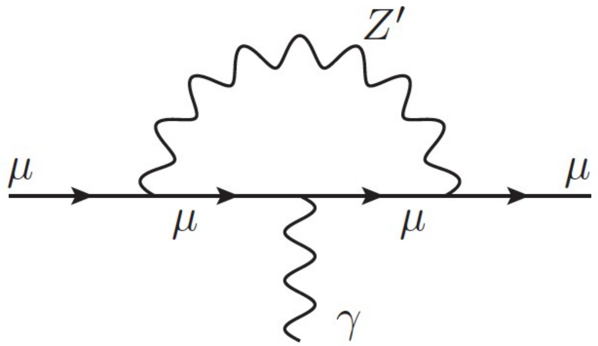
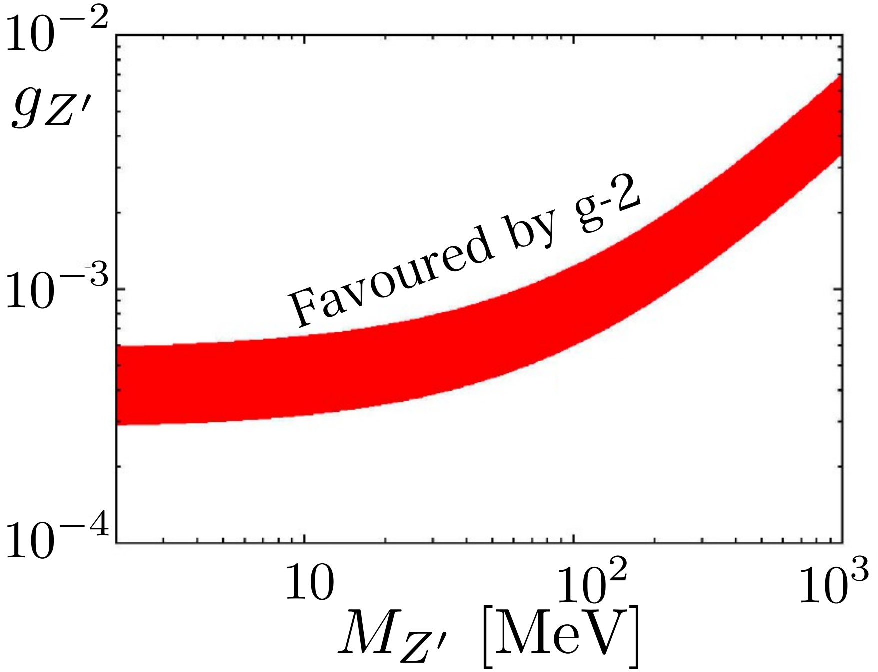




Gap in muon g-2

$$a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}} = (26.1 \pm 8.0)\cdot 10^{-10}$$

To fill the gap, we need

$$\Delta a_\mu^{Z'} \simeq 20\text{-}30\cdot 10^{-10}$$

which corresponds to...

Muon g-2 in gauged leptonic force

Gauged leptonic force

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

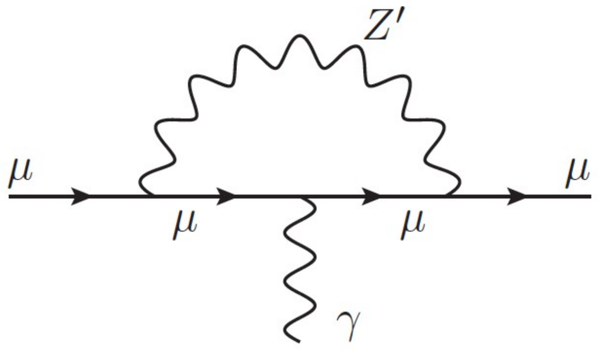
contributes to muon g-2

New contribution to muon g-2

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

$$\Delta a_\mu^{Z'} = \frac{g_{Z'}^2}{12\pi^2}\frac{m_\mu^2}{M_{Z'}^2} \qquad M_{Z'} \gg m_\mu$$

$$\Delta a_\mu^{Z'} = \frac{g_{Z'}^2}{8\pi^2} \qquad M_{Z'} \ll m_\mu$$



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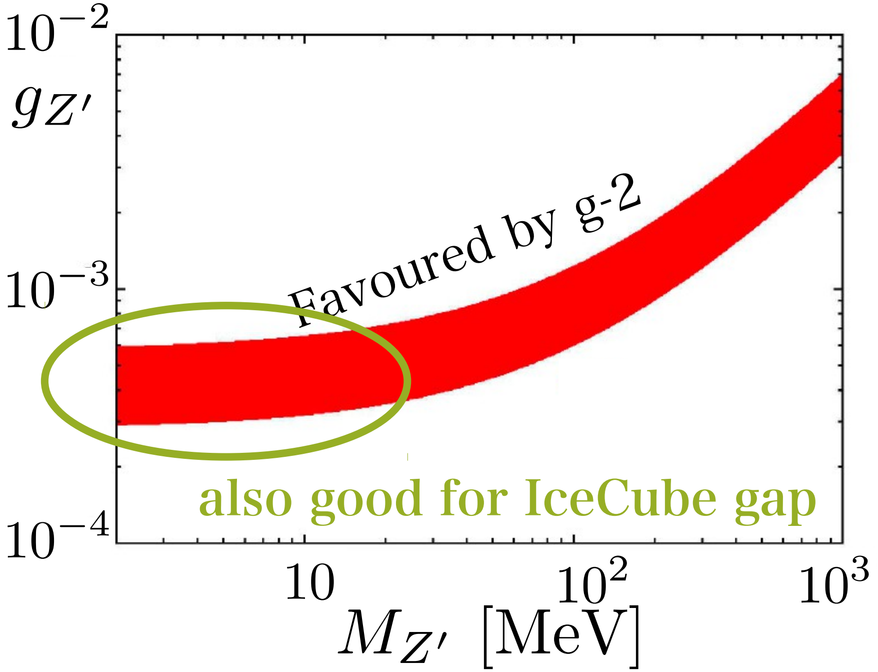


■ Lab bounds to MeV leptonic force

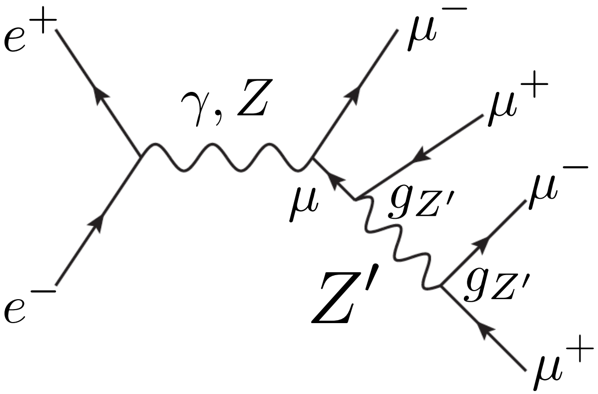
■ Colliders

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

$$e^+e^- \rightarrow 4\mu$$

$$PP(P\bar{P}) \rightarrow 4\mu, 2\mu 2\tau$$

$$g_{Z'} \lesssim 0.1 \text{ at } M_{Z'} \gtrsim \mathcal{O}(10) \text{ GeV}$$



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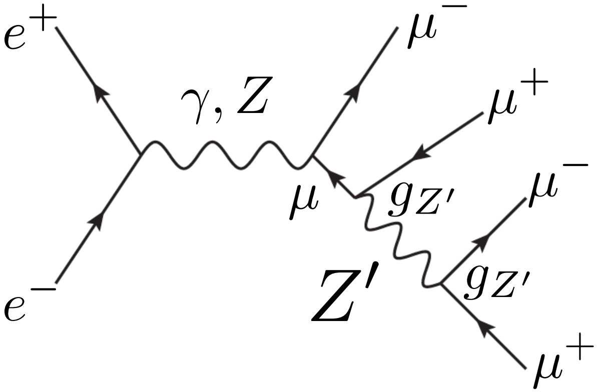

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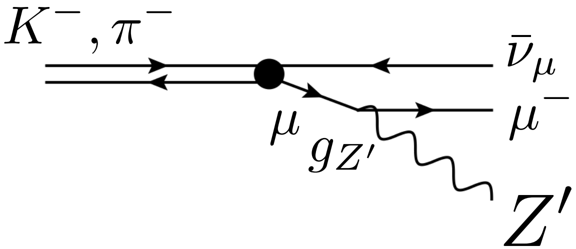
■ Rare meson decays

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



$$K^-, \pi^- \to \mu^- \bar{\nu}_\mu Z'$$

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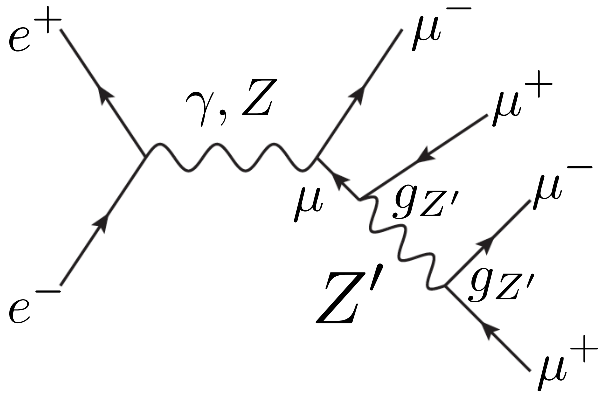

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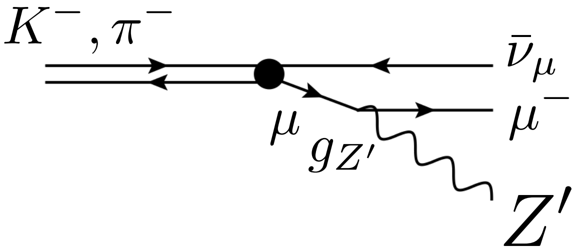
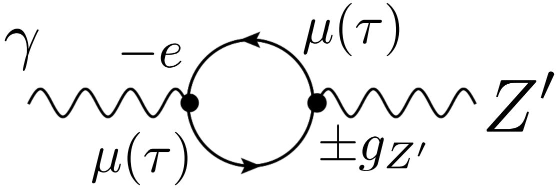


Photon-Z' mixing

Holdom PLB166 (1986) 196.

Kinetic mixing

$$\epsilon_{\gamma Z'} = \frac{8}{3}\frac{e g_{Z'}}{(4\pi)^2} \ln\frac{m_\tau}{m_\mu} = 7 \cdot 10^{-6} \left[\frac{g_{Z'}}{5 \cdot 10^{-4}}\right]$$



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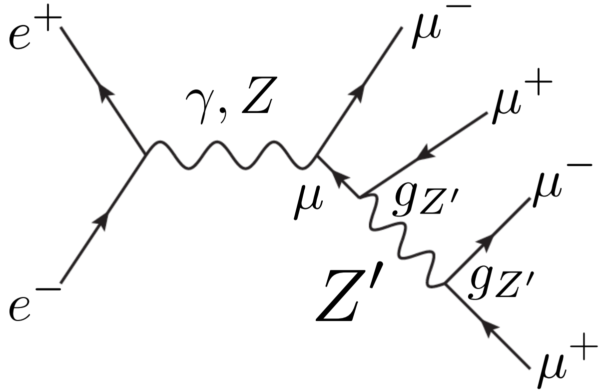

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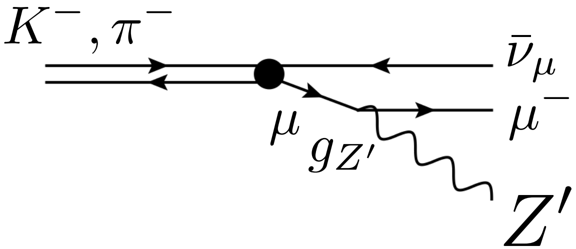

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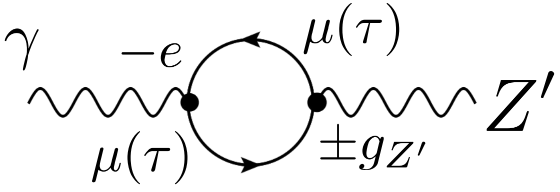


Most relevant constraints are

Trident and **Neutrino-electron scattering through the kinetic mixing**

*For bounds from cosmology (BBN, CMB, SN1987A), cf. Refs. in Ng-Beacom and Kamada-Yu.

■ Lab bounds to MeV leptonic force

■ Neutrino trident process

Altmannshofer et al., PRL 113 (2014) 091801

in neutrino-nucleon scattering events

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

  37 events (±12.4)

  CCFR collaboration, PRL **66** (1991) 3117

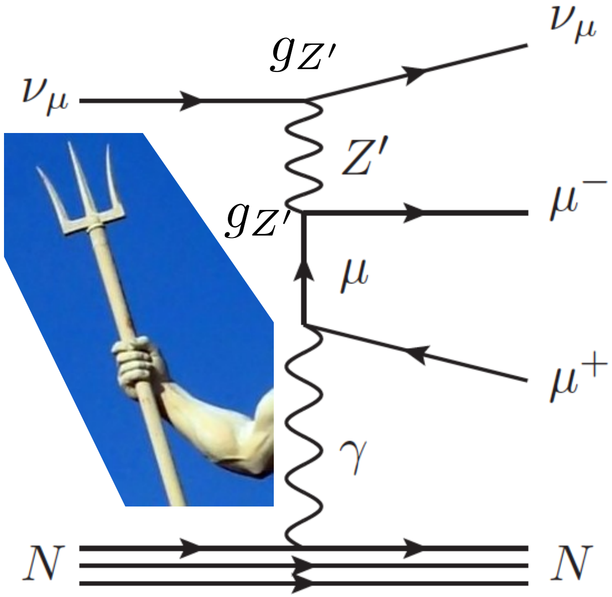
  excavated recently

  (only cited ~15 times before 2014)

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

  45.3 events (±2.3)

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



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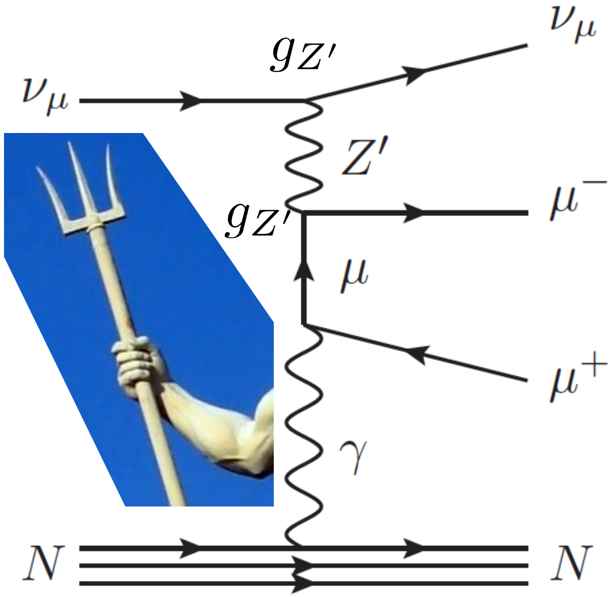

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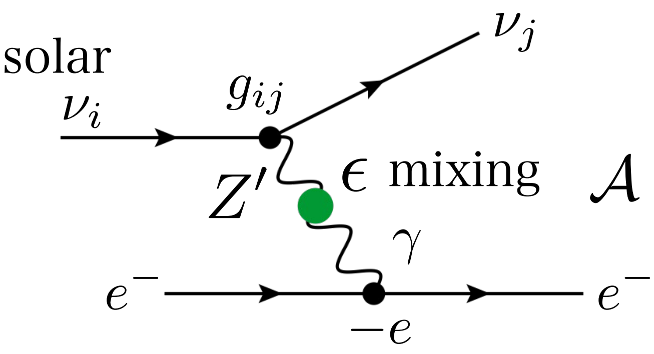
Neutrino-electron scattering

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

at the Borexino detector



$$\mathcal{A} \propto \frac{\epsilon e g_{Z'}}{q^2 - M_{Z'}^2}$$

Observation of solar nu is
consistent with SM and SSM→ constrains $g_{Z'}$ and $M_{Z'}$

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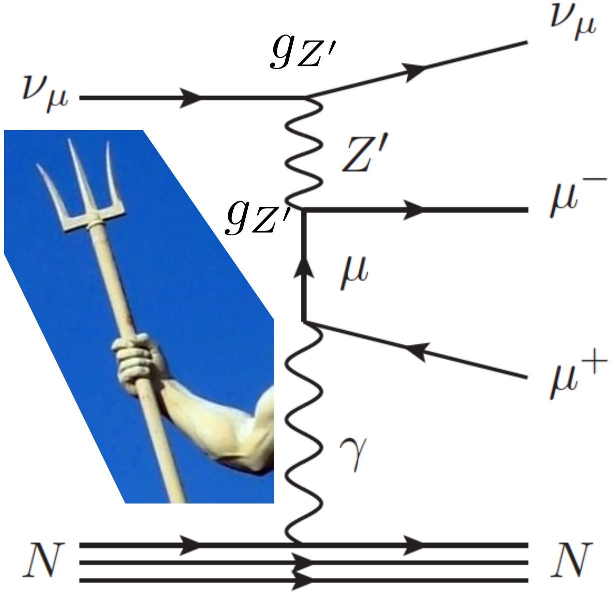

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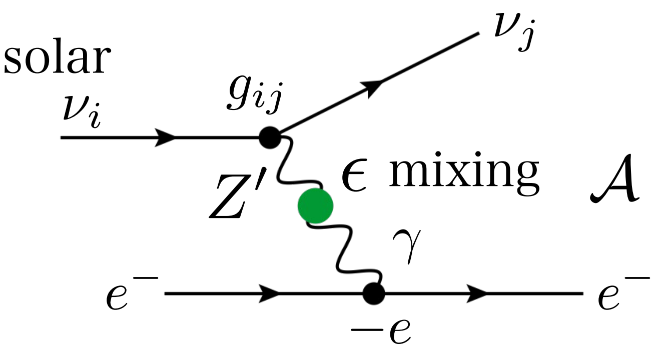

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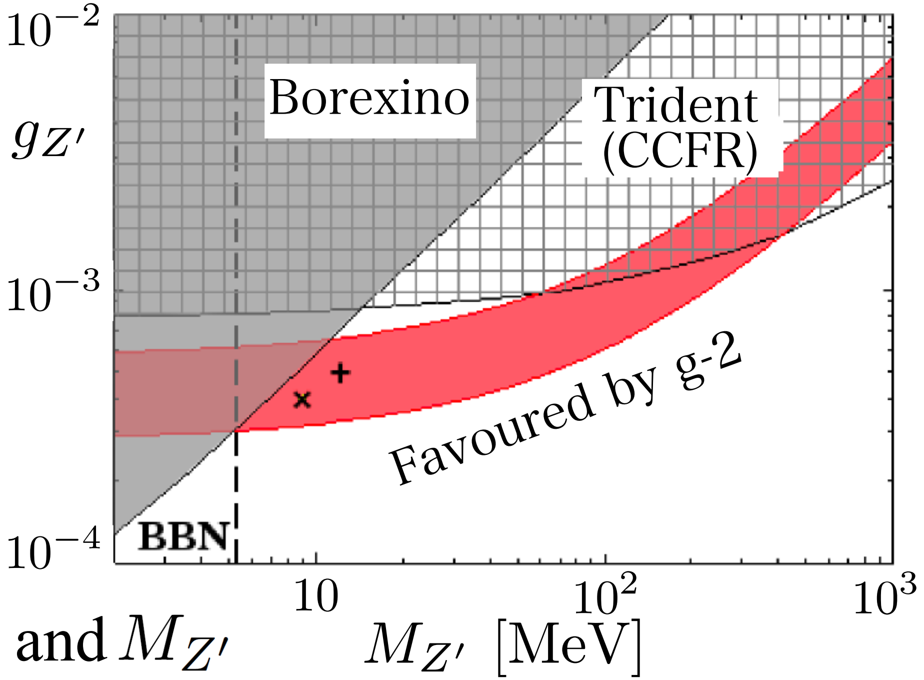

Observation of solar nu is consistent with SM and SSM→ constrains $g_{Z'}$ and $M_{Z'}$

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 neutrino trident and neutrino-electron scattering

3 A solution to the gaps

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

■ Evolution eq. of neutrino density

■ Number density is evolved with

e.g., Ng Beacom PR**D90** (2014) 065035, Ioka Murase PTEP **6** (2014) 061E01

1.Redshift 2.Source 3.Scattering

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

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

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4.Regeneration

(and same for anti-neutrino)

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(and same for anti-neutrino)

1. Energy loss due to Redshift

$$b = H(z) E_{\nu_i}$$

*Relation between “distance” and “redshift”

$$\frac{\mathrm{d}z}{\mathrm{d}t} = -(1+z)H(z)$$

Energy of neutrino at z

E_ν

Redshift →

Energy of neutrino, measured at IceCube $(z=0)$

$E_\nu|_{\mathrm{obs.}} = E_\nu/(1+z)$

■ Evolution eq. of neutrino density

■ Number density is evolved with

e.g., Ng Beacom PR**D90** (2014) 065035, Ioka Murase PTEP **6** (2014) 061E01

1.Redshift

2.Source

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

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Explains both FermiLAT Gamma and IceCube Nu

(and same for anti-neutrino)

2. Injection from sources – We adopt the benchmark source

$$\mathcal{L}_{\nu_i}(z, E_{\nu_i}) = \mathcal{W}(z) \mathcal{L}_0(E_{\nu_i})$$

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

■ Flux@source = power law × cut-off

$$\mathcal{L}_0(E_{\nu_i}) = \mathcal{Q}_{\nu_i} E_{\nu_i}^{-s_\nu} \mathrm{e}^{-\frac{E_{\nu_i}}{E_{\mathrm{cut}}}}$$

Normalization

Energy cut-off

■ Star Formation Rate for z-distribution of the sources

Spectral index (~2.1-2.2)

Evolution eq. of neutrino density

Number density is evolved with

e.g., Ng Beacom PR**D90** (2014) 065035, Ioka Murase PTEP **6** (2014) 061E01

1.Redshift 2.Source **3.Scattering**

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

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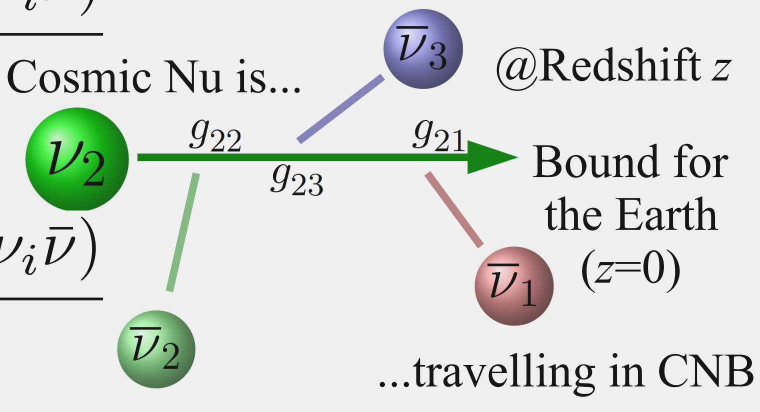
3 chances for scattering



(and same for anti-neutrino)

3. Scattering – kicks out the neutrinos with $E_{\nu_i} = E_{\mathrm{res}} = M_{Z'}^2/(2m_{\nu_j})$

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

$$s = 2m_{\nu_j} E_{\nu_i}$$

Evolution eq. of neutrino density

Number density is evolved with

e.g., Ng Beacom PR**D90** (2014) 065035, Ioka Murase PTEP **6** (2014) 061E01

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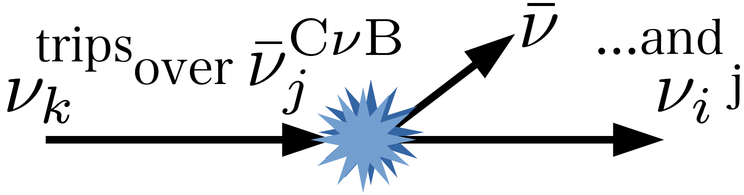
4.Regeneration

(and same for anti-neutrino)

4. Regeneration (=Injection after scattering)

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



ν_k trips over $\bar{\nu}_j^{\mathrm{C}\nu\mathrm{B}}$ $\bar{\nu}$ ...and ν_i joins in $\tilde{n}_{\nu_i}$

$E_{\nu_k} > E_{\nu_i}$

$s = 2 m_{\nu_j} E_{\nu_k}$

Evolution eq. of neutrino density

Number density is evolved with

e.g., Ng Beacom PR**D90** (2014) 065035, Ioka Murase PTEP **6** (2014) 061E01

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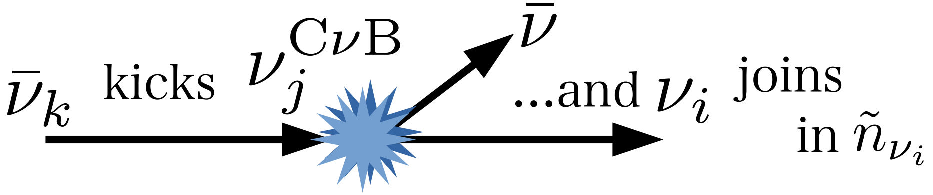
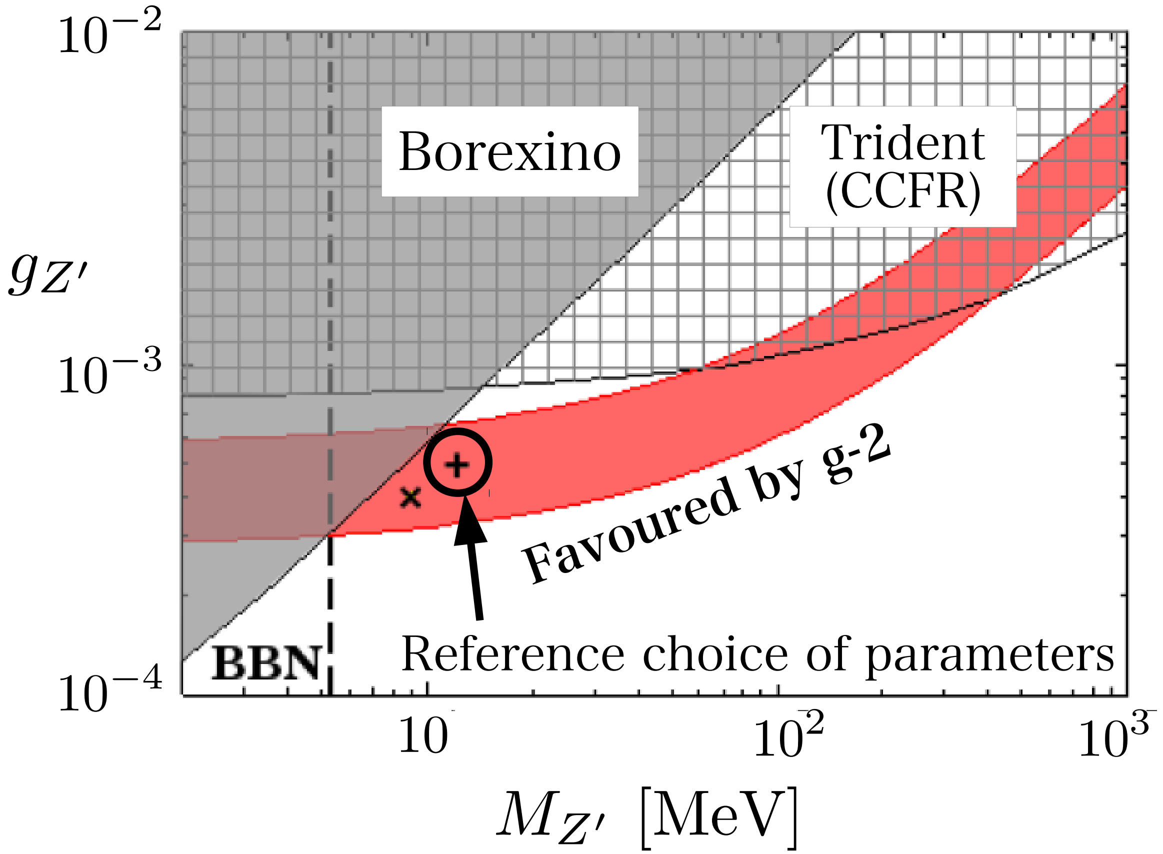


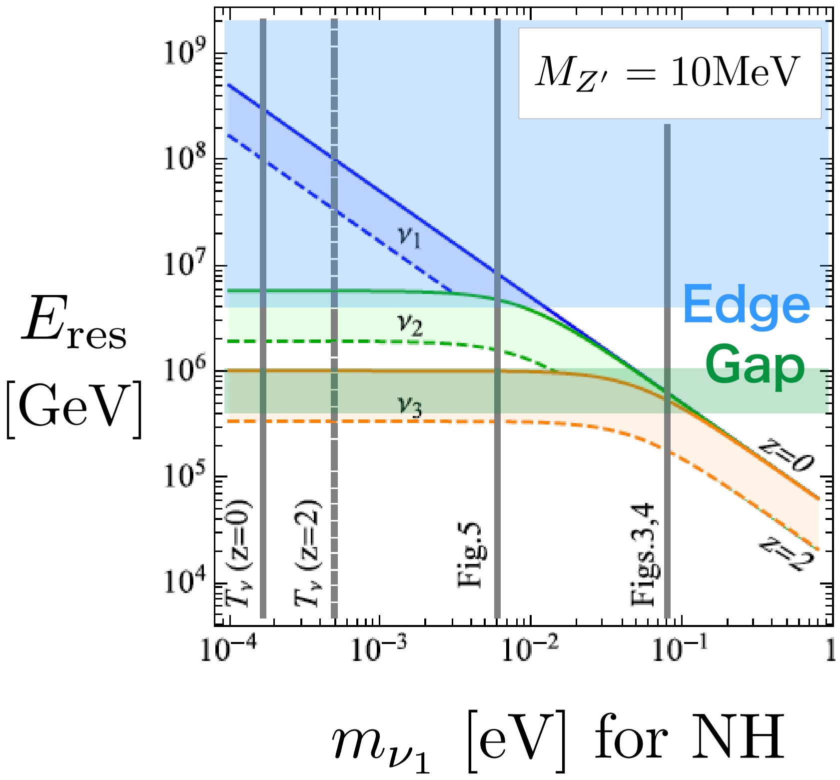
$$s = 2 m_{\nu_j} E_{\bar{\nu}_k}$$

Reference choice of parameters

To address both the Gaps...



3 chances for scattering



Parameter choice

g-2 requires...

$$g_{Z'} \simeq 5 \cdot 10^{-4}$$

$$5 \text{ MeV} \lesssim M_{Z'} \lesssim 100 \text{ MeV}$$

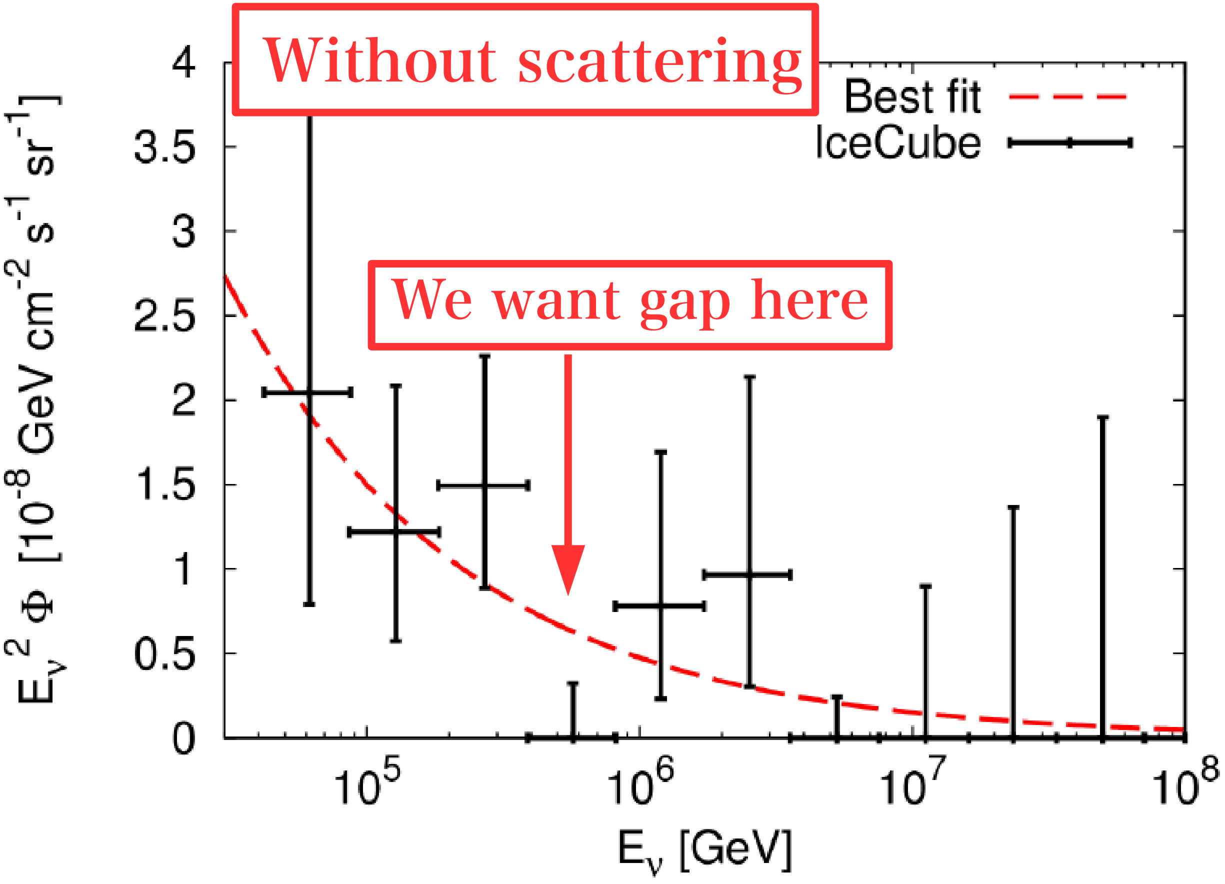
IceCube Gap requires...

large $g_{Z'}$ small $M_{Z'}$ to dig deep

$m_{\nu_1} \lesssim 10^{-1}$ eV @$M_{Z'} \sim 10$ MeV

to set $E_{\rm res} \sim$ PeV

■ Solve the diff. eqs. and derive $\tilde{n}_\nu(E_\nu)$ at $z = 0$



■ **Power-law spectrum**

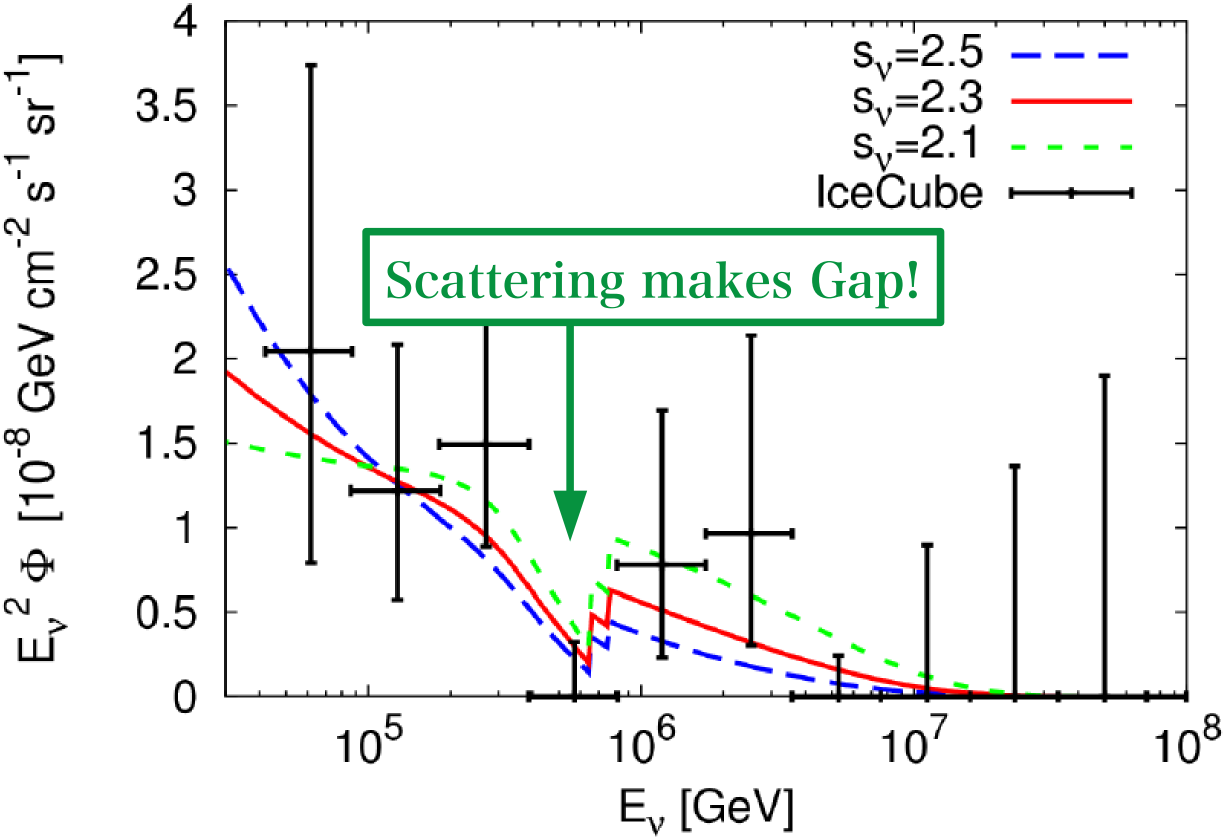
$$\phi_\nu(E_\nu) = \phi_0 \left[\frac{E}{100\ \mathrm{TeV}}\right]^{-s_\nu}$$

■ **Best-fit spectral index without the gap**

$$s_\nu\big|_{\text{best-fit}} = 2.5$$

Numerical results

Solve the diff. eqs. and derive $\tilde{n}_\nu(E_\nu)$ at $z = 0$



Scattering makes Gap!

Model parameters

$$m_{\nu_1} = 0.08 \text{ eV (NH)}$$

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

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

Energy cut-off at

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

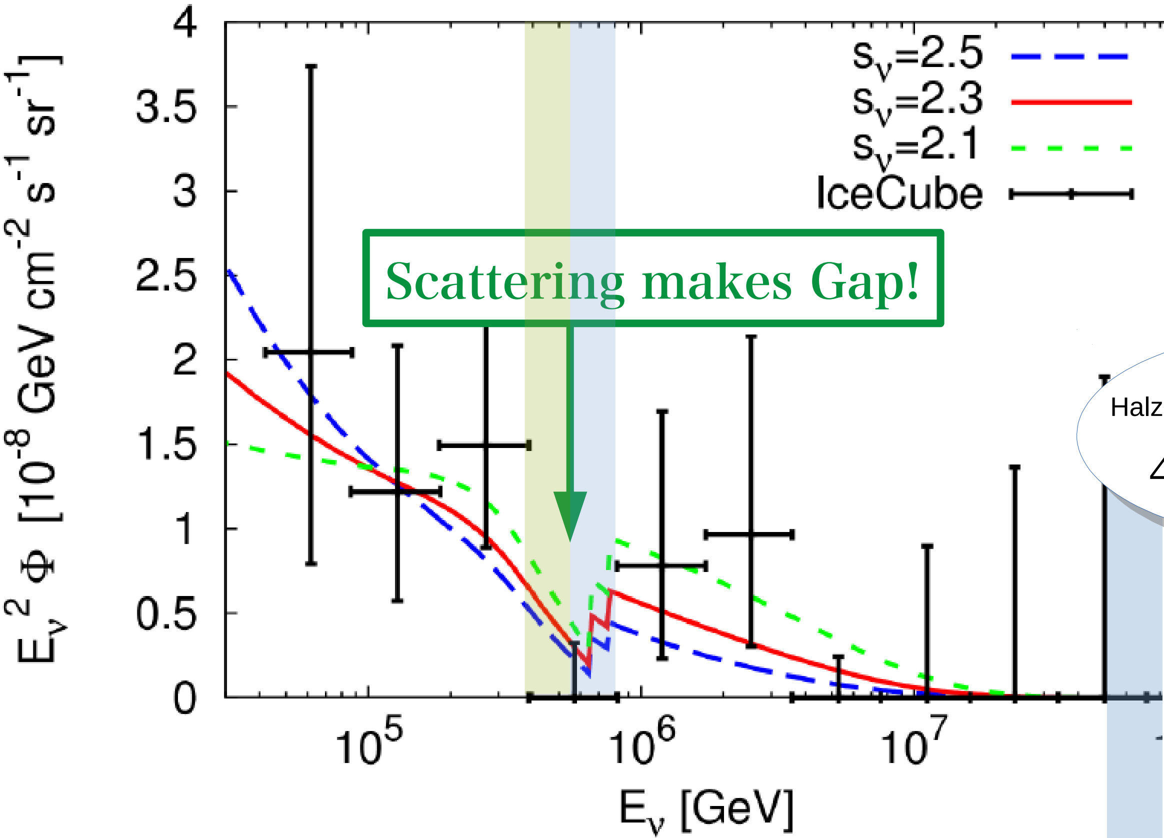
Gap is successfully reproduced

- Contribution to **muon g-2** is $\boxed{a_\mu^{Z'} = 24.2 \cdot 10^{-10}}$
- The width of the gap is, more or less, appropriately reproduced.
- The secret interaction with this size is not enough for "Gap".

Prediction: Not "Gap" but "Dimple"

Numerical results

Solve the diff. eqs. and derive $\tilde{n}_\nu(E_\nu)$ at $z = 0$

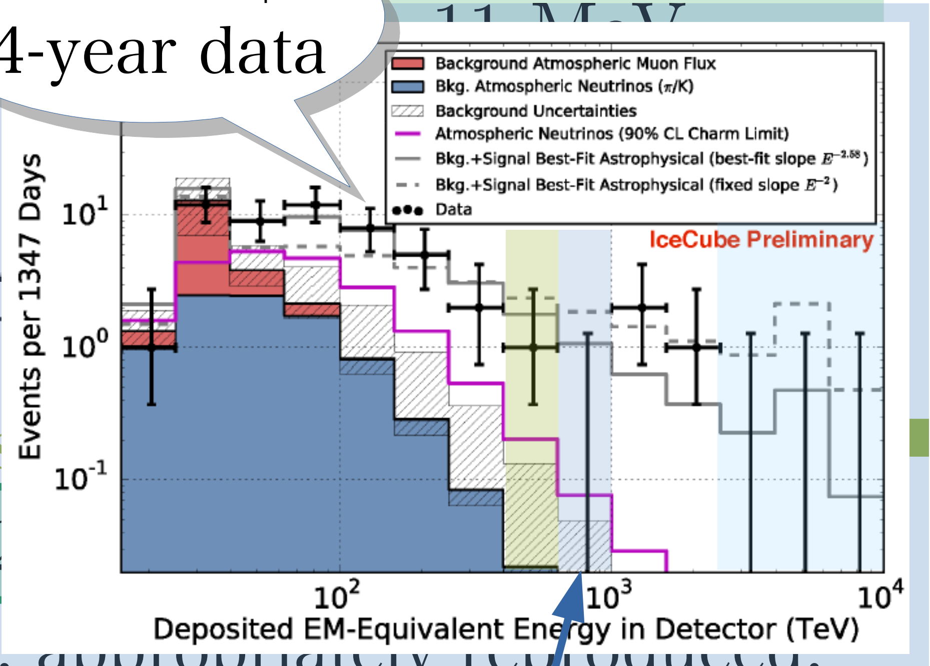


Model parameters

$$m_{\nu_1} = 0.08 \text{ eV (NH)}$$

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

11 MeV



Botner at IPA 2015
Halzen at Neutrino telescope 2015
4-year data

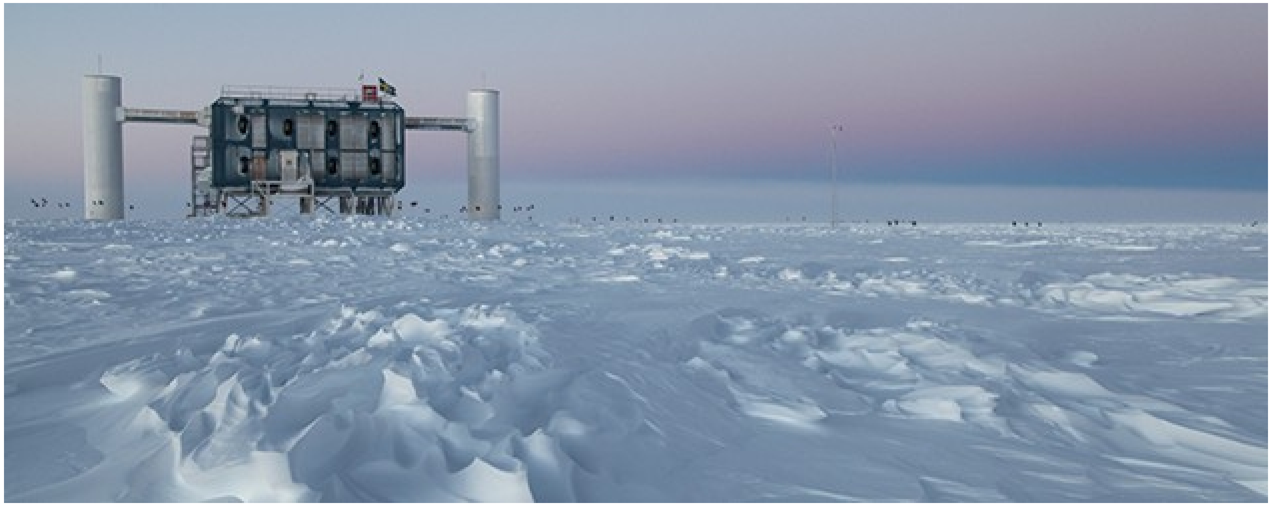
Gap???

Gap is s

- Contribution to muon g-2 is $a_\mu^{Z'} = 2$
- The width of the gap is, more or less, appropriately reproduced.
- The secret interaction with this size is not enough for “Gap”.

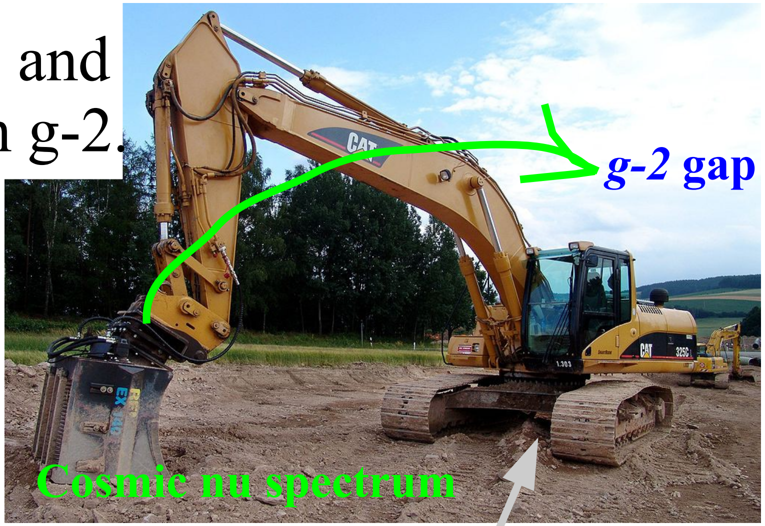
Prediction: Not “Gap” but “Dimple”

Summary



IceCube collaboration

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
"*U(1)* leptonic force Lmu-Ltau"

Reference choice of parameters	Benchmark source
$g_{Z'} = 5 \cdot 10^{-4}$	Diffuse flux from pp souces
$M_{Z'} = 11\ \mathrm{MeV}$	$z \sim \mathrm{SFR}$
$m_{\nu_1} = 0.08\ \mathrm{eV}\ \mathrm{(NH)}$	$s_\nu \sim 2.2$

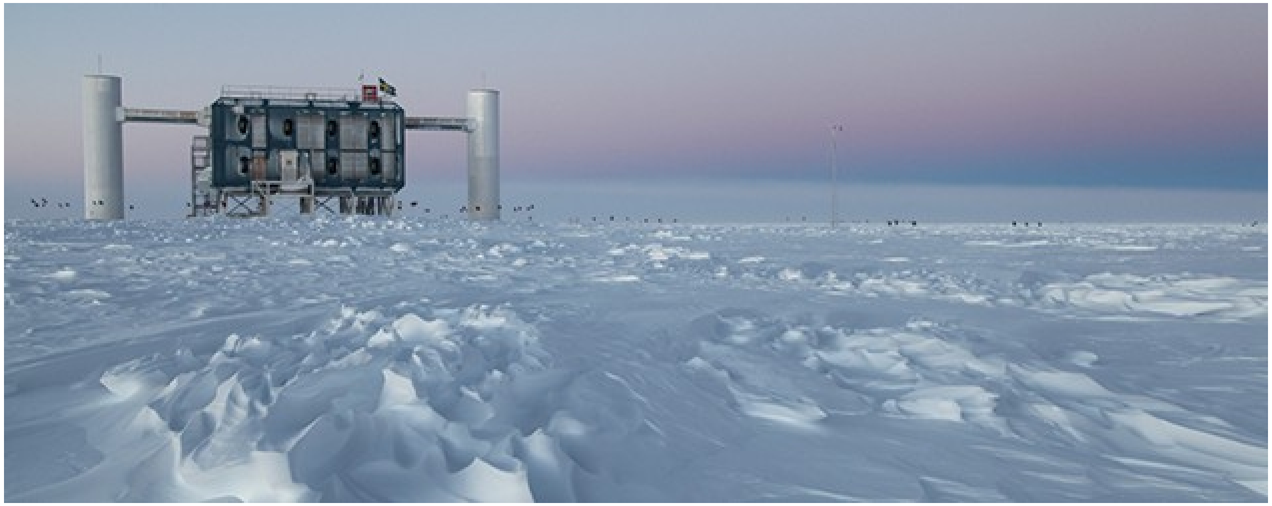
- IceCube Gap (Dimple) is reproduced.
- $a_\mu^{Z'} = 24.2 \cdot 10^{-10}$ g-2 Gap is filled.

■ But there are many "we did not..."

- ...take account of the CNB temperature effect.
  (though it is irrelevant for our choice of parameters).
- ...discuss details of the model.

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

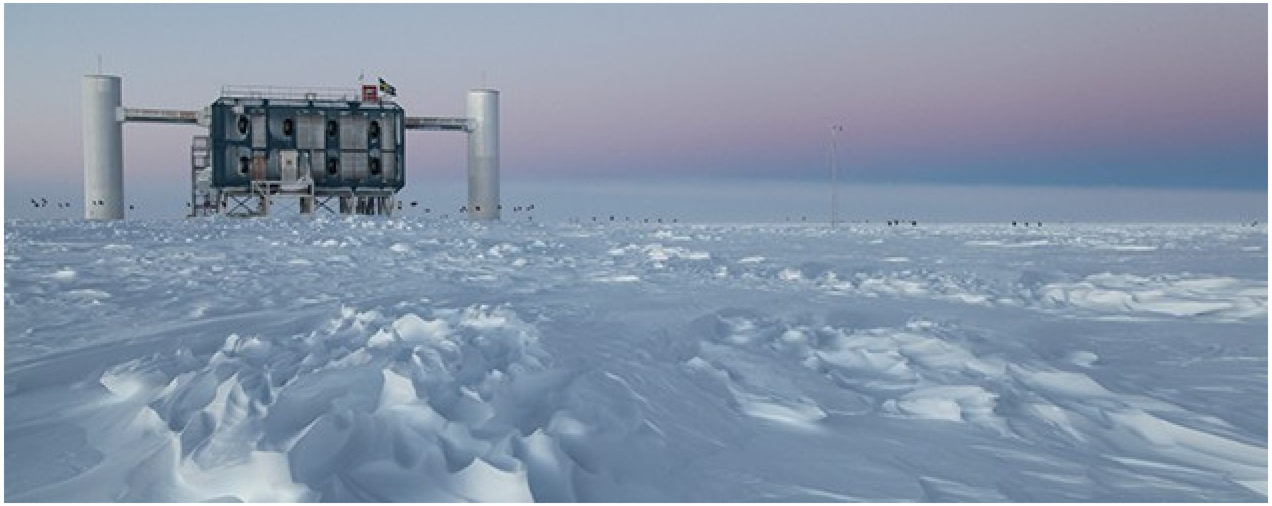
■ IceCube has opened the door to the new era of neutrino astronomy



IceCube collaboration

- IceCube can also be a new probe to new physics in the lepton sector

- IceCube has opened the door to the new era of neutrino astronomy



IceCube collaboration

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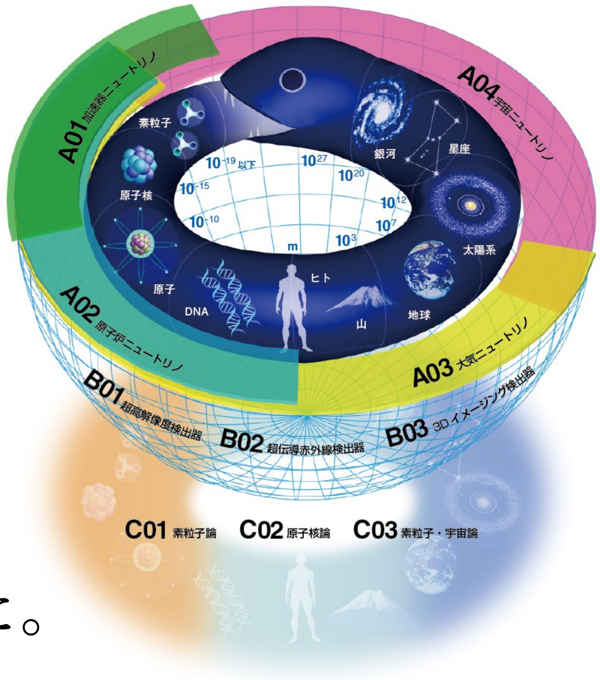
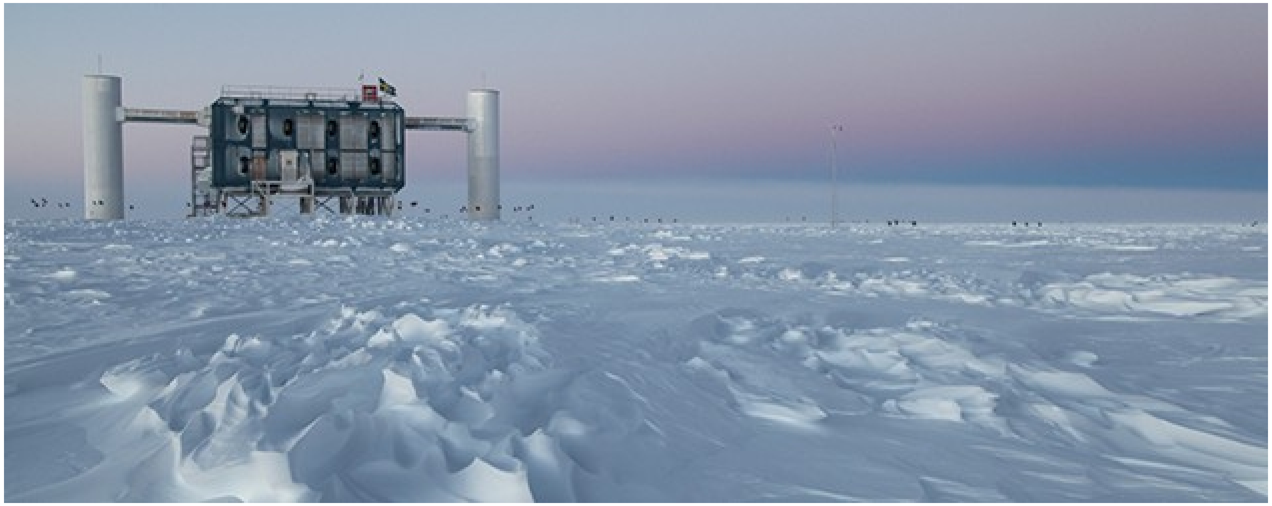
新学術領域
「ニュートリノフロンティアの融合と進化」

科研費
KAKENHI



ご清聴ありがとうございました。

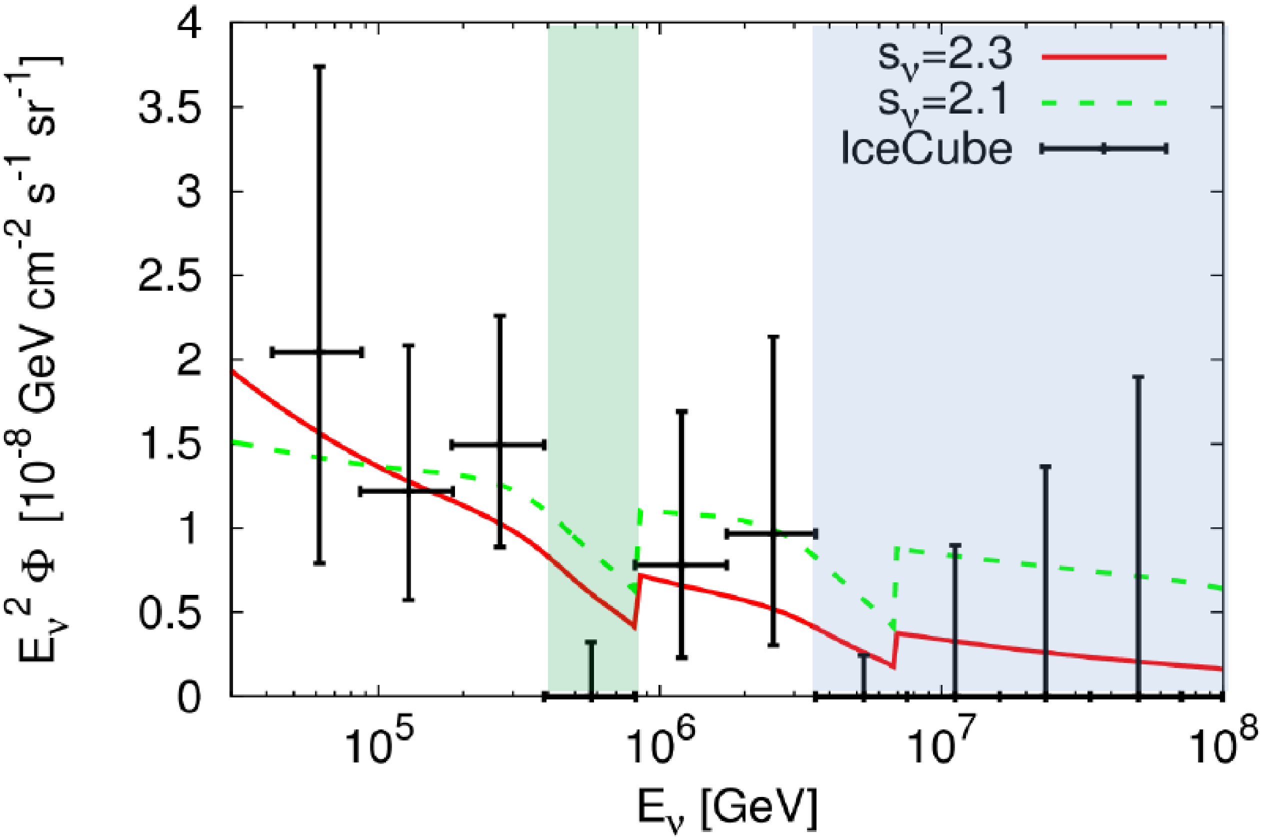
Back up



IceCube collaboration

Another choice of parameters

Gap + Edge



Model parameters

$$m_{\nu_3} = 6\cdot10^{-3}\ \mathrm{eV}\ (\mathrm{IH})$$

$$g_{Z'} = 4\cdot10^{-4}$$

$$M_{Z'} = 9\ \mathrm{MeV}$$

No energy cut-off

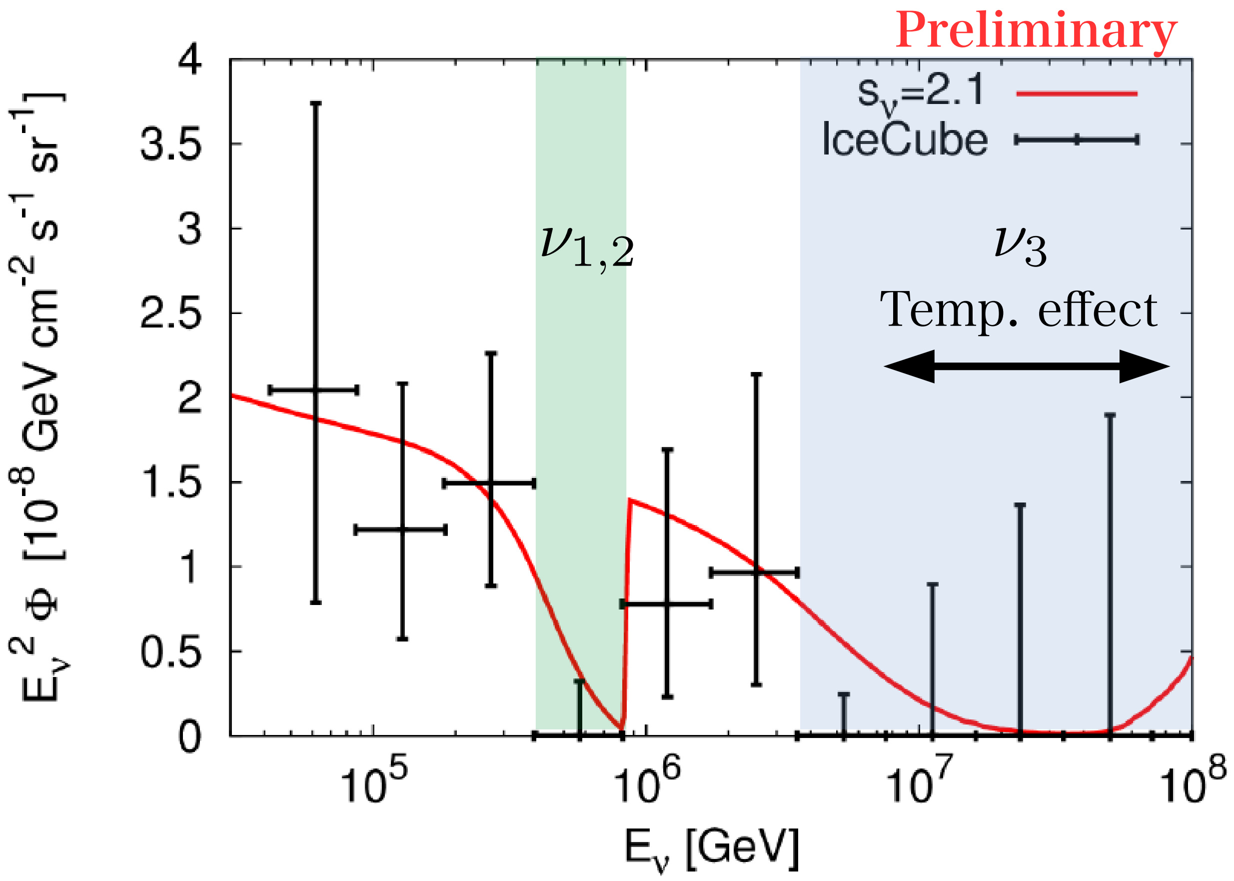
It is hard to reproduce the edge

The CNB temperature effect broaden the edge…

…which was not taken into account in the evolution eq.

■ CNB temperature effect makes the edge

■ Gap + Edge



■ Model parameters

$$m_{\nu_3} = 1 \cdot 10^{-3}\ \text{eV (IH)}$$

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

Excluded by Trident

$$M_{Z'} = 9\ \text{MeV}$$

■ No energy cut-off

CNB temperature effect works…

To have the CNB temperature effect…

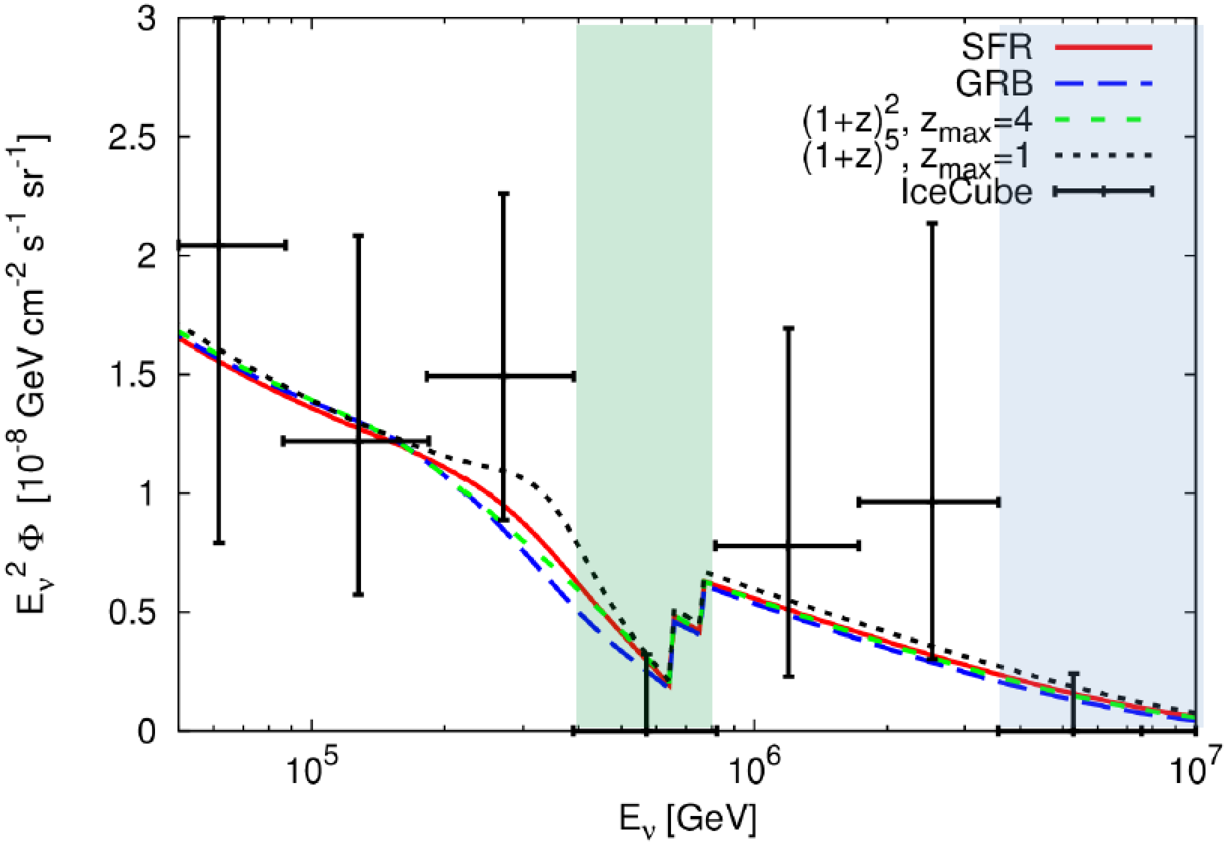
we need “large coupling” and/or “light Z'”

excluded by Trident

excluded by Borexino

The other choices for source

Source dependence



Model parameters

$$m_{\nu_1} = 0.08 \text{ eV (NH)}$$

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

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

Energy cut-off at

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

Gap is successfully reproduced

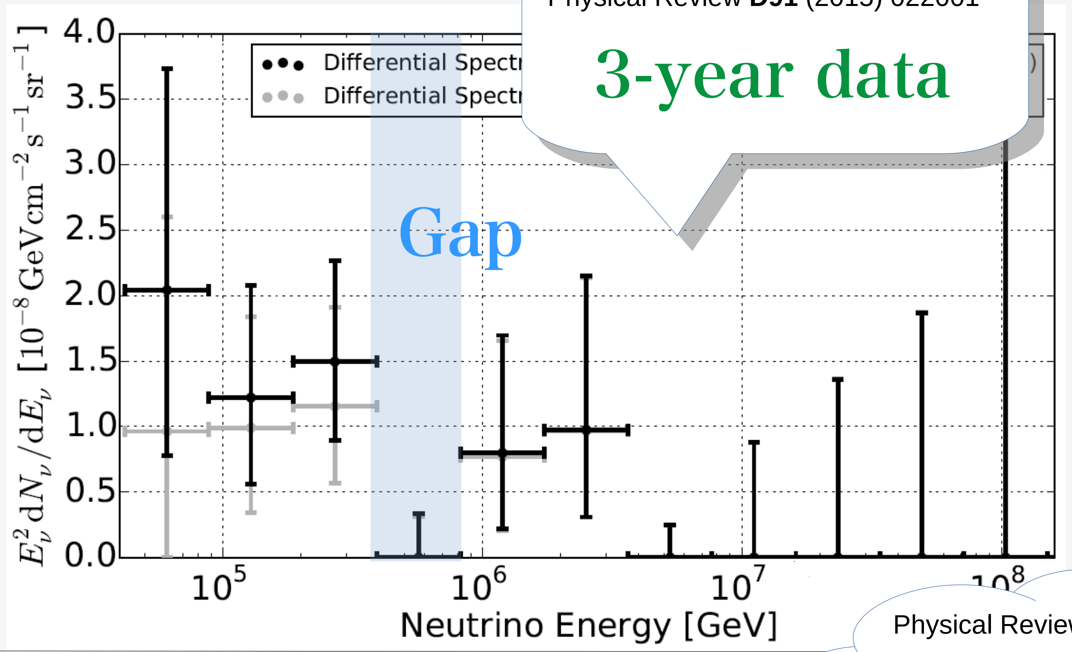
The shape of the spectrum does not depend so much on the distribution of the sources.

* Here we adjust the normalization of the fluxes to fit to the observation

■Spectrum of high energy cosmic neutrino

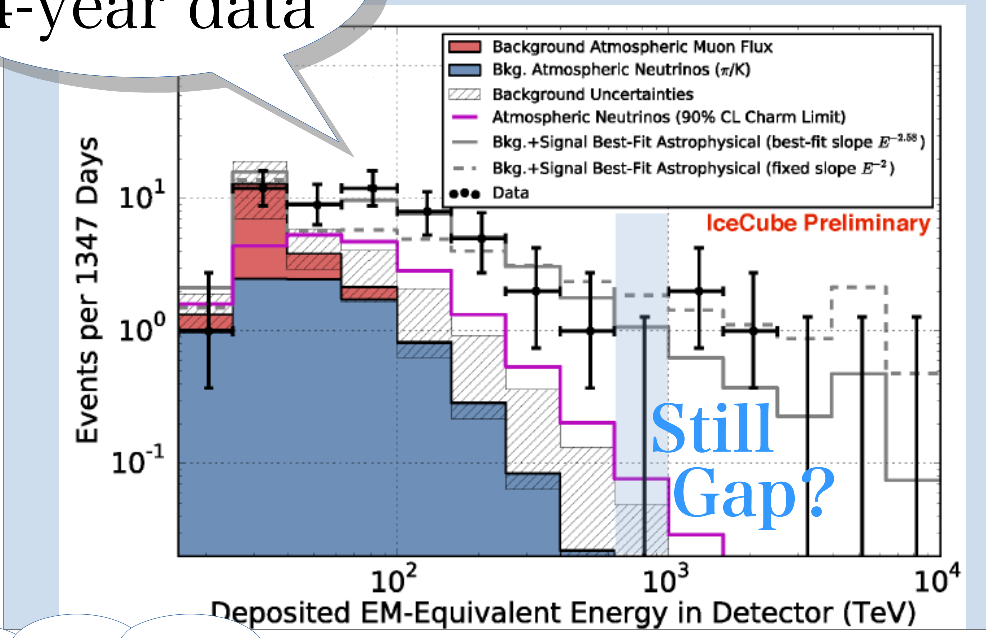
Physical Review **D91** (2015) 022001

3-year data



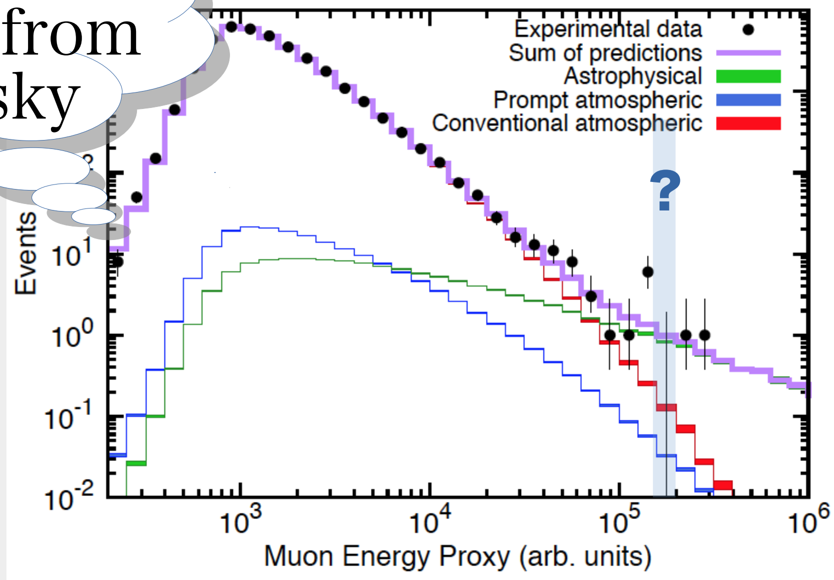
Botner at IPA 2015
Halzen at Neutrino telescope 2015

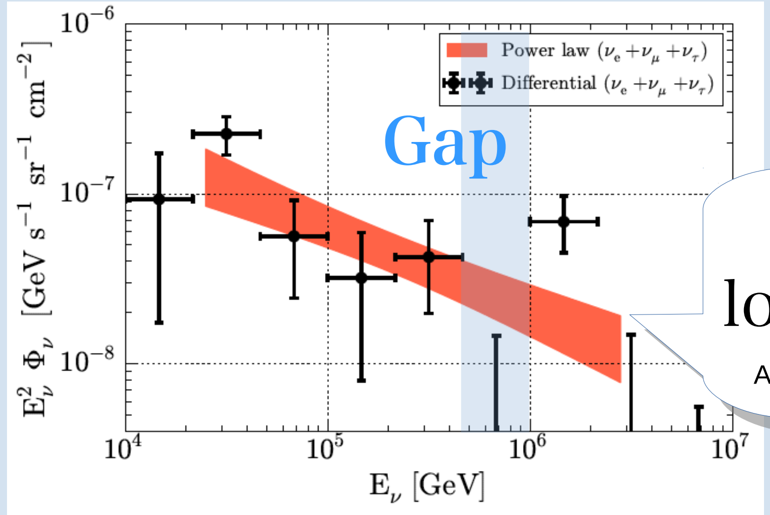
4-year data



Physical Review Letters **115** (2015) 081102

Muon events from northern sky



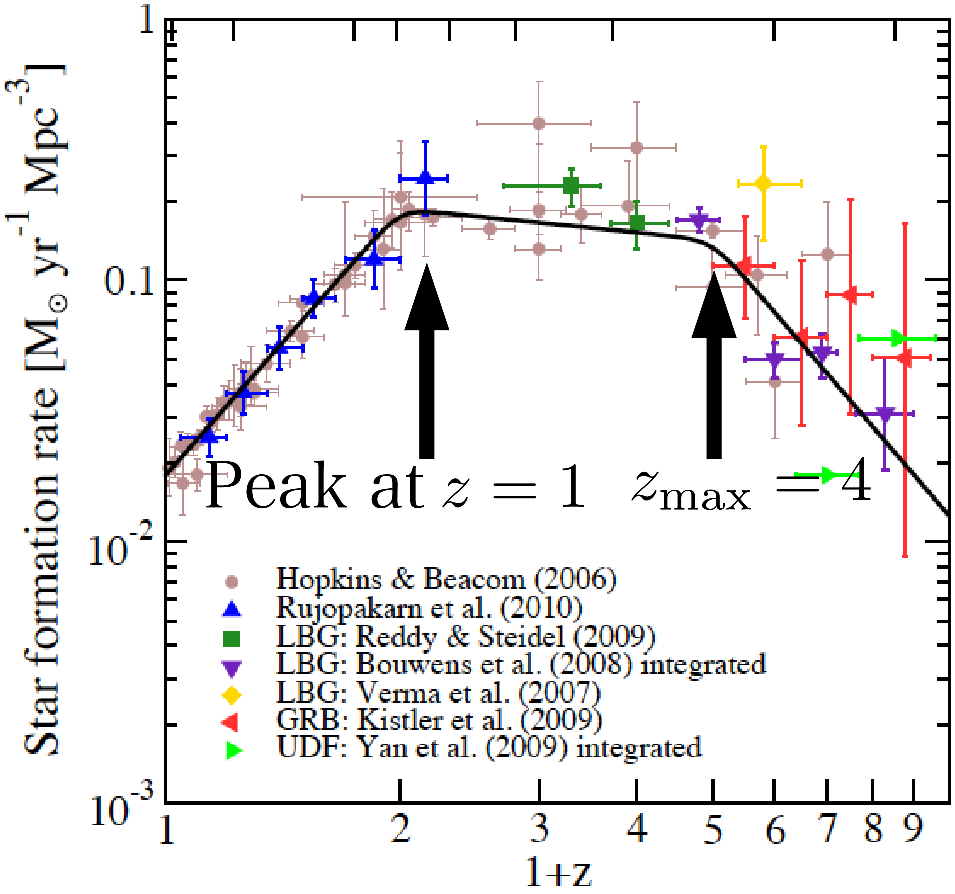


2-year
low E threshold

Astrophysical Journal **809** (2015) 98

Star formation rate

taken from Horiuchi Beacom Astrophys. J. **723** (2010) 329-341



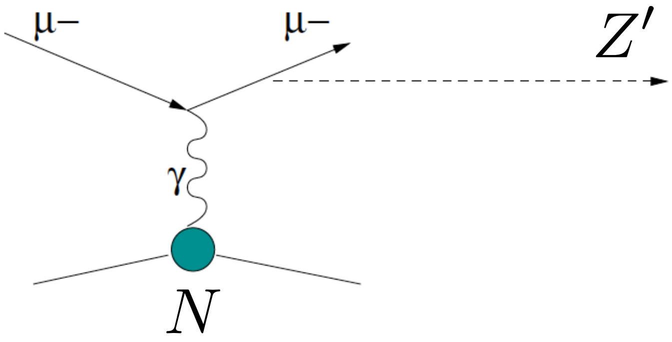
Peak at $z = 1$ $z_{\text{max}} = 4$

■ Lab bounds in future

■ Muon-Nucleon scattering

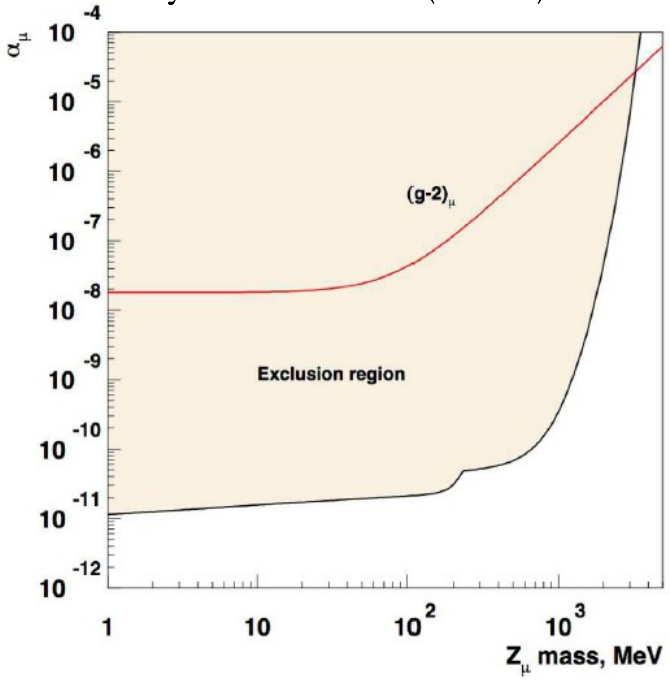
Gninenko Krasnikov Matveev Phys.Rev. **D91** (2015) 095015

$$\mu N \to \mu X Z'$$



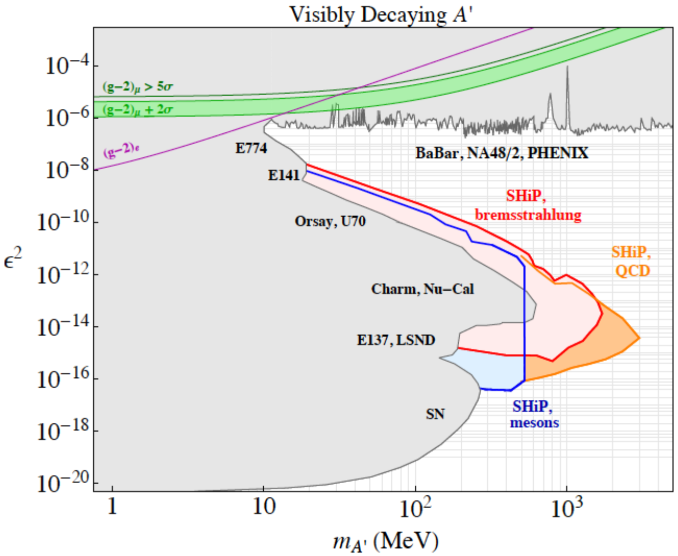
$$E_\mu = 150 \text{ GeV}$$

$$N_\mu = 10^{12}$$



■ Proton beam dump

SHiP collaboration arXiv.1504.04855

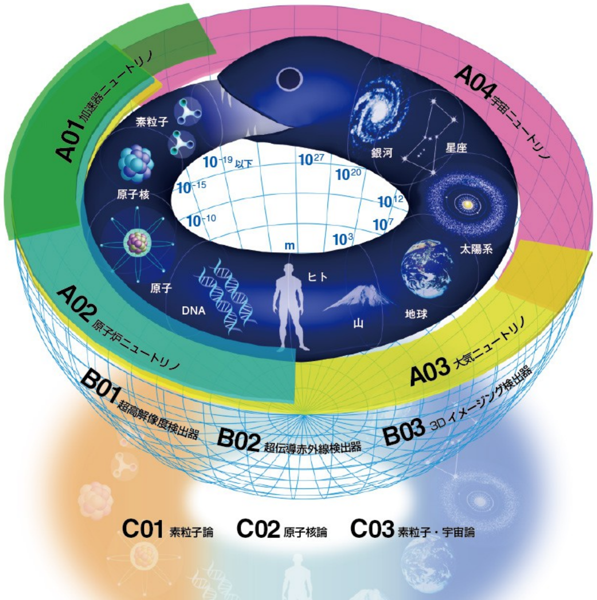


$$E_p = 400 \text{ GeV}$$

$$N_p = 2 \cdot 10^{20}$$

Z' can be produced through the kinetic mixing but it decays into “invisible” (neutrinos)...

* Z' can decay into “visible” through the mixing, but the branching ratio should be extremely small.


A01 加速器ニュートリノ
A02 原子炉ニュートリノ
A03 大気ニュートリノ
A04 宇宙ニュートリノ
B01 超高解像度検出器
B02 超伝導赤外線検出器
B03 3D イメージング検出器
C01 素粒子論
C02 原子核論
C03 素粒子・宇宙論
素粒子
原子核
原子
DNA
ヒト
山
地球
太陽系
星座
銀河
10^-19 以下
10^-15
10^-10
m
10^3
10^7
10^12
10^20
10^27