Lμ-Lτ対称性

2024／5／31　佐藤丈(SATO, Joe)

（横浜国立大学 Yokohama National University）

YNU 横浜国立大学
YOKOHAMA National University

Plan to talk

- 1. Introduction
- 2 . Lepton Flavor
- 2.1 探索
- 2.2 レプトンフレーバー保存則
- 3.Standard Modelを超える物理
- 3.1 ニュートリノ振動
- 3.2 ミューオンの異常磁気能率
- 3.3 IceCUbe Gap
- 3.4 Hubble tension
- 4.Lμ -Lτ **ゲージ対称性**
- 5. Summary

1. Introduction

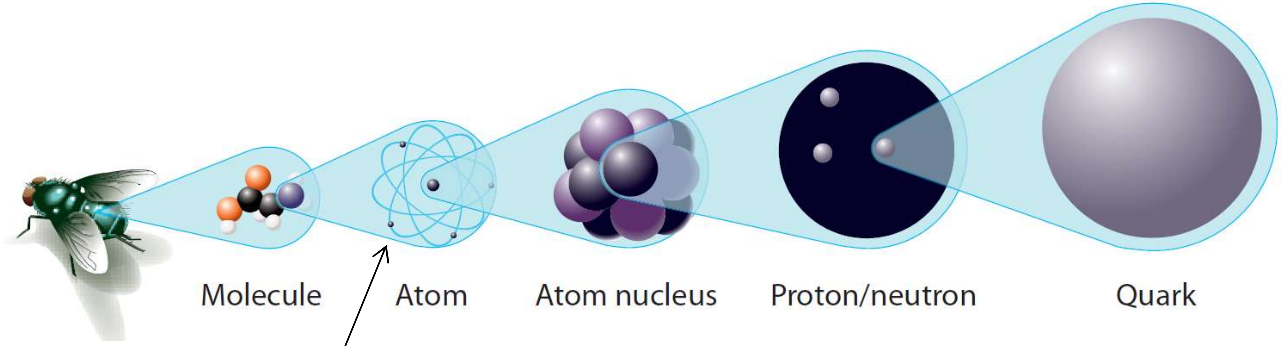
素粒子物理学が目指すもの

この世界（宇宙）を構成する
根本的な存在（素粒子）
と
それらの間に働く相互作用（力）
を解明すること

素粒子とは？

物質を細分化してたどり着く最も小さい存在

http://nobelprize.org/nobel_prizes/physics/laureates/2008/info.pdf

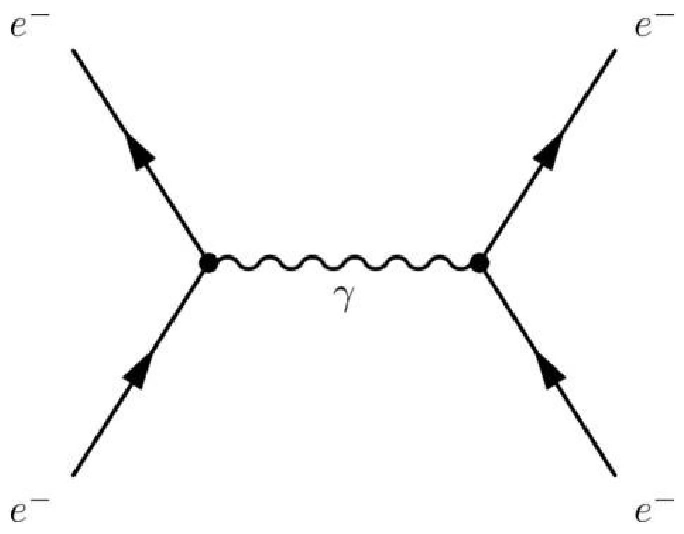


分子　原子　原子核　陽子/中性子　クオーク

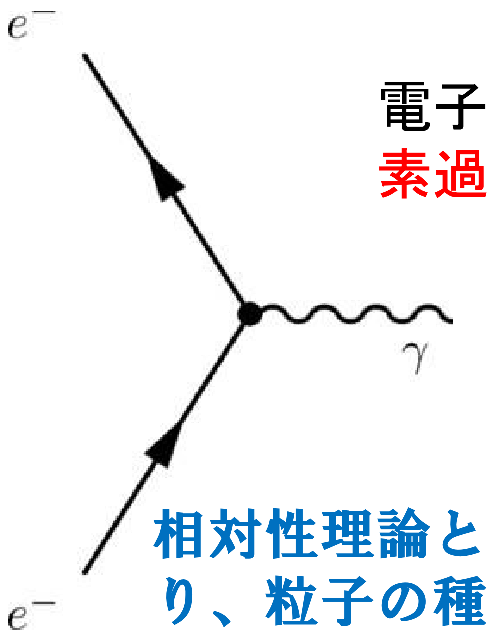
電子 ← 素粒子

相互作用とは？

素粒子と素粒子の衝突仕方



電子・電子散乱
e: 電子、γ：光子（電磁波）



電子と光子の衝突
素過程

相対性理論と量子力学により、粒子の種類を指定すると相互作用は決まる

素粒子物理学

物理学：理論と実験

南部陽一郎(2008年ノーベル賞受賞)によると

素粒子論

湯川秀樹が
1934年にパイ中間子の存在を
理論的に予言したことに始まる物理学の一分野

➡ 1949年ノーベル賞

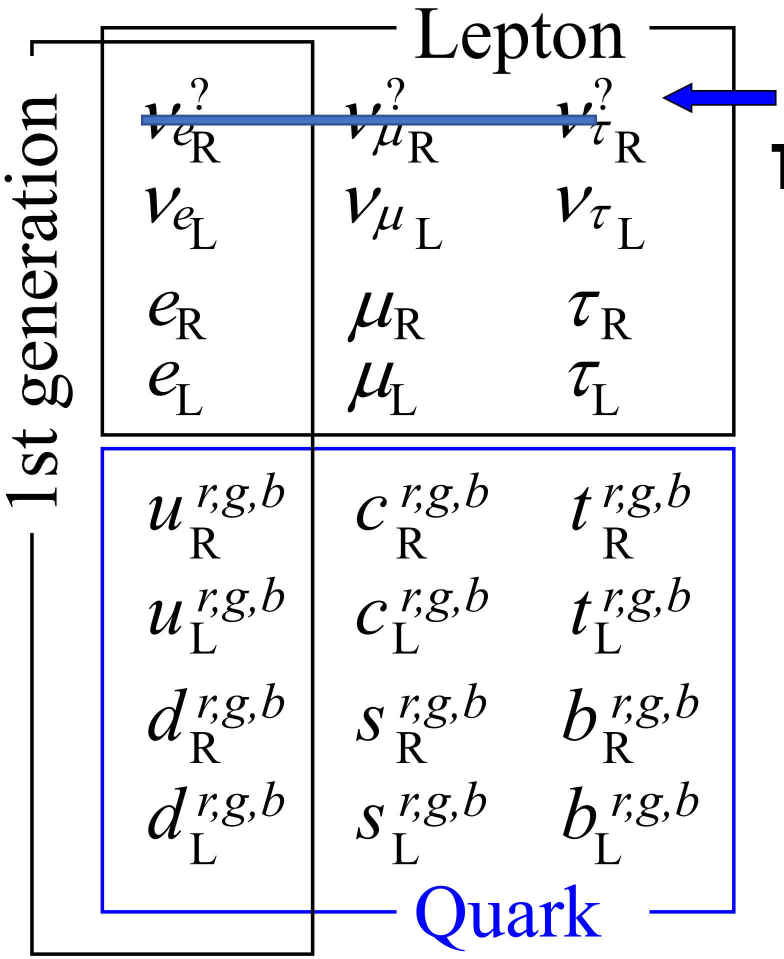
素粒子実験

アーネストローレンスが
1930年にサイクロトロン(素粒子加速器)の基礎理論を発表

➡ 1939年ノーベル賞

Standard Model

$SU(3) \times SU(2) \times U(1)$ gauge group



Lepton

~~$\nu_{e_R}^{?}$~~	~~$\nu_{\mu_R}^{?}$~~	~~$\nu_{\tau_R}^{?}$~~
ν_{e_L}	ν_{μ_L}	ν_{τ_L}
e_R	μ_R	τ_R
e_L	μ_L	τ_L
$u_R^{r,g,b}$	$c_R^{r,g,b}$	$t_R^{r,g,b}$
$u_L^{r,g,b}$	$c_L^{r,g,b}$	$t_L^{r,g,b}$
$d_R^{r,g,b}$	$s_R^{r,g,b}$	$b_R^{r,g,b}$
$d_L^{r,g,b}$	$s_L^{r,g,b}$	$b_L^{r,g,b}$

Quark

1st generation

Higgs

Not exist in SM

Though collider experiments OK

Neutrino Oscillation

Dark Matter

Matter dominance

Muon anomalous moment ?

日本に於ける素粒子物理学
ノーベル賞を例に取ると

湯川秀樹が1934年にパイ中間子の存在を
理論的に予言したことに始まる物理学の一分野

1949年ノーベル賞

朝永振一郎：量子電気力学の基礎的研究（1947年）

1965年ノーベル賞

小柴昌俊：ニュートリノの検出（超新星1987A、太陽ニュートリノなど）

2002年ノーベル賞

小林誠・益川敏英：小林益川理論（CP対称性の破れと6種類のクオーク）

南部陽一郎：自発的対称性の破れ

2008年ノーベル賞

梶田隆章：ニュートリノ振動

2015年ノーベル賞

詳しく知りたい人は横浜国立大学素粒子論研究室へどうぞ

理論

現象を説明するための仮設・模型（モデル）
より少ない仮定でより多くのことを説明したい

実験による検証
- どの理論が「よい」理論か。そもそも間違っていないか
- 未知の現象はないか

2．レプトンフレーバー

ニュートリノが0質量であることから自動的に出てくる保存「電荷」

電子数、ミューオン数、タウ数

L_e　　L_μ　　L_τ

	e^-	ν_e	μ^-	ν_μ	τ^-	ν_τ
L_e	1	1				
L_μ			1	1		
L_τ					1	1

反粒子は－１

例

$$\pi^- \to \mu^- \bar{\nu}_\mu$$

L_μ　０　＝　１＋（－１）

２．１　荷電レプトンによるレプトンフレーバー破れの探索

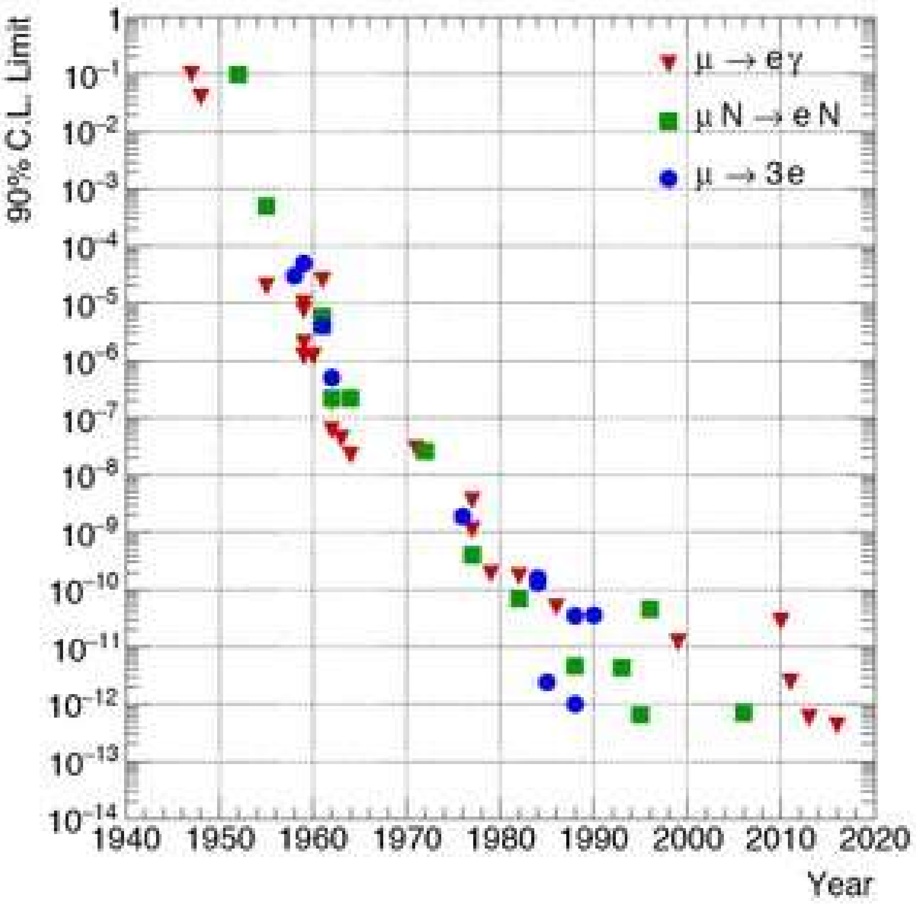
ニュートリノに質量があると、一般には
レプトンフレーバーは保存しないので、

$$\mu^- \rightarrow e^- \ \gamma$$

$L_\mu \quad 1 = 0 + 0$

$L_e \quad 0 = 1 + 0$

が起こりうる。



LFV from muon decay

Upper limit on Br

$$\mu^+ \to e^+\gamma \quad < \quad 5.7\times10^{-13}$$
$$\mu^+ \to e^+e^+e^- \quad < \quad 1.0\times10^{-12}$$
$$\mu^-\mathrm{Ti} \to e^-\mathrm{Ti} \quad < \quad 6.1\times10^{-13}$$
$$\mu^-\mathrm{Au} \to e^-\mathrm{Au} \quad < \quad 7\times10^{-13}$$

MEG experiment updates/discovers(?)

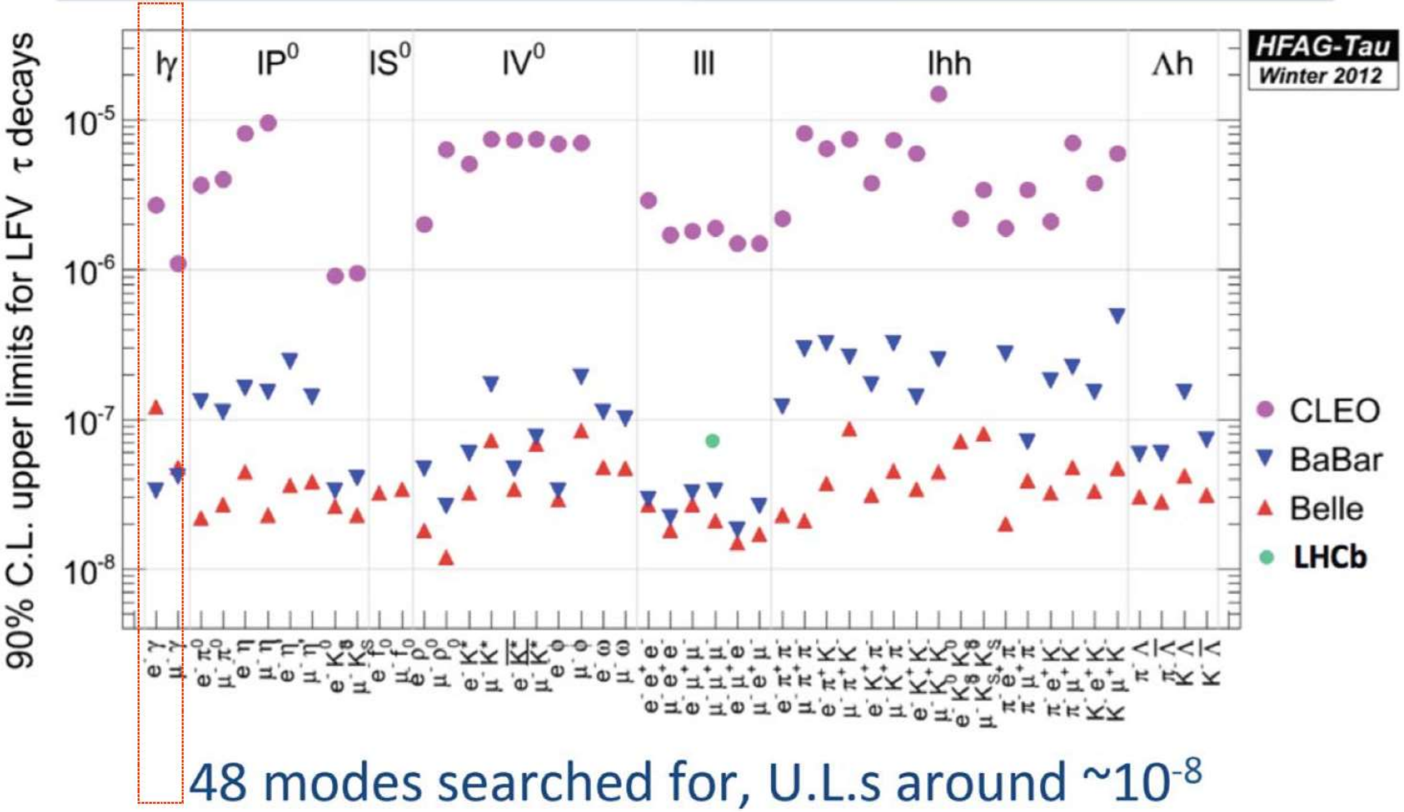
$$\mu^+ \to e^+\gamma$$

COMET/Mu2E will discover(?)

$$\mu^- \to e^-$$

In near future

τ の崩壊



48 modes searched for, U.L.s around $\sim 10^{-8}$

2.2 Lepton flavor保存の導出：ネーターの定理

Lepton Part Only

$$L_i = \begin{pmatrix} \nu_{Li} \\ e_{Li} \end{pmatrix}, \quad e_{Ri}, \quad (i = 1, 2, 3)$$

Kinetic Part

$$\mathcal{L}_k = \bar{L}_i i \not{D}_L L_i + \bar{e}_{Ri} i \not{D}_R e_{Ri}$$

$$D_{L\mu} = \begin{pmatrix} \partial_\mu + \frac{i}{2} g_1 B_\mu - g_2 \frac{i}{2} W_\mu^0, & g_2 \frac{i}{\sqrt{2}} W_\mu^+ \\ g_2 \frac{i}{\sqrt{2}} W_\mu^-, & \partial_\mu + \frac{i}{2} g_1 B_\mu + \frac{i}{2} g_2 W_\mu^0 \end{pmatrix}$$

$$D_{R\mu} = \partial_\mu + i g_1 B_\mu$$

$$\mathcal{L}_k = \mathcal{L}_{k,diag} + \mathcal{L}_{k,W}$$

$$\mathcal{L}_{k,diag} = \bar{\Phi}_j i \not{D} \Phi_j \qquad \Phi_j = \{\nu_{Li}, e_{Li}, e_{Ri}\}$$

「内積」の形

$$D_\mu = \partial_\mu - ieQA_\mu - ig_Z (T_3 - Q \sin\theta_w^2) Z_\mu$$

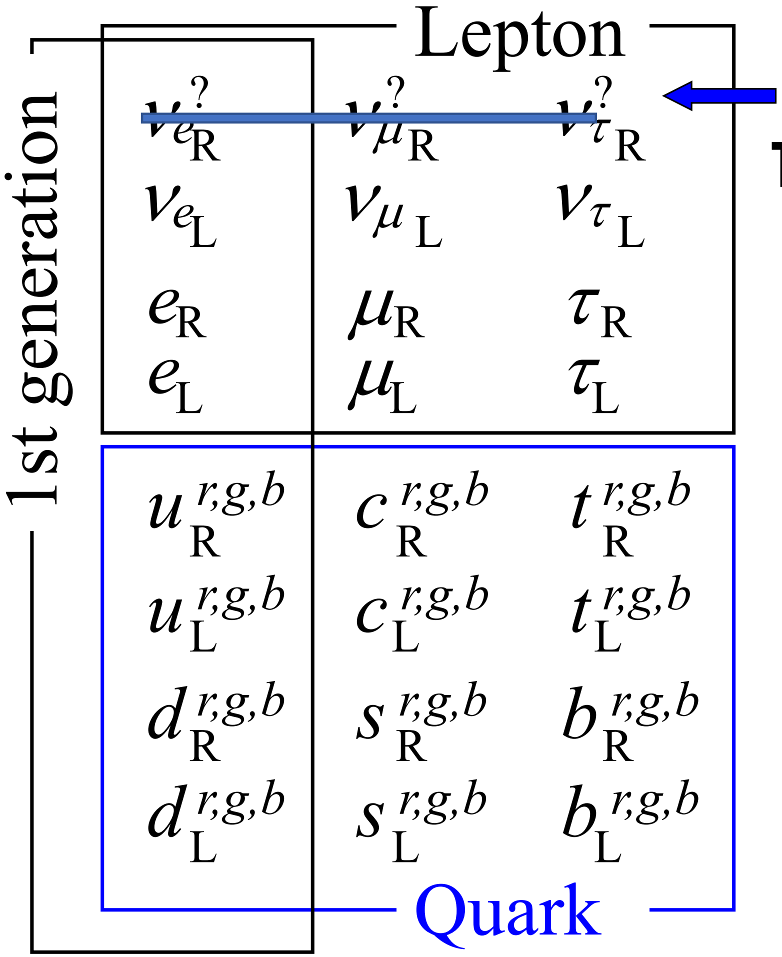
$$U_l \quad , \qquad l = \nu_L,\ e_L,\ e_R, \quad 3 \times 3 \ \mathrm{Unitary Matrix}$$

$$l \quad \to \quad U_l l \ \left(e_{Li} \to (U_{e_L} e_L)_i \text{など} \right)$$

と、基底を変えても同じ形の式が成立 U_l は互いに違うもので良い

Standard Model

SU(3) × SU(2) × U(1) gauge group



1st generation

Lepton

$\cancel{\nu_{e\,R}^{?}}$	$\cancel{\nu_{\mu\,R}^{?}}$	$\cancel{\nu_{\tau\,R}^{?}}$
$\nu_{e\,L}$	$\nu_{\mu\,L}$	$\nu_{\tau\,L}$
e_R	μ_R	τ_R
e_L	μ_L	τ_L

Quark

$u_R^{r,g,b}$	$c_R^{r,g,b}$	$t_R^{r,g,b}$
$u_L^{r,g,b}$	$c_L^{r,g,b}$	$t_L^{r,g,b}$
$d_R^{r,g,b}$	$s_R^{r,g,b}$	$b_R^{r,g,b}$
$d_L^{r,g,b}$	$s_L^{r,g,b}$	$b_L^{r,g,b}$

Higgs

Not exist in SM

Though collider experiments OK

Neutrino Oscillation

Dark Matter

Matter dominance

Muon anomalous moment ?

2.2 Lepton flavor保存の導出：ネーターの定理

Lepton Part Only

$$L_i = \begin{pmatrix} \nu_{Li} \\ e_{Li} \end{pmatrix}, \quad e_{Ri}, \quad (i = 1, 2, 3)$$

Kinetic Part

$$\mathcal{L}_k = \bar{L}_i i \not{D}_L L_i + \bar{e}_{Ri} i \not{D}_R e_{Ri}$$

$$D_{L\mu} = \begin{pmatrix} \partial_\mu + \frac{i}{2} g_1 B_\mu - g_2 \frac{i}{2} W^0_\mu, & g_2 \frac{i}{\sqrt{2}} W^+_\mu \\ g_2 \frac{i}{\sqrt{2}} W^-_\mu, & \partial_\mu + \frac{i}{2} g_1 B_\mu + \frac{i}{2} g_2 W^0_\mu \end{pmatrix}$$

$$D_{R\mu} = \partial_\mu + i g_1 B_\mu$$

$$\mathcal{L}_k = \mathcal{L}_{k,diag} + \mathcal{L}_{k,W}$$

$$\mathcal{L}_{k,diag} = \bar{\Phi}_j i \not{D} \Phi_j \qquad \Phi_j = \{\nu_{Li}, e_{Li}, e_{Ri}\}$$

「内積」の形

$$D_\mu = \partial_\mu - ieQA_\mu - ig_Z(T_3 - Q\sin\theta_w^2) Z_\mu$$

$$U_l \quad , \qquad l = \nu_L,\ e_L,\ e_R, \quad 3 \times 3\ \mathrm{UnitaryMatrix}$$

$$l \quad \rightarrow \quad U_l l \ (e_{Li} \rightarrow (U_{e_L} e_L)_i \text{など})$$

と、基底を変えても同じ形の式が成立U_l は互いに違うもので良い

$$\mathcal{L}_{k,W} = ig_2 \frac{1}{\sqrt{2}} W_\mu^+ \bar{\nu}_{Li} \gamma_\mu e_{Li} \ + \ h.c.$$

こちらを不変に保つには $U_{\nu_L} = U_{e_L}$ が必要

Higgs Part

$$\mathcal{L}_H = Y_{ij} \bar{L}_i e_{Rj} + h.c.$$

Y_{ij} **3 × 3 複素行列 :: 二つのユニタリ行列で対角化出来る**

$$Y_{ij} \longrightarrow Y_{diag} = \mathrm{diag}\{y_e, y_\mu, y_\tau\} = U_L Y_{ij} U_R^\dagger$$

$$L_\alpha \equiv U_{L\alpha i} L_i = \begin{pmatrix} U_{L\alpha i} \nu_{Li} \\ U_{L\alpha i} e_{Li} \end{pmatrix}, \quad e_{R\alpha} \equiv U_{Ri} E_{Ri}, \quad \alpha = e, \mu, \tau$$

➡

$$\begin{aligned} \mathcal{L}_H &= Y_\alpha \bar{L}_\alpha e_{R\alpha} + h.c. \\ &= h^+ \left(y_e \bar{\nu}_{eL} e_R + y_\mu \bar{\nu}_{\mu L} \mu_R + y_\tau \bar{\nu}_{\tau L} \tau_R \right) \\ &\quad + h^0 \left(y_e \bar{e}_L e_R + y_\mu \bar{\mu}_L \mu_R + y_\tau \bar{\tau}_L \tau_R \right) + h.c. \end{aligned}$$

運動項も $U_{\nu_L} = U_{e_L}$ が成立しているので不変

$$\mathcal{L}_{k,diag} = \bar{\Phi}_\alpha i \not{D} \Phi_\alpha \qquad \Phi_\alpha = \{\nu_{\alpha L}, e_{\alpha L}, e_{\alpha R}\}$$

$$\mathcal{L}_{k,W} = ig_2 \frac{1}{\sqrt{2}} W_\mu^+ \bar{\nu}_{\alpha L} \gamma_\mu e_{\alpha L} \ + \ h.c.$$

フレーバー基底で「対角化」された形

$$\mathcal{L}_{k,W} = ig_2 \frac{1}{\sqrt{2}} W_\mu^+ \bar{\nu}_{Li} \gamma_\mu e_{Li} \ + \ h.c.$$

こちらを不変に保つには $U_{\nu_L} = U_{e_L}$ が必要

Higgs Part

$$\mathcal{L}_H = Y_{ij} \bar{L}_i e_{Rj} + h.c.$$

Y_{ij} **3 × 3 複素行列 :: 二つのユニタリ行列で対角化出来る**

$$Y_{ij} \longrightarrow Y_{diag} = \mathrm{diag}\{y_e, y_\mu, y_\tau\} = U_L Y_{ij} U_R^\dagger$$

$$L_\alpha \equiv U_{L\alpha i} L_i = \begin{pmatrix} U_{L\alpha i} \nu_{Li} \\ U_{L\alpha i} e_{Li} \end{pmatrix}, \quad e_{R\alpha} \equiv U_{Ri} E_{Ri}, \quad \alpha = e, \mu, \tau$$

➡
$$\begin{aligned} \mathcal{L}_H &= Y_\alpha \bar{L}_\alpha e_{R\alpha} + h.c. \\ &= h^+ \left(y_e \bar{\nu}_{eL} e_R + y_\mu \bar{\nu}_{\mu L} \mu_R + y_\tau \bar{\nu}_{\tau L} \tau_R \right) \\ &\quad + h^0 \left(y_e \bar{e}_L e_R + y_\mu \bar{\mu}_L \mu_R + y_\tau \bar{\tau}_L \tau_R \right) + h.c. \end{aligned}$$

運動項も $U_{\nu_L} = U_{e_L}$ が成立しているので不変

$$\mathcal{L}_{k,diag} = \bar{\Phi}_\alpha i \not{D} \Phi_\alpha \qquad \Phi_\alpha = \{\nu_{\alpha L}, e_{\alpha L}, e_{\alpha R}\}$$

$$\mathcal{L}_{k,W} = ig_2 \frac{1}{\sqrt{2}} W_\mu^+ \bar{\nu}_{\alpha L} \gamma_\mu e_{\alpha L} \ + \ h.c.$$

フレーバー基底で「対角化」された形

残った対称性　：：レプトンフレーバー

$$\Phi_\alpha = \{\nu_{L\alpha}, e_{L\alpha}, e_{R\alpha}\} \quad \alpha = e, \mu, \tau$$

同じフレーバーを持つものが対で現れる。
→あるフレーバーのみの位相を変換してもラグランジアンは不変
→そのフレーバーの個数が保存する。

$$\{e'_L, e'_R, \nu'_{eL}\} = \exp\{-i\theta_e\}\{e_L, e_R, \nu_{eL}\}$$ と変換

$$\begin{aligned} \mathcal{L'}_{k,W} &= ig_2 \frac{1}{\sqrt{2}} W_\mu^+ \bar{\nu}'_e \gamma_\mu e'_L \ + \ h.c. \\ &= ig_2 \frac{1}{\sqrt{2}} W_\mu^+ \bar{\nu}_e e^{i\theta} \gamma_\mu e^{-i\theta} e_L + h.c = \mathcal{L}_{k,W} \end{aligned}$$ など

ネーターの定理より保存「電流」の存在が分かる。
それぞれのフレーバーに対し

$$j^\mu_\alpha = \bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\alpha} + \bar{e}_{L\alpha}\gamma^\mu e_{L\alpha} + \bar{e}_{R\alpha}\gamma^\mu e_{R\alpha}$$

第０成分の空間積分は「電荷」を与え、それが保存することを定理は保証する。

$$Q_\alpha = \int d^3x j^0_\alpha$$

たとえば $\alpha = e$ に対して、生成消滅演算子で書くと

$$Q_e = L_e = \int d^3p \sum_{l=\nu_{eL},e_L,e_R} b_l^\dagger(\mathbf{p})b_l(\mathbf{p}) - d_l^\dagger(\mathbf{p})d_l(\mathbf{p})$$

$b^\dagger b$	number operator for particle
$d^\dagger d$	number operator for anti − particle

電子とニュートリノ	$L_e = +1$
陽電子と反電子ニュートリノ	$L_e = -1$

$L_\mu,\ L_\tau$ も同様

3．標準理論を超える物理

- 標準理論

高い精度で確立。**18個のパラメタで「全て」の現象を説明**

- ただし、完璧ではない ..

ニュートリノ振動 **(Neutrino masses and lepton mixing)、暗黒物質、物質優勢、**

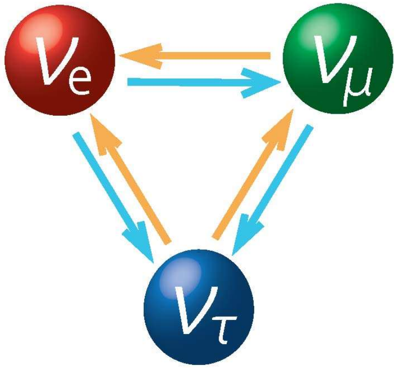
$g_{\mu}-2$:ミューオンの異常磁気能率 Hubble-tension IceCube-Gap

- 純理論的にも？

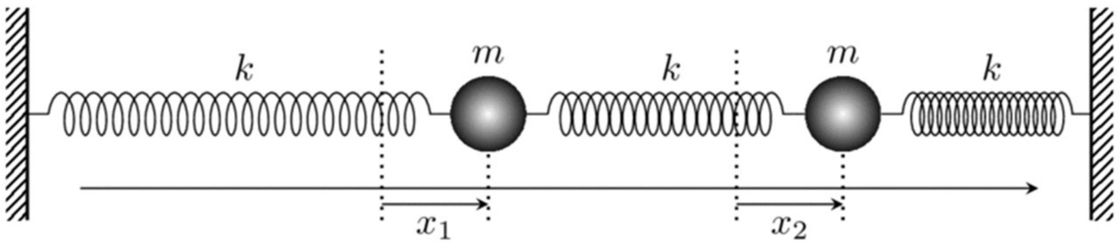
Too many params, Charge quantization, Why three gauges? Why three generations ?

3.1ニュートリノ振動

ニュートリノは変身する！！



連成振動との類似性



玉の揺れ幅が入れ替わる

対応

ν_e が ν_μ と入れ替わる

ニュートリノ振動 vs うなり

類似の方程式

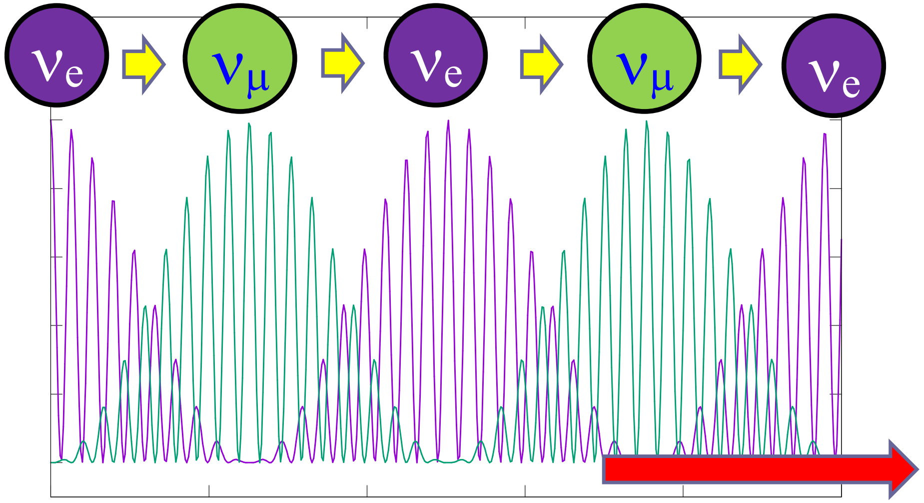
ニュートリノの遷移振幅

混合の元が必要！！

質量が必要！！

$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta \ \sin^2 \left(1.27 \, \frac{m_i^2 - m_j^2}{4E} L \right)$$

対応



飛行距離（L）によって変化

うなりの変位

$$A^2 \sin^2(\omega_{\mathrm{av}} t) \sin^2 \left(\frac{\omega_1 - \omega_2}{2} t \right)$$

他の粒子が存在すると、一般には

$$\{\alpha'_L, \alpha'_R, \nu'_{\alpha L}\} = \exp\{-i\theta_\alpha\}\{\alpha_L, \alpha_R, \nu_{\alpha L}\} \quad \alpha = e, \mu, \tau$$

と変換したときにラグランジアンが不変にならない。

→一般にレプトンフレーバーは定義出来ない。
→保存量とならない。 $Y_{\alpha i}$

例　ニュートリノ質量（一番簡単な質量の例）、右巻きニュートリノ ν_{Ri} を導入

$$\mathcal{L}_H \quad += \quad \tilde{H} Y_{\alpha i} \bar{L}_\alpha \nu_{Ri} + h.c.$$

対角化出来ない。∵Lを回転する自由度は残っていないから
→フレーバーの基底で「対角化」できない。

ニュートリノの質量の固有状態は $\mathcal{L}_H \quad = \quad h^0 Y_{\alpha i} \bar{\nu}_{L\alpha} \nu_{Ri}$ を対角化することで得られるので、

$$Y_{\alpha i} \to U^\dagger_{MNS} Y_{\alpha i} U^\dagger_{\nu_R} = \mathrm{diag}\{y_{\nu_e}, y_{\nu_\mu}, y_{\nu_\tau}\}$$

に対し、ニュートリノの質量固有状態は $\nu_{Li} = U^\dagger_{MNS} \nu_\alpha$ でえられる。

$$W^+_\mu \bar{\nu}_{\alpha L} \gamma_\mu e_{\alpha L} = W^+_\mu \bar{\nu}_{Li} U^\dagger_{MNS} \gamma_\mu e_{\alpha L}$$

「対角的」でなくなる。→ニュートリノ振動の種

ニュートリノ振動

ニュートリノに質量を与える機構が必要

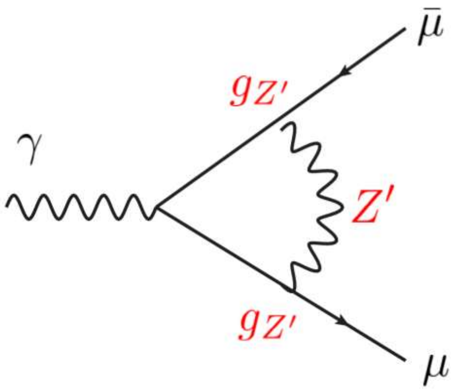
3.2 **Muon g-2 discrepancy** motivation to muonic force

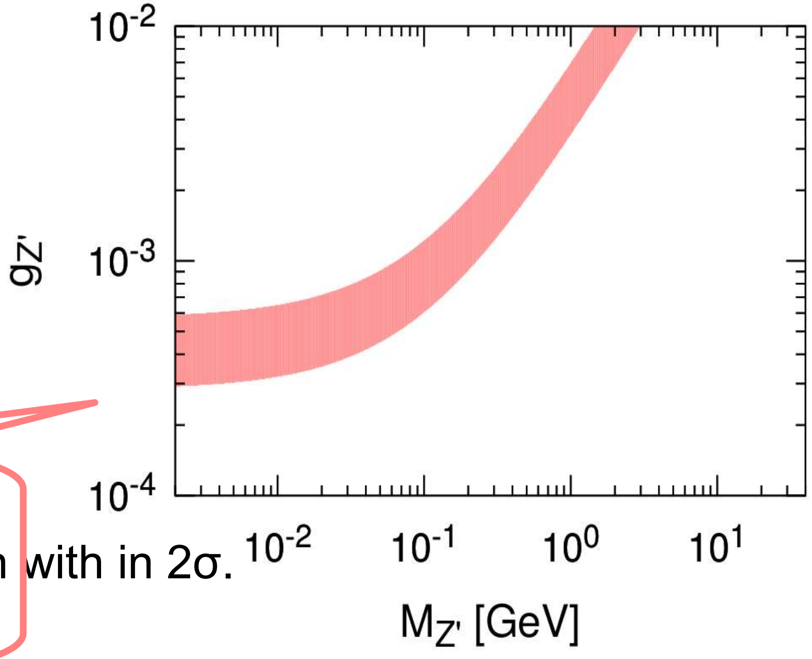
Hagiwara, Liao, Martin, Nomura, Teubner, JPG38, 085003 (2011)

- The discrepancy between theory(SM) and experiment is

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (26.1 \pm 8.0) \cdot 10^{-10} (3.3\sigma)$$

- In $L_\mu - L_\tau$ models, we have an additional contribution.





The discrepancy of muon g-2 can be explained in the red region with in 2σ.

ニュートリノ振動

ニュートリノに質量を与える機構が必要

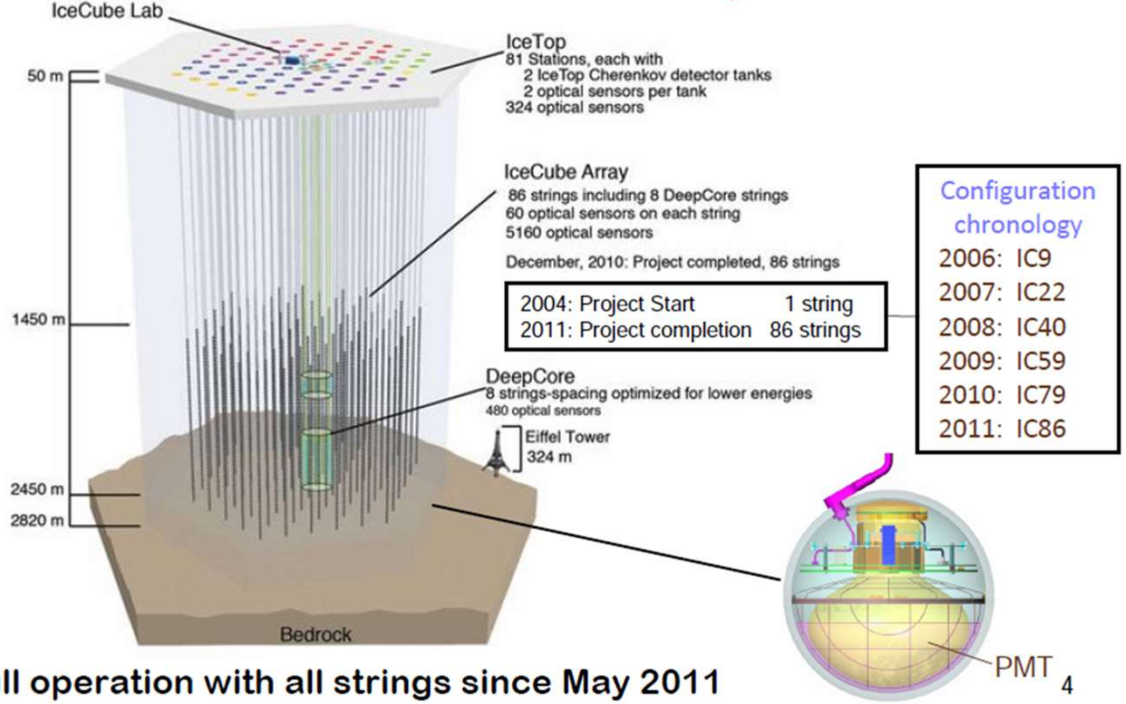
ミューオンの異常磁気能率

ミューオン的なものに特異的に働く力が必要

3.3 IceCube Gap

The IceCube Neutrino Observatory

Completed: Dec 2010



IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors

IceCube Array
86 strings including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors

December, 2010: Project completed, 86 strings

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

DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors

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

Full operation with all strings since May 2011

Digital Optical Module (DOM)

Observe
High Energy Neutrinos
Including
Cosmic Neutrino

High energy cosmic neutrino

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

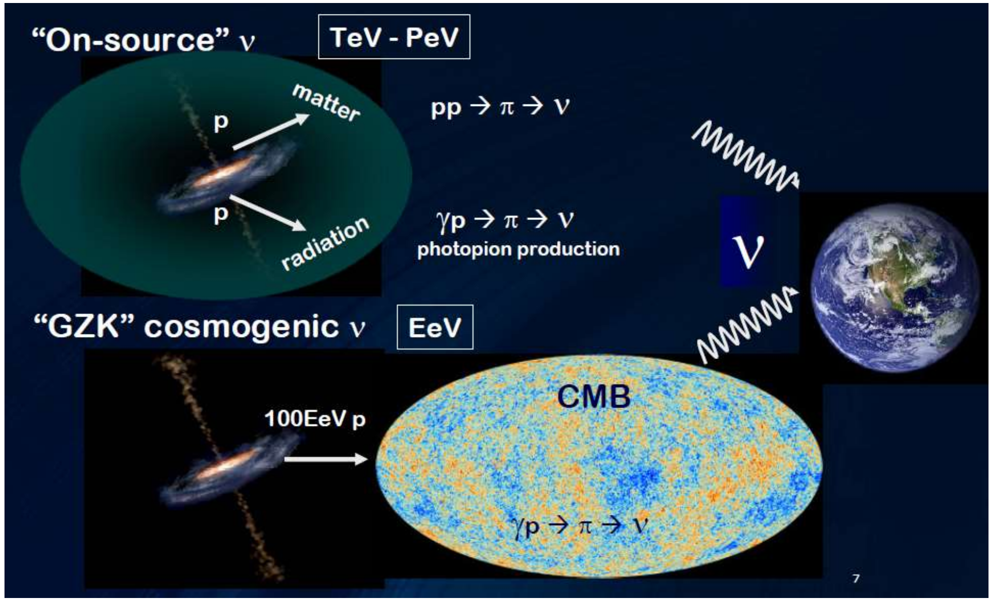
@ Source

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

oscillation

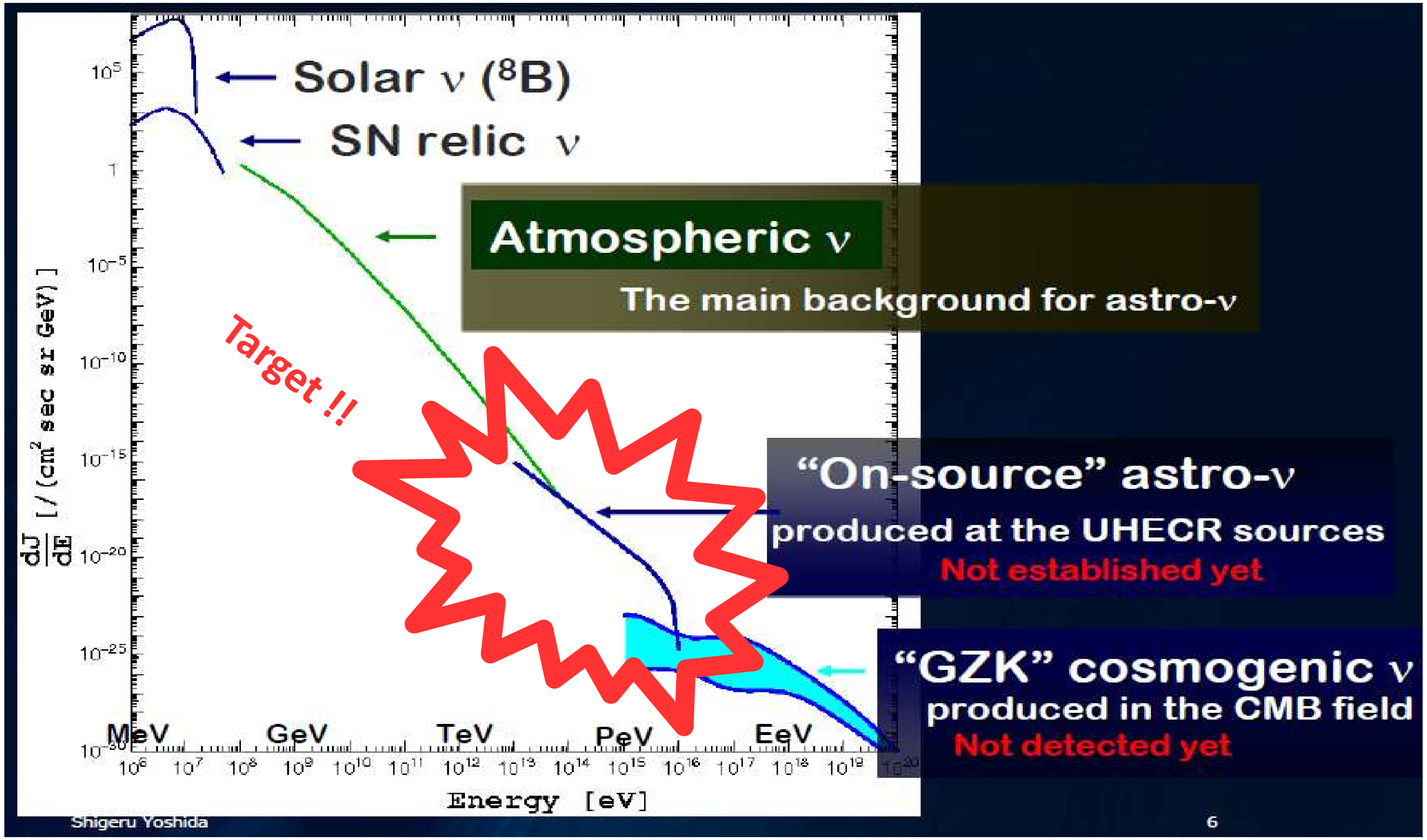
@ Earth

$$\simeq 1:1:1$$



High energy cosmic neutrino

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

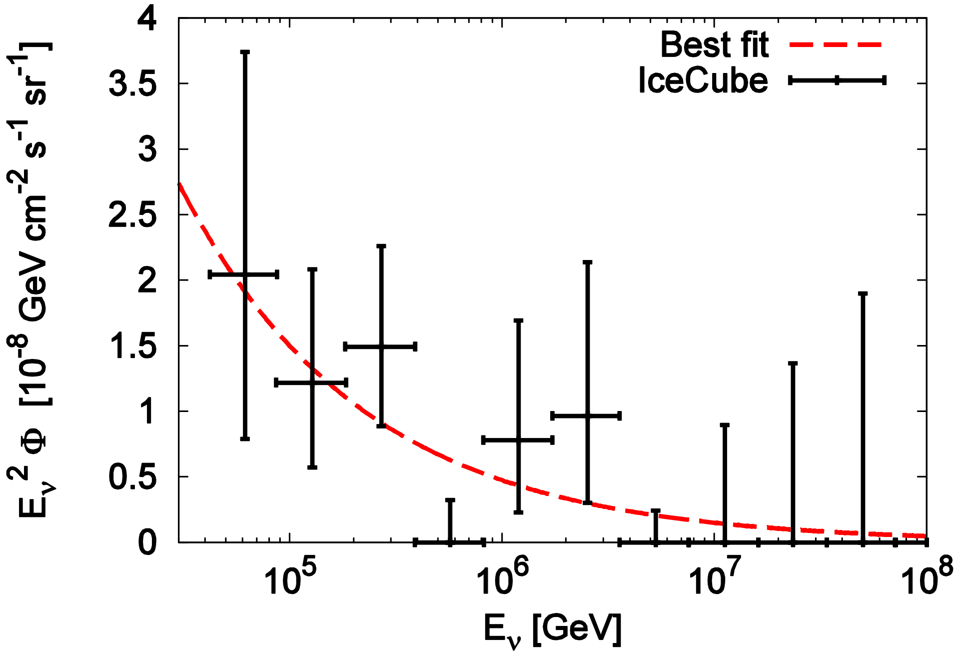


γ

Three-year data

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

[PRL 113 (2014), 101101]



1. It rejects a purely atmospheric explanation at 5.7 sigma.

2. The data are consistent with equal (1:1:1) flavor ratios and isotropic arrival directions.

3. The best-fit power low is

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

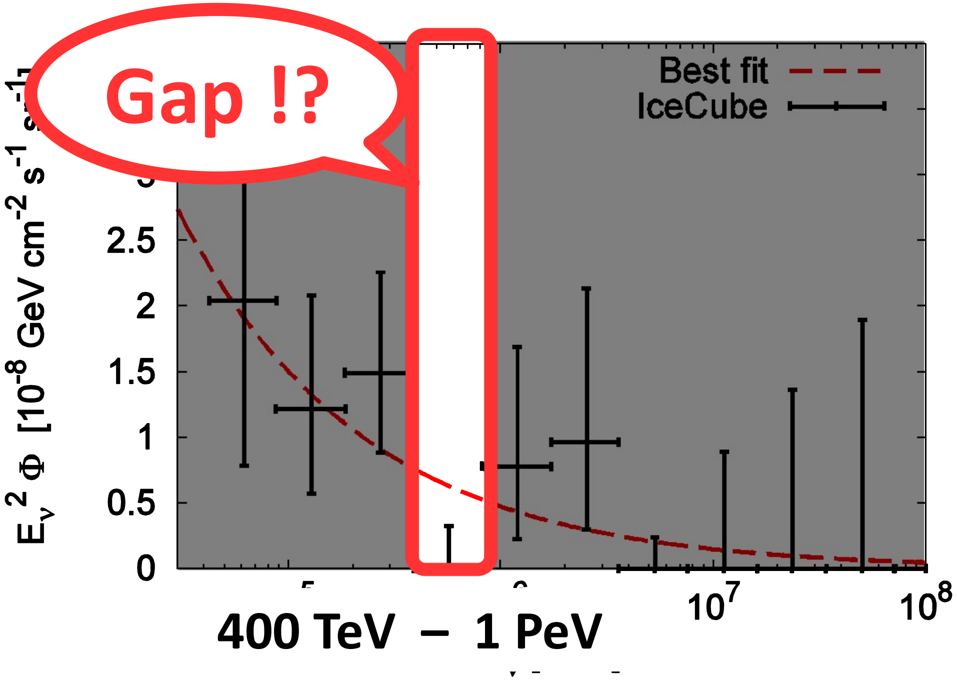
※ Combined analysis:
[Astrophys. J. 809 (2015) 1, 98]

γ

Gap or fluctuation?

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

[PRL 113 (2014), 101101]



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

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

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

ニュートリノ振動

ニュートリノに質量を与える機構が必要

ミューオンの異常磁気能率

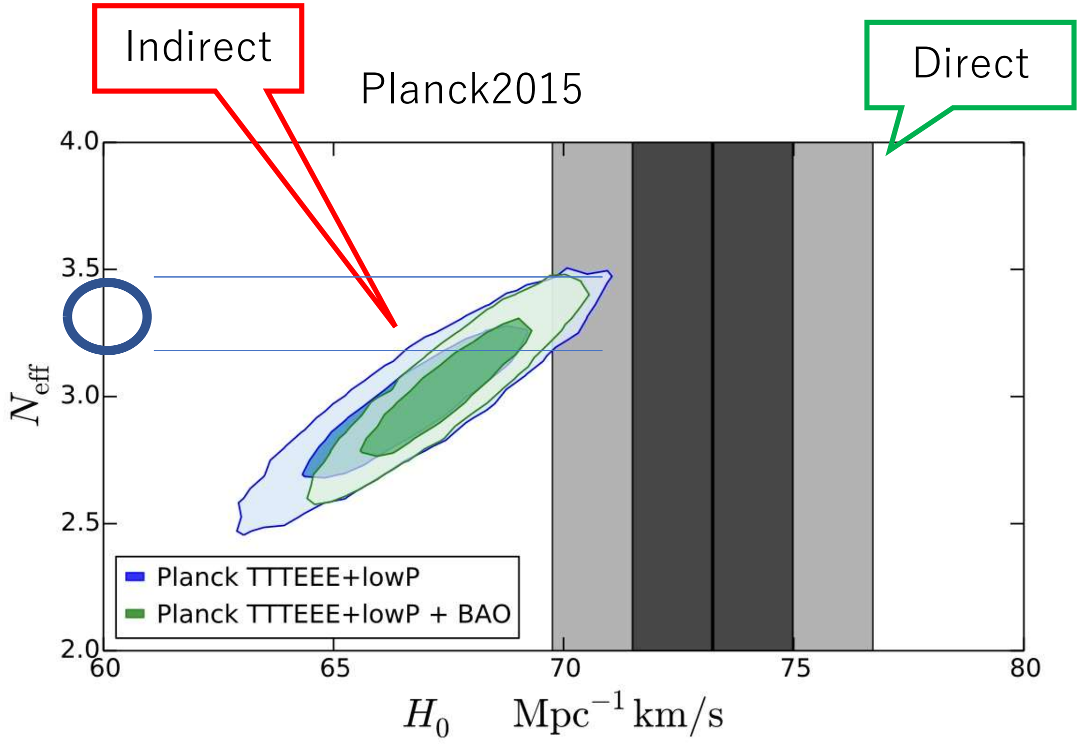
ミューオン的なものに特異的に働く力が必要

IceCube Gap

ニュートリノに働く新しい力が必要

3.4 Hubble Tension

Hubble Tension : Tension between two methods to measure H_0


Indirect

Planck2015

Direct

José Luis Bernal, et al. Journal of Cosmology and Astroparticle Physics, Vol. 2016, No. 10, p. 019 (2016)

Indirect : CMB measurement

with ΛCDM

Far universe, far past

Direct : original definition

$$cz = H_0 d$$

Near universe, near past

N_{eff} 3.3-3.5 > 3.04

New particle ?

ニュートリノ振動

ニュートリノに質量を与える機構が必要

ミューオンの異常磁気能率

ミューオン的なものに特異的に働く力が必要

IceCube Gap

ニュートリノに働く新しい力が必要

Hubble tension

ニュートリノ的な新しい粒子が必要

2. Phenomenology

- 2.1 IceCube Gap

  (PRD 91 (2015) 3 037301, PRD 93 (2016) 7 076006)
- 2.2 Hubble Tension

  (PTEP 2021 (2021) 10 103, arXiv 2306.?????

4. A new gauged U(1): Lμ - Lτ

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

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

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

New gauge coupling

New gauge boson

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

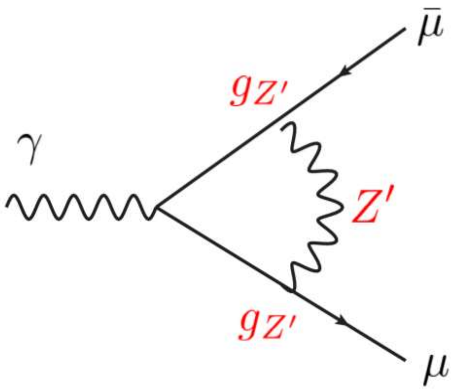
4.1 **Muon g-2 discrepancy** motivation to muonic force

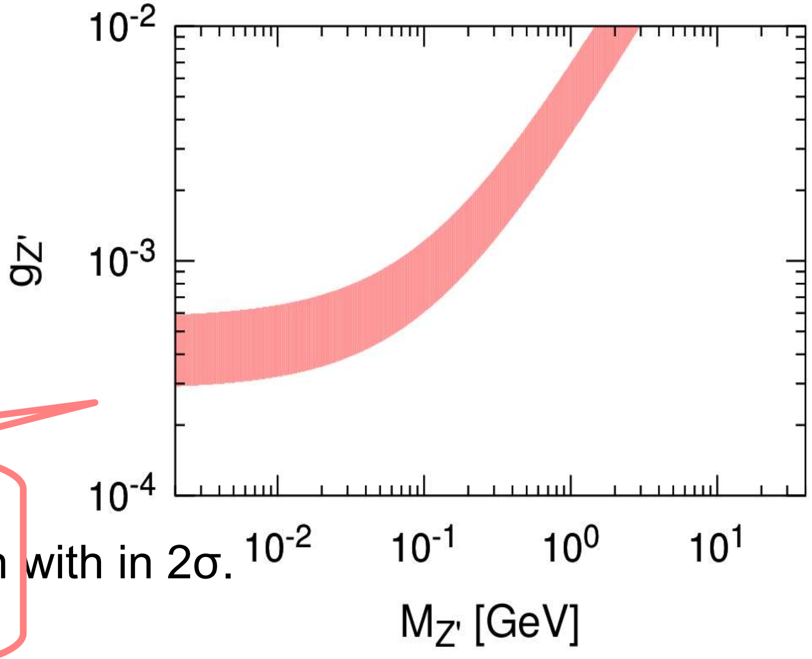
Hagiwara, Liao, Martin, Nomura, Teubner, JPG38, 085003 (2011)

- The discrepancy between theory(SM) and experiment is

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (26.1 \pm 8.0) \cdot 10^{-10} (3.3\sigma)$$

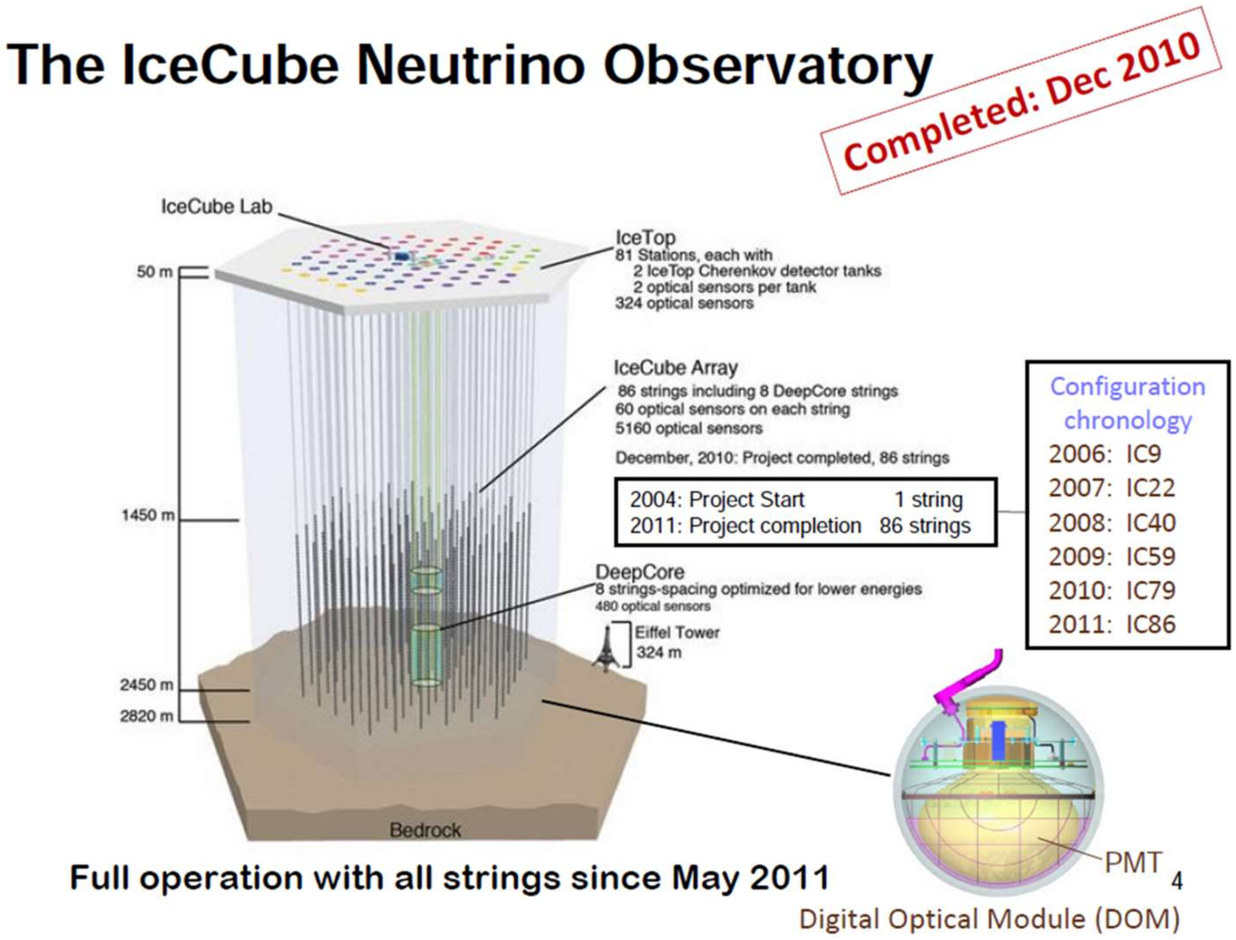
- In $L_\mu - L_\tau$ models, we have an additional contribution.





The discrepancy of muon g-2
can be explained in the red region with in 2σ.

4.2 IceCube Gap



The IceCube Neutrino Observatory

Completed: Dec 2010

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

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

Full operation with all strings since May 2011

Digital Optical Module (DOM)

Observe

High Energy Neutrinos

Including

Cosmic Neutrino

High energy cosmic neutrino

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

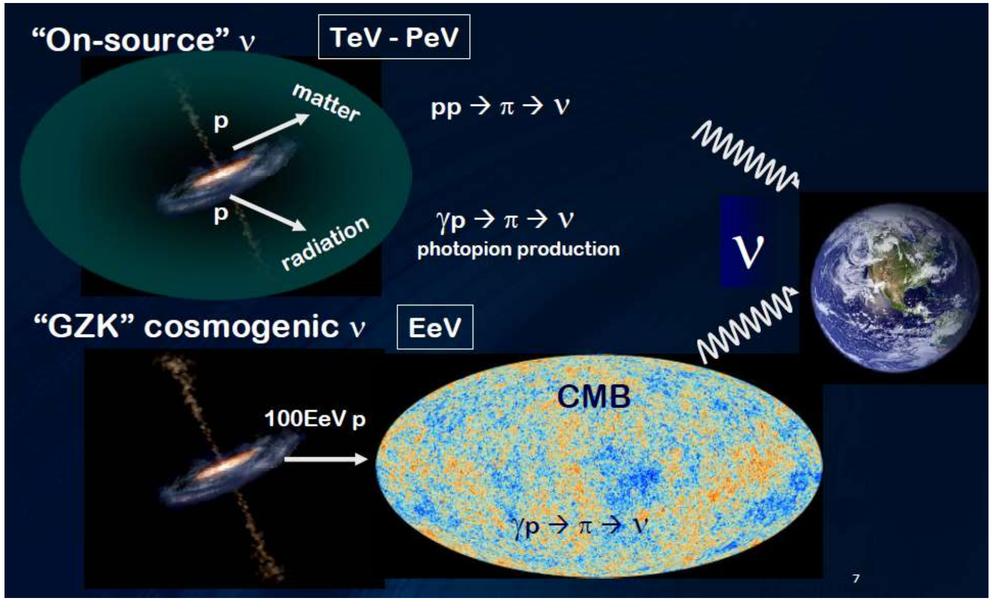
@ Source

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

oscillation

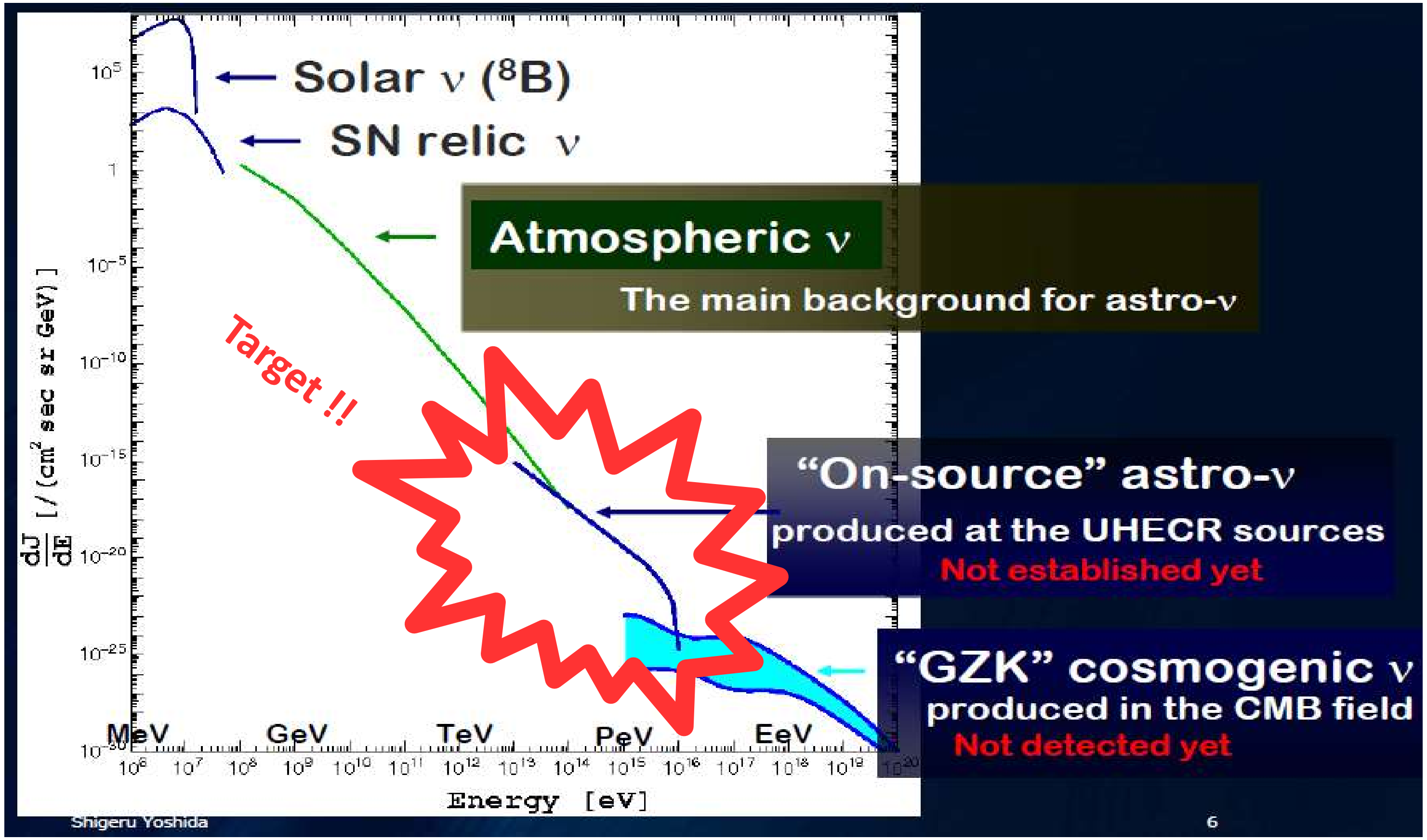
@ Earth

$$\simeq 1 : 1 : 1$$



High energy cosmic neutrino

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



Solar ν (^{8}B)

SN relic ν

Atmospheric ν

The main background for astro-ν

Target !!

"On-source" astro-ν

produced at the UHECR sources

Not established yet

"GZK" cosmogenic ν

produced in the CMB field

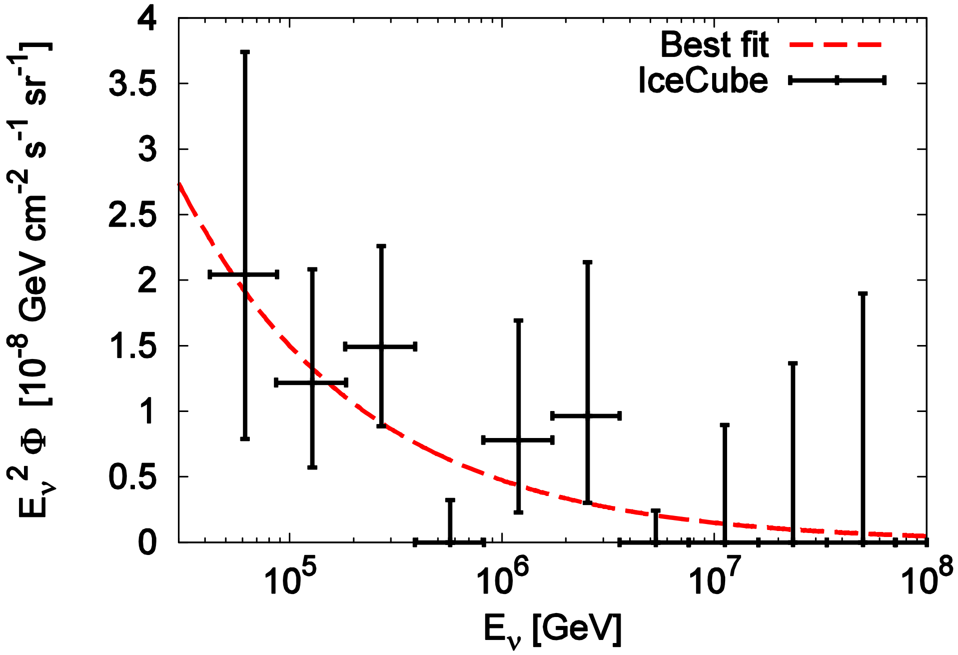
Not detected yet

γ

Three-year data

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

[PRL 113 (2014), 101101]



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

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

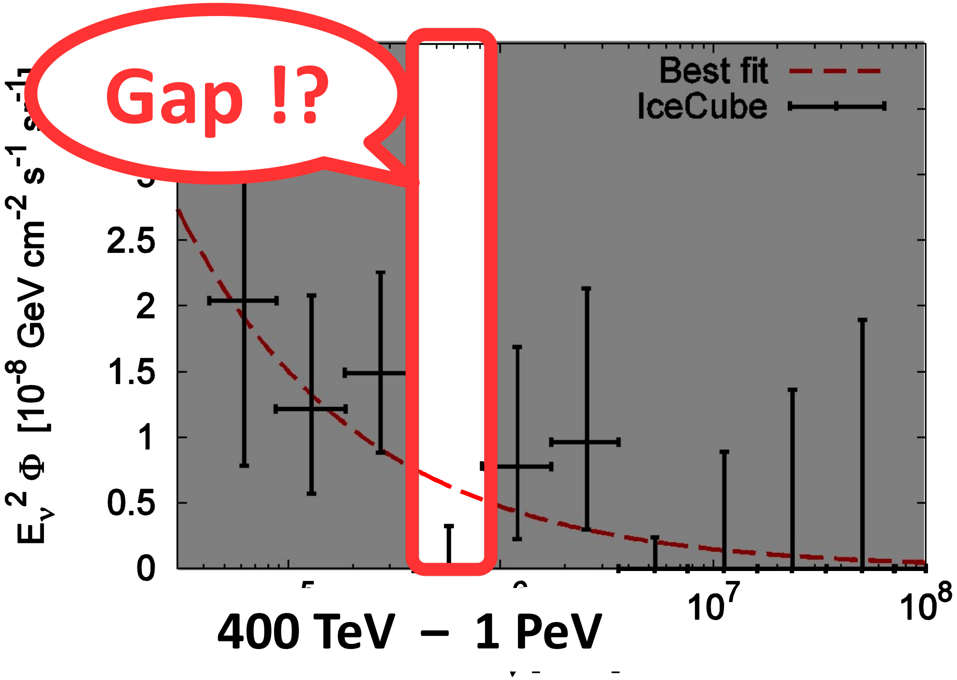
※ Combined analysis:
[Astrophys. J. 809 (2015) 1, 98]

γ

Gap or fluctuation?

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

[PRL 113 (2014), 101101]



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

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

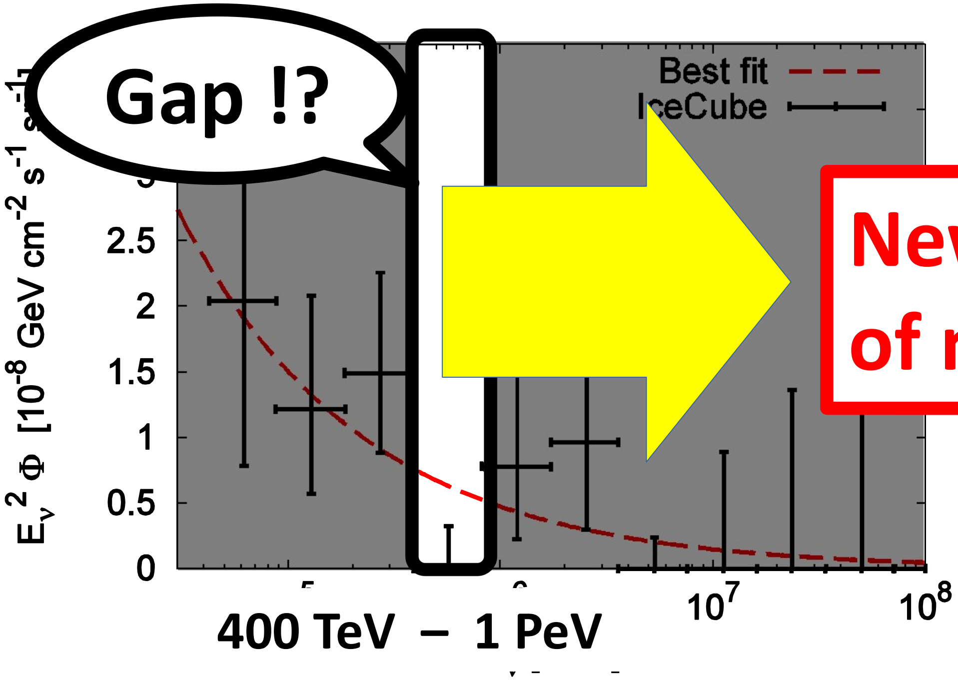
※ Combined analysis:
[Astrophys. J. 809 (2015) 1, 98]

γ

Gap or fluctuation?

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

[PRL 113 (2014), 101101]



1. It rejects a purely atmospheric explanation at 5.7 sigma.

New interactions s of neutrinos ??

3. The best-fit power low is

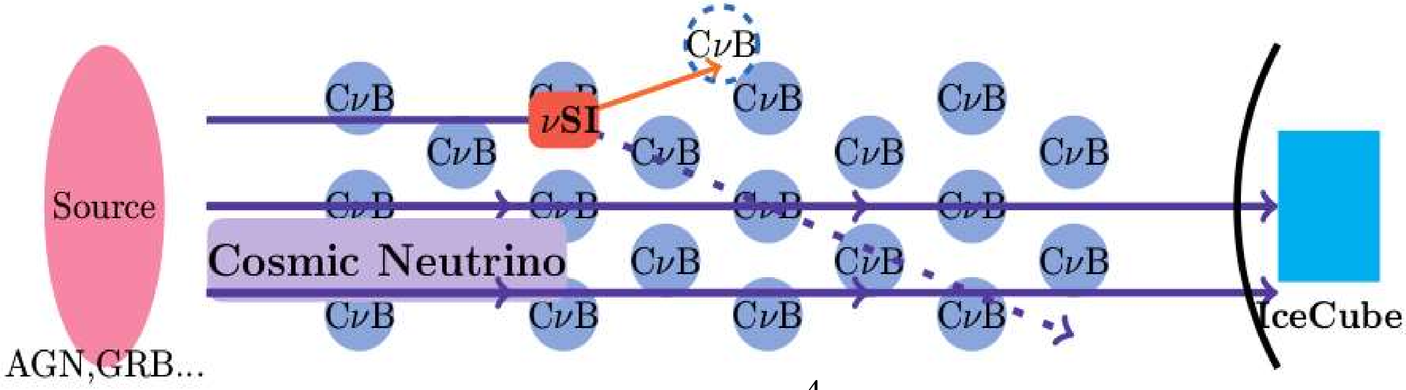
$$\Phi(E) = \phi \left[\frac{E_\nu}{100\mathrm{TeV}}\right]^{-2.5}$$

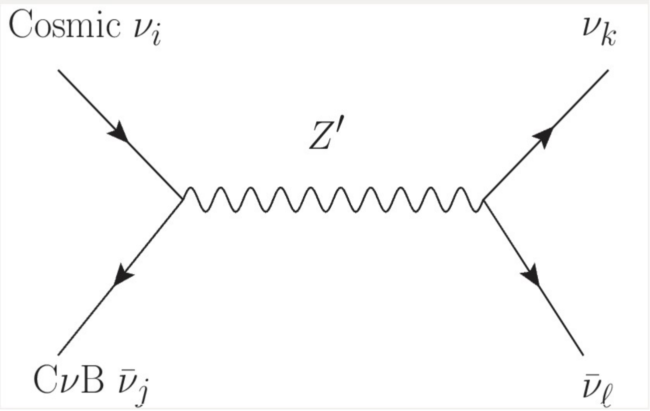
※ Combined analysis:
[Astrophys. J. 809 (2015) 1, 98]

Secret neutrino interaction

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

The Gap may indicate *Secret Neutrino Interaction (νSI)*.





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

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

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

$$\sqrt{s} = \sqrt{(p_{\mathrm{Cosmic}} + p_{\mathrm{C\nu B}})^2}$$

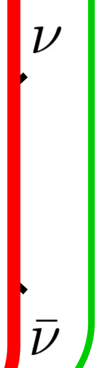
$$\simeq \sqrt{2 E_{\mathrm{Cosmic}} m_\nu} \simeq \mathbf{MeV}$$

500 TeV

10^{-3} eV

Secret neutrino interaction

Rough estimation of the mass of X and its coupling.



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

(1)

M

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

(2) To attenuate sufficient amount of cosmic neutrino:

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

A new gauged U(1): mu - tau

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

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

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

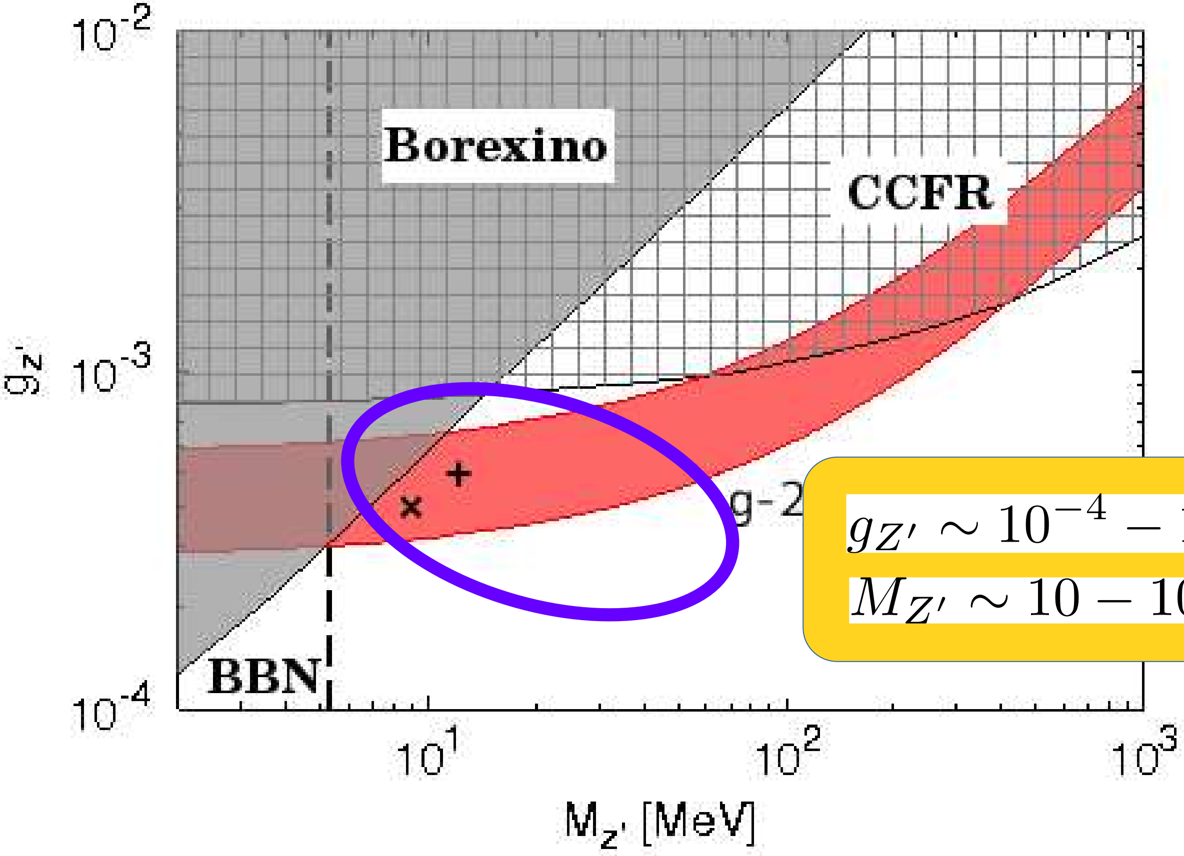
$$+ g_{Z'} (\underbrace{\bar{\nu}_\mu \gamma^\rho P_L \nu_\mu - \bar{\nu}_\tau \gamma^\rho P_L \nu_\tau + \bar{\mu} \gamma^\rho \mu - \bar{\tau} \gamma^\rho \tau}_{L_\mu - L_\tau}) Z'_\rho$$

New gauge coupling

New gauge boson

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

Parameter region



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

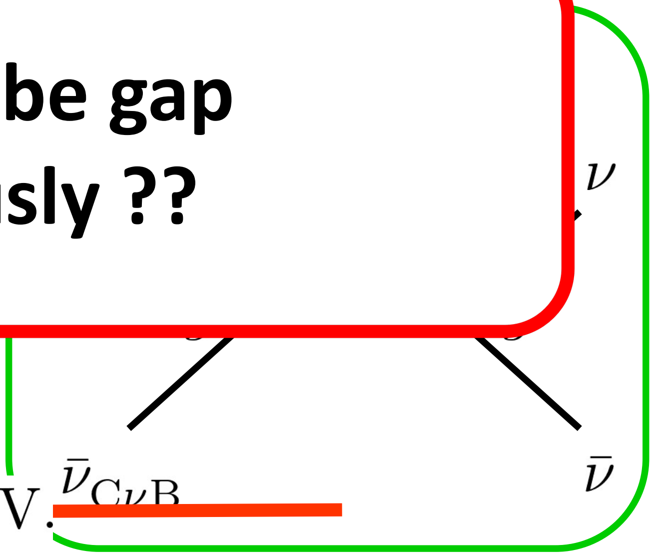
$M_{Z'} \sim 10 - 100 \text{ MeV}$

Secret neutrino interaction

Rou the mass of X and its coupling

Challenge

g-2 and IceCube gap simultaneously ??



(1) Resonant condition requires:

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

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

(2) To attenuate sufficient amount of cosmic neutrino:

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

Propagation of neutrinos

A propagation equation for cosmic neutrino:

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

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

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

c: speed of light

z: redshift parameter

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

Gap: Source distribution

Diffuse neutrino flux for several types of source distribution.

Normal hierarchy

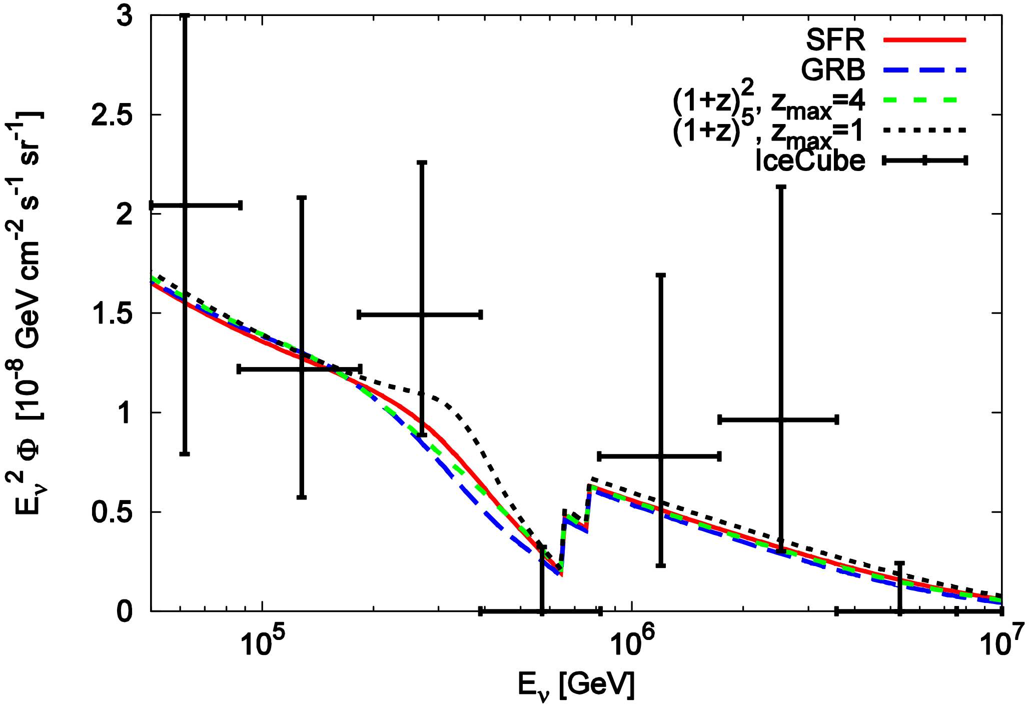
$m_1 = 0.08$ eV

(quasi-degenerate)

$M_{Z'} = 11$ MeV

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

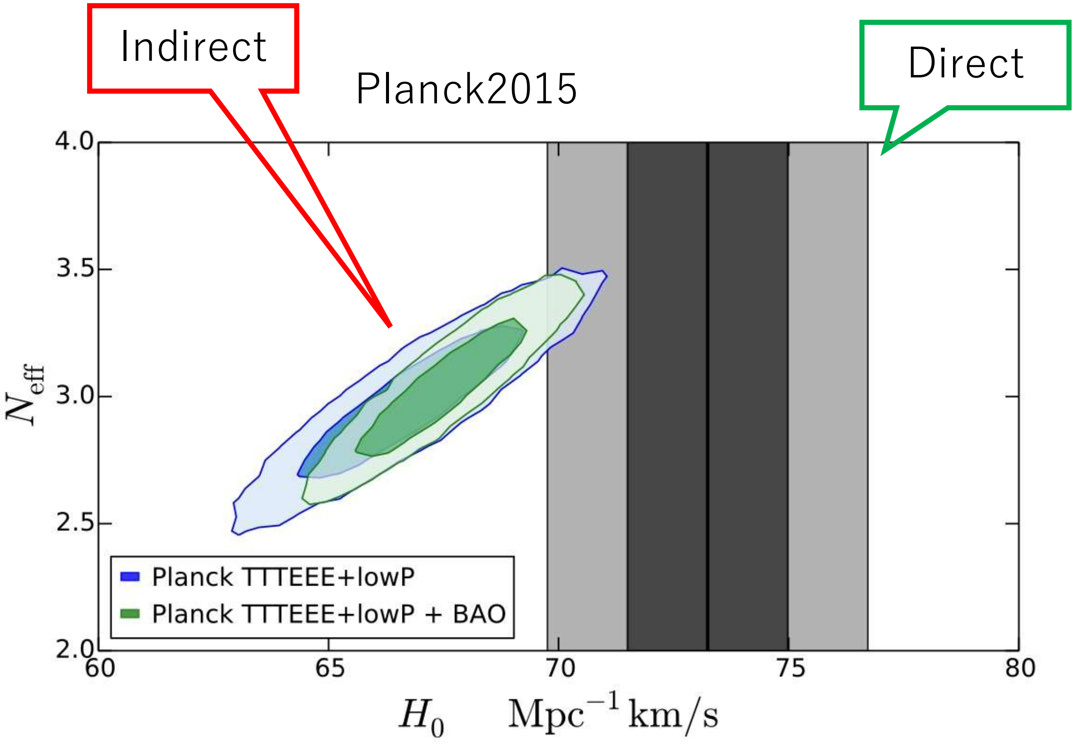
($E_{\rm cut} = 10^7$ GeV)



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

4.3 Hubble Tension

Hubble Tension : Tension between two methods to measure H_0



José Luis Bernal, et al. Journal of Cosmology and Astroparticle Physics, Vol. 2016, No. 10, p. 019 (2016)

Indirect : CMB measurement

with ΛCDM

Far universe, far past

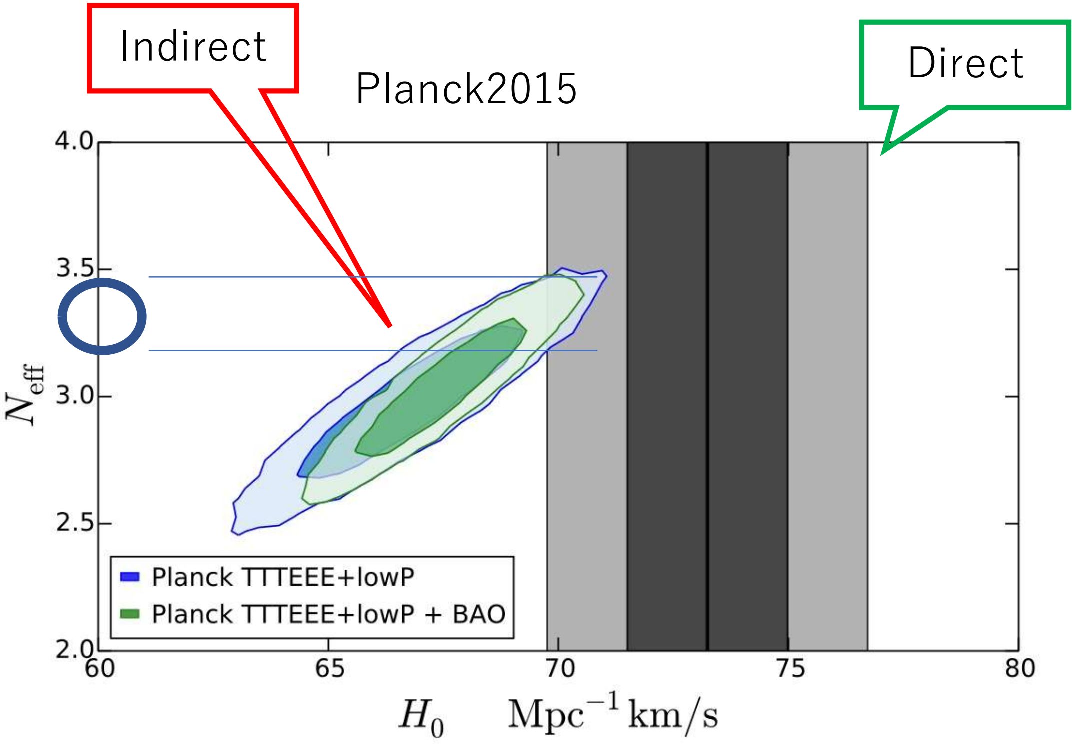
Direct : original definition

$$cz = H_0 d$$

Near universe, near past

In SM $N_{\rm eff}$ = 3.04
K.Akita and M.Yamaguchi Journal of Cosmology and Astroparticle Physics, Vol. 2020, No. 08, p. 012 (2020)

Hubble Tension : Tension between two methods to measure H_0



José Luis Bernal, et al. Journal of Cosmology and Astroparticle Physics, Vol. 2016, No. 10, p. 019 (2016)

Indirect : CMB measurement

with ΛCDM

Far universe, far past

Direct : original definition

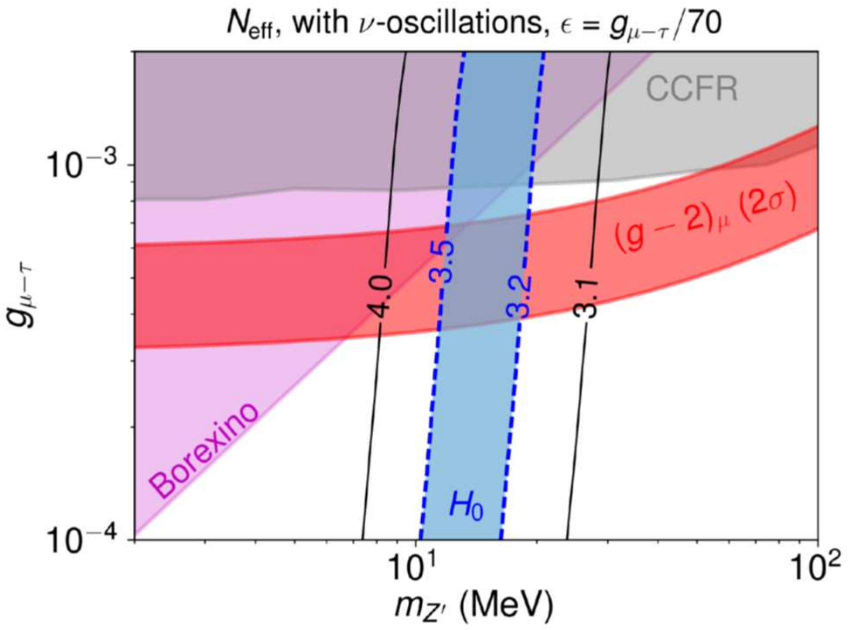
$$cz = H_0 d$$

Near universe, near past

N_{eff} 3.3-3.5 > 3.04

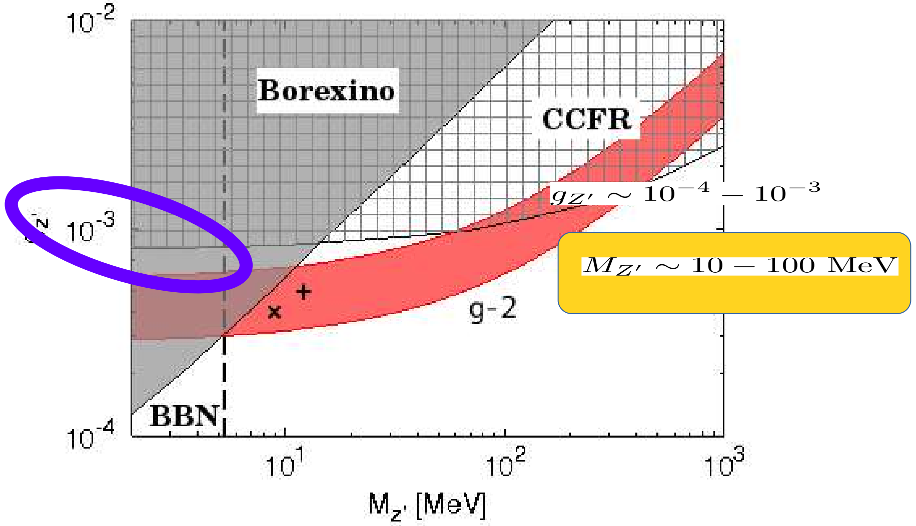
New particle ?

Solution by Lμ − Lτ Gauge Boson



M. Escudero, D. Hooper, G. Krnjaic, and M. Pierre,
“Cosmology with A Very Light Lμ − Lτ Gauge Boson,”
JHEP 03 (2019) 071 `[arXiv:1901.02010]`

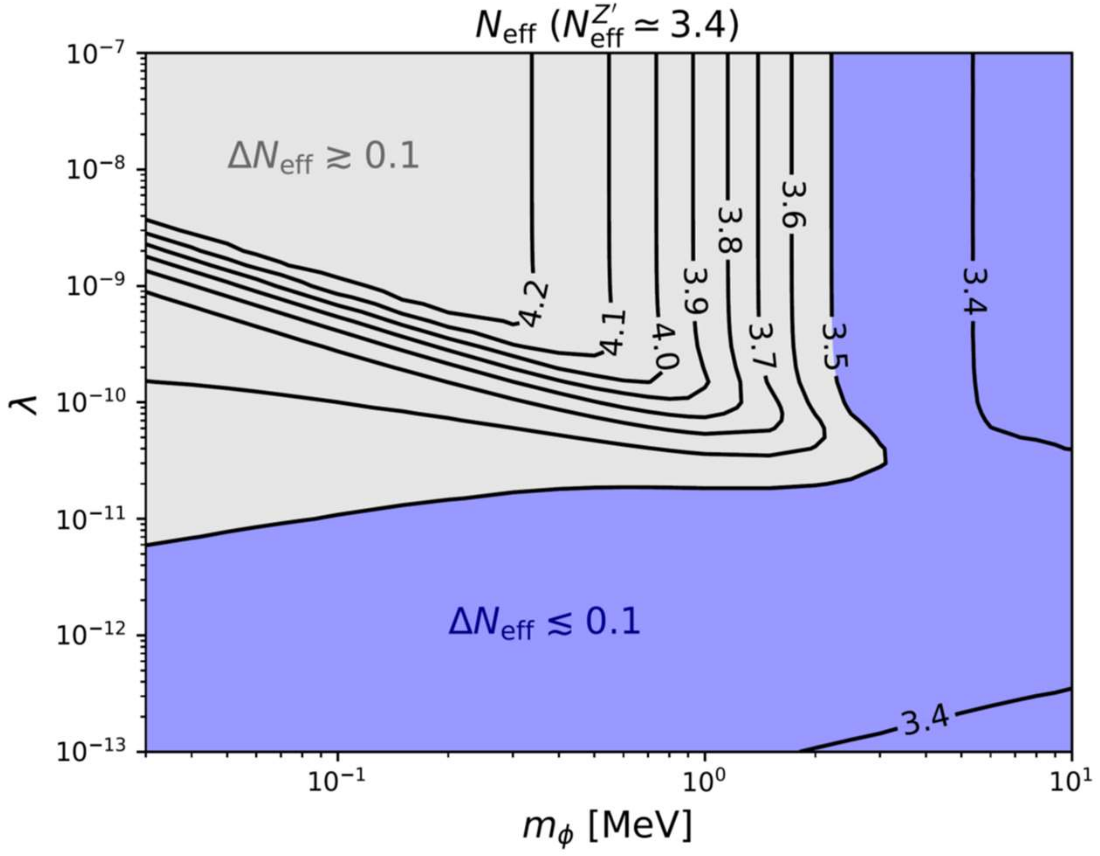
Cf.



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

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

PRD 93 (2016) 7 076006



1MeV

$$N_{\text{eff}}^{Z'} \simeq 3.4$$

$(m_{Z'}, g_{Z'})$ $(13\,\text{MeV}, 5.0 \times 10^{-4})$

Suitable for both g-2 and icecube
Majoron is included

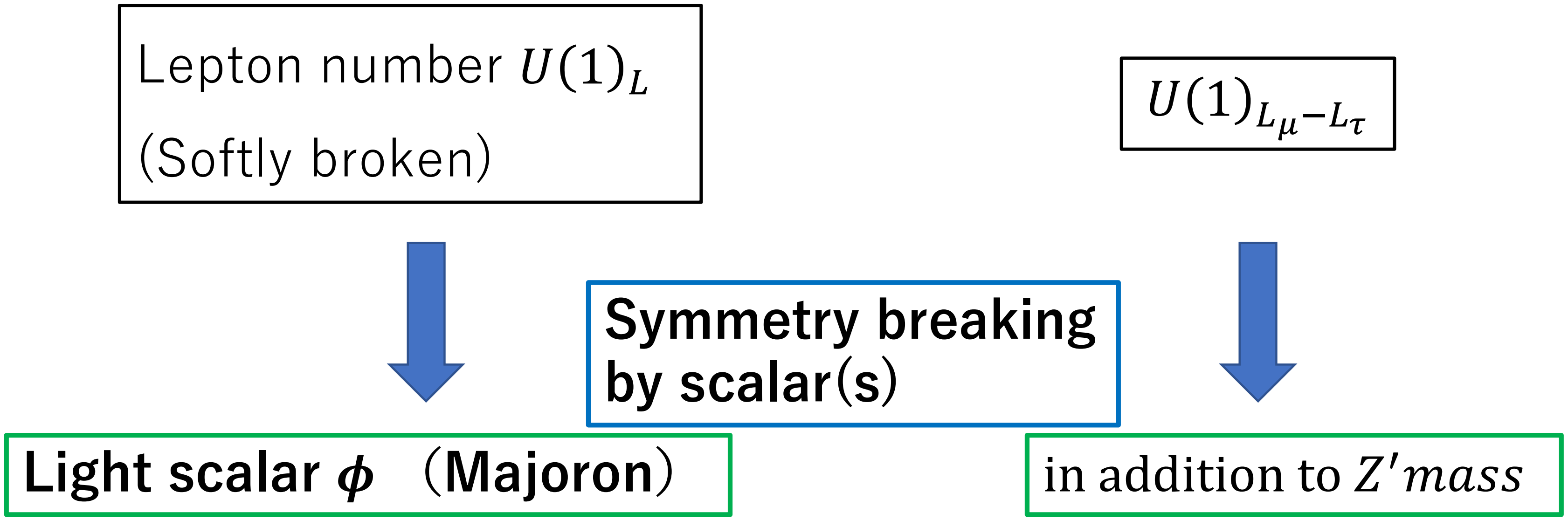
Asai,Asano,JS,Yang, 2309.01162

4.4.ニュートリノ質量とレプトン混合

- (PRD 100 (2019) 9 095012)

Renormalizable $\boldsymbol{L_\mu - L_\tau}$ model see next subsection

$G_{\mathrm{SM}} \times U(1)_{L_\mu - \mathrm{L}_\tau} \times U(1)_L$



Lepton number $U(1)_L$

(Softly broken)

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

Symmetry breaking by scalar(s)

Light scalar ϕ （Majoron）

in addition to $Z'mass$

Renormalizable $L_\mu - L_\tau$ model

- **Z' ingeraction**

$$\mathcal{L}_{Z'} = -\frac{1}{4} Z'^{\rho\sigma} Z'_{\rho\sigma} + \frac{1}{2} m_{Z'}^2 Z'^{\rho} Z'_{\rho} + g_{\mu-\tau} Z'_{\rho} J^{\rho}_{\mu-\tau}$$

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

$$J^{\rho}_{\mu-\tau} \equiv \bar{\mu}\gamma^{\rho}\mu + \bar{\nu}_\mu\gamma^{\rho} P_L \nu_\mu - \bar{\tau}\gamma^{\rho}\tau - \bar{\nu}_\tau\gamma^{\rho} P_L \nu_\tau$$

- **ϕ**

$$\mathcal{L}_{\phi} = h_{\alpha\beta}\, \bar{\nu}_{L,\alpha}\, \nu^{c}_{L,\beta}\, \phi + h.c.$$

- $Z' \leftrightarrow \nu_{\alpha'}\bar{\nu}_{\alpha'}$ （$\alpha' = \mu, \tau$）
- $\phi \leftrightarrow \nu_\alpha \nu_\beta$
- $Z'\nu_\alpha \leftrightarrow \phi\bar{\nu}_\beta$ （$\nu \leftrightarrow \bar{\nu}$もあり）
- $Z'\phi \leftrightarrow \nu_\alpha \nu_\beta$ （$\nu \leftrightarrow \bar{\nu}$もあり）

Should be included

Large μ - τ mixing from neutrino oscillation

➡

Suggesting a symmetry between μ - τ flavor !?

➡

Lμ -Lτ is one of such a symmetry.

Indeed many physicists make models based on it to explain neutrino mass and lepton mixing !!

Zero texture and large mixing

Merits of the symmetry

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

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

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

- Thus, the mass matrix is given by

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

$\longleftrightarrow$

Large mixing

Zero texture and large mixing

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

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

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

- Thus, the mass matrix is given by

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

$$M_{\text{Majorana}} = \begin{pmatrix} \times & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & 0 \end{pmatrix} \xrightarrow{\cancel{U(1)_{L\mu - L\tau}}} M_{\text{Majorana}} = \begin{pmatrix} \times & 0 & \times \\ 0 & 0 & \times \\ \times & \times & 0 \end{pmatrix}$$

Zero textures

Zeros in neutrino mass matrix gives constraint = prediction

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

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

- One zero yields two conditions.
- Zero textures

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

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

- Zero-minor textures

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

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

- One ca che

Testable !

Our model

Majoron here !

Particle contents

2 generations

$\cancel{U(1)}_L$

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

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

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

5. Summary

$L_\mu - L_\tau$ is very interesting in phenomenology, explaining

muon anomalous magnetic moment
IceCube Gap
Hubble tension etc.

Probably relevant with neutrino mass and lepton mixing

It is a gauged family symmetry

Suggesting Grand-Grand Unification , gauge and family unification

Candidate framework

Nonlinear supersymmetric realization ?, Coset Space Dimensional Reduction ?
CosetSpace structure seems interesting