KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Overview of Lorentz and CPT violation search in the neutrino sector

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I. Introduction to Lorentz Invariance Violation (LV)

Why people like Lorentz invariance

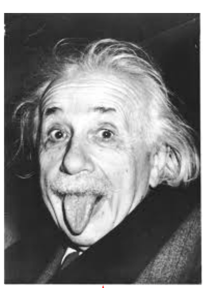
- Lorentz invariance is one of our most fundamental symmetries
  → underlying all our physics laws!

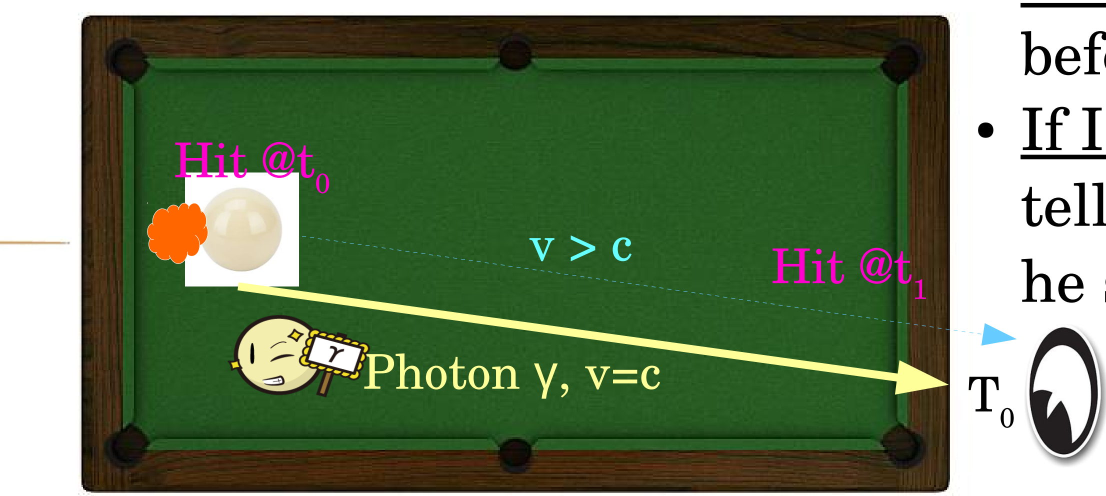
- <u>What are the consequences of breaking the Lorentz invariance ?</u>

  - 1. Physics depends on the observer referential
    → Measure different mixing angle θ at different time of the year…

  - 2. c may depend on observer referential→ Tachyons ($v > c$) are possible

  - 3. Causality can be broken (consequence of #2) :





- <u>Since v > c :</u> see Albert missing before he shot.
- <u>If I send information @v>c :</u> tell Albert he will miss before he shots

So, why bothering you with Lorentz violation ?

- Pragmatic viewpoint : All fundamental symmetries should be tested.
  Physics/Lagrangian is Euclidean invariant ?
  → c invariant under boost / rotation (Michelson and Morley)
  → Physics is Minkowski invariant.

- Dreamer/Theorist/My viewpoint: **Predicted in some theories beyond the Standard Model** (string, quantum loop or non-commutative geometry).

- Arises as a consequence of merging SM w/ gravity → occurs at the Planck Mass Scale $M_P = 10^{19}$ GeV.

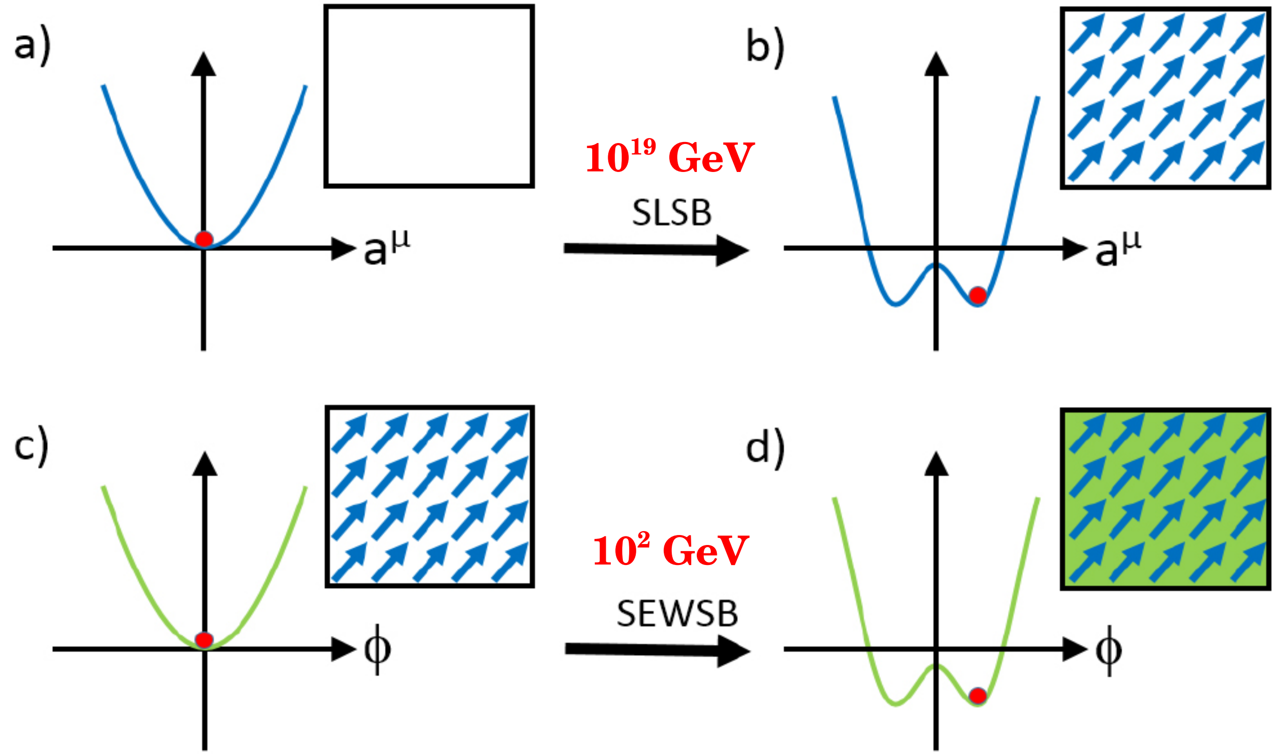
- Highly supressed @GeV scale → Never observed so far.

- So, how to test its effects ?
  → @low energy ($E \ll M_P$) → Construct an effective theory.

How to build a LV theory at low energy ($E < M_P$) ?

- Naively : Add LV corrections to the SM Lagrangian scaling with ~ E / M_p.
- But, this explicit symmetry breaking violates causality and vacuum stability at high energy !
- Effective theory : Standard Model Extension = SM Lagrangian + all terms allowing a LV symmetry breaking **spontaneous** symmetry breaking.

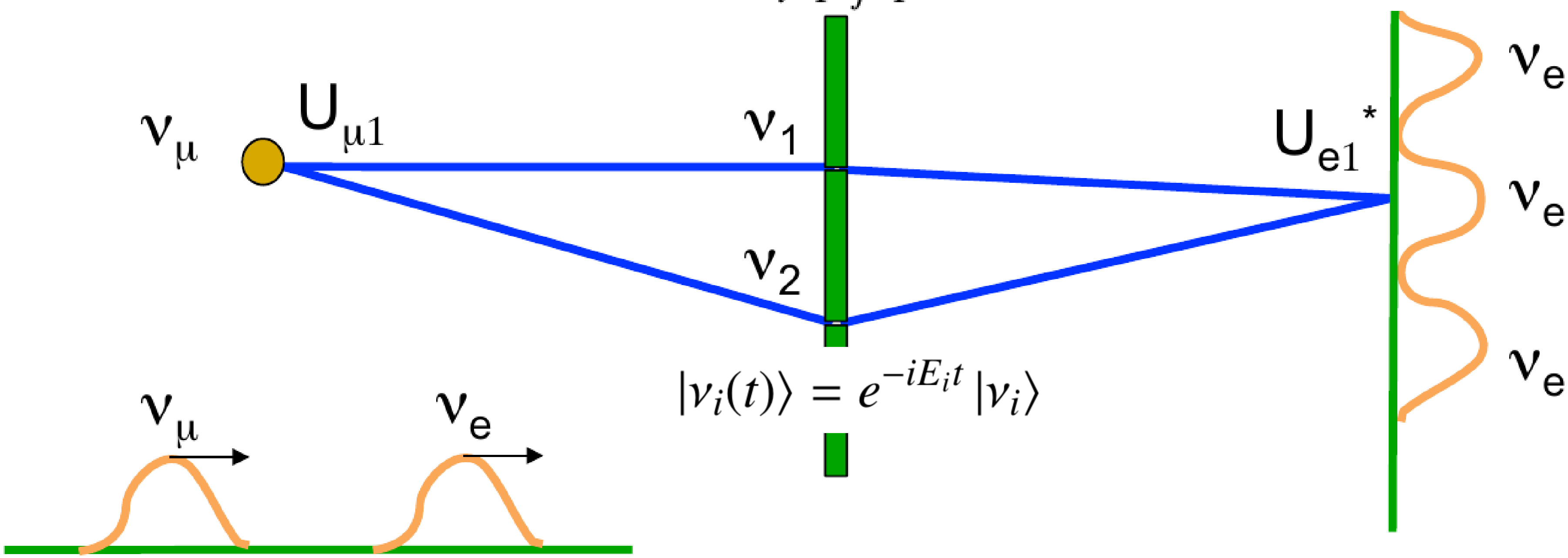
Example of a LV vector field a^μ => Preferential direction



- <u>Arises due to energy difference between mass states / energy eigenstates :</u>

$$P_{\nu_\alpha \to \nu_\beta}(t) \equiv |\langle \nu_\beta(t)|\nu_\alpha\rangle|^2 = \sum_{i=1}^{N}\sum_{j=1}^{N} U^*_{\alpha i} U_{i\beta} U_{\alpha j} U^*_{j\beta} e^{-i(E_i - E_j)t}$$

T. Katori



$$|\nu_i(t)\rangle = e^{-iE_i t}|\nu_i\rangle$$

- Phase difference due to energy (so mass) difference between ν_1 and ν_2 i.e. the Hamiltonian eigenstates : $i\frac{d}{dt}|\nu_i(t)\rangle = H|\nu_i(t)\rangle \overset{invacuum}{=} E_i|\nu_i(t)\rangle$

- Phase difference therefore depends on E, but also on L naturally.

- How the Hamiltonian looks like when LV is allowed ?

Hamiltonian for neutrino in SME

- <u>Hamiltonian eigenstates are modified → Neutrino oscillations modified :</u>

Neutrino-Antineutrino basis

$$\mathcal{H}_{ab} = |\vec{p}|\delta_{ab}\begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix} + \frac{1}{2|\vec{p}|}\begin{pmatrix}(m'^2)_{ab} & 0\\ 0 & (m'^2)^*_{ab}\end{pmatrix} + \frac{1}{|\vec{p}|}\begin{pmatrix}[(a_L)^\mu p_\mu - (c_L)^{\mu\nu} p_\mu p_\nu]_{ab} & -i\sqrt{2}p_\mu(\epsilon_+)_\nu[(g^{\mu\nu\sigma}p_\sigma - H^{\mu\nu})C]_{ab}\\ i\sqrt{2}p_\mu(\epsilon_+)^*_\nu[(g^{\mu\nu\sigma}p_\sigma + H^{\mu\nu})C]^*_{ab} & [-(a_L)^\mu p_\mu - (c_L)^{\mu\nu} p_\mu p_\nu]^*_{ab}\end{pmatrix}$$

Removed by rephasing

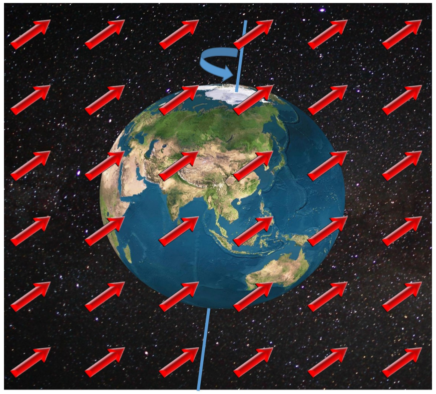
Standard 3 flavour oscillations

LV term

- 3-flavour PMNS model modified → Increase/decrease oscillation.
  + Oscillation can happen even for massless neutrinos

- <u>2 types of coefficients :</u> a_L are CPT-odd and c_L are CPT-even coefficient
  → a_L has dimension ∝ E → Oscillation x E → Different than sterile ν.

- Oscillation depends on particle direction p^μ
  <=> Oscillation depends on sidereal time (Earth rotation)

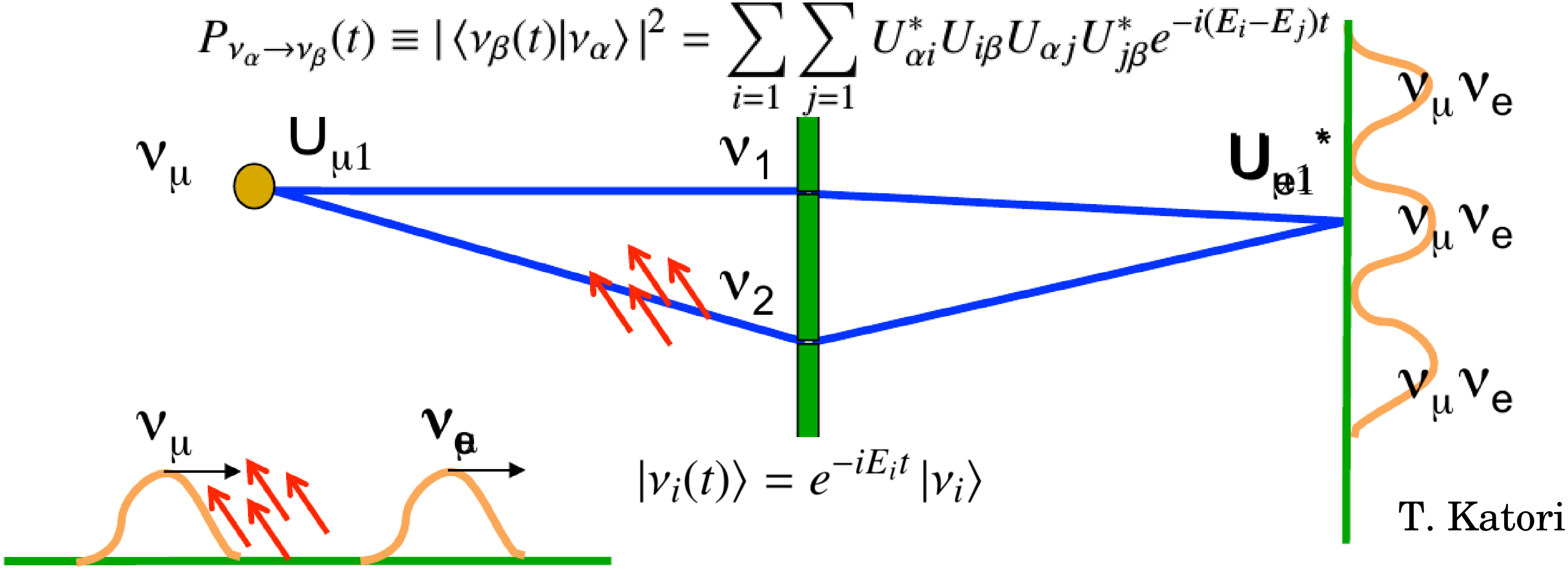


- ν ↔ $\bar{\nu}$ oscillations possible, ν can go faster than light...

Neutrino oscillations with Lorentz invariance

- Arises due to energy difference between mass states / energy eigenstates :

$$P_{\nu_\alpha \to \nu_\beta}(t) \equiv |\langle \nu_\beta(t)|\nu_\alpha\rangle|^2 = \sum_{i=1}^{N}\sum_{j=1}^{N} U^*_{\alpha i}U_{i\beta}U_{\alpha j}U^*_{j\beta}e^{-i(E_i-E_j)t}$$



$$|\nu_i(t)\rangle = e^{-iE_i t}|\nu_i\rangle$$

- LV field couples differently to ν_1 and ν_2
  → New phase difference → modify oscillation pattern compared to PMNS

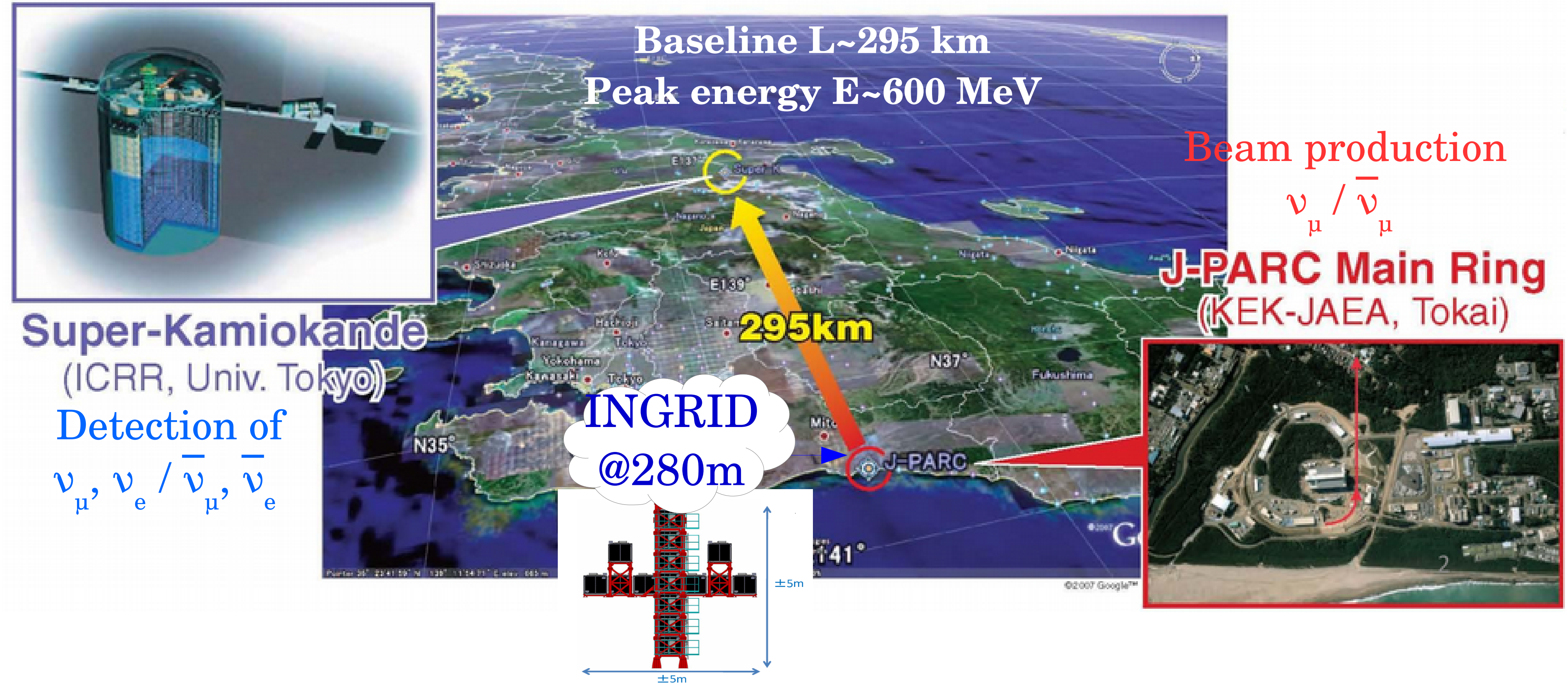
- LV coupling of ν_1 and ν_2 varies with E
  → additional E dependency of oscillation pattern.

- LV couples differently wrt ν direction → Osc. depends on sidereal time

II. LV search 1st method : Sidereal modulation search using T2K

The T2K experiment

- ν_e appearance in a ν_μ beam and ν_μ disappearance → See A. Cervera's talk



- But this time, we focus on the INGRID near detector → @280m.

- @280m : No standard PMNS oscillation can happen at this distance.

- <u>If any oscillation @INGRID :</u> Sterile neutrino, Lorentz violation effect….

Sidereal time dependent oscillations @280m

- **Oscillation probability at near detectors :**

$$P_{\nu_\mu \to \nu_x} = \left(\frac{L}{hc}\right)^2 |(C_{\mu x}) + (A_s)_{\mu x} \sin(\omega_\oplus T_\oplus) + (A_c)_{\mu x} \cos(\omega_\oplus T_\oplus) + (B_s)_{\mu x} \sin(2\omega_\oplus T_\oplus) + (B_c)_{\mu x} \cos(2\omega_\oplus T_\oplus)|^2$$

$T_\oplus$ the sidereal time, and $\omega_\oplus = \frac{2\pi}{23^h 56^m 04.0982^s}$ the sidereal angular phase

- L^2 dependency (neutrino baseline).
- 5 effective parameters C, Ac, As, Bc, Bs → $(C)_{ab} = (C)^{(0)}_{ab} + E(C)^{(1)}_{ab}$ With :
- 28 SME parameters a_L(GeV), c_L

$$(C)^{(0)}_{ab} = (a_L)^T_{ab} - \hat{N}^Z (a_L)^Z_{ab}$$

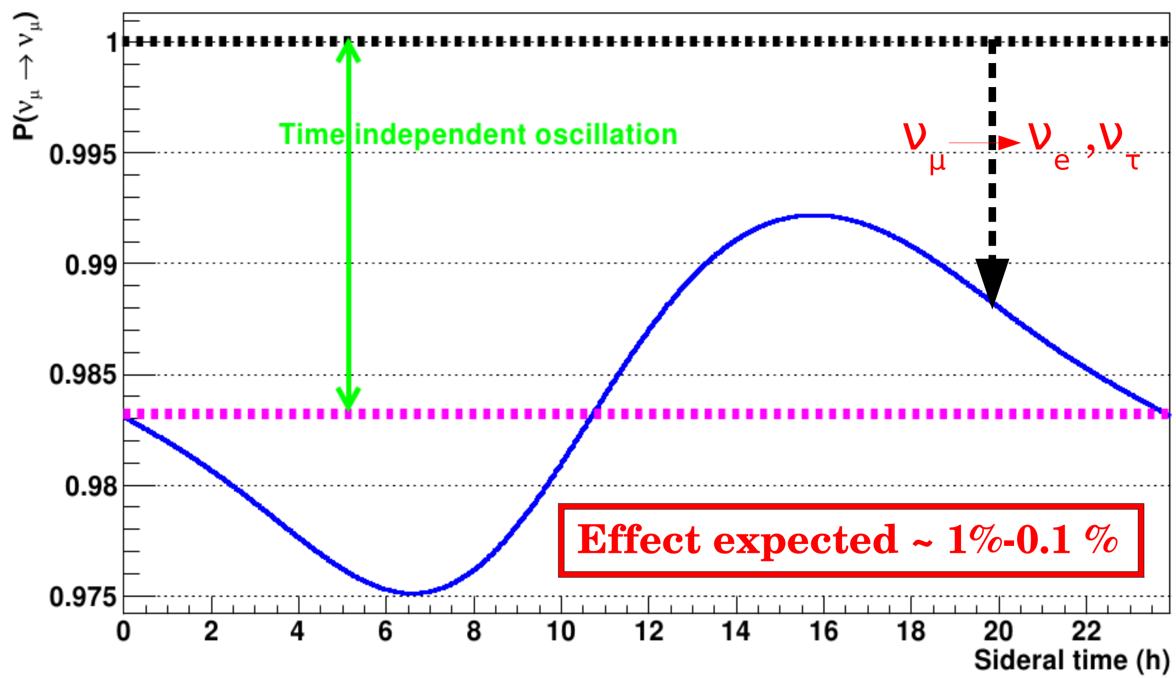
$$(C)^{(1)}_{ab} = -\frac{1}{2}(3 - \hat{N}^Z \hat{N}^Z)(c_L)^{TT}_{ab} + 2\hat{N}^Z (c_L)^{TZ}_{ab} + \frac{1}{2}(1 - 3\hat{N}^Z \hat{N}^Z)(c_L)^{ZZ}_{ab}$$

- E (e.g. C^0) and E^2 (e.g. C^1) dependency
- All parameters are direction depdendent except a^T and c^{TT}.
- **Focus on ν_μ disappearance** (higher statistics) → Constraint μ→τ and μ→e.

- **Oscillation probability at near detectors :**

$$P_{\nu_\mu \to \nu_x} = (\frac{L}{hc})^2 |(C_{\mu x}) + (A_s)_{\mu x} \sin(\omega_\oplus T_\oplus) + (A_c)_{\mu x} \cos(\omega_\oplus T_\oplus) + (B_s)_{\mu x} \sin(2\omega_\oplus T_\oplus) + (B_c)_{\mu x} \cos(2\omega_\oplus T_\oplus)|^2$$

$T_\oplus$ the sidereal time, and $\omega_\oplus = \frac{2\pi}{23^h 56^m 04.0982^s}$ the sidereal angular phase



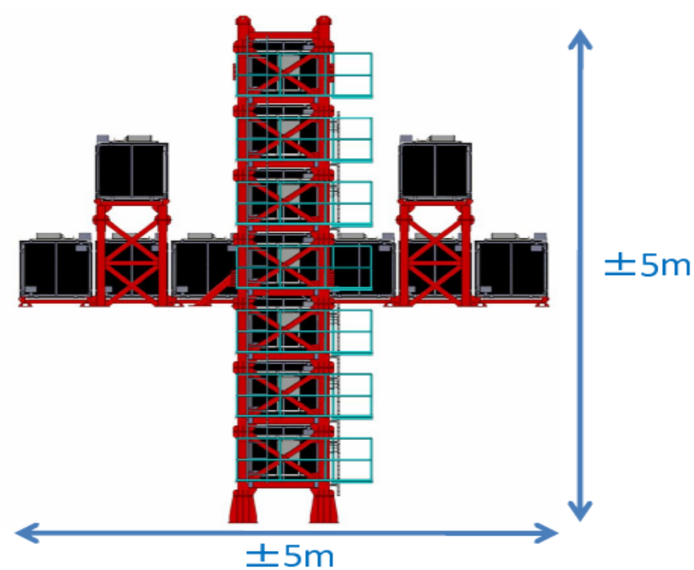
- Time-independent oscillation : alternative hypothesis to sterile to explain short baseline disappearance (LSND, MiniBooNE…)

- Sidereal time oscillation : higher sensitivity ➡ **This work**

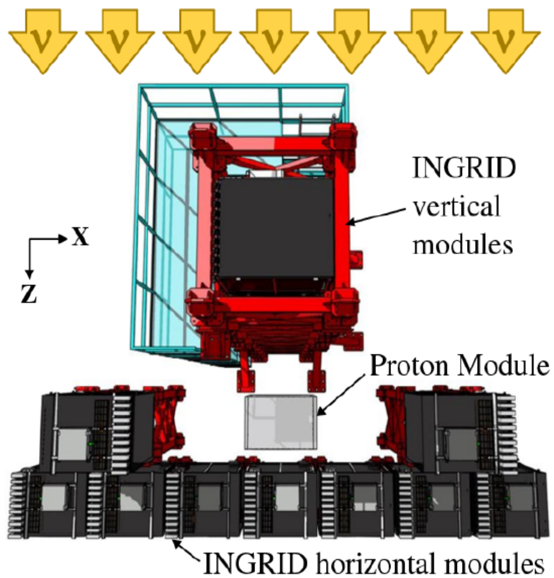
Ingredient #2 : a detector → INGRID

- **14 modules in a cross shape structure** + 2 shoulder modules

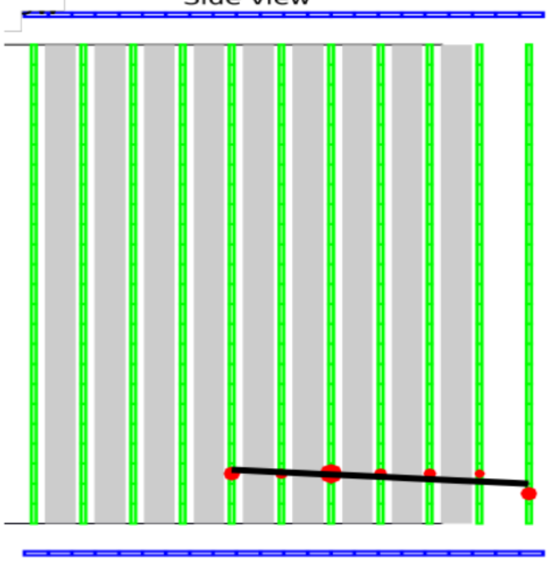
<u>Front view :</u>



<u>Side view :</u>



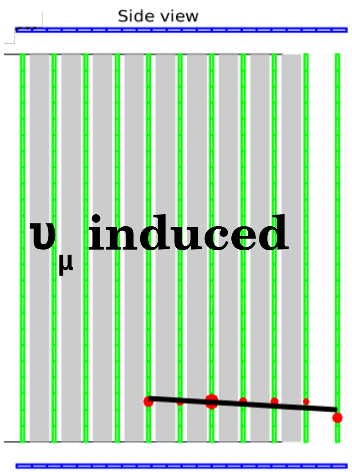
ν_μ induced

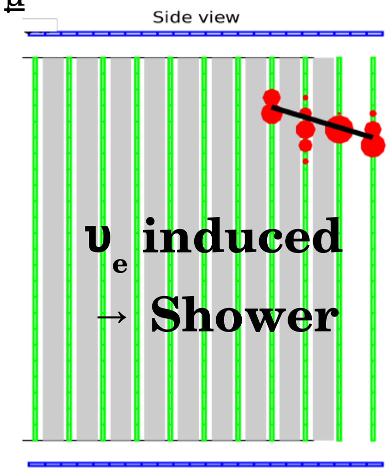


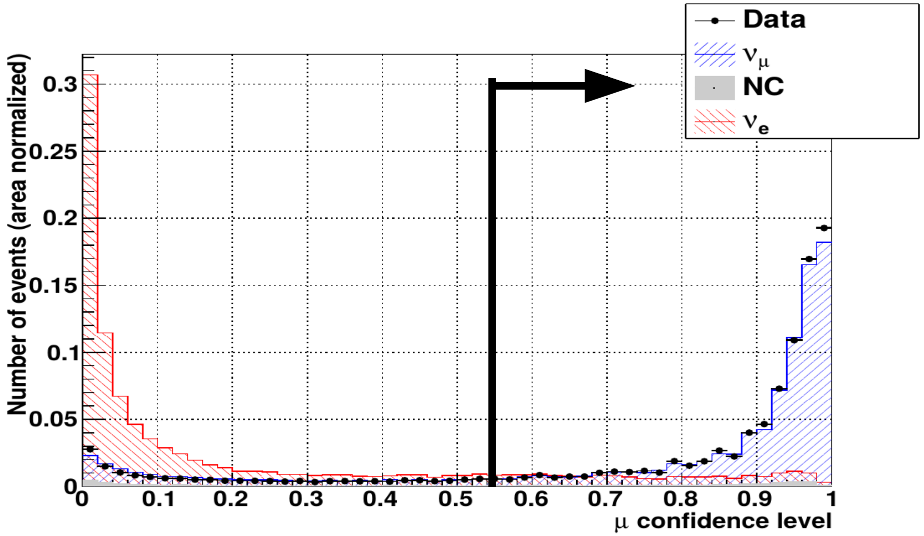
- **<u>1 Module =</u>** 1.4 m³ sandwich of :
  - **9 iron planes** (interaction)
  - **11 X/Y scintillator planes** (detection)
- **<u>Data sample :</u>** (almost) full T2K POT from Run 1 (2010) to Run 4 (2013) : 6.6×10^{20} POT → Correspond to **6.8×10^{6} events**

Ingredient #3 : build pure ν_μ sample

- Generate a pure ν_μ sample :

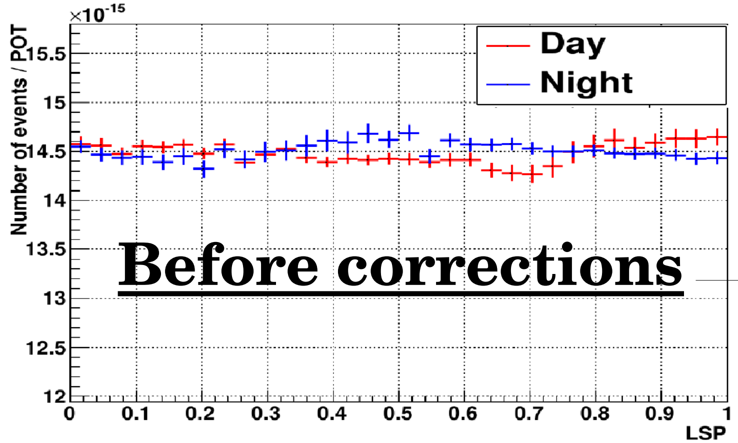


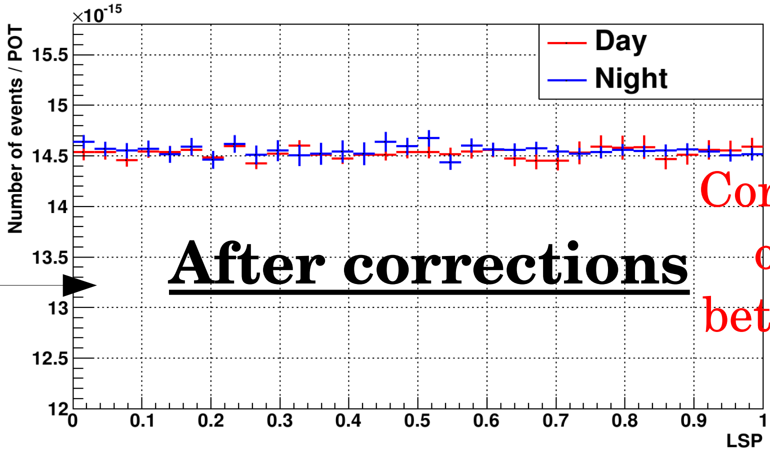




- Ingredient #4 : Correct time-dependent sources (+evaluate systematics) :
  - From ν_μ beam (tidal effect, re-alignement of beam…)
  - From INGRID : gain, dark noise variation with time etc.

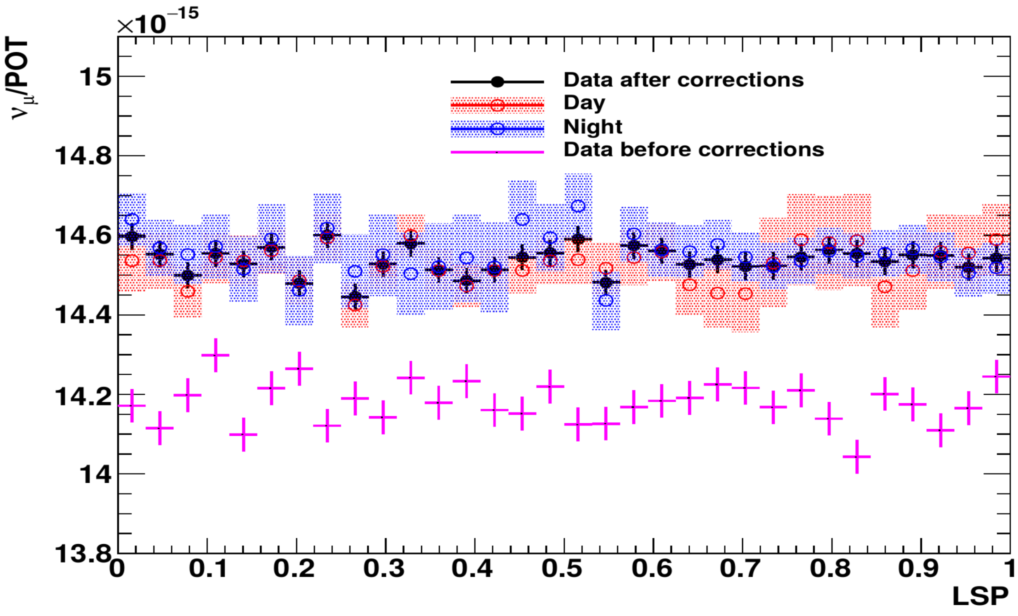
- Validation : Compare day&night → **should agree w/ or w/o LV effect**





Corrections washed out differences between harmonics

Data distribution with sidereal time



Associated systematics

Source	Systematic uncertainty (%)
Pile-up	0.01
MPPC dark noise	0.01
MPPC gain variation	0.06
Beam position	0.03
Rate correction	0.05
Total systematic	0.08

Statistical uncertainty : 0.2 %

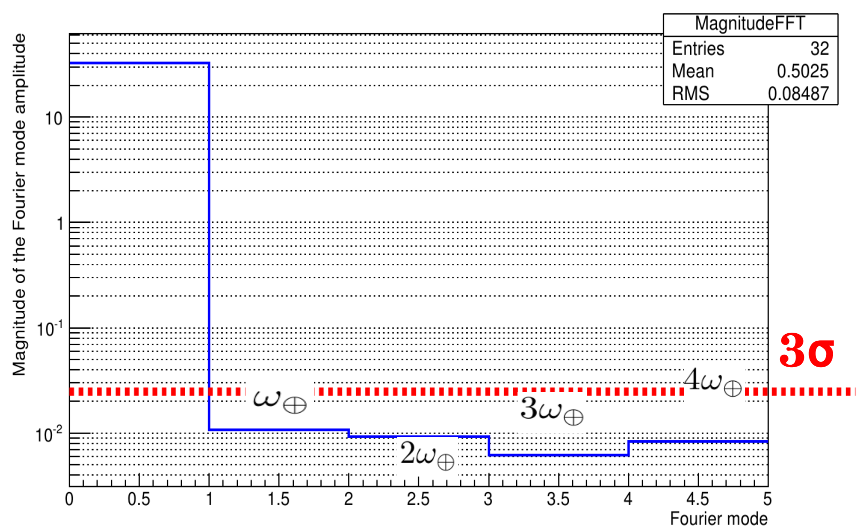
→ Systematic error is negligible

→ Advantage of sidereal dependency

$$P_{\nu_\mu \to \nu_x} = (\frac{L}{hc})^2 |(C)_{\mu x} + (A_s)_{\mu x} \sin(\omega_\oplus T_\oplus) + (A_c)_{\mu x} \cos(\omega_\oplus T_\oplus) + (B_s)_{\mu x} \sin(2\omega_\oplus T_\oplus) + (B_c)_{\mu x} \cos(2\omega_\oplus T_\oplus)|^2$$

→ Can be developed in 5 harmonics : constant, $\omega_\oplus$, $2\omega_\oplus$, $3\omega_\oplus$ and $4\omega_\oplus$

- 1st Step : Search for deviation to 3-flavour SM = « no oscillation »
  → Fast Fourier transform
  → Compatible with a flat signal within 3σ.



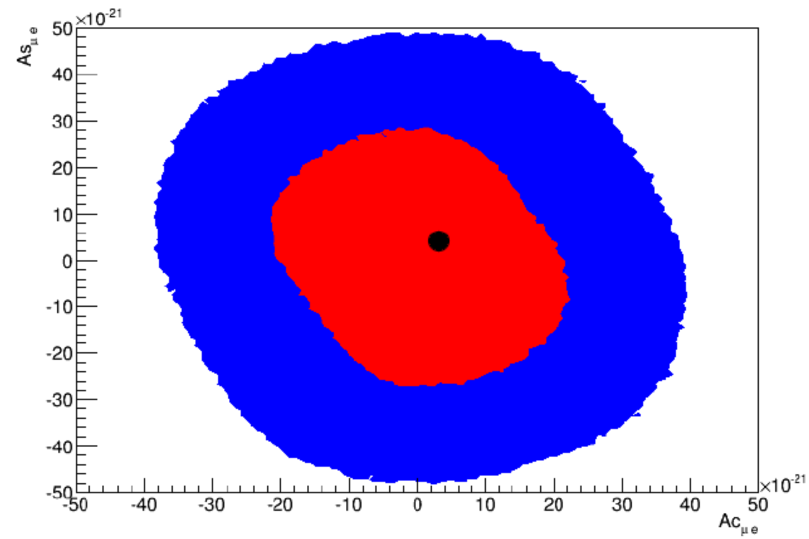
Likelihood fit result

- <u>2nd Step : extract limit on the SME coefficients :</u>
  → Full binned likelihood method to preserve correlations (crucial)

- **Too many correlations** to perform a fit of the 28 SME parameters : a, c

- Fit all 10 effective parameters C, A_c, A_s, B_c, B_s for $\mu \rightarrow \tau$ and $\mu \rightarrow e$.

x10^{-20} GeV	$\mathcal{C}_{\mu e}$	$(\mathcal{A}_c)_{\mu e}$	$(\mathcal{A}_s)_{\mu e}$	$(\mathcal{B}_c)_{\mu e}$	$(\mathcal{B}_s)_{\mu e}$
BF $\pm$ 68% C.L Limits	$-0.3^{+1.3}_{-1.3}$	$0.3^{+1.5}_{-1.5}$	$0.4^{+1.9}_{-2.0}$	$-1.2^{+1.3}_{-1.3}$	$2.0^{+1.6}_{-1.6}$
95% C.L Limits	3.0	3.2	3.8	2.6	3.1
95% C.L Sensitivity	2.8	3.5	3.5	3.7	3.5
	$\mathcal{C}_{\mu\tau}$	$(\mathcal{A}_c)_{\mu\tau}$	$(\mathcal{A}_s)_{\mu\tau}$	$(\mathcal{B}_c)_{\mu\tau}$	$(\mathcal{B}_s)_{\mu\tau}$
BF $\pm$ 68% C.L Limits	$-0.8^{+1.4}_{-1.2}$	$-0.4^{+1.5}_{-1.5}$	$-3.2^{+2.0}_{-1.9}$	$-0.4^{+1.4}_{-1.2}$	$1.1^{+1.6}_{-1.6}$
95% C.L Limits	3.0	3.2	3.8	2.7	3.1
95% C.L Sensitivity	3.0	2.9	3.1	3.8	3.7



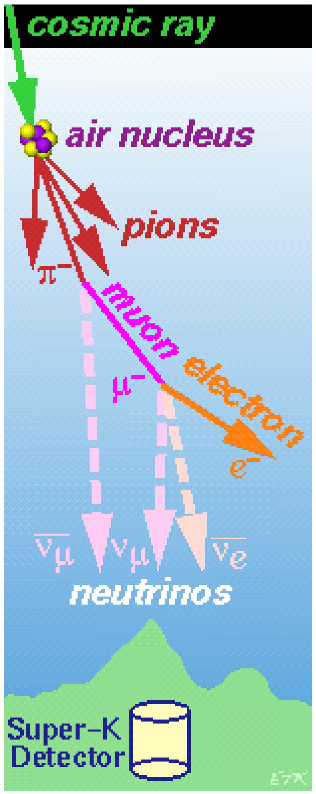
- Constraints ~ 10^{20} GeV → oscillations able to probe for LV at E > $M_P = 10^{19}$ GeV !

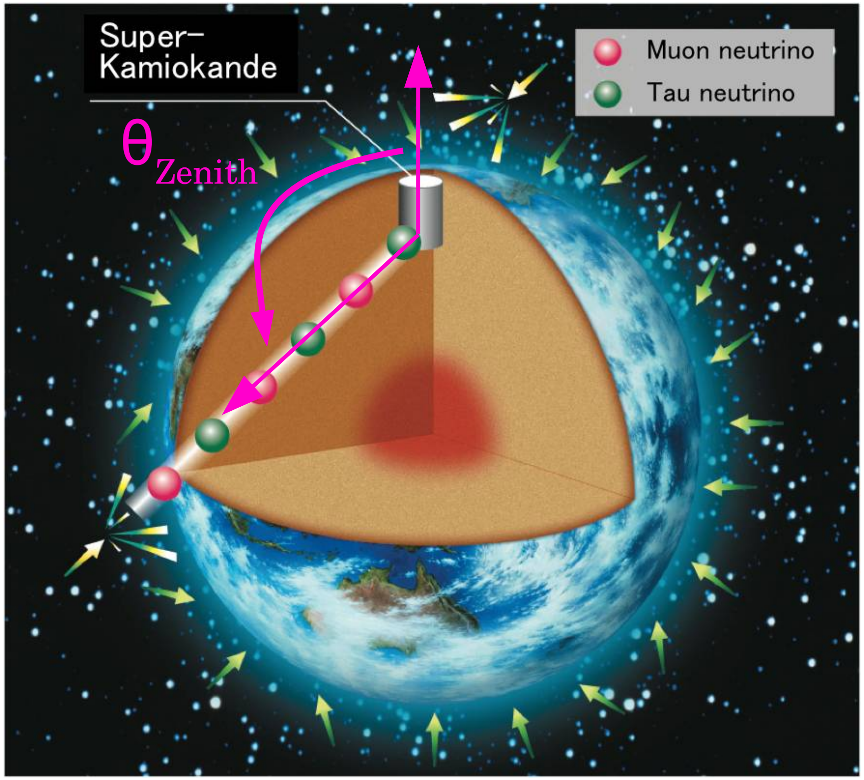
- **World-leading correlated constraints on almost all parameters**

II. LV search 2nd method :
Time-indepedendent modifications of the 3-flavour standard oscillation with Super-Kamiokande

LV search using atmospheric neutrino @SK

- Super-Kamiokande is a 50kT water Cherenkov detector → G. Pronost talk.
- Large Physics Portfolio → Focus here on atmospheric neutrinos.





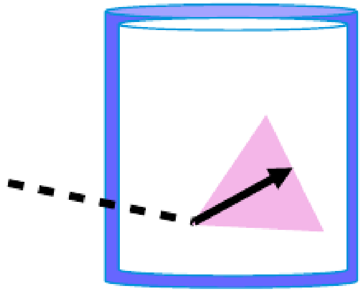
- Cosmic ray produces ν_μ and ν_e in a ~ 1/2 ratio.
- Flux spread from ~100 MeV to 1 TeV.

- Oscillation search : Measure number of ν_μ & ν_e as a function of L and E.
- L is determined by measuring the zenith angle θ_{Zenith}
  → L varies from 10 km to 13000km.

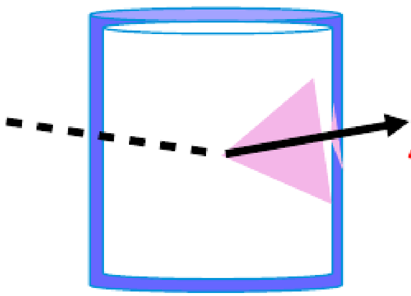
LV search using atmospheric neutrino @SK

- E is determined using sample separation and energy deposited in SK :

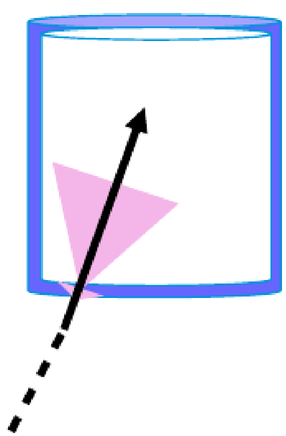
Fully Contained (FC)



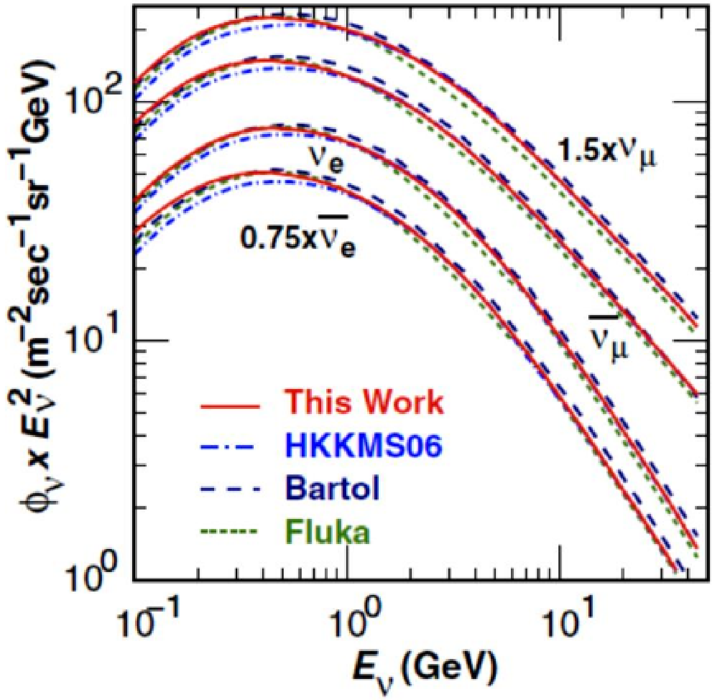
Partially Contained (PC)

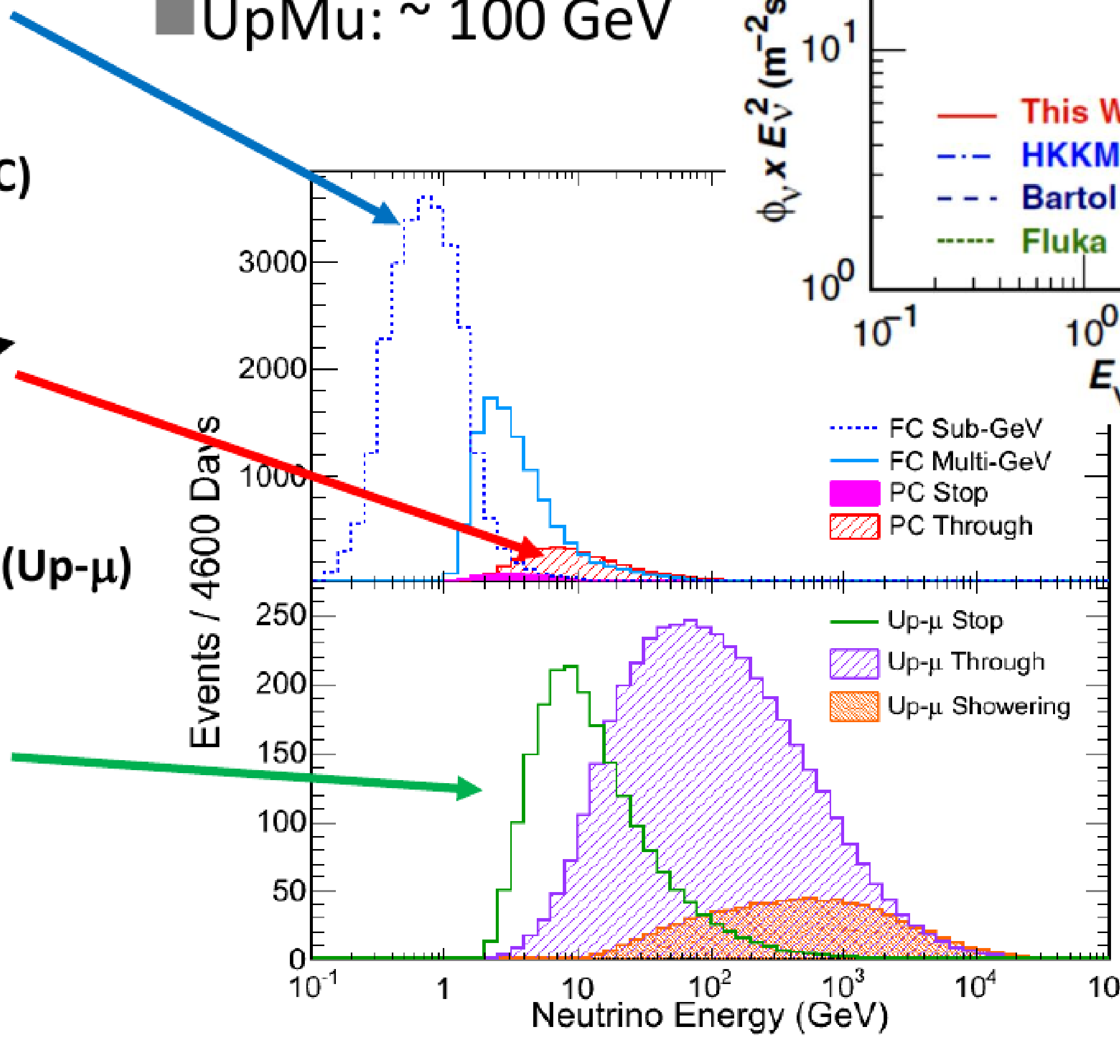


Upward-going Muons (Up-μ)



- Average energies
  - FC: ~ 1 GeV
  - PC: ~ 10 GeV
  - UpMu: ~ 100 GeV





Y. Hayato

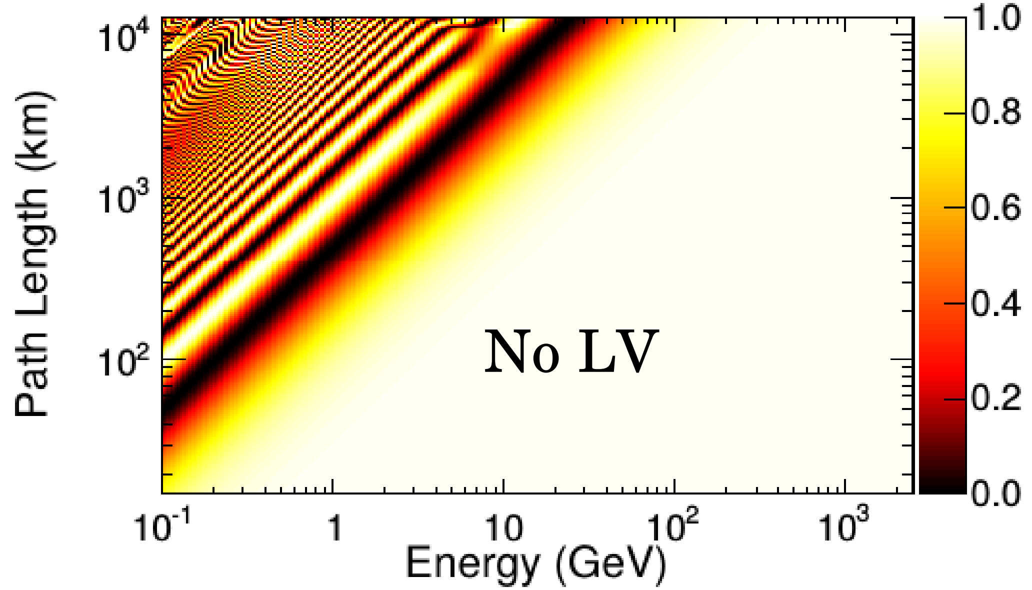
LV search using atmospheric neutrino @SK

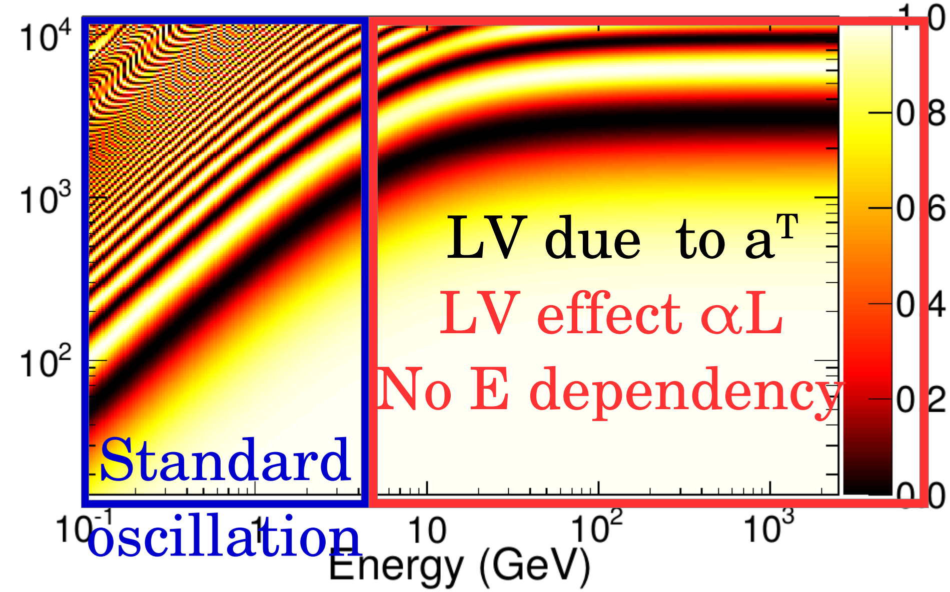
- Evaluate sidereal-time independent effect of Lorentz Violation
  → Deviation to 3ν model → Complementary to T2K result.

- Long-baseline oscillation hamiltonian can be re-written :

$$H = \underbrace{U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{pmatrix} U^\dagger}_{\text{PMNS oscillation}} \pm \underbrace{\sqrt{2}G_F \begin{pmatrix} N_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}}_{\text{Matter effect}} \pm \underbrace{\begin{pmatrix} 0 & a^T_{e\mu} & a^T_{e\tau} \\ (a^T_{e\mu})^* & 0 & a^T_{\mu\tau} \\ (a^T_{e\tau})^* & (a^T_{\mu\tau})^* & 0 \end{pmatrix} - \frac{4E}{3} \begin{pmatrix} 0 & c^{TT}_{e\mu} & c^{TT}_{e\tau} \\ (c^{TT}_{e\mu})^* & 0 & c^{TT}_{\mu\tau} \\ (c^{TT}_{e\tau})^* & (c^{TT}_{\mu\tau})^* & 0 \end{pmatrix}}_{\text{LV effects}}$$

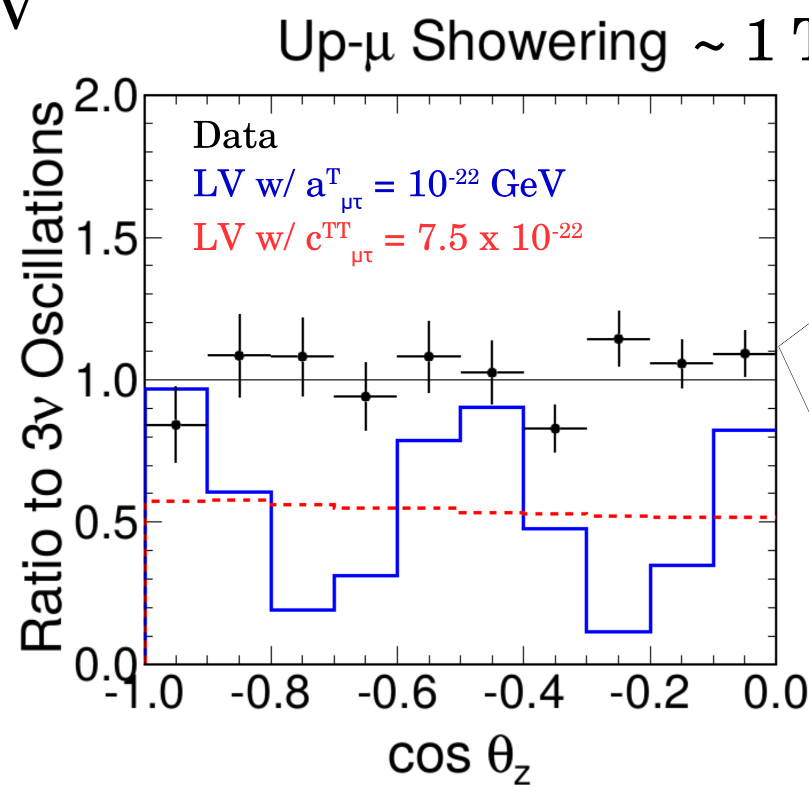
- Measure c^{TT} (effect $\propto LE$) and a^T ($\propto L$) only → Not measured by T2K.

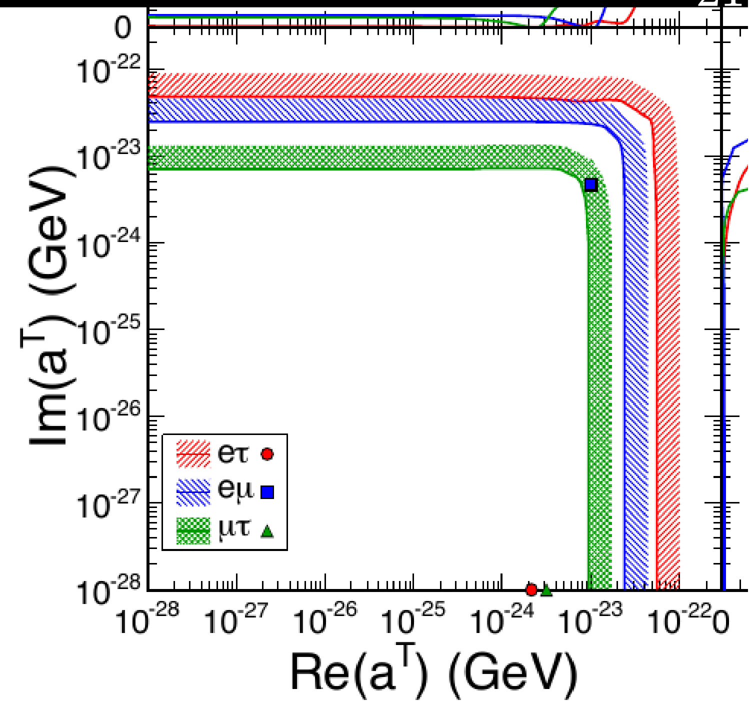


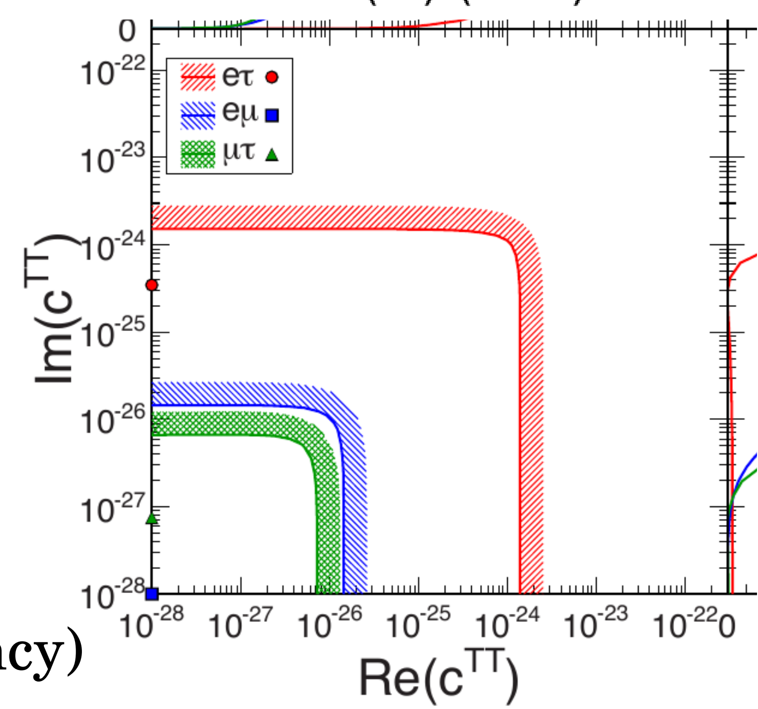


- Discrimination using > 5 GeV sample → Partially contained and upward

- Do likelihood fit on all the atmospheric samples assuming LV







- Compatibility with no-LV scenario: $\Delta\chi^2 < 1.4$

- World-leading limits on time-independent parameters
  → $a^{TT} < 10^{-23}$ GeV
  → $c^{TT} < 10^{-27}$ (High sensitivity from E-dependency)

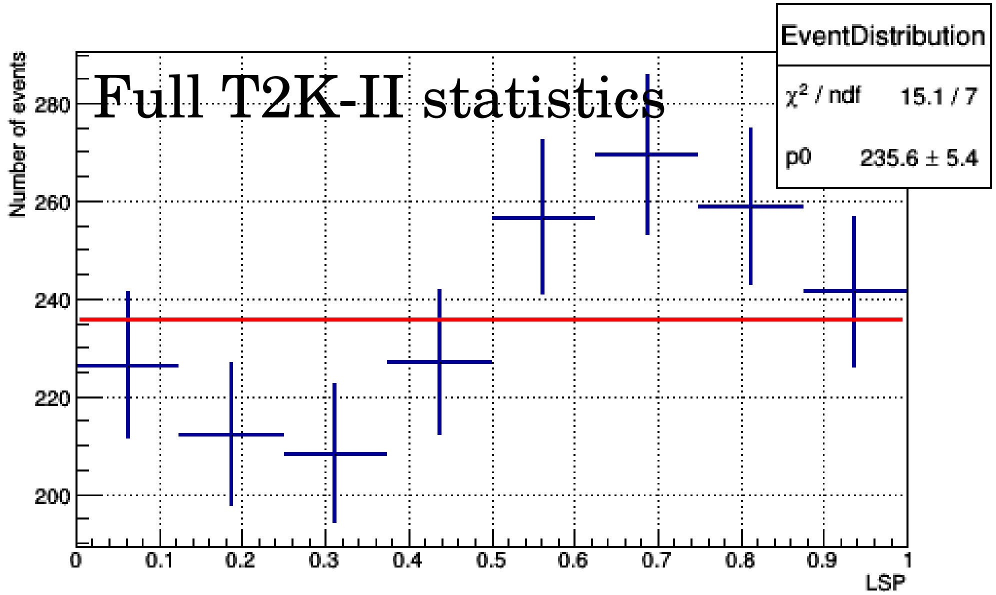
IV. Potential of future experiments to detect Lorentz Violation

Future Long-Baseline oscillation potential

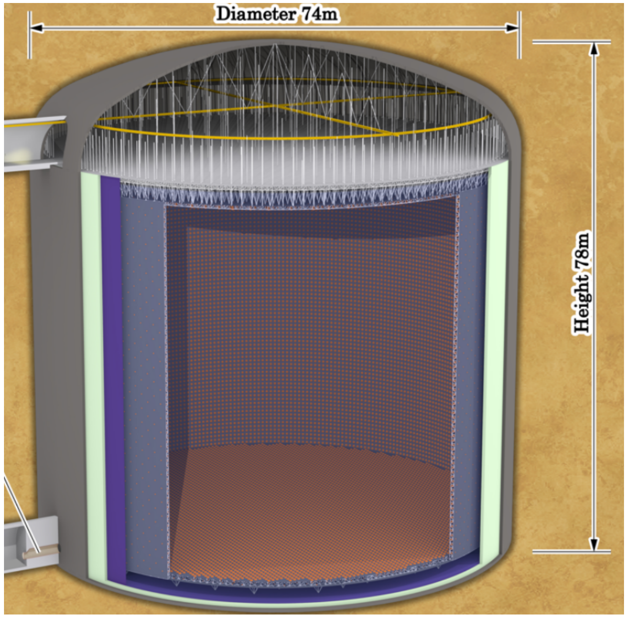
- Scales with baseline L and energy E → LBL experiments, at high energy.

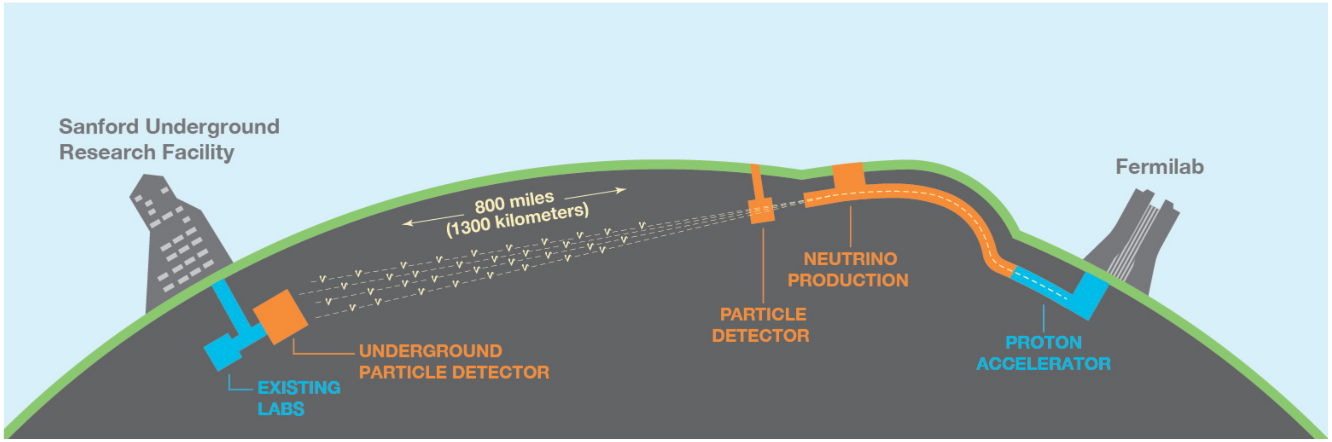
- Near future : T2K-II LBL or NoνA.

- Sensitivity to $a_L \sim 10^{-24}$ GeV
  → 4 orders of magnitudes better than current limits.



- Future generation → Especially DUNE and atmospheric HK



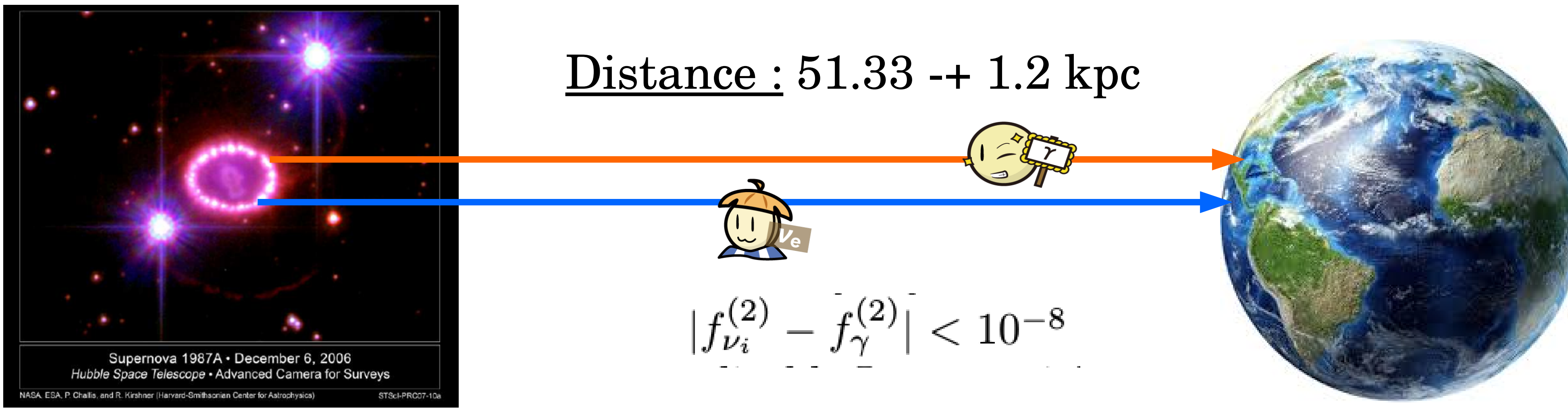


L = 1300 km + higher energy broad-band beam

LV using speed-of-light measurements

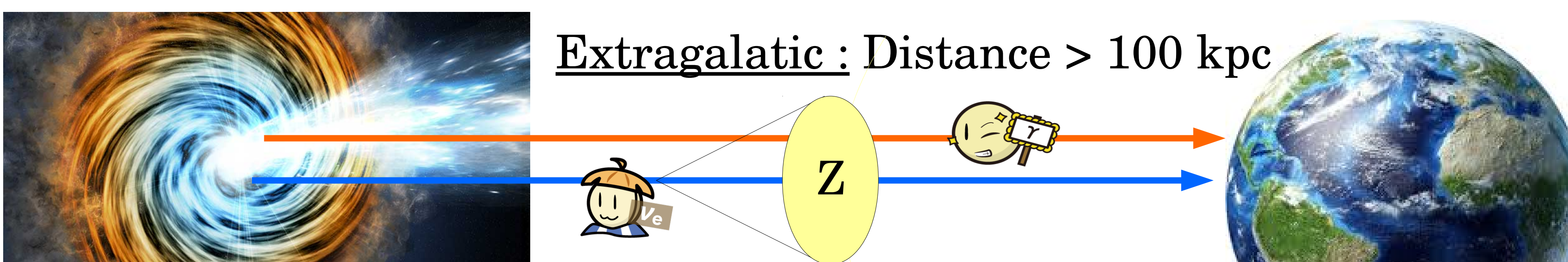
- Time-of-flight using accelerators (MINOS, T2K and OPERA) : neutrino time-of-flight compatible with the speed of light → Bound up to ~10^{-4} GeV

- Most stringent direct constraints comes from 1987a.



$$|f^{(2)}_{\nu_i} - f^{(2)}_{\gamma}| < 10^{-8}$$

- Ultra-high energy neutrino (astrophysical)

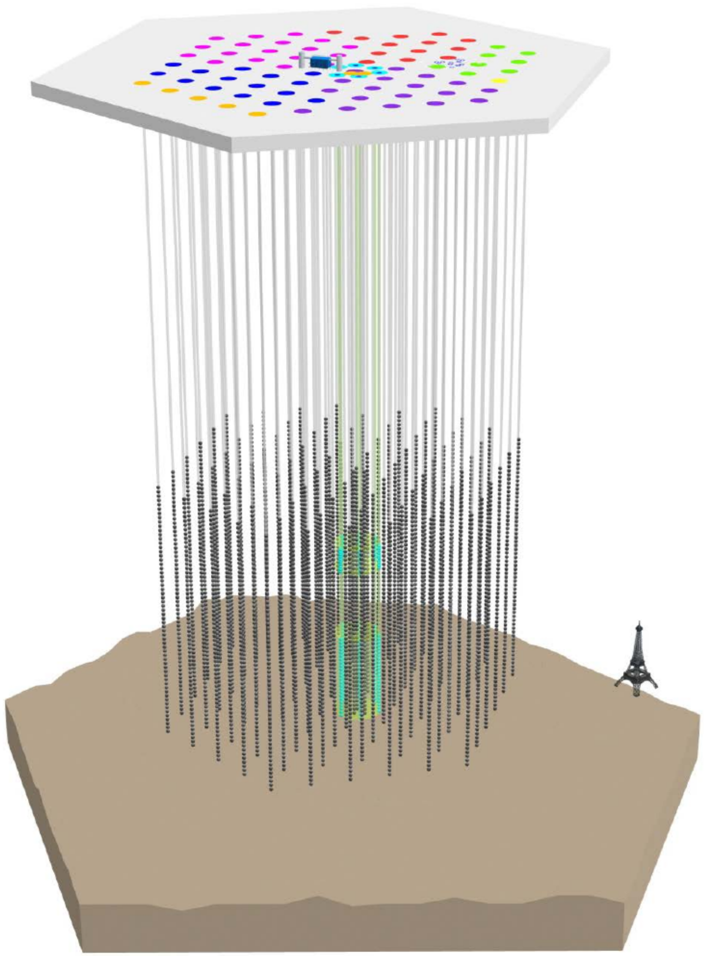


If v > c → Vacuum Cherenkov radiation (Couples to Z boson) → → limits physics up to 10^{-20} GeV

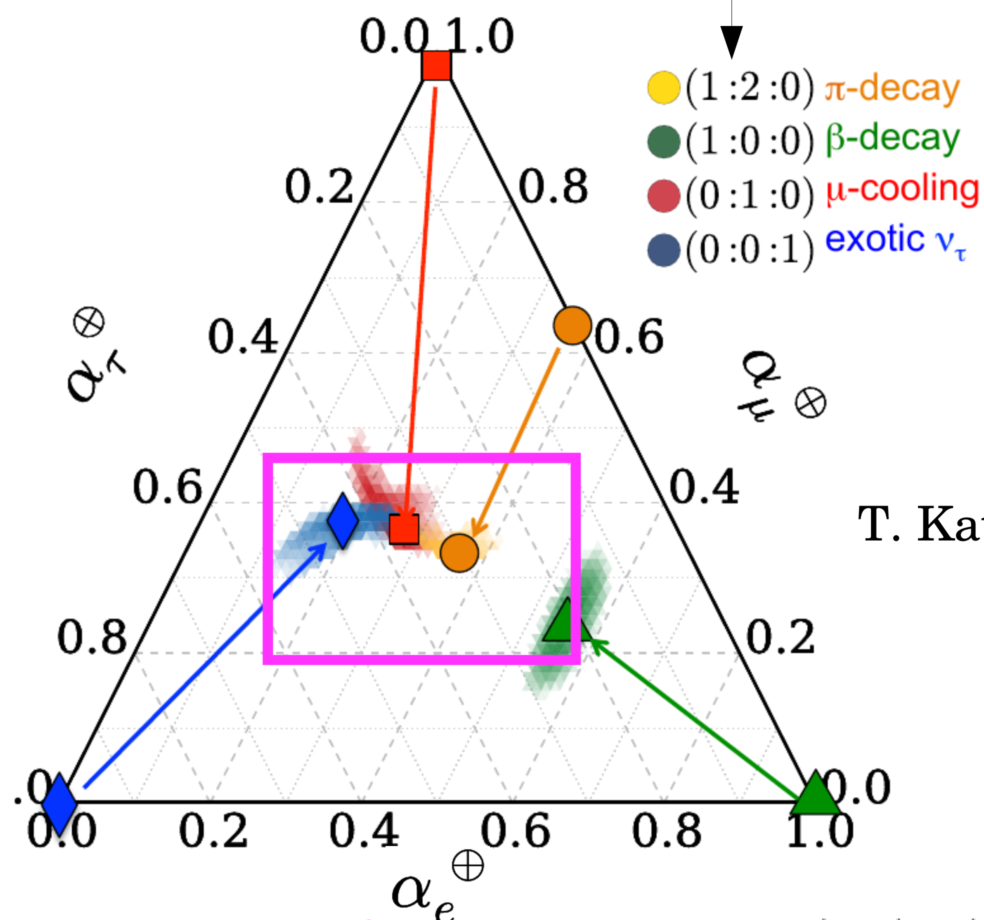
Ultra-High Energy neutrinos @IceCube

- But can use neutrino oscillation of UHE ν (E > 0.5 TeV) → Use IceCube

- Absolute flux has large uncertainties→Use flavour ratio : $\alpha_\beta^\oplus = \bar{\phi}_\beta^\oplus / \sum_\gamma \bar{\phi}_\gamma^\oplus$



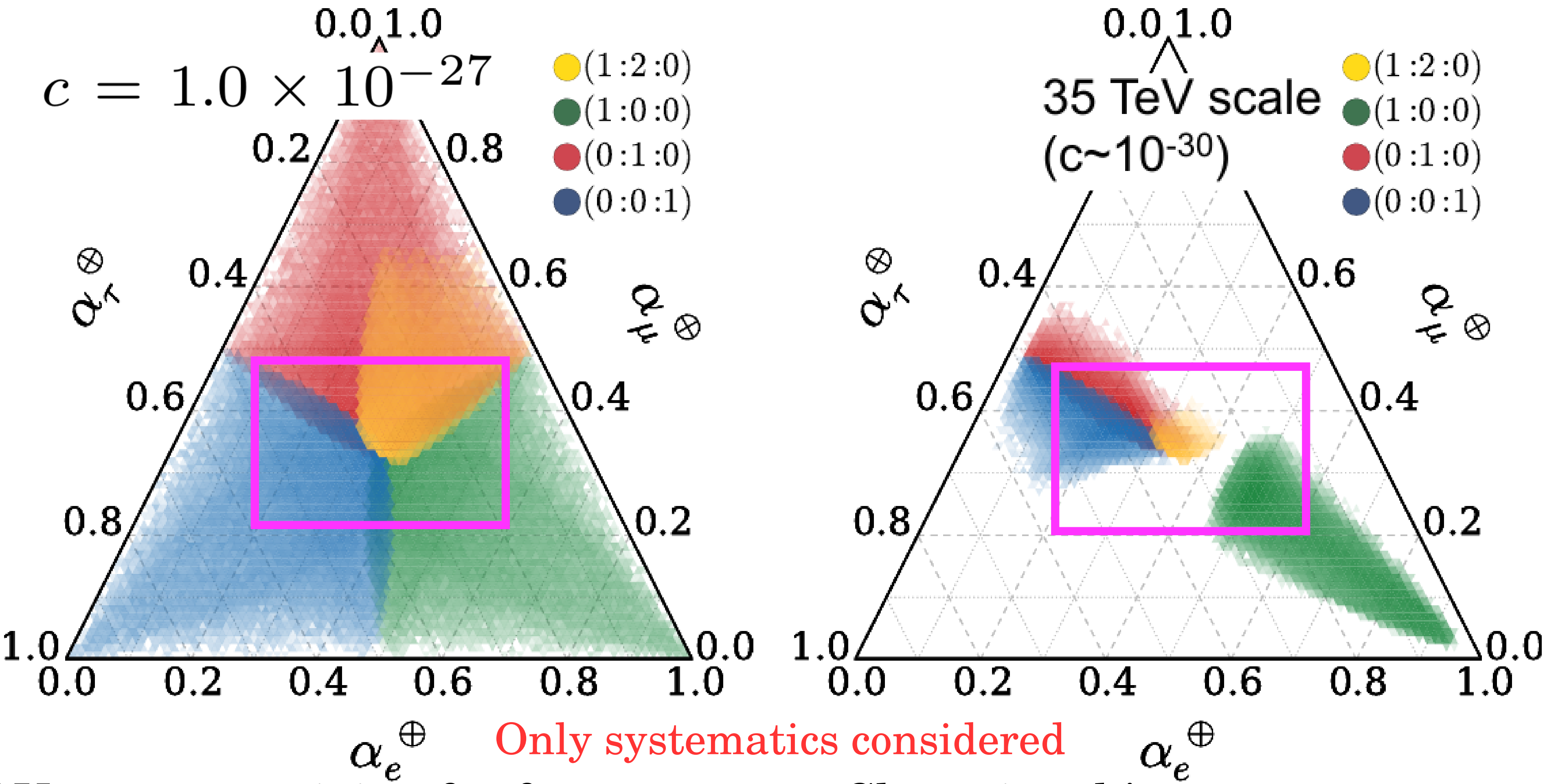
4 UHE ν production models :



T. Katori

- Standard oscillation :
  →Almost equal mixing when arriving on Earth : $(\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1)$

- Effect of LV coefficients ~ 10^{-27} ~ SK atmospheric sensitivity.



- LV moves ν-mixing far from center → Clear signal !

- Pros : Potentially the world-leading sensitivity → > 10^{-30} GeV
  Cons : Seems model independent … if believe UHE flavour model ratio !

Conclusions

- Lorentz violation is predicted by some theories beyond the SM.

- Highly supressed @GeV scale … But interferences experiment, as neutrino oscillation, can probe for it !

- Can be searched through different signatures :
    - Modifications of PMNS mixing.
    - NB : @short baseline, can mimic sterile ν (w/ different E-dependency)
    - Sidereal-time-dependent oscillations.
    - Speed-of-light measurements (lower sensitivity).
    - ….

- Has been searched extensively in this generation of experiments :
  → No LV up to E~$10^{20} – 10^{27}$ GeV

- There is no sign of new physics @TeV for now → Let's search it at the Planck scale in the next years !

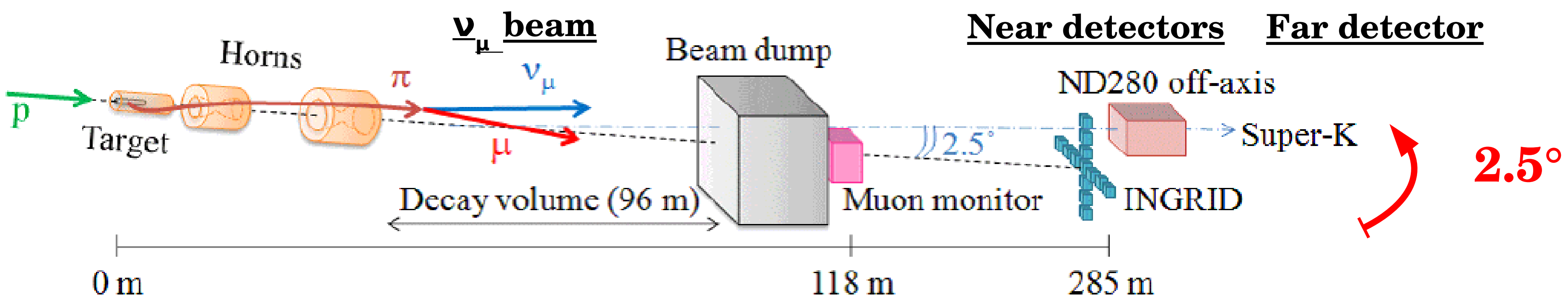
Additonal slides

Effective parameters expression in terms of SME parameters

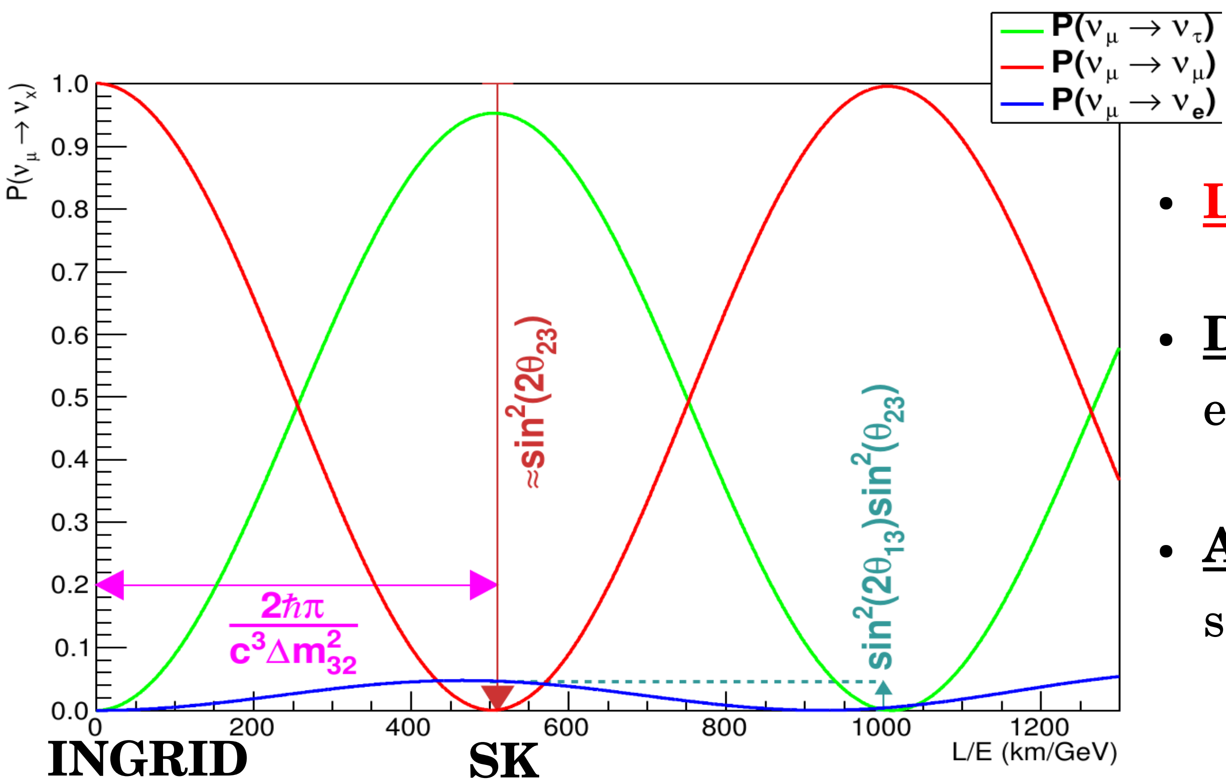
$$
\begin{aligned}
(\mathcal{C}^{(1)})_{ab} &= (\widetilde{a}_L)^T_{ab} - \hat{N}^Z(\widetilde{a}_L)^Z_{ab} \\
&\quad -\tfrac{1}{2}(3-\hat{N}^Z\hat{N}^Z)E(\widetilde{c}_L)^{TT}_{ab} + 2\hat{N}^Z E(\widetilde{c}_L)^{TZ}_{ab} \\
&\quad +\tfrac{1}{2}(1-3\hat{N}^Z\hat{N}^Z)E(\widetilde{c}_L)^{ZZ}_{ab}, \\
(\mathcal{A}^{(1)}_s)_{ab} &= \hat{N}^Y(\widetilde{a}_L)^X_{ab} - \hat{N}^X(\widetilde{a}_L)^Y_{ab} \\
&\quad -2\hat{N}^Y E(\widetilde{c}_L)^{TX}_{ab} + 2\hat{N}^X E(\widetilde{c}_L)^{TY}_{ab} \\
&\quad +2\hat{N}^Y\hat{N}^Z E(\widetilde{c}_L)^{XZ}_{ab} - 2\hat{N}^X\hat{N}^Z E(\widetilde{c}_L)^{YZ}_{ab}, \\
(\mathcal{A}^{(1)}_c)_{ab} &= -\hat{N}^X(\widetilde{a}_L)^X_{ab} - \hat{N}^Y(\widetilde{a}_L)^Y_{ab} \\
&\quad +2\hat{N}^X E(\widetilde{c}_L)^{TX}_{ab} + 2\hat{N}^Y E(\widetilde{c}_L)^{TY}_{ab} \\
&\quad -2\hat{N}^X\hat{N}^Z E(\widetilde{c}_L)^{XZ}_{ab} - 2\hat{N}^Y\hat{N}^Z E(\widetilde{c}_L)^{YZ}_{ab}, \\
(\mathcal{B}^{(1)}_s)_{ab} &= \hat{N}^X\hat{N}^Y E\big((\widetilde{c}_L)^{XX}_{ab} - (\widetilde{c}_L)^{YY}_{ab}\big) \\
&\quad -\big(\hat{N}^X\hat{N}^X - \hat{N}^Y\hat{N}^Y\big)E(\widetilde{c}_L)^{XY}_{ab}, \\
(\mathcal{B}^{(1)}_c)_{ab} &= -2\hat{N}^X\hat{N}^Y E(\widetilde{c}_L)^{XY}_{ab} \\
&\quad -\tfrac{1}{2}\big(\hat{N}^X\hat{N}^X - \hat{N}^Y\hat{N}^Y\big)E\big((\widetilde{c}_L)^{XX}_{ab} - (\widetilde{c}_L)^{YY}_{ab}\big).
\end{aligned}
\tag{47}
$$

The T2K Experiment

- Observation of ν_e appearance in a ν_μ beam and ν_μ disappearance & their antineutrino equivalents



Oscillation probability @ 3 flavours in L/E : assuming a ν_μ beam



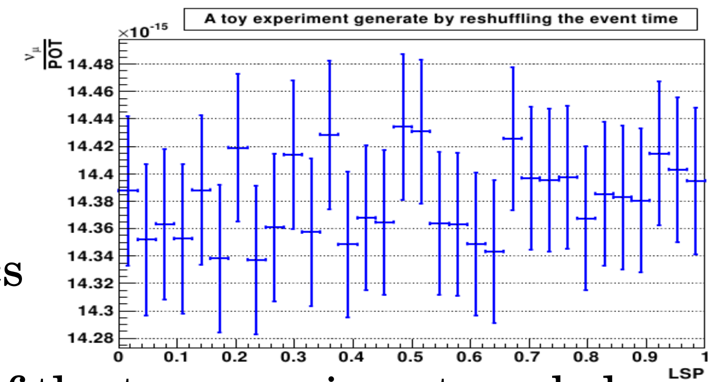
- **L (baseline) / E (energy) dependent**
- **Disappearance of ν_μ :** expected high $\nu_\mu \to \nu_\tau$ oscillation
- **Appearance of ν_e :** small $\nu_\mu \to \nu_e$ oscillation

Benjamin Quilain

Null hypothesis test with Fourier transform

- Null hypothesis = no sidereal modulation of neutrino event with LSP

- Detection threshold ↔ 3σ deviation from null hypothesis
  → 1 detection threshold for each of the 5 magnitude associated to the 5 harmonics (constant, $\omega_\oplus$, $2\omega_\oplus$, $3\omega_\oplus$ and $4\omega_\oplus$)

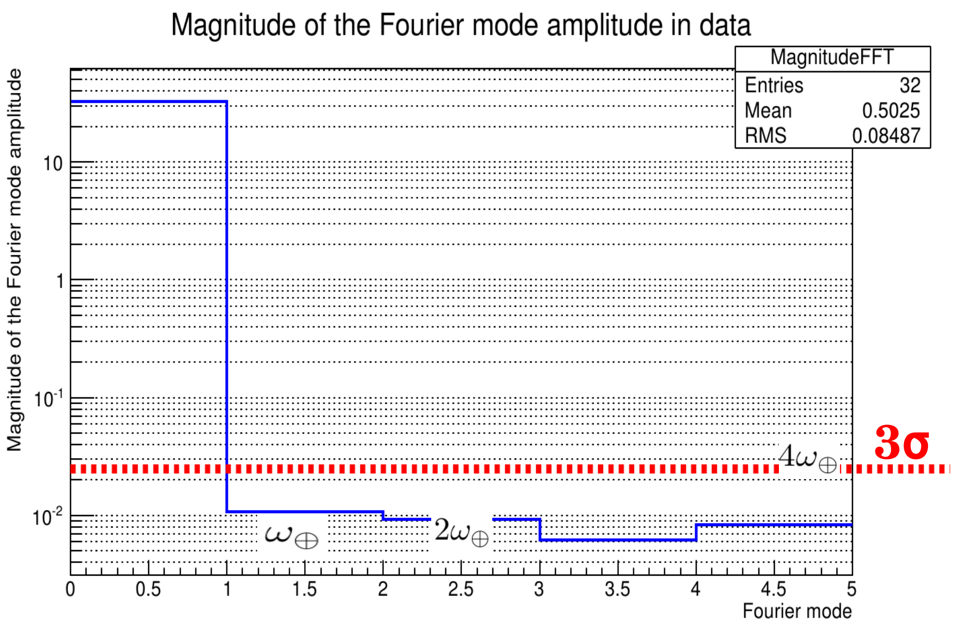


- Method :

1. Generate 10,000 toy experiment without LV signal
2. For each toy → FFT → Magnitude for each 5 harmonics
3. After 10,000 toys → For each 5 magnitudes

→ determines the the amplitude value at which 99.6 % of the toy experiment are below

- Open the data :



Conclusions :

- Compatible with a flat signal within 3σ
- No evidence for Lorentz violation

Parameter extraction using Fourier transform

$$P_{\nu_\mu\rightarrow\nu_x} = (\frac{L}{hc})^2|(C)_{\mu x}+(A_s)_{\mu x}\sin(\omega_\oplus T_\oplus)+(A_c)_{\mu x}\cos(\omega_\oplus T_\oplus)+(B_s)_{\mu x}\sin(2\omega_\oplus T_\oplus)+(B_c)_{\mu x}\cos(2\omega_\oplus T_\oplus)|^2$$

- Associated constraints are evaluated for each of the 14 SME parameters : a_L, c_L

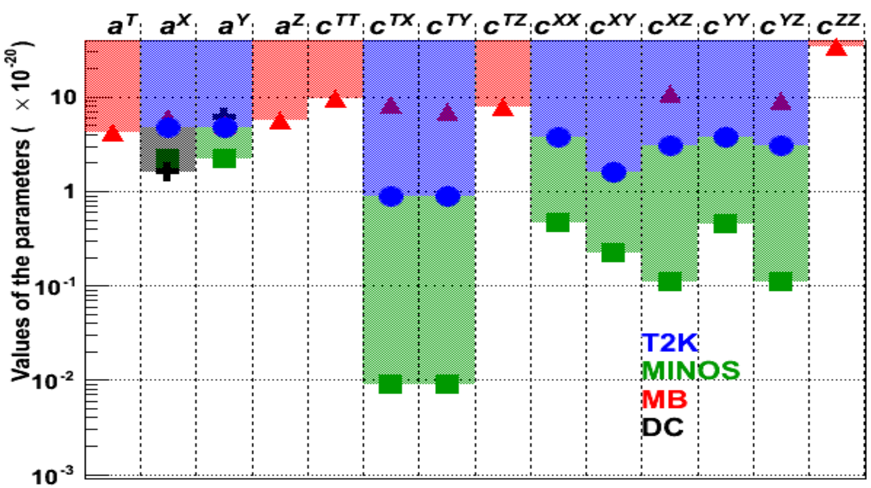
→ Generate signal toys → FFT → test when crossing the 3σ threshold

→ « A la MINOS » → all parameters = 0 except one → assume that the full 3σ effect comes from 1 parameter

- Deduce T2K 3σ upper limits

	$\times 10^{-20}$		$\times 10^{-20}$
a_L^X	4.8 GeV	a_L^Y	4.8 GeV
c_L^{TX}	0.9	c_L^{TY}	0.9
c_L^{XX}	3.8	c_L^{XY}	1.6
c_L^{XZ}	3.1	c_L^{YY}	3.8
c_L^{YZ}	3.1		

- World leading existing limits :



« Raw » sensitivity results

- T2K is more sensitive than MiniBooNE but less than MINOS : MINOS baseline ~ 1km
  - MINOS higher flux energy (~3 GeV) → higher sensitivity to c^{ij} coefficients

Comparison w/ world leading limits & limits of FFT method

- **World leading existing limits :** **MiniBooNE** and **MINOS** experiments :

x 10^{-20}	x 10^{-20}
a^X_L=4.0 GeV (5.6 GeV) (2.2 GeV)	a^Y_L=4.0 GeV (5.9 GeV) (2.2 GeV)
c^{TX}_L=0.8 (4.6) (0.009)	c^{TY}_L=0.8 (4.9) (0.009)
c^{XX}_L=3.1 (/) (0.46)	c^{XY}_L=1.6 (/) (0.45)
c^{XZ}_L=2.3 (6.2) (0.11)	c^{YY}_L=3.1 (/) (0.11)
c^{YZ}_L=2.6 (6.5) (0.22)	

T2K is more sensitive than MiniBooNE but less than MINOS

MINOS baseline : 1km

- **MINOS / T2K (INGRID) :** FFT = most sensitive technique to sidereal variations...

- … It does not allow to extract correct limits on coefficients

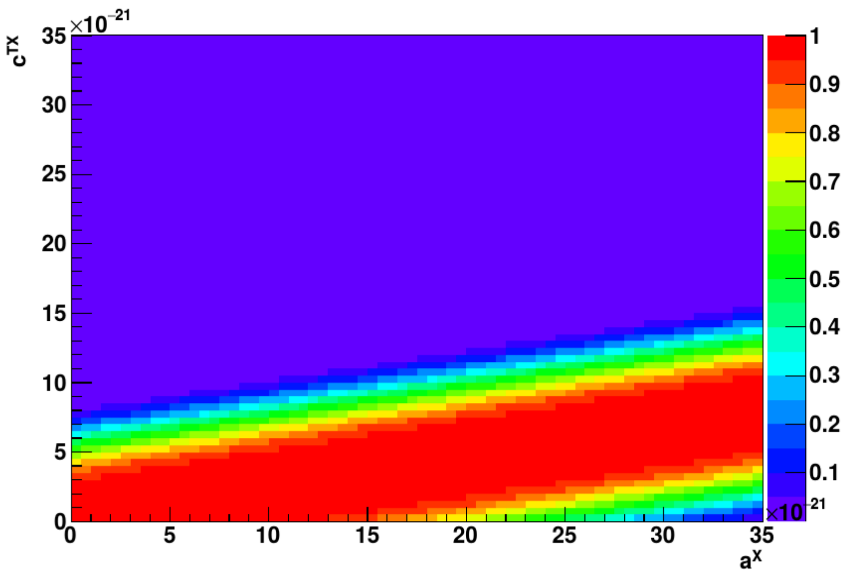
- **Assume no correlation :** but 14 parameters for 4 observables ...

=> There are (large) correlations between parameters

Correlations between the SME parameters

- → But… 14 parameters for 4 observables… → Expect very important correlations !

- Probability to detect a LV effect (a deviation > 3σ from null hypothesis)



- If c^{TX}>0 → T2K has less detection ability than if c^{TX}=0 → Here : neglect correlations → over-estimate the sentivity !!

- Here : two parameters, and only 2-points correlations… → reality much more complex !!

- Correlations depends on position on Earth & beamline direction → change w/ experiments !

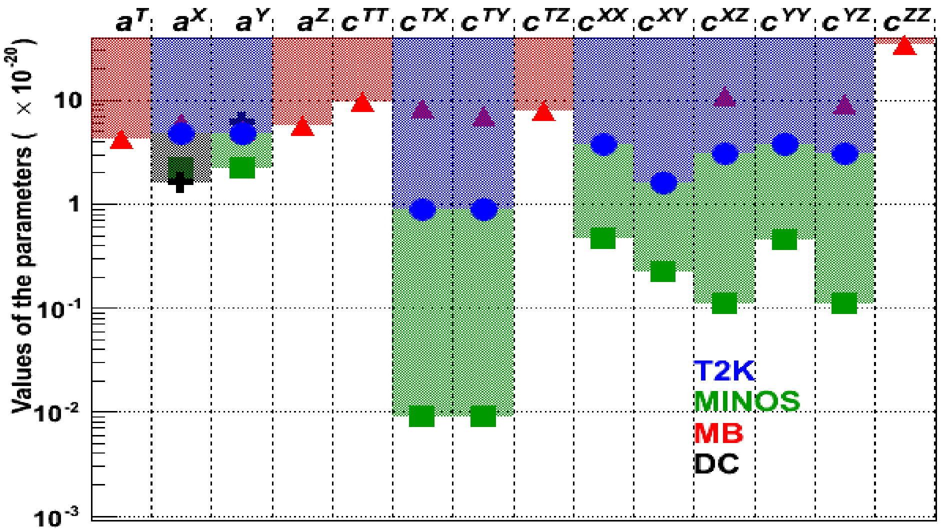
Conclusions :

1. Large correlations between parameters

2. Wrong to consider « uncorrelated sensitivity » : → if larger correlation at MINOS (different direction) → remove a signal that might be seen @T2K !

Results of Lorentz violation search

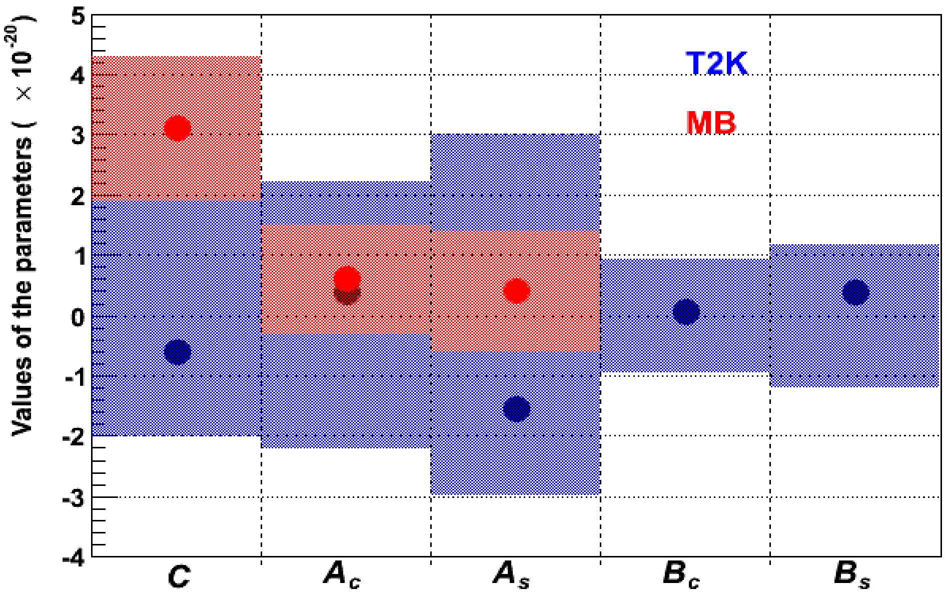
- Extraction of the 3σ constraints on parameters : « à la MINOS » → assumes no correlations



- **<u>T2K sensitivity within best in the world</u>** (more sensitive than MiniBooNE but less than MINOS)...
- … assuming no correlations ! but 14 parameters for 4 observables …

→ **Large correlations between parameters**

- 2. Likelihood method of 5 effective parameters C, A_c, A_s, B_c, B_s & use correlations



<u>Conclusions :</u>

- No evidence for Lorentz violation
- Higher sensitivity than MiniBooNE (slightly higher error but 5 param. fit)
- High correlations between parameters is confirmed

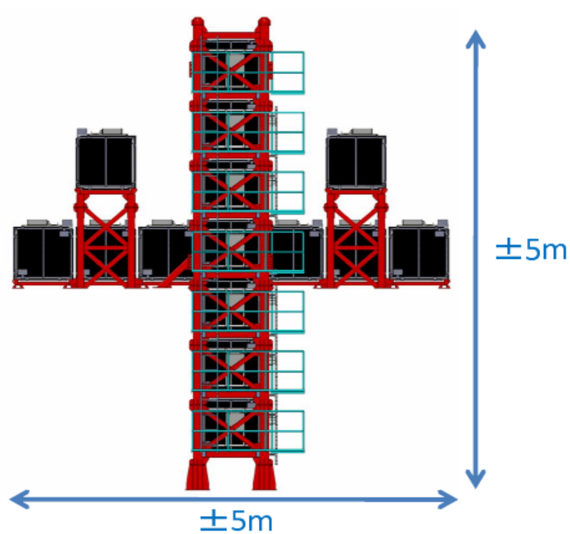
Future sensitivity of near detectors

1. Near detectors : INGRID → used the FFT & MINOS method for simplicity

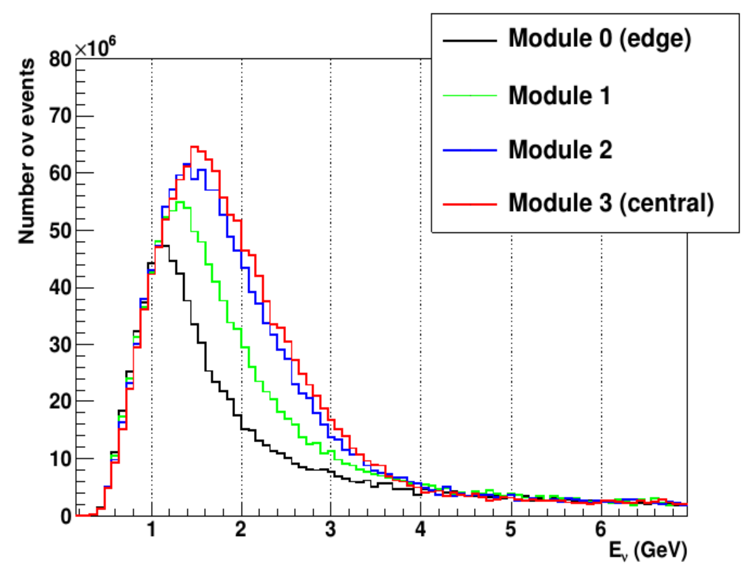
x 10^{-20}	x 10^{-20}
a^X 4.8 → 2.1 GeV	a^Y 4.8 → 2.1 GeV
c^{TX} 0.9 → 0.05	c^{TY} 0.9 → 0.05
c^{XX} 3.8 → 2.0	c^{YY} 3.8 → 2.0
c^{XY} 1.6 → 1.0	c^{YZ} 3.1 → 1.6
c^{XZ} 3.1 → 1.6	

→ Small improvement for (a_L) coefficients, one order of magnitude for (c_L) (energy dependent)

→ Improve this analysis using different energy samples :



→ Different modules
→ Different off-axis angles
→ different fluxes



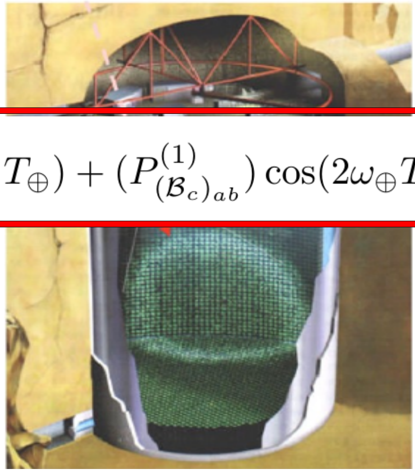
→ Disentangle the effect of the different parameters → reduce correlations

→ **But Gain ~ order of magnitude on top of the INGRID 2x10²² POT table…**

Future sensitivity of far detector

2. At far detector : Lorentz violation in Super-K

ν_τ appearance probability @SK~Disappearance probability @SK :



$$P_{\nu_\mu\to\nu_x} = (P^{(0)}_{\nu_\mu\to\nu_x}) + \frac{2L}{(\hbar c)^2}(P^{(1)}_C) + (P^{(1)}_{(\mathcal{A}_s)_{ab}})\sin(\omega_\oplus T_\oplus) + (P^{(1)}_{(\mathcal{A}_c)_{ab}})\cos(\omega_\oplus T_\oplus) + (P^{(1)}_{(\mathcal{B}_s)_{ab}})\sin(2\omega_\oplus T_\oplus) + (P^{(1)}_{(\mathcal{B}_c)_{ab}})\cos(2\omega_\oplus T_\oplus$$

P^0 : standard 3 flavours oscillation

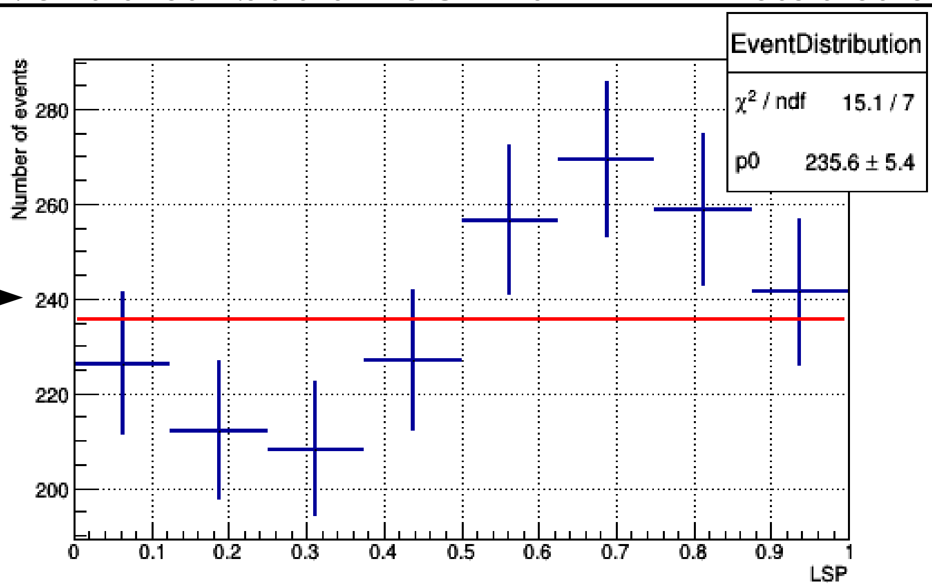
P^1 = (C, Ac, As, Bc, Bs as short baseline) x standard 3 flavours oscillation

- L dependency (L^2 dependency for ND) & linear in C, Ac, As, Bc, Bs → Large effect @SK

→ Simulation assuming **4 order of magnitudes** LV effect than current INGRID constraints

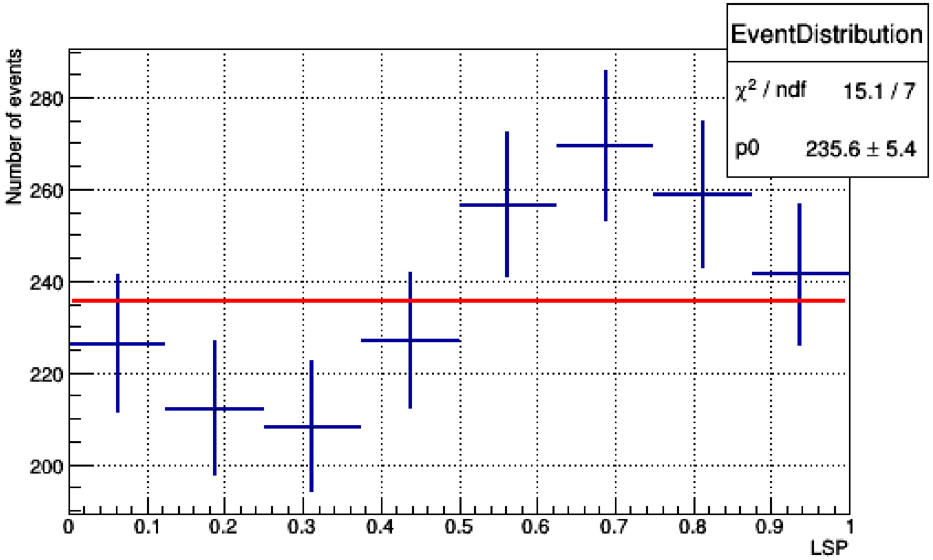
x 10^{-20}		x 10^{-20}	
a^X	4.8 x 10^{-4} GeV	a^Y	4.8 x 10^{-4} GeV
c^{TX}	0.9 x 10^{-4}	c^{TY}	0.9 x 10^{-4}
c^{XX}	3.8 x 10^{-4}	c^{YY}	3.8 x 10^{-4}
c^{XY}	1.6 x 10^{-4}	c^{YZ}	3.1 x 10^{-4}
c^{XZ}	3.1 x 10^{-4}		

Event distribution @SK for T2K-II statistics



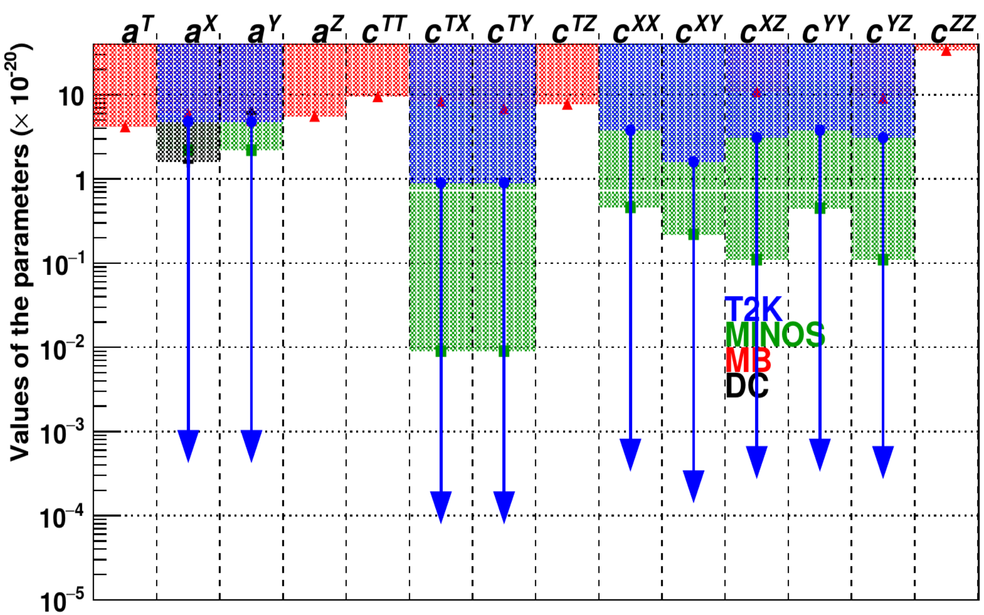
Plans for the future : far detector

Event distribution @SK for T2K-II statistics



→ Clear LV effect → sensitivity ~ 10^{-24} GeV

Experimental contraints on parameters : « no correlation sensitivity »



→ Will be the world leading constraints !!!

→ And this is very conservative :
ν & $\bar{\nu}$ →separation will increase with SK-Gadolinium

→ ν contamination in $\bar{\nu}$-mode might be reduced → increase focusing horn current: 250kA → 320kA

SK atmospheric neutrinos

Six fits are performed for the real and imaginary parts of a^T and c^{TT} in the three sectors, $e\mu$, $e\tau$, and $\mu\tau$. The real and imaginary parts of each coefficient are fit simultaneously, but otherwise the coefficients are fit independently following the procedure typical for SME analyses [12].

LV Parameter		Limit at 95% C.L.	Best Fit	No LV $\Delta\chi^2$	Previous Limit	
$e\mu$	$\mathrm{Re}\,(a^T)$	1.8×10^{-23} GeV	1.0×10^{-23} GeV	1.4	4.2×10^{-20} GeV	[58]
	$\mathrm{Im}\,(a^T)$	1.8×10^{-23} GeV	4.6×10^{-24} GeV			
	$\mathrm{Re}\,(c^{TT})$	8.0×10^{-27}	1.0×10^{-28}	0.0	9.6×10^{-20}	[58]
	$\mathrm{Im}\,(c^{TT})$	8.0×10^{-27}	1.0×10^{-28}			
$e\tau$	$\mathrm{Re}\,(a^T)$	4.1×10^{-23} GeV	2.2×10^{-24} GeV	0.0	7.8×10^{-20} GeV	[59]
	$\mathrm{Im}\,(a^T)$	2.8×10^{-23} GeV	1.0×10^{-28} GeV			
	$\mathrm{Re}\,(c^{TT})$	9.3×10^{-25}	1.0×10^{-28}	0.3	1.3×10^{-17}	[59]
	$\mathrm{Im}\,(c^{TT})$	1.0×10^{-24}	3.5×10^{-25}			
$\mu\tau$	$\mathrm{Re}\,(a^T)$	6.5×10^{-24} GeV	3.2×10^{-24} GeV	0.9	–	
	$\mathrm{Im}\,(a^T)$	5.1×10^{-24} GeV	1.0×10^{-28} GeV			
	$\mathrm{Re}\,(c^{TT})$	4.4×10^{-27}	1.0×10^{-28}	0.1	–	
	$\mathrm{Im}\,(c^{TT})$	4.2×10^{-27}	7.5×10^{-28}			

- <u>But can use neutrino oscillation of UHE ν (E > 0.5 TeV)</u> → Use IceCube

8. Standard flavour triangle diagram

There are 3 UHE neutrino production models

i. pion decay dominant model, 1:2:0

ii. electron neutrino dominant model, 1:0:0

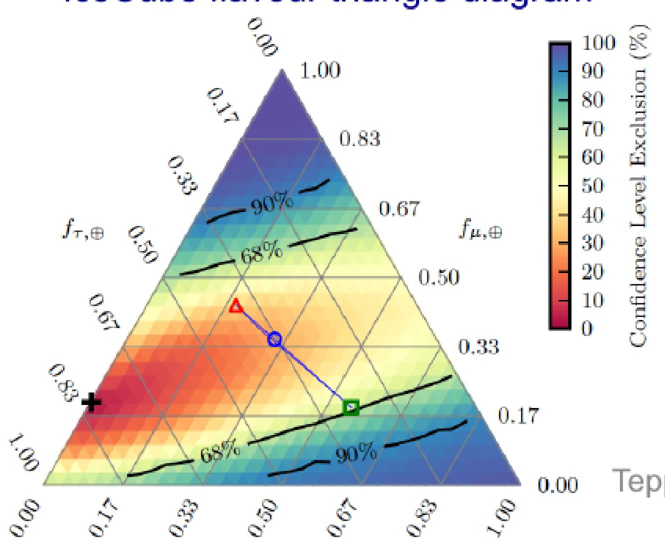
iii. muon neutrino dominant model, 0:1:0

iv. tau neutrino dominant model, 0:0:1

Initial flavour ratio is modified on the Earth due to neutrino mixing

IceCube collaboration
PRL114(2015)171102

IceCube flavour triangle diagram



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