First Test of Lorentz Violation with a Reactor-based Antineutrino Experiment

村上 明

Outline

- 物理背景
  - Spontaneous Lorenz symmetric breaking
  - Standard Model Extension
- ニュートリノ物理における Lorentz violation
  - Lorentz violationと"ニュートリノ振動"
- 実験紹介と測定結果
  - LSND
  - MiniBooNE
  - Double Chooz

インディアナ大学 のアラン・コステレツキー教授(V. Alan Kostelecky)のHP

http://physics.indiana.edu/~kostelec/faq.html

Lorentz violation

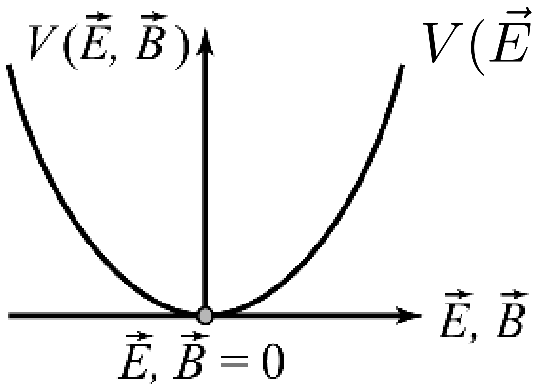
- Lorentz violation CPT violation はプランクスケールの物理で起こることが予測されている
  - ひも理論、余剰次元、etc
- 測定したいけど、難しい
  - プランクスケール : O(~1e19GeV)の物理
  - 超高エネルギーの加速器の建設→難しい
    - 宇宙物理ならいけそうな気がする
  - 我々のエネルギー領域(~GeV)では、1e19程度抑制
    - 超精密測定→十分期待できる
- なるべく、Standard Modelに準ずる枠組みで解析したい
  - Spontaneous Lorentz violation (SLSB), Standard Model Extension (SME)

Spontaneous Lorentz Symmetry Breaking (SLSB)

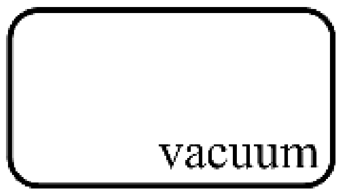
- Lorentz violationをなるべく自然に導入→Spontaneous Symmetry Breaking (SSB)をベース

Spontaneous Symmetry Breaking (SSB)

Electromagnetic field



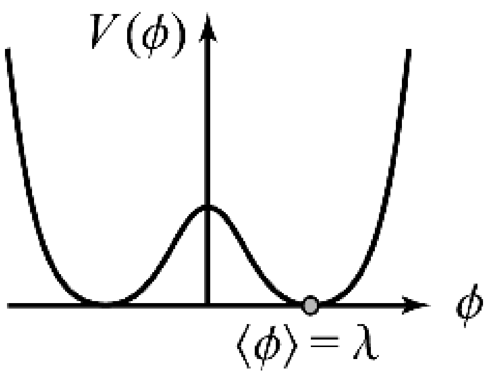
$$V(\vec{E},\vec{B}) = \frac{1}{2}\left(\vec{E}^2 + \vec{B}^2\right)$$



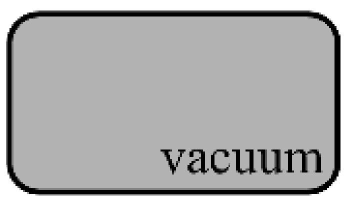
基底状態: E=B=0

→ 真空期待値=0

Higgle field (Higgs scalar Φ)



$$V(\phi) = (\phi^2 - \lambda^2)^2$$



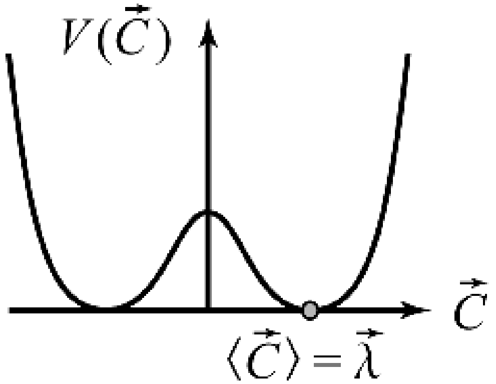
メキシカンハット型ポテンシャル

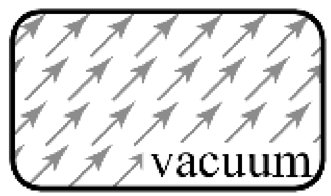
→ 自発的対称性の破れ

真空期待値<Φ>=±λ (scalar)

Spontaneous Lorentz Symmetry Breaking (SLSB)

- プランクスケールでは、スカラー場でなく、ベクトル場に依存するポテンシャル (例: ひも理論はスカラーではなく、ベクトル場から構成)



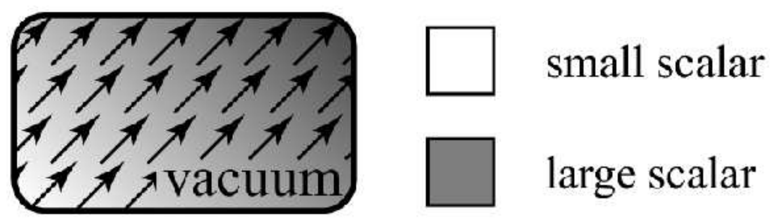


$$V(\vec{C}) = (\vec{C}^2 - \lambda^2)^2 \,.$$

基底状態 $\vec{C}_{vac} \equiv \langle \vec{C} \rangle = \vec{\lambda},$

$\vec{\lambda}^2 \; = \; \lambda^2$ (Constant)

SpaceTime dependent Scalar の例 : スカラー場に濃淡をつける



- Varying coupling ξ(x), scalar field φ and Φ
- Lagrangian contains "$\xi(x)\partial^{\mu}\varphi\partial\mu\Phi$"

→(部分積分) :"$\partial^{\mu}\xi(x)\varphi\partial_{\mu}\Phi$"

4次元の傾き(淡→濃) = 好まれる方向

粒子がこのスカラー場と相互作用する際、

この方向に垂直か平行かで変わってくる

(実際の理論(宇宙の成り立ち)では、*SLSB* → *SSB* の順番で起こるらしい)

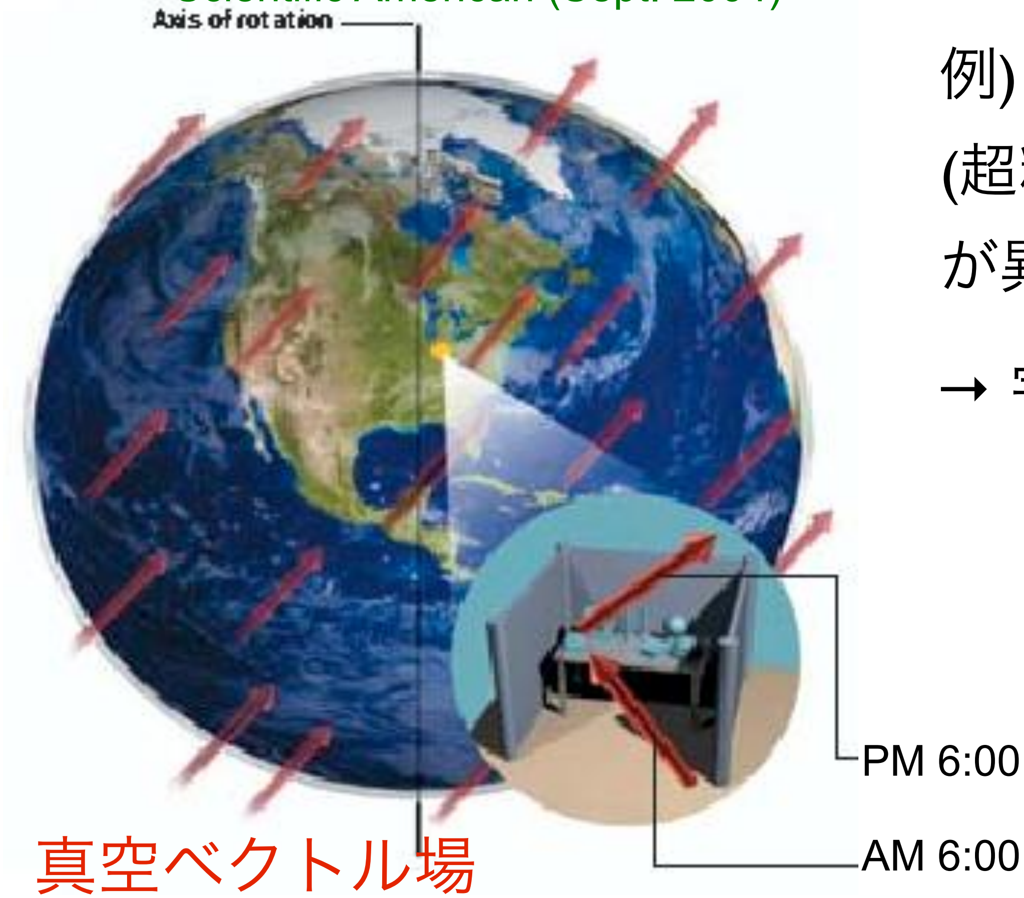
Spontaneous Lorentz Symmetry Breaking (SLSB)

- 宇宙を満たす真空ベクトル場と粒子(SM particle)の相互作用をチェック

$$Ł = i\psi\gamma_\mu\partial^\mu\bar{\psi} + m\psi\bar{\psi} + \boxed{\psi\gamma_\mu a^\mu\bar{\psi}} + \boxed{\psi\gamma_\mu c^{\mu\nu}\partial_\nu\bar{\psi}} + \cdots \ .$$

- 物理観測量の地球の自転周期に対する依存性を調べる
  - 地球自転周期 = 恒星時間(Sidereal time)周期 = 23h56m4.1s (<24h)

Scientific American (Sept. 2004)



例) 朝(AM 6:00)と夕方(± 6:00)に測定した(超精密な)物理量(例: 原子の超微細構造)が異なっているかもしれない。

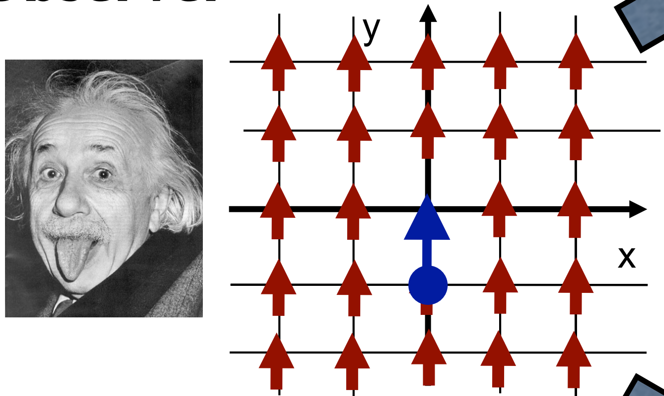
→ 宇宙の指向性、Lorentz violationに繋がる

Lorentz trans. under vacuum vector field

- 宇宙の真空に指向性があると、Lorentz transformationはどうなるか

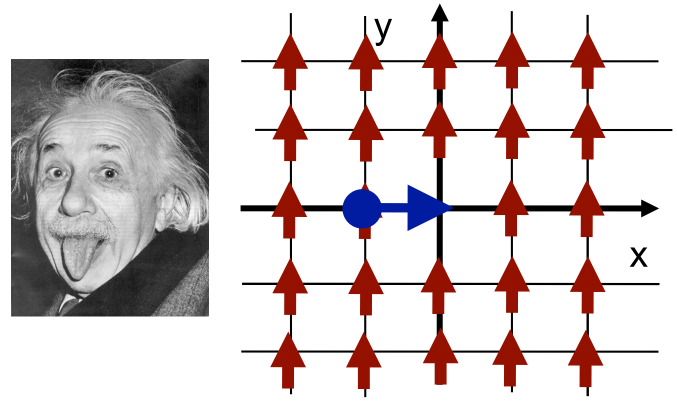
Observer

SM particle (moving)



Background vector field (in fixed coordinate)

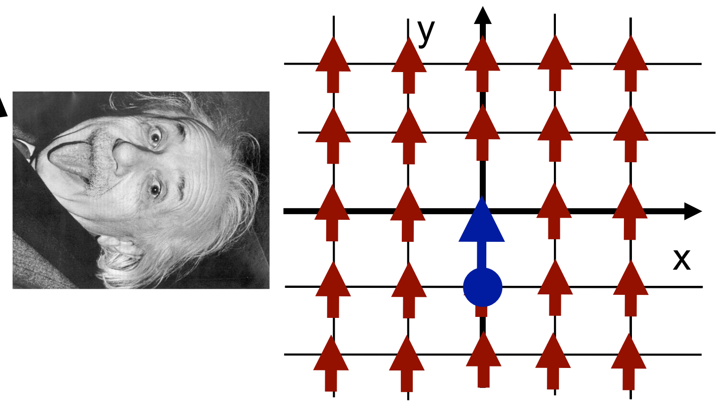
(1) 粒子を変換(Particle Lorentz trans.)



ベクトル場との関係性が変化

→ **Particle Lorentz violation**

(2) 観測者の系を変換(Observer Lorentz trans.)



ベクトル場との関係性は不変

→ **Lorentz symmetry**

Standard Model Extension

- Standard Modelに真空”ベクトル場”との相互作用(Particle Lorentz violation)の摂動項を追加したもの

ニュートリノ物理に関する最小限のSMEラグランジアン

$$\mathcal{L} = \frac{1}{2} i \bar{\psi}_A \Gamma^\mu_{AB} \overleftrightarrow{D_\mu} \psi_B - \bar{\psi}_A M_{AB} \psi_B + h.c.$$

A,B : Majorana basis flavor space (6×6)

$$\Gamma^\nu_{AB} \equiv \gamma^\nu \delta_{AB} + c^{\mu\nu}_{AB}\gamma_\mu + d^{\mu\nu}_{AB}\gamma_5\gamma_\mu + e^\nu_{AB} + i f^\nu_{AB}\gamma_5 + \frac{1}{2} g^{\lambda\mu\nu}_{AB}\sigma_{\lambda\mu},$$

$$M_{AB} \equiv m_{AB} + i m_{5AB}\gamma_5 + a^\mu_{AB}\gamma_\mu + b^\mu_{AB} + \frac{1}{2} H^{\mu\nu}_{AB}\sigma_{\mu\nu}.$$

Nonzero term in SM (blue boxes: $\gamma^\nu \delta_{AB}$, $m_{AB} + i m_{5AB}\gamma_5$)

Additional SME term (red boxes: remaining terms)

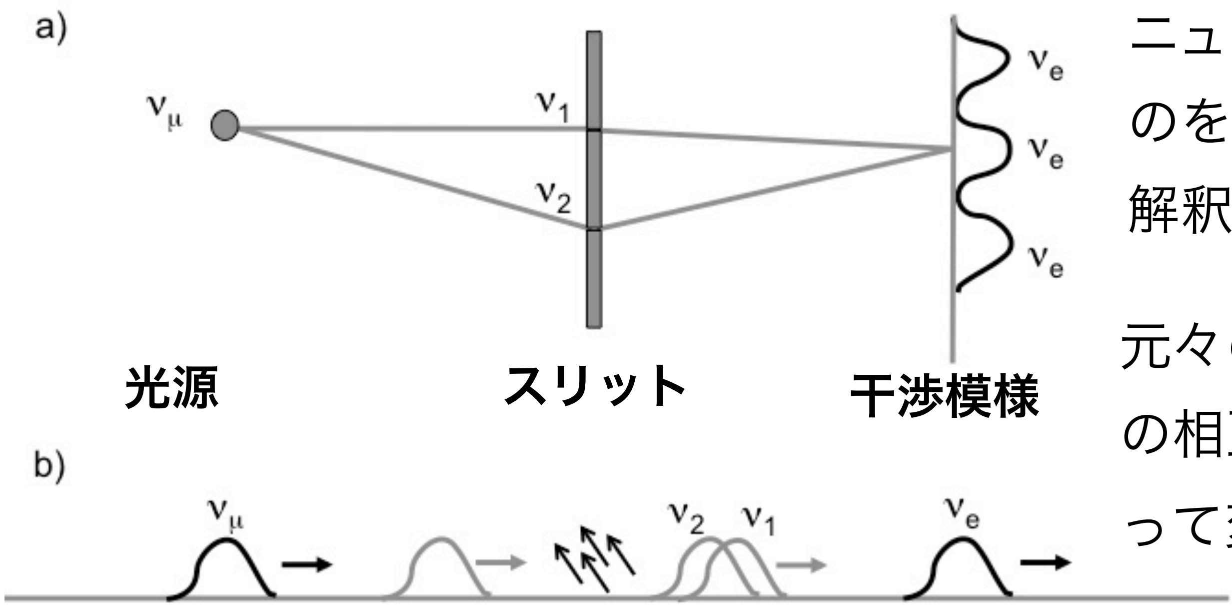
SME coefficient (a,b,c,d,e,f,g) symmetry
- CPT-odd & Lorentz-violation : a, b, e, f, g (vector)
- CPT-even & Lorentz-violation : c,d, H (tensor)

場の理論で、一般的に*“CPT violation*があると、*Lorentz violation*が起こる *(CPT violation*は*Lorentz violation*の十分条件*)” (O.W. Greenberg)*と矛盾しない

Lorentz violationとニュートリノ振動

- Lorentz violationに対して高い感度の実験が期待できる

(乱暴ですが)ニュートリノ振動を二重スリットの干渉として考える



ニュートリノ振動でフレーバーが変わるのをを二重スリットの干渉の結果として解釈する

元々のνμのν1とν2の干渉具合が、何らかの相互作用(ν1とν2の郡速度が変化)によって変わり、新しい混ざり具合νeになる

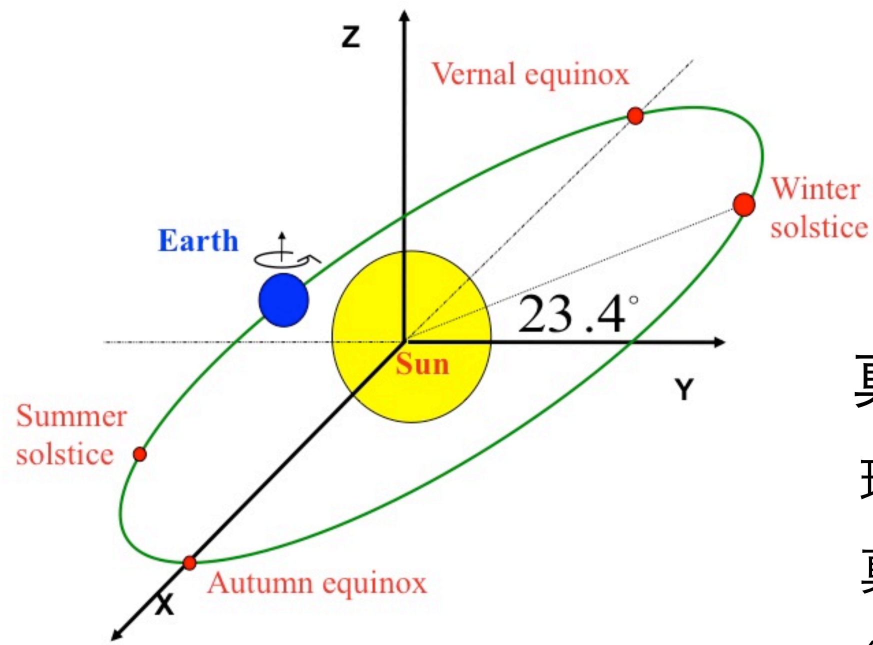
地球の自転位置によって真空ベクトル場の向きが変わるので、
恒星時間によって、ニュートリノ振動の位相が変わる (厳密には郡速度の違いでは振動は起きない)

位相差 ~ **Δm^2 / Energy ~ 1e-21 GeV (@1GeV neutrino)**

→ プランクスケールの物理に感度あり！

Lorentz violation測定: 座標系

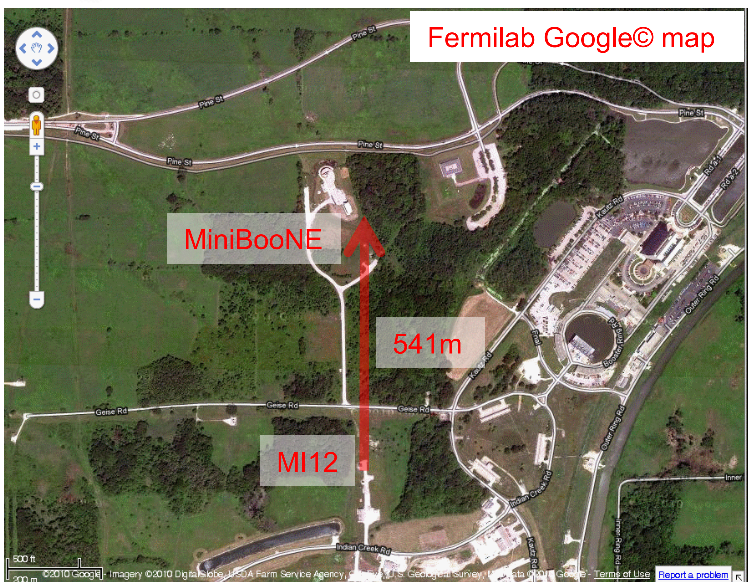
- 座標系：太陽中心座標系 (この業界では一般的)



Z軸: 地球の自転軸
X軸: 秋分点の方向
Y軸: 右手系座標になるように選択

真空ベクトル場は太陽系内で均一と仮定

理由:
真空スカラー場は地球でも遠方の星でも不変
(星の燃焼メカニズム)
→真空ベクトル場も同程度で均一といっても
おかしくない



MiniBooNE beamline

Neutrino beam line is described in
Sun-centered coordinate

Lorentz violation測定:ニュートリノ振動

- Effective Hamiltonian for νa→νb w/ SME coefficient (a_L, c_L)

$$(h_{\rm eff})_{ab} = |\vec{p}|\,\delta_{ab}\begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix} + \frac{1}{2|\vec{p}|}\begin{pmatrix}(\widetilde{m}^2)_{ab} & 0\\ 0 & (\widetilde{m}^2)^*_{ab}\end{pmatrix}$$

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

Lorentz violation

- p : momentum
- (For anti-neutrino, CPT-odd a_L → $-a_L$)

- "Neutrino oscillation" probability (ex:shot-baseline → neutrino mass term negligible)

$$P_{\nu_\mu\to\nu_e} \simeq \frac{L^2}{(\hbar c)^2}\Big|(\mathcal{C})_{e\mu} + (\mathcal{A}_s)_{e\mu}\sin\omega_\oplus T_\oplus + (\mathcal{A}_c)_{e\mu}\cos\omega_\oplus T_\oplus + (\mathcal{B}_s)_{e\mu}\sin 2\omega_\oplus T_\oplus + (\mathcal{B}_c)_{e\mu}\cos 2\omega_\oplus T_\oplus\Big|^2.$$

A~C : a_L, c_L combination

$$(\mathcal{C})_{e\mu} = (\mathcal{C}^{(0)})_{e\mu} + E(\mathcal{C}^{(1)})_{e\mu}$$
$$(\mathcal{A}_s)_{e\mu} = (\mathcal{A}_s^{(0)})_{e\mu} + E(\mathcal{A}_s^{(1)})_{e\mu}$$
$$(\mathcal{A}_c)_{e\mu} = (\mathcal{A}_c^{(0)})_{e\mu} + E(\mathcal{A}_c^{(1)})_{e\mu}$$
$$(\mathcal{B}_s)_{e\mu} = E(\mathcal{B}_s^{(1)})_{e\mu}$$
$$(\mathcal{B}_c)_{e\mu} = E(\mathcal{B}_c^{(1)})_{e\mu}$$

$$(\mathcal{C}^{(0)})_{e\mu} = (a_L)^T_{e\mu} + \hat{N}^Z(a_L)^Z_{e\mu}$$
$$(\mathcal{C}^{(1)})_{e\mu} = -\frac{1}{2}(3-\hat{N}^Z\hat{N}^Z)(c_L)^{TT}_{e\mu} + 2\hat{N}^Z(c_L)^{TZ}_{e\mu} + \frac{1}{2}(1-3\hat{N}^Z\hat{N}^Z)(c_L)^{ZZ}_{e\mu}$$
$$(\mathcal{A}_s^{(0)})_{e\mu} = \hat{N}^Y(a_L)^X_{e\mu} + \hat{N}^X(a_L)^Y_{e\mu}$$
$$(\mathcal{A}_s^{(1)})_{e\mu} = -2\hat{N}^Y(c_L)^{TX}_{e\mu} + 2\hat{N}^X(c_L)^{TY}_{e\mu} + 2\hat{N}^Y\hat{N}^Z(c_L)^{XZ}_{e\mu} - 2\hat{N}^X\hat{N}^Z(c_L)^{YZ}_{e\mu}$$
$$(\mathcal{A}_c^{(0)})_{e\mu} = -\hat{N}^X(a_L)^X_{e\mu} + \hat{N}^Y(a_L)^Y_{e\mu}$$
$$(\mathcal{A}_c^{(1)})_{e\mu} = 2\hat{N}^X(c_L)^{TX}_{e\mu} + 2\hat{N}^Y(c_L)^{TY}_{e\mu} - 2\hat{N}^X\hat{N}^Z(c_L)^{XZ}_{e\mu} - 2\hat{N}^Y\hat{N}^Z(c_L)^{YZ}_{e\mu}$$
$$(\mathcal{B}_s^{(1)})_{e\mu} = \hat{N}^X\hat{N}^Y((c_L)^{XX}_{e\mu} - (c_L)^{YY}_{e\mu}) - (\hat{N}^X\hat{N}^X - \hat{N}^Y\hat{N}^Y)(c_L)^{XY}_{e\mu}$$
$$(\mathcal{B}_c^{(1)})_{e\mu} = -\frac{1}{2}(\hat{N}^X\hat{N}^X - \hat{N}^Y\hat{N}^Y)((c_L)^{XX}_{e\mu} - (c_L)^{YY}_{e\mu}) - 2\hat{N}^X\hat{N}^Y(c_L)^{XY}_{e\mu}$$

sidereal frequency $\omega_\oplus = \dfrac{2\pi}{23h56m4.1s}$

sidereal time $T_\oplus$

Solar time : 24h 00m 0.0s
Sidereal time : 23h 56m 4.1s
→ 3m55.9s diff.

"Sidereal time independent param." と **"time dependent param."** の計5つをフィットして求める

実際には簡単な右式の3パラメータの場合も使う

$$P_{\nu_\mu\to\nu_e} \simeq \frac{L^2}{(\hbar c)^2}\left|(\mathcal{C})_{e\mu} + (\mathcal{A}_s)_{e\mu}\sin\omega_\oplus T_\oplus + (\mathcal{A}_c)_{e\mu}\cos\omega_\oplus T_\oplus\right|^2$$

→ *Assuming nature only has CPT-odd SME coefficients*

LSND experiment

LSND collaboration,
PRD72(2005)076004

LSND is a short-baseline neutrino oscillation experiment at Los Alamos.

$$\bar{\nu}_\mu \xrightarrow{oscillation} \bar{\nu}_e + p \rightarrow e^+ + n$$

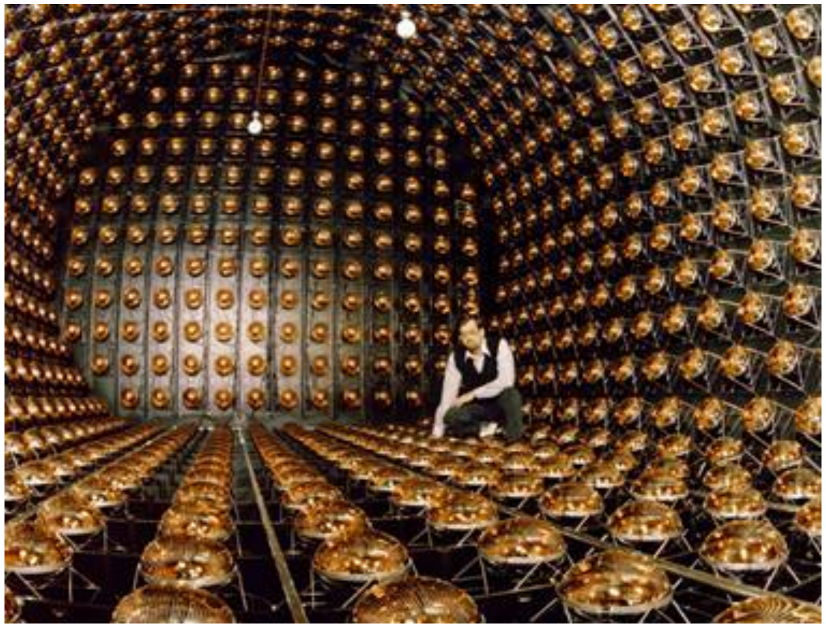
$$n + p \rightarrow d + \gamma$$

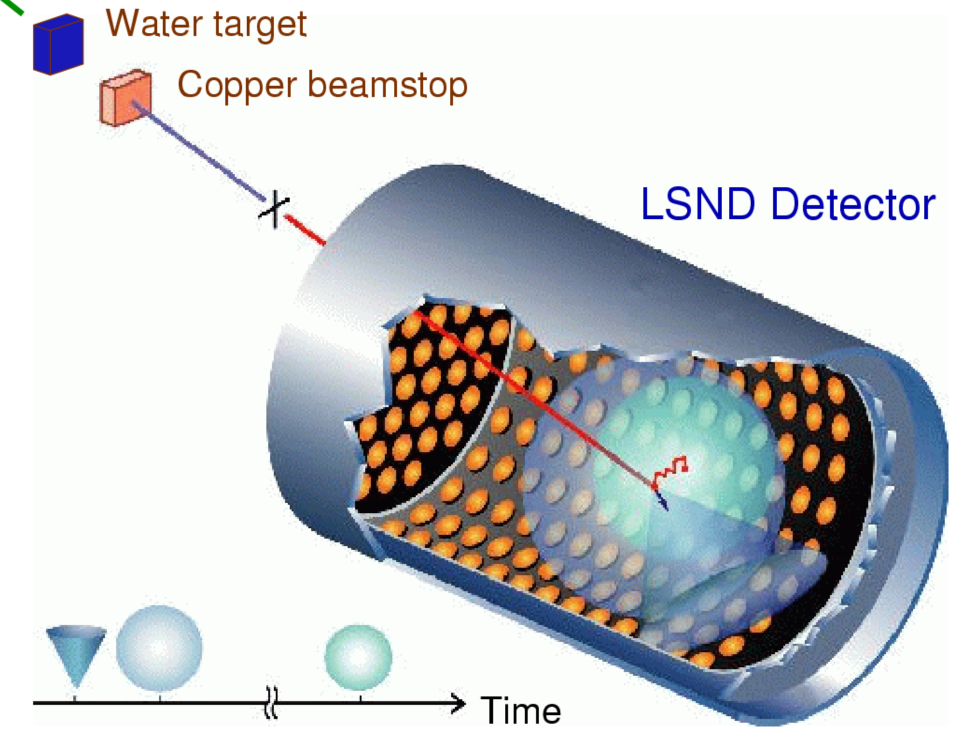
LSND saw the 3.8σ excess of electron antineutrinos from muon antineutrino beam; since this excess is not understood by neutrino Standard Model, it might be new physics

800 MeV proton beam from
LANSCE accelerator

L/E~30m/30MeV~1

LSND detector





LSND experiment

LSND collaboration, PRD72(2005)076004

LSND is a short-baseline neutrino oscillation experiment at Los Alamos.

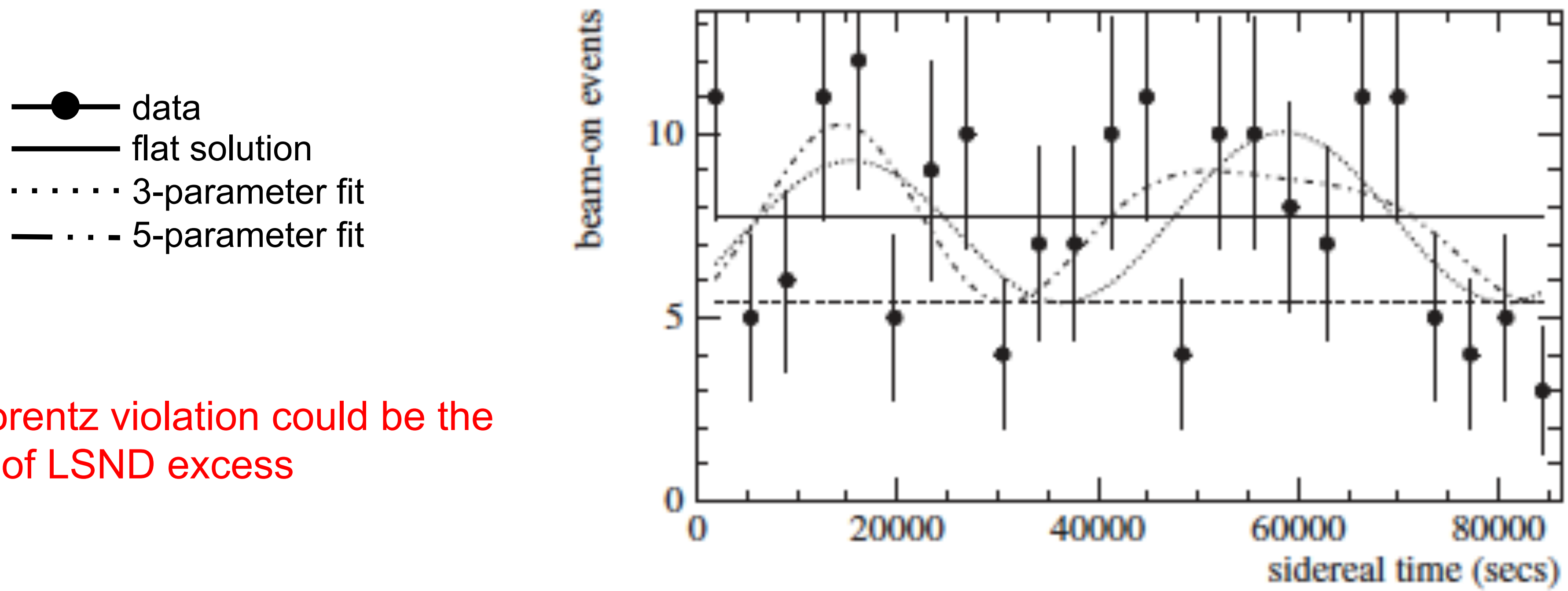
$$\bar{\nu}_{\mu} \xrightarrow{oscillation} \bar{\nu}_{e} + p \rightarrow e^{+} + n$$

$$n + p \rightarrow d + \gamma$$

LSND saw the 3.8σ excess of electron antineutrinos from muon antineutrino beam; since this excess is not understood by neutrino Standard Model, it might be new physics

Data is consistent with flat solution, but sidereal time solution is not excluded.

LSND oscillation candidate sidereal time distribution



Small Lorentz violation could be the solution of LSND excess

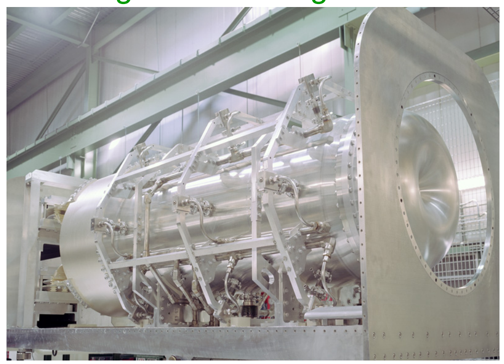
MiniBooNE

MiniBooNE collaboration, ArXiv:1109.3480

- Short base line neutrino oscillation experiment @ Fermi lab (2002-2012)
- Primary goal : νμ → νe appearance search
- Change Horn current direction → Neutrino / Anti-Neutrino mode
- Oscillation peak ~ 800 MeV (for neutrino) / ~600MeV (for anti-neutrino)

FNAL Booster

Magnetic focusing horn



~520m →

MiniBooNE detector

primary beam (8 GeV protons) → secondary beam (2 GeV pions) → tertiary beam (700 MeV neutrinos)

νe appearance

$$\nu_\mu \xrightarrow{oscillation} \nu_e + n \rightarrow p + e^-$$

$$\bar{\nu}_\mu \xrightarrow{oscillation} \bar{\nu}_e + p \rightarrow n + e^+$$

νeCCQE事象を解析に使用

Cherenkov detector (12.2m)

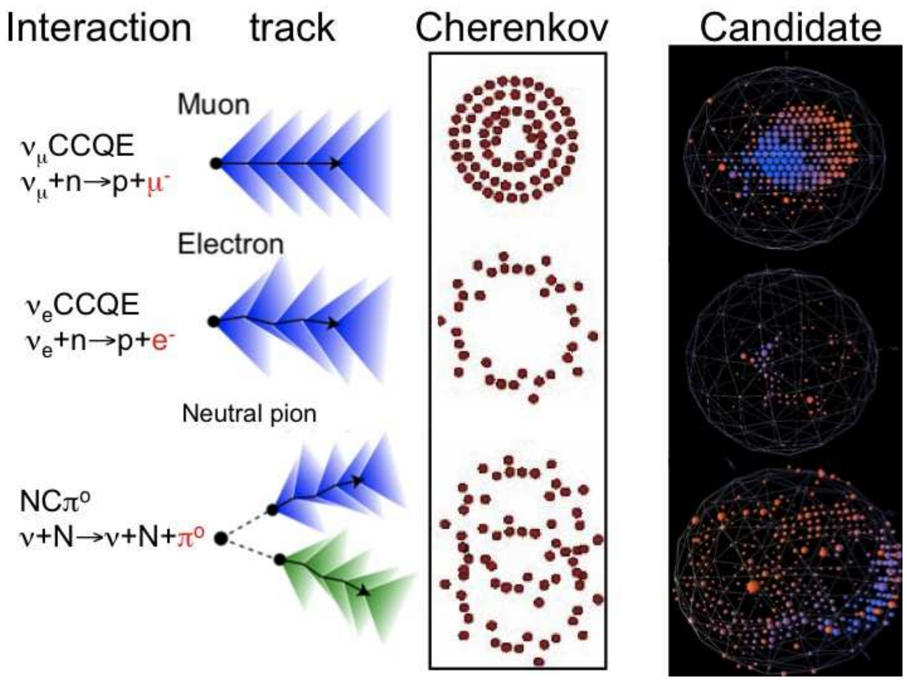
- 800 ton of mineral oil (CH2)
- 8 inch PMT x 1280 (inner)

MiniBooNE oscillation analysis

MiniBooNE collaboration, ArXiv:1109.3480

- Single Cherenkov ring, Electron-like

$$E_\nu^{QE} = \frac{2(M_n - B)E_\mu - ((M_n - B)^2 + m_\mu^2 - M_p^2)}{2 \cdot [(M_n - B) - E_\mu + \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu]}$$



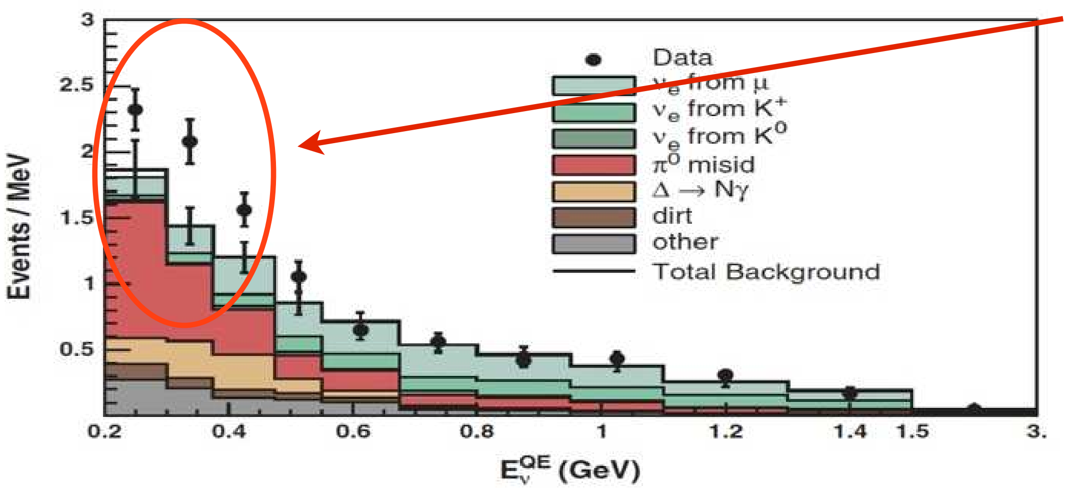
- Main Back ground
  - NCπ0からのgammaの一つをelectronとmisIDする
    - 測定したNCπ0 production rate をsimulationに入れる
  - Intrinsic beam νe
    - Contamination<0.5% ~ appearance contribution=0.5%
    - νμ(anti-νμ) rateを測定し、simulationに入れる $\pi^+ \to \nu_\mu \mu^+$, $\mu^+ \to \bar{\nu}_\mu \nu_e e^+$
    - SciBooNEの測定から不定性(Kaon production)を抑える

→ νe appearance Signal / all background ~ 1/3 at oscillation

MiniBooNE oscillation analysis

MiniBooNE collaboration, ArXiv:1109.3480

Neutrino mode result (νe appearance search)



Pick up Excess of νe at low-E (<475MeV)

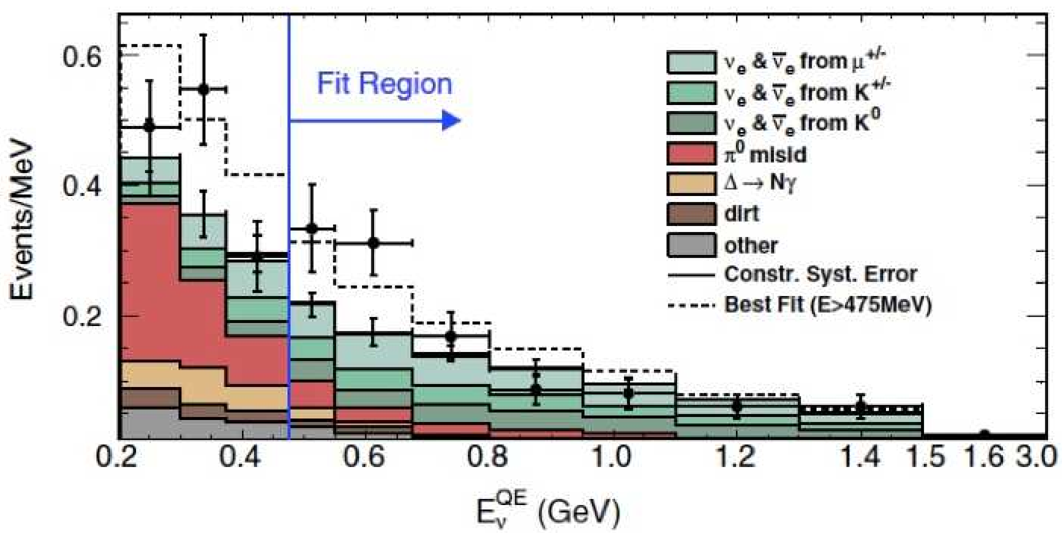
→ νe app. candidate

- Obs. : 544 events / 6.46e20 POT
- Exp. : 409.8 ± 23.3(stat.) ± 38.3(syst.)

Not predicted by neutrino Standard Model (νSM)

→ New physics ?

Anti-neutrino mode result (anti-νe appearance search)



Excess in low-E & high-E (475~1300MeV)

Combine both region

→ anti-νe app. candidate

- Obs. : 241 events / 5.66e20 POT
- Exp. : 200.7 ± 15.5(stat.) ± 14.3(syst.)

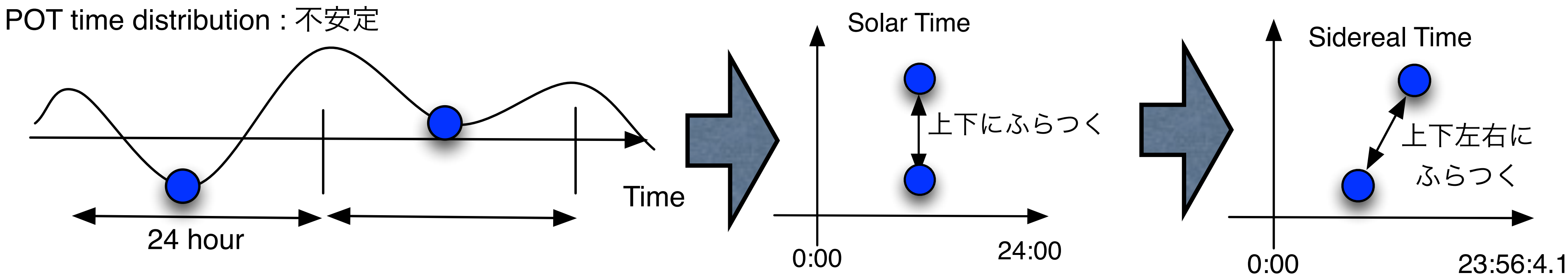
Not predicted by neutrino Standard Model (νSM)

→ New physics ?

Time-dependent systematics

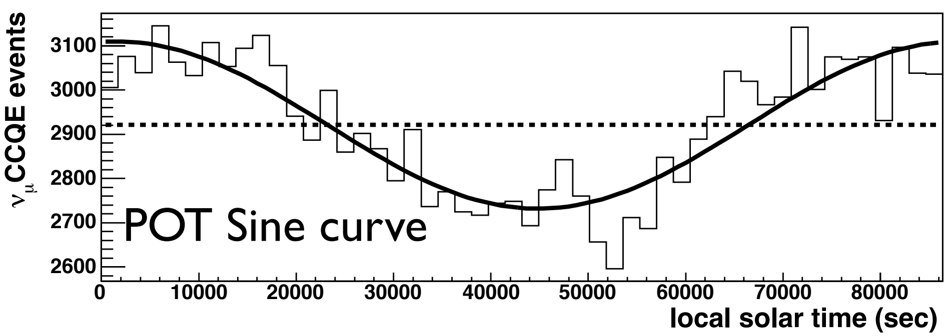
MiniBooNE collaboration, ArXiv:1109.3480

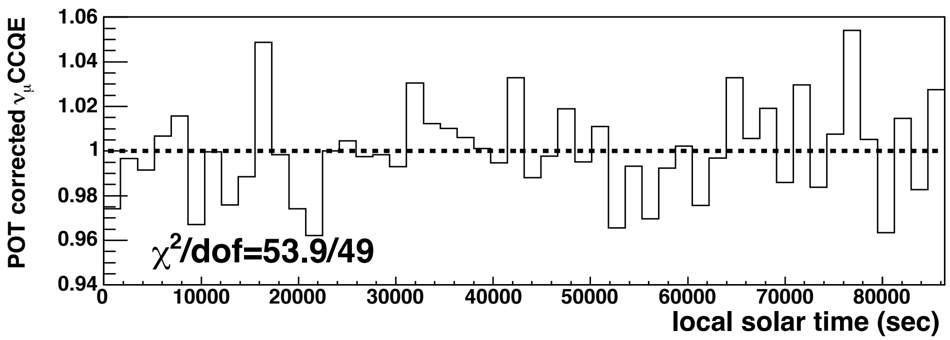
時間情報:GPS time stamp (local solar time) → Solar time/sidereal timeの変換に注意



Check Time dependent systematics (day-night effects) (ex: electronics noise)

High Stat νμ CCQE sample to check all of these effect





Flat POT normalized distribution

→ ふらつきは主にビーム運転状況

(夜:Maximum POT → 昼:減少)

データ取得が1年間を通して均一でないと、

24h周期のふらつきが恒星時間の関数

(23h56m4.1s)で現れる

→ 最大3%の24h周期の揺らぎ < Stat fluctuation

→ Flat Background time distribution を仮定

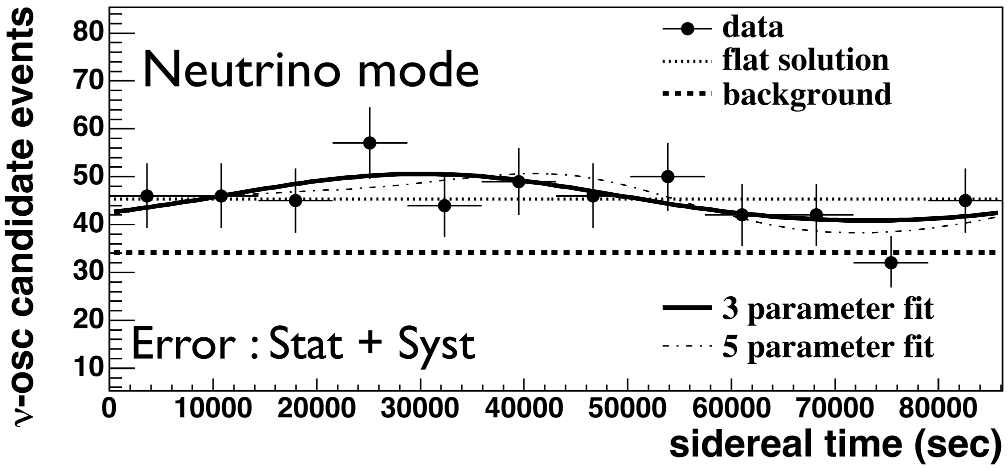
Sidereal time oscillation

MiniBooNE collaboration,
ArXiv:1109.3480

Maximize Unbinned likelihood using PDF based on sidereal time oscillation probability

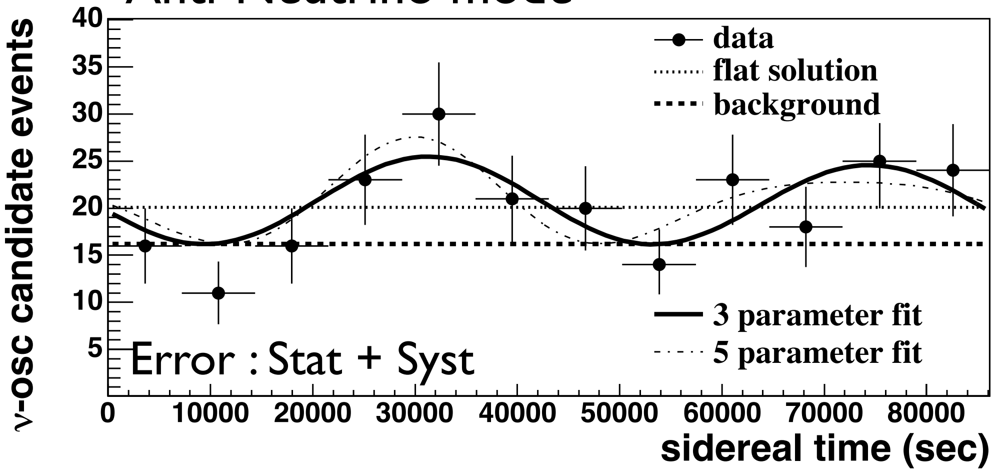
At 5 params fitting, fit errors are big due to the strong correlations of params

→ Do fitting w/ 3 params (remove Bs and Bc)



Neutrino mode:
- Flat distribution is best
  - C(time-independent) is dominant
- 26.9% compatibility assuming flat distribution

Anti-Neutrino mode



Anti-Neutrino mode:
- Fit solutions look more different from the flat
  - Non-zero (As)eμ and (Ac)eμ solution
- Only 3% compatibility assuming flat distribution

*Anti-Neutrino解析は全体の半分のデータしか入っていない

Limits for SME coefficiency

MiniBooNE collaboration,
ArXiv:1109.3480

各SMEパラメータに対して、1e-19 ~ 1e-20 GeVの制限をつけた

Table 1. List of SME coefficient limits, derived from 2σ limits of fitting parameters, setting all but one of the SME coefficients to be zero.

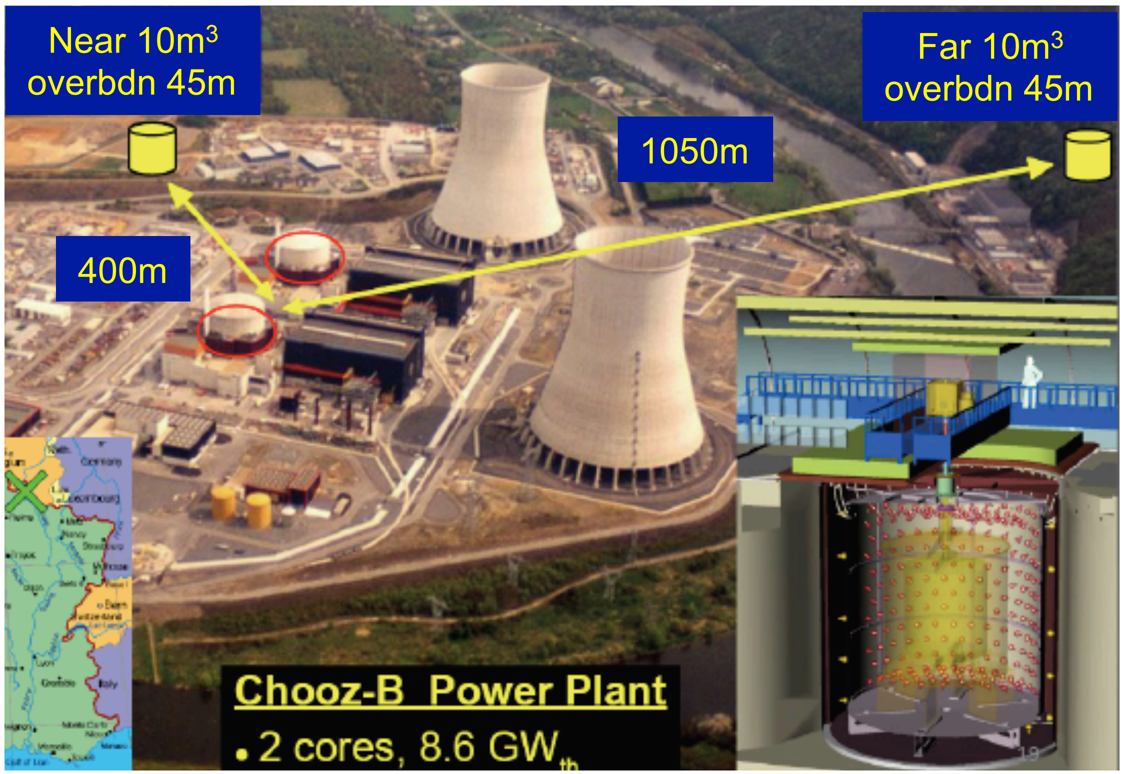
Coefficient	eμ (ν mode low energy region)	eμ ($\bar{\nu}$ mode combined region)
$\mathrm{Re}(a_L)^T$ or $\mathrm{Im}(a_L)^T$	4.2×10^{-20} GeV	2.6×10^{-20} GeV
$\mathrm{Re}(a_L)^X$ or $\mathrm{Im}(a_L)^X$	6.0×10^{-20} GeV	5.6×10^{-20} GeV
$\mathrm{Re}(a_L)^Y$ or $\mathrm{Im}(a_L)^Y$	5.0×10^{-20} GeV	5.9×10^{-20} GeV
$\mathrm{Re}(a_L)^Z$ or $\mathrm{Im}(a_L)^Z$	5.6×10^{-20} GeV	3.5×10^{-20} GeV
$\mathrm{Re}(c_L)^{XY}$ or $\mathrm{Im}(c_L)^{XY}$	—	—
$\mathrm{Re}(c_L)^{XZ}$ or $\mathrm{Im}(c_L)^{XZ}$	1.1×10^{-19}	6.2×10^{-20}
$\mathrm{Re}(c_L)^{YZ}$ or $\mathrm{Im}(c_L)^{YZ}$	9.2×10^{-20}	6.5×10^{-20}
$\mathrm{Re}(c_L)^{XX}$ or $\mathrm{Im}(c_L)^{XX}$	—	—
$\mathrm{Re}(c_L)^{YY}$ or $\mathrm{Im}(c_L)^{YY}$	—	—
$\mathrm{Re}(c_L)^{ZZ}$ or $\mathrm{Im}(c_L)^{ZZ}$	3.4×10^{-19}	1.3×10^{-19}
$\mathrm{Re}(c_L)^{TT}$ or $\mathrm{Im}(c_L)^{TT}$	9.6×10^{-20}	3.6×10^{-20}
$\mathrm{Re}(c_L)^{TX}$ or $\mathrm{Im}(c_L)^{TX}$	8.4×10^{-20}	4.6×10^{-20}
$\mathrm{Re}(c_L)^{TY}$ or $\mathrm{Im}(c_L)^{TY}$	6.9×10^{-20}	4.9×10^{-20}
$\mathrm{Re}(c_L)^{TZ}$ or $\mathrm{Im}(c_L)^{TZ}$	7.8×10^{-20}	2.9×10^{-20}

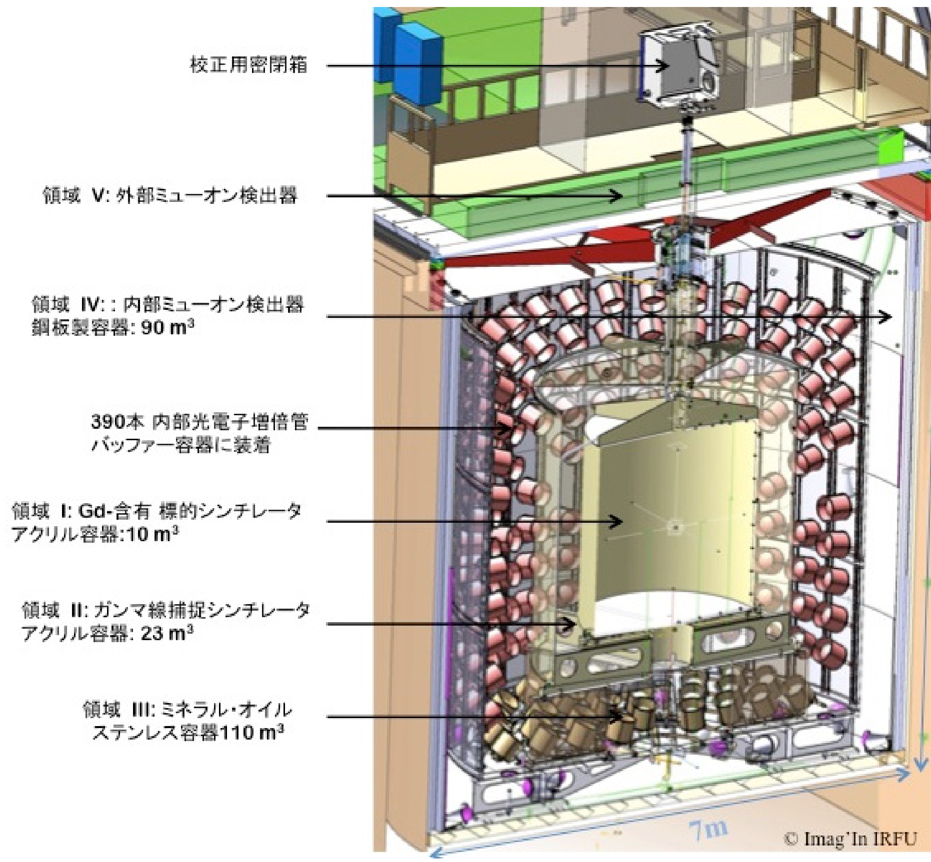
これらの制限は、LSNDの超過データをLorentz violationで説明できるSMEパラメータの値を棄却

Double Chooz

arXiv:1209.5810v1

- Reactor neutrino oscillation experiment in France
  - anti-νe disappearance
- Used data in Lorentz violation : 2011 4/13 ~ 2012 5/15 (227.9 live days)
  - Same used for latest result : $\sin^2 2\theta_{13}$=0.109 ± 0.03(stat) ± 0.025(syst)





Double Chooz oscillation analysis

- Select anti-νe + P → e+ + n (inverse beta decay: IBD)
- Delayed double coincidence → 8249 events

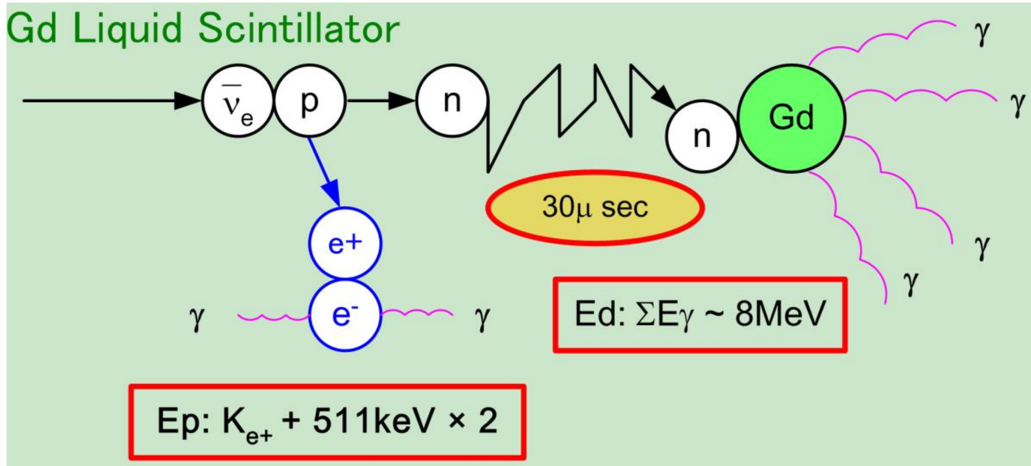


TABLE V. Summary of observed IBD candidates, with corresponding signal and background predictions for each integration period, before any oscillation fit results have been applied.

	Reactors Both On	One Reactor $P_{th} < 20\%$	Total
Livetime [days]	139.27	88.66	227.93
IBD candidates	6088	2161	8249
ν reactor B1	2910.9	774.6	3685.5
ν reactor B2	3422.4	1331.7	4754.1
Cosmogenic isotope	174.1	110.8	284.9
Correlated FN & SM	93.3	59.4	152.7
Accidentals	36.4	23.1	59.5
Total prediction	6637.1	2299.7	8936.8

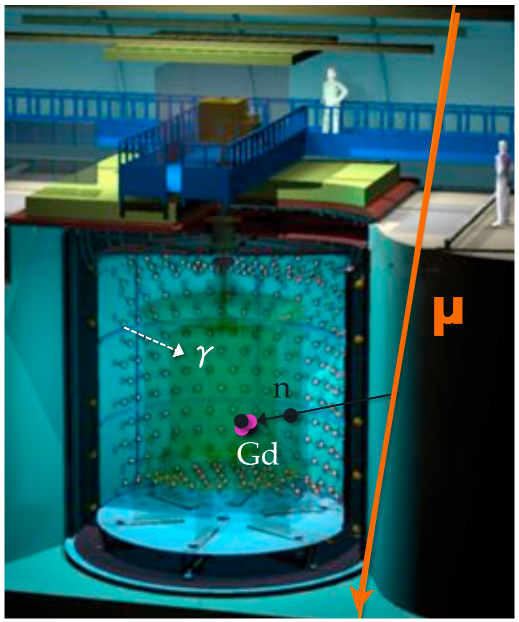
TABLE VI. Summary of signal and background normalization uncertainties in this analysis relative to the total prediction.

Source	Uncertainty [%]
Reactor flux	1.67%
Detector response	0.32%
Statistics	1.06%
Efficiency	0.95%
Cosmogenic isotope background	1.38%
FN/SM	0.51%
Accidental background	0.01%
Total	2.66%

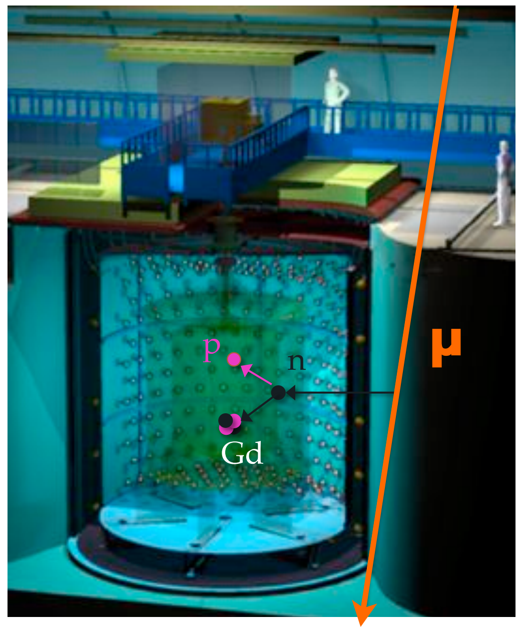
Background time dependency

Total background in oscillation analysis = 497 events

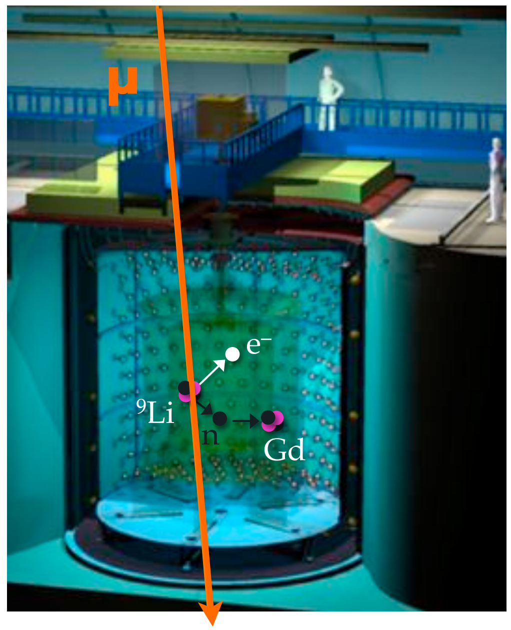
Accidental coincidence
(Ex: Environment γ + Fast neutron)



Fast neutron + stop μ
Fast-n → captured on Gd
Stop μ → delay



9-Lithium
9Li → e- + N + 8Be
(τ ~ 200msec)

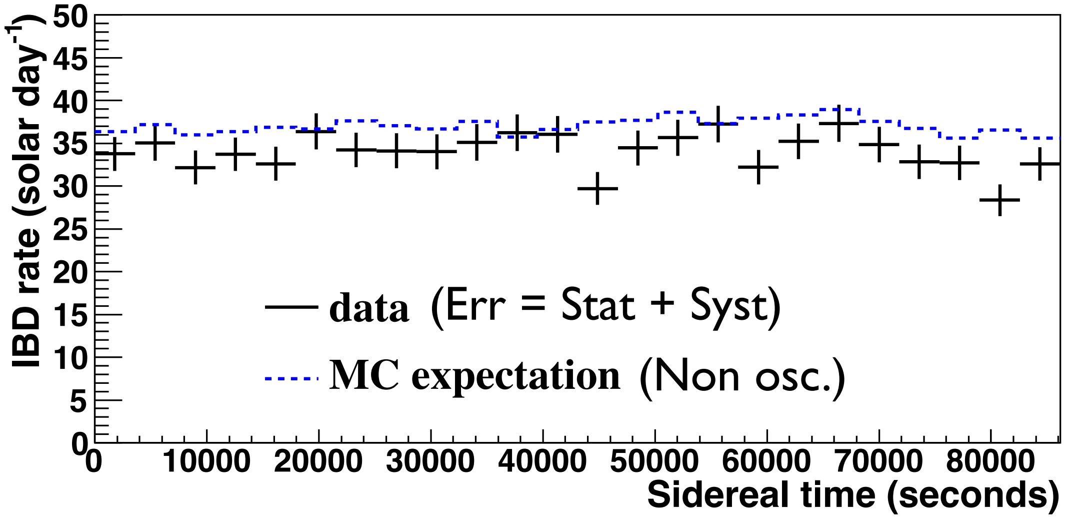


There comes from cosmic ray → Check muon veto rate stability

Maximum variation of muon veto rate (sidereal time) ~ 0.5%
→ BG variation in time ~ 0.03% effect for diapp. prob. → Negligible

Event rate Time-dependency

Background-subtracted IBD event rate



- Physics run(1時間)毎では安定

- MC expectation (IBD cross-section, flux, detector response, etc) varied run-by-run

Thermal core operation
- Time interval < 1min
- Power uncertainty ~ 0.5% of total

- 0~23.934 hours (1 sidereal day)を24binsに分割
- MC normalization はDAQ time stampに基づく各ランの測定時間に応じて run-by-runに計算 (Nominal anti-νe spectrum normalized by Bugey 4)
- Human activities (cores turned on/off, detector calibration, etc)によるday-night effect を MC prediction に well-accounted
  - Correlated uncertainties associated human activities are included a covariance matrix (include all stat & syst errors)

Neutrino oscillation from Lorentz violation

In 3 active flavor neutrino oscillation framework

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \simeq 1 - \frac{|(h_{\text{eff}})_{\bar{e}\bar{\mu}}|^2 L^2}{(\hbar c)^2} - \frac{|(h_{\text{eff}})_{\bar{e}\bar{\tau}}|^2 L^2}{(\hbar c)^2}$$

Prob(anti-νe → anti-νμ)

Prob(anti-νe → anti-ντ)

$$= 1 - \frac{L^2}{(\hbar c)^2}\left[\,|\,(\mathcal{C})_{\bar{e}\bar{\mu}} + (\mathcal{A}_s)_{\bar{e}\bar{\mu}} \sin\omega_\oplus T_\oplus + (\mathcal{A}_c)_{\bar{e}\bar{\mu}} \cos\omega_\oplus T_\oplus \right.$$
$$+ (\mathcal{B}_s)_{\bar{e}\bar{\mu}} \sin 2\omega_\oplus T_\oplus + (\mathcal{B}_c)_{\bar{e}\bar{\mu}} \cos 2\omega_\oplus T_\oplus|^2$$
$$+ |\,(\mathcal{C})_{\bar{e}\bar{\tau}} + (\mathcal{A}_s)_{\bar{e}\bar{\tau}} \sin\omega_\oplus T_\oplus + (\mathcal{A}_c)_{\bar{e}\bar{\tau}} \cos\omega_\oplus T_\oplus$$
$$\left. + (\mathcal{B}_s)_{\bar{e}\bar{\tau}} \sin 2\omega_\oplus T_\oplus + (\mathcal{B}_c)_{\bar{e}\bar{\tau}} \cos 2\omega_\oplus T_\oplus\,|^2\,\right]$$

10 amplitude
5 free parameters
→ Too much & complicated

"e-τ fit" : assumption P(→anti-νμ)=0

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \simeq 1 - \frac{L^2}{(\hbar c)^2}\left[\,|\,(\mathcal{C})_{\bar{e}\bar{\tau}} + (\mathcal{A}_s)_{\bar{e}\bar{\tau}} \sin\omega_\oplus T_\oplus \right.$$
$$+(\mathcal{A}_c)_{\bar{e}\bar{\tau}} \cos\omega_\oplus T_\oplus + (\mathcal{B}_s)_{\bar{e}\bar{\tau}} \sin 2\omega_\oplus T_\oplus$$
$$\left. +(\mathcal{B}_c)_{\bar{e}\bar{\tau}} \cos 2\omega_\oplus T_\oplus\,|^2\,\right]$$

Double Choozの最大感度を考えると、同時にフィットしても、あまり得はしない

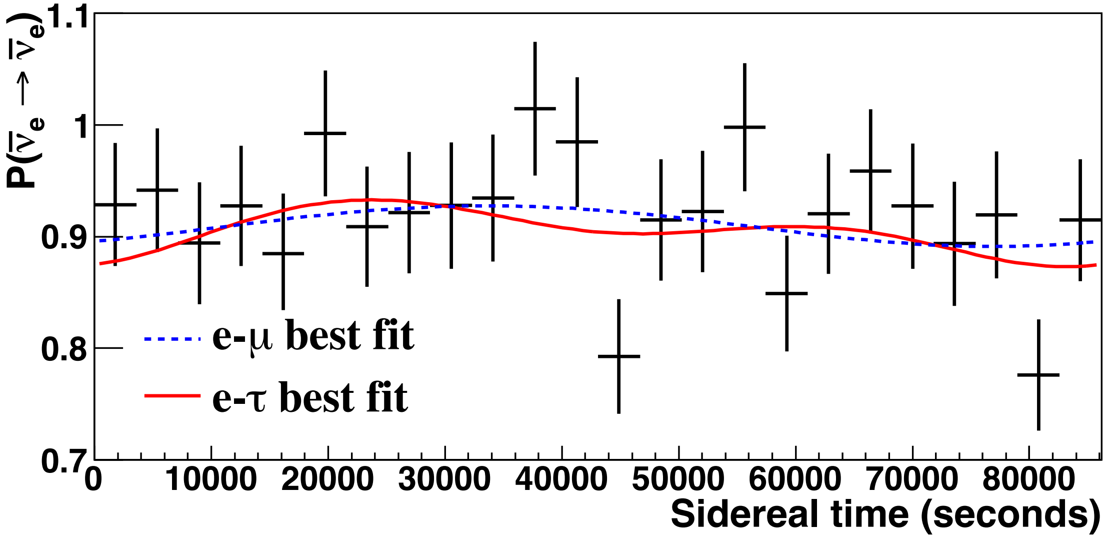
"e-μ fit" : assumption P(→anti-ντ)=0,

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \simeq 1 - \frac{L^2}{(\hbar c)^2}\left[\,|\,(\mathcal{C})_{\bar{e}\bar{\mu}} + (\mathcal{A}_s)_{\bar{e}\bar{\mu}} \sin\omega_\oplus T_\oplus \right.$$
$$\left. +(\mathcal{A}_c)_{\bar{e}\bar{\mu}} \cos\omega_\oplus T_\oplus\,|^2\,\right]$$

(remove CPT-even coefficients as MINOS, MiniBooNE)

Lorentz-violating analysis result

- Least square fitting w/ total error matrix (stat + correlated syst) for BG-subtracted data



χ2/ndf
e-μ fit : 28.8/21
e-τ fit : 27.7/19
flat fit : 30.6/23

For both fit, time independent C is dominated

Δχ2 = χ2(flat hypothesis) - χ2(min)
→ Δχ2(data) < Δχ2(pesudo-exp)
- e-μ fit : 41.8%
- e-τ fit : 60.0%

No time dependent indication

	BF parameter (10^{-20} GeV)	2σ limit
$(\mathcal{C})_{\bar{e}\bar{\tau}}$	5.8	7.8
$(\mathcal{A}_s)_{\bar{e}\bar{\tau}}$	-0.4	6.6
$(\mathcal{A}_c)_{\bar{e}\bar{\tau}}$	0.4	7.0
$(\mathcal{B}_s)_{\bar{e}\bar{\tau}}$	0.0	5.4
$(\mathcal{B}_c)_{\bar{e}\bar{\tau}}$	0.5	5.4
$(\mathcal{C})_{\bar{e}\bar{\mu}}$	5.8 ± 1.7	—
$(\mathcal{A}_s)_{\bar{e}\bar{\mu}}$	-0.4 ± 0.7	1.9
$(\mathcal{A}_c)_{\bar{e}\bar{\mu}}$	0.5 ± 0.8	5.5

Limits on SME coefficients by constant χ2
Ex: 1σ (2σ) limit w/ constant Δχ2 = 5.9 (11.3) for e-τ fit (5 params)

“Norm-fit w/ only C” = “Rate-only θ_{13} analysis”
→ 今の測定精度では Lorentz violation と (mass, θ_{13}) oscillation の結果が区別できない

Summary

- Standard Model を拡張することで、我々の現在のエネルギー領域でもLorentz violationの測定ができる(かも)
- すでに多くの実験でLorentz violationの解析がされているが、兆候はまだ見つかっていない
  - LSNDやMiniBooNE(anti-neutrino mode)でSidereal modulationっぽいものが見えているが、両者の結果は矛盾する
  - 各振動モードでの現在のパラメータ制限
    - νe ⇔ νμ : <1e-20 GeV (LSND, MiniBooNE, MINOS)
    - νμ ⇔ ντ : <1e-23 GeV (MINOS, IceCube)
    - νe ⇔ ντ : <1e-21 GeV (Double Chooz)
- MiniBooNE anti-neutrinoのフルデータ解析や、別の解析アプローチ、宇宙物理からの制限など、まだやることはある(と思う)

2. Modern tests of Lorentz violation

The last meeting of Lorentz and CPT violation was in summer 2010.
Next meeting will be in summer 2013

インディアナ大学 のアラン・コステレツキー教授(V. Alan Kostelecky)のHP
http://www.physics.indiana.edu/~kostelec/faq.html

CPT'10

MEETING LINKS

Meeting Home
Registration
Program
Proceedings
Travel
Accommodations

LOCAL LINKS

IU Physics
IU Astronomy
IU Bloomington
Bloomington area

Fifth Meeting on

CPT and Lorentz Symmetry

June 28-July 2, 2010

Indiana University, Bloomington

The *Fifth Meeting on CPT and Lorentz Symmetry* will be held in the Physics Department, Indiana University in Bloomington, Indiana, U.S.A. on June 28-July 2, 2010. The meeting will focus on tests of these fundamental symmetries and on related theoretical issues, including scenarios for possible violations.

Topics include:

- searches for CPT and Lorentz violations involving
  - birefringence and dispersion from cosmological sources
  - clock-comparison measurements
  - CMB polarization
  - collider experiments
  - electromagnetic resonant cavities
  - equivalence principle
  - gauge and Higgs particles
  - high-energy astrophysical observations
  - laboratory and gravimetric tests of gravity

07/10/12 Teppei Katori, MIT

2010 meeting

Topics:

* searches for CPT and Lorentz violations involving
  - birefringence and dispersion from cosmological sources
  - clock-comparison measurements
  - CMB polarization
  - collider experiments
  - electromagnetic resonant cavities
  - equivalence principle
  - gauge and Higgs particles
  - high-energy astrophysical observations
  - laboratory and gravimetric tests of gravity
  - matter interferometry
  - neutrino oscillations
  - oscillations and decays of K, B, D mesons
  - particle-antiparticle comparisons
  - post-newtonian gravity in the solar system and beyond
  - second- and third-generation particles
  - space-based missions
  - spectroscopy of hydrogen and antihydrogen
  - spin-polarized matter
* theoretical studies of CPT and Lorentz violation involving
  - physical effects at the level of the Standard Model, General Relativity, and beyond
  - origins and mechanisms for violations
  - classical and quantum issues in field theory, particle physics, gravity, and strings

Back up

Sidereal time (恒星時間)

- 春分点の見かけの日周運動によって計られる時間

恒星時は春分点の時角として定義される（あるいは、その時に真南に見える星の赤経としても定義できる）。春分点が子午線を通過する時、すなわち赤経0時の線がちょうど頭上にある時にその場所の地方恒星時は00:00である。グリニッジ恒星時はイギリス・グリニッジでの子午線（本初子午線）上で測った春分点の時角である。

まず、日本標準時(JST)から9時間を引き、世界時(UT)を求める。

世界時(UT) = 日本標準時(JST) - 9時

UTの現在のグレゴリオ暦での年をY、月をM、日をD、時間をh、分をm、秒をsとする。ただし、1月と2月はそれぞれ前年（Yの値を-1する）の13月、14月として代入する（例: 2010年1月1日の場合、Y=2009, M=13, D=1）。このときユリウス通日(JD)は、次の式で求められる。

$$JD = [365.25Y] + \left[\frac{Y}{400}\right] - \left[\frac{Y}{100}\right] + [30.59(M-2)] + D + 1721088.5 + \frac{h}{24} + \frac{m}{1440} + \frac{s}{86400}$$

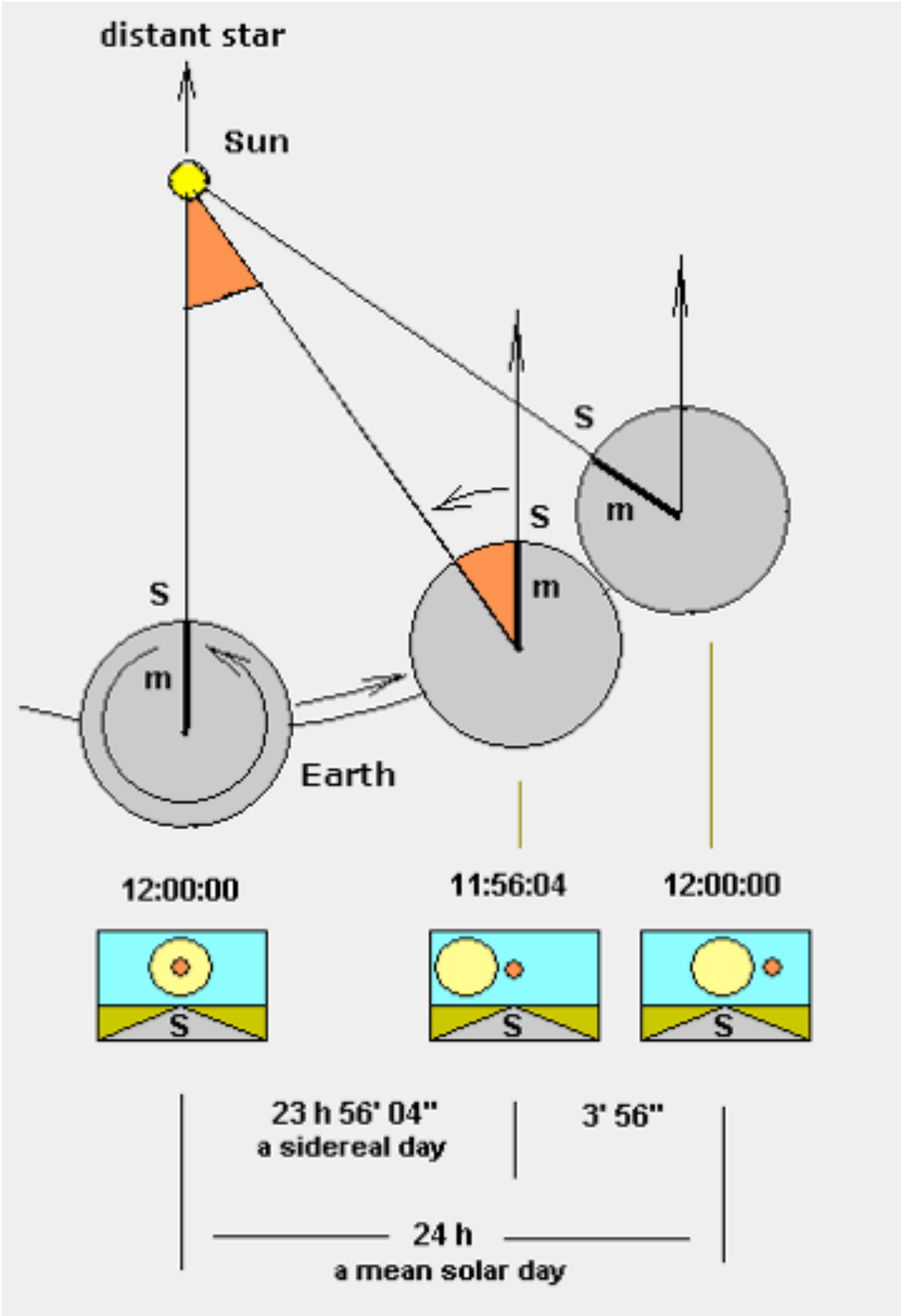
[]の記号は小数点以下を切り捨て整数だけをとる意味とする。次に、TJD (Truncated Julian Day - NASAが導入した世界時1968年3月24日0時からの日数) を次の式で求める。

$$TJD = JD - 2440000.5$$

平均春分点に準拠するグリニッジ恒星時（歳差のみを考慮に入れた平均恒星時）は、次の式で求めることができる（hは時間の単位。度数法で表記された角度を15で割ったものと同じ）。

$$\bar{\theta}_G = 24^h \times (0.671262 + 1.0027379094 \times TJD)$$

Sidereal time (恒星時間)



Solar time (24h) と Sidereal time

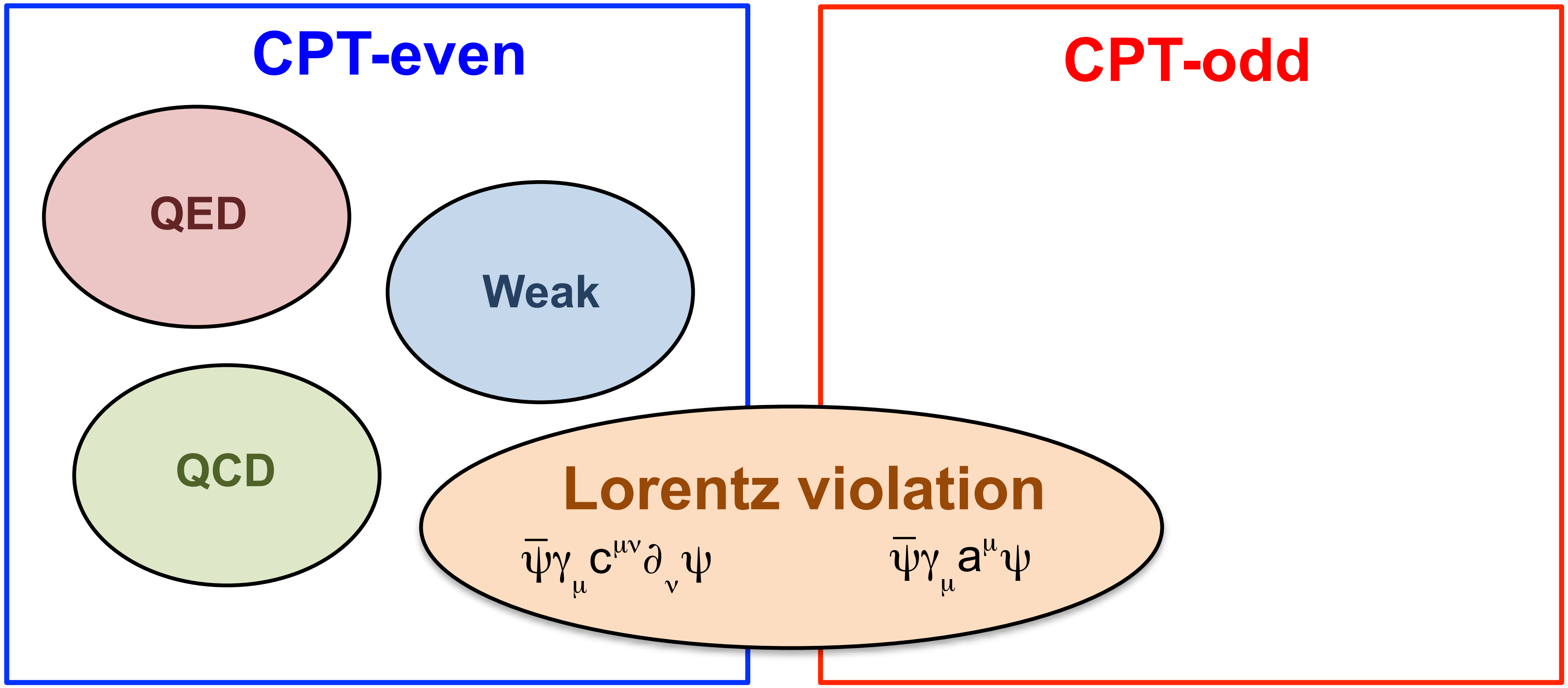
(23h56m04s)の違い

2. What is CPT violation?

CPT symmetry is the invariance under CPT transformation

$$L \xrightarrow{CPT} \Theta L \Theta^{-1} = L' = L, \qquad \Theta = CPT$$

CPT is the perfect symmetry of the Standard Model, due to CPT theorem



CPT-odd Lorentz violating coefficients (odd number Lorentz indices, ex., a^{μ} , $g^{\lambda\mu\nu}$)
CPT-even Lorentz violating coefficients (even number Lorentz indices, ex., $c^{\mu\nu}$, $\kappa^{\alpha\beta\mu\nu}$)

L-E diagram

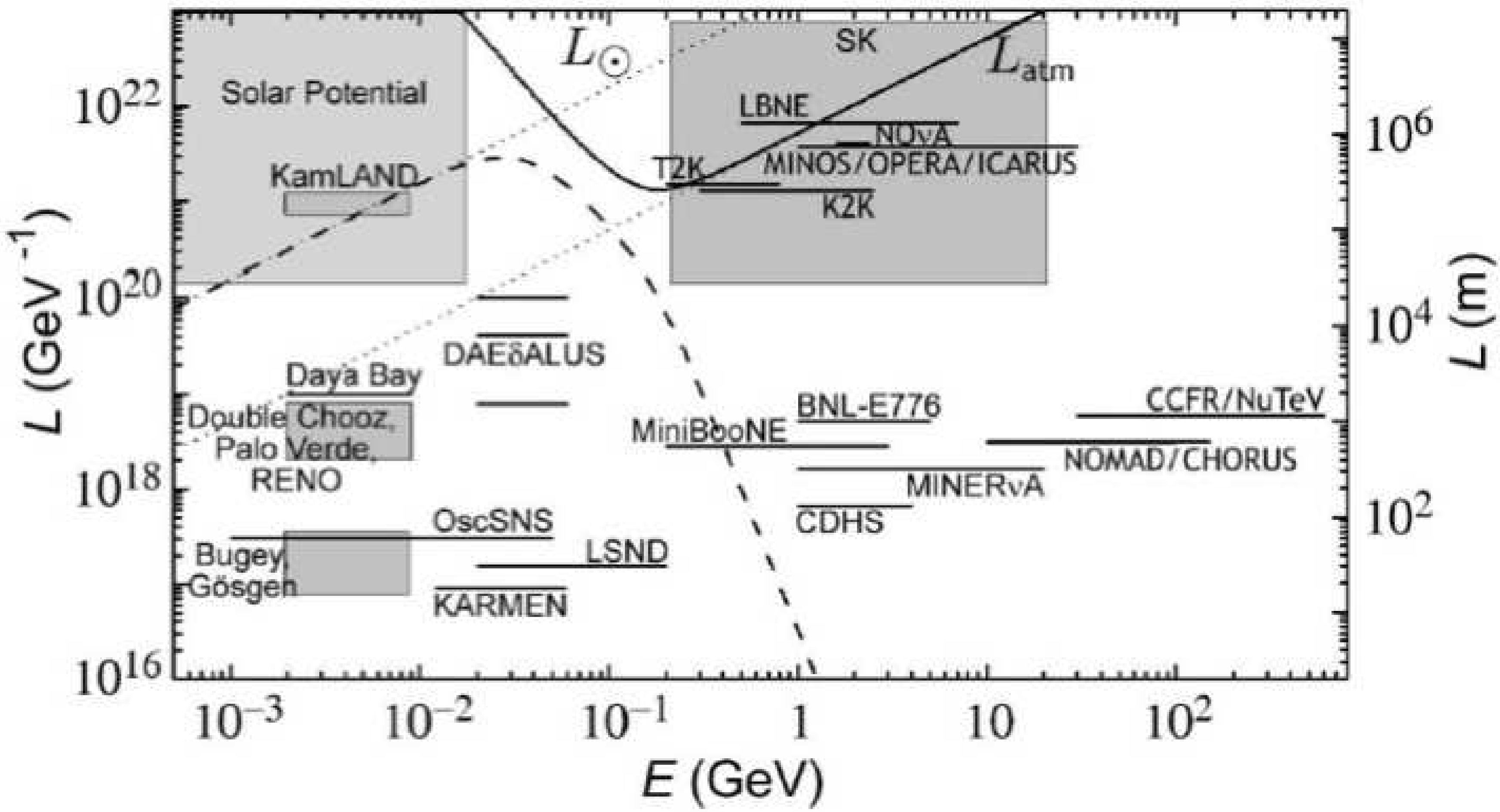


Fig. 4. L-E diagram with the νSM (two straight dotted lines) and the Puma model (two dashed and solid curves).

MiniBooNE Unbined likelihood

$$\Lambda = \frac{e^{-(\mu_s+\mu_b)}}{N!} \prod_{i=1}^{N} (\mu_s \mathcal{F}_s^i + \mu_b \mathcal{F}_b^i) \times \frac{1}{\sqrt{2\pi{\sigma_b}^2}} \exp\left(-\frac{(\bar{\mu}_b - \mu_b)^2}{2{\sigma_b}^2}\right)$$

N, the number of observed candidate events

μ_s, the predicted number of signal events, the function of fitting parameters

μ_b, the predicted number of background events, floating within 1σ range

$\mathcal{F}_s$, the PDF for the signal, the function of sidereal time and fitting parameters

$\mathcal{F}_b$, the PDF for the background, not the function of the sidereal time

σ_b, the 1σ error on the predicted background

$\bar{\mu}_b$, the central value of the predicted total background events