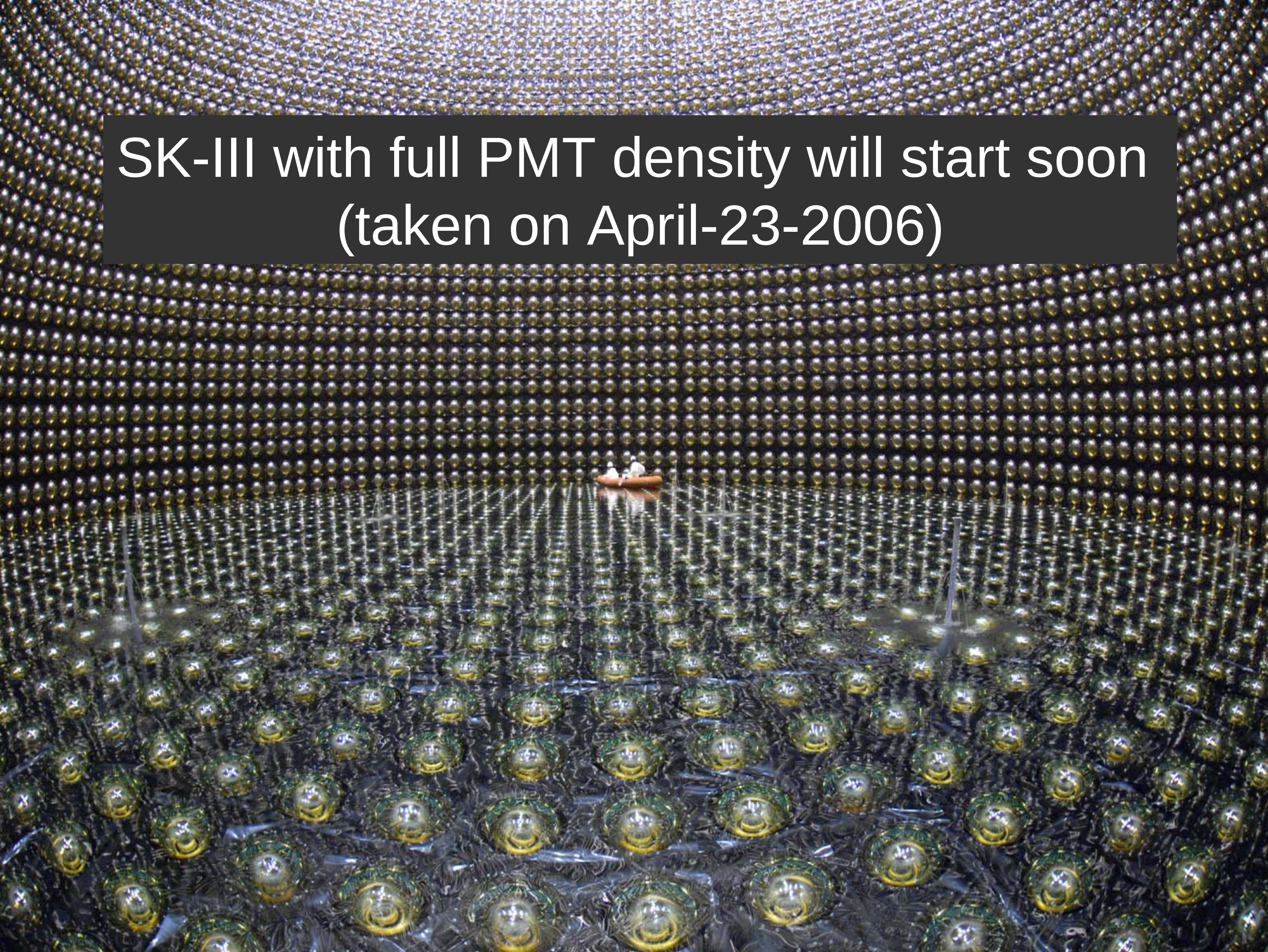
Super-Kamiokande-IIIでの物理

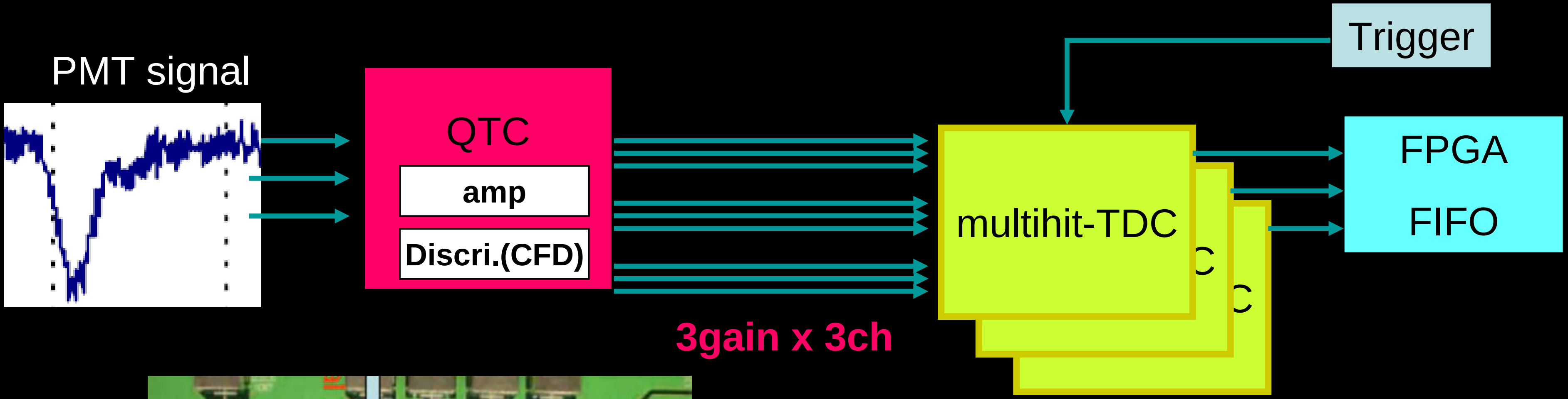
将来計画勉強会（3）　宇宙ニュートリノ研究部門
2006年6月29日

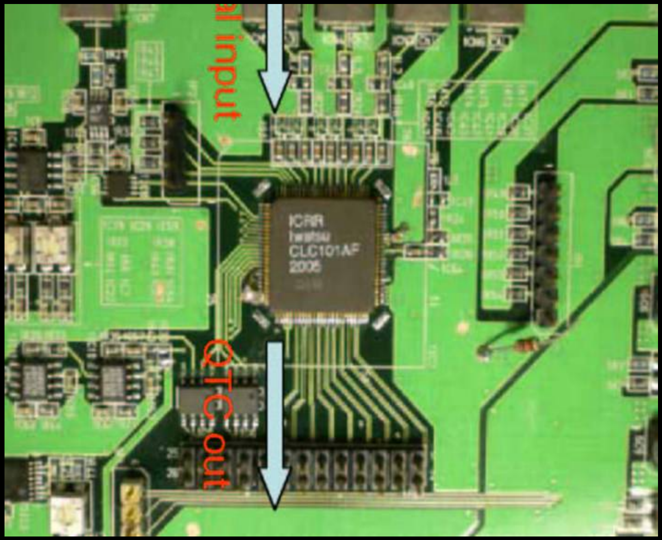
塩澤　真人



SK-III with full PMT density will start soon
(taken on April-23-2006)

電子機器も入れ替える予定





最初のQTCchip+評価ボード

2004	カスタムASICの開発開始
2005	基板全体の設計
2006	ボードの試作、試験
2007	システム全体の開発、試験
2008	大量生産、 スーパーカミオカンデ入れ替え

今後～10年の安定したデータ収集。

高感度、高精度、高速なデータ収集装置の開発。

ハードウエアトリガーなし(エレキのエネルギー閾値なし)。

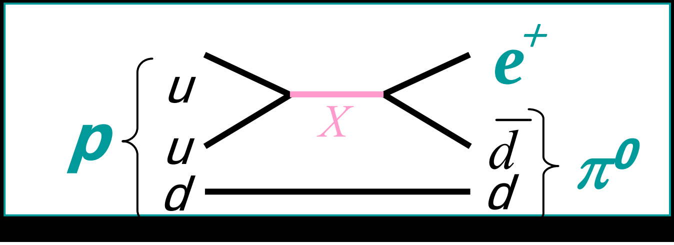
これから何ができるか？

- 陽子崩壊
- 超新星爆発
- ニュートリノ物理学（精密測定）
  - 加速器ニュートリノ－＞次のトーク（早戸）で
  - 大気ニュートリノ
  - 太陽ニュートリノ

統計　SK1（4年）＋SK2（2年）
＋SK3（~14年(2020までで)）
SK20年＝0.45Mton・years
(10~20年がこのトークでのデータ統計の目安)

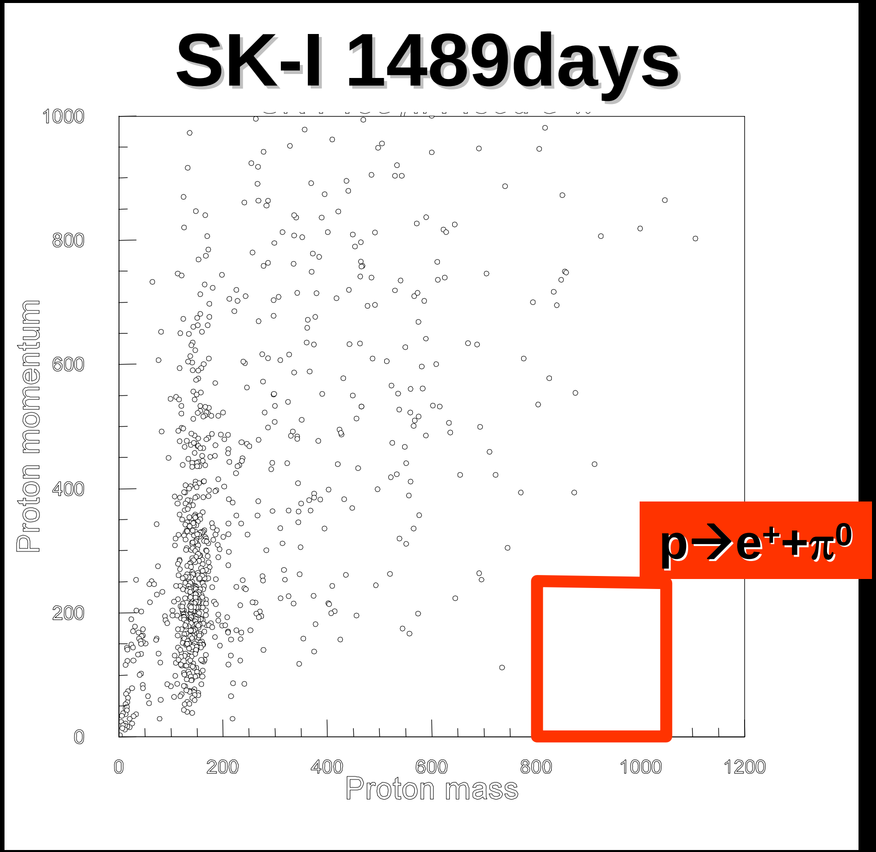
陽子崩壊探索

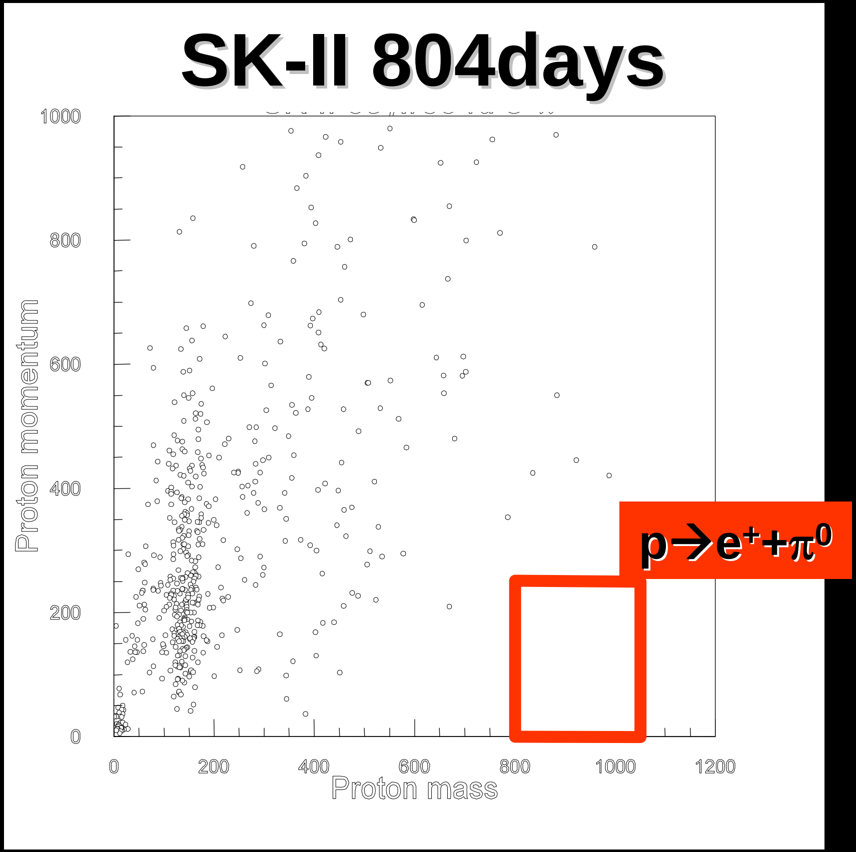
陽子崩壊の探索



ε~40%, BG~0.05ev/year

e^+ and π^0 are back-to-back

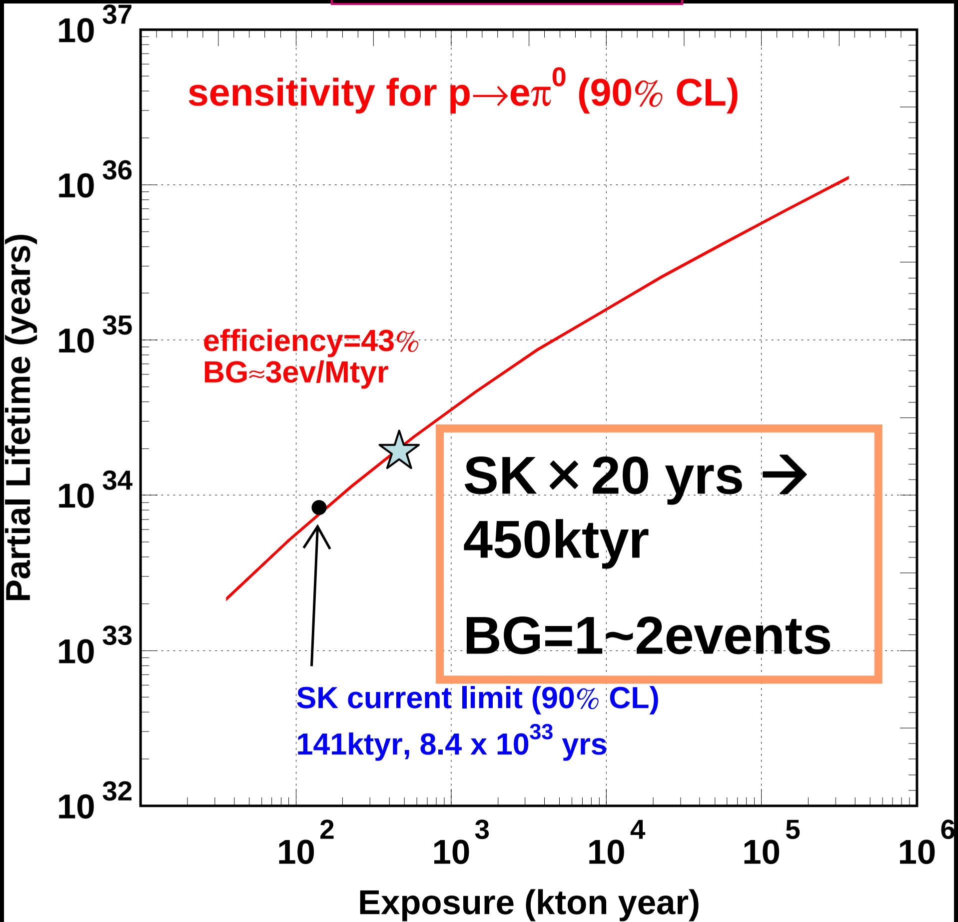

SK-I 1489days


SK-II 804days

τ_p/Branch > 8.4 x 10^{33} years (90% CL)

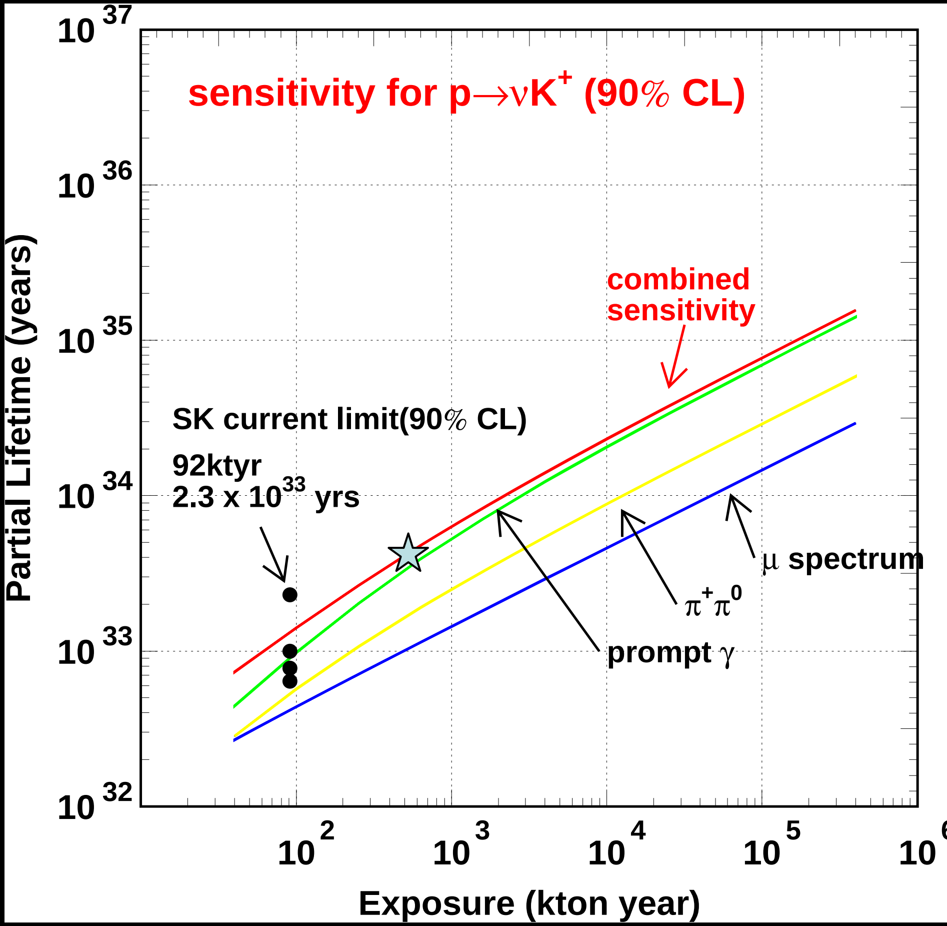
Null signalの場合の将来の感度

$p \to e^+\pi^0$



$\tau/B \to 2 \times 10^{34}$ yrs
(SK 20yrs, 90%CL)

$p \to \nu K^+$

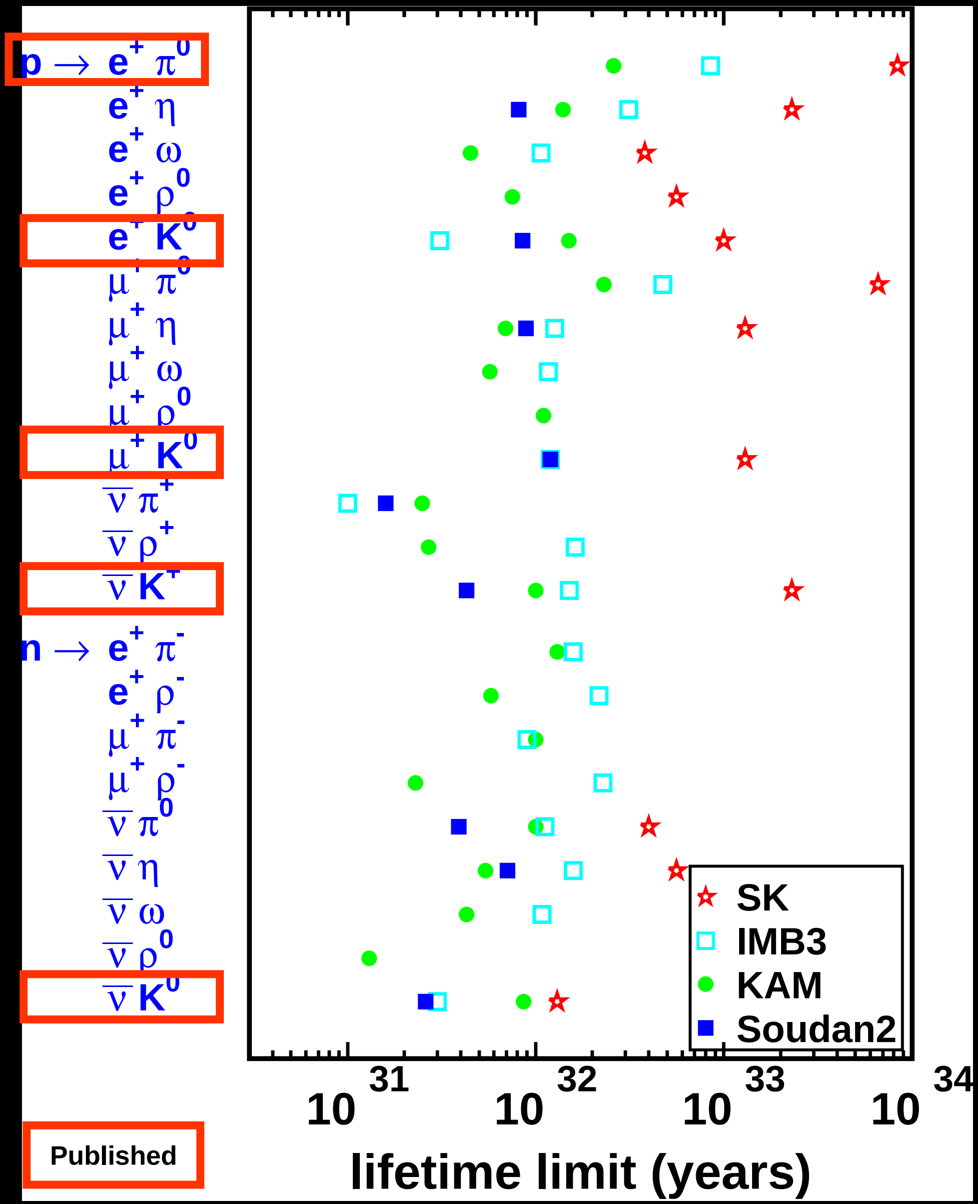


$\tau/B \to 4 \times 10^{33}$ yrs
(SK 20yrs, 90%CL)

他の核子崩壊も探索する

World record更新

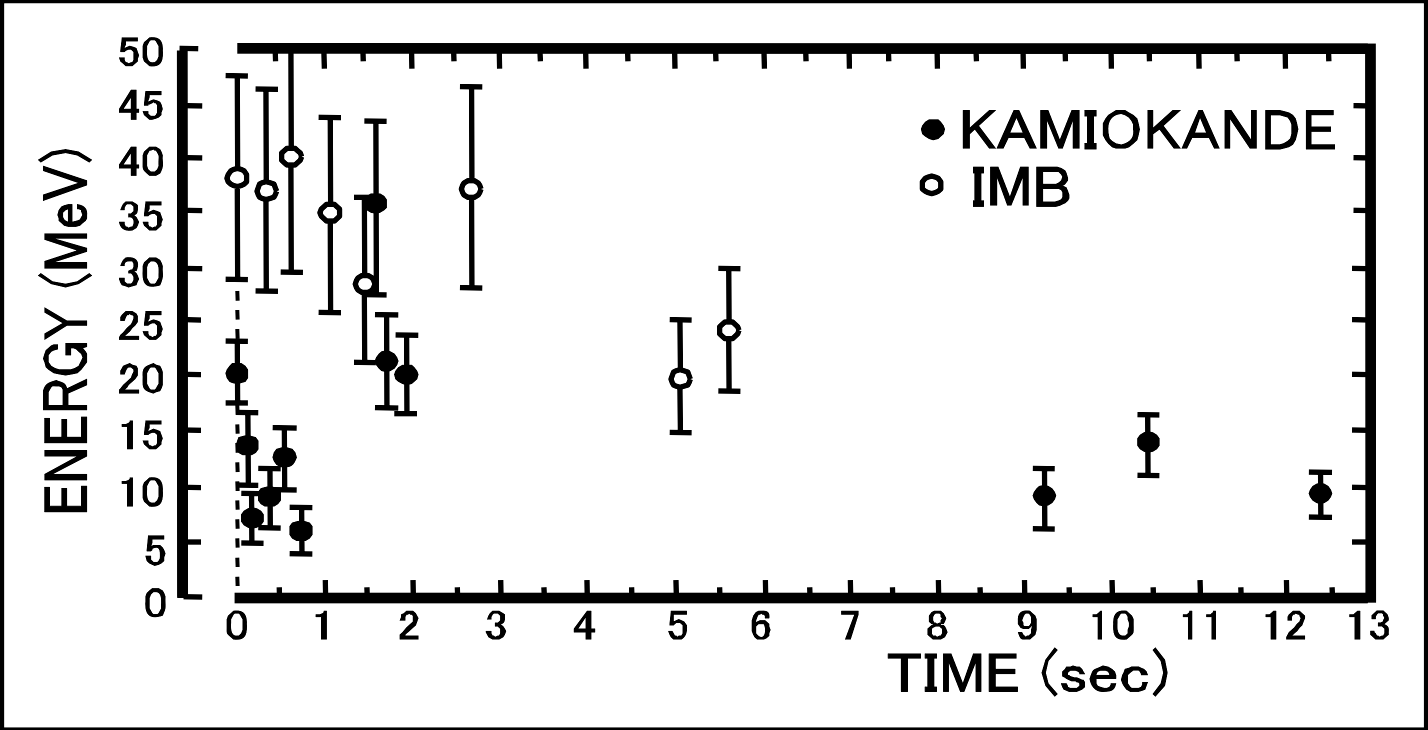
他に(B－L)非保存崩壊モード等も解析する



超新星爆発ニュートリノ

超新星SN1987a

Supernova SN1987a



観測された現象から得られた爆発のエネルギー(~3 x 10^{53} erg)は超新星爆発のシナリオと一致。

しかし、19現象では温度等爆発の詳細な情報は得られなかった。

超新星爆発のメカニズムは未だに解明されていない。

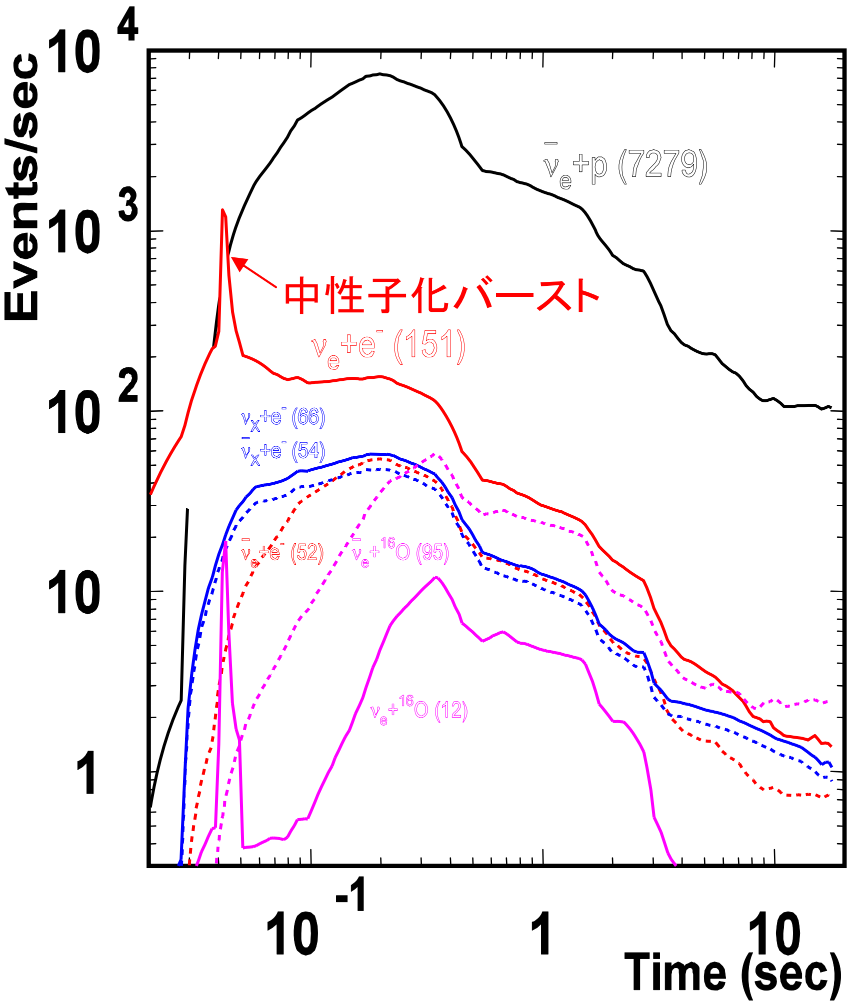
より高統計の観測データが必要。

A few SN per century in Milky Way

スーパーカミオカンデで期待される現象の数

Neutrino flux and energy spectrum from Livermore simulation

(T.Totani, K.Sato, H.E.Dalhed and J.R.Wilson, ApJ.496,216(1998))



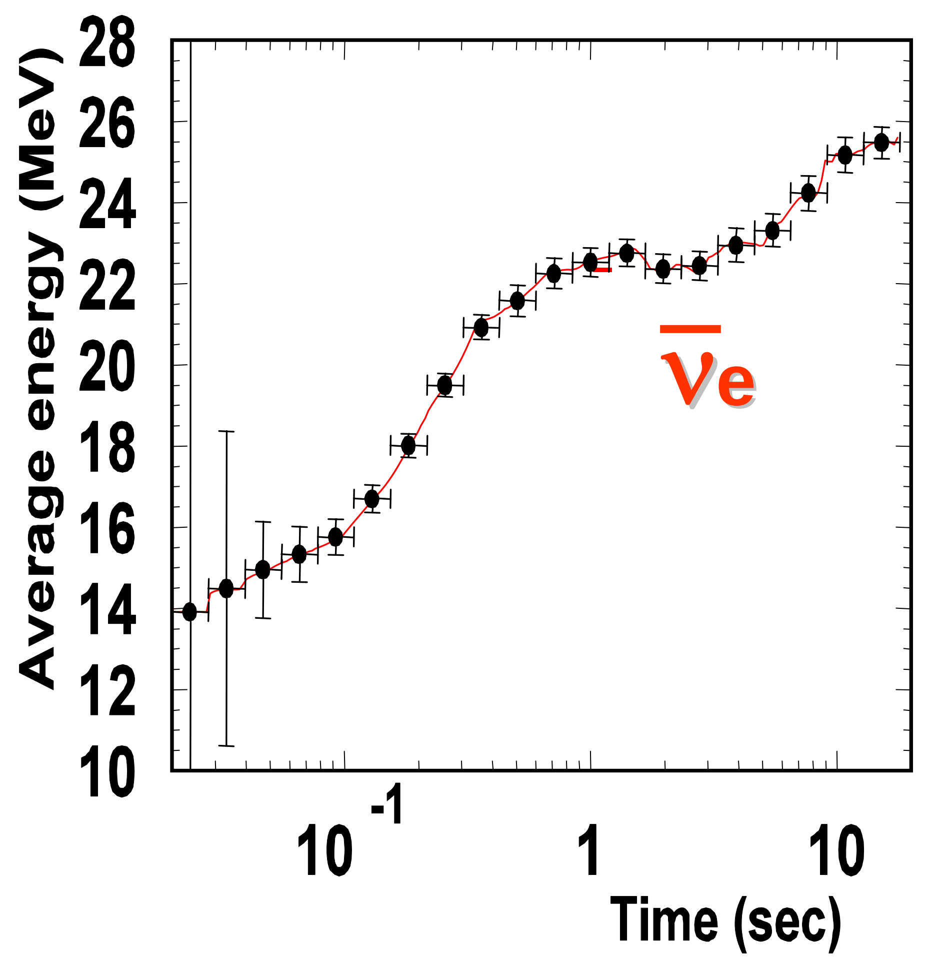
5MeV threshold

~7,300 $\bar{\nu}_e$+p events
~300 ν+e events
~100 $\overset{(-)}{\nu}_e$+^{16}O events

for 10 kpc supernova

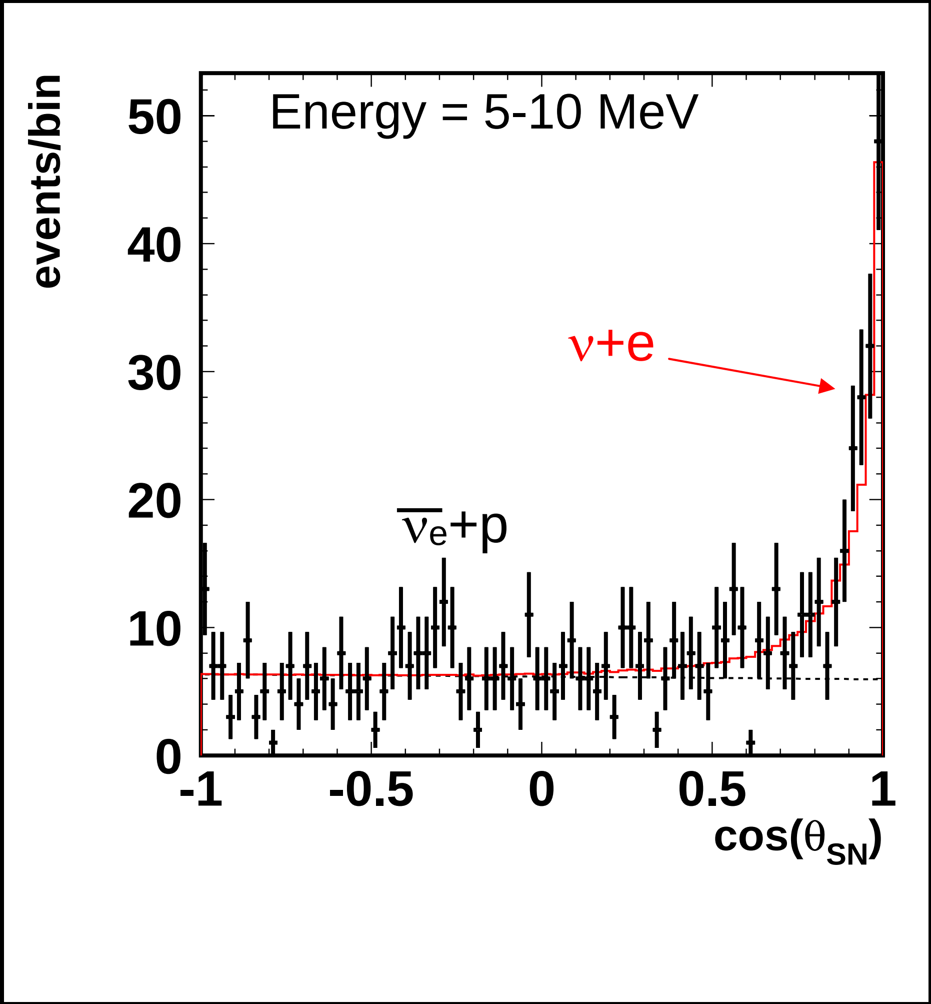
銀河中心でおきれば、
全部で8000イベント
近い数が期待される。

平均温度の変化



爆発の時間発展を詳細にみることができる。

方向分布

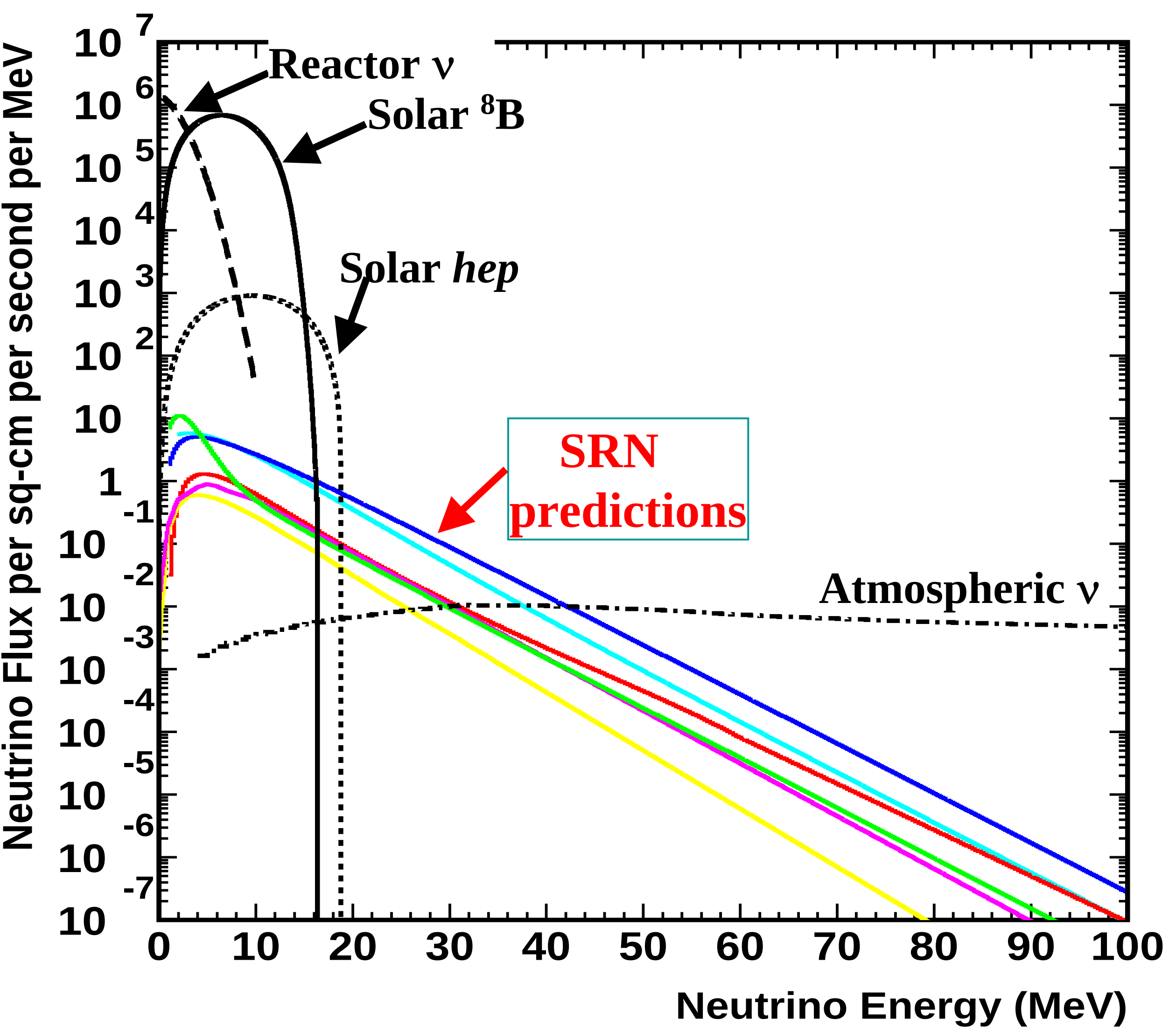


- 超新星の方向がわかる
- $\nu_e+\nu_x$ extractionが可能

より低いレートでの検出

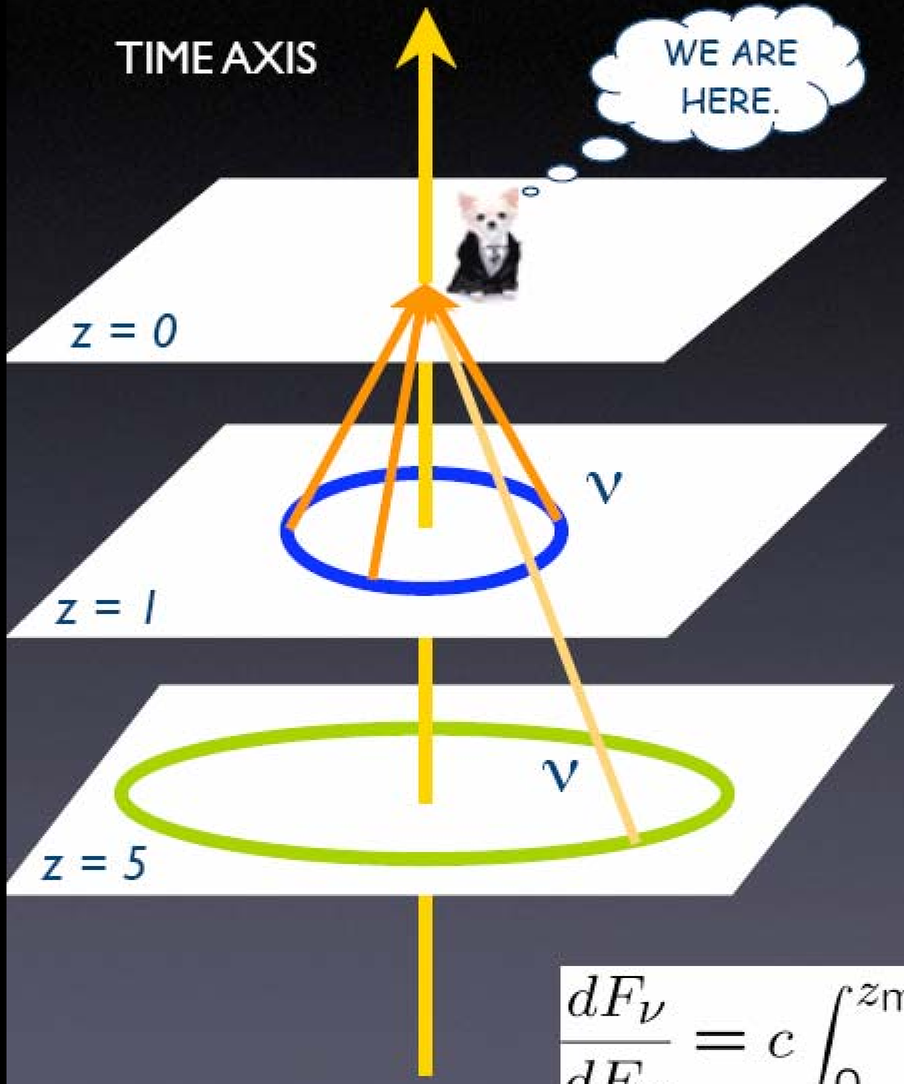
- 遠方(~1Mpc)での超新星
  - Nν>=2 in 10sec ←→BG~2 in 20years
  - negligible BG for Nν>=3 in 10sec

- past (cosmological) supernova neutrino (supernova relic neutrino)



2. Formulation and Models

How to Calculate the SRN Flux

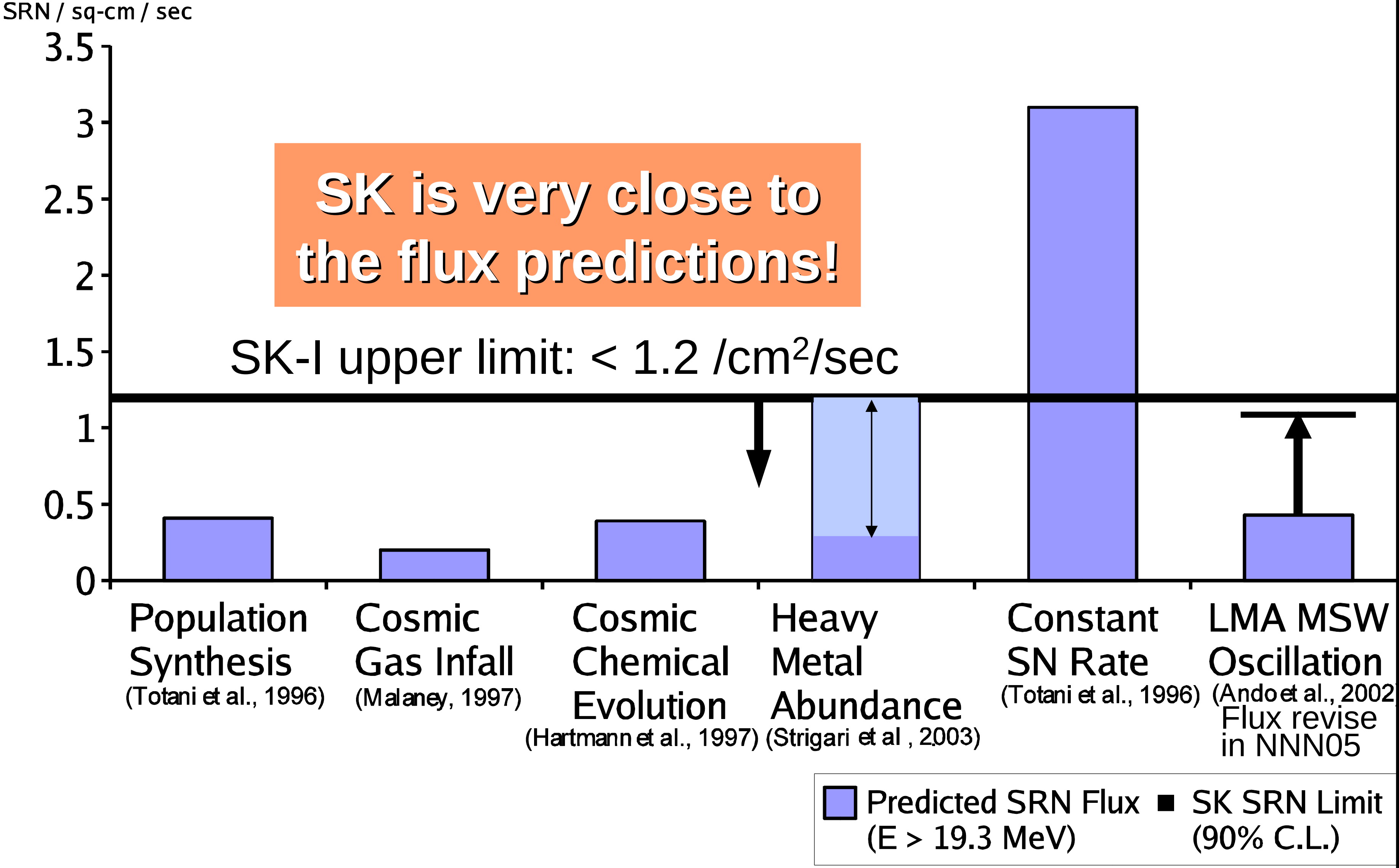


We need information concerning...

1. Neutrino spectrum emitted from each supernova explosion
2. Neutrino oscillation within supernovae and the Earth
3. Supernova rate

$$\frac{dF_\nu}{dE_\nu} = c\int_0^{z_{\mathrm{max}}} R_{\mathrm{SN}}(z)\frac{dN_\nu(E'_\nu)}{dE'_\nu}(1+z)\frac{dt}{dz}dz$$

SK SRN Flux Limits vs. Theoretical Predictions
(E_ν> 19.3 MeV)



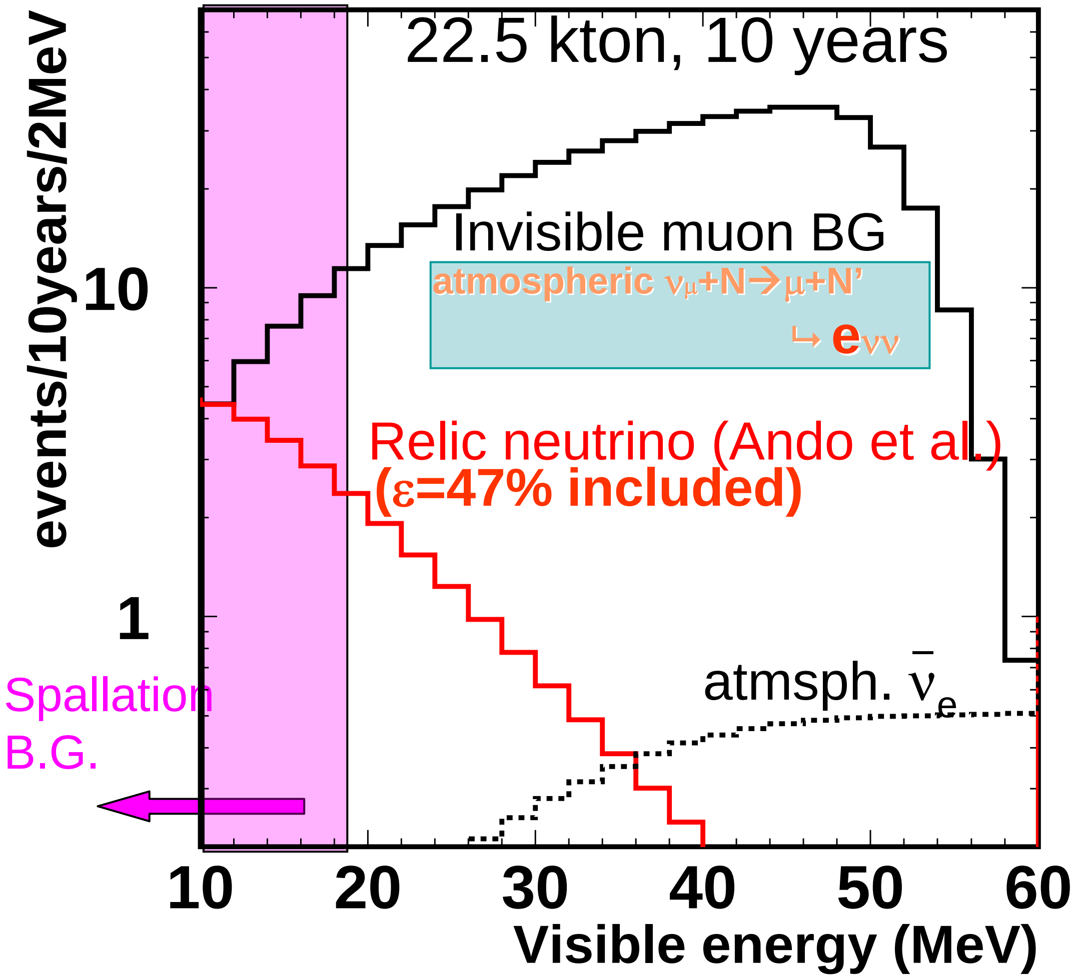
SK is very close to the flux predictions!

SK-I upper limit: < 1.2 /cm^2/sec

Flux revise in NNN05

Expected SRN event rate

Relic model: S.Ando, K.Sato, and T.Totani, Astropart.Phys.18, 307(2003) with flux revise in NNN05.



SRN signal: 8.8(17.6)
Background: 101(202)

in 18-30 MeV

for 10(20) years

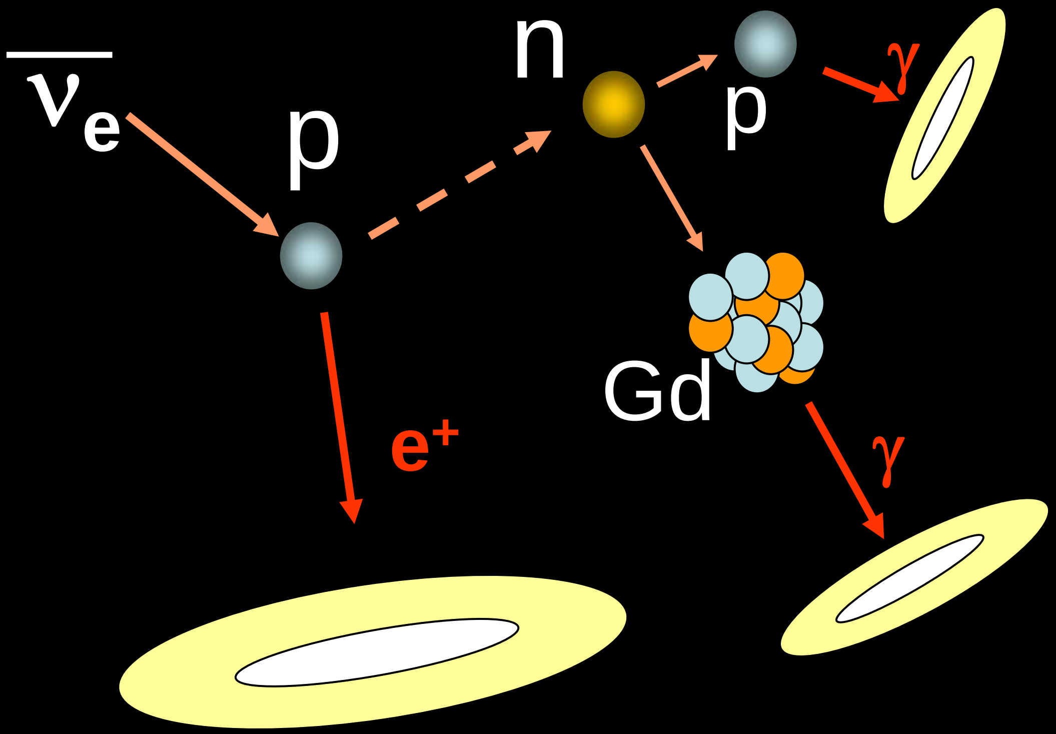
(assuming detection efficiency of 47%)

Invisible muon BG must be reduced.

&

Spallation BG must be reduced.

Possibilities of $\overline{\nu}_e$ tagging



Positron and gamma ray vertices are within ~50cm.

Possibility 1

n+p→d + γ

2.2MeV γ-ray

ΔT = ~ 200 μsec

Number of hit PMT is about 6 in SK-III

Possibility 2

n+Gd →~8MeV γ

ΔT = several 10th μsec

Add 0.2% $GdCl_3$ in water

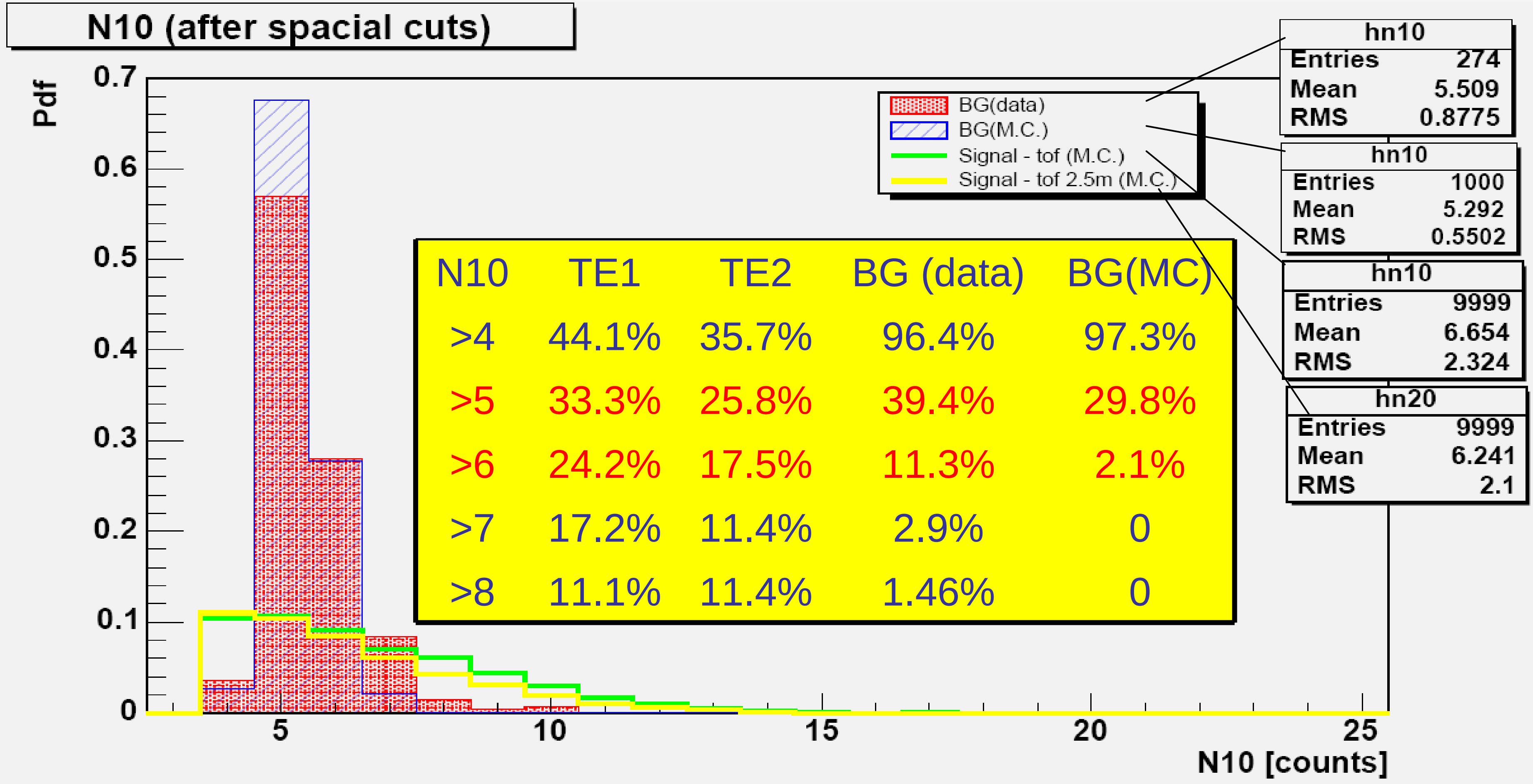
(ref. Vagins and Beacom)

- invisible μ, spallation, solar ν BG are reducible
- it reduces deadtime due to spallation cut etc.
- it opens energy window of 10-18MeV

Zhi Deng, Nov.2005 collab. meeting

N(10nsec) for 2.2MeV gamma

0.6 < Anisotropy < 0.86 && 0.1 < dirks < 0.3, not optimized



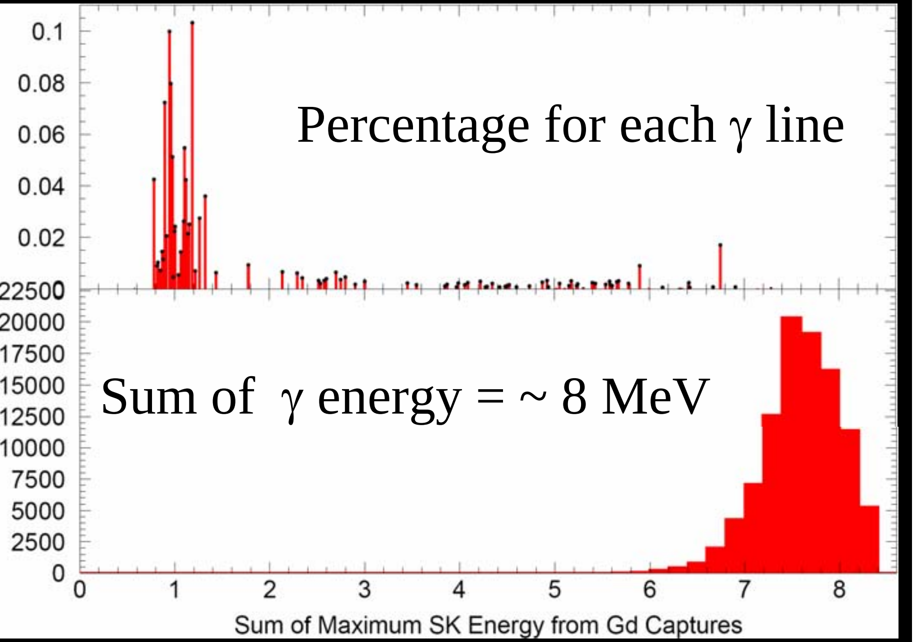
N10	TE1	TE2	BG (data)	BG(MC)
>4	44.1%	35.7%	96.4%	97.3%
>5	33.3%	25.8%	39.4%	29.8%
>6	24.2%	17.5%	11.3%	2.1%
>7	17.2%	11.4%	2.9%	0
>8	11.1%	11.4%	1.46%	0

R&D is going on to improve the tagging efficiency.

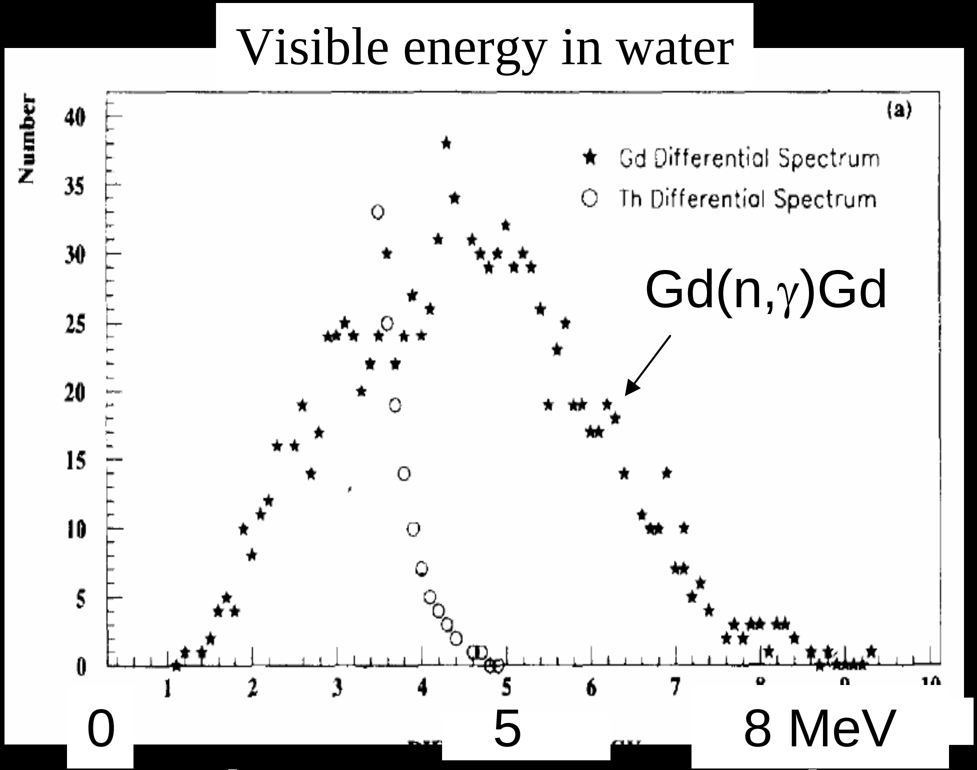
$\overline{\nu}_e$ identification: possibility 2

J.Beacom and M.Vagins, Phys.Rev.Lett.93:171101,2004

~0.2% $GdCl_3$ solution. Detect neutrons by Gd(n,γ)Gd reaction.


Percentage for each γ line

Sum of γ energy = ~ 8 MeV


Visible energy in water

Gd(n,γ)Gd

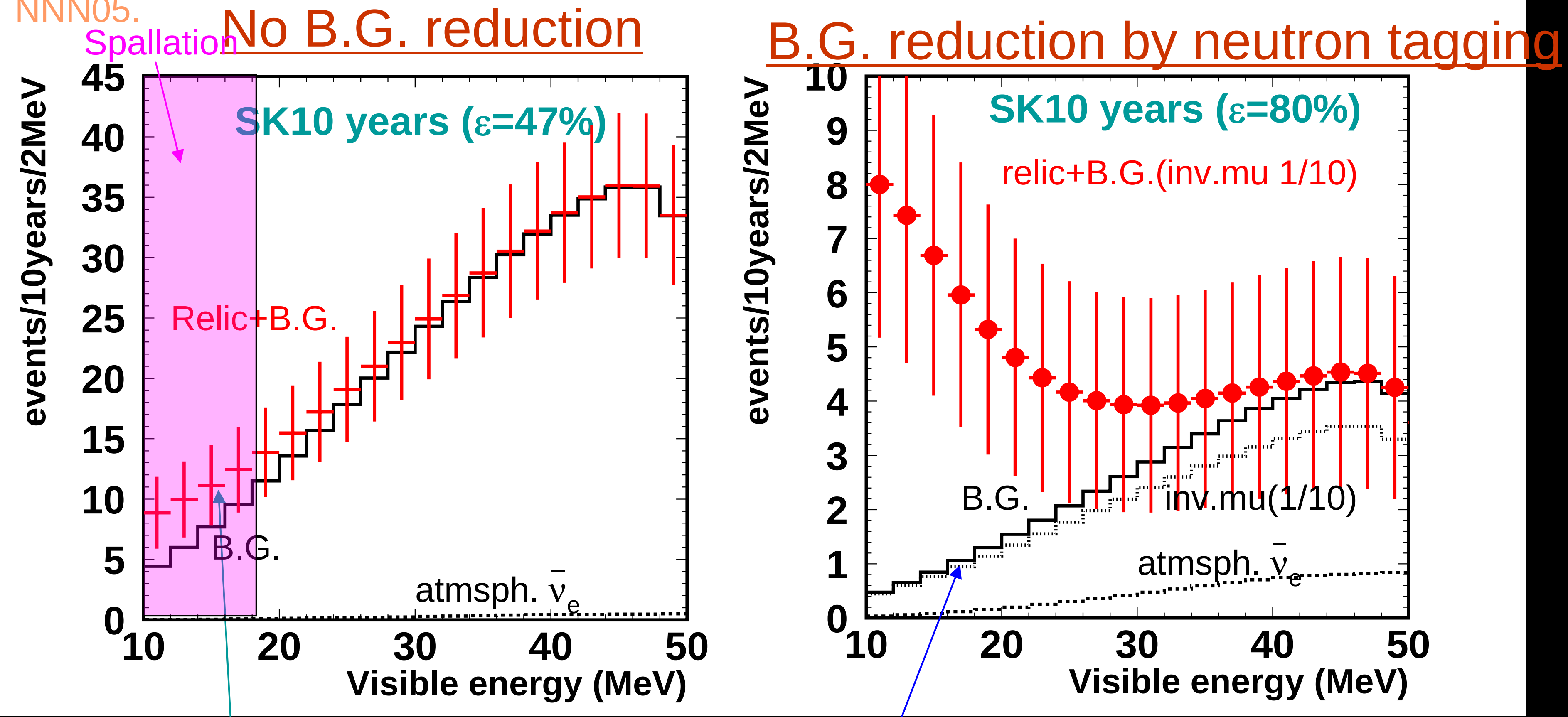
Simulation in C.K.Hargrove et al., N.I.M. A357, 157-169(1995)

Higher light yield.

Questions: water transparency, how to operate water purification system, corrosion of materials

Possibility of SRN detection

Relic model: S.Ando, K.Sato, and T.Totani, Astropart.Phys.18, 307(2003) with flux revise in NNN05.



Hard to distinguish

Statistically <1σ excess (10yrs, E_{vis} =18-30 MeV)

~1.2σ for SK20yrs

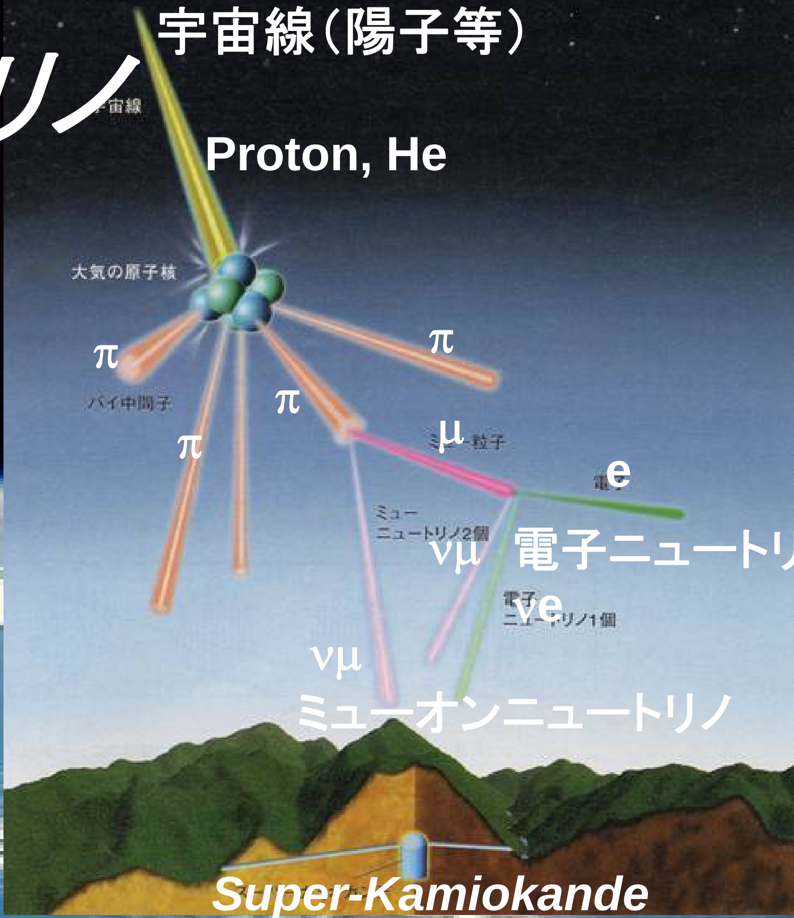
Assuming 90% of invisible muon B.G. can be reduced by neutron tagging.

Signal: 22.7, B.G. 13.1(E_{vis} =15-30 MeV)

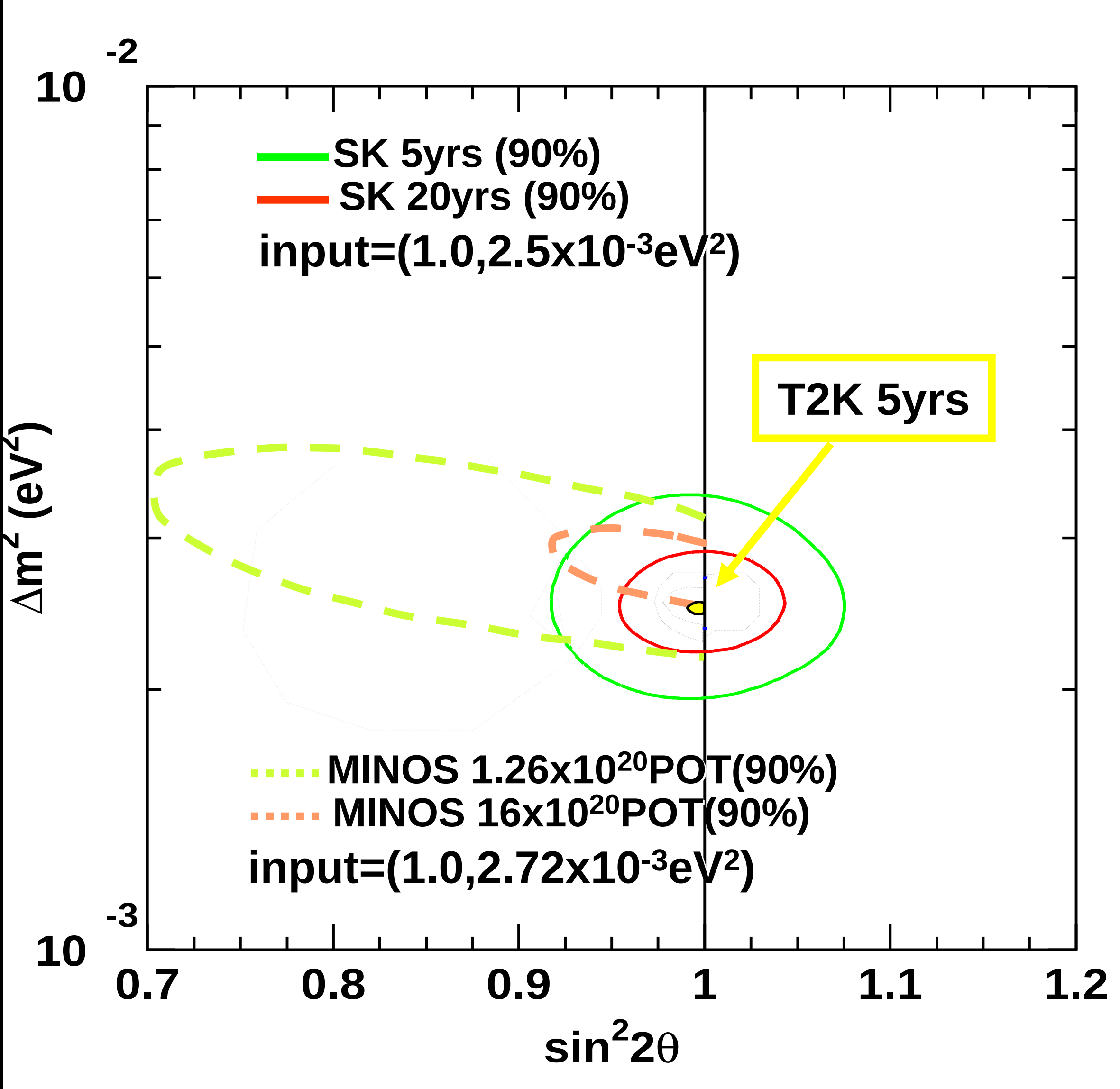
Signal: 44.8, B.G. 14.7(E_{vis} =10-30 MeV)

大気ニュートリノ


地球の大気


宇宙線(陽子等)
Proton, He
大気の原子核
π
π
パイ中間子
π
π
μ
e
ミュー
ニュートリノ2個
νμ
電子ニュートリ
νe
νμ
ミューオンニュートリノ
Super-Kamiokande

νμ←→ντ two-flavor analysis (sensitvity study by fake data(MC))



statistical error dominant

- $\delta(\sin^2 2\theta) \propto 1/\mathrm{sqrt}(\mathrm{exposure})$
- $\delta(\Delta m^2) \propto 1/\mathrm{sqrt}(\mathrm{exposure})$

SK will be compared with accelerator neutrino exps.

Two-flavor → standard three-flavor

$$(\nu_e, \nu_\mu, \nu_\tau)^T = U(\nu_1, \nu_2, \nu_3)^T$$ U: MNS matrix

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

unknown

solar ν, reactor ν

atm ν
K2K

upper limit
by CHOOZ

oscillation drivers; $\Delta m_{12}^2 = \Delta m_{solar\nu}^2,\ \Delta m_{23}^2 = \Delta m_{atm\nu}^2$

Standard three neutrino scheme

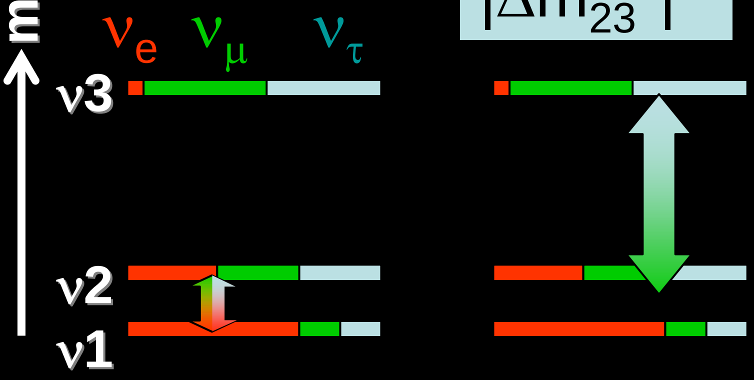
ν mass and mixing parameters:

θ_{12}, θ_{23}, θ_{13}, δ, Δm_{12}^2, $\Delta m_{13}^2 (=\Delta m_{23}^2)$

Known:

θ_{12}, Δm_{12}^2

θ_{23}, $|\Delta m_{23}^2|$



Solar,

KamLAND

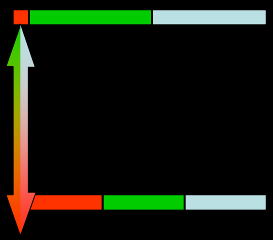
Atmospheric

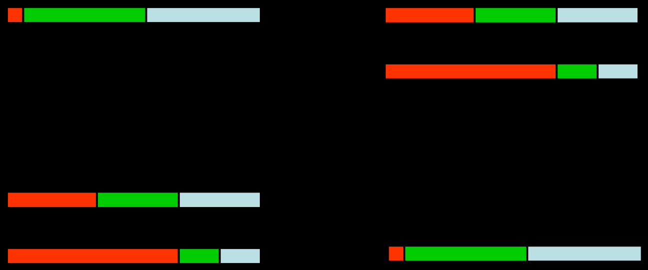
Long baseline

Unknown:

θ_{13}

Sign of Δm_{23}^2





If $\theta_{23} \neq \pi/4$,
is it $>\pi/4$ or $<\pi/4$?

CP ?

How much can we learn from atmospheric neutrinos in Super-K?

oscillation effects in νe

Pares and Smirnov hep-ph/0309312 (at Sub-GeV range)

$$\frac{\Psi(\nu e)}{\Psi_0(\nu e)} - 1 \cong P_2(r \cdot c_{23}^2 - 1)$$

LMA

$$- r \cdot \tilde{s}_{13} \cdot \tilde{c}_{13}^2 \cdot \sin 2\vartheta_{23}(\cos\delta_{CP} \cdot R_2 - \sin\delta_{CP} \cdot I_2)$$

interference

$$+ 2\tilde{s}_{13}^2(r \cdot s_{23}^2 - 1)$$

ϑ_{13} resonance

r : μ/e flux ratio (~2 at low energy)

$P_2 = |A_{e\mu}|^2$: 2ν transition probability ν_e → $\nu_{\mu\tau}$ in matter

$R_2 = \mathrm{Re}(A^*_{ee}A_{e\mu})$

$I_2 = \mathrm{Im}(A^*_{ee}A_{e\mu})$

A_{ee} : survival amplitude of the 2ν system

$A_{e\mu}$: transition amplitude of the 2ν system

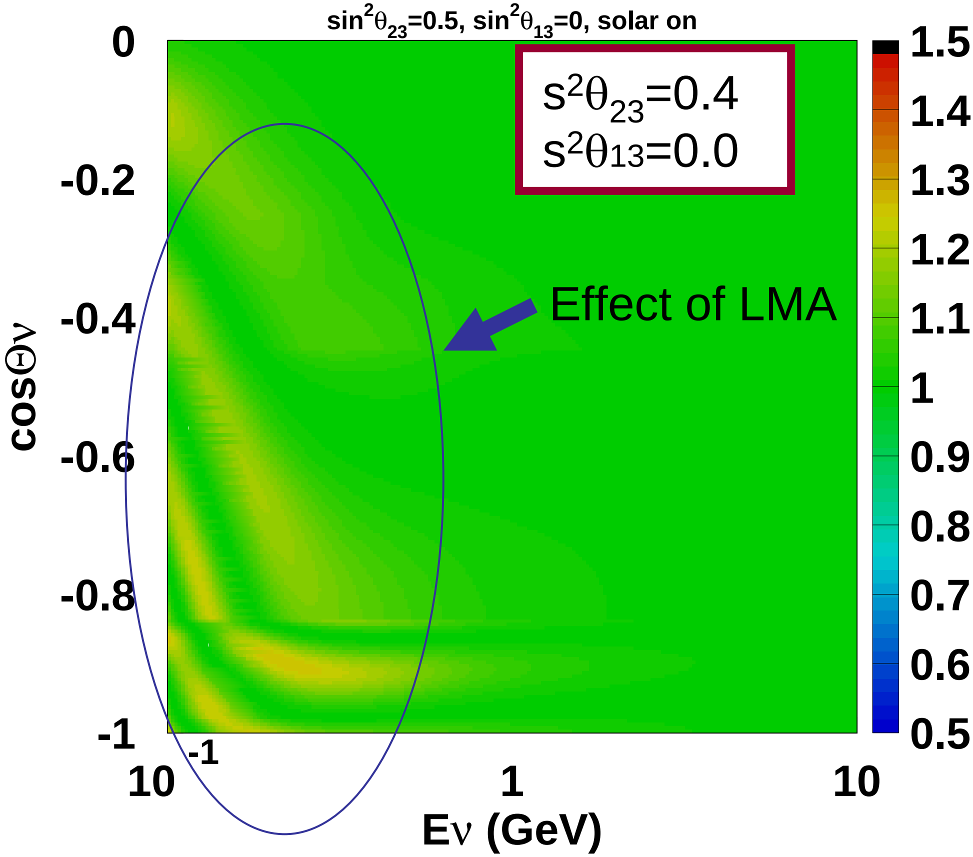
Expected oscillated ν_e

Atmν should also oscillate by (θ_{12},Δm_{12}^2)

In addition, we may have non-zero θ_{13}.

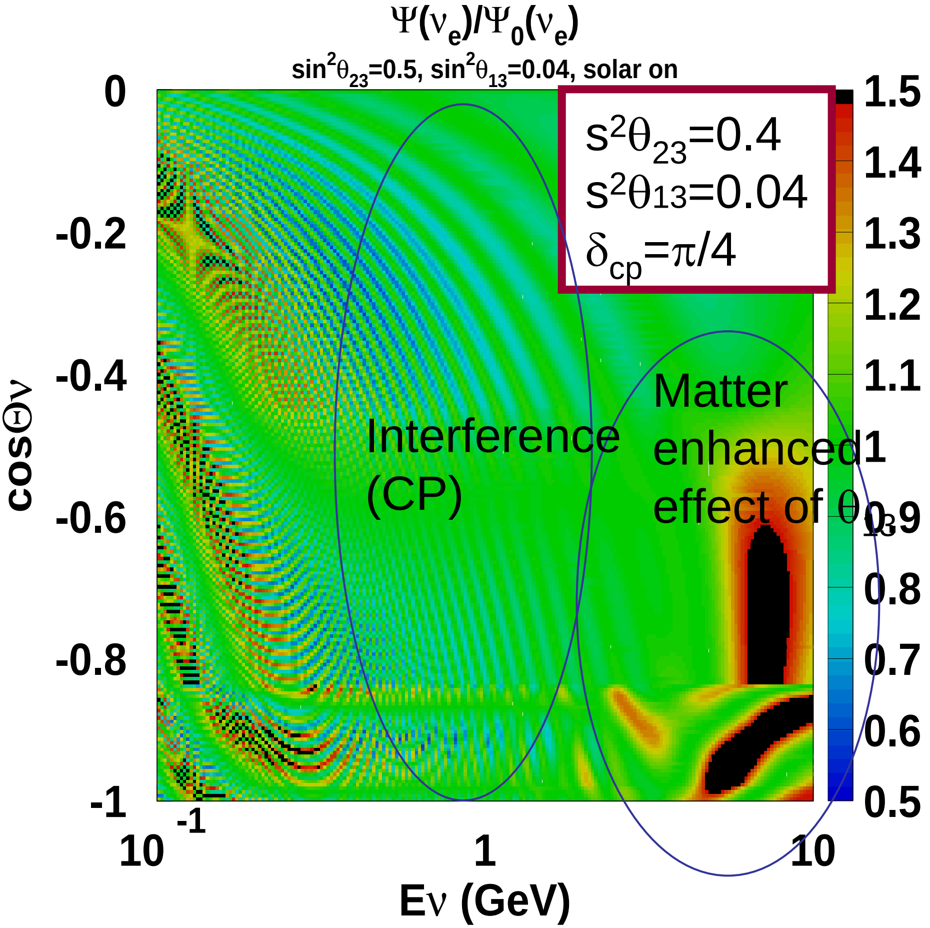
$s^2 2\theta_{12}=0.825$
$\Delta m^2_{12}=8.3\times10^{-5}$
$\Delta m^2_{23}=2.5\times10^{-3}$
(always assumed later in this talk)

$$\frac{\nu_e\ \ flux(osc)}{\nu_e\ \ flux(no\ osc)}$$



$s^2\theta_{23}=0.4$
$s^2\theta_{13}=0.0$

Effect of LMA



$s^2\theta_{23}=0.4$
$s^2\theta_{13}=0.04$
$\delta_{cp}=\pi/4$

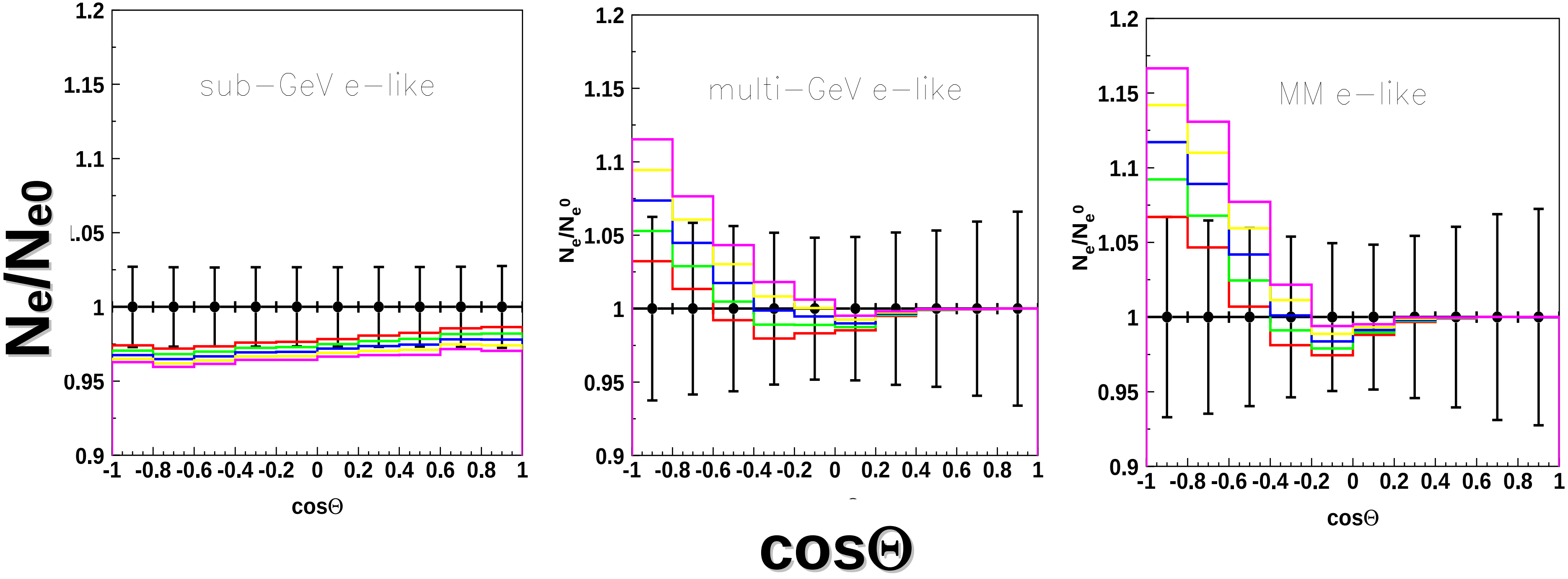
Interference (CP)

Matter enhanced effect of θ_{13}

effect of θ_{23} after ν interactions

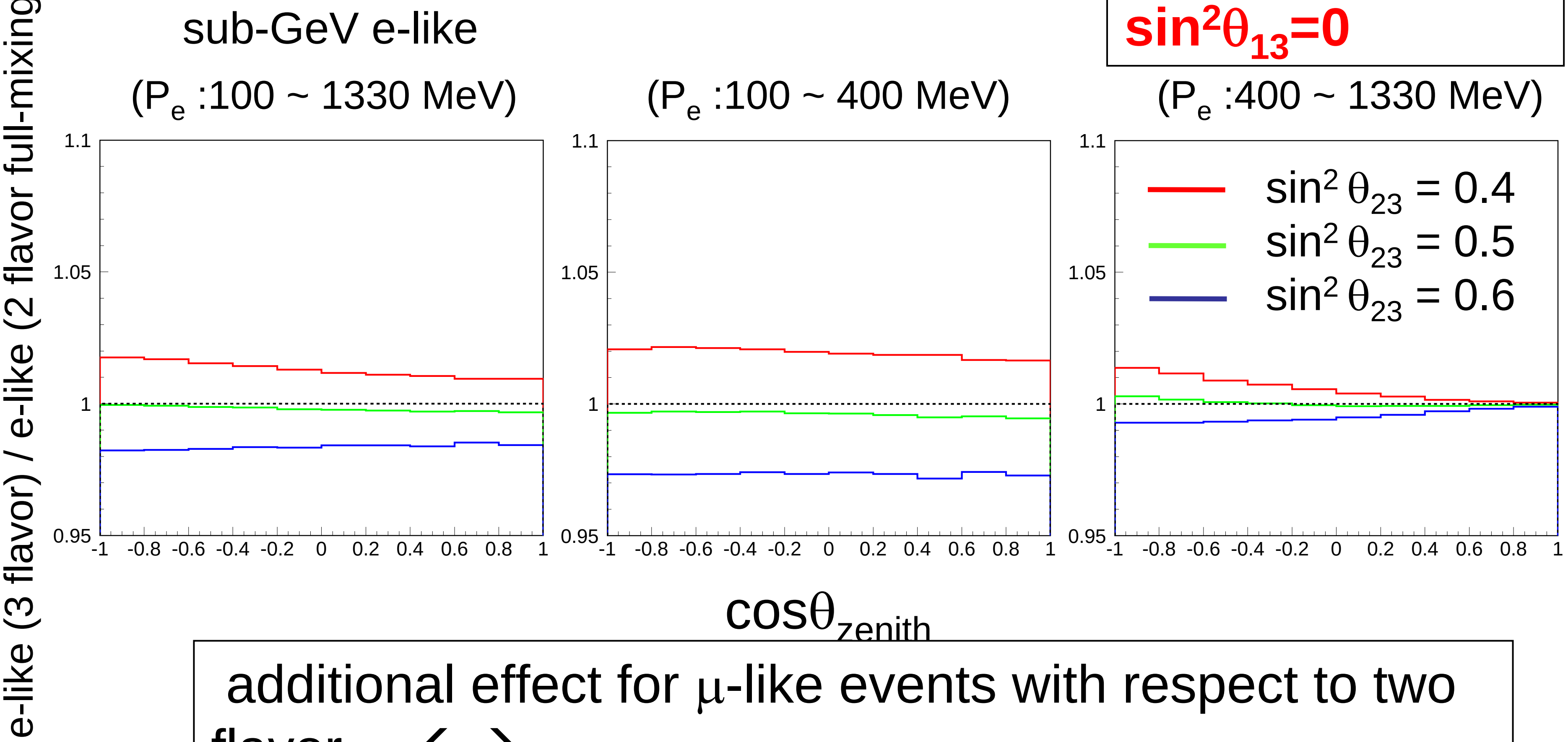
$s^2 2\theta_{12}=0.825$
$s^2\theta_{23}=0.4 \sim 0.6$
$s^2\theta_{13}=0.04$
$\delta cp=45^o$
$\Delta m^2_{12}=8.3e-5$
$\Delta m^2_{23}=2.5e-3$

no osc. with 20yrs stat.error
$s^2_{23}=0.40$
0.45
0.50
0.55
0.60



Effect of the solar term to sub-GeV e-like zenith angle

Δm^2_{12} = 8.3×10^{-5} eV^2
Δm^2_{23} = 2.5×10^{-3} eV^2
$\sin^2 2\theta_{12} = 0.82$
$\sin^2\theta_{13}=0$



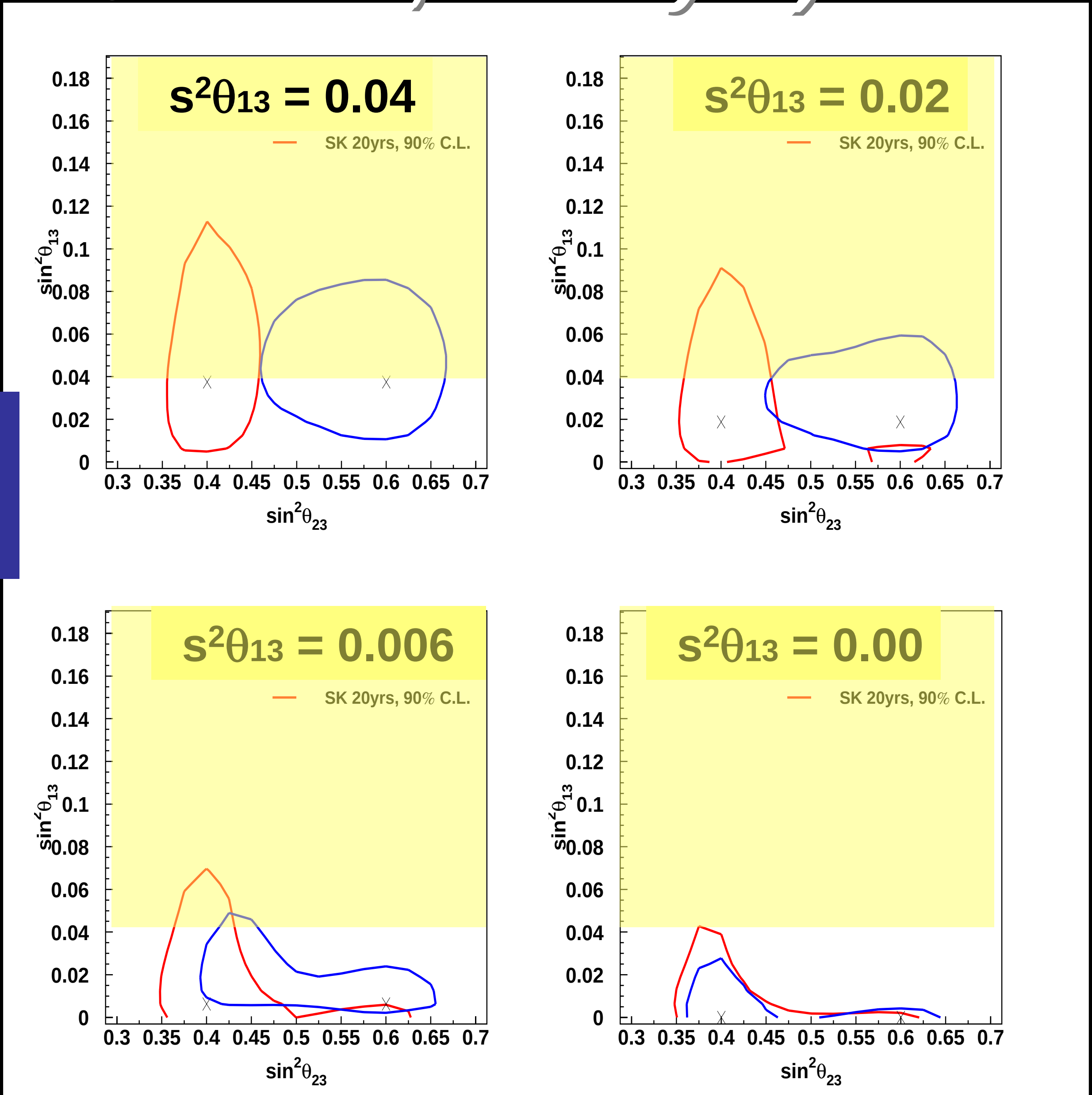
additional effect for μ-like events with respect to two flavor νμ←→ντ

even if $\theta_{13}=0$, θ_{23} octant can be investigated.

Discrimination of θ_{23} octant ($\sin 2^2\theta_{23}=0.96$, SK20yrs)

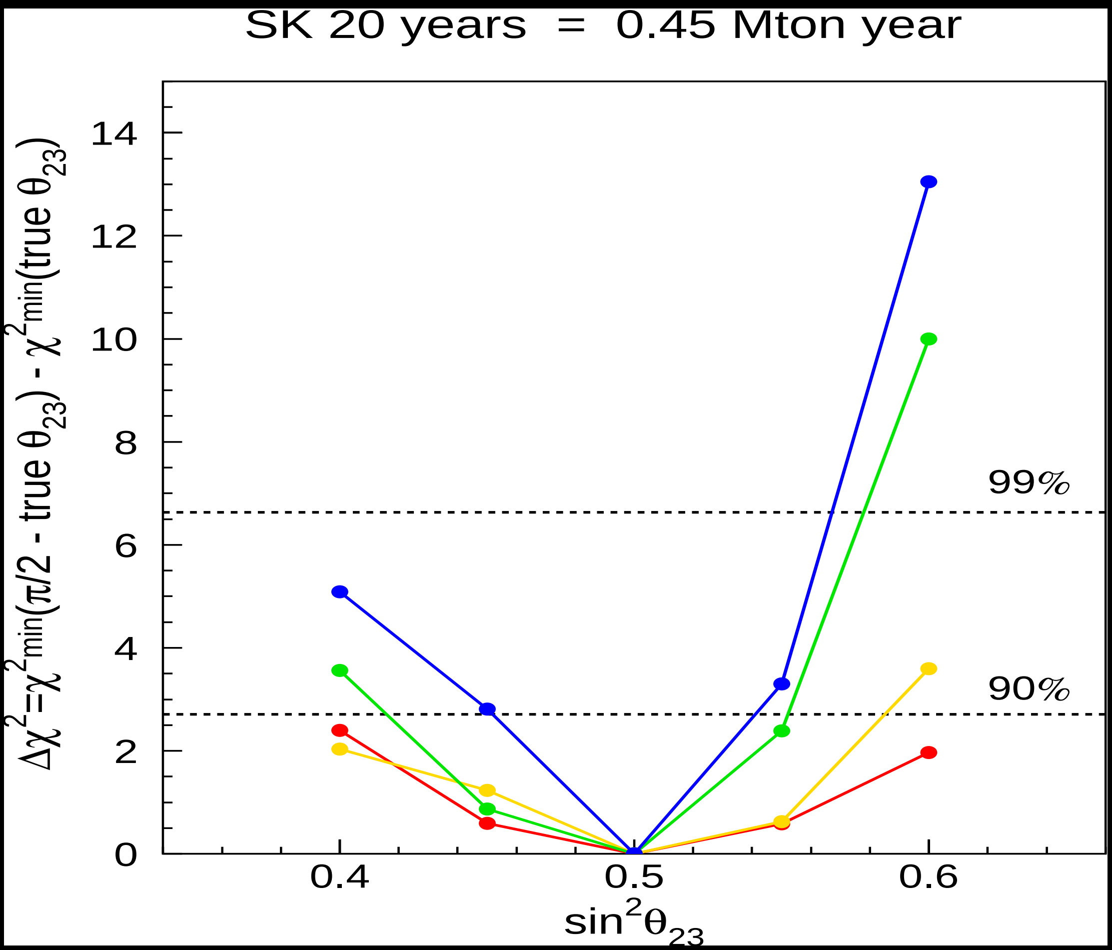
$s^2 2\theta_{12}=0.825$
$s^2\theta_{23}=0.4$ or 0.6
$s^2\theta_{13}=0.00\sim0.04$
$\delta cp=45^o$
$\Delta m^2_{12}=8.3e\text{-}5$
$\Delta m^2_{23}=2.5e\text{-}3$

$s^2\theta_{23} = 0.40$ or 0.60
←→ $s^2 2\theta_{23}=0.96$



With 20yrs SK, discrimination is possible for large θ_{13}.

Discrimination btw θ_{23} and $(\pi/2-\theta_{23})$

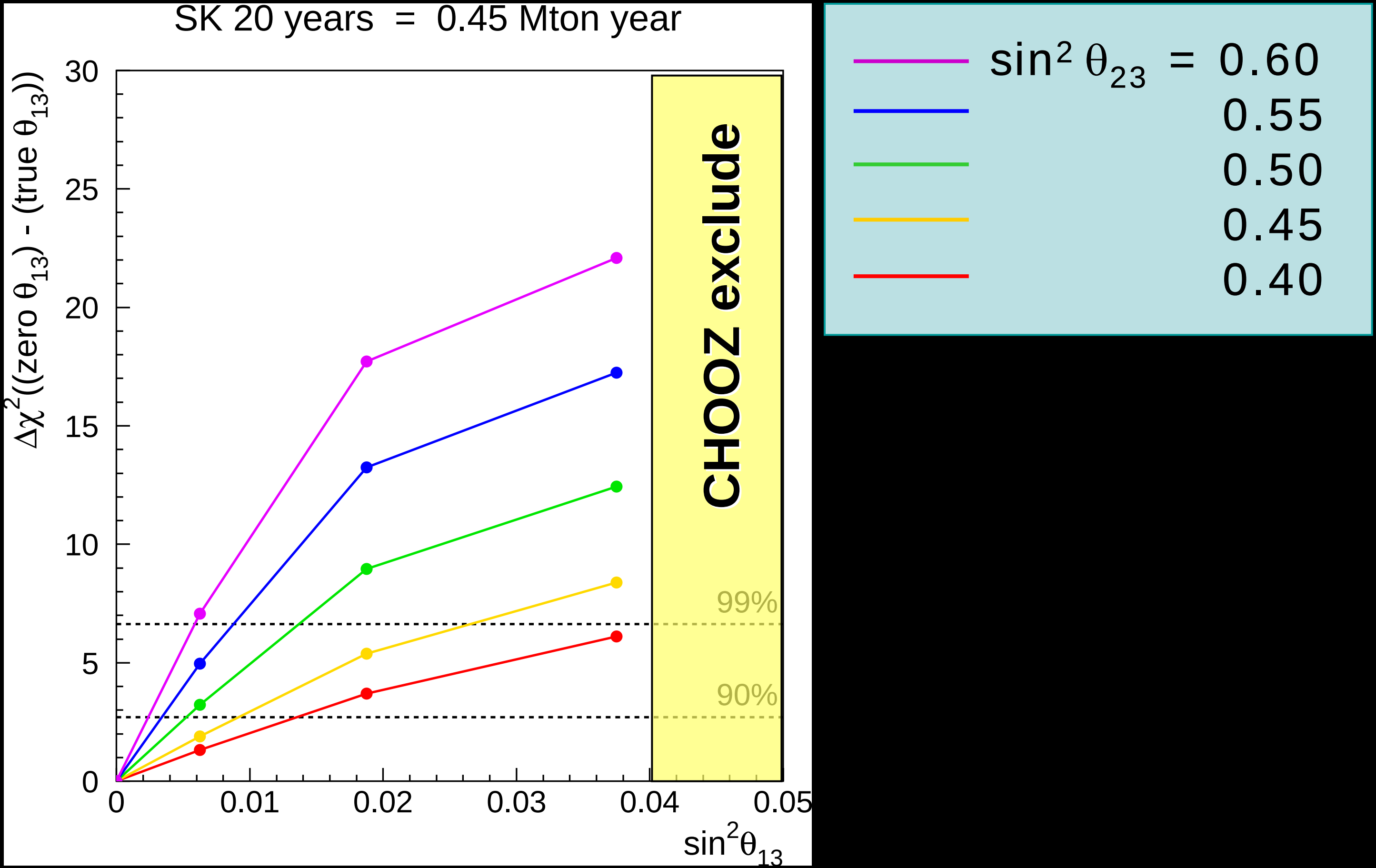


Discrimination of $\sin^2\theta_{23}$=0.4 and 0.6 is possible for large θ_{13}.

→May need more data statistics.

Statistical significance of non-zero θ_{13}

$s^2 2\theta_{12}=0.825$
$s^2\theta_{23}=0.4 \sim 0.6$
$s^2\theta_{13}=0.00 \sim 0.04$
$\delta cp=45^o$
$\Delta m^2_{12}=8.3e\text{-}5$
$\Delta m^2_{23}=2.5e\text{-}3$



If θ_{13} is close to CHOOZ limit,
significance of non-zero θ_{13} will be >90%.

Test of non-standard mechanisms

e.g. Neutrino oscillations:

$$P(\nu\mu \to \nu\mu) = 1 - \sin^2 2\vartheta \sin^2\left(1.27\frac{\Delta m^2 L}{E_\nu}\right)$$

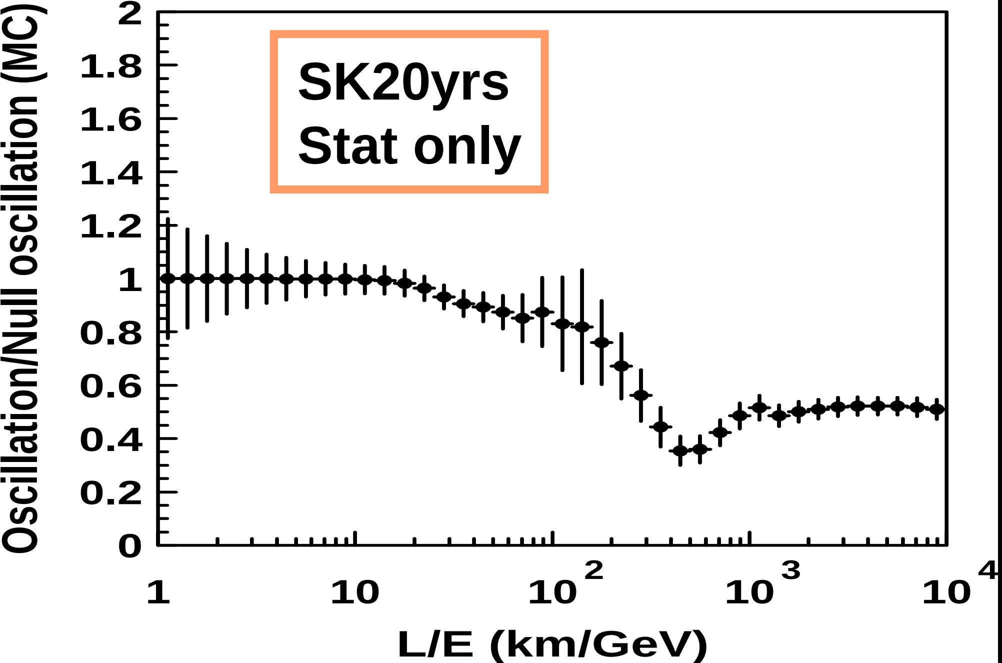
Neutrino decay :

$$P(\nu\mu \to \nu\mu) = \left(\cos^2\vartheta + \sin^2\vartheta \times \exp\left(-\frac{m}{2\tau}\frac{L}{E_\nu}\right)\right)^2$$

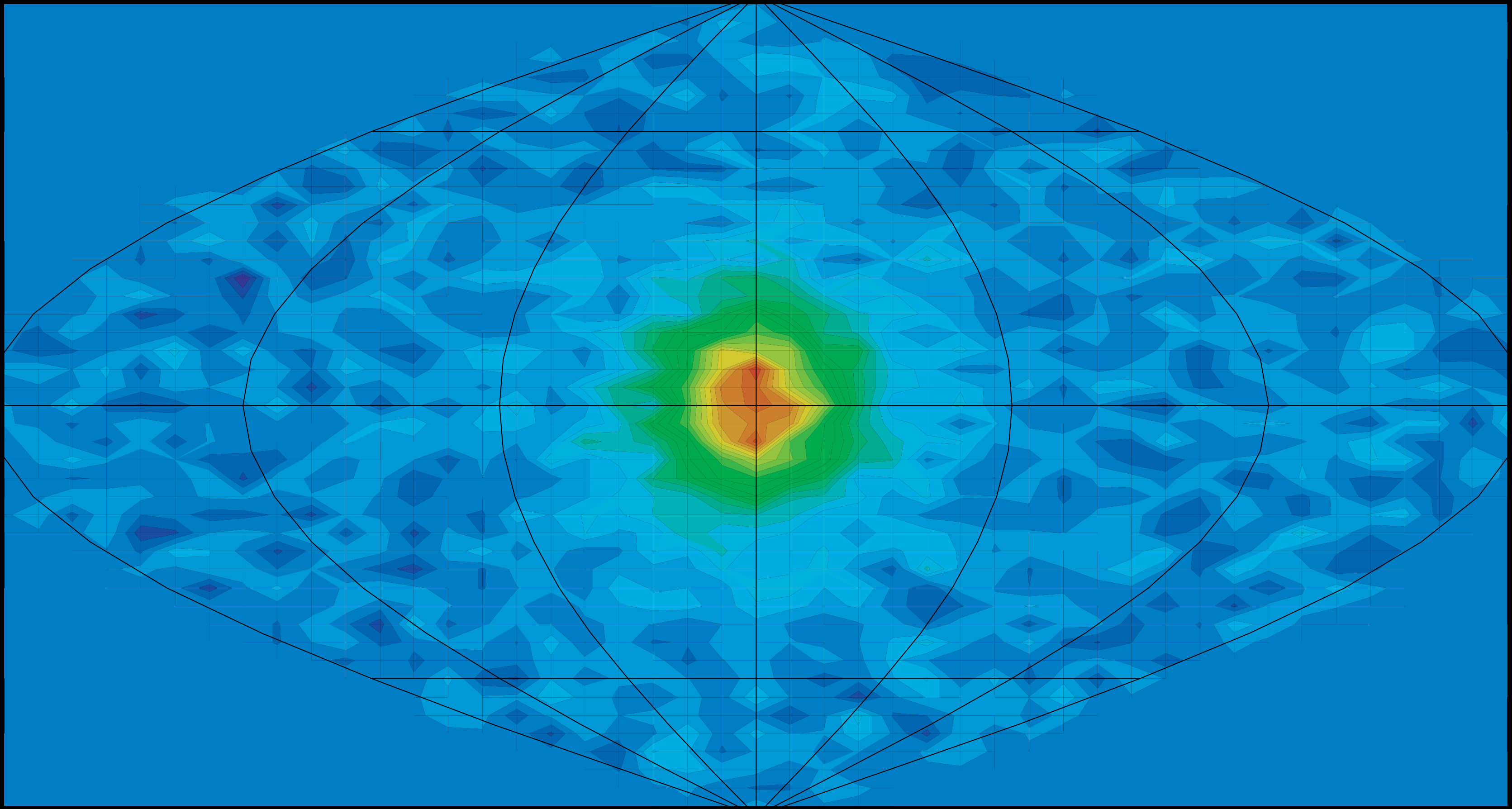
Neutrino decoherence :

$$P(\nu\mu \to \nu\mu) = 1 - \frac{1}{2}\sin^2 2\vartheta\left(1 - \exp(-\gamma_0 \frac{L}{E_\nu})\right)$$

Lorentz invariance violation, MaVans, …. :

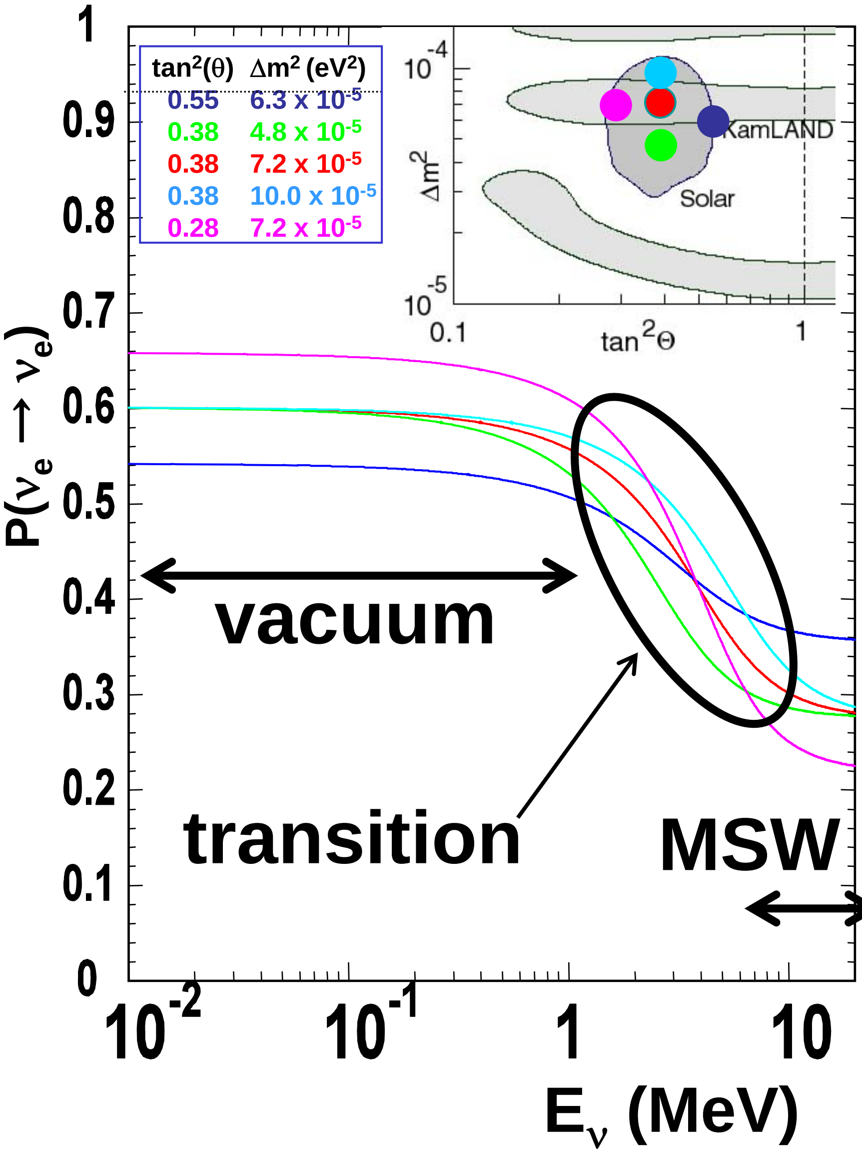


太陽ニュートリノ

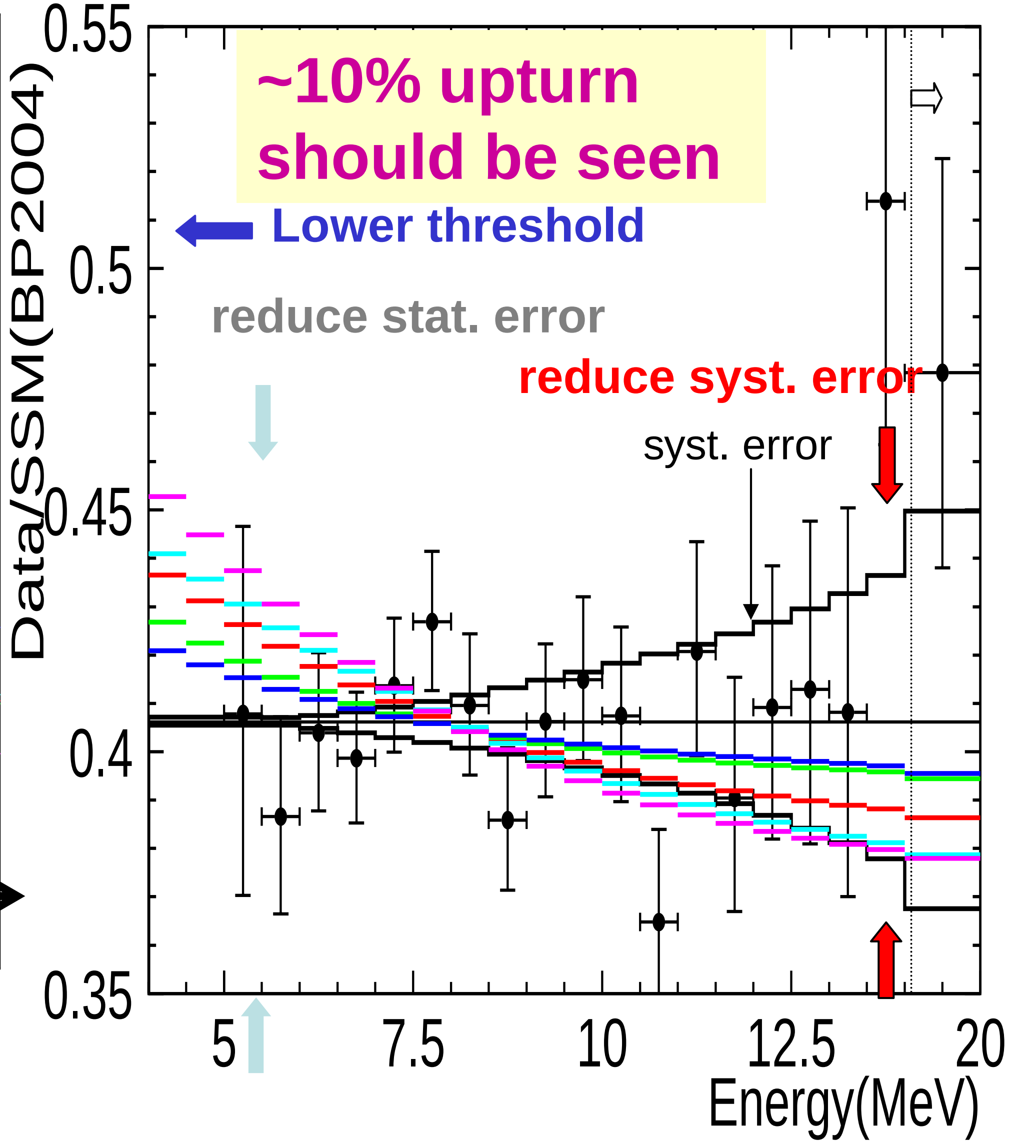


Possibility of detecting spectrum distortion

ν_e survival probability



Recoil electron spectrum



~10% upturn should be seen

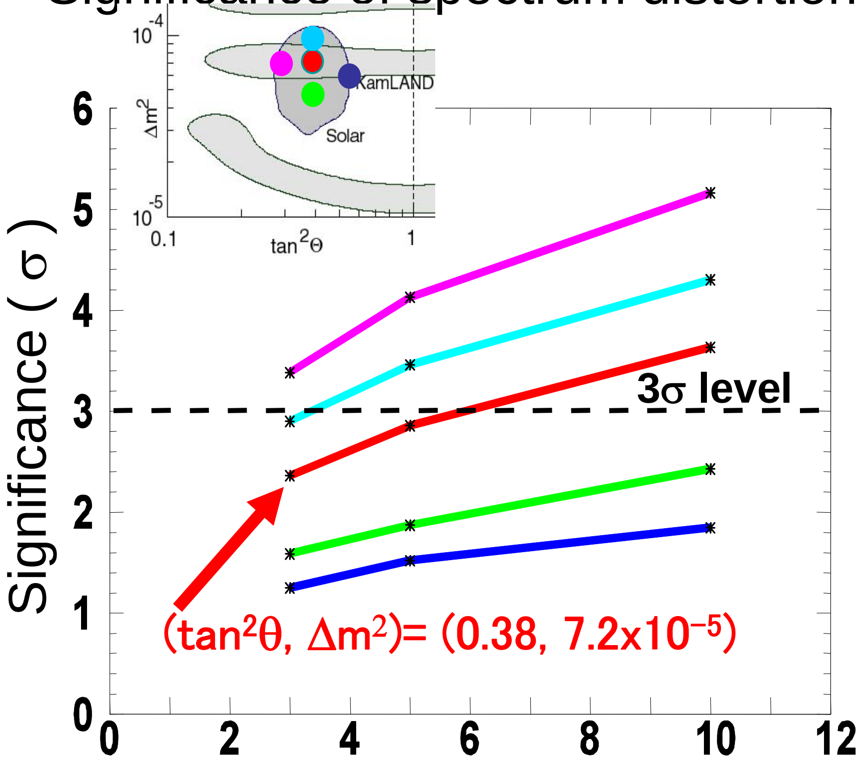
Lower threshold

reduce stat. error

reduce syst. error

Spectral distortion

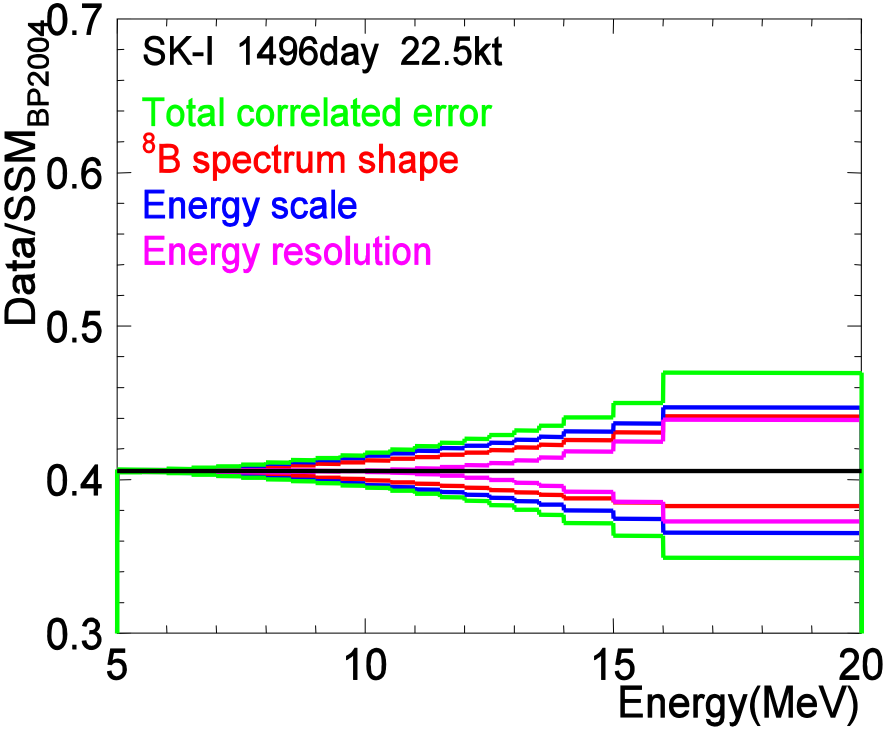
Significance of spectrum distortion



Live time (years)

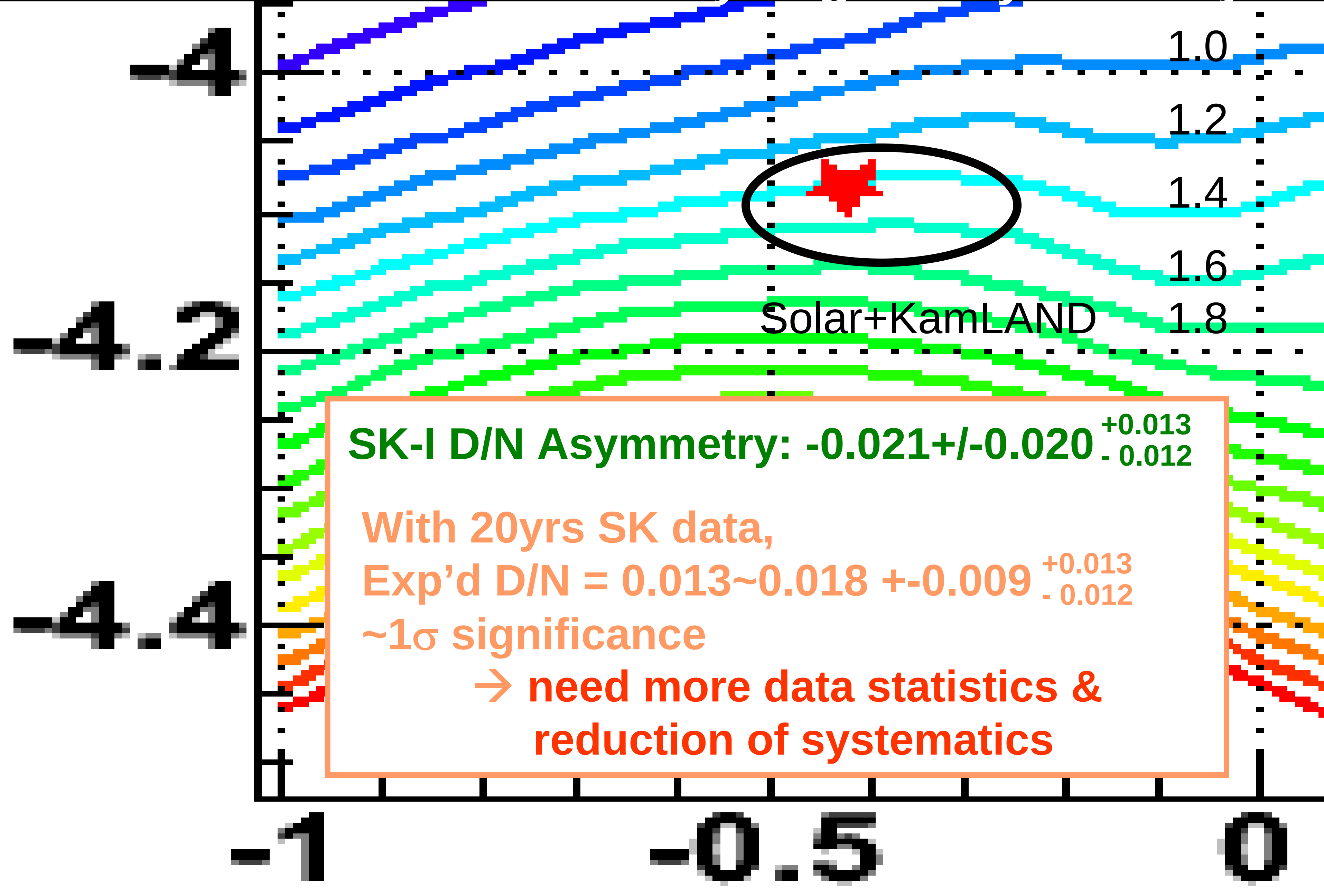
- **>~2σ at SK10yrs**
- **>~3σ at SK20yrs**

Current breakdown of correlated systematic errors



- **Better energy scale calibration (~+/-0.4%) is needed.**
- **Better ^{8}B spectrum shape prediction is needed.**

地球の物質効果→day/night asymmetry



SK-I D/N Asymmetry: -0.021+/-0.020 $^{+0.013}_{-0.012}$

With 20yrs SK data,
Exp’d D/N = 0.013~0.018 +-0.009 $^{+0.013}_{-0.012}$
~1σ significance

→ need more data statistics &
reduction of systematics

Future Prospect of SK-III

- **nucleon decay searches**
  - 2×10^{34}yrs (4×10^{33}yrs) for $e\pi^0$ (νK^0)
  - many remaining decay modes

- **Supernova**
  - detailed mechanism by ν burst (a few per century)
  - aim to discover relic neutrinos by new technique (neutron tagging)

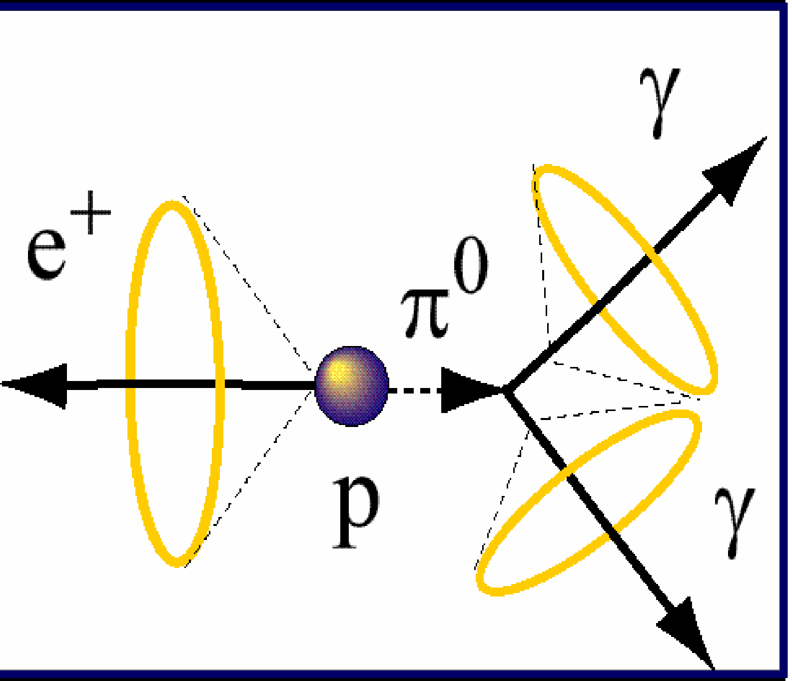
- **atmospheric ν**
  - If θ_{13} is close to CHOOZ and $\Delta m^2_{23}>0$, chance to measure θ_{13} and θ_{23} octant
  - test of non-standard scenarios

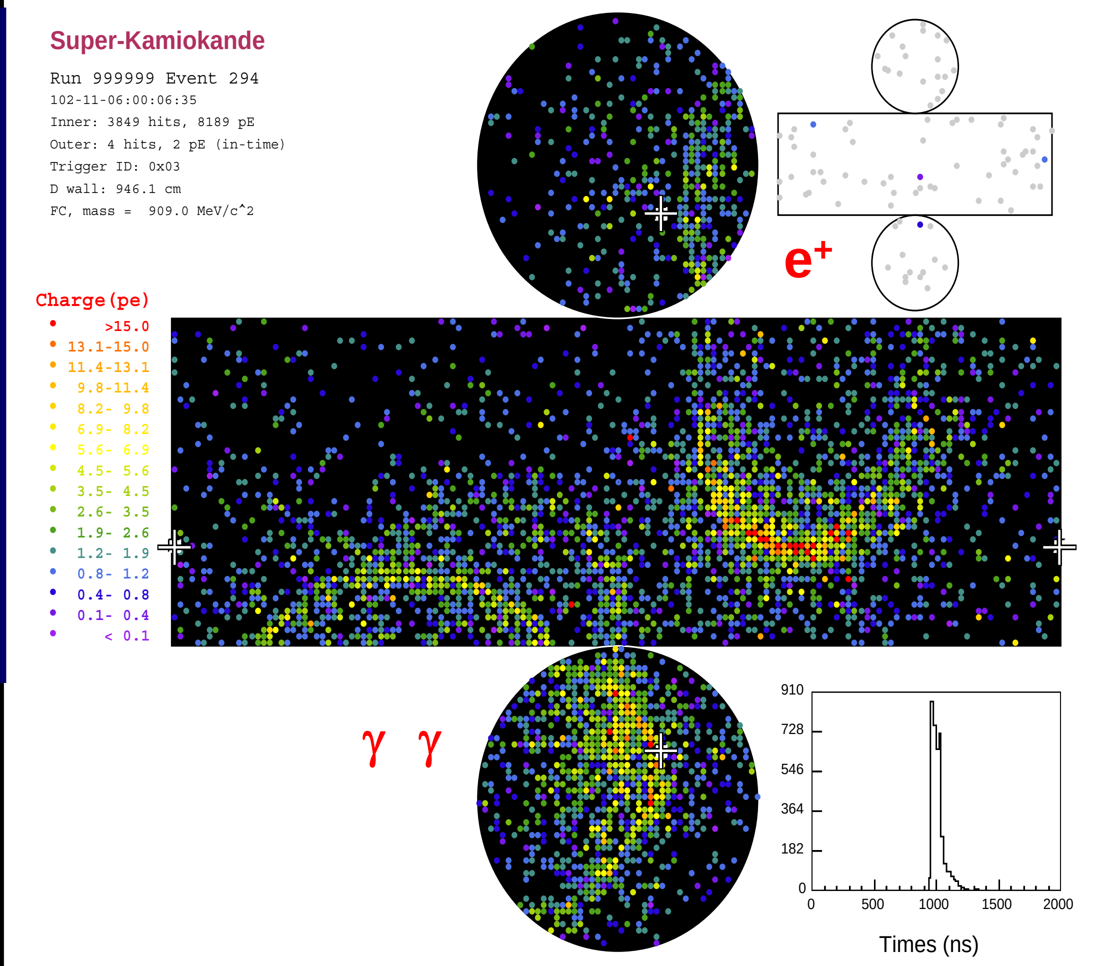
- **solar ν**
  - aim to measure spectrum distortion by reducing BG, systematics, and energy threshold.

supplements

SK-IIIではこのような現象を捉えたい

$p \rightarrow e^+\pi^0$ シミュレーション





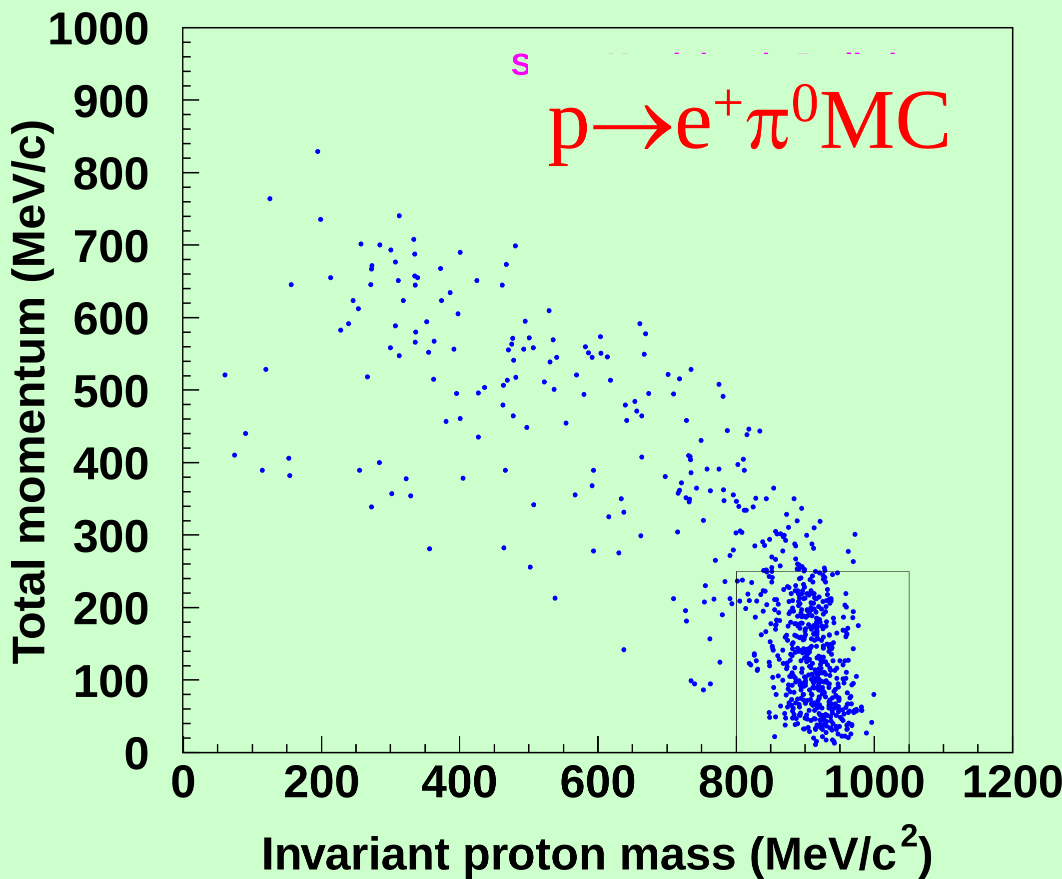
Super-Kamiokande

```
Run 999999 Event 294
102-11-06:00:06:35
Inner: 3849 hits, 8189 pE
Outer: 4 hits, 2 pE (in-time)
Trigger ID: 0x03
D wall: 946.1 cm
FC, mass =  909.0 MeV/c^2
```

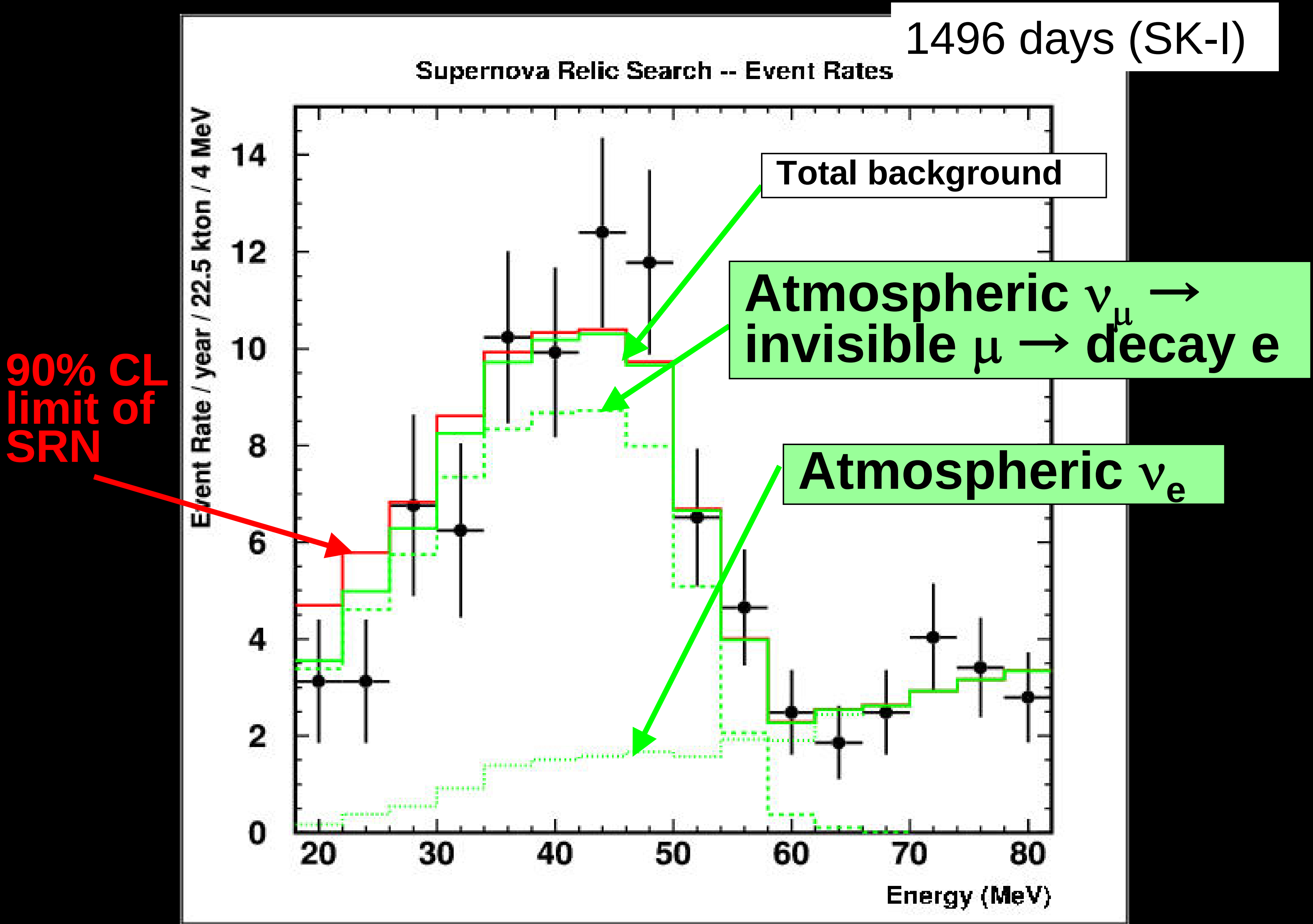
Expected BG = 1~2 event /SK20年（0.45Mtyrs）

- 2 or 3 rings
- All rings are electron-like
- no decay electron
- $85 < m_\pi < 185 \mathrm{MeV}/c^2$ (3-ring)
- $800 < m_p < 1050 \mathrm{MeV}/c^2$
- $p_{total} < 250 \mathrm{MeV}/c$

Efficiency = 40%



Energy spectrum of SK-I (>18MeV)



1496 days (SK-I)

Total background

Atmospheric $\nu_\mu \rightarrow$ invisible $\mu \rightarrow$ decay e

Atmospheric ν_e

90% CL limit of SRN