Super-Kamiokande

High Energy Group

Research Status

Oscillation analysis : zenith angle
sterile neutrino
LIV

proton decay
solar WIMP search

12/20-21 2013,
ICRR annual
workshop

Koun Choi,
Nagoya university

remind er

atmospheric neutrino oscillation

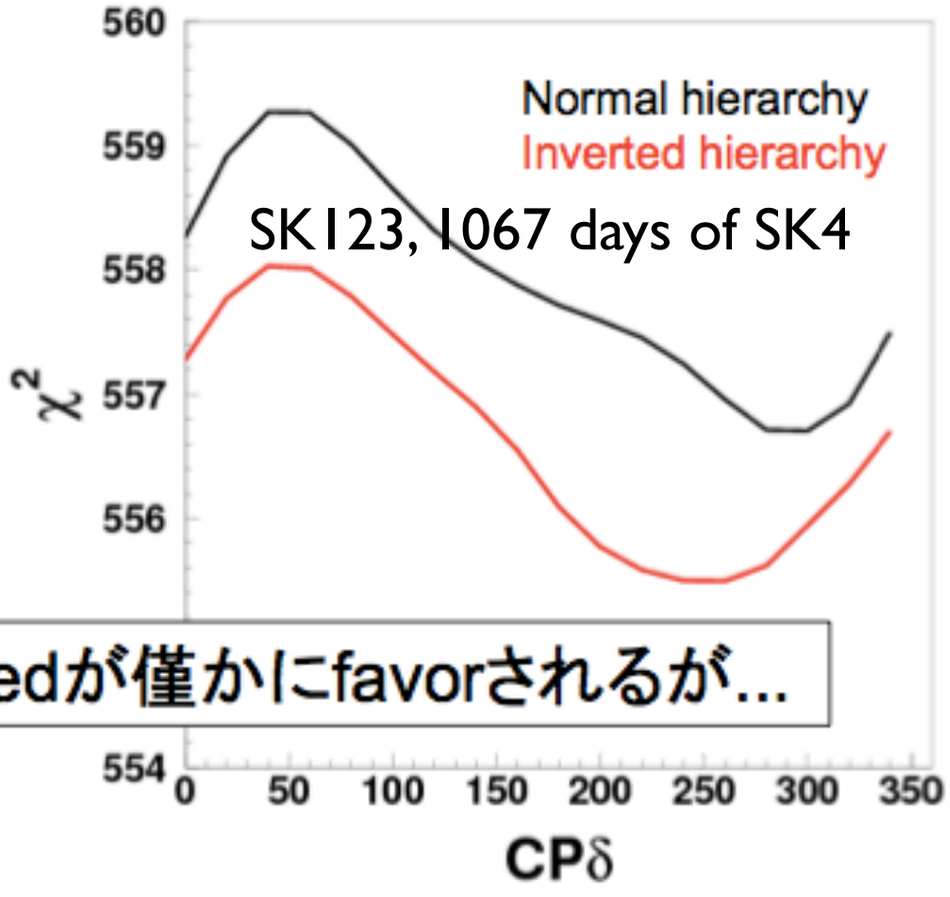
three flavor zenith angle analysis

Normal hierarchy: χ^2_{min} **= 556.7 / 477 dof**

Inverted hierarchy: χ^2_{min} **= 555.5 / 477 dof**

$$\chi^2_{min}(NH)\ \chi^2_{min}(IH) = 1.2$$

(Sensitivity for mass hierarchy:
χ^2(IH)- χ^2(NH) = 1.06
χ^2(NH)- χ^2(IH) = 0.90)



Normal hierarchy

***$\sin^2\theta_{13}$ fixed to be 0.025 (reactor)**

χ^2_{min} = 556.7 / 477 dof

Δm^2_{32}	$2.66^{+0.15}_{-0.40}\times10^{-3}eV^2(1\sigma)$	
$\sin^2\theta_{23}$	0.425	0.391 - 0.619 at 90%CL
δCP	300°	All allowed at 90% CL

Inverted hierarchy

***$\sin^2\theta_{13}$ fixed to be 0.025 (reactor)**

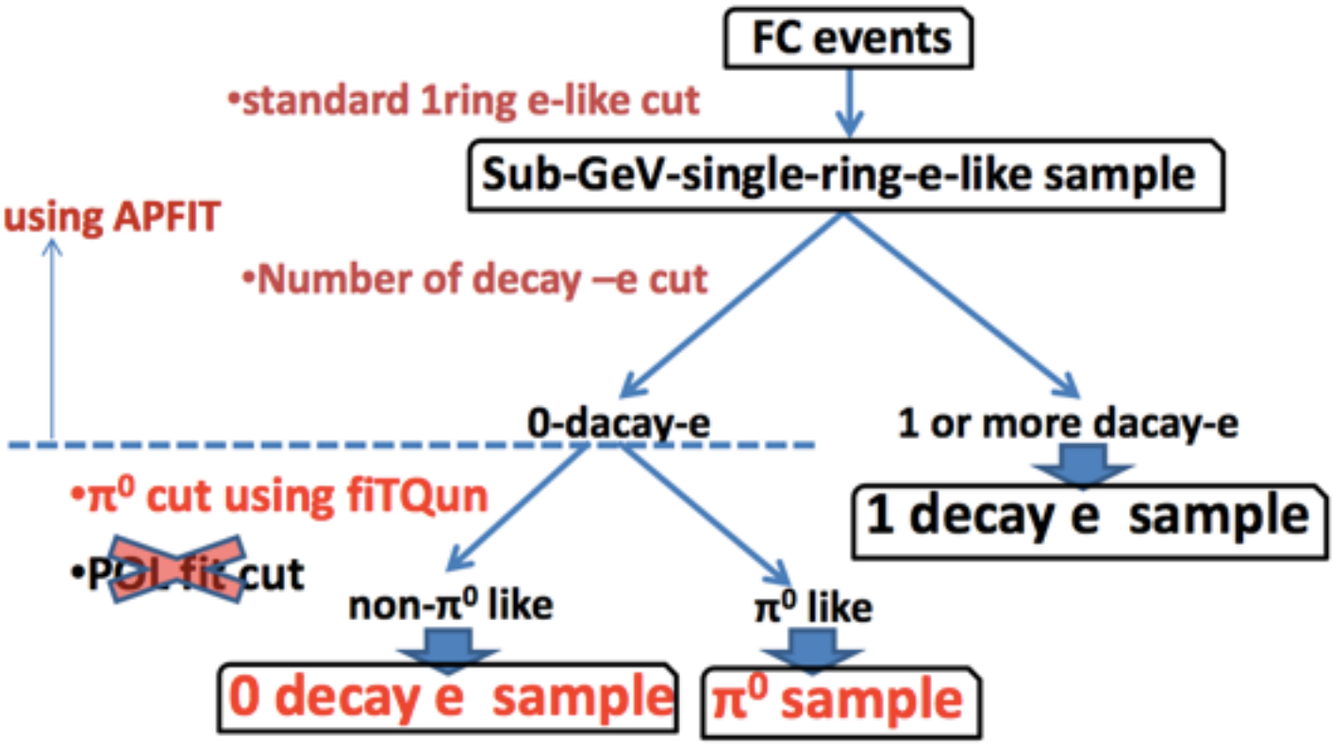
χ^2_{min} = 555.5 / 477 dof

Δm^2_{32}	$2.66^{+0.17}_{-0.23}\times10^{-3}eV^2(1\sigma)$	
$\sin^2\theta_{23}$	0.575	0.393 - 0.630 at 90%CL
δCP	300°	All allowed at 90% C.L.

2012 ICRR workshop K.Okumura

improv
ement

- Added more data (live time 1097 → 1417 days)
- New fitter (FitQun) selected sub-GeV 1-ring e-like sample



Purity of 0decay e sample (%)

	POL fit	FitQun
CC $\nu_e + \nu_e$	95.7	96.6 ←1% better
CC $\nu_\mu + \nu_\mu$	0.3	0.3
NC	4.0	3.1

Purity of π^0 sample (%)

	POL fit	FitQun
CC $\nu_e + \nu_e$	20.5	17.2
CC $\nu_\mu + \nu_\mu$	1.8	1.7
NC	77.7	81.1 ←3% better

- Introduced pulls for osc parameters
- New MC & reconstruction, update of sys errors, improved & bug fixed in oscillation probability computation, etc

result

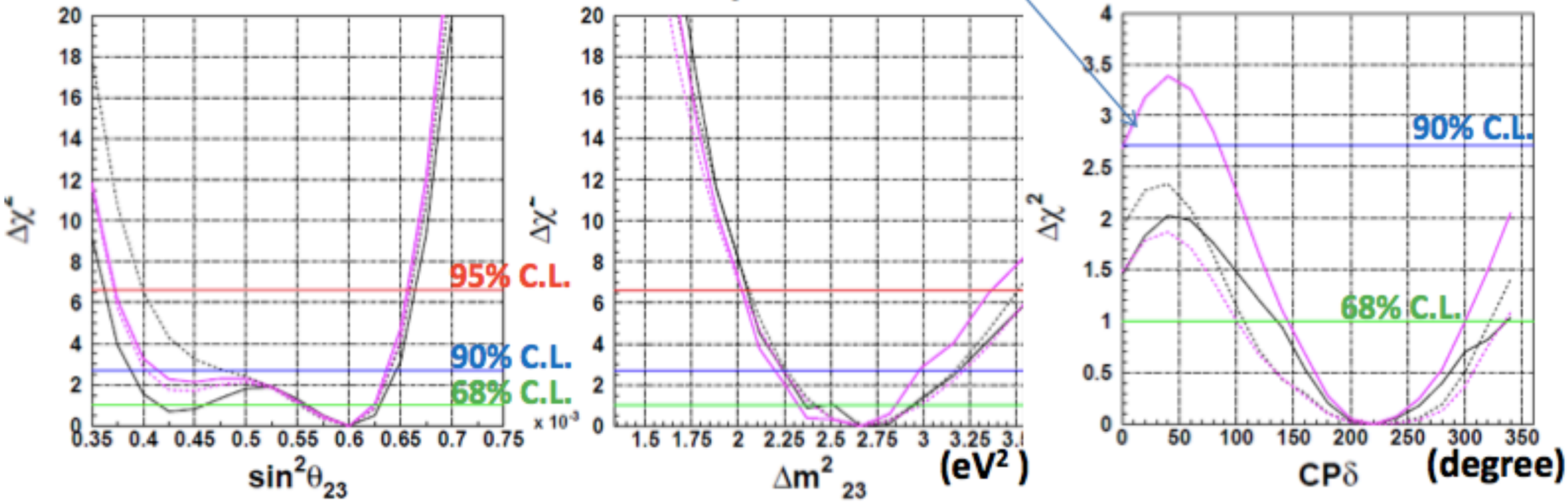
Normal

Sensitivity normal (asuumed @best fit)

Inverted

Sensitivity inverted (asuumed @best fit)

δCP is more reject on inverted



	Normal		Inverted	
	Best fit	90% C.L.	Best fit	90% C.L.
$\sin^2\theta_{23}$	0.60	0.39 - 0.65	0.60	0.41 - 0.64
Δm^2_{23} ($\times 10^{-3}$ eV^2)	2.67	2.25 - 3.19	2.67	2.20 – 2.09
δCP	220°	all allowed	220°	80 ° -

	χ^2 min
NH	564.0/477 d.o.f
IH	562.5/477 d.o.f

Θ_{13}=0.025(fixed)

χ^2_{min} (NH)-χ^2_{min} (IH)=1.5

Sensitivity for mass hierarchy

χ^2 (NH)-χ^2 (IH)=1.8

introd
uction

atmospheric neutrino oscillation

sterile neutrino search

2012 Alex Himmel

- Short-baseline-related: $|U_{\mu 4}|^2$
  - Driven by new Δm^2
  - Creates fast oscillations across a wide range of ν_μ samples

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

- Atmospheric/long-baseline: $|U_{\tau 4}|^2$
  - Accessible *only* at long distances
  - Oscillations into ν_s instead of ν_τ
  - Introduces NC matter effect

What can Super-K tell us?

It is most useful because of what it is *not* sensitive to:

The size of the sterile mass splitting →	SBL-like oscillations appear "fast"
The number of sterile neutrinos →	3+1 and 3+N models look the same

New analysis strategy :

SK1-4 1631days data used,
fast oscillation assumed.
2 separate analyses ;
i) limit on $|U\mu_4|^2$, standard νe matter effect
ii) limit on $|U\tau_4|^2$ (with $|U\mu_4|^2$), NC matter effect

result

fit for $|U\mu 4|^2$

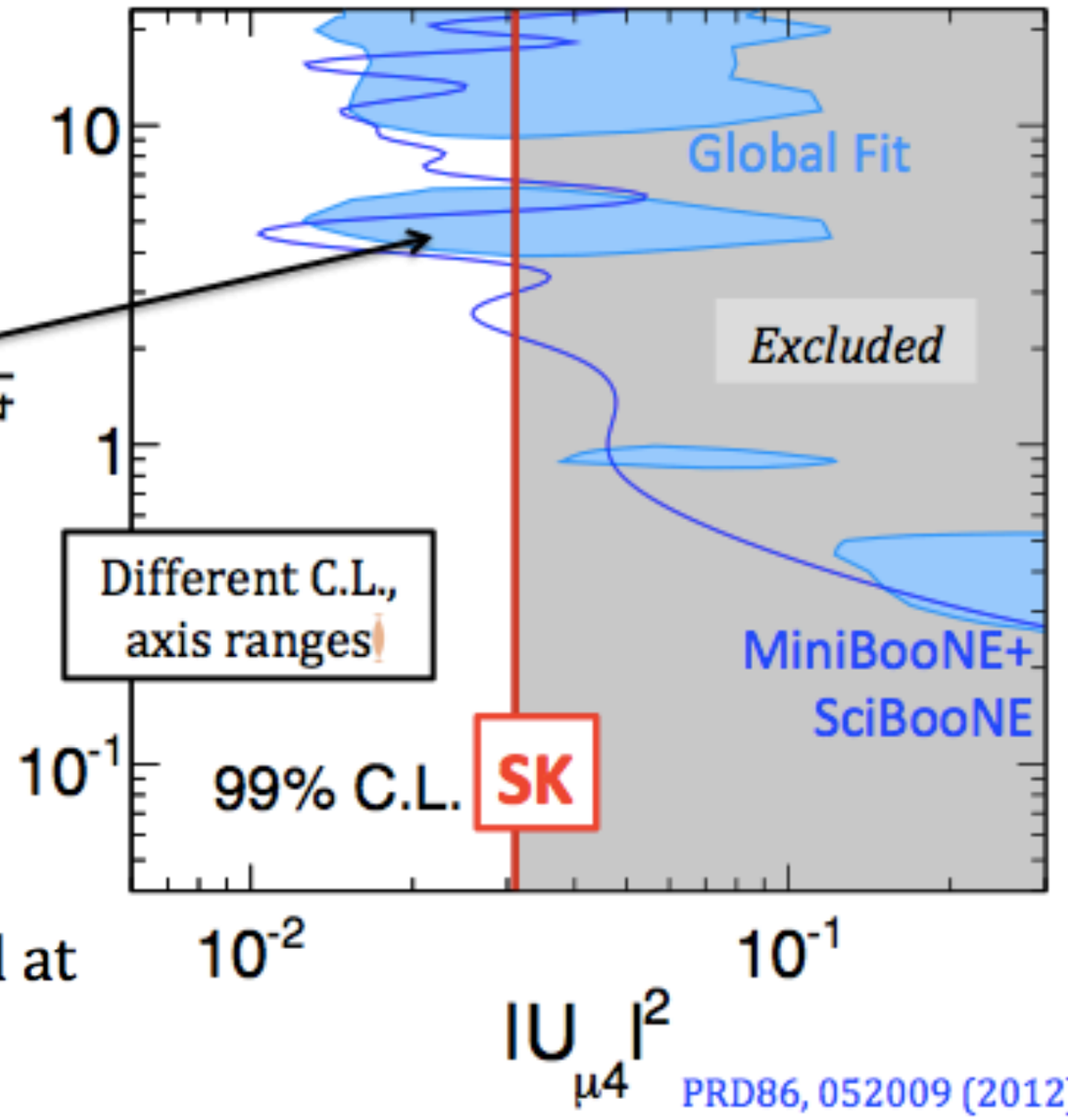
2012 Alex Himmel

Reactors/Ga $\sim |U_{e4}|^2$
SBL ν_μ->ν_e $\sim |U_{e4}|^2|U_{\mu 4}|^2$

Global fit to both by theorists, assuming 3+1, gives allowed region in $|U_{\mu 4}|^2$

We can exclude a large part of this global allowed region at 99%

Fast-oscillation assumption valid at virtually any Δm^2

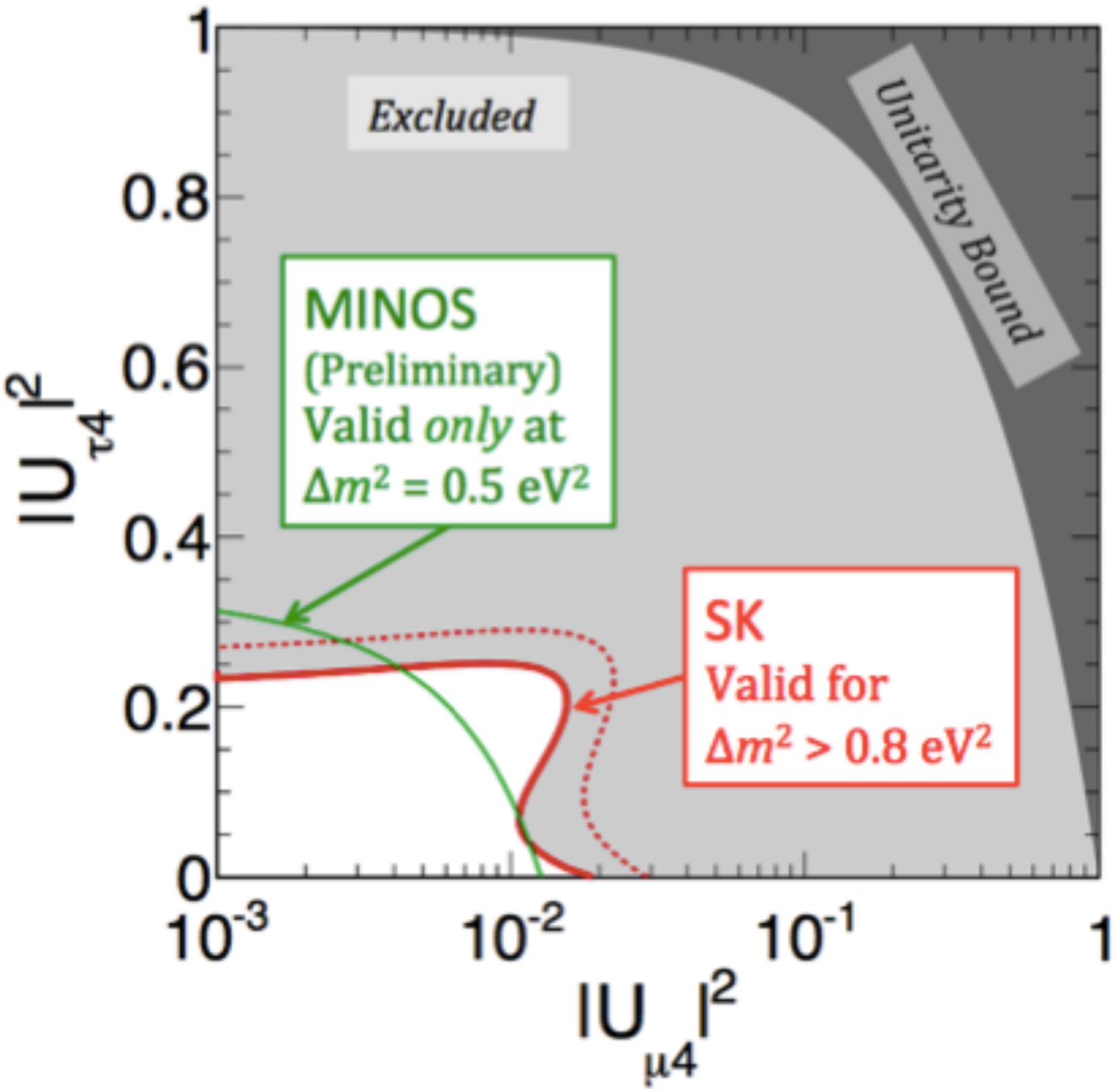


PRD86, 052009 (2012)
JHEP 1305:050, 2013

result

fit for $|U\tau 4|^2$

2012 Alex Himmel



Constraint from *not* seeing sterile matter effect

Our fast oscillation assumption good to 0.8 eV^2

$\sin^2(\Delta m^2 L/4E)$ starts oscillate below 0.8eV^2

a little more detail in back up slides but the best will be keeping an eye on the new paper coming soon

atmospheric neutrino oscillation

Lorentz invariance violation search

2012 Tarek
Akiri

- The Standard Model Extension (SME) has all the features of the SM but adds all general Lorentz violating terms (arXiv:1112.6395)
- LV can be treated as a perturbative effect

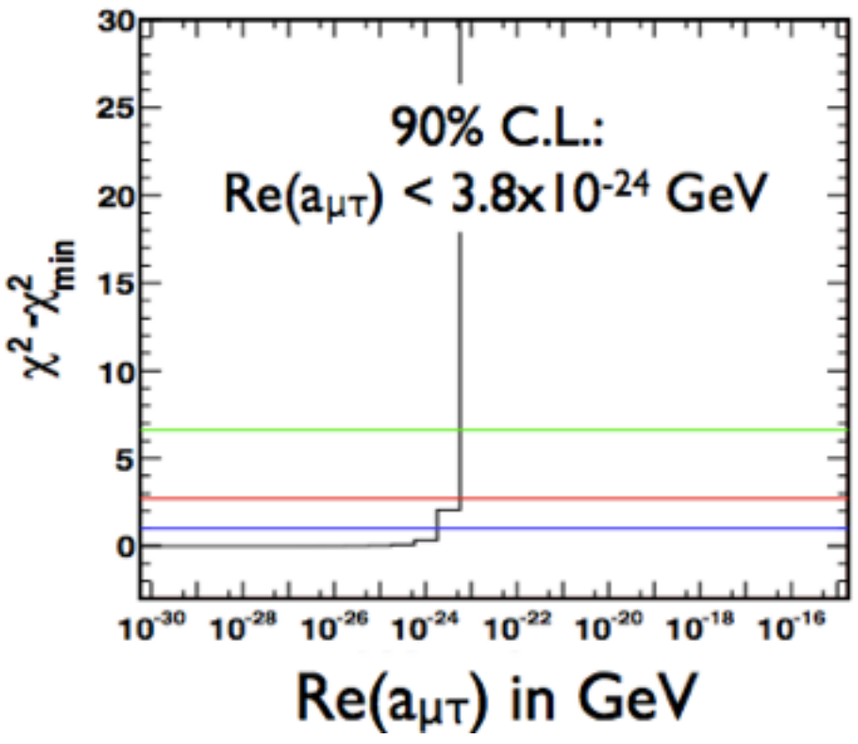
$\nu \to \nu$ $\quad$ $\nu \to \bar{\nu}$

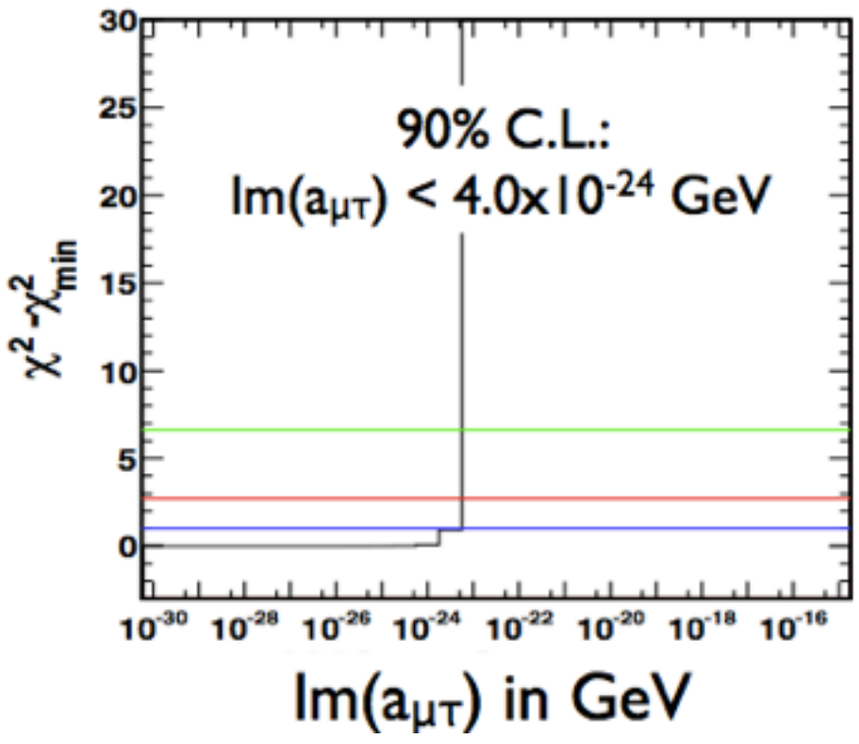
$$\delta h = \frac{1}{|\boldsymbol{p}|} \begin{pmatrix} \widehat{a}_{\text{eff}} - \widehat{c}_{\text{eff}} & -\widehat{g}_{\text{eff}} + \widehat{H}_{\text{eff}} \\ -\widehat{g}^{\dagger}_{\text{eff}} + \widehat{H}^{\dagger}_{\text{eff}} & -\widehat{a}^{T}_{\text{eff}} - \widehat{c}^{T}_{\text{eff}} \end{pmatrix}$$

- There is then 9 complex a and c parameters (18 independent parameters in total) for isotropic model, up to 1st order

$$\delta h = \frac{1}{|p|} \begin{pmatrix} a_{ee} - c_{ee} & a_{e\mu} - c_{e\mu} & a_{e\tau} - c_{e\tau} \\ a^{*}_{e\mu} - c^{*}_{e\mu} & a_{\mu\mu} - c_{\mu\mu} & a_{\mu\tau} - c_{\mu\tau} \\ a^{*}_{e\tau} - c^{*}_{e\tau} & a^{*}_{\mu\tau} - c^{*}_{\mu\tau} & a_{\tau\tau} - c_{\tau\tau} \end{pmatrix}$$

- Lorentz violation effects calculated up to 2nd Order
- Performed the analysis for 3 sectors: $\mu\tau$, eμ and eτ each one having 4 coefficients: Re(a), Im(a), Re(c), Im(c)
- Fitted 3 parameters at a time: δCP and the real and imaginary parts of the LV coefficient.
- Performed the fit for both the normal and inverted hierarchy and Tested 1417.4 days SK4 data





result

Comparison with existing results

2012 Tarek Akiri

Table S4. Maximal sensitivities for the neutrino sector

arxiv:0801.0287v6

$d=3$	Coefficient	$e\mu$	$e\tau$	$\mu\tau$	Coefficient	$e\mu$	$e\tau$	$\mu\tau$
	$\mathrm{Re}\,(a_L)^T$	10^{-20} GeV	10^{-19} GeV	–	$\mathrm{Im}\,(a_L)^T$	–	10^{-19} GeV	–
		10^{-23} GeV	10^{-23} GeV	10^{-24} GeV		10^{-23} GeV	10^{-23} GeV	10^{-24} GeV

$d=4$	Coefficient	$e\mu$	$e\tau$	$\mu\tau$	Coefficient	$e\mu$	$e\tau$	$\mu\tau$
	$\mathrm{Re}\,(c_L)^{TT}$	10^{-19}	10^{-17}	–	$\mathrm{Im}\,(c_L)^{TT}$	–	10^{-17}	–
		10^{-26}	10^{-24}	10^{-26}		10^{-26}	10^{-24}	10^{-26}

➟ Improvement of about 3-4 orders of magnitude on existing dimension 3 coefficients!!

➟ Improvement of about 7 orders of magnitude on existing dimension 4 coefficients!!

Also the 1st constraint on the μτ LV parameters using a common SME framework

new paper will appear soon

result

proton decay search

2012
M.Miura

- Updated to 1417.4 days (260 kt・year exposure)

- $\mathbf{p \rightarrow e^{+}\pi^{0}}$

  New pion scattering :
  - efficiency rate decreased (45% → 40%) ,
  - BG rate increased

  Updated Lifetime limit (90% CL) : > 13.5 x 1E33 year

	Exp. (kton・yr)	Eff(%)	BKG	Data
SK1	91.7	44.6±0.7	0.20	0
SK2	49.2	43.5±0.7	0.11	0
SK3	31.9	45.2±0.7	0.06	0
SK4	46.9	45.0±0.7	0.08	0
Total	219.7		0.45	0

old interaction model

	SK1	SK2	SK3	SK4
Eff (%)	39.2	38.5	40.1	39.6
BKG	0.27	0.15	0.07	0.22
Data	0	0	0	0

new interaction model

result

- **p → νK^+**

  Updated fitter (apfit) applied :
  - total BG : 0.55 → 0.37 : 30% reduced for prompt γ method,
  - almost no difference for $\pi^+\pi^0$ method.

  Updated combined lifetime limit : > 5.9 x1E33 years
  (Previous official: 4.0x1E33 yrs @220kt・yrs)

- **p → e$\nu\nu$** & **p → $\mu\nu\nu$**

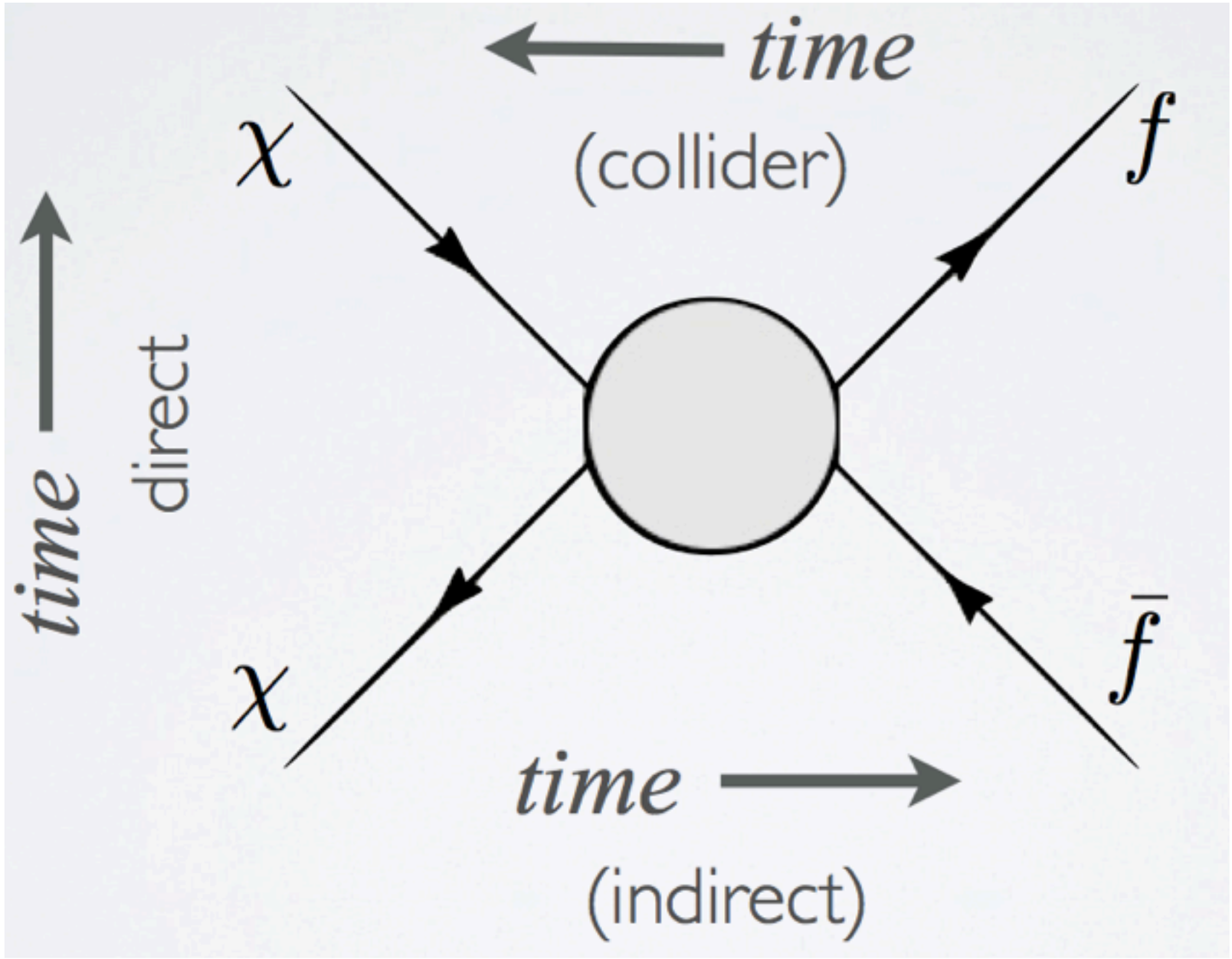
  A first 3-body analysis of purely leptonic decay modes
  Used a spectrum fitting technique
  First result : 1.7E32/1.9E32 yrs respectively (a order improved compared to PDG)

2012 M.Miura & V.Takhistov

introd
uction

WIMP search

+ indirect
solar/Earth
neutrino
search

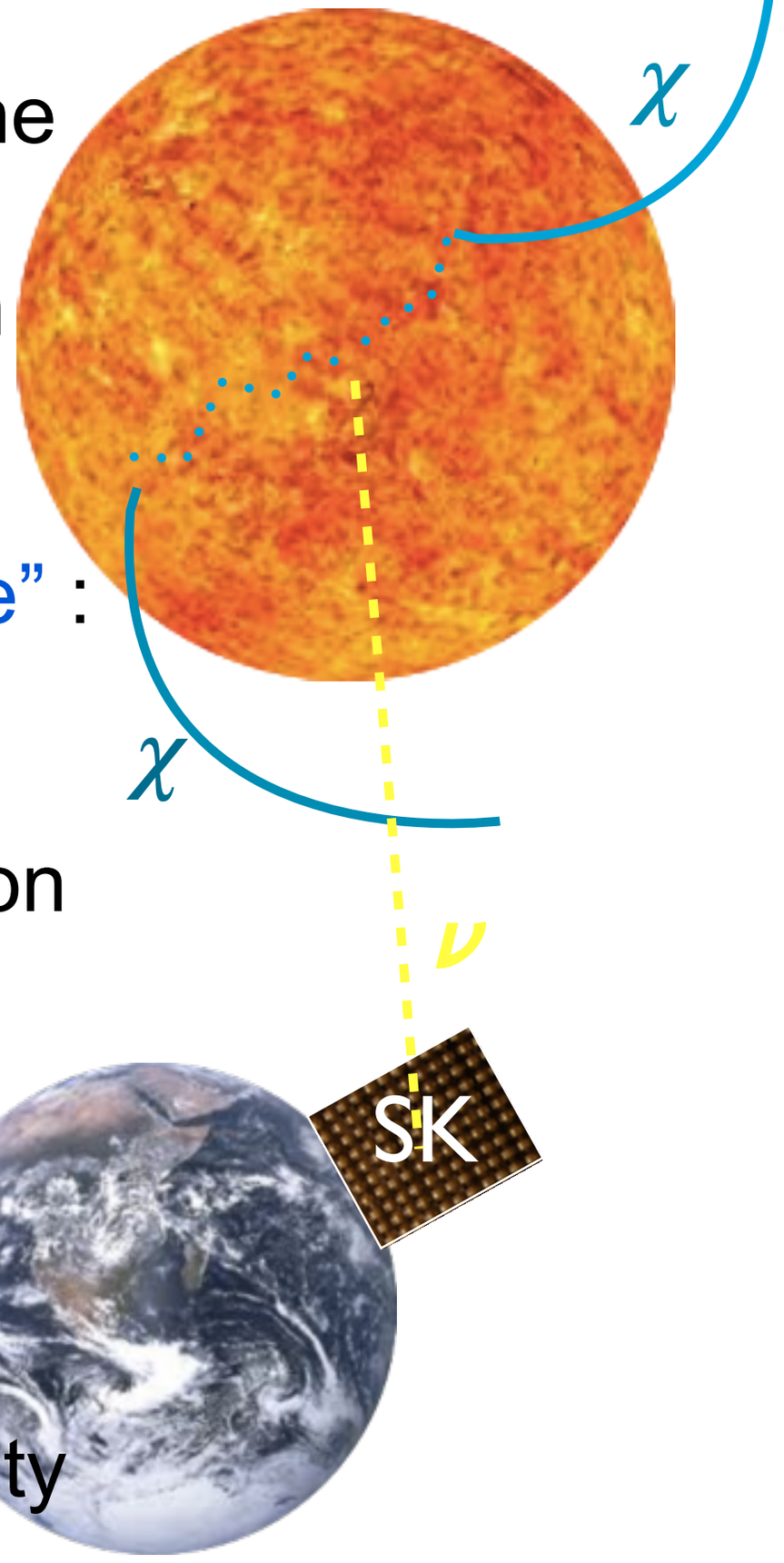


(Galactic center, halo, dwarf, etc,
with neutrino, gamma ray, anti-particles,
etc...)

introd
uction

Indirect solar WIMP search

• WIMP capture and annihilation inside the Sun → neutrino escapes
• The scattering process is the same with direct detection → limit on the WIMP-nucleon scattering cross-section
"a large Hydrogen WIMP detector for free" :
Strong sensitivity to SD cross-section

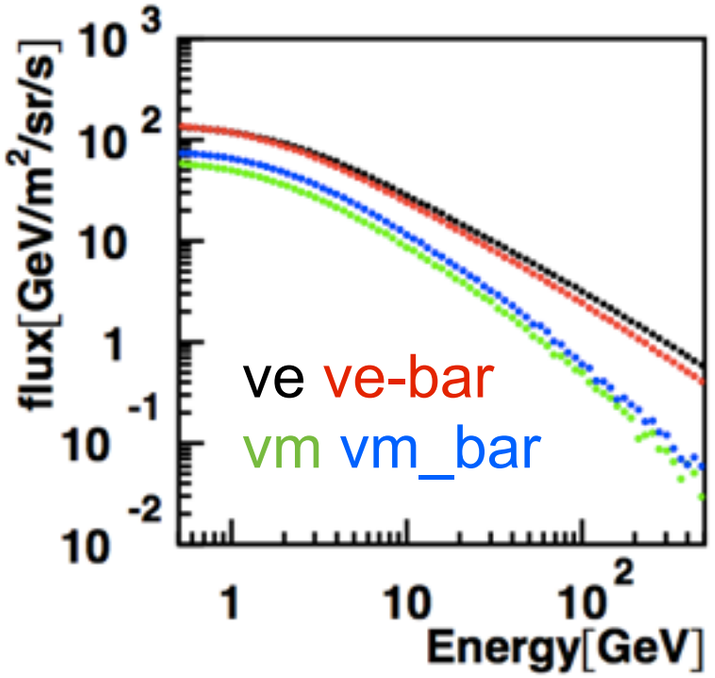


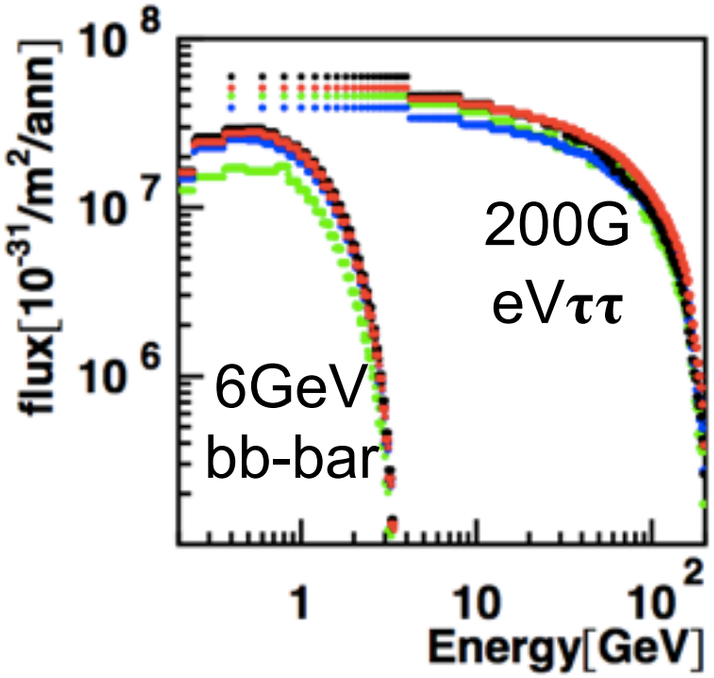
• Equilibrium between capture -annihilation takes critical role :
capture ∝ (annihilation) ∝ neutrino flux

• BG : atmospheric neutrinos (however directional information helps)
• bonus : small nuclear-physics uncertainty

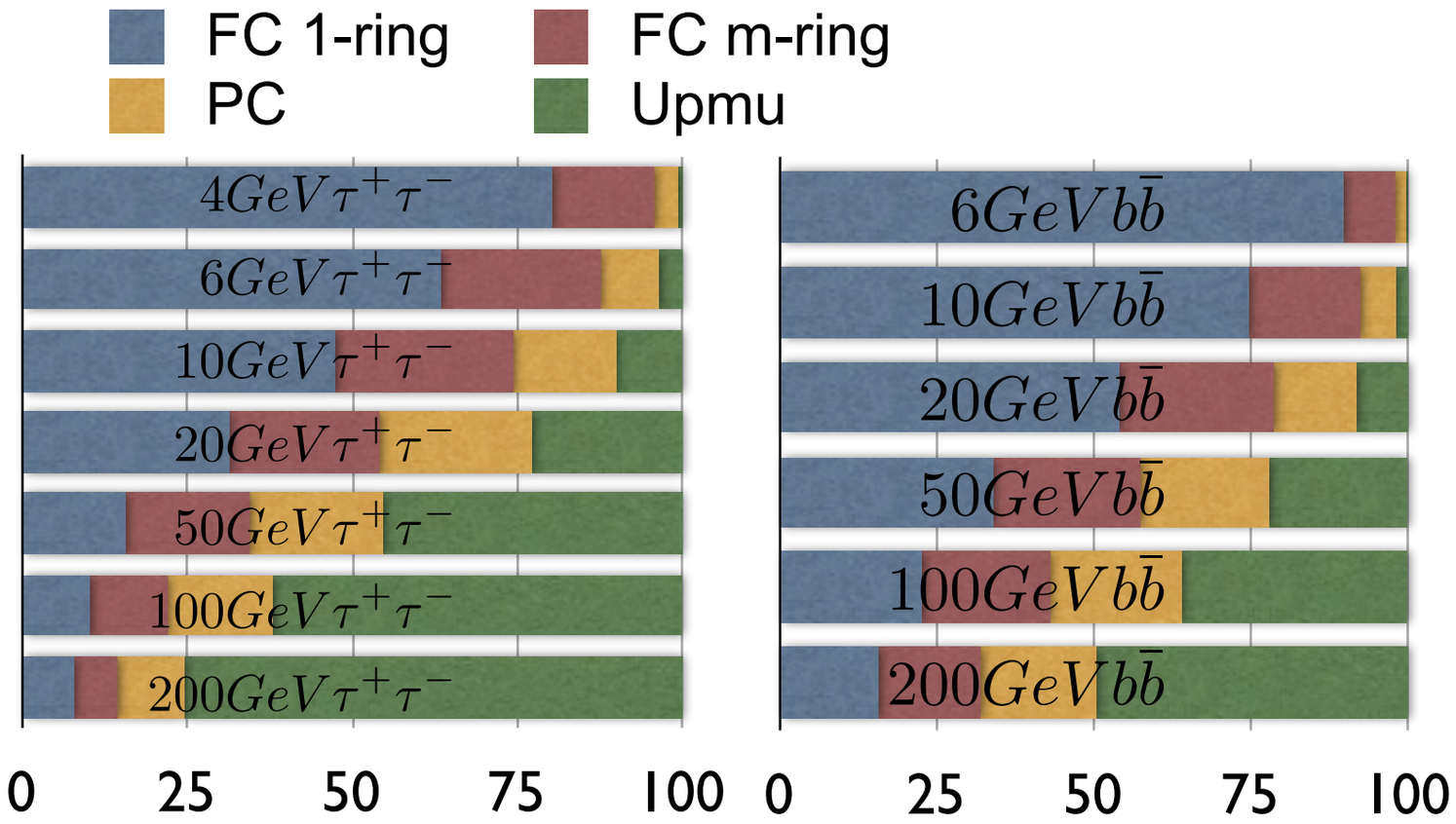
Light WIMP search in SK

1) used 'contained events'



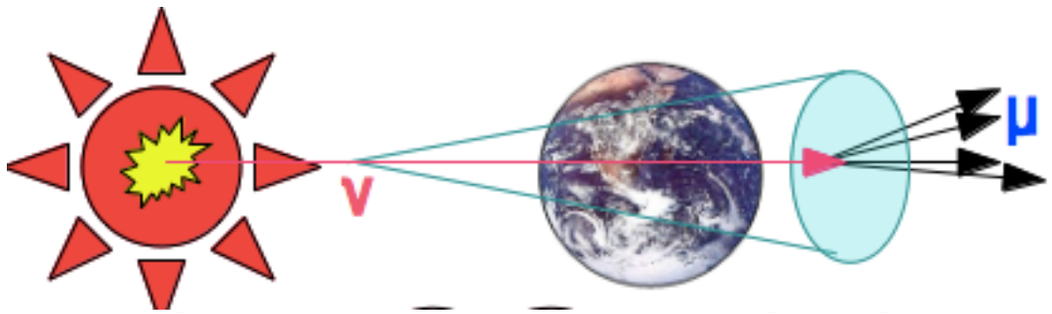


➠ True energy spectrum of atmospheric(L) / WIMP neutrino flux(R)

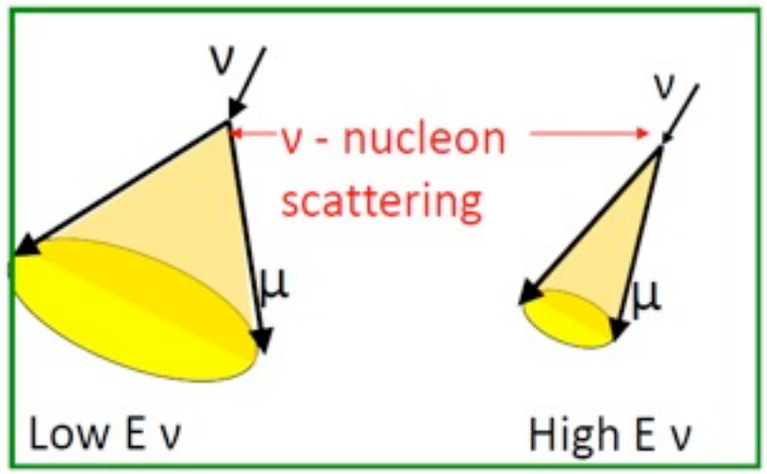


➠ By using contained events, signal acceptance significantly increase for light WIMPs.

2) Test signal contribution by pulled χ^2 method



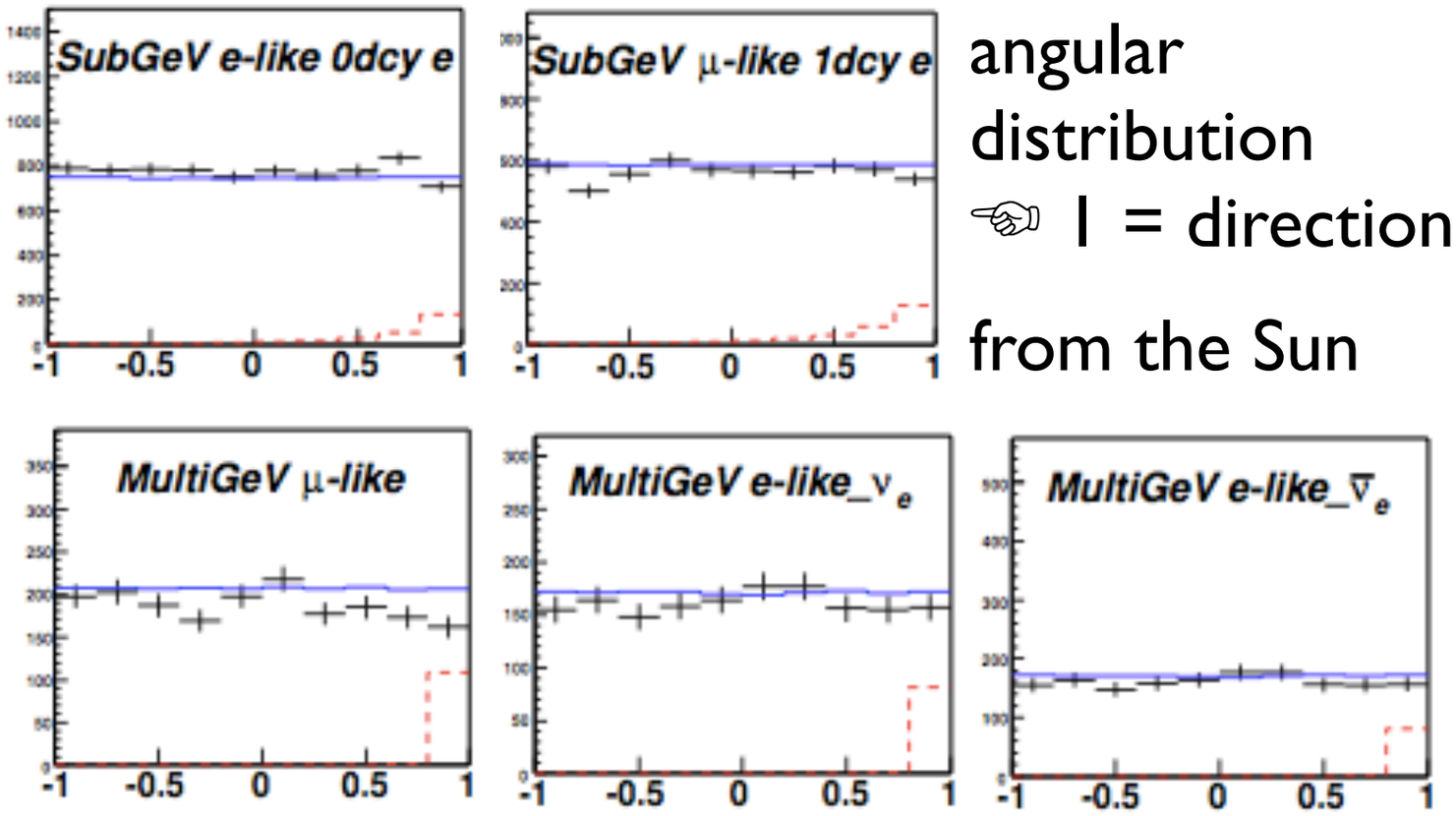
previous upmu analysis :
look into signal region
(90% angular cut)



Fit SK data to “atmospheric neutrino + WIMP induced neutrino”
to find best fit value of WIMP contribution

$$\chi^2 = 2\Sigma_{n=1}^{\#ofbins}[N_n^{BG}(1+\Sigma_j f_j^n \epsilon_j) + \beta N_n^{WIMP}(1+\Sigma_k f_k^n \epsilon_k) - N_n^{data} + N_n^{data} ln(\frac{N_n^{data}}{N_n^{BG}(1+\Sigma_j f_j^n \epsilon_j) + \beta N_n^{WIMP}(1+\Sigma_k f_k^n \epsilon_k)})] + \Sigma_j(\frac{\epsilon_j}{\sigma_j}) + \Sigma_k(\frac{\epsilon_k}{\sigma_k})$$

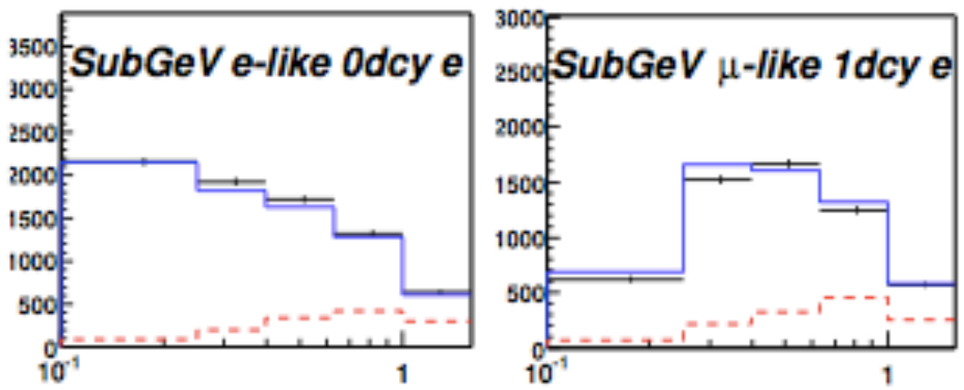
used SK I-IV data (3903days)
fully used energy & angle & flavor information



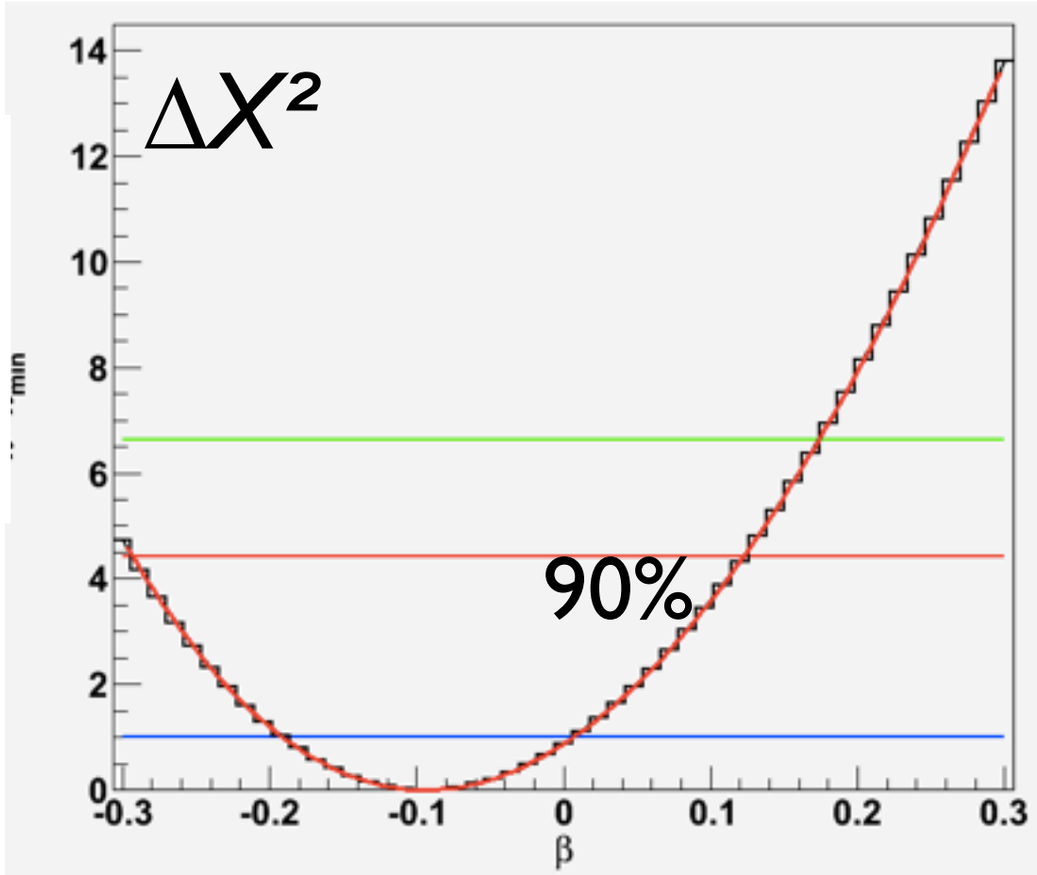
angular distribution

☜ l = direction

from the Sun



momentum distribution



SK events ∝ flux ∝ annihilation ∝ capture ∝ scattering cross-section.

- - - : SK I-IV Data

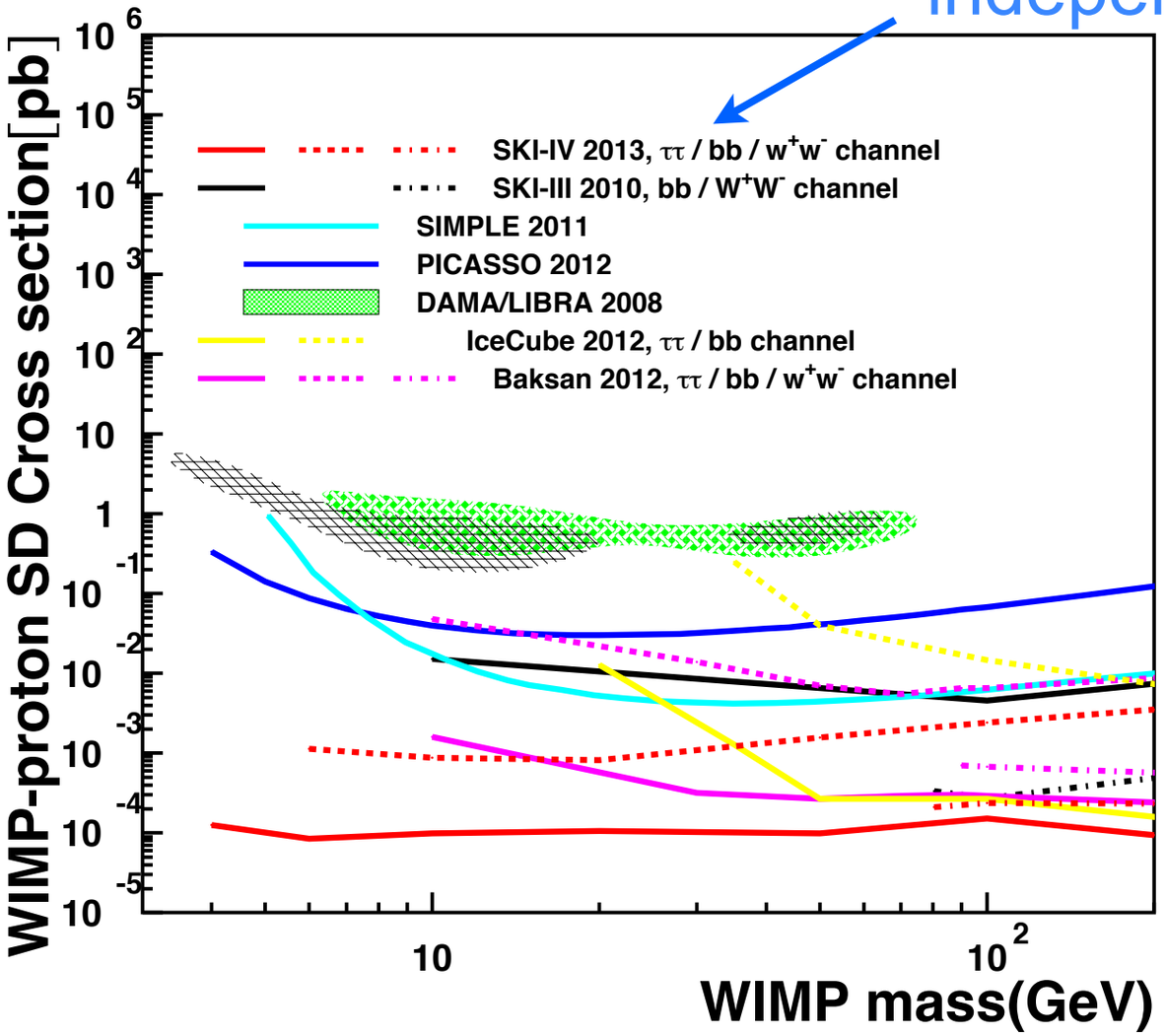
——— : Atmospheric neutrino MC

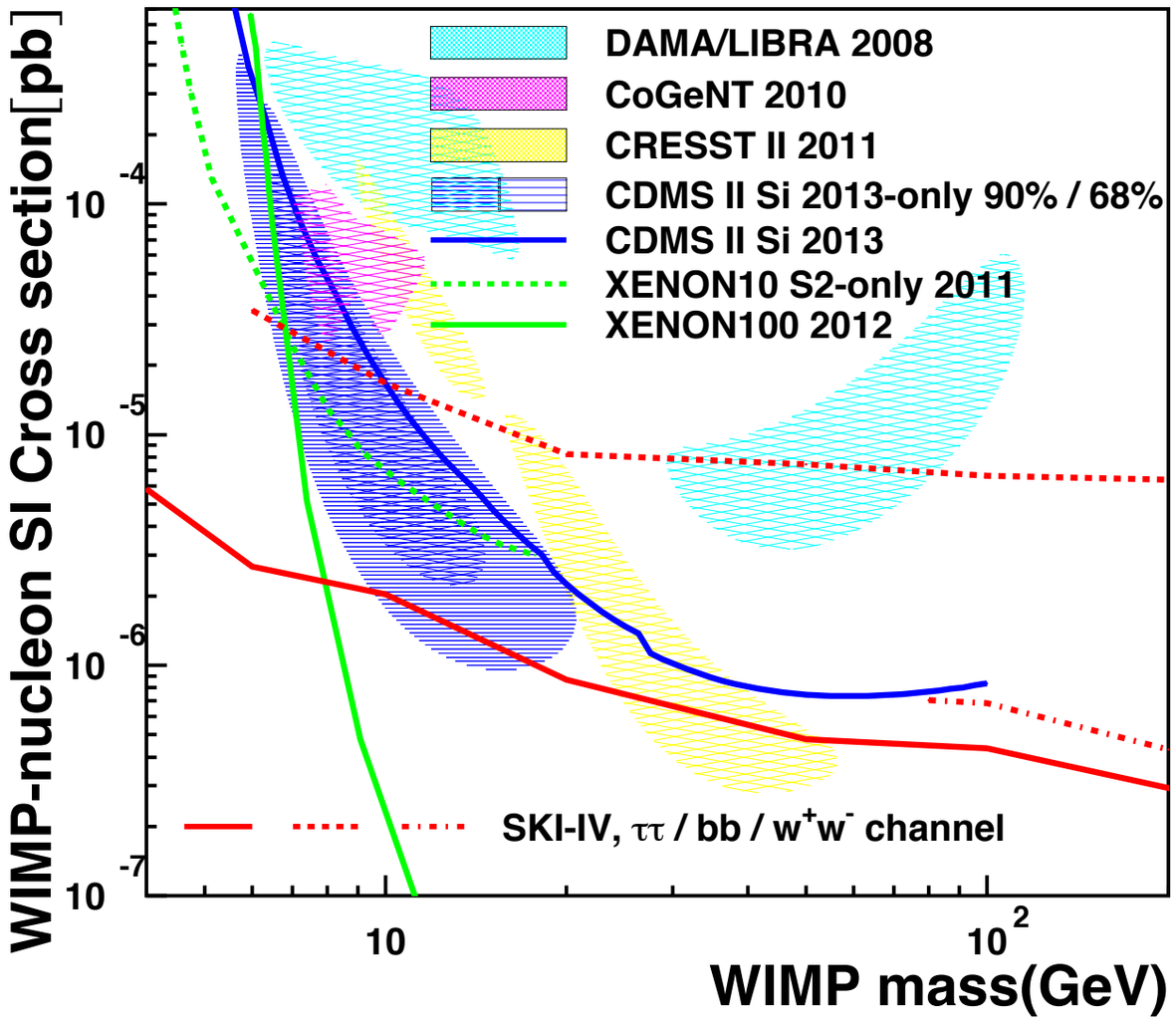
——— : WIMP induced neutrino MC (for 6GeV bb-bar sample, with arbitrary normalization)

result

90% Upper limit on SD/SI scattering X-section

result shown in 3 lines to be model independent





The result surprisingly competes with human-maid direct detectors.

→ important result from a very different detection strategy & uncertainties than direct searches.

new paper will appear sooner or later

Summary

- 3 flavor oscillation zenith angle analysis : updated result shows χ2(NH)- χ2(IH) = 1.5
- Sterile neutrino search : excludes a large part of global allowed signal, provides a clean Δm^2-independent constraint useful for the community
- LIV search : first result on $\mu\tau$ LV parameters, 3-7 orders improved limits on eμ, eτ sectors.
- Proton decay : $p \rightarrow e^+\pi^0$, νK^+ updated, first 3-body results on $p \rightarrow e\nu\nu$ & $\mu\nu\nu$ channel : a order improved compared to PDG
- Solar WIMP search : world-best limit in SD cross-section below 200GeV, rules out large space for SI cross-section for >4GeV WIMPs with $\tau\tau$ channel.
- + neutron tagging, etc many physics which couldn't be covered.

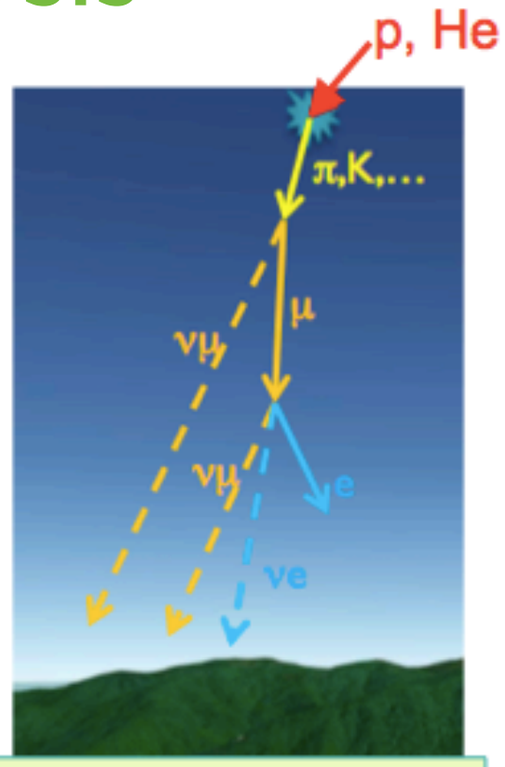
Back Up

three flavor zenith angle analysis

2012 K.P.Maggie

Introduction

- Given large $\sin^2 2\theta_{13}$
  aim of atmospheric neutrino studies:
  - To solve $\sin^2\theta_{23}$ octant degeneracy ($\theta_{23} > 45°$ or $\theta_{23} < 45°$)
  - To obtain complementary information on δ_{CP}
  - Mass hierarchy determination
- Full 3-flavor analysis includes solar term, ν_e due to matter effect and their interference:



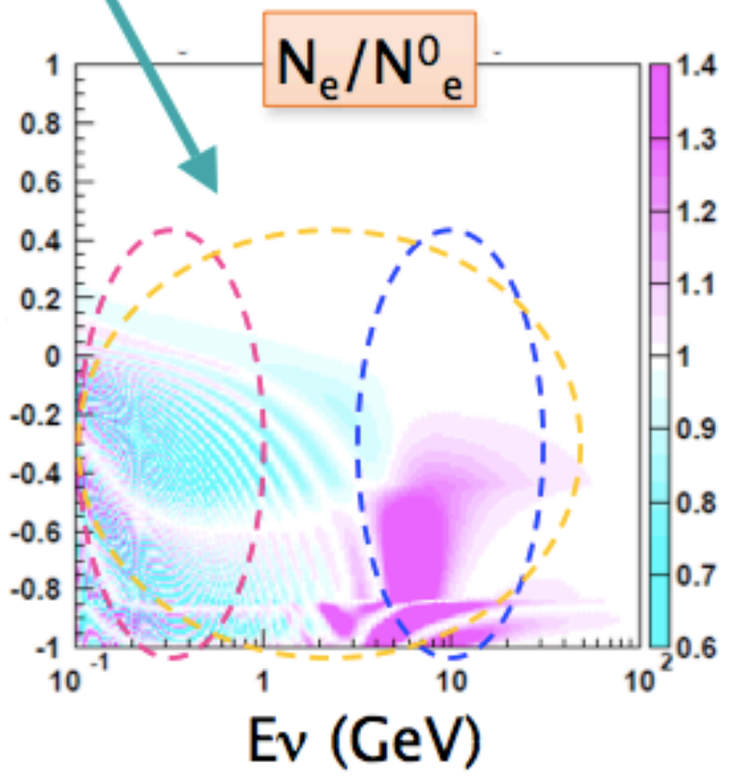
$$\frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} \approx P_2 \bullet (r \bullet \cos^2\theta_{23} - 1)$$ solar term

interference

$$-r \bullet \sin\tilde{\theta}_{13} \bullet \cos^2\tilde{\theta}_{23} \bullet \sin 2\theta_{23} \bullet (\cos\delta \bullet R_2 - \sin\delta \bullet I_2)$$

$$+2\sin^2\tilde{\theta}_{13} \bullet (r \bullet \sin^2\theta_{23} - 1)$$ θ_{13} resonance

Solar term @ sub-GeV
θ_{13} resonance @ multi-GeV
interference @ sub- and multi-GeV



*By using statistically enhanced ν_e and anti-ν_e sample, this resonance term would reveal the neutrino mass hierarchy

$P_2 = \sin^2 2\theta_{12,M} \sin^2(\phi_m/2)$ where ϕ_m is the phase oscillation in matter

$r = \nu_\mu / \nu_e$ flux ratio as a function of energy

$R_2 = -\sin 2\theta_{12,M} \cos 2\theta_{12,M} \sin^2(\phi_m/2)$

$I_2 = (-1/2) \sin 2\theta_{12,M} \sin\phi_m$

$\theta_{13} \approx \theta_{13,M}$

three flavor zenith angle analysis

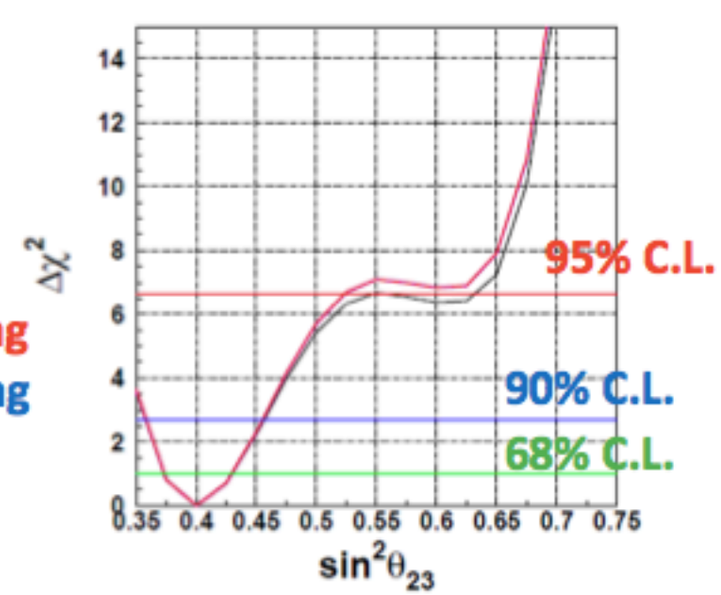
Contribution of update

- Update of Sub-GeV single ring e-like sample (new π^0 cut)
- Update of method of reweighting oscillation parameter
  - oscillation probability computation

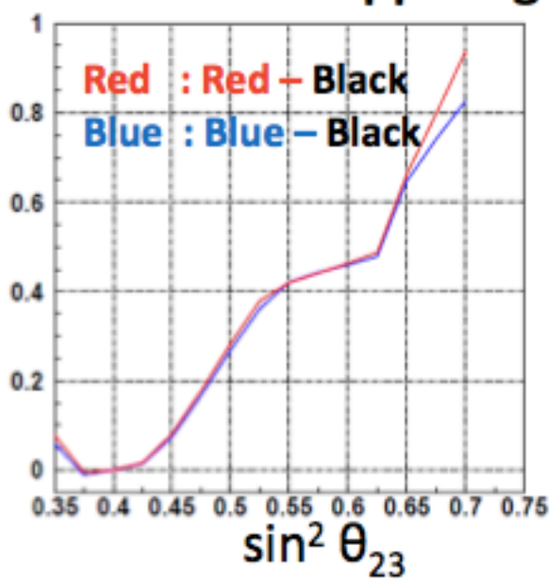
Sensitivity study
@SK1,2,3,4 exposure

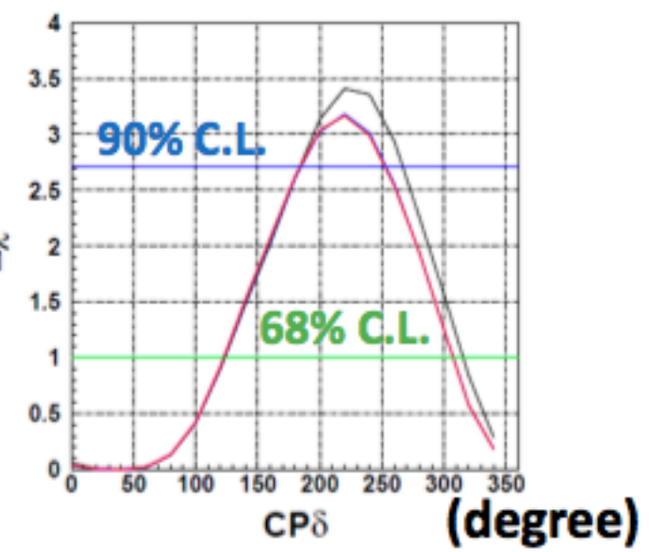
Red : new π^0 cut
+ update of reweighting
Blue : update of reweighting
Black: Maggie's analysis

Assumption (normal hierarchy)	
$\sin^2\theta_{23}$	0.4
Δm^2_{23}	2.37×10^{-3} eV^2
δCP	40 degree

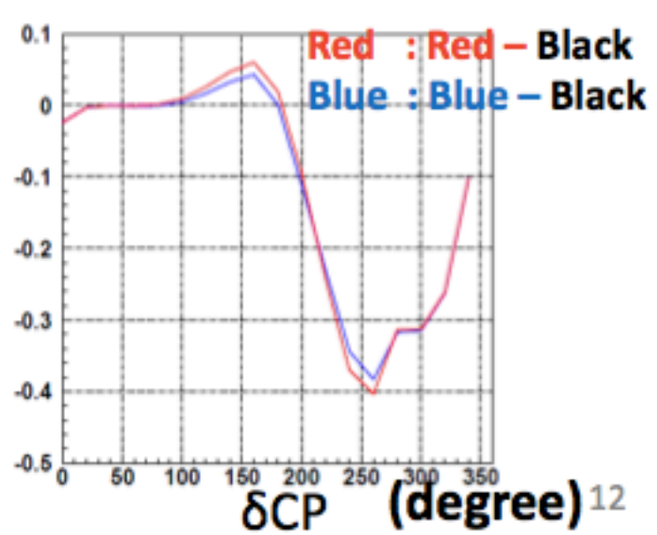


Subtraction on upper figure





Subtraction on upper figure

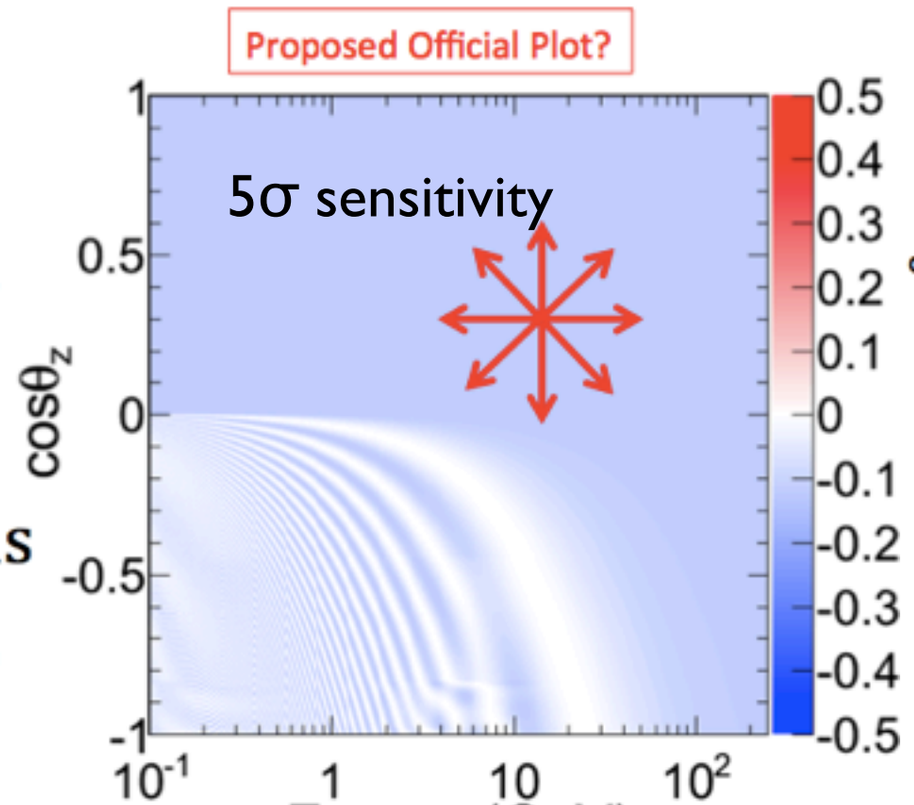


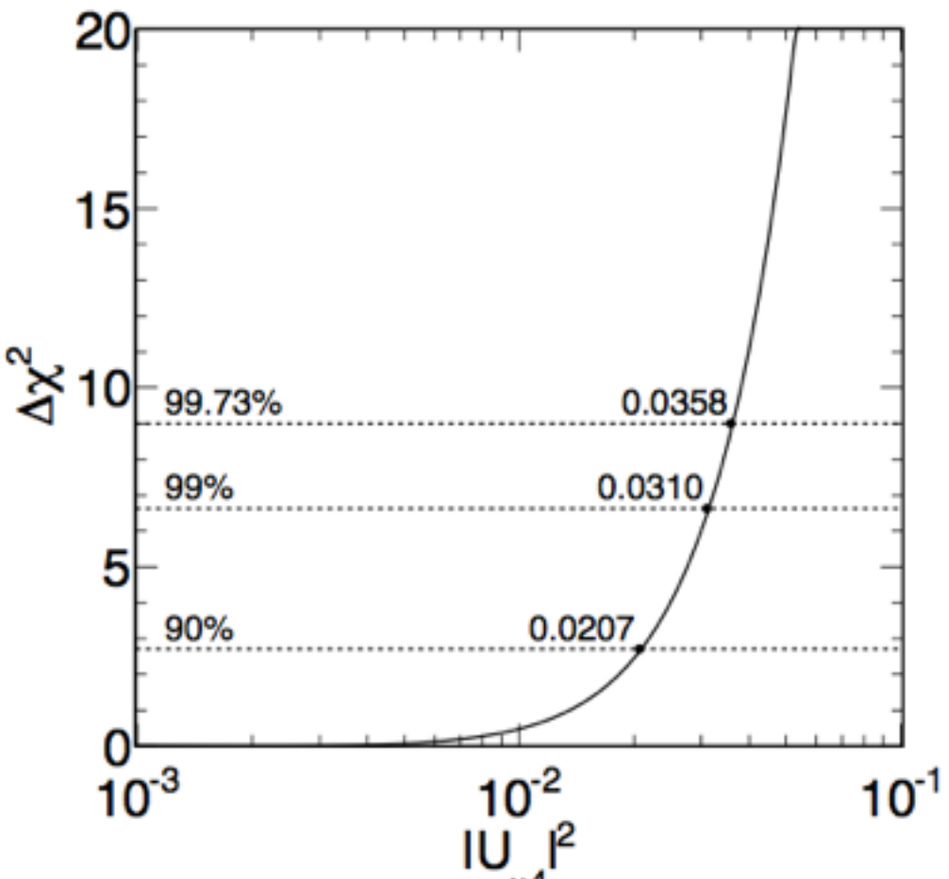
sterile neutrino search

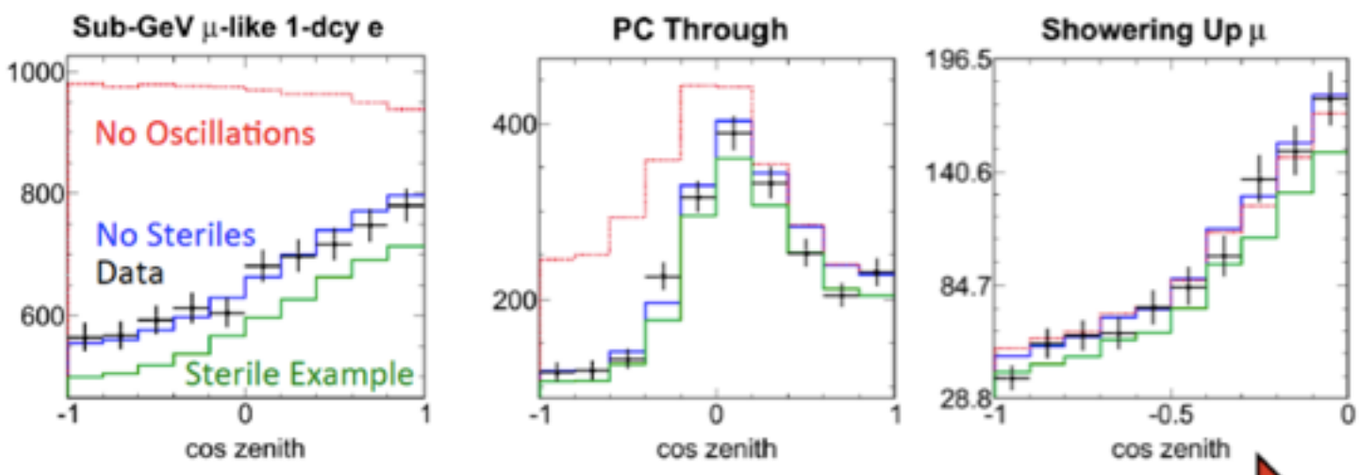
2012 Alex Himmel

3+1 ΔOscillogram

- At right is the *difference* in oscillation prob. due to sterile effects.
- The blue means $P_{\mu\mu}$ is lower ~everywhere.
  - Except at the points where $P_{\mu\mu} = 0$ already







$|U_{\mu 4}|^2 < 0.021$ at 90% C.L.

$|U_{\mu 4}|^2 < 0.031$ at 99% C.L.

Best Fit $|U_{\mu 4}|^2$ 0.0020

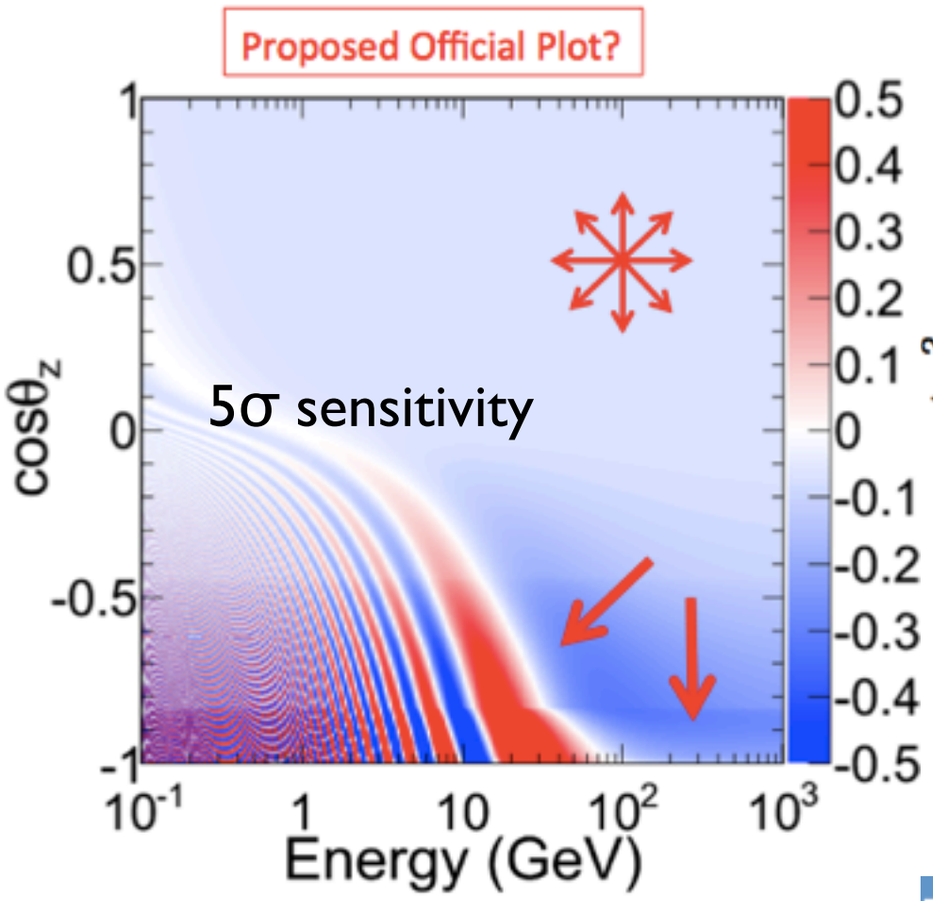
Primary effect is extra ν_μ disappearance at all path lengths

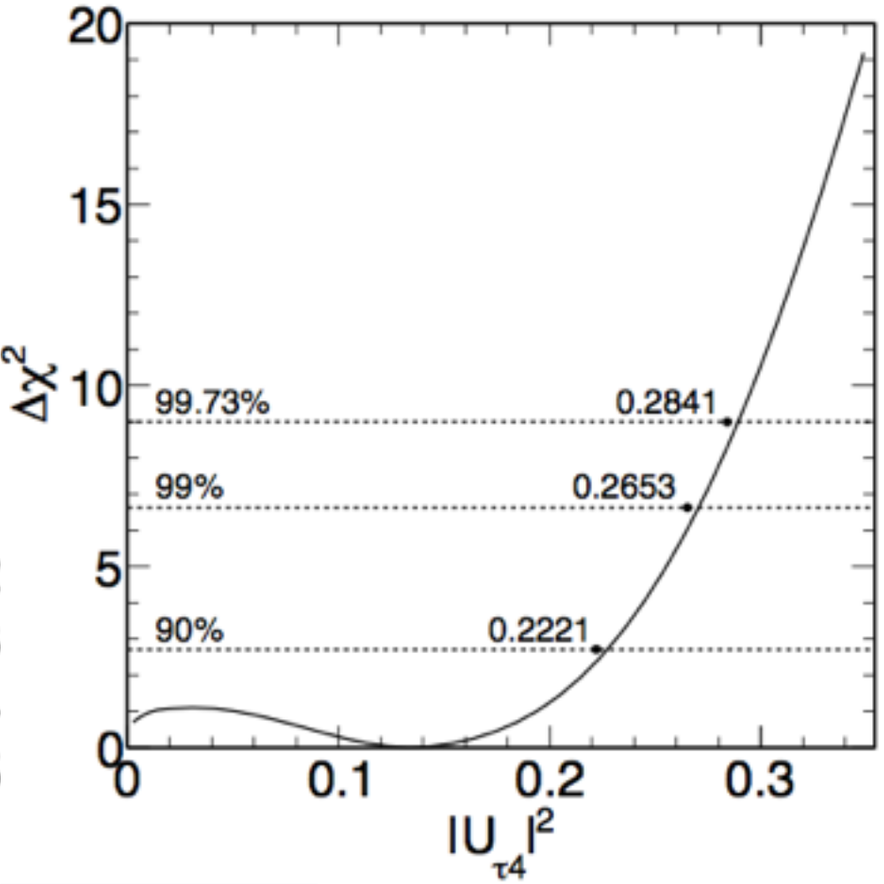
sterile neutrino search

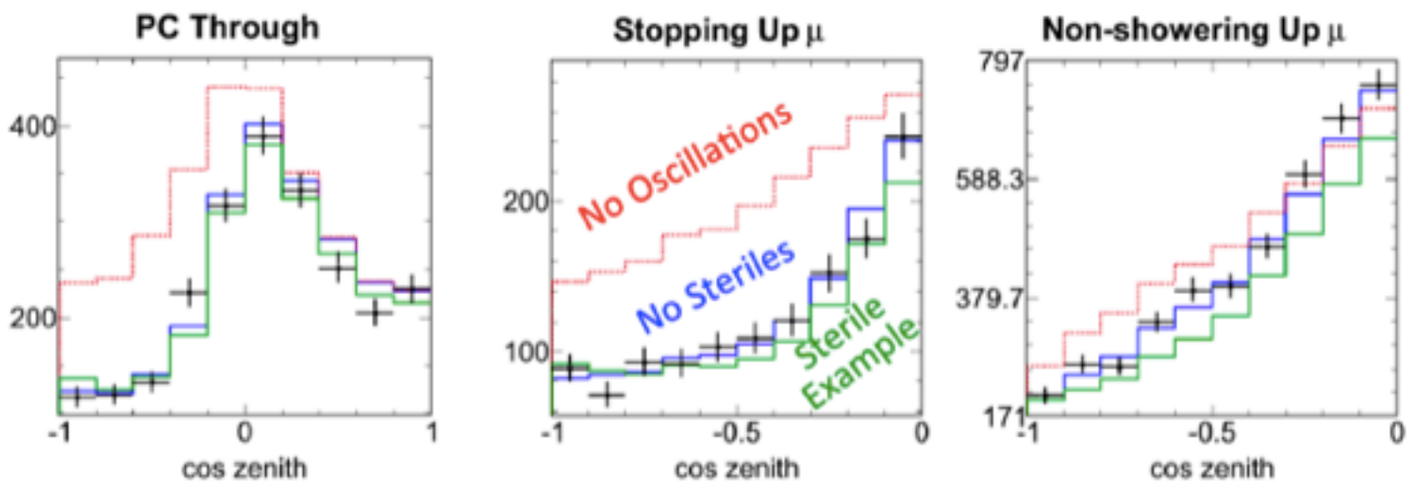
2012 Alex Himmel

2+1 Δoscillogram

- Large enhancement of sterile effect at high L and large E due to matter
- Alternating red-blue are horizontal shifts of the oscillation minima
- Still see the all-over effect we had before







Best Fit $(|U_{\tau 4}|^2, |U_{\mu 4}|^2)$

(0.133, 0.001)

$|U_{\tau 4}|^2 < 0.22$ at 90% C.L.

$|U_{\tau 4}|^2 < 0.27$ at 99% C.L.

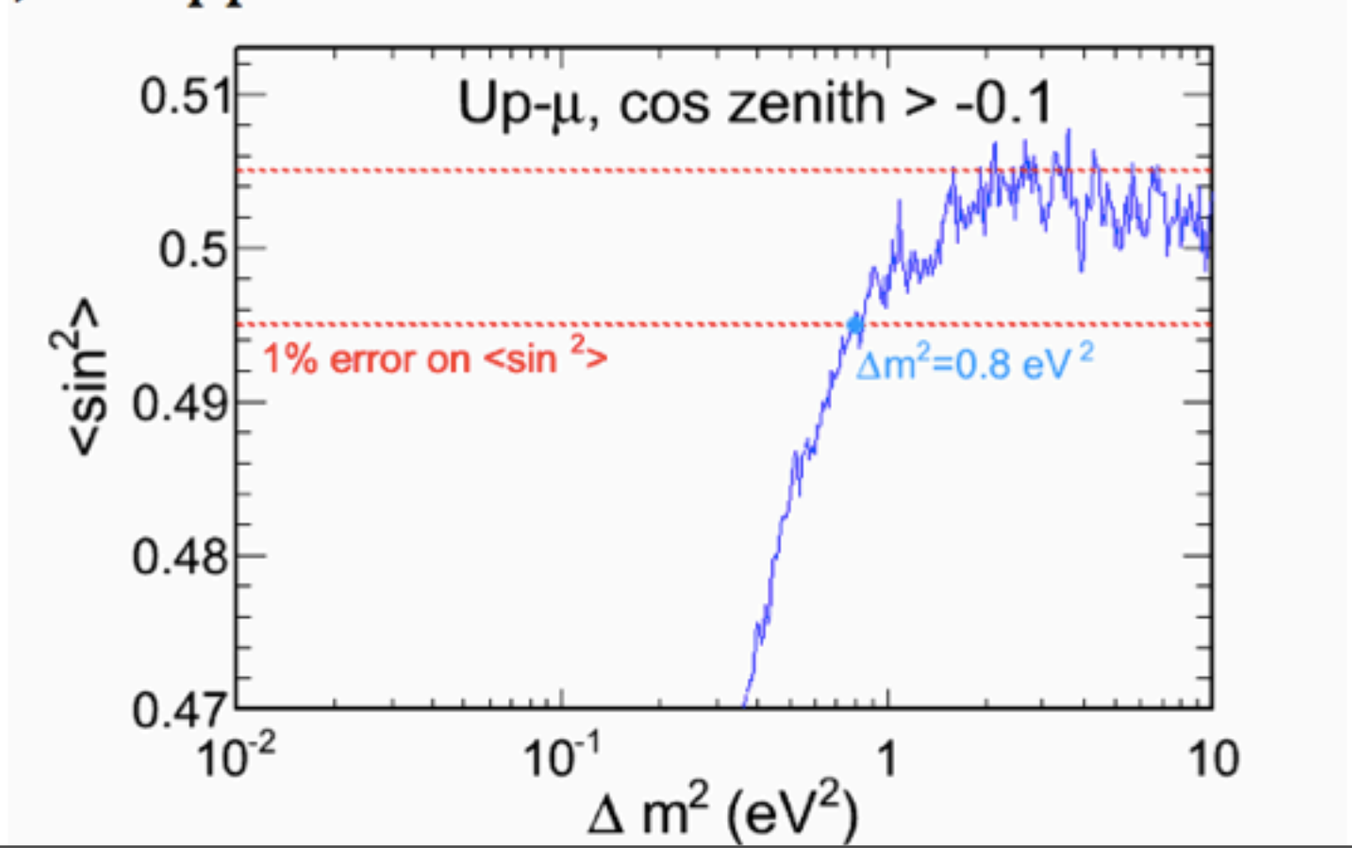
- NC Matter effects create shape distortion in PC/Up-μ zenith distribution

sterile neutrino search

When is Δm^2_{41} no longer "large"?

- When do the oscillations no longer appear fast?
  - This will be the worst at short L's and large E's, so lets focus on Up-μ with $\cos\theta_z > -0.1$
  - Loop through all these events and calculate the mean of $\sin^2(\Delta m^2 L/4E)$ for various Δm^2

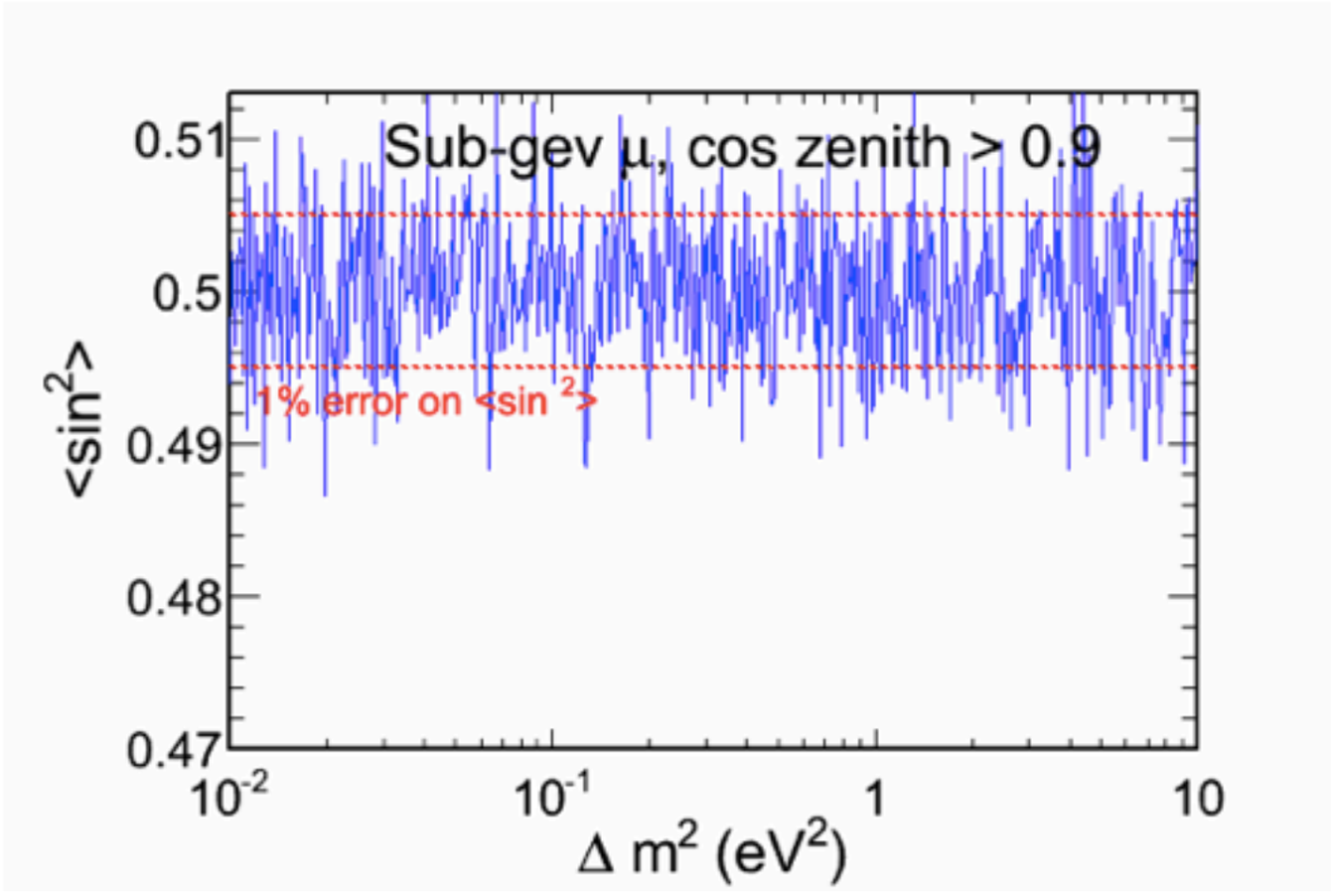
- Doing this, the approximation is valid down to ~0.8 eV^2



sterile neutrino search

When is Δm^2_{41} no longer "large"?

- However, the limit on $|U_{\mu 4}|^2$ is driven by the low $|U_{\tau 4}|^2$ region.
  - In this region, the dominant samples are Sub-GeV muons
  - Almost no power comes from Up-μ
- For these samples, the "large" assumption is ~always valid so $|U_{\mu 4}|^2$ limit really is a vertical line in Δm^2 to a good approximation



Lorentz invariance violation search

2012 Tarek Akiri

How well can SK do?

Table S4. Maximal sensitivities for the neutrino sector

arxiv:0801.0287v6

$d=3$	Coefficient	$e\mu$	$e\tau$	$\mu\tau$	Coefficient	$e\mu$	$e\tau$	$\mu\tau$
	$\mathrm{Re}\,(a_L)^T$	10^{-20} GeV	10^{-19} GeV	–	$\mathrm{Im}\,(a_L)^T$	–	10^{-19} GeV	–

MiniBooNE

Double Chooz

$d=4$	Coefficient	$e\mu$	$e\tau$	$\mu\tau$	Coefficient	$e\mu$	$e\tau$	$\mu\tau$
	$\mathrm{Re}\,(c_L)^{TT}$	10^{-19}	10^{-17}	–	$\mathrm{Im}\,(c_L)^{TT}$	–	10^{-17}	–

MiniBooNE:

L=500 m, E≈700 MeV

➟ $a \approx 2\times10^{-19}/L(\mathrm{km}) \approx 10^{-19}$ GeV & $c \approx 2\times10^{-19}/(L(\mathrm{km})\times E(\mathrm{GeV})) \approx 10^{-19}$

Double Chooz:

L=1 km, <E>=3 MeV

➟ $a \approx 2\times10^{-19}/L(\mathrm{km}) \approx 10^{-19}$ GeV & $c \approx 2\times10^{-19}/(L(\mathrm{km})\times E(\mathrm{GeV})) \approx 10^{-17}$

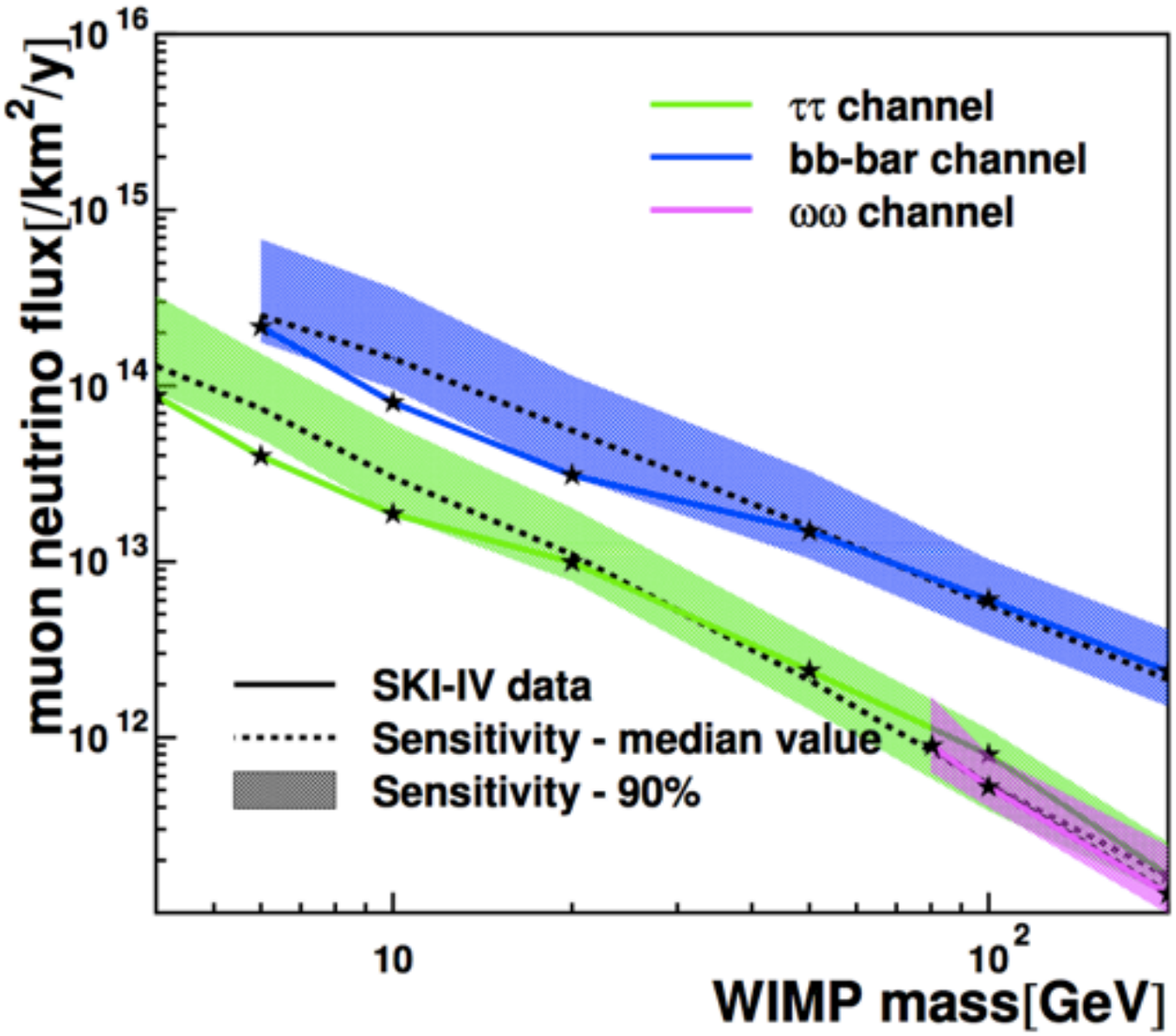
Super-Kamiokande:

L=10000 km, E≈100 GeV

➟ $a \approx 2\times10^{-19}/L(\mathrm{km}) \approx 10^{-23}$ GeV & $c \approx 2\times10^{-19}/(L(\mathrm{km})\times E(\mathrm{GeV})) \approx 10^{-25}$

Solar WIMP search

90% upper limit on WIMP-induced muon neutrino flux



Solar WIMP search

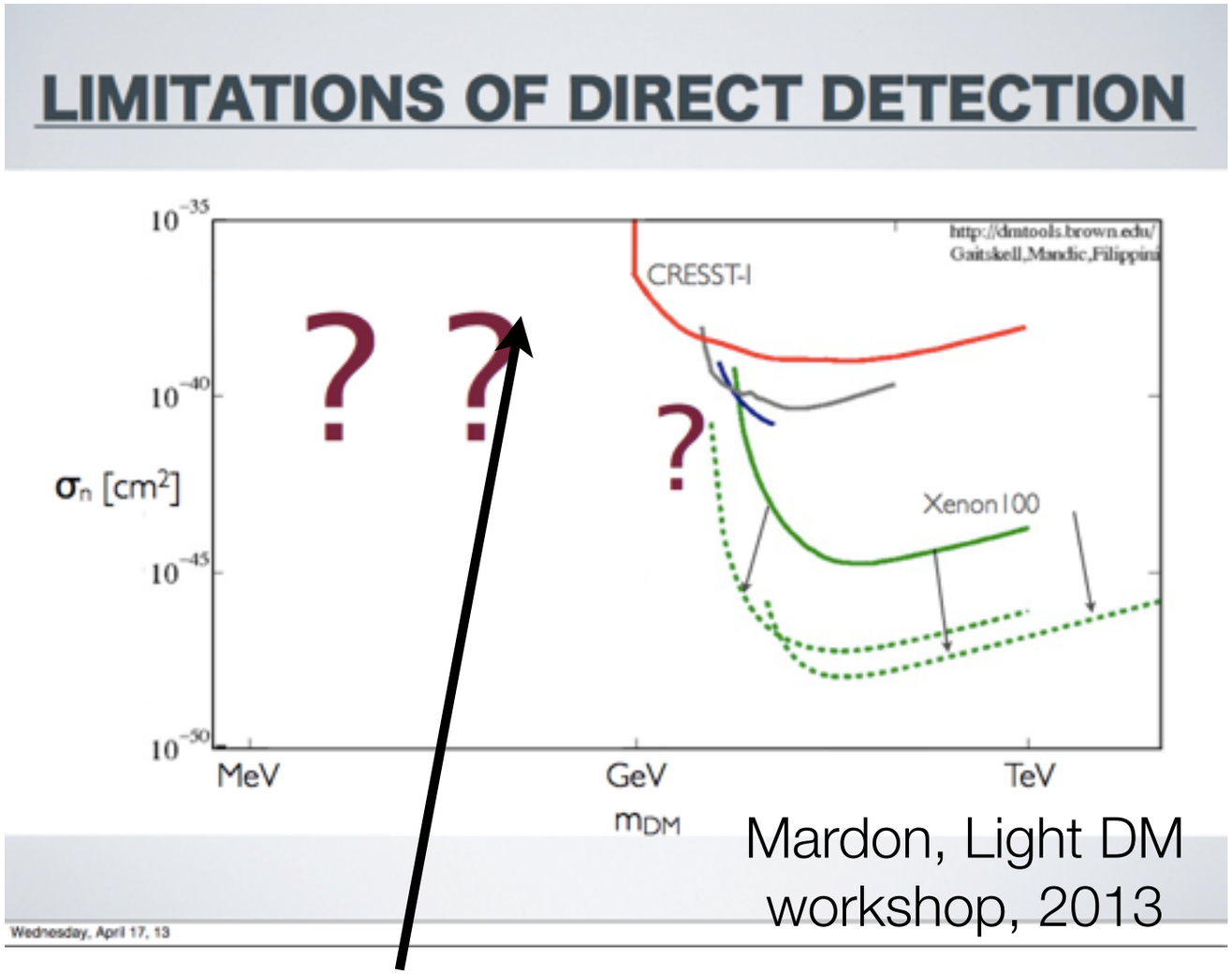
Interpretation to SI WIMP-proton cross section

- Doesn't sun only have sensitivity for SD?
  - Capture from hydrogen is kinematically suppressed

$$\sigma_i^{SI} = \sigma_p^{SI} I^2 \frac{\mu_i^2}{\mu_p^2}$$

- But the Sun is huge & heavier elements capture energetic WIMPs more efficiently

- Our limit can show interesting interpretation on SI coupling WIMP too.



compete here with future detectors(XENON, LUX, superCDMS, PICO, DAMIC...)