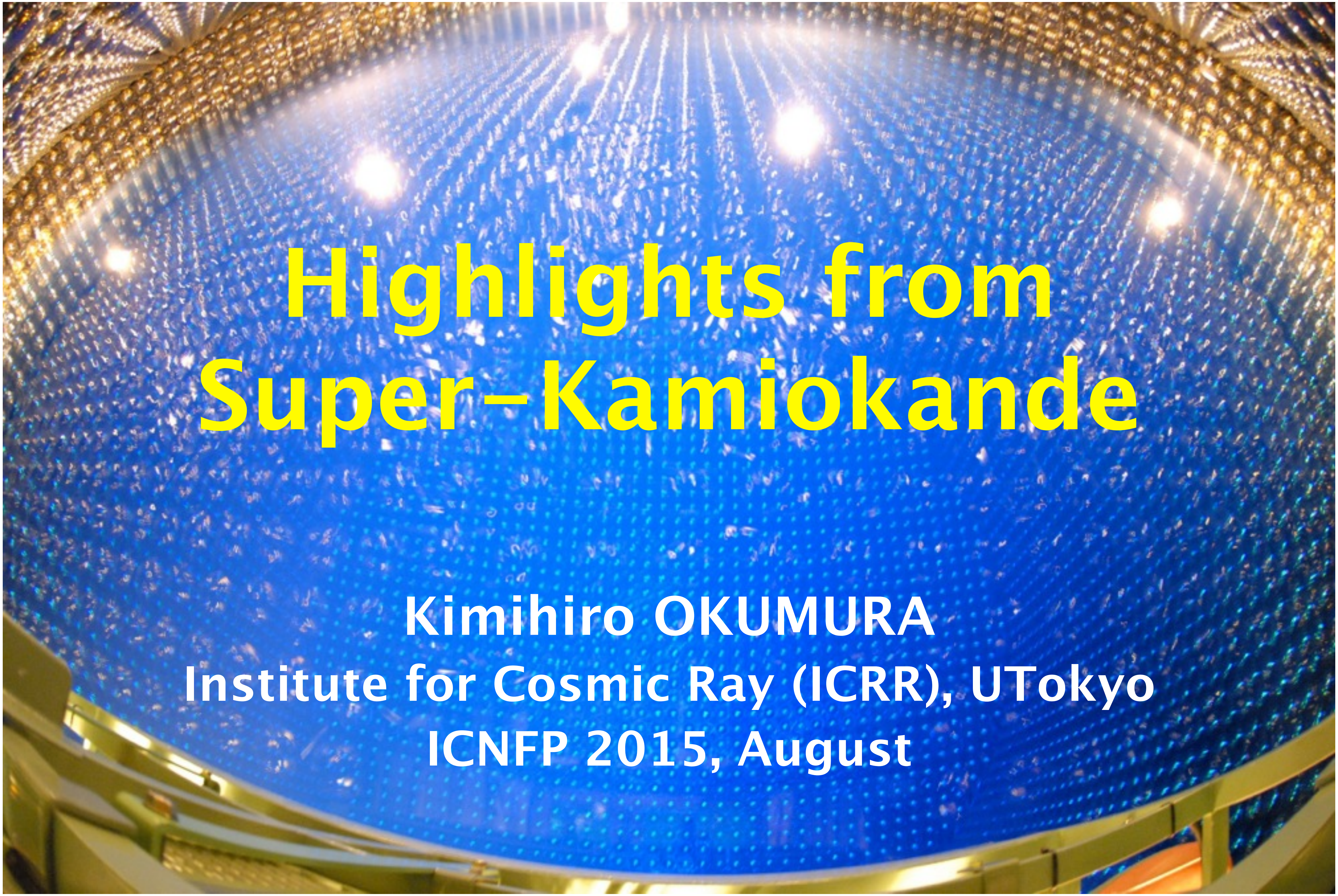


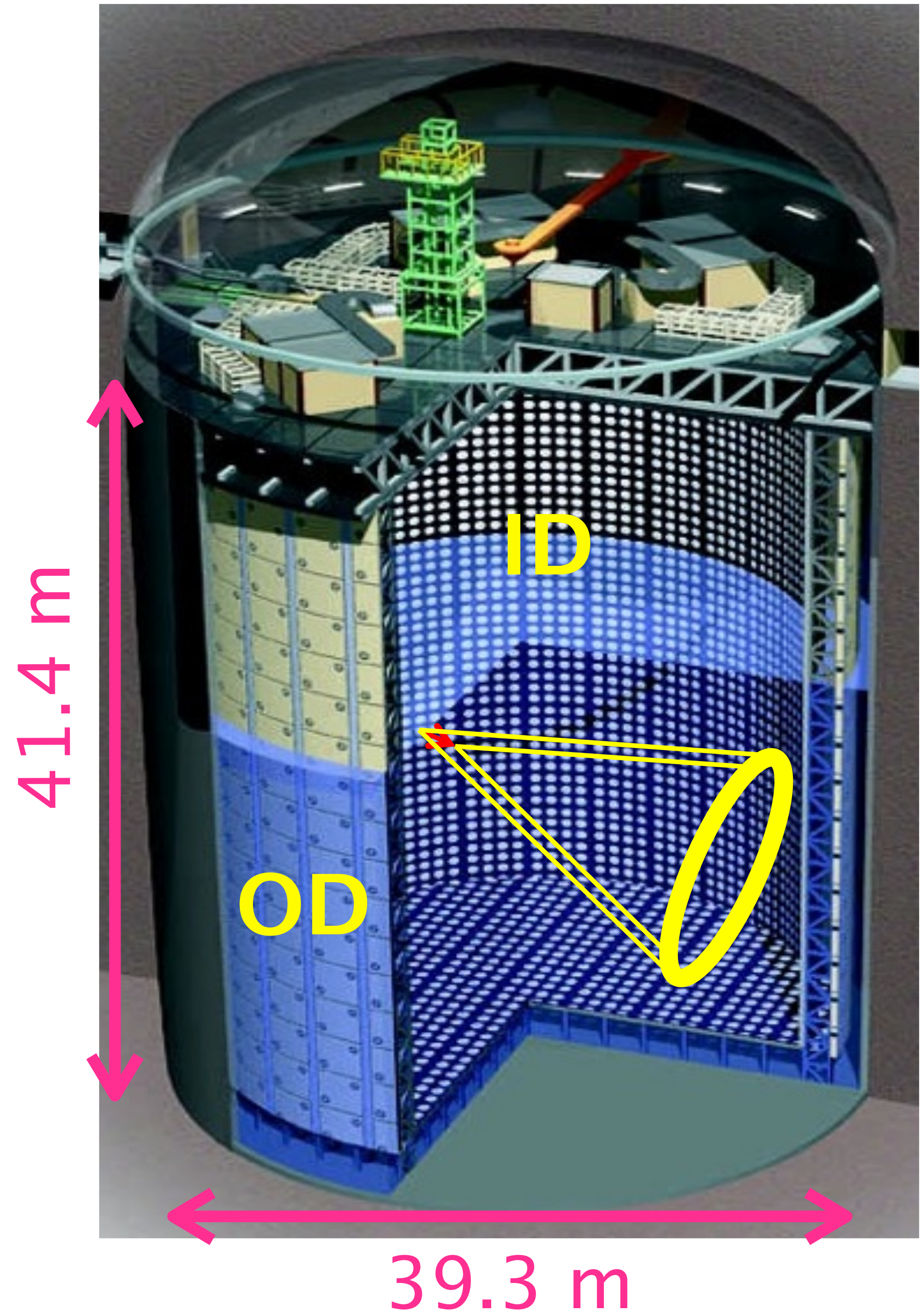
Highlights from Super-Kamiokande

Kimihiro OKUMURA

Institute for Cosmic Ray (ICRR), UTokyo

ICNFP 2015, August

Super-K detector



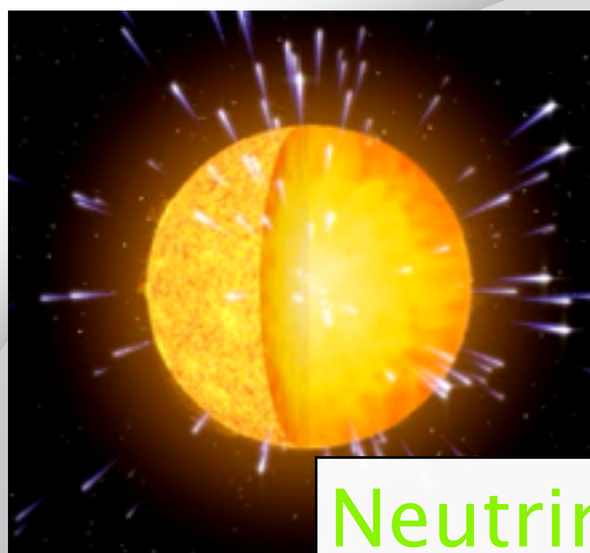
- Water Cherenkov imaging detector
- 1000 m underground in Kamioka mine
- 50 kton volume (fiducial 22.5 kton)
- 11129 20” PMTs in inner detector (ID) for Cherenkov ring imaging
- 1885 8” PMTs for outer detector (OD)

Phase	Period	# of PMTs
SK-I	1996.4 ~ 2001.7	11146 (40%)
SK-II	2002.10 ~ 2005.10	5182 (20%)
SK-III	2006.7 ~ 2008.8	11129 (40%)
SK-IV	2008.9 ~	

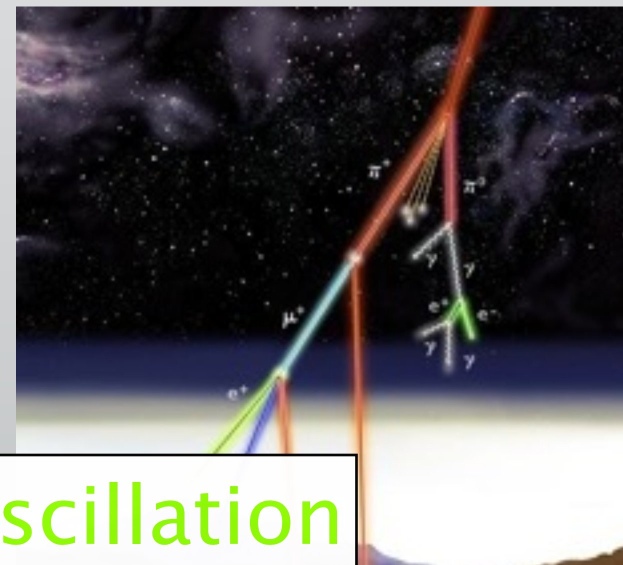
Super-K physics

Multi-purpose detector with rich physics

solar neutrino

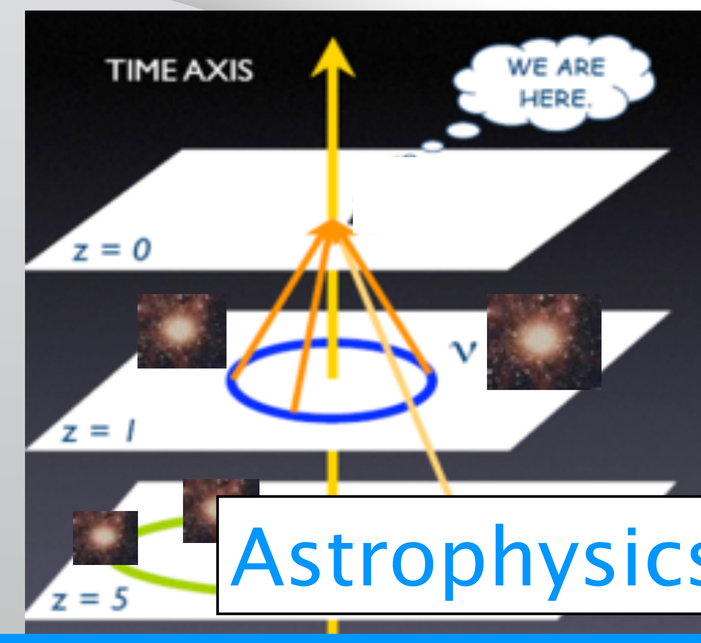


atmospheric ν



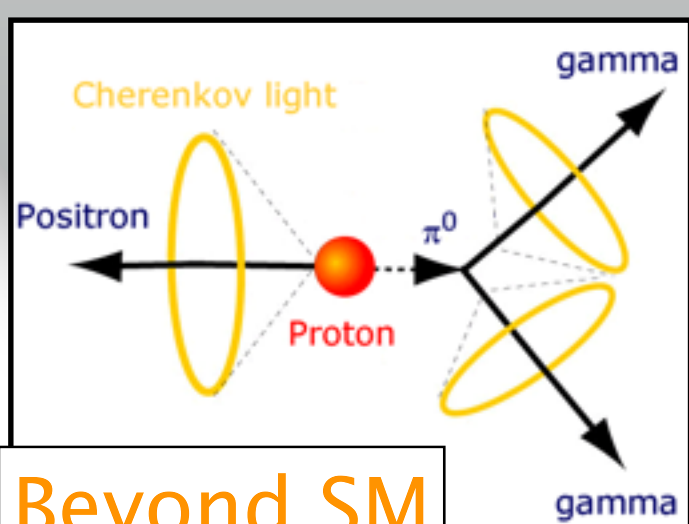
Neutrino oscillation

supernova (relic) ν

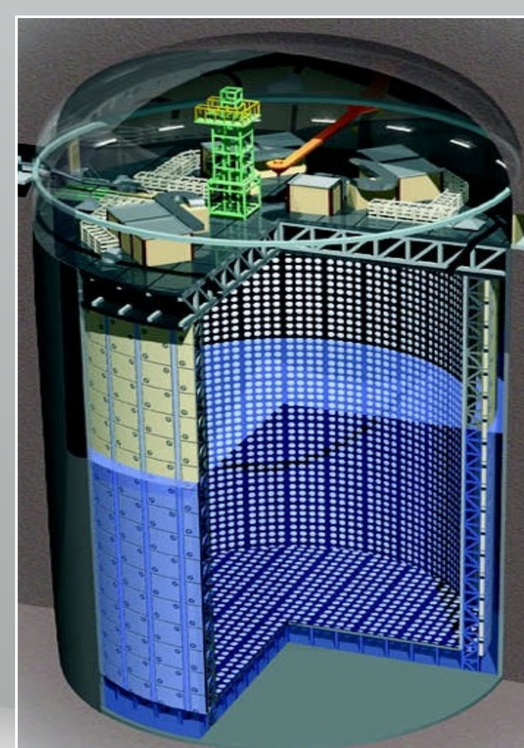


Astrophysics

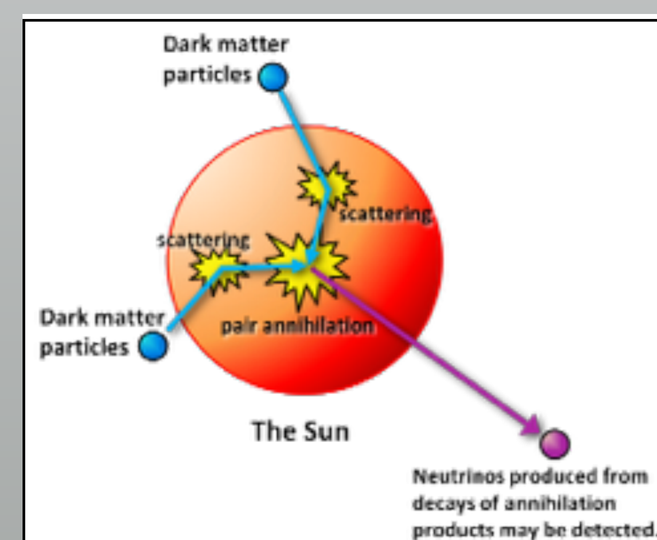
Proton decay



Beyond SM



indirect WIMP search



Also used as far detector of T2K experiment (LBL)

Contents of this talk

- *Neutrino oscillation physics*
  - ✳ Atmospheric neutrino
  - ✳ Solar neutrino
- *Dark matter*
  - ✳ indirect WIMP search from Sun
- *News*
  - ✳ SuperK-Gd project

Neutrino oscillation

flavor state — PMNS matrix — mass state

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 1 & 0\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

+ Majonara phas

atmospheric, LBL

$$\Delta m^2_{32} = (2.44 \pm 0.06) \times 10^{-3}\mathrm{eV}^2$$
$$\sin^2\theta_{23} = 0.437^{+0.033}_{-0.023}$$

Reactor, LBL

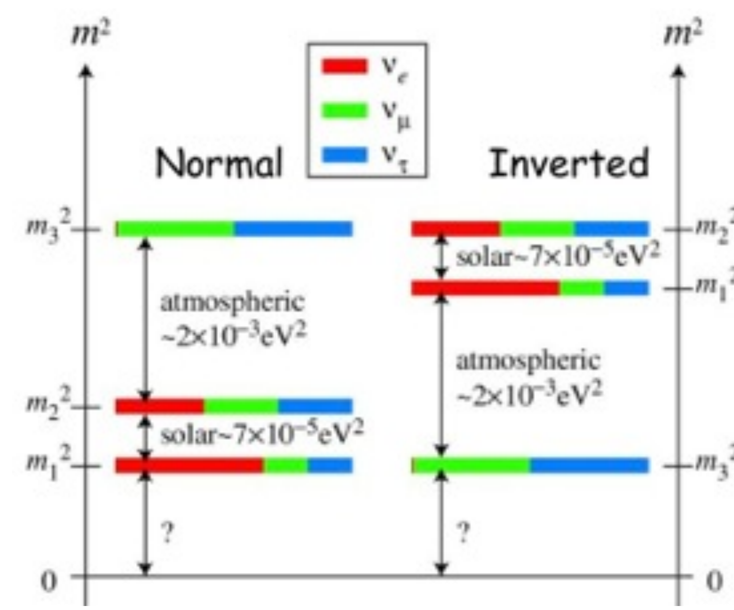
$$\sin^2\theta_{13} = 0.0234^{+0.0020}_{-0.0019}$$

solar, KamLAND

$$\Delta m^2_{21} = 7.54^{+0.26}_{-0.22} \times 10^{-5}\mathrm{eV}^2$$
$$\sin^2\theta_{12} = 0.308 \pm 0.017$$

- All mass splitting and mixing angles are measured by solar/atmos./ reactor/ LBL
- Still unknown:
  - ✳ CP violation phase (δ_{CP})
  - ✳ Mass hierarchy (Normal or Inverted)
  - ✳ θ_{23} octant ($\theta_{23} > \pi/4$ or $\theta_{23} < \pi/4$)

Mass hierarchy (MH):



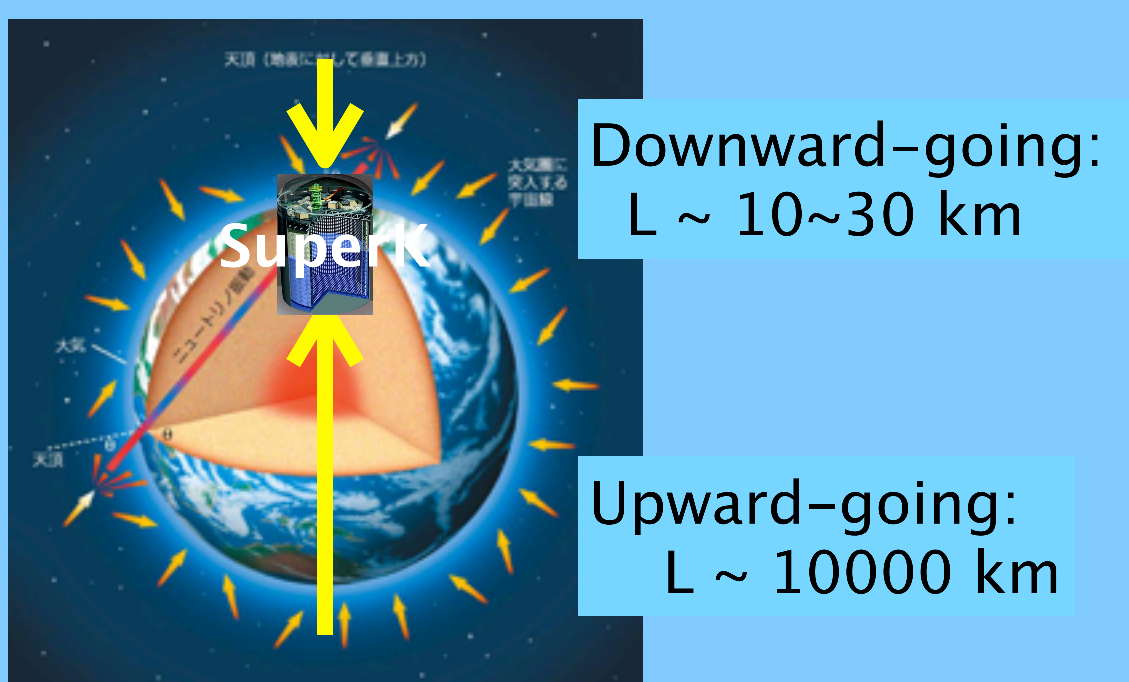
Normal ($\Delta m^2_{32}>0$)

Inverted ($\Delta m^2_{32}<0$)

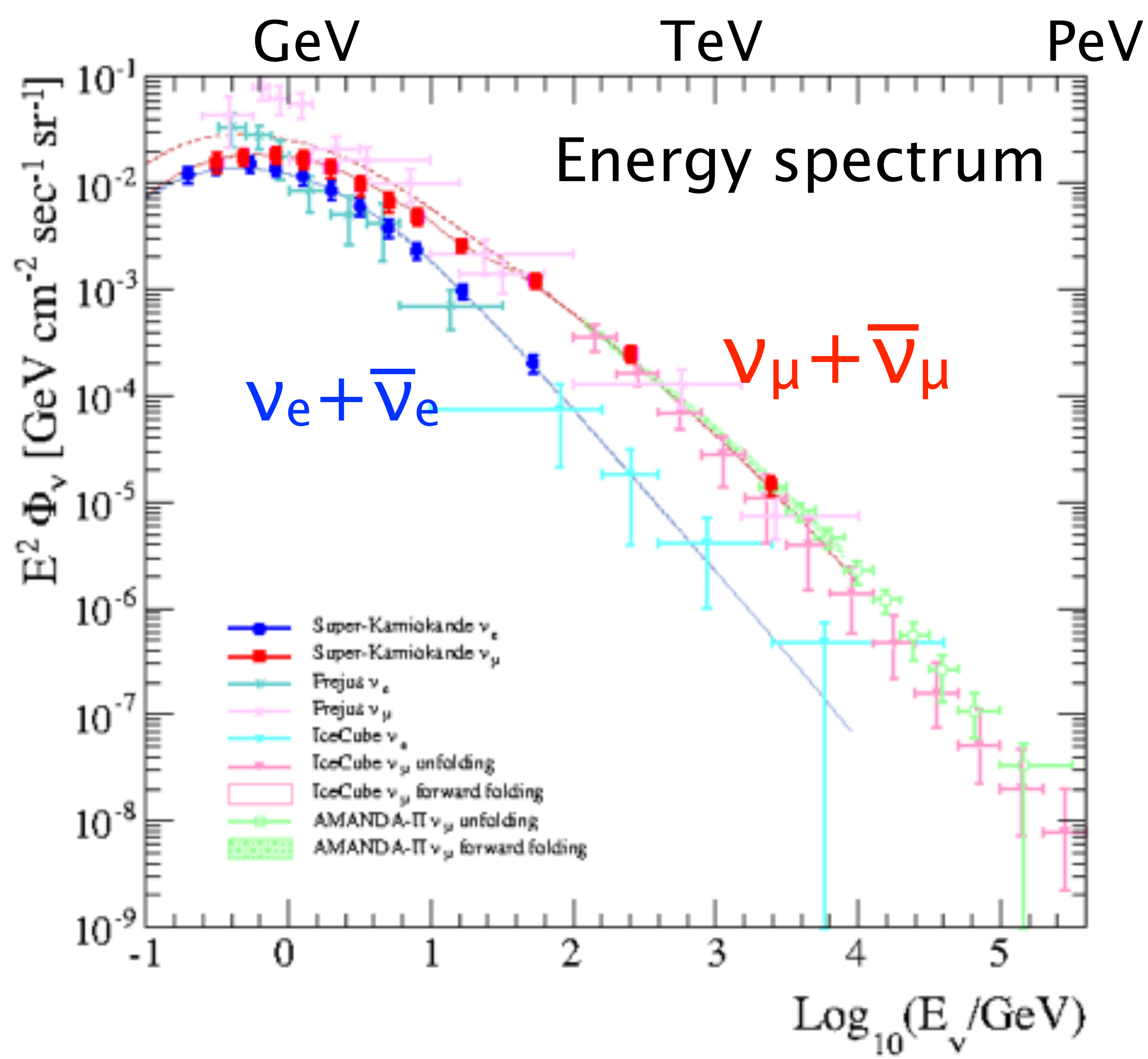
Atmospheric neutrino

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\quad \hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\quad \hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$$

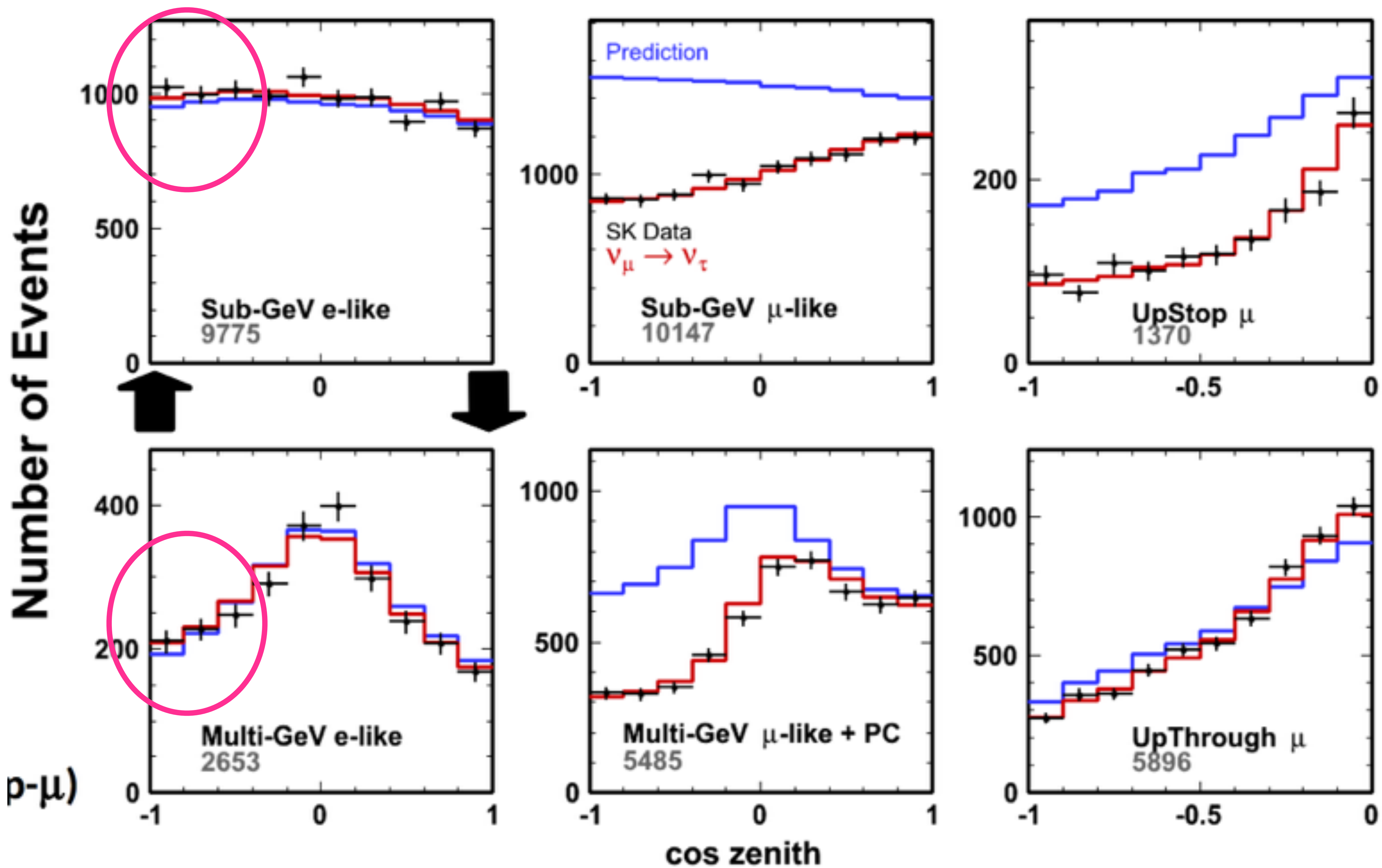


- Decay products from cosmic ray interaction with atmosphere
- Energy ranges from sub-GeV over TeV
- Atm. ν's are suitable for oscillation study

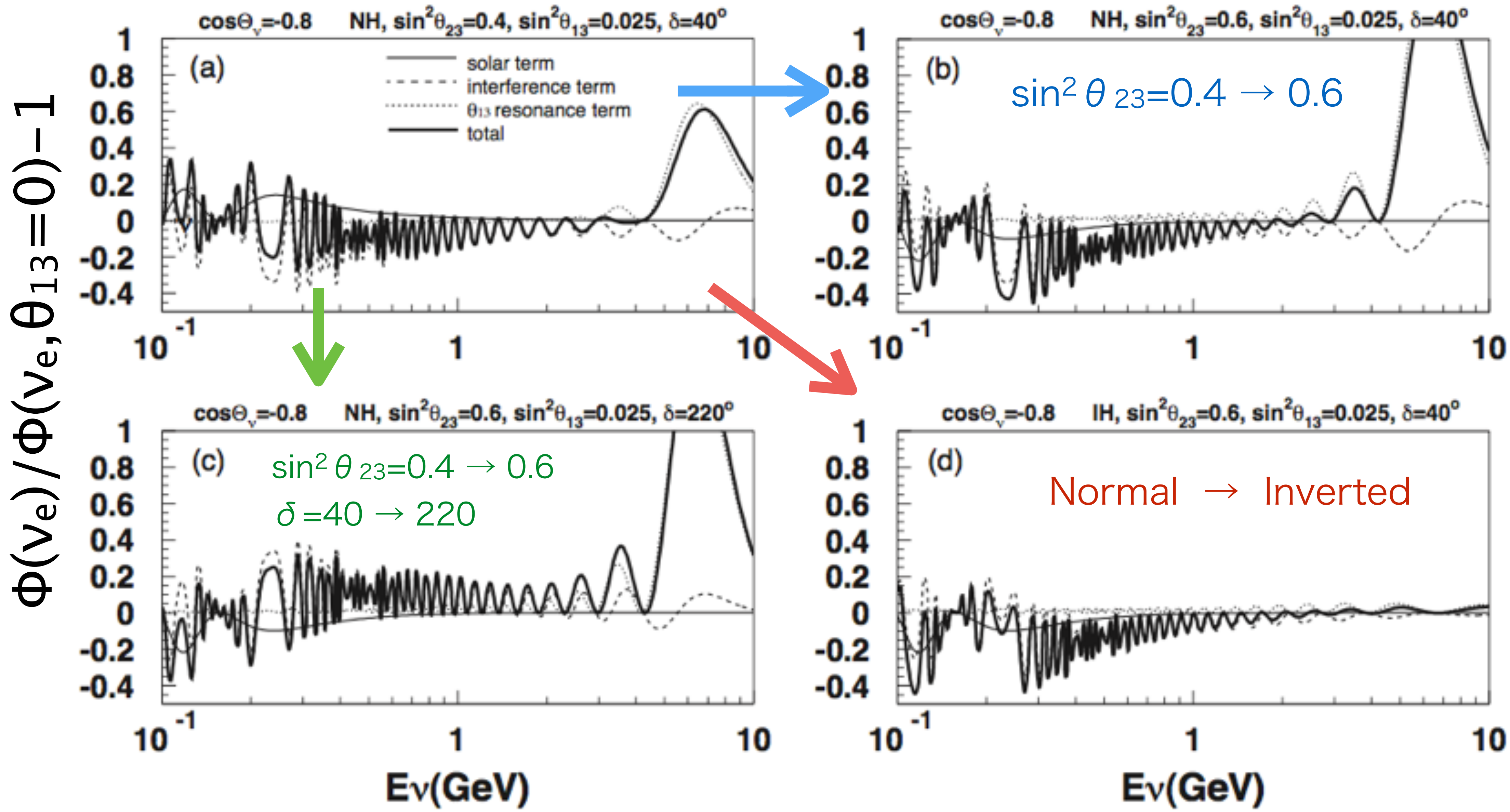


Super-K atmospheric sample

- $\nu_\mu \to \nu_\tau$ is dominant, but sensitive to other osc. parameters
- Interested in upward $\nu_\mu \to \nu_e$ containing sub-dominant effect



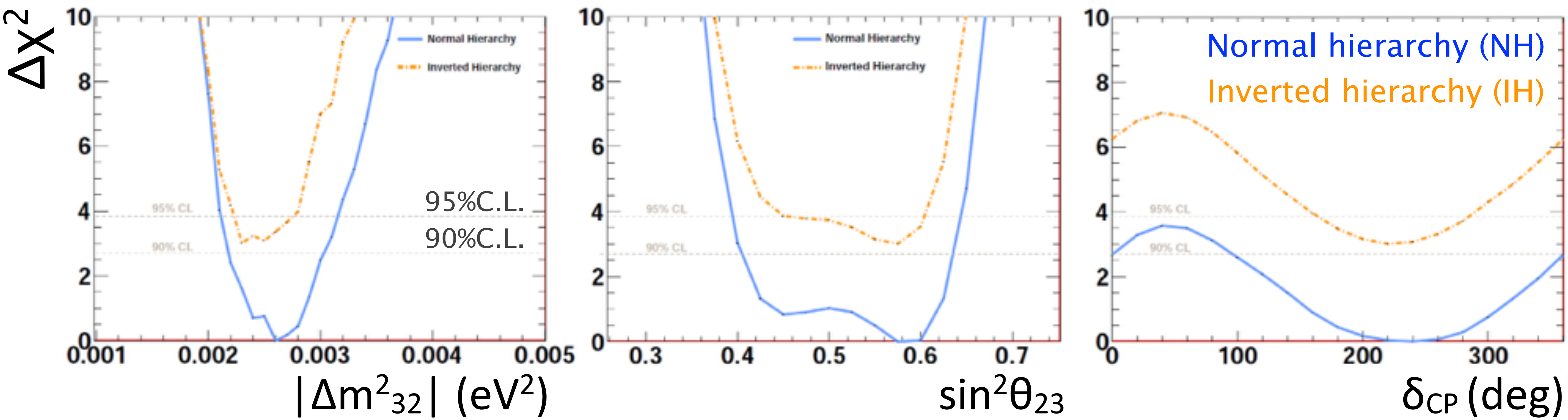
$\nu_\mu \to \nu_e$ effect in atmospheric ν



- Multi-GeV: resonant-like peak due to matter effect in Earth
  - appear in ether ν or $\bar{\nu}$, and depends on mass hierarchy
  - θ_{23} octant changes size of resonance peak
- sub-GeV : flux normalization changes by CP phase δ_{CP}

Oscillation fit result

- χ^2 scan for δ_{CP}, θ_{23}, Δm^2_{32}, MH. (θ_{13} is fixed for reactor).
- SuperK data favored normal hierarchy, but not significant (χ^2_{NH}-χ^2_{IH}= -3.0)

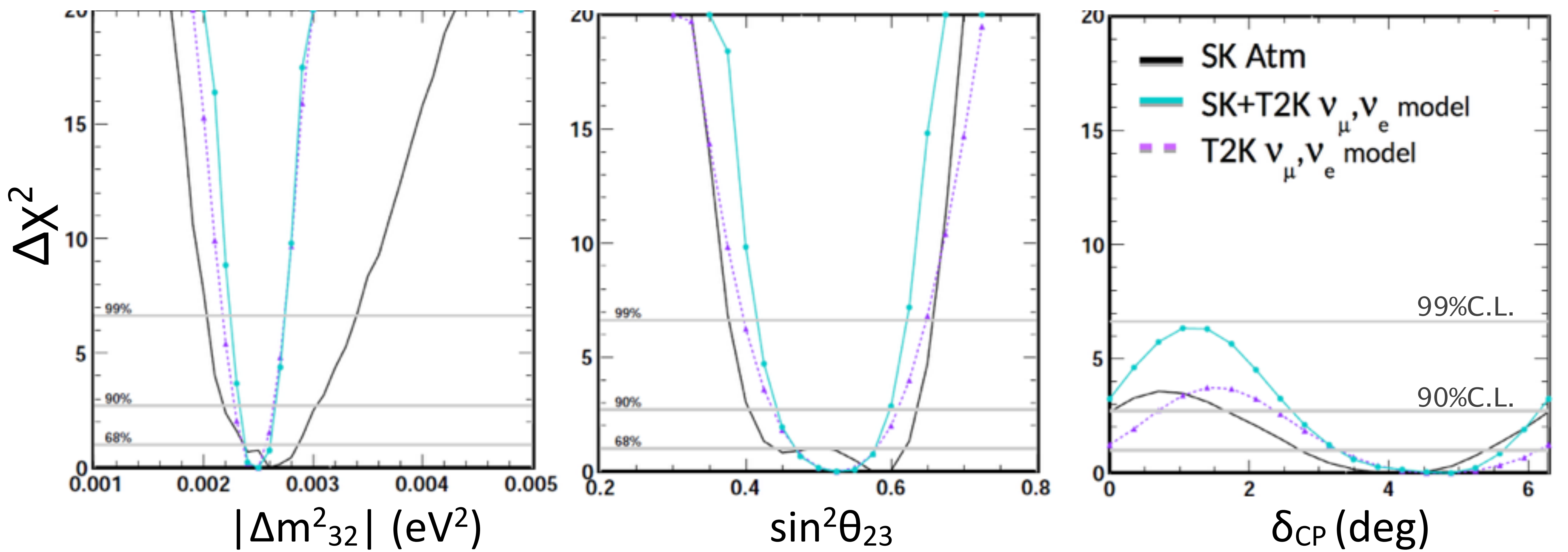


Fit (517dof)	χ^2	$\sin^2\theta_{13}$ (fix)	δ_{CP}	$\sin^2\theta_{23}$	Δm^2_{32}
Normal	582.4	0.0238	240	0.575	2.6×10^{-3}
Inverted	585.4	0.0238	220	0.575	2.3×10^{-3}

Preliminary

Fit with T2K published data (NH)

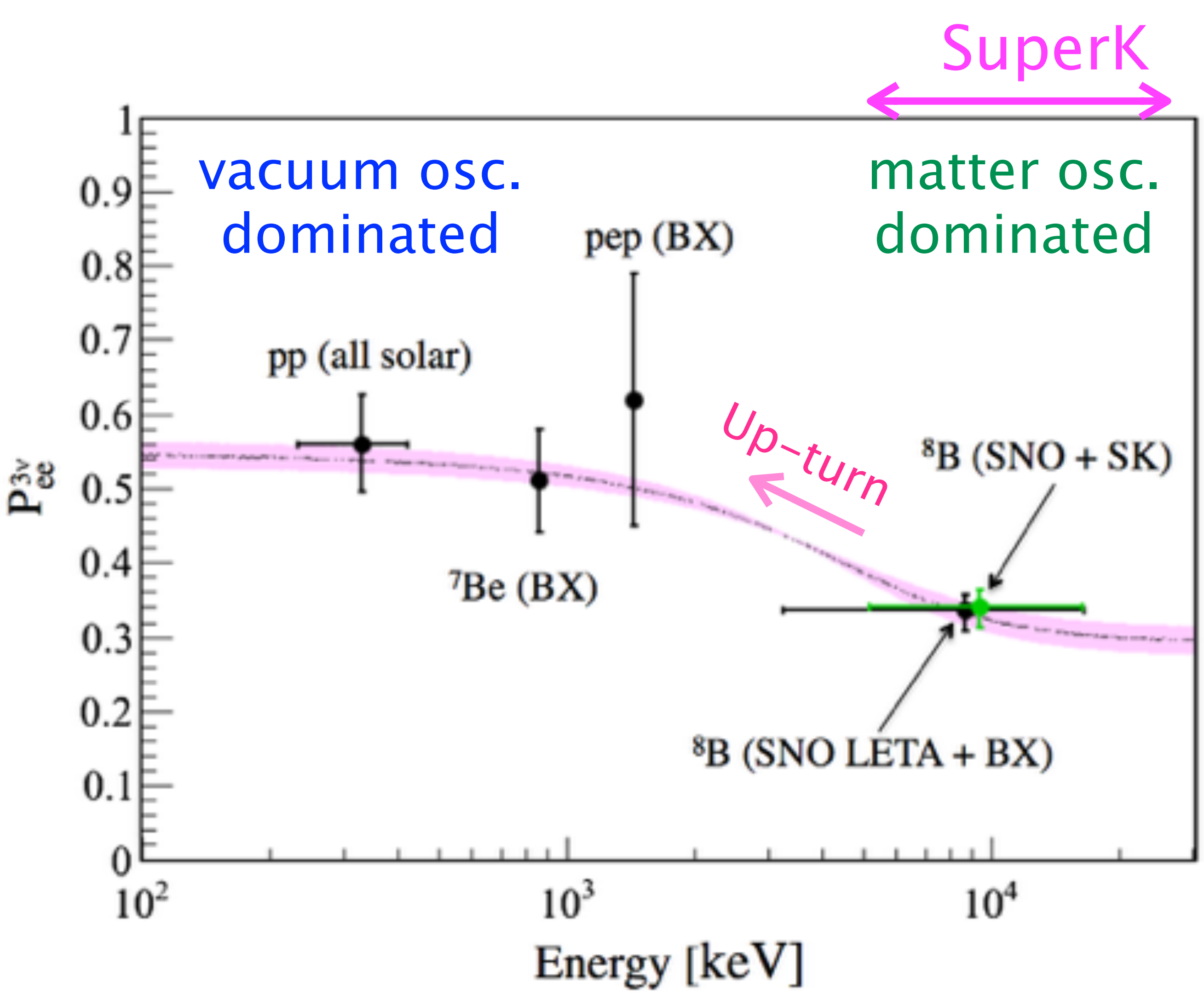
- Introduce constraint from modeled T2K data for better sensitivity
- $\chi^2_{NH}-\chi^2_{IH}$= -3.2 (SK only : -3.0)
- SK and T2K favors δ_{CP}~-π/2, but CP conservation ($\sin\delta_{CP}$=0) allowed

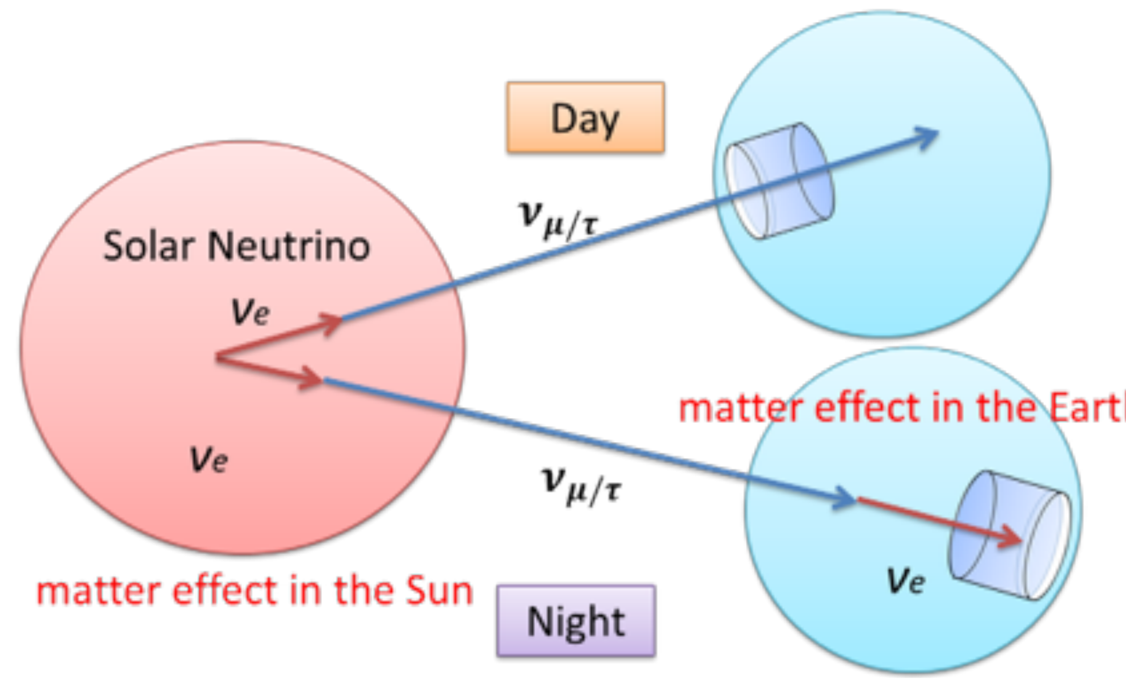


Fit (585dof)	χ^2	$\sin^2\theta_{13}$ (fix)	δ_{CP}	$\sin^2\theta_{23}$	Δm^2_{32}
Normal	651.5	0.0238	280	0.525	2.5×10^{-3}
Inverted	654.7	0.0238	240	0.550	2.4×10^{-3}

Physics motivation of solar neutrino

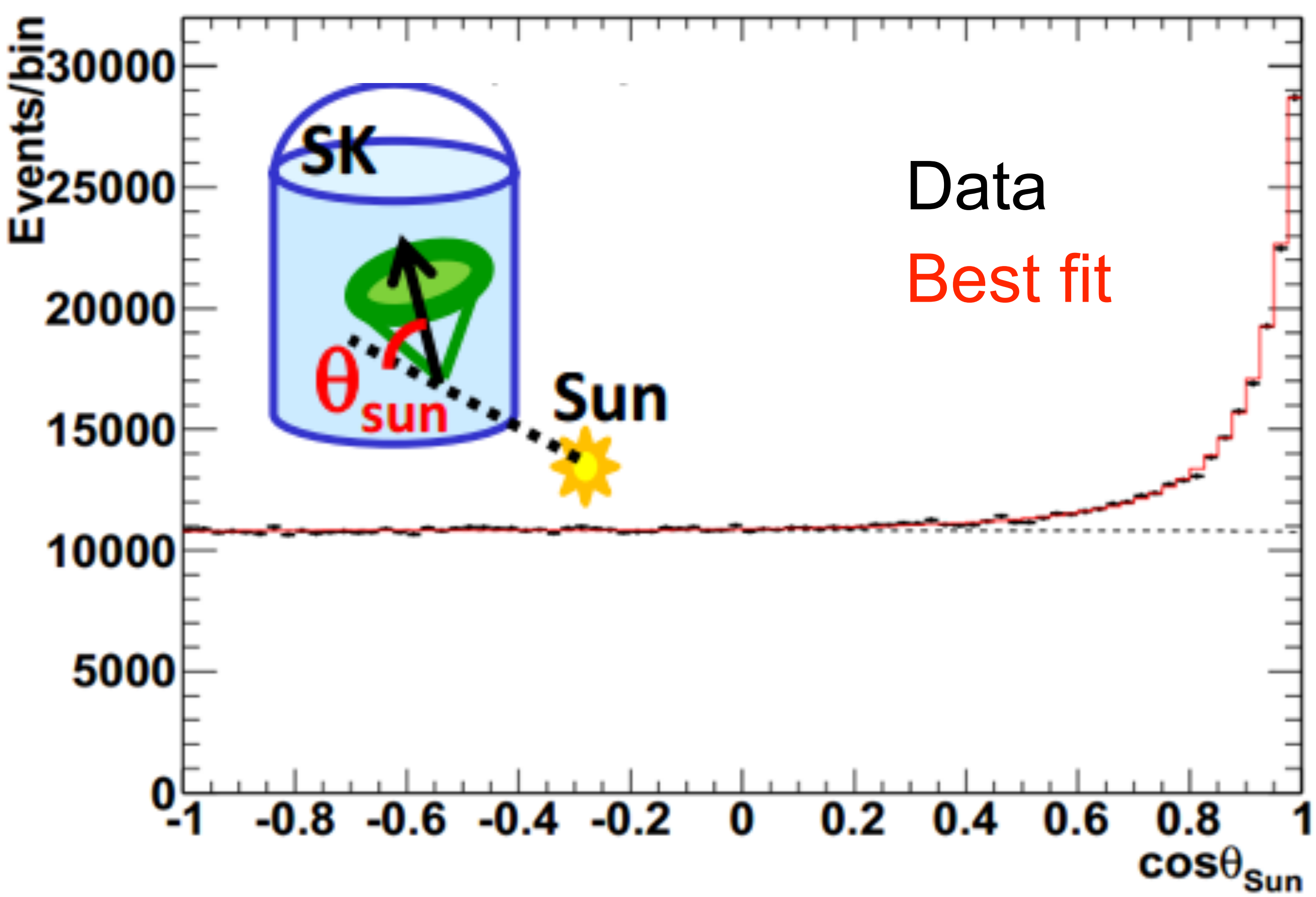
1. Spectrum distortion
   - "Up-turn" by MSW oscillation is expected around 3MeV
2. Day / Night flux asymmetry
   - Regeneration of ν_e in Earth's matter effect will enhance night flux

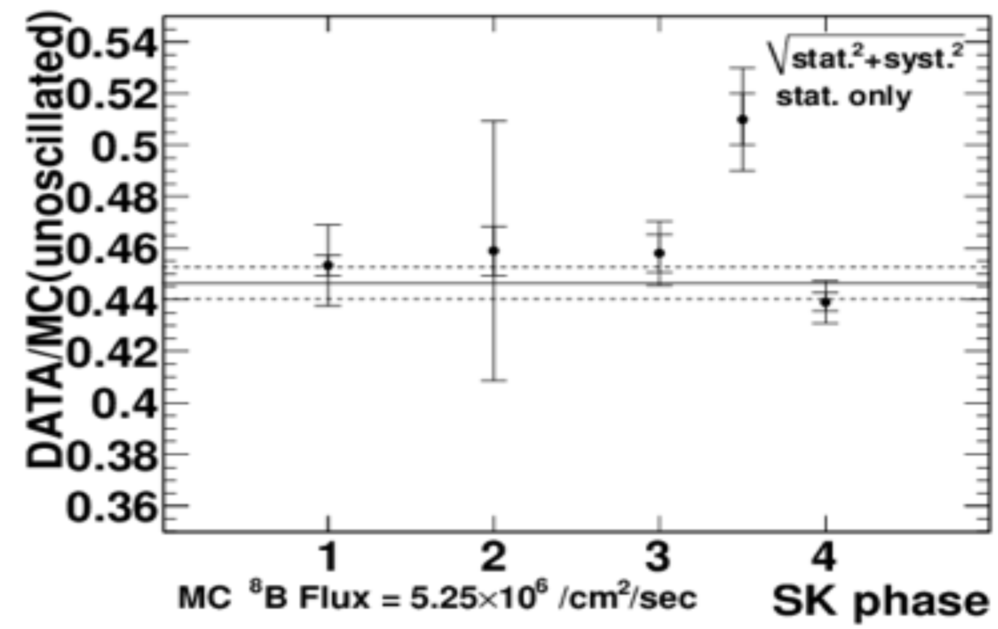




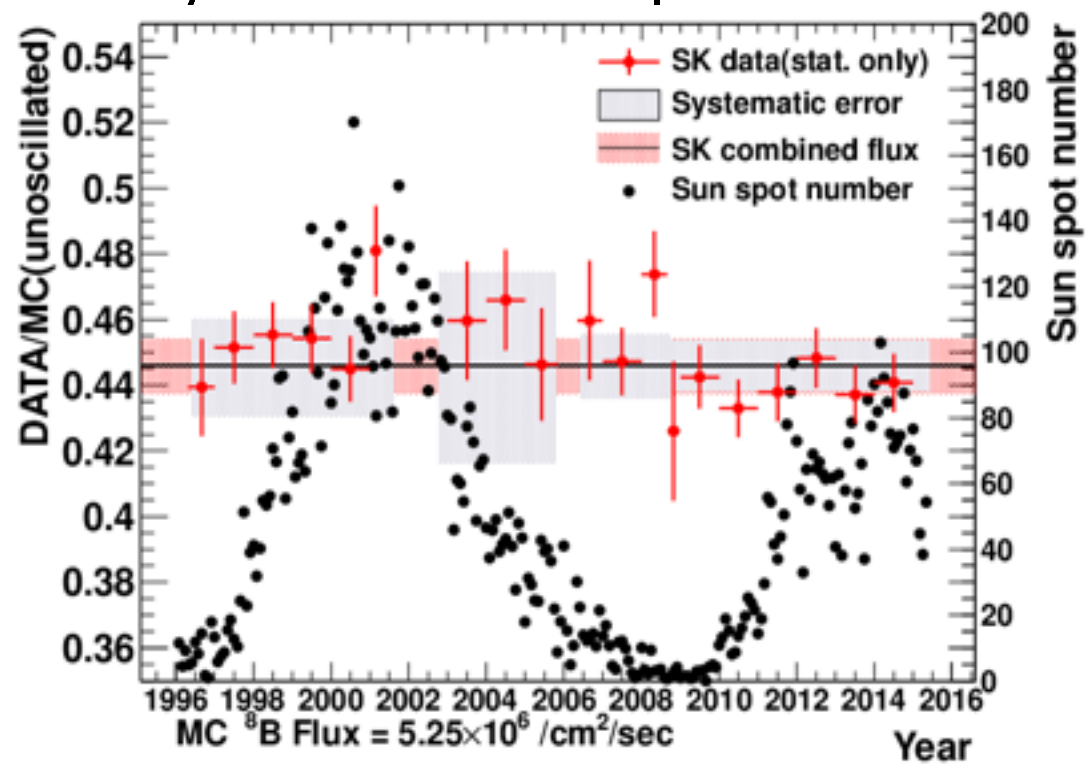
$$A_{\mathrm{DN}} = \frac{\Psi_{\mathrm{day}} - \Psi_{\mathrm{night}}}{(\Psi_{\mathrm{day}} + \Psi_{\mathrm{night}})/2}$$

Observed ^{8}B solar neutrino flux





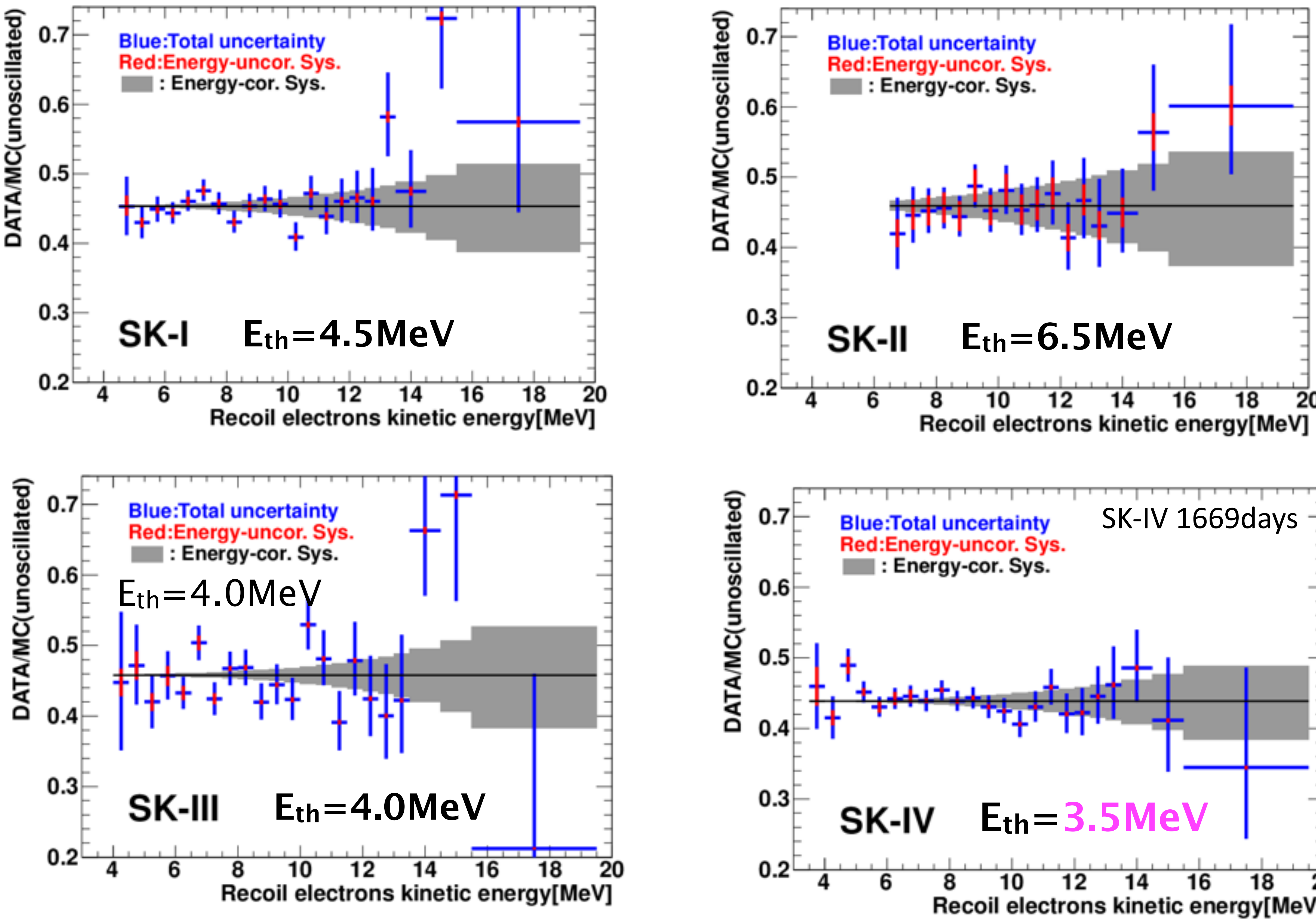
Yearly flux with sun spot number



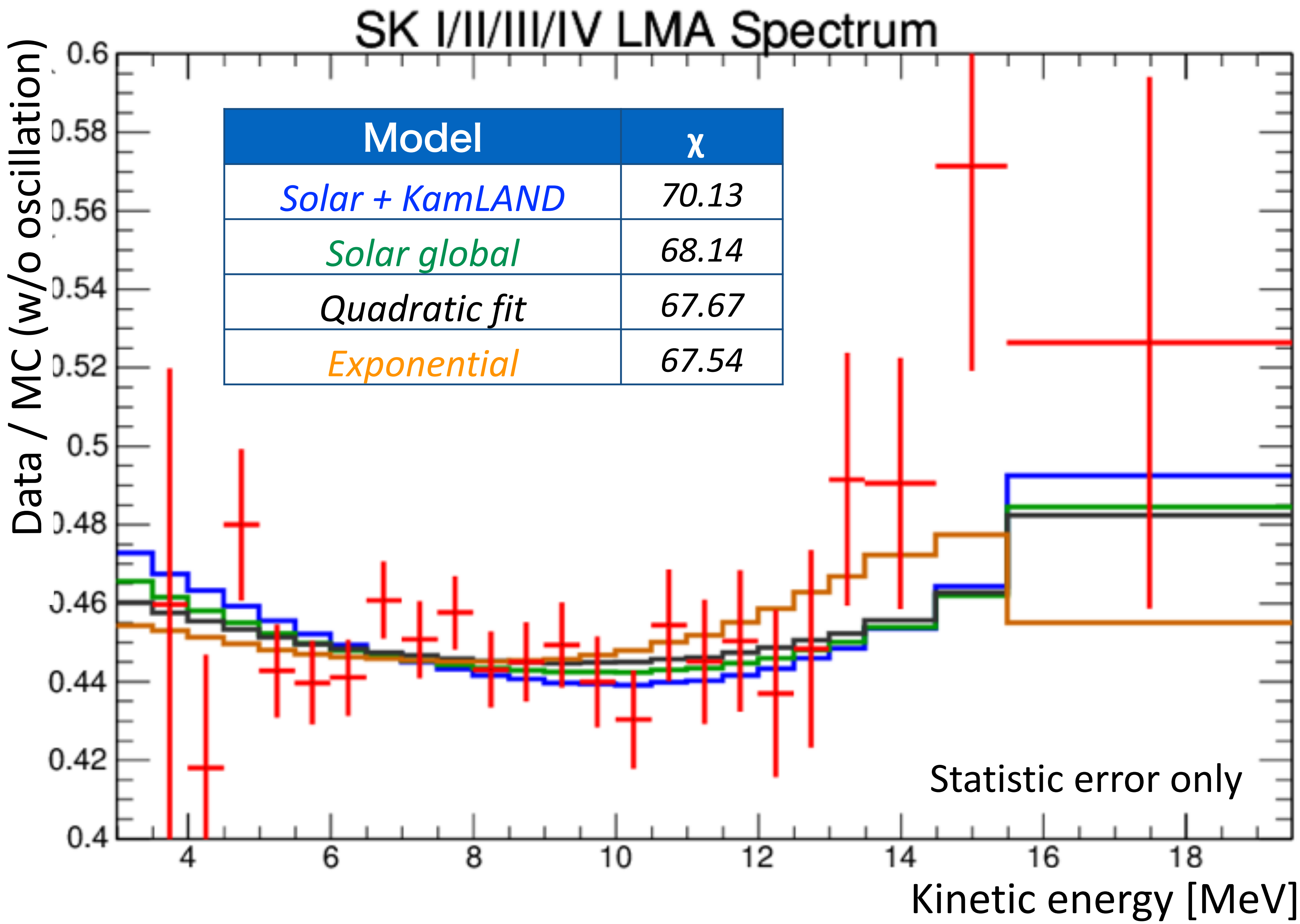
- ~77 k solar events in SK I-IV
- Data/MC = 0.4459 ± 0.0084 (stat.+syst.)
- Measurement consistent within uncertainties among SuperK phases
- No correlation seen with sun spot number (p-value=0.786)

Preliminary

Recoil electron spectrum



SK I-IV combined spectrum

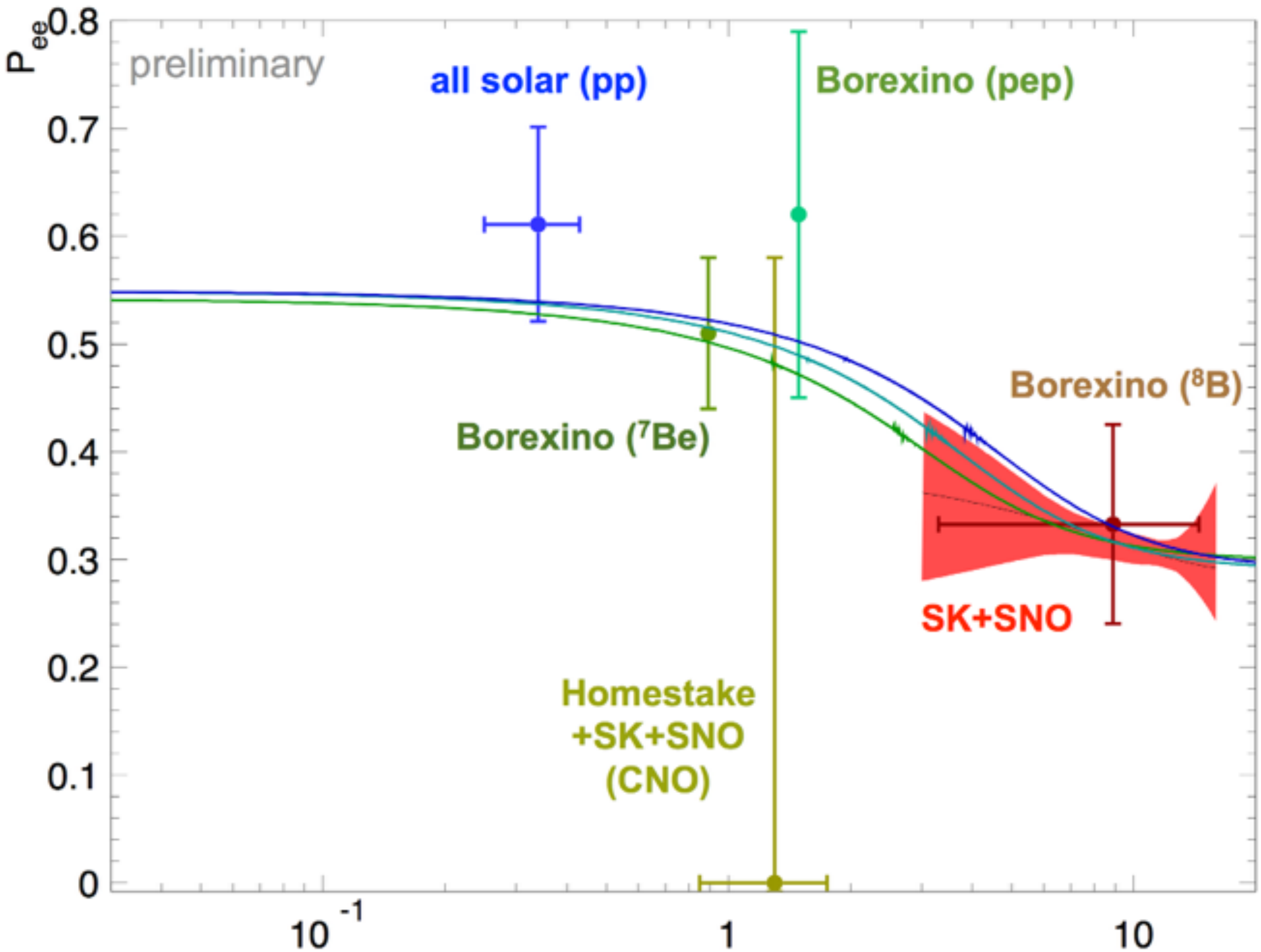


Model	χ
Solar + KamLAND	*70.13*
Solar global	*68.14*
Quadratic fit	*67.67*
Exponential	*67.54*

- MSW is slightly disfavored (~1.7σ for solar+KL, ~1.0σ for solar global)
- Still spectral "up-turn" is not observable

Preliminary

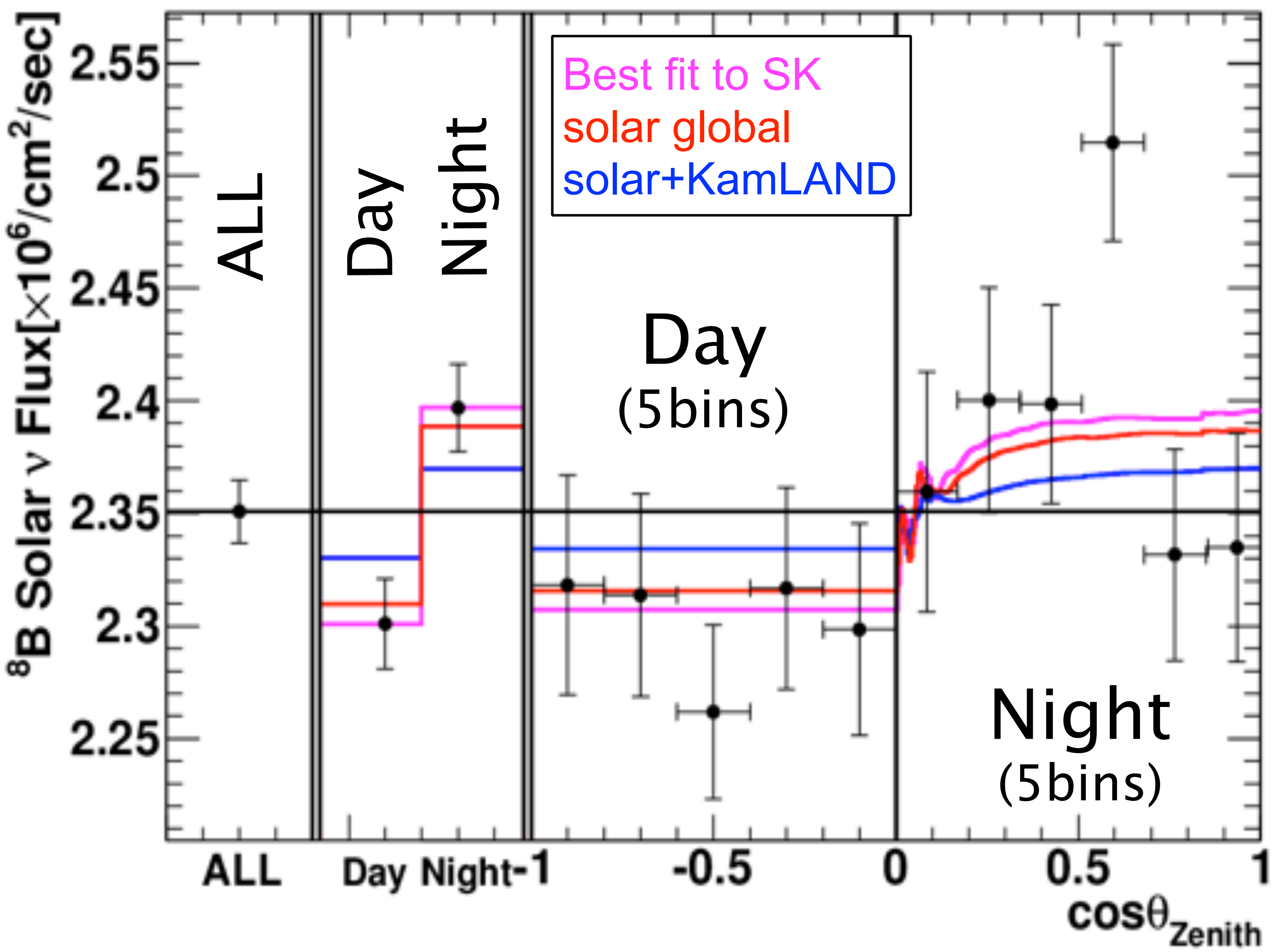
SK I-IV combined spectrum

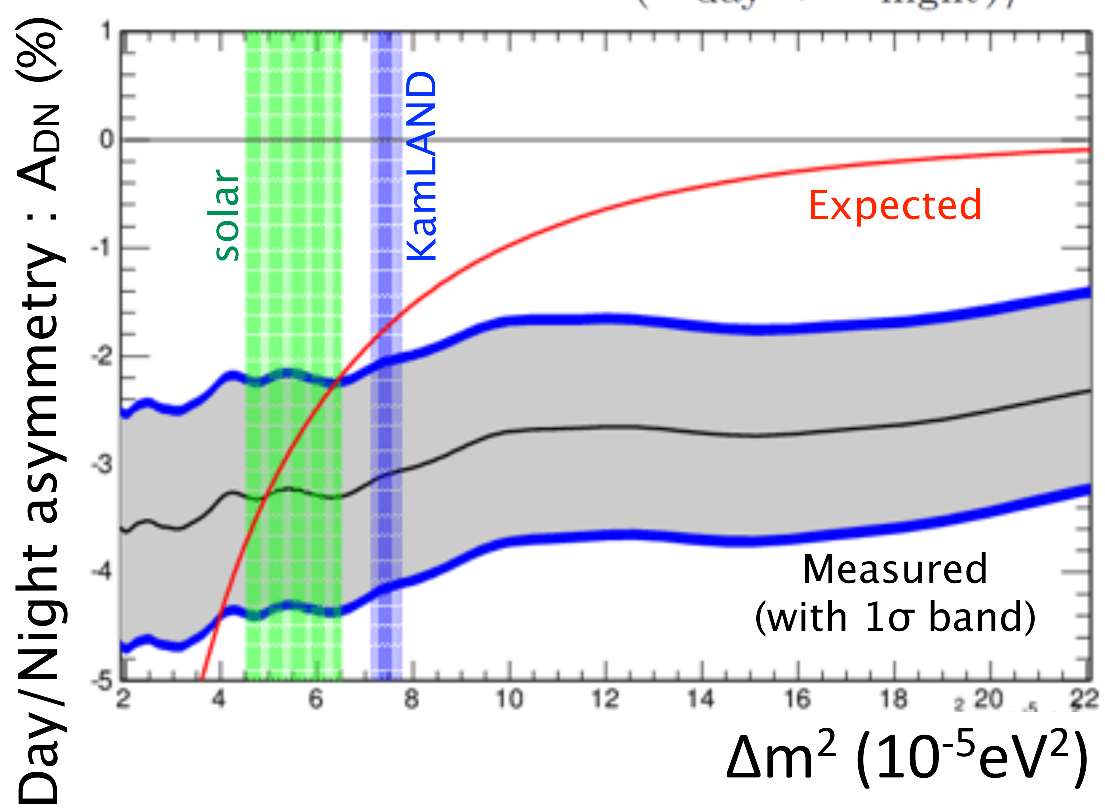


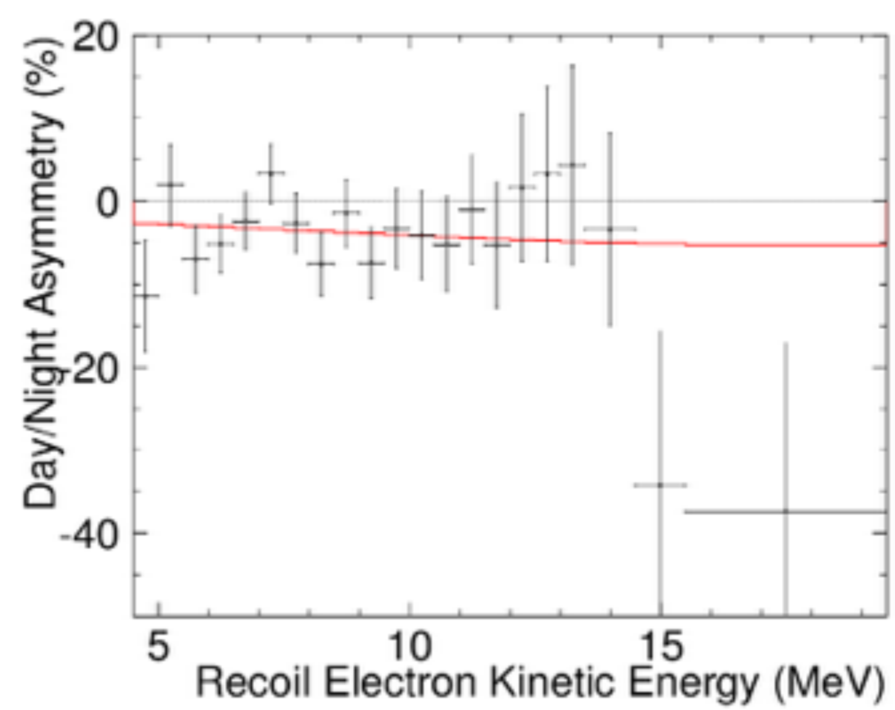
- MSW is slightly disfavored (~1.7σ for solar+KL, ~1.0σ for solar global)
- Still spectral “up-turn” is not observable

Day/Night flux asymmetry

$$A_{DN} = \frac{\Psi_{day} - \Psi_{night}}{(\Psi_{day} + \Psi_{night})/2}$$



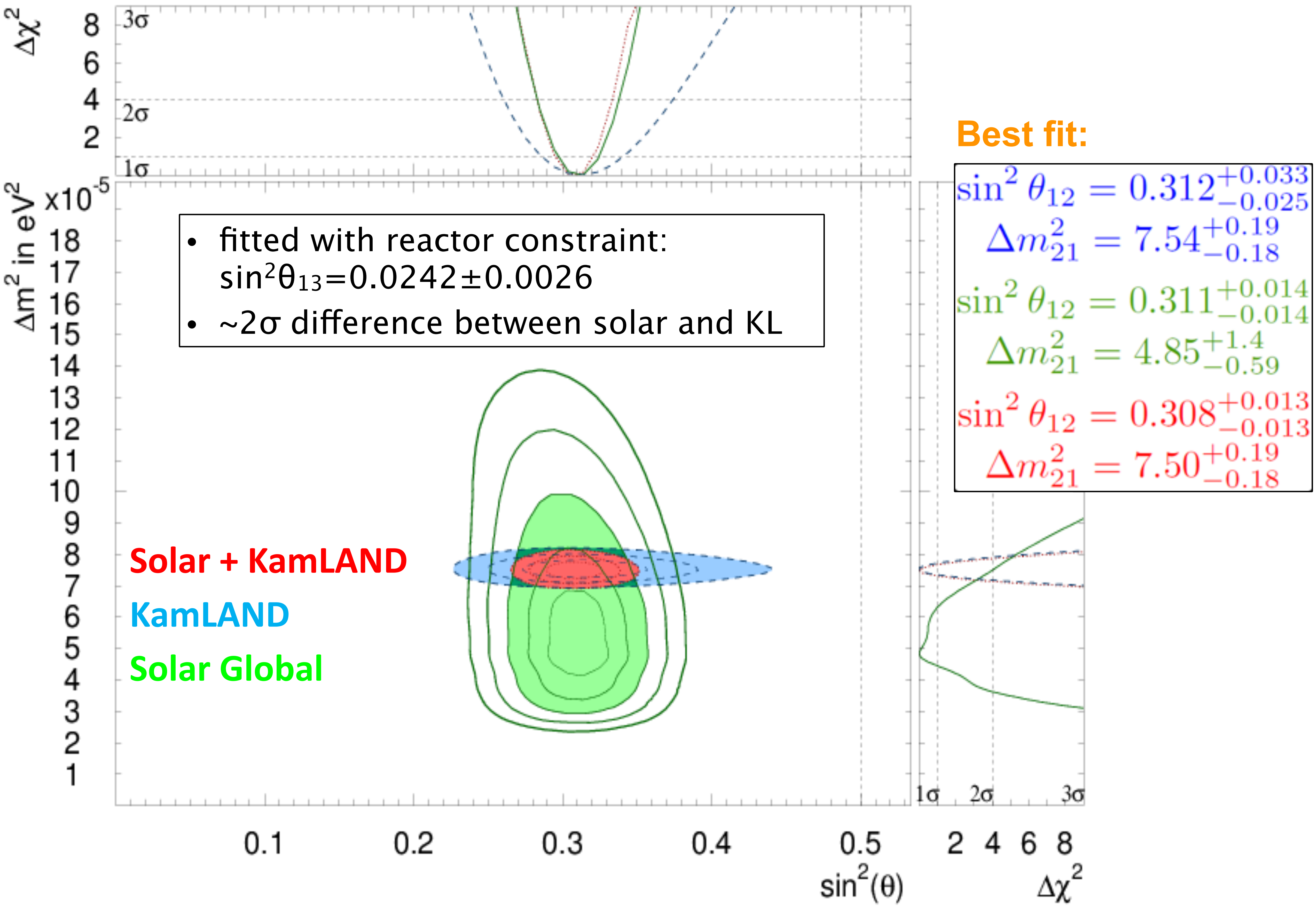




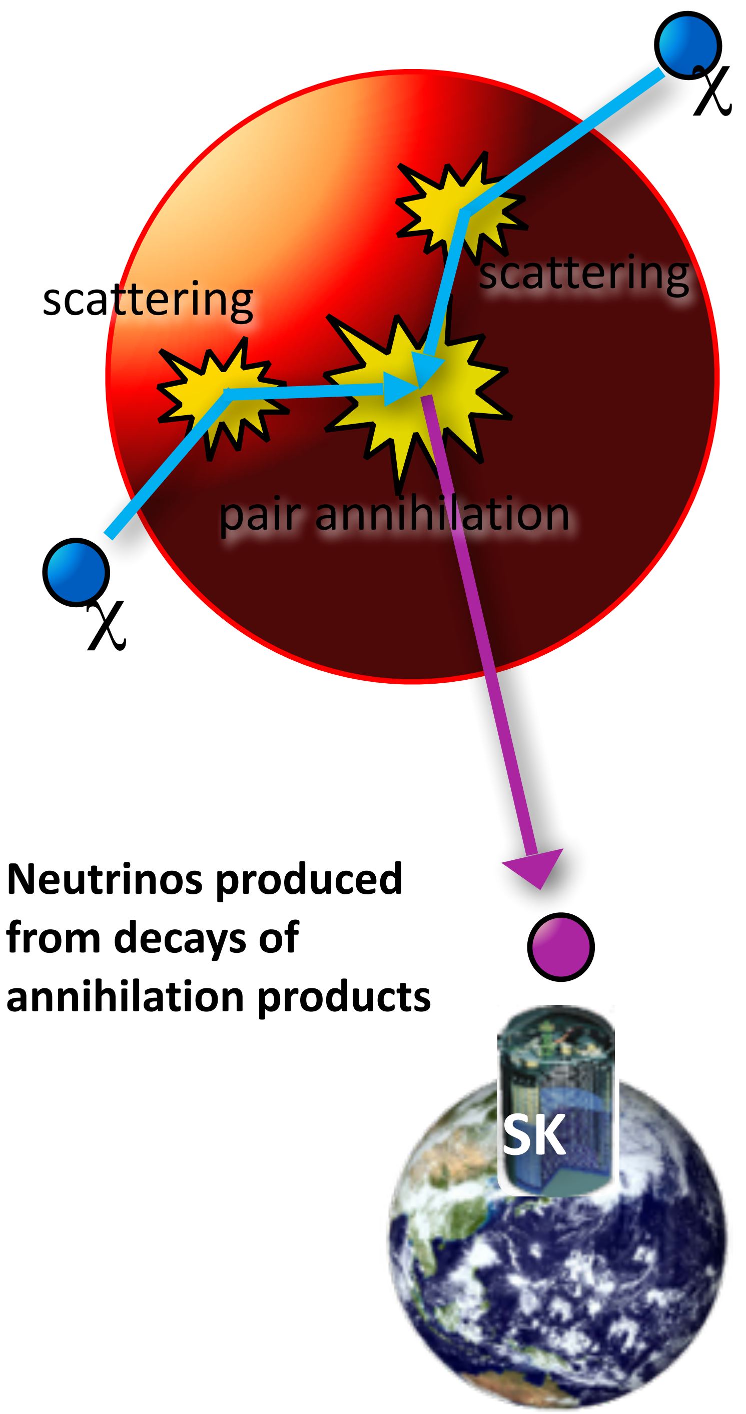
- ~3% higher flux expected for night
- ~3σ difference seen btwn day and night
- Direct indication of matter effect in Earth
- Better agreement for solar Δm^2

Preliminary

Status of solar / KL oscillation fit

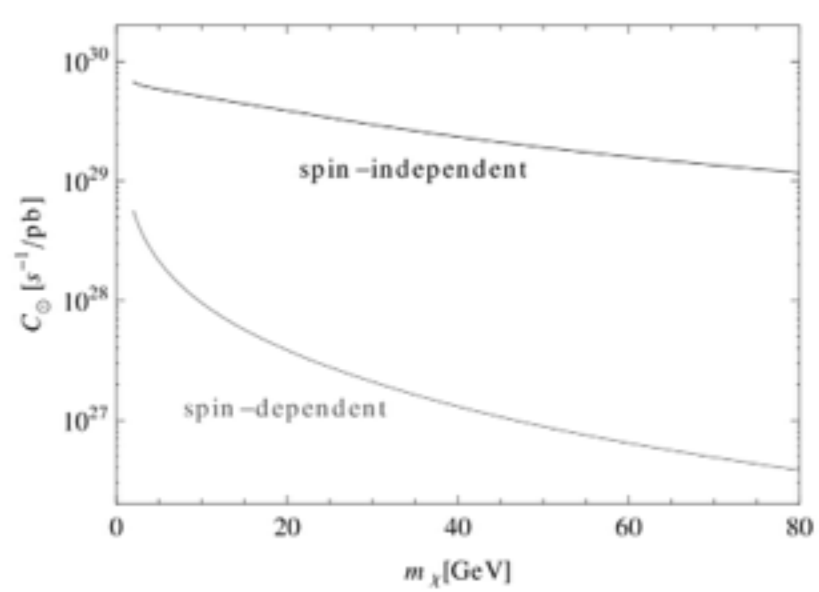


Solar WIMP search by SuperK

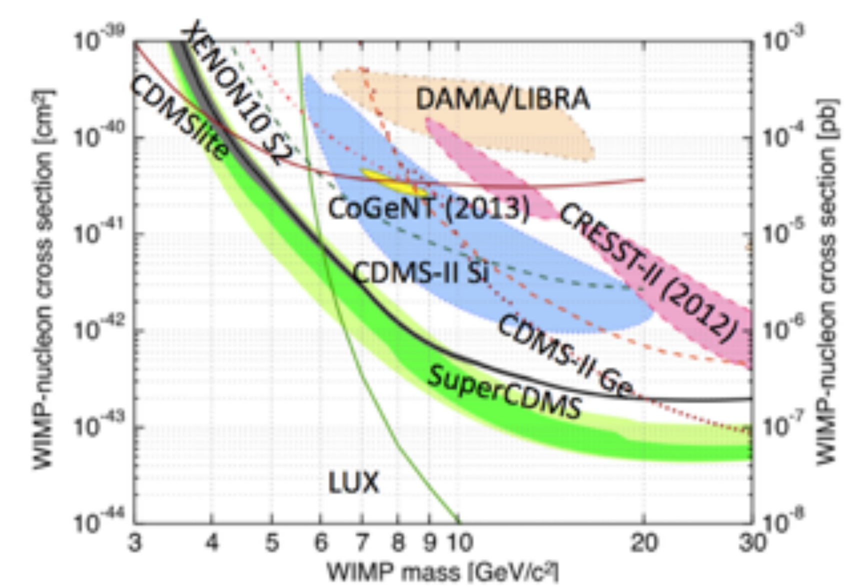


- DM, trapped in the center of Sun, could annihilate and produce neutrinos via $\chi\chi \rightarrow \tau^{+}\tau^{-}/b\bar{b}/W^{+}W^{-}$
- Tighter limits on spin-independent (SD) scattering due to hydrogen-rich composition of Sun
- Recent direct DM experiments report event excess / annual modulation below 30 GeV/c^2

Capture rate inside the Sun

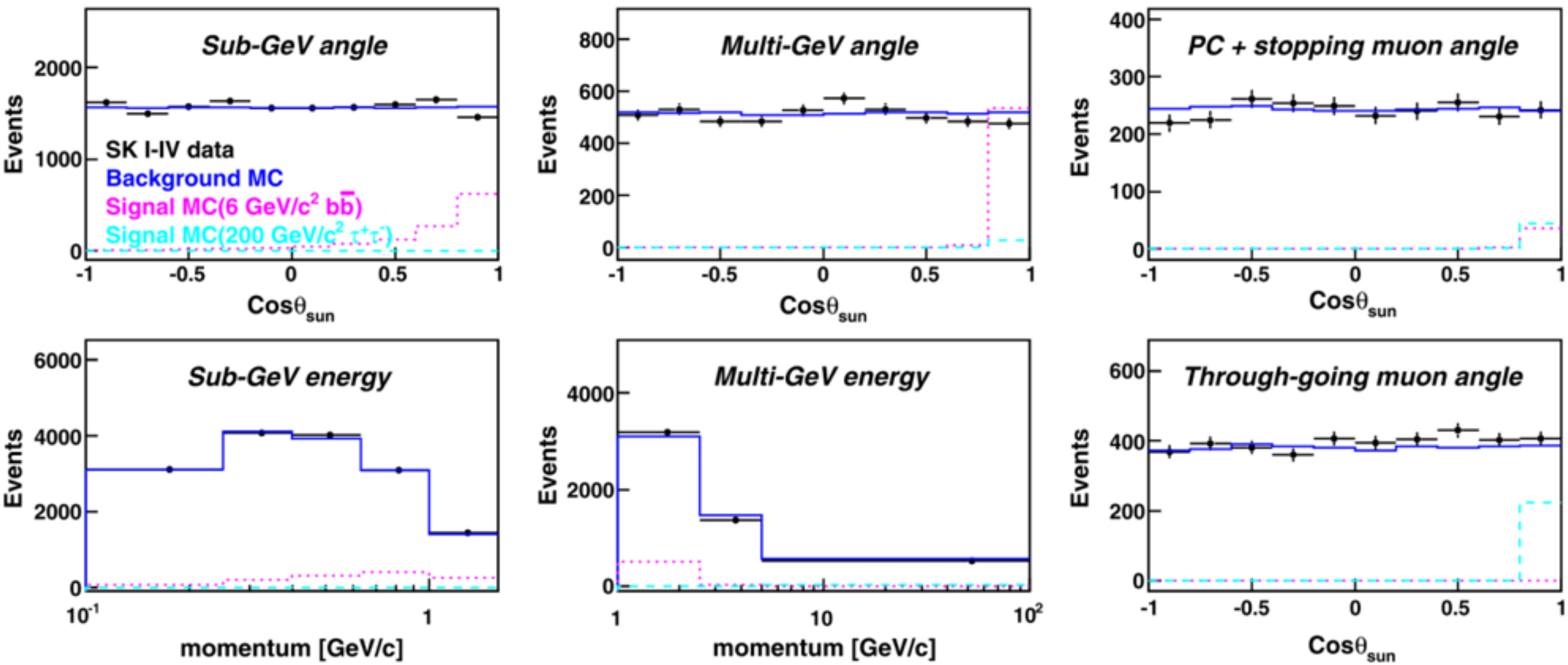


Allowed regions and limits from several experiments (SI interaction)



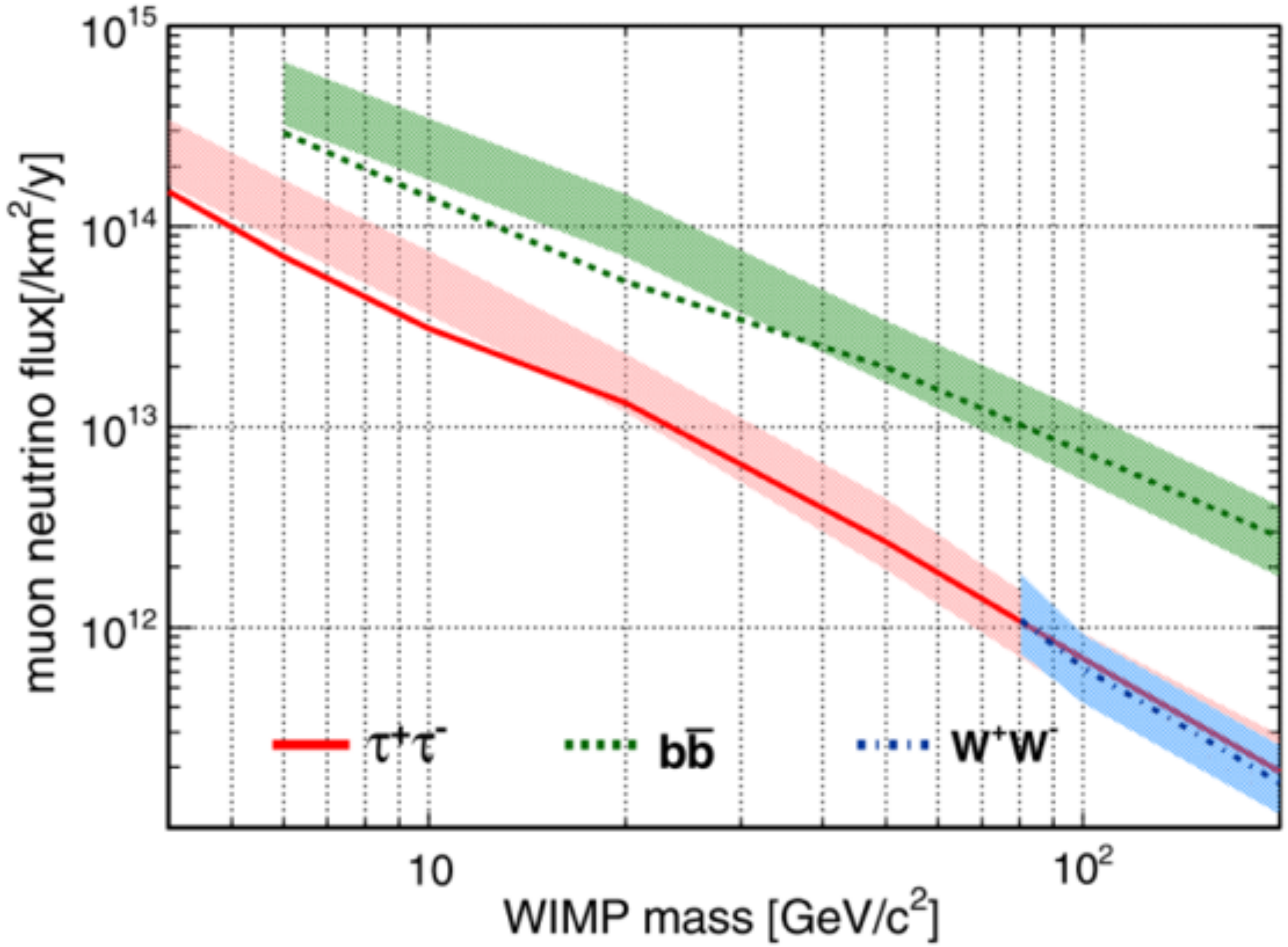
Super-K WIMP analysis

- SuperK’s sensitivity to GeV energies are suitable for light WIMP search
- WIMP signal has angular correlations with Sun’s direction



Limit on neutrino flux from WIMP annihilation

Upper limit on muon neutrino flux



- Simulate $\chi\chi$ —> $\tau^+\tau^-/b\bar{b}/W^+W^-$ for 4~200 GeV/c^2 and apply fit to data
- No significant excess are seen. upper limit (90% C.L.) was set on neutrino flux
- DarkSUSY 5.0.6 is utilized to convert to WIMP-proton cross sections

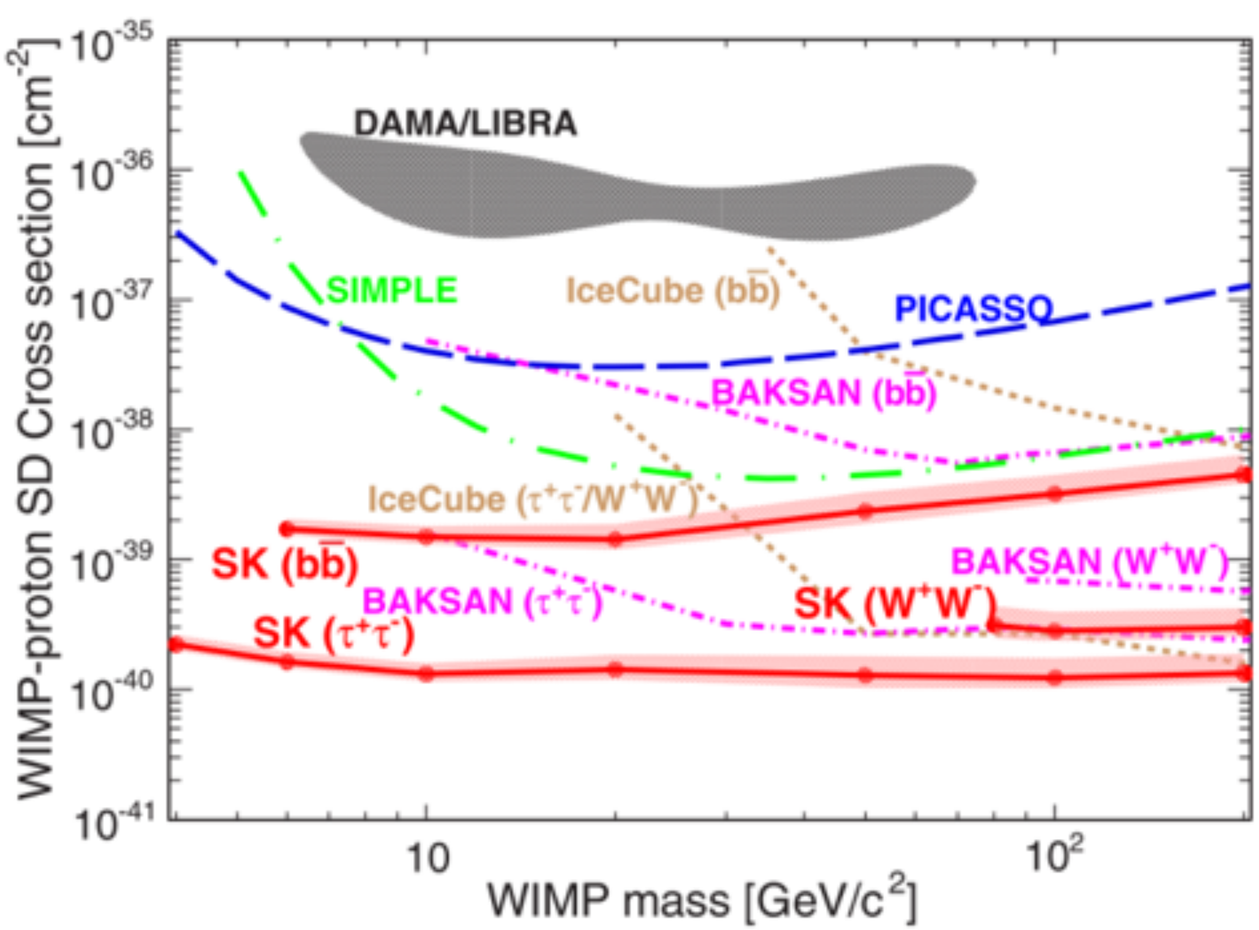
Assumptions:
- SI or SD interaction
- Standard DM halo
- Mono channel annihilation (bb, tt, WW)
- BS2005-OP model of solar composition
- Equilibrium btwn capture and annihilation

PRL 114, 143301 (2015)

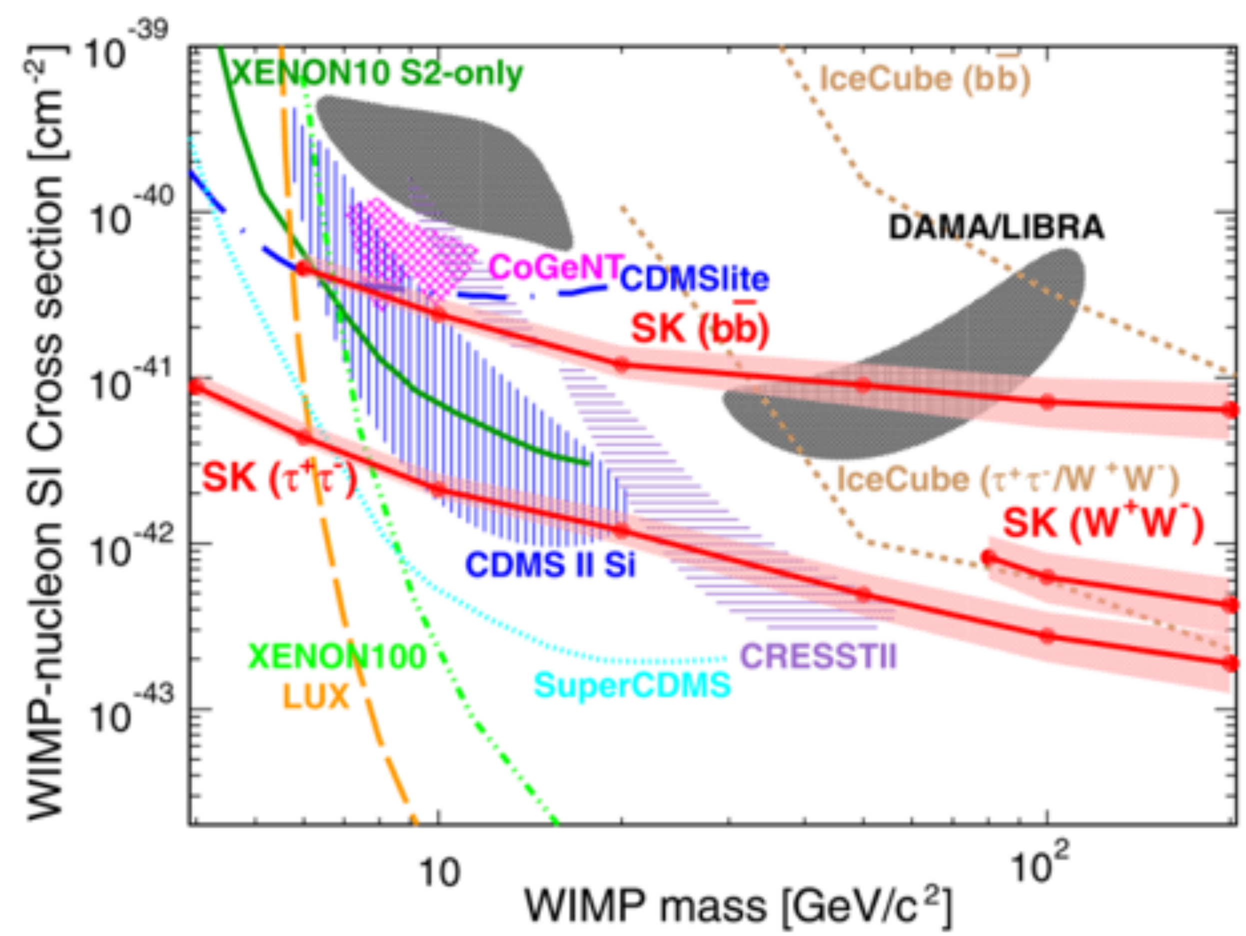
90% C.L. limit on SD/SI cross section

- SD interaction: current best limits were set below 200 GeV/c2 even for the softest (bb) channel
- SI interaction: some fraction of allowed regions are ruled out

SD interaction



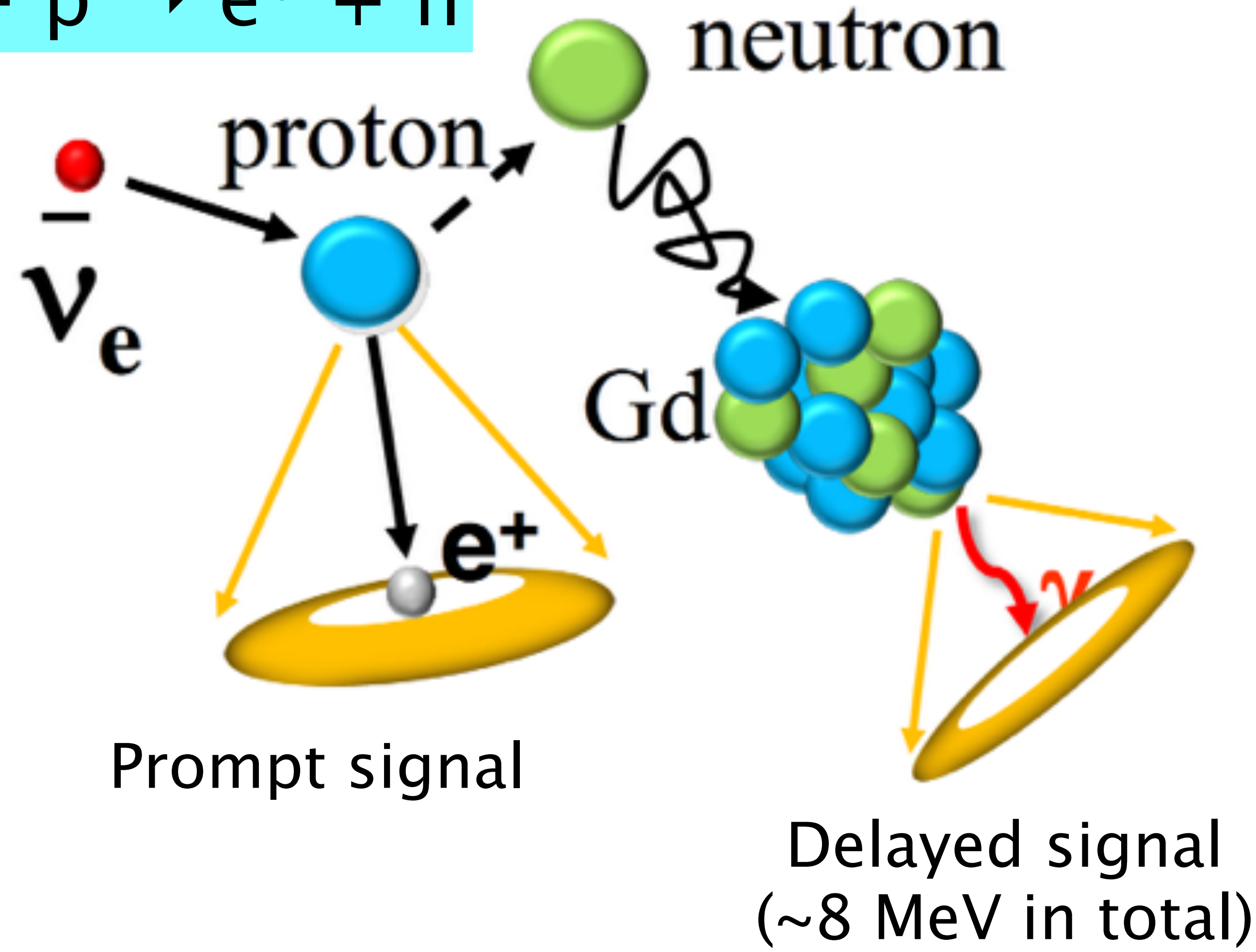
SI interaction
(Isospin conservation fp/fn=1)

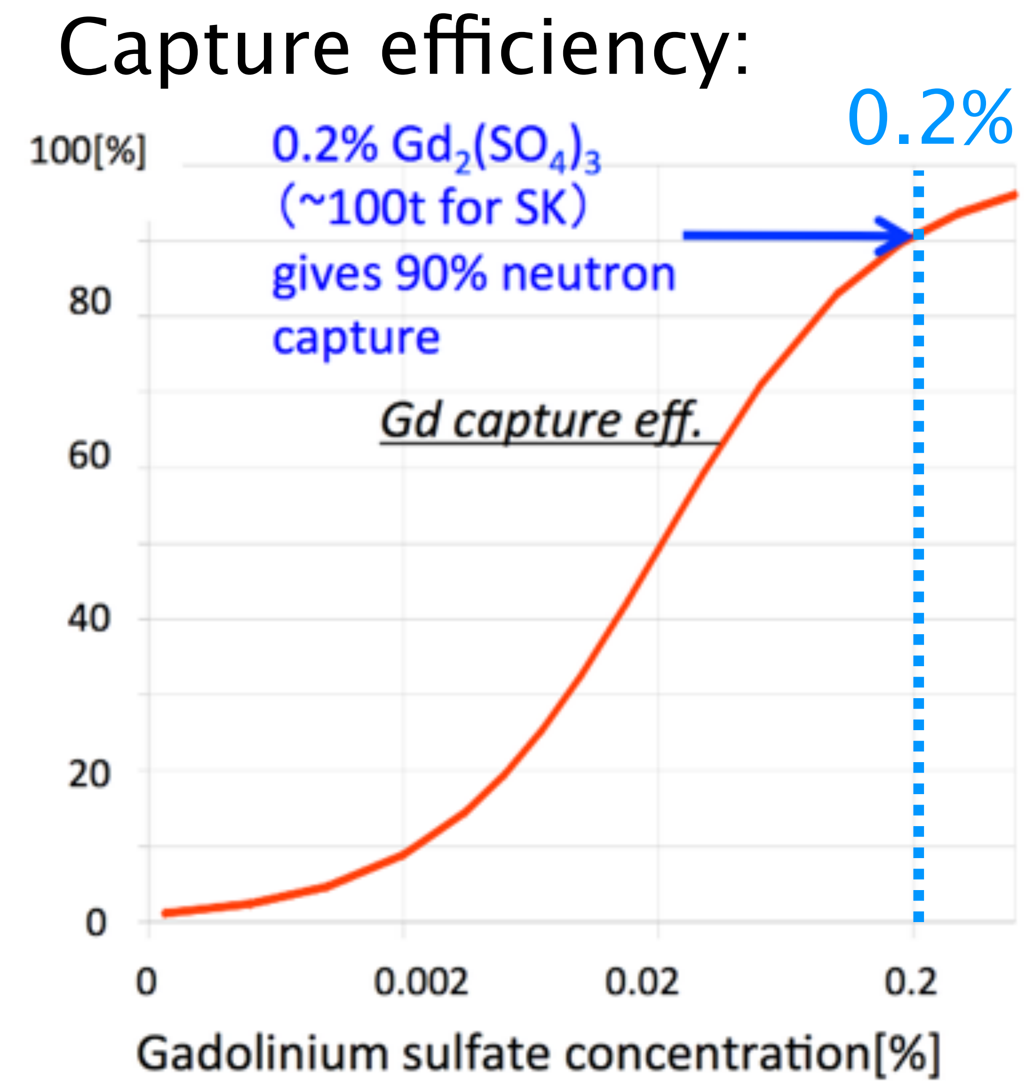


PRL93,171101 (2004)

SuperK-Gd project *(was known as GADZOOKS!)*

$\bar{\nu}_e + p \rightarrow e^+ + n$



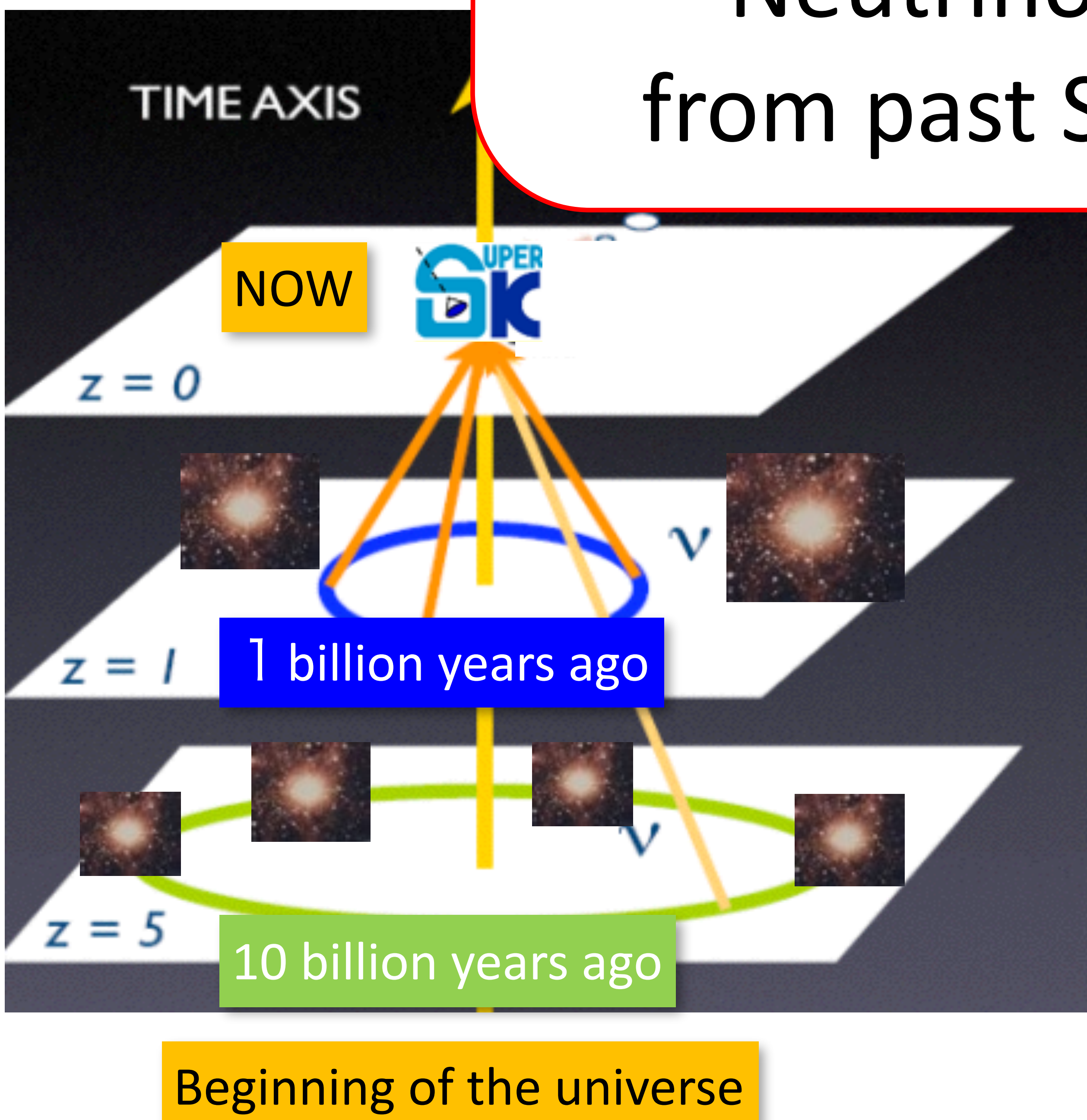


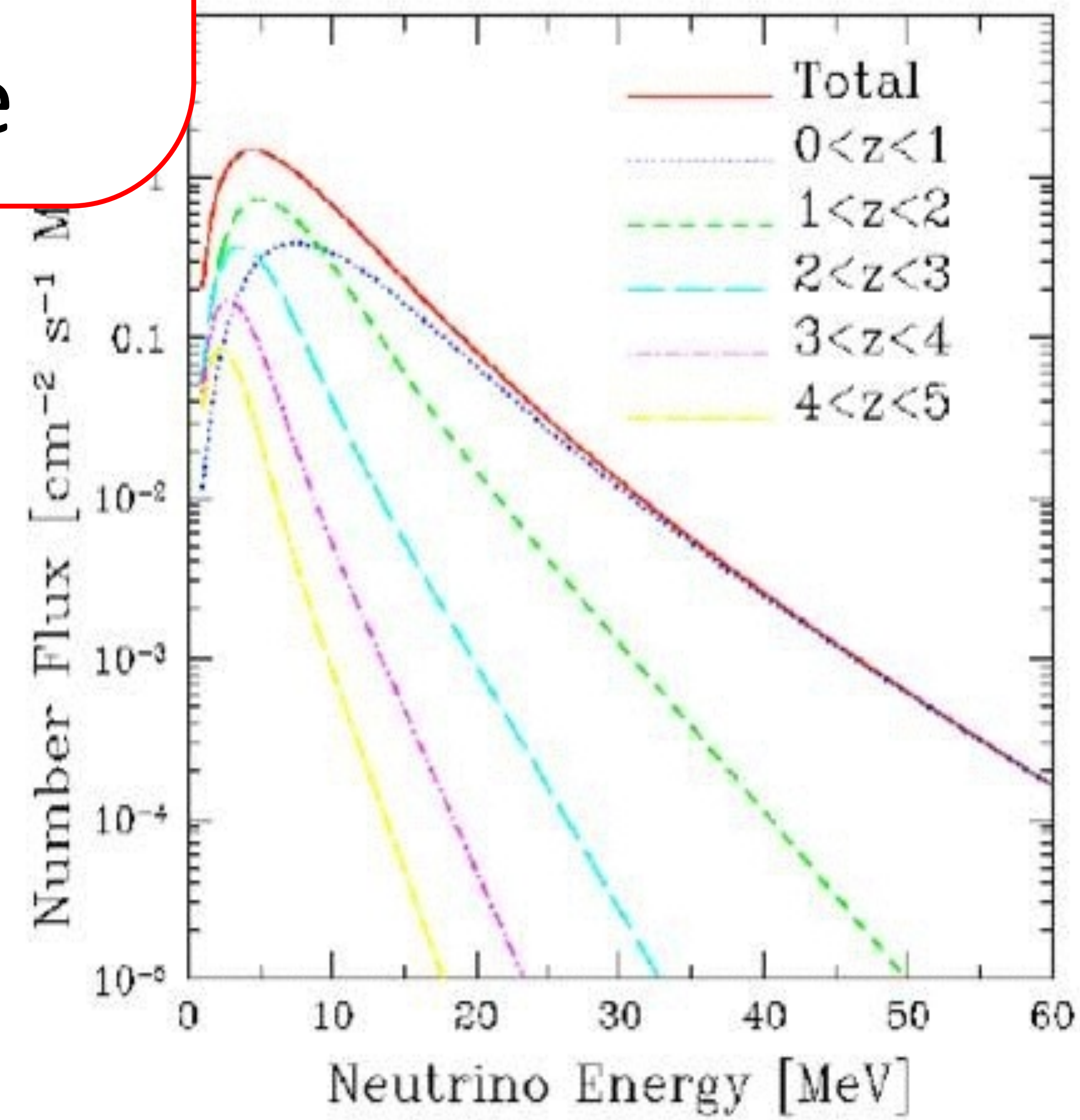
- Add 0.2% $Gd_2(SO_4)_3$ in water to enhance neutron capture
- multiple gammas (~8MeV in total) emitted from Gd by neutron capture
- Possible to identify anti-neutrino interaction with delayed coincidence

Supernova Relic Neutrino (SRN)

10^{10} stellar/galaxy ×10^{10} galaxy ×0.3%(become SNe) ~*O*(10^{17})SNe

Neutrinos
from past SNe



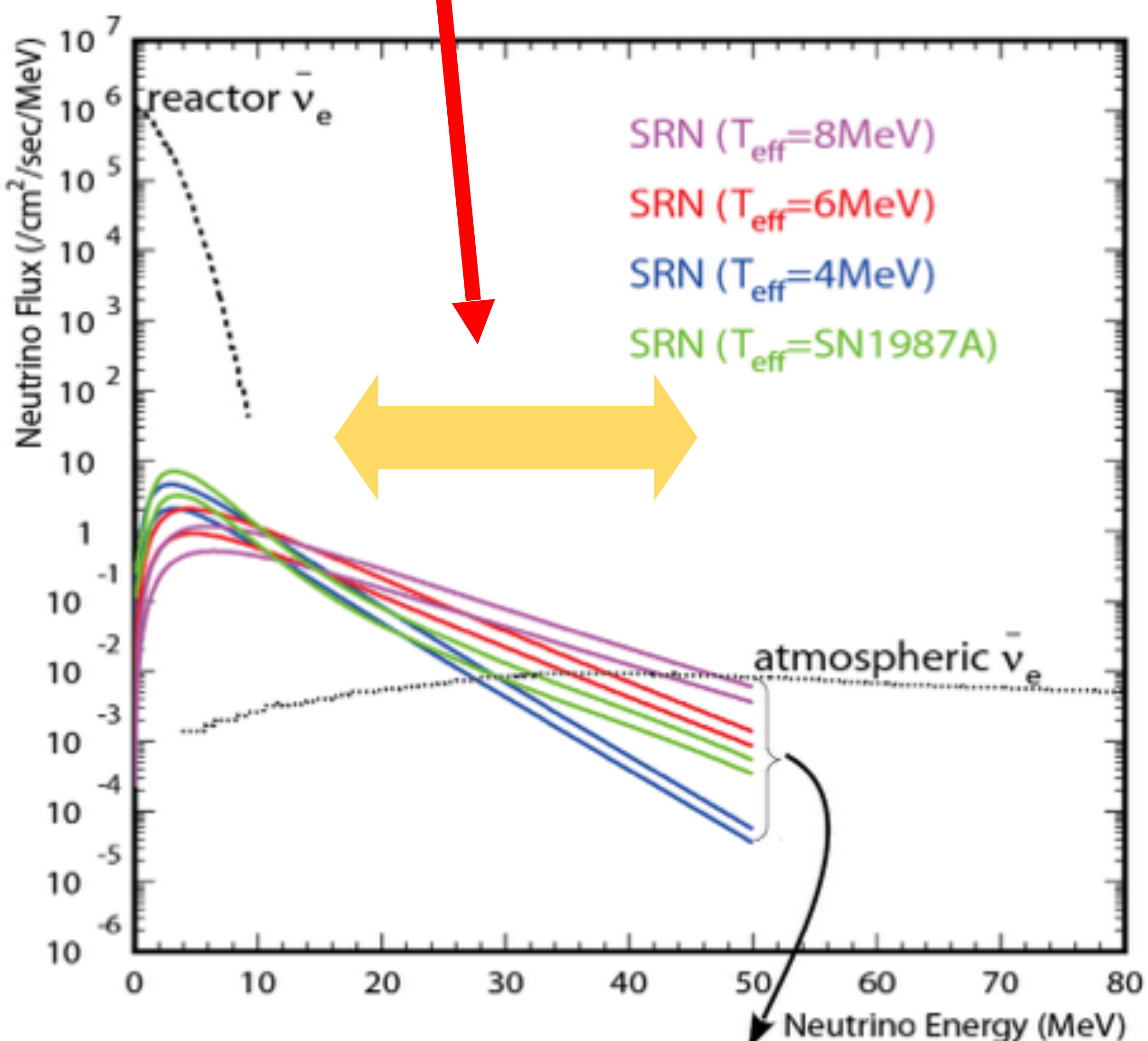


S.Ando, Astrophys.J. 607, 20(2004)

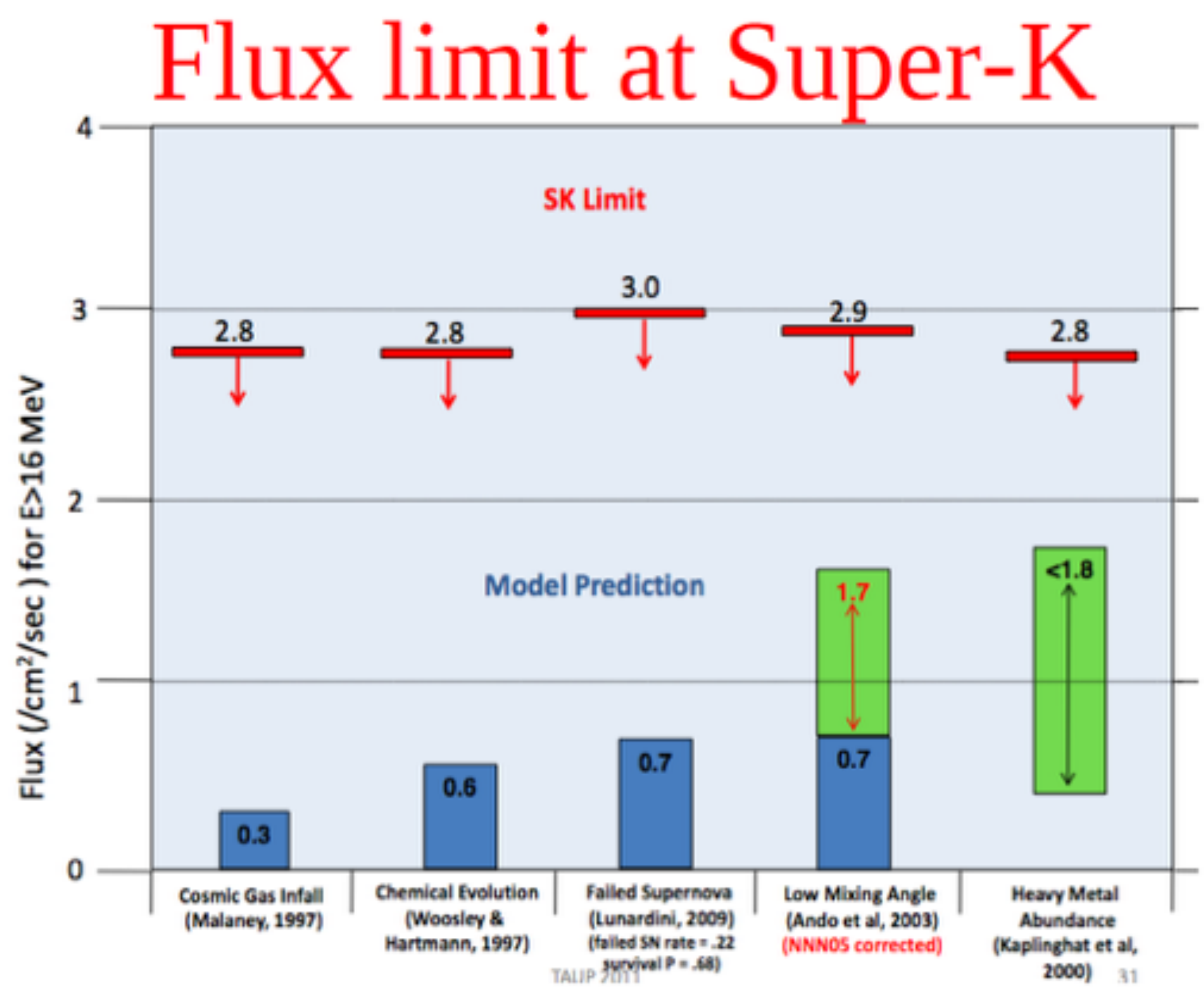
Theoretical flux prediction : 0.3~1.5 /cm2/s (17.3MeV threshold)

Search for SRN at Super-K

Search window for SRN at SK : From ~10MeV to ~30MeV



Phys.Rev. D 79, 08013 (2009)



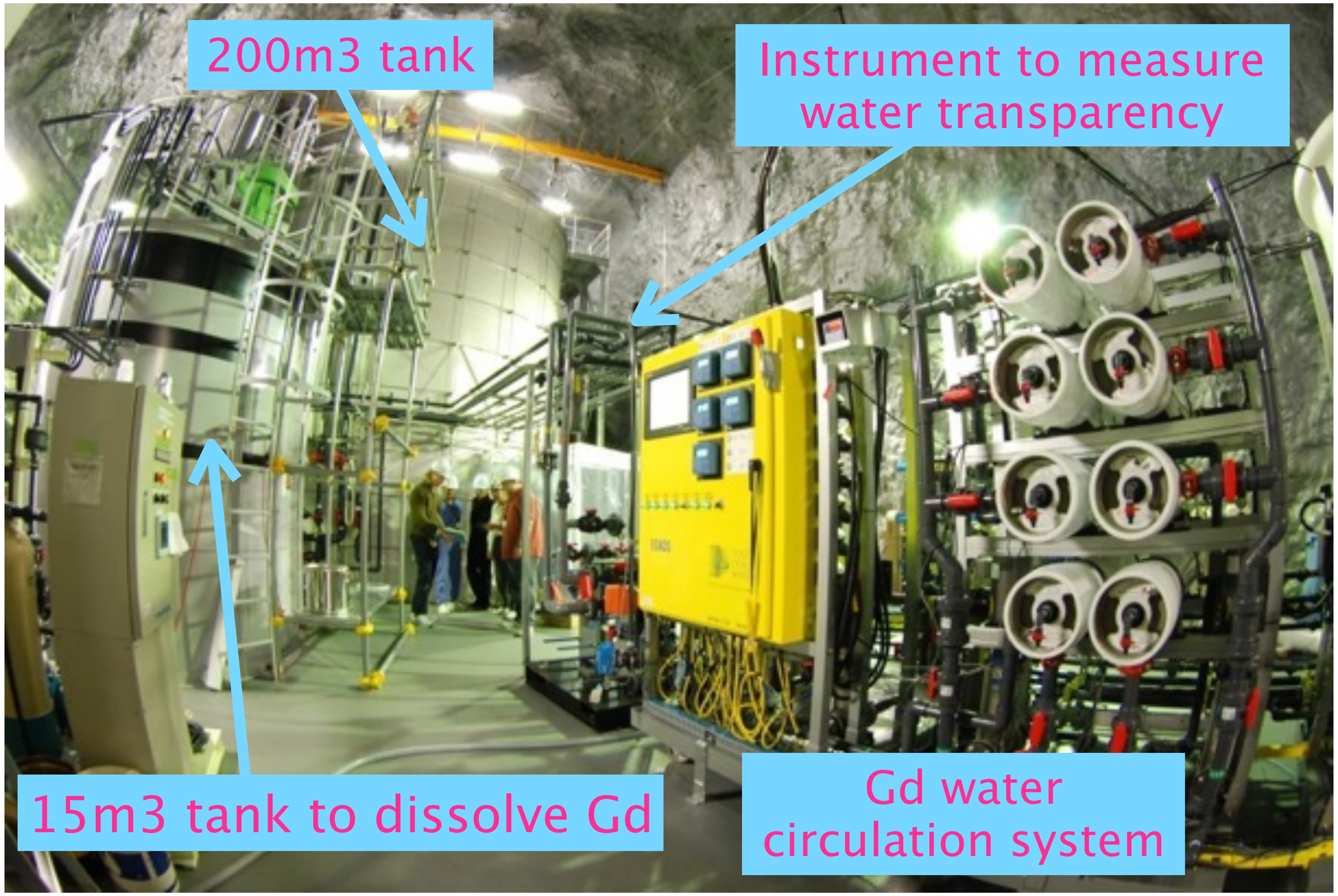
Phys. Rev. D 85, 052007 (2012)

Now SRN search is limited by atmospheric neutrino BG

We need BG reduction by the neutron tagging!

EGADS

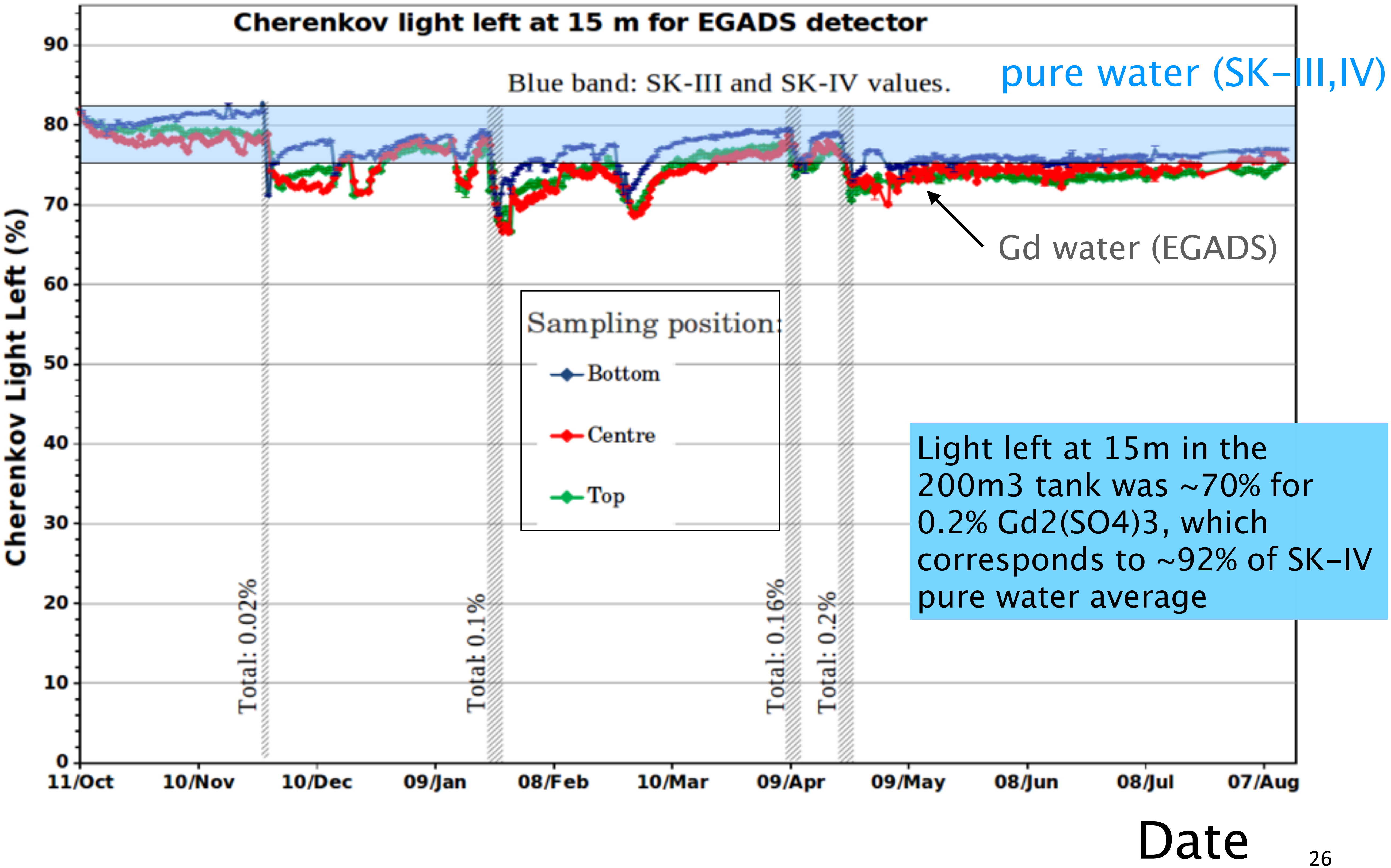
(Evaluating Gadolinium's Action on Detector System)



Test tank was build with same detector materials as Super-K, and study Gd water quality

Gd dissolving test has been performed from Oct 2014 to Apr 2015

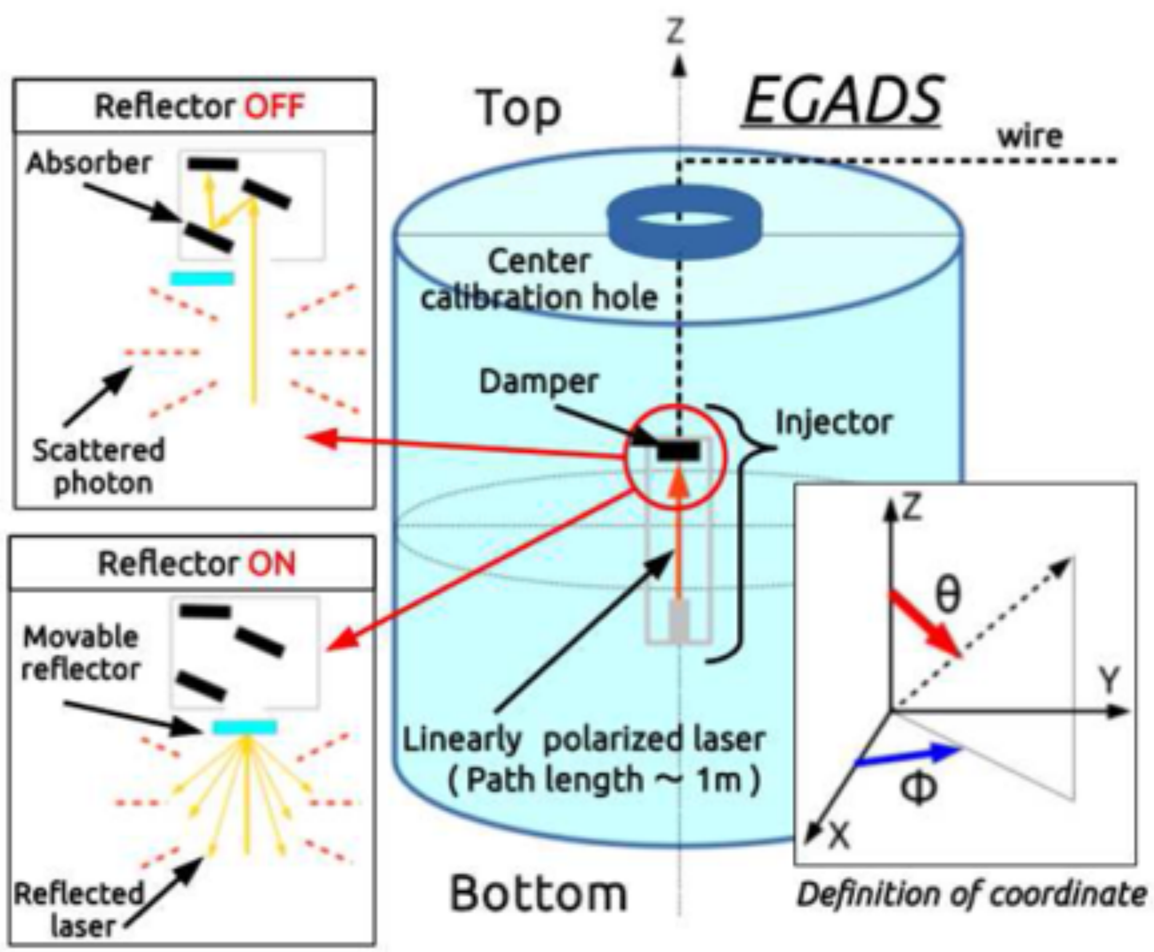
Transparency of Gd water in EGAS

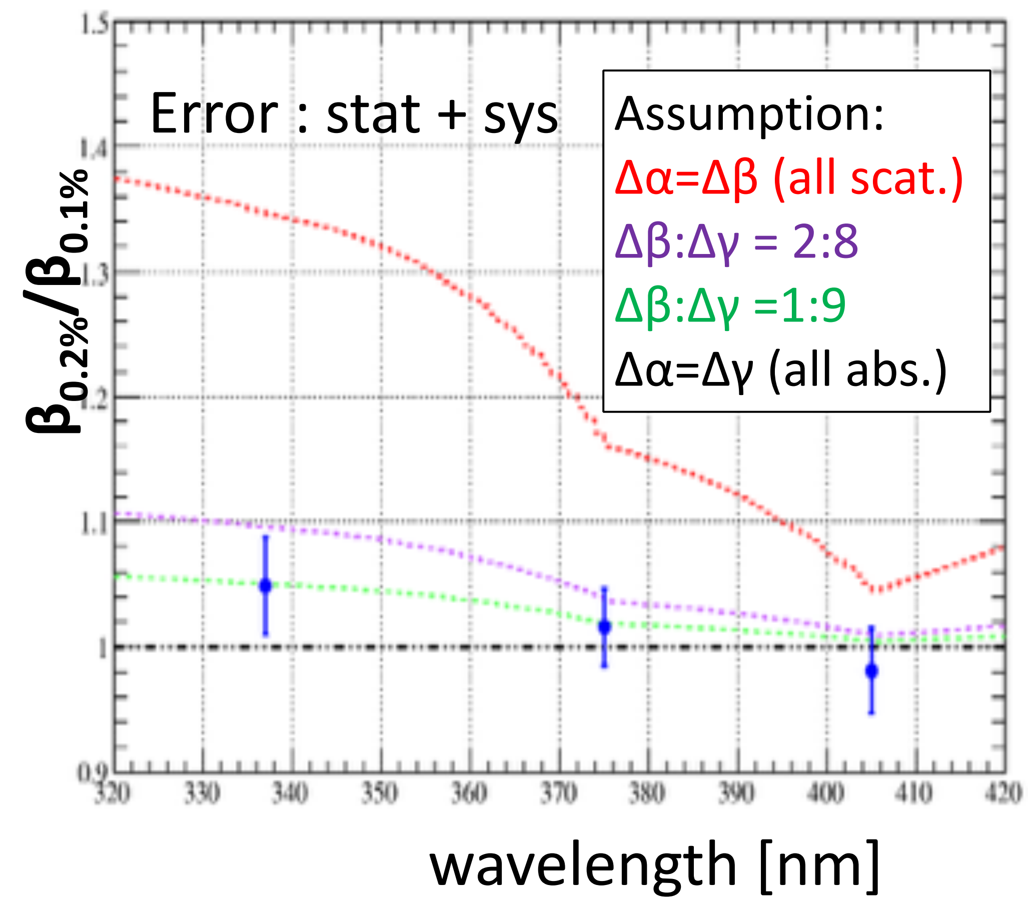


Light left at 15m in the 200m3 tank was ~70% for 0.2% $Gd_2(SO_4)_3$, which corresponds to ~92% of SK-IV pure water average

Rayleigh Scattering measurement

- Increase of scattering lights in Gd water may affect detector performance
- Measure fraction of scattering light by laser injector
- No significant increase of scattered light was observed



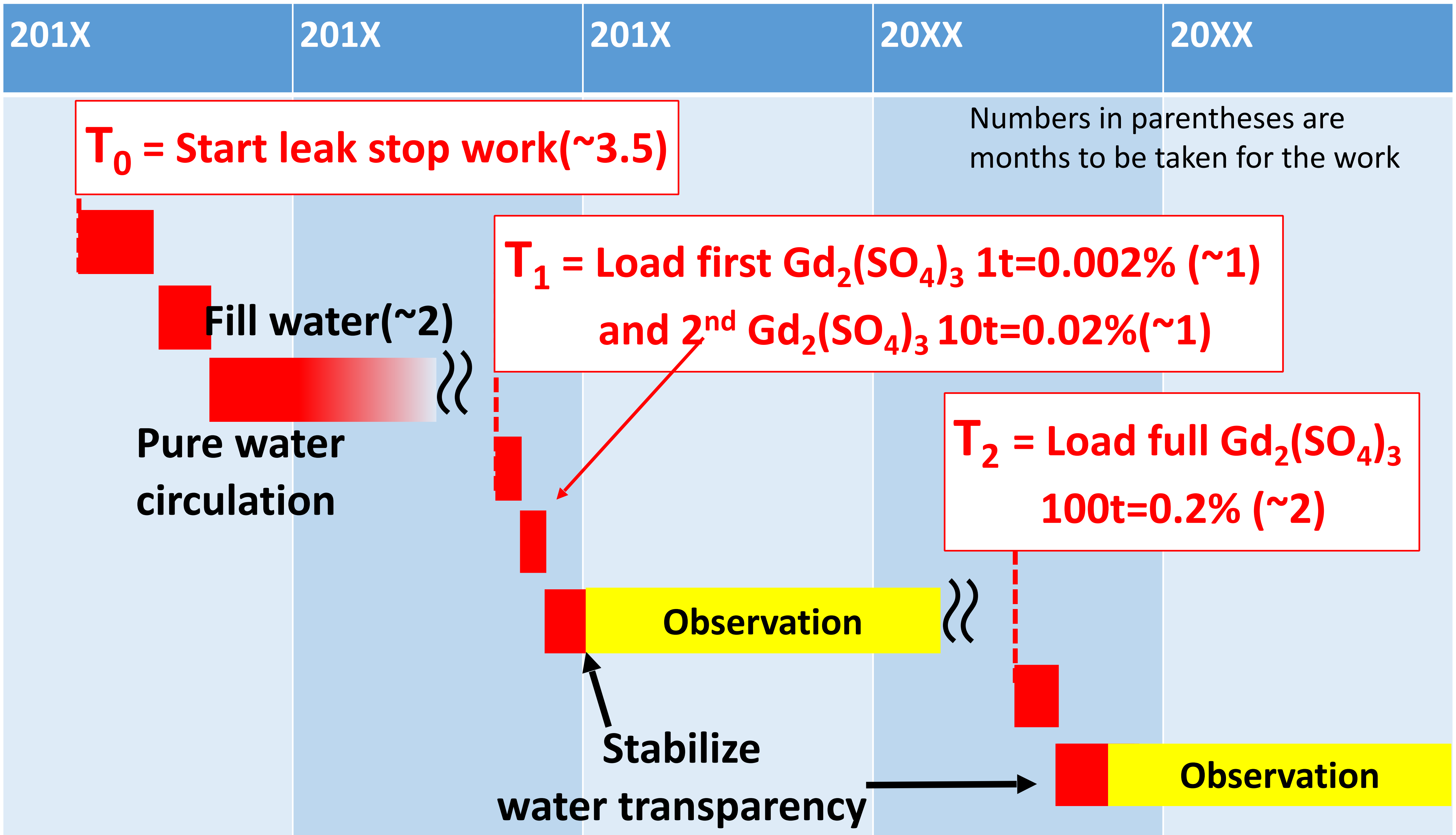


Official statement from SuperK collaboration

On June 27, 2015, the Super-Kamiokande collaboration approved the SuperK-Gd project which will enhance anti-neutrino detectability by dissolving gadolinium to the Super-K water.

The actual schedule of the project including refurbishment of the tank and Gd-loading time will be determined soon taking into account the T2K schedule.

Timeline of SuperK-Gd



In order to set T_0, T_1,&T_2, T2K schedule will be also taken into account

Summary

- *Atmospheric neutrino*
  - there is ~1 σ preference in normal hierarchy
  - indicate δ_{CP} ~ -π/2, but still CP conservation allowed
- *Solar neutrino*
  - energy spectrum slightly disfavor expected distortion
  - first indication of terrestrial matter effect at ~3σ
- *Indirect solar WIMP search*
  - Strongest limit for SD in 4-200 GeV/c^2
  - Partially reject SI allowed regions indicated by direct exp.
- *News on SuperK Gd project*
  - Aim to detect SNR using neutron capture by adding Gd
  - SuperK Gd project approved by collaboration