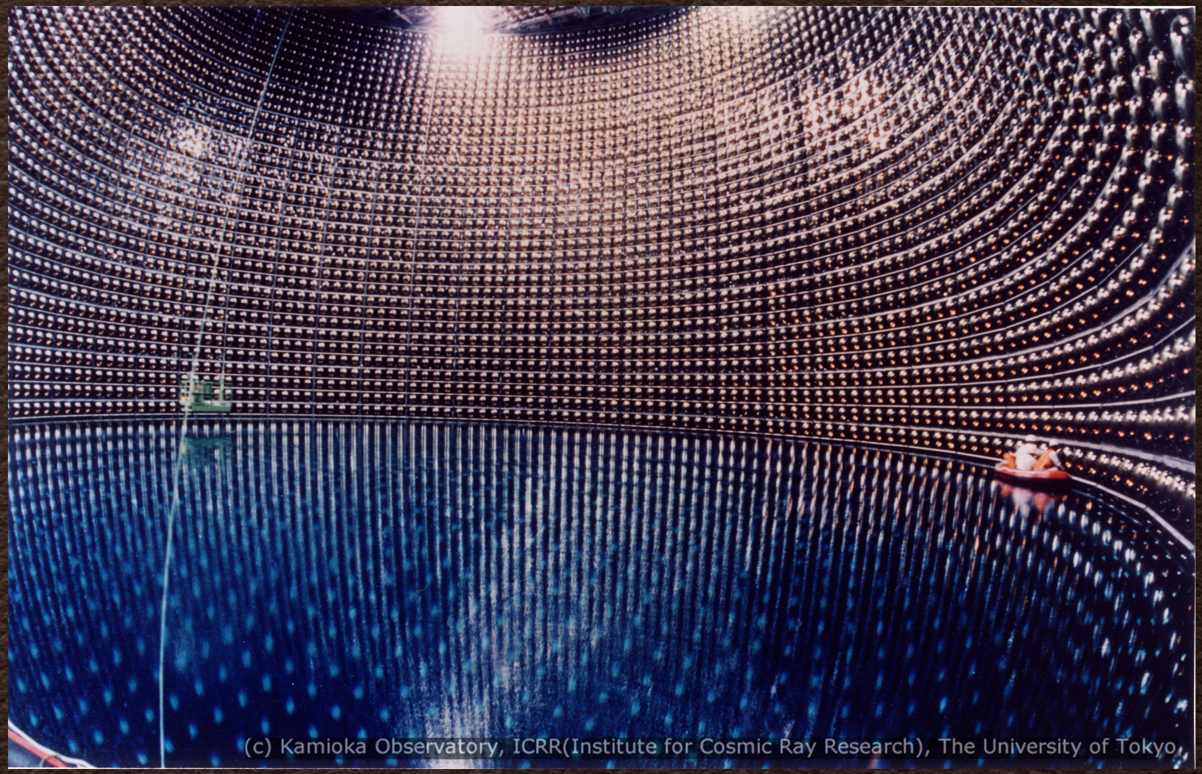
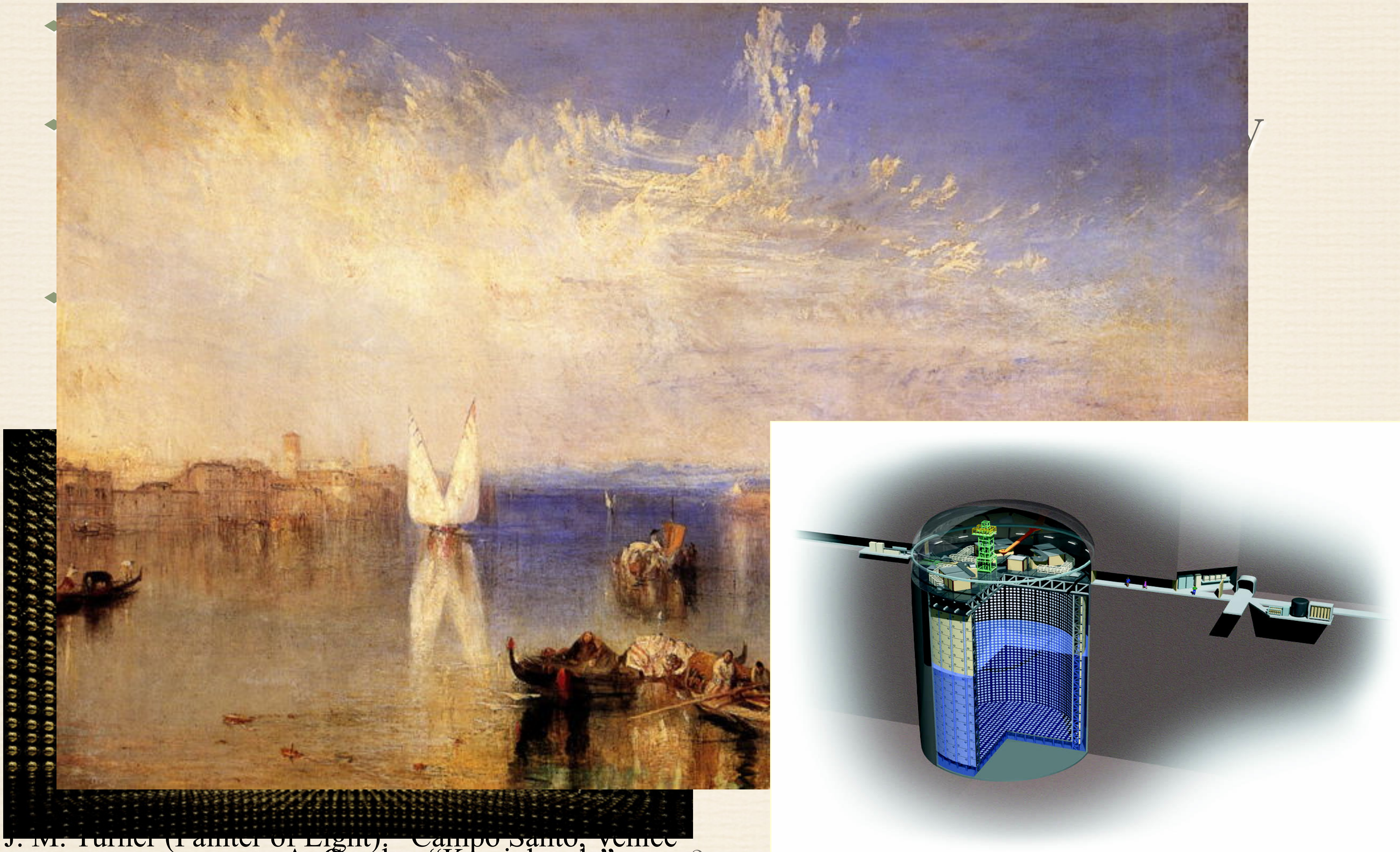
The Painter with Light: Two Decades of Super-Kamiokande

Seminar at MPIK
2016.6.29
Michael Smy
UC Irvine



The Painter of Light

The Detector

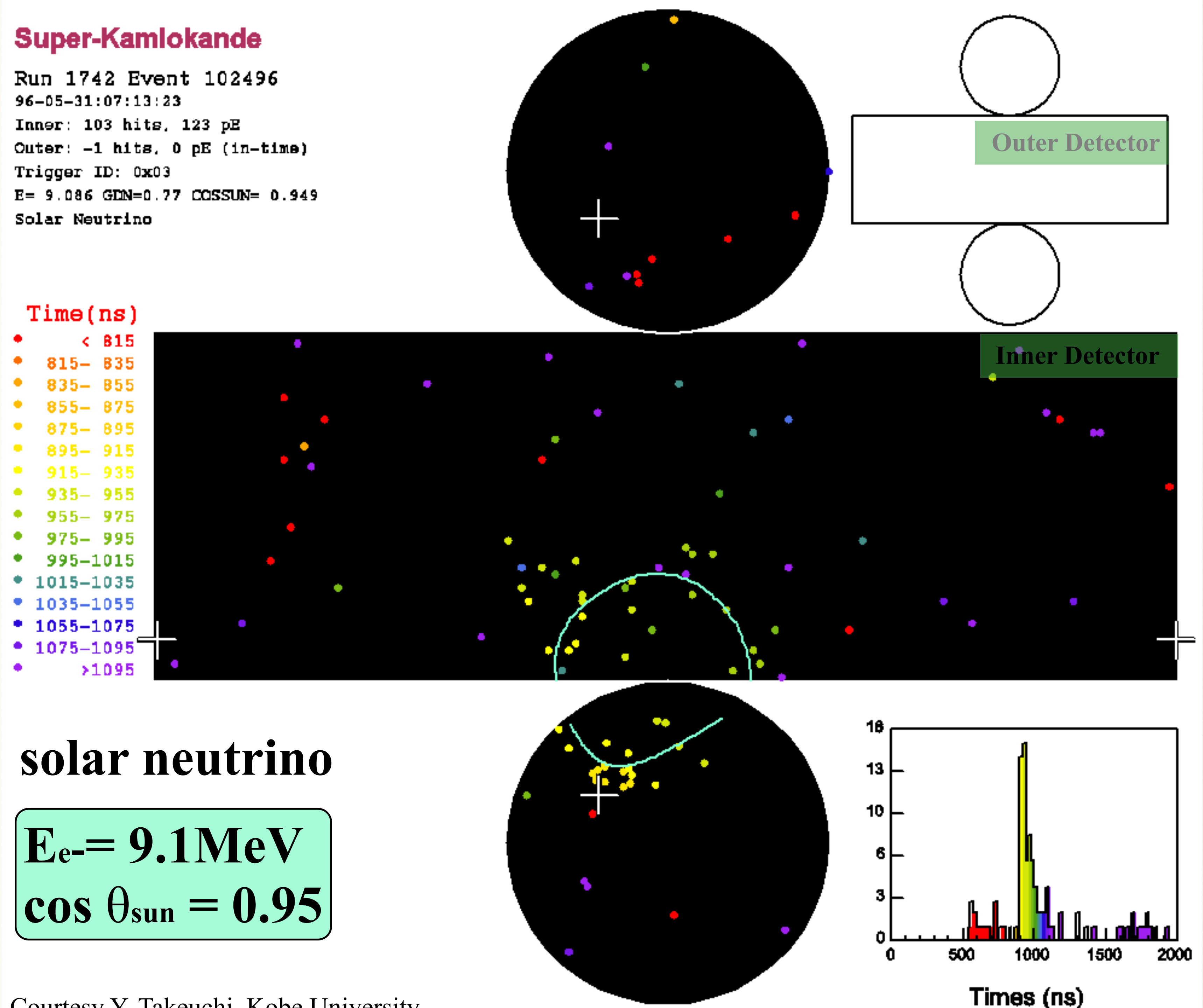


J. M. Turner (Painter of Light): "Campo Santo, Venice"

A. Gursky: "Kamiokande"

Particle Detection in Super-K

- PMT timing ➛ vertex reconstruction: **20cm (high energy)-60cm (low energy electrons)**
- hit pattern ➛ particle ID and direction reconstruction: **few (high energy muons) to 30^0 (low energy electrons)**
- brightness ➛ energy: **14% @ 10 MeV** (≈6 hits/MeV above threshold)

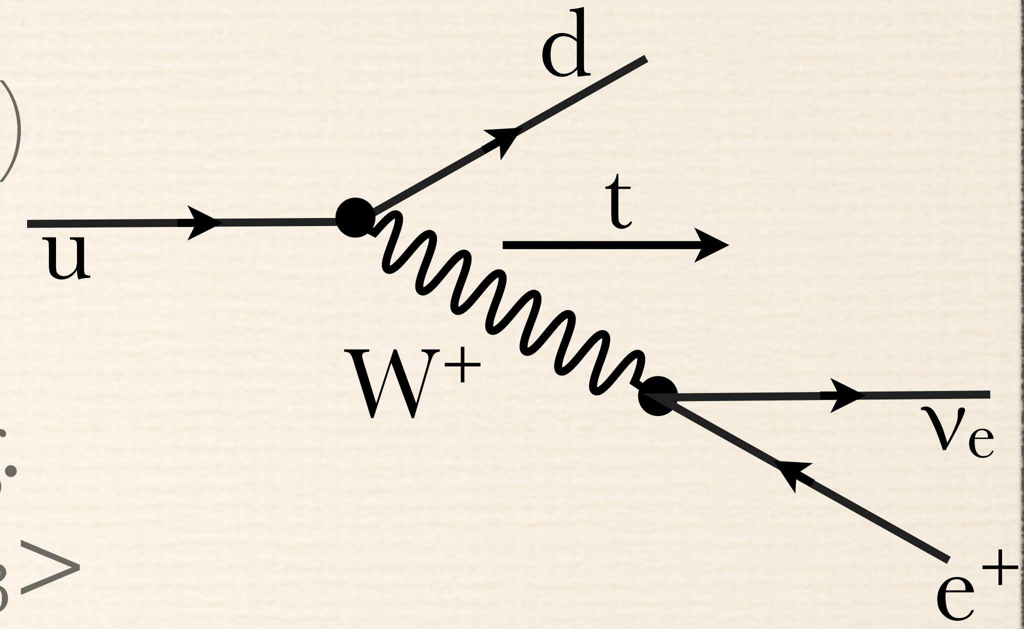


Courtesy Y. Takeuchi, Kobe University

20th Anniversary Party: Super-K started taking data in April 1996

Neutrino Oscillations: Mass and Weak Eigenstates

- weak or flavor eigenstate if ν's created by W's (e.g. β^+ decay: ν_e's)



- linear comb. of mass eigenstates (neutrinos with definite mass): e.g. $|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$

PMNS Matrix

$$\begin{pmatrix} |\nu_e > \\ |\nu_\mu > \\ |\nu_\tau > \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} |\nu_1 > \\ |\nu_2 > \\ |\nu_3 > \end{pmatrix}$$

- ν's propagate as mass eigenstates, (usual plane wave $e^{i(\vec{p}\cdot\vec{r}-Et)/\hbar}$) $E^2=m^2c^4+p^2c^2$: $p \approx E/c - m^2c^3/(2E)$

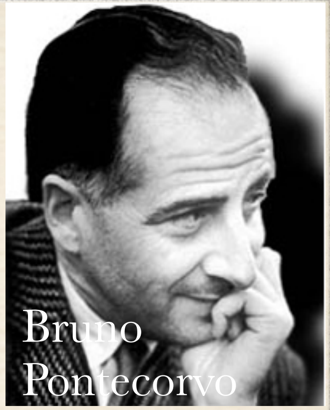
- component phases of $|\nu_e\rangle$ shift with time/distance: ν oscillations

phase shift after distance L

$$\Delta\varphi_{ij}(L) = \frac{m_i^2 - m_j^2}{2E}\frac{c^3}{\hbar}L = \frac{\Delta m_{ij}^2 c^3}{2E\hbar}L$$

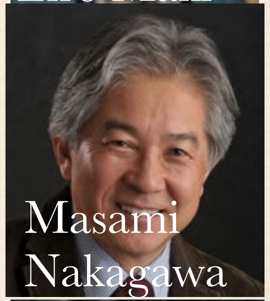
PMNS Matrix

(Pontecorvo-Maki-Nakagawa-Sakata)



- parametrize: three angles, one phase:
  - solar angle θ_{12} governing solar ν oscillation
  - reactor angle θ_{13} governing reactor ν oscillation
  - atmospheric angle θ_{23} governing atm. ν oscillation
  - oscillation CP-violating phase δ (ν beams)
- (two more CP phases α_1, α_2 if ν's are Majorana-particles)
- use $c_{ij}=\cos\theta_{ij}$ and $s_{ij}=\sin\theta_{ij}$,

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



- approximate numerical values:

$$\begin{pmatrix} 0.826 & 0.544 & 0.075 + i0.130 \\ -0.462 + i0.070 & 0.613 + i0.046 & 0.635 \\ 0.305 + i0.083 & -0.569 + i0.055 & 0.757 \end{pmatrix}$$

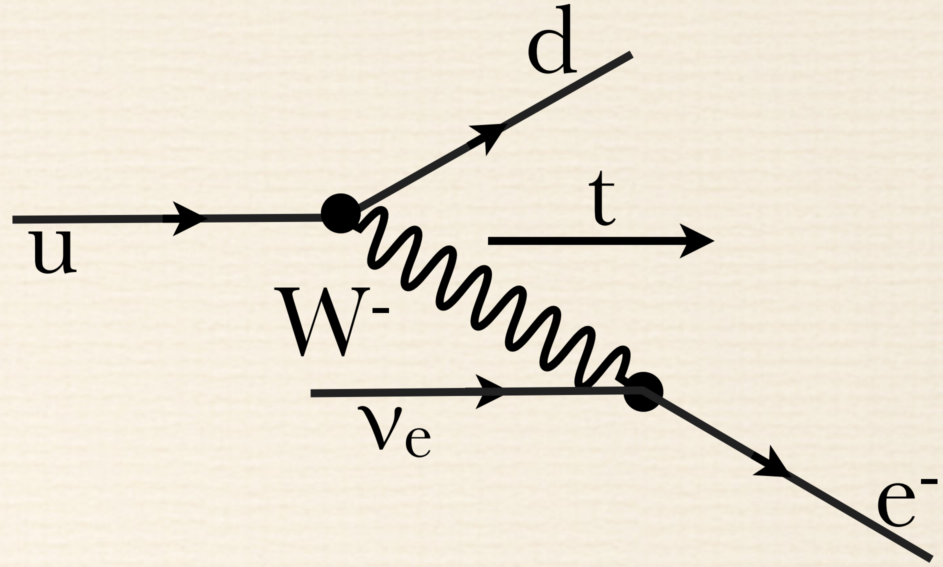
Quark and Lepton Mixing

- in weak interactions, down-type quarks mix just as ν's
- quark mixing angles are small; biggest is Cabibbo Angle
- big neutrino mixing angles: first discovered by Super-K in 1998 (θ_{23} from atm. ν), 2000 (θ_{12} from solar ν) and Super-K/T2K in 2011 (θ_{13} from an intense ν-beam)
- now: θ_{12} from Super-K/SNO, θ_{13} from Daya-Bay/Reno/Double Chooz, θ_{23} from Super-K/T2K

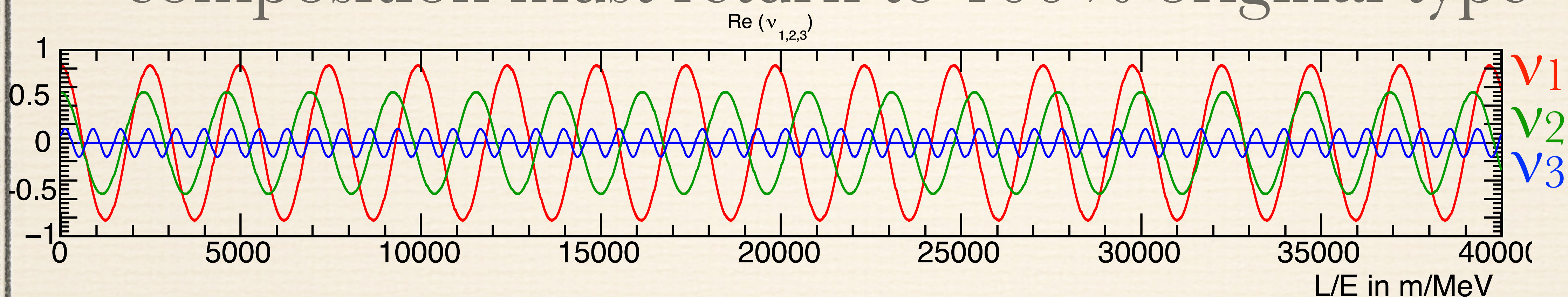
	θ_{12}	θ_{13}	θ_{23}	δ
quarks	13.04	0.201	2.38	69
leptons	33.36	8.66	40.0 or 50.4	300

Neutrino Flavor Oscillation

- when neutrinos are detected by conversion to lepton (W's): after distance L there probability of detecting a different type



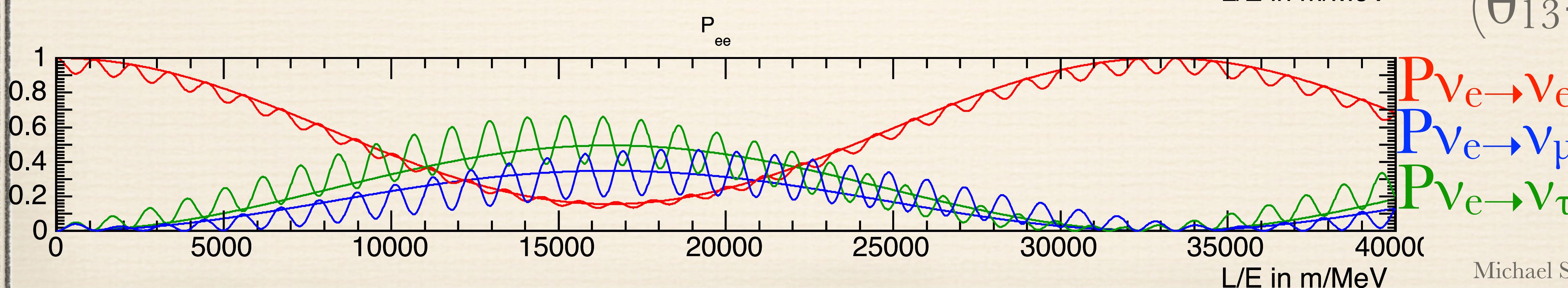
- "disappearance" of production type may not be complete at any L, but composition must return to 100% original type



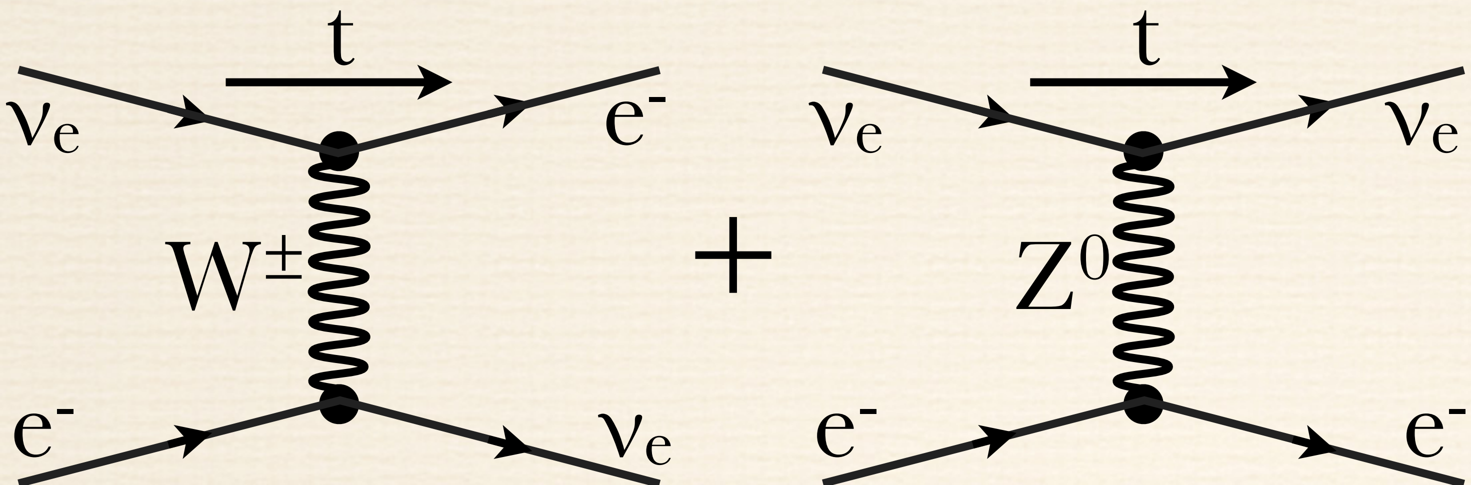
ν_e: $\nu_1+\nu_2$

$\nu_{\mu/\tau}$: $\nu_1-\nu_2$

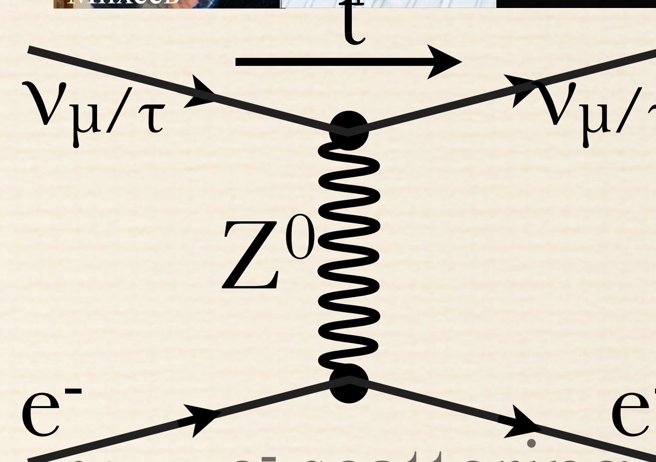
$(\theta_{13}=0)$



MSW Effect



ν_e forward-scattering off electrons



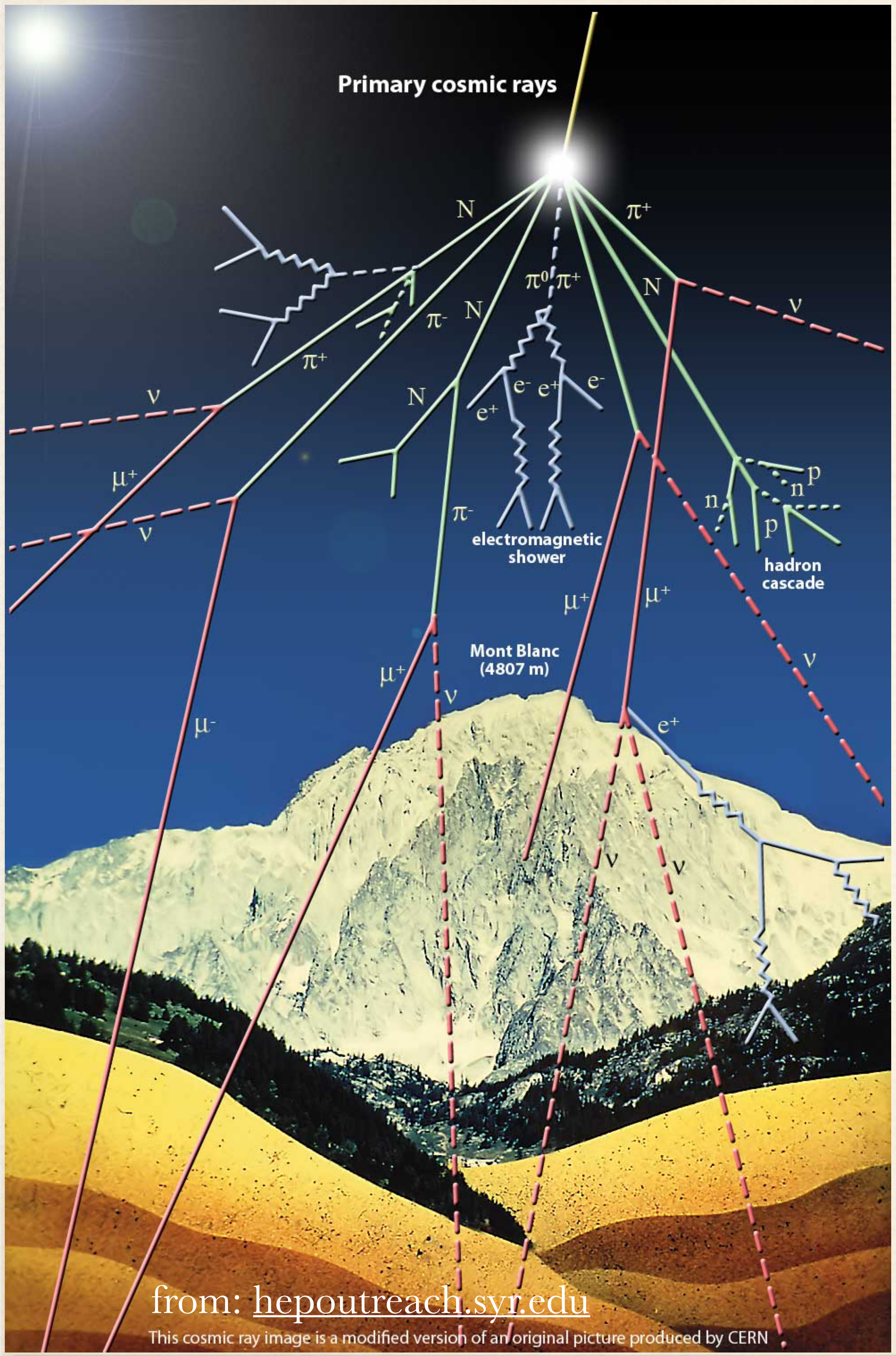
$\nu_{\mu/\tau}$-e^- scattering

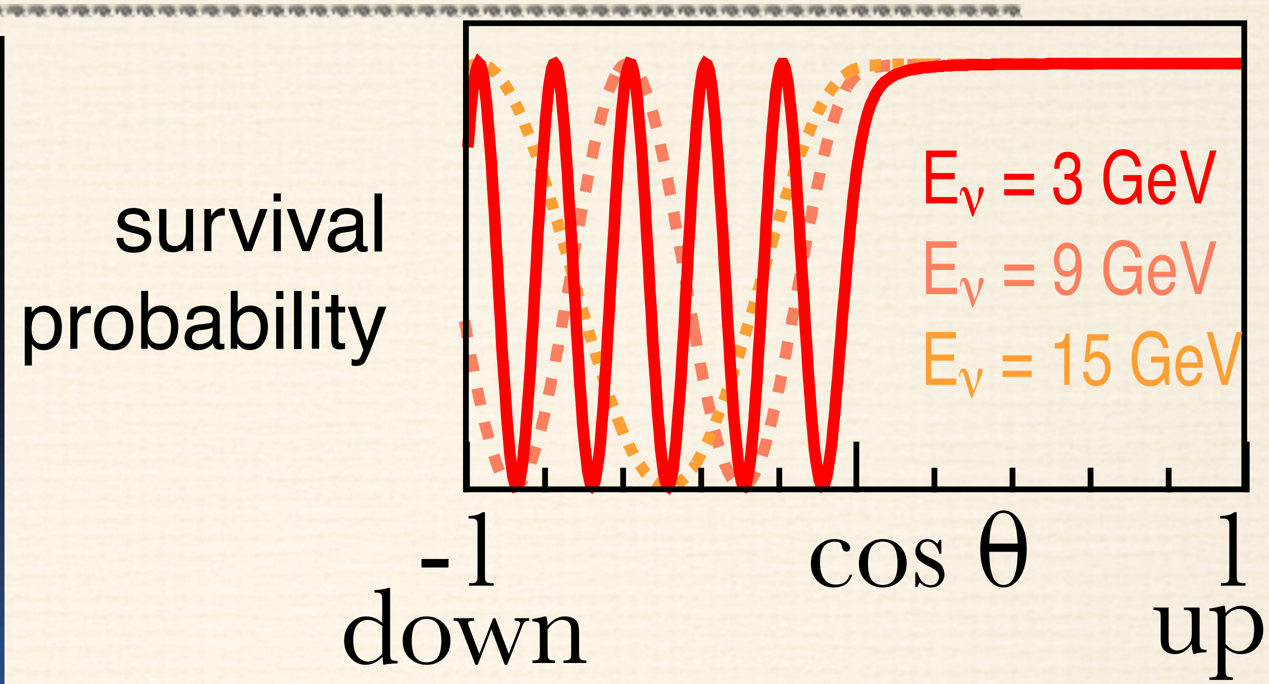
- matter interactions: phase shifts affecting ν oscillations
- sun: adiabatic conversion to ν_2 (ρ_e changes "slowly" in the sun)
- earth: resonant conversion at the resonance energy
- extra "potential" of ν_e (compared to $\nu_{\mu/\tau}$) in a "Hamiltonian"
- similar to light propagation in medium ("index of refraction"), use effective mixing angle and Δm^2

$$H_{matter} = \kappa\rho_e \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \frac{1}{2E} U^\dagger_{PMNS} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U_{PMNS} \qquad \kappa = \sqrt{2}G_F$$

Atmospheric Neutrinos

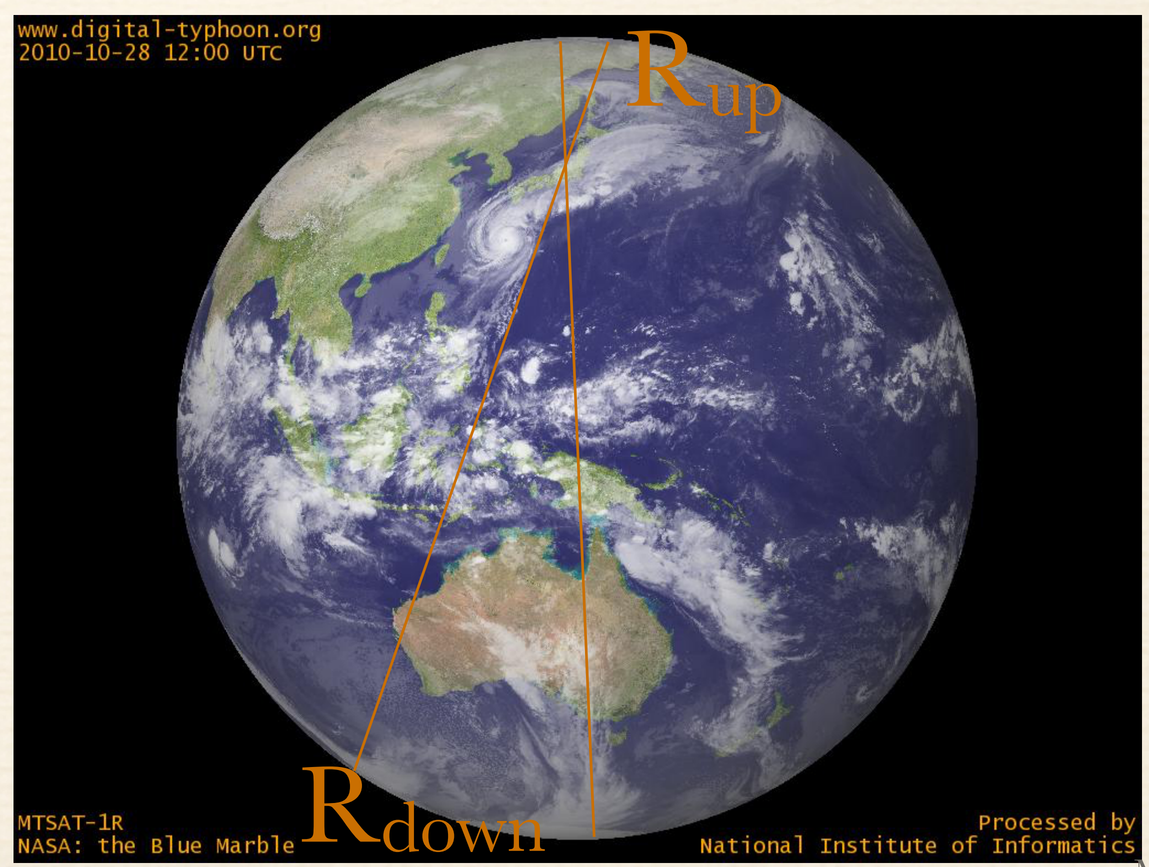
Atmospheric Neutrinos



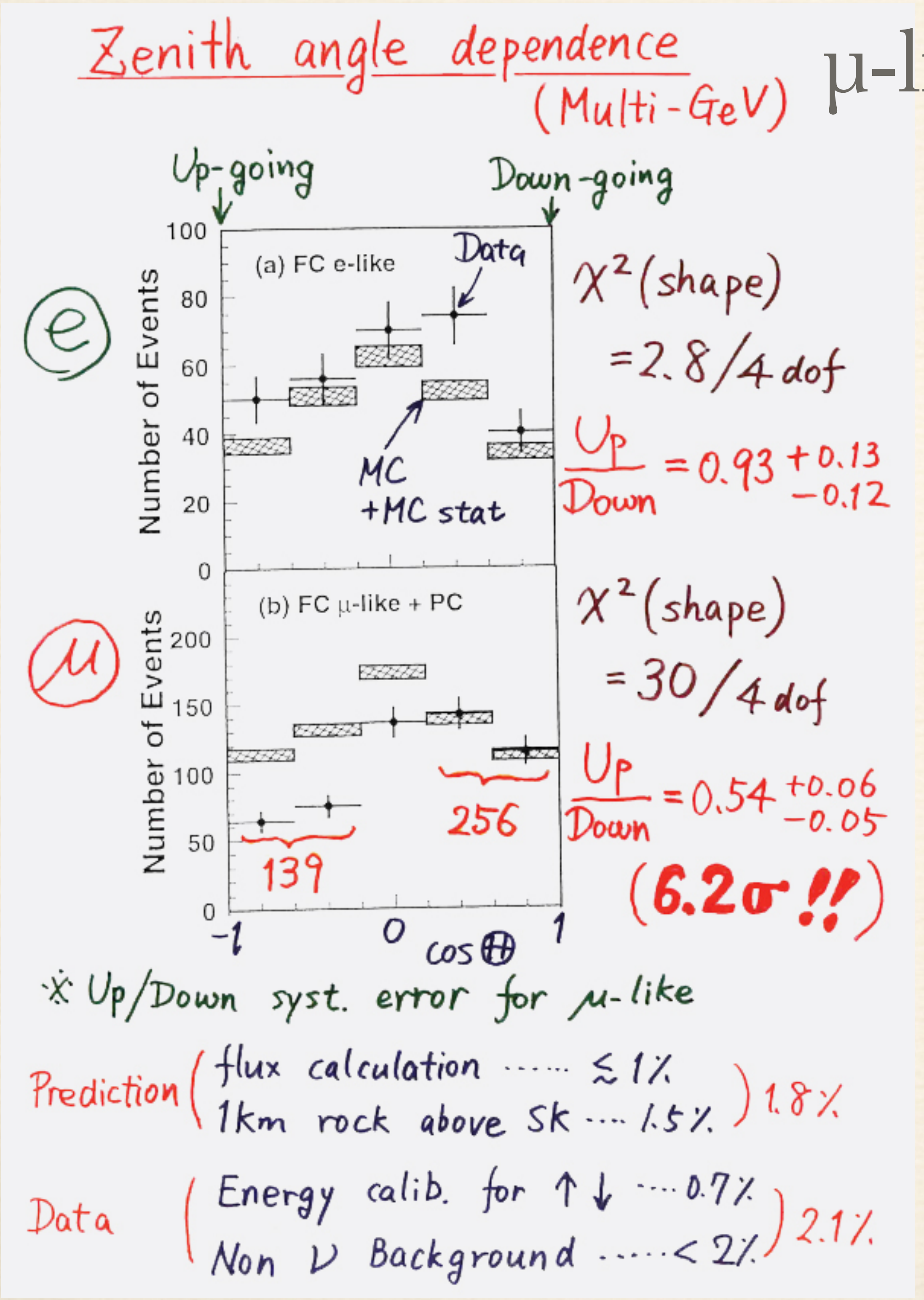


w/o osc.:
$R_{up}=R_{down}$

from: Ed Kearns, Boston University



Discovery of Neutrino Oscillation



μ-like

T. Kajita in Takayama (1998)

Courtesy Ed Kearns, Boston University

Discovery of Neutrino Oscillation

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Evidence for Oscillation of Atmospheric Neutrinos

Y. Fukuda,[1] T. Hayakawa,[1] E. Ichihara,[1] K. Inoue,[1] K. Ishihara,[1] H. Ishino,[1] Y. Itow,[1] T. Kajita,[1] J. Kameda,[1] S. Kasuga,[1] K. Kobayashi,[1] Y. Kobayashi,[1] Y. Koshio,[1] M. Miura,[1] M. Nakahata,[1] S. Nakayama,[1] A. Okada,[1] K. Okumura,[1] N. Sakurai,[1] M. Shiozawa,[1] Y. Suzuki,[1] Y. Takeuchi,[1] Y. Totsuka,[1] S. Yamada,[1] M. Earl,[2] A. Habig,[2] E. Kearns,[2] M.D. Messier,[2] K. Scholberg,[2] J.L. Stone,[2] L.R. Sulak,[2] C.W. Walter,[2] M. Goldhaber,[3] T. Barszczxak,[4] D. Casper,[4] W. Gajewski,[4] P.G. Halverson,[4,*] J. Hsu,[4] W.R. Kropp,[4] L.R. Price,[4] F. Reines,[4] M. Smy,[4] H.W. Sobel,[4] M.R. Vagins,[4] K.S. Ganezer,[5] W.E. Keig,[5] R.W. Ellsworth,[6] S. Tasaka,[7] J.W. Flanagan,[8,†] A. Kibayashi,[8] J.G. Learned,[8] S. Matsuno,[8] V.J. Stenger,[8] D. Takemori,[8] T. Ishii,[9] J. Kanzaki,[9] T. Kobayashi,[9] S. Mine,[9] K. Nakamura,[9] K. Nishikawa,[9] Y. Oyama,[9] A. Sakai,[9] M. Sakuda,[9] O. Sasaki,[9] S. Echigo,[10] M. Kohama,[10] A.T. Suzuki,[10] T.J. Haines,[11,4] E. Blaufuss,[12] B.K. Kim,[12] R. Sanford,[12] R. Svoboda,[12] M.L. Chen,[13] Z. Conner,[13,‡] J.A. Goodman,[13] G.W. Sullivan,[13] J. Hill,[14] C.K. Jung,[14] K. Martens,[14] C. Mauger,[14] C. McGrew,[14] E. Sharkey,[14] B. Viren,[14] C. Yanagisawa,[14] W. Doki,[15] K. Miyano,[15] H. Okazawa,[15] C. Saji,[15] M. Takahata,[15] Y. Nagashima,[16] M. Takita,[16] T. Yamaguchi,[16] M. Yoshida,[16] S.B. Kim,[17] M. Etoh,[18] K. Fujita,[18] A. Hasegawa,[18] T. Hasegawa,[18] S. Hatakeyama,[18] T. Iwamoto,[18] M. Koga,[18] T. Maruyama,[18] H. Ogawa,[18] J. Shirai,[18] A. Suzuki,[18] F. Tsushima,[18] M. Koshiba,[19] M. Nemoto,[20] K. Nishijima,[20] T. Futagami,[21] Y. Hayato,[21,§] Y. Kanaya,[21] K. Kaneyuki,[21] Y. Watanabe,[21] D. Kielczewska,[22,4] R.A. Doyle,[23] J.S. George,[23] A.L. Stachyra,[23] L.L. Wai,[23,‖] R.J. Wilkes,[23] and K.K. Young[23]

(Super-Kamiokande Collaboration)

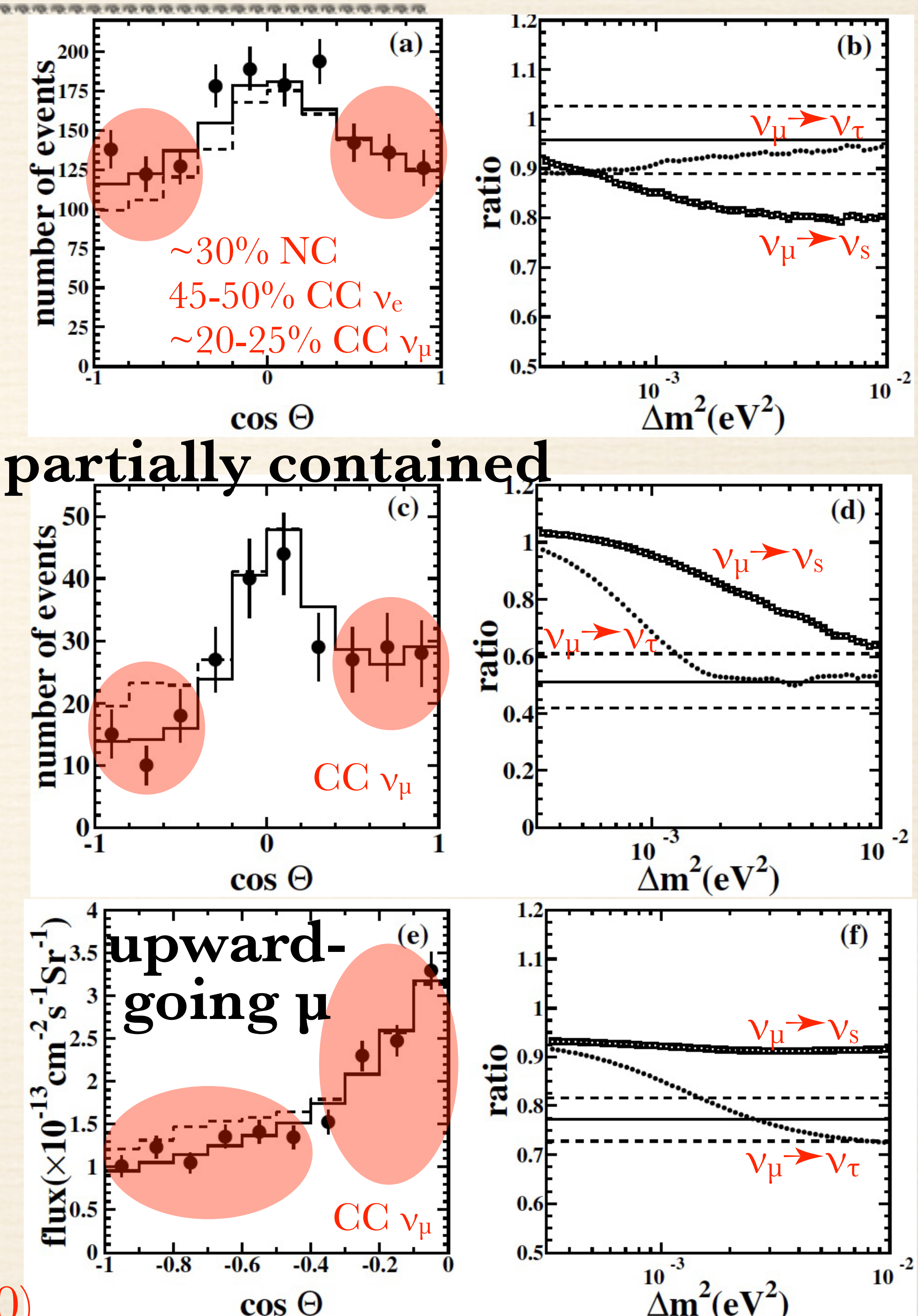
cited 4,845 times

PRL 81, 1562 (1998)

PRL 82, 2644 (1999)

Oscillation to $\nu_\mu \rightarrow \nu_\tau$ or $\nu_\mu \rightarrow \nu_s$?

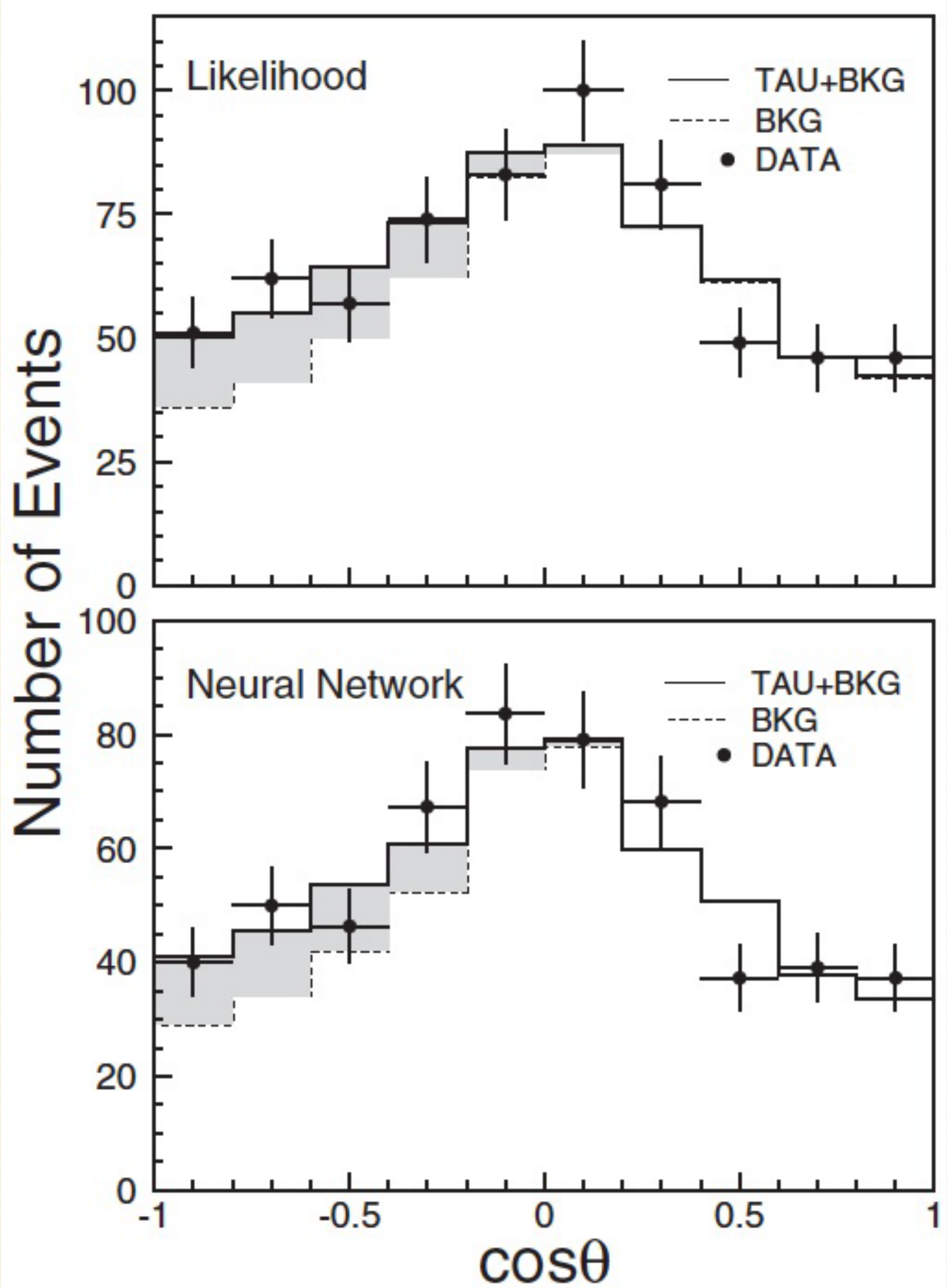
- use three different samples:
  - a π^0 enhanced sample to look for oscillation effects in NC interactions
  - a high energy ν_μ sample to look for matter effects
  - an even higher energy ν_μ sample
- to limit systematics take up/down ratios
- answer: $\nu_\mu \rightarrow \nu_\tau$!



PRL 85 3999 (2000)

Search for the oscillated ν_τ's

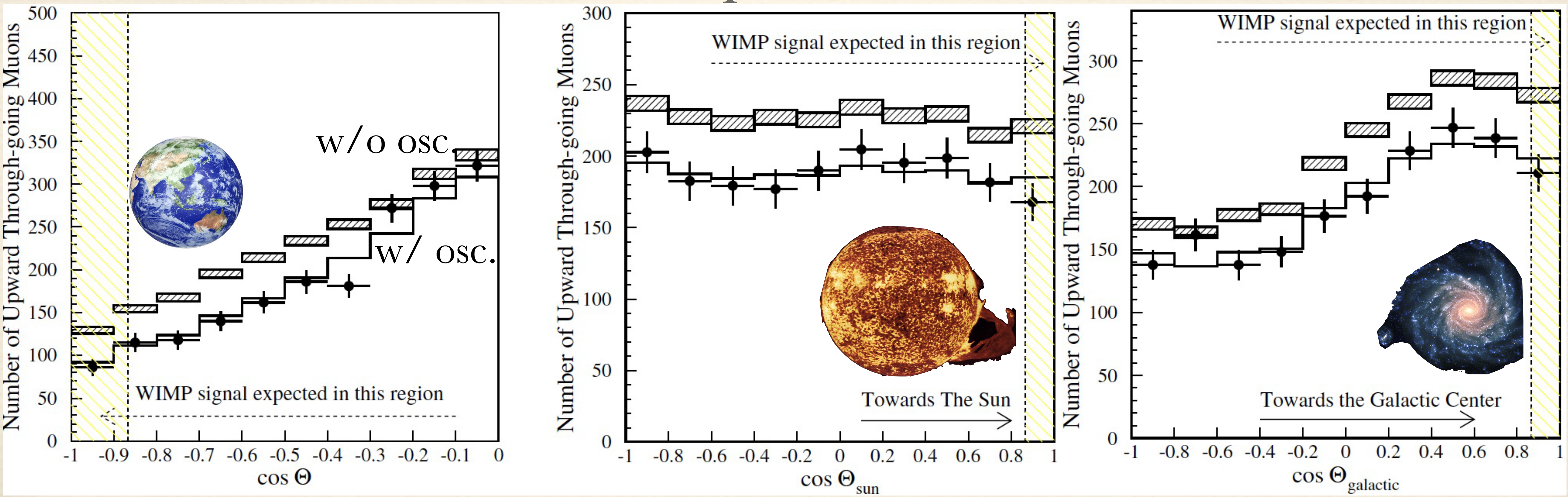
- fairly high energy because of τ lepton threshold
- use event shape variables (e.g. sphericity) to make an enriched sample
- purity is still low…
- look for excess in upward direction



PRL 97, 171801 (2006)

Search for WIMP Annihilation

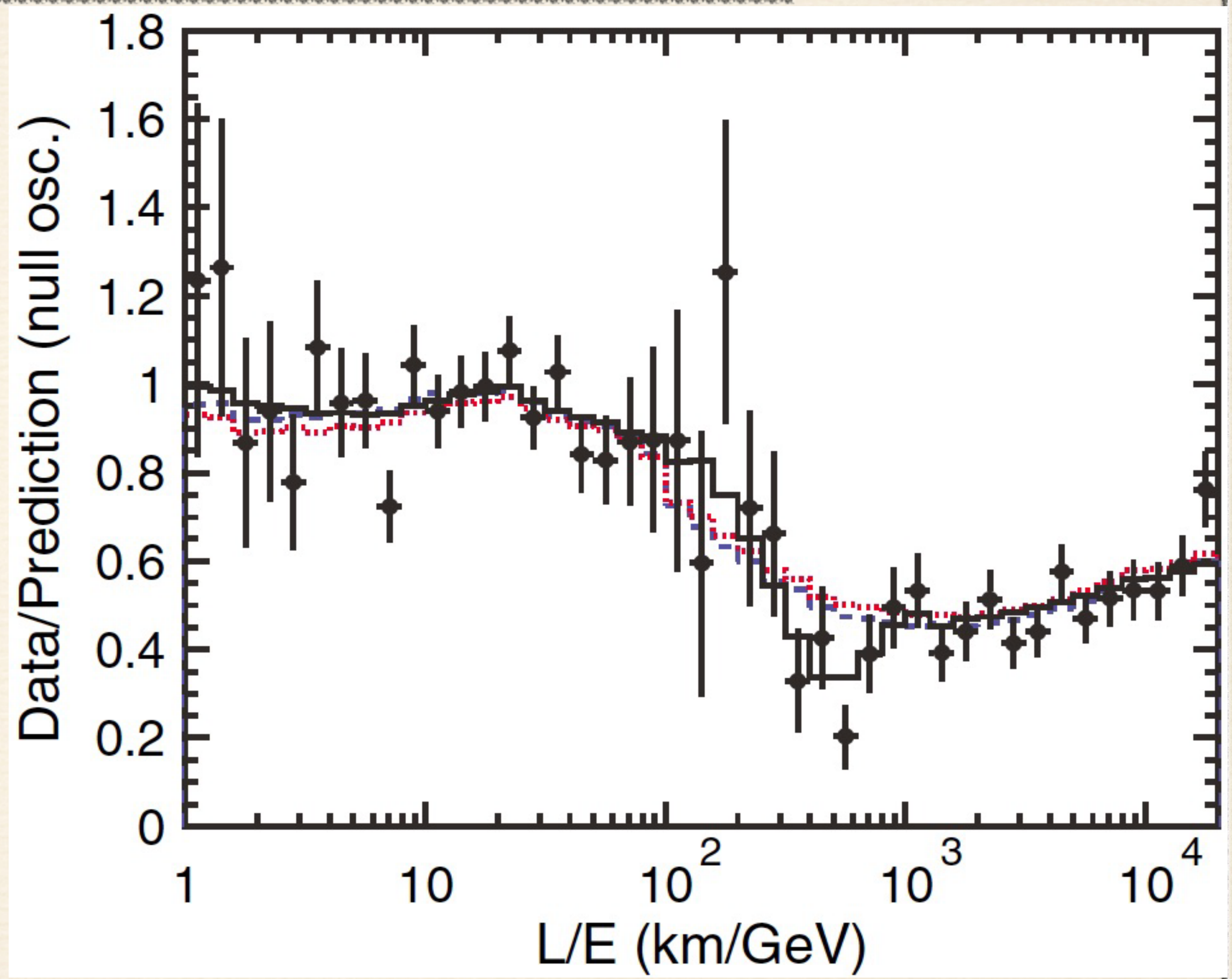
- WIMPs get trapped in gravity wells when they interact with matter (single scattering)
- equilibrium: capture rate=annhil. rate; annihil. rate measurement implies WIMP cross section



PRD 70, 083523 (2004)

Search for the Oscillation Pattern

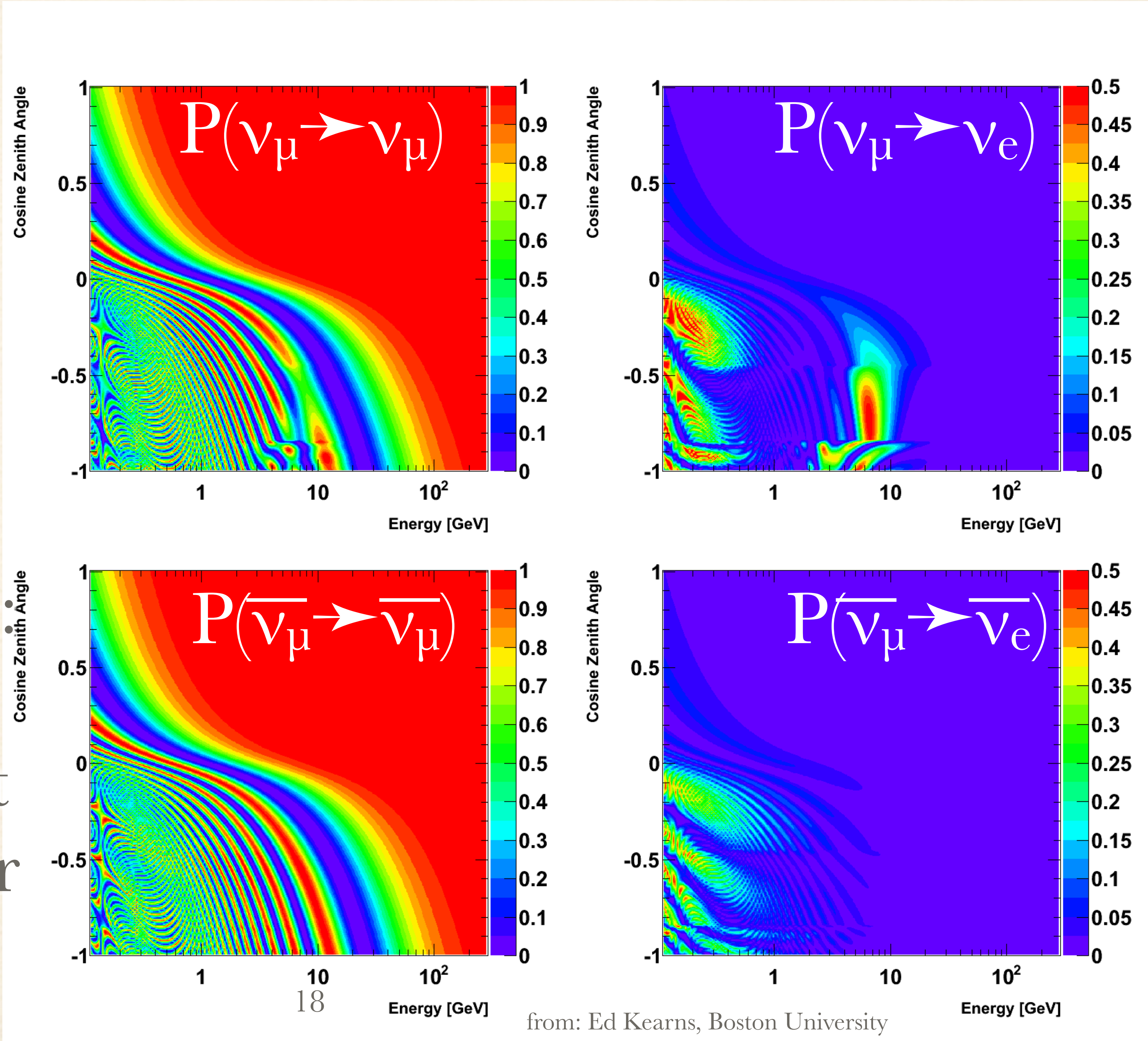
- angular resolution of outgoing lepton limits the oscillation pattern
- make cut on energy and zenith angle to select high resolution event
- observe the oscillatory pattern



Phys. Rev. Lett. **93**, 101801

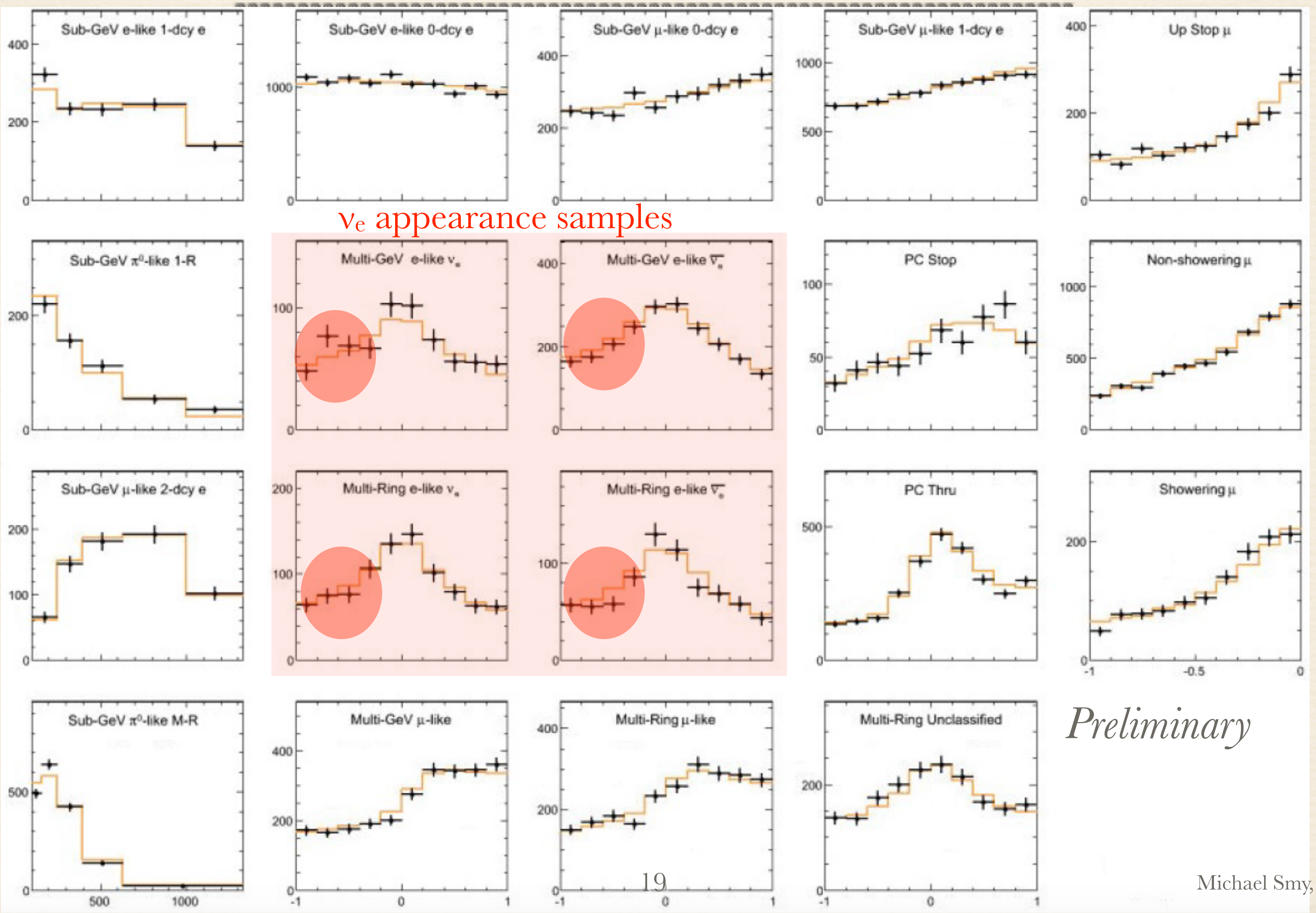
Current and Future Measurements

- mass ordering
- octant of θ_{23} ($<45^0$ or $>45^0$)
- CP violation δ
- rich laboratory: large energy range, different samples, matter effects…



from: Ed Kearns, Boston University

Super-K Atmospheric ν Data



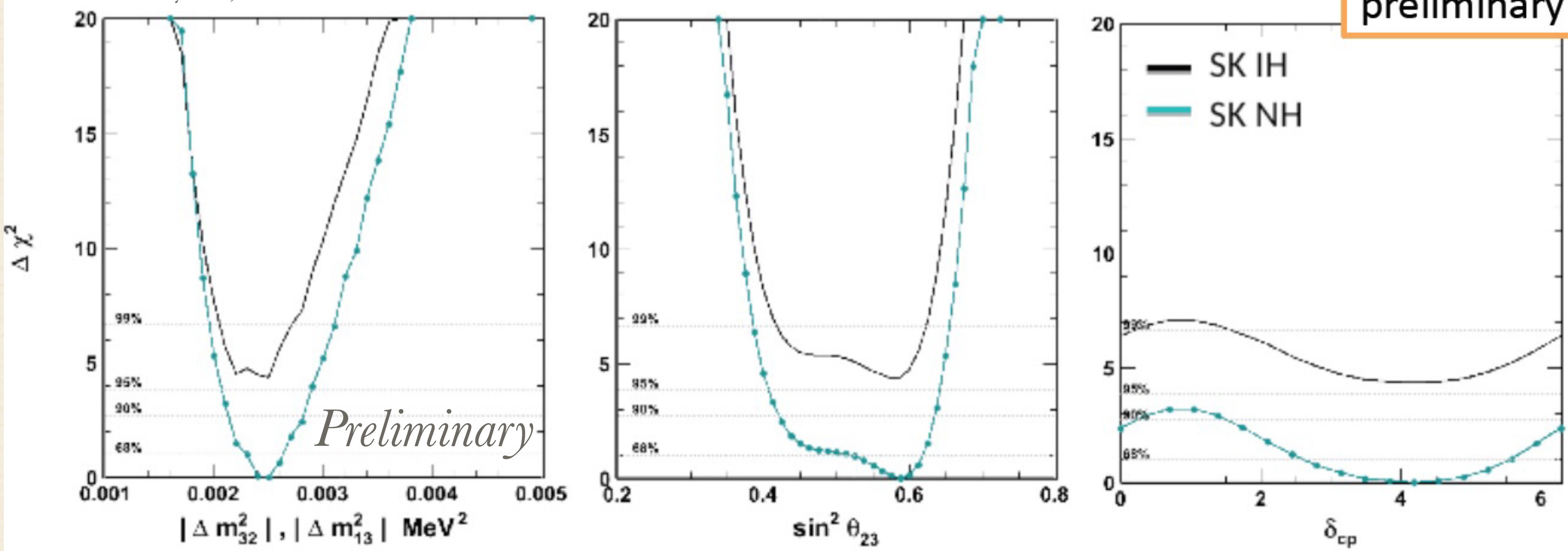
Michael Smy, UC Irvine

Oscillation Fit

SK only parameter determination

from: S. Moriyama, ICRR Neutrino 2016

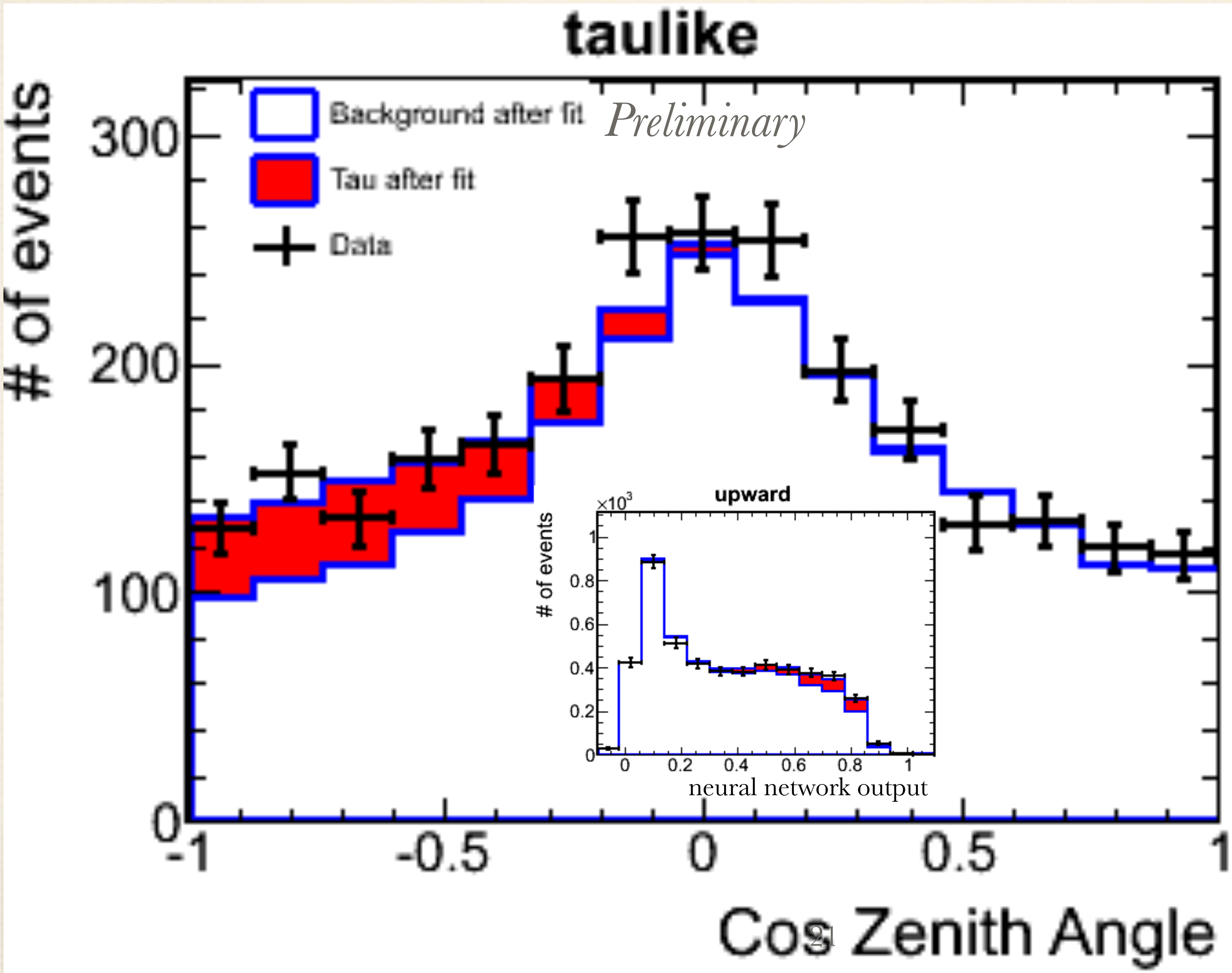
preliminary



Fit (517 dof)	χ^2	$\sin^2\theta_{13}$	δ_{CP}	$\sin^2\theta_{23}$	$\|\Delta m^2_{32}\|$ eV^2
SK (NH)	571.74	0.0219 (fix)	4.189	0.587	2.5×10^{-3}
SK (IH)	576.08	0.0219 (fix)	4.189	0.575	2.5×10^{-3}

- slight preference for normal mass ordering ($\Delta\chi^2$=4.3)
- very slight preference for $\delta_{CP}=-\pi/2$

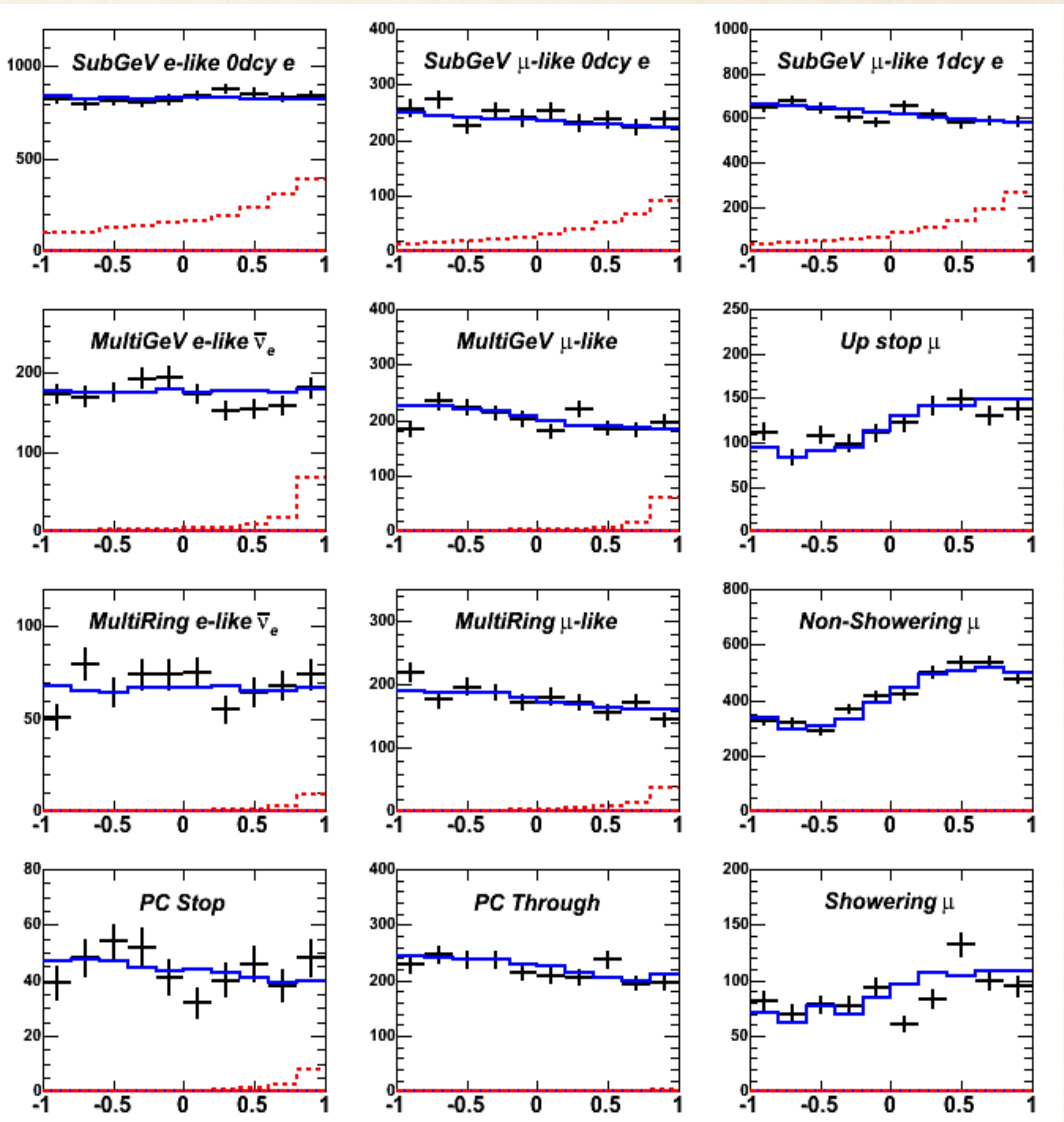
τ Appearance



- ν_τ comp. fit: 1.46 ± 0.31 ($4.6\ \sigma$)

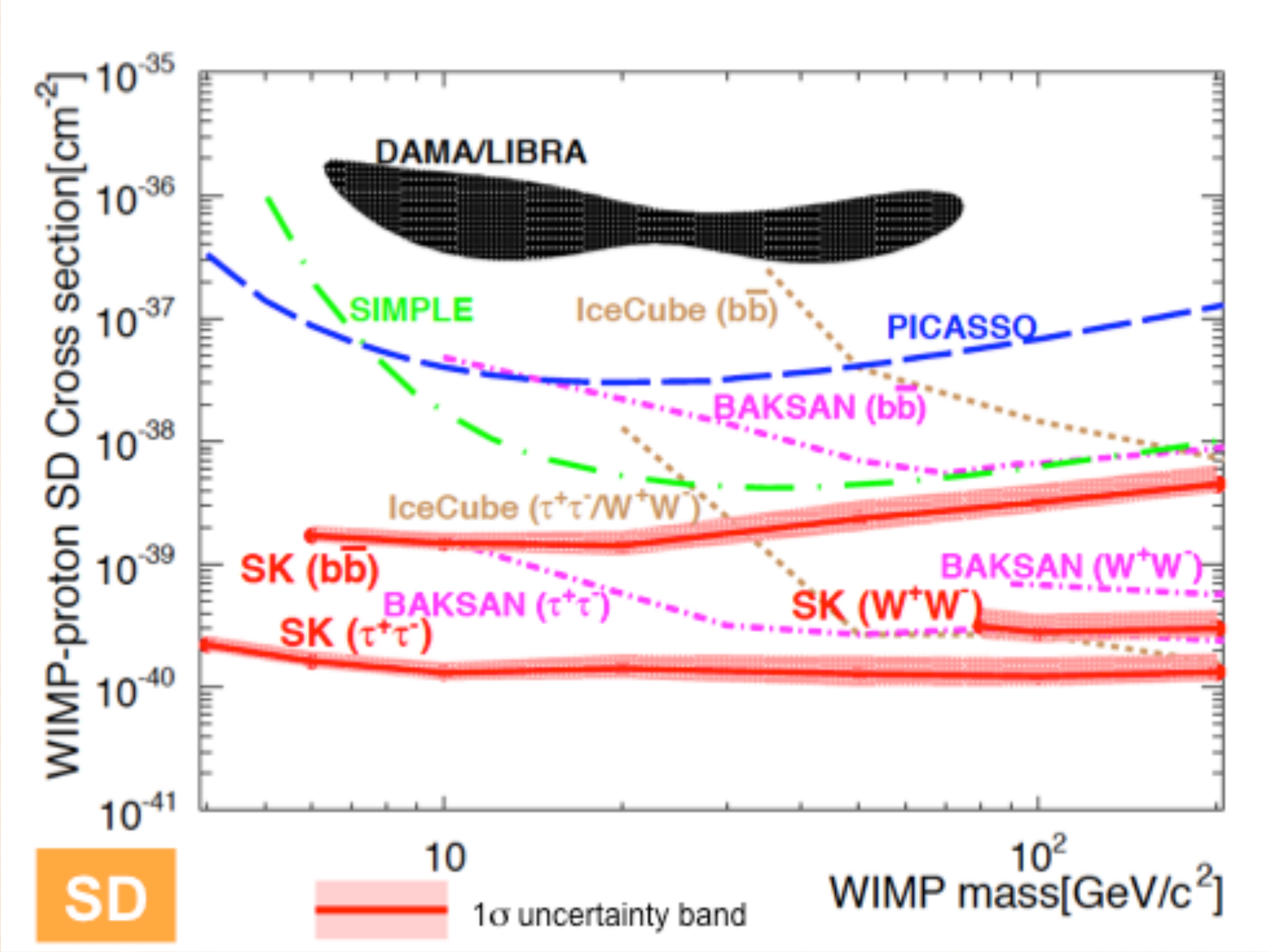
WIMPs: Present Solar Search

- analysis of all data sets
- first serious search for CP violation
- more electrons than expected and less positrons
- amplifies reach



Courtesy P. Mijakowski, National Centre for Nuclear Research, Warsaw

WIMPs: Limits from Solar Search



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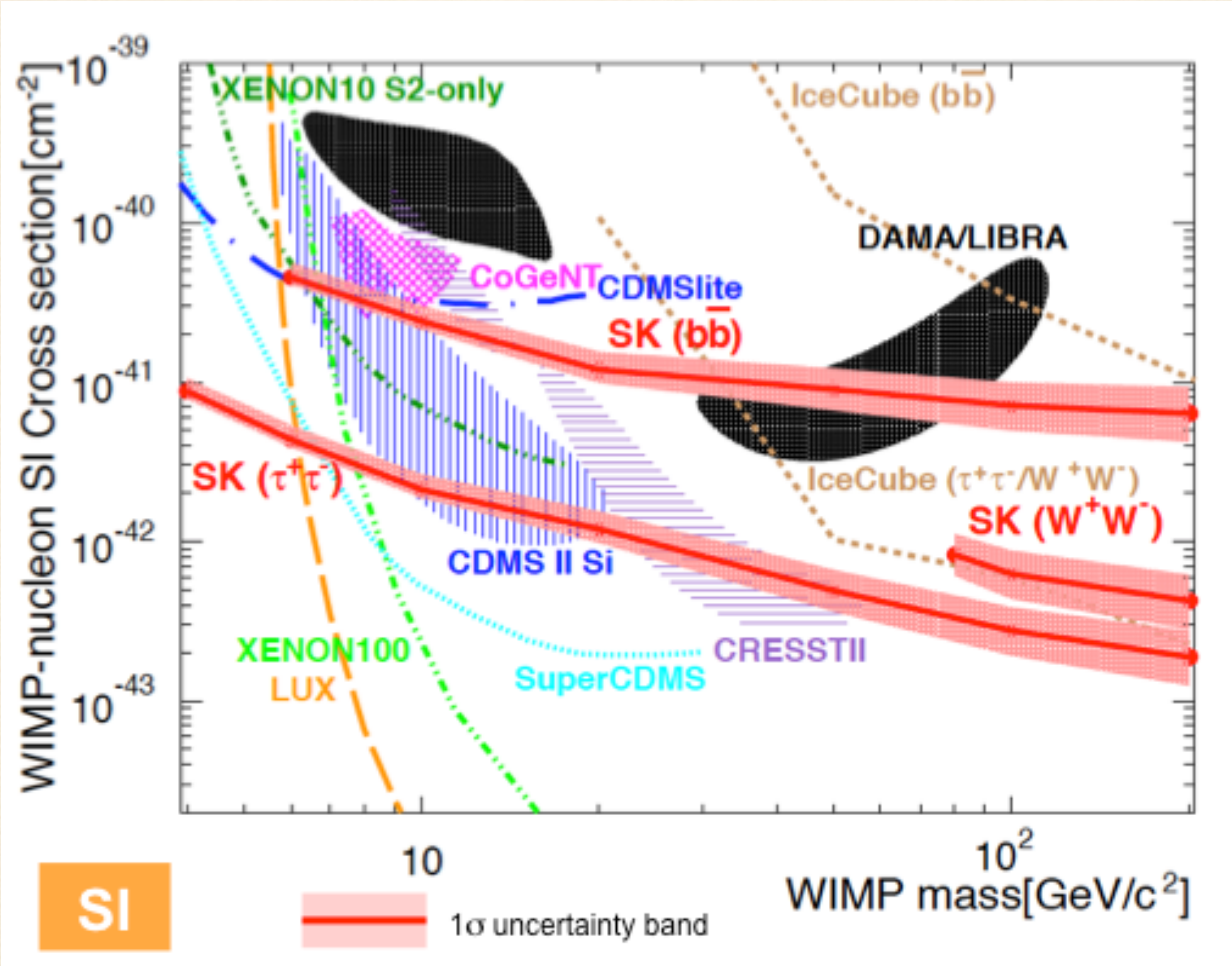
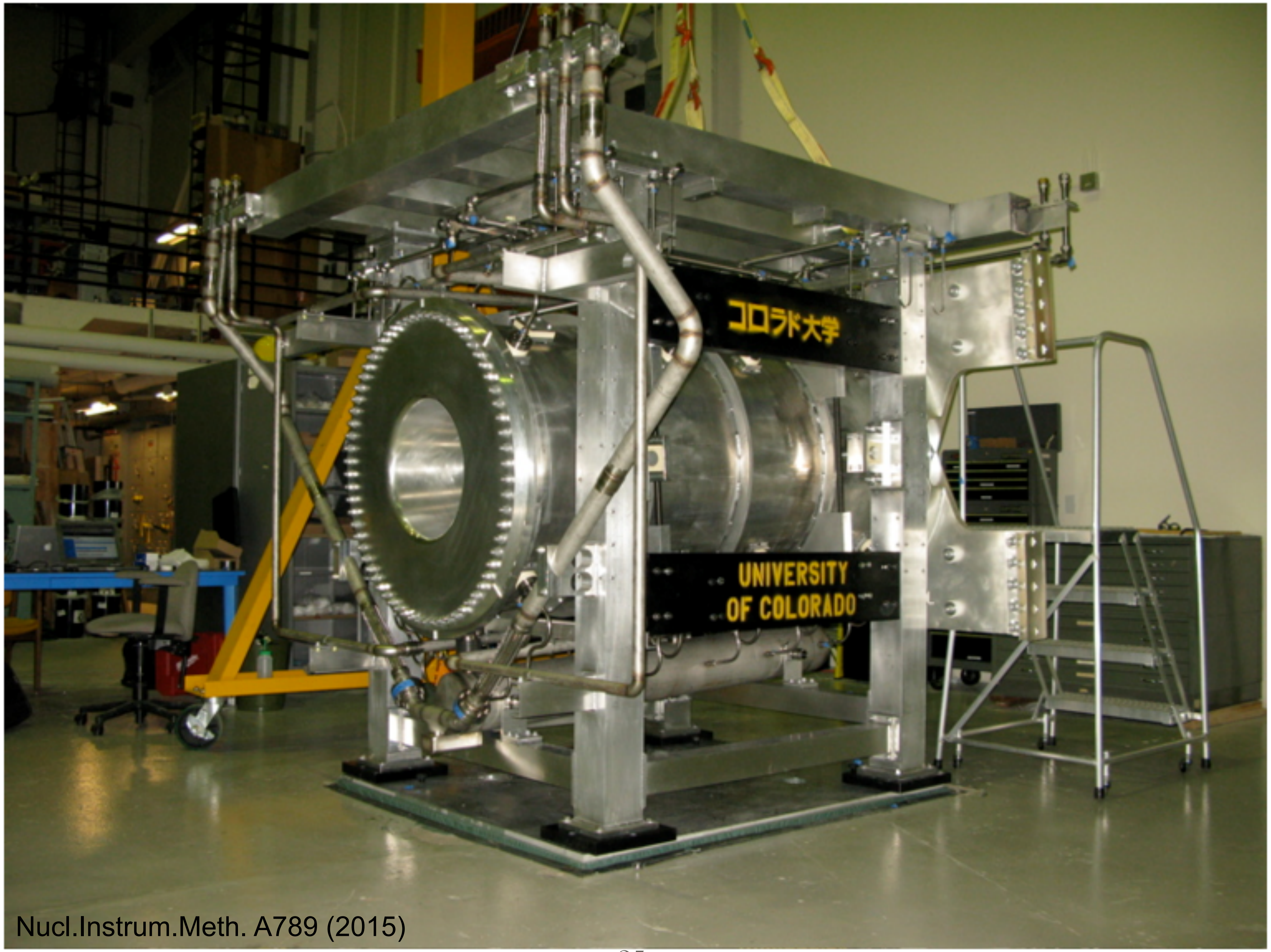


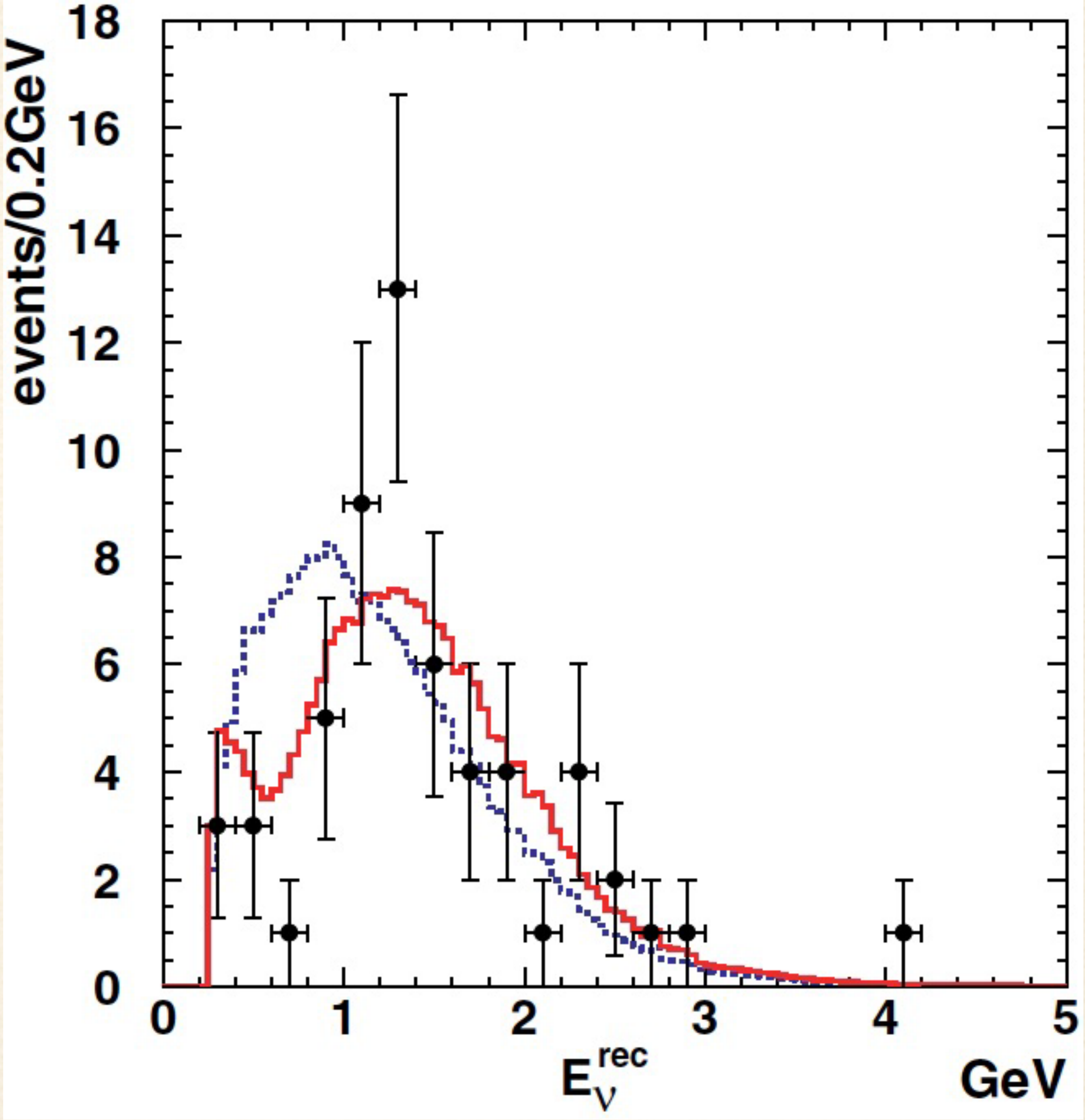
Courtesy P. Mijakowski, National Centre for Nuclear Research, Warsaw

Accelerator Neutrinos



K2K: KEK to Kamioka

- on axis beam produced by a 12 GeV proton beam hitting an Al target at KEK
- beam is focussed by a horn and send over 250km to Super-K
- predominantly ν_μ
- confirm disappearance of ν_μ and even a “dip” in the oscillation pattern

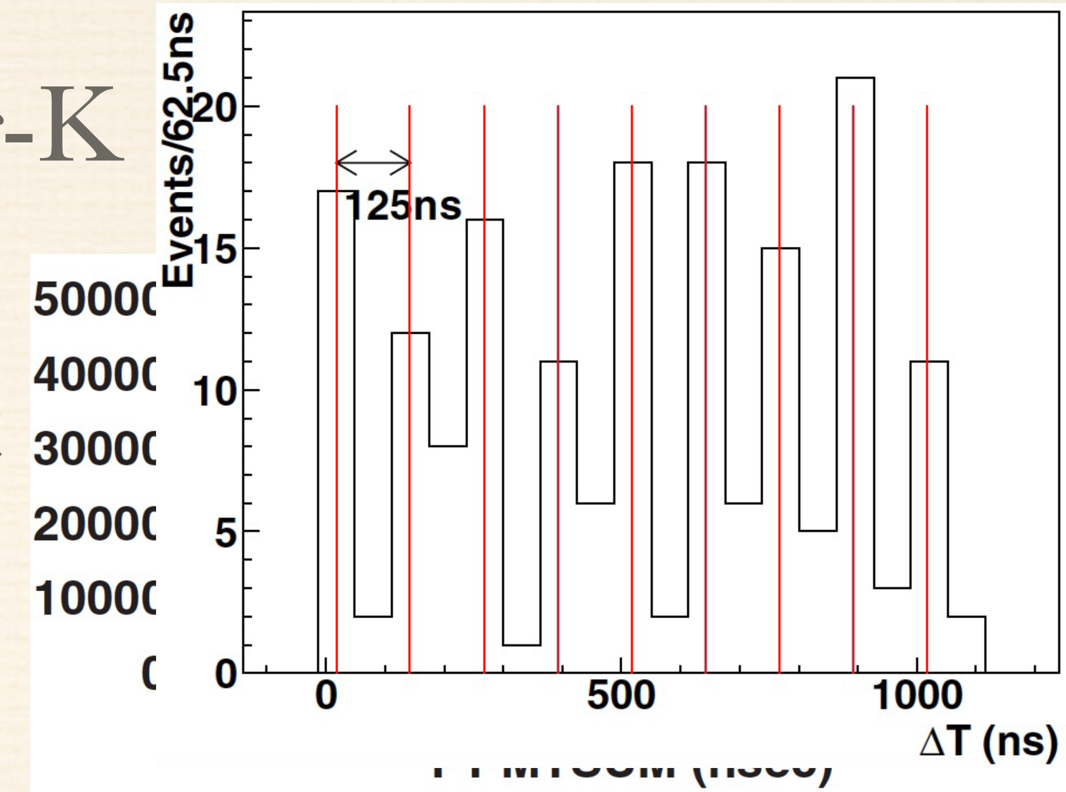


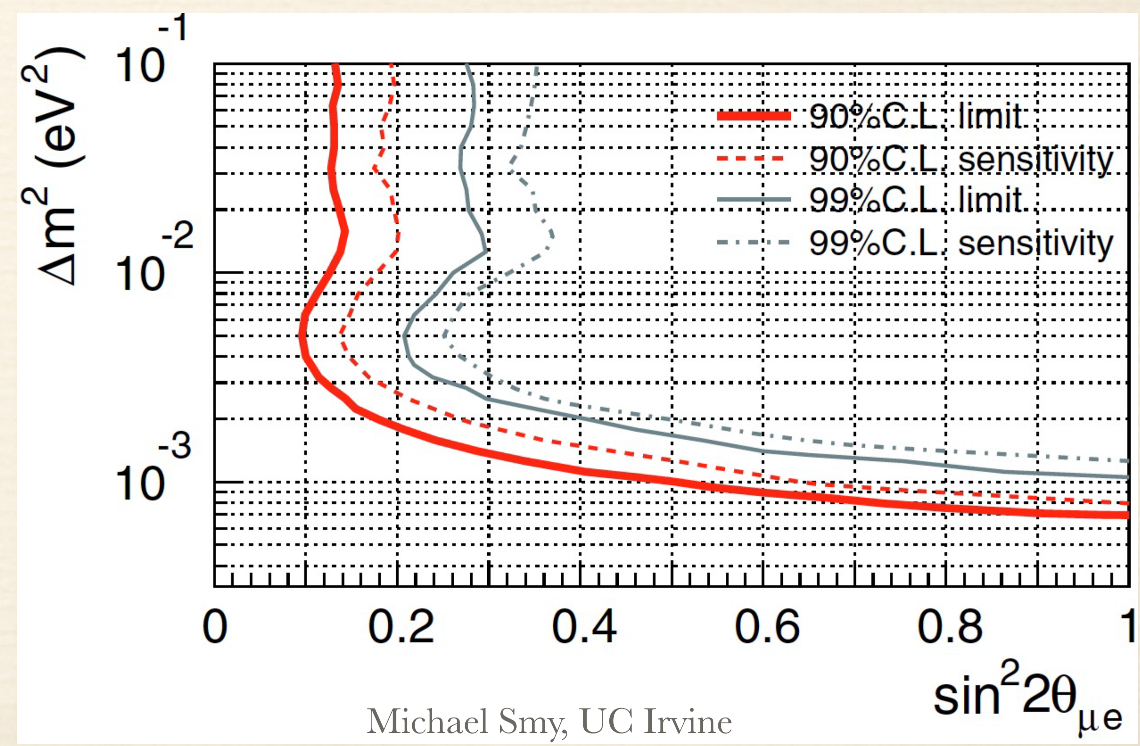
K2K: KEK to Kamioka

- use “1kt”, a mini-version of Super-K as near detector as well as fine-grained detectors
- first long-distance transmission via neutrinos: the nine-bunch structure of the proton beam
- first search of $\nu_\mu \rightarrow \nu_e$: 1 candidate, 1.7 expected background

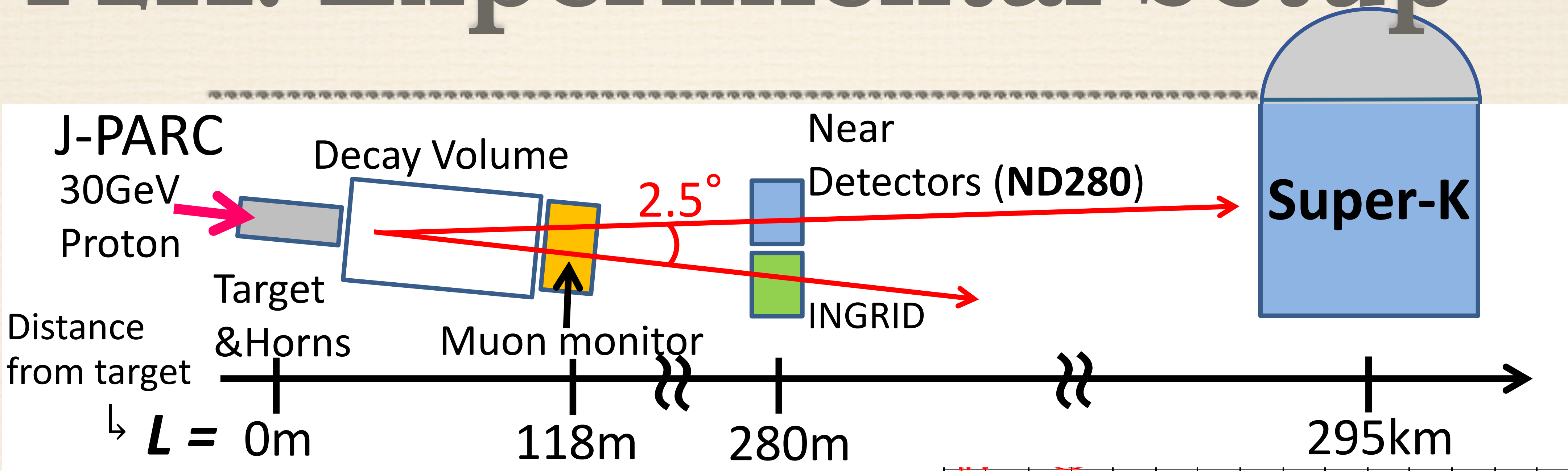
Super-K

1kt





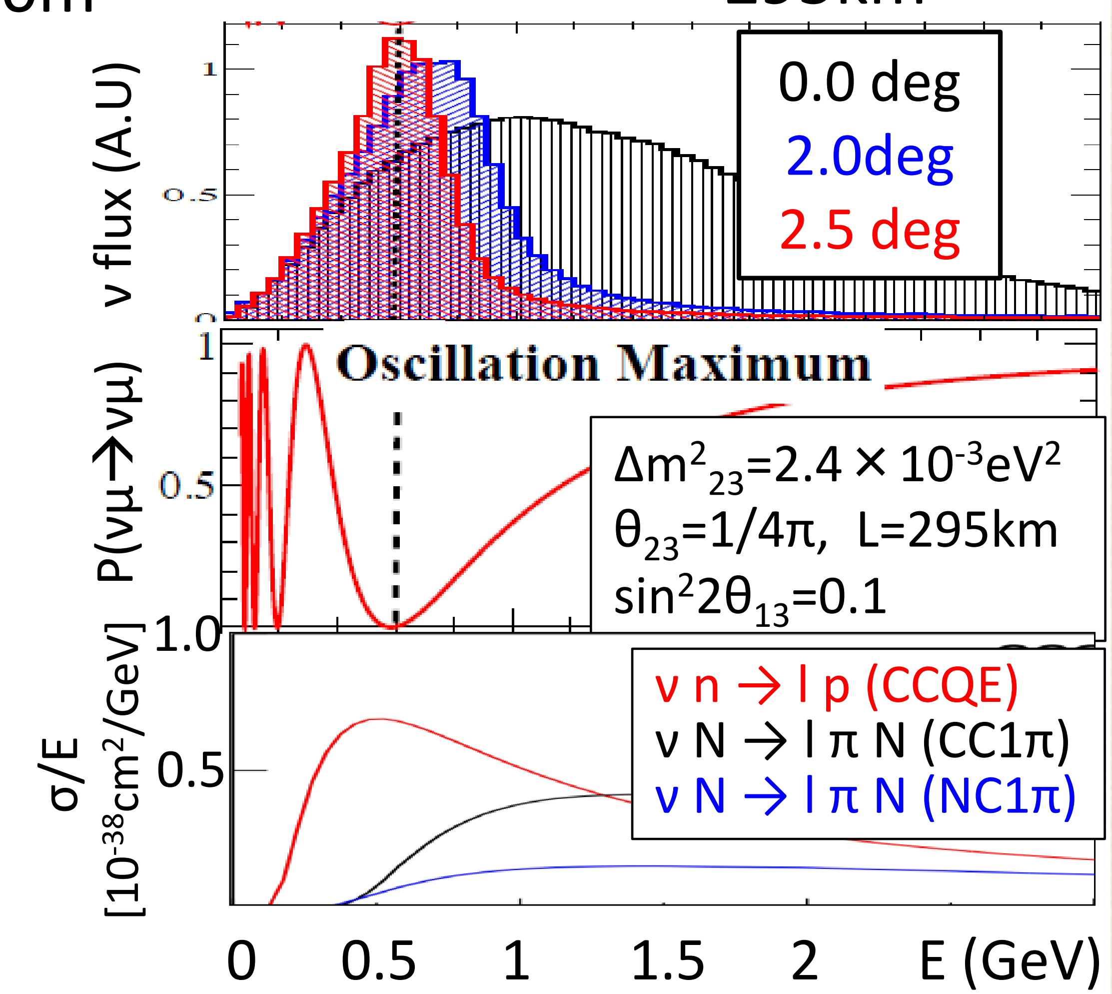
T2K: Experimental Setup



- Secondary π^+(and K^+) from 30 GeV protons focused by three E.M. horns

- ν_μ beam (mainly $\pi^+ \rightarrow \mu^+ + \nu_\mu$)

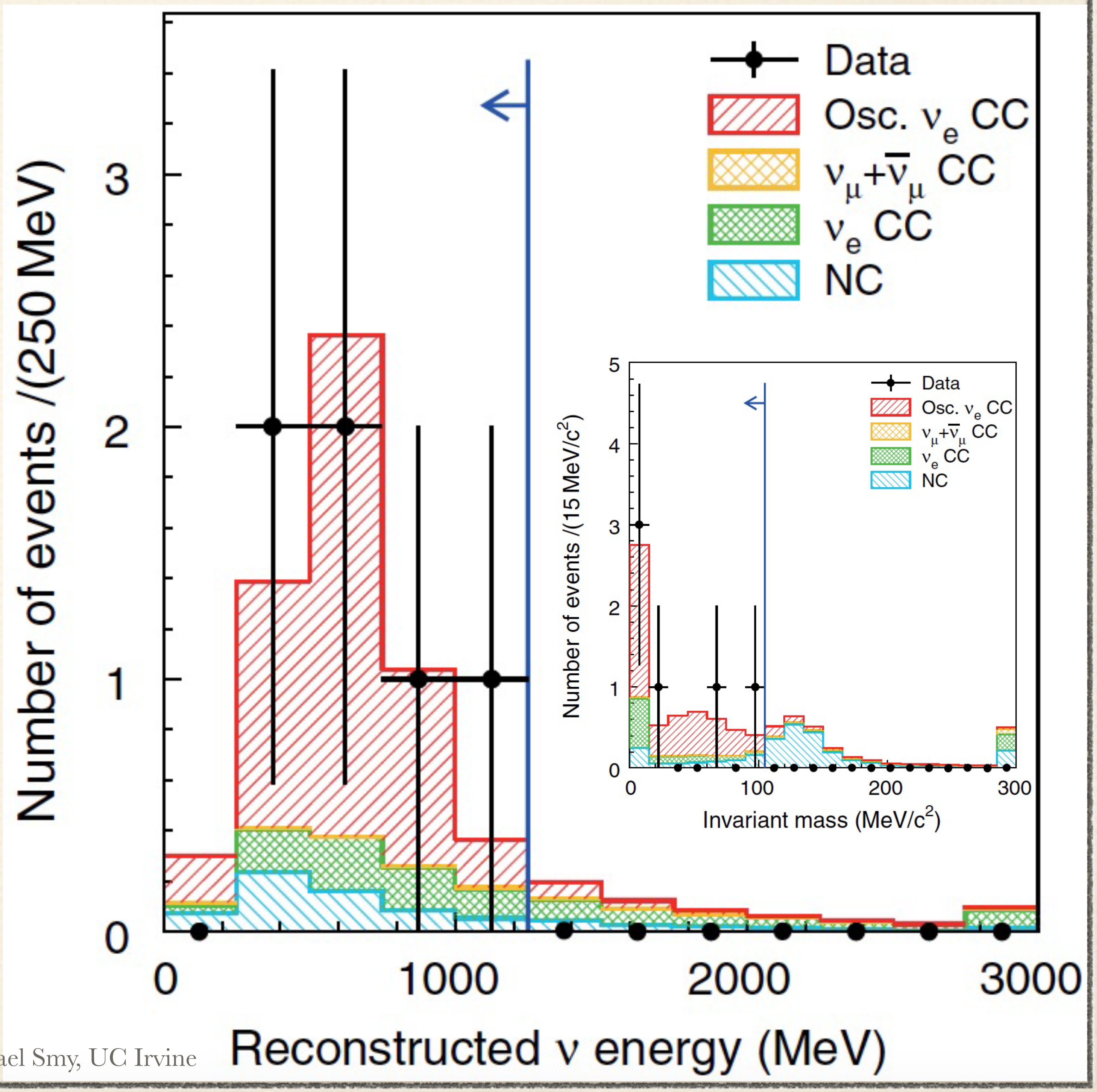
- Off axis neutrino beam(2.5°)
  - Narrow band @ osc. max
  - Reduce BG from high energy
  - ν direction stability < 1mrad



Courtesy M. Ikeda, Kyoto University

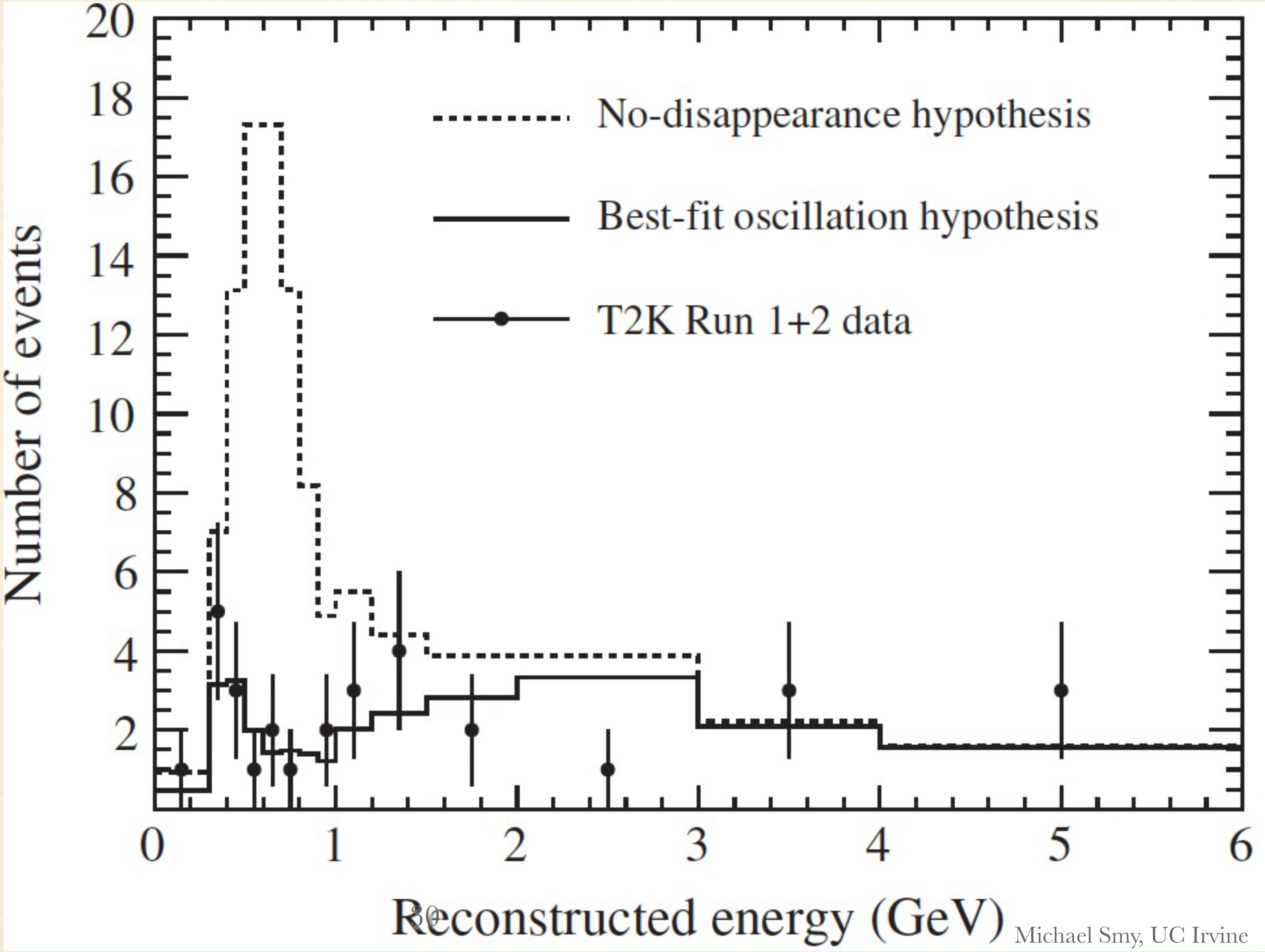
Discovery of $\nu_\mu \rightarrow \nu_e$

- using POLfit, a reconstruction tool that always assume two e-like rings, can control π^0 background
- data taking was temporarily delayed by a 9.0 earthquake
- eventually, statistical significance exceeded seven sigma

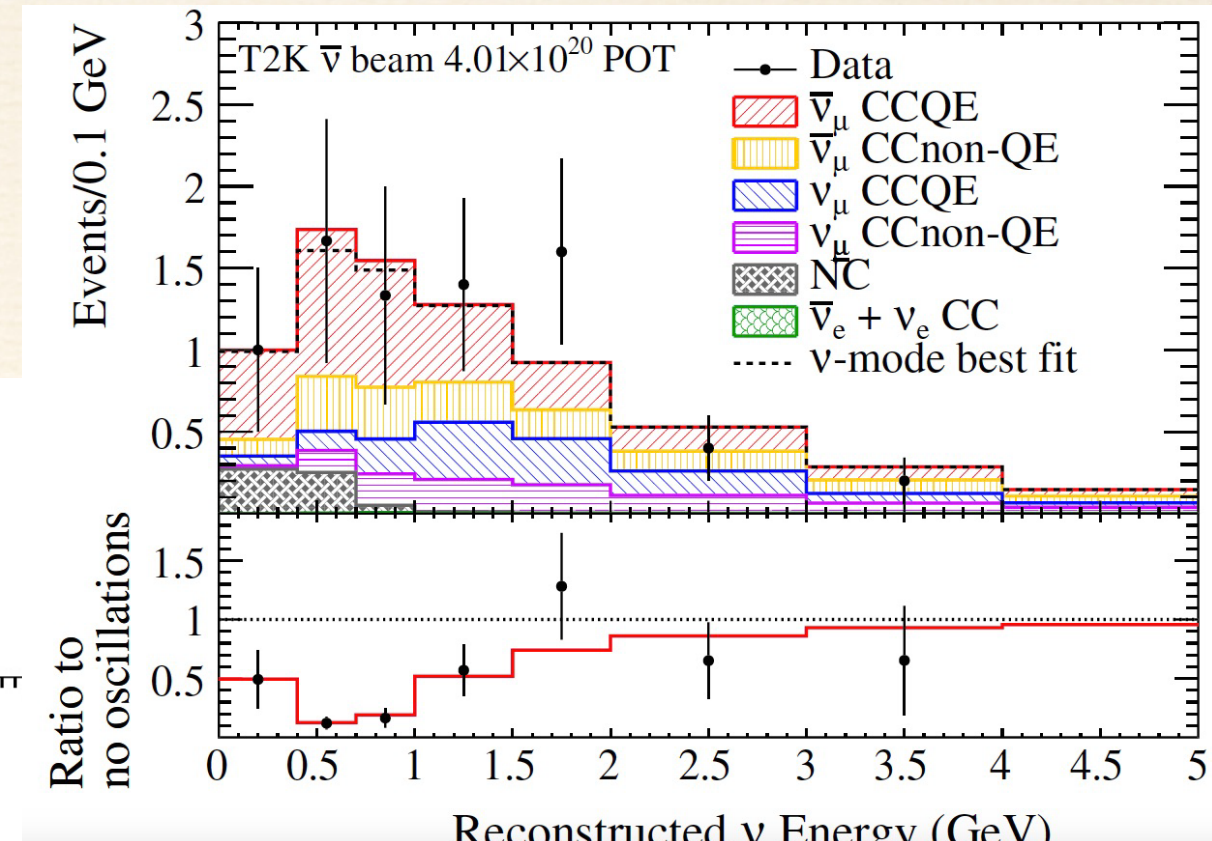


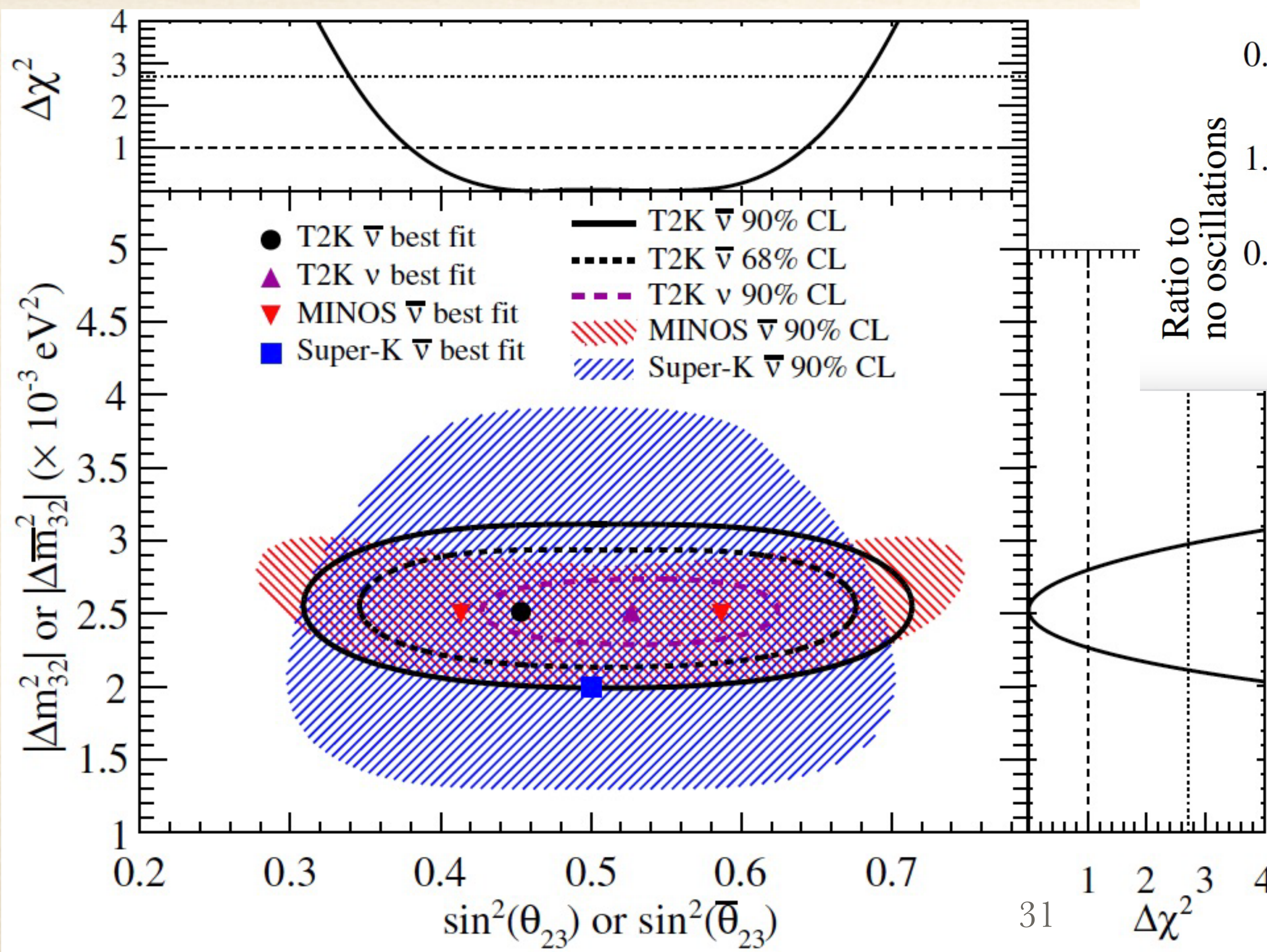
Maximal Disappearance: T2K $\nu_\mu \rightarrow \nu_\mu$

- almost all events are gone!
- eventually, the world's best measurement of θ_{23}
- disadvantage: hard to pinpoint the "dip"



Maximal Disappearance: T2K $\bar{\nu}_\mu \to \bar{\nu}_\mu$

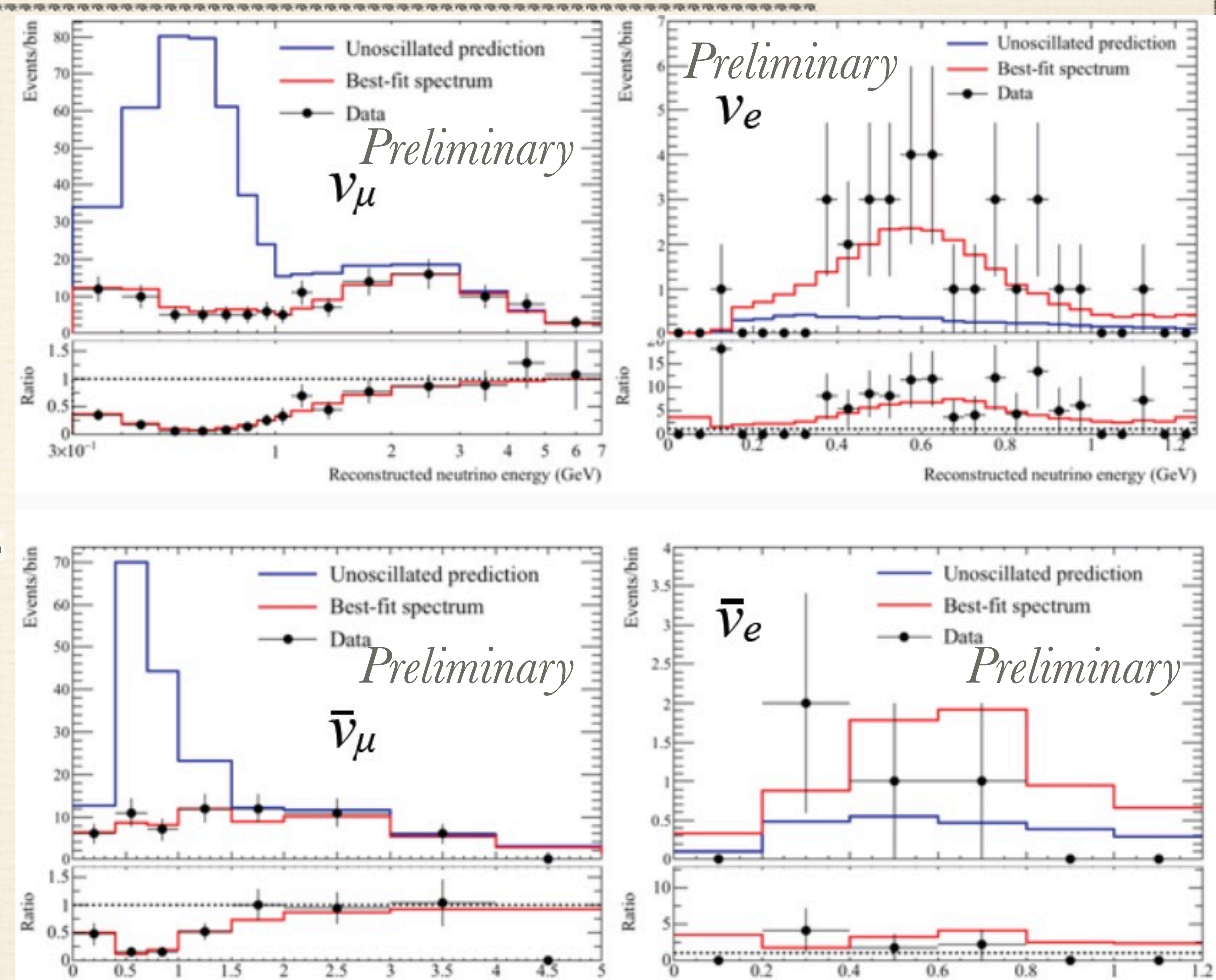




- checks CPT invariance
- consistent with muon disappearance
- larger backgrounds

T2K Results (so far) $\nu_\mu \rightarrow \nu_e$

- analysis of all data sets
- first serious search for CP violation
- more electrons than expected and less positrons
- amplifies CP reach



H. Tanaka, Neutrino 2016

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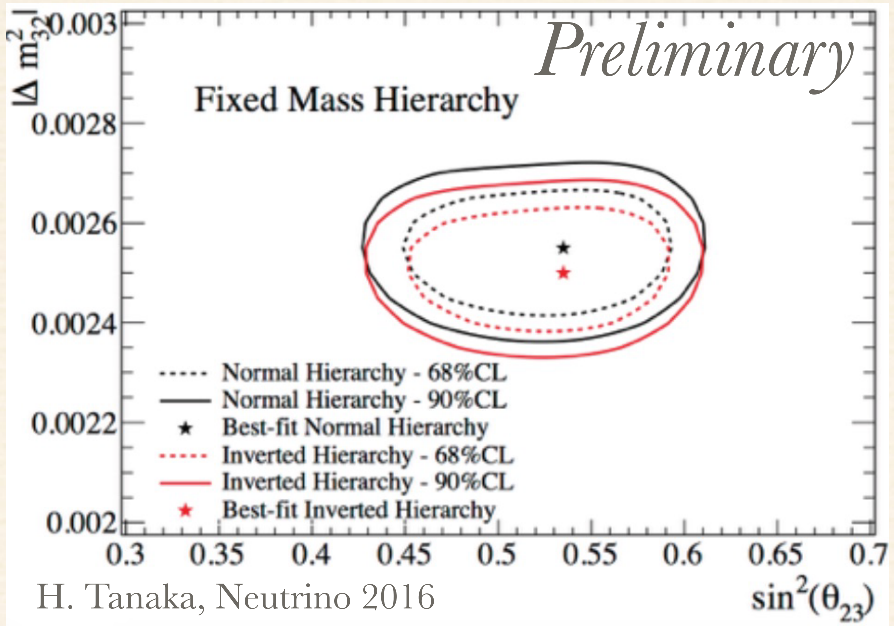
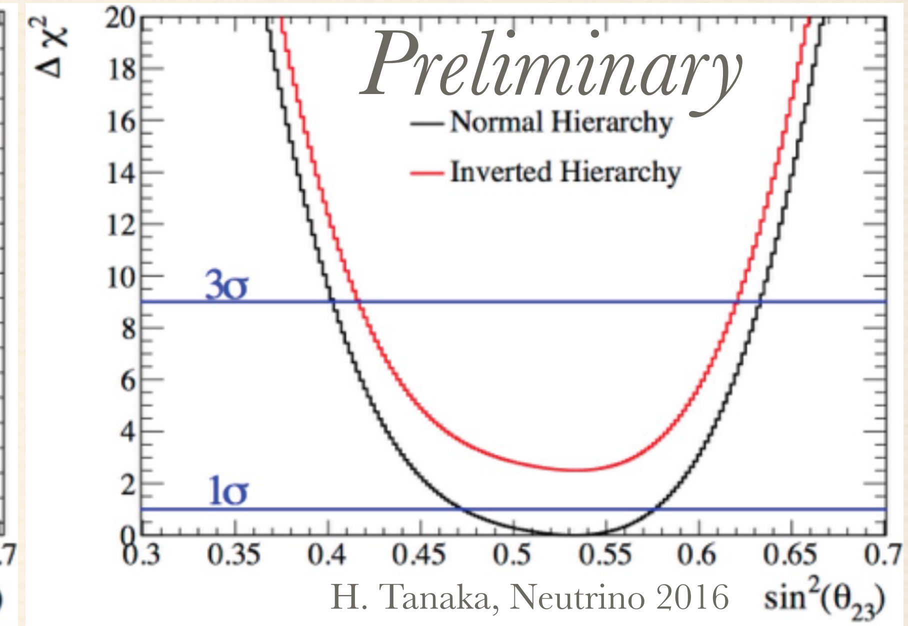
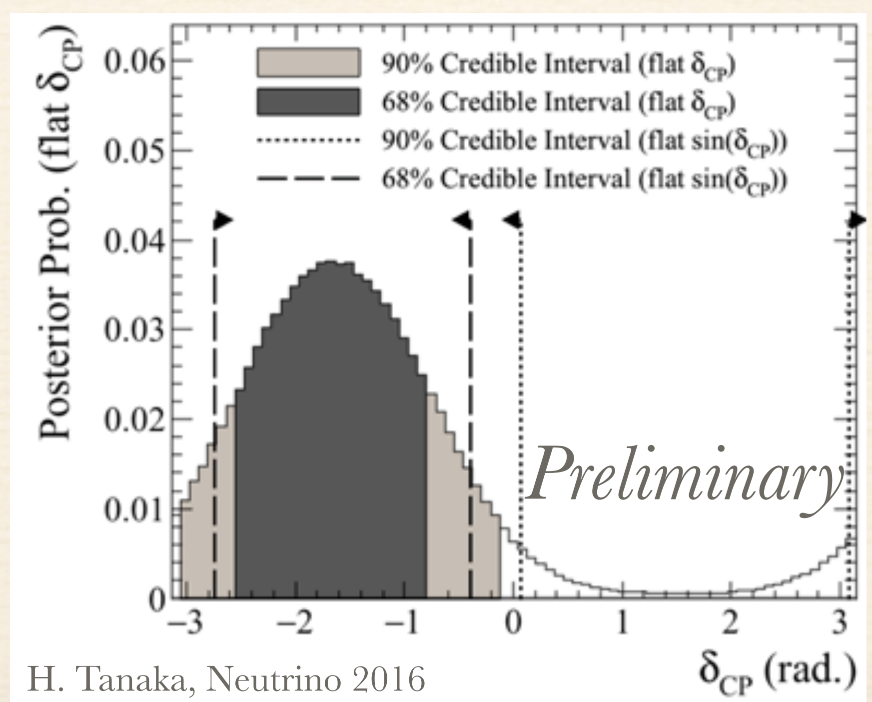
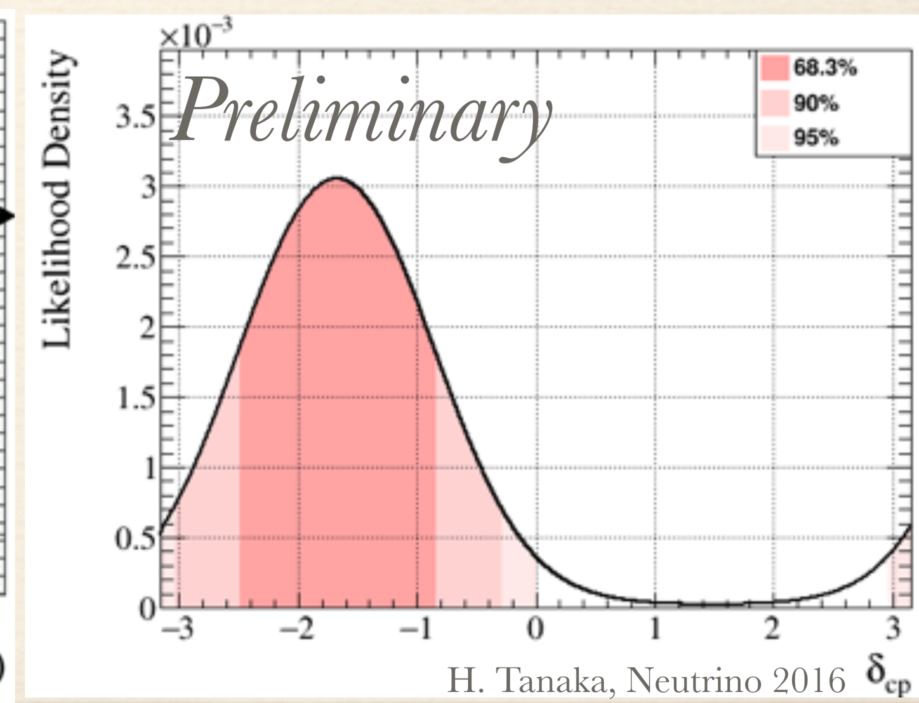




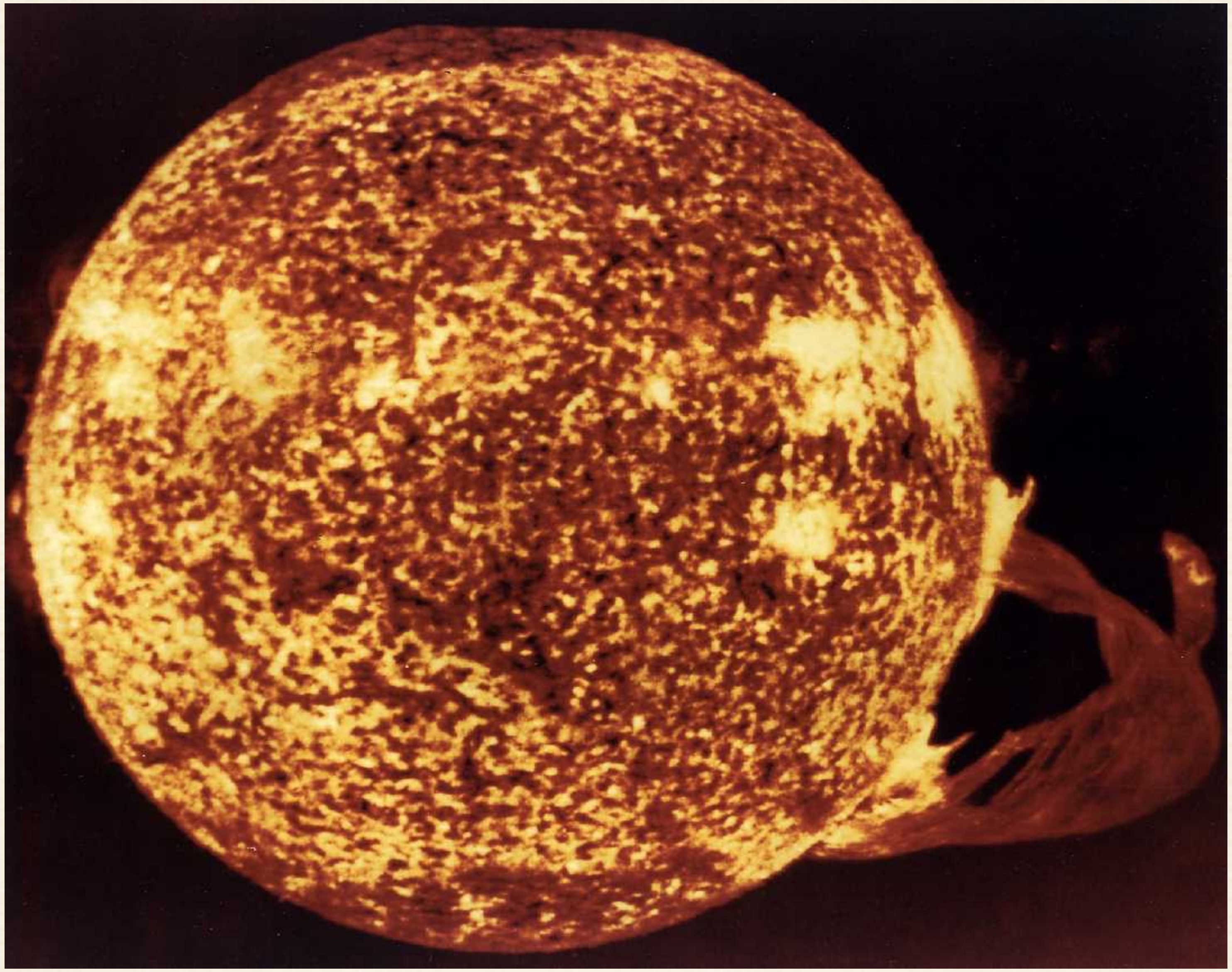
Bayesian analysis
use reconstructed energy



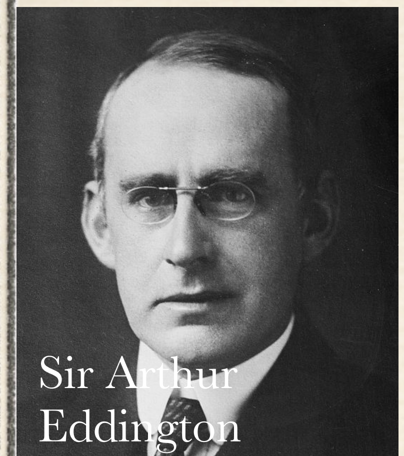
Bayesian analysis
use momentum, angle

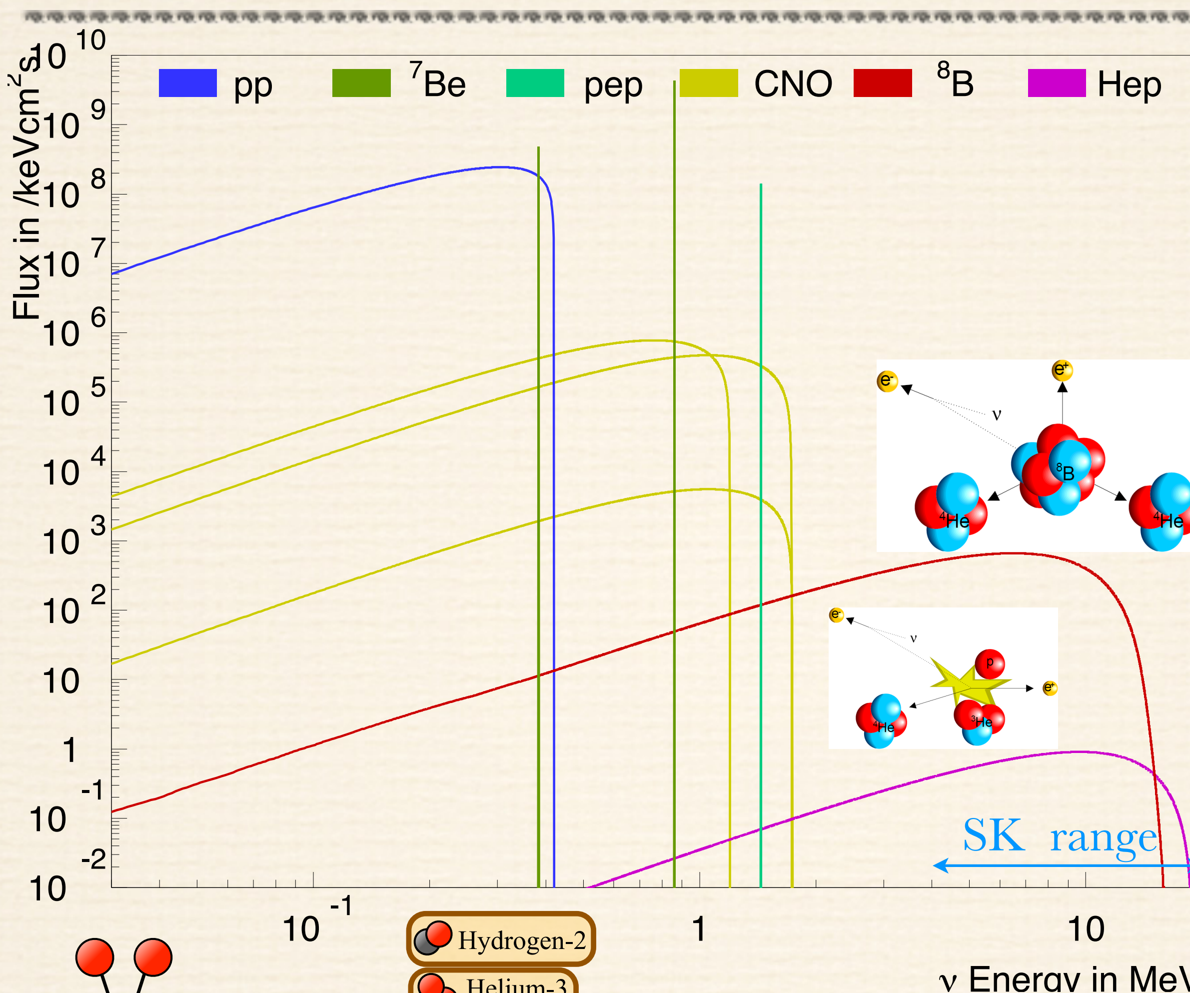


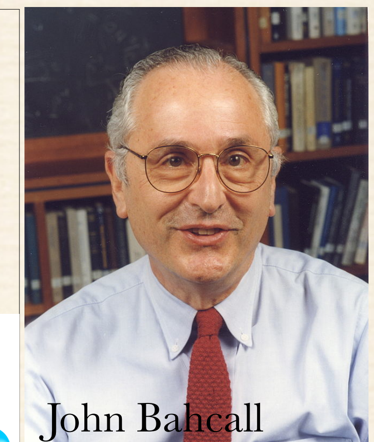
Solar Neutrinos

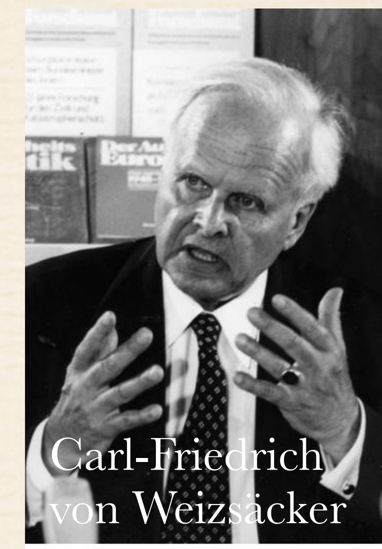


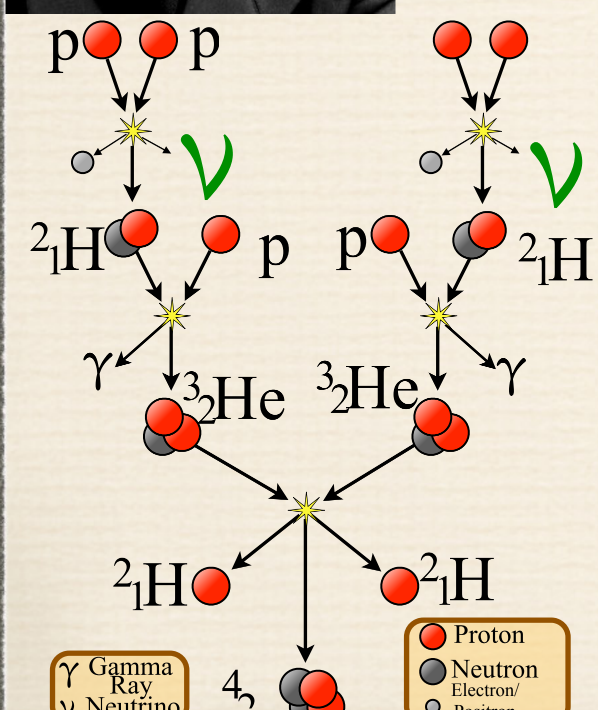
Solar Fusion and Solar Neutrinos

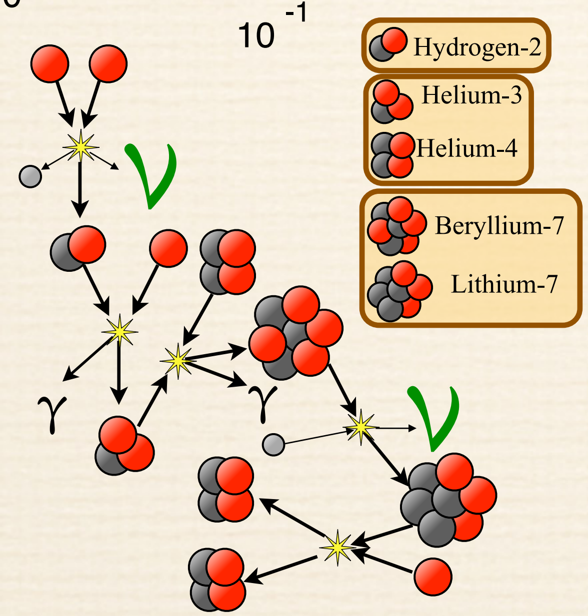




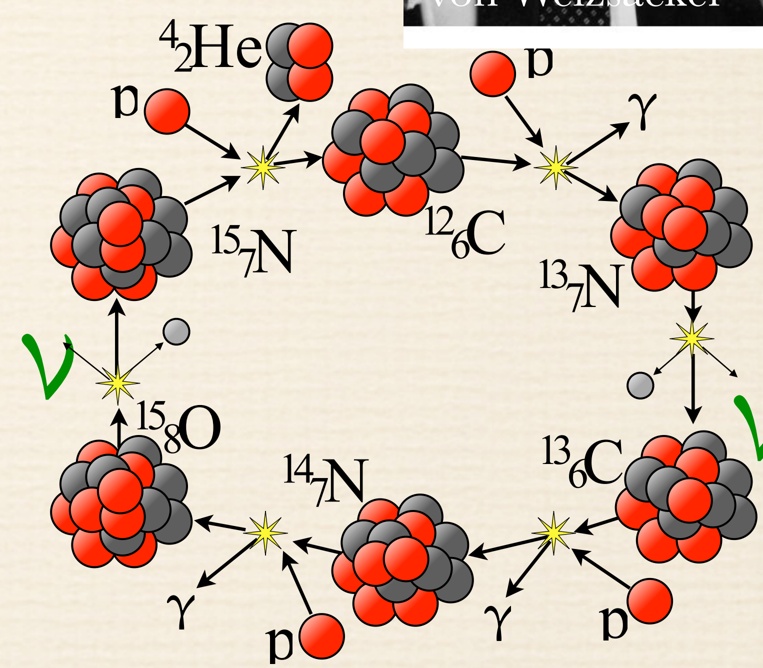








$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e$$



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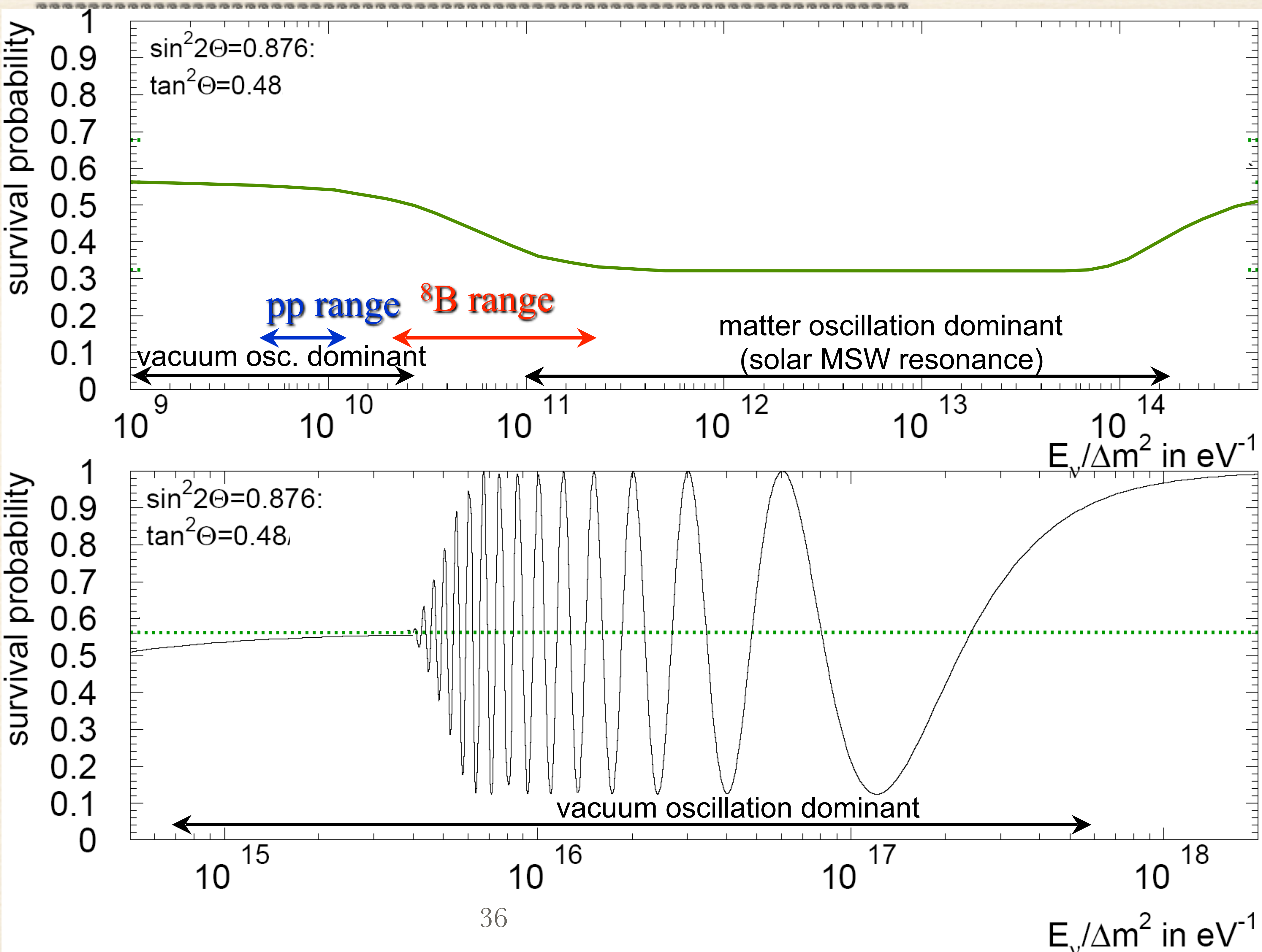
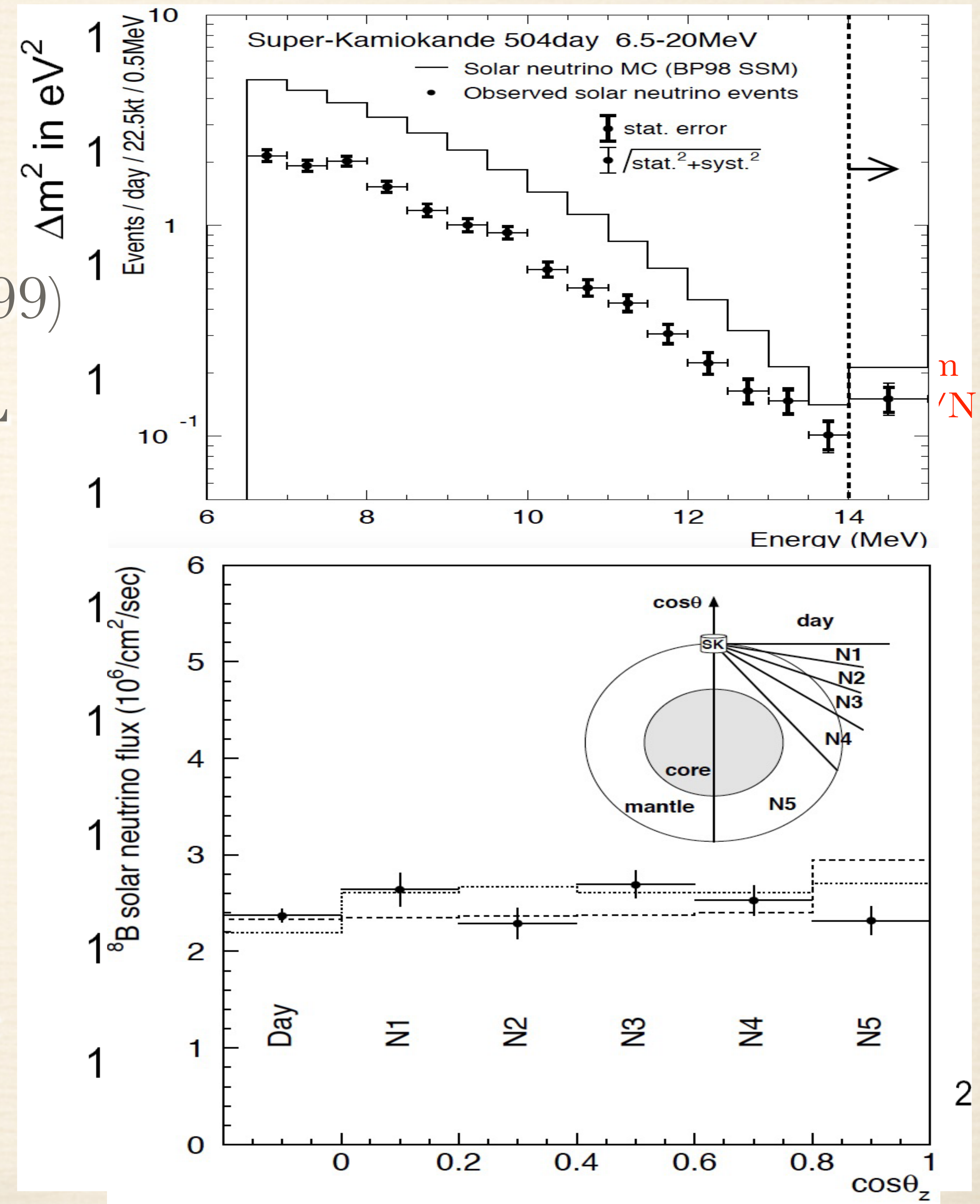
Solar Neutrino Survival Probability

- large mixing: very broad resonance
- solar ν's are on the edge
- for pp, only averaged vacuum oscillations
- coherence already lost above resonance
- strong Earth effects in the same region

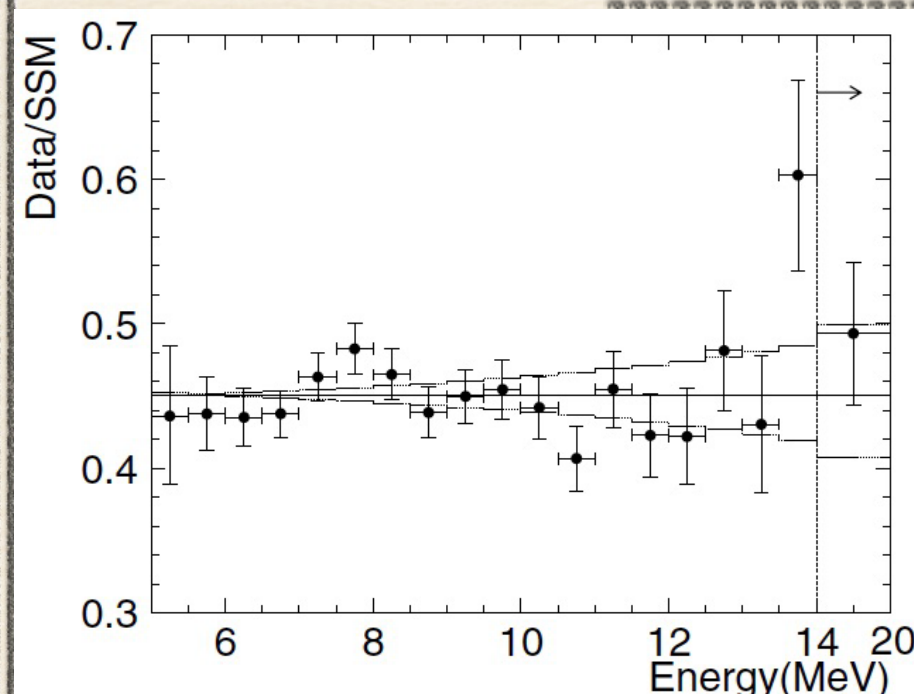


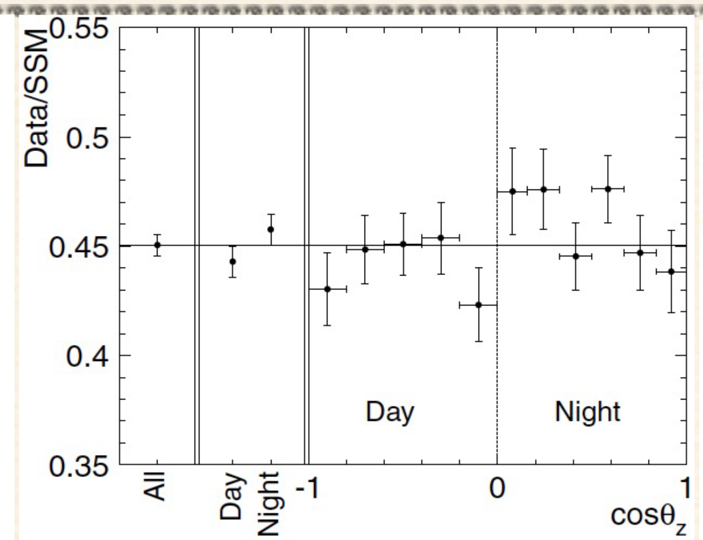
Constrain Neutrino Oscillation Parameters

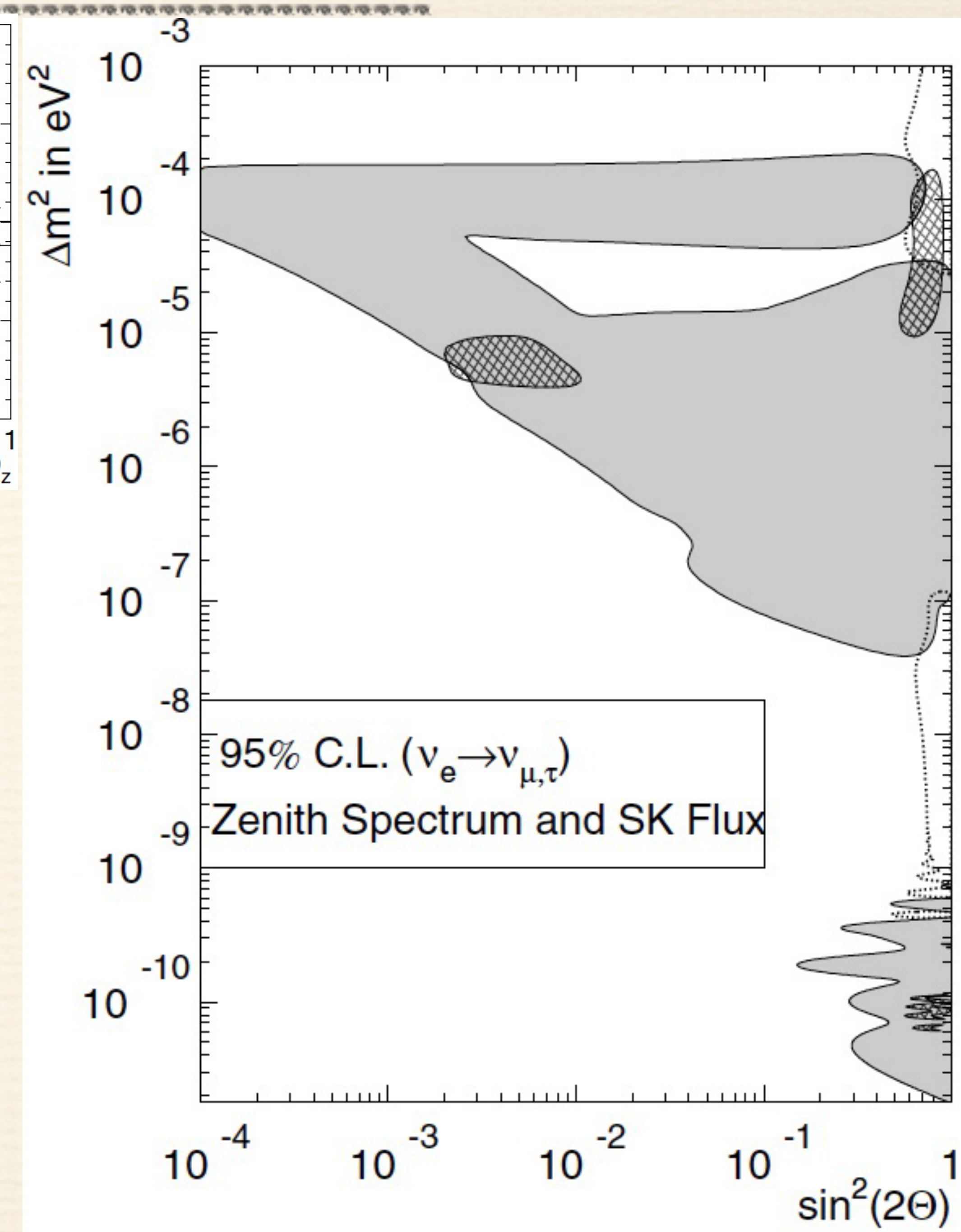
- many different, disjoint regions of oscillations parameters called SMA, LMA, Low and Vacuum
- day/night analysis: PRL 82, 1810 (1999)
- recoil electron spectrum analysis: PRL 82, 2430 (1999)
- at Neutrino 2000 in Sudbury: exclude small mixing and sterile neutrino oscillations at 95% C.L.
- beginning of the end of the "small mixing" paradigm
- it took two more years to convince the field this is correct…



A year later…



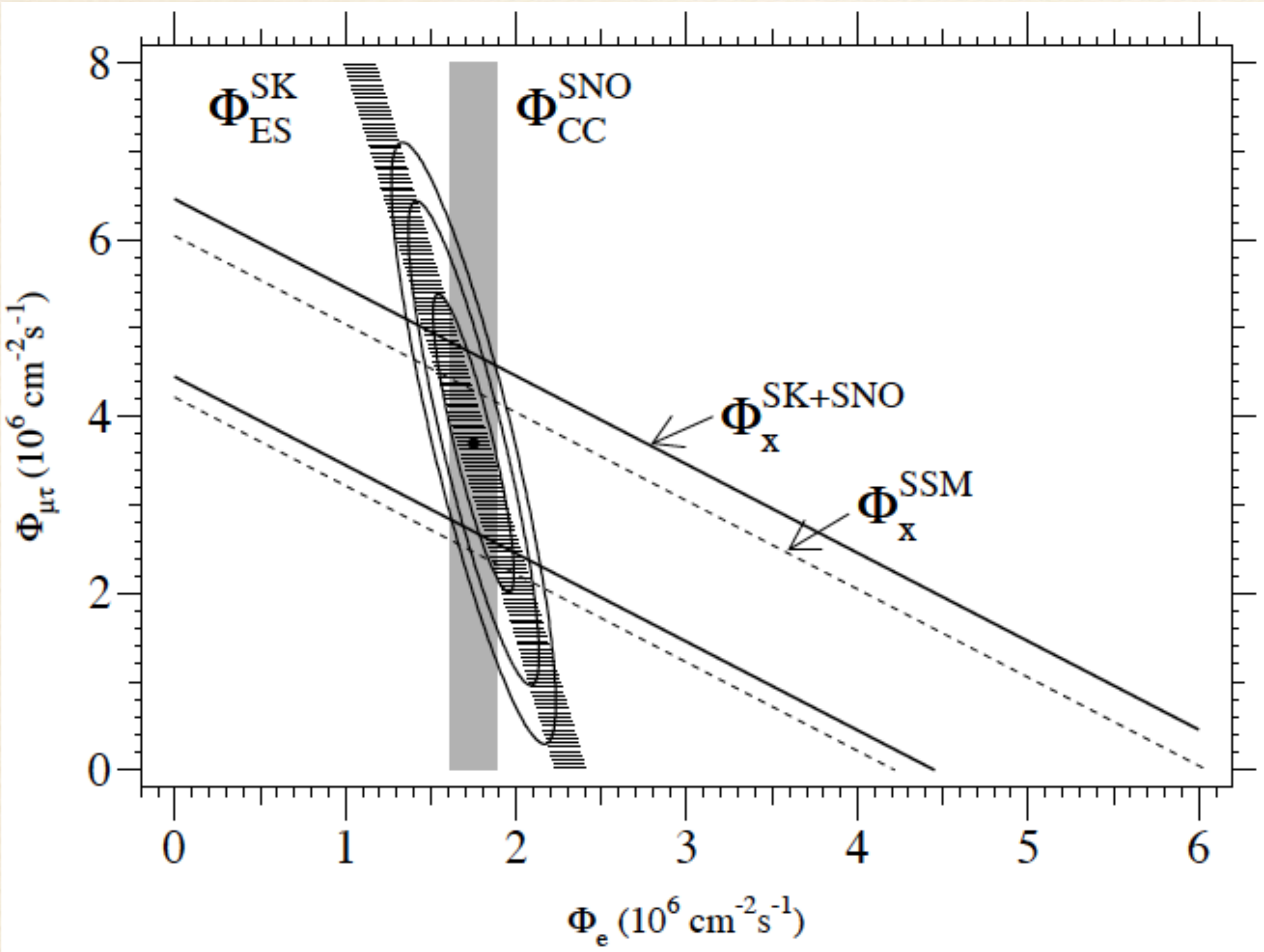




- careful study of recoil electron spectrum and solar zenith angle variation excluded also the Low solution favoring a single region of parameter space: LMA

"double paper"
Phys.Rev.Lett. 86 (2001) 5656-5665

The Discovery of Solar ν Oscillation

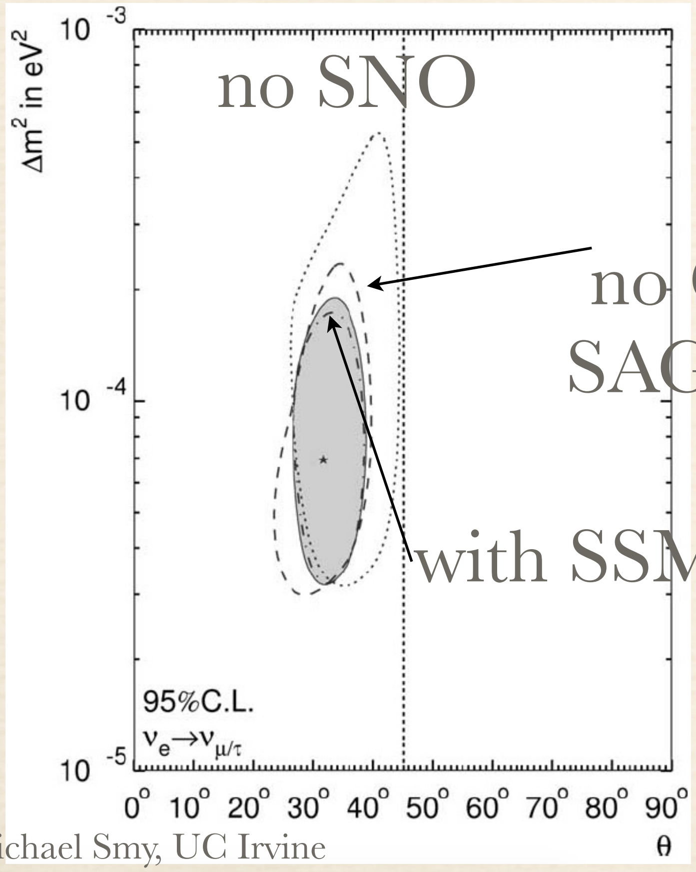


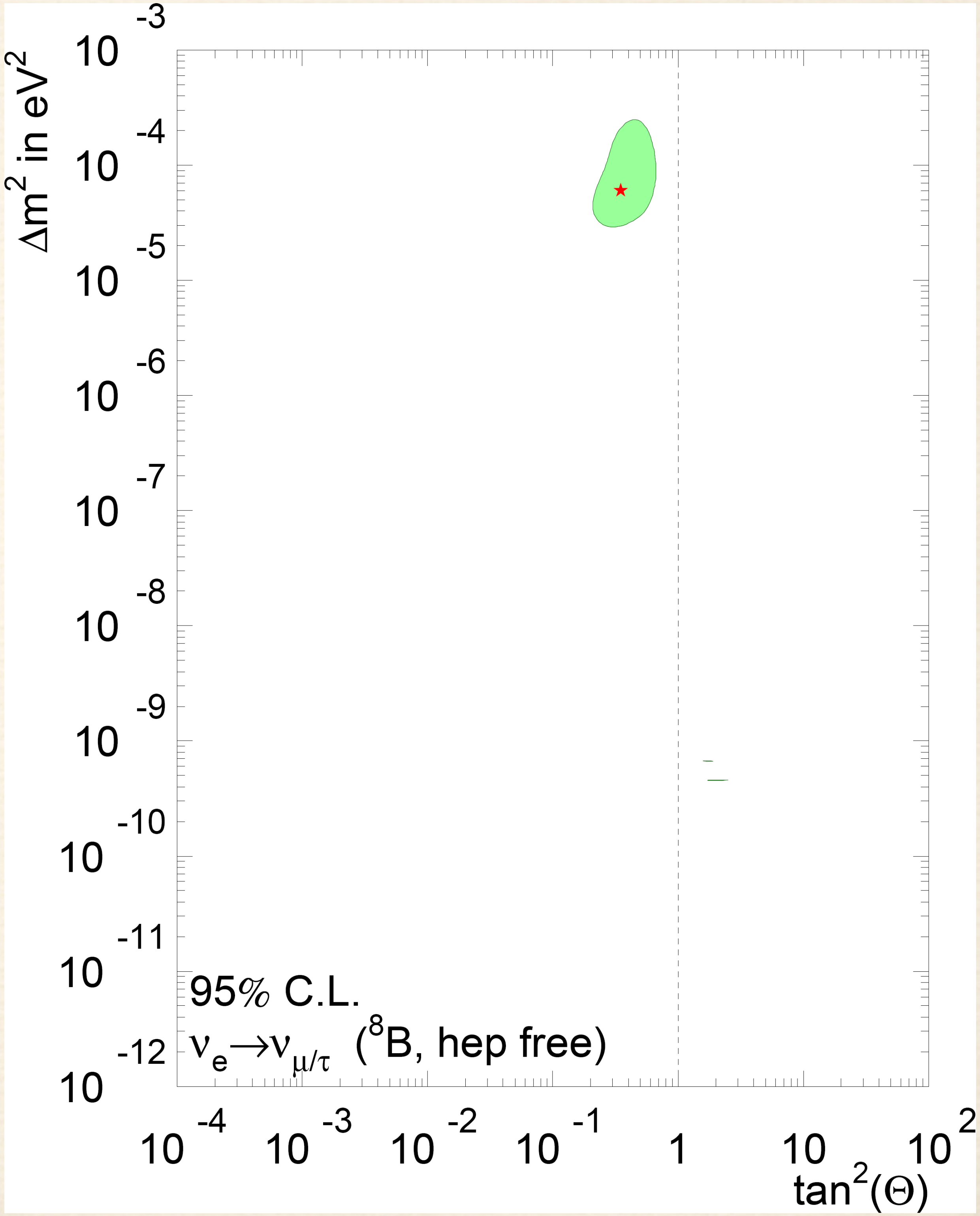
- difference between SNO's pure charged-current solar neutrino interaction rate and Super-K's electron elastic scattering rate demonstrate solar neutrino flavor conversion
- SNO's rate and Super-K's recoil e^- spectrum strongly exclude small mixing

A. McDonald receives the Vanne Cocconi prize on behalf of SNO two years ago

Unique Solution in Global Analysis

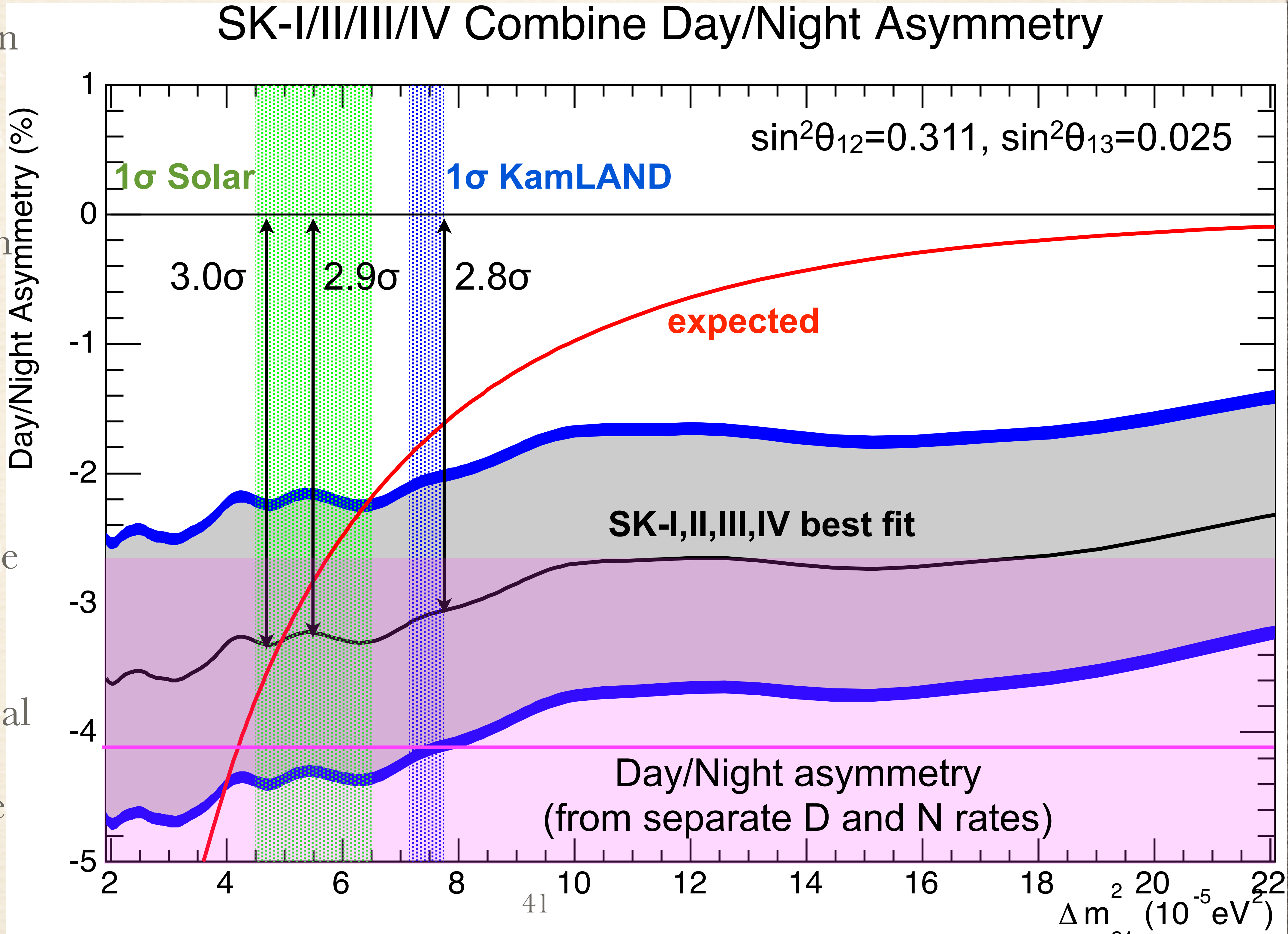
- immediately confirmed and strengthened by SNO's NC measurement
- robust (leaving out some data sets)
- eventually confirmed by KamLAND





Present Super-K Day/Night

- first indication (~3 sigma) of matter effects
- likelihood fit to solar zenith angle distribution
- depends slightly on Δm^2_{21}
- less vulnerable to detector asymmetries
- lower statistical errors than from separate D, N rates



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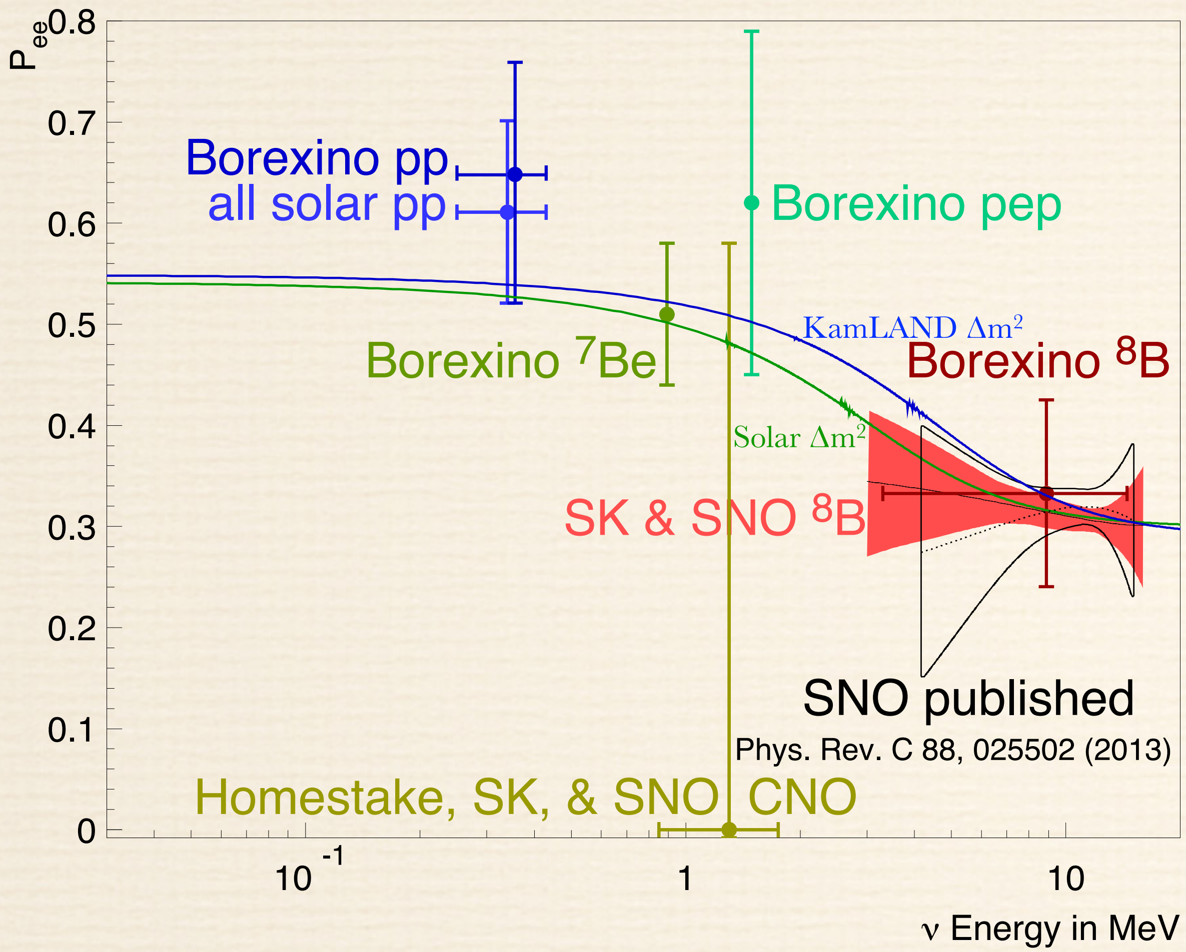
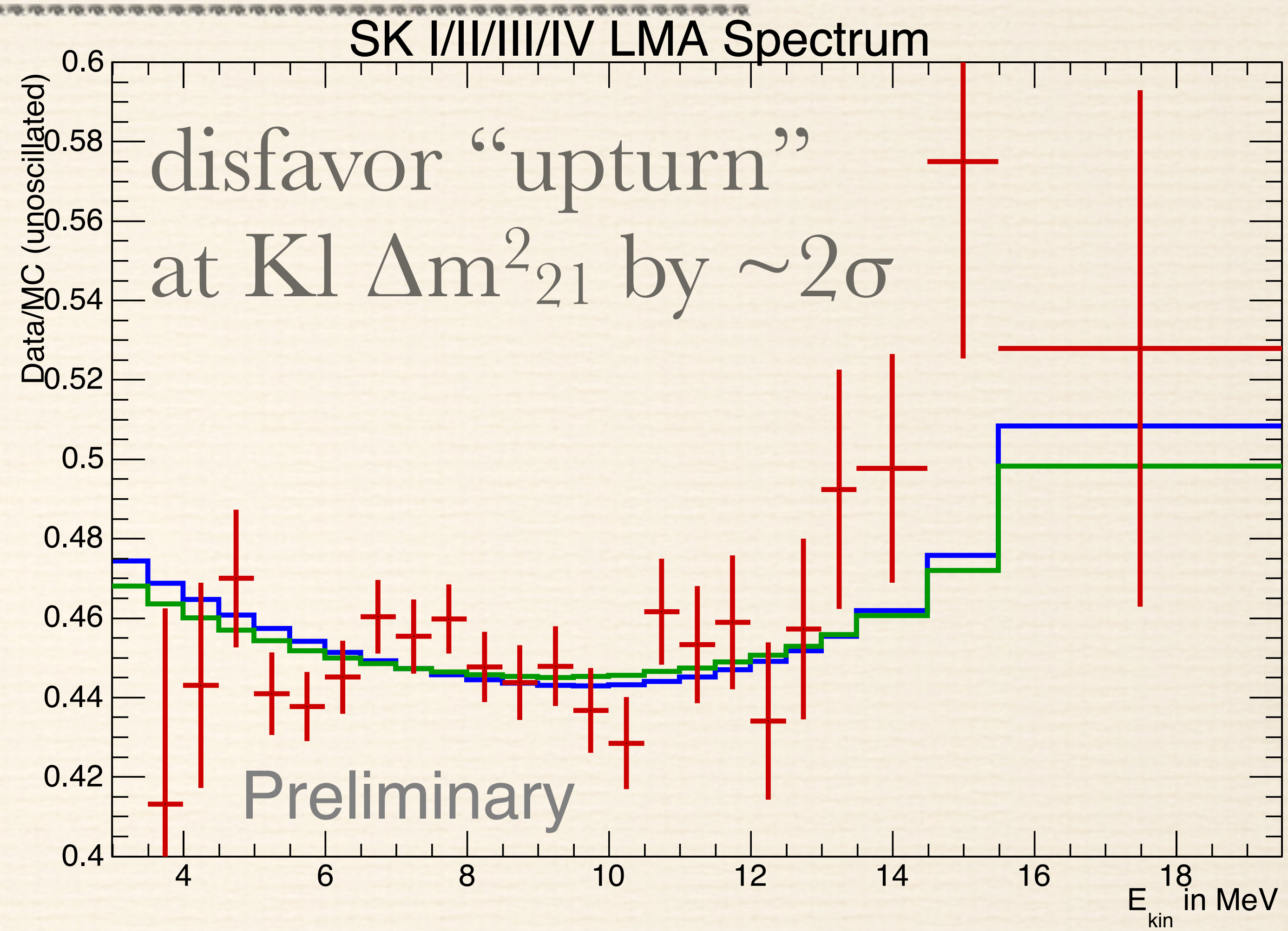
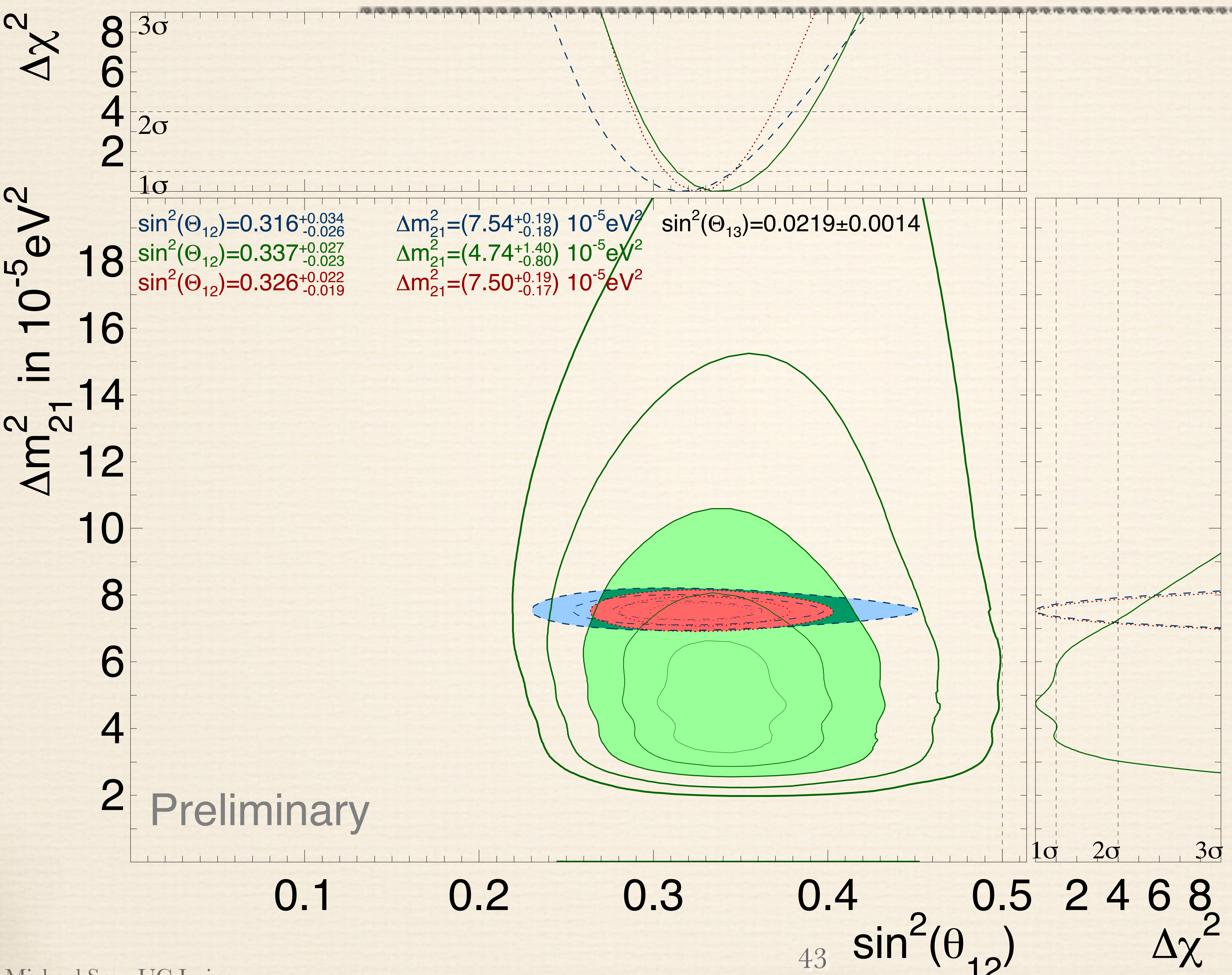
SK Spectrum analysis





- most precise probe of transition region from vacuum oscillation to MSW adiabatic conversion: ~50% less uncertainty on Pee
- complementary to SNO: SNO is most precise in MSW region

Current Oscillation results



favor lower $\Delta m^2{}_{21}$ than KamLAND's by more than two sigma

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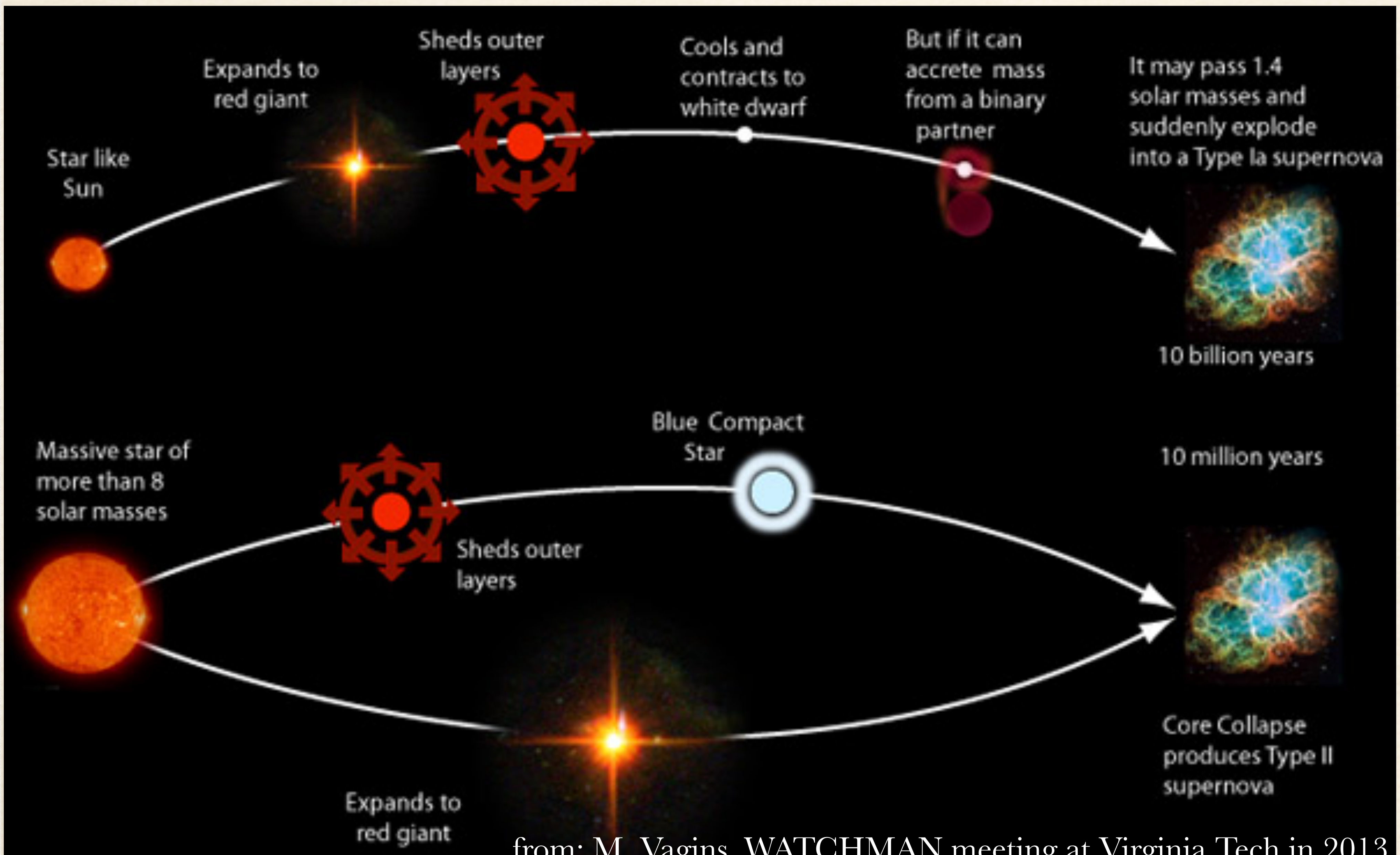
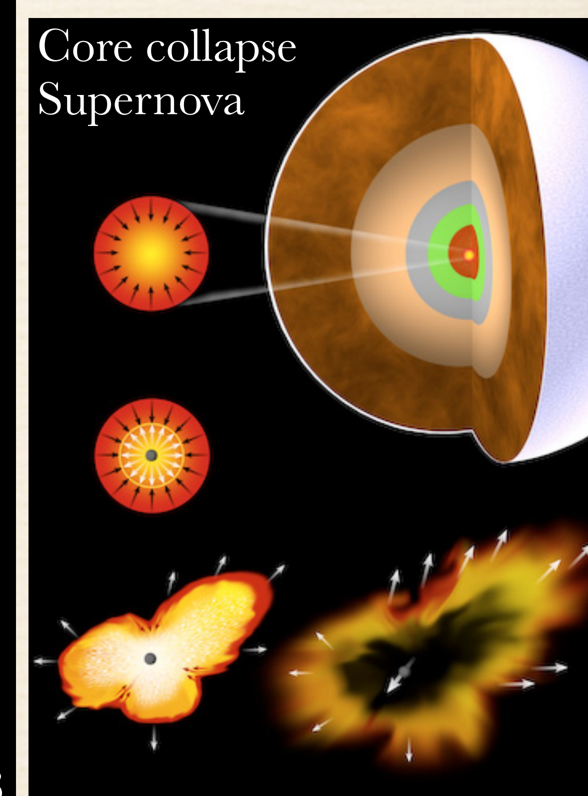
Supernova Explosions

- origin of heavy elements >He (or stars would just keep theirs)
- production of elements heavier than Fe
- very energetic, interesting events: core collapse supernovae release about three sextillion Yottawatts for ~10 seconds!

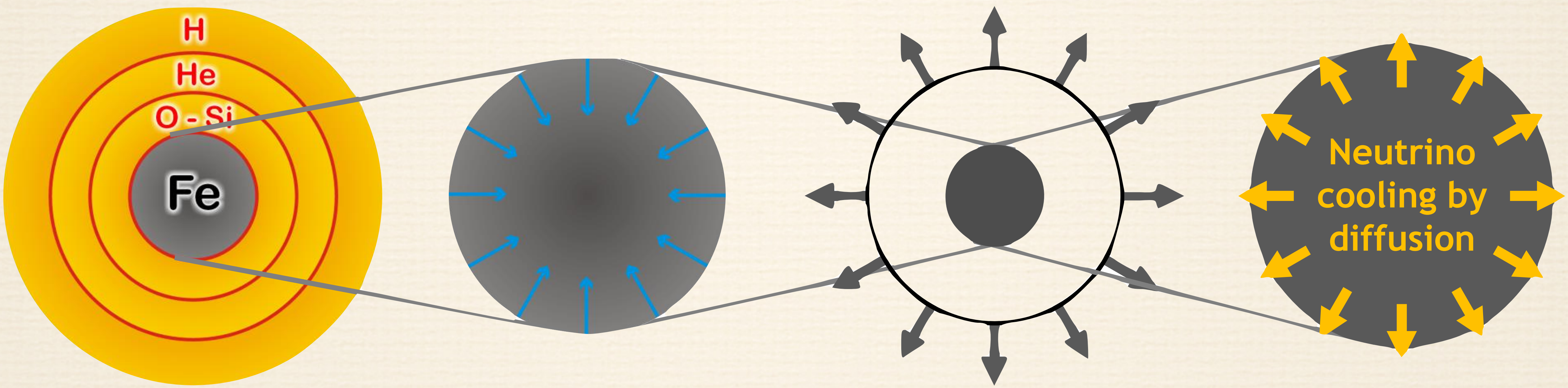


from: M. Vagins, WATCHMAN meeting at Virginia Tech in 2013



Core-Collapse Supernova Explosion: The ν Bomb!

End state of a massive star $M \gtrsim 6\text{–}8\, M_\odot$	Collapse of degenerate core	Bounce at ρ_{nuc} Shock wave forms explodes the star	Grav. binding E $\sim 3 \times 10^{53}$ erg emitted as nus of all flavors

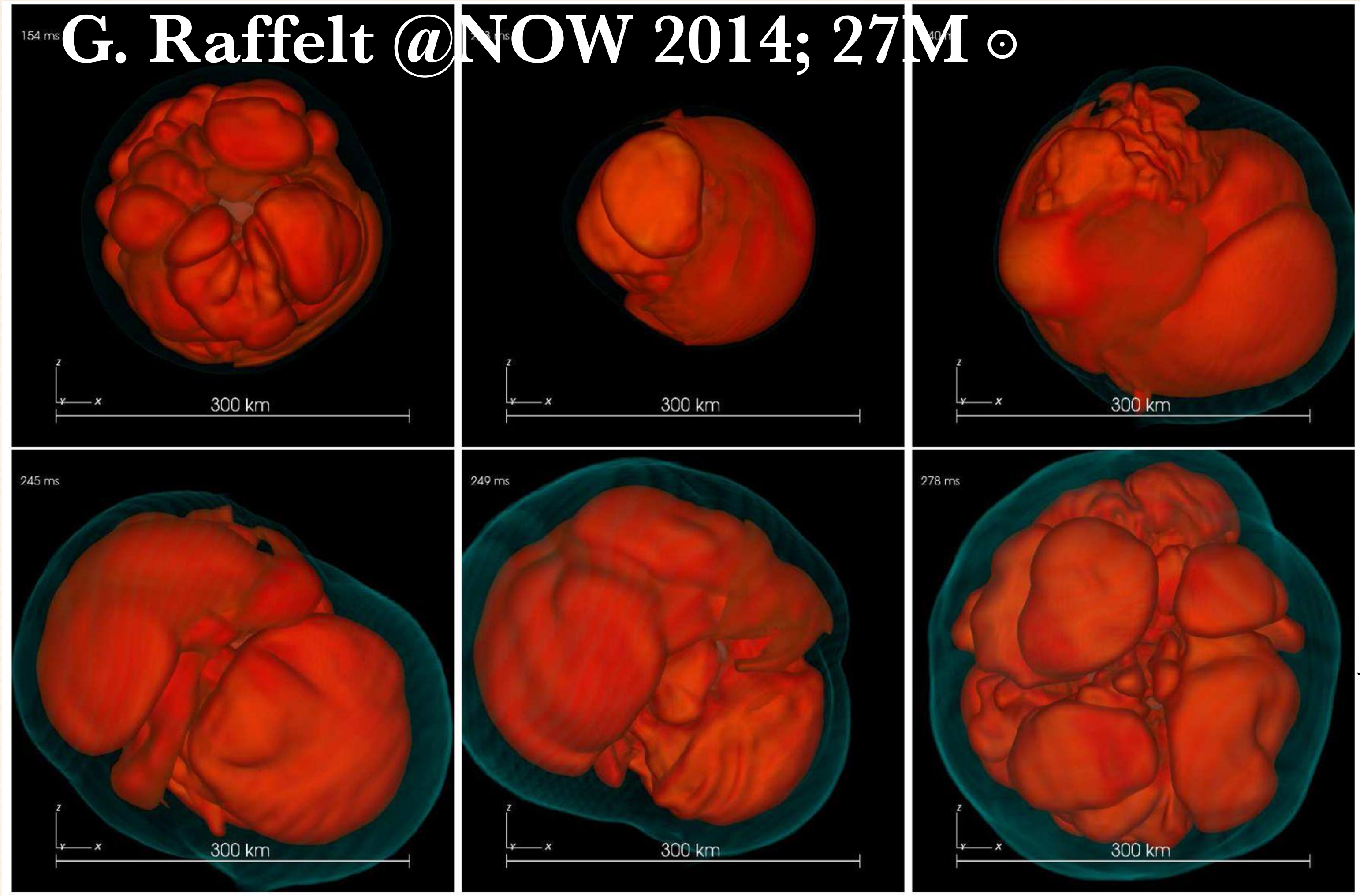


- ~99% of energy released into neutrinos
- ~0.01% goes into light emission!
- must understand neutrinos to understand these events!

Courtesy G. Raffelt @ NOW 2014

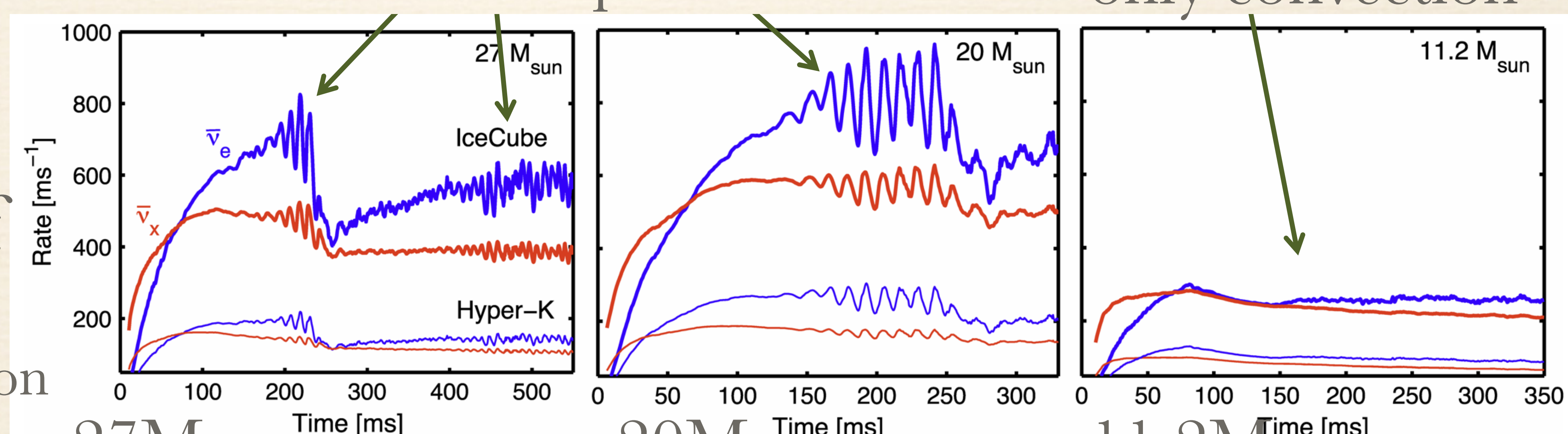
Neutrinos Power the Explosion

- simulations: shock rebound stalls after about 600ms
- stalled shock wave needs energy to start re-expansion against ram pressure of inflating stellar core
- neutrinos can supply fresh energy!
- SASI is 3D "sloshing" of shock wave
  (=standing accretion shock instability)



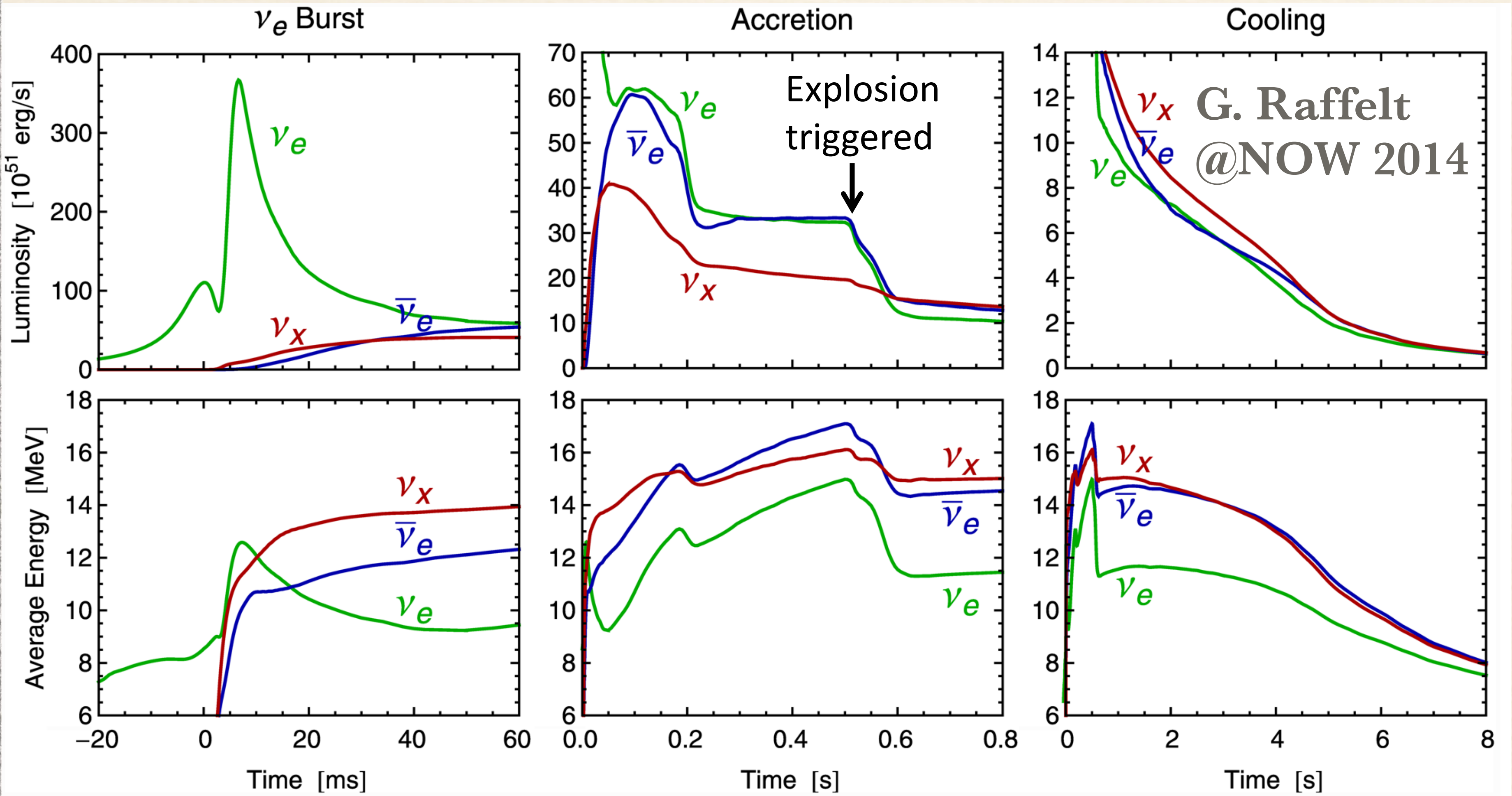
SASI episodes

only convection



27M$_\odot$ 20M$_\odot$ 11.2M$_\odot$

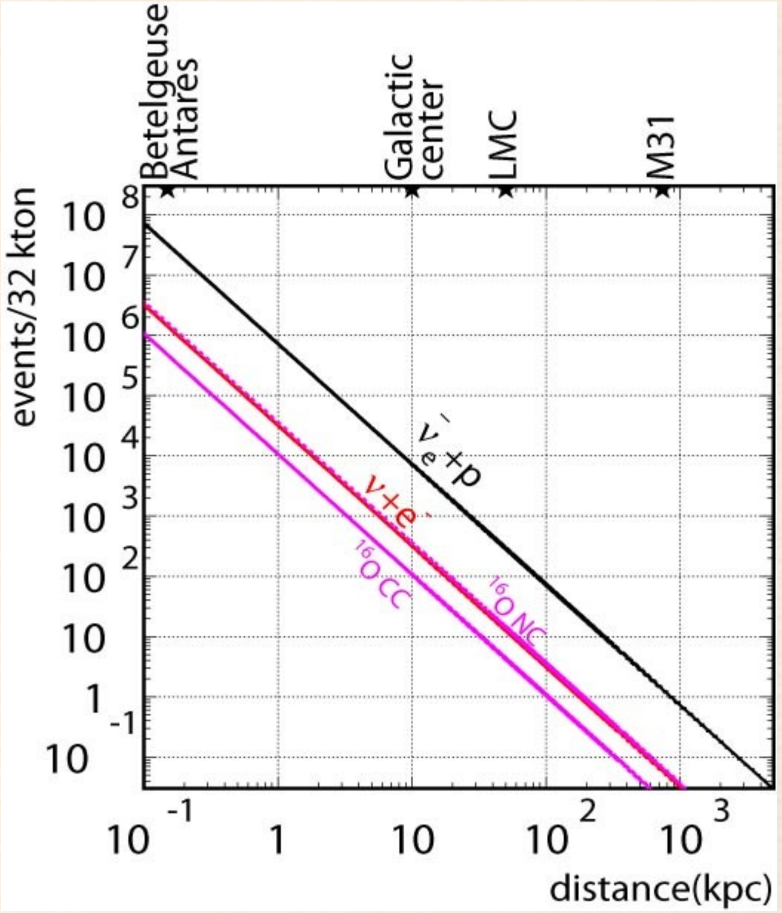
Supernova ν Emission



shock breakout; outer core de-leptonization

shock stalls ~150km; in-falling matter powers ν's

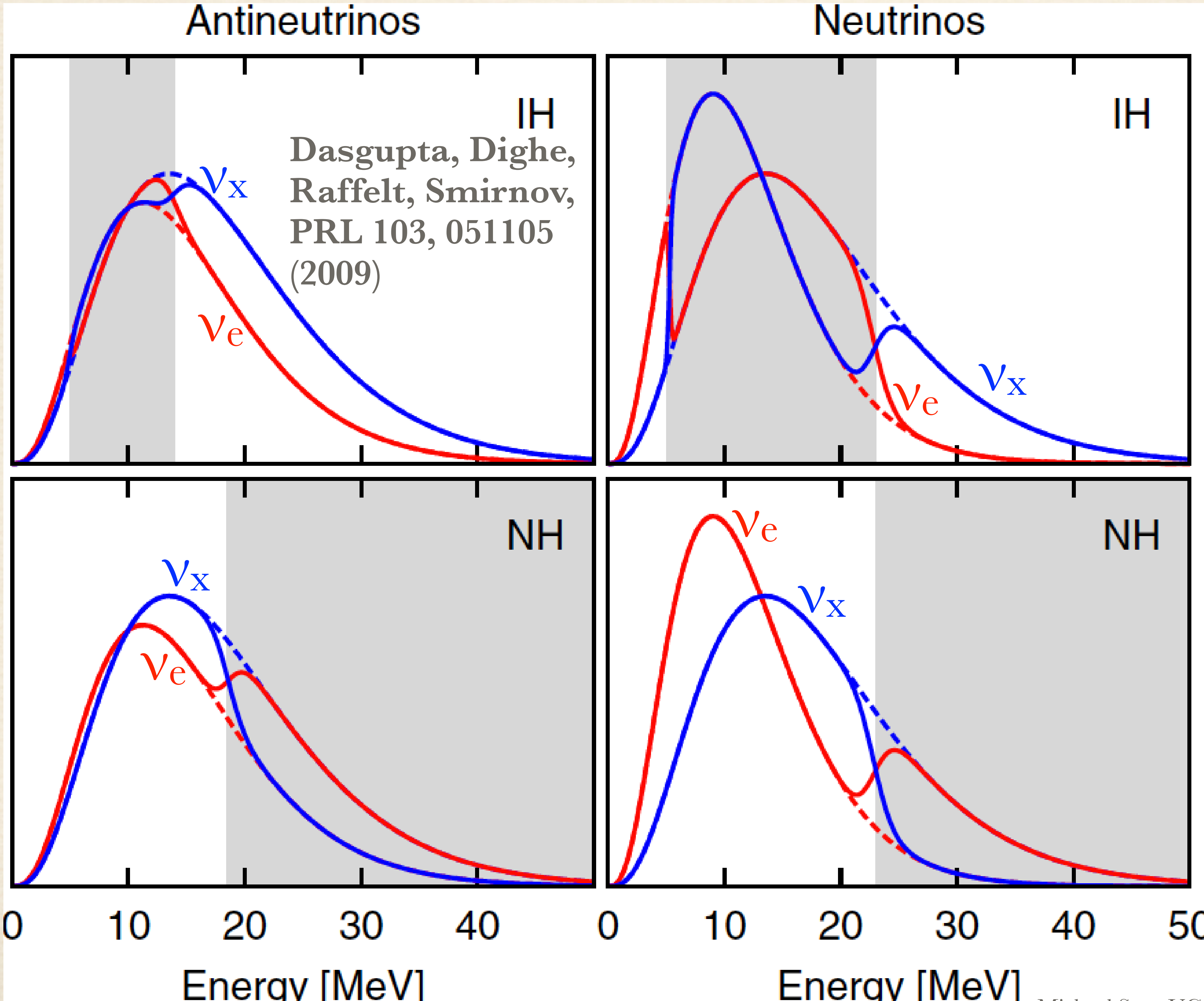
cooling on neutrino diffusion time scale



SN ν events in Super-K

- water detectors: mostly $\overline{\nu}_e$'s; liquid Argon TPCs (LBNF) ν_e's
- see ν_e burst with LArTPC, cooling with water detector

ν-ν Interaction: Only in SN!



- neutrinos trapped by dense PNS
- ν_x escape at earlier (higher T)
- non-linear ν self-interaction "swaps" the spectra
- depends on mass ordering

Supernovae in our Backyard

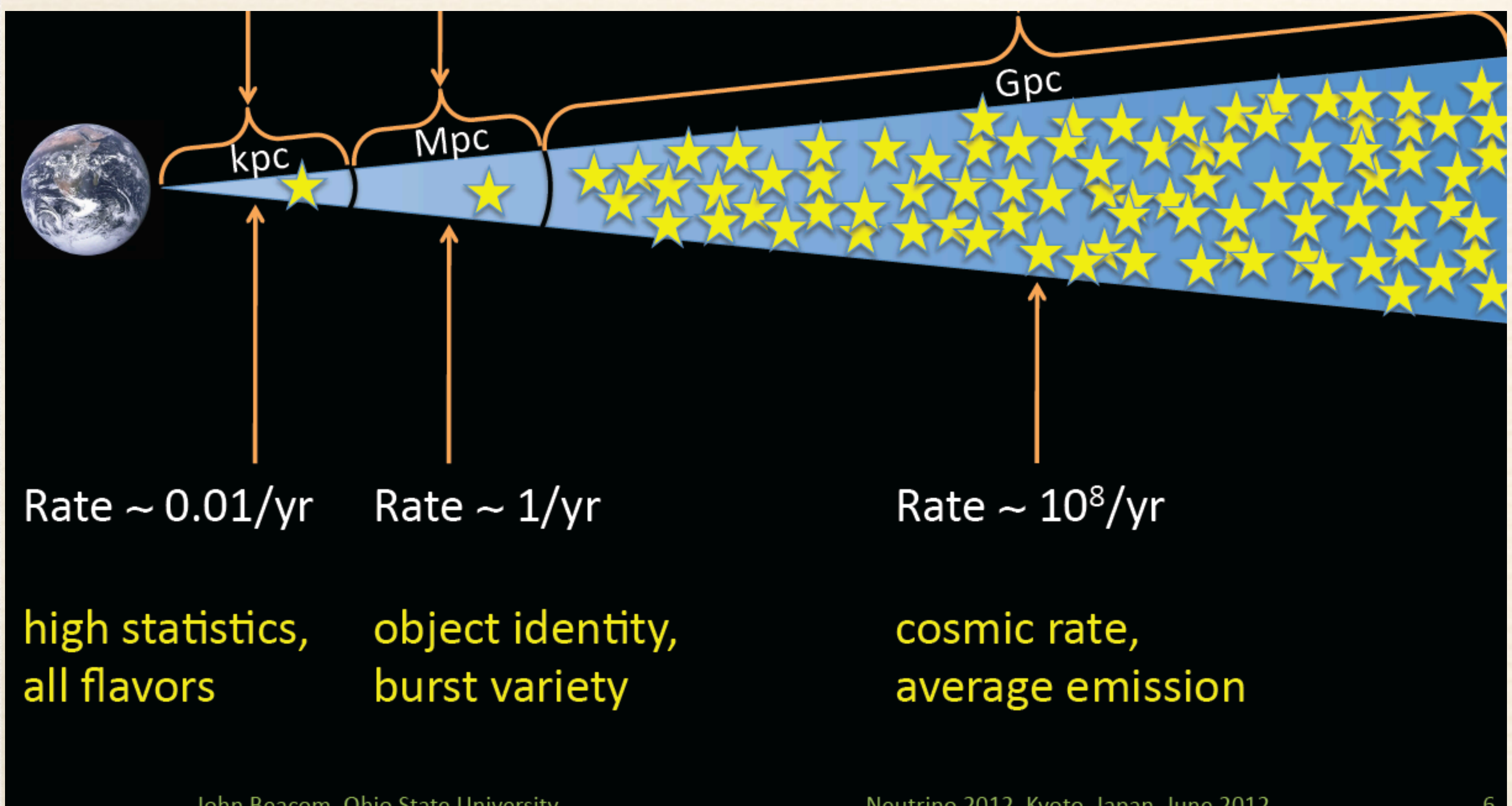
- 3/9 remnants: not core collapse SN
- six observed core collapse explosions in ~1800 years
- see only ~20%: ~2 CCSN/century

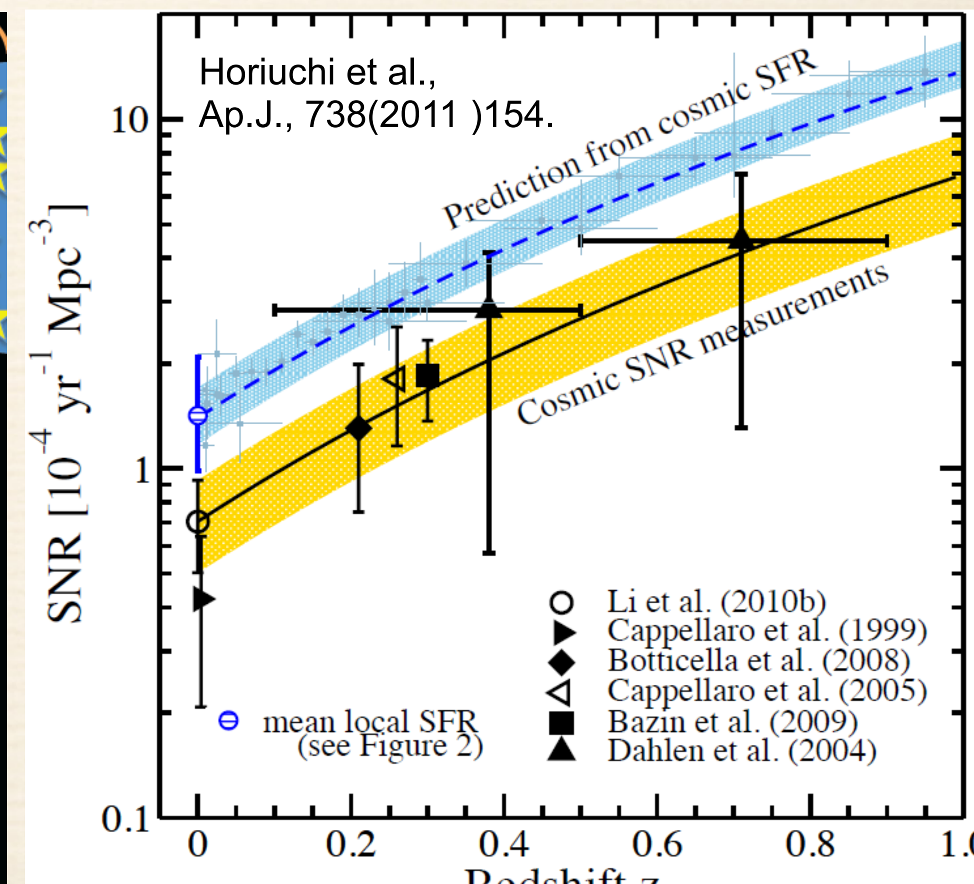
… and SN1885a (M31) SN 1987a (LMC)

from: M. Vagins, WATCHMAN meeting at Virginia Tech in 2013

Diffuse, Distant SN Flux

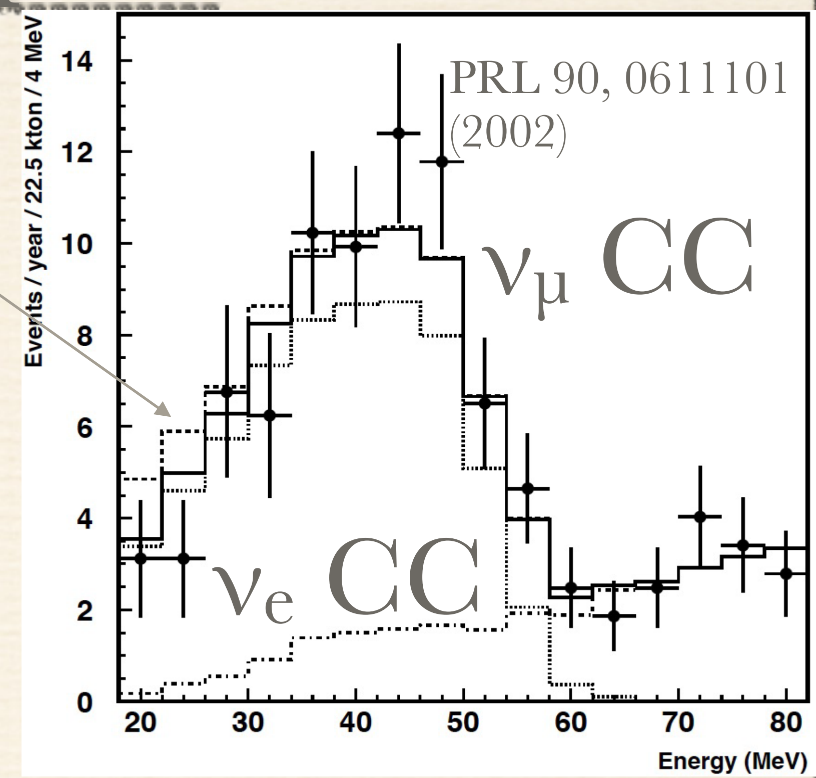
- galactic core collapse supernova neutrinos: a long journey, a long wait! (PhD students should finish <50yr)
- … so look beyond our galaxy: CC SN rate about 1 Hz!
- resulting neutrino interaction rate is a few per year in Super-K
- **observed SN rate** only ~half of **prediction from star formation**
- a problem with the observation? or the prediction? neutrinos would tell!

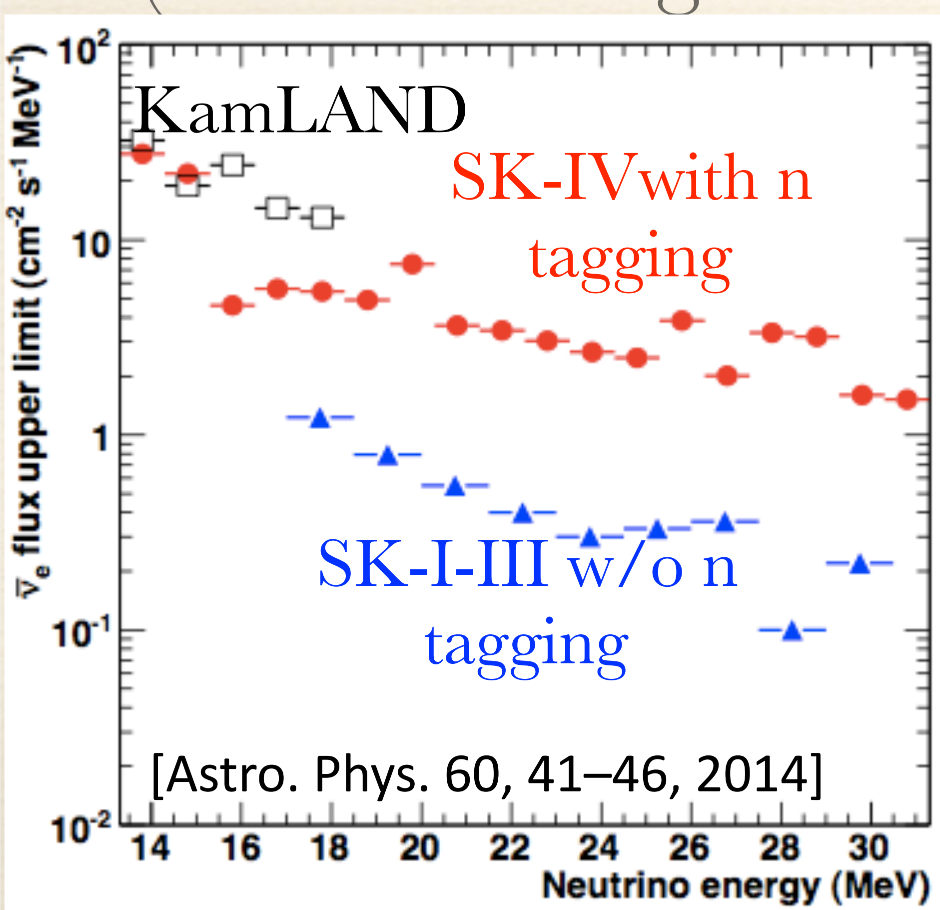


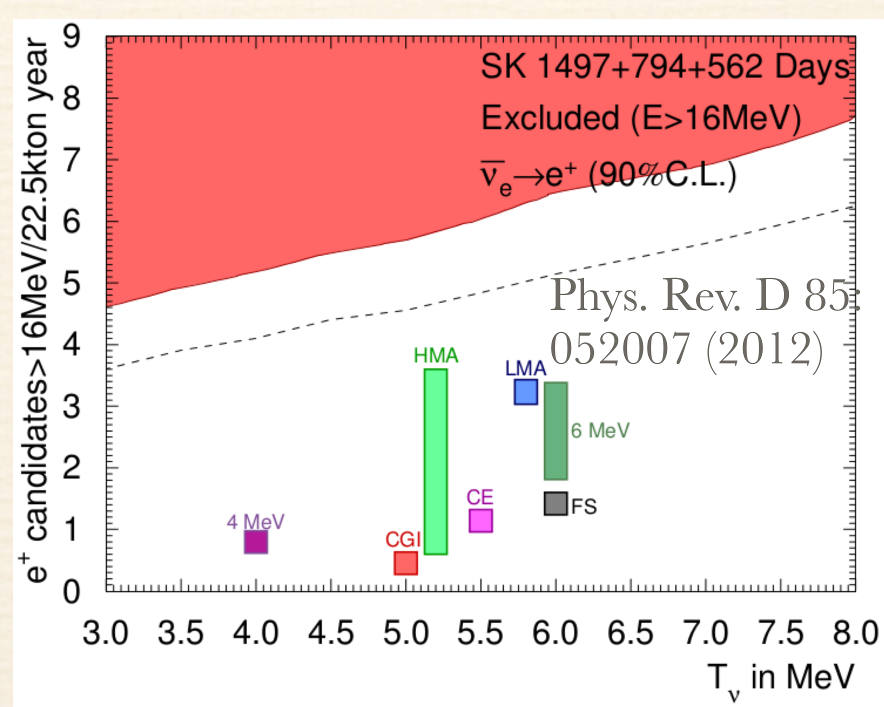


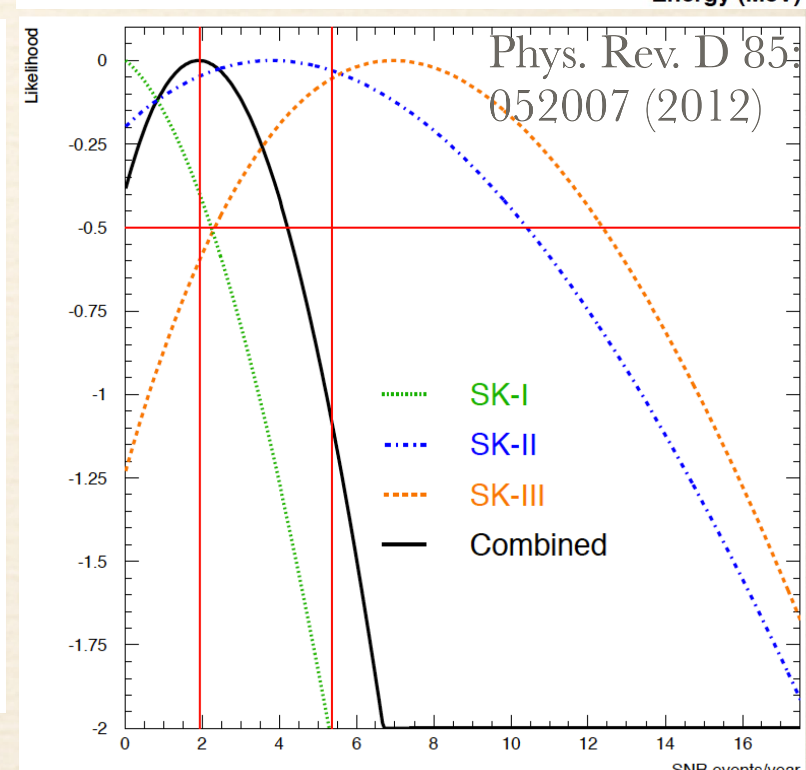
Super-K's Diffuse, Distant SN ν Search Using IBD: $\bar{\nu}_e + p \rightarrow e^+ + n$

- SK I-III: 2±2 events/yr
- SK-IV only analyzed with n tagging (10-20% efficiency)
- atm. ν NC background will important (even with high efficiency tagging)





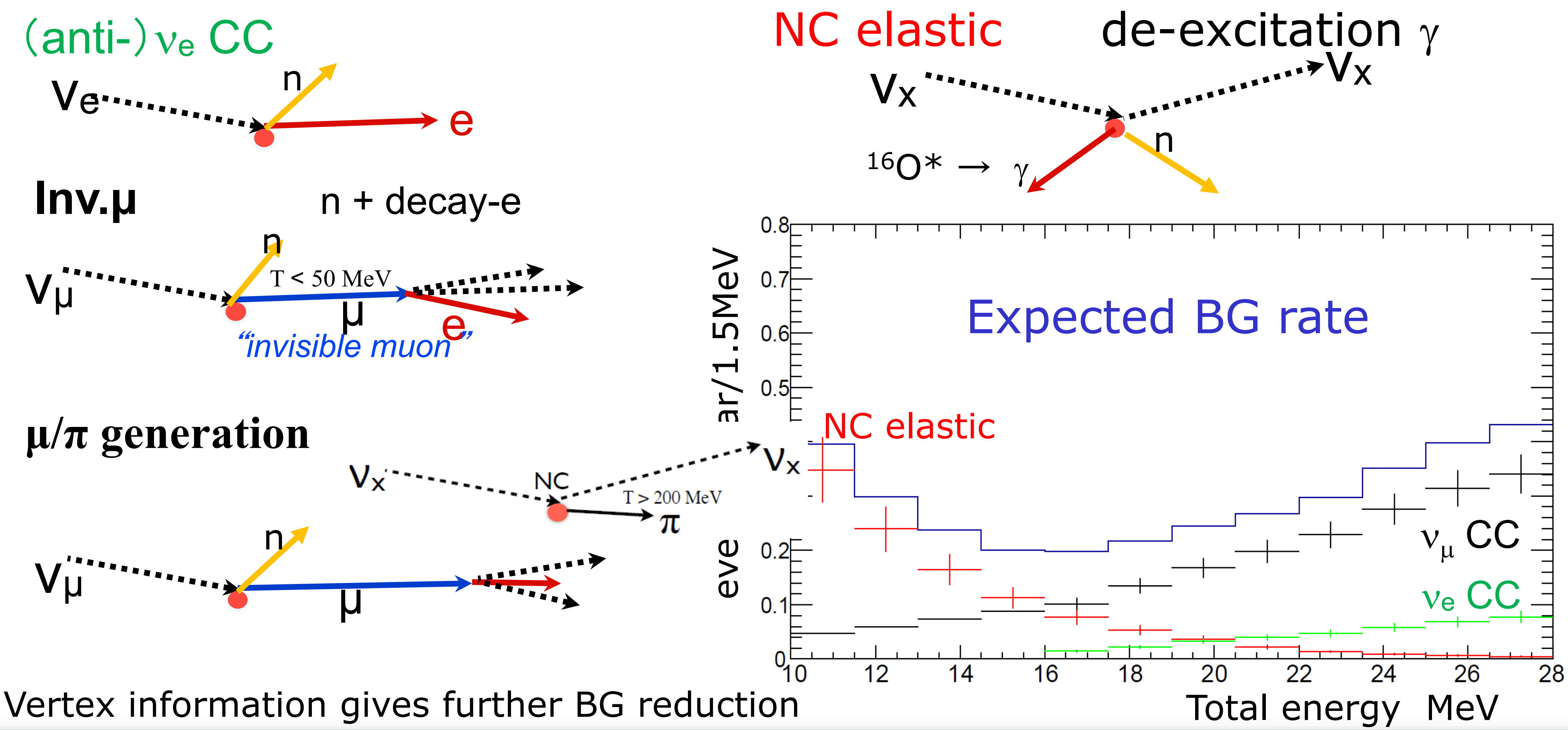




Atmospheric Background with Gd n tagging

BG source: atmospheric neutrino

- CC
- NC



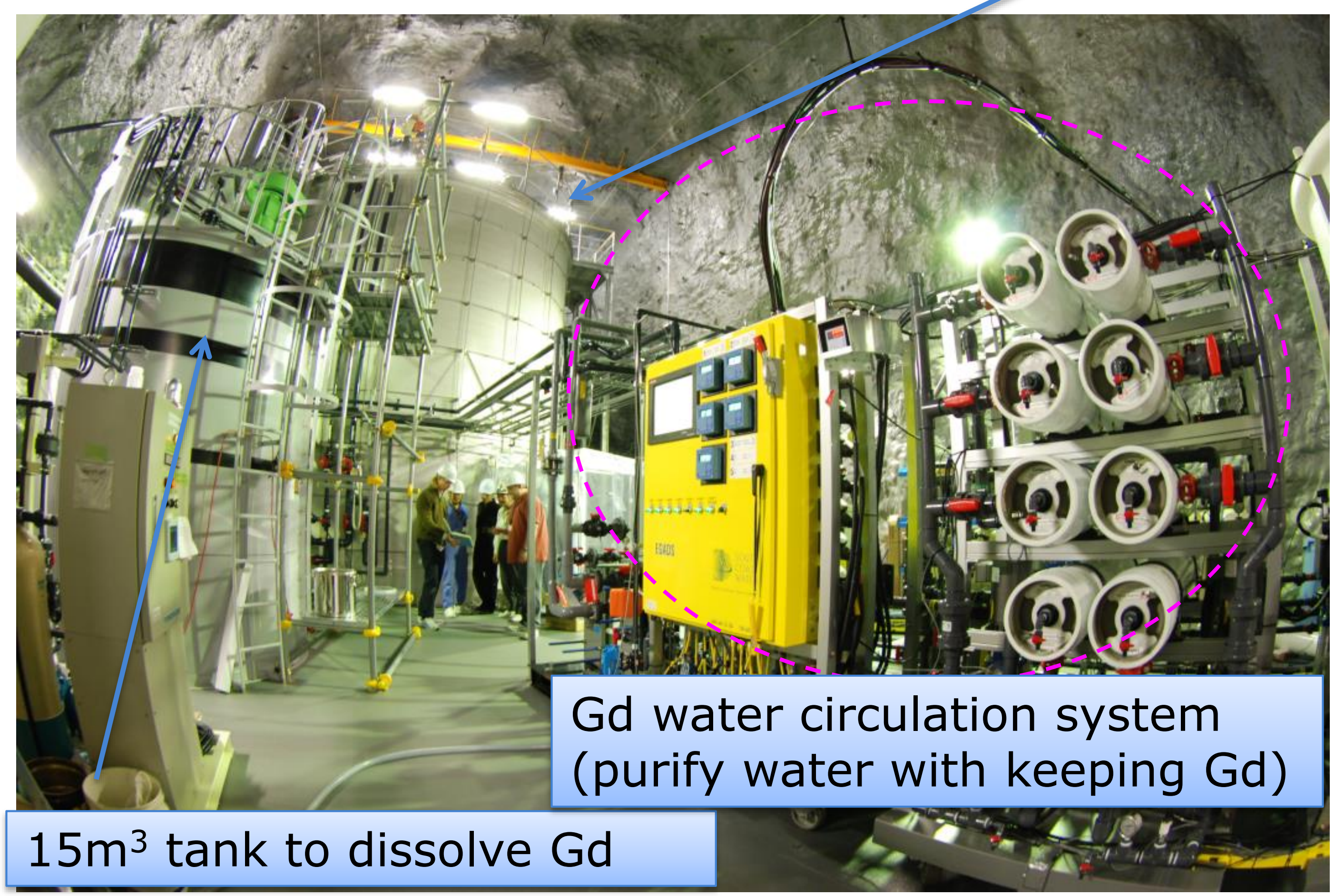
N.B. Vertex information gives further BG reduction

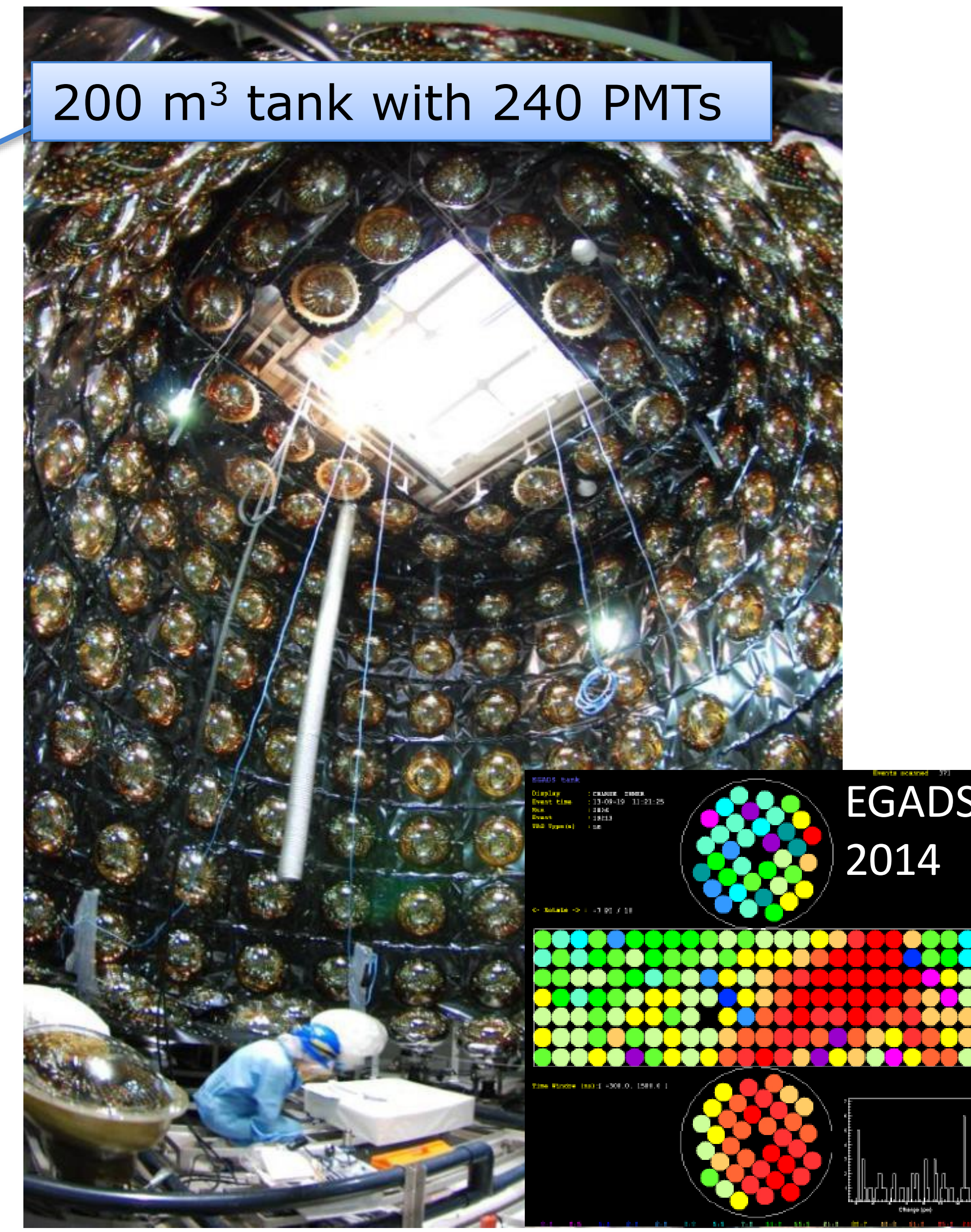
EGADS

EGADS

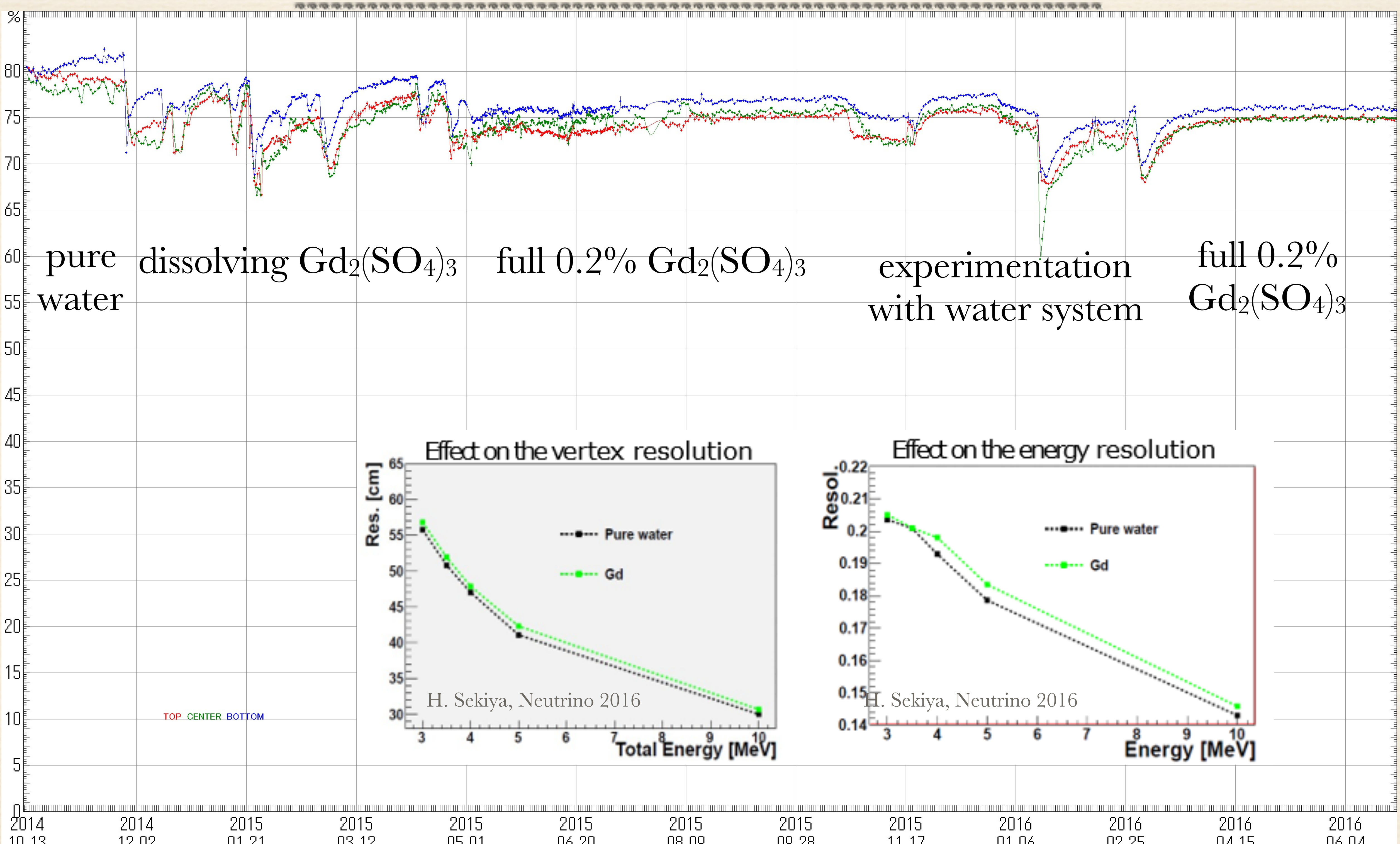
Evaluating Gadolinium's Action on Detector Systems

- To study the Gd water quality with actual detector materials.
- The detector fully mimic Super-K detector.
  : SUS frame, PMT and PMT case, black sheets, etc.



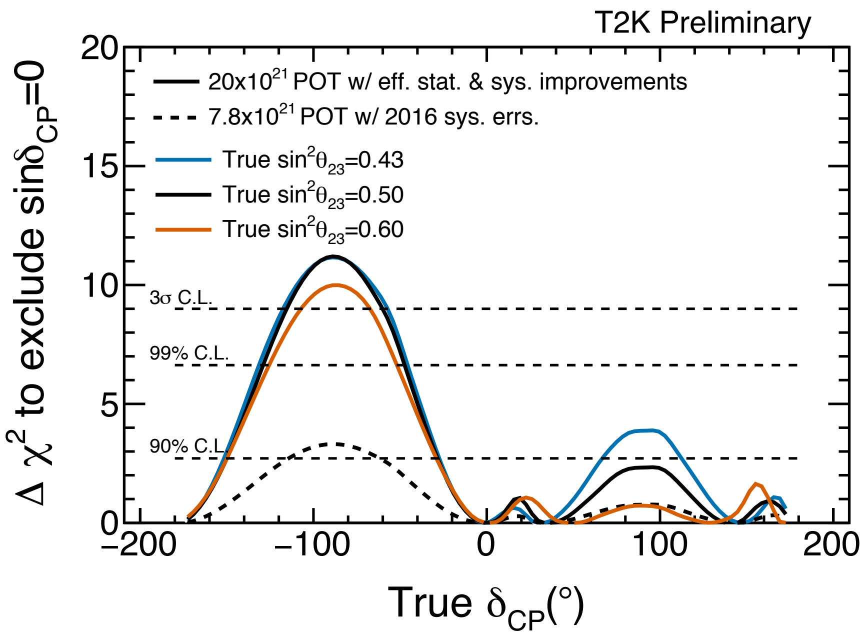


EGADS

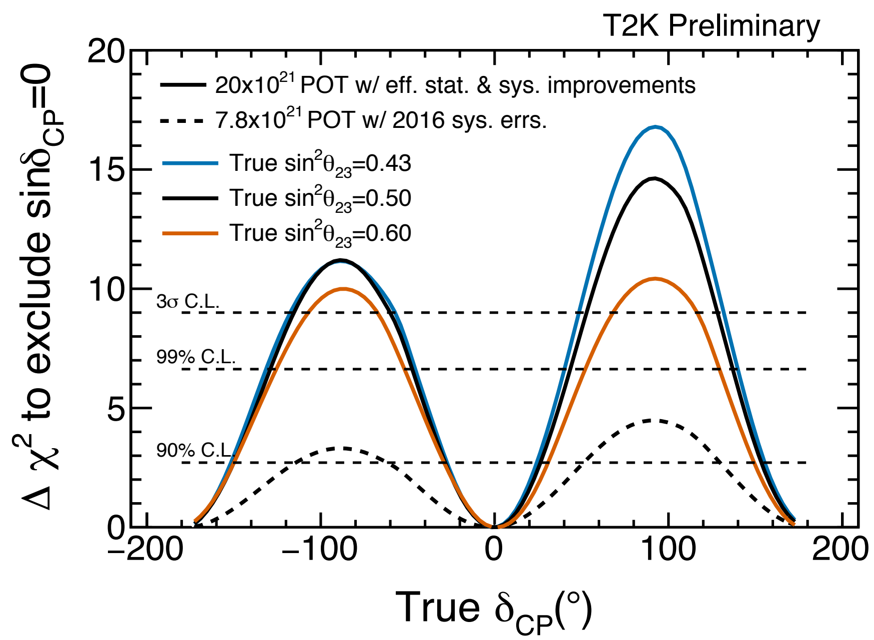


%
pure water
dissolving $Gd_2(SO_4)_3$
full 0.2% $Gd_2(SO_4)_3$
experimentation with water system
full 0.2% $Gd_2(SO_4)_3$
TOP CENTER BOTTOM
2014 10.13
2014 12.02
2015 01.21
2015 03.12
2015 05.01
2015 06.20
2015 08.09
2015 09.28
2015 11.17
2016 01.06
2016 02.25
2016 04.15
2016 06.04
Effect on the vertex resolution
Res. [cm]
Pure water
Gd
Total Energy [MeV]
H. Sekiya, Neutrino 2016
Effect on the energy resolution
Resol.
Pure water
Gd
Energy [MeV]
H. Sekiya, Neutrino 2016

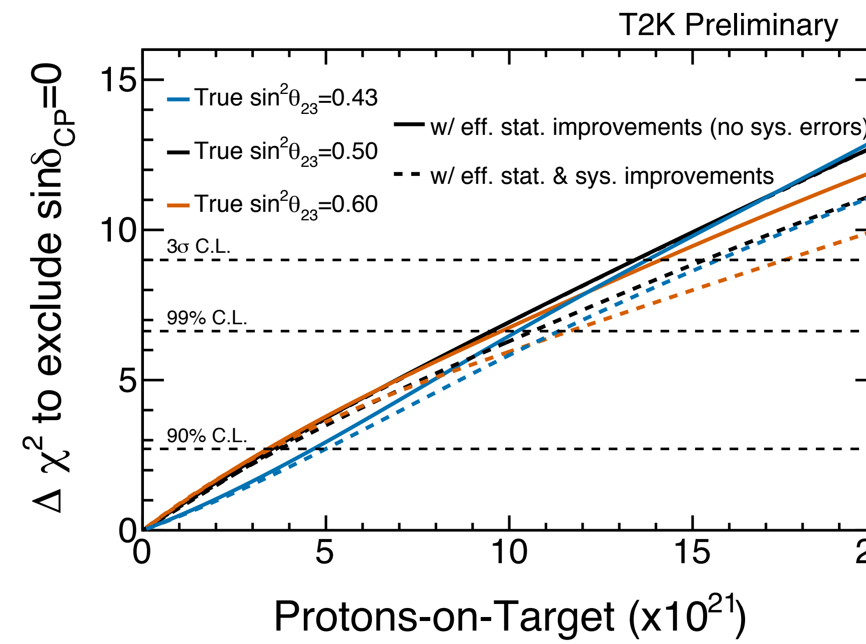
T2K-II: PHYSICS POTENTIAL



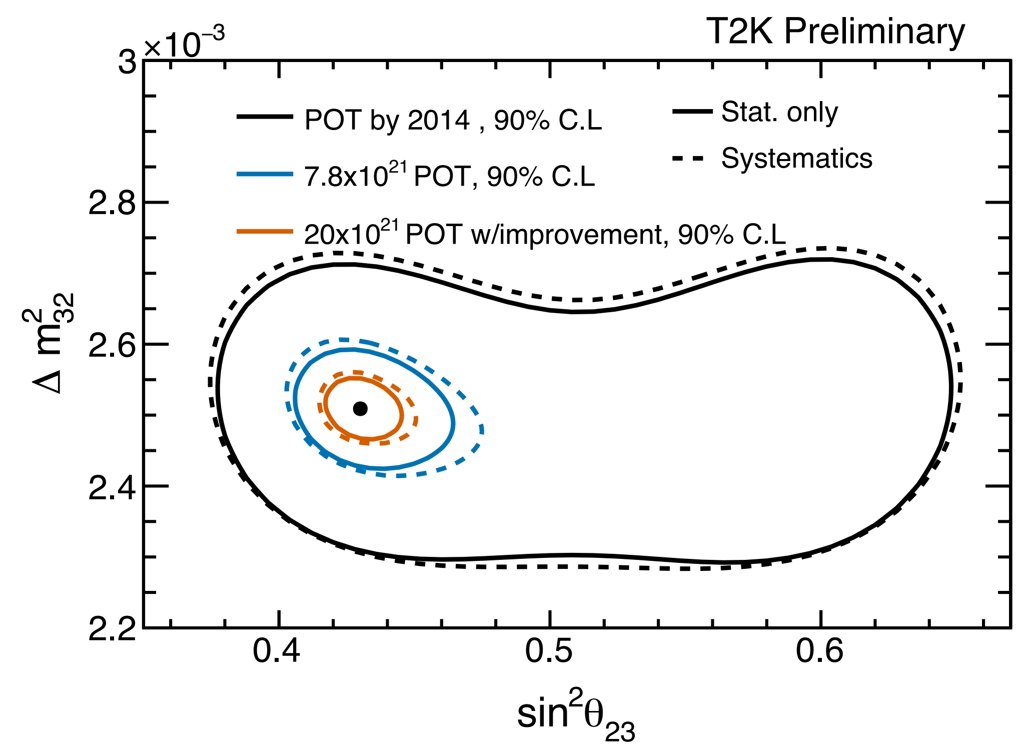
hierarchy unknown



external hierarchy input



- Assumes ~50% increase in effective statistics/POT
  - increase horn current to design (320 kA): ~+10%
  - SK multi-ring samples and fiducial volume increase: ~+40%
- ~3 σ sensitivity to CP violation for favourable (and currently favoured) parameters
- Precise measurement of θ_{23}:
  - octant resolution if θ_{23} at edge of currently allowed values
  - otherwise, measure θ_{23} to ~1.7°



H. Tanaka, Neutrino 2016

Summary

- Rich physics program
- still producing interesting physics
- more is yet to come: T2K phase II and SK-Gd

Decay Mode	$\lvert\Delta(B-L)\rvert$	$\tau/\mathcal{B}$ (90%C.L.)
$p \to e^+\pi^0$	0	1.7×10^{34} yrs.
$p \to \mu^+\pi^0$	0	7.8×10^{33} yrs.
$p \to \nu K^+$	$0(\overline{\nu}), 2(\nu)$	6.6×10^{33} yrs.
$p \to \mu^+ K^0$	$0(\overline{\nu}), 2(\nu)$	6.6×10^{33} yrs.
$p \to e^+\eta$	0	4.2×10^{33} yrs.
$p \to \mu^+\eta$	0	1.3×10^{33} yrs.
$p \to e^+\rho^0$	0	7.1×10^{32} yrs.
$p \to \mu^+\rho^0$	0	1.6×10^{32} yrs.
$p \to e^+\omega^0$	0	3.2×10^{32} yrs.
$p \to \mu^+\omega^0$	0	7.8×10^{32} yrs.
$p \to \nu\pi^+$	$0(\overline{\nu}), 2(\nu)$	3.9×10^{32} yrs.
$p \to e^+\nu\nu$	$0(\overline{\nu}\nu), 2(\nu\nu, \overline{\nu}\overline{\nu})$	1.7×10^{32} yrs.
$p \to \mu^+\nu\nu$	$0(\overline{\nu}\nu), 2(\nu\nu, \overline{\nu}\overline{\nu})$	2.2×10^{32} yrs.
$p \to e^+X$[a]	$0(X?)$	7.9×10^{32} yrs.
$p \to \mu^+X$[a]	$0(X?)$	4.1×10^{32} yrs.
$n \to e^+\pi^-$	0	2.0×10^{33} yrs.
$n \to \mu^+\pi^-$	0	1.0×10^{33} yrs.
$n \to e^+\rho^-$	0	7.0×10^{31} yrs.
$n \to \mu^+\rho^-$	0	3.6×10^{31} yrs.
$n \to \nu\pi^0$	$0(\overline{\nu}), 2(\nu)$	1.1×10^{33} yrs.
$n \to \nu\gamma$	$0(\overline{\nu}), 2(\nu)$	5.5×10^{32} yrs.
$pp \to K^+K^+$	2	1.7×10^{32} yrs.[b]
$pp \to \pi^+\pi^+$	2	7.2×10^{31} yrs.[b]
$np \to e^+\nu$	$0(\overline{\nu}), 2(\nu)$	2.6×10^{32} yrs.[b]
$np \to \mu^+\nu$	$0(\overline{\nu}), 2(\nu)$	2.0×10^{32} yrs.[b]
$np \to \tau^+\nu$	$0(\overline{\nu}), 2(\nu)$	3.0×10^{31} yrs.[b]
$np \to \pi^+\pi^0$	2	1.7×10^{32} yrs.[b]
$nn \to \pi^0\pi^0$	2	4.0×10^{32} yrs.[b]
$n - \overline{n}$ oscillations	2	1.9×10^{32} yrs.

Michael Smy, UC Irvine

- SK spectrum disfavors KamLAND Δm^2_{21} by ~two sigma
- SK favors solar Δm^2_{21} over KamLAND's by more than two sigma

SK spect fit	$\sin^2(\theta_{12})$	$\sin^2(\theta_{13})$	Δm^2_{21} [10^{-5}eV^2]	φ_{8B} [10^6/cm^{2}sec]	φ_{hep} [10^6/cm^{2}sec]	χ^2_{spec}	#σ
solar	0.304	0.02	4.84	5.50	1.9	73.86	1.2
solar+KL	0.304	0.02	7.50	5.28	1.9	76.60	2.1
SK spect fit	c_0/e_0	c_1/e_1	c_2/e_2	φ_{8B}	φ_{hep}	χ^2_{spec}	#σ
quadratic	0.334	0.0010	0.0005	5.25	14	72.33	0.0
exponential	0.336	0.0000	-	5.24	14	72.36	0.2

SK D/N & spectrum fit	$\sin^2(\theta_{12})$	$\sin^2(\theta_{13})$	Δm^2_{21} [10^{-5}eV^2]	φ_{8B} [10^6/cm^{2}sec]	φ_{hep} [10^6/cm^{2}sec]	χ^2_{DNsp}	#σ
solar	0.304	0.02	4.84	5.50	1.9	64.00	0
solar+KL	0.304	0.02	7.50	5.28	1.9	69.18	2.3