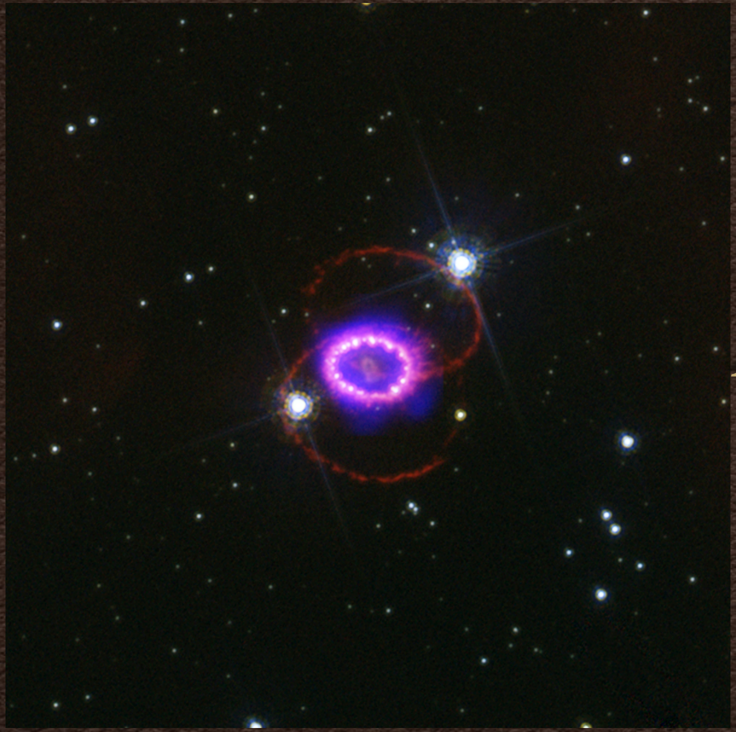
Super-Kamiokande with Gd



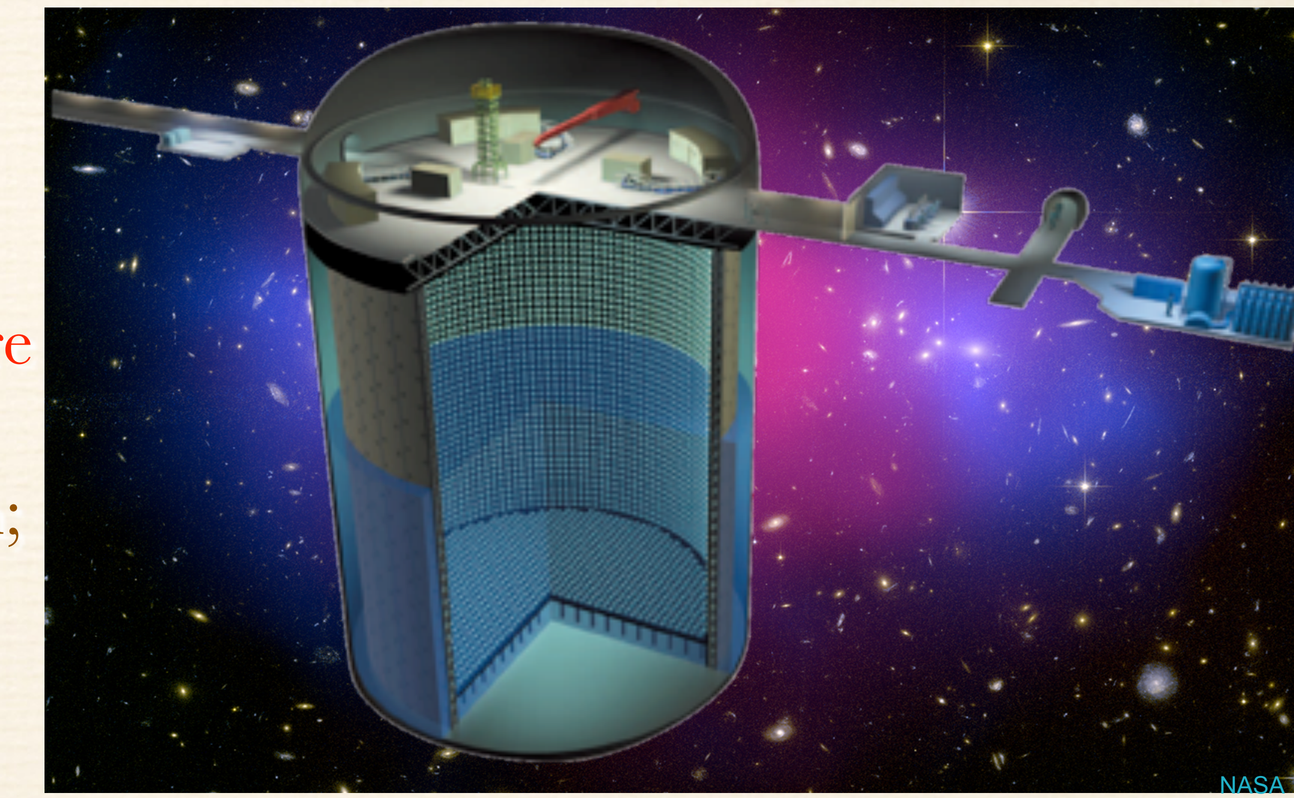
Michael Smy, UC Irvine

XIX International Workshop on Neutrino Telescopes

February 22nd, 2021

25 Years of Neutrino- and Astrophysics with Super-Kamiokande!

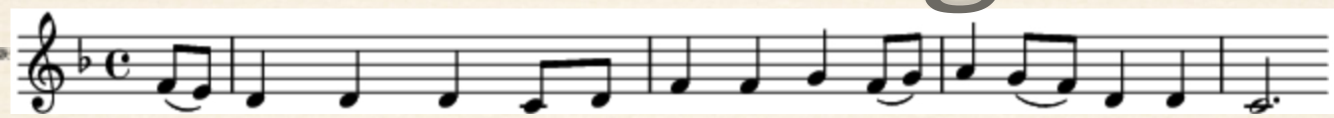
- 1998: discovery of atmospheric neutrino flavor transformation and neutrino mass
- 2000: solar mixing angle is large
- 2001: discovery of solar neutrino flavor transformation with SNO; uniquely measure oscillation parameters (with all solar data)
- 2004: discovery of atmospheric ν oscillation; confirmation from K2K with ν_μ beam
- 2011: first indication of positive θ_{13} from T2K with ν_μ neutrino beam
- 2012: first evidence for τ appearance
- 2013: first direct indication of matter effects on ν oscillations (solar ν day/night effect)
- 2013: first observation of $\nu_\mu \rightarrow \nu_e$ appearance
- 2017: first hint of CP violation in ν oscillations



- 50,000 ton water Cherenkov detector
  - ID: 32,000 tons (FV 22,500 tons); 11,129 PMTs (SK-I 11,146 PMTs)
  - OD: 18,000 tons; 1,885 PMTs

layout by Y. Suzuki, ICRR (Michael Smy, UC Irvine)

In Kamioka Town, Under Mountains Down, One Morning Last July…



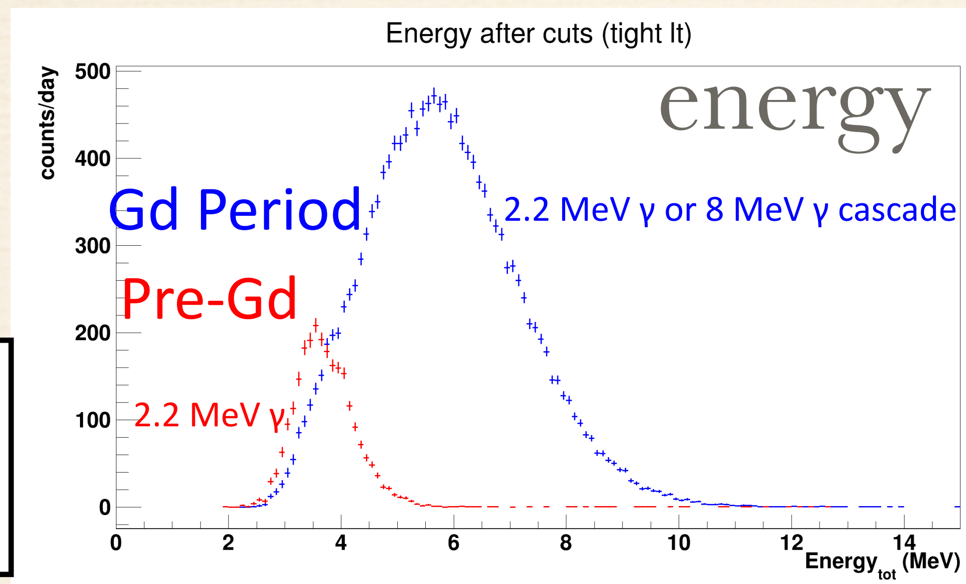
Star of the County Down (Irish Ballad)

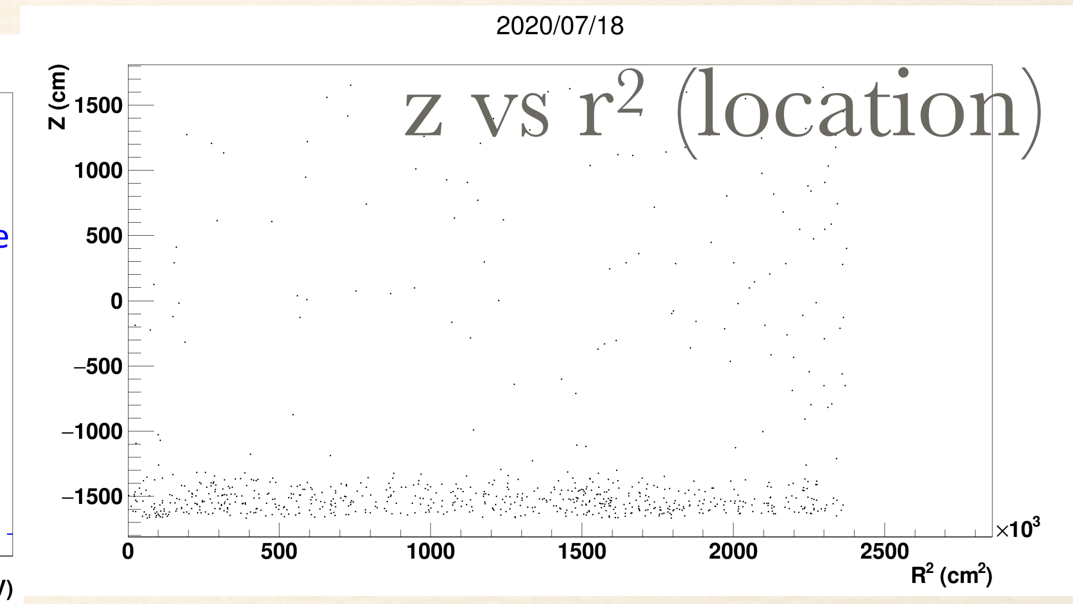
… Super-K started injecting $Gd_2(SO_4)_3$ to reach 0.011% Gd concentration

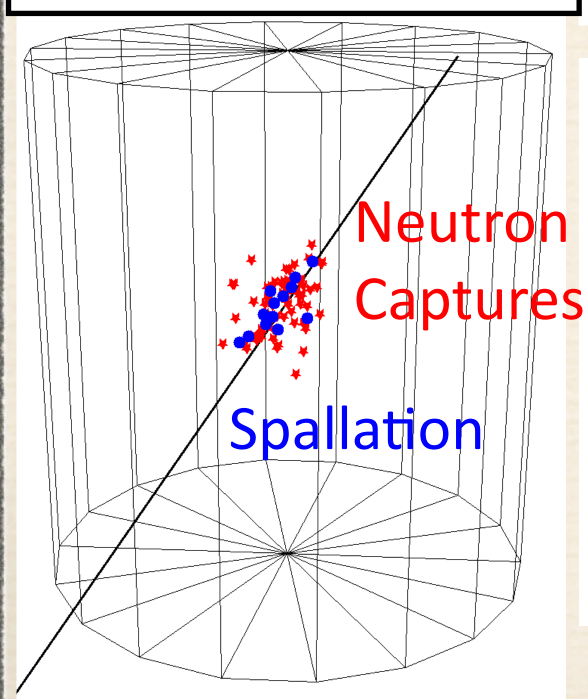
use neutrons generated by showering muons to track Gd injection progress

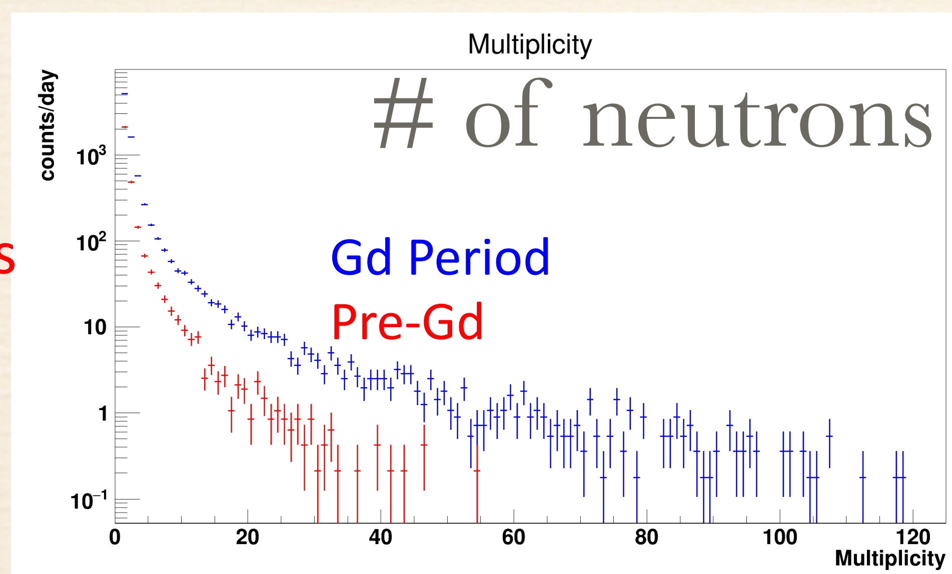
showers containing neutrons produce radioactive nuclei (spallation); important bkgd for MeV physics

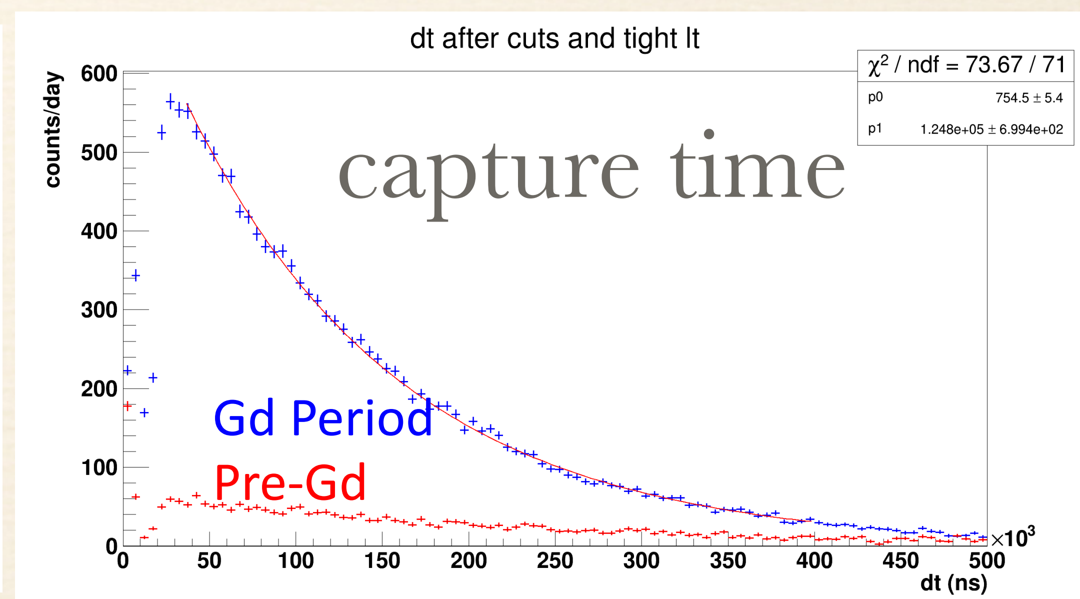
detailed discussion in the presentation from Alice Coffani:
→ Wed 24th, 12:15
Parallel Room 1









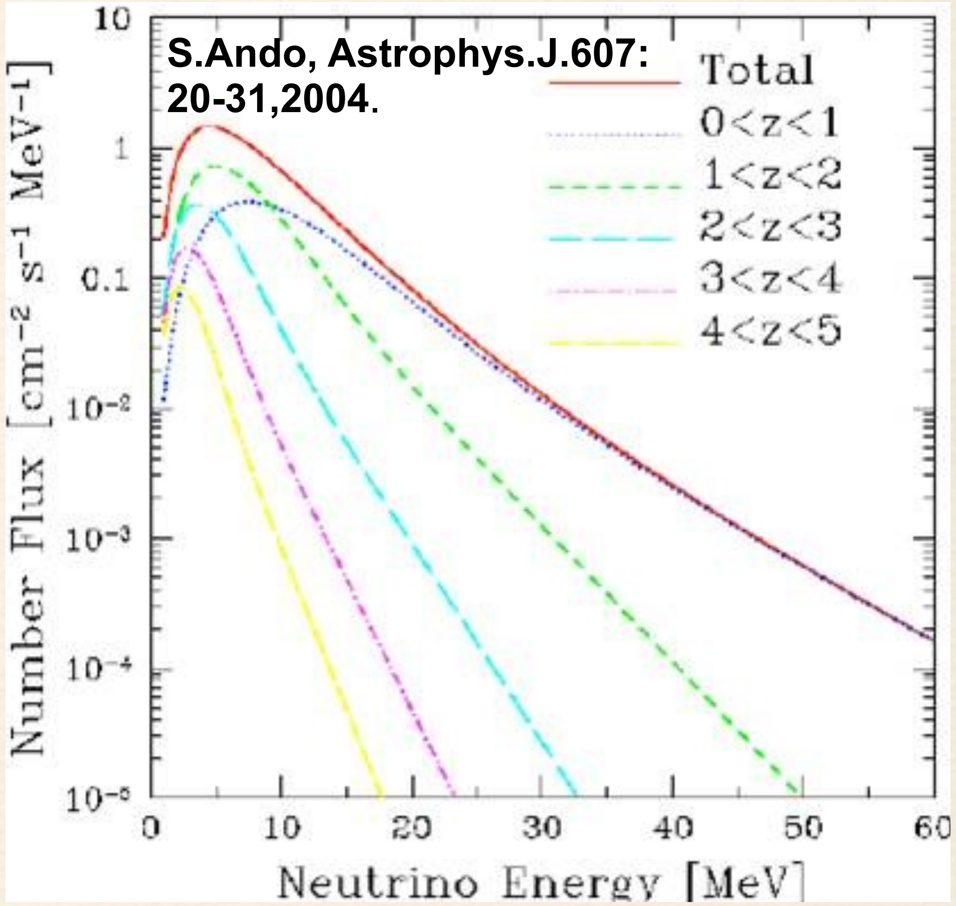


Courtesy S. Locke, UCI

This Succes is owed to the 2018 Preparation of the SK Tank

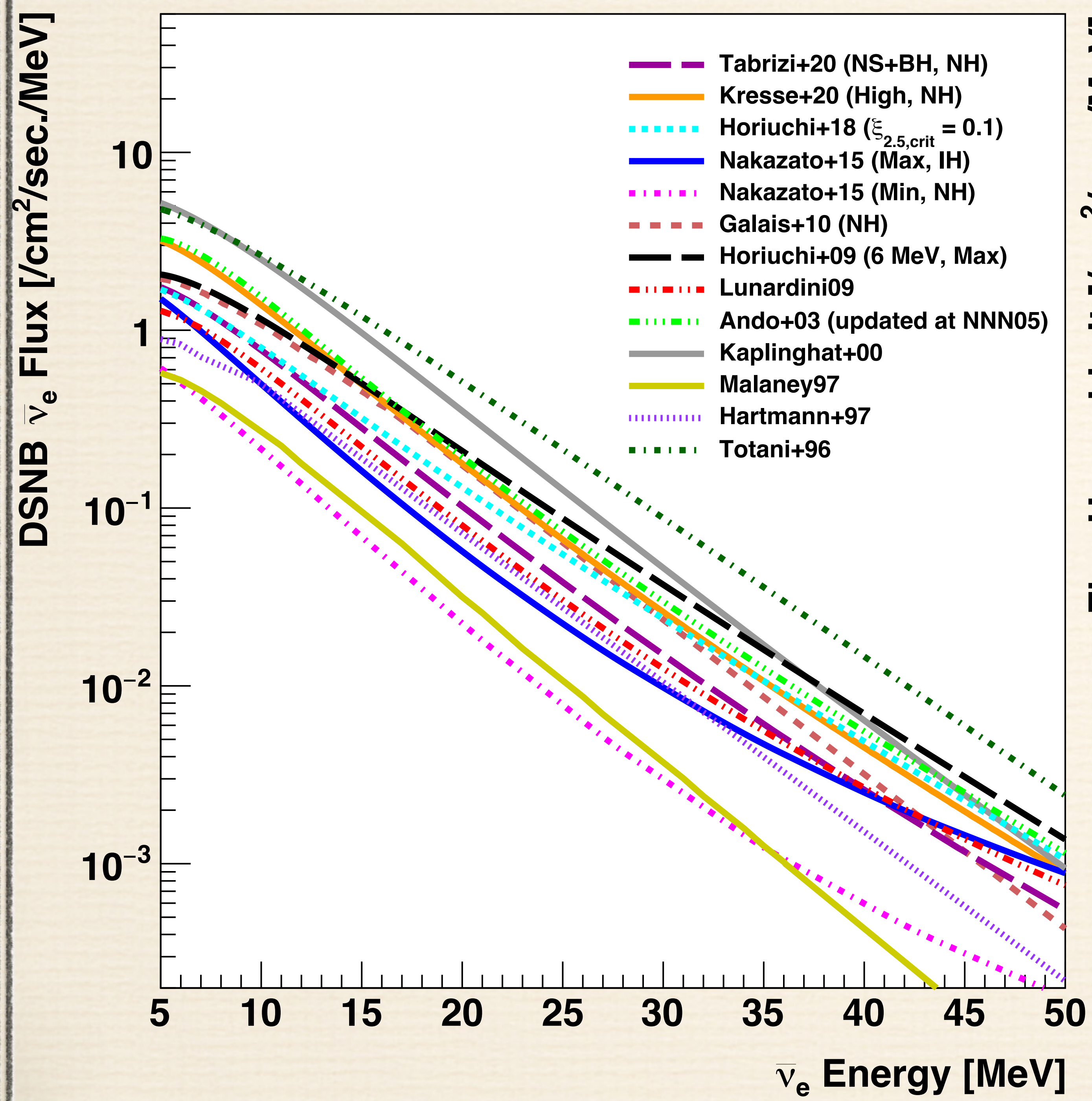
Search for Distant Supernova Neutrinos

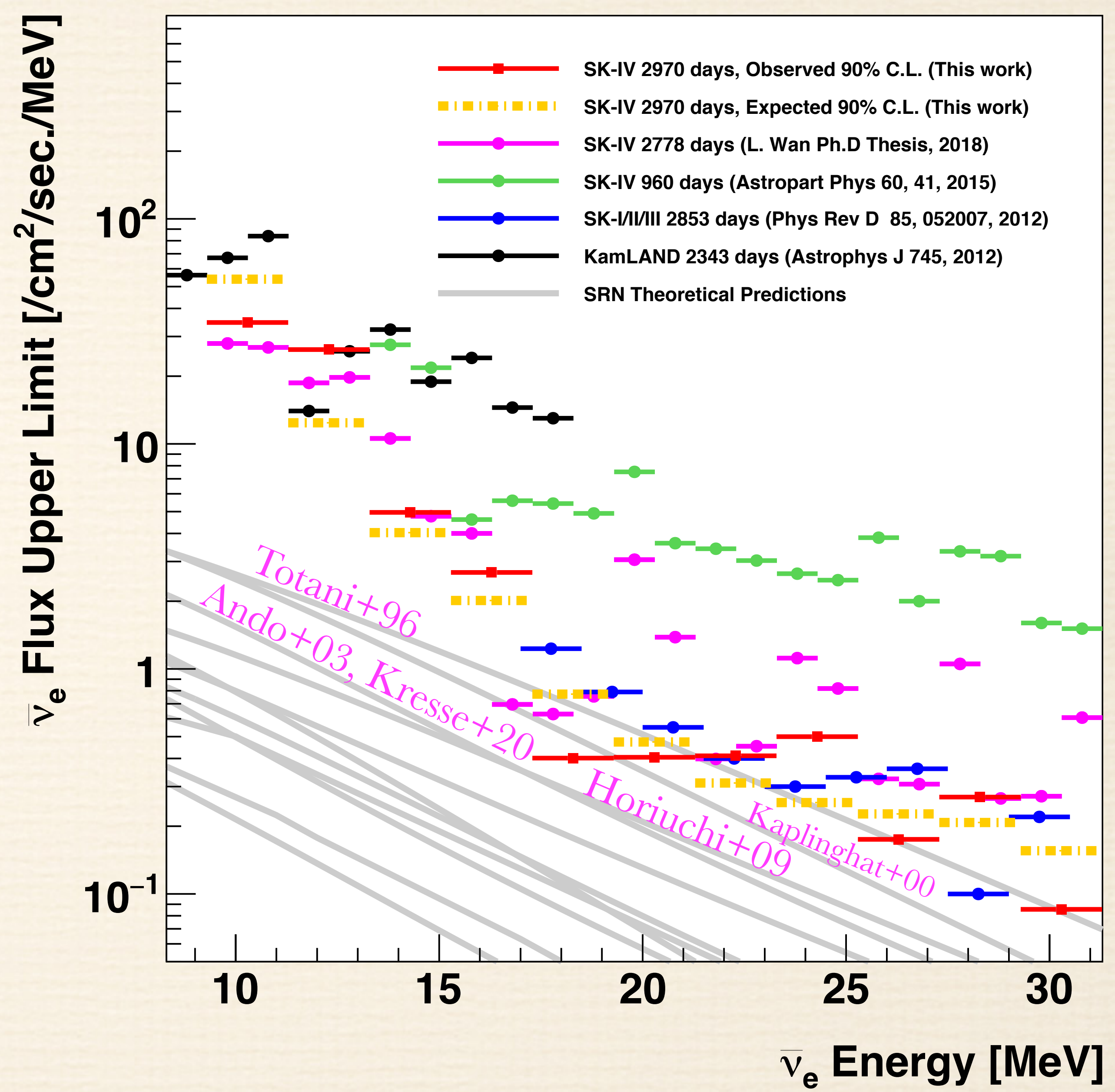
- "distant": farther than Andromeda (M31, NGC224), $z \lesssim 1$ (to be above reactor spectrum) with $\ll 1$ exp. interactions
- constant, diffuse (isotropic positrons from IBD), and low (~few/year) signal rate between 10 and 30 MeV



- delayed coincidence of neutron capture is import handle to distinguish from radioactive and neutrino backgrounds
- flux=cosmic star formation history ⊗ initial mass function ⊗ supernova fraction ⊗ neutrinos/supernova

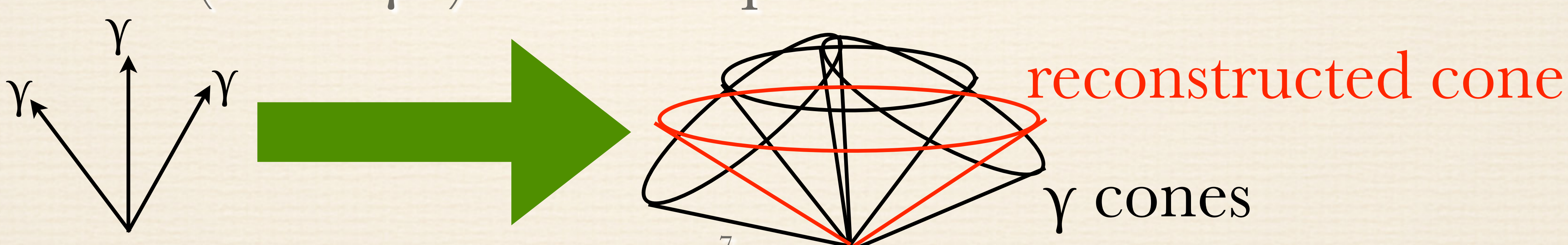
Model Predictions/Present Limits



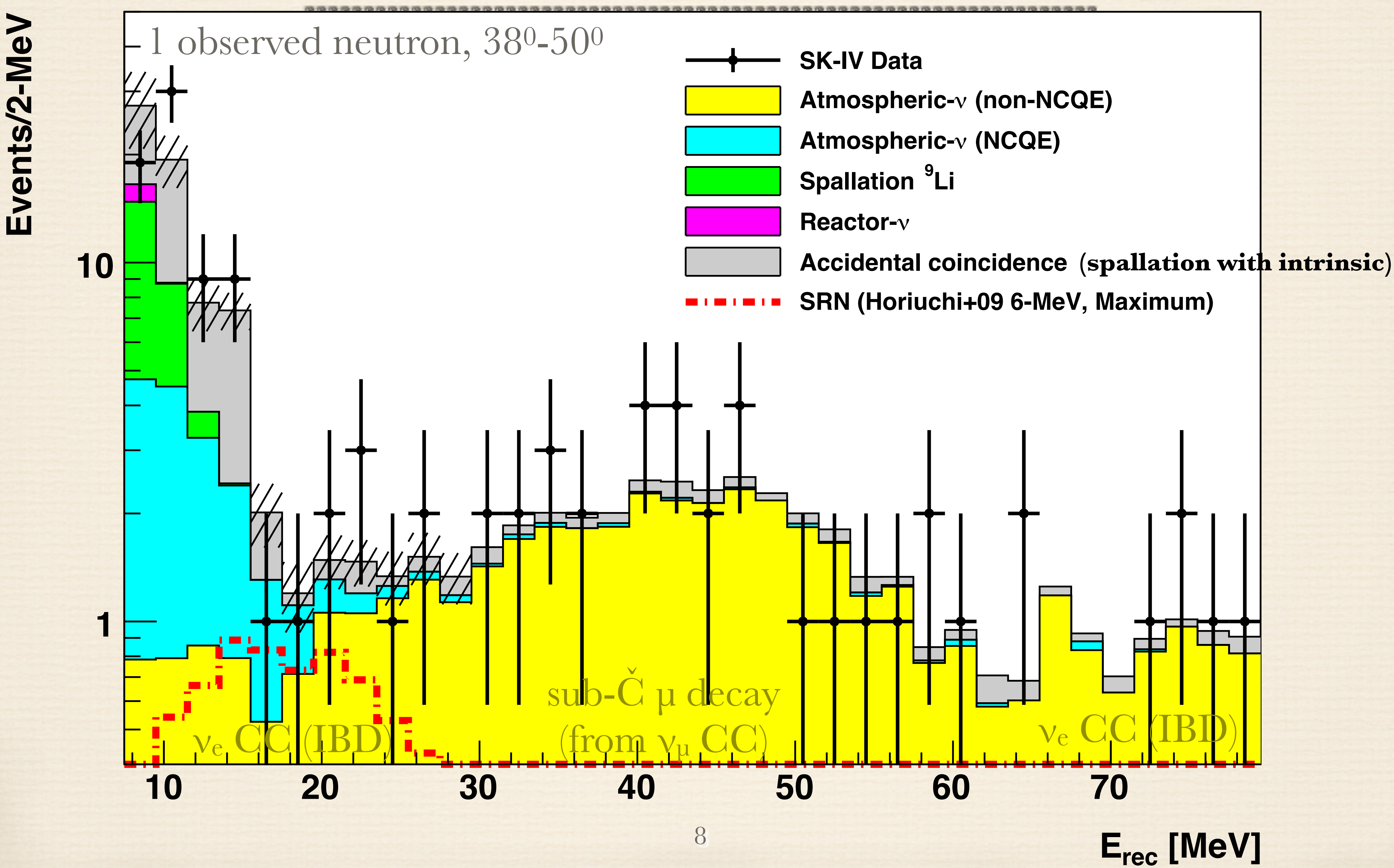


Signal and Sidebands in SK-IV w/o Gd

- one and only one 2.2 MeV γ candidate, ε_{tag}=O(0.1)
- reconstruct Cherenkov angle:
  - signal region: a positron Cherenkov cone opening angle reconstructs as 38^0-50^0
  - low energy muons/pions: smaller opening angle
  - large angles: overlay of multiple Cherenkov cones (from γ's) in atmospheric ν NC interactions



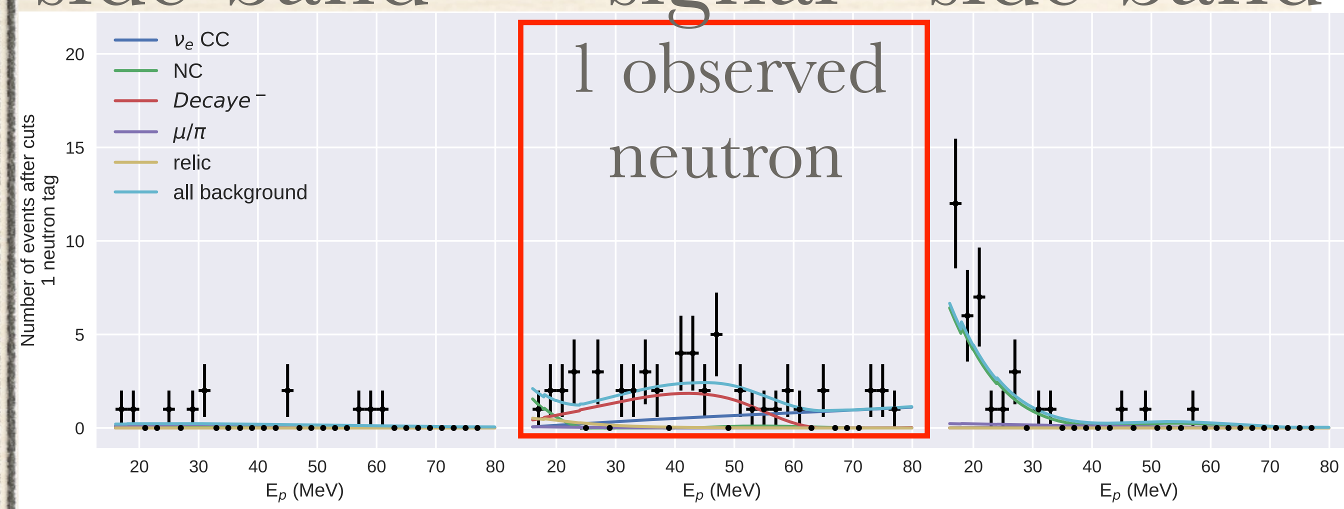
SK-IV Data, Signal and Background



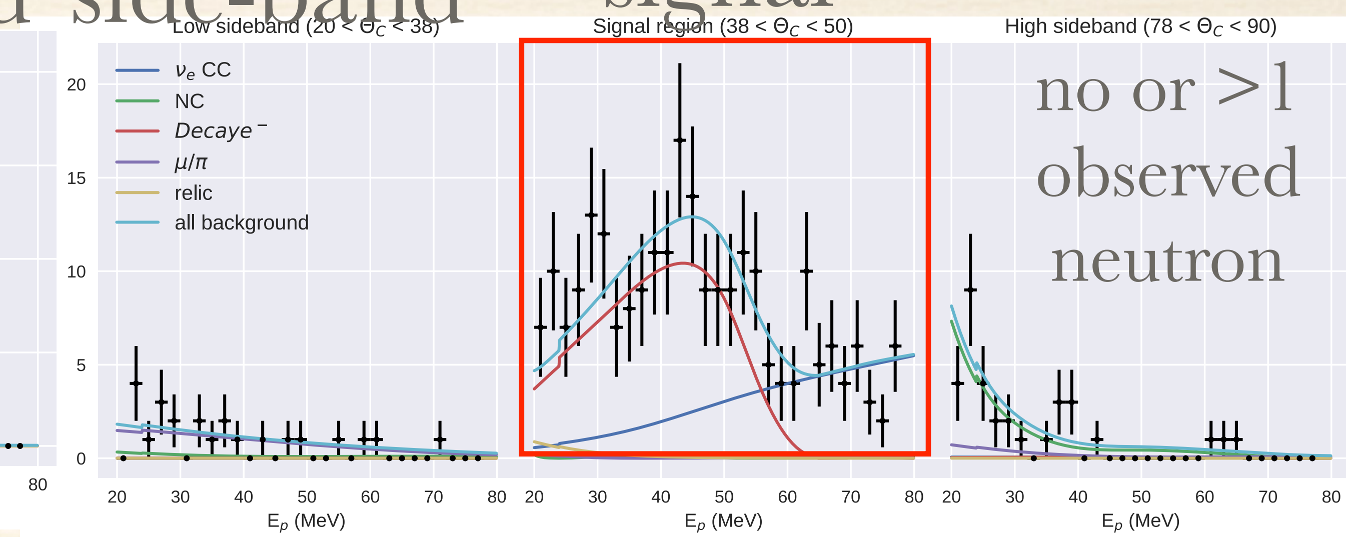
Fit to SK-IV Energy Spectra using various Models (e.g. Ando+03)

side-band signal side-band side-band signal side-band

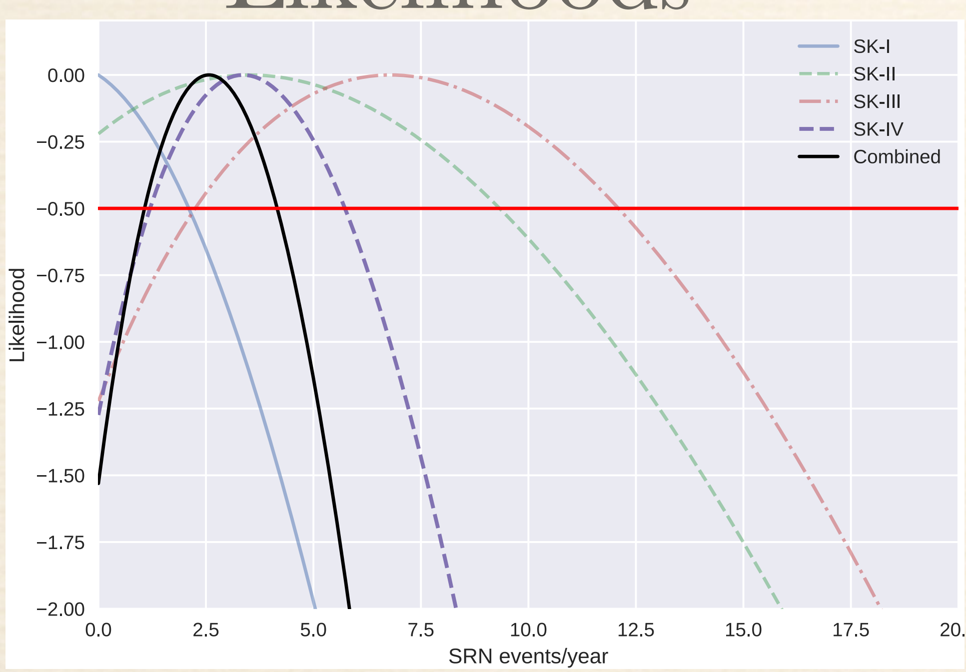
1 observed neutron



no or >1 observed neutron



Likelihoods



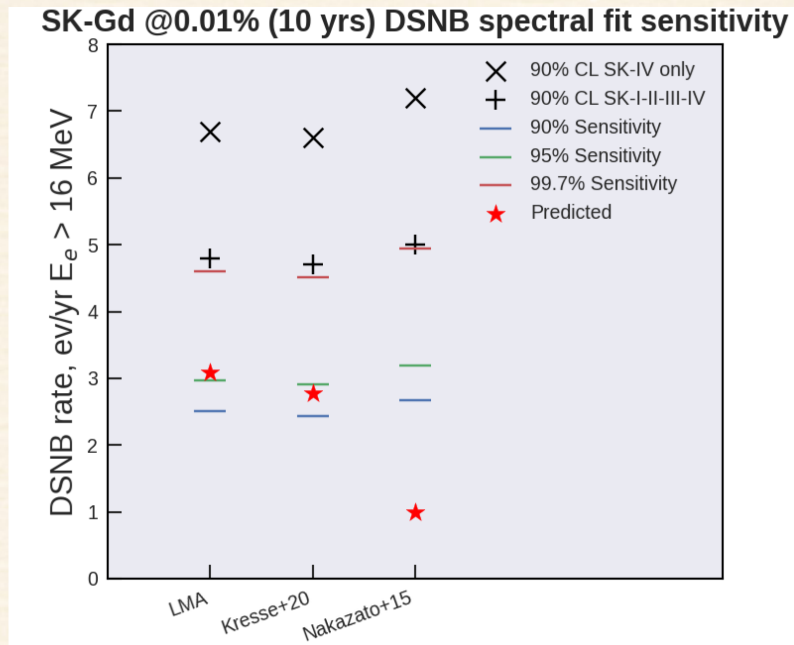
Φ_ν [cm^{-2} sec^{-1}] (for E_ν>17.3 MeV)	Best fit		90% CL limit					Pred.
Model	SK4	All	SK1	SK2	SK3	SK4	All	
Totani+96 Constant	$1.9^{+1.3}_{-1.1}$	$1.4^{+0.8}_{-0.8}$	2.4	6.8	7.9	3.7	2.6	4.67
Malaney97 CGI	$1.8^{+1.3}_{-1.8}$	$1.4^{+0.8}_{-0.8}$	2.3	7.2	7.7	3.7	2.6	0.26
Hartmann+97 CE	$1.9^{+1.3}_{-1.2}$	$1.4^{+0.8}_{-0.8}$	2.4	7.0	7.8	3.7	2.6	0.63
Kaplinghat+00 HMA	$1.8^{+1.3}_{-1.2}$	$1.4^{+0.8}_{-0.8}$	2.3	7.1	7.8	3.7	2.6	3.00
Ando+03 (updated 05)	$1.9^{+1.3}_{-1.2}$	$1.5^{+0.9}_{-0.8}$	2.5	7.1	7.9	3.8	2.7	1.74
Lunardini09 Failed SN	$1.9^{+1.3}_{-1.2}$	$1.5^{+0.9}_{-0.8}$	2.5	7.5	8.1	3.8	2.7	0.72
Horiuchi+09 6 MeV, max	$1.9^{+1.3}_{-1.2}$	$1.5^{+0.9}_{-0.9}$	2.5	6.9	8.0	3.8	2.7	1.94
Galais+10 (NH)	$1.9^{+1.3}_{-1.2}$	$1.4^{+0.8}_{-0.8}$	2.3	7.1	7.8	3.7	2.6	1.49
Nakazato+15 (min, NH)	$1.8^{+1.3}_{-1.2}$	$1.4^{+0.9}_{-0.8}$	2.4	7.3	7.8	3.7	2.7	0.19
Nakazato+15 (max, IH)	$1.9^{+1.3}_{-1.2}$	$1.5^{+0.9}_{-0.9}$	2.5	7.1	8.0	3.8	2.7	0.53
Horiuchi+18 $\xi_{2.5}=0.1$	$1.9^{+1.3}_{-1.2}$	$1.5^{+0.9}_{-0.9}$	2.5	6.9	8.1	3.8	2.7	1.23
Horiuchi+18 $\xi_{2.5}=0.5$	$1.7^{+1.3}_{-1.2}$	$1.4^{+0.8}_{-0.8}$	2.3	7.6	7.5	3.6	2.5	0.55
Kresse+20 (High, NH)	$1.9^{+1.3}_{-1.2}$	$1.5^{+0.9}_{-0.8}$	2.4	7.2	7.9	3.7	2.7	1.57

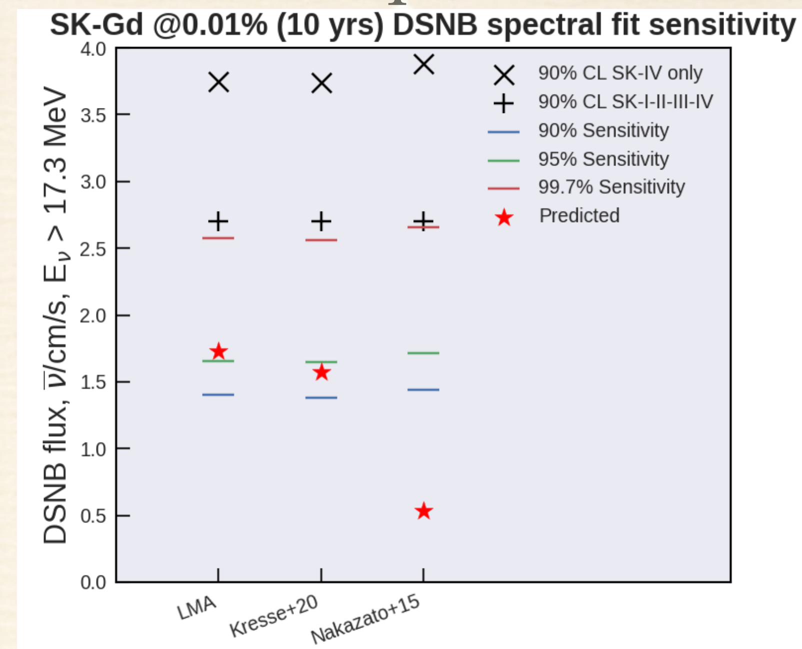
detailed results in the presentation from Alberto Giampaolo last week:
→ Fri 19th, 12:15 Parallel Room 2

Sensitivity with Gd (10 years)

- currently: 0.011% Gd concentration, ~50% neutron captures on Gd

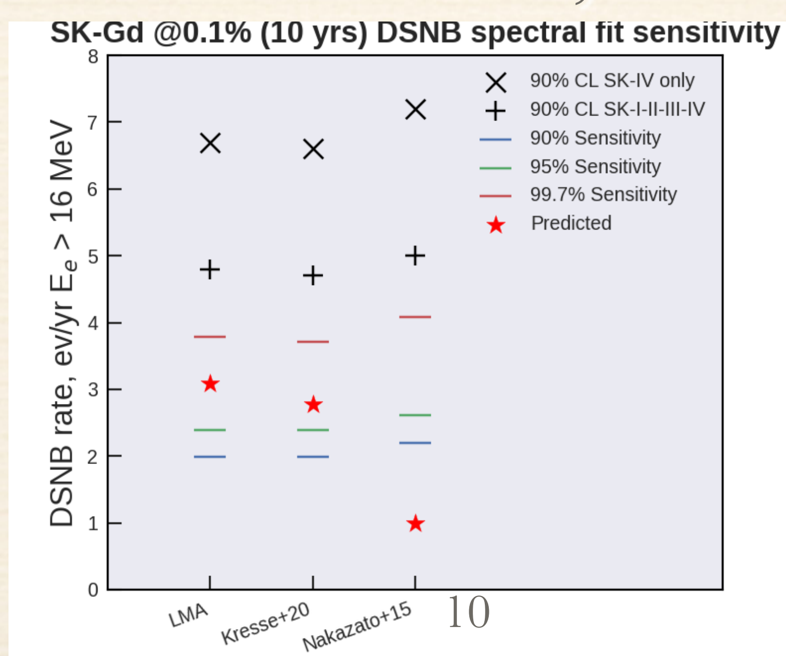
ε_{tag}=O(0.5)

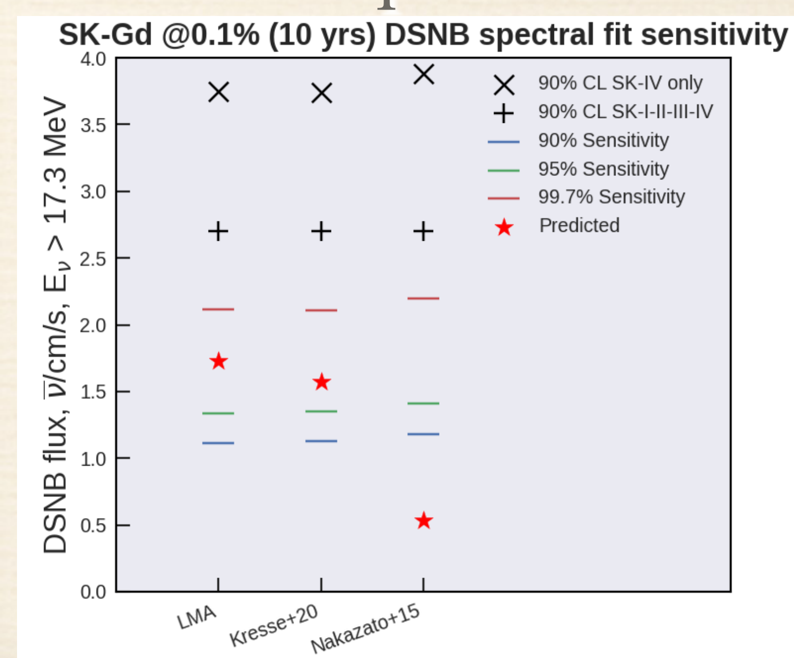




- eventually: 0.1% Gd concentration, ~90% neutron captures on Gd

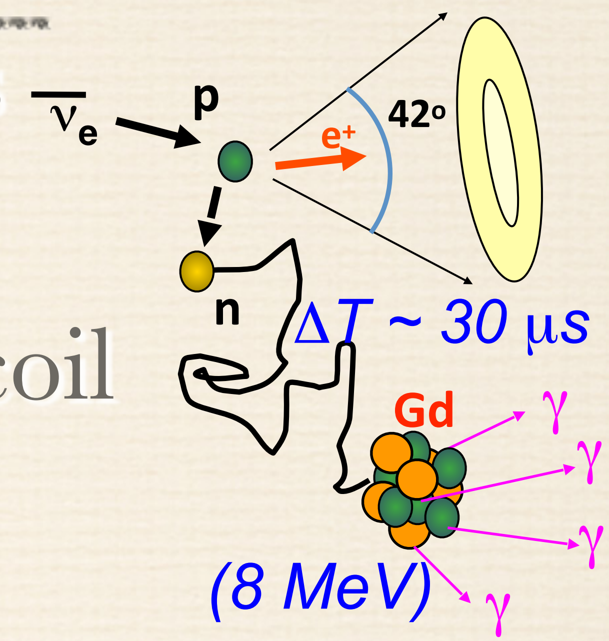
ε_{tag}=O(0.9)

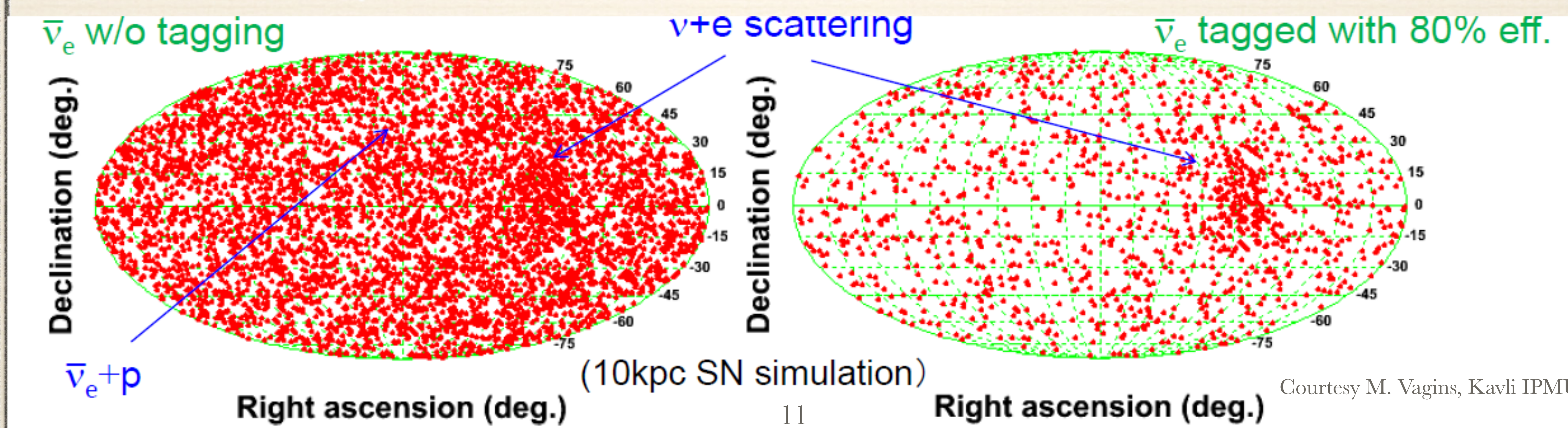




Galactic Supernova Neutrinos

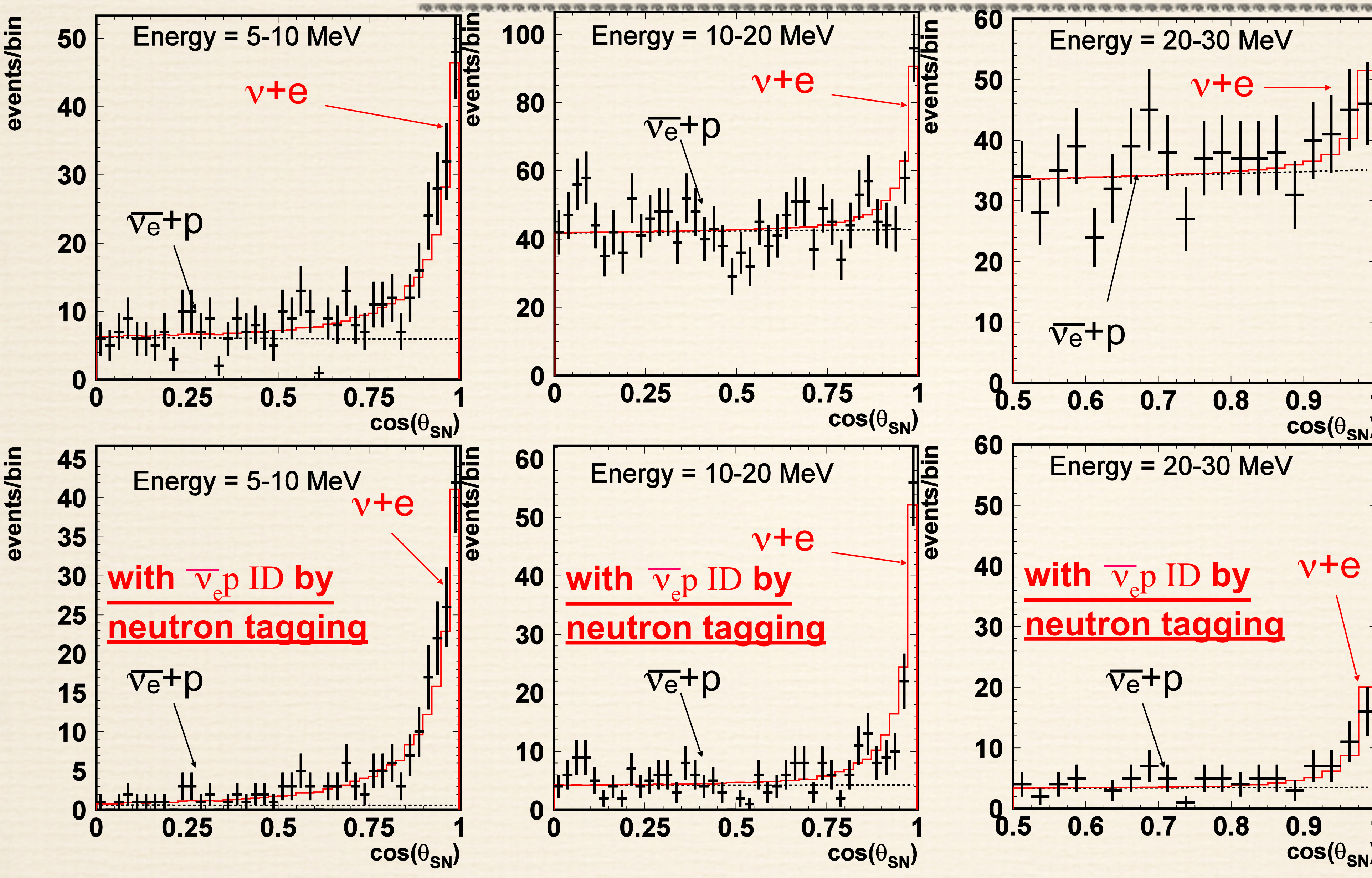
- dominant channel: IBD of $\overline{\nu_e}$'s on protons
- sub-dominant channel: elastic scattering $\nu_x + e^- \longrightarrow \nu_x + e^-$ (dominated by ν_e's); recoil electrons follow neutrino direction
- with Gd: separate those two channels, improve sensitivity to late burst

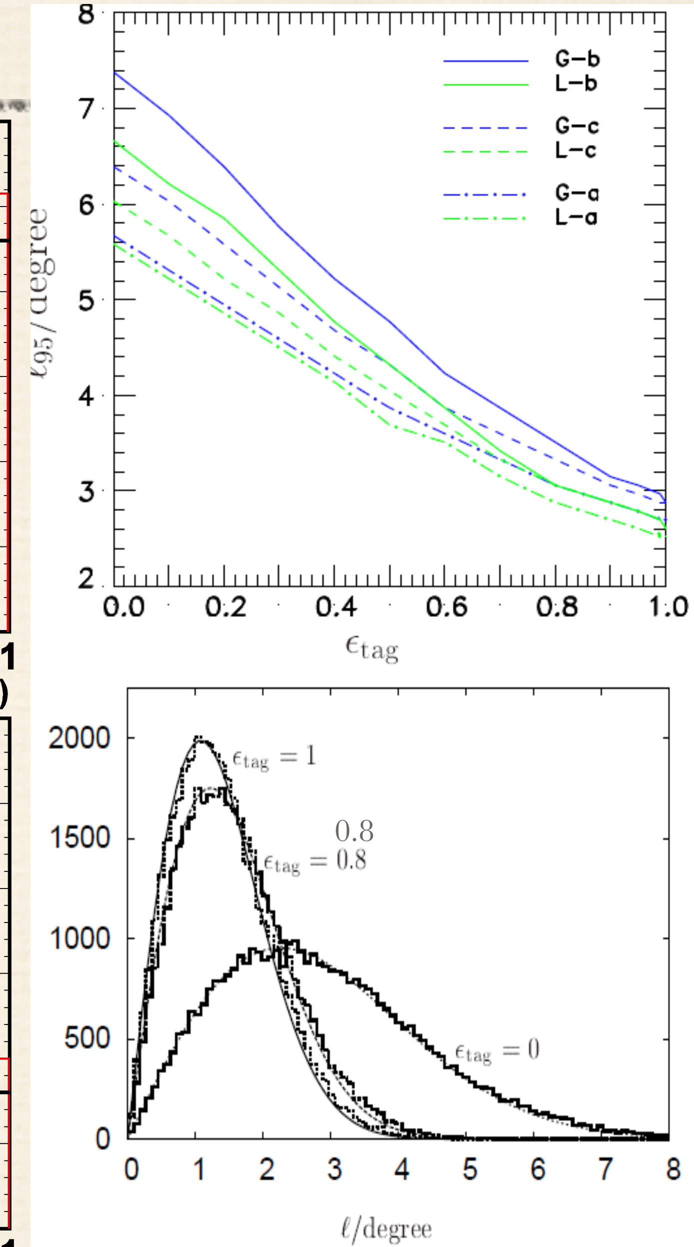




Courtesy M. Vagins, Kavli IPMU

Galactic Supernova Neutrinos





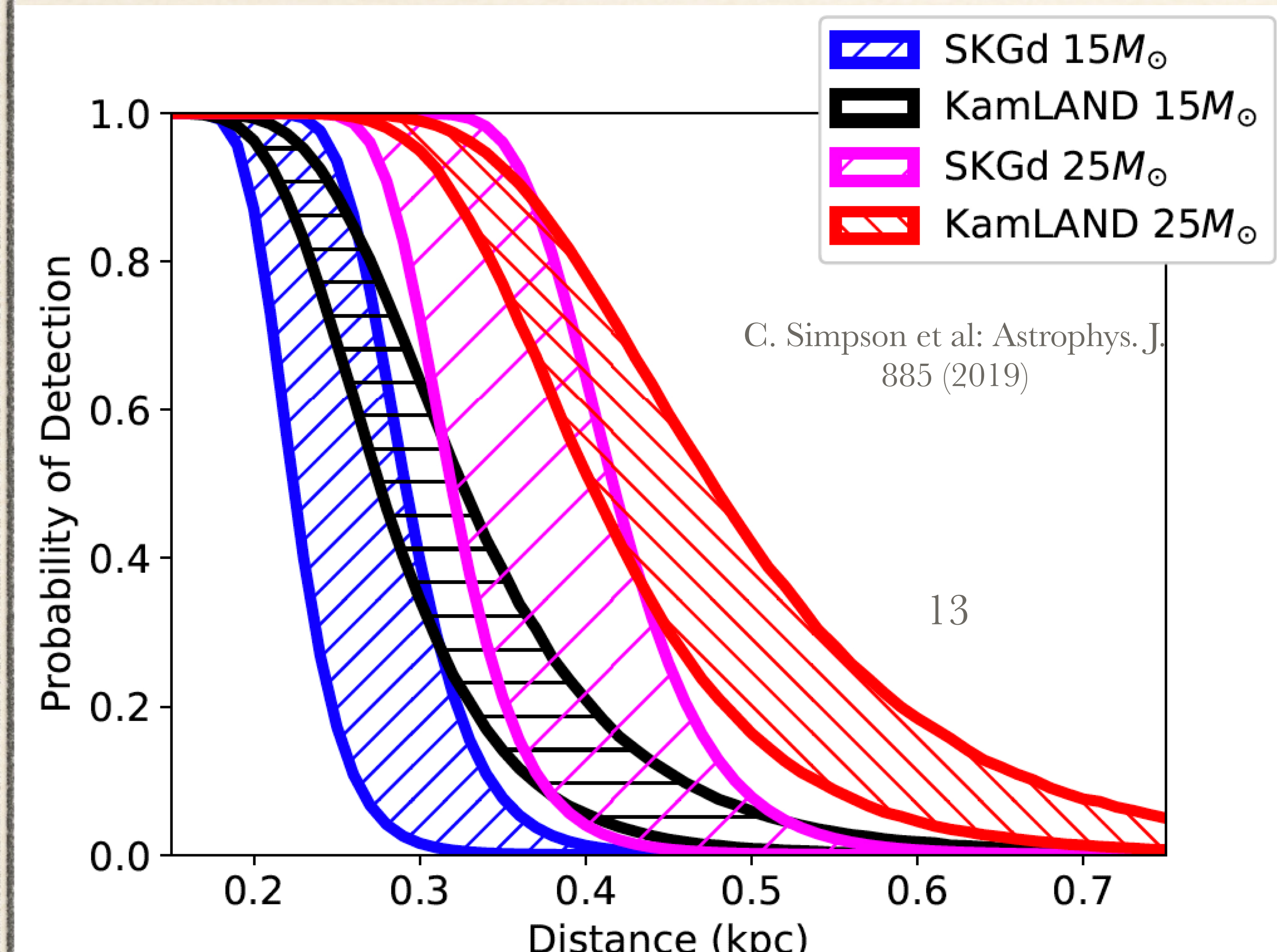
Thomas, Sekikoz,

Raffelt, Kachelriess, Dighe hep-ph/0307050v2

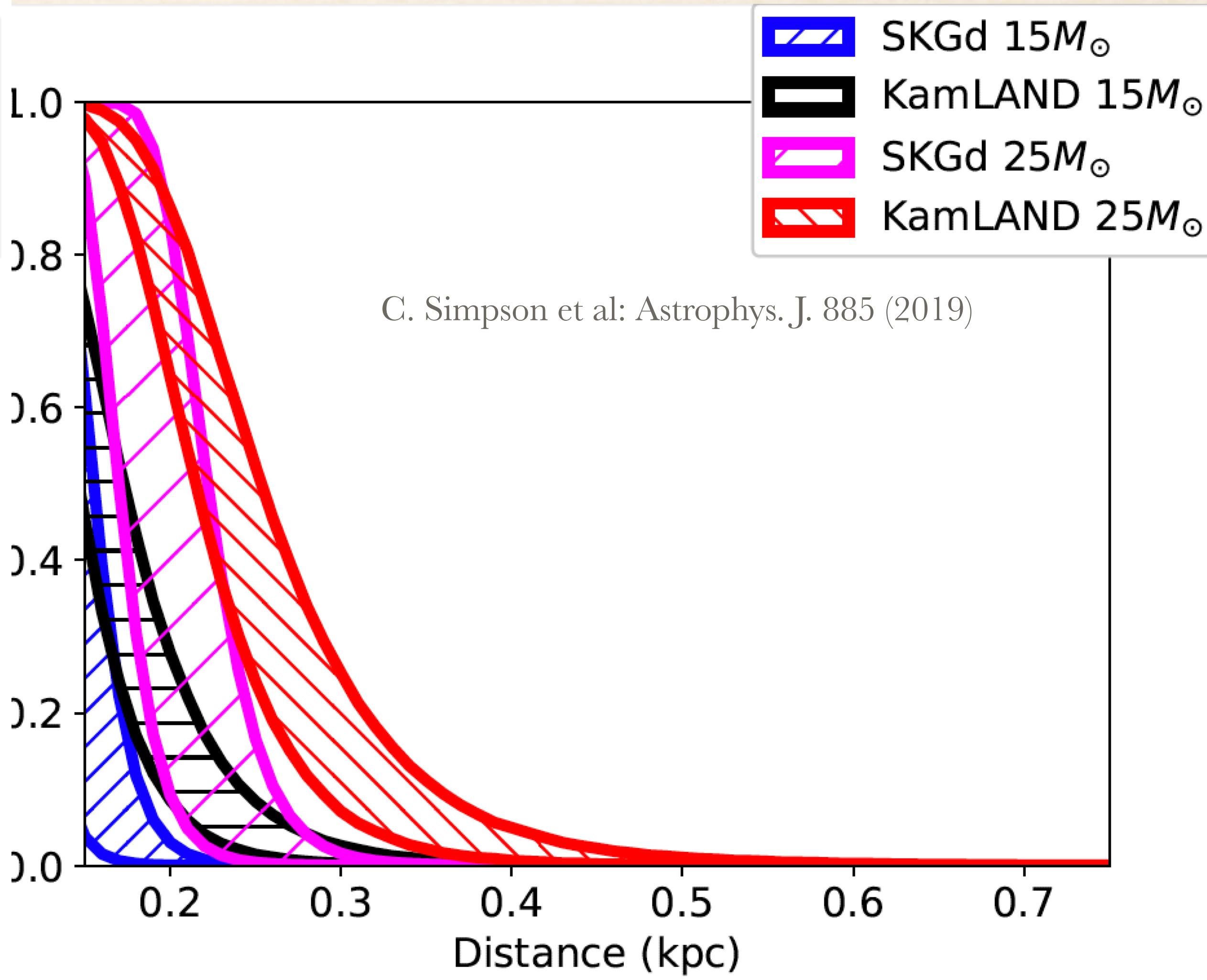
- improve ES signal and flavor decomposition of galactic SN ν burst
- improve angular resolution by factor of two!

Courtesy M. Nakahata, ICRR

Galactic Supernovae: Pre-SN Alert from Si-Burning ν's



normal mass ordering

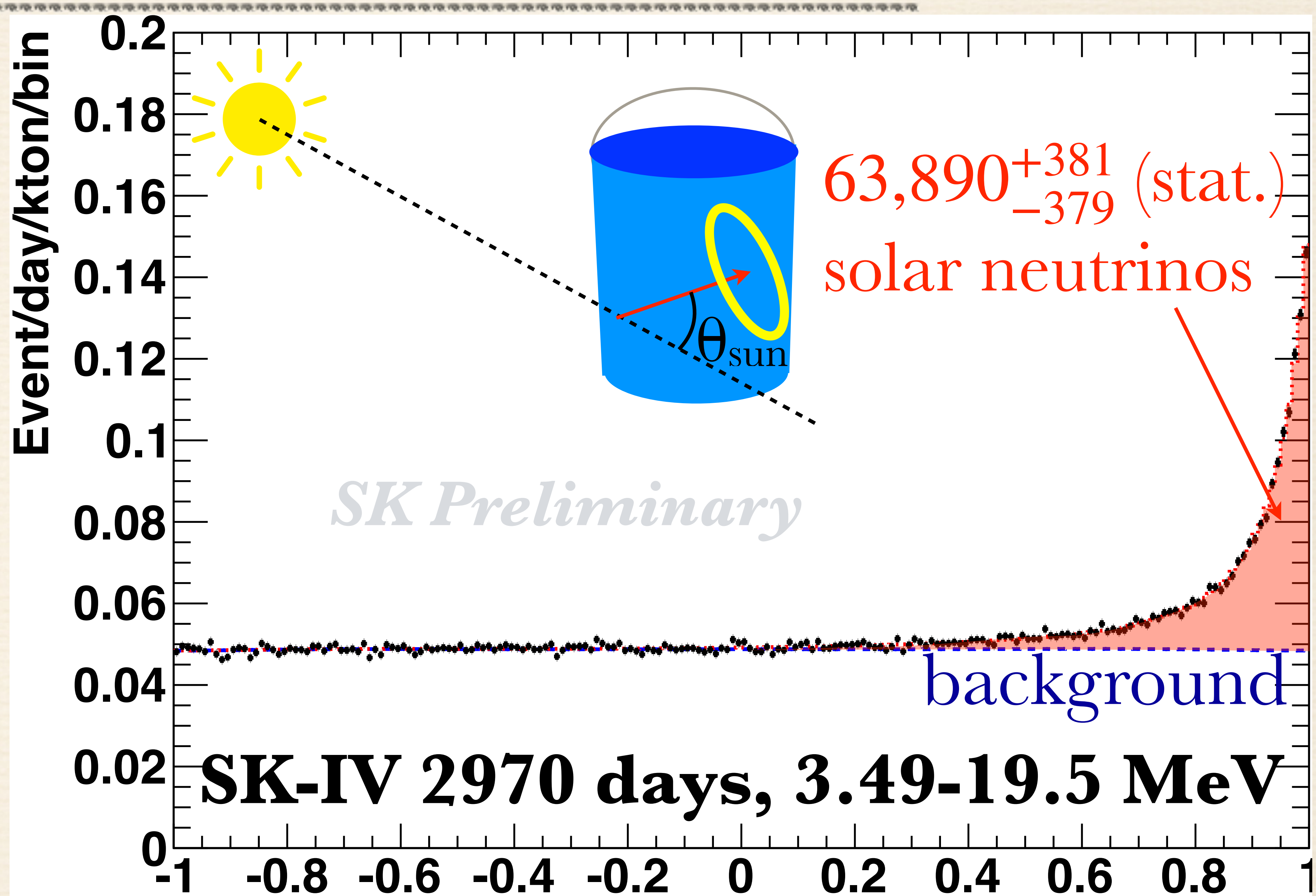


inverted mass ordering

- detection in ~48 hour period before SN
- only viable for massive stars in the neighborhood (e.g. Betelgeuse)
- some model dependence of 5σ detection range; it is similar to KamLAND's

Solar ^{8}B Neutrinos

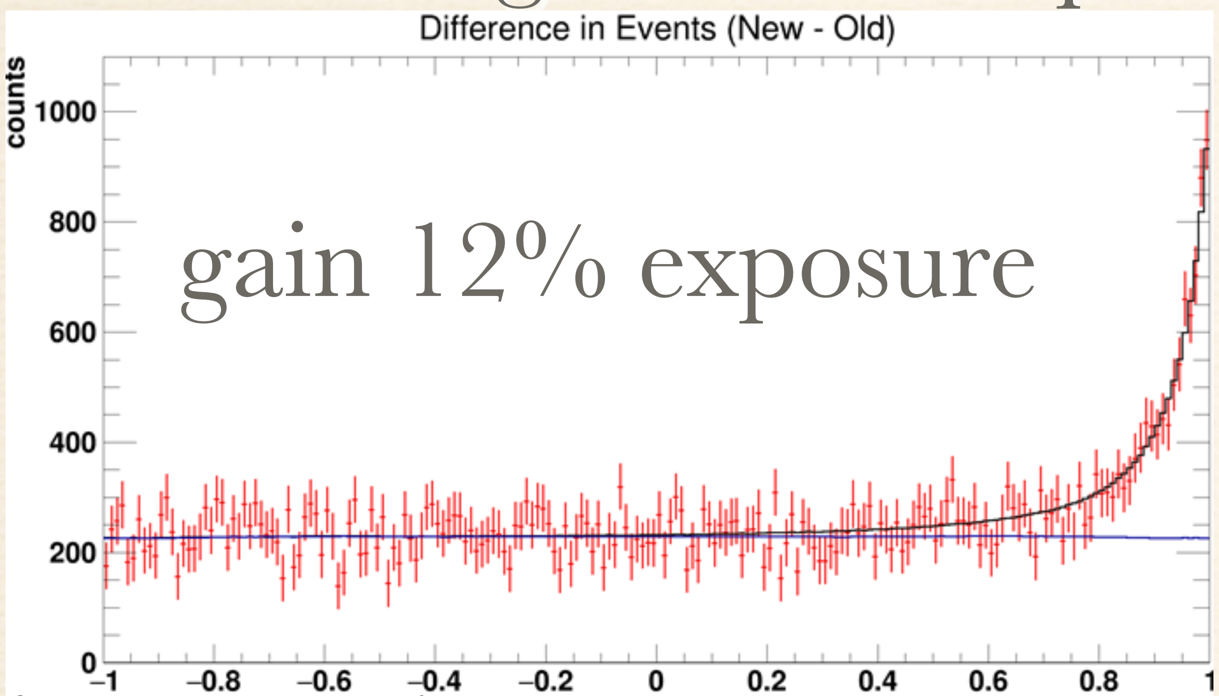
- high statistics observations
- solar core temperature
- observe solar ν oscillation; determination of parameters
- investigate solar matter effects
- study terrestrial matter effects



- found ν osc.: θ_{12} consistent with SNO, Δm^2_{21} a bit smaller than KamLAND
- no evidence (but slight hint) of MSW energy "edge", hint of terrestrial matter effects

What's New?

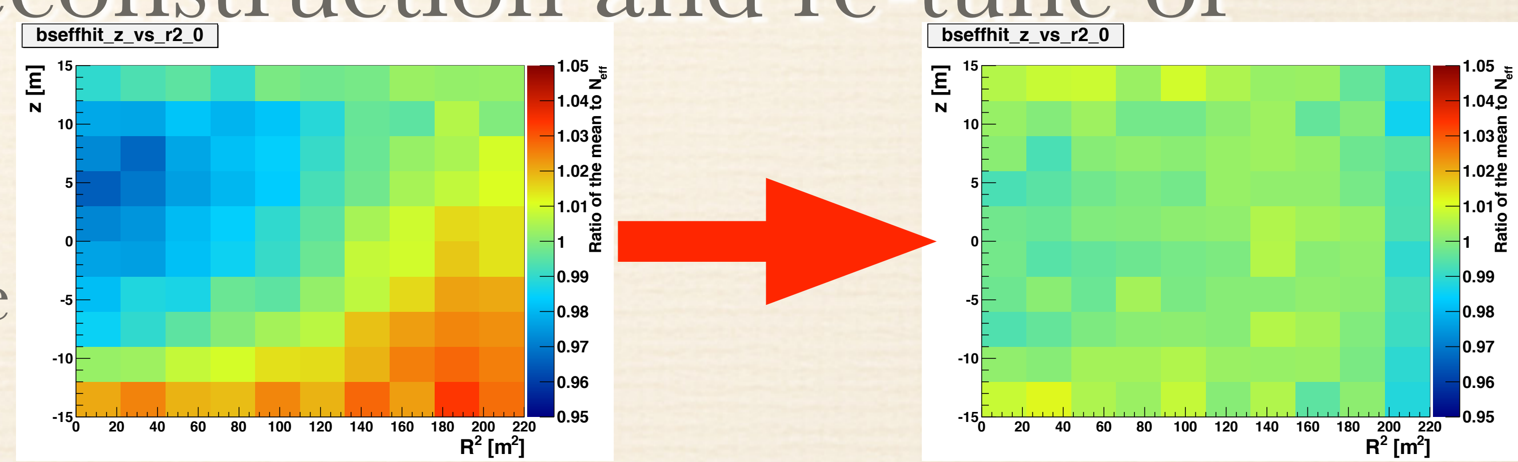
- improved removal of cosmogenic radioactive events using neutron captures on hydrogen



this method will improve further with Gd-enhanced neutron tagging as showers with less neutrons (neglected now due to small detection efficiency) will also be flagged

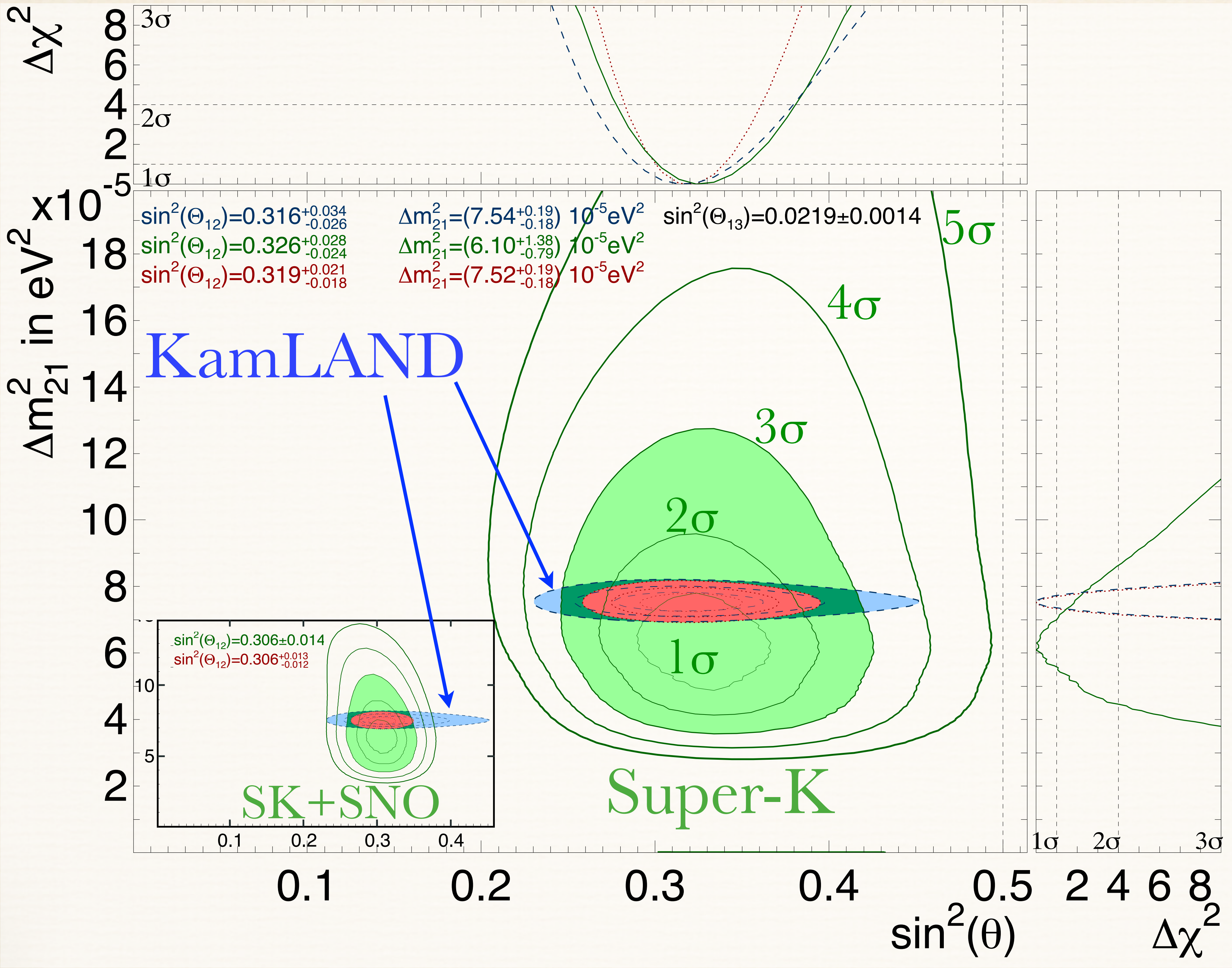
- improved energy reconstruction and re-tune of the energy scale

pos. dependence



- improved detector simulation

Fit Solar ν Oscillation Parameters

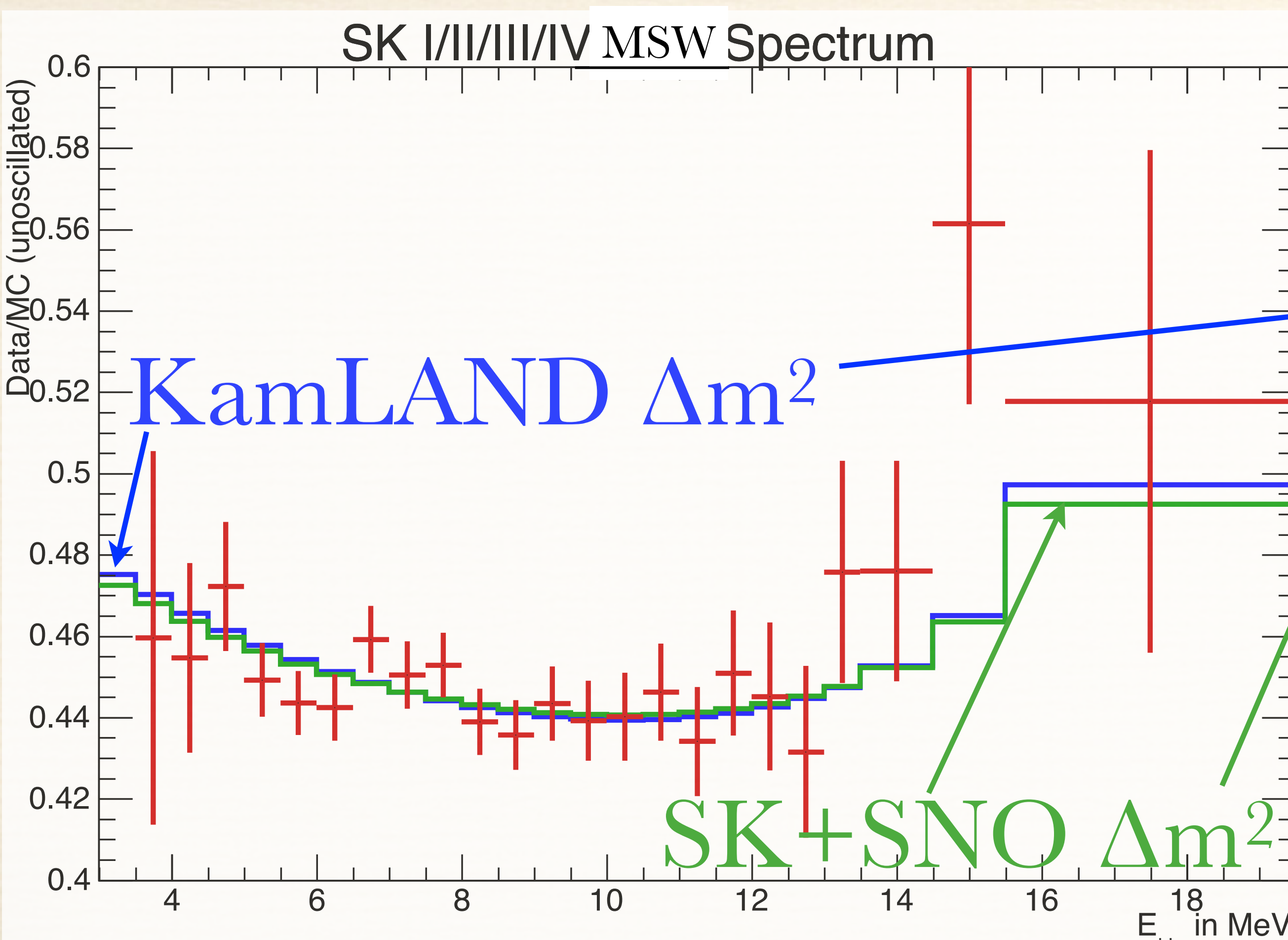


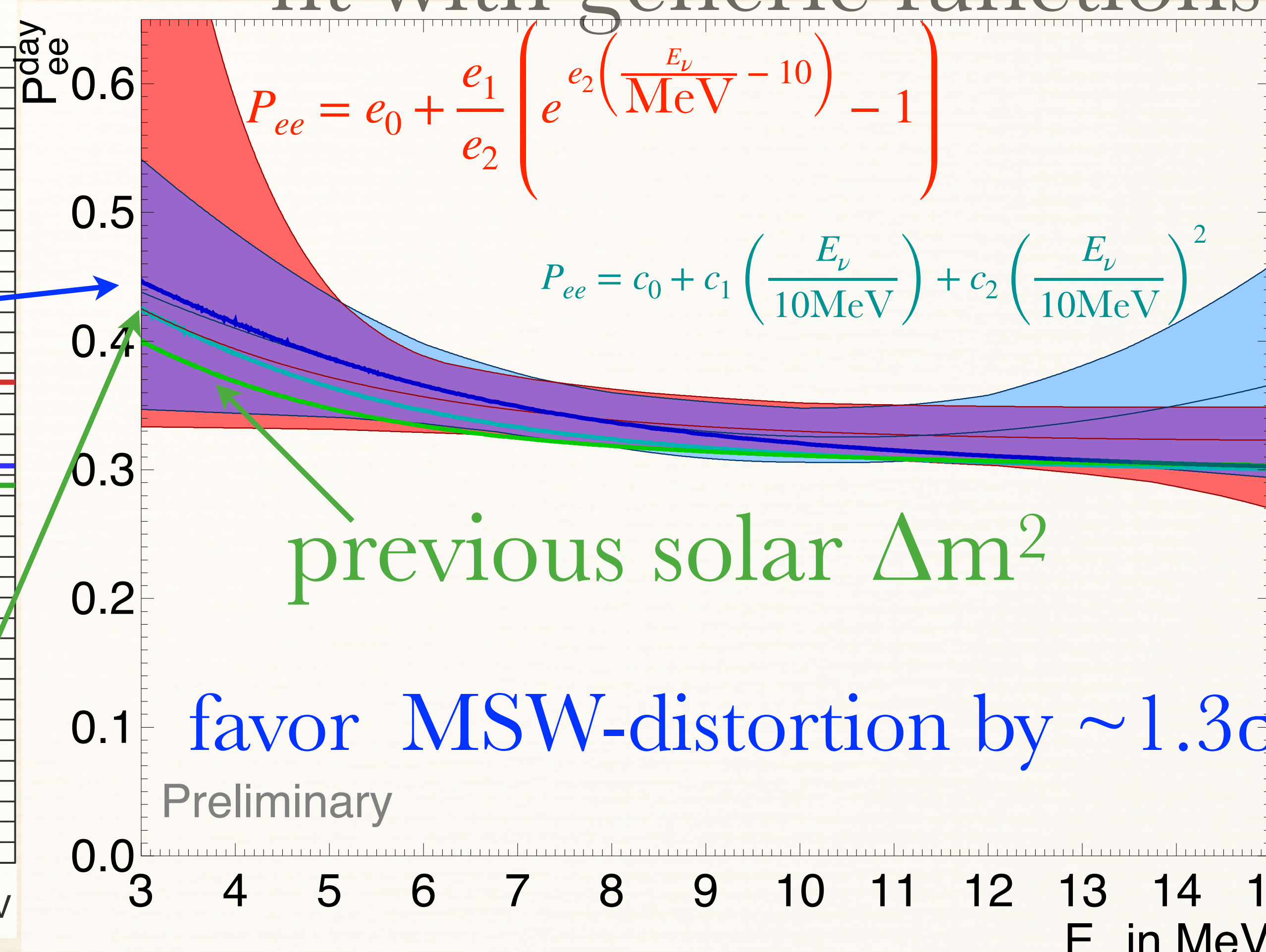
- use rate, spectral and day/night rate variation
- larger value of Δm^2_{21} than before
- less tension (1.4 σ) with KamLAND
- addition of SNO data improves mixing angle constraint, but no effect on Δm^2_{21} or tension with KL

Test Solar Matter Effects

- MSW adiabatic conversion >5 MeV, transitions to vacuum oscillation <1 MeV $\Longrightarrow$energy dependent survival probability P_{ee} from $\sin^2\theta_{12}$ to $1-\frac{1}{2}\sin^2 2\theta_{12}$

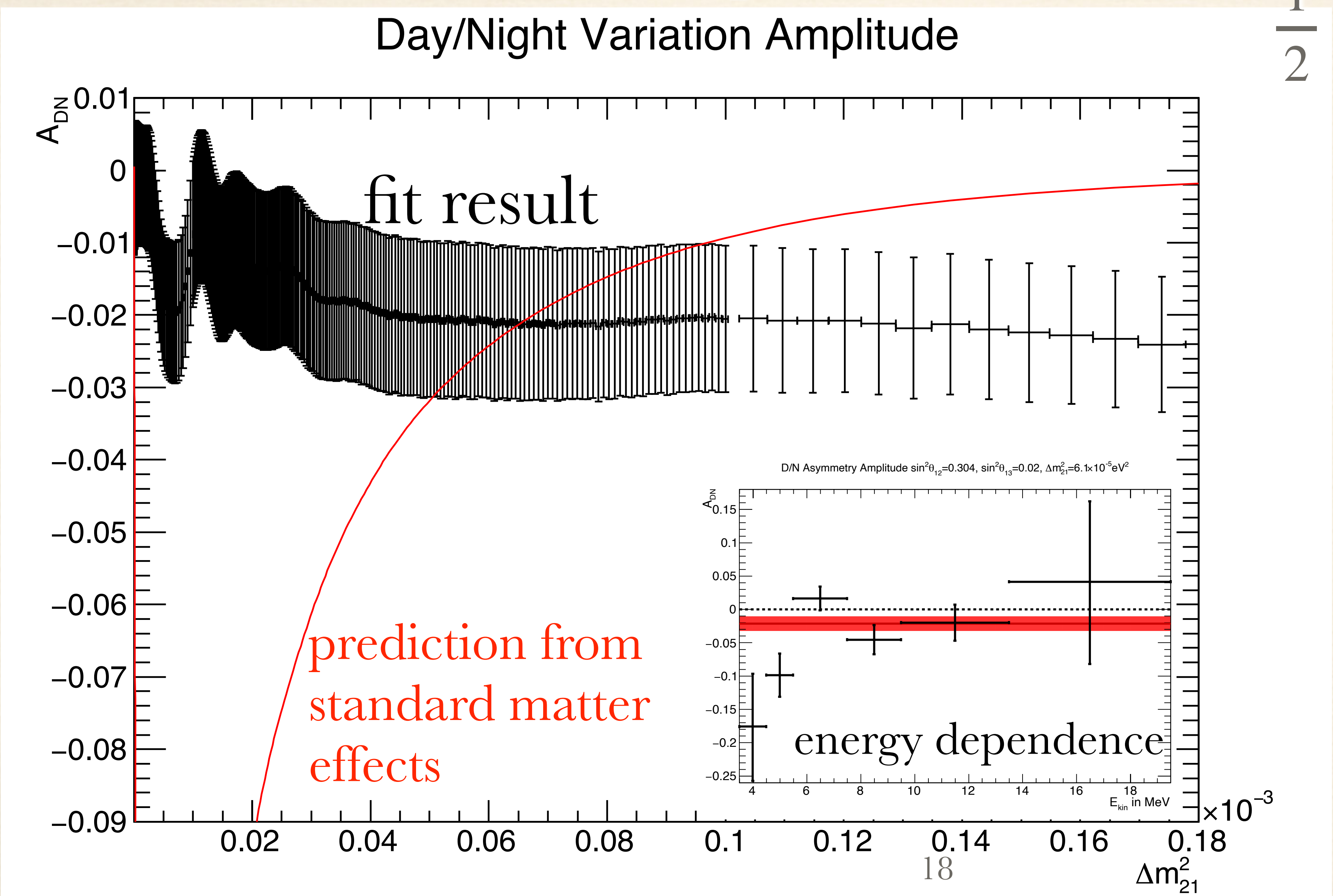
fit with generic functions





Test Earth Matter Effects

- fit amplitude of day/night solar neutrino interaction rate variation expressed as $A_{DN} = \frac{R_D - R_N}{\frac{1}{2}(R_D + R_N)}$



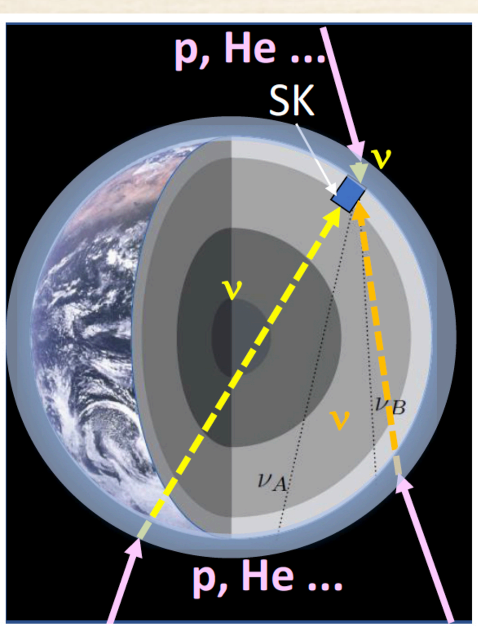
fit result in SK-IV:

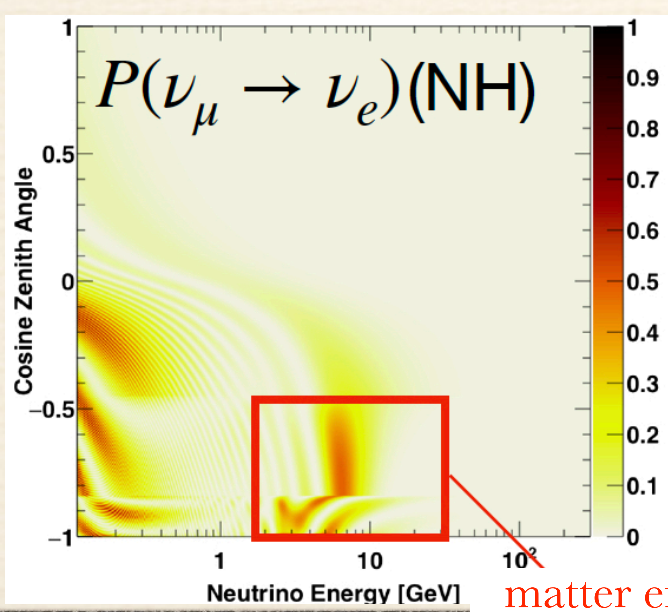
$A_{DN} = -0.021 \pm 0.011$

fit result varies somewhat with Δm^2_{21} and negligibly with θ_{12}

Atmospheric (and Cosmic) Neutrinos

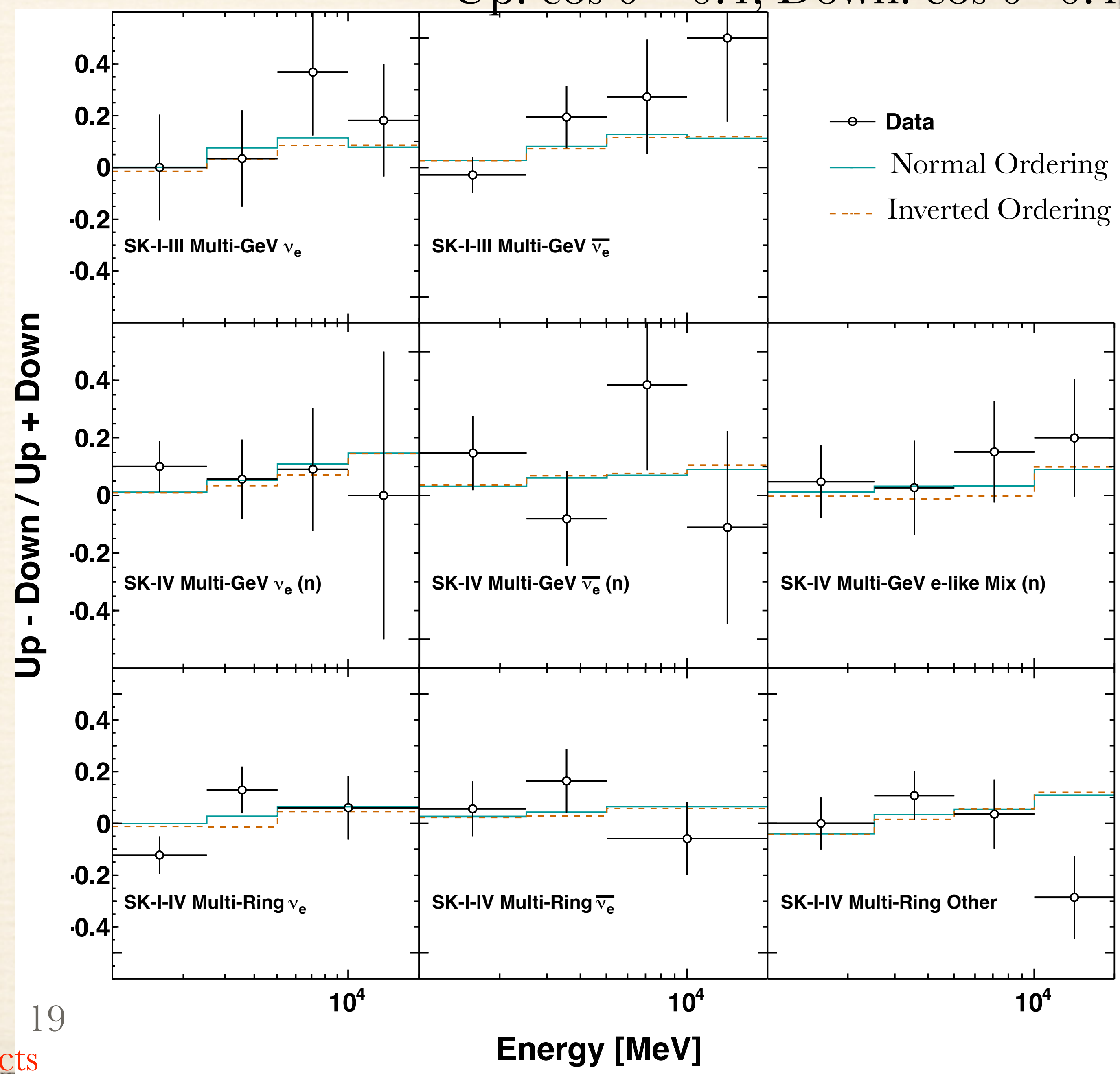
- O(GeV) neutrinos measure neutrino oscillation parameters from zenith angle and energy distributions from many samples
- combined analysis using 364.8kton years
- sensitive to matter effects
- neutron-tagging to distinguish ν from $\bar{\nu}$: ~25% tagging eff.
- new BDT based event selection for multi-track events





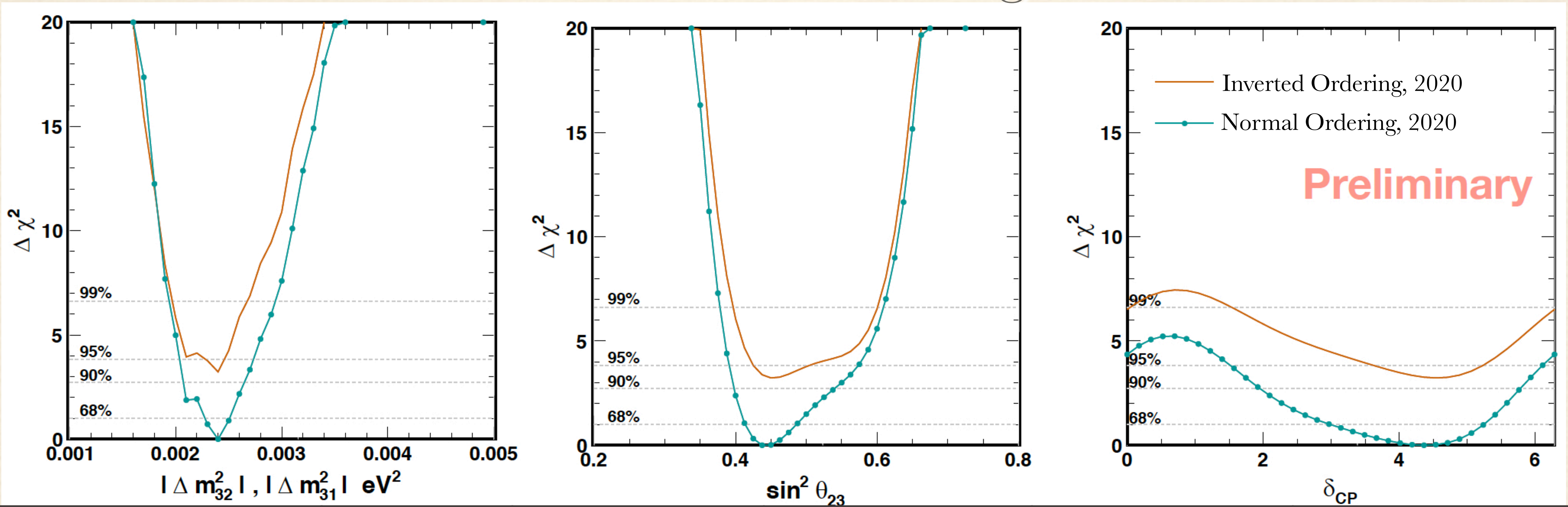
matter effects

Up: cos θ<-0.4, Down: cos θ>0.4



Atmospheric Neutrinos

- oscillation parameters/mass ordering: prefer first θ_{23} octant, $\delta_{CP}\sim 3\pi/2$ and disfavor inverted ordering at 71.4-90.3% C.L.



930 bins	χ^2	$\sin^2\theta_{13}$	δ_{CP}	$\sin^2\theta_{23}$	Δm^2_{23} in 10^{-3}eV^2
SK: normal ordering	1037.5	0.0218	$4.36^{+0.88}_{-1.39}$	$0.44^{+0.05}_{-0.02}$	$2.40^{+0.11}_{-0.12}$
SK: inverted ordering	1040.7	0.0218	$4.54^{+0.88}_{-1.32}$	$0.45^{+0.09}_{-0.03}$	$2.40^{+0.09}_{-0.32}$

detailed results in the presentation from Pablo Fernandez:
$\rightarrow$ Wed 24th, 10:00 Parallel Room 3)

Atmospheric Neutrinos: Search for Non-Standard Interactions (NSI)

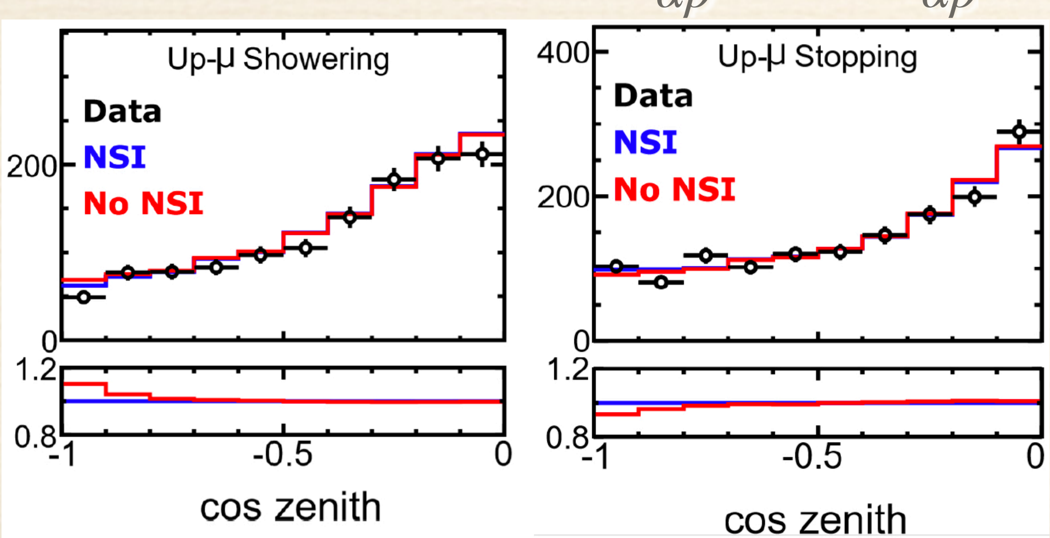
μ-τ sector NSI:

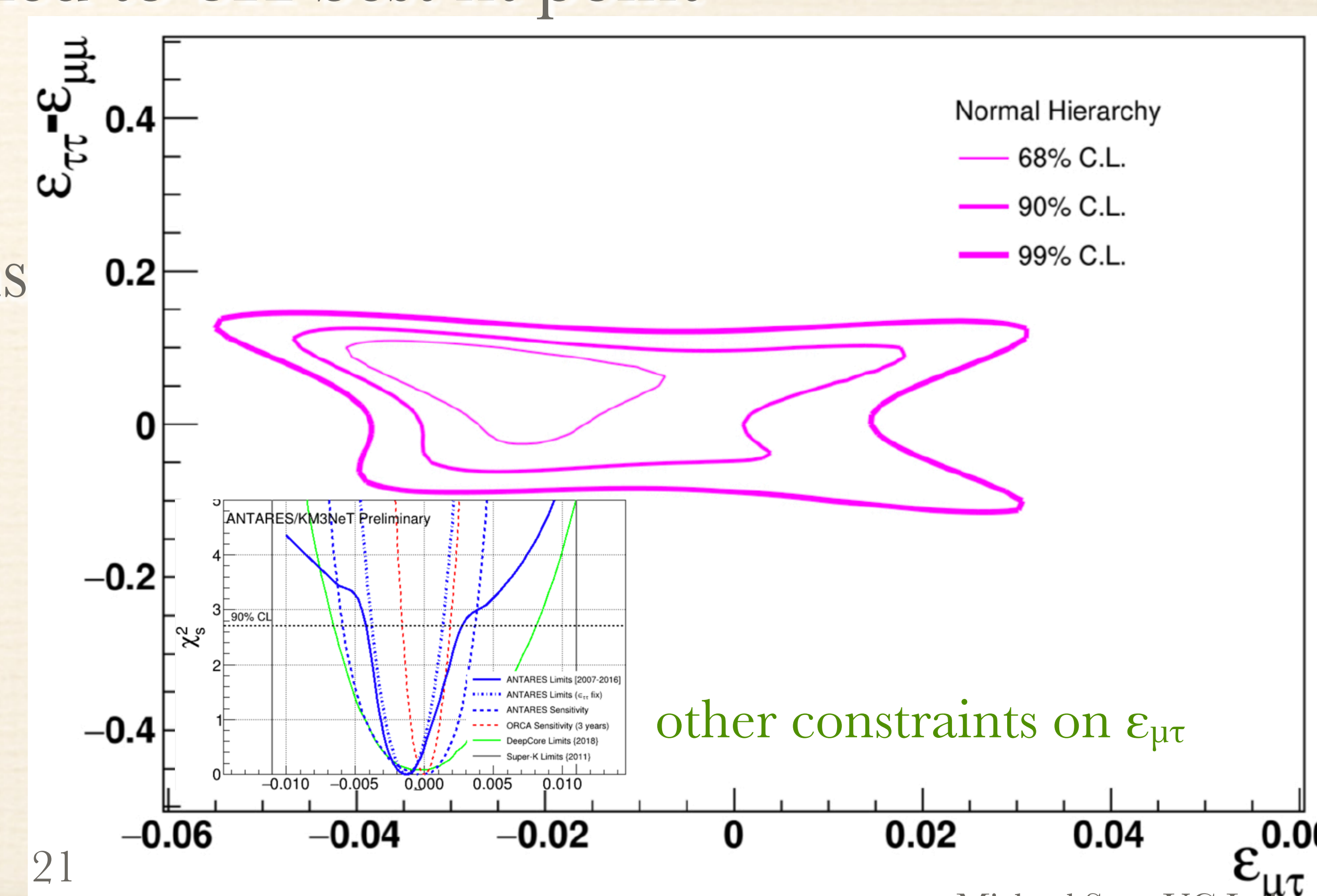
$$H = \boxed{\frac{1}{2E} U_{PMNS} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^{\dagger}_{PMNS}} + V_{matter} + \boxed{\sqrt{2} G_F N_f(\vec{r}) \begin{pmatrix} \epsilon_{ee} & \epsilon^*_{e\mu} & \epsilon^*_{e\tau} \\ \epsilon_{e\mu} & \epsilon_{\mu\mu} & \epsilon^*_{\mu\tau} \\ \epsilon_{e\tau} & \epsilon_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}}$$

vacuum oscillation

NSI

- fit to 25 years of SK data
- (standard) oscillation parameters fixed to SK best fit point
- set all $\varepsilon_{e\alpha}=0$
- oscillation probabilities invariant under simultaneous transformations $\Delta m^2 \rightarrow -\Delta m^2$ and $\epsilon_{\alpha\beta} \rightarrow -\epsilon_{\alpha\beta}$





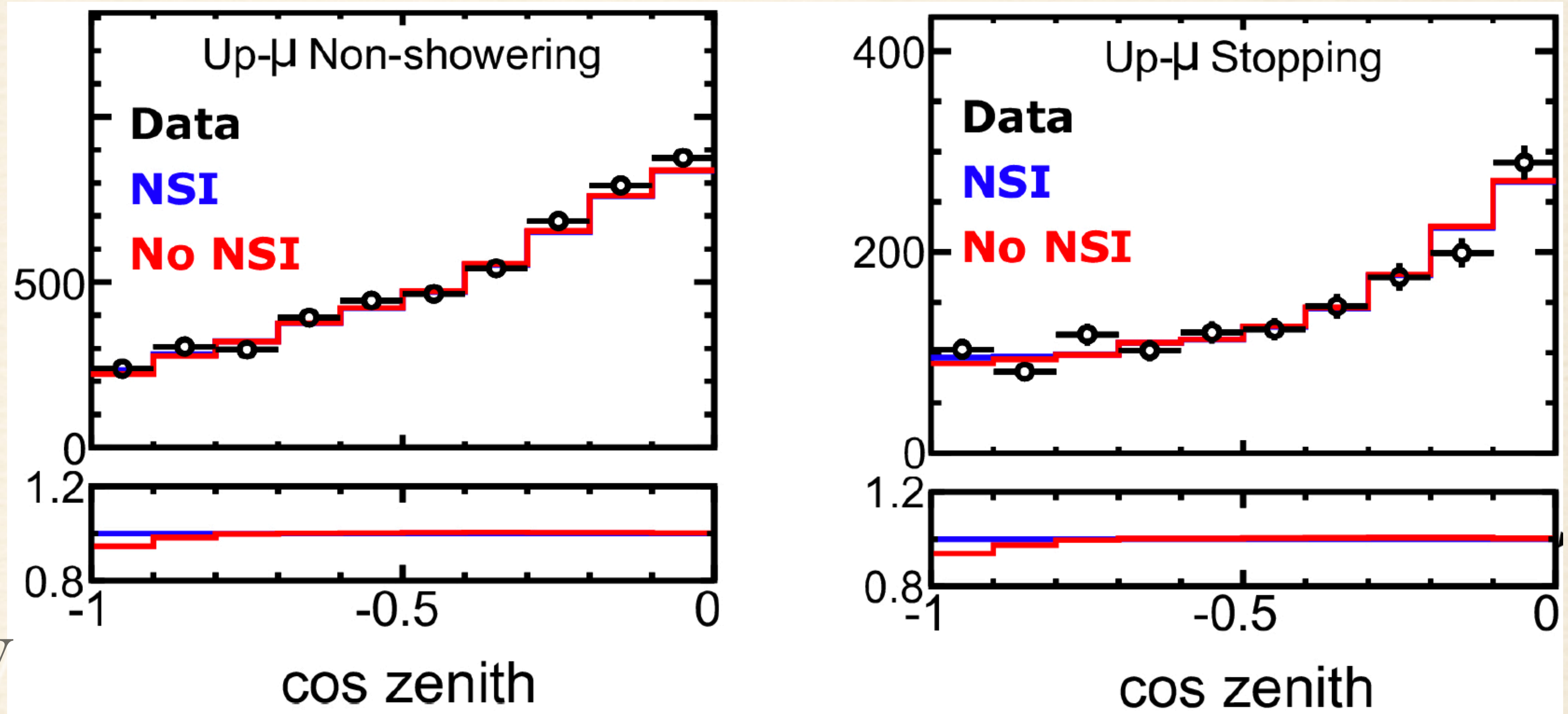
other constraints on $\varepsilon_{\mu\tau}$

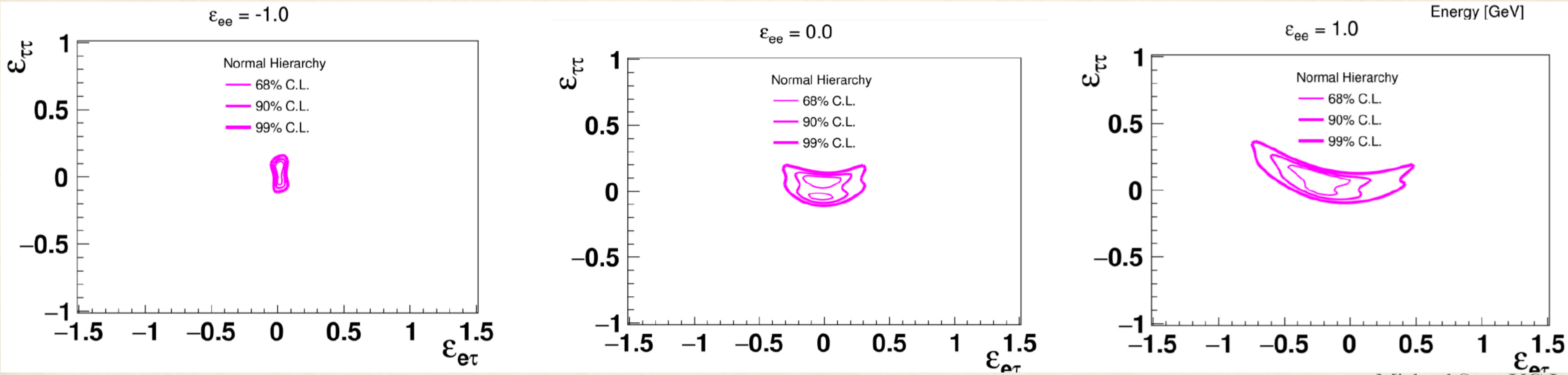
Michael Smy, UC Irvine

Atmospheric Neutrinos: Search for Non-Standard Interactions (NSI)

e-τ sector NSI:

- (standard) oscillation parameters fixed to SK best fit point
- set all $\varepsilon_{\mu\alpha}=0$
- excess in upward-going ν_e's≳5 GeV
- excess in upward-going ν_μ's 20-80 GeV



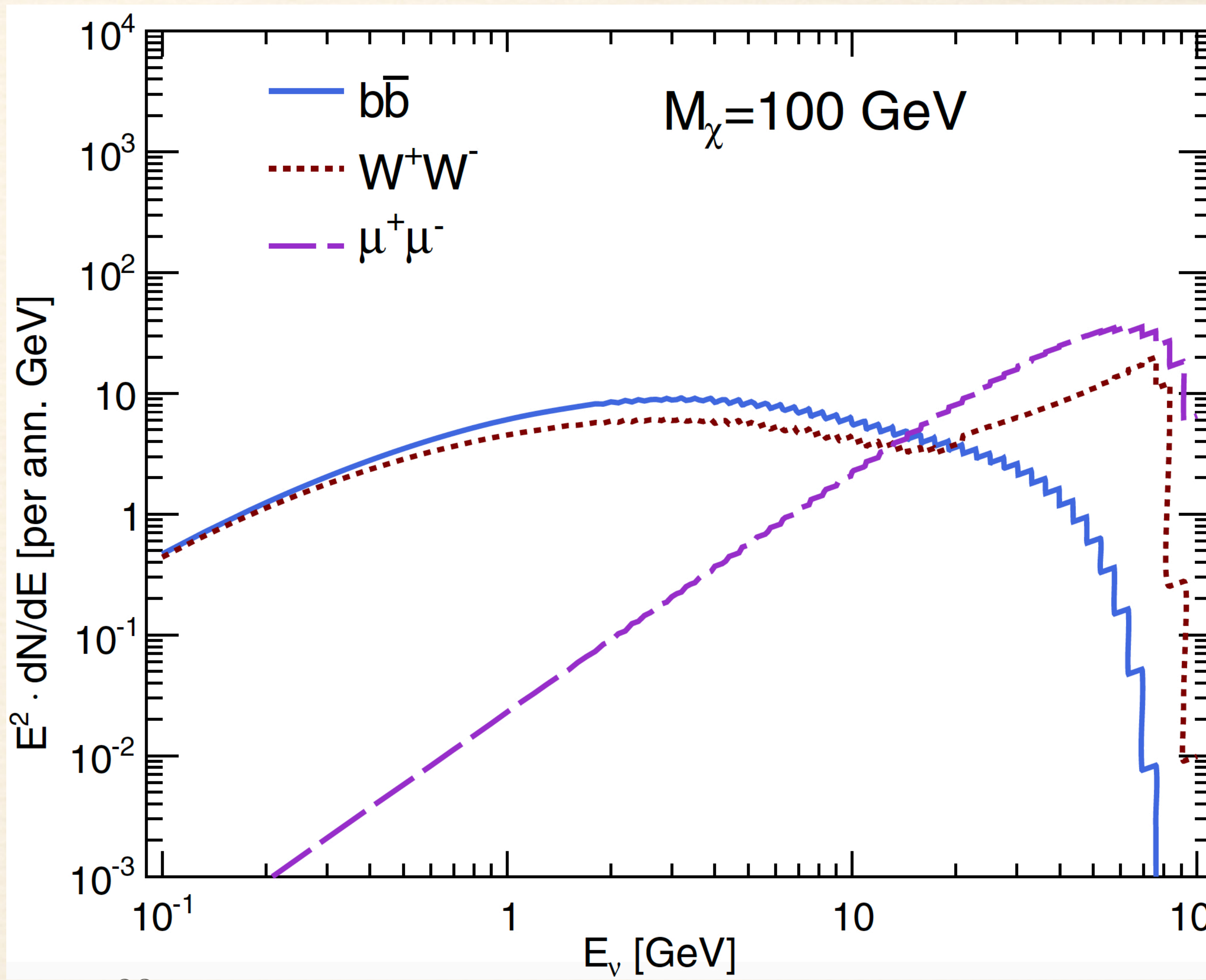


Search for Dark Matter Annihilation at the Galactic Center and Halo

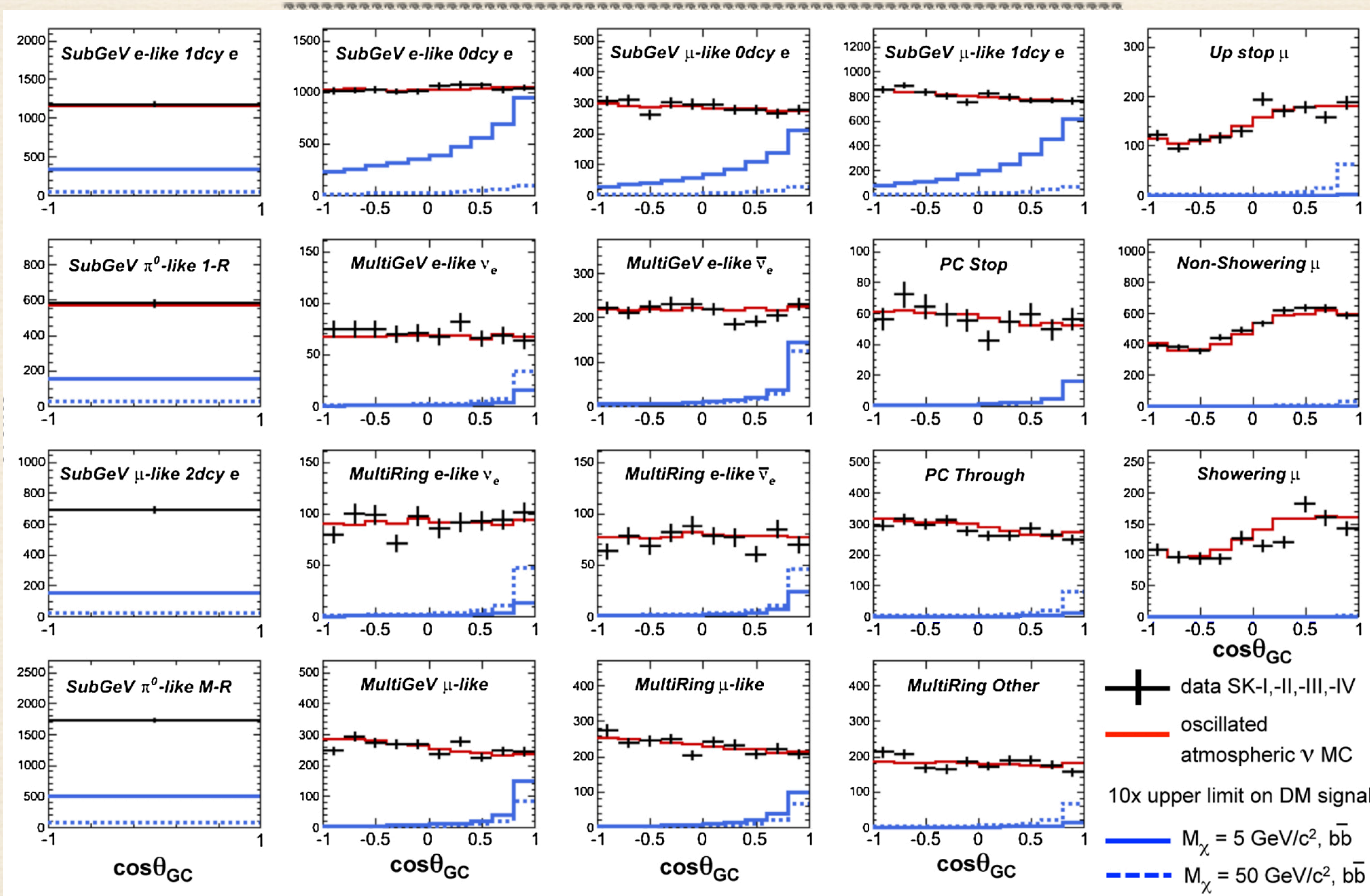
- published last year in PRD **102**, 072002
- assume WIMP pair annihilation into a single channel with 100% BR: $\chi\chi \rightarrow b\bar{b}, W^+W^-, \mu^+\mu^-, \nu\bar{\nu}$ to predict ν energy spectra
- search for (directional) signal on top of atmospheric neutrino background

PHYSICAL REVIEW D **102,** 072002 (2020)

Indirect search for dark matter from the Galactic Center and halo with the Super-Kamiokande detector

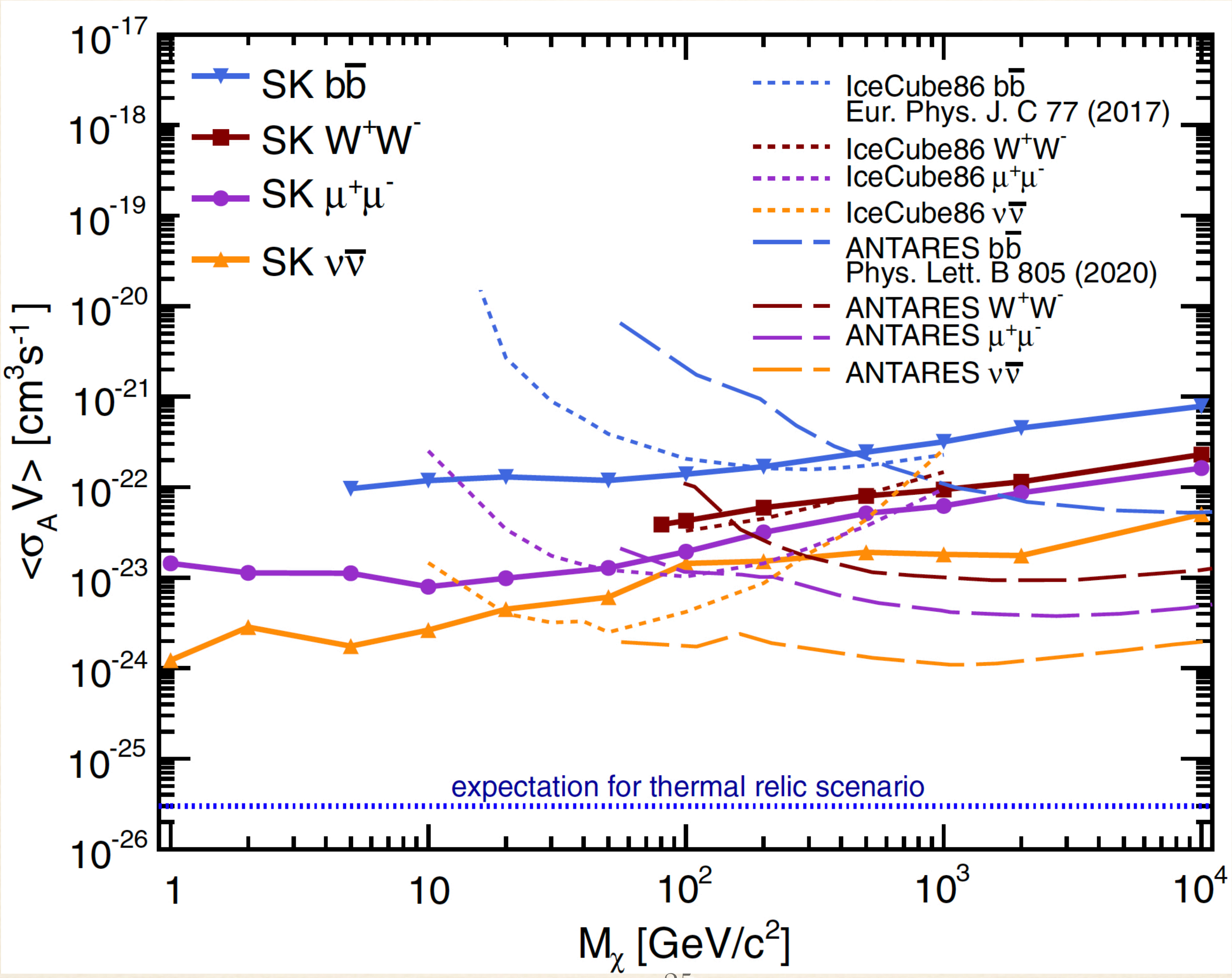


Search for Dark Matter Annihilation at the Galactic Center and Halo



Michael Smy, UC Irvine

Super-Kamiokande Limits

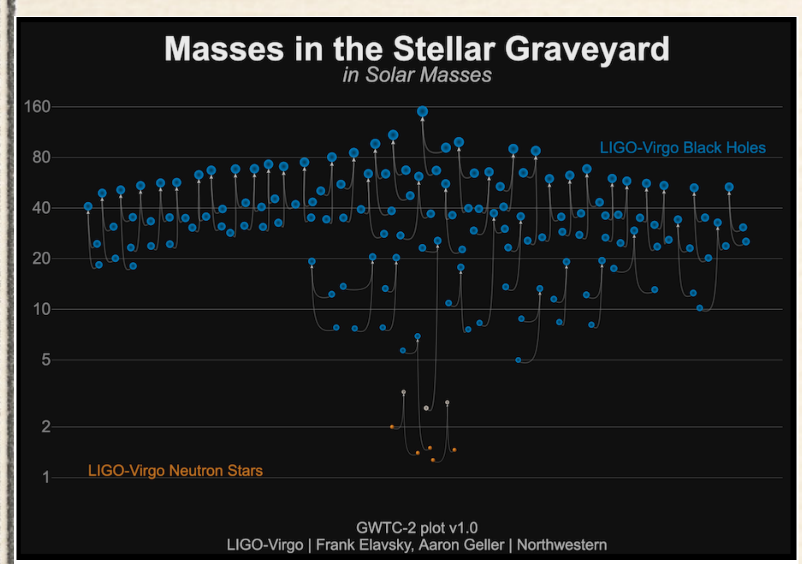


Michael Smy, UC Irvine

Looking for Neutrinos Related to Gravitational Wave Events

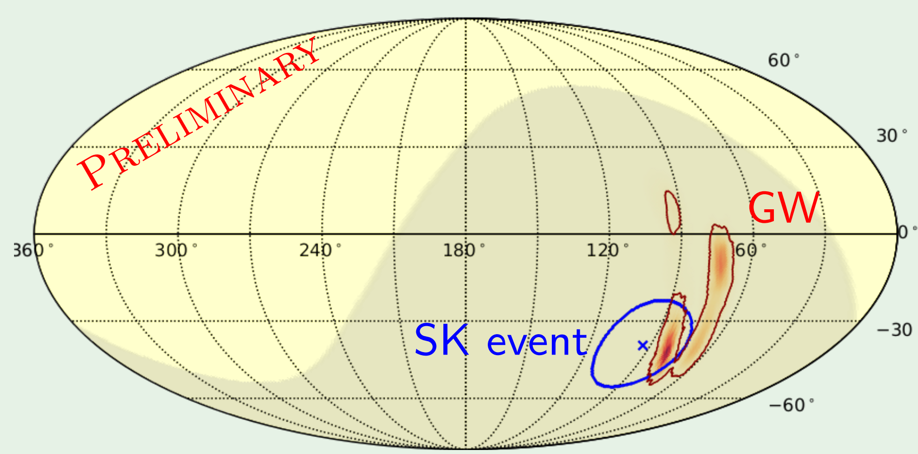
last October, LIGO-Virgo collaborations released catalogue of confirmed Gravitational Wave events (GWTC-2)

look in both the SuperKamiokande MeV and GeV scale samples within 500 sec of the GW time.
$\Longrightarrow$ no significant excess observed (with respect to the expected background)



Most significant observation

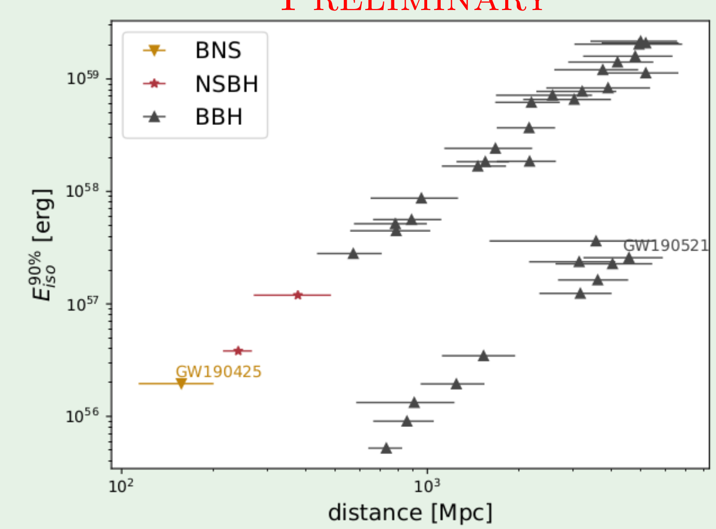
SK neutrino in coincidence with GW190602_175927:



associated post-trial p-value 7.8%

Neutrino flux/$E_{\rm iso}$ limits

For each GW + stacking analysis

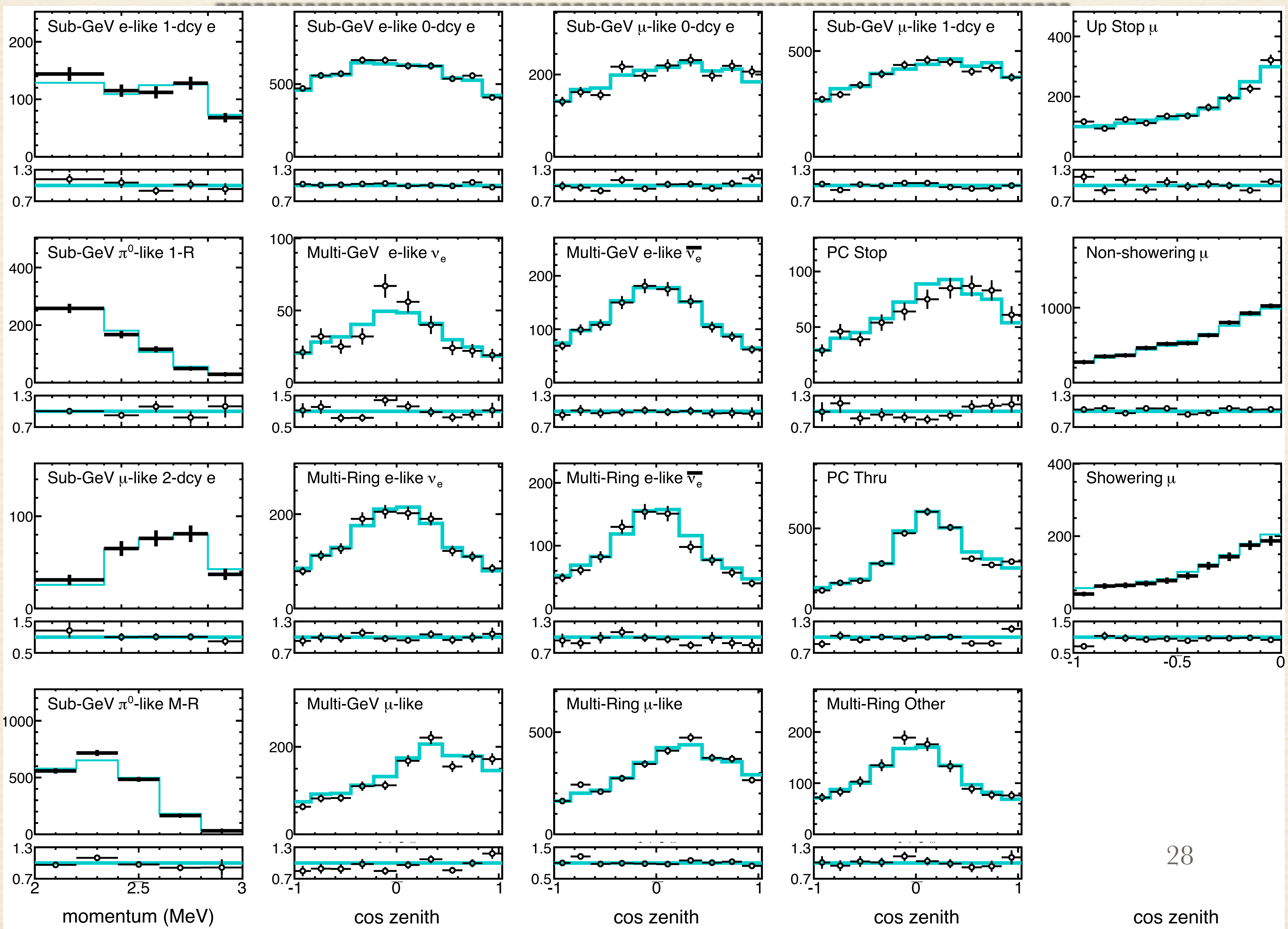


detailed results in the presentation from Mathieu Lamoreux:
→ tomorrow morning (Tue 23rd, 10:20 Parallel Room 2)

Summary and Outlook

- Super-K data offers 25 years of exciting neutrino physics from MeV's to TeV's, but naturally statistical and systematic improvements have slowed down in recent years
- with the addition of $Gd_2(SO_4)_3$ we start a new era allowing us to use new handles enhancing previous analyses and starting new ones (e.g. reactor neutrinos)
- expect us to gradually increase the Gd loading in the next years (reach 0.03% in May 2022) to fully access these new physics opportunities

Atm. ν Samples w/o Neutron Tag



Neutron Tagged Atm. ν Samples