Solar And Supernova Neutrinos at Super-Kamiokande and SK-Gd

International Workshop on Next Generation Nucleon Decay and Neutrino Detectors
Vancouver, 2018.11.2

Michael Smy,
UC Irvine

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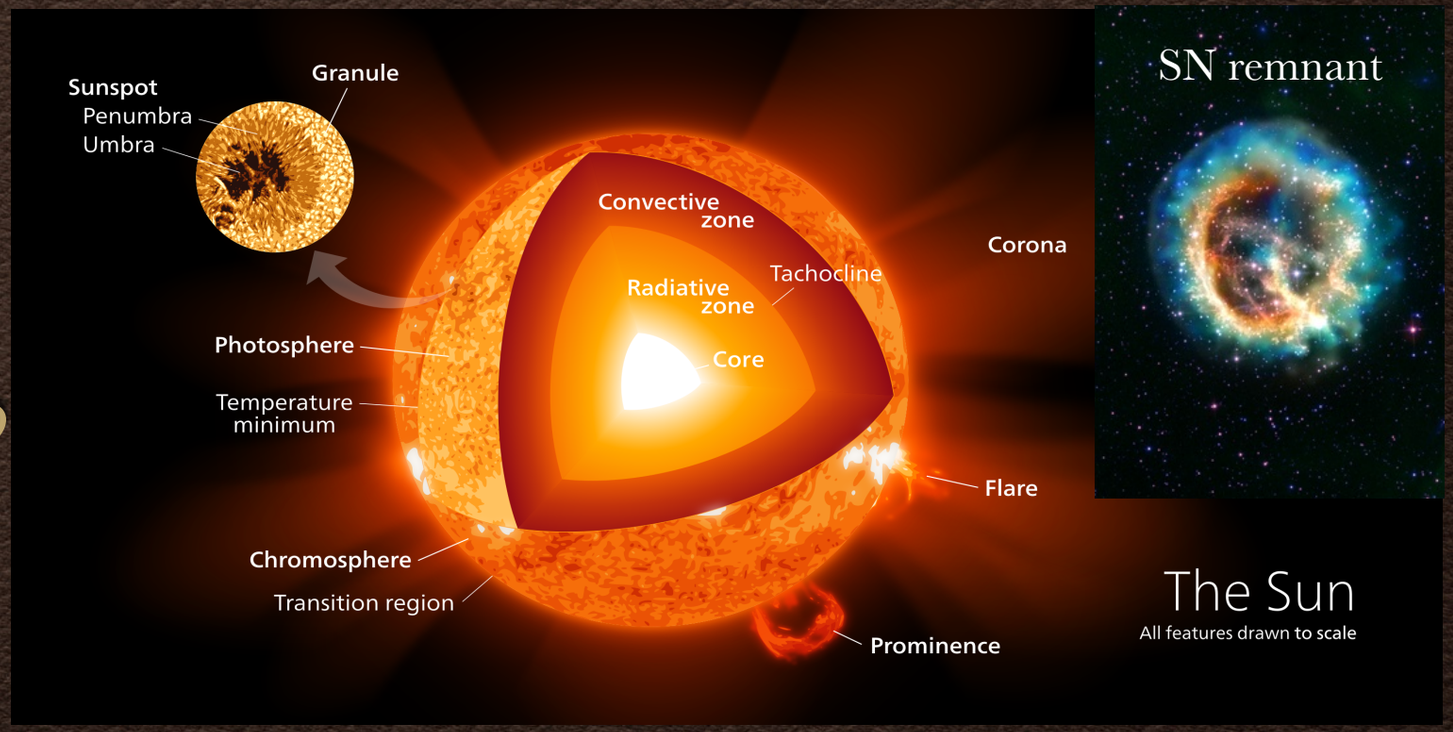


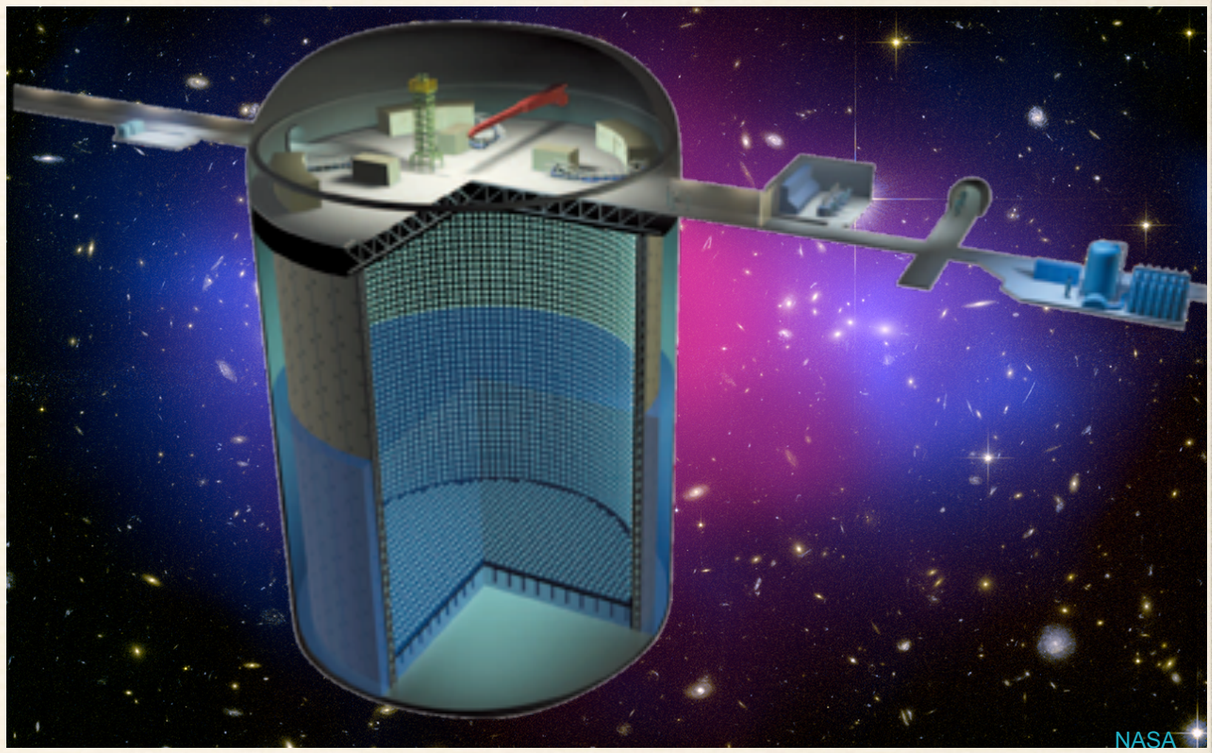
22 Years of Super-Kamiokande!

96 | 97 | 98 | 99 | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13 | 14

4 Super-Kamiokande-I 6 Accident 12 SK-II 5,182 PMTs 11 full repair 7 SK-III 9 Super-Kamiokande-IV

K2K-I K2K-II earth-quake T2K

- 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

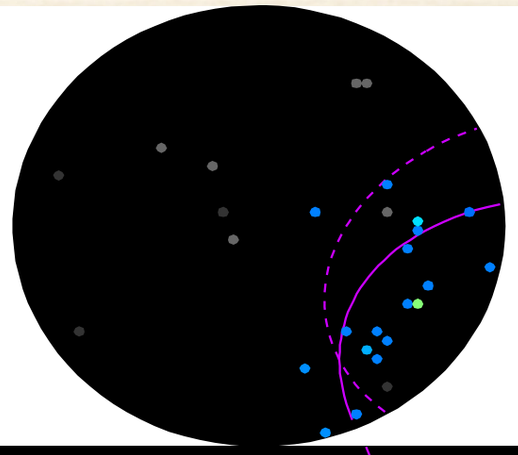
layout by Y. Suzuki, ICRR (Michael Smy, UC Irvine)

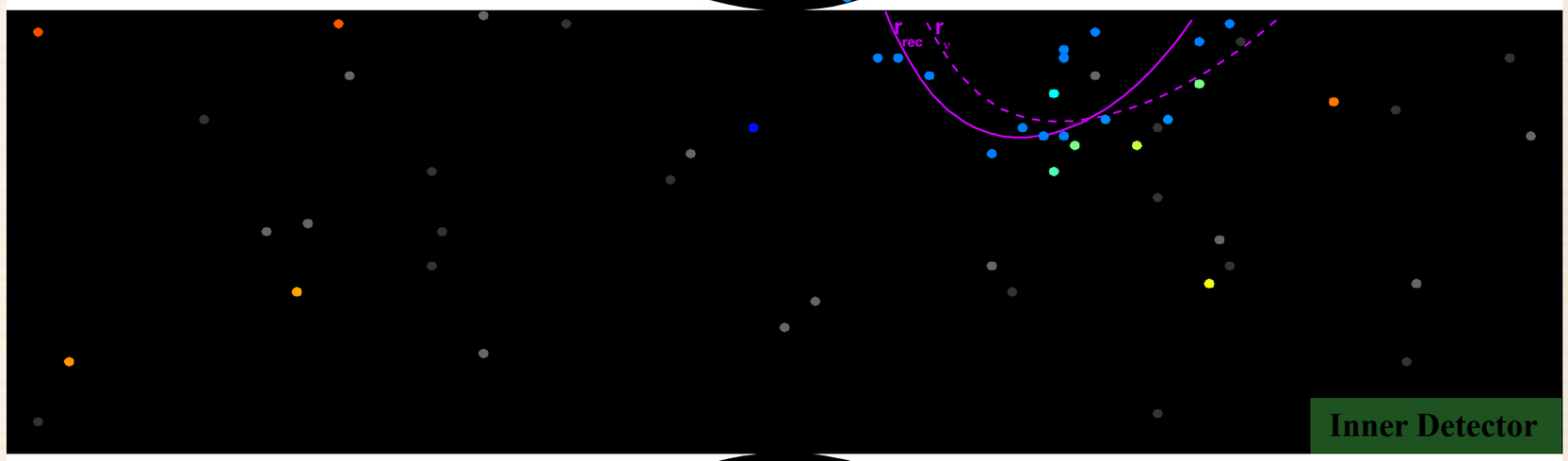
Low Energy Electron Detection in Super-Kamiokande

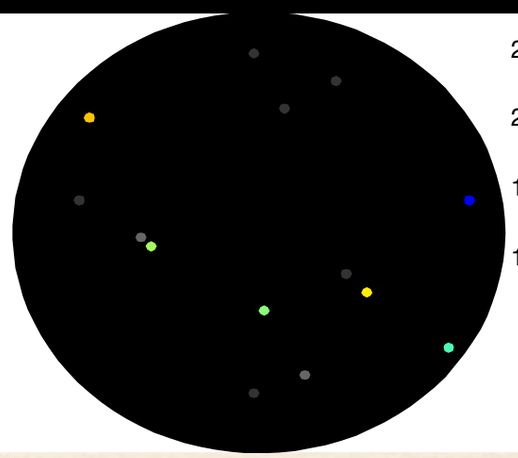
- PMT timing ➔ vertex reconstruction: **20cm (high energy)-60cm (low energy electrons)**
- hit pattern ➔ (particle ID and) direction reconstruction: **~30⁰**
- brightness ➔ energy: **14% @ 10 MeV** (≈6 hits/MeV above threshold)

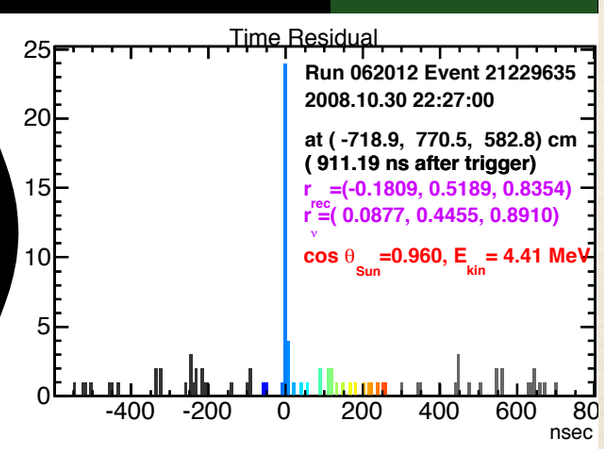
solar neutrino

E^{kin}_{e-}=4.4MeV
cos θ_{sun}=0.96

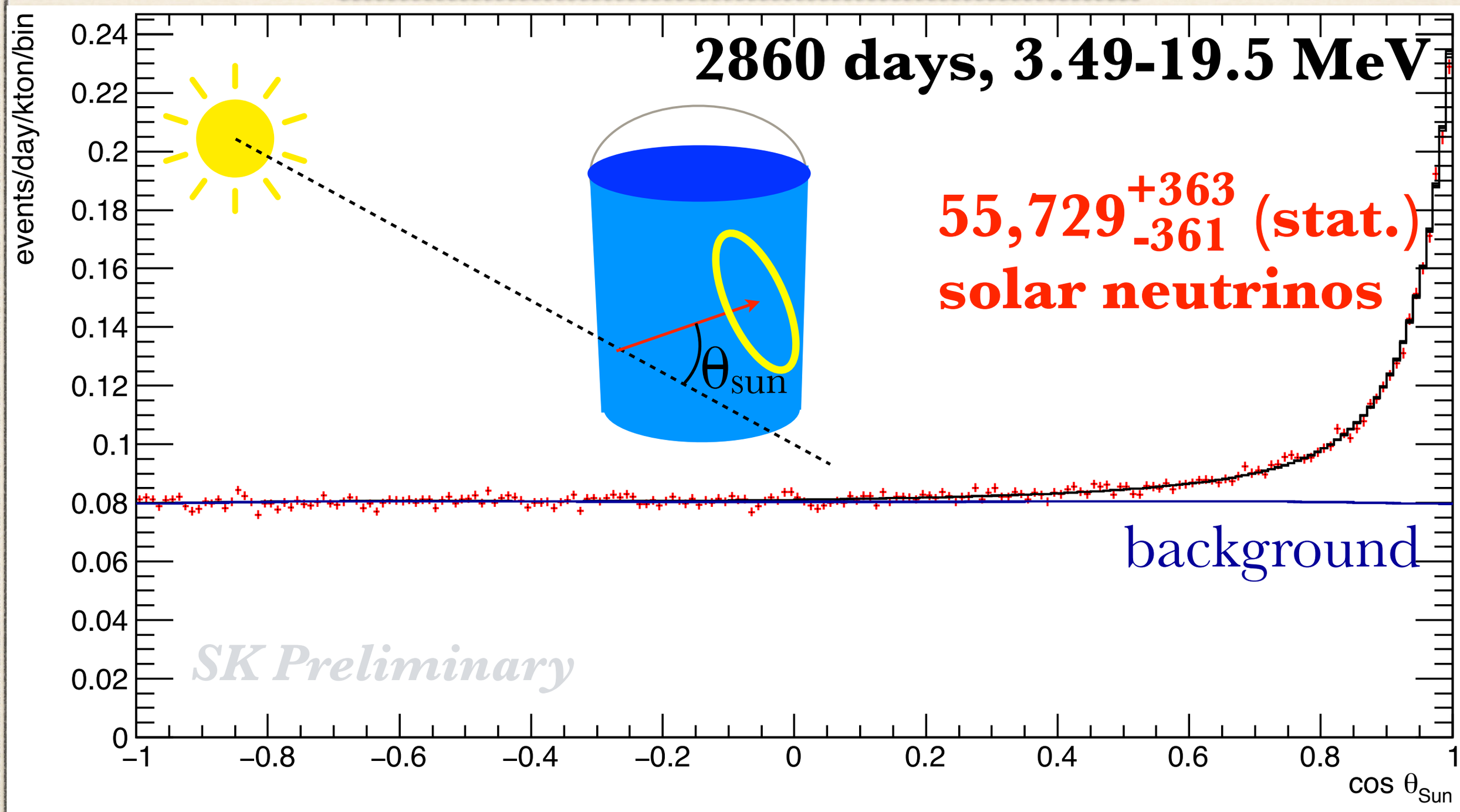






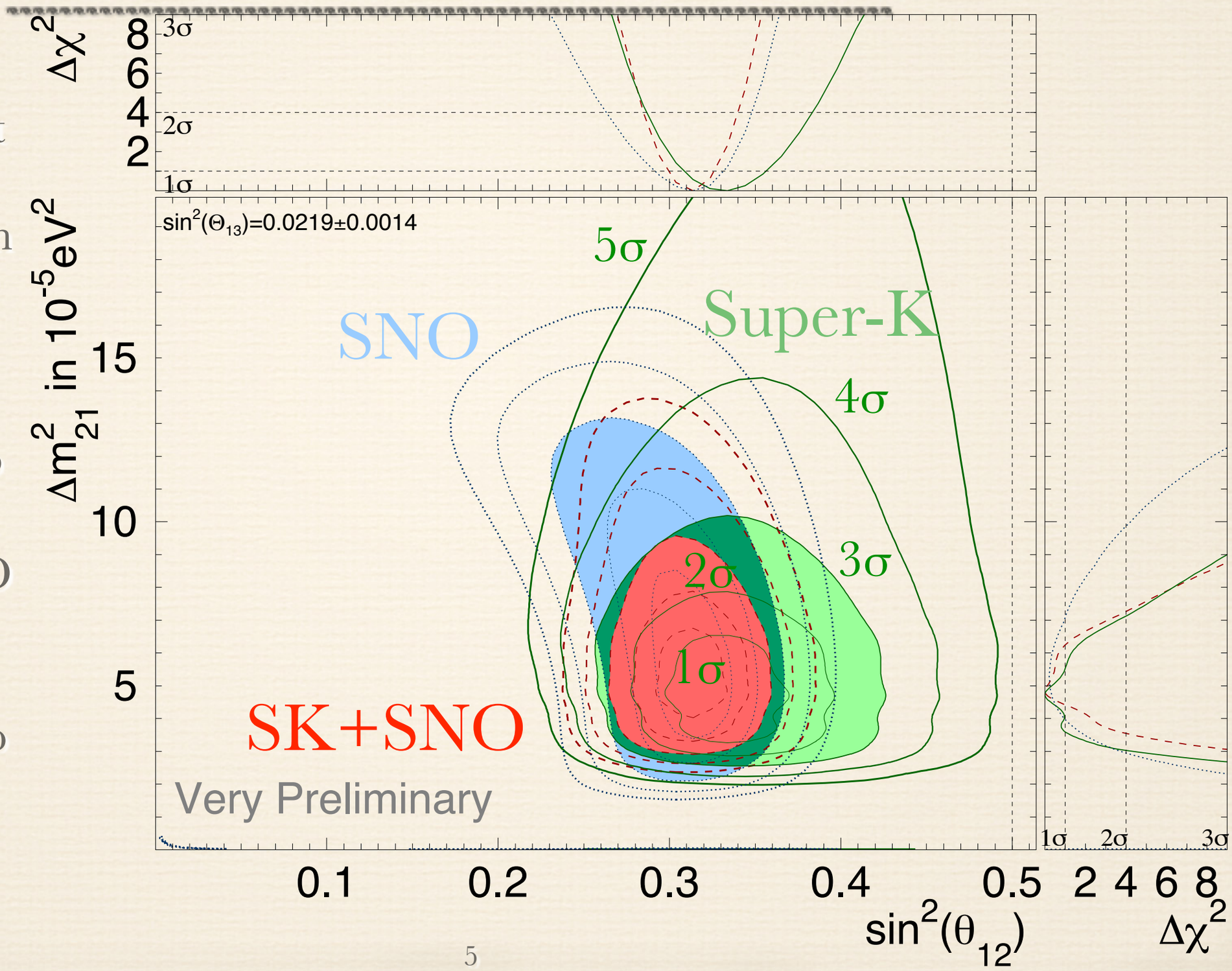


Solar ^{8}B Neutrinos: Elastic Scattering off Electrons in Super-Kamiokande IV



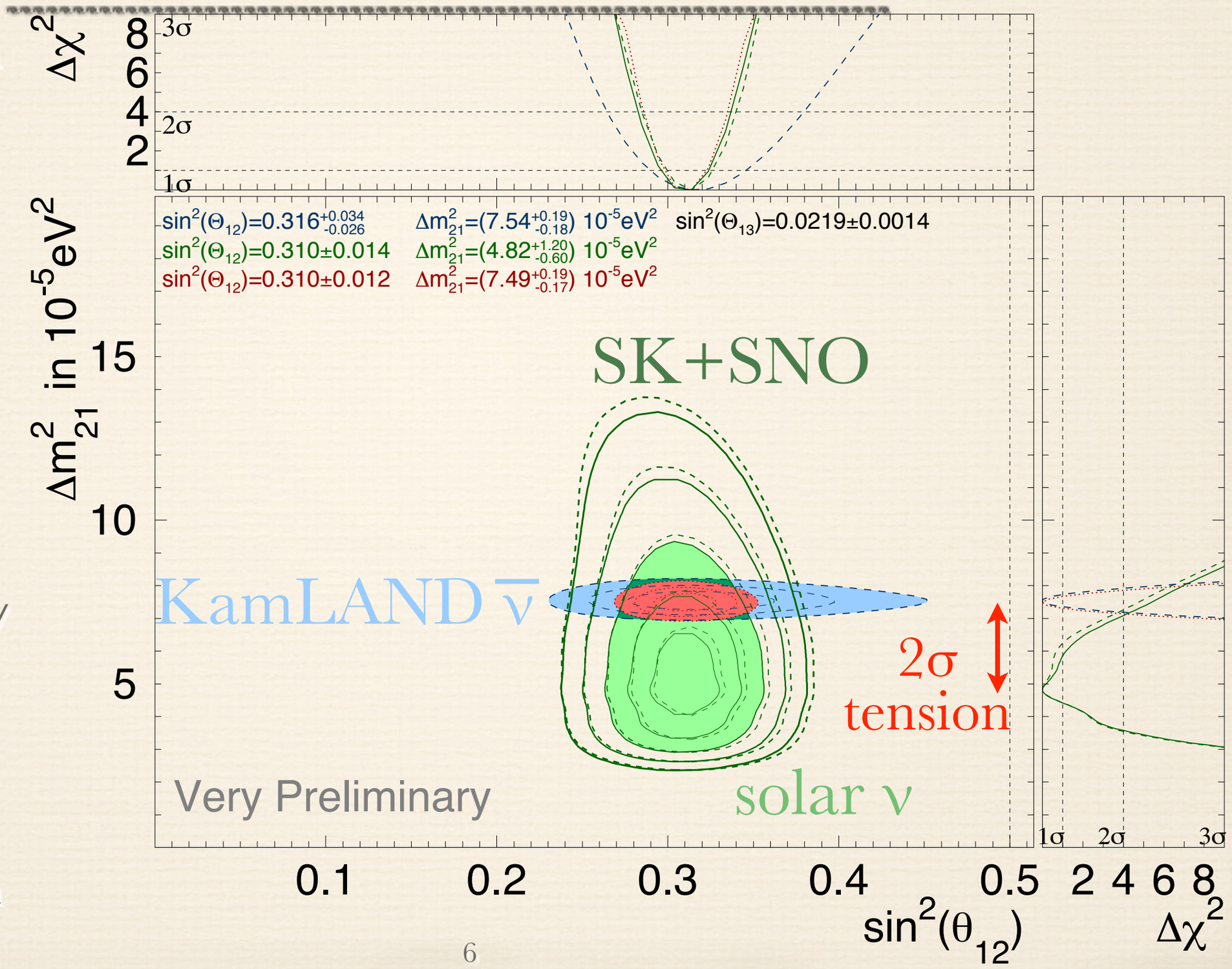
^{8}B Solar Neutrino Oscillations

- Super-K: best neutrino determination of Δm^2_{21}
- Super-K: significantly contributes to $\sin^2\theta_{12}$
- together SNO and Super-K define global solar neutrino fit

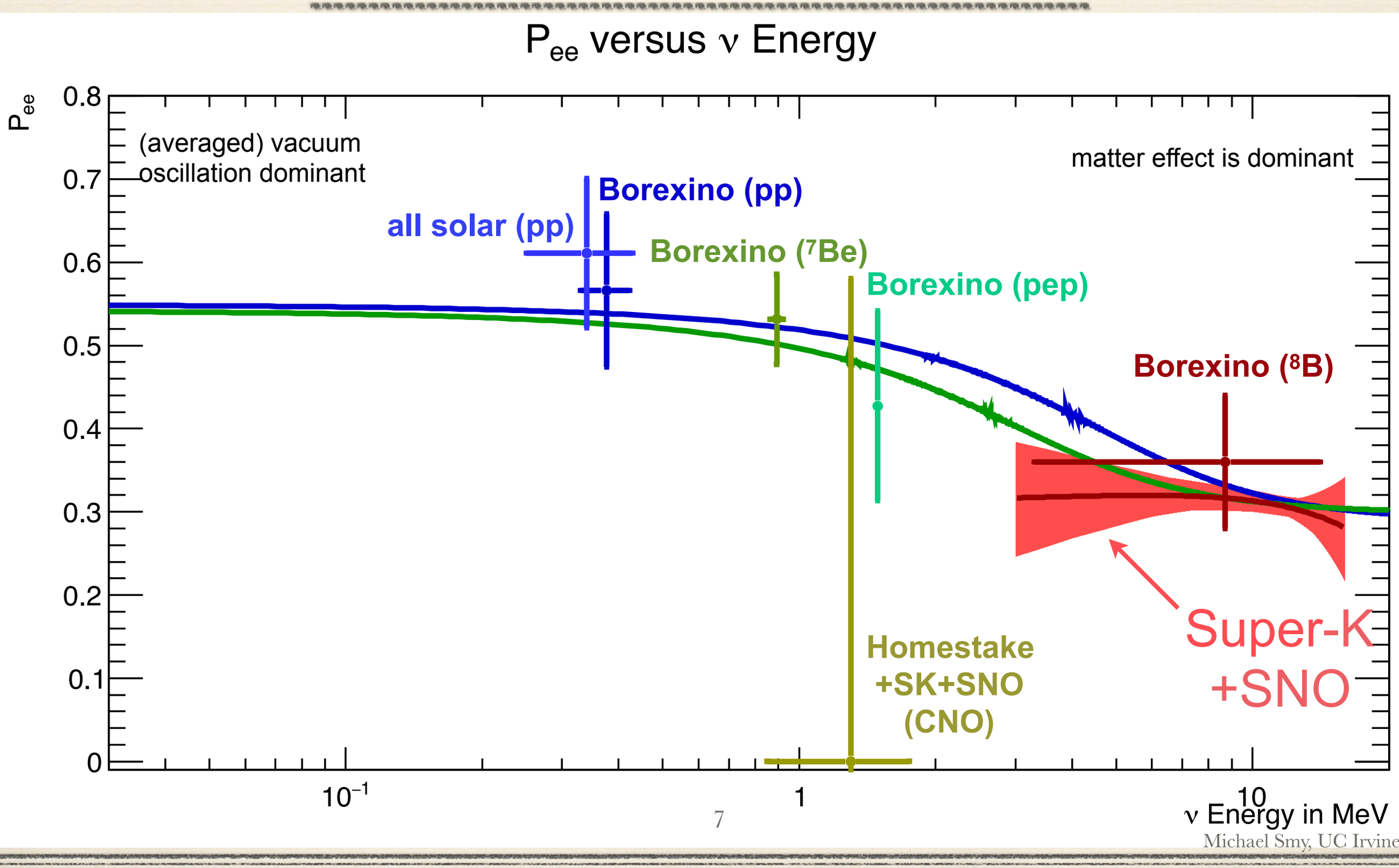


Solar Neutrino Oscillations

- SNO+Super-K define global solar neutrino fit
- agreement with $\overline{\nu}_e$ data for $\sin^2\theta_{12}$
- 2σ tension in for Δm^2_{21}
- tension from Super-K day/night rate variation (direct test of matter effect) and spectrum



Solar Neutrino Flavor Conversion Probability: MSW Effect



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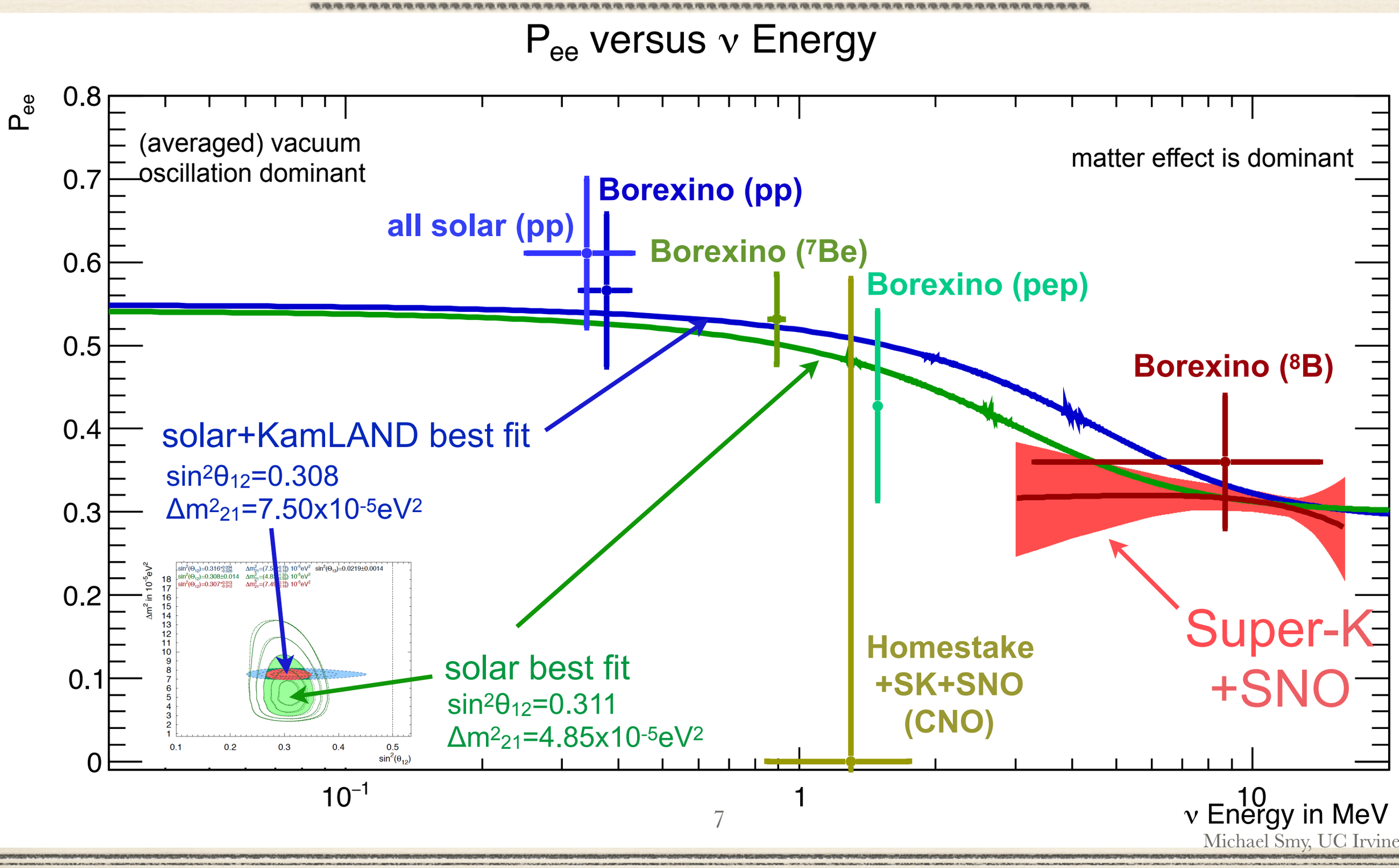
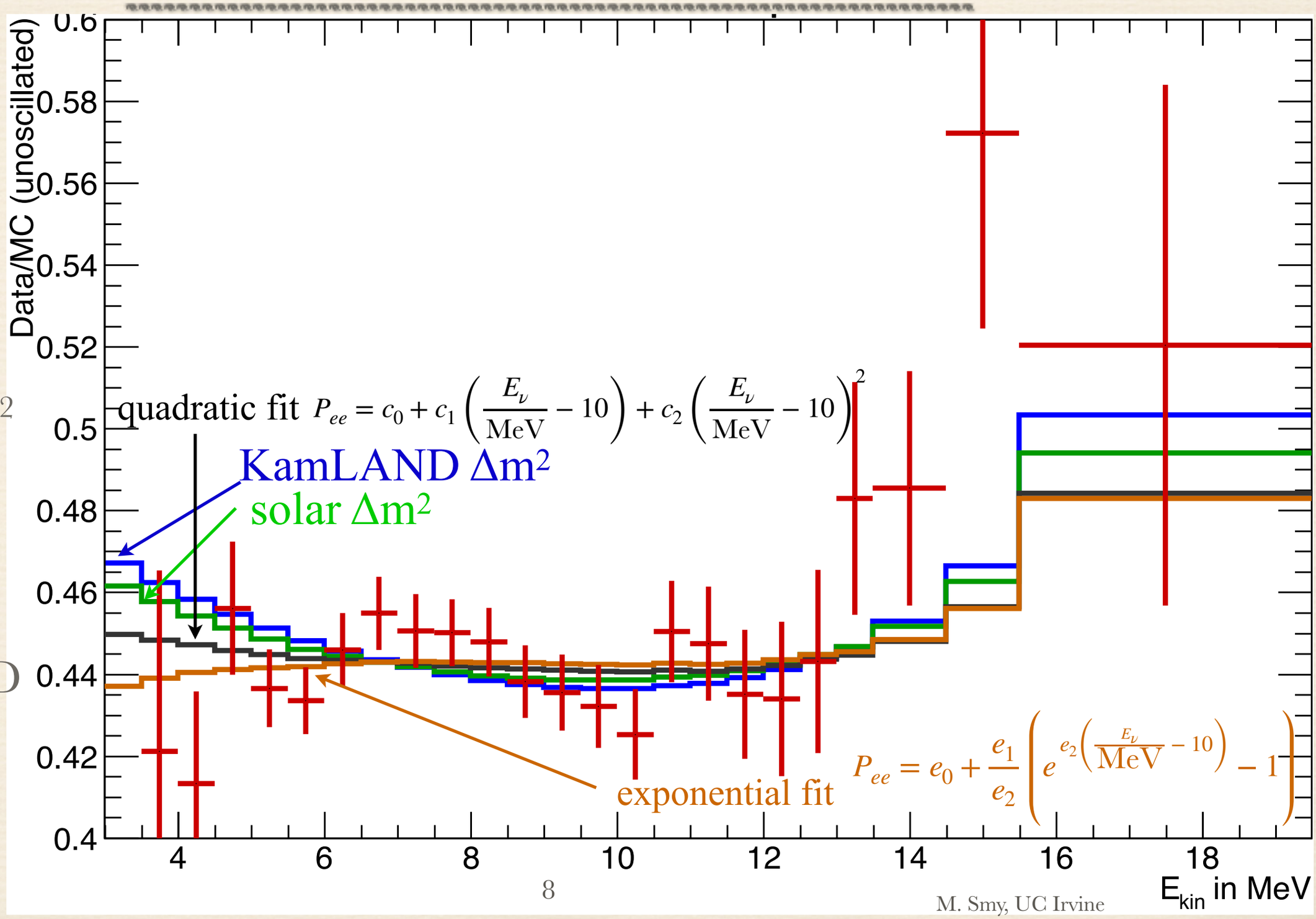


Test Adiabatic Conversion: Energy Dependence of Data/unosc. MC

latest Super-K recoil e- spectral data: consistent with solar best fit Δm^2 within 1σ, but $\sim 2\sigma$ tension with KamLAND measure-ment



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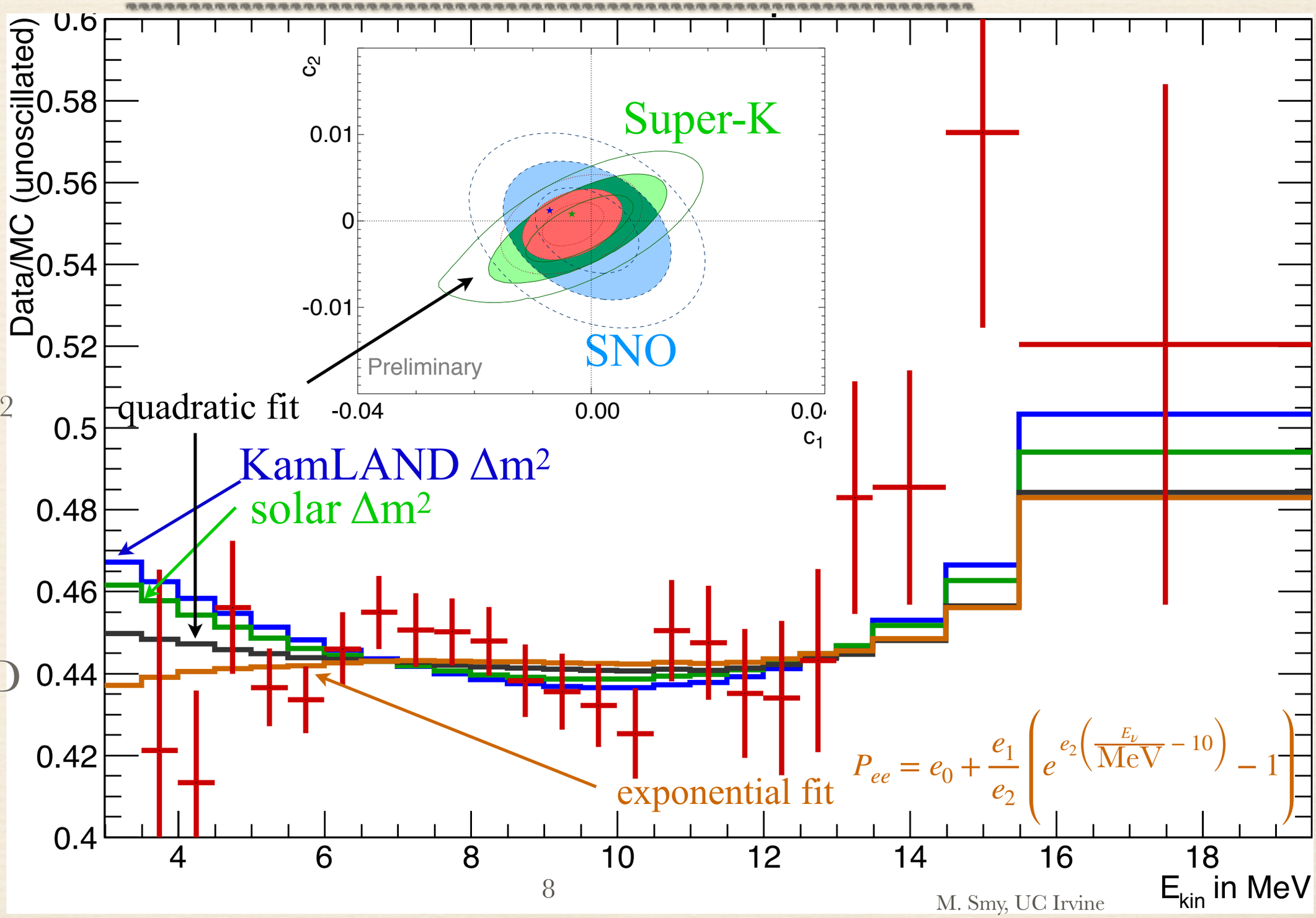
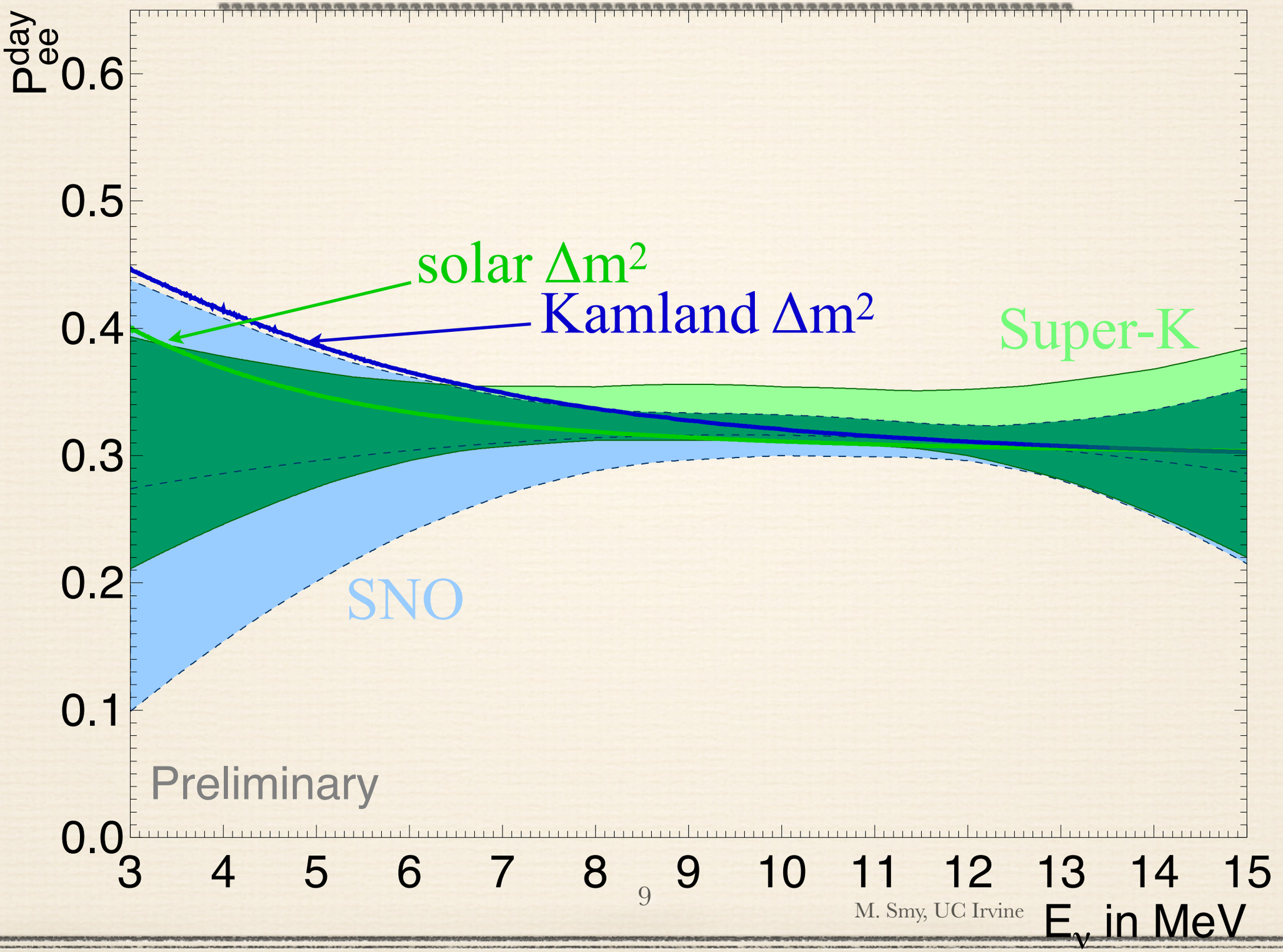


Super-K and SNO: resulting P_{ee}



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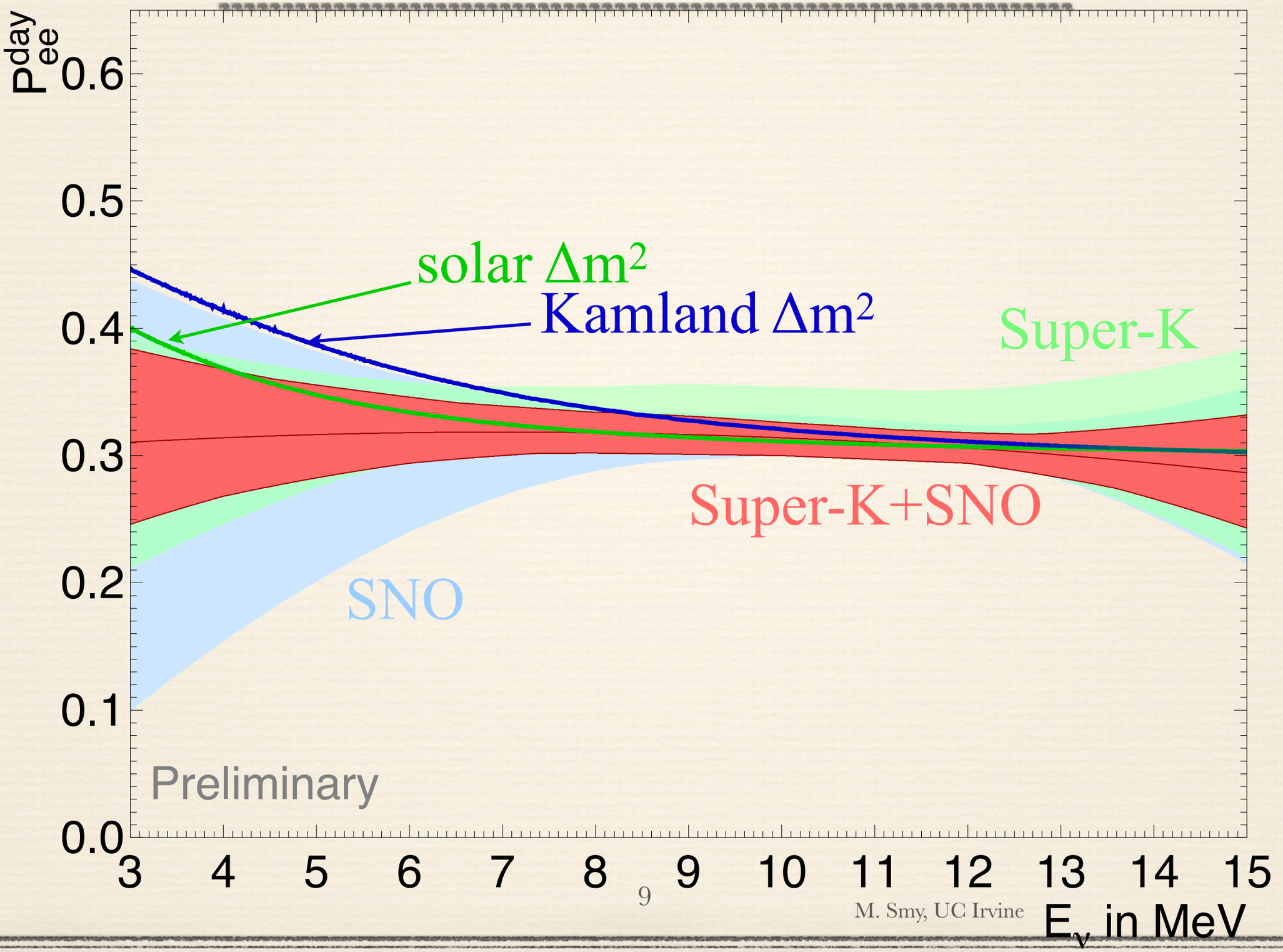
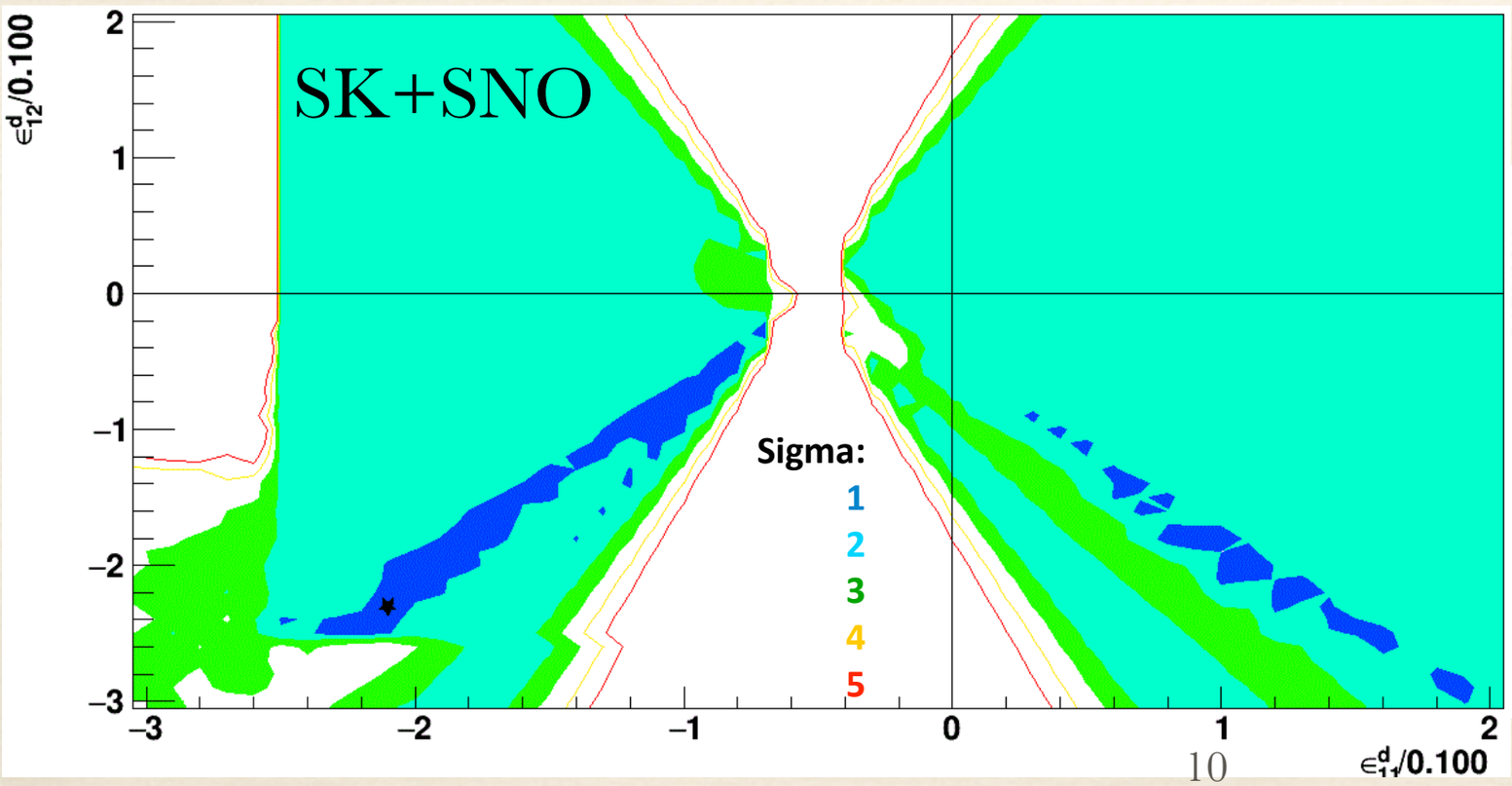


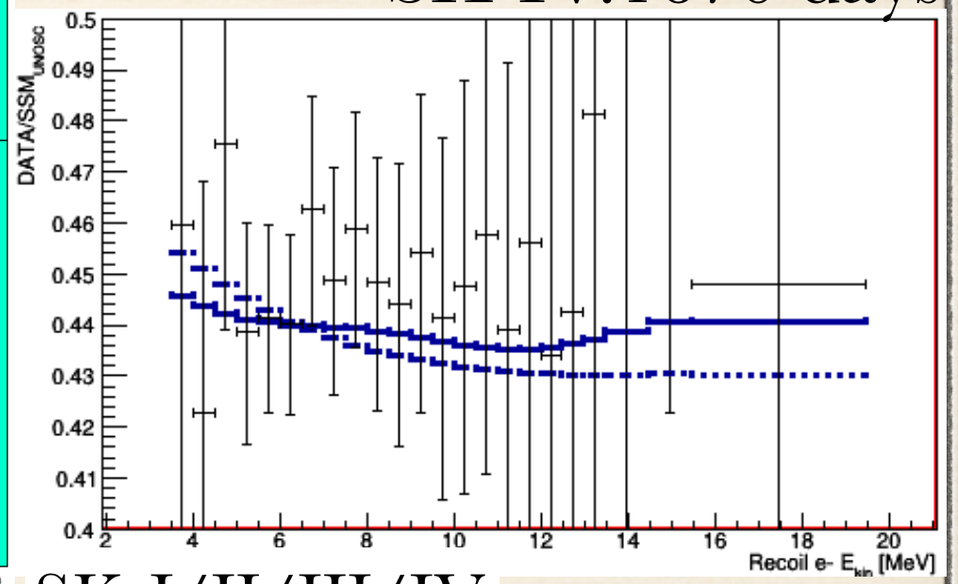
Search for Non-Standard Interactions

- extend Hamiltonian $H_{matter} = \kappa\rho_e \begin{pmatrix} 1+\varepsilon_{ee} & 0 & \varepsilon^*_{e\tau} \\ 0 & 0 & 0 \\ \varepsilon_{e\tau} & 0 & \varepsilon_{\tau\tau} \end{pmatrix} + \frac{1}{2E} U^\dagger_{PMNS} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U_{PMNS}$
- is able to explain the lack of spectral distortion
- to reduce # of parameters, use ε_{11}, and ε_{12} (mass basis) instead of ε_{ee}, $\varepsilon_{e\tau}$ and $\varepsilon_{\tau\tau}$
- one ε_{ij} is sum of electron-, up-quark, down-quark terms; turn each on by itself



down-quark

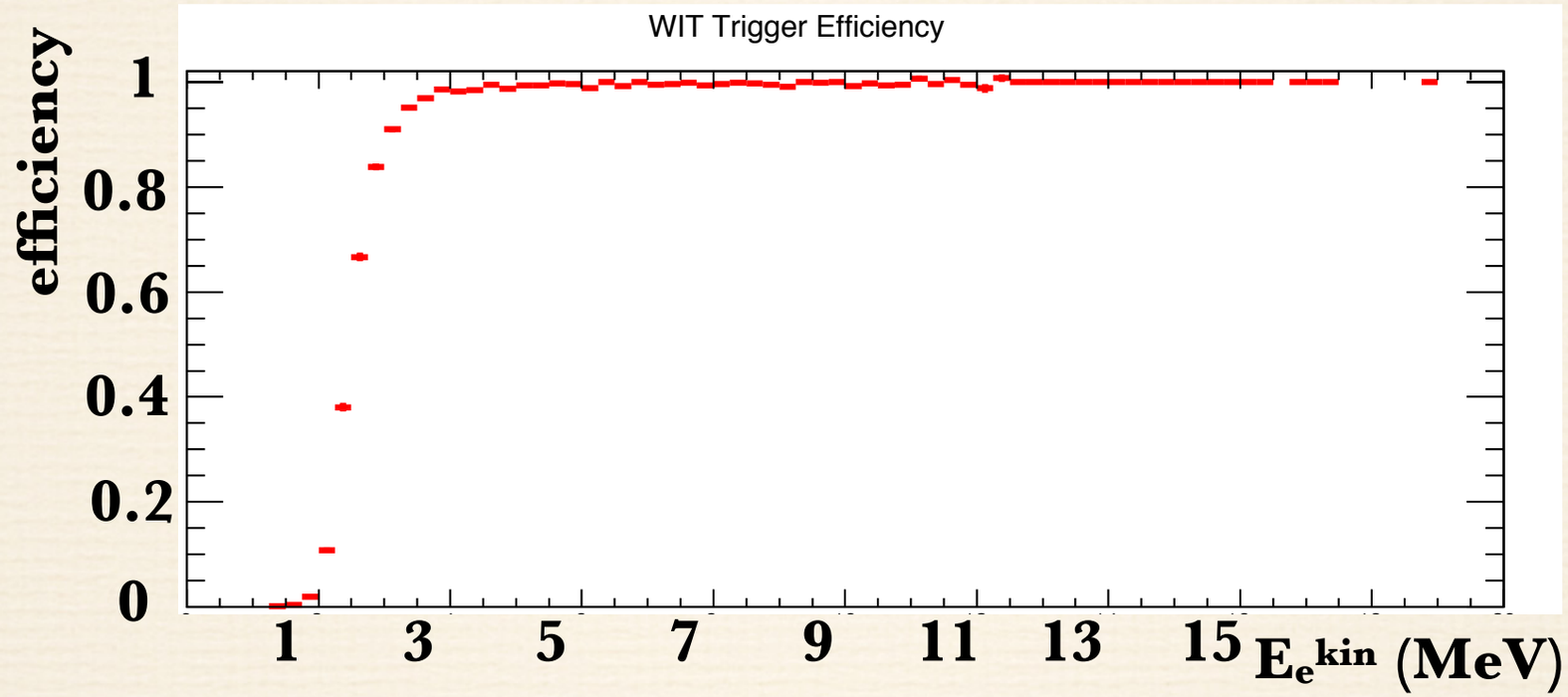
SK-IV:1670 days



SK-I/II/III/IV

Probe MSW: Future Improvements

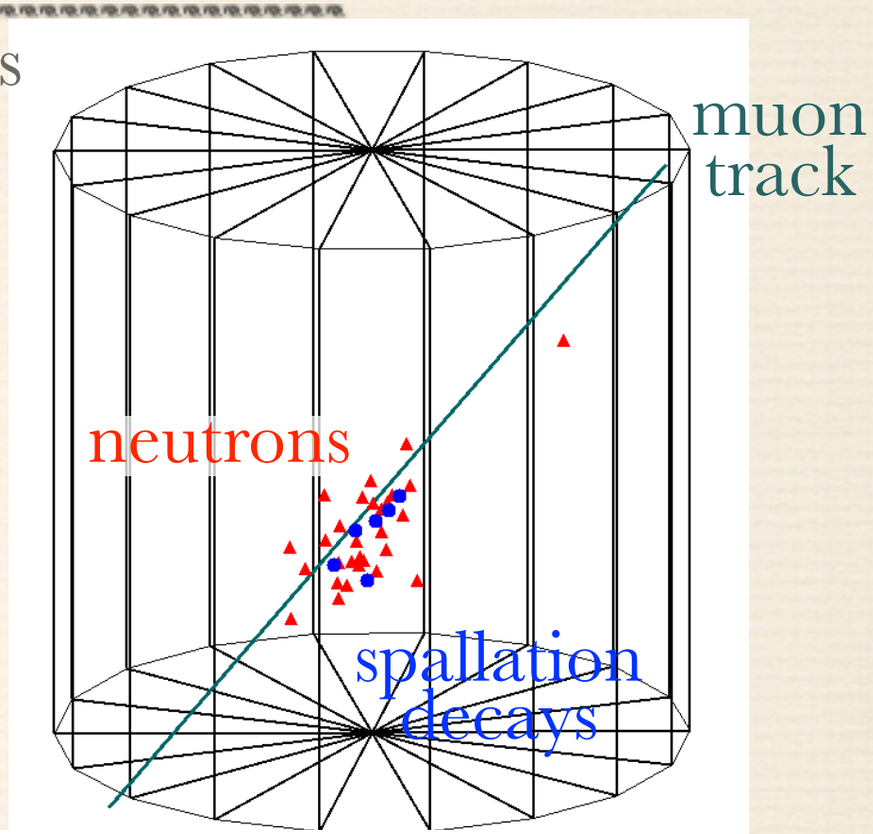
- lower threshold: Wideband Intelligent Trigger has >90% efficiency for kinetic energies >2.5 MeV

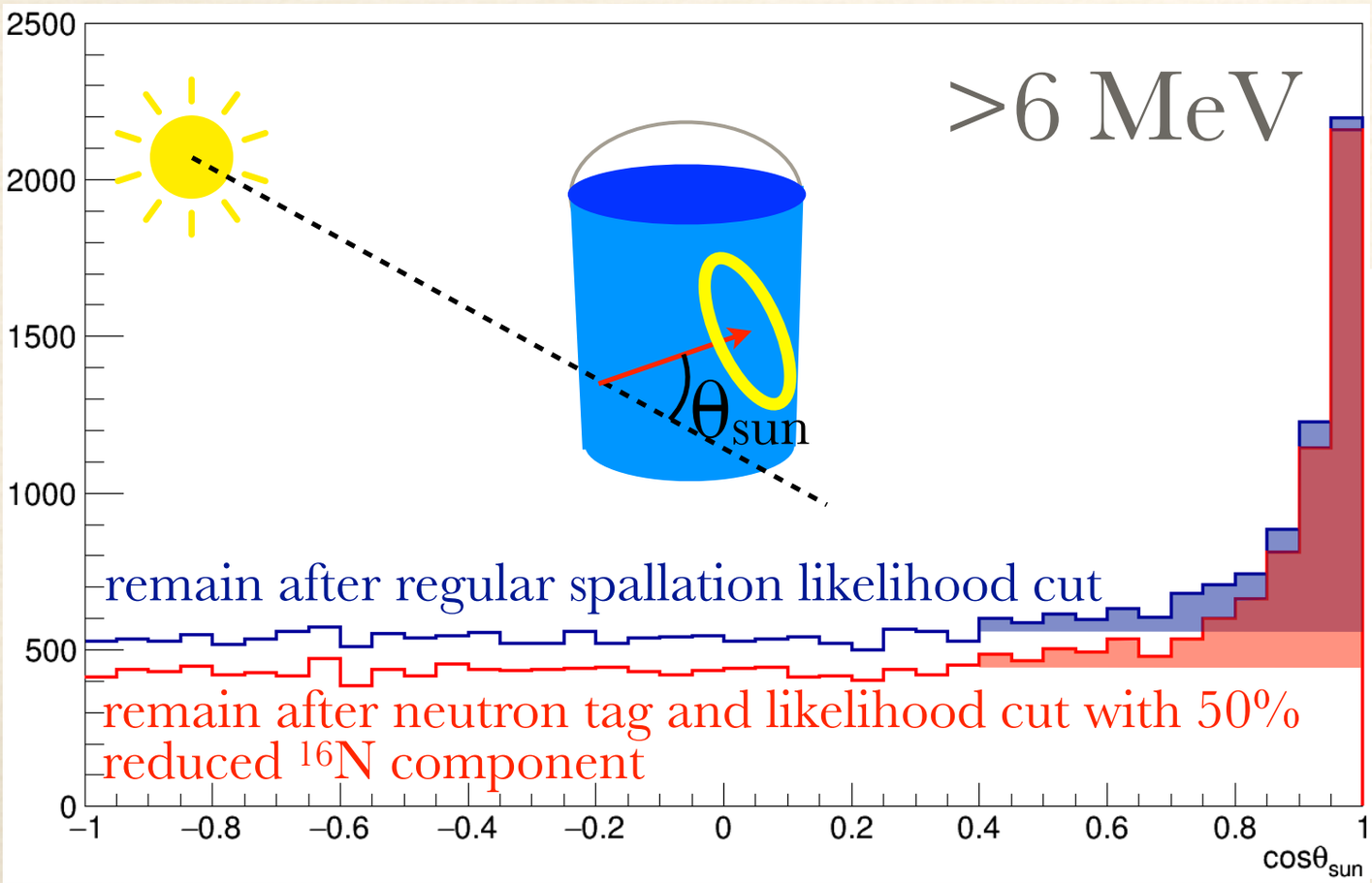


- smaller spectral systematic uncertainty with better calibration:
  - linear accelerator injecting single electrons with E=5-18 MeV
  - Deuterium-Tritium generator to make ^{16}N with 14 MeV n's
  - cosmic muon induced spallation to make ^{16}N

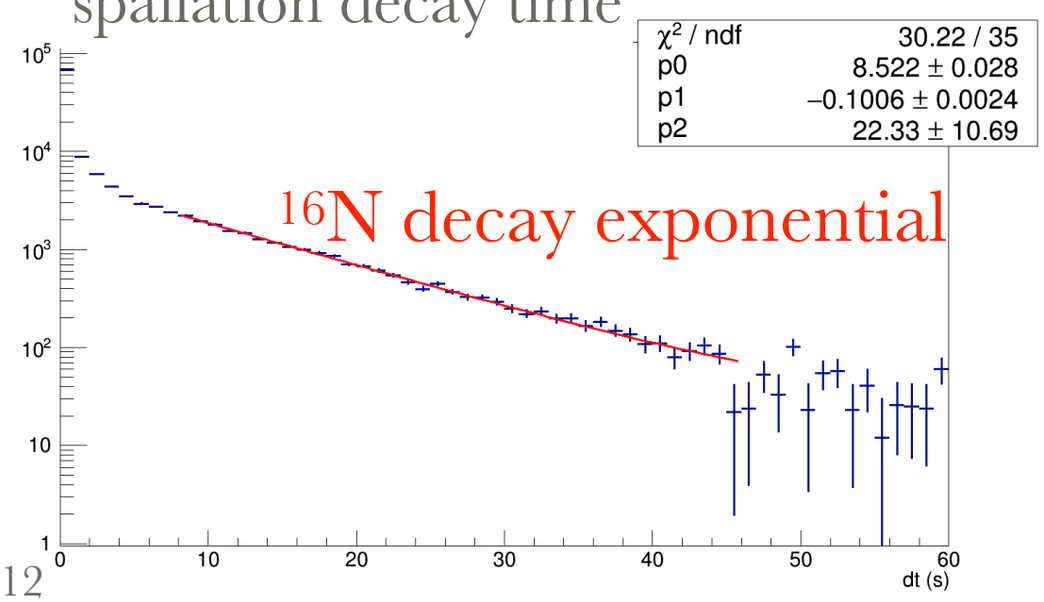
Tag Spallation Events With Neutrons

- neutrons after a muon indicate hadronic showers which produce basically all spallation nuclei:
- use WIT to trigger and reconstruct 2.2 MeV γ's from neutron captures on hydrogen
- **~10% less signal loss, ~20% more background suppression without tuning!**

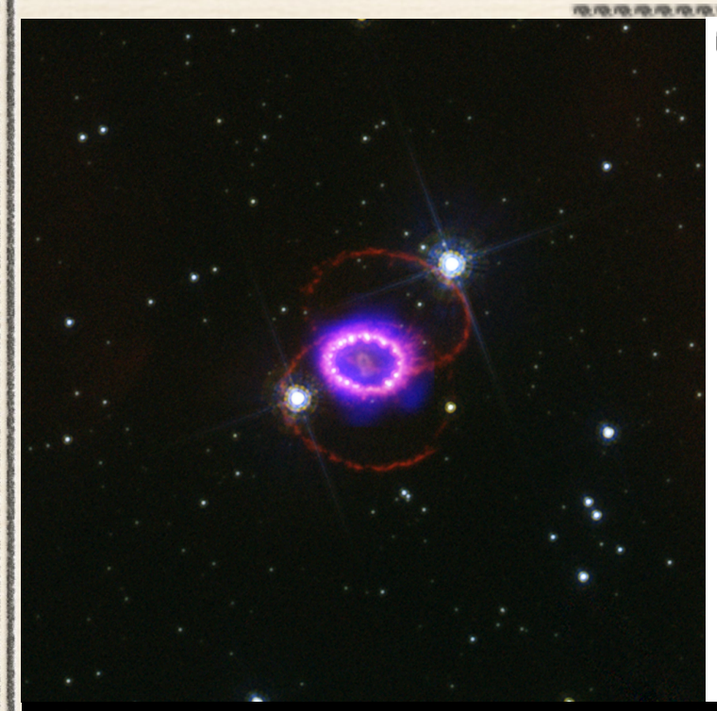


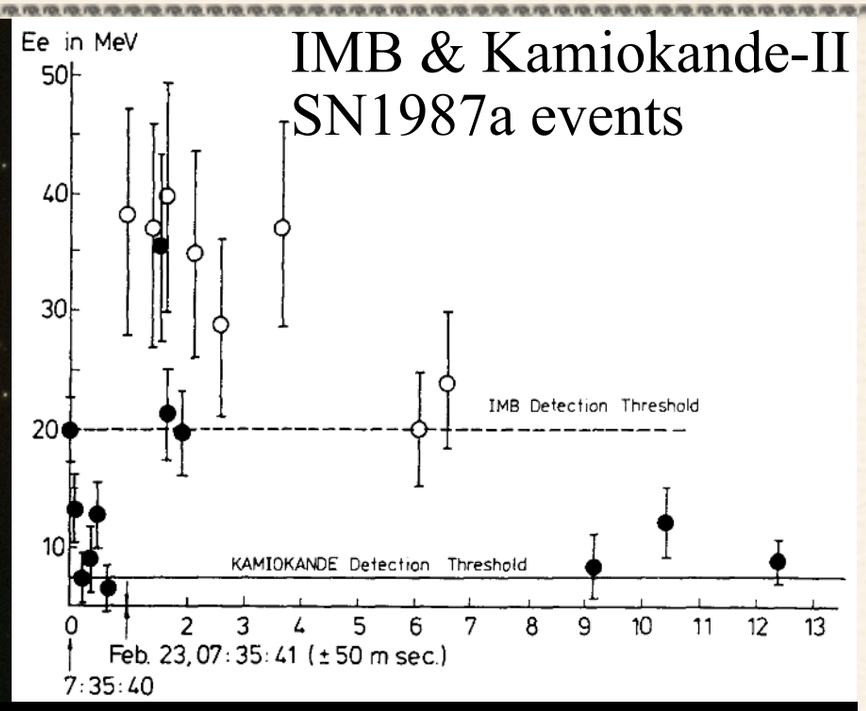


spallation decay time

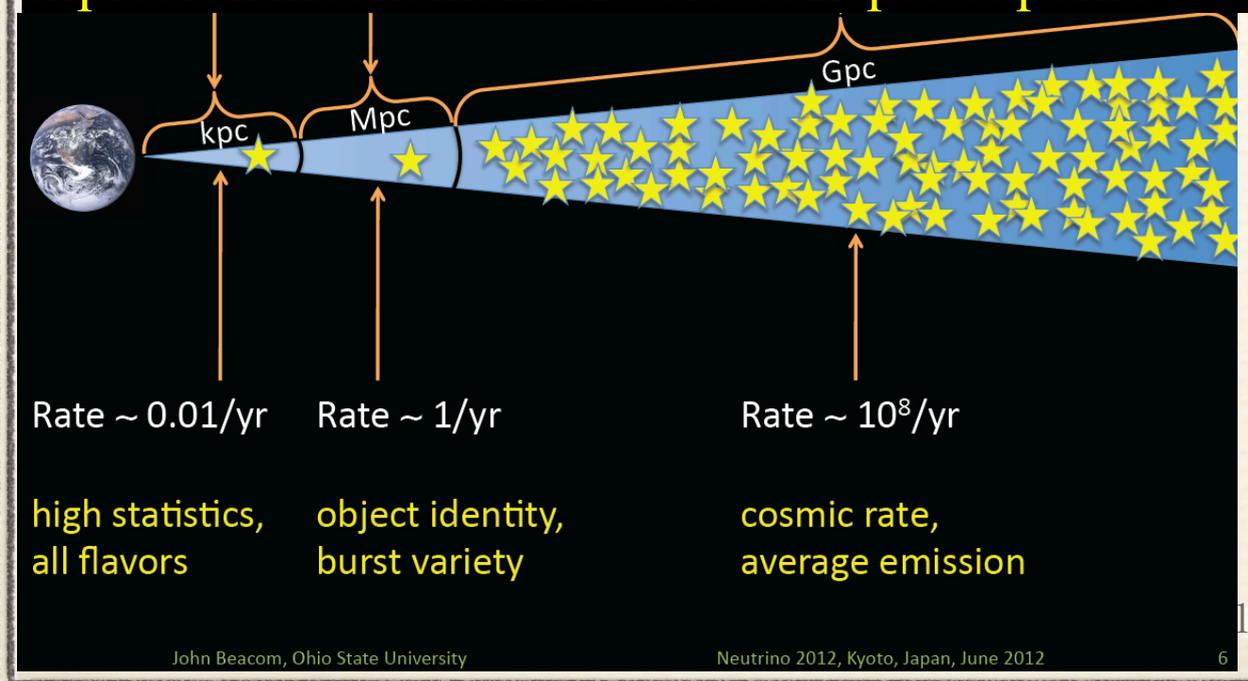


Supernova Neutrinos: A Long Journey, A Long Wait…





These few events confirmed the basic picture about the explosion mechanism of core-collapse supernovae

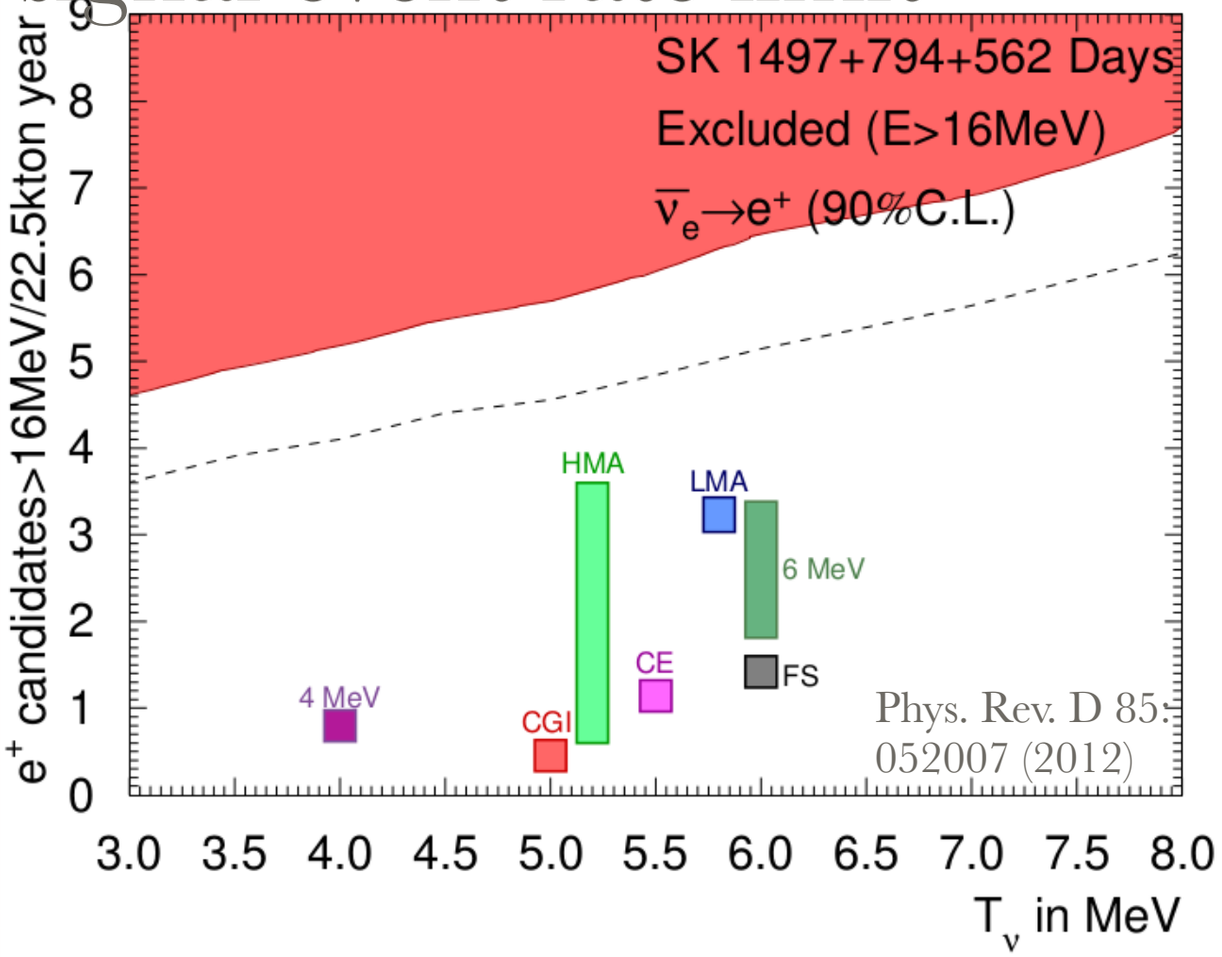


- ~10^{53}erg in 10s (>99% ν's): or ~1sextillion YW
- ~10^4 events in Super-K at 10kpc (galactic center)

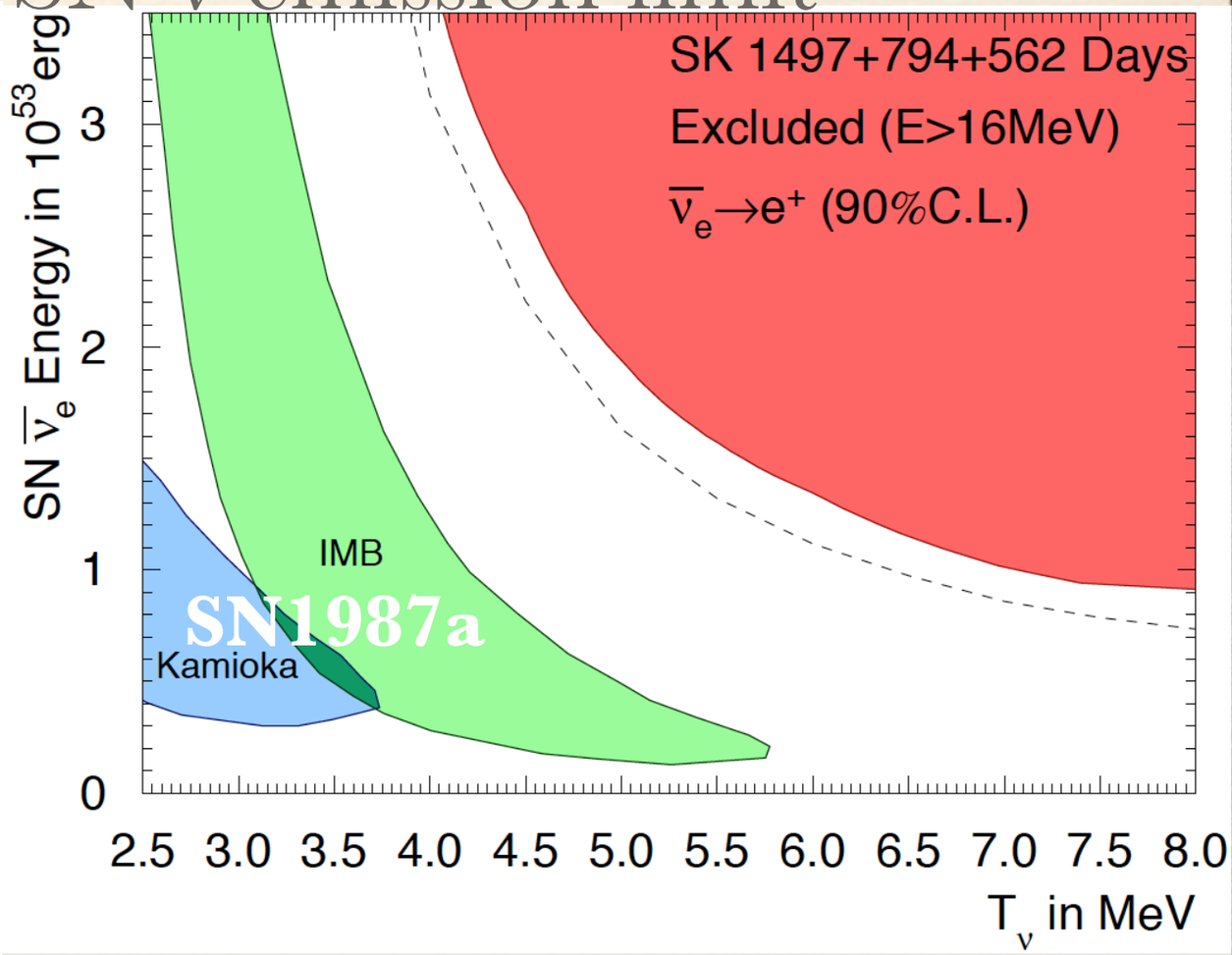
- ~2-3/galaxy/century!
- mini-bursts? (only ~1 event at 1MPc)
- diffuse, distant supernova (z~1)

Super-K's Diffuse, Distant SN Search

signal event rate limit



SN ν emission limit



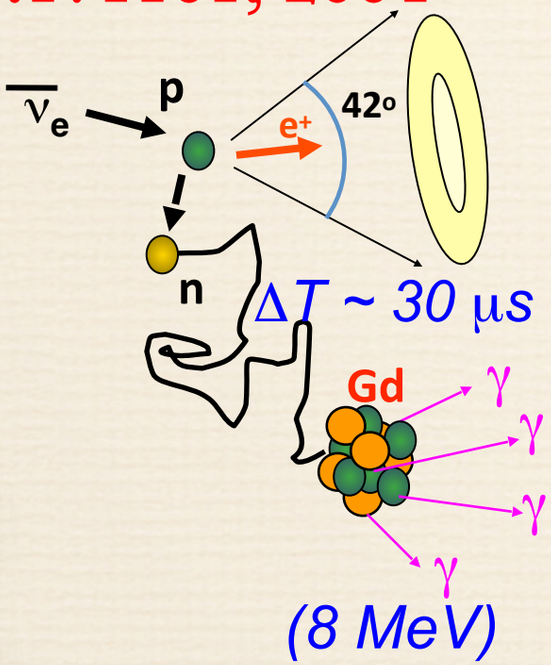
- event rate limits are close to theoretical predictions
- neutrino emission limits are close to expectations based on SN 1987a
- must reduce background for discovery!

Tag IBD with Neutrons

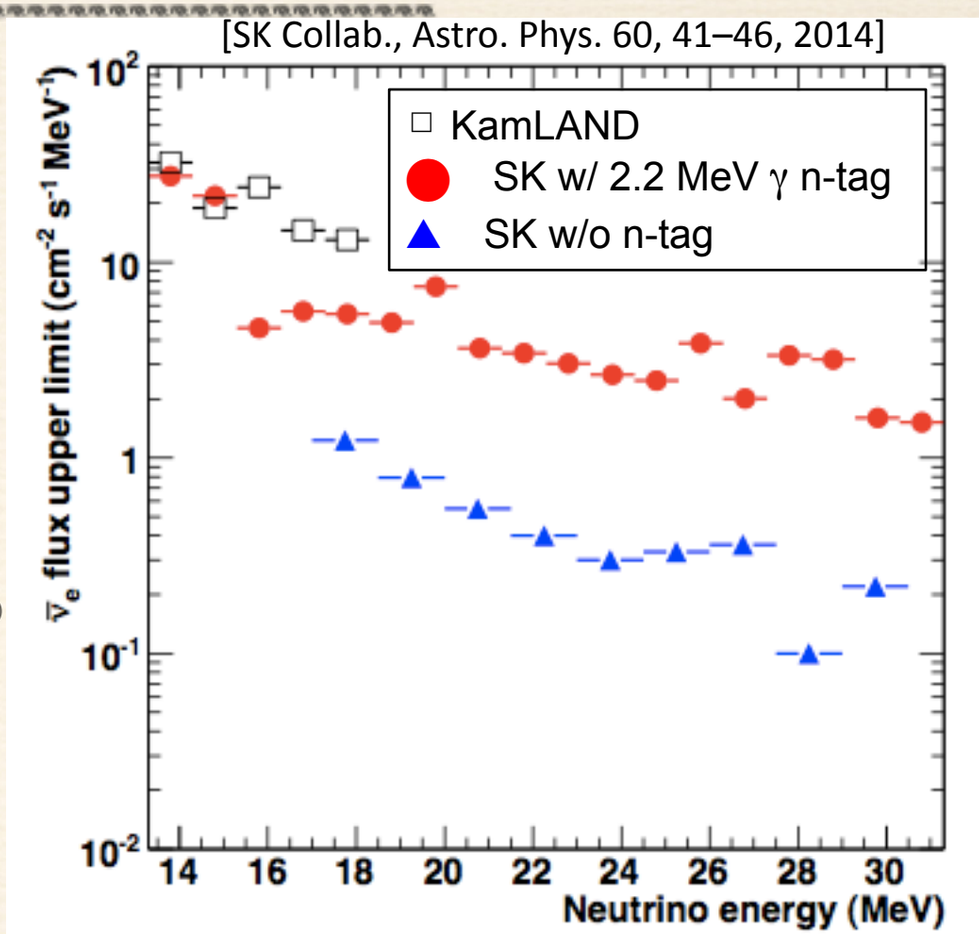
capture neutrons on Hydrogen:

- ~7 photoelectrons from 2.2 MeV γ
- efficiency only 10-15%
- limit actually gets worse…

idea from J. Beacom and M. Vagins: dissolve 0.1% Gd ions to capture neutrons ***Phys. Rev. Lett.,* 93:171101, 2004**

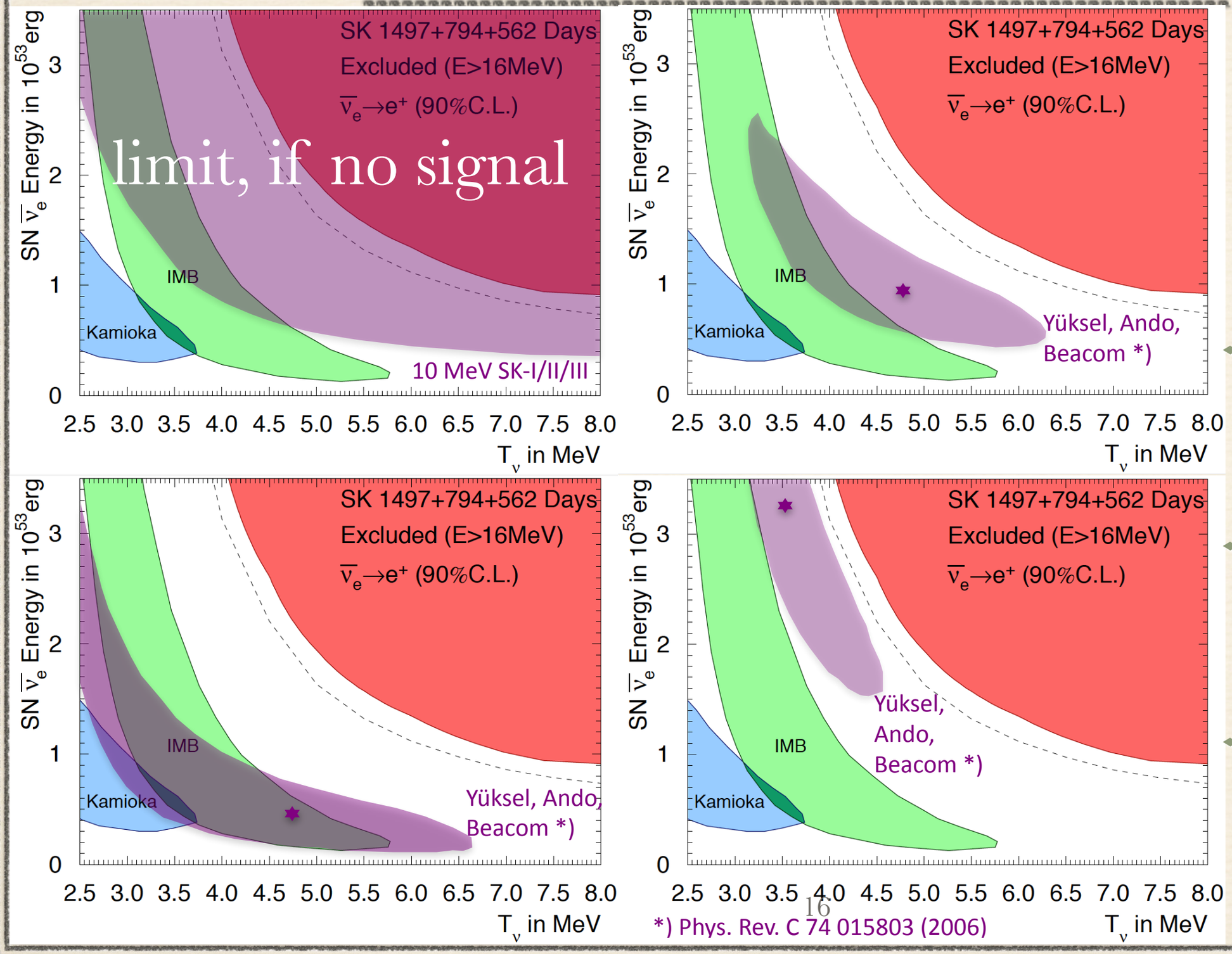


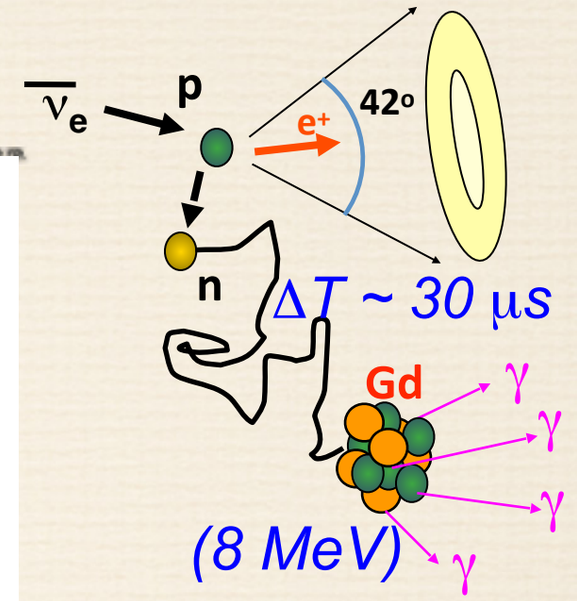
[SK Collab., Astro. Phys. 60, 41–46, 2014]



- giant cross section (49000barn) ⟹ tighter time correlation (30 μsec), higher multiplicity (3-4 γ's), higher energy (8 MeV): more distinct signature! (reduce accidental coincidences by >100)
- use $Gd_2(SO_4)_3$

IBD with Gd-n Tag: Sensitivity Estimates





- gain sensitivity from lower threshold!
- discovery, if best models are correct!
- exclude wide range of models, if no signal

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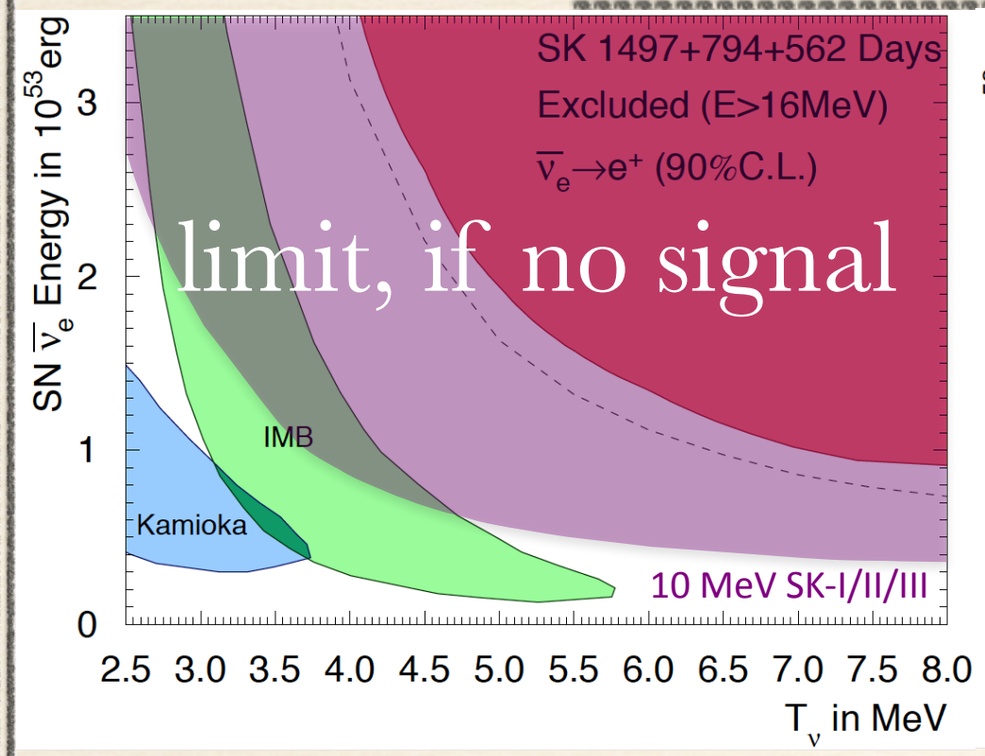
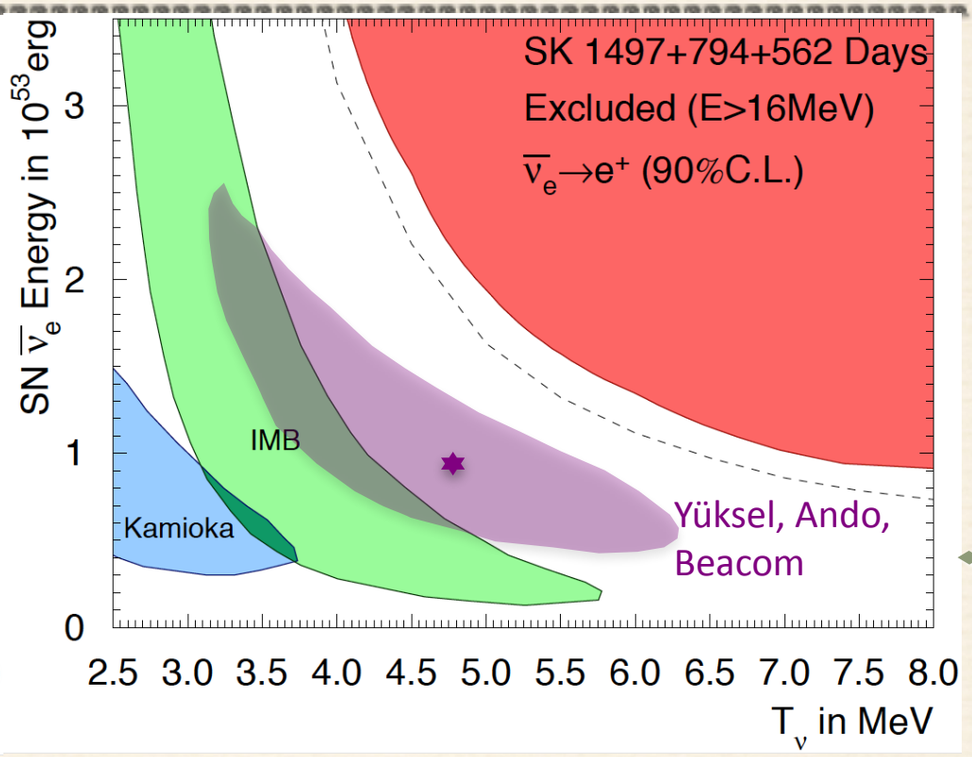
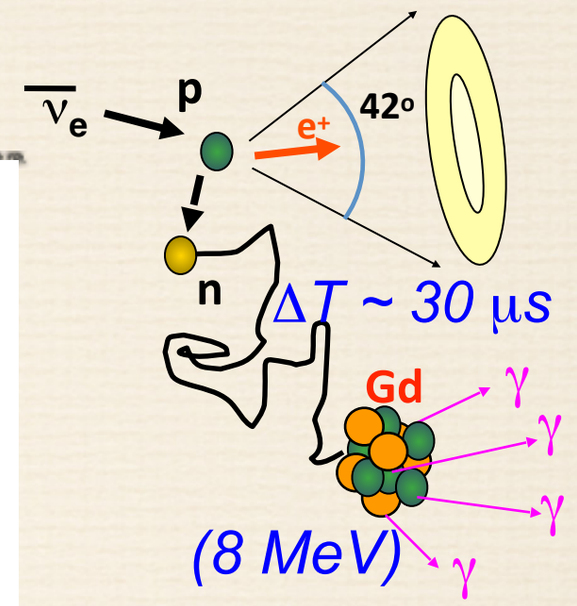




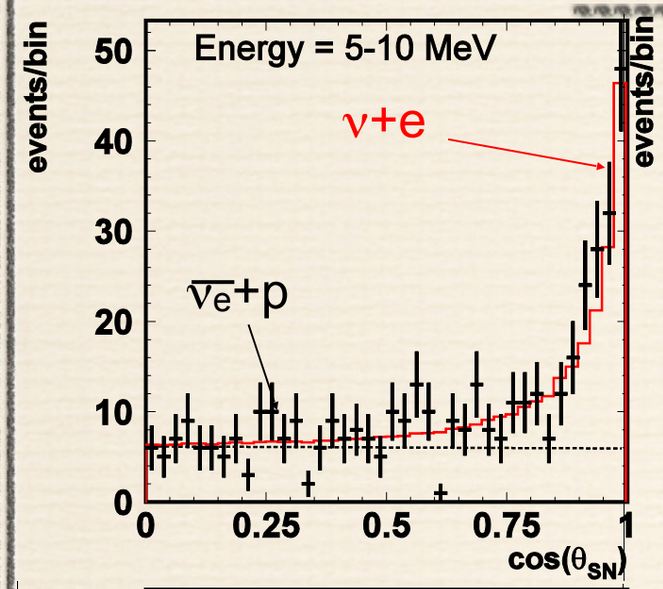


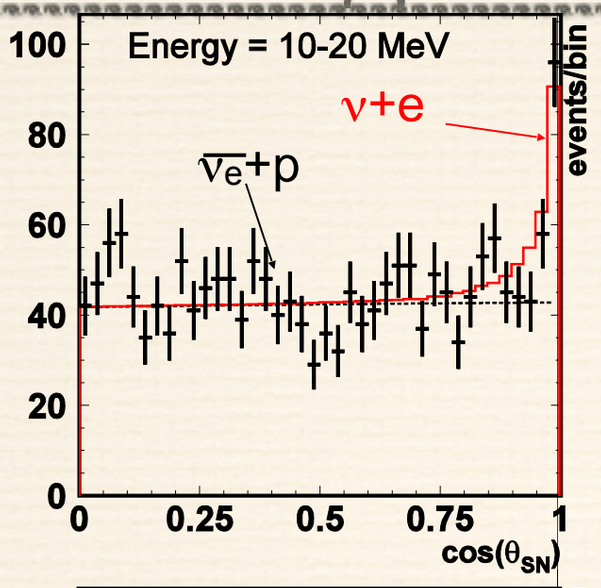
↓Expected # of signals and backgrounds through SK-Gd 10 years observation

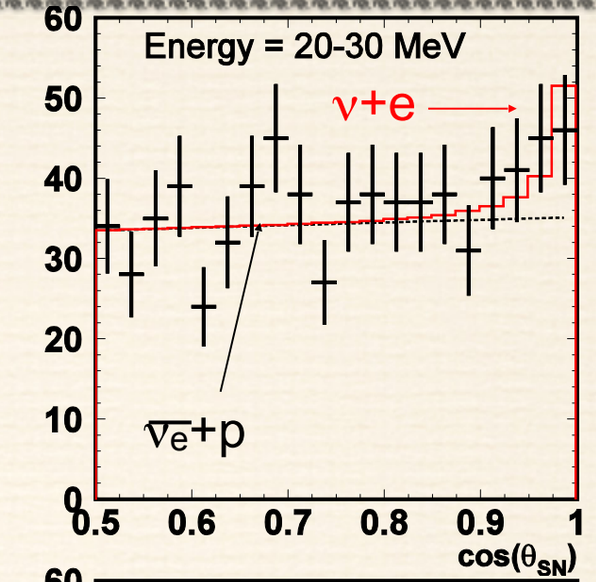
HBD model	10–16 MeV	16–28 MeV	Total	significance
T_{eff} = 8 MeV	11.3	19.9	31.2	5.3 σ
T_{eff} = 6 MeV	11.3	13.5	24.8	4.3 σ
T_{eff} = 4 MeV	7.7	4.8	12.5	2.5 σ
T_{eff} = SN1987A	5.1	6.8	11.9	2.1 σ
BG	10	24	34	–

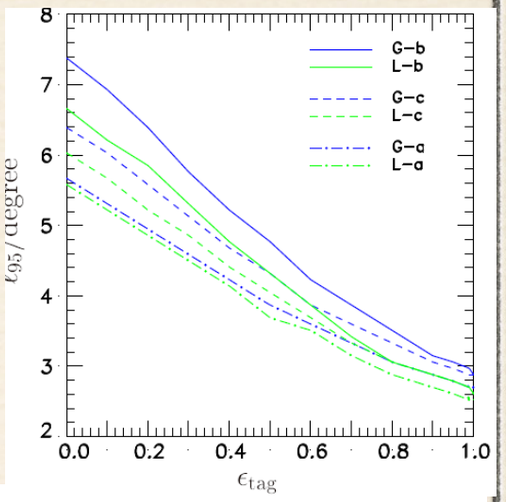
- gain sensitivity from lower threshold!
- discovery, if best models are correct!
- exclude wide range of models, if no signal

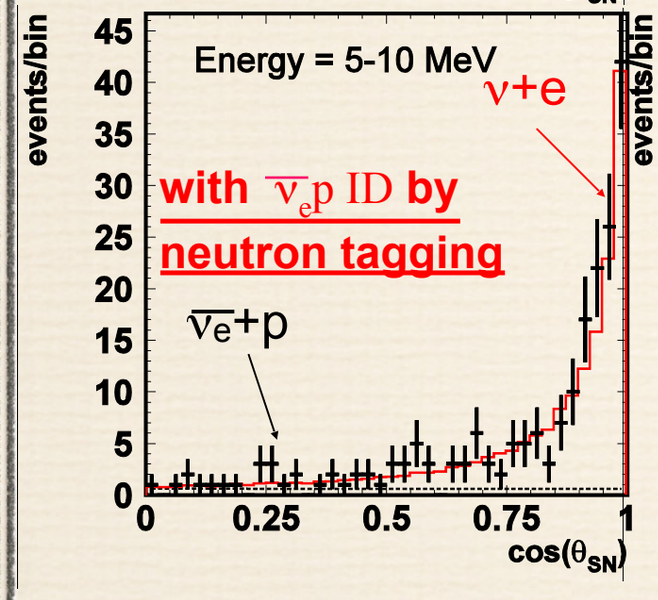
SN Bursts: Separate Flavors and Improve Pointing to Supernova

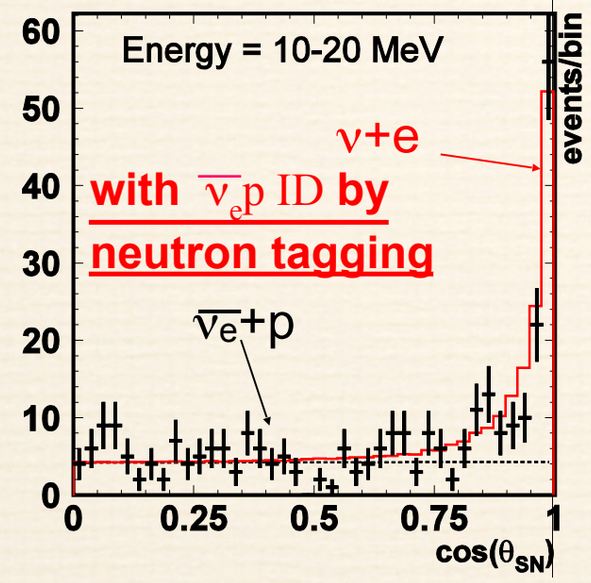


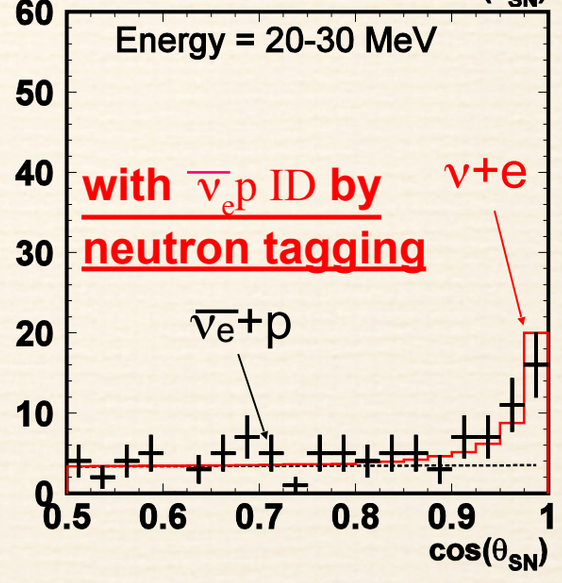


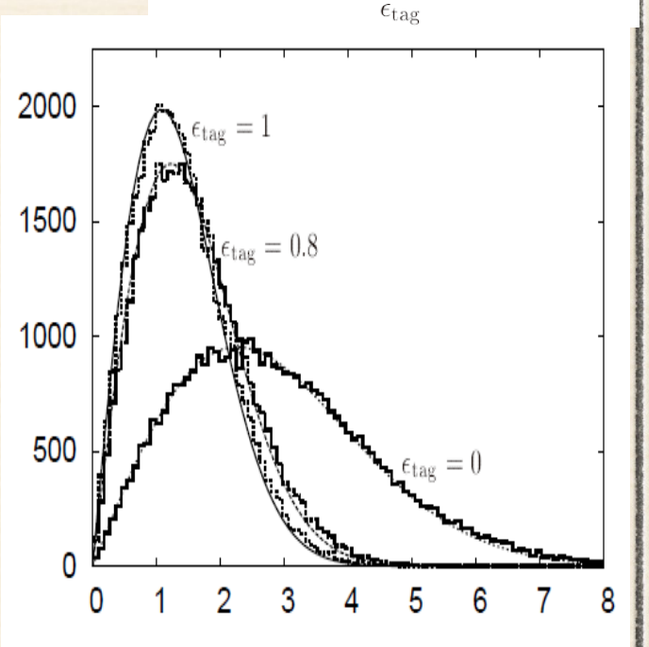












Thomas, Sekikoz,

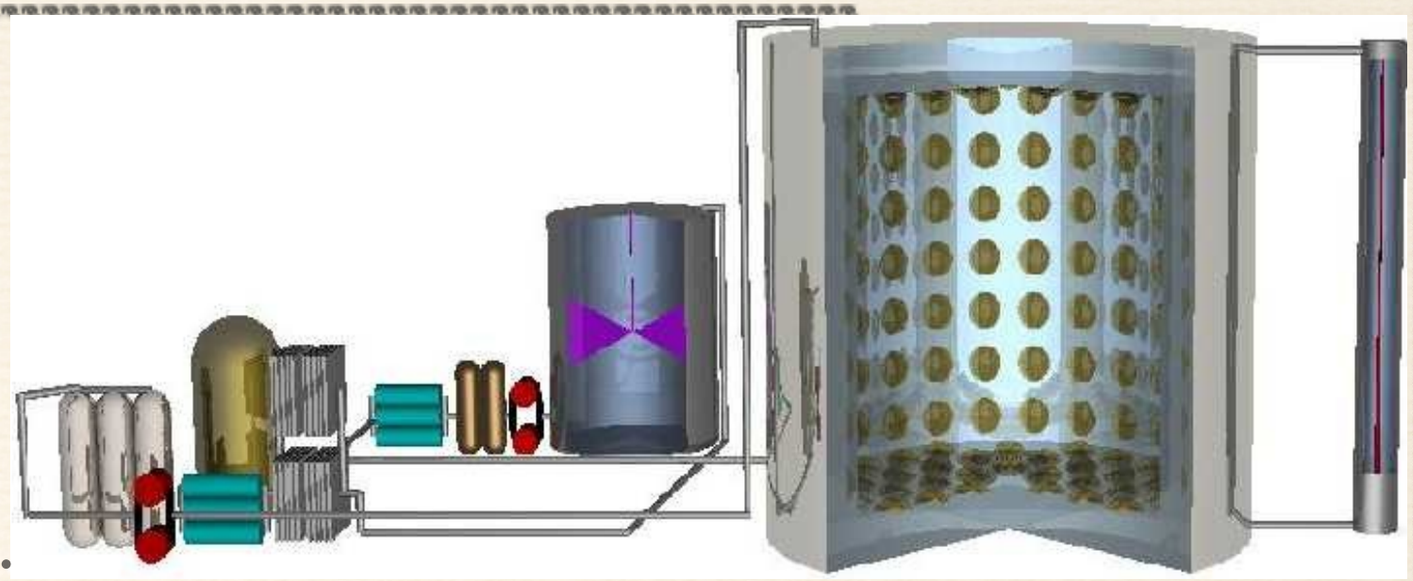
Raffelt, Kachelriess, Dighe hep-ph/0307050v2

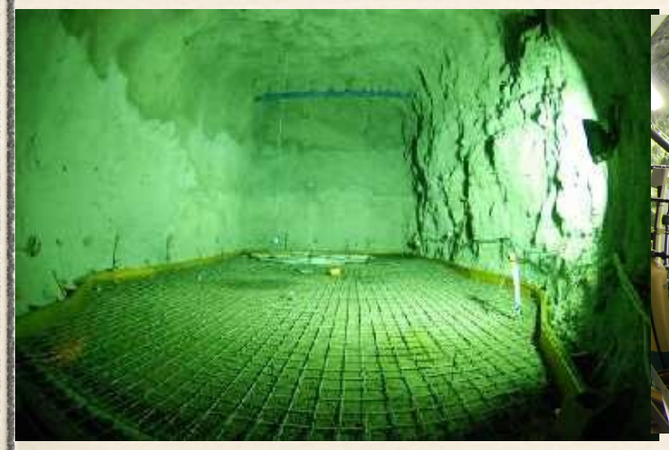
- improve ES signal and flavor decomposition of galactic SN ν burst
- improve angular resolution by factor of two!

Courtesy M. Nakahata, ICRR

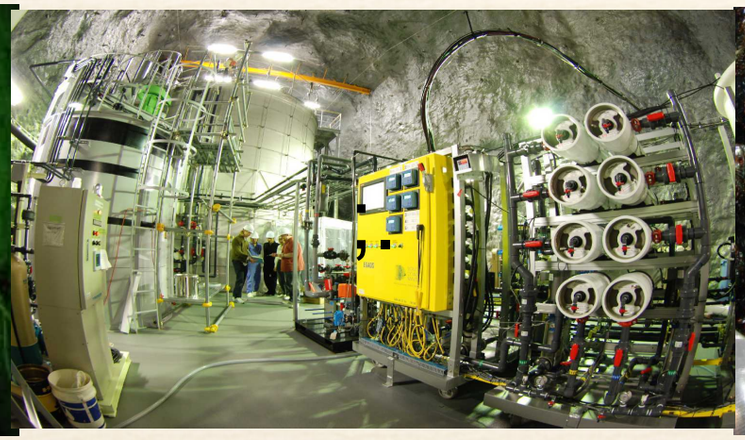
EGADS

- 200t test detector
- proof of principle
- check compatibility
- check light attenuation
- measured Gd concentration
- developed Gd solution and removal technology
- developed calibration techniques



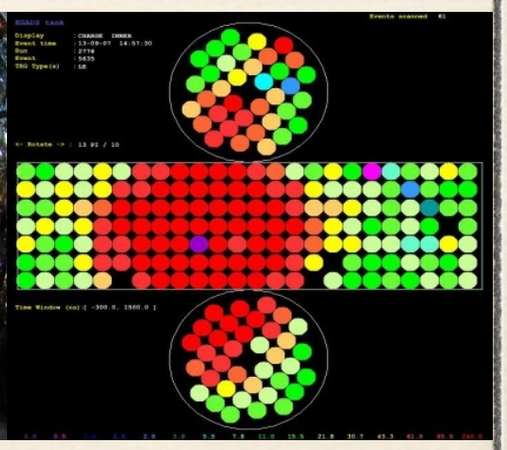


12/2009



11/2011

8/2013

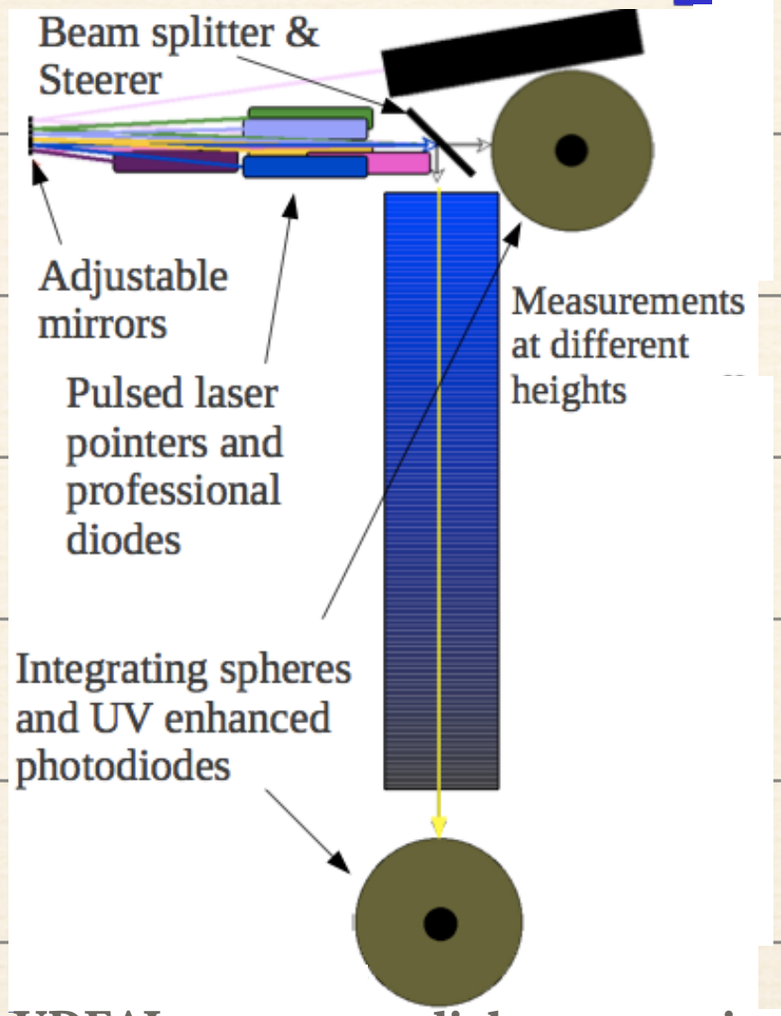


9/2013

Courtesy Mark Vagins, UC Irvine

First Injection of Gd in Tank

SK-III and SK-IV Ultrapure Water = 74.7% - 82.1%@ 15 m



UDEAL to measure light attenuation of water samples drawn from EGADS

Courtesy LLuis Martí, Kavli IPMU

Light @ 15 meters in the 200-ton tank

0 10 20 30 40 50 60 70 80

0 100 200 300 400

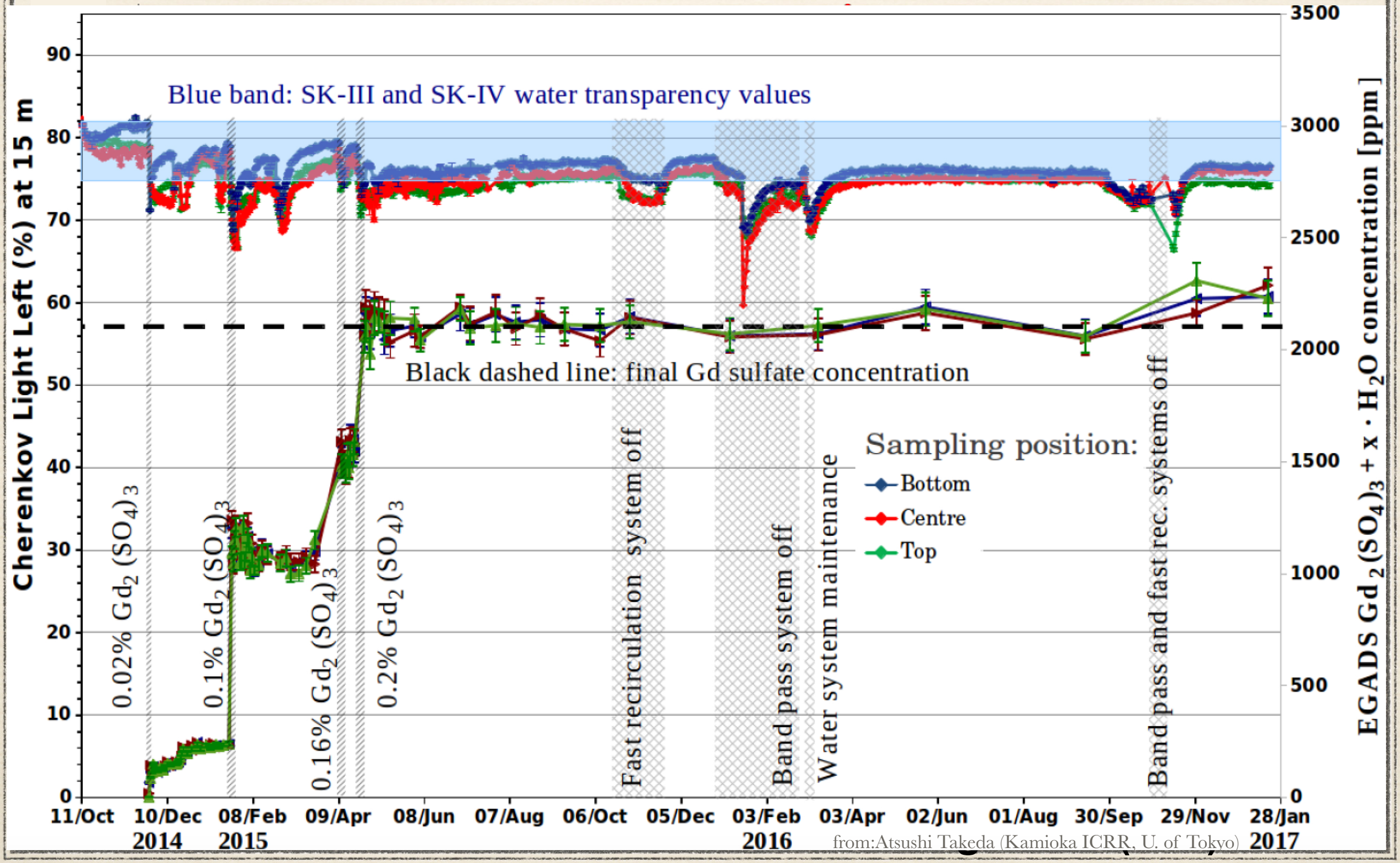
kg of $Gd_2(SO_4)_3*8H_2O$

light yield

capture efficiency

Gd n capture efficiency in 200-ton tank

Now: Inside Normal SK-IV Range at full concentration with fully functional Gd-Water Detector



from:Atsushi Takeda (Kamioka ICRR, U. of Tokyo)

SK-Gd Schedule

A planned time line toward SK-Gd

31st of May, 2018
Tank open work (TOW) for refurbishment started

2018	2019	2020	202X	202X+n

TOW

Water filling
(~2.5 months)

Pure water

T_1 : 10 tons $Gd_2(SO_4)_3$

Observation (0.02%)
~50% n efficiency

Including water stabilization

T_2 : 100 tons $Gd_2(SO_4)_3$

Observation (0.2%)
~90% n efficiency

begin of data taking with Gd is decided in coordination with T2K; we aim for ~2020

16

from:Atsushi Takeda (Kamioka ICRR, U. of Tokyo)

SK-Gd Schedule

A planned time line toward SK-Gd

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TOW

Water filling
(~2.5 months)

you are here:
Super-K ¼ full!

Pure water

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Observation (0.02%)
~50% n efficiency

T_2 : 100 tons $Gd_2(SO_4)_3$

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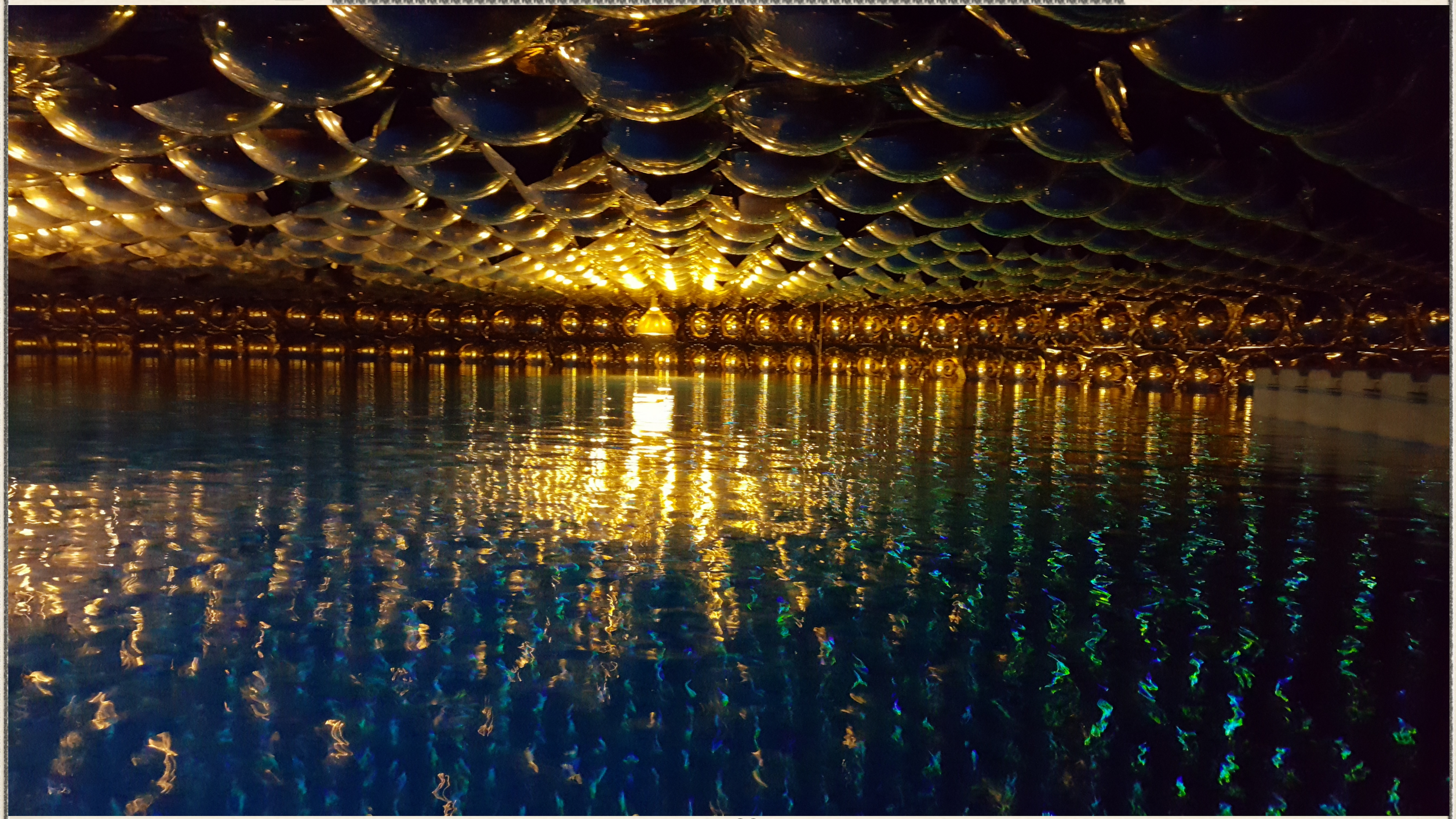
Instead of Summary: Super-K Tank Open Work



Instead of Summary:
Super-K Tank Open Work