Low Energy ν X-Rays of the Stars (and Earth)

"Snowmass" Neutrino Working Group Meeting
SLAC, March 7th 2013

Michael Smy, UC Irvine

Low Energy ν Interactions in H_2O Probe...

- neutrino oscillation parameters θ_{12}, θ_{13}, and Δm^2_{21} (solar neutrinos) as well as mass hierarchy (supernova neutrinos)
- matter effects on neutrino oscillations in the Earth (non-resonant, small-amplitude quasi-vacuum oscillations!!!)
- matter effects on neutrino oscillations in the Sun (MSW resonance producing maximum conversion)
- solar core temperature
- neutrino self-interactions (supernova neutrinos)
- supernova explosion models

I Oscillation Parameters

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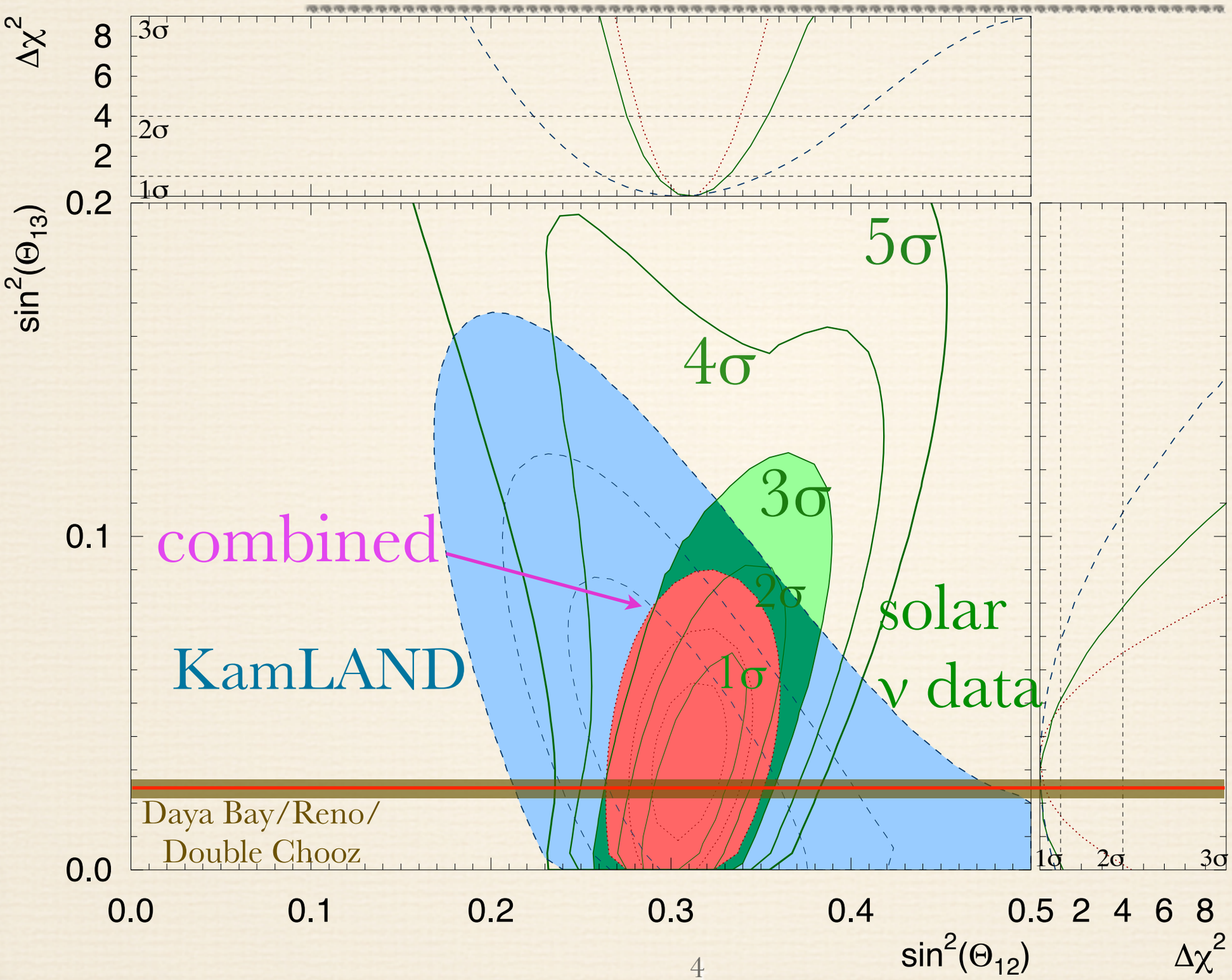
Low Energy ν Oscillation Parameters



solar ν and KamLAND data favor positive θ_{13} at ~2σ level; θ_{13} value very consistent with Daya Bay's and Reno's measurements

given Daya Bay/Reno/Double Chooz's small θ_{13} -uncertainty, solar ν results are θ_{13}-independent!

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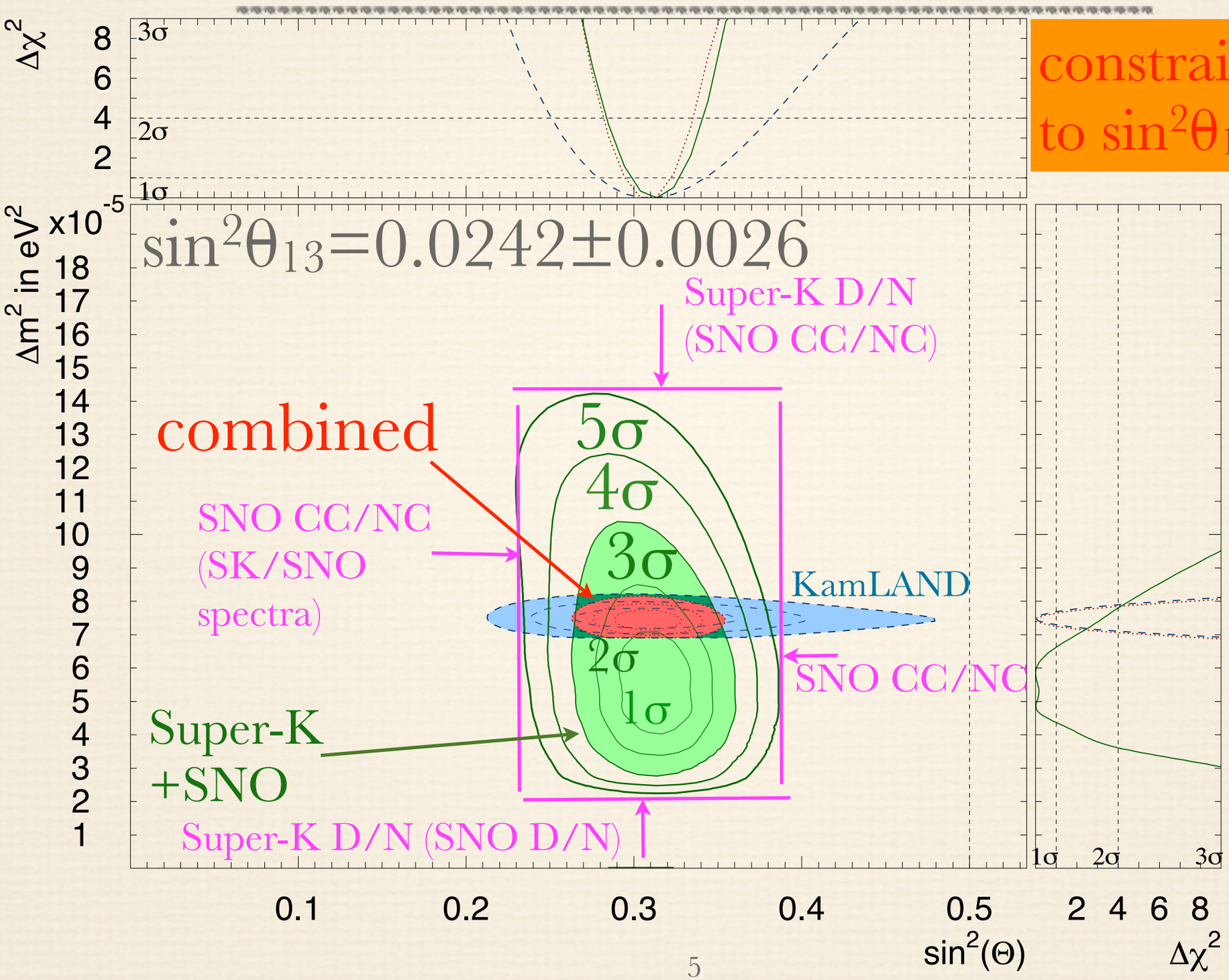
Oscillation Parameters (Water Č ν Data)



constrain $\sin^2\theta_{13}$ to $\sin^2\theta_{13}=0.025$

difference in best fit Δm^2 between solar data & KamLAND

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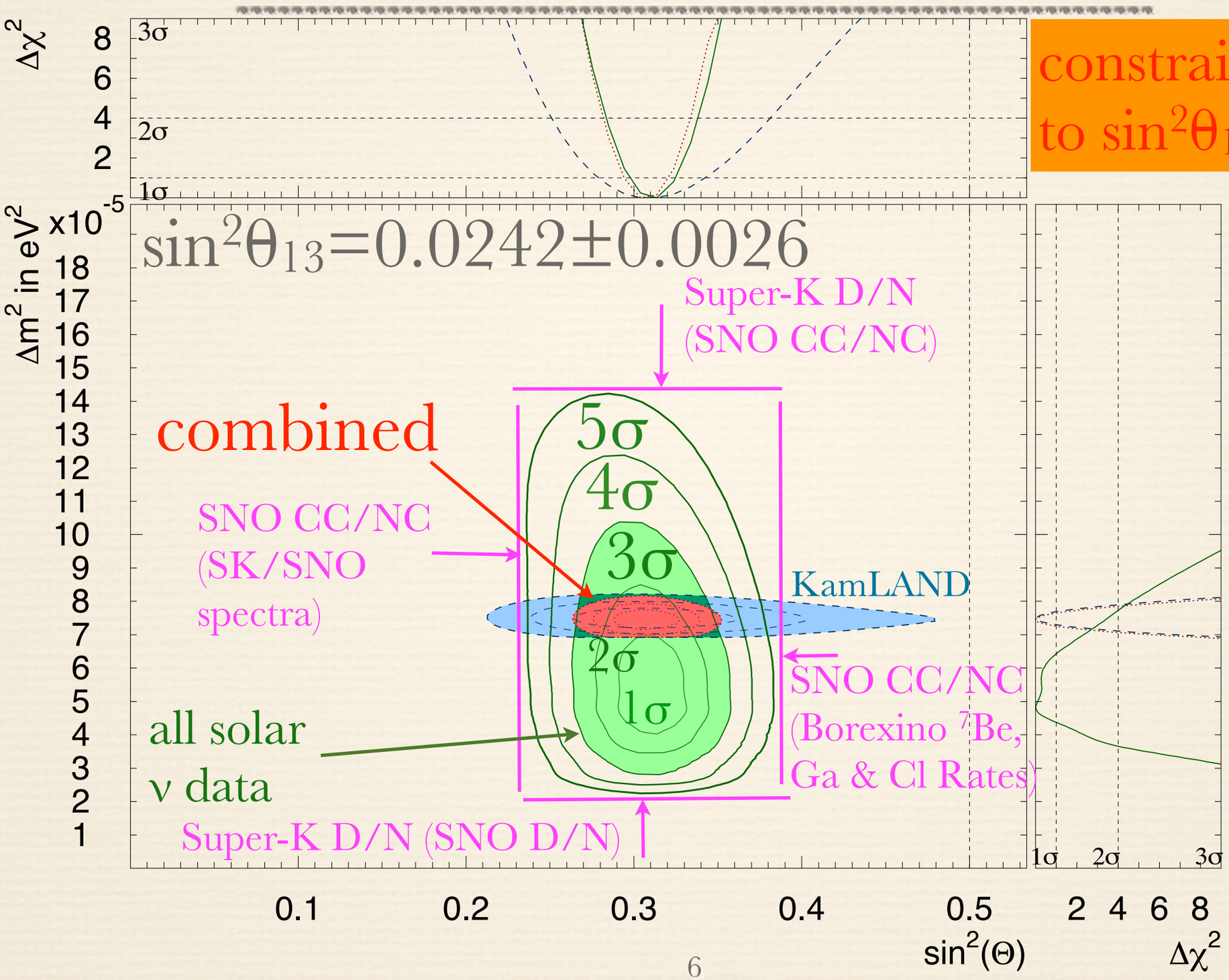
Oscillation Parameters (all Solar ν Data)



constrain $\sin^2\theta_{13}$ to $\sin^2\theta_{13}$=0.025

difference in best fit Δm^2 between solar data & KamLAND

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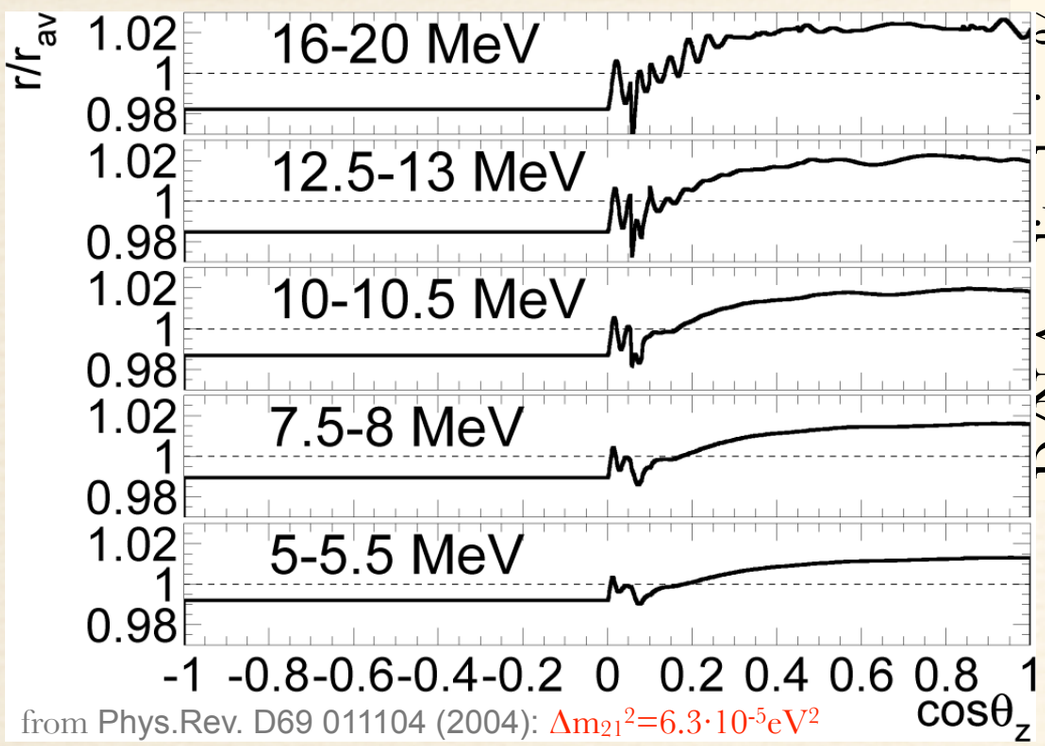
II Earth Matter Effects on Solar ν Osc.

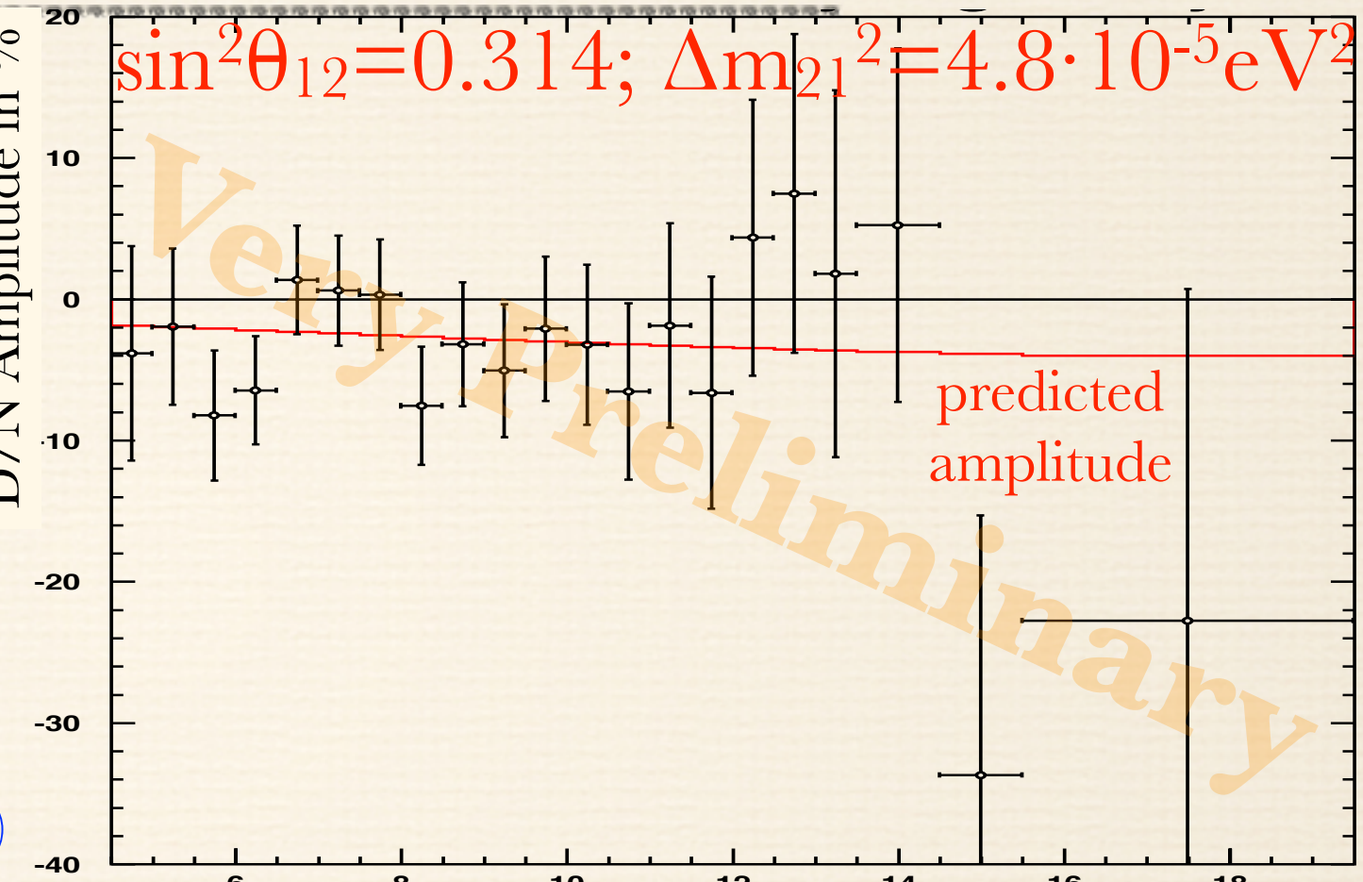
- direct test of matter effects: put a big chunk of matter in a ν beam once a day
- small amplitude: giant detectors!
- measures solar Δm^2 with high precision using neutrinos
- sensitive to Earth matter profile (PREM)
- incredibly, equatorial-polar radius difference is not negligible already

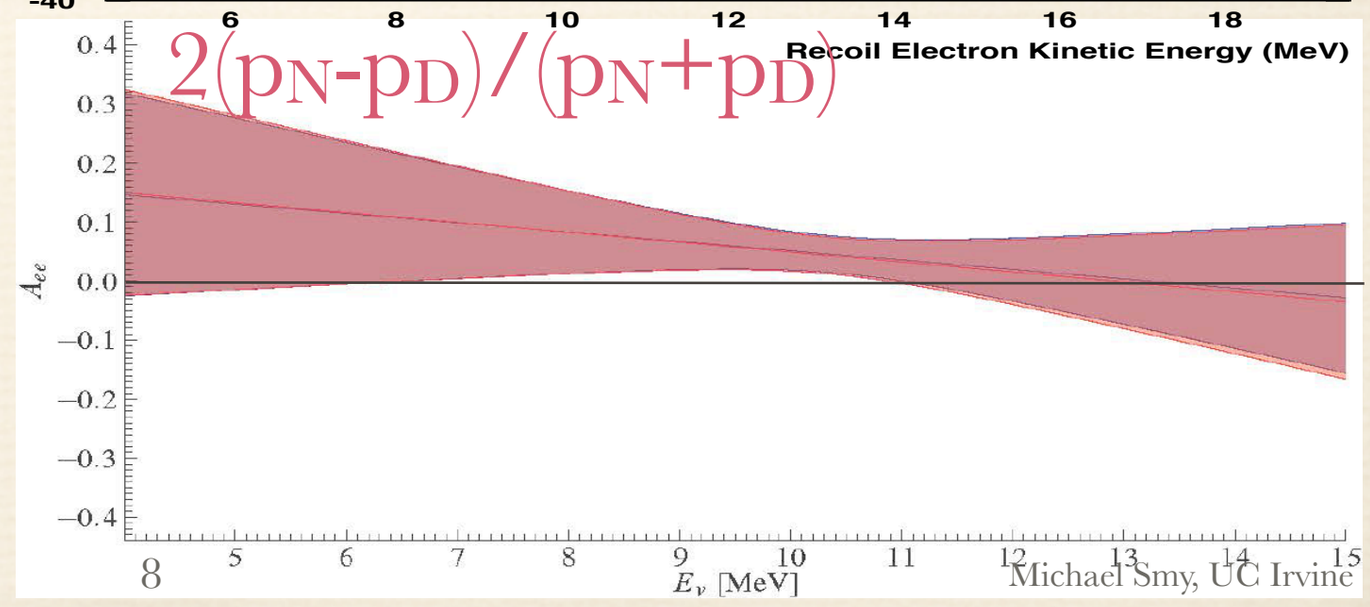
Day/Night Variation of Super-K and SNO Solar ν Event Rate



from Phys.Rev. D69 011104 (2004): $\Delta m_{21}^2=6.3\cdot10^{-5}eV^2$

Day/Night Asym.: $A_{DN}=2(\phi_D-\phi_N)/(\phi_D+\phi_N)$





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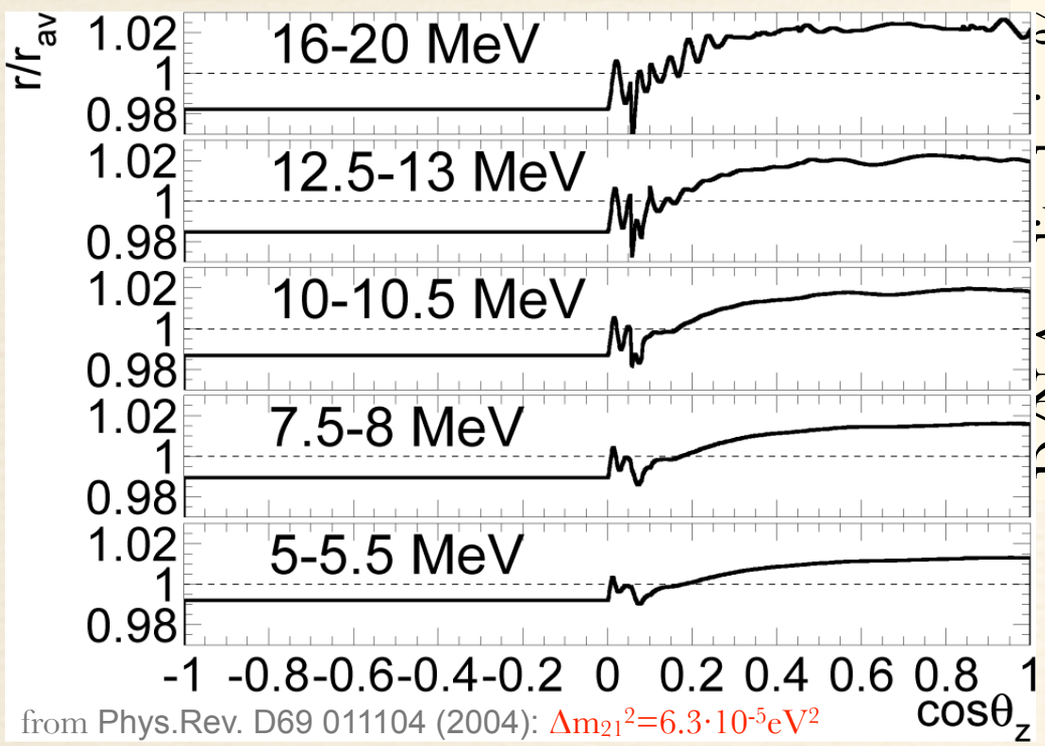

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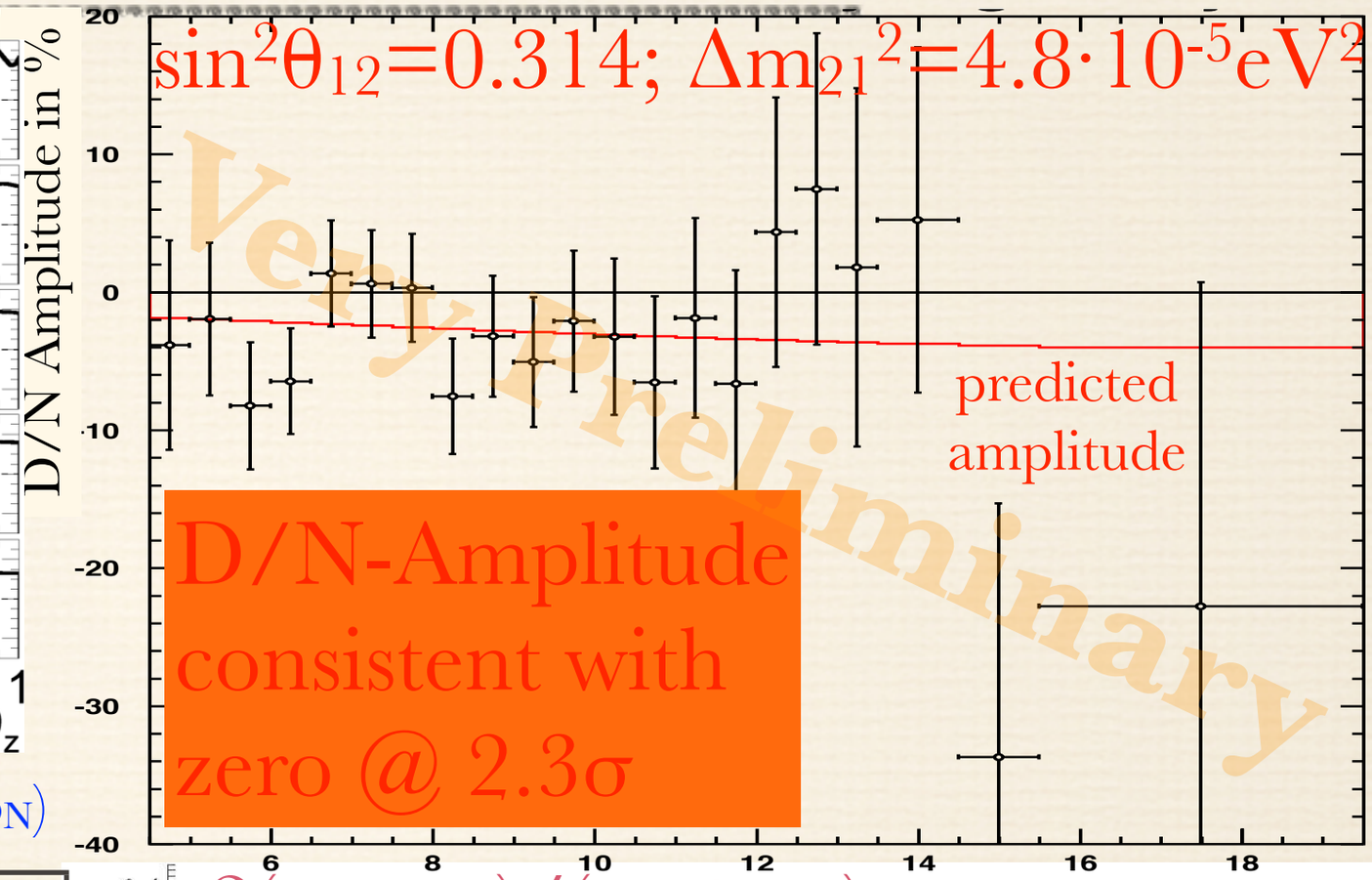
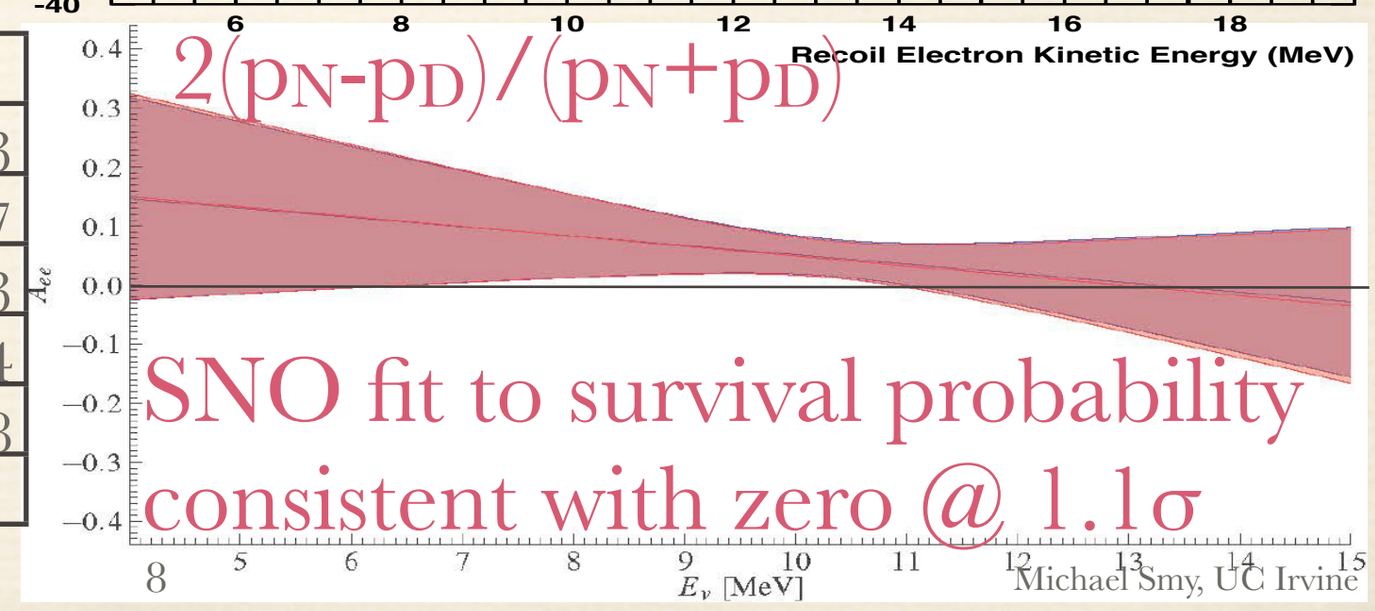


Day/Night Asym.: $A_{DN}=2(\phi_D-\phi_N)/(\phi_D+\phi_N)$

experiment	D/N amplitude	A_{DN}
SK-I	-2.0±1.7±1.0%	-2.1±2.0±1.3
SK-II	-4.3±3.8±1.0%	-6.3±4.2±3.7
SK-III	-4.3±2.7±0.7%	-5.9±3.4±1.3
SK-IV	-2.8±1.9±0.7%	-5.2±2.3±1.4
SK comb.	**-2.8±1.1±0.5**	-4.0±1.3±0.8
SK & SNO	**-2.6±1.0%**	

Very Preliminary



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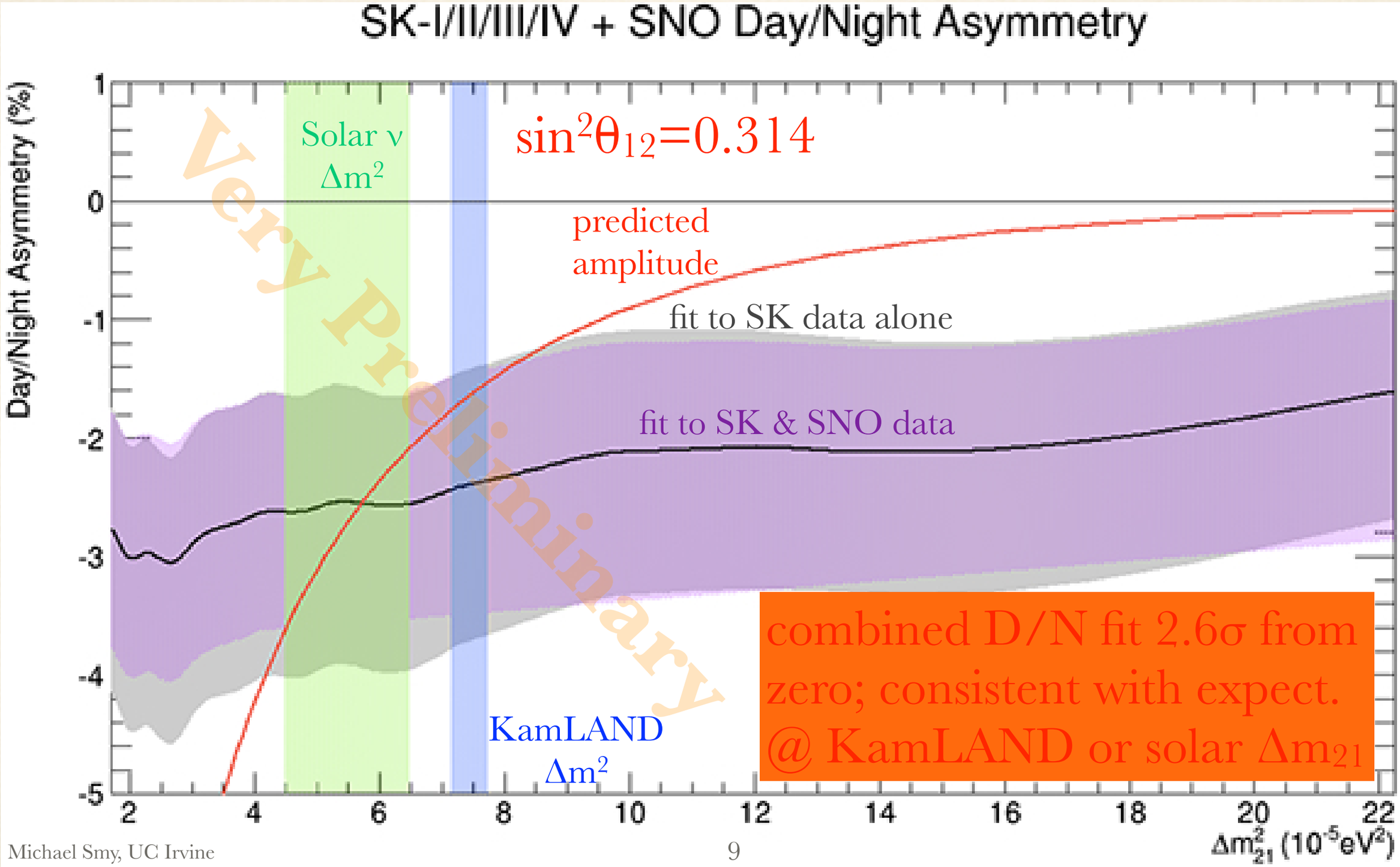
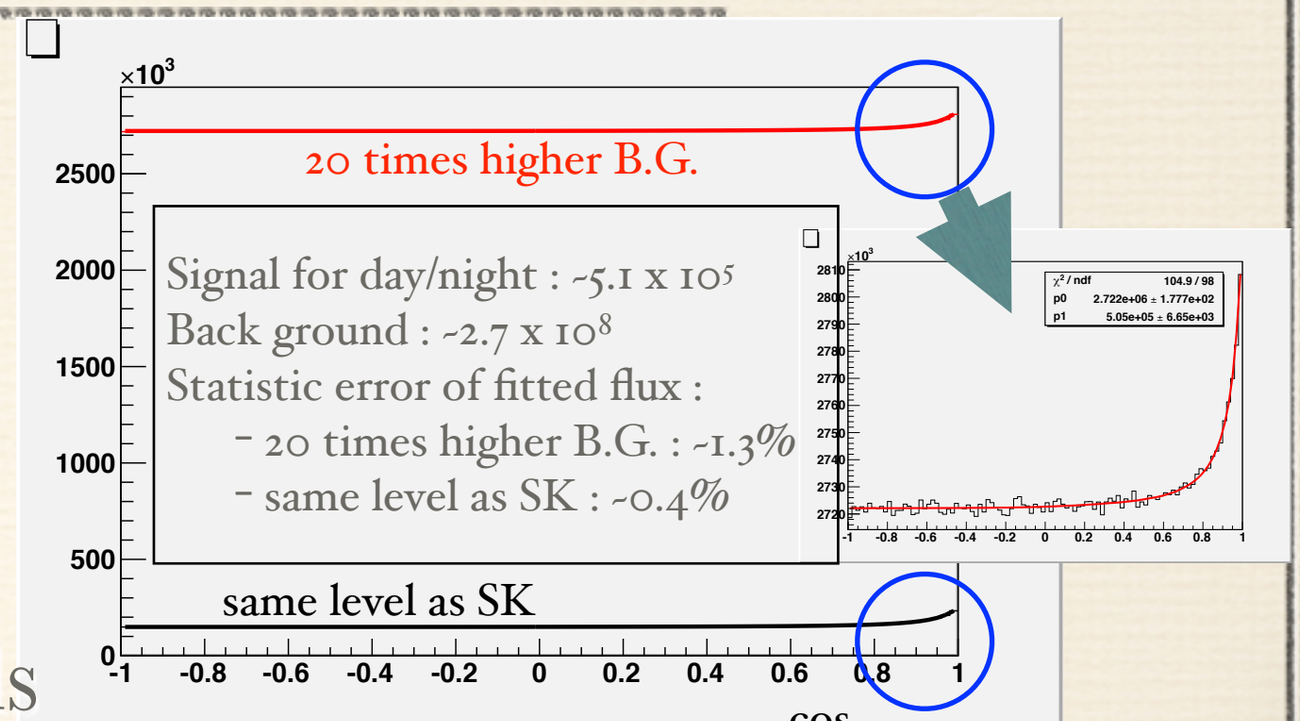
SK/SNO Day/Night Fits at various Δm^2

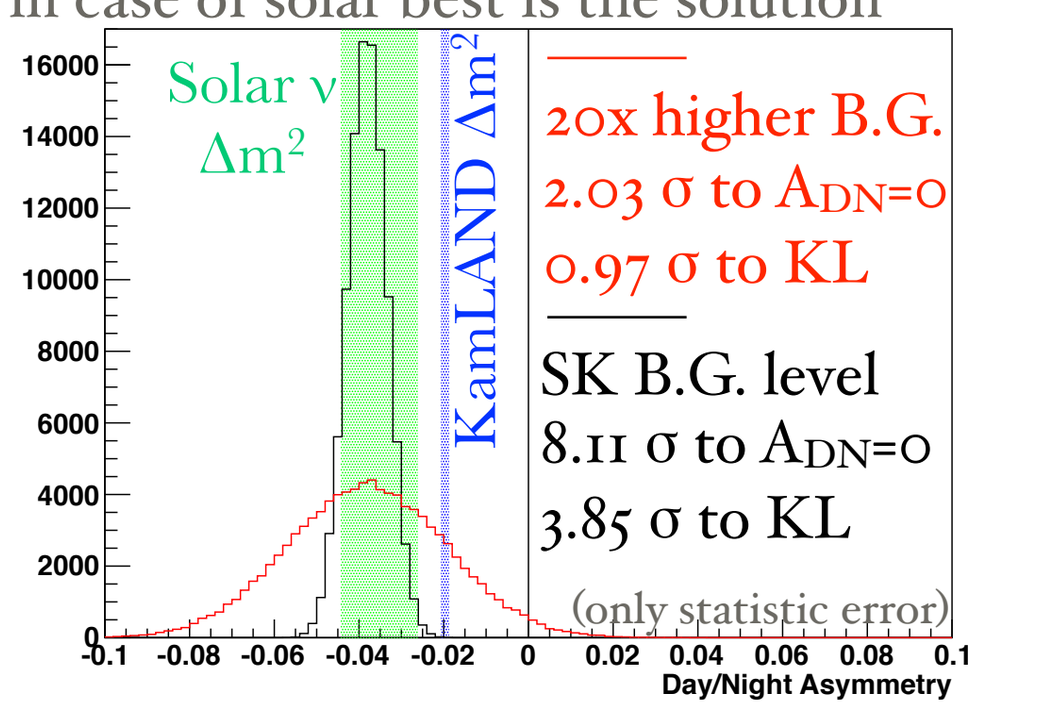


Solar Day/Night Effect at Hyper-K

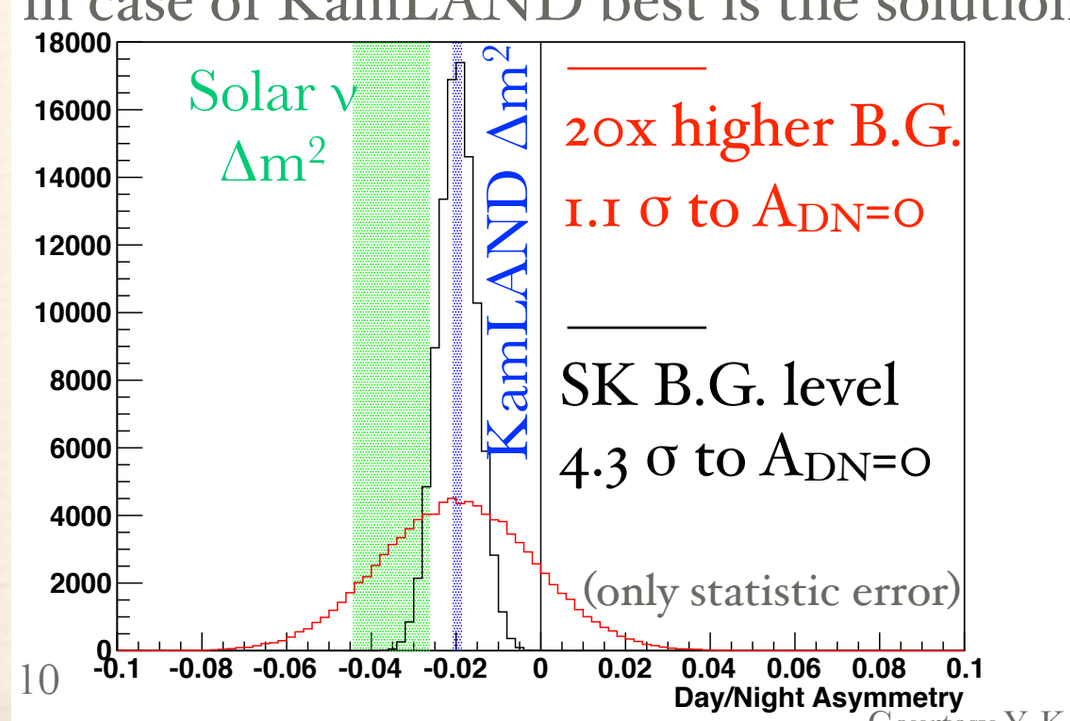
- Hyper-K might be shallower than SK
- spallation background!
- study two true Δm^2 and two background levels



in case of solar best is the solution



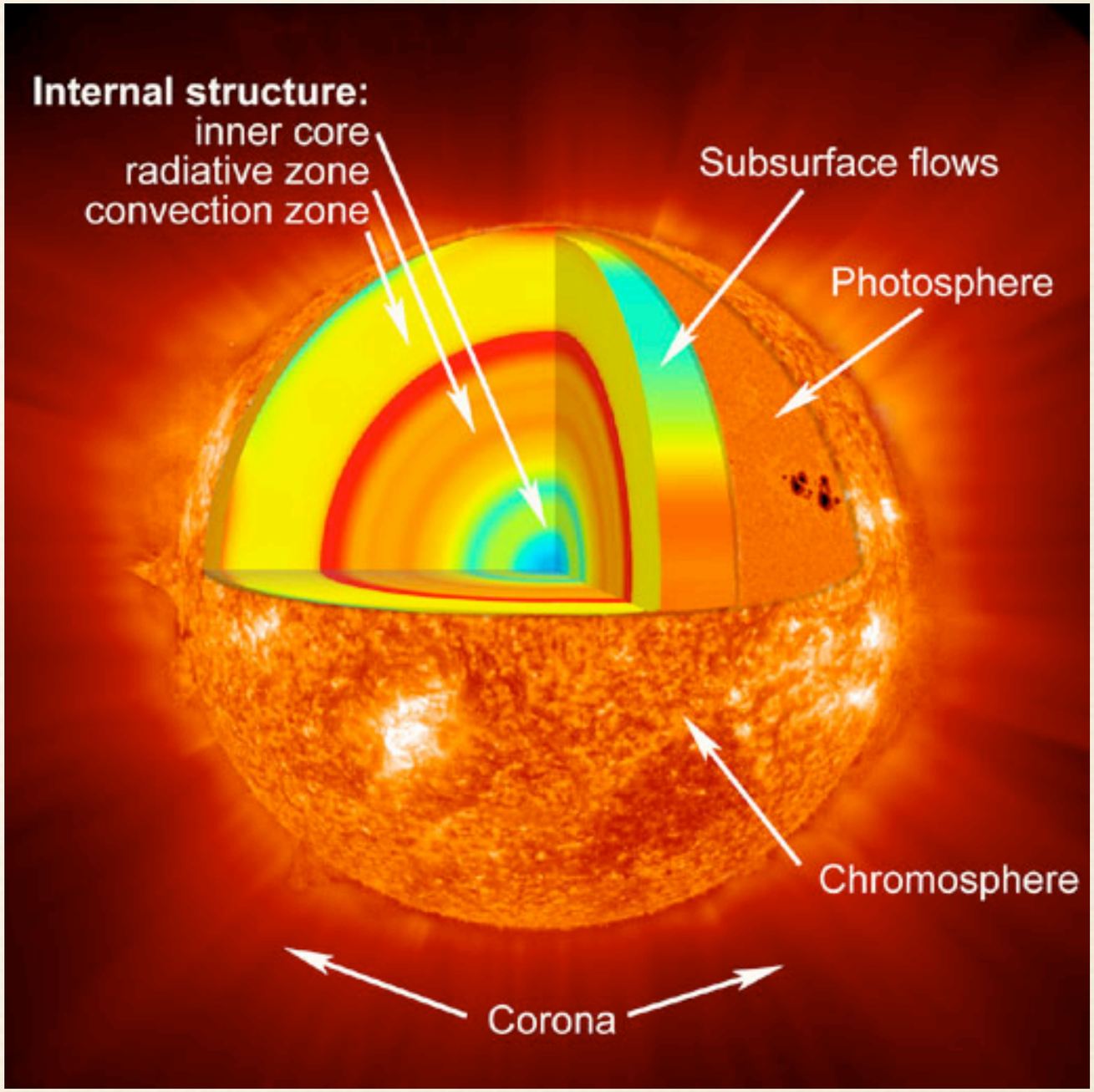
in case of KamLAND best is the solution



Courtesy Y. Koshio, ICRR

III Probing the Solar Core

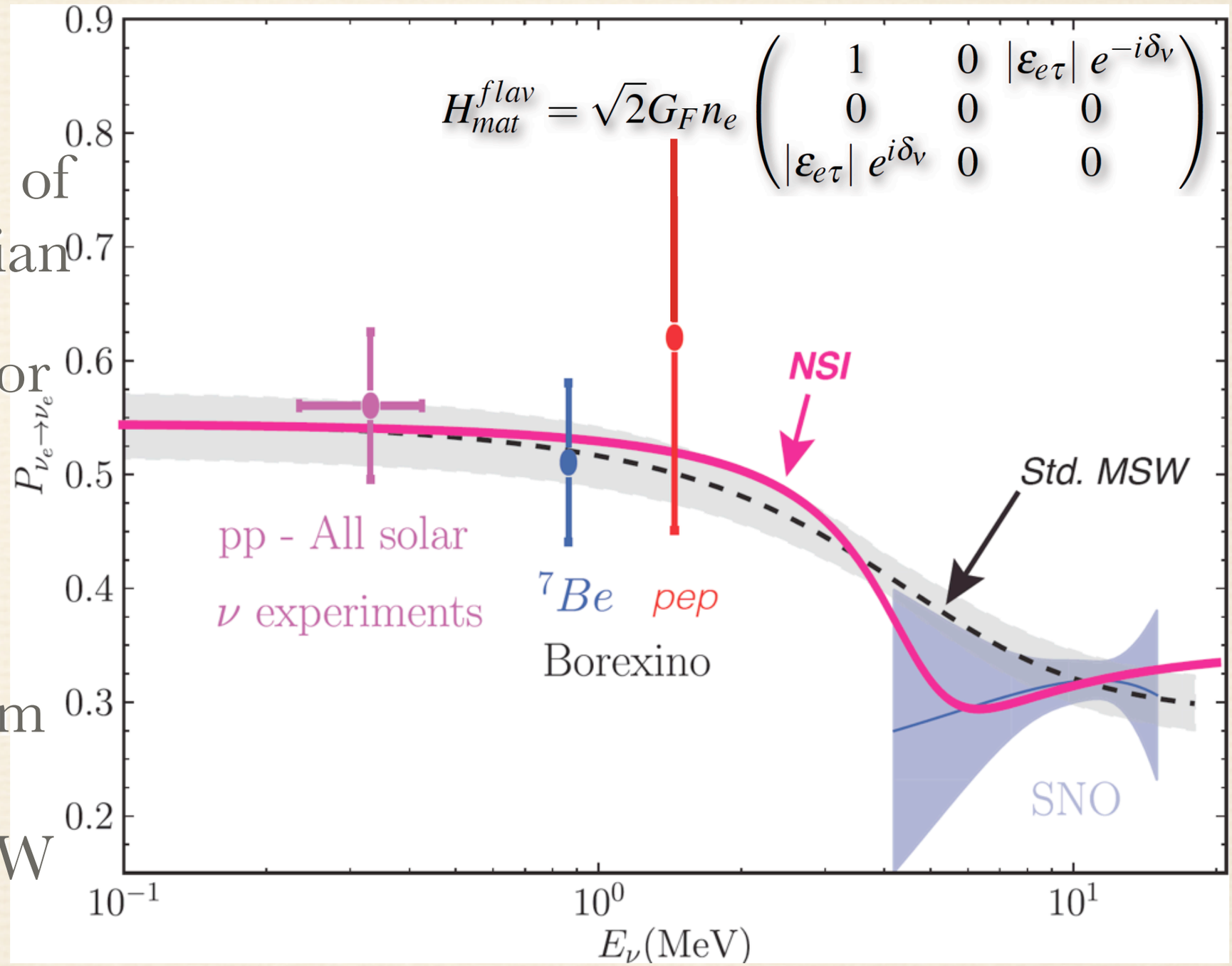
- solar models
- solar matter effects (high matter density: 10xEarth's core)
- non-standard interactions (high matter density)



Do We Really Understand Solar MSW?

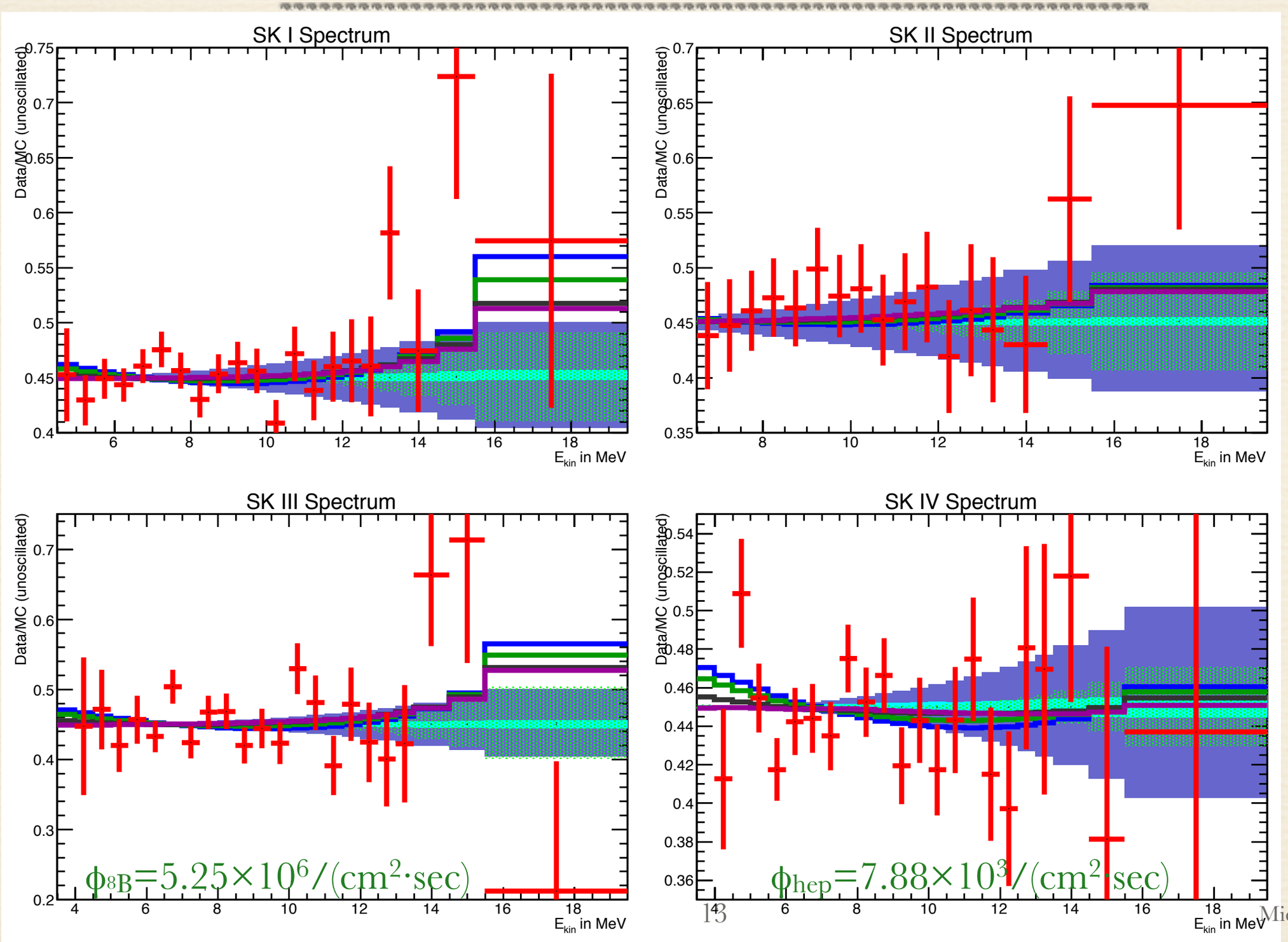
Non-Standard interactions:

- simple extension of MSW Hamiltonian
- SNO data disfavor MSW "upturn", so NSI fits data somewhat better
- Super-K spectrum also shows no evidence for MSW upturn



Courtesy A. Friedland, LANL

Super-K Fit to MSW Oscillation Transition



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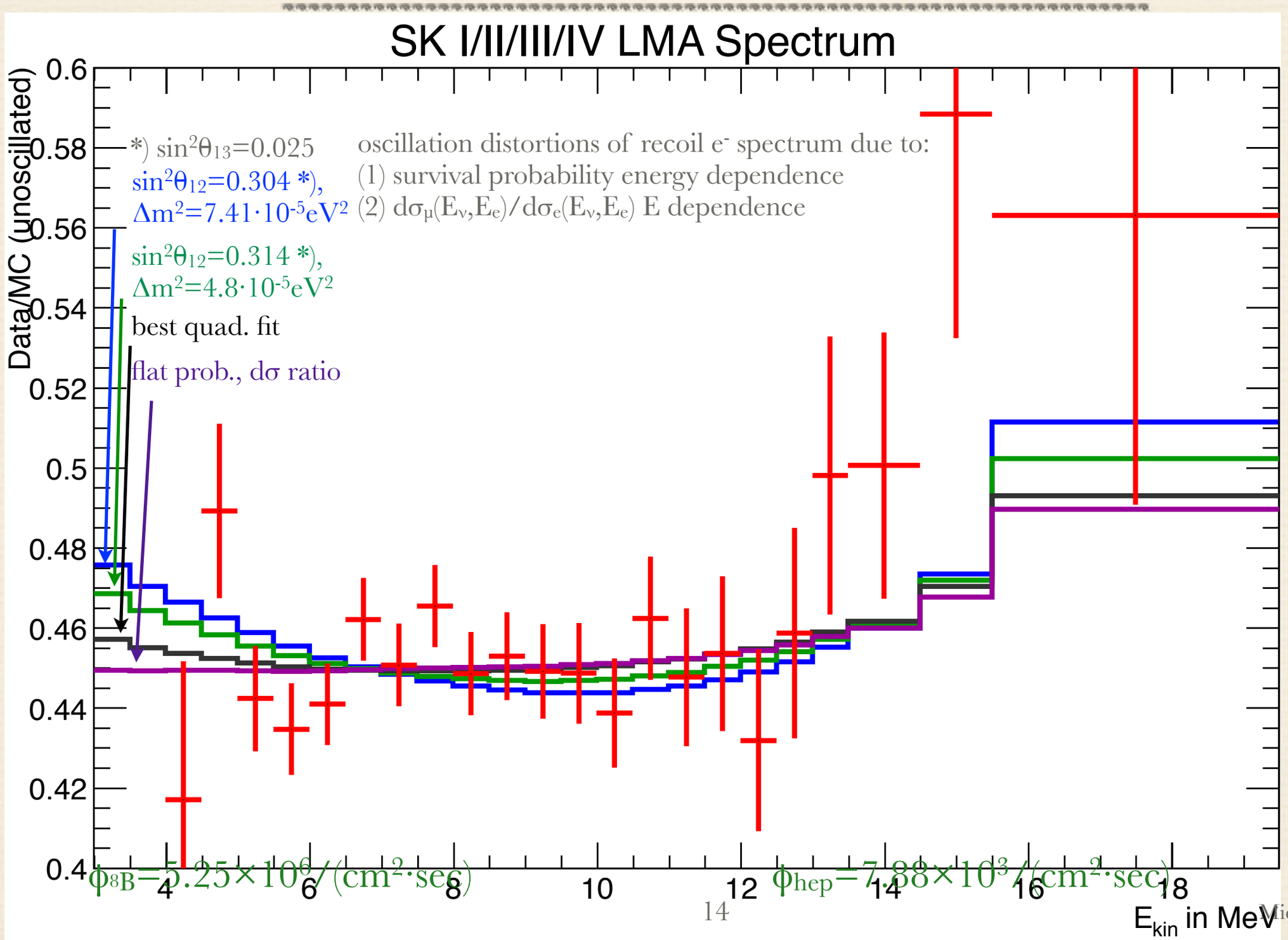

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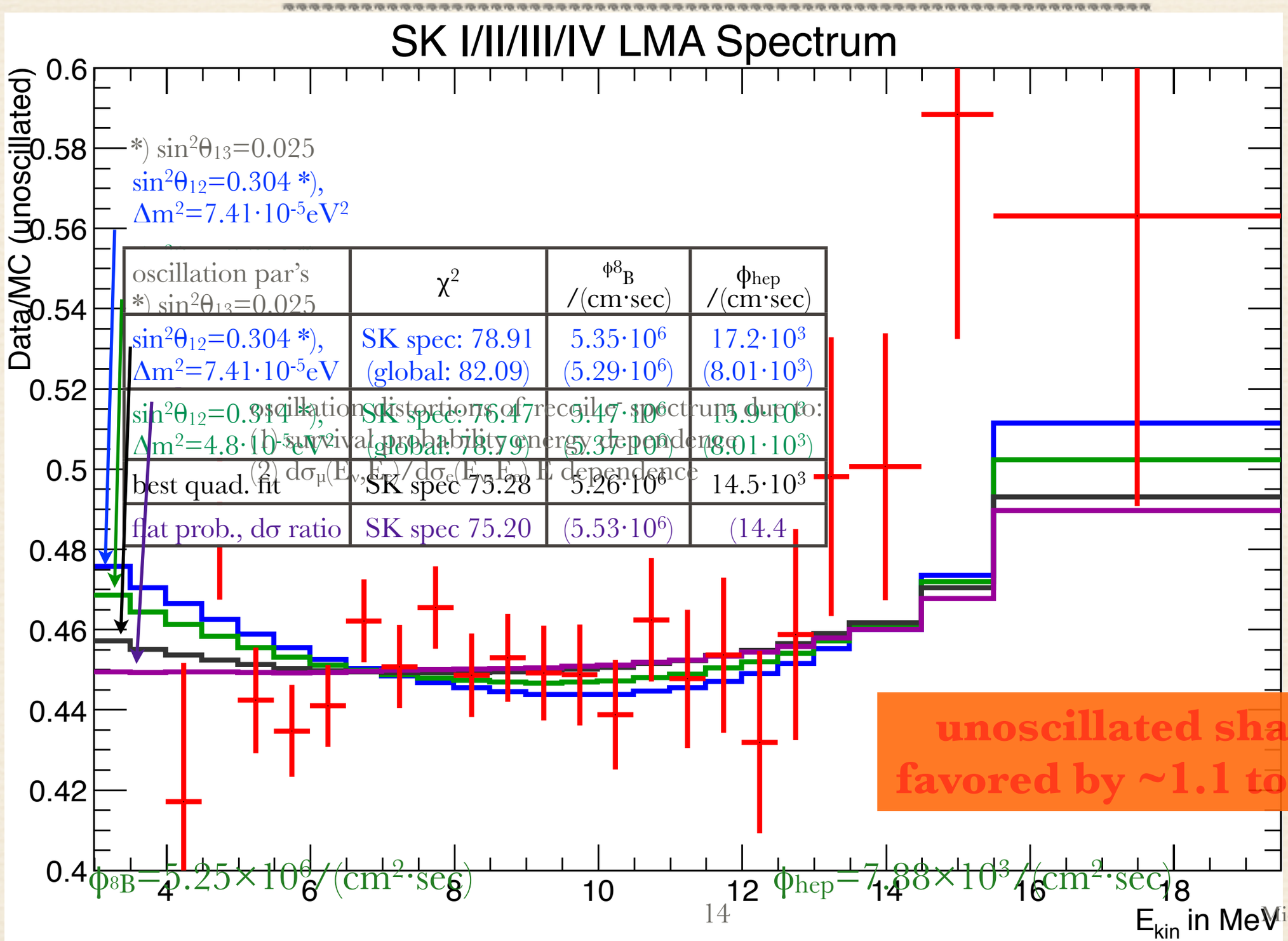

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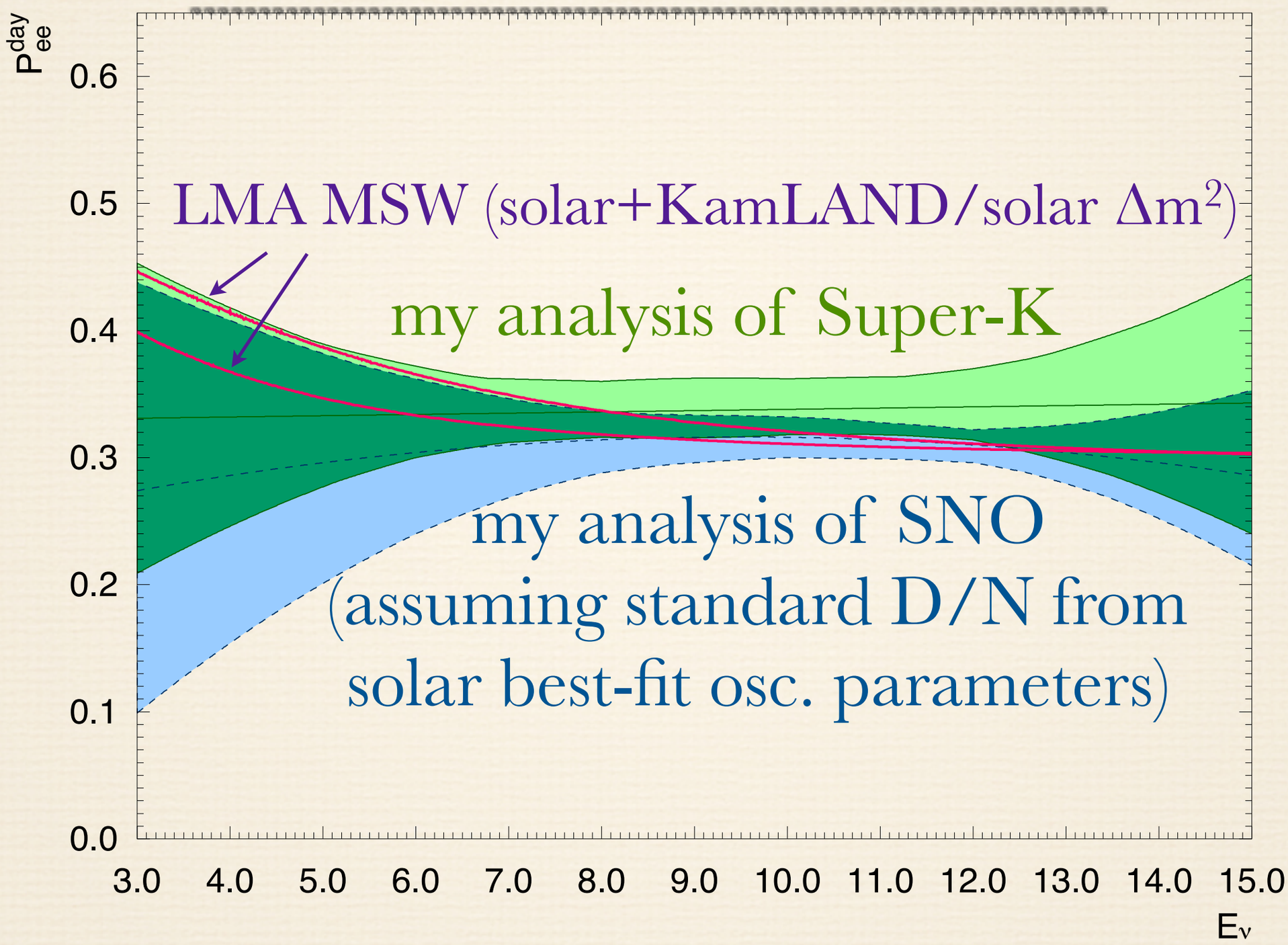
Fitting Quadratic P_{ee} to SK-I/II/III/IV Spectra



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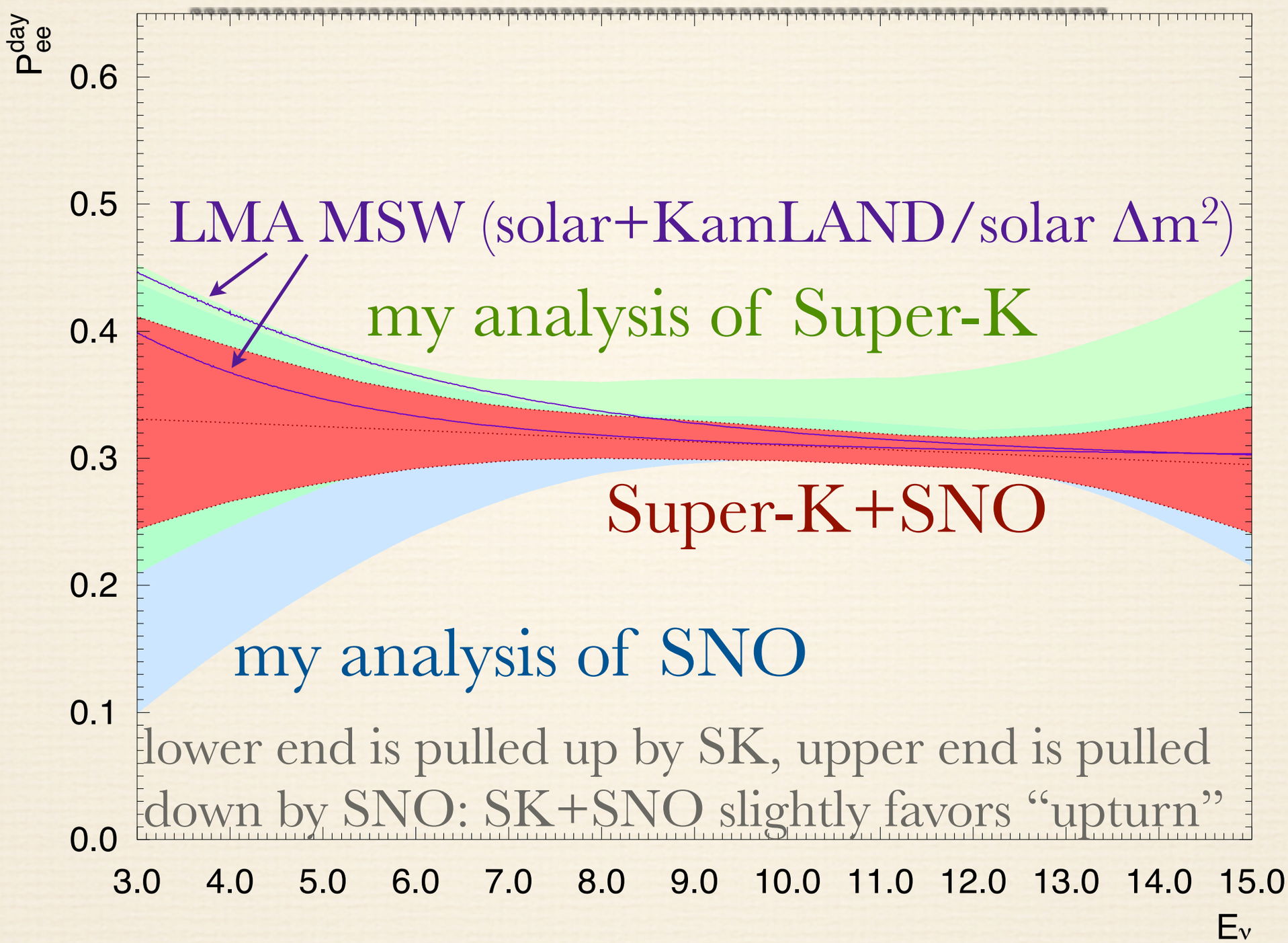
Fitting Quadratic P_{ee} to SK-I/II/III/IV Spectra



lower end is pulled up by SK, upper end is pulled down by SNO: SK+SNO slightly favors "upturn"

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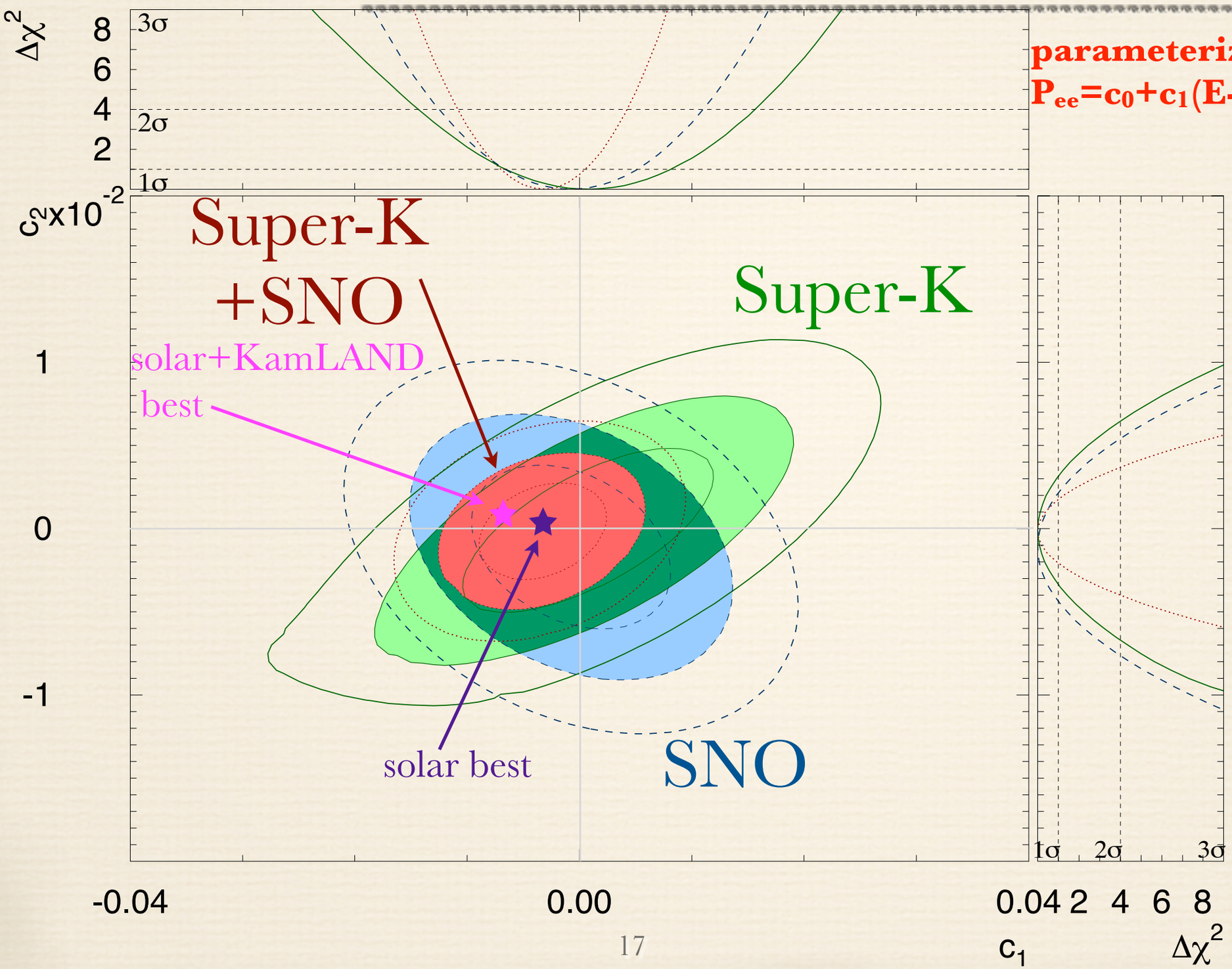
Contours of Shape Coefficients



parameterize survival prob. as
$P_{ee}=c_0+c_1(E\text{-}10MeV)+c_2(E\text{-}10MeV)^2$

c_0 is marginalized

complementarity between SK and SNO data

consistent with undistorted, and with solar best fit parameters; NSI very slightly disfavored

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Future Progress on Testing MSW Resonance

- Super-K will increase statistics, perhaps lower energy threshold
- Hyper-K won't have a low threshold; tight systematic uncertainties, etc.; a giant, low threshold water Cherenkov detector is probably unaffordable with present technology
- so this is it (or close to it), from water Cherenkov for a while
- large liquid scintillator detector might see enough CC interactions on ^{13}C...
- SNO+ might do a precision measurement of pep, but P_{ee}(1.4 MeV) is not so different from P_{ee}(860keV)
- $P_{ee}<0.5$ over a wide range of energy implies a resonant-like conversion mechanism (however, not the MSW resonance)

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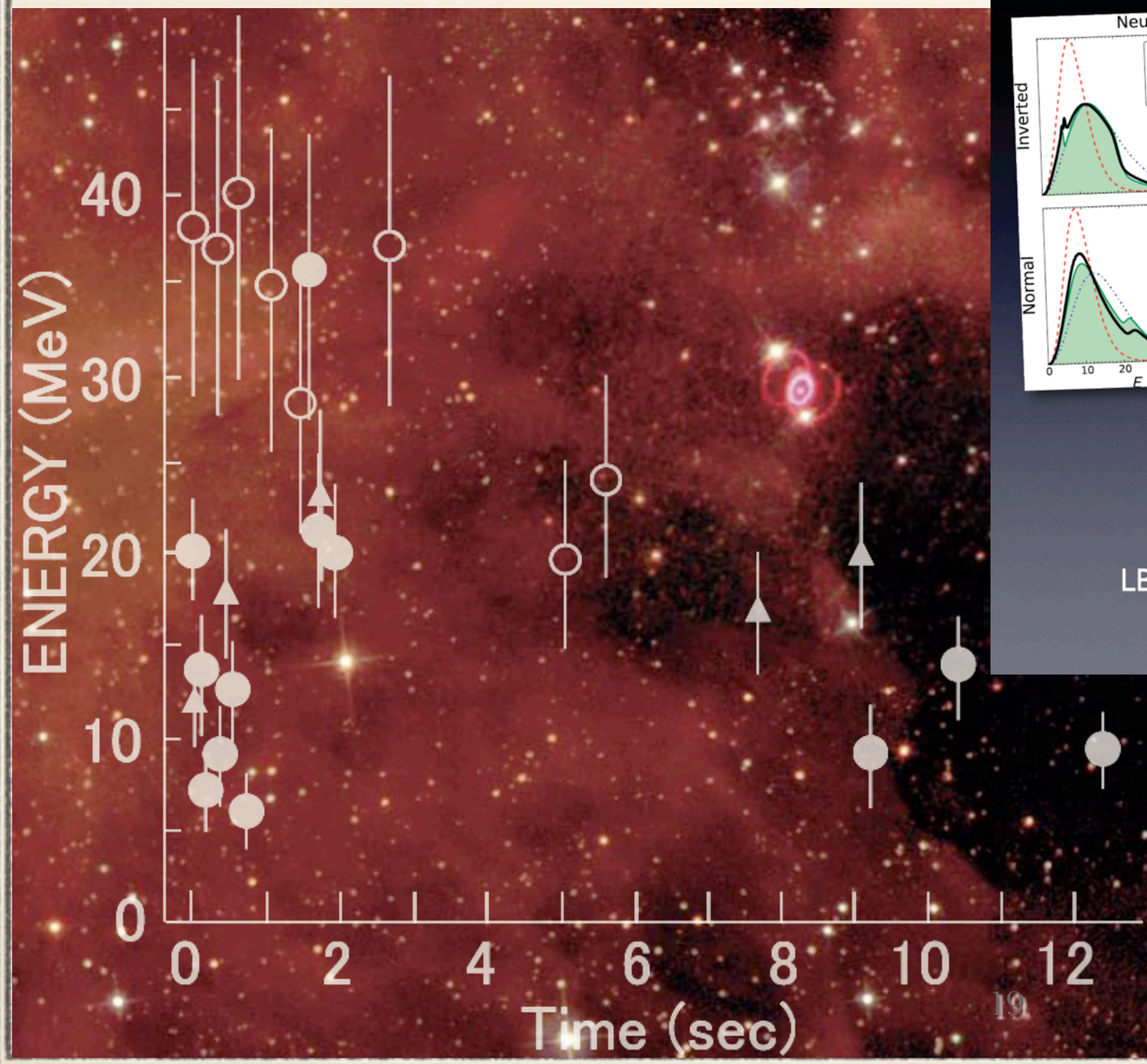
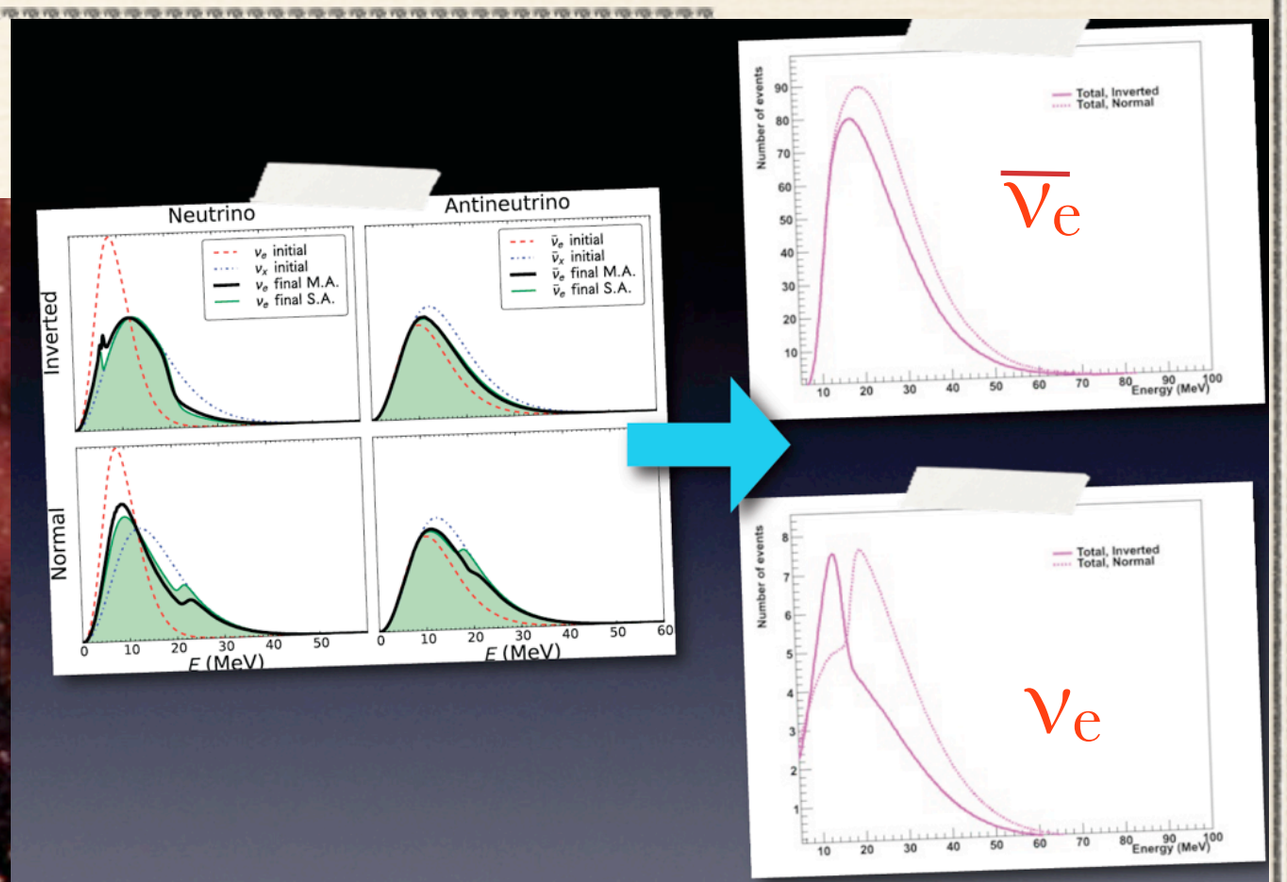
IV Studying Stellar ν Explosions

- only way to study SN core





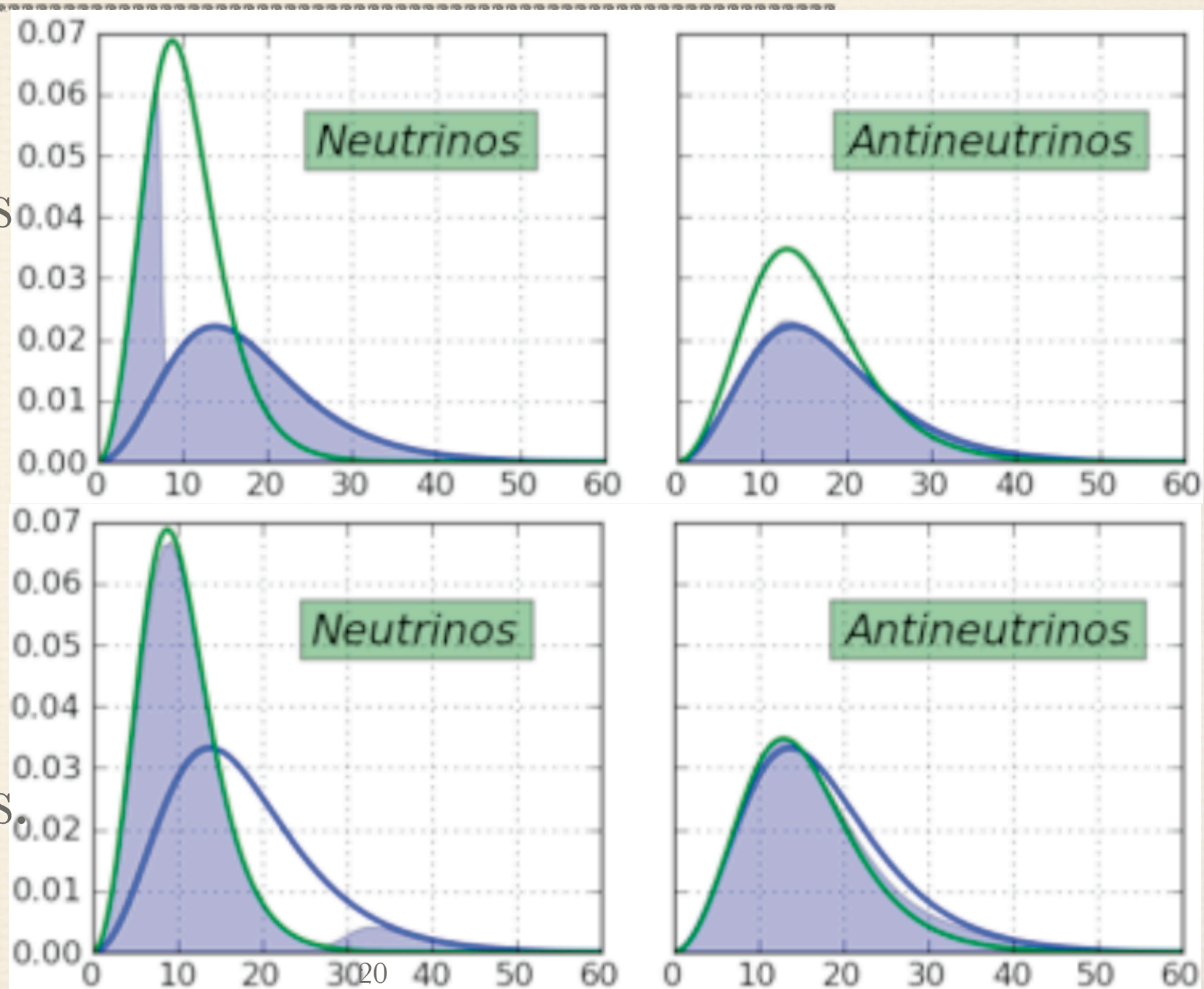
LBNE physics report: SN working group (arXiv:1110.6249)
* spectra by Duan & Friedland
* detector modeling by Kate Scholberg & co

- only way to see ν flavor self-interactions!
- very sparse data

Collective Oscillations: Spectral Swaps

qualitatively different spectral patterns depending on

- emitted spectra
- sign of the hierarchy
- neutrino vs. anti-neutrino



Courtesy A. Friedland, LANL

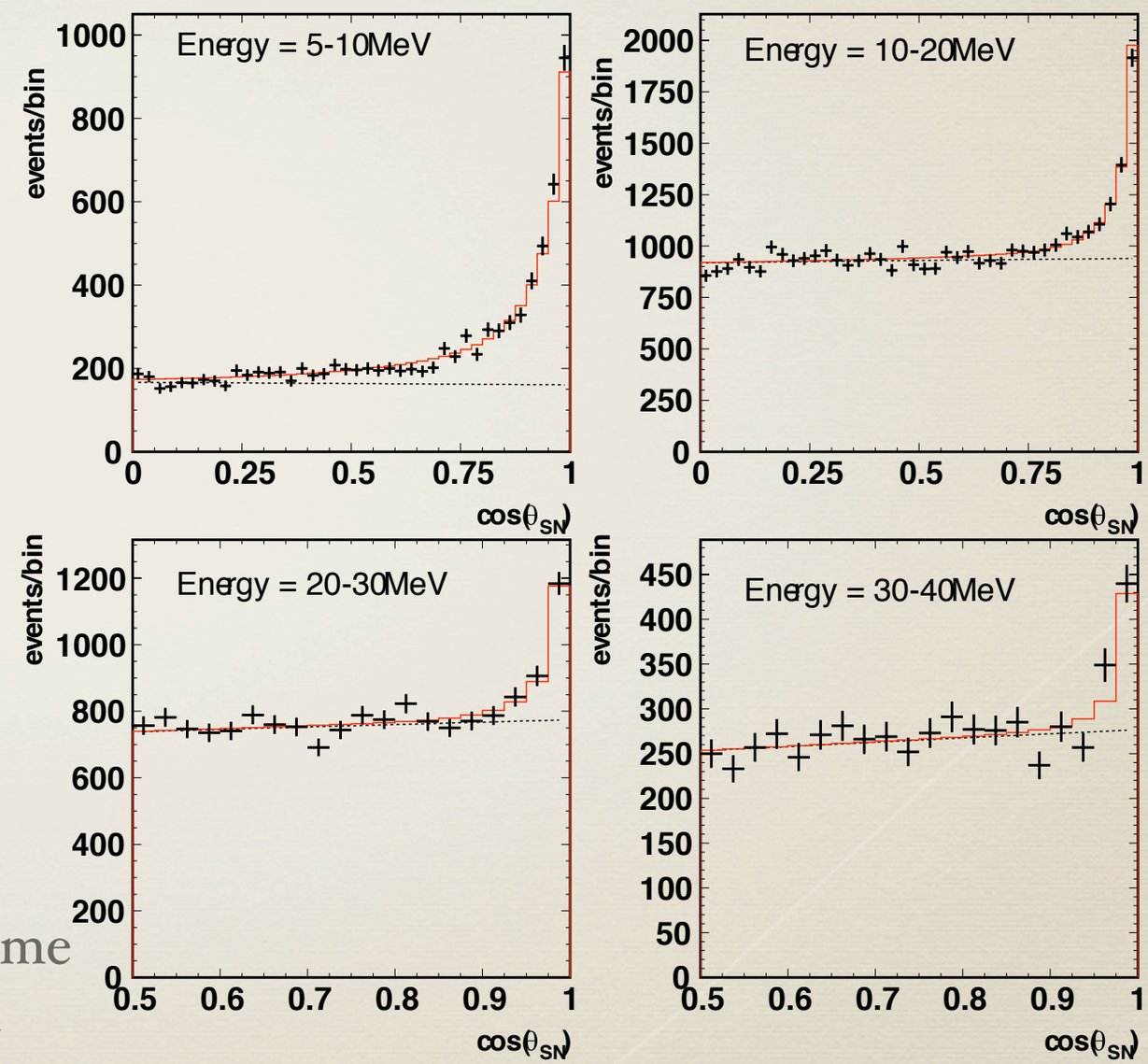
Galactic Supernova Events in Hyper-Kamiokande

@ 10 kpc

Inverse beta ($\bar{\nu}_e + p \rightarrow e^+ + n$)	162,000~228,000
electron scattering ($\nu + e^- \rightarrow \nu + e^-$)	6,000~7,000
ν_e ^{16}O charged current	300~14,000
$\bar{\nu}_e$ ^{16}O charged current	2,000~13,000
total	170,000~260,000

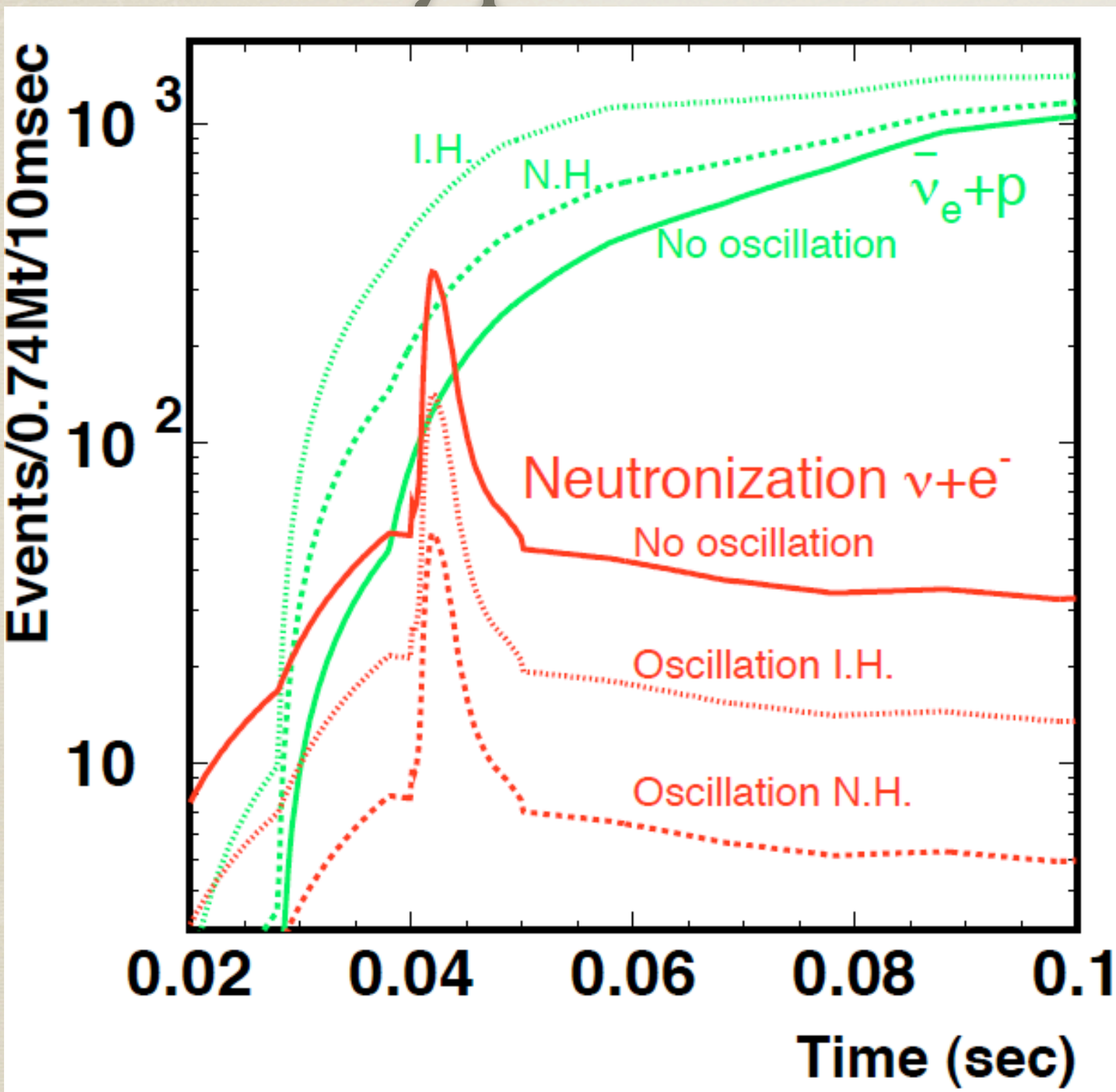
6.5MeV (kin.) energy threshold / 0.74Mton volume
No/NH/IH neutrino oscillation are assumed
spallation B.G. is ignorable.
(~20 events/0.74Mton/18sec.)

angular distributions



Courtesy Y. Koshio, ICRR

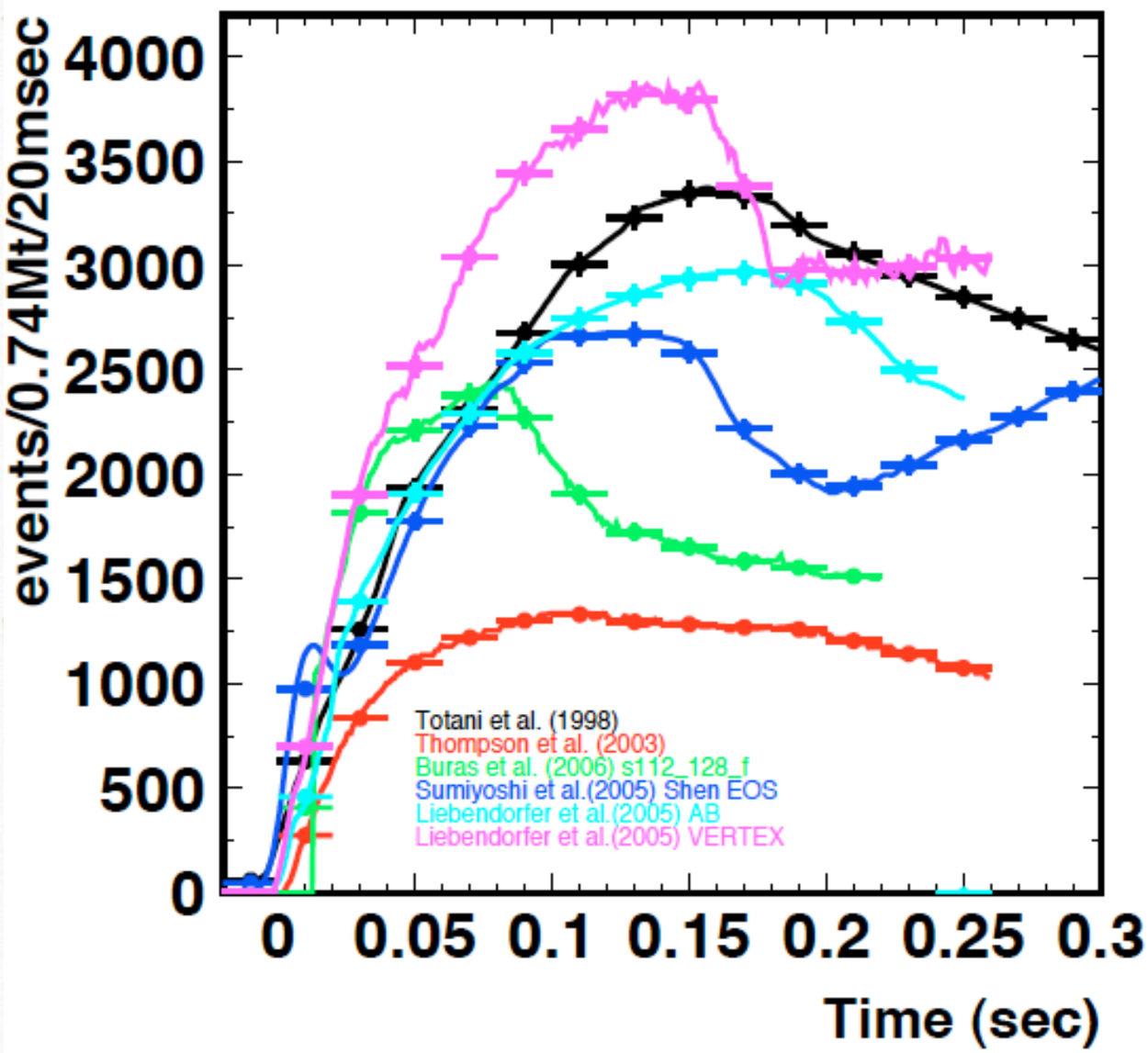
Galactic Supernova in Hyper-Kamiokande

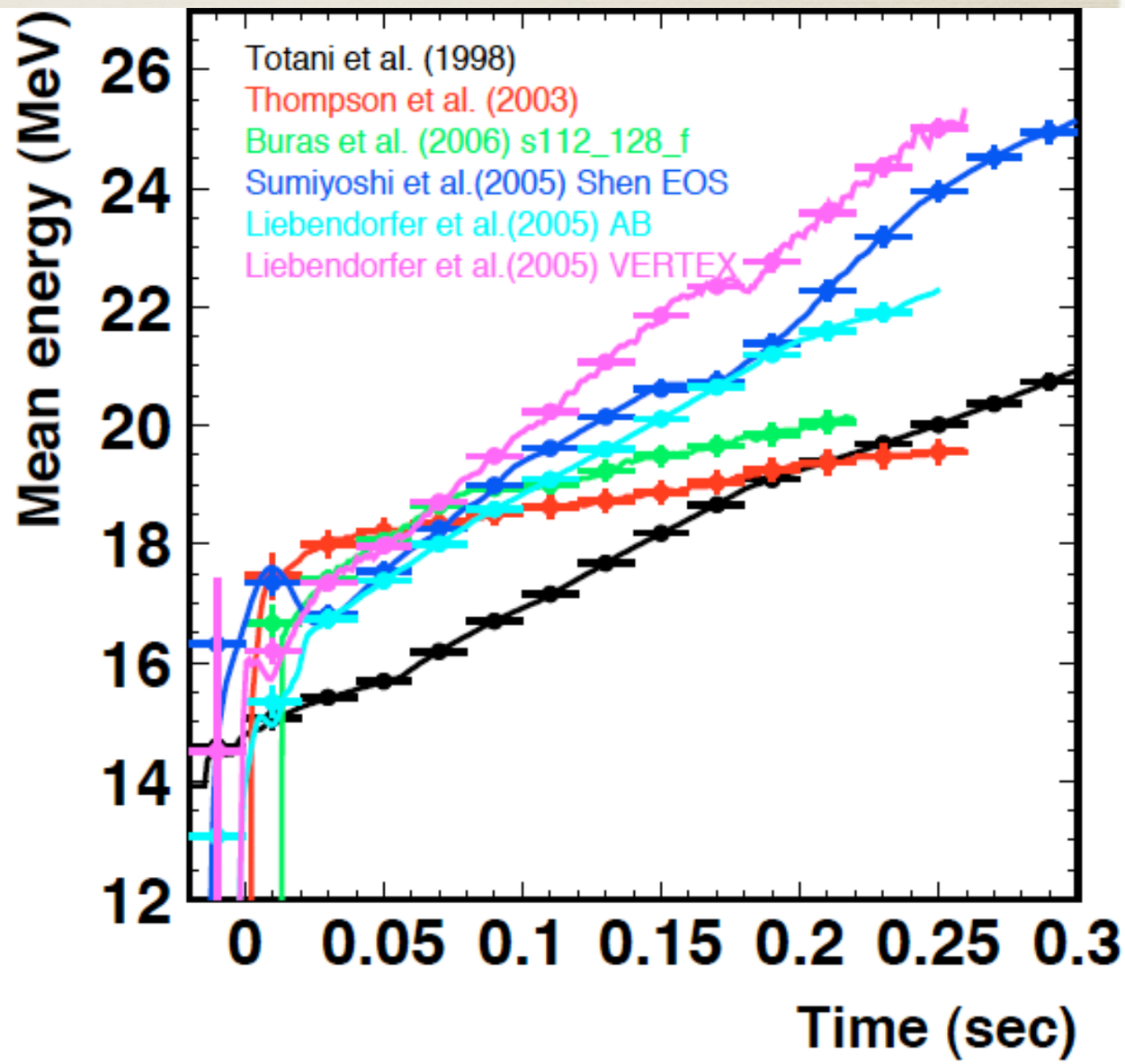


separate elastic scattering via angular distribution; if Gd doped, also tag n captures of inverse β's

Hyper-K LOI

Galactic Supernova in Hyper-Kamiokande

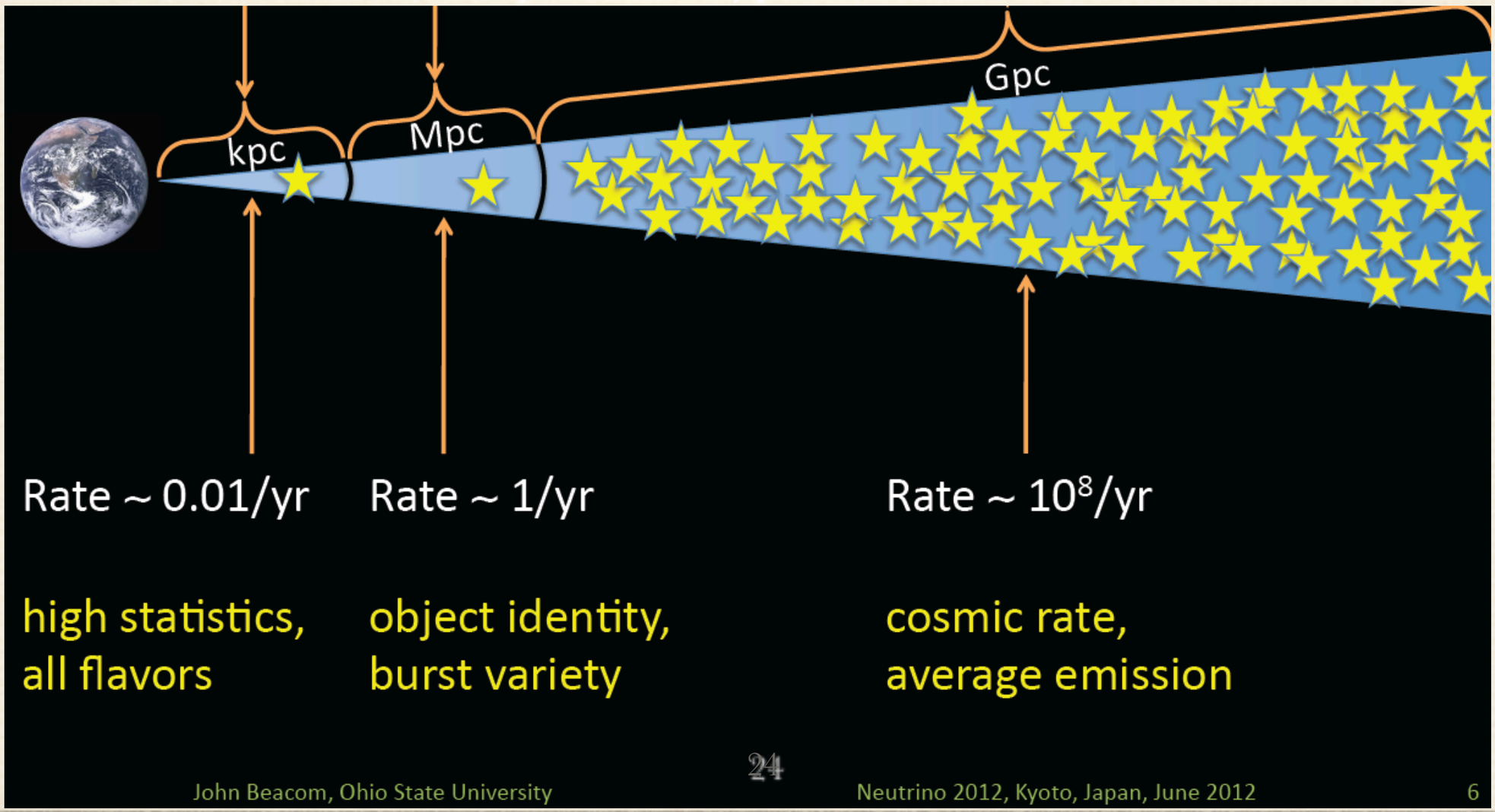




Hyper-K LOI

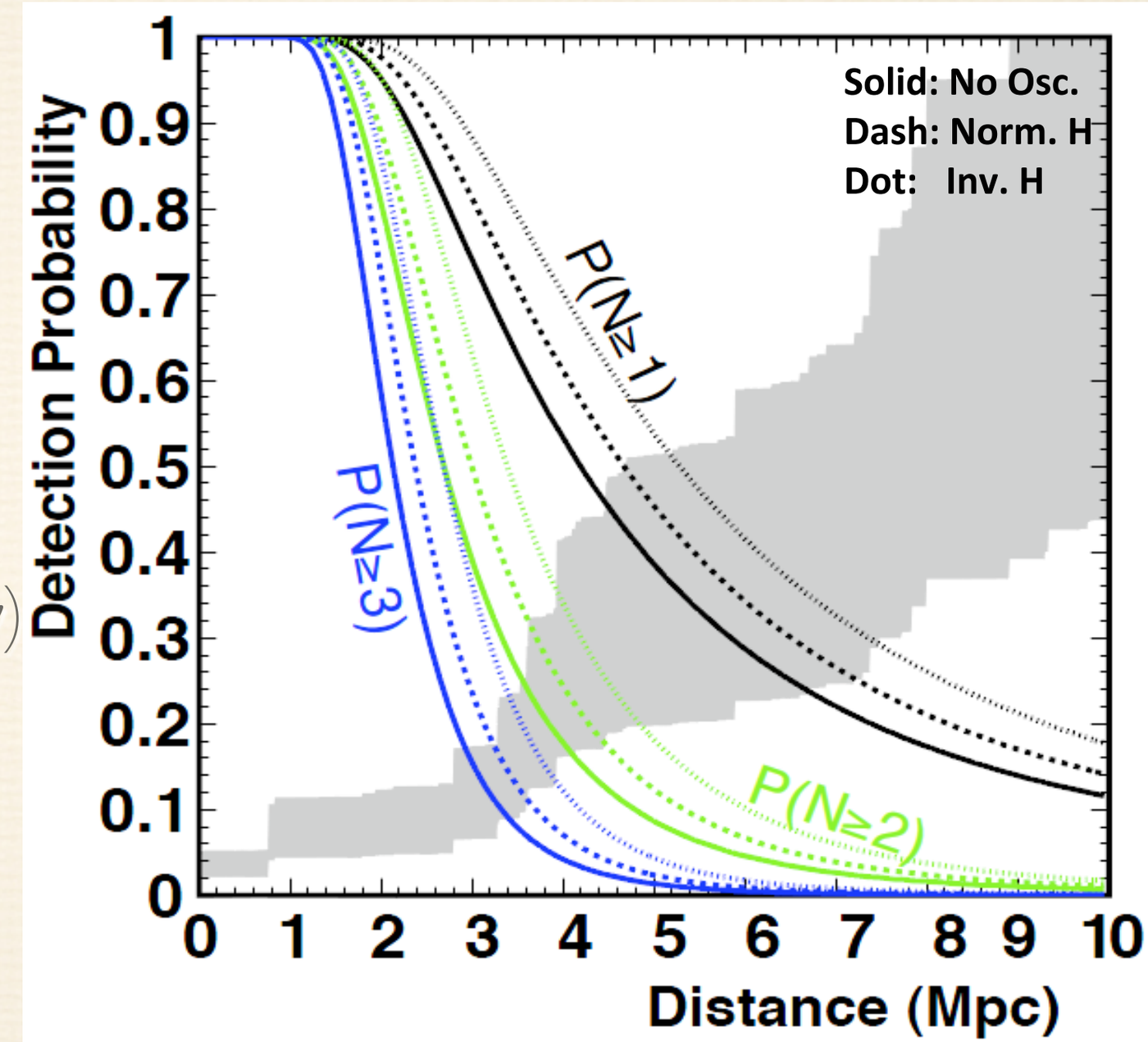
Three Ways To Detect Supernova ν's

- Burst (many events): Super-K, IceCube, KamLAND, Borexino, SNO+, LVD, Nova, ...
- Mini-Burst (~1 event): Hyper-K
- Diffuse (<<1 event): Super-K, Hyper-K



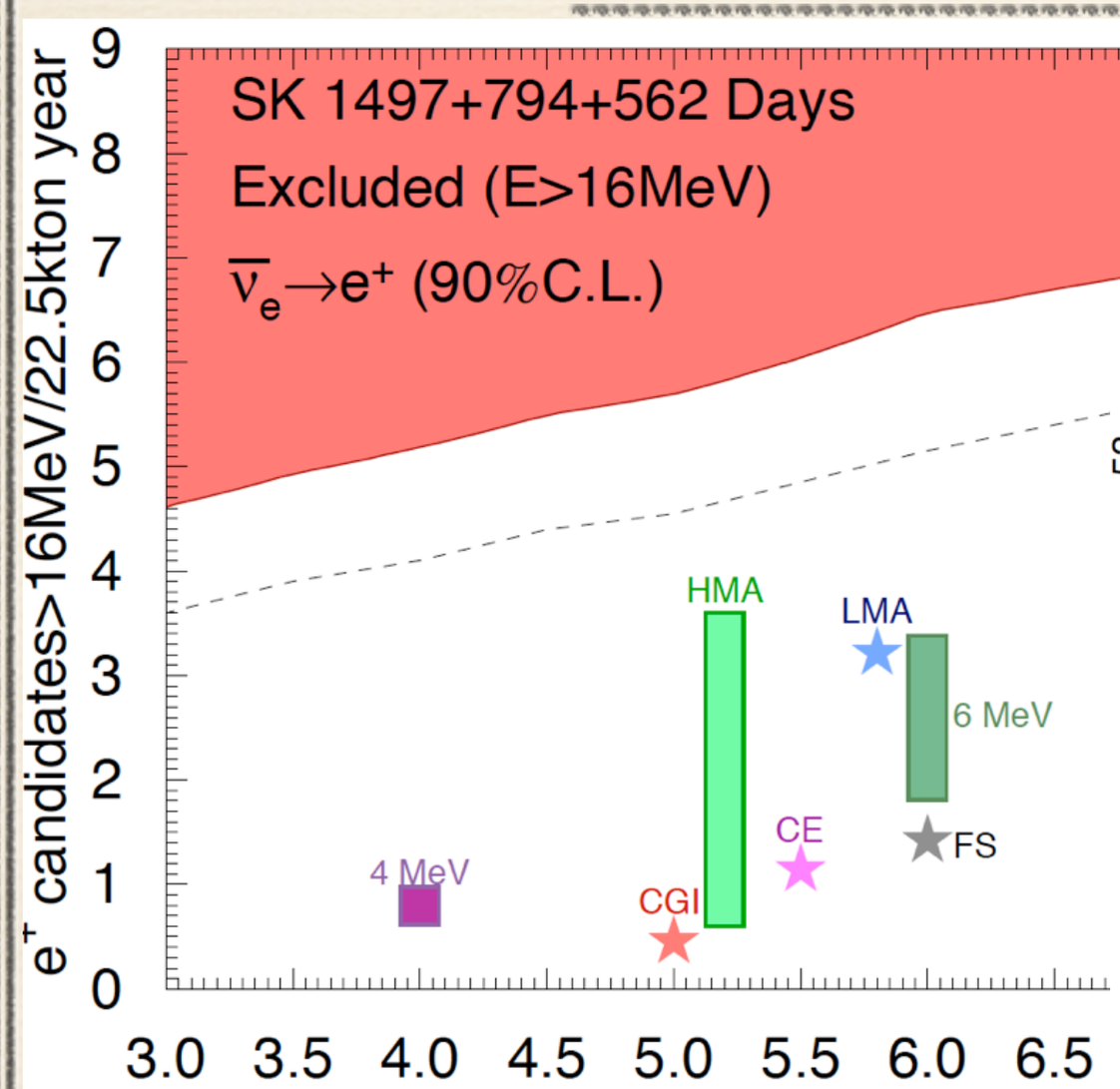
Mini-Bursts in Hyper-K

- grey area: Ando et. al's cumulative supernova rate
- check, if nearby bright transients are core-collapse supernovae (only need one, golden ν)
- reasonable detection probabilities up to ~4 Mpc
- really need 10 Mton detector!

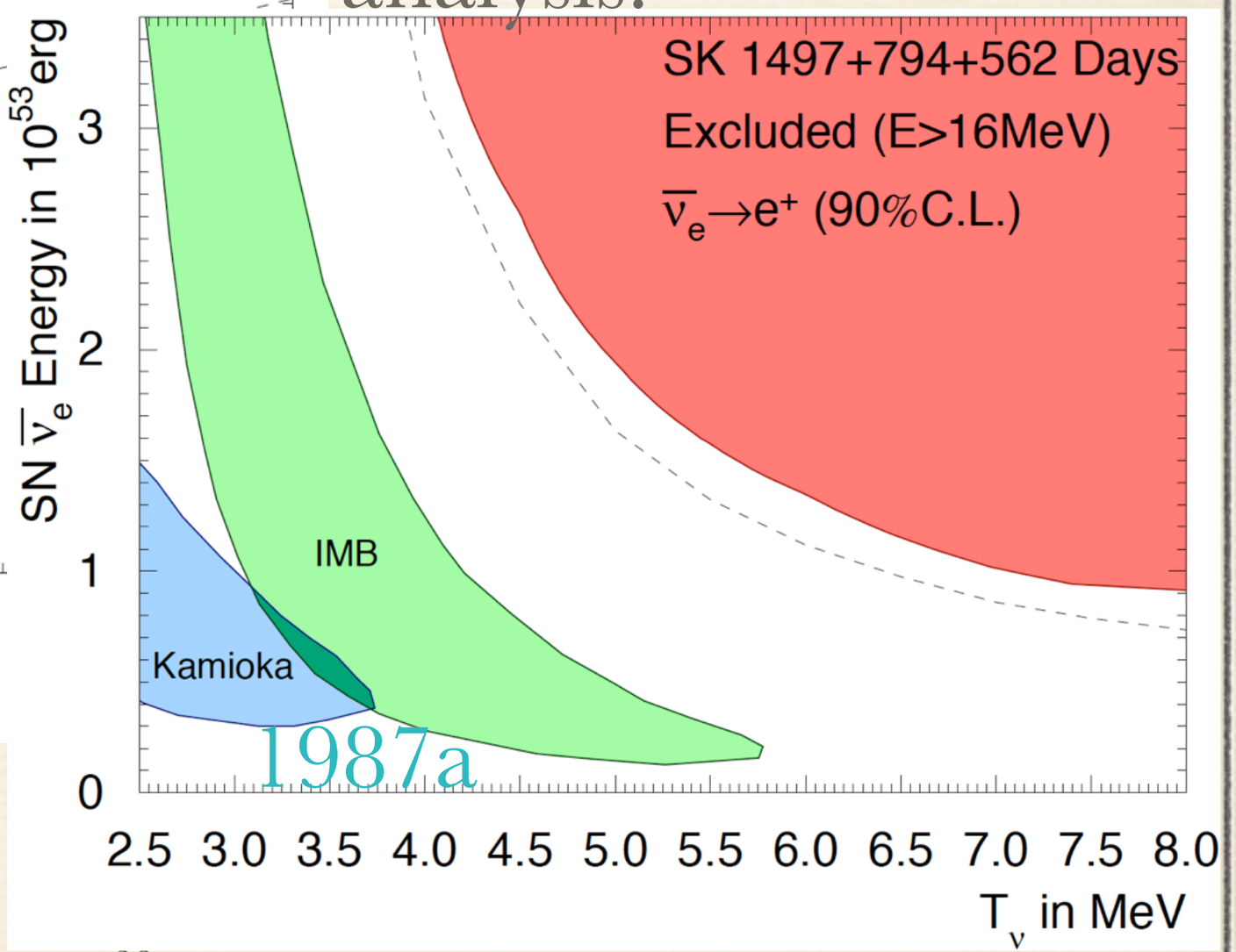


Courtesy Y. Takeuchi, Kobe University

Super-K's Diffuse, Distant SN Search



twice the livetime and much improved analysis!



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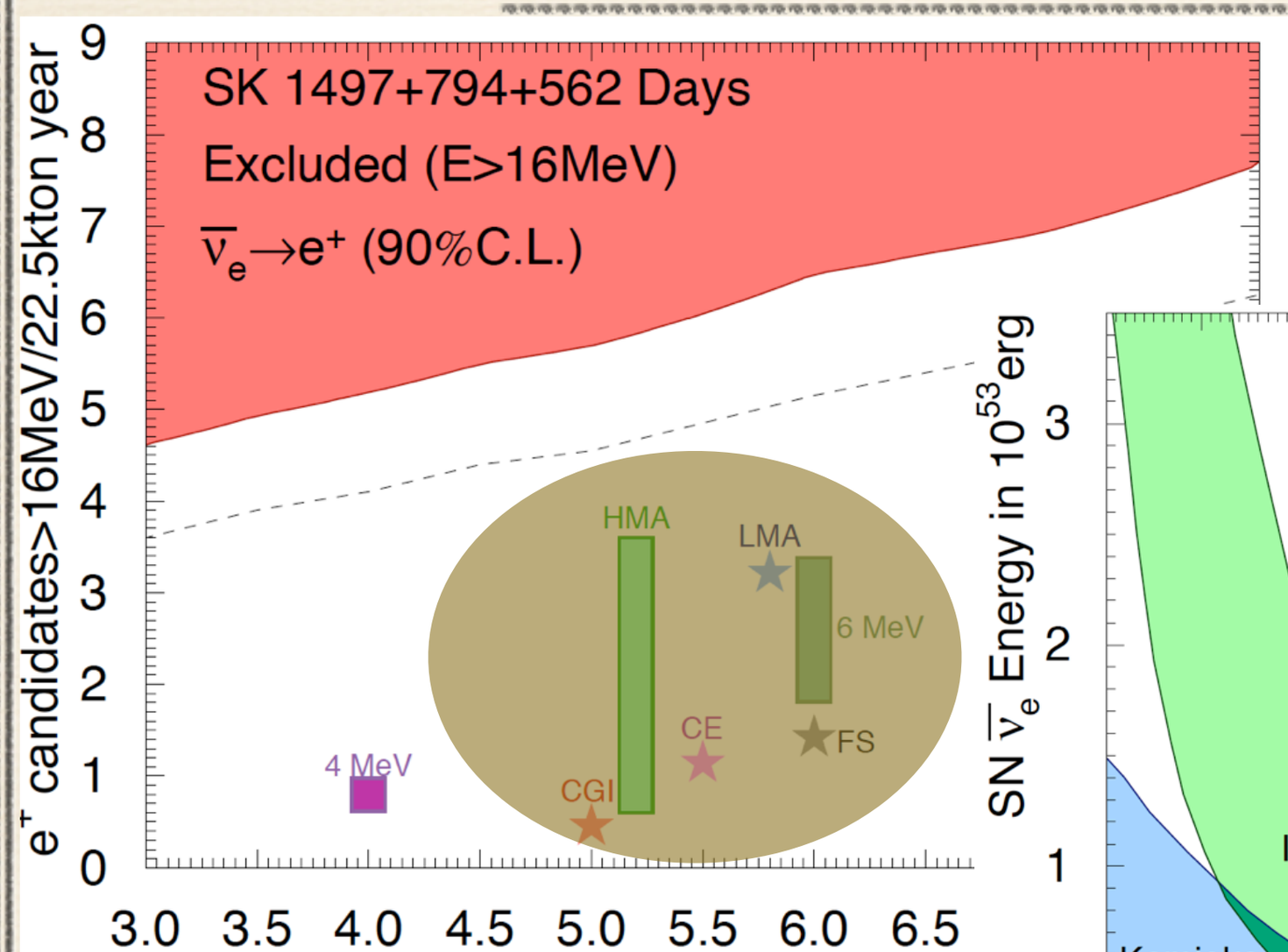

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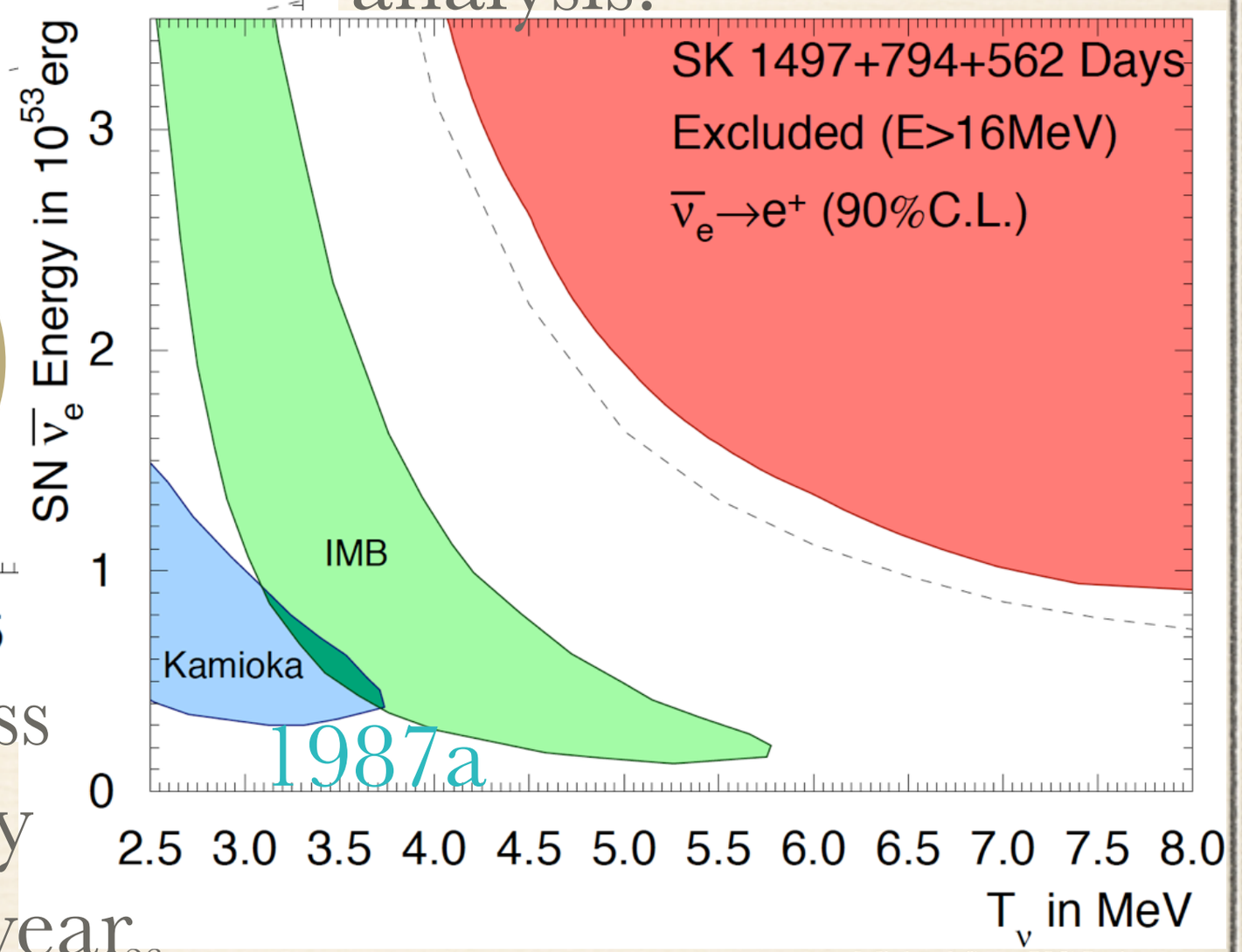

with ~1σ signal-like excess

exclusion is comparatively weak; best fit ~2 events/year

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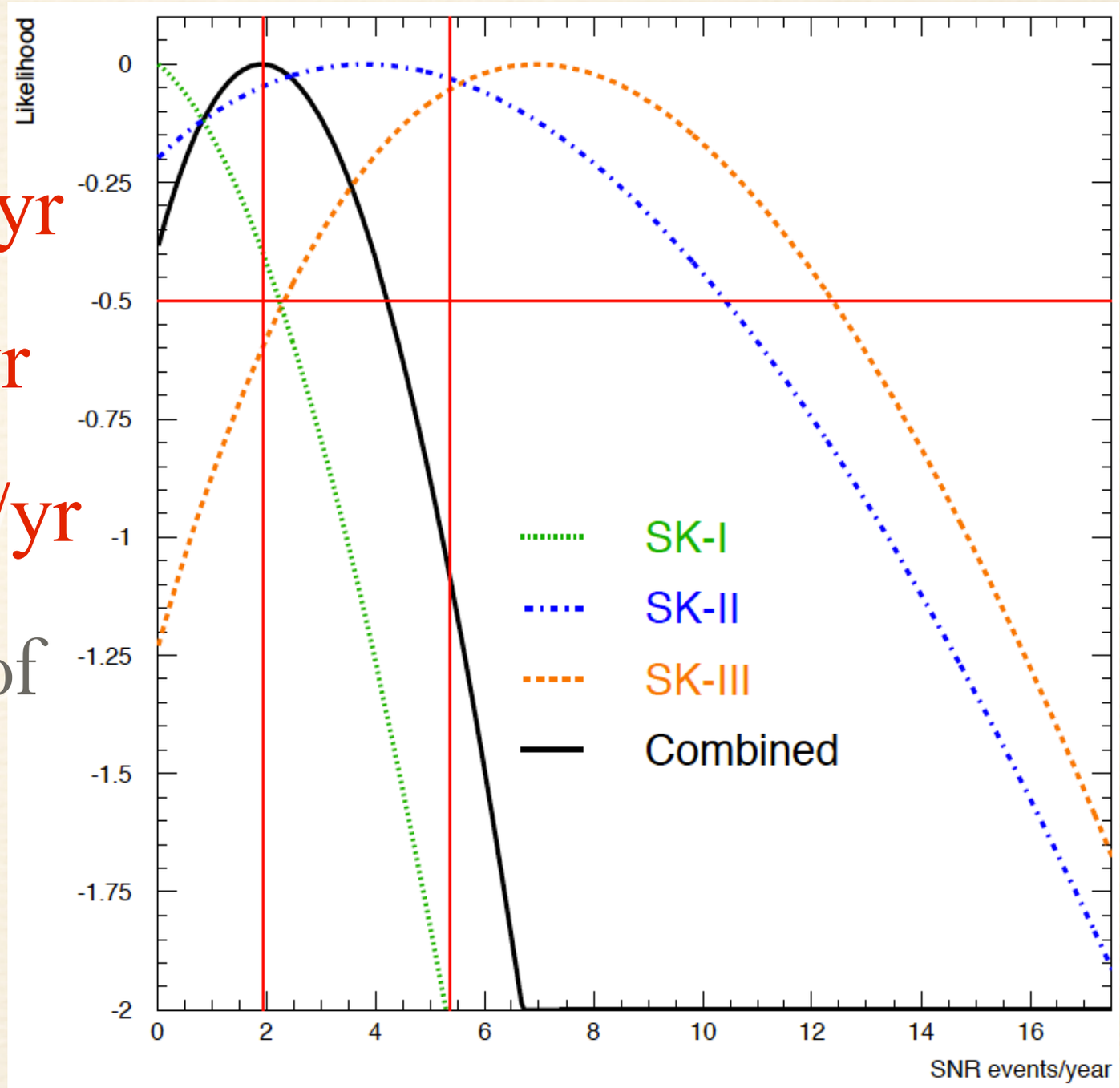
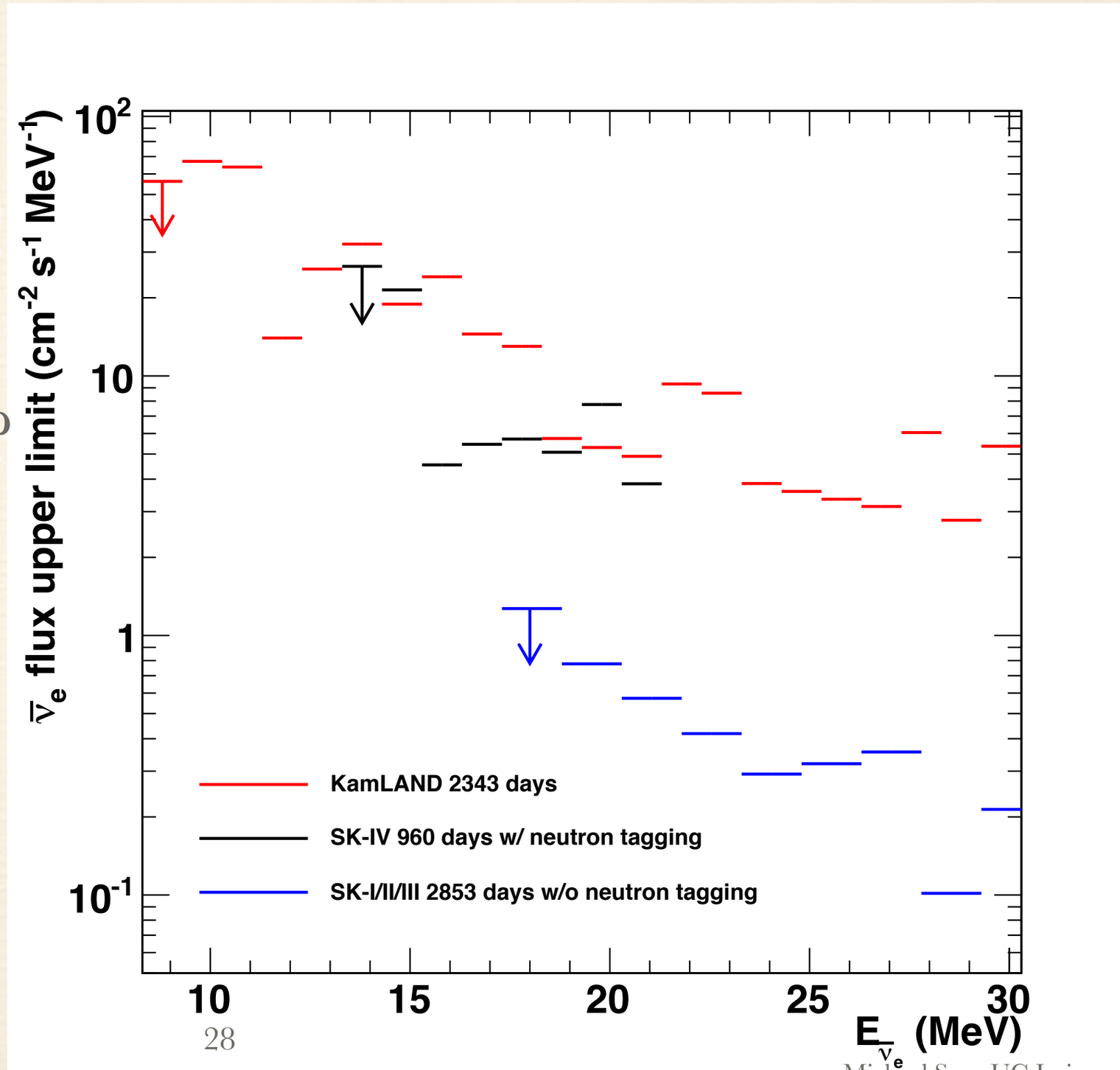
Super-K's Diffuse, Distant SN Search

- SK-I: -0.3±2.3/yr
- SK-II: 4±6.5 events/yr
- SK-III: 7±5 events/yr
- SK I-III: 2±2 events/yr
- SK IV: ~1070 days of unanalyzed data; SK I-IV can probe ~1.65 events/year



Other Techniques for Diffuse Search

- Super-K's n tagging efficiency too poor: need GADZOOKS!
- KamLAND too small: LENA, DB2??
- SNO's limit on ν_e's: <70/(cm^{2}sec) between 22.9 and 36.9 MeV
- no interesting LAr limits on ν_e's in sight



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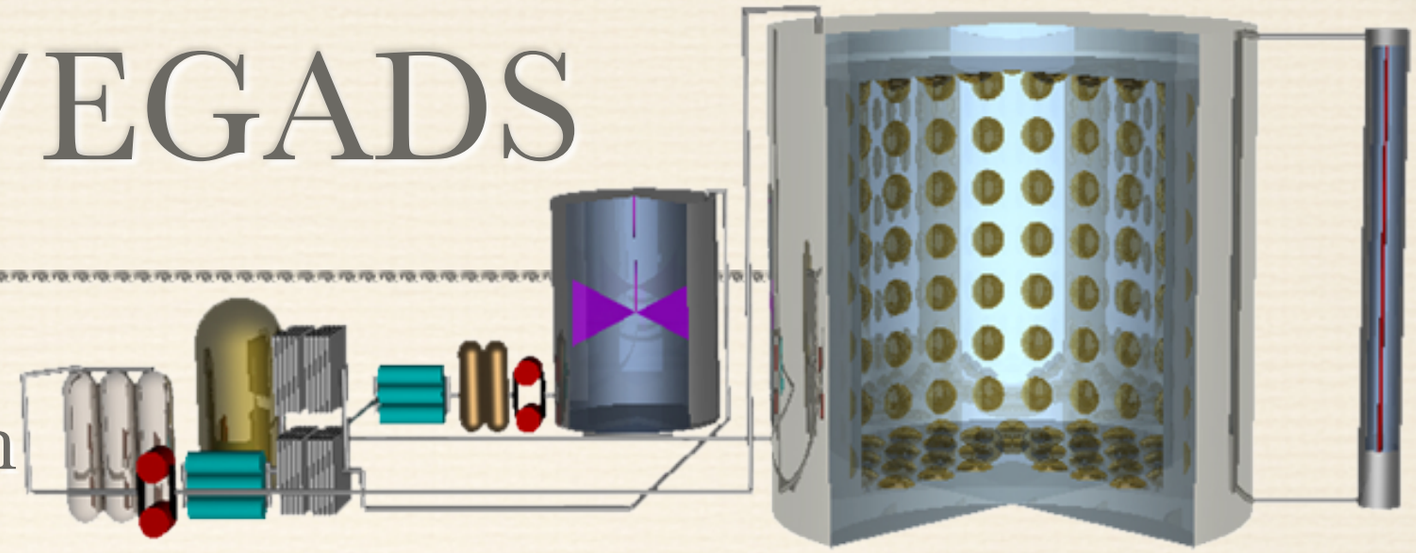
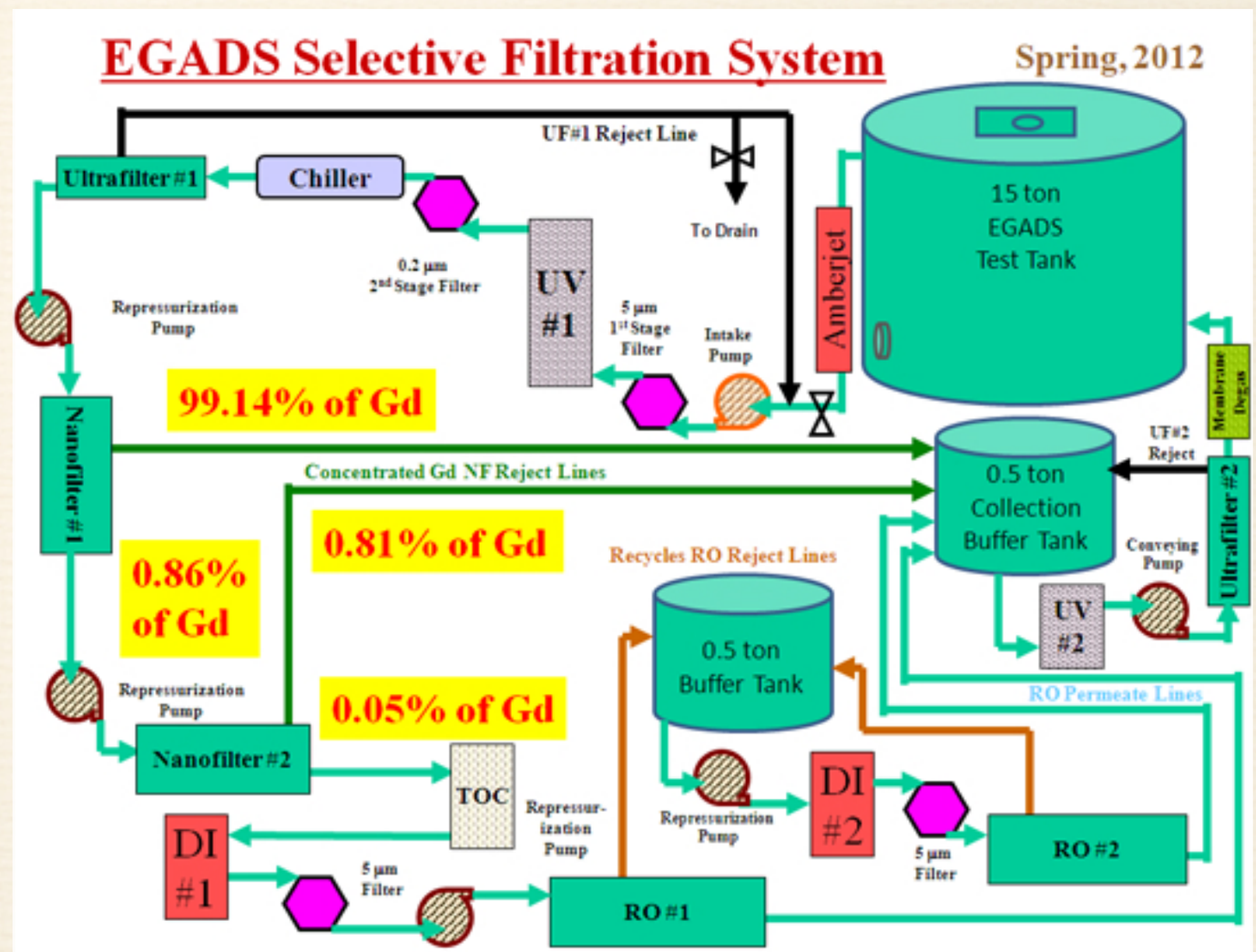
GADZOOKS!/EGADS



- to improve Super-K's n tagging efficiency need n captures on something other than H (a single 2.2 MeV γ): Gd (8 MeV multiple γ's)
- study selective filtration, materiel effects, water transparency etc. in test facility: EGADS
- two tanks: 15t (originally for pre-mixing) and 200t (model detector)



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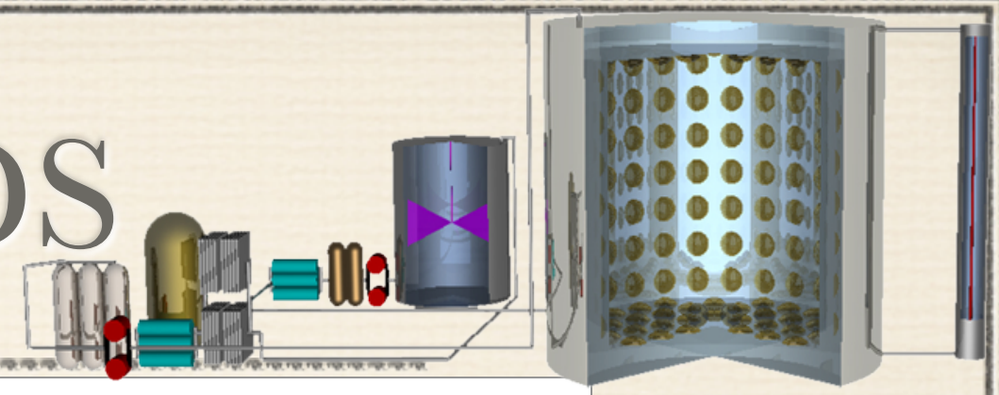

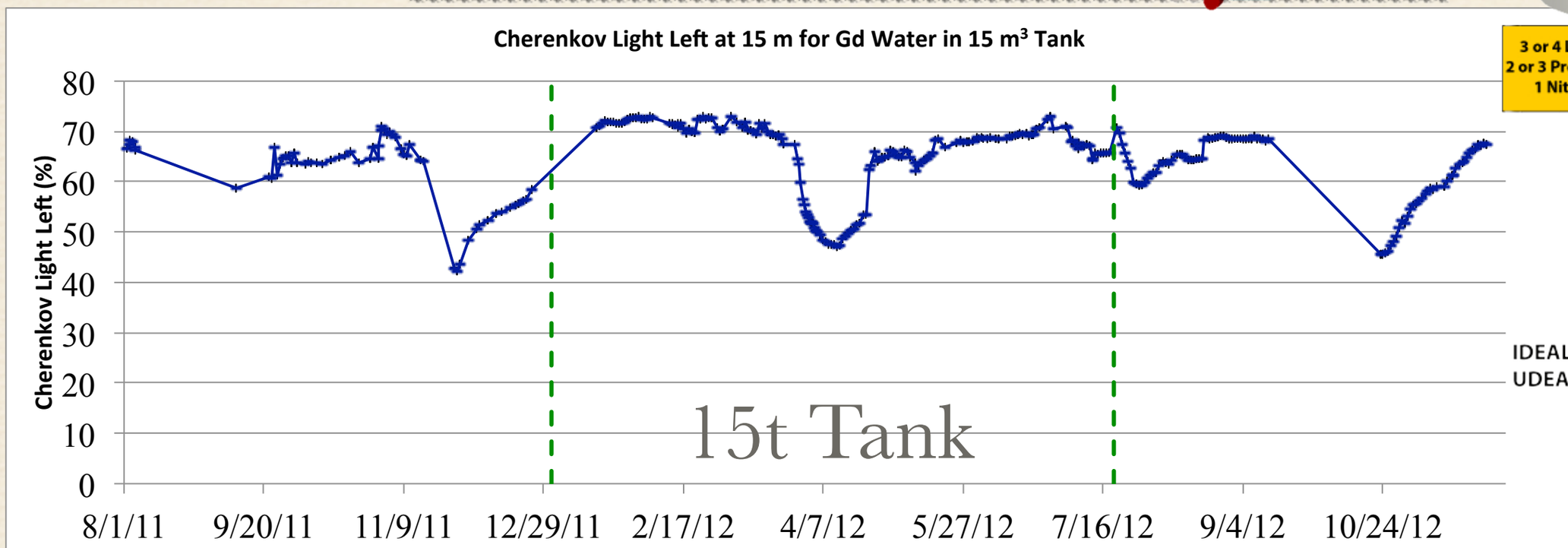

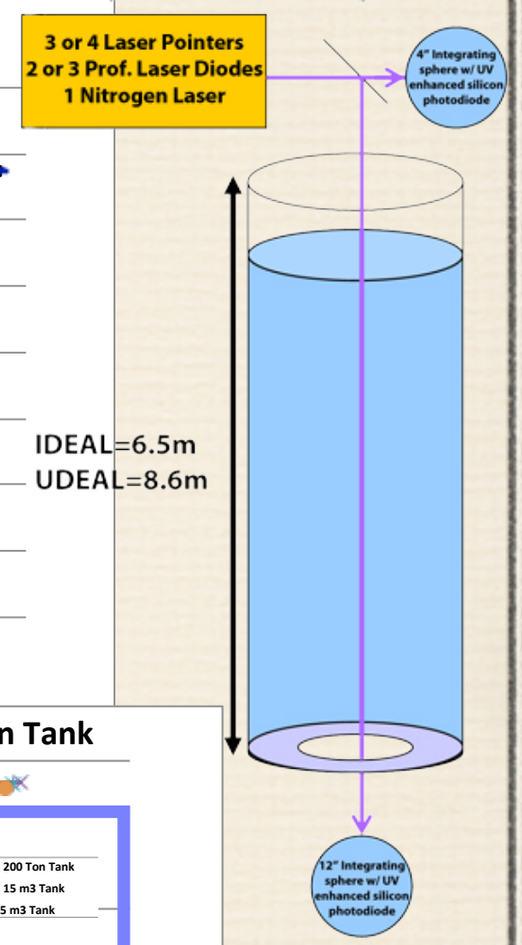

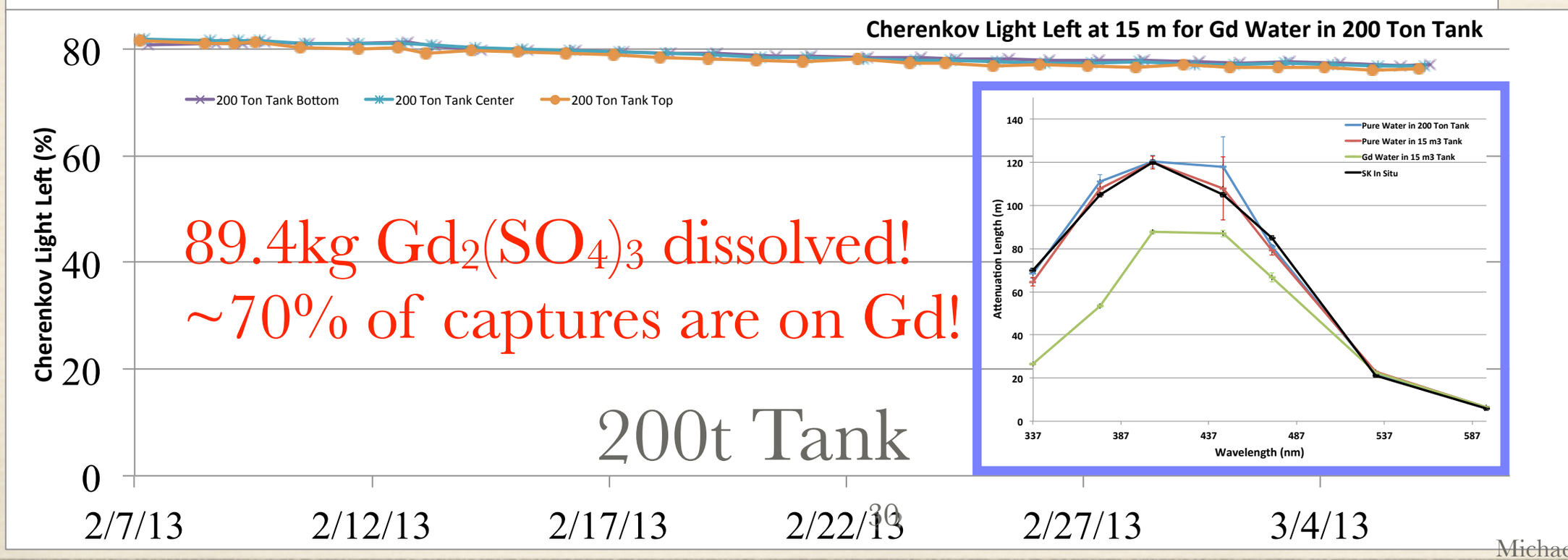

89.4kg $Gd_2(SO_4)_3$ dissolved!

~70% of captures are on Gd!

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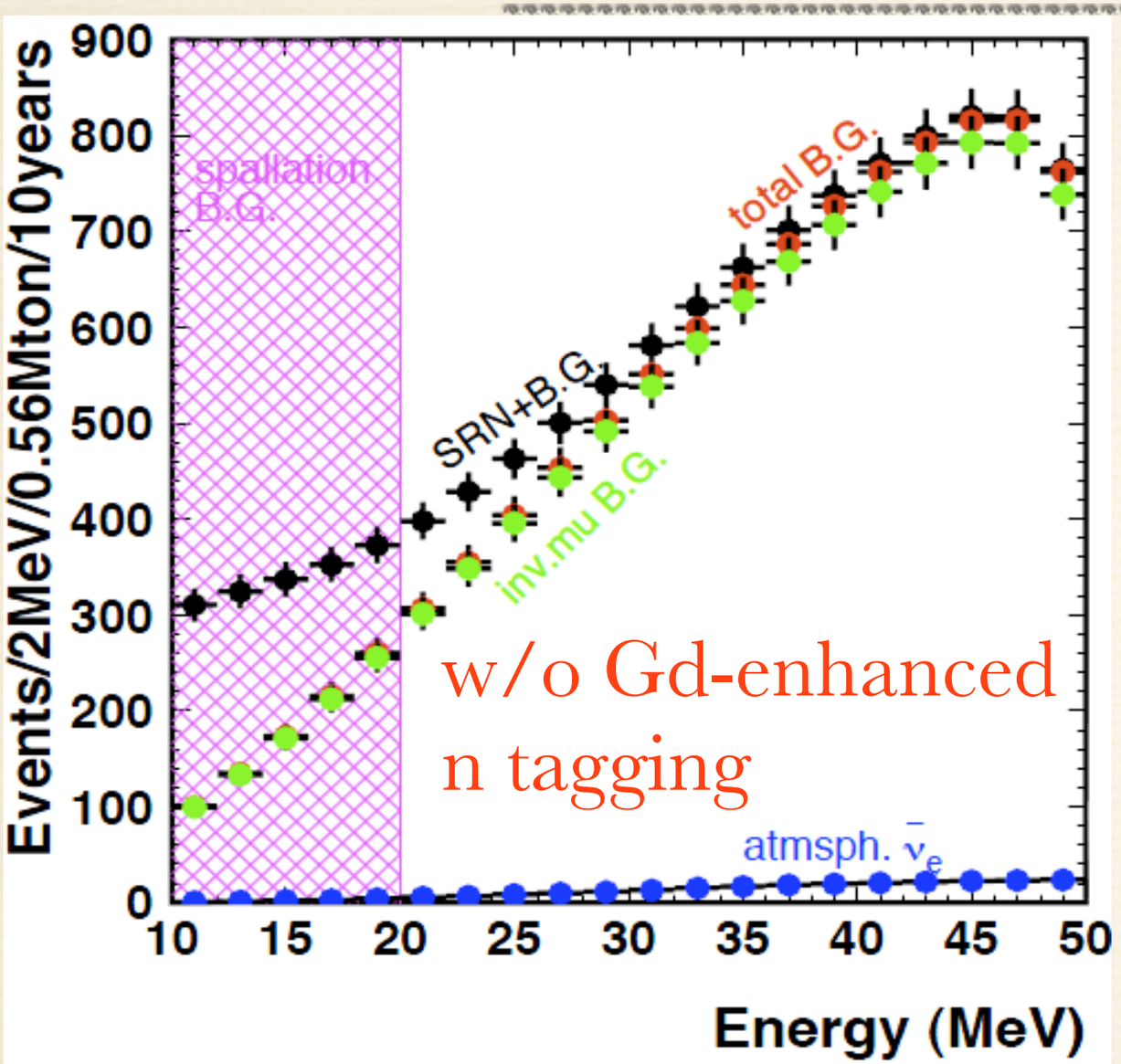
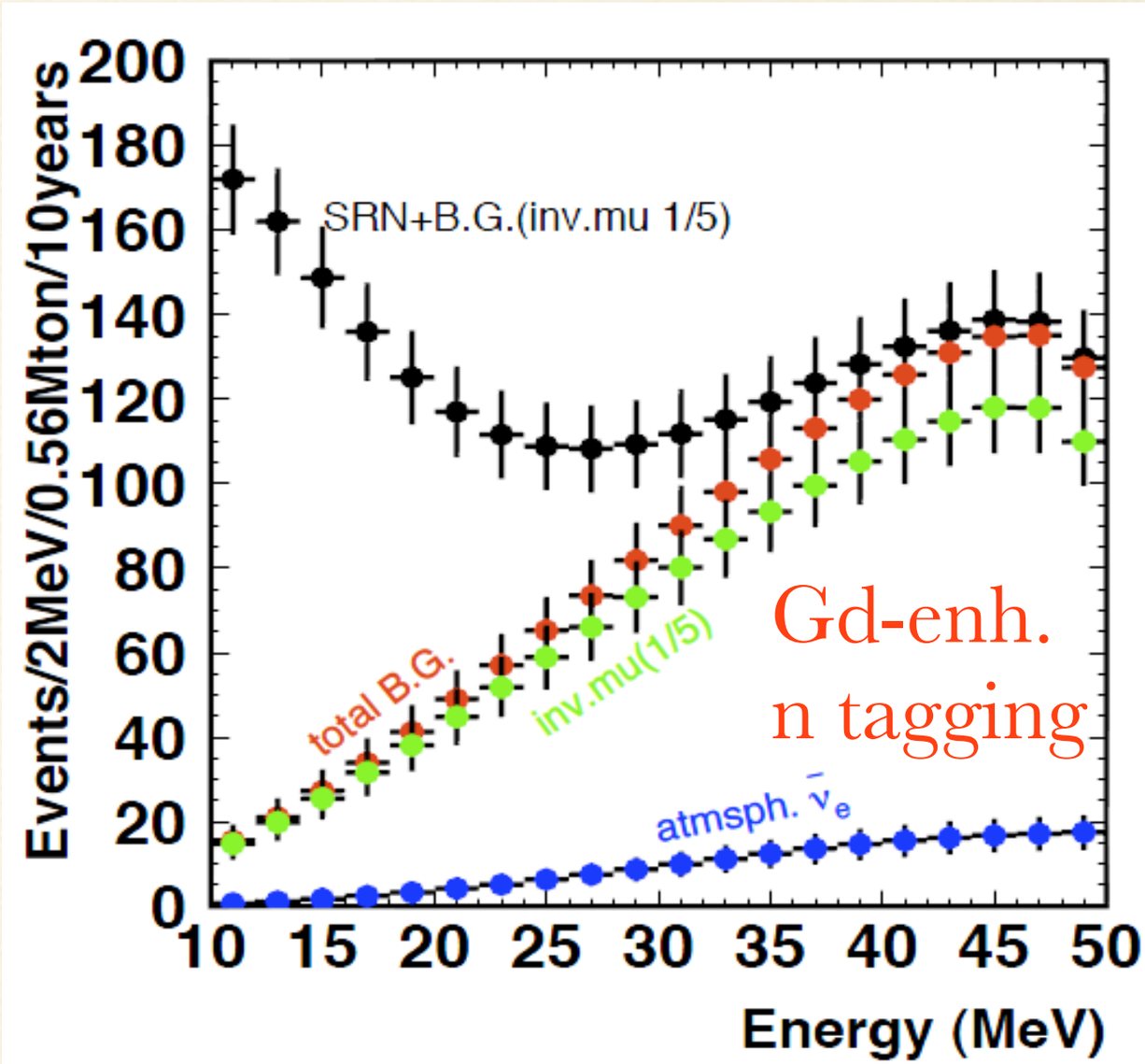
Diffuse Supernova ν's in Hyper-K





- move from discovery of diffuse flux to study of the "typical" supernova
- really needs Gd-enhanced n tagging to work (Hyper-K might be shallow!)

Courtesy Y. Takeuchi, Kobe University

Conclusions

- low energy neutrinos in water offer many interesting physics probes
- current data is from SNO and Super-K; more data (with lower threshold) expected from Super-K, and perhaps Hyper-K (?)
- observe SN neutrino burst with very high statistics, if SN is in the milky way
- Hyper-K could see extragalactic SN neutrino bursts
- Super-K's diffuse SN neutrino limit is tantalizingly close to prediction
- with Gd doping, Super-K should discover diffuse SN neutrinos
- Hyper-K with Gd doping will study diffuse SN neutrinos and obtain typical SN neutrino emission spectra