Supernova Relic Neutrinos at Super-Kamiokande

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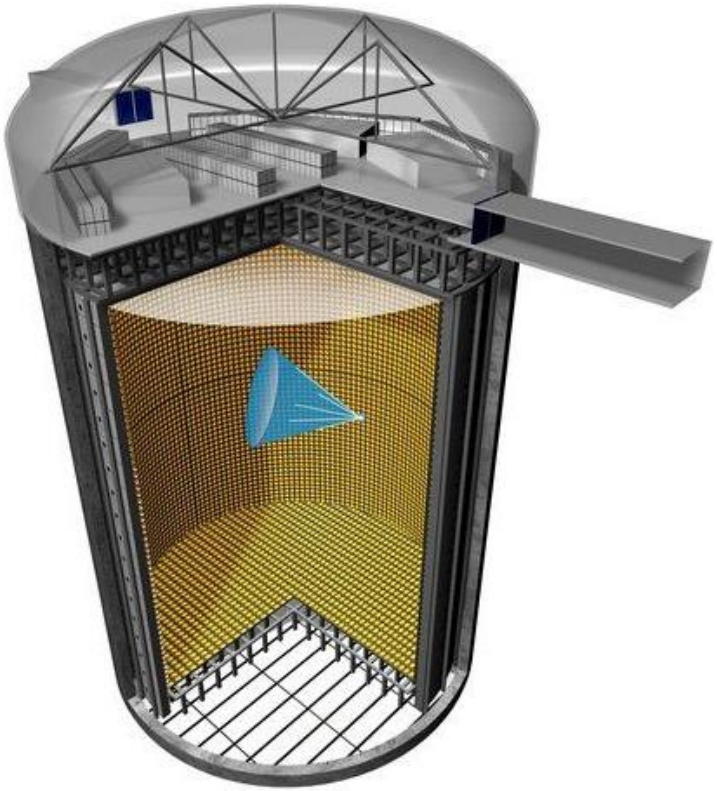
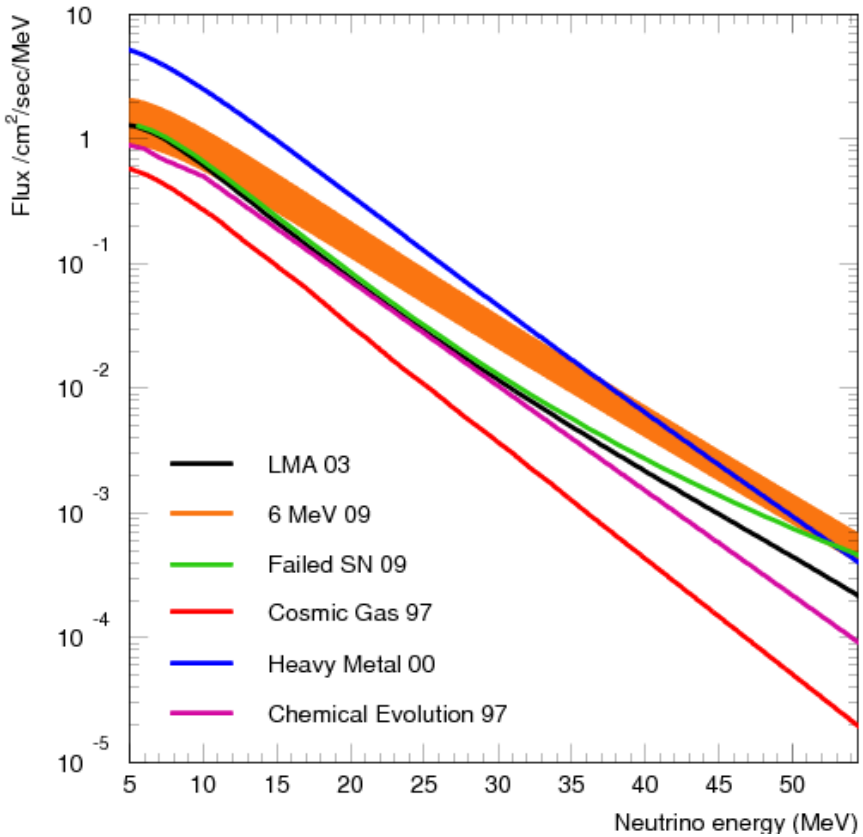
Super-Kamiokande (SK)

SK is 50 kton water Cherenkov detector in the Kamioka mine, Japan (2700 mwe). It began operation in 1996. The data is divided into segments: SK-I, II, III, and IV. This study focuses on SK-I/II/III.



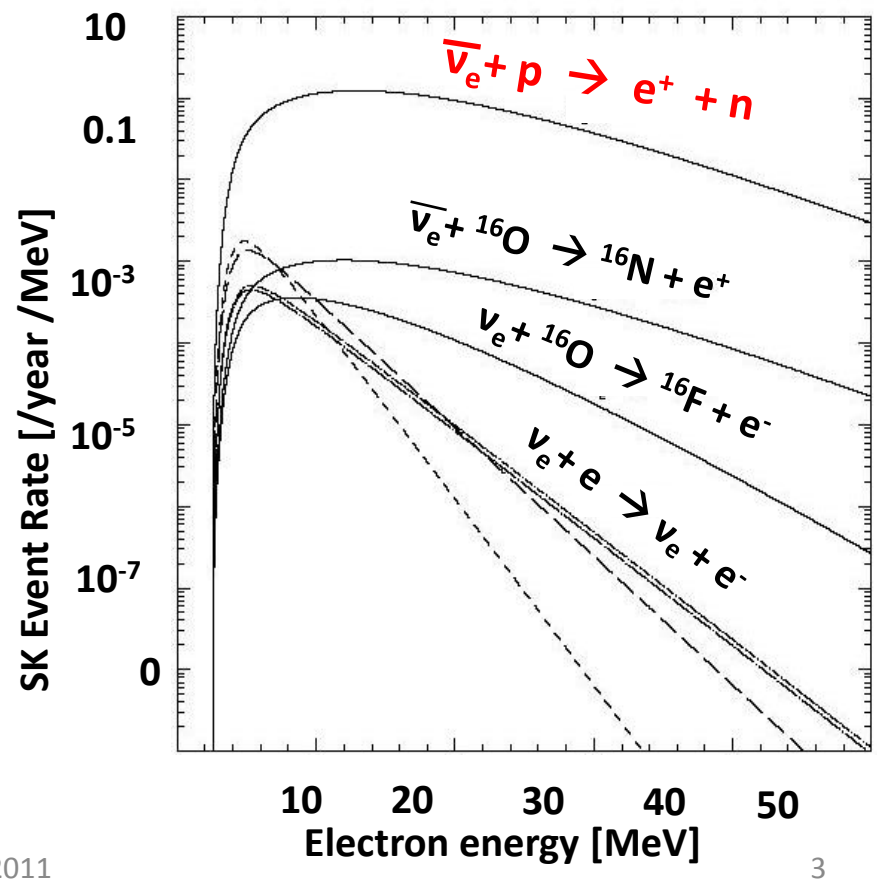
Period	Live time	# ID PMTs / % coverage	Comment
SK-I	1497 days	11146 / 40%	Experiment start
SK-II	791 days	5182 / 19 %	After accident
SK-III	562 days	11129/ 40%	After repair
SK-IV	running now	11129/ 40%	New electronics

The SN1987A neutrinos are the only neutrinos ever detected from outside the solar system!

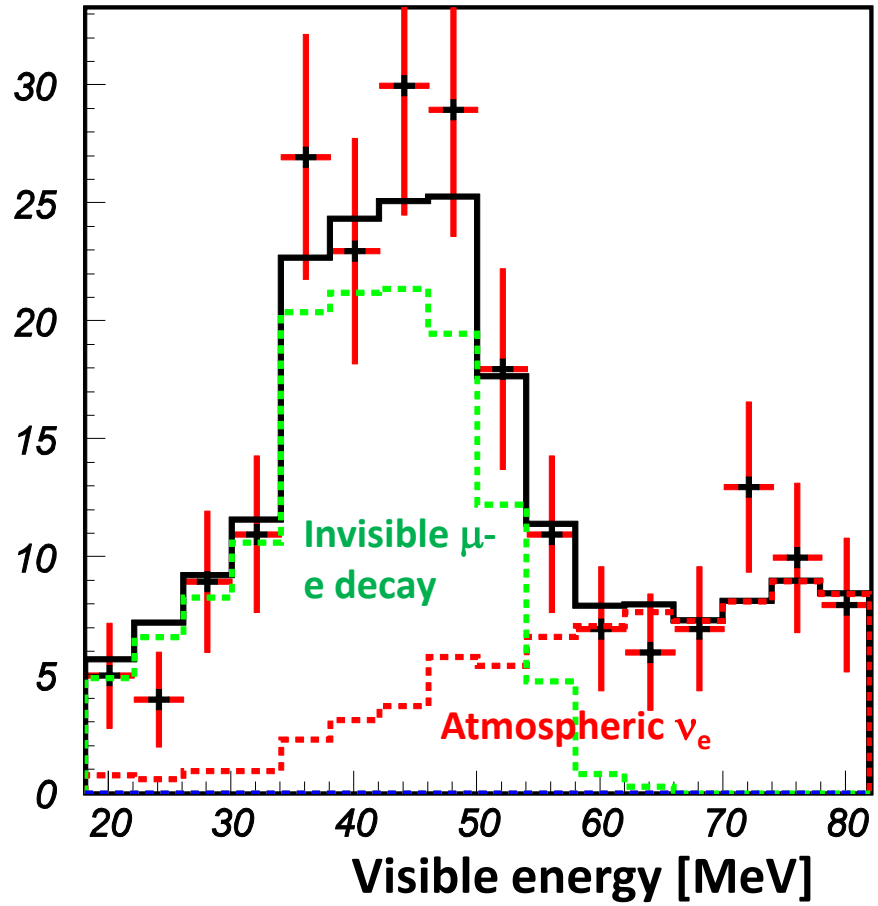


Supernova Relic Neutrinos (*SRN*s) are a diffuse neutrino signal from all past supernovae.

At Super-Kamiokande (SK), we can look for SRNs without waiting for a galactic supernova. The main interaction mode for SRNs in SK is charged current quasi-elastic interaction (inverse β decay)



- SRN rate in SK is low (few a year expected), and difficult to search for among the numerous backgrounds
- Most backgrounds can be fully eliminated:
  - Spallation
  - Solar neutrinos
  - radioactive backgrounds
- Some must be modeled:
  - Atmospheric ν backgrounds
- World's current best flux limit from 2003 SK study
- This study is <u>now improved</u>



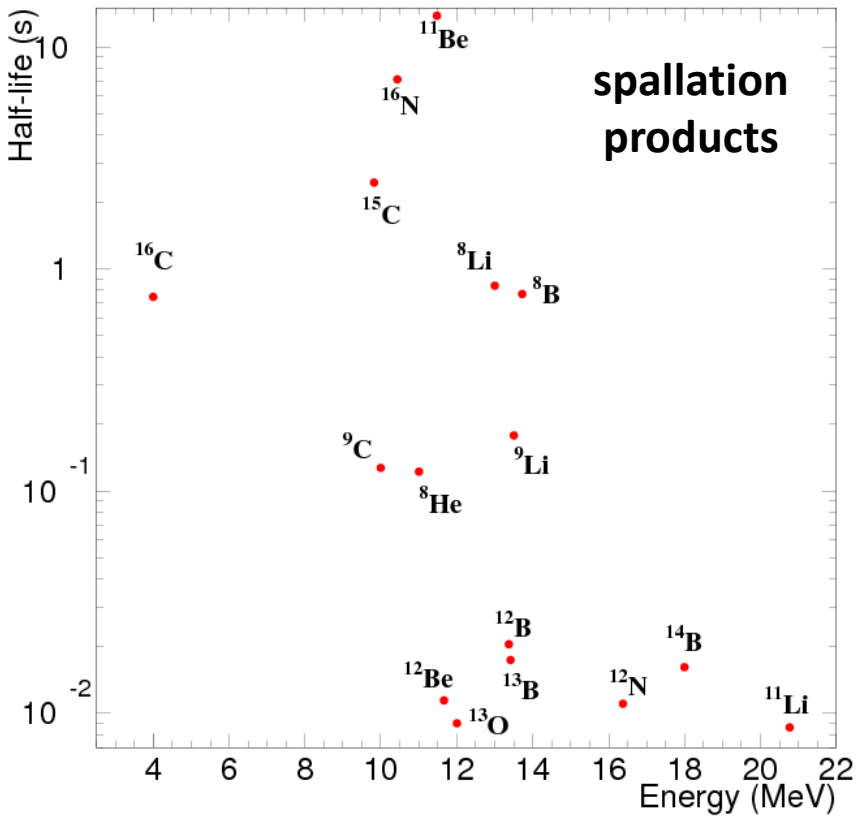
M. Malek, et al, Phys. Rev. Lett. 90, 061101 (2003)

2003 final data sample. SRN events were searched for using a χ^2 fit, in an energy window of 18-82 MeV, with two modeled atmospheric backgrounds

Spallation cut improvement

- Cosmic ray muon spallation occurs < ~21 MeV; more as E lowers
- Spallation determines lower energy threshold
- Must be spall 'free'
- Cut highly improved
- E threshold now lowered from 18→ 16 MeV
- Efficiency of 2003 data:

  64% → 91%



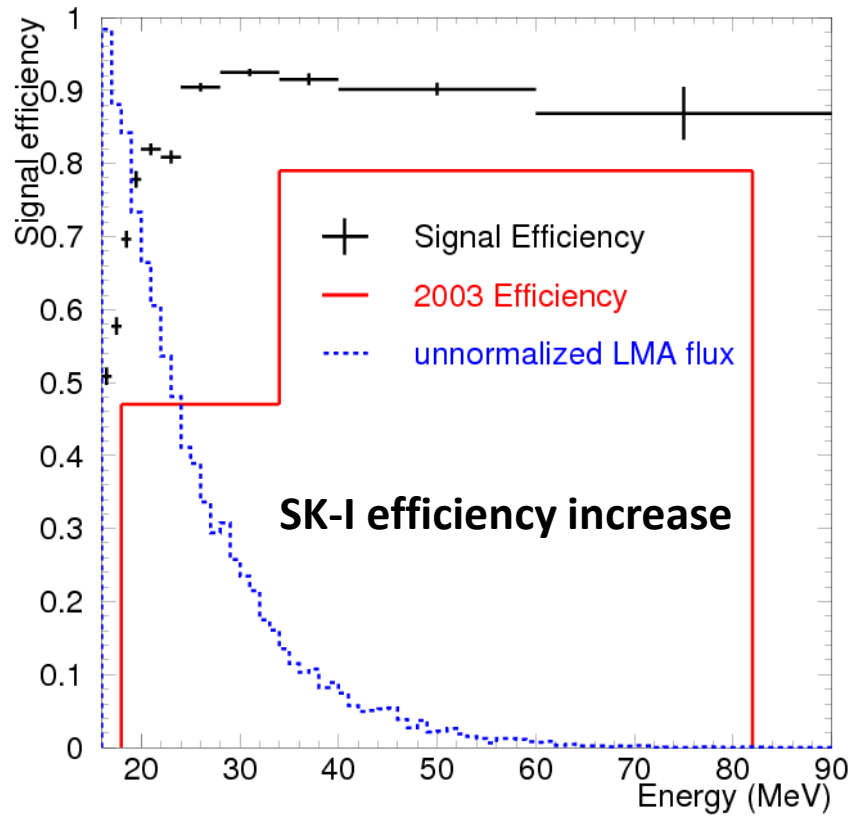
Improvements:

New method of tracking spallation along muon track! (with dE/dx info)

New tuning, better fitters, muon ID

Other improvements in event selection:

- More data
  - (1497 → 2853 live days)
- Lower energy threshold
  - (18 MeV → 16 MeV)
  - SK-II E thresh: 17.5 MeV
- More improved cuts:
  - Solar neutrino cut
  - radioactivity cut
  - new pion cut
  - many more



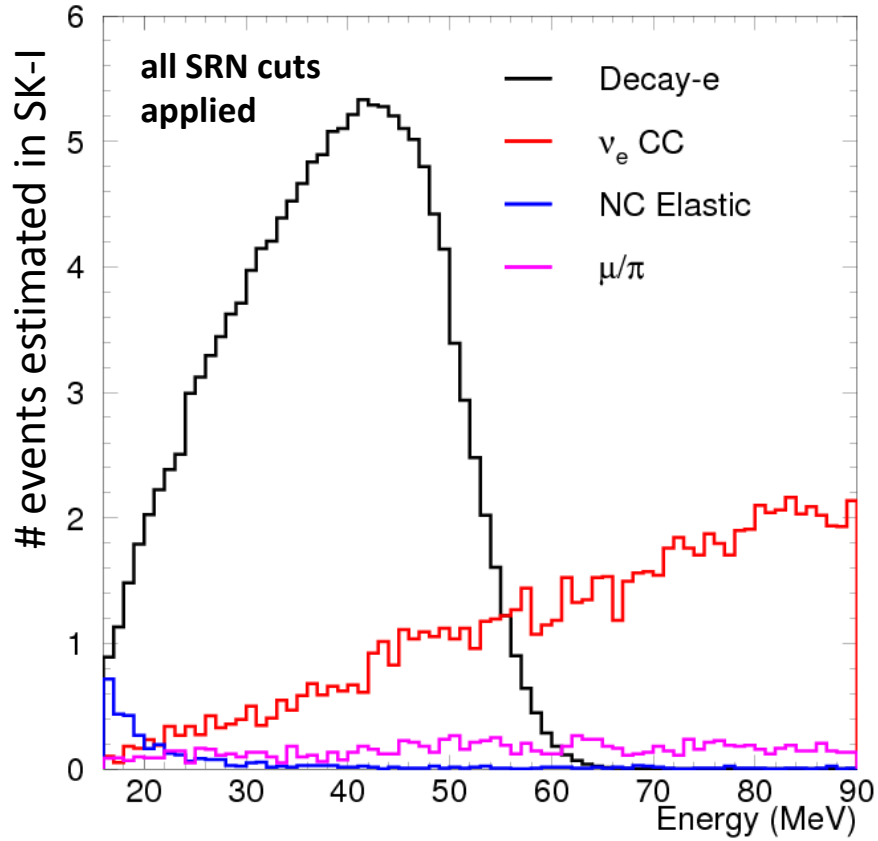
Cut	SK-I	SK-II	SK-III
Noise Reduction	99% (1%)	99% (1%)	99% (1%)
Spall + Solar	88% (1%)	87% (1.4%)	89% (1%)
Incoming event	98% (0.5%)	95% (0.3%)	96% (0.3%)
Pion	98% (0.2%)	97% (0.5%)	98% (0.5%)
Cherenkov angle	95% (0.4%)	88% (3%)	94% (0.3%)
Other cuts	98% (2%)	98% (2%)	98% (2%)
Total	78.5% (2.5%)	69.2% (4.0%)	76.7% (2.5%)

final efficiencies (based on LMA MC)

Remaining Backgrounds

- Final sample still mostly backgrounds, from atmospheric ν interactions; modeled w/ MC
- 1) **ν_μ CC events**
  - muons from atmospheric ν_μ's can be sub-Cherenkov; their decay electrons mimic SRNs
  - modeled with decay electrons
- 2) **ν_e CC events**
  - indistinguishable from SRNs
- 3) **NC elastic**
  - low energy mostly
- 4) **μ/π events**
  - combination of muons and pions remaining after cuts

SK-I backgrounds



Backgrounds 1) and 2) were considered in the 2003 study.

Backgrounds 3) and 4) are new!

Fitting method

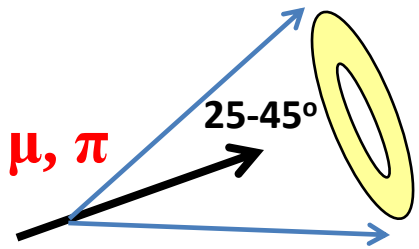
- 2003 study used a binned χ^2 method to extract a SRN signal from the final data, assuming backgrounds
- We discovered the binning can have significant effect on result
- Moved to unbinned maximum likelihood method
- Now we model and search for many different SRN models, each with our four remaining backgrounds

$$L = \prod_{i=1}^{N_{events}} \left(\sum_{j=1}^{5} c_j F_j(E_i) \right) e^{\left(-\sum_{j=1}^{5} c_j\right)}$$

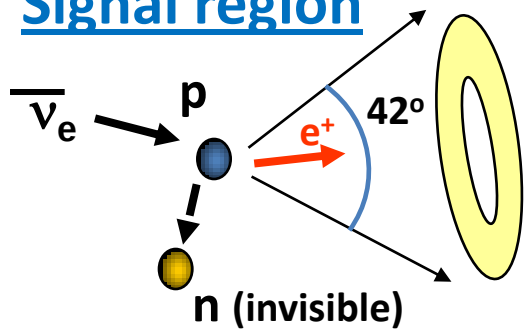
Where:
F is the PDF for a particular channel;
E is the event energy;
c is the magnitude of each channel; and
i represents a particular event, and
j represents a channel:
1= SRN model
2-5 = background channels

<u>systematics considered</u>:
cut inefficiency systematic error
energy scale and resolution
background spectrum errors (conservative)

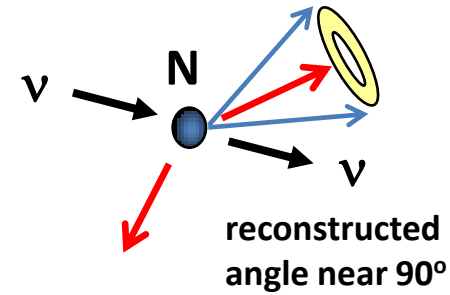
Low angle events



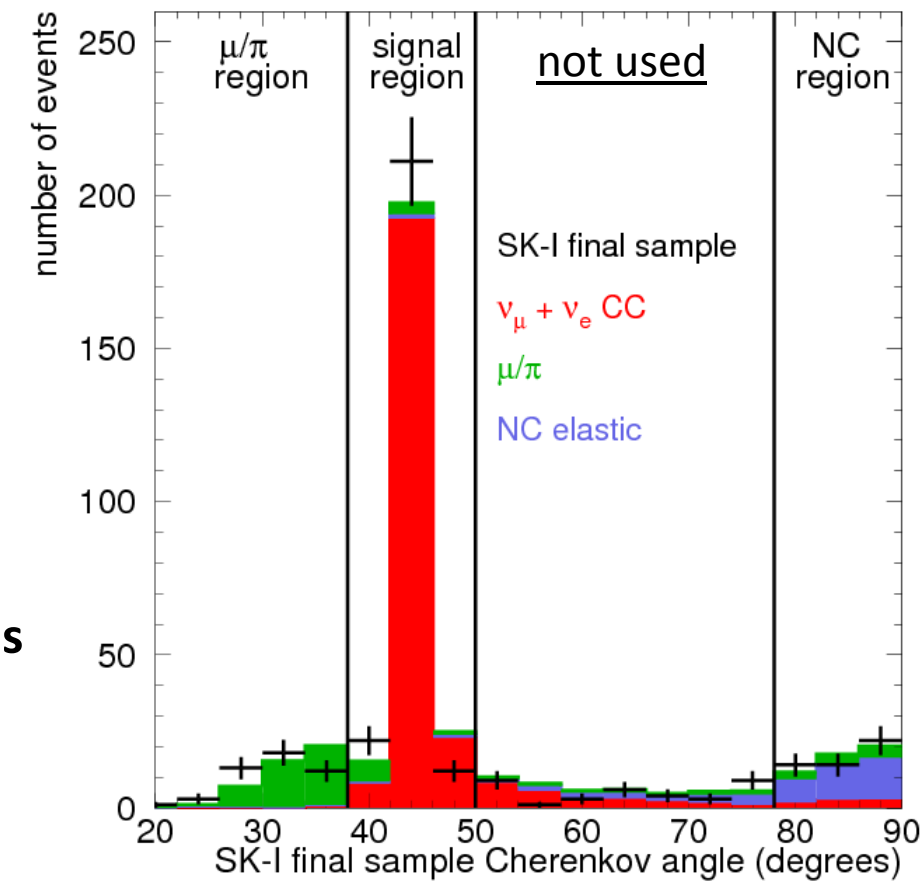
Signal region



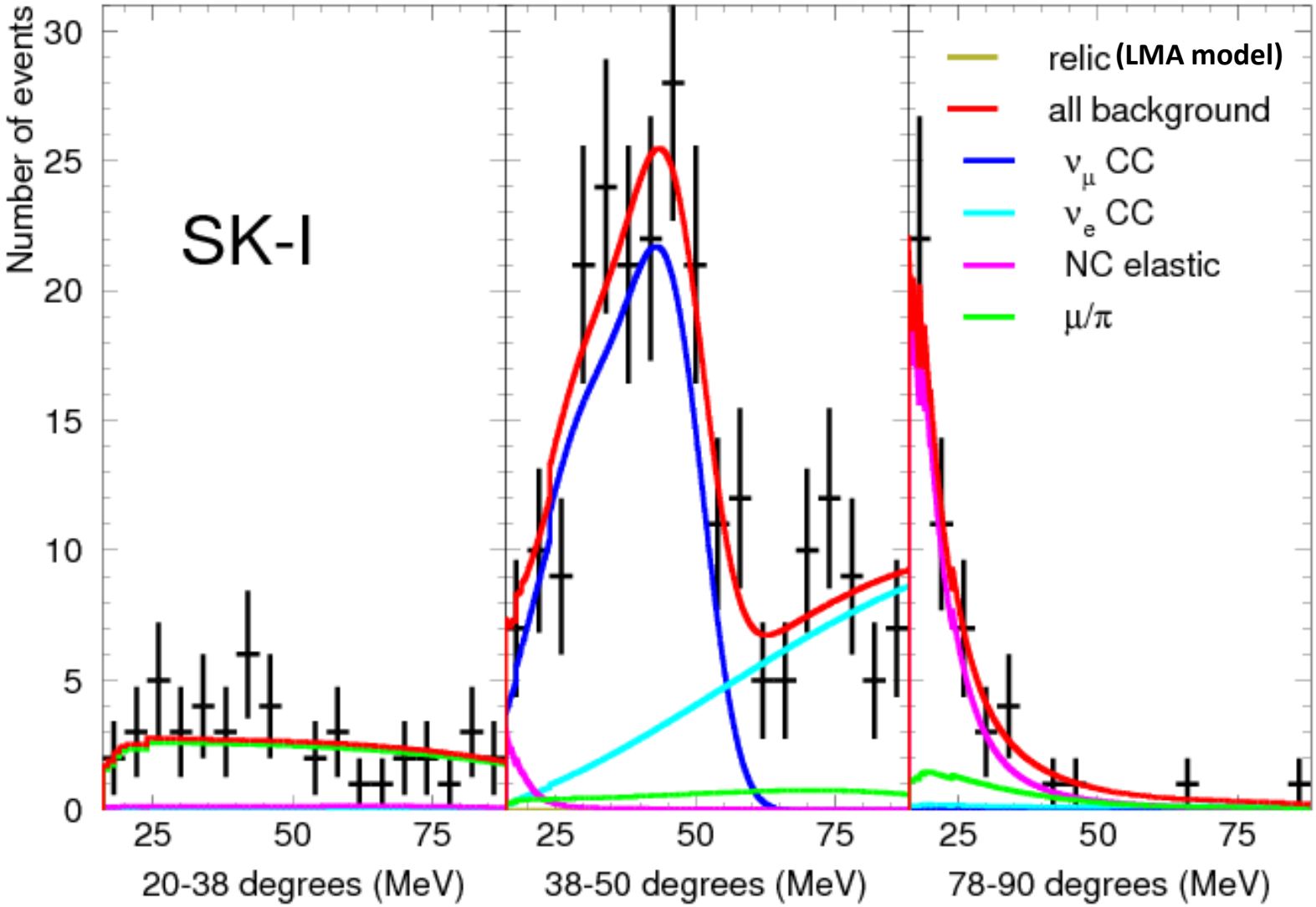
NC region



- SRN events expected (98% SK-I) in the central, signal region (38-50°)
- 'Sidebands' previously ignored
- Now that we consider new background channels, sidebands useful
  - NC elastic events occur at high C. angles
  - μ/π events occur at low C. angles
- We now fit all three C. angle regions <u>simultaneously</u>
- Sidebands help normalize new backgrounds in signal region

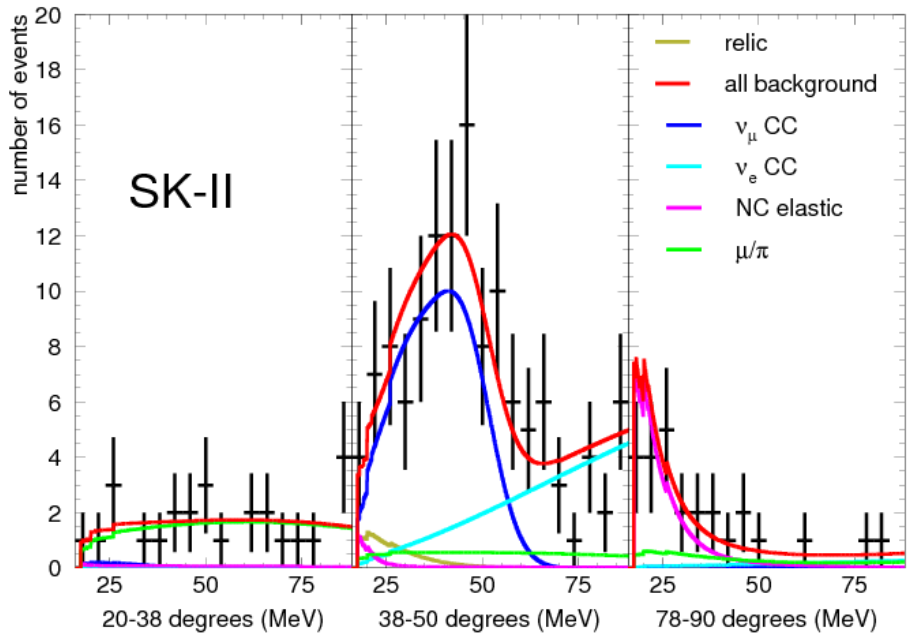


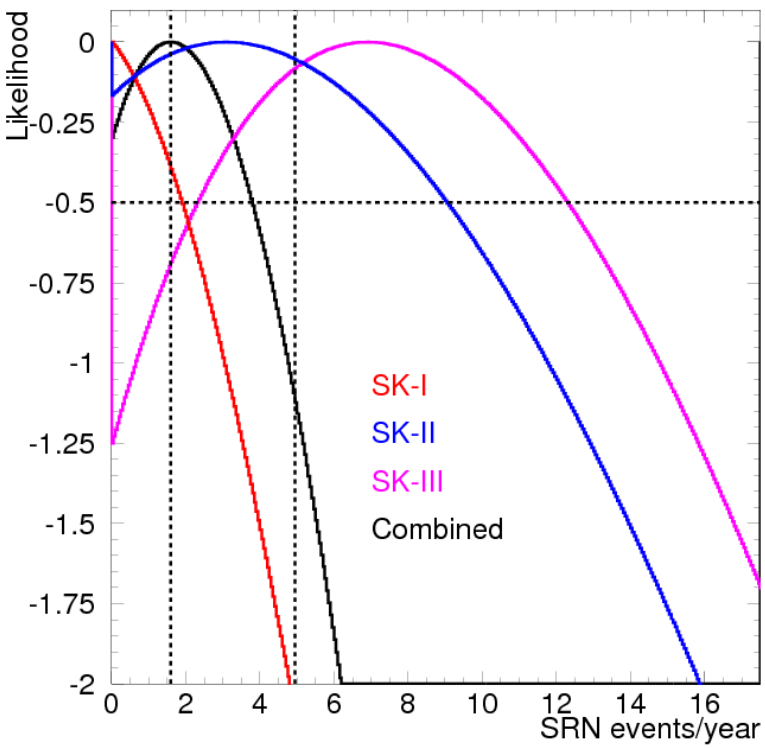
SK-I finds <u>no evidence</u> for SRNs

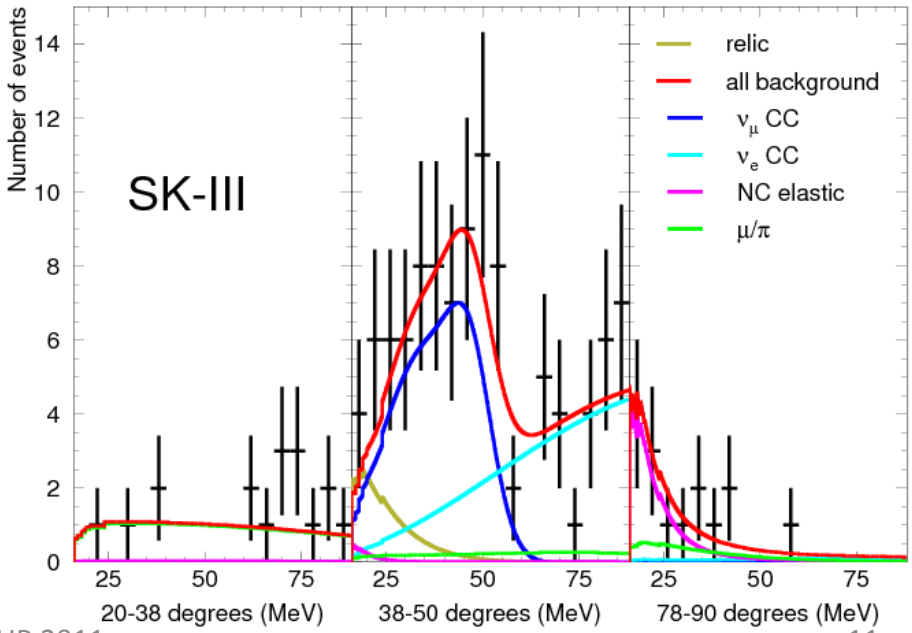


SK-II and SK-III give <u>positive fit</u> for SRNs (no significance)

Likelihoods (as fxn of SRN events) combined for a total result (limit)







New Results: flux limits (ν cm^{-2}s^{-1}, 90% cl)

E_{e+} > 16 MeV	SK-I	SK-II	SK-III	Combined	Predicted
LMA (03)	<2.5	<7.7	<8.0	<2.9	1.7
Cosmic gas Infall (97)	<2.1	<7.5	<7.8	<2.8	0.3
Heavy Metal (00)	<2.2	<7.4	<7.8	<2.8	0.4 - 1.8
Failed Supernova (09)	<2.4	<8.0	<8.4	<3.0	0.7
Chemical Evolution (97)	<2.2	<7.2	<7.8	<2.8	0.6
6 MeV (09)	<2.7	<7.4	<8.7	<3.1	1.5

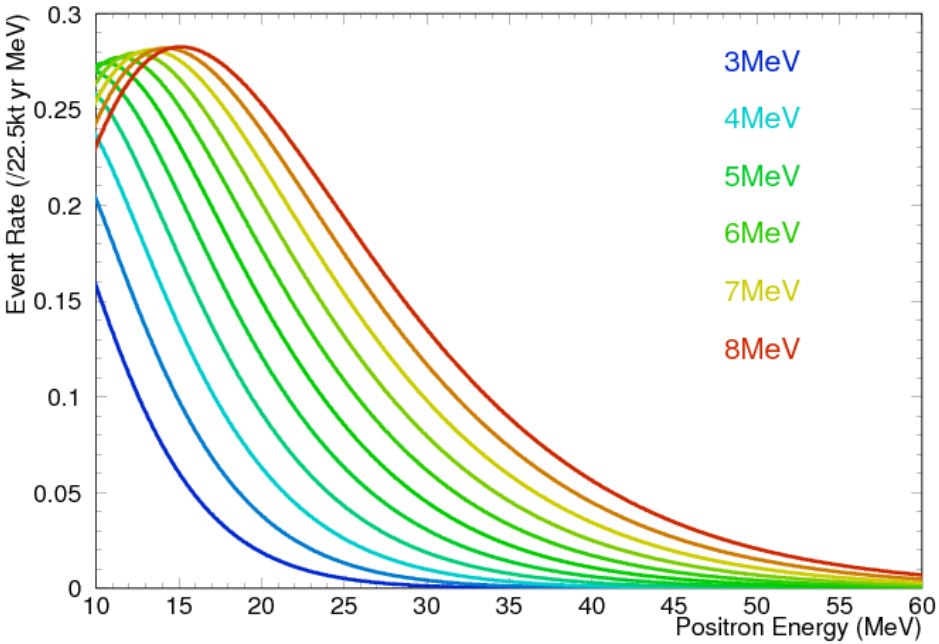
COMPARISON TO PUBLISHED LIMIT	/cm^2/s >18 MeV
Published limit	1.2
cross section update to Strumia-Vissani	1.2 → 1.4
Gaussian statistics → Poissonian statistics in fit	1.4 → 1.9
New SK-I Analysis: E_{THRESH} 18 → 16 MeV ε = 52% →78 % (LMA) (small statistical correlation in samples) improved fitting method takes into account NC	1.9→1.7
New SK-I/II/III combined fit	1.7 → 2.0 (2.9 > 16 MeV)

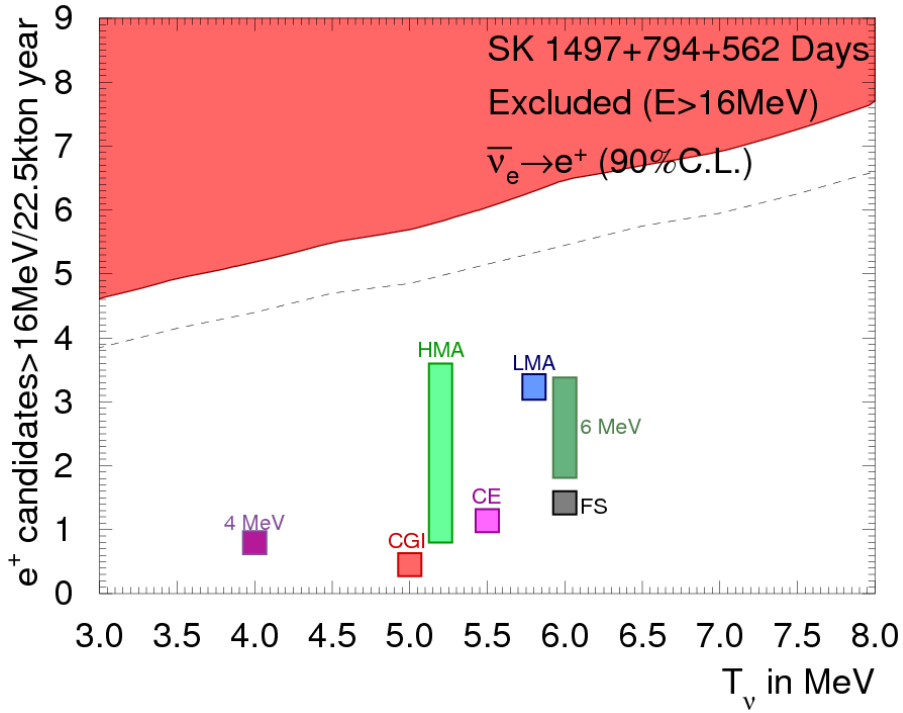
Limit Re-parameterization

- Elements of models now well known (very low error on cosmic star formation rate, initial mass functions, etc.)
- Elements are sufficiently known to recast new models into only 2 free parameters:
  - SN average ν luminosity
  - Temperature of a F-D spectrum
- Older models may use outdated parameters (i.e. incorrect star formation rate), care must be taken comparing with new results

J. Beacom - Ann.Rev.Nucl.Part.Sci.60:439,2010
Yuksel, et al. - Astro-ph/0509297v2,
Horiuchi, et al. - Phys.Rev.D79:083013,2009
Ando, Sato - New Journal of Phys 6 (2004) 170

Positron spectra seen in SK resulting from F-D ν E spectrum

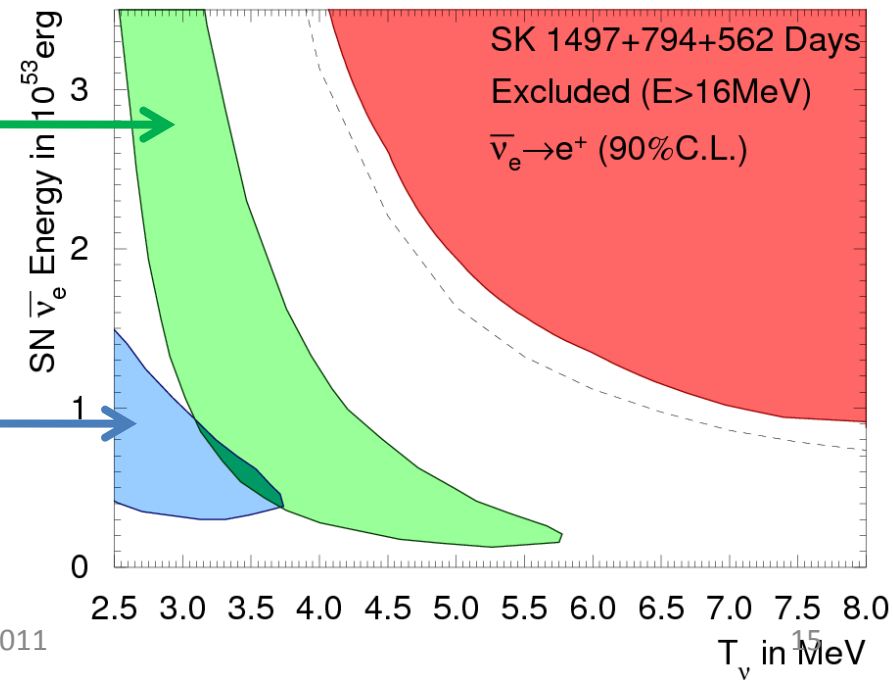




LMA = Ando et al (LMA model)
HMA = Kaplinghat, Steigman, Walker (heavy metal abundance)
CGI = Malaney (cosmic gas infall)
FS = Lunardini (failed SN model)
CE = Hartmann/Woosley (chemical evolution)
4/6 MeV = Horiuchi et al ν temp

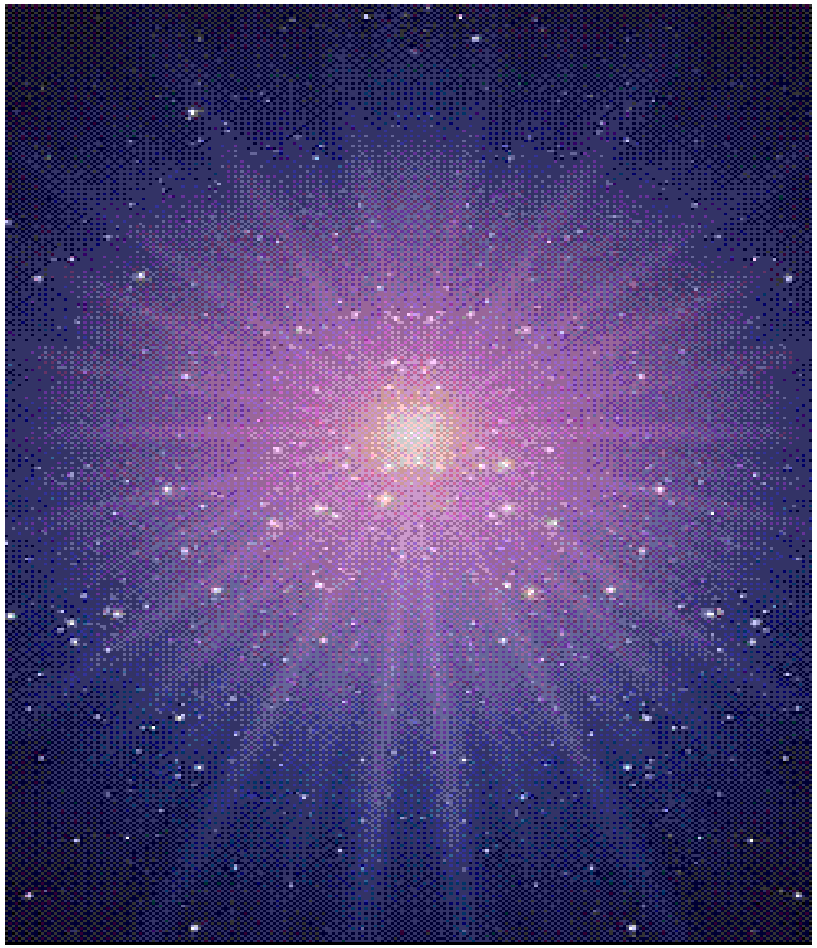
IMB 1987A allowed

Kamiokande 1987A allowed



Outlook

- New SRN SK study ready
- Many improvements, now detailed, fully considered
  - **better efficiency**
  - **more data**
  - **lower E threshold**
  - **new backgrounds considered**
  - **new fit, systematics**
- Paper out soon
- SK-II/III shows excess; no statistical significance. Hint of a signal? Statistical fluctuation?
- How to get certainty? Gd



GADZOOKS! - The Future of the SRN?

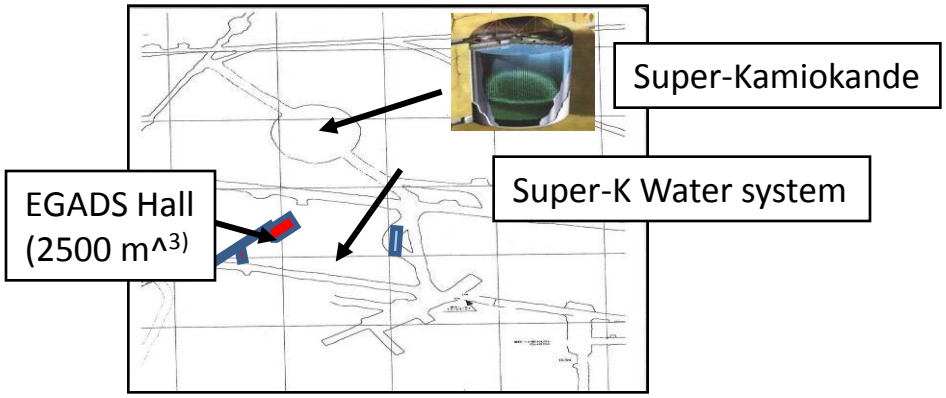
IPMU Professor Mark Vagins and Fermilab theorist John Beacom proposed GADZOOKS! – Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande, Super! [*Phys. Rev. Lett.*, **93**:171101, 2004].

Adding gadolinium to Super-K's water would make neutrons visible, allowing:

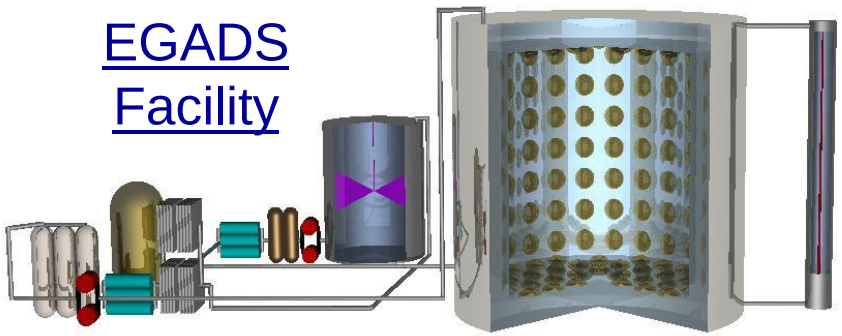
- Rapid discovery and measurement of the diffuse supernova neutrino flux
  → determine total and average SN ν energy, rate of optically failed SN
- High statistics measurement of the neutrinos from Japan's power reactors
  → greatly improved precision of Δm^2_{12}
- De-convolution of a galactic supernova's ν signals → 2X pointing accuracy
- Sensitivity to very late-time black hole formation following a galactic SN
- Early warning of an approaching SN ν burst (up to one week) from Si fusion
- Proton decay background reduction → about 5X, vital for future searches
- Matter- vs. antimatter-enhanced atmospheric ν samples → CPT violation?

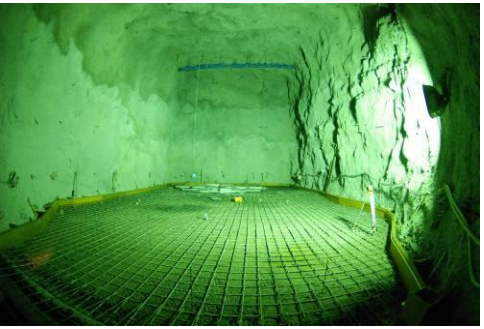
EGADS

Following seven years of above ground studies in the US and Japan, we are now building a dedicated Gd test facility in the Kamioka mine, complete with its own water filtration system, 240 50-cm PMT's, and DAQ electronics. This 200 ton-scale R&D project is called EGADS – Evaluating Gadolinium's Action on Detector Systems.



EGADS Facility





12/2009

2/2010

6/2010

12/2010

By 2012, EGADS will have demonstrated conclusively whether or not gadolinium loading of Super-Kamiokande will be safe and effective.

If it works, then this is the likely future of water Cherenkov detectors.

Latest EGADS News

- **Egads test tank construction, water system complete**
  - **EGADS pure water transparency > SK**
- **Gd removal system ready**
  - **10^6 removal in single pass**
- **Gd introduced in system**
  - **dissolved into water system, no problems**
  - **Gd water system circulation 99.97% efficient**
  - **Preliminary Gd water transparency good**
- **PMTs prepped, installed soon**
- **Electronics and DAQ by end of 2011**
- **Full experimental program on track for 2012**

- Thanks for your attention!

BACKUPS

List of models and references

- Cosmic Gas Infall – Malaney - R. A. Malaney, Astroparticle Physics 7, 125 (1997)
- Chemical evolution - D. H. Hartmann and S. E.Woosley, Astroparticle Physics 7, 137 (1997)
- Heavy Metal Abundance - M. Kaplinghat, G. Steigman, and T. P. Walker, Phys. Rev. D 62, 043001 (2000)
- Large Mixing Angle - S. Ando, K. Sato, and T. Totani, Astroparticle Physics 18, 307 (2003) (updated NNN05)
- Failed Supernova - C. Lunardini, Phys. Rev. Lett. 102, 231101 (2009) (assume Failed SN rate = 22%, EoS = Lattimer-Swesty, and survival probability = 68%.)
- 6/4 MeV FD spectrum - S. Horiuchi, J. F. Beacom, and E. Dwek, Phys. Rev. D 79, 083013 (2009).

Spallation Cut

- 4 variable likelihood cut
- The 4 variables:
  - $dl_{Longitudinal}$ ← NEW!
  - dt
  - $dl_{Transverse}$
  - Q_{Peak}

  } OLD likelihood
- Use new, better μ fitters
- Tuned for each muon type (i.e. single, multiple, stopping μ)
- **Improvements allow lowering of energy threshold to 16 MeV!**

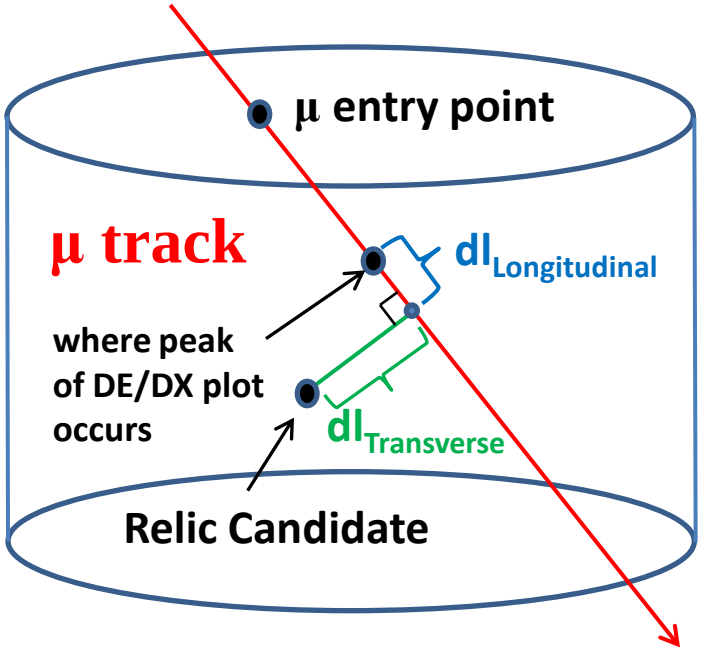
New Cut (SK-I/III):

16 < E < 18 MeV: 18% signal inefficiency

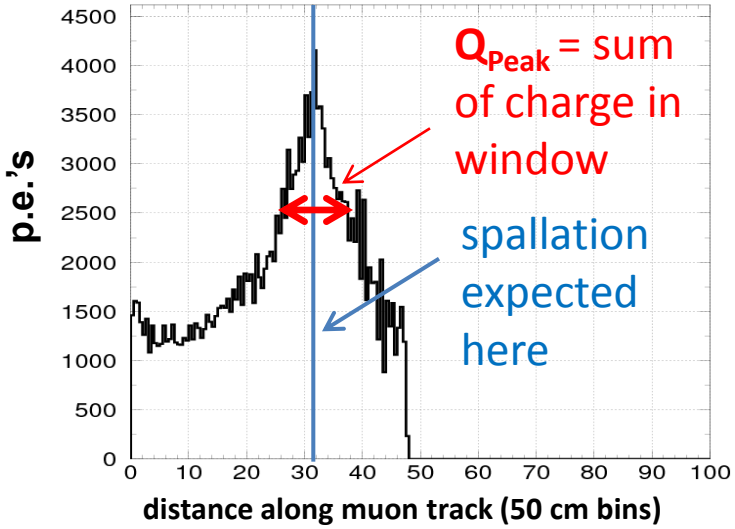
18 < E < 24 MeV: 9% signal inefficiency

Old cut (likelihood + 150 ms hard cut)

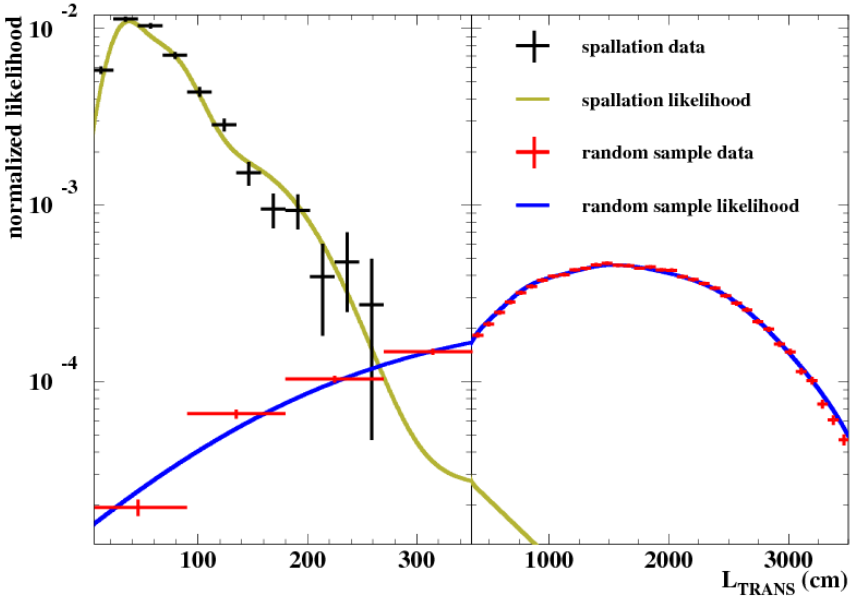
18 < E < 34: 36% signal inefficiency

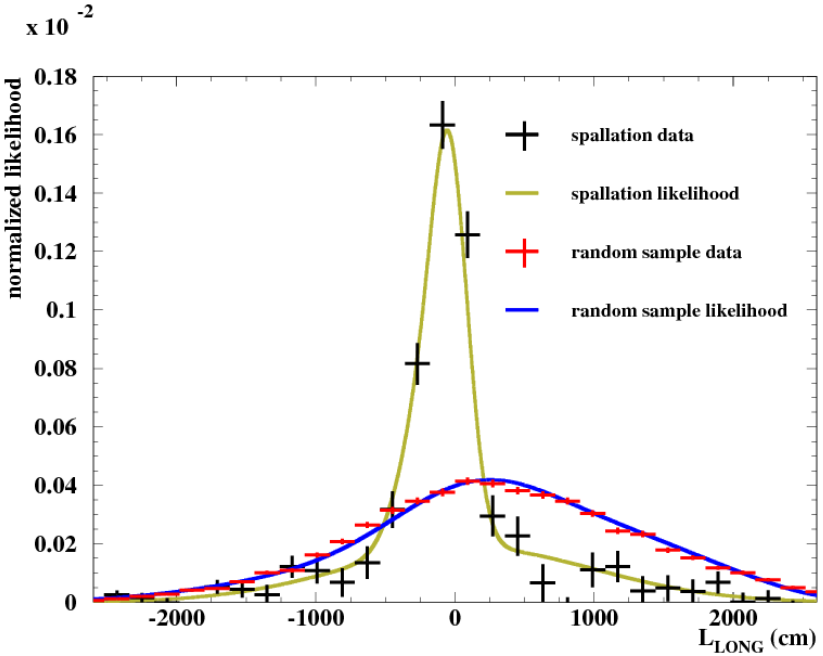


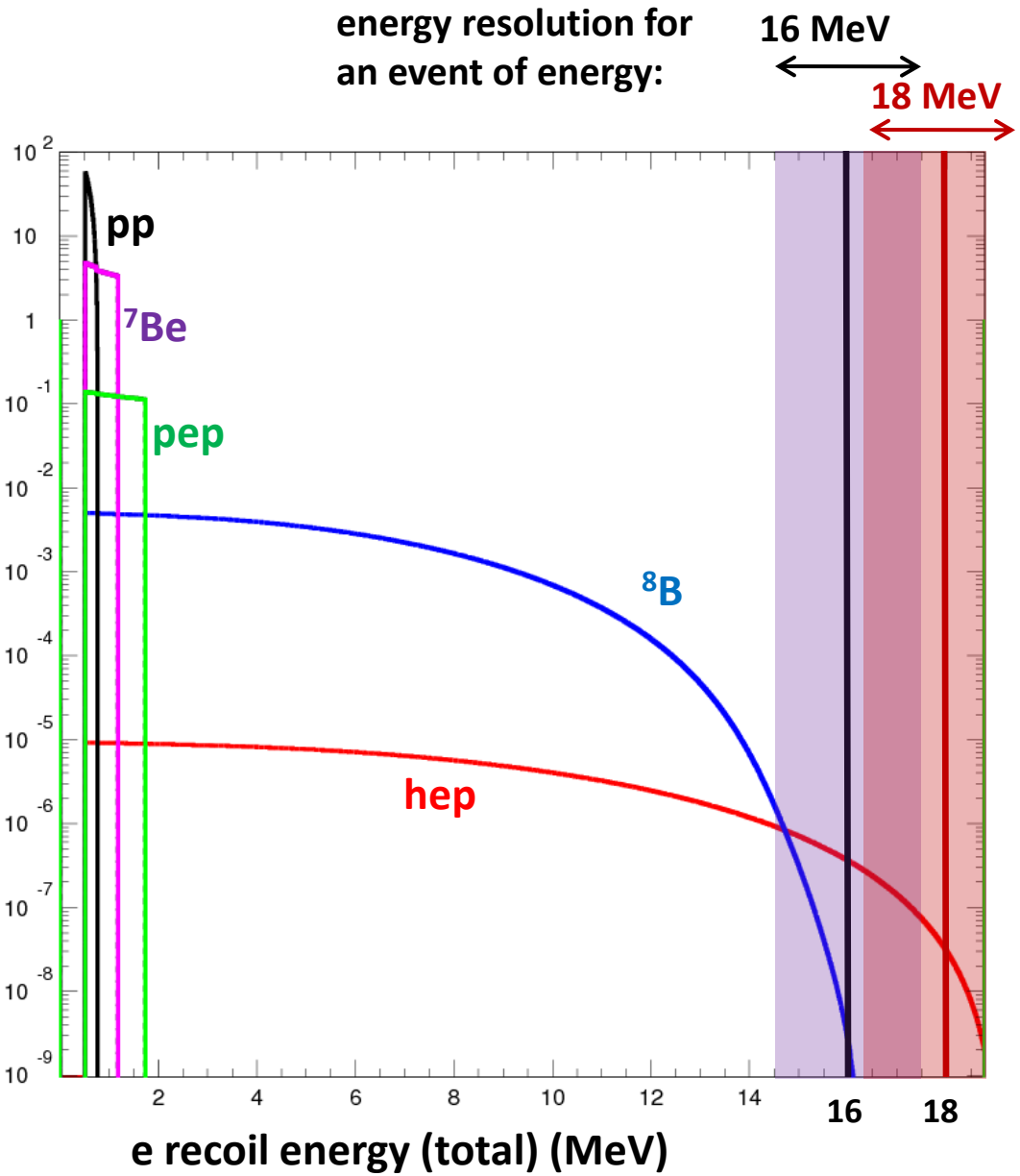
dE/dx Plot



spallation distance variables





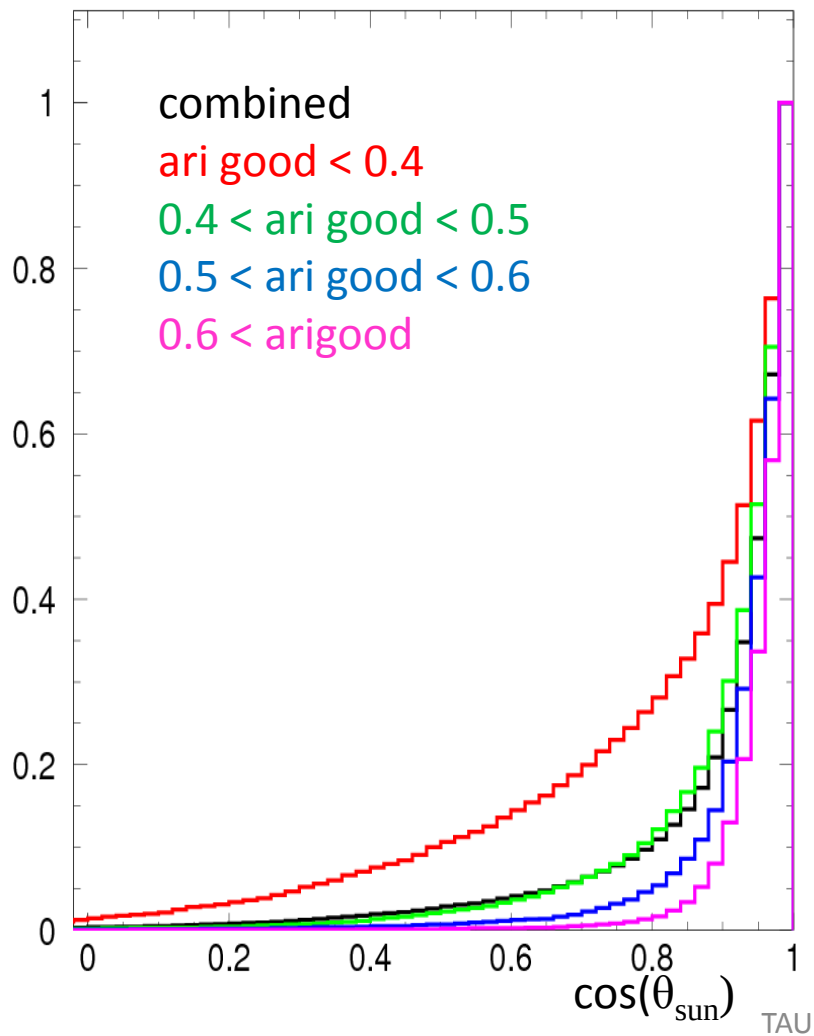


Solar ν Events

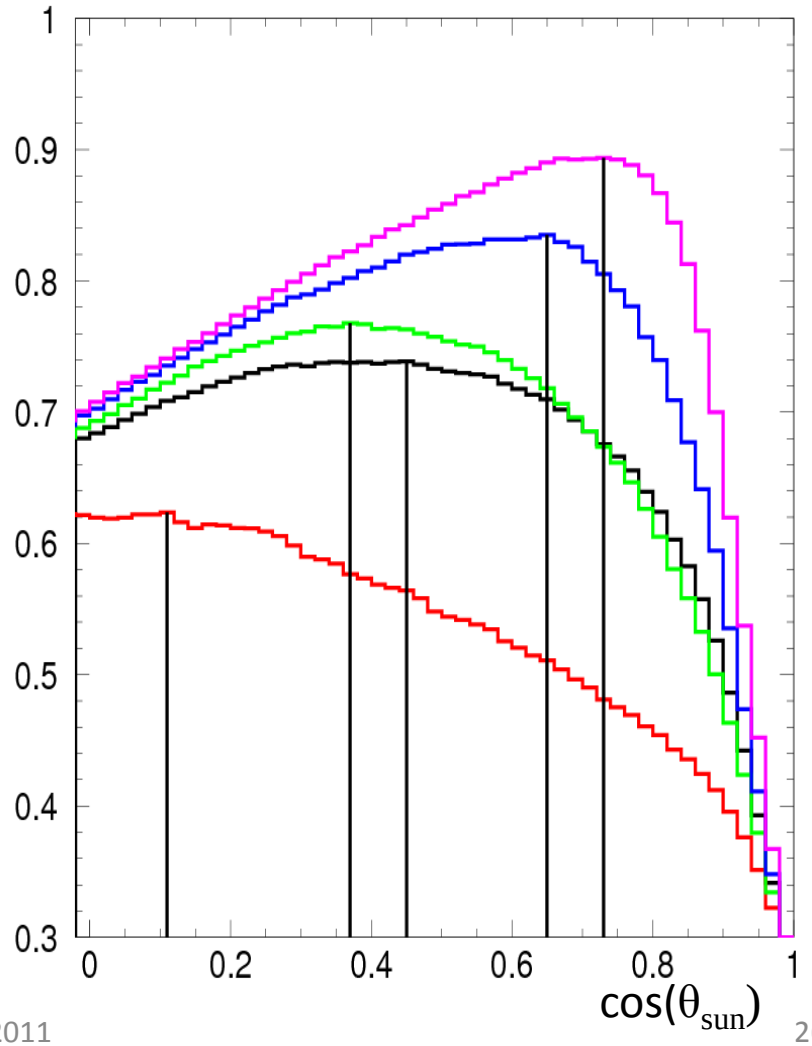
- Solar ^{8}B and hep neutrino are a SRN background (hep at 18 MeV, and both at 16 MeV, because of energy resolution)
- Cut criteria is optimized using ^{8}B/hep MC
- New cut is now energy dependent, tuned in 1 MeV bins

Coulomb multiple scattering is estimated ('arigood'); more scattering, more deviation from solar direction. Each energy bin is broken into 'arigood' bins; cut in each bin tuned using 'significance' function to maximize signal/background$^{1/2}$

integrated $\cos(\theta_{sun})$



significances



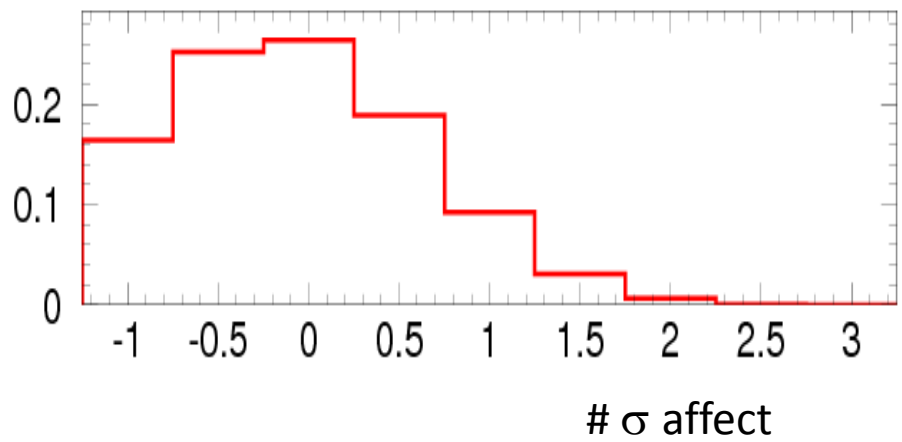
Systematics: NC elastic

- Keep spectra the same
- Change normalization in signal region by 100%
  - $+1\sigma$ = double (14.8% SK-I)
  - -1σ = 0%
- Because of physical bound, apply error asymmetrically (-1σ to $+3\sigma$)
- Instead of standard Gaussian weighing function (appropriate for symmetric case), use a <u>weighted Gaussian</u> function
- Maintain necessary properties:
  - expectation value = 0
  - variance = σ^2

SK-I NC elastic normalization

20-38°	38-50°	78-90°
5.6%	7.4%	87%

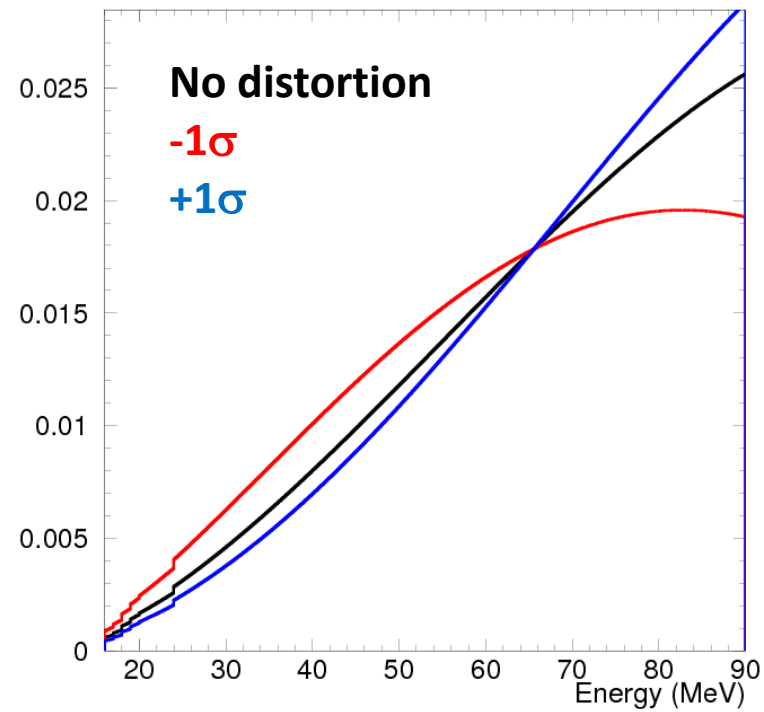
Weighing function applied (weighted Gaussian)

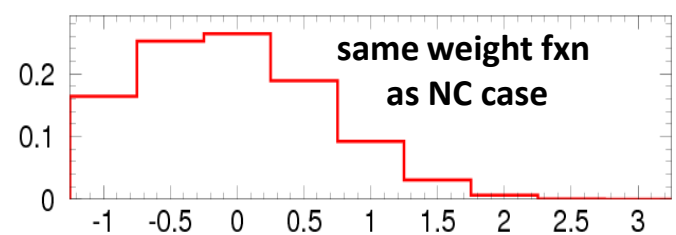


Systematics: ν_e CC

- For ν_e CC case, keep normalization, distort spectrum
- Use large error of 50% at 90 MeV (0 distortion at 16 MeV, linear between)
- Use same range (-1 to 3 σ) and weighing function as NC case
- -2 σ would bring spectrum to 0 at 90 MeV, which is unphysical

SK-I ν_e CC PDF





Systematics: Inefficiency

- **Define:**
  - **r = # relic events we see in data**
  - **R = # relic events actually occurring in detector**
  - **ε = efficiency (SK-I/II/III dependent)**
  - **assume ε follows a probability distribution P(ε)**
  - **assume P(ε) is shaped like Gaussian w/ width σ_{ineff}**
  - **then we alter likelihood:**

	σ_{ineff}
SK-I:	3.5%
SK-II:	4.7%
SK-III:	3.4%

$$L'(R) = \int_{\varepsilon=0}^{1} L(\varepsilon R)\varepsilon P(\varepsilon)d\varepsilon$$

then the 90% c.l. limit R_{90} is such that

$$\int_{0}^{R_{90}} L(R)dR = 0.9$$

Systematics: energy scale, resolution

- Method:
  - Use MC, parameterize effects
  - ie for e-res, parameterize :

$$f_{e\text{-resolution}}(E) = (E_{true} + (E_{recon} - E_{true}) * error)$$

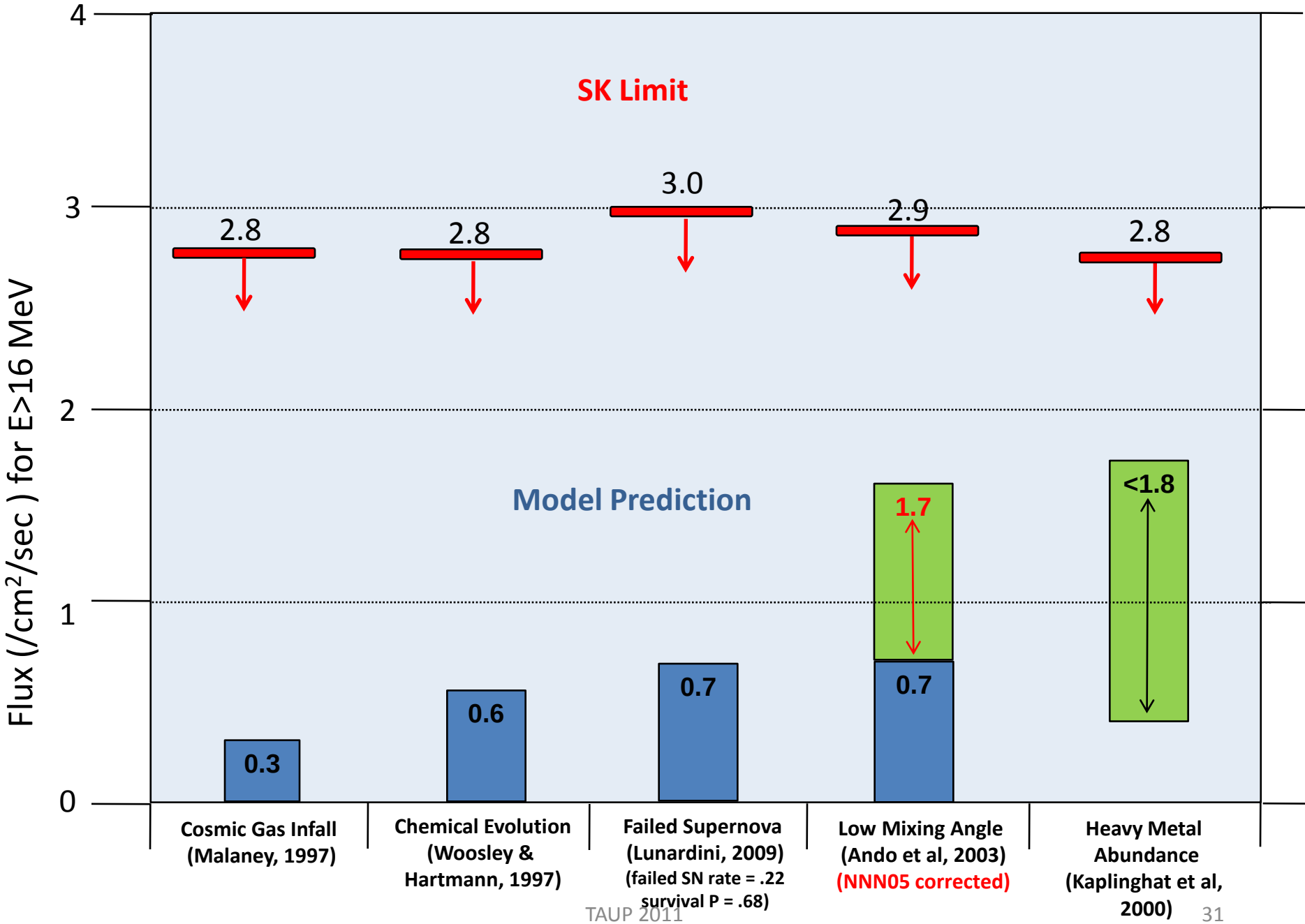
	e-scale	e-res
SK-I:	1%	2.5%
SK-II:	1.5%	2.5%
SK-III:	1%	2.5%

- $\delta(E) = (f_{e\text{-scale}}(E)^2 + f_{e\text{-resolution}}(E)^2)^{1/2}$

$$\rho(E_i) \longrightarrow \rho(E_i, \varepsilon) = c(1 + \delta(E_i)\varepsilon)\rho(E_i)$$

$$L(\varepsilon) = \prod_{i=1}^{N_{events}} \left(r\rho(E_i, \varepsilon) + m\mu(E_i) + e\zeta(E_i) \right)$$

$$L' = N \int_{\varepsilon=-\infty}^{\infty} e^{-\varepsilon^2/2} L(\varepsilon) d\varepsilon$$


Flux (/cm²/sec) for E>16 MeV
4
3
2
1
0
SK Limit
2.8
2.8
3.0
2.9
2.8
Model Prediction
0.3
0.6
0.7
0.7
1.7
<1.8
Cosmic Gas Infall (Malaney, 1997)
Chemical Evolution (Woosley & Hartmann, 1997)
Failed Supernova (Lunardini, 2009) (failed SN rate = .22 survival P = .68)
Low Mixing Angle (Ando et al, 2003) (NNN05 corrected)
Heavy Metal Abundance (Kaplinghat et al, 2000)