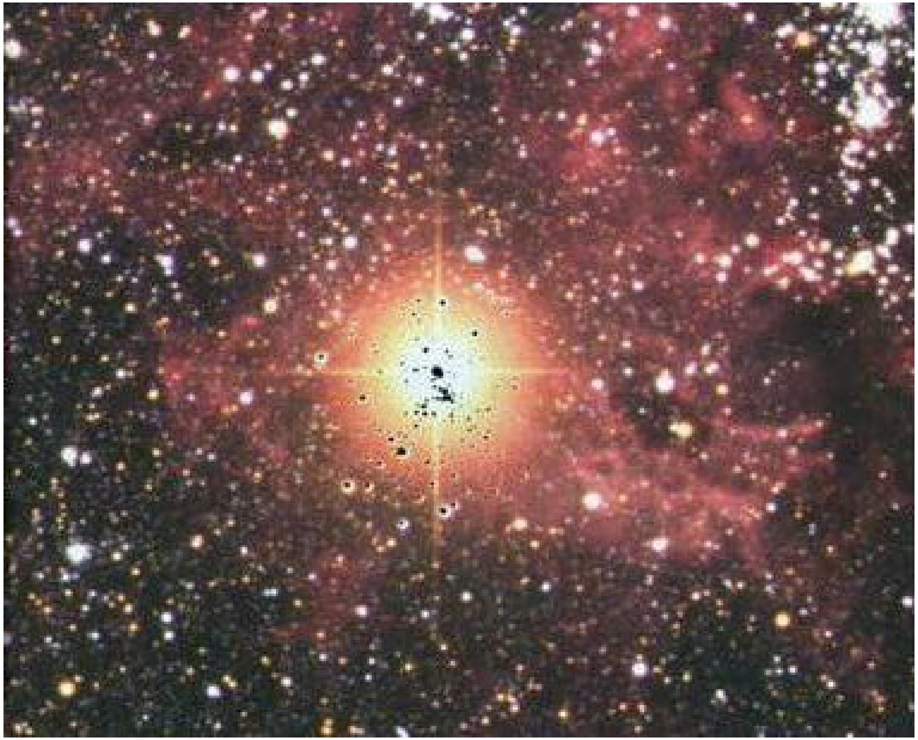
Searching for Supernova Relic Neutrinos



Dr. Matthew Malek
University of Birmingham – HEP Seminar
11 May 2011

Outline

- Introduction: A Brief History of Neutrinos
- Theory
  - Supernova Neutrino Emission
  - Supernova Relic Neutrinos
- Super-Kamiokande Detector
- Data Reduction
- Analysis and Results
- Conclusions and Future

Enter The Neutrino

• 1910s - 1920s: Studies of nuclear β decays $N_1 \rightarrow N_2 + e^-$

Did not appear to conserve energy! nuclei electron

• 1930: Wolfgang Pauli postulated Neutrinos in order to save energy conservation

$$N_1 \rightarrow N_2 + e^- + \nu$$

"I have done a terrible thing. I have postulated a particle that cannot be detected"

ν has no charge, no mass, very feeble interaction, just a bit of energy

• 1956: ν finally discovered by Cowan and Reines.

Used nuclear reactor as source of neutrinos. Nobel prize 1995

In The Mine, But Looking At The Stars

- First solar neutrino detector:
  - Homestake mine, S. Dakota
  - Ray Davis, Brookhaven
  - 1967 – 1998
  - 615 tons of C_2Cl_4 (cleaning fluid!)
  - "Radiochemical" detector:

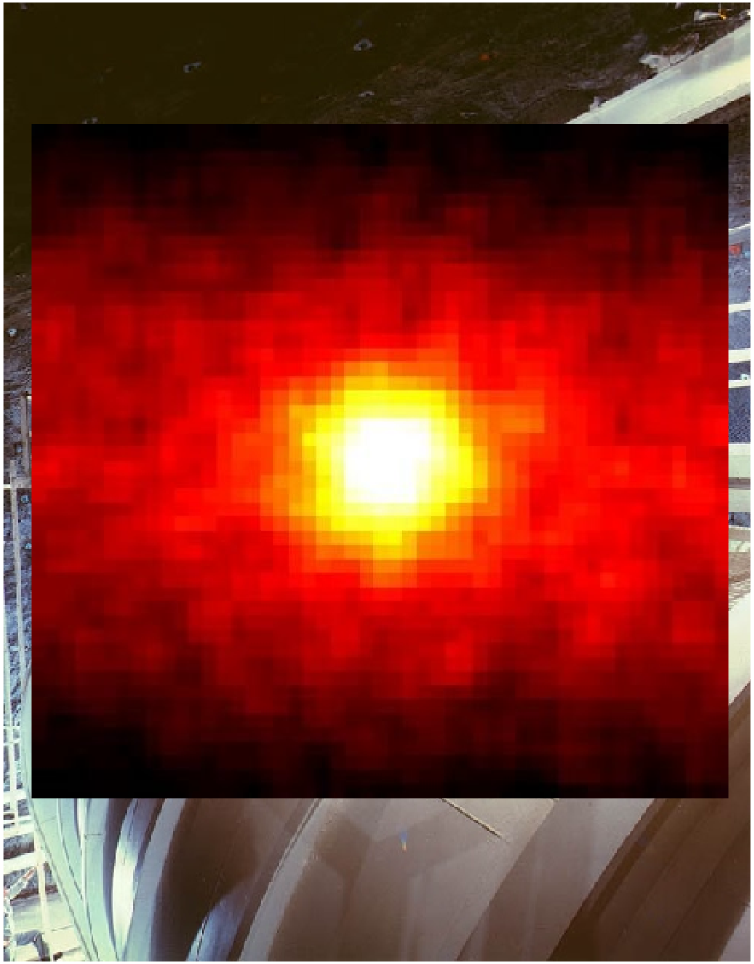
$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar^* + e^-$$

<u>Good News:</u>

First discovery of solar ν!

<u>Bad News:</u>

Far fewer than anticipated!



Supernova Neutrinos: The Plot Thickens

- On 23-Feb-1987, a burst of ν came from Sanduleak -69° 202 in Large Mag. Cloud. (now known as Supernova 1987a)

- 19 (or 20) SN neutrinos seen in two water Cherenkov experiments:
  - 11 (or 12) at KamiokaNDE
  - 8 at the competing IMB

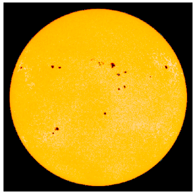
- Hundreds of papers written analysing these few neutrinos!

- Between solar and supernova ν detections, the field of neutrino astronomy was born!

- In 2002, Ray Davis and Masatoshi Koshiba shared Nobel Prize for this accomplishment (along with discovery of x-ray astronomy).

Supernova Progenitors

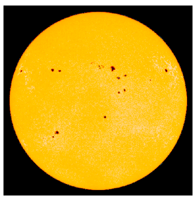
Main Sequence



H core

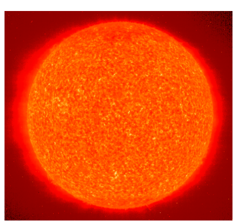
Supernova Progenitors

Main
Sequence



H core

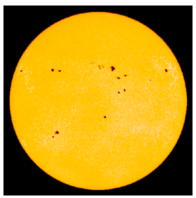
Red
Giant



He core
+ H shell

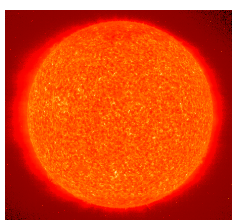
Supernova Progenitors

Main Sequence



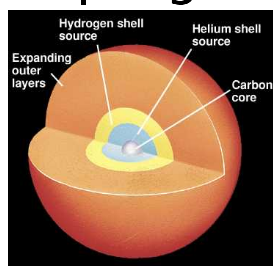
H core

Red Giant



He core + H shell

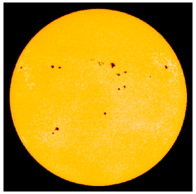
Supergiant



C & O core
He & H shells

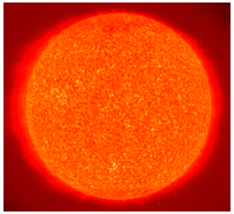
Supernova Progenitors

Main Sequence



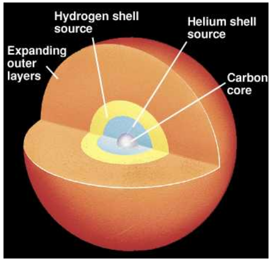
H core

Red Giant



He core + H shell

Supergiant

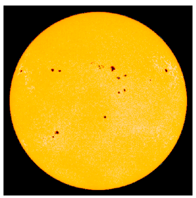


C & O core
He & H shells

m > 8 M?

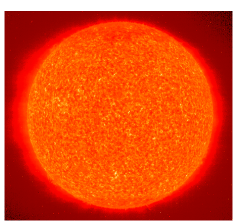
Supernova Progenitors

Main Sequence



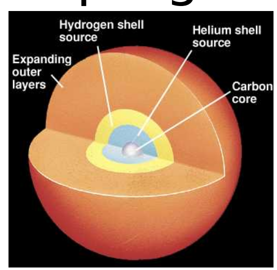
H core

Red Giant



He core
+ H shell

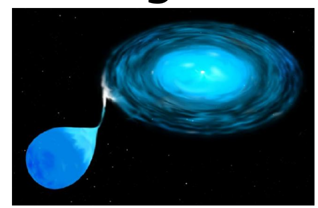
Supergiant



C & O core
He & H shells

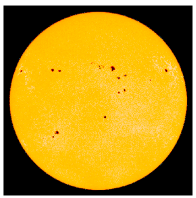
m > 8 M?

Accreting White Dwarf



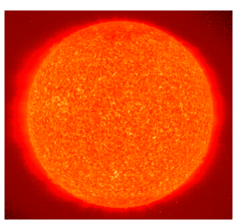
Supernova Progenitors

Main Sequence



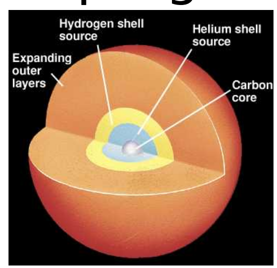
H core

Red Giant



He core
+ H shell

Supergiant



C & O core
He & H shells

m > 8 M?

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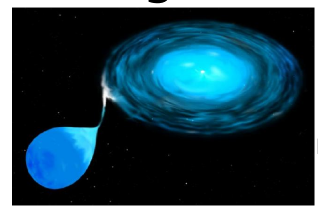
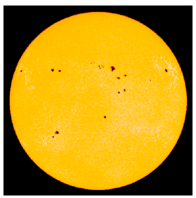


Carbon deflagration supernova

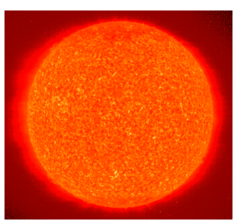
Supernova Progenitors

Main Sequence



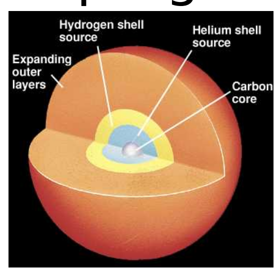
H core

Red Giant



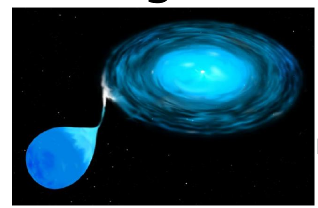
He core + H shell

Supergiant



C & O core
He & H shells

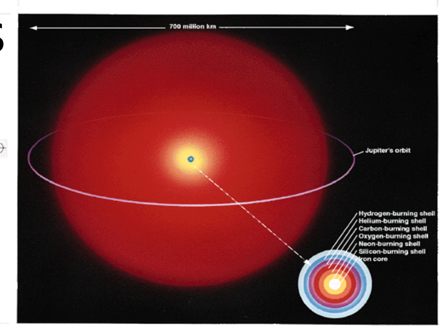
Accreting White Dwarf



Carbon deflagration supernova

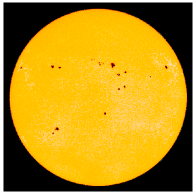
$m > 8$ M?

“Onion” Shells (H,He,C,O,Ne,Si,Fe)



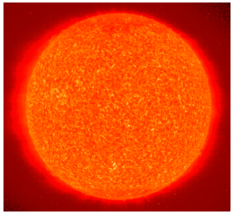
Supernova Progenitors

Main Sequence



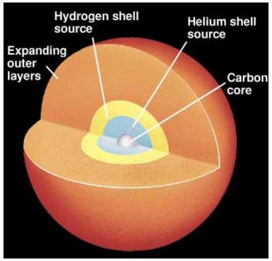
H core

Red Giant



He core + H shell

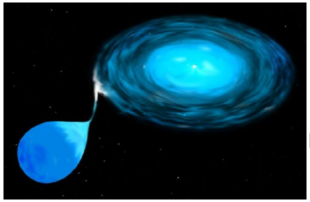
Supergiant



C & O core
He & H shells

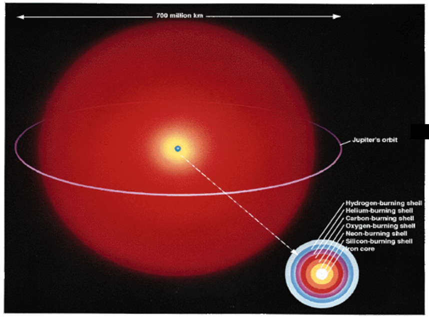
m > 8 M?

Accreting White Dwarf



Carbon deflagration supernova

"Onion" Shells
(H,He,C,O,Ne,Si,Fe)



Core Collapse!

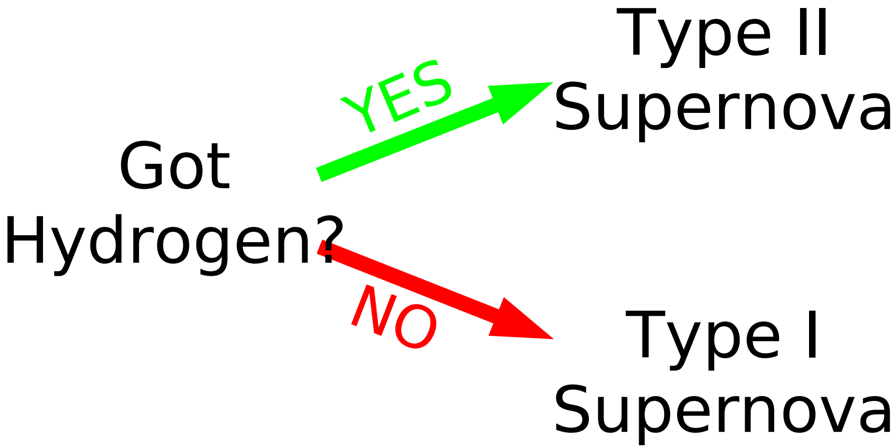
Supernova Classification

Classify by spectral lines :

Got
Hydrogen?

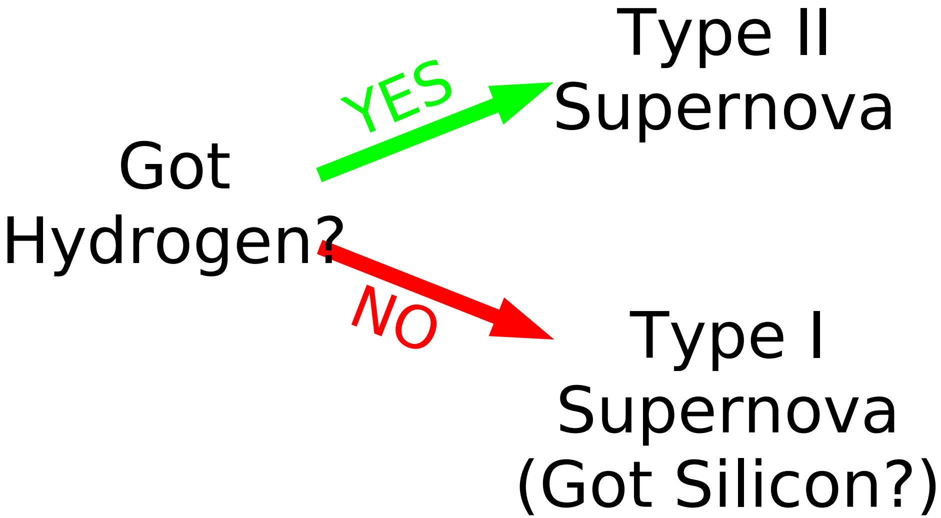
Supernova Classification

Classify by spectral lines :



Supernova Classification

Classify by spectral lines :



Supernova Classification

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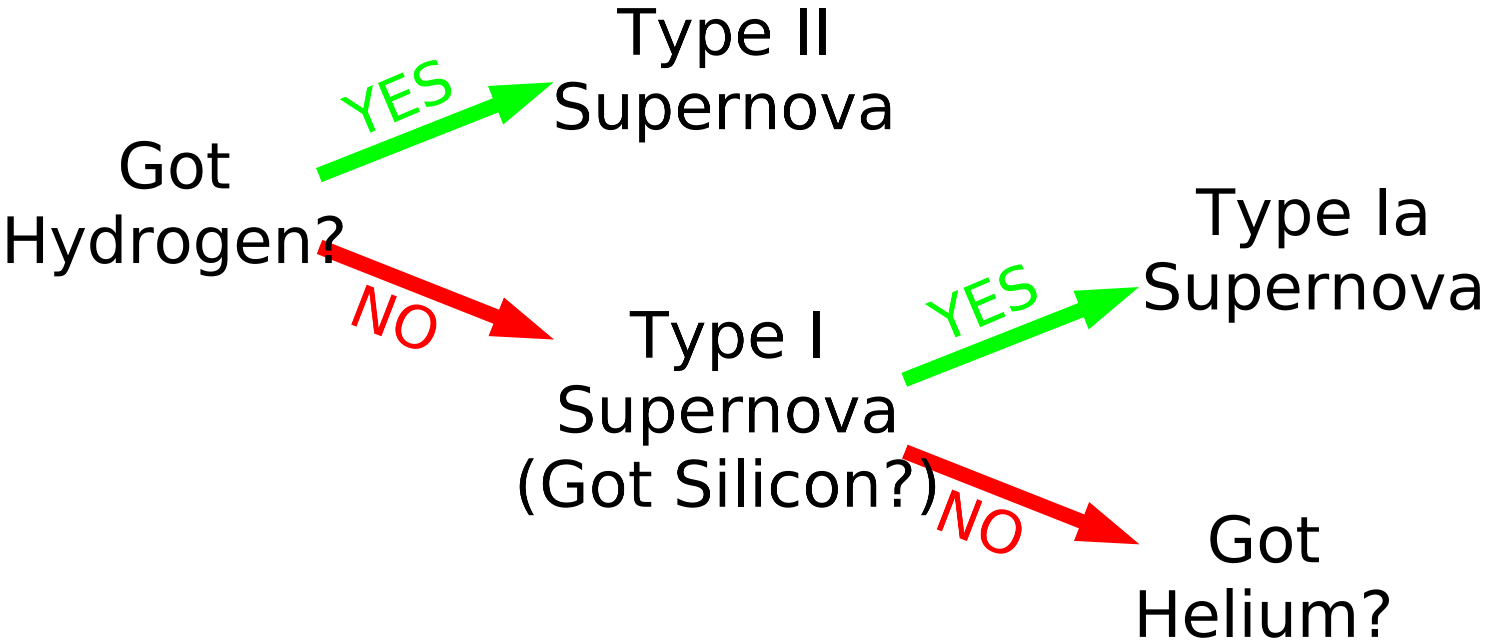
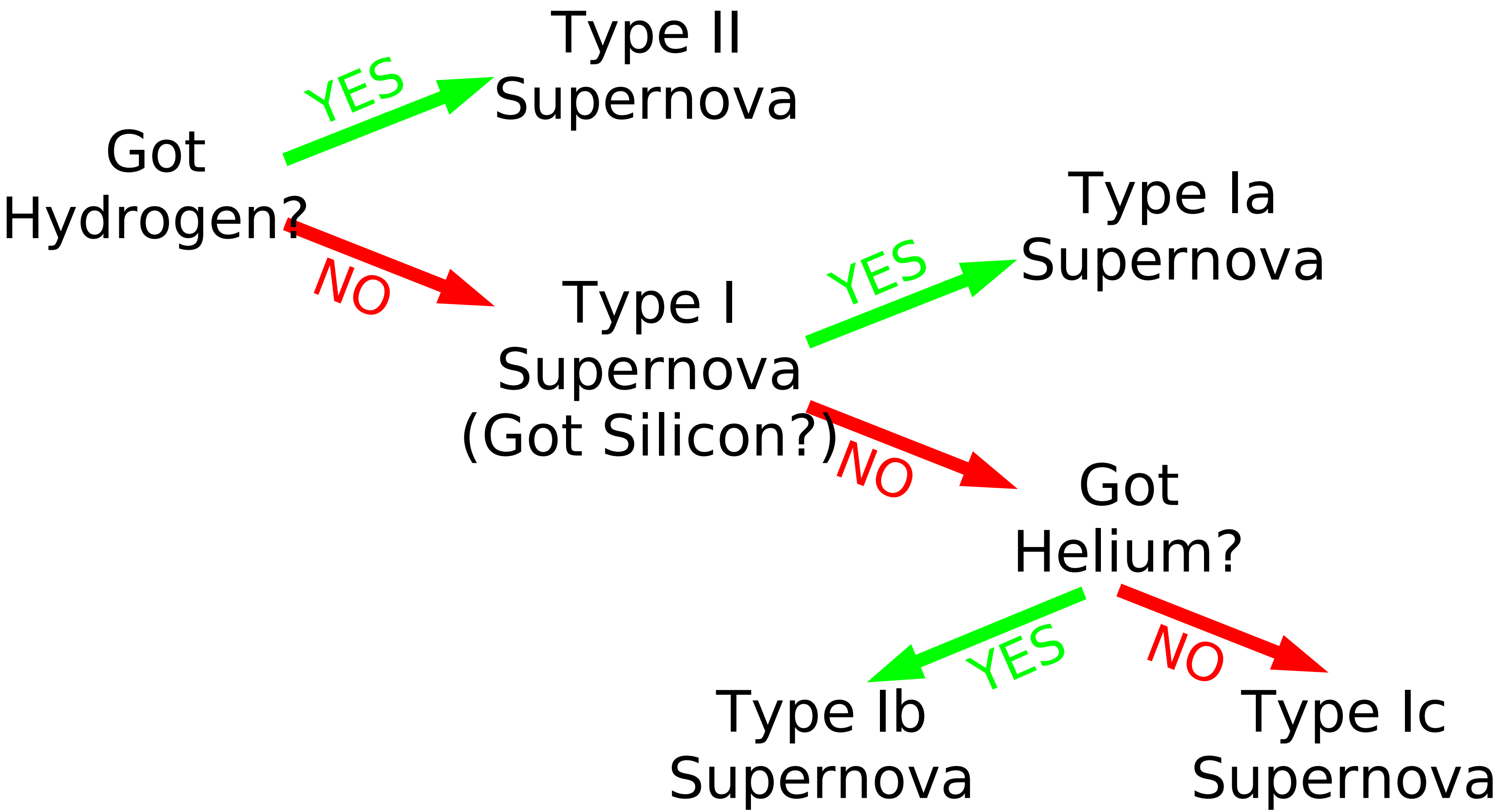


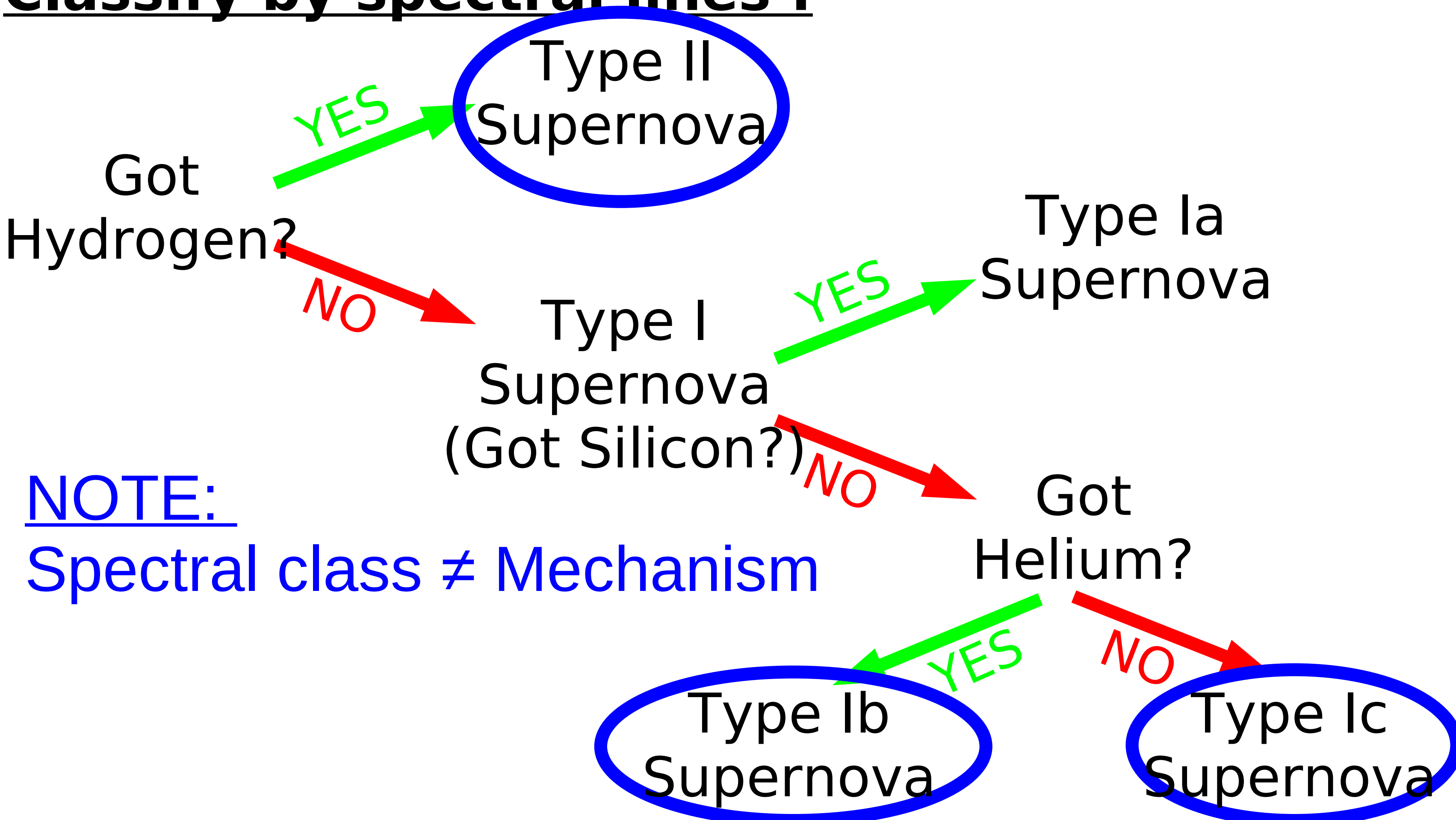
Supernova Classification

Classify by spectral lines :



Supernova Classification

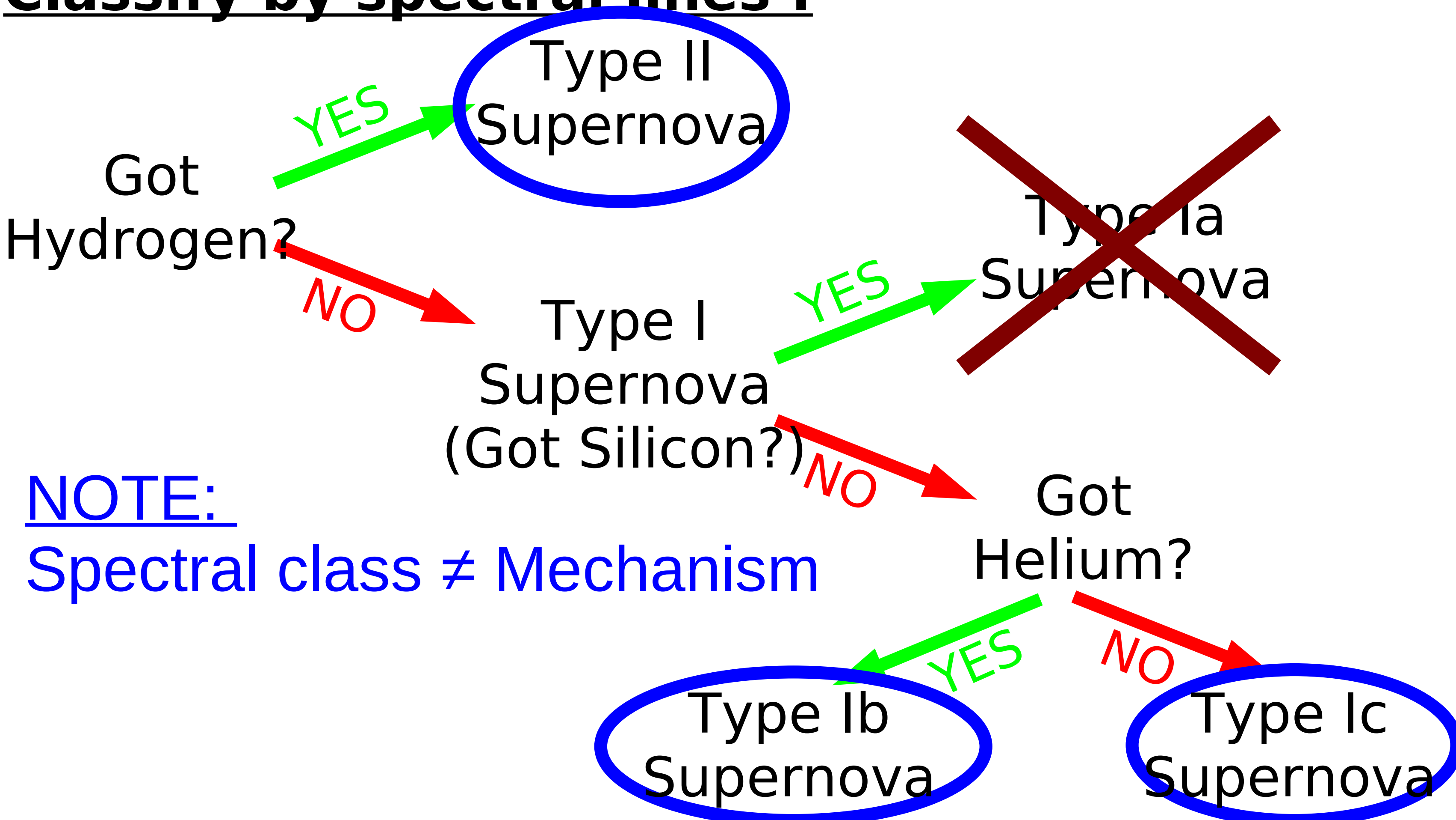
Classify by spectral lines :



NOTE:
Spectral class ≠ Mechanism

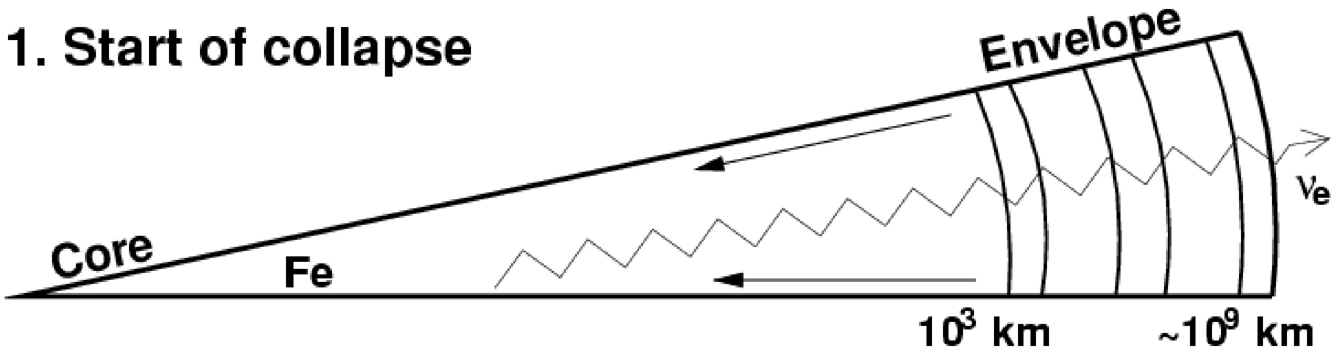
Supernova Classification

Classify by spectral lines :



NOTE:
Spectral class ≠ Mechanism

Supernova Neutrino Emission: *Start of the Collapse*

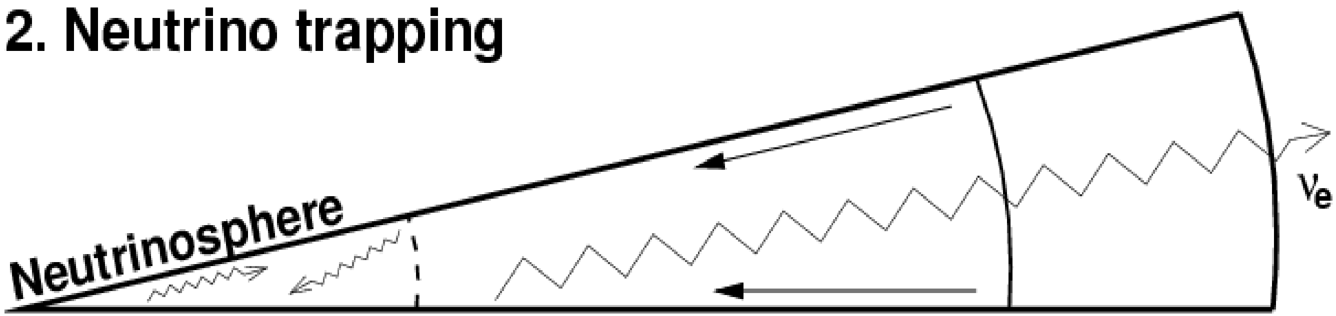


- Electrons captured on nuclei produce ν_e via:

$$e^- + A(N,Z) \rightarrow \nu_e + A(N+1,Z-1)$$

- Mean free path of neutrinos > core size
- Neutrinos escape promptly

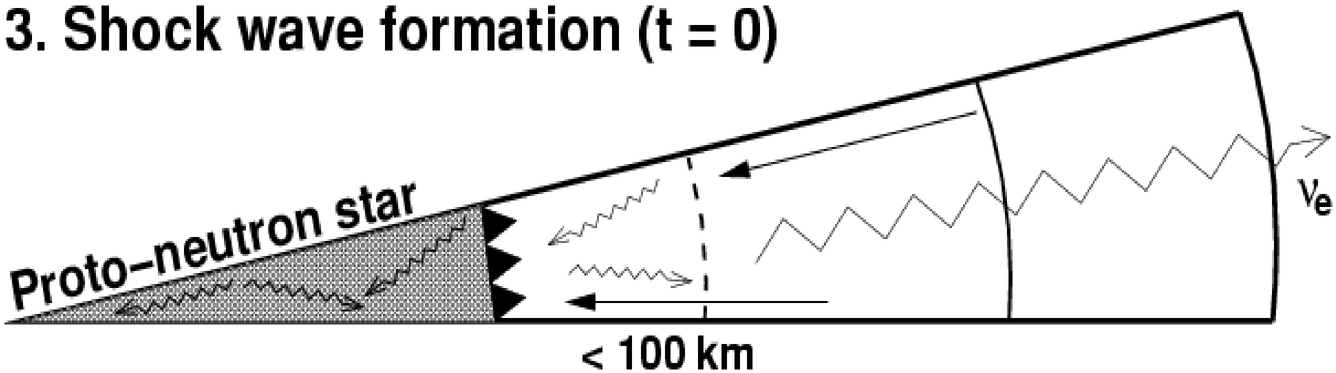
Supernova Neutrino Emission: *Neutrino Trapping*



- Core density increases as collapse continues
- Mean free path of neutrinos shrinks w/ increasing density
- ν trapped by coherent scattering off nuclei:

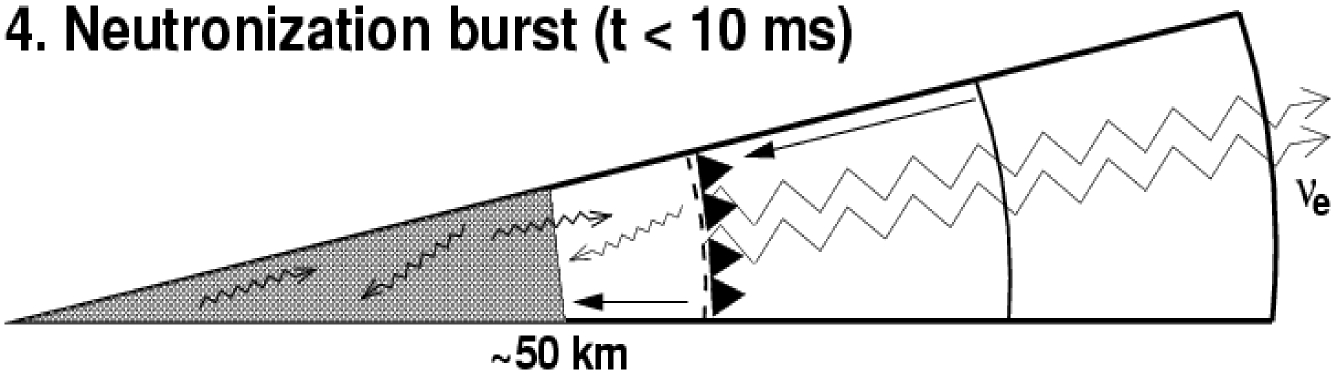
$$\nu + A(N,Z) \rightarrow \nu + A(N,Z)$$

Supernova Neutrino Emission: *Shock Wave Formation*



- Inner core reaches nuclear densities
- Neutron degeneracy halts gravitation attraction
- Inner core rebounds, causing shock wave
- Shock wave propagates through outer core
- ν-sphere larger; ν still emitted from outer core

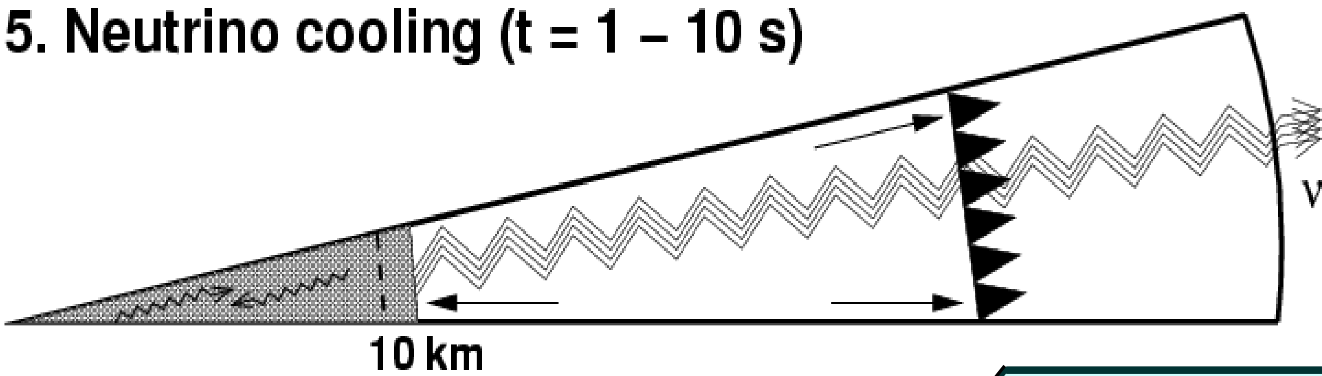
Supernova Neutrino Emission: *Neutronization Burst*



- Shock slows infall and dissociates nucleons
- Shock loses 8 MeV per dissociated nucleon
- Electrons captured on dis. protons produce ν_e via:

$$e^- + p \rightarrow \nu_e + n$$

Supernova Neutrino Emission: *Neutrino Cooling*



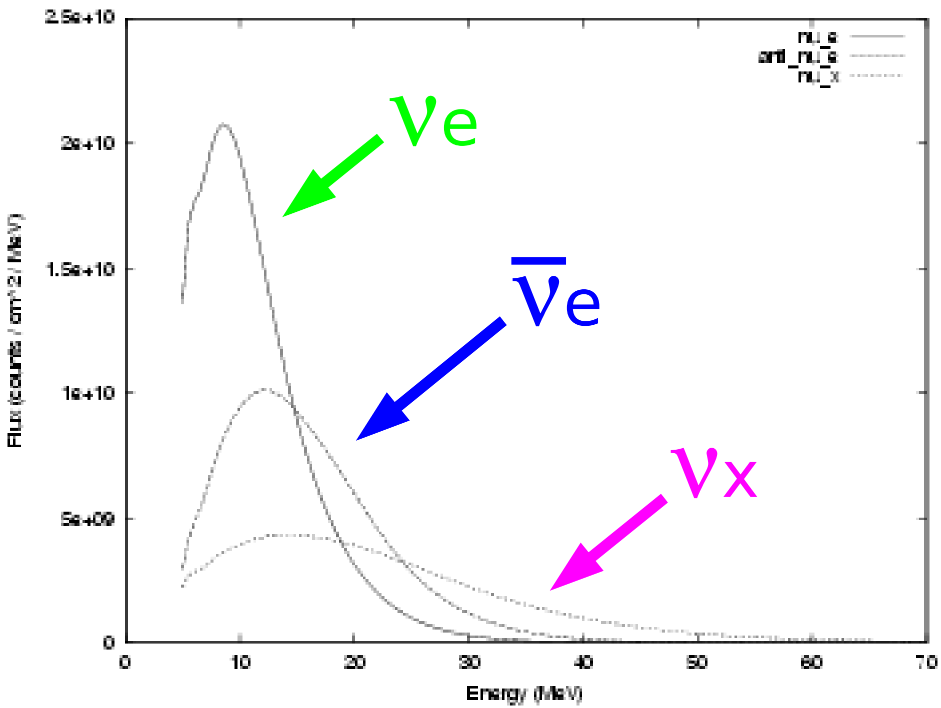
- $E_{grav} \longrightarrow E_{therm}$ ($\sim 10^{53}$ erg)
- $T \simeq 40$ MeV
- Proto-neutron star cools:
- Neutron star (or black hole?) left behind

$$e^- + p \rightarrow \nu_e + n$$
$$e^+ + n \rightarrow \bar{\nu}_e + p$$
$$e^- + e^+ \rightarrow \nu + \bar{\nu}$$
$$e^\pm + N \rightarrow e^\pm + N + \nu + \bar{\nu}$$
$$N + N \rightarrow N + N + \nu + \bar{\nu}$$
$$\gamma (+ e^\pm) \rightarrow \nu + \bar{\nu}$$

Supernova Neutrino Energy Spectra

ν_μ and ν_τ do not experience CC $\longrightarrow$ smaller ν-sphere $\longrightarrow$ higher E

More n than p in proto-neutron star $\longrightarrow$ $\bar{\nu}_e$ decouples before ν_e



K.Takahashi, M.Watanabe & K.Sato, Phys. Lett. B **510**, 189

Average ν Energies:

$< E_{\nu_e} > = 13$ MeV

$< E_{\bar{\nu}_e} > = 16$ MeV

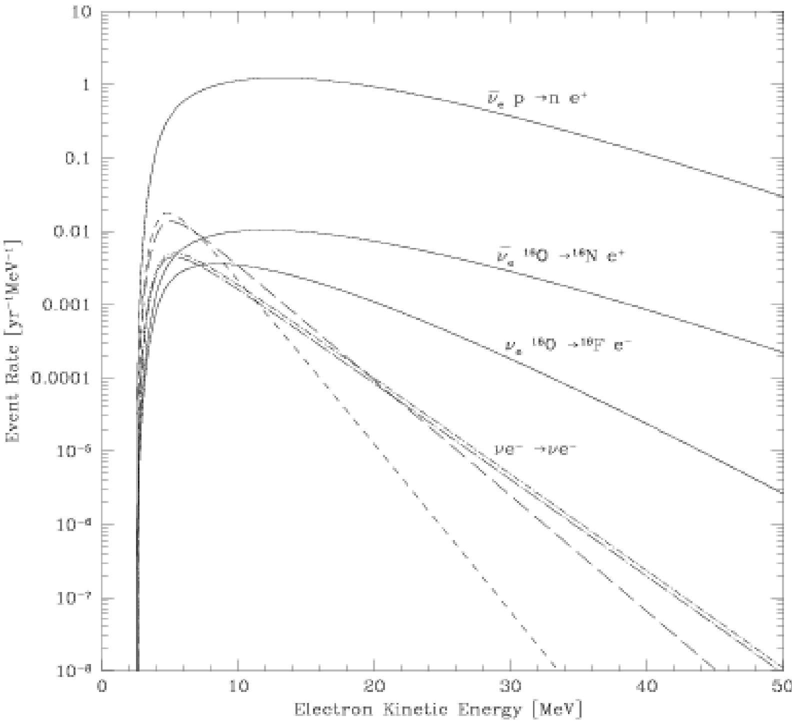
$< E_{\nu_x} > = 23$ MeV

Supernovae Relic Neutrinos

- To date, only SN ν burst seen on 23-Feb-1987 (Sanduleak -69^0 202)
- Diffuse backgrnd of SN relic ν should exist! (Called 'SRN')
- All 6 types of ν emitted in SN <u>BUT</u> we only search for $\bar{\nu}_e$
- Inverse β x-section dominant:

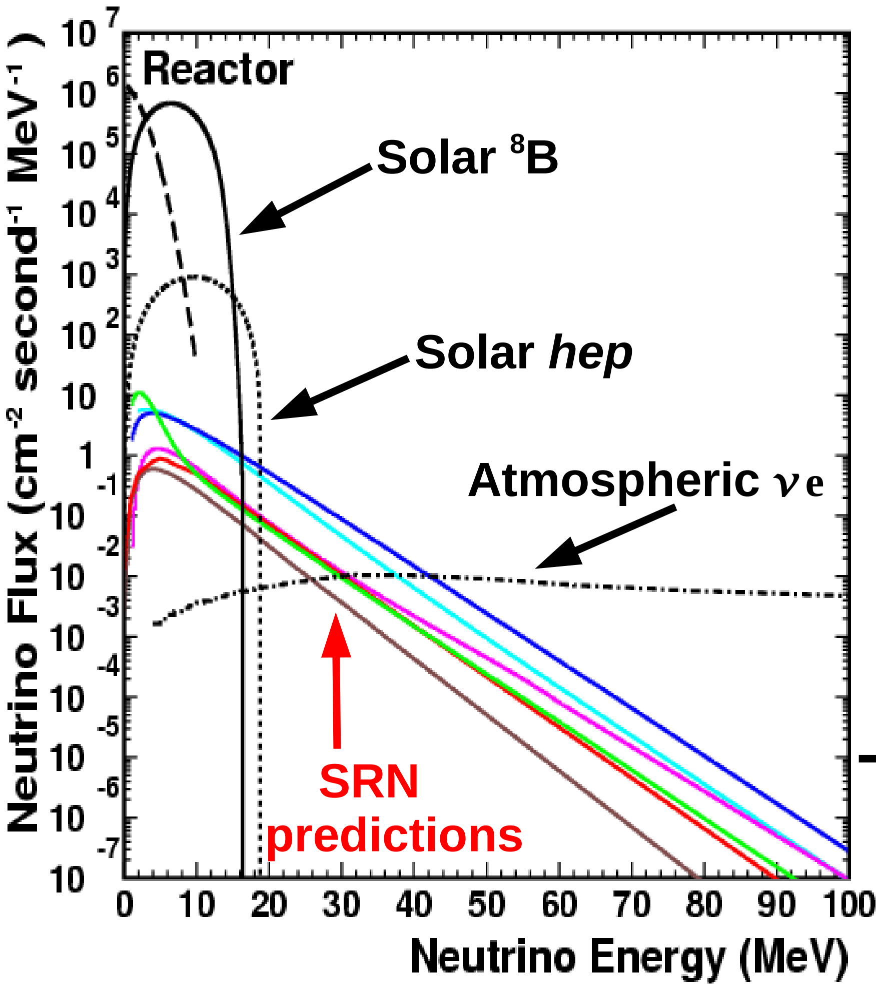
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$(E_e = E_\nu - 1.3 \text{ MeV})$$



T.Totani & K.Sato, Astropart. Phys. **3**, 367

Theoretical Models

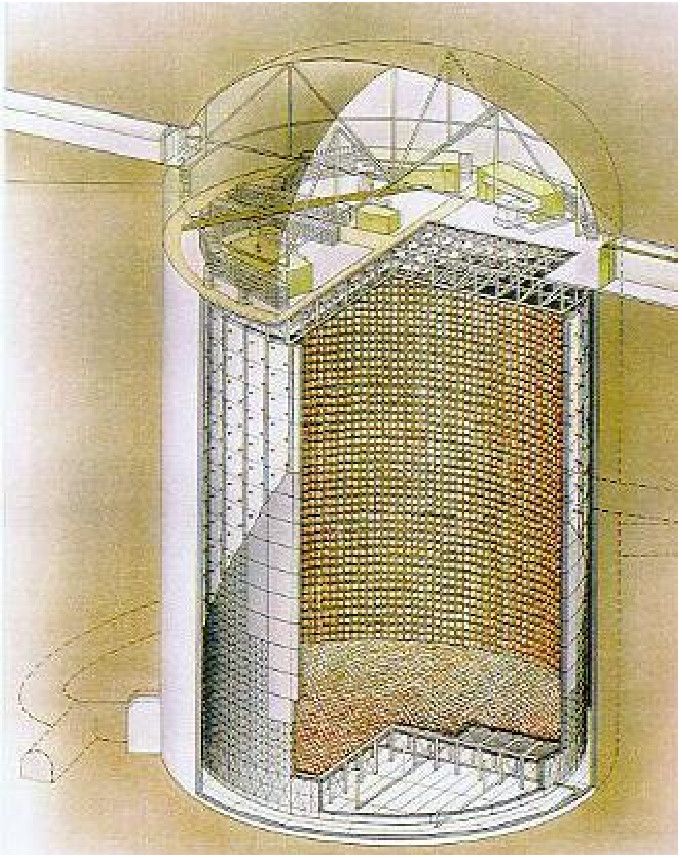


- Predictions generated from SN model, cosmology, etc.
- SRN detection provides info on SN rate, SFR, galaxy ev.
- Low thresh → probe high Z
- Flux predictions:

$F_{SRN} = 2 - 54\ \bar{\nu}_e\ cm^{-2}\ s^{-1}$

Population synthesis (Totani *et al.*, 1996)
Constant SN rate (Totani *et al.*, 1996)
Cosmic gas infall (Malaney, 1997)
Cosmic chemical evolution (Hartmann *et al.*, 1997)
Heavy metal abundance (Kaplinghat *et al.*, 2000)
LMA ν oscillation (Ando *et al.*, 2002)

The Super-Kamiokande Detector

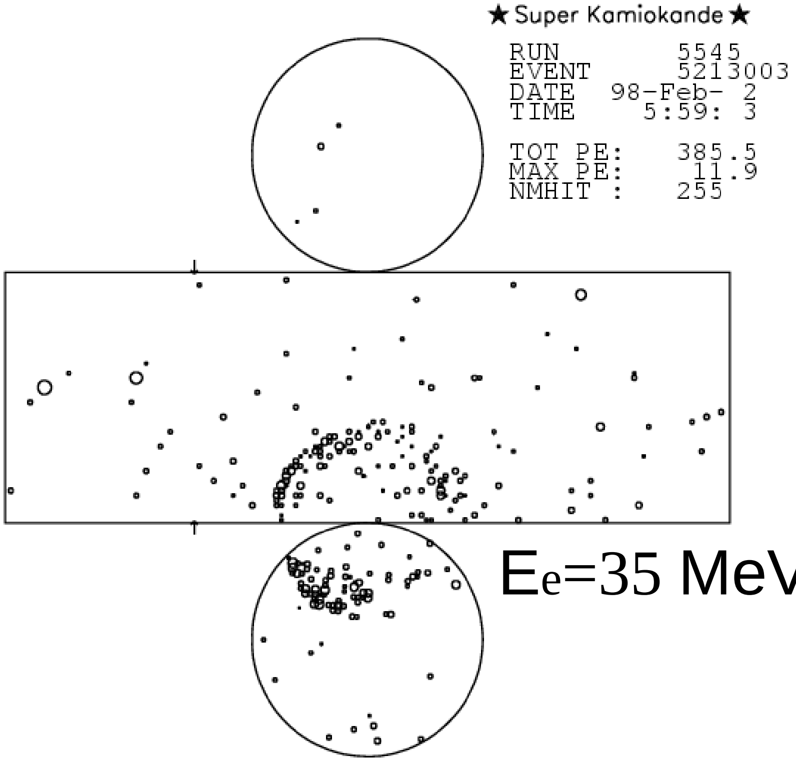


- 50,000 ton water Cherenkov detector
- Located 1,000 m underground
- 11,146 inward-facing 50 cm PMTs view fiducial volume (22,500 t)
- 1,885 outward-facing 20 cm PMTs monitor incoming events
- 5 MeV energy threshold

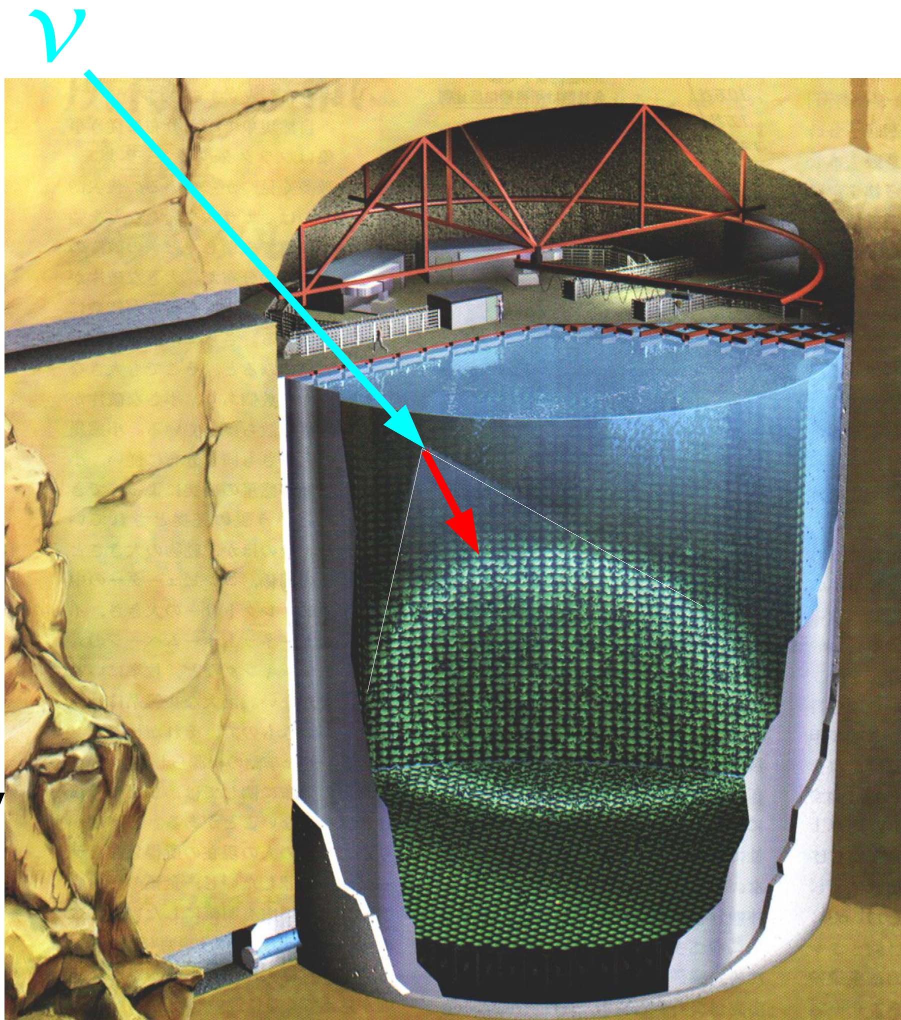
Detection Method

Solar: $\nu_e + e^- \rightarrow \nu_e + e^-$

SN: $\overline{\nu}_e + p \rightarrow e^+ + n$

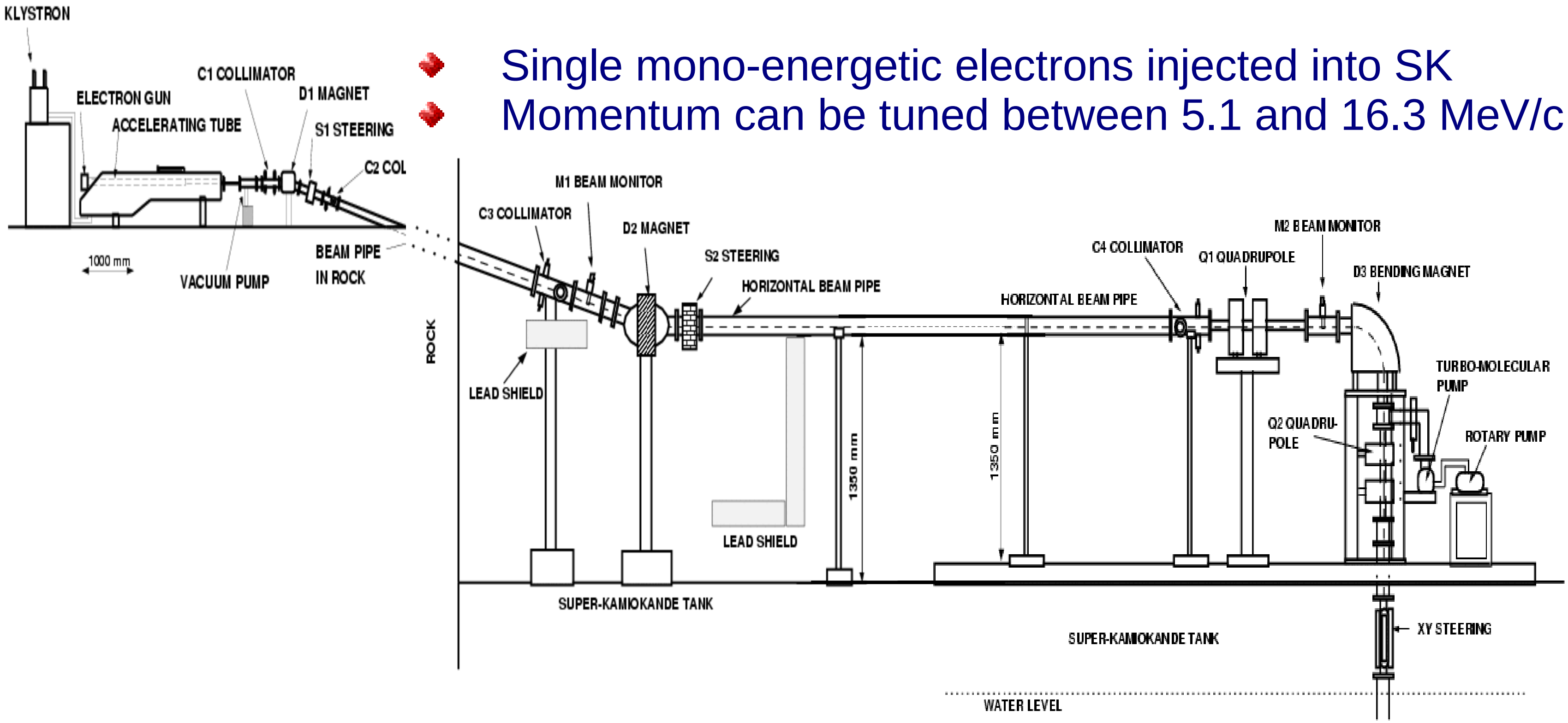


E_e=35 MeV



The LINAC Calibration System

- Single mono-energetic electrons injected into SK
- Momentum can be tuned between 5.1 and 16.3 MeV/c



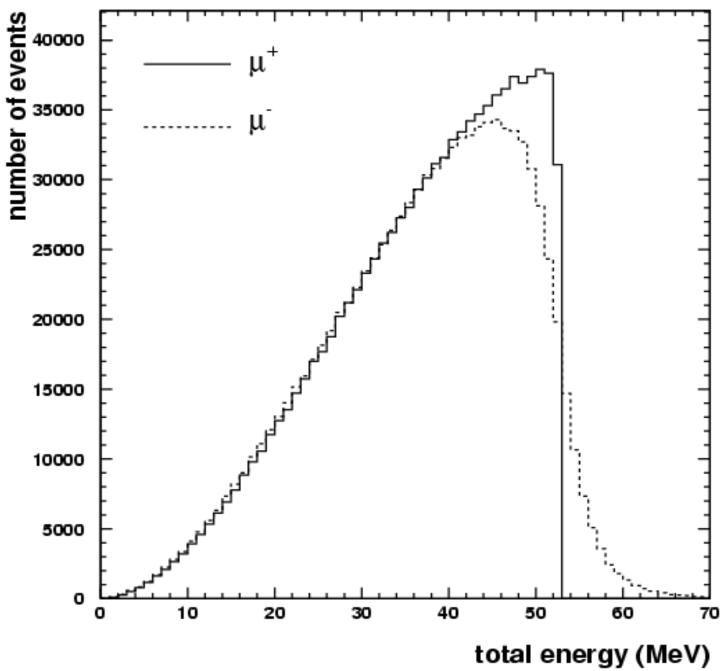
- Position of LINAC electrons known to within few mm
- LINAC used to calibrate absolute energy scale, & detector resolutions (angular, vertex and energy)

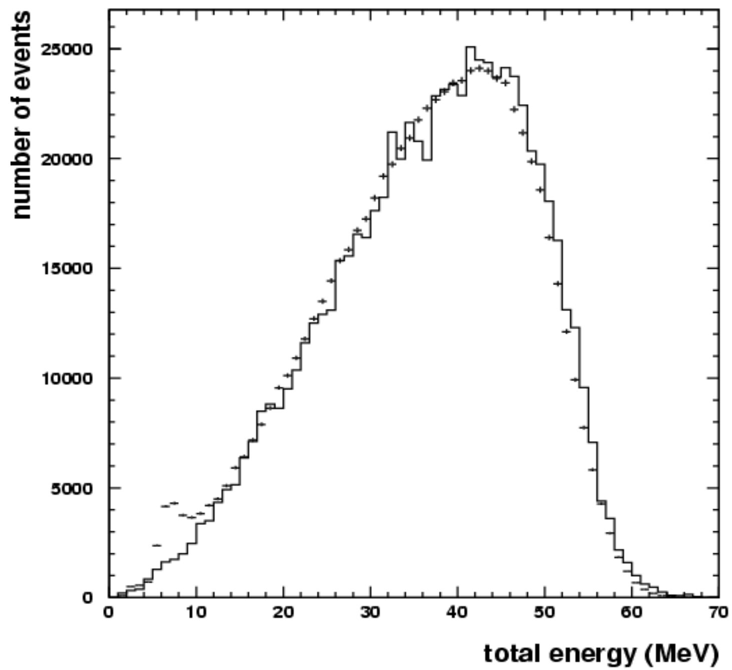
Energy Calibration for E > 18 MeV

Use μ-e decay for E-scale

μ^+ gives basic Michel spec.

μ^- can be captured on ^{16}O





Ave. μ-e event has E = 37 MeV

Systematics: 1.23% ± 0.24%

SRN Data Reduction

We cannot 'tag' SRN events! Understanding BG vital!

Reducible

- μ induced spallation
- Atmospheric ν_μ
- Nuclear de-excitation γ
- Solar neutrinos

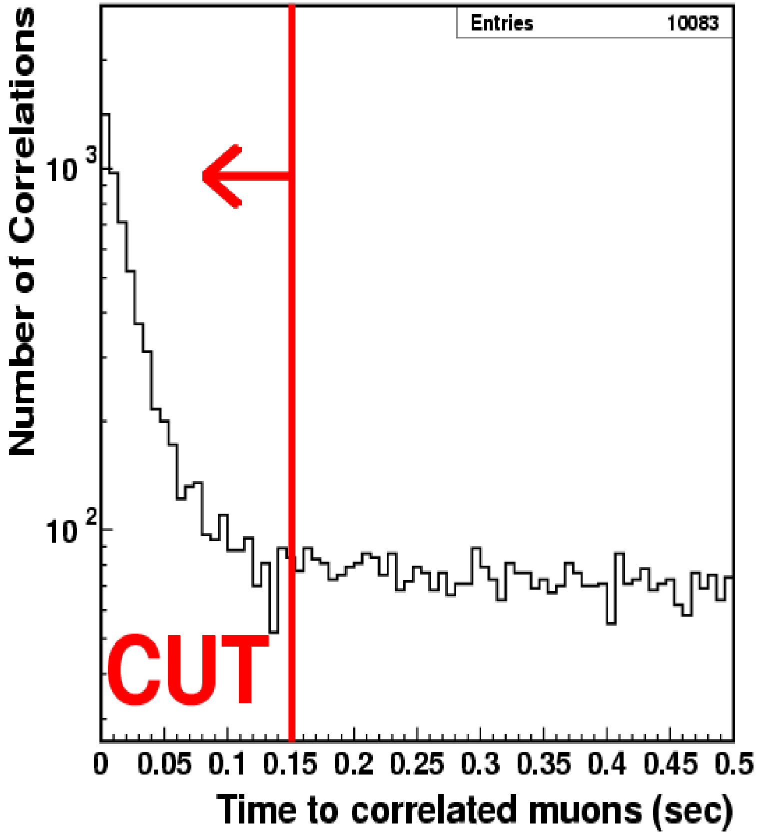
Irreducible

- Atmospheric ν_e
- Atm. $\nu_\mu \rightarrow \mu \rightarrow$ Decay-e [Muon is "invisible"]

Strategy: Remove 'reducible' BG with cuts
Differentiate 'irreducible' BG from SRN signal by shape

Spallation Cut

- Cosmic ray μ spall ^{16}O nuclei
  → emit β particles
- E_β = 3-21 MeV ; $\tau_\beta > 8.5$ msec
  Apply spallation cut to data w/ E < 34 MeV (due to E_{res} of SK)
- Cut all events with $\Delta T < 0.15s$.
  Likelihood func. uses ΔT & ΔL to cut long-lived spallation
- Ability to remove spallation sets lower threshold (18 MeV)

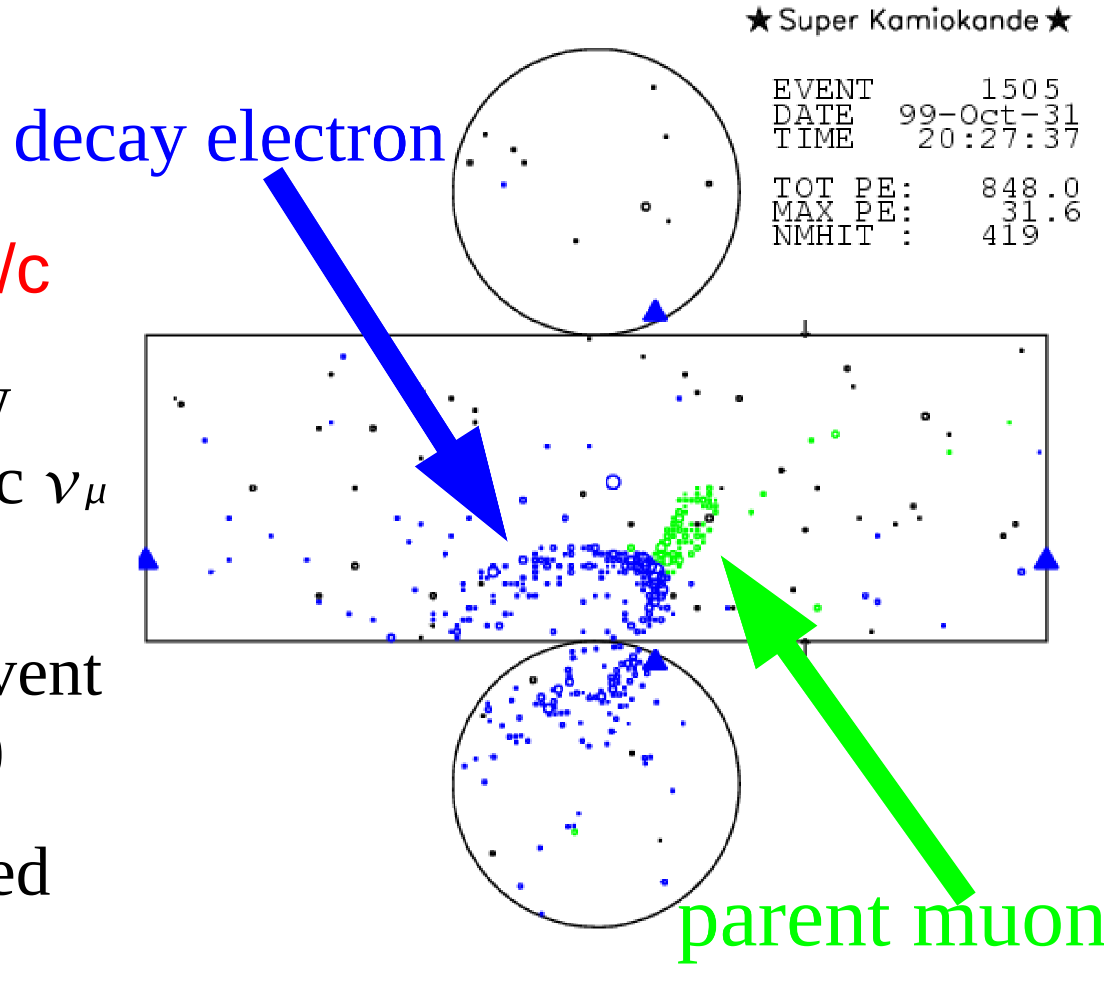


Sub-Event Cut

- Cut designed to remove μ with:

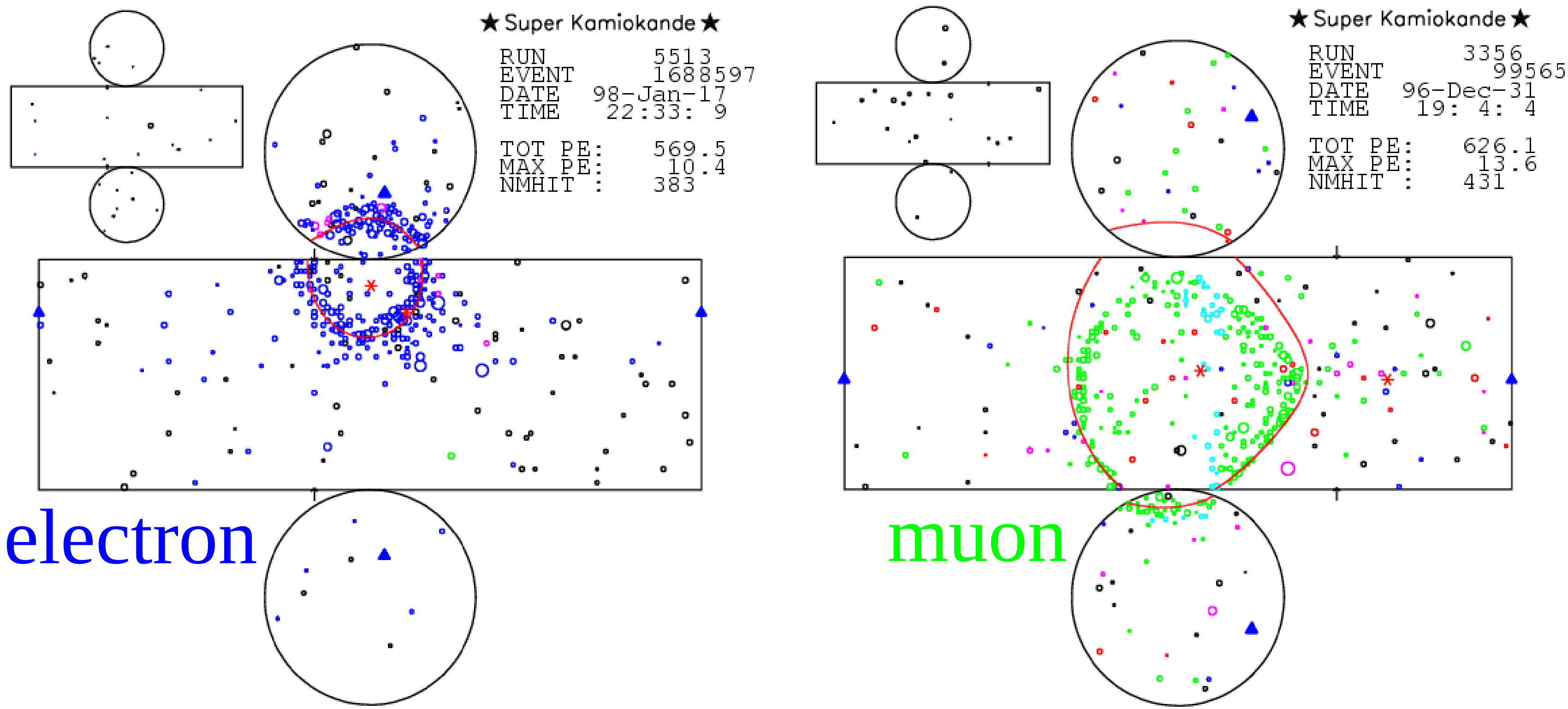
  $p_\mu < 350$ MeV/c

- μ created from low energy atmospheric ν_μ
- Search for decay electron in same event (two timing peaks)
- 34% of μ eliminated

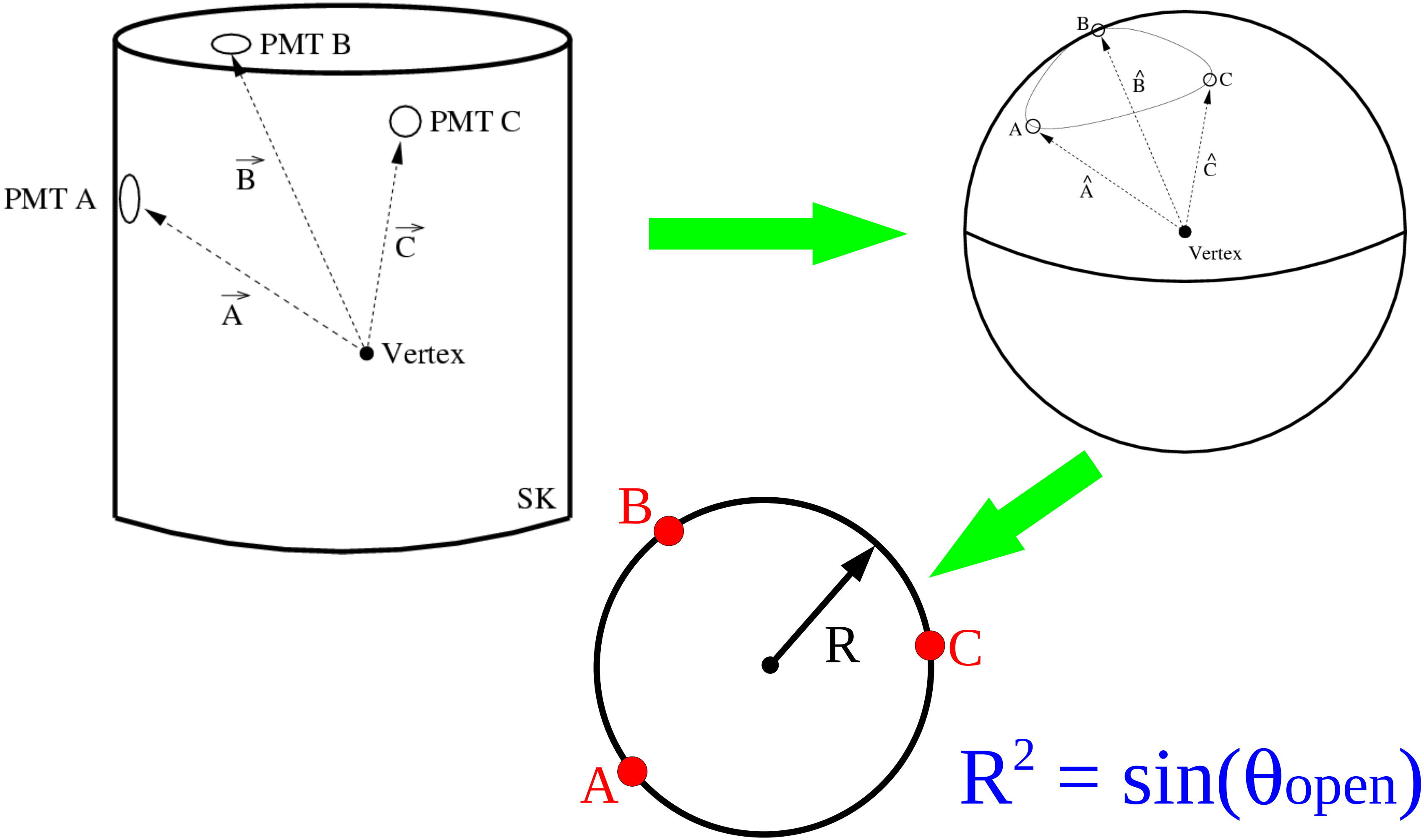


Cherenkov Angle Cut: *Basic Idea*

- Remaining μ tagged by Cherenkov angle
- Look for a collapsed ring: $\cos(\theta_C) = 1 / (n \bullet \beta)$

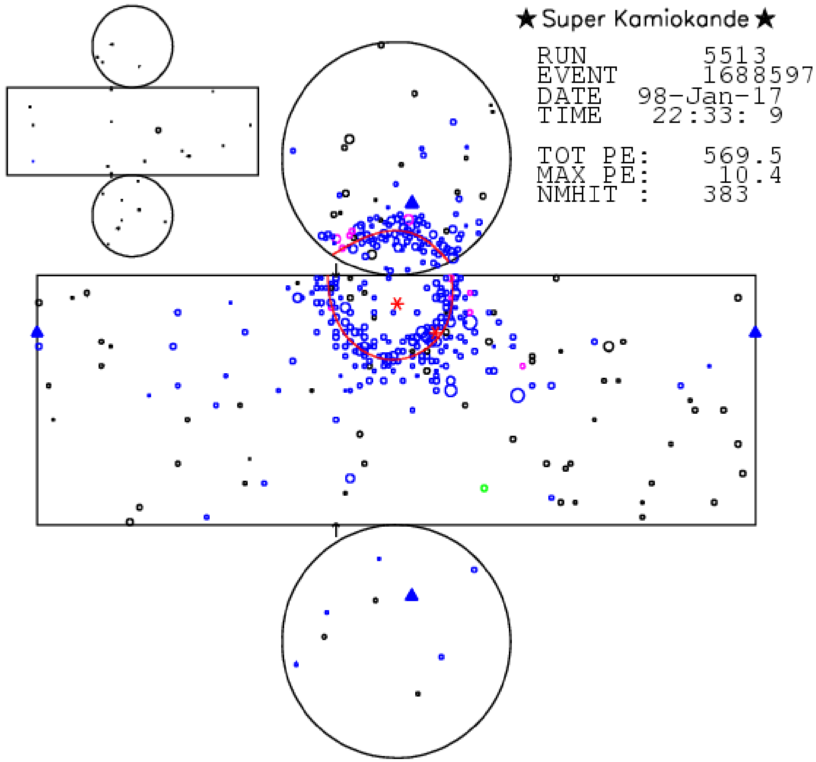


Cherenkov Angle Cut: *Reconstruction Method*



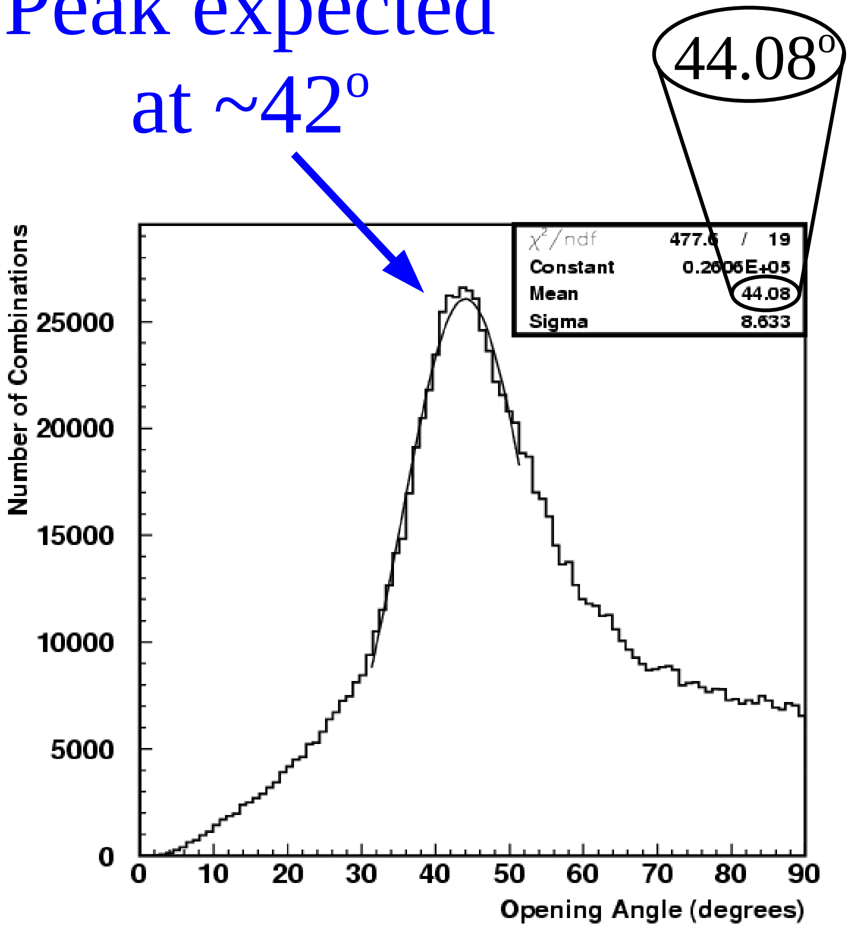
$$R^2 = \sin(\theta_{open})$$

Cherenkov Angle Cut:
Electron Reconstruction

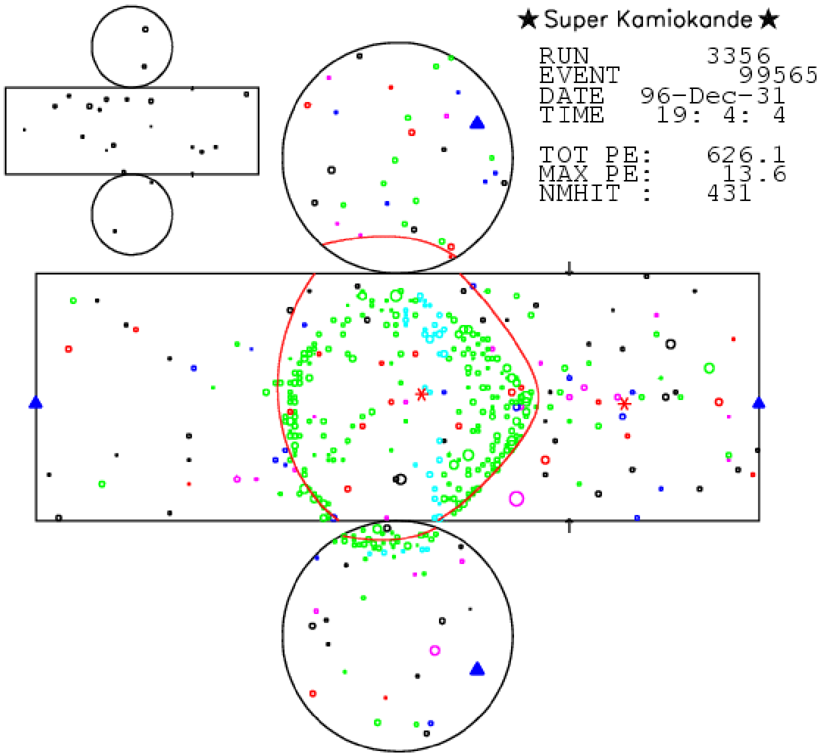


(Ee = 59 MeV)

Peak expected at ~42°

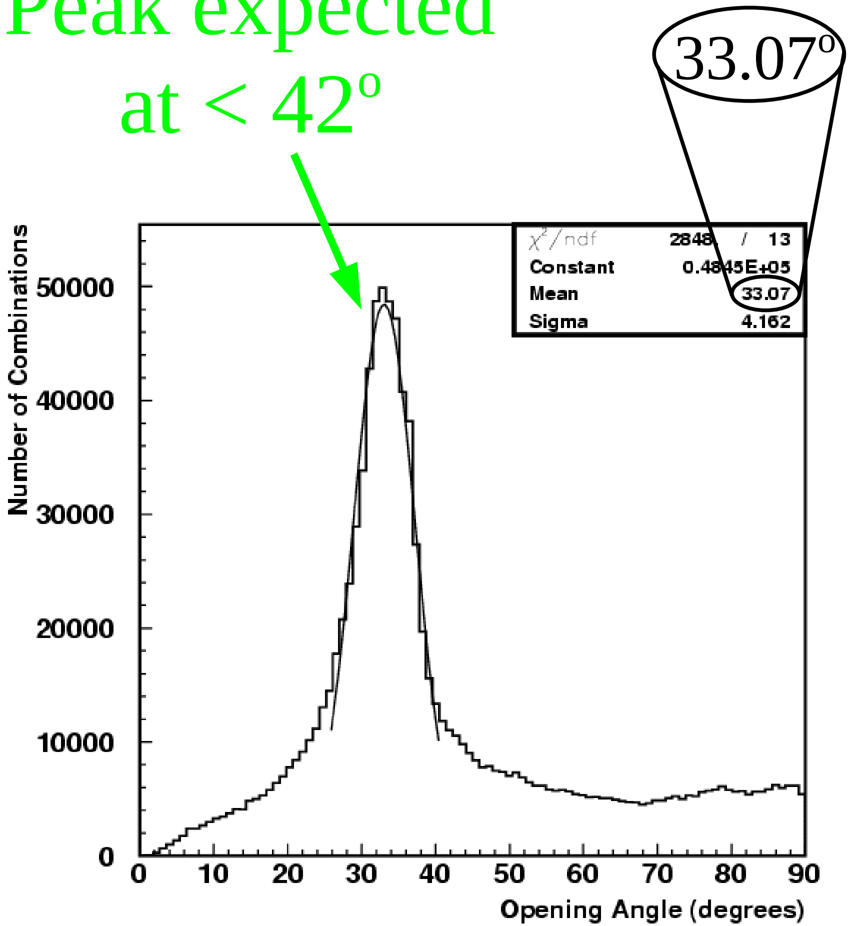


Cherenkov Angle Cut: *Muon Reconstruction*



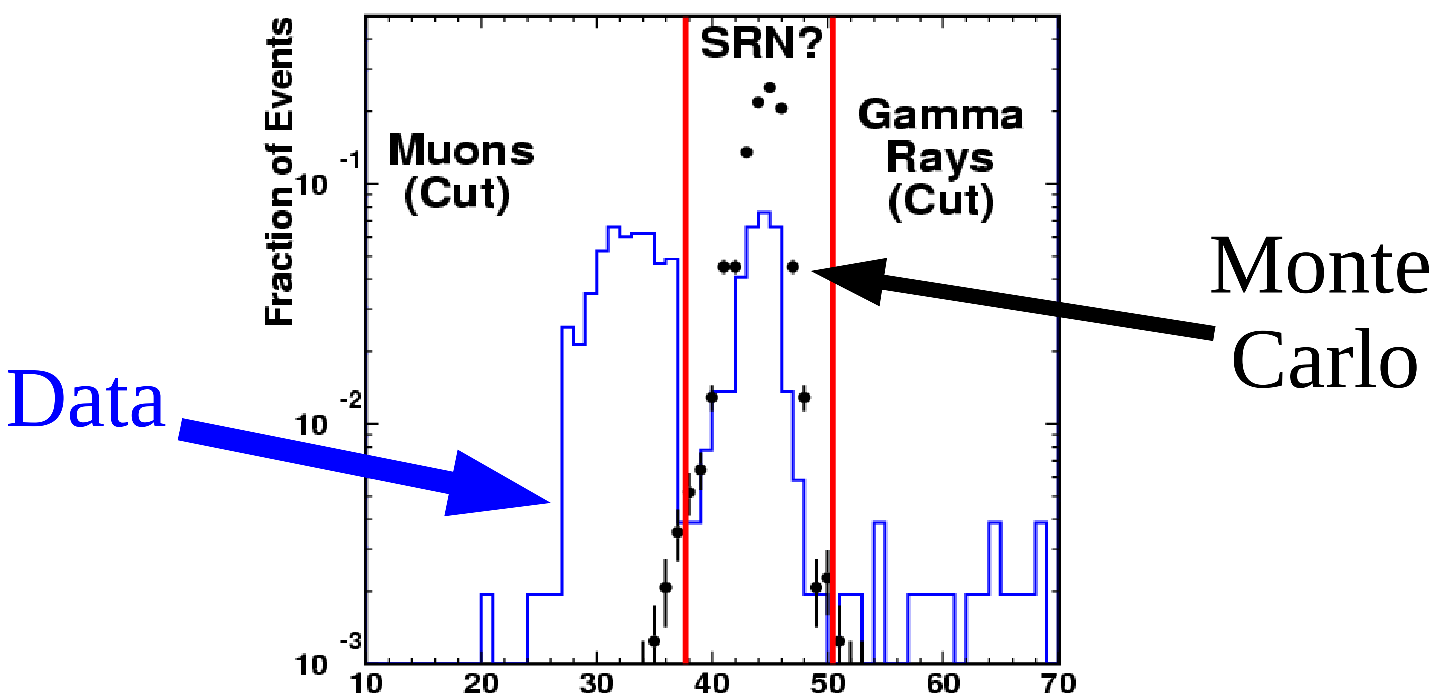
(Eμ = 68 MeV)

Peak expected at < 42°

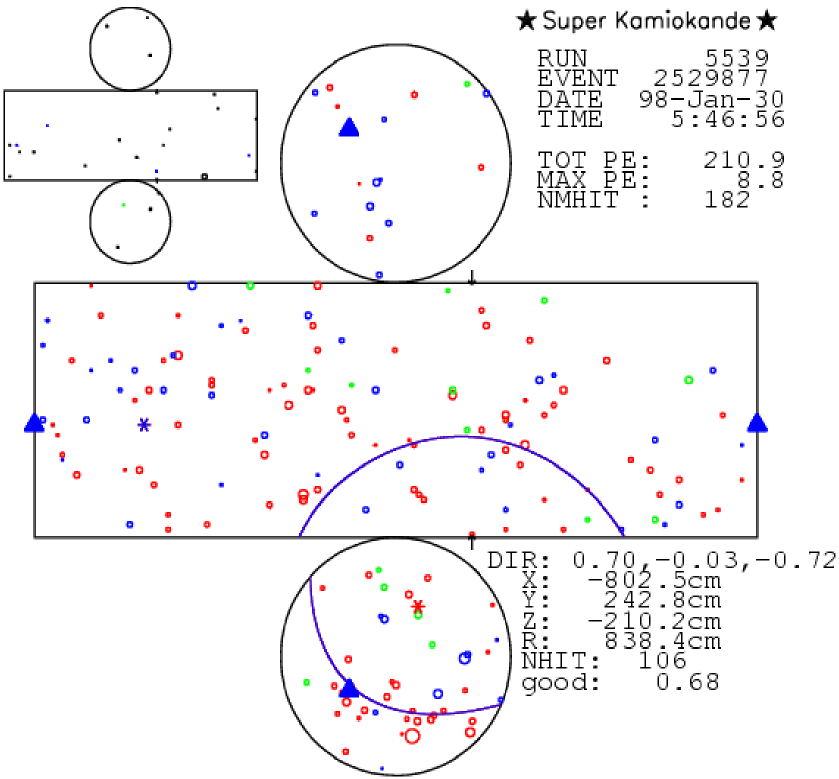


Cherenkov Angle Cut: *Cut Results*

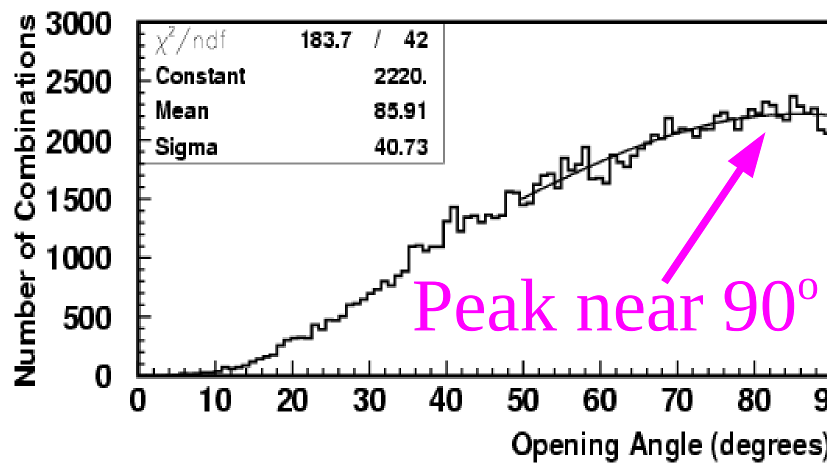
- Cut events w/ $\theta_C < 38^0$ to remove > 97% of μ
- Cut events w/ $\theta_C > 50^0$ to remove nuclear de-excitation events

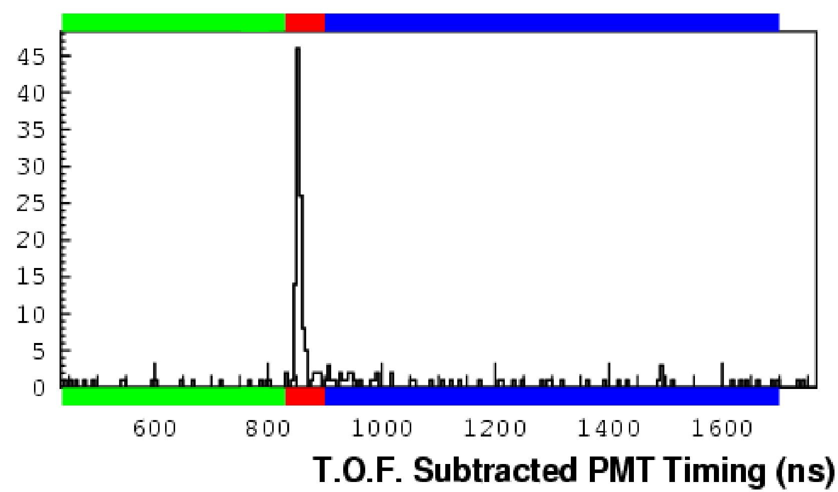


Cherenkov Angle Cut: *Multi-γ Reconstruction*



(E = 20 MeV)



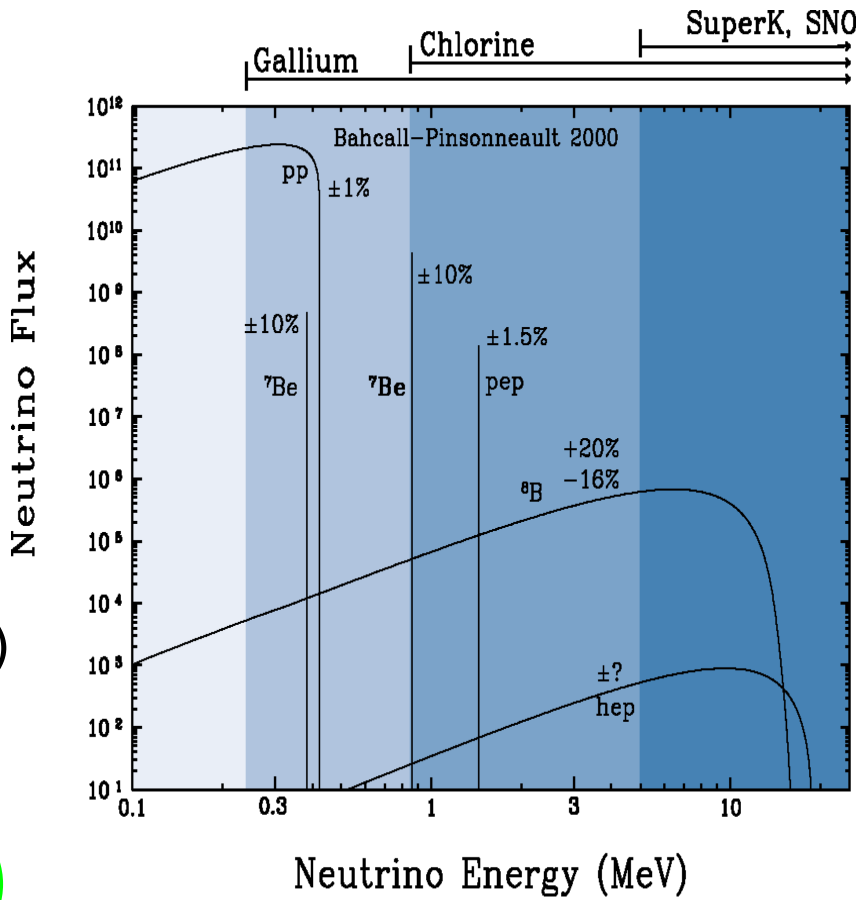


Solar Direction Cut: *Motivation*

- **Solar neutrinos:**
  created by nuclear fusion in the Sun

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

- Flux & spectra calculated by the Standard Solar Model



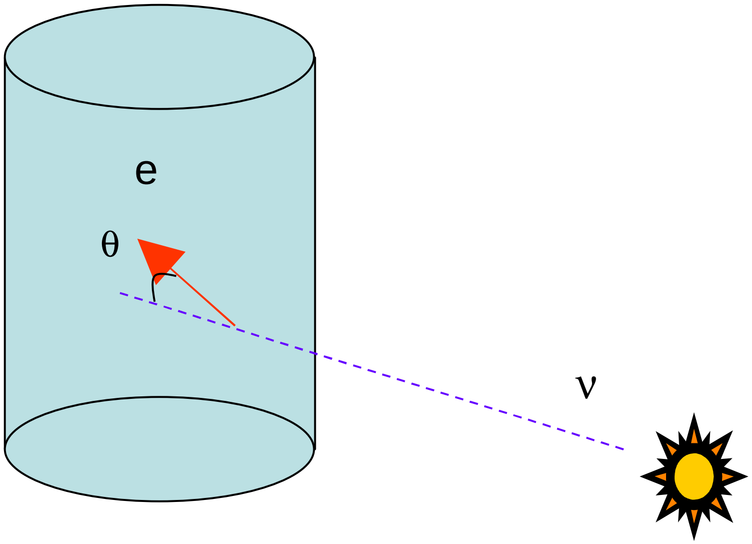
Flux:

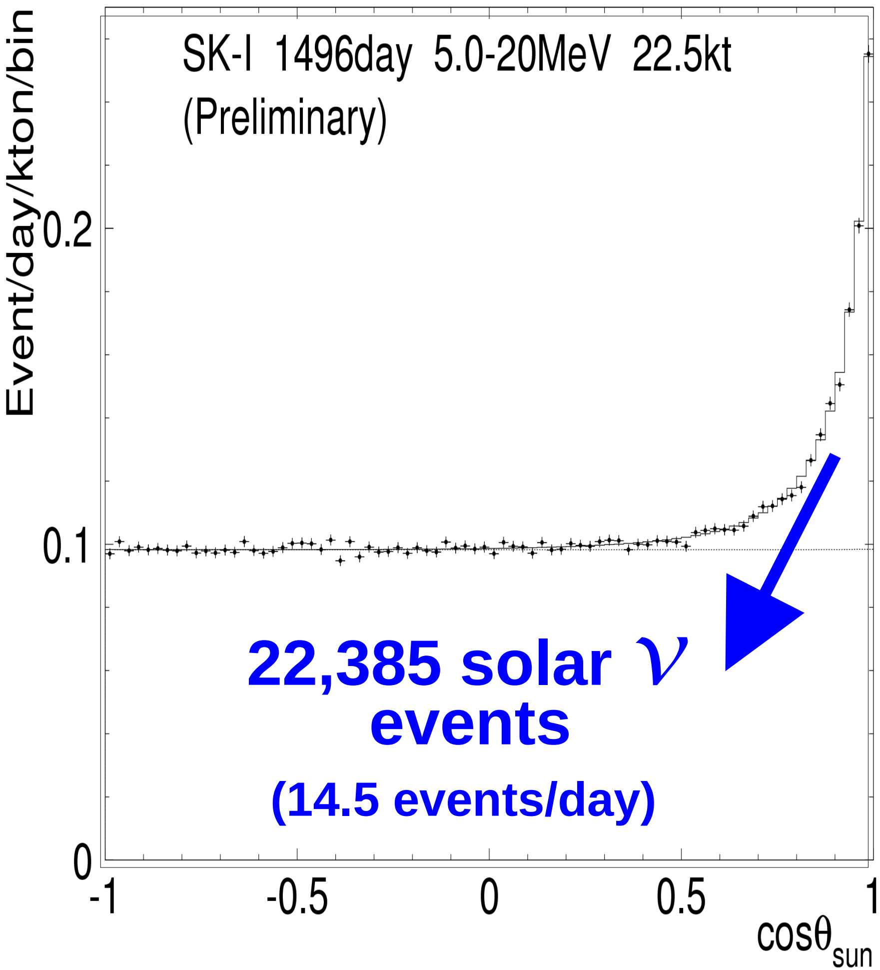
[Units are (10^{10} cm $^{-2}$ sec $^{-1}$)]

pp	5.96	(1.00±0.01)
pep	1.40×10^{-2}	(1.00±0.015)
hep	9.3×10^{-7}	(1.00±???)
^{7}Be	4.82×10^{-1}	(1.00±0.10)
^{8}B	5.05×10^{-4}	$\left(1.00\ {}^{+0.20}_{-0.16}\right)$

http://www.sns.ias.edu/~jnb

Solar Neutrino Detection





^{8}B flux :

2.35 ± 0.02 ± 0.08 [x 10^6 /cm²/sec]

$0.465 \pm 0.005^{+0.016}_{-0.015}$ x SSM

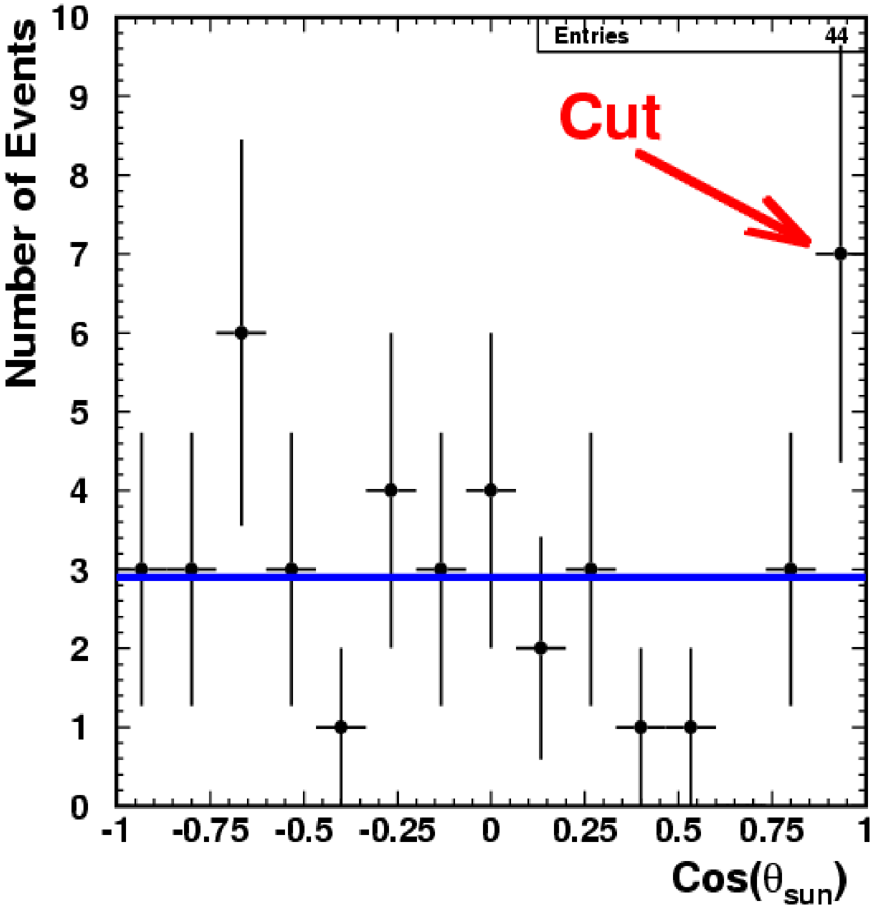
22,385 solar ν events

(14.5 events/day)

Solar Direction Cut

- 18 MeV threshold is below *hep* cut-off → SSM predicts 1.06 events
- Potential contamination from ^{8}B due to smearing
- Remove all events that point back to 30° of Sun AND have E < 34 MeV

E = 18 – 34 MeV



Reduction Summary

1602 events — Before spa. cut (E = 18 – 82 Mev)

992 events — After spallation cut (E < 34 MeV)

828 events — After sub-event cut

278 events — After θ_C cut

271 events — After solar ν cut (E < 34 MeV)

Reduction Summary (cont.)

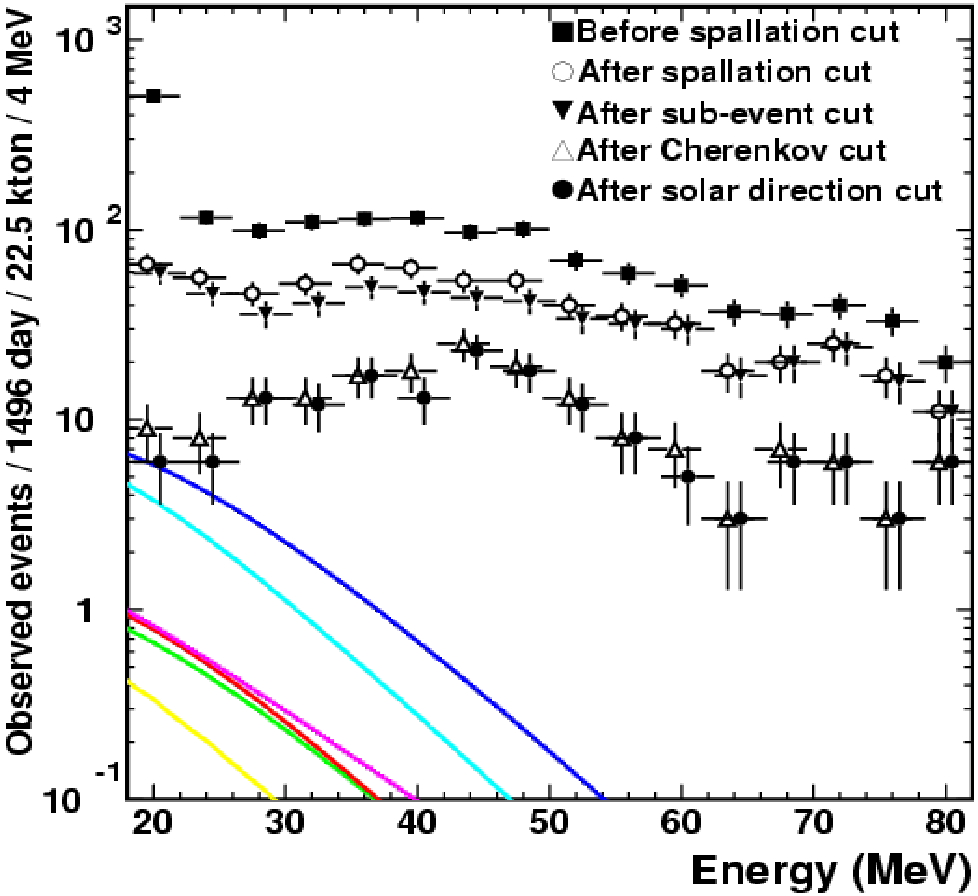
Final Efficiencies

For E ≤ 34 MeV,

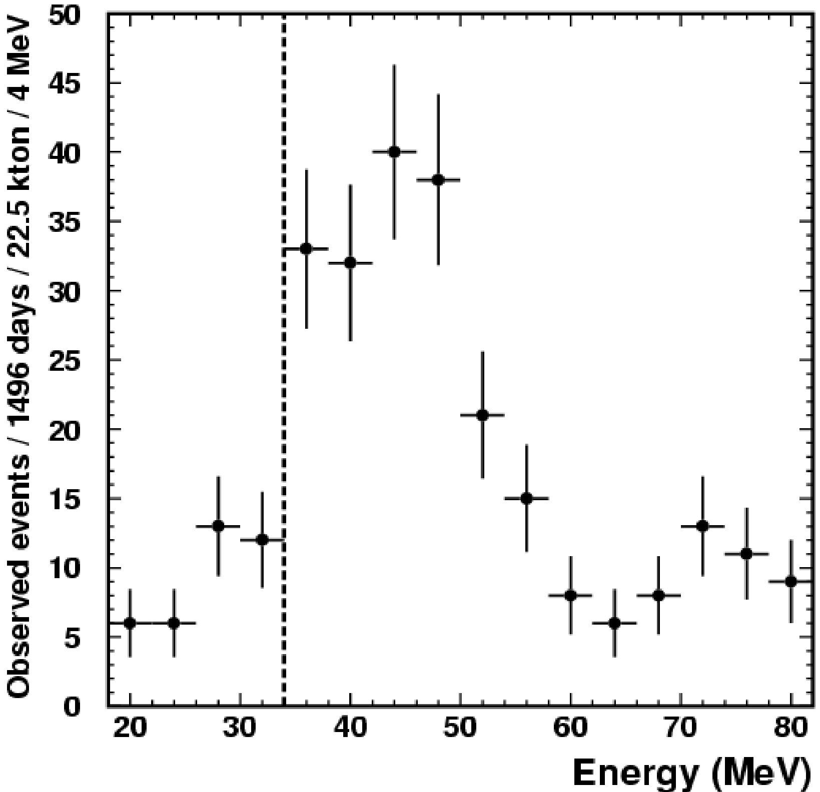
$\varepsilon = 47\% \pm 0.4\%$

For E > 34 MeV,

$\varepsilon = 79\% \pm 0.5\%$

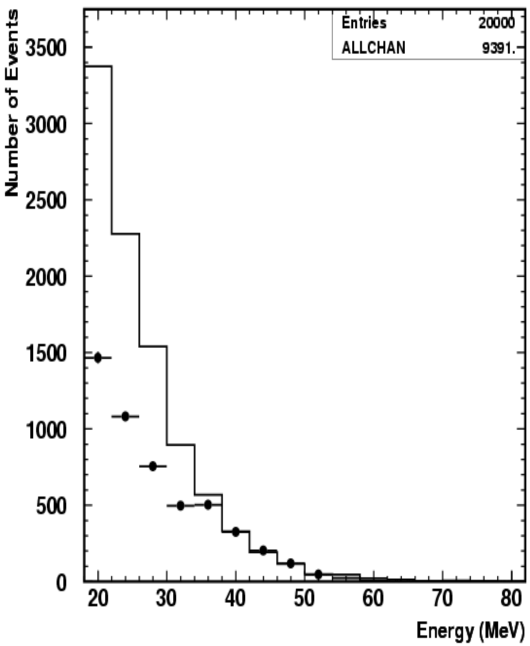


Final Data Sample

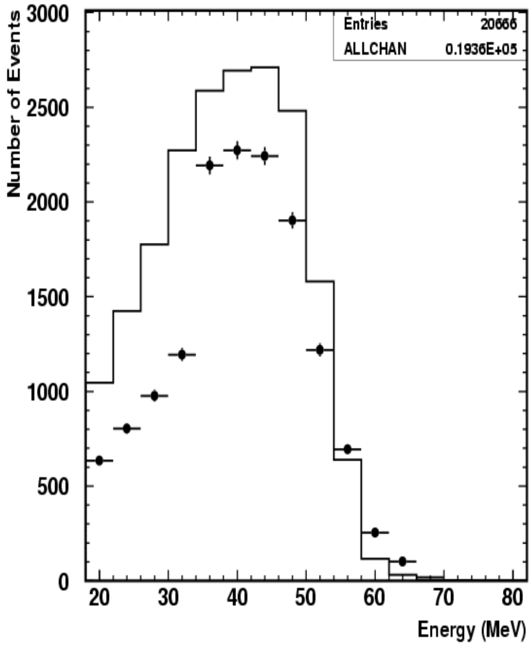


Signal & BG Shapes: Monte Carlo

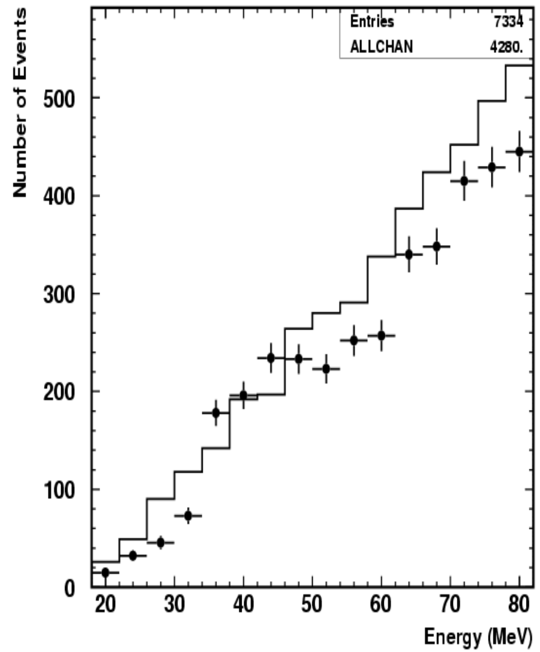
SRN Signal:



Decay-e:



Atm. ν_e:

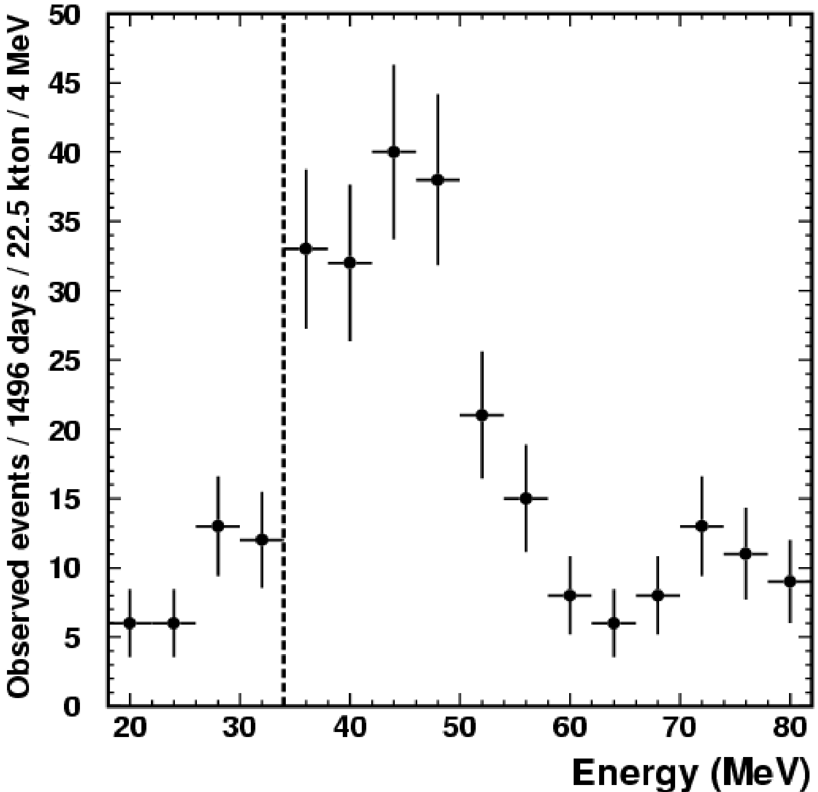


Signal falls sharply w/ inc. energy; BG shape rises

$\rightarrow$ Use shape difference to extract SRN signal

Fitting the Final Data

$$\chi^2 = \sum_{l=1}^{16} \frac{[(\alpha \bullet A_l) + (\beta \bullet B_l) + (\gamma \bullet C_l) - N_l]^2}{\sigma_{stat}^2 + \sigma_{sys}^2}$$



Fitting the Final Data

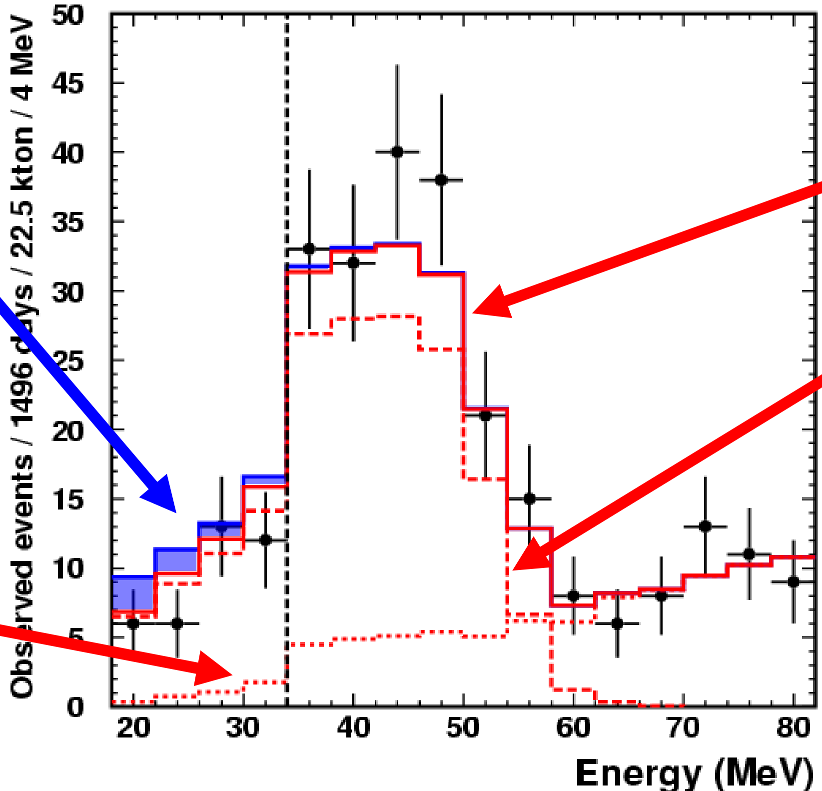
$$\chi^2 = \sum_{l=1}^{16} \frac{[(\alpha \bullet A_l) + (\beta \bullet B_l) + (\gamma \bullet C_l) - N_l]^2}{\sigma_{stat}^2 + \sigma_{sys}^2}$$

Total B.G. + 90% C.L. SRN limit

Total background (Atm. + decay e)

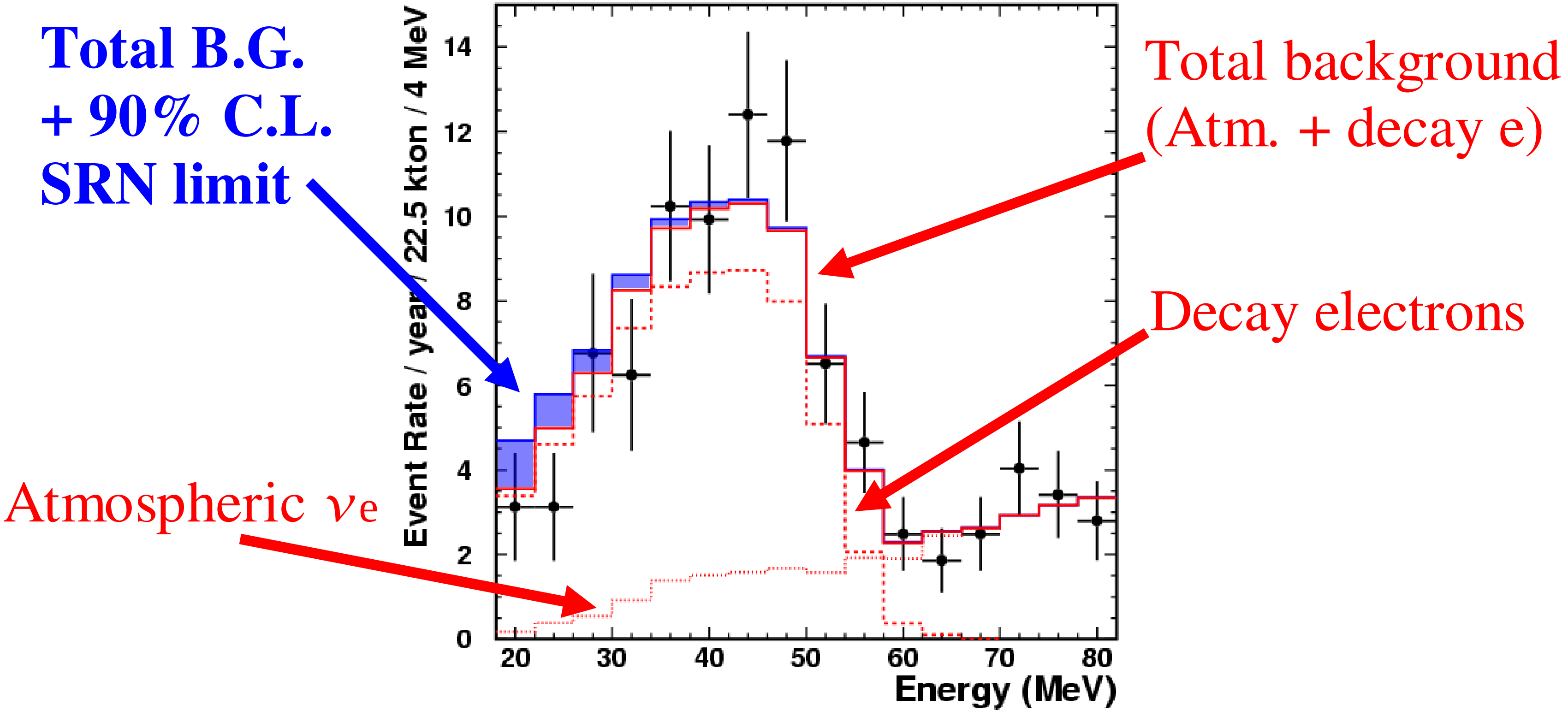
Decay electrons

Atmospheric ν_e



Efficiency-Corrected Data

$$N_i' = \frac{N_i}{\varepsilon(E_i)} \times \frac{365\ \text{days}}{\tau}$$



Background Event Rates

<u>Michel Electrons</u>

- Best fit to data:

  174 ± 16 events

- Expected from MC:

  145 ± 43 events

<u>Atmospheric</u> (ν_e)

- Best fit to data:

  88 ± 12 events

- Expected from MC:

  75 ± 23 events

Expected backgrounds fit data well!
Best fit to α (# SRN events) is ZERO for all six models.

Flux Calculation

Use 90% C.L. limit on α to get full spectrum flux limits:

Where:

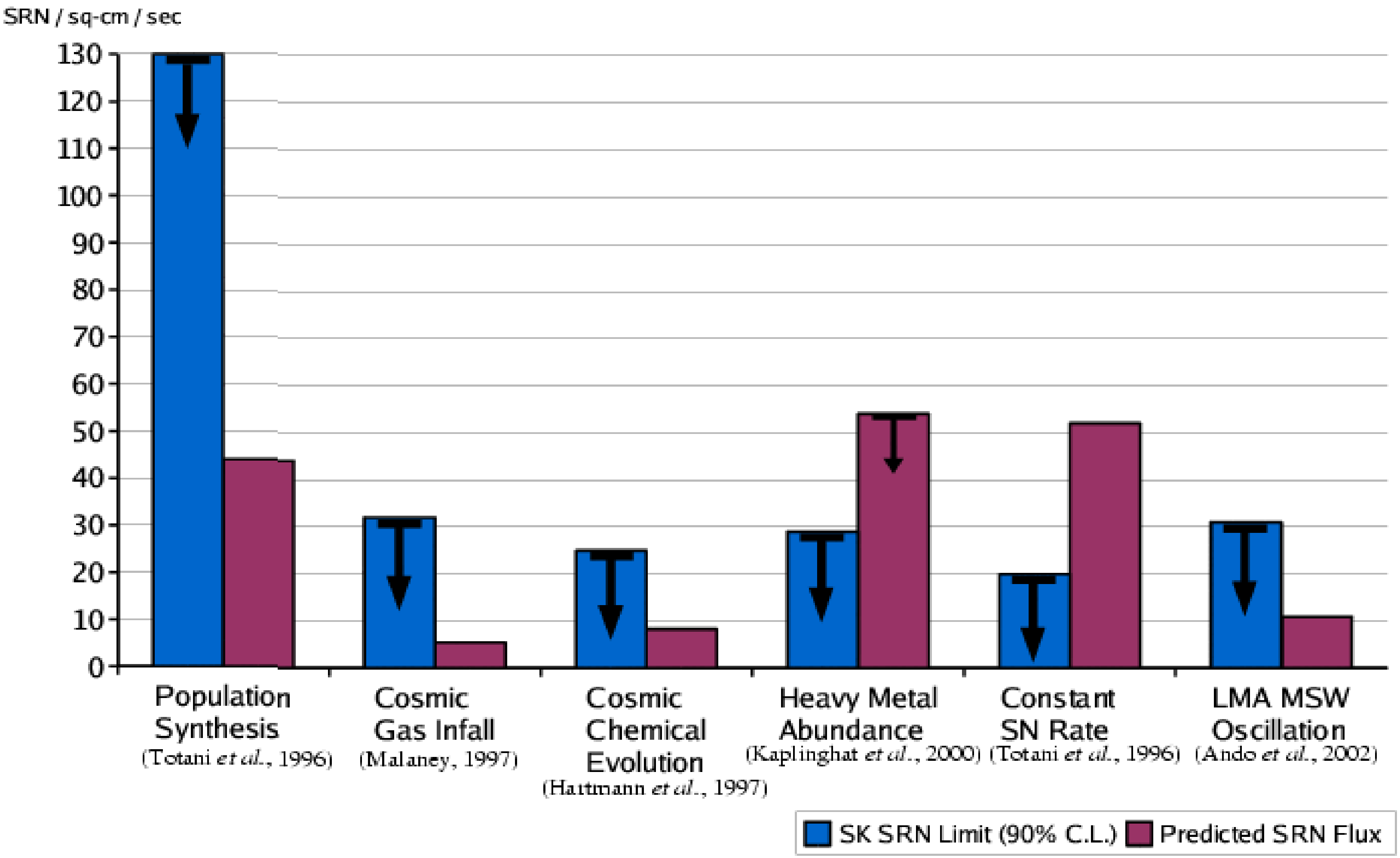
$$F = \frac{\alpha_{90}}{N_p \times \tau \times \int f(E_\nu)\, \sigma(E_\nu)\, \varepsilon(E_\nu)\, dE_\nu}$$

- N_p = # of free protons in SK = 1.5×10^{33}
- τ = detector livetime = 1496 days = 1.29×10^{8} seconds
- $f(E_\nu)$ = normalized SRN spectrum shape function
- $\sigma(E_\nu)$ = cross section = $9.52 \times 10^{-44}\, E_e\, p_e$
- Integral runs from E_ν = 19.3 MeV to 83.3 MeV

SRN Search Results

Theoretical Model	SK SRN Rate Limit	SK SRN Flux Limit	Predicted SRN Flux
Population Synthesis	<3.2 Evts / 22.5 kton yr	<130 $\bar{\nu}_e$ / cm^2 sec	44 $\bar{\nu}_e$ / cm^2 sec
Cosmic Gas Infall	<2.8 Evts / 22.5 kton yr	<32 $\bar{\nu}_e$ / cm^2 sec	5.4 $\bar{\nu}_e$ / cm^2 sec
Cosmic Chemical Evolution	<3.3 Evts / 22.5 kton yr	<25 $\bar{\nu}_e$ / cm^2 sec	8.3 $\bar{\nu}_e$ / cm^2 sec
Heavy Metal Abundance	<3.0 Evts / 22.5 kton yr	<29 $\bar{\nu}_e$ / cm^2 sec	<54 $\bar{\nu}_e$ / cm^2 sec
Constant SN Rate	<3.4 Evts / 22.5 kton yr	<20 $\bar{\nu}_e$ / cm^2 sec	52 $\bar{\nu}_e$ / cm^2 sec
LMA Neutrino Oscillation	<3.5 Evts / 22.5 kton yr	<31 $\bar{\nu}_e$ / cm^2 sec	11 $\bar{\nu}_e$ / cm^2 sec

SK Flux Limits vs. Theoretical Predictions



Constant SN Model

- SRN flux scales with SN rate
- 90% C.L. limit on flux $\rightarrow$ 90% C.L. limit on SN rate
- Prediction of 52 $\bar{\nu}_e$ cm^{-2} sec^{-1} corresponds to SN rate of 1.6×10^3 SN $year^{-1}$ Mpc^{-3} (based on ^{16}O abundance)
- SK limit of 20 $\bar{\nu}_e$ cm^{-2} sec^{-1} corresponds to SN rate limit of 6.2×10^2 SN $year^{-1}$ Mpc^{-3} ⟵ TOO LOW!
- Previous best limit (Kam-II) was 780 $\bar{\nu}_e$ cm^{-2} sec^{-1}
- SK limit is better by factor of 39!

Model-Insensitive Limit

- Full spectrum flux limits have strong model dependence, based on spectrum in low energy regions.
- Remove model dependence and get flux in directly observable region (E_ν > 19.3 MeV):

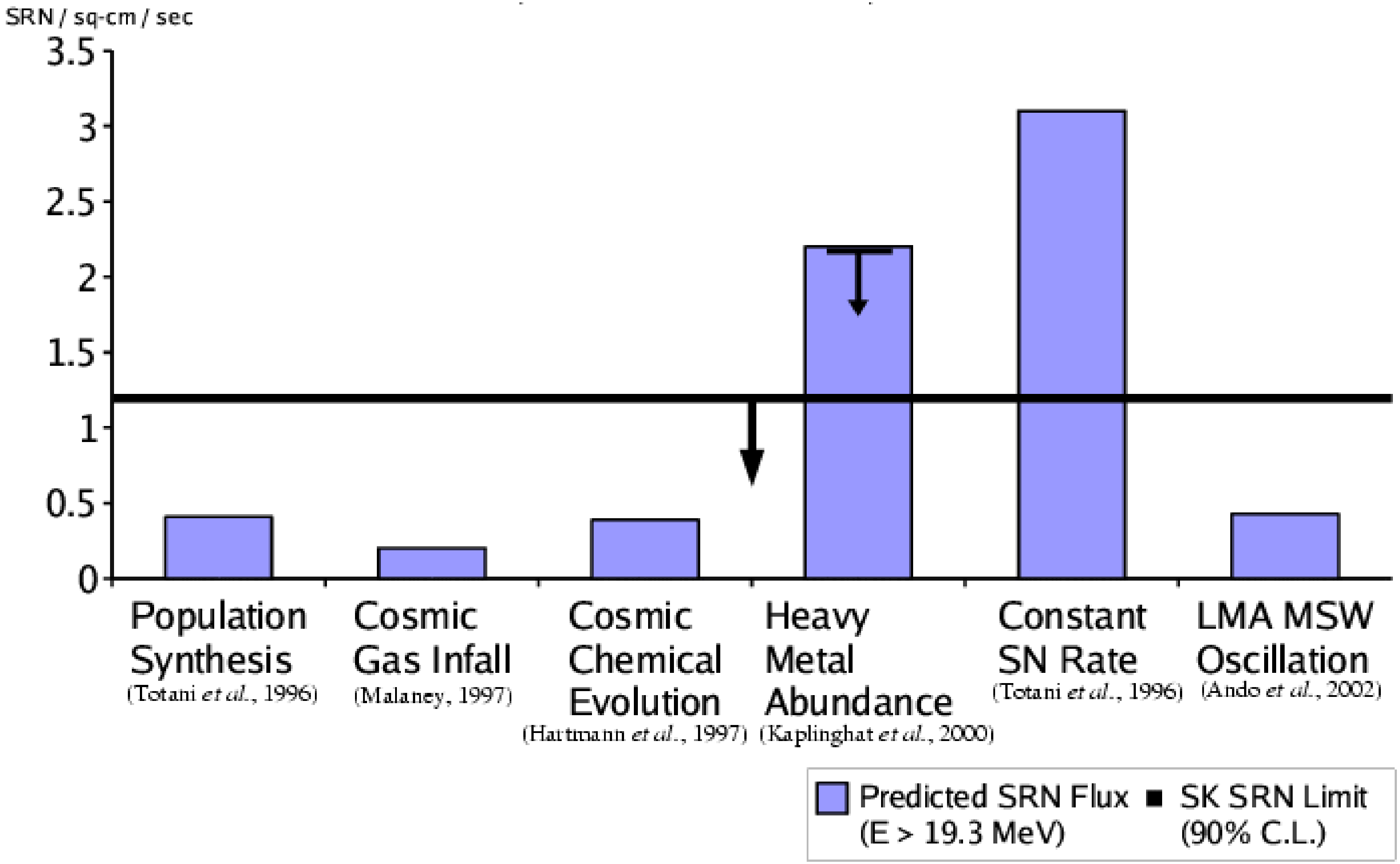
$$F_{insen.} = F \times \frac{\int_{19.3\ \mathrm{MeV}}^{\infty} f(E\nu)\, dE\nu}{\int_{0}^{\infty} f(E\nu)\, dE\nu}$$

- For all models, this limit is same: $< 1.2\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$
- Compare with previous limit: $< 226\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$
[From Kamiokande-II, see W. Zhang *et al.* Phys. Rev. Lett. **61**, 385]

Model-Insensitive Results

Theoretical Model	SRN Flux Limit ($E\nu$ > 19.3 MeV)	Predicted SRN Flux ($E\nu$ > 19.3 MeV)
Population Synthesis	<1.2 $\bar{\nu}_e$ / cm^2 sec	0.41 $\bar{\nu}_e$ / cm^2 sec
Cosmic Gas Infall	<1.2 $\bar{\nu}_e$ / cm^2 sec	0.2 $\bar{\nu}_e$ / cm^2 sec
Cosmic Chemical Evolution	<1.2 $\bar{\nu}_e$ / cm^2 sec	0.39 $\bar{\nu}_e$ / cm^2 sec
Heavy Metal Abundance	<1.2 $\bar{\nu}_e$ / cm^2 sec	<2.2 $\bar{\nu}_e$ / cm^2 sec
Constant SN Rate	<1.2 $\bar{\nu}_e$ / cm^2 sec	3.1 $\bar{\nu}_e$ / cm^2 sec
LMA Neutrino Oscillation	<1.2 $\bar{\nu}_e$ / cm^2 sec	0.43 $\bar{\nu}_e$ / cm^2 sec

Model-Insensitive Results vs. Flux Predictions



Other Experiments

KamLAND

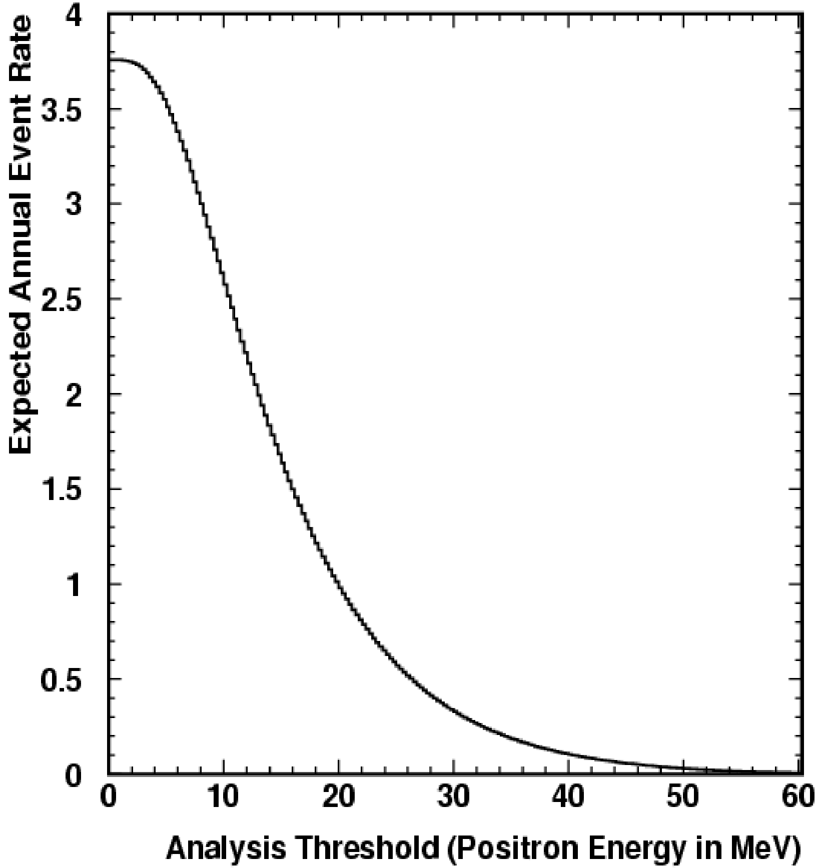
- Lq. Scintillator (408 t fid) detector
- 1.8 MeV threshold
- After inverse β: $n + p \rightarrow d + \gamma$ ($E\gamma = 2.2$ MeV)
- By searching for the delayed γ, virtually all BG can be removed
- Threshold can be set at ~10 MeV (below which reactor ν dominate)
- Expected event rate is 0.1 ev/year due to small fiducial volume

SNO

- 1 kt heavy water w/ salt added
- With D_2O: $n + d \rightarrow {}^3H + \gamma$ ($E\gamma = 6.3$ MeV)
- With NaCl: $n + {}^{35}Cl \rightarrow {}^{36}Cl + \gamma$ ($E\gamma = 8.6$ MeV)
- Search for delayed γ after an e^+
- Event rate 0.03 ev/yr for thresh. of E > 10 MeV

Possible Upgrade for SK?

- Neutron detection in SK via Gadolinium?
- Gd has large x-section
- 100 t (0.2%) in SK to catch > 90% n
- Capture $\rightarrow$ 8 MeV γ cascade
- Above 12 MeV thresh. ~2 SRN/year expected
- First SRN discovery??



Water Cherenkov: The Next Generation

DUSEL	Hyper-Kamiokande
• 650 kton total volume	• 1,000 kton total volume
• 440 kton fiducial volume (= 20 × SK)	• 540 kton fiducial volume (= 24 × SK)
• sensitivity ∝ (exposure)$^{1/2}$	• Current plans call for depth of 1400 – 1900 m.w.e
• First approximation: Detection within 3 yrs	• Too shallow for SRN search!
• If Gd works in SK, scale it to larger detectors	• Depth might not pose a problem with Gd-enriched Hyper-K
• May see ~40 SRN/yr → measure E spectrum?	• HK may see ~50 SRN / yr → Neutrino cosmology??

Supernova Relic Neutrinos: A Summary

- SRN signal would manifest as distortion of Michel spectrum
- Above E_e = 18 MeV, no distortion seen $\longrightarrow$ flux limits can be set
- The Super-Kamiokande flux limits on the SRN are 1-2 orders of magnitude better than previous limits
- Some SRN models can be constrained or rejected
- An increase in sensitivity of factor 3-6 is needed to probe all models
- Future experiments (DUSEL, Hyper-Kamiokande) may be able to observe SRN due to higher statistics
- New methods, such as enhancing Super-Kamiokande with Gd, have been proposed to detect the SRN