# Supernova relic neutrino search and atmospheric neutral current at Super-Kamiokande

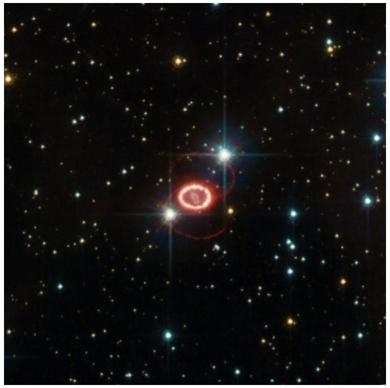
Linyan WAN for Super-Kamiokande collaboration

Tsinghua University

2018/06/18

# Supernova and CCSN neutrino

- Supernova burst is a titanic explosion in the last evolutionary stages of a massive star’s life.
- Happening 2~3 per century in our galaxy.
- Shed light on star evolution and heavy element synthesis.

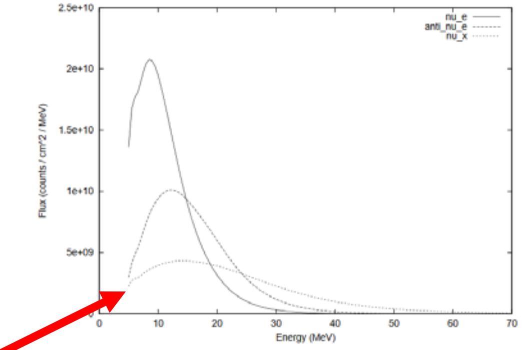


- Core collapse supernova radiates energy mostly by neutrinos.

| Type by light spectrum | | Burst model | Main energy output |
|---|---|---|---|
| SN I | SN Ia | Thermal runaway | Kinetic energy |
| | SN Ib | Core Collapse (SuperNova) | Neutrino (99%) |
| SN II | | | |

# Supernova Relic Neutrino

- Are cumulative neutrino fluxes from all past core-collapse supernova bursts, inside and outside Milky Way.



- Expected energy range ~10 MeV.
- Are also called **D**iffused **S**upernova **N**eutrino **B**ackground.
- Can be detected using terrestrial neutrino detectors of large fiducial volume, such as liquid scintillator or water.

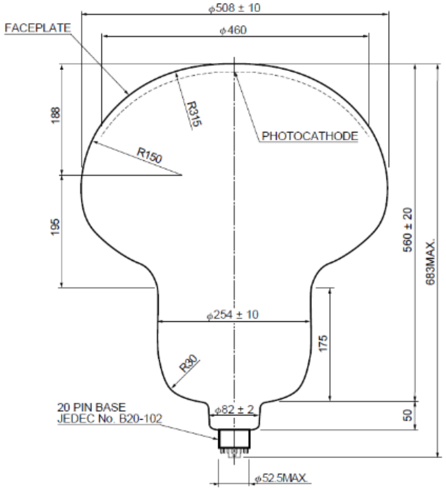
$$\frac{dF_\nu}{dE_\nu} = \boxed{\frac{c}{H_0}} \int_0^{z_{max}} \boxed{R_{SN}(z)} \boxed{\frac{dN_\nu\left(E_\nu'\right)}{dE_\nu'}} \boxed{(1+z)\frac{dz}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}}$$

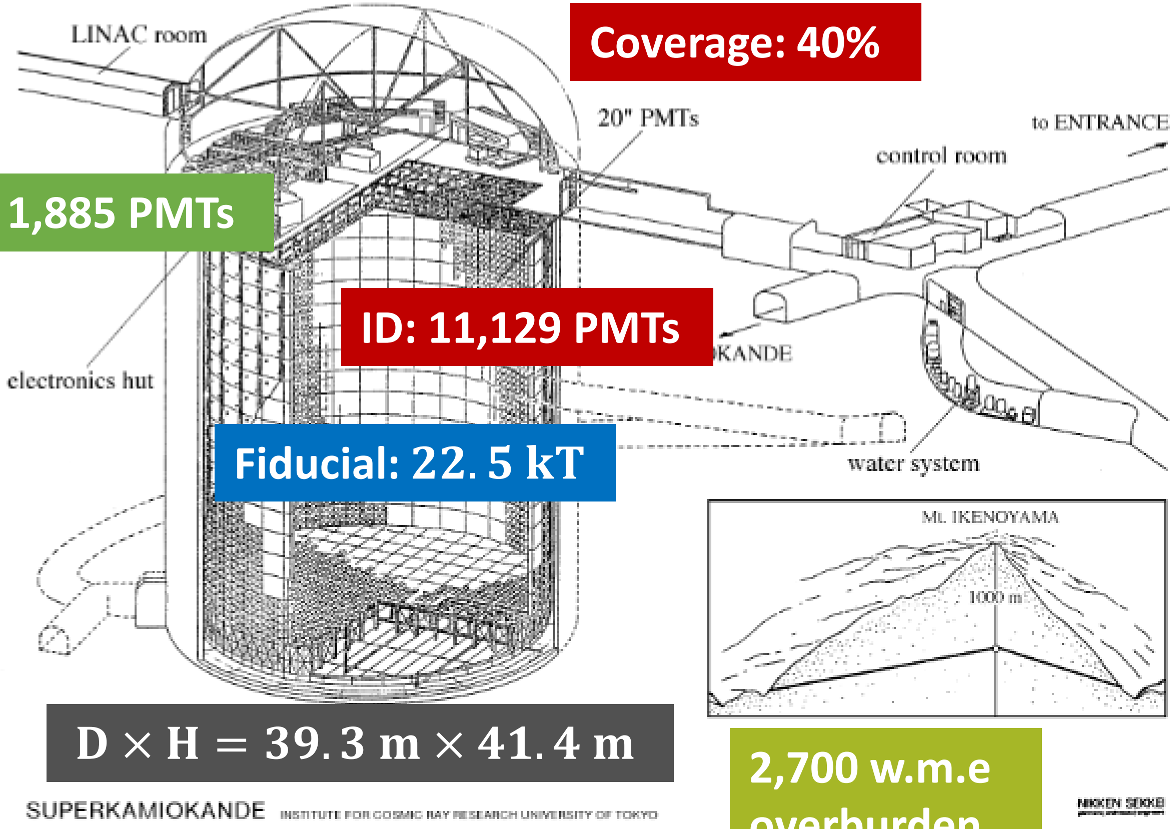
**Time-space transformation**

# Super-Kamiokande

**1996 ~ so far**

**20’’ PMT**





**Coverage: 40%**

**OD: 1,885 PMTs**

**ID: 11,129 PMTs**

**Fiducial: 22.5 kT**

$\mathrm{D} \times \mathrm{H} = 39.3\ \mathrm{m} \times 41.4\ \mathrm{m}$

**2,700 w.m.e overburden**

# Super-Kamiokande

☐ Water Cherenkov:

$$\cos\theta_c = \frac{1}{\beta n(\lambda)}$$

Enable particle identification

☐ Energy Threshold:

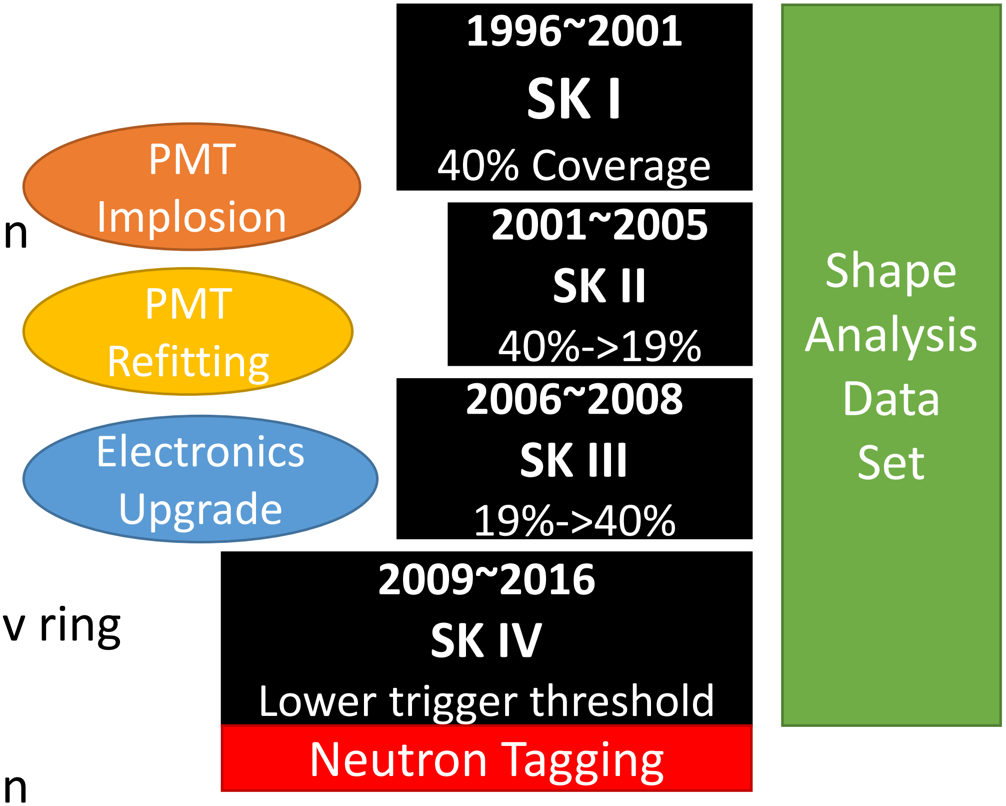
$$E_{thr}\left(e^{+/-}\right) \approx 0.77\ \mathrm{MeV}$$
$$E_{thr}\left(\mu^{+/-}\right) \approx 157\ \mathrm{MeV}$$

☐ Direction:

Reconstruct from Cherenkov ring

☐ Water Transparency:

$\sim 120\ \mathrm{m}$ by decay electron



**1996~2001**
**SK I**
40% Coverage

PMT Implosion

**2001~2005**
**SK II**
40%->19%

PMT Refitting

**2006~2008**
**SK III**
19%->40%

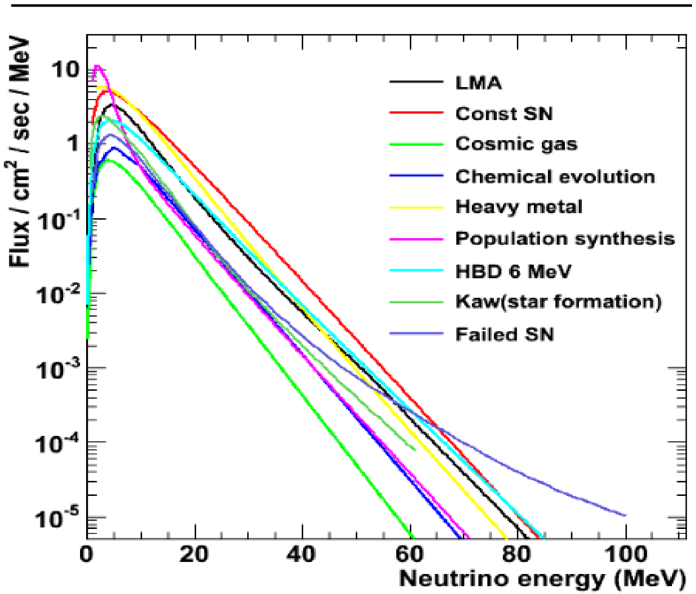
Electronics Upgrade

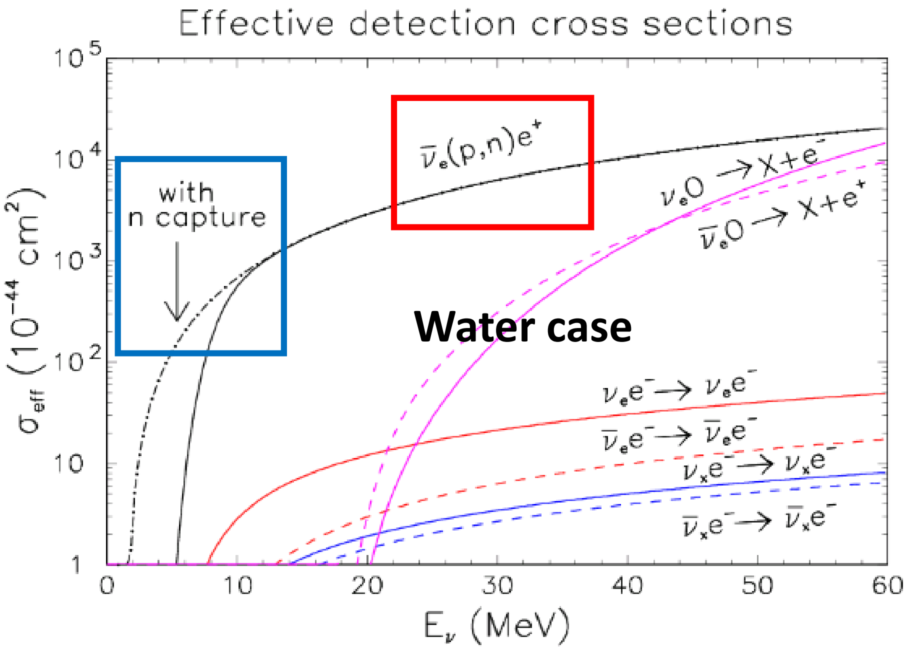
**2009~2016**
**SK IV**
Lower trigger threshold

Neutron Tagging

Shape Analysis Data Set

# Inverse beta decay





- Inverse Beta Decay
  $$\bar{\nu}_e + p \rightarrow n + e^+$$

**An SRN detector should detect the IBD positron (and gamma).**

- Neutron Capture
  $$n + p \rightarrow D + \gamma$$

☐ H Capture $\tau \approx 200\ \mu s$ $E_\gamma = 2.2$ MeV
☐ Gd Capture $\tau \approx 30\ \mu s$ $E_\gamma \approx 8.0$ MeV

# Neutron tagging

- Without neutron tagging, **spallation background** dominates **below 16 MeV**.

- Neutron tagging has been enabled in **SK-IV** by the improvement of FEE and trigger scheme. However, it is difficult in water due to the inefficiency to detect 2.2 MeV $\gamma$.

- Using a **multi-variate analysis** of discrimination variables including **hit pattern, hit time, charge, and vertex information**, an Ntag algorithm is constructed with **20%~30%** efficiency at different energy.

# Neutral-current background

Neutral Current Quasi-Elastic (NCQE) on oxygen:

Primary process:

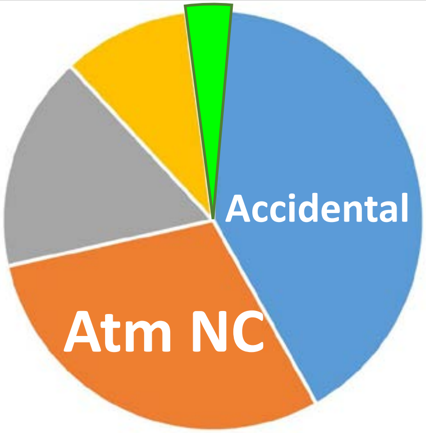
$$\nu + {}^{16}\mathrm{O} \rightarrow \nu + \boxed{n} + {}^{15}\mathrm{O} + \boxed{\gamma' s}$$

Secondary process:

$$\boxed{n} + {}^{16}\mathrm{O} \rightarrow X + \boxed{\gamma' s}$$

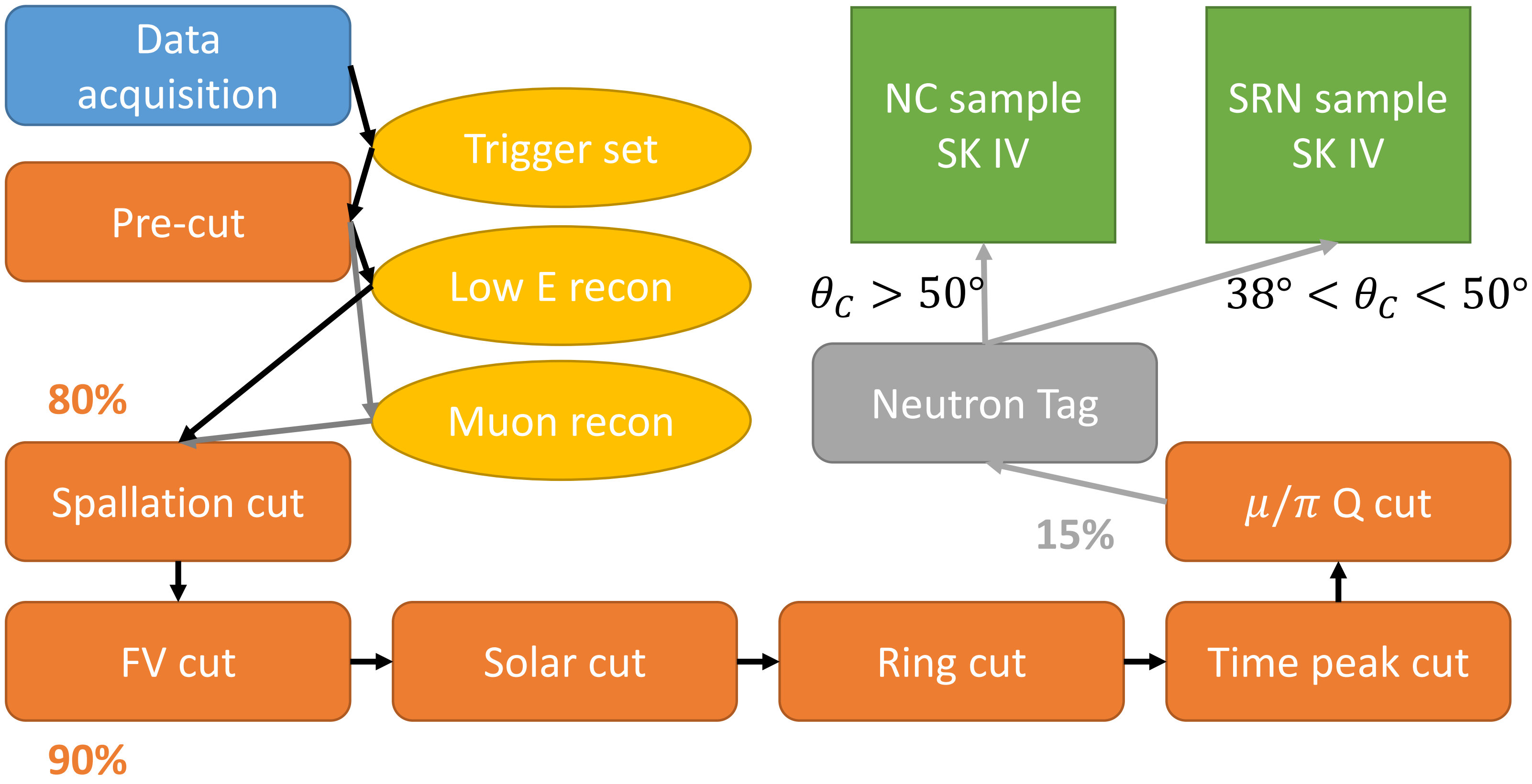
De-excitation $\gamma$'s as a signature to detect NCQE (1-10 MeV).

Emitted nucleon can be captured and emit 2.2 MeV gamma or further collide on another nucleus.



- Accidental can be removed in SK-Gd.
- Atmospheric NC is irreducible, dominated by NCQE.
- SRN signal.

# Atmospheric NCQE data reduction


Data acquisition

Trigger set

Pre-cut

Low E recon

Muon recon

80%

Spallation cut

FV cut

90%

Solar cut

Ring cut

Time peak cut

$\mu/\pi$ Q cut

15%

Neutron Tag

$\theta_C > 50°$

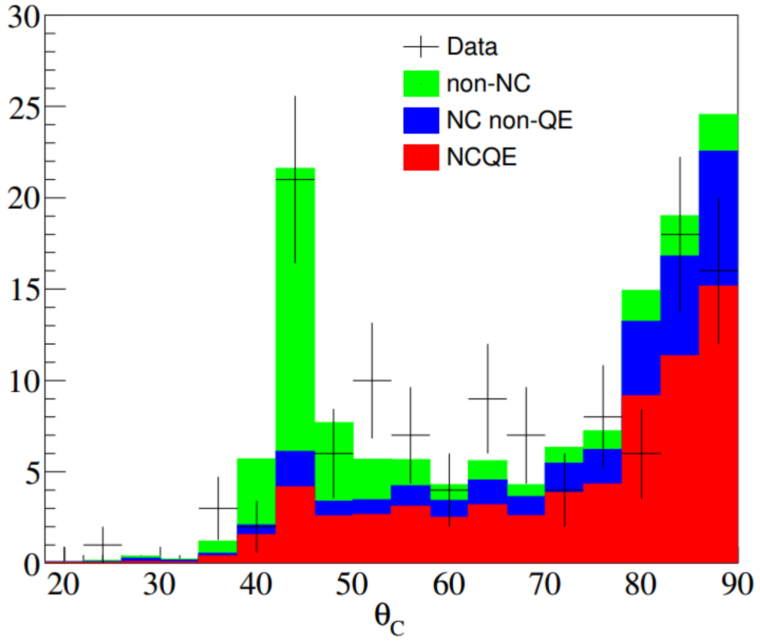
$38° < \theta_C < 50°$

NC sample SK IV

SRN sample SK IV

# Cherenkov angle distribution

**NCQE** signals are $\gamma$’s and tend to cluster in isotropic regions above 50°;
**NC non-QE’s** are mainly pion channels, and the signals are de-excitation $\gamma$’s after pion absorption;
**Non-NC** backgrounds are mainly electron-like events peaking at 42°, including reactor neutrinos, 9Li, and atmospheric CC.

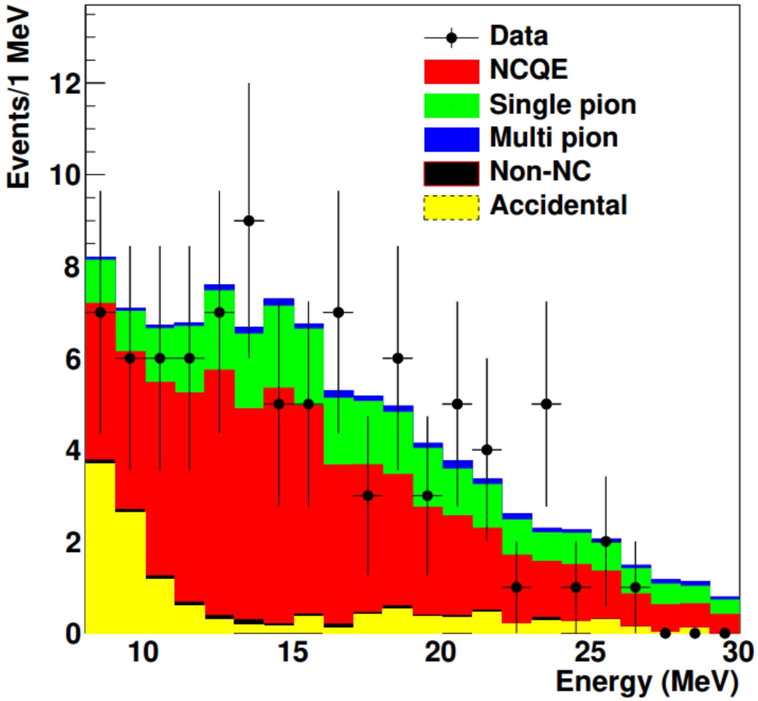


# Atmospheric NCQE MC & data

The final sample consists of **89 events** and is validated by a neutron capture time fitting.

The expected number of events is:

- **NCQE: 58.0**
- **Single pion: 23.1**
- **Multi pion: 2.4**
- **Non-NC w/ neutron: 1.3**
- **Accidental: 13.7**



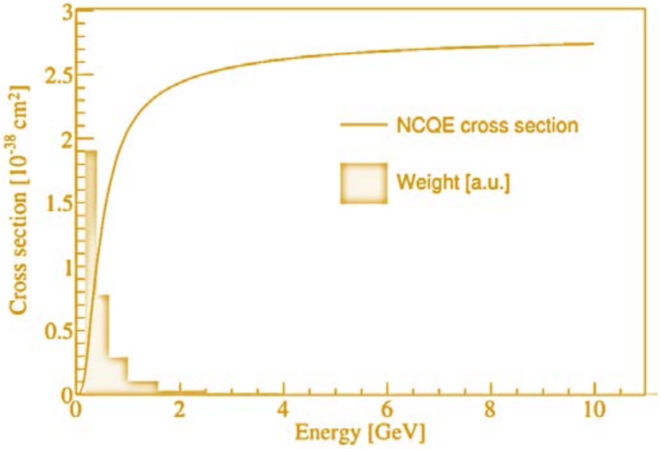
In total, **98.5 events expected** against **89 events observed**, within **1$\sigma$** statistical uncertainty.

# Cross-section calculation

$$< \sigma_{\text{NCQE}}^{\text{theory}} > = \frac{\int_{160\text{ MeV}}^{10\text{ GeV}} \sum_{i=\nu,\bar{\nu}} \phi_i(E_\nu) \times \sigma_i(E_\nu)_{\text{NCQE}}^{\text{theory}} dE_\nu}{\int_{160\text{ MeV}}^{10\text{ GeV}} \sum_{i=\nu,\bar{\nu}} \phi_i(E_\nu) dE_\nu}$$
$$= 1.14 \times 10^{-38}\ \text{cm}^2$$

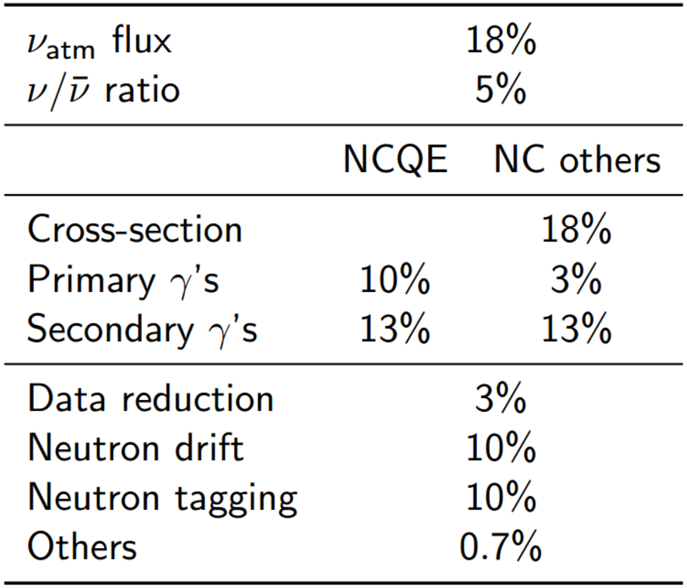
$$< \sigma_{\text{NCQE}}^{\text{observed}} > \approx \frac{N_{\text{tot}}^{\text{obs}} - N_{\text{acc}}^{\text{obs}} - N_{\text{others}}^{\text{obs}} - N_{\text{NCothers}}^{\text{exp}}}{N_{\text{NCQE}}^{\text{exp}}} \times < \sigma_{\text{NCQE}}^{\text{theory}} >$$
$$= \frac{89 - 13.7 - 1.3 - (23.1 + 2.4 + 0.0)}{58.0} \times 1.14 \times 10^{-38}\ \text{cm}^2$$
$$= (0.95 \pm 0.12_{\text{stat.}}) \times 10^{-38}\ \text{cm}^2$$

The cut-off at 160 MeV and 10 GeV is due to present atmospheric neutrino flux measurement. Related systematics have been considered.



# Systematics

- Flux uncertainty from SK-IV measurement.
- Ratio & $\gamma$ emission evaluated from theoretical disagreement between models.
- Data reduction and neutron drift from MC.
- Neutron tagging from calibration data.



| | | |
|---|---|---|
| $\nu_{\text{atm}}$ flux | 18% | |
| $\nu/\bar{\nu}$ ratio | 5% | |
| | NCQE | NC others |
| Cross-section | | 18% |
| Primary $\gamma$'s | 10% | 3% |
| Secondary $\gamma$'s | 13% | 13% |
| Data reduction | 3% | |
| Neutron drift | 10% | |
| Neutron tagging | 10% | |
| Others | 0.7% | |

Table: Uncertainties in NCQE measurement

- ➢ The average NCQE cross-section from atmospheric neutrinos on oxygen is measured to be

$$\mathbf{\left(0.95 \pm 0.12\ (stat.)^{+0.49}_{-0.32}\ (sys.)\right) \times 10^{-38}\ cm^{2}}.$$

# Conclusion

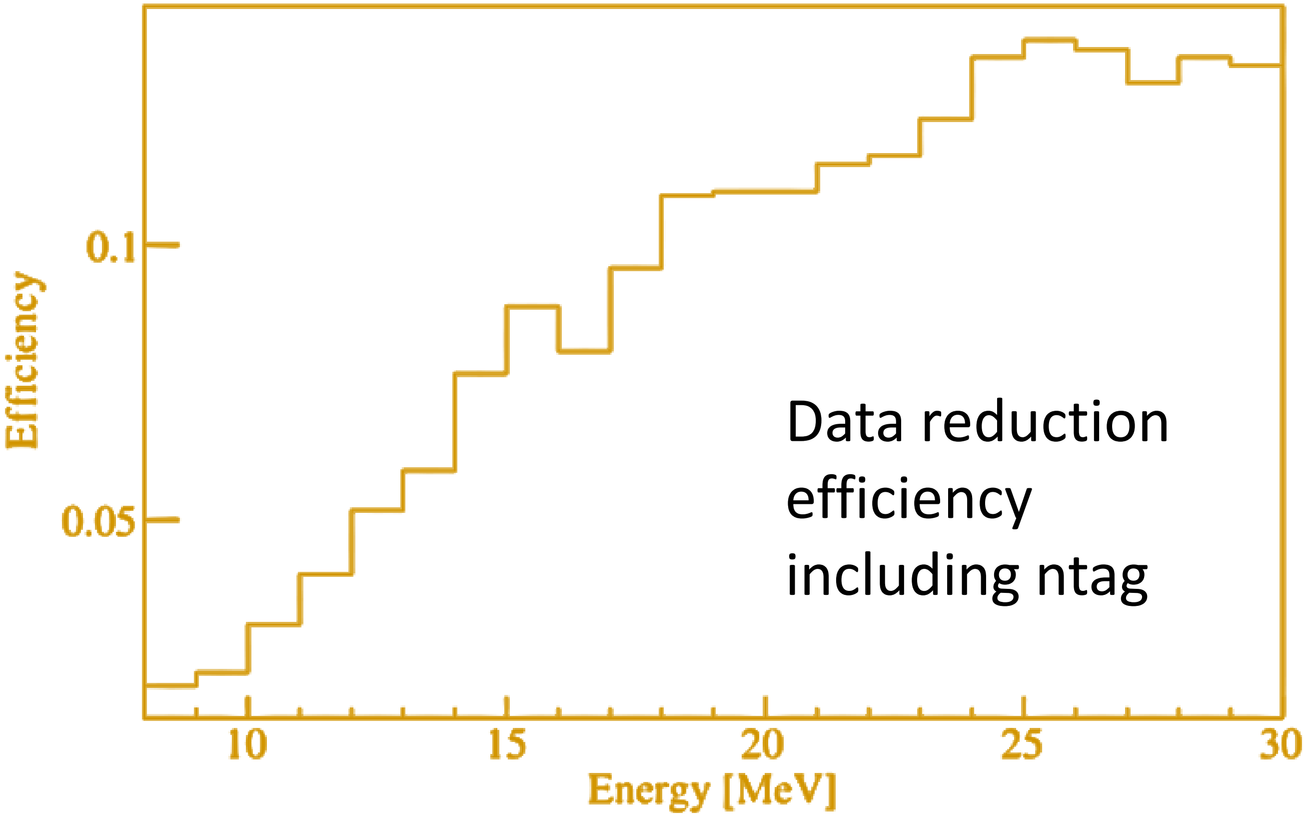
- We observed 89 events in the NC sample after data reduction and neutron tagging, against 98.5 events expected.
- The atmospheric neutrino average NCQE cross-section is measured to be

$$\left(\mathbf{0.95 \pm 0.12\ (stat.)^{+0.49}_{-0.32}\ (sys.)}\right) \times \mathbf{10^{-38}\ cm^2}$$

- The uncertainty is dominated by systematic, which could improve in future experiment (SK & HK for flux, ND280 etc. for NCother X-sec, RCNP for primary and secondary, SK-Gd for ntag efficiency).

# Backup

# Efficiency



Data reduction
efficiency
including ntag