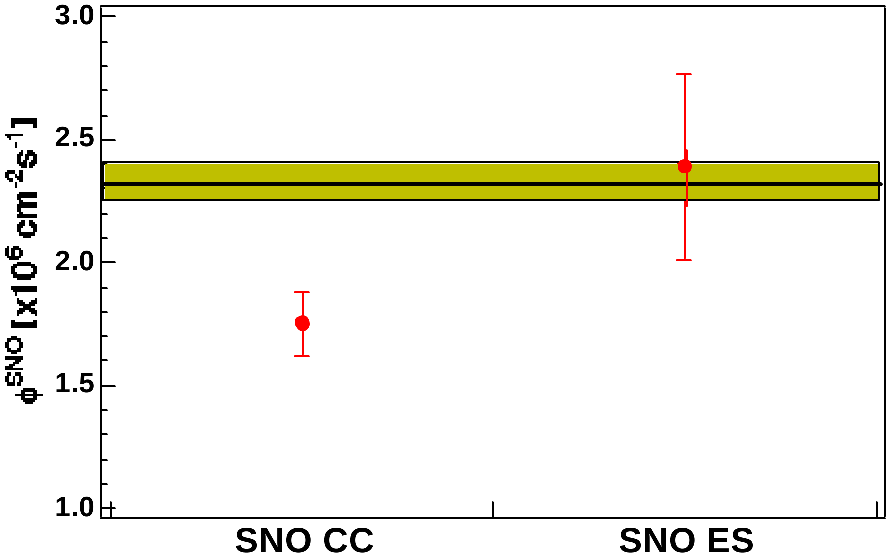
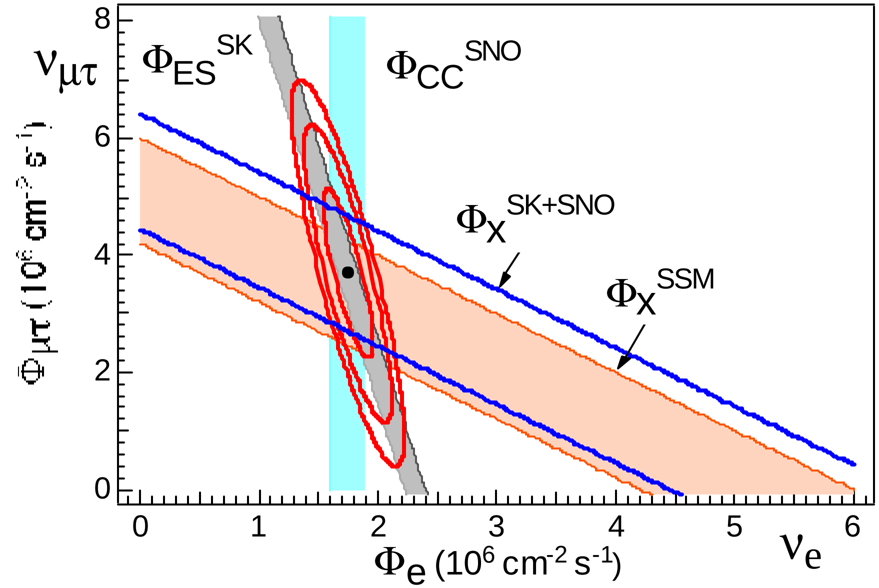


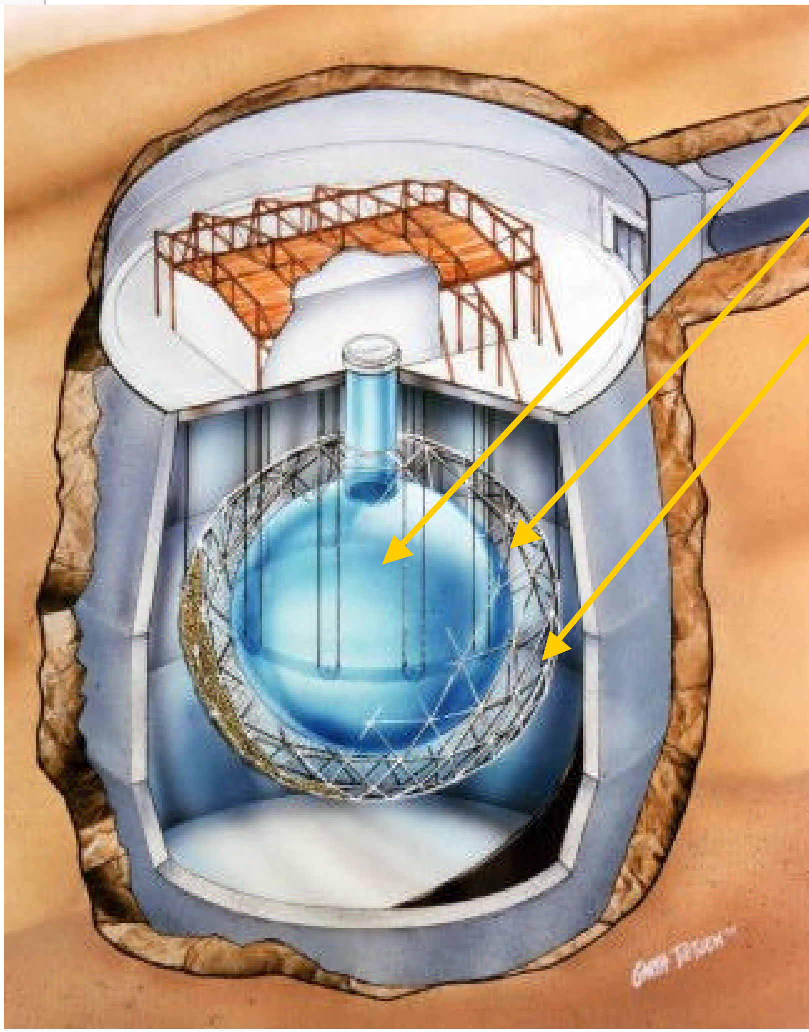


What Else Can SNO Do?

Muons and Atmospheric Neutrinos
Supernovae
Anti-Neutrinos
Baryon Number Non-Conservation

The SNO Detector

2092 m below surface (~6010 m.w.e)



1000 tonnes D_2O (99.92% pure)

1700 tonnes of internal H_2O

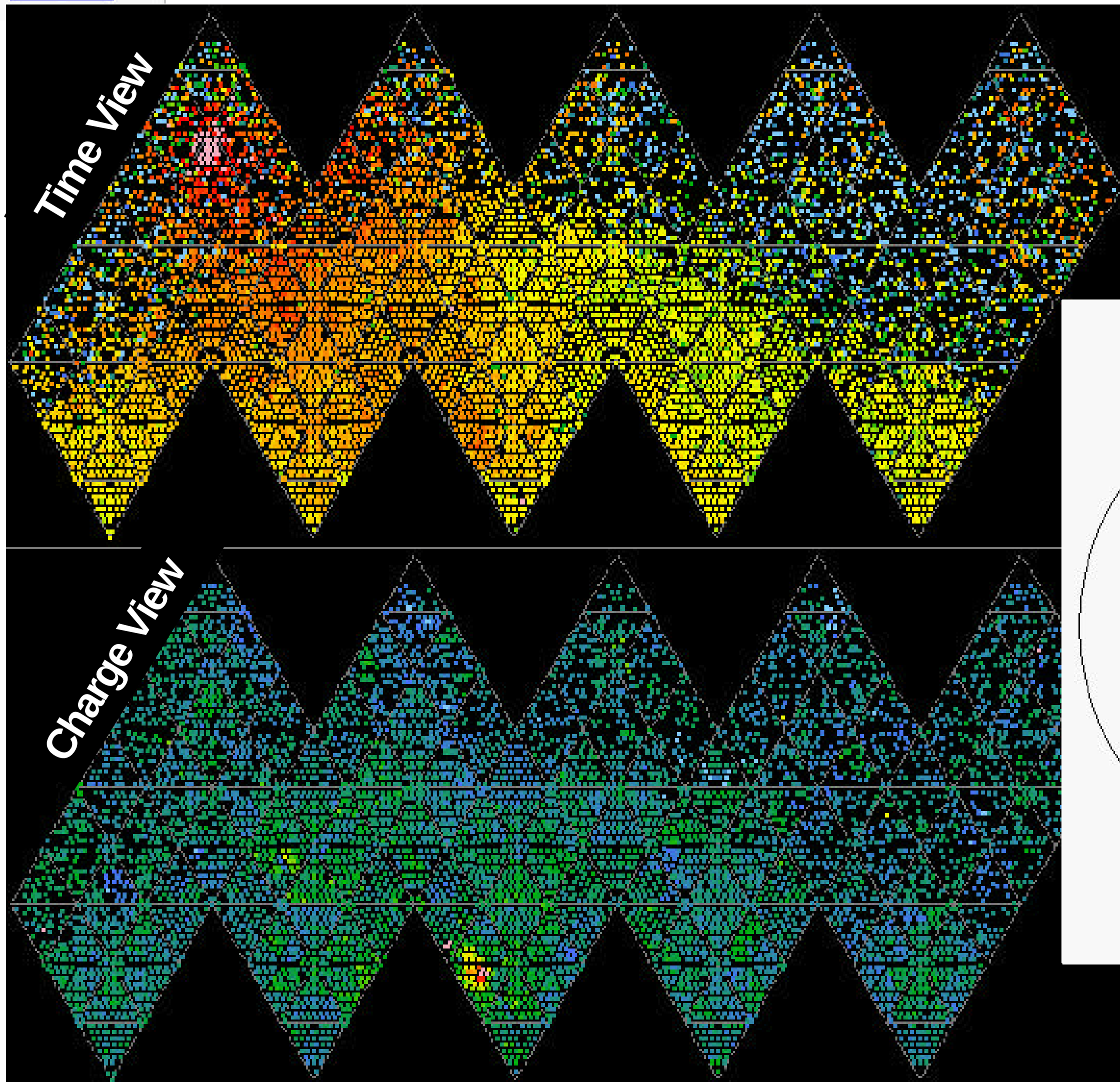
9456 8" diameter PMTs

<u>D_2O permits neutrino detection by:</u>

- charged current (CC) break up of D
- elastic scatter (ES) of e^-
- neutral current (NC) break up of D

3 NC detection phases

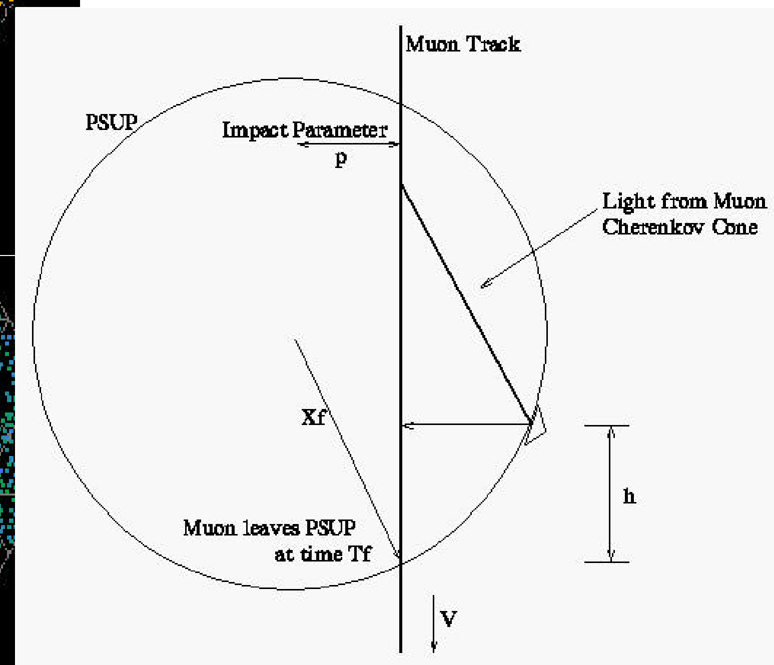
Muons



Very energetic events

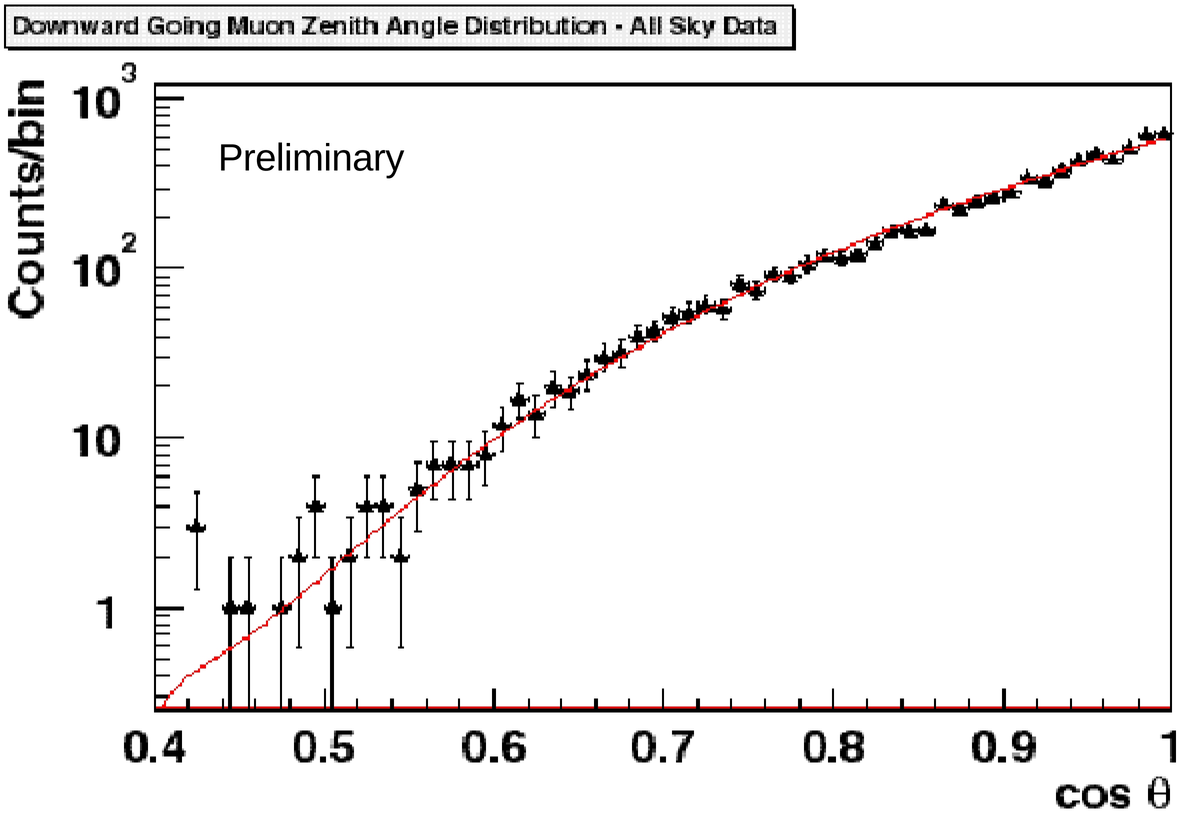
Reconstruction by time and Cherenkov cone hypothesis

1.5^0 resolution within in 7.5 m



~70 muons per day through 8.5 m detector

Muon Zenith Angle Distribution

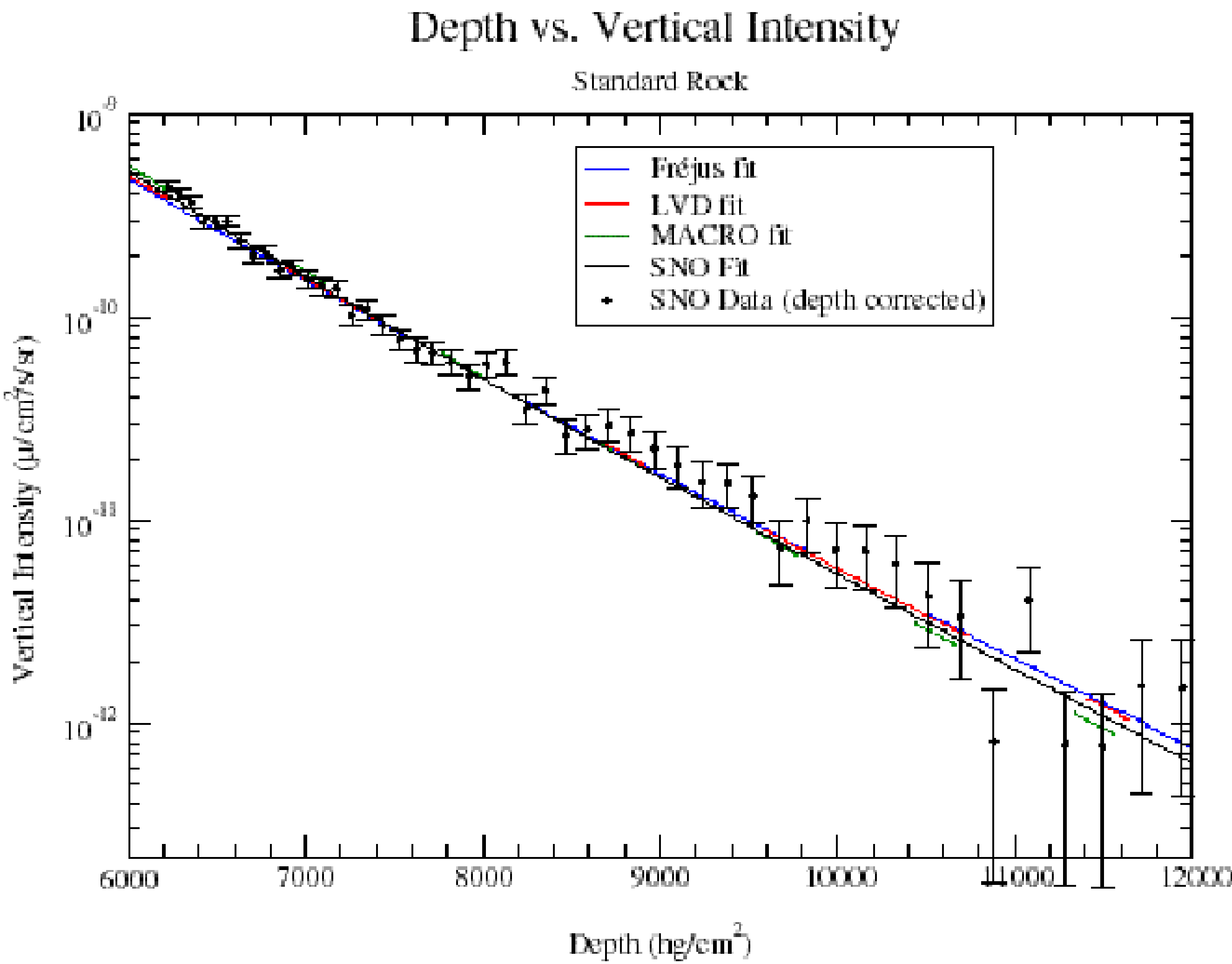


- 149 live days
- 7.5 m impact parameter cut
- 7579 muons

Solid curve from calculation:

- Parameterization of surface muon flux
- MUSIC muon propagation

Muon Zenith Angle Distribution



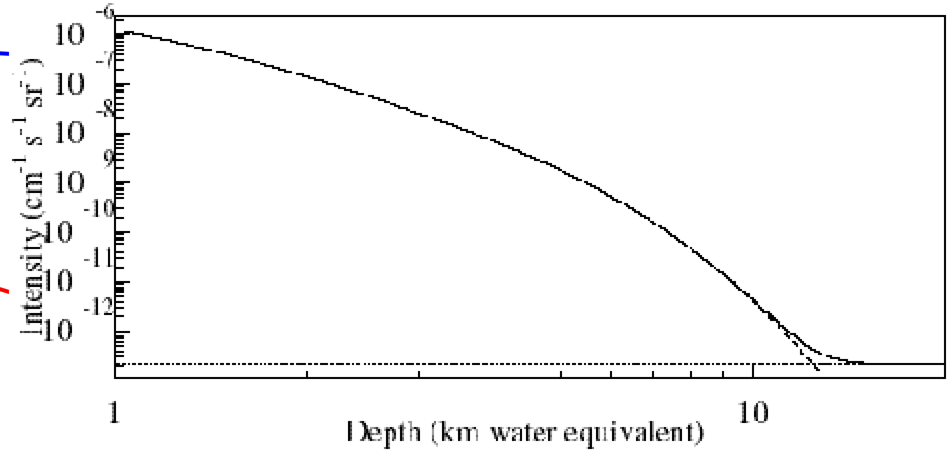
Empirical parameterization of flux vs depth:
$I(x)=A(x_0/x)^2\exp(-x/x_0)$

Measured muon flux tells us our detector is working for high energy events and that we know how to model the flux

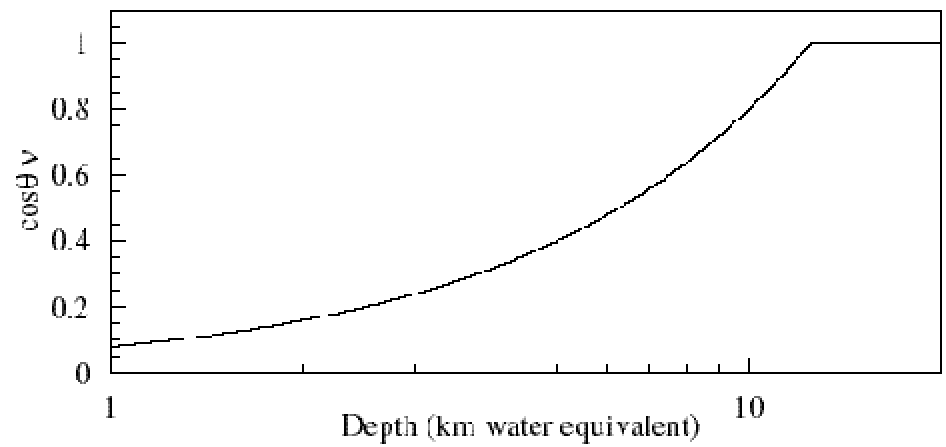
Muon Flux vs. Depth

Atmospheric muons

Atmospheric neutrino-induced muons

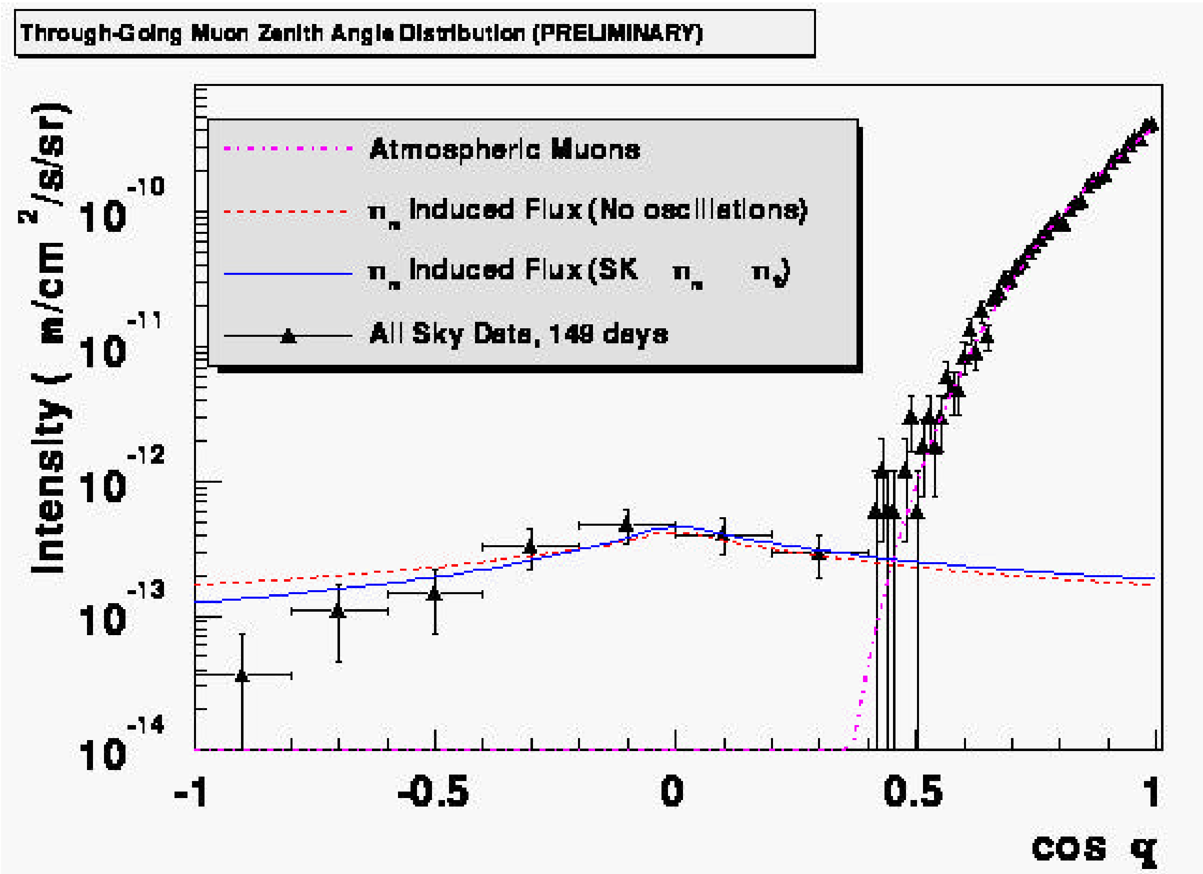


Zenith angle for neutrino-induced muon flux ε atmospheric muon flux



SNO becomes neutrino dominated at cosθ=0.5 (60º)

Muon Zenith Angle



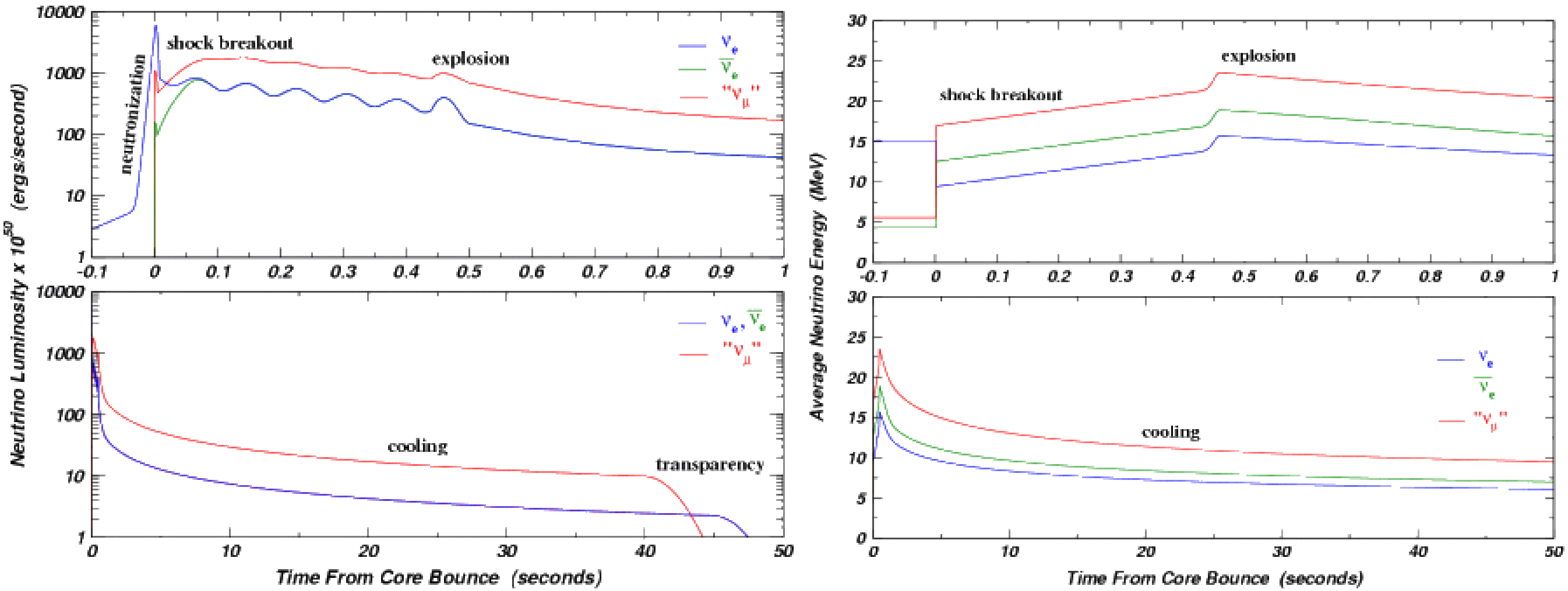
- atmospheric neutrino signal seen well above horizon
- atmospheric neutrino signal consistent with no oscillation hypothesis (χ^2/DOF = 6.29/6)
- neutrino signal more consistent with SK oscillation parameters (χ^2/DOF = 3.90/6)
- SNO can limit theoretical neutrino flux uncertainty (20%) in a few years

Supernovae

A massive star > 8 M exhausts its fuel
M_{core} ~ 1.4 M

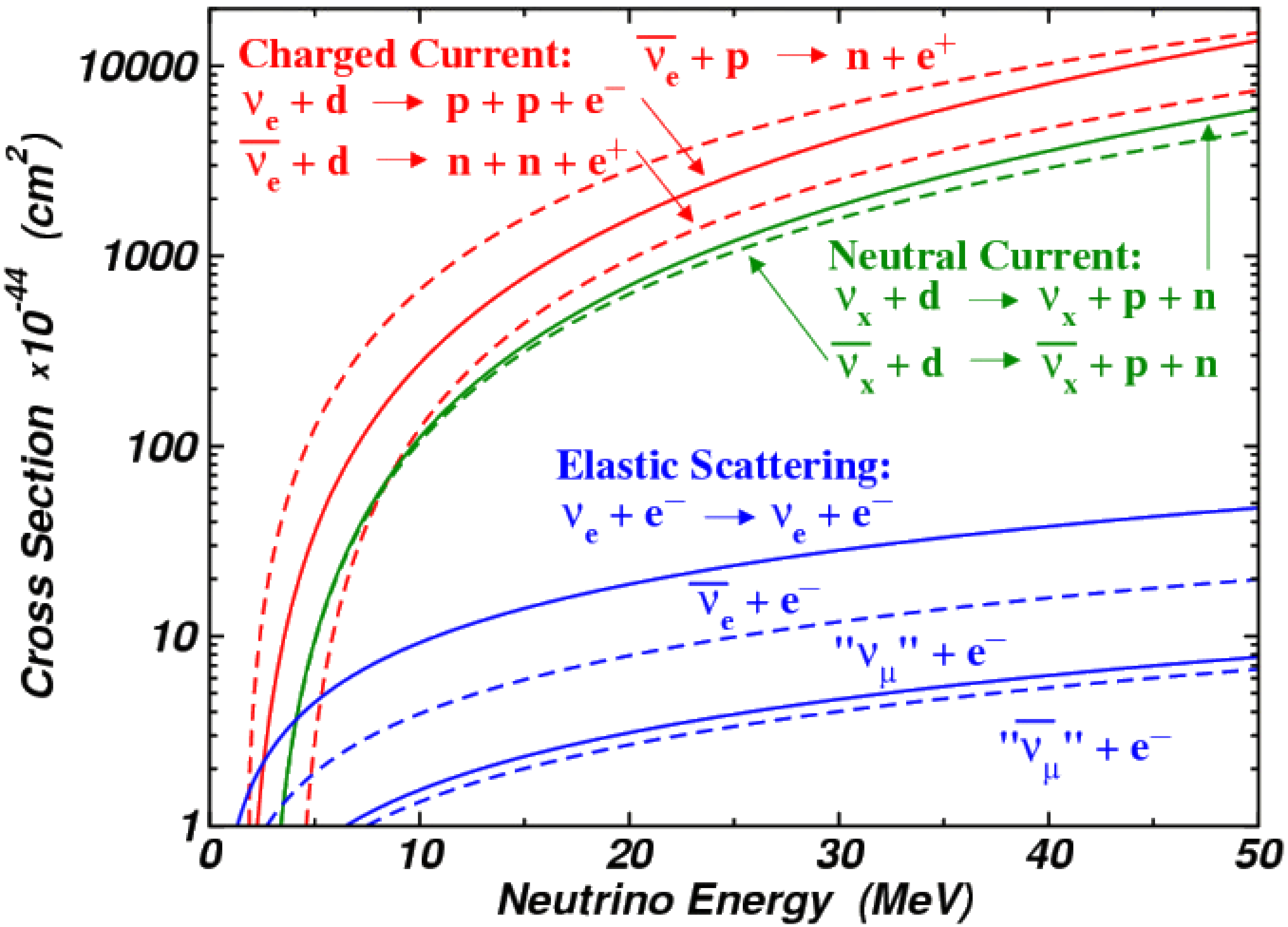
Gravitational collapse supernova (Type II)
E_b ~ 3 x 10^{53} ergs released

~99% of energy carried off by neutrinos
Energy --> SN mechanism, ν oscillations
Time --> ν mass, oscillations, black holes
CC-NC --> ν oscillations



(After SN model of Burrows et al. (1992))

Supernova Neutrino Cross Sections



Supernova Detection Simulation

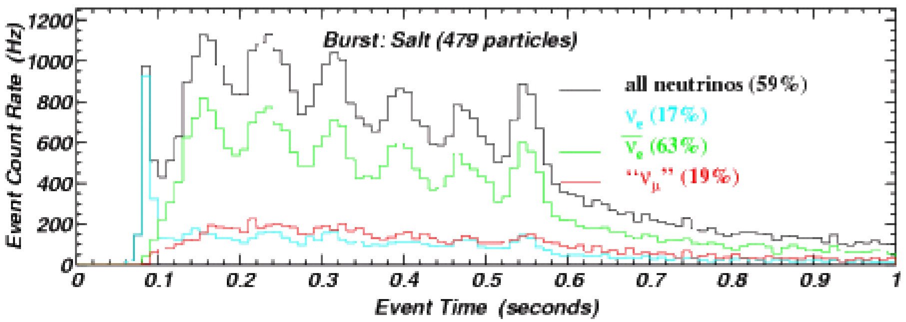
Burrows model SN at 10 kpc

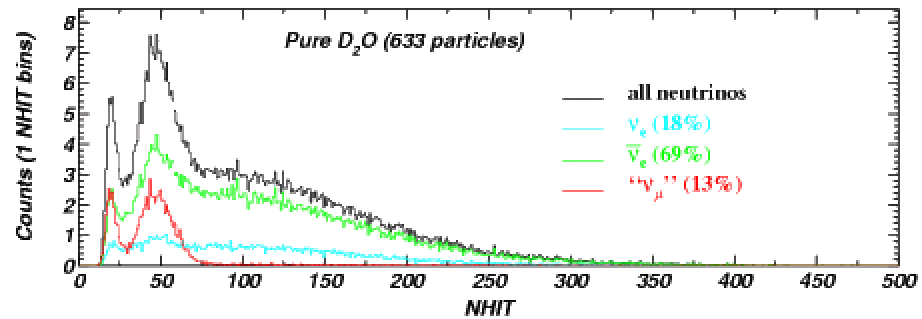
Neutrino Reaction	Type	SNO Counts [e = 100%]	SNO Counts [Monte Carlo]
$\bar{\nu}_e + p_{H_2O} \rightarrow n + \mathbf{e}^+$	CC	329	320
$\nu_e + d \rightarrow p + p + \mathbf{e}^-$	CC	83	81
$\bar{\nu}_e + d \rightarrow \mathbf{n} + \mathbf{n} + \mathbf{e}^+$	CC	53 (x 3)	91 [D_2O] 142 [salt] 110 [NCD]
$\bar{\nu}_e + d \rightarrow \bar{\nu}_e + p + \mathbf{n}$	NC	36	13 [D_2O] 30 [salt] 20 [NCD]
$\nu_e + d \rightarrow \nu_e + p + \mathbf{n}$	NC	36	14 [D_2O] 31 [salt] 20 [NCD]
"ν_μ" + d → "ν_μ" + p + **n**	NC	186	70 [D_2O] 159 [salt] 102 [NCD]
$\nu_e + e^- \rightarrow \nu_e + \mathbf{e}^-$	ES	25	18
$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + \mathbf{e}^-$	ES	9	5
"ν_μ" + e^- → "ν_μ" + $\mathbf{e}^-$	ES	12	10

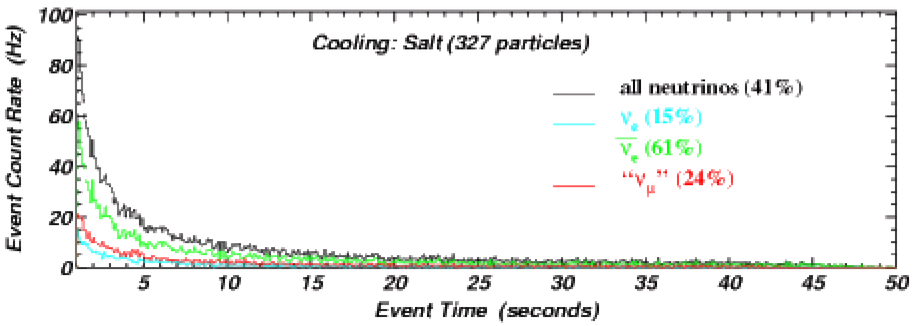
TOTAL SNO SN COUNTS: 875 622 [D_2O] 796 [salt] 686 [NCD]

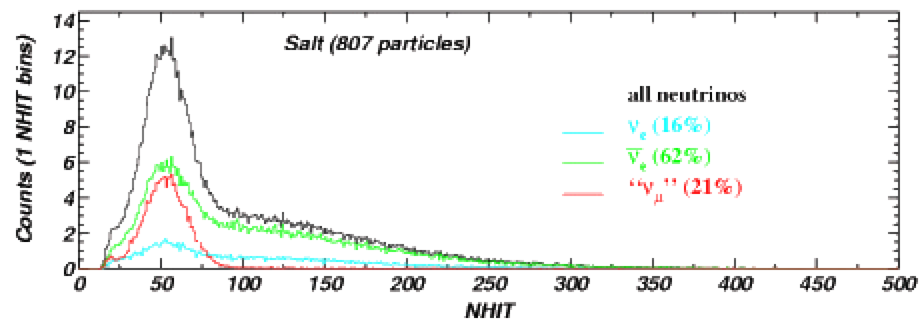
SNO Neutrino Counts

For full SNO detector and Burrows model of 100 SN at 10 kpc scaled to 1 SN





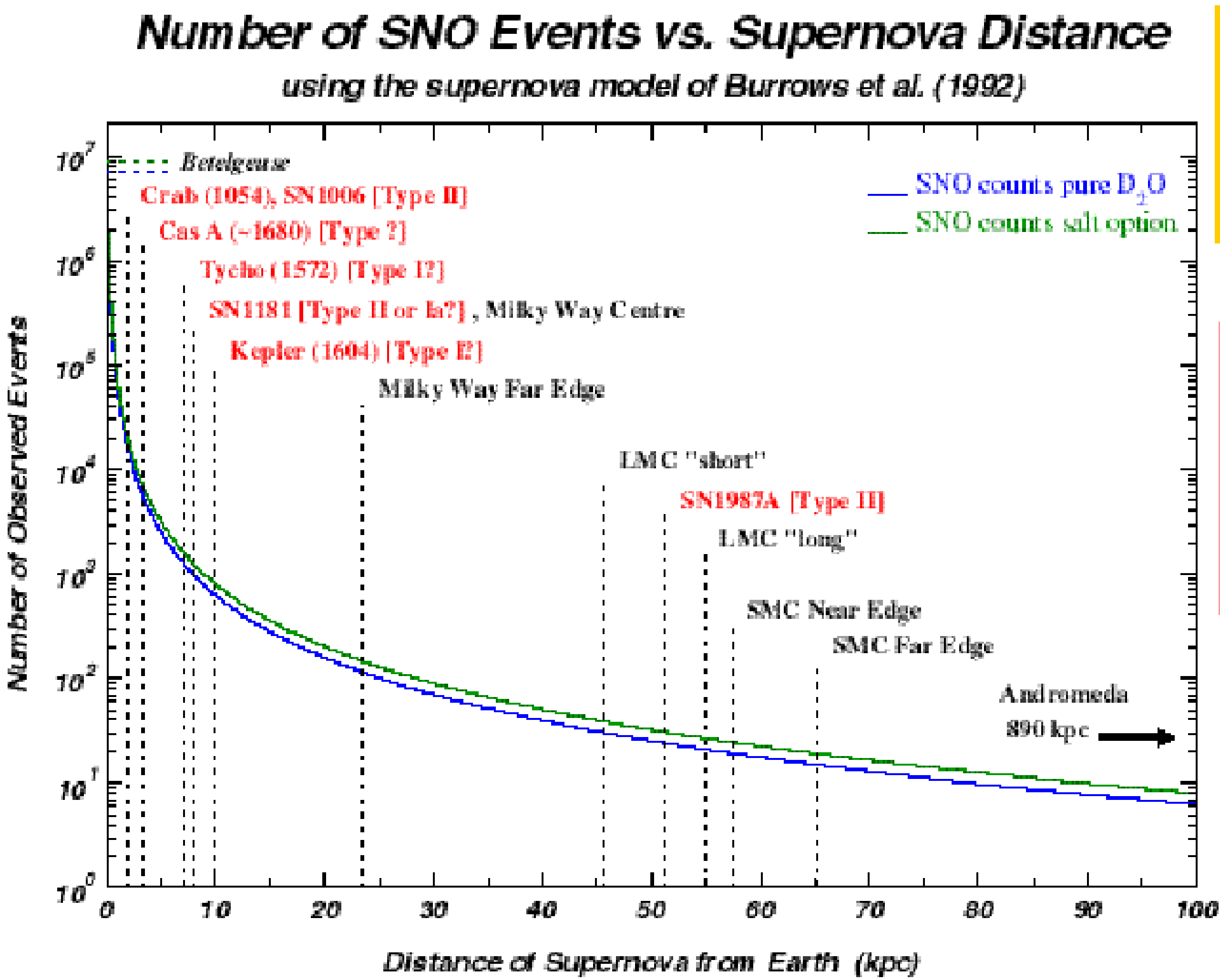




2 MHz burst capability for SNO DAQ may reveal structure in time distribution

Energy spectrum will reveal neutrino content

Suernova Sensitivity



Online Alert Condition:
- > 50 events
- ε 34 PMTs (~4 MeV)
- 2 s time window

Detector configuration, event energy spectrum and position, time and direction checked for candidate SN burst

e sensitive to
nova in our
/ (~28 kpc).

Antineutrino Detection in SNO

All potential solar $\bar{\nu}$ background

$$\bar{\nu}_x + d \rightarrow \bar{\nu}_x + p + n$$

indistinguishable from ν
NC reaction

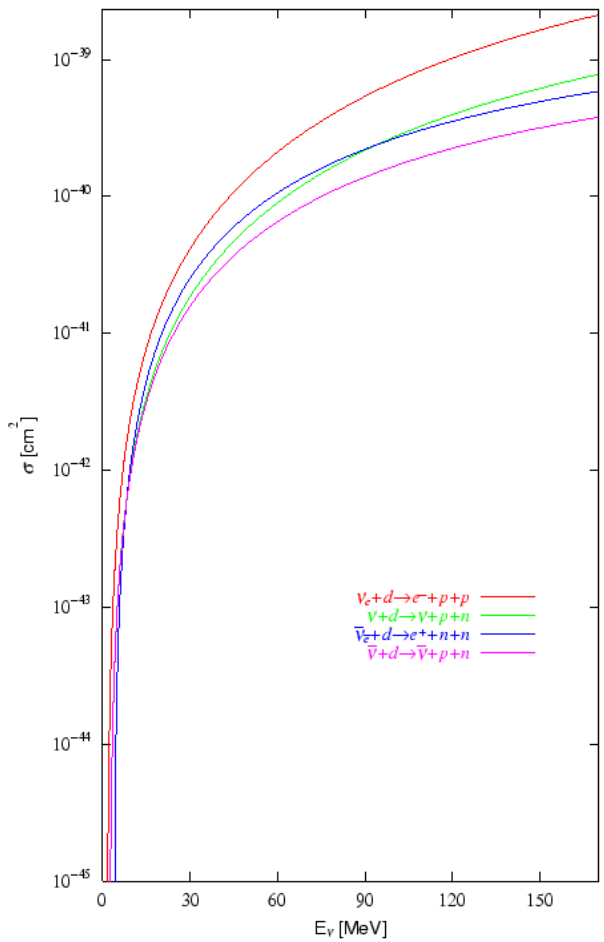
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

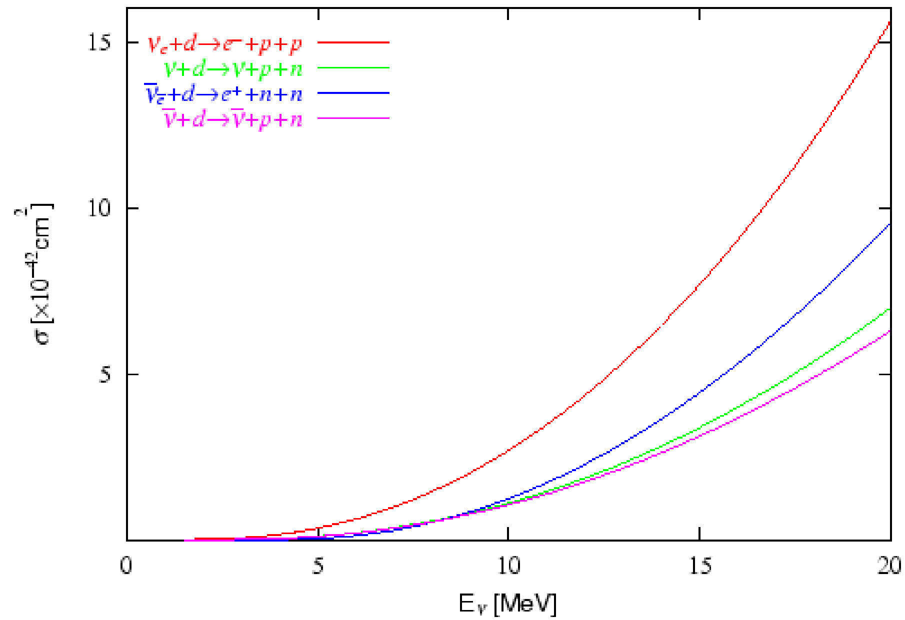
occurs in H_2O
difficult to identify

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

potential 3-fold coincidence

Neutrino/Antineutrino Cross Sections on Deuterium

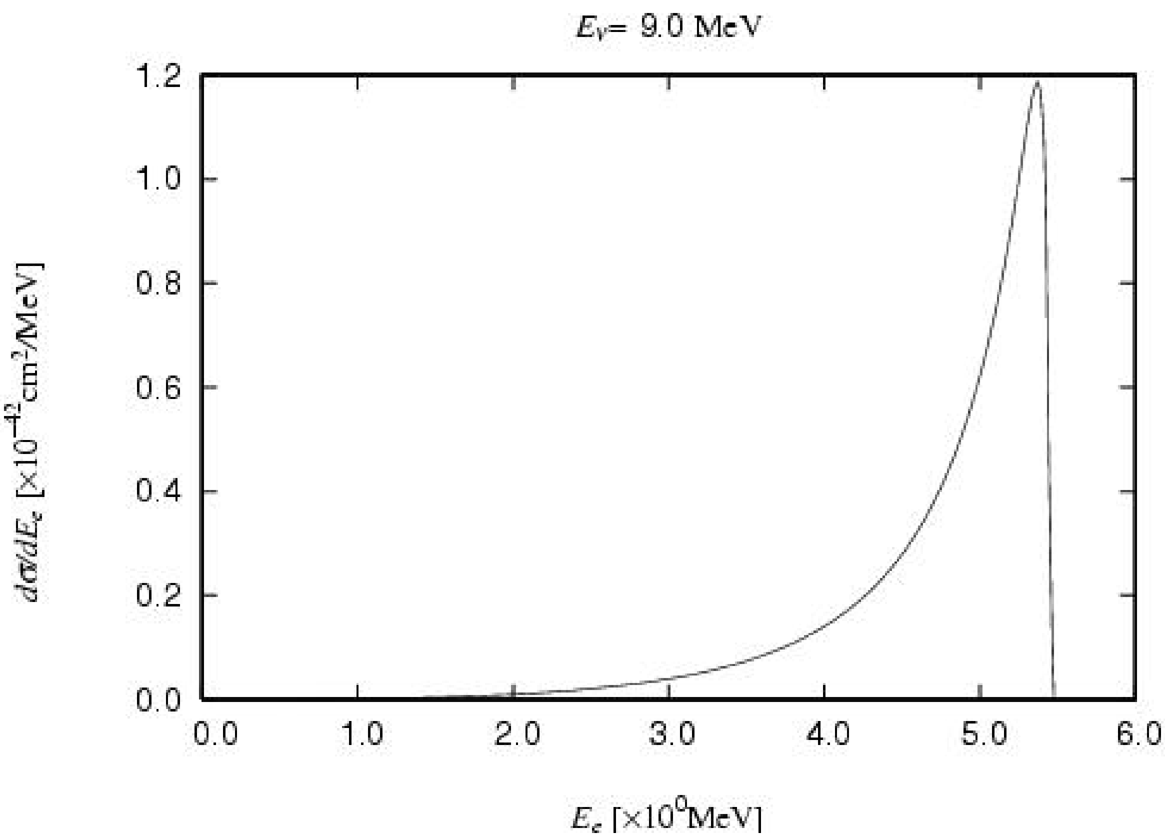




- 4 MeV threshold for signal of interest
- $\sigma(\bar{\nu})^{CC} \sim \sigma(\nu)^{CC}/2$ --> could regenerate "signal"

From NSGK: http://nuc003.psc.sc.edu/~kubodera/NU-D-NSGK/

Positron energy spectrum



Positron energy related to incident antineutrino energy
(From NSGK)

Positron spectrum may tell about source

Potential Antineutrino Sources

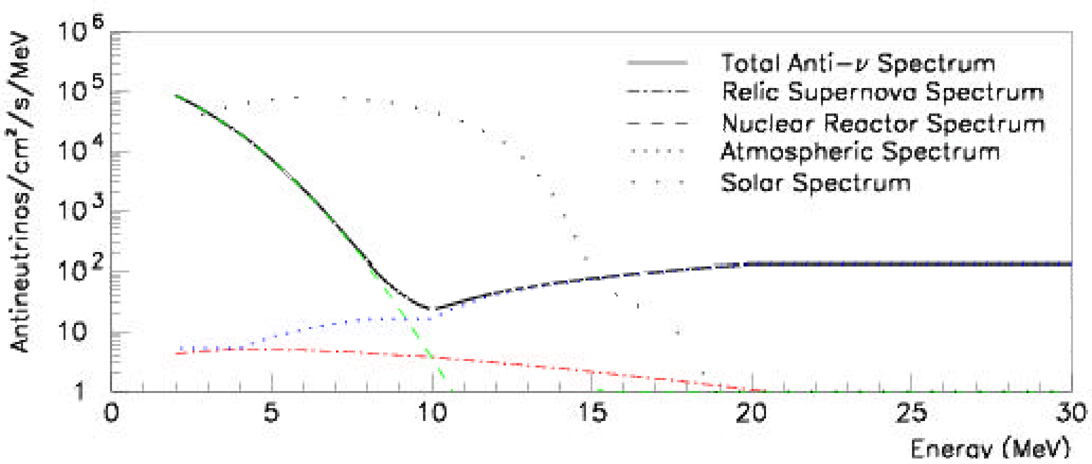
• Geophysical - energy below interaction threshold

• Atmospheric - $\mu^- \rightarrow e^- + \nu_e + \overline{\nu}_\mu$
• Nuclear Reactors - CHOOZ, Palo Verde, KamLAND, ...
• Relic Supernovae - 99% of energy in neutrinos and antineutrinos, and lots of old supernovae over the lifetime of the universe

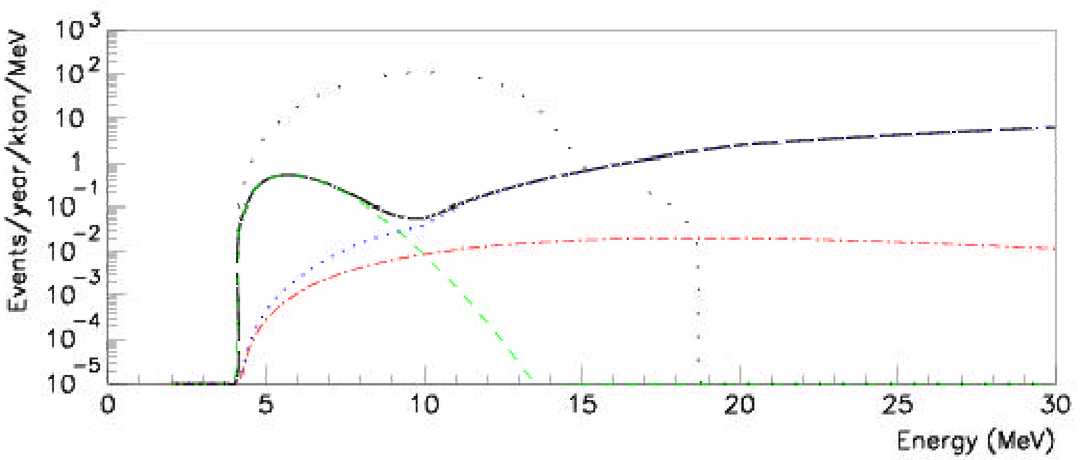
• Solar - must invoke jumping mechanism; assume some fraction of SSM flux (12% is 1σ SNO *vs*. SSM range)

$$\nu_e^L \xrightarrow{\text{Spin-flavor mag. moment transisiton}} \overline{\nu}_\mu^R \xrightarrow{\text{mass oscillations}} \overline{\nu}_e^R$$

Differential Fluxes and Expected Rates



Solar assumes 12% of SSM



Antineutrino events/yr/kton
Atmospheric: 8.4
Reactors: 1.4
Relic SN: 0.2

Solar: 558.8

Accidental Coincidences

$$R_{n\text{-fold}} = R_1\,(1 - \exp(-R_1 t))^{(n-1)}$$

$R_{n\text{-fold}}$ = accidental n-fold coincidence rate
R_1 = singles event rate
t = coincidence window duration

We can set our sensitivity by choosing energy threshold to give a particular event rate

Baryon Number Non-Conservation

GUT models generally predict non-conservation of baryon number:

- proton decay (τ (p --> $e^+ + \pi^0$) > 10^{33} years)

- $n\bar{n}$ oscillations ($\Delta B = 2$, 2 GeV for $n\bar{n}$ annihilation)

Best limits for $n\bar{n}$ oscillations are from neutrons bound in nucleii where nuclear effects suppress the reaction (τ (n --> $\bar{n}$) > 10^8 sec from ^{16}O in Kamiokande)

<u>SNO may do better for $n\bar{n}$:</u>

- lower muon background
- weaker nuclear suppression in ^2H

Conclusion

Plenty of good other physics to be done

All topics presented will require a lot more data:

• atmospheric neutrinos: ~3 years statistics for flux model constraint

• supernova and $n\bar{n}$ oscillations: 0 to greater than detector lifetime?

• antineutrinos: ~10 events/year from expected sources
unexpected sources may surprise us

Be patient
Be encouraged