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Thanks: Olivier Simard, Pierre-Luc Drouin, Stan Seibert and Gabriel Orebi Gann

The Final Cut at the Sudbury Neutrino Observatory

Alain Bellerive

Canada Research Chair

Carleton UNIVERSITY

Canada's Capital University

SNO

Outline

- Why ?
- Neutrinos From the Sun
- Sudbury Neutrino Observatory (SNO)
- Observables
- Solar Neutrino Flux
- Mixing Parameters

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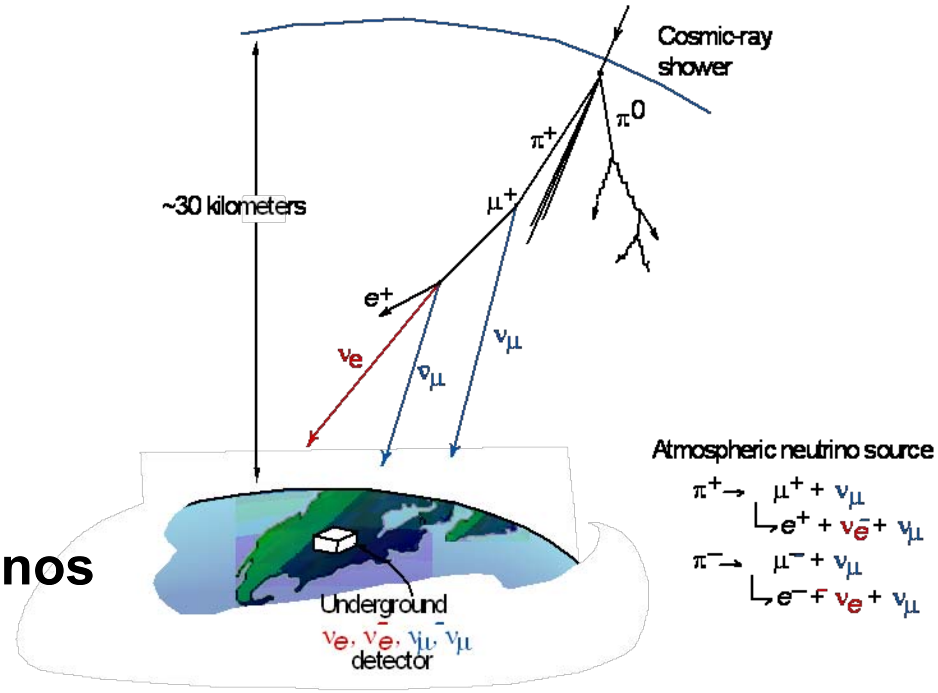
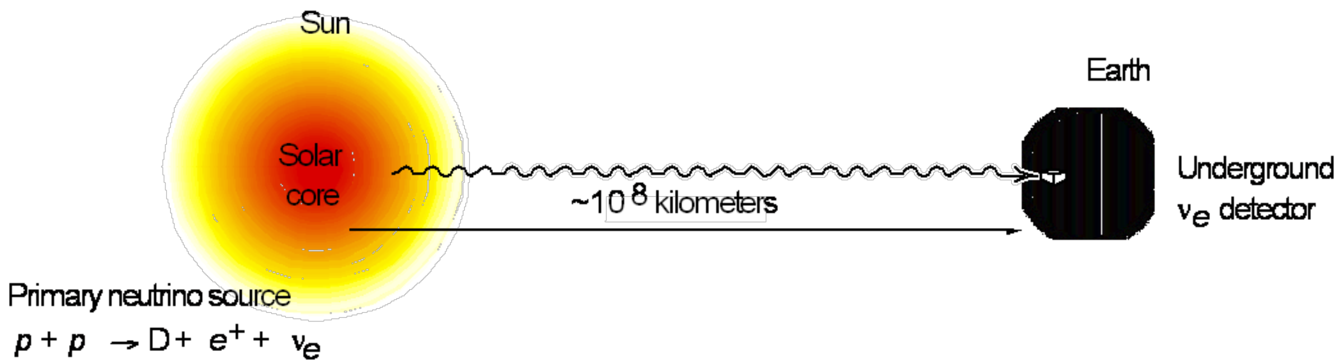
Evidence for Neutrino Mixing

First evidence of neutrino oscillation

$$\frac{\nu_\mu}{\nu_e} \neq 2$$

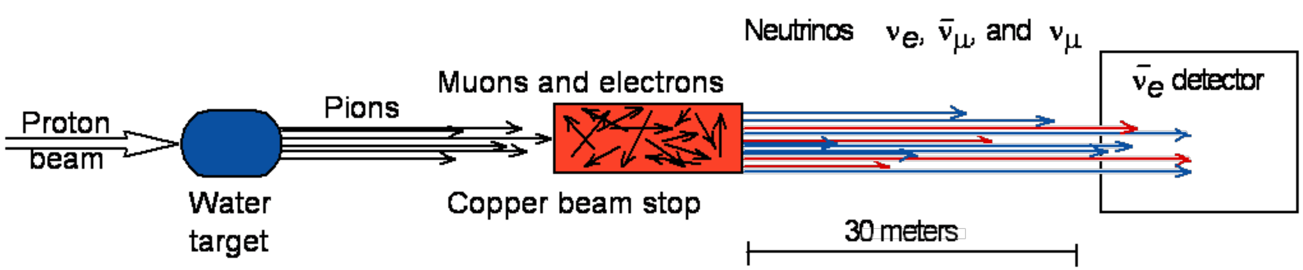
Atmospheric Neutrinos
high energies





Solar Neutrinos
low energies

Today's talk !!!



Beamstop Neutrinos
tunable energies

Future!

Neutrino Mixing

As in the quark sector one defines a neutrino mixing matrix which relates the mass and weak eigenstates

Mixing Matrix

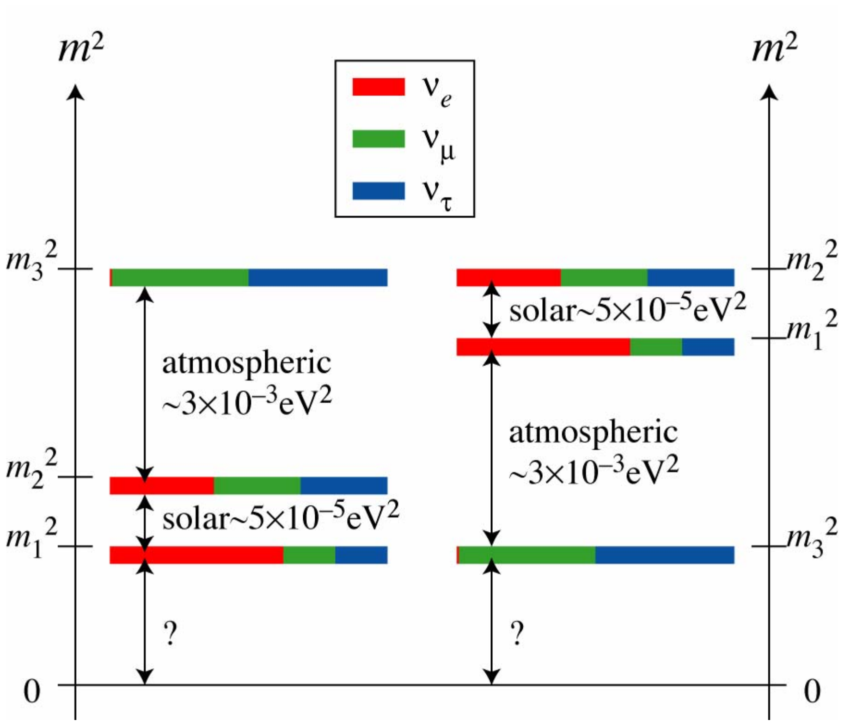
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Quark:	$\theta_{12} \approx \pi / 14$	$\theta_{23} \approx \pi / 76$	yes	$\theta_{13} \approx \pi / 870$
Neutrino:	$\theta_{12} \approx \pi / 6$	$\theta_{23} \approx \pi / 4$	???	$\theta_{13} < \pi / 20$

$$U_{\alpha i} = \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar}} \cdot \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric}} \cdot \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix}}_{\text{CP violation}} \cdot \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}}_{\text{short-baseline}}$$

where $c_{ij} = \cos\theta_{ij}$, and $s_{ij} = \sin\theta_{ij}$

Neutrino Mass



Mass hierarchy with $\Delta m^2_{12} > 0$ is assumed
Is it ???

Note the small υ_e component in υ_3 from atmospheric results $P(\upsilon_\mu \rightarrow \upsilon_\mu)$!!!

Neutrino can only mix (quantum effect) if there are mass differences between the states

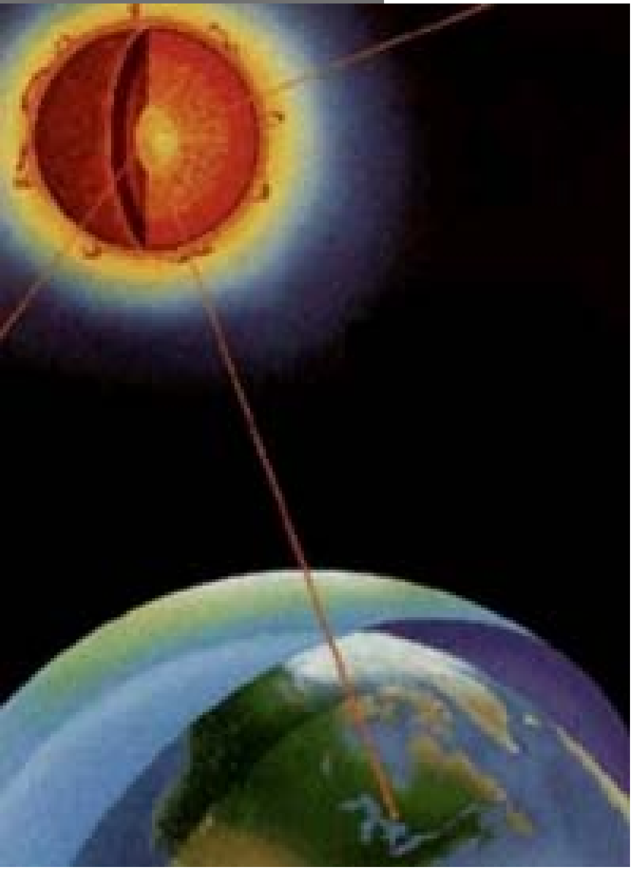
It implies neutrinos have masses which leads to physics beyond the Minimal Standard Model

The First Piece

Solar Neutrino Flux

- The Sun produces υ_e in fusion nuclear reactions
- Solar neutrino oscillation occurs inside the Sun
- Survival probability depends on the neutrino energy

Solar Neutrinos



$p + p \rightarrow {}^{2}H + e^{+} + \nu_e$ $p + e^{-} + p \rightarrow {}^{2}H + \nu_e$

99.75%   0.25%

${}^{2}H + p \rightarrow {}^{3}He + \gamma$

85%   ~15%   ~10^{-5}%

${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$

${}^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu_e$

${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

15.07%   0.02%

${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \gamma + \nu_e$

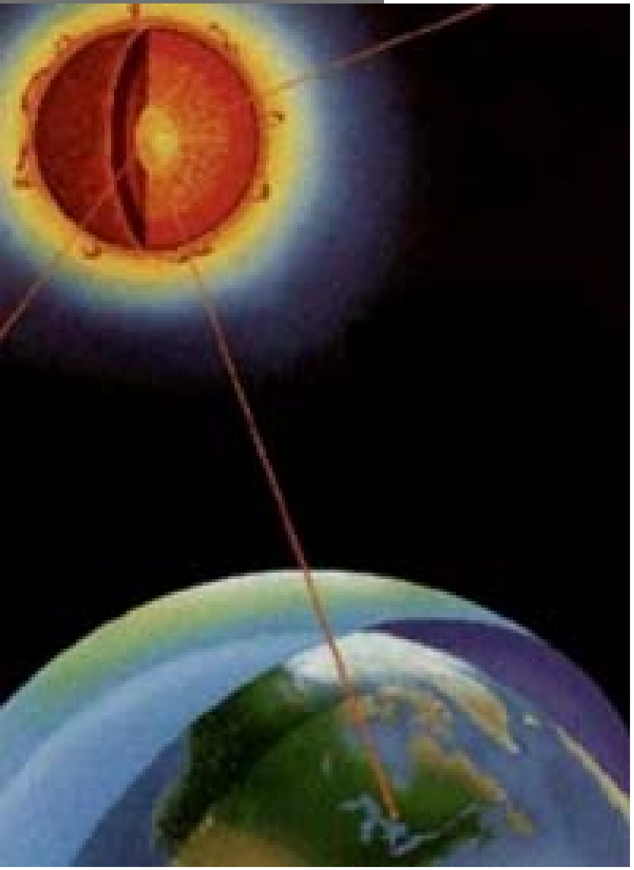
${}^{7}Be + p \rightarrow {}^{8}B + \gamma$

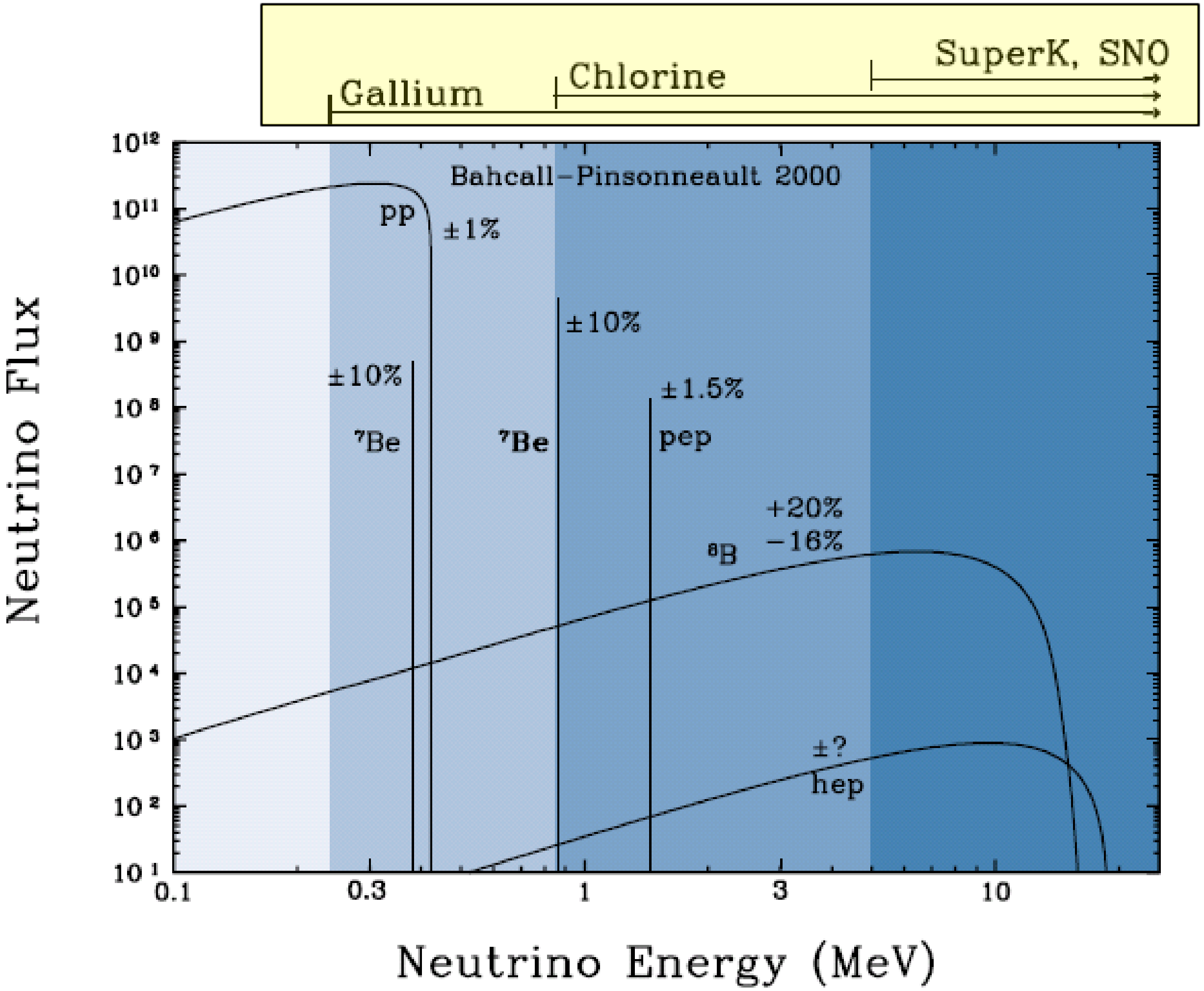
${}^{7}Li + p \rightarrow \alpha + \alpha$

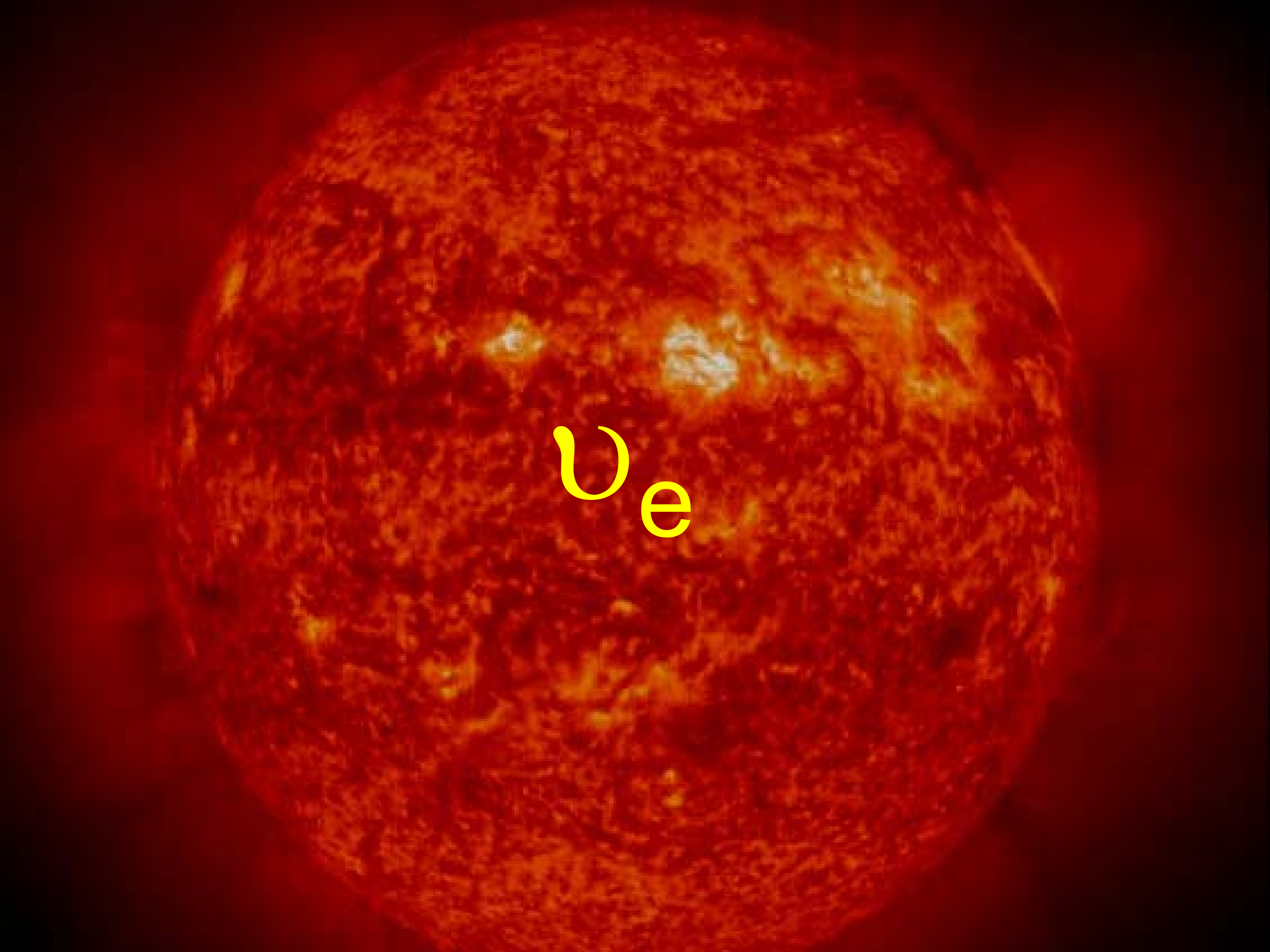
${}^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + \nu_e$

${}^{8}Be^{*} \rightarrow {}^{4}He + {}^{4}He$

Solar Neutrinos






ν_e

Solar Neutrino Mixing

$P_{ee} \equiv P(\upsilon_e \rightarrow \upsilon_e)$

$P_{ee} = \cos^4(\theta_{13})\sin^2(2\theta_{12})\ \sin^2(\varphi)$

$P_{ee} \approx \sin^2(2\theta_{12})\ \sin^2(\varphi)$

where $\varphi = 1.27\Delta m^2_{12}$ L / E

Physics:

Δm^2_{12} & $\sin(2\theta_{12})$

Experiment:

Distance (L) & Energy (E)

Survival Probability
3 Parameters !

$$\Delta m^2_{12} = m^2_2 - m^2_1$$

signed quantity

θ_{12} = solar mixing

θ_{13} = small

The state evolves with time or distance

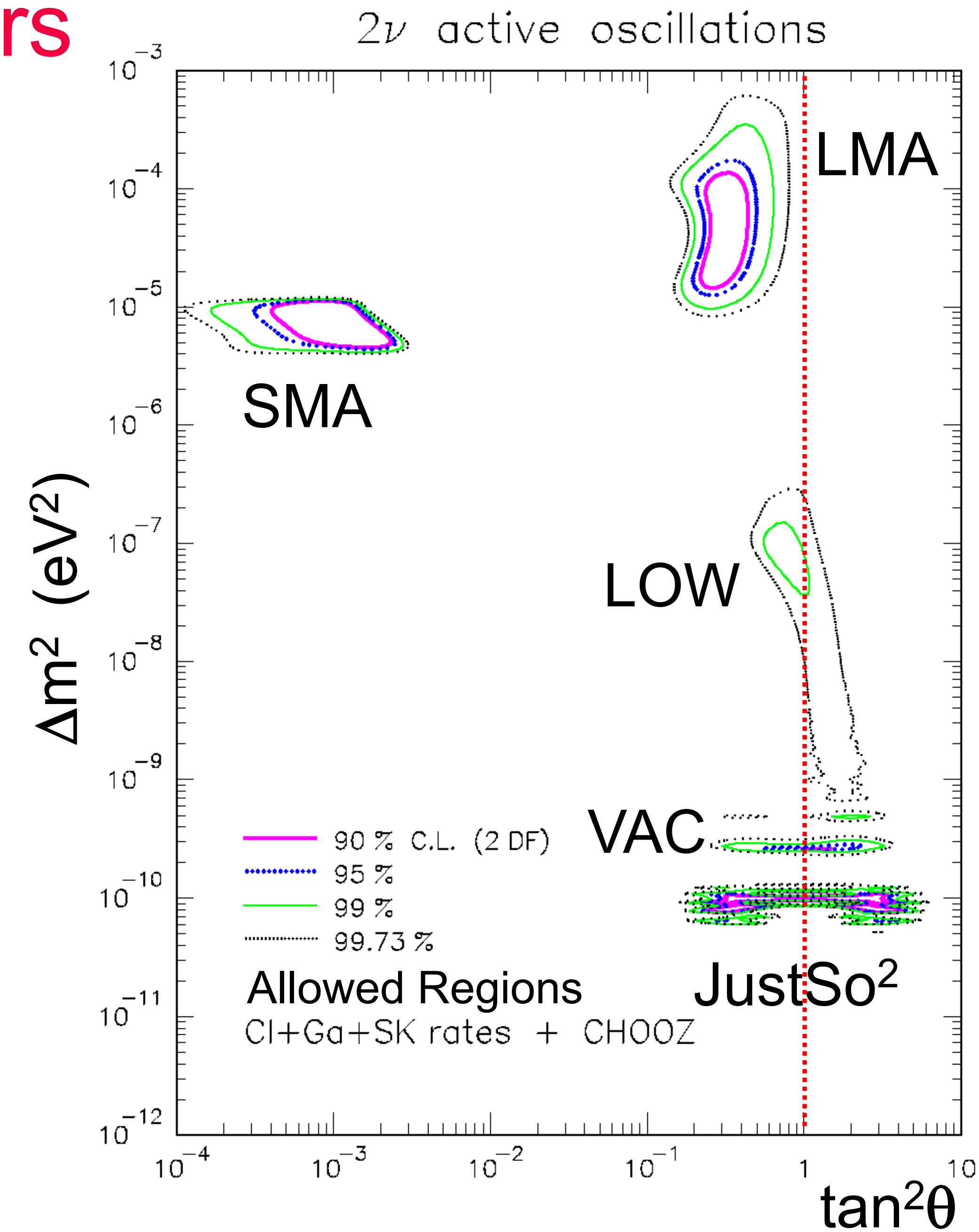
Mixing Parameters

Combination of the Chlorine, Gallium, SK, and CHOOZ restricted the mixing parameters

Pre SNO

$$\Delta m^2 = \Delta m_{12}^2$$

$$\theta = \theta_{12} \qquad \theta_{13} = 0$$



Phys.Rev. D64 (2001) 093007

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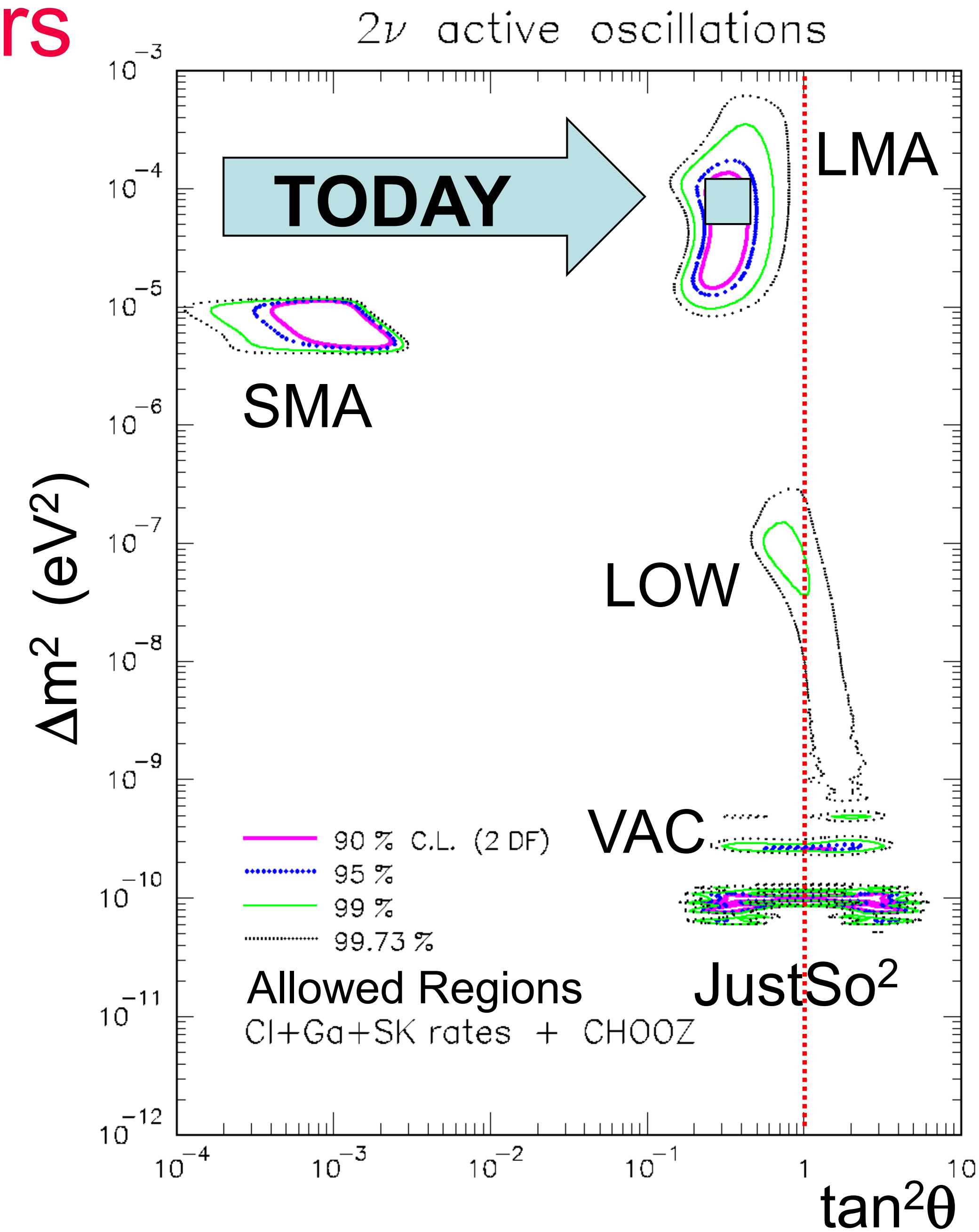

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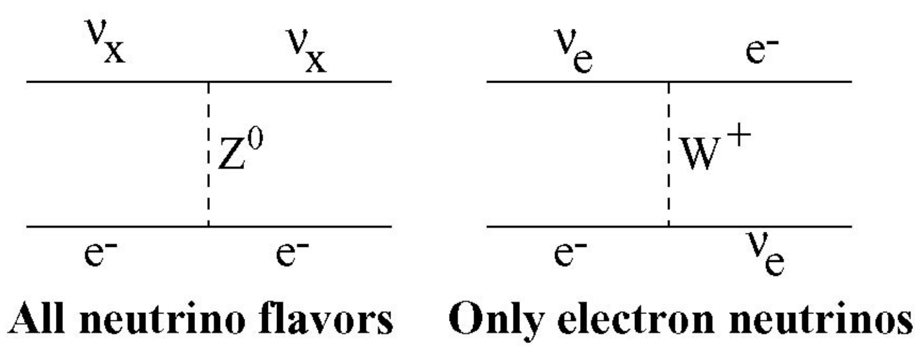
Matter-Enhanced Neutrino Oscillations

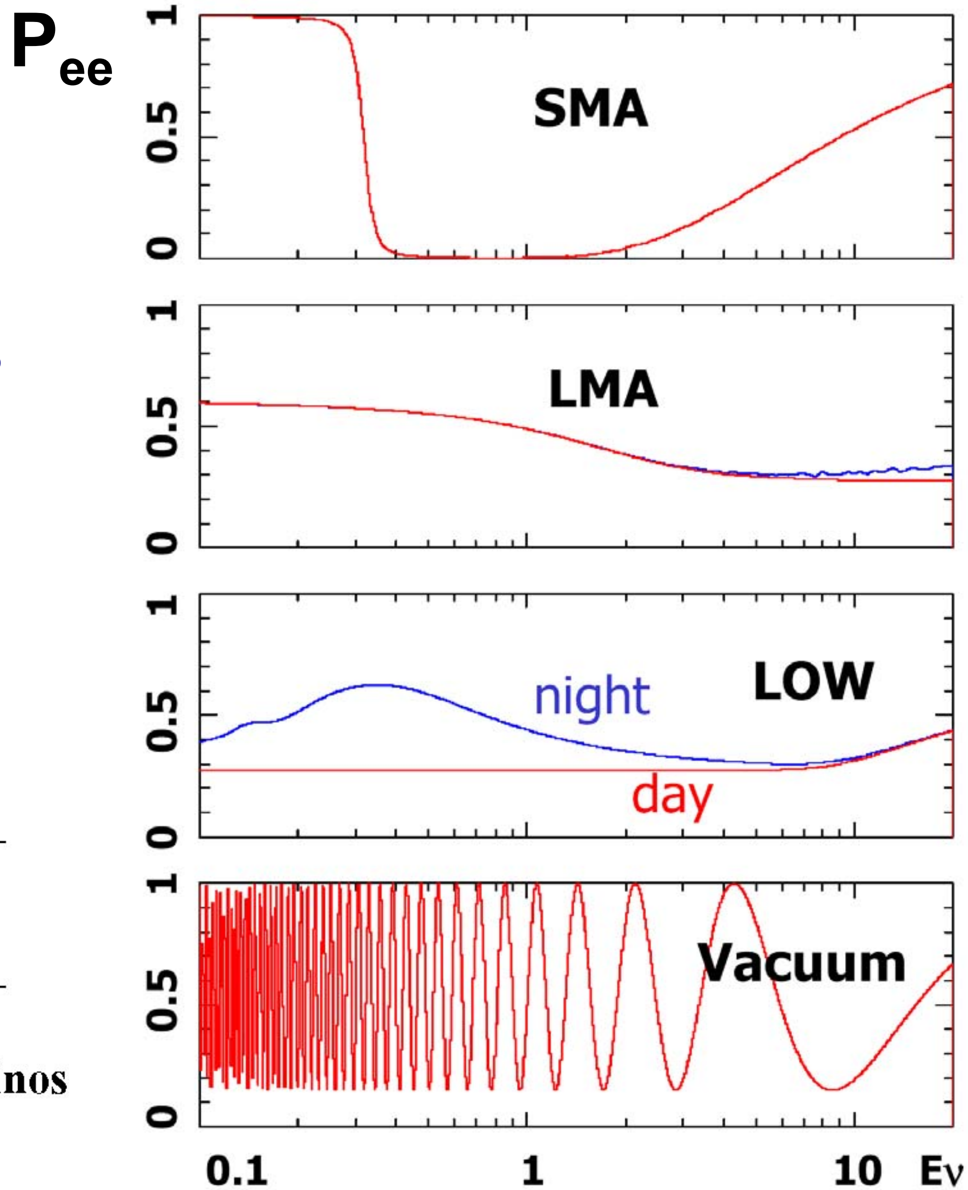
Neutrinos produced in weak state ν_e

$\Rightarrow$ High density of electrons in the Sun

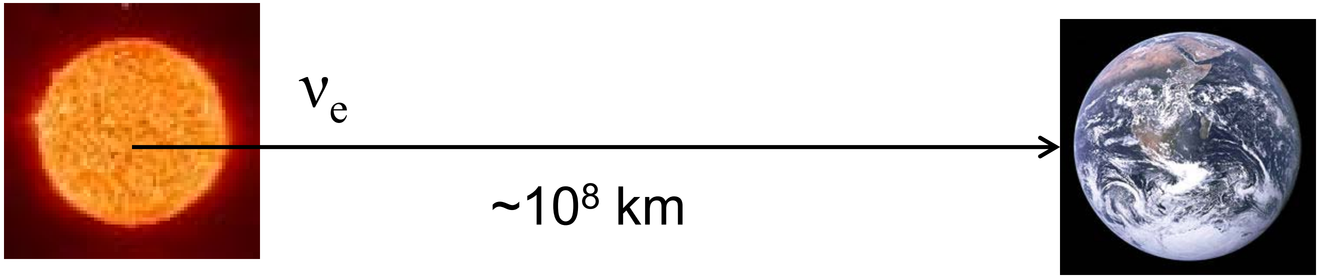
$\Rightarrow$ Superposition of mass states $\nu_{1,2,3}$ changes through the MSW resonance effect

$\Rightarrow$ Solar neutrino flux detected on Earth consists of $\nu_e + \nu_{\mu,\tau}$





Solar Neutrino Problem (Pre SNO)



$\overline{P}_{ee}$

Measured $\neq$ Predicted

Neutrino reactions

$$\nu_e + {}^{37}\mathrm{Cl} \to e^- + {}^{37}\mathrm{Ar}$$

$$\nu_e + {}^{71}\mathrm{Ga} \to e^- + {}^{71}\mathrm{Ge}$$

$$\nu_l + e^- \to \nu_l + e^-$$

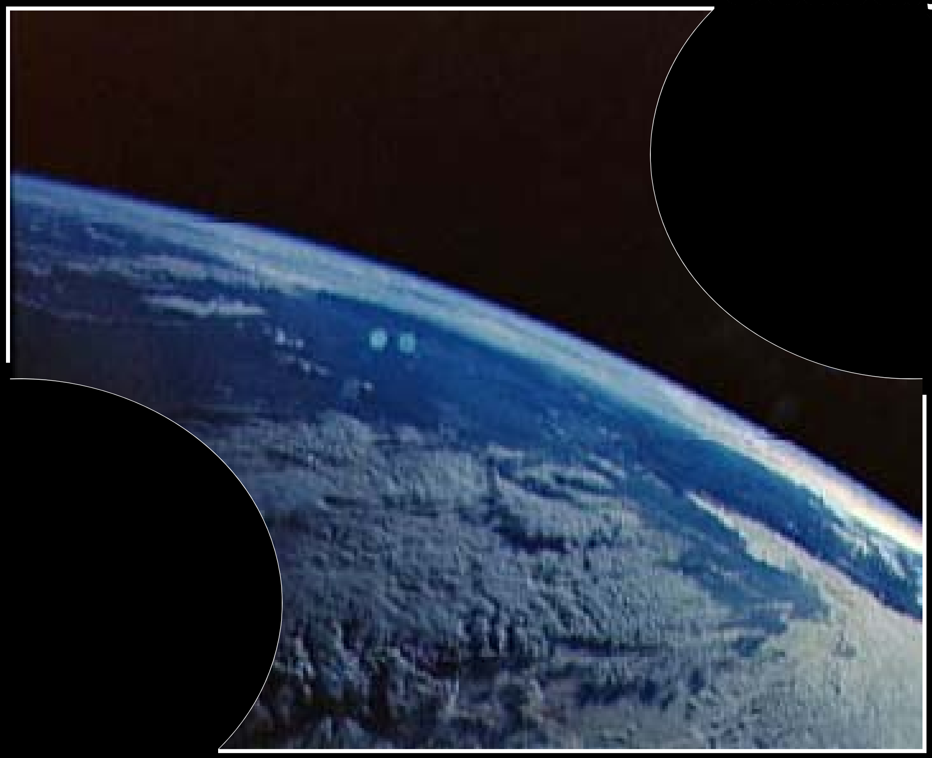
Experiment	Medium	Threshold (MeV)	Measured/SSM
Homestake	Chlorine	0.814	0.34±0.03
SAGE+GALLEX/GNO	Gallium	0.2332	0.52±0.03
SuperK	H_2O	7.0	0.406±0.013

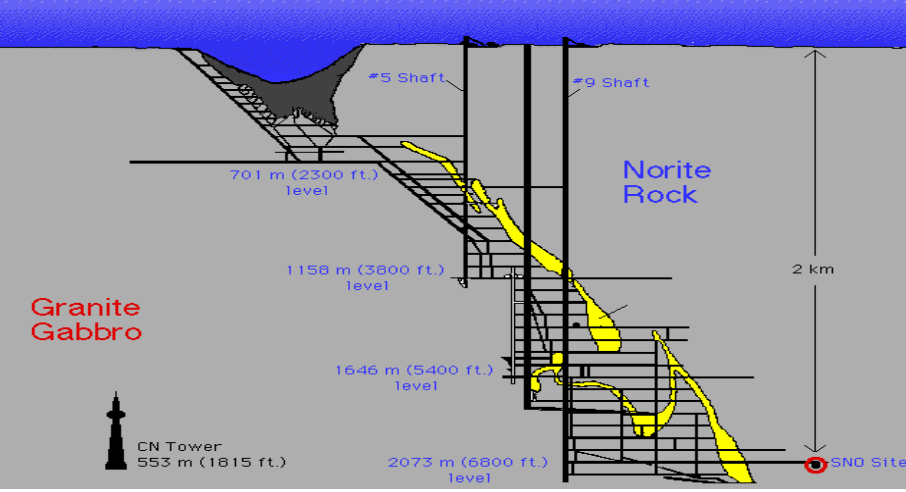
Source: arXiv:hep-ph/0406294

The Second Piece:

Observables

Sudbury Neutrino Observatory





Sudbury Neutrino Observatory

6000 mwe overburden

1000 tonnes D_2O

12 m Diameter Acrylic Vessel

1700 tonnes Inner Shield H_2O

Support Structure for 9500 PMTs, 60% coverage

5300 tonnes Outer Shield H_2O

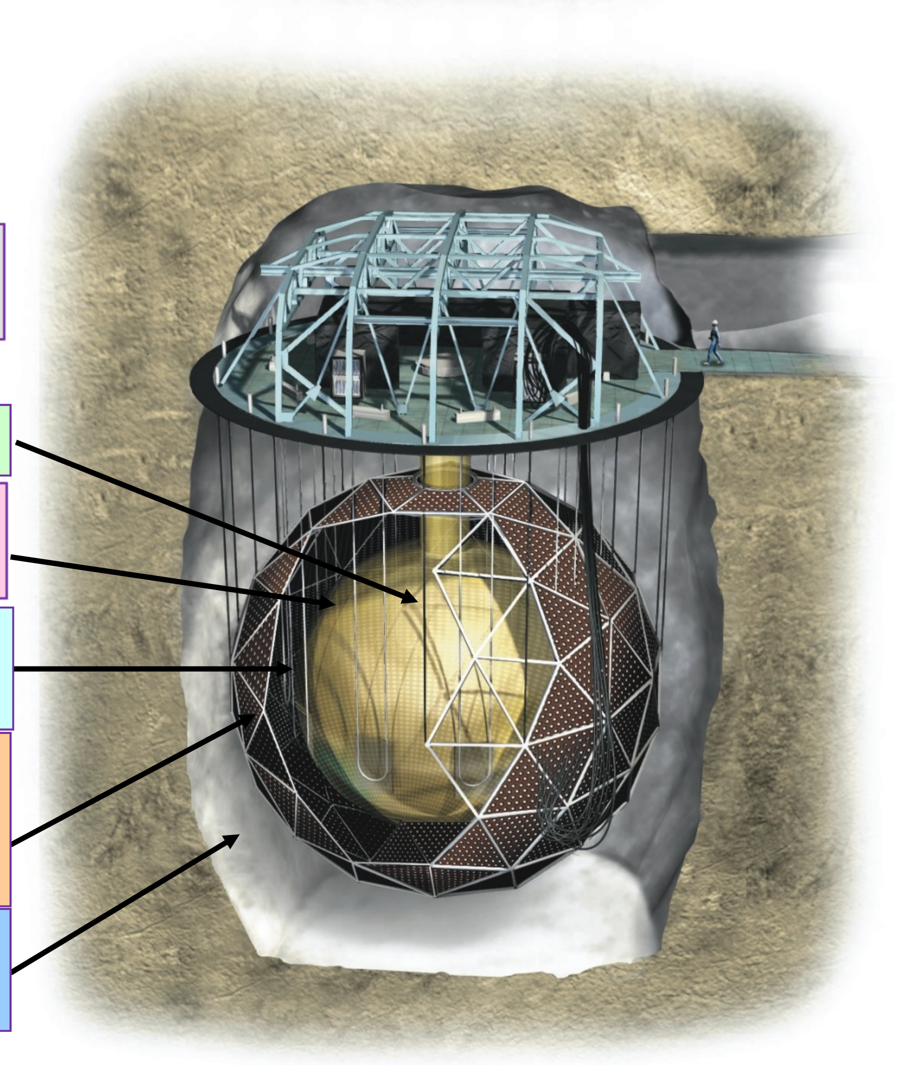
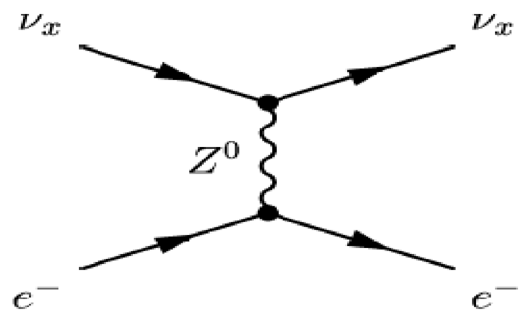


Image courtesy National Geographic

Neutrino reactions within SNO

Elastic-scattering (ES):

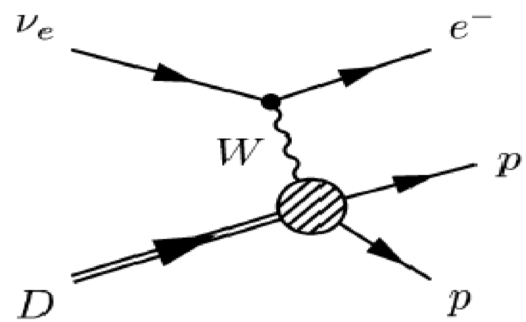
$$\nu_x + e^- \rightarrow \nu_x + e^-$$



ν_e mainly strong directional sensitivity

Charged-currents (CC):

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

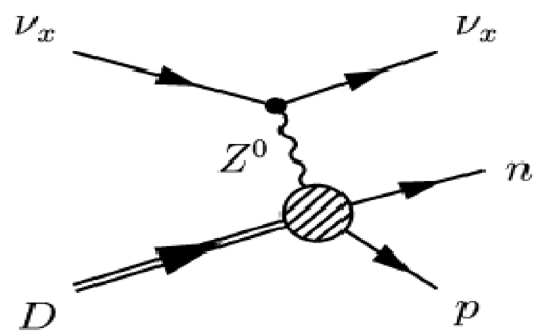


ν_e only

E_e well correlated with E_ν

Neutral-currents (NC):

$$\nu_x + d \rightarrow p + n + \nu_x$$



All flavors equally

Total neutrino flux

Key signatures for ν mixing with SNO

Flavor change ? $P_{ee}(E_\upsilon) \neq 1$?

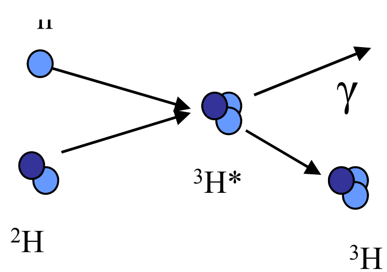
$$\frac{\Phi_{CC}}{\Phi_{ES}} = \frac{\nu_e}{\nu_e + 0.154(\nu_\mu + \nu_\tau)}$$

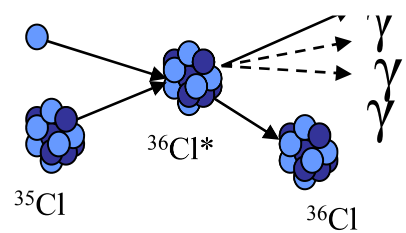
$$\frac{\Phi_{CC}}{\Phi_{NC}} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau}$$

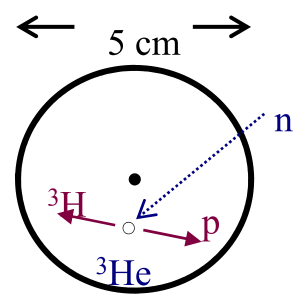
Three methods to detect neutrons

$$\nu_x + d \rightarrow \nu_x + P + n$$

Phase I (D_2O) Nov. 99 - May 01	Phase II (Salt+D_2O) July 01 - Sep. 03	Phase III (^3He+D_2O) Nov. 04 - Nov. 06
	2 tons of NaCl added	
n captures on Deuterium $^2H(n,\gamma)^3H$	n captures on Chlorine $^{35}Cl(n,\gamma's)^{36}Cl$	n captures on ^3He $^3He(n,p)^3H$
$\sigma = 0.0005b$ 6.25 MeV single γ PMT array readout	$\sigma = 44b$ 8.6 MeV multiple γs PMT array readout	$\sigma = 5330b$ 0.764 MeV(p,^3H) NCD readout



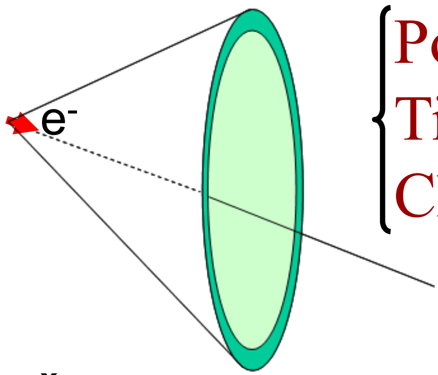




$$n + {}^3He \rightarrow p + {}^3H$$

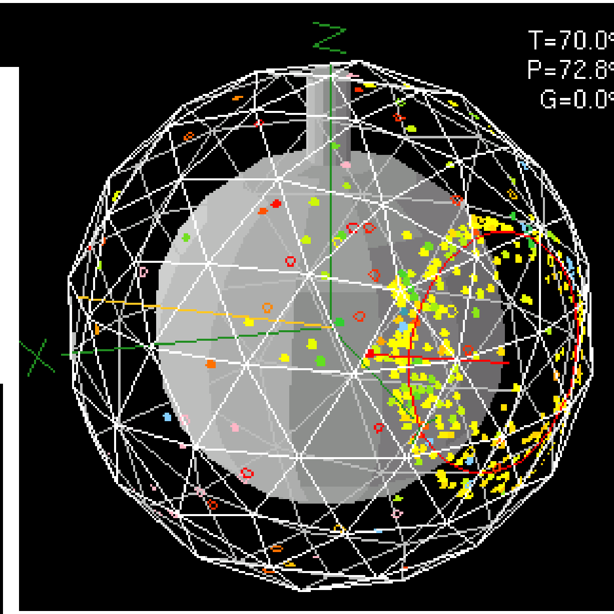
Neutrino Detection

PMT array measurement:

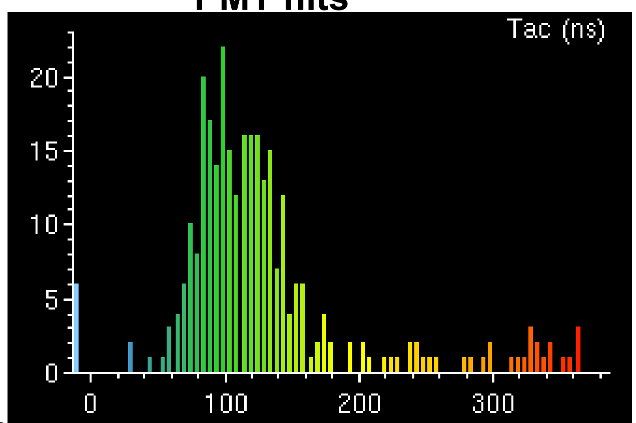


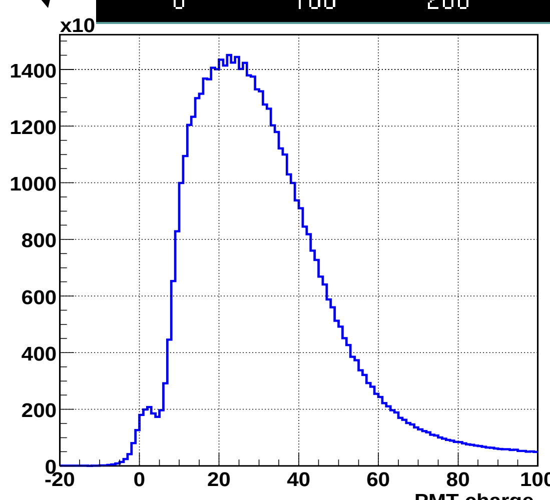
Čerenkov photons

- Position
- Time
- Charge



PMT hits





e^- from **CC** or **ES** reaction

Compton-scattered e^- of γ's from *n*-capture from **NC** reaction

vertex
direction
energy

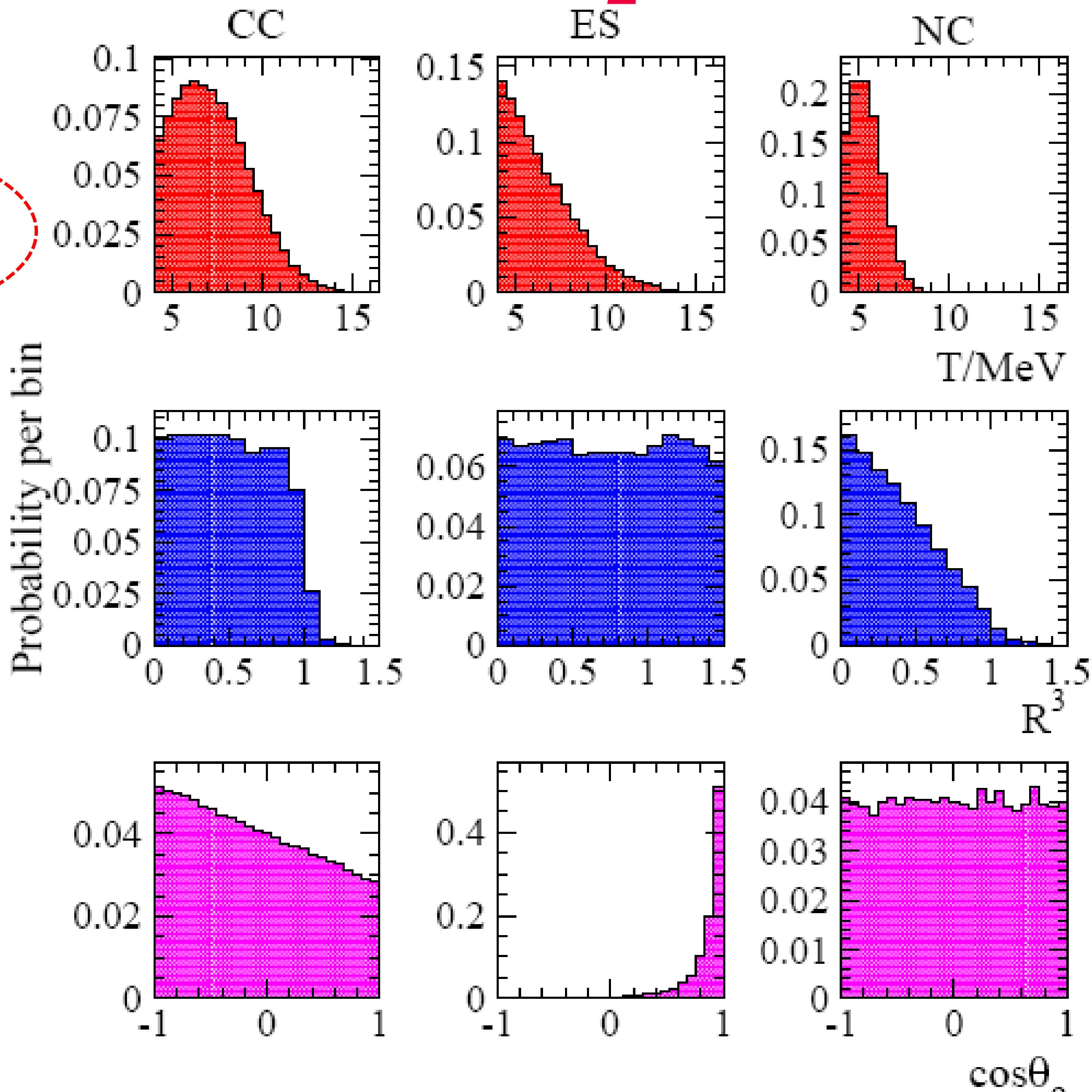
Pattern Recognition

Neutrino Observables D_2O Phase

Kinetic Energy Distribution

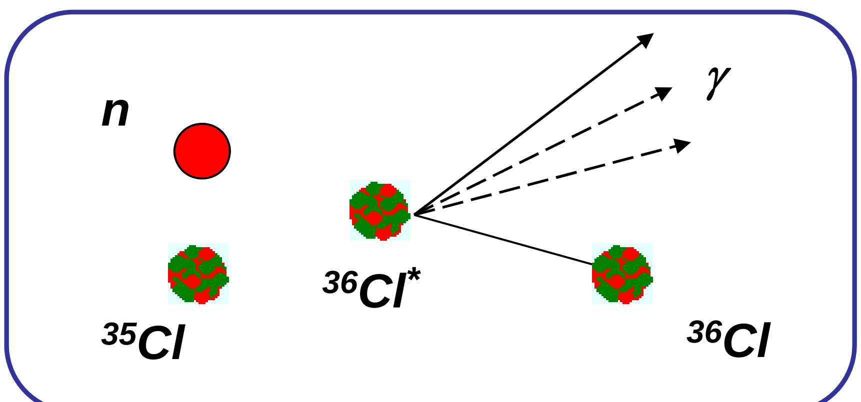
Radial Distribution (R^3, $R_{AV}=1$)

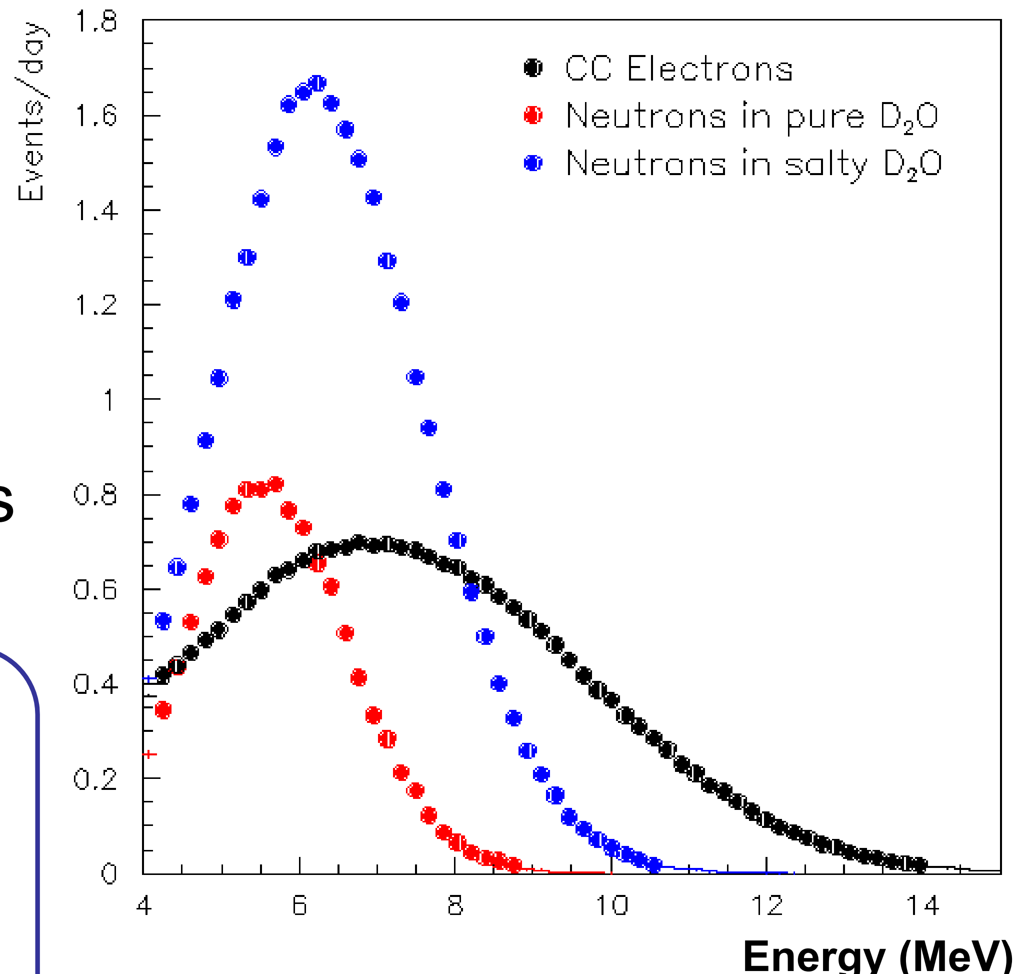
Solar Direction Distribution



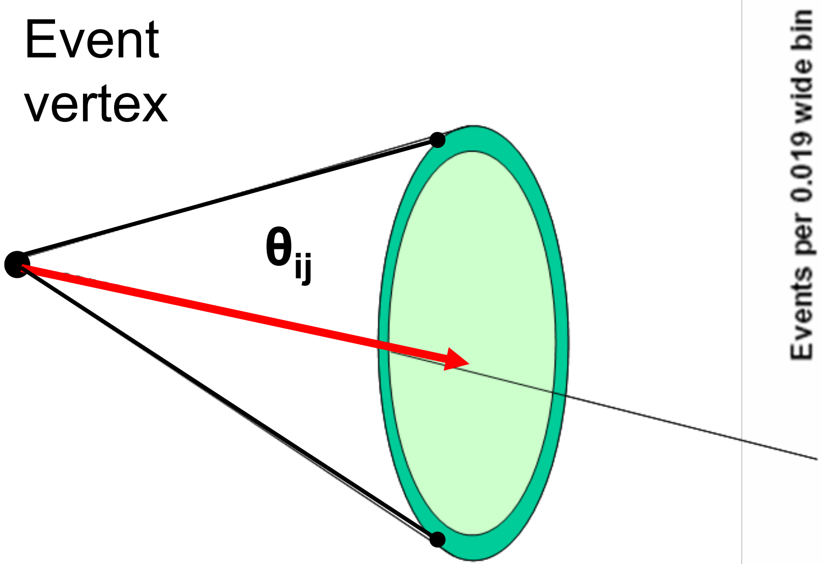
Advantages of Salt: more sensitive

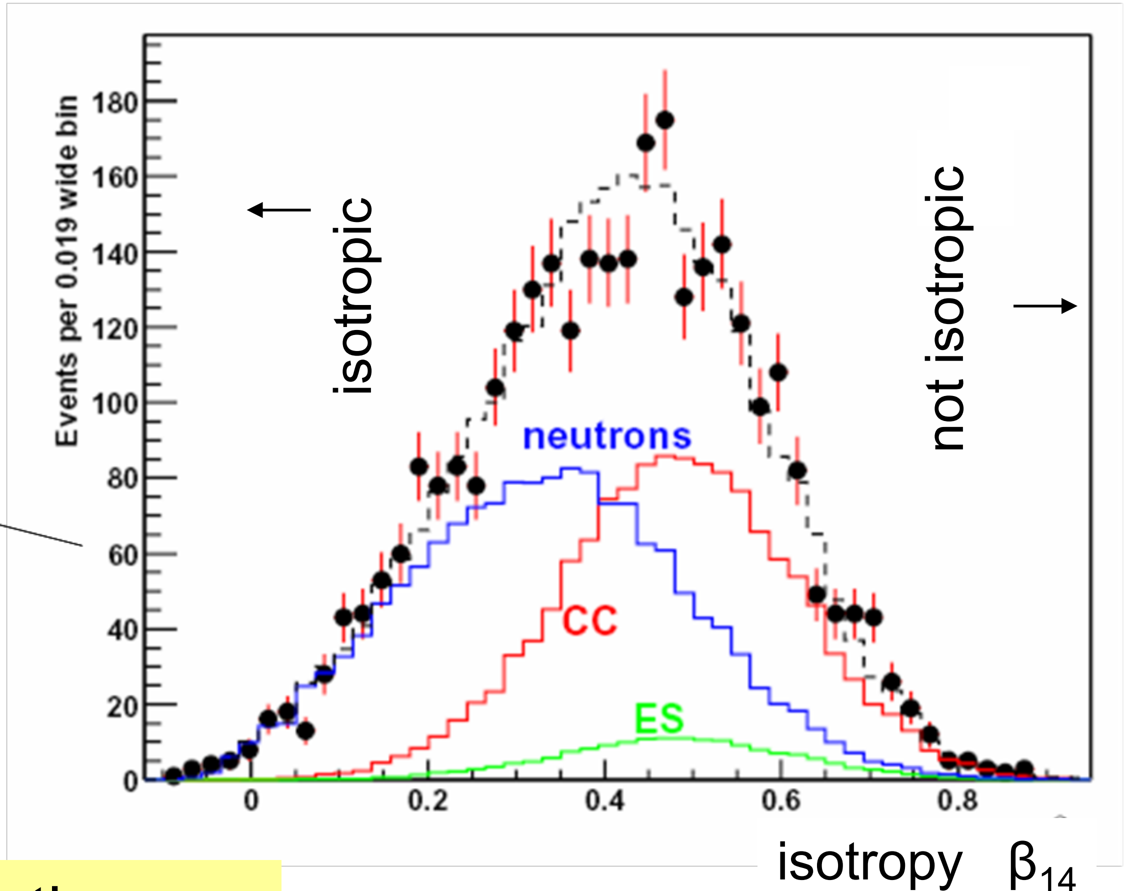
- Neutrons capturing on ^{35}Cl provide higher neutron energy above threshold.
- Higher capture efficiency
- Gamma cascade changes the angular profile.





Advantages of salt: event isotropy

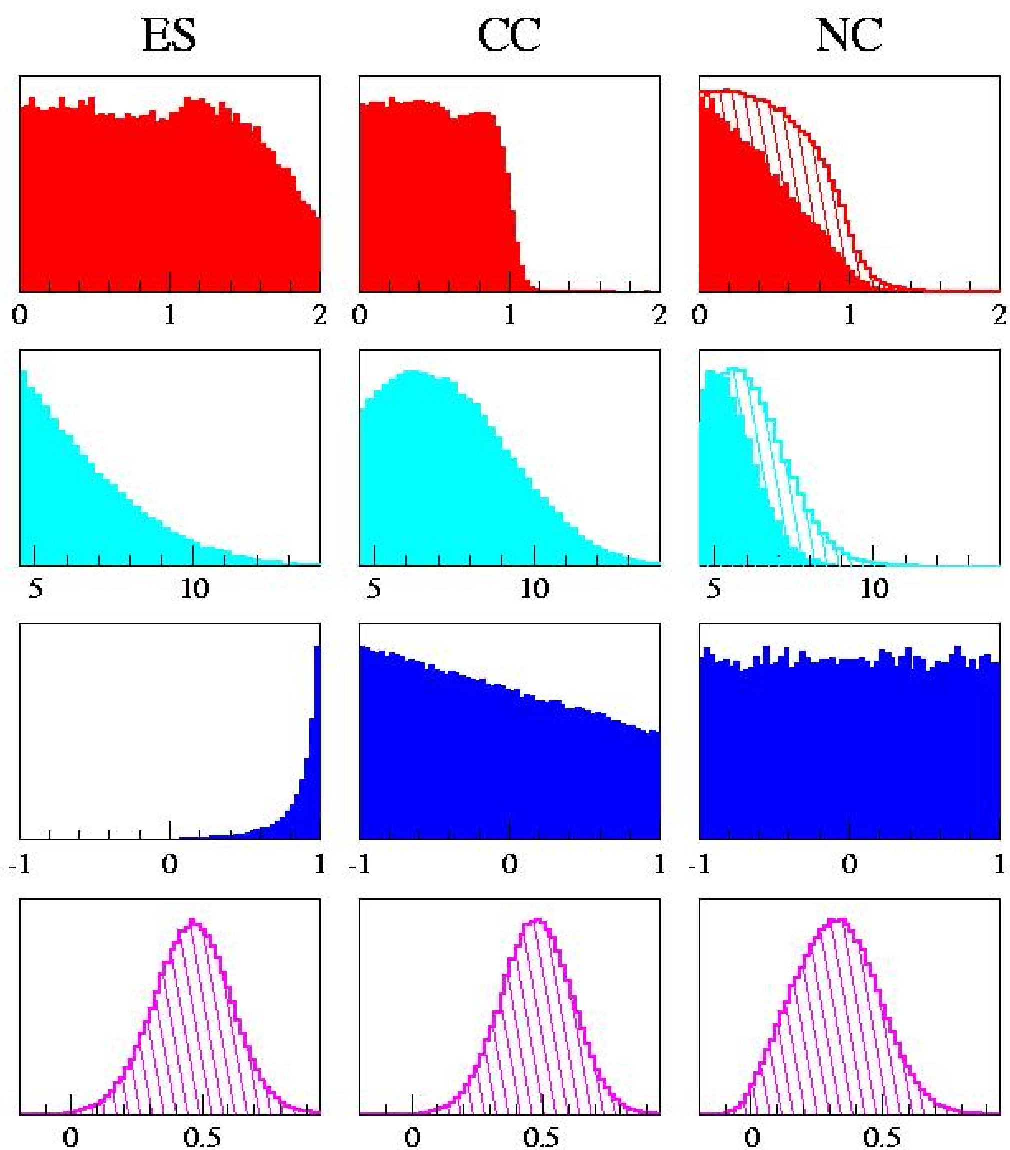




Isotropy variable, β_{14} , function of angles between each pair of hit PMTs ($\boldsymbol{\theta_{ij}}$) in event [similar to *thrust* in collider physics]

β_{14} powerful discriminating variable between NC and CC/ES events

Neutrino Observables Salt Phase



Radial Distribution (R^3, R_{AV}=1)

Energy Distribution (MeV)

Solar Direction Distribution

Isotropy Distribution

NC changed due to larger $\sigma_{n\gamma}$

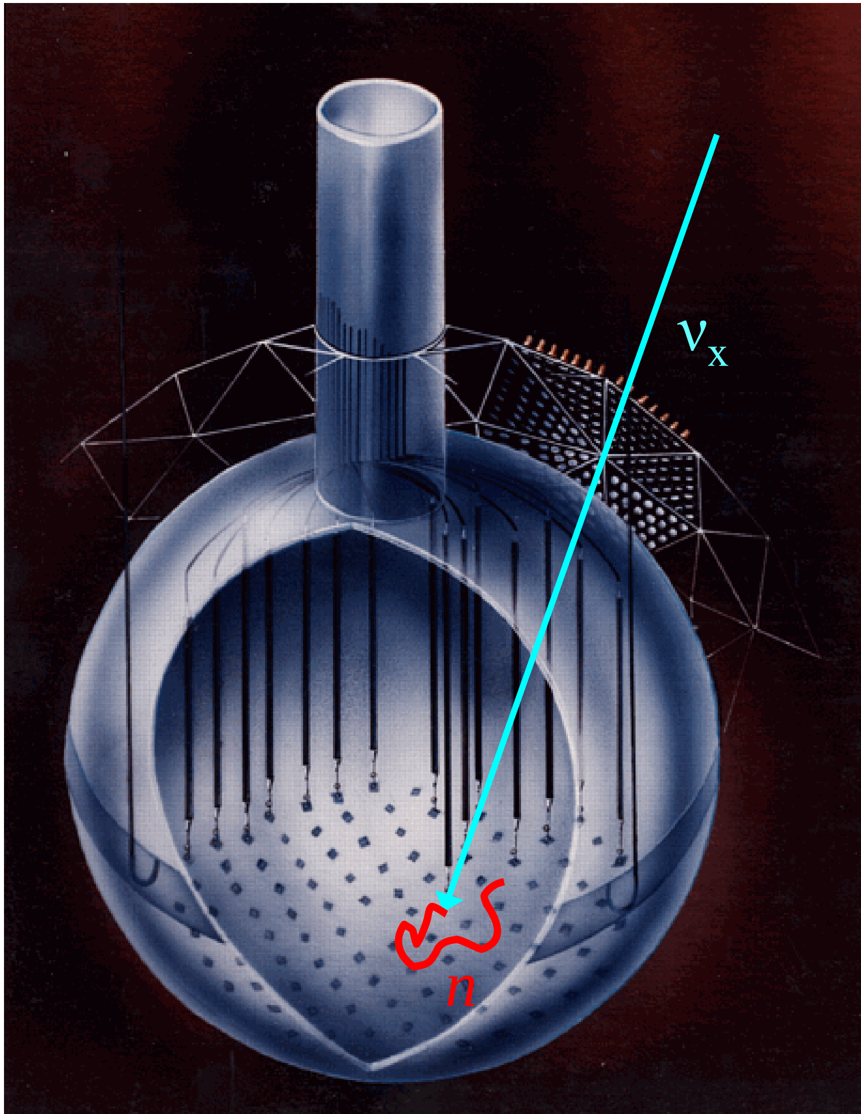
NC shifted to higher energy

Unchanged

All new due to multiple γ's

SNO Phase III ^{3}He Proportional Counters

^{3}He Propotional Counters (NCD)

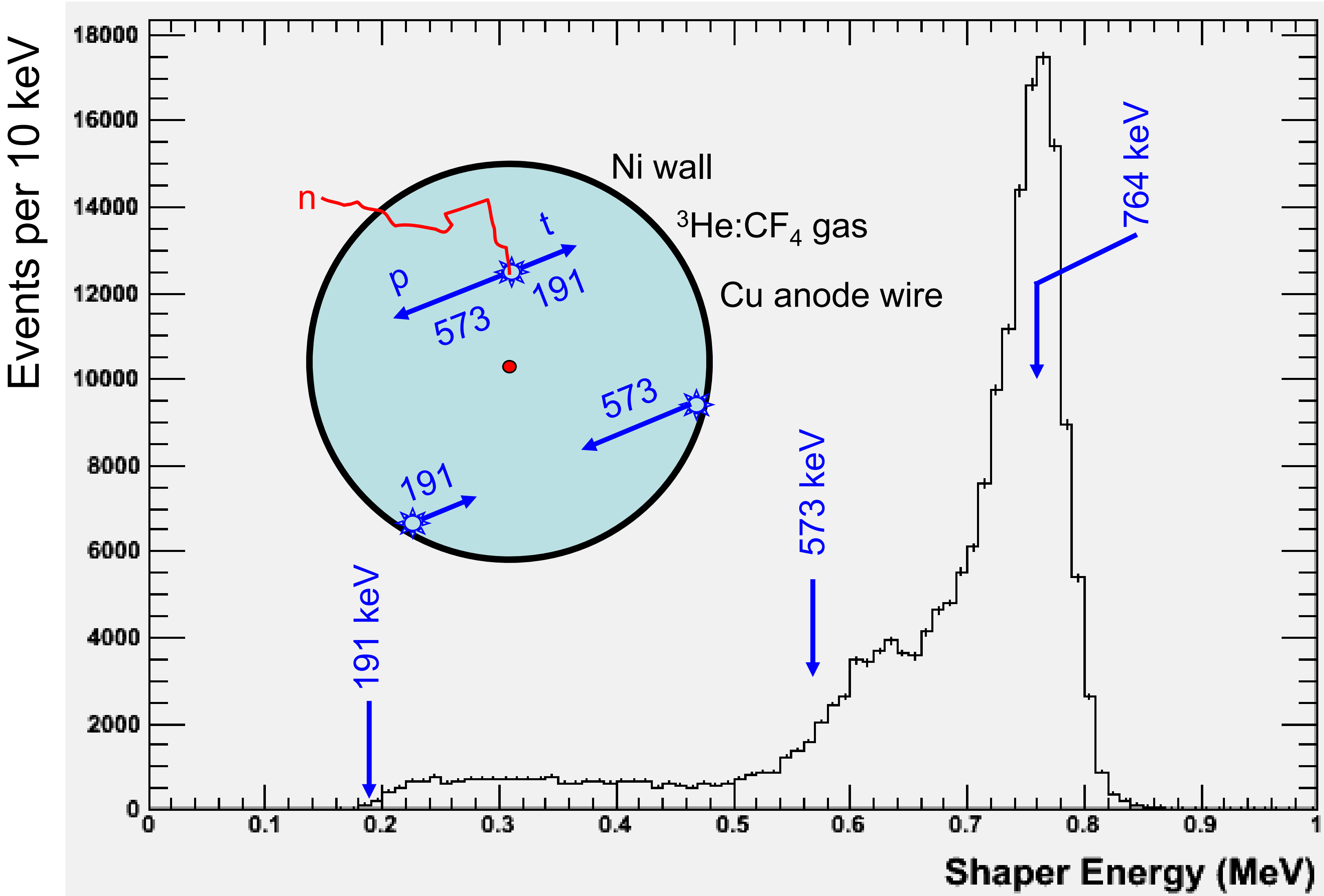


Physics Motivation

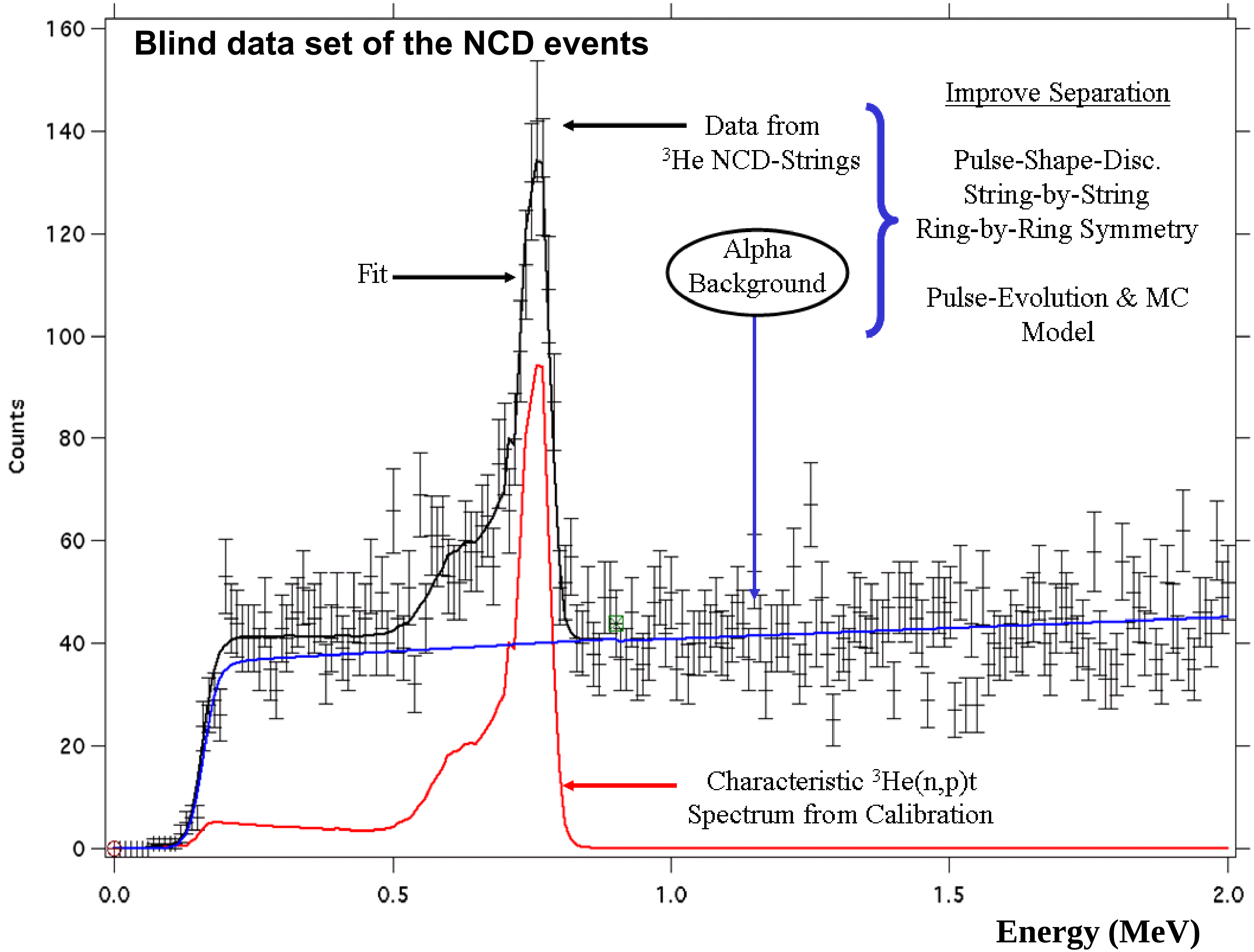
Event-by-event separation. Measure NC and CC in separate data streams – break the statistical correlation

Different systematic uncertainties than neutron capture on deuteron or NaCl

Neutrino Observable NCD Phase



SNO Phase III with NCD's



Arranging the Pieces:

Solar Neutrino From the Sun

- Simultaneous fit of all the phases
- Lower energy threshold for the D_2O and Salt phases
- CC and ES spectrum for the NCD phase
- Consistently fit for P_{ee} with no model assumption

Update – improvement – new stuff

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- Tune up the Monte Carlo on calibration data based on 5 years of operational experience
- Improve optics (especially at large radii)
- New energy estimator (improve energy resolution by 6%)
- Reduced the energy thresholds

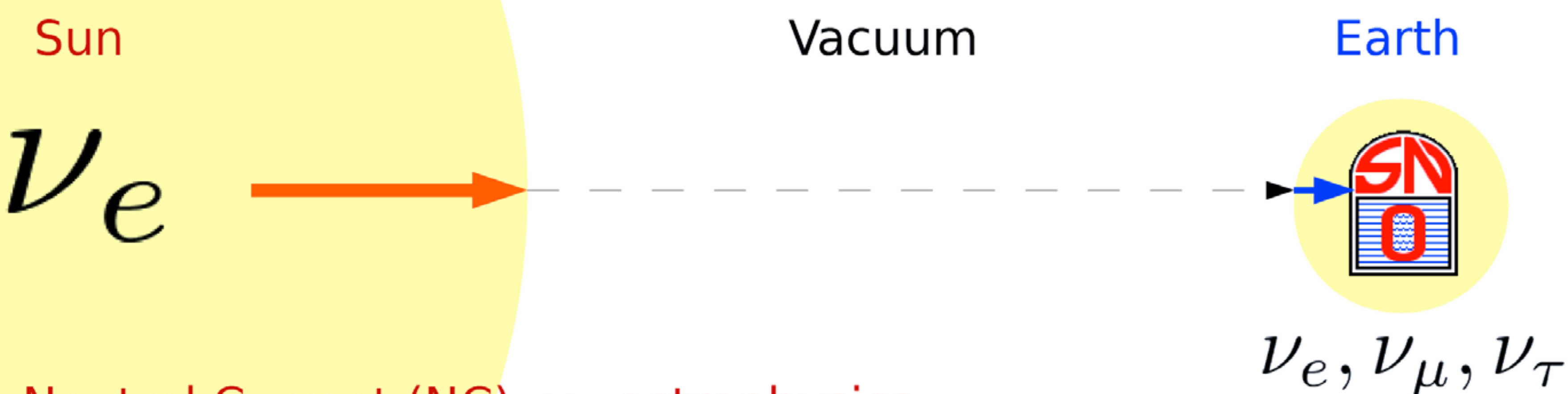
  D_2O (5 → 3.5 MeV) and Salt (5.5 → 3.5 MeV)

  Improve CC statistics by ~40% & NC by ~70%

  Allow to fit the background wall
- Investigate Pulse Shape Discrimination NCD
- Implement signal extraction to permit simultaneous 3-phase fitting which propagate all the systematic uncertainty to likelihood space

What SNO is all About

SNO is a unique opportunity to study both particle physics and astrophysics



Neutral Current (NC): ν_x, astrophysics.

Measurement of the total rate of solar neutrinos.
Solar neutrino flux, understanding of stars, nuclear fusion rates...

Charged Current (CC): ν_e, particle physics.

Measurement of the survival probability of electron neutrinos.
Weak interactions, lepton flavor conversion, neutrino mass...

What SNO is all About

SNO performs a combined analysis of the 3 phases with lower threshold

CC/NC: shown to be different than 1.0
Proof of oscillations, neutrino mass, new physics...

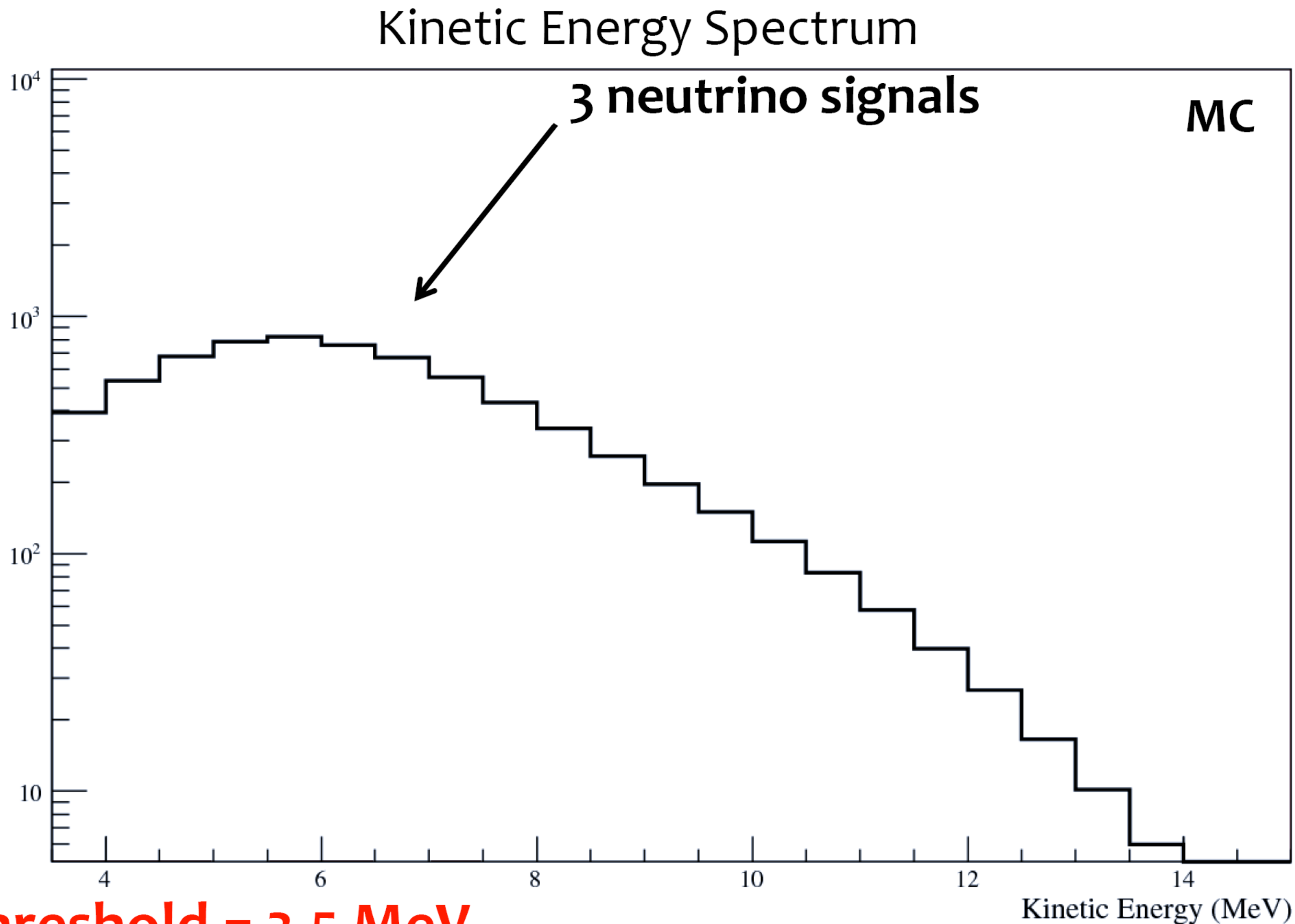
CC/NC: turn into measurement of the survival probability
Experimentally, function of neutrino energy.

$$P_{\nu_e \rightarrow \nu_e} \equiv P_{ee}$$

$$\frac{dCC}{dT} = \int \underline{P_{ee}(E_\nu)} \frac{d\Phi(\nu_e)}{dE_\nu} dE_\nu \int \frac{d\sigma}{dT_e}(E_\nu, T_e) \frac{dR}{dT}(T_e, T) dT_e$$

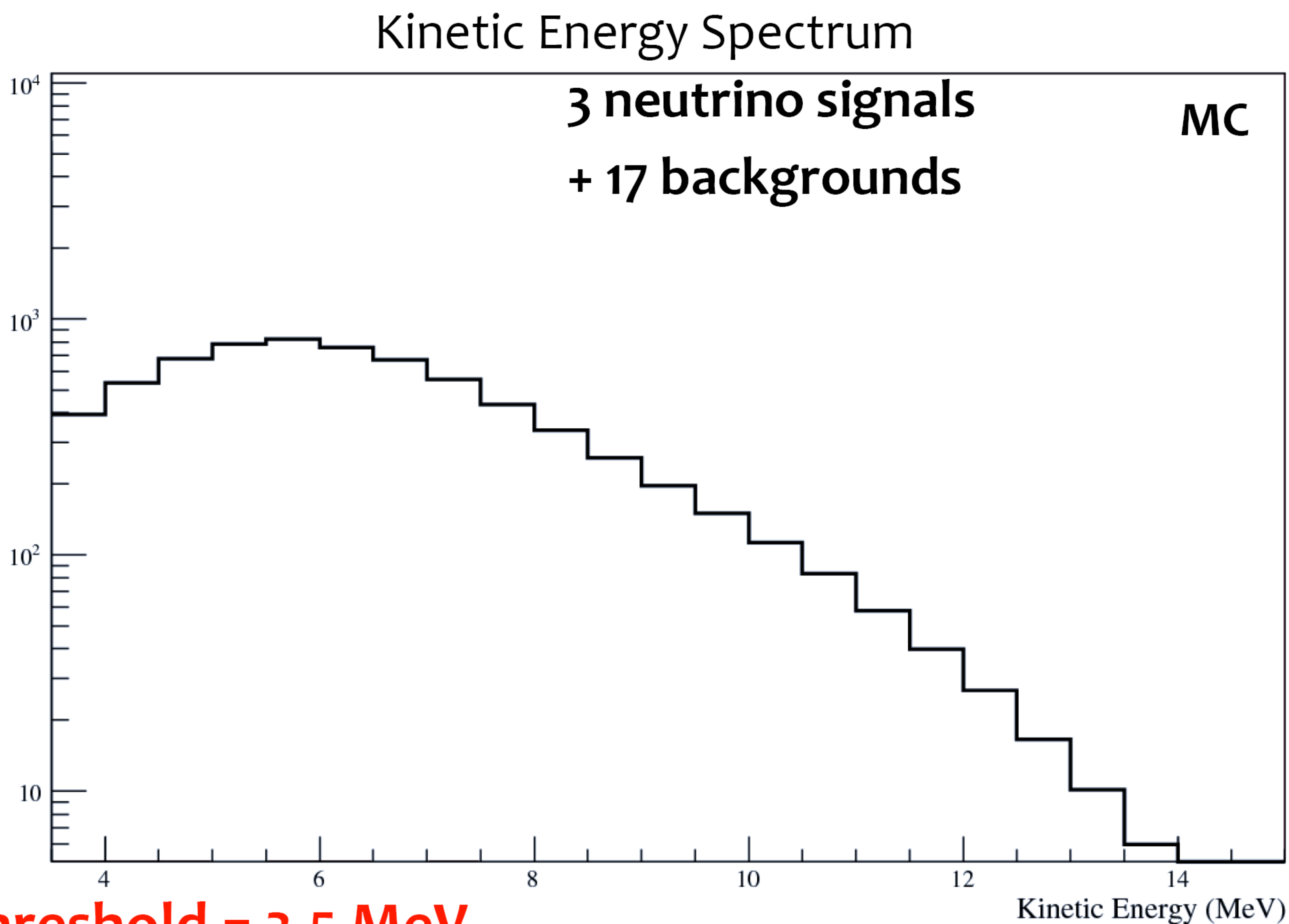
P_{ee}: use the measurement to understand its functional form.
Phenomenological study of the neutrino oscillation parameters.

Going A Step Further (Down)



Threshold = 3.5 MeV

Going A Step Further (Down)



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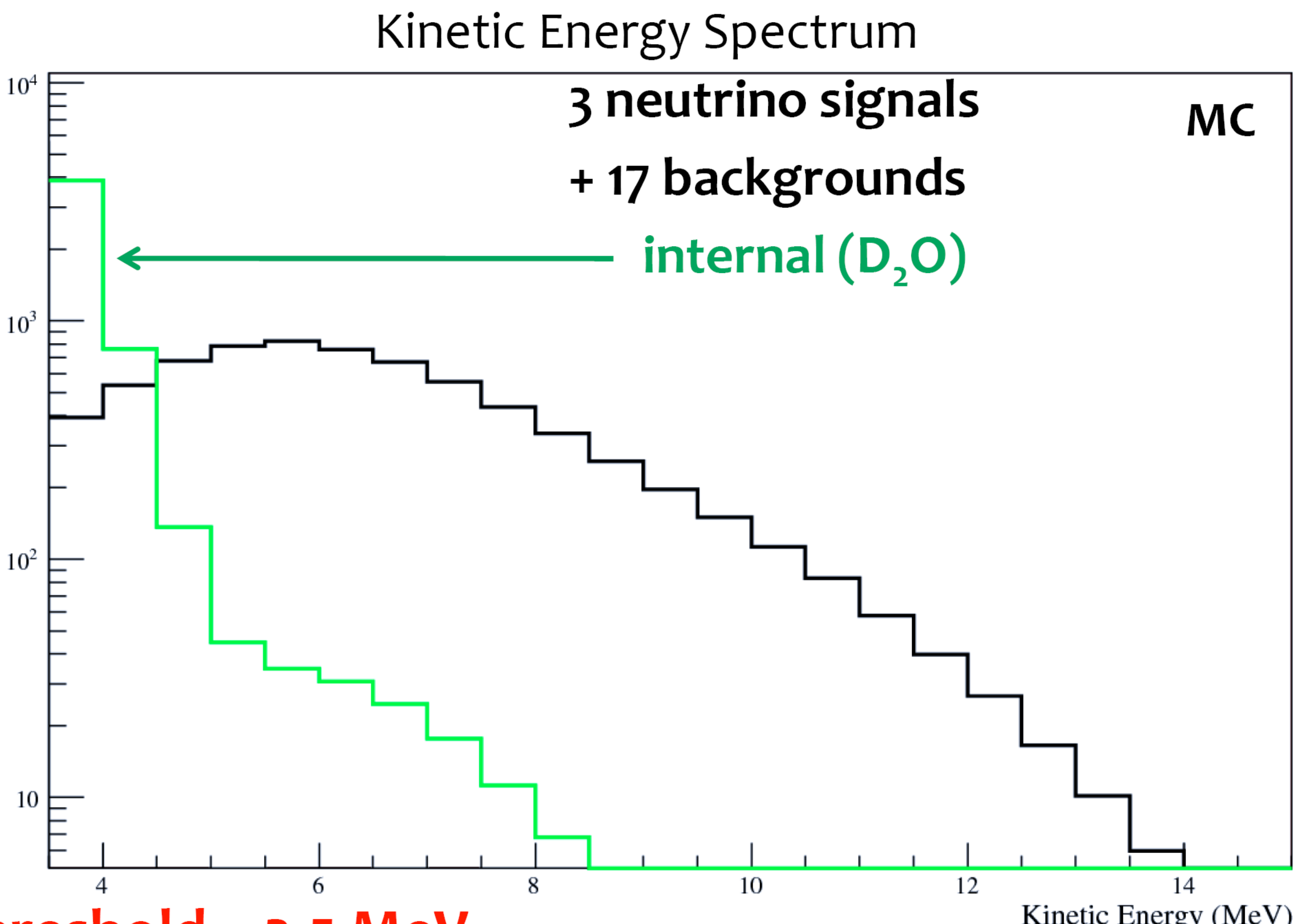

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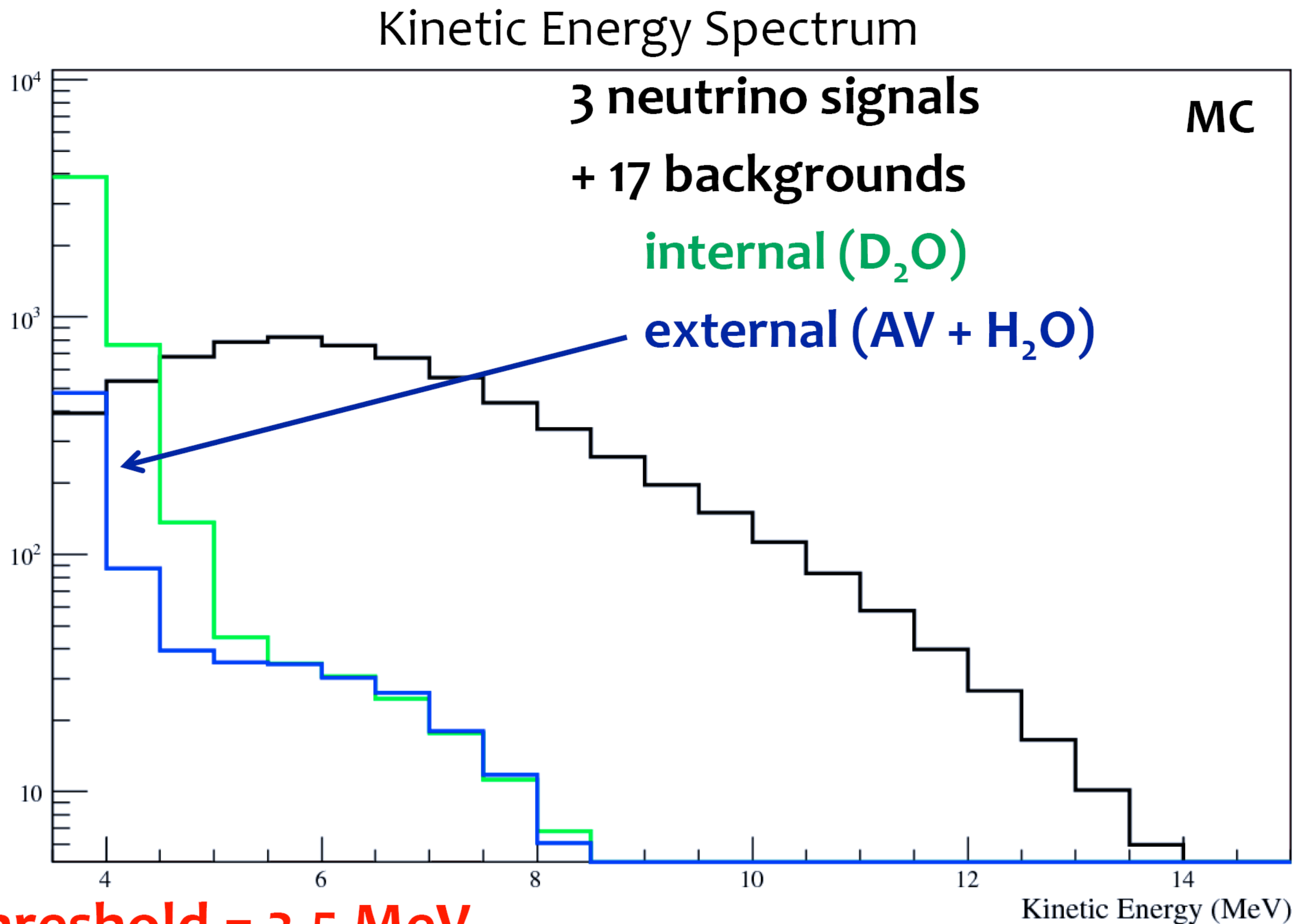
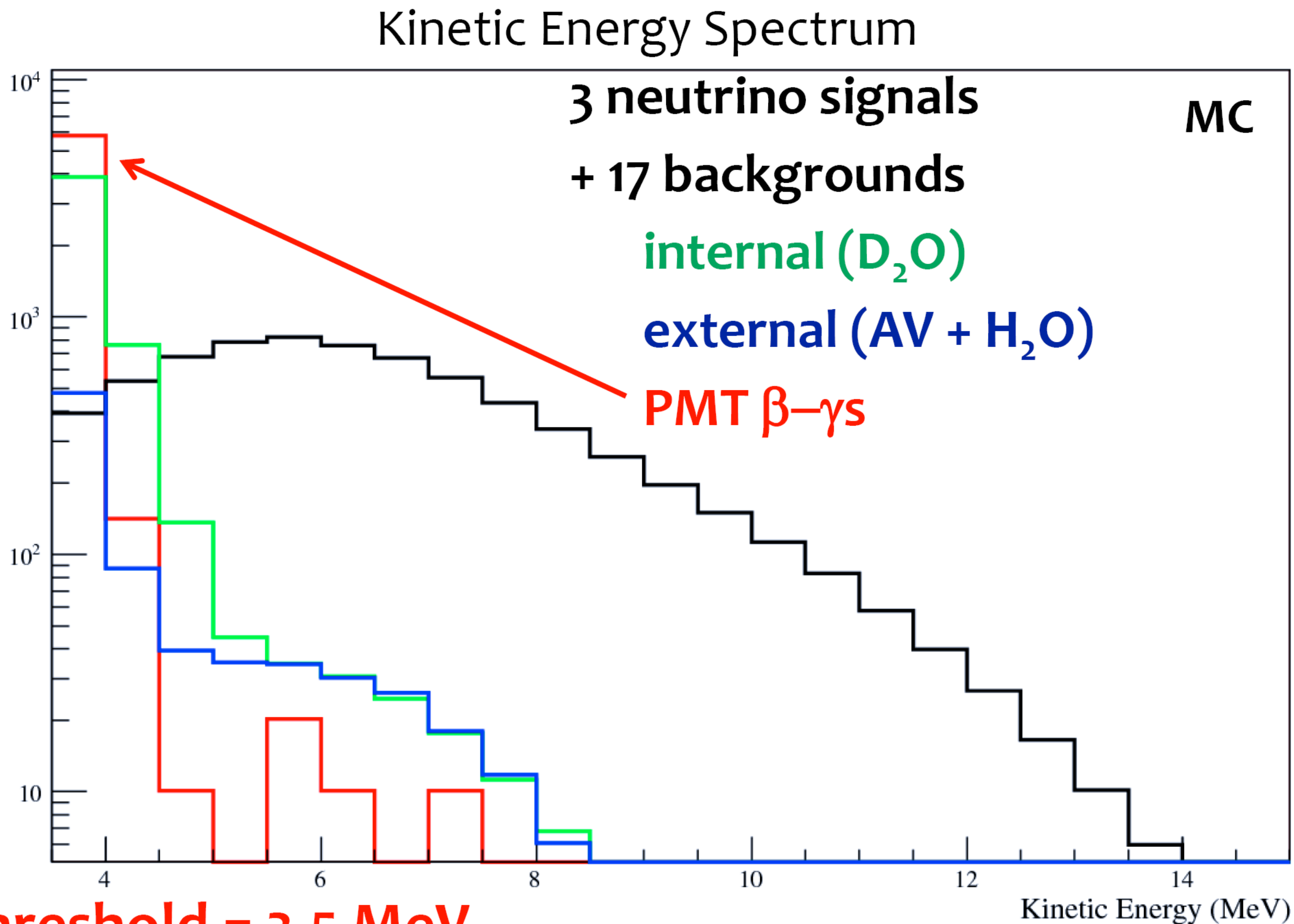
Going A Step Further (Down)



Threshold = 3.5 MeV

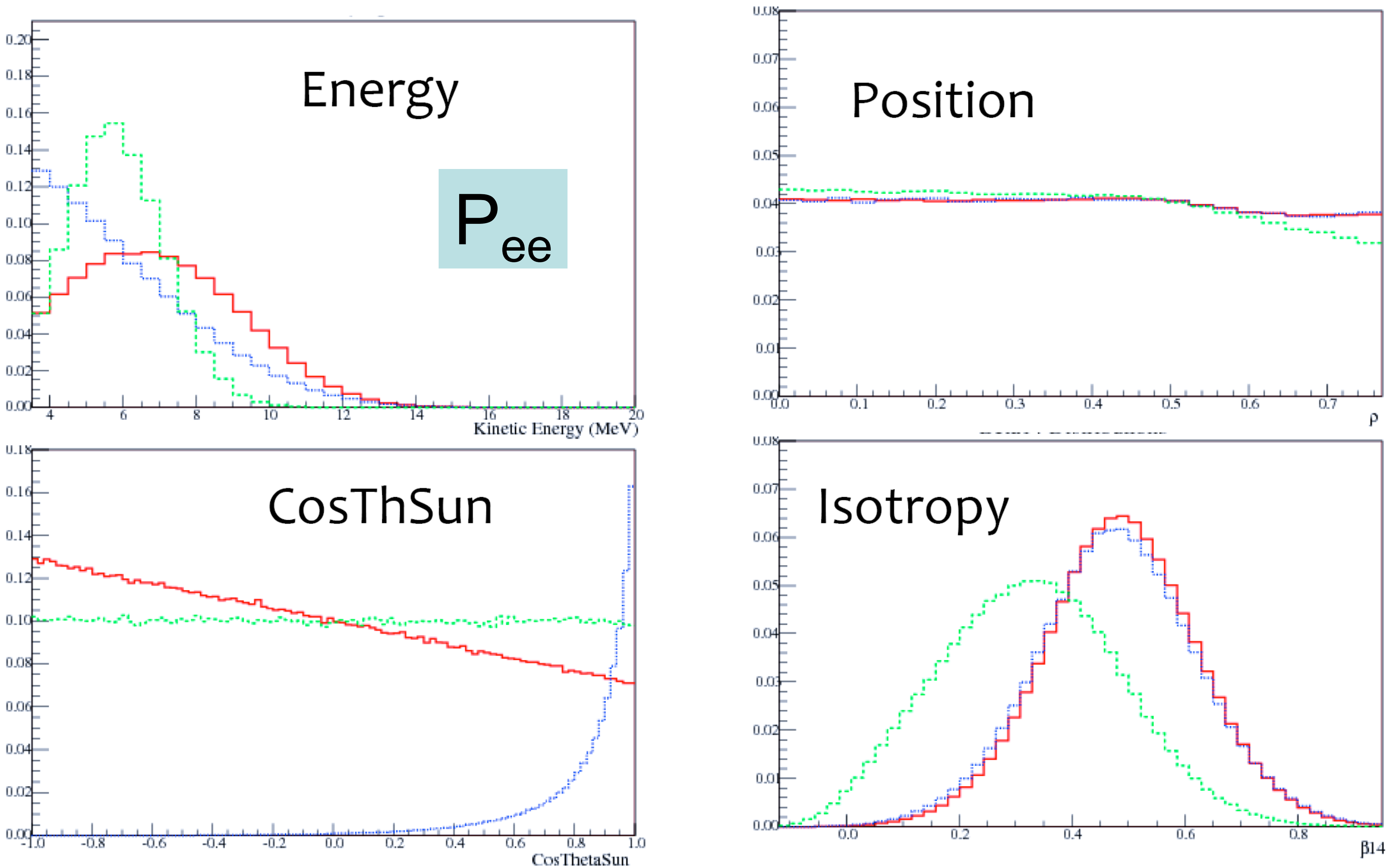
Going A Step Further (Down)



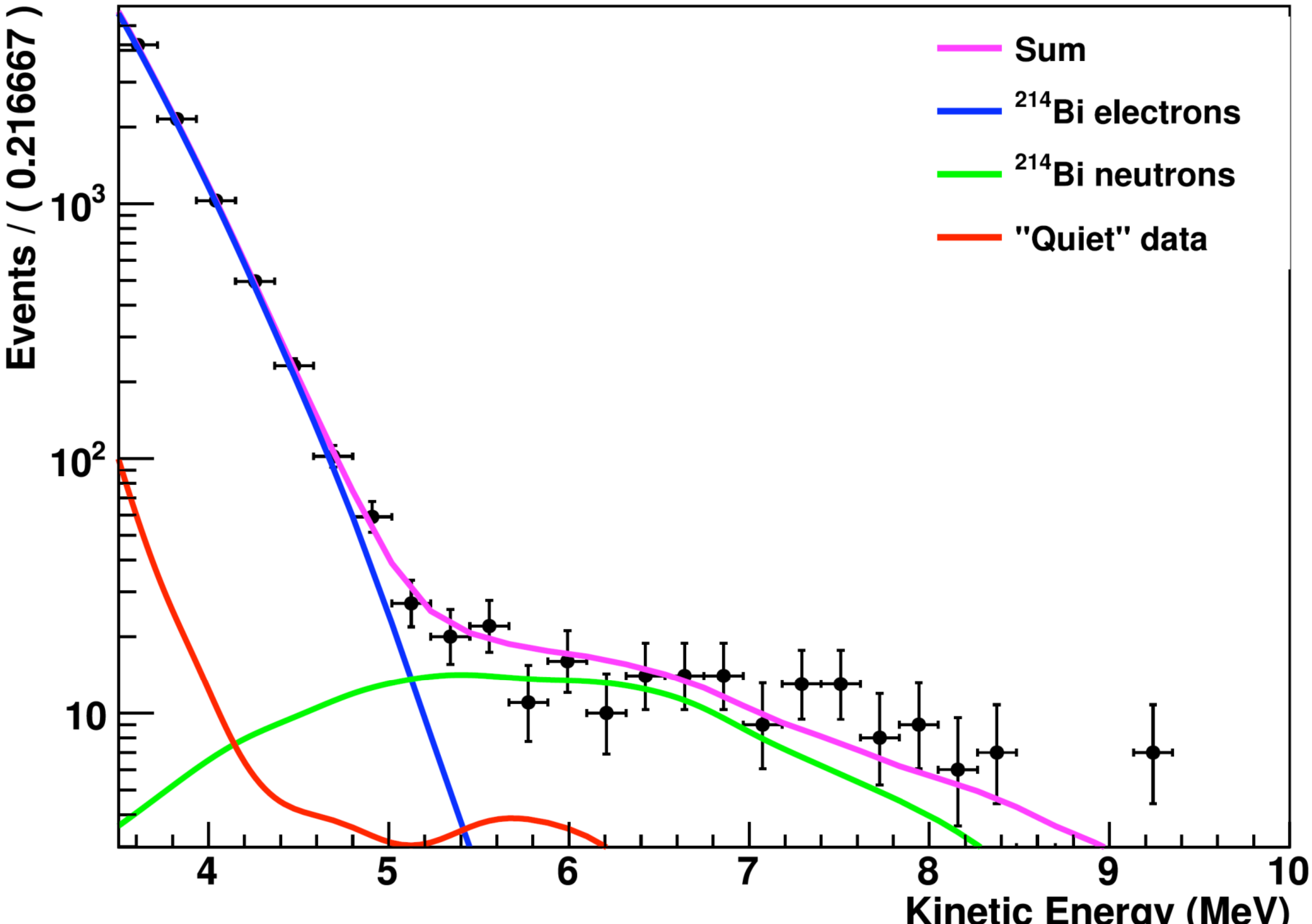
Threshold = 3.5 MeV

Approach

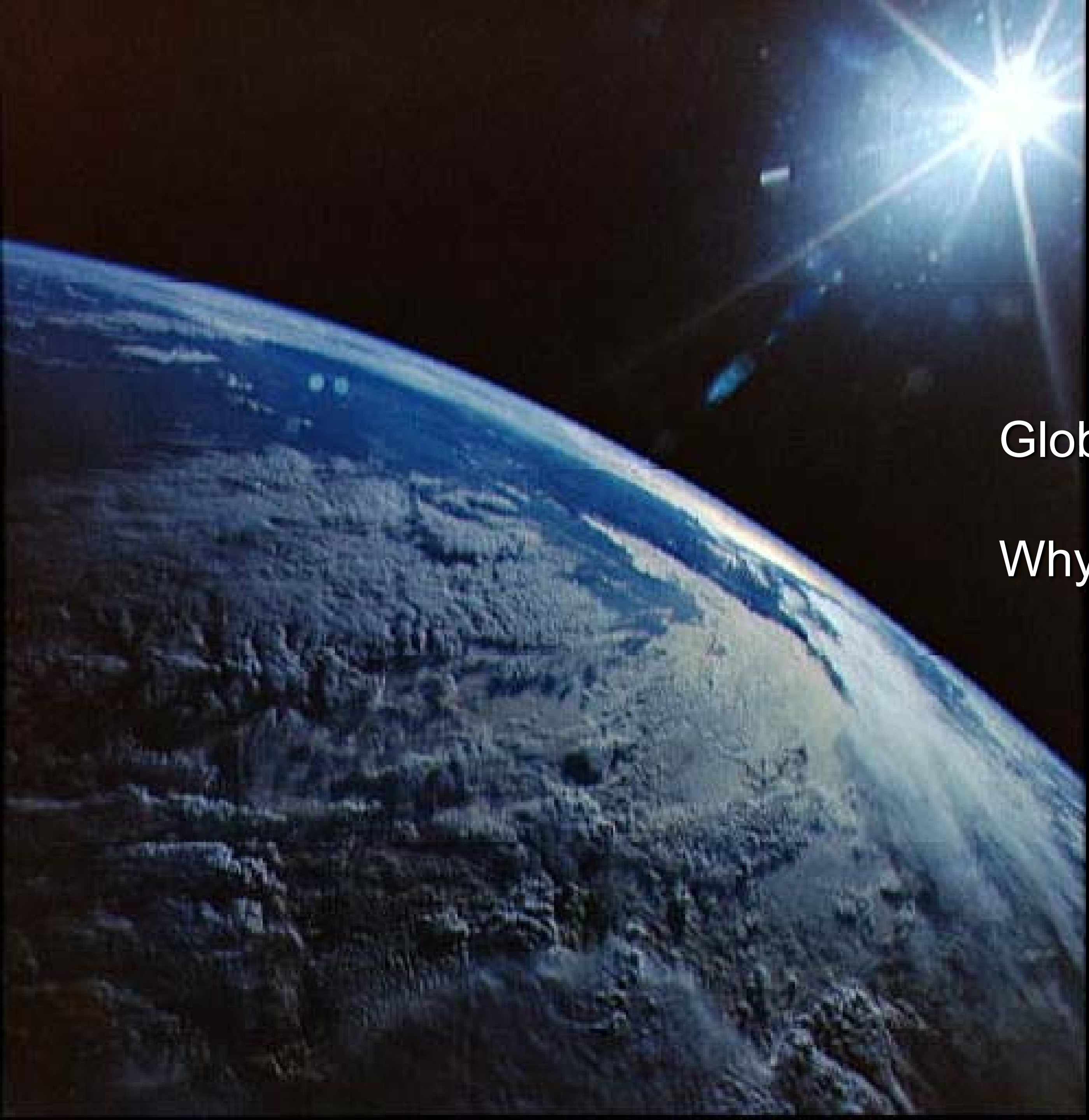
Charged Current (CC)
Elastic Scattering (ES)
Neutral Current (NC)



Rn Spike



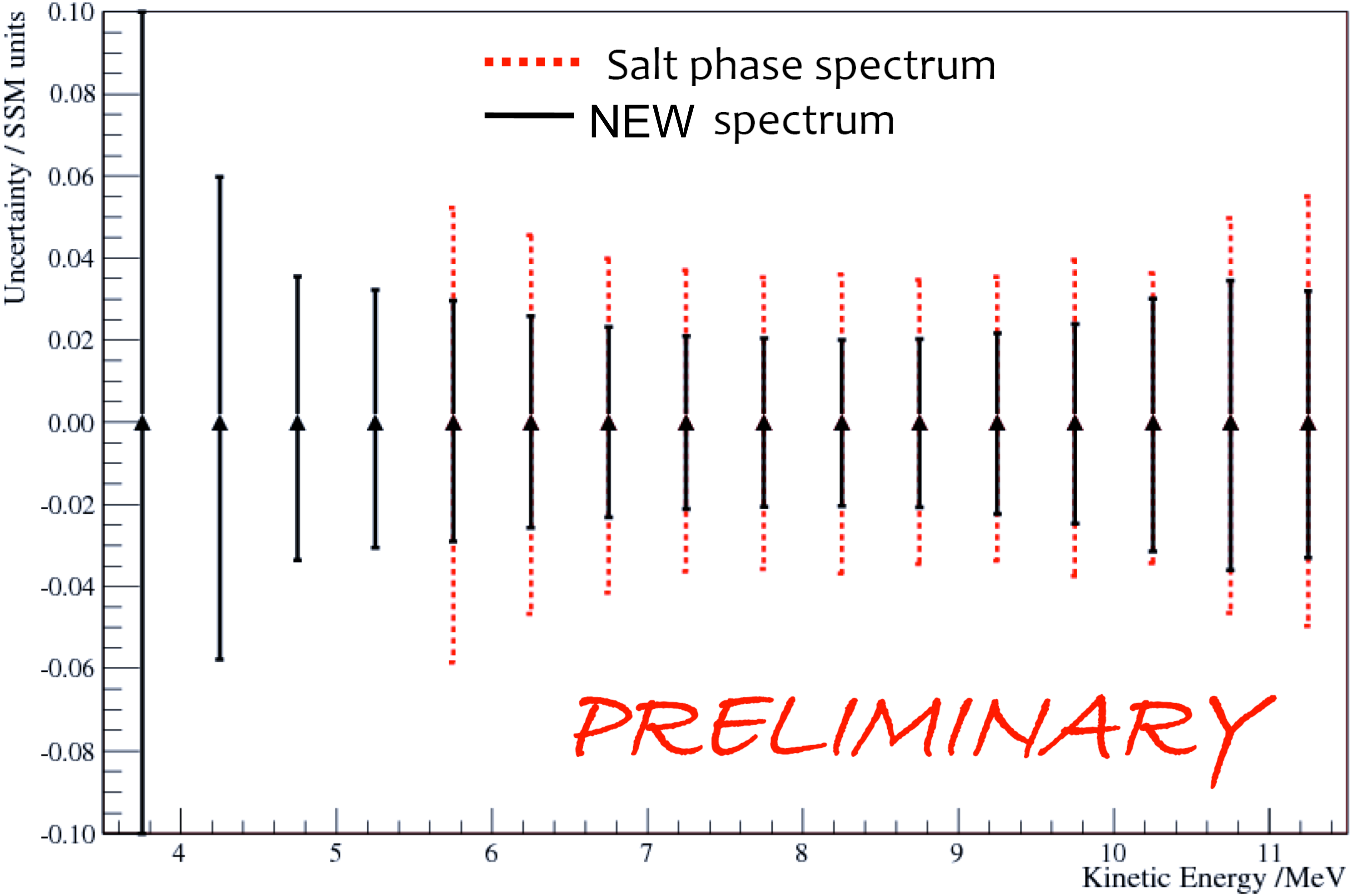
Sum
^{214}Bi electrons
^{214}Bi neutrons
"Quiet" data
Events / (0.216667)
10^3
10^2
10
4
5
6
7
8
9
10
Kinetic Energy (MeV)



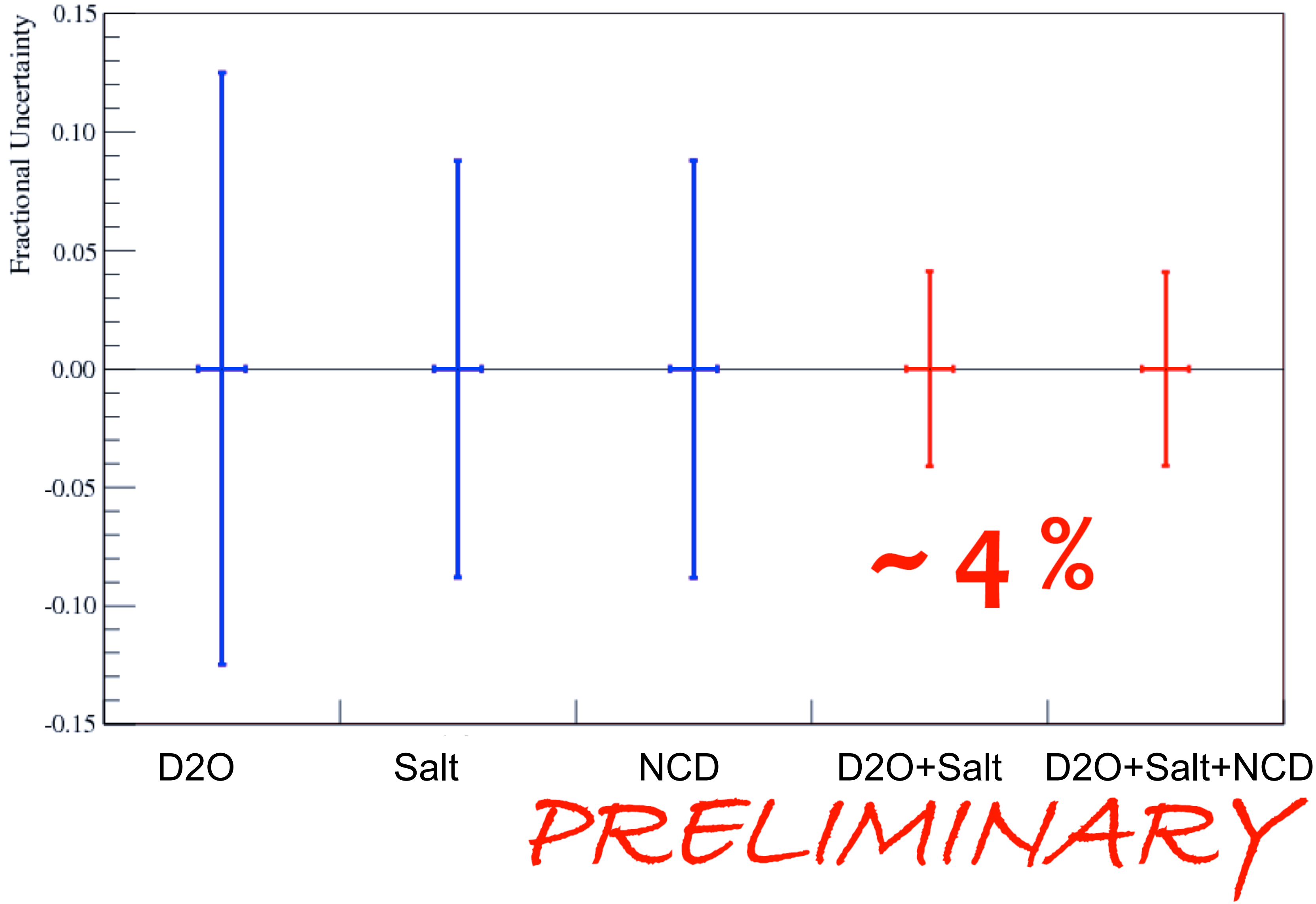
Global View:

Why !?

CC Spectrum **Uncertainties**

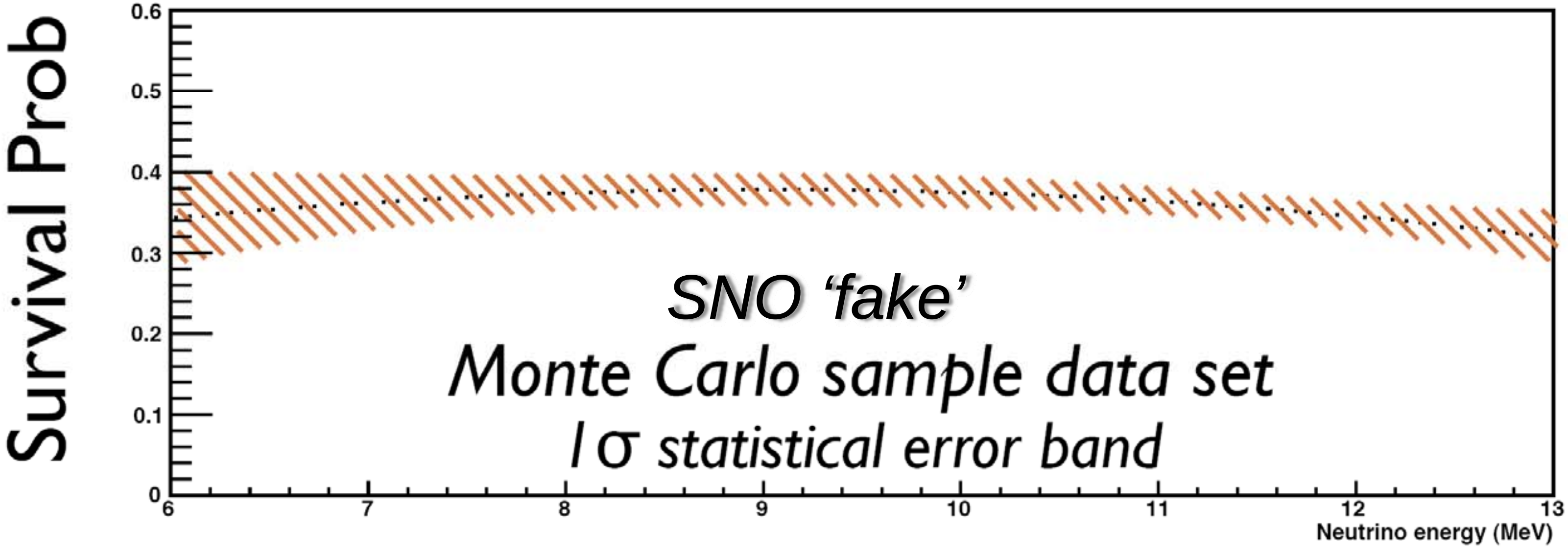


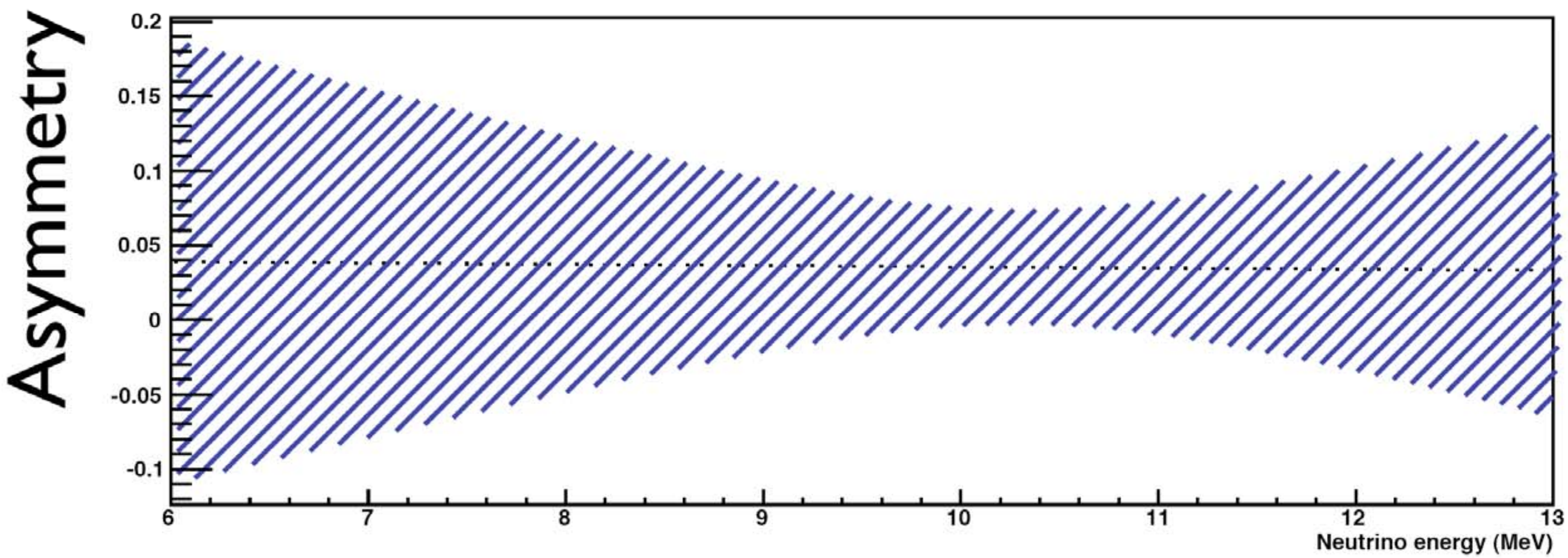
NC Flux **Uncertainties**



Pee

Polynomial Survival Probability





Global Fit

- 7 experiments, ~150 observables, ~80 systematics and 1 common model (8 fluxes, 21 systematics).

Borexino (Italy):
1 flux, 1 obs., 1 syst.

GALLEX/GNO (Italy):
8 fluxes, 1 obs., 1 syst.

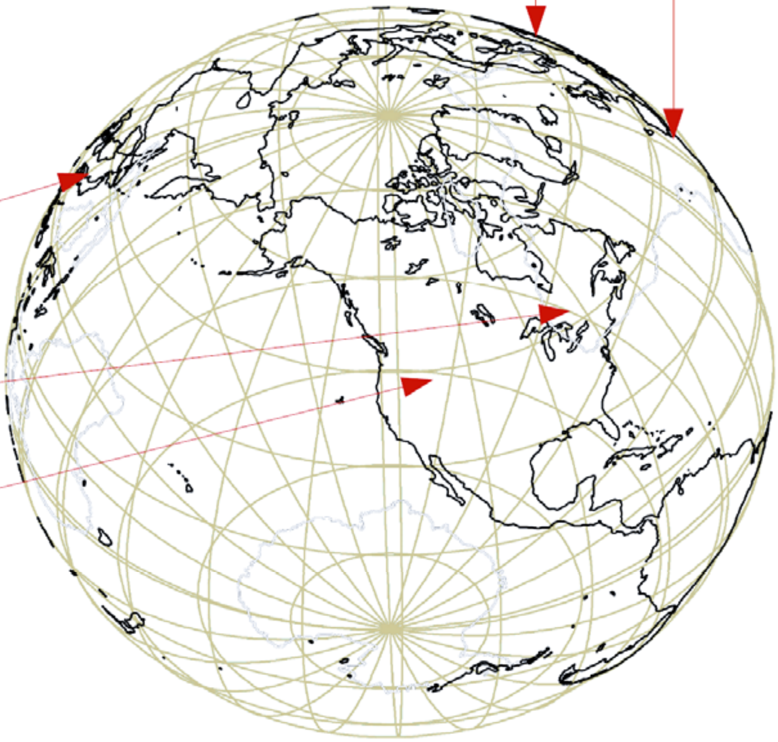
SAGE (Russia):
8 fluxes, 1 obs., 1 syst.

Super-Kamiokande (Japan):
2 fluxes, 77 obs., 30 syst.

KamLAND (Japan):
0 flux (reactor), 16 obs., 4 syst.

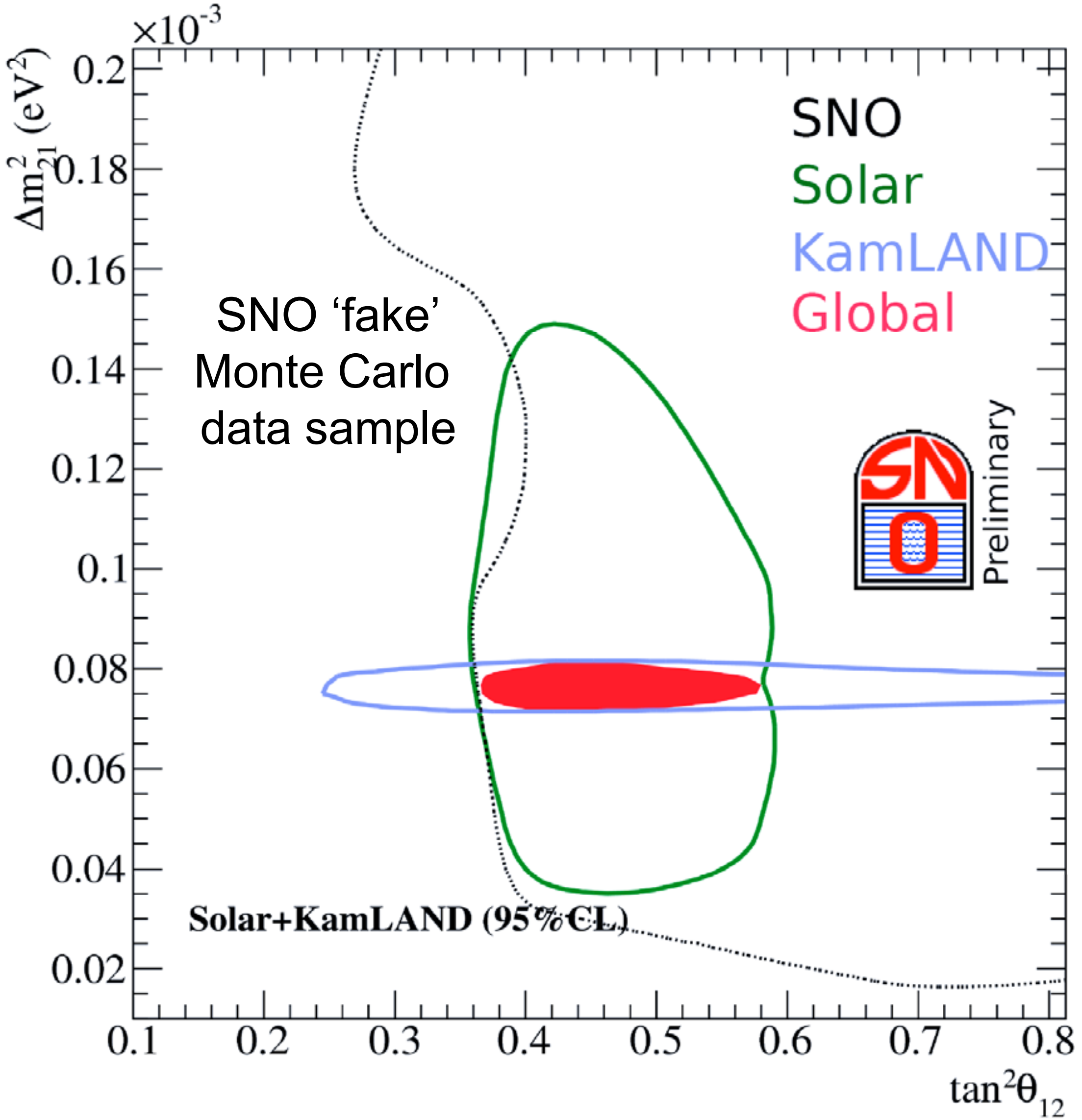
SNO (Canada):
2 fluxes, 69 obs., >40 syst.

Homestake (USA):
7 fluxes, 1 obs., 1 syst.



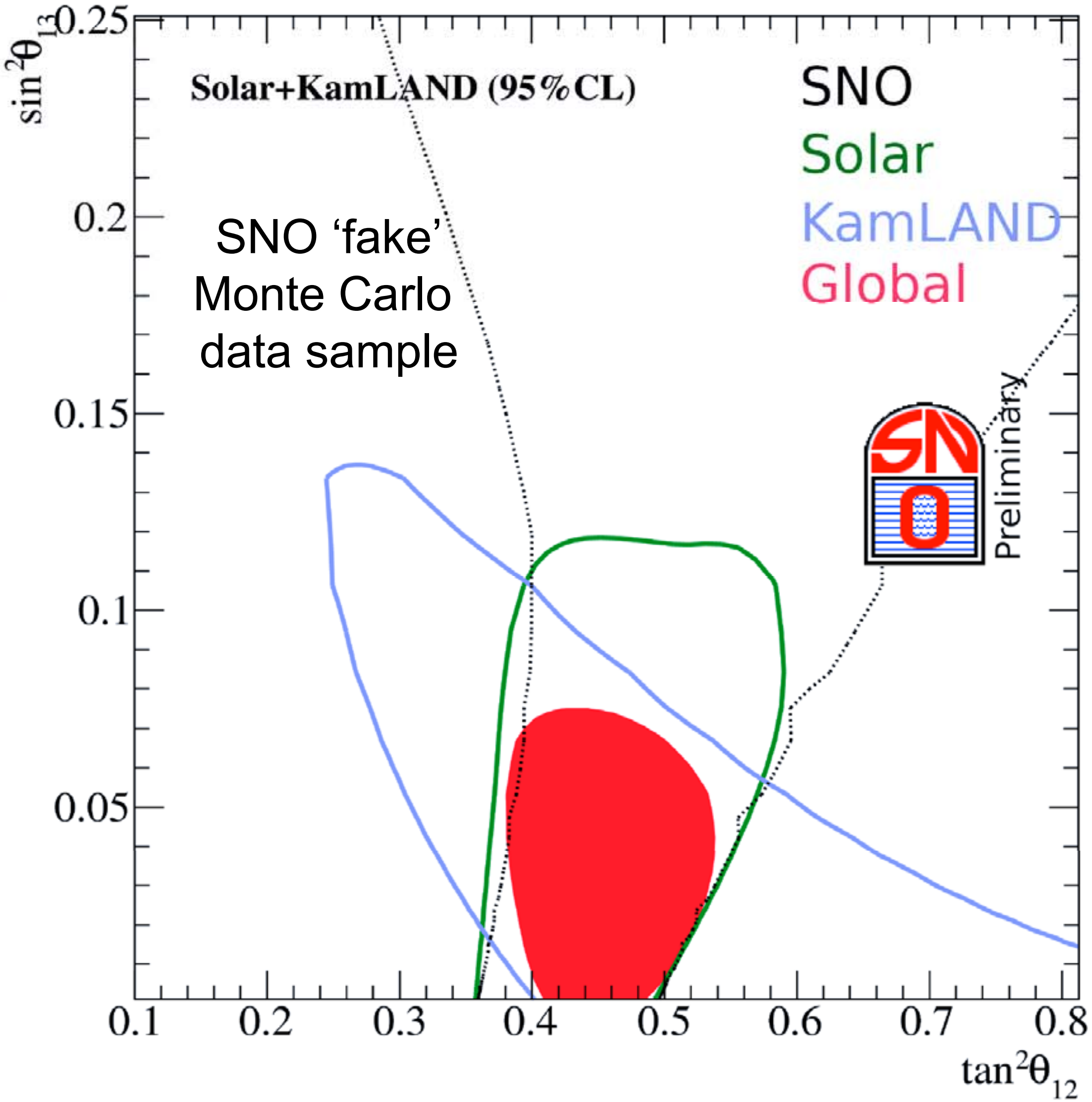
Leading Effect: $\tan^2\theta_{12}, \Delta m^2_{21}$

- SNO data from two first phases.
- Uncertainty on $\tan^2\theta_{12}$ decreases compared to previous analyses, even with the effect of $\sin^2\theta_{13}$.
- Precision on Δm^2_{21} dominated by KamLAND.



Sub-leading Effect: $\sin^2\theta_{13}$

- SNO data from two first phases.
- Precision on $\tan^2\theta_{12}$ allows to see the effect of $\sin^2\theta_{13}$.
- Signs of $\sin^2\theta_{13}>0$.



Conclusion & Future

- First paper (2001)
- Direct evidence of solar neutrino flavour transformation (2002)…but assumed $P_{ee}= 1$
- Confirmation of solar neutrino oscillations in 2005 with full salt results and 2008 with first NCD paper
- Total flux in agreement with SSM and at more than 5σ level:

$$\phi_{\mu\tau} > 0$$

$$\Delta m^2_{12} > 0 \qquad P_{ee} < 1$$

$$\phi_{e\mu\tau} = \phi_{SSM}$$

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- Great physics out of SNO
- Archival solar physics publications in 2009 with a consistent 3-phase fit of all SNO data
- From solving SNP to precision physics