# The Low Energy Threshold Analysis of the First Two Phases of the Sudbury Neutrino Observatory

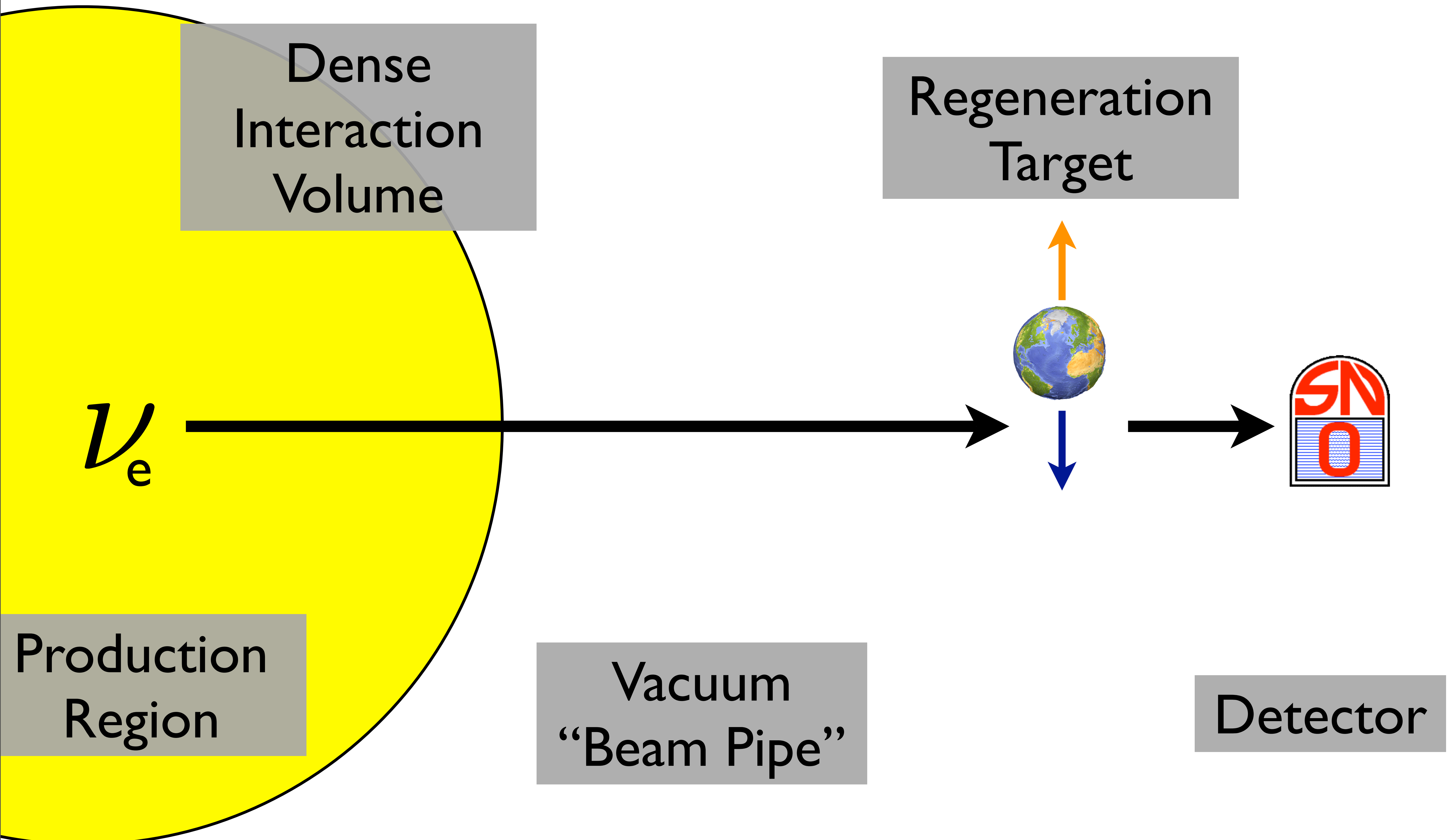
Stanley Seibert
Los Alamos National Laboratory

PHENO 10 Symposium
May 11, 2010

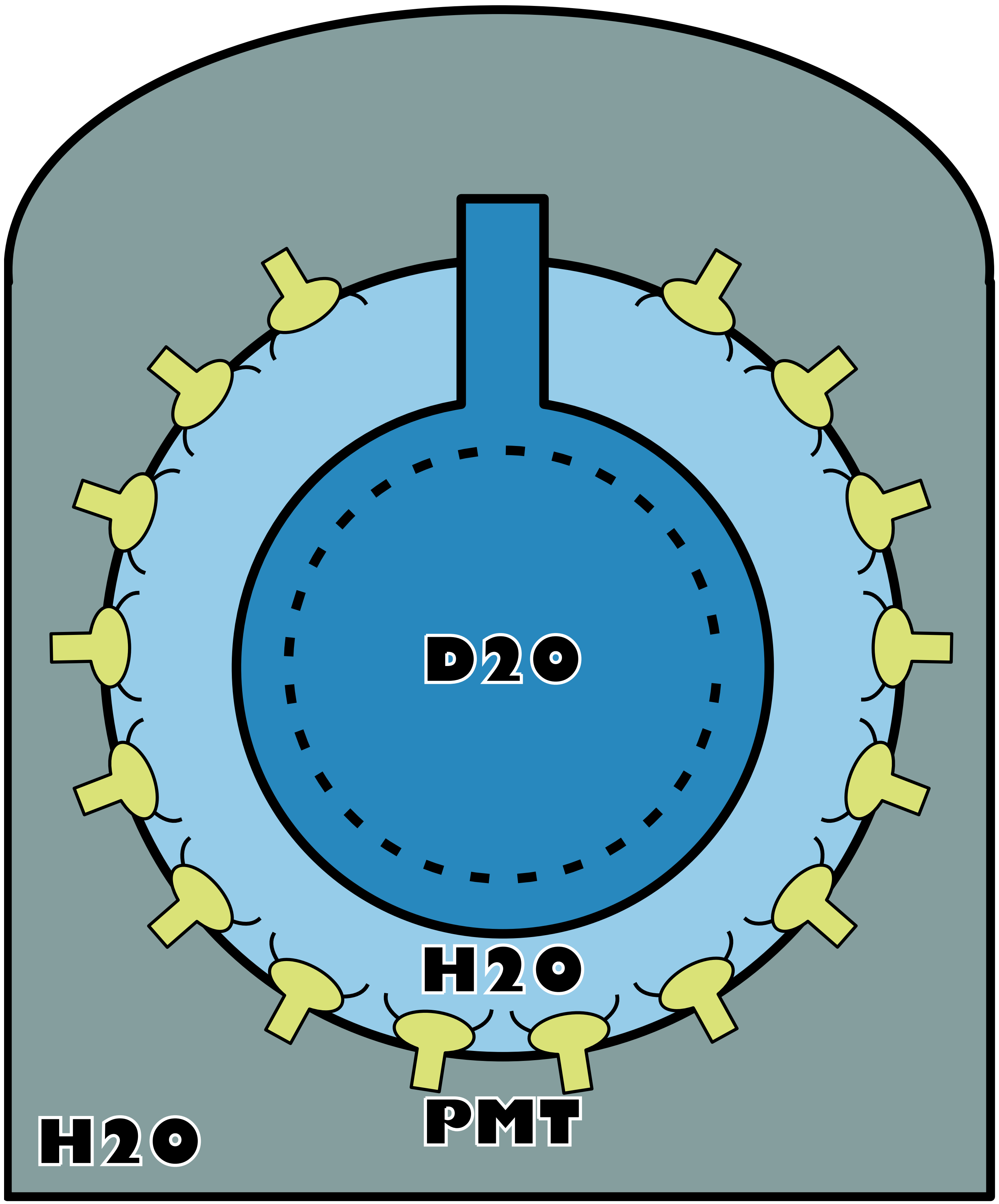
arXiv:0910.2984

Los Alamos
NATIONAL LABORATORY

# Solar Neutrino Experiments



# The Sudbury Neutrino Observatory

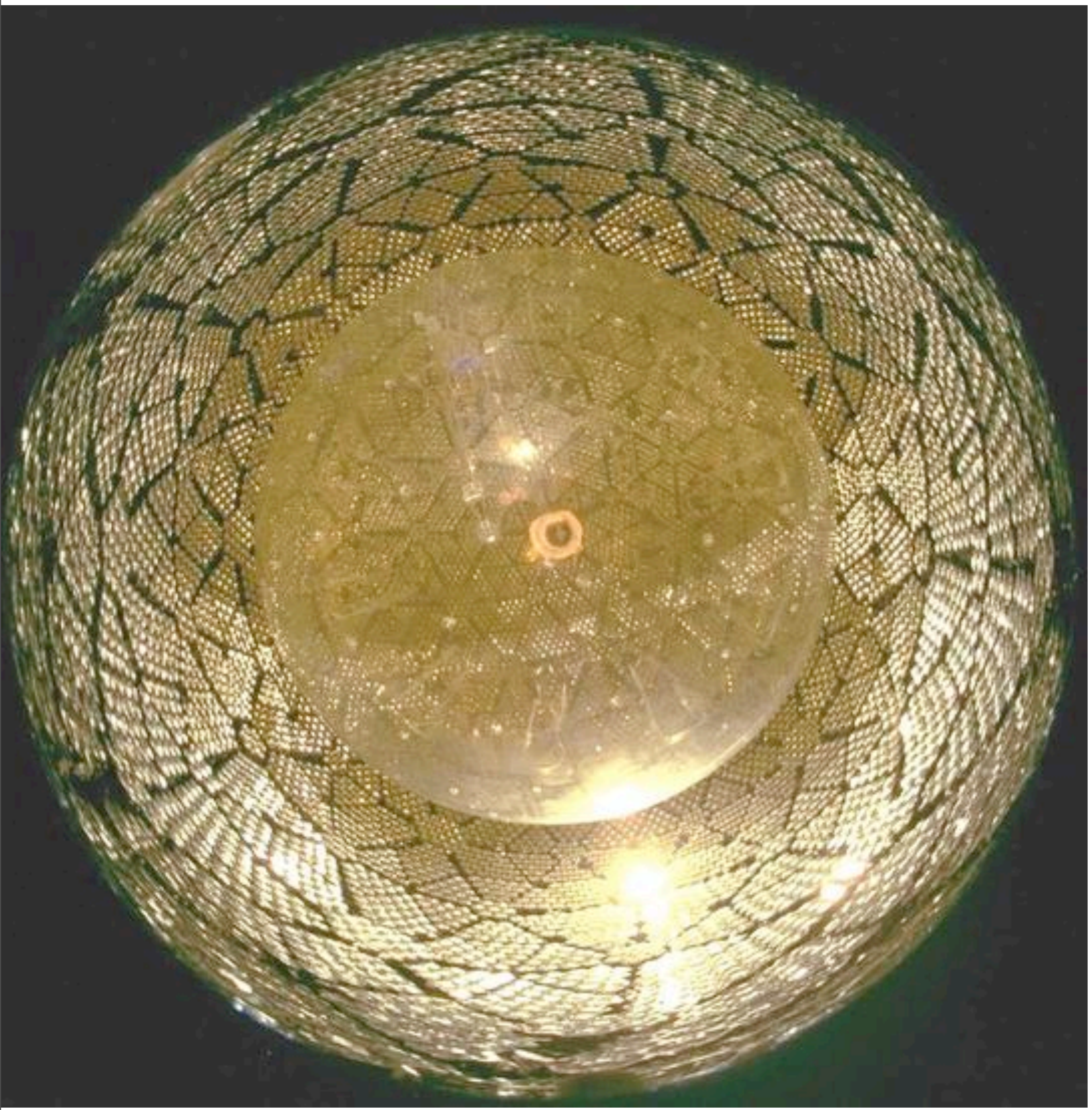



1 kiloton D2O target
1.7 kiloton inner H2O shield
5.7 kiloton outer H2O shield
9456 PMTs
➡54% solid angle coverage

R = 550 cm fiducial volume
R = 600 cm acrylic vessel

Low background:
~6000 m.w.e. shielding
D2O U/Th < $10^{-14}$ g/g
H2O U/Th < $5\times10^{-13}$ g/g

# The Sudbury Neutrino Observatory



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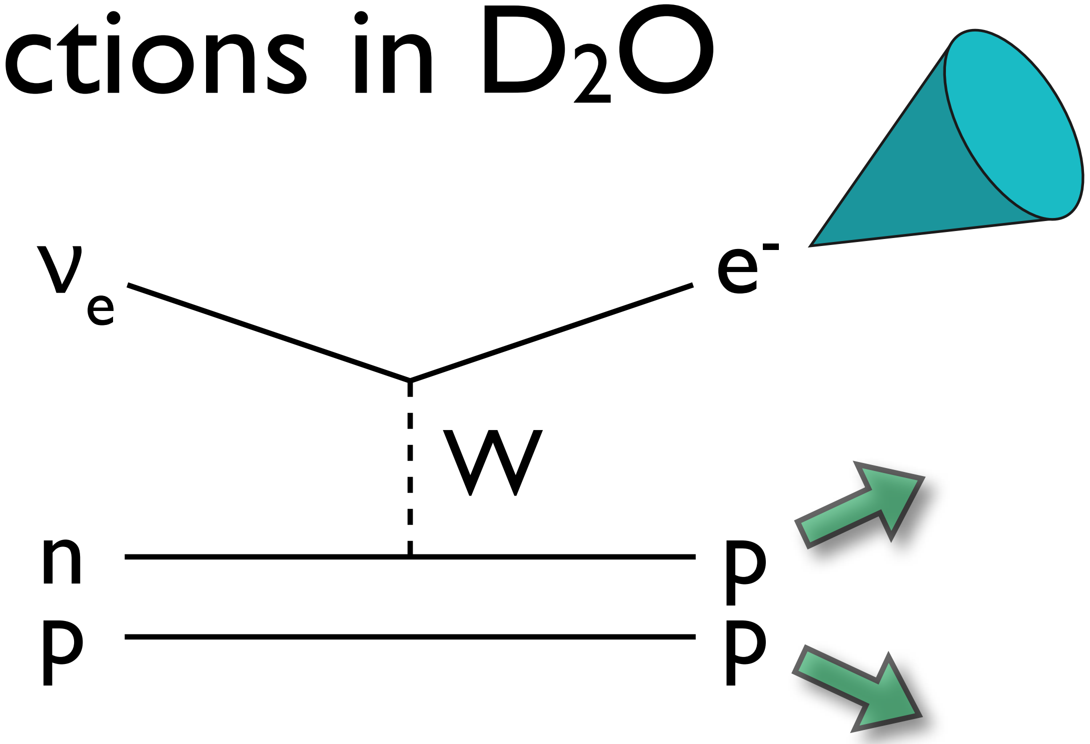
# Neutrino Interactions in $D_2O$

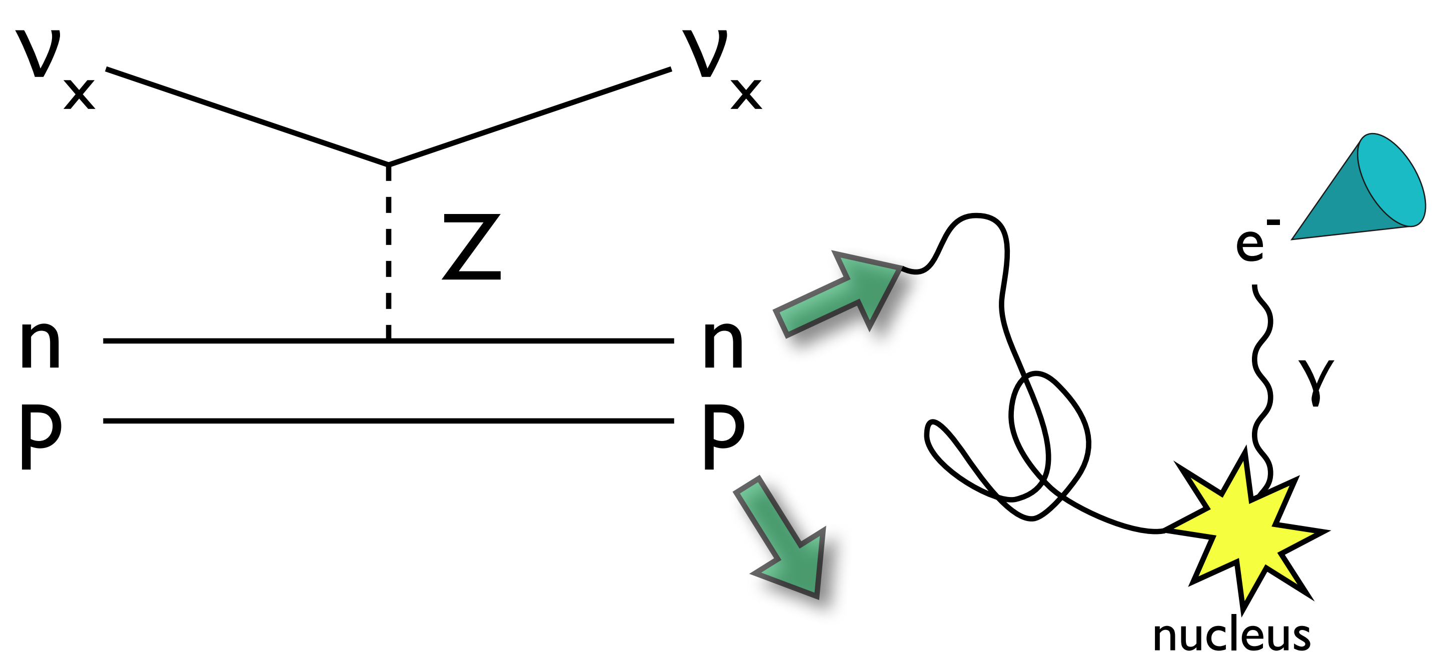
## Charged Current (CC)

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



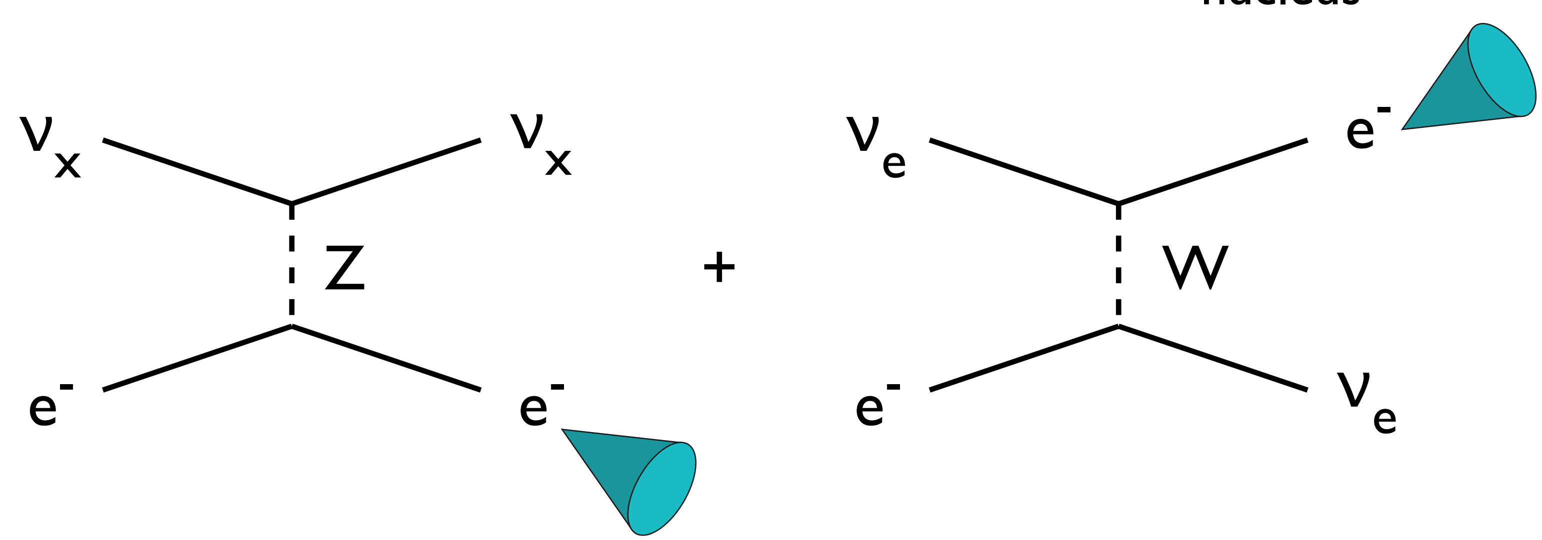

## Neutral Current (NC)

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




## Elastic Scattering (ES)

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



# Neutrino Interactions in $D_2O$

## Charged Current (CC)

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

**It's all just Cherenkov light!**

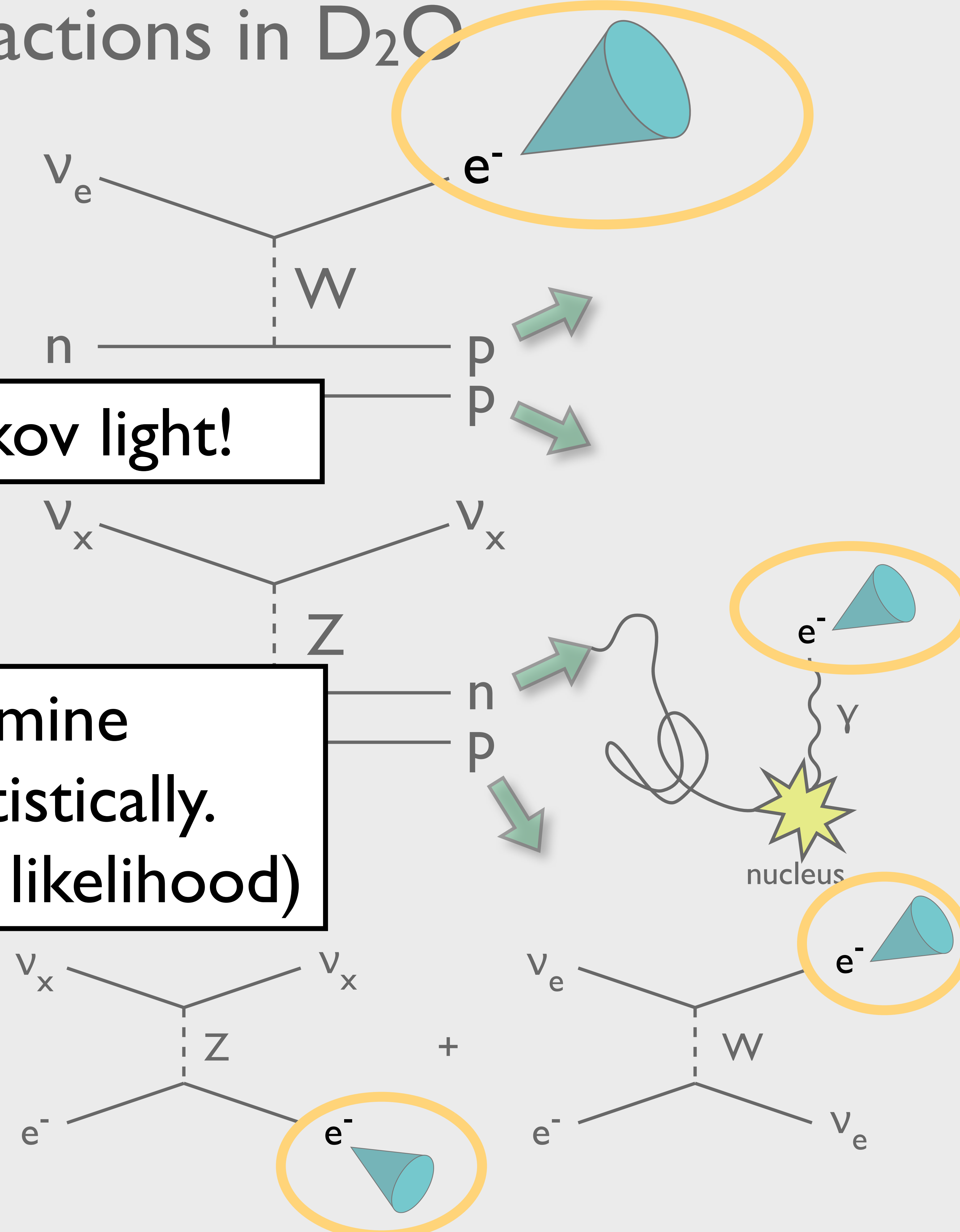
## Neutral Current (NC)

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

**Need to determine reaction rates statistically. (Extended maximum likelihood)**

## Ela

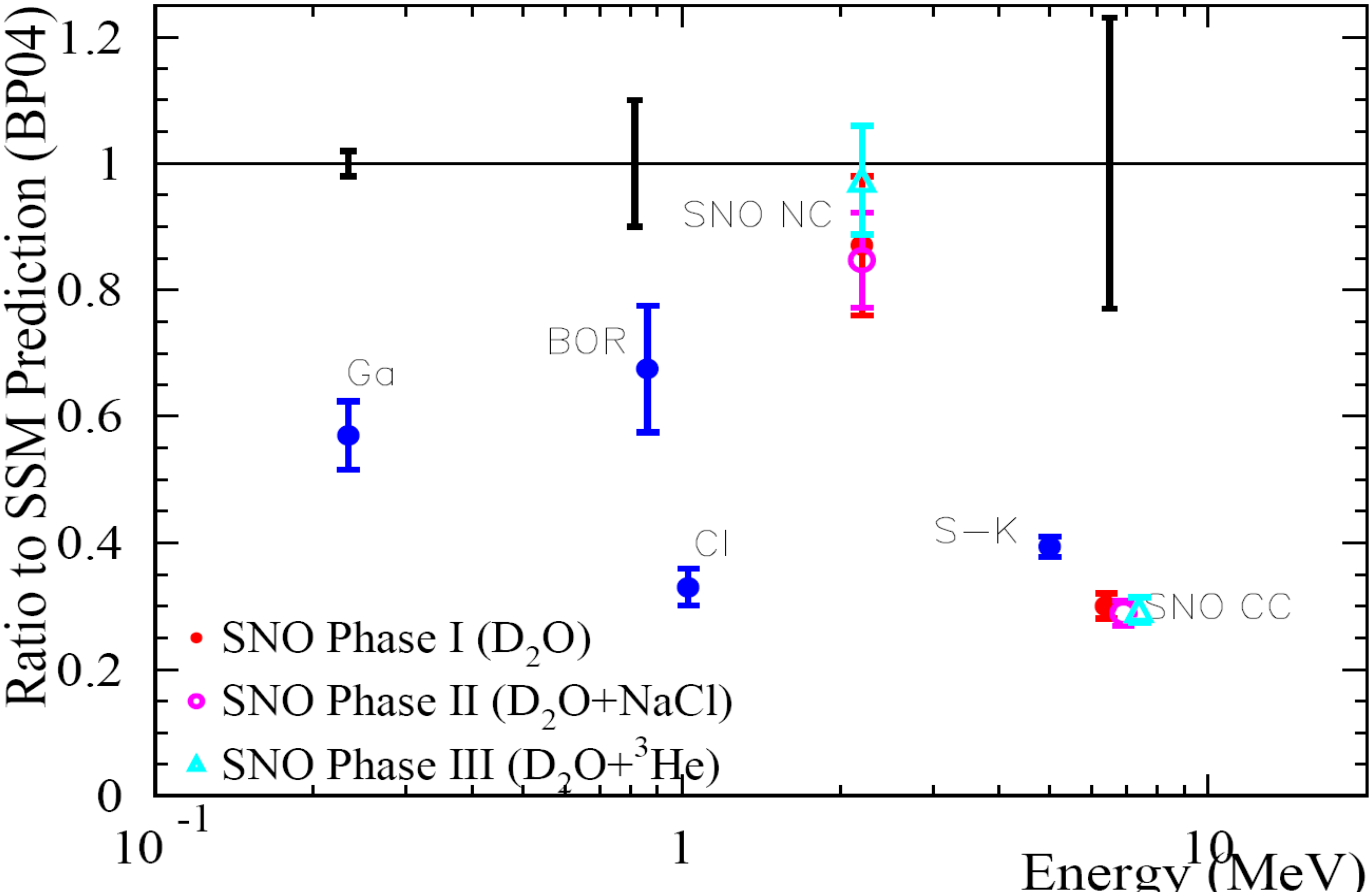
$$\nu_x + e \quad \rightarrow \nu_x + e$$



# Phases of SNO

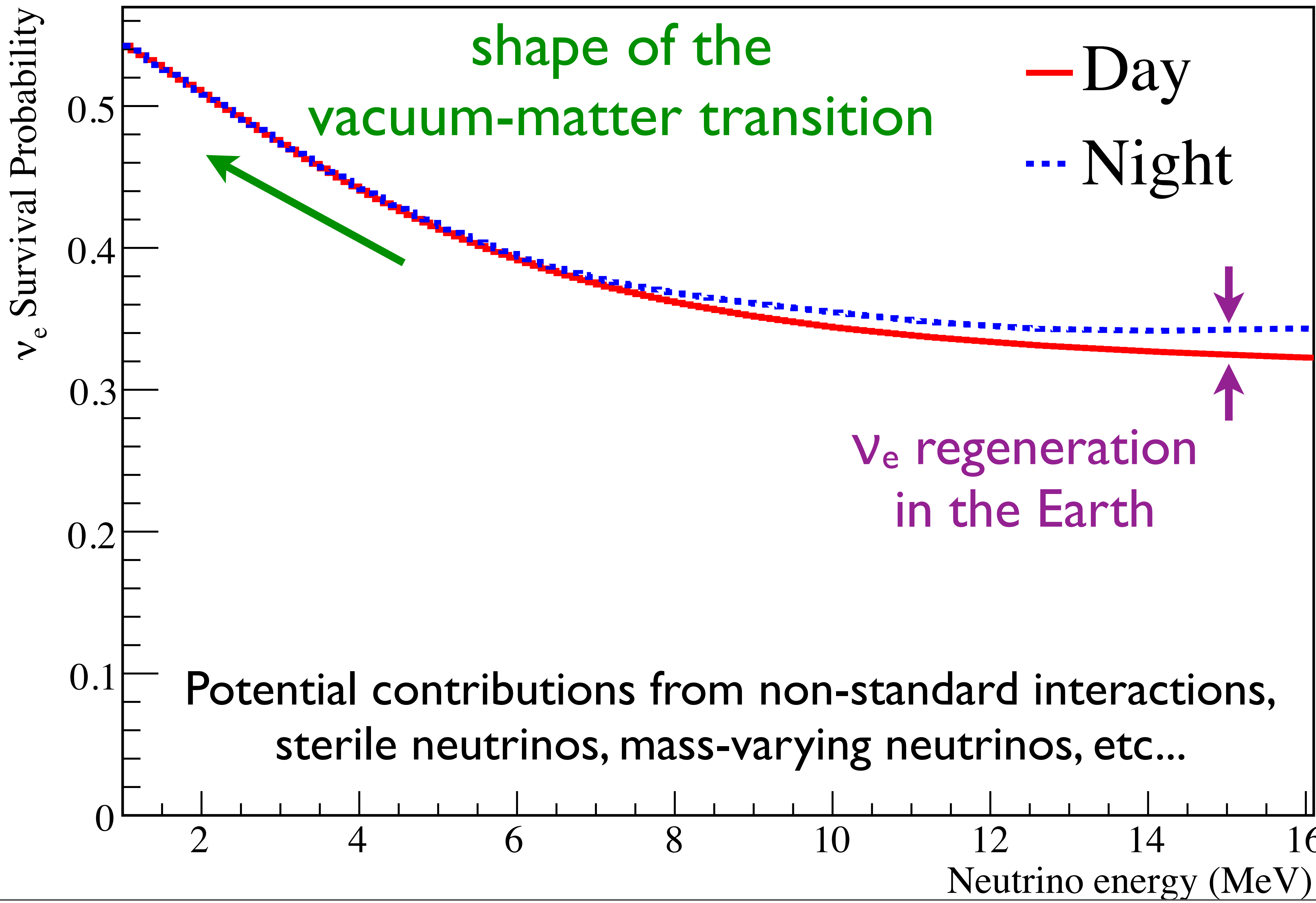
| | | |
|---|---|---|
| Phase 1 "D2O" | Target Material: | 1 kton 99.92% pure D2O |
| | Neutron Capture Cross Section: | 0.5 mb on $^{2}H$ |
| | Neutron Signature: | 6.25 MeV $\gamma$ |
| Phase 2 "Salt" | Target Material: | 1 kt D2O + 2 ton NaCl |
| | Neutron Capture Cross Section: | 44 b on $^{35}Cl$ |
| | Neutron Signature: | 8.25 MeV $\gamma$ cascade |
| Phase 3 "NCD" | Target Material: | 1 kt D2O + $^{3}He$ counters |
| | Neutron Capture Cross Section: | 5333 b on $^{3}He$ |
| | Neutron Signature: | 764 keV p+$^{3}H$ track |

# Measured Solar Neutrino Fluxes



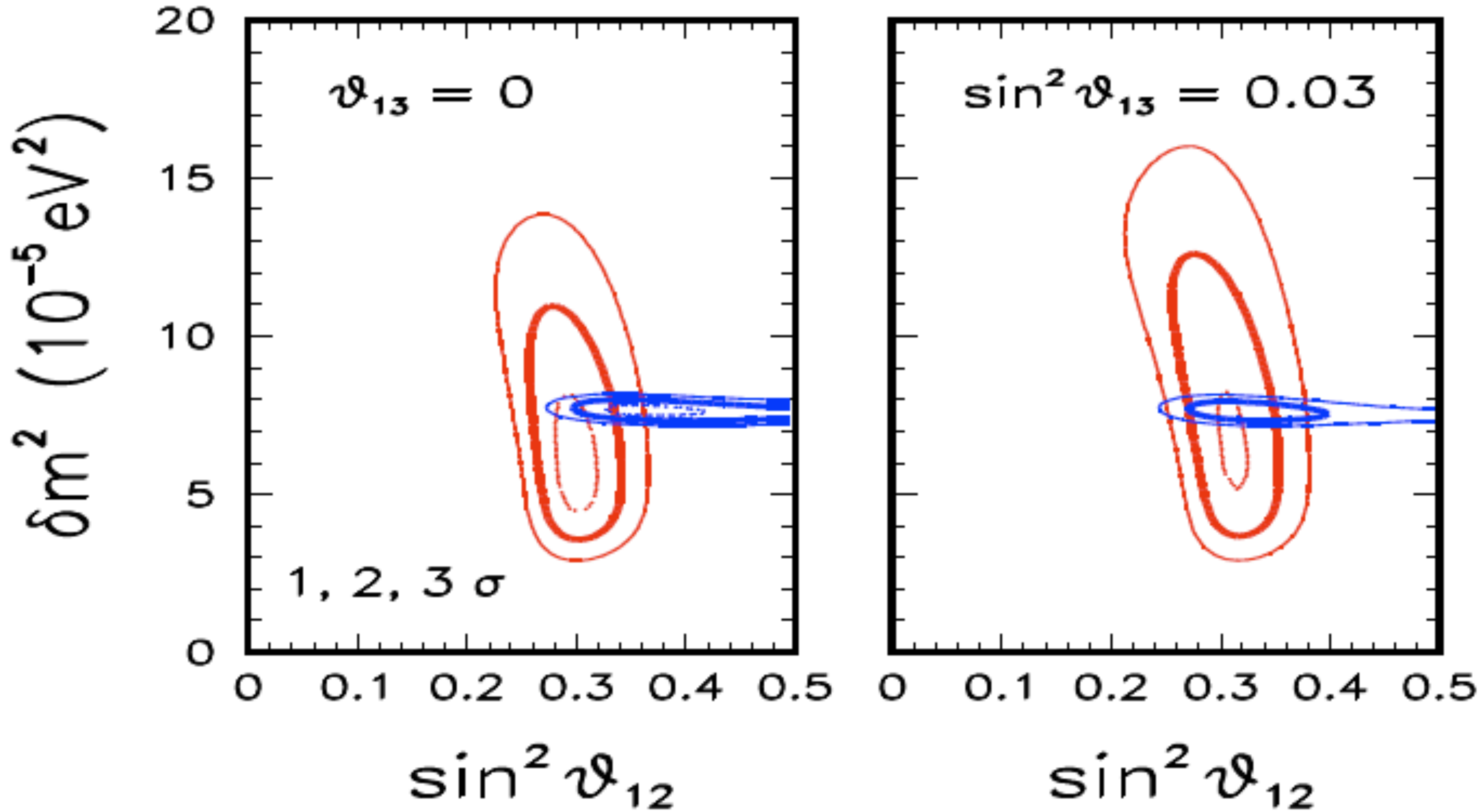
# What else could SNO teach us?

## MSW predicts additional phenomena not well observed.



# What else could SNO teach us?

Tension between SNO and KamLAND can indicate $\theta_{13}$




G.L. FOGLI [1,2*], E. LISI [2], A. MARRONE [1,2], A. PALAZZO [3], A.M. ROTUNNO [1,2]

arXiv:0905.3549v1

# The Low Energy Threshold Analysis

(A "last 20% analysis" of the first two phases)

1) Lower threshold to 3.5 MeV
2) Combine 2 phases in a joint-phase fit
3) Reduce backgrounds (E res & Cuts)
4) Improve MC simulation
5) Reduce systematic uncertainties
6) Create PMT $\beta$-$\gamma$ PDF directly from data
7) Improved Signal Extraction approach
8) Improved oscillation analysis

# The Low Energy Threshold Analysis

(A "last 20% analysis" of the first two phases)

1) Lower threshold to 3.5 MeV

2) Combine 2 phases in a joint-phase fit

3) Re

4) Im

5) Re

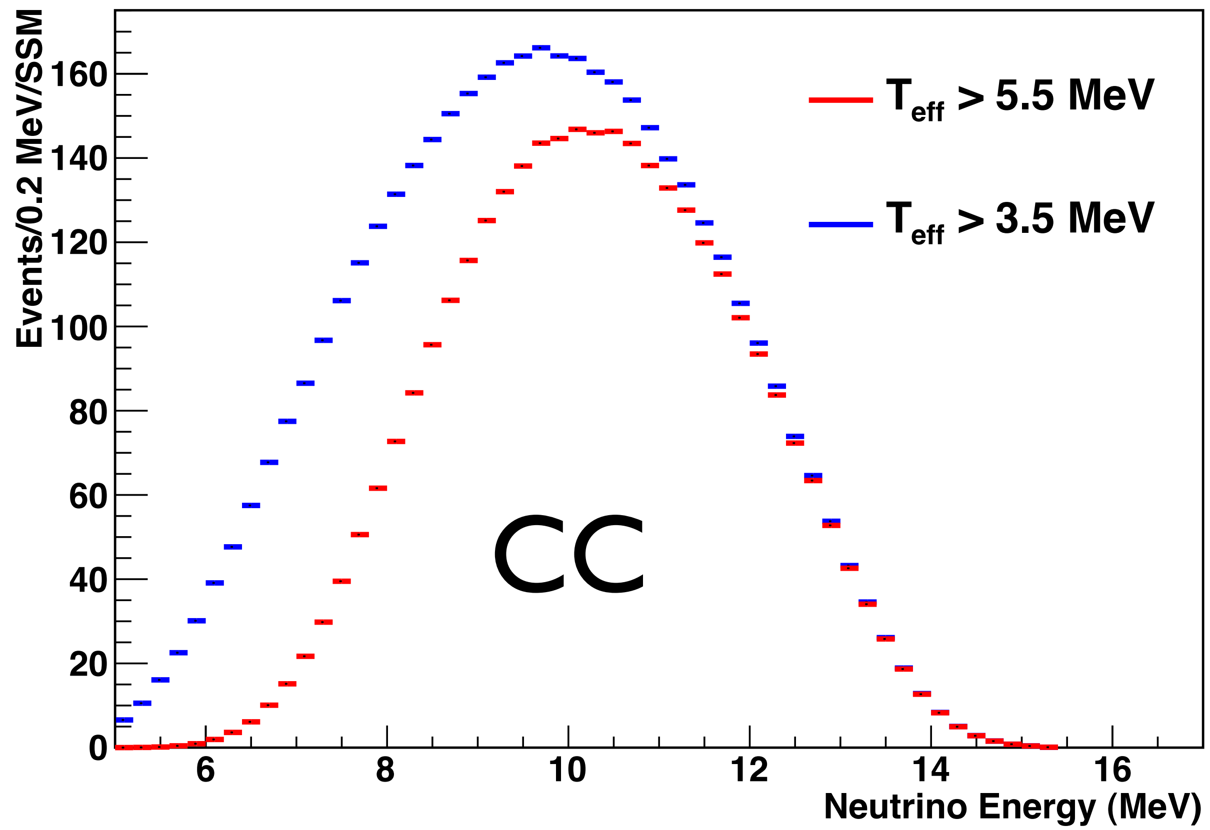
6) Cr ... ta

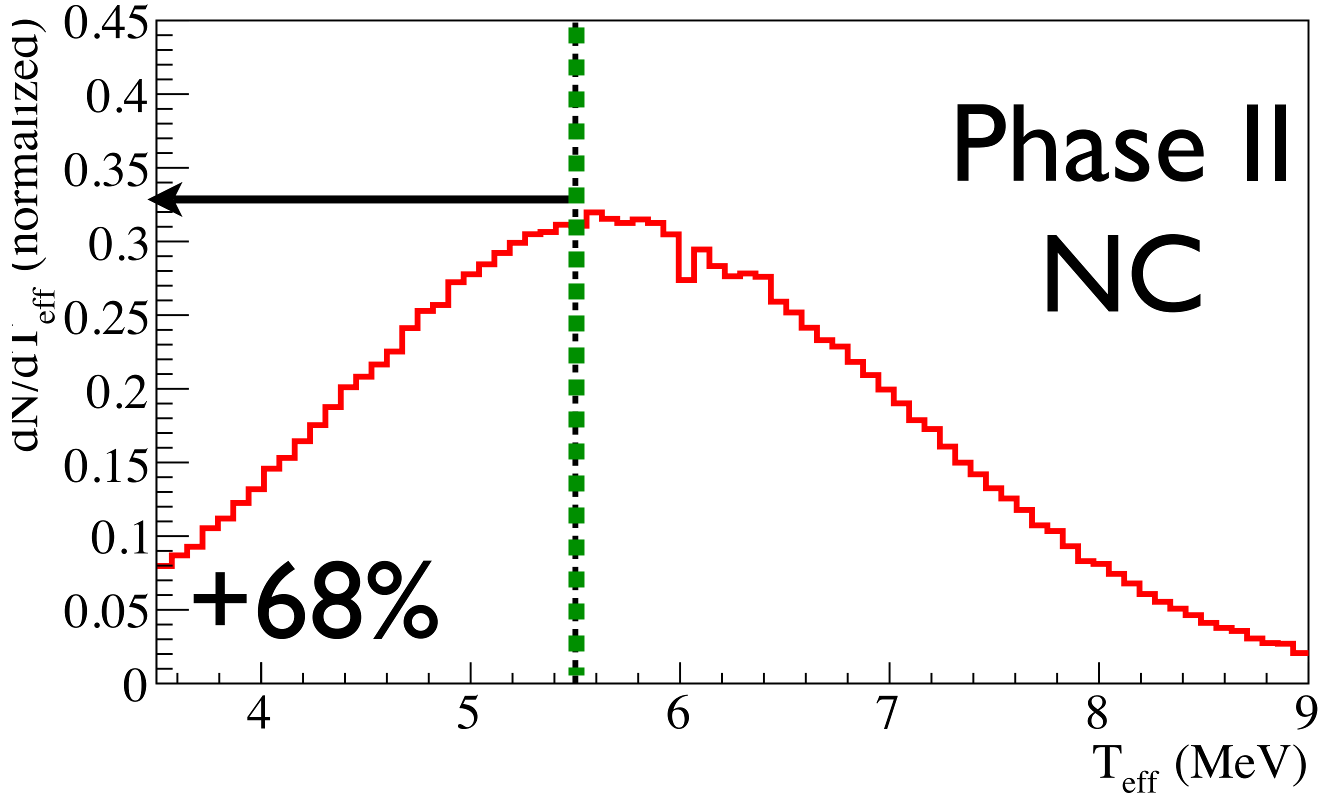
7) Improved Signal Extraction approach

8) Improved oscillation analysis

Lowest ever energy threshold for analysis of water-Cherenkov data!

# 3.5 MeV Analysis Threshold



# Signal Extraction with Backgrounds!

D2O
Acrylic Vessel
H2O

×

$^{214}$Bi *(Uranium/Radon)*
$^{208}$Tl *(Thorium)*

+

PMT $^{208}$Tl

+

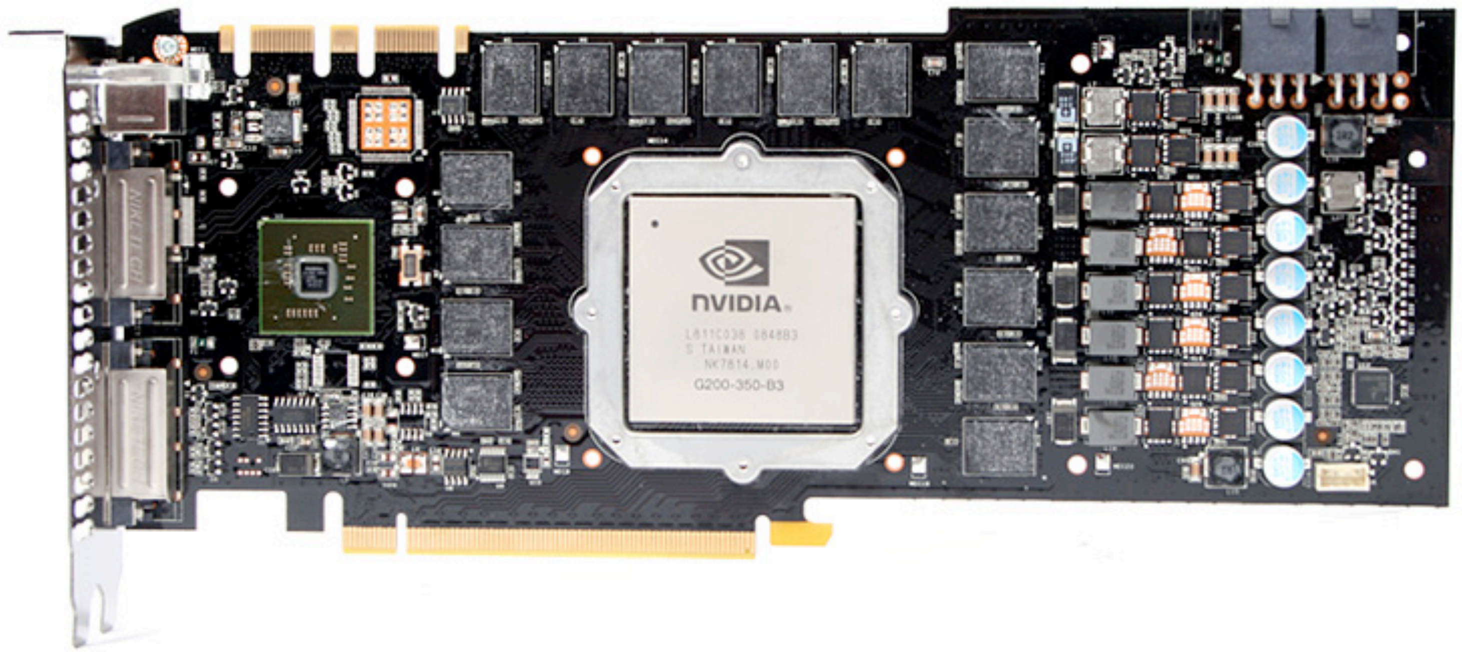
$^{24}$Na *(Neutron activation of salt)*

+

AV Surface Neutrons

# GPU Acceleration of Likelihood Function

3D graphics cards are *designed* for data-parallel calculations.




The speed and flexibility of the GPU allowed us to use kernel estimation to create our PDFs and to float detector systematics in the likelihood function during optimization!

# Signal Extraction: Two Fit Models

Model 1: "Unconstrained Fit"

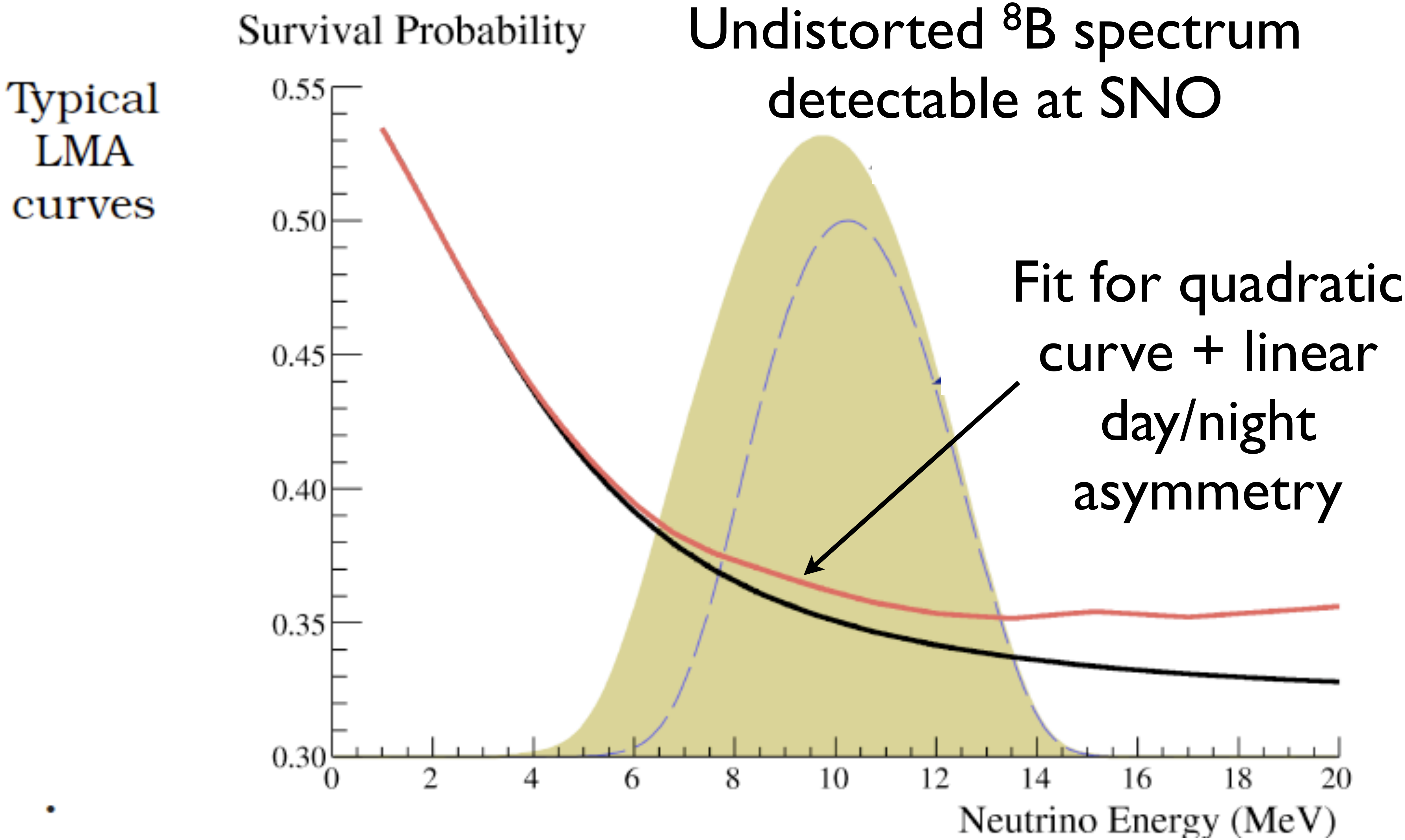
- Allow CC and ES flux to vary independently in each reconstructed electron energy bin
- Used in previous SNO papers
- Most flexible, but has unphysical number of degrees of freedom

Model 2: Polynomial survival probability fit

- Distort the CC and ES PDFs in a continuous way using neutrino energy, not reconstructed electron energy
- Enforce unitarity between CC, ES, NC signals
- Require the $\nu_e$ survival probability to be a smooth function

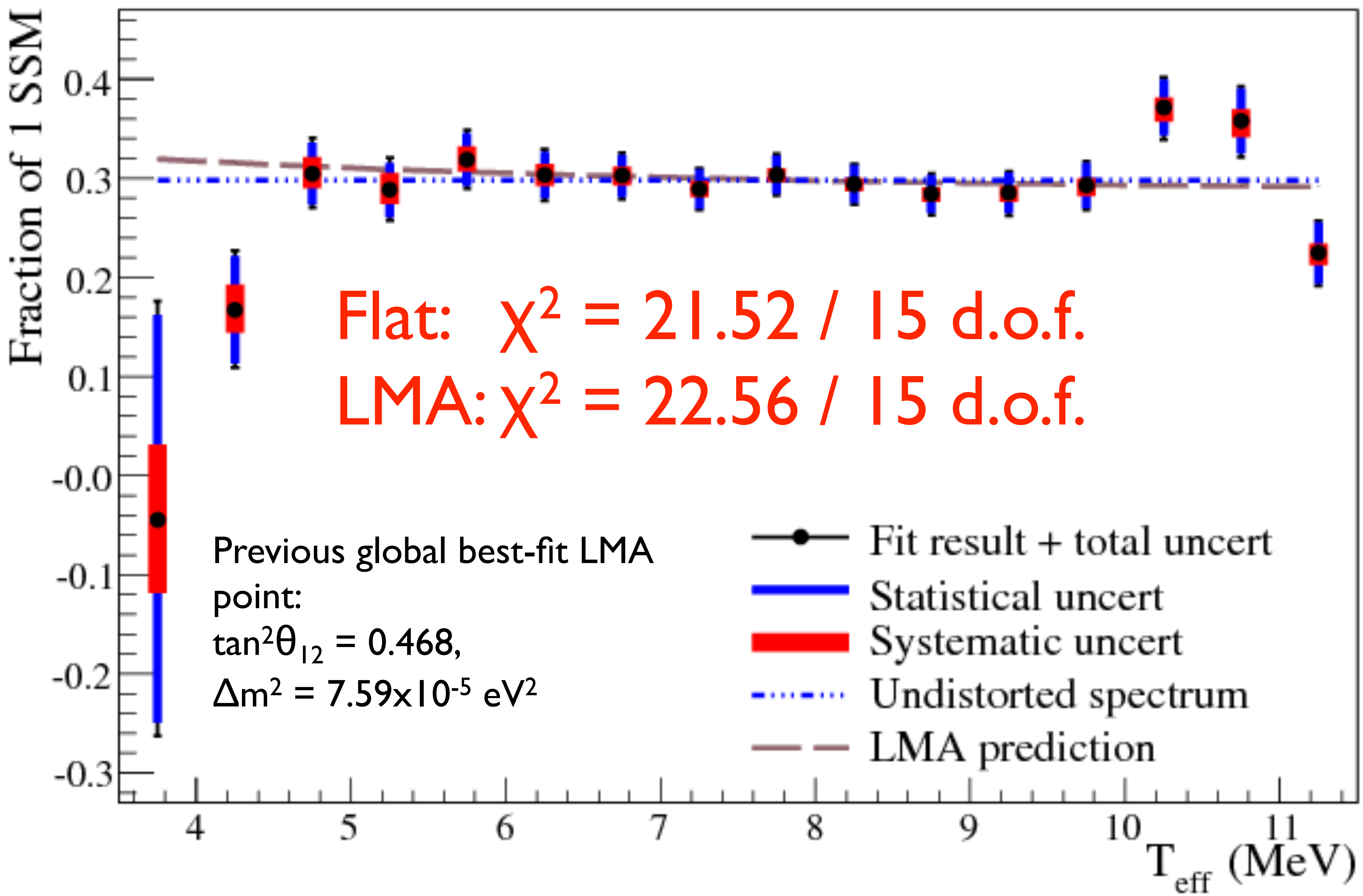
*Both: Float detector uncertainties in likelihood optimizaton!*

# Signal Extraction in Neutrino Energy

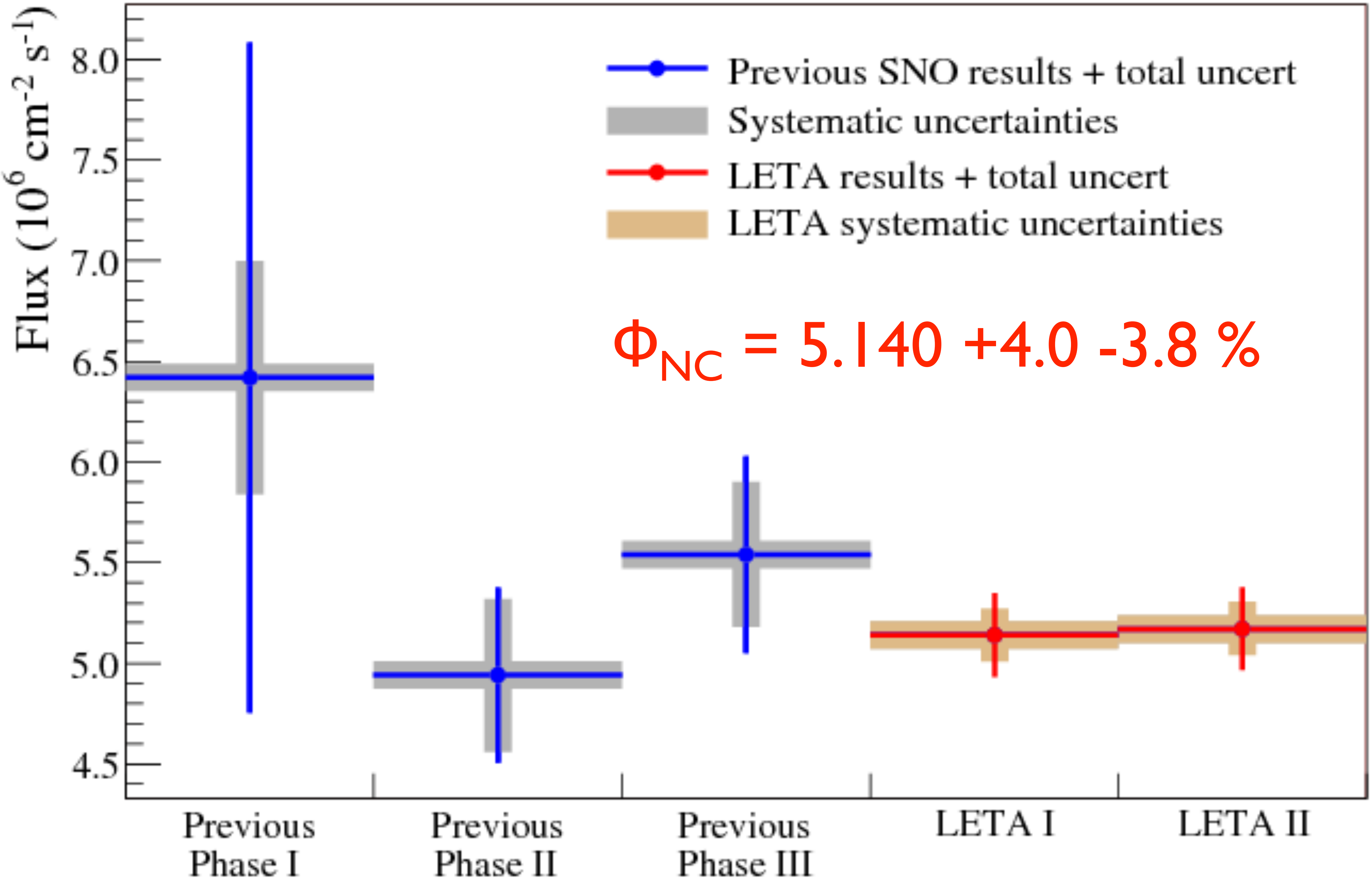


# Results

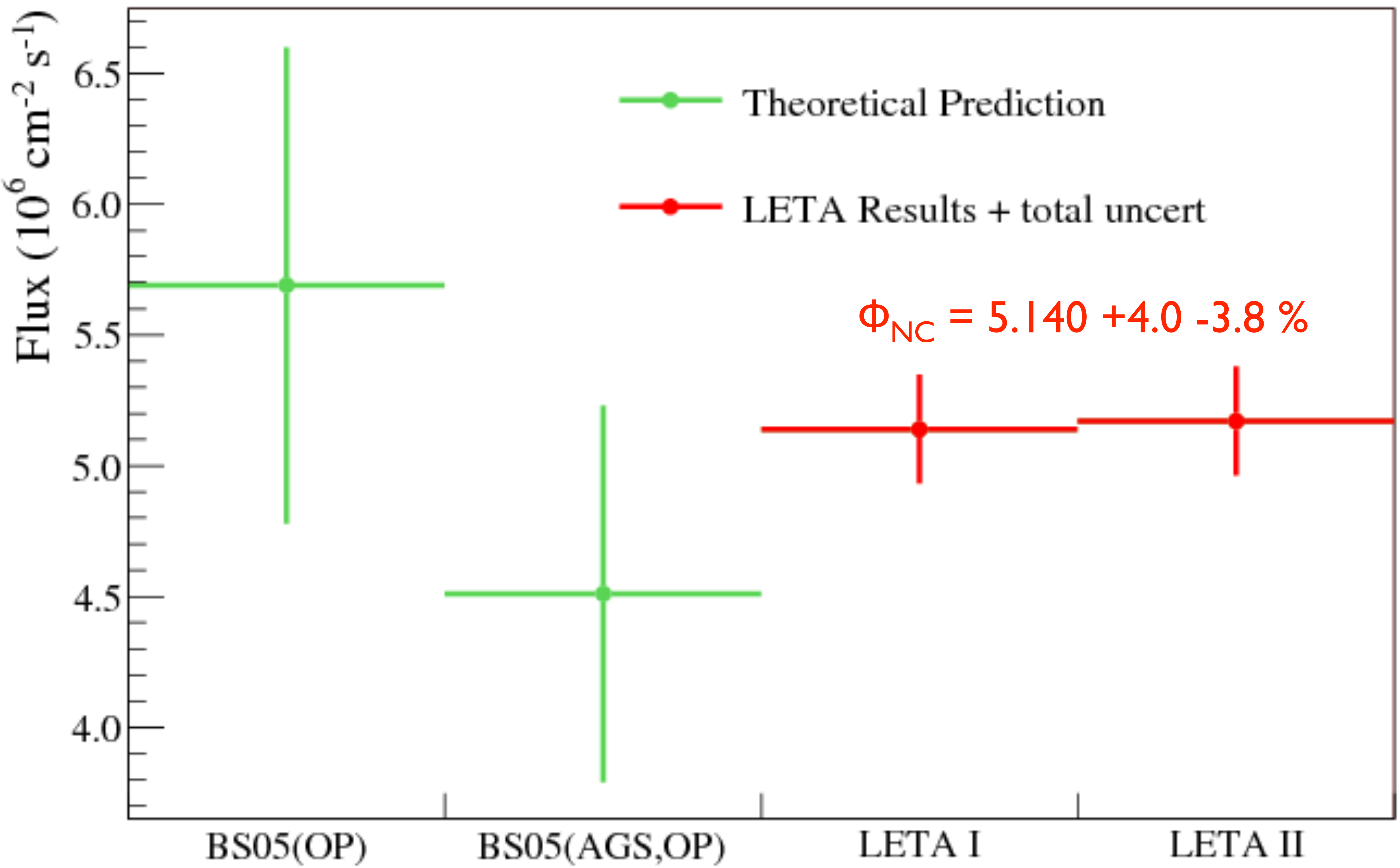
# CC Recoil-Electron Spectrum



# $^8$B Flux Result

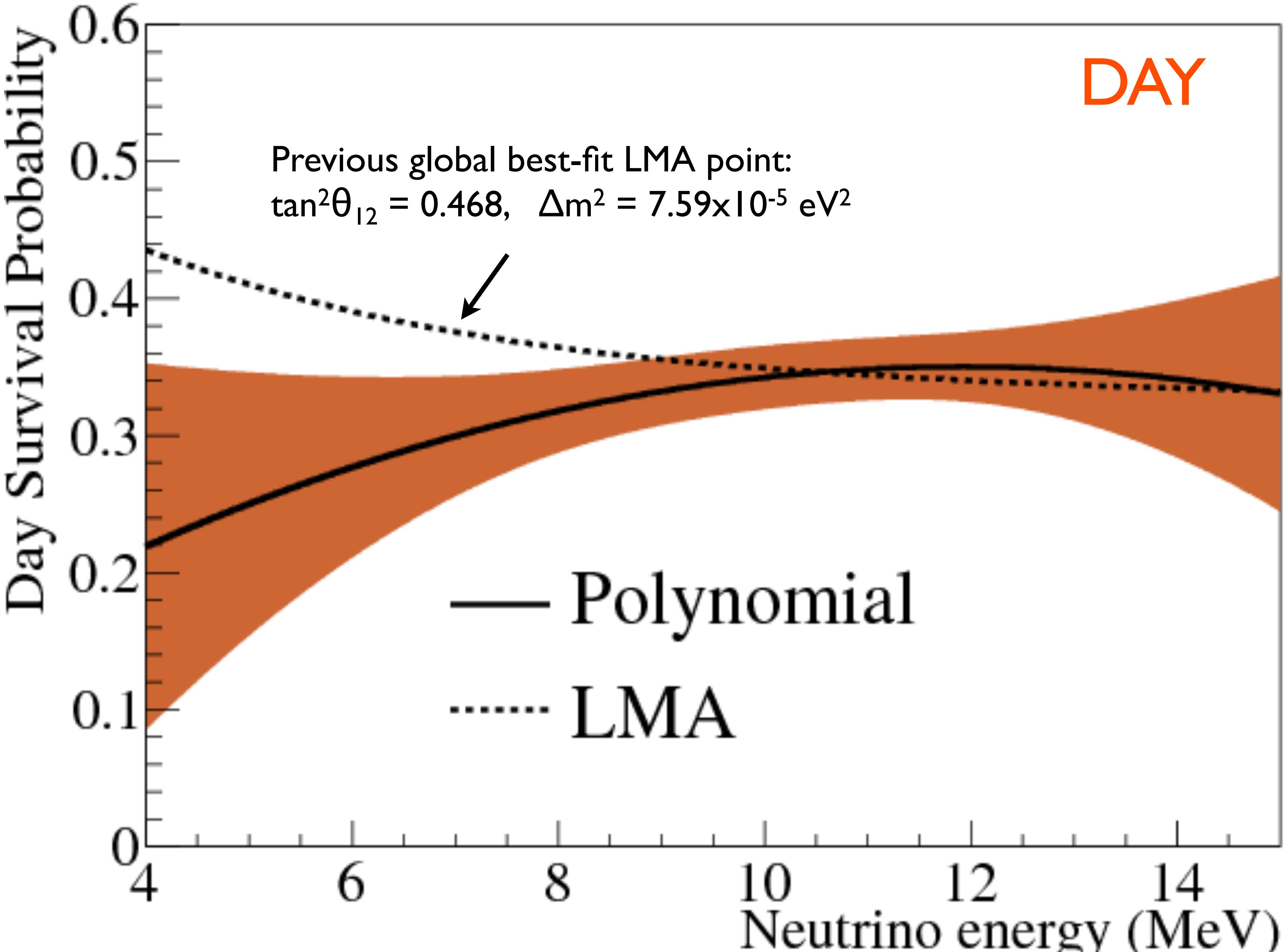


# $^8$B Flux Result




J. N. Bahcall, A. M. Serenelli, and S. Basu, AstroPhys. J. **621**, L85 (2005)

# Polynomial Survival Probability



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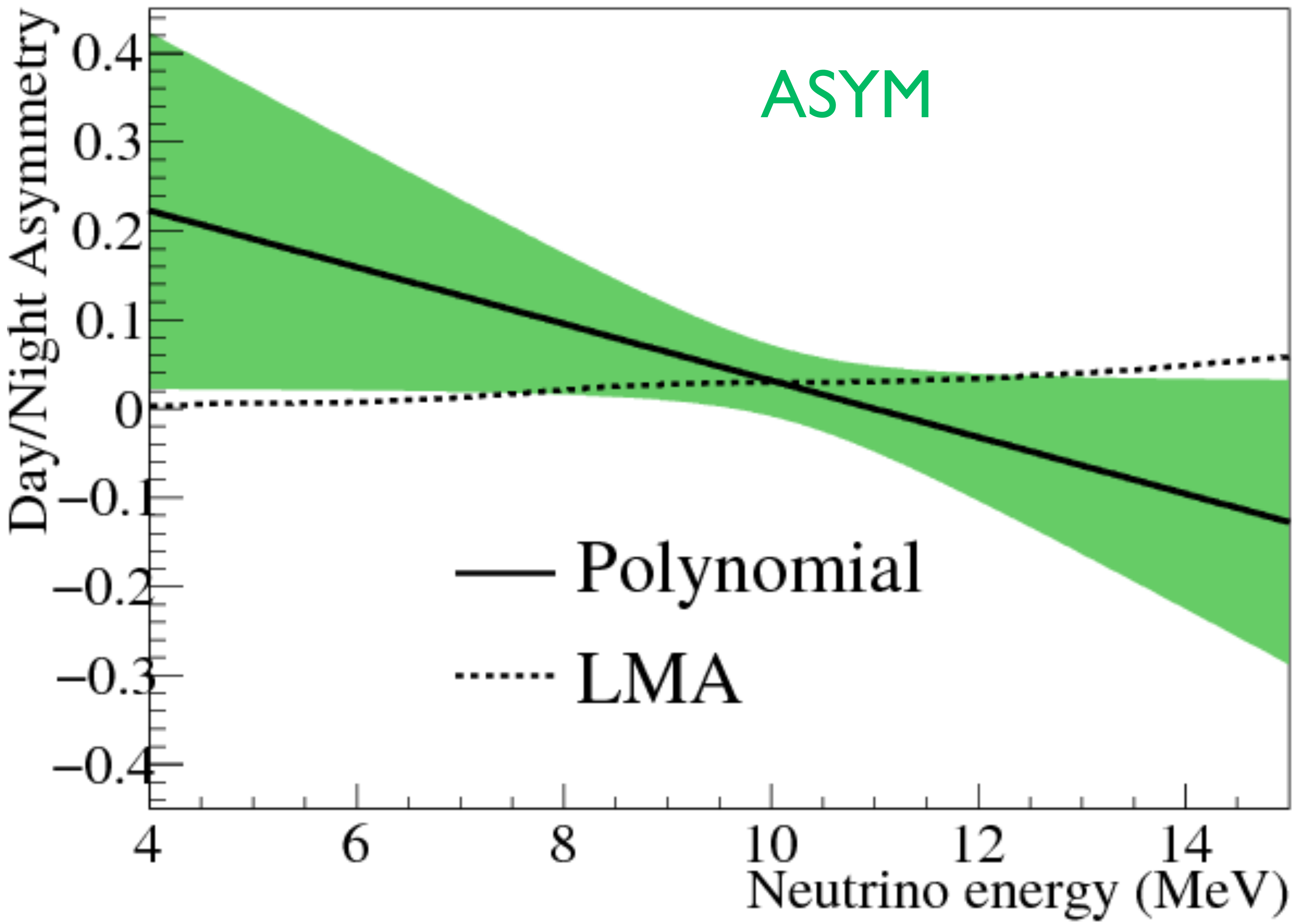

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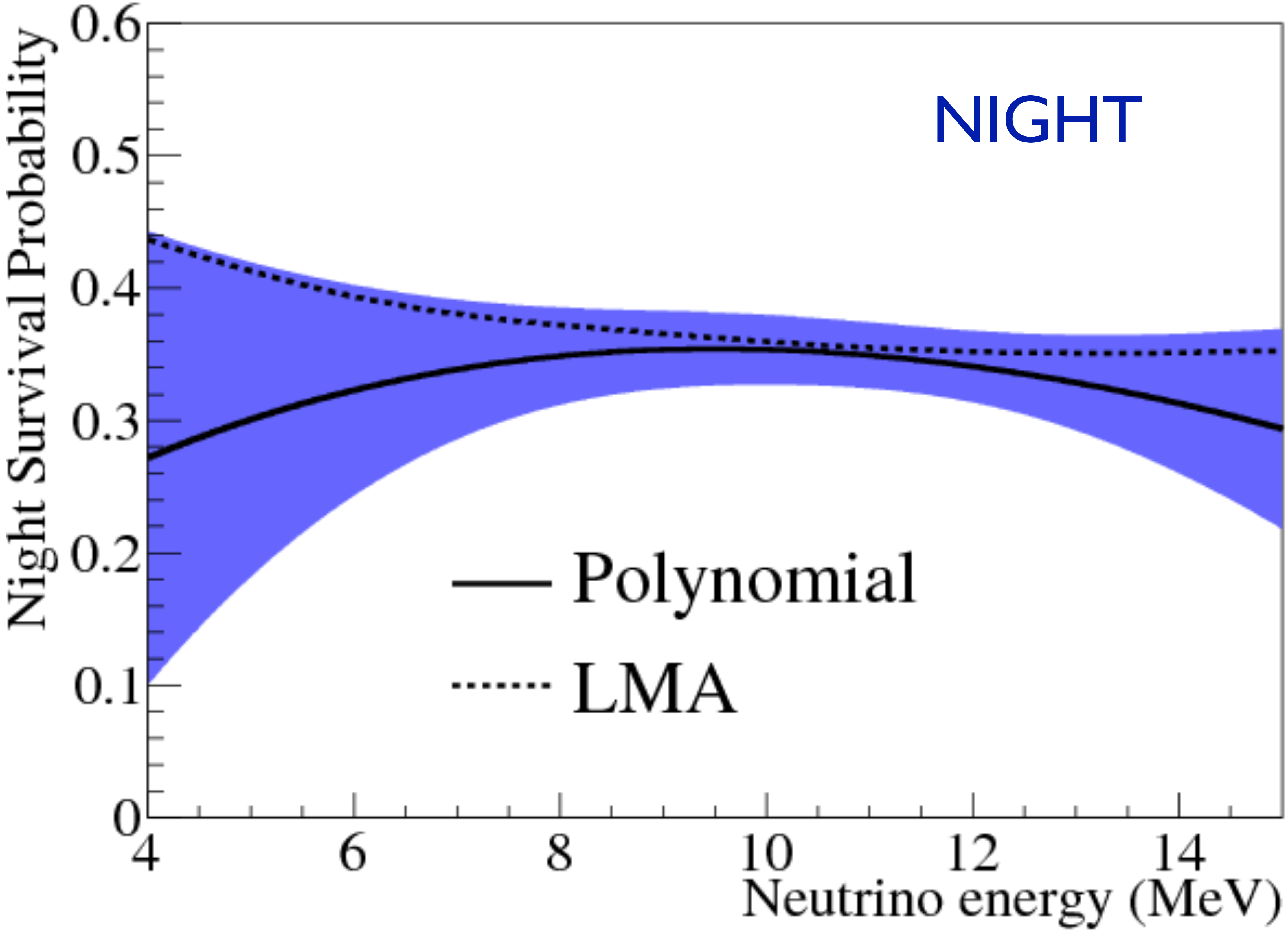


# Polynomial Summary

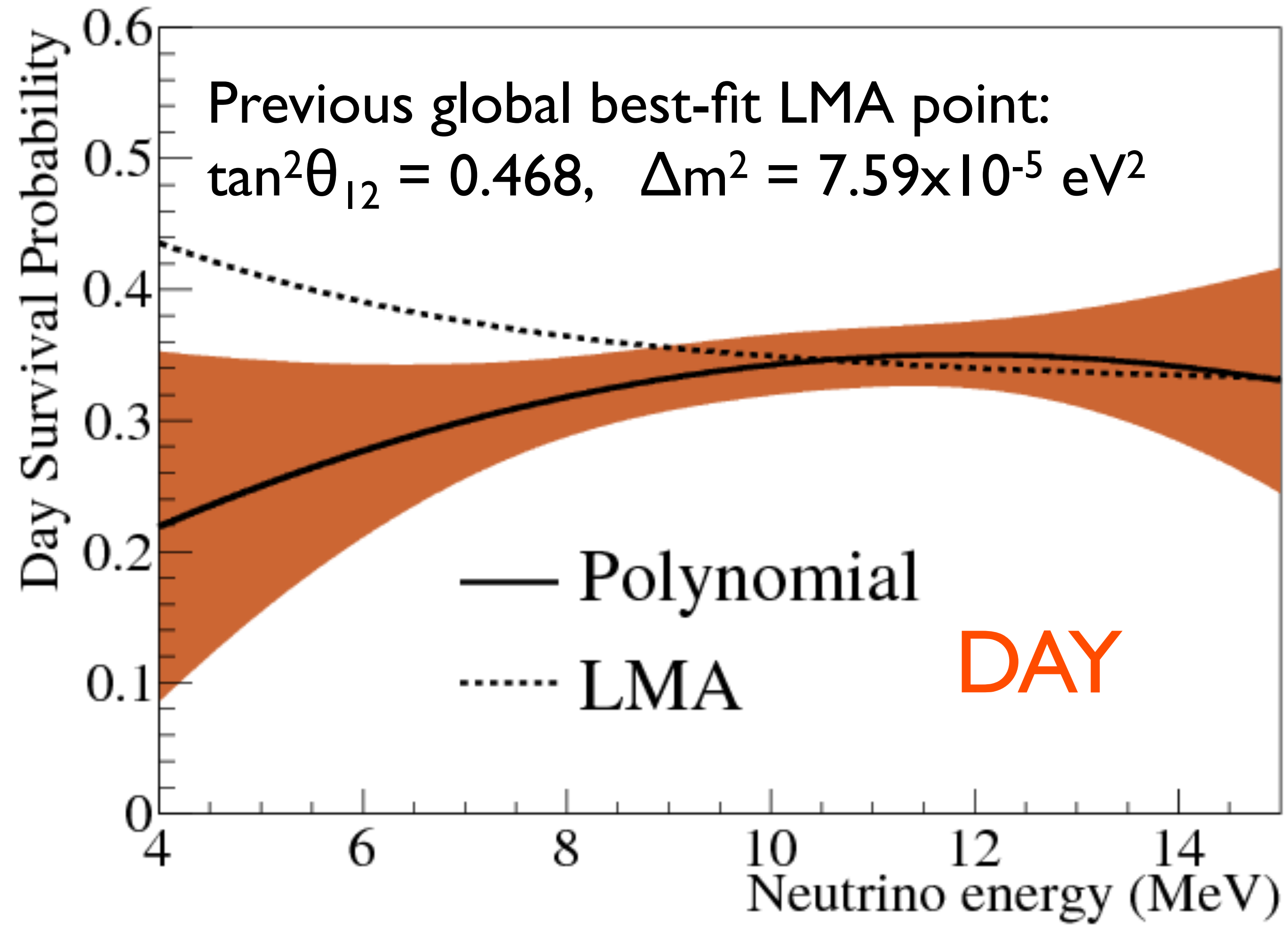
No distortion, no a/s:

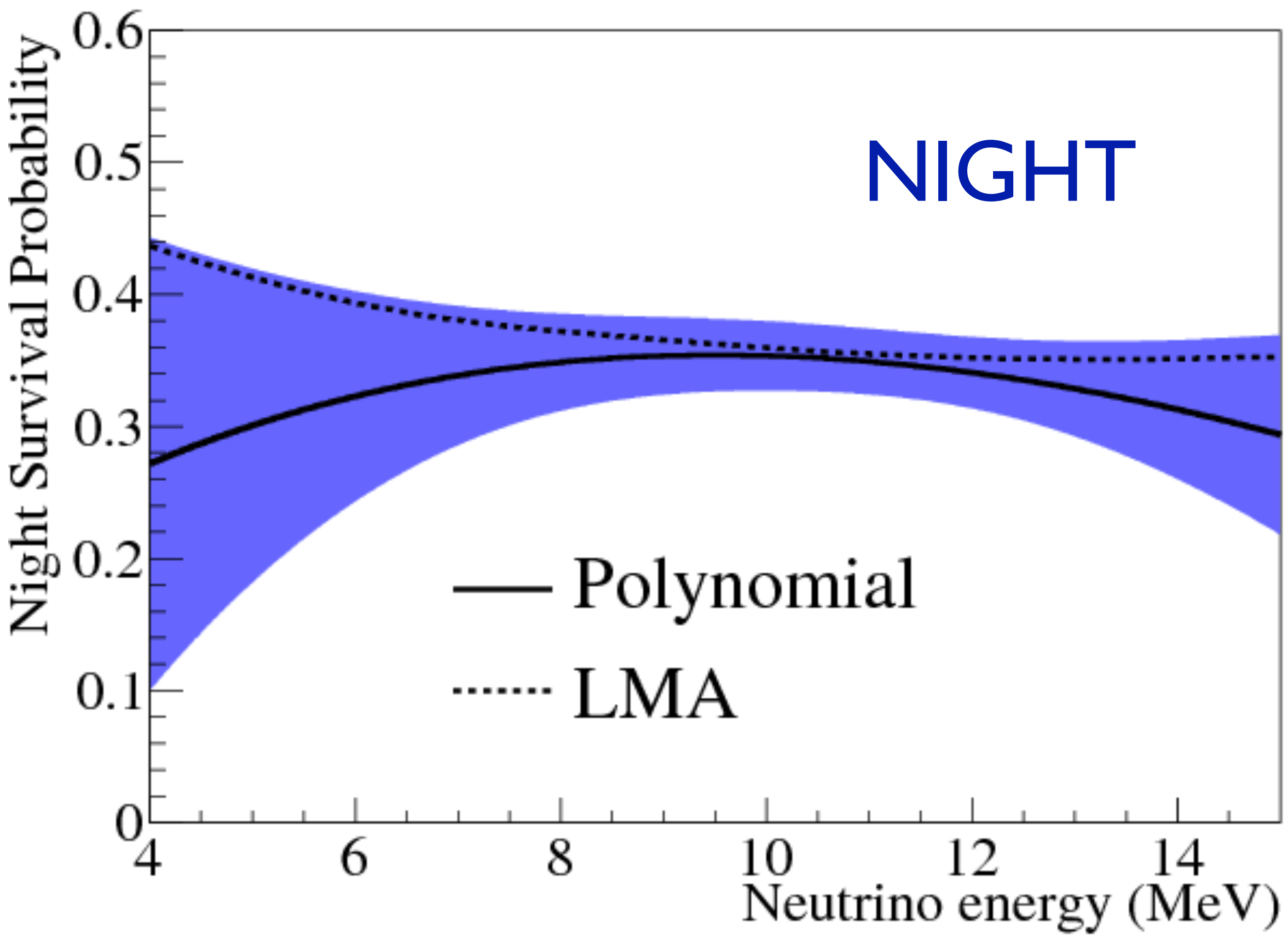
$\Delta\chi^2 = 1.94$ / 4 d.o.f.

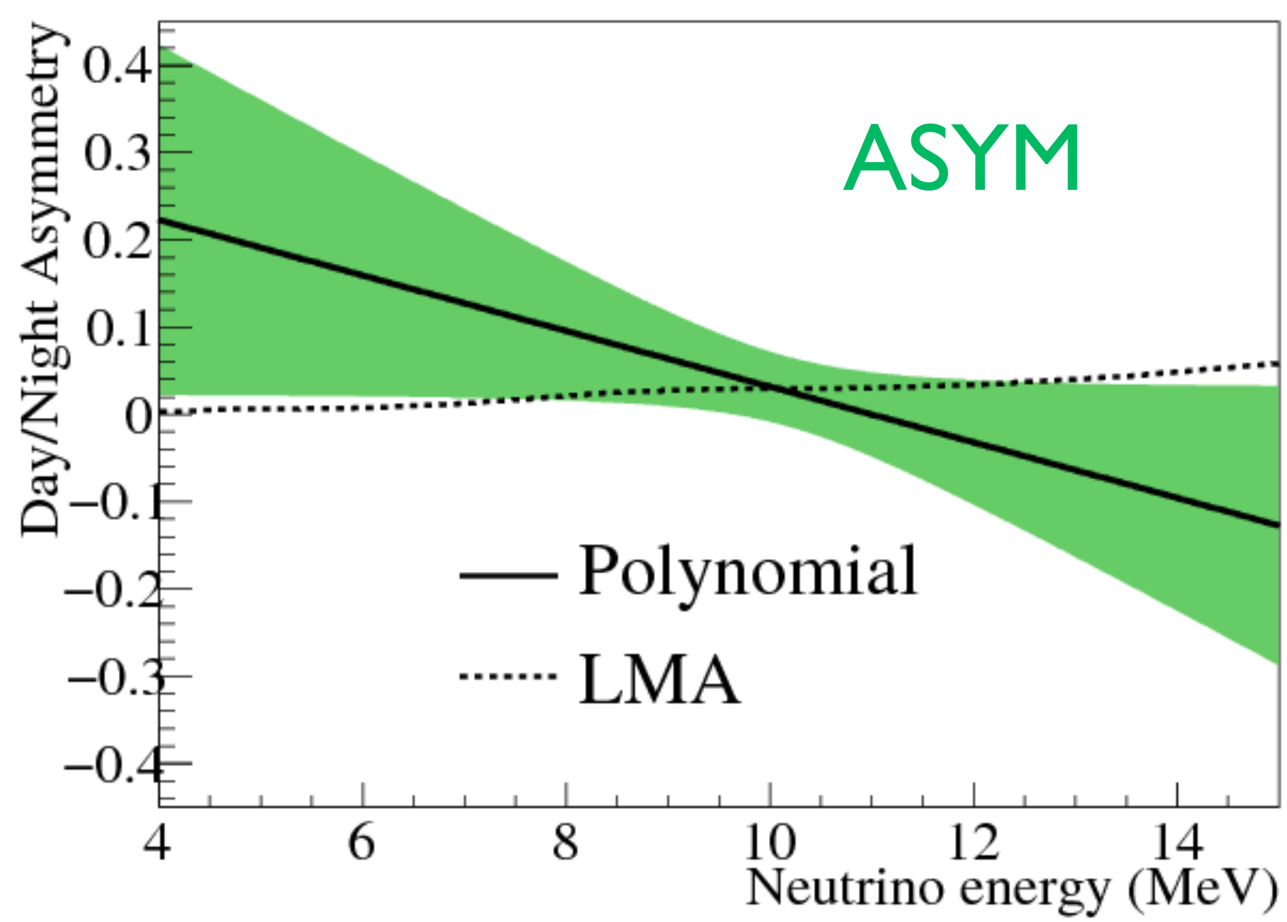
LMA-prediction:

$\Delta\chi^2 = 3.90$ / 4 d.o.f.

$\Phi_{8B} = 5.046 +3.8 -3.9$ %



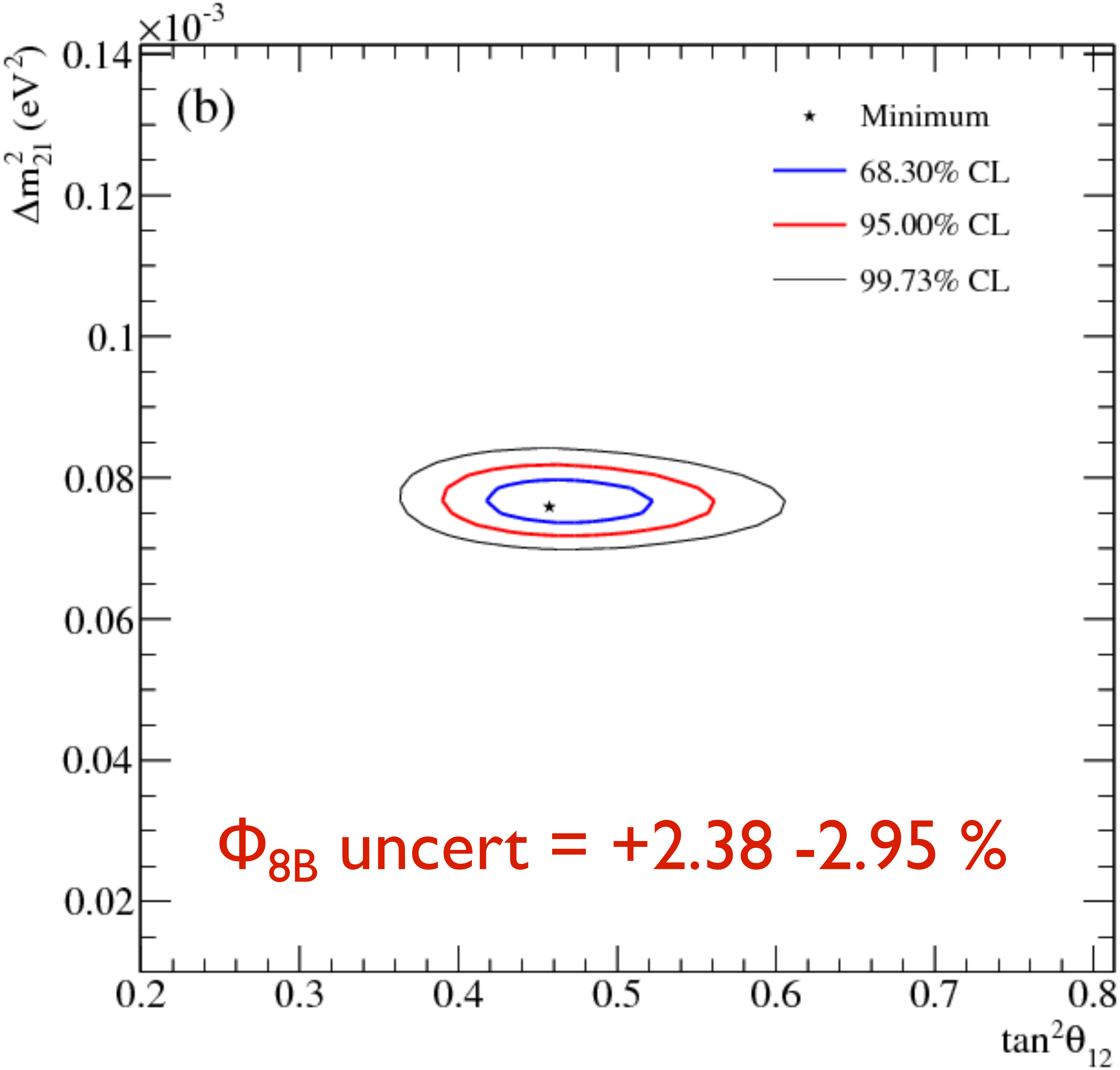
# Oscillation Analyses: Solar + KamLAND

LETA paper 2009:
LETA joint-phase fit
+ Phase III
+ all solar expts
+ KamLAND

Best-fit LMA point:

$\tan^2\theta_{12}$ = 0.457 (+0.040 -0.029)

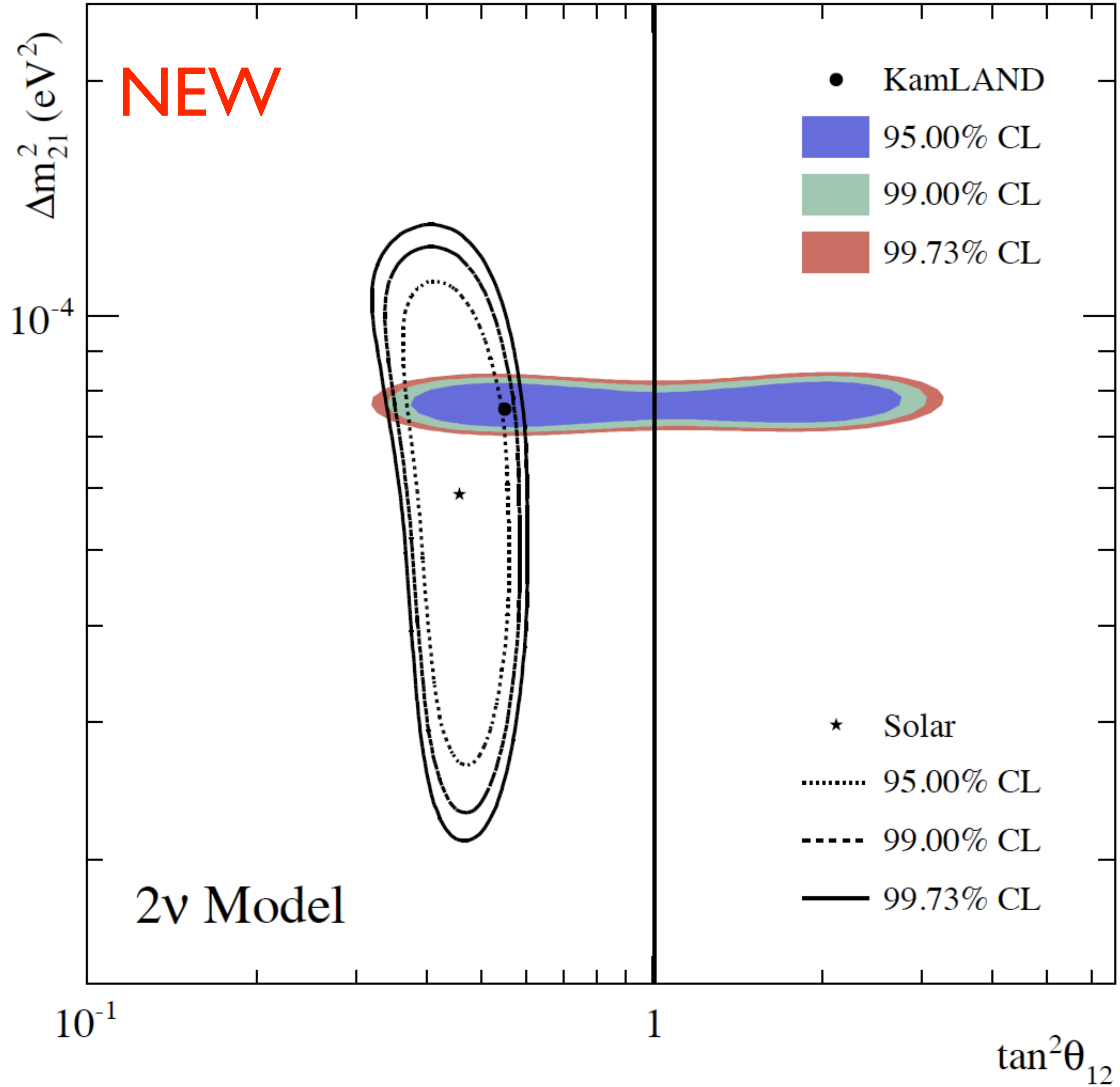
$\Delta m^2 = 7.59\times10^{-5}$ eV$^2$ (+0.20 -0.21)




$\Phi_{8B}$ uncert = +2.38 -2.95 %

# Solar + KamLAND 2-flavor Overlay

LETA paper 2009:
LETA joint-phase fit
+ Phase III
+ all solar expts
+ KamLAND



# Solar + KamLAND 3-flavor Overlay

LETA paper 2009:
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+ all solar expts
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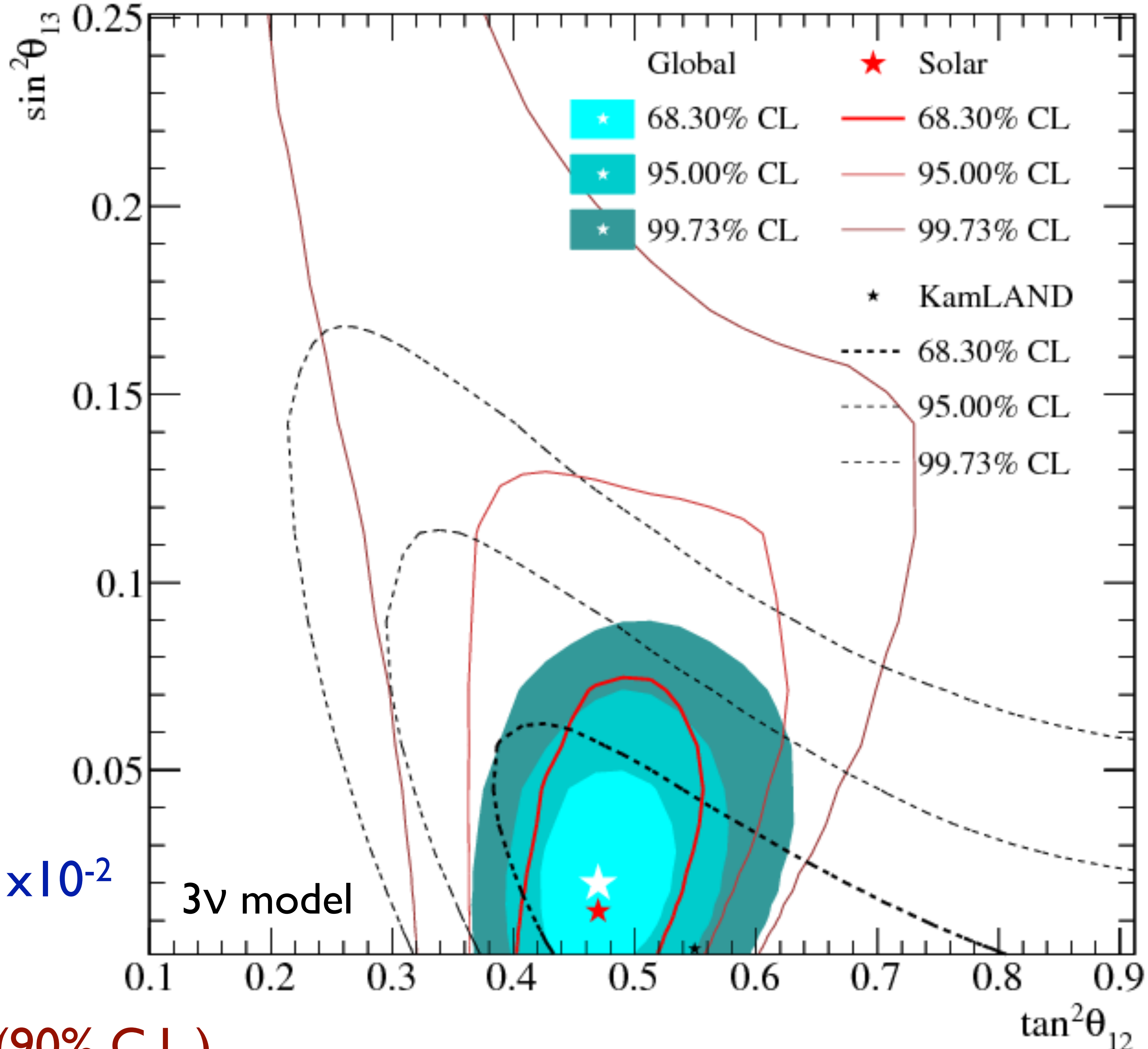



3-flavor analysis:

Best-fit:

$\sin^2\theta_{13} = 2.00 + 2.09 - 1.63 \times 10^{-2}$

$\sin^2\theta_{13} < 0.051$ (90% C.L.)

CHOOZ: $\sin^2\theta_{13} < 0.053$ (90% C.L.)

# Summary

Model-independent measure of the 8B flux:

$\Phi_{NC} = 5.140 +4.0 -3.8\% \ (10^6 \ cm^{-1} \ s^{-1})$

Measure of the 8B flux assuming unitarity:

$\Phi_{8B} = 5.046 +3.8 -3.9\% \ (10^6 \ cm^{-1} \ s^{-1})$

Best fit global MSW (2-flavor) mixing parameters:

$\tan^2\theta_{12} = 0.457 \quad (+0.040 -0.029)$

$\Delta m^2 = 7.59 \times 10^{-5} \ eV^2 \ (+0.20 -0.21)$

$\Phi_{8B}$ uncert = +2.38 -2.95%

3-flavor oscillation analysis:

$\sin^2\theta_{13} = 2.00 +2.09 -1.63 \times 10^{-2} \Rightarrow \sin^2\theta_{13} < 0.057$ (95% C.L.)

For details, see the preprint:

arXiv:0910.2984

Final joint three-phase SNO analysis due out in 2010.

SNO+ collaboration now has stewardship of the SNO detector and is funded to look for:

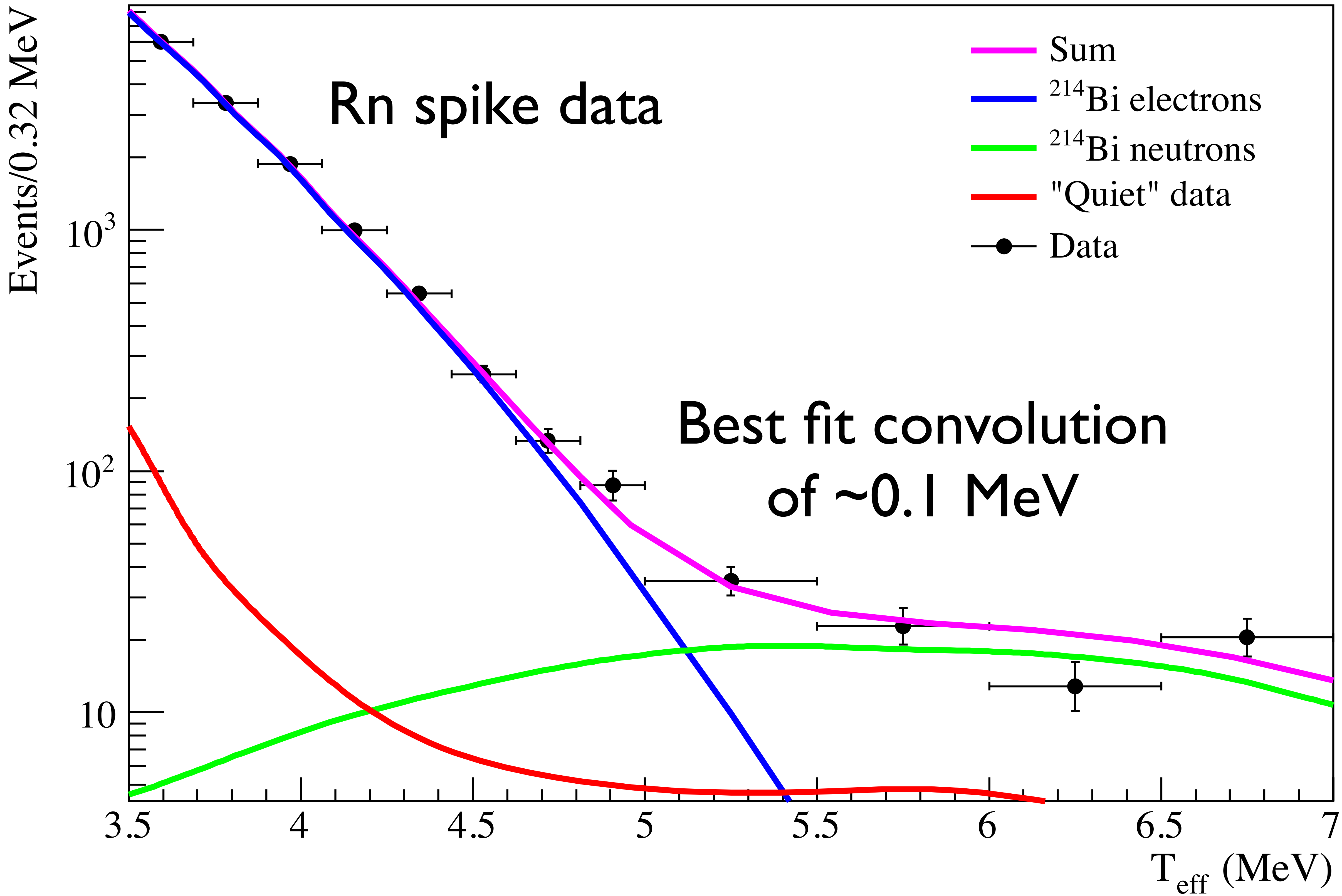
double-beta decay

pep/CNO solar neutrinos

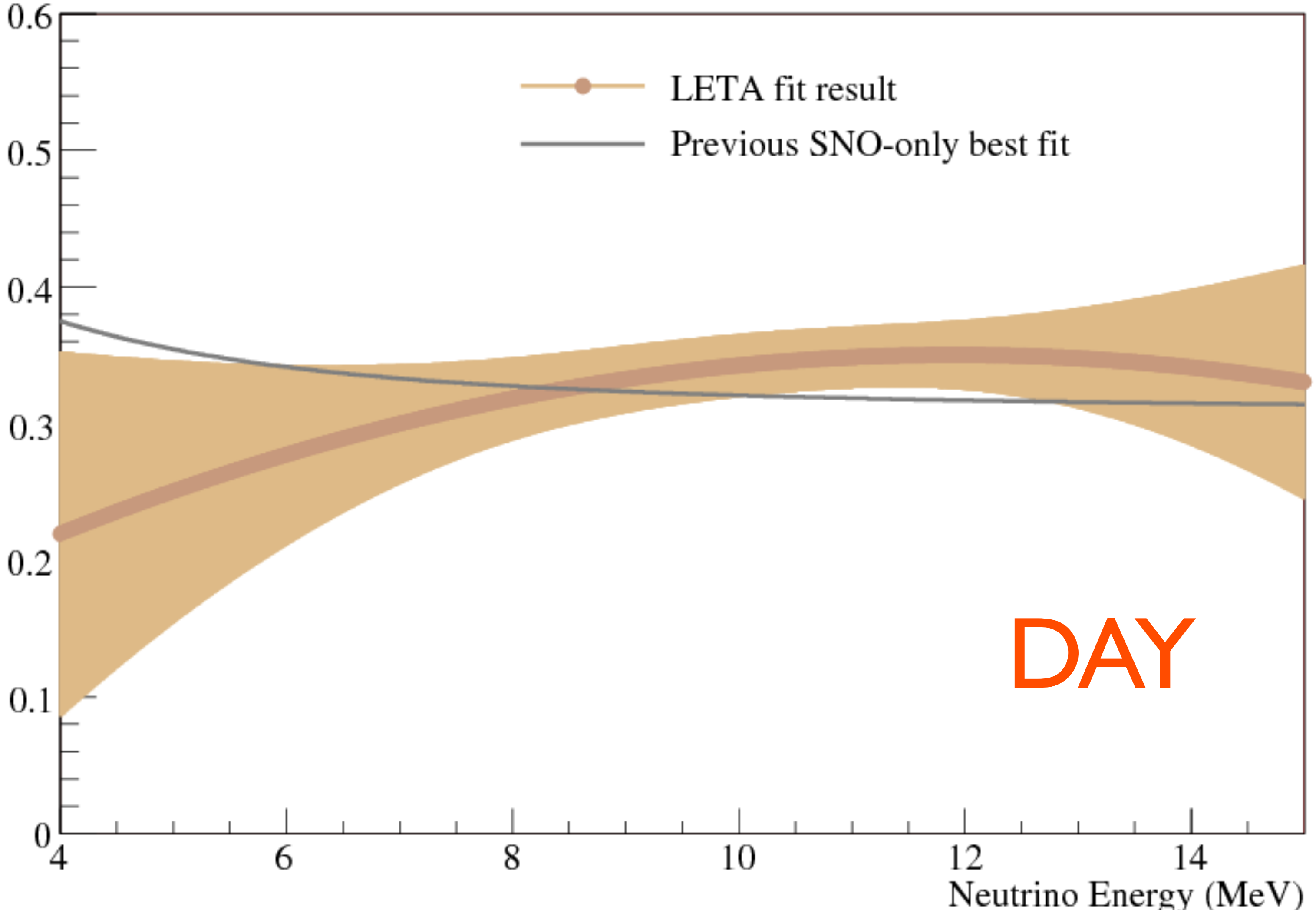
and geoneutrinos!

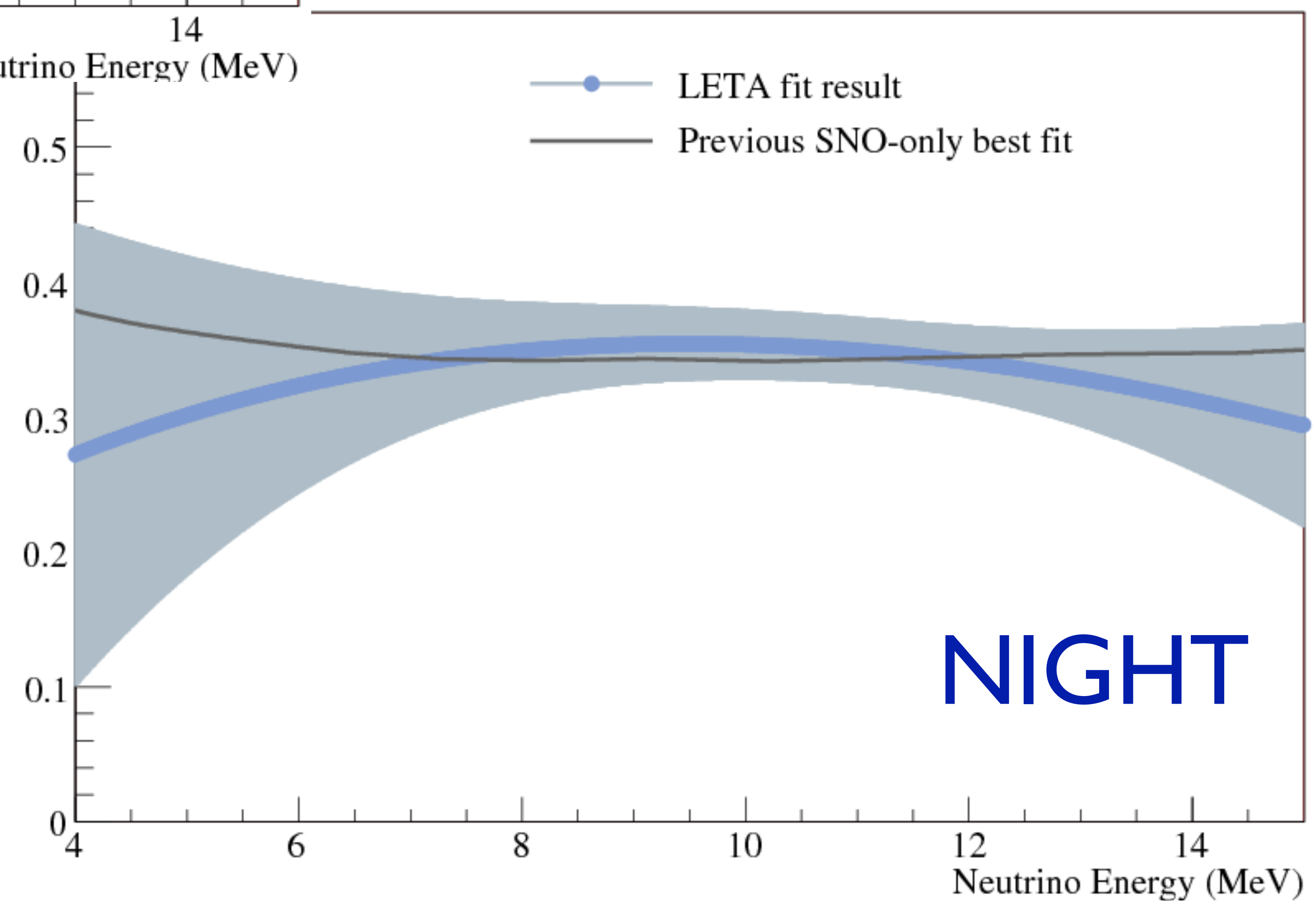
# Backup Slides

# Understanding Systematics at Low Energies



# Survival Probability



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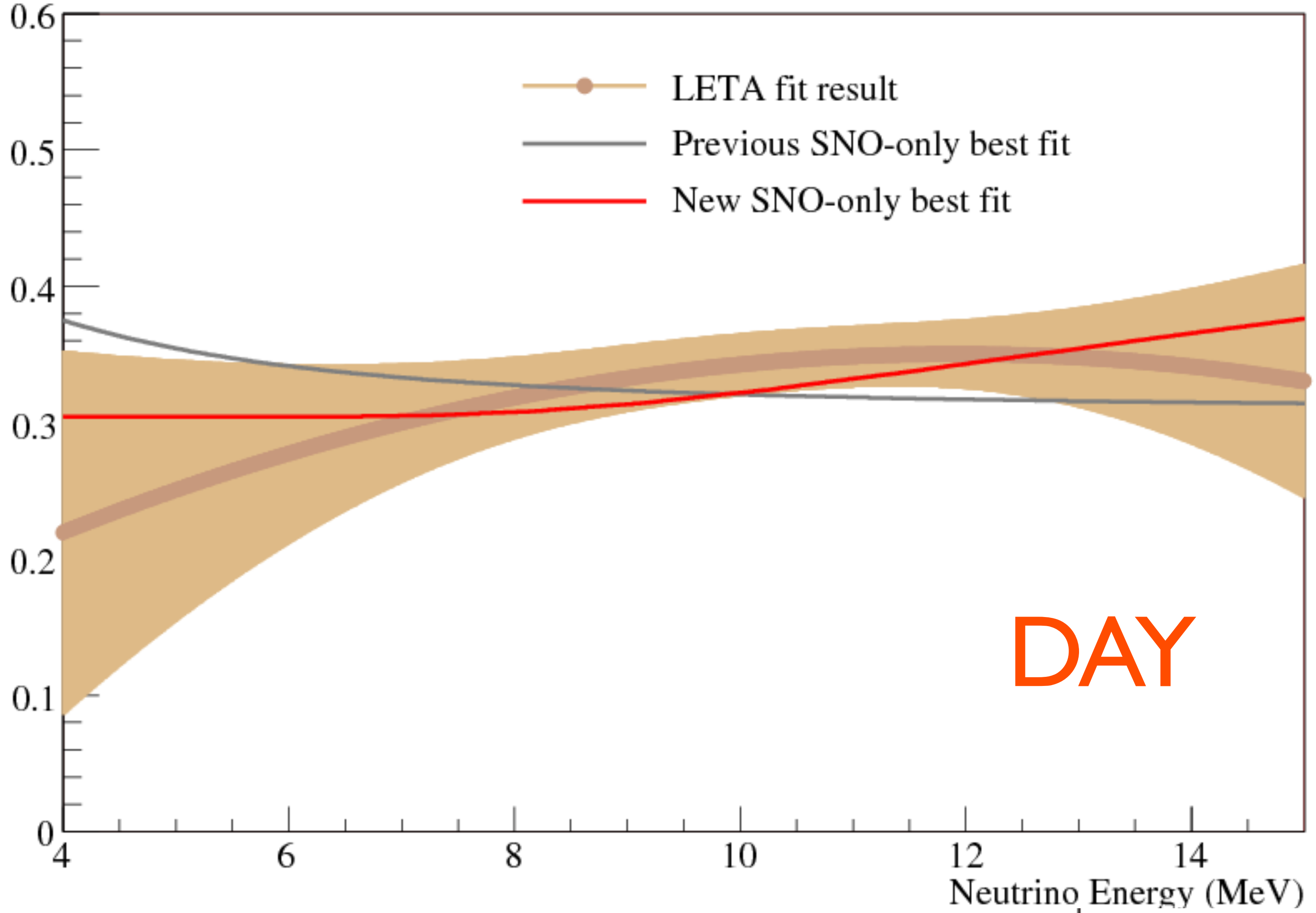
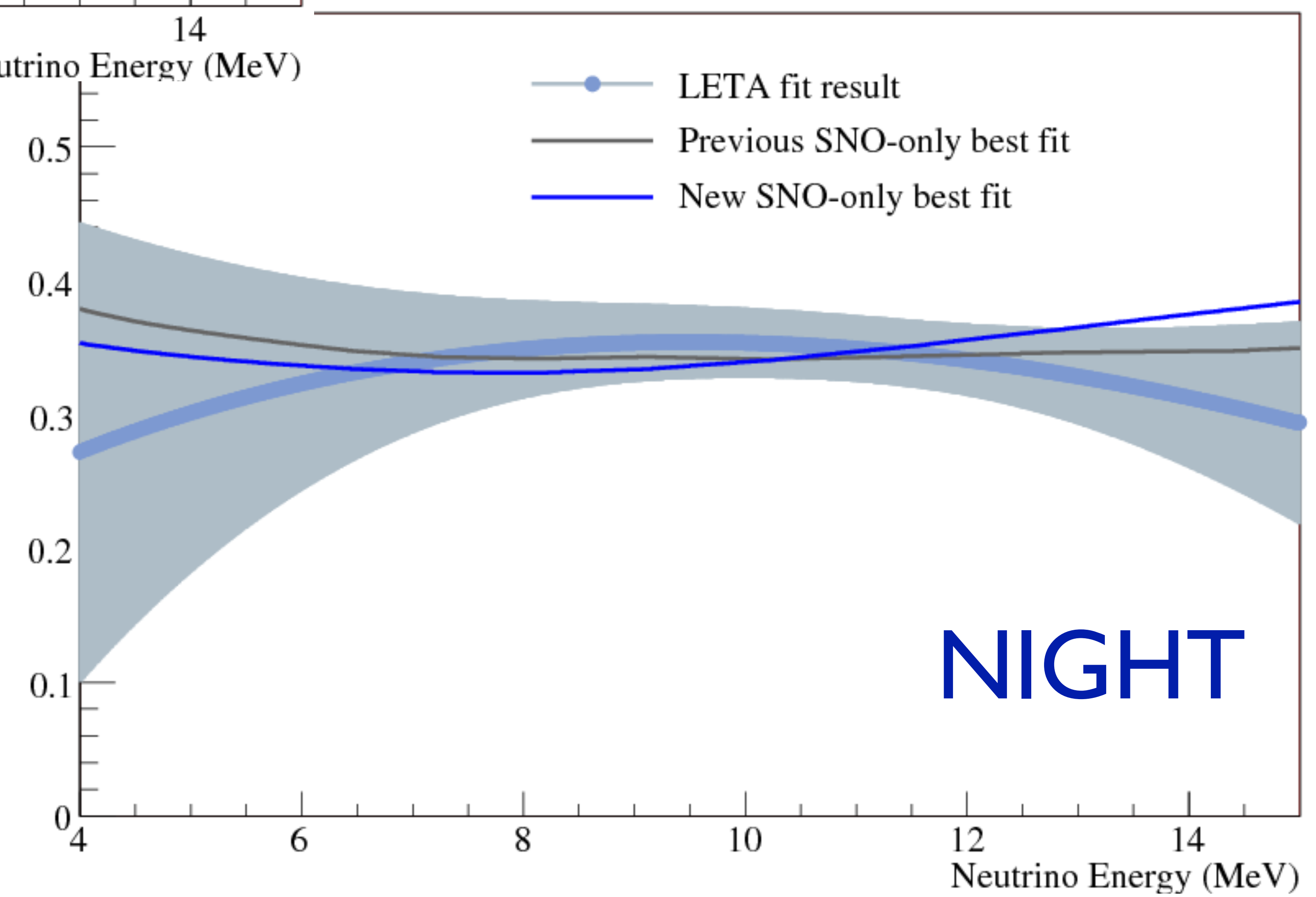
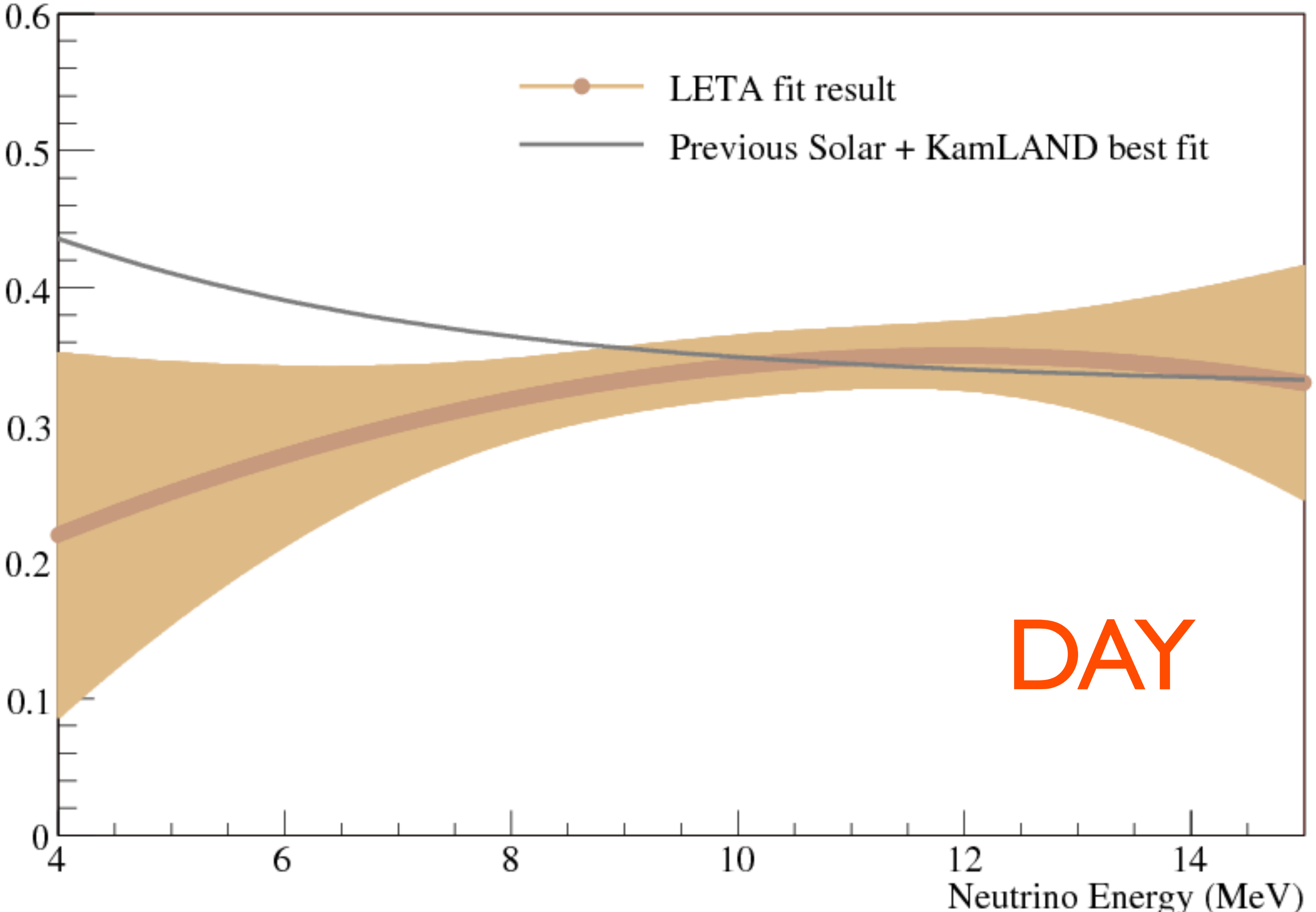
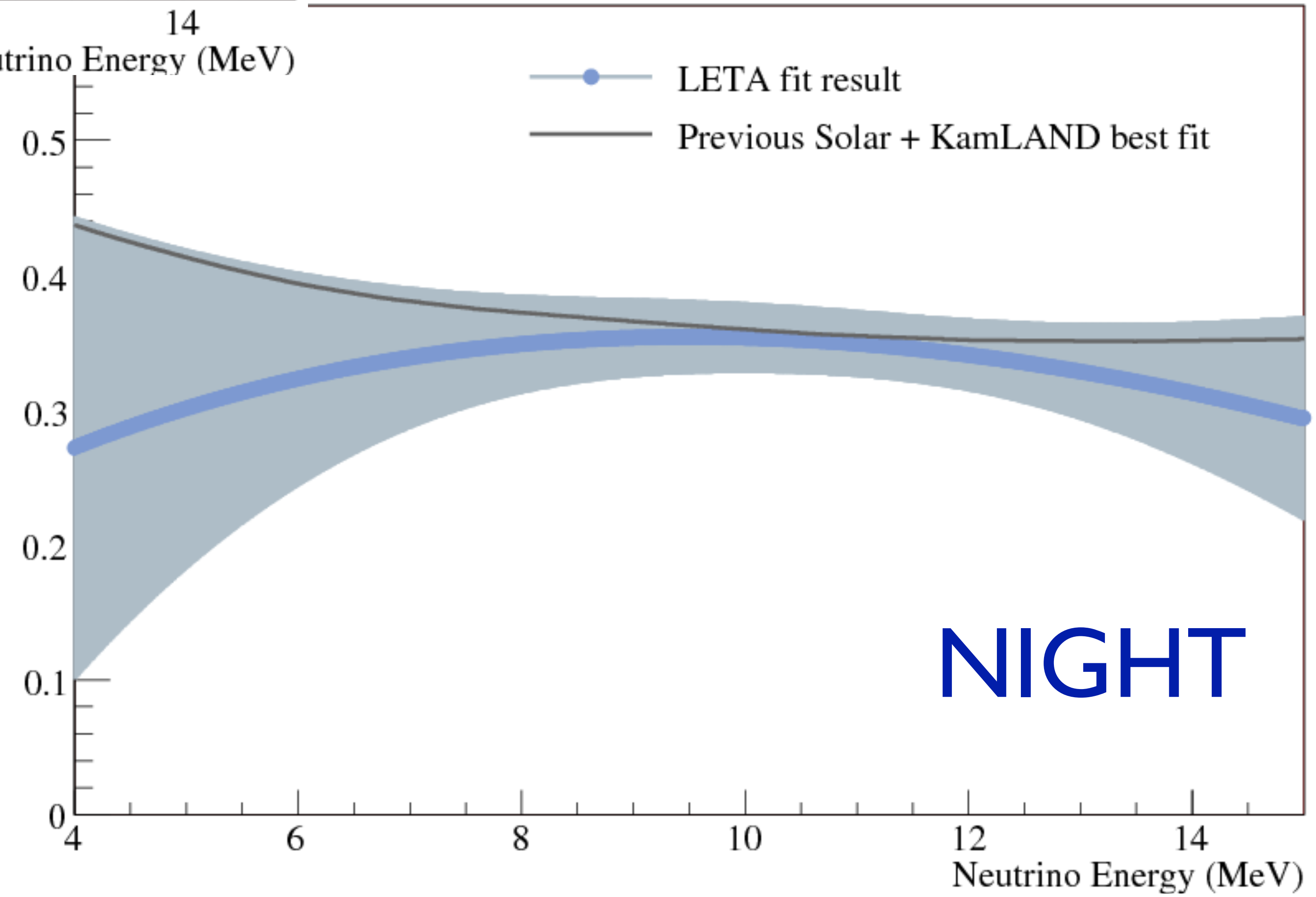


# Survival Probability



# Polynomial Fit Parameters

| Parameter | Value | Stat | Syst | D/N Syst |
|---|---|---|---|---|
| $a_0$ | 0.0325 | $^{+0.0366}_{-0.0360}$ | $^{+0.0059}_{-0.0092}$ | $^{+0.0145}_{-0.0148}$ |
| $a_1$ | −0.0311 | $^{+0.0279}_{-0.0292}$ | $^{+0.0104}_{-0.0056}$ | $^{+0.0140}_{-0.0129}$ |
| $c_0$ | 0.3435 | $^{+0.0205}_{-0.0197}$ | $^{+0.0111}_{-0.0066}$ | $^{+0.0050}_{-0.0059}$ |
| $c_1$ | 0.00795 | $^{+0.00780}_{-0.00745}$ | $^{+0.00308}_{-0.00335}$ | $^{+0.00236}_{-0.00240}$ |
| $c_2$ | −0.00206 | $^{+0.00302}_{-0.00311}$ | $^{+0.00148}_{-0.00128}$ | $^{+0.00057}_{-0.00074}$ |

TABLE XXVI: Extracted polynomial parameter values, statistical uncertainties, average systematic uncertainties, and day/night systematic uncertainties from the survival probability fit.

| | $\Phi_{^8\mathrm{B}}$ | $a_0$ | $a_1$ | $c_0$ | $c_1$ | $c_2$ |
|---|---|---|---|---|---|---|
| $\Phi_{^8\mathrm{B}}$ | 1.000 | −0.166 | 0.051 | −0.408 | 0.103 | −0.246 |
| $a_0$ | −0.166 | 1.000 | −0.109 | −0.263 | 0.019 | −0.123 |
| $a_1$ | 0.051 | −0.109 | 1.000 | −0.005 | −0.499 | −0.031 |
| $c_0$ | −0.408 | −0.263 | −0.005 | 1.000 | −0.101 | −0.321 |
| $c_1$ | 0.103 | 0.019 | −0.499 | −0.101 | 1.000 | −0.067 |
| $c_2$ | −0.246 | −0.123 | −0.031 | −0.321 | −0.067 | 1.000 |

TABLE XXVII: Correlation matrix for the polynomial survival probability fit.

# MSW Parameters: 2-Flavor Analysis

| Oscillation analysis | $\tan^2\theta_{12}$ | $\Delta m^2_{21}(\mathrm{eV}^2)$ |
|---|---|---|
| SNO (LOW) | $0.437^{+0.058}_{-0.058}$ | $1.15^{+0.38}_{-0.18} \times 10^{-7}$ |
| SNO (LMA) | $0.457^{+0.038}_{-0.042}$ | $5.50^{+2.21}_{-1.62} \times 10^{-5}$ |
| Solar | $0.457^{+0.038}_{-0.041}$ | $5.89^{+2.13}_{-2.16} \times 10^{-5}$ |
| Solar+KamLAND | $0.457^{+0.040}_{-0.029}$ | $7.59^{+0.20}_{-0.21} \times 10^{-5}$ |
| | $\chi^2_{\mathrm{min}}/\mathrm{ndf}$ | $\Phi_{^8\mathrm{B}}$ $(\times 10^6\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1})$ |
| SNO (LOW) | 6.80/9 | $5.013^{+0.176}_{-0.199}$ |
| SNO (LMA) | 8.20/9 | $4.984^{+0.205}_{-0.182}$ |
| Solar | 67.5/89 | $5.104^{+0.199}_{-0.148}$ |
| Solar+KamLAND | 82.8/106 | $5.013^{+0.119}_{-0.148}$ |

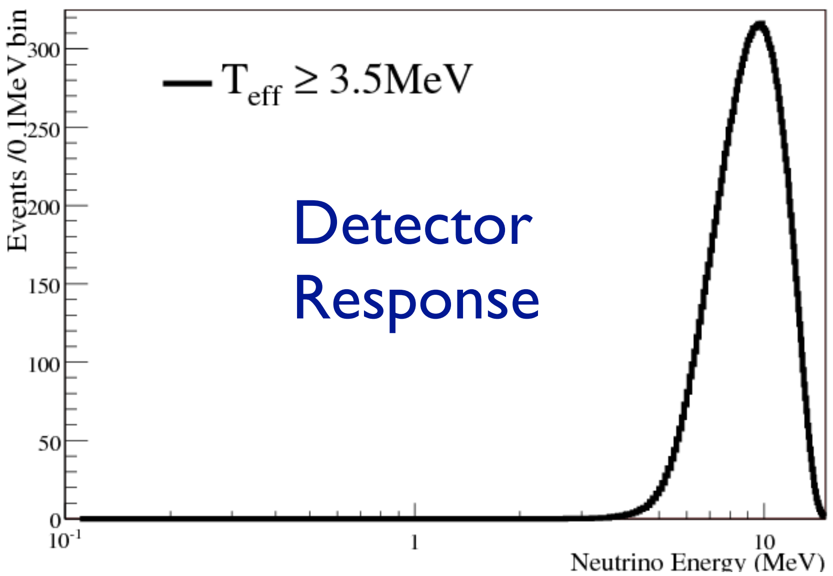
TABLE XX: Best-fit neutrino oscillation parameters and extracted $^8$B flux from a two-flavor oscillation analysis. The 'SNO' results are from the combined LETA + Phase III oscillation analysis. Uncertainties listed are $\pm 1\sigma$ after the $\chi^2$ was minimized with respect to all other parameters.

# MSW Parameters: 3-Flavor Analysis

| Oscillation analysis | $\tan^2\theta_{12}$ | $\Delta m^2_{21}(\mathrm{eV}^2)$ |
|---|---|---|
| Solar | $0.468^{+0.052}_{-0.050}$ | $6.31^{+2.49}_{-2.58}\times 10^{-5}$ |
| Solar+KamLAND | $0.468^{+0.042}_{-0.033}$ | $7.59^{+0.21}_{-0.21}\times 10^{-5}$ |
| | $\chi^2_{\mathrm{min}}/\mathrm{ndf}$ | $\Phi_{^8\mathrm{B}}$ $(\times 10^6\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1})$ |
| Solar | 67.4/89 | $5.115^{+0.159}_{-0.193}$ |
| Solar+KamLAND | 81.4/106 | $5.087^{+0.171}_{-0.159}$ |
| | $\sin^2\theta_{13}(\times 10^{-2})$ | |
| Solar | $< 8.10$ (95% C.L.) | |
| Solar+KamLAND | $2.00^{+2.09}_{-1.63}$ | |

TABLE XXI: Best-fit neutrino oscillation parameters and extracted $^8$B flux from a three-flavor oscillation analysis. Uncertainties listed are $\pm 1\sigma$ after the $\chi^2$ was minimized with respect to all other parameters.

# Polynomial Fit Interpretation

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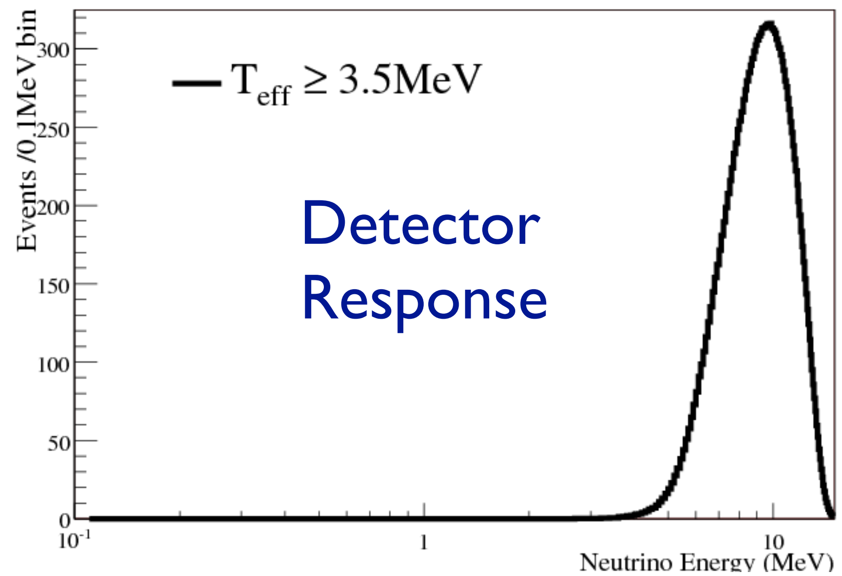


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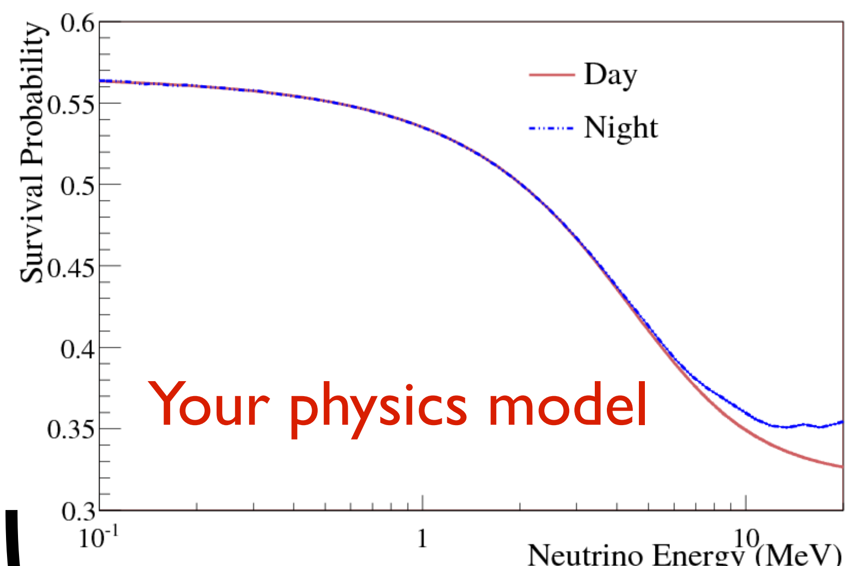



$P_{ee}^{DAY}(E_\nu) = f(c0, c1, c2)$

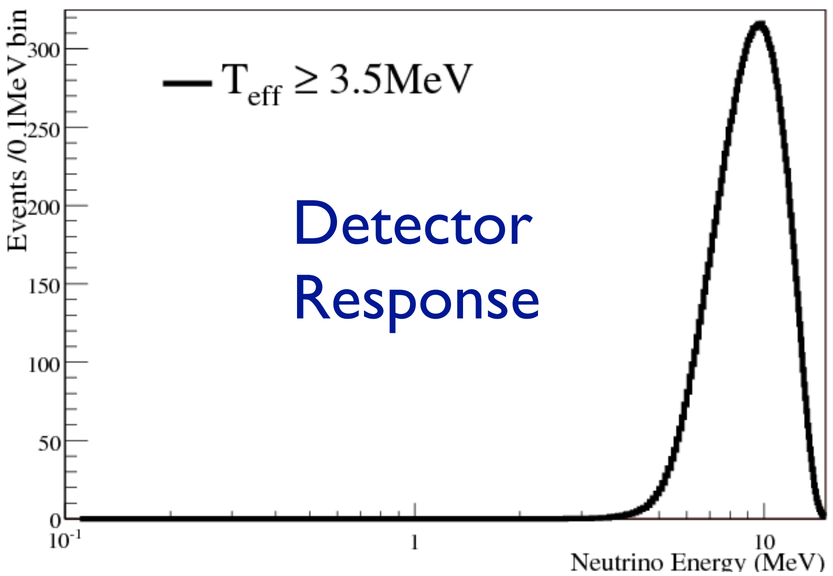
$P_{ee}^{ASYM}(E_\nu) = f(a0, a1)$

$P_{ee}^{NIGHT}(E_\nu) = f(P_{ee}^{DAY}(E_\nu)\ ,\ P_{ee}^{ASYM}(E_\nu))$

Polynomial model

Vary c0, c1, c2, a0, a1 parameters to best match your physics model to a polynomial

# Polynomial Fit Interpretation

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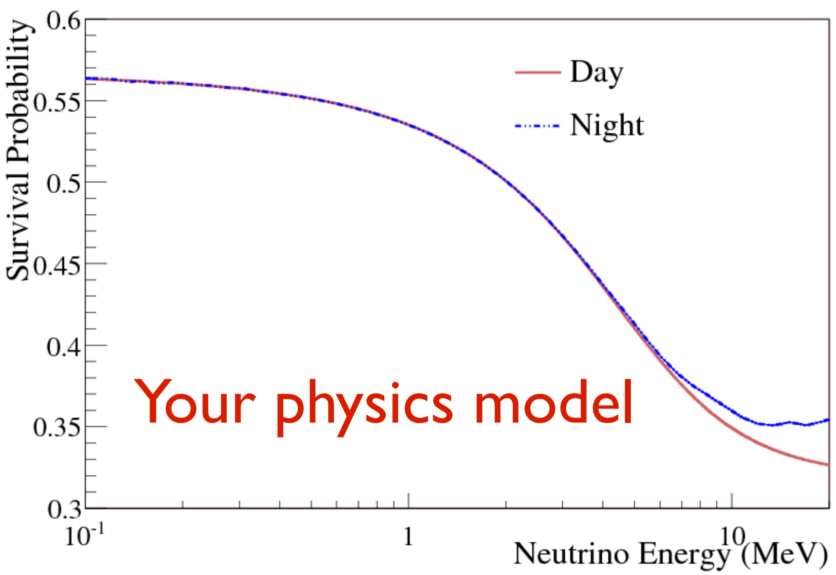


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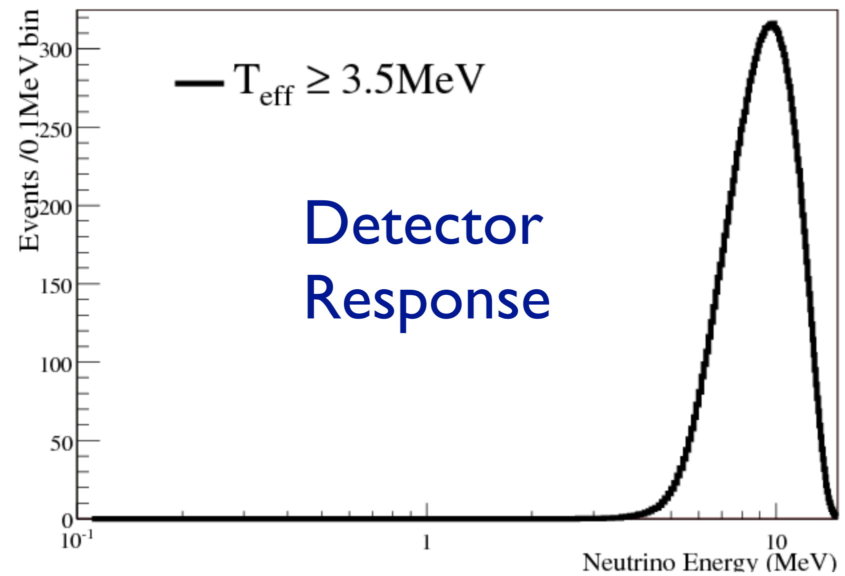



✖

$P_{ee}^{DAY}(E_\nu) = f(c0, c1, c2)$

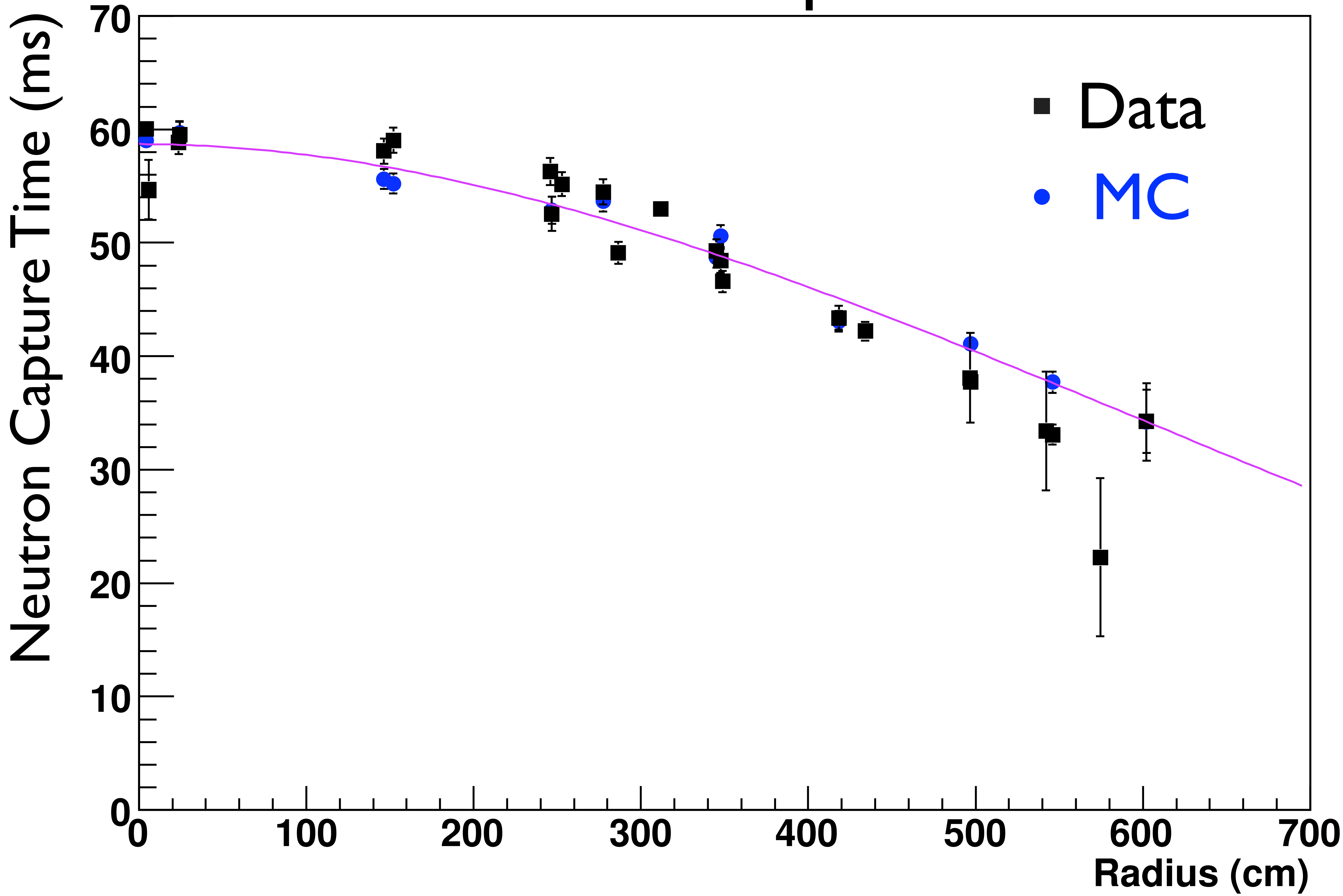
$P_{ee}^{ASYM}(E_\nu) = f(a0, a1)$

$P_{ee}^{NIGHT}(E_\nu) = f(P_{ee}^{DAY}(E_\nu), P_{ee}^{ASYM}(E_\nu))$

Polynomial model

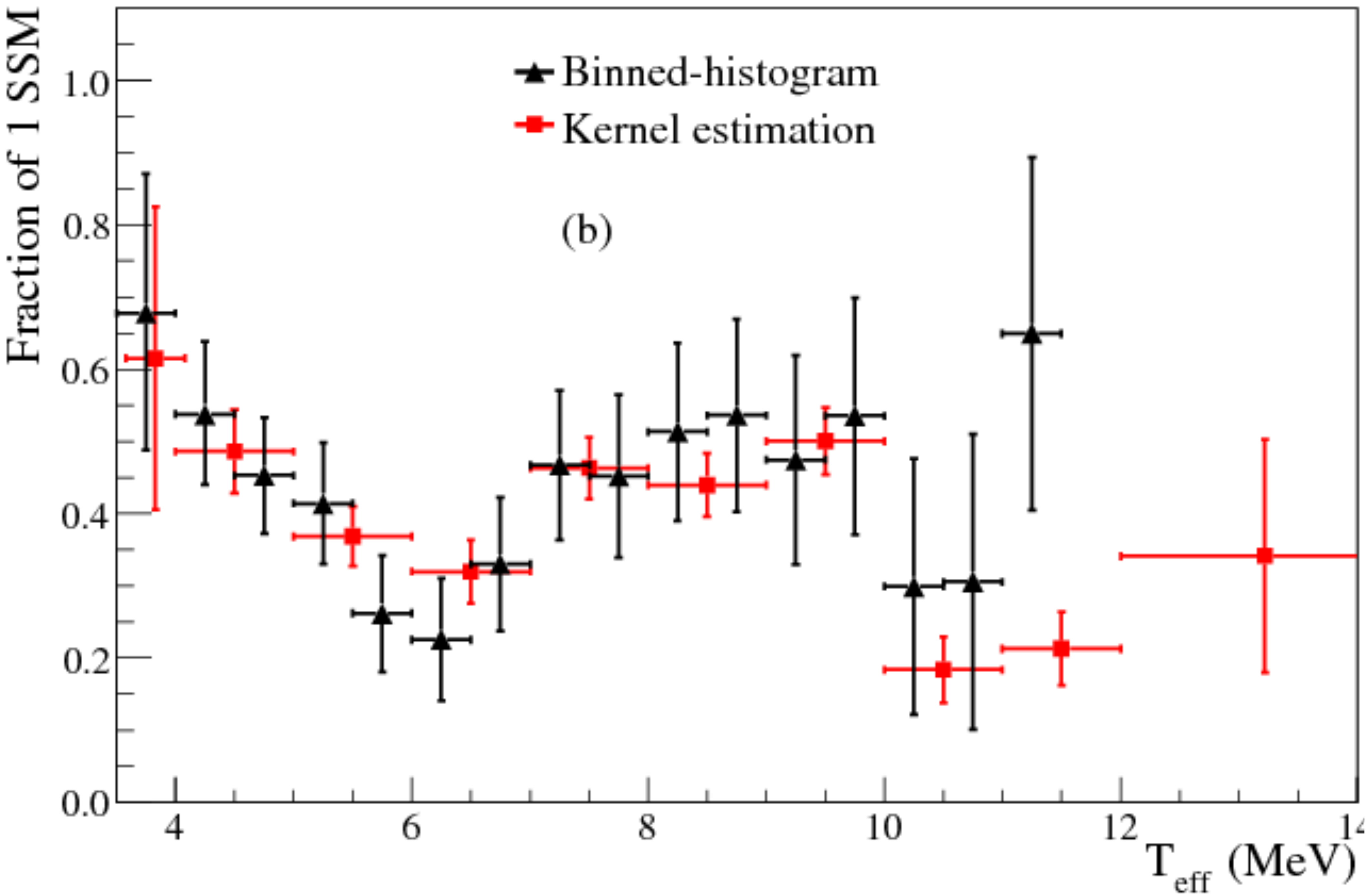
5D $\chi^2$ test:
Model parameters
vs
Signal extraction fit result

# 5) Reduce Systematic Uncertainties: Neutron Capture

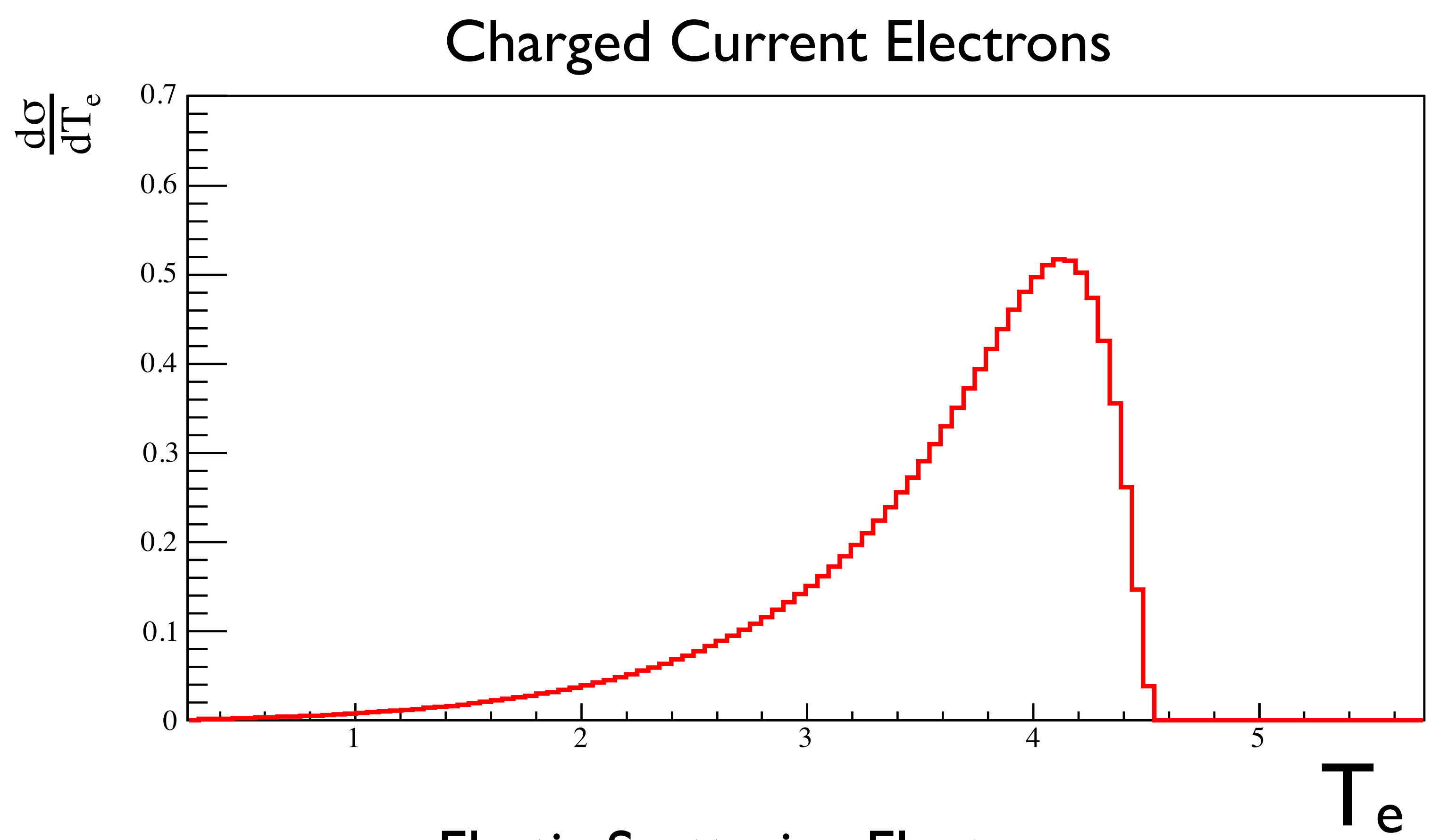


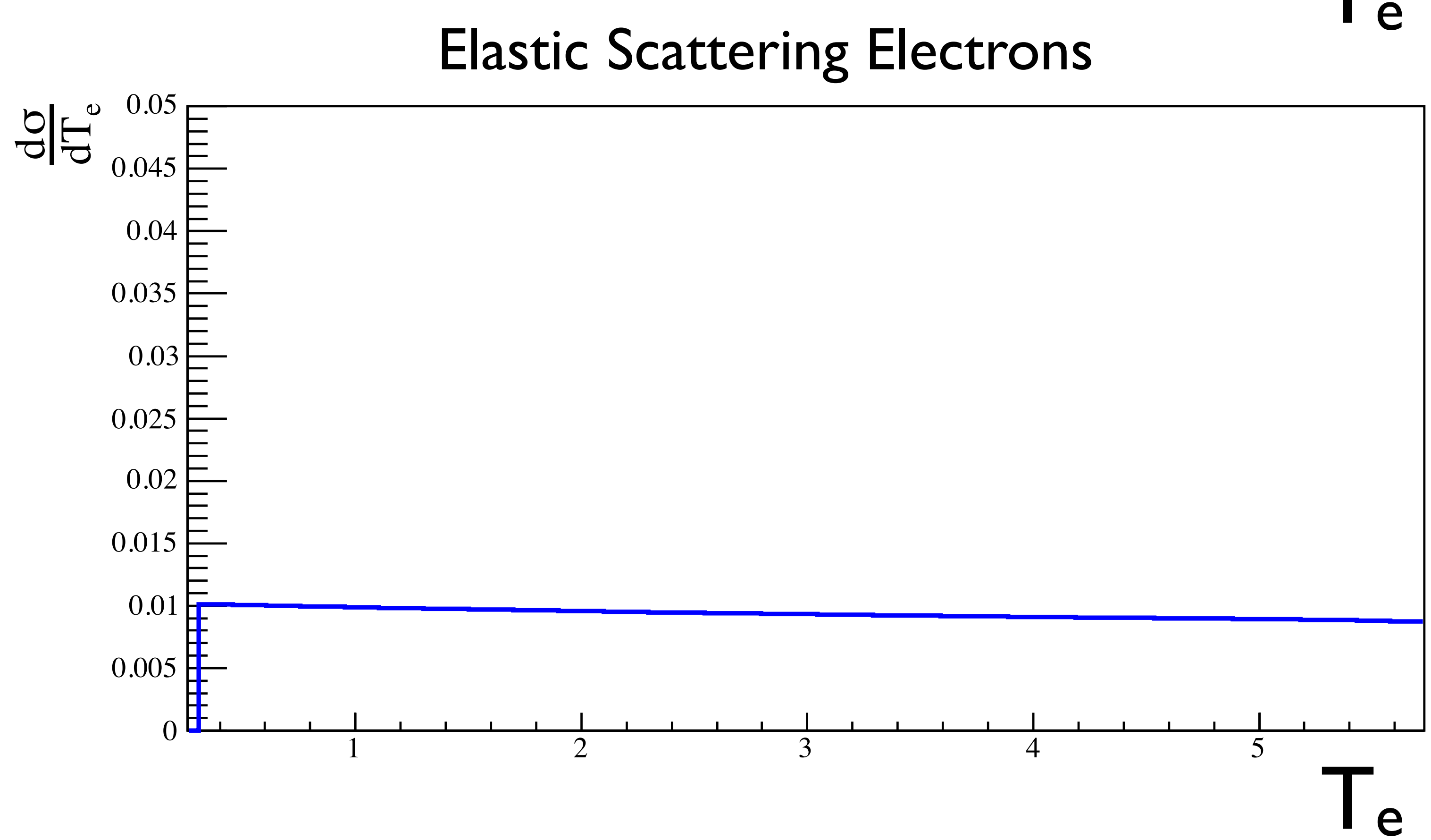

*$D_2O$ phase*

# ES Recoil-Electron Spectrum



# CC Electrons as measure of ν energy




$T_\nu = 6$ MeV

# Solar+KamLAND Survival Probability