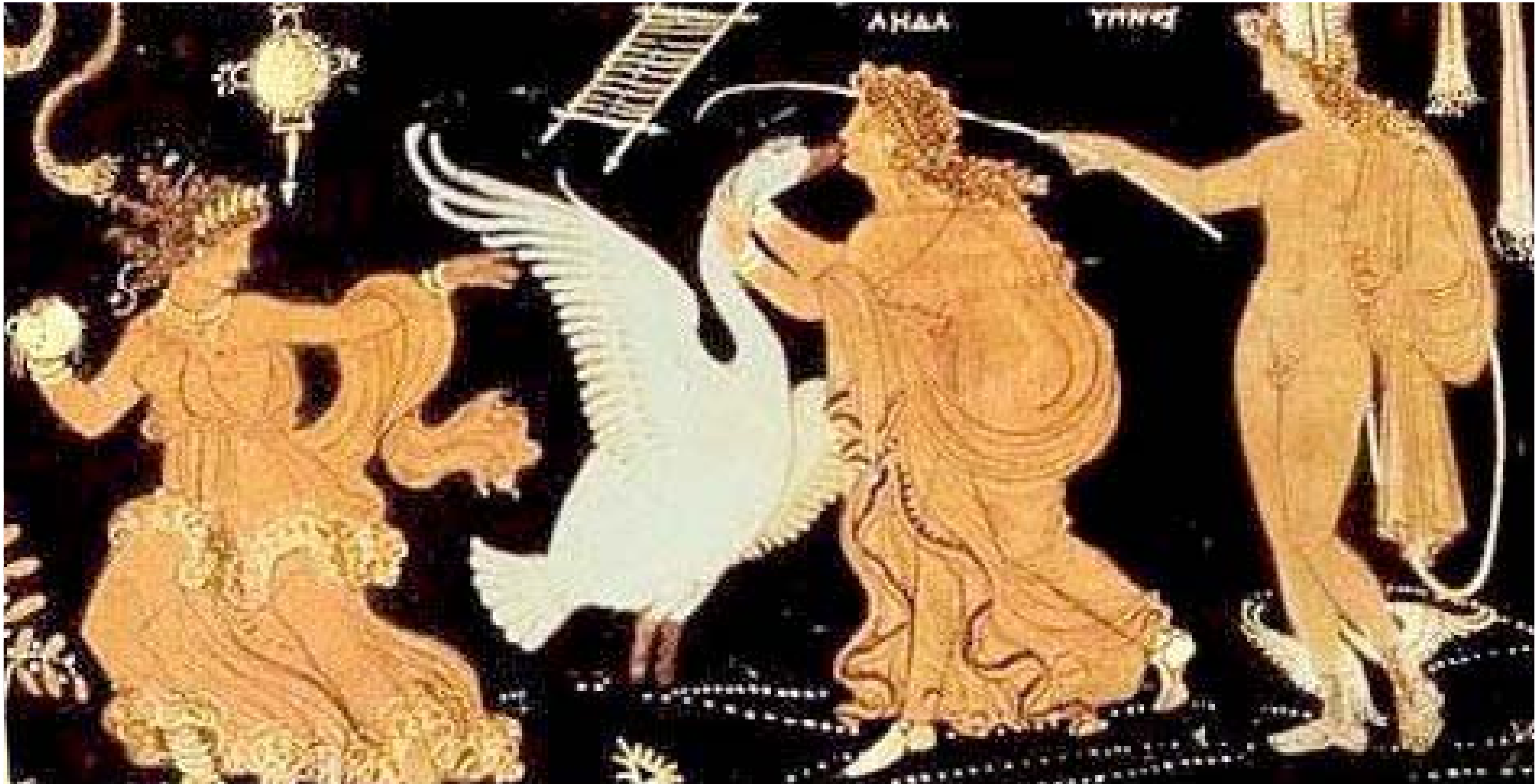
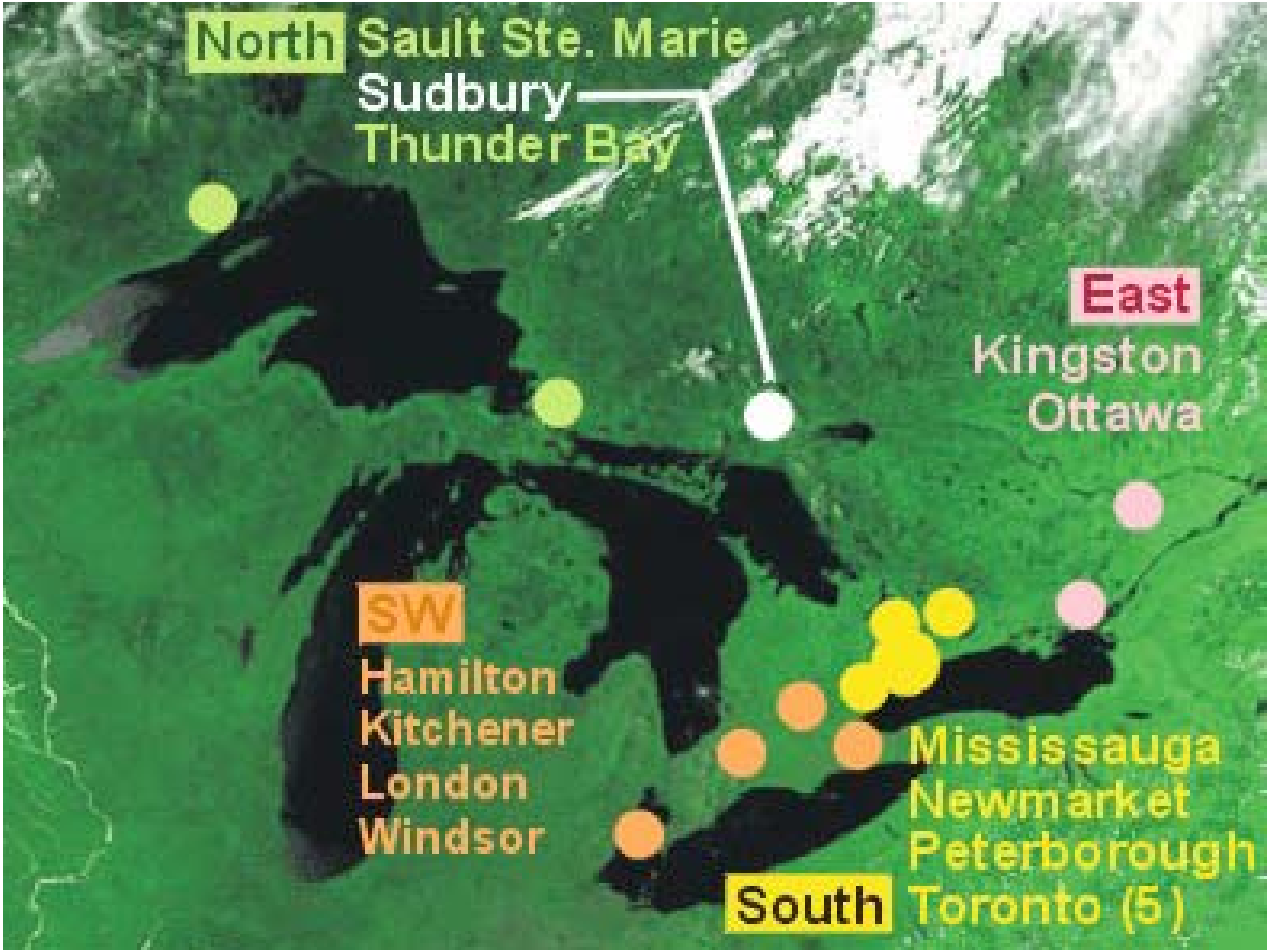


Low Energy Threshold Analysis

of SNO Data

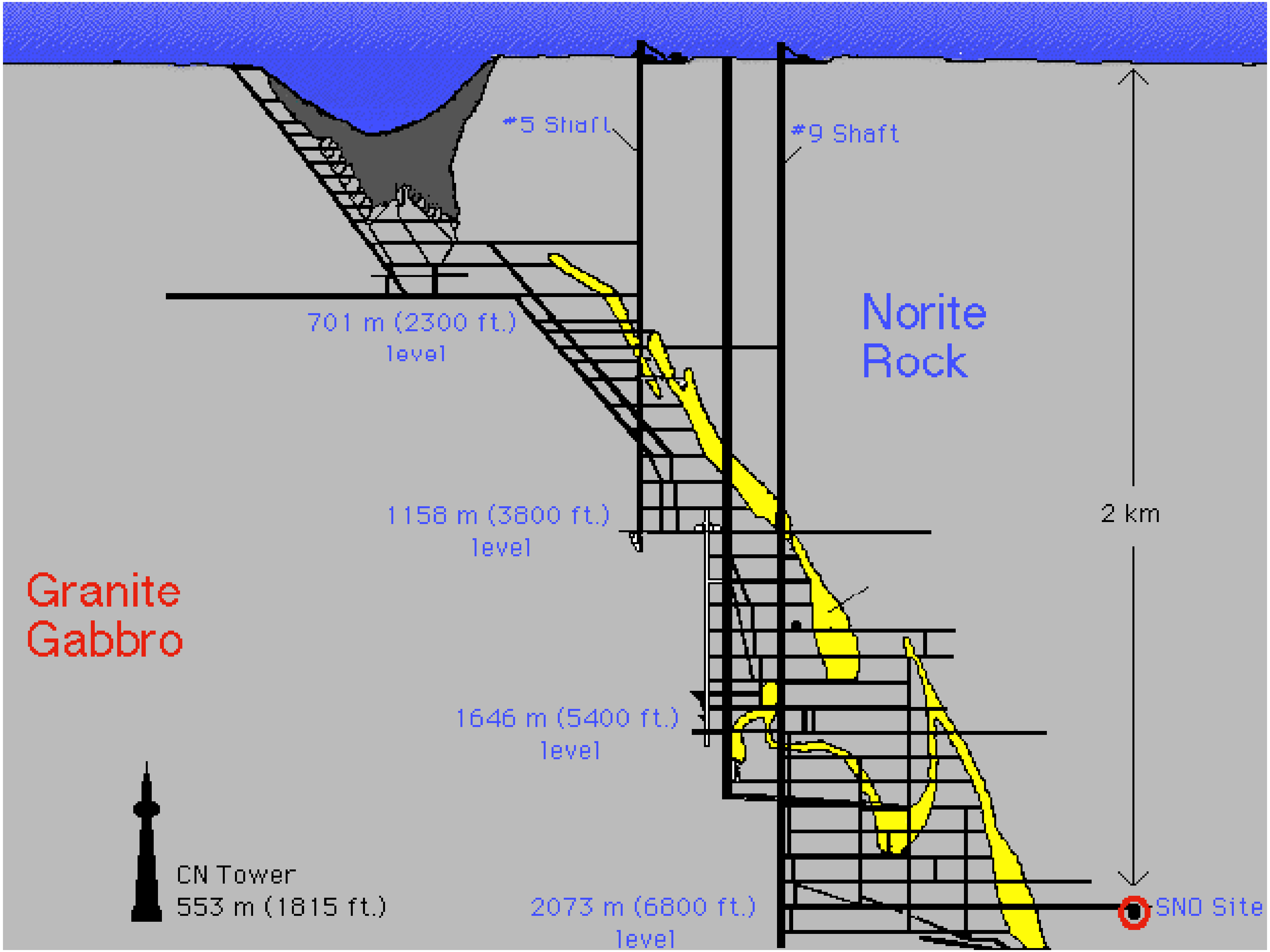
S. Biller, Oxford University

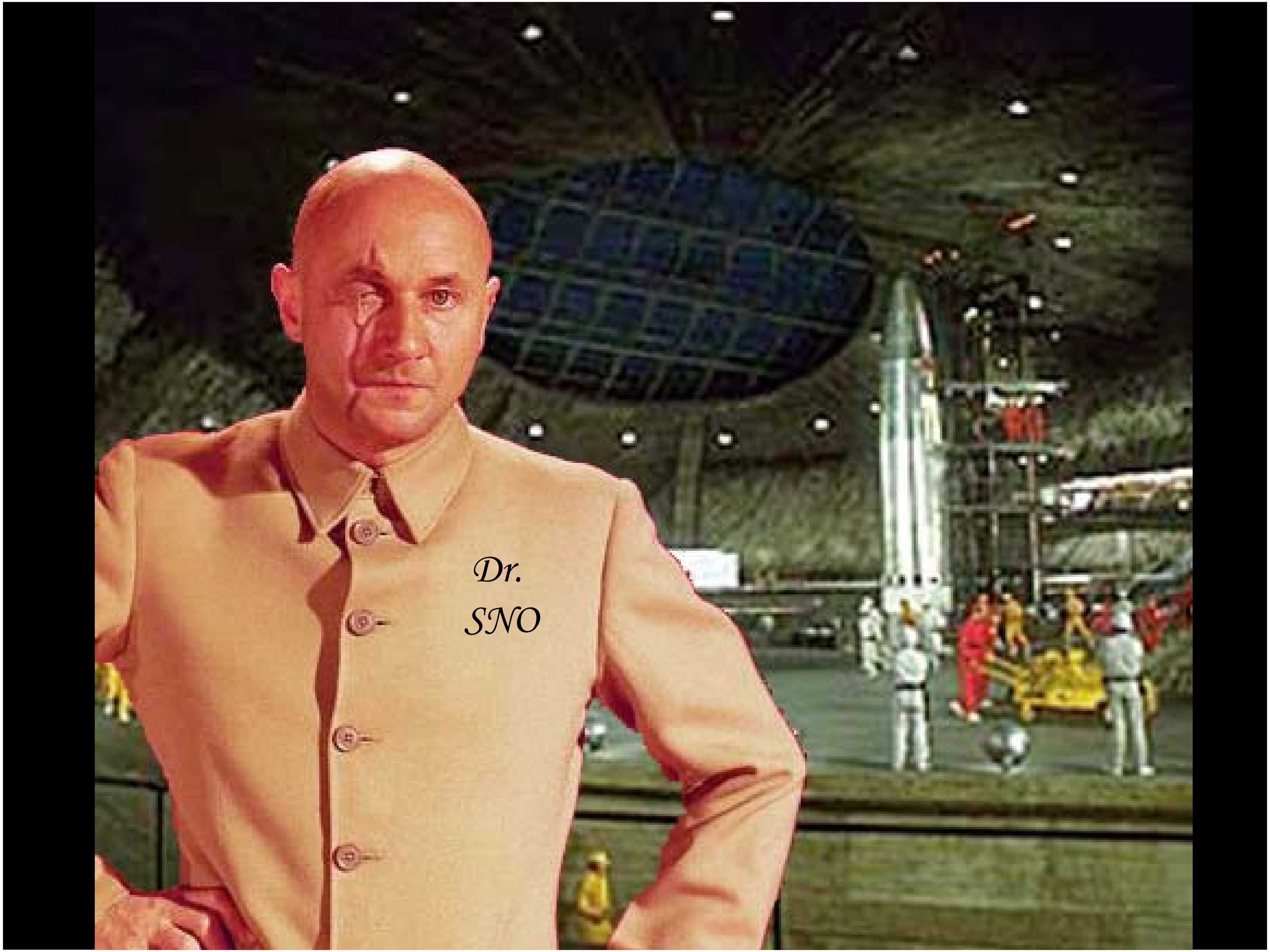

North
Sault Ste. Marie
Sudbury
Thunder Bay
East
Kingston
Ottawa
SW
Hamilton
Kitchener
London
Windsor
Mississauga
Newmarket
Peterborough
South
Toronto (5)

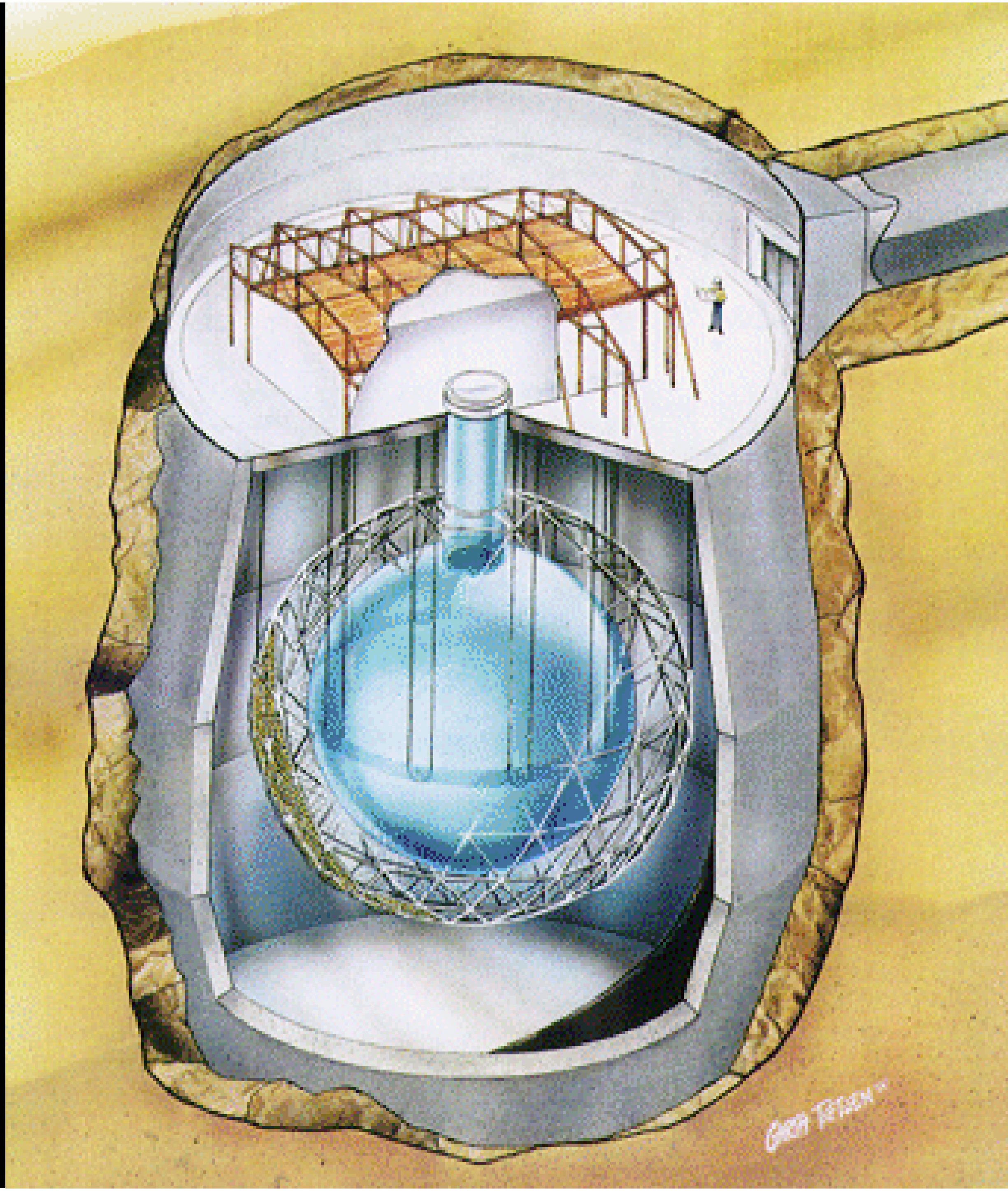

TIMBITS
20
Snack Pack
TIMBITS

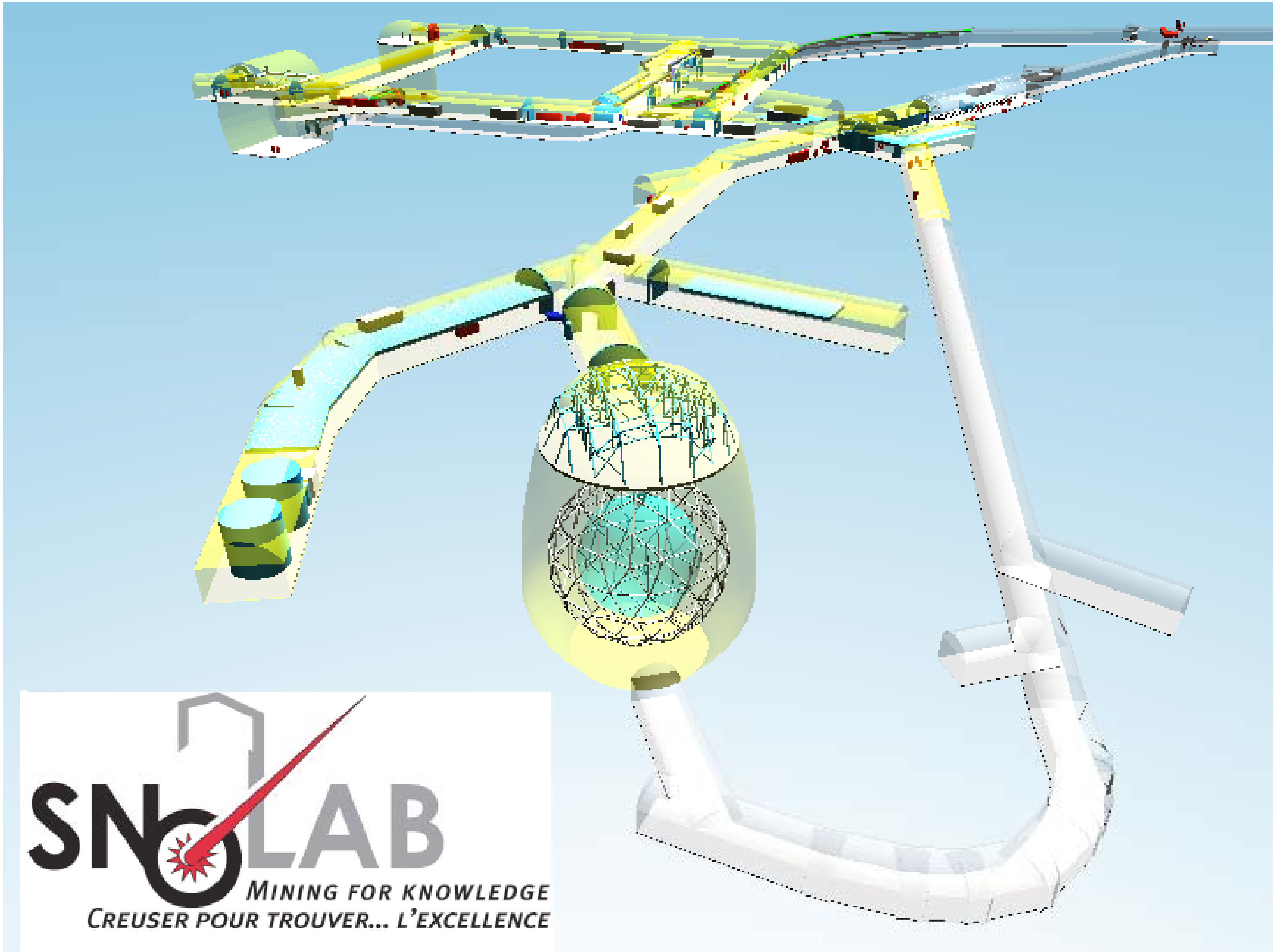

Tim Hortons
Tim Hortons
Coffee

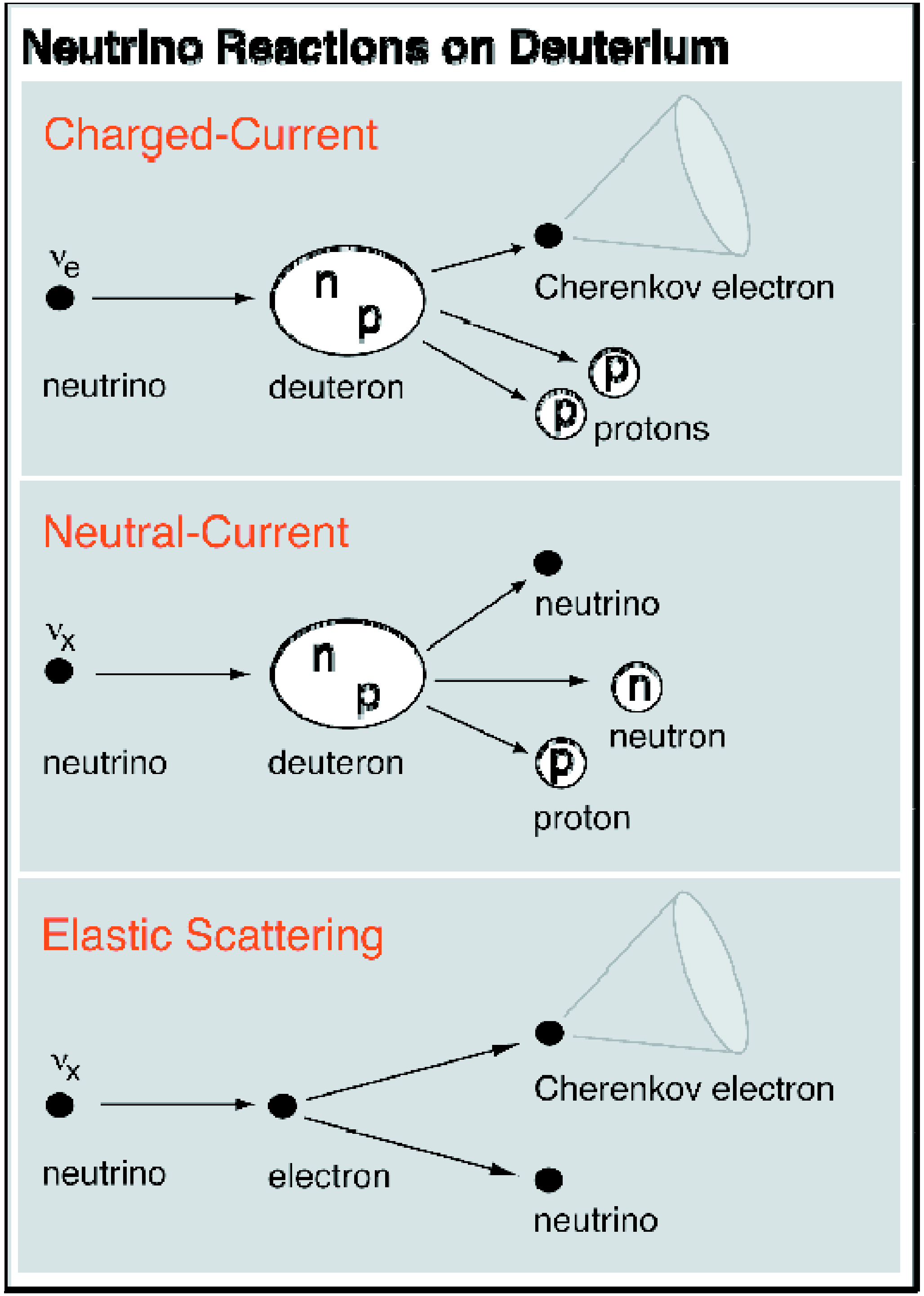

MEATBIRD
BEACH
TOWN OF WALDEN


#5 Shaft
#9 Shaft
Norite Rock
701 m (2300 ft.) level
1158 m (3800 ft.) level
2 km
Granite Gabbro
1646 m (5400 ft.) level
CN Tower 553 m (1815 ft.)
2073 m (6800 ft.) level
SNO Site


Dr.
SNO

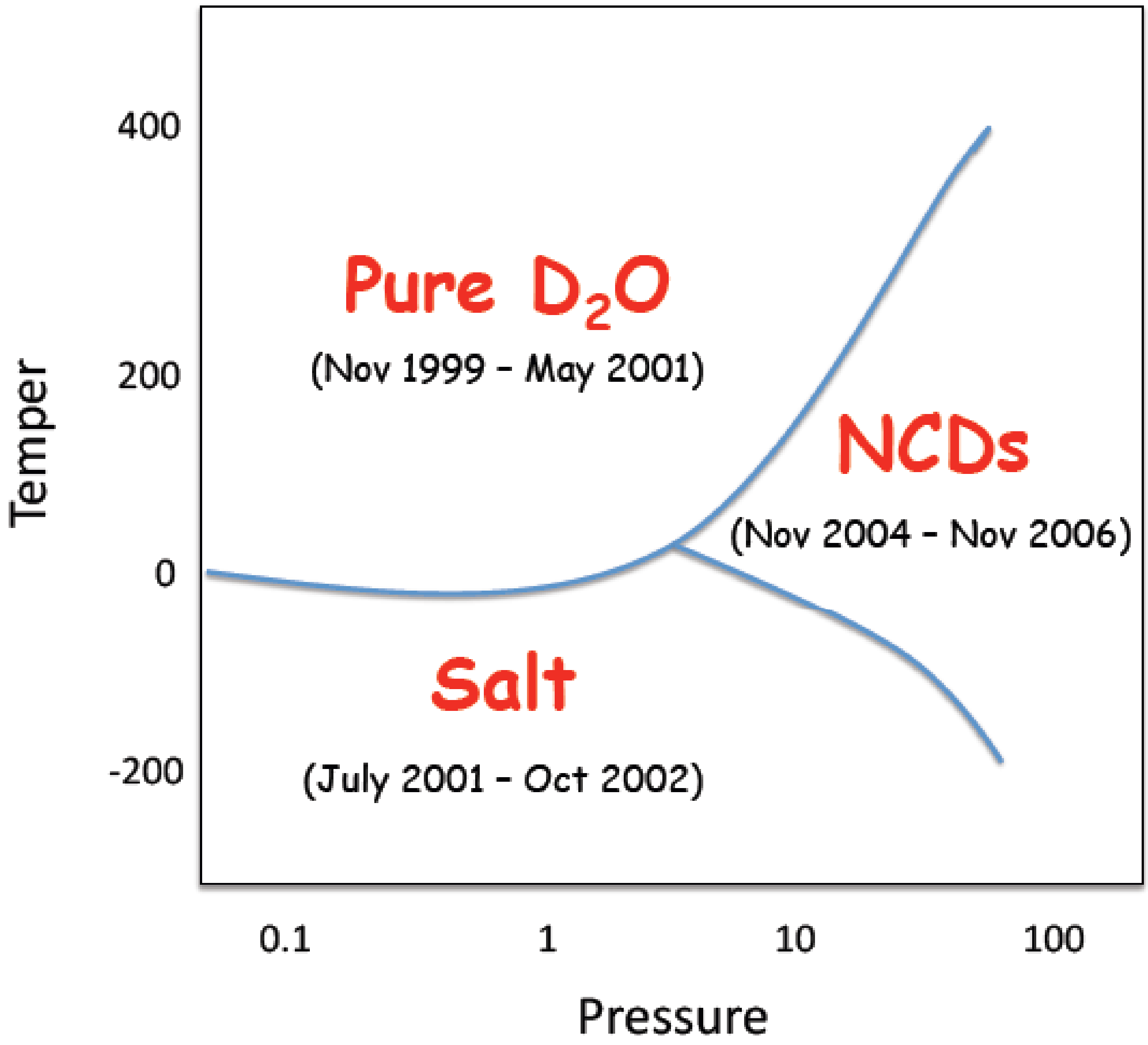



SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE



Neutrino Reactions on Deuterium
Charged-Current
ν_e
neutrino
n p
deuteron
Cherenkov electron
p
p
protons
Neutral-Current
ν_x
neutrino
n p
deuteron
neutrino
n
neutron
p
proton
Elastic Scattering
ν_x
neutrino
electron
Cherenkov electron
neutrino

Phases of SNO:



BBC NEWS

You are in: Sci/Tech
Monday, 18 June, 2001, 16:24 GMT 17:24 UK

Ghostly particle mystery 'solved'

The underground neutrino detector viewed from above

By BBC News Online science editor Dr David Whitehouse

An international team of physicists claims to have solved a 30-year-old mystery: the puzzle of the missing solar neutrinos.

In the past, scientists detected only about a third of the

'High confidence'

The research was carried out at the Sudbury Neutrino Observatory (SNO), Ontario, in collaboration with Oxford University, UK.

"We now have high confidence that the discrepancy is not caused by problems with the models of the Sun but by changes in the neutrinos themselves as they travel from the core of the Sun to the Earth," says Dr Art McDonald, SNO project director and professor of physics at Queen's University in Kingston, Ontario, Canada.

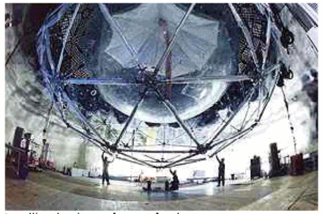
Light detectors around the water tank detect the neutrinos

"It's taken longer than we thought, but it's all been well worthwhile," says Dr Steve Biller, of Oxford University. "We've pushed the limits of engineering, chemistry... and patience, in order to push the limits of physics."

Fundamental particles

Neutrinos are fundamental part... are often called 'ghostly' becau... weakly with other forms of mat...

They come in three types: the e...



Installing the giant underground tank

But despite its large size the SNO only detects about 10 neutrinos a day.

'Mind-boggling'

"The engineering requirements alone are mind-boggling. We were breaking new ground in every sense and there were times that we weren't sur... we were going to make it," says Professor Nick Jelley of Oxford University.

"It is incredibly exciting, after all the years spent by s... many people building SNO, to see such intriguing results coming out of our first data analysis - with so...

The New York Times ON THE WEB

June 19, 2001

Sun's Missing Neutrinos: Hidden in Plain Sight

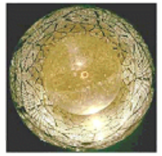
By KENNETH CHANG

After three decades of searching, physicists have tracked down subatomic particles that have eluded them for 30 years. The particles, it turns out, were right there all the while but had hidden themselves as if by magic.

"We've solved a 30-year-old puzzle of the missing neutrinos of the Sun," said Dr. Arthur B. McDonald, director of the Sudbury Neutrino Observatory, near Sudbury, Ontario. In doing so, though, the researchers have answered questions about neutrino behavior and the fate of the universe.

Neutrinos are ghostly particles, one of the fundamental building blocks of the universe, like quarks, electrons and photons. Billions of them, produced by fusion reactions within the Sun, fly ...ry second. ...electric ...unnoticed. In ...noticed. In ...detectable. ...an ...e for ...n, N.J., ...utrinos ...gh one ...e about 30 ...he 1970's ...more than ...s were ...edictions, ...lined

A drawing of the neutrino detector, built 1-mile underground and immersed in water within a cavity 110 feet deep.



Lawrence Berkeley National Laboratory
The bottom of the neutrino detector.

...her different result." The data ran contrary to his hopes of finding a ...w kind of neutrino.

...ill, he said, the Sudbury results look "quite solid."

Neutrinos come in three types (physicists call them flavors): electron neutrinos, muon neutrinos and tau neutrinos, named according to the subatomic particles they usually associate with. Muon and tau particles are heavier particles that otherwise act like electrons. The neutrinos produced by the Sun are all electron neutrinos.

Spotting the rare occasions when a neutrino collides with another particle requires large quantities of material for the neutrinos collide with.

The detector in the Sudbury Neutrino Observatory consists of a 40-foot-wide acrylic sphere containing 1,000 tons of heavy water, in which the two hydrogen atoms of the water molecules have been replaced with deuterium atoms, a heavier version of hydrogen. The sphere is submerged within a 10-story cavity that was carved out of a nickel mine 1 1/4 miles underground and filled with 40,000 tons of ordinary water.

Occasionally, an electron neutrino will slam into one of the deuterium atoms in the heavy water, splitting it into a proton and a neutron. Detectors around the sphere of heavy water are able to spot the debris. The other two types of neutrinos cannot break up deuterium. The scientists have seen 1,169 such collisions since the experiment began in 1999.

The researchers compared their results with earlier neutrino counts from the Super-Kamiokande neutrino experiment in Japan, which primarily detects collisions between electron neutrinos and electrons. But muon and tau neutrinos can also occasionally bounce off electrons.

If all the neutrinos reaching Earth from the Sun were of the electron variety, then the neutrino rates measured by Super-Kamiokande and Sudbury should match up. But Super- Kamiokande detected more. Since the Sun produces only electron neutrinos - the production of muon and tau neutrinos require higher-energy events, like matter falling into black holes or an exploding star - that means some of them must change into muon or tau neutrinos.

"It's the first direct evidence for the changing of solar neutrinos from electron type to another type," Dr. Klein said. Most physicists had considered neutrino morphing to be the most likely explanation for the missing neutrinos.

Dr. Caldwell's theory was that the electron neutrinos were changing into "sterile" neutrinos that did not interact with ordinary matter. "It looks like they've done a very thorough job," he said. "It then is a real question if there is any room for a sterile neutrino. I don't see much hope for it right now."

According to the equations of particle physics, for this transformation of flavors to occur, at least one of the neutrino types must possess a smidgeon of mass. Coupled with earlier experimental results, the researchers conclude that each of the three neutrino flavors weigh, at ...

LA NACION

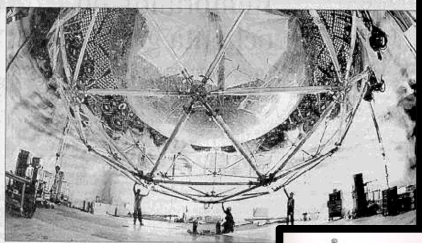
Buenos Aires, miércoles 20 de junio de 2001

En un observatorio canadiense

Detectan una partícula fantasmal

Permite explicar la transformación de los neutrinos, ladrillos elementales del univers...

- El hallazgo se produjo luego de tres décadas de investigaciones
- Los expertos midieron el comportamiento de estos componentes en su viaje desde el Sol hacia la Tierra



La esfera del detector de neutrinos con el que se realizaron las medicio...

Un dibujo del detector de neutrinos

Un misterio resuelto

CNN

Physicists solve weighty neutrino mystery

June 19, 2001 Posted: 11:33 AM EDT (1533 GMT)

(AP) -- Solving a 30-year-old scientific mystery, physicists have found the most convincing evidence yet that neutrinos -- elusive subatomic particles that were thought to have no mass whatsoever -- have a tiny wisp of heft after all.

...tists ...eories ...n this ... a ...keley ... the ... are

Express & Star

WOLVERHAMPTON The Millennium City

Telephone 01902 31 31 31 — Tuesday, June 19, 2001 — www.westmidlands.com

Solved: riddle of missing neutrino

A 30-year-old mystery surrounding a tiny elementary particle has been solved using a £34 million monster machine buried two kilometres underground.

British physicists were among those celebrating after unravelling the riddle of the missing neutrinos. Neutrinos are ghostly elementary particles of matter with no electric charge and very little mass. Scientists have calculated that huge numbers of solar electron-neutrinos should be showering the Earth - but only a fraction of the expected amount are ever detected. So how are the missing neutrinos explained?

It took a gigantic engineering project, massive investment, and an international team of 100 scientists to find the answer.

The scientists said they had discovered that the "missing" electron-neutrinos were there all along, but in disguise. On their way to Earth, they changed into other kinds of neutrino called muon and tau neutrinos.

This was revealed by the Sudbury Neutrino Observatory 2,000 metres below ground near Sudbury, Ontario, Canada.

YOMIURI ON-LINE

YomyClub ヨミークラブ YOMIURI ON-LINE — オレにピッタリ来るサイトないかなぁ…

14:37 / 2001.6.19(火) 更新 | ENGLISH | 購読はこちら | イベント | インパクアメリカ横断ウオーク

ヨミークラブ | 新着情報 | @マネー | 教育メール | 大手小町 | @CARS | 芸能 | SPORTS | W杯2002

社会

「太陽ニュートリノに問題」解決へ進展

太陽から地球に到達する素粒子「ニュートリノ」が、理論予測の半分以下しか検出されない「太陽ニュートリノ問題」の解決を目指していたサドベリー・ニュートリノ観測所（カナダ・オンタリオ州）は、１８日（日本時間１９日）、「ニュートリノに質量があることが原因」と発表した。東大宇宙線研究所グループが測定器「スーパーカミオカンデ」で得た、昨年夏の発表内容を支持する結果。太陽ニュートリノは、太陽の中心部で核融合反応が起きるときに発生しており、太陽構造の理論の不備が「太陽ニュートリノ問題」の原因である可能性も残されていたが、今回の発表で否定された。

同観測所は、地下約２キロにある球形水槽に、約１０００トンの「重水」と呼ばれる特殊な水をため、そこで起きる反応を使って太陽からのニュートリノを１９９９年春から観測してきた。ニュートリノが持つエネルギーなどを測定し、「スーパーカミオカンデ」の結果とも比較した結果、やはりニュートリノ質量が太陽ニュートリノ問題の原因であることを突き止めた。

(6月19日14:37)

▶社会面一覧

How Do You Do Better?

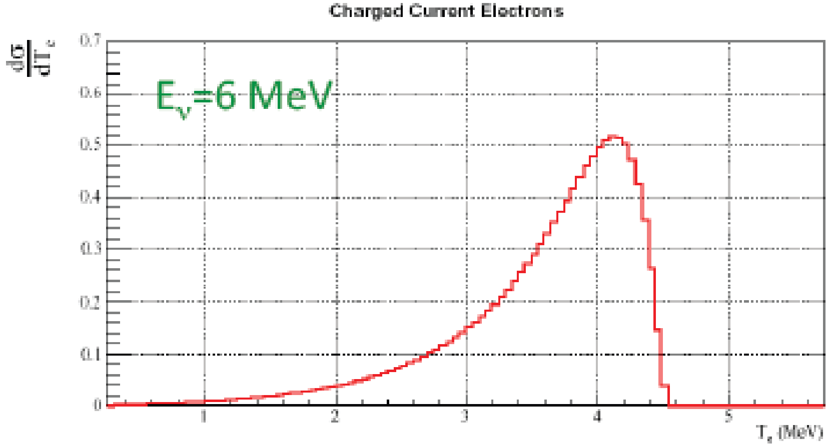
➡ Do It Again!

D_2O and Salt phases had the lowest analysis energy thresholds, best spectral information and simplest detector configurations (good place to start):

- Do a more careful combined signal extraction from these phases
- Lower analysis energy threshold as much as possible
- Take more time to understand and reduce systematic uncertainties
- Put more effort into modeling low energy backgrounds
- Take advantage of recent improvements in algorithms and simulations
- Pay closer attention to propagation of correlated uncertainties

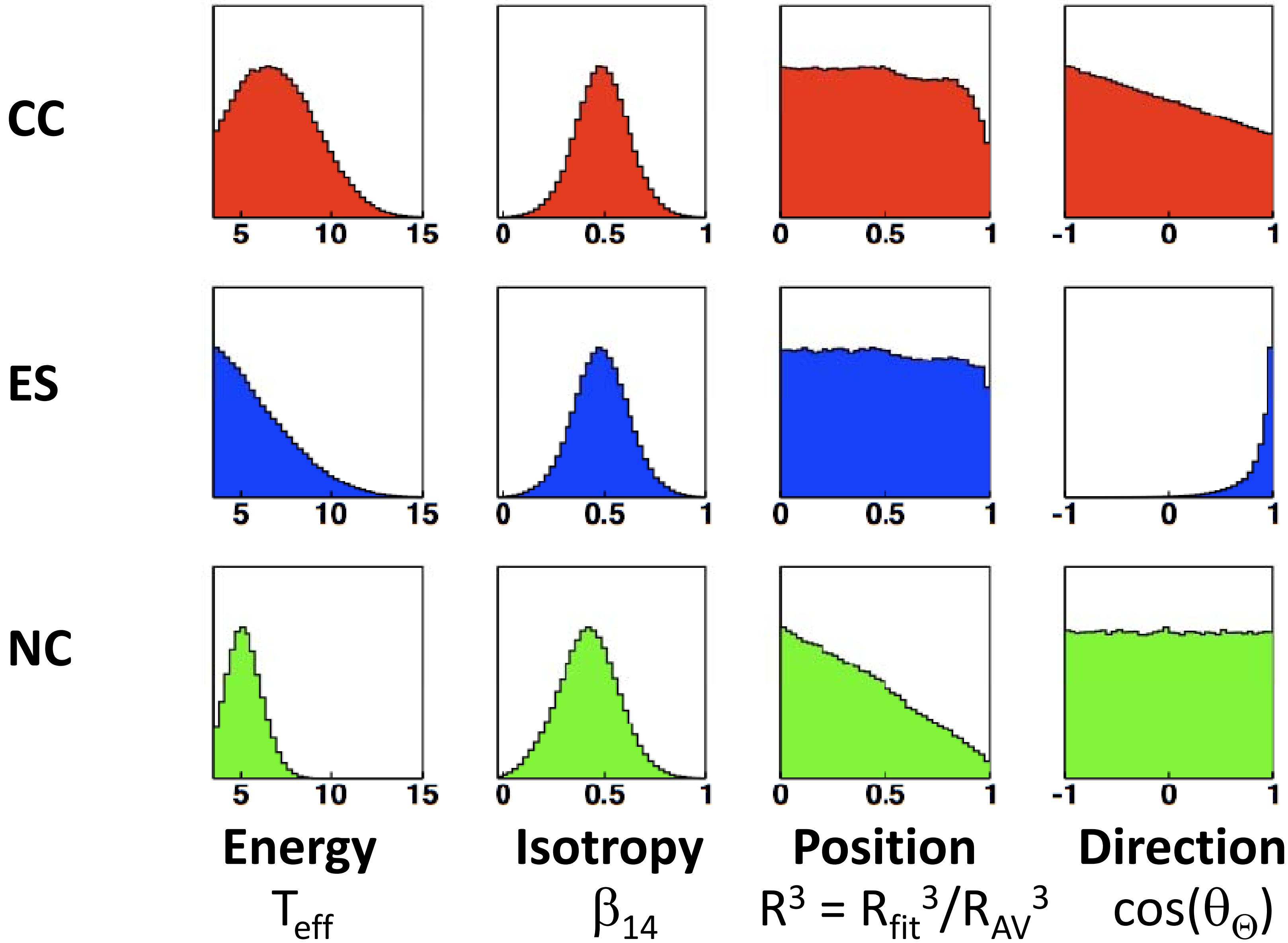
Advantages of Low Threshold Analysis

- ν_e Statistics

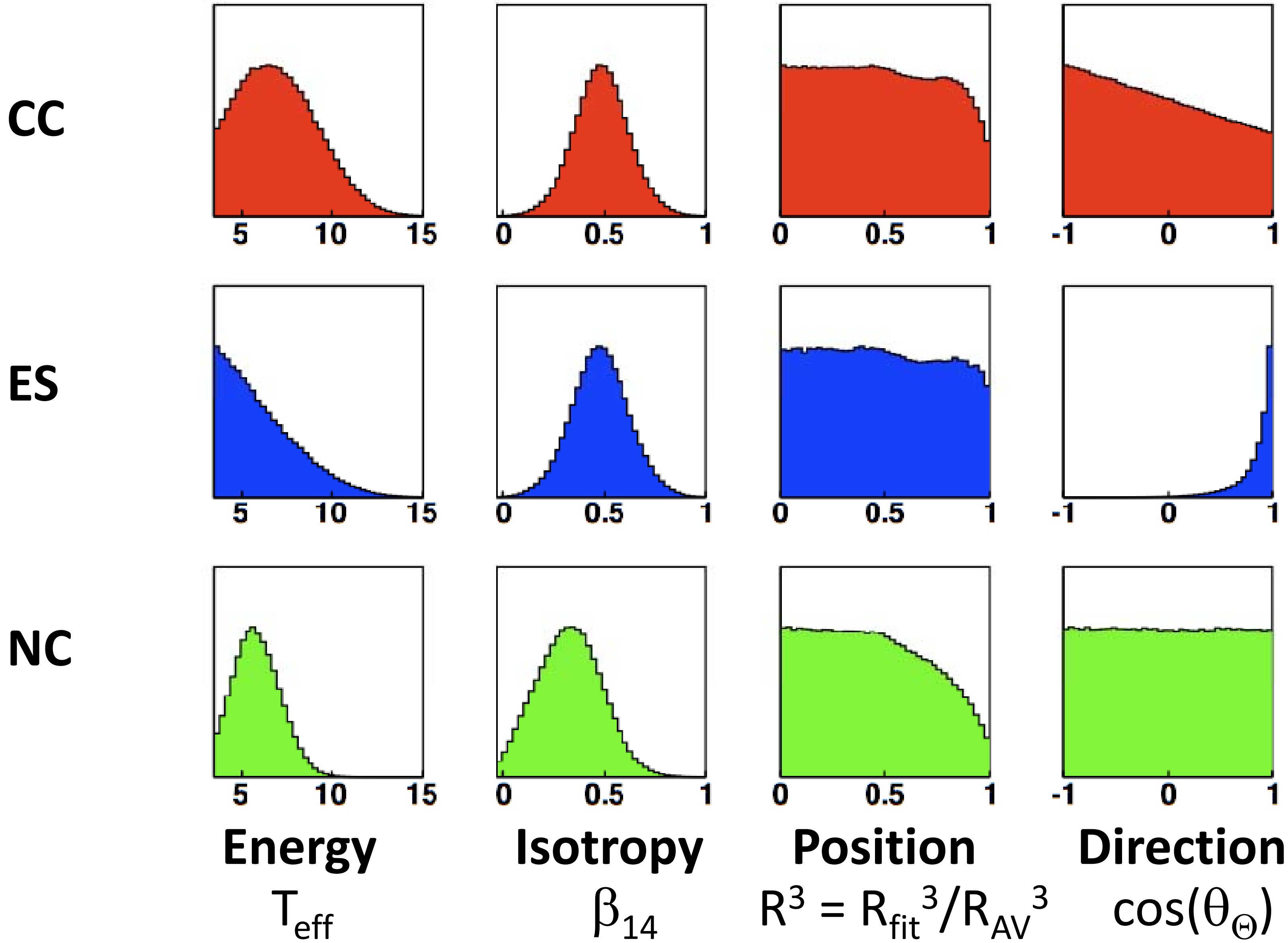


Getting There:

Event Separation: D_2O



Event Separation: Salt

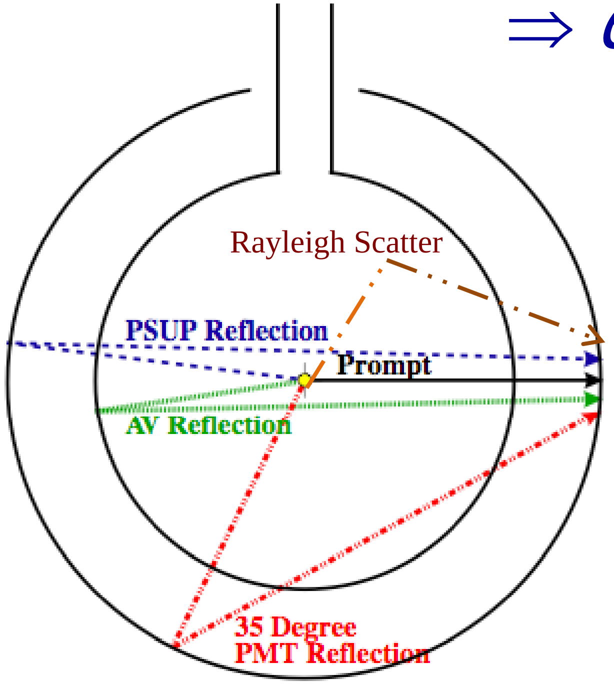


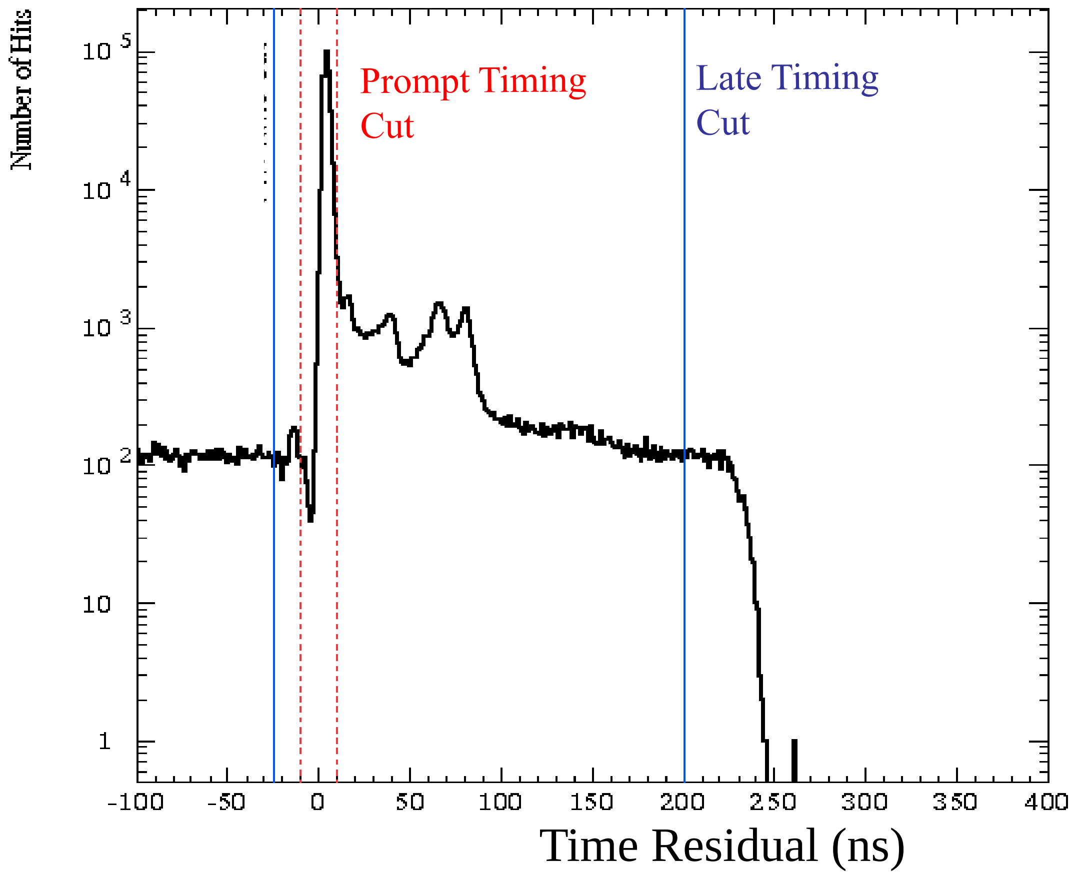
Improved Energy Estimator

Uses all hits: 12% more

⇒ 6% improvement in resolution

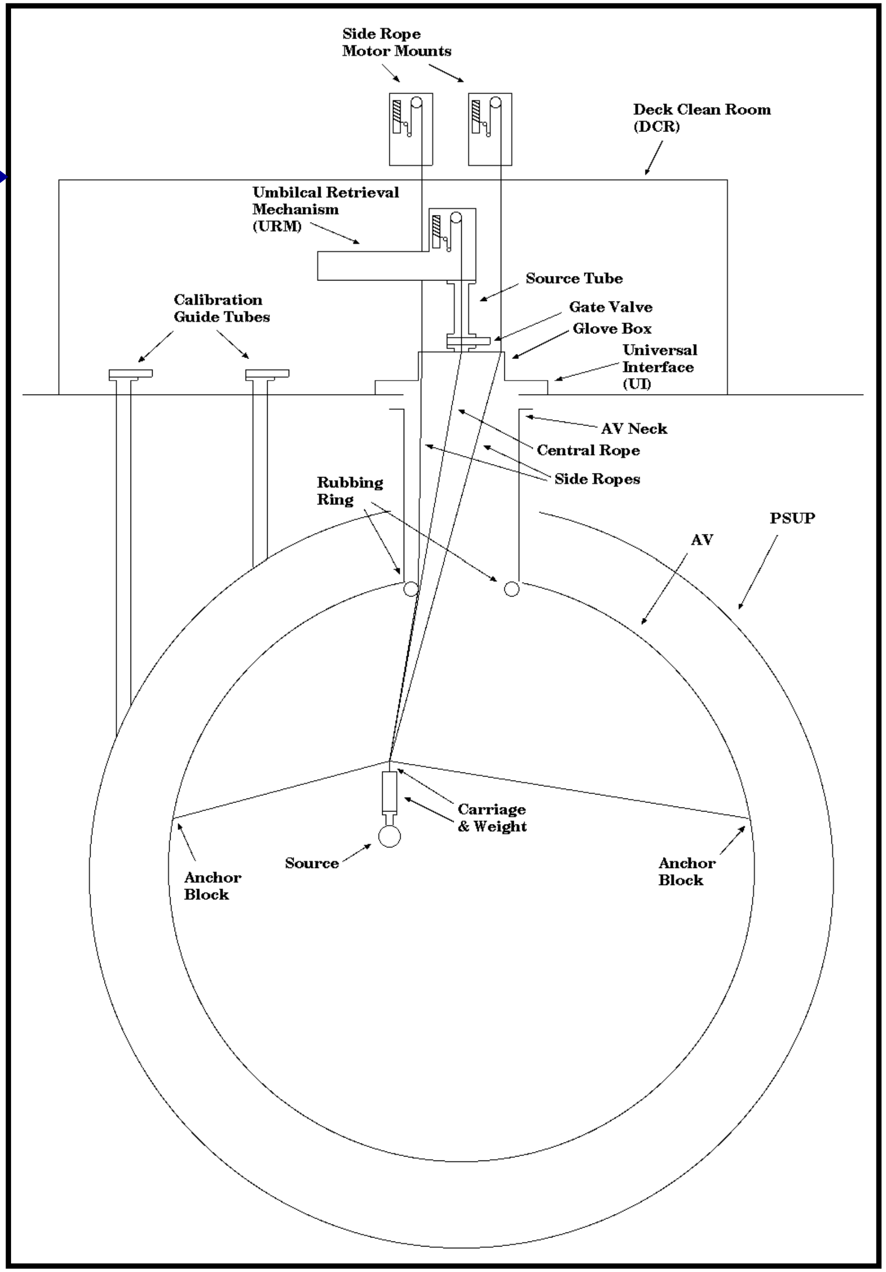
⇒ 60% reduction of internal backgrounds





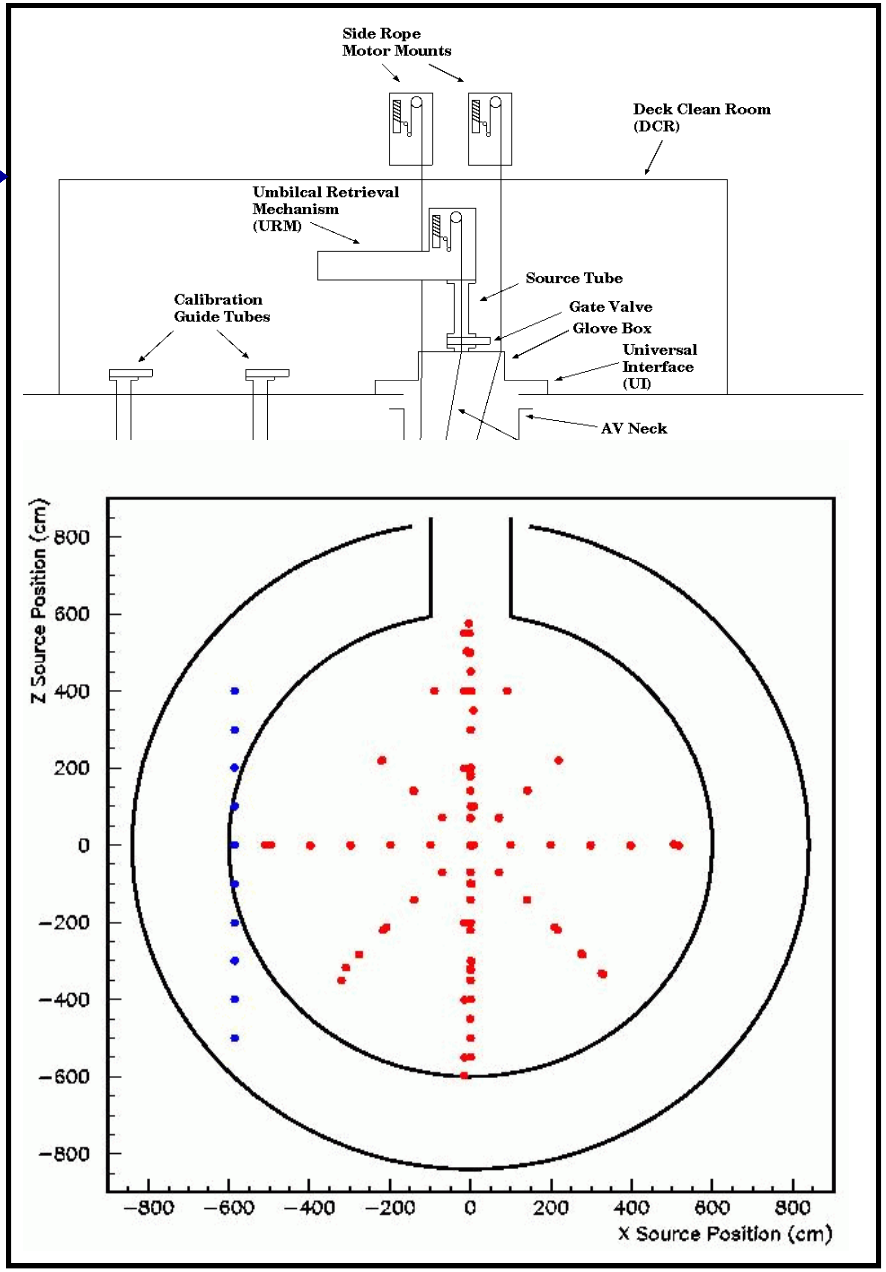
5) Reduce Systematic Uncertainties

Manipulator system allows flexible source placement



5) Reduce Systematic Uncertainties

Manipulator system allows flexible source placement

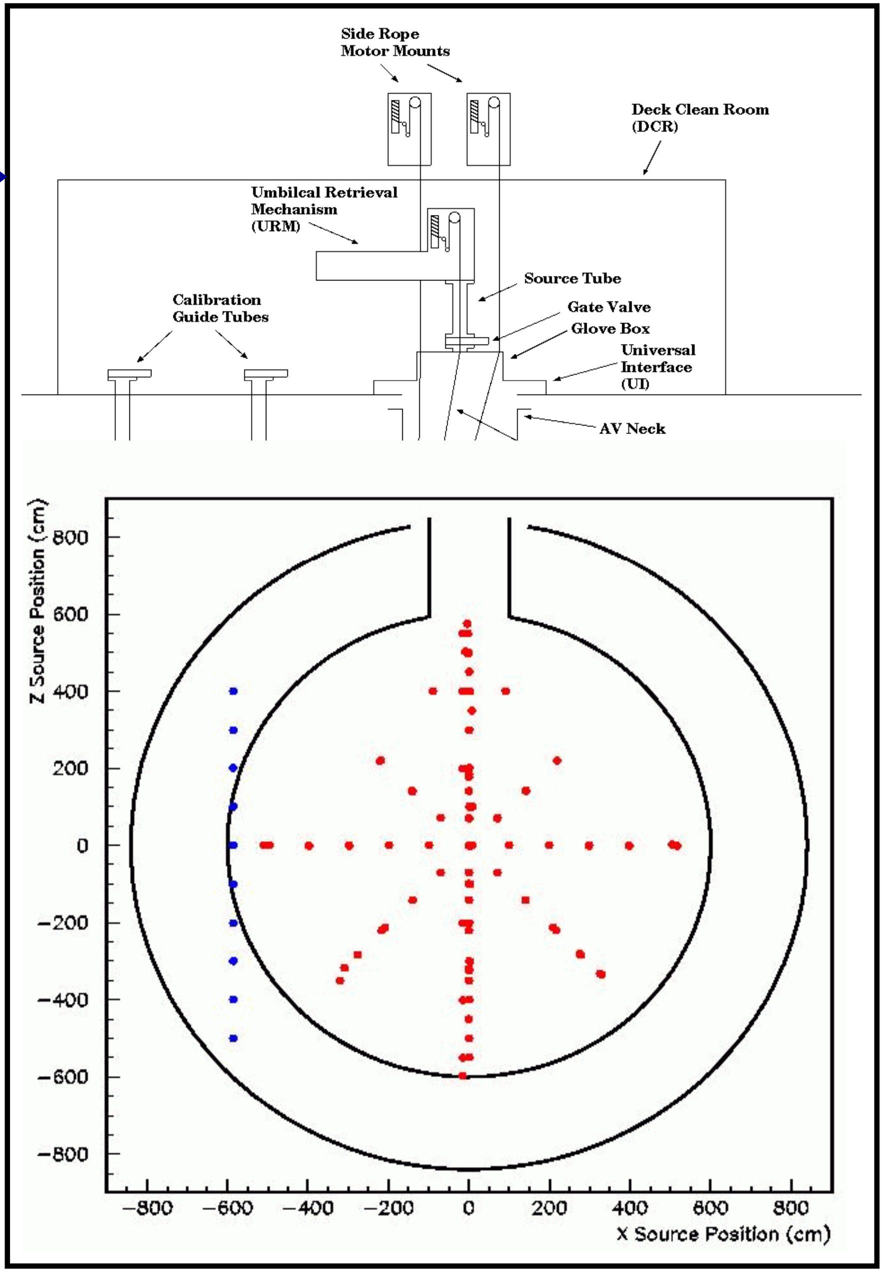


5) Reduce Systematic Uncertainties

Manipulator system allows flexible source placement

Better use of diverse calibration sources

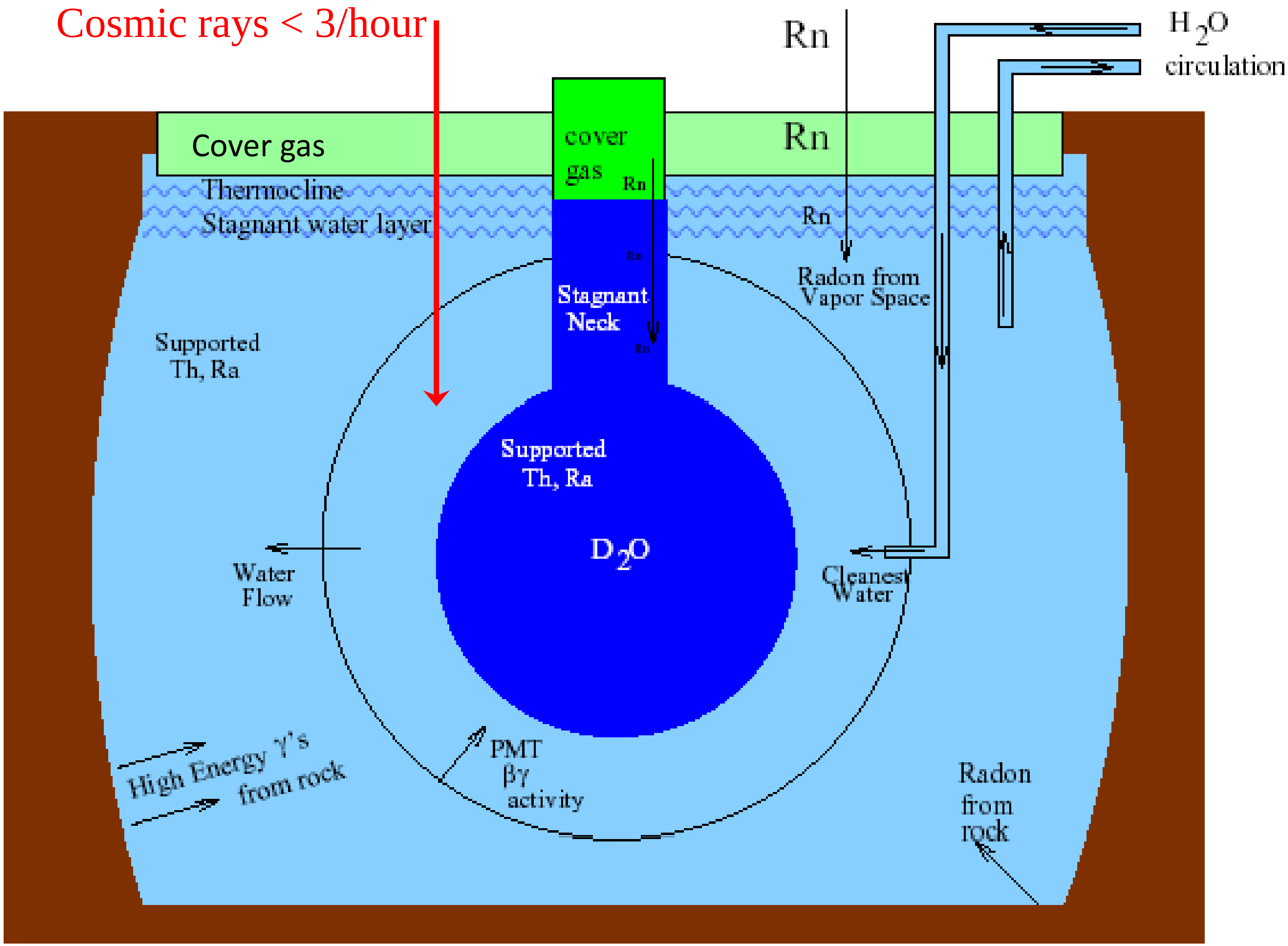
^{16}N → 6.13MeV γs
pT → 19.8MeV γs
^{8}Li → βs <15MeV
Cf, AmBe ns, → n captures
Muon-spallation neutrons
Encapsulated U, Th; Rn spikes
Diffusing laser source

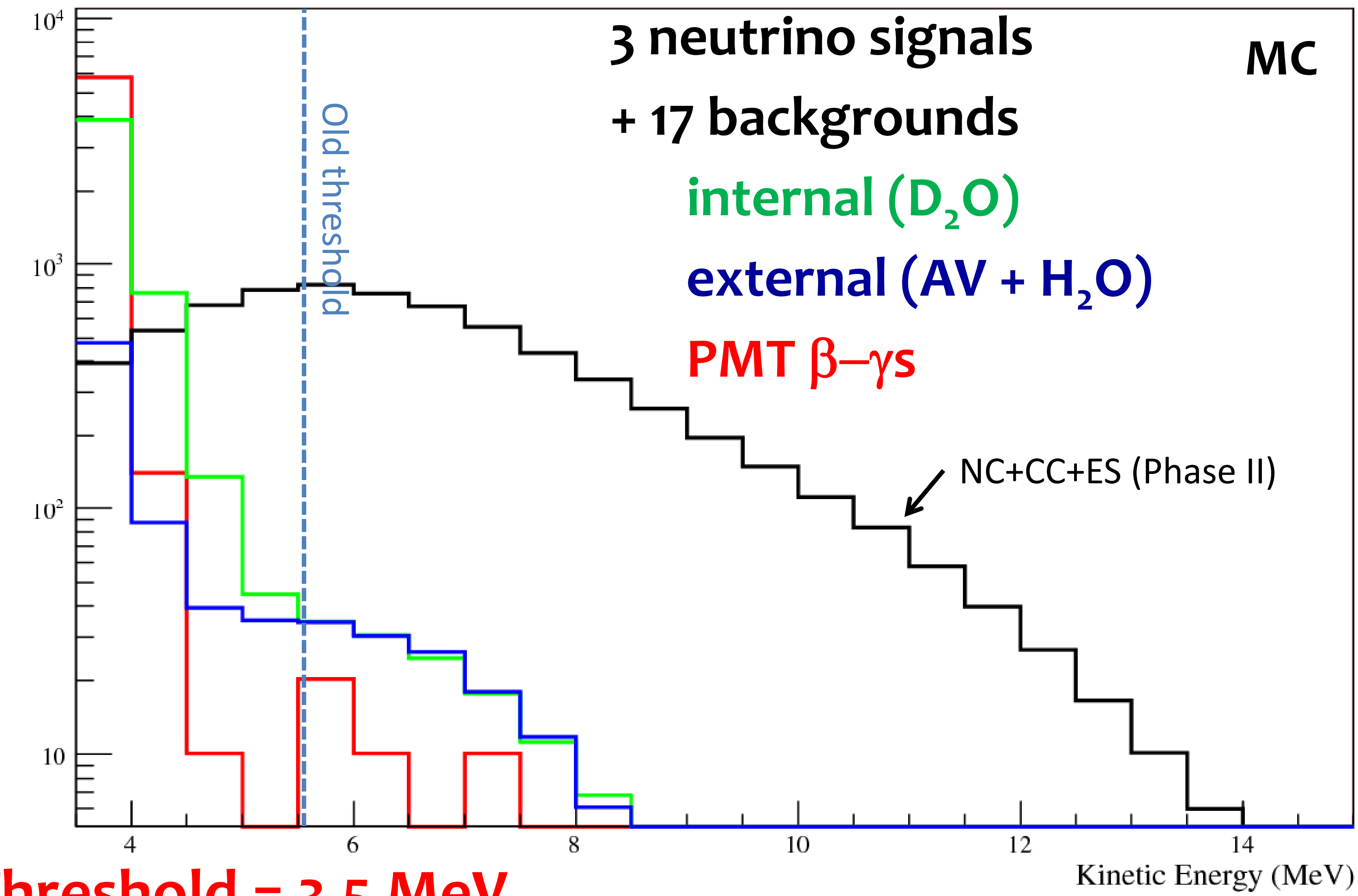


5) Reduce Systematic Uncertainties

	Old (D2O,salt)	**New**
Energy	Scale: 1.2%	**< 0.5%**
	Resn: 4.5, 3.4%	**< 2%**
β_{14}	Electron: 0.85%	**0.24 %**
R^3	Fid Vol: 3%	**< 1%**
$\cos\theta_{sun}$	Ang Resn: 16%	**11%**
"Contamination"		
Normalization (neutrons, others)	Ncap: >2%	**1.2%**
PMT β-γ distributions		

3) Radioactive Backgrounds





Threshold = 3.5 MeV

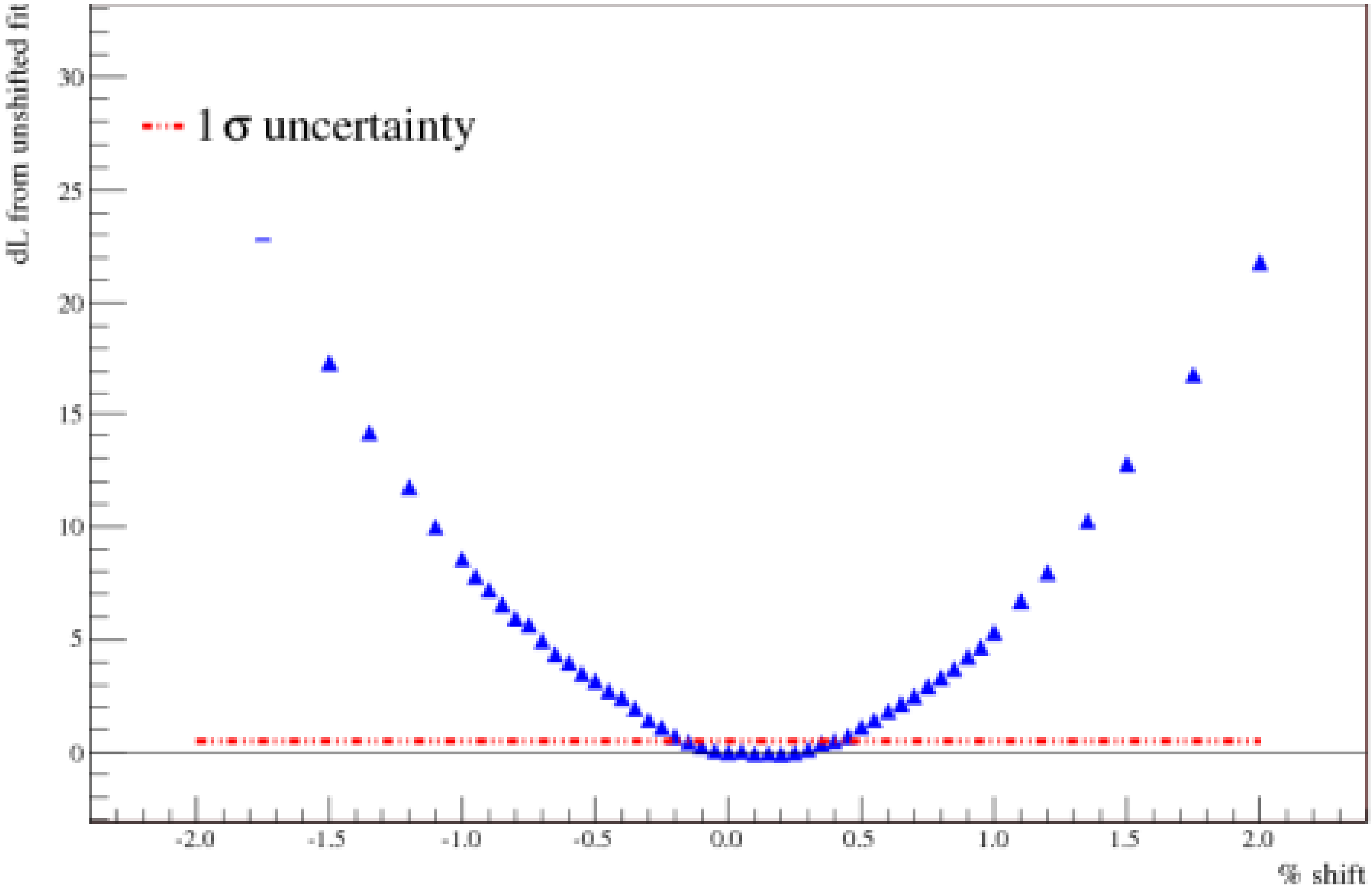
Ideal (and correct!) Way To Propagate Uncertainties:

"Float" uncertainties as variable parameters in Likelihood fit, appropriately constrained by any independently determined bounds.

In 4 dimensions with >50 parameters and limited MC statistics for PDFs ?!

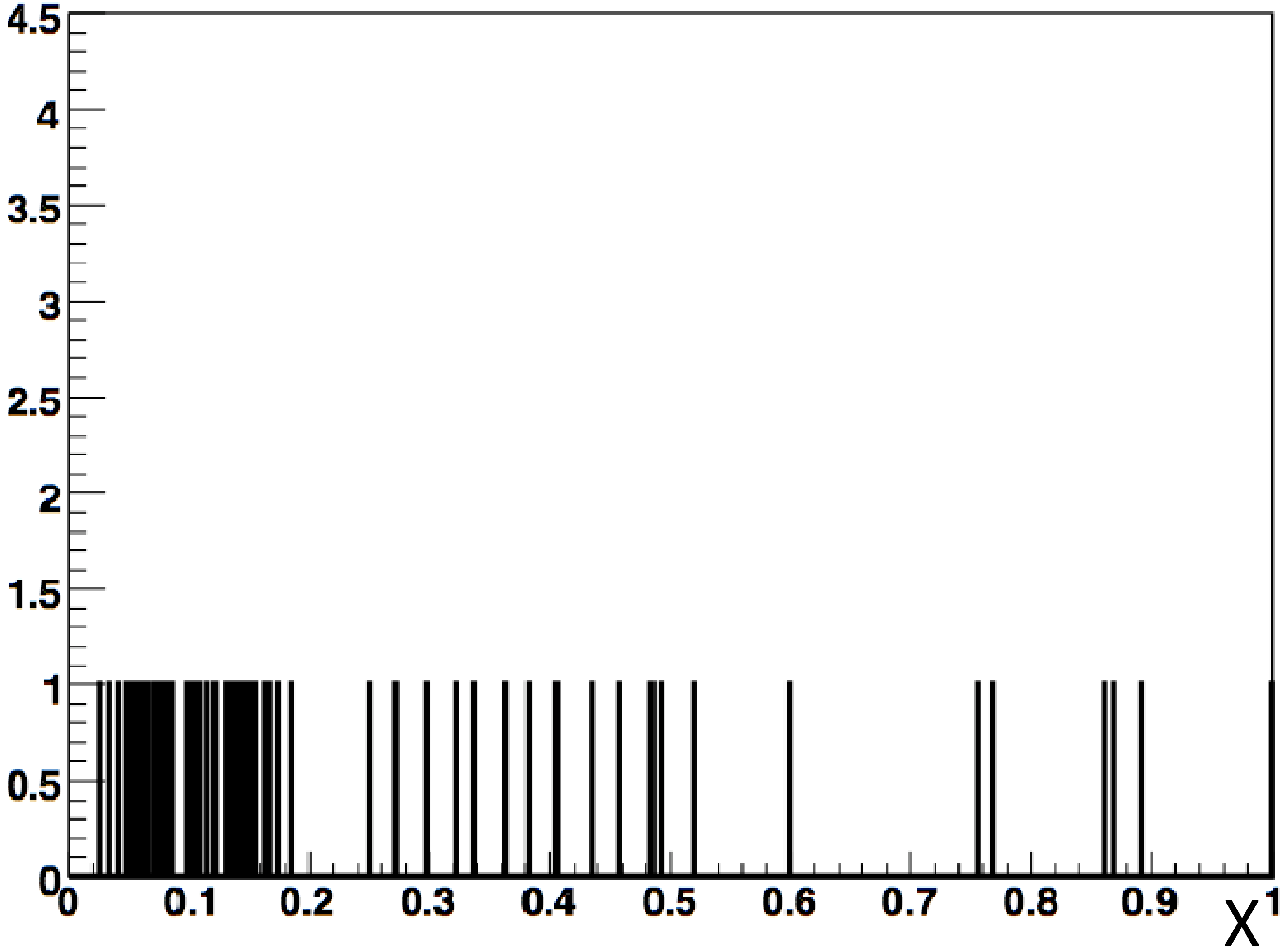
Two Approaches:

1) Float Dominant Systematics via a "Brute Force" Iterative Scan of the Likelihood Space (shift & smear the rest)

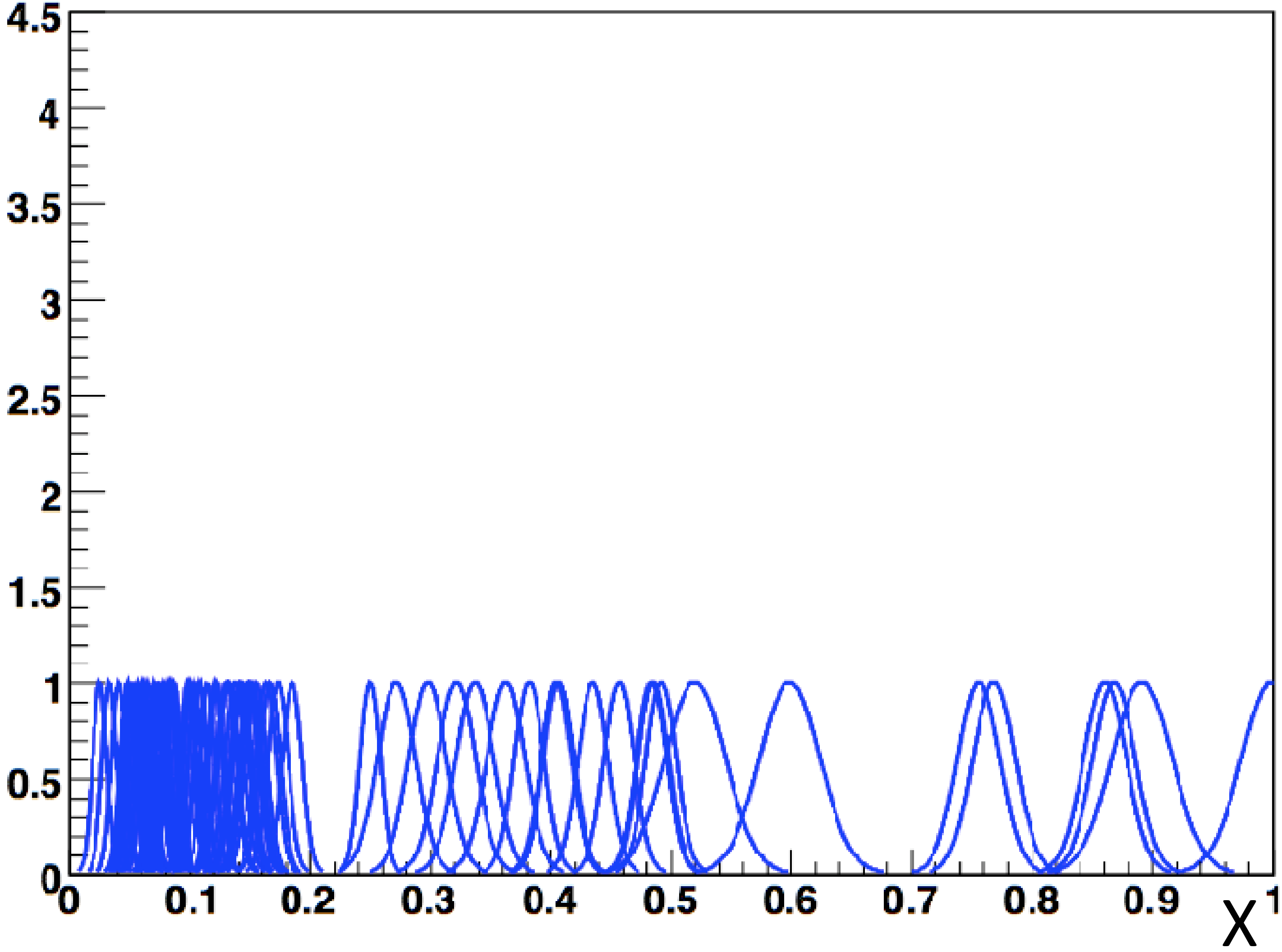


2) ~~Colonel~~ Kernel Estimated PDFs

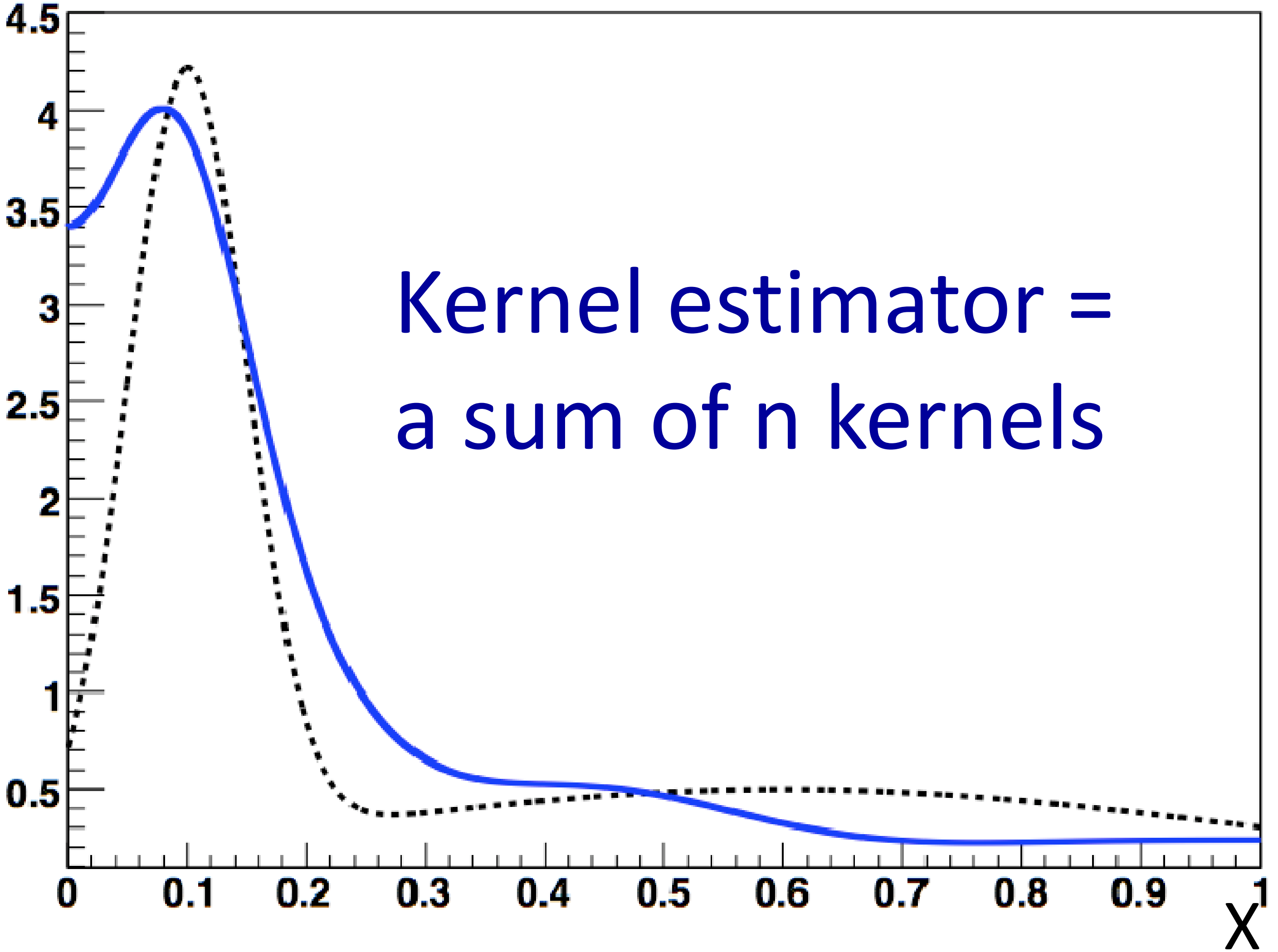
1-D toy model



1-D toy model

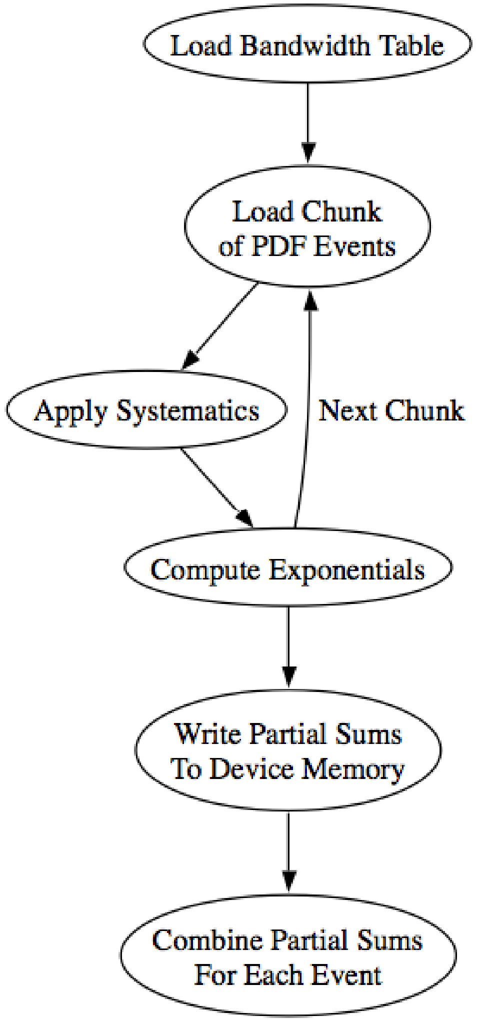


1-D toy model



4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
X
Kernel estimator =
a sum of n kernels

Approach is very (prohibitively) CPU intensive
… so don't use CPUs!!



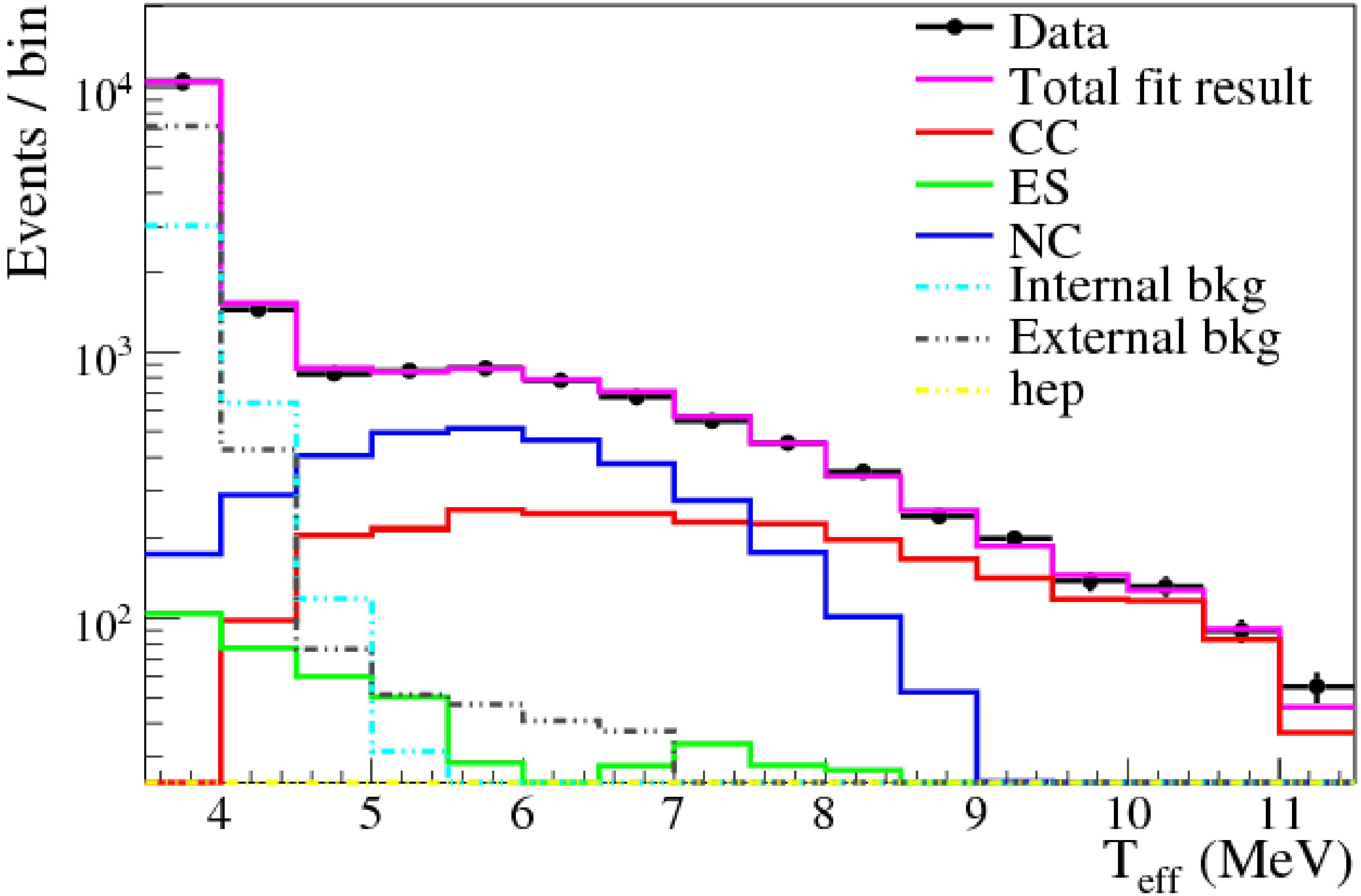
Blindness Strategy:

1) Test both methods on many, independent MC sets
2) Test both methods on 1/3 of data (statistical blindness)
3) Freeze and apply to full data set.

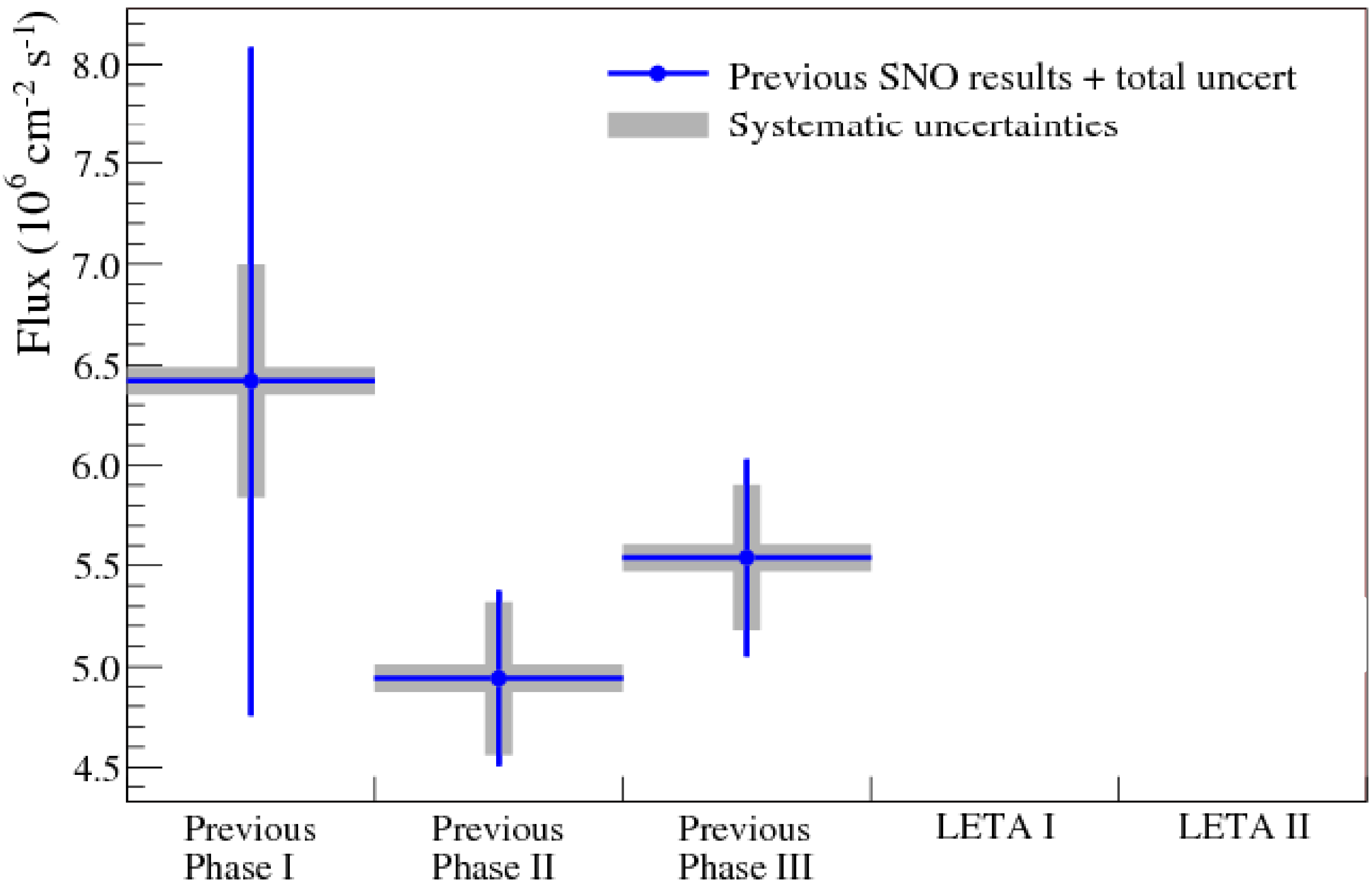
Results!

$\chi^2 = 13.6 / 16$

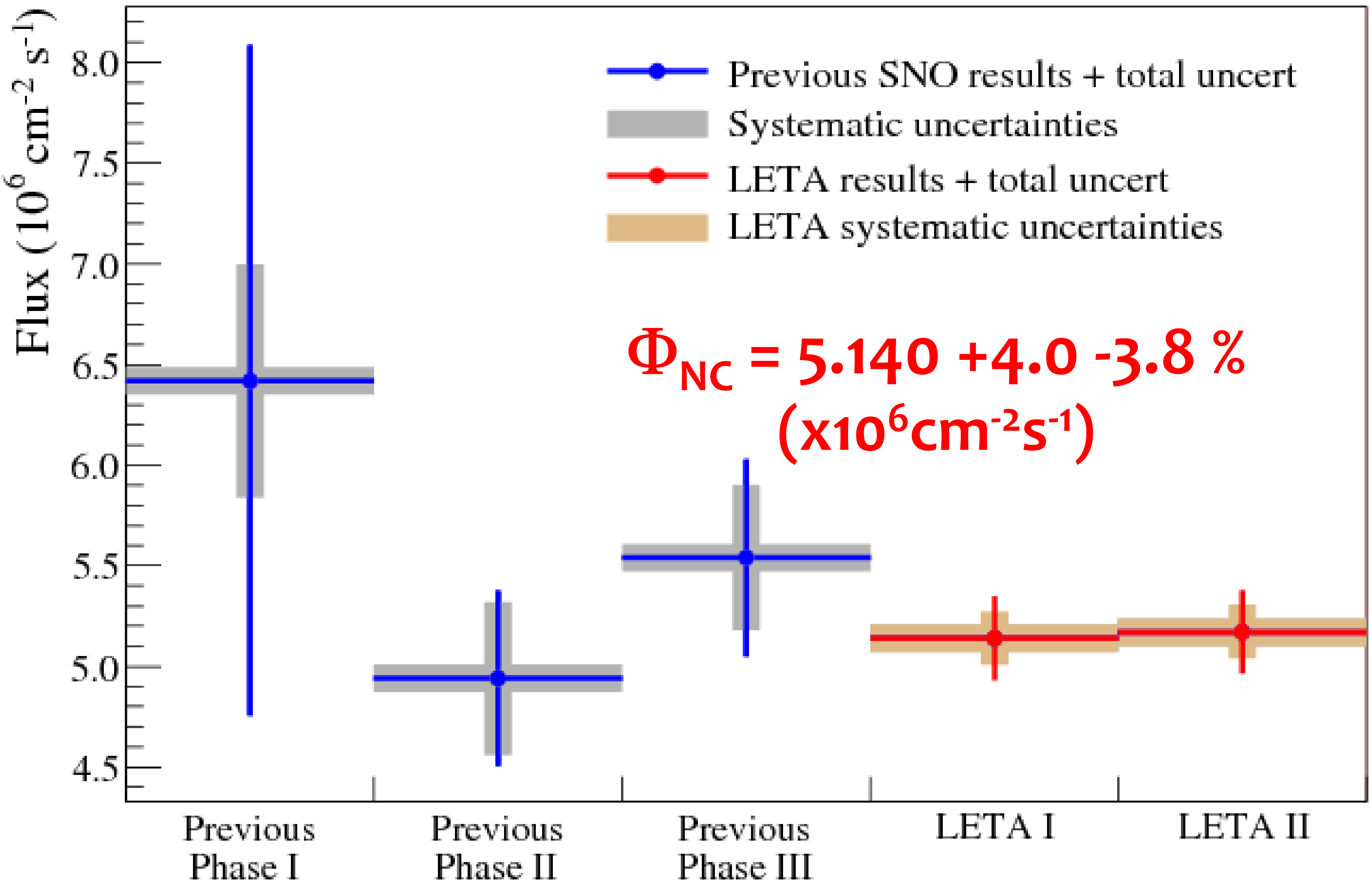
Fit Result



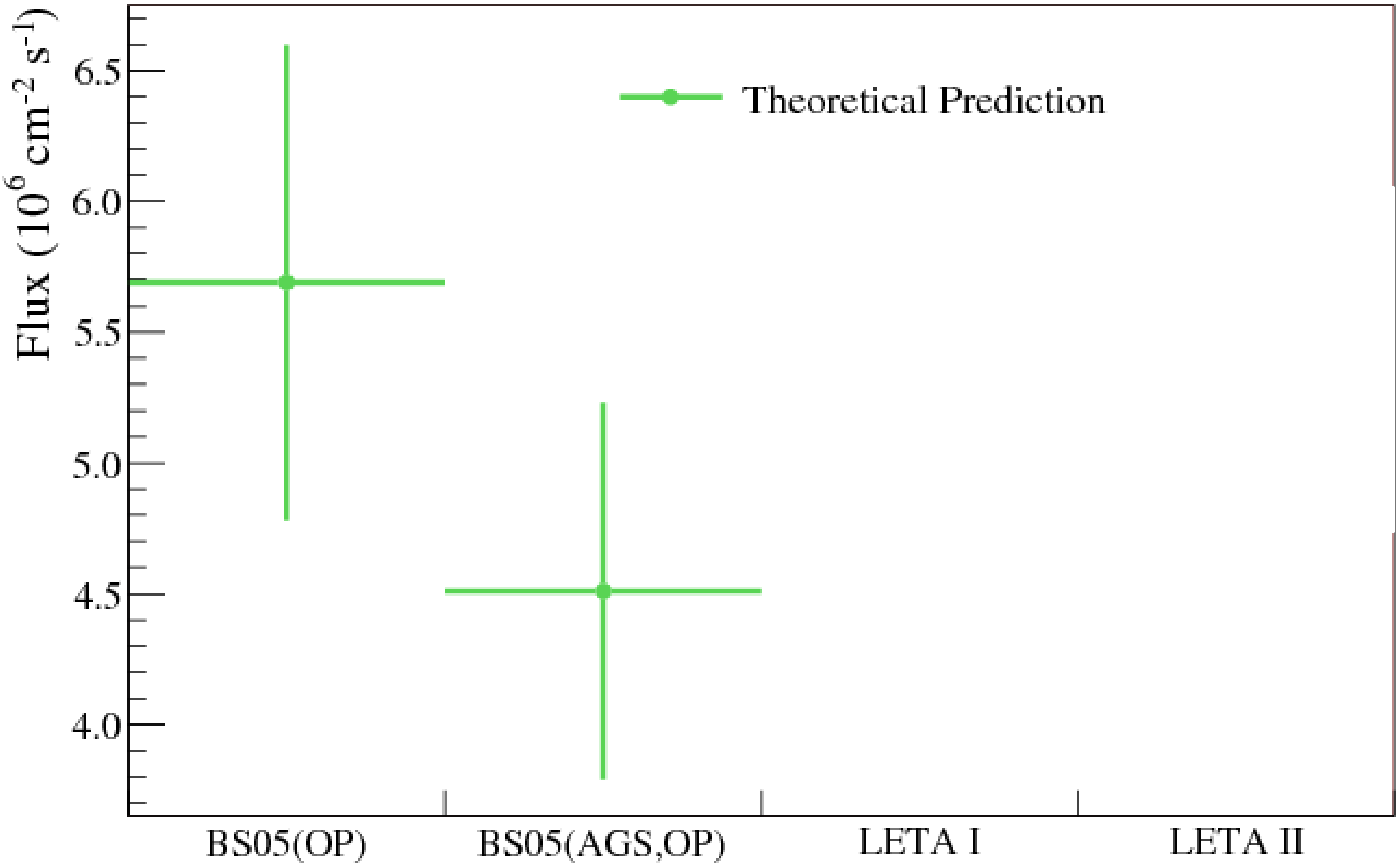
^{8}B Flux Result



^{8}B Flux Result

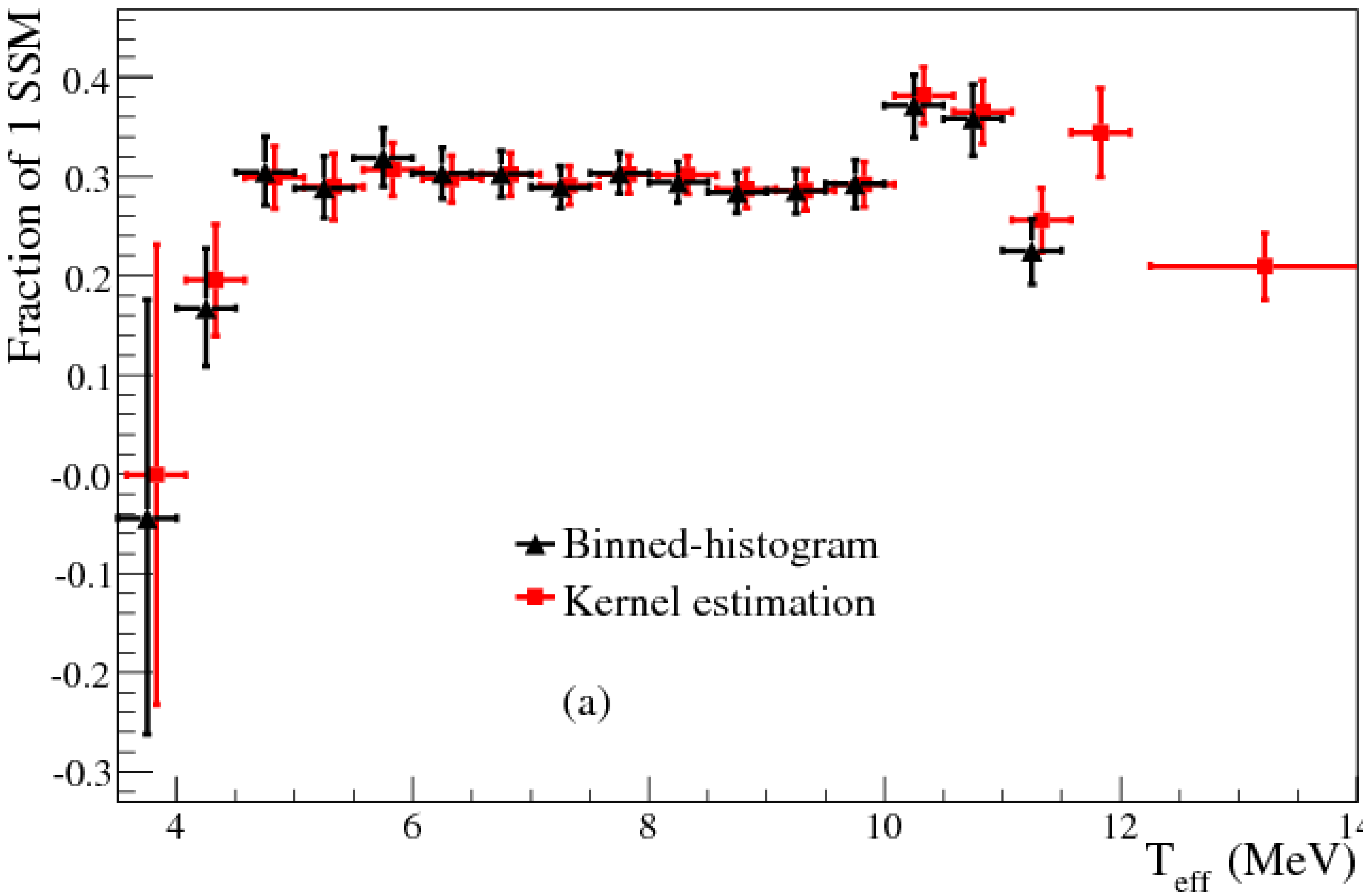


^{8}B Flux Result



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

CC Recoil-Electron Spectrum

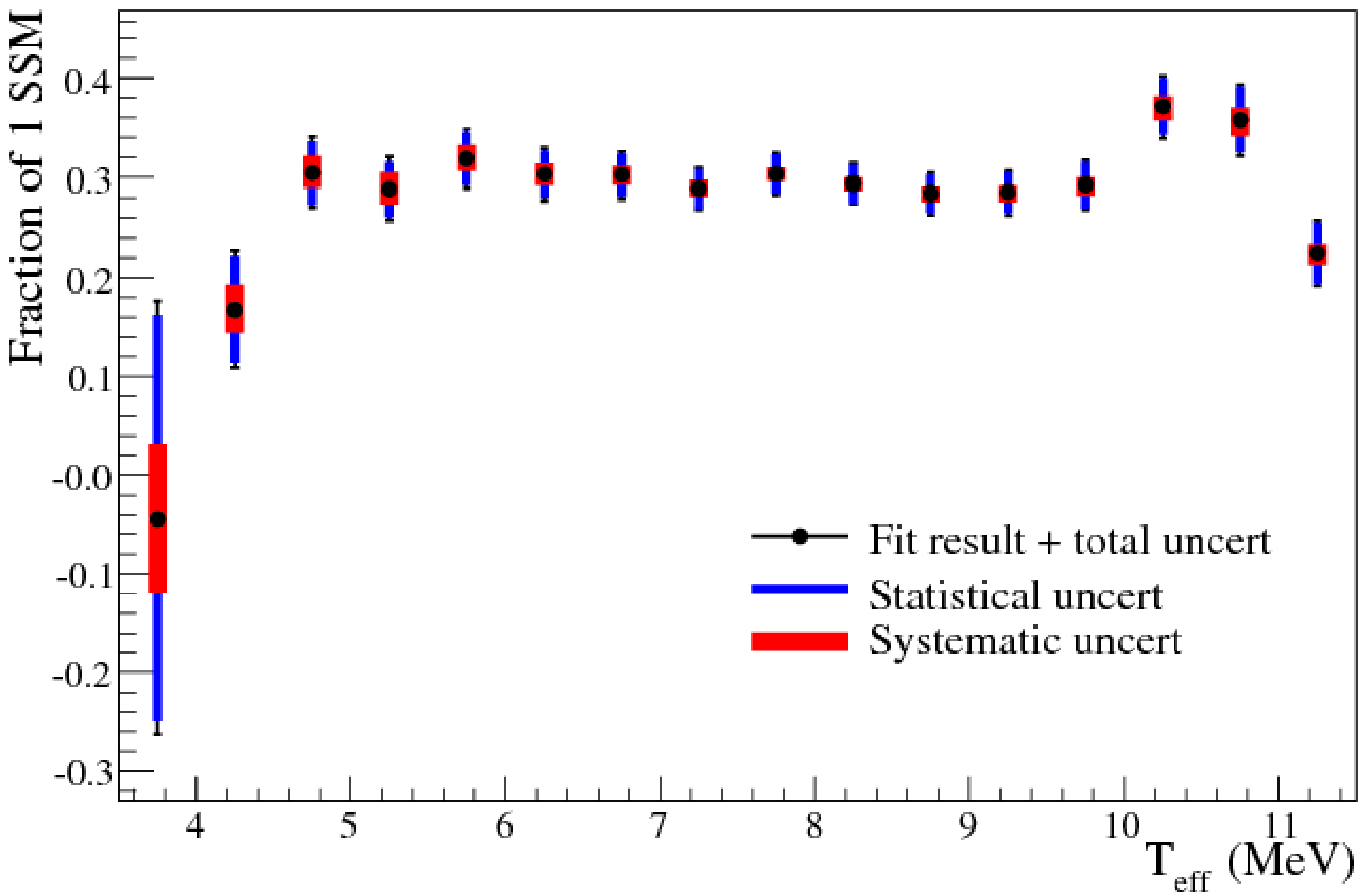


Systematic	Phase	Effect on rate /%			
Angular resn (+)	I				
Angular resn (−)	I				
Angular resn (+)	II				
Angular resn (−)	II				
Axial scale (+)	I				
Axial scale (−)	I				
Axial scale (+)	II				
Axial scale (−)	II				
Z scale (+)	I				
Z scale (−)	I				
Z scale (+)	II				
Z scale (−)	II				
X offset (+)	I				
X offset (−)	I				
X offset (+)	II				
X offset (−)	II				
Y offset (+)	I				
Y offset (−)	I				
Y offset (+)	II				
Y offset (−)	II				
Z offset (+)	I				
Z offset (−)	I				
Z offset (+)	II				
Z offset (−)	II				
X resn	I				
X resn	II				
Y resn	I				
Y resn	II				
Z resn	I				
Z resn	II	0.115	−1.354	0.023	−0.418

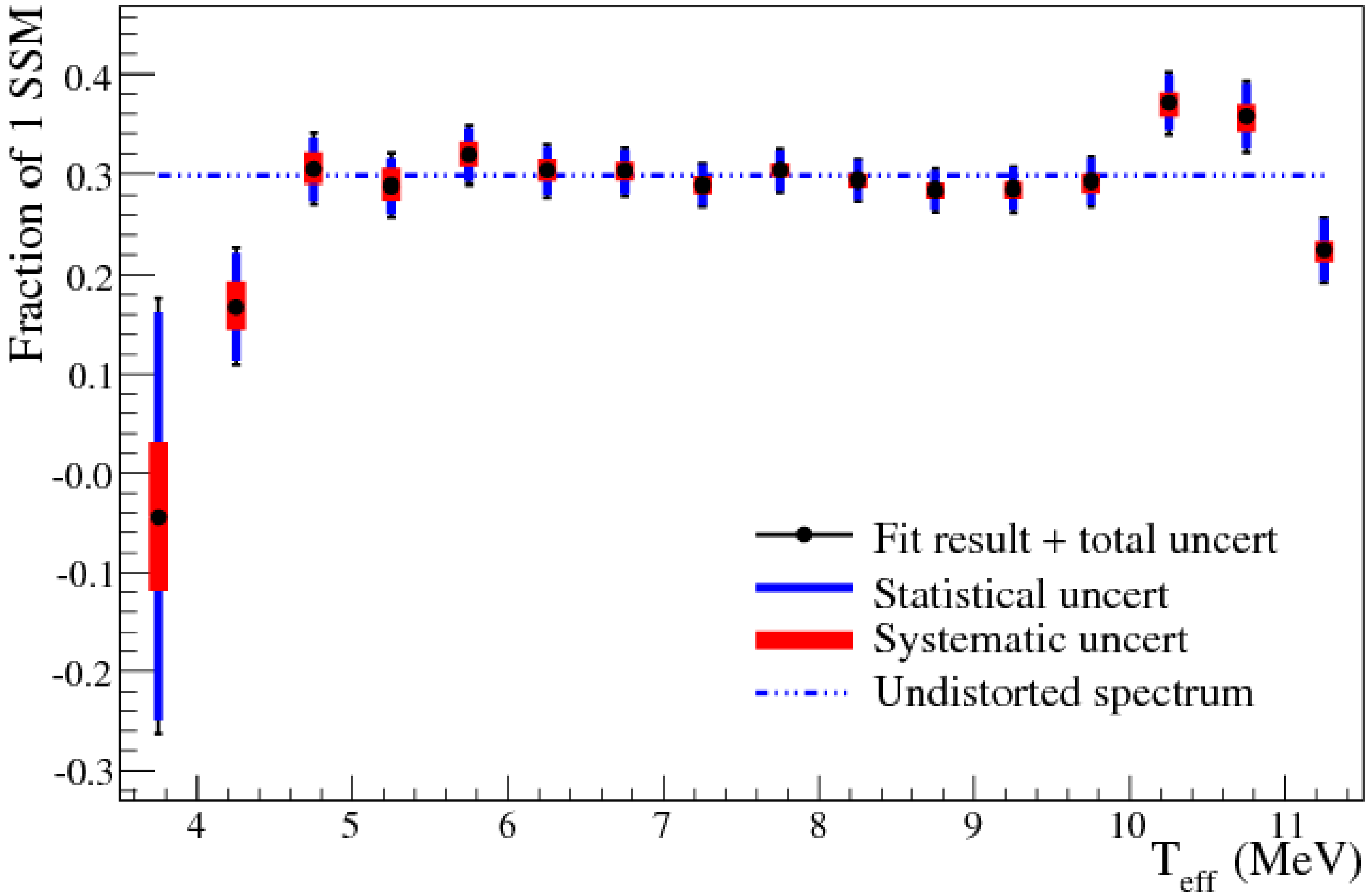
Systematic	Phase	Effect on rate /%			
		NC	CC1	CC12	ES0
T_{eff} scale (+)	I, II	−0.293	−2.037	−2.144	−0.156
T_{eff} scale (−)	I, II	0.137	0.475	0.913	0.035
T_{eff} scale (+)	I	0.030	−0.956	−0.337	−0.148
T_{eff} scale (−)	I	−0.084	1.659	0.652	0.236
T_{eff} scale (+)	II	−0.307	0.317	−1.094	0.105
T_{eff} scale (−)	II	0.177	−0.493	0.584	−0.133
T_{eff} resn (elec) (+)	I	0.008	−3.999	−0.013	−0.439
T_{eff} resn (elec) (−)	I	−0.030	7.656	0.017	1.399
T_{eff} resn (elec) (+)	II	0.653	−5.005	−0.006	−0.531
T_{eff} resn (elec) (−)	II	−0.716	6.597	0.027	0.480
T_{eff} resn (neut) (+)	I, II	0.065	−0.054	−0.023	−0.006
T_{eff} resn (neut) (−)	I, II	−0.041	−0.058	0.046	0.013
T_{eff} linearity (+)	I, II	0.130	−0.160	0.379	−0.125
T_{eff} linearity (−)	I, II	−0.132	0.287	−0.372	0.301
β_{14} elec scale (+)	I, II	0.634	−5.064	−0.082	−0.648
β_{14} elec scale (−)	I, II	−0.622	5.559	0.086	0.607
β_{14} neut scale (+)	I, II	0.719	−1.962	−0.040	−0.068
β_{14} neut scale (−)	I, II	−0.411	1.204	0.029	0.048
β_{14} elec width (+)	I, II	0.306	−1.263	−0.079	−0.027
β_{14} elec width (−)	I, II	−0.286	2.342	0.058	0.099
β_{14} neut width (+)	I, II	0.067	−0.240	−0.002	−0.014
β_{14} neut width (−)	I, II	−0.054	0.217	0.012	0.017
β_{14} E−dep (+)	I, II	0.227	1.661	−0.054	0.299
β_{14} E−dep (−)	I, II	−0.246	−0.999	0.068	−0.228

Systematic	Phase	Effect on rate /%			
		NC	CC1	CC12	ES0
	I	0.397	−0.277	−1.735	0.378
	I	−0.230	0.119	1.027	−0.233
	II	−0.698	0.794	−1.144	0.322
	II	0.825	−0.994	1.376	−0.389
)	I, II	−0.357	−0.519	−0.434	−0.451
)	I, II	1.039	1.299	1.136	1.171
	I, II	−0.180	0.134	−0.002	0.026
	I, II	0.183	−0.100	0.004	−0.023
	I	−0.049	−0.797	0.003	−0.074
	I	0.044	0.829	−0.001	0.084
	II	−1.306	0.616	−0.001	0.062
	II	1.338	−0.612	0.003	−0.060
	I, II	−0.759	0.040	−0.000	−0.001
	I, II	0.770	−0.053	0.001	−0.011
	II	0.028	−0.751	0.008	−0.056
	II	0.067	−0.463	0.003	−0.182
(+)	I	0.009	−6.482	−0.003	−1.469
(−)	I	0.002	3.217	0.004	0.821
(+)	II	0.046	−0.814	0.001	−0.196
(−)	II	0.011	−0.328	0.003	0.010
(+)	I	−0.048	−2.875	0.003	−0.402
(−)	I	0.035	1.746	0.000	0.238
(+)	II	0.023	−2.371	0.002	−0.185
(−)	II	0.004	0.870	−0.000	0.440
	I	0.053	5.674	−0.004	0.774
	I	−0.016	−2.113	0.003	−0.203
	II	−0.005	0.735	−0.000	0.370
	II	0.001	−1.014	0.003	−0.111
)	I	−0.042	−2.271	0.002	−0.714
)	I	0.062	0.559	0.000	0.509
)	II	−0.516	4.456	0.029	0.396
)	II	0.524	−4.102	−0.027	−0.802
)	I	0.075	−1.388	−0.001	−0.008
)	I	−0.070	0.192	0.005	0.060
PMT β_{14} width (+)	II	0.357	−1.054	−0.006	0.257
PMT β_{14} width (−)	II	−0.365	1.394	0.009	−0.459

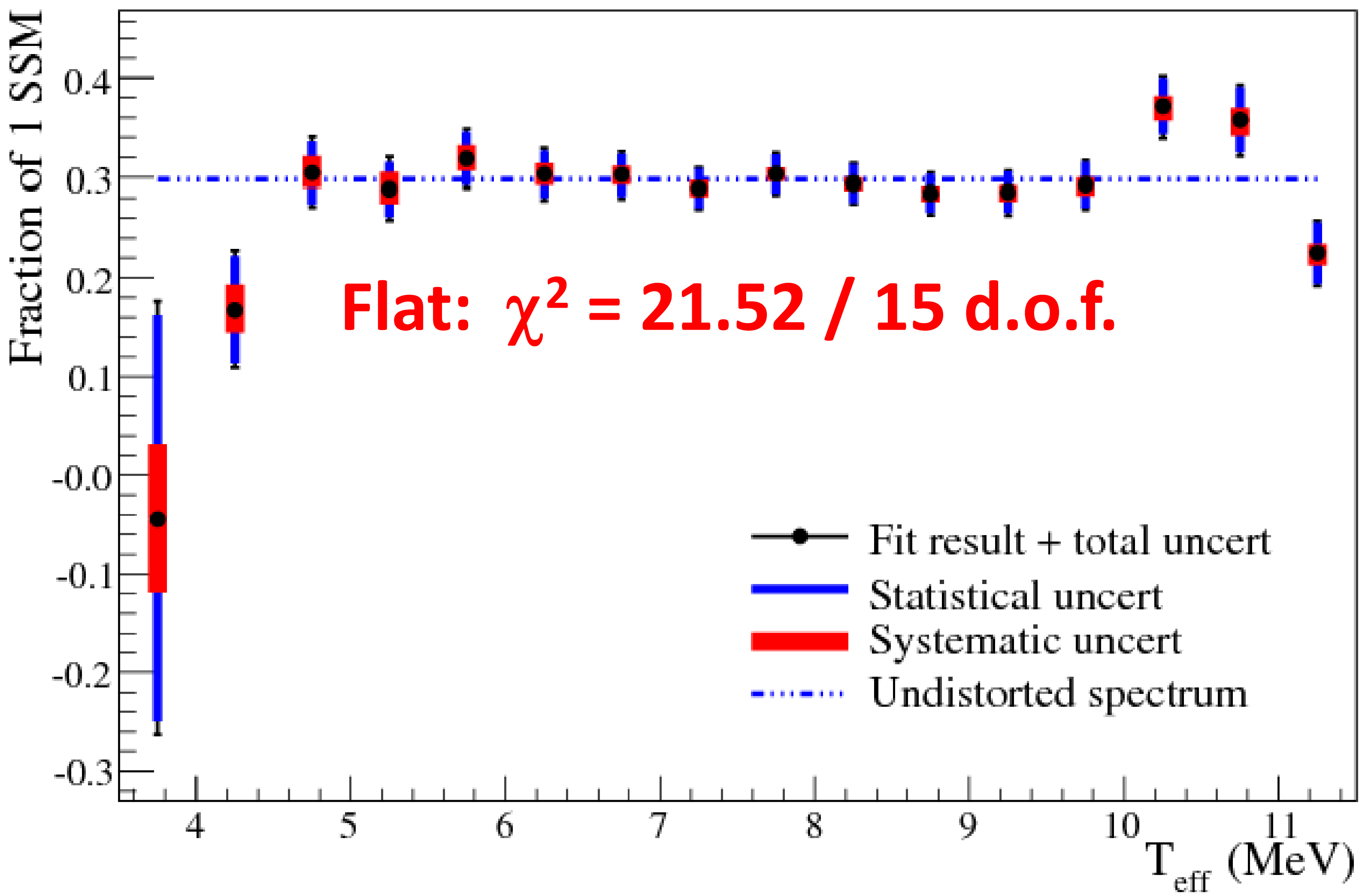
CC Recoil-Electron Spectrum



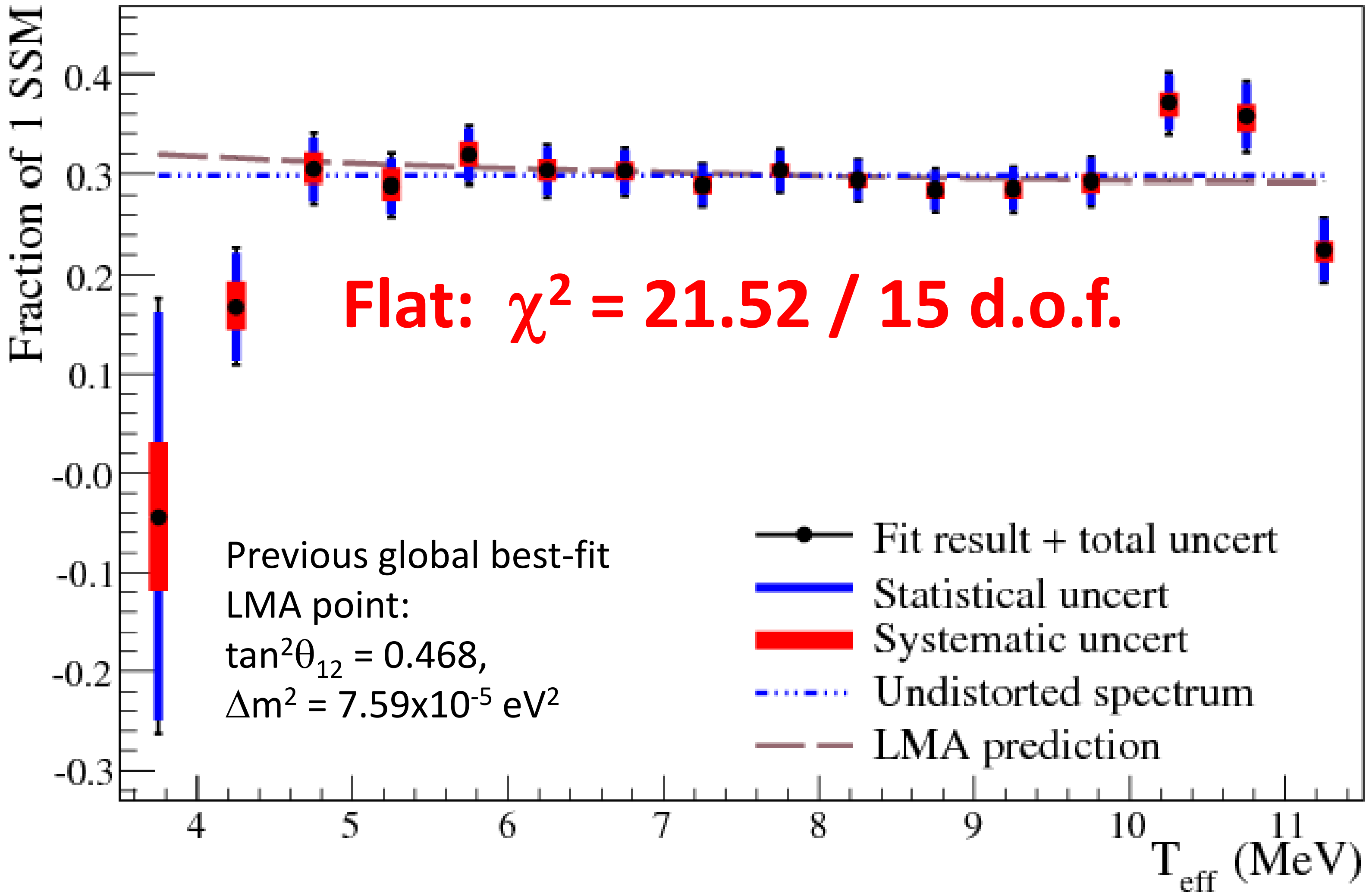
CC Recoil-Electron Spectrum



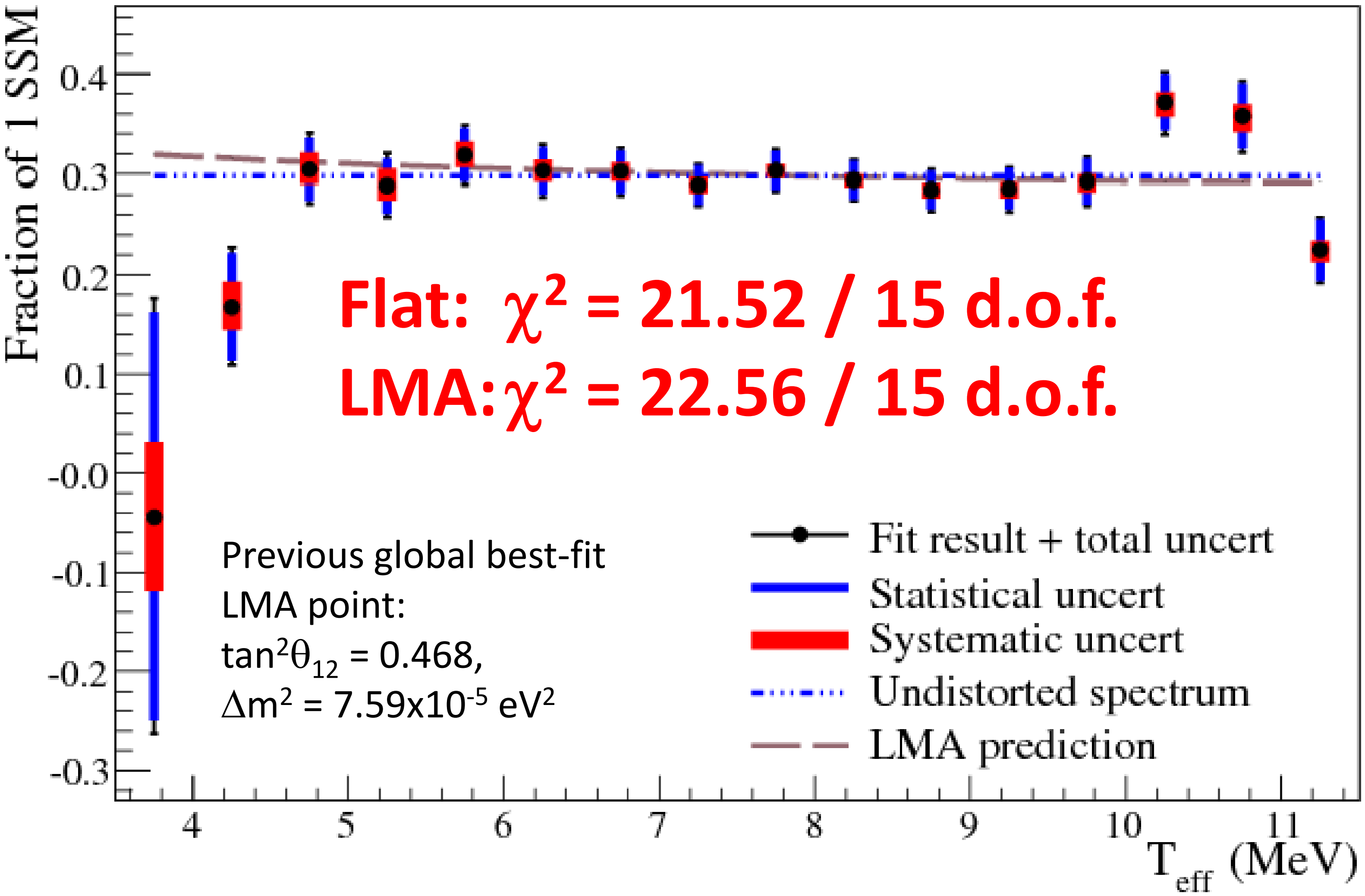
CC Recoil-Electron Spectrum



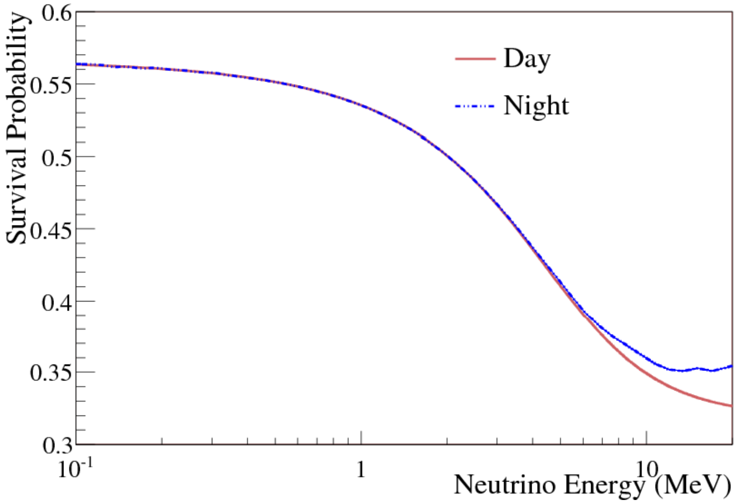
CC Recoil-Electron Spectrum



CC Recoil-Electron Spectrum



Direct Fit for Energy-Dependent Survival Probability



Neutrino signal directly described by 6 parameters:

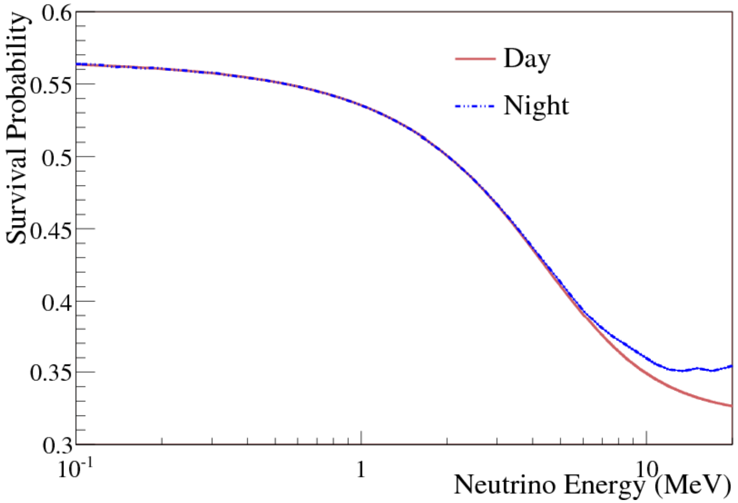
1. Φ_{8B}: total ^{8}B neutrino flux
2. c0, c1, c2: quadratic expansion of the ν_e daytime P_{ee} around E_ν = 10 MeV
3. a0, a1: linear expansion of a day/night asymmetry around E_ν = 10 MeV

$$P_{ee}^{DAY}(E_\nu) = c0 + c1\,(E_\nu - 10\text{ MeV}) + c2\,(E_\nu - 10\text{ MeV})^2$$

$$P_{ee}^{ASYM}(E_\nu) = a0 + a1\,(E_\nu - 10\text{ MeV})$$

$$P_{ee}^{NIGHT}(E_\nu) = P_{ee}^{DAY}(E_\nu) \times \frac{[1 + (1/2)*P_{ee}^{ASYM}(E_\nu)]}{[1 - (1/2)*P_{ee}^{ASYM}(E_\nu)]}$$

Direct Fit for Energy-Dependent Survival Probability



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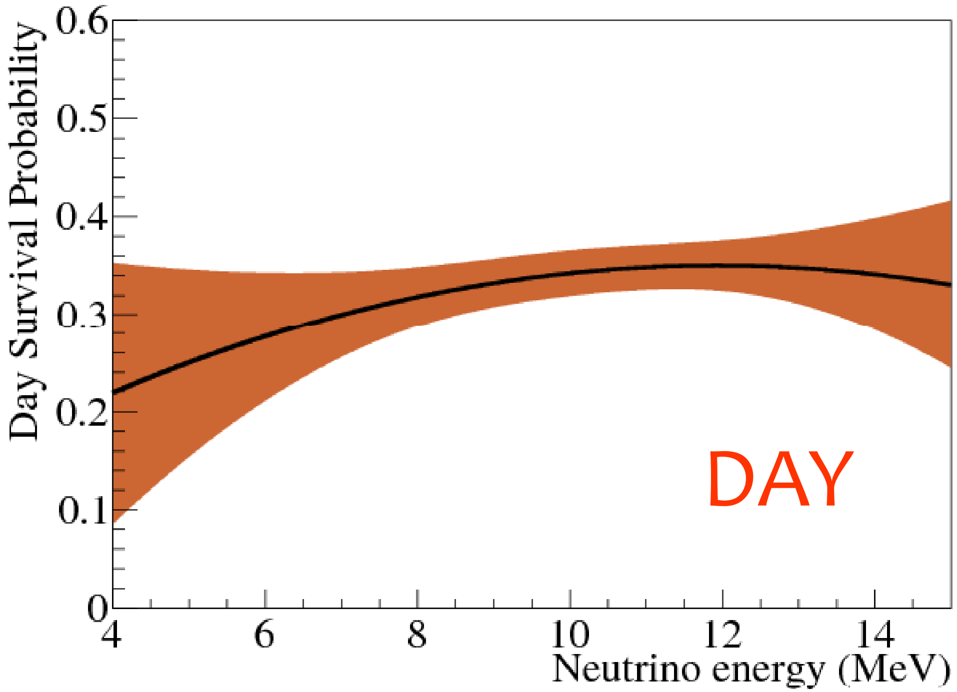
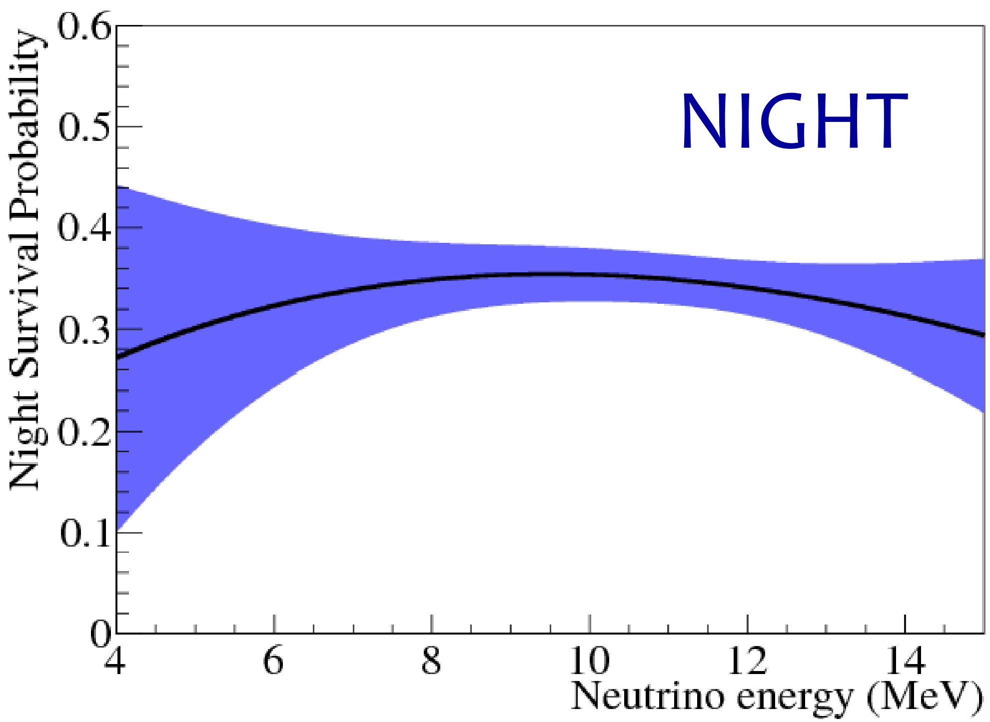
$$P_{ee}^{NIGHT}(E_\nu) = P_{ee}^{DAY}(E_\nu) \times \frac{[1 + (1/2)*P_{ee}^{ASYM}(E_\nu)]}{[1 - (1/2)*P_{ee}^{ASYM}(E_\nu)]}$$

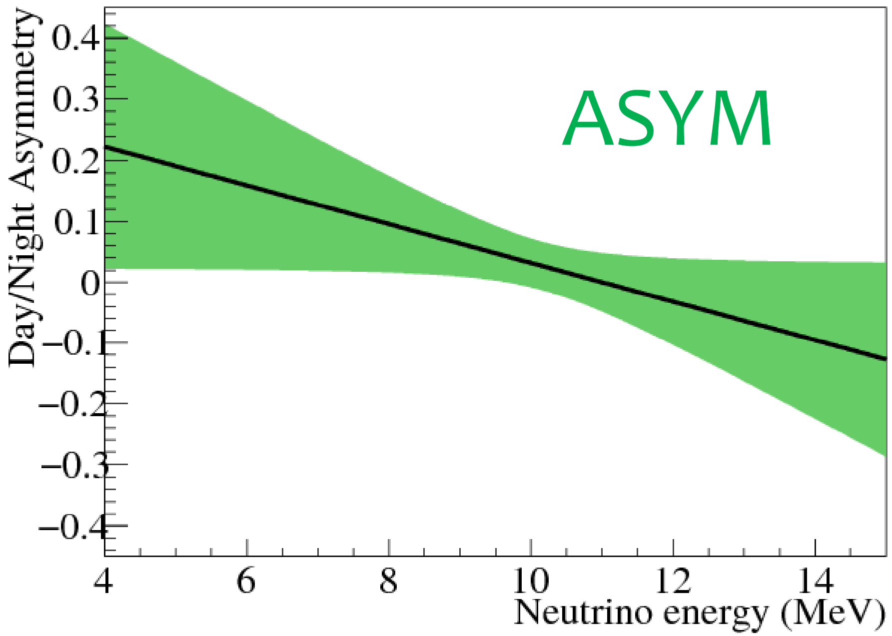
Φ_{8B} = 5.046 +3.8 -3.9 %

Assuming unitarity

Direct Fit for Energy-Dependent Survival Probability



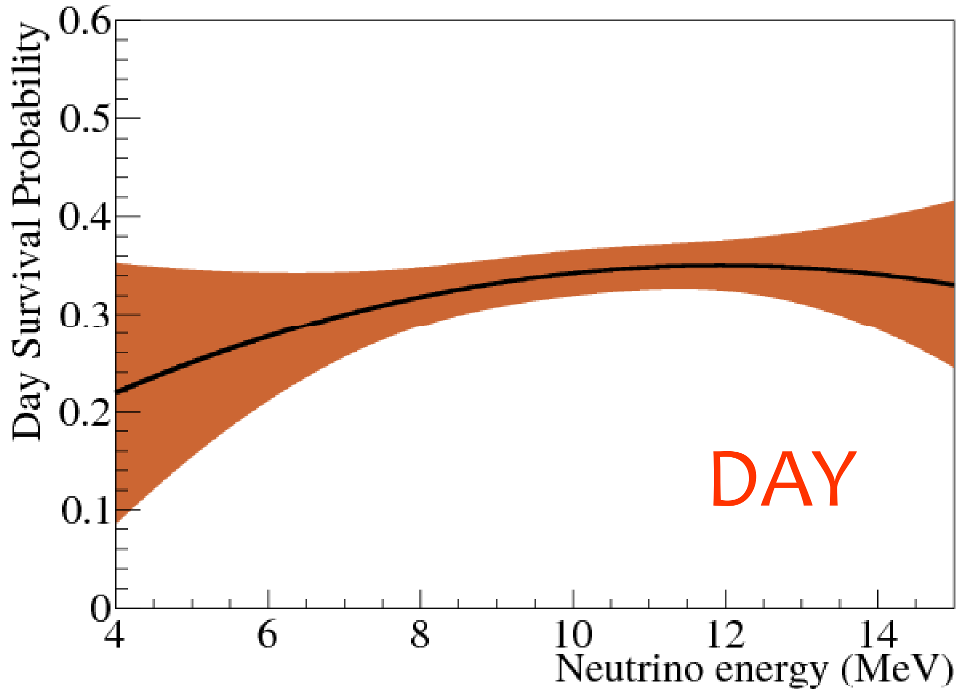


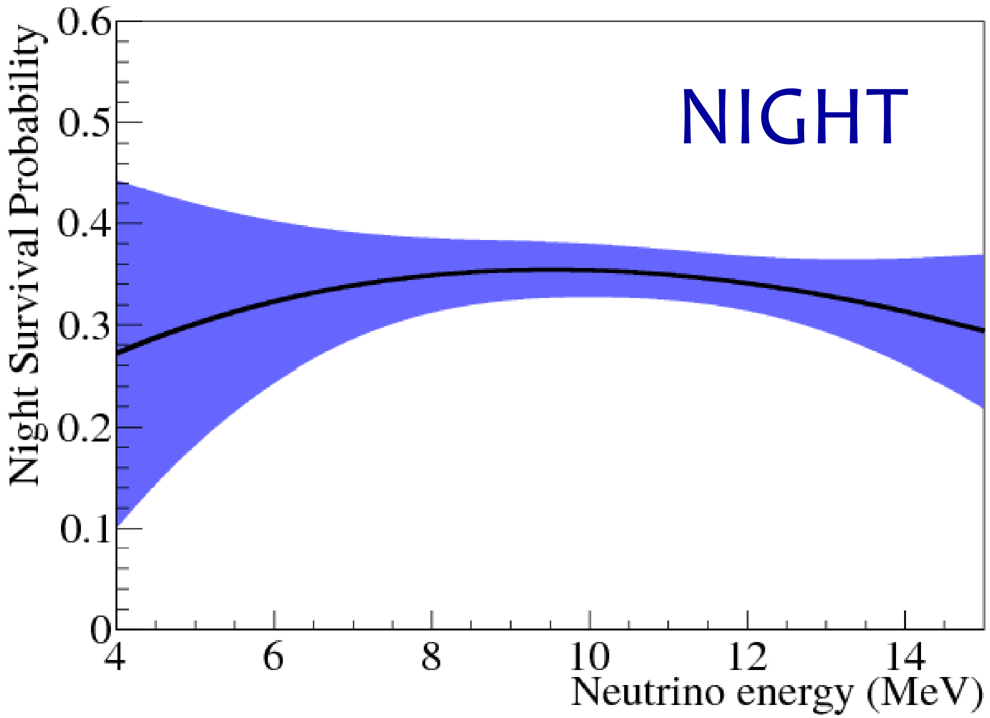


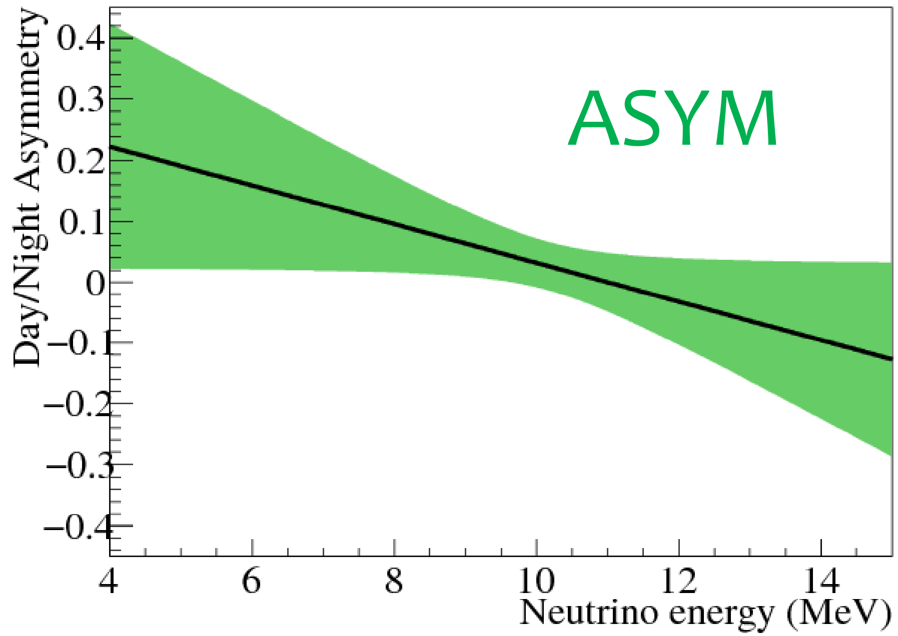
Direct Fit for Energy-Dependent Survival Probability

No distortion, no a/s:

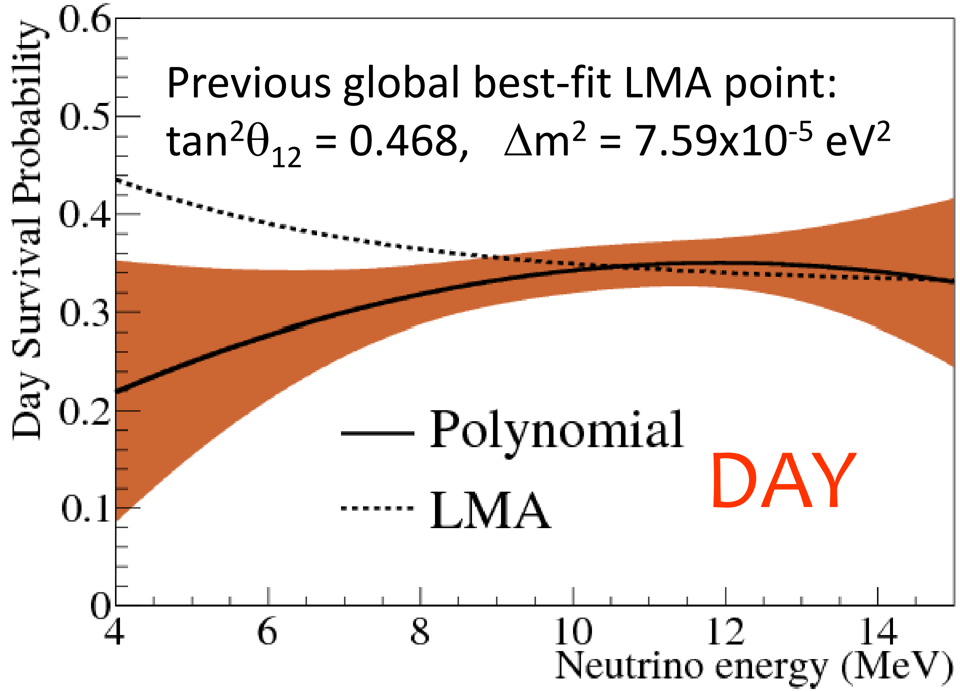
$\Delta\chi^2$ = 1.94 / 4 d.o.f.







Direct Fit for Energy-Dependent Survival Probability

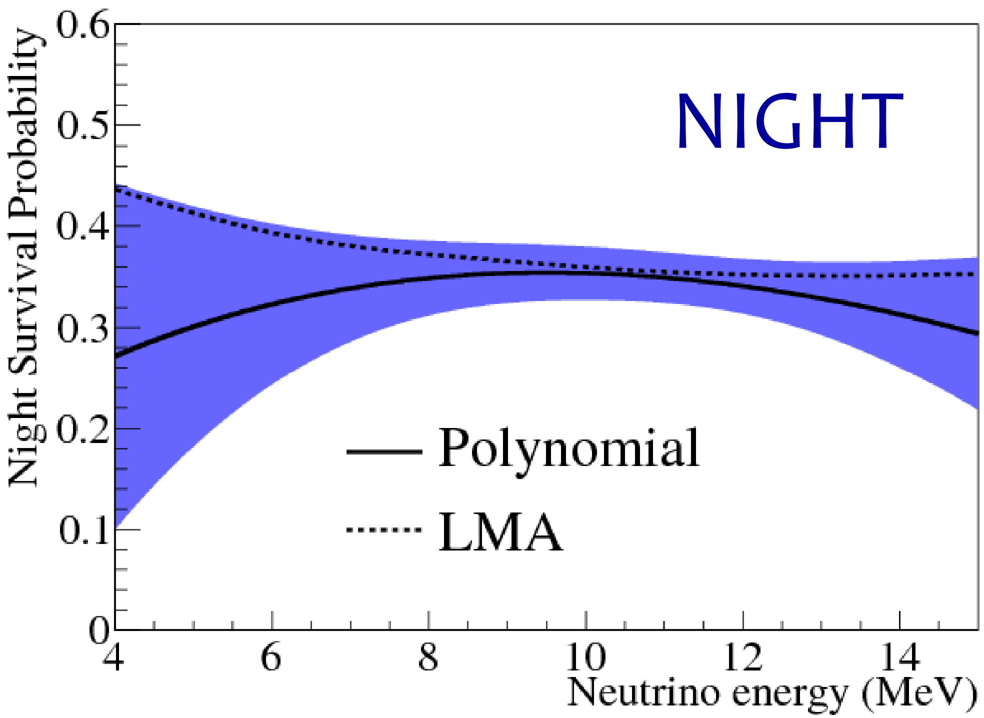


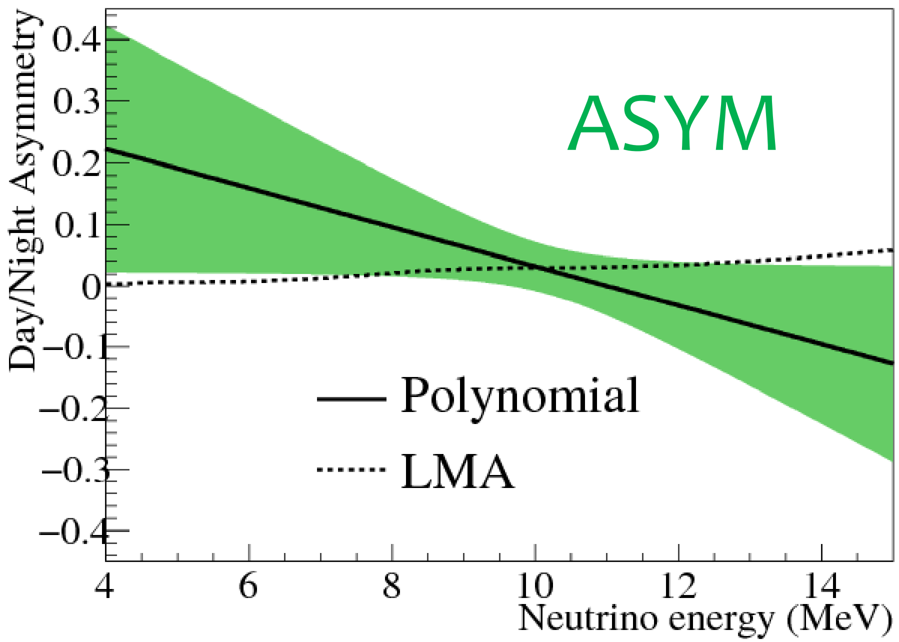
No distortion, no a/s:

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

LMA-prediction:

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

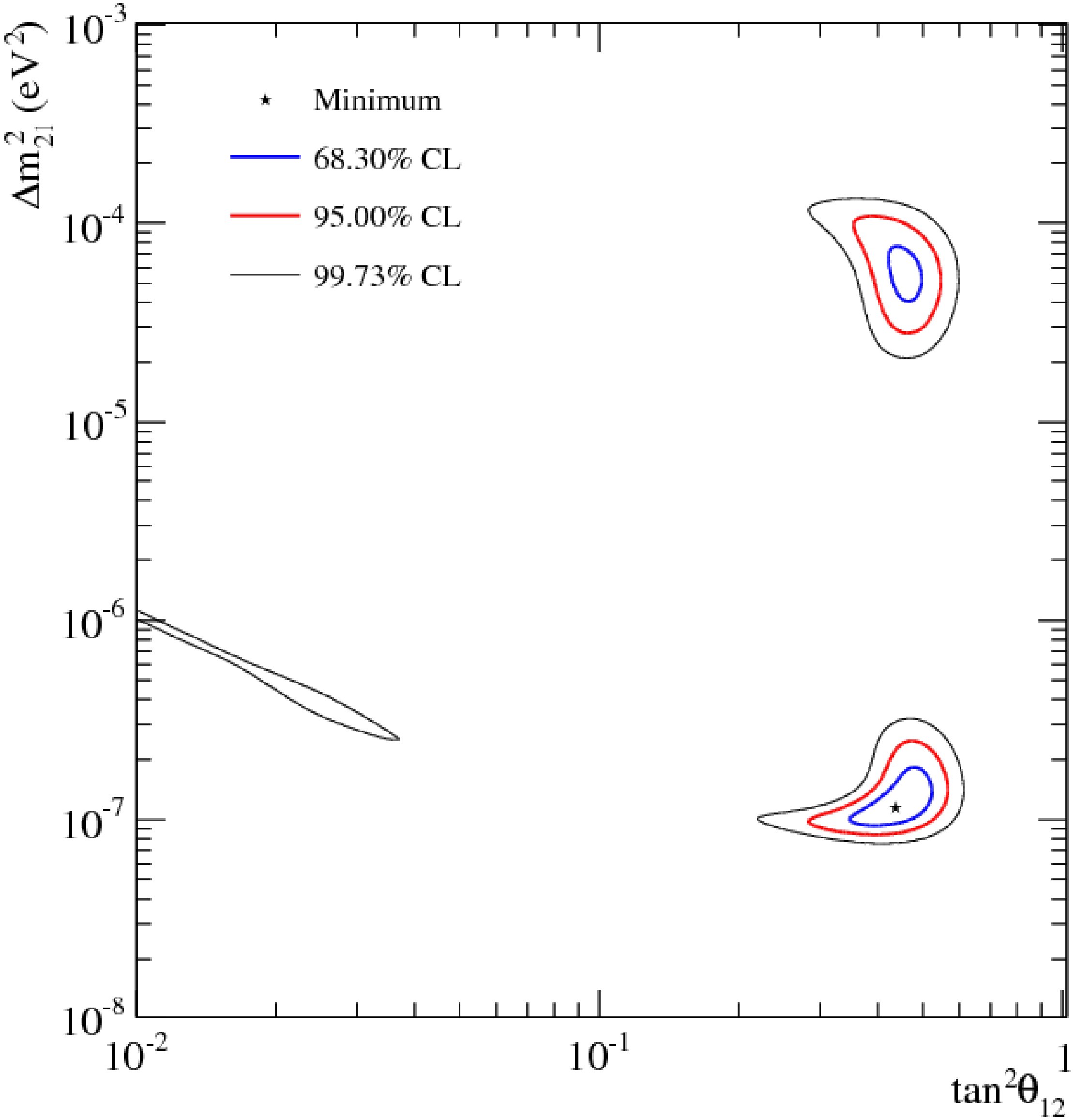




Oscillation Analyses: LETA

LETA paper 2009:
LETA joint-phase fit
+ Phase III

Best-fit point:
$\tan^2\theta_{12}$ = 0.437,
$\Delta m^2 = 1.15\text{x}10^{-7}$ eV^2



Oscillation Analyses: LETA

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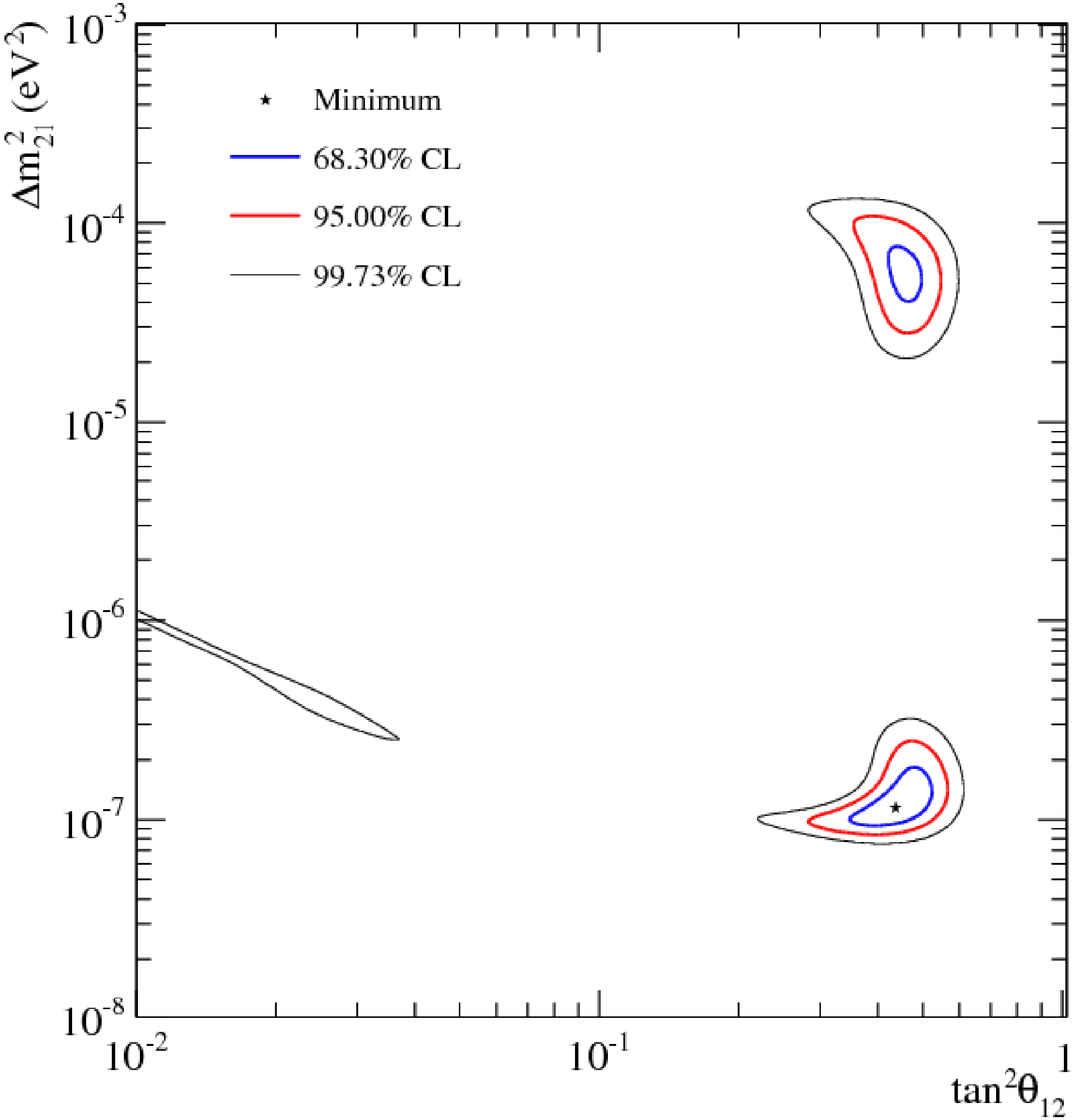


Best-fit LMA point:

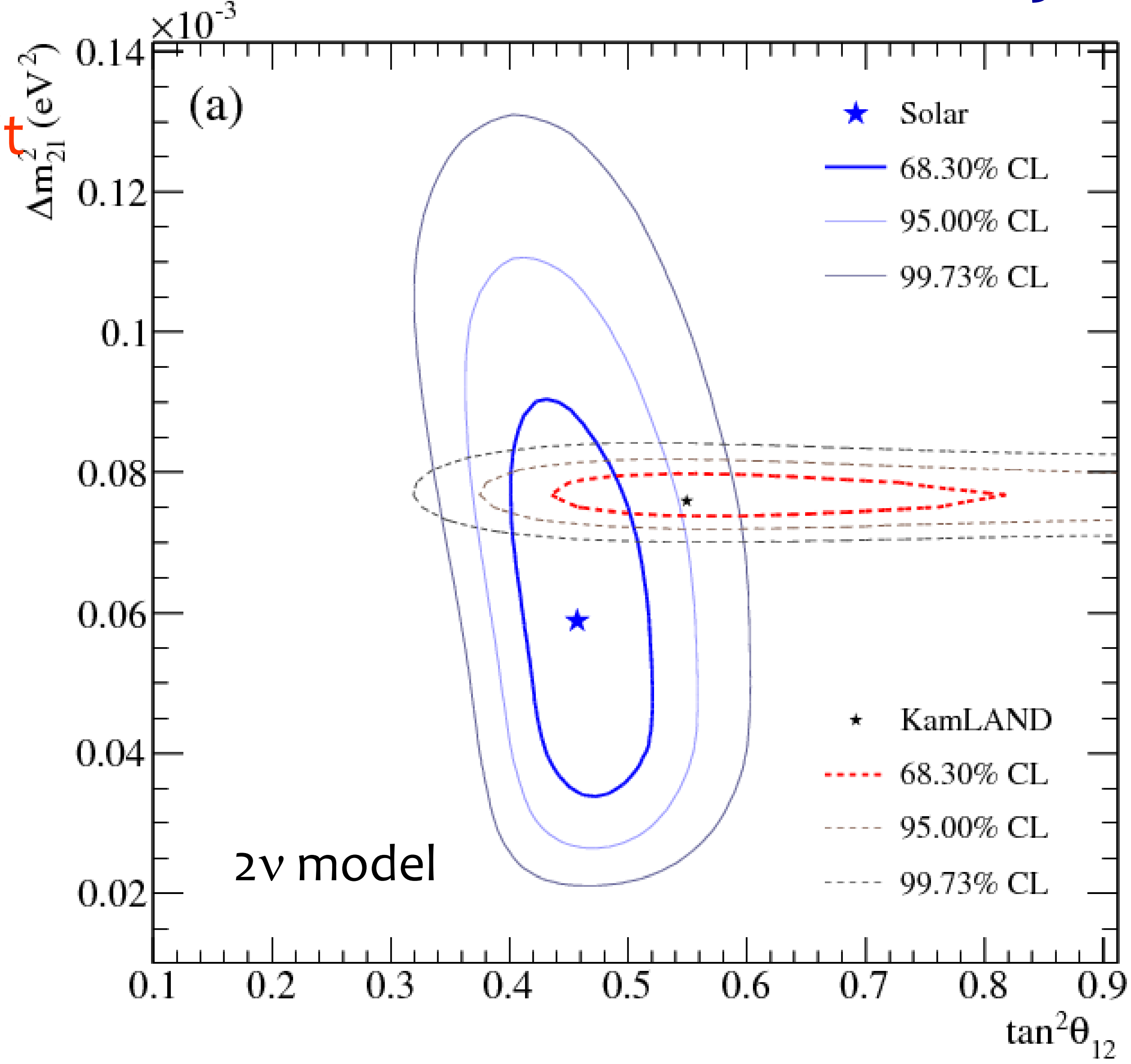
$\tan^2\theta_{12}$ = 0.457
(+0.038 -0.042)

$\Delta m^2 = 5.50 \times 10^{-5}$ eV^2
(+2.21 -1.62)

Solar + KamLAND 2-flavor Overlay

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

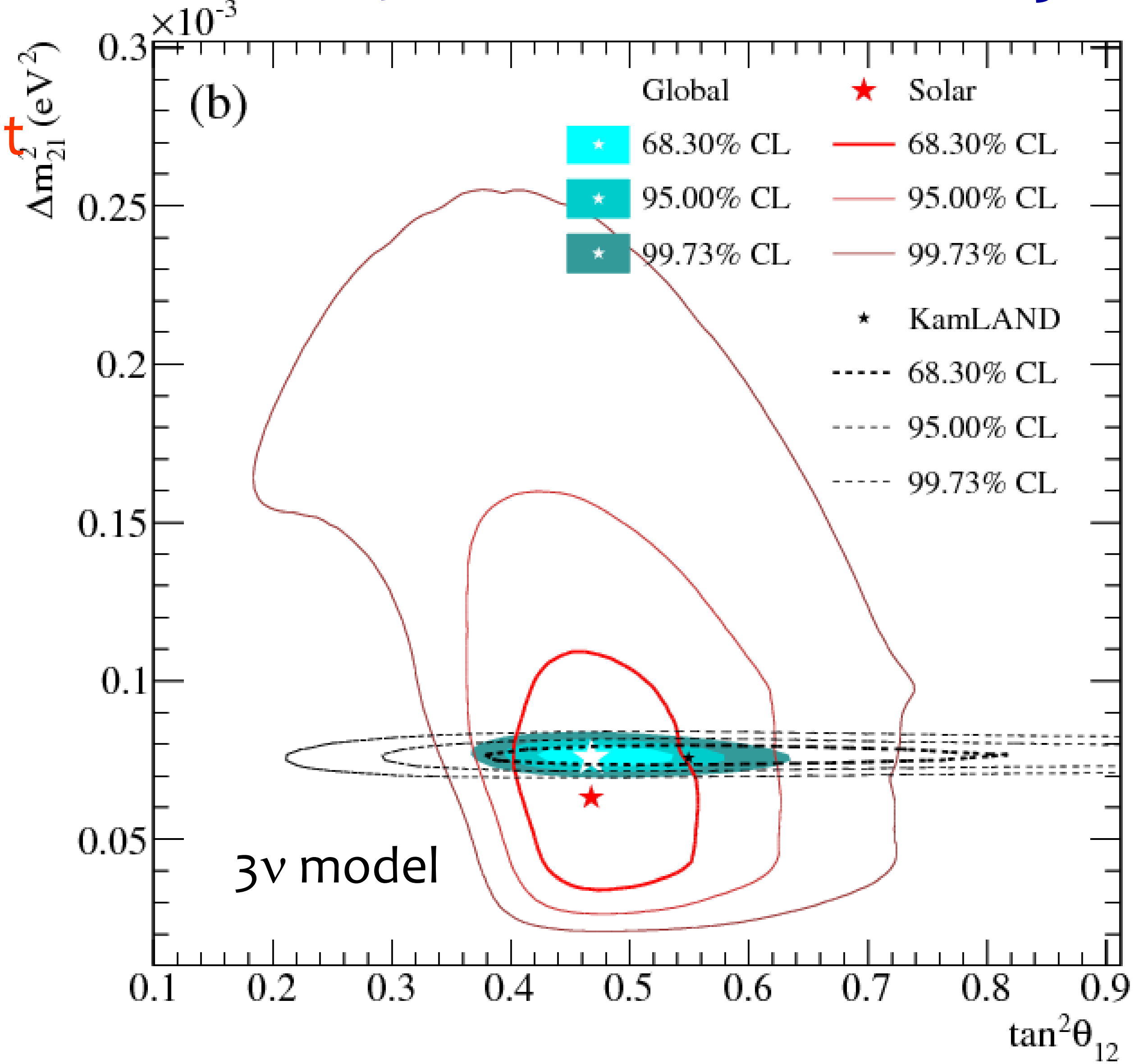
2-flavor overlay:



Solar + KamLAND 3-flavor Overlay

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

3-flavor overlay:



Solar + KamLAND 3-flavor Overlay

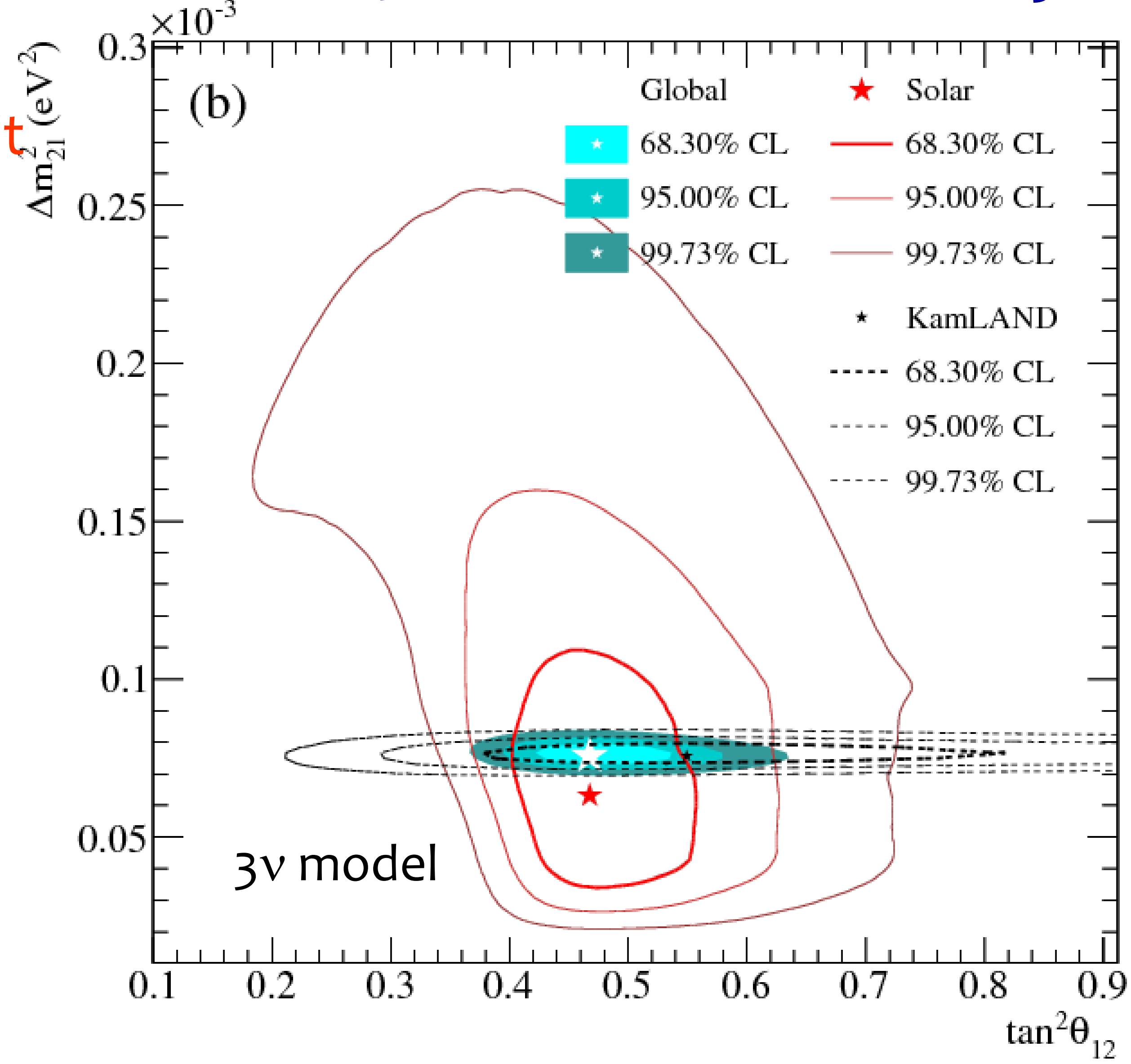
LETA paper 2009:
LETA joint-phase fit
+ Phase III
+ all solar expts
+ KamLAND

3-flavor overlay:

Best-fit LMA point:

$\tan^2\theta_{12} = 0.468$
$(+0.042\ -0.033)$

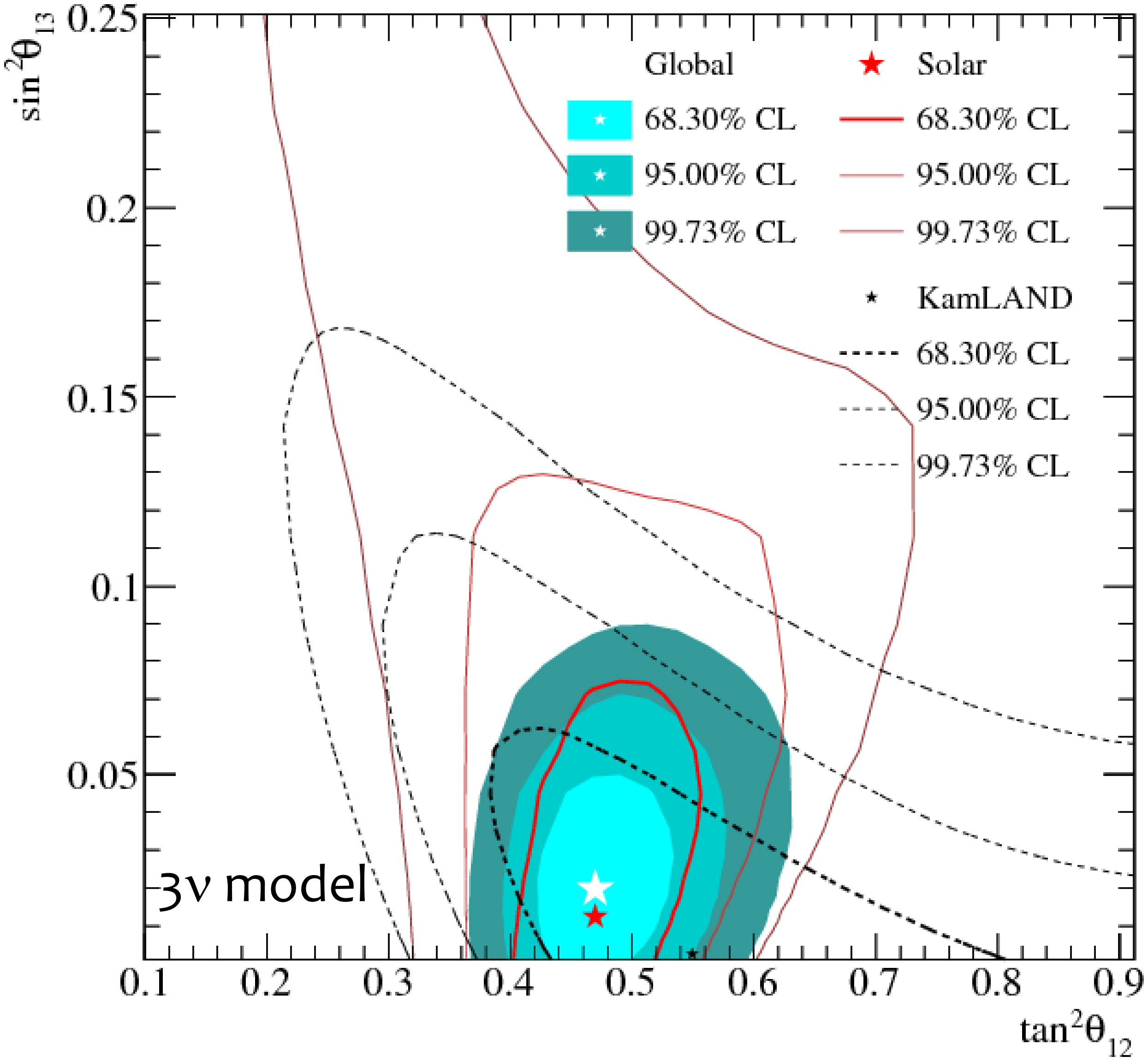
$\Delta m^2 = 7.59 \times 10^{-5}\ eV^2$
$(+0.21\ -0.21)$



Solar + KamLAND 3-flavor Overlay

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

3-flavor analysis:



Solar + KamLAND 3-flavor Overlay

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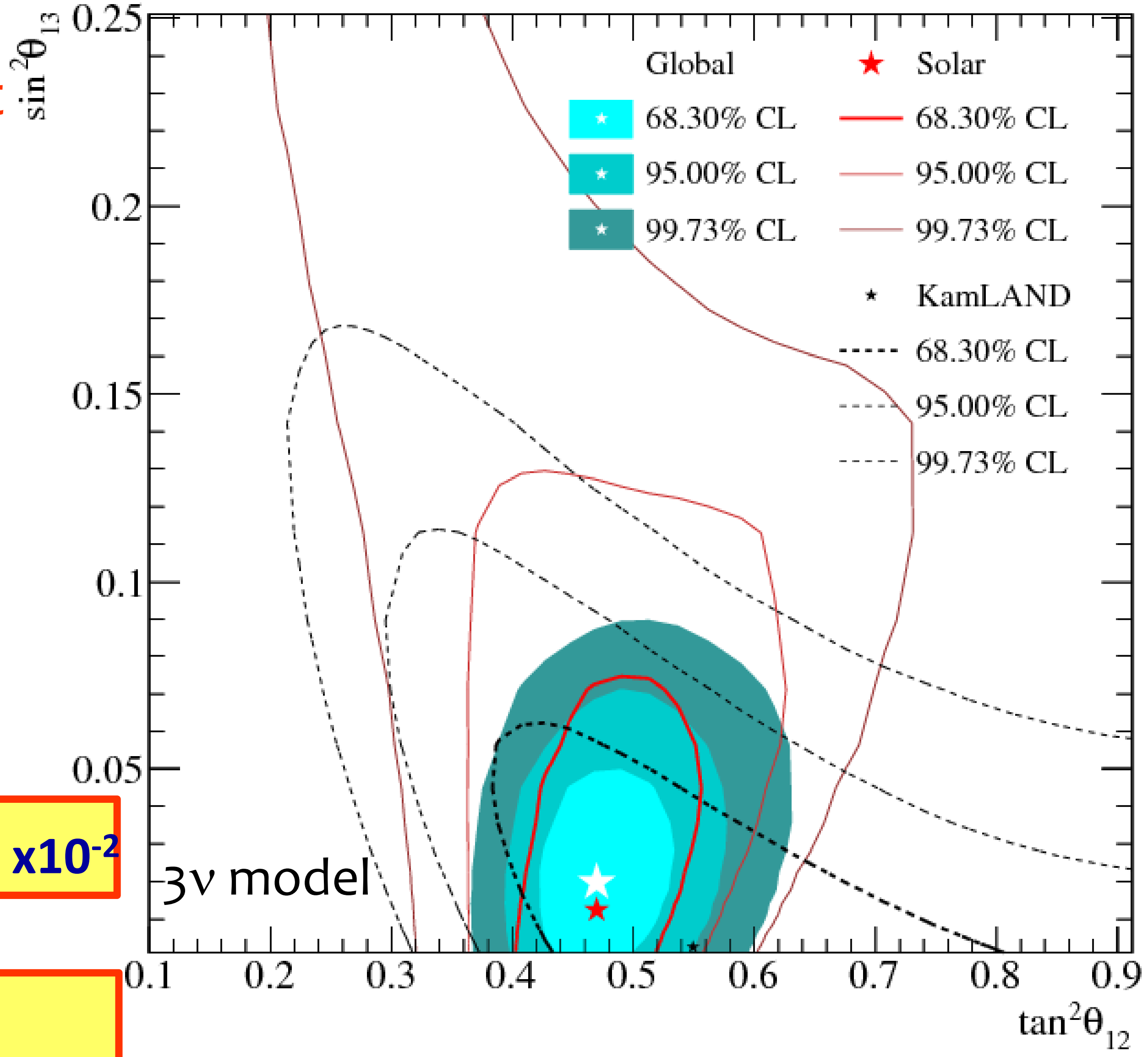

3-flavor analysis:

Best-fit:

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

$\Rightarrow$

$\sin^2\theta_{13} < 0.057$ (95% C.L.)

Summary

1. Model-independent measure of the ^{8}B flux:

$$\Phi_{NC} = 5.140 \; +4.0 \; -3.8 \; \%$$

2. Measure of the ^{8}B flux assuming unitarity:

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

3. Best fit global MSW parameters (2-flavor):

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

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

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

4. 3-flavor oscillation analysis:

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

arXiv:0910.2984 [nucl-ex]