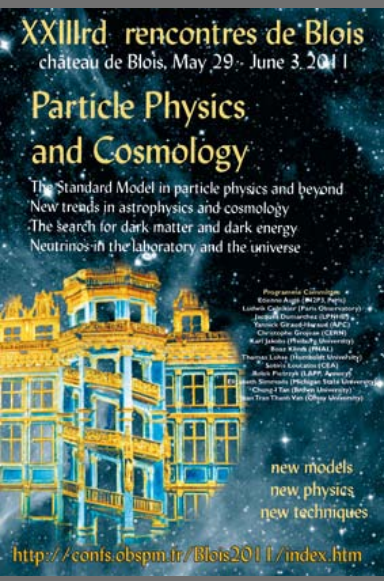
Canada Research Chairs | Chaires de recherche du Canada



Final Results of the Sudbury Neutrino Observatory

Alain Bellerive

On behalf of the SNO Collaboration

Carleton UNIVERSITY
Canada's Capital University

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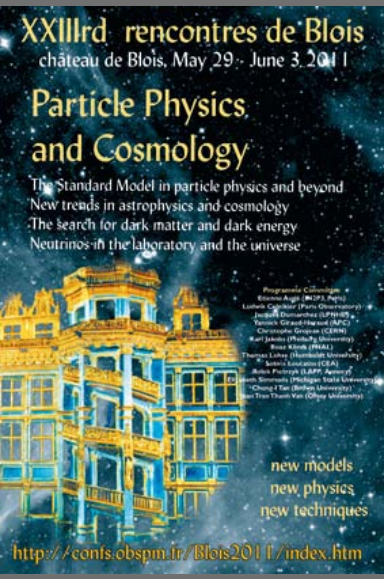


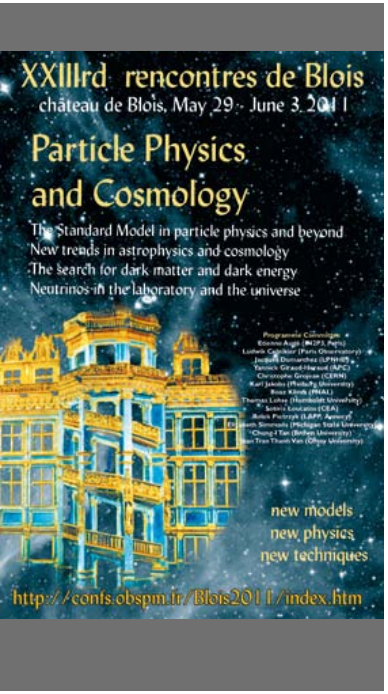
From Solving the Solar Neutrino Problem to Precision Physics

Alain Bellerive

On behalf of the SNO Collaboration

Carleton UNIVERSITY
Canada's Capital University

Outline



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- Introduction
- Solar Neutrino Flux (update)
- The Sudbury Neutrino Observatory
- The new stuff for 2011 (3-phase) !!!
  - New hep neutrino results
  - Expected ^{8}B neutrinos survival probability
- Constraints on Oscillation Parameters
- Future Prospects

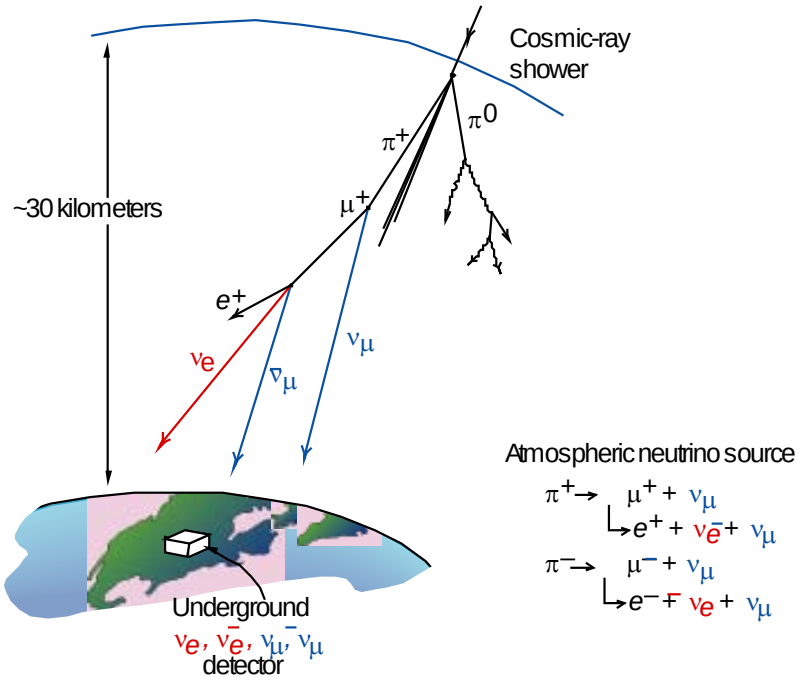
Evidence for Neutrino Mixing

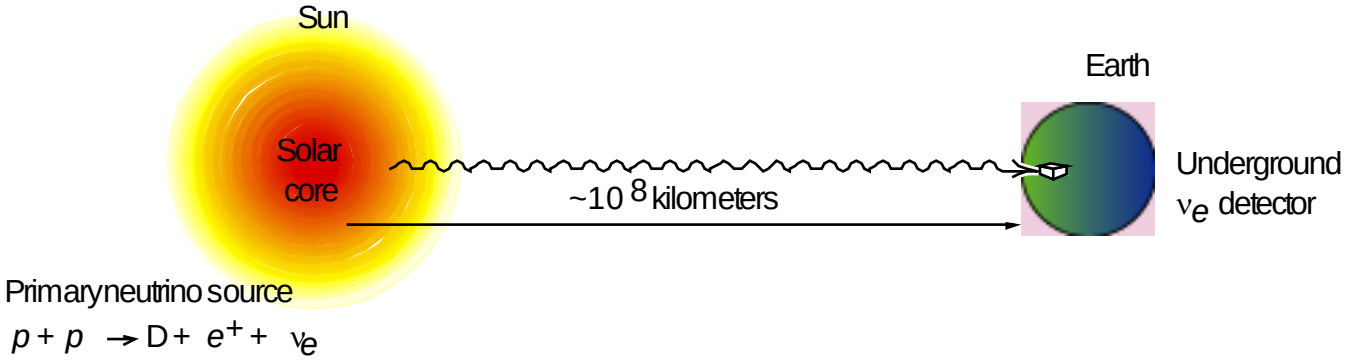
First evidence of neutrino oscillation

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

Atmospheric Neutrinos high energies

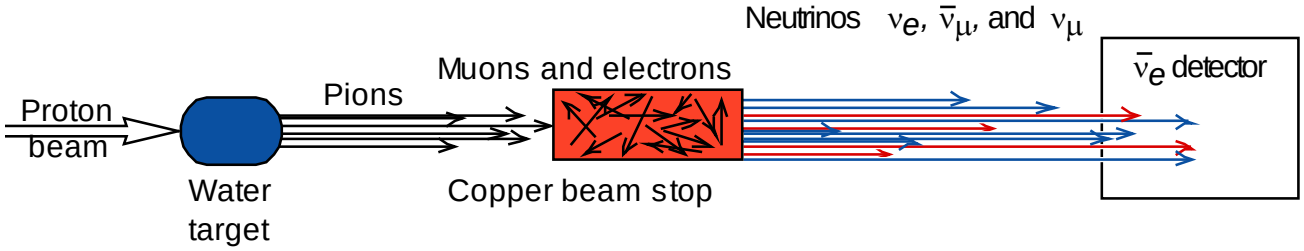
Parallel Session Talk by Dr. Yoshihisa Obayashi





Solar Neutrinos low energies

Today's talk !!!



Beamstop Neutrinos tunable energies

The First Piece

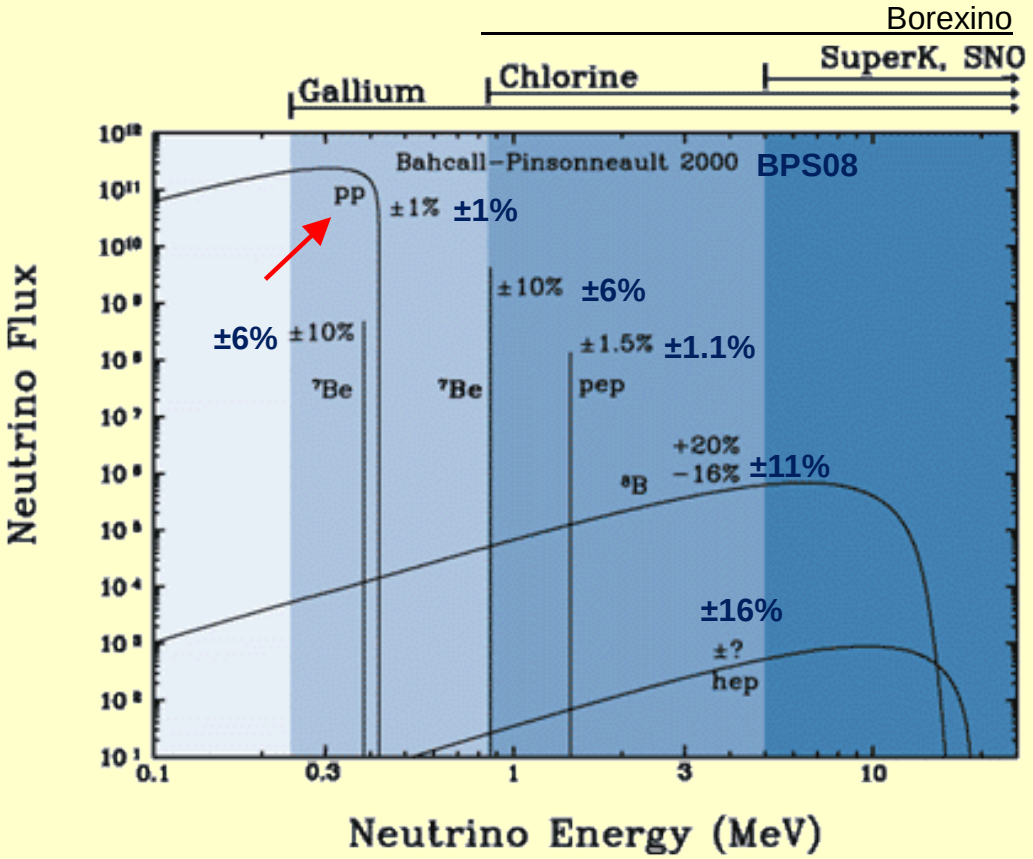
Solar Neutrino Flux and Physical Observables

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

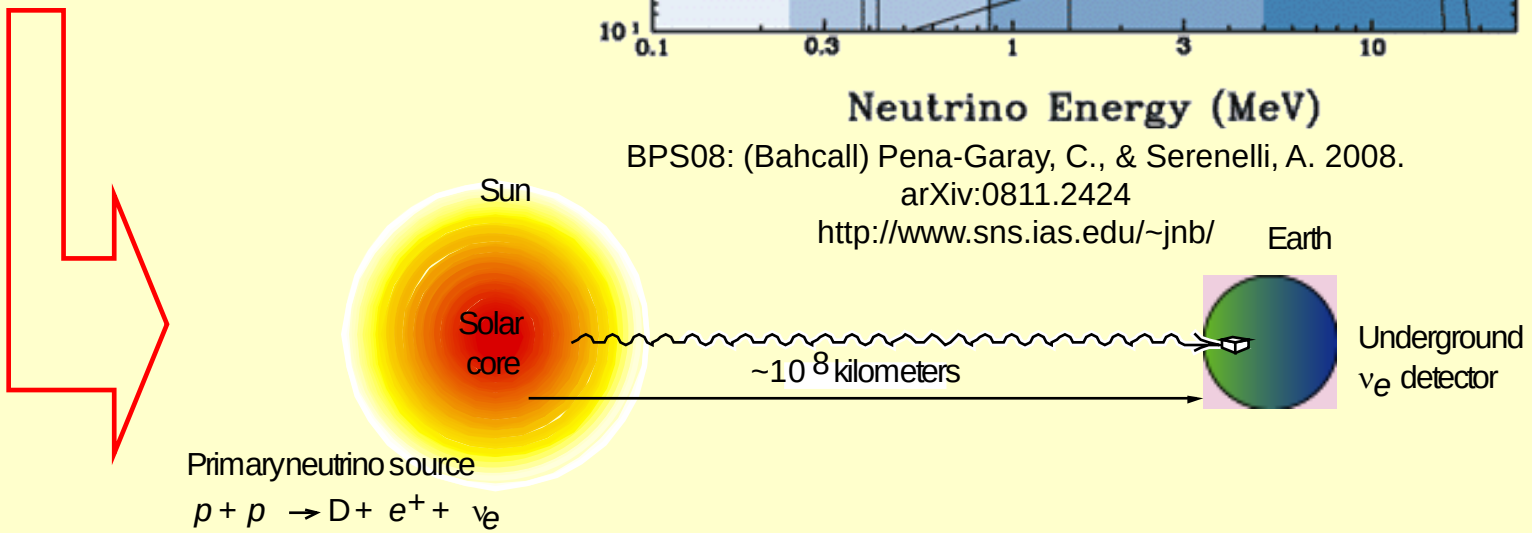
Neutrino Production in the Sun

Light Element Fusion Reactions

★ $p + p \rightarrow {}^2H + e^+ + \nu_e$	99.75 %
$p + e^- + p \rightarrow {}^2H + \nu_e$	0.25 %
${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$	~10^{-5} %
${}^7Be + e^- \rightarrow {}^7Li + \nu_e$	15 %
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$	0.02 %



BPS08: (Bahcall) Pena-Garay, C., & Serenelli, A. 2008. arXiv:0811.2424 http://www.sns.ias.edu/~jnb/



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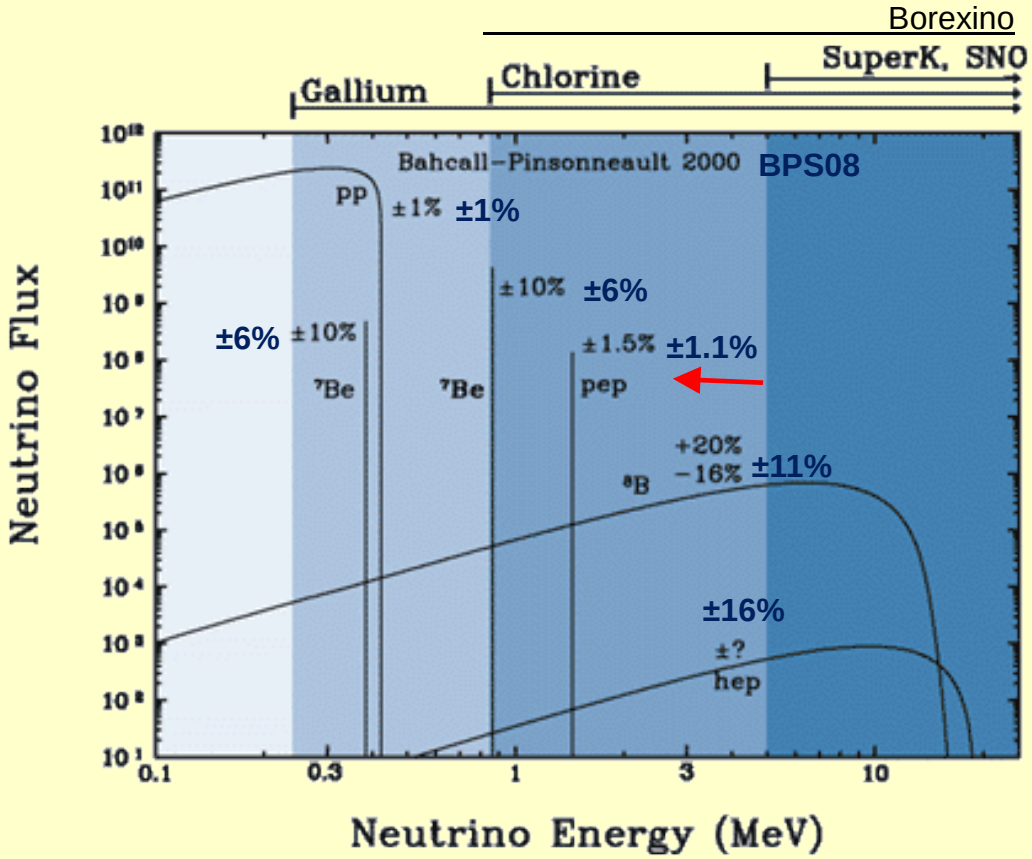

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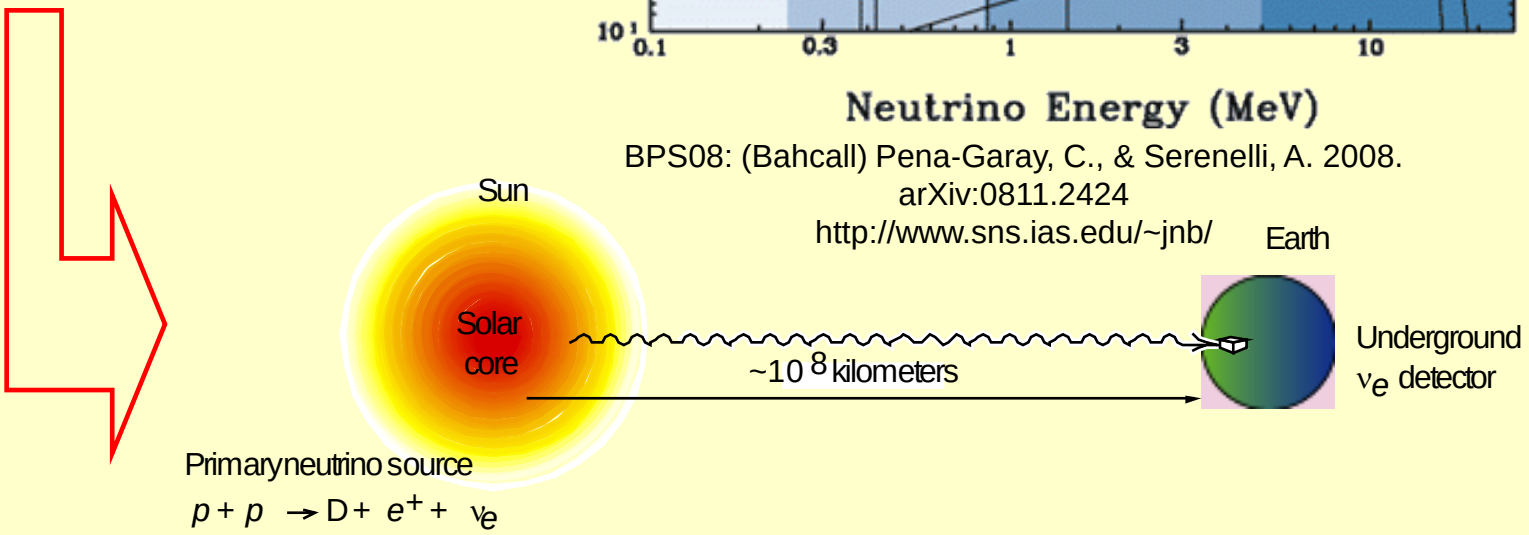

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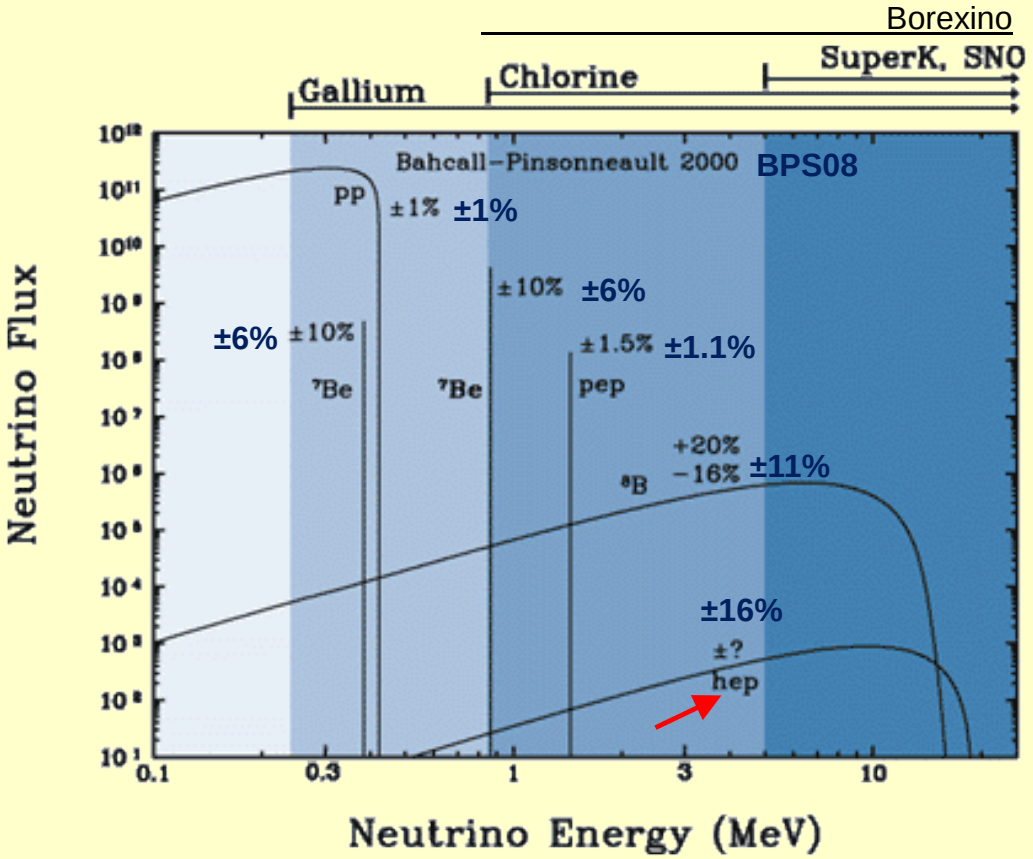

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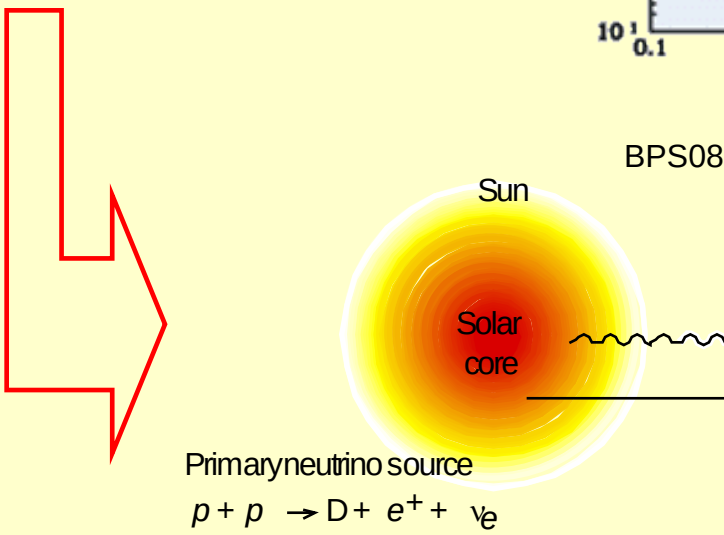

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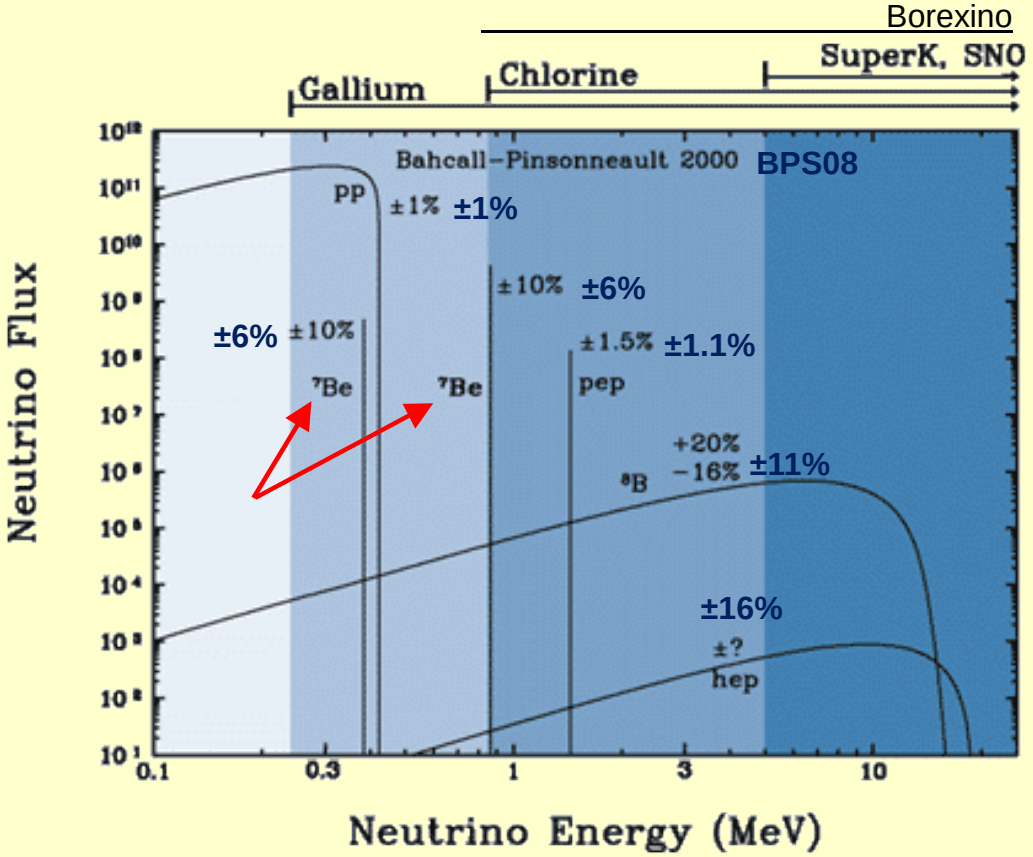

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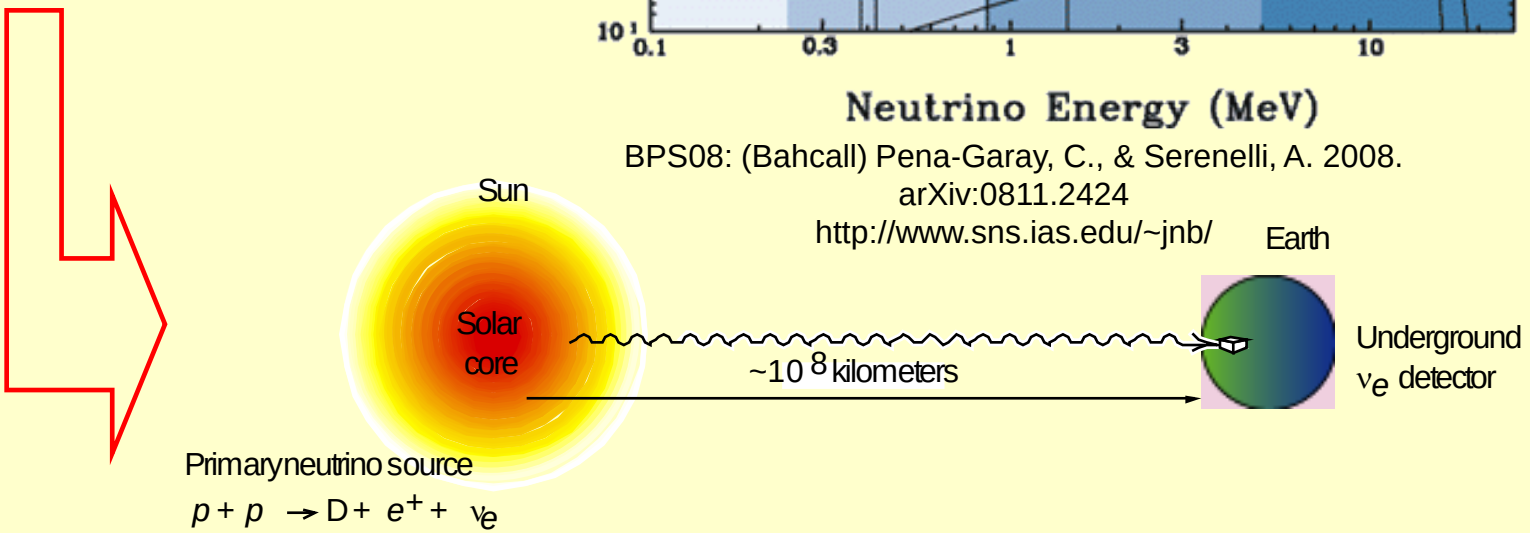

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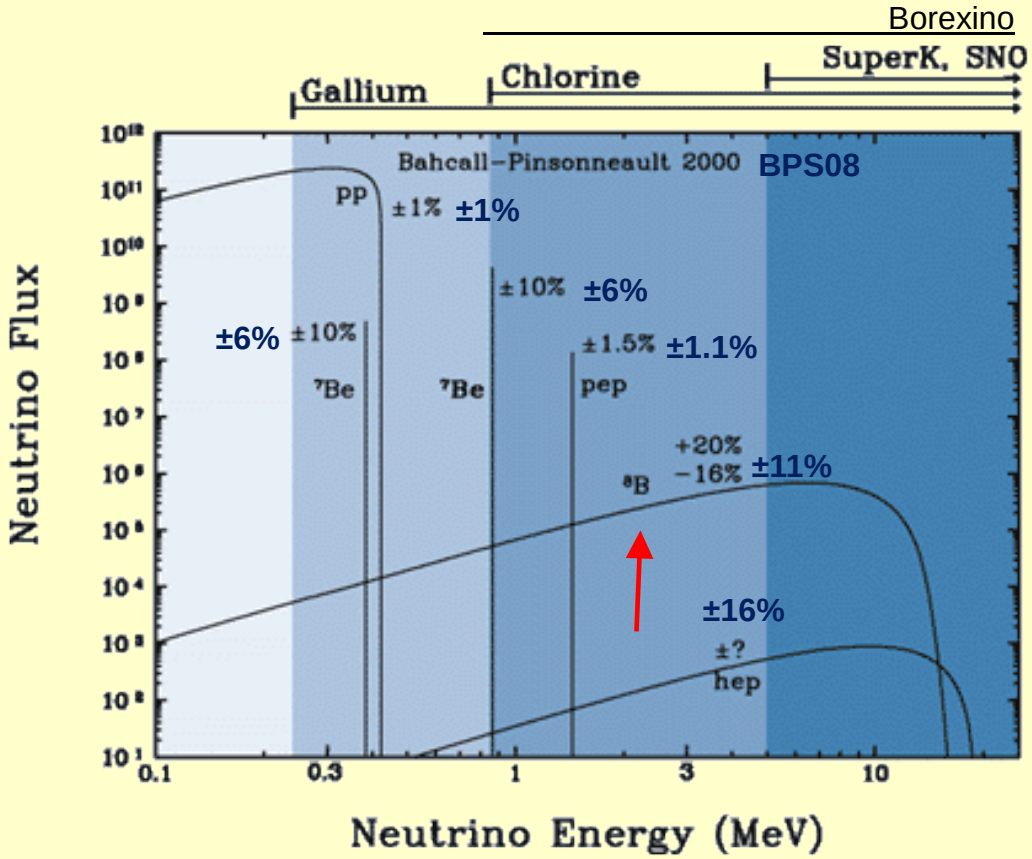

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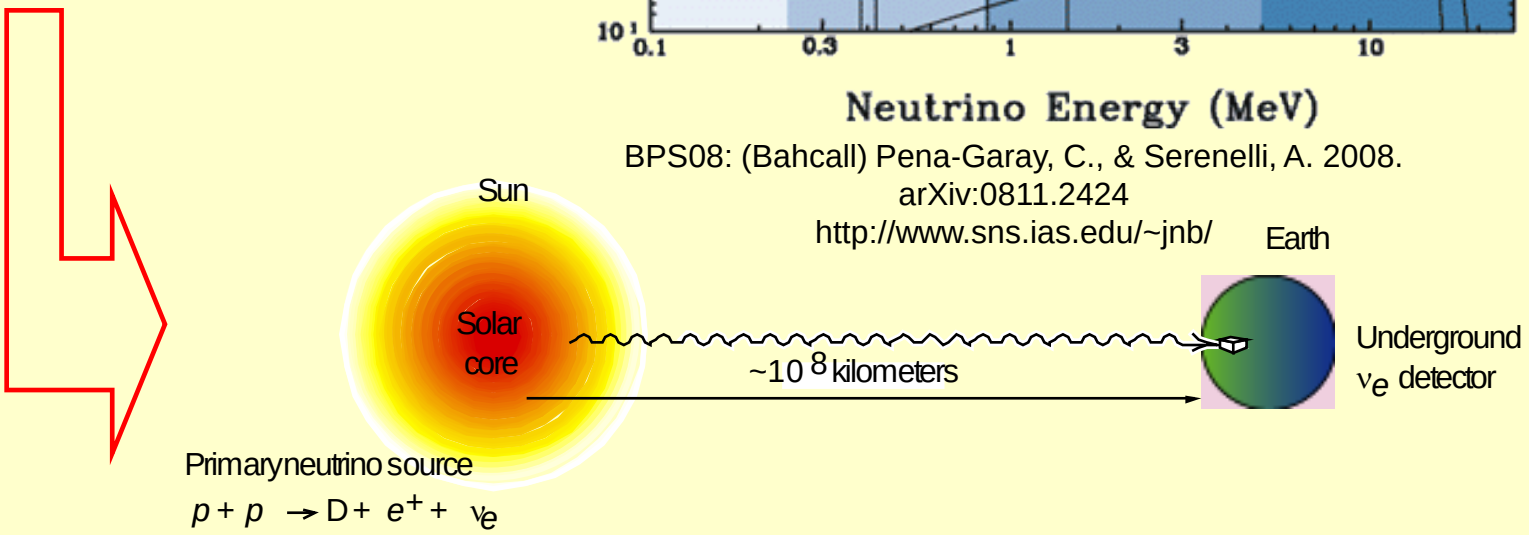
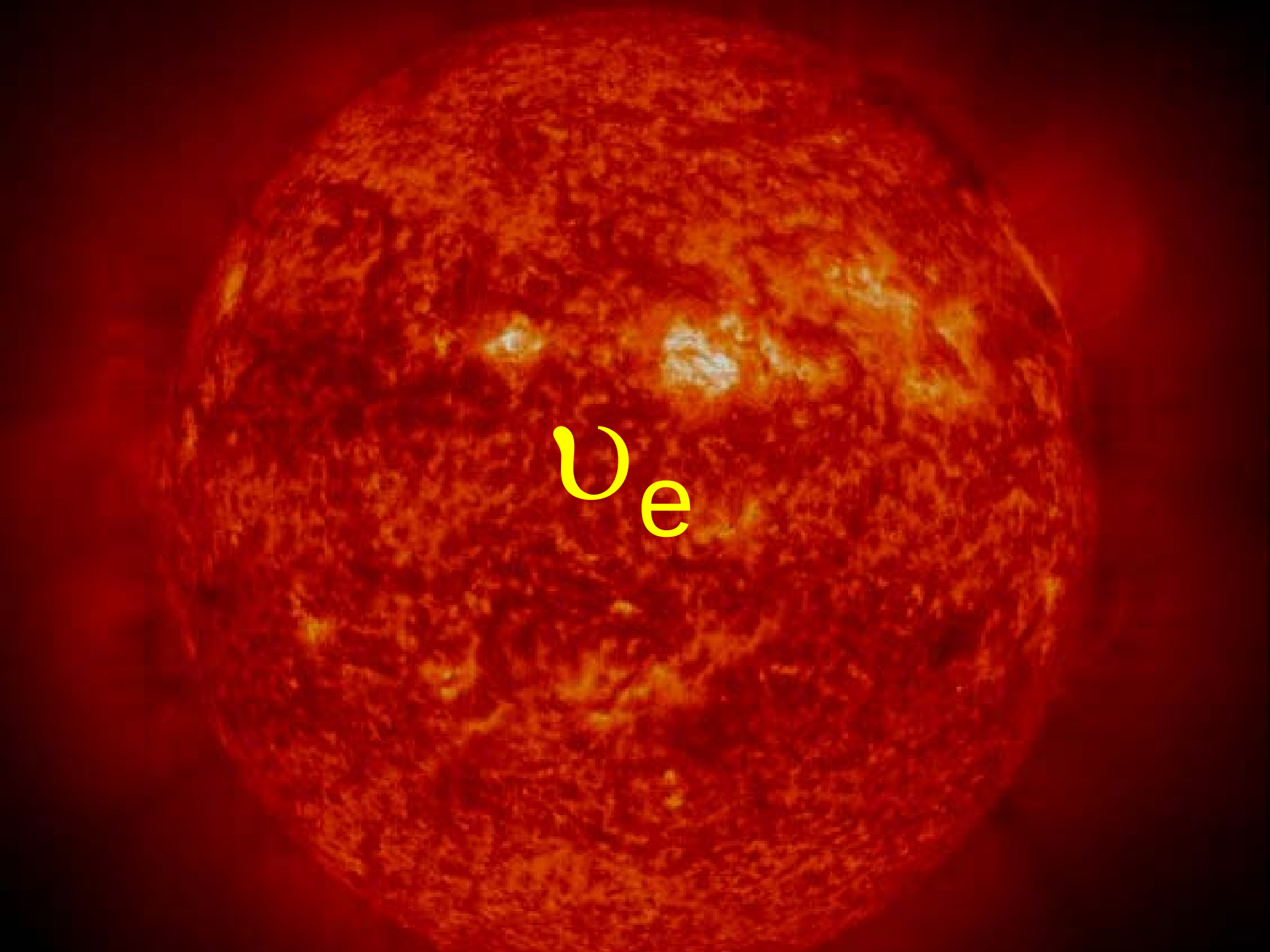



υ_e

Solar Neutrino Mixing

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

$P_{ee} = \cos^4(\theta_{13})[1-\sin^2(2\theta_{12})\sin^2(\varphi)]$

$P_{ee} \approx 1-\sin^2(2\theta_{12})\sin^2(\varphi)$

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

Main Solar 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

$$\theta_{12} = \text{solar mixing}$$

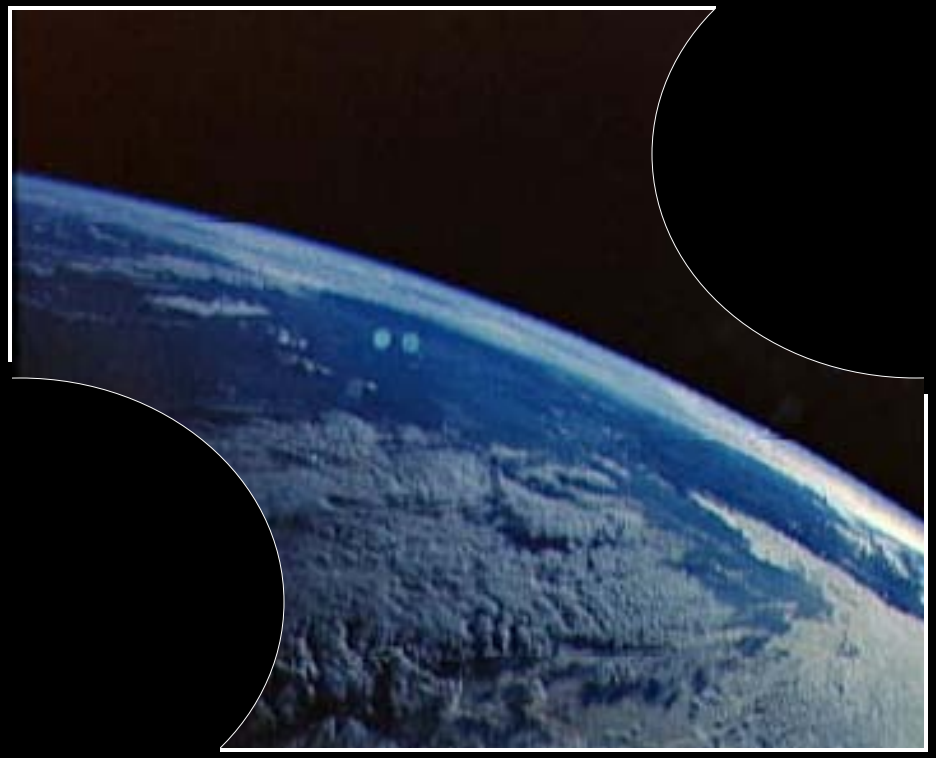
$$\theta_{13} = \text{small}$$

$$\Delta m^2_{31} = \pm 2.3 \times 10^{-3}\ \text{eV}^2$$

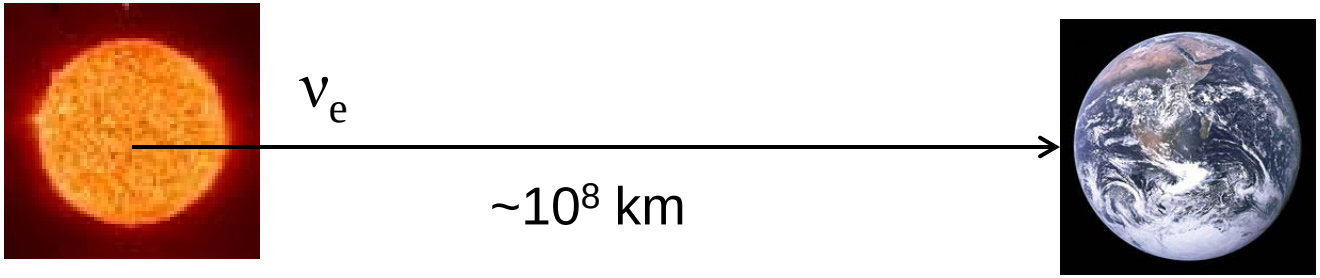
The state evolves with time or distance

The Second Piece:

Pre-SNO (~2001)



Solar Neutrino Problem (Pre SNO)



Measured ≠ Predicted $\overline{P}_{ee}$

Neutrino reactions

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

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

$$\nu_l + e^- \rightarrow \nu_l + e^-$$

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

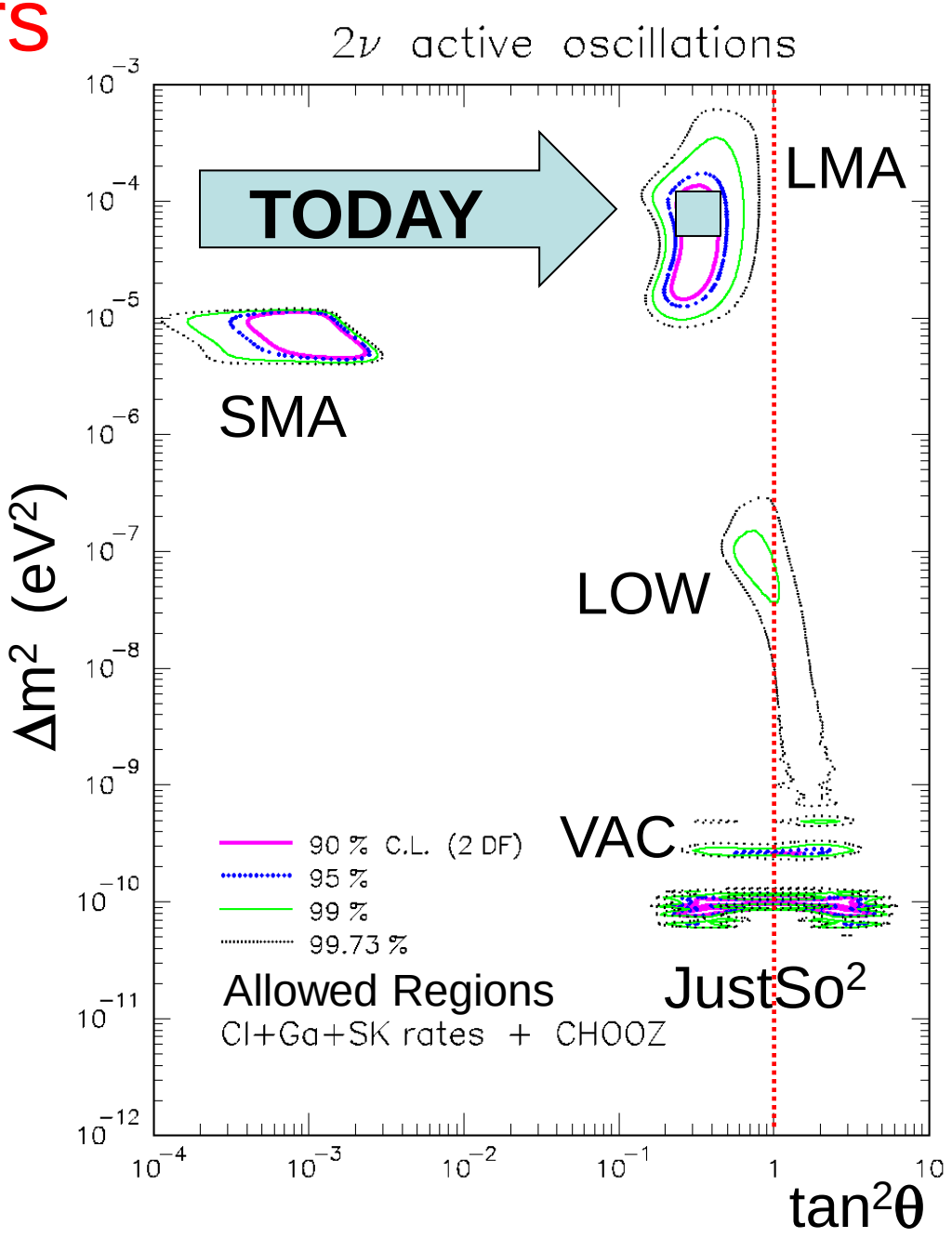
Mixing Parameters

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

Pre SNO (~2001)

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

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



Phys.Rev. D64 (2001) 093007

Arranging the Pieces:

The Sudbury Neutrino Observatory

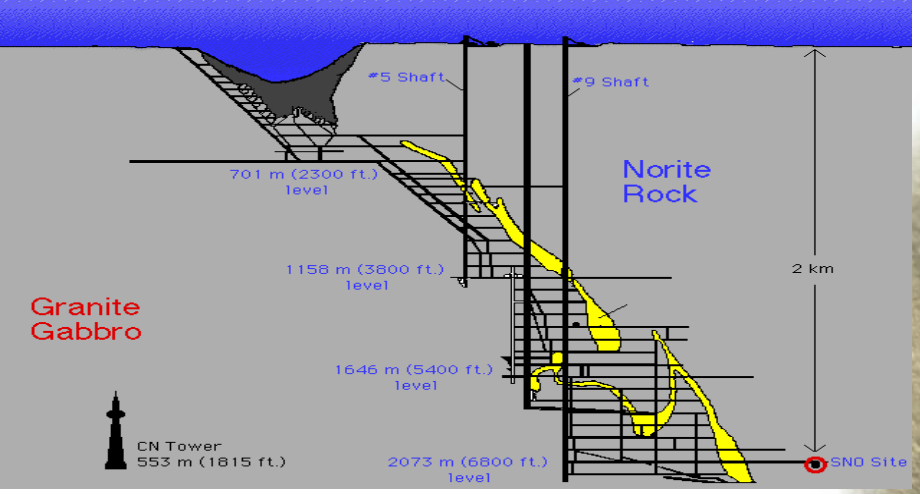


Image courtesy National Geographic

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

17.8 m

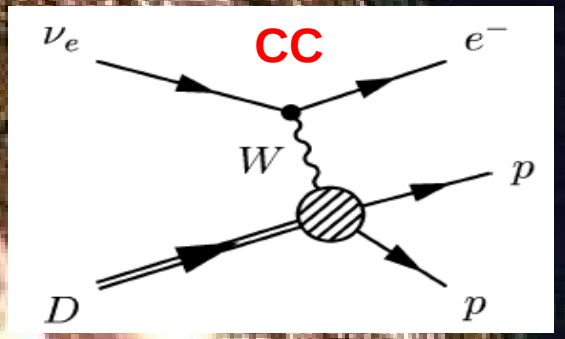
SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE

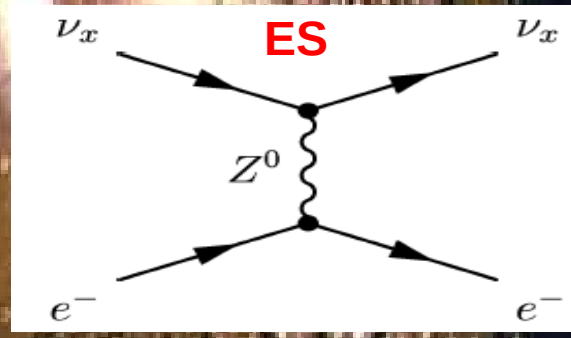
Key signatures for ν mixing with SNO

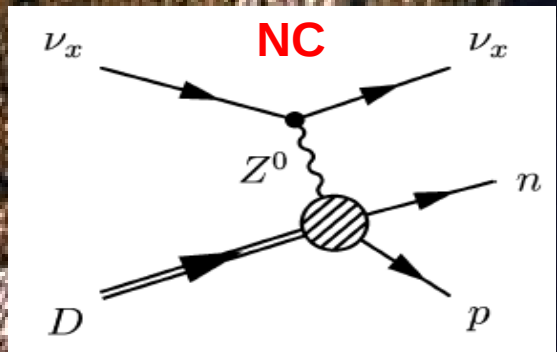
Flavor change ? $P_{ee}(E_\upsilon) \neq 1$!

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

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

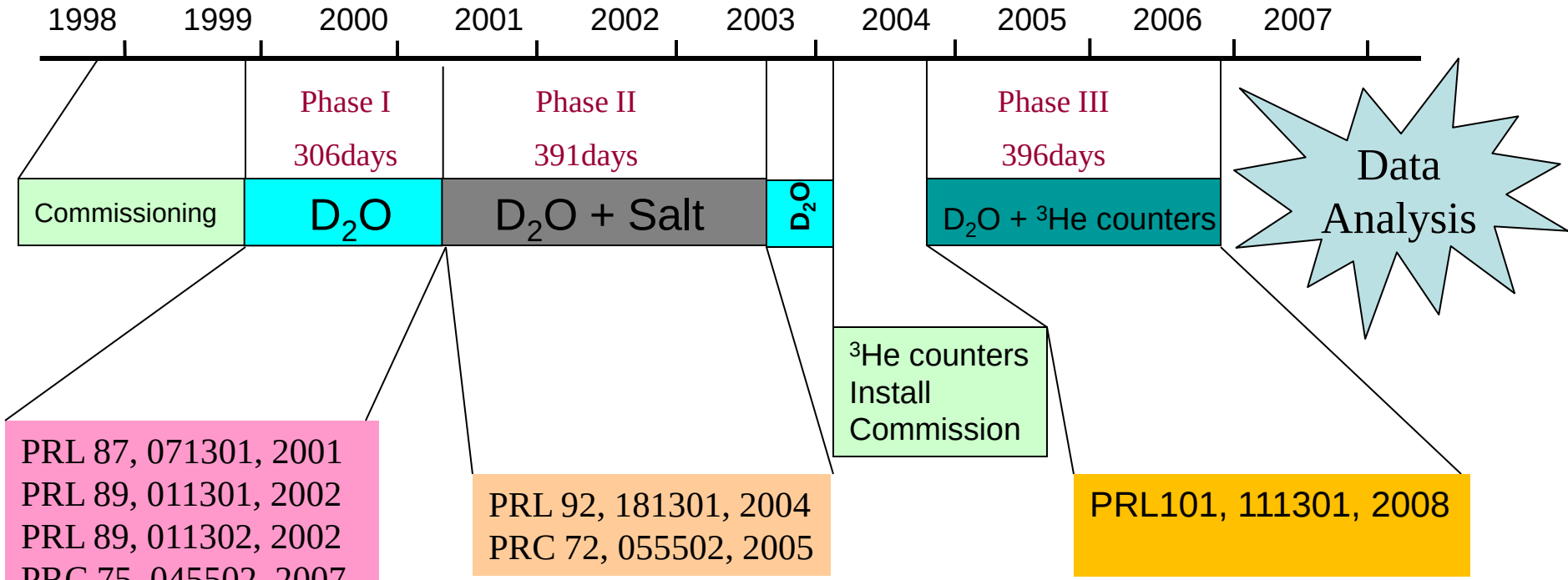






Timeline of SNO

Total of ~1100 live-days



PRC, 055504, 2010

Combined Phase I-II
Low Energy Threshold Analysis

Upcoming… Phase I-II-III combined analysis

Soon!

SNO Phases I+II Major Improvements

- Tune up the Monte Carlo on calibration data based on 5 years of operational experience - Reduction of systematic uncertainties
- Improve optics (especially at large radii) with late light and new energy estimator (improve energy resolution by 6%)

Energy Threshold

D_2O phase

T_{eff} = 5 → 3.5 MeV

Salt phase

T_{eff} = 5.5 → 3.5 MeV

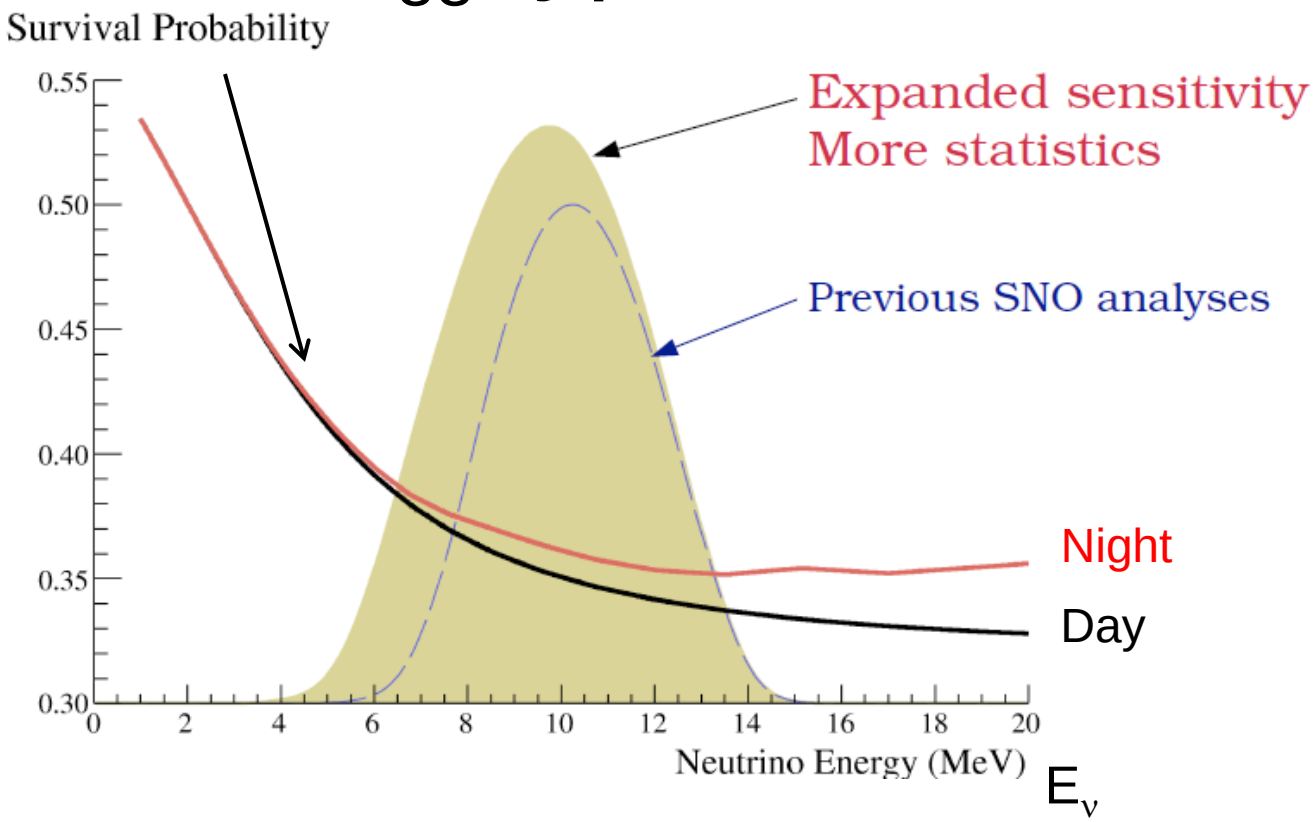
Improve statistics

CC by ~40%

NC by ~70%

Allow to fit the background wall

P_{ee} typical LMA



SNO Phases I+II

Direct joint-phase fit of P_{ee}

$$\Phi(^8B) = 5.046^{+0.159\ +0.107}_{-0.152\ -0.123}$$

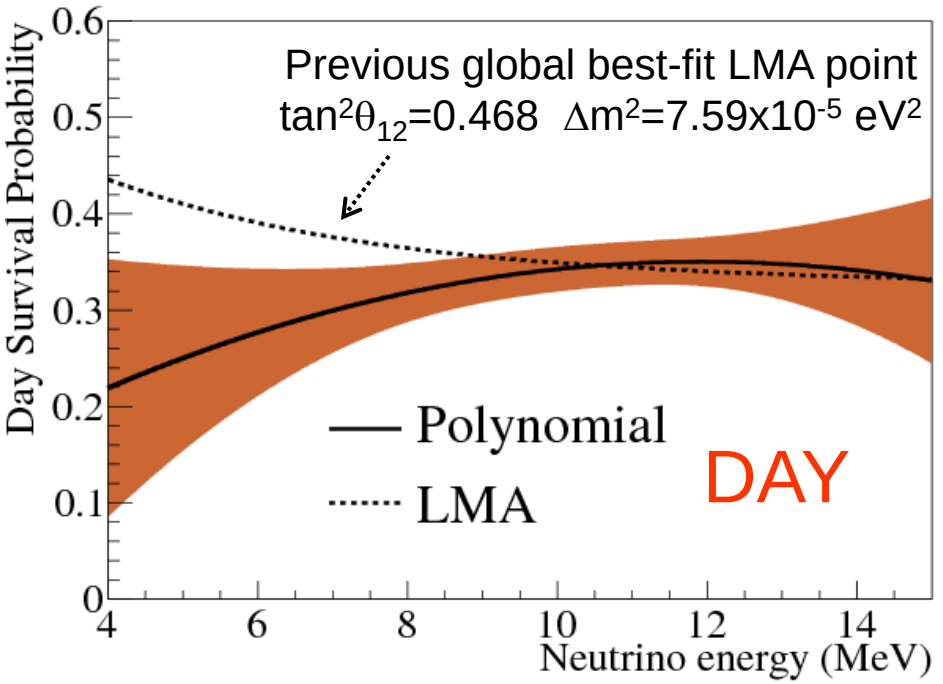
in units of 10^6 cm^{-2} s^{-1}

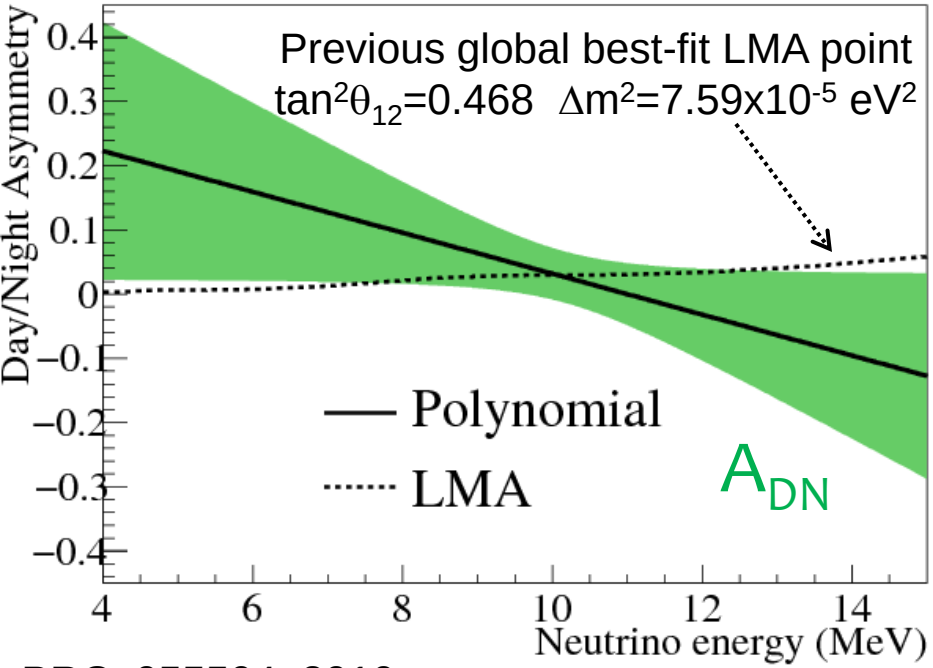
No distortion, no D/N:

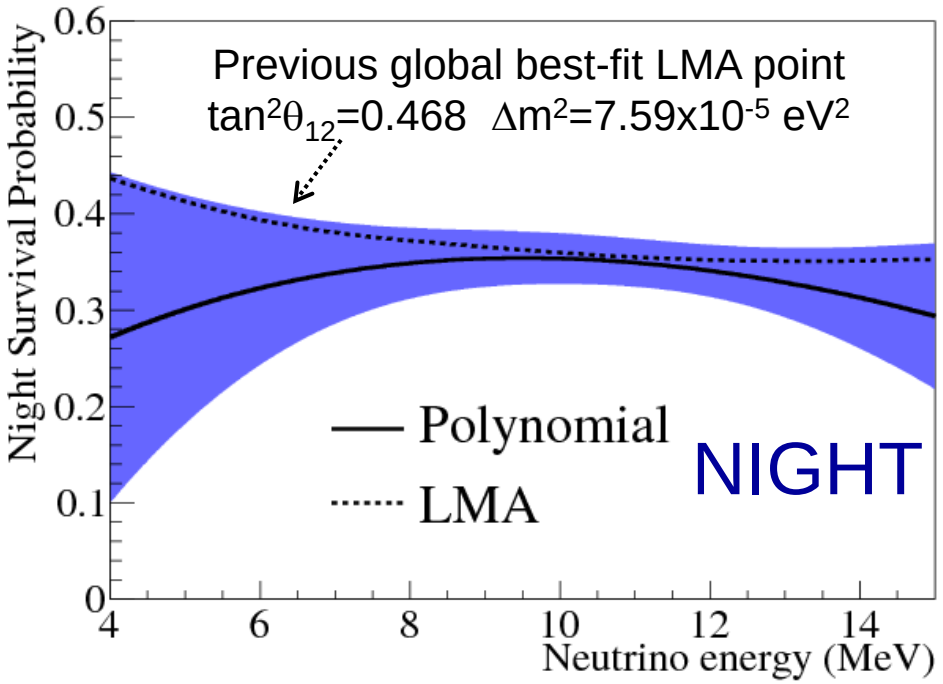
$\Delta\chi^2$ = 1.94 / 4 d.o.f.

LMA-prediction:

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



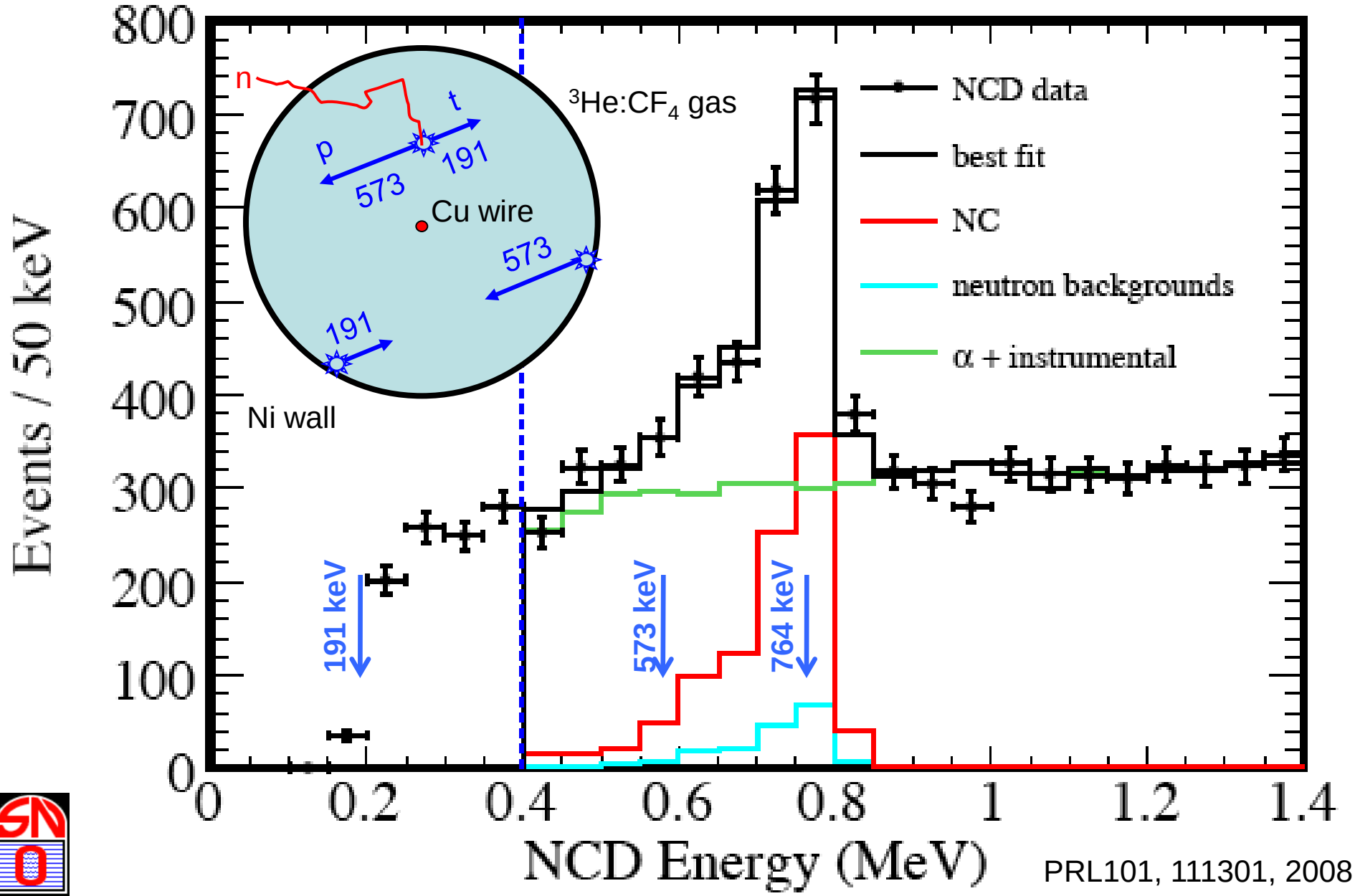




PRC, 055504, 2010

SNO NCD's Phase III

$$\frac{\phi_{CC}^{SNO}}{\phi_{NC}^{SNO}} = 0.301 \pm 0.033(\text{total}).$$



PRL101, 111301, 2008

Global View

Data Sets Solar Oscillation Analysis

- Radiochemical : Cl, Ga
  - Ga rate: 66.1 ±3.1 SNU SAGE+GNO/GALLEX [PRC80, 015807(2009)]
  - Cl rate: 2.56 ±0.23 [Astrophys. J. 496 (1998) 505]

- SK
  - SK-I 1496 days, zenith spectrum E ≥ 5.0 MeV
  - SK-II 791 days, spectrum + D/N E ≥ 7.5 MeV

- Borexino
  - ^{7}Be rate: 49 ± 5 cpd/100tons [PRL101, 091302(2008)]

- SNO
  - Phase I + II (PMT Low Energy threshold E ≥ 4.0 MeV)
  - Phase III (NCD and PMT E ≥ 6.5MeV)

- KamLAND reactor experiment: 2008 [PRL100, 221803 (2008)]

- ^{8}B spectrum: W. T. Winter et al., PRC 73, 025503 (2006).

Oscillation Analyses: Global Solar

Best-fit LMA point:

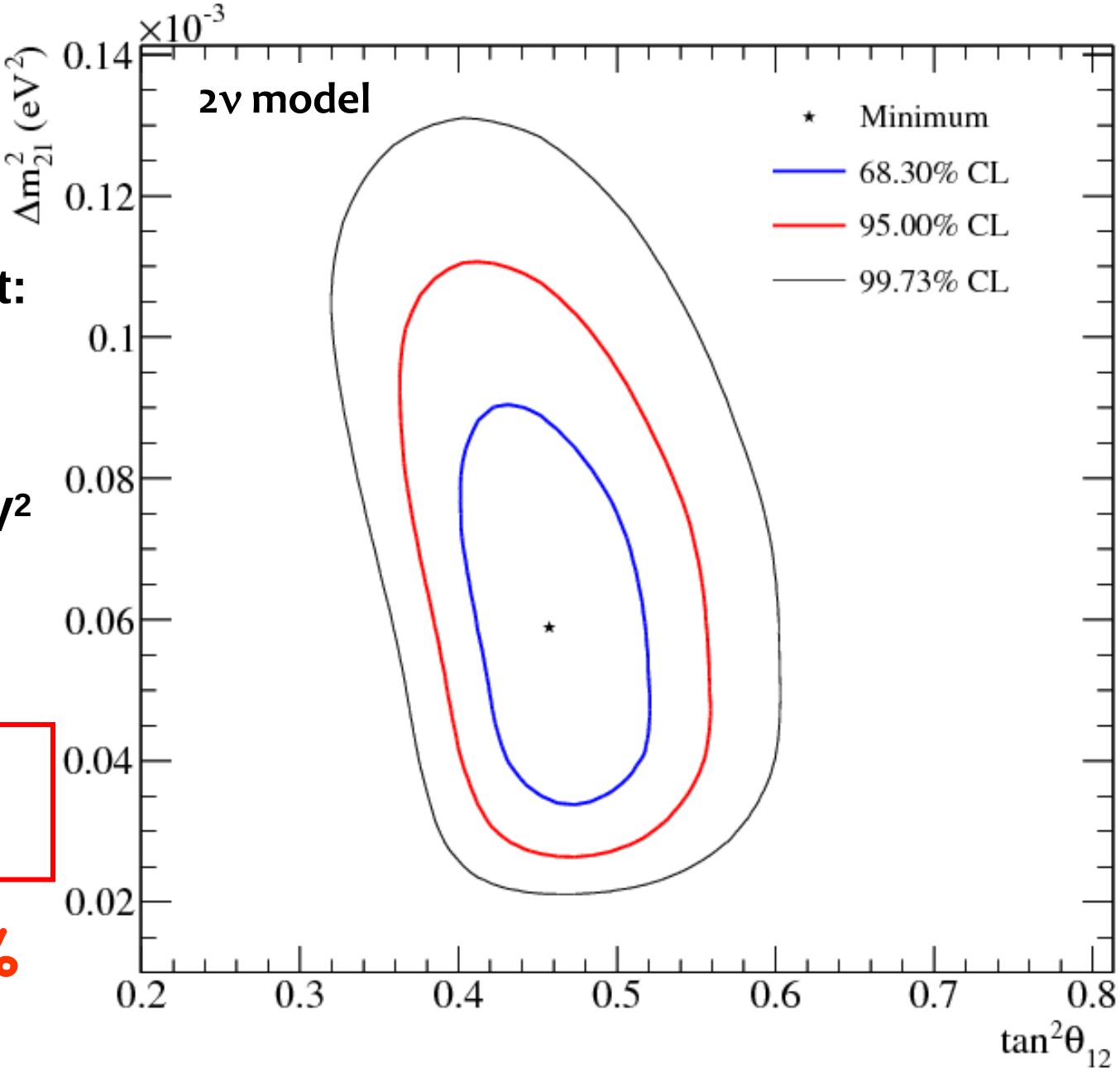
$\tan^2\theta_{12} = 0.457$
$(+0.038\ -0.041)$

$\Delta m^2_{12} = 5.89 \times 10^{-5}\ eV^2$
$(+2.13\ -2.16)$

$\Phi(^8B) = 5.104$

in units of $10^6\ cm^{-2}\ s^{-1}$

$\Delta\Phi_{8B} = {}^{+3.90}_{-2.95}\ \%$



Solar + KamLAND 2-flavor

Best-fit LMA point:

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

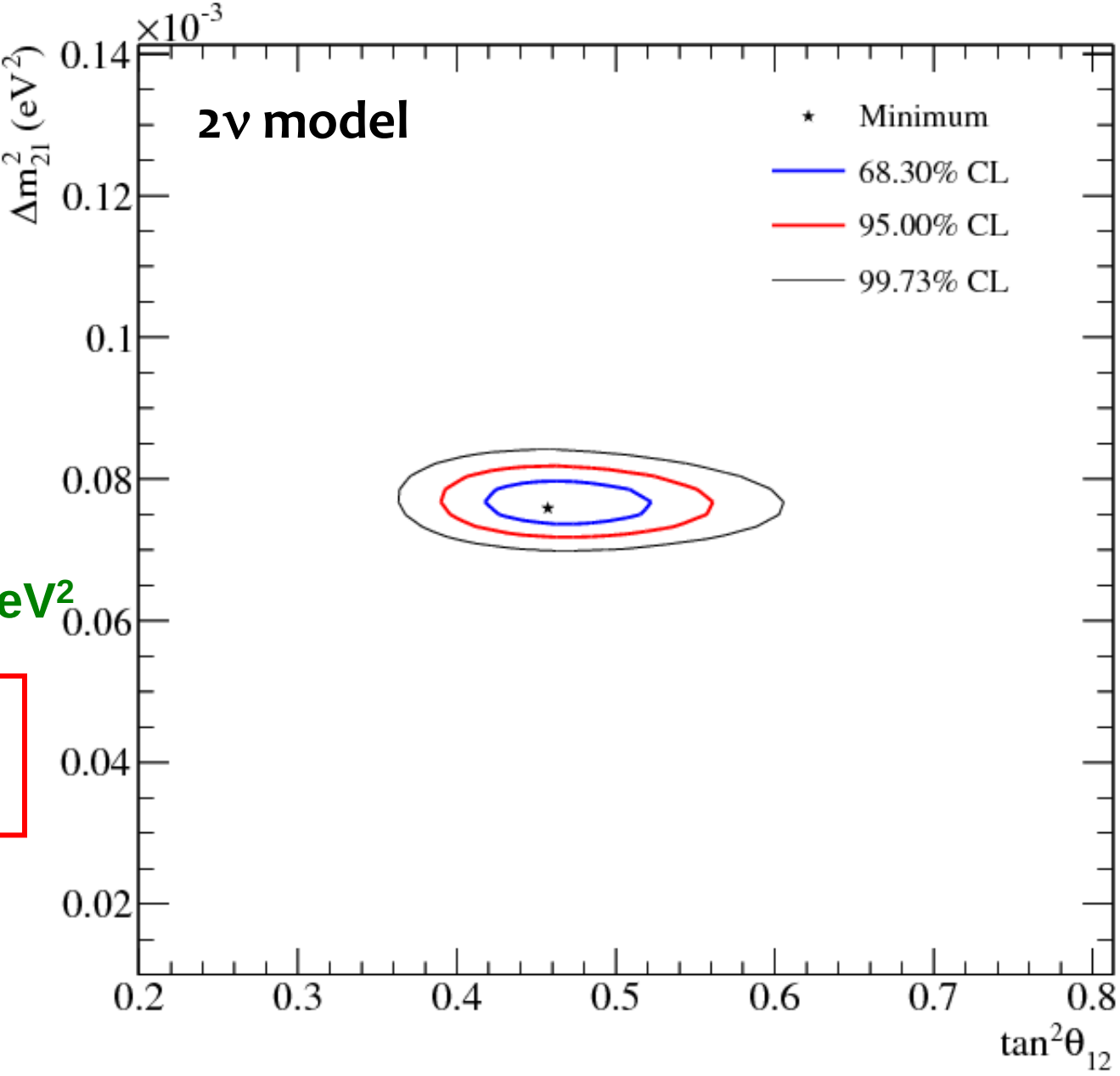
$\theta_{12} = 34.06\ ^{+1.16}_{-0.84}$ deg

$\Delta m^2_{12} = 7.59\ ^{+0.20}_{-0.21}$ x10^{-5} eV^2

Φ(8B) = 5.013

in units of 10^6 cm^{-2} s^{-1}

$\Delta\Phi_{8B} = \ ^{+2.37}_{-2.95}$ %



Solar + KamLAND 3-flavor

Best-fit LMA point:

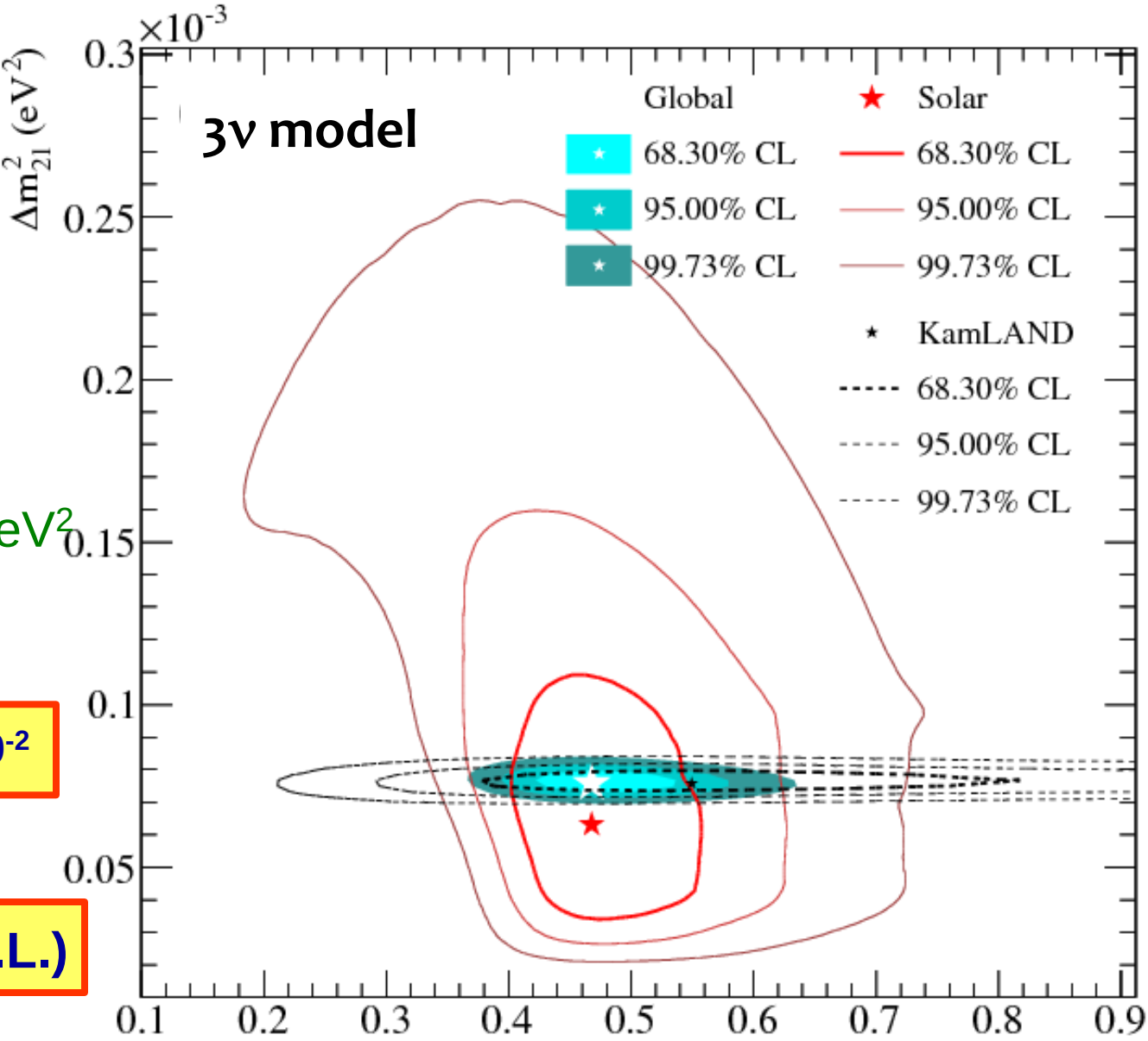
$\tan^2\theta_{12} = 0.468\ ^{+0.042}_{-0.023}$

$\Delta m^2_{12} = 7.59\ ^{+0.21}_{-0.21}\ x10^{-5}\ eV^2$

Best-fit:

$\sin^2\theta_{13} = 2.00\ ^{+2.09}_{-1.63}\ x10^{-2}$

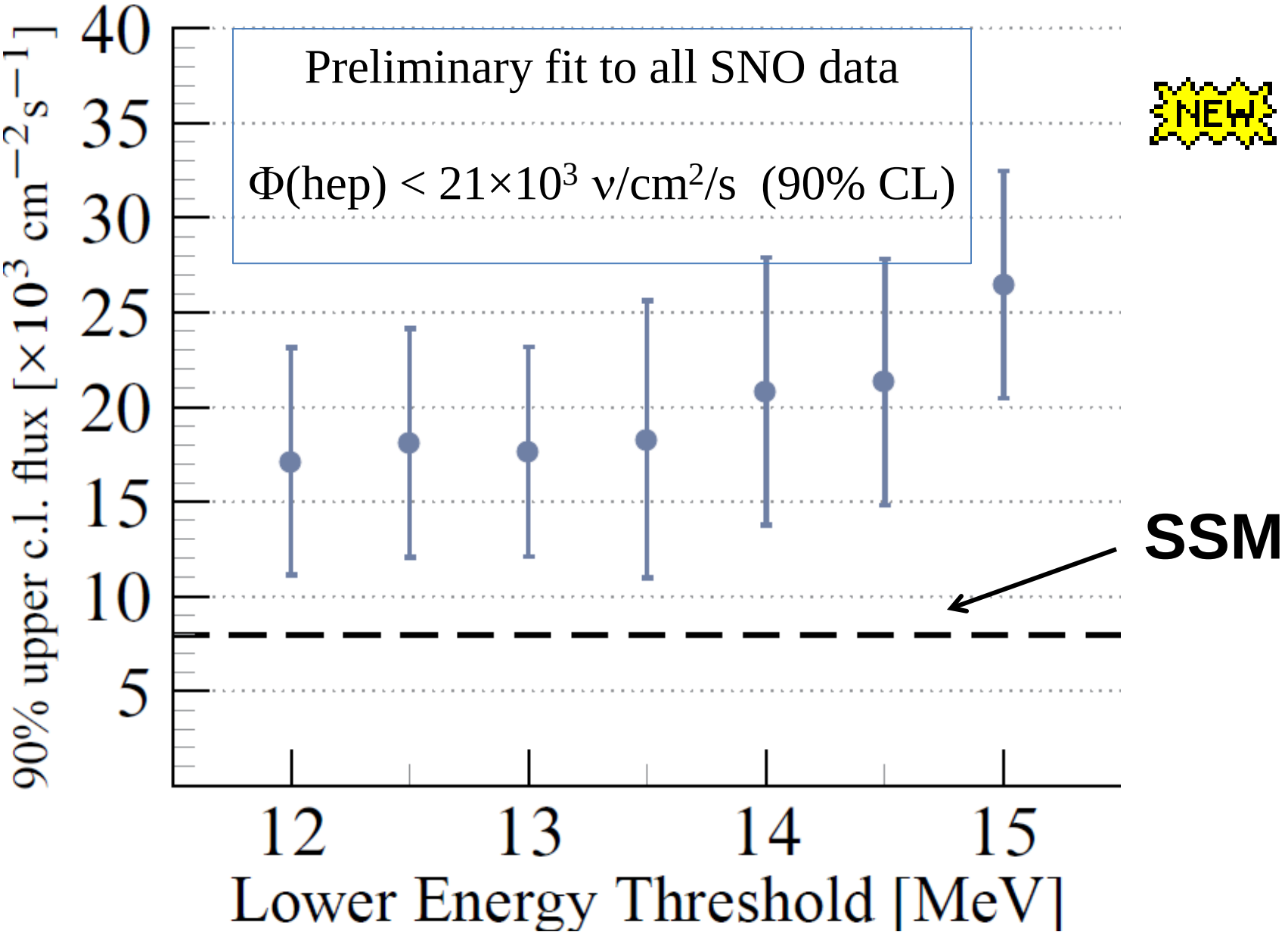
$\sin^2\theta_{13} < 0.057$ (95% C.L.)



Remark: SNO and SK global oscillation analyses consistent

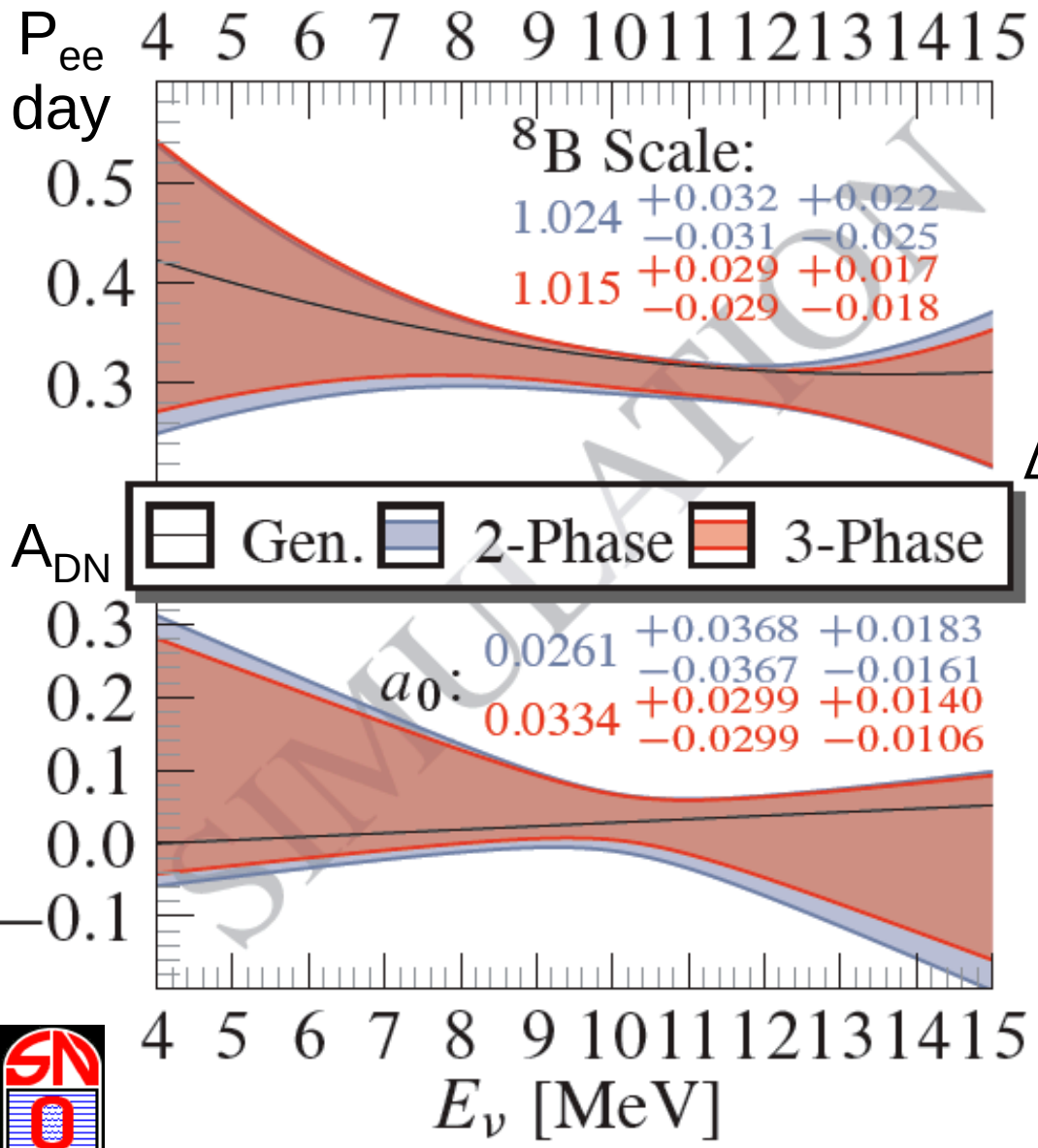

Newest
stuff for
summer
2011 !!!

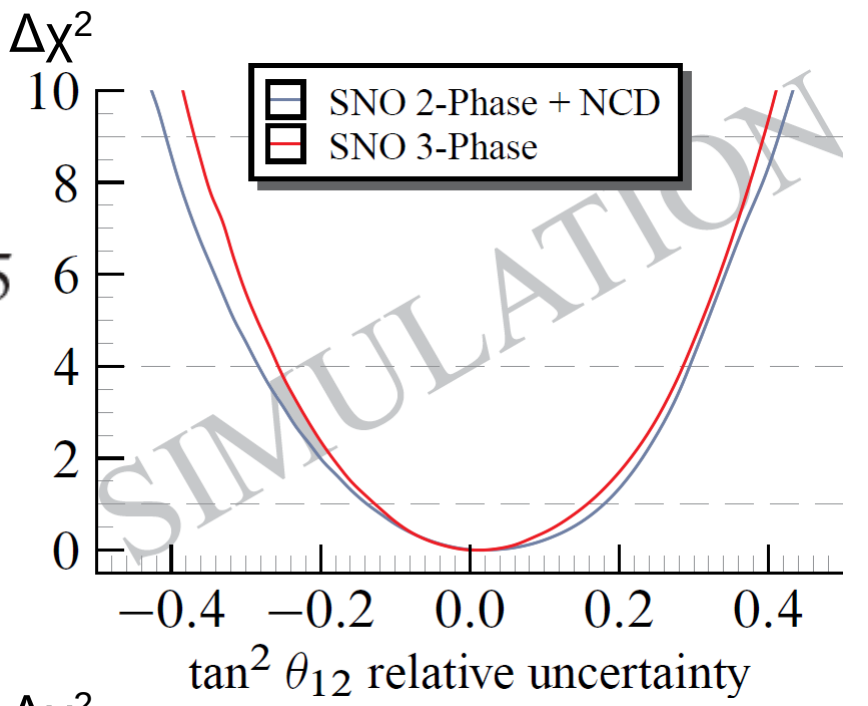
SNO hep neutrino sensitivity (3-phase)

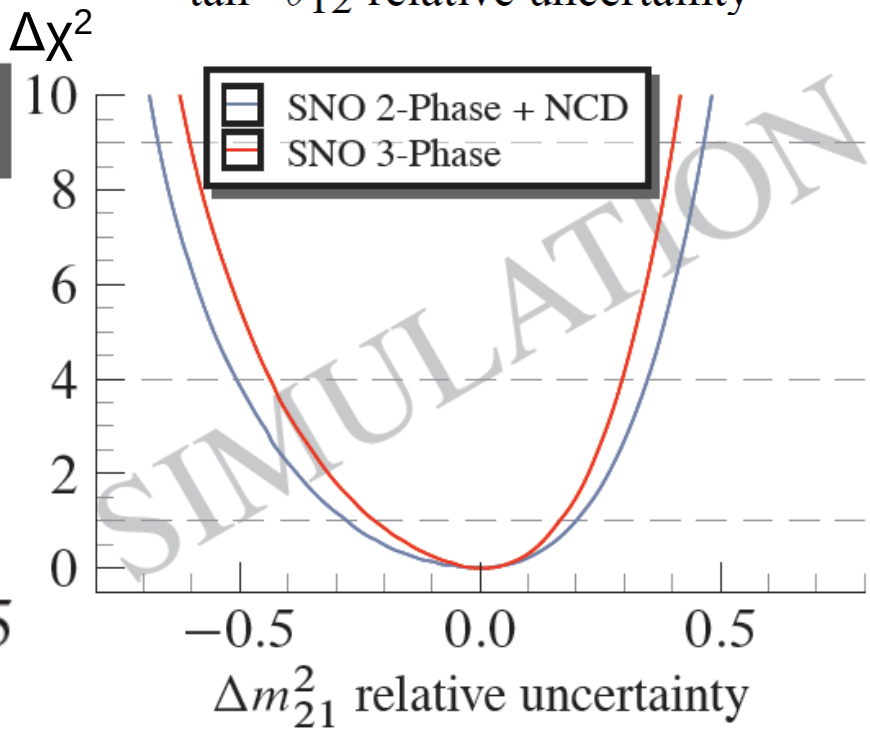


SNO Full 3-Phase

Expected improvement



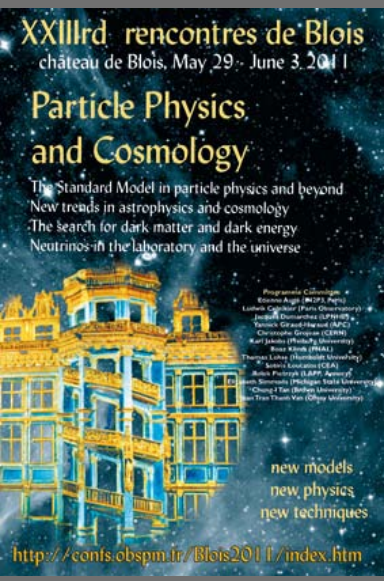




Conclusion & Future

- Great physics out of solar neutrino experiments
  From solving SNP to precision physics
- Direct evidence of solar neutrino oscillation by SNO
- Global solar solution favors LMA (Cl+Ga+SK+BX+SNO)

- **SNO**: 3-flavour analysis
- Upcoming new and final SNO I+II+III publication
  Almost ready… to be expected for TAUP 2011
- Expect further improvement with SNO 3-phase analysis
  The only model-independent fit of solar survival probability



Merci !

Thank you!

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