Future Solar Neutrino Physics

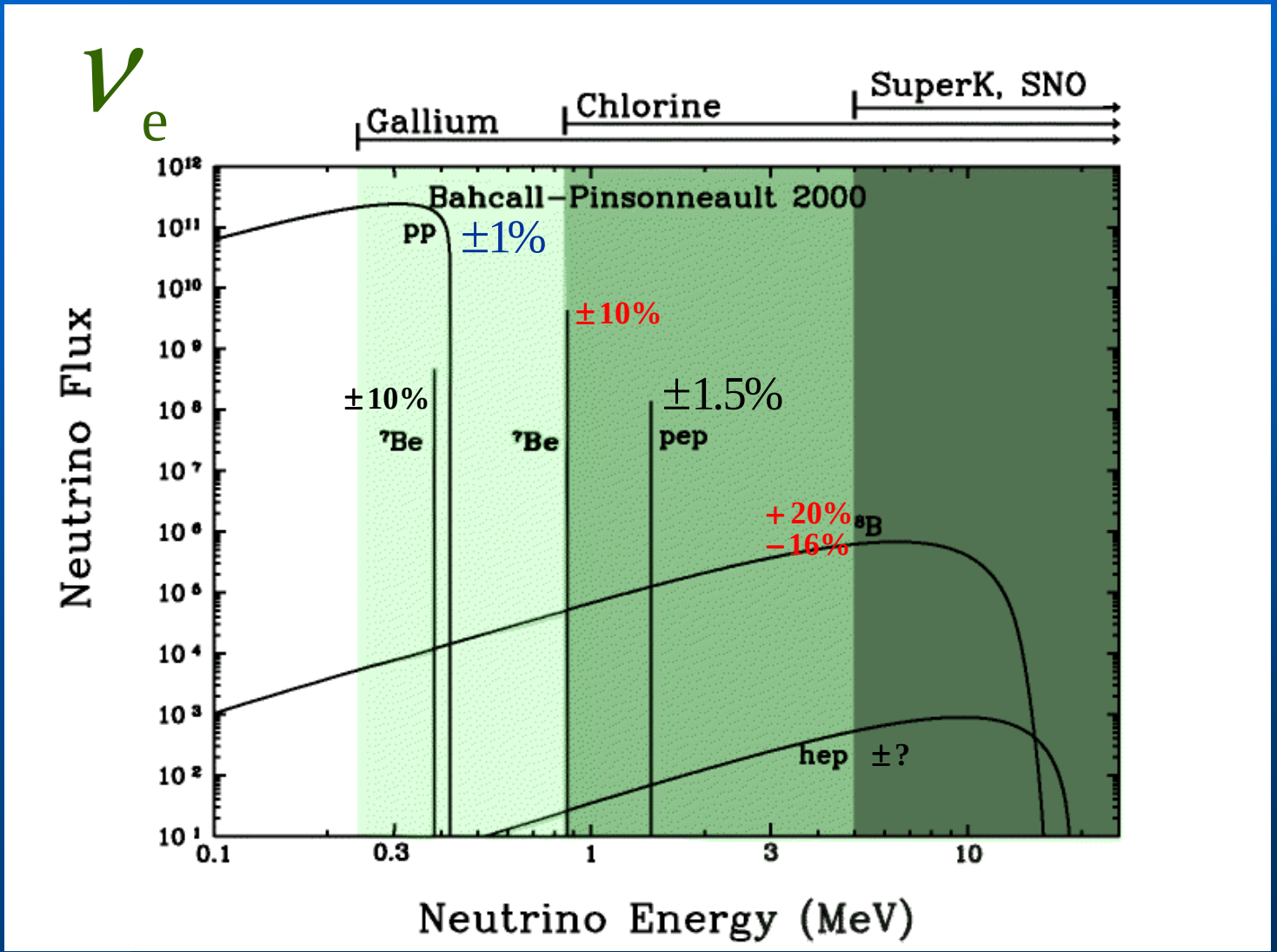
Carlos Peña Garay

IAS

Outline

- **Present**
- **2003-2005**
- **Beyond 2005**

Solar Neutrinos

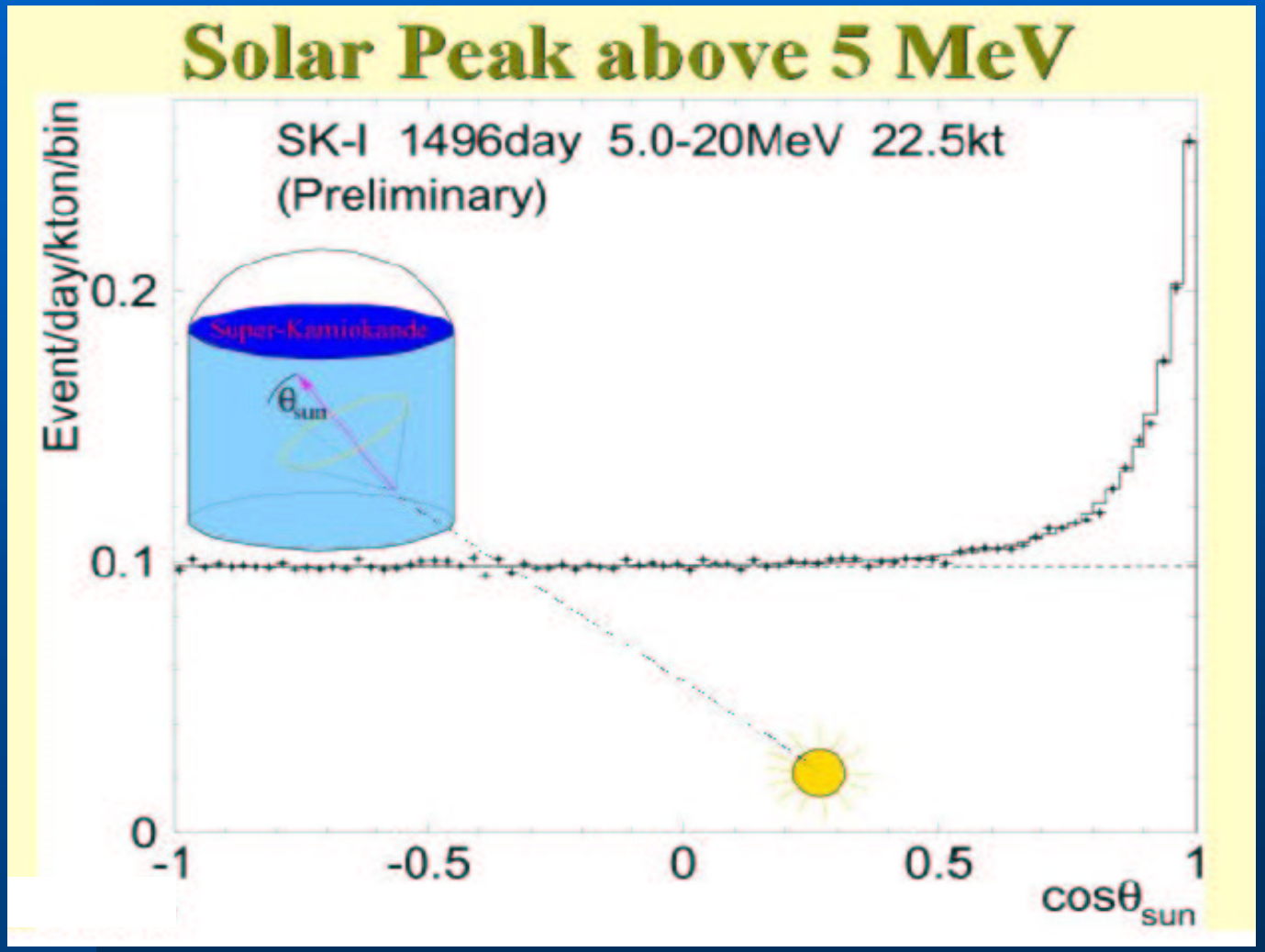


Star νars

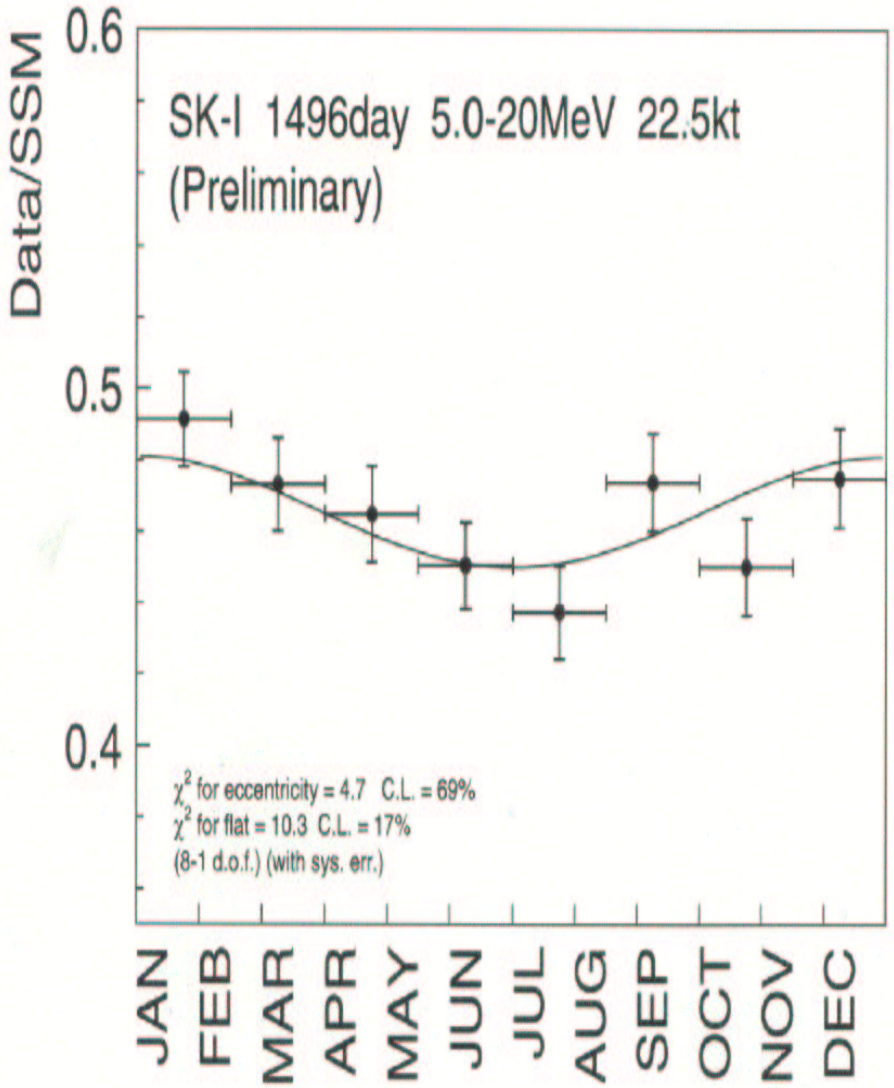
IV. A new hope **Super-Kamiokande**

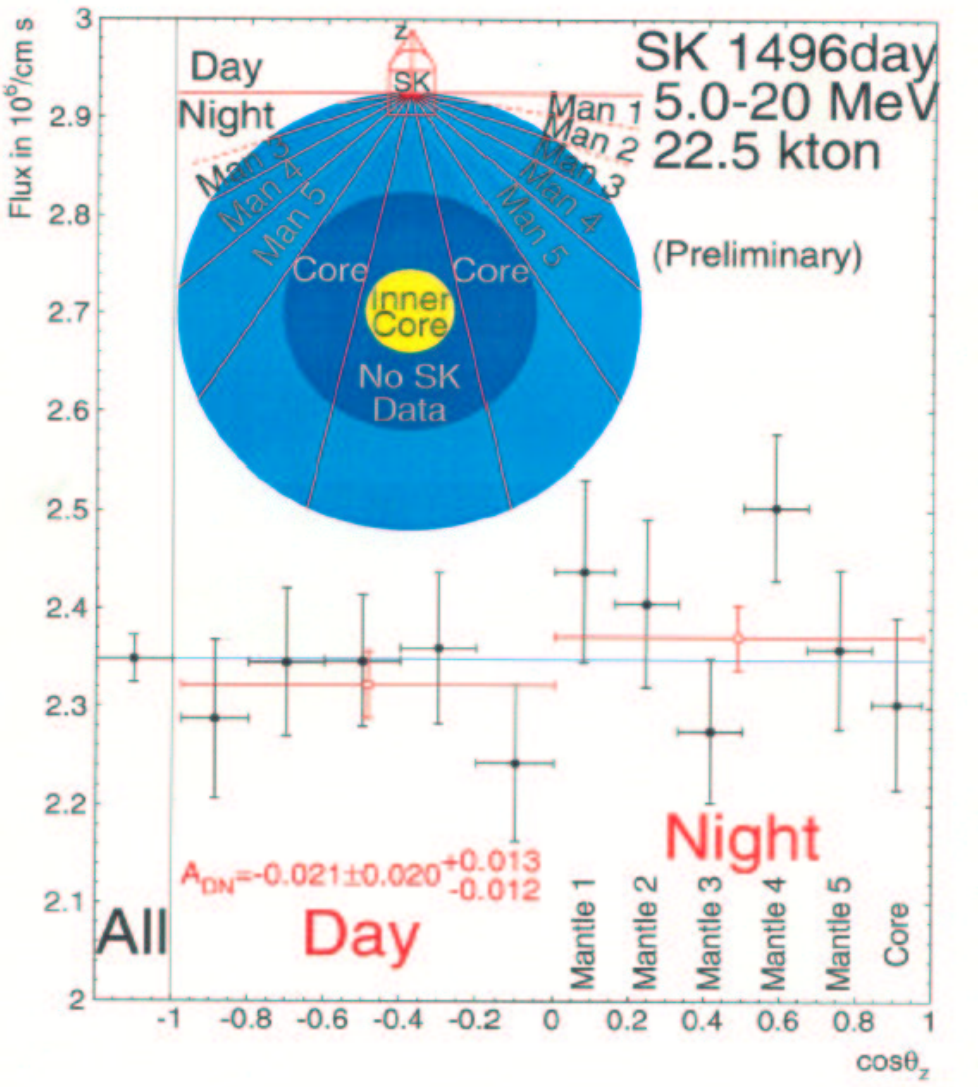
SK ES

$$\phi_{ES} = 2.39 \pm 0.02 \pm 0.08 \times 10^{6}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

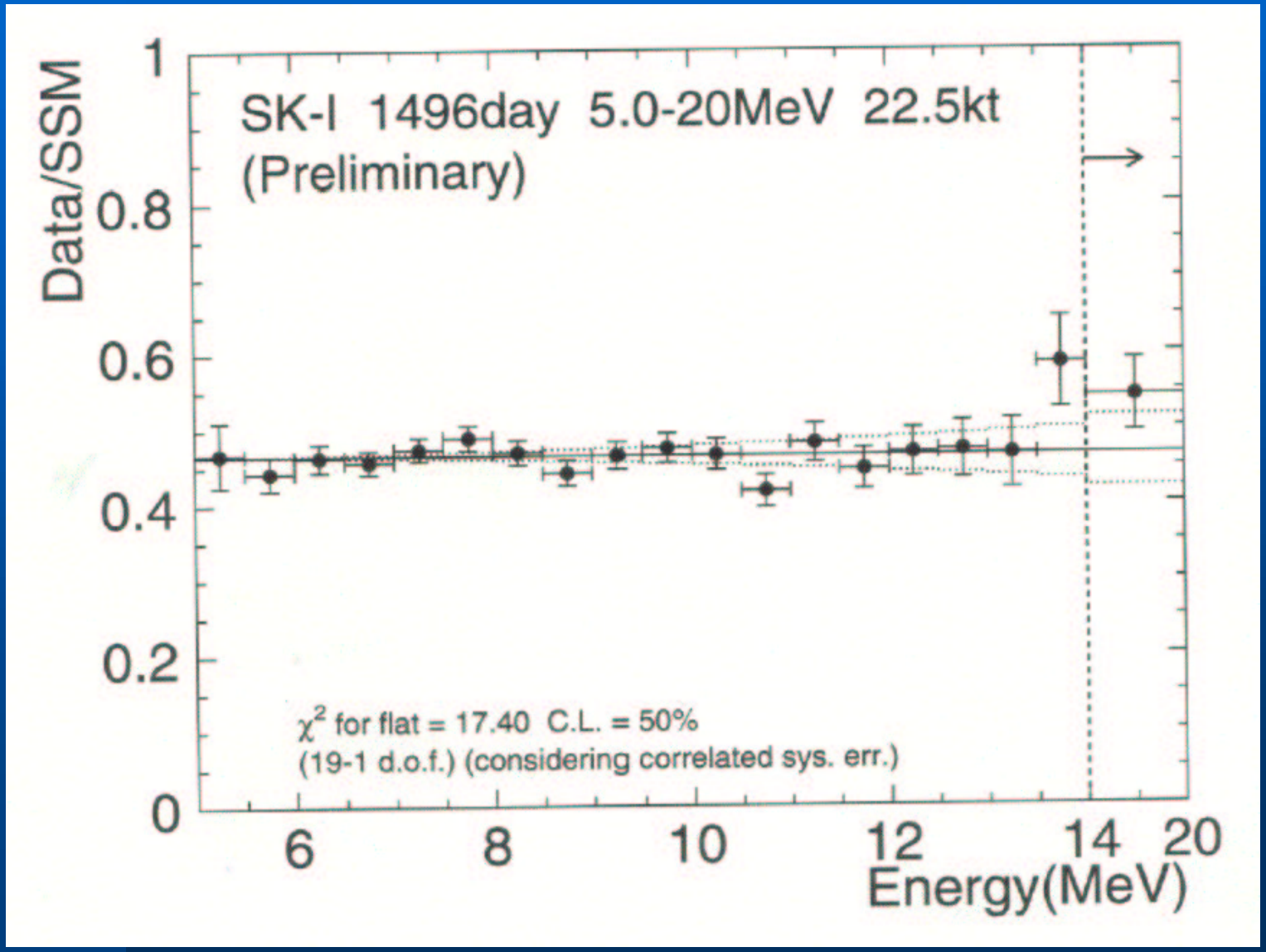


SK ES


Data/SSM
0.6
0.5
0.4
SK-I 1496day 5.0-20MeV 22.5kt
(Preliminary)
χ² for eccentricity = 4.7 C.L. = 69%
χ² for flat = 10.3 C.L. = 17%
(8-1 d.o.f.) (with sys. err.)
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC


Flux in 10⁶/cm s
3
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
Day
Night
SK
Man 1
Man 2
Man 3
Man 4
Man 5
Core
Core
Inner Core
No SK Data
SK 1496day
5.0-20 MeV
22.5 kton
(Preliminary)
A_DN=-0.021±0.020 +0.013 -0.012
All
Day
Night
Mantle 1
Mantle 2
Mantle 3
Mantle 4
Mantle 5
Core
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
cosθz

SK ES


SK-I 1496day 5.0-20MeV 22.5kt
(Preliminary)
Data/SSM
1
0.8
0.6
0.4
0.2
0
χ^2 for flat = 17.40 C.L. = 50%
(19-1 d.o.f.) (considering correlated sys. err.)
6
8
10
12
14
20
Energy(MeV)

A Trilogy

$$[ES] = f_B \{P_{ee} + (1 - P_{ee}) \frac{\sigma_{\mu/\tau}}{\sigma_e}\}$$

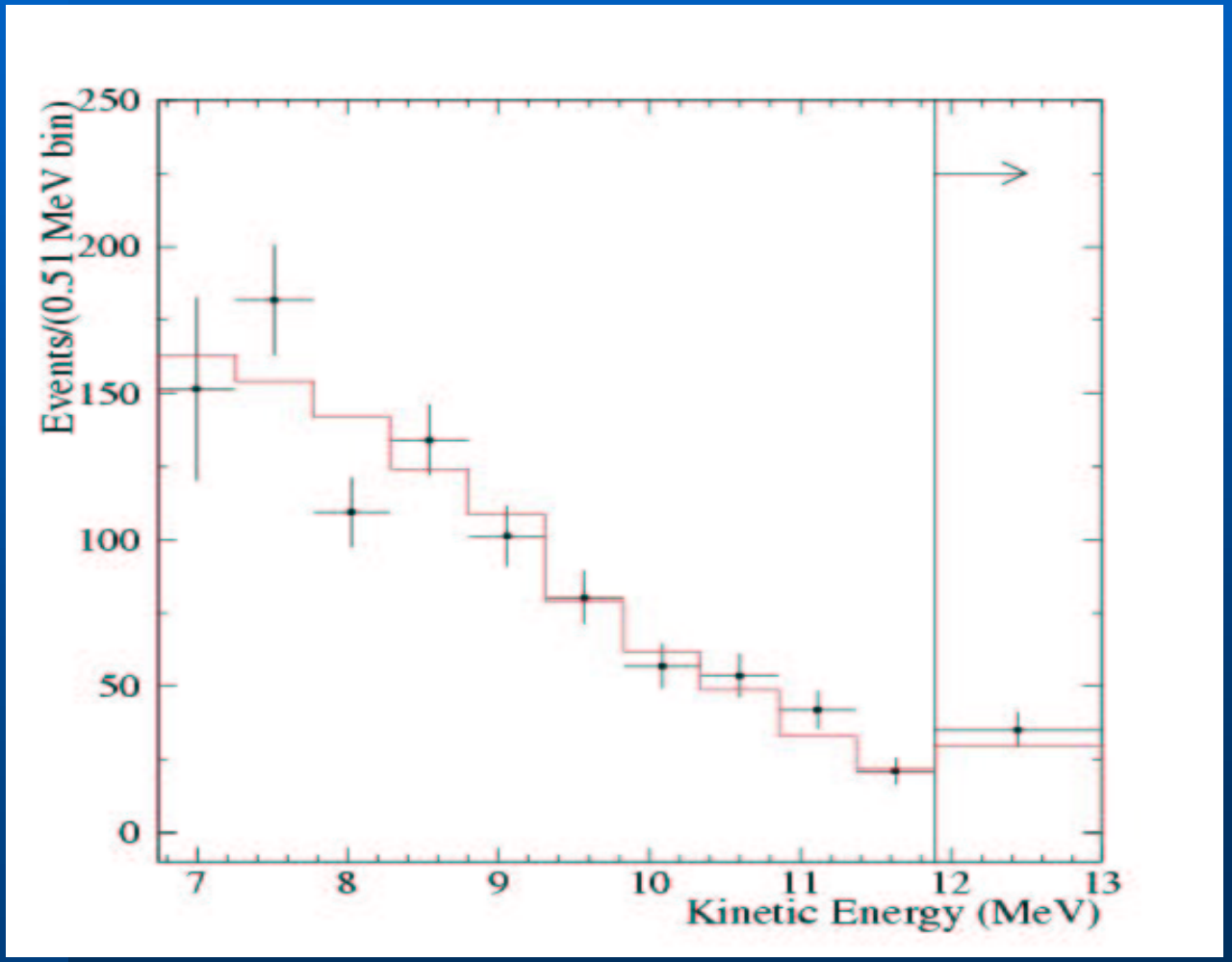
Star νars

IV. A new hope **Super-Kamiokande**

V. The Empire strikes back **SNO CC**

SNO CC

$$\phi_{CC} = 1.75 \pm 0.07^{+0.12}_{-0.11} \pm 0.05 \times 10^{6}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$



A Trilogy

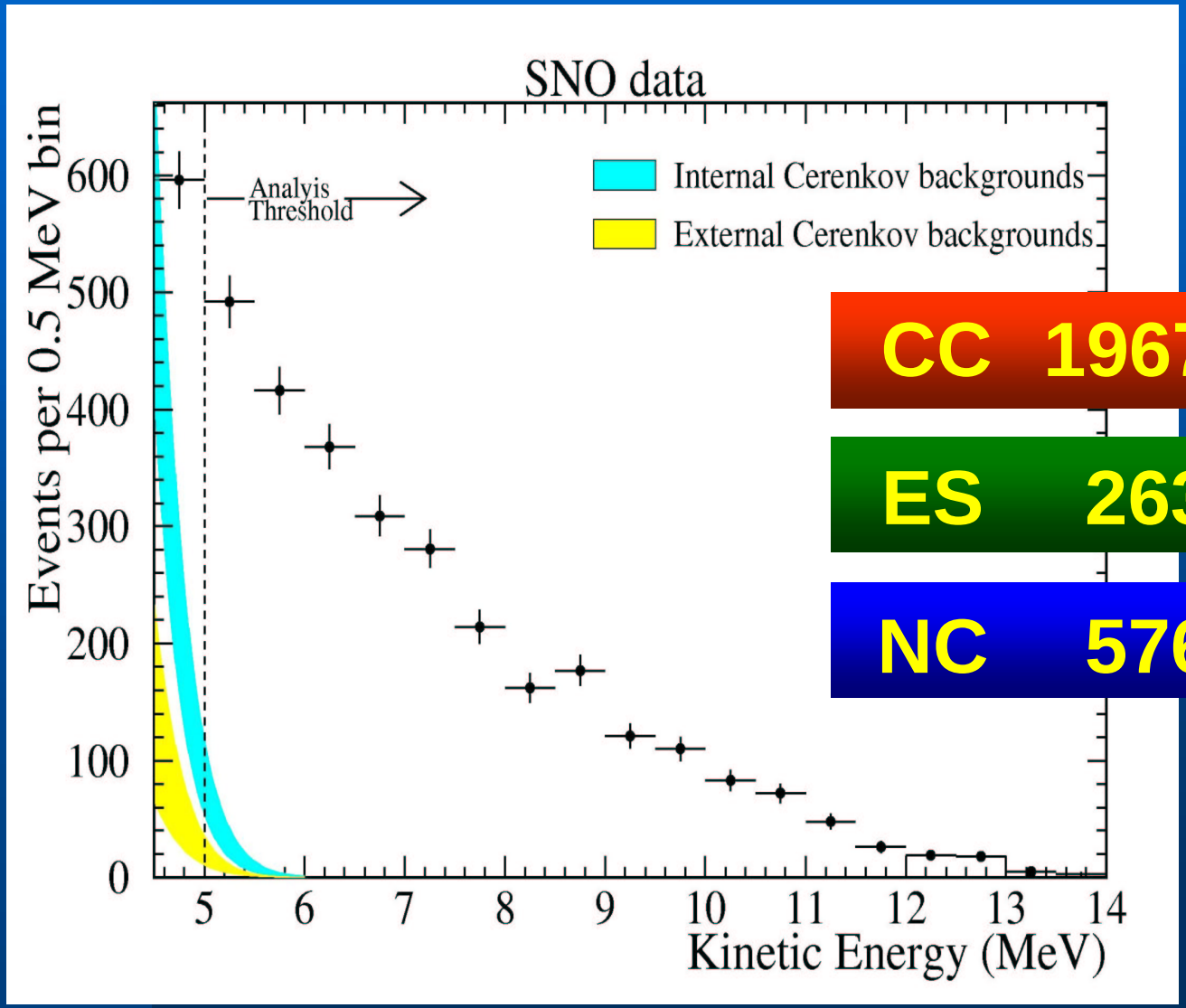
$$[ES] = f_B \{P_{ee} + (1 - P_{ee}) \frac{\sigma_{\mu/\tau}}{\sigma_e}\}$$

$$[CC] = f_B \; P_{ee}$$

Star νars

IV. A new hope — Super-Kamiokande
V. The Empire strikes back — SNO CC
VI. Return of the Jedi — SNO NC

SNO NC



CC $1967.7^{+61.9}_{+60.9}$

ES $263.6^{+26.4}_{+25.6}$

NC $576.5^{+49.5}_{+48.9}$

A Trilogy

$$[ES] = f_B \{P_{ee} + (1 - P_{ee}) \frac{\sigma_{\mu/\tau}}{\sigma_e}\}$$

$$[CC] = f_B \; P_{ee}$$

$$[NC] = f_B$$

Star νars

I. The phantom menace — Homestake

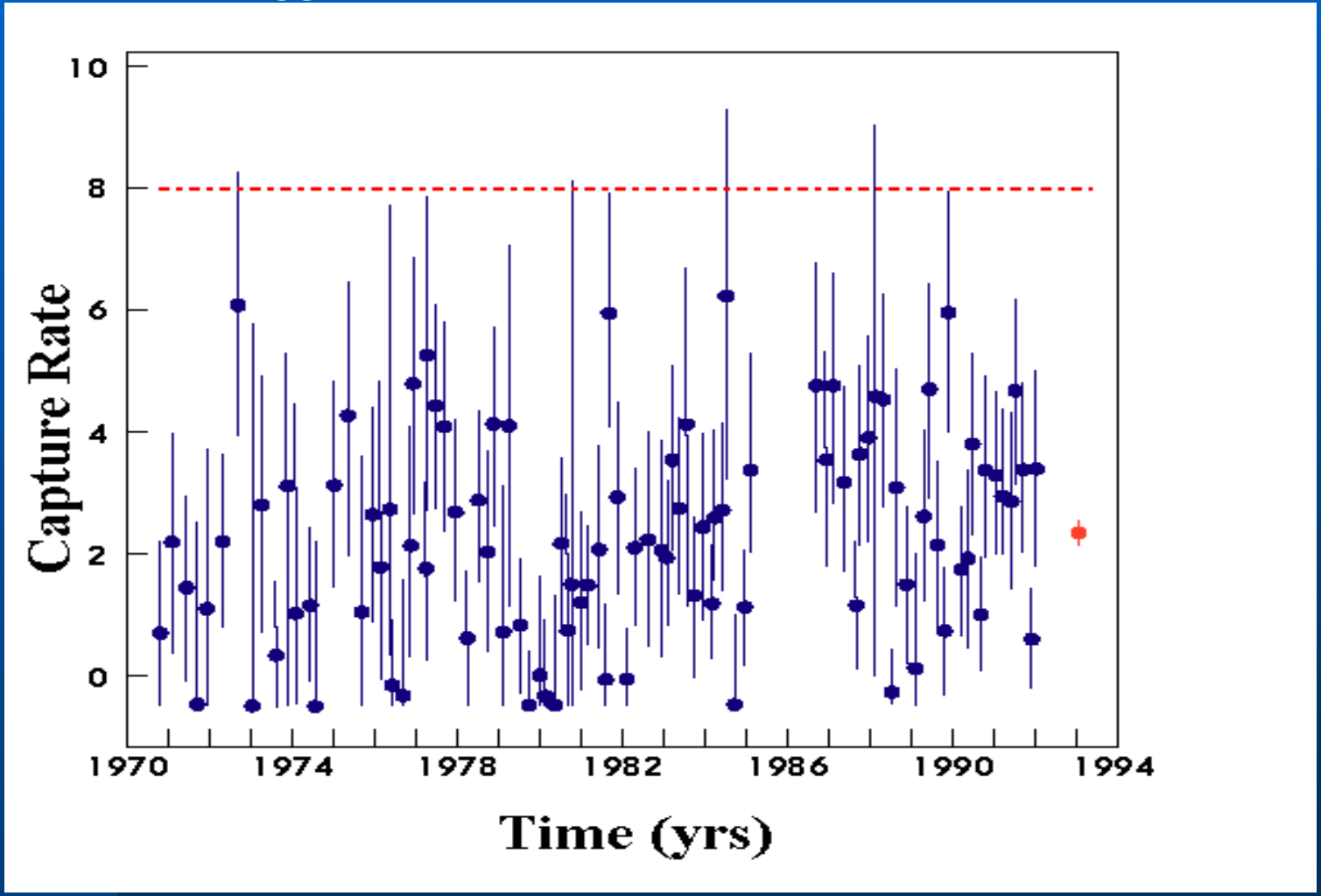
IV. A new hope — Super-Kamiokande

V. The Empire strikes back — SNO CC

VI. Return of the Jedi — SNO NC

Homestake

$$N_{CC} = 2.56 \pm 0.23 \text{ SNU}$$



Star νars

I. The phantom menace — Homestake

II. Attack of the clones — SAGE, GALLEX

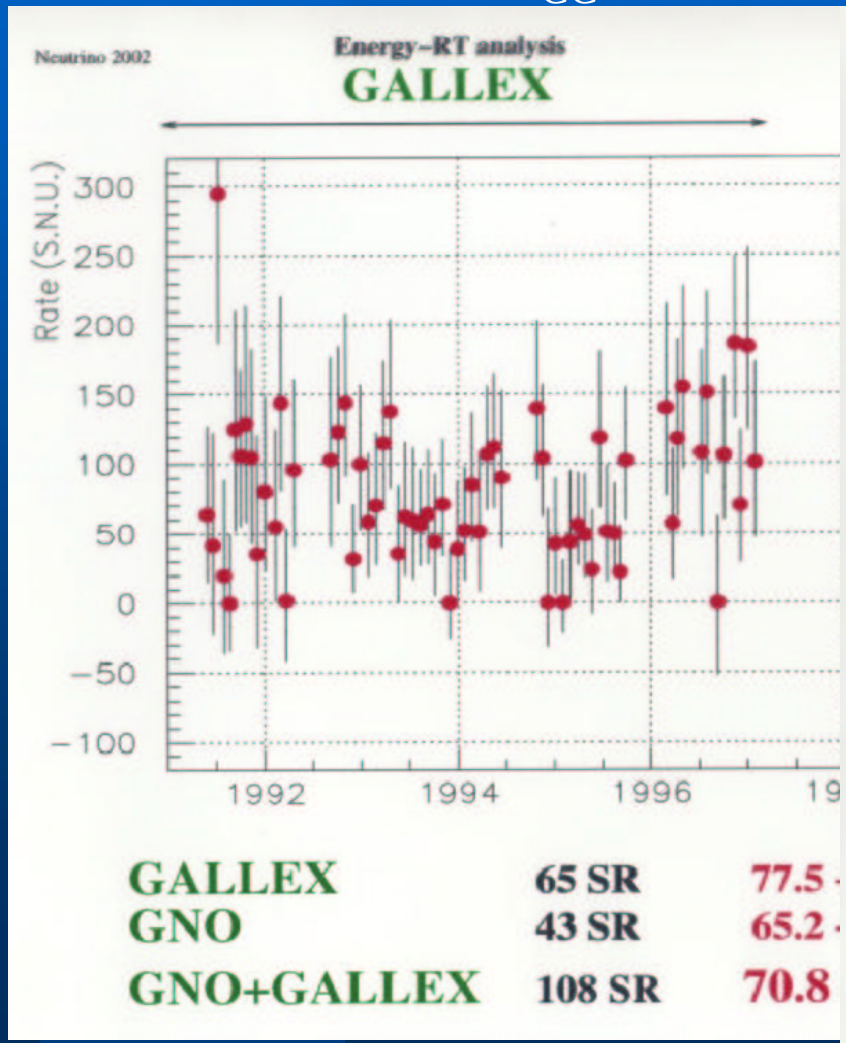
IV. A new hope — Super-Kamiokande

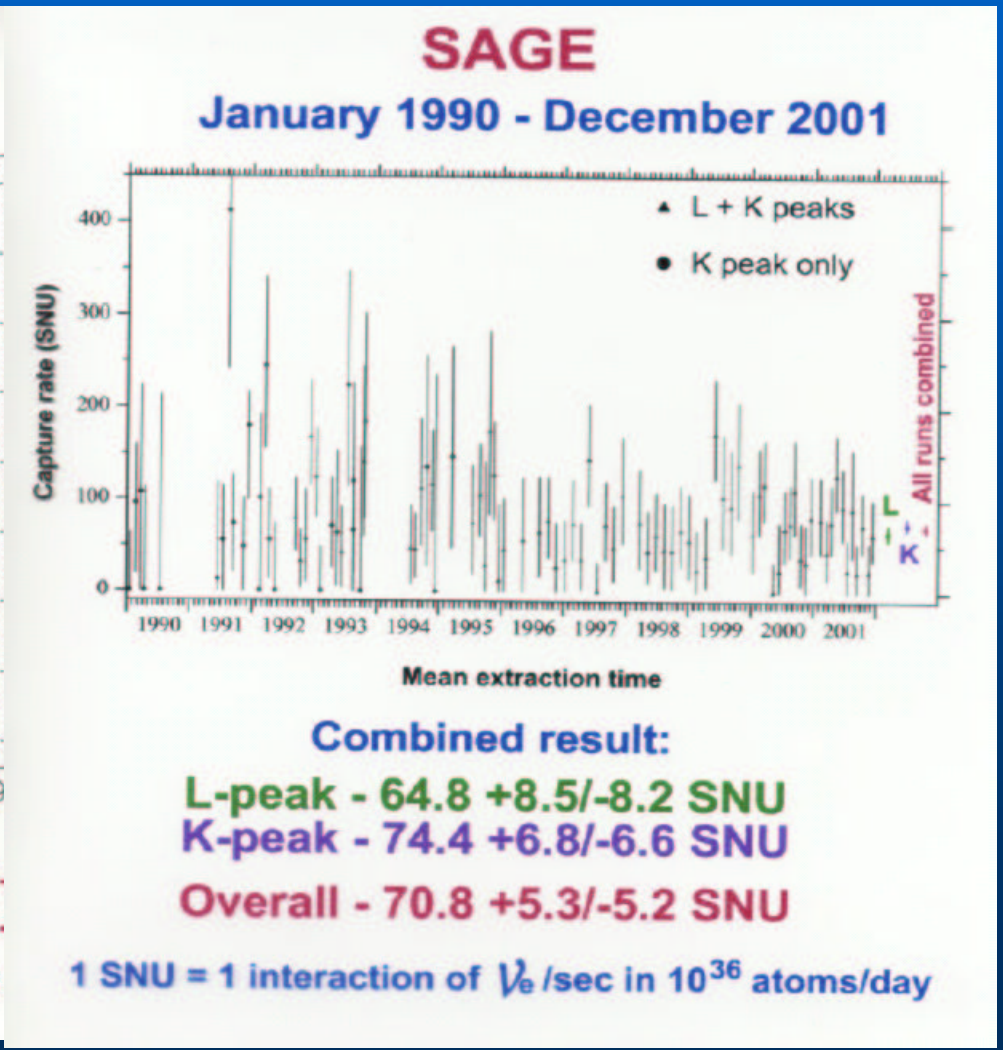
V. The Empire strikes back — SNO CC

VI. Return of the Jedi — SNO NC

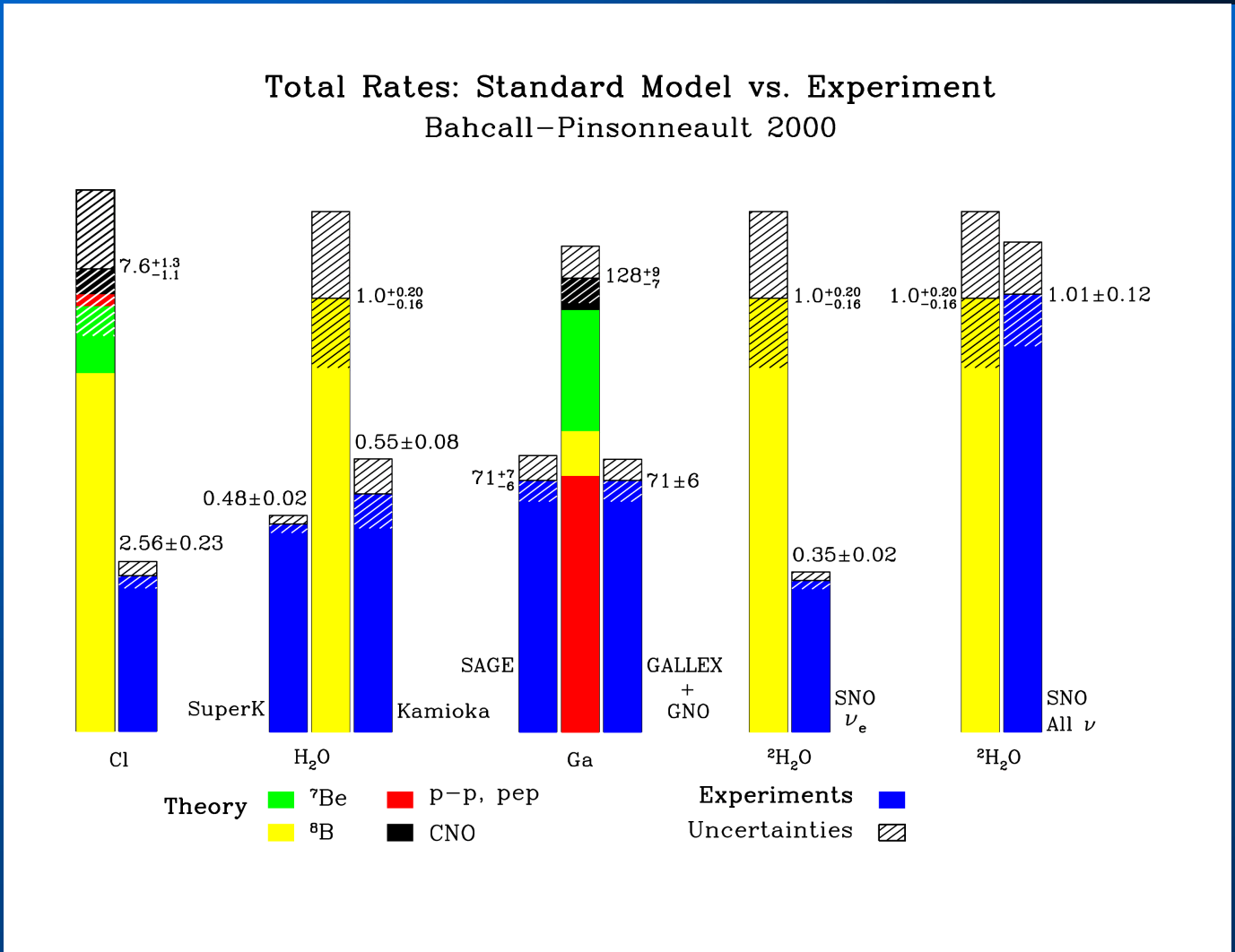
GALLEX/GNO - SAGE

$$N_{CC} = 70.8 \pm 4.4 \ \text{SNU}$$





A Solar Neutrino "Opportunity"



7 Experiments; 34 years; 0.01% of the flux.

Star νars

I. The phantom menace — Homestake

II. Attack of the clones — SAGE, GALLEX

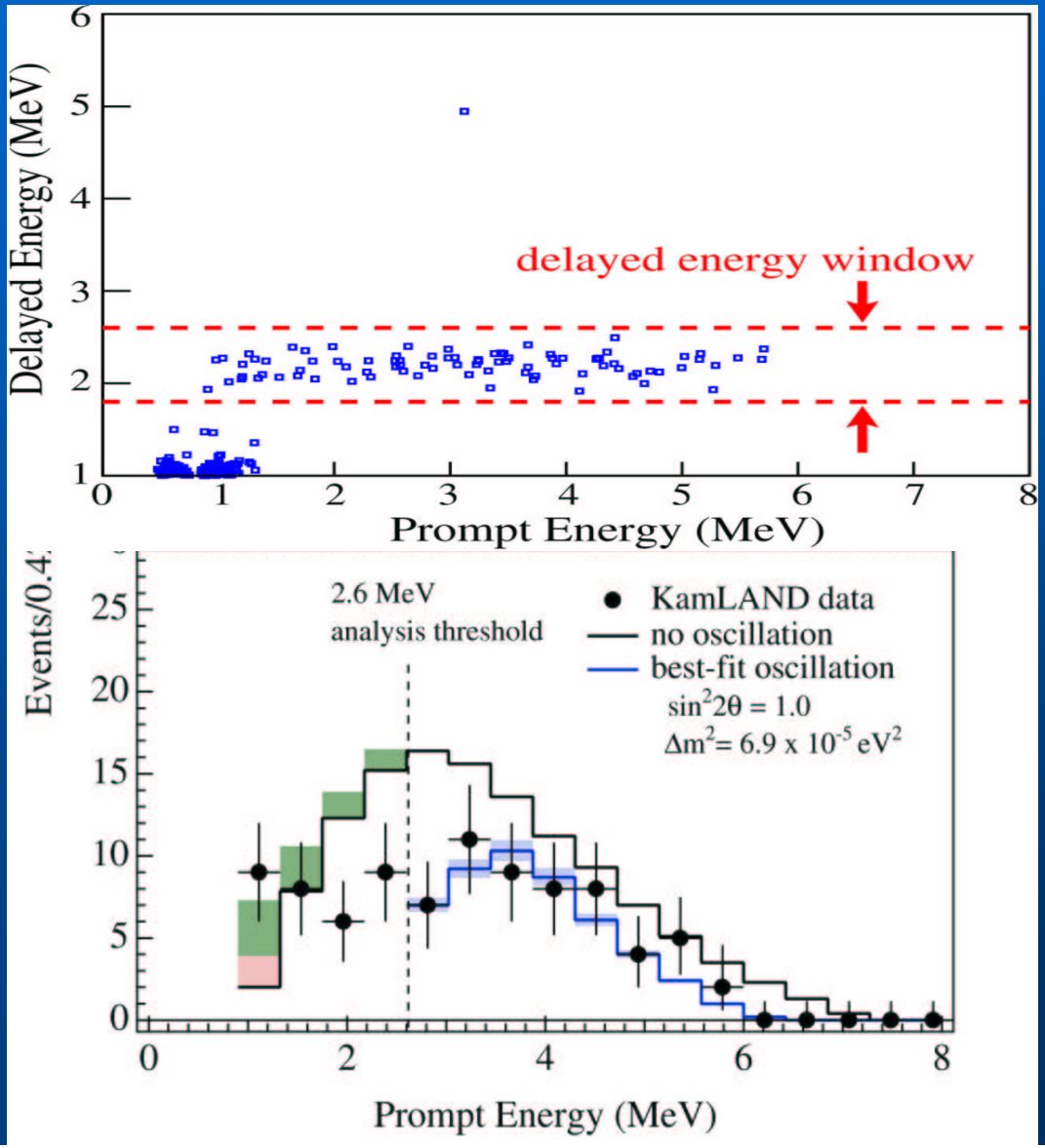
III.

IV. A new hope — Super-Kamiokande

V. The Empire strikes back — SNO CC

VI. Return of the Jedi — SNO NC

KamLAND



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

prompt delayed

$$N_{expected} = 86.8 \pm 5.6$$

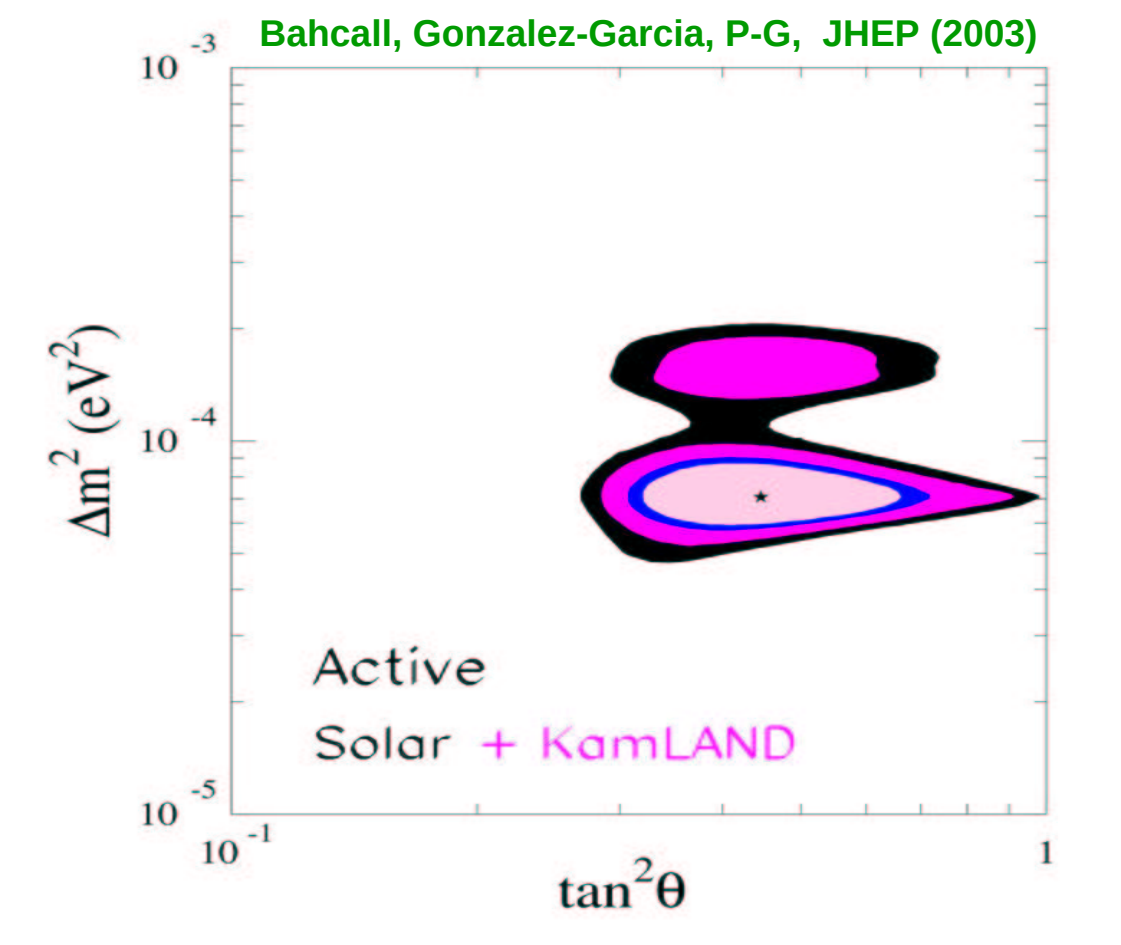
$$N_{obs} = 54$$

$$N_{bkgd} = 0.95 \pm 0.99$$

KamLAND coll., hep-ex/0212021

$162\ ton \cdot yr$

Where we are : LMA



90 % *CL*
95 % *CL*
99 % *CL*
99.73% *CL*

+

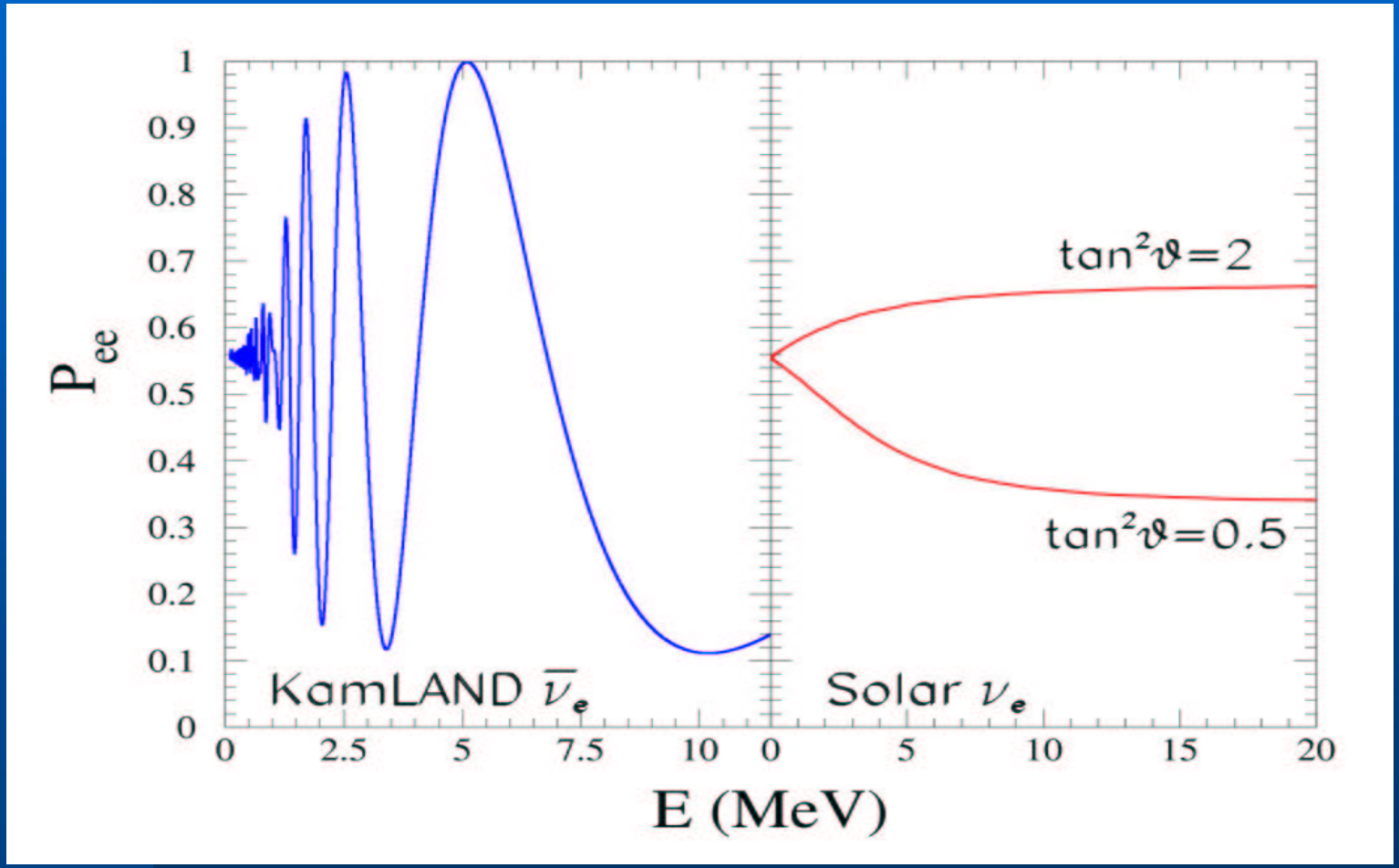
$f_B = 1.0 \pm 0.06$

$\sin^2\eta \leq 0.13$

$f_{B,\,sterile} = 0.0\ ^{+0.09}_{-0.00}$

Creminelli et al, hep-ph/0102234, Barger et al, hep-ph/0212126, Fogli et al, hep-ph/0212127, Maltoni et al, hep-ph/0212129, Bandyopadhyay et al, hep-ph/0212146, Nunokawa et al, hep-ph/0212202, Aliani et al,hep-ph/0212212, de Holanda et al,hep-ph/0212270,Balantekin et al,hep-ph/0301072,…

Where we are : LMA



high energy solar neutrinos : ok!

low energy solar neutrinos ?

Reactors in Japan or Japanese in 3’

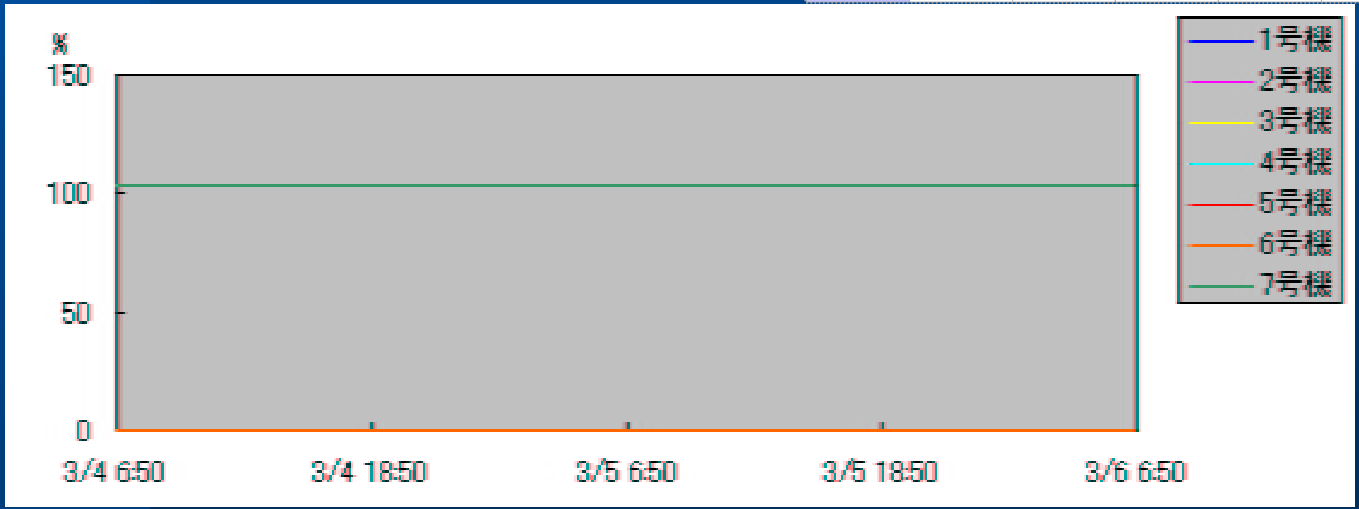
ありがとう、安田さん！

2003- : Japanese reactors

Reactor Site	Distance (km)	# of reactors	Therm. Power (max) (GW)	Max. Flux (10^5 $\bar{\nu}_e$ /cm^2/s)	Max.Event rate events/kt-year
Kashiwazaki	160	7	24.6	4.25	348
Ohi	180	4	13.7	1.90	154
Takahama	191	4	10.2	1.24	102
Hamaoka	214	4	10.6	1.03	84
Tsuruga	139	2	4.5	1.03	84
Shiga	81	1	1.6	1.08	89
Mihama	145	3	4.9	1.03	84
Fukushima-1	344	6	14.2	0.53	44
Fukushima-2	344	4	13.2	0.49	40
Tokai-II	295	1	3.3	0.17	14
Shimane	414	2	3.8	0.10	8
Ikata	561	3	6.0	0.08	7
Genkai	755	4	6.7	0.05	4
Onagawa	430	2	4.1	0.10	8
Tomari	784	2	3.3	0.02	2
Sendai	824	2	5.3	0.03	3
Total		51	130	13.1	1075

2003: Kashiwazaki 1/7 柏崎刈羽

号機	1号機	2号機	3号機	4号機	5号機	6号機	7号機
最新値	定期検査中	停止中	定期検査中	定期検査中	定期検査中	定期検査中	



2003: Hamaoka 1/4

浜岡

2003: Fukushima-1 2/6 福島

2003: Fukushima-2 0/4 福島第二

2003:

大飯	Ohi	4/4
高浜	Takahama	4/4
敦賀	Tsuruga	2/2
美浜	Mihama	3/3
…	…	

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Fukushima-1	344	6	14.2	0.53	44
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Shimane	414	2	3.8	0.10	8
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Onagawa	430	2	4.1	0.10	8
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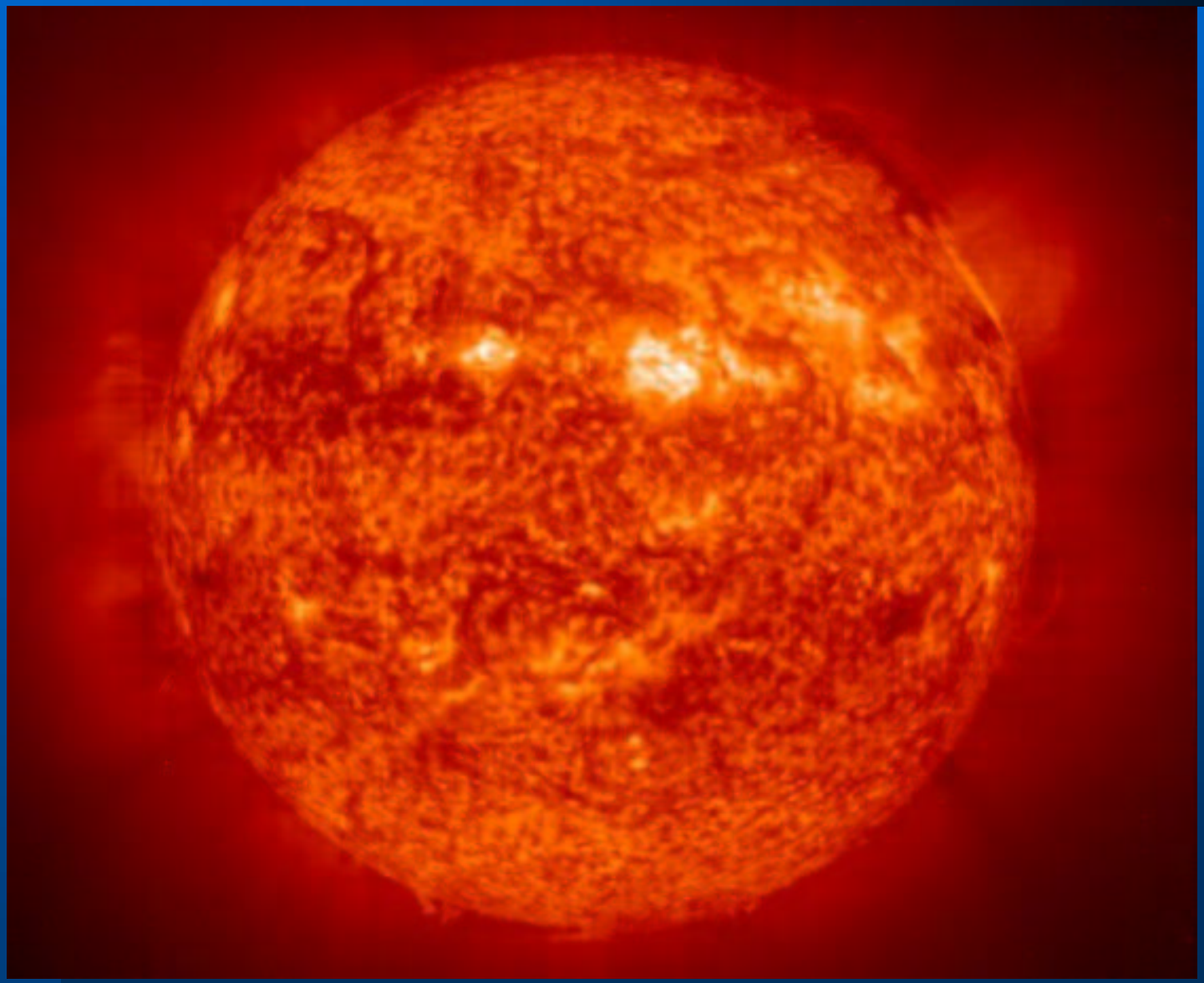
柏崎刈羽 ？

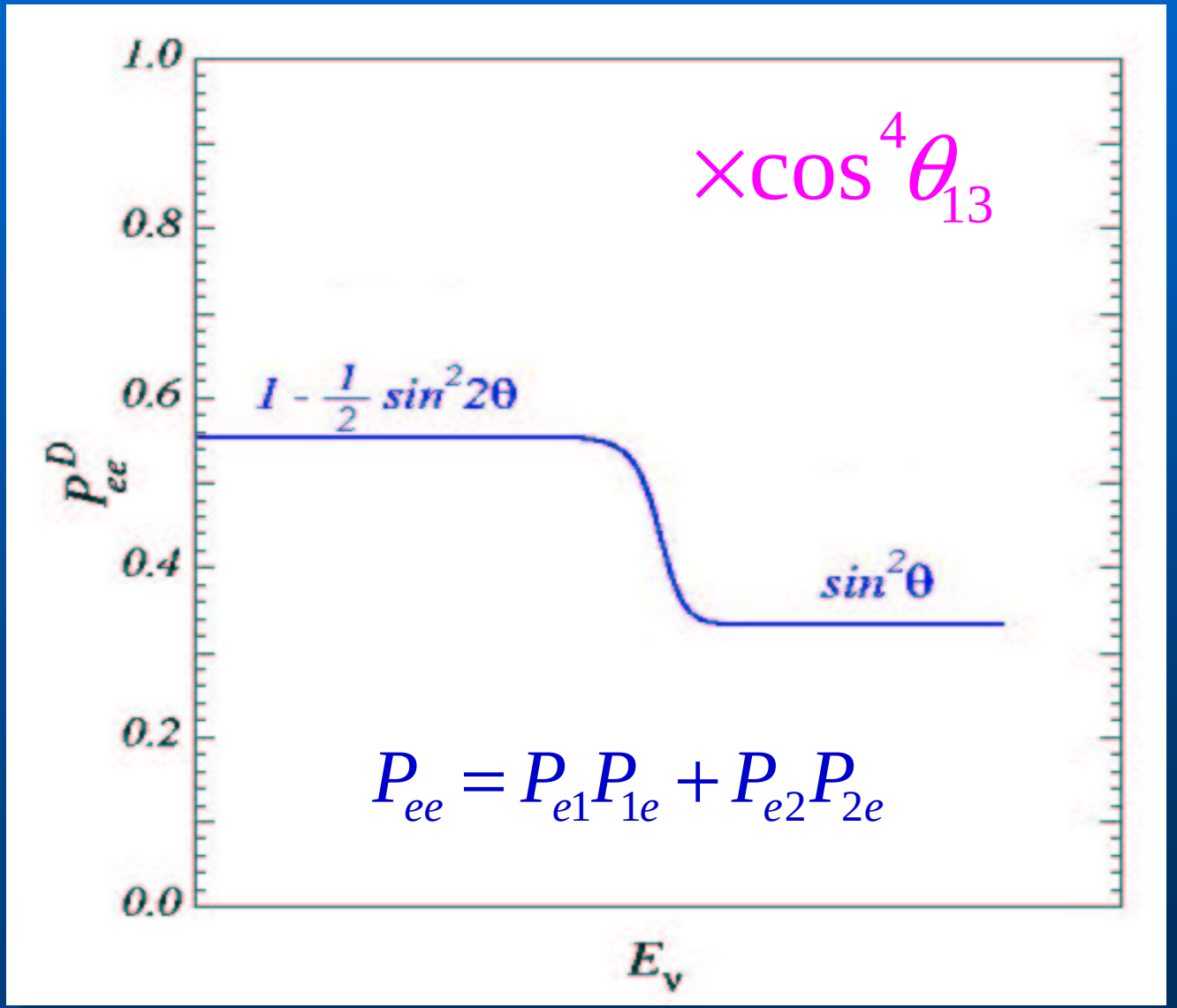
2003- : Solar Neutrinos …



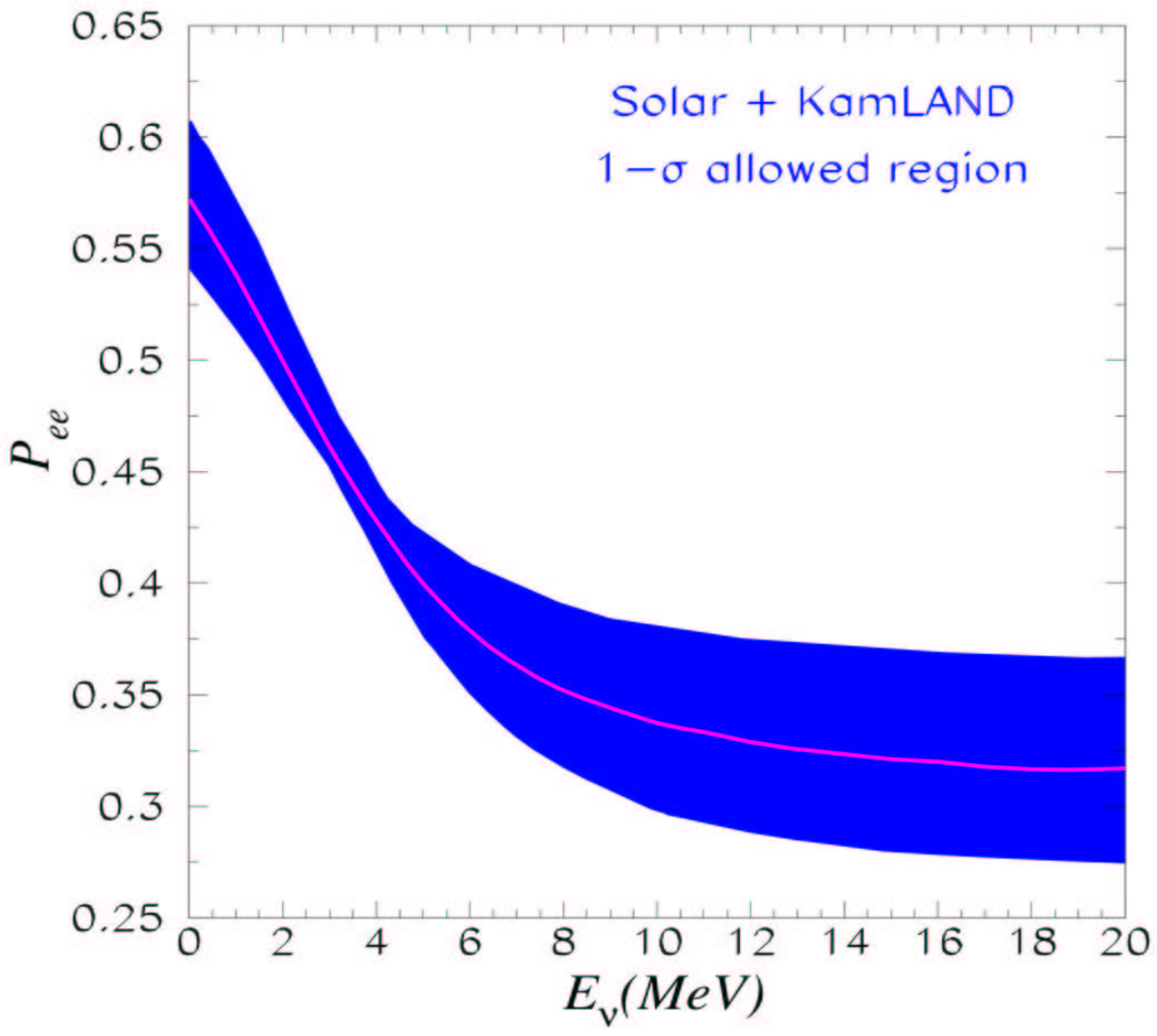
…in Particle Physics & Astrophysics:

- **Oscillations, matter effects, θ_{12}**
- **LMA + subleading :**
  - **LMA + Non-standard interactions**
- **99.95 % of solar neutrinos E < 5 MeV**
- **Stringent tests of SSM : Be, CNO**

Where we are : LMA

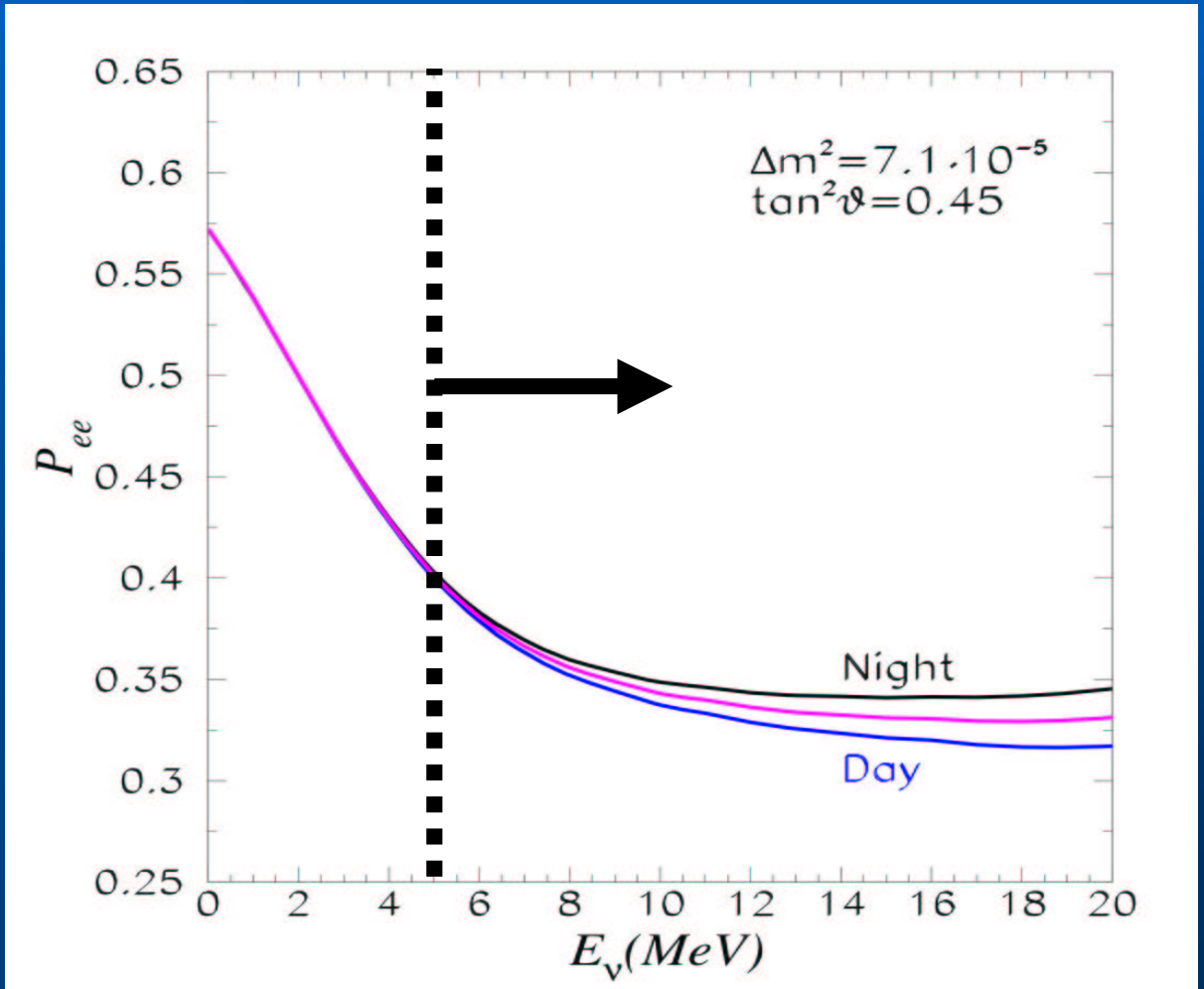


Where we are : LMA



Future: Time Dependence

$$P^N = P^D - (1-2P_c)\cos 2\theta_{m,0} f_{REG}$$



Prediction

$$A_{D/N}(ES)$$

$$1.9 \pm 0.4$$

~ Megaton

Prediction

$$A_{D/N}(CC)$$

$$3.3^{+0.7}_{-0.6}$$

Future: Low Energy

^{7}Be- ν

ES

BOREXINO

KamLAND-II

TPC

CC

LENS

MOON

SIREN

pp - ν

ES

XMASS

CLEAN

HERON

TPC

Genius

…..

CC

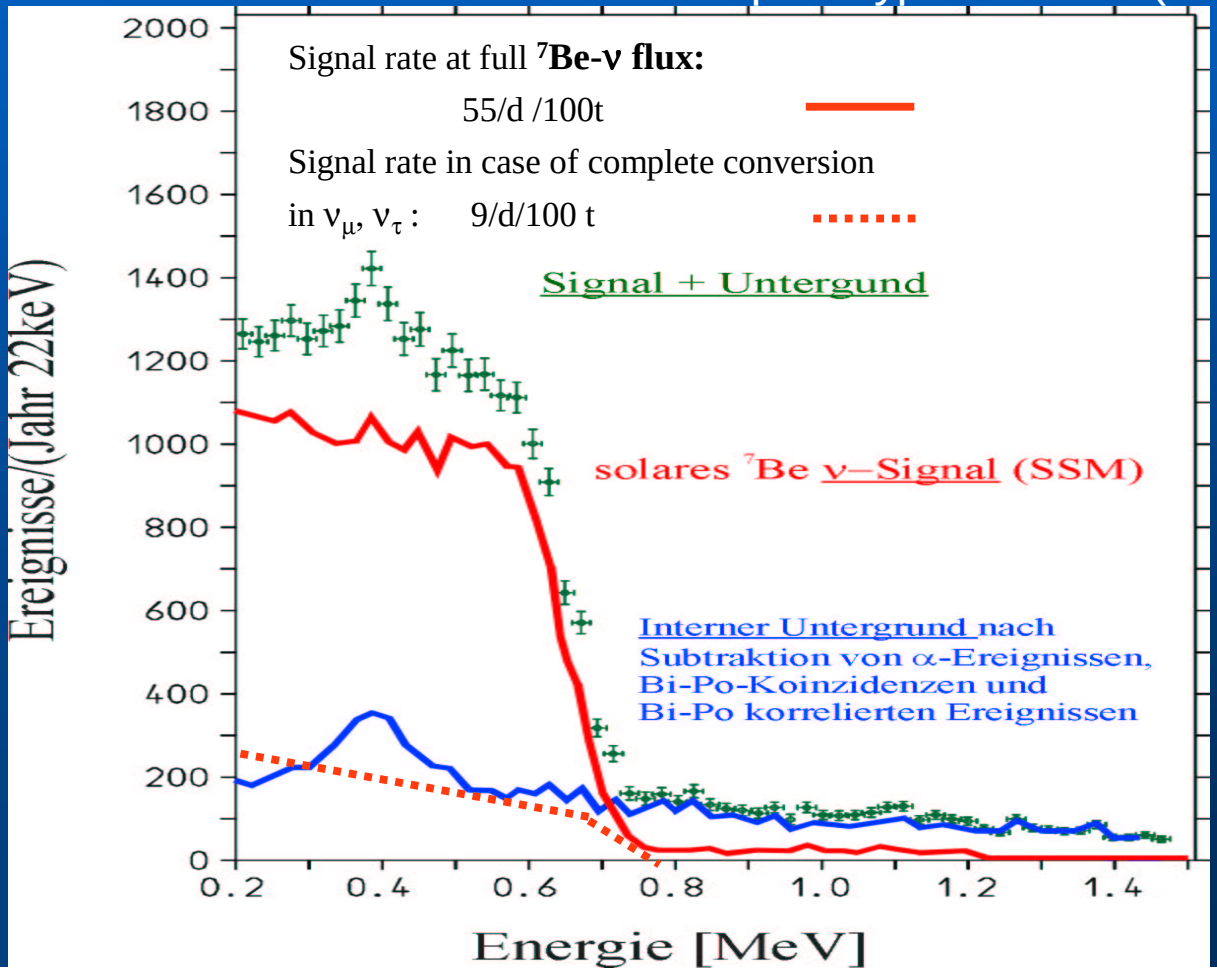
LENS

MOON

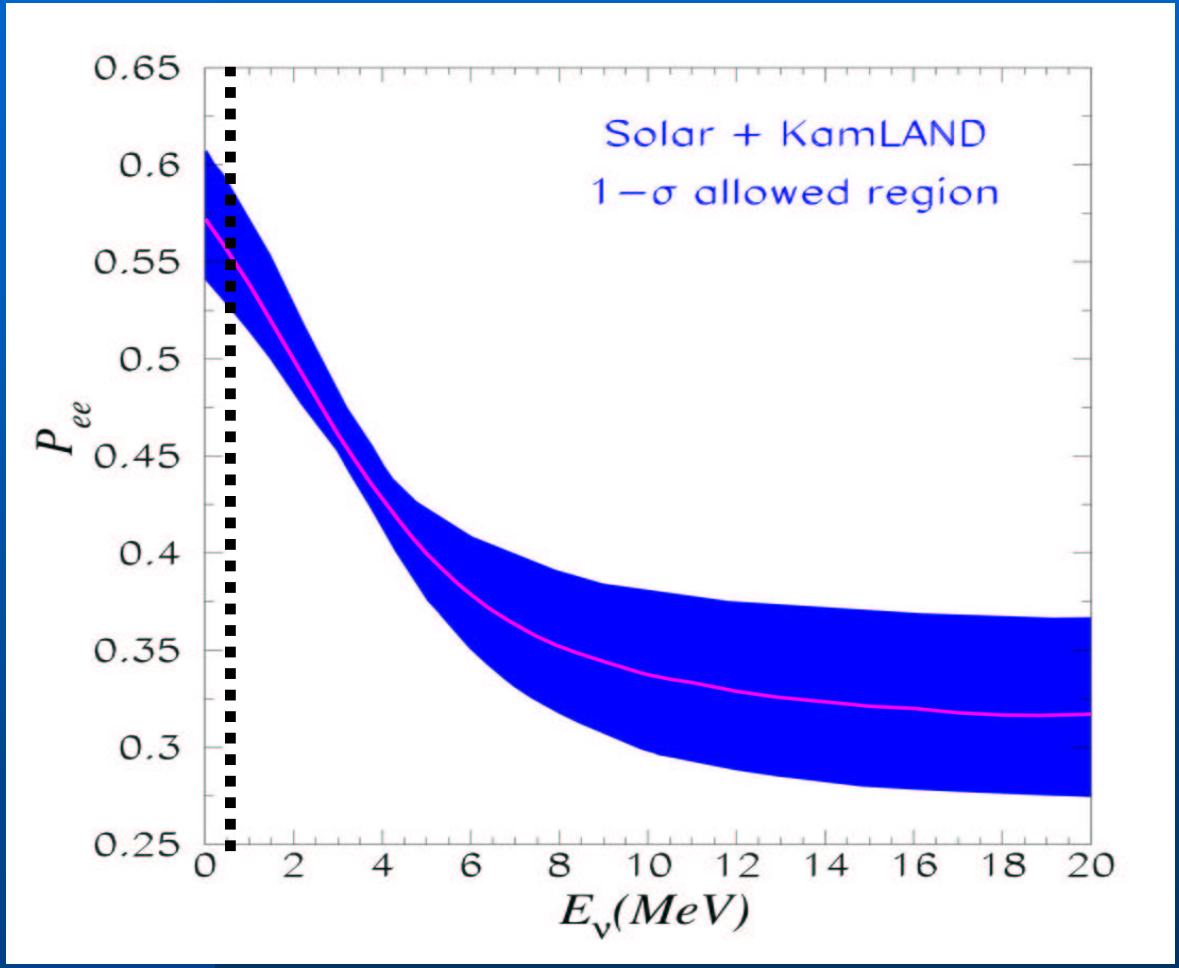
SIREN

^{7}Be ES Signature

Experimental Challenge:
ultra-purity of detector components
(<10^{-16} gU,Th/g), techniques developed
in prototype detector (CTF)



^{7}Be ES :



$\delta_{\Delta m^2}, \delta_\theta$ δ_{SSM}

Prediction $R_{Be} = 0.64 \pm 0.02 \pm 0.06$

Future: Low Energy

^{7}Be- ν

ES

BOREXINO

KamLAND-II

TPC

CC

LENS

MOON

SIREN

pp - ν

ES

XMASS

CLEAN

HERON

TPC

Genius

…..

CC

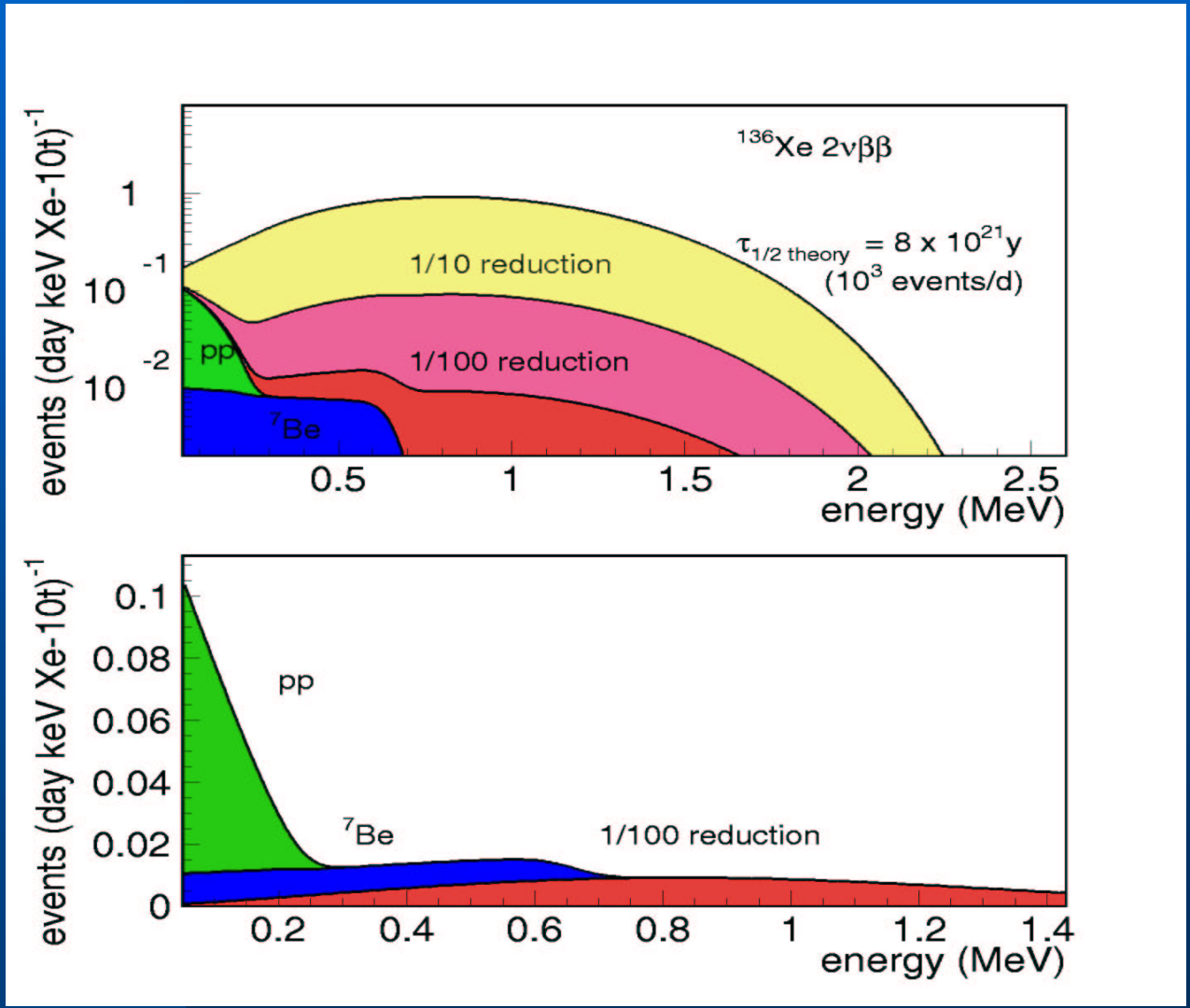
LENS

MOON

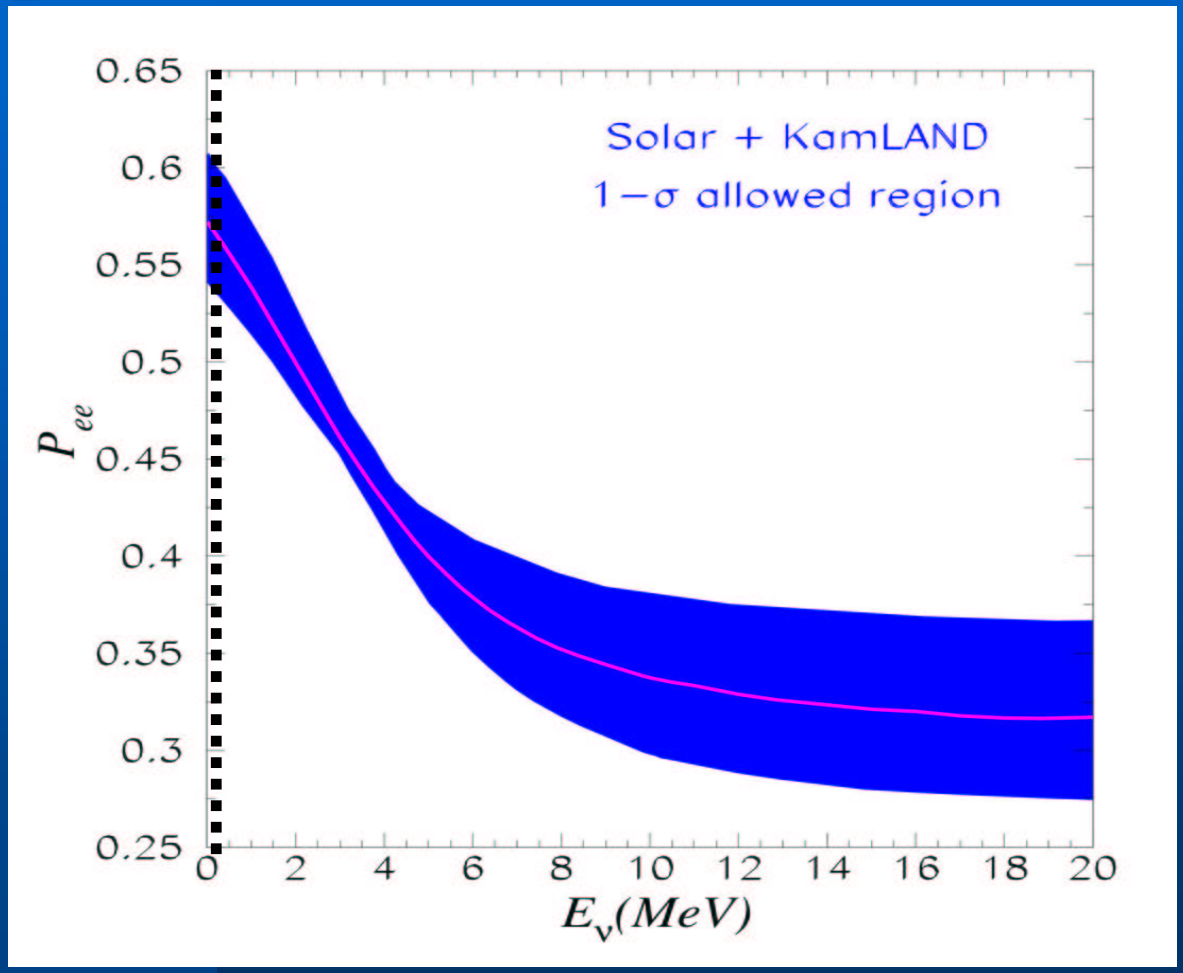
SIREN

pp ES Signature

Experimental Challenge



pp ES:

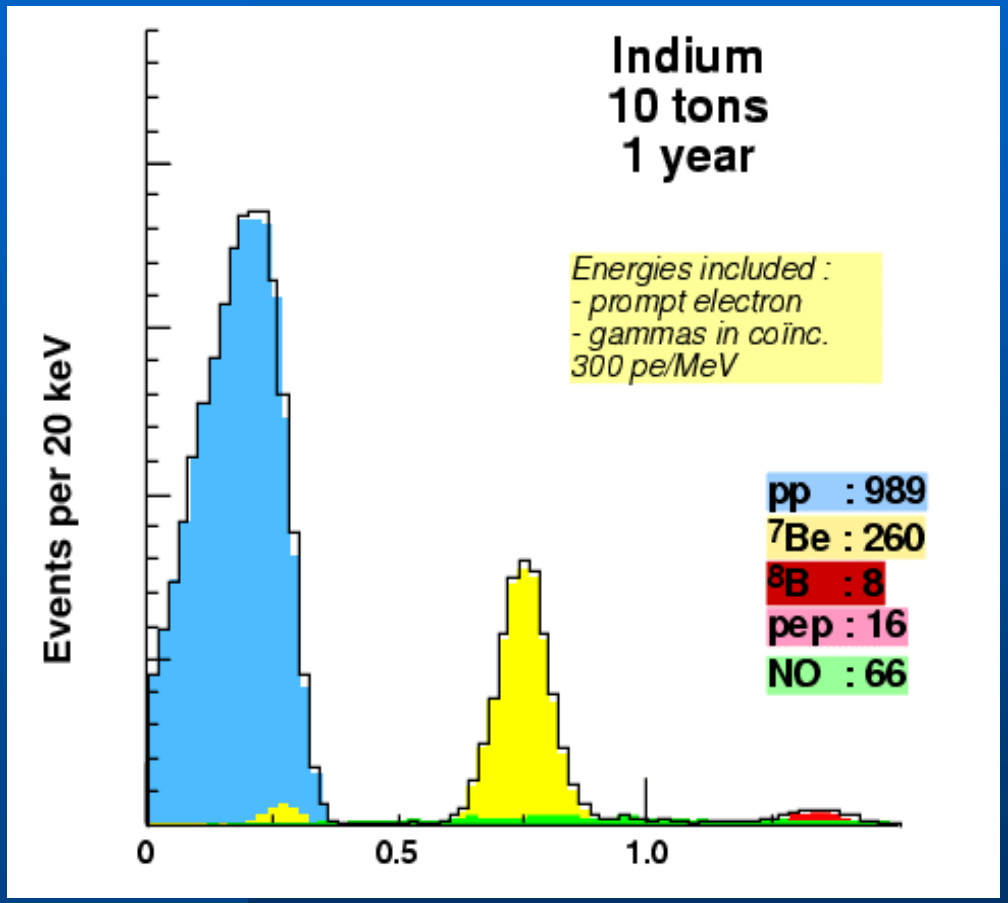


$\delta_{\Delta m^2}, \delta_\theta$

δ_{SSM}

Prediction $R_{pp} = 0.70 \pm 0.02 \pm 0.01$

pp, ^{7}Be CC Signature



Challenge:
Bgd from ^{115}**In β-decay** 486 keV
& Bremsstrahlung

⇒ ^{7}Be ok!

⇒ **pp-ν ? Under study**

Trilogy : Test of NC NSI

$$[\mathrm{ES}] = f_B \left\{ P_{ee}(\varepsilon, \varepsilon') \frac{\sigma_e(\varepsilon_{\alpha e}^{e,P})}{\sigma_e} + (1 - P_{ee}(\varepsilon, \varepsilon')) \frac{\sigma_{\mu/\tau}(\varepsilon_{\alpha\mu}^{e,P}, \varepsilon_{\alpha\tau}^{e,P})}{\sigma_e} \right\}$$

$$[\mathrm{CC}] = f_B \; P_{ee}(\varepsilon, \varepsilon')$$

$$[\mathrm{NC}] = f_B (1 + 2\varepsilon^A)$$

Similar analysis to constrain $L_{1,A}$: Chen, Heeger, Robertson PRC (2003)

Trilogy : Test of NC NSI

NC,CC,ES + KamLAND future bounds:

$$\left| \varepsilon_{\tau\tau}^{l,P} \right| \leq 0.3$$

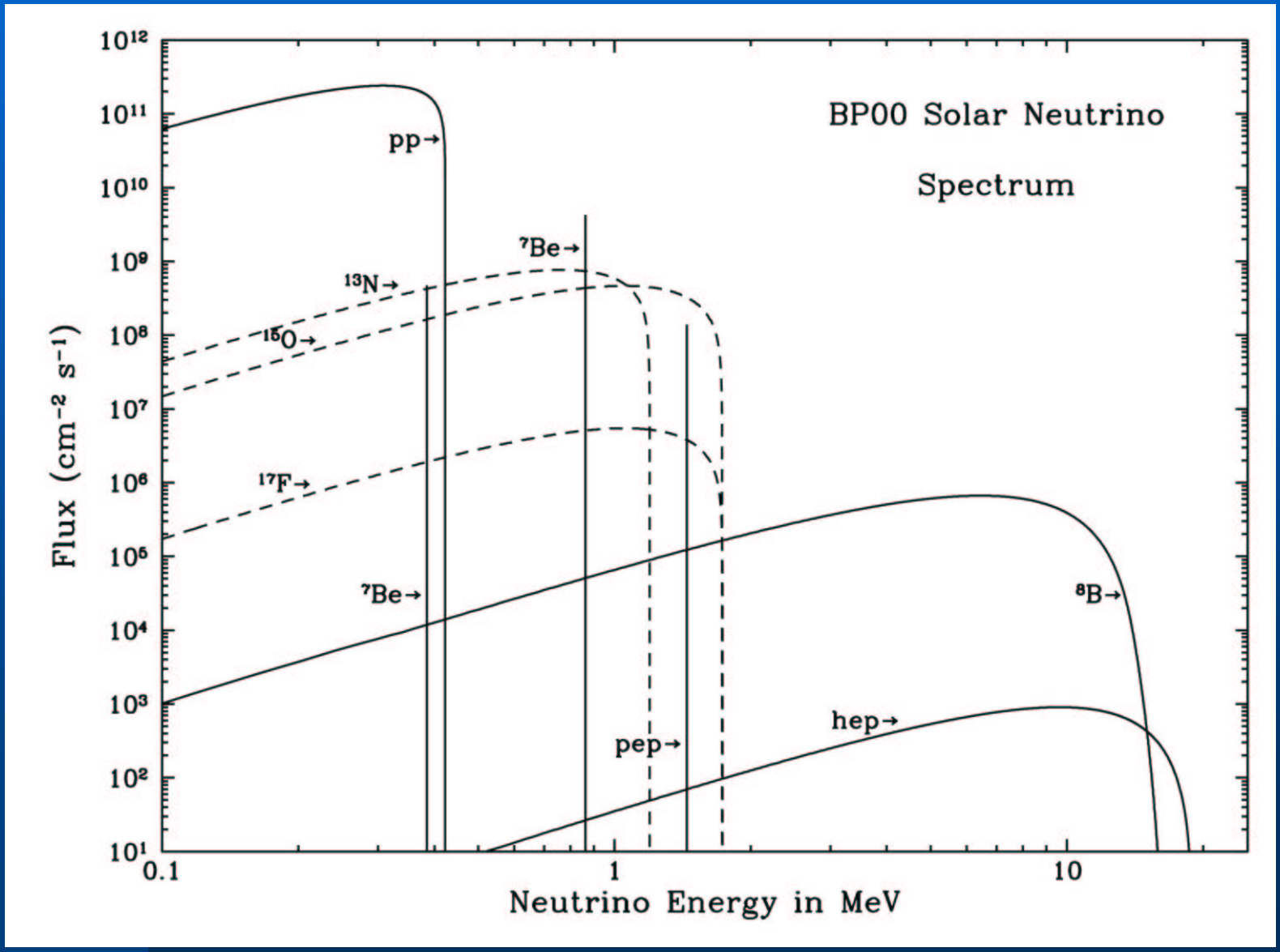
Davidson, P-G, Rius, Santamaria JHEP (2003)

^{7}Be:

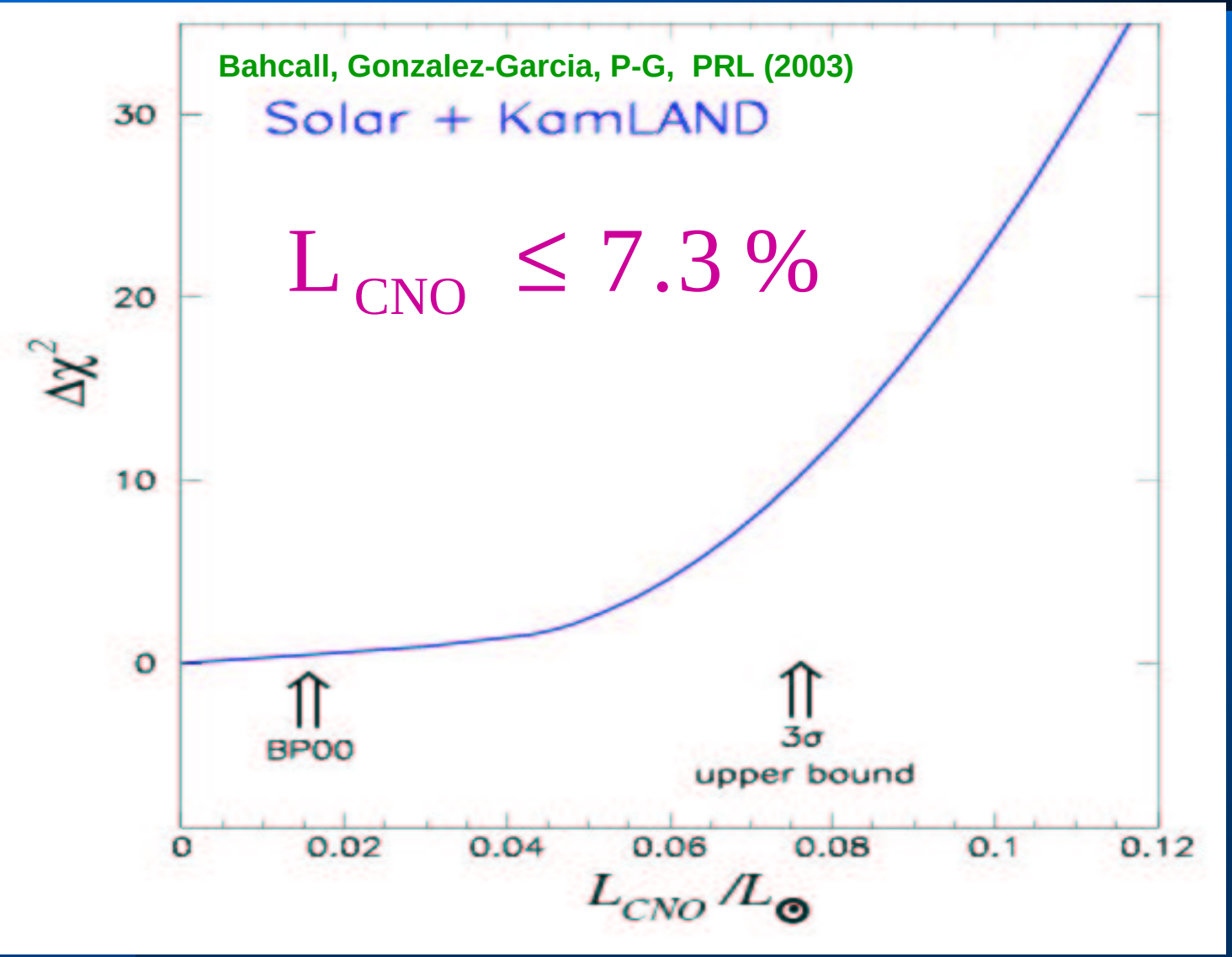
Berezhiani, Raghavan, Rossi NPB (2002)

pp ES:

BP00 : pp chain + CNO cycle



Does the sun shine by pp or CNO ?



Conclusions

- **Solar and KamLAND : LMA confirmed**

- **Signal of oscillations, matter effects**
- **θ_{12} challenge**
- **Test of NSI in ^{7}Be**

- **99.99 % of solar neutrinos E < 5 MeV**
- **Stringent tests of SSM : ^{7}Be, CNO**