SOLAR NEUTRINOS

Extraordinary Neutrino Beam Free of Charge

For NEUTRINO PHYSICS:

- WELL DEFINED HIGHEST FLUX ($\sim 10^{11} cm^{-2} s^{-1}$)
- PURE FLAVOR SOURCE - ν_e only
- LONGEST BASELINE (10^8 km)
- HIGH DENSITY UP TO 160 g/cm^3; ~ 10^{11} g/cm^2 path
- LOWEST ENERGIES (keV to MeV)
- PRESENCE OF HIGH MAGNETIC FIELDS
- FULL SPECTRUM: ENERGY DEPENDENT EFFECTS

Best tools for investigating neutrino flavor phenomena in Vacuum and in Matter

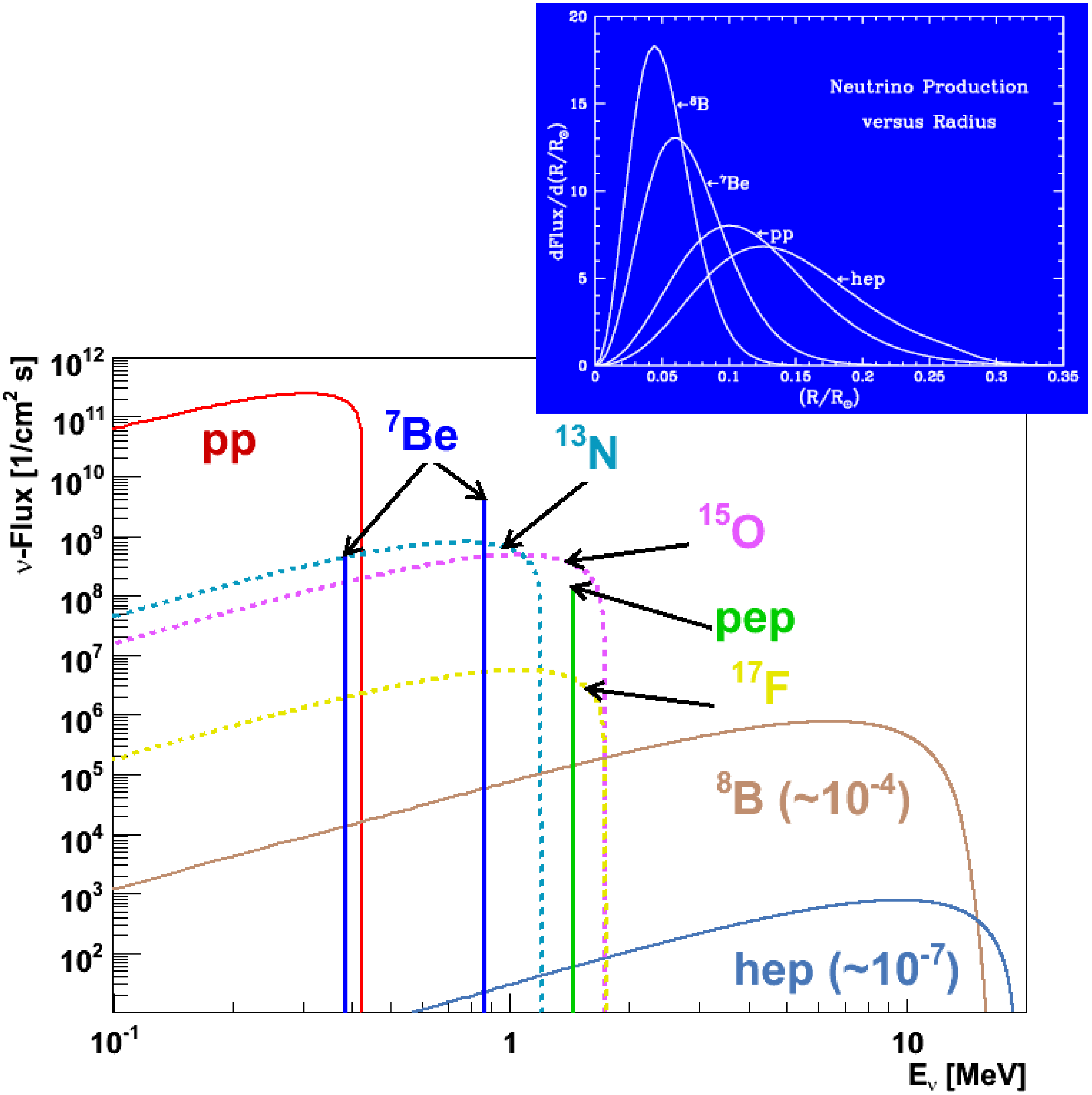
For ASTROPHYSICS

Best tool for unprecedented look at how a real Star works
- in the past, present and future

Solar Neutrinos

What we know:

- **Standard Solar Model**
- Missing ν_e (Cl, Ga, SK, SNO)
- Flavor mixing happens (SNO)



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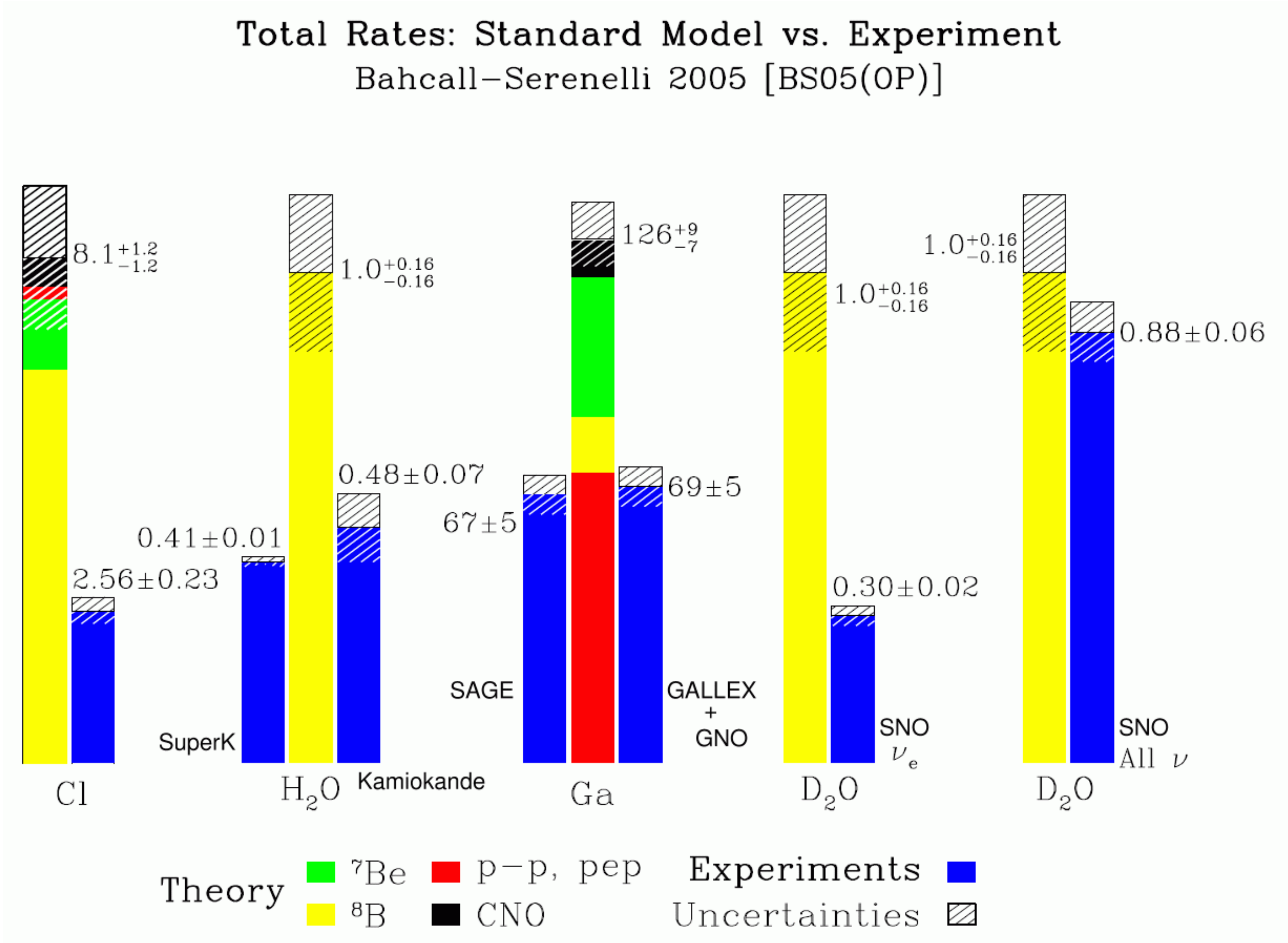

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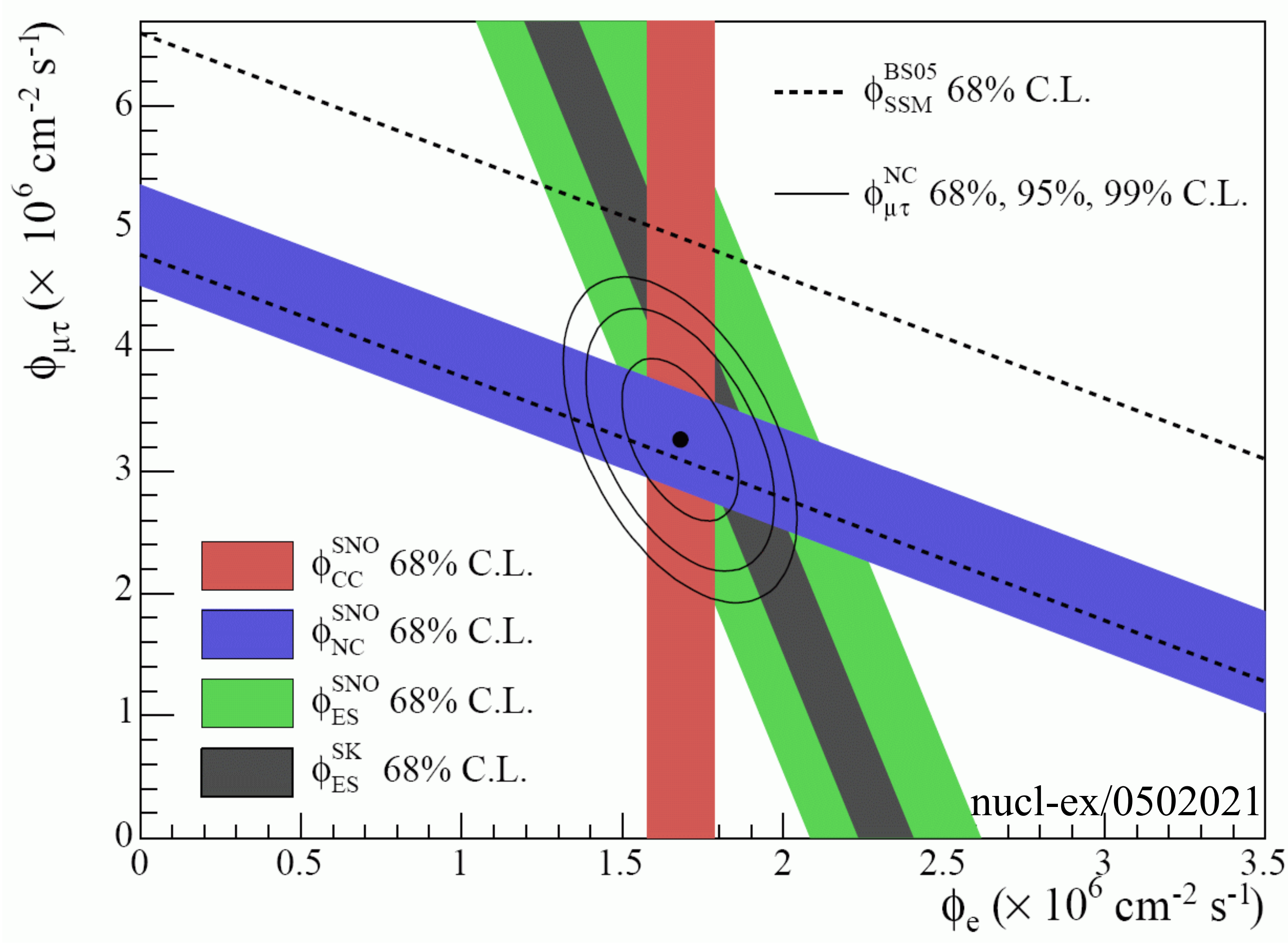
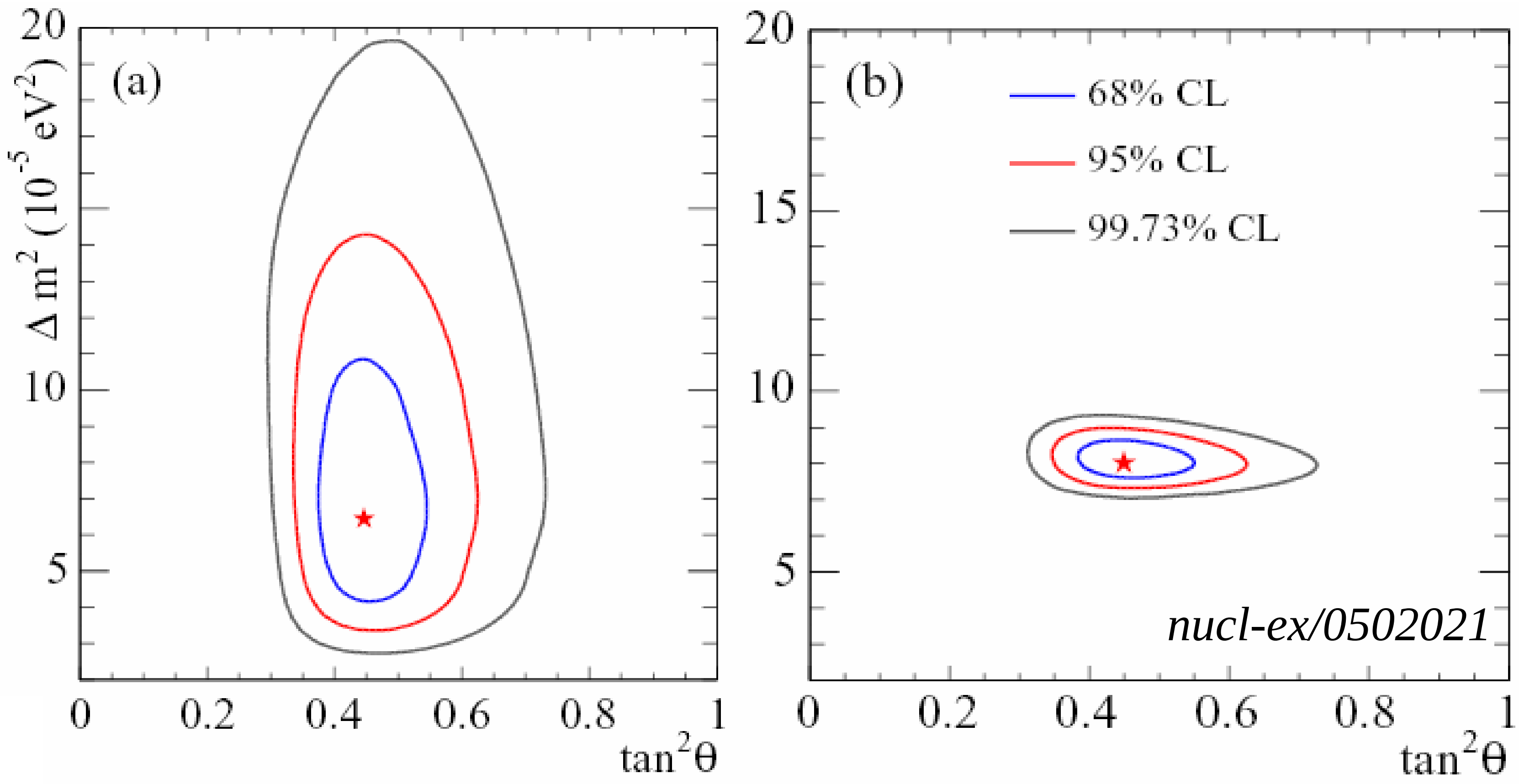


Neutrino Oscillation Explanation

MSW explanation: resonant conversion at ^{8}B energies



Solar data: Δm_{12}^2, θ

add anti-neutrinos (KamLAND) (assumes CPT): Δm_{12}^2, θ

MSW-LMA is based on the *combined* results from many complementary experiments

Neutrino Oscillation Explanation

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ e^{i\phi_2}\nu_2 \\ e^{i\phi_3}\nu_3 \end{pmatrix}$$

$$= \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ e^{i\phi_2}\nu_2 \\ e^{i\phi_3}\nu_3 \end{pmatrix}$$

Adding atmospheric neutrino oscillations…

$m_2^2 - m_1^2 = 7.92(1 \pm 0.09) \times 10^{-5}\ eV^2$

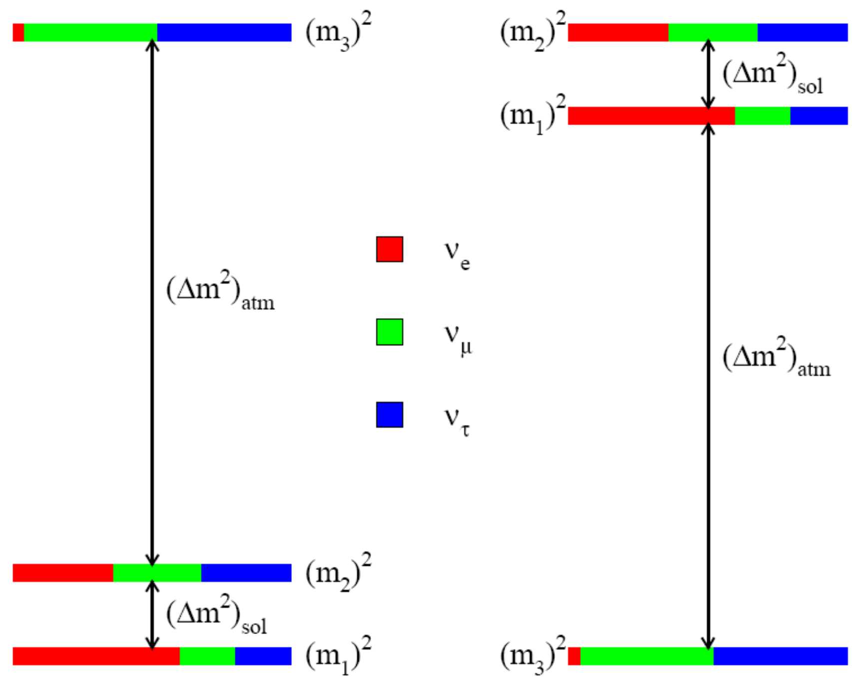
$|m_3^2 - m_2^2| = 2.4(1^{+0.21}_{-0.26}) \times 10^{-3}\ eV^2$

$\sin^2\theta_{12} = 0.314(1^{+0.18}_{-0.15})$

$\sin^2\theta_{23} = 0.44(1+^{0.41}_{-0.22})$

$\sin^2\theta_{13} = 0.9^{+2.3}_{-0.9} \times 10^{-2}$ [1]

$(m_1+m_2+m_3) < 0.3eV$ (95%CL WMAP) [2]



normal hierarchy　　inverted hierarchy

[1]G.L. Fogli, E. Lisi, A. Marrone, and A. Palazzo, hep-ph/0506083. (95%CL)
[2]A.Goobar, S.Hannestad, E.Mortsell and H.Tu, [arXiv:astro-ph/0602155].

Solar ν's have already demonstrated neutrino oscillations, but that's just the beginning…

"**Is this picture really correct**?"

"Do nuclear reactions fully account for the Sun's energy output today?"

"What *else* don't we know about neutrinos?"

$L_{\odot}^{\nu}$ assume proton-proton & CNO mechanisms

use *measured* ν–fluxes @ Earth

use self-consistent neutrino model

calculate ν–fluxes @ Sun

→ energy generated in Sun

$L_{\odot}^{hf}$ energy generated in Sun *measured* by photon flux

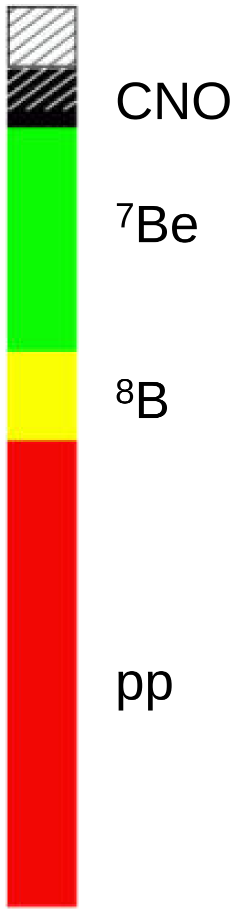
$$L_{\odot}^{\nu} / L_{\odot}^{hf} = 1.4\binom{0.2}{0.3}_{1\sigma}\binom{0.7}{0.6}_{3\sigma} \text{ (Bahcall)};$$

$$1.12(.21) \text{ (Robertson)}$$

J.N.Bahcall and C.Pena-Garay, JHEP **0311**, 4 (2003) [arXiv:hep-ph/0305159].
R.G.H.Robertson, Prog. Part. Nucl. Phys. **57**, 90 (2006) [arXiv:nucl-ex/0602005].

Why is this 'required' match so poorly known?

Three main contributions:	pp	0.914
@ the Sun according to SSM	^{7}Be	0.072
	CNO	0.014
	(^{8}B	0.00009)



- ^{8}B (SK, SNO) known very well
- ^{7}Be + ^{8}B (Cl – mostly sensitive to ^{8}B)
- pp + ^{7}Be + ^{8}B (Ga)

⇨ in principle can deduce pp-ν flux in SSM

Problem: yield weighted by cross-section

=> limited sensitivity of Gallium experiments to pp-ν :

(& in addition, hard to disentangle *integral* CC measurements from MSW conversion in SSM)

What if $L_{\odot}^{\nu} \neq L_{\odot}^{hf}$? MUST check it.

Is θ_{13} not zero?

overall normalization at low energies $\propto \cos^4(\theta_{13})$

Is the Sun getting hotter or colder?

ν's take ~8 min to reach Earth

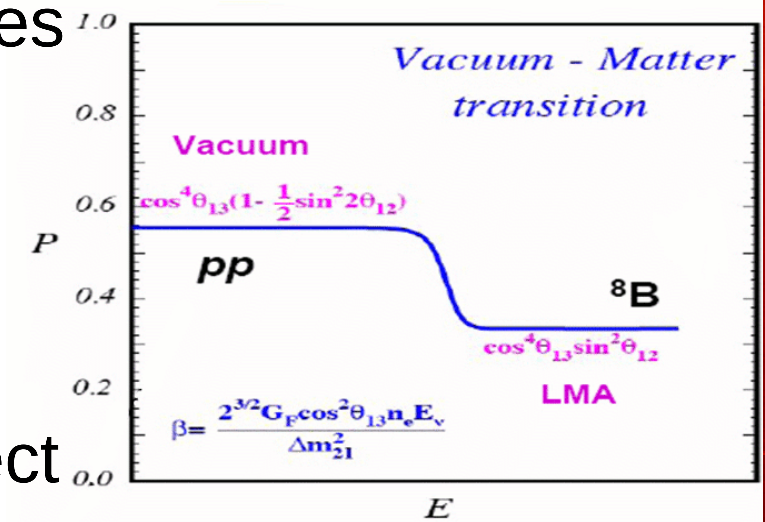
γ's reflect energy produced ~40,000 yrs ago

Is there a subdominant energy source in the sun?

if θ_{13} measured with reactors, a low pp neutrino flux may indicate other energy sources

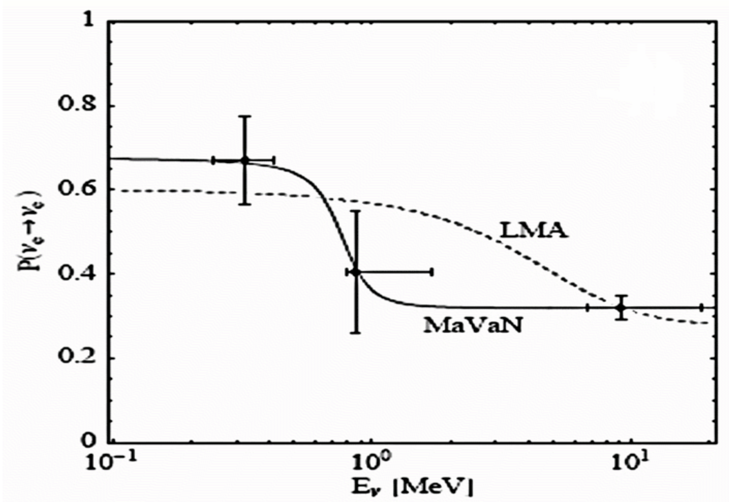
Is the MSW mechanism correct?

- is it really vacuum oscillation at low energies?
- slight discrepancy with Cl data and ^{8}B spectral upturn & d/n effect



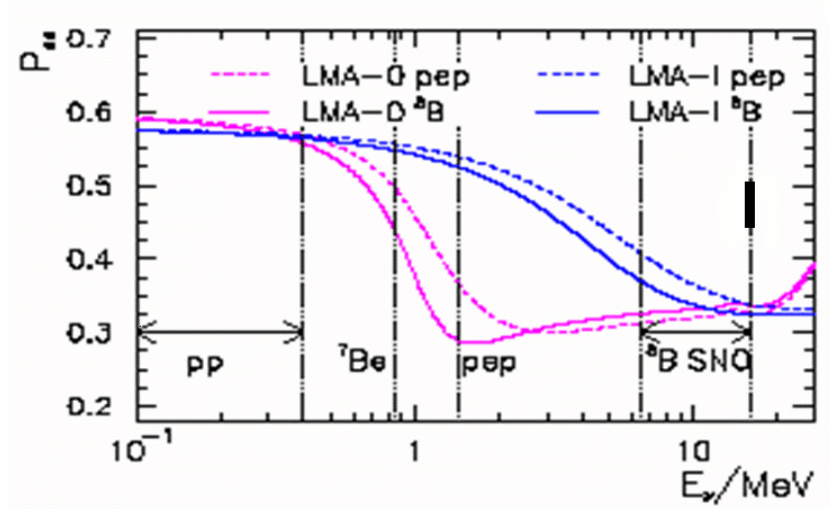
J. N. Bahcall and C. Pena-Garay, JHEP 0311, 004 (2003) [arXiv:hep-ph/0305159].

Are there non-standard mechanisms involved?



Mass-varying neutrinos

Barger, Huber, Marfatia, arXiv:hep-ph/0502196v2 30 sep 2005



Non-standard interactions

A.Friedland, C.Lunardini and C.Pena-Garay, Phys. Lett. B 594, 347 (2004) [arXiv:hep-ph/0402266].
O.G.Miranda, M.A.Tortola and J.W.F.Valle, arXiv:hep-ph/0406280.

still need pp flux to confirm, since luminosity constraint is built into these predictions

Are there sterile neutrinos?

P. C. de Holanda and A. Yu. Smirnov, Phys.Rev.D **69**, 113002 (2004).

what if LSND proves to be correct?

Is CPT violated in the neutrino sector?

do ν_e and $\bar{\nu}_e$ (from KamLAND) observations give the same results?

How much does the CNO cycle contribute?

To answer these questions with confidence we need *both* charged current and electron scattering measurements of solar neutrinos at *both* pp and ^{7}Be/pep energies!

- any forced re-interpretation of solar result would have a major impact on much more expensive neutrino programs

- experiments already underway and some in advanced R&D can accomplish these goals

Community Consensus

SAWG

“The highest priority of the Solar and Atmospheric Neutrino Experiment Working Group is the development of a real-time, precision experiment that measures the pp solar neutrino flux.”

APS executive summary recommendation:

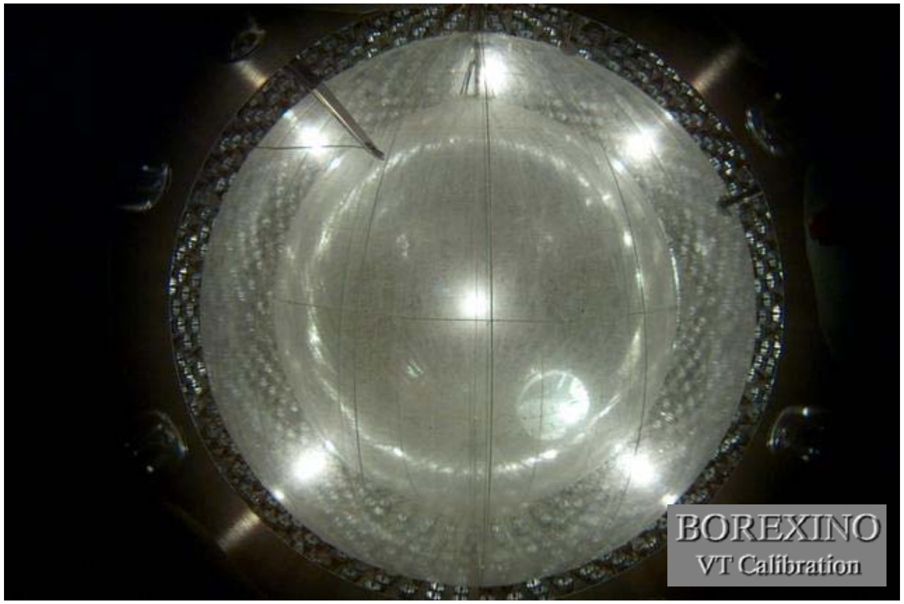
“WE RECOMMEND DEVELOPMENT OF AN EXPERIMENT TO MAKE PRECISE MEASUREMENTS OF THE LOW-ENERGY NEUTRINOS FROM THE SUN.”

Need agencies to address recommendation.

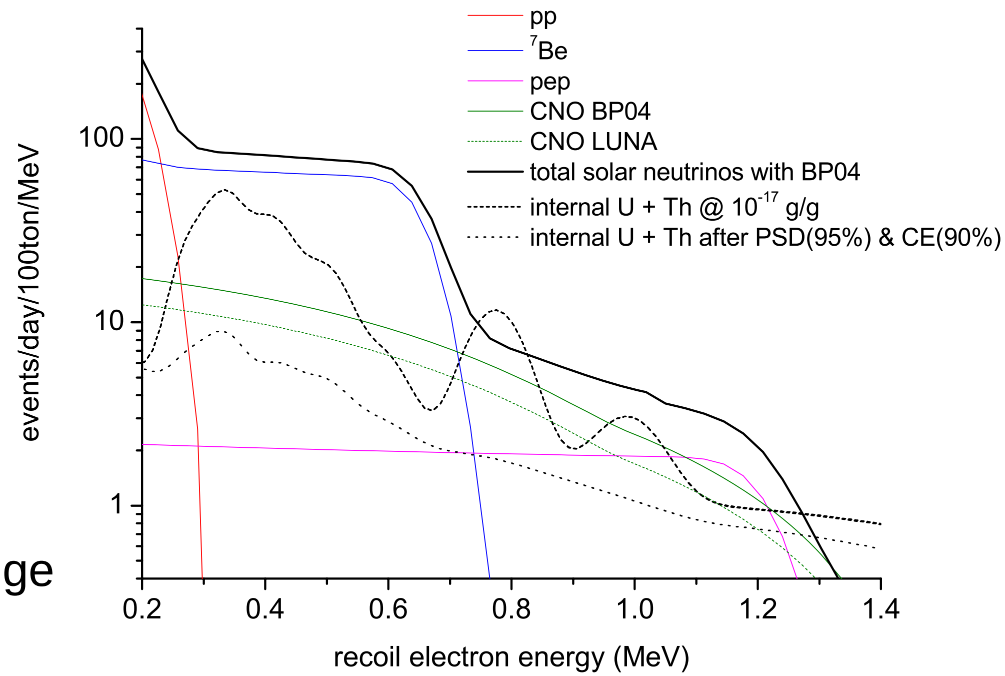
Solar program needs capstone experiments

Measuring the ^{7}Be flux (elastic scattering)

- **Borexino**
- KamLAND
  - 100 ton FV scintillator
  - measure ^{7}Be flux to 5%
    - ‘purity’ @ 10^{-16} g/g U,Th eq
    - 95% psd
    - 90% ce
  - perhaps see pep?
    - above, plus:
    - ‘purity’ @ 10^{-17} g/g
    - ^{11}C tagged
  - to be filled in 2006
  - CTF @ ~ 4×10^{-16} g/g; ^{210}Pb challenge



Borexino spectrum after Neutrino 2004



NSF support for US groups

Measuring the ^{7}Be flux (elastic scattering)

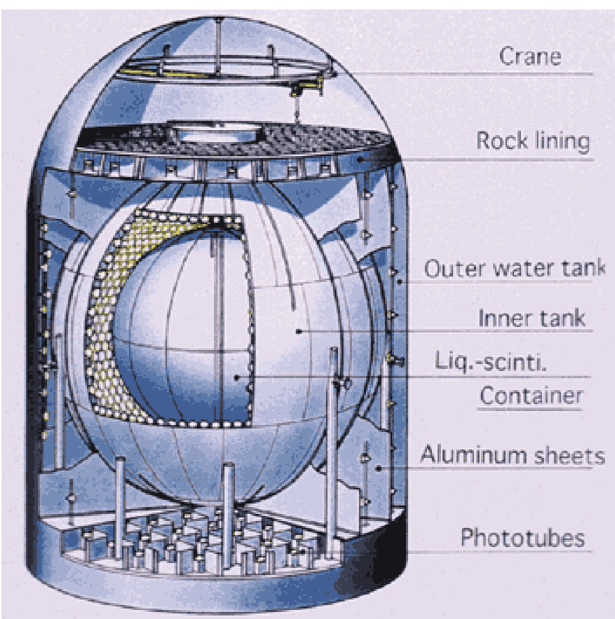
- Borexino
- **KamLAND**

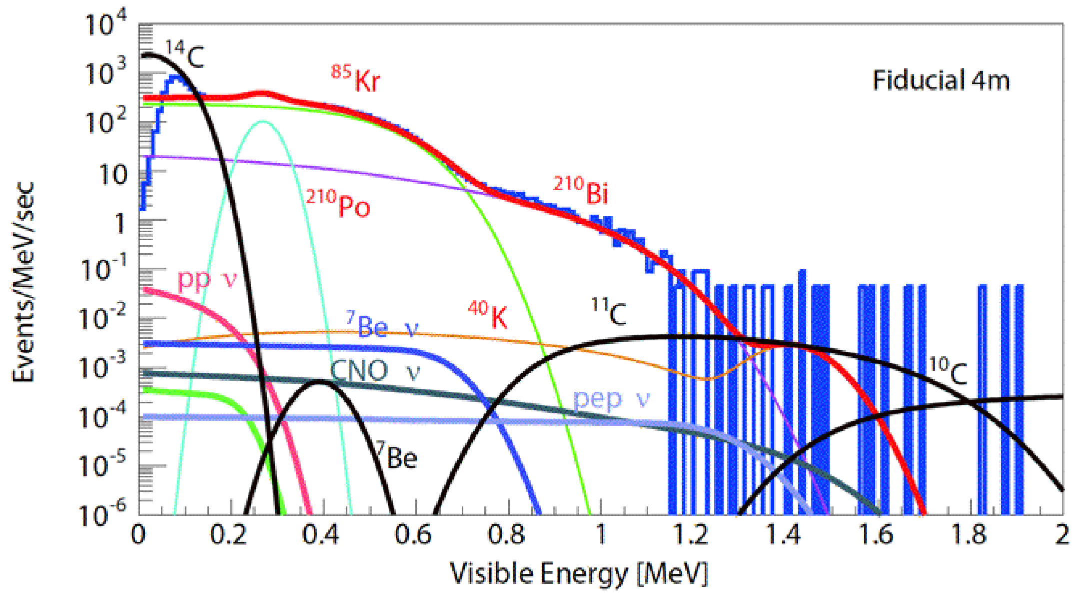
300 ton FV scintillator

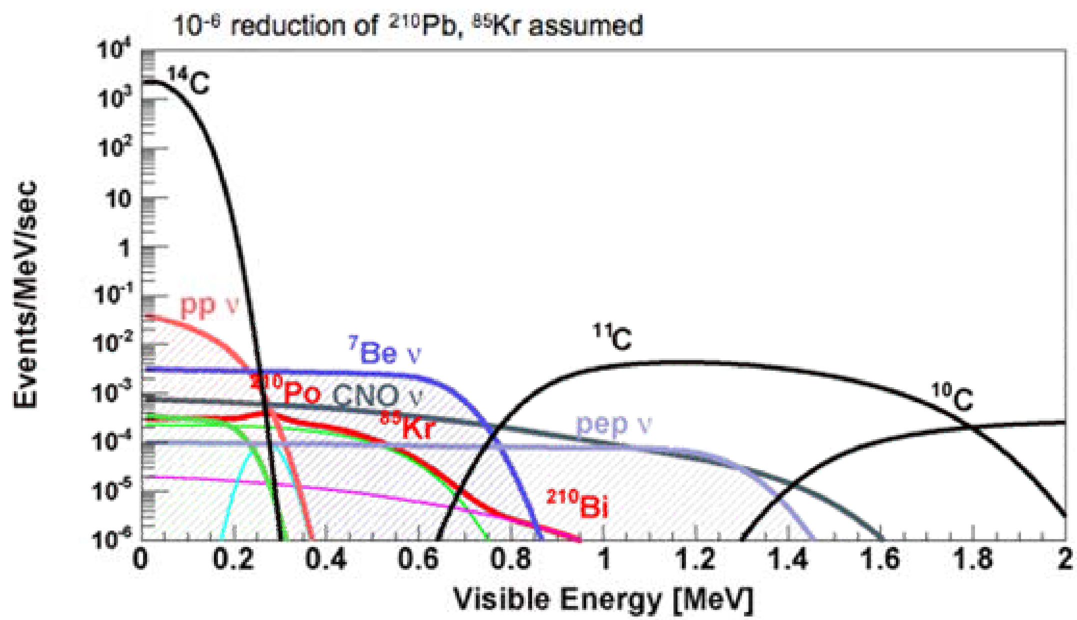
^{210}Pb bkgd challenge

purification to start Sept 06

need ~ 10^5 reduction



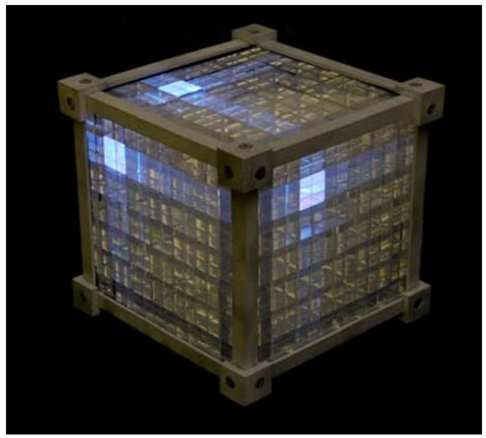


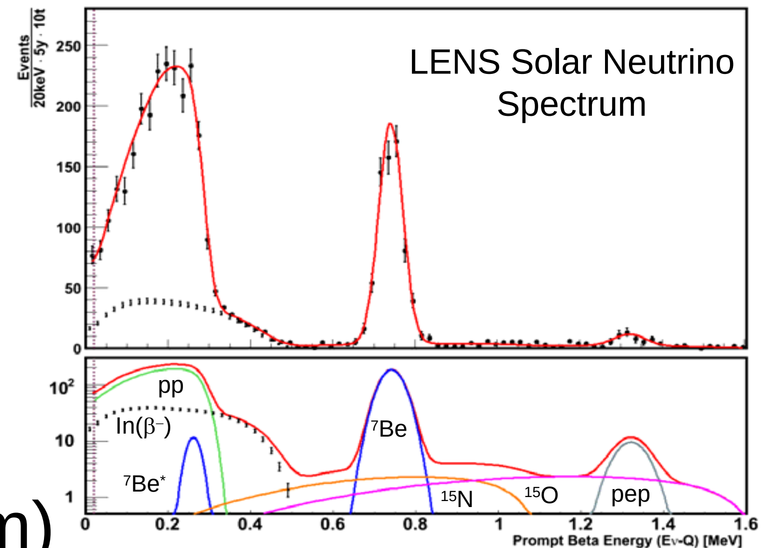


Measuring the pp-ν flux – charged current

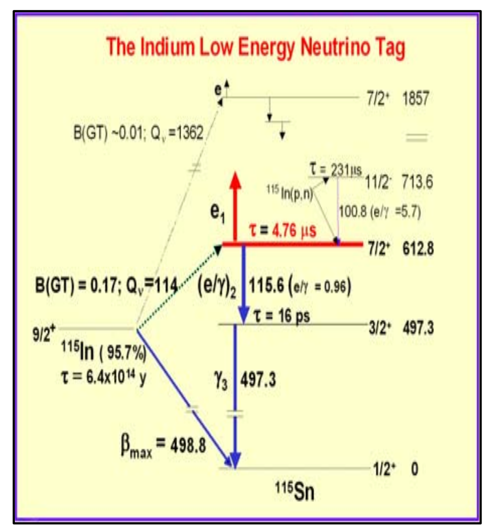
- **LENS**
- Moon

$$\nu_e + {}^{115}In \rightarrow \underbrace{e^-}_{\text{solar signal}} + \underbrace{\gamma + (\gamma / e^-)}_{\text{delayed tag } (\tau = 4.76\,\mu s)} + {}^{115}Sn$$



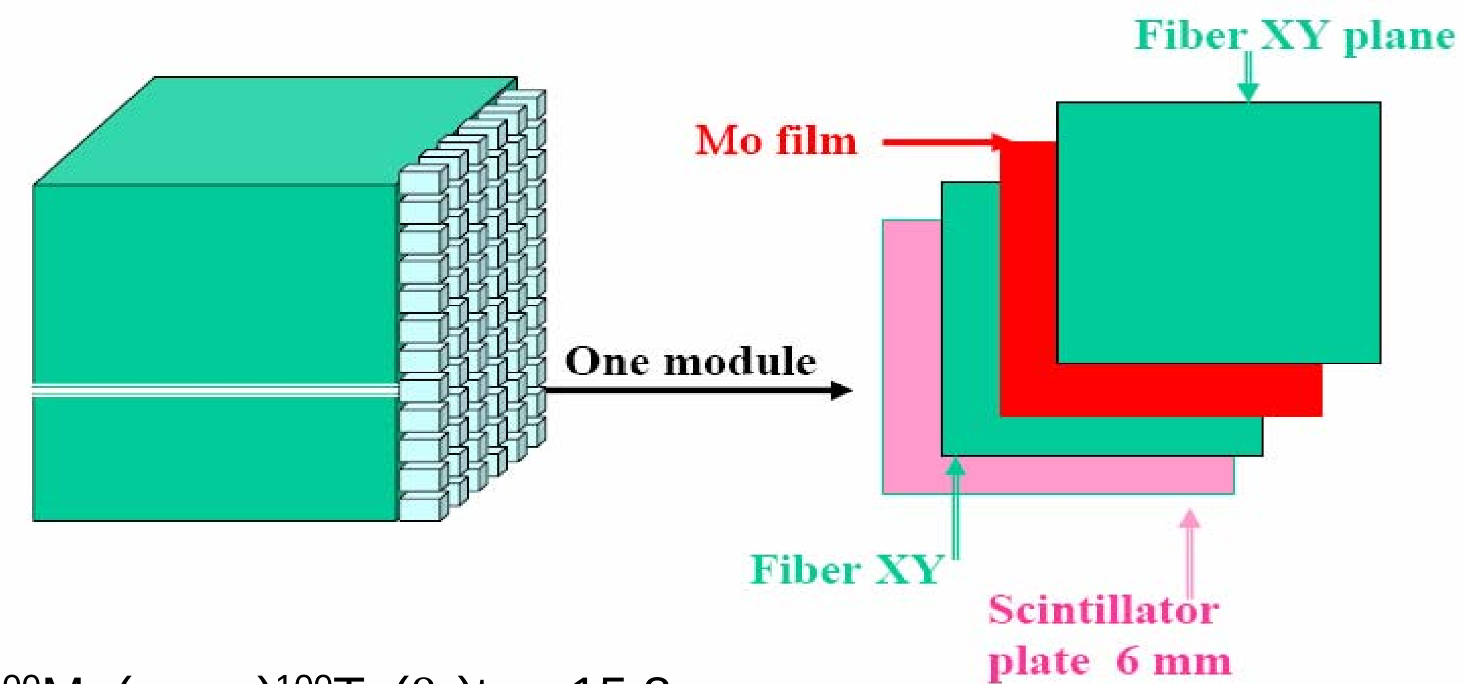


- E_{th}=114 keV (95% of pp spectrum)
- Measure pp-ν flux @ 3%
- Determine CNO-fraction
- Measure T_{sun} by change in mean energy of ^{7}Be line – maybe (hep-ph/9309292)
- needs separate calibration experiment



Measuring the pp-ν flux – charged current

- LENS
- **Moon**



$^{100}Mo(\nu_e,e^-)^{100}Tc(\beta^-)t_{1/2}$=15.8s

E_{th}=168 keV (85% of pp spectrum)

30 tons natural Mo

360 ν's yr^{-1}

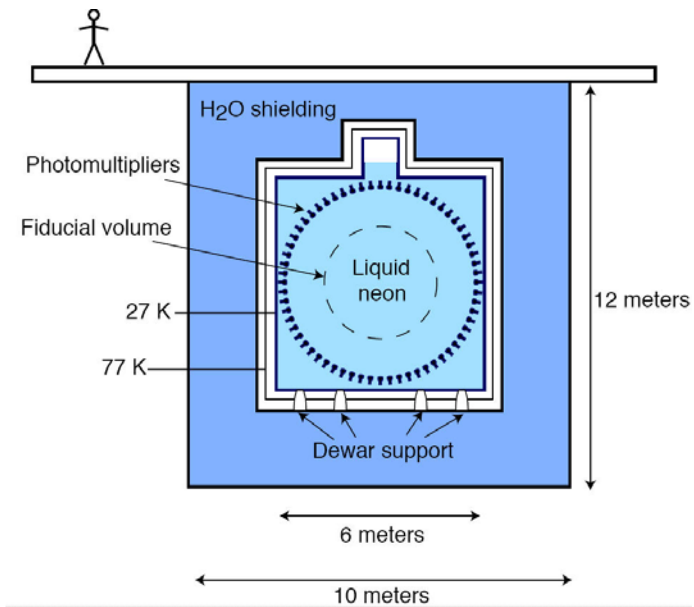
one of three design options shown

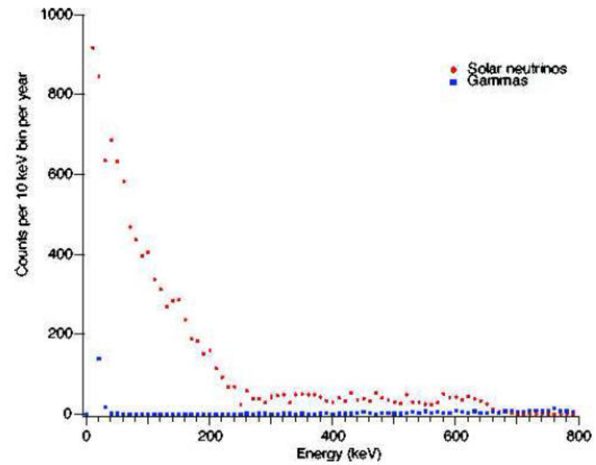
Measuring the pp-ν flux – elastic scattering

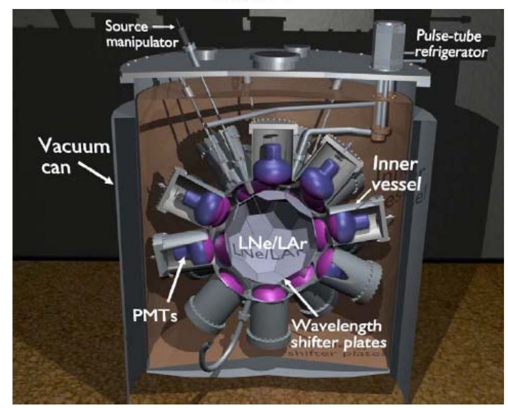
- **CLEAN**
- Heron
- TPC
- XMass
- SNO+

elastic scattering experiments (NC & CC)

complementary use: look for Dark Matter







"mini-CLEAN"

10 ton FV of liquid Ne

20 keV threshold

4 pe / keV

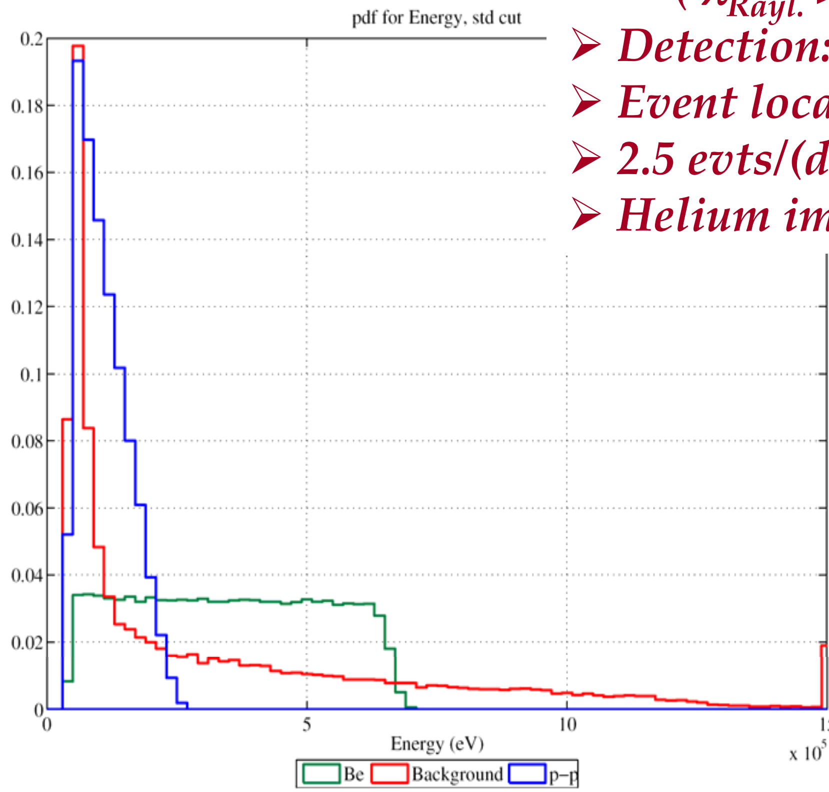
absence of long-lived isotopes; density of 1.2 g/cm3; $60k/ton Ne

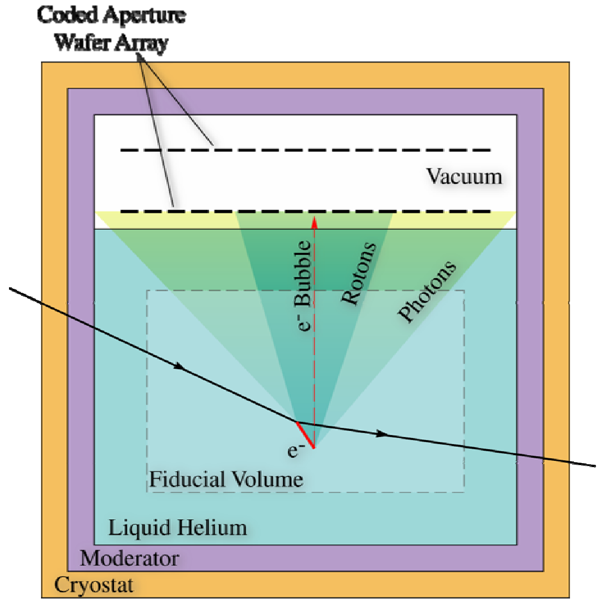
1% measurement of pp and ^{7}Be solar neutrinos

Measuring the pp-ν flux – elastic scattering

- CLEAN
- **Heron**
- TPC
- XMass
- SNO+

- *Total Helium mass 22 tonnes at 50mK.*
- *No internal backgnd (superfluid self-cleaning).*
- *Scintillation/rotons or Scintillation/e-bubbles.*
- *Scintillation: 35% of E_e into 16 eV UV ($\lambda_{Rayl.}$ > 200 meter; self-transparent; η=1.04).*
- *Detection:2400 wafer calorimeters above liquid.*
- *Event location: coded aperture array; few cm.).*
- *2.5 evts/(day-tonne) LMA (pp+Be) E_e > 45 keV .*
- *Helium immune to muon spallation/capture.*





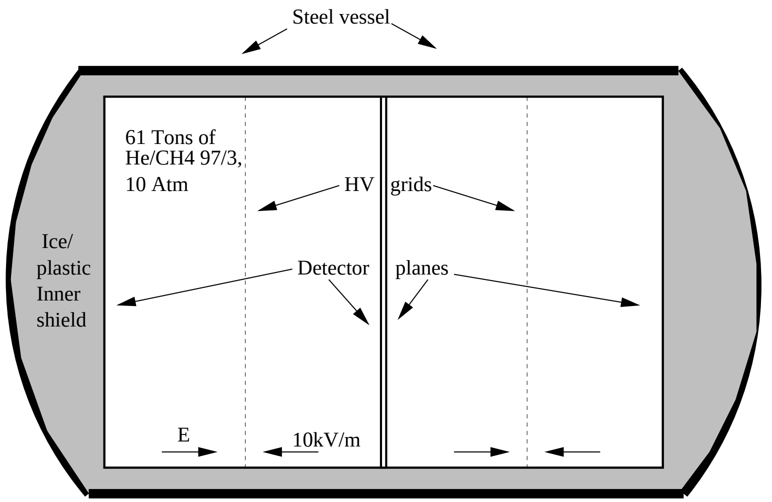
PP flux should be determined to <1.5% (one sigma)
^{7}Be flux should be determined to <5% (one sigma)
Some sensitivity to annual total flux variation due to solar orbit

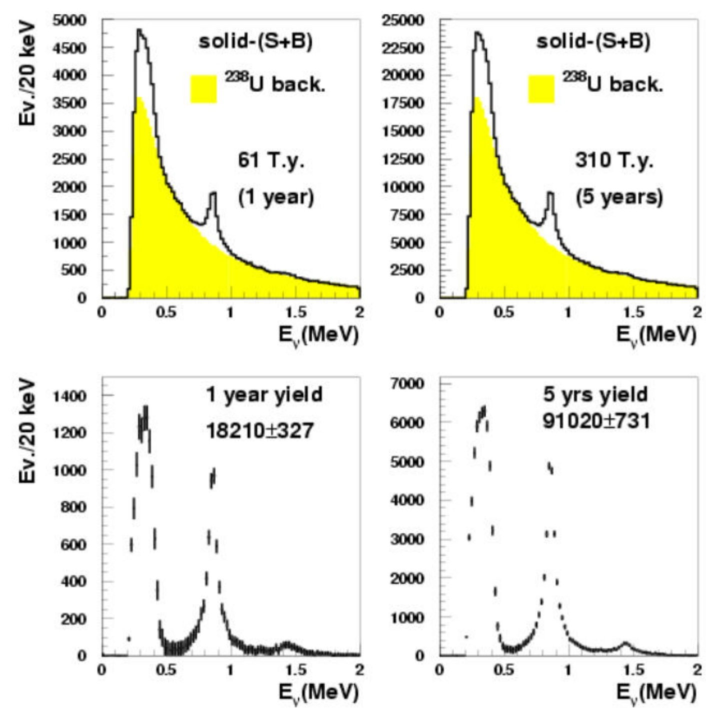
Measuring the pp-ν flux – elastic scattering

- CLEAN
- Heron
- **TPC**
- XMass
- SNO+

He/CH4 @ 10 atm → target mass 7 tons

14m diam x 20 m length

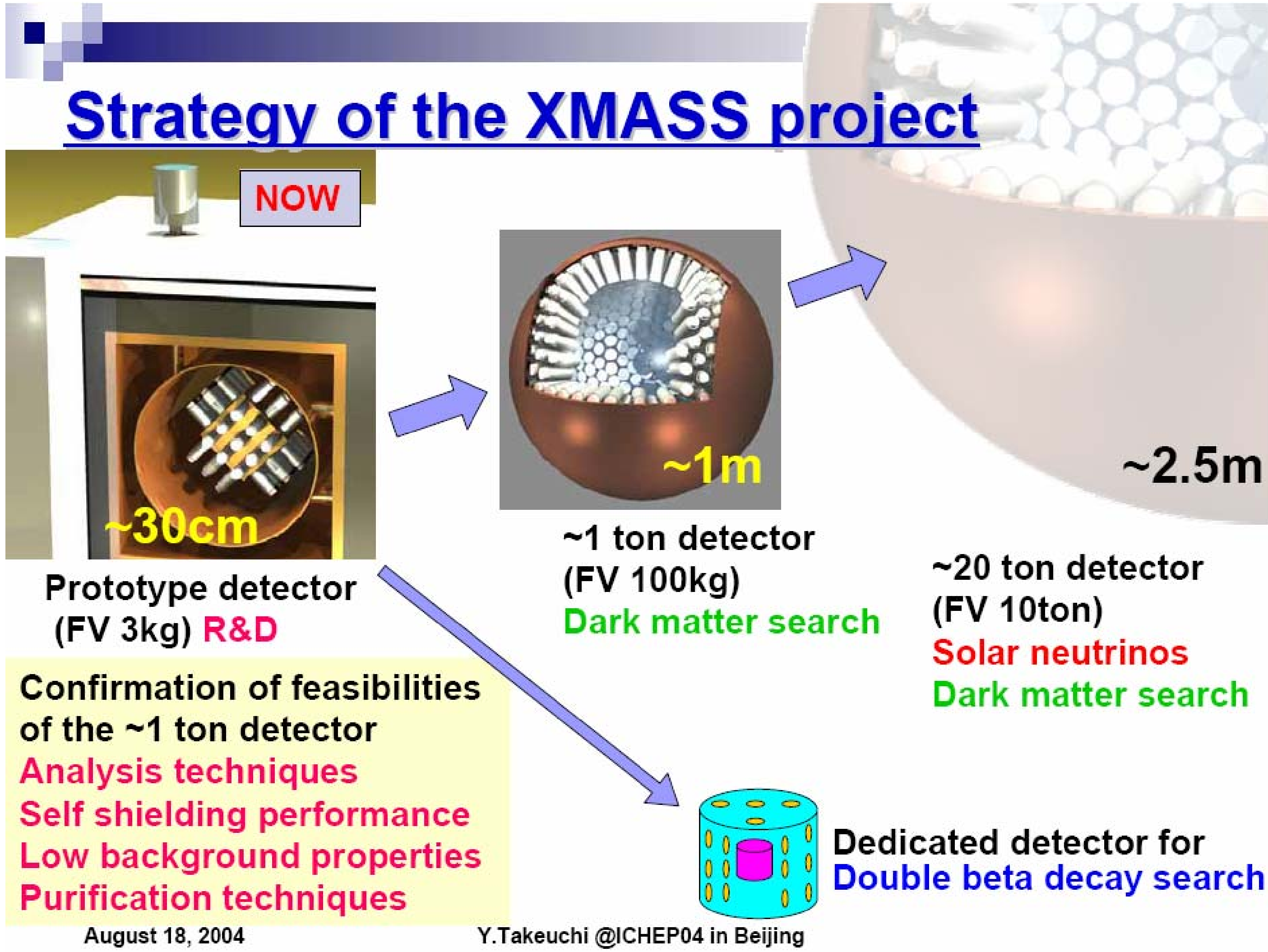




Use e⁻ recoil direction to determine incident ν energy

Measuring the pp-ν flux – elastic scattering

- CLEAN
- Heron
- TPC
- **XMass**
- SNO+



- Internal BG
  - ^{85}Kr:
    Kr/Xe< 4×10^{-15}g/g
    → 1/ 250
  - U/Th:
    U.Th/Xe < 1×10^{-16}g/g
    → 1/ 100 ~ 1/ 200
  - Rn:
    Rn(in Liq) < 10μBq/m^3
- need isotope separation
  if $\tau_{1/2}(2\nu\beta\beta) < 8 \times 10^{23}$y

Measuring the pep-ν flux – elastic scattering

- CLEAN
- Heron
- TPC
- XMass
- **SNO+**

12 m diameter Acrylic Vessel

18 m diameter support structure; 9500 PMTs (~60% photocathode coverage)

1700 tonnes inner shielding H_2O

5300 tonnes outer shielding H_2O

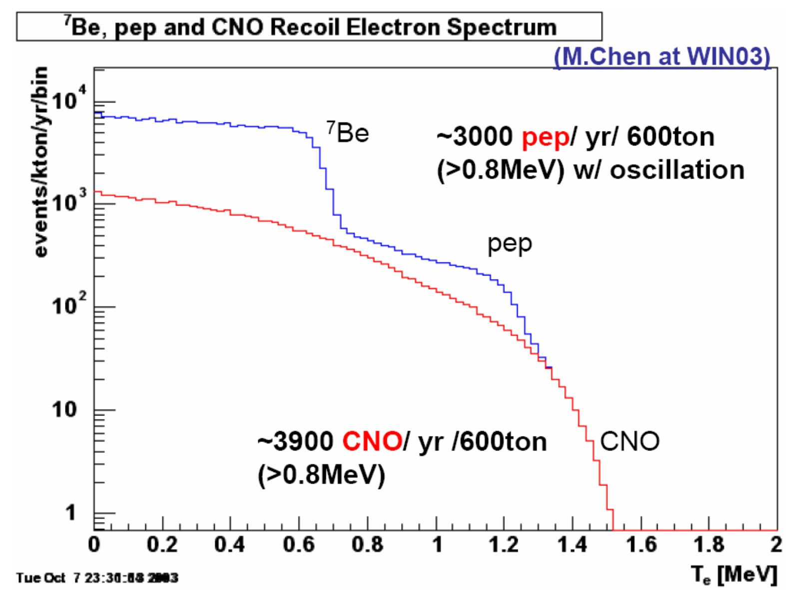
Urylon liner radon seal

depth: 2092 m (~6010 m.w.e.) ~70 muons/day

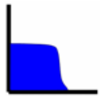
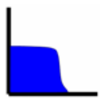
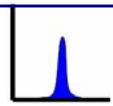
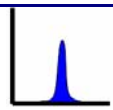
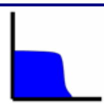
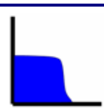
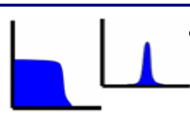
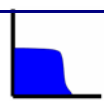
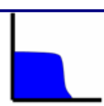
Scintillator: Linear Alkylbenzene

- compatible with acrylic
- high flash point 130 °C
- low toxicity
- cheap, (common feedstock for LAS detergent)
- plant in Quebec makes 120 kton/year

1.5% pep – depth means ^{11}C bkgd low



Summary

Experiment	**mono-energetic ν response**	**Solar ν Sensitivity**	**%pp 5 yr**	**%^{7}Be 5 yr**	**Status**
Borexino		^{7}Be, pep?		5	results in a few years
KamLAND		^{7}Be, CNO?		5	results in a few years
LENS		pp ⇔ CNO	3	5	ready to prototype
MOON		pp ⇔ CNO			r&d only (for now)
CLEAN		pp ⇔ ^{7}Be	1	< 3	ready to prototype
HERON		pp ⇔ ^{7}Be	1.5	5	r&d only (for now)
TPC	 ?	pp ⇔ ^{7}Be			r&d
XMass		pp, ^{7}Be			100 kg prototype
SNO+		^{7}Be, pep	1.5(pep)		TDR Fall 06, construct 07

This program will *individually* measure:

• pp flux	3% (CC);	1.5% (ES)
• ^{7}Be flux	4% (CC);	3% (ES)
• pep flux	15% (CC);	3% (ES)
• CNO flux	8% (CC); ?	

this is the best and perhaps only way probe the extremely fertile solar ν parameter space to:

- test the assumptions underlying the MSW explanation
- find clear signs of new neutrino properties and interactions
- test the ubiquitous luminosity constraint
- establish if nuclear energy fully accounts for the Sun’s current energy release

We should follow in the footsteps of Bahcall and Davis, who have shown the impact of studying solar neutrinos has far reaching and profound consequences