Neutrino Physics and status of SNOLAB

Art McDonald

Queen's University, Kingston, Canada

IPMU, March 11, 2008

- Motivation for Underground Laboratories
- Overview of Neutrino Physics measurements
- Motivation for future solar neutrino, double beta decay measurements
- Status of SNOLAB and future experimental program

Apparently underground laboratories have a long history!

GAIUS PLINIUS secundus
1st Century A.D

NATURALIS HISTORIA
Chapter on ASTRONOMY and COSMOLOGY

……. I believe that there are some crazy people who go inside mines to study the stars……..

You will hear from three of us (crazy people):
McDonald: Low Energy Neutrinos, Double Beta Decay - SNOLAB
Suzuki: Atmospheric, accelerator neutrinos – Kamioka
Gaitskill: Dark Matter detection

Neutrino Physics

What have we learned so far?

Neutrino properties

1) Evidence for neutrino flavor change (oscillation):

- Atmospheric: Super-K
- Solar: SNO (Solar model independent test, supported by other measurements).
- Reactor: Kamland shows flavor change clearly, same parameters as solar.
- LSND?: MiniBoone does not see effects compatible with oscillation at LSND
- Neutrino parameter limits set by many experiments: Reactor, Accelerator

2) Neutrino Mass:

- Mass differences only defined from oscillations
- Mass Limit < 2.8 eV from tritium beta decay
- Double Beta Decay: Limits so far: Mass limit < ~ 0.4 eV if Majorana.
- Limits from Astrophysics: Large Scale structure < 1 eV.

3) Number of light neutrinos:

- Z width: 2.981 +- 0.008 active types
- Big Bang Nucleosynthesis: ~ 3 active neutrino types
- No specific evidence for sterile neutrinos.
- Limits on sterile from solar, atmospheric measurements.

Neutrino properties

-The most favored explanation for the data to date is Neutrino Oscillations of 3 active massive neutrino types.

-Other possibilities are not completely ruled out, but less favored
- Flavor Changing Neutral Currents
- Resonant Spin Flavor Precession for solar neutrinos
- Violation of Equivalence Principle
- CPT Violation
- Sterile neutrinos

In the discussion to follow, I will concentrate on the favored basis of Neutrino Oscillations with three active massive neutrinos and consider the further information to be obtained on this basis (including some further study of the sub-dominant effects above).

Using the oscillation framework:

If neutrinos have mass: $$|\nu_l\rangle = \sum U_{li} |\nu_i\rangle$$

For 3 Active neutrinos. (MiniBoone has recently ruled out LSND result)

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Maki-Nakagawa-Sakata-Pontecorvo matrix

(Double β decay only)

$$= \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & e^{-i\alpha_3/2+i\delta} \end{pmatrix}$$

Solar,Reactor	Atmospheric	CP Violating Phase	Reactor, Accel.	Majorana Phases

$$where\ c_{ij} = \cos\theta_{ij},\ and\ s_{ij} = \sin\theta_{ij}$$

Range defined for Δm_{12}, Δm_{23}

For two neutrino oscillation in a vacuum: (a valid approximation in many cases)

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2 (1.27 \frac{\Delta m^2 L}{E})$$

Matter Effects – the MSW effect

(Mikheyev, Smirnov, Wolfenstein)

$$i\frac{d}{dt}\begin{bmatrix}\nu_e\\ \nu_x\end{bmatrix} = H\begin{bmatrix}\nu_e\\ \nu_x\end{bmatrix}$$

$$\mathbf{H} = \begin{bmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \boxed{\sqrt{2}G_F N_e} & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{bmatrix}$$

The extra term arises because solar ν_e have an extra interaction via W exchange with electrons in the Sun or Earth.

In the oscillation formula:

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{(\omega - \cos 2\theta)^2 + \sin^2 2\theta}$$

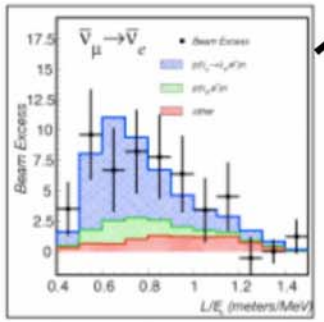
$$\omega = -\sqrt{2}G_F N_e E / \Delta m^2$$

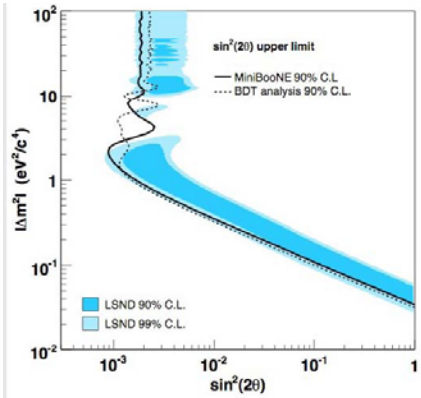
MSW effect can produce an energy spectrum distortion and flavor regeneration in Earth giving a Day-night effect.
If observed, matter interactions define the mass heirarchy.

Neutrino LANDscape

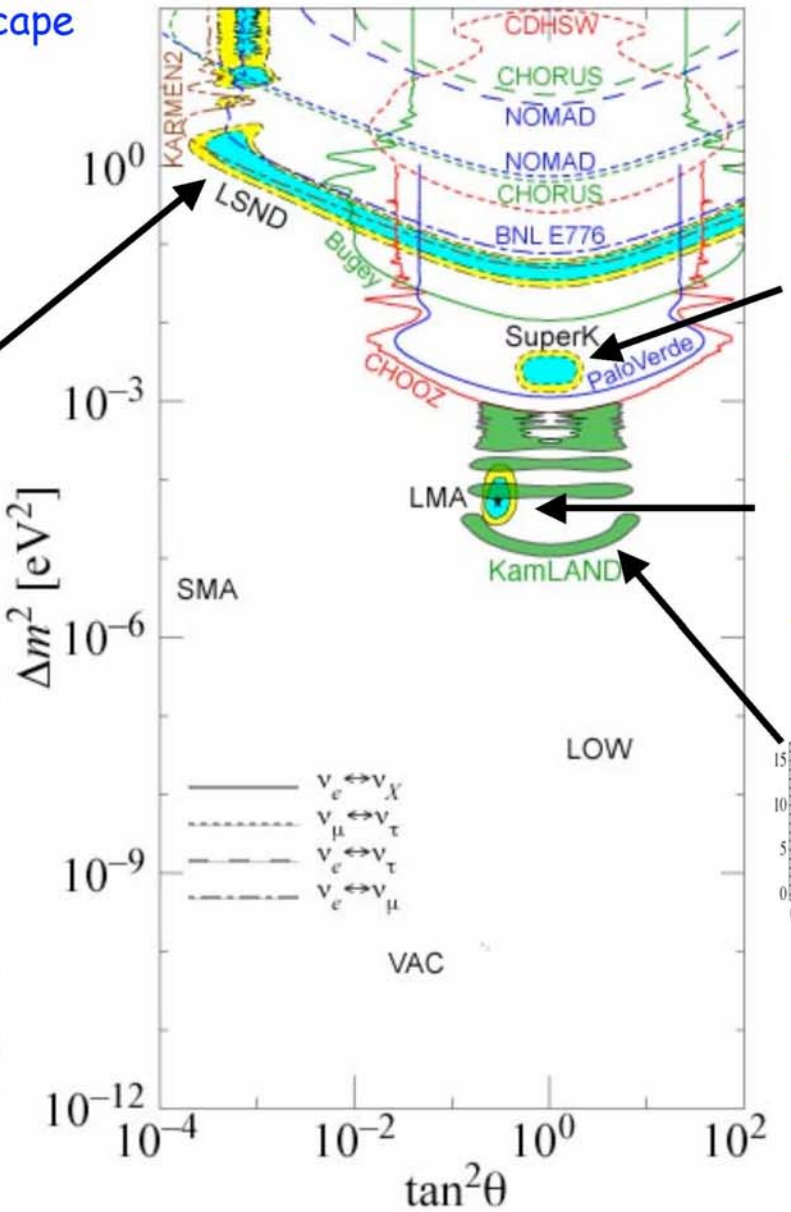
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

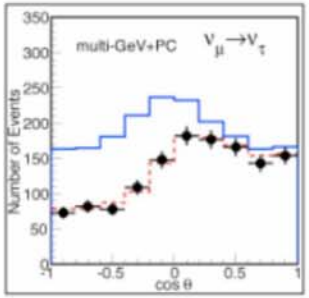
LSND





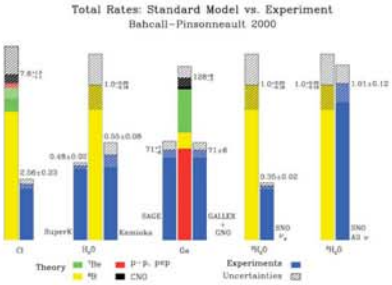
Now ruled out
By MiniBoone





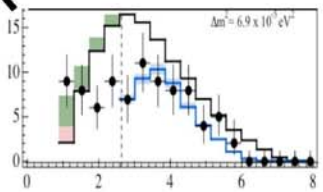
SuperK

$\nu_\mu \rightarrow \nu_\tau$



Solar

$\nu_e \rightarrow \nu_x$

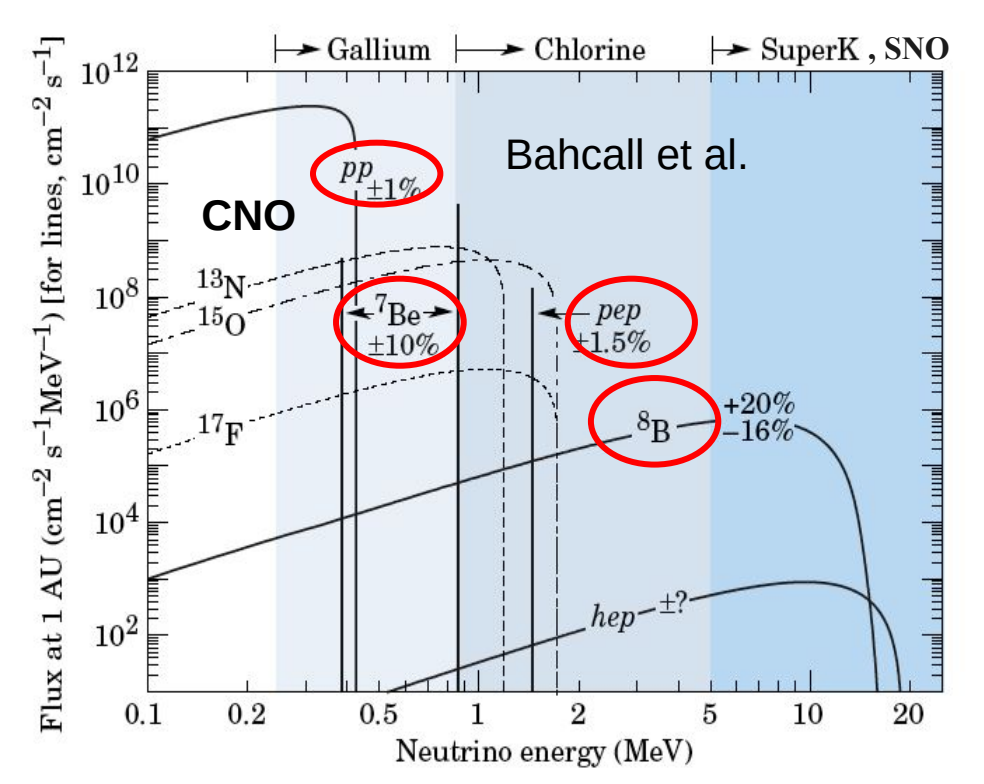


KAMLAND
Reactor

$\bar{\nu}_e \rightarrow \bar{\nu}_x$

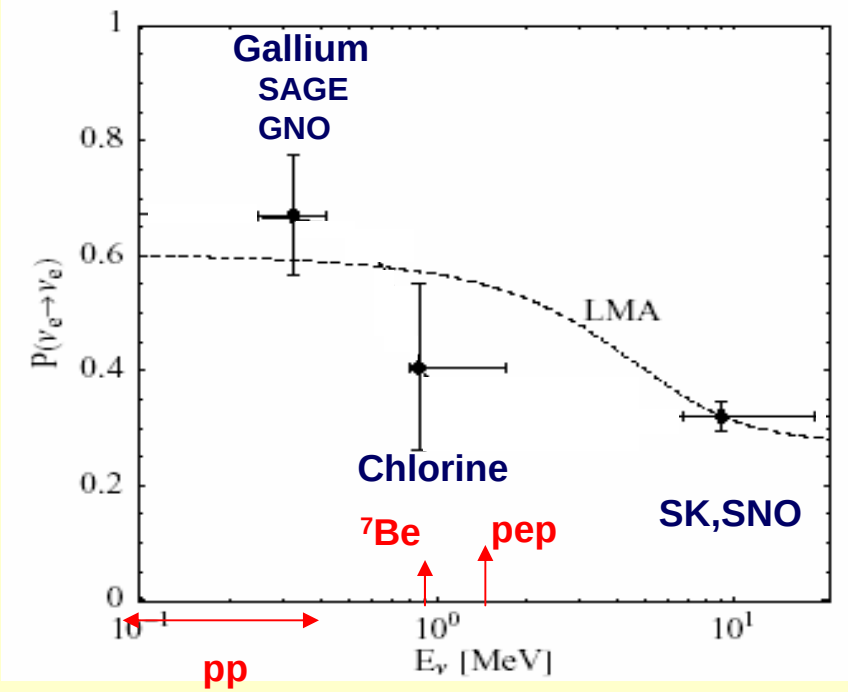
Oscillations for Solar Neutrinos

Solar Model Flux Calculations



Matter Interaction Effect:LMA

Current Data for ν_e Survival



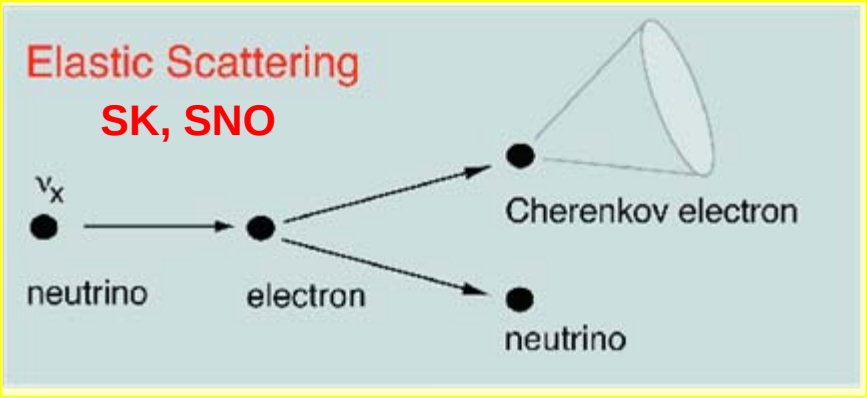
Until 2001/2, it was uncertain whether low ν_e fluxes came from oscillations or solar models

Neutrino Detection in H_2O & D_2O

Elastic Scattering (ES)

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

ν_x, but enhanced for ν_e by a factor of 6

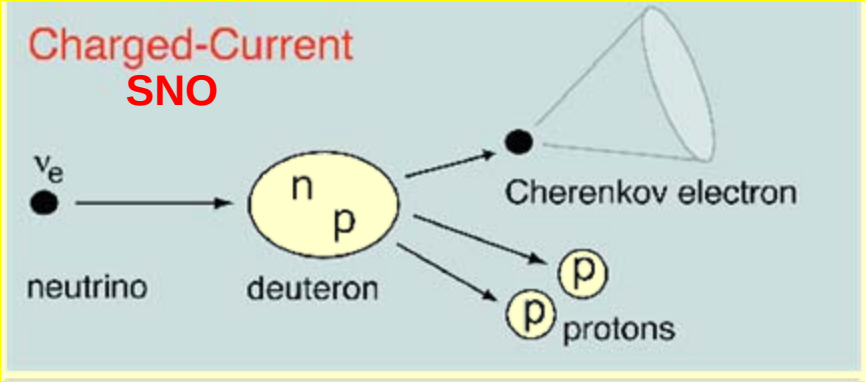


Charged-Current (CC)

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

$E_{thresh} = 1.4$ MeV

ν_e only

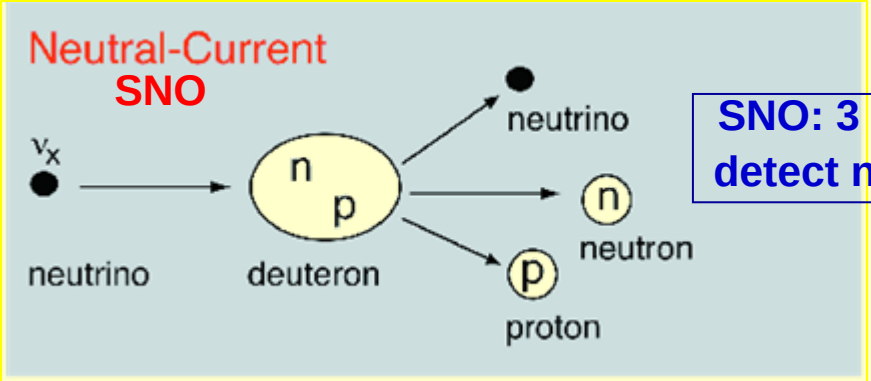


Neutral-Current (NC)

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

$E_{thresh} = 2.2$ MeV

Equally sensitive to ν_e ν_μ ν_τ



SNO: 3 ways to detect neutrons

Solar Neutrino Physics From SNO (+SK)

Clear Evidence: Flavor change + active neutrino appearance

SNO June 2001 (with SK)

$$\frac{\Phi_{CC}}{\Phi_{ES}} = \frac{\nu_e}{\nu_e + 0.15\,(\nu_\mu + \nu_\tau)}$$

3.3 σ

April 2002

Sept. 2003
March 2005

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

5.3 σ

> 7 σ

With salt in SNO

Total ^{8}B Solar Neutrino Flux

June 2001

$$\Phi_x = \Phi_{CC} + (\Phi_{ES} - \Phi_{CC}) \times (1/0.15)$$

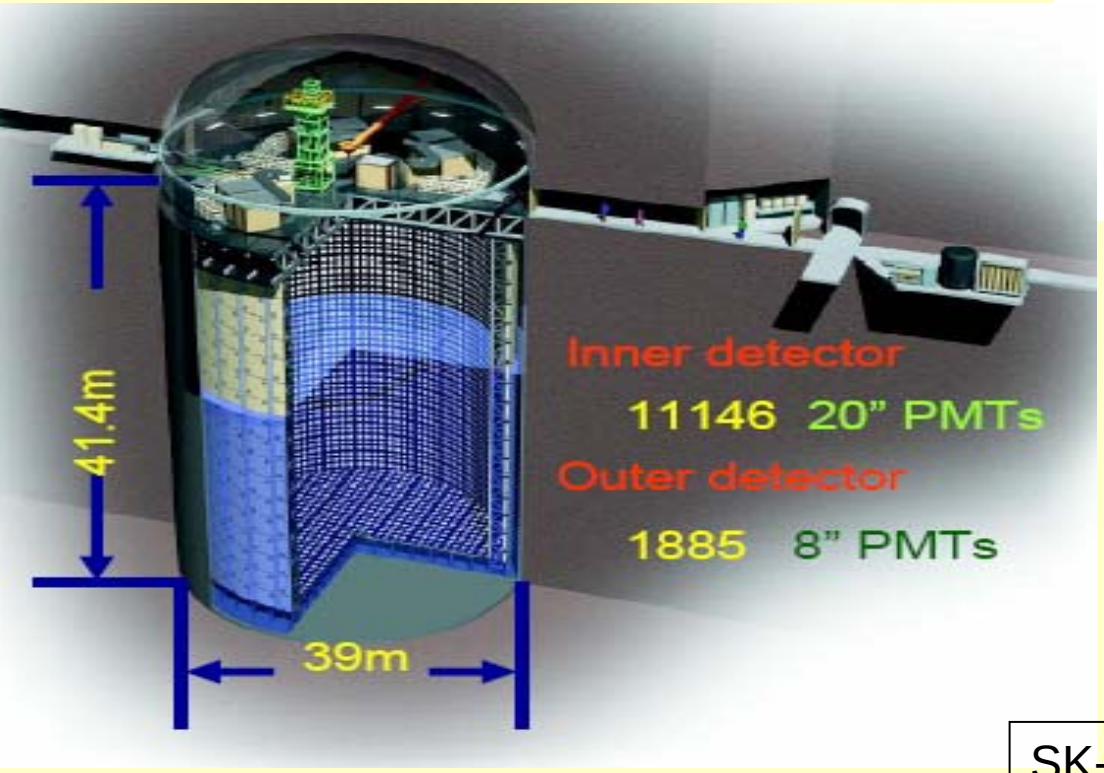
April 2002
Sept. 2003
March 2005

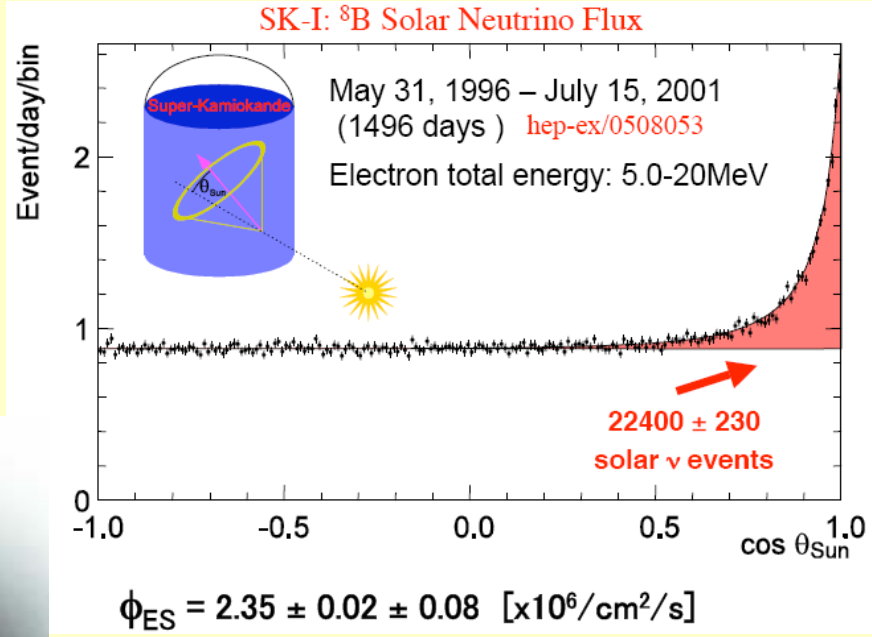
$$\Phi_x = \Phi_{nc}$$

~10%

Super-Kamiokande III

- SK-III reconstructed April 2006
- 40% photocathode coverage
- tank filled July 11, 2006
- purifying water since October 2006





SK-I day-night asymmetry converted to ν_e asymmetry

$$\frac{N-D}{(N+D)/2} = 0.033 \pm 0.031^{+0.019}_{-0.020}$$

SK-1 obtained beautiful data on energy spectrum but saw no distortion.

The Sudbury Neutrino Observatory: SNO

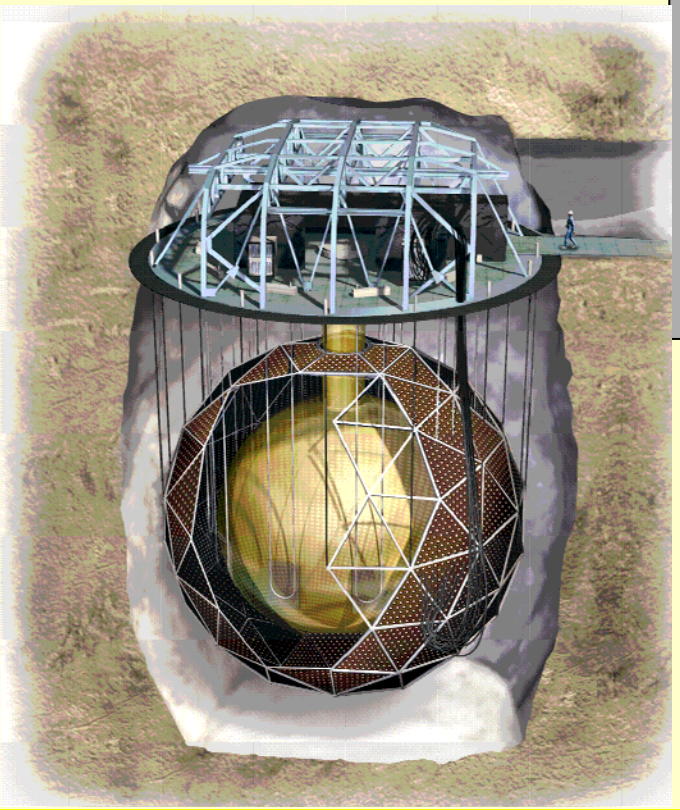
Acrylic vessel (AV)
12 m diameter

1000 tonnes D_2O
($300 million)

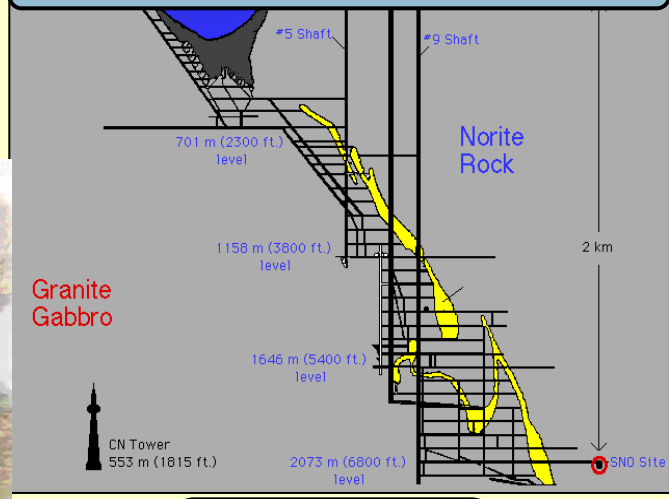
1700 tonnes H_2O
inner shielding

5300 tonnes H_2O
outer shielding

~9500 PMT's



6800 feet (~2km) underground



Creighton mine
Sudbury, CA

Entire detector
Built as a Class 2000
Clean room:
70,000 showers
to date.

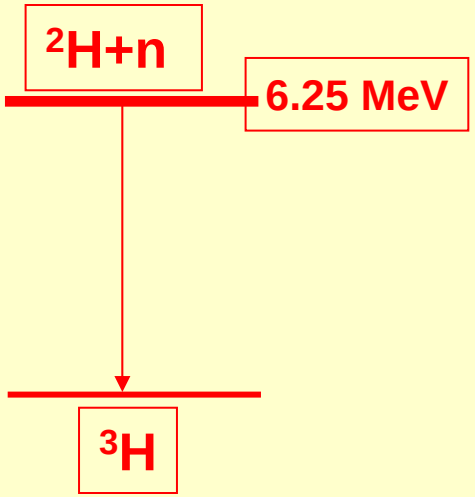
"The Sudbury Neutrino Observatory" , The SNO Collaboration
Nuclear Instruments and Methods in Physics Research A449 (2000) pp. 172-207

The heavy water has recently been returned and development work is in progress on SNO+ with liquid scintillator and ^{150}Nd additive.

SNO: 3 neutron (NC) detection methods (systematically different)

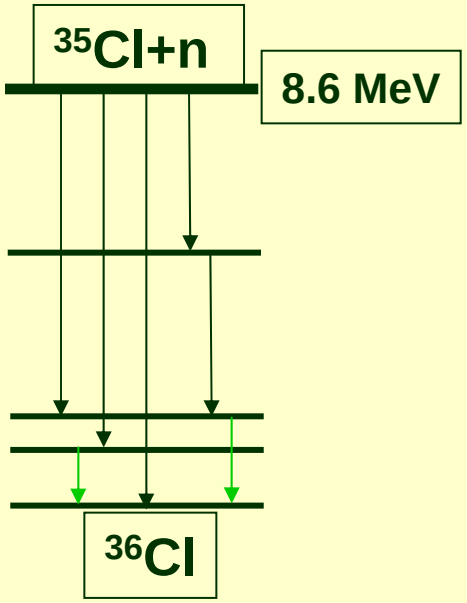
Phase I (D_2O)
Nov. 99 - May 01

n captures on
$^2H(n, \gamma)^3H$
Effc. ~14.4%
NC and CC separation by energy, radial, and directional distributions



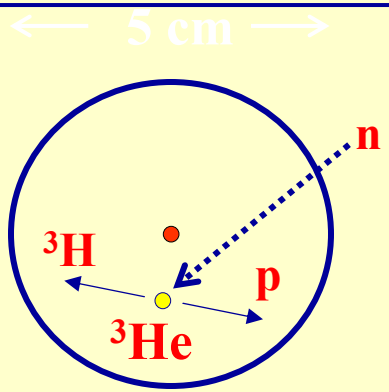
Phase II (salt)
July 01 - Sep. 03

2 t NaCl. n captures on
$^{35}Cl(n, \gamma)^{36}Cl$
Effc. ~40%
NC and CC separation by event isotropy



Phase III (^3He)
Nov. 04-Dec. 06

40 proportional counters
$^3He(n, p)^3H$
Effc. ~ 30% capture
Measure NC rate with entirely different detection system.

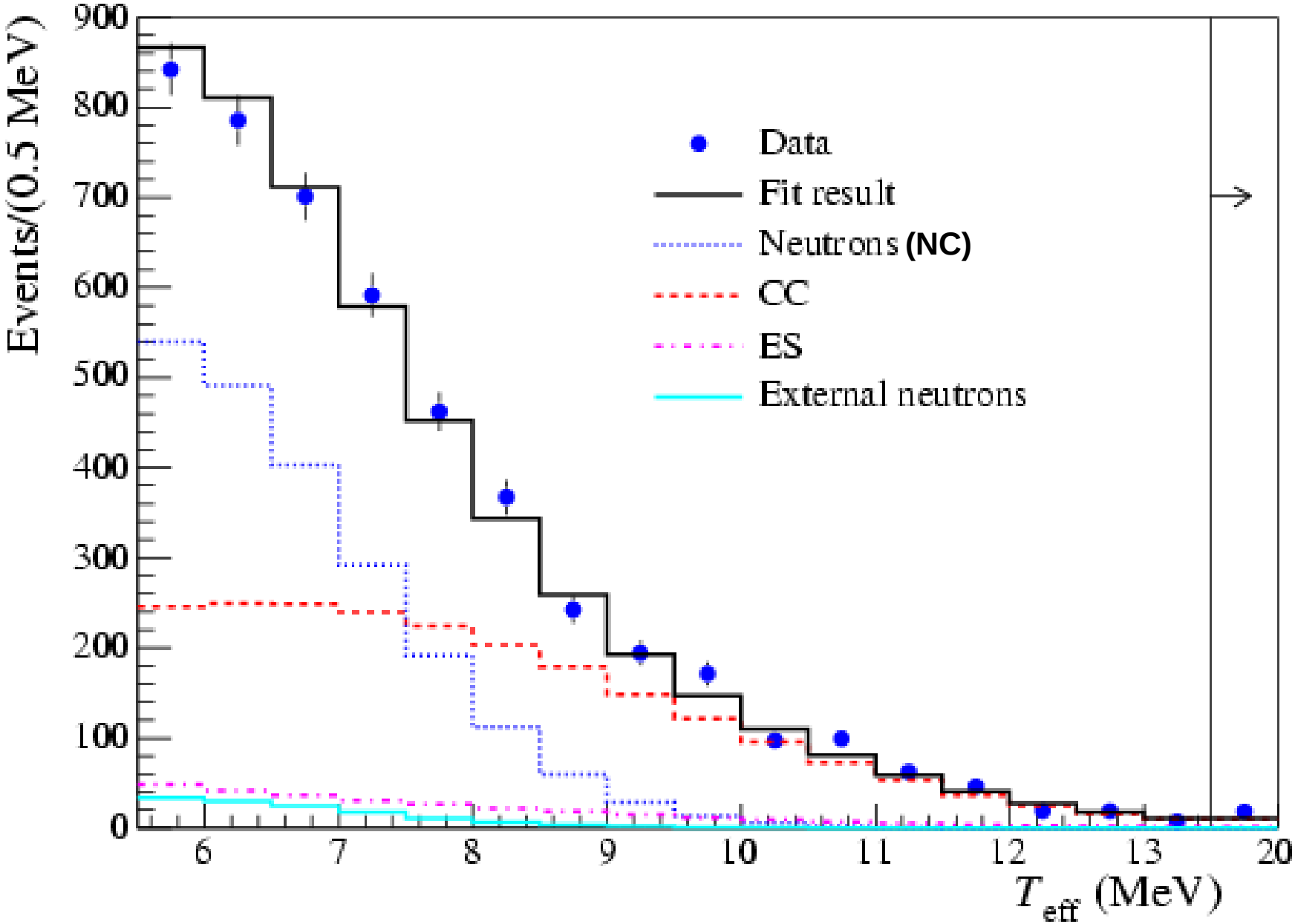


$$n + {}^3He \rightarrow p + {}^3H$$

SNO Phase 2 data: 391 live days with salt hep-ex/0502021 March 2005

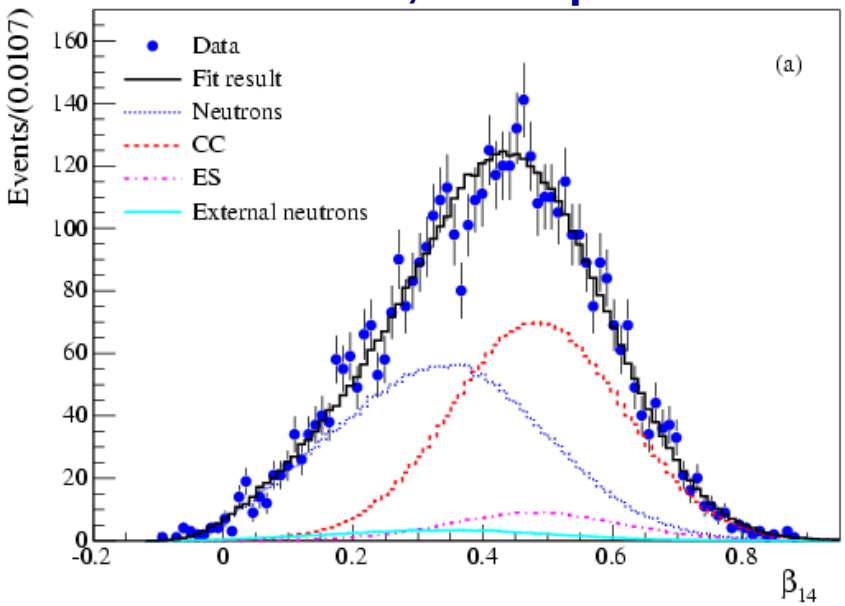
Total Spectrum

"Blind" analysis of data

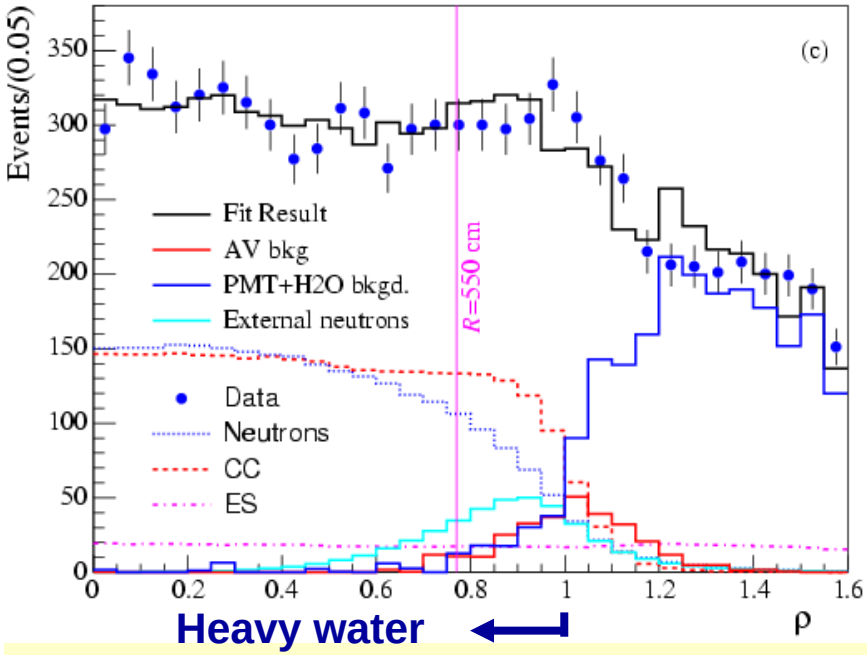


SNO Phase 2 with salt

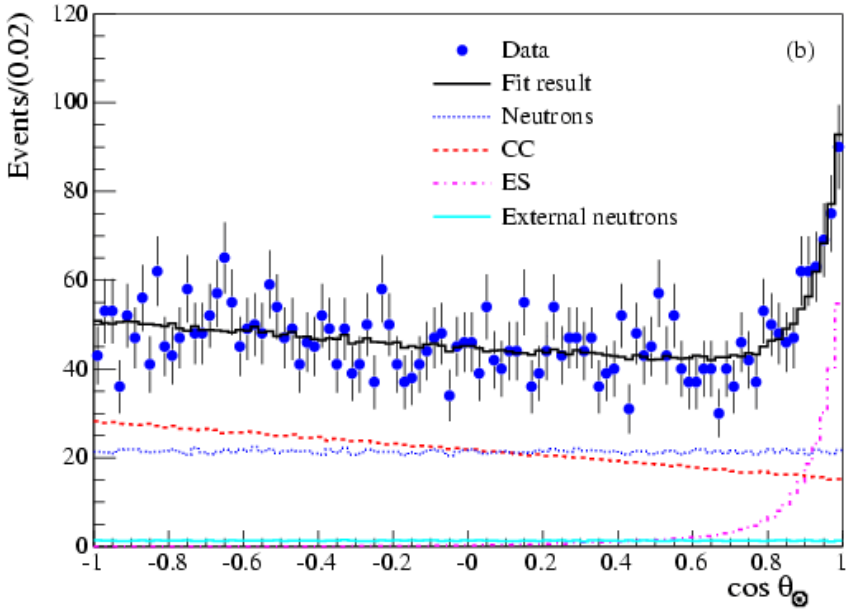
ISOTROPY: NC, CC separation



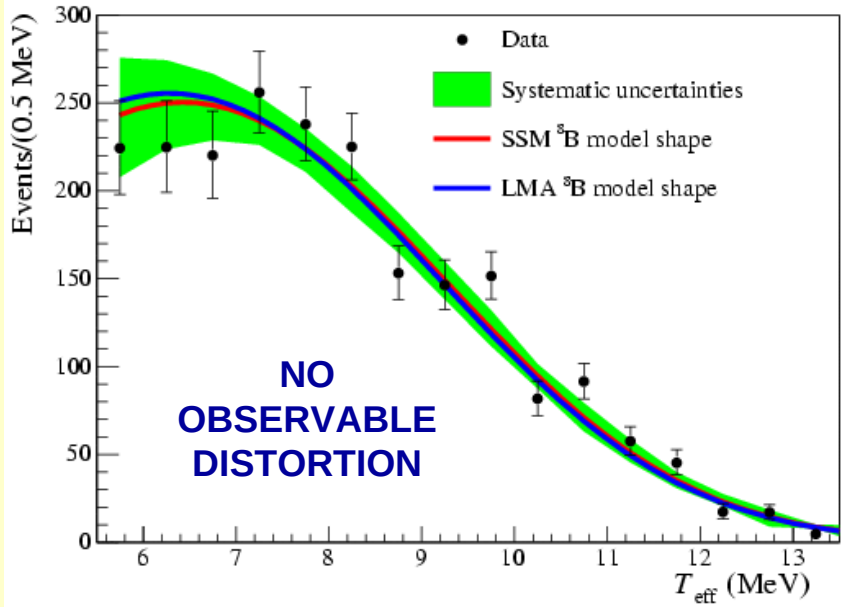
EVENTS VS VOLUME: Bkg < 10%

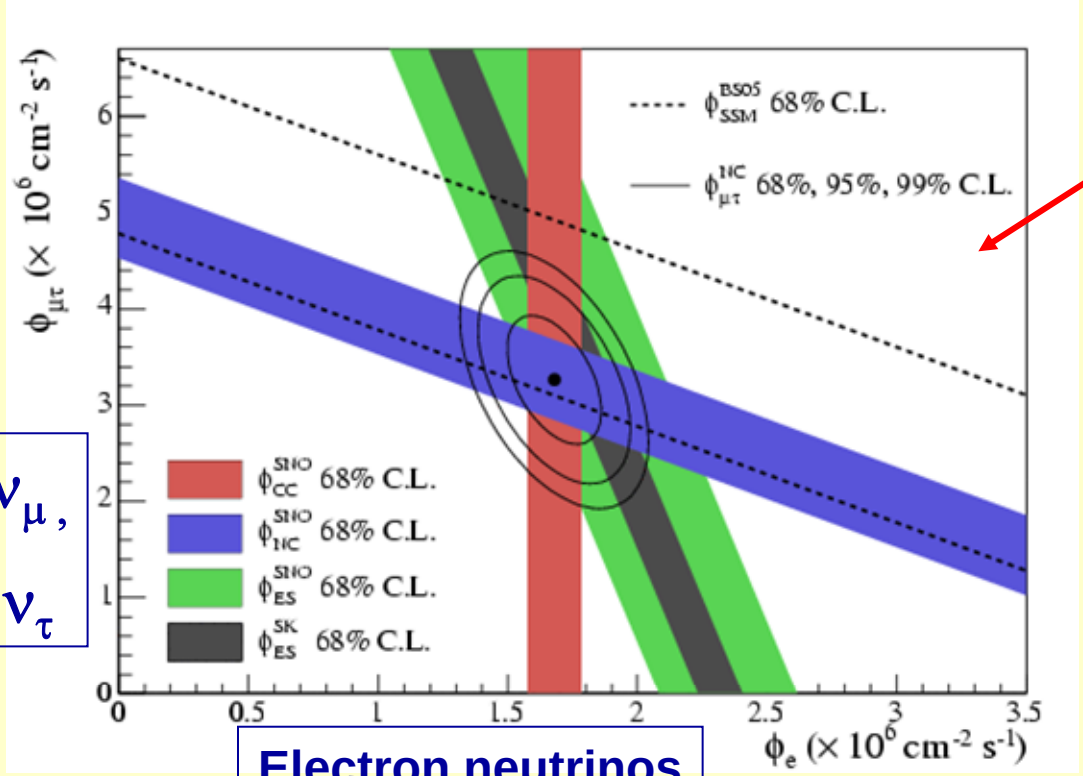


DIRECTION FROM SUN



ENERGY SPECTRUM FROM CC REACTION





ν_μ, ν_τ

Electron neutrinos

Flavor change determined by > 7 σ.

CC, NC FLUXES MEASURED INDEPENDENTLY

The Total Flux of Active Neutrinos is measured independently (NC) and agrees well with solar model

Calculations:

5.82 +- 1.3 (Bahcall et al),

5.31 +- 0.6 (Turck-Chieze et al)

$$\phi_{CC} = 1.68\ ^{+0.06}_{-0.06}(\text{stat.})^{+0.08}_{-0.09}(\text{syst.})$$

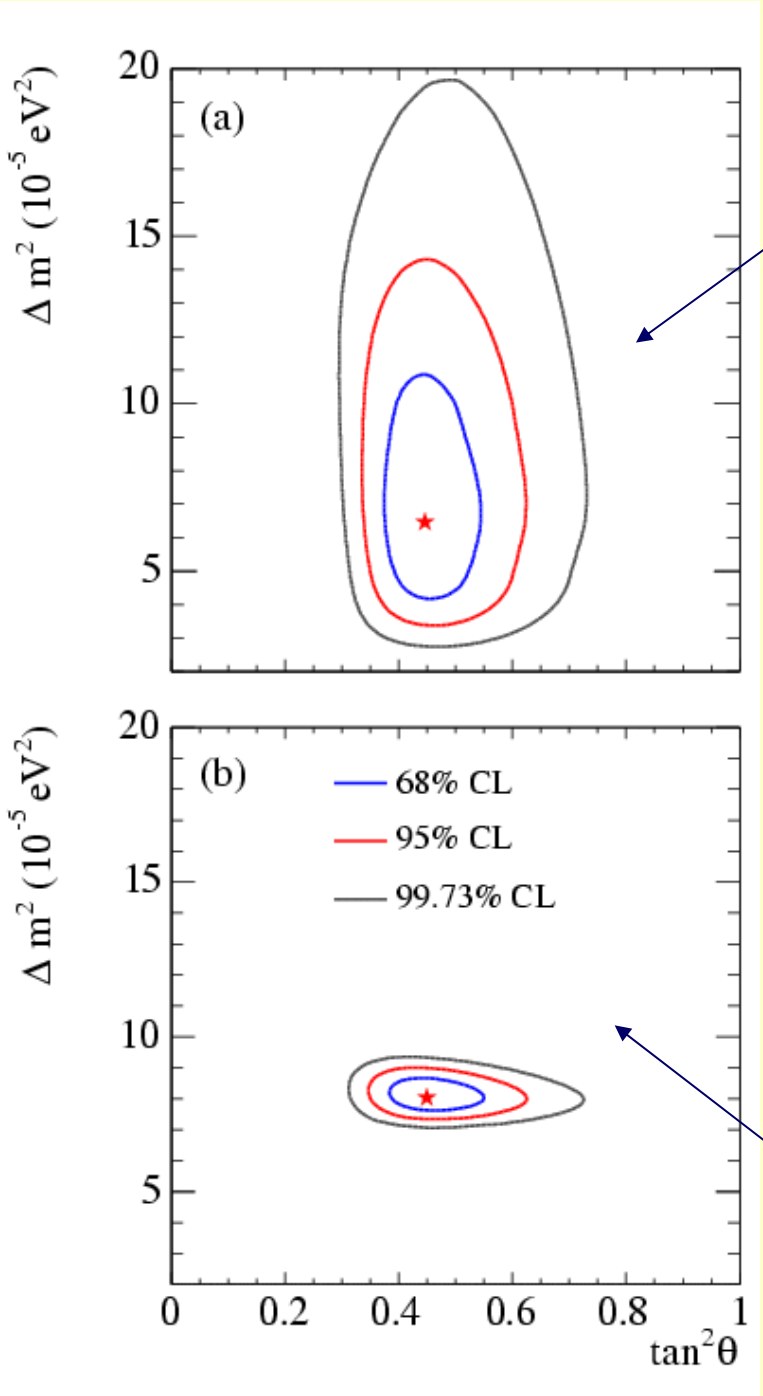
$$\phi_{NC} = 4.94\ ^{+0.21}_{-0.21}(\text{stat.})^{+0.38}_{-0.34}(\text{syst.})$$

$$\phi_{ES} = 2.35\ ^{+0.22}_{-0.22}(\text{stat.})^{+0.15}_{-0.15}(\text{syst.})$$

(In units of $10^6\,\text{cm}^{-2}\text{s}^{-1}$)

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.34 \pm 0.023(\text{stat.})^{+0.029}_{-0.031} = \cos^4\theta_{13}\sin^2\theta_{12}$$

Improved accuracy for θ_{12}.



SOLAR ONLY AFTER NEW SNO SALT DATA

Large mixing Angle (LMA) Region only

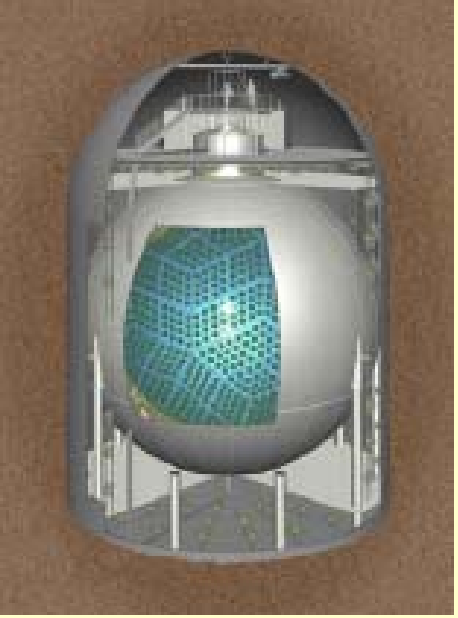
- The solar results define the mass hierarchy ($m_2 > m_1$) through the Matter interaction (MSW)

- SNO: CC/NC flux defines $\tan^2\theta < 1$ (ie Non - Maximal mixing) by more than 5 standard deviations

LMA for solar ν predicts very small spectral distortion, small (~ 3 %) day-night asymmetry, as observed by SK, SNO

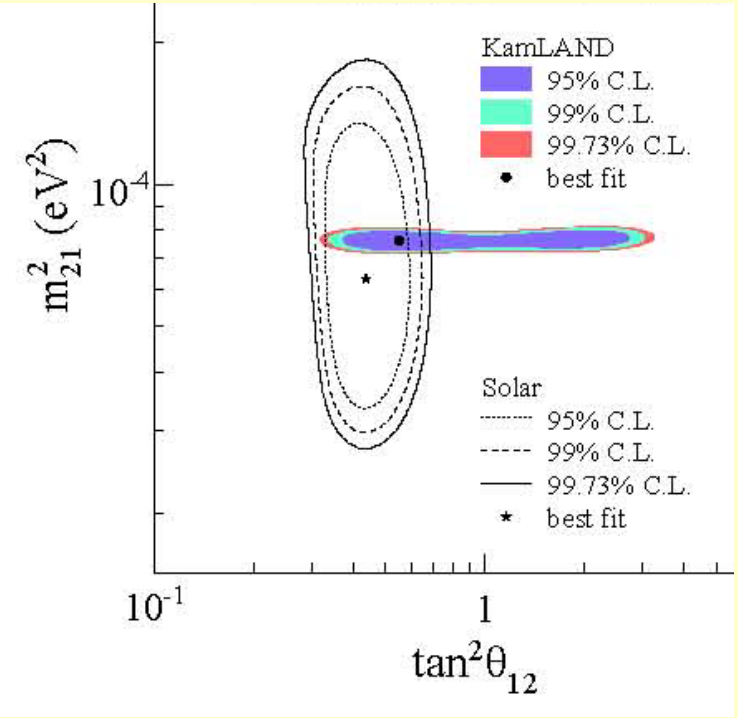
$$\mathrm{Asym}_{\mathrm{salt}+D_2O} = 0.037 \pm 0.040$$

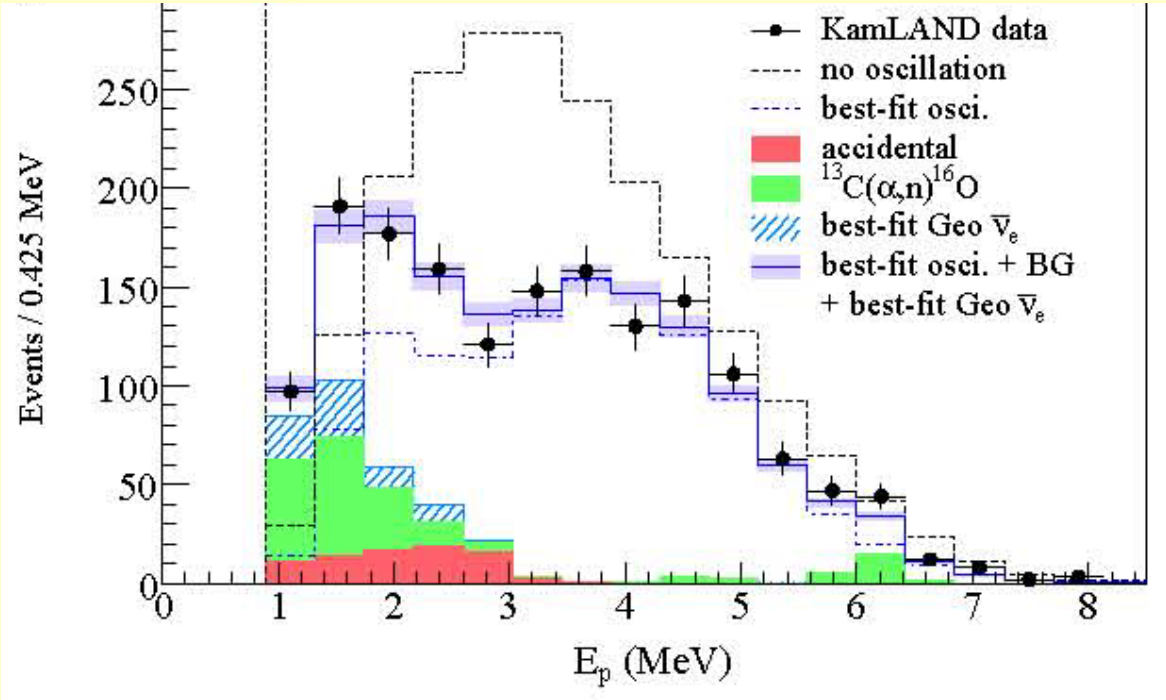
SOLAR PLUS KAMLAND (assuming CPT) (Reactor $\bar{\nu}$'s)



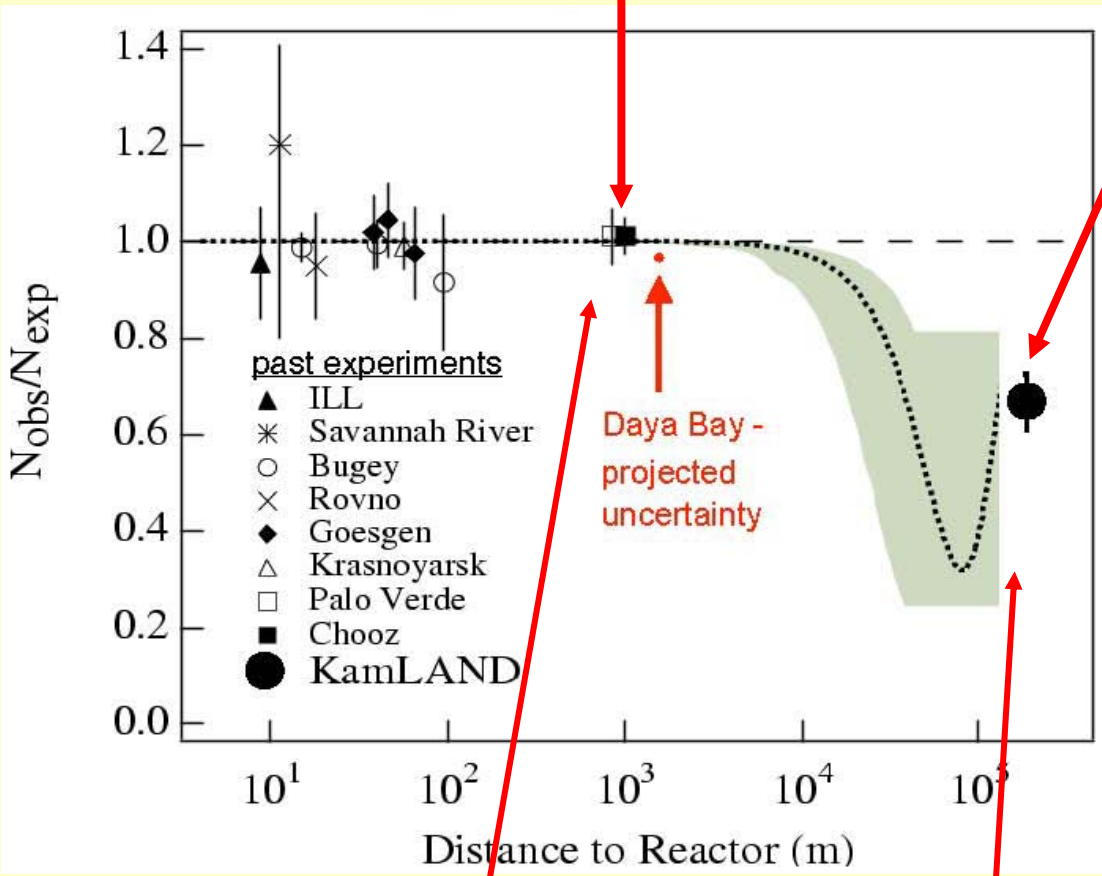
New KamLAND result reported this month

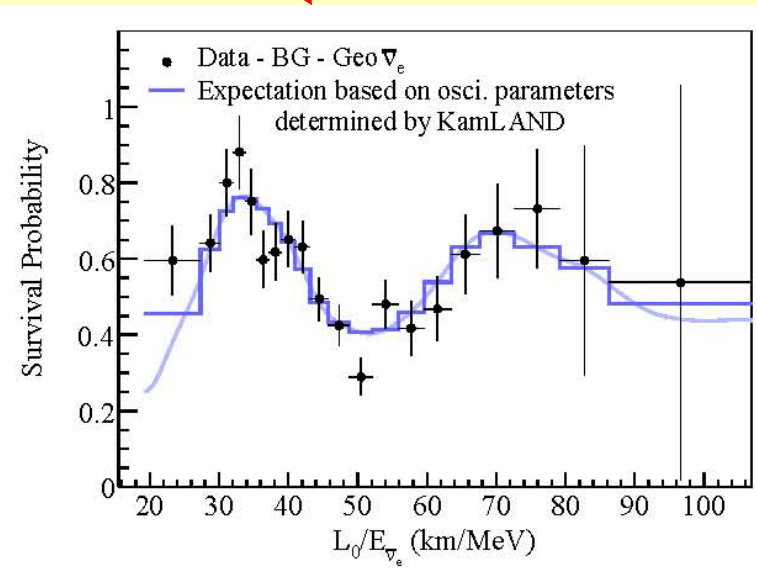
- 182 GW of reactor power in Japan, Korea
- Average distance 180 km
- 2881 ton-years
- Undistorted spectrum rejected at more than 5 σ
- arXiv:0801.4589v2 [hep-ex]





$$P(\bar{\nu}_e \to \bar{\nu}_e) \cong 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{atm} L}{4E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{12} L}{4E}\right).$$





Kamland Latest Result

CHOOZ, PALO VERDE Limit θ_{13}. Future reactor expts. with multiple distances to measure θ_{13}.

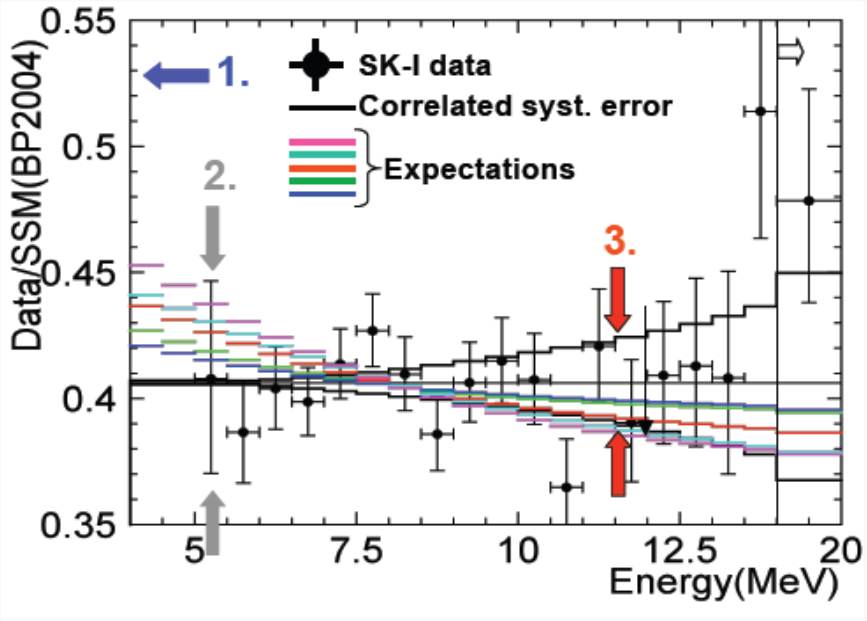
KAMLAND

SK-III Goal

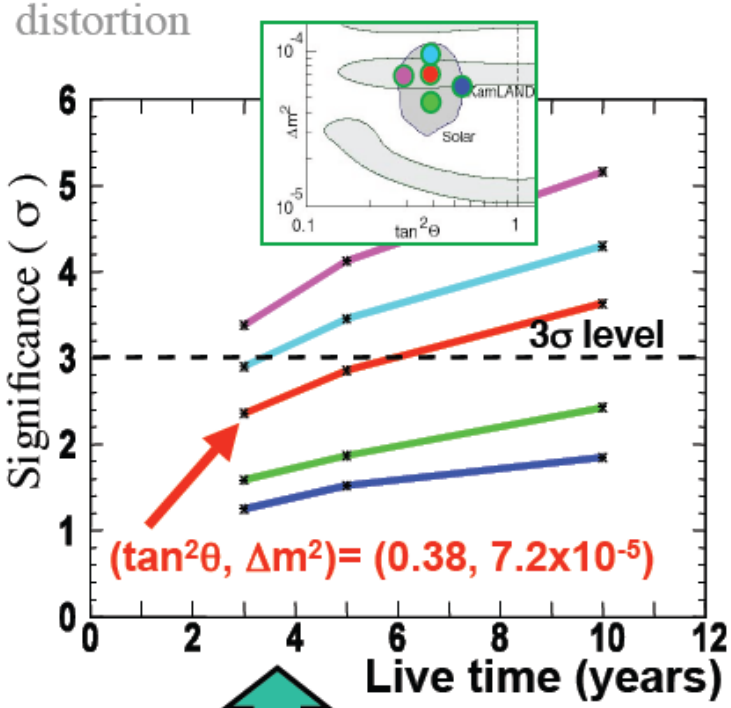
Future prospects by SK-III

Recoil electron spectrum

~10% upturn should be seen



Significance of spectrum distortion

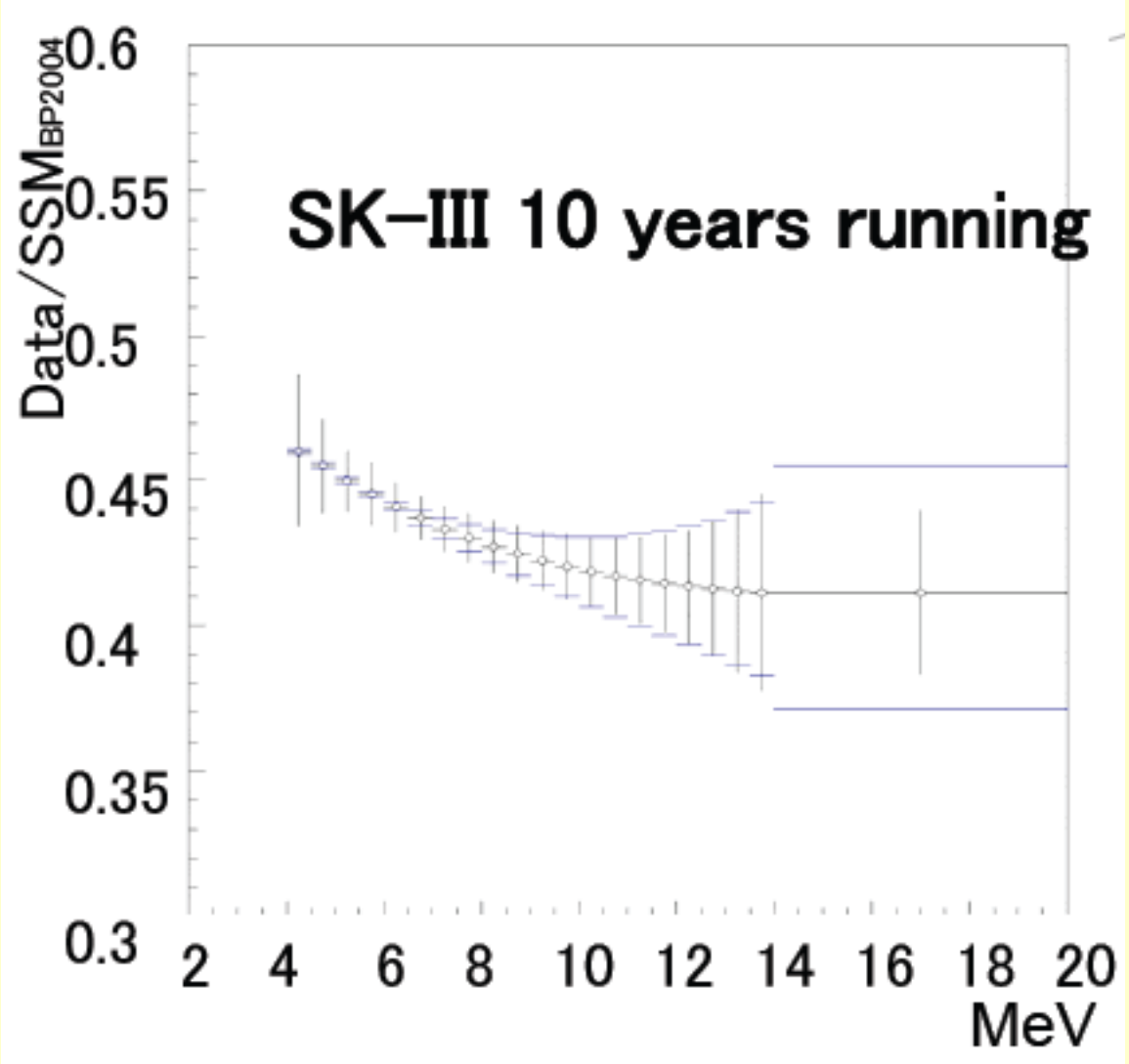


Need to:

1. Lower threshold
2. Reduce stat. error
3. Reduce energy-correlated syst. error

Assumptions:

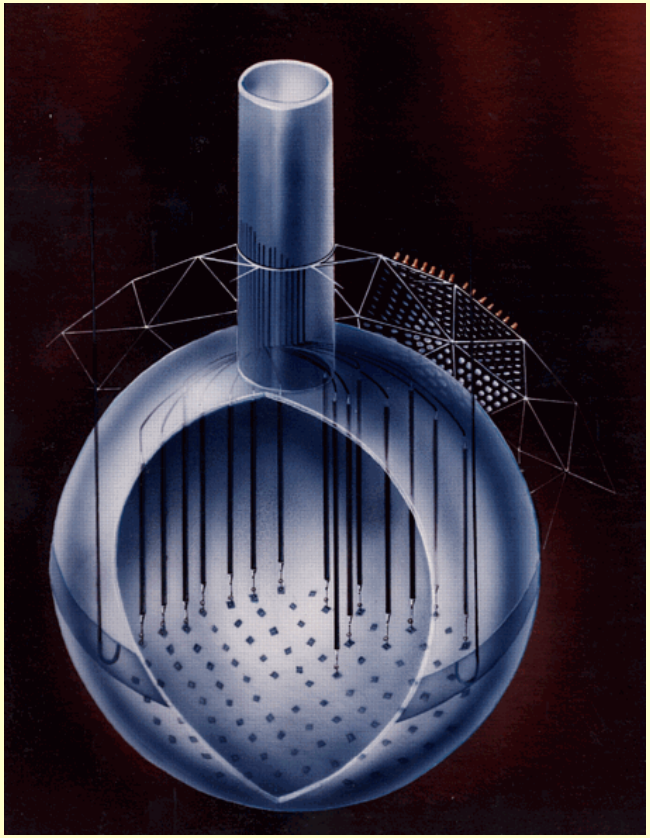
- 4.0MeV threshold
- 4.0-5.5MeV background: x 0.3
  (same BG as SK-I above 5.5MeV)
- Correlated systematic error: x 0.5


SK-III 10 years running
Data/SSM$_{BP2004}$
0.6
0.55
0.5
0.45
0.4
0.35
0.3
2
4
6
8
10
12
14
16
18
20
MeV

Present Phase: SNO Phase III

Neutral-Current Detectors (NCD):
An array of ^{3}He proportional counters

40 strings on 1-m grid
~440 m total active length



- Search for spectral distortion
- Improve solar neutrino flux by breaking the CC and NC correlation (ρ = -0.53 in Phase II):

  CC: Cherenkov Signal $\Rightarrow$ **PMT Array**

  NC: n+^{3}He $\Rightarrow$ **NCD Array**

- Improvement in θ_{12}, as

$$\frac{\phi^{CC}}{\phi^{NC}} \approx \sin^4\theta_{13} + \cos^4\theta_{13}\sin^2\theta_{12}$$

Correlations	D_2O unconstrained	D_2O constrained	Salt unconstrained	NCD
NC,CC	-0.950	-0.520	-0.521	~0
CC,ES	-0.208	-0.162	-0.156	~-0.2
ES,NC	-0.297	-0.105	-0.064	~0

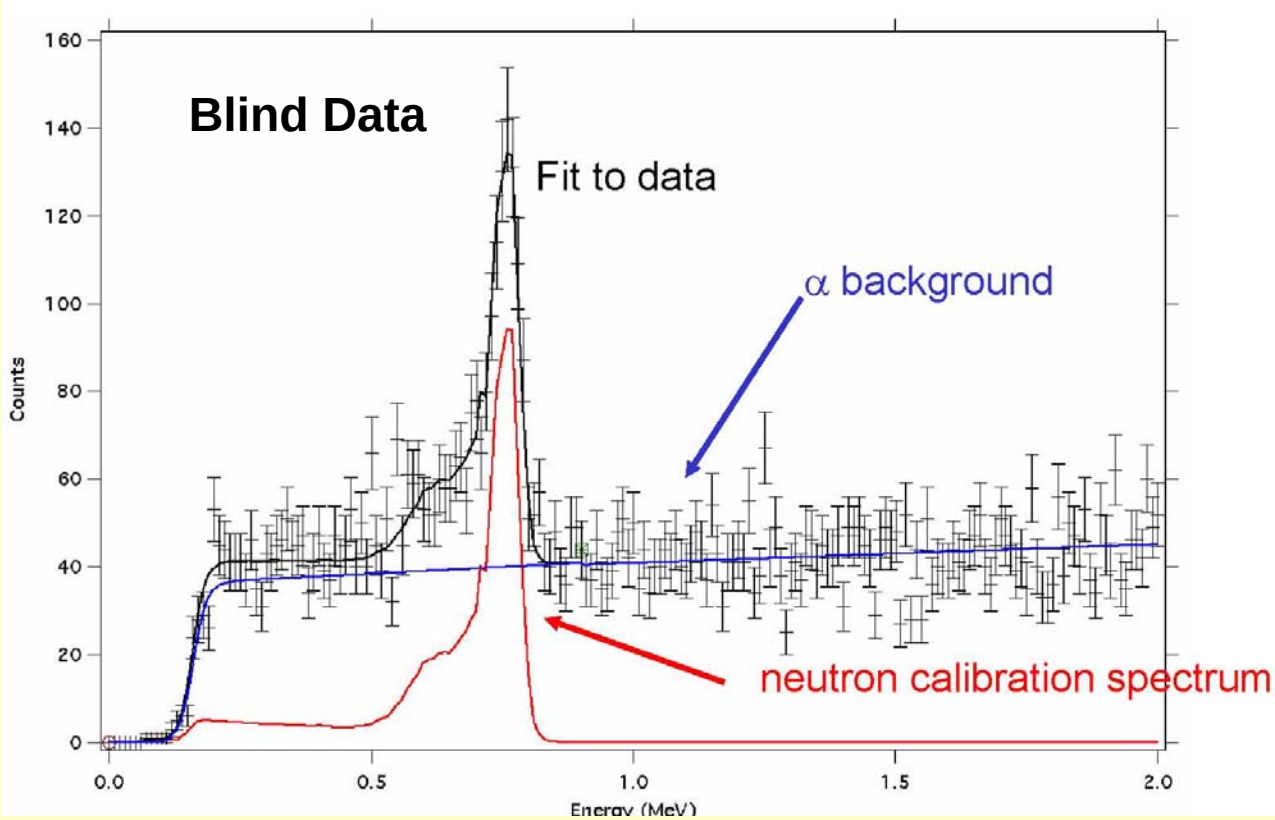
Blind Analysis

Phase III production data taking Dec 2004 to Dec 2006. D_2O now removed.

SNO NCD Signals

$n + {}^3He \rightarrow p + {}^3H \quad (q=768\ keV)$

Pulse shape analysis to discriminate neutrons and alphas underway

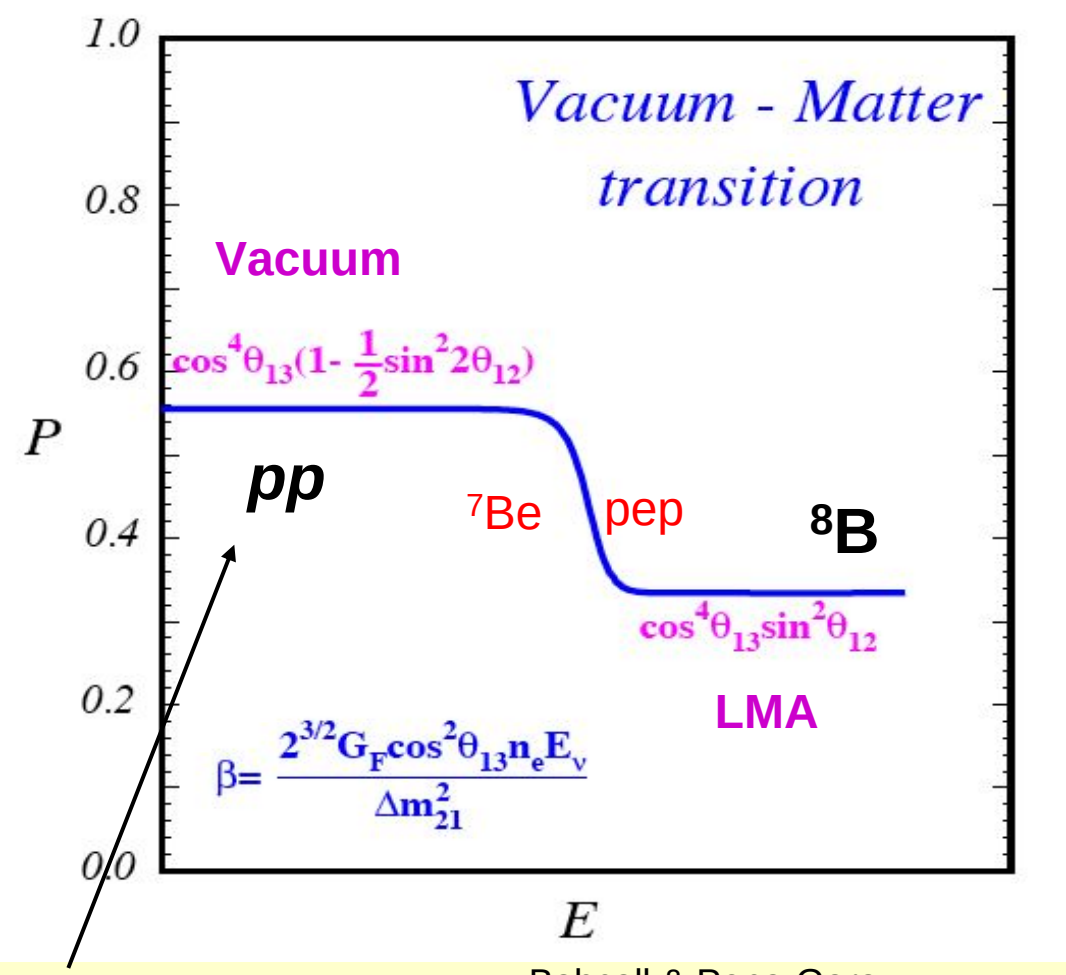


Another analysis is almost complete that combines data from the first two SNO Phases and reduces the threshold by ~ 1 MeV.

This also provides improved accuracy on CC/NC flux ratio and therefore θ_{12} mixing matrix element.

Very low Background. About one count per 2 hours in region of interest.
Can be reduced by a large factor through pulse shape discrimination.

Future solar neutrino measurements
pp, ^{7}Be, pep, ^{8}B



Bahcall & Pena-Garay
hep-ph/0305159

- **Compare ES, CC**
- **Compare ES, SSM**

- **NEUTRINO PHYSICS**

- Confirm matter effects (MSW).

- Improve Θ_{12}, Θ_{13}.

- Search for effects of sterile ν, Non-Standard Interactions, Mass-varying neutrinos.

- **SOLAR PHYSICS**

- Accurate measurement of neutrino luminosity (pp, pep).

- Test solar modelling

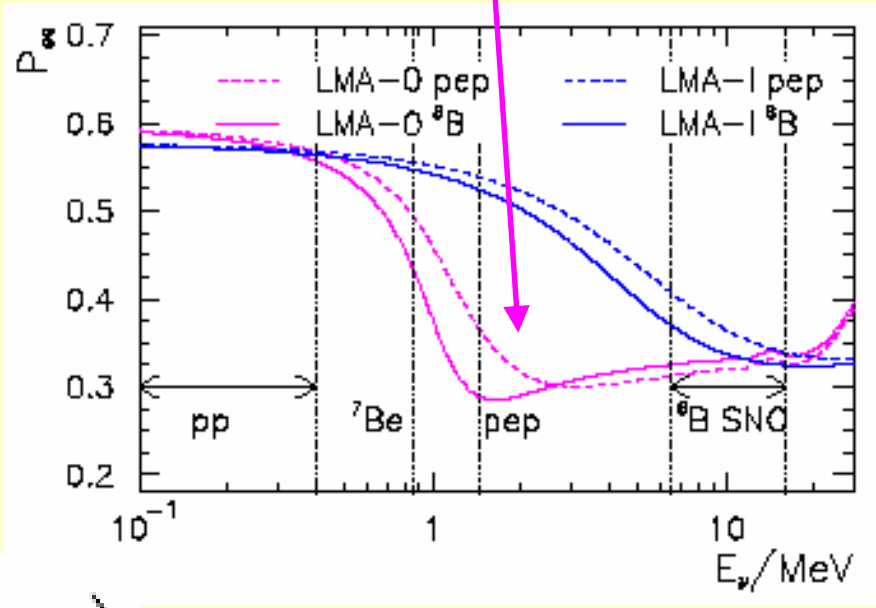
- Observe CNO neutrinos.

New Physics

$$L^{NSI} = -2\sqrt{2}G_F(\bar{\nu}_\alpha\gamma_\rho\nu_\beta)(\epsilon^{f\tilde{f}L}_{\alpha\beta}\bar{f}_L\gamma^\rho\tilde{f}_L + \epsilon^{f\tilde{f}R}_{\alpha\beta}\bar{f}_R\gamma^\rho\tilde{f}_R) + h.c. \quad (1)$$

NC non-standard Lagrangian

Friedland, Lunardini, Peña-Garay, hep-ph/0402266



- non-standard interactions
- mass-varying neutrinos

Barger, Huber, Marfatia, hep-ph/0502196

~ =

$$\begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \sqrt{2}\,G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}$$

Sterile Neutrinos:
de Holanda and Smirnov hep-ph/0307266

pep, ^{7}Be solar neutrinos are at
An excellent energy to test for new physics

Solar Model Chemical Controversy

- Bahcall, Serenelli and Basu Solar Model 2005

PREDICTED SOLAR NEUTRINO FLUXES FROM SEVEN SOLAR MODELS

Model	*pp*	pep	hep	^{7}Be	^{8}B	^{13}N	^{15}O	^{17}F
BP04(Yale)	5.94	1.40	7.88	4.86	5.79	5.71	5.03	5.91
BP04(Garching)	5.94	1.41	7.88	4.84	5.74	5.70	4.98	5.87
BS04	5.94	1.40	7.86	4.88	5.87	5.62	4.90	6.01
BS05(^{14}N)	5.99	1.42	7.91	4.89	5.83	3.11	2.38	5.97
BS05(OP)	5.99	1.42	7.93	4.84	5.69	3.07	2.33	5.84
BS05(AGS, OP)	6.06	1.45	8.25	4.34	4.51	2.01	1.45	3.25
BS05(AGS, OPAL)	6.05	1.45	8.23	4.38	4.59	2.03	1.47	3.31

- Helioseismology “incompatible” with low metallicity solar models.
- Measurements of pep and ^{7}Be can sort out matter interactions of ν`s as well as solar models.

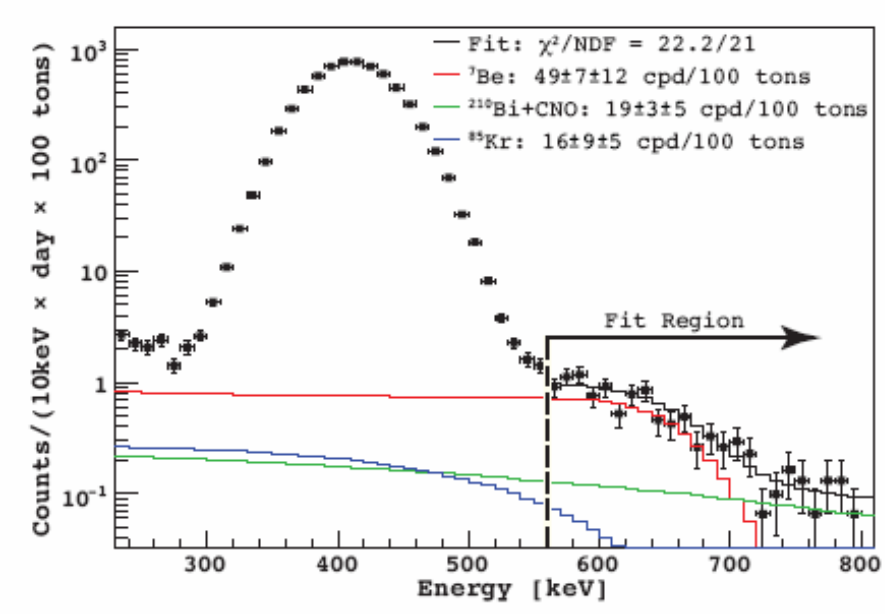
Future Experiments

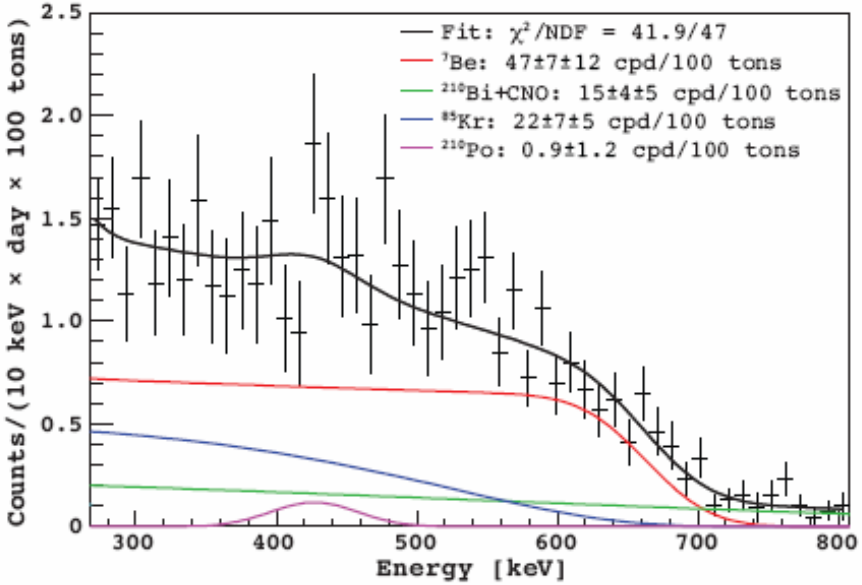
- charged-current reaction (ν_e only)
  - LENS (In) *pp*
  - MOON (Mo) *pp*

- neutrino-electron elastic scattering (ν_e + small $\nu_{\mu,\tau}$)

  - BOREXINO ^{7}Be, pep
  - KAMLAND ^{7}Be, pep
  - SNO+ *pep*
  - XMASS *pp*
  - CLEAN *pp*

First Results From Borexino in Gran Sasso





300 tons of liquid scintillator (100 tons fiducial)

measured rate of ^{7}Be neutrinos

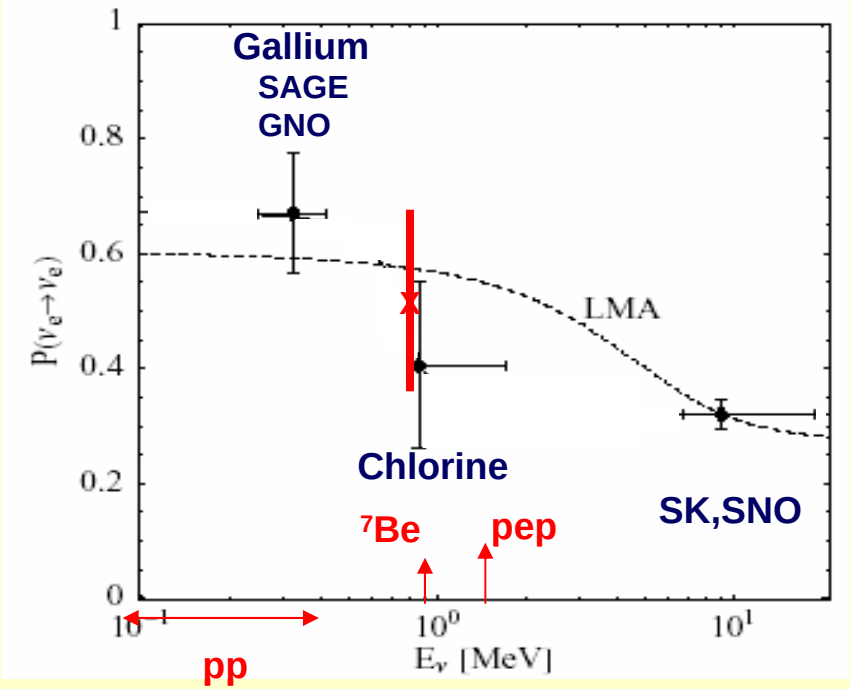
- **$47 \pm 7_{stat} \pm 12_{syst}$ counts/day**

no oscillation expectation

- **75 ± 4 counts/day**

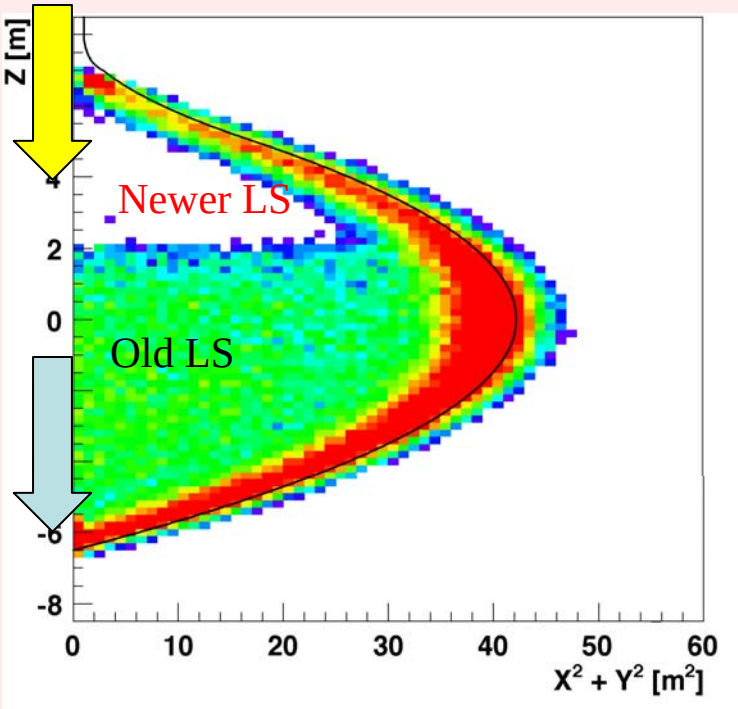
theoretical prediction with oscillations

- **49 ± 4 counts/day**



KamLAND solar measurements

First distillation campaign ended in July 2007



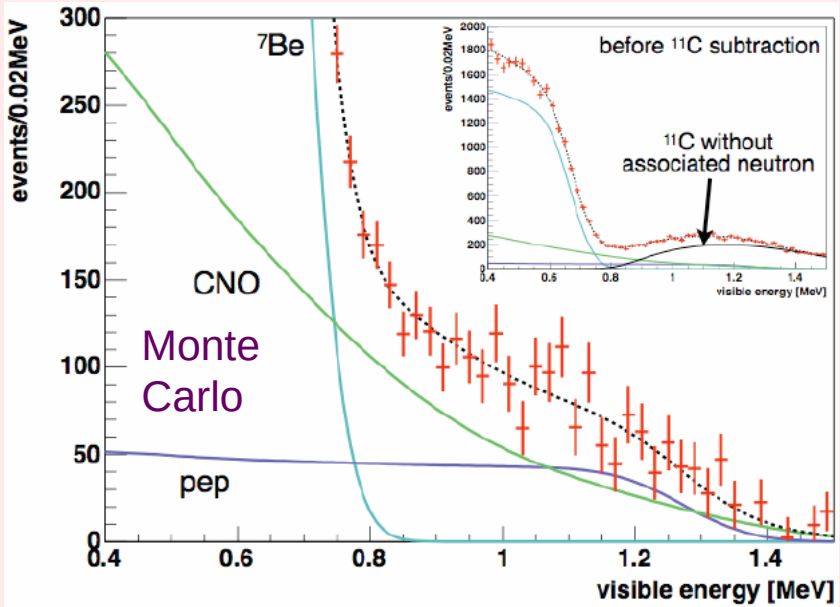
Purified Liquid Scintillator : 1000 tons

Distillation and N_2 purge against ^{85}Kr, ^{210}Bi, ^{210}Po, ^{40}K

Not yet reached the goal but significant progress.

Second purification campaign to come.

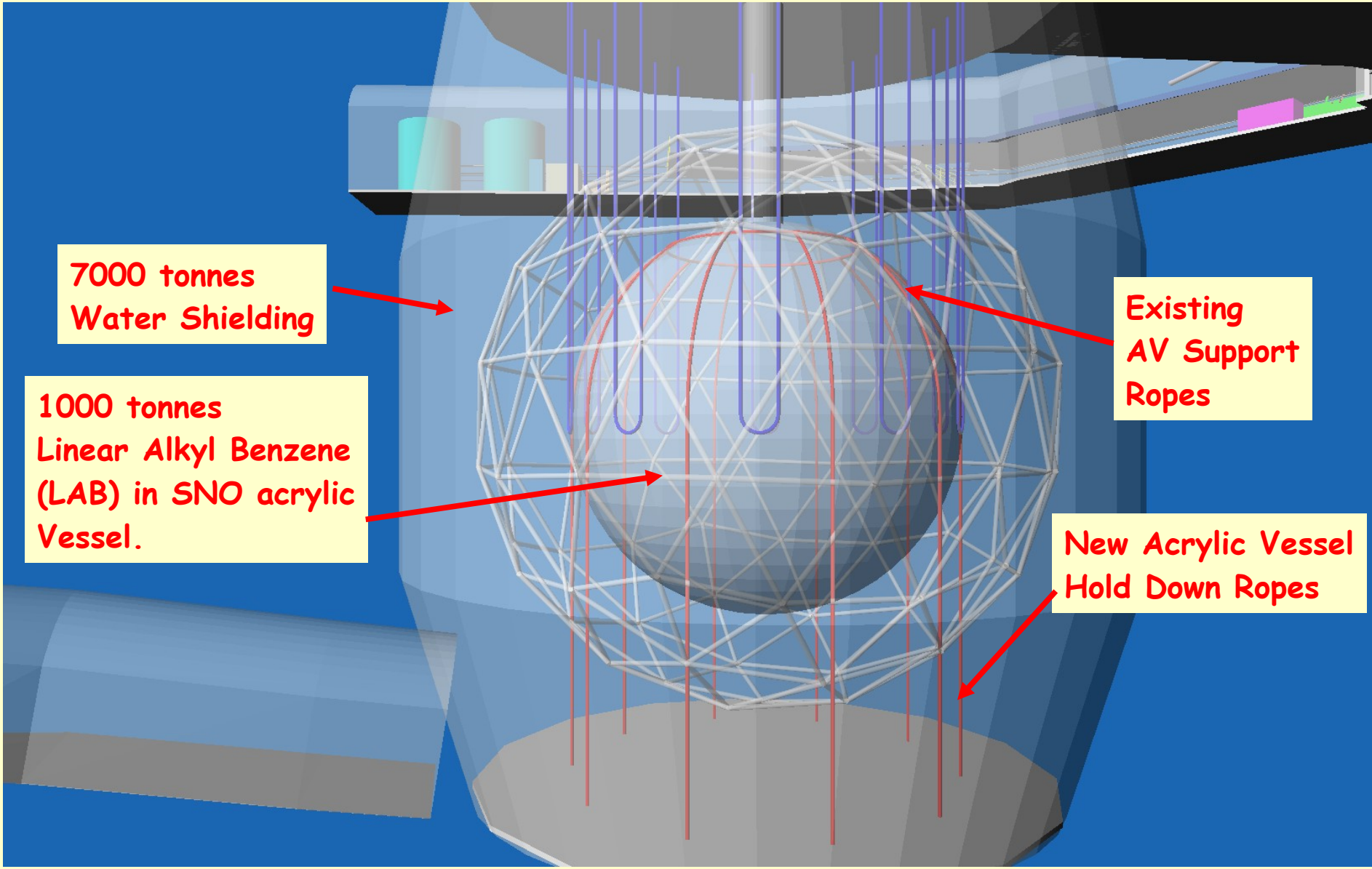
Parallel efforts toward CNO ν observation

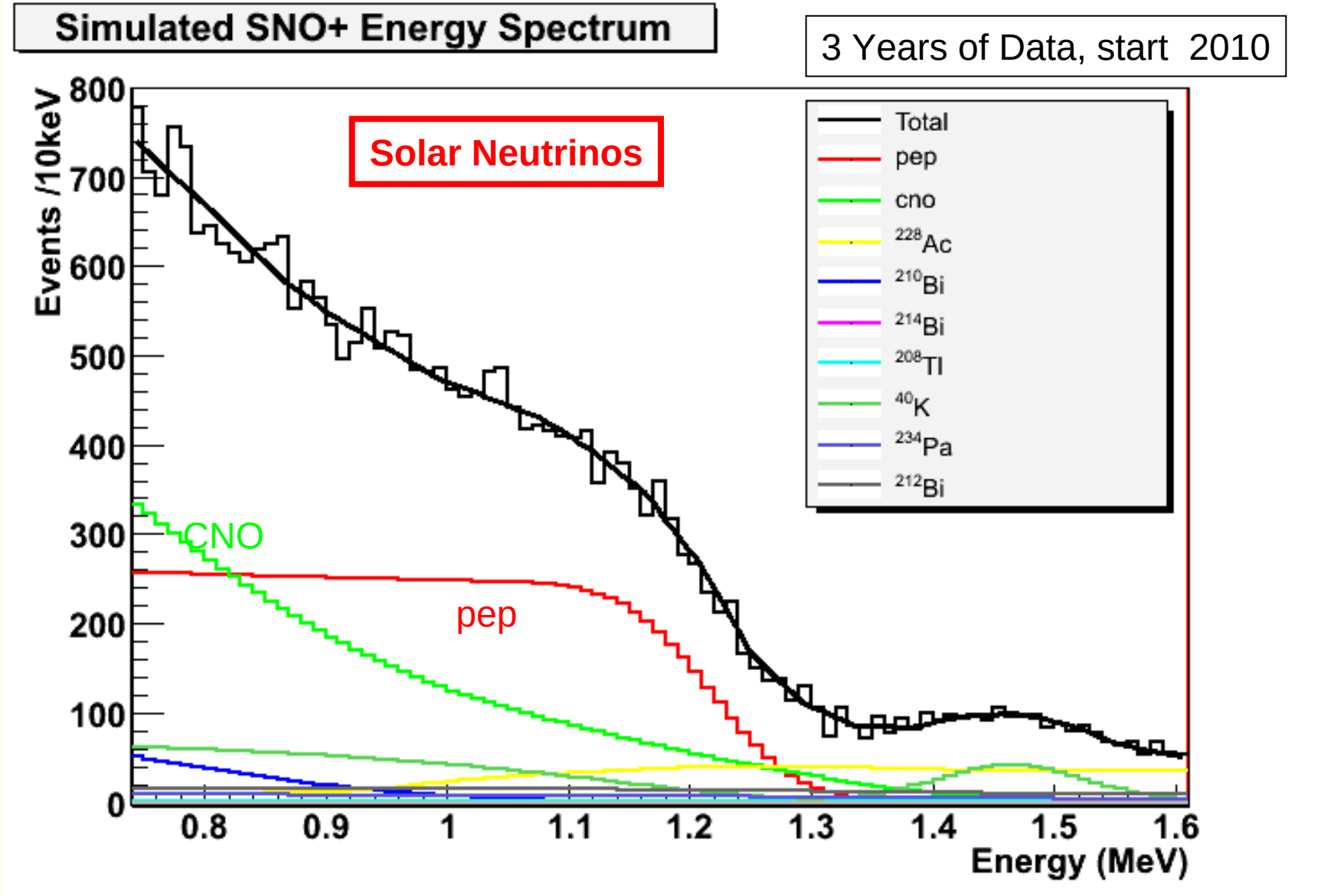


FADC / ch
1GHz
200MHz X 3

New dead-time-free electronics have been developed and tested aiming at ^{11}C rejection.

SNO+ (1000 tonnes highly purified Liquid Scintillator): 2010





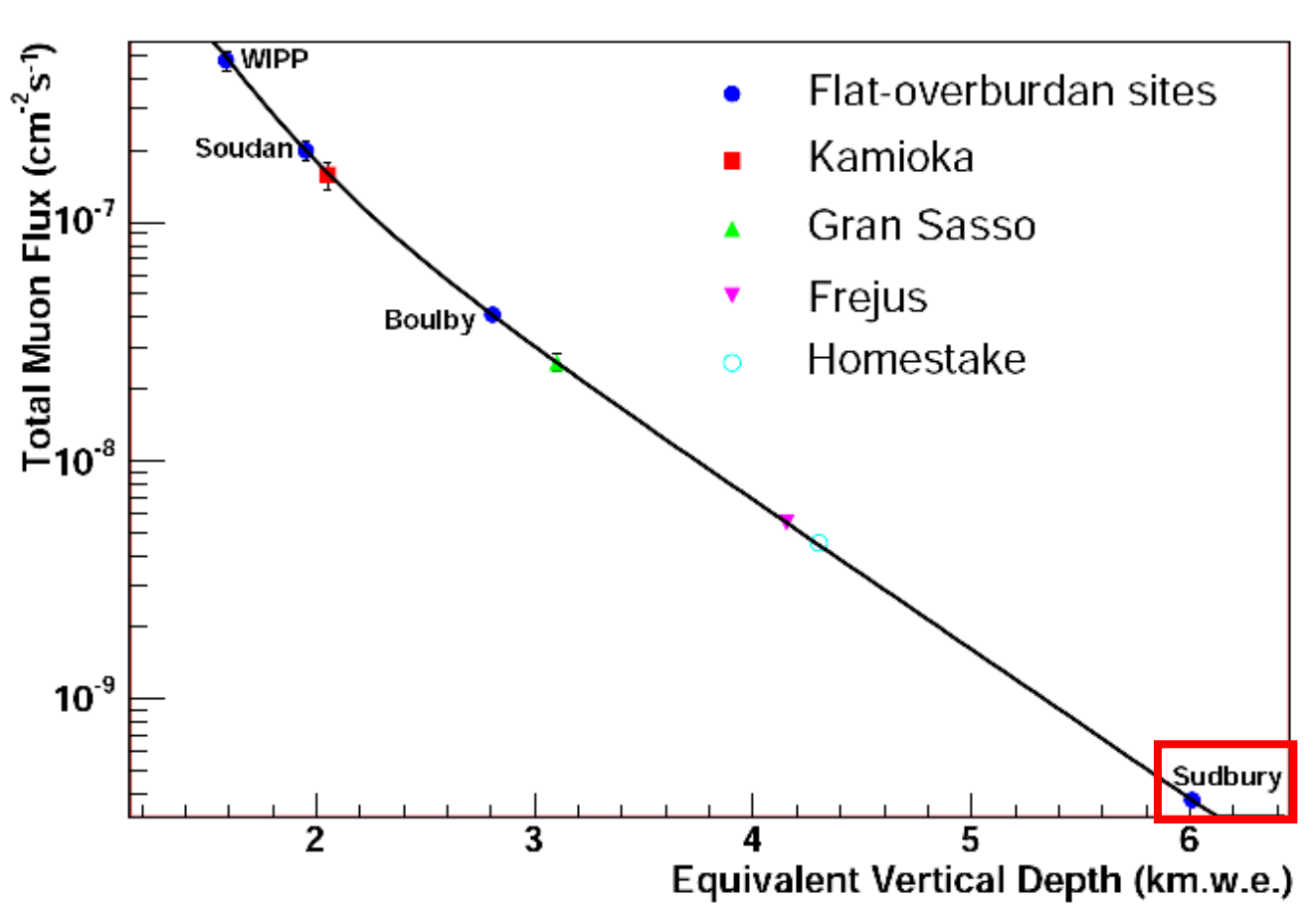
Backgrounds assumed at Kamland observed values plus their purification objectives for ^{210}Bi, ^{40}K. Negligible background from ^{11}C at SNOLAB depth.

New International Underground Facility: SNOLAB

Phase 1 Experimental area: Available 2008
Cryopit addition: Excavation nearly completed. Available 2009.
Total additional excavated volume in new lab: 3 times SNO volume.

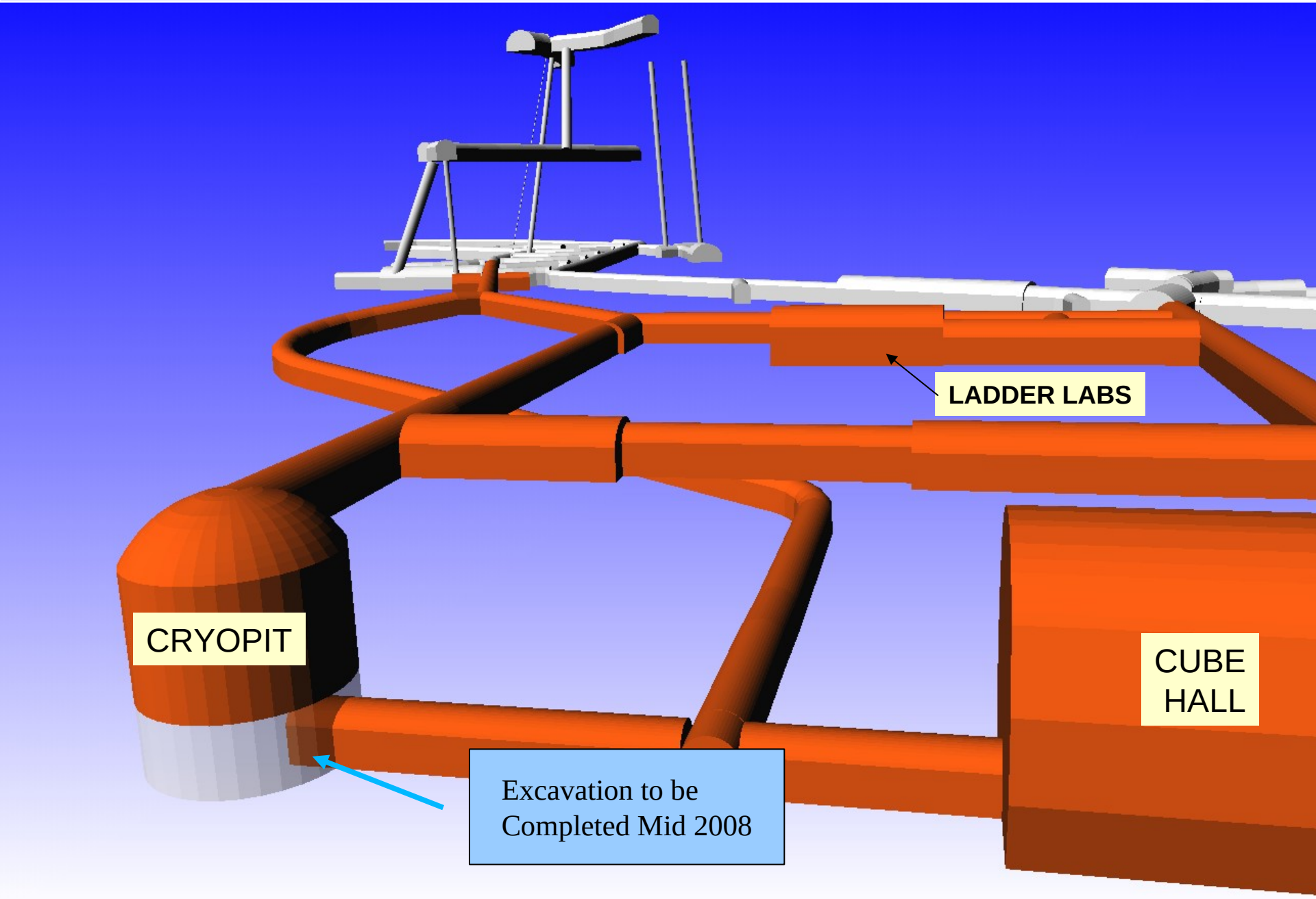
For Experiments that benefit from a very deep and clean lab:

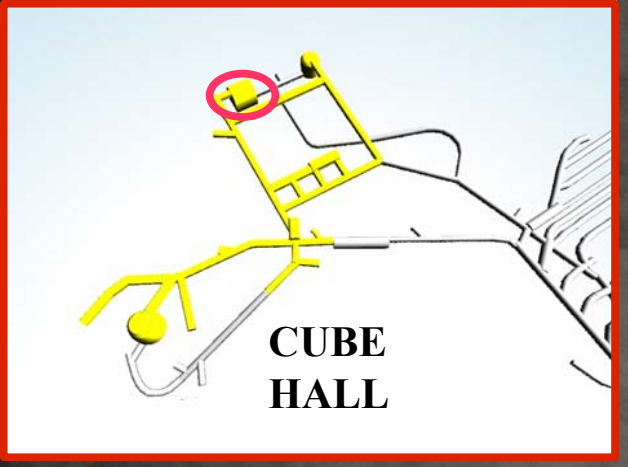
- **ν - less Double Beta Decay**
- **Dark Matter**
- **Solar Neutrinos**
- **Geo – neutrinos**
- **Supernova ν `s**



SNOLAB (Same depth as SNO: 2 km)

Excavation Status





Now walls are washed and painting nearly complete

Letters of Intent/Interest for SNOLAB

Dark Matter:

Timing of Liquid Argon/Neon Scintillation: DEAP-1 (7 kg), MINI-CLEAN (100 kg), DEAP/CLEAN (1 Tonne)

Freon Super-saturated Gel: PICASSO

Silicon Bolometers: SUPER-CDMS (25 kg)

6 th Workshop and Experiment Review Committee
Aug 22, 23, 2007
www.snolab.ca
RED IMPLIES APPROVED FOR SITING

Neutrino-less Double Beta Decay:

^{150}Nd: Organo-metallic in liquid scintillator in SNO+

^{136}Xe: EXO (Gas or Liquid) (Longer Term)

CdTe: COBRA (Longer Term)

Solar Neutrinos:

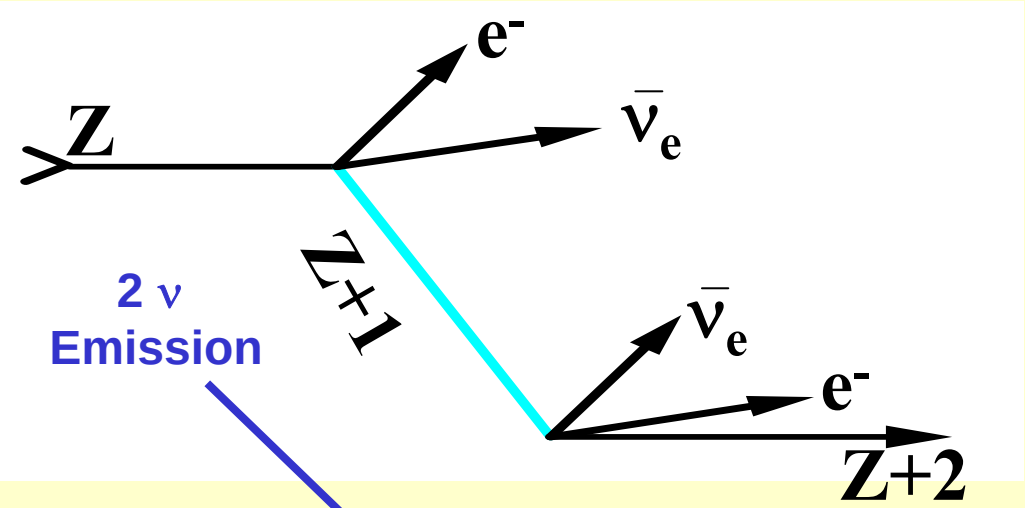
Liquid Scintillator: SNO+ (also Reactor Neutrinos, Geo-neutrinos)

Liquid Ne: CLEAN (also Dark Matter) (Longer Term)

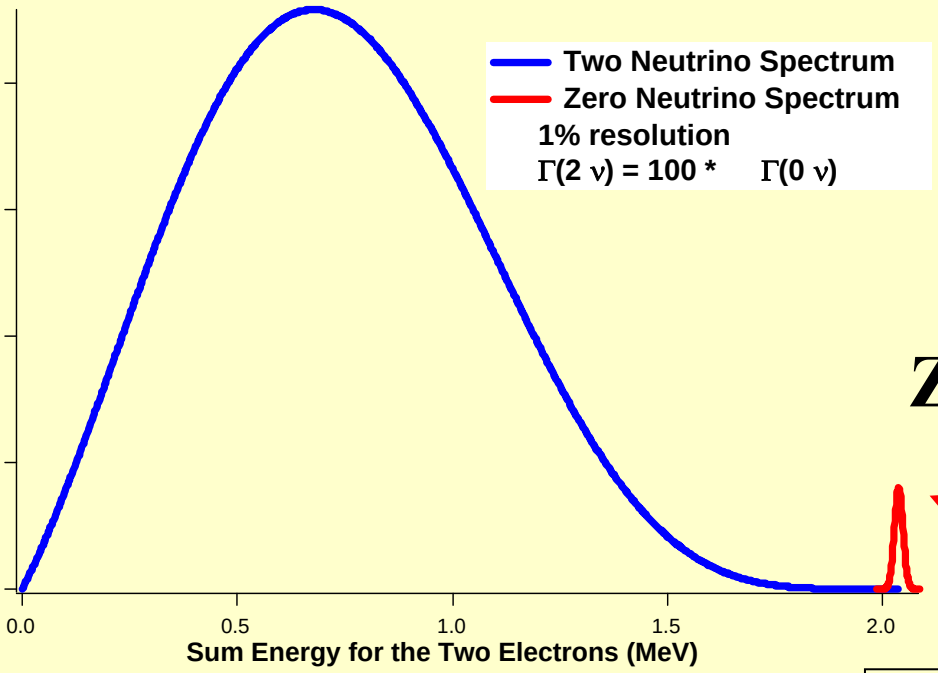
SuperNovae:

SNO+: Liquid scintillator; HALO: Pb plus SNO ^{3}He detectors.

Neutrinoless Double β Decay



2 ν Emission

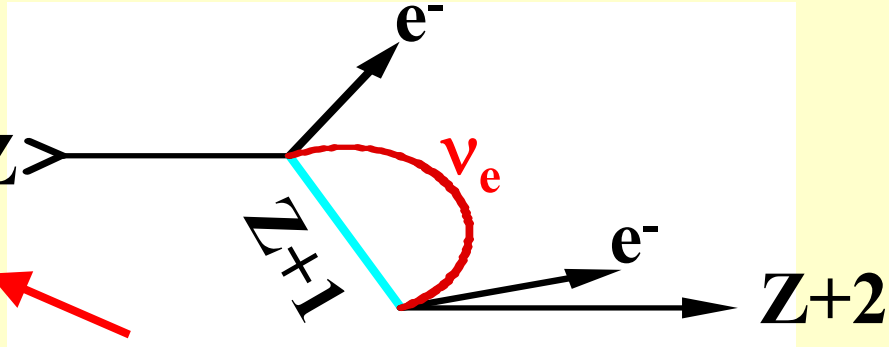


Summed Electron Energy

Requires:

- Neutrino = Anti-neutrino (Majorana particles)
- Finite ν mass
- Lifetimes > ~10^{26} years

Imply ν mass < 0.1 eV



Neutrinoless

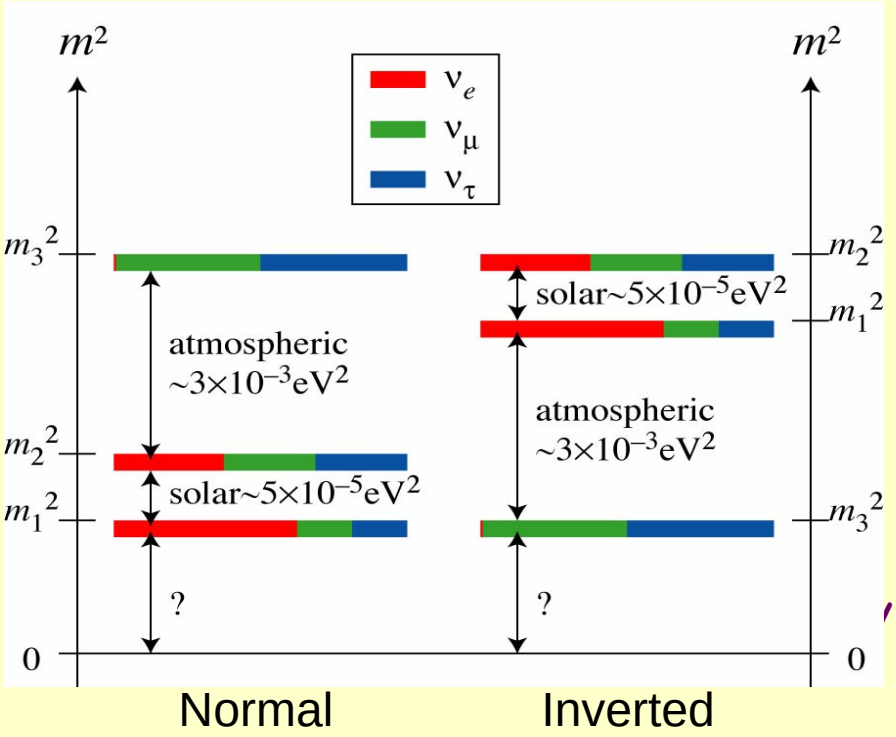
$$T_{1/2} = F(Q_{\beta\beta}, Z)\, |M^{0\nu}|^2 \langle m_{\nu\beta\beta}\rangle^2$$

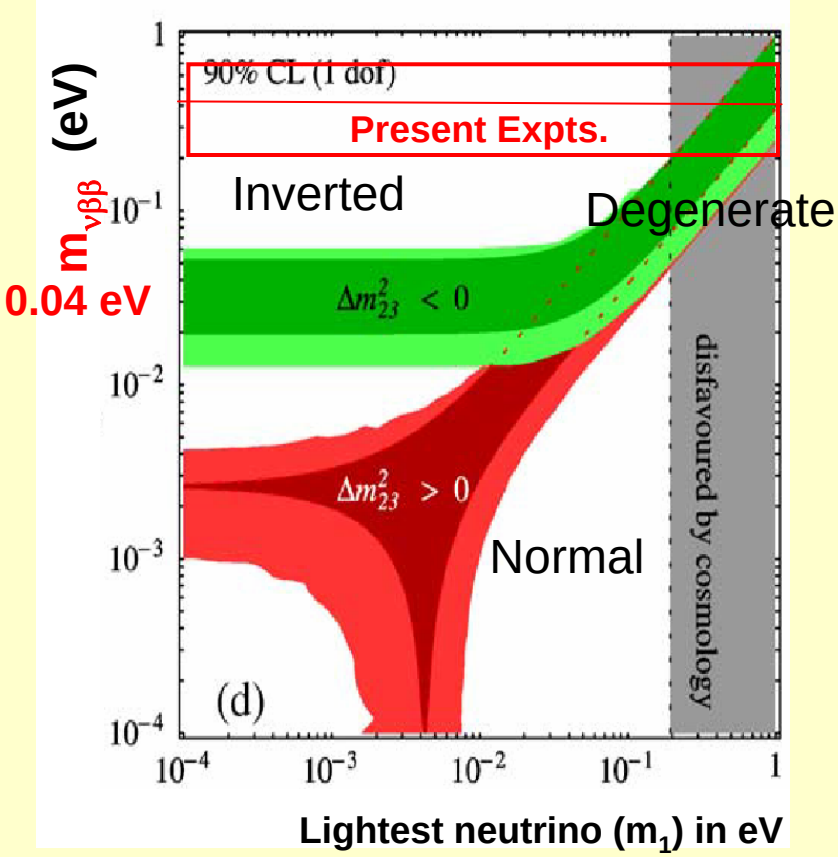
Measuring Effective ν Mass

$$m_{\nu\beta\beta} = |\sum_i U_{ei}^{\,2}\, m_i|$$

$$m_{\nu\beta\beta} = |m_1 \cos^2\theta_{13}\cos^2\theta_{12} + m_2\, e^{2i\alpha} \cos^2\theta_{13}\sin^2\theta_{12} + m_3\, e^{2i\beta} \sin^2\theta_{13}|$$

Mass Hierarchies





Want sensitivity <~ 0.04 eV

large mass/low background

INTERESTING FOR LEPTOGENESIS

Summary: F. Piquemal - TAUP 2007

Experiment	Isotope	Enriched isotope mass (kg)	$T_{1/2}$ (yr)	$<m_\nu>$ (eV)	Start	Status
CUORE	^{130}Te	203	$2.1\ 10^{26}$	0.03 - 0.07*	2011	Funded
GERDA phase I	^{76}Ge	17.9	$3.\ 10^{25}$	0.2 – 0.5*	2009	Funded
phase II		40	$2.\ 10^{26}$	0.07 – 0.2*	2011	Funded
Majorana	^{76}Ge	30 - 60	1.10^{26}	0.1 – 0.3*	2011	R&D
EXO-200 (Liquid, gas)	^{136}Xe	200	$6.4\ 10^{25}$	0.2 - 0.7*	2008	Liquid Funded
SuperNEMO	^{82}Se	100	$2.\ 10^{26}$	0.05- 0.09*	2011	R&D
	^{150}Nd	100	10^{26}	0.07		
CANDLES	^{48}Ca	0.5		~0.5	2008	Funded
MOON II	^{100}Mo	120		0.09 – 0.13	?	R&D
DCBA	^{150}Nd	20			?	R&D
SNO+	^{150}Nd	56 - 500		0.03-0.08	2010	R&D
COBRA	^{116}Cd, ^{130}Te	420	?	?	?	R&D

* Calculation with NME from Rodim et al., Suhonen et al., Caurier et al. PMN07

SNO+: Neutrino-less Double Beta Decay: ^{150}Nd

- Nd is one of the most favorable double beta decay candidates with large phase space due to high endpoint: 3.37 MeV.

- Ideal scintillator (Linear Alkyl Benzene) has been identified. More light output than Kamland, Borexino, no effect on acrylic.
- Nd metallic-organic compound has been demonstrated to have long attenuation lengths, stable for more than a year.
- 1 tonne of Nd will cause very little degradation of light output.

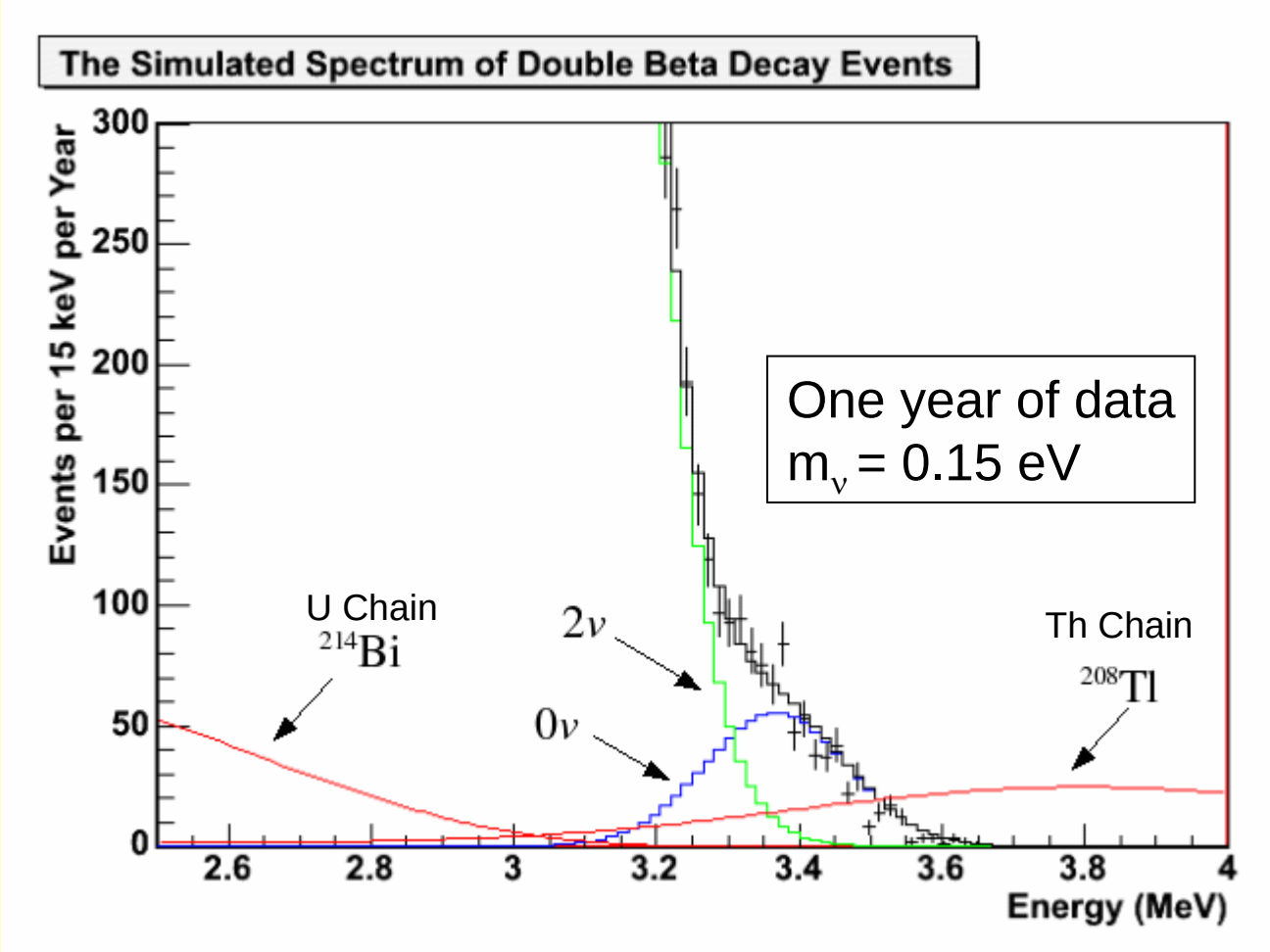
- Isotopic abundance 5.6% (in SNO+ 1 tonne Nd = 56 kg ^{150}Nd)
- Collaboration with SuperNemo to enrich ^{150}Nd using French laser isotope facility. CEA/IN2P3 agrees to prototype study in 07/08. Possibility of hundreds of kg of isotope production.

- SNO+ Capital proposal to be submitted Oct. 2008.
- Plan to start with natural Nd in 2010.

SNO+ (^{150}Nd ν - less Double Beta Decay)

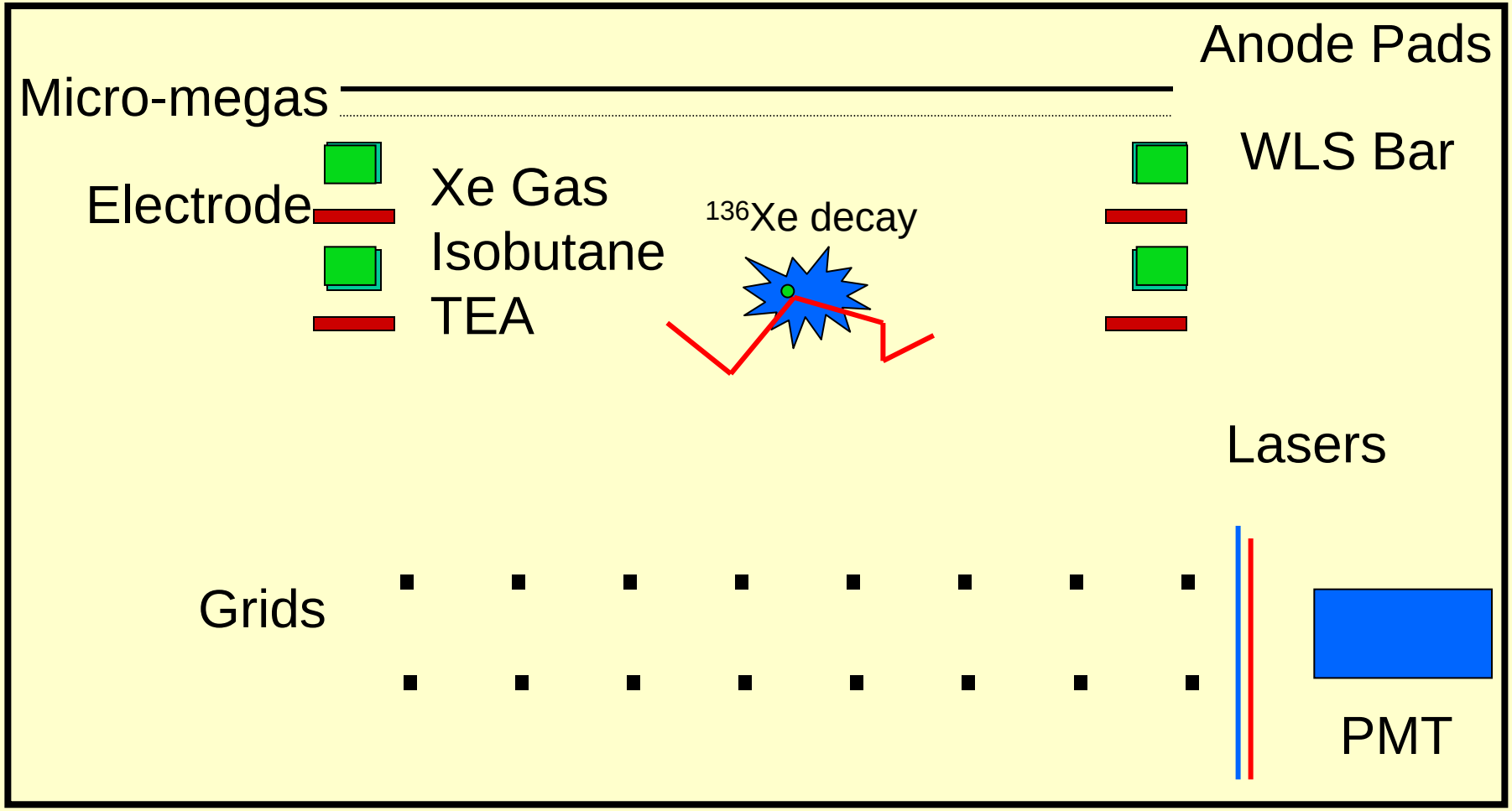
0ν: 1057 events per year with 500 kg ^{150}Nd-loaded liquid scintillator in SNO+.

Simulation assuming light output and background similar to Kamland.



Sensitivity: Natural Nd (56 kg isotope): $m_{\nu\beta\beta}$ ~ 0.1 eV
500 kg enriched ^{150}Nd: $m_{\nu\beta\beta}$ ~ 0.03 eV

R&D in Canada: EXO-gas double beta counter



For 200 kg, 10 bar, box is 1.5 m on a side

Electrons

Ba Ion

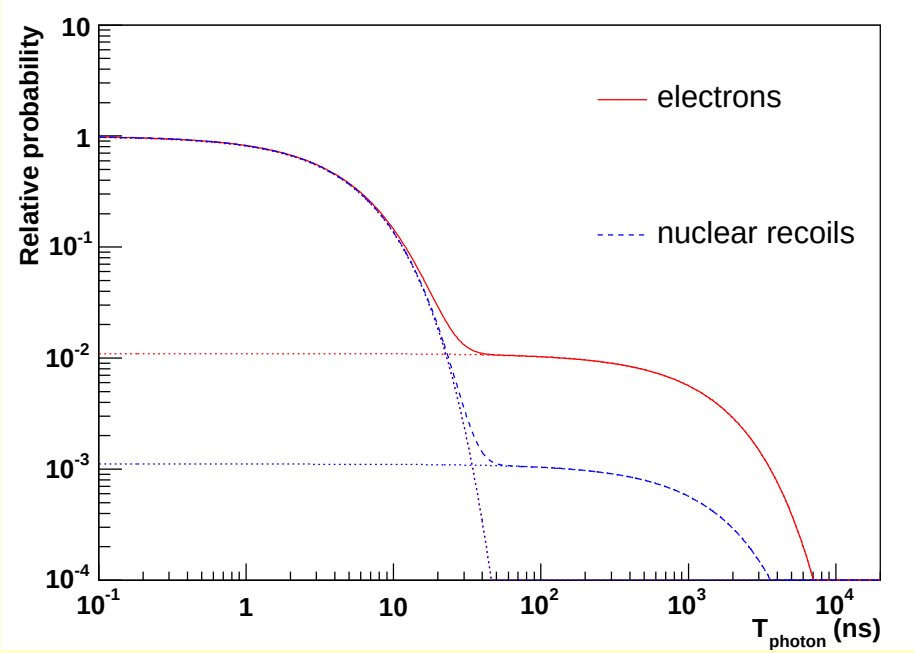
DARK MATTER

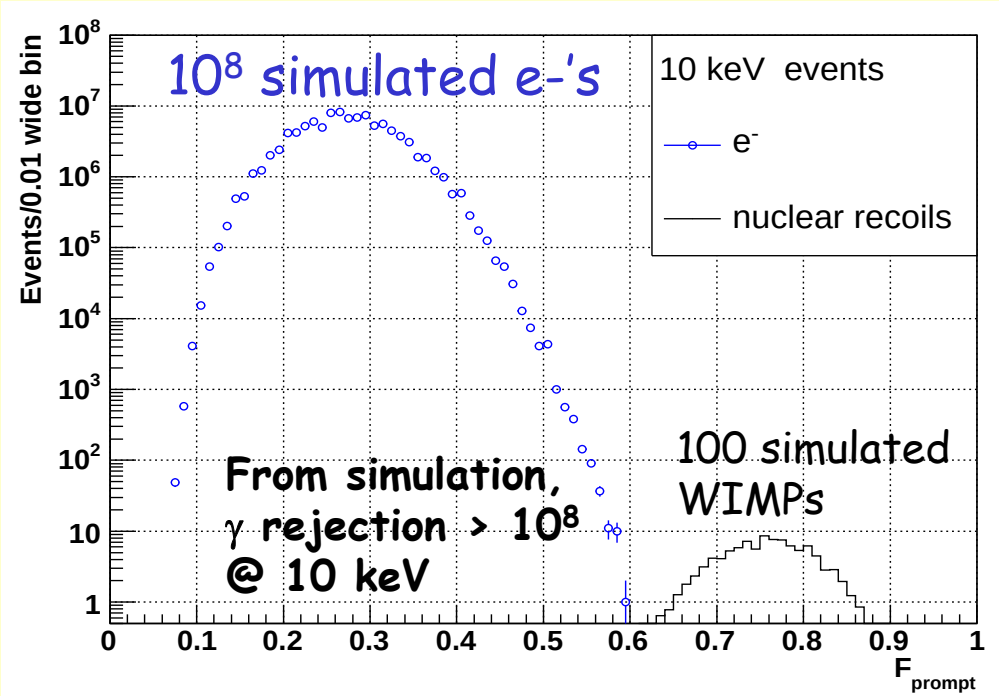
DEAP/CLEAN: 1 Tonne Fiducial Liquid Argon

- Scintillation time spectrum for Ar enables WIMP recoils to be separated from gammas from ^{39}Ar background.

- Simulation indicates that ^{39}Ar and other gamma-beta backgrounds can be discriminated from WIMPS using only scintillation light for up to 1 tonne fiducial Volume of liquid argon.

- DEAP and CLEAN collaborations have come together to build new detectors with a simple and easily scaled technology at SNOLAB.



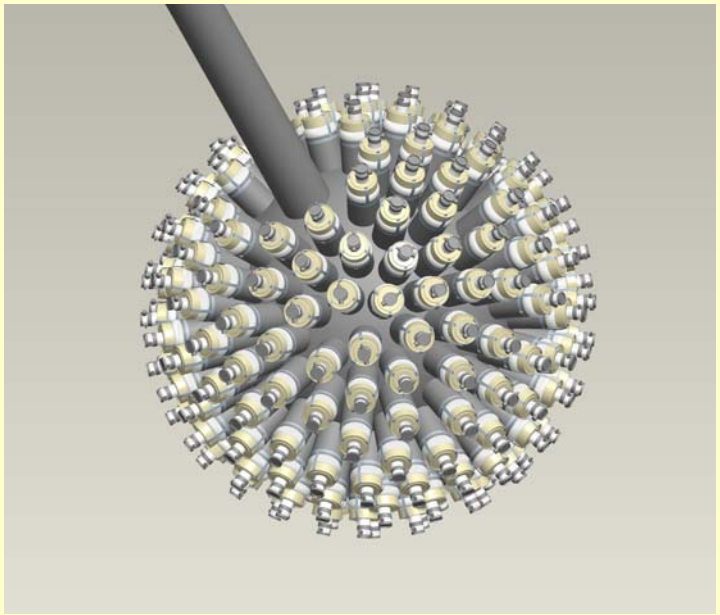


M.G. Boulay & A. Hime, astro-ph/0411358

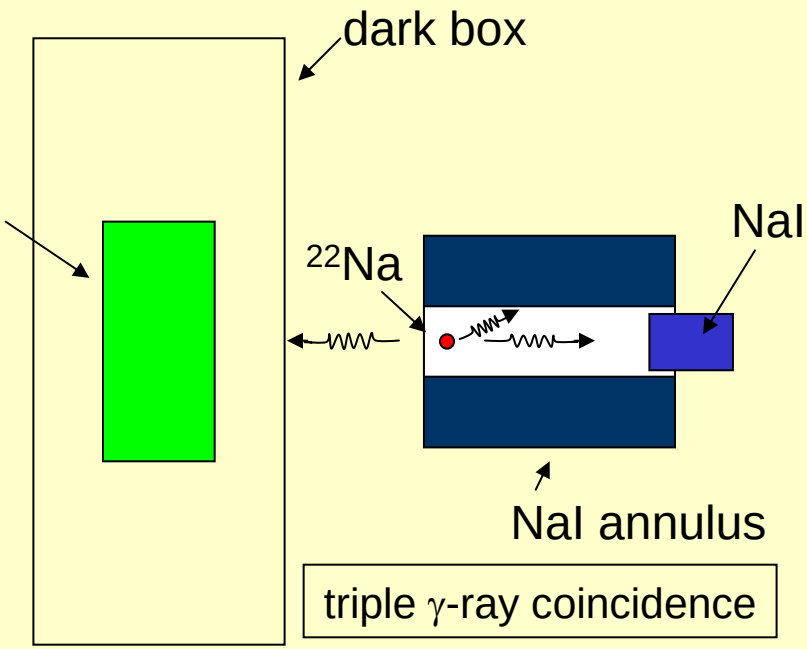
Dark Matter detection with liquid Argon

Very simple concept made possible by
Detecting light only: Acrylic vessel with Ar, surrounded by PMT's (sound familiar?)

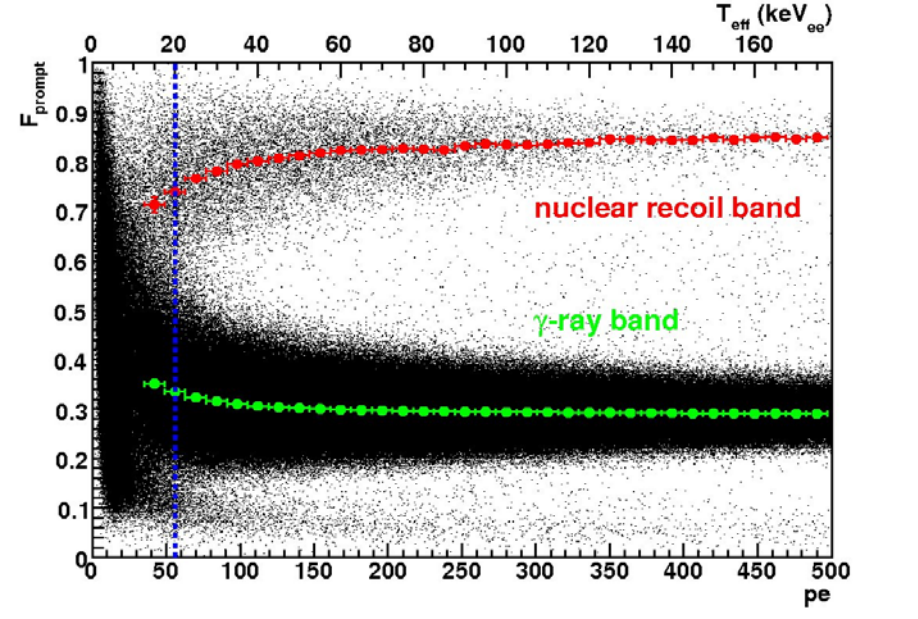
Program:
DEAP-1 (7Kg) now operating Underground
Mini-Clean (2008/9): 360kg (100 kg fiducial)
DEAP/CLEAN (2010): 3600 kg (1000 kg fducial)



Tests of discrimination with DEAP-1

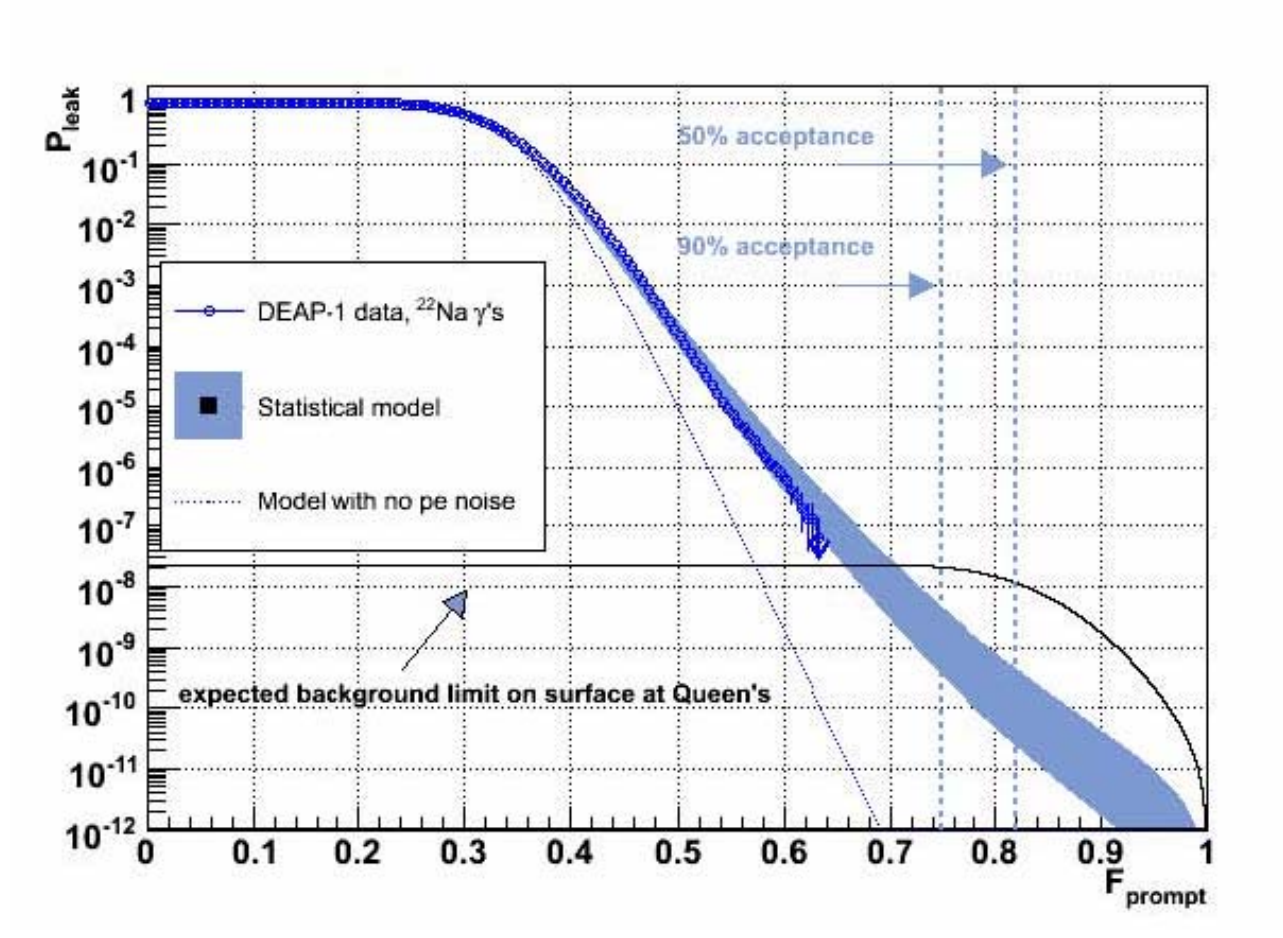


triple γ-ray coincidence



DEAP-1 discrimination tests using 511 keV gammas

Ran DEAP-1 on surface to background limit (6 x 10^{-8} PSD) then moved to SNOLAB where it is now running underground for further PSD studies and DM search.

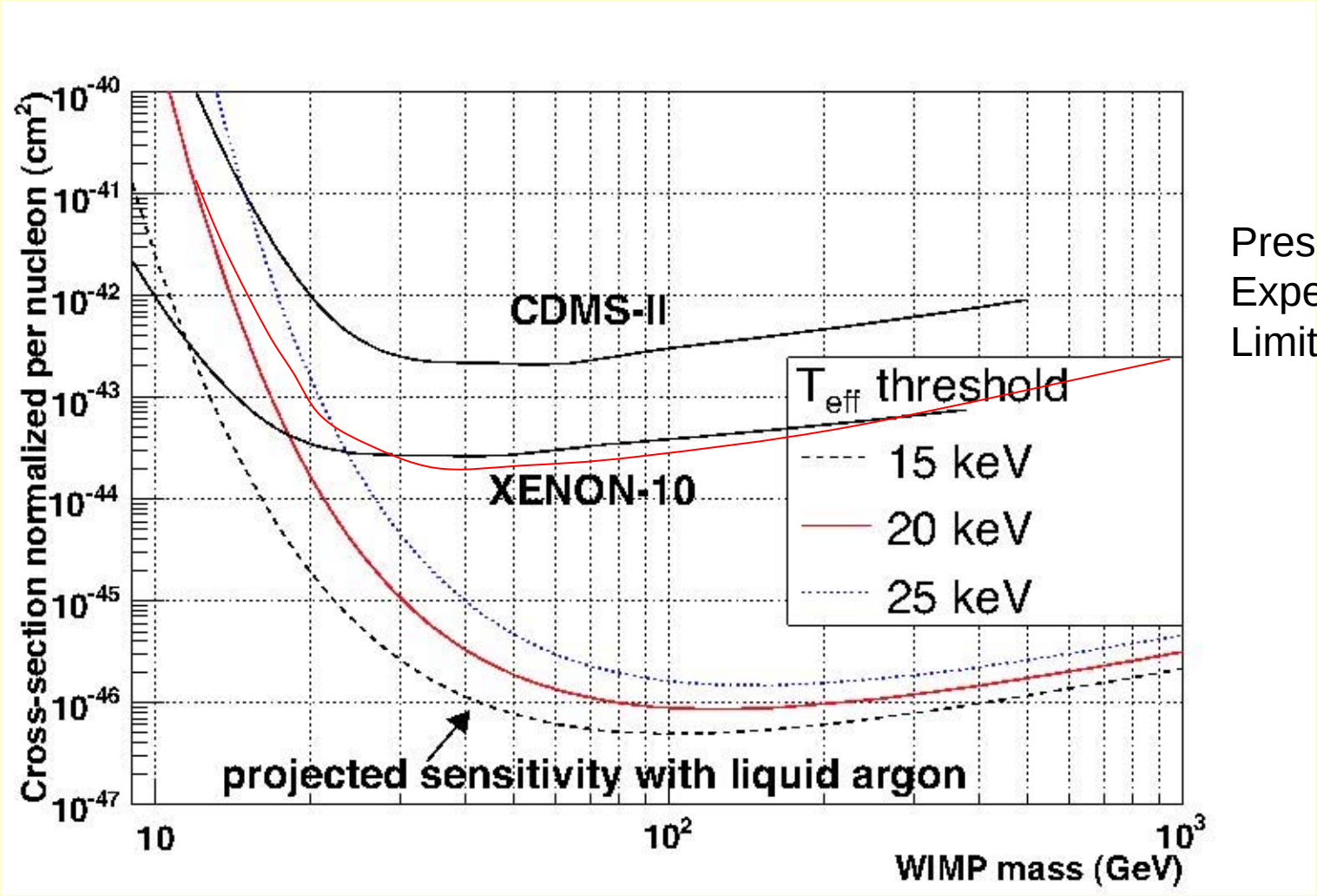


PSD agrees with statistical model over seven orders of magnitude.

Projection: Light alone is sufficient for 10^9 background reduction needed for 1 tonne DM experiment with natural Ar.

PSD already sufficient for 1 tonne fiducial Ar if depleted x 20 in ^{39}Ar. (See Galbiati et al)

WIMP Sensitivity with 1 tonne of argon



Present Experimental Limits

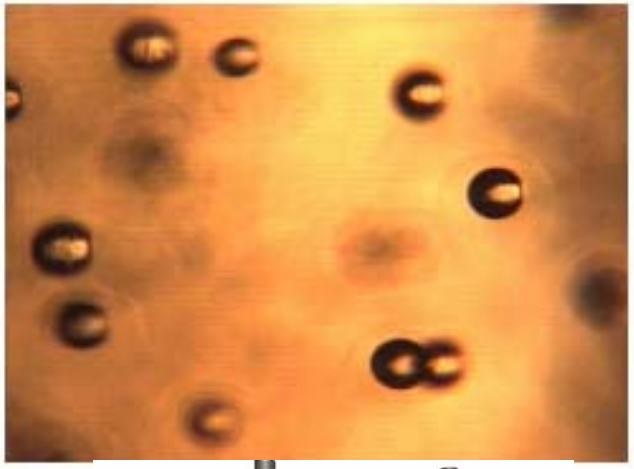
For nominal threshold of 20 keV visible energy, 1000 kg LAr for 3 years is sensitive to 10^{-46} cm^2. Present schedule: Mini-CLEAN 100 kg Fiducial: 2009, DEAP/CLEAN: 1000 kg Fiducial: 2010

WIMP-Nucleus Spin-Dependent Interaction

The Superheated Droplet Detector

- droplets superheated at ambient T & P
- 50 to 100μm droplets of carbofluorides dispersed in polymerised gel
- active liquids:

  C_4F_{10} (T_b=-1.7 °C) , C_3F_8 (T_b=-36.7 °C)
- …used for n-dosimetry (BTI-Chalk River)
- Recoil energy threshold E_{rec} = O(keV)
- insensitive to β, γ and cosmic μ radiation

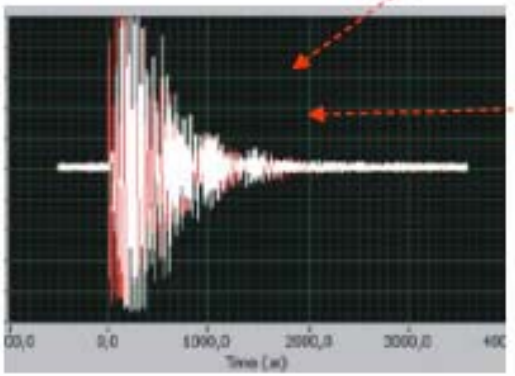


Fluorine is very sensitive for the spin-dependent interaction

Montreal, Queen's

Indiana, Pisa, BTI

Picasso



Acoustic Signal

Up to 2.6 kg being run in 2007-08

CONCLUSIONS

- **Astroparticle physics is an exciting and growing field with continuing contributions to both particle physics and astronomy.**

- **If you can go deep and clean in a dedicated laboratory, you can address very fundamental questions that are otherwise inaccessible.**

- **Look for many new results in the next few years in neutrino physics, dark matter, double beta decay, with the potential for very fundamental discoveries.**