Measuring the Neutrino Luminosity of the Sun & Search for Sterile Neutrinos

LENS & MINILENS

International Workshop on "Double Beta Decay and Neutrinos"
Osaka, June 12, 2007

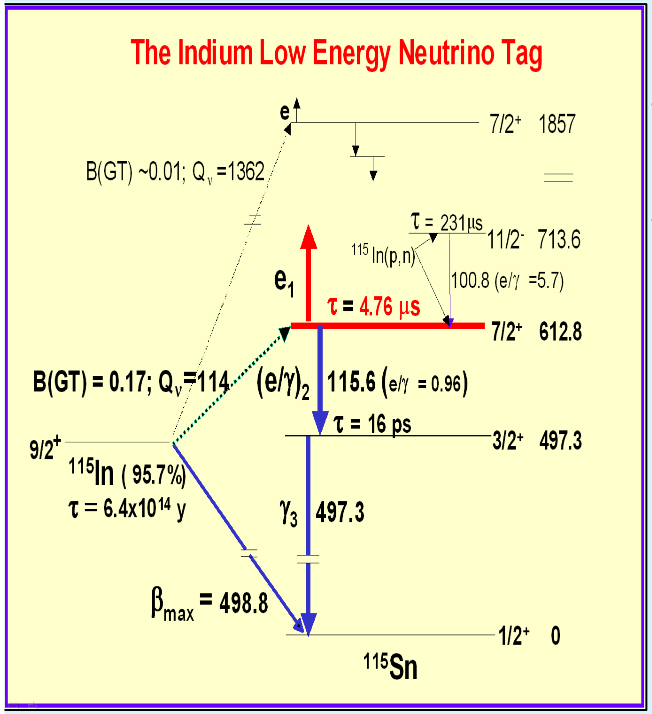
Christian Grieb for the LENS Collaboration
Virginia Tech

LENS-Indium: Foundations

CC ν-capture in ^{115}In to excited isomeric level in ^{115}Sn

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

Tag: Delayed emission of (e/γ)+ γ
Threshold: 114 keV → pp-ν's
^{115}In abundance: ~ 96%
CC-capture: Faithful reproduction of ν spectrum



Background Challenge:

- Indium-target is radioactive! (t = 6x10^{14} y)
- ^{115}In β-spectrum overlaps pp-ν signal

Basic background discriminator:

Time/space coincidence tag

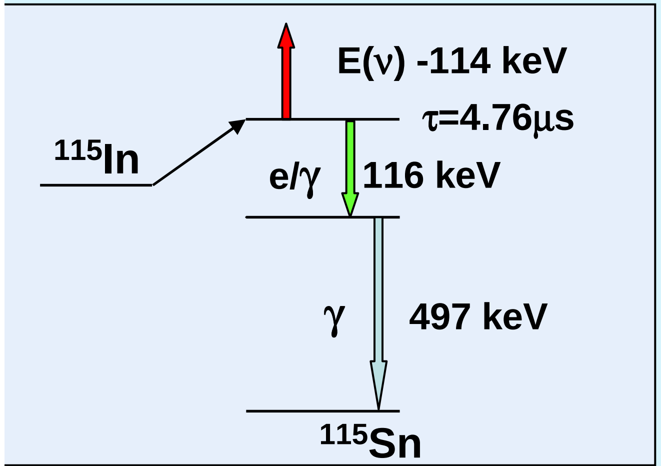
Tag energy: $E_{\nu\text{-tag}} = E_{\beta max}$ +116 keV

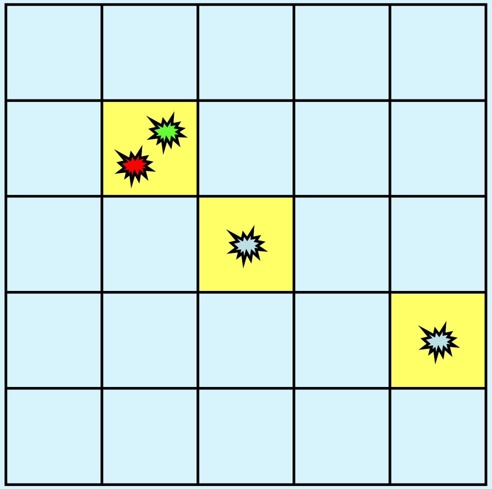
Requires spatial resolution of < 10cm

^{7}Be, CNO & LENS-Cal signals not affected by Indium-Bgd!

Indium β^--Background Structure – Space / Time coincidence

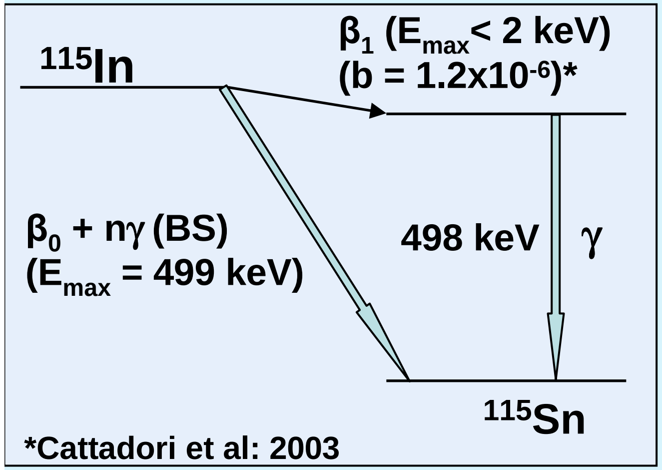
Signal



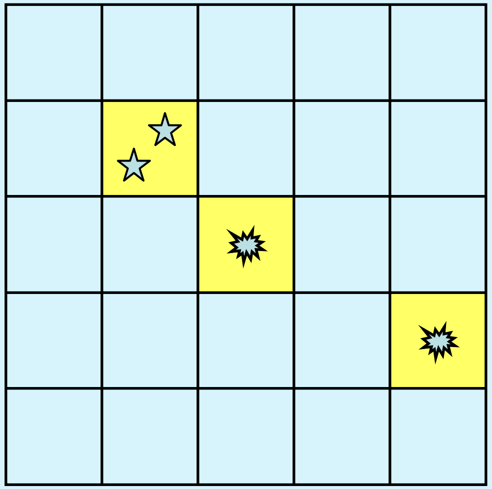


Signal Signature:

Prompt e^- (✹)
followed by
low energy (e^-/γ) (✹)
and
Compton-scattered γ (✹)
-> time/space coincidence
-> tag fixed energy 613keV
->compton scattered shower



Background



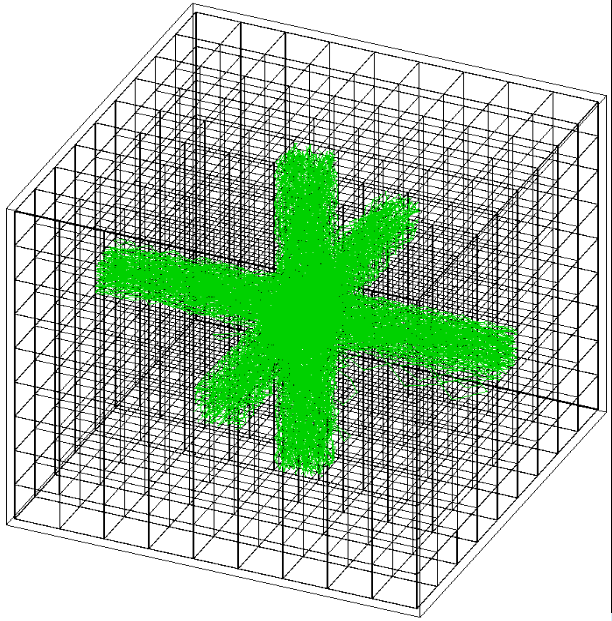
Background:

Random time and space coincidence between two β-decays (☆);
Extended shower (✹) can be created by:

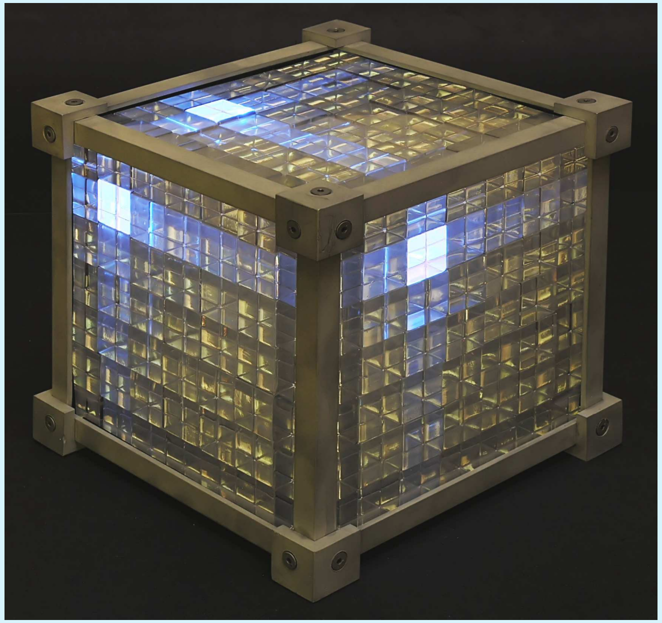
a) 498 keV γ from decay to excited state;
b) Bremsstrahlungs γ-rays created by β;
c) Random coincidence (~10 ns) of more β-decays;

Or any combination of a), b) and c).

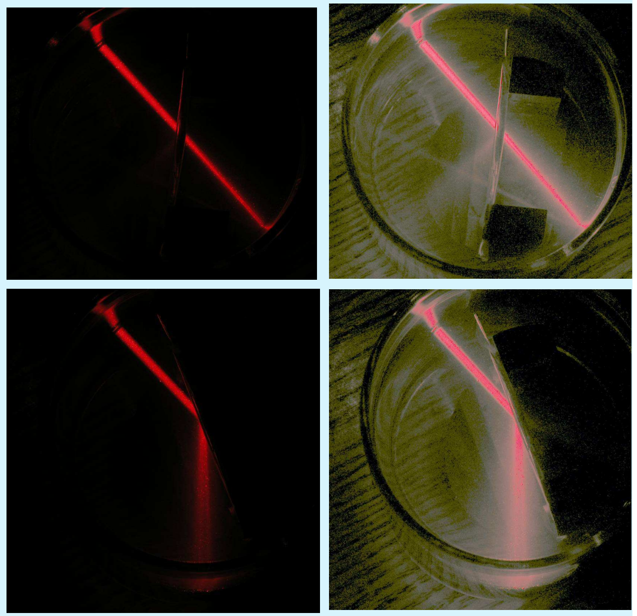
New Detector Technology -
The Scintillation Lattice Chamber



Light propagation in GEANT4



Concept



Test of double foil mirror in liq. @~2bar

3D Digital Localizability of Hit within one cube

→ ~75mm precision vs. 600 mm (±2σ) by TOF in longitudinal modules

→ x8 less vertex vol. → x8 less random coinc. → Big effect on Background

→ Hit localizability independent of event energy

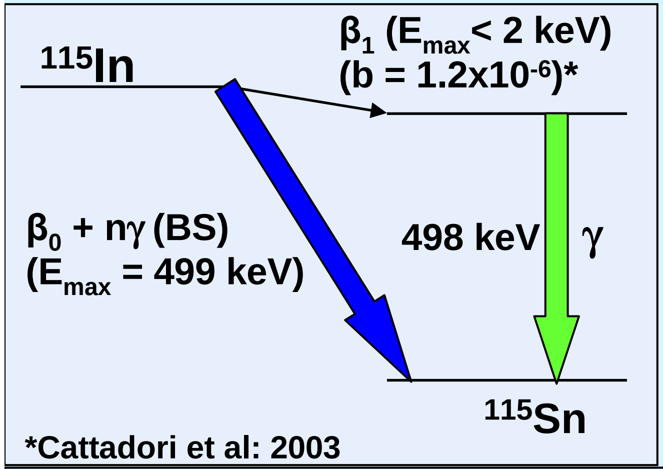
In-Background Rejection

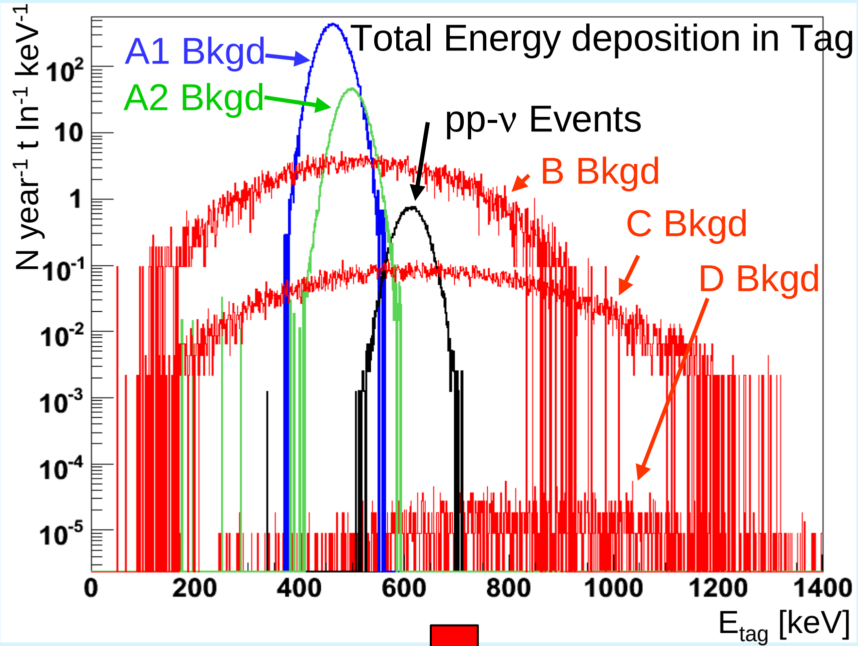
Background rejection steps:

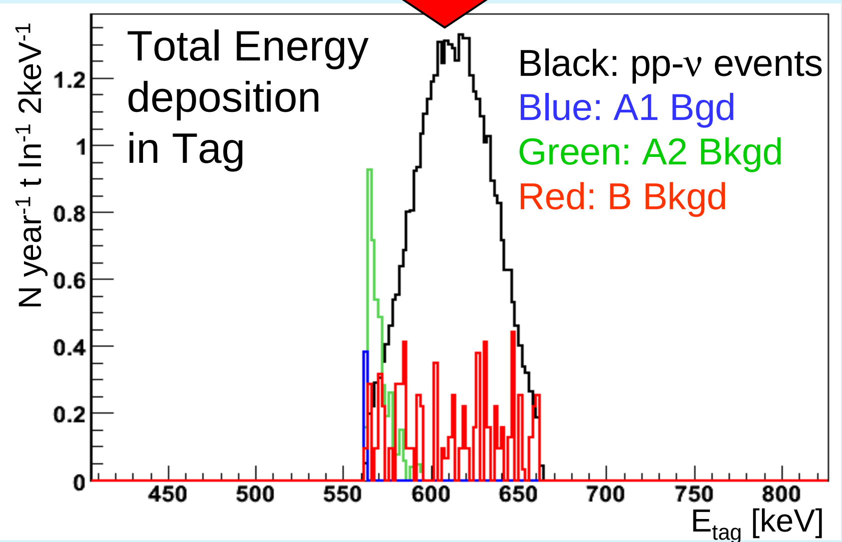
1. Time/space coincidence in the same cell required for trigger;
2. Tag requires at least three 'hits';
3. Narrow energy cut;
4. Tag topology: multi-β vs. Compton shower;

Classification of events according to hit multiplicity;

Cut parameters optimized for each event class ➡ improved efficiency;







Indium β^--Background Rejection - MC Results

Results of GEANT4 Monte Carlo simulation (cell size = 7.5cm)

	Signal (pp) y^{-1} t In)$^{-1}$	Bgd (In) y^{-1} (t In)$^{-1}$
RAW rate	62.5	79×10^{11}
A. Tag in Space/Time delayed coincidence with prompt event in vertex	50	2.76×10^{5}
B. + ≥3 Hits in tag shower	46	2.96×10^{4}
C. +Tag Energy = 613 keV	44	306
D. +Tag topology	40	13 ± 0.6

Reduction by ~$3 \cdot 10^7$ through time/space coincidence

⇨Signal / Background ~3 with pp-ν event detection efficiency 64%

⇨Remember: only pp-ν events affected by Indium Background, ^{7}Be, pep and CNO Background-free

⇨LENS is a feasible detector:
125t of liquid scintillator for ~2000 pp-ν events in 5 years with full spectroscopic information plus ^{7}Be, pep and CNO

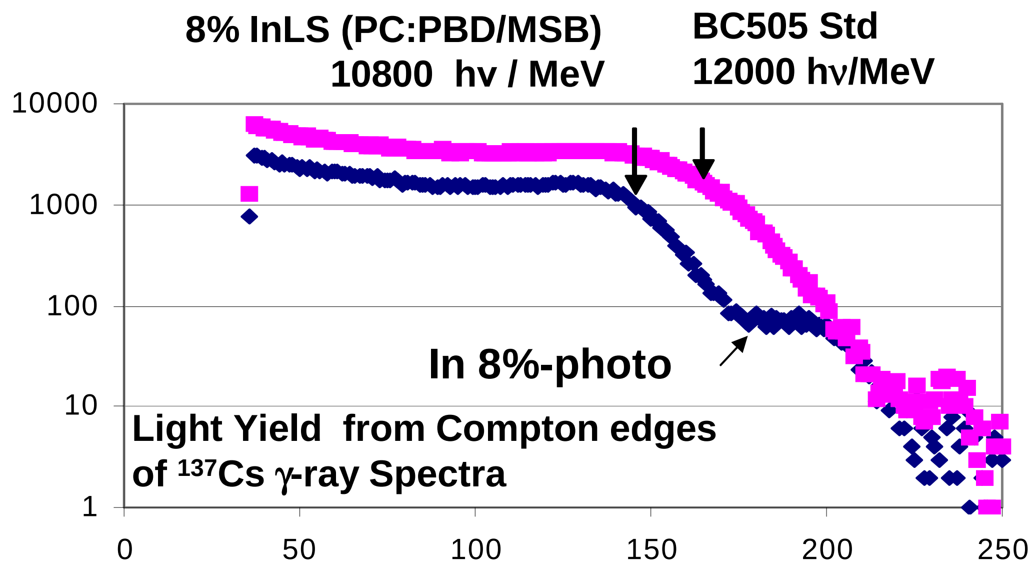
Indium Liquid Scintillator Status

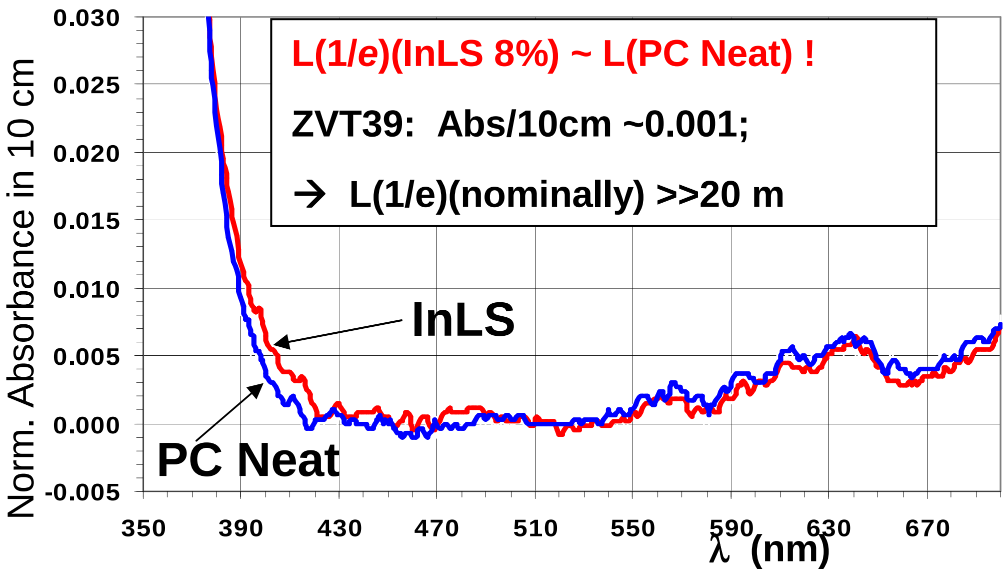
Milestones unprecedented in metal LS technology

LS technique relevant to many other applications

1. Indium concentration ~8%wt (higher may be viable)
2. Scintillation signal efficiency (working value): 9000 hν/MeV
3. Transparency at 430 nm: L(1/*e*) (working value): 10m
4. Chemical and Optical Stability: at least 1 year
5. InLS Chemistry - Robust

Basic Bell Labs Patent, filed 2001, awarded 2004





LENS Expected Result: Low Energy Solar ν-Spectrum

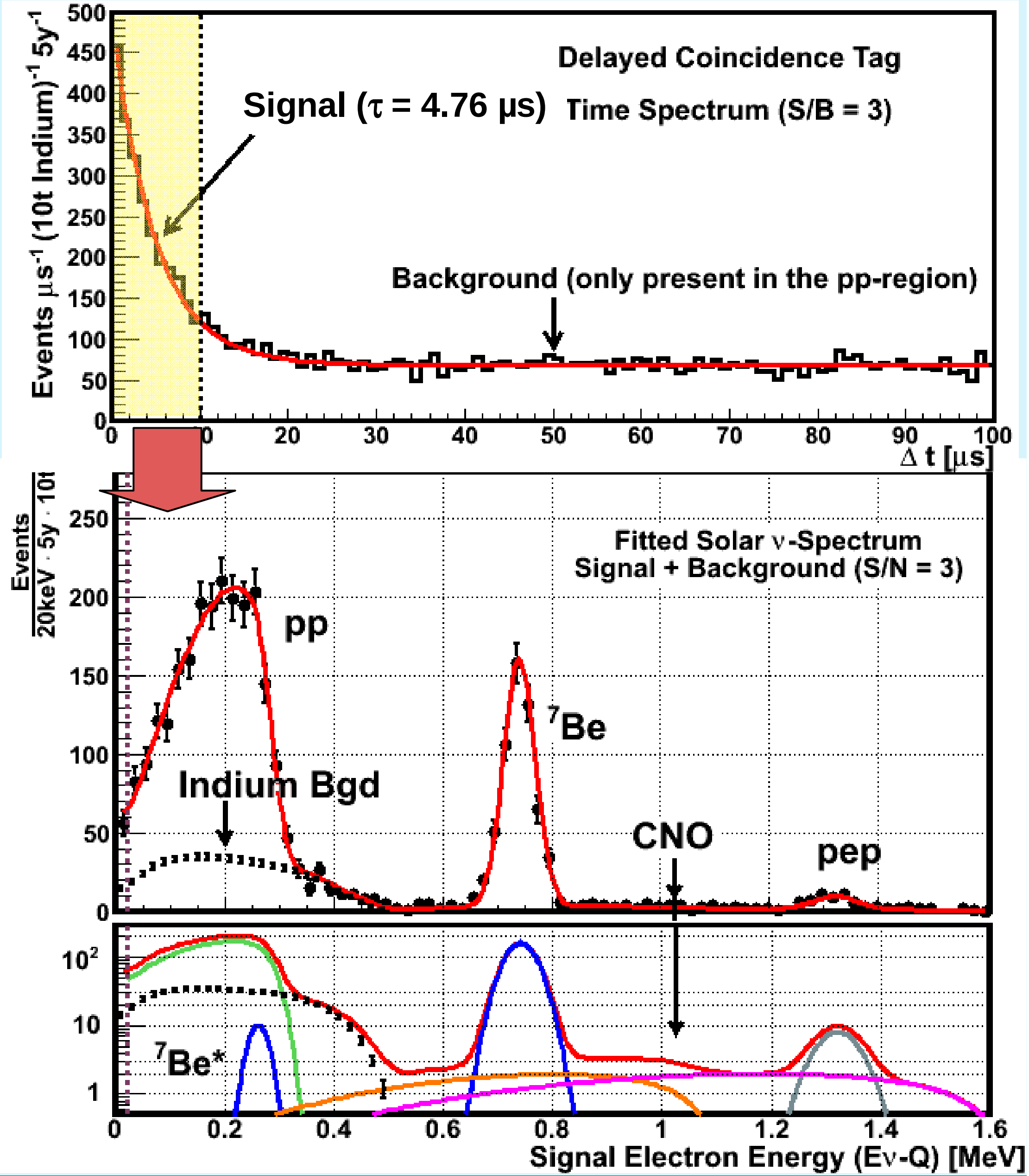
>98% Flux <2MeV

LENS-Sol Signal
=
SSM(low CNO) + LMA
x
Detection Efficiency ε

pp: ε = 64%
^{7}Be: ε = 85%
pep: ε = 90%

→ Rate: pp 40 pp ev. /y /t In
→ 2000 pp ev./ 5y/10t In → ±2.5%
→ Design Specification: S/N ≥ 3

Access to pp ν spectral *shape* for the first time



Solar Luminosity: Neutrino vs. photon

Energy Balance:

Measured *neutrino* fluxes at earth
+ oscillation physics
⇨ nuclear reaction rates
⇨ energy release in the sun

$$L_{\nu-\mathrm{inferred}} \stackrel{?}{=} L_{h\nu}$$

Solar luminosity as measured by *photon* flux

Will be met under these conditions:

1. Fusion reactions are the *sole* source of energy production in the sun
2. The sun is in a quasi-steady state (change in 40,000 years is negligible)
3. The neutrino oscillation model is correct & no other physics involved;

From a single detector:

⇨ Test of astrophysics, solar model;
Test of neutrino physics (LMA-MSW at low E, NSI, mass-varying νs, Θ_{13}, …);

Neutrino inferred Luminosity of the Sun - Experimental Status

***Predicted* relative neutrino fluxes at the sun (SSM):**

Main contributions:

pp	0.91
^{7}Be	0.074
(CNO	0.014)
^{8}B	0.00009

***Measured* neutrino fluxes at the earth:**

^{8}B	(SK, SNO) known very well
^{7}Be + ^{8}B	(Cl) sensitive mostly to ^{8}B
pp + ^{7}Be + ^{8}B	(Ga)
^{7}Be	(Borexino, Kamland – in the future)

⇨ in principle can deduce pp-ν flux

Problem: disentangling fluxes from individual neutrino sources

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$$L_{\nu(\text{inferred})} / L_{h\nu} = 1.4\begin{pmatrix}0.2\\0.3\end{pmatrix}_{1\sigma}\begin{pmatrix}0.7\\0.6\end{pmatrix}_{3\sigma}$$

J.N.Bahcall and C.Peña-Garay, JHEP **0311**, 4 (2003)

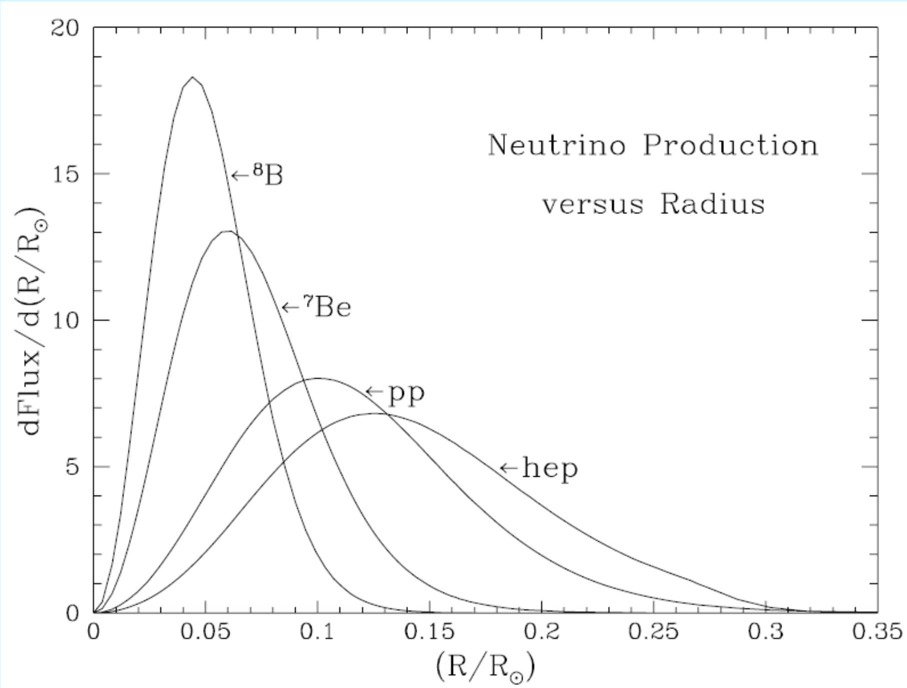
$$L_{\nu(\text{inferred})} / L_{h\nu} = 1.2(0.2)$$

R.G.H.Robertson, Prog. Part. Nucl. Phys. **57**, 90 (2006)

Experimental status – No useful constraint!

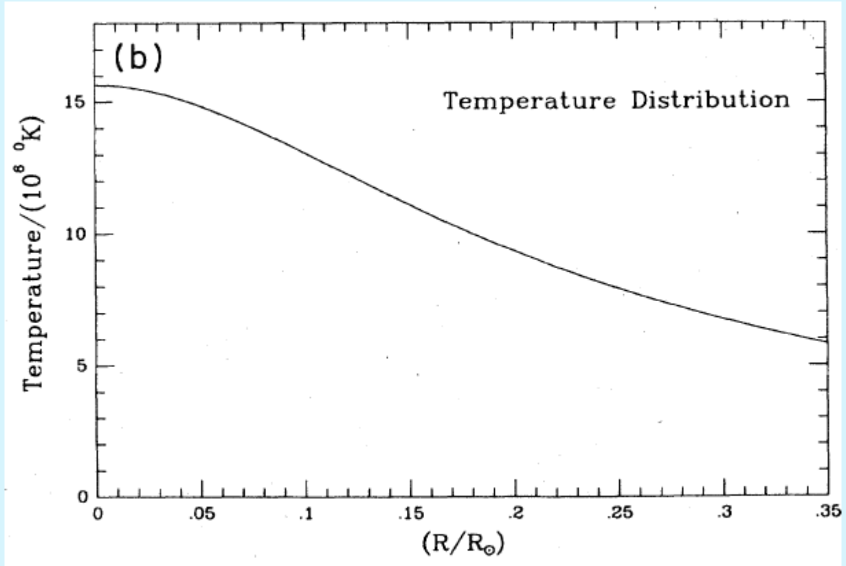
Probing the Temperature Profile of Energy Production in the Sun with LENS

Neutrino Production



J. N. Bahcall and R. Ulrich, *Rev. Mod. Phys.* **60**, No. 2, p. 297 (1988)

Temperature Profile



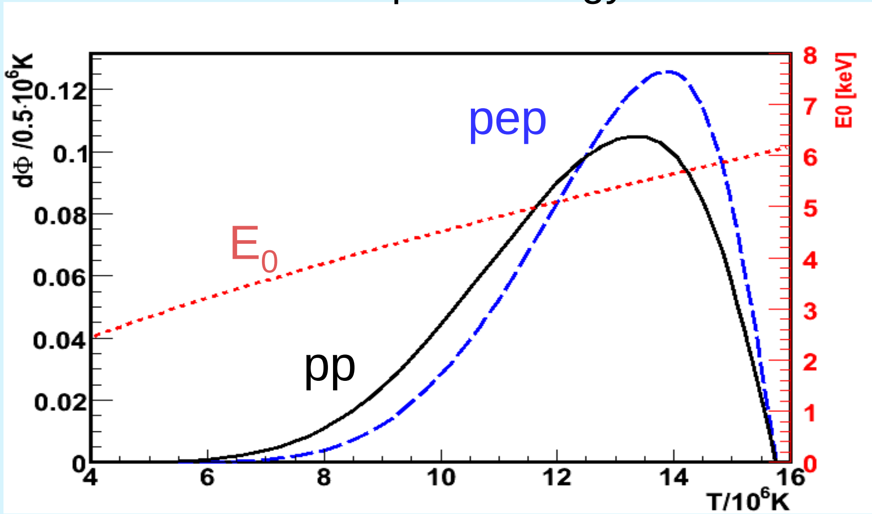
J. N. Bahcall and R. Ulrich, *Rev. Mod. Phys.* **60**, No. 2, p. 297 (1988)

Temperature in the Solar Core impacts Neutrino *Energies, not just relative fluxes*

Relative kinetic particle energies add to the Q-value of capture and fusion reactions.

Not all energies contribute evenly:

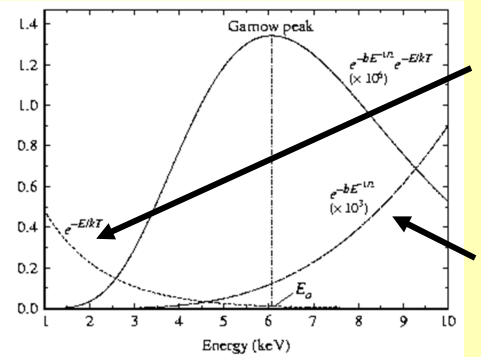
pp- and pep neutrino production temperature and related Gamow peak energy:



pp-fusion:

Gamow Peak at

$$E_0 = 5.91keV \cdot (T / 1.5 \cdot 10^7 K)^{2/3}$$



Maxwellian energy distribution
X
Tunneling probability

pp endpoint shifted up by ~5.2keV

J.N. Bahcall, *Phys. Rev. D* **44**(6), 1644(1991)

^{7}Be electron capture: maxwellian energy distribution shifts mean energy of ^{7}Be ν line by Δ<E> ~ 1.29 keV

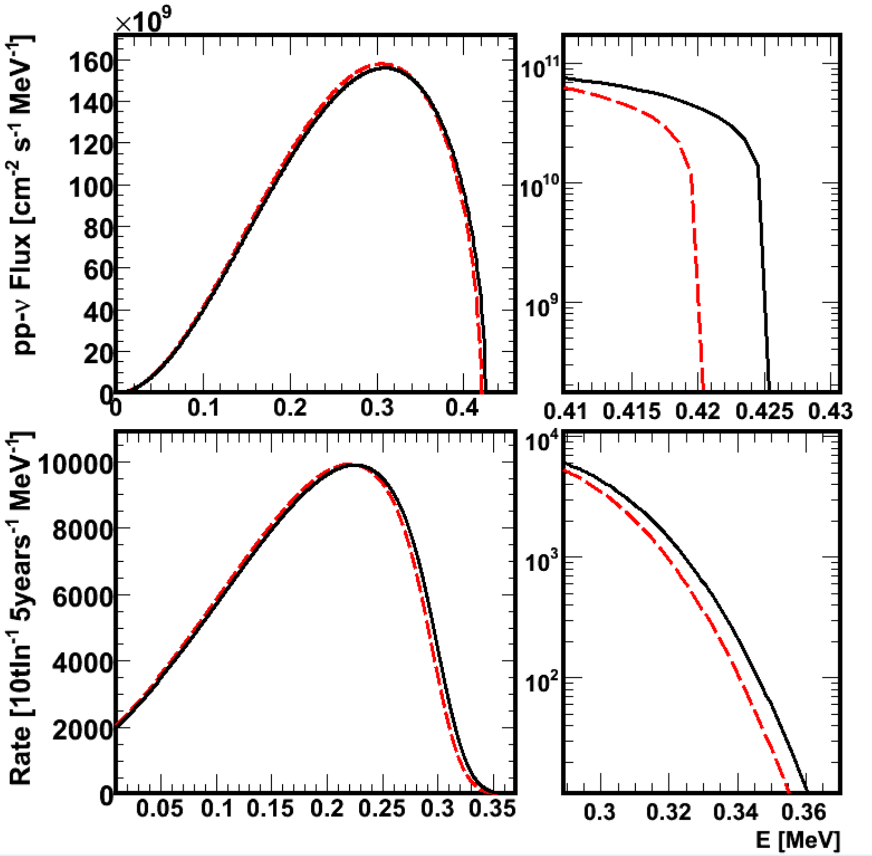
J.N. Bahcall, *Phys. Rev. D* **49**(8), 3923 (1994)

hep: $E_0 = 10.73keV \cdot (T / 1.5 \cdot 10^7 K)^{2/3}$

J.N. Bahcall, *Phys. Rev. D* **44**(6), 1644(1991)

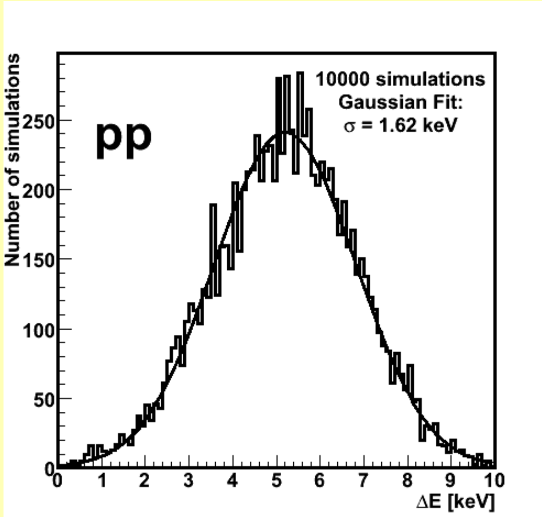
pep: combination, delta Δ<E> ~ 6.6 keV

Probing the Temperature Profile of Energy Production in the Sun with LENS



Top: pp-ν spectrum with/without Gamow shift

Bottom: Signal spectrum in LENS with/without Gamow shift
12t Indium - 6years - δE/E=6% at 300keV



Measured Gamow shift in improved LENS: 10000 simulations with ~3000 pp ν events each σ=1.62keV

C. Grieb and R.S. Raghavan, Phys.Rev.Lett.98:141102,2007

Conclusion: Slightly improved LENS can detect the predicted Gamow shift in the pp-ν endpoint ΔE=5.2keV with 95% confidence.

LENS-Cal Neutrino Sources

Source	DecayMode /Produced by	τ	E_ν (keV)	$E_e = E_\nu - 0.114$ keV	Background
^{37}Ar Haxton	EC/ (n, α)	50.5 d	814(100%)	700	Int. Bremss. 0-814; ~$\Sigma 5\text{x}10^{-4}$ hν/decay
^{51}Cr RSR Kuzmin	EC/ (n,γ)	40.1 d	751 (90%)	637	320γ (10%) Imp. γ's (MeV) %??
^{65}Zn Louis Alvarez	EC(β^+)/ (n,γ)	353 d	1350 (50%)	1236	1115 γ (50%); 511 γ (2%); Imp. γ's.

Neutrino Energy typically 700 keV

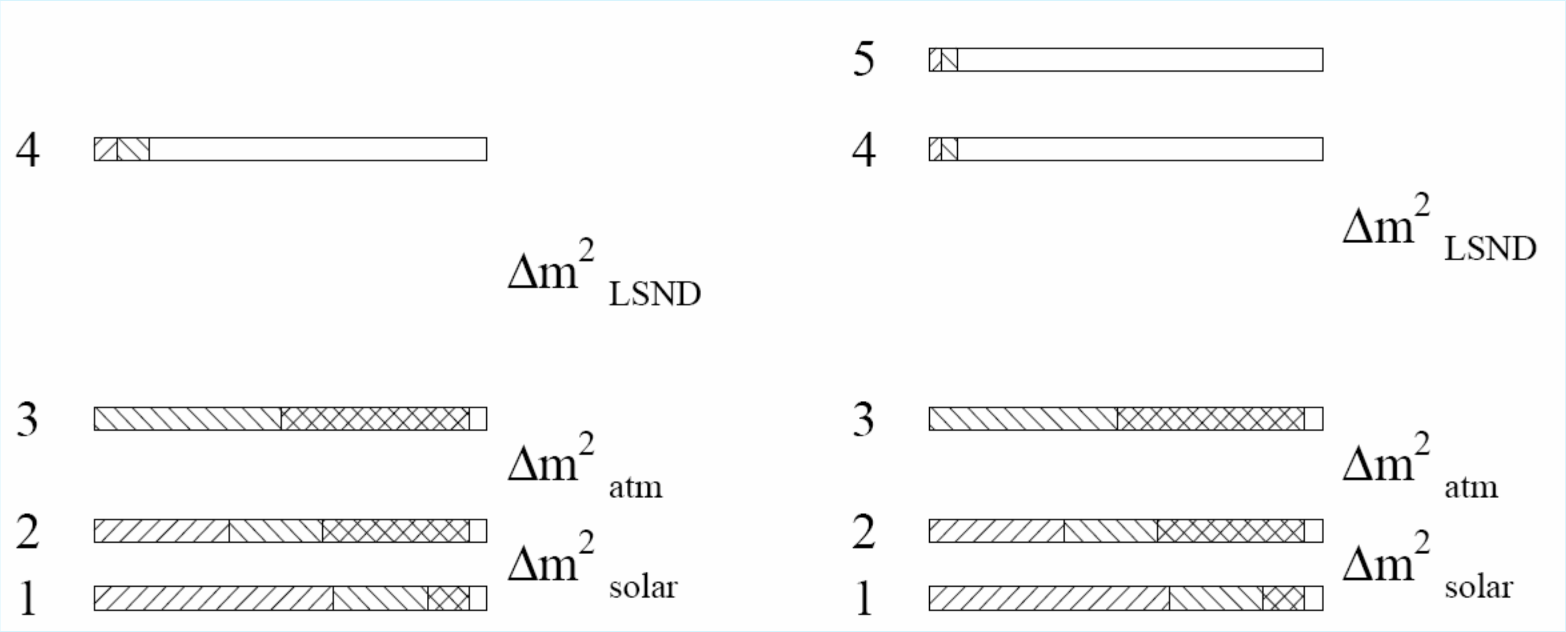
Sterile Neutrinos – Physics beyond the Standard Model

- Fourth (fifth) mass state with high mass splitting triggered by LSND appearance of $\bar{\nu}_e$ from $\bar{\nu}_\mu$ beam at *short* base line ~30m!

- Implies $\Delta m^2 \sim 1 eV^2$

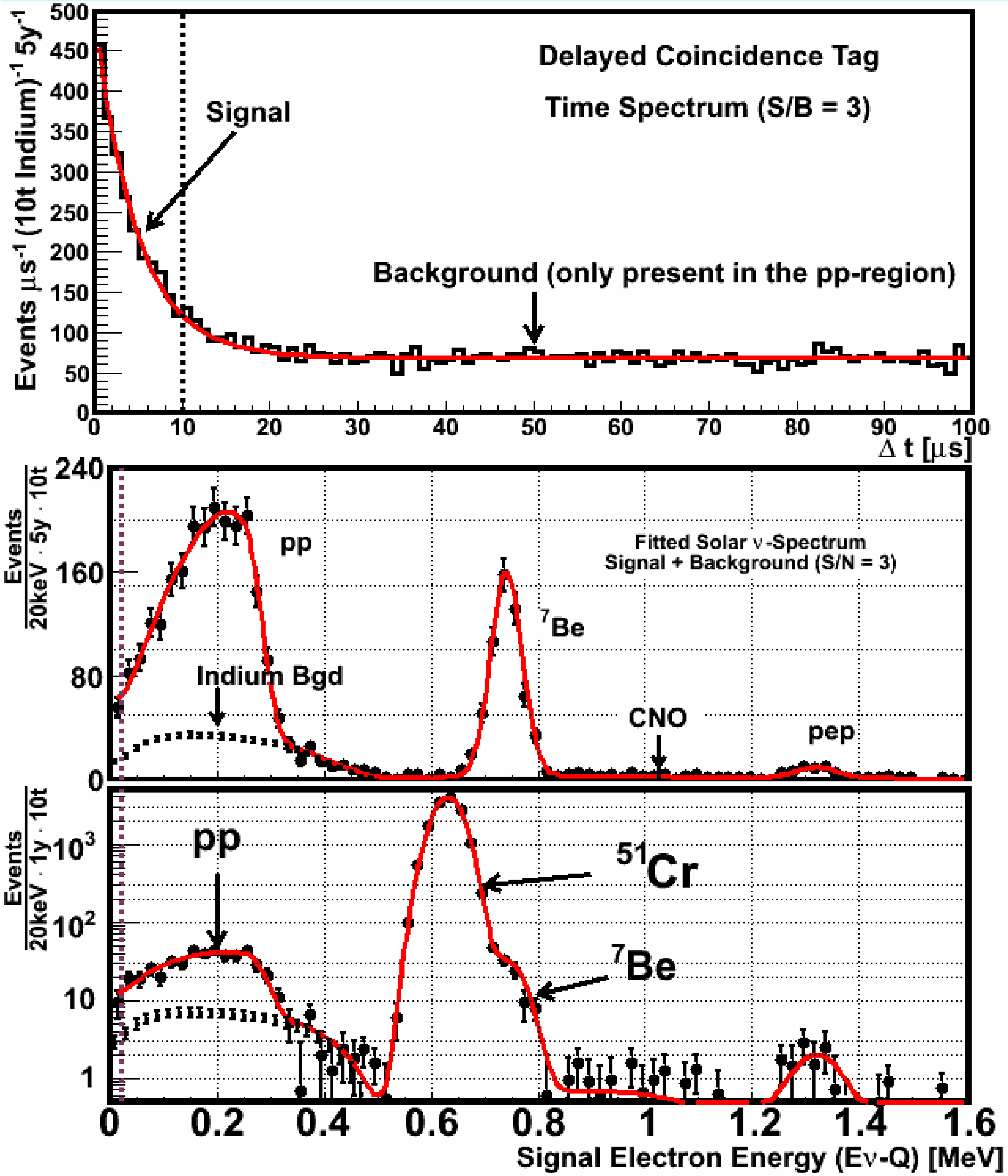
- Also motivated from cosmology

(3+1) (3+2)



Sorel et. al., Phys.Rev.D70:073004,2004.

LENS - Unique Test for Sterile Neutrinos



Already planned: LENS-Cal
MCi Cr Source in LENS to calibrate ν_e capture cross section on ^{115}In

Parasitic measurement
For sterile neutrinos

Active - Sterile oscillation of
monochromatic 753 keV
pure e-flavored neutrinos
via
Spatial distribution of
flavor survival in ~5 m

Active-Sterile Oscillations

Active - Sterile Neutrino Oscillations in LENS

Survival probability of ν_e:

$$P_{ee} \approx 1 - 4U_{e4}^2(1-U_{e4}^2)\sin^2 x_{41} - 4U_{e5}^2(1-U_{e5}^2)\sin^2 x_{51}$$

- Cross terms such as $U_{e4}^2 U_{e5}^2$ are neglected
- $x_{ij} = 1.27 \Delta m_{ij}^2 (eV^2) L(m) / E_\nu (MeV)$

Model	Δm_{ij}^2 (eV^2)	U^2	$\sin^2 2\theta_{ee} = 4U^2(1-U^2)$
3+1	0.92_{14}	0.0185	0.073
3+2a	0.92_{14}	0.0146	0.057
	22.1_{15}	0.0013	0.005
3+2b	0.46_{14}	0.0081	0.032
	0.89_{15}	0.0156	0.062

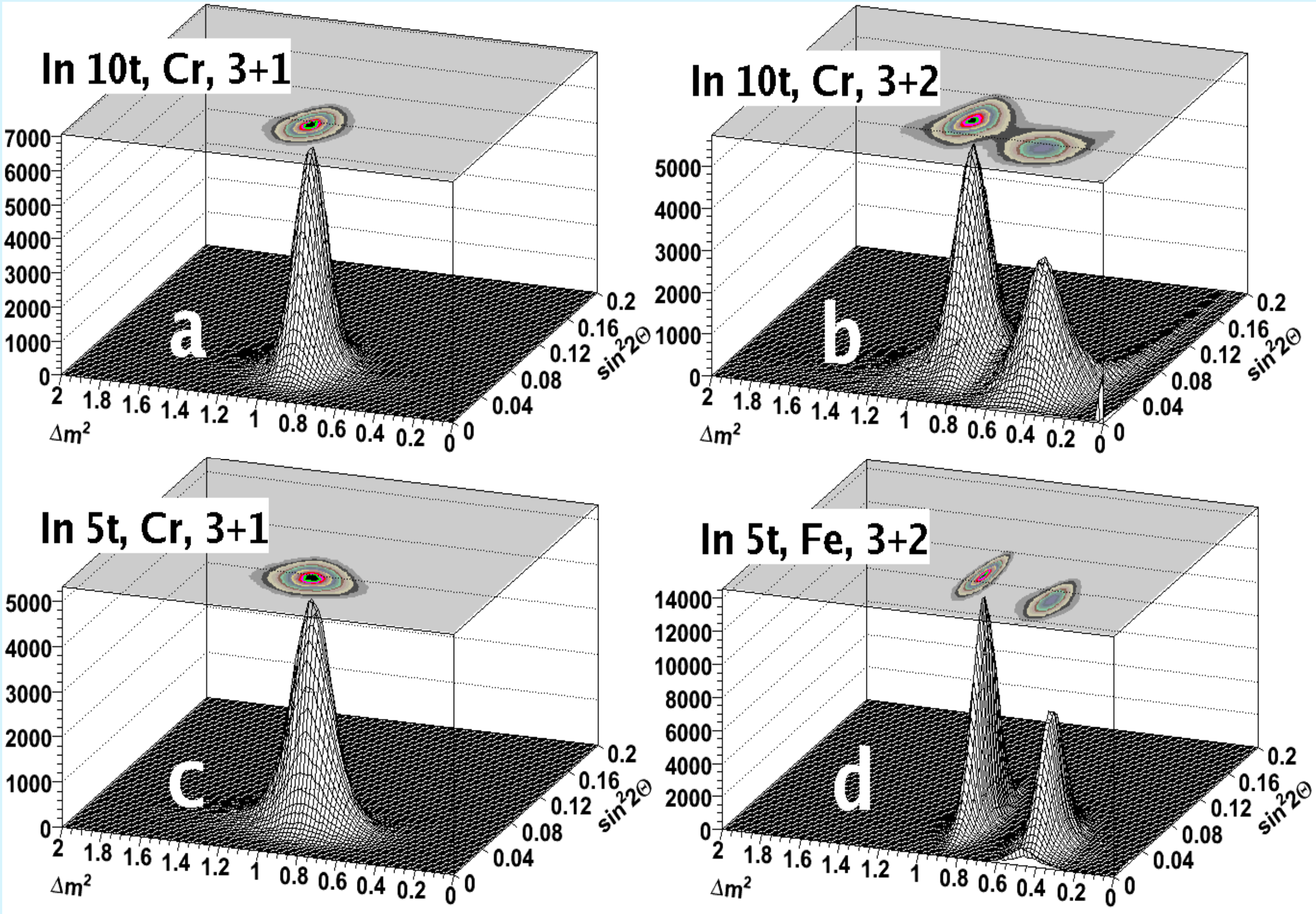
Active – sterile mass splittings and mixing parameters compatible with LSND and the null SBL data (from Sorel et al., Phys. Rev.D70:073004,2004)

With $\Delta m^2 \sim 1$ eV²
and $E_\nu \sim 0.753$ MeV (from ^{51}Cr),
full flavor recovery occurs in ~2m,
directly observable in a lab-scale detector.

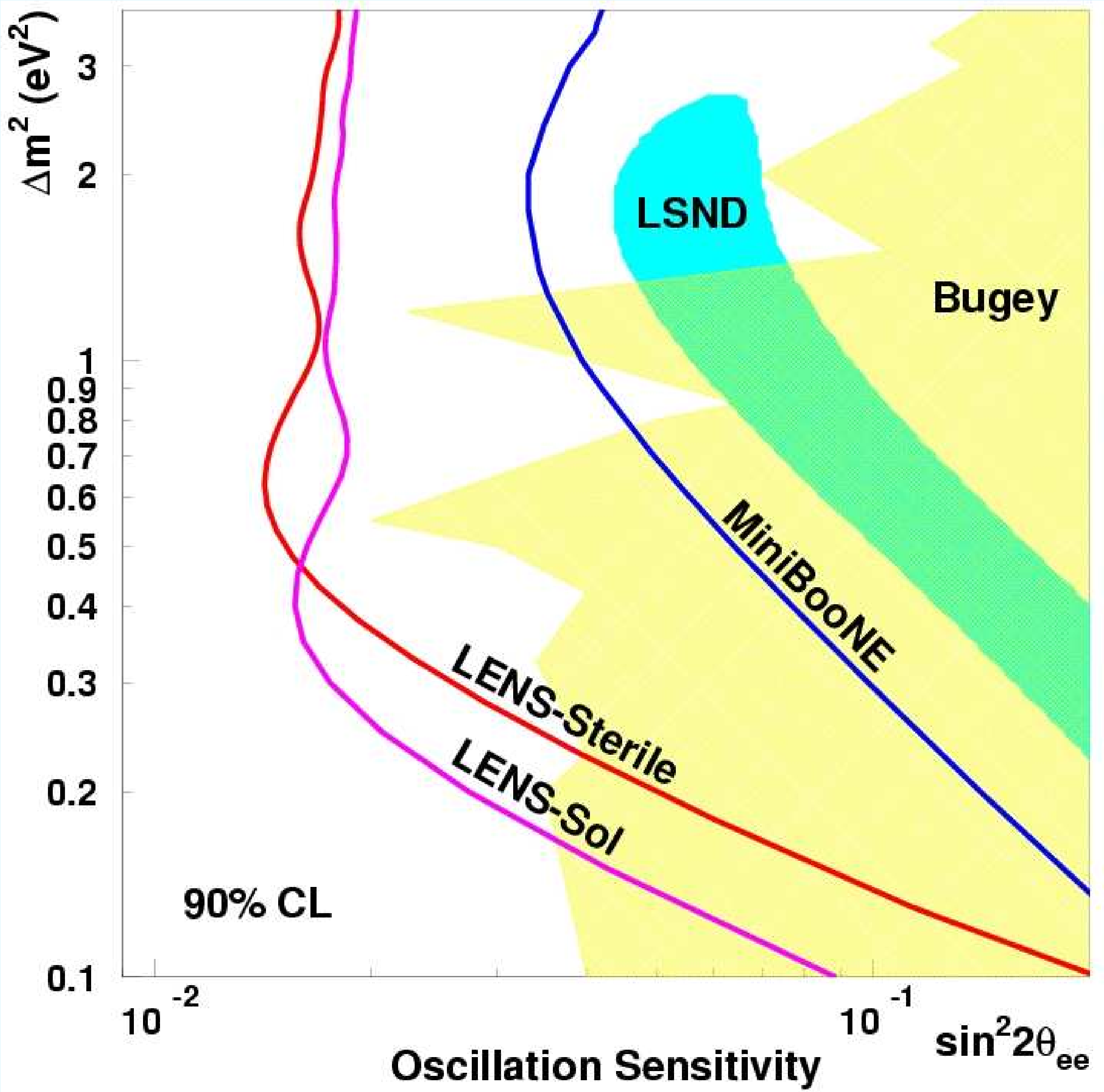
Configuration	ρ_{In} (wt. %)	$d_{detector}$ (meters)	m_{In} (tons)	m_{total} (tons)
A – LENS-Sol	8	5.1	9.9	125
B – LENS-Sterile	15	3.3	5.1	34

Design options for LENS

Statistical precision of oscillation parameter measurement in LENS



Active – Sterile Oscillation Sensitivity with LENS



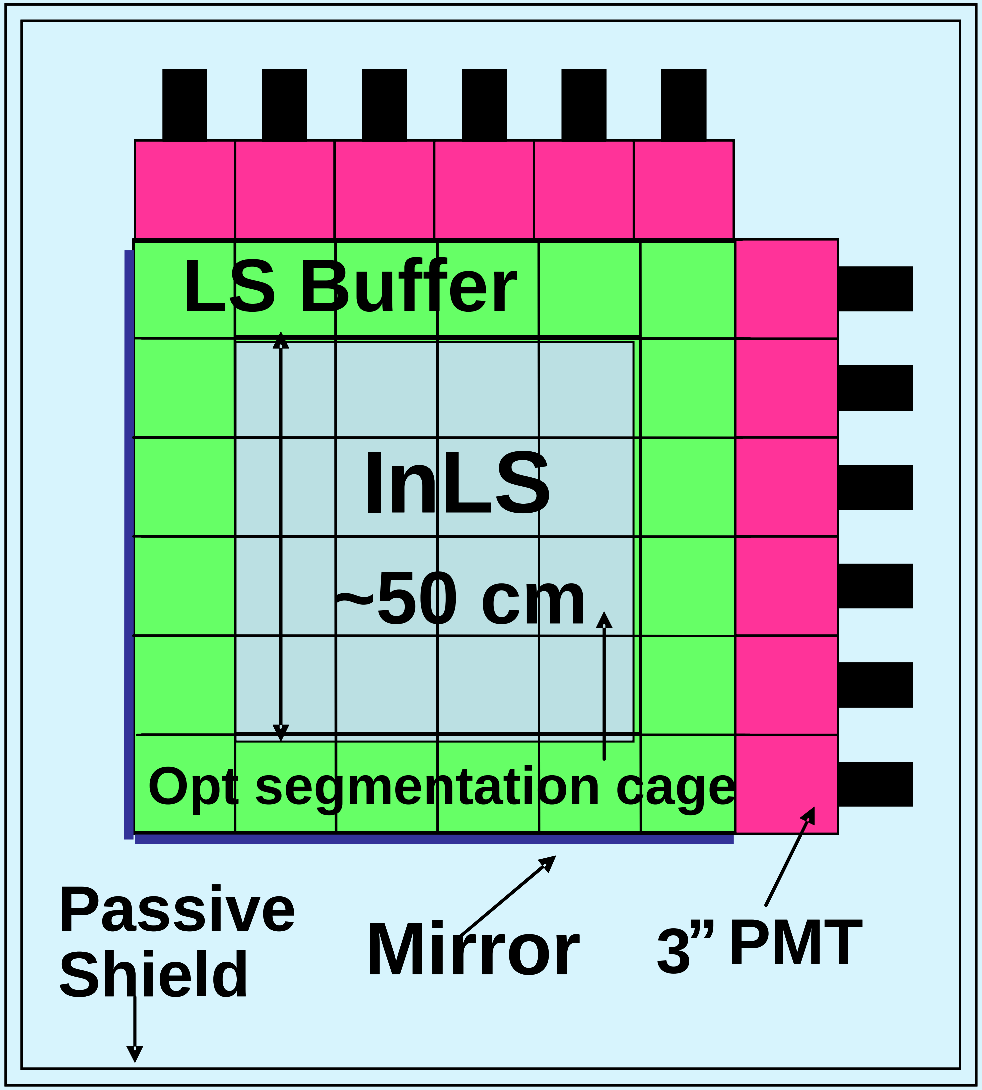
MINILENS

Final Test detector for LENS
- NSF funded

- InLS : 128 L
- Liquid Scintillator Buffer
- 3'' pmt's : ~150

- **Test detector technology**
  →Medium Scale InLS production
  →Design and construction
- **Test background suppression of In radiations by 10^{-11}**
  Expect ~ 5 kHz In β-decay singles rate; adequate to test trigger design, DAQ, and background suppression schemes
- **Demonstrate In solar *signal* detection in the presence of high background (via "proxy")**

⇨ Direct blue print for full scale LENS



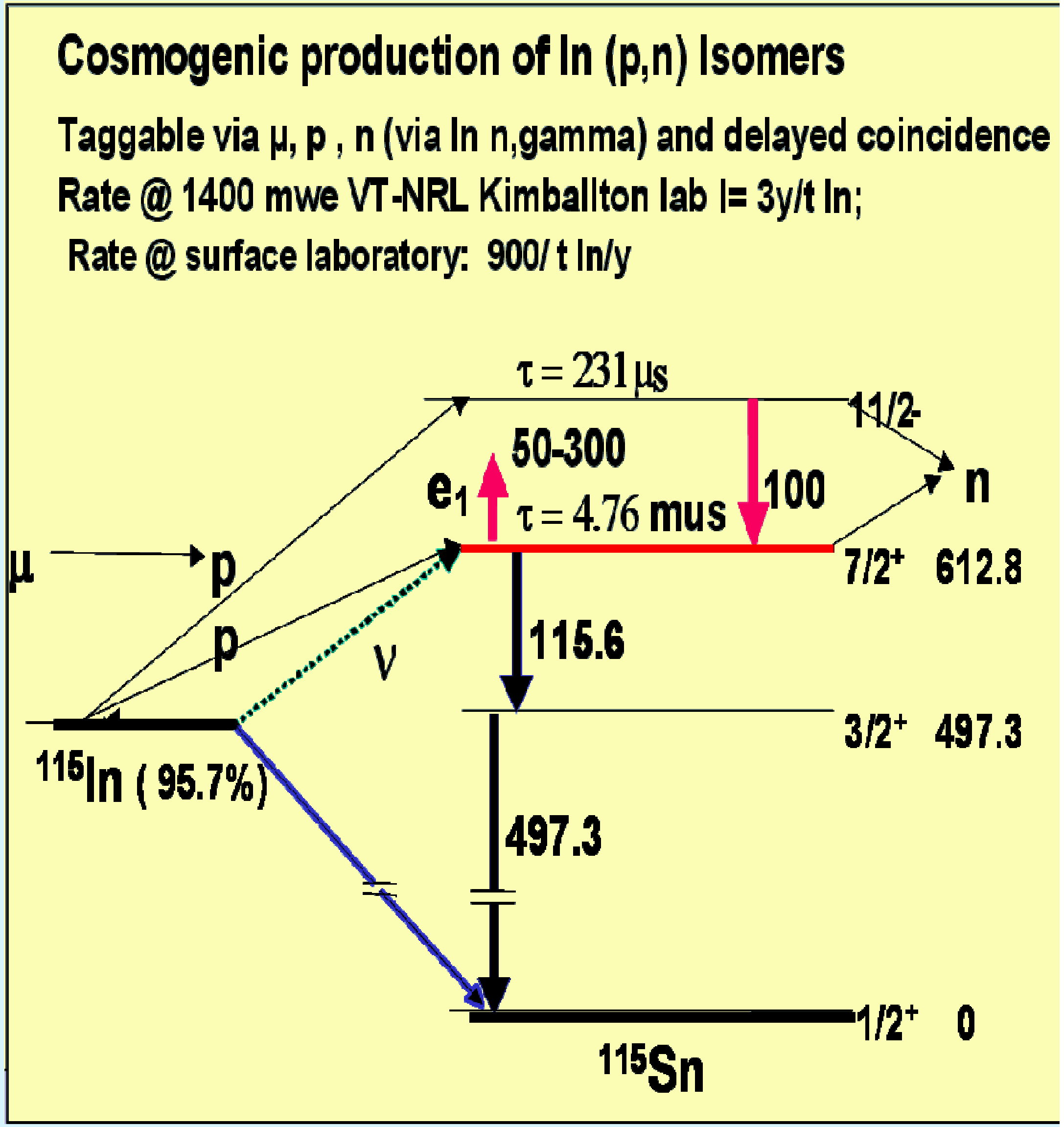
Proxy pp-ν events in MINILENS

Proxy pp nu events in MINILENS from cosmogenic $^{115}In(p,n)^{115}Sn$ isomers

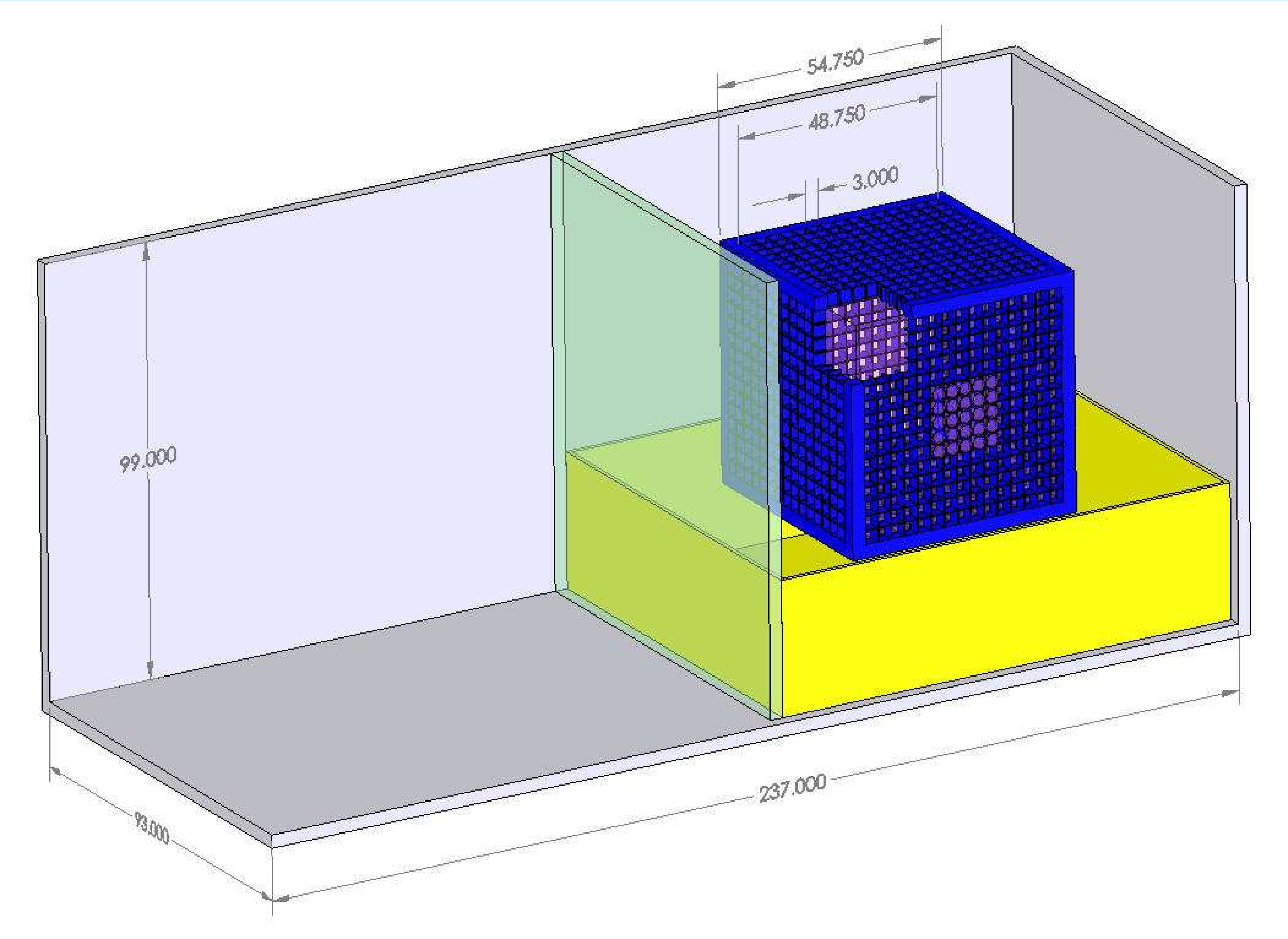
- **Pretagged via μ, p tracks**
- **Post tagged via n and 230 μ s delay**

→ Gold plated 100 keV events (proxy pp), Tagged by same cascade as In-ν events

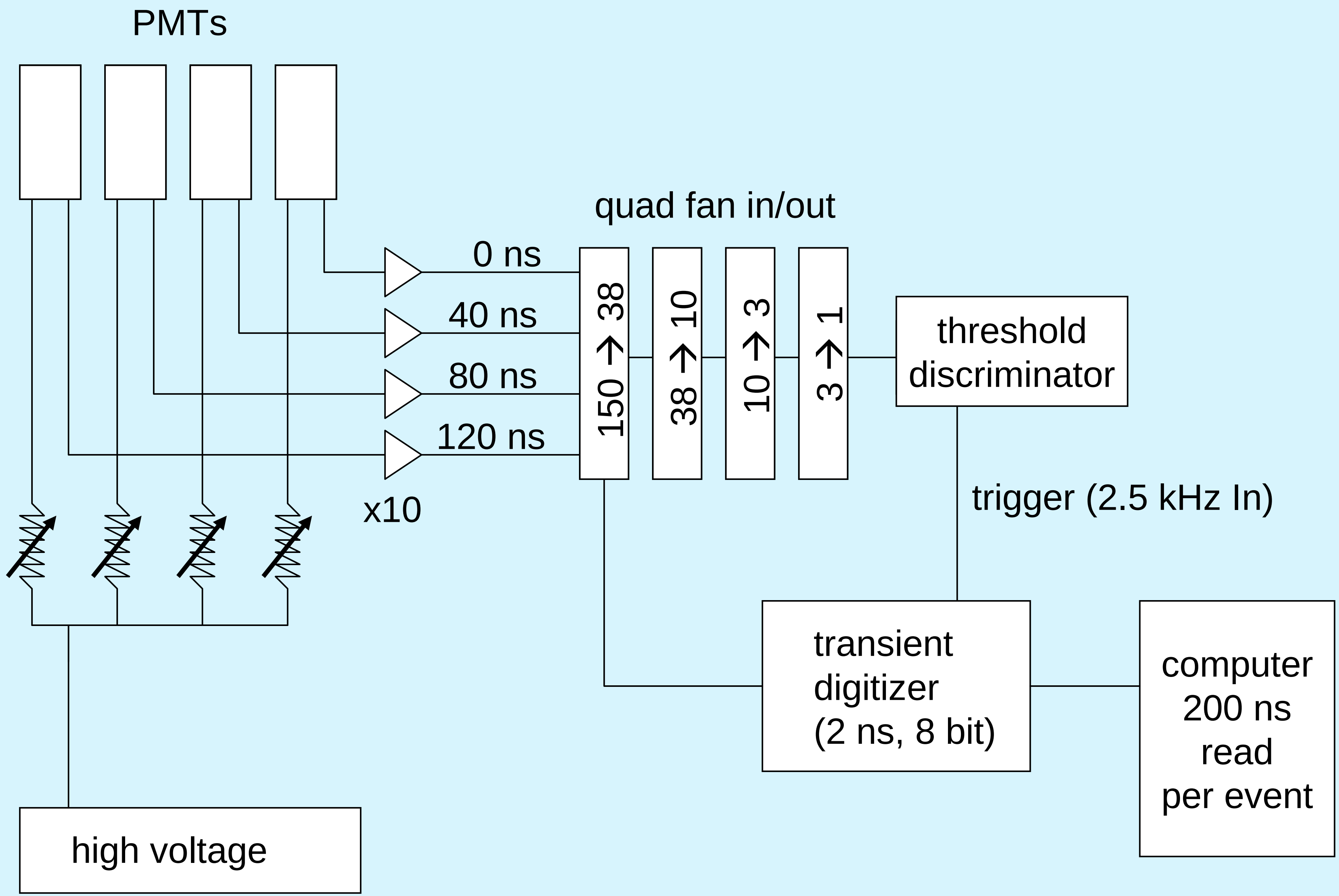
→ Demonstrate *In-ν Signal* detection even in MINILENS



MINILENS concept

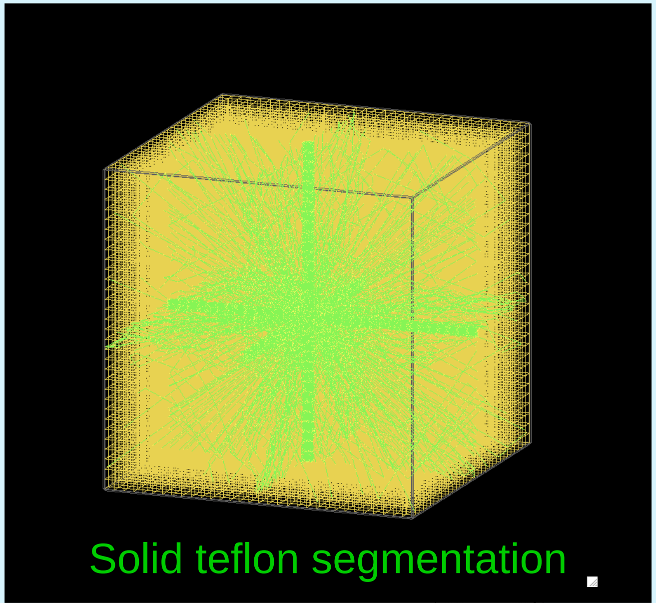


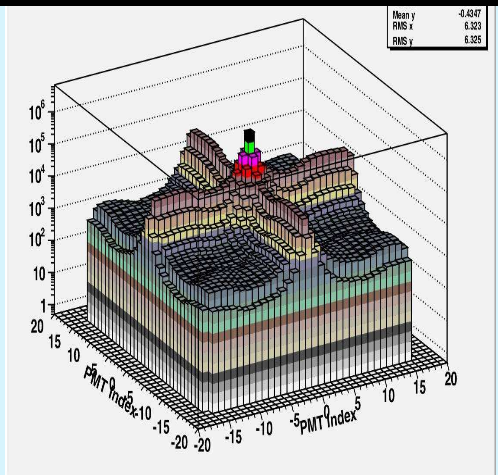
MINILENS Electronics



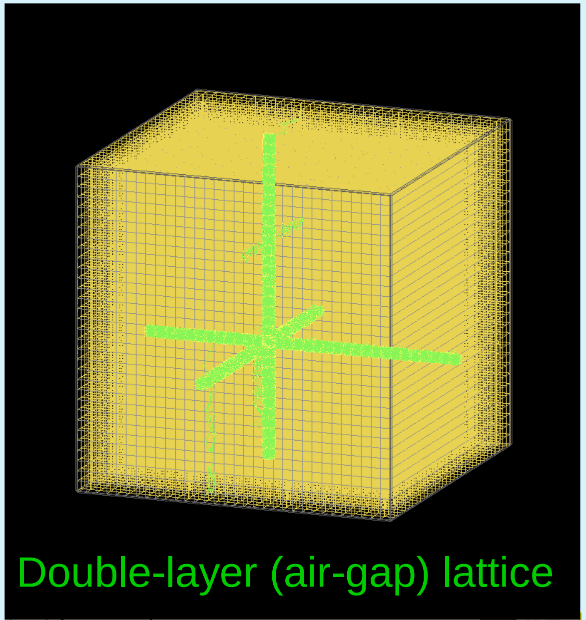
Options for Lattice Structure

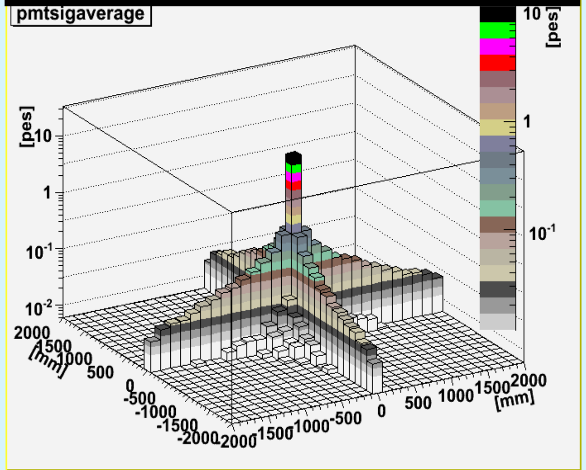
Single Foil





Double Foil





Summary

Major breakthroughs in LENS:

- Indium liquid scintillator synthesis
- New detector technology (Scintillation Lattice Chamber)
- GEANT4 Simulation of Indium β^- background

→ Basic feasibility of In-LENS-Sol secure (10t In, 125t In-LS)

Science in LENS:

Measure solar ν-spectrum below 2MeV

→ ν Luminosity of the sun
→ Gamow shift of pp-ν spectrum probes the T profile
→ Search for active - sterile neutrinos
→ Test of Astrophysics & ν physics in one experiment

Now:

Build MINI-LENS - 130 liter InLS detector
Test all the concepts and the technology developed so far
& demonstrate Indium solar signal detection

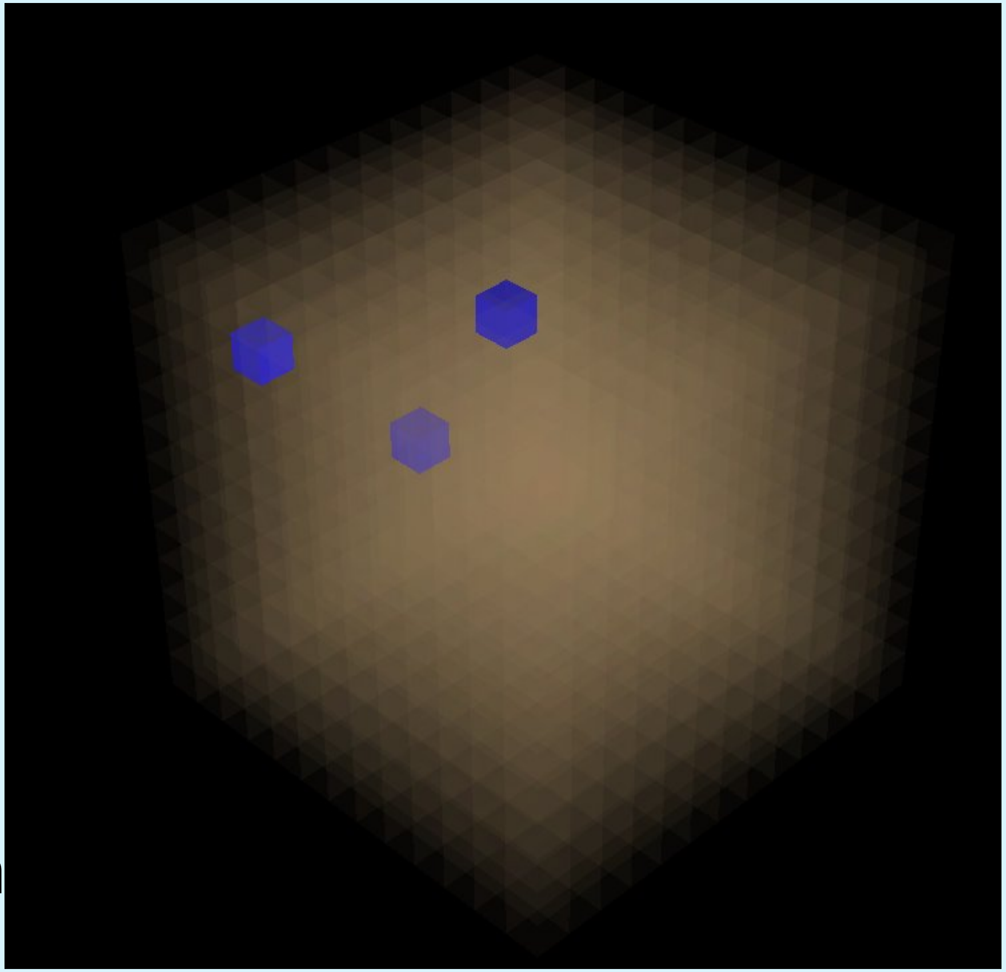
LENS-Sol / LENS-Cal Collaboration (Russia-US: 2004-)

Russia:	**INR (Moscow):**	I. Barabanov, L. Bezrukov, V. Gurentsov, V. Kornoukhov, E. Yanovich;
	IPC (Moscow):	N. Danilov, G. Kostikova, Y. Krylov
	INR (Troitsk)	I: J. Abdurashitov, V. Gavrin. et al.
		II: V. Betukhov, A. Kopylov, I. Oriachov, E.Solomontin
U. S.:	**BNL:**	R. L. Hahn, M. Yeh;
	U. N. Carolina:	A. Champagne, H. Back;
	ORNL:	J. Blackmon, C. Rascoe, A. Galindo-Uribarri, Q. Zeng;
	Princeton U. :	J. Benziger;
	SCSU:	Z. Chang;
	Virginia Tech:	C. Grieb, J. Link, M. Pitt, R.S. Raghavan, D. Rountree, R.B. Vogelaar;

Additional Slides

Signal Reconstruction

- Event localization relies on PMT hit pattern (NOT on signal timing)
- Algorithm finds best solution for event pattern to match PMT signal pattern
- System is overdetermined, hardly affected by unchannelled light
- Timing information + position ⇨ shower structure



LENS Design Figures of Merit

Cell Size [mm]	Cube size [M]	pe/ MeV	Det. Eff [%]	Nu /t In/y	Bgd /t In/y	S/N	M (In) [tons]	M (InLS) tons	PMTs
75	5	900	64	40	13	3	10	125	13300* (3”)
125	~6	950	40	26	9	2.9	15.3	190	6250* (5”)

*Pmt’s on three sides only

LENS is a feasible detector,

125t of liquid scintillator and ~13300 photomultiplier channels

for ~2000 pp-ν events in 5 years with full spectroscopic information plus ^{7}Be, pep and CNO

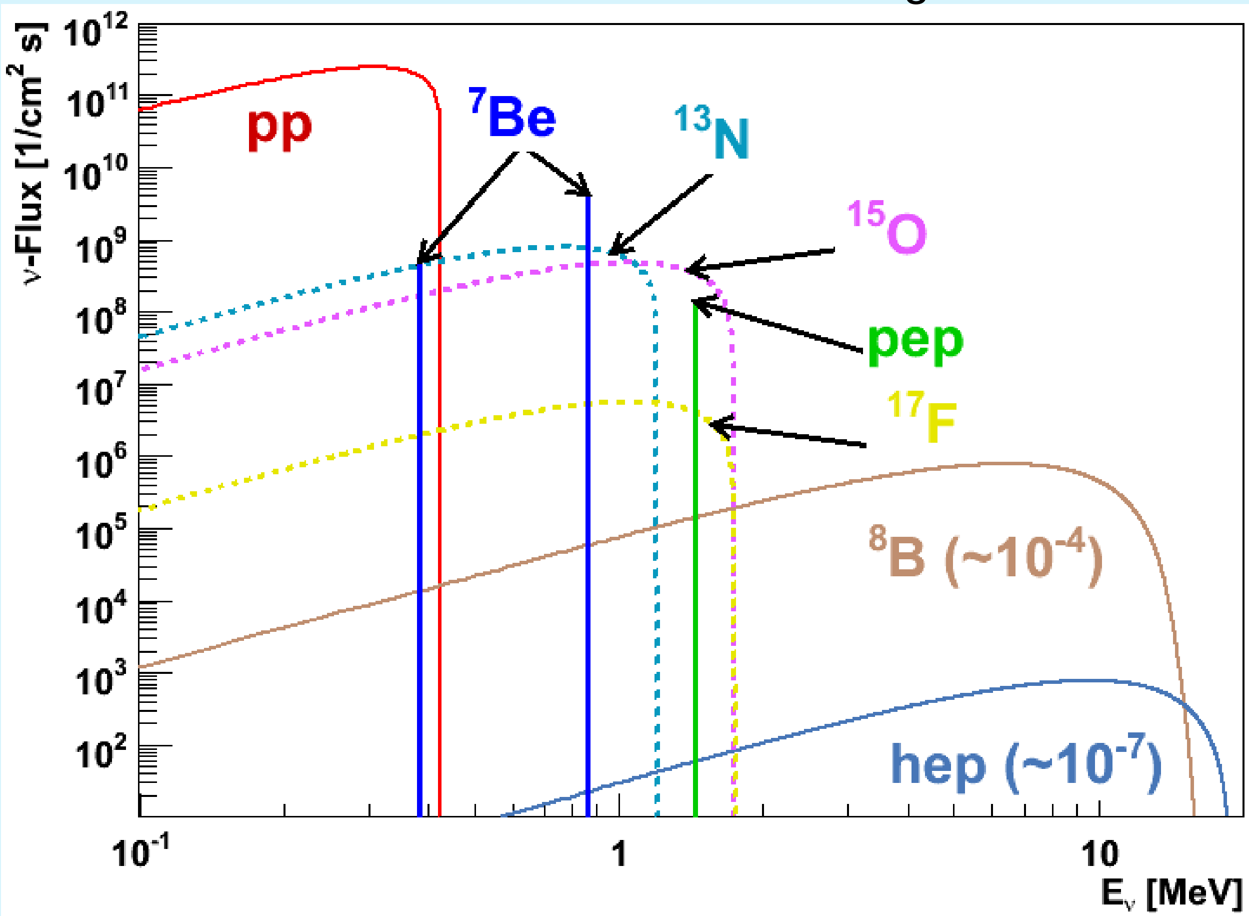
Test of Solar Models

Solar models predict relative intensities in the pp-chain

Reaction rates depend on temperature profile and abundances

Cross check with measured fluxes (using neutrino oscillation physics)

Solar Neutrino fluxes at the earth according to SSM



Data taken from John N. Bahcall, M.H. Pinsonneault, Phys.Rev.Lett.92, 121301 (2004)

Neutrino Inferred Solar Luminosity

Nuclear fusion reactions in the solar core

pp-chain
+ CNO cycle
H.A. Bethe Phys.Rev.**55,** 434 (1939)

No solar model needed

Nuclear reactions in the pp-chain:

Reaction	Number	Q (MeV)	$<q_{\nu_e}>$ (MeV)	S_0 (keV barns)	(dS/dE) (barns)	Lifetime (yr)
$^1H(p,e^+\nu_e)^2H$	1	1.442	0.265	$4.07(1 \pm 0.051) \times 10^{-22}$	4.52×10^{-24}	10^{10}
$^1H(p\ e^-,\nu_e)H$	2	1.442	1.442	[see Eq. (5), Paper I]		10^{12}
$^2H(p,\gamma)^3He$	3	5.494		2.5×10^{-4}	7.9×10^{-6}	10^{-8}
$^3He(p,e^+\nu_e)^4He$	4	19.795	9.625	8×10^{-20}		10^{12}
$^3He(^3He,2p)^4He$	5	12.860		$5.15(1 \pm 0.17) \times 10^3$	-0.9	10^5
$^3He(^4He,\gamma)^7Be$	6	1.586		$0.54(1 \pm 0.06)$	-3.1×10^{-4}	10^6
$^7Be(e^-,\nu_e)^7Li$	7	0.862 0.384	0.862 0.384	[see Eq. (9), Paper I]		10^{-1}
$^7Li(p,\alpha)^4He$	8	17.347		$52(1 \pm 0.5)$	0	10^{-5}
$^7Be(p,\gamma)^8B$	9	0.137		$0.0243(1 \pm 0.22)$	-3×10^{-5}	10^2
$^8B(e^+\nu_e)^8Be^*$ $^8Be^*(\alpha)^4He$	10	17.980	6.710			10^{-8}

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