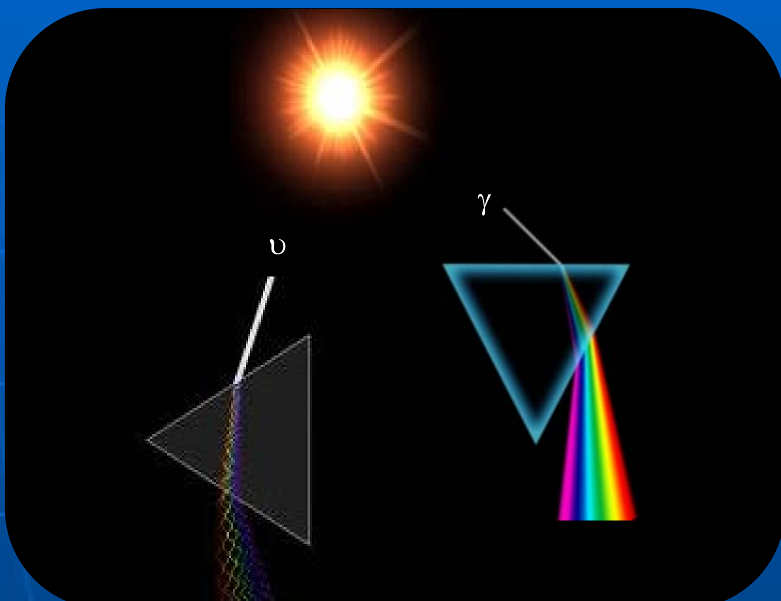
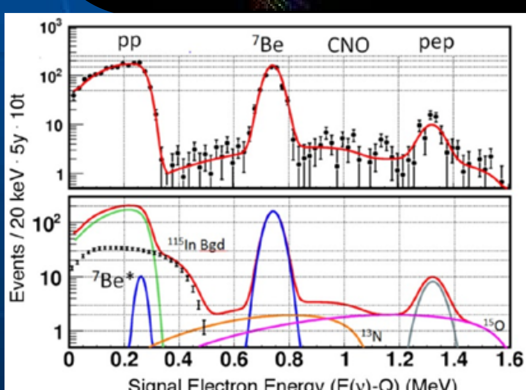
Getting at the physics still hidden in the solar neutrino spectrum





R. Bruce Vogelaar

Center for Neutrino Physics
Virginia Tech

KITP November 3, 2014

A story of productive interplay between the Standard Solar Model (SSM) and Standard Particle Model (SM) with input from Astrophysics & Cosmology & Reactors & Accelerators

- Solar Neutrinos
- Oscillations
- Getting the Parameters
- New issues?
  (CNO neutrinos?)

- Atmospheric Neutrinos
- Oscillations
- Getting the Parameters
- New issues?
  (sterile neutrinos?)

- What is underway today (Borexino)?
- Next Generation Detectors?
- Other ideas?

Just so you know, I am currently a member of

- Borexino (23 years!)
- LENS (15 years!)
- NuLat (3 months)

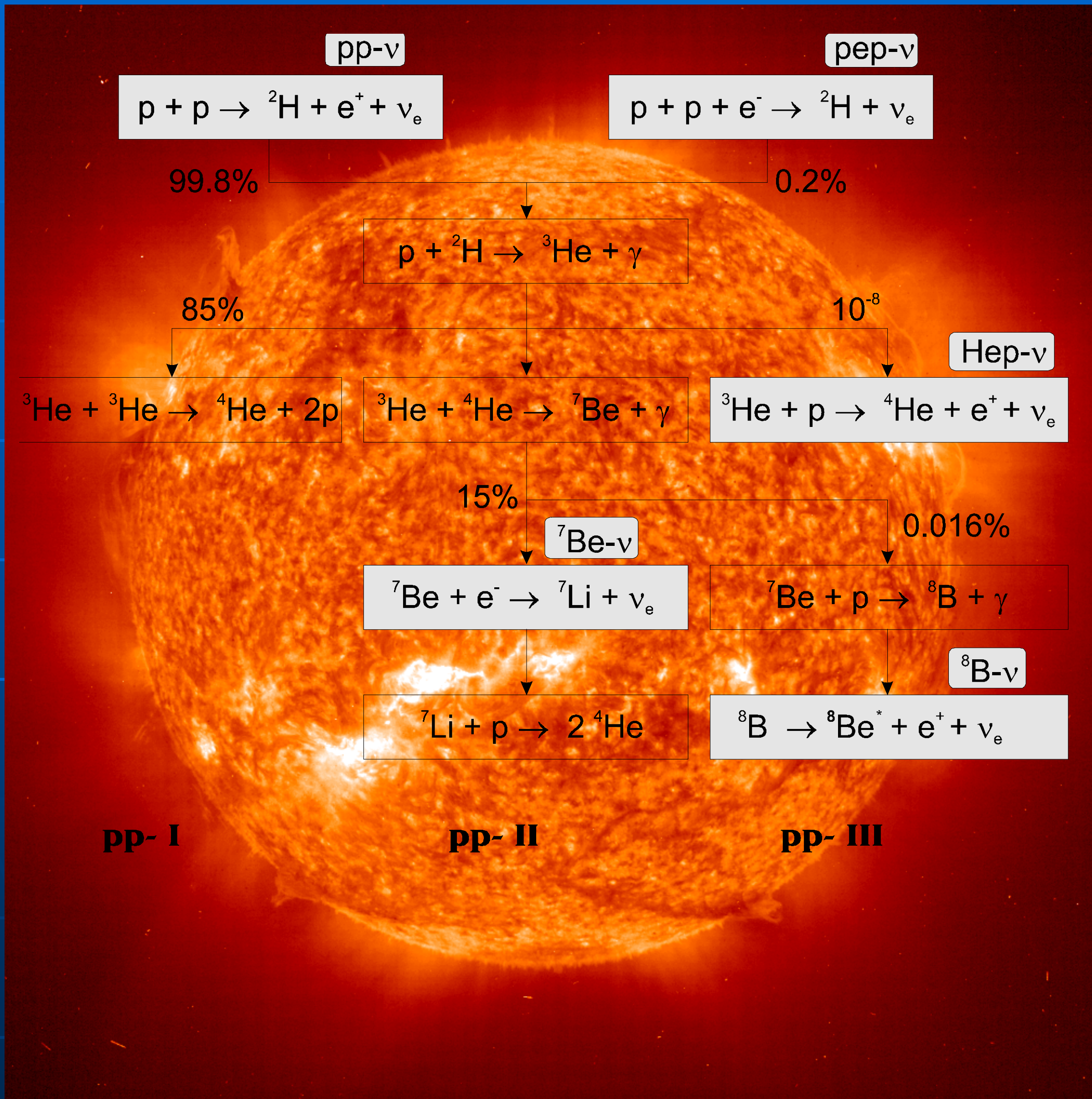
Made use of excellent summary talks by Wick Haxton &

Gabriel Orebi Gann

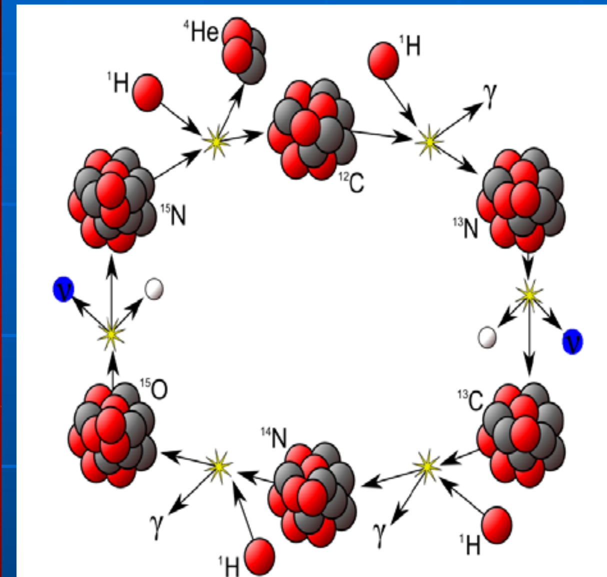
- Fundamental Symmetries, Neutrinos, Neutrons and related Nuclear Astrophysics Long-Range Plan Town Meeting
- Berkeley Solar Neutrino Workshop

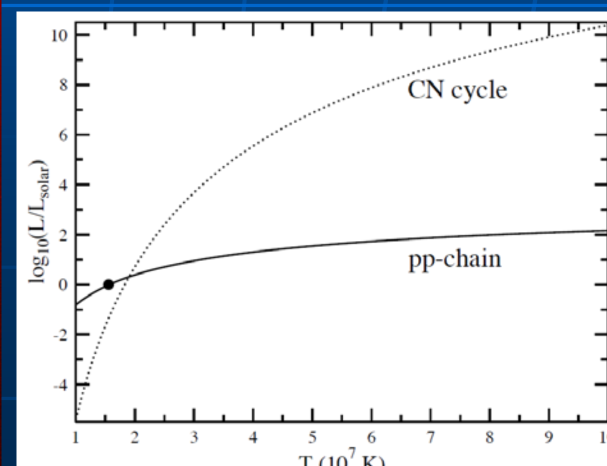
and of course, see the next talk by Aldo Serenelli (Institute of Space Sciences) Solar Models and Neutrinos: Latest Developments

$4\,{}_{1}H_{0} \rightarrow {}_{2}He_{2}\ (+2e^{+} + 2\nu_{e})$

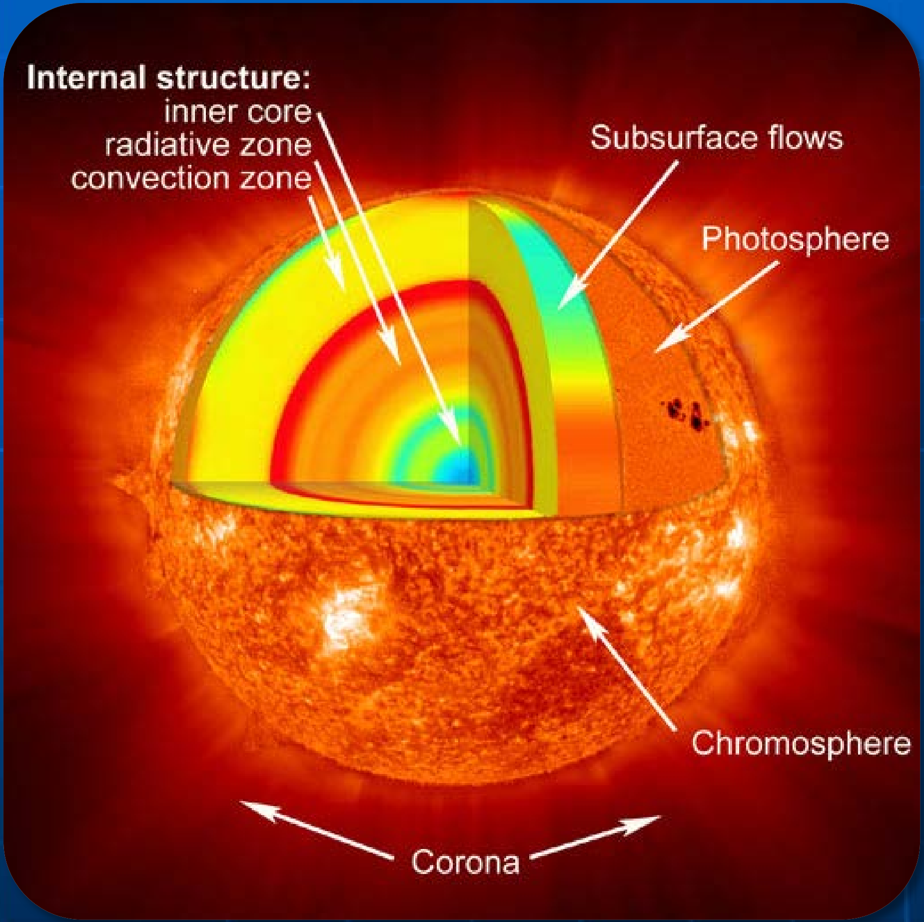


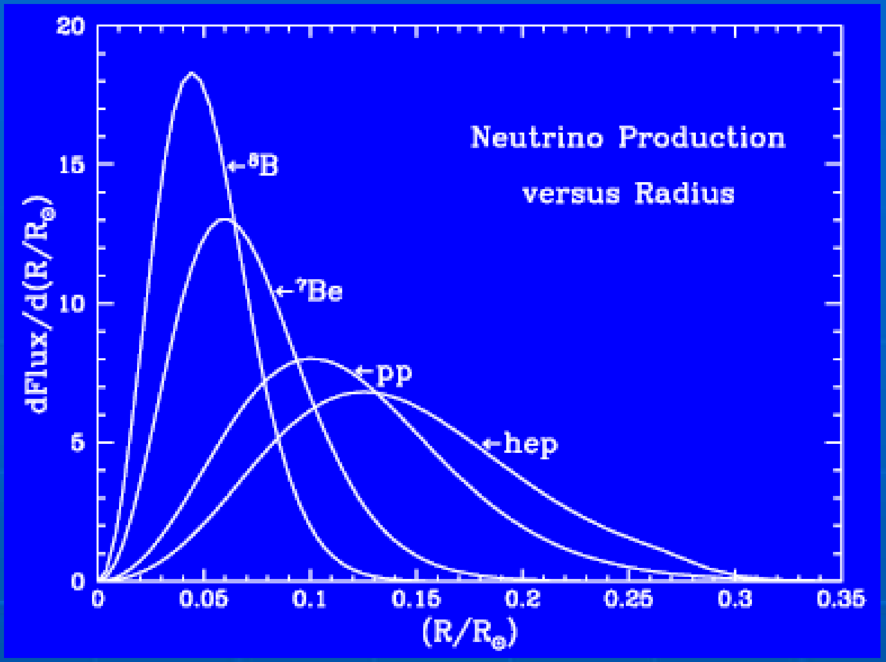
CNO chain:
^{13}N, ^{15}O, and ^{17}F neutrinos

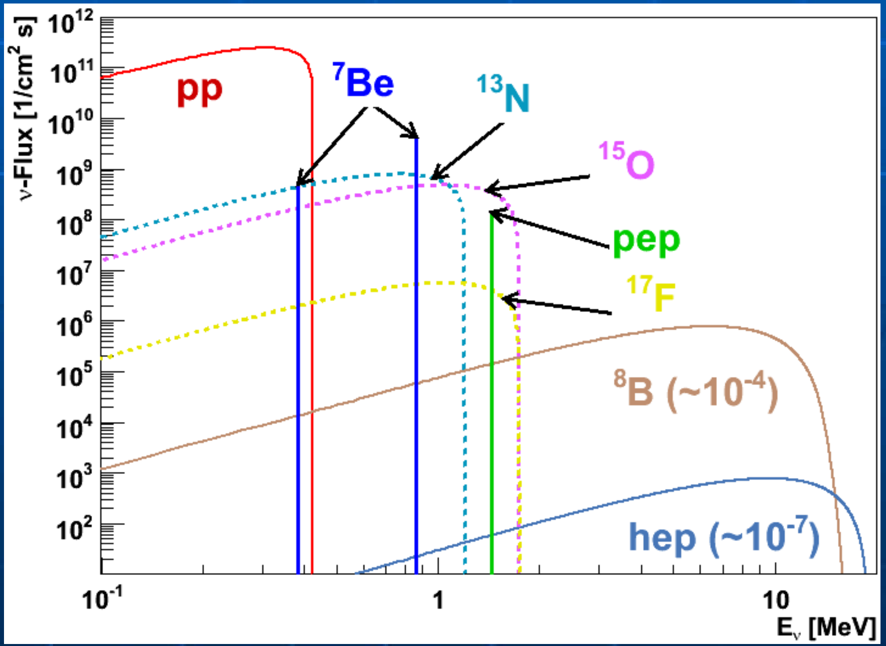


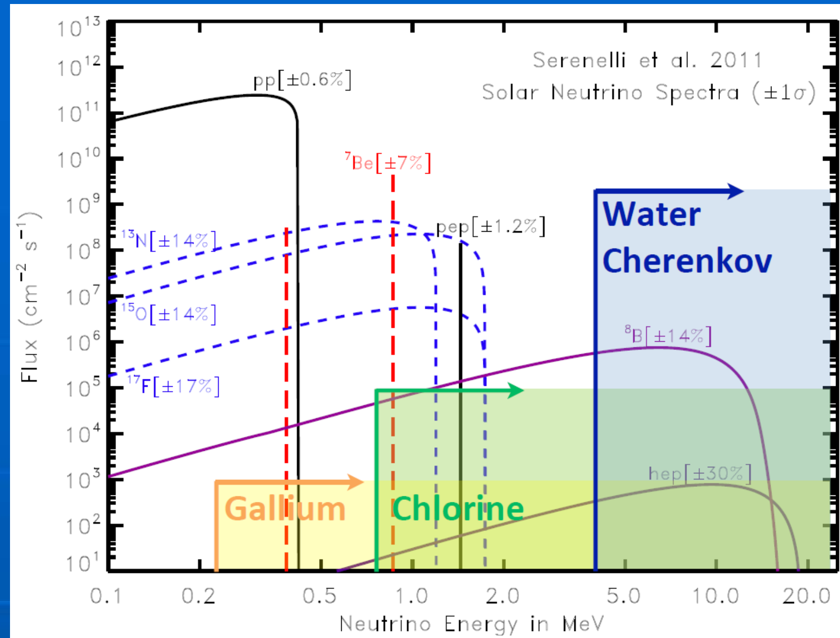


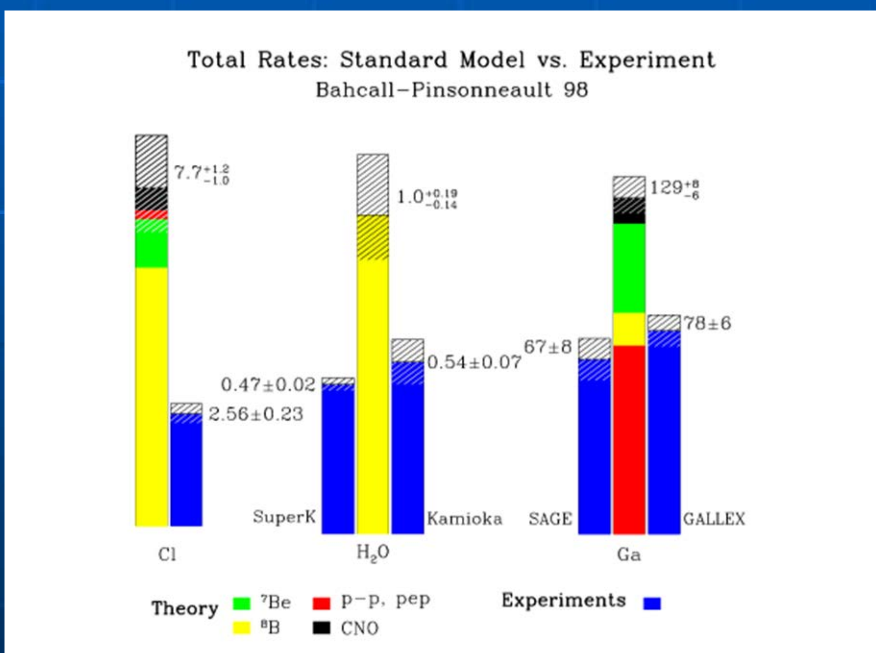
Solar Neutrinos











Vacuum Oscillation –or- “matter effect + MSW resonance”?

In free space:

$$E^2 = p^2 + m^2_{free}$$

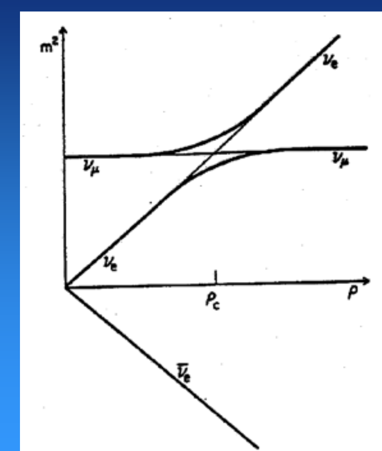
In matter, ν_e interact with e^- through the charged weak current as well as the neutral weak current.

$$V = G\sqrt{2}N_e$$

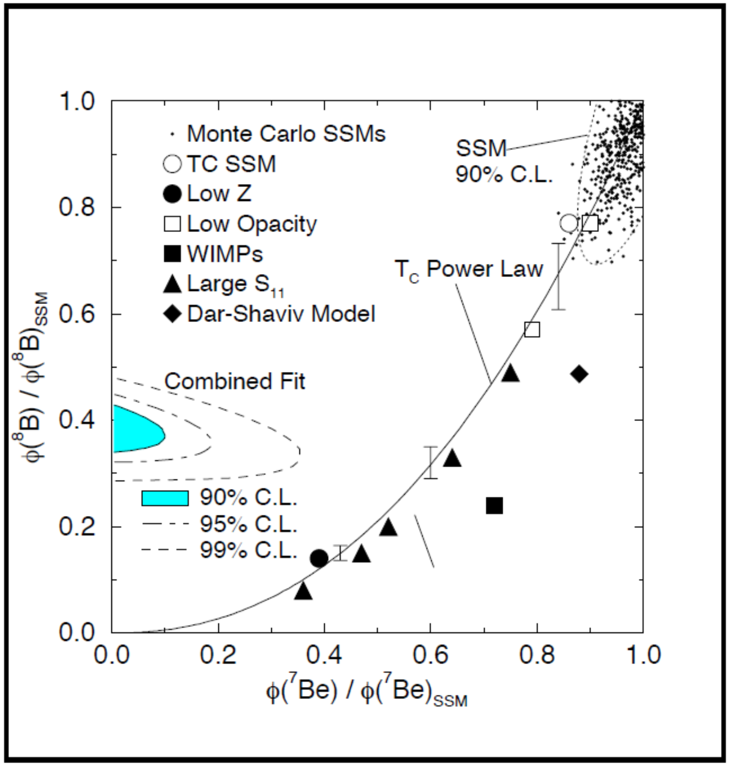
In a potential:

$$(E - V)^2 = p^2 + m^2_{free}$$

$$E^2 = p^2 + m^2_{free} + 2EV + V^2$$



Pretty Compelling Evidence for Oscillations



Hata et al.

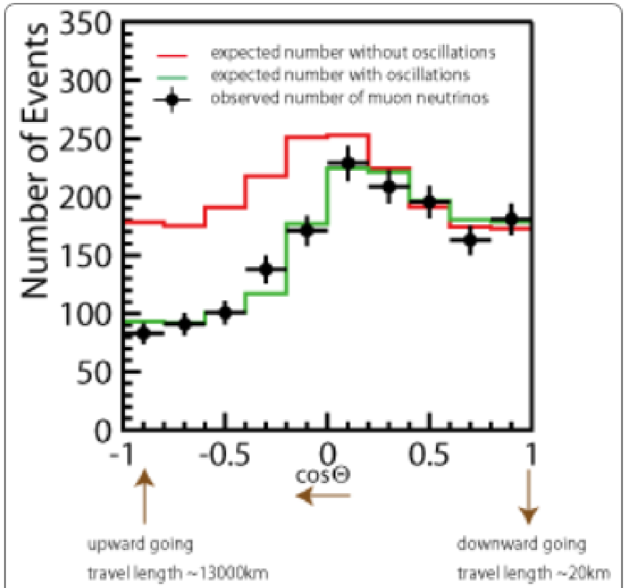
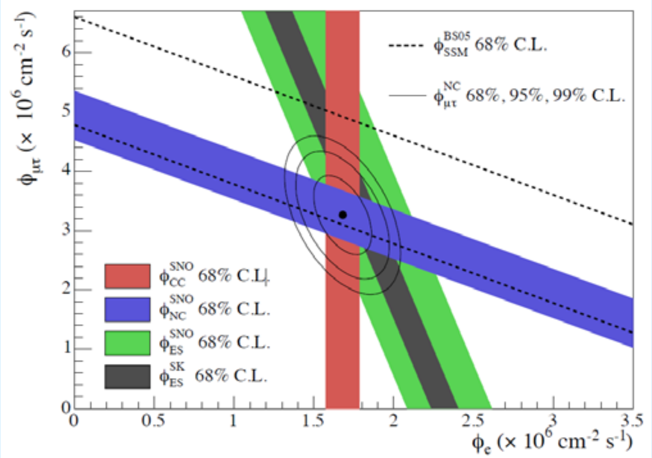


Figure 12: typical zenith angle distribution, from Super-K. The amount by which the data fall short of the expectation (red line) increases as the distance travelled increases.

Explanations and Parameters

θ_{12}

SNO
KamLAND (LMA)



Borexino

Be-7
pep
pp
CNO – tough

pretty much what was expected

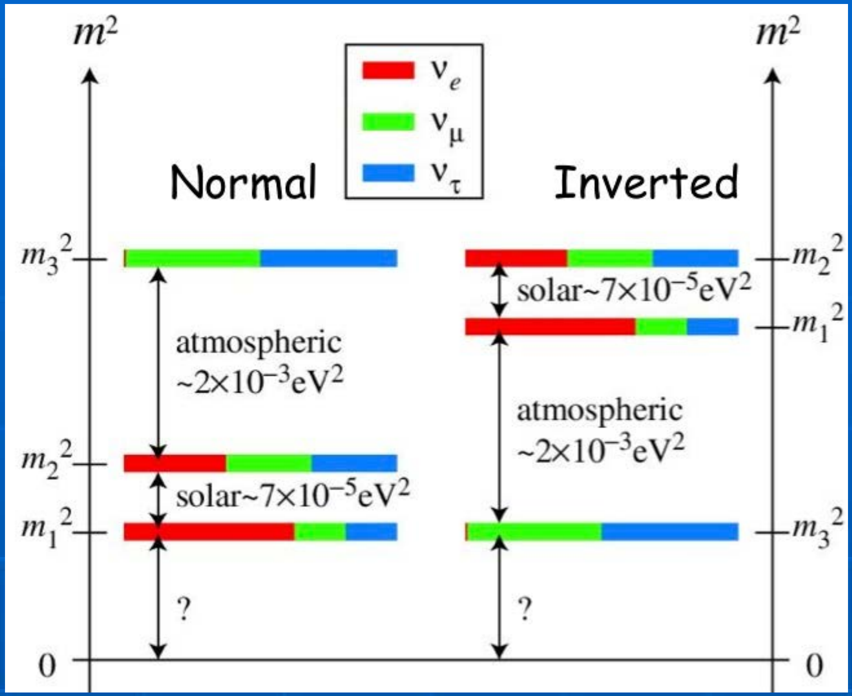
θ_{23}

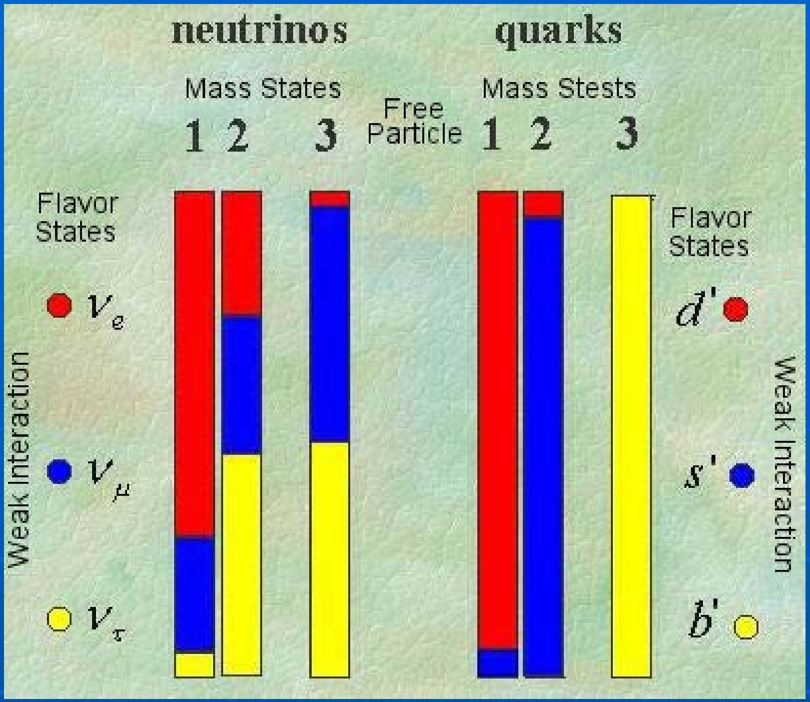
SuperK
K2K
Minos

θ_{13}

Daya Bay
Double Chooz
Reno

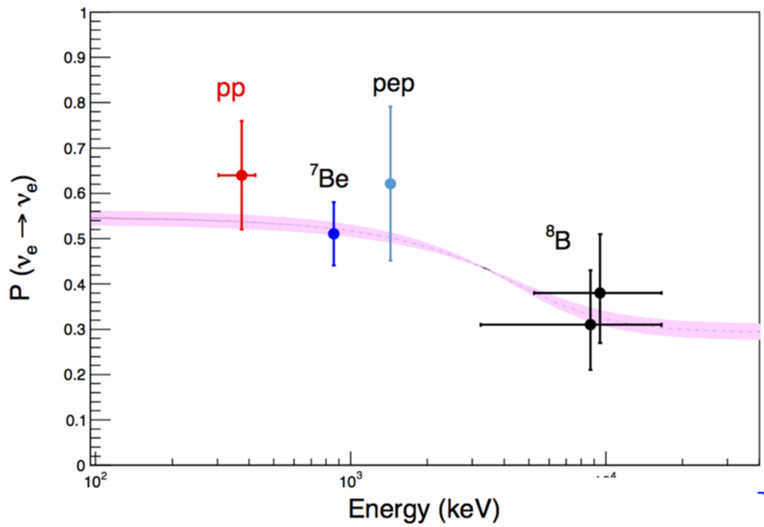
fortuitously large enough to allow looking for δ_{CP} but otherwise not surprising





- $\sin^2(2\theta_{13}) = 0.092 \pm 0.017$[15]
- $\tan^2(\theta_{12}) = 0.457\ ^{+0.040}_{-0.029}$. This corresponds to $\theta_{12} \equiv \theta_{sol} = 34.06\ ^{+1.16}_{-0.84}{}^\circ$ ("sol" stands for solar)[16]
- $\sin^2(2\theta_{23}) > 0.92$ at 90% confidence level, corresponding to $\theta_{23} \equiv \theta_{atm} = 45 \pm 7.1^\circ$ ("atm" stands for atmospheric)[16]
- $\Delta m^2_{21} \equiv \Delta m^2_{sol} = 7.59\ ^{+0.20}_{-0.21} \times 10^{-5}\ \mathrm{eV}^2$[16]
- $|\Delta m^2_{31}| \approx |\Delta m^2_{32}| \equiv \Delta m^2_{atm} = 2.43\ ^{+0.13}_{-0.13} \times 10^{-3}\ \mathrm{eV}^2$[16]
- δ, α_1, α_2, and the sign of Δm^2_{32} are currently unknown

RESEARCH ARTICLE

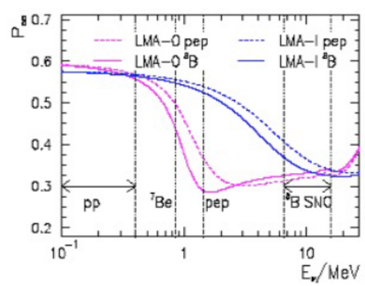


Extended Data Figure 2 | Survival probability of electron-neutrinos produced by the different nuclear reactions in the Sun. All the numbers are from Borexino (this paper for *pp*, ref. 17 for ^{7}Be, ref. 18 for *pep* and ref. 19 for ^{8}B with two different thresholds at 3 and 5 MeV). ^{7}Be and *pep* neutrinos are mono-energetic. *pp* and ^{8}B are emitted with a continuum of energy, and the reported $P(\nu_e \to \nu_e)$ value refers to the energy range contributing to the measurement. T the MSW-LMA considering the other componen represent the ± energy range us

Probing the Unknown

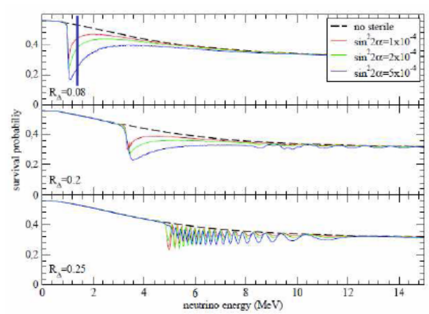
Non-standard physics effects can alter the shape / position of the "MSW rise"

Non-standard interactions (flavour changing NC)



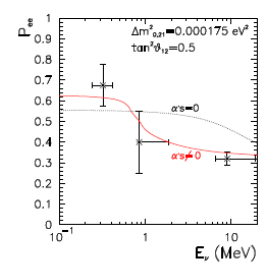
Friedland, Lunardini, Peña-Garay, PLB 594, (2004)

Sterile Neutrinos



Holanda & Smirnov PRD 83 (2011) 113011

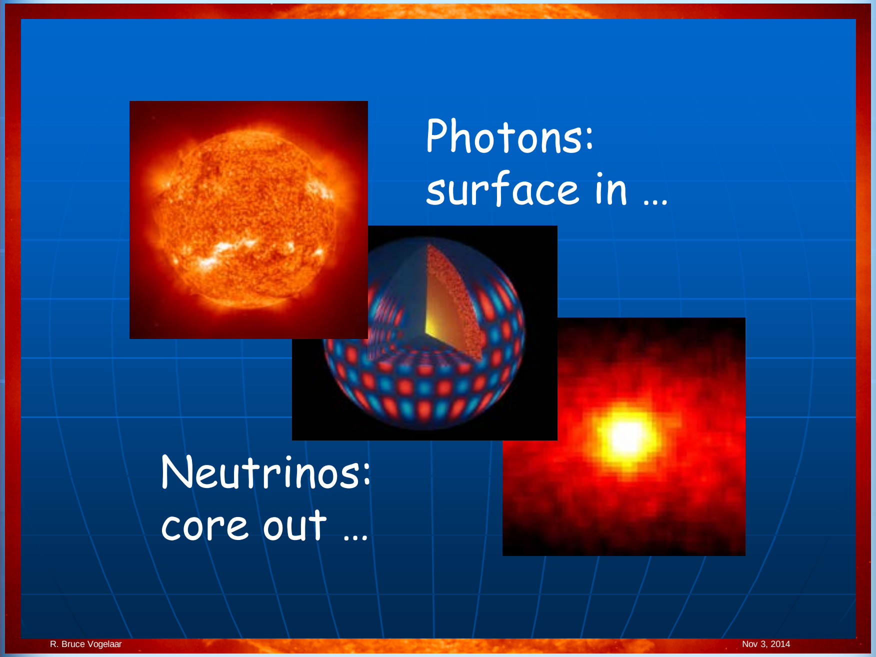
Mass varying neutrinos (MaVaNs)



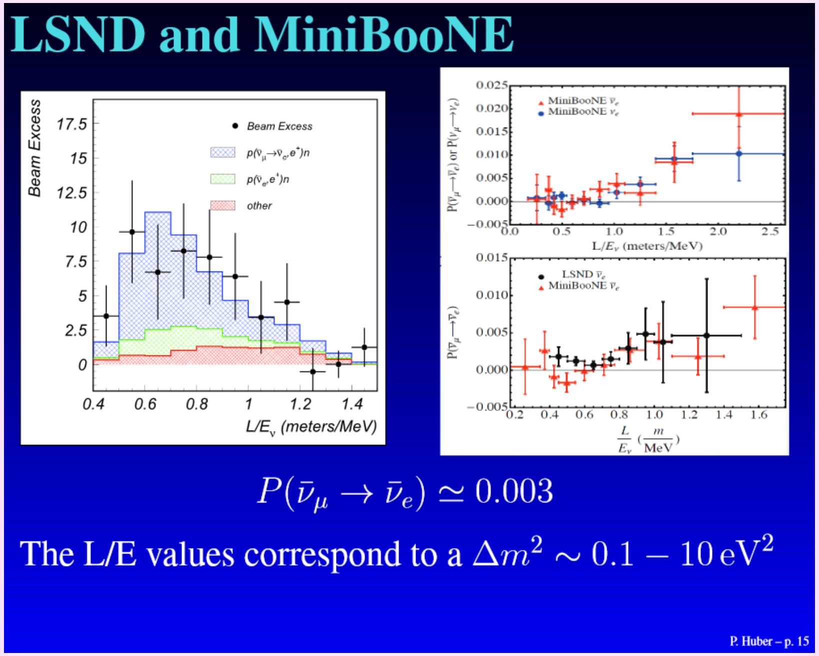
M.C. Gonzalez-Garcia, M. Maltoni Phys Rept 460:1-129 (2008)

But there are some new issues…

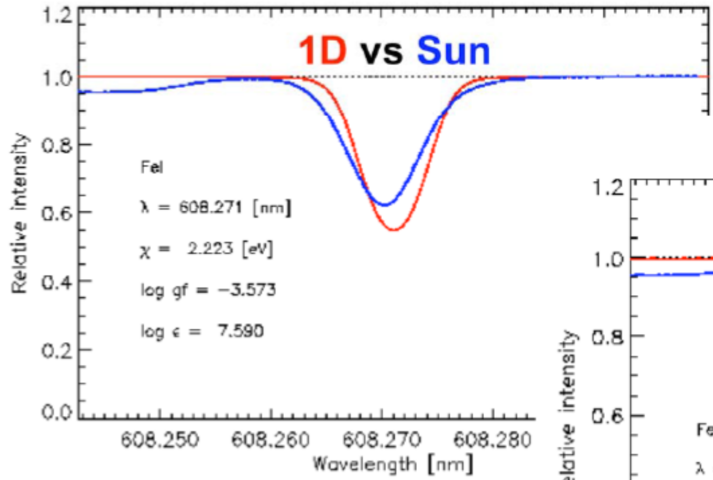
Solar metallicity
Helioseismology



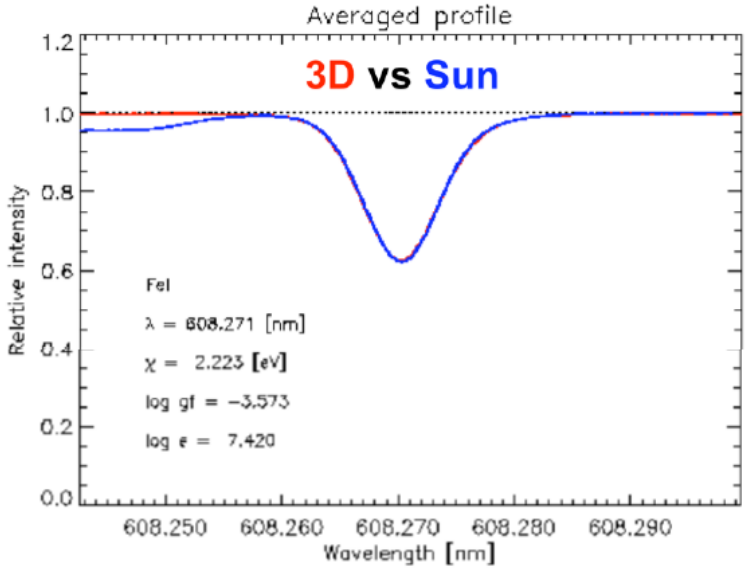
LSND
Reactor Anti-neutrino Anomaly



Solar metallicity
Helioseismology

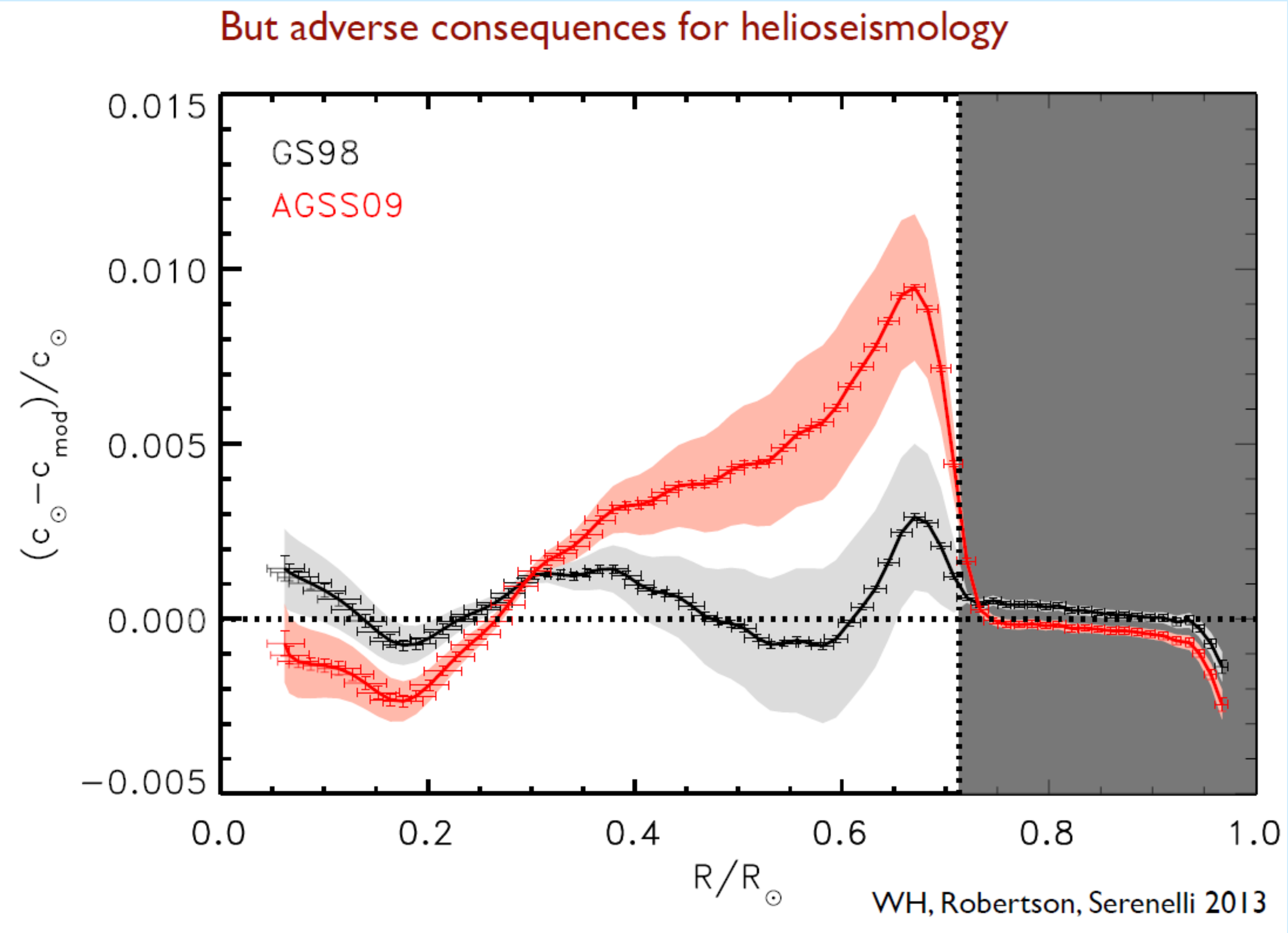


Averaged line profiles (from Asplund 2007)



- ❑ Spread in abundances from different C, O lines sources reduced from ~ 40% to 10%
- ❑ But abundances significantly reduced Z: 0.0169 ⇒ 0.0122
- ❑ Makes sun more consistent with similar stars in local neighborhood
- ❑ Lowers SSM ^{8}B flux by 20%

Solar metallicity
Helioseismology



Solar metallicity
Helioseismology

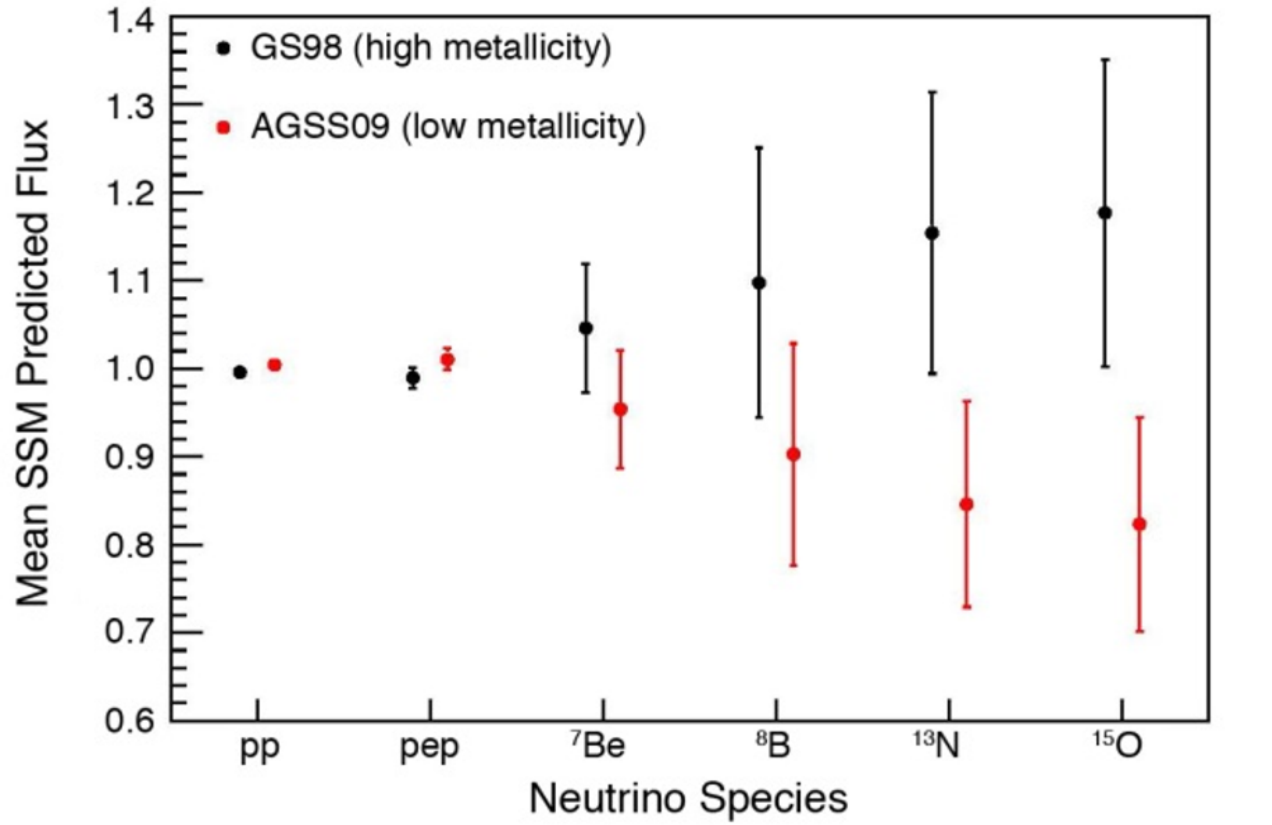
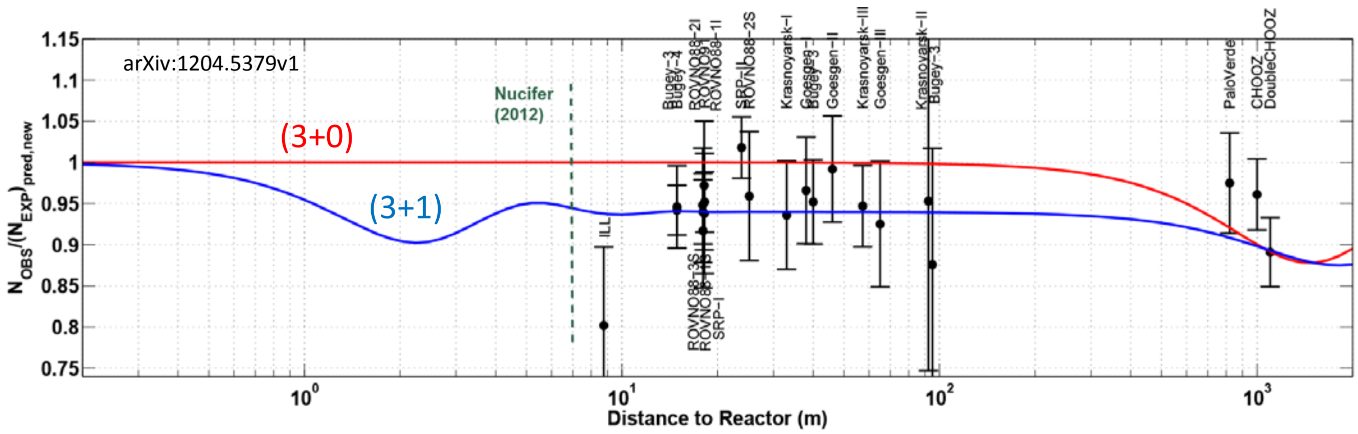


Figure 3 : Comparison of predicted solar ν fluxes under the two abundance assumptions (from Ref. [Sal12]).

LSND

Reactor Anti-neutrino Anomaly (and strange 5 MeV bump…)



- **Gallium anomaly (2.8σ)**
  Calibration runs with radioactive neutrino sources at solar radiochemical experiments Gallex/SAGE
  → deficit in the detected ν_e rate: R = 0.76 ± 0.09
- **Reactor antineutrino anomaly (~2.5σ)**
  re-evaluation of reactor neutrino spectra results
  → rate deficit in all short-baseline (L=10-100m) reactor neutrino experiments: R = 0.927 ± 0.23

Borexino is still running…

INFN

Milano

München

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK
Heidelberg

Hamburg

Mainz

Gran Sasso

Perugia

Genova

Napoli

TU Dresden

Jagiellonian Kraków

the Borexino Collaboration

JINR Dubna

Virginia Tech

Houston

Paris

SINP MSU
Moscow

Los Angeles

Princeton

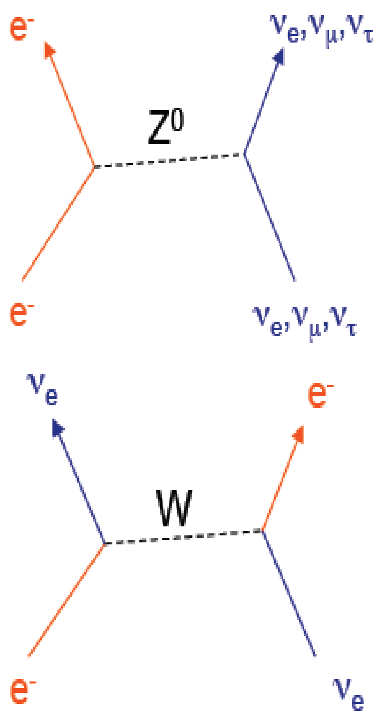
UMass Amherst

St. Petersburg

Kurchatov Moscow

Detection principle

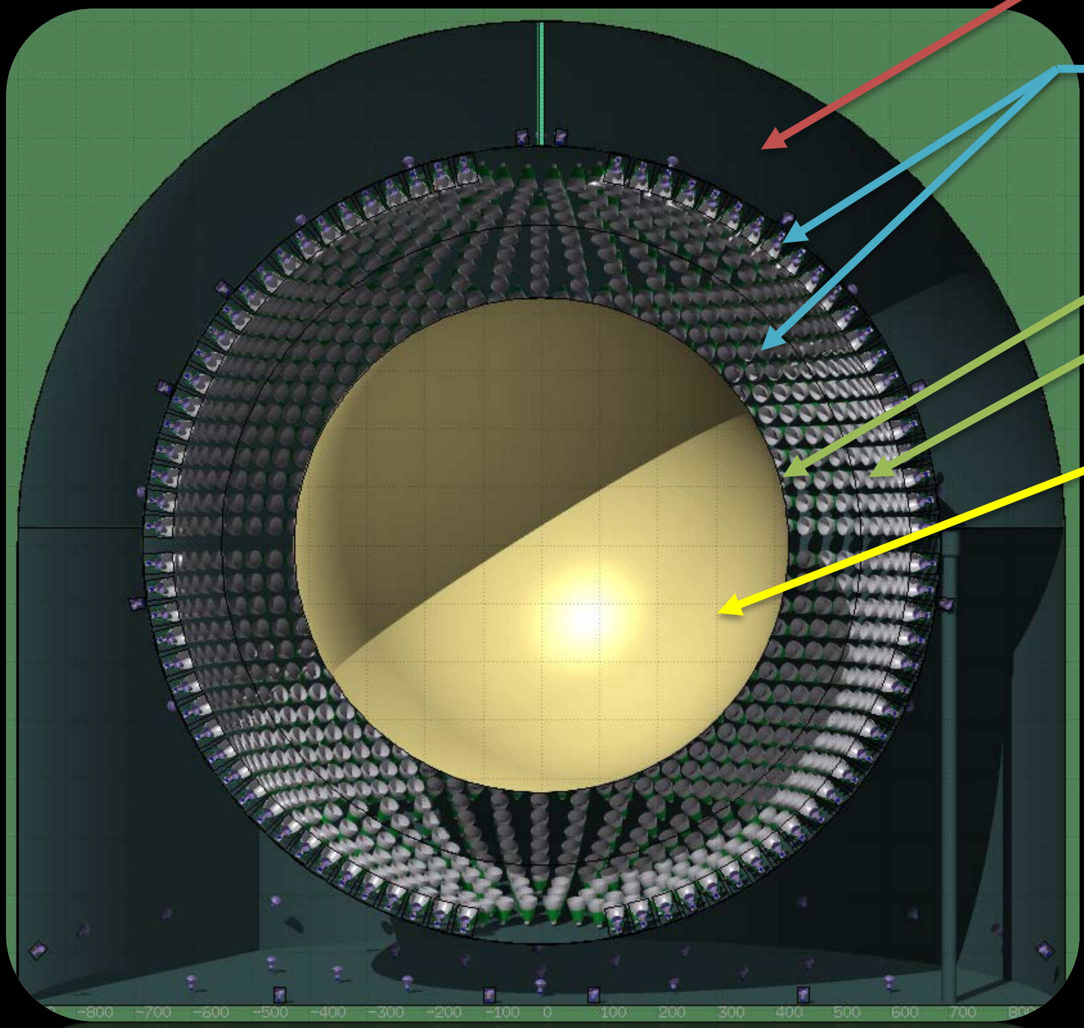
- Neutrino elastic scattering on electrons of liquid scintillator: **$e^- + \nu \rightarrow e^- + \nu$;**
- Scattered electrons cause the scintillation light production;
- **<u>Advantages</u>**:
  - Low energy threshold (~ 0.2 MeV);
  - High light yield and a good energy resolution;
  - Good position reconstruction;
- **<u>Drawbacks :</u>**
  - Info about the ν directionality is lost ;
  - ν-induced events can't be distinguished from the events of β/γ natural radioactivity;



Extreme radiopurity is a must for a precision low energy neutrino spectroscopy!!!

- Rn in Borexino ~ 1×10^{-10} Bq/kg
- Rn in air ~ 10 Bq/kg

BOREXINO detector



External water tank

γ and n shield, μ water Čerenkov d.

208 PMT in water V = 2100 m^3

Stainless Steel Sphere:

2212 PMT + light concentrators

V =1350 m^3

Nylon vessels (150 μm)

Internal: 4.25 m

Outer: 5.50 m

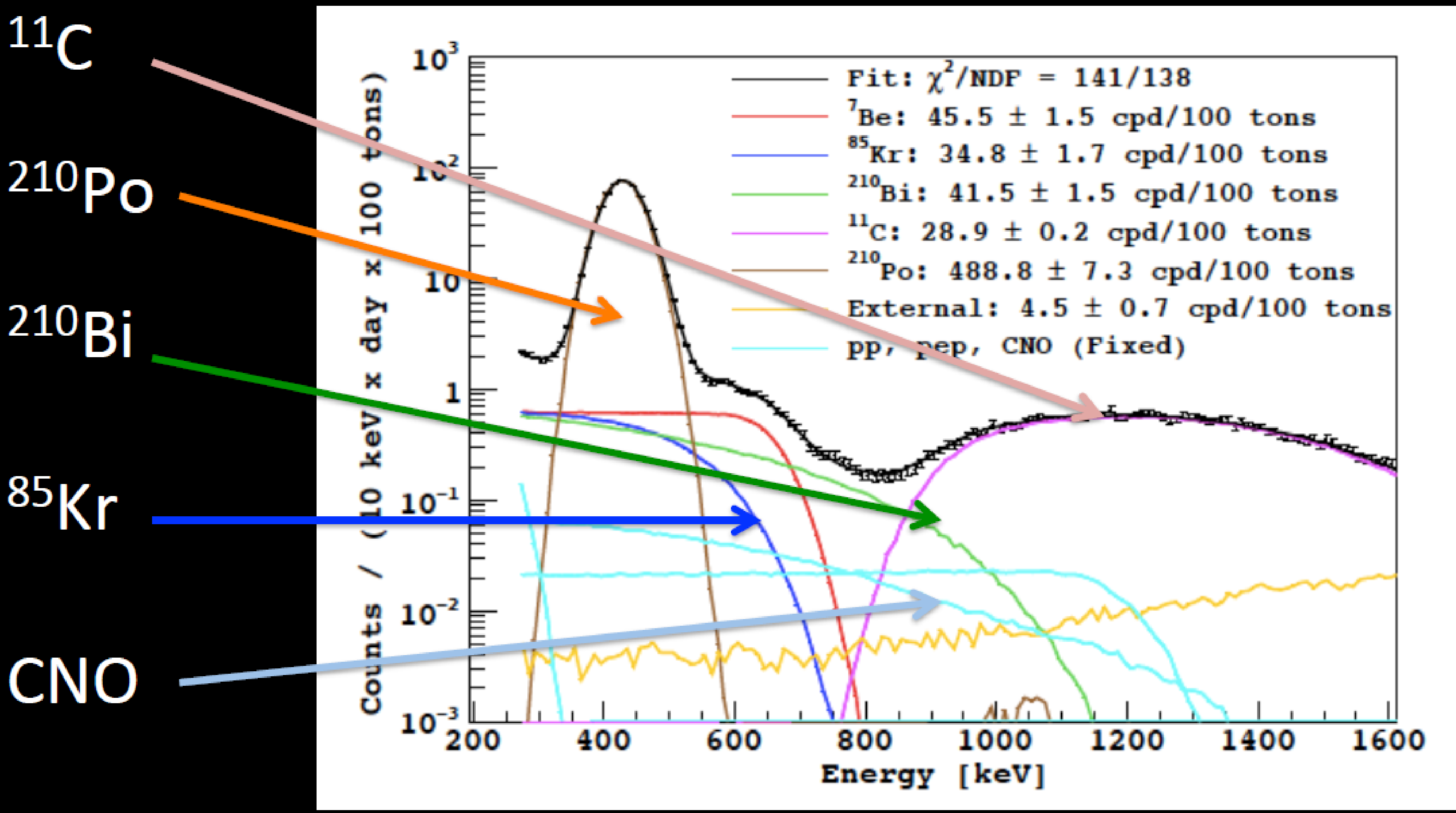
Scintillator:

300 t PC+PPO

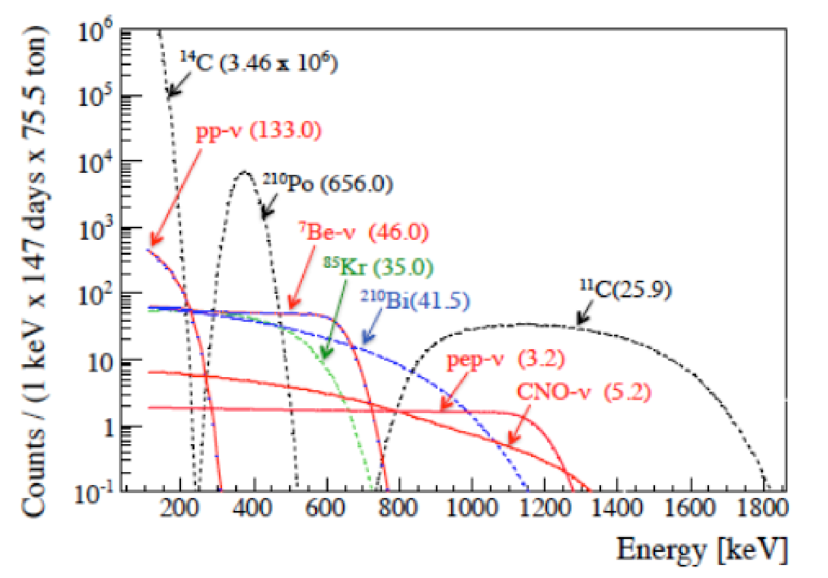
Extreme radio-purity

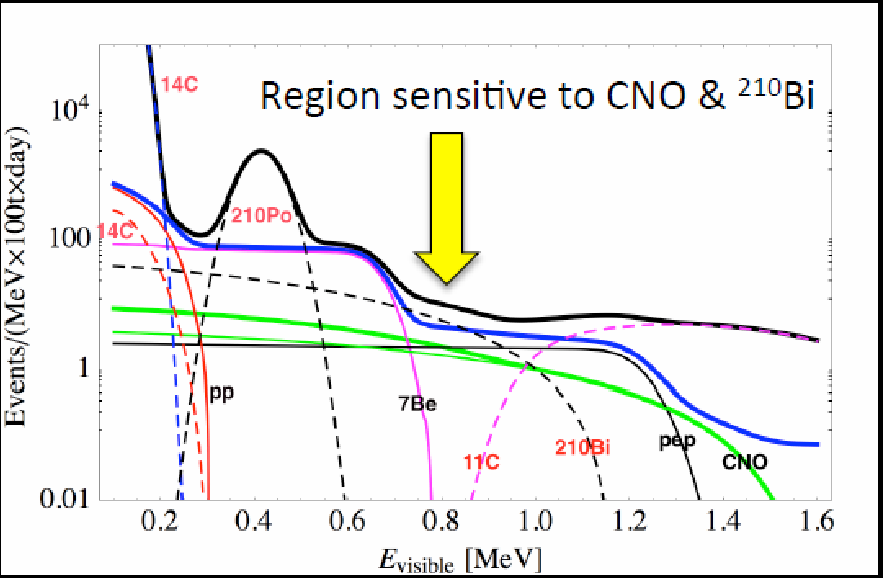
The characteristic onion like structure of the detector, with fluid volumes of increasing radiological purity towards the center of the detector.

Energy spectrum with backgrounds



Backgrounds before & after Water Extraction + N_2 Stripping

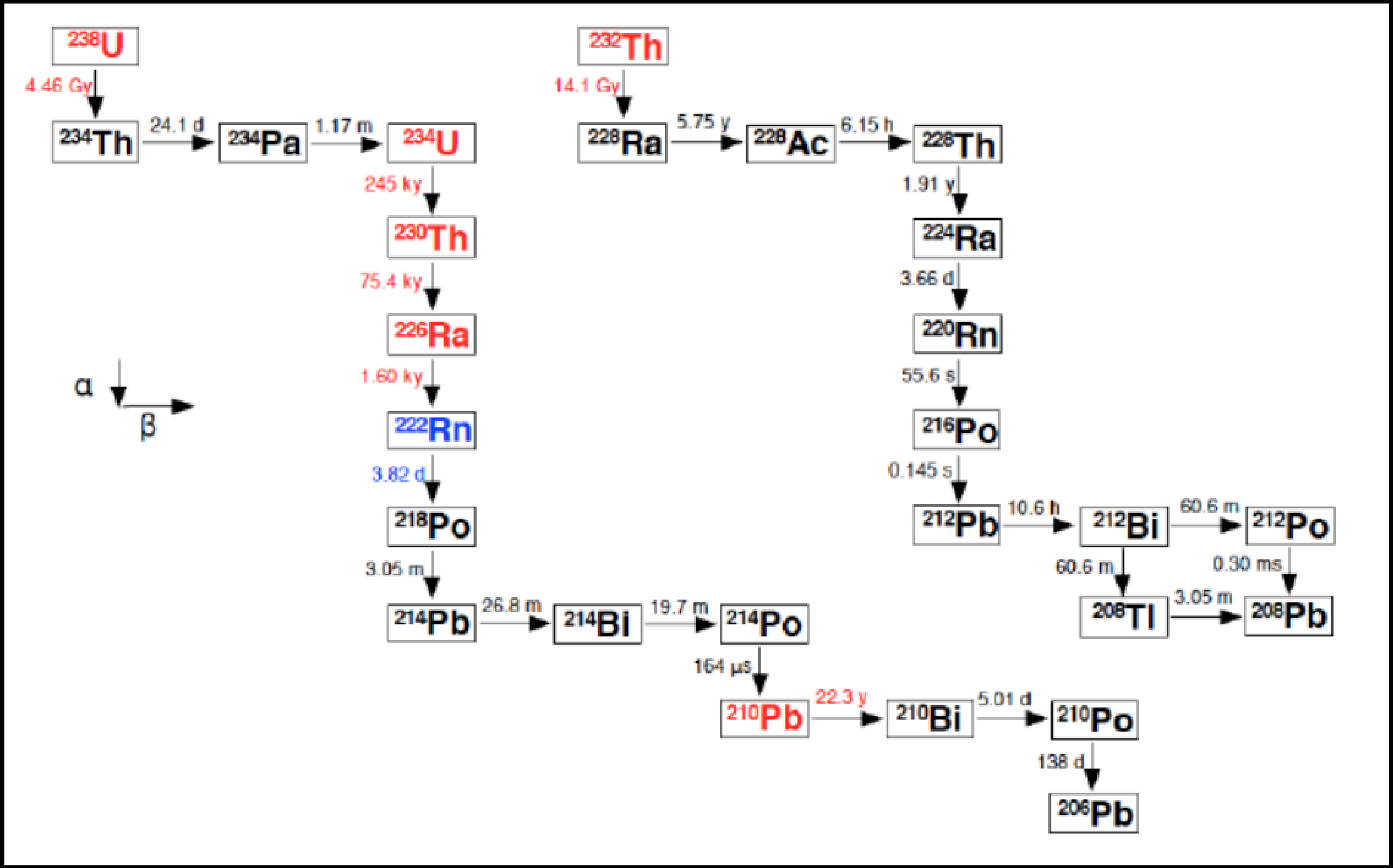




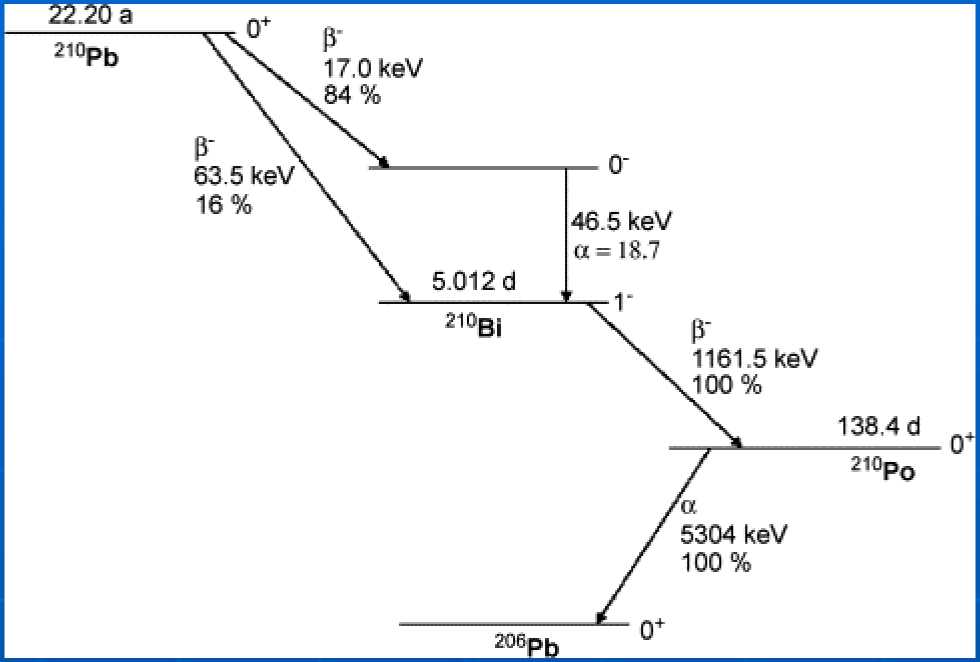
Before re-purification 2008-2010
Rates in parentheses are in cpd/100t.
Without ^{11}C cuts. See arXiv1308.0443v1.

After re-purification 2012-2013
(with ^{11}C cuts)

The ^{238}U and ^{232}Th Decay Chains



Radon in air deposits ^{210}Pb (22 yr) on nylon foil, which later contaminates scintillator with ^{210}Bi (1 MeV β) and ^{210}Po (5 MeV α).



^{210}Pb is 'invisible' to us

CNO rate (cpd/100t):
– High metallicity: 4.5
– Low metallicity: 3.0

Conjecture...

3 years of data we already have could allow first measurement of CNO ***IF*** we could determined the ^{210}Bi... (currently about 20 cts/100t/d)

Need to keep convective currents from mixing into fiducial volume on time-scales of over tens of days to get measurement.

This is HARD in practice with large open volumes.

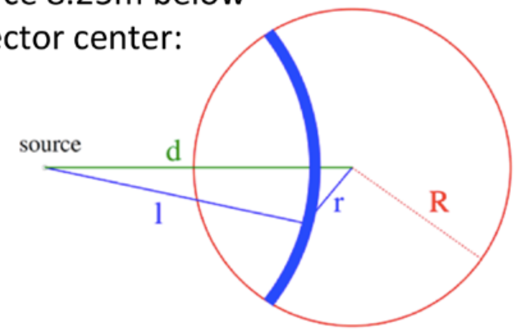
With purification, we should be able to get the ^{210}Pb down first.

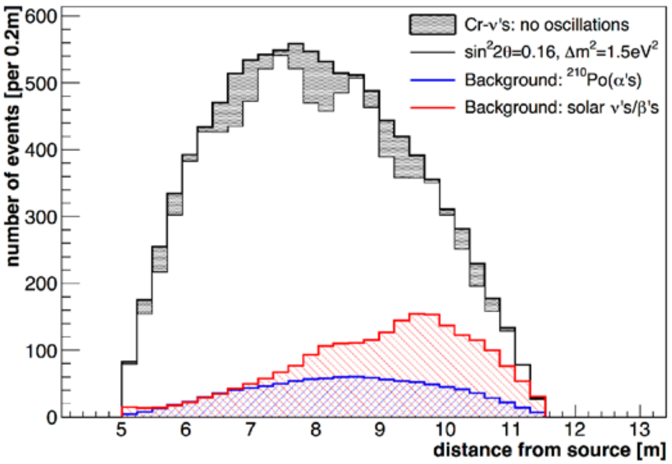
We are tantalizingly close.....

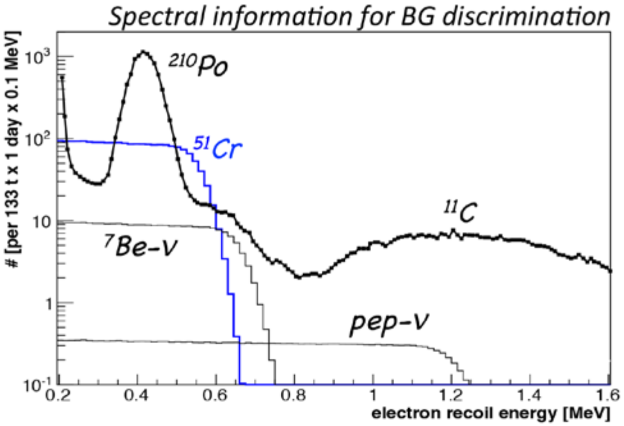
The reality of ‘multi-tasking’ at Borexino…

Expected signal for CrSOX

Source 8.25m below detector center:







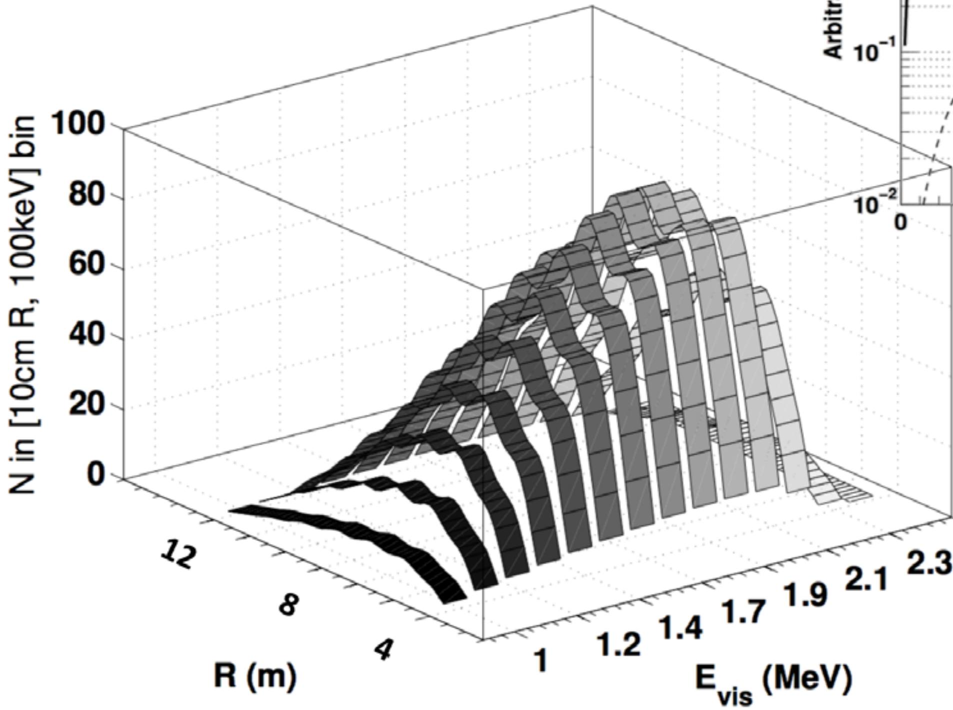
Expected distance distribution:

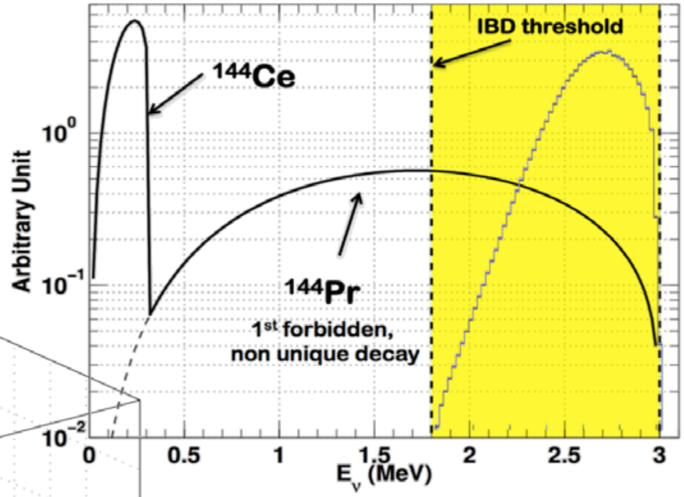
- geometry x $1/r^2$ dependent flux
- oscillations shown for best-fit values → waves discernible
- spatial resolution: ~20 cm

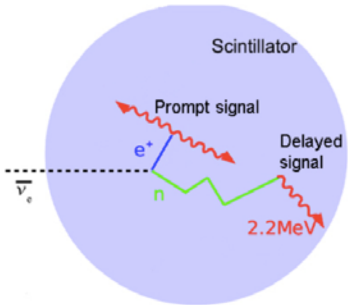
Expected signal for CeSOX

Extended energy spectrum

→ distance + energy dependence of oscillation pattern is observed



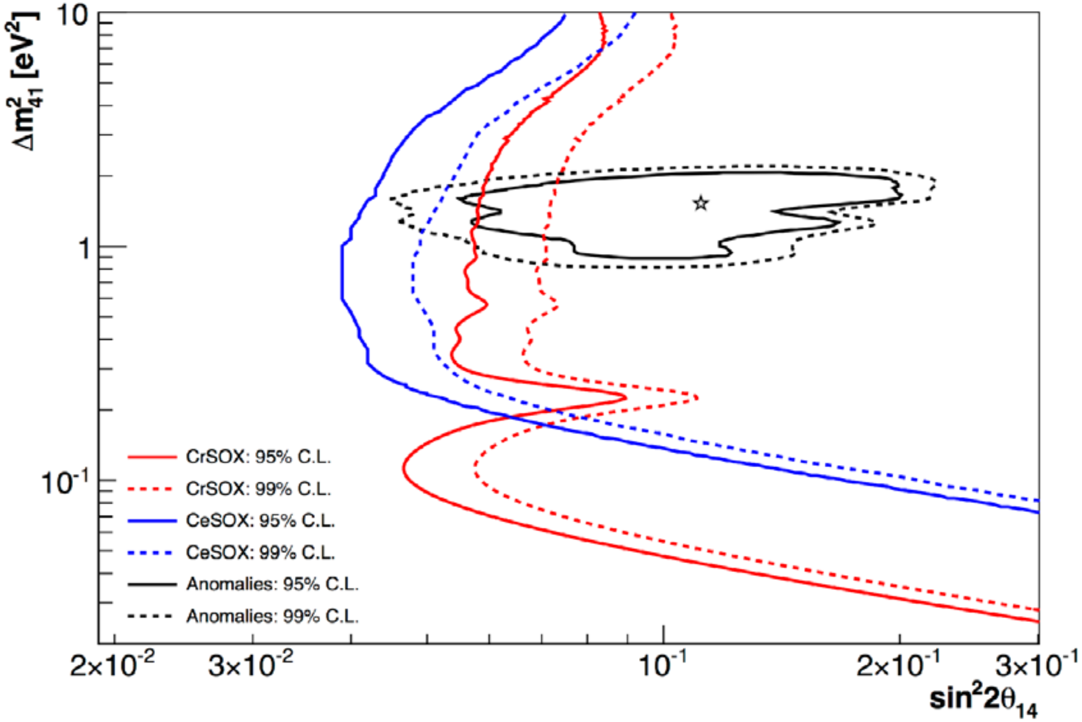




IBD coincidence signature

→ almost background-free

Sensitvity of CrSOX/CeSOX



CrSOX

Activity: 10 MCi

Fiducial radius: 3.3 m

1% source error

1% FV error

1% background error

CeSOX

Activity: 100 kCi

Fiducial radius: 4 m

1% source error

1% FV error

no relevant background

→ SOX could discover/exclude best fit value at >5σ

→ 95% C.L. region of anomalies can be covered

Precision and/or Mult-task Detectors

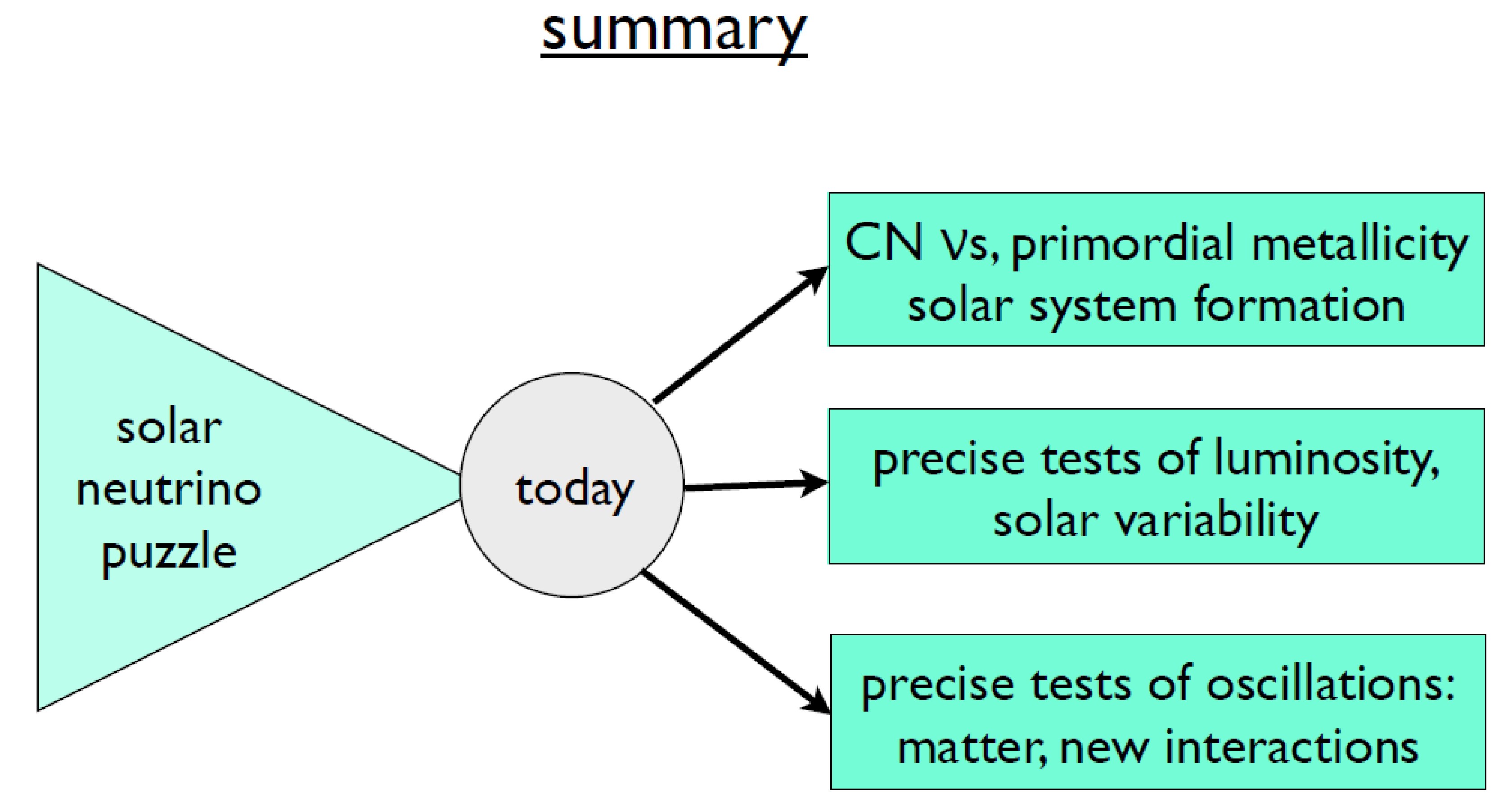
SNO+
JinPing
JUNO
Cryogenic
CC hybrid
CC scintillator

Luminosity
CNO
Transition Region
also

Dark matter
Proton Decay
Geoneutrinos
SN monitoring
etc...

yet funding and time-scales remain daunting….

Wick Haxton captured it this way:



Gabriel Orebi Gann captured it this way:

Physics Beyond the SNP

(1) Searching for new physics:

ν_e survival probability shape

(2) Understanding stellar formation:

The metallicity of the Sun's core

(3) Confirming MSW:

The Day / Night effect

(4) Probing energy loss/generation mechanisms:

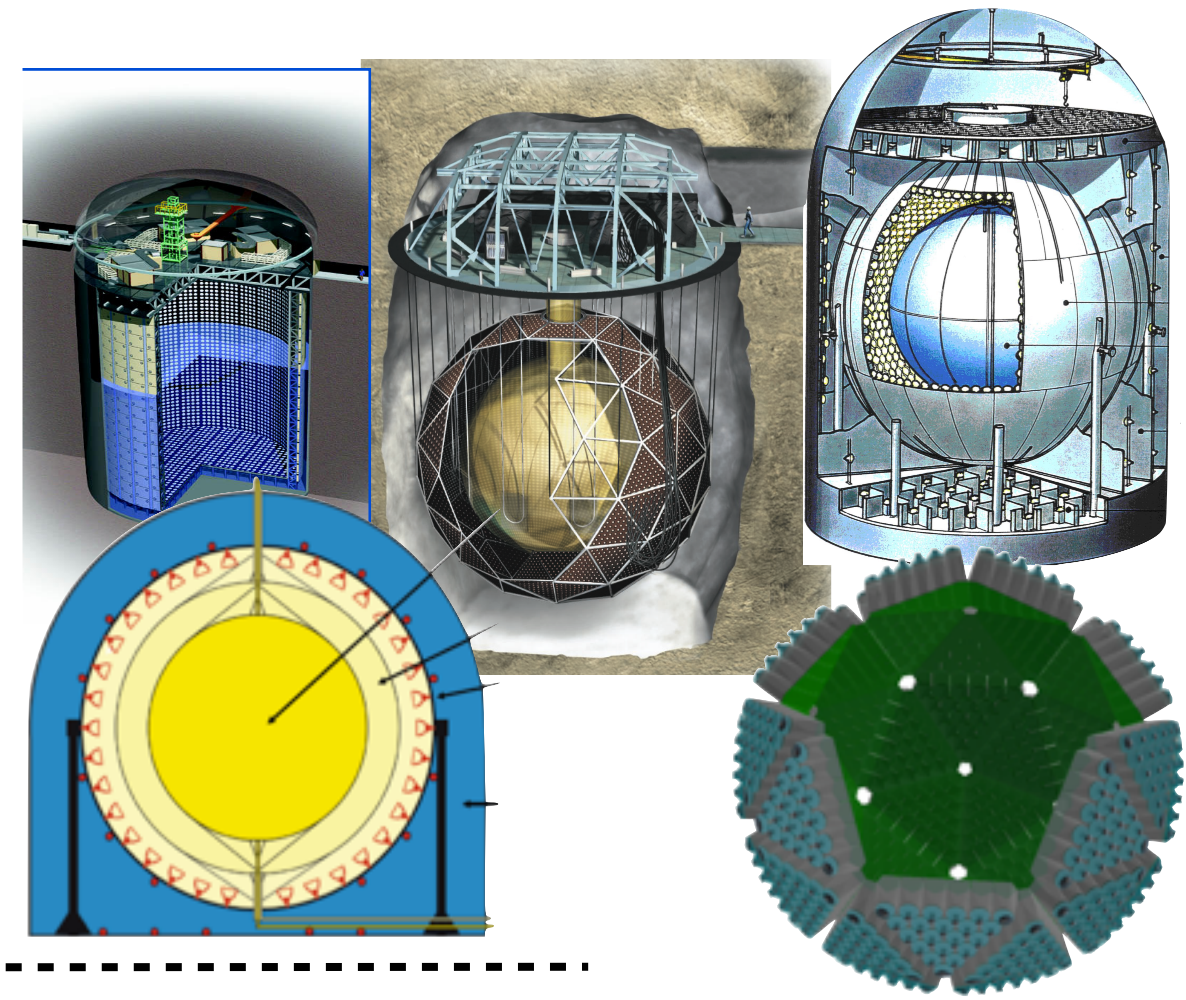
Neutrino luminosity ($\mathcal{L}_\nu$)

(5) Searching for symmetry:

Precision flux & oscillation parameter measurements

Experimental Program

- Elastic Scattering detection
  - Large-scale water Cherenkov
  - Large-scale liquid scintillator
  - Inorganic scintillator



Experimental Program

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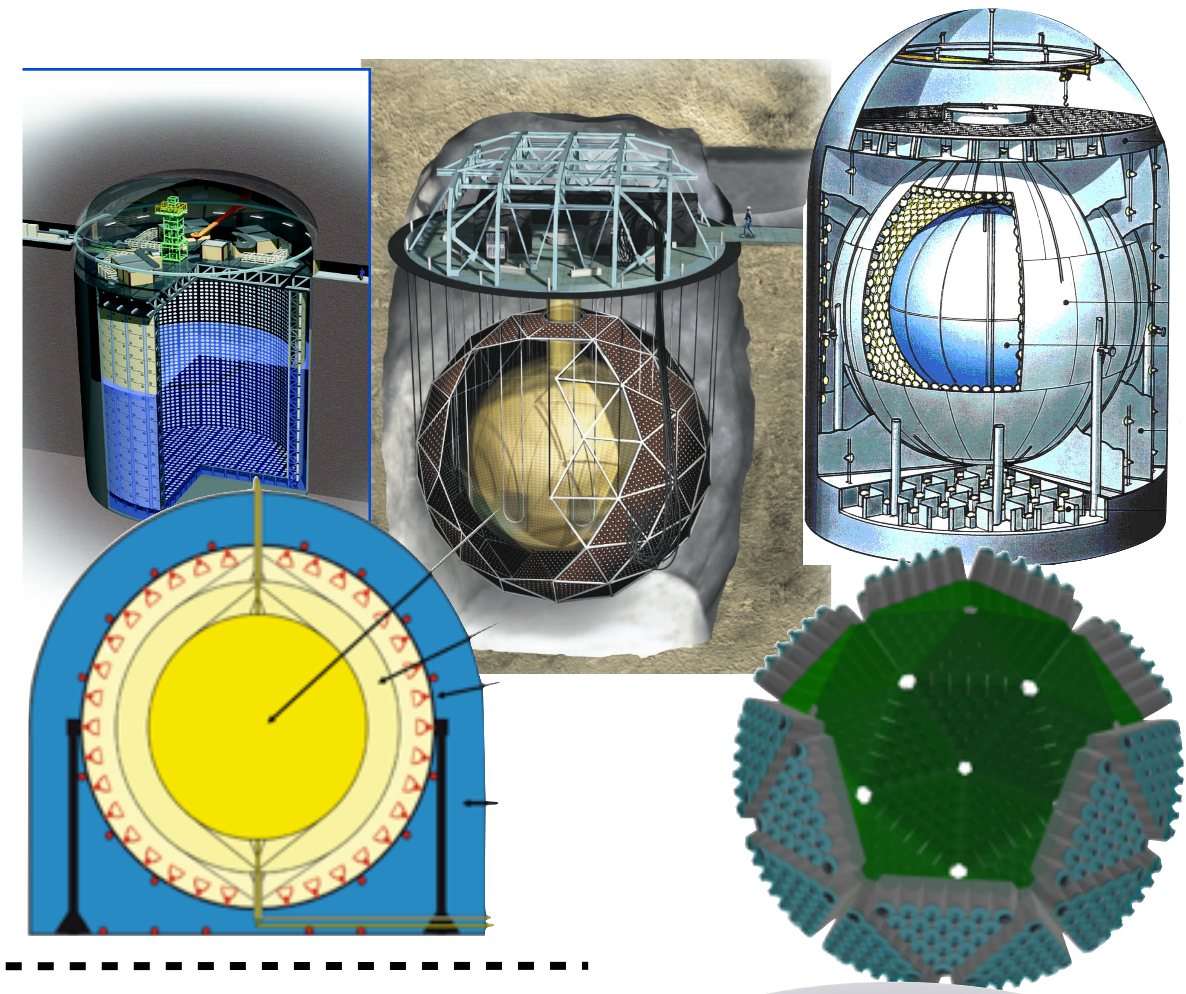
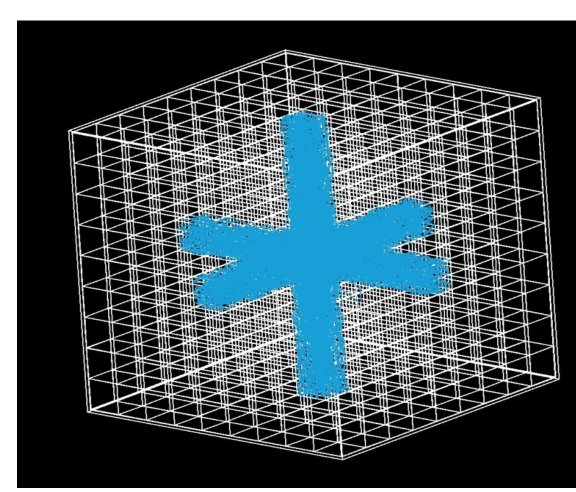
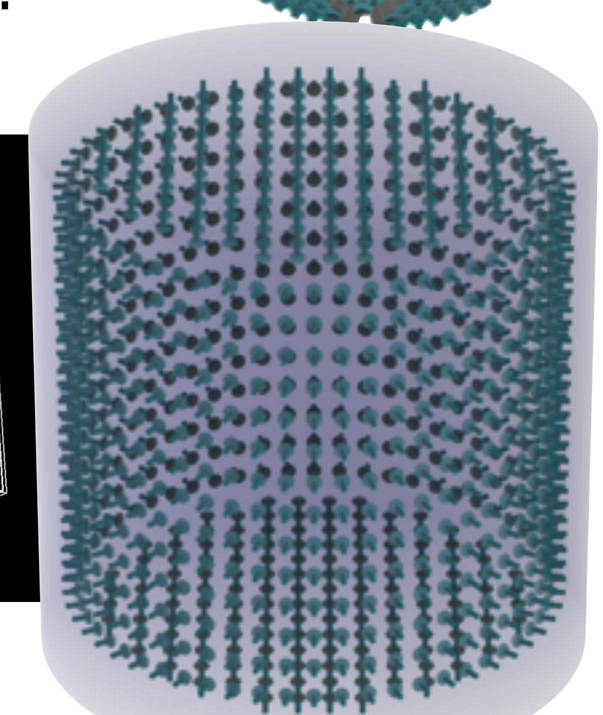


- Charged Current detection
  - Segmented detector
  - Large-scale water-based LS

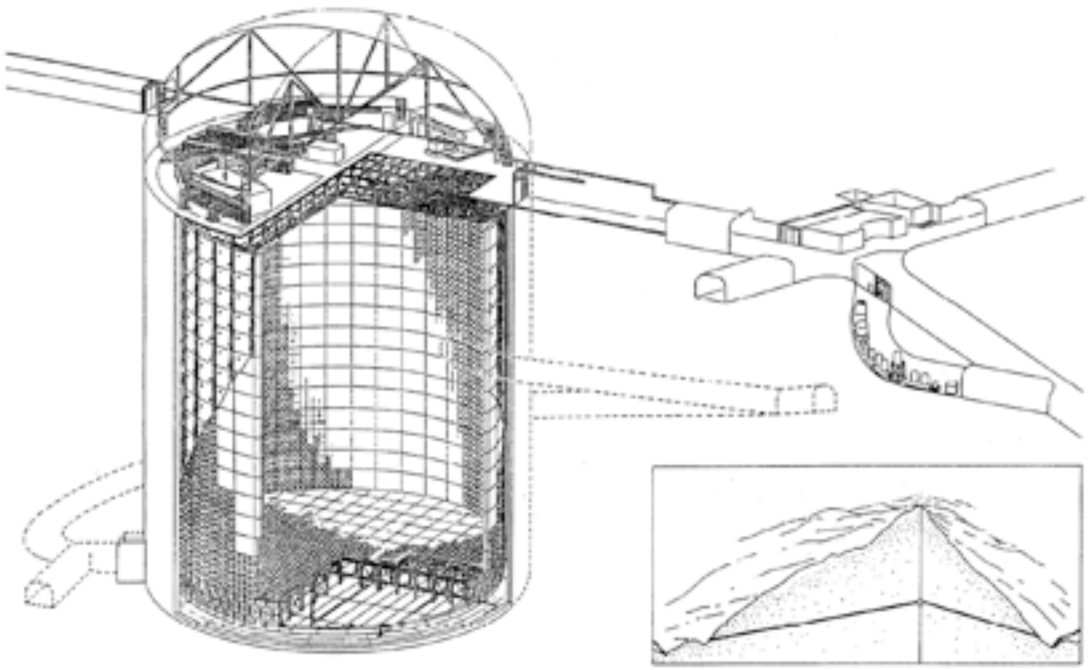




Large-Scale WCD

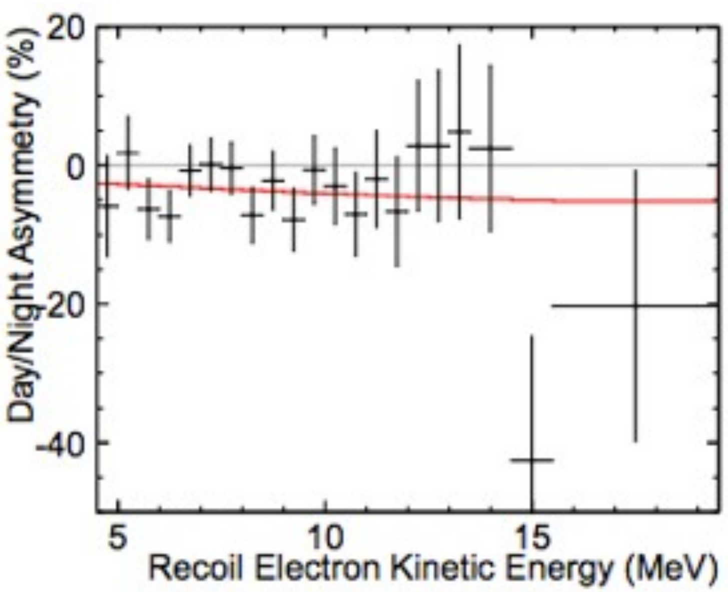
High stats
Low t/h
Low bkg

Super-Kamiokande



Super-Kamiokande
Combined analysis of SK I-IV

PRL 112 (2014) 091805

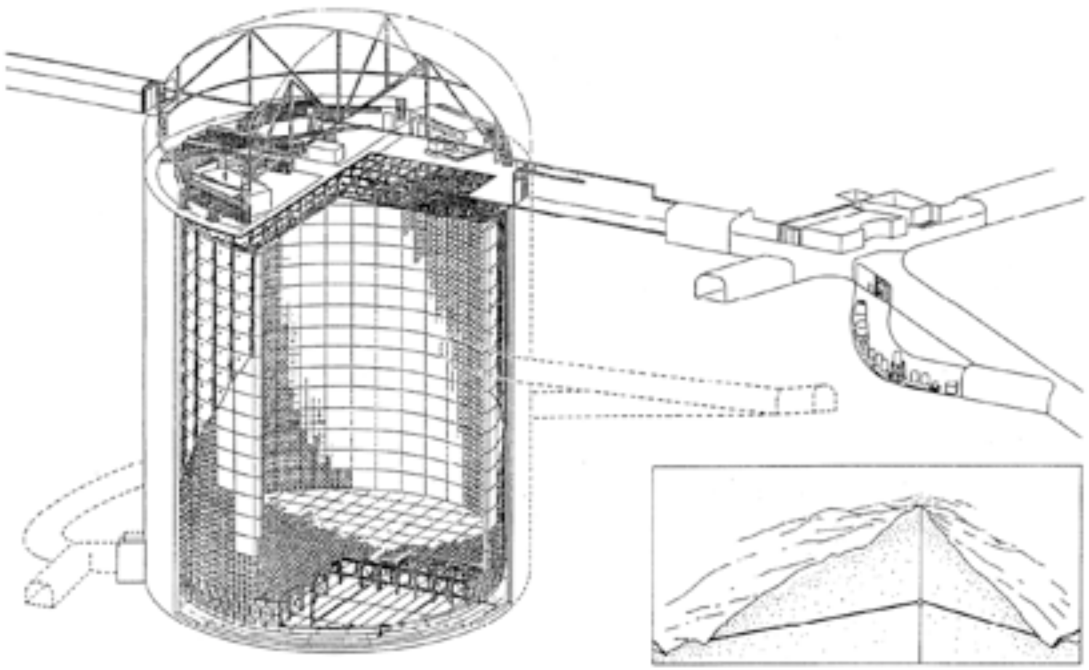


A_{DN} = -3.2%
± *1.1 (stat)*
± *0.5 (syst)*
= 2.7σ

Large-Scale WCD

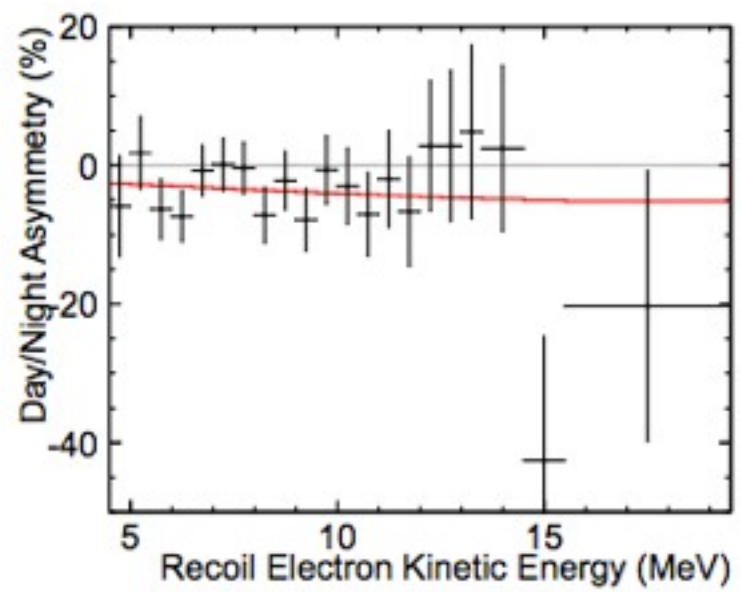
- ✓ High stats
- ☐ Low t/h
- ☐ Low bkg

Super-Kamiokande



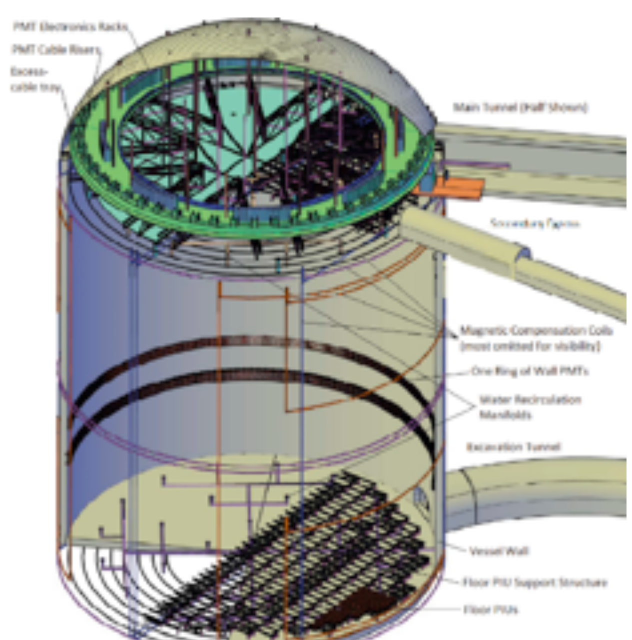
Super-Kamiokande
Combined analysis of SK I-IV

PRL 112 (2014) 091805



A_{DN} = -3.2%
± *1.1 (stat)*
± *0.5 (syst)*
= 2.7σ

Hyper-Kamiokande



- 0.99e6 T (20* Super-K)
- 1750 mwe depth
- 115,000 8B ES / year
- 0.5% sensitivity to D-N amplitude variation
- 4σ confirmation of MSW

arXiv: 1309.0184

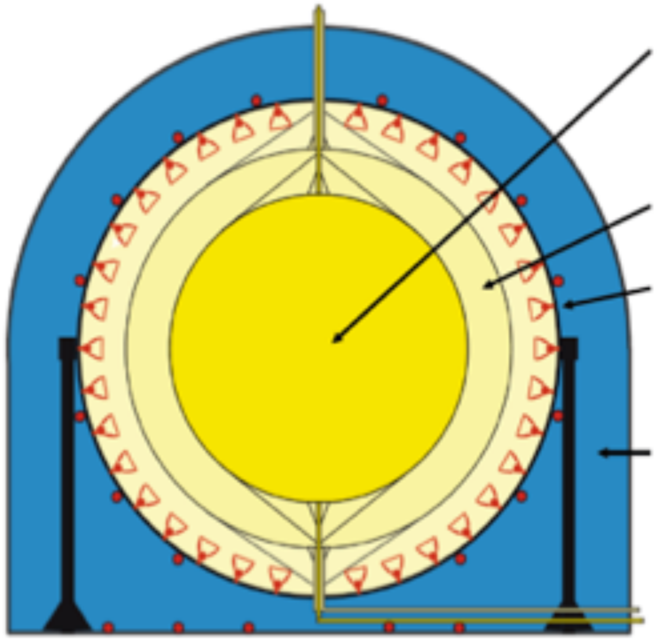
Large-Scale LS: Borexino

High stats
Low t/h
Low bkg

Unprecedented low LS background!

<0.8 counts per year /100t!

- ^{238}U < 8 x 10^{-20} g/g (^{214}Bi-^{214}Po)
- ^{232}Th <1 x 10^{-18} g/g (^{212}Bi-^{212}Po)
- ^{210}Bi = 20 ± 5 cpd/100t
- ^{85}Kr < 5 cpd/100t



Large-Scale LS: Borexino

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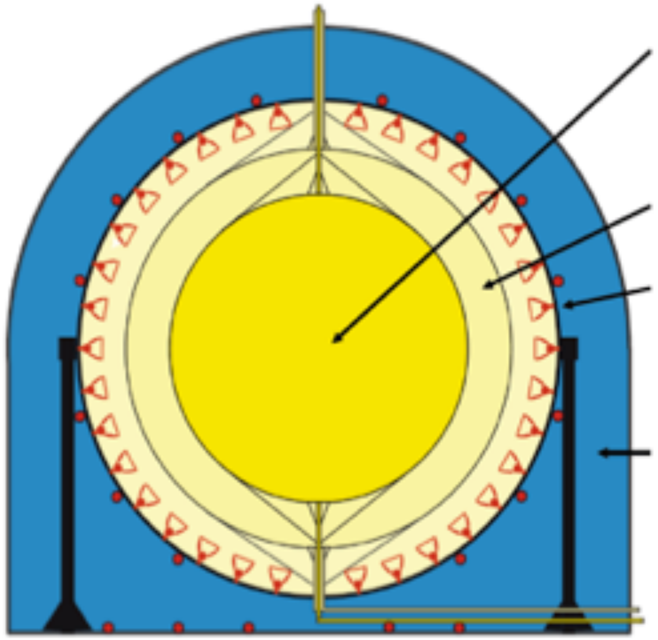

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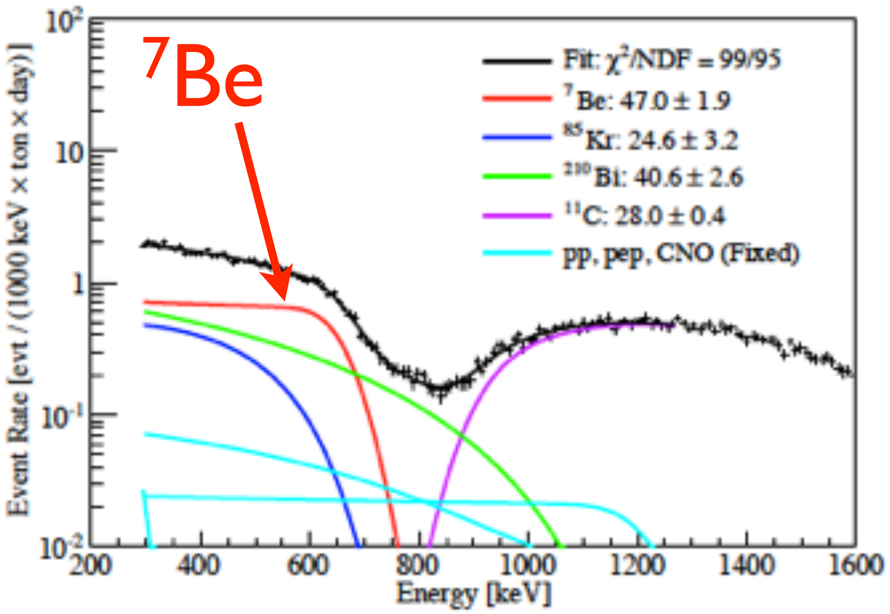
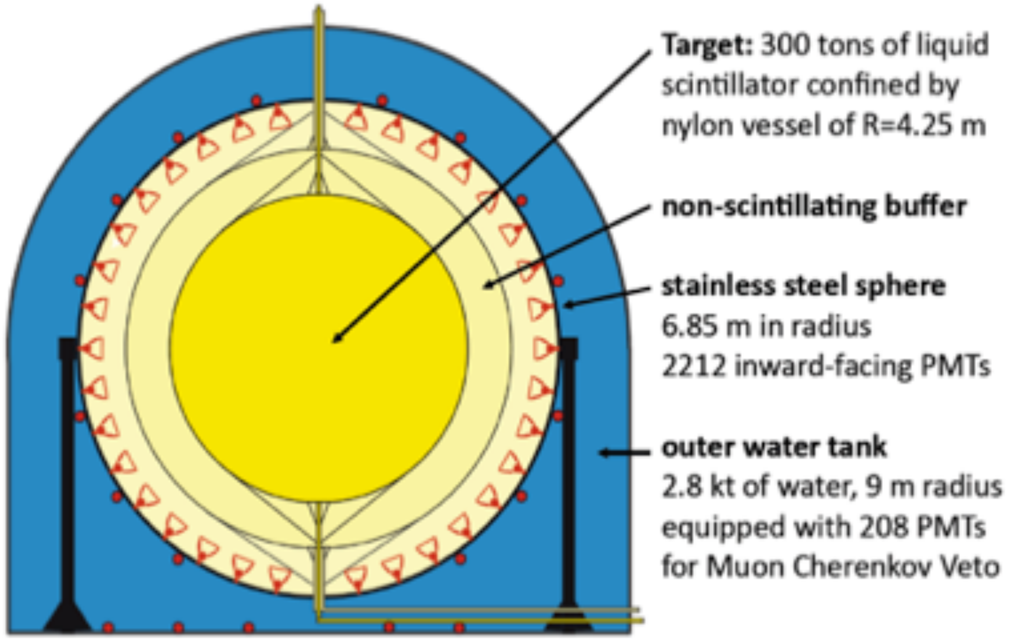


Phys. Rev. Lett. 107:141302 (2011)



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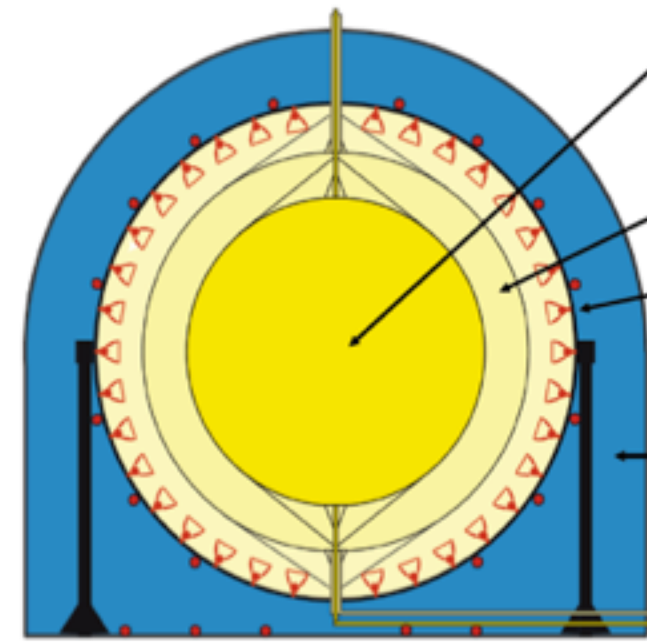

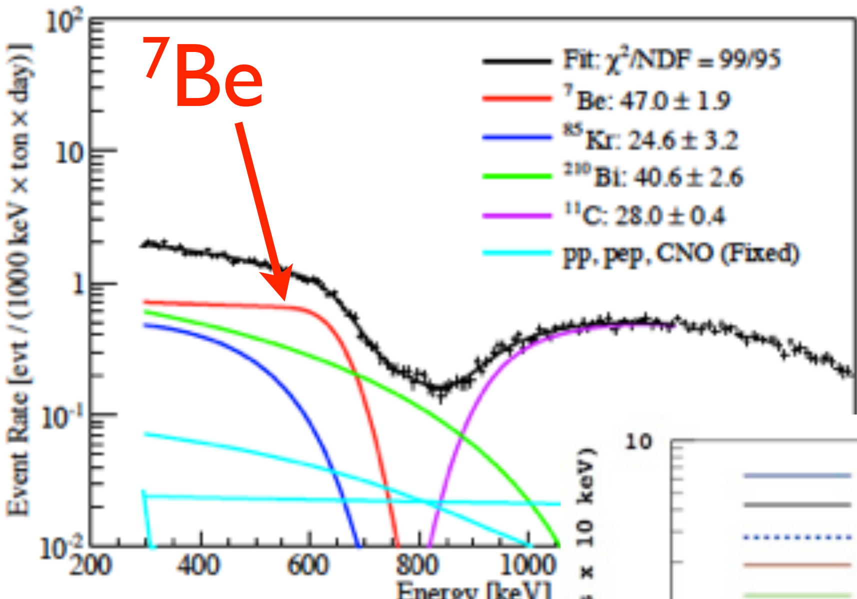

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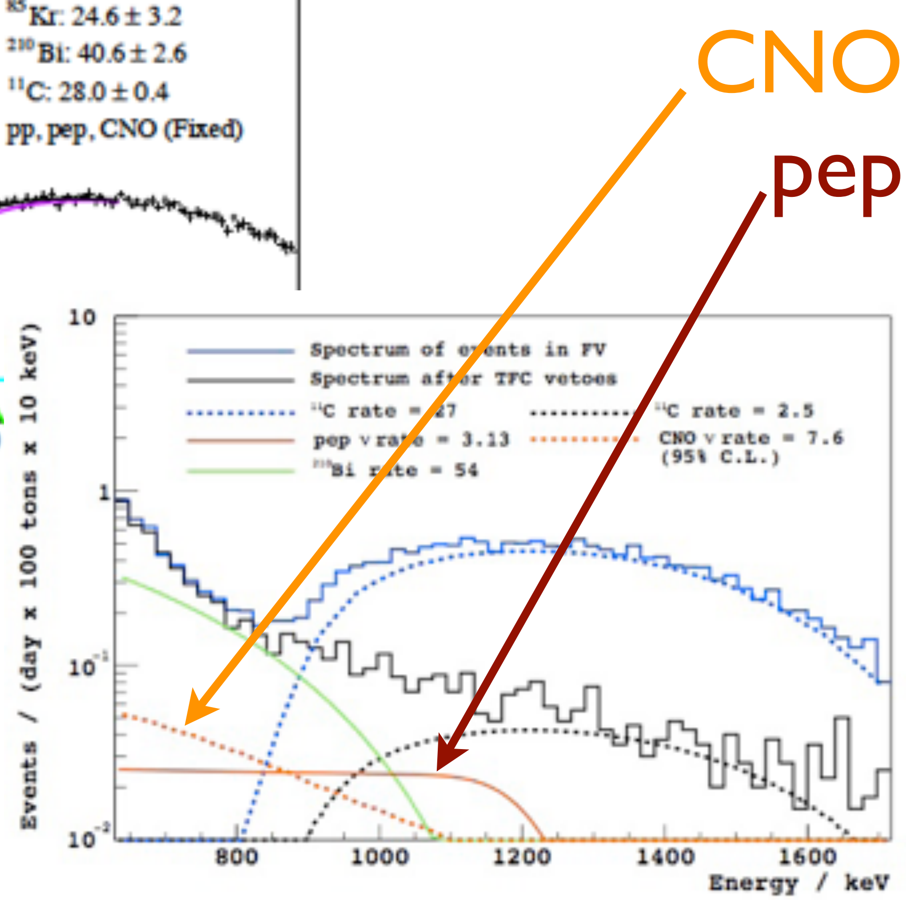

Phys. Rev. Lett. 108:051302 (2012)

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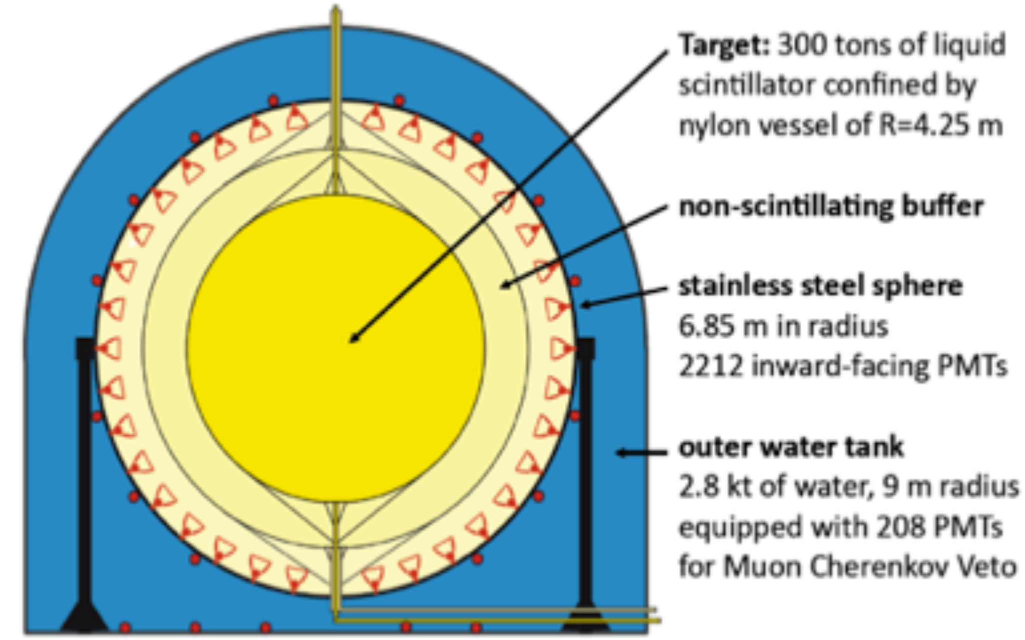

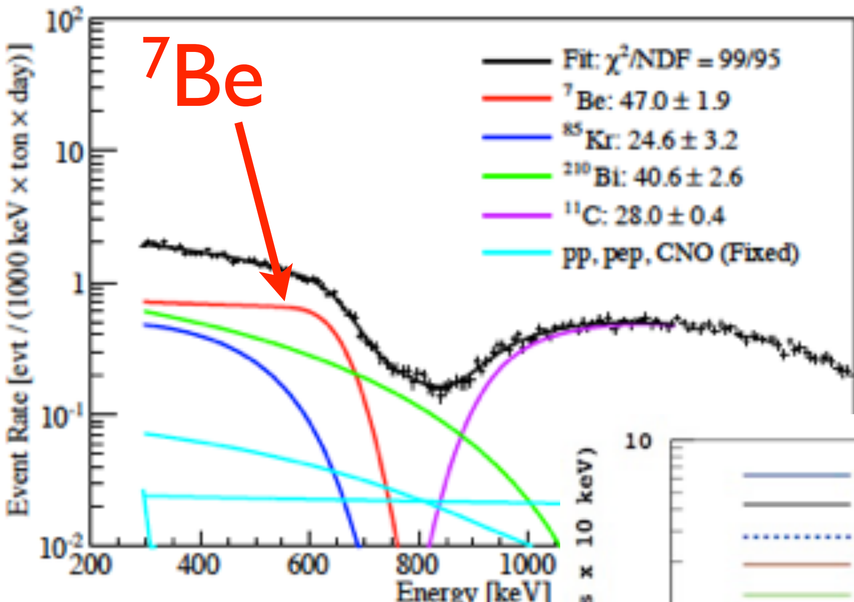

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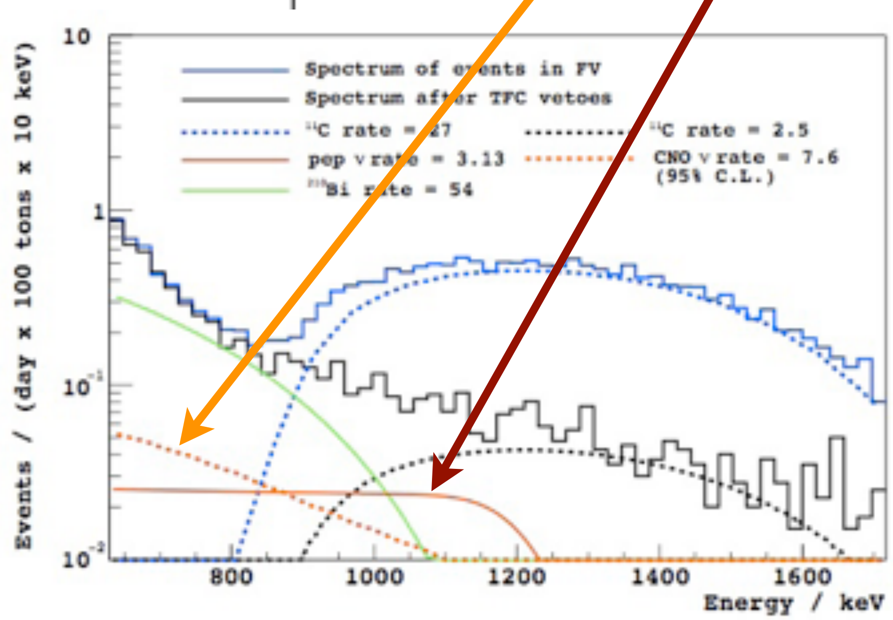

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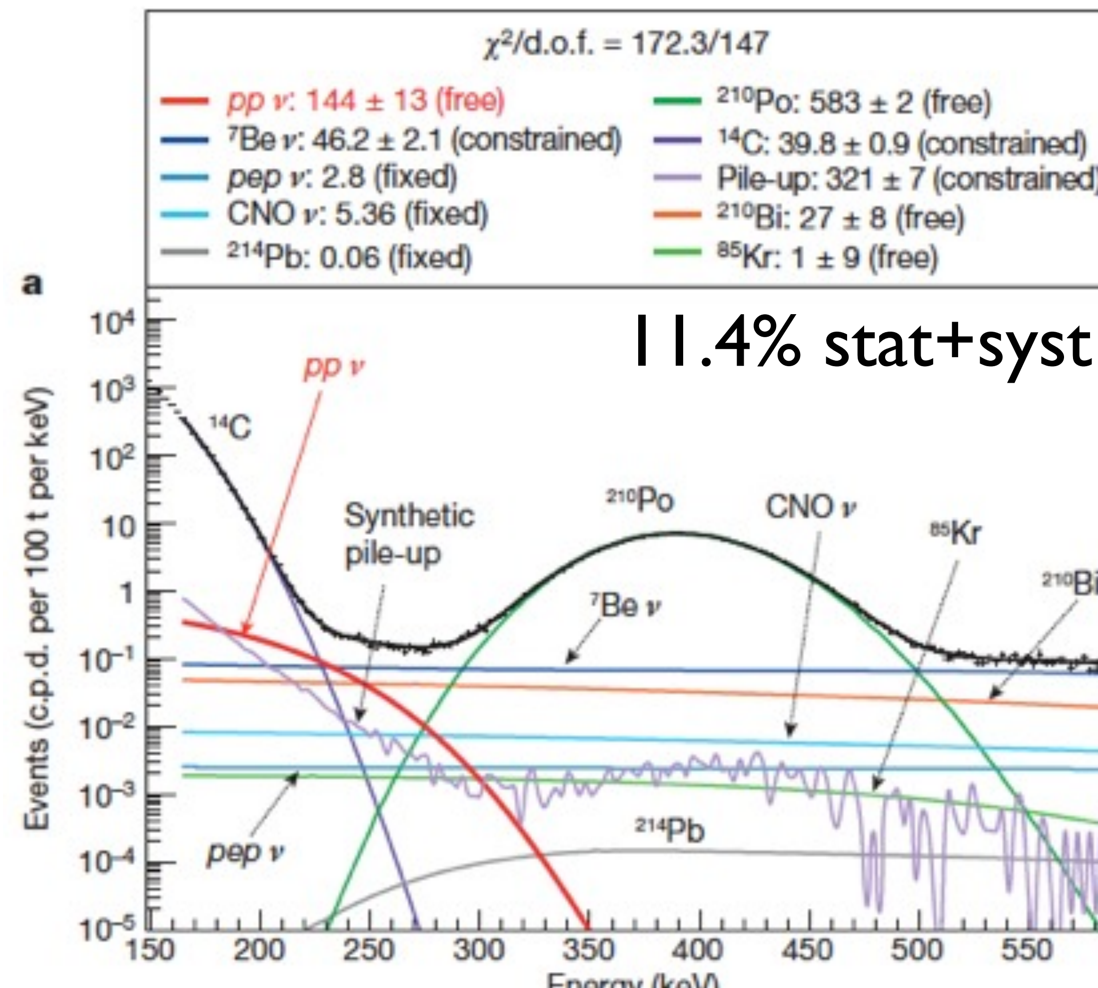
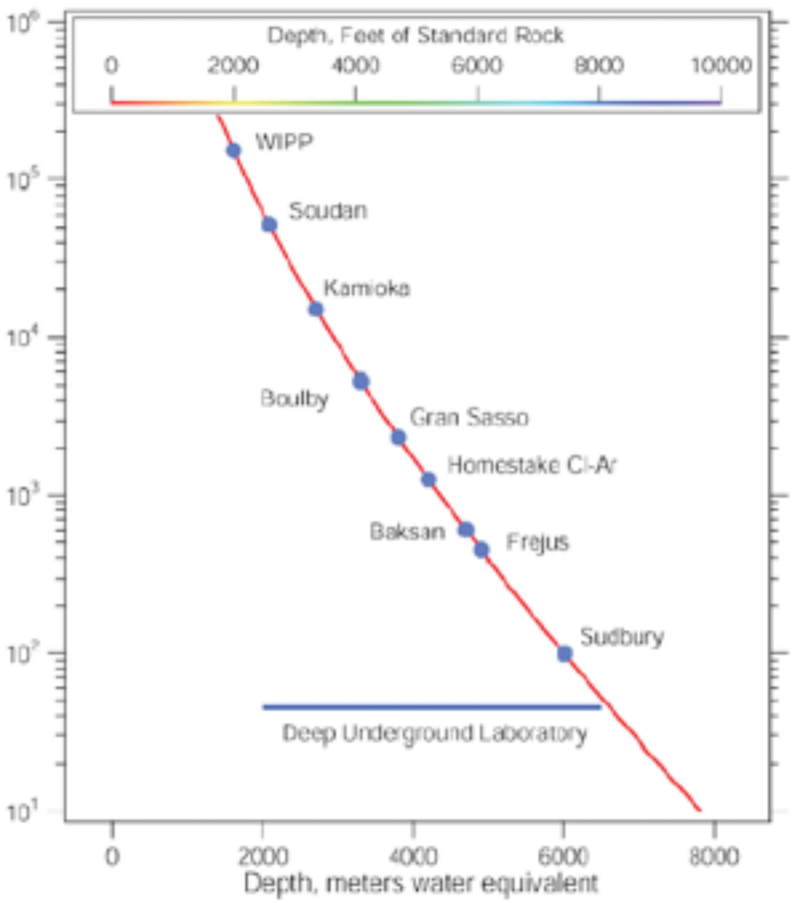
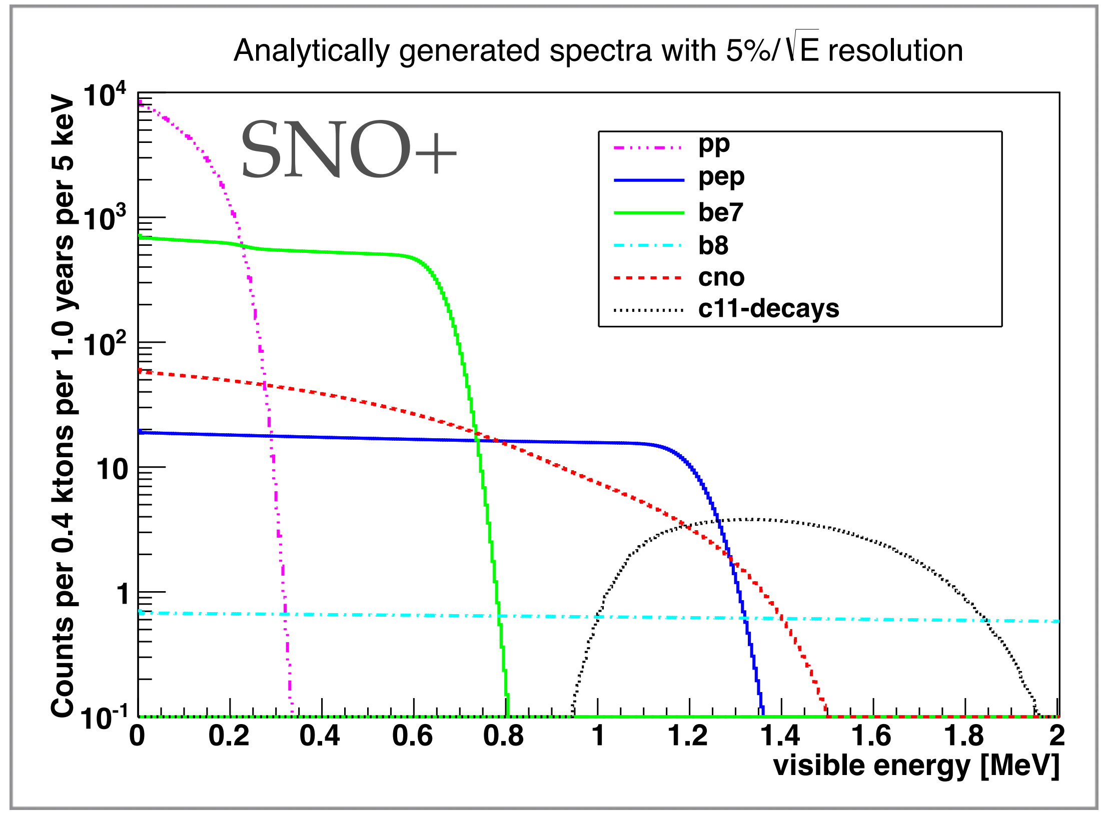


Large-Scale LS: SNO+

- High stats
- Low t/h
- Low bkg





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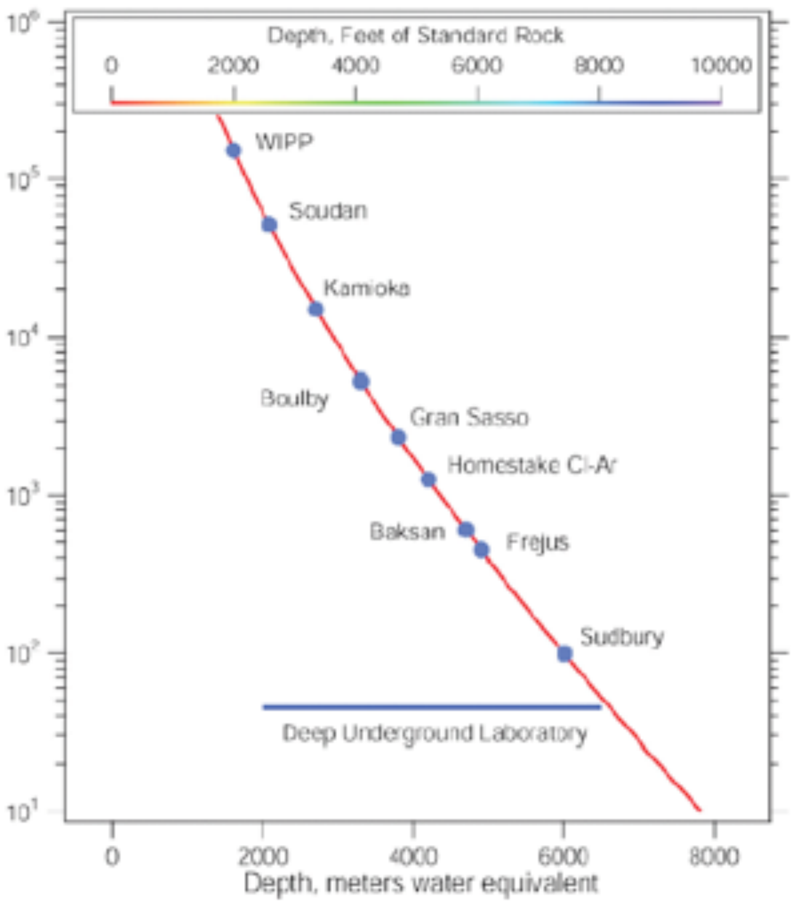
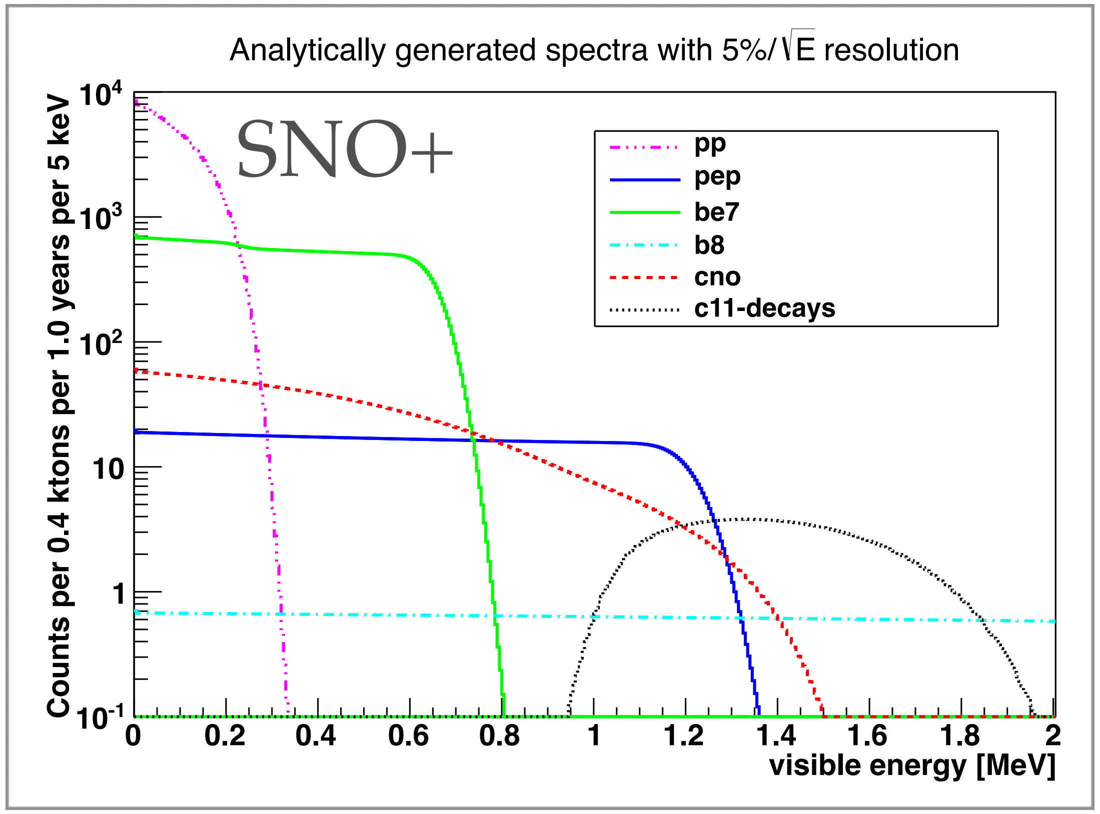
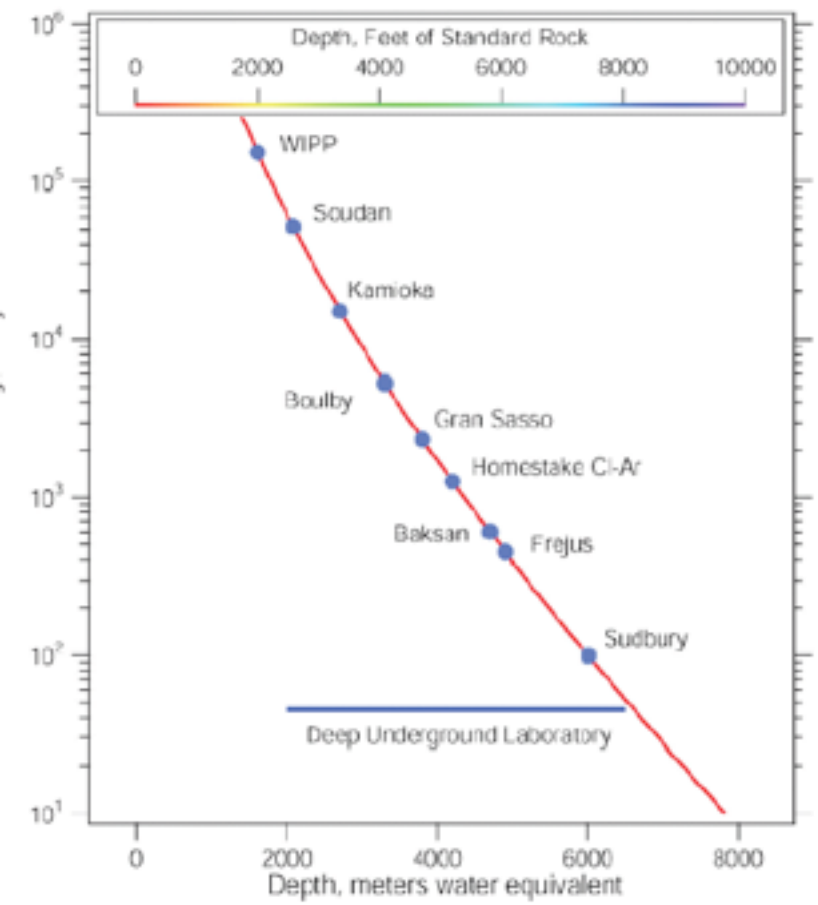


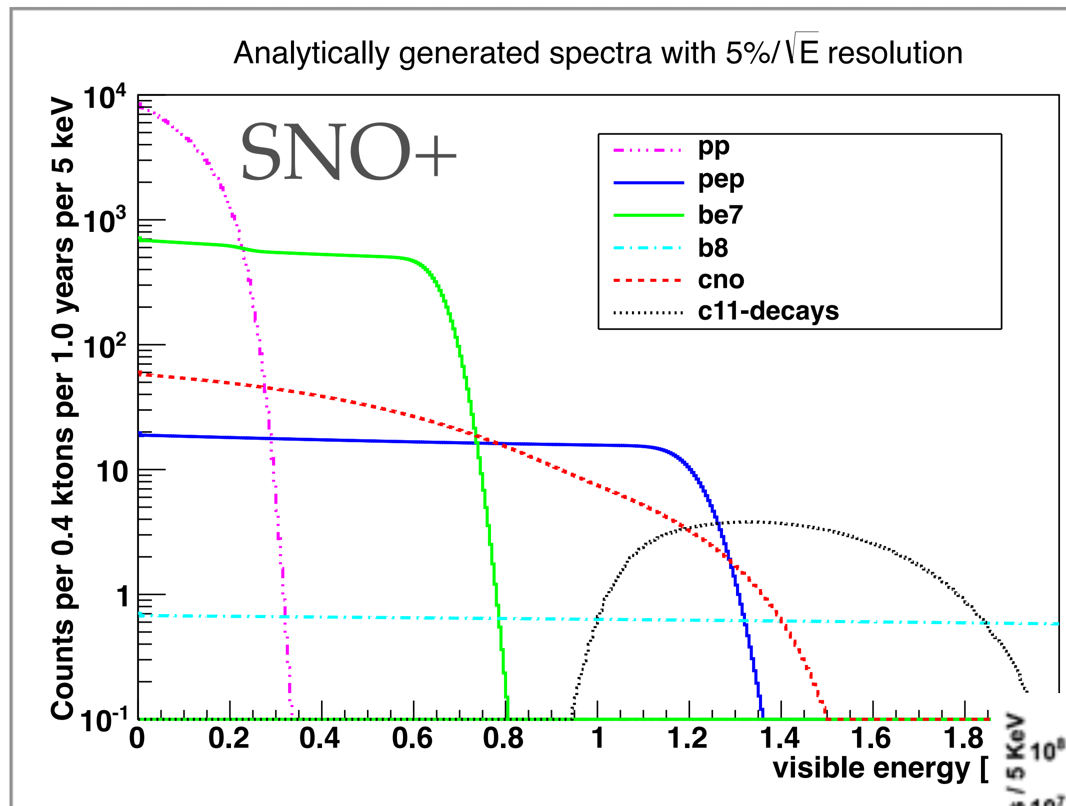


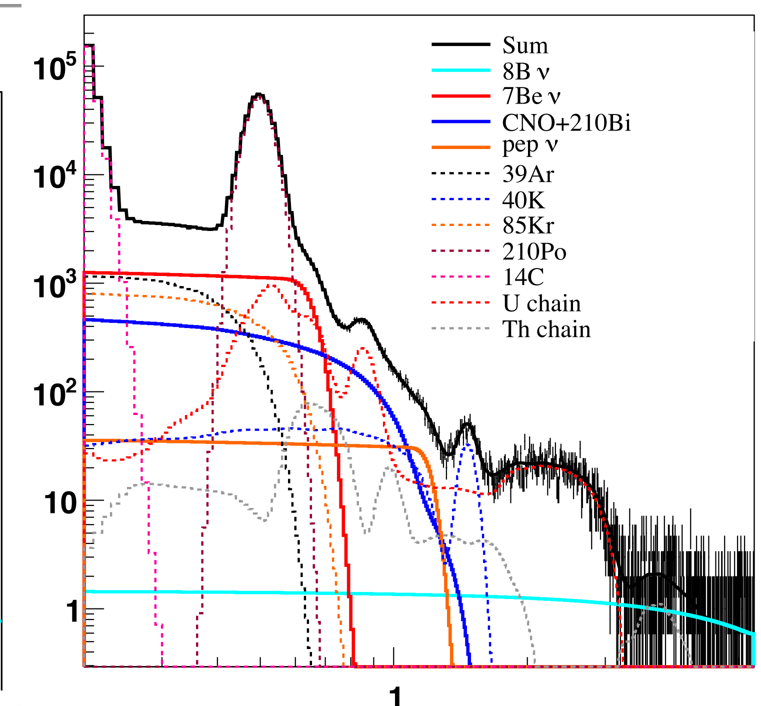
- 1 year livetime
- 50% fiducial volume (negligible external bkg)
- **Assuming Borexino-level purification levels**

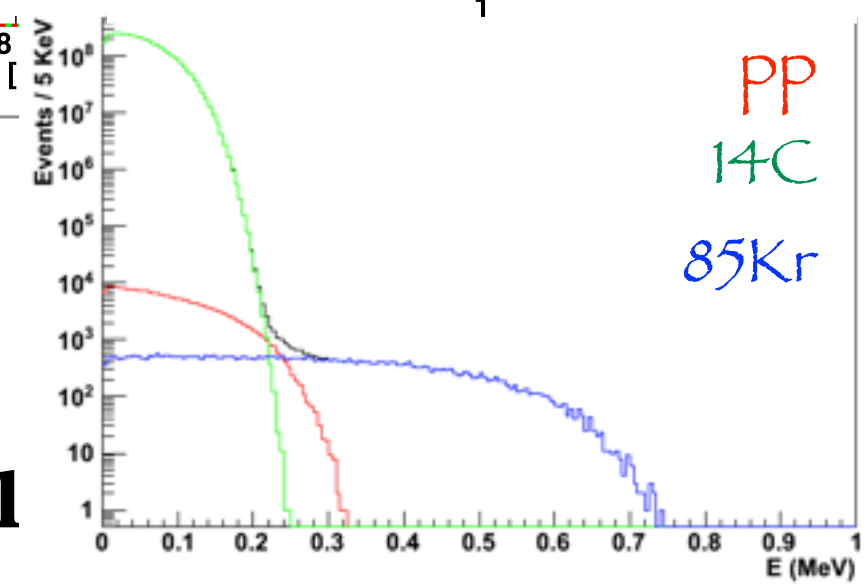
Large-Scale LS: SNO+

- ✓ High stats
- ✓ Low t/h
- ✓ Low bkg









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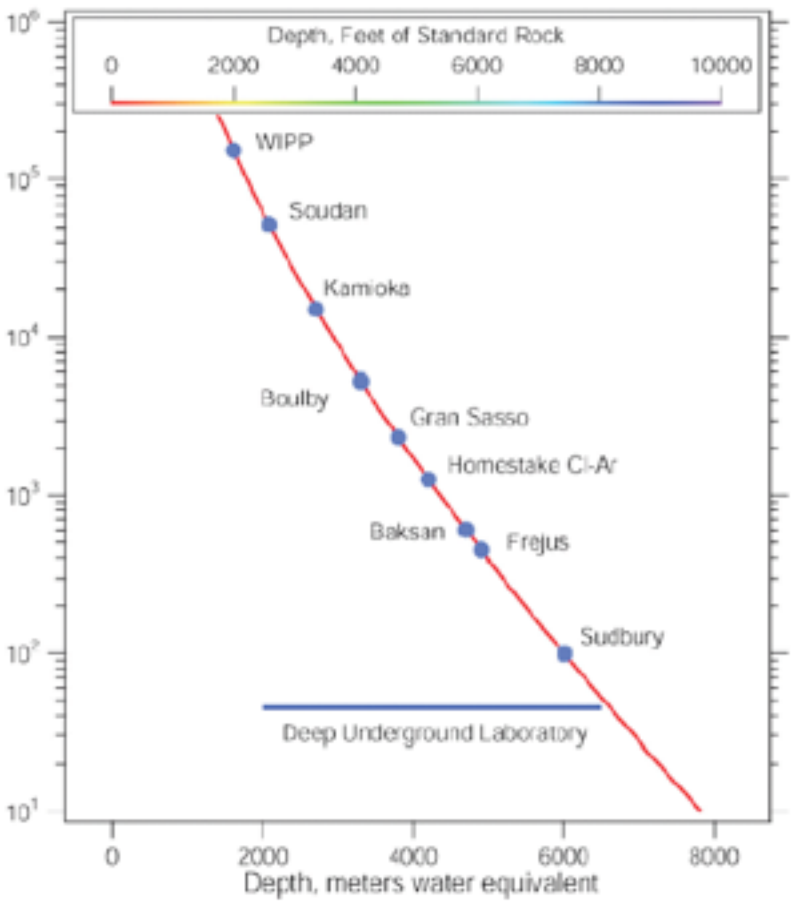
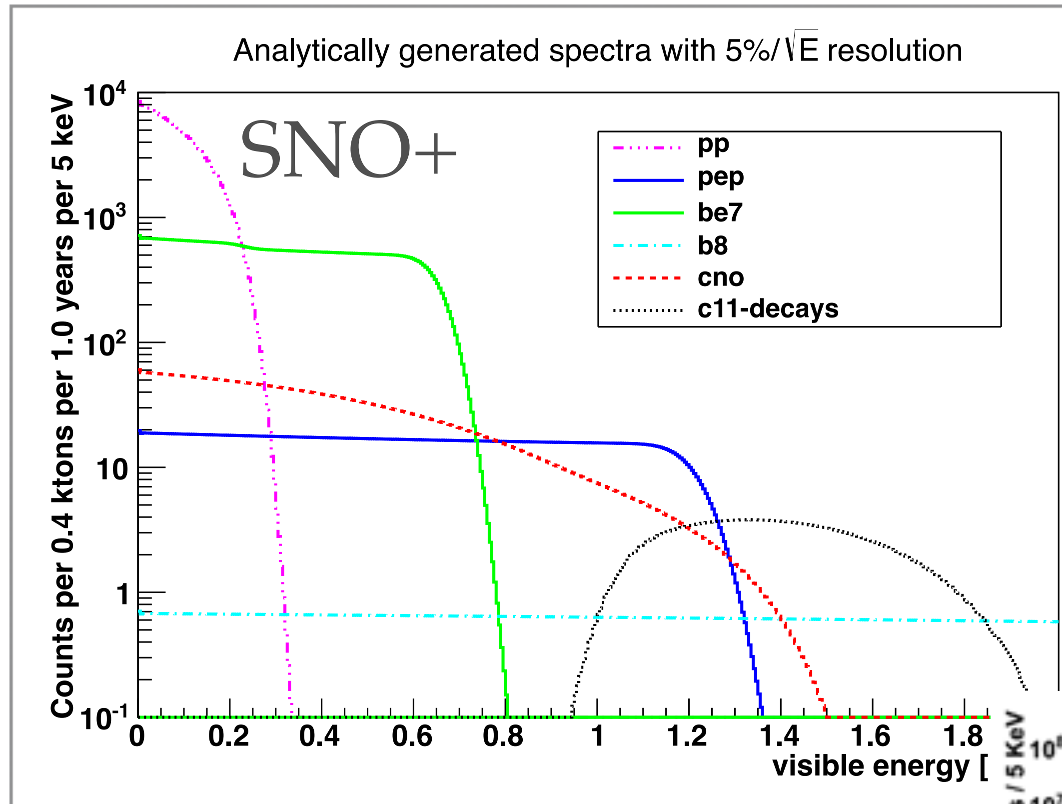
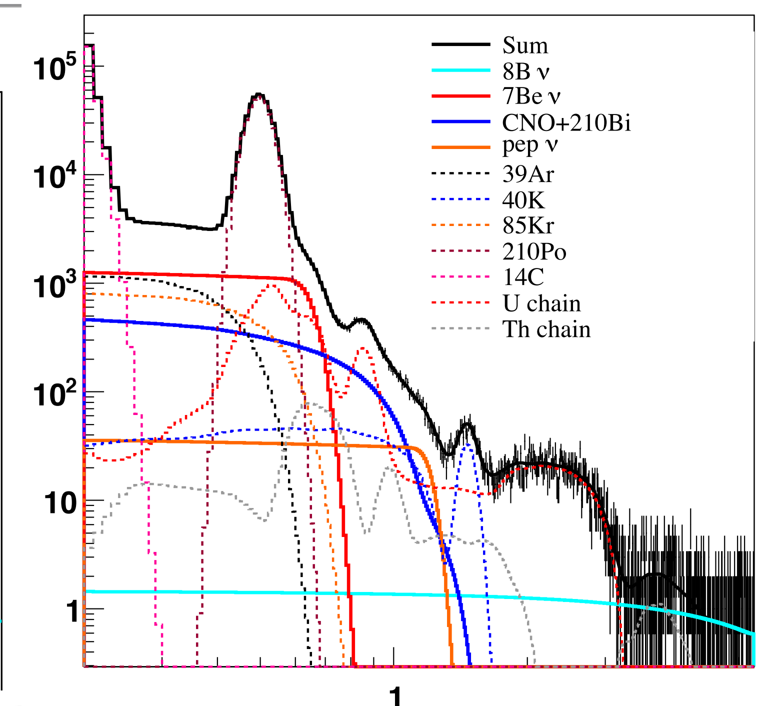
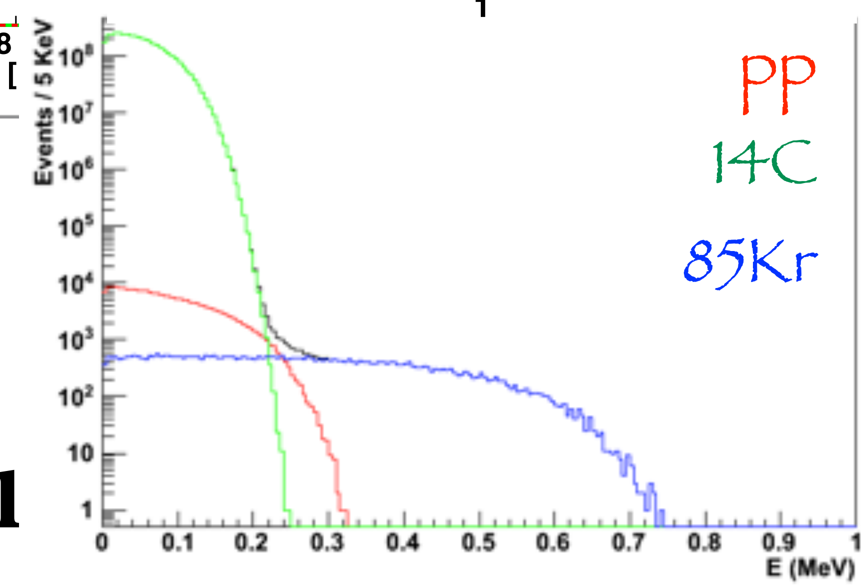








- 1 year livetime
- 50% fiducial volume (negligible external bkg)
- **Assuming Borexino-level purification level**

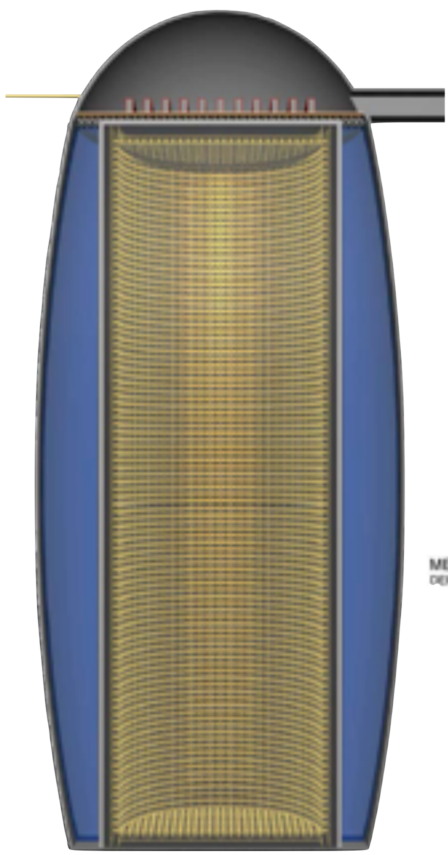
	pep	^{8}B	^{7}Be	pp	CNO
1 yr	9%	7.5%	4%	~ a few %	~ 15 %
2 yr	6.5%	5.4%	2.8%		

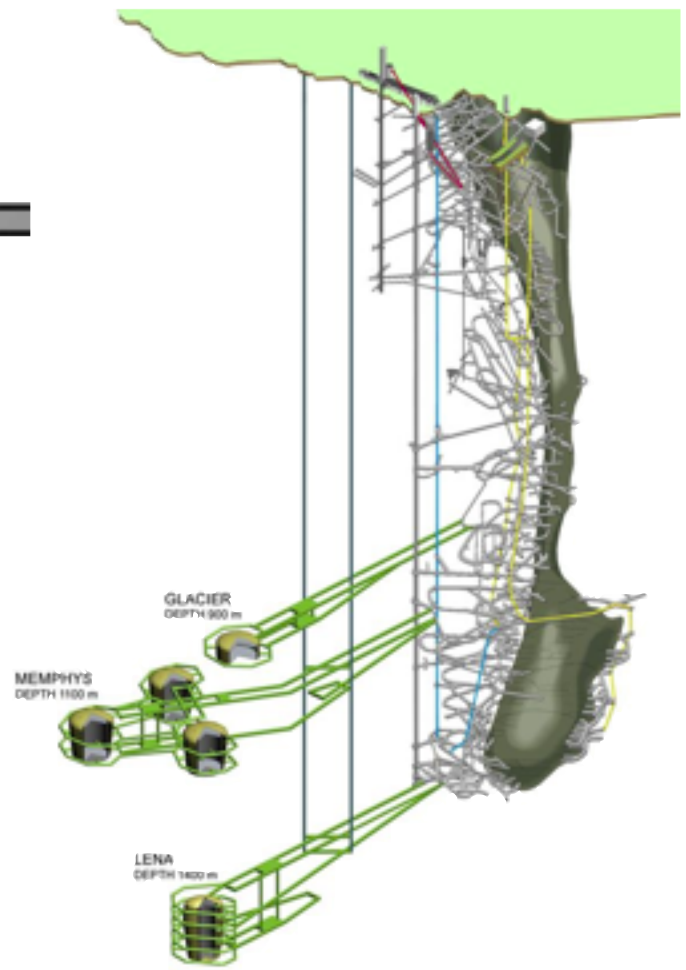
(pp dependent on ^{14}C, ^{85}Kr)
(CNO dependent on ^{210}Bi)

High stats
Low t/h
Low bkg

Large-Scale LS

LENA





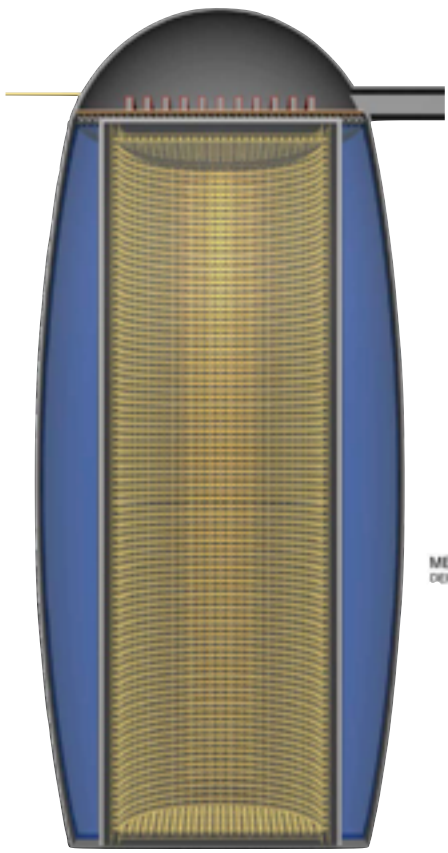
- 50kT LS (30kT FV solar), 30% coverage
- Unprecedented statistics at low energy
  - 3σ discovery potential for 0.1%-amplitude temporal modulations in ^{7}Be flux
  - CNO detection
  - Low-energy ^{8}B spectrum (+ CC on ^{13}C)

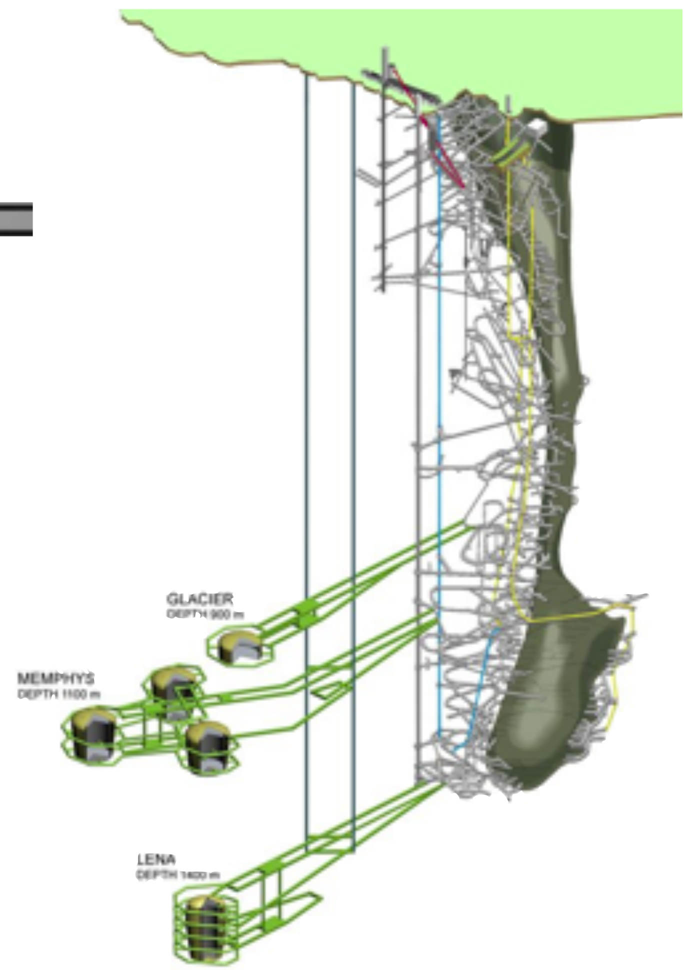
High stats
Low t/h
Low bkg

Large-Scale LS

High stats
Low t/h
Low bkg

LENA





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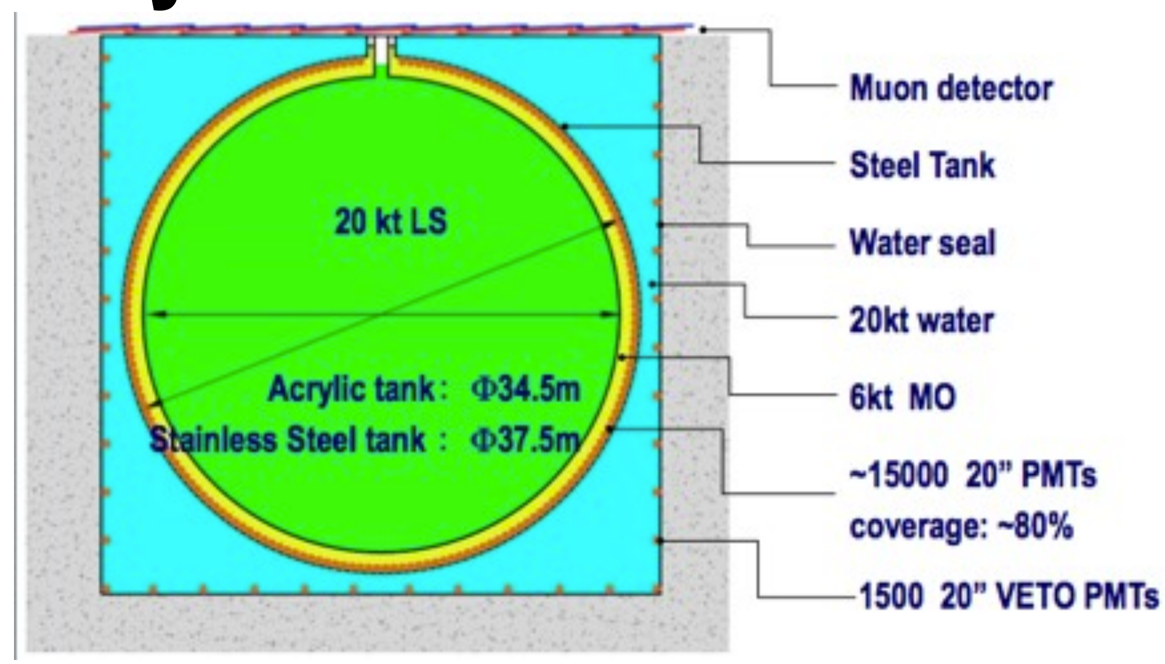
JUNO



- 20kT LS detector
- 700m rock overburden
- Goal of 3% / $\sqrt{E}$ resolution

	Current	JUNO
Δm^2_{12}	~3%	~0.6%
Δm^2_{23}	~5%	~0.6%
$\sin^2\theta_{12}$	~6%	~0.7%
$\sin^2\theta_{23}$	~20%	N/A
$\sin^2\theta_{13}$	~14% → ~4%	~ 15%

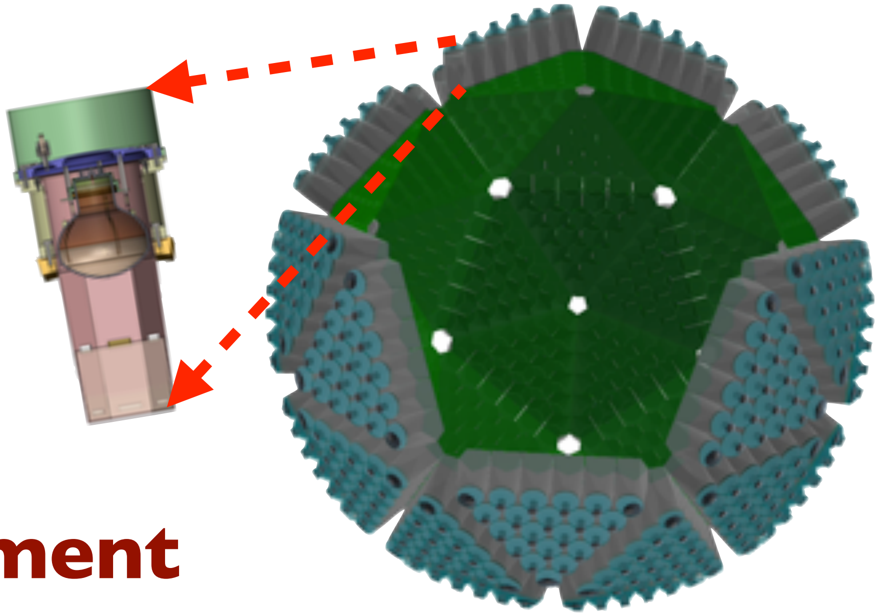
Inorganic LS

- [ ] High stats
- [x] Low t/h
- [x] Low bkg

LNe (CLEAN):

50-T scale

Background-free fiducial volume



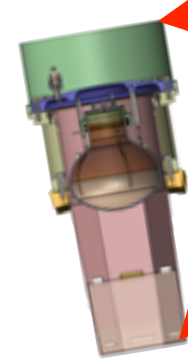
⇛ **%-level (ES) pp measurement**

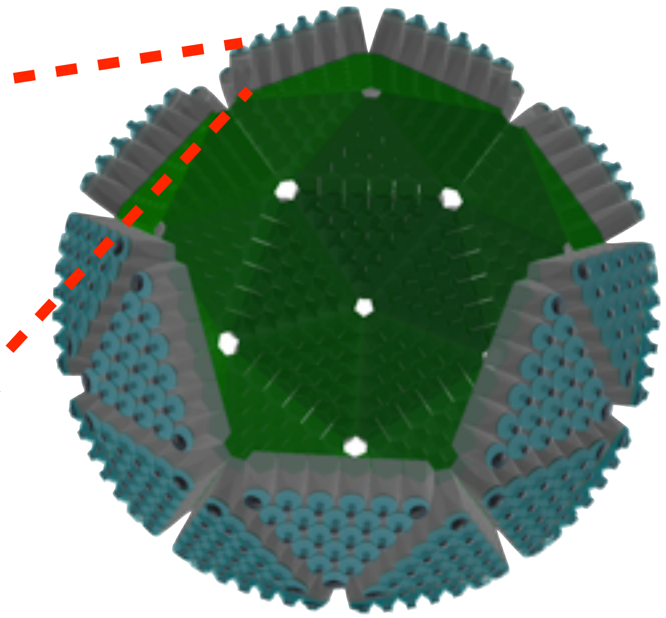
Inorganic LS

- ☐ High stats
- ☑ Low t/h
- ☑ Low bkg

LNe (CLEAN):

50-T scale
Background-free fiducial volume





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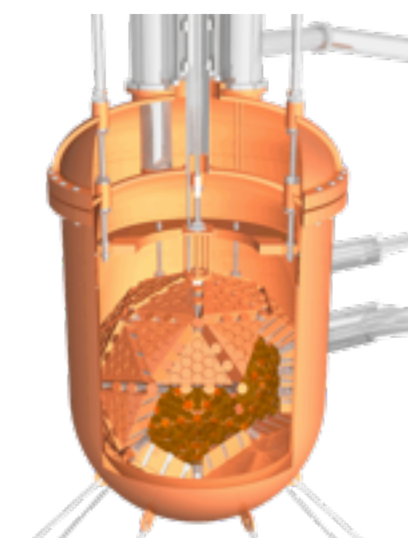
Liquid xenon (XMASS, LZ):

T-scale experiments
Requires *100 depletion of ^{136}Xe



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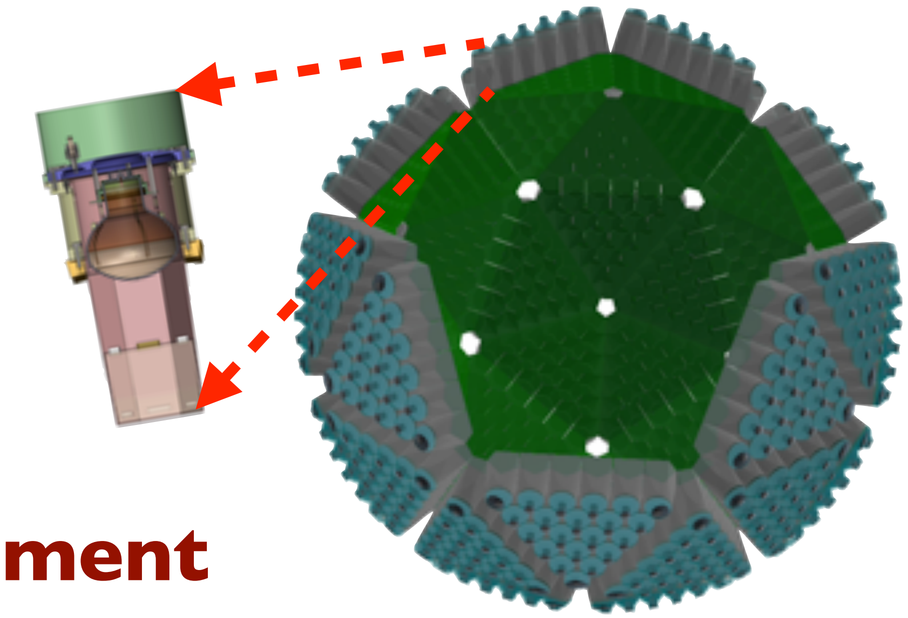

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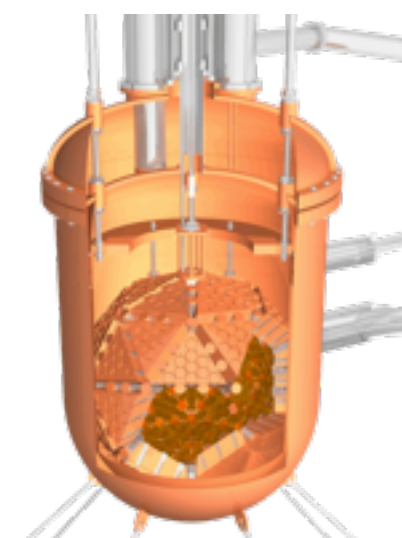


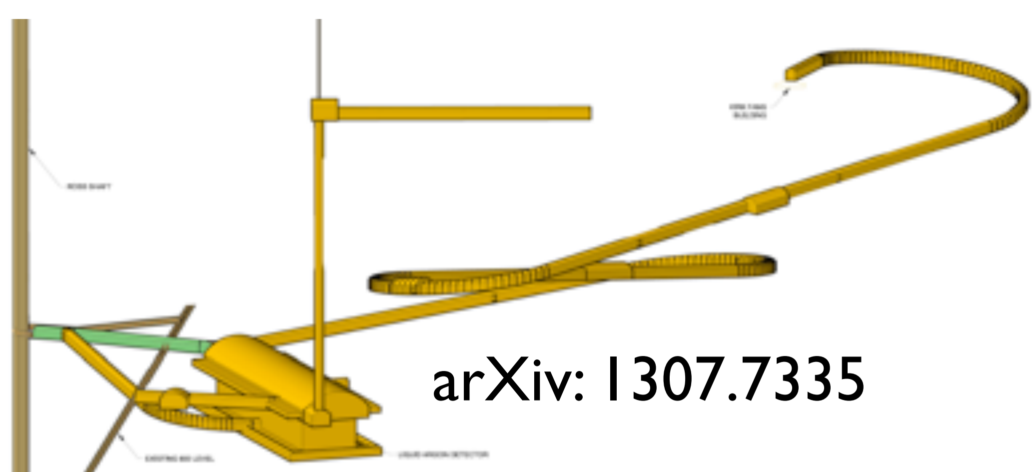
LBNF

- 40kT LAr
- + 50kT WCD? - p5
- CC on ^{40}Ar, E_{th} = 5MeV

☐ High stats
☐ Low t/h
☑ Low bkg

$$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$$

Transition	Rate (evts/day)
Fermi	31
Gamow-Teller	88



arXiv: 1307.7335

- [ ] High stats
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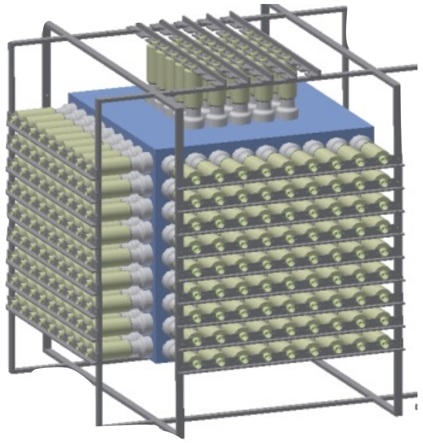
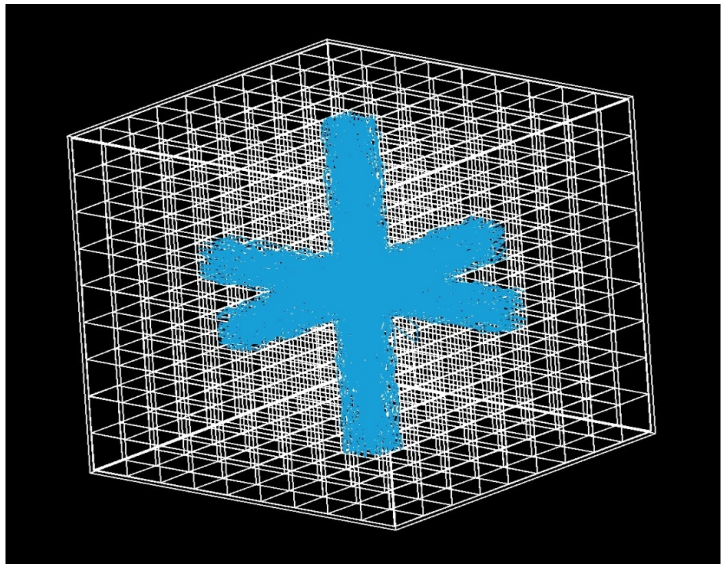
CC Detection: LENS

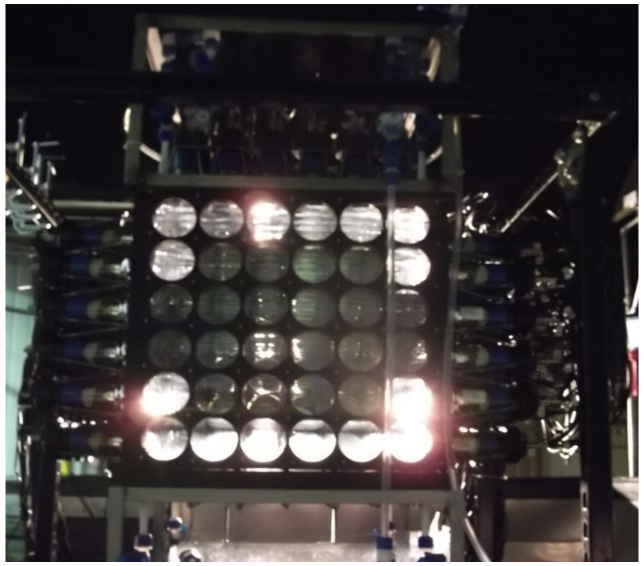


$$\nu_e + {}^{115}In \longrightarrow {}^{115}Sn^* + \beta^-$$

$$\tau = 4.76\mu s \;\; \hookrightarrow \gamma(115\mathrm{keV}) + \gamma(497\mathrm{keV}) + {}^{115}\mathrm{Sn}$$

- Delayed triple coincidence helps reject ^{115}In bkg (need 10^{11} rejection)
- Q = 115keV : 95% of pp spectrum
- Segmentation helps reject ext bkgs





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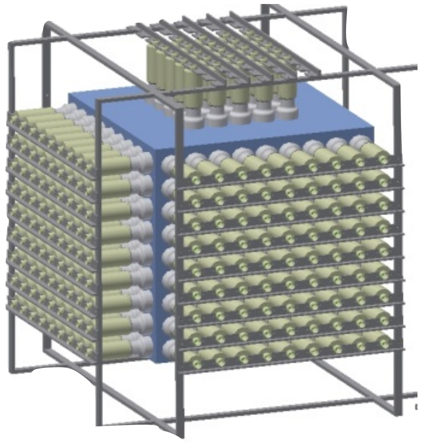
CC Detection: LENS



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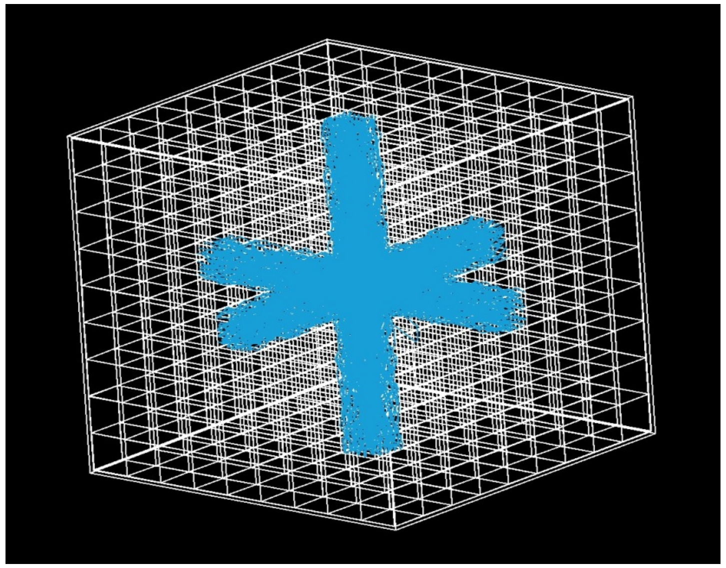

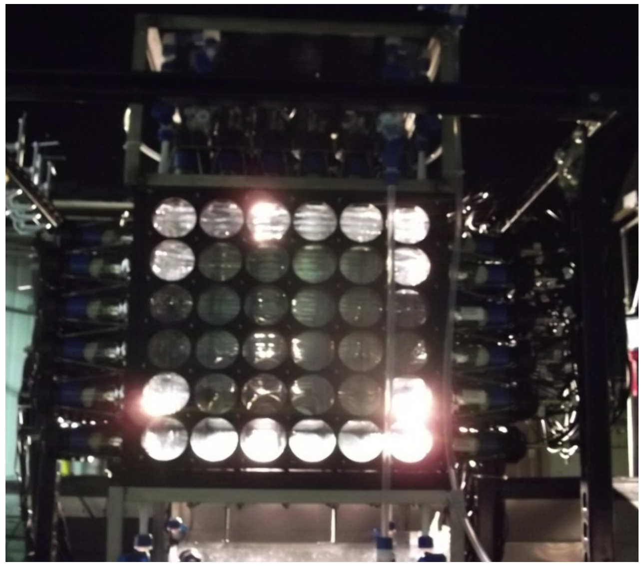

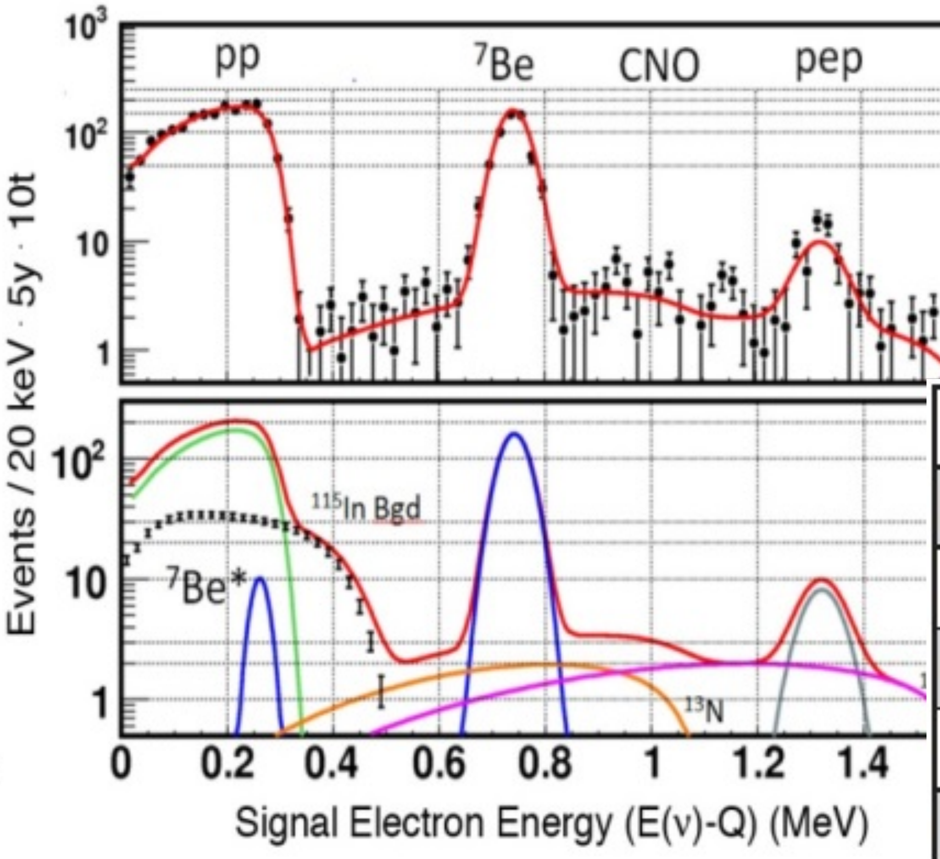

GS98 | AGSS09

Source	pp	7Be	CNO*	CNO†
Flux (/cm2/s)	6.00E+10	4.70E+09	4.97E+08	3.74E+08
Flux (SNU) [Bah88]	468	116	15	11
Cross section[Rap85]	1.00E-44	2.50E-44	2.50E-44	2.50E-44
Survival probability	56	54	54	54
Rate (per ton year)	26	6.2	1.2	0.9
Rate (10 tons · 5 yr)	**1296**	**310**	**58**	**43**

High stats
Low t/h
Low bkg

The ASDC

- ASDC: Advanced Scintillation Detector Concept (see ASDC talk, Monday, J. R. Klein)

- Water Cherenkov ⇒ water-based LS

Nucl. Inst. & Meth. A660 51 (2011)
http://underground.physics.berkeley.edu/WbLSWorkshop.html

- Load large water Cherenkov detector with e.g. ^{7}Li for CC interaction

"Salty water Cherenkov detectors" W.C. Haxton PRL 76 (1996) 10

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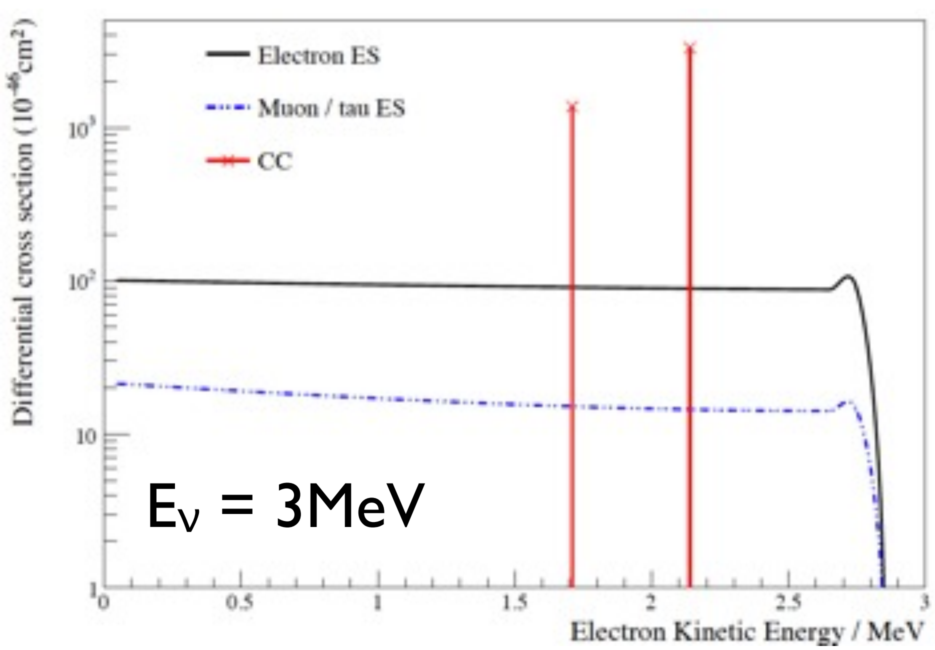

Cross section from W. C. Haxton

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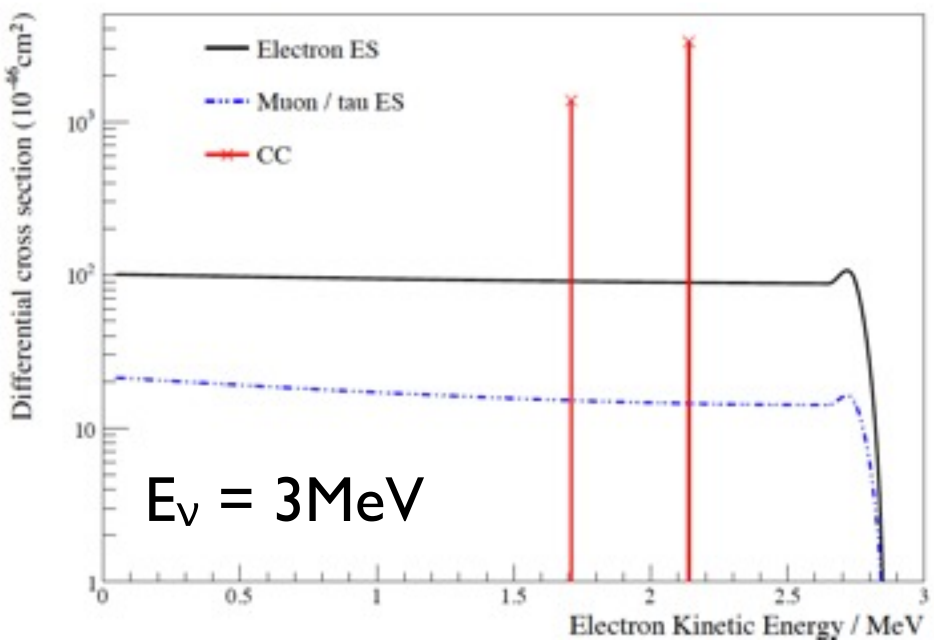

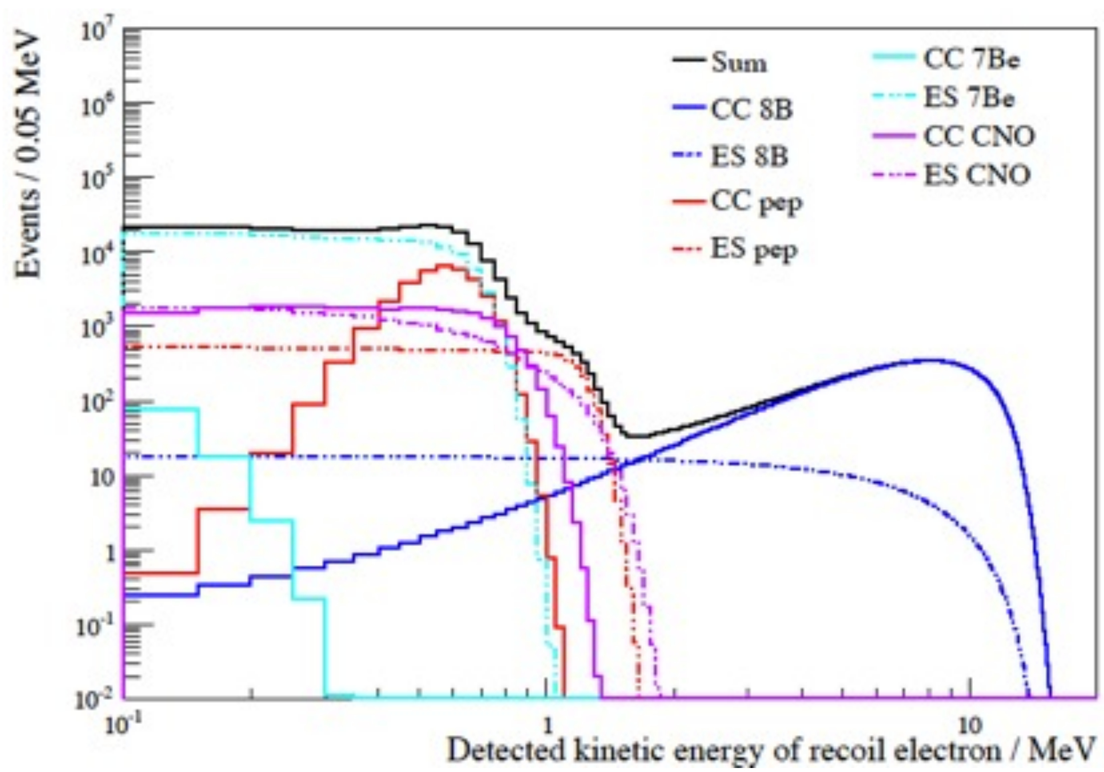

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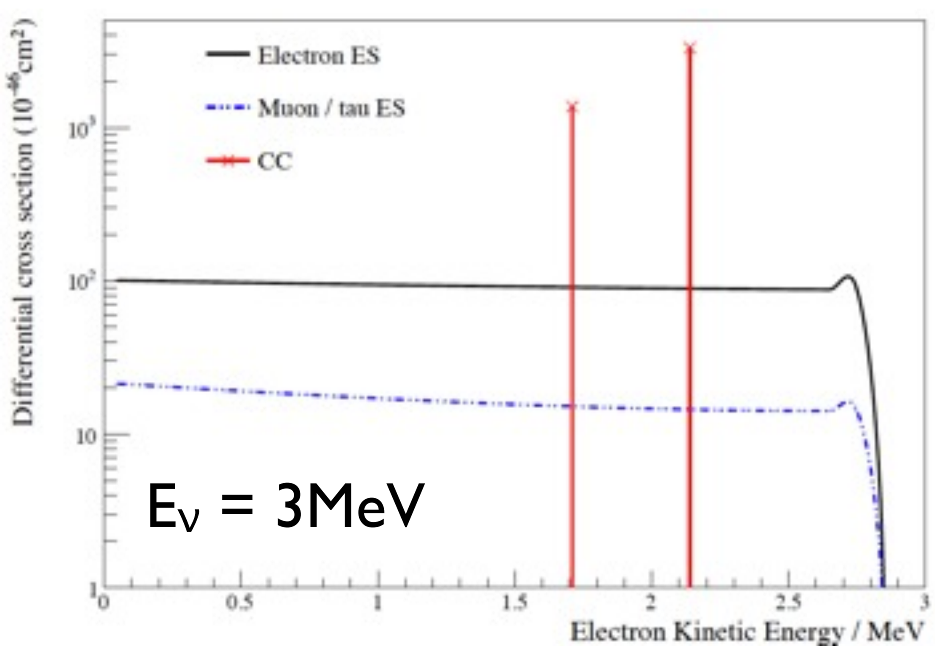
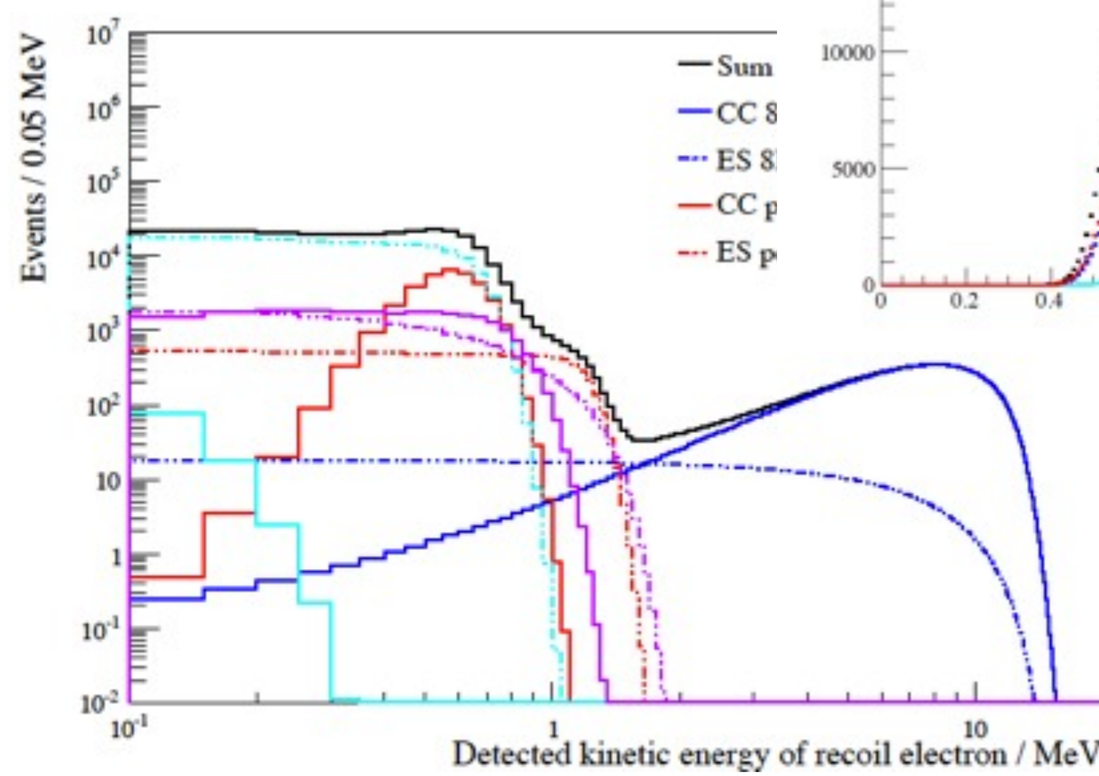
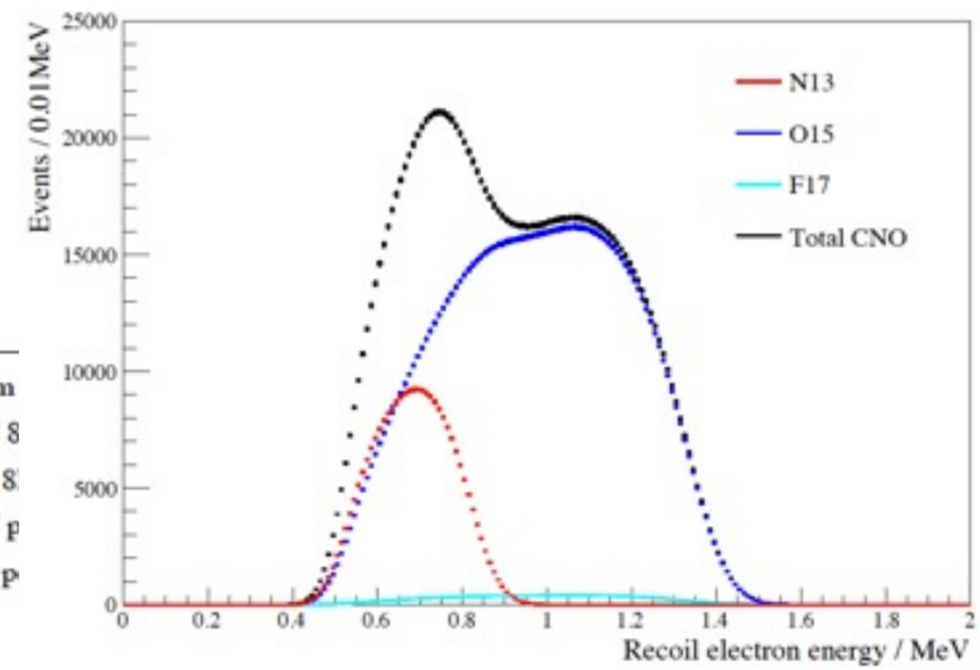
- Load large water Cherenkov detector with e.g. ^{7}Li for CC interaction

"Salty water Cherenkov detectors" W.C. Haxton PRL 76 (1996) 10







Cross section from W. C. Haxton

Is ultra-clean segmentation possible? NuLat

- LENS detector design.
- Applied to reactor neutrinos
- Potential for other applications?