SNOLAB

HOMESTAKE DUSEL DEEP UNDERGROUND SCIENCE AND ENGINEERING LABORATORY

South Dakota HOMESTAKE

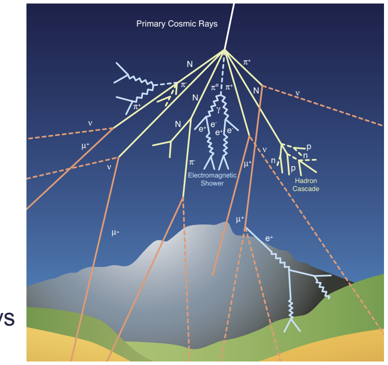
NNPSS-TSI Special Lecture

Underground (Neutrino) Physics

Mark Chen
Queen's University and the
Canadian Institute for Advanced Research

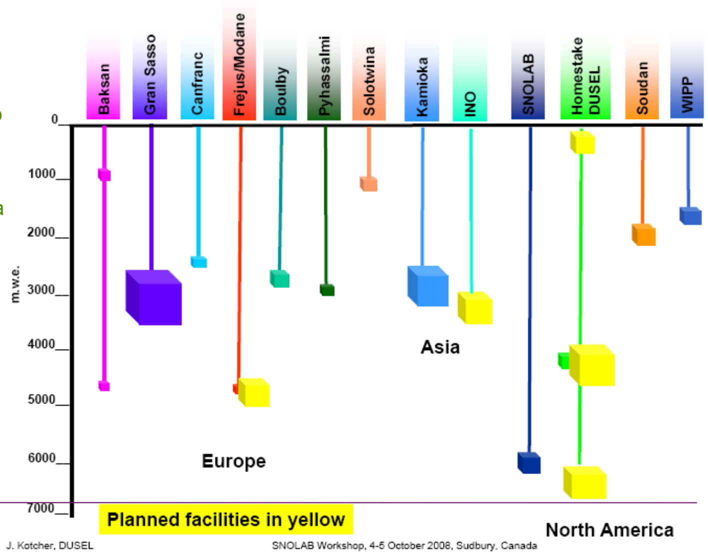
Physics and Astrophysics Underground

- searching for rare processes
  - neutrinoless double beta decay
  - proton decay
- detecting very weakly-interacting particles
  - neutrinos
  - dark matter particles (WIMPs)
- requires ultra-low backgrounds
  - underground location for cosmic rays
  - shielding from neutrons and gamma rays
  - detector materials with low radioactivity



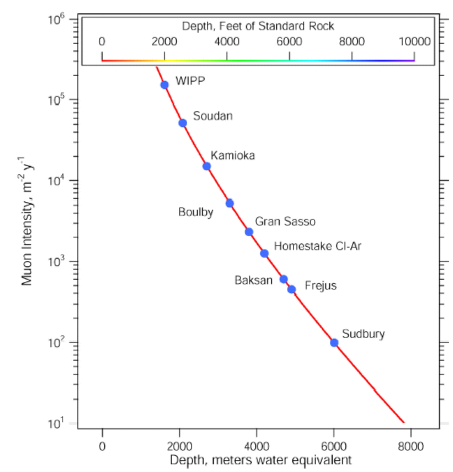
Underground Labs

not shown:
- Yangyang Lab in Korea [~2100 m.w.e.]
- planned China JinPing Deep Underground Laboratory [~7500 m.w.e.]



Muon Background versus Depth

- cosmic ray muons are a direct background in some experiments
- more often the concern is what muons produce in spallation, muon-induced hadronic showers and μ⁻ capture reactions:
  - fast neutrons
  - "cosmogenic" activated isotopes
- these are important backgrounds in most experiments; they are reduced with depth underground



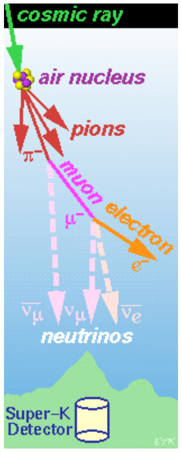
This Lecture is an Overview of Some of the Experimental Activity in this Field

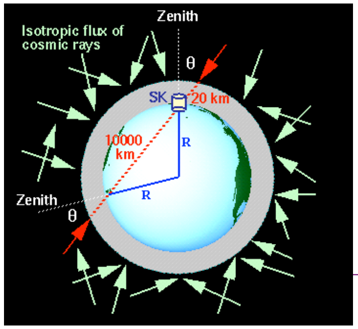
- neutrino physics
  - solar and atmospheric neutrino detectors
- double beta decay
- dark matter

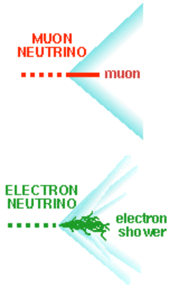
- will not talk about these underground physics topics
  - proton decay
  - long baseline accelerator neutrino experiments
  - reactor neutrino experiments
  - supernova neutrinos
  - geo neutrinos
  - UHE neutrino observatories (astrophysical neutrino sources)
  - underground accelerators for nuclear astrophysics experiments
  - gravitational waves

Atmospheric Neutrinos

- neutrinos produced by cosmic ray interactions in the atmosphere
- expect a ratio for $\nu_e : \nu_\mu$ of approximately 1 : 2
- primary cosmic ray flux (E > ~10 GeV) is isotropic hence atmospheric neutrino flux should be up/down symmetric



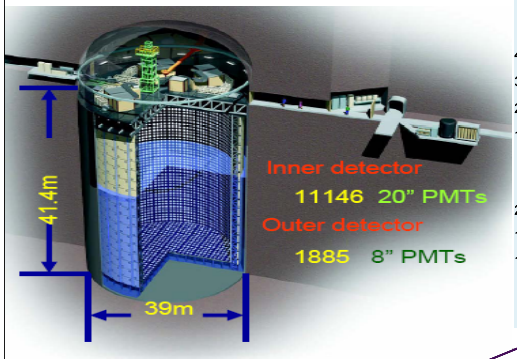


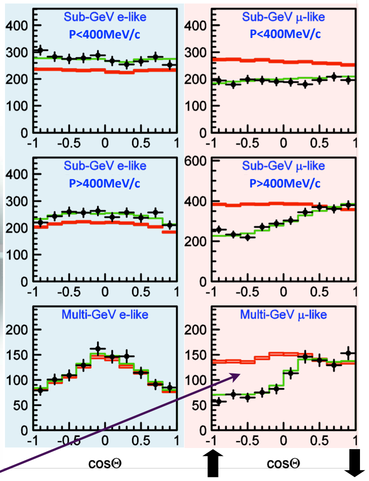


from Boston University Super-K web site

Super-Kamiokande Detector

- Super-Kamiokande 22.5 kton fiducial volume water Čerenkov detector
- uses sharpness/fuzziness of Čerenkov ring to distinguish ν_μ from ν_e





1998: Discovery of Neutrino Oscillations

above: SK-I and SK-II combined results

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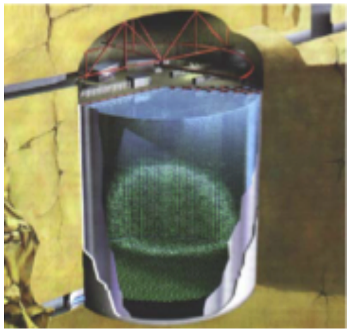

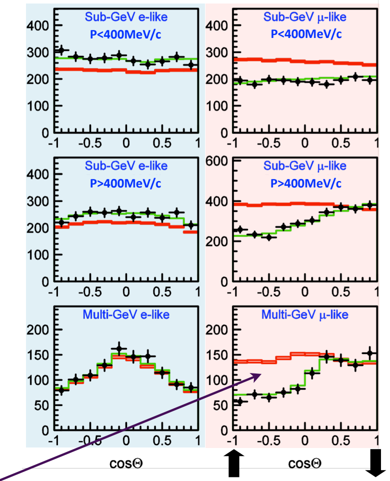

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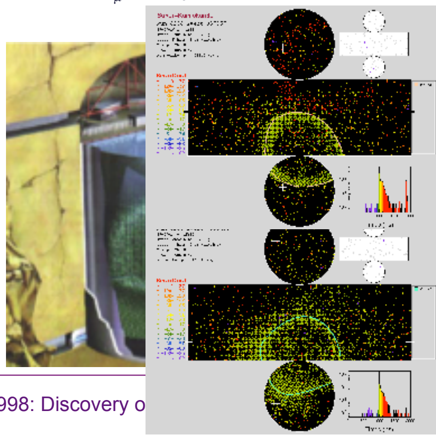

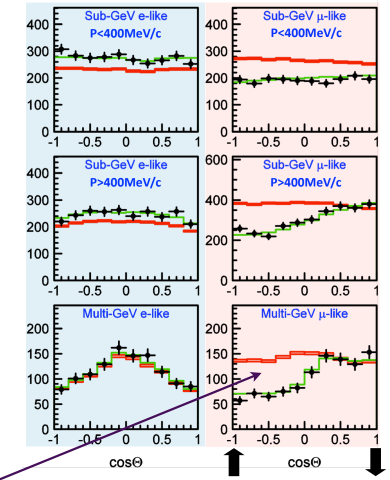

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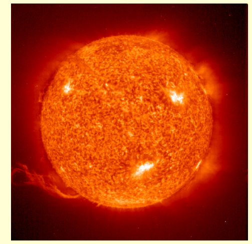
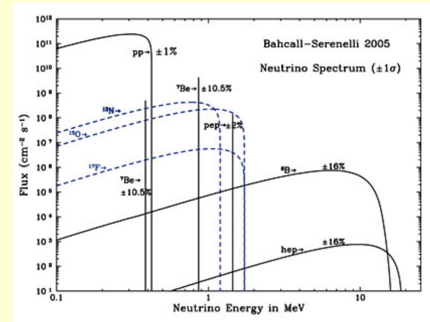
Solar Neutrinos





***pp* Solar Fusion Chain**

$p + p \rightarrow {}^2H + e^+ + \nu_e$ $\quad$ $p + e^- + p \rightarrow {}^2H + \nu_e$

${}^2H + p \rightarrow {}^3He + \gamma$

${}^3He + {}^3He \rightarrow {}^4He + 2p$ $\quad$ ${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

${}^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e$ $\quad$ ${}^7Be + p \rightarrow {}^8B + \gamma$

${}^7Li + p \rightarrow \alpha + \alpha$ $\quad$ ${}^8B \rightarrow 2\alpha + e^+ + \nu_e$

***CNO* Cycle**

${}^{12}C + p \rightarrow {}^{13}N + \gamma$ $\quad$ ${}^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$

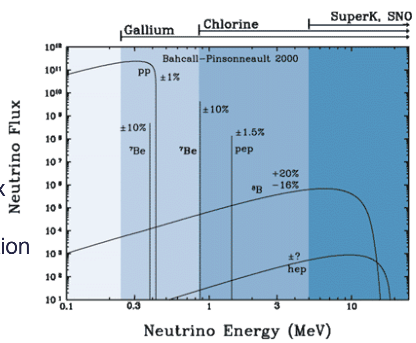
${}^{13}C + p \rightarrow {}^{14}N + \gamma$

${}^{14}N + p \rightarrow {}^{15}O + \gamma$ $\quad$ ${}^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$

${}^{15}N + p \rightarrow {}^{12}C + \alpha$

Solar Neutrino Experiments

- water (and heavy water) Čerenkov
  - Super-K [Japan] and SNO [Canada]
  - detect higher energy ${}^8B$ solar ν
- radiochemical experiments
  - SAGE [Russia], Chlorine [USA], Gallex and GNO [Italy]
  - measured the integral flux above reaction threshold
- liquid scintillator
  - Borexino [Italy]
  - planned SNO+ [Canada]
  - can detect lower energy solar ν's like ${}^7Be$ and pep using neutrino-electron scattering

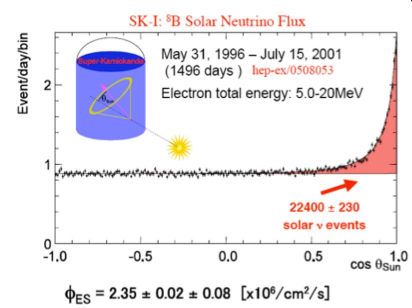


measured / no oscillation expectation

Chlorine	0.34 ± 0.03
Gallium	0.52 ± 0.03
Super-K	0.46 ± 0.02

The "Solar Neutrino Problem"

Solar Neutrinos in Super-K



$\phi_{ES} = 2.35 \pm 0.02 \pm 0.08$ [$\times 10^6$/cm²/s]

SK-I day-night asymmetry converted to SNO-style ν_e asymmetry

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

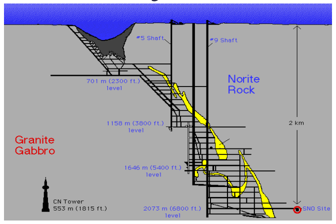
$$\nu_e + e^- \rightarrow \nu_e + e^-$$

~6 times higher cross section than

$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$

SK-IV is running; aiming to lower backgrounds and thresholds to see the spectrum upturn at lower energies predicted by MSW LMA

Sudbury Neutrino Observatory



1000 tonnes D_2O

12 m diameter Acrylic Vessel

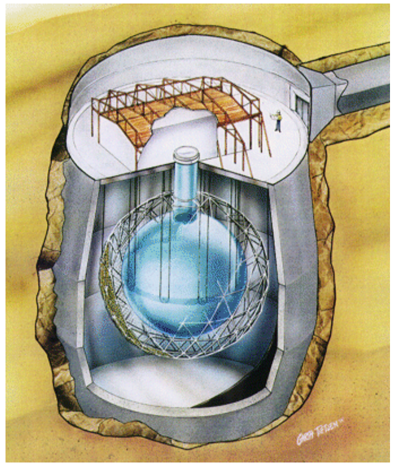
18 m diameter PMT support structure

9500 PMTs (~60% photocathode coverage)

7000 tonnes shielding H_2O

Urylon liner radon seal

depth: 6010 m.w.e. [~70 muons/day]



Neutrino Reactions in SNO

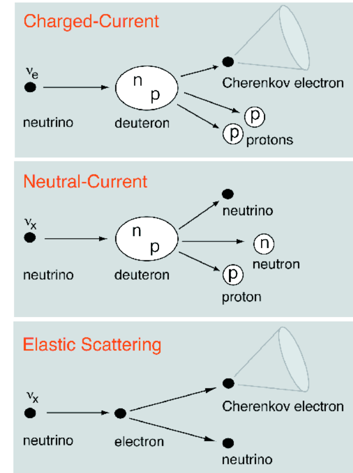
CC $\nu_e + d \rightarrow p + p + e^-$

- only detects ν_e flavor
- good measure of neutrino energy spectrum

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

- measures total ^8B ν flux from the Sun
- equal cross section for all active ν flavors

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



Three Phases of SNO

Pure D_2O	**Salt**	**^{3}He Counters**
Nov 99 – May 01	**Jul 01 – Sep 03**	**Nov 04 – Nov 06**
$n + d \rightarrow t + \gamma$	$n + {}^{35}Cl \rightarrow {}^{36}Cl + \gamma$	$n + {}^3He \rightarrow t + p$
(E_γ = 6.25 MeV)	($E_{\Sigma\gamma}$ = 8.6 MeV)	proportional counters σ = 5330 b
	enhanced NC rate and separation	event-by-event separation
PRL **87**, 071301 (2001) PRL **89**, 011301 (2002) PRL **89**, 011302 (2002) PRC **75**, 045502 (2007)	PRL **92**, 181301 (2004) PRC **72**, 055502 (2005)	PRL **101**, 111301 (2008)

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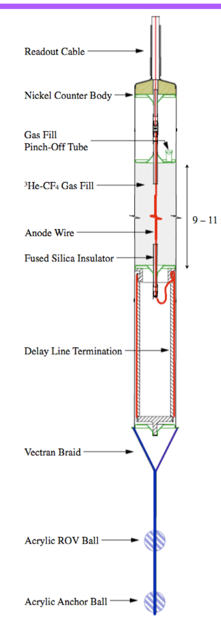

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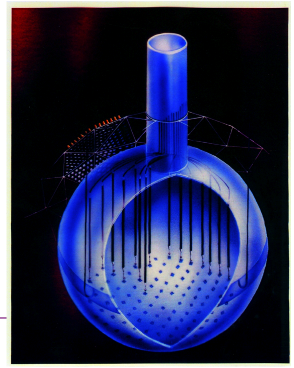


391-Day Salt Phase Flux Results (2005)

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.340 \pm 0.023 \,^{+0.029}_{-0.031}$$

$$\Phi_{CC}(\nu_e) = 1.68 \,^{+0.06}_{-0.06}\,(\text{stat.})\,^{+0.08}_{-0.09}\,(\text{syst.}) \times 10^6\ \text{cm}^{-2}\,\text{s}^{-1}$$

$$\Phi_{NC}(\nu_x) = 4.94 \,^{+0.21}_{-0.21}\,(\text{stat.})\,^{+0.38}_{-0.34}\,(\text{syst.}) \times 10^6\ \text{cm}^{-2}\,\text{s}^{-1}$$

BS05(OP) Standard Solar Model Flux Calculation:
$(5.69 \pm 0.91) \times 10^6\ \text{cm}^{-2}\,\text{s}^{-1}$

2001 and 2002: Solar Neutrino Problem Solved by Direct Observation of Solar Neutrinos Changing Flavor ➔ produced as electron neutrinos but only 0.34 surviving as ν_e

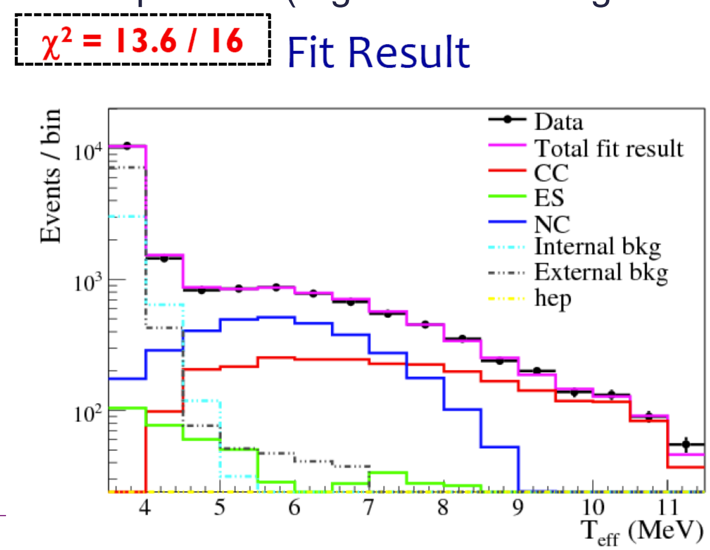
...the NC measurement is also confirmation that solar models are correct and that energy generation in stars is understood!

New SNO Results arXiv:0910.2984

accepted for publication in Phys Rev C

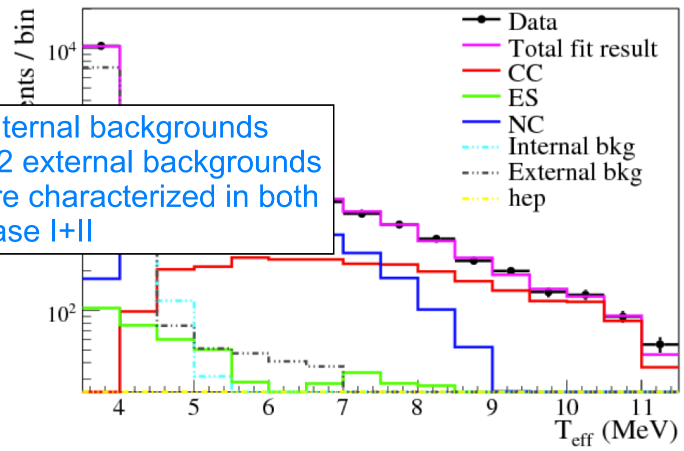
- lower energy threshold analysis (LETA)
- combined Phase I+II joint fit
  - signal extraction in each phase helps constrain the other
  - improvement is better than just simple statistical combination
- improved simulations and analysis (e.g. energy resolution is slightly better helping suppress steep background tails)
- reduced systematic uncertainties
- different signal extraction techniques
- 3-neutrino oscillation analysis

Extracted Spectrum (Signals and Background)



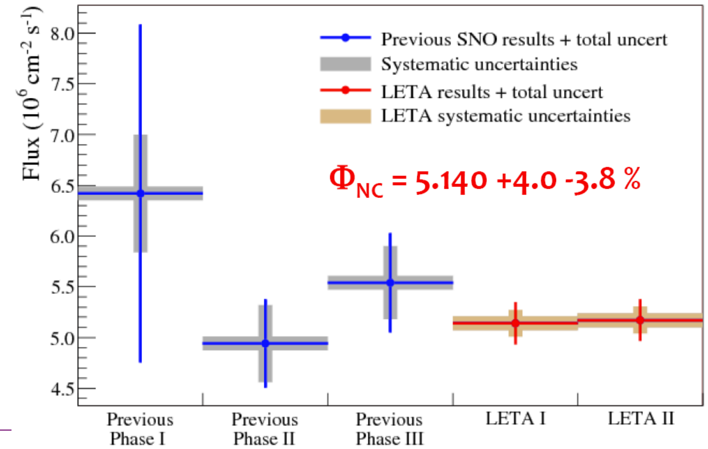
Extracted Spectrum (Signals and Background)

$\chi^2 = 13.6 / 16$ Fit Result



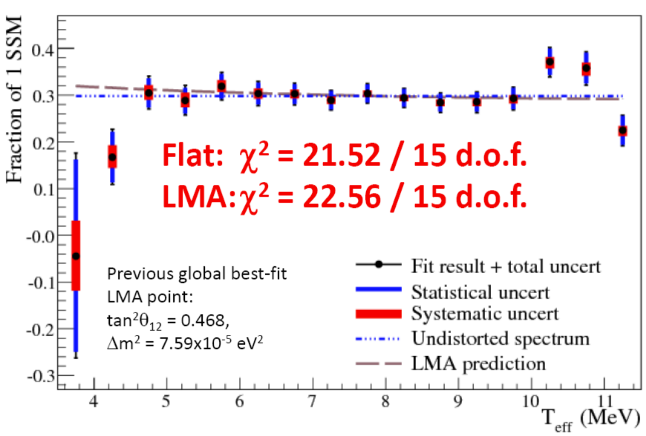
5 internal backgrounds
+ 12 external backgrounds
were characterized in both
Phase I+II

New SNO Low Energy Threshold Analysis
^{8}B Solar Neutrino Flux Measurements



Spectrum from CC Events

CC Recoil-Electron Spectrum

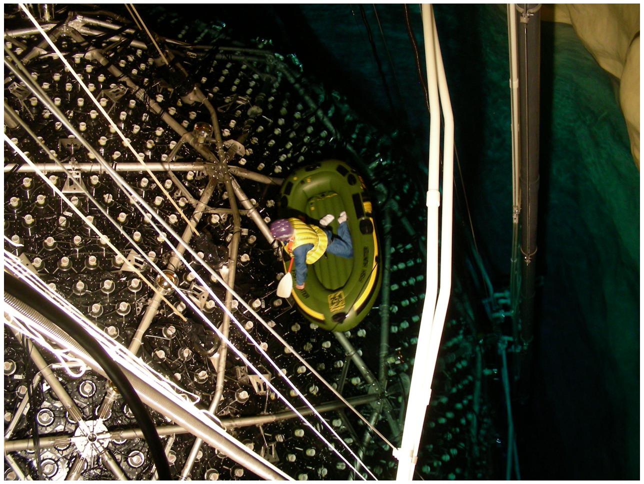


SNO Heavy Water is Returned

- the Sudbury Neutrino Observatory finished taking data with heavy water
- $300 million heavy water has been removed and returned to Atomic Energy of Canada Limited
  - Nov 28, 2006
    - end of data taking and detector turned off
  - May 28, 2007
    - heavy water removed...every last drop!

- we are moving on to SNO+ and are going to fill the detector with liquid scintillator...more on SNO+ later

Draining SNO and Boating Inspections



Entering the SNO Cavity – Bosun's Chair

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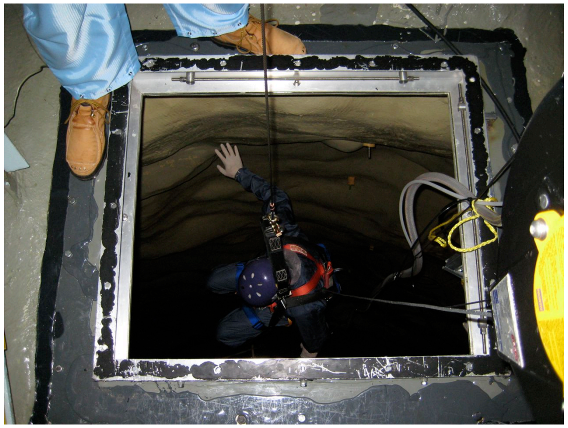
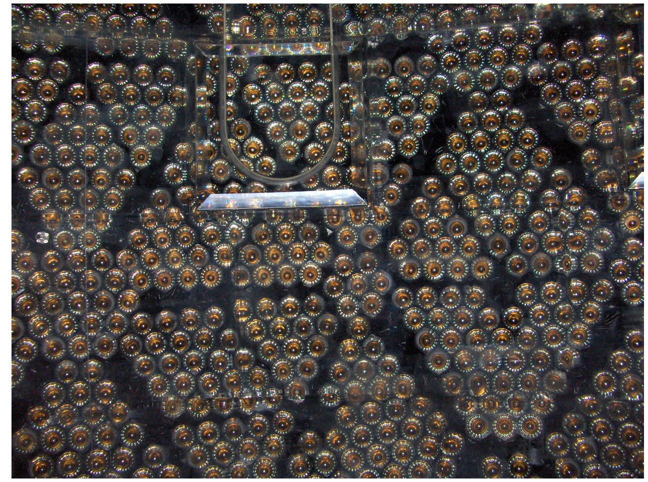


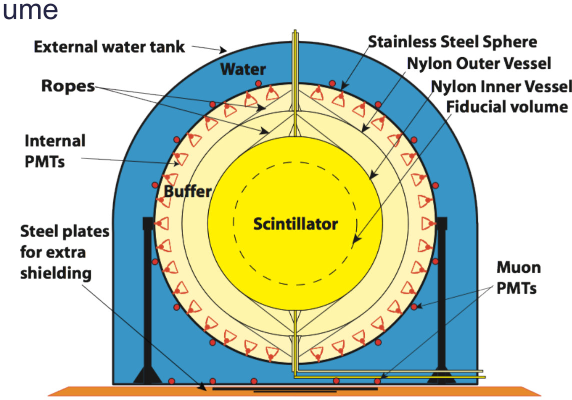
Entering the SNO Cavity – Bosun's Chair

Looking Out From Inside the SNO AV



Borexino

- 300 tons of pseudocumene-based scintillator
- 100 ton fiducial volume
- ^{7}Be solar ν
  - ν-e scattering
- 2212 8" PMTs
- light yield
  - ~500 p.e./MeV
- detector filled
  - May 15, 2007
- first results
  - Aug 16, 2007



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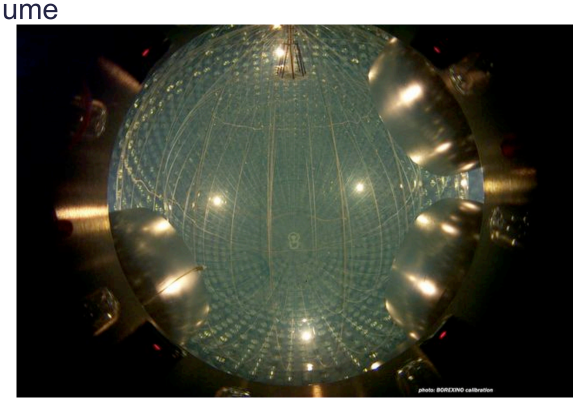
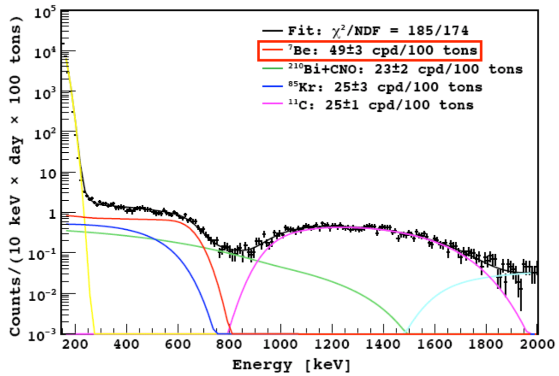


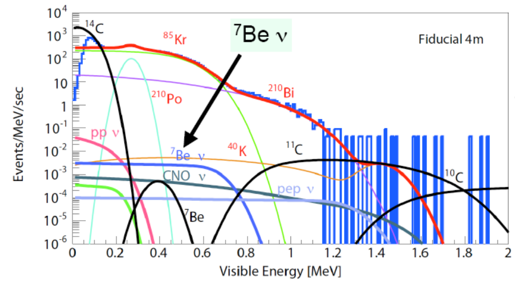
Borexino 2008 Results

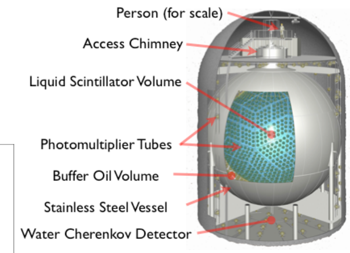
- electron recoil spectrum (alphas removed using PSD)
- 41.3 ton-yr fiducial exposure
- ^{7}Be solar ν signal 49±3 counts/day/100 tons
  - unoscillated expectation for SSM 74 counts/day/100 tons



KamLAND

- 1000 tons (80% dodecane, 20% pseudocumene)
- 1880 PMTs (17" and 20")
  - 34% photocathode coverage
- singles spectrum shows ^{210}Pb and ^{85}Kr also ^{40}K contamination





need to purify their liquid scintillator to achieve solar ν sensitivity

goal: 10^5 to 10^6 reduction

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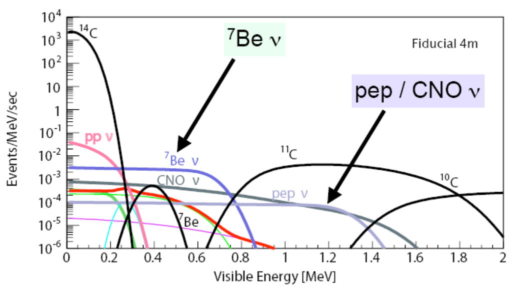

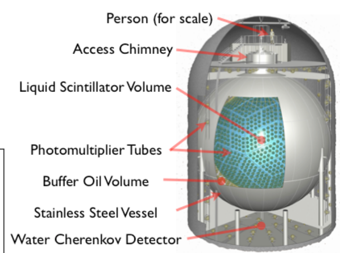

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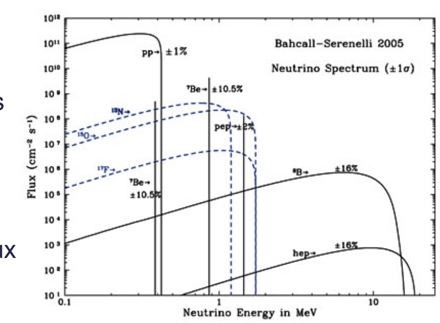
Solar Neutrinos: What's Known Putting It All Together

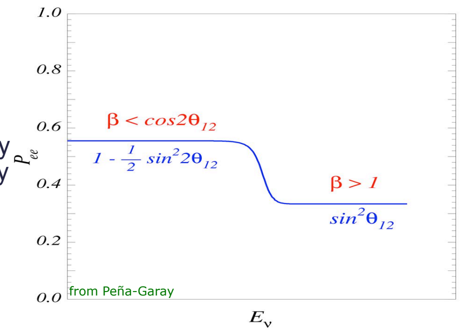
- ^{8}B solar ν well studied
  - by SNO and Super-K
- there are good data on *pp* solar ν's from the Ga experiments
  - must determine contribution of ^{8}B and ^{7}Be, subtract, and you get *pp* from the Ga experiments
- Borexino has measured the ^{7}Be flux



***pep* and *CNO* solar neutrinos are the next targets and SNO+ aims to detect these**

Neutrino-Matter Interaction

- exploring the vacuum-matter transition is sensitive to new physics
- new neutrino-matter couplings (either FCNC or lepton universality violating) can be parameterized by a new "MSW" term ε
- where is the relative effect of new physics the largest?
  - at resonance!



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

Hamiltonian for neutrino propagation in the Sun

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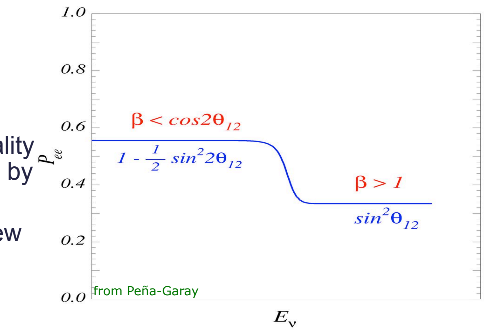

- for $\Delta m^2 = 8 \times 10^{-5}$ eV², θ = 34° N_e at the centre of the Sun

→ E is 1-2 MeV

***pep* solar neutrinos: good place to look for new physics**

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

Hamiltonian for neutrino propagation in the Sun

Neutrino-Matter Interaction

P_{ee} curve with non-standard interactions

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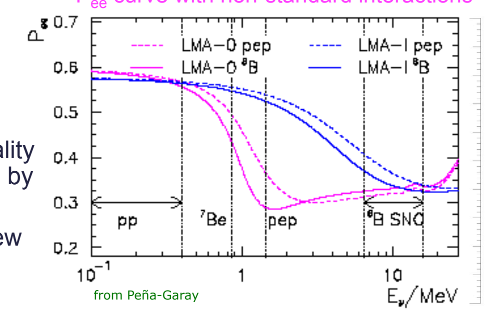

from Friedland, Lunardini, Peña-Garay, hep-ph/0402266

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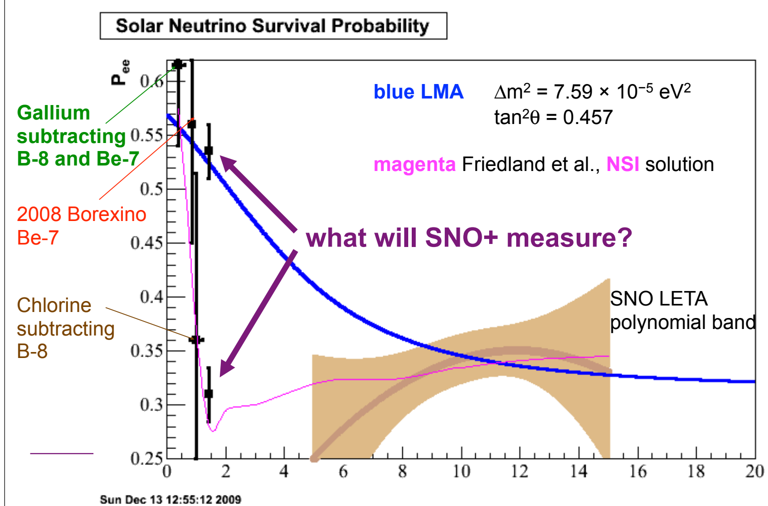
→ E is 1-2 MeV

***pep* solar neutrinos: good place to look for new physics**

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

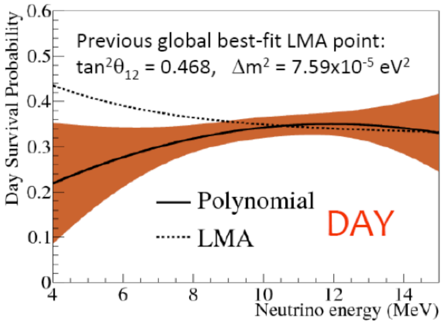
Hamiltonian for neutrino propagation in the Sun

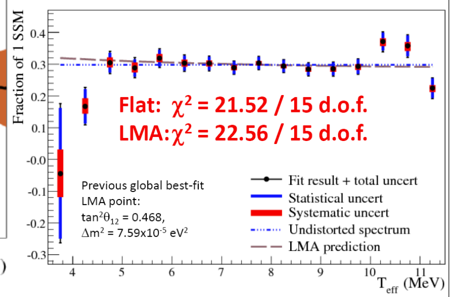
Survival Probability for Solar Neutrinos: All Experimental Data Distilled



Recall the SNO Low Energy Threshold Analysis

CC Recoil-Electron Spectrum





SNO CC/NC is a direct measure of the survival probability
- hence, can extract the survival probability versus neutrino energy

Borexino Has Detected ^{8}B Solar Neutrinos

- lowest energy bin seems low also!

arXiv:0808.2868v2

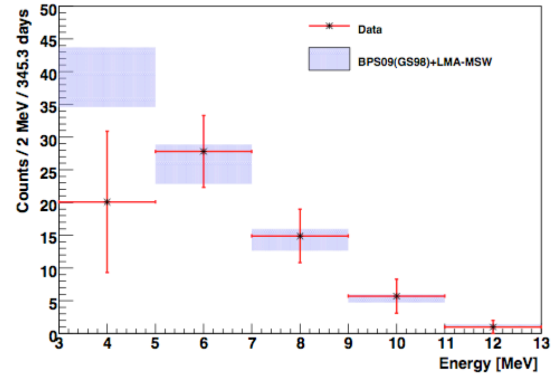
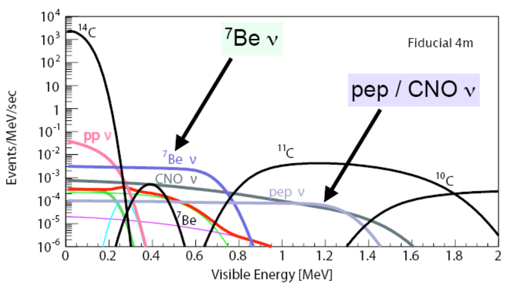


Figure 7: Comparison of the final spectrum after data selection and background subtraction (red dots) to Monte Carlo simulations (blue) of oscillated ^{8}B ν interactions, with amplitude from the Standard Solar Model BPS09(GS98)

Measuring the *pep* and *CNO* Neutrino Flux

- underground cosmogenic background from ^{11}C is eliminated at SNOLAB depths of 6000 mwe
  - muon flux is ~700 times lower than Kamioka, ~100 times lower than Gran Sasso

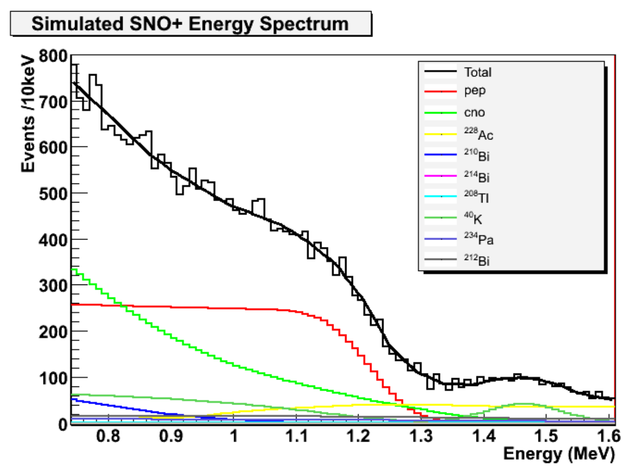


^{11}C has a 20 min half-life – challenging to veto or tag this background for ~10,000 muons/day

SNO+ will have ~70 muons/day

figure from KamLAND: solar neutrinos in KamLAND and cosmogenic carbon backgrounds

SNO+ pep and CNO Solar Neutrino Signals



an accurate measurement of the rate of pep solar neutrino interactions:

$R = \Phi P_{ee} \sigma$

flux is calculated in SSM to ±1.5%

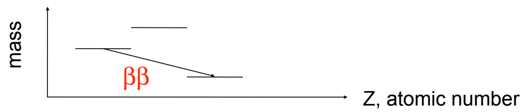
cross section is known (ν-e scattering)

yields an accurate measure of the survival probability

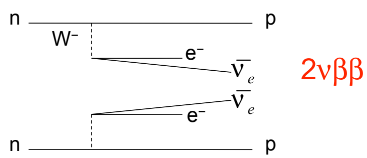
3600 *pep* events/(kton·year), for electron recoils >0.8 MeV

Double Beta Decay

- some nuclei cannot β decay but can undergo double beta decay, a very rare process
  - e.g. ^{76}Ge has half-life 1.3 × 10^{21} years



- even rarer is neutrinoless double beta decay (has never been observed *and confirmed*)



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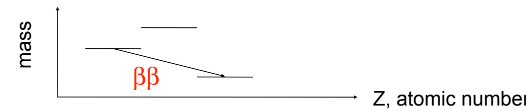

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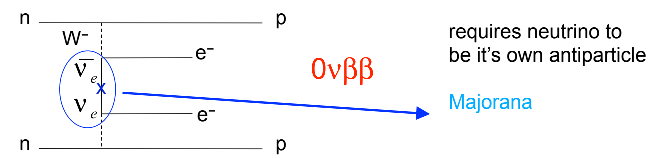
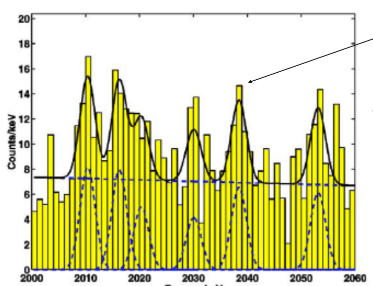


Claim of Observation of 0νββ

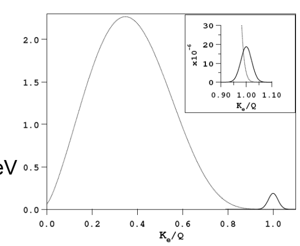
- subset of the Heidelberg-Moscow collaboration reanalyzed the data
  - 11 kg of enriched ^{76}Ge



peak at 2039 keV

there are also peaks from known and unexpected gamma-ray lines

from H.V. Klapdor-Kleingrothaus et al., Phys. Lett. B **586**, 198 (2004)

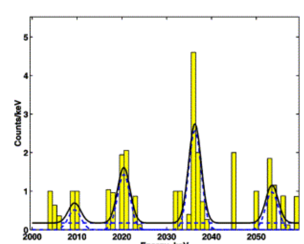


from S. Elliott and P. Vogel

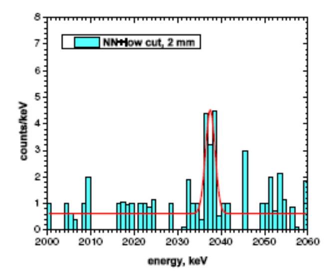
signature of 0νββ: peak at the decay endpoint

Claim of Observation of 0νββ

- with pulse shape analysis to select single site events (keep betas and reject gammas)



H.V. Klapdor-Kleingrothaus et al. (2004) analysis with PSA



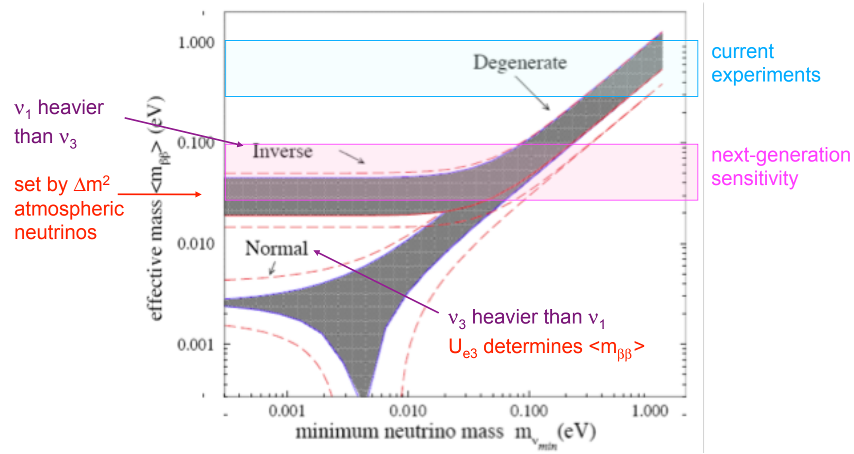
H.V. Klapdor-Kleingrothaus et al. (2006) analysis with "improved" PSA

Significance of Neutrinoless Double Beta Decay

- if neutrinos are Majorana particles
  - lepton number is not conserved (introduced ad hoc in the Standard Model so this is fine to shed)
  - offers a "simpler" theory for massive neutrinos
- light neutrino exchange can mediate the 0νββ process
  - rate (i.e. half-life) depends on effective Majorana neutrino mass
  - upcoming double beta decay experiments probe neutrino mass scales down to interesting levels suggested by the inverted neutrino mass hierarchy
- potential connection to cosmology via CP-violating Majorana phases, $\Delta L \neq 0$ and leptogenesis
- definite connection to physics at higher energy scales (e.g. Majorana neutrino mass terms and the see-saw mechanism)
- the lowest order extension to the Standard Model is a dimension-5 operator that's unique…and it's Majorana neutrino mass

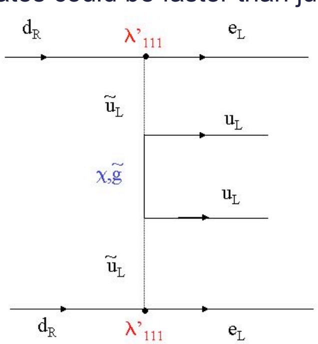
$$[T^{0\nu}_{1/2}(0^+ \to 0^+)]^{-1} = G^{0\nu}(E_0, Z)\left|M^{0\nu}_{GT} - \frac{g_V^2}{g_A^2}M^{0\nu}_F\right|^2 \langle m_{\beta\beta}\rangle^2 \qquad \langle m_{\beta\beta}\rangle = \left|\sum_i |U_{ei}|^2 m_{\nu_i} e^{i\alpha_i}\right|$$

Neutrino Mass Hierarchy and 0νββ



Other New Physics and 0νββ

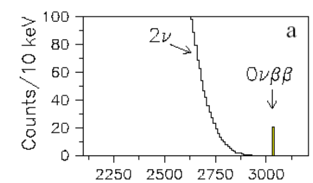
- e.g. (one of many) R-parity violating supersymmetry contributes to the decay rate (measured half-life)
- rates could be faster than just light neutrino exchange

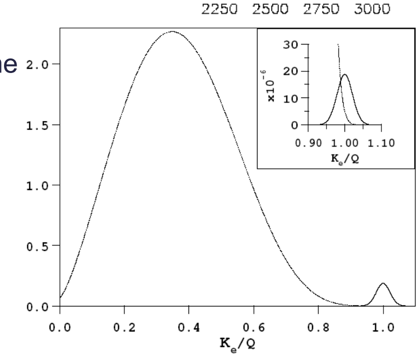


observation of neutrinoless double beta decay implies Majorana neutrino mass even if new physics determines the decay rate "Schecter-Valle theorem"

Experimental Approaches

- low backgrounds required (always)
- good energy resolution at endpoint to find 0νββ peak
- tracking can help – identify two electrons originating from the same point
- if neutrinoless double beta decay occurs, we should see it in many isotopes
- hence, many experiments with different approaches desirable





ββ Isotopes

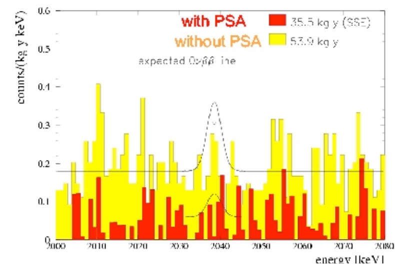
scintillators
semiconductors
tracking
bolometer/calorimeter

isotope	Q-value [MeV]	natural abundance
^{48}Ca	4.27	0.19%
^{150}Nd	3.37	5.6%
^{96}Zr	3.35	2.8%
^{100}Mo	3.03	9.6%
^{82}Se	3.00	8.7%
^{116}Cd	2.80	7.5%
^{130}Te	2.53	34%
^{136}Xe	2.48	8.9%
^{76}Ge	2.04	7.8%

Experiments Using These Isotopes
CANDLES
SNO+
MOON
SuperNEMO
C0BRA
CUORE
EXO, KamLAND-Zen
GERDA, Majorana

ββ Experiments: Semiconductors

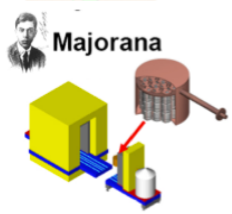
- Ge diodes have excellent energy resolution
- can use pulse shape analysis to select single site events to reject gamma background
- Heidelberg-Moscow [Gran Sasso]
  - ~11 kg 86% enriched ^{76}Ge
  - $t_{1/2} > 1.9 \times 10^{25}$ yr (90% CL)
  - $<m_\nu> < 0.35$-1.05 eV (90% CL)
  - 0.06 counts/keV/kg/yr at $Q_{\beta\beta}$
- IGEX [Canfranc] similar results



Future Semiconductor Experiments

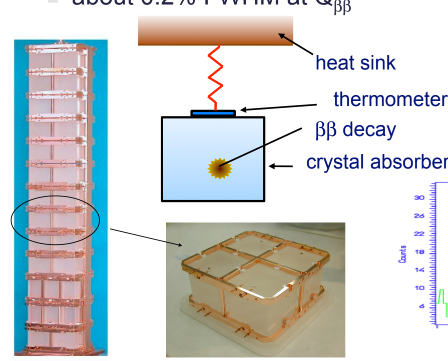
- segmented crystals and/or arrays of crystals
  - reject multiple Compton gamma background
- GERDA [Gran Sasso]: bare crystals in LAr
  - less material, less background
  - LAr scintillation gamma veto
- Majorana [DUSEL]: high-purity electroformed copper cryostats
- background goal: 10^{-3} to 10^{-4} counts/keV/kg/yr

GERDA	17.9 kg enriched Ge then expand to 40 kg	start 2010
Majorana	60 kg enriched Ge then expand to 500 kg	start 2013?
C0BRA	0.42 kg CdZnTe operating	R&D



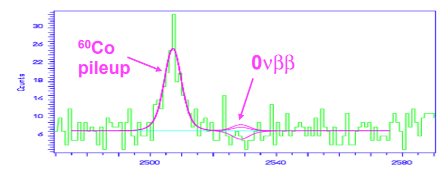
ββ Experiments: Bolometers

- bolometers of TeO_2 also have excellent energy resolution
  - about 0.2% FWHM at $Q_{\beta\beta}$



Cuoricino has 10.4 kg of ^{130}Te running in Gran Sasso since 2003

now building CUORE [Gran Sasso] 750 kg of TeO_2 or 203 kg of ^{130}Te, start data taking in 2012-2013



results from 11.83 kg-yr exposure

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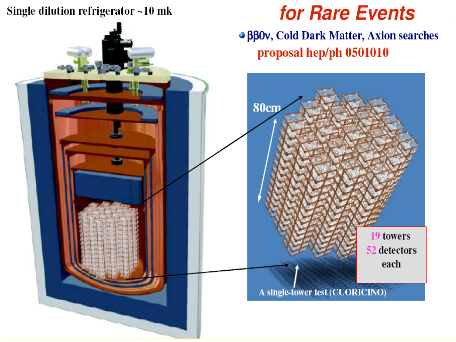

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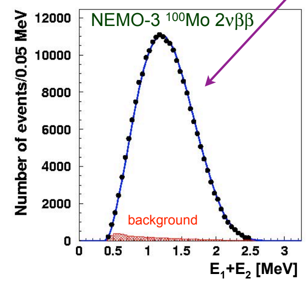
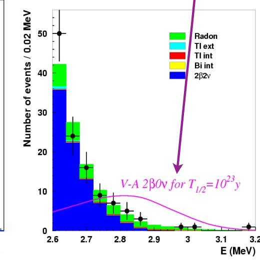
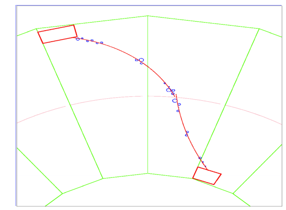
ββ Experiments: Tracking Detectors

- NEMO-3 [Modane] currently running with several ββ isotopes (e.g. 7 kg ^{100}Mo) on source foils
  - strong background rejection
  - $<10^{-3}$ counts/keV/kg/yr
  - worse energy resolution than calorimeters

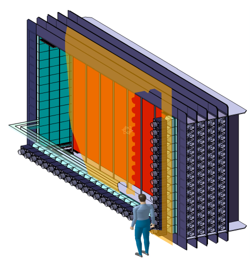




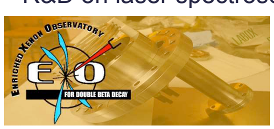


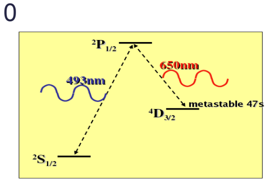
Future ββ Tracking Experiments

- isotope on source foils
  - SuperNEMO [Canfranc] 100 kg ^{82}Se
    - R&D, proposed start 2014-2017
  - MOON [Japan] ^{100}Mo
    - R&D aiming for 20 kg
- Xe TPC (gas TPC allows tracking)
  - EXO-200 [WIPP] 200 kg enriched ^{136}Xe
    - liquid Xe detector; data taking starts 2010
  - R&D on laser spectroscopy tagging of Ba



SuperNEMO module
5 kg isotope source foil





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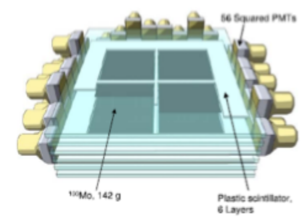
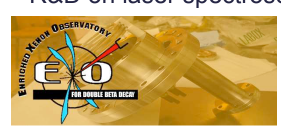
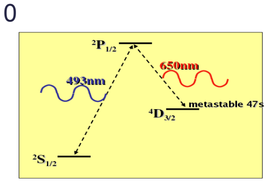


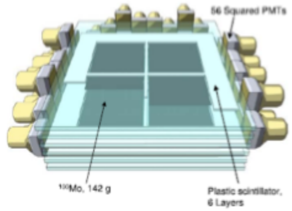
MOON prototype
142 g of ^{100}Mo





Future ββ Tracking Experiments

- *note: angular distributions and single electron energy distributions can be measured – important if 0νββ signal observed to discern mechanisms*
  - R&D aiming for 20 kg



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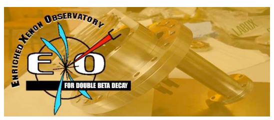
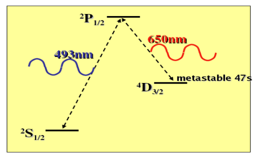


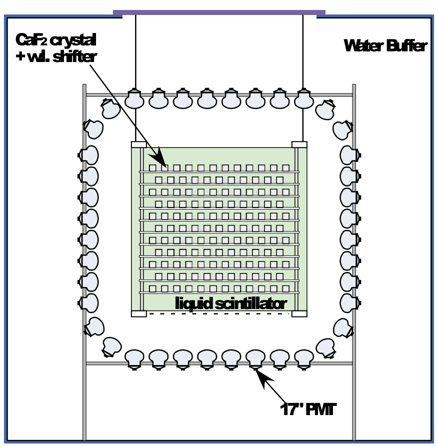


ββ Experiments: Scintillators

- “economical” way to build a detector with a **large** amount of isotope
- several isotopes can be made into (or put in) a scintillator
- ultra-low background can be achieved (e.g. phototubes stand off from the scintillator, self-shielding of fiducial volume)
- with a liquid scintillator, possibility to purify *in-situ* to further reduce backgrounds
- but with scintillator, energy resolution is relatively poor
  - but fitting spectrum endpoint shape works with “high” statistics and low background
- prefer high endpoint isotopes with $Q_{\beta\beta}$ above 2.6 MeV line from ^{208}Tl and above 3.2 MeV ^{214}Bi endpoint from radon

CANDLES

CAlcium fluoride for studies of Neutrino and Dark matters by Low Energy Spectrometer



- undoped CaF_2 crystals
  - ^{48}Ca (0.187%)
  - 305 kg (III-chika) 0.4 kg ^{48}Ca
    then expand to 3.4 tons (IV)
- new excavation in Kamioka for CANDLES-III; start data taking in 2009
- Liquid Scintillator (LS)
  - 4π active shield
  - also wavelength shifts light
- Photomultiplier
  - large photo-coverage
- Water buffer
  - Passive shield

Candles

CANDLES

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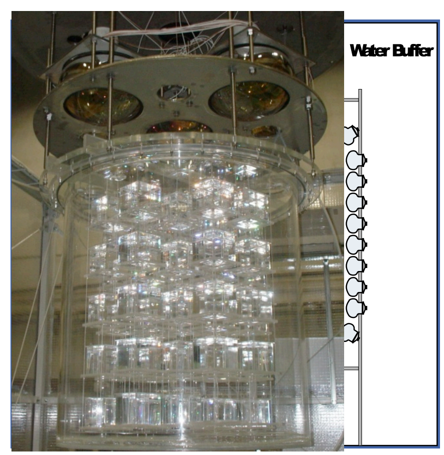

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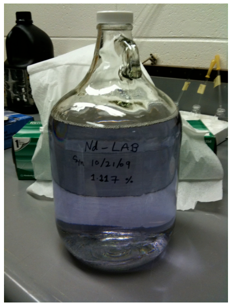
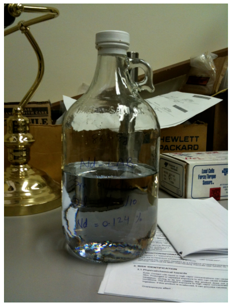
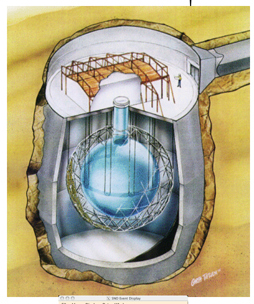
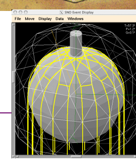
Candles

SNO+ Double Beta Decay

- we plan to fill SNO with Nd-loaded liquid scintillator, start data taking in 2012
- 0.1% Nd in 780 tonnes of scintillator
  - with natural Nd corresponds to 44 kg of ^{150}Nd isotope

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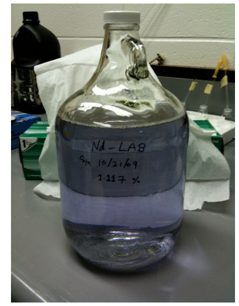
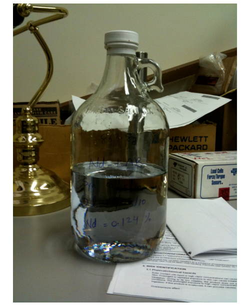
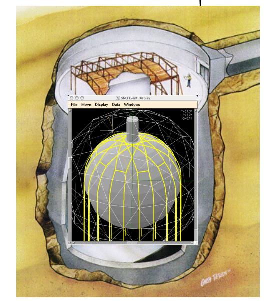
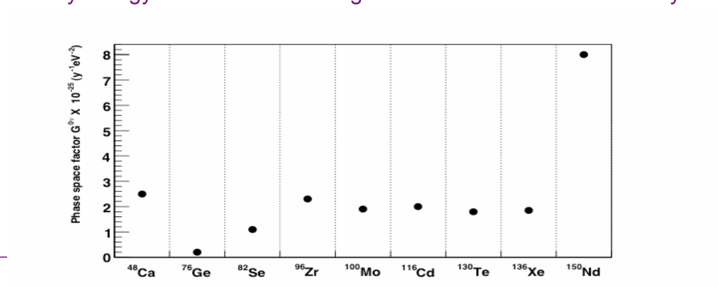




SNO+ Double Beta Decay with Nd

- SNO+ will use 0.1% (by weight) Nd-loaded liquid scintillator for a total deployed mass of 780 kg natural Nd
  - 44 kg of ^{150}Nd isotope
- ^{150}Nd has the second highest double beta endpoint at 3.37 MeV and the highest phase space factor
  - its decay energy is above most backgrounds from natural radioactivity

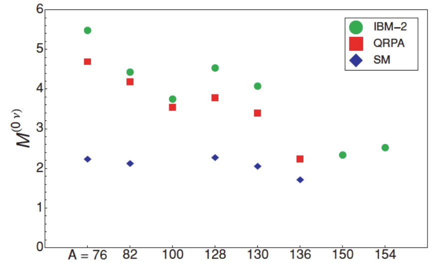


^{150}Nd $0\nu\beta\beta$ Rate

- largest phase space factor of all $\beta\beta$ isotopes
  - 44 kg ^{150}Nd equivalent to (considering only the phase space)
    - ~170 kg of ^{136}Xe
    - ~180 kg of ^{130}Te
    - ~750 kg of ^{76}Ge
- rate is: $(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2 \langle m_{\beta\beta}\rangle^2$
- decay rate per quantity [kg] of isotope goes as 1/A (already included in the above comparison)
- the nuclear matrix element...

Nuclear Matrix Element and Deformation

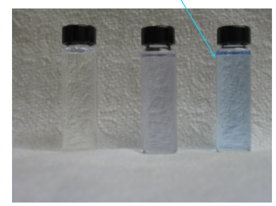
- recent NME calculations attempt to include the effect of deformation of ^{150}Nd-^{150}Sm nuclei
- e.g. Interacting Boson Model (IBM-2) of Barea and Iachello handles “the effects of deformation up to quadrupole deformation (d bosons)”

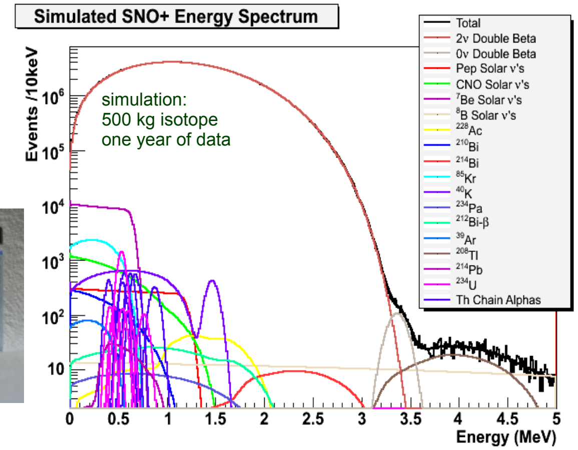


from Barea and Iachello

0νββ Signal for <m_ν> = 0.150 eV

0ν: 1000 events per year with 1% natural Nd-loaded liquid scintillator in SNO+





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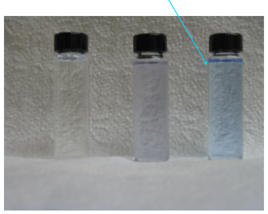
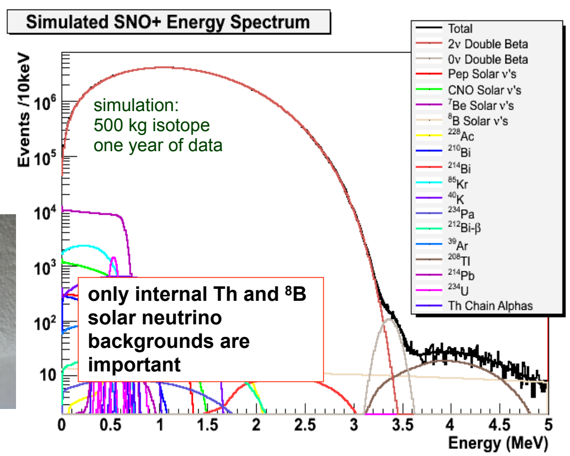
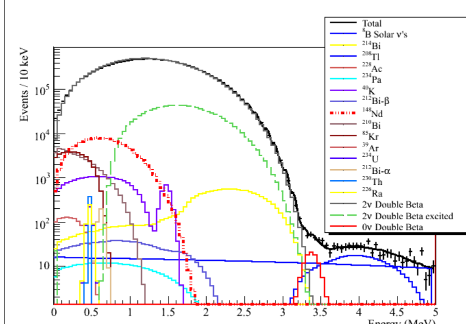


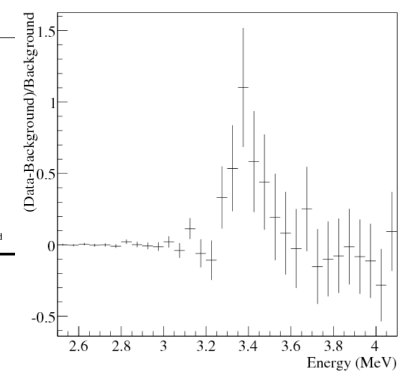


SNO+ 0νββ Simulations

double beta decay signal at the “KKDC level”

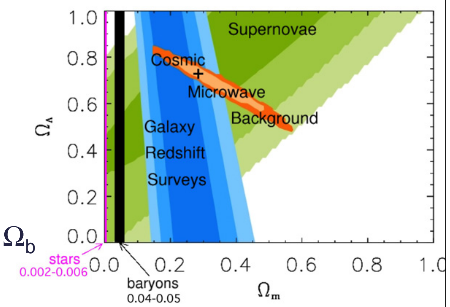


simulation of signals and backgrounds for **one year** data

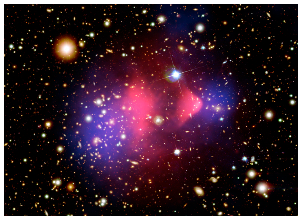


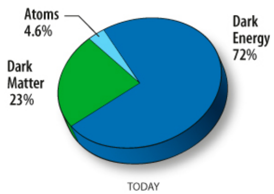
residual to fit with <m_ν>=0.27 eV

Dark Matter



- cosmology has a remarkable concordance of observations around the Λ_{CDM} model
- BBN and WMAP tell us $\Omega_m >> \Omega_b$
- weak lensing images the distribution of dark matter

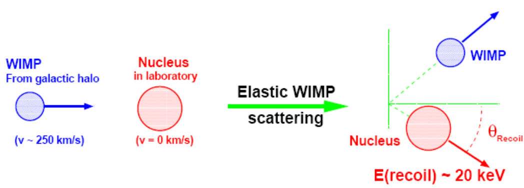




The Lowdown on Dark Matter

- dark matter particles are non-baryonic
- they are weakly interacting (practically collisionless)
- dark matter clumps together and provides the seed for ordinary matter to clump, forming galaxies, stars, clusters, etc.
- is mostly made of particles that are "cold" or non-relativistic
  - decouple when annihilation rate ≈ expansion
  - suggests the EW scale for the annihilation cross section
- …but we don't know what these particles are!
- supersymmetry is a leading candidate
  - provides stable relics that are weakly interacting massive particles or WIMPs (at the EW scale)
  - usually it's the neutralino χ that's considered

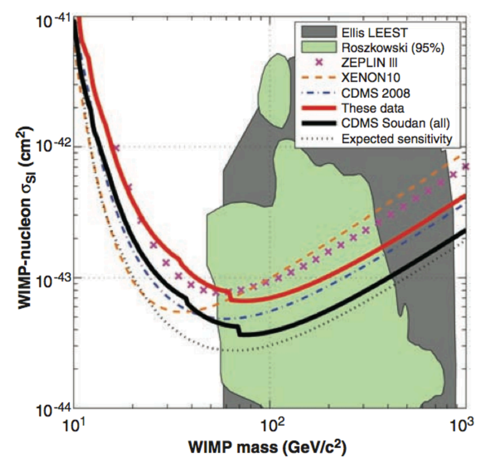
Direct Detection of Dark Matter



- event rates are low; recoil energies are low (keV)
- next-generation experiments require:
  - nuclear recoil discrimination
  - size (10^{-46} cm^2 is ~1 event/yr/ton)
- fast neutrons become the major background concern
- depth is absolutely required…fast neutrons produced by muons
  - at Soudan: ~0.8 n/yr/kg
  - at SNOLAB: ~1 n/yr/ton

Other Characteristics of an Ideal DM Detector

- directionality (very hard!)
- recoil energy spectrum measured (good resolution to see subtle changes)
- low threshold
- array of detectors (absence of multiple interactions)
- uniform rate throughout volume
- dependence on A^2
- annual modulation
- coverage of SUSY-allowed regions



CDMS limits from March 2010

Direct Detection Techniques

- this recent figure is already obsolete!
  - many worldwide dark matter efforts
- identifying nuclear recoils can come from reading out two observables
- some detectors have superb nuclear recoil discrimination from just one measurement (e.g. DEAP uses only liquid argon scintillation pulse shape)

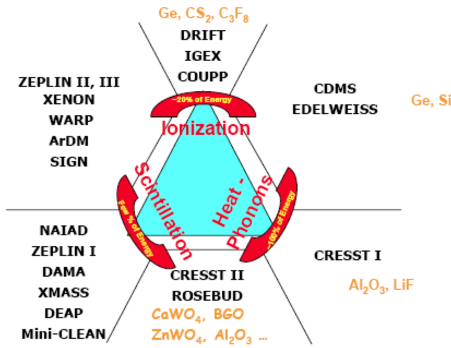


figure from B. Sadoulet

Noble Liquids

- easily and economically scalable to 1 ton or more
- excellent nuclear recoil discrimination
- pure, low backgrounds
- good self-shielding properties

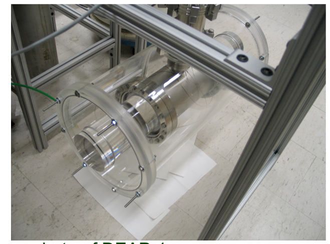
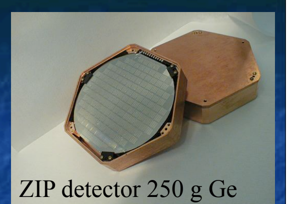


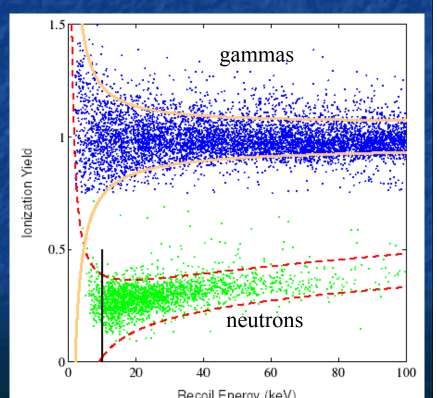
photo of DEAP-1

photo of XENON10

CDMS (Cryogenic Dark Matter Search)

- detect phonons (temperature rise) and ionization in array of bolometers: T~ 20 mK
- energy resolution is good
- threshold is low
- array of detectors
- different targets (Si and Ge)


ZIP detector 250 g Ge



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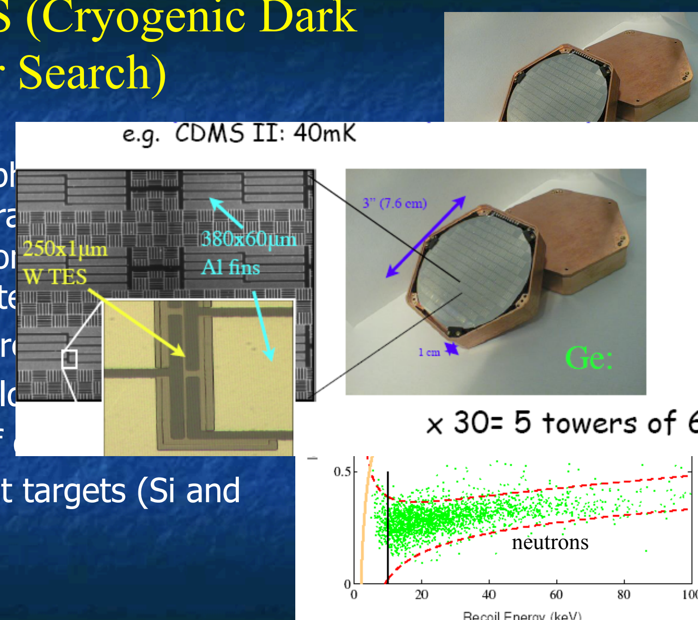

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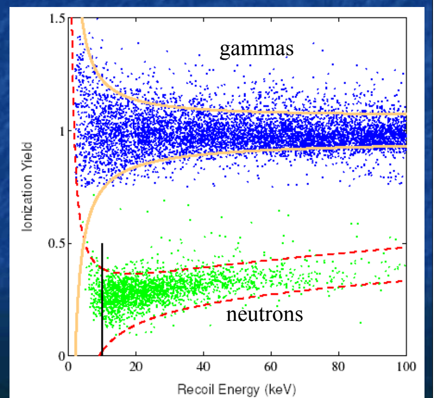
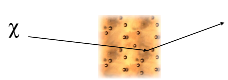


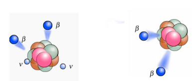
Future Dark Matter Experiments

- noble liquids moving to O(100)kg scale in the next year or two; O(1)ton scale soon after (2012-2013)
- cryogenic bolometers ionization-phonon detectors building at the O(25)kg scale; plans for O(1)ton
- new ideas being developed
  - bubble chamber (e.g. COUPP)
  - detectors sensitive to recoil direction (e.g. low-pressure TPC)

Concluding Remarks

- large underground neutrino detectors can explore many physics topics
  - Super-K water Čerenkov: atmospheric neutrinos, solar neutrinos, proton decay, long baseline detector (T2K far detector), supernova neutrinos
  - Borexino, KamLAND, SNO+ liquid scintillator: solar neutrinos, reactor antineutrinos, geoneutrinos, supernova neutrinos
- high priority physics goals require underground labs
  - search for neutrinoless double beta decay
  - search for dark matter





Extra Slides

- photos of SNOLAB
- experiments at SNOLAB