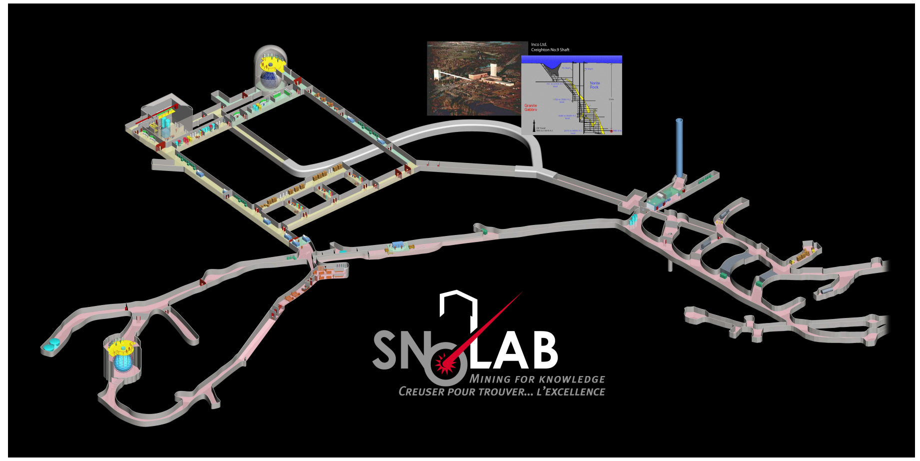
Deep Underground Astroparticle Physics at SNOLAB



Eric Vázquez Jáuregui

SNOLAB

Particle Astrophysics Seminar
Batavia IL, USA; July 30, 2012

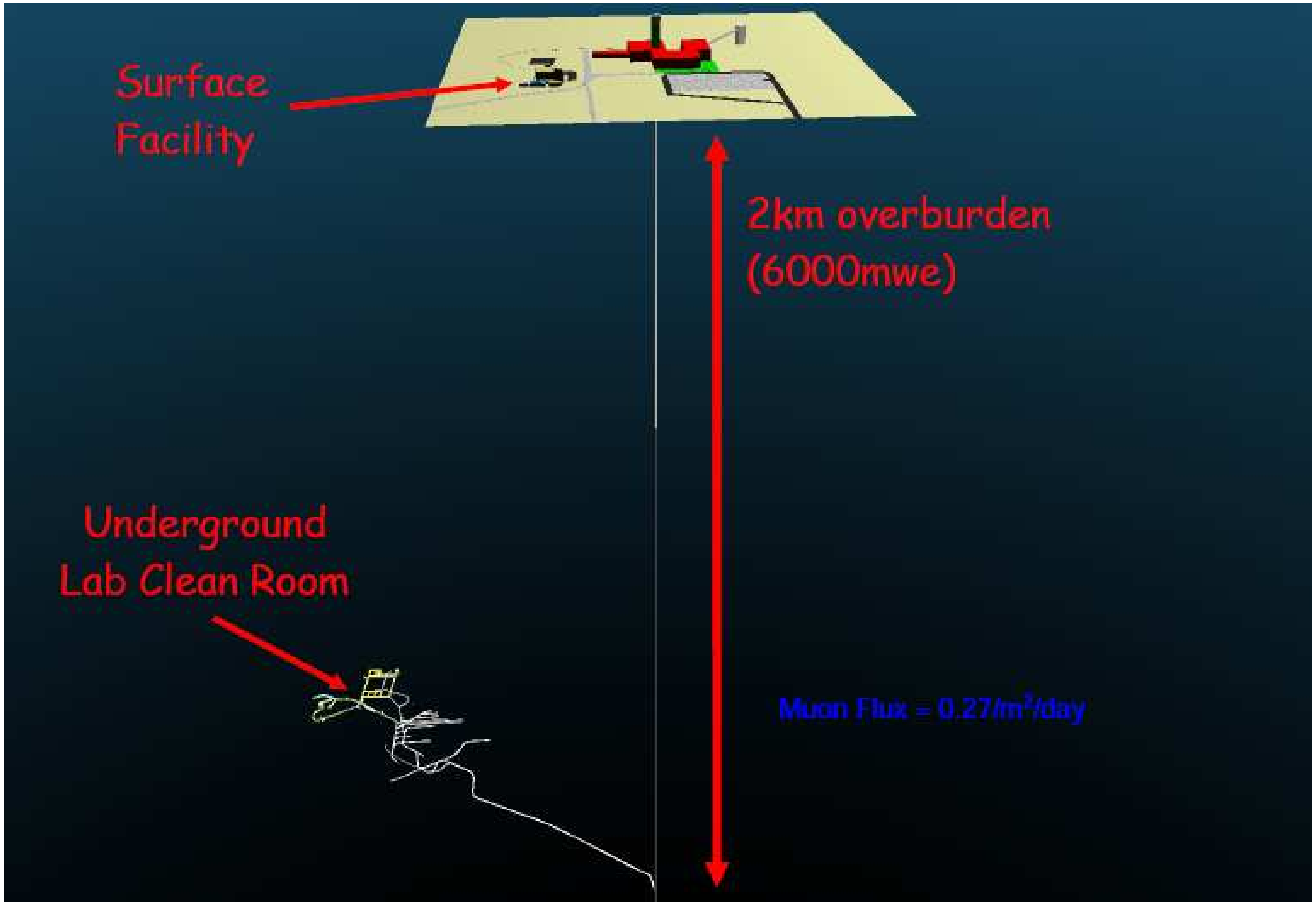
Outline

- **SNOLAB facility**
- **Neutrino Physics programme**
  - **SNO+ and HALO**
- **Dark Matter programme**
  - **DEAP, MiniCLEAN, PICASSO and COUPP**
- **Future experiments and underground science**
- **Final remarks**

SNOLAB objectives

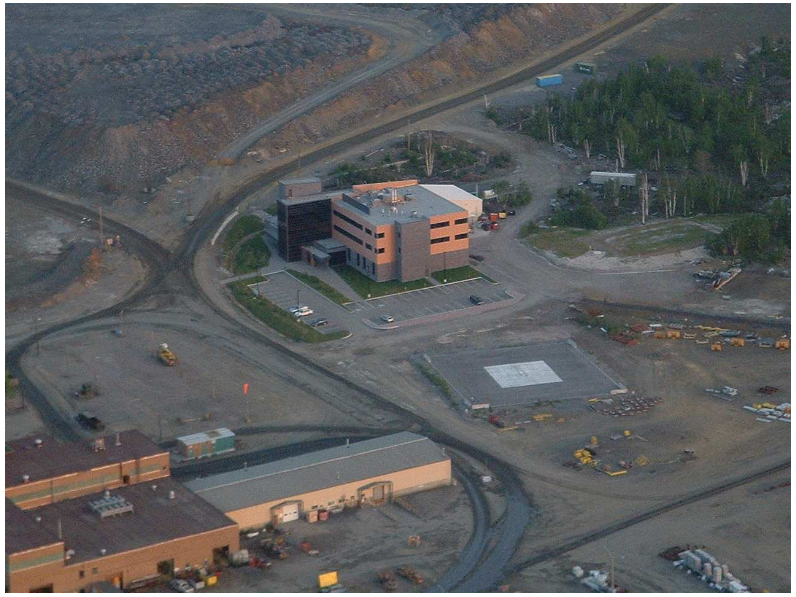
- To promote an International programme of Astroparticle Physics
- To provide a very deep experimental laboratory to shield sensitive experiments from penetrating Cosmic Rays
- To provide a very clean laboratory at better than class 2000 to mitigate against contamination of experiments
- To provide infrastructure for, and support to, the expts.
- Focus on dark matter, double beta decay, solar & SN experiments requiring depth and cleanliness of SNOLAB. Also provide space for prototyping of future experiments
- Large scale expts (ktonne, not Mtonne)
- Goal has been to create a significant amount of space for an active experimental programme to support current generation of experiments as early as possible

SNOLAB

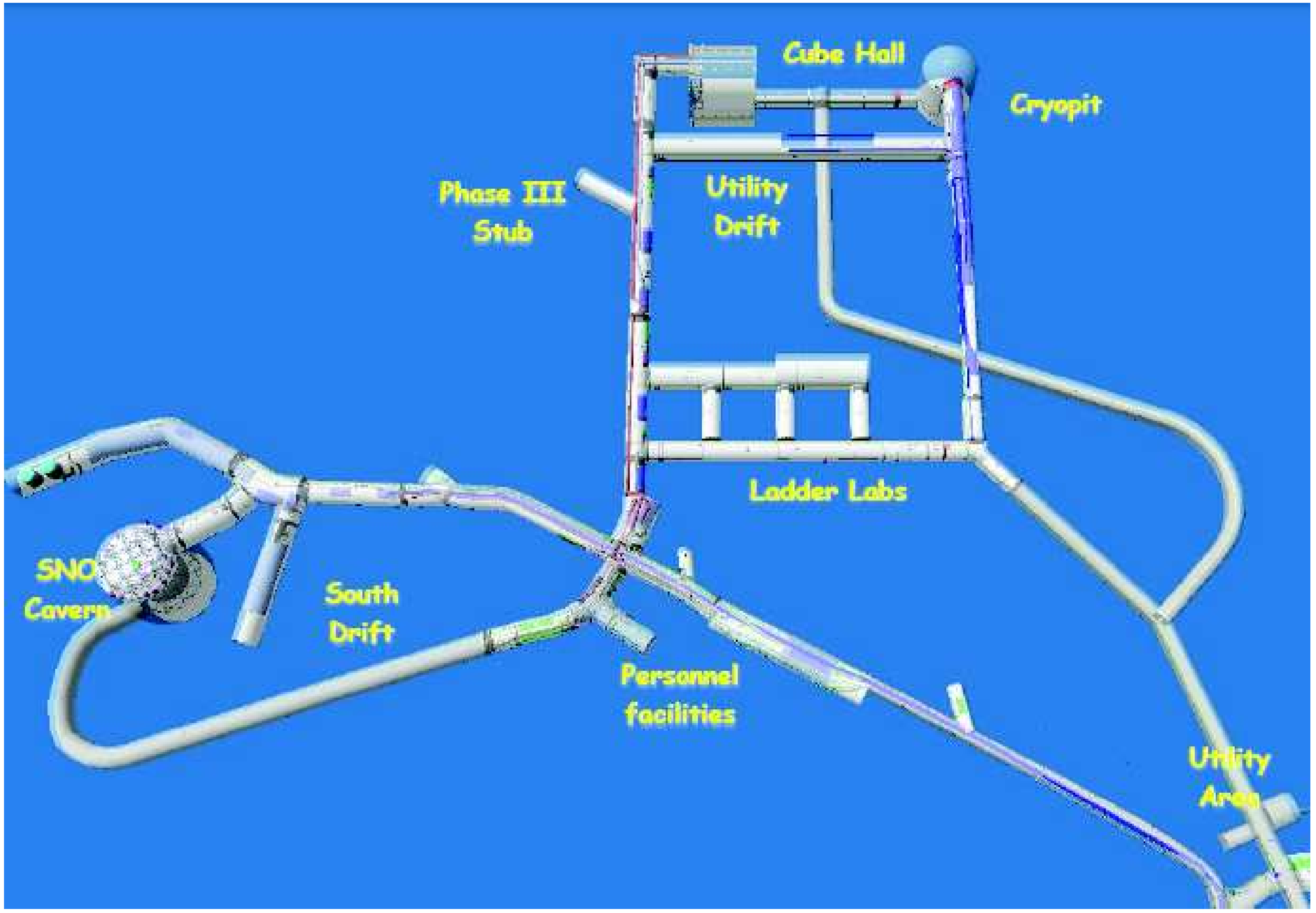


2 km underground near Sudbury, Ontario

Surface Facilities



Underground Layout



Deepest and cleanest large-space international facility

Ultra-low radioactivity background environment Class 2000

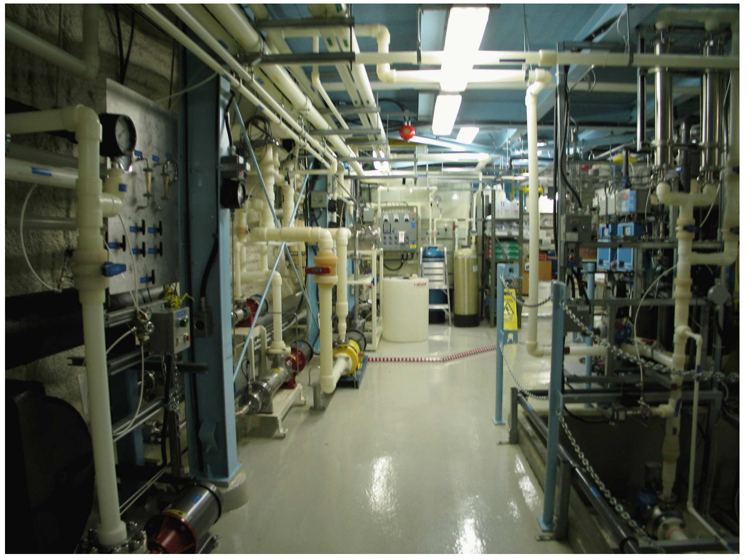
Underground Laboratory

Underground Laboratory

- **600V 3 phase 60Hz**
- **Air Handler Units (AHUs) to provide clean air and remove waste heat**

Underground Laboratory

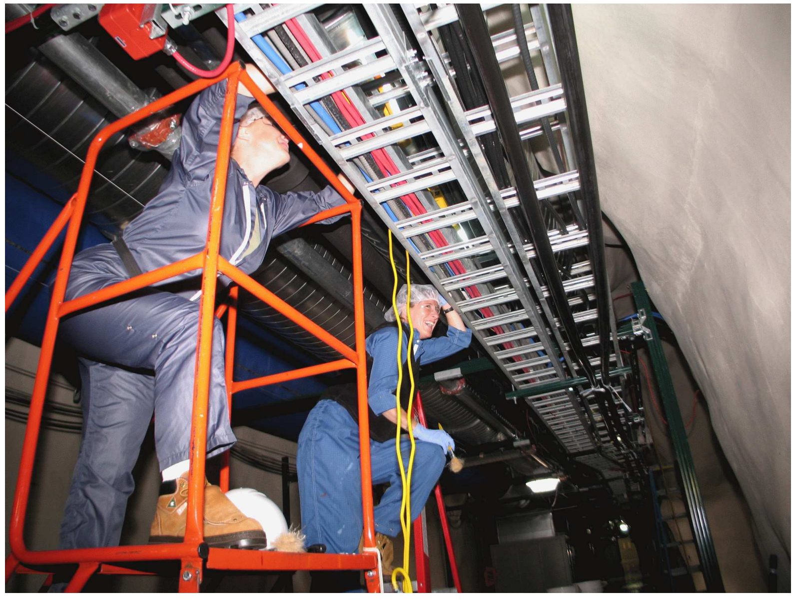
- Ultrapure water from the SNO water purification plant
- LN_2 supplied by transport dewar from surface



- HPGe Gamma Counter
  2 additional counters soon
- Rn/Ra Emanation (electrostatic counters, radon emanation)

Underground Laboratory

- Spraying shotcrete
- Painting
- Washing
- Hand-cleaning



Underground Laboratory

SNO+

Double Beta Decay

What we know:

-Neutrinos have mass

-Squared mass differences

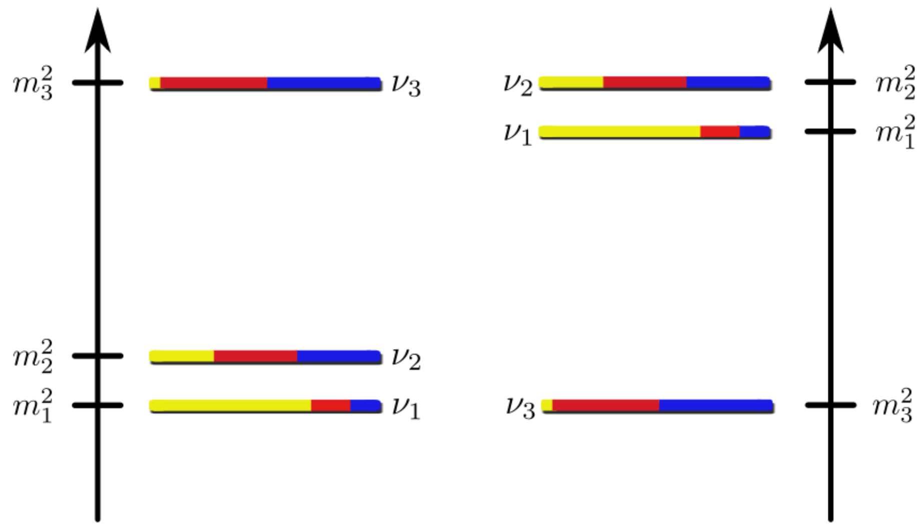
What we don't know:

-Absolute mass scale

-Mass hierarchy

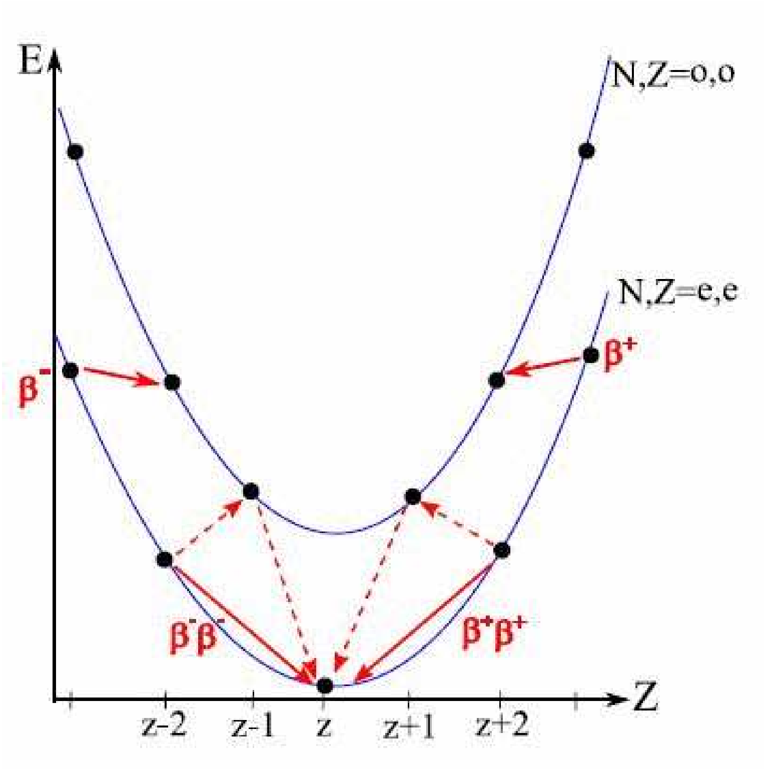
-Dirac vs Majorana

- **Dirac neutrino** (ΔL=0, $\nu \neq$ anti ν)
- **Majorana neutrino** (ΔL=2, $\nu =$ anti ν)

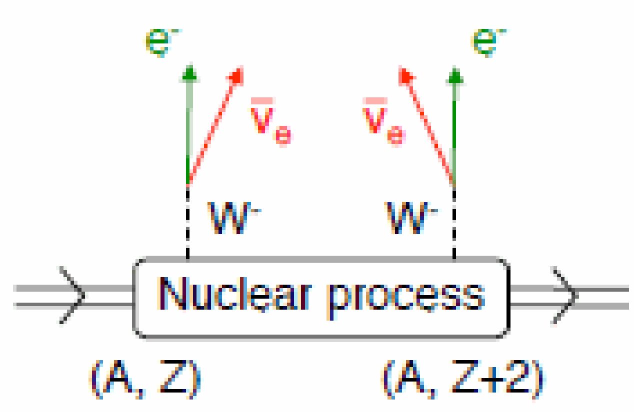


Double Beta Decay

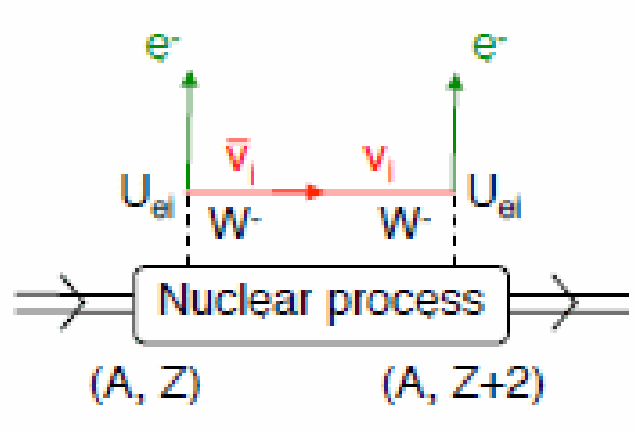
Beta decay
is energetically forbidden



- **35 isotopes in nature**
- $\mathbf{T_{1/2} > 10^{20}}$ **yrs**



$$(A, Z) \rightarrow (A+2, Z) + 2e^- + 2\bar{\nu}_e$$



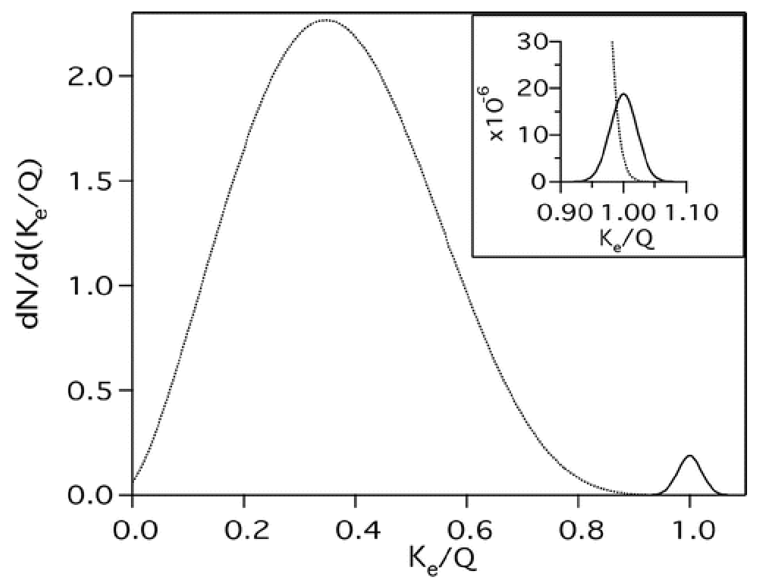
$$(A, Z) \rightarrow (A+2, Z) + 2e^-$$

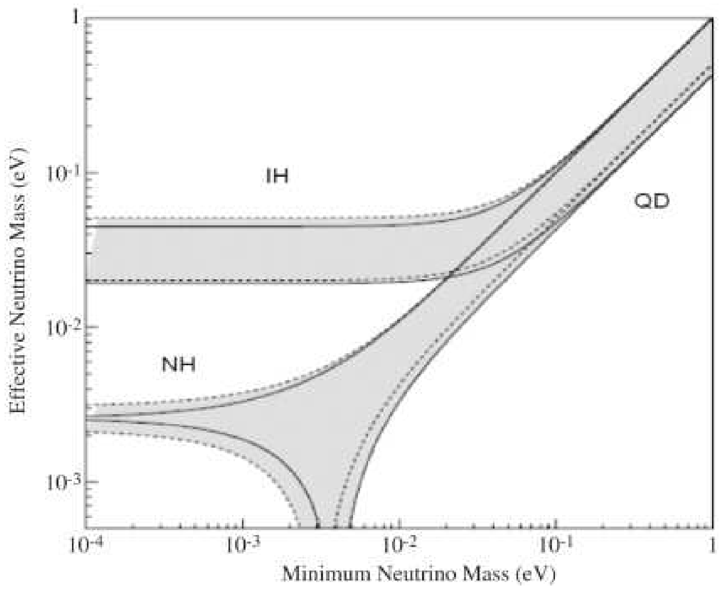
Double Beta Decay

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}|\mathcal{M}^{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

- $G^{0\nu}$: Phase space factor
- $\mathcal{M}^{0\nu}$:Nuclear matrix element
- $\langle m_{\beta\beta}\rangle$: effective ν mass

  $\langle m_{\beta\beta}\rangle = \sum_i U^2_{ei} m_i$



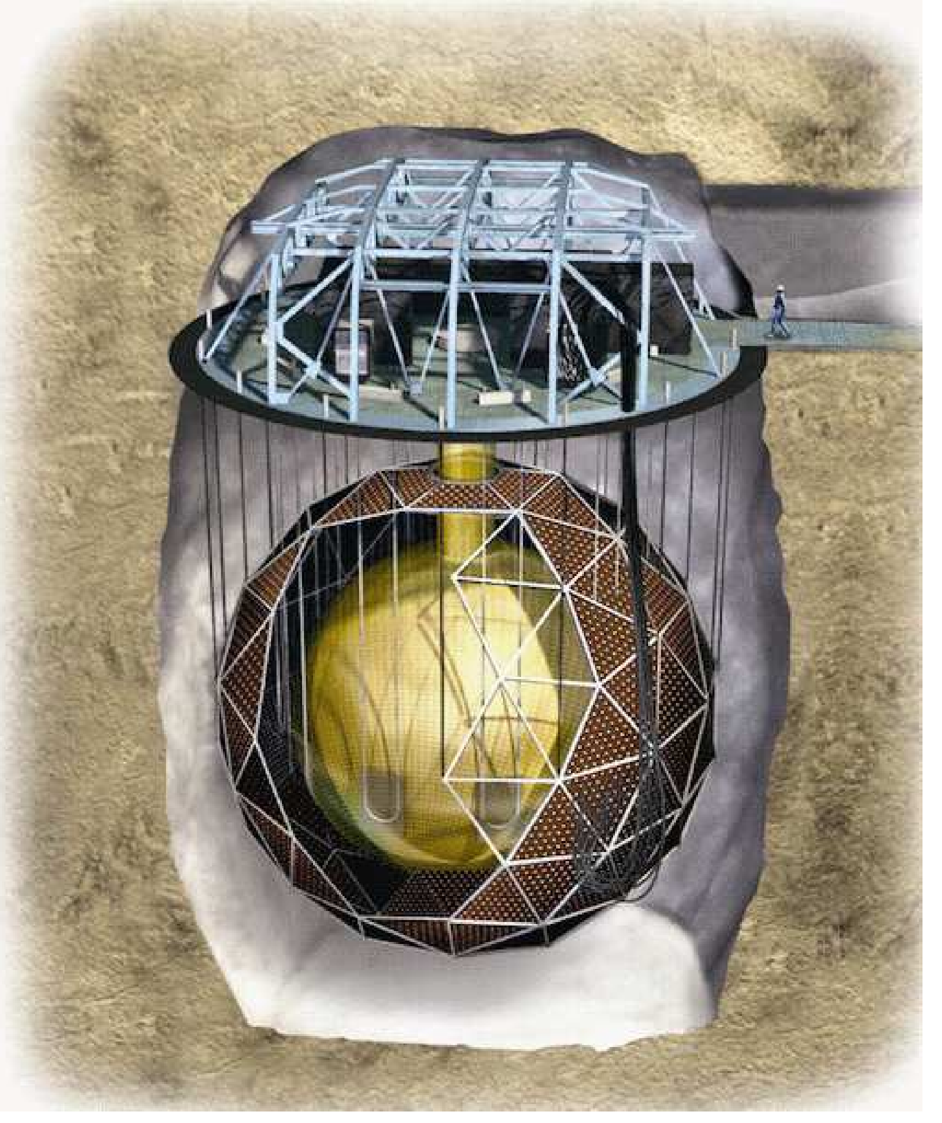


$$[T^{0\nu}_{1/2}]^{-1} \propto \alpha\eta\sqrt{\frac{M\times t}{\Delta E\times B}}$$

- isotopic abundance, efficiency
- high mass, long exposure
- low background, good energy resolution

SNO+ detector

- Acrylic vessel
  $\phi = 12$ m
- Liquid scintillator
  (LAB+PPO)
  780 tonnes
- 1700 tons H_2O inner
- 5700 tons H_2O outer
- 9500 PMTs



SNO+ Physics Goals

- Double beta decay with ^{150}Nd
- Low energy solar neutrinos
- Geo-neutrinos
- Reactor neutrinos oscillation
- Supernova neutrinos
- Nucleon decay

LS and ^{150}Nd

LS = LAB+PPO

- Compatible with acrylic
- Inexpensive
- High light yield
- Safe

Properties:

- Density = 0.86 g/cm^3
- Flash point = 140 C
- Boiling point = 278-314 C
- Water solubility = 0.041 mg/L

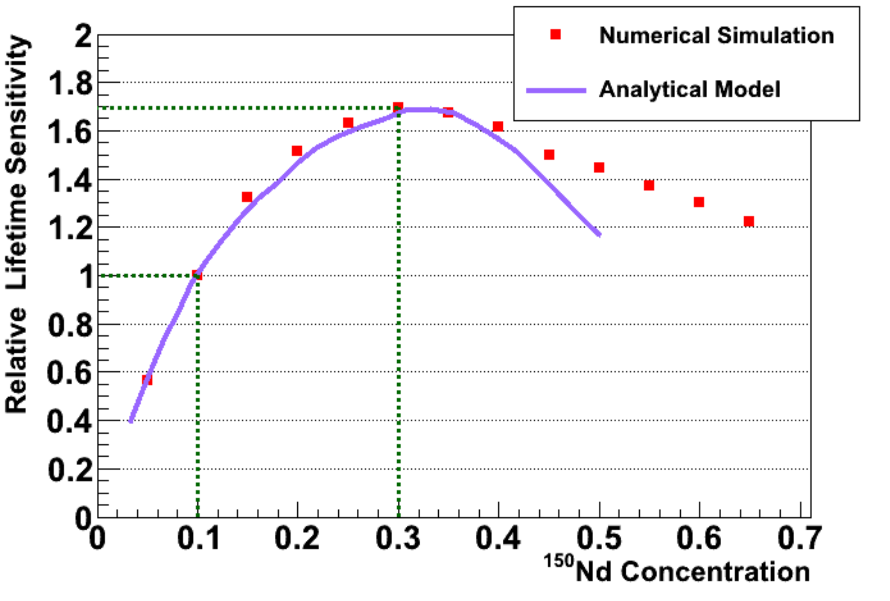
Neodymium-150

- 5.6% natural abundance
  43.7 kg (0.1% Nd loading)
- 3.37 MeV endpoint
  above most backgrounds
  2nd highest of $\beta\beta$ isotopes
- $0\nu\beta\beta$ rate is one of the fastest
  (same effective Majorana mass)
  largest phase-space factor
- $2\nu\beta\beta$ half-life:
  ground state = 9.1×10^{18} y
  0^+ excited state $\sim 1.3 \times 10^{20}$y

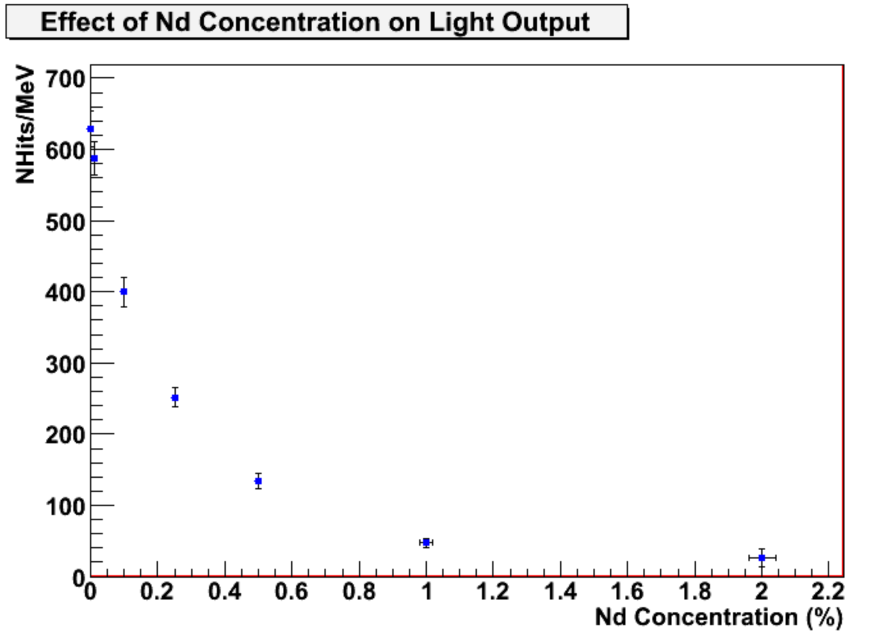
Double Beta Decay Phase

How much Nd?

- Optimal loading at 0.3% (131.1 kg)
- Run at 0.1% (43.7 kg) initially



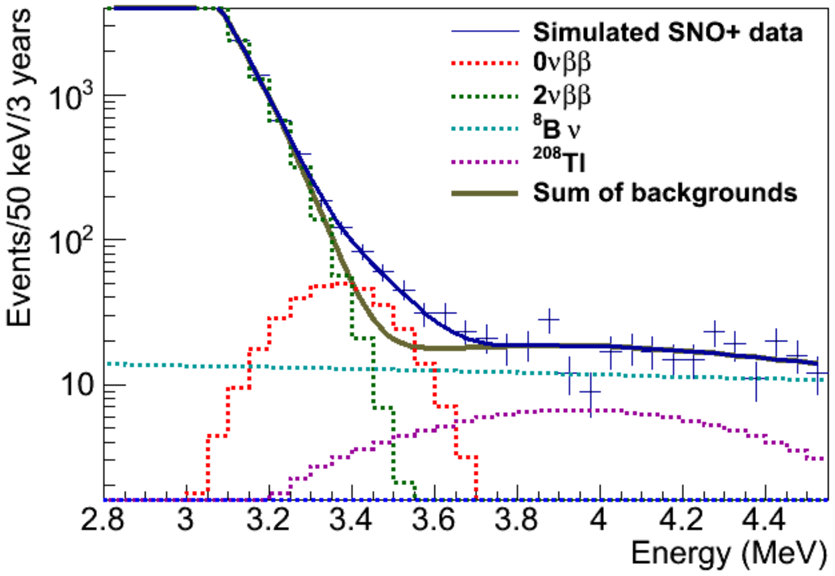
- 400 pe/MeV (6.4% FWHM resolution @ 3.37 MeV)
- 200 pe/MeV (9.0% FWHM resolution @ 3.37 MeV)



Double Beta Decay Phase

Energy spectrum simulation

- Effective ν mass $\sim$ 350 meV
- Nuclear matrix element: IBM-2
- Fiducial volume cut: 50%
- Live time: 2.4 y



$\sim$ 360 $0\nu\beta\beta$ events for 0.3%

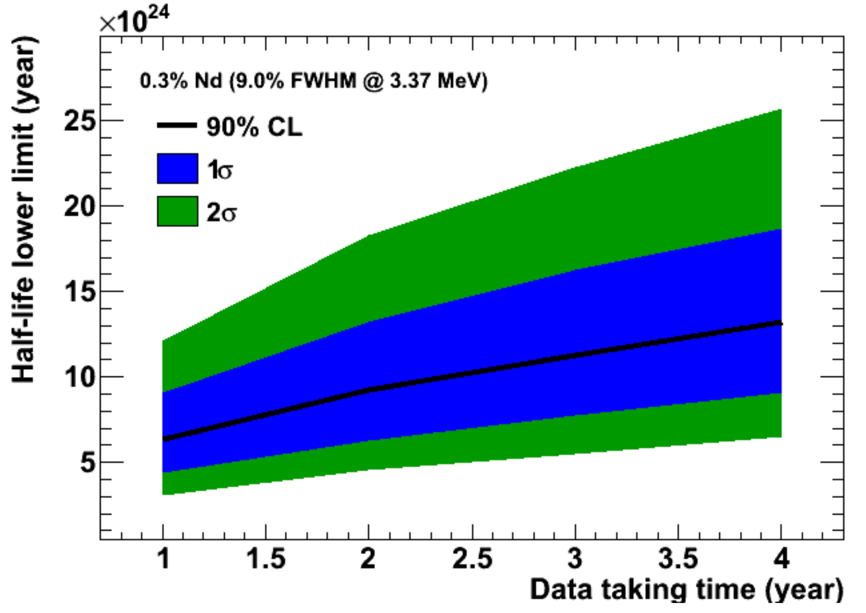
- Solar ^{8}B
- ^{150}Nd $2\nu\beta\beta$
- ^{214}Bi: tagged and removed (ϵ=99.98%)
- ^{208}Tl: tagged and removed (ϵ=90%)

^{8}B: 440 events/year $_{(0,5)MeV}$
^{214}Bi: 2.3 events/year (3%)
^{208}Tl: 52.9 events/year (3%)

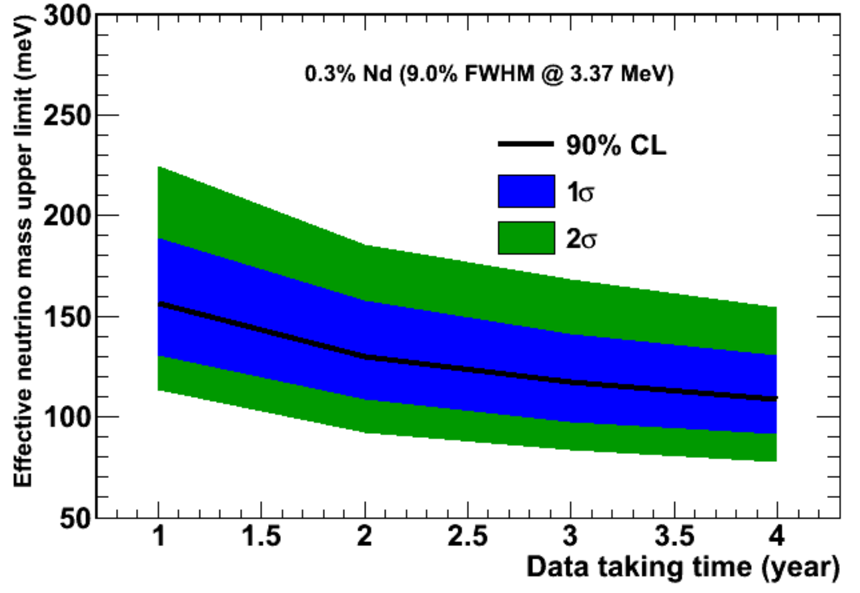
Double Beta Decay: Sensitivity

Lifetime and mass

- 0.3% loading
- Nuclear matrix element: IBM-2 (Barea and Iachello, Phys. Rev. C 79 (2009))
- Fiducial volume cut: 50%
- 80% live time



- Solar ^{8}B
- ^{150}Nd $2\nu\beta\beta$
- ^{214}Bi: tagged and removed (ϵ=99.98%)
- ^{208}Tl: tagged and removed (ϵ=90%)

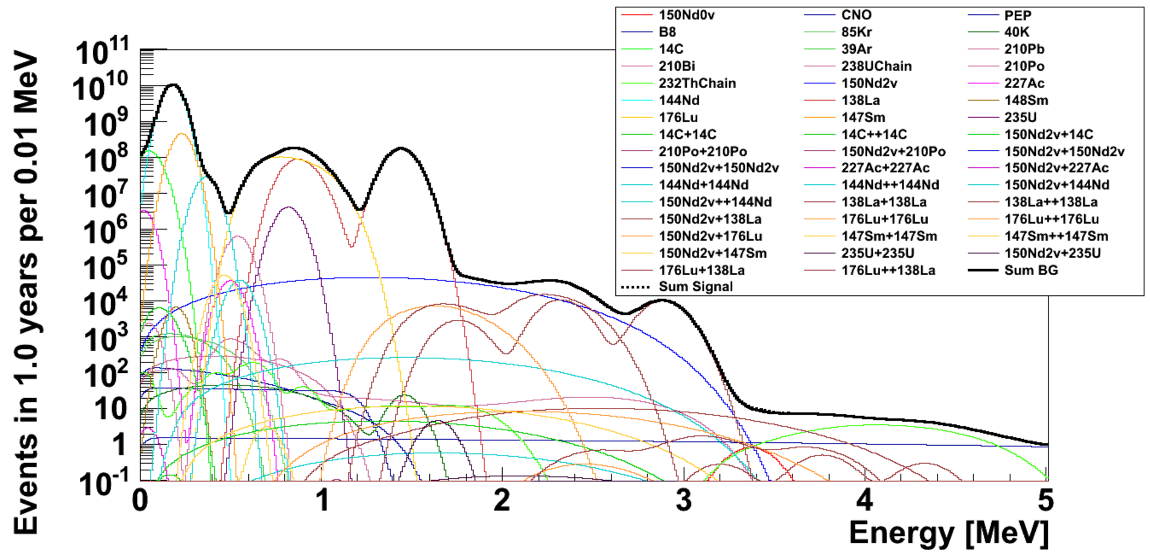


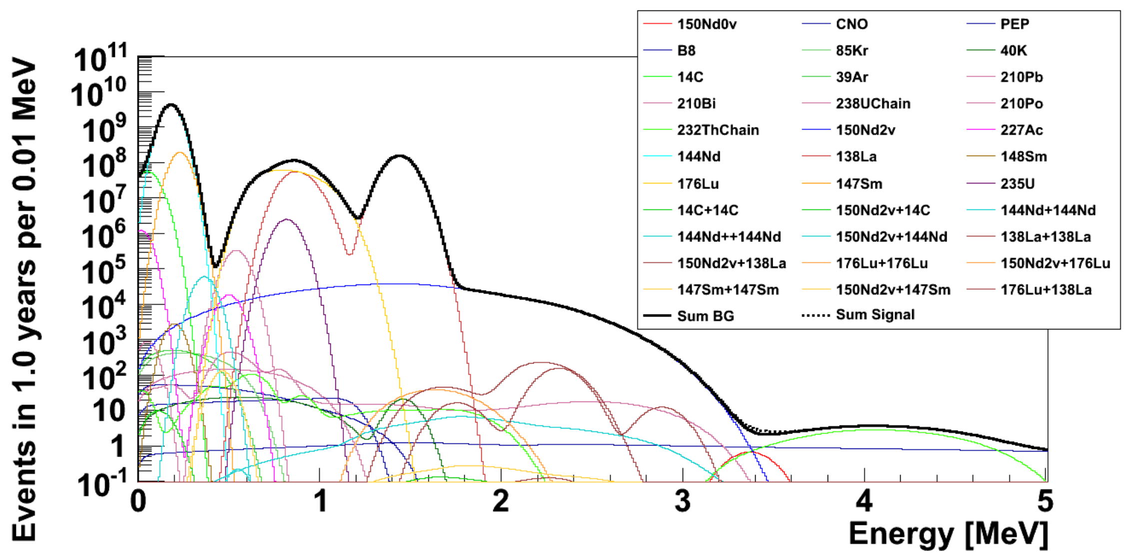
Double Beta Decay: Pileup

Pileup rejection

- Nd related background: ^{144}Nd, ^{150}Nd
- Thorium, Uranium
- Rare earth & others: ^{138}La, ^{176}Lu, ^{40}K, ^{85}Kr,
- Cosmogenic activated: Ce, Pm, Nd

99% pileup rejection signal sacrifice: < 10% at 3MeV

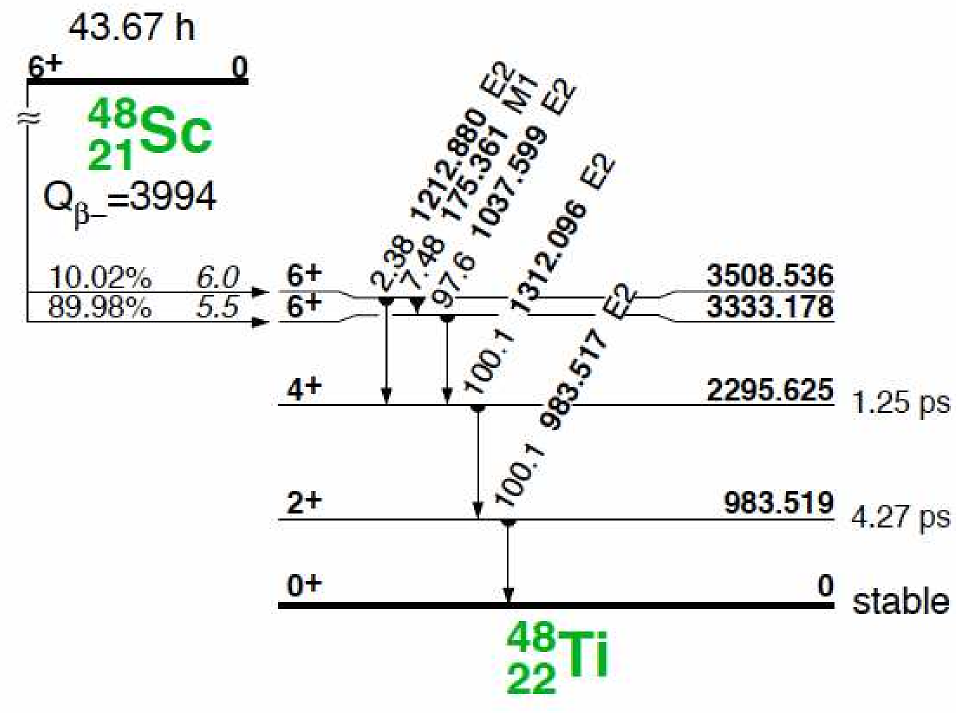




Double Beta Decay: Calibration

Energy

- ^{48}Sc $\beta - \gamma$ source
- β^- for a tagged source (0.66 MeV)
- Sum E(γ) = 3.33 MeV (90% BR)
- Half life = 44 hrs
- 14 MeV-n activation on Ti
- D-T generator (site or Dresden)
- Source in R&D phase

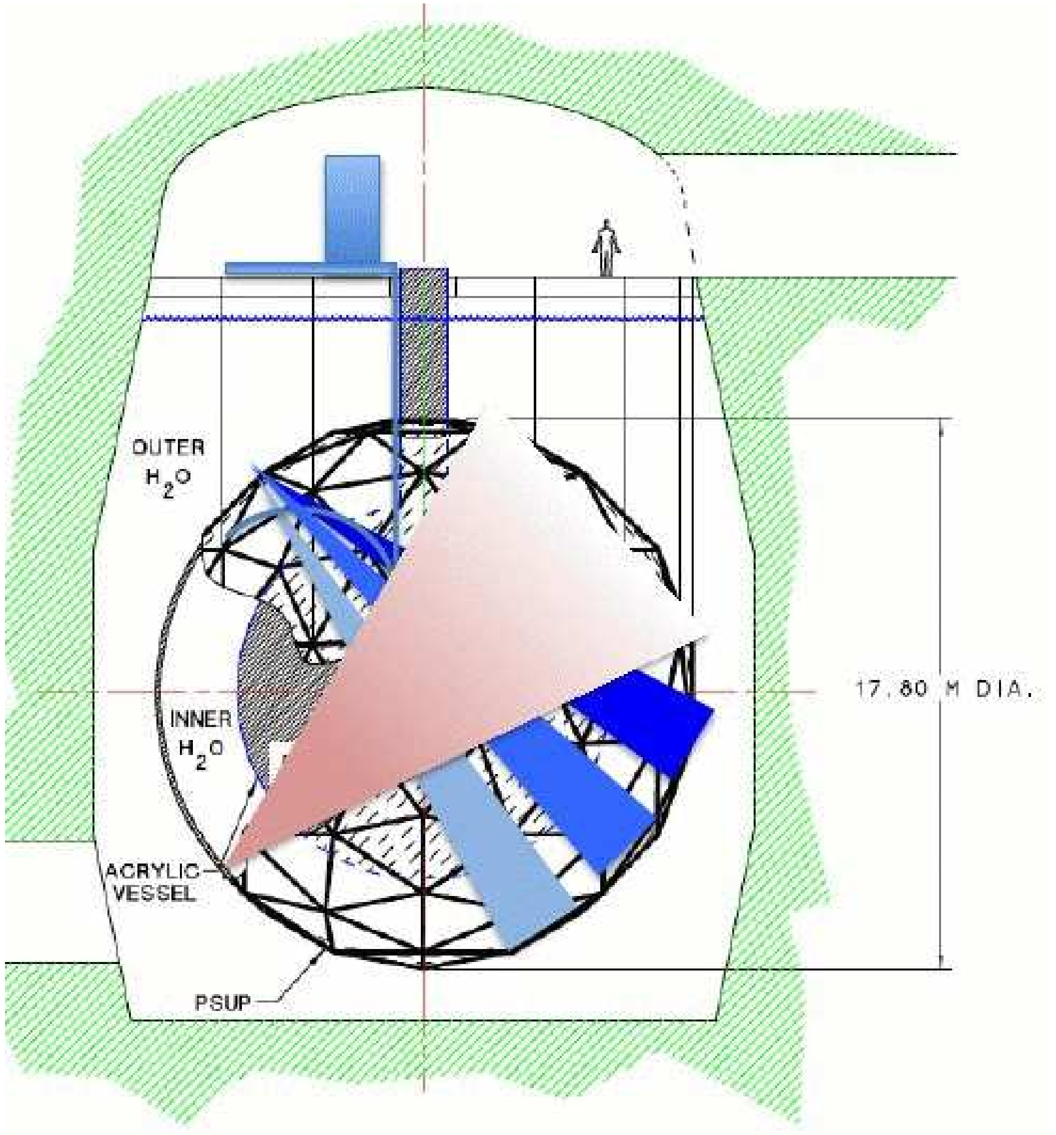


Also several more calibration sources at different energies: AmBe, ^{65}Zn, ^{90}Y, ^{57,60}Co, ^{24}Na, ^{8}Li, ^{16}N

Double Beta Decay: Calibration

Optics

- **ELLIE:**
  Embedded LED
  Light Injection Entity
- **LED driven fibers mounted on the phototube sphere to monitor**
- **PMT timing calibration and gain**
- **Scattering and attenuation lengths**
- **Wavelength, opening angle, position, direction**



Double Beta Decay: Purification

- multistage distillation (to remove heavy metals, improves UV transparency)
- N_2/water vapor gas stripping (to remove Rn, Kr, Ar, O_2)
- water extraction (to remove K, Ra, Bi)
- metal scavenging (assay for solar phase) (to remove Ra, Bi, Pb)
- micro filtration
- $NdCl_3$ purification by pH adjustment co-precipitation

- Th: 10^{-17} g/g ($\sim$ 3 cpd for ^{208}Tl and ^{228}Ac)
- U: 10^{-17} g/g ($\sim$ 9 cpd for ^{210,214}Bi)
- ^{40}K: 1.3 $\times 10^{-18}$ g/g ($\sim$ 23 cpd)
- ^{85}Kr, ^{39}Ar ($<$ 100 cpd)

Process system



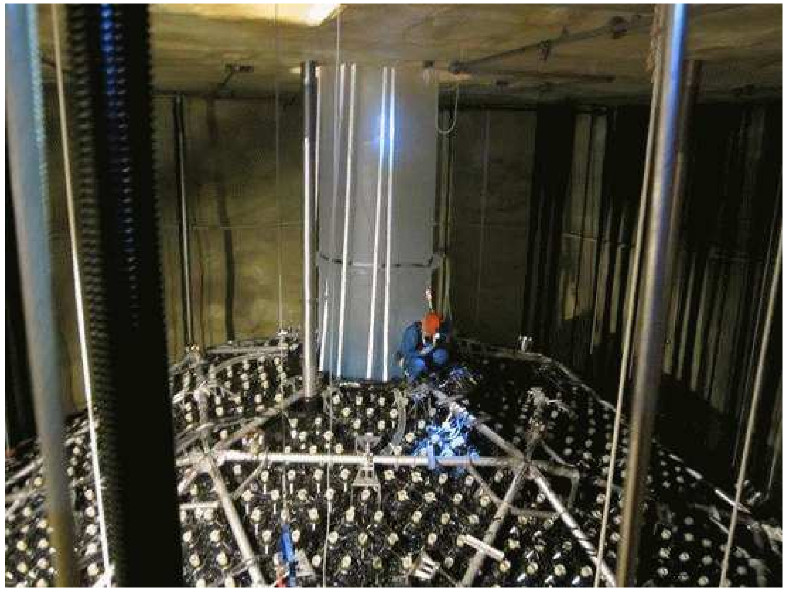

Double Beta Decay: Upgrade

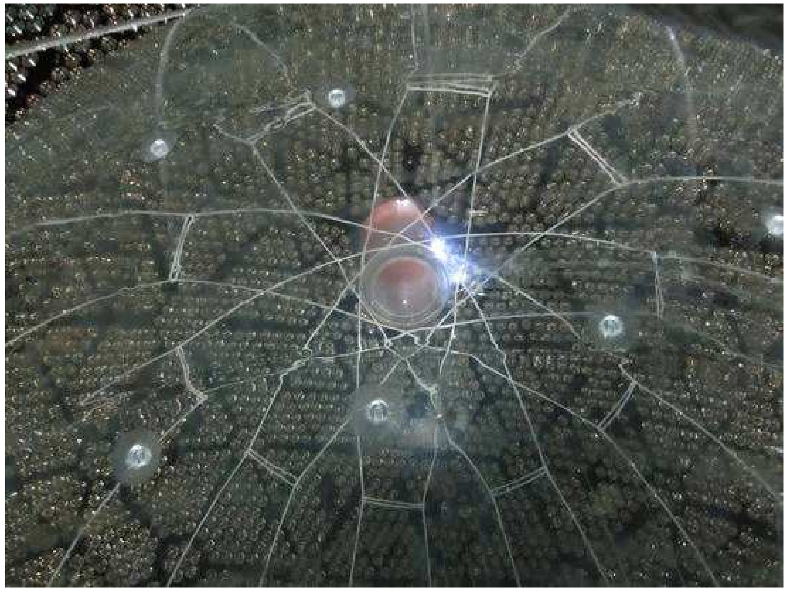
Once it is running:

- Enrichment
  - Investigating some 1-2 options
  - Nd enriched to 80% ^{150}Nd: increases statistics $\times 16$
  - Most backgrounds remain constant
- Other isotopes

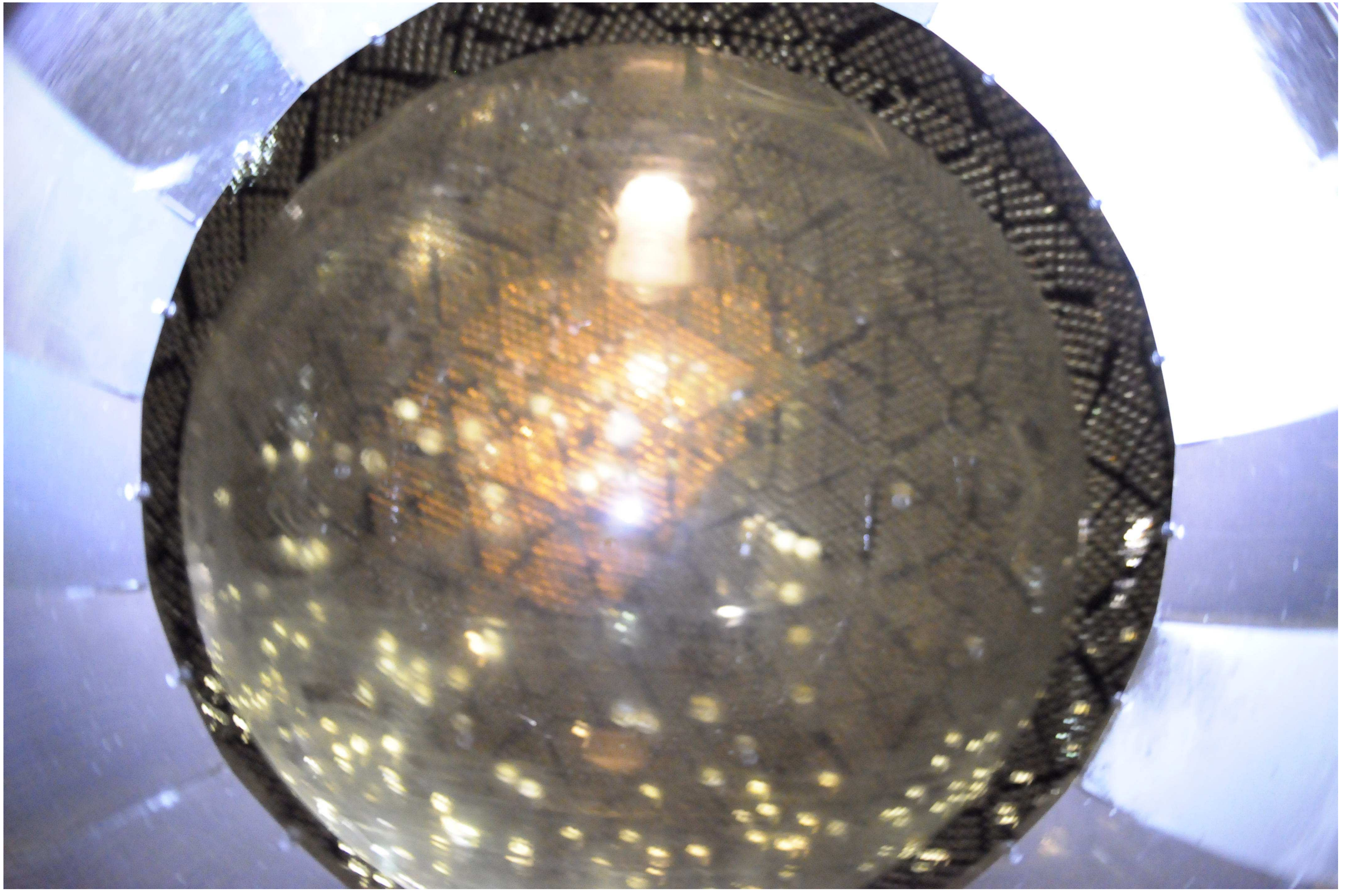
Several possibilities and options

SNO+ detector





SNO+ detector



SNO+ detector

Timeline

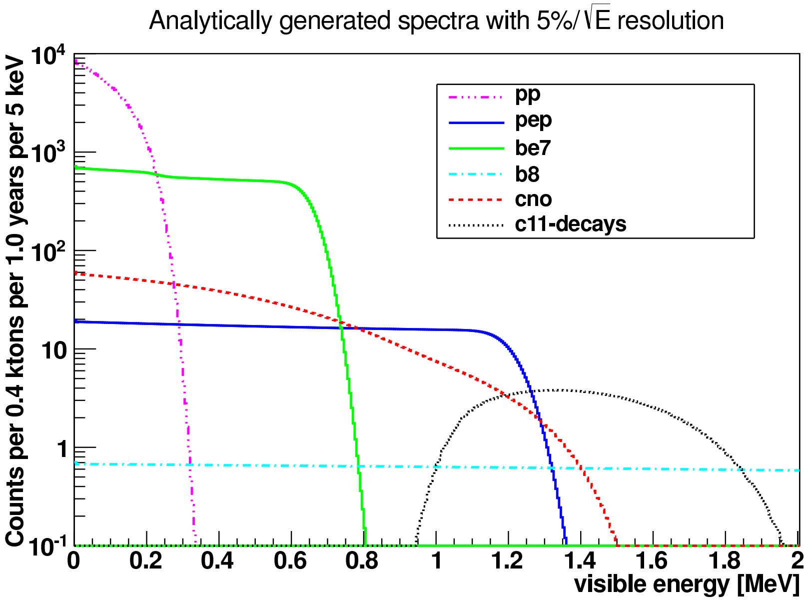
- **2012**
  - **Finish work in cavity**
  - **Process system construction**
- **2013**
  - **Water phase**
  - **Scintillator filling**
  - **Scintillator phase**
- **2014**
  - **Nd-loading**
  - **Double Beta Decay phase**

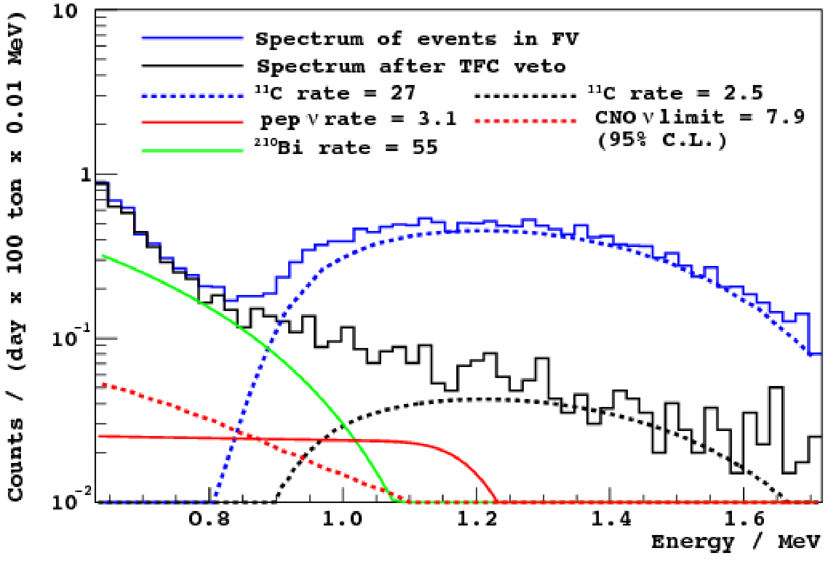
Low Energy Solar Neutrinos

pep and CNO neutrinos

- Depth and size for precised pep measurement: 3600 pep events/(kton-year), for electron recoils > 0.8 MeV $\pm 5\%$ (stat, syst) after 3 years

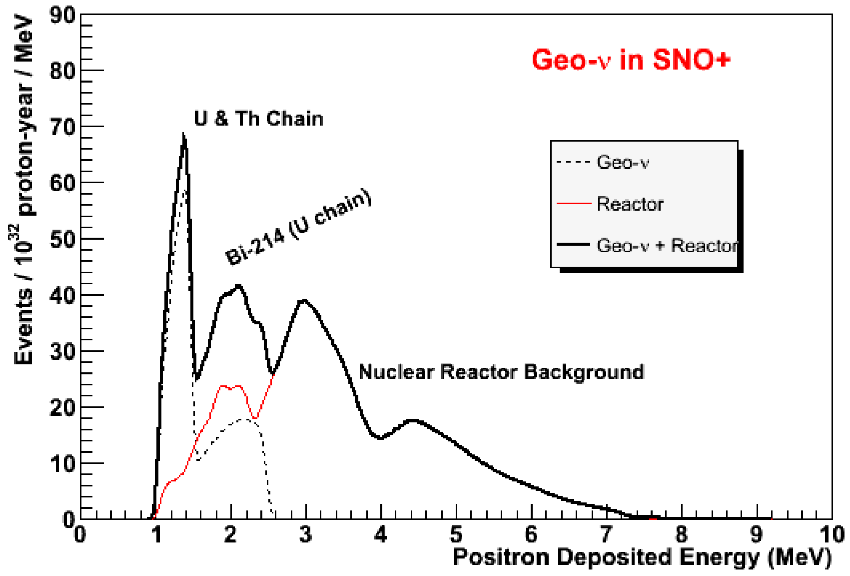
- Reduction of ^{11}C for CNO measurement: $\pm 7\%$ (stat) after 3 years



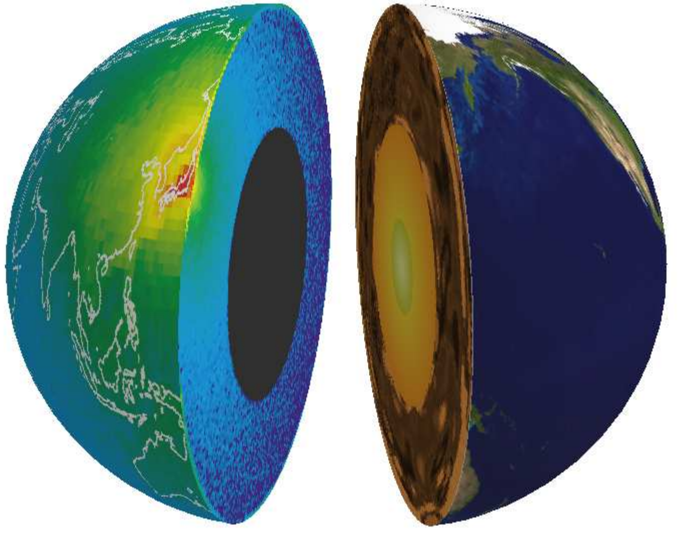


Geo-neutrinos

anti-ν_e from β^- decays (U, Th) to explore chemical composition of Earth's crust & mantle



- Check models of Earth heat production
- Low reactor background in SNO+: Reactor/Geo ∼1.1
- Geo-ν in SNO+ mainly from two reservoirs:
  - mantle
  - old, thick continental crust (very local region well-studied



SNO+ Supernova Signal

- **Elastic scattering:**
  - 8 evts: $\nu_e + e^- \rightarrow \nu_e + e^-$
  - 3 evts: anti-$\nu_e + e^- \rightarrow$ anti-$\nu_e + e^-$
  - 4 evts: $\nu_{\mu,\tau} + e^- \rightarrow \nu_{\mu,\tau} + e^-$
  - 2 evts: anti-$\nu_{\mu,\tau} + e^- \rightarrow$ anti-$\nu_{\mu,\tau} + e^-$

- **Charged Current:**
  - 263 evts: anti-$\nu_e + p \rightarrow n + e^+$
  - 27 evts: $\nu_e + {}^{12}C \rightarrow {}^{12}N + e^-$
  - 7 evts: anti-$\nu_e + {}^{12}C \rightarrow {}^{12}B + e^+$

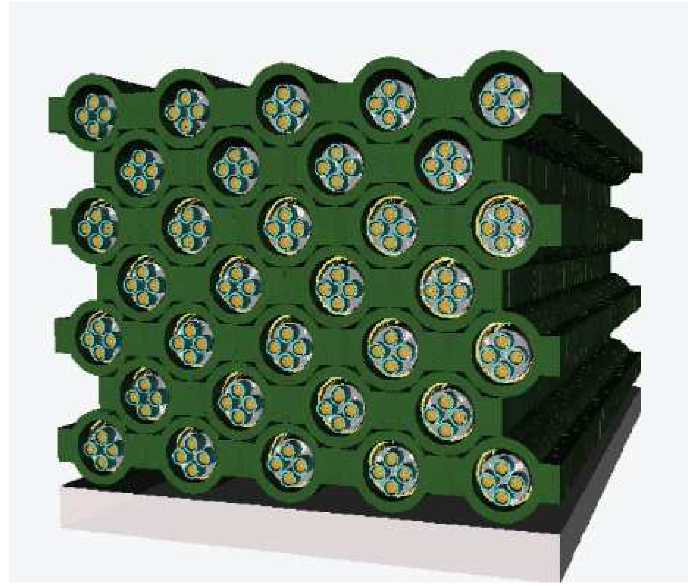
- **Neutral Current:**
  - 58 evts: $\nu_x + {}^{12}C \rightarrow {}^{12}C^*(15.11\text{MeV}) + \nu_x$
  - 273 evts: $\nu_x + p \rightarrow \nu_x + p$

More about Calibrations

- ^{60}Co: 0.32 MeV β, 2.5 MeV summed γ. Energy scale, multivertex reconstruction, pile-up
- ^{8}Li: Cerenkov source. Only Cerenkov, no scintillation. PMT efficiency, LAB absorption/re-emission timing
- AmBe: n, 4.4 MeV γ. Light yield, neutron propagation, reconstruction, Nd absorption
- ^{16}N: 6 MeV γ. Energy scale, sacrifice and contamination, check detector model in water fill
- radon source ball. Alpha quenching, beta response, scintillator timing response
- low energy gamma source: to be determined. Energy scale, reconstruction, position dependence
- camera system: six cameras spaced around the phototube sphere. Locate sources within 1 cm, monitor AV position

Helium And Lead Observatory

- **Helium:**
  available ^{3}He neutron detectors from the final phase of SNO
- **Lead:**
  lead blocks from a decommissioned cosmic ray monitoring station
  - high ν-Pb cross-sections
  - low n-capture cross-sections
  - complementary sensitivity to water Cerenkov and liquid scintillator SN detectors



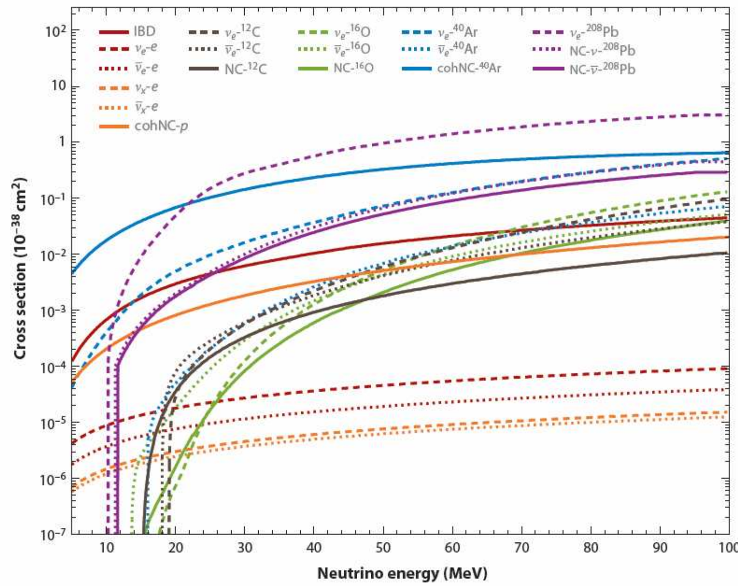


Figure 2
Cross sections per target for relevant interactions. See **http://www.phy.duke.edu/~schol/snowglobes** for references for each cross section plotted. Abbreviations: IBD, inverse β decay; NC, neutral current.

HALO Supernova Signal

- **Charged Current:**
  - $\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Bi} + \mathrm{n} + \mathrm{e}^-$
  - $\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Bi} + 2\mathrm{n} + \mathrm{e}^-$

- **Neutral Current:**
  - $\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Pb} + \mathrm{n}$
  - $\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Pb} + 2\mathrm{n}$

HALO is operational

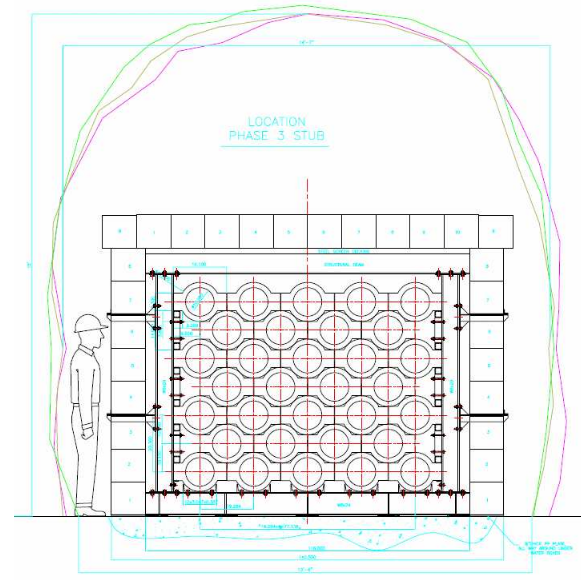
Part of SNEWS once the behaviour of the detector is well understood

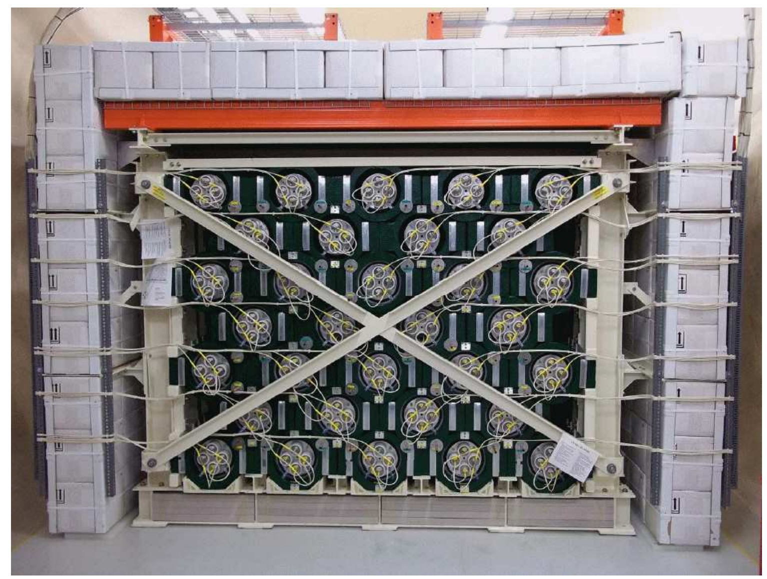
HALO Supernova Signal

79 tons of Pb for a SN at 10 kpc:
(FD distribution with T=8 MeV for ν_μ's and ν_τ's)

- **68 neutrons through ν_e charged current channels**
  - **30 single neutrons**
  - **19 double neutrons**
- **20 neutrons through ν_x neutral current channels**
  - **8 single neutrons**
  - **6 double neutrons**

~88 neutrons liberated
~1.1 n/tonne of Pb





DEAP

Dark Matter Experiment with Argon and Pulse-shape Discrimination:

- scattered nucleus detected via scintillation
- pulse shape discrimination for suppression of β/γ events
- LAr advantages:
  - is easily purified and high light yield
  - is well understood
  - has an easily accessible temperature ($85K$)
  - allows a very large detector mass with inform response
- Detectors:
  - DEAP-1: prototype, 7 kg LAr, 2 PMTs
  - DEAP-3600: 3600 kg LAr, 255 8" PMTs

DEAP

Backgrounds in liquid argon dark matter detector:

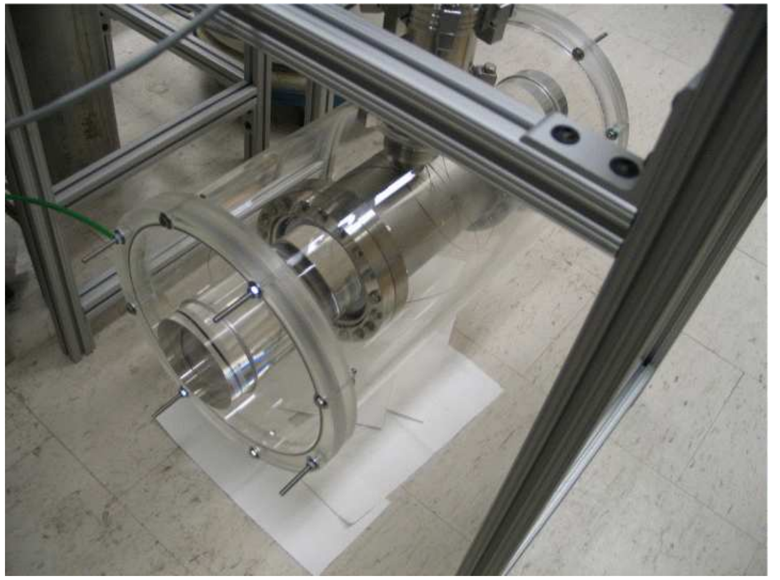
- **β/γ events:**
  dominated by ^{39}Ar, 1 Bq/kg
  PSD to distinguish from recoils, use depleted argon

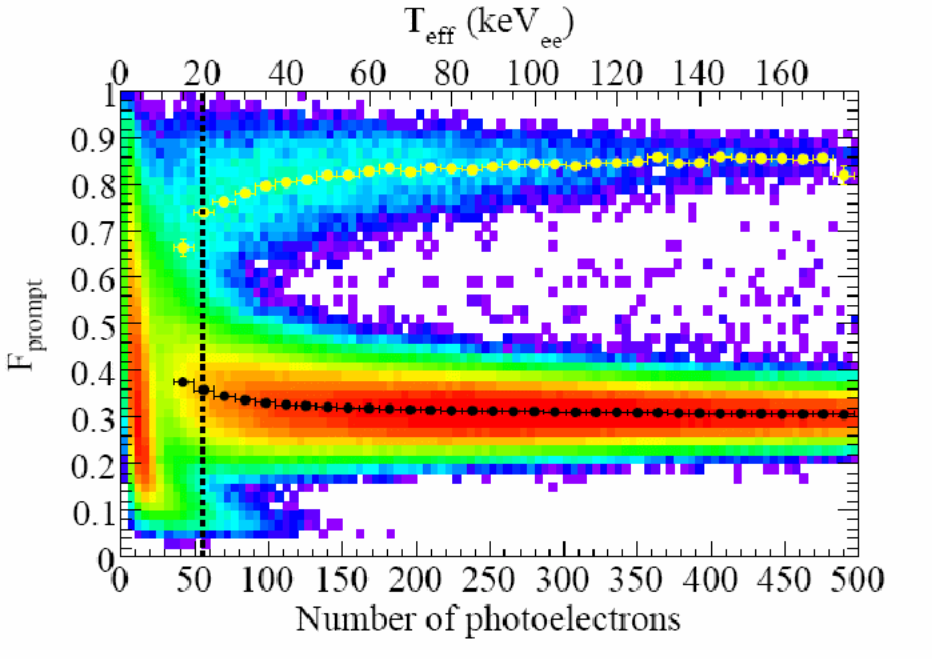
- **neutron recoils:**
  (α,n), fission, μ induced
  clean detector materials, shielding

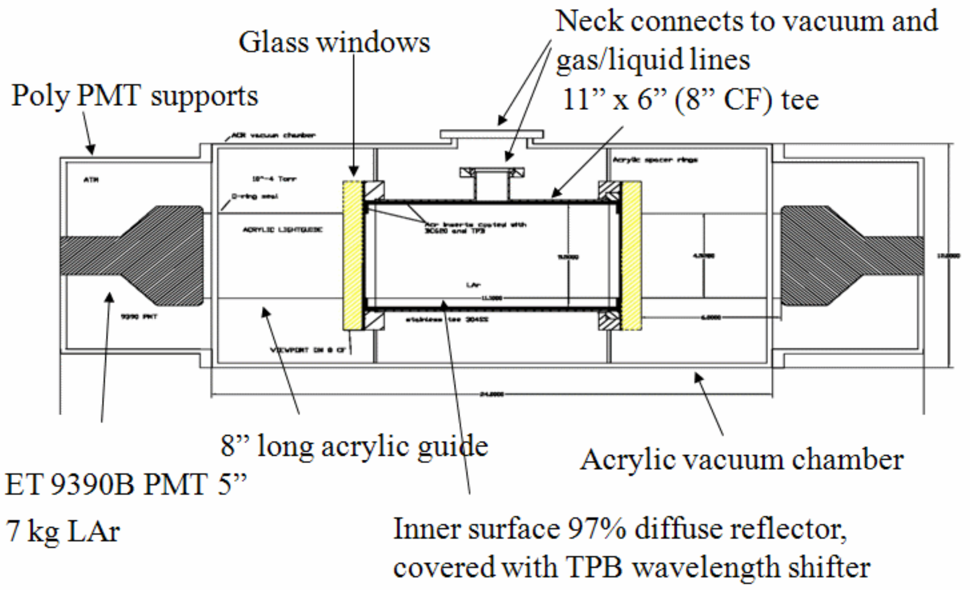
- **surface events:**
  Rn daughters and other impurities
  clean surfaces in-situ, position reconstruction

DEAP-1

Demonstrate discrimination between electromagnetic events and nuclear recoils γ suppression better than: 3×10^{-8}, 120-240 PE, using tagged γ source



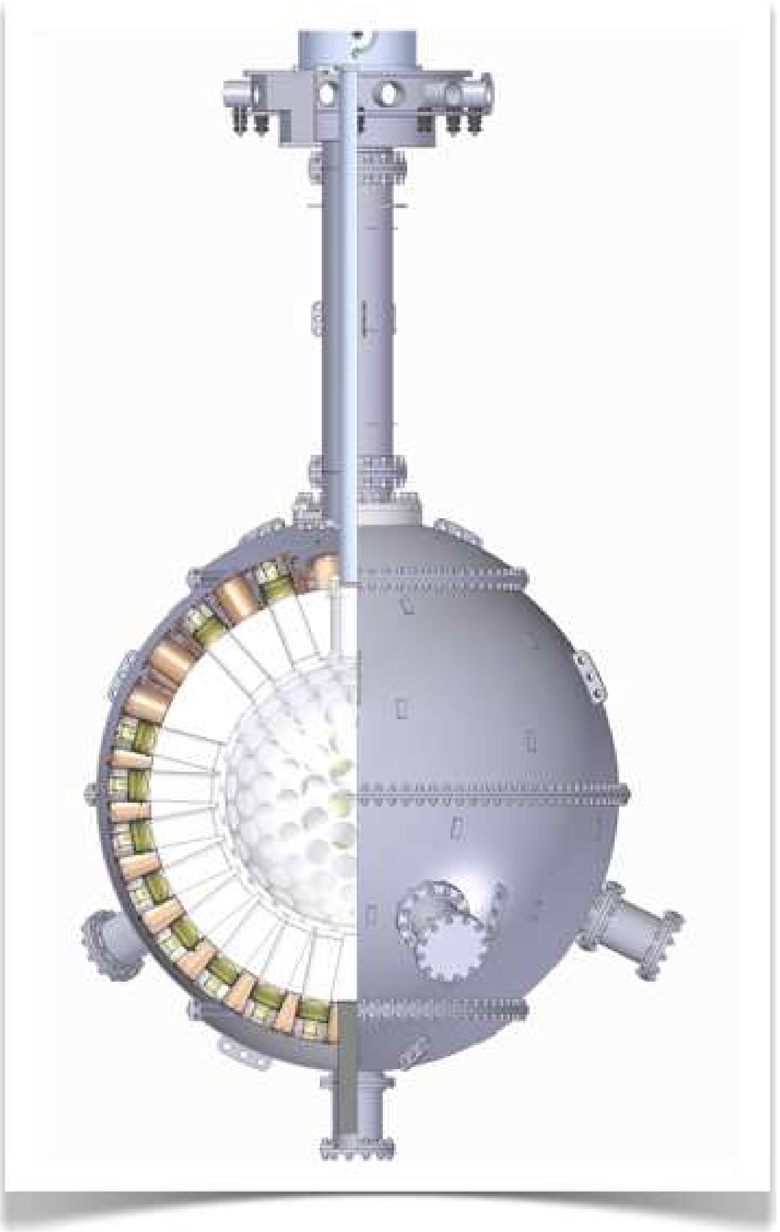




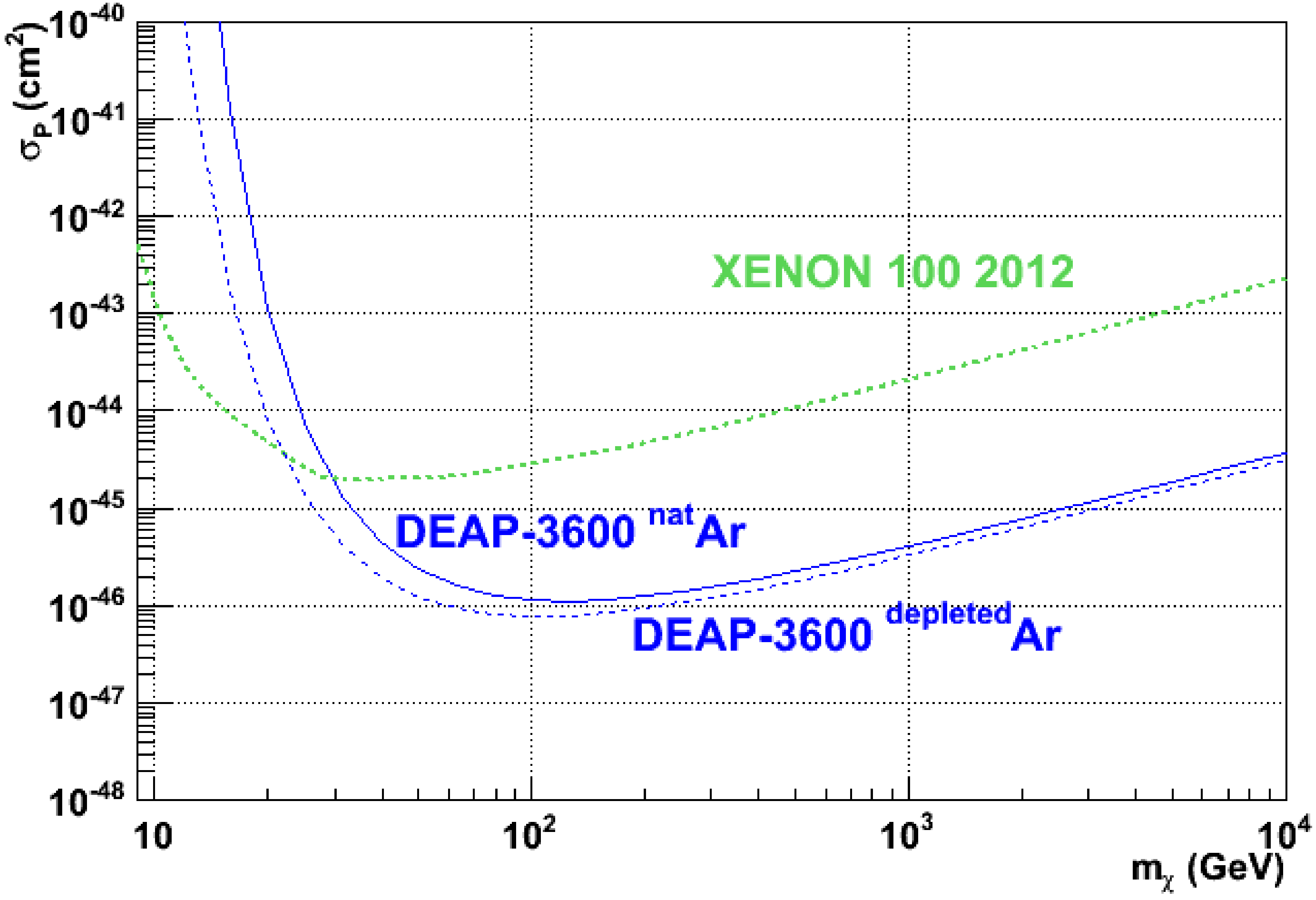
DEAP-1

DEAP-3600

- **3600 kg argon (1000 kg fiducial) in ultra-clean AV**
- **Vessel is "resurfaced" in-situ to remove Rn daughters**
- **TPB wavelength shifter deposition**
- **255 Hamamatsu R5912 HQE 8" PMTs (75% coverage)**
- **50 cm light guides PE shielding for neutron moderation**
- **8 m water shield in Cube Hall**



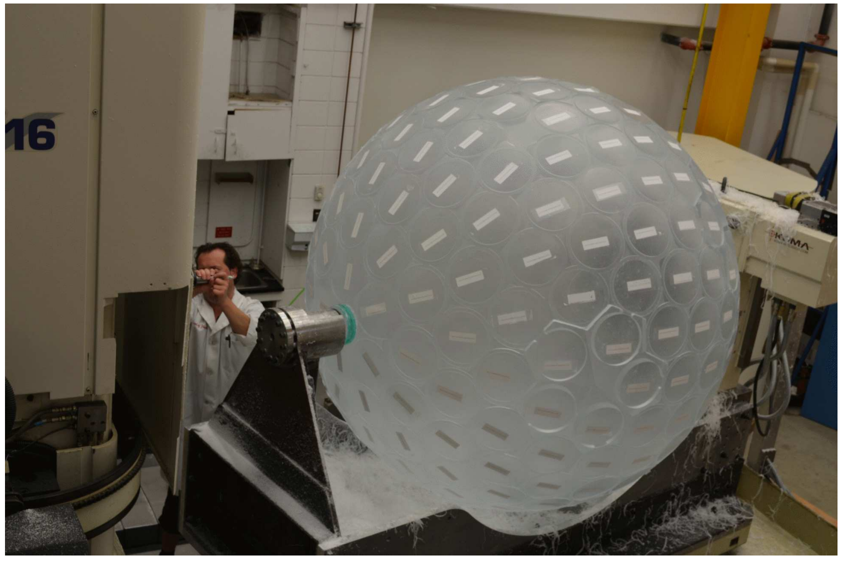
DEAP-3600



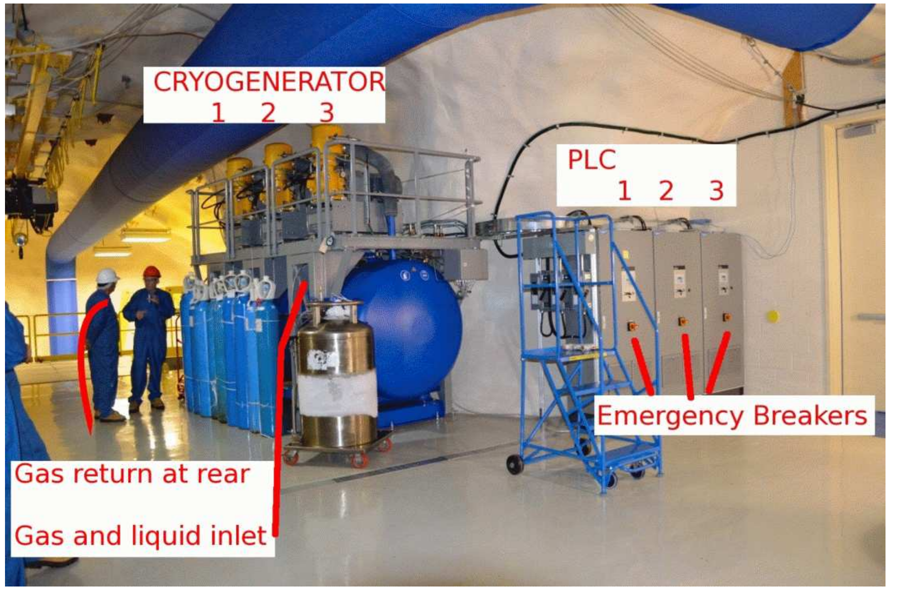
σ_P (cm^2)
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
XENON 100 2012
DEAP-3600 ^{nat}Ar
DEAP-3600 ^{depleted}Ar
10
10^2
10^3
10^4
m_χ (GeV)

DEAP-3600

DEAP-3600



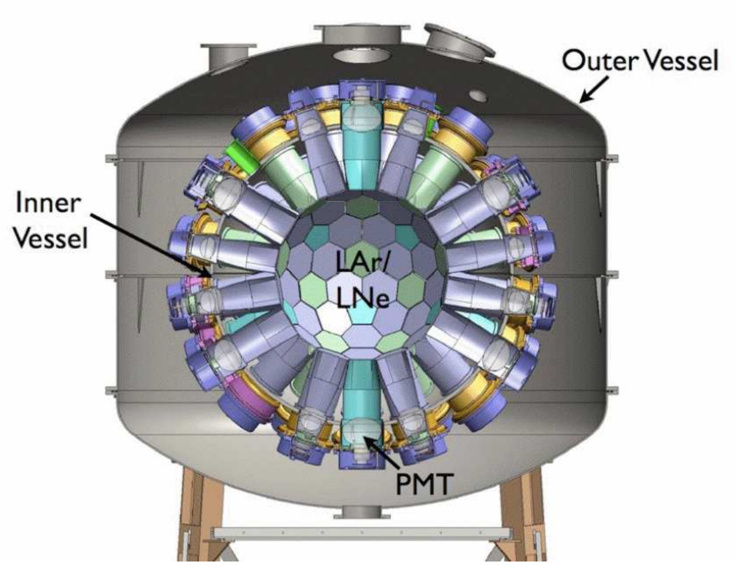
DEAP-3600

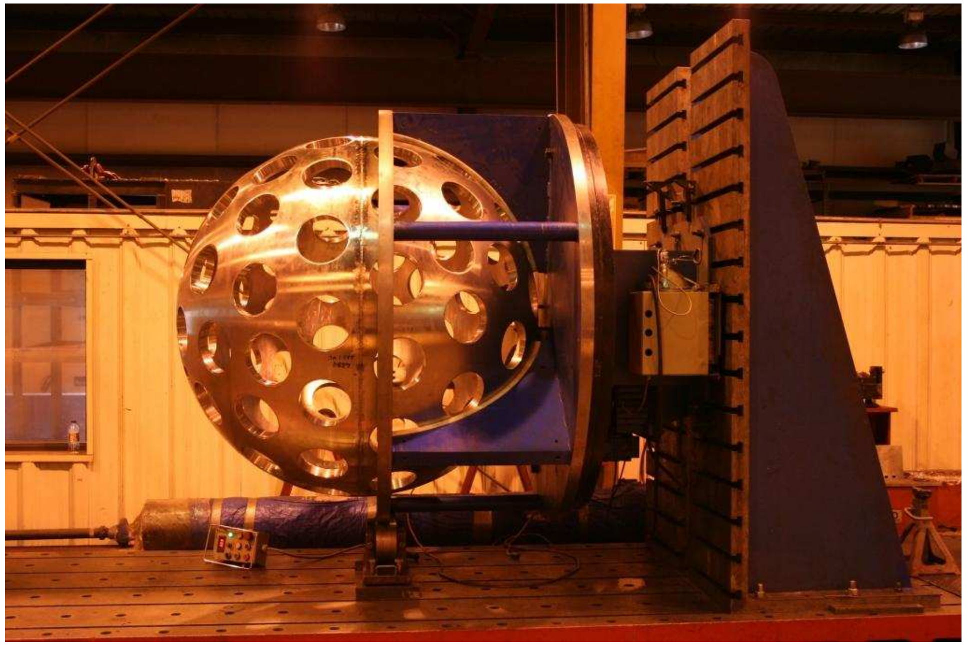

CRYOGENERATOR
1 2 3
PLC
1 2 3
Emergency Breakers
Gas return at rear
Gas and liquid inlet

MiniCLEAN

MiniCLEAN

- 500 kg cryogenic liquid (150 kg fiducial) with 92 PMTs
- Material interchangeable between argon y neon
- spin-independent WIMP-nucleo cross section sensitivity of 10^{-45} cm^2

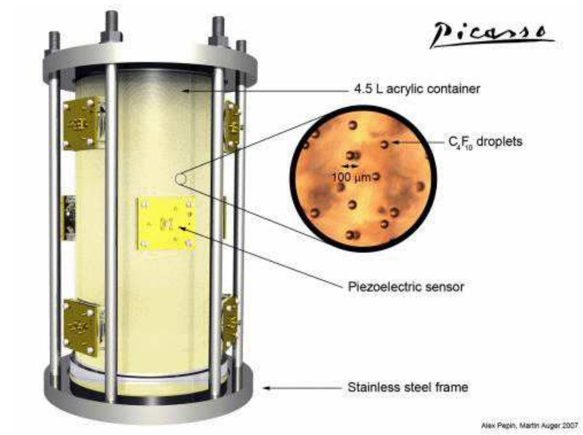




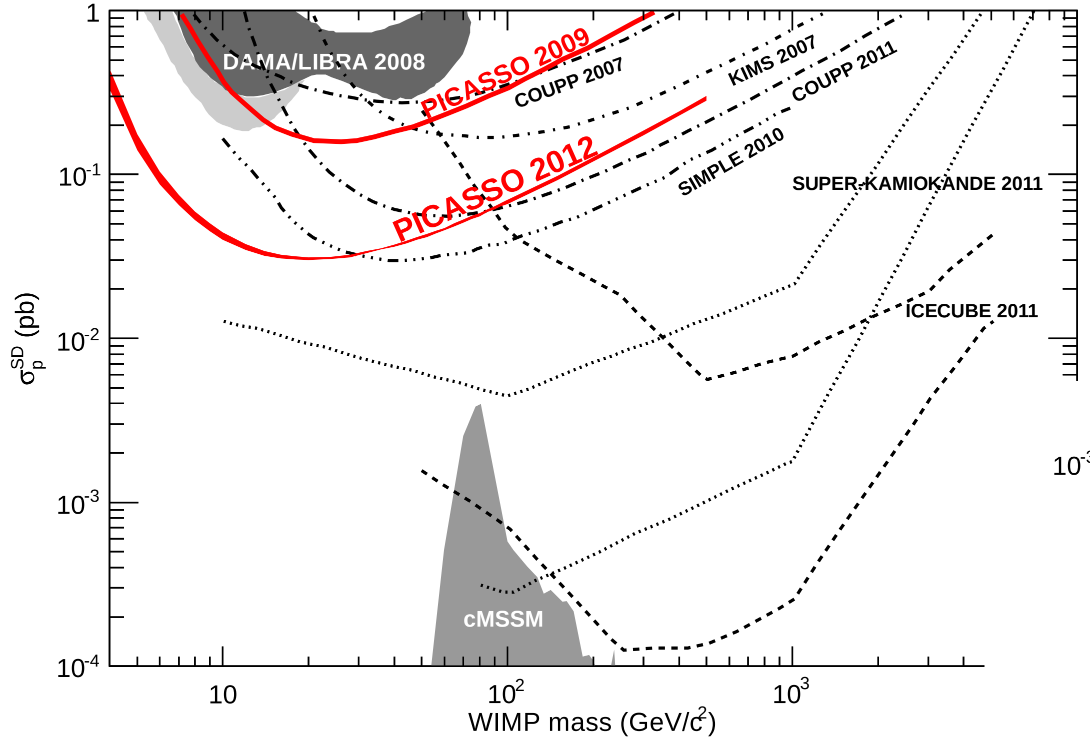
PICASSO

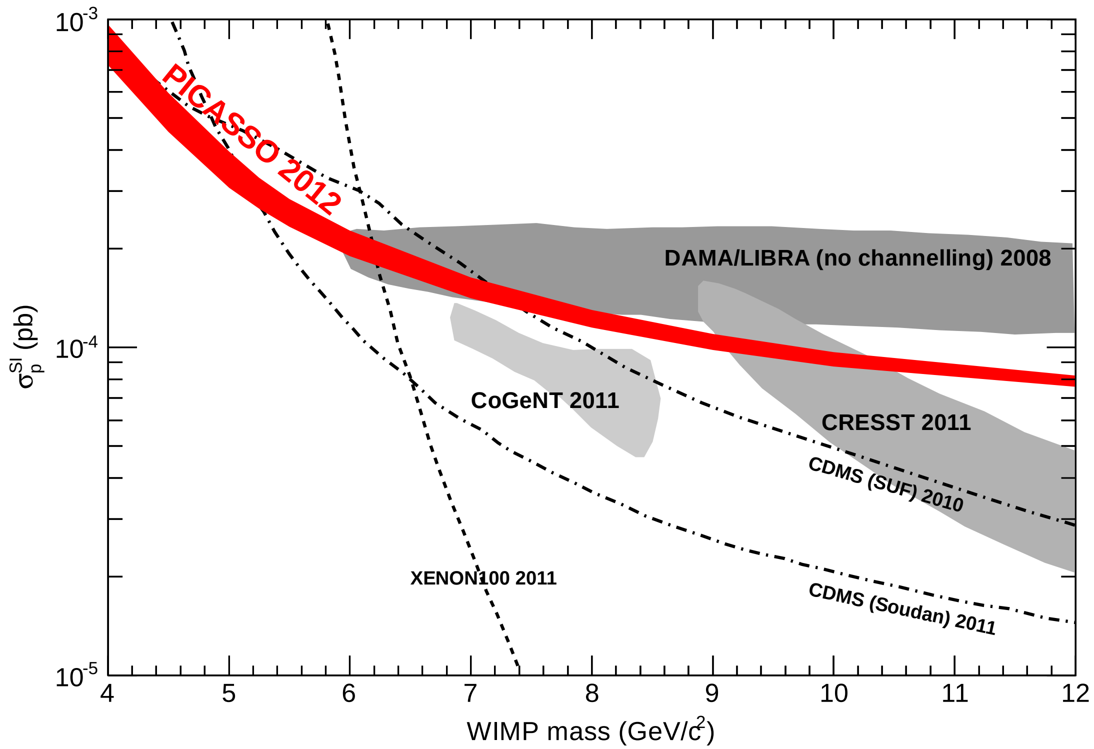
PICASSO

- Suspended droplets of C_4F_{10} in an inactive polymerized gel matrix
- The energy deposited by a nuclear recoil triggers a phase transition
- The acoustic signal can be recorded by piezoelectric transducers
- recoil energy thresholds as low as 1.7 keV
- total target mass of 0.72 kg of ^{19}F and an exposure of 114 kg-day



PICASSO limits

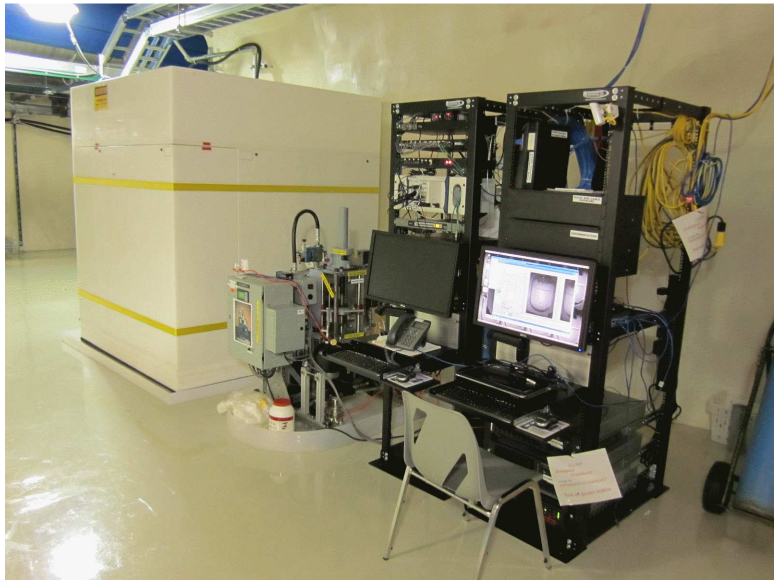




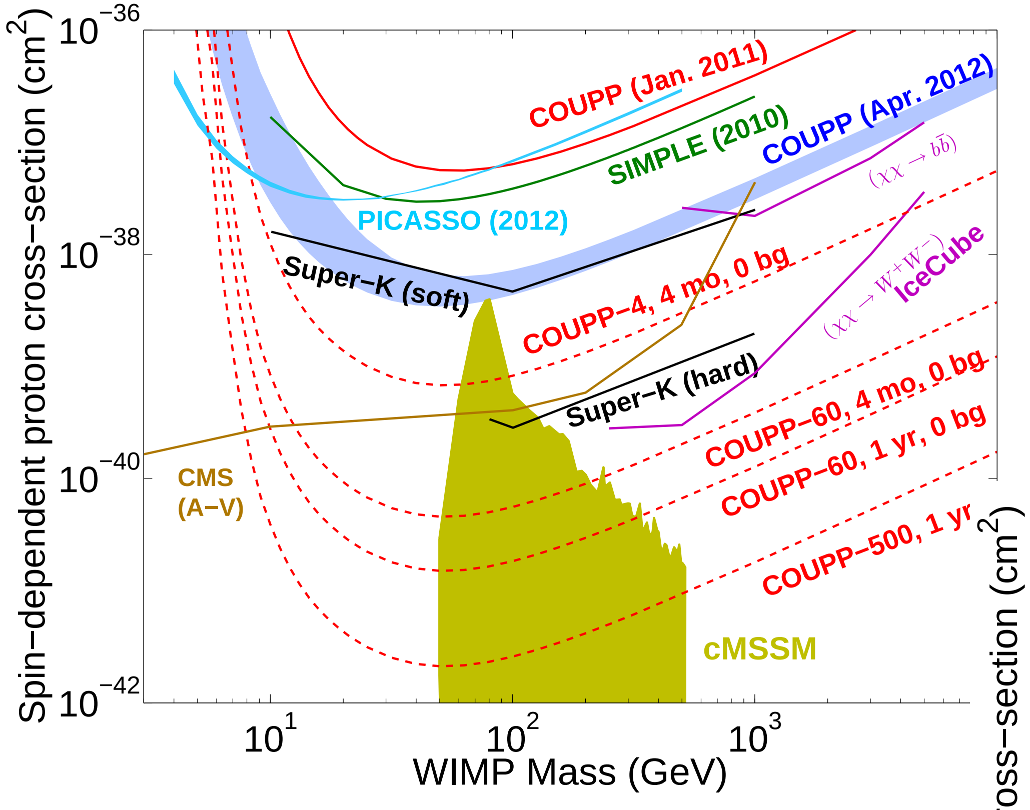
COUPP

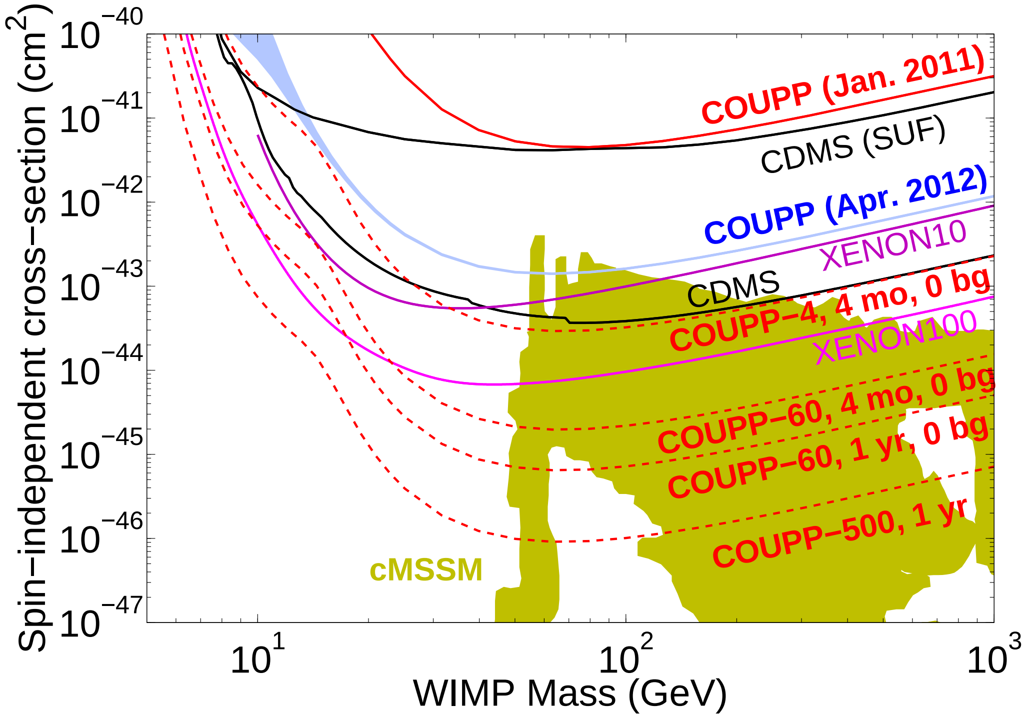
COUPP

- COUPP-4kg currently running at SNOLAB
- COUPP-60kg running by the end of the year
- COUPP-500kg: a tonne scale detector, inexpensive and versatile ready by 2016



COUPP limits





Future experiments and underground science

Future Experiments and Underground Science

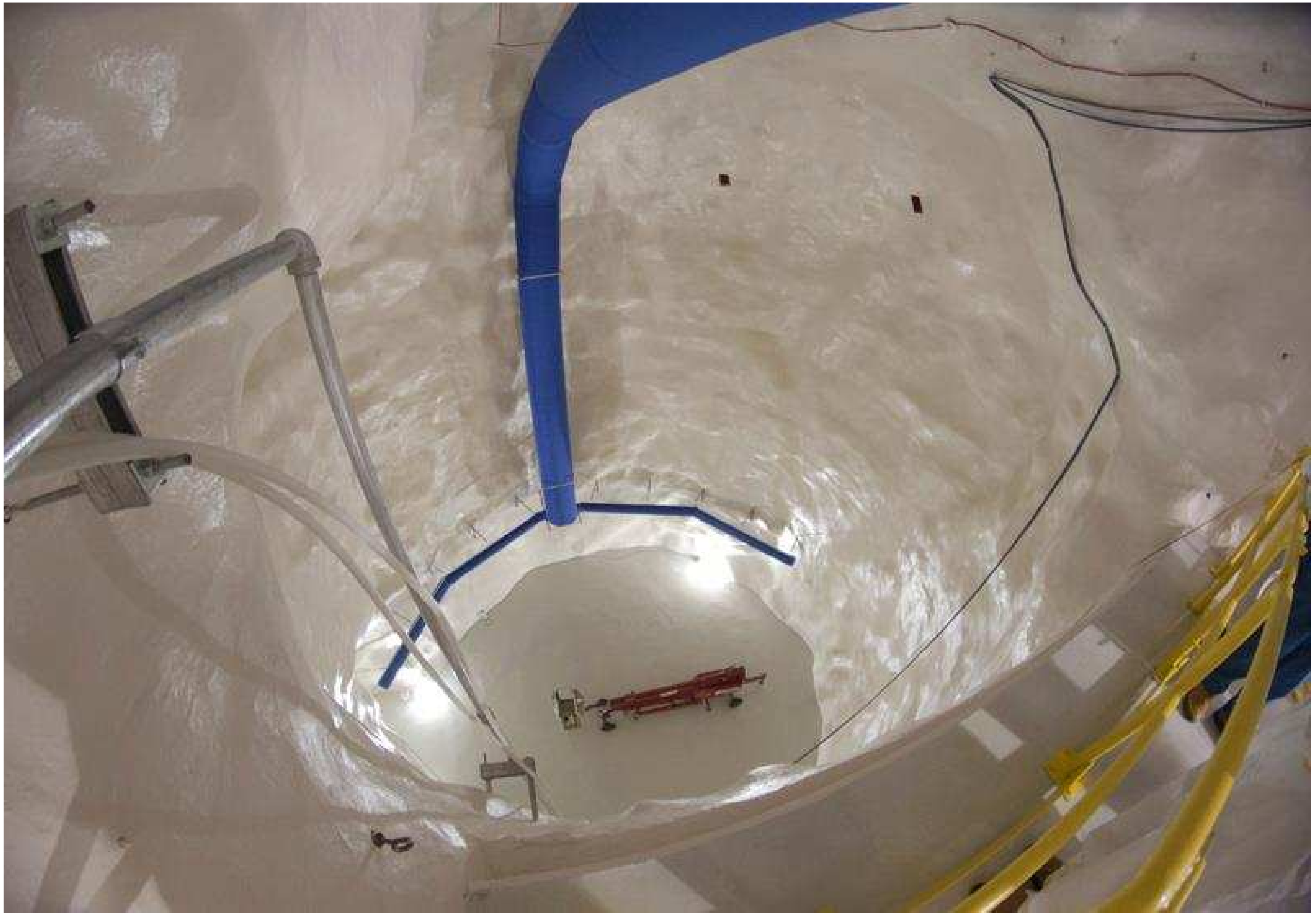
SNOLAB hosting more experiments:

- **DAMIC: moving from Fermilab (2012)**
- **a test facility for CDMS (2012)**
- **SuperCDMS for dark matter**
- **EXO-gas and COBRA for neutrinoless double beta decay**

Underground Science:

- **PUPS: an experiment for the observation of seismic signals at various depths in very hard rock (completed)**
- **Geology, mining and deep sub-surface life**

Still more space at SNOLAB



Final remarks

- The physics program at SNOLAB is making important contributions to experimental research in Astroparticle Physics
- Detectors for supernovae and double beta decay, for solar neutrinos, geo-neutrinos and reactor neutrino oscillations are being built
- Dark matter research experiments at SNOLAB sensitive to spin dependent and/or independent interactions
- Searches are underway with noble gases and superheated liquids detectors; solid state detectors will be deployed soon
- SNOLAB is becoming one of the leading facilities in experimental research in Astroparticle Physics