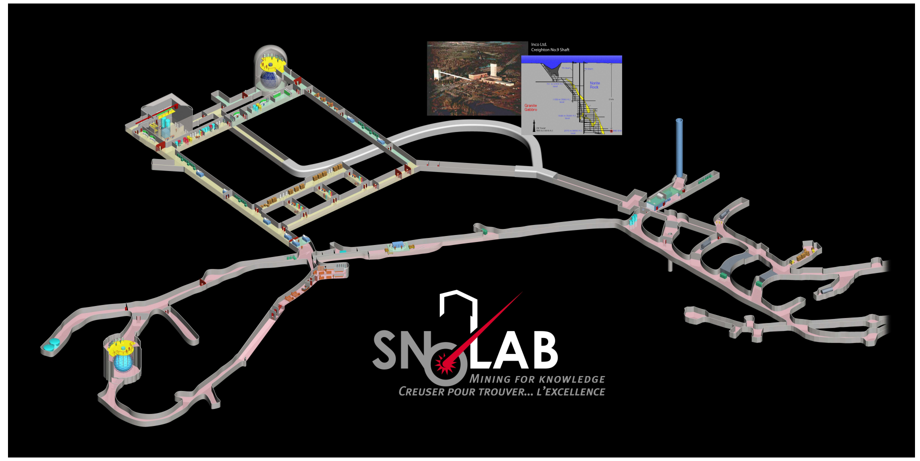
Deep Underground Astroparticle Physics at SNOLAB



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SNOLAB

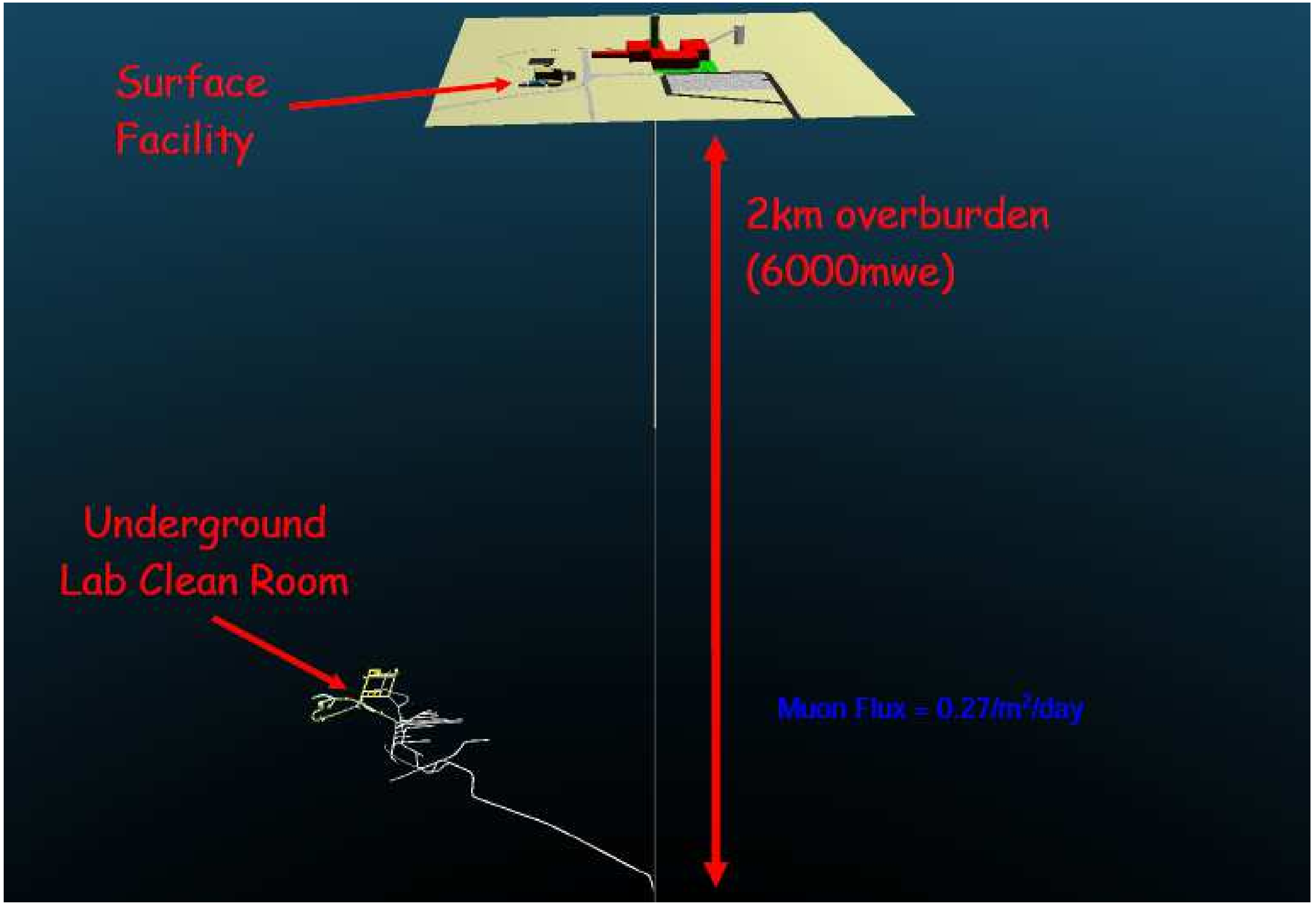
Instituto de Ciencias Nucleares - UNAM
Ciudad de México; Marzo 19, 2013

Outline

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

SNOLAB facility

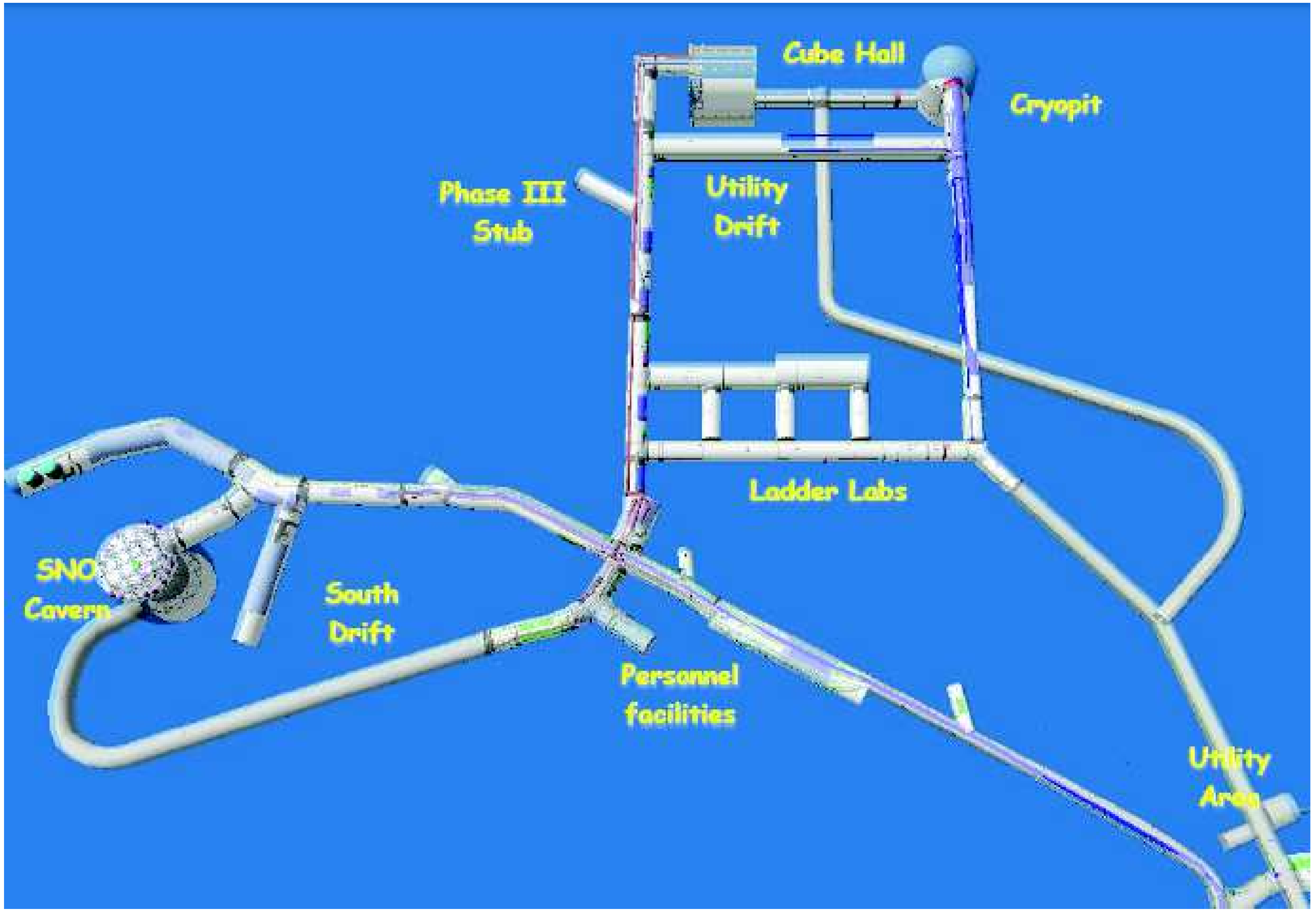
SNOLAB



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 chambers)

Underground Laboratory

- Spraying shotcrete
- Painting
- Washing
- Hand-cleaning

Underground Laboratory



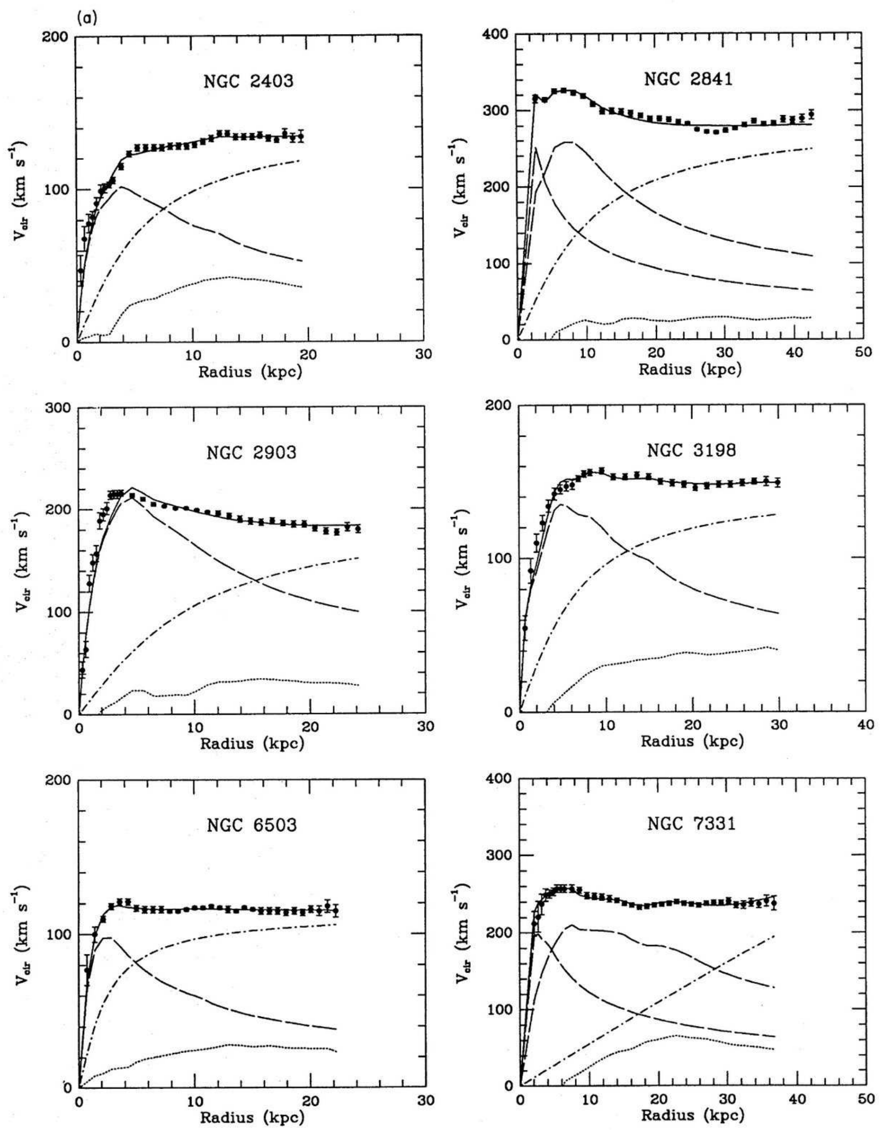

Stephen Hawking at SNOLAB

Dark Matter programme

$>$ 95% of the composition of the Universe is still unknown

Rotation curves of galaxies

Scale $\sim 10^{21-22}$m

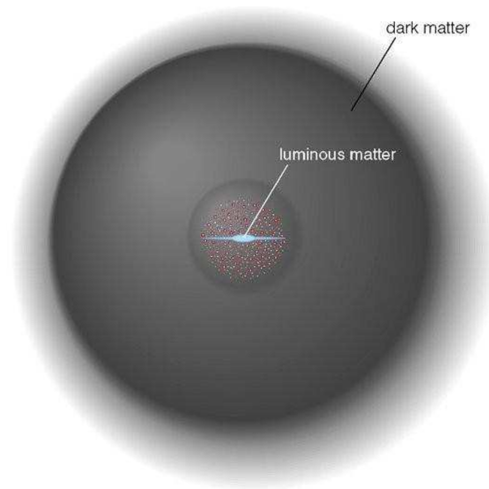


From Newtonian dynamics:

$$F = \frac{mv^2}{r} = G\frac{mM}{r^2}$$
$$v(r) \propto r^{-1/2}$$

For constant v:

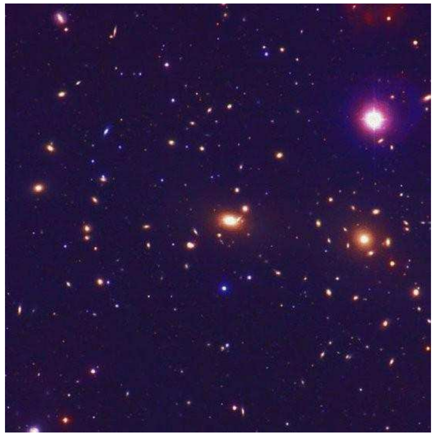
$$M(r) \propto r$$
$$\rho(r) \propto r^{-2}$$

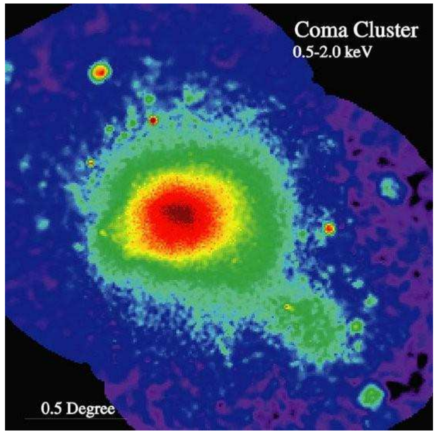


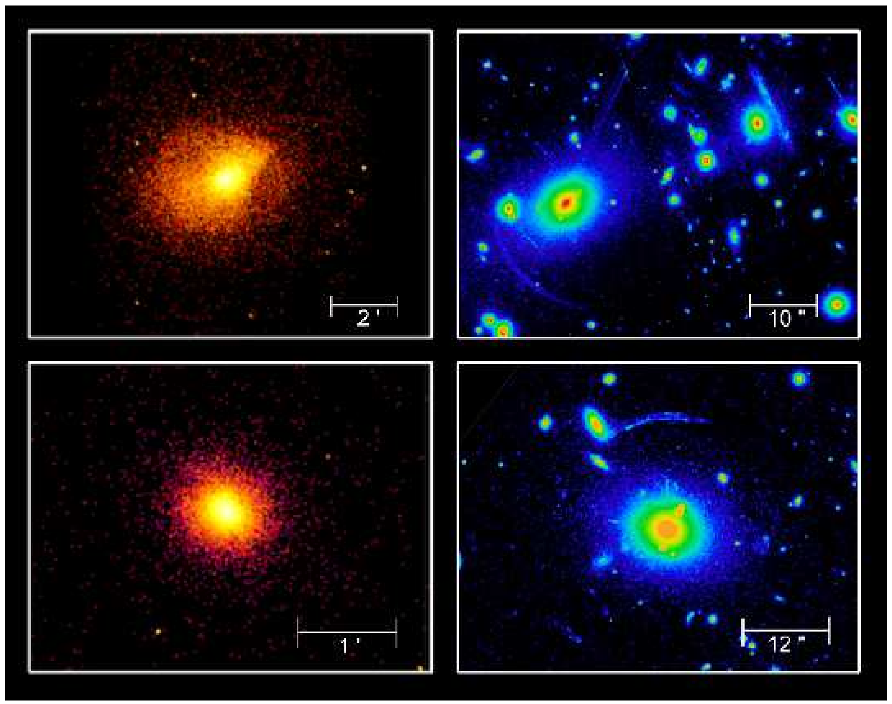
Fritz Zwicky (1933)

Galaxy clusters: x rays

Scale $\sim 10^{22}$m







X rays radiated by the intracluster medium (hot gas)

temperature and distribution of gas

↓

average speed of gas molecules

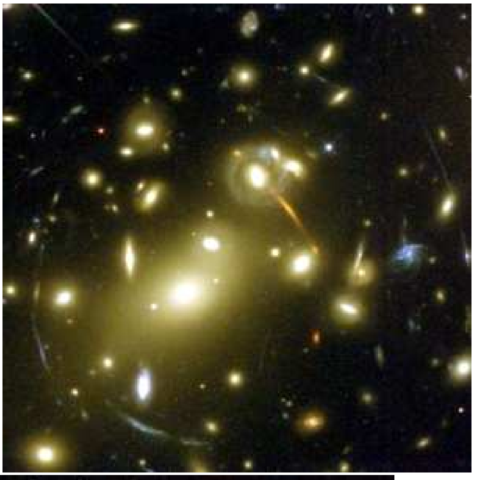
↓

mass

Cluster masses obtained by x-ray measurements agree well with the galactic velocity method

Galaxy clusters: gravitational lensing

Scale $\sim 10^{22}$m



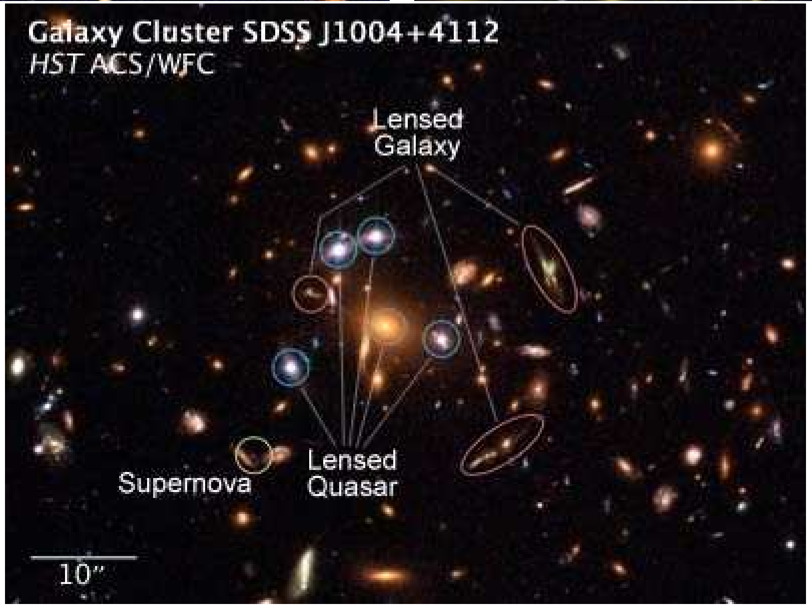
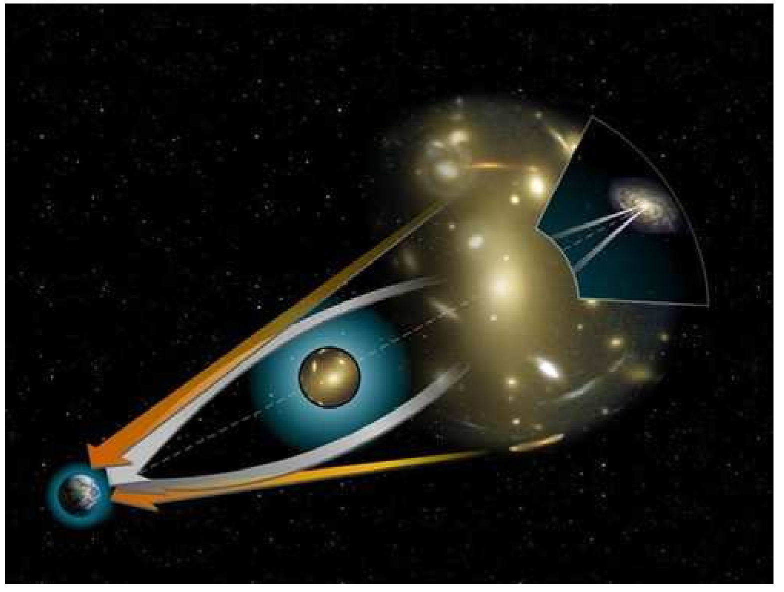


Image distortion by gravitational potential

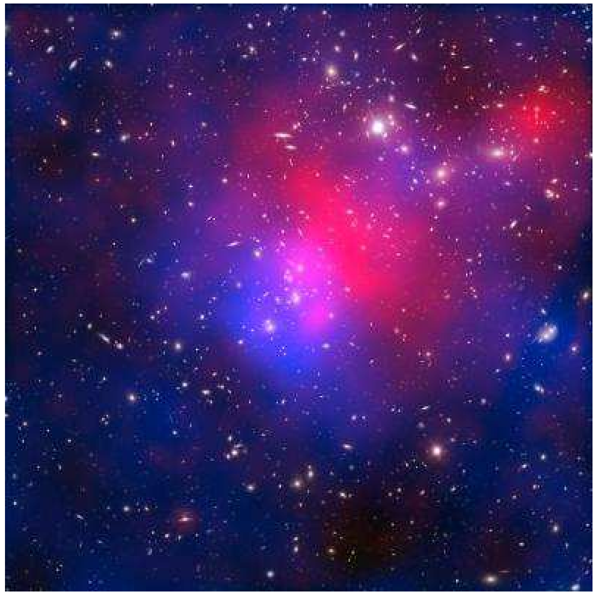
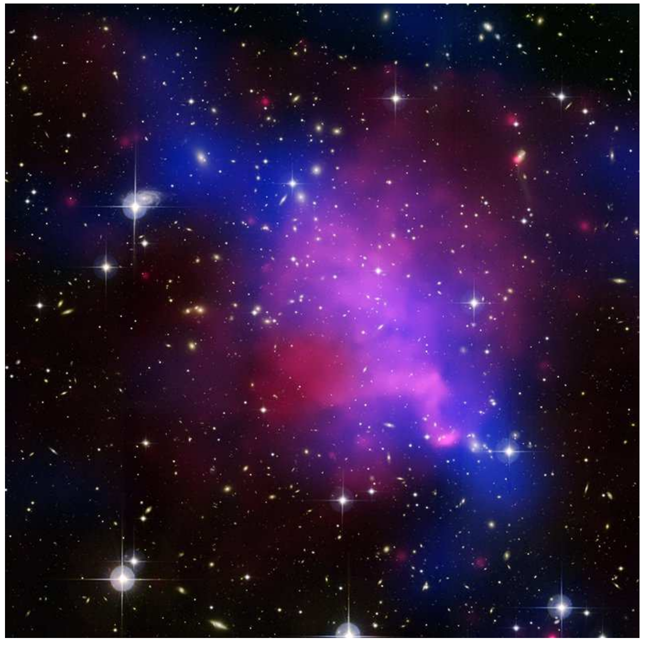
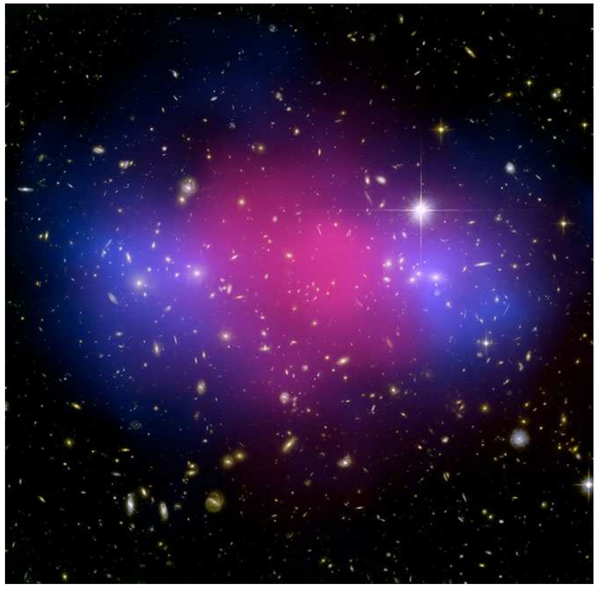
strong/weak

sensitive to total mass

Rotational curves and x-ray measurements agree with gravitational lensing

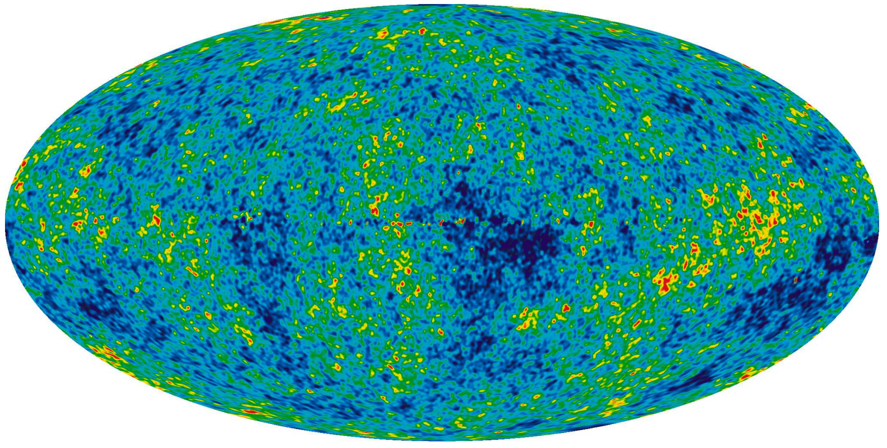


Colliding clusters

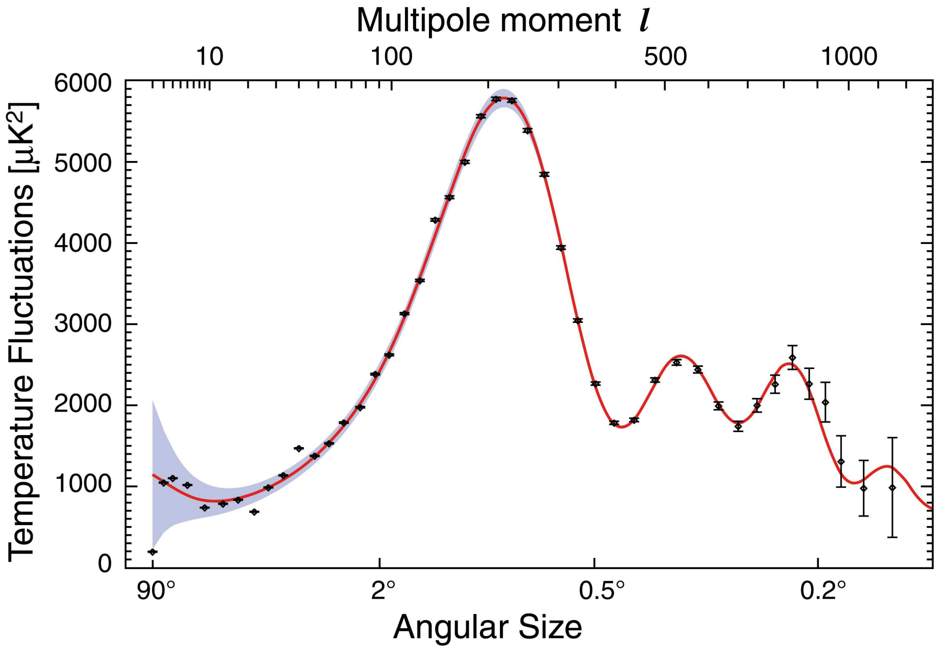





Cosmic Microwave Background

CMB angular power spectrum depends on several parameters, including Ω_b, Ω_c, Ω_Λ



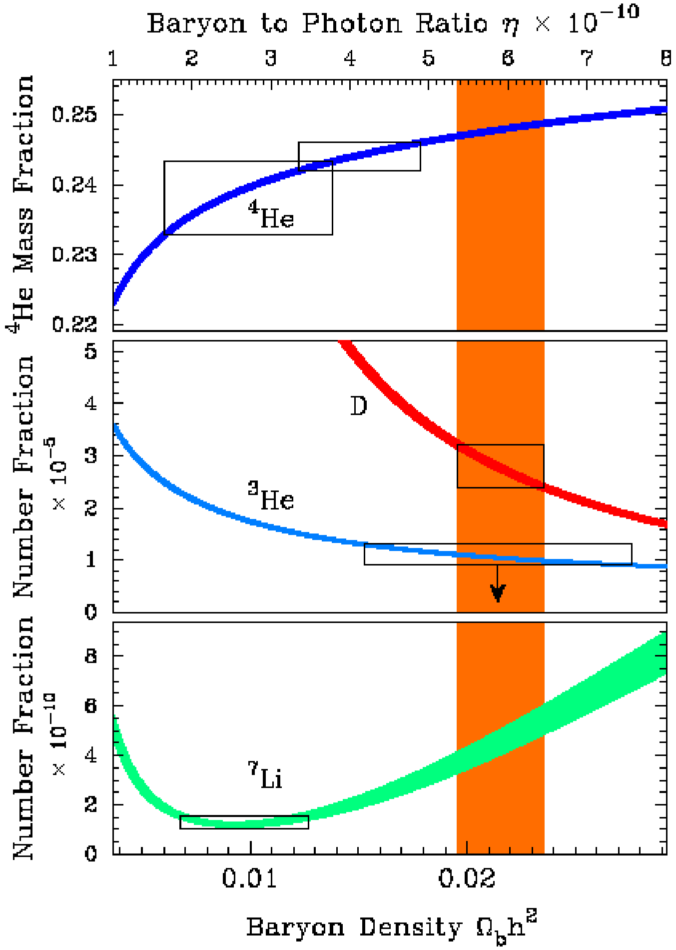
$$\Omega_{tot} = 1.080^{+0.093}_{-0.071}$$

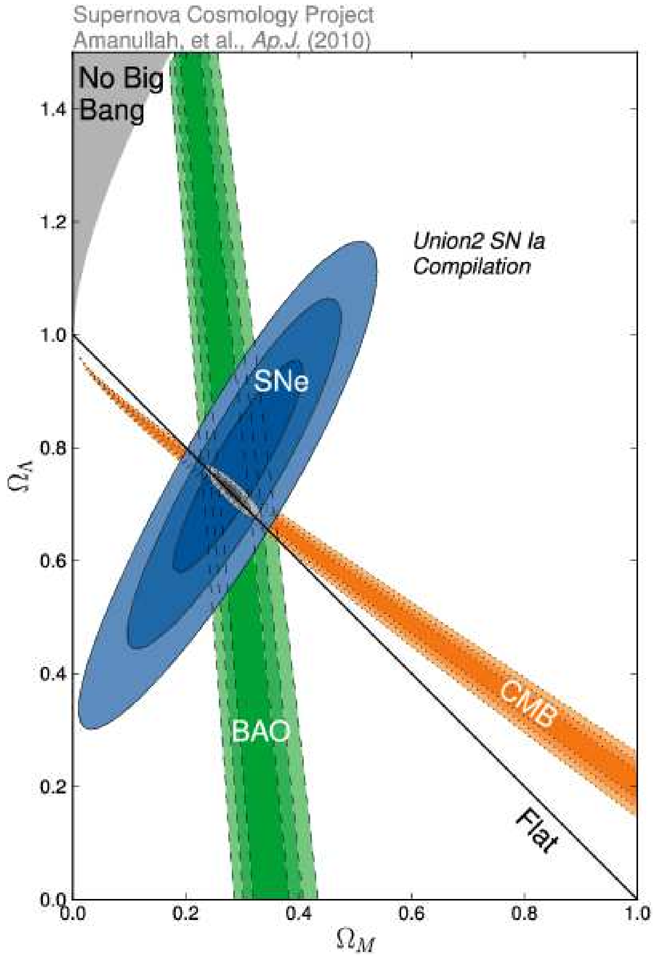


- $\Omega_b = 0.0449 \pm 0.0028$
- $\Omega_c = 0.222 \pm 0.026$
- $\Omega_\Lambda = 0.734 \pm 0.029$

Precision cosmology

Abundance of primordial elements
combined with predictions
from Big Bang Nucleosynthesis



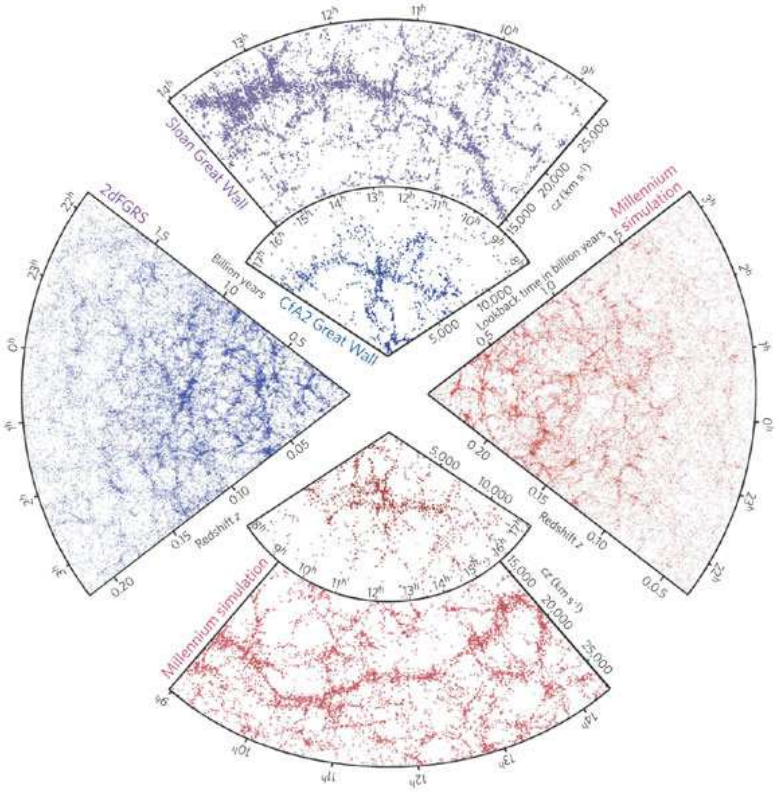


Λ_{CDM} (Lambda Cold Dark Matter)
Standard model of cosmology

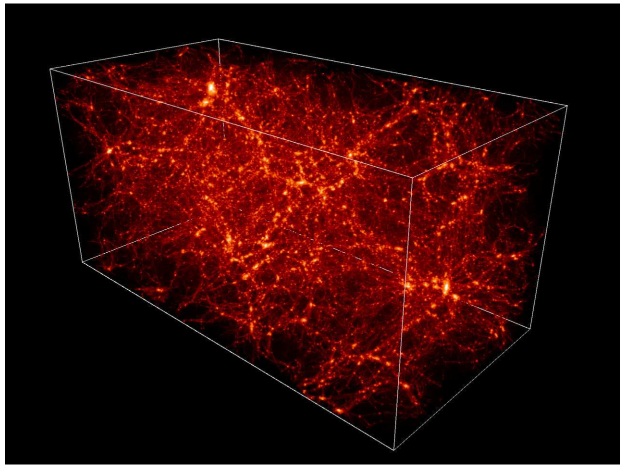
Structure formation

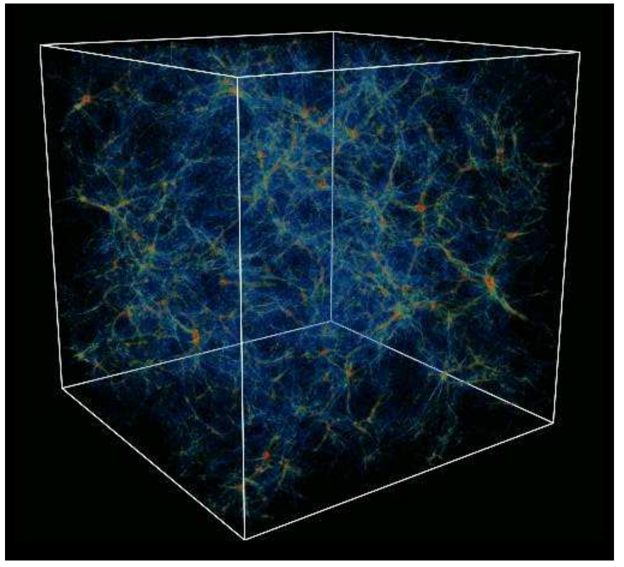
Simulations of structure formation

Structure growth depends on the amount and type of dark matter



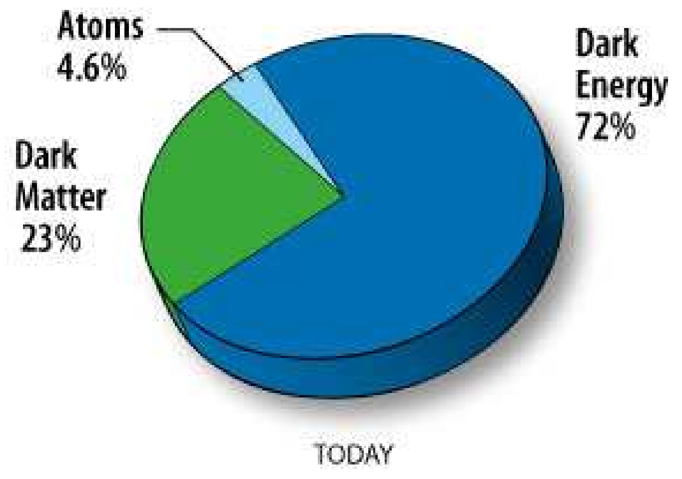
All viable models are dominated by cold dark matter

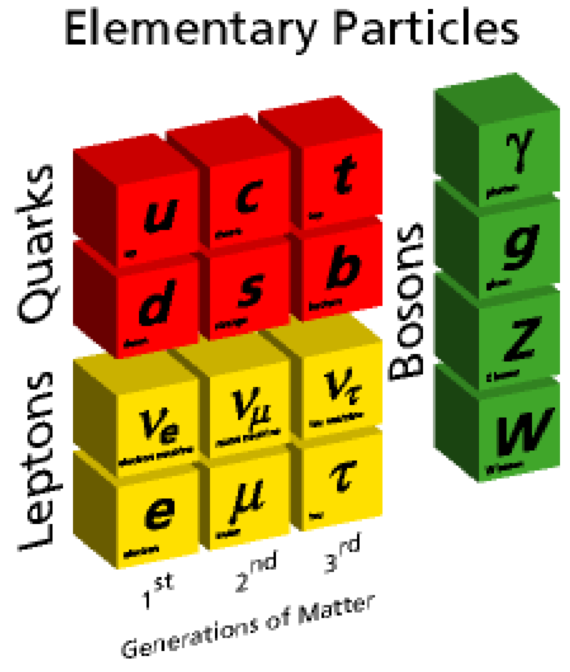




Dark matter

- Gravitationally interacting
- Stable or long-lived
- Cold or warm
  not hot (relativistic)
- Non-baryonic
- Electrically neutral
- No Color





Physics beyond the Standard Model

Detection methods

- **Astrophysics / Cosmology:**
  measurement of gravitational effects

- **Direct detection:**
  WIMP scattering

- **Indirect detection:**
  from annihilation or decay

- **Accelerator-based creation and measurement**

Direct detection

- Detect tiny energy deposits
- Background suppression:
  - Deep sites to reduce cosmic ray flux
  - Passive/active shielding
  - Careful choice and preparation of material
- Background discrimination
- Large target mass

COUPP Collaboration

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KICP Kavli Institute for Cosmological Physics at the University of Chicago
SNOLAB Mining for knowledge / Creuser pour trouver... l'excellence
Northwestern University
Fermilab
Indiana University South Bend
Virginia Tech

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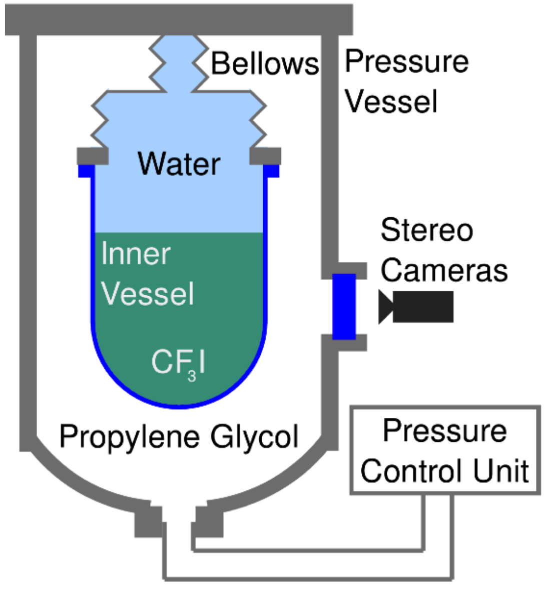
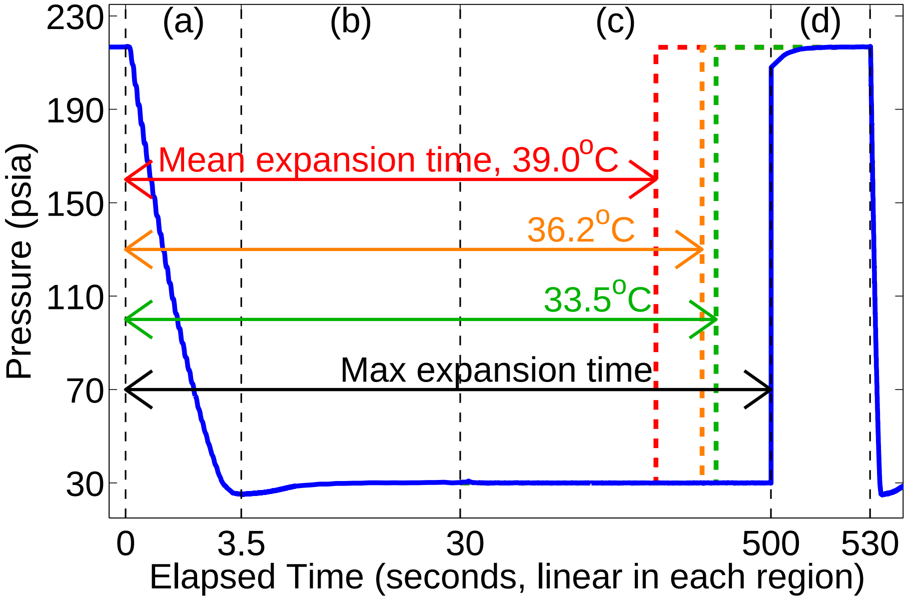
U.S. Department of Energy
NSF
Universitat Politècnica de València
The Kavli Foundation

COUPP bubble chambers

- Target material: superheated CF_3I spin-dependent/independent (C_3F_8, C_4F_{10})
- Particles interacting evaporate a small amount of material: bubble nucleation
- Cameras record bubbles
- Piezo sensors detect sound
- Recompression after each event



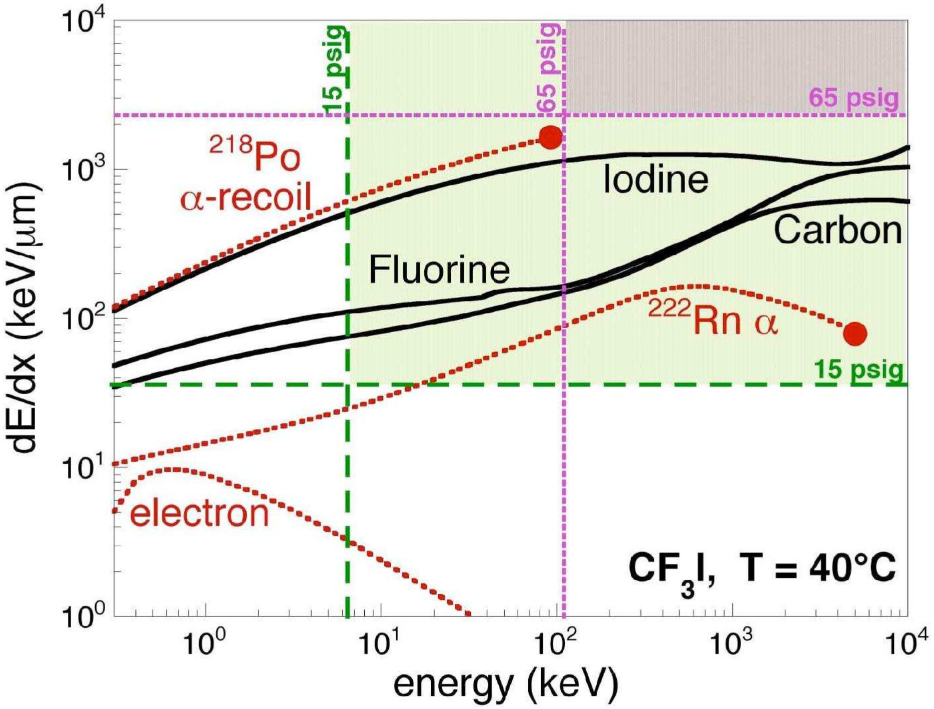


COUPP bubble chambers

- The ability to reject electron and gamma backgrounds by arranging the chamber thermodynamics such that these particles do not even trigger the detector
- The ability to suppress neutron backgrounds by having the radioactively impure detection elements far from the active volume and by using the self-shielding of a large device and the high granularity to identify multiple bubbles
- The ability to build large chambers cheaply and with a choice of target fluids
- The ability to increase the size of the chambers without changing the size or complexity of the data acquisition
- Sensitivity to spin-dependent and spin-independent WIMP couplings

Dependence of bubble nucleation on the total deposited energy and dE/dx

- Region of bubble nucleation at 15 psig
- Backgrounds: electrons, ^{218}Po, ^{222}Rn
- Signal processes of Iodine, Fluorine and Carbon nuclear recoils



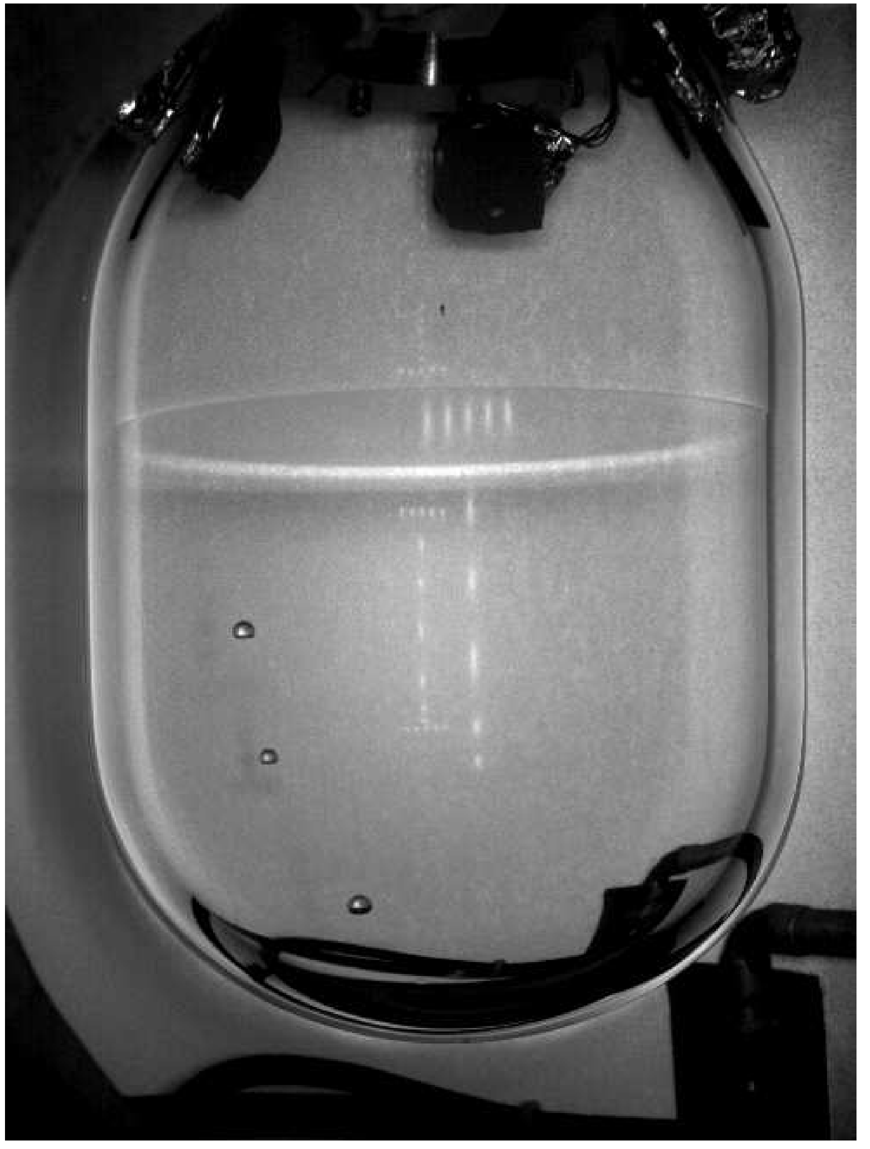
insensitive to electrons and gammas

COUPP bubble chambers

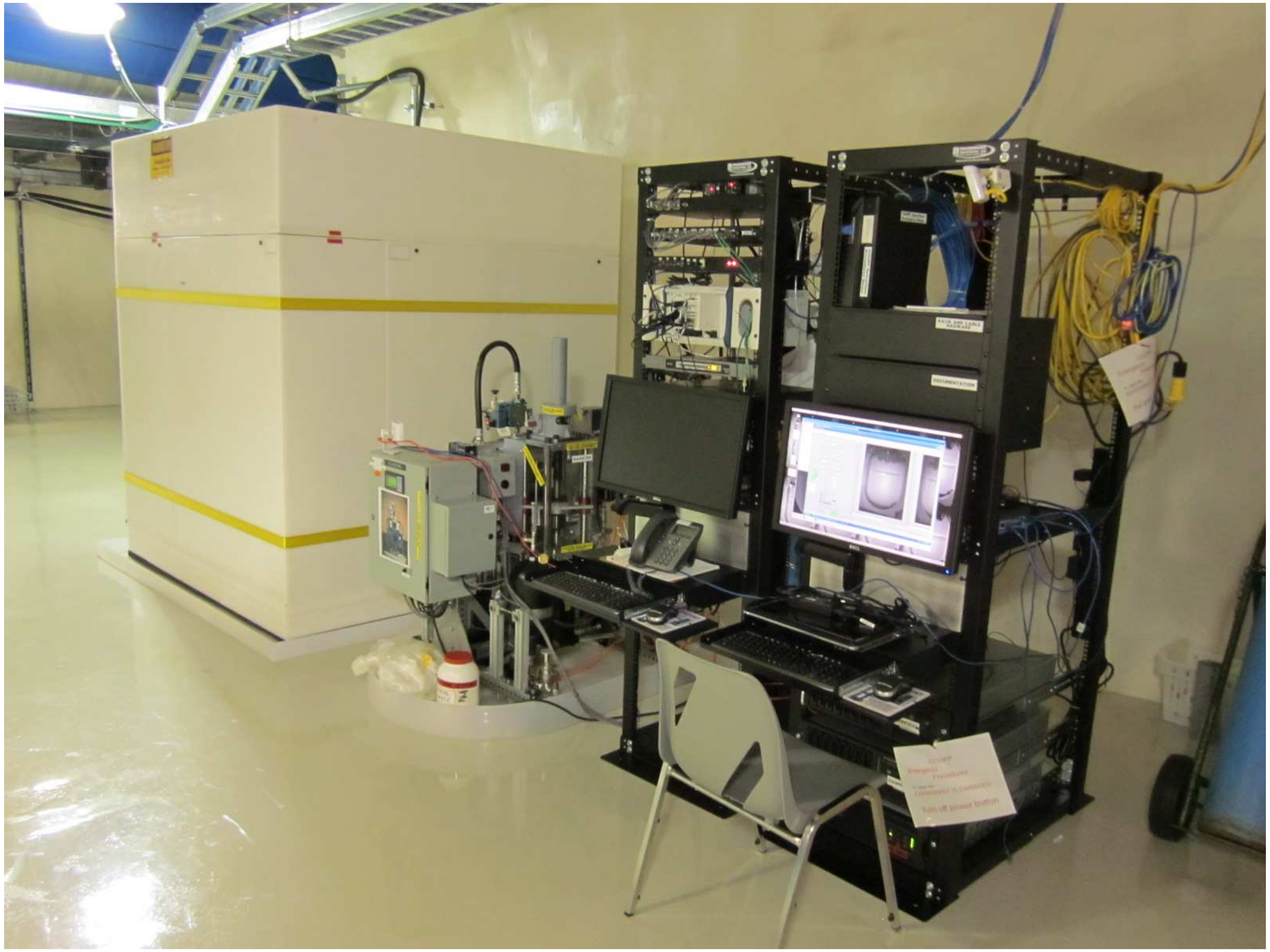
- **Alpha decays:**
  Nuclear recoil and
  40 μm alpha track
  1 bubble

- **Neutrons:**
  Nuclear recoils
  mean free path $\sim$20 cm
  3:1 single-multiple ratio
  in COUPP4

- **WIMPs:**
  Nuclear recoil
  mean free path $> 10^{12}$ cm
  1 bubble

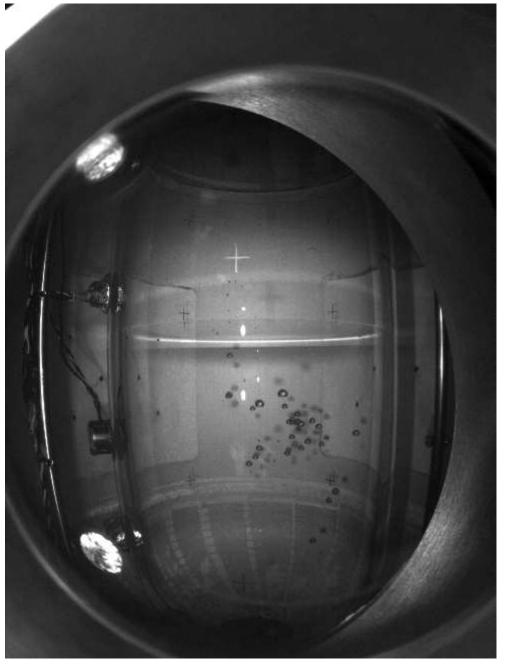


COUPP4



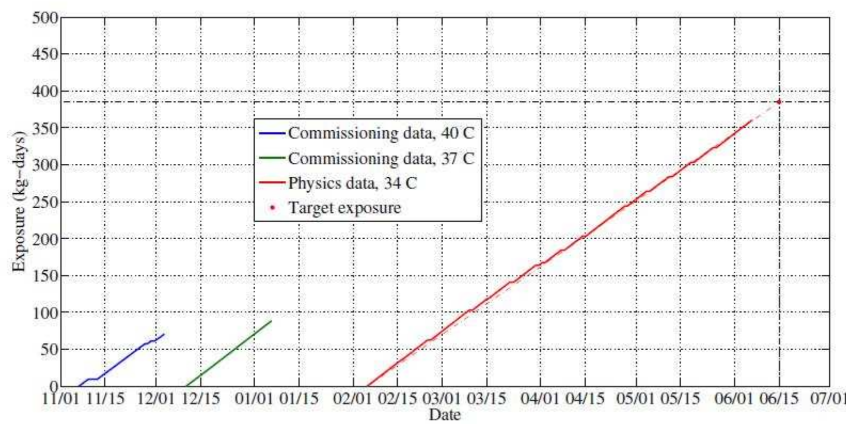
COUPP4 features

- Energy: threshold detector
- Background suppression:
  - UG at SNOLAB
  - Water shielding
  - Clean materials
- Background discrimination:
  - Neutrons:
    multiples bubbles
    Nuclear recoil, $l \sim 20$ cm
  - α: acoustic parameter
    Nuclear recoil, 40 μm track
- Large target mass:
  getting there



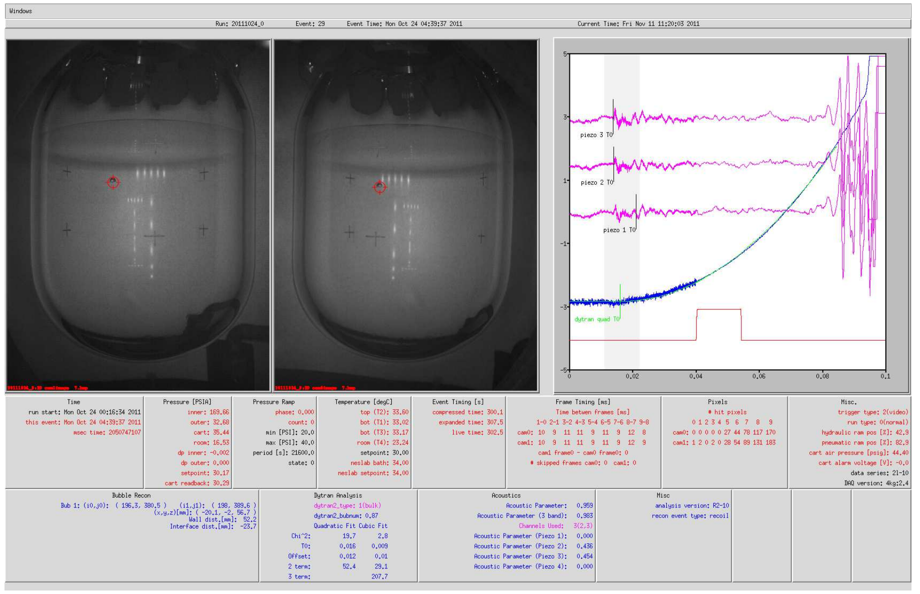
COUPP4 at SNOLAB

- Installation in summer 2010
- First Physics run begins Nov. 3, 2010
  (second Physics run in 2012)
- Run settings (P=30.5 psia):
  - 17.4 days at 8 keV (39^{o}C)
  - 21.9 days at 10 keV (36^{o}C)
  - 97.3 days at 15 keV (33.5^{o}C)
- 4.048 kg of CF_3I
- Calibrations:
  - Neutron calibration runs: AmBe and ^{252}Cf
  - Continuous source of ^{222}Rn



COUPP4 at SNOLAB: data analysis

- Examination of images: algorithm searching for clusters among pixels that changed between consecutive frames
- Examination of pressure rise: fit to the rate of pressure rise by a quadratic time dependence for bubbles in the bulk
- Examination of the acoustic signal



hand-scanned to resolve disagreement

overall efficiency for all data quality and fiducial volume cuts is $82.5 \pm 1.9\%$

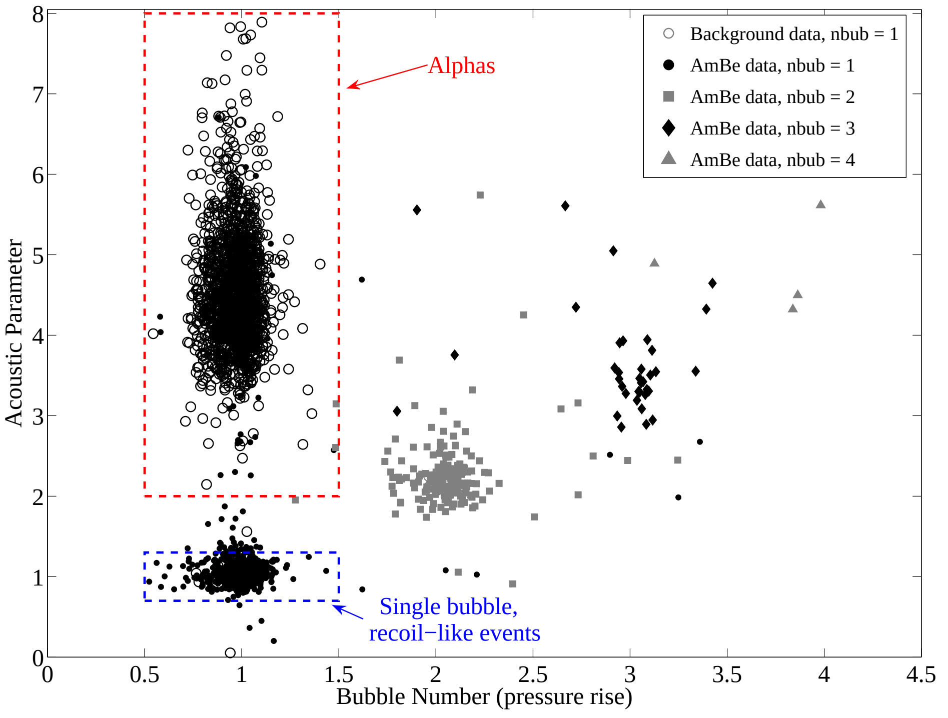
COUPP4 at SNOLAB

Acoustic transducer signals digitized with a 2.5 MHz sampling rate and recorded for 40 ms for each event

The nuclear recoil acceptance of the AP cut $95.8 \pm 0.5\%$

3 ways of counting:

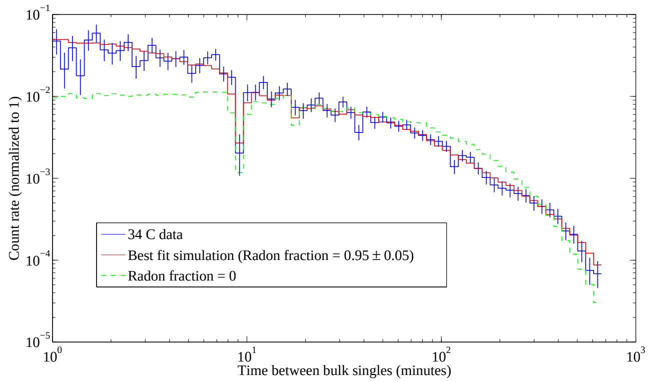
- Images: cameras
- Pressure rise: transducer
- Acoustic parameter: piezos

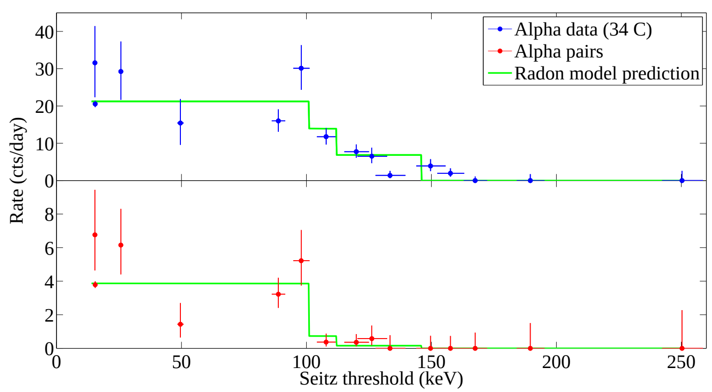


COUPP4 at SNOLAB: calibrations

Radon fraction $= 0.95 \pm 0.05$

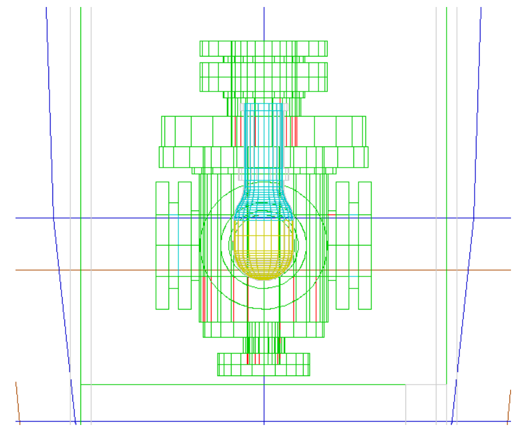
^{222}Rn (101 keV),
^{218}Po (112 keV),
^{214}Po (146 keV)

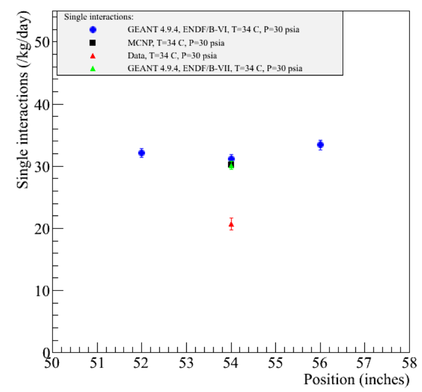


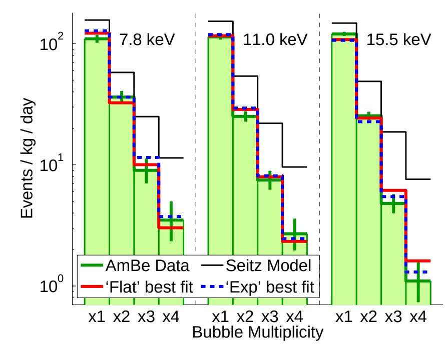


GEANT and MCNP simulations

- Bubble rate is 50% higher

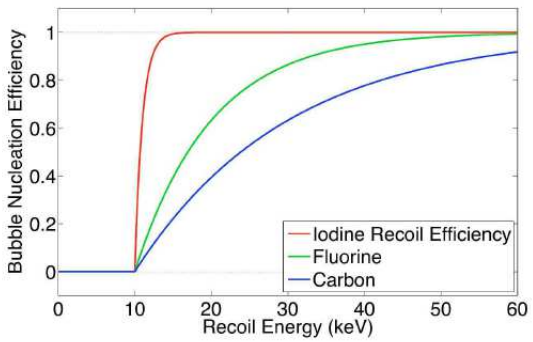




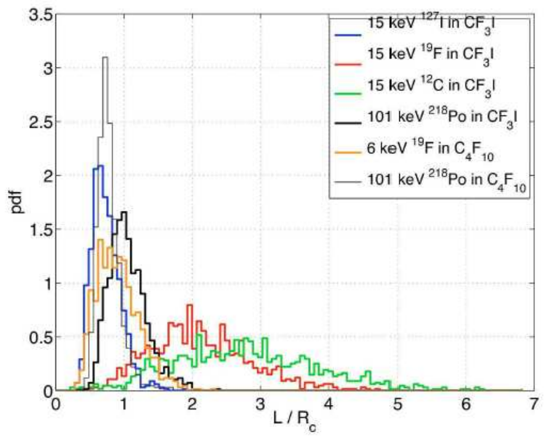


COUPP4 at SNOLAB: calibrations

- Lower efficiency for ^{19}F and ^{12}C recoils
- Seitz model for ^{127}I recoils



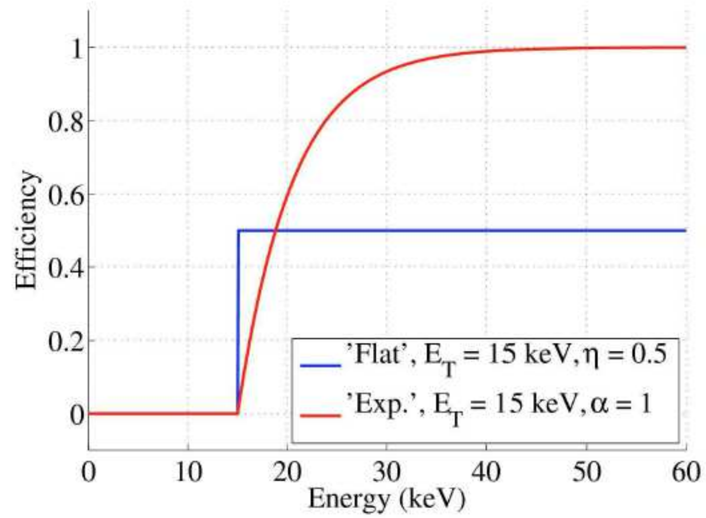
SRIM → TRIM calculation



Seitz model:

- 6 keV ^{19}F recoils, C_4F_{10} (PICASSO)
- 101 keV ^{218}Po recoils, C_4F_{10} (PICASSO)
- 101 keV ^{218}Po recoils, CF_3I

Understand efficiency for 15 keV recoils in CF_3I



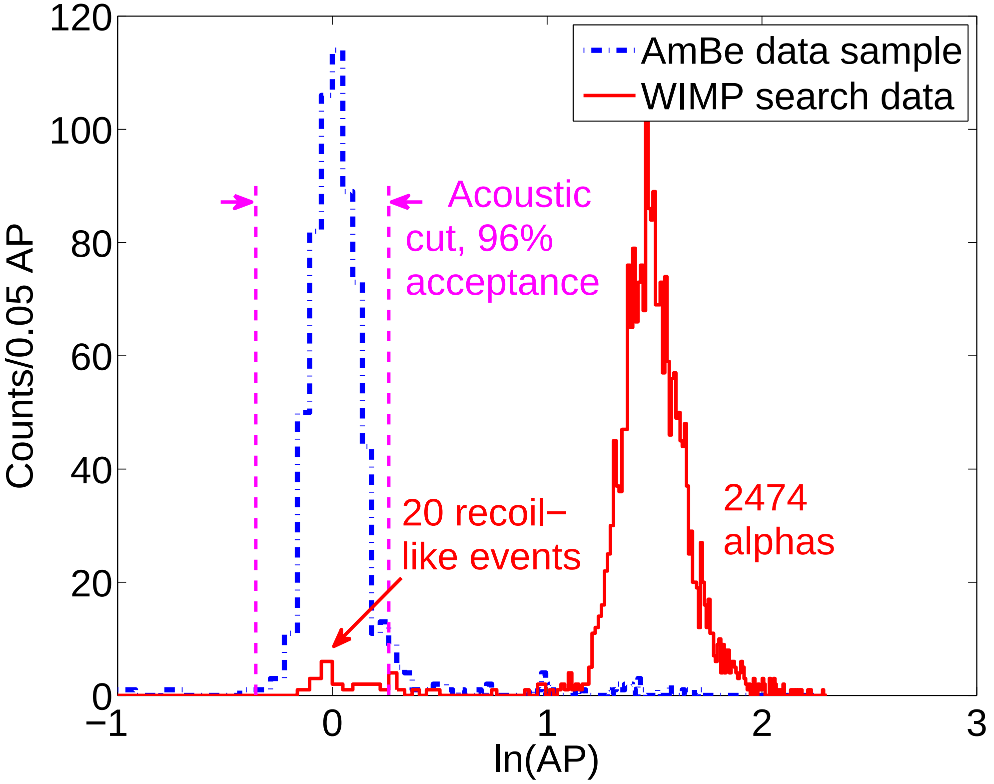
COUPP4 at SNOLAB: results

456 kg-days, 2474 alphas
1733 alphas (15 keV data)

5.3 alpha decays/ kg-day
95% from radon

$> 98.9\%$ α rejection
$> 99.3\%$ (15 keV data)

- 6 events at 8 keV
- 6 events at 10 keV (2 triples)
- 8 events at 15 keV (1 double)



20 WIMP candidates

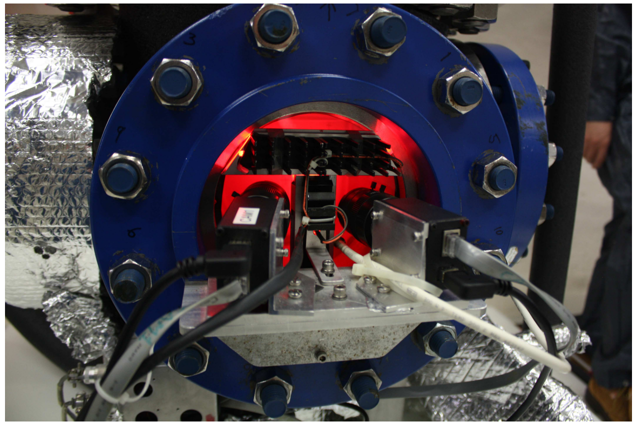
(Neutrons from rock: < 1/year)

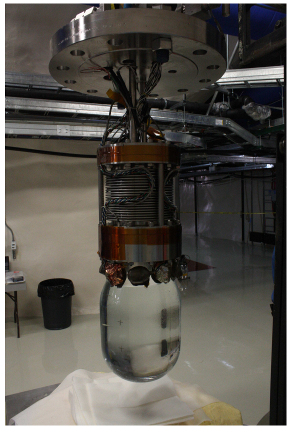
COUPP4 at SNOLAB: results

Internal neutron background

- View-ports:
  0.5 ppm ^{238}U and 0.8 ppm ^{232}Th, ($\sim$ 5 events)
- Piezos:
  4.0 ppm ^{238}U, 1.9 ppm ^{232}Th and ^{210}Pb, ($\sim$ 2 events)

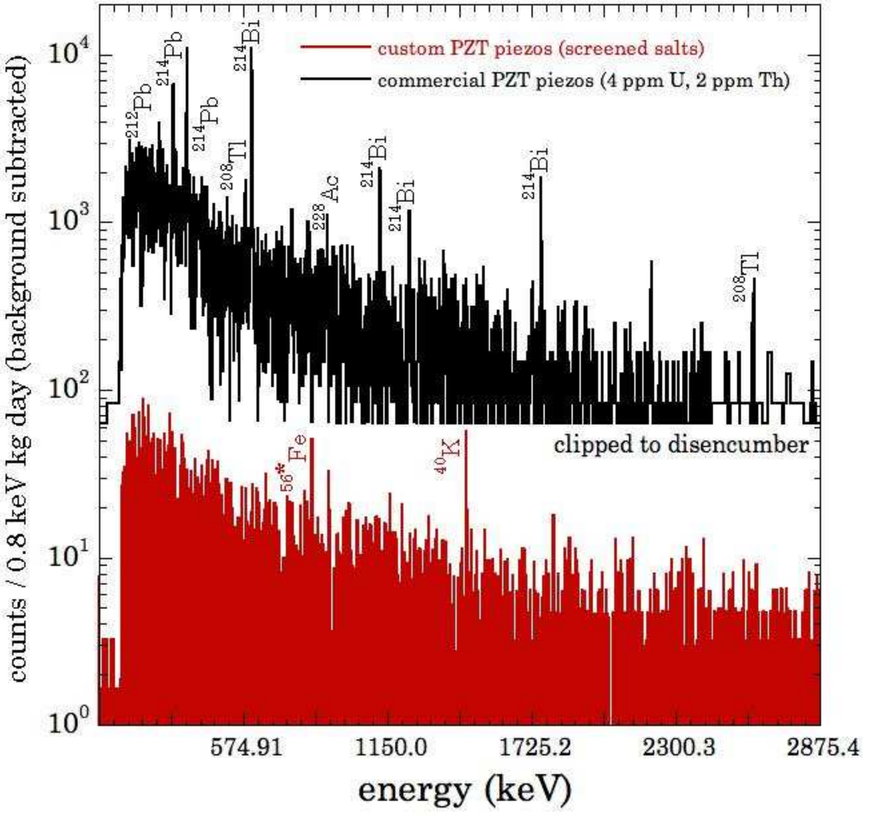
Fission and (α,n) on light elements





New piezos built (low background salts)

New view-ports (synthetic silica)

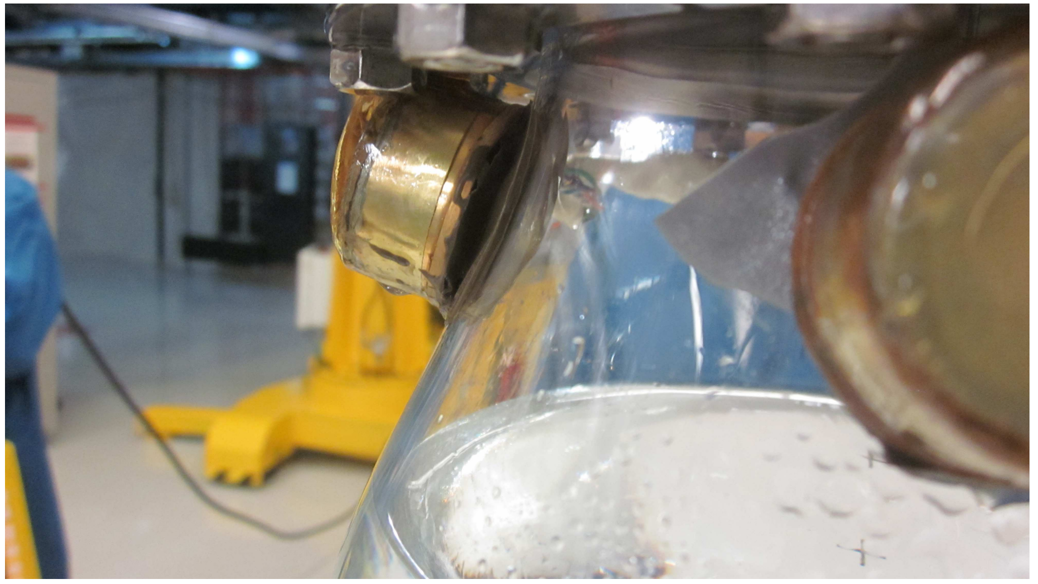


COUPP4 at SNOLAB: Physics run II

- New physics run in 2012
- 8 singles, 1 double, 1 triple
- Replace more components
- ICP-MS assay

Hydraulics failed

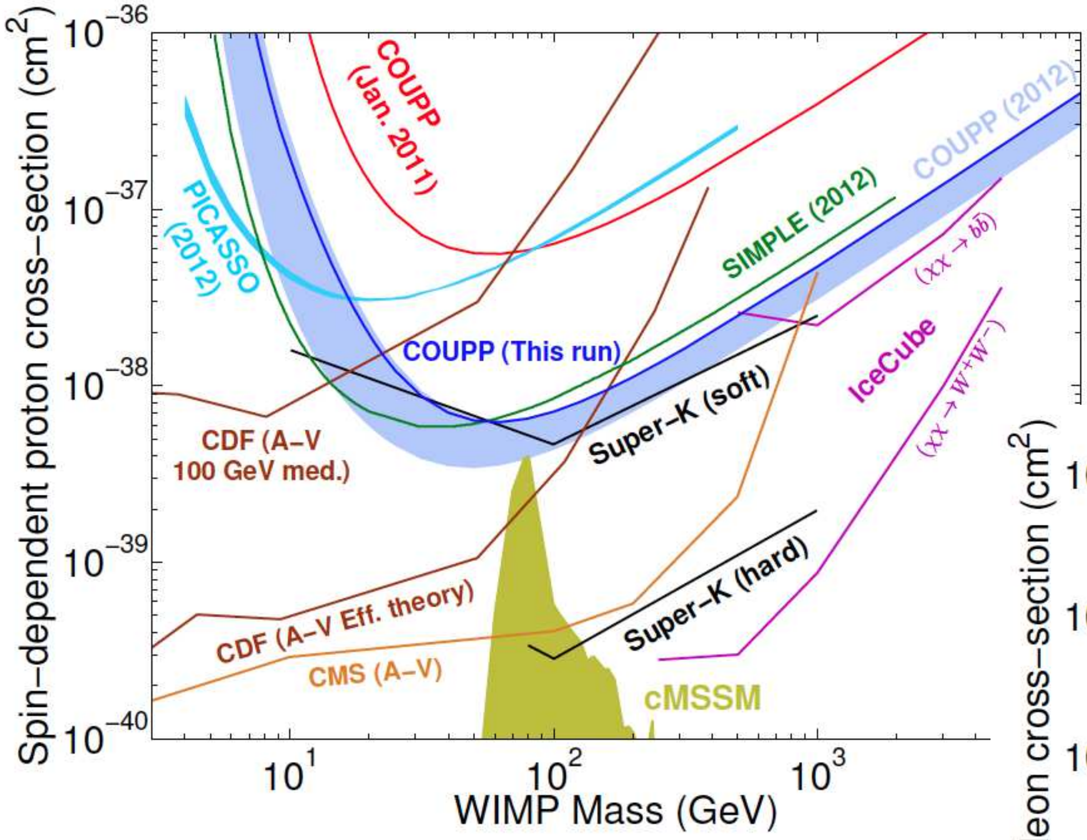
Piezos detached from IV

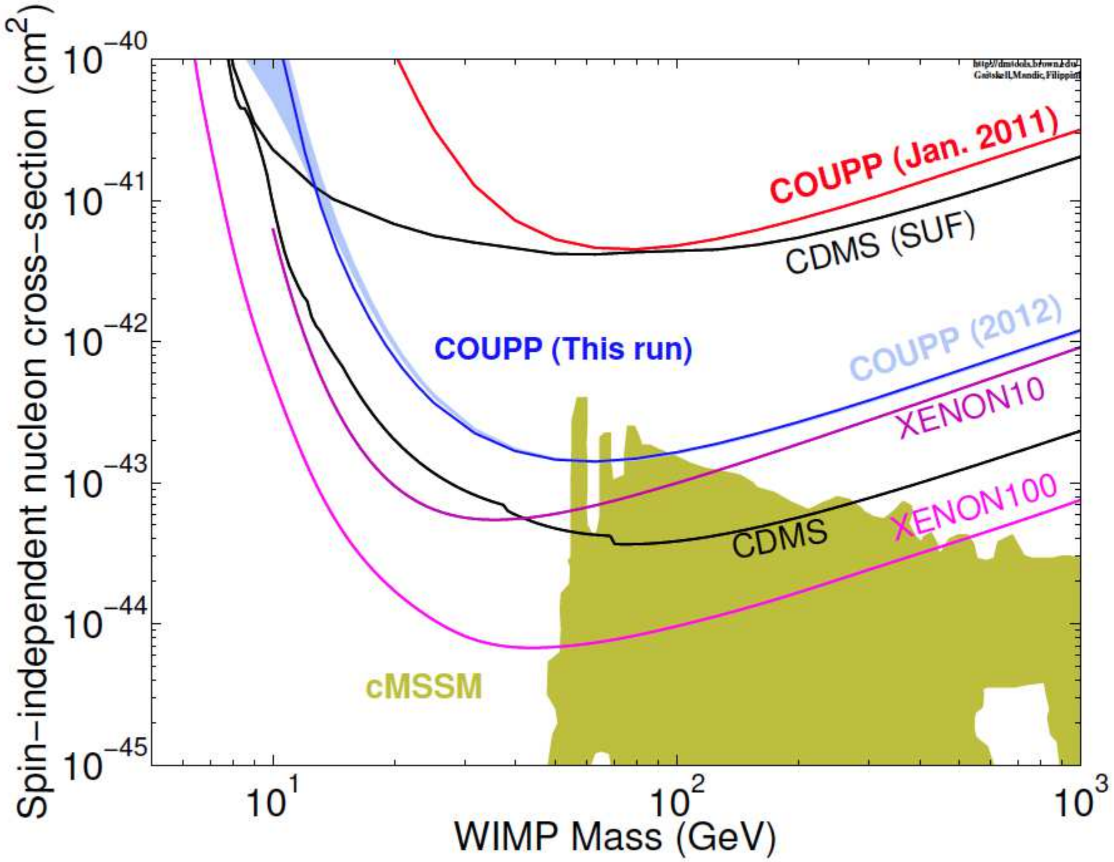


Refurbishing the detector

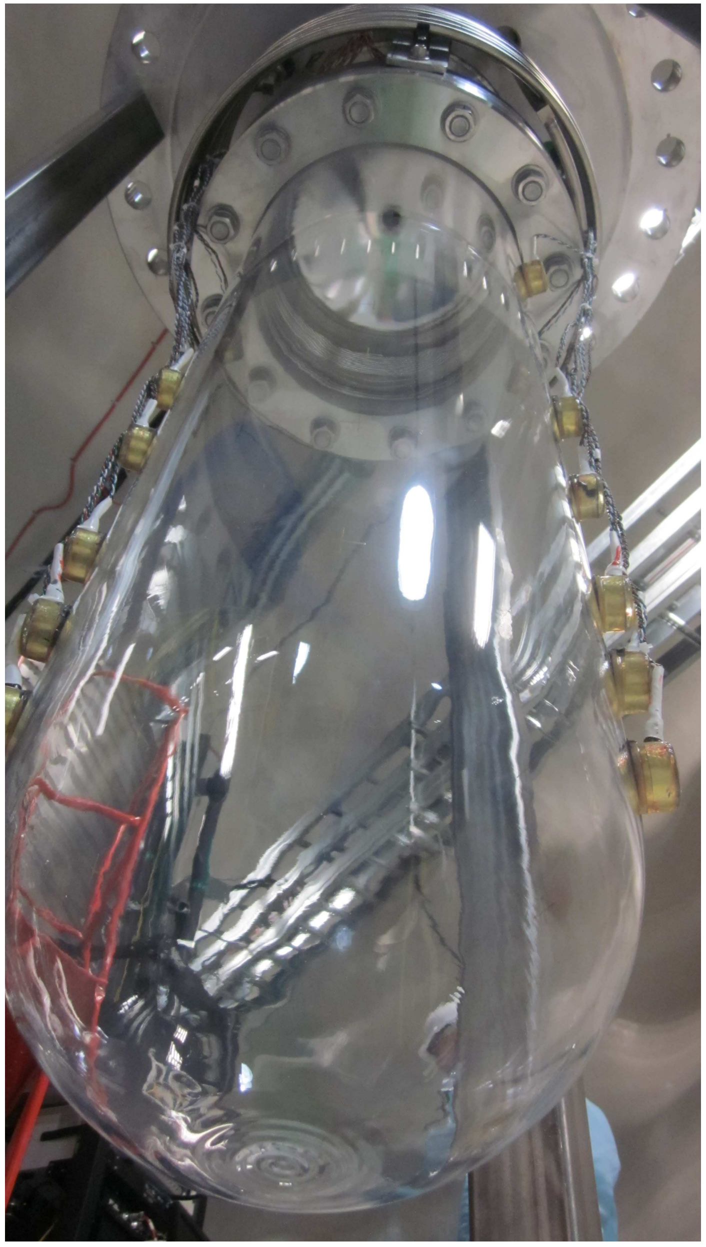
Different target material

COUPP4 at SNOLAB: sensitivity

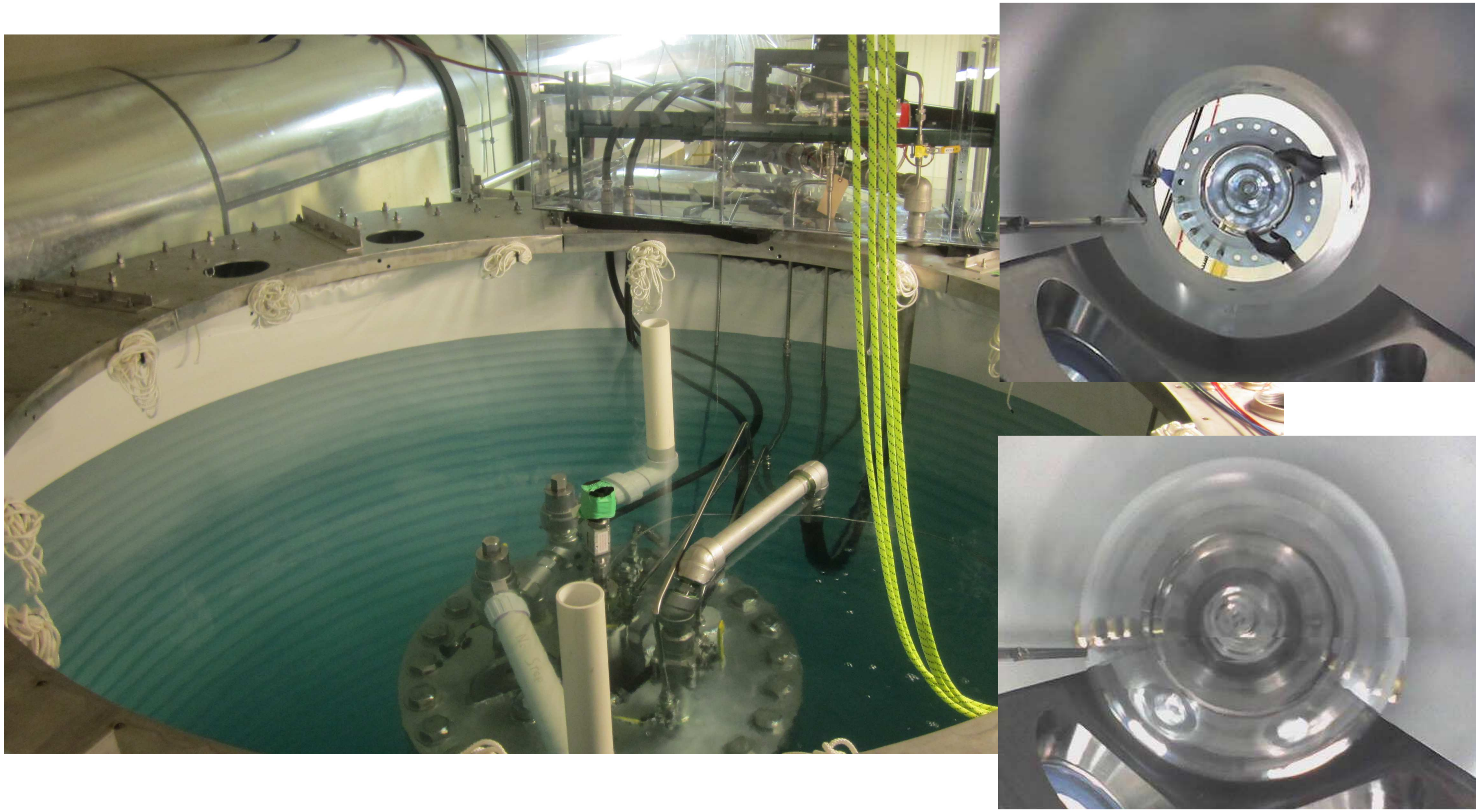




COUPP60 at SNOLAB



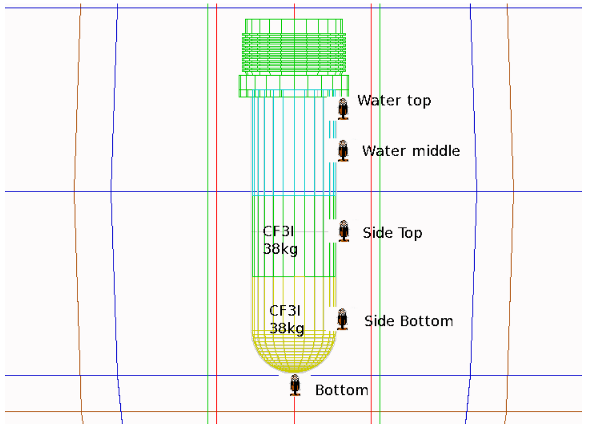
COUPP60 at SNOLAB



COUPP60

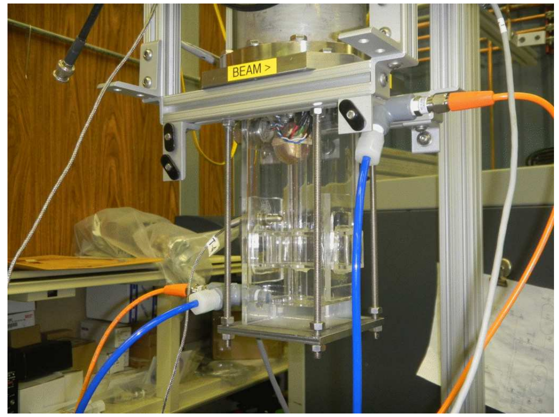
Engineering run at Fermilab: successful commissioning COUPP60 moved to SNOLAB

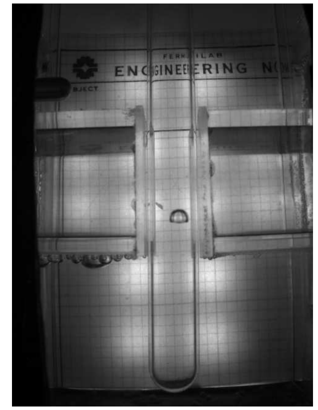
- Ready for physics run by the end of the month



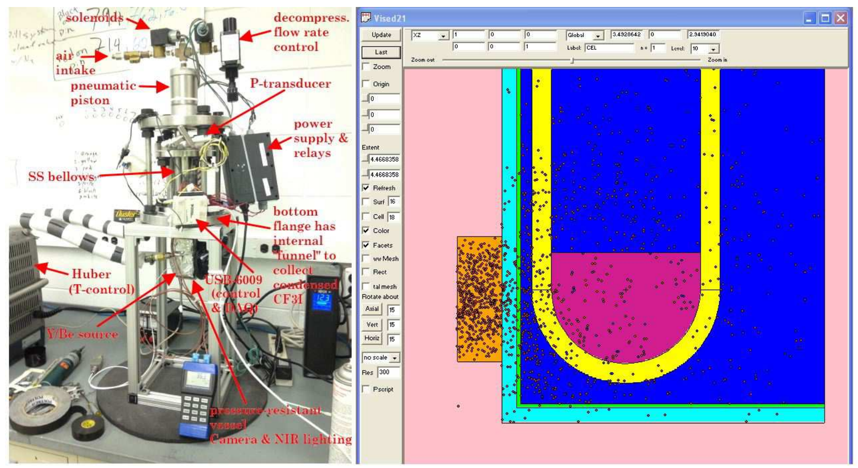
Calibrations

- γ and neutron calibrations
  - AmBe and ^{252}Cf
  - ^{60}Co and ^{133}Ba





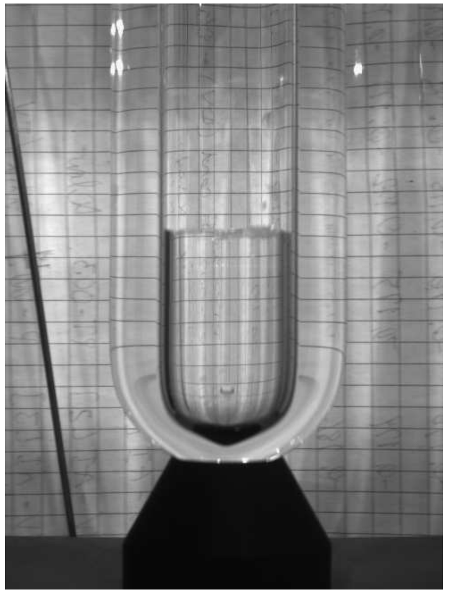
- COUPP Iodine Recoil Threshold Experiment
  - Low energy Iodine recoils
  - π beam and silicon trackers
- ^{88}Y/Be calibration chamber
  - Understand response to low energy recoils
  - Monochromatic low energy neutrons

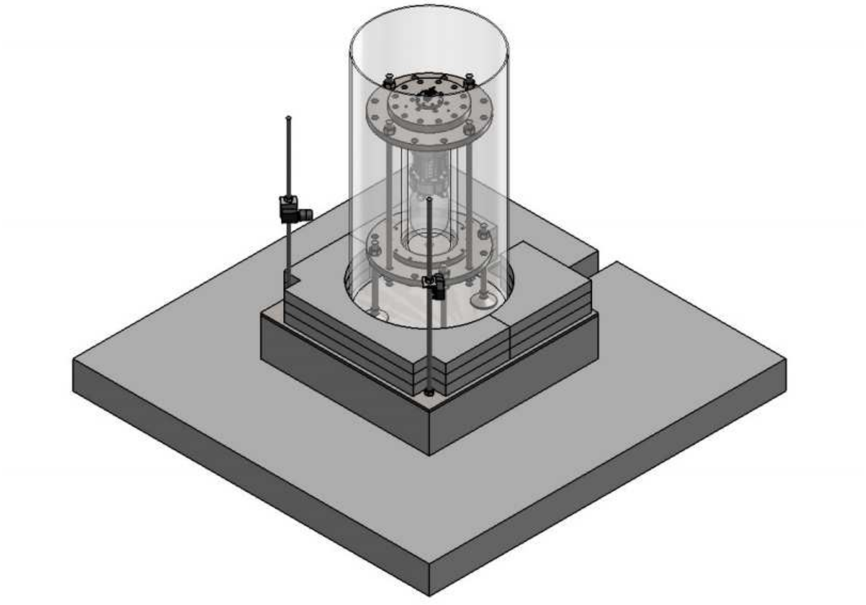


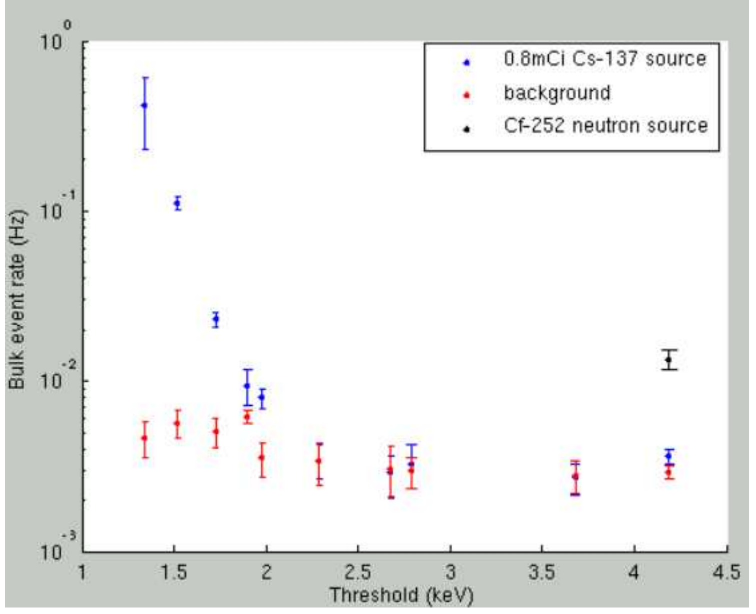
COUPP4-Lite

- C_3F_8 as target material
- spin-dependent sensitivity
- Low energy threshold
- new hydraulics
- new pressure vessel

Physics run by mid 2013



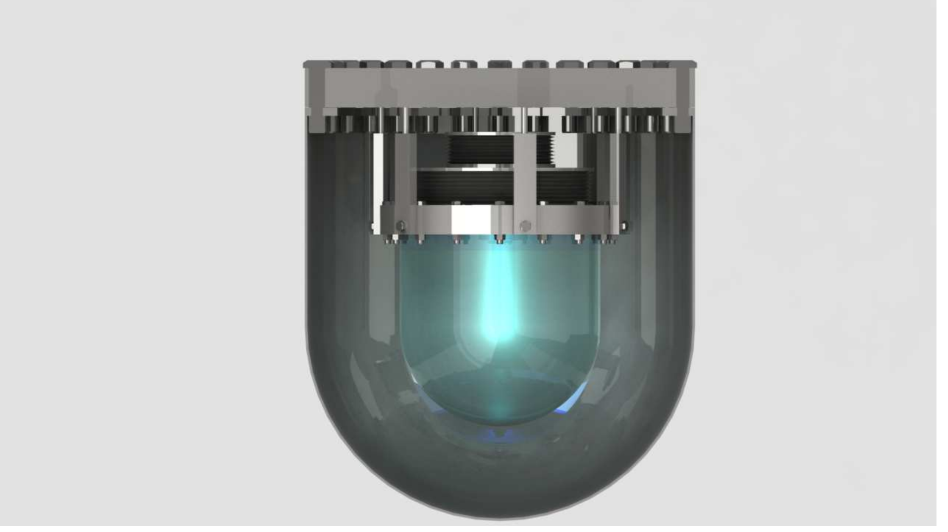




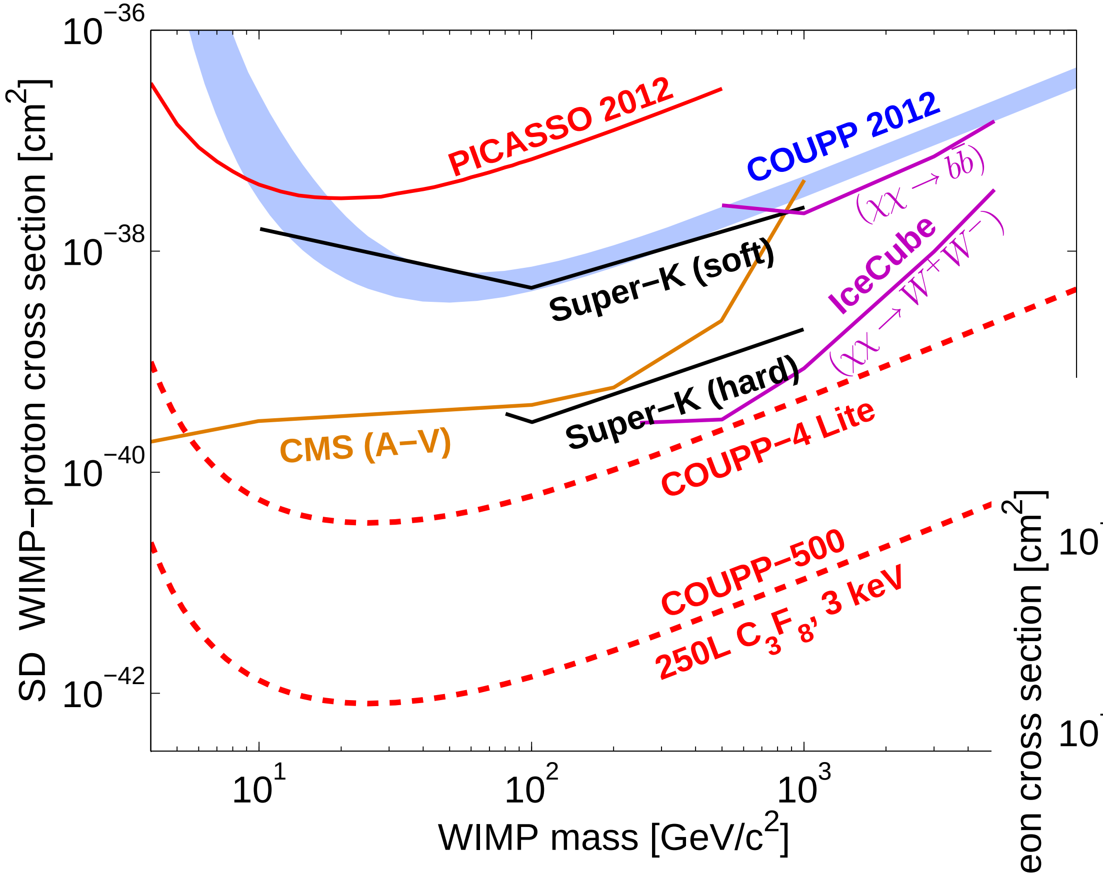
COUPP500

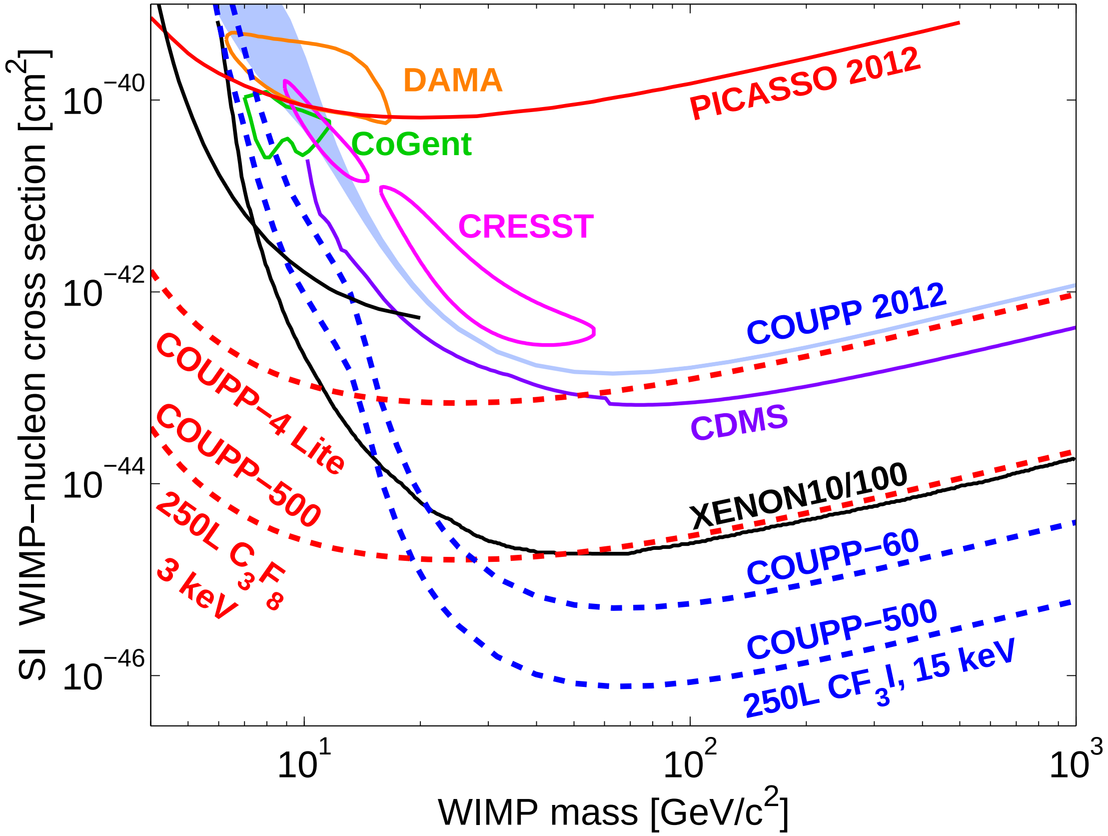
- $> 10^{10}$ γ/β insensitivity
- $> 99.3\%$ acoustic α discrimination
- Multi-target capability
  SD- and SI-coupling
  High- and low-mass WIMPs
- Easily scalable,
  inexpensive to replicate
- Growing collaboration
  Newly merged with
  PICASSO

R&D phase



COUPP sensitivity plots





Neutrino Physics programme

Double Beta Decay

What we know:

-Neutrinos have mass

-Squared mass differences

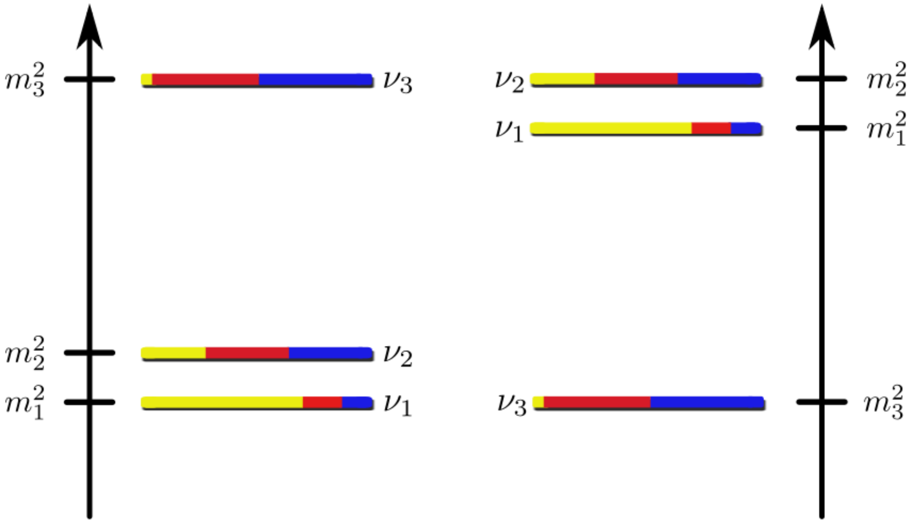
What we don't know:

-Absolute mass scale

-Mass hierarchy

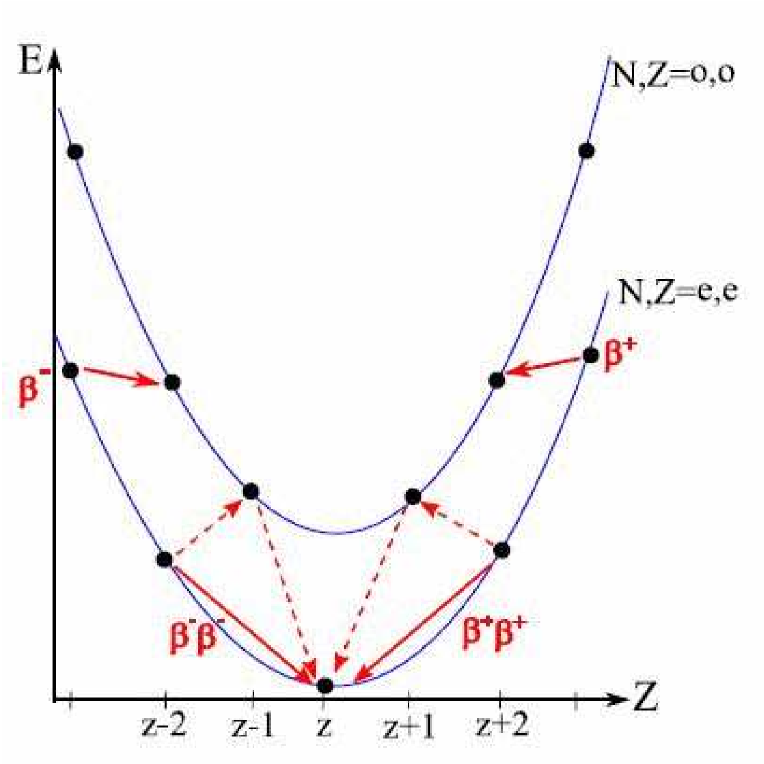
-Dirac vs Majorana

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

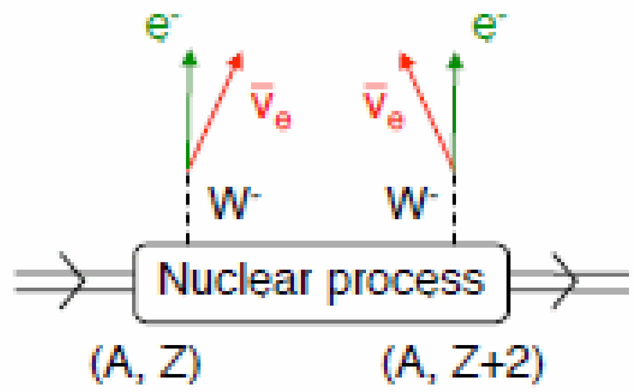


Double Beta Decay

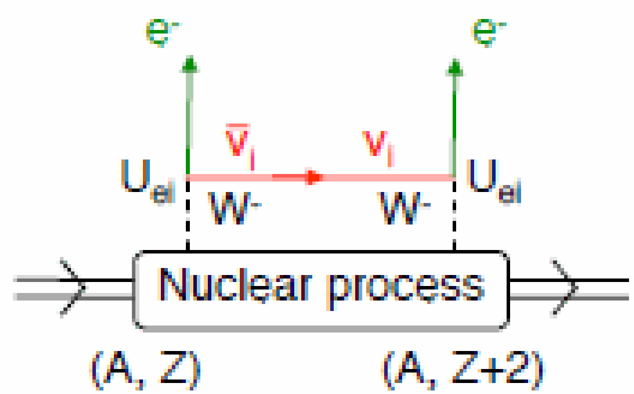
Beta decay is energetically forbidden



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



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

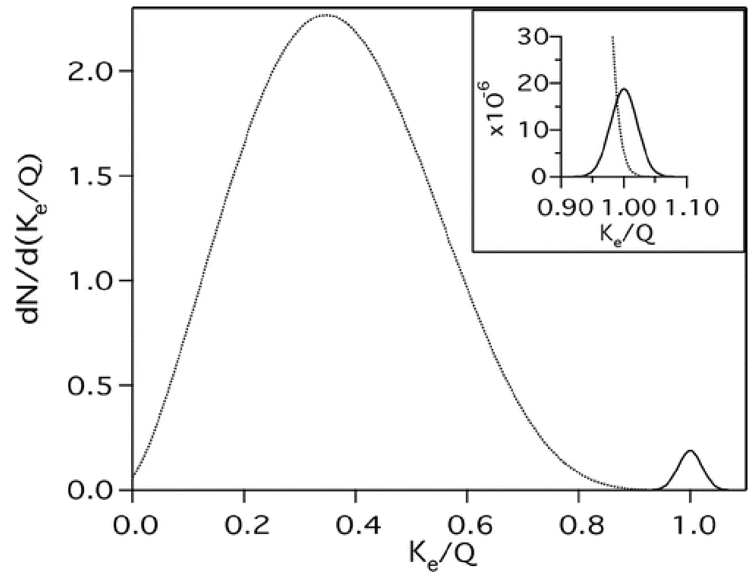


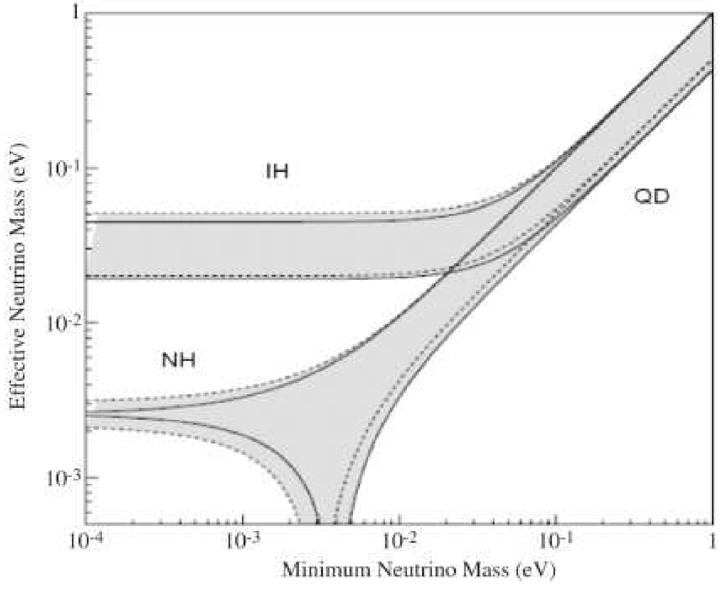
$$(A, Z) \rightarrow (A+2, Z)+2e^{-}$$

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+ Collaboration

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Black Hills State University:
K. Keeter

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University of California, Berkeley / LBNL:
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Dresden University of Technology:
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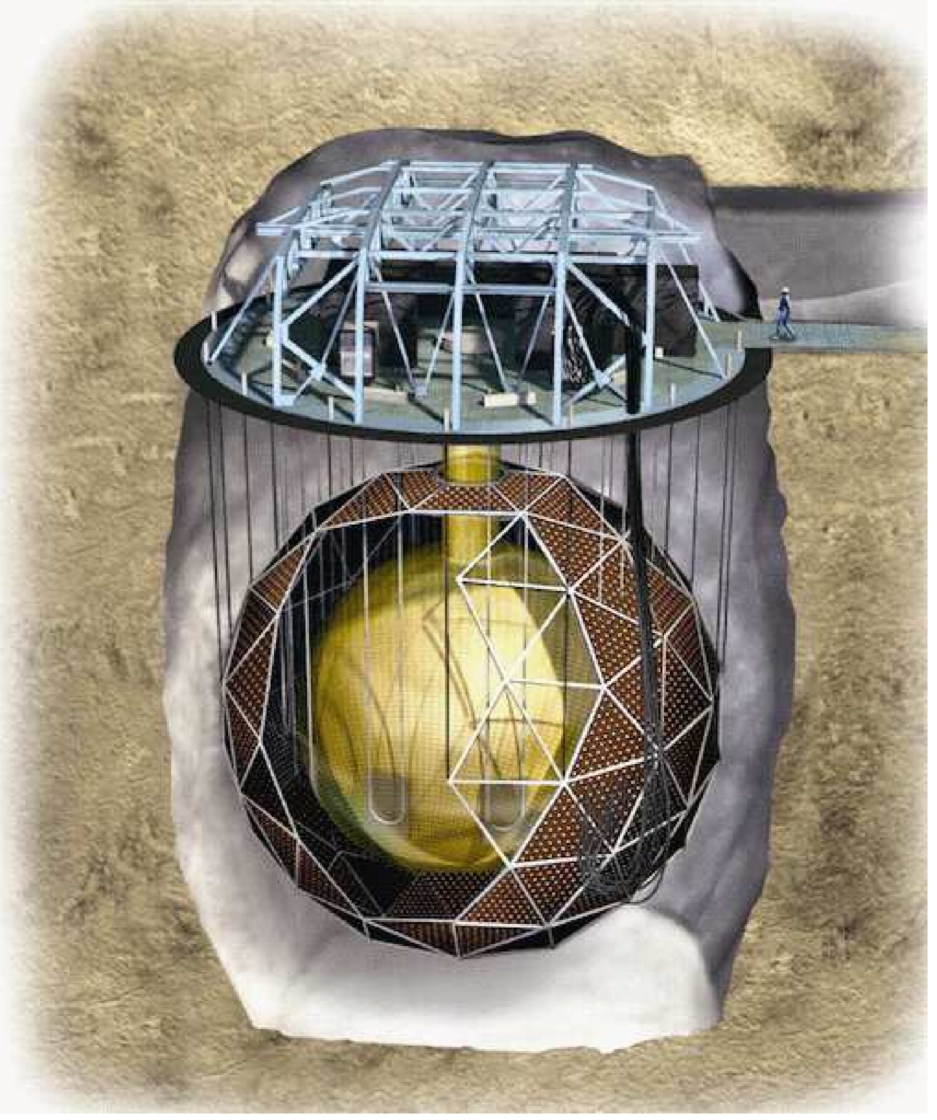
TRIUMF:
R. Helmer

University of Washington:
S. Enomoto, J. Kaspar, J. Nance, D.Scislowski, N. Tolich, H. Wan Chan Tseung

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 (water phase)

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

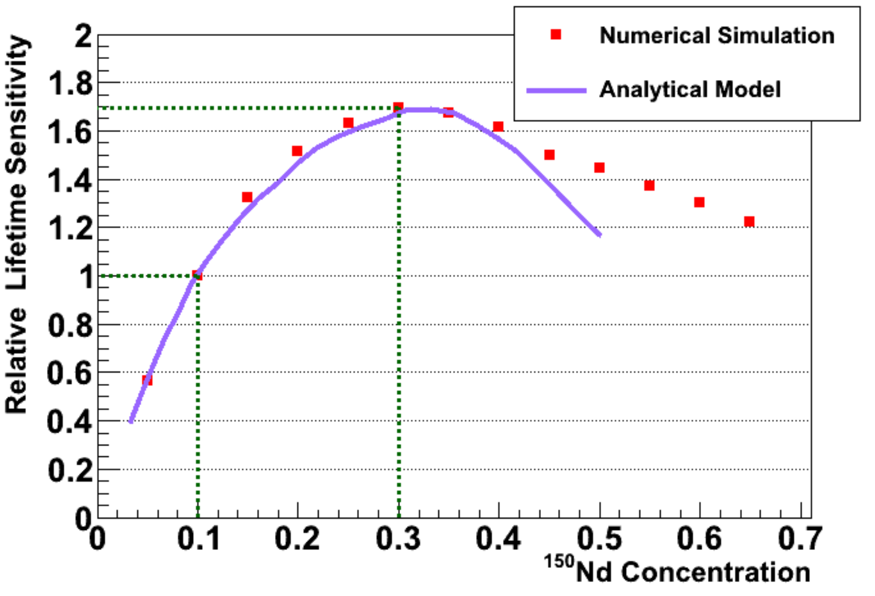
Neodymium-150

- 5.6% natural abundance
  43.7 kg (0.1% Nd loading)
- 3.37 MeV endpoint
  above most backgrounds
  2^{nd} 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

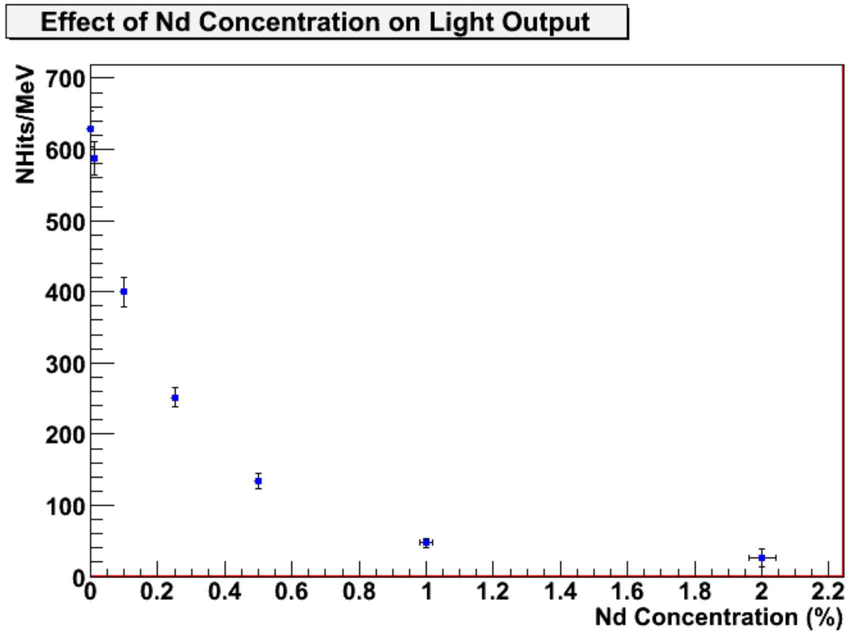
Double Beta Decay Phase

How much Nd?

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



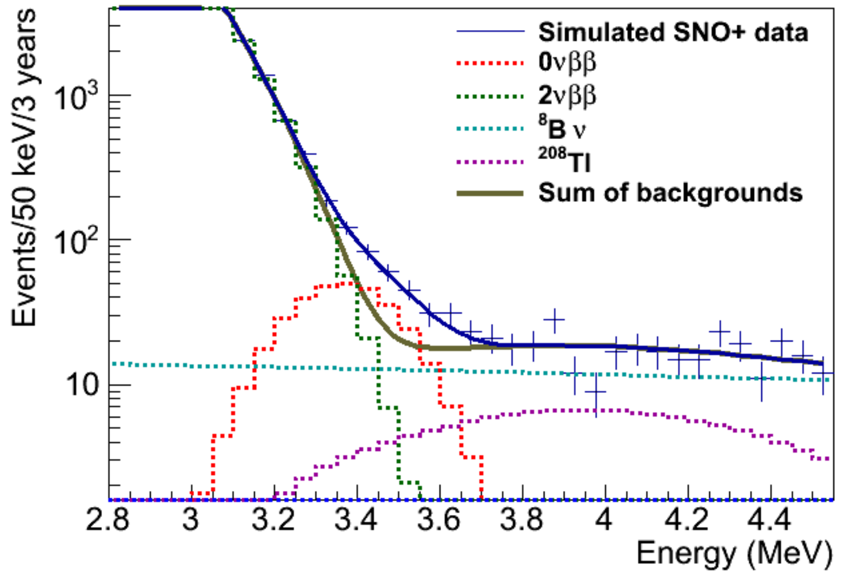
- 400 pe/MeV (6.4% FWHM resolution @ 3.37 MeV)
- 200 pe/MeV (9.0% FWHM resolution @ 3.37 MeV)



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 $_{(0,5)MeV}$

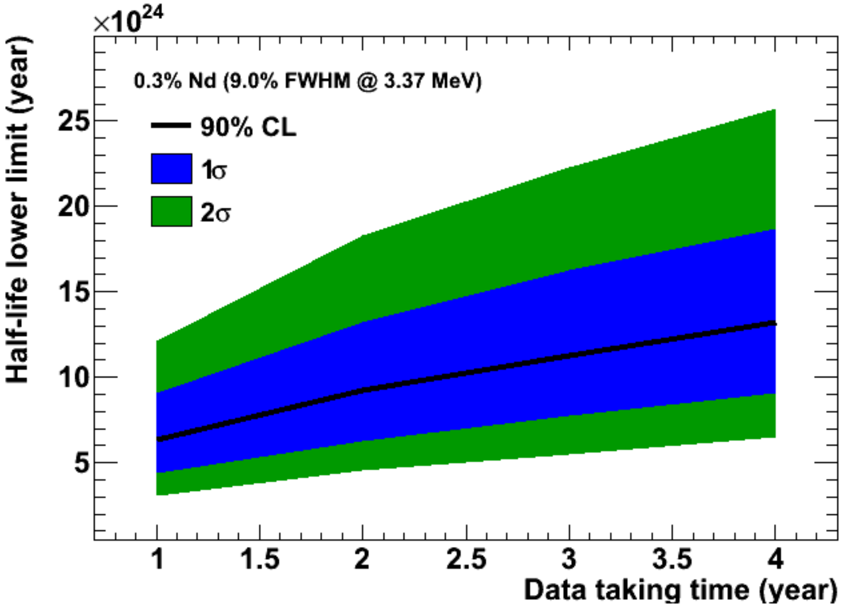
^{214}Bi: 2.3 events/year (3%)

^{208}Tl: 52.9 events/year (3%)

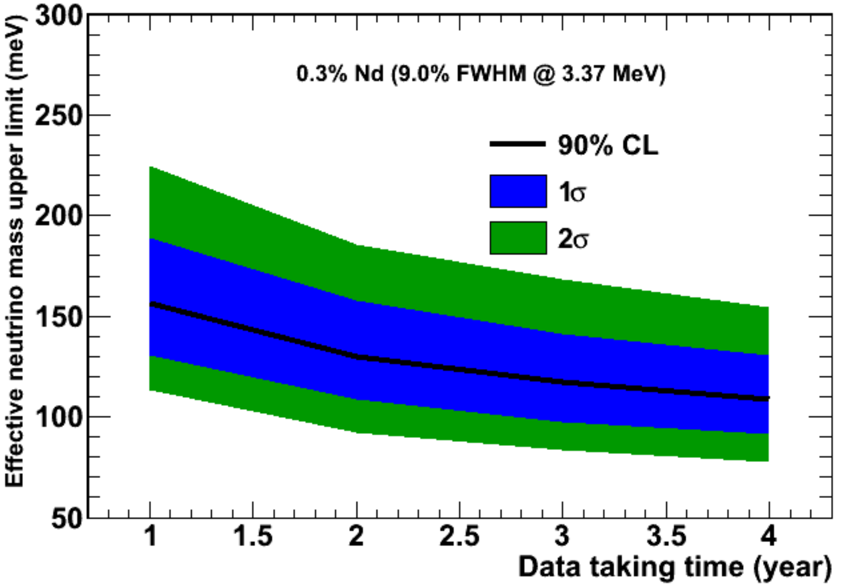
Double Beta Decay: Sensitivity

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



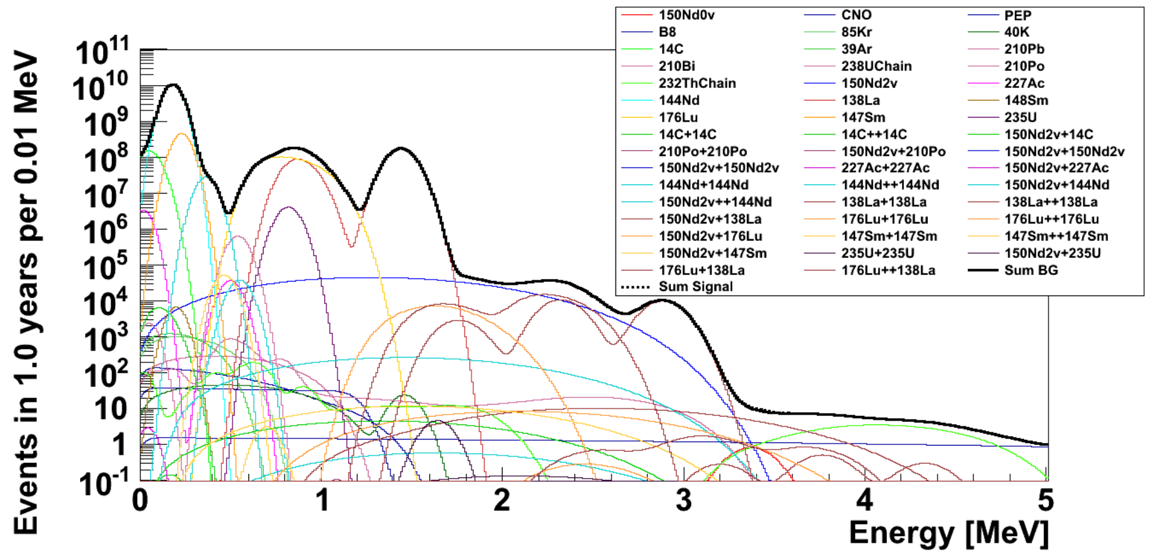
- Solar ^{8}B
- ^{150}Nd $2\nu\beta\beta$
- ^{214}Bi: tagged and removed (ϵ=99.98%)
- ^{208}Tl: tagged and removed (ϵ=90%)

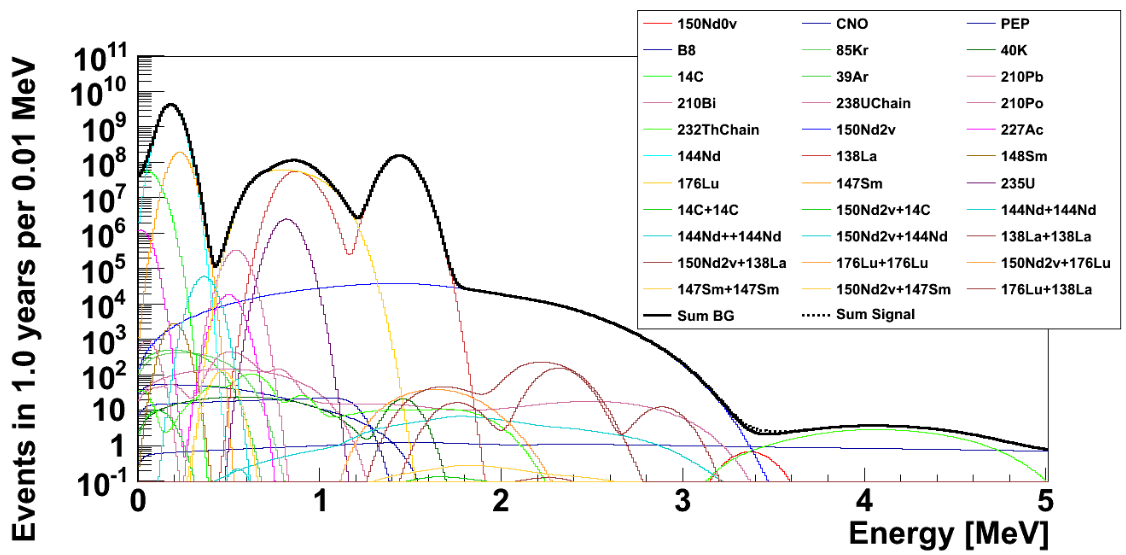


Pileup rejection

- 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

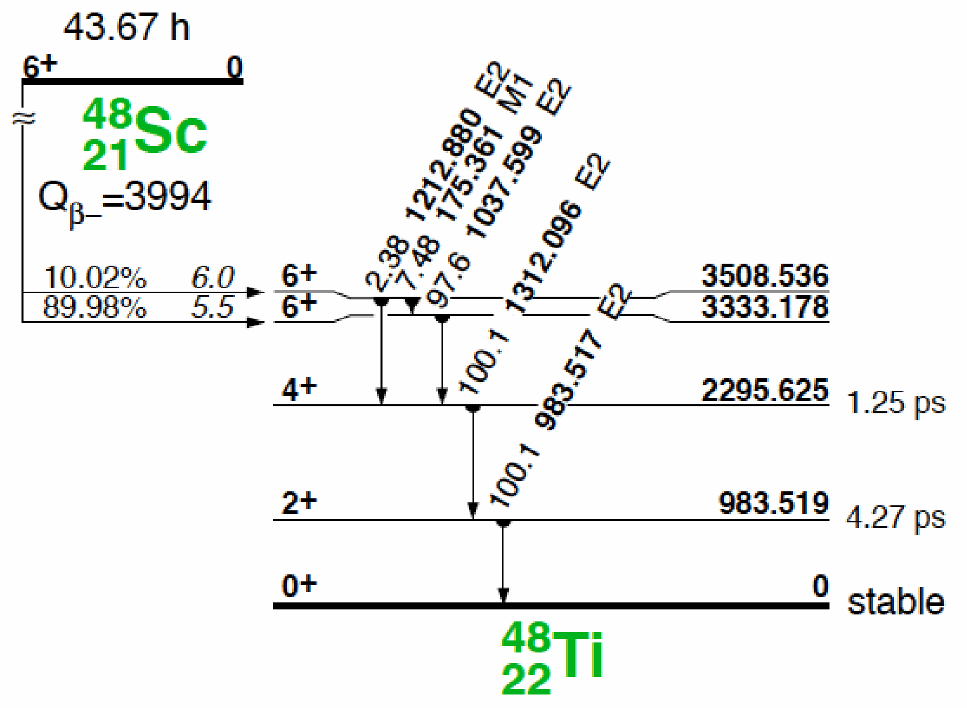




Double Beta Decay: Calibration

Energy

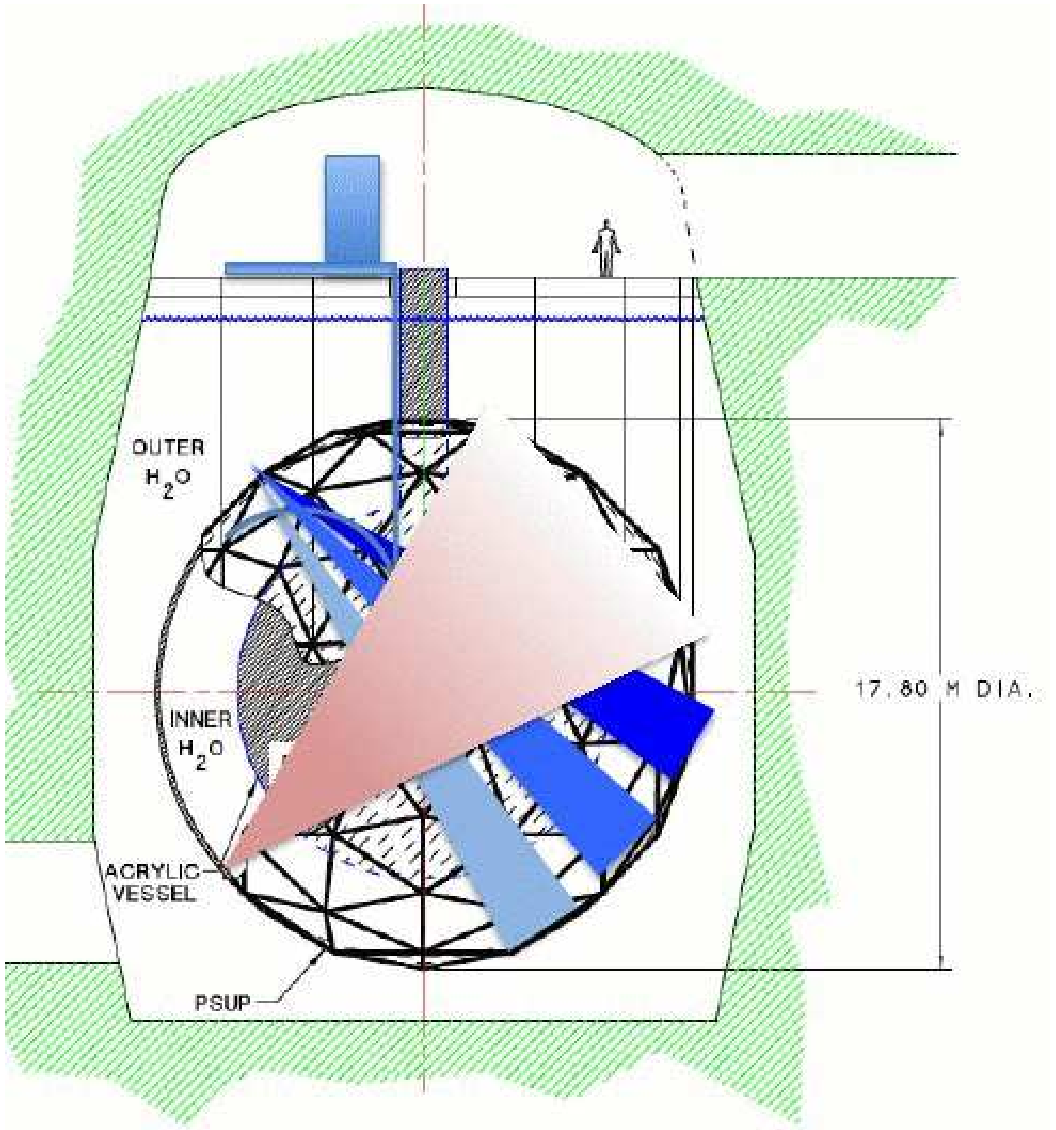
- ^{48}Sc $\beta - \gamma$ source
- β^- for a tagged source (0.66 MeV)
- Sum E(γ) = 3.33 MeV (90% BR)
- Half life = 44 hrs
- 14 MeV-n activation on Ti
- D-T generator (site or Dresden)
- Source in R&D phase



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

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**



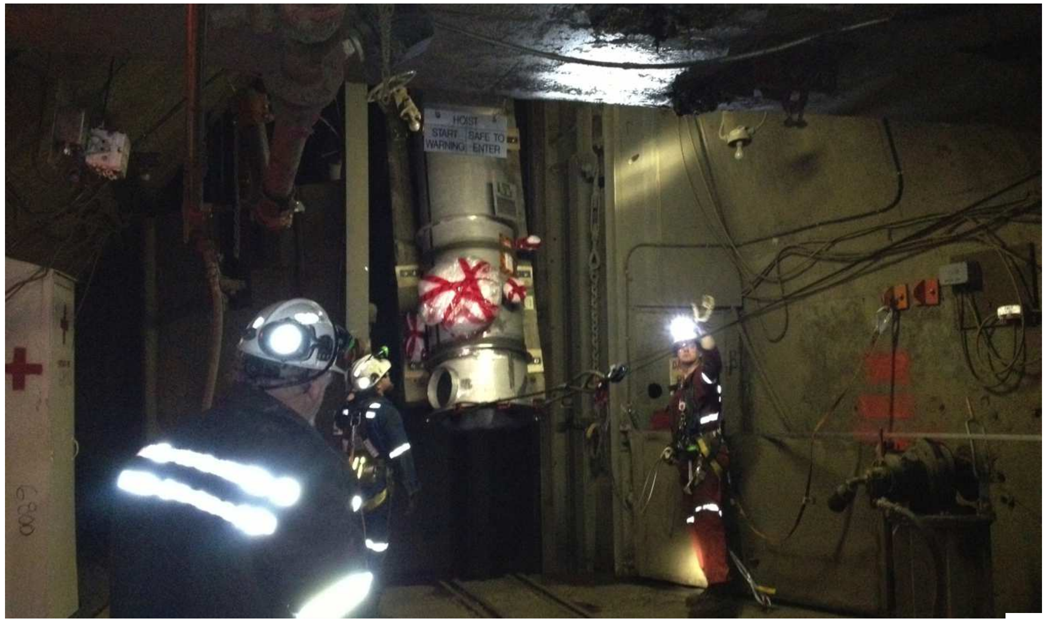
Double Beta Decay: Purification

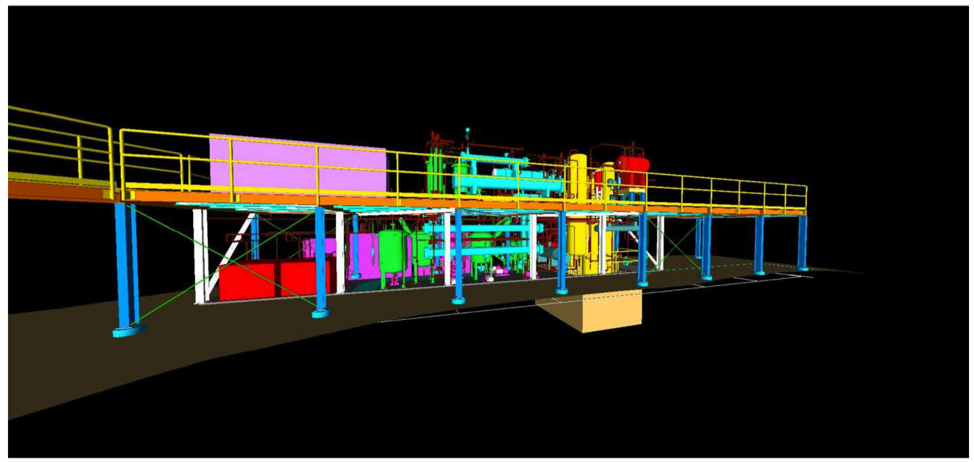
- multistage distillation (to remove heavy metals, improves UV transparency)
- N_2/water vapor gas stripping (to remove Rn, Kr, Ar, O_2)
- water extraction (to remove K, Ra, Bi)
- metal scavenging (assay for solar phase) (to remove Ra, Bi, Pb)
- micro filtration
- $NdCl_3$ purification by pH adjustment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

Process system





Double Beta Decay: Upgrade

Once it is running:

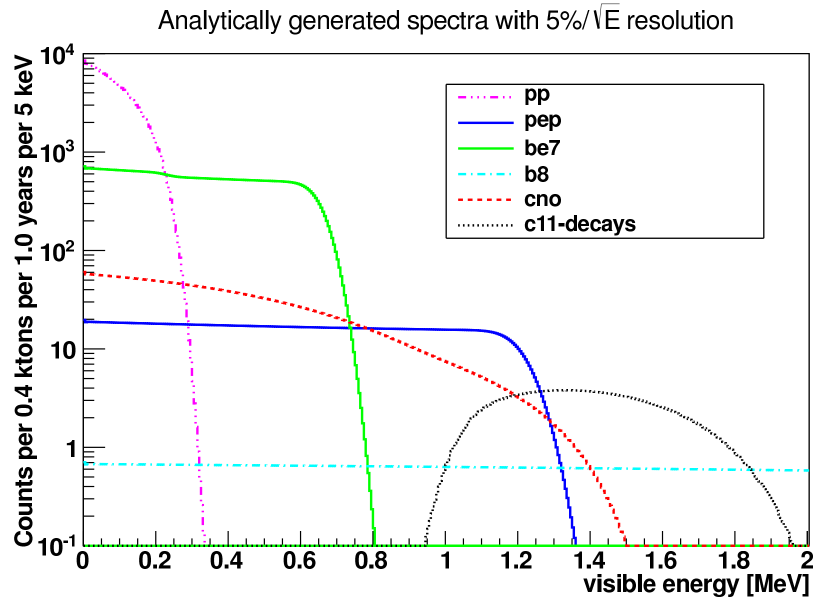
- **Enrichment**
  - **Investigating some 1-2 options**
  - **Nd enriched to 80% ^{150}Nd: increases statistics $\times 16$**
  - **Most backgrounds remain constant**
- **Other isotopes**

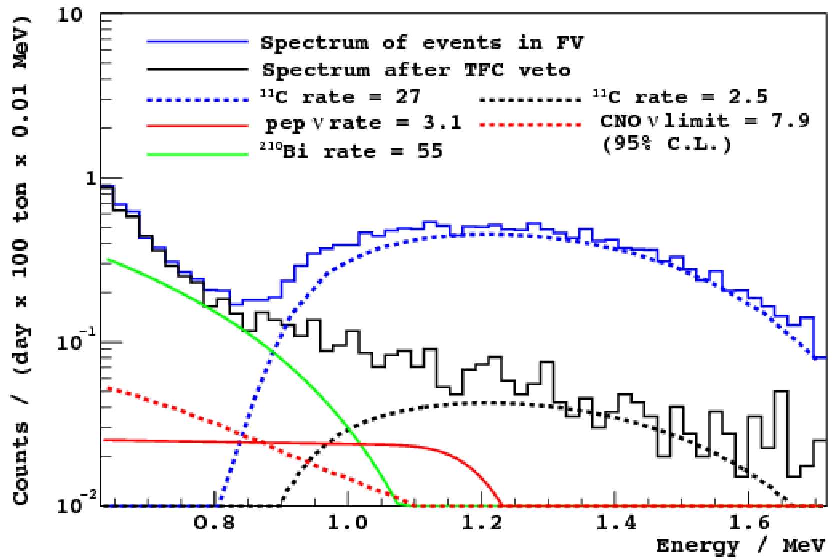
Several possibilities and options

pep and CNO neutrinos

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

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

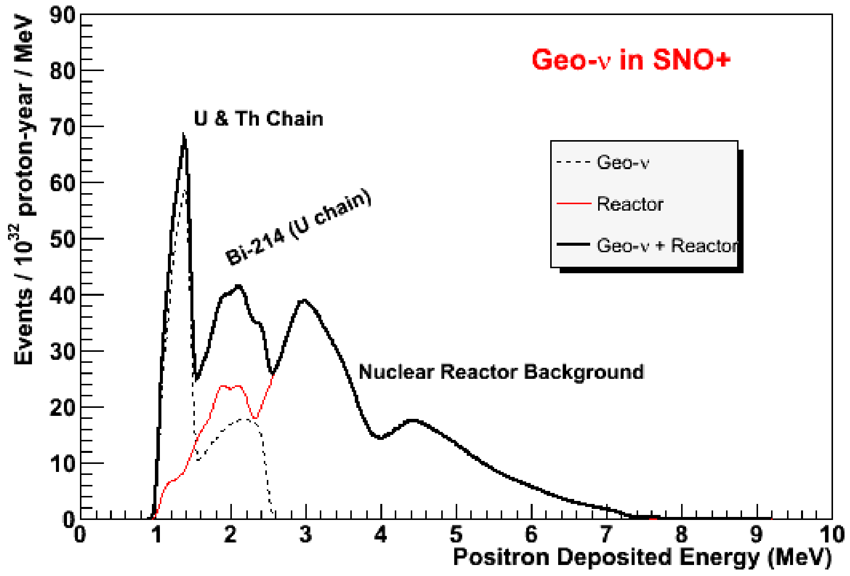


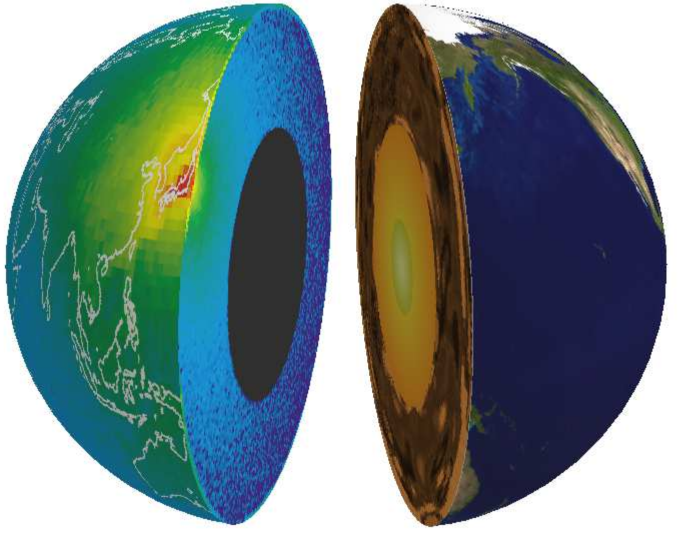


Geo-neutrinos

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





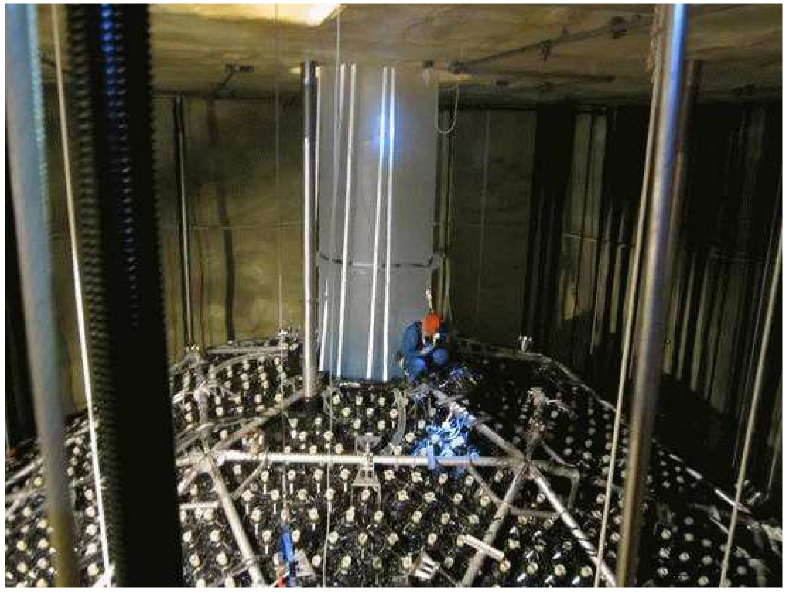
SNO+ Supernova Signal

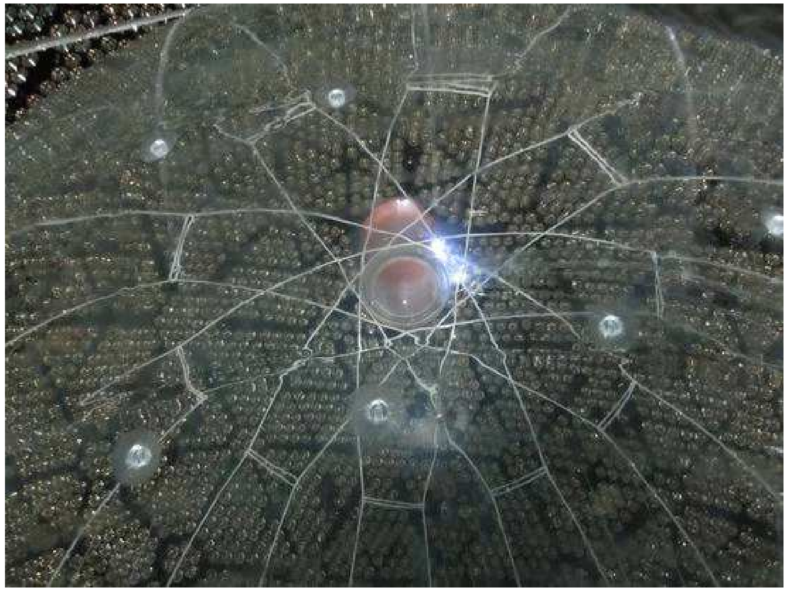
- **Elastic scattering:**
  - 8 evts: ν_e + e^- → ν_e + e^-
  - 3 evts: anti-ν_e + e^- → anti-ν_e + e^-
  - 4 evts: $\nu_{\mu,\tau}$ + e^- → $\nu_{\mu,\tau}$ + e^-
  - 2 evts: anti-$\nu_{\mu,\tau}$ + e^- → anti-$\nu_{\mu,\tau}$ + e^-
- **Charged Current:**
  - 263 evts: anti-ν_e + p → n + e^+
  - 27 evts: ν_e + ^{12}C → ^{12}N + e^-
  - 7 evts: anti-ν_e + ^{12}C → ^{12}B + e^+
- **Neutral Current:**
  - 58 evts: ν_x + ^{12}C → $^{12}C^*$(15.11MeV) + ν_x
  - 273 evts: ν_x + p → ν_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**

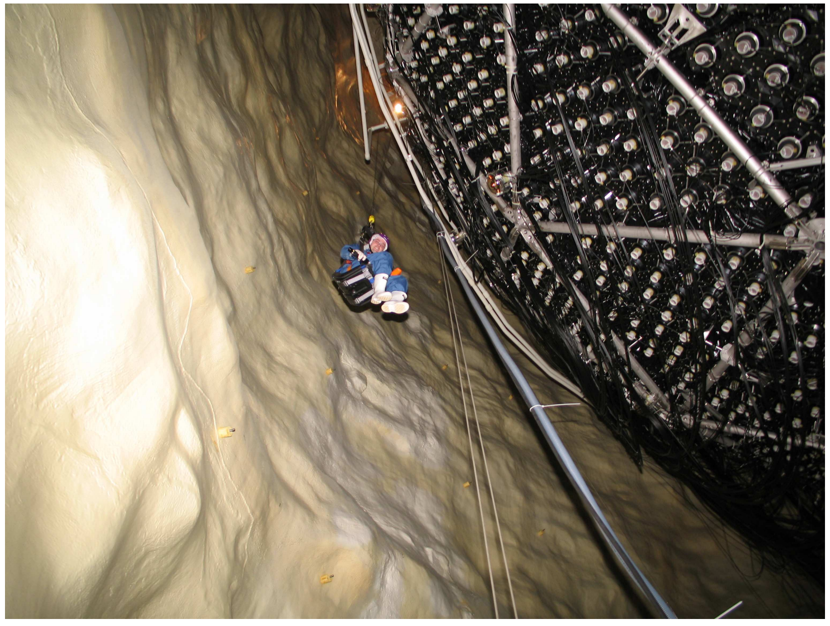
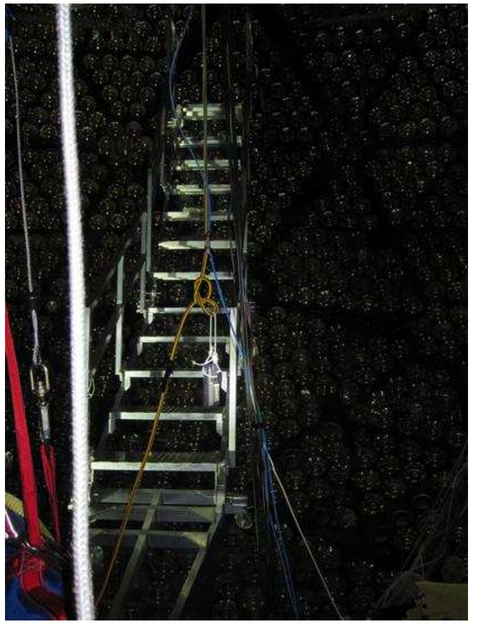
SNO+ detector



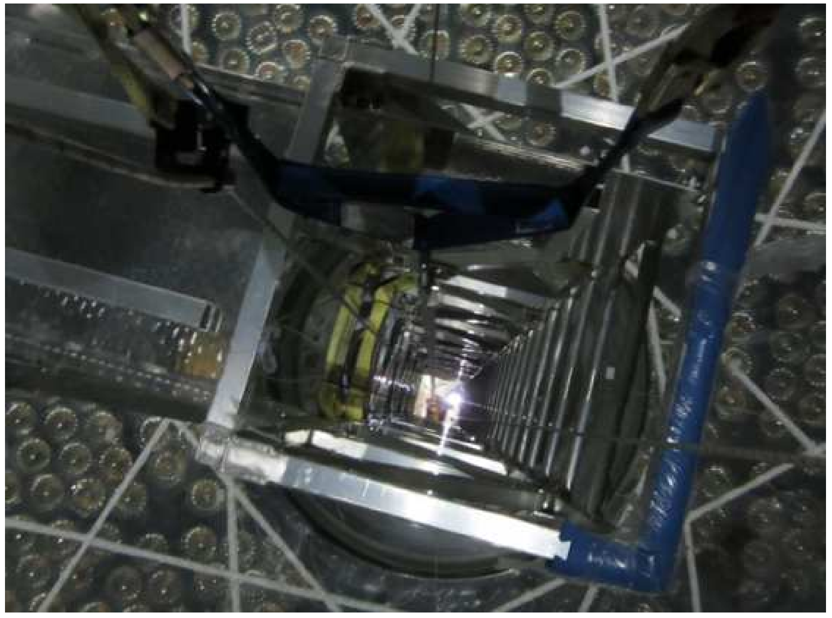


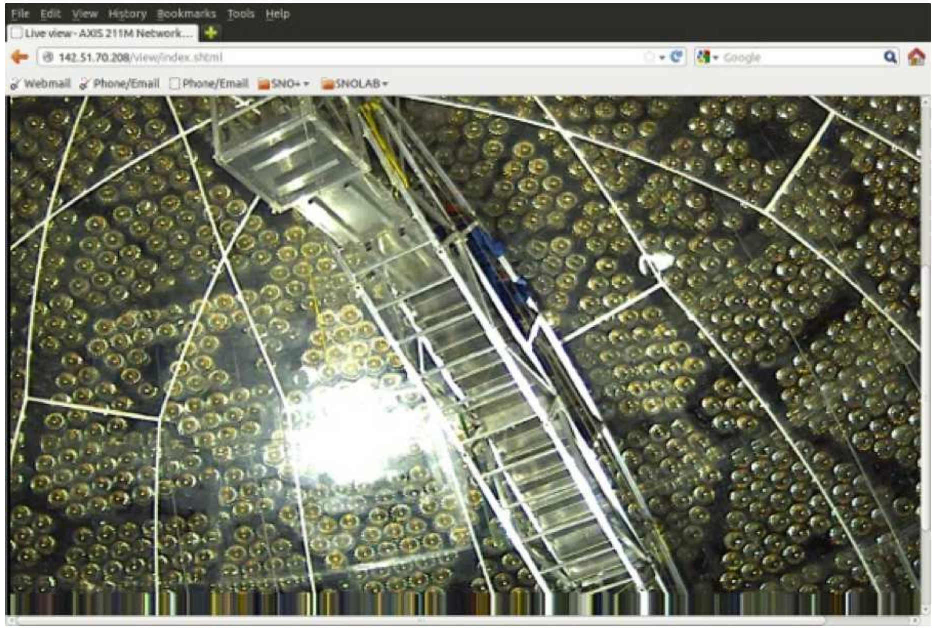
SNO+ detector



SNO+ detector





Timeline

- **2013**
  - **Finish work in cavity**
  - **Process system construction**
  - **Water phase**

- **2014**
  - **Process system commissioning**
  - **Scintillator filling**
  - **Scintillator phase**

- **2014-2015**
  - **Nd-loading**
  - **Double Beta Decay phase**

More experiments at SNOLAB

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 uniform response
- Detectors:
  - DEAP-1: prototype, 7 kg LAr, 2 PMTs
  - DEAP-3600: 3600 kg LAr, 255 8” PMTs

Backgrounds in liquid argon dark matter detector:

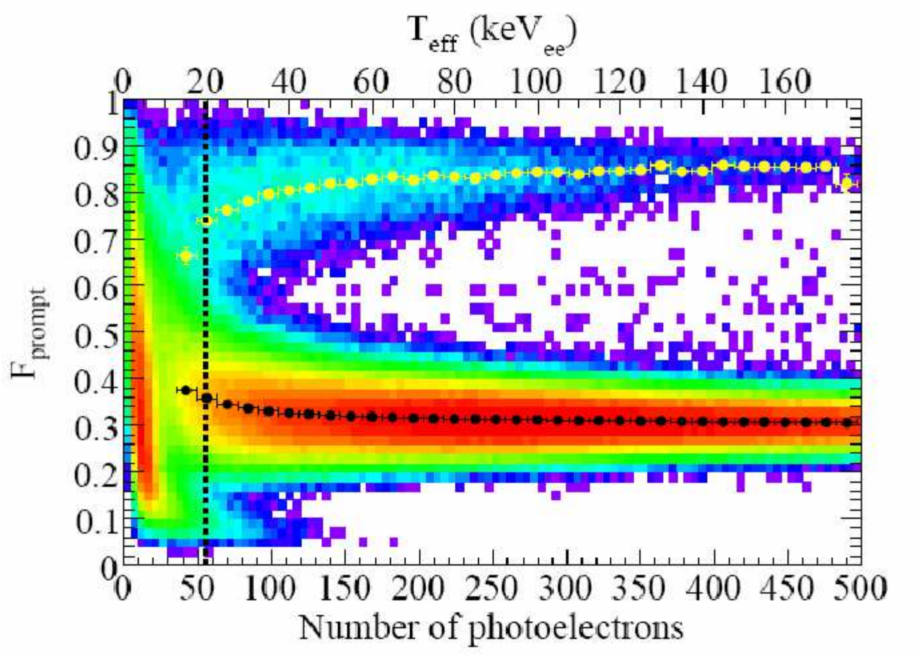
- **β/γ events:**
  dominated by ^{39}Ar, 1 Bq/kg
  PSD to distinguish from recoils, use depleted argon

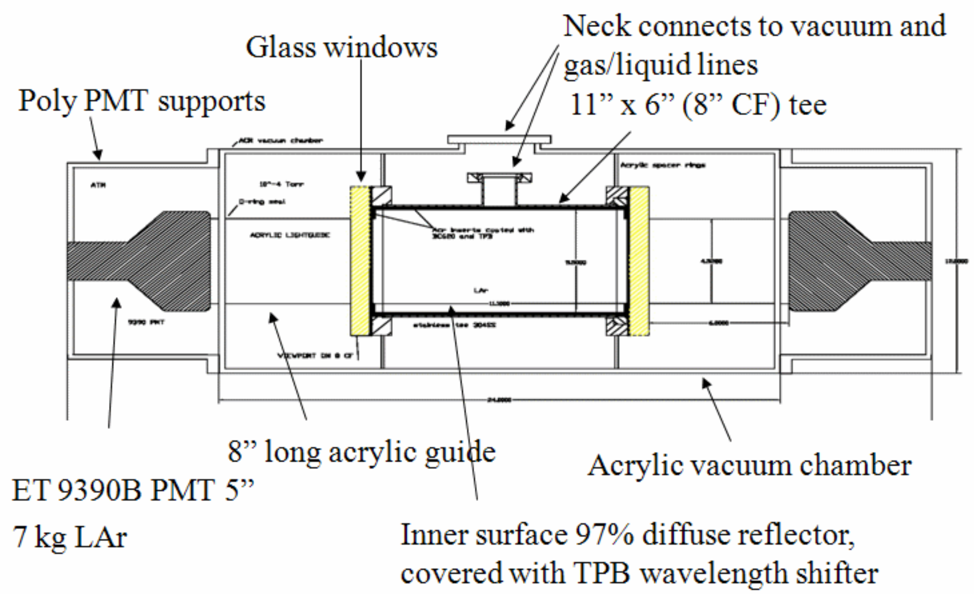
- **nuclear recoils:**
  (α,n), fission, μ induced
  clean detector materials, shielding

- **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

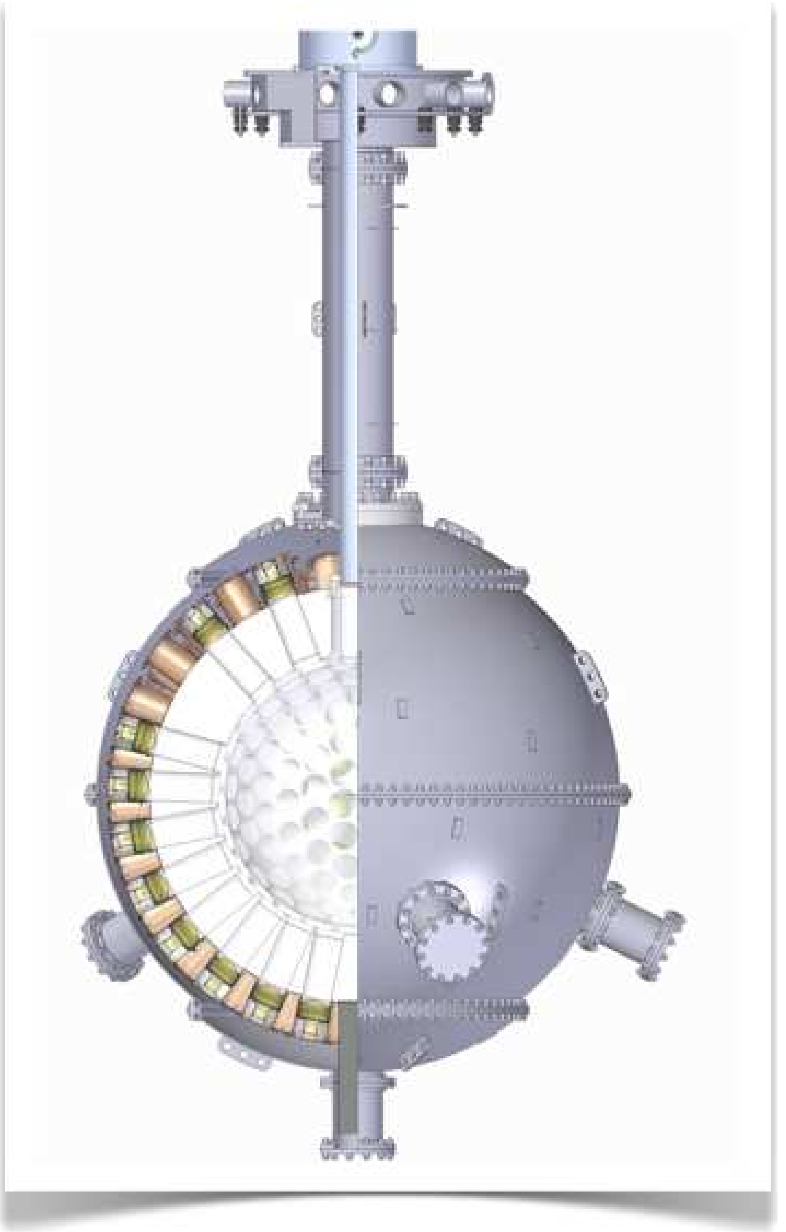




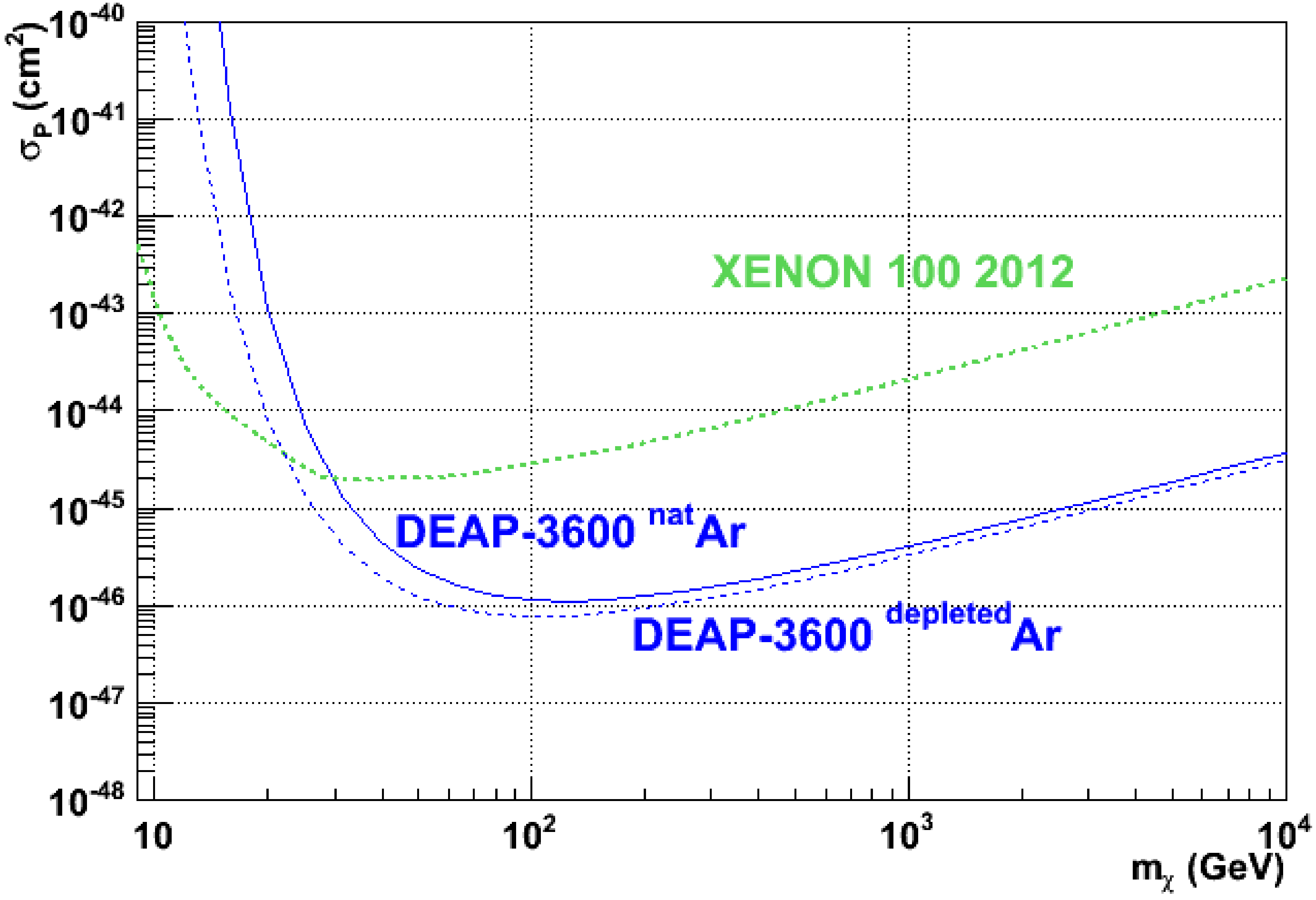
DEAP-1

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

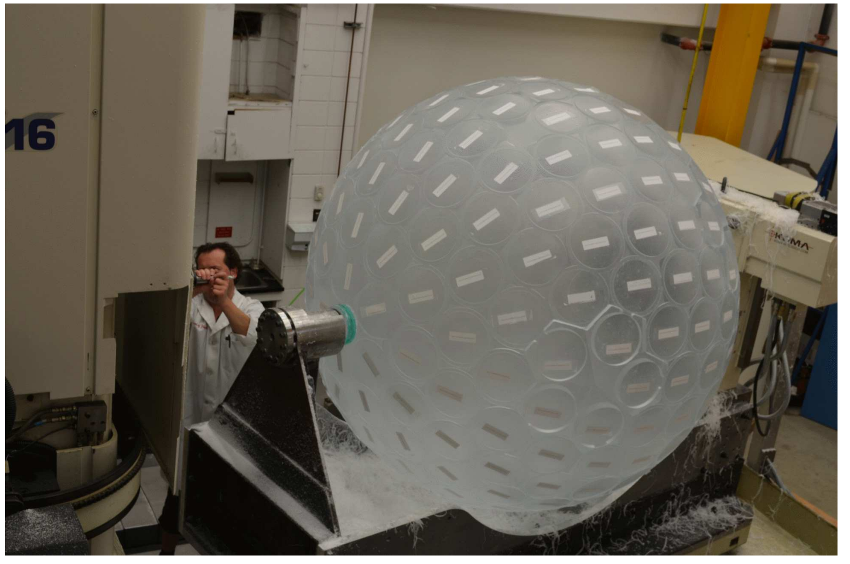


σ_P (cm^2)
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10
10^2
10^3
10^4
m_χ (GeV)
XENON 100 2012
DEAP-3600 ^{nat}Ar
DEAP-3600 ^{depleted}Ar

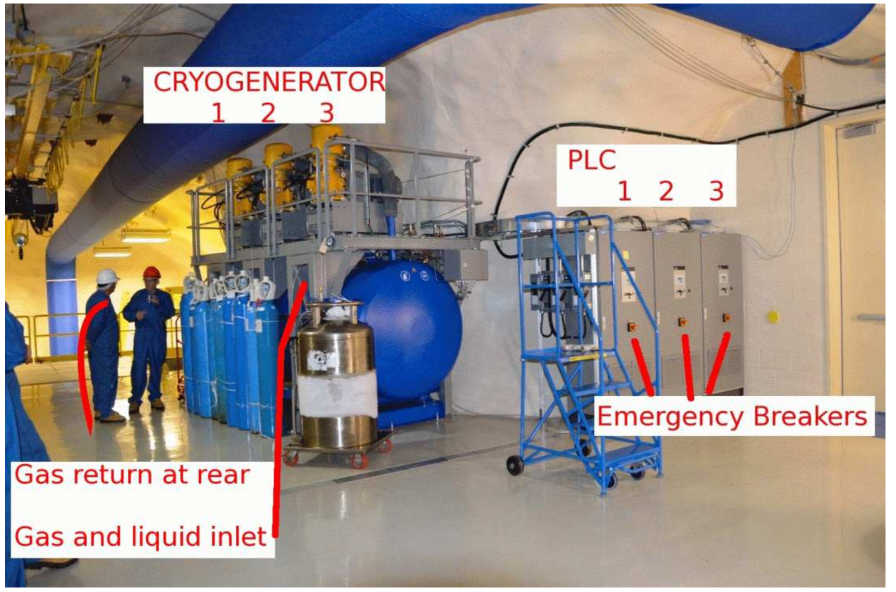
DEAP-3600

DEAP-3600



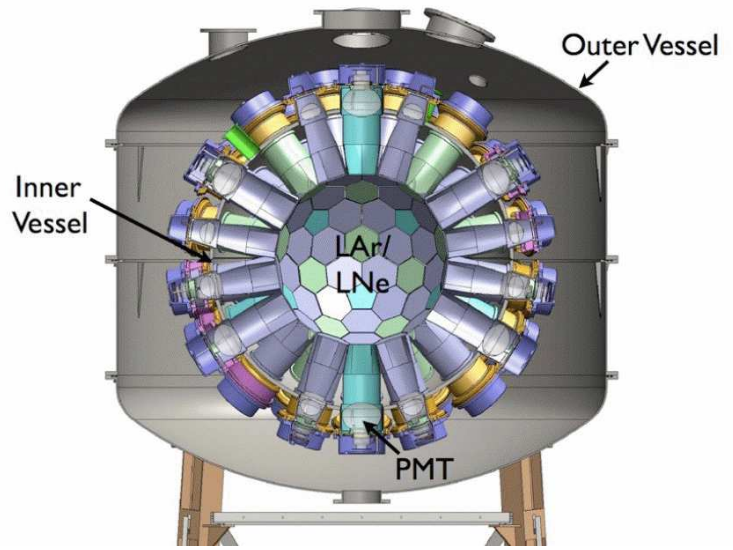
DEAP-3600

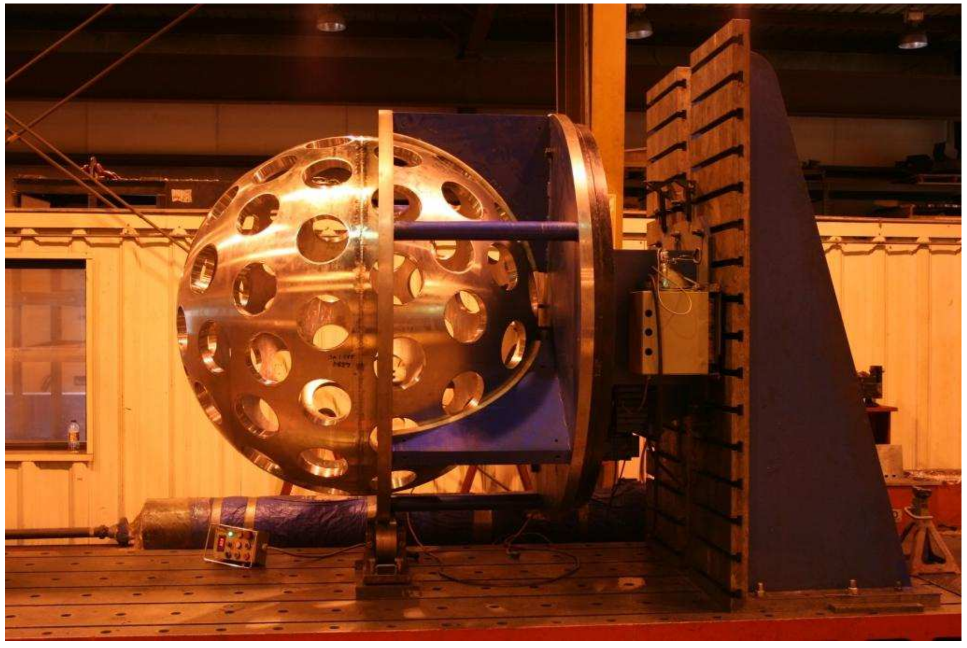

CRYOGENERATOR
1 2 3
PLC
1 2 3
Emergency Breakers
Gas return at rear
Gas and liquid inlet

DEAP-3600

MiniCLEAN

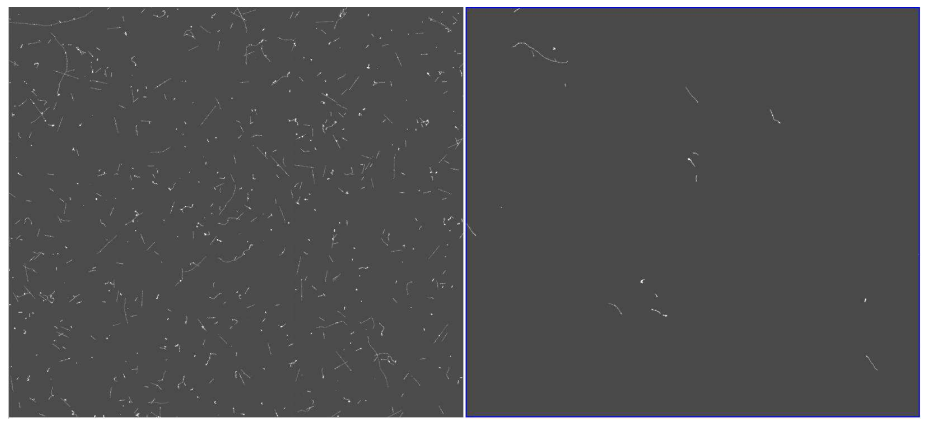
- 500 kg cryogenic liquid (150 kg fiducial) with 92 PMTs
- Material interchangeable between argon y neon
- spin-independent WIMP-nucleo cross section sensitivity of 10^{-45} cm^2





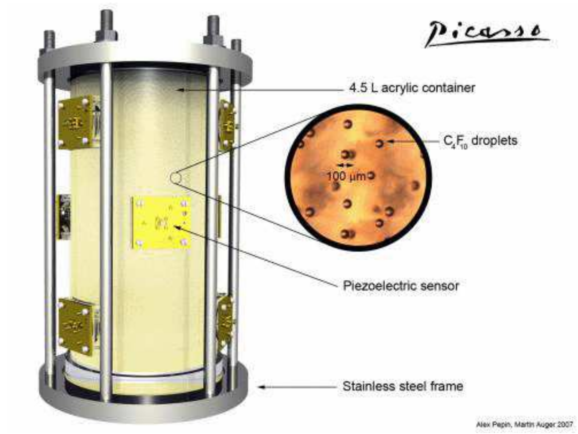
DAMIC

- charge-coupled devices as target material (Si)
- extremely low electronic readout noise
- very low threshold of approx. 40 eV_{ee}
- uses ten 250 microns thick CCDs
- high resistivity silicon
- fully depleted a low voltages
- active mass of 10 grams
- deployed underground a few months ago, fully operational

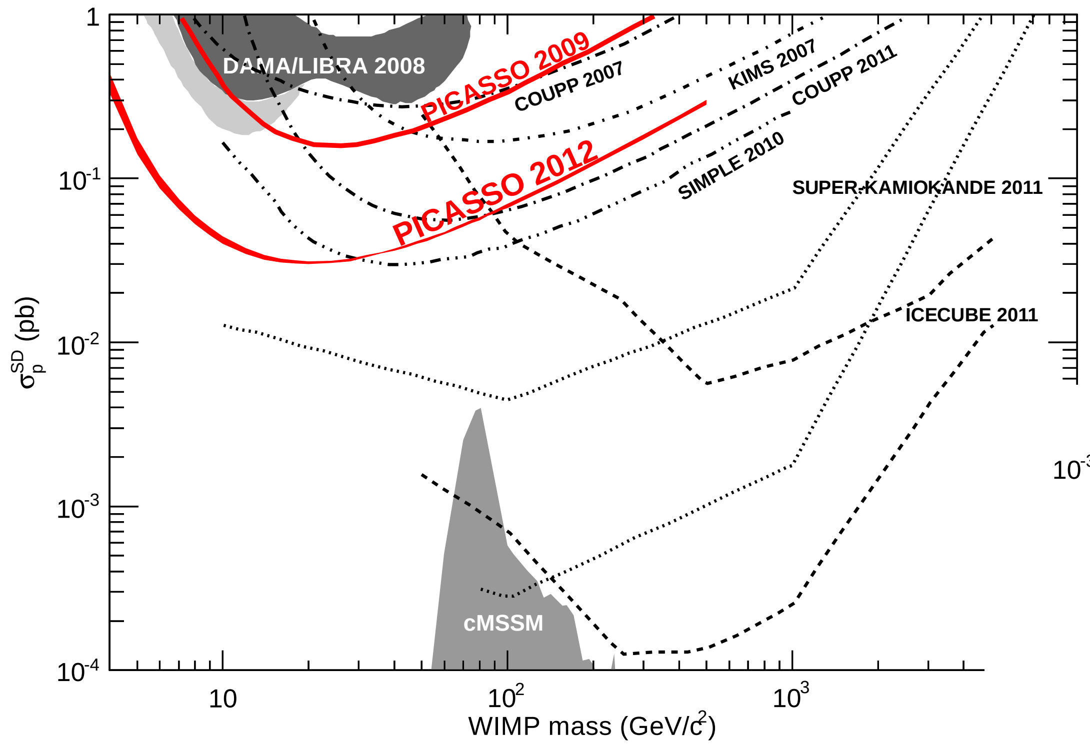


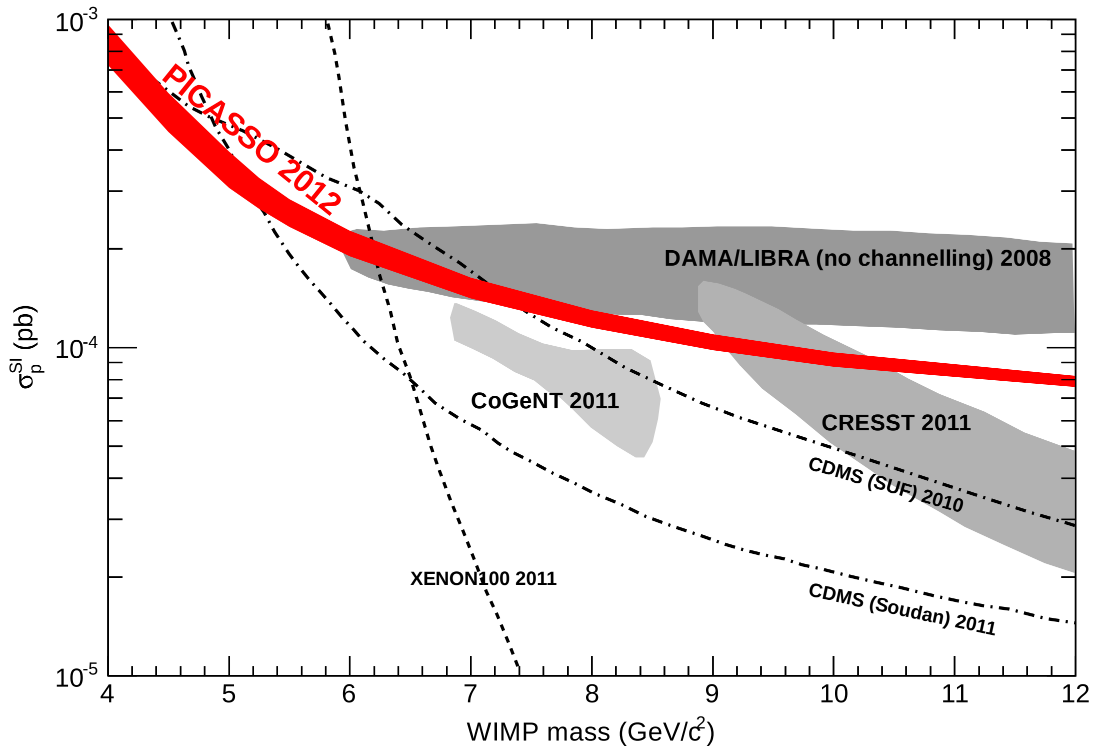
PICASSO

- 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



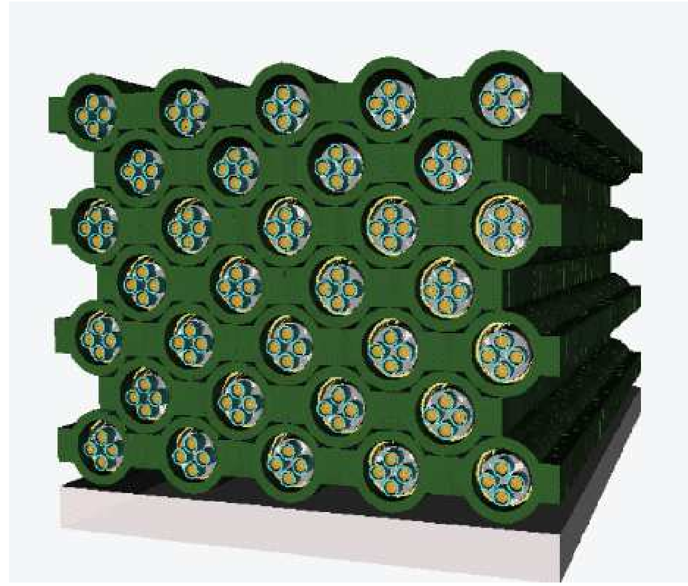
PICASSO limits





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



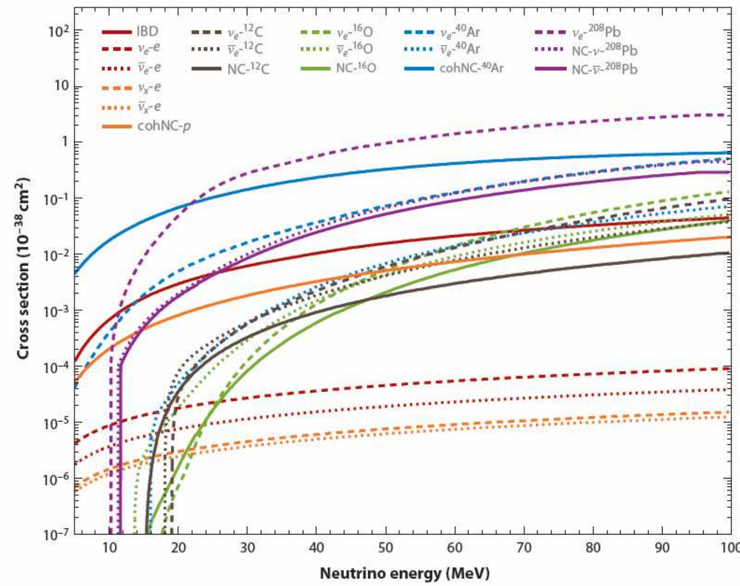


Figure 2

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

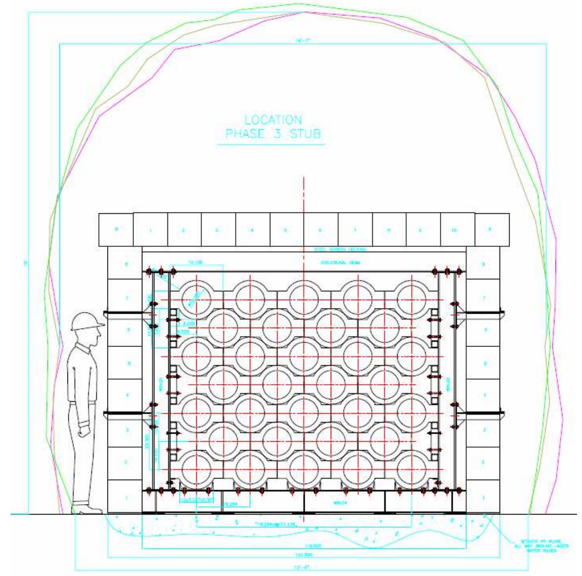
Part of SNEWS once the behaviour of the detector is well understood

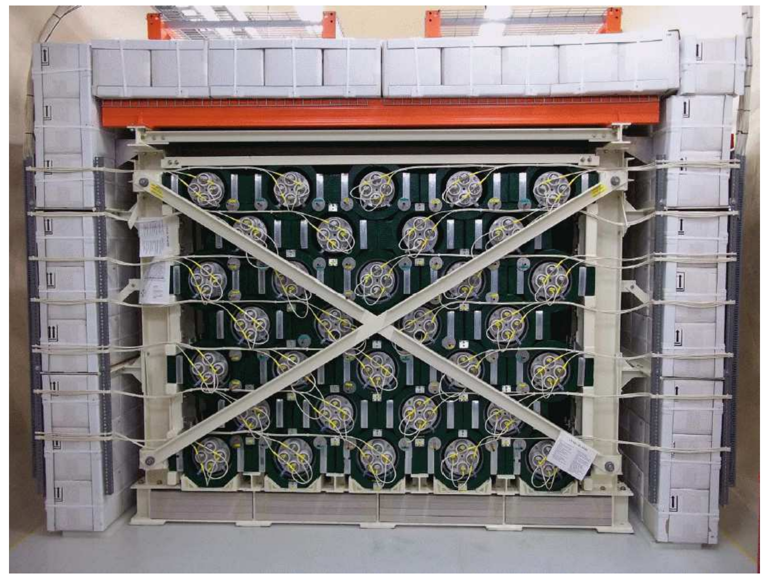
HALO Supernova Signal

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**

$\sim$88 neutrons liberated
$\sim$1.1 n/tonne of Pb





Future Experiments and Underground Science

SNOLAB hosting more experiments:

- **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