SNOLAB: home of SNO+ & DEAP3600

Exploring the invisibles
using large liquid scintillator detectors

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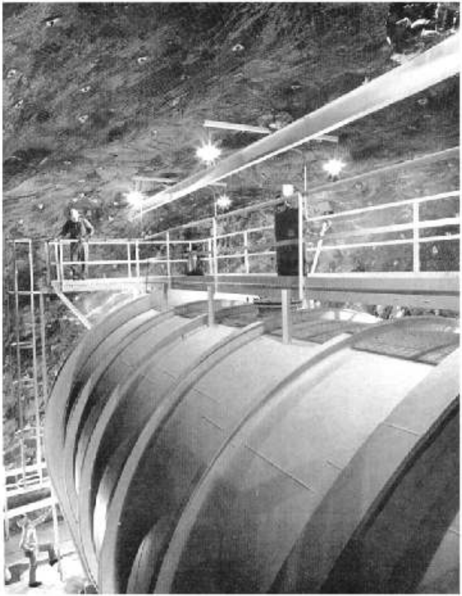
Outline

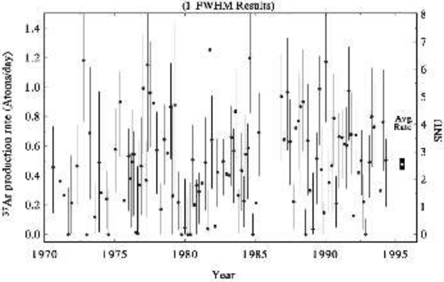
1. Some history
2. SNOLAB
3. Current questions in neutrino physics
4. The SNO+ experiment and its programme
5. Motivation for Dark Matter
6. The DEAP programme

The Sudbury Neutrino Observatory

Some history

The Solar Neutrino problem - Ray Davis' experiment



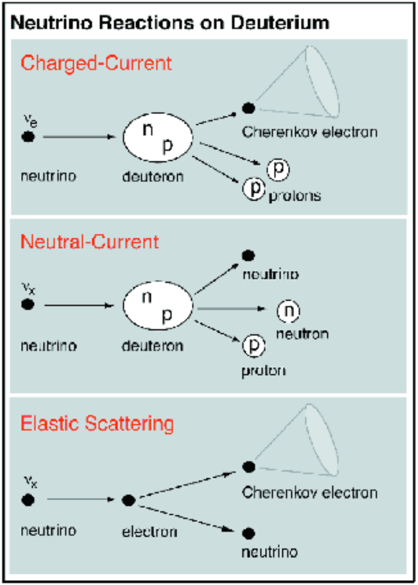


Only observed 1/3 of the expected solar electron-neutrino flux.

Nobel prize in 2002.
(After the puzzle was conclusively solved by SNO.)

Use D_2O as target for solar neutrinos

Herb Chen published his idea in 1985.



Neutrino Reactions on Deuterium

Charged-Current

Neutral-Current

Elastic Scattering

SNO: Sudbury Neutrino Observatory

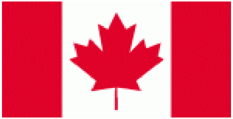
- Observed the expected neutral current flux (any neutrino) to be consistent with the expected solar neutrino flux.
- Confirmed Davis' charge current flux (electron neutrino) being 1/3 of the total flux.

Discovered neutrino flavour change from the Sun in 2002.

We now know that this is due to: neutrino oscillations.

SNO continued to determine one of the parameters associated with this model and the solar neutrino fluxes most accurately!

SNOLAB



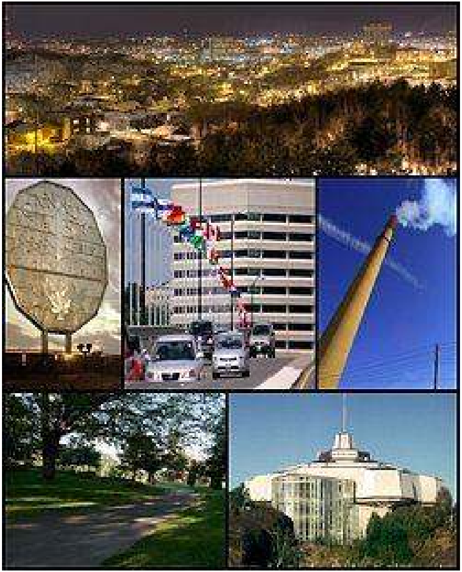
The stage for the next generation of discoveries

Location


Sault Sainte Marie
Sudbury
North Bay
Ottawa
Montreal (Montréal)
Saint-Jean
Cornwall
Plattsburgh
VERMONT
Green Bay
Fond Du Lac
MICHIGAN
Milwaukee
Grand Rapids
Flint
Barrie
Peterborough
Kingston
Watertown
Oshawa
Toronto
Stratford
Brantford
Lockport
Buffalo
St Thomas
NEW YORK
MOHAWK
Saratoga Spring
Albany
Detroit
Erie
Ithaca
Chicago
South Bend
Toledo
Cleveland
Akron
Canton
Fort Wayne
PENNSYLVANIA
Kingston
Poughkeepsie
Wilkes-Barre
Stamford
New York
Allentown
Altoona
Pittsburgh

Northern mining town

Features



SNOLAB facility above ground

Going underground!

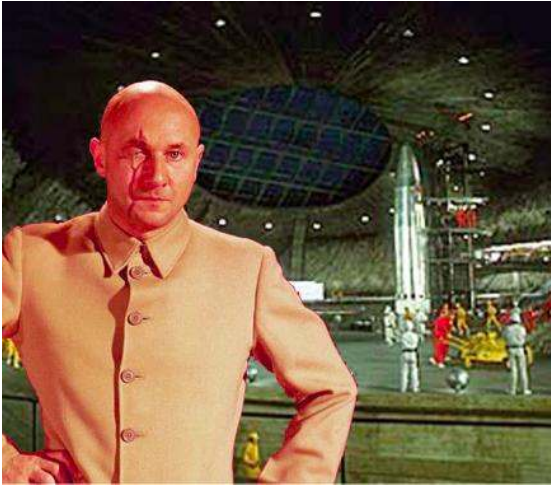
Actually, recent more stringent safety regulations make this image a little out of date...

Walk to mine shaft no. 9

It gets really cold in the winter

6800 feet underground - ready to walk a similar distance

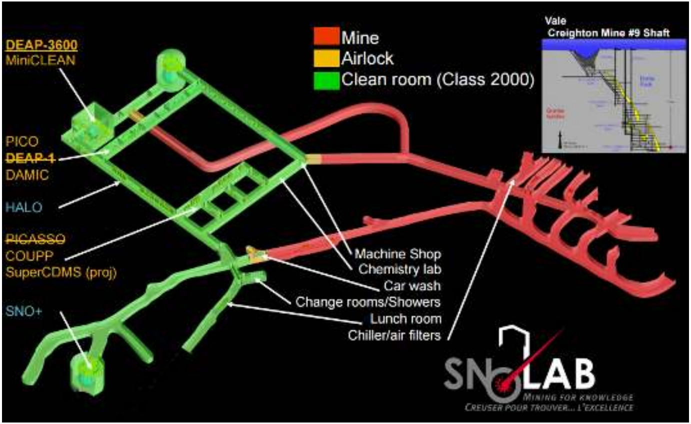
Arriving at SNOLAB can feel like ...



Reality, after required shower and change into clean outfit

SNOLAB facility underground

Do visit: www.snolab.ca/facility/vr-tour

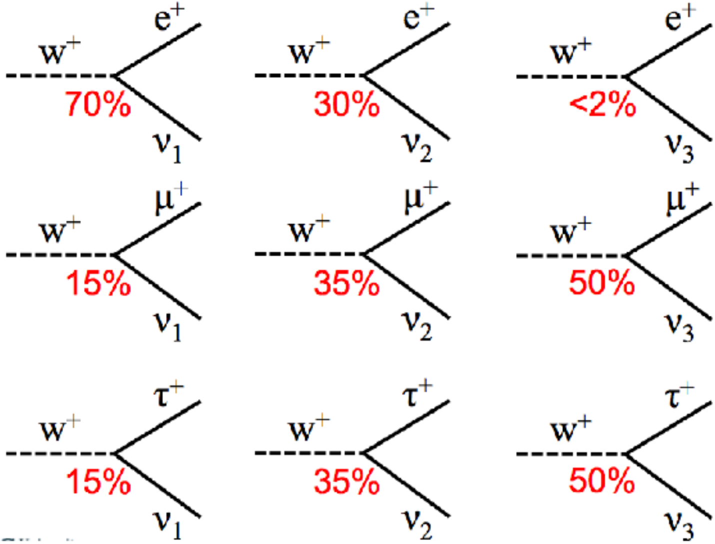


10,000 square feet class 2000 cleanroom
2078 m deep or 6010 m.w.e.: μ flux only 0.27 m^{-2} day^{-1}, 120 Bq m^{-3} $^{222}\mathrm{Rn}$
`http://snolab2008.snolab.ca/snolab_users_handbook_rev02.pdf`

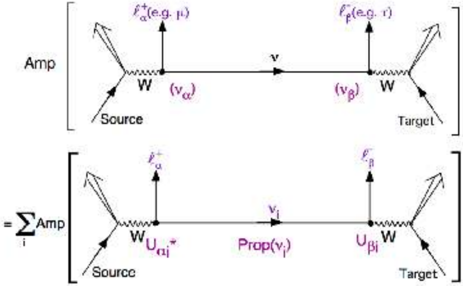
Worth visiting!

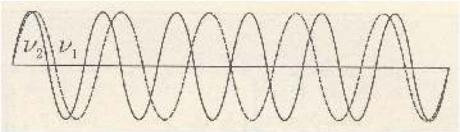
Current questions in neutrino physics

Neutrinos: mass and flavour eigenstates are different



Neutrino oscillations





Mass eigenstates with the same energy propagate differently.

Neutrino oscillation phenomology

$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} e^{\left(-i \frac{\Delta m^2_{kj} L}{2E}\right)}$$

$$\Delta m^2_{kj} \equiv m^2_k - m^2_j$$

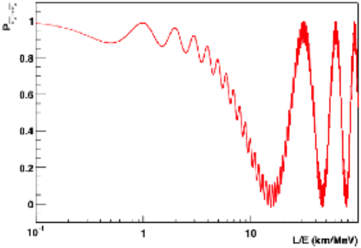
Pontecorvo Maki Nakagawa Sakata (PMNS) matrix:

$$U =$$

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{bmatrix}$$

$$\begin{bmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{bmatrix}$$

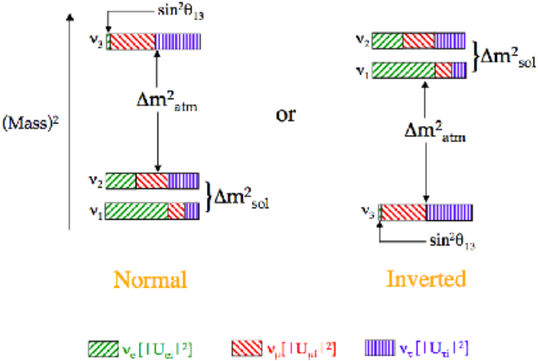
$$\begin{bmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

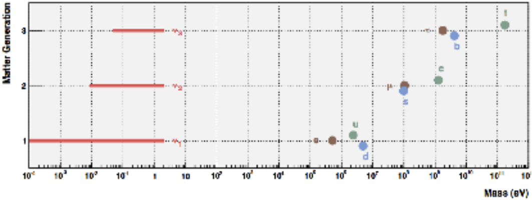


Oscillation of neutrino flavour for reactor neutrinos.

Long beamlines: matter effects!

Summary of what we know about neutrinos





Neutral, only weakly interacting.

parameter	value
N_ν	2.984 ± 0.008
$\sin^2 2\theta_{12}$	0.846 ± 0.021
$\sin^2 2\theta_{23}$	$0.999^{+0.001}_{-0.018}$
$\sin^2 2\theta_{13}$	0.093 ± 0.008
Δm^2_{21}	$(7.53 \pm 0.18) \times 10^{-5}$ eV^2
Δm^2_{32}	$(2.44 \pm 0.06) \times 10^{-3}$ eV^2
m_e	< 2 eV
$\sum m_k$	< 0.23 eV
$m_{\beta\beta}$	$\lesssim 100$ meV

Source: PDG.

Neutrino masses & see-saw mechanism

As the neutrino is completely neutral, it could be a Majorana particle.
Effectively, it is indistinguishable from its anti-particle.

The mass term can be written as:

$$\mathcal{L} = -m_D \left(\bar{N}_R \nu_L + \bar{\nu}_L N_R\right) - \frac{1}{2} m_M \bar{N}_R N_R + h.c.$$

or:

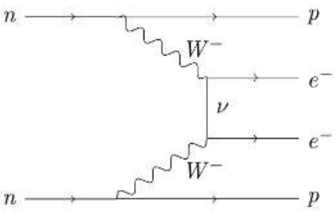
$$\mathcal{L} = \frac{1}{2}(\bar{\nu}_L, \bar{N}_R) \begin{pmatrix} 0 & m_D \\ m_D^T & m_M \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R \end{pmatrix}$$

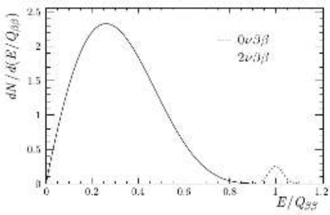
Assuming $N_R \gg \nu_L$, we find the two following eigenvalues:

- (Nearly) right-handed particles with mass m_M.
- (Nearly) left-handed particles with mass m_D^2 / m_M.

See-saw: the heavier m_M, the lighter the left-handed neutrino is.

Neutrinoless double-beta decay





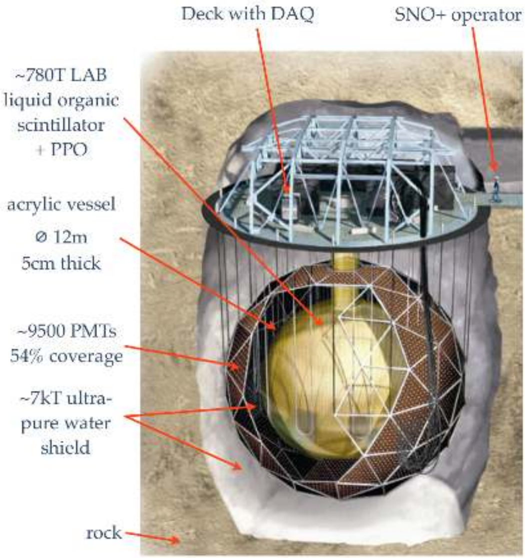
Rare: $\Gamma = G|M|^2 m_{\beta\beta}^2$, $T_{1/2}^{0\nu\beta\beta} > 10^{21}$ year (!!)

Consequences of observation:

- Violation of lepton number by 2
- Schechter-Valle theorem (1982): if neutrinoless double-beta decay is observed, this must mean that neutrinos are Majorana particles!
- Explanation of why neutrinos are so much lighter.
- Combined with CP-violation for heavy neutrino, could imply leptogenesis
- Absolute mass scale hints via $m_{\beta\beta}$

The SNO+ experiment and its programme

The SNO+ experiment



- Low-energy solar neutrinos
- Supernova neutrinos
- Reactor anti-neutrinos
- Geo-neutrinos
- Invisible nucleon decay
- Other exotic searches
- Neutrinoless double-beta decay

The SNO+ collaboration

Queen's University
University of Alberta
Laurentian University
SNOLAB
TRIUMF

BNL, AASU
Penn, UNC, BHSU
U. Washington
UC Berkeley/LBNL
Chicago, UC Davis

Oxford
Sussex
QMUL
Liverpool
Lancaster

LIP Lisboa
LIP Coimbra

TU Dresden

UNAM

SNO+ ‘target’ material

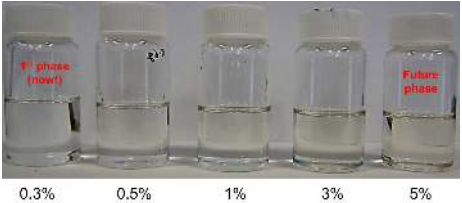
Linear alkylbenzene (LAB) + 2,5-diphenyloxazole (PPO) fluor + Te

LAB-based scintillator:

- Around 10,000 photons/MeV
- Attenuation lenght of about 20 m
- Safe to handle
- Acrylic compatible
- $\beta - \alpha$ timing discrimination

$0\nu\beta\beta$ **isotope choice**:

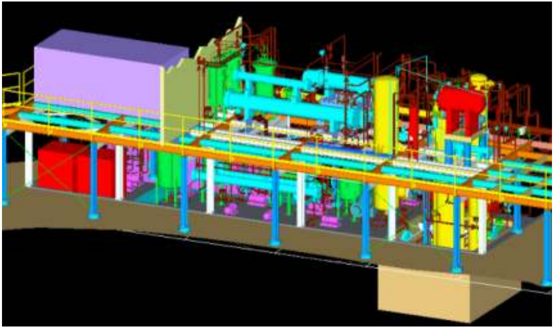
- High natural abundance of $^{130}\mathrm{Te}$ in $^{nat}\mathrm{Te}$ (34%)
- Favourable rate of $2\nu\beta\beta$ to $0\nu\beta\beta$
- No optical absorption lines
- Stable in liquid scintillator



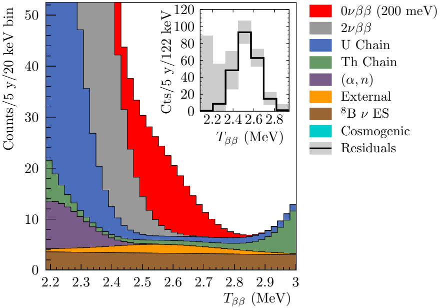
Loading in scintillator due to developments at BNL

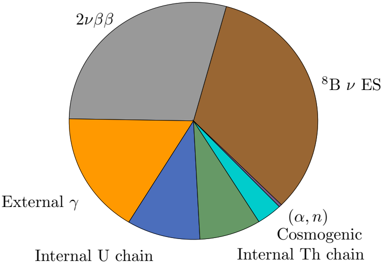
(NIM A 660 51 (2011) (M. Yeh et al.))

Scintillator plant



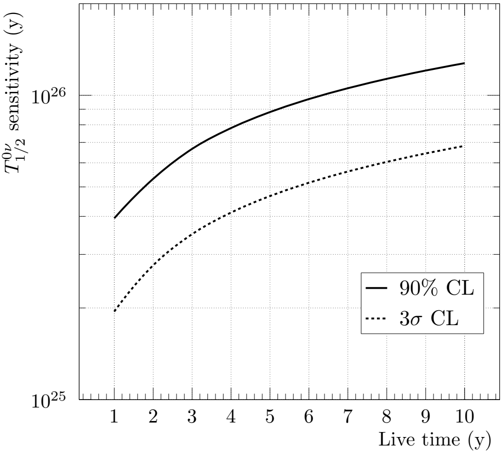
The expected signal and background





- 5 years with 0.3% $^{\mathrm{nat}}$Te
- 200 p.e./MeV 4.5% resolution at $Q_{\beta\beta}$
- Fiducial volume: 3.5 m (20%)
- Energy window: $-\sigma/2 \rightarrow 3\sigma/2$ around $Q_{\beta\beta}$
- Assume BiPo tags 100% efficient for separate triggers

Sensitivity



90% C.L. limits

- **1 year**

  $\hat{T}^{0\nu\beta\beta}_{1/2} = 3.9 \times 10^{25}$ year,
  $\hat{m}_{\beta\beta} \approx 105\ meV$
- **5 years**

  $\hat{T}^{0\nu\beta\beta}_{1/2} = 9.4 \times 10^{25}$ year,
  $\hat{m}_{\beta\beta} \approx 68\ meV$

using:
$M = 4.03$ (IMB)
$G = 3.69 \times 10^{-14}\ \mathrm{y}^{-1}$.

Current status and outlook

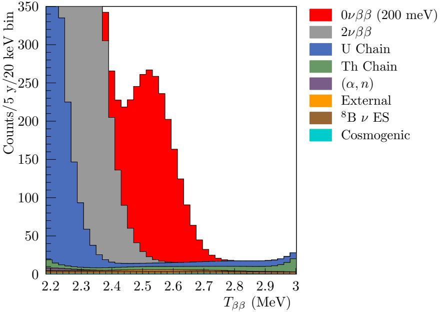
- **NOW**
  Filling with water
  Commissioning runs of the detector
  Commissioning the scintillator plant
- **2015, second half**: *water fill*
  Soak Rn daughters from vessel
  Calibrations and background measurements
  Invisible nucleon decay, supernova live
- **2016, first half**: *scintillator fill*
  Soak Rn daughters from vessel
  Calibrations and scintillator measurements
  Reactor anti-neutrino, geo-neutrinos, solar neutrinos, supernova live
- **2016, second half**: *Te-loaded scintillator*
  Neutrinoless double-beta decay search
  Calibrations
  Reactor anti-neutrino, geo-neutrinos, solar neutrinos, supernova live

SNO+ phase II - planning for success

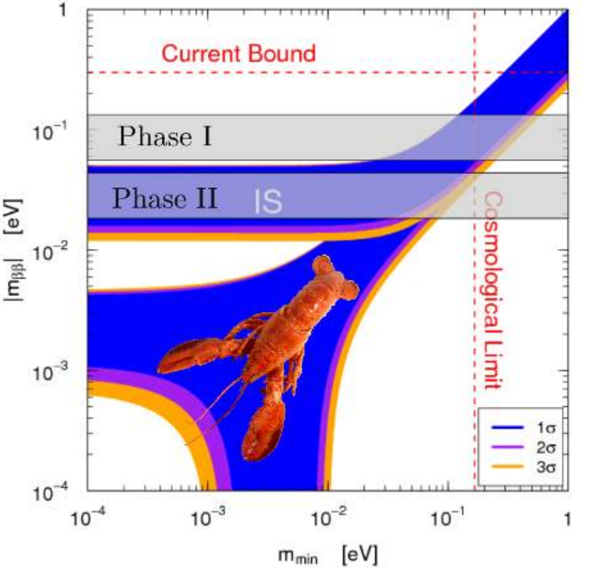
Increase to 8 tonne of $^{nat}\mathrm{Te}$
(3% loading),
along with increased light yield, using:

- Upgraded PMT array
- Secondary fluor R&D
- Considering central balloon in vessel

$\hat{T}_{1/2}^{0\nu\beta\beta} = 8 \times 10^{26}$ year,
90% C.L. in 5 years



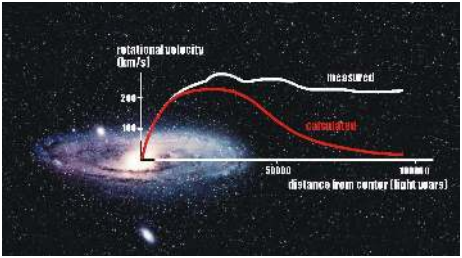
SNO+ phases in context

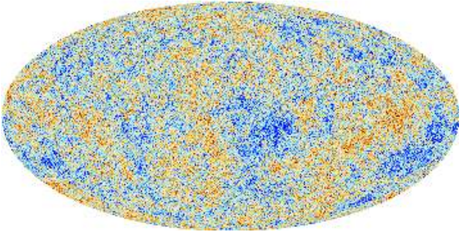


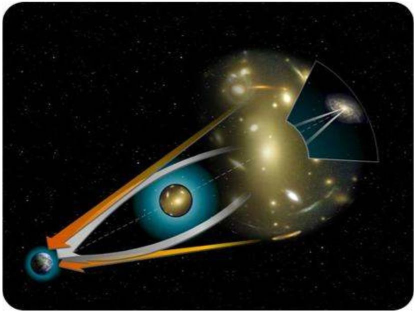
adapted from Bilenky & Giunti


PICASSO
mini CLEAN
DEAP-3600
COUPP
SNOLAB, SUDBURY

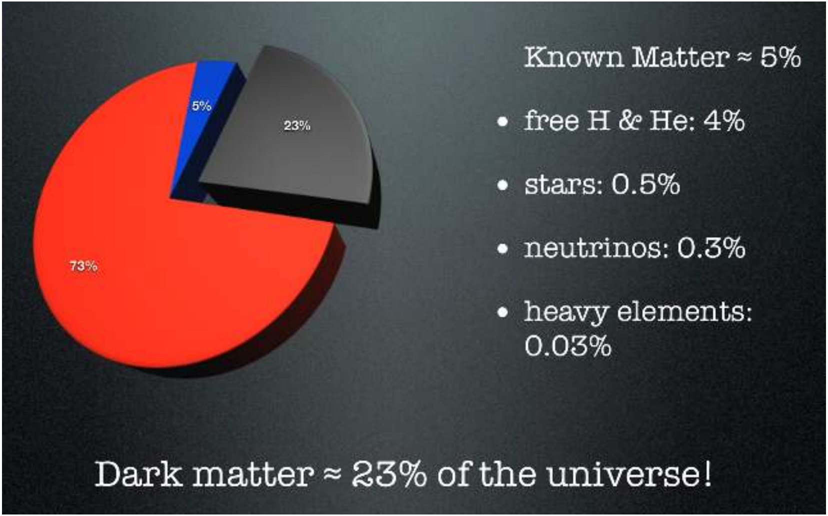
Why look for Dark Matter?


rotational velocity (km/s)
200
100
measured
calculated
50000
100000
distance from center (light years)





Loads of unknown stuff out there!



Known Matter ≈ 5%

- free H & He: 4%
- stars: 0.5%
- neutrinos: 0.3%
- heavy elements: 0.03%

Dark matter ≈ 23% of the universe!

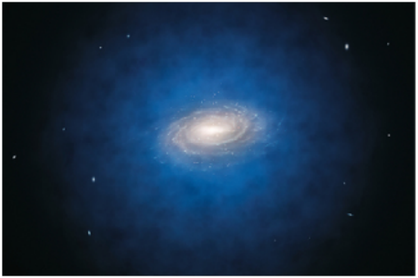
Dark Matter candidates

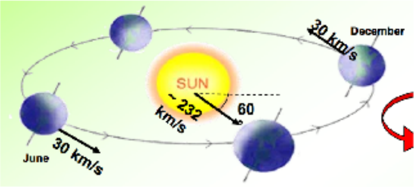
Looking for Dark Matter

There are many ways...

- Looking for signatures at the LHC
- Looking for annihilation signatures in the Sun, or wider galaxy
- Using astrophysical observations

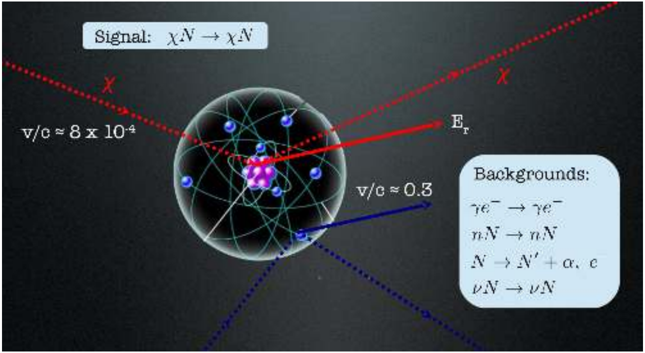
All indirect - only direct detection has the potential to establish what the dark matter actually is.





WIMP scattering

WIMP: weakly massive interactive particle



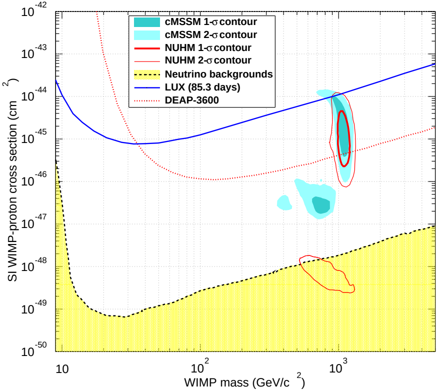
The exact interaction mechanism is unknown, so the search is for:

- Spin independent cross section:
  coherent scattering, enhanced A^2 dependent cross section.
- Spin dependent cross section:
  no such enhancement.

Physics reach for Direct Detection of WIMPs

Low range (1-10 GeV): Requires complicated models.

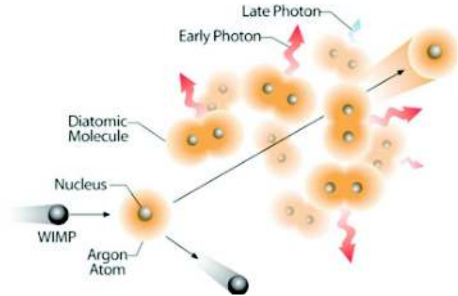
High range (100 GeV-1 TeV): Favoured by simple extensions of the SM



`http://cedar.berkeley.edu/plotter`, Roszkowski et al, JHEP 1408 (2014) 067, J. Billard et al., Phys. Rev. D 89 (2014) 023524

Detection principle in single-phase argon

Direct Detection of Dark Matter



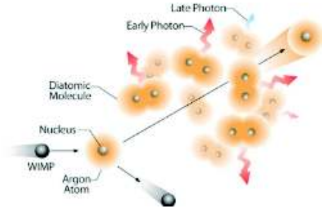
SIGNAL

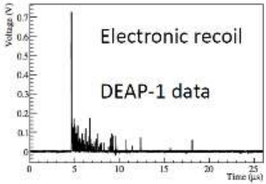
- Coherent WIMP-nucleus scattering *Lewin and Smith, Astroparticle Physics 6, 87-112 (1996)*

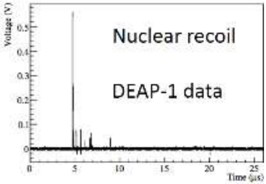
(MAIN) BACKGROUNDS

- electromagnetic radioactivity ($^{39}\mathrm{Ar}, ^{85}\mathrm{Kr}$) – reducible
- surface α particles – reducible
- external neutrons – reducible
- neutrinos – irreducible

Scintillation of argon



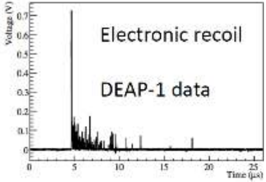


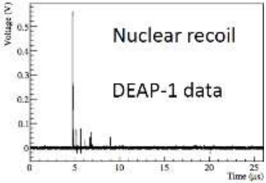


- Excitation and ionisation leads to the production of $Ar_2{}^*$.
- Light (128 nm) is produced with the dissociation of $Ar_2{}^*$. (Shifted to 420 nm by TPB wavelength shifter.)
- Two molecular states of $Ar_2{}^*$; singlet and triplet, with very different lifetimes: 7 ns vs. 1.5 μs.

PSD: Pulse Shape Discrimination

Ar: singlet and triplet excited states have well separated lifetimes





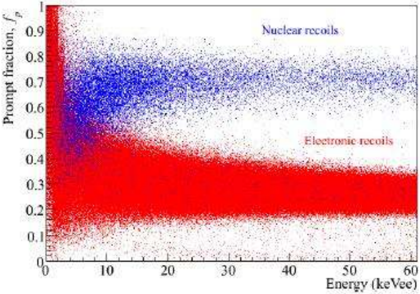
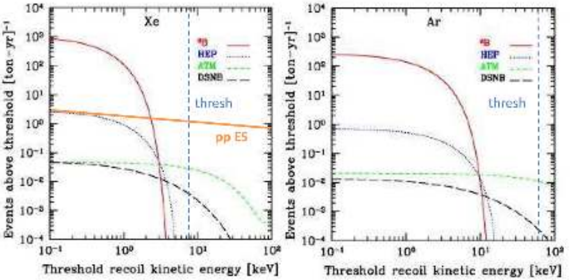


FIG. 7: A scatter plot of f_p vs. energy for tagged electronic and nuclear recoils, where $\xi = 90$ ns.

Neutrino backgrounds

- Scaling to the multi-tonne scale is only cost-effective using noble gases.
- The ultimate limit for non-directional direct-detection Dark Matter experiments are neutrino backgrounds.



Neutrino backgrounds for Ar and Xe, adapted from L.E. Strigari, ArXiv:0903.3630

The dominant background in Xenon is ES from pp neutrinos.

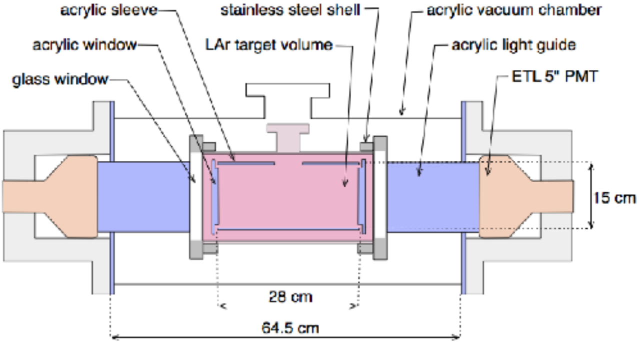
In argon, with many orders of magnitude higher discrimination, the ES background is insignificant and the background is dominated by coherent scattering of atmospheric neutrinos and approximately two orders of magnitude lower.

DEAP-1

The past

DEAP-1 design

7 kg LAr target in various configurations



Key results:
Significant background reduction, detailed background model (arXiv:1211.0909).
Shown PSD to work (arXiv:1203.0604).
Monte-Carlo extension to larger detectors with better coverage 1shows that 10^{10} discrimination is achievable.

DEAP-3600

The present

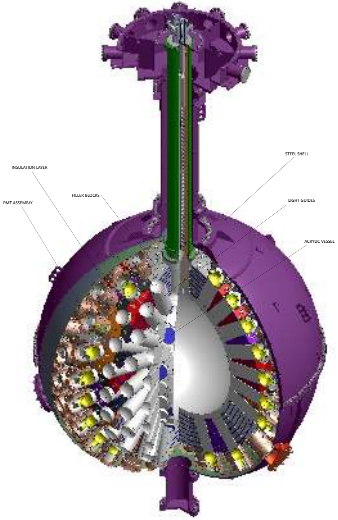
The DEAP collaboration

University of Alberta
Carleton University
Queens University
Laurentian University
SNOLAB

TRIUMF
Rutherford Appleton Laboretory
Royal Holloway, University of London
University of Sussex

70 collaborators from UK and Canada

DEAP-3600 design



- Contains 3600 kg argon target (1000 kg fiducial) in a sealed, ultra-clean acrylic vessel.
- The acrylic vessel is resurfaced in-situ to remove deposited Rn daughters after construction.
- TPB is then deposited in a clean, vacuum environment.
- Array of 255 Hamamatsu R5912 HQE PMTs 8-inch (32% QE, 75% coverage).
- Connected with 50 cm light guides + PE shielding provide neutron moderation.
- Detector in 8 m water shield at SNOLAB.

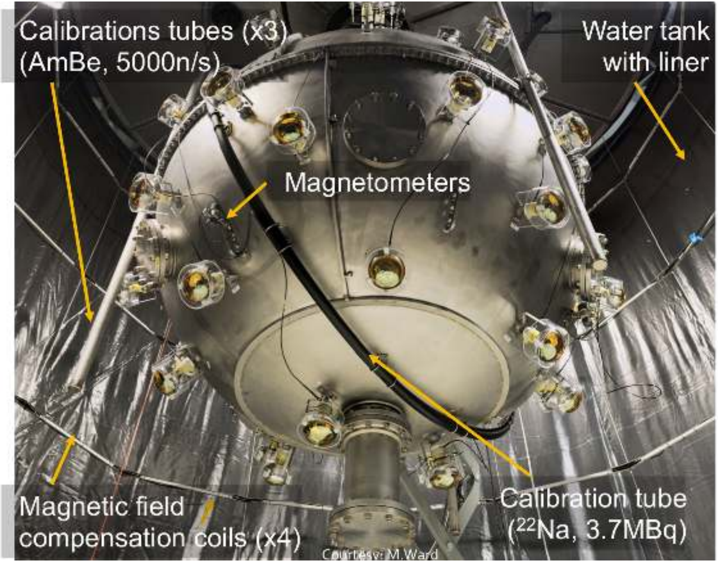
DEAP-3600: basic parameters

Parameter	**Value**
Light yield	8 pe per keVee
Nuclear quenching factor	0.25
Analysis threshold	15 keVee (60 keVr)
Total argon mass (radius)	3600 kg (80 cm)
Fiducial mass (radius)	1000 kg (60 cm)
Position reconstruction resolution	< 6.5 cm

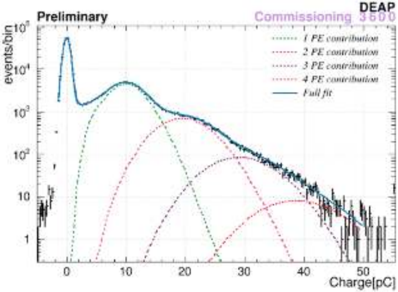
Bakcground specification	**Target**
Radon in argon	< 1.4 nBq/kg
Surface α	$< 100\ \mu$Bq/m^2
Neutrons in fiducial volume	< 2 pBq/kg
β/γ events (after PSD)	< 2 pBq/kg

Total backgrounds	< 0.3 **events in 3 tonne-year**

Look inside the water tank



Commissioning



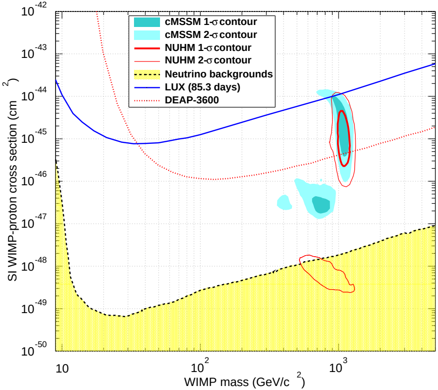
Next:

- Wavelength shifter evaporation (few days)
- Insertion of the cooling coil next
- Cooling: within the next couple of months

DATA: END OF THE SUMMER
LEADING SENSITIVITY: END OF THE YEAR

Reminder

Sensitivity expected at 100 GeV: 10^{-46} cm^2, 90% C.L. after 3 yrs

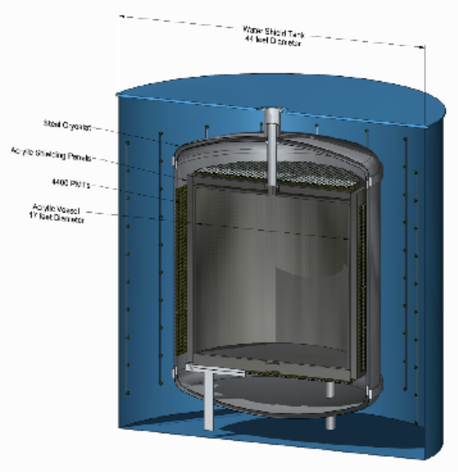


`http://cedar.berkeley.edu/plotter`, Roszkowski et al, JHEP 1408 (2014) 067, J. Billard et al., Phys. Rev. D 89 (2014) 023524

DEAP 50-tonne

The future

Going beyond DEAP-3600



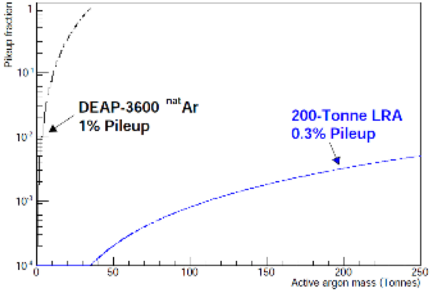
Basic design concept: this will be optimized based on more detailed Monte-Carlo studies.

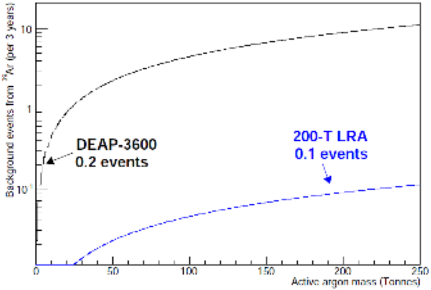
- Single-phase LAr,
  50 tonnes fiducial mass
  (150 tonnes LRA target,
  240 tonnes buffer).
- Reconstruction: impurity constraints for surface backgrounds can be relaxed.
- Large inner vessel:
  Initial discussion with Reynolds polymers are very encouraging.
- Surrounded by 12" clear, ultra-low background acrylic panels
- R&D on PMT alternative: SiPMs (less radioactivity than PMTs)
- Large double-walled cryostat with immersed in water shield.
- Planned location: SNOLAB cryopit.

Pile-up from $^{39}\mathrm{Ar}$

PSD requirements imply 10 μs event window:
this leads to pile-up with $^{nat}\mathrm{Ar}$

$\Rightarrow$ This requires LRA (Low Radioactivity Argon)



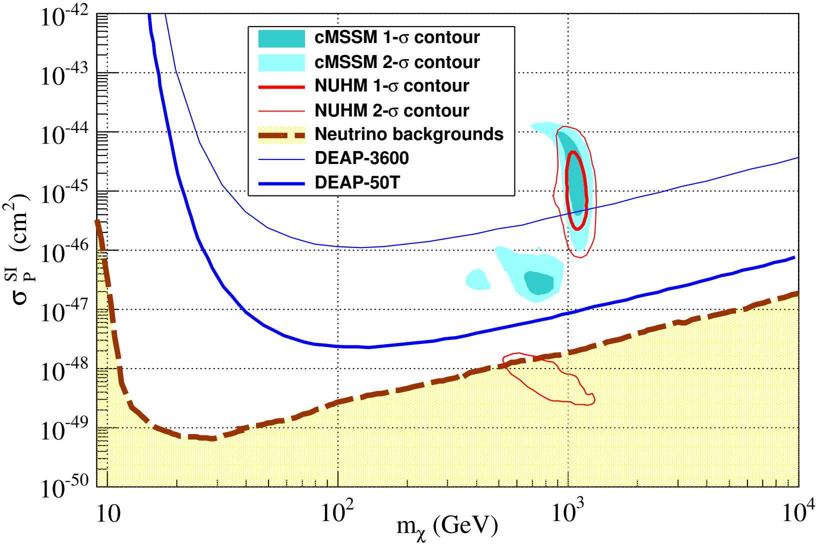


Depleted Argon

LRA from US National Helium Reserve,
located in the Cliffside Storage Facility outside Amarillo, TX.
Princeton and Fermilab collaboration, successful operation
NIM A 587:46-51 (2008)
AIP Conf. Proc. 1338:217-220 (2011)

- 150 kg of Ar collected, factor 160 reduction in $^{39}\mathrm{Ar}$
- DEAP and DarkSide are collaborating to upgrade to 50 kg/hr facility (enough for DEAP3600).
- Funded by CFI and NSF.
- Future upgrade to 100 kg/hr envisaged.

Expected sensitivity



Hopefully I've given you a flavour of the exciting fundamental physics currently coming online in SNOLAB!