Deep Underground Measurements in Fundamental Physics and Astrophysics

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FERMILAB
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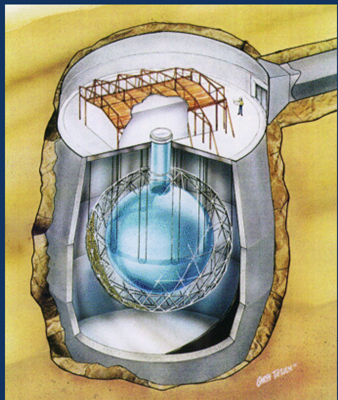
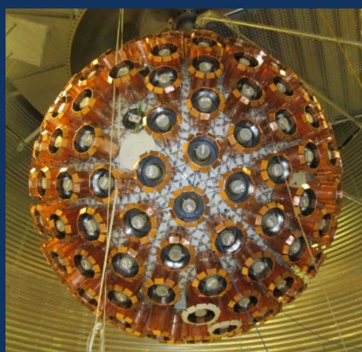
Neutrinos and Dark Matter at SNOLAB

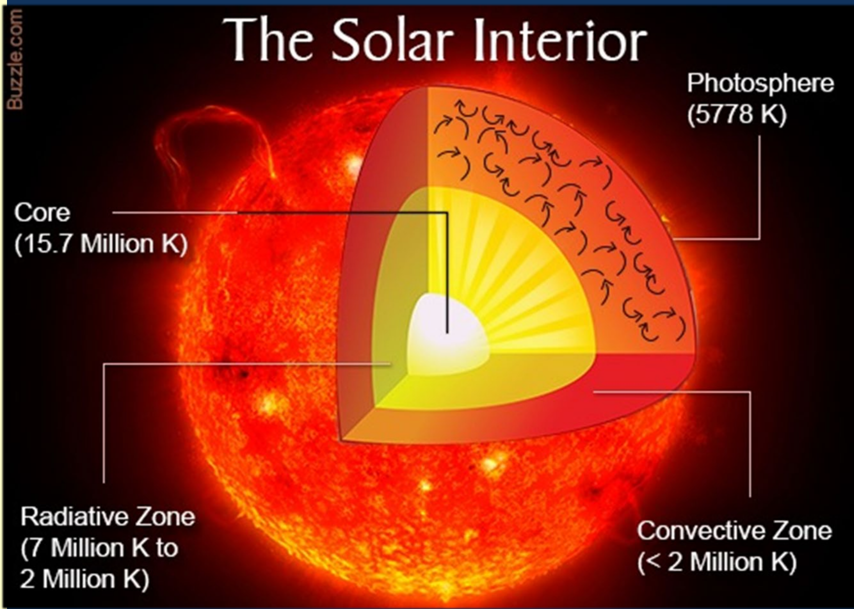


Sudbury Neutrino Observatory (SNO) (NOW SNO+)



DEAP Dark Matter Experiment

Sudbury, Canada



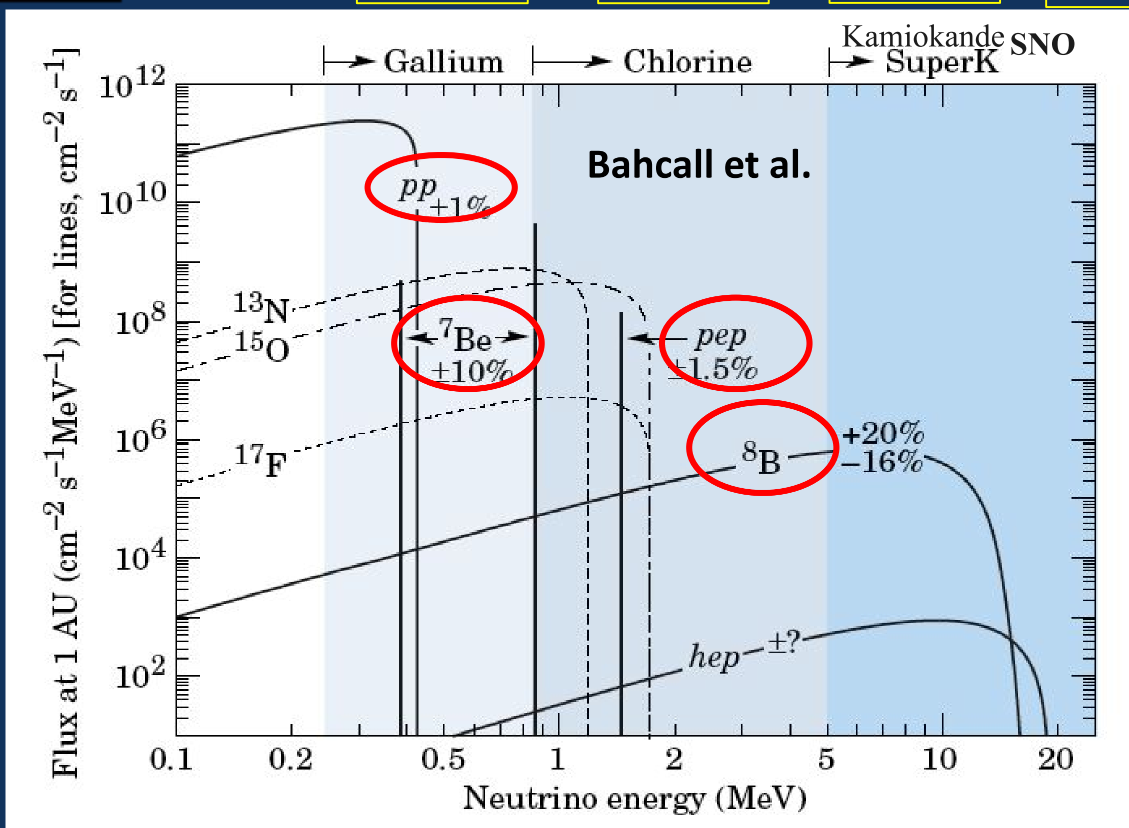
NEUTRINO FLUXES
FROM THE SOLAR CORE

EXPERIMENTS

1992 on | **1968 on** | **1989 on** | **2001 on**

HOW DOES THE SUN BURN?

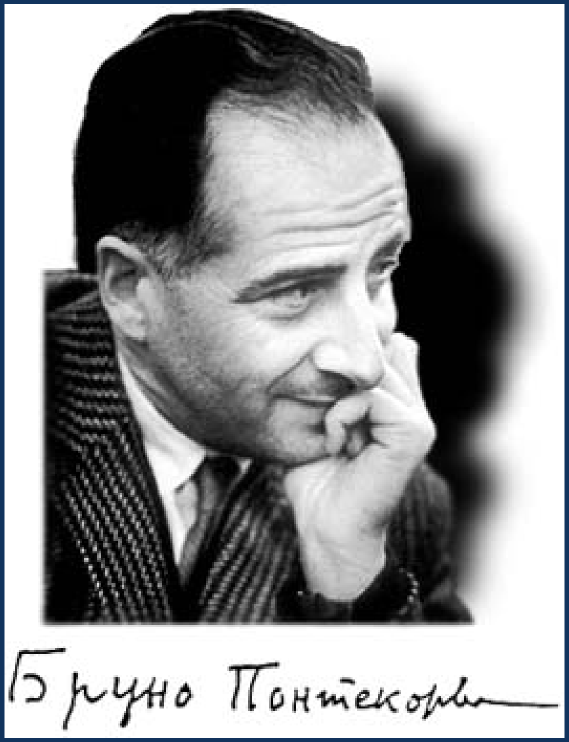
Nuclear fusion reactions produce enormous numbers of electron neutrinos



Pioneers of Solar Neutrino Physics: Davis, Bahcall, Pontecorvo & Gribov

1968: Davis' Measurements of electron neutrinos with Chlorine-based detector show 3 times fewer than Bahcall's calculations.

Ray Davis: Nobel Laureate 2002



1968: Gribov and Pontecorvo suggest flavor change (oscillation) of electron neutrinos to muon neutrinos as a possible reason.

The major scientific question that SNO set out to answer starting in 1984

- DAVIS' EXPERIMENT WITH CHLORINE OBSERVED TOO FEW OF THE ELECTRON FLAVOUR NEUTRINOS PRODUCED IN THE SUN, COMPARED TO SOLAR MODEL CALCULATIONS BY BAHCALL

- EITHER :

1. THE SOLAR MODEL CALCULATIONS WERE INCOMPLETE OR INCORRECT

OR

2. THE ELECTRON NEUTRINOS CREATED IN THE SUN ARE CHANGING TO ANOTHER FLAVOUR AND ELUDING THE PAST EXPERIMENTS THAT WERE SENSITIVE MAINLY TO ELECTRON NEUTRINOS ALONE.

In 1984, Herb Chen proposed that with ~1000 tonnes of Heavy Water (D_2O), one could measure separately electron neutrinos and the sum of all three flavours and answer the question clearly.

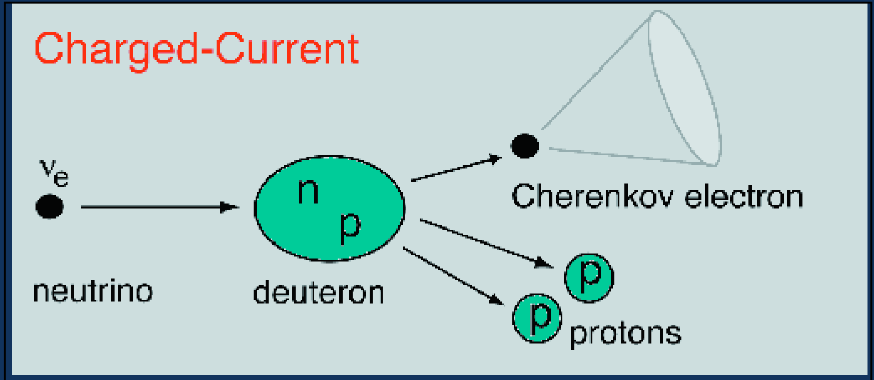
Unique Signatures in SNO (D_2O)

(1 in 6400 molecules in ordinary water are D_2O. We used >99.75% D_2O)

Electron Neutrinos (CC)

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

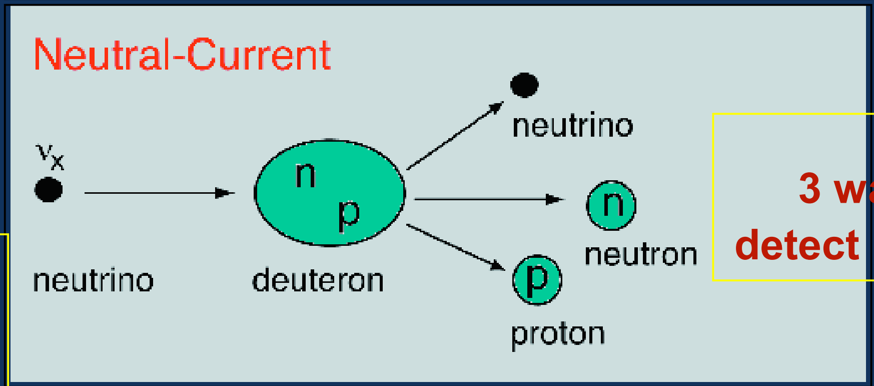
$E_{thresh} = 1.4$ MeV



Equal Sensitivity All Types (NC)

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

$E_{thresh} = 2.2$ MeV



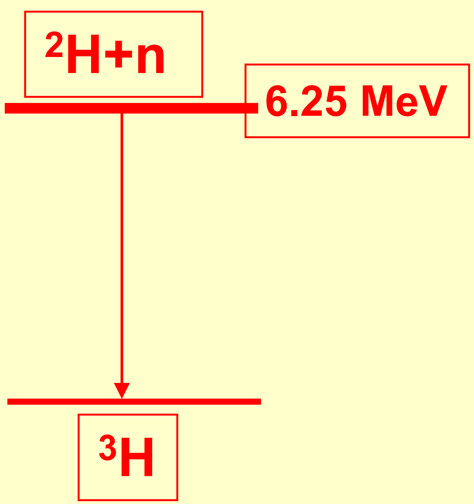
3 ways to detect neutrons

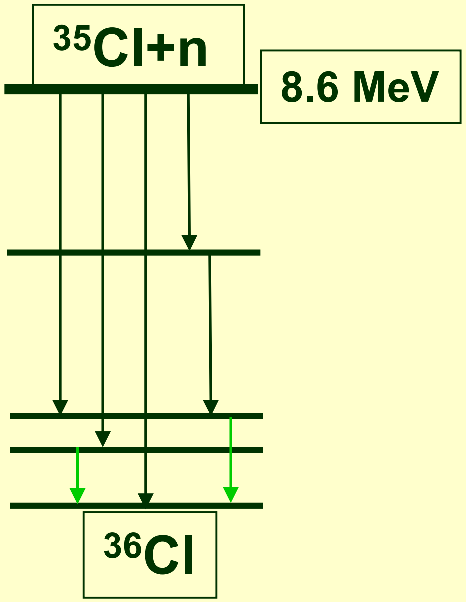
Comparing these two reactions tells if electron neutrinos have changed their type.

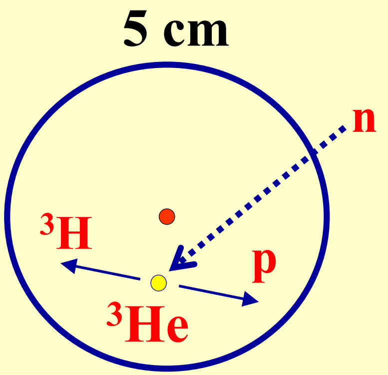
Radioactivity must be carefully controlled because gamma rays can also break apart deuterium and produce a free neutron. Less than one decay per day per ton of water from U, Th.

3 neutron (NC) detection methods (systematically different)

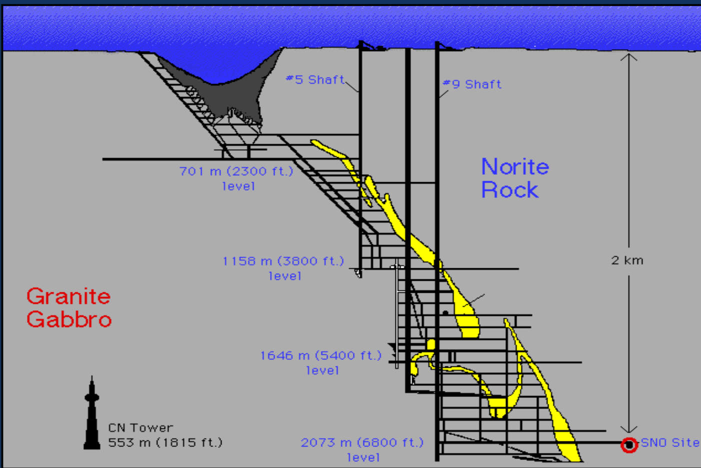
Phase I (D_2O) Nov. 99 - May 01	Phase II (salt) July 01 - Sep. 03	Phase III (^{3}He) Nov. 04-Dec. 06
n captures on $^2H(n, \gamma)^3H$ Effc. ~14.4% NC and CC separation by energy, radial, and directional distributions	2 tonnes of NaCl n captures on $^{35}Cl(n, \gamma)^{36}Cl$ Effc. ~40% NC and CC separation by event isotropy	400 m of proportional counters $^3He(n, p)^3H$ Effc. ~ 30% capture Measure NC rate with entirely seperate detection system.





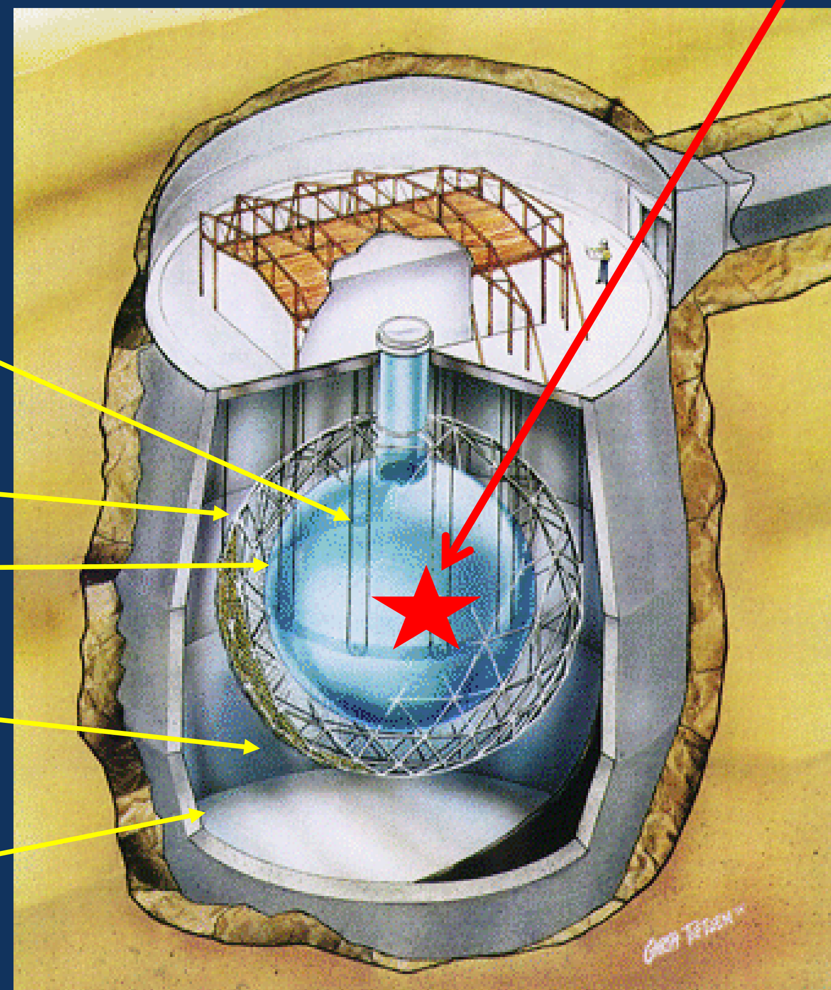


$$n + {}^3He \rightarrow p + {}^3H$$



Sudbury Neutrino Observatory (SNO)

NEUTRINO



1000 tonnes of heavy water: D_2O
\$ 300 million on Loan for \$1.00

9500 light sensors

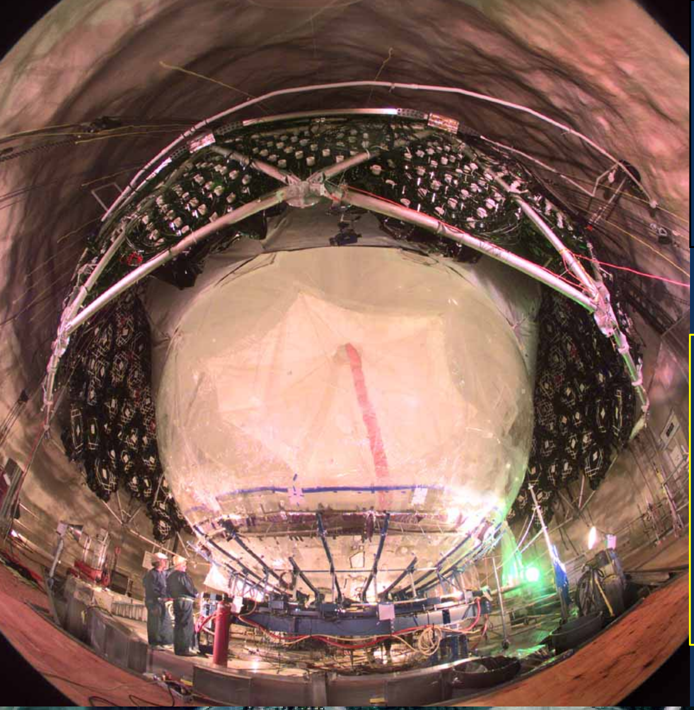
12 m Diameter Acrylic Container

Ultra-pure Water: H_2O.

Urylon Liner and Radon Seal

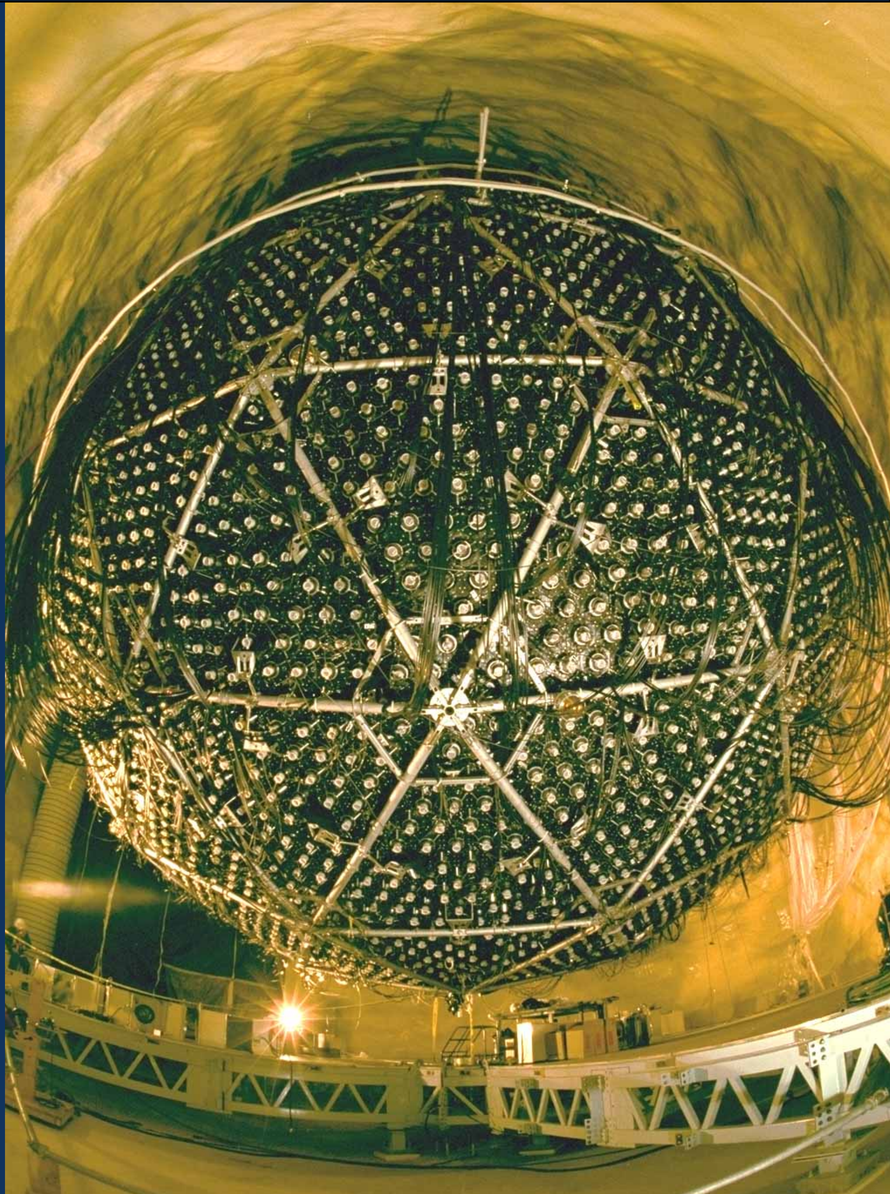
34 m or ~ Ten Stories High!

2 km below the ground



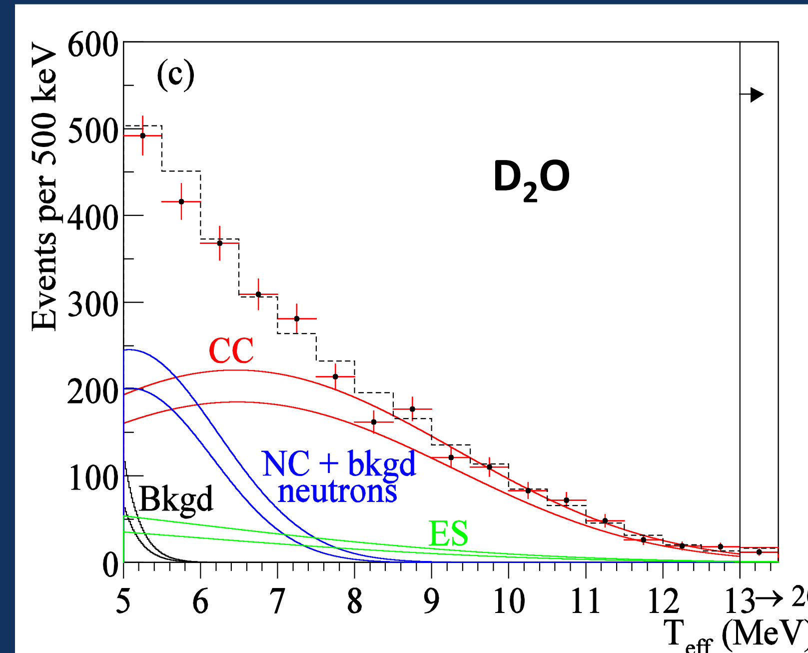
SNO: One million pieces transported down in the 3 m x 3 m x 4 m mine cage and re-assembled under ultra-clean conditions. Every worker takes a shower and wears clean, lint-free clothing.

70,000 showers during the course of the SNO project

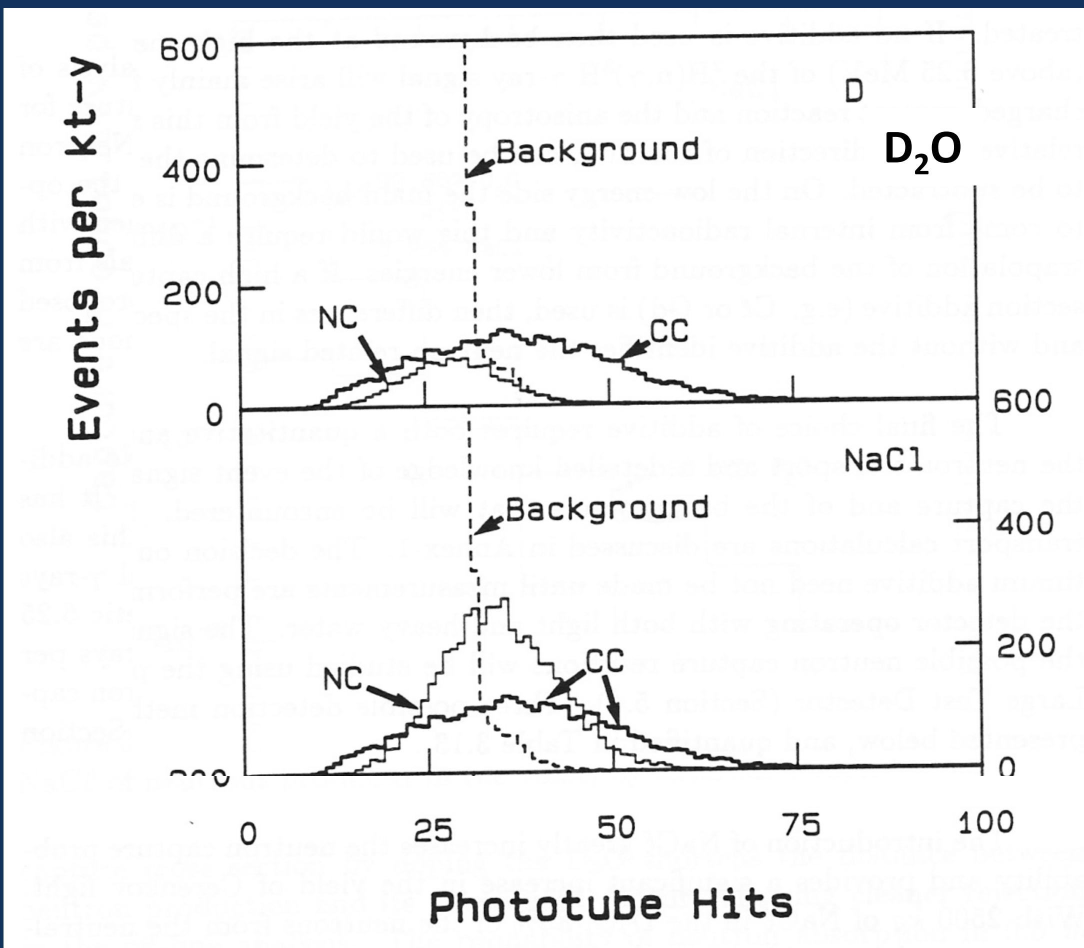


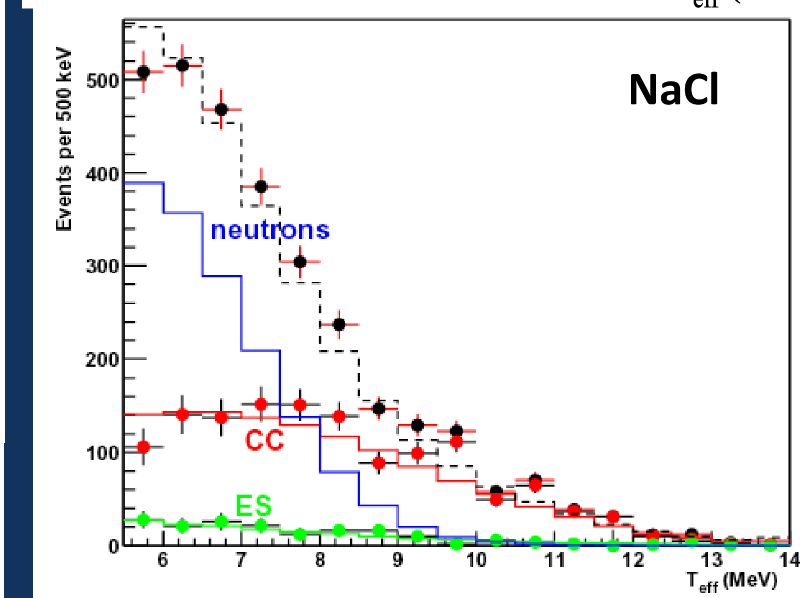
SNO results from Pure D_2O and Salt Phases

As measured 1999-2003

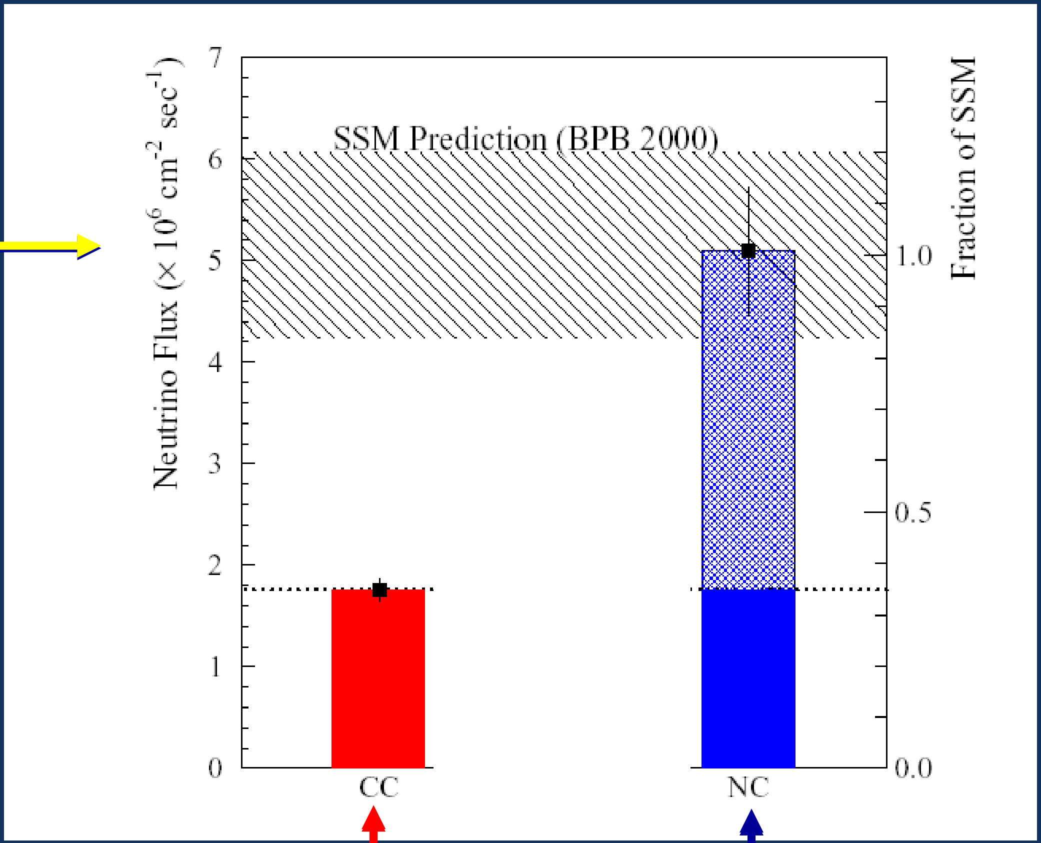


As simulated in 1987





SOLAR MODEL



Excellent Agreement With the Solar Model Calculations

SNO USED HEAVY WATER TO MEASURE TWO SEPARATE THINGS

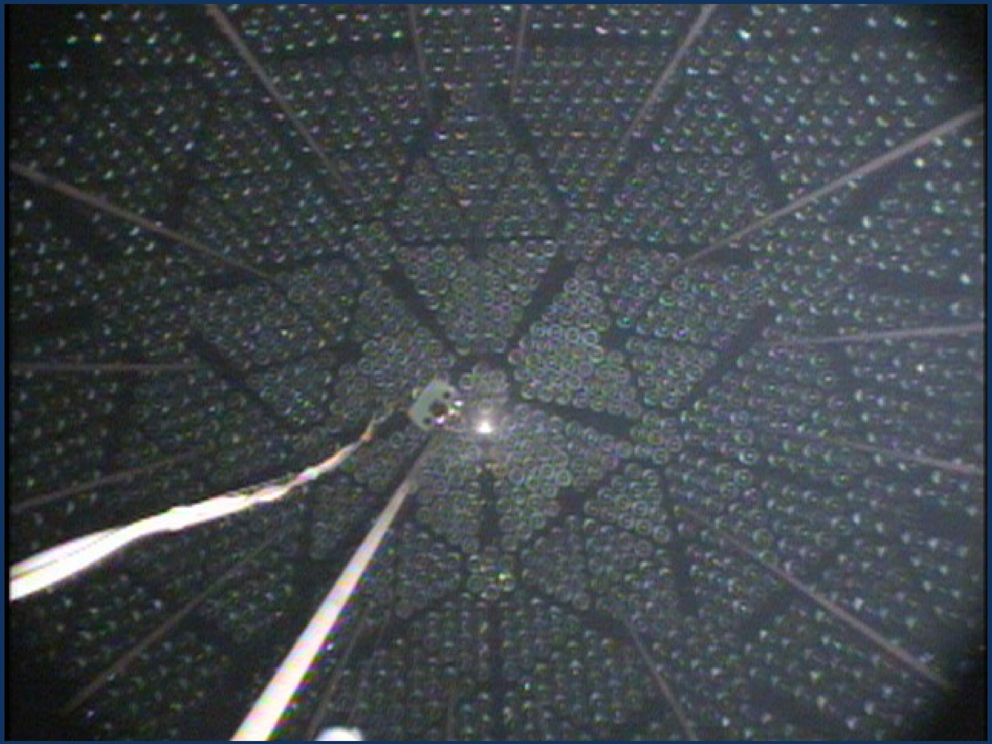
LESS THAN ONE CHANCE IN 10 MILLION FOR “NO CHANGE IN NEUTRINO TYPE”

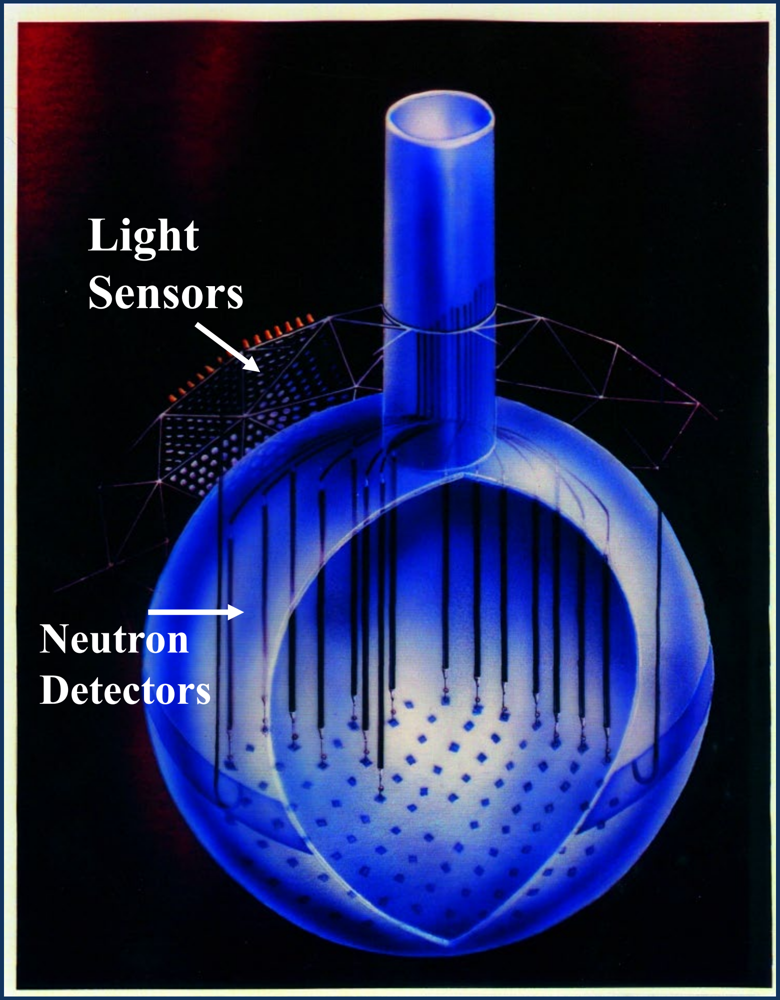
ELECTRON NEUTRINOS

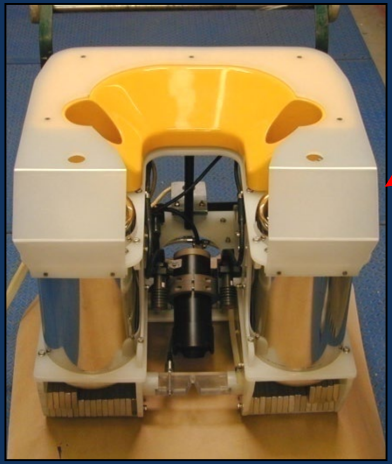
ALL NEUTRINO TYPES

SNO MEASUREMENTS IN 2001-02 PROVIDE A CLEAR DEMONSTRATION THAT NEUTRINOS CHANGE THEIR FLAVOR:
2/3 OF THE ELECTRON NEUTRINOS HAVE CHANGED TO MU, TAU NEUTRINOS ON THE WAY FROM THE SOLAR CORE TO EARTH.

Phase 3: 400 m of Ultra Low Background Neutron Counters installed in the heavy water by a remotely controlled submarine







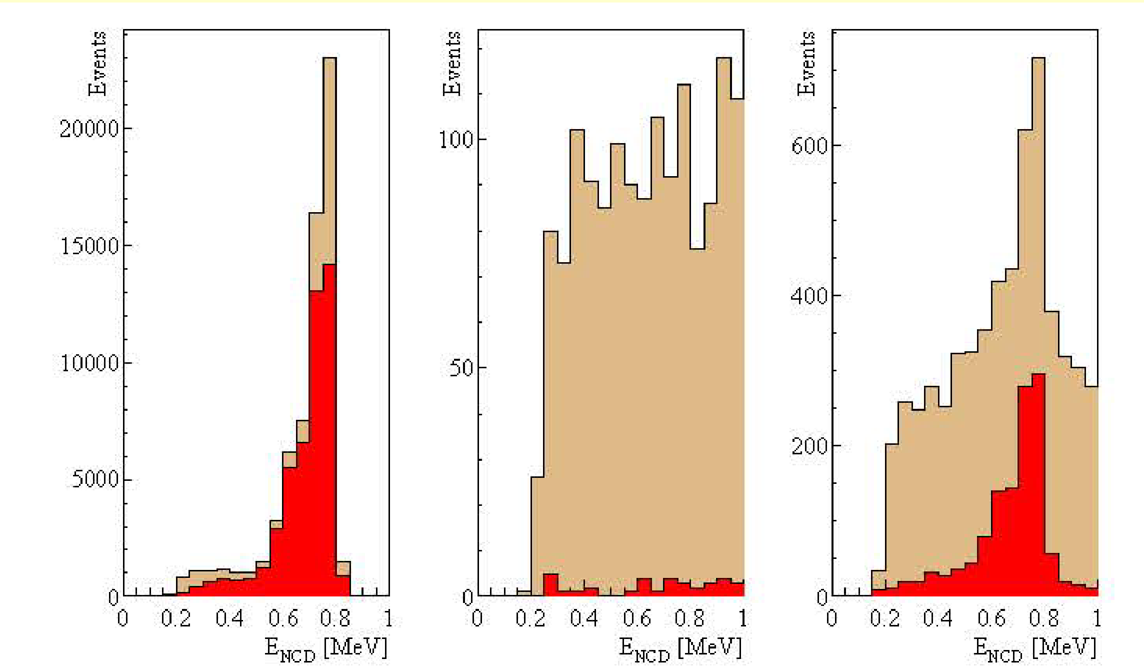
The original Submarine …

The Neutron Counters were made by chemical vapor deposition, creating very low-radioactivity nickel.

Final Complete Analysis of SNO solar data

The SNO Collaboration (B. Aharmim et al) Phys. Rev. C 88, 025501 (2013)

NCD pulse shape analysis to identify neutron events



^3He detectors: neutron source | **^4He detectors: alpha backgnd** | **^3He detectors: neutrino data**

$$CC/NC = 0.317 \pm 0.016(stat) \pm 0.009(syst)$$

implies flavor change at far more than 7 σ and shows that θ_{12} is non-maximal by more than 5 σ.

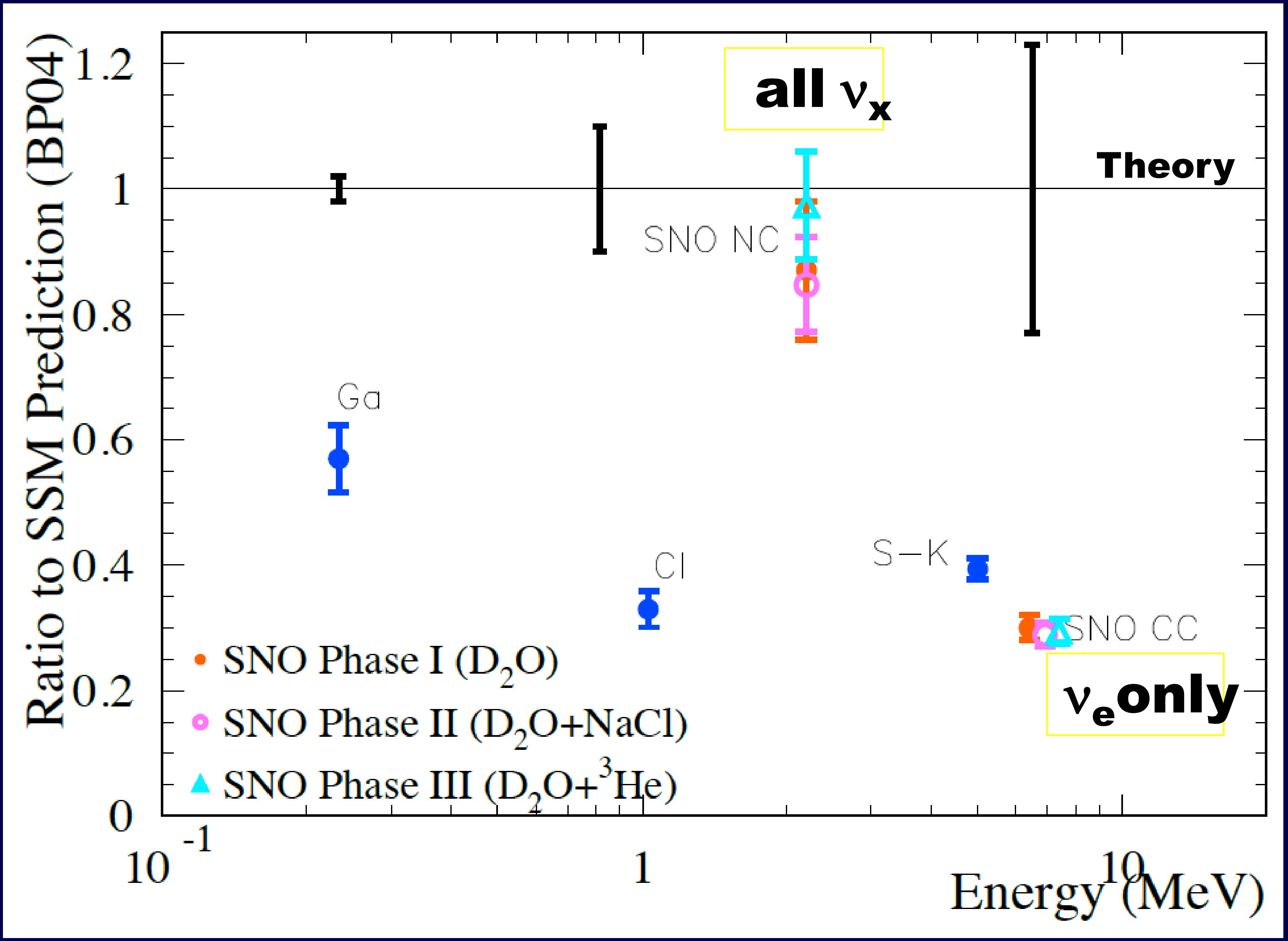
Full joint analysis of solar data from all three phases provides best sensitivity with all correlations, backgrounds, systematic uncertainties included.

Individual results from all three phases are very consistent within uncertainties

$$\Phi_{^8B} = 5.25 \pm 0.16 \; ^{+0.11}_{-0.13}$$

More accurate than current solar models and lying between the fluxes predicted for two values of metallicity in the sun

Solar Neutrino Problem Resolved



273 SNO Physics Paper Authors and 2016 Breakthrough Prize Winners: Adam Cox, Aksel L. Hallin, Alain Bellerive, Alan Smith, Alan Poon, Alexander Wright, Allan Myers, Alysia Marino, André Krüger, André Roberge, Andre Krumins, Andrew Ferraris, Andrew Hime, Anett Schülke, Anthony Noble, Araz Hamian, Arthur McDonald, Aubra Anthony, Azriel Goldschmidt, Barry Robertson, Bassam Aharmim, Bei Cai, Benjamin Monreal, Bernard Nickel, Berta Beltran, Bhaskar Sur, Blair Jamieson, Brandon Wall, Brent VanDevender, Brian Morissette, Bruce Cleveland, Bryan Fulsom, Bryce Moffat, Carsten Krauss, Catherine Mifflin, Charles Currat, Charles Duba, Charlotte Sims, Christian Nally, Christian Ouellet, Christine Kraus, Christopher Kyba, Christopher Howard, Christopher Jillings, Christopher Tunnell, Christopher Waltham, Clarence Virtue, Colin Okada, Darren Grant, David Anglin, David Sinclair, David Waller, David Wark, Davis Earle, Diane Reitzner, Dimpal Chauhan, Doug Hallman, Douglas Cowen, Douglas McDonald, Duncan Hepburn, Ed Frank, Edward Clifford, Michael Dragowsky, Emmanuel Bonvin, Eric Norman, Erik Saettler, Etienne Rollin, Eugene Guillian, Eugene Beier, Fabrice Fleurot, Feng Zhang, Ferenc Dalnoki-Veress, Fraser Duncan, Gabriel D. Orebi Gann, Geoffrey Miller, George Doucas, George Ewan, Gerhard Bühler, Gersende Prior, Gordana Tešić, Gordon,McGregor, Gregory Harper, Guy Jonkmans, Gwen Milton, Hadi Fergani, Hamish Robertson, Hans Bichsel, Hans Mes, Hardy Seifert, Hay Boon Mak, Heidi Munn, Helen M. O'Keeffe, Hendrick Labranche, Henry Lee, Hok Seum Wan Chan Tseung, Huaizhang Deng, Hui-Siong Ng, Ian Lawson, Ilan Levine, Ira Blevis,Jacques Farine, James Cameron, James Hall, James Loach, James Leslie, Jaret Heise, Jason Detwiler, Jason Hewett, Jason Pun, Jason Goon, Jeanne Wilson, Jeffrey Secrest, Jeremy Lyon, Jerry Wilhelmy, Jessica Dunmore, Jian-Xiong Wang, Jimmy Law, Jocelyn Monroe, John Amsbaugh, John Boger, John Orrell, John Simpson, John Wilkerson, Jon Hykawy, Jose Maneira, Joseph Formaggio, Joseph Banar, Joseph Germani, Joshua Klein, Juergen Wendland, Kai Zuber, Kara Keeter, Kareem Kazkaz, Karsten Heeger, Katherine Frame, Kathryn Schaffer, Keith Rielage, Kennneth McFarlane, Kevin Graham, Kevin Lesko, Kevin McBryde, Khalil Boudjemline, Klaus Kirch, Laura Kormos, Laura Stonehill, Laurel Sinclair, Louise Heelan, Malcolm Fowler, Manuel Anaya, Marc Bergevin, Marcus Thomson, Maria Isaac, Marie DiMarco, Mark Boulay, Mark Chen, Mark Howe, Mark Kos, Mark Neubauer, Martin Moorhead, Masa Omori, Melin Huang, Melissa Jerkins, Michael Bowler, Michael Browne, Michael Lay, Michael Lowry, Michael Miller, Michael Thorman, Michal Shatkay, Mike Schwendener, Miles Smith, Minfang Yeh, Miriam Diamond, Mitchell Newcomer, Monica Dunford, Morley O'Neill, Mort Bercovitch, Myung Chol Chon, Naeem Ahmed, Nathaniel Tagg, Neil McCauley, Nicholas Jelley, Nicholas West, Nikolai Starinsky, Nikolai Tolich, Noah Oblath, Noel Gagnon, Nuno Barros, Olivier Simard, Patrick Tsang, Paul Keener, Peter Wittich, Peter Doe, Peter Watson, Peter Skensved, Peter Thornewell, Philip Harvey, Pierre Luc Drouin, Pillalamarr Jagam, Ranpal Dosanjh, Reda Tafirout, Reena Meijer Drees, Reyco Henning, Richard Allen, Richard Ford, Richard Helmer, Richard Hemingway, Richard Kouzes, Richard Hahn, Richard Lange, Richard Ott, Richard Taplin, Richard Van Berg, Richard Van de Water, Rizwan Haq, Robert Black, Robert Boardman, Robert Stokstad, Robert Heaton, Robert Komar, Robin Ollerhead, Rushdy Ahmad, Ryan MacLellan, Ryan Martin, Ryuta Hazama, Salvador Gil, Sarah Rosendahl, Scott Oser, Sean McGee, Shahnoor Habib, Sherry Majerus, Simon Peeters, Stanley Seibert, Steffon Luoma, Steven Elliott, Steven Biller, Steven Brice, Teresa Spreitzer, Thomas Andersen, Thomas J. Radcliffe, Thomas J. Bowles, Thomas Kutter, Thomas Sonley, Thomas Steiger, Timothy Van Wechel, Tom Burritt, Tudor Costin, Tyron Tsui, Vadim Rusu, Vladimir Novikov, Walter Davidson, William Frati, William Handler, William Heintzelman, William Locke, William McLatchie, Xin Chen, Xin Dai, Yaroslav Tserkovnyak, Yasuo Takeuchi, Yekaterina Opachich, Yuen-Dat Chan **Including 12 who have passed away:** Herbert Chen, John C. Barton, John Cowan, Andre Hamer, Clifford Hargrove, Barry C. Knox, Jan Wouters, Peter Trent, Robert Storey, Keith Rowley, Hugh Evans, and Neil Tanner

Fermilab Researchers

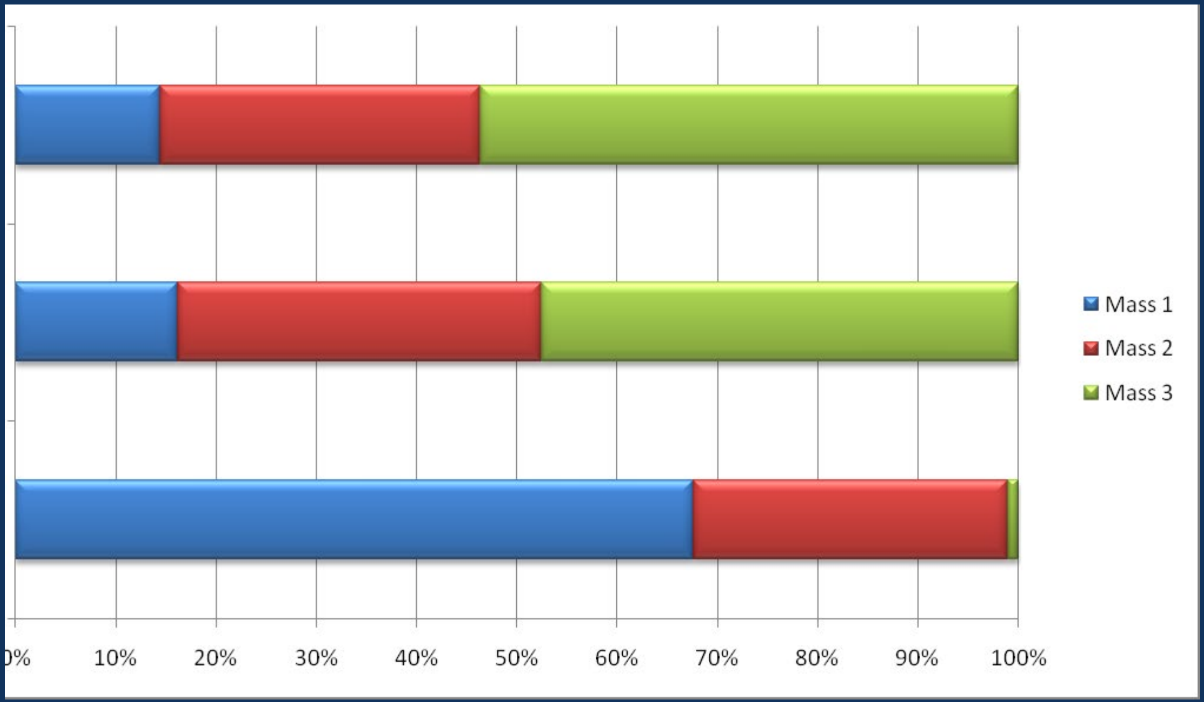
NEUTRINO OSCILLATIONS AND NEUTRINO MASS

Neutrino Flavors (Electron, Muon, Tau) can be expressed as combinations of Masses (1,2,3)

Tau Neutrino

Muon Neutrino

Electron Neutrino



Quantum mechanics states

Created in a unique Flavor State

The mass fractions change as the neutrino travels

After traveling there is a finite probability to be detected as a different flavor type

As of today: Oscillation of 3 massive active neutrinos is clearly the dominant effect:

If neutrinos have mass: $|\nu_l\rangle = \sum U_{li} |\nu_i\rangle$

Flavor (e, μ, τ) Mass 1,2.3

For 3 Active neutrinos.

Pontecorvo-Maki-Nakagawa-Sakata matrix

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

(Double β decay only)

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & e^{-i\alpha_3/2+i\delta} \end{pmatrix}$$

✓ Atmospheric, Accel. | ? CP Violating Phase | ✓ Reactor, Accel. | ✓ Solar,Reactor | ? Majorana CP Phases

where $c_{ij} = \cos\theta_{ij}$, and $s_{ij} = \sin\theta_{ij}$

✓ Range defined for Δm_{12}, Δm_{23}

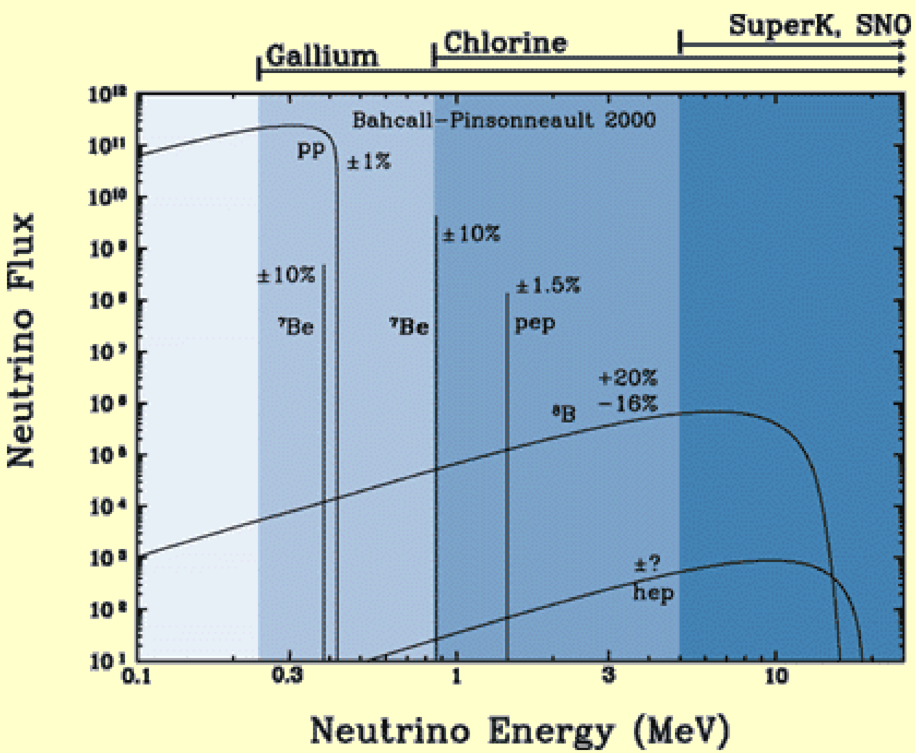
For two neutrino oscillation in a vacuum: (a valid approximation in many cases)

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 (1.27 \frac{\Delta m^2 L}{E})$$

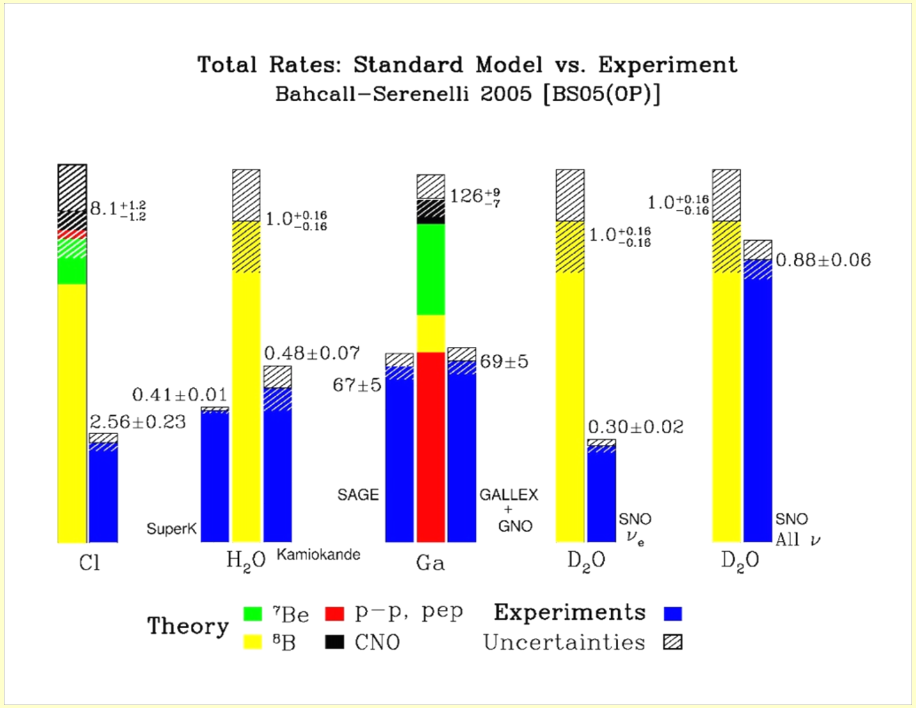
Interactions with high electron density can influence the process in the sun and the earth

Combining SNO with other solar measurements

Solar Fluxes: Bahcall et al



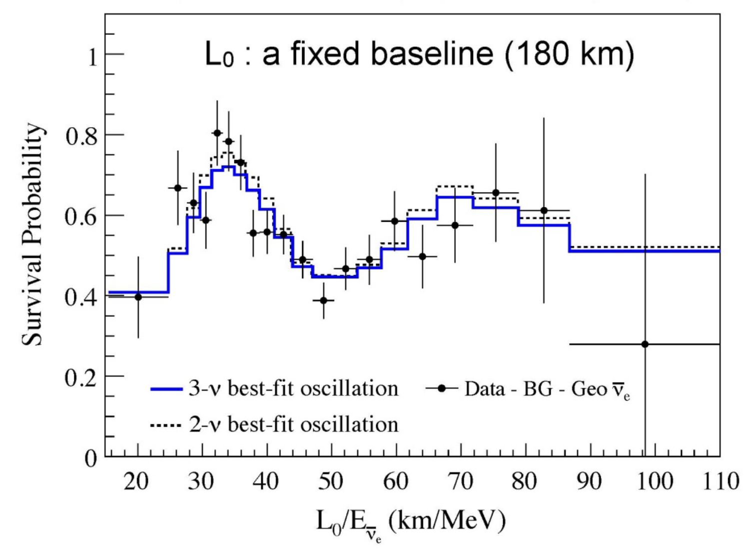
Experiment vs Solar Models



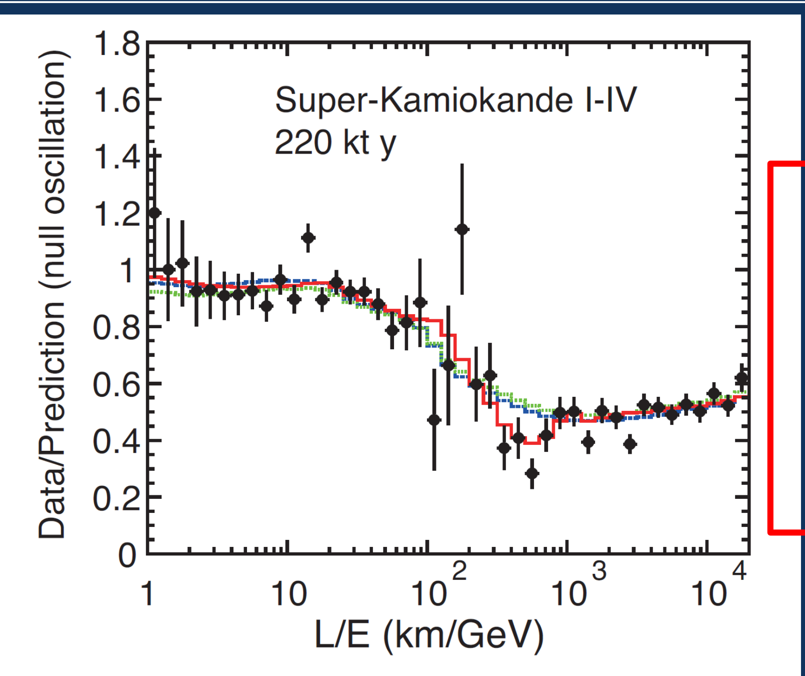
The analysis concludes that the electron neutrinos are converted to a pure Mass 2 state by interaction with the dense electrons in the sun via the Mikheyev-Smirnov-Wolfenstein (MSW) effect. This interaction determines that Mass 2 is greater than Mass 1 as well as determining Δm_{12}^2 and the mixing parameter θ_{12} .

Oscillation Patterns (Various Neutrino Sources)

KamLAND Reactor Neutrinos



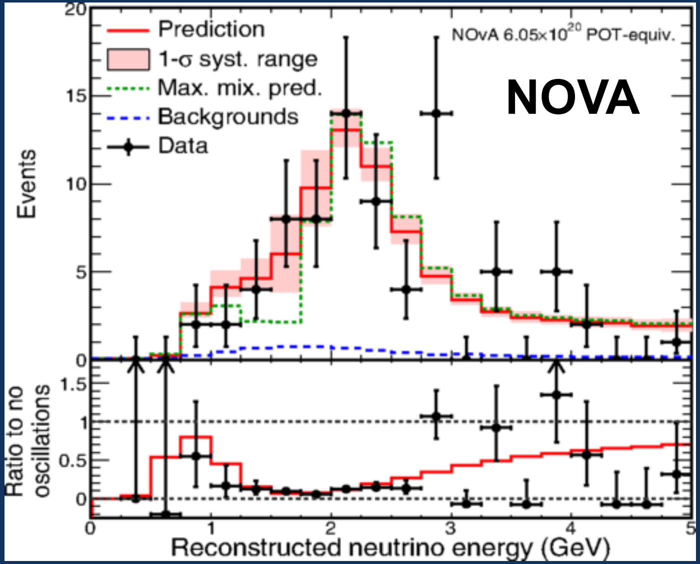
Atmospheric Neutrinos: SuperKamiokande, Oscillation reported 1998: Nobel Prize: Kajita 2015



ν_μ **oscillation**

Disfavored: Neutrino decay, Decoherence

Accelerator Neutrinos: NOVA, T2K, MINOS

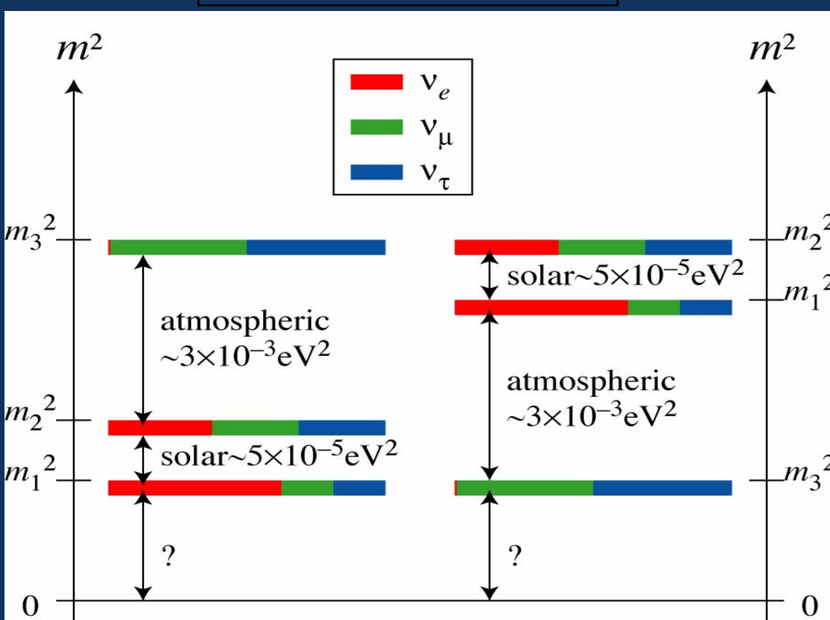


Such oscillations can only occur if neutrinos have the ability to "sense" elapsed time in their rest frame and change type as time evolves. If they can do that, Einstein's theory of relativity requires that they travel at slightly less than the speed of light and thus have a finite rest mass.

SUMMARY OF RESULTS FOR THREE ACTIVE ν TYPES

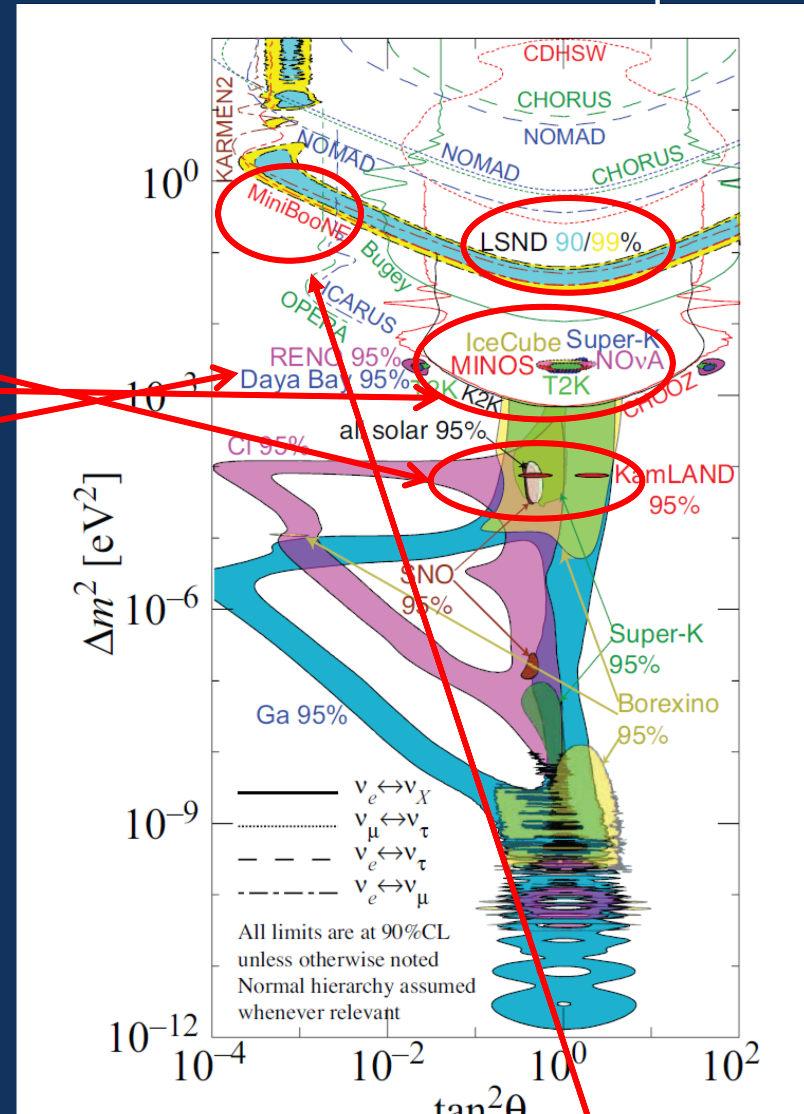
Parameter	best-fit	3σ
Δm^2_{21} [10^{-5} eV ^{2}]	7.37	6.93 – 7.97
$\lvert\Delta m^2\rvert$ [10^{-3} eV ^{2}]	2.50 (2.46)	2.37 – 2.63 (2.33 – 2.60)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	0.437	0.379 – 0.616
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	0.569	0.383 – 0.637
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	0.0214	0.0185 – 0.0246
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	0.0218	0.0186 – 0.0248
δ/π	1.35 (1.32)	(0.92 – 1.99)
		((0.83 – 1.99))

Mass Hierarchies



Normal Inverted

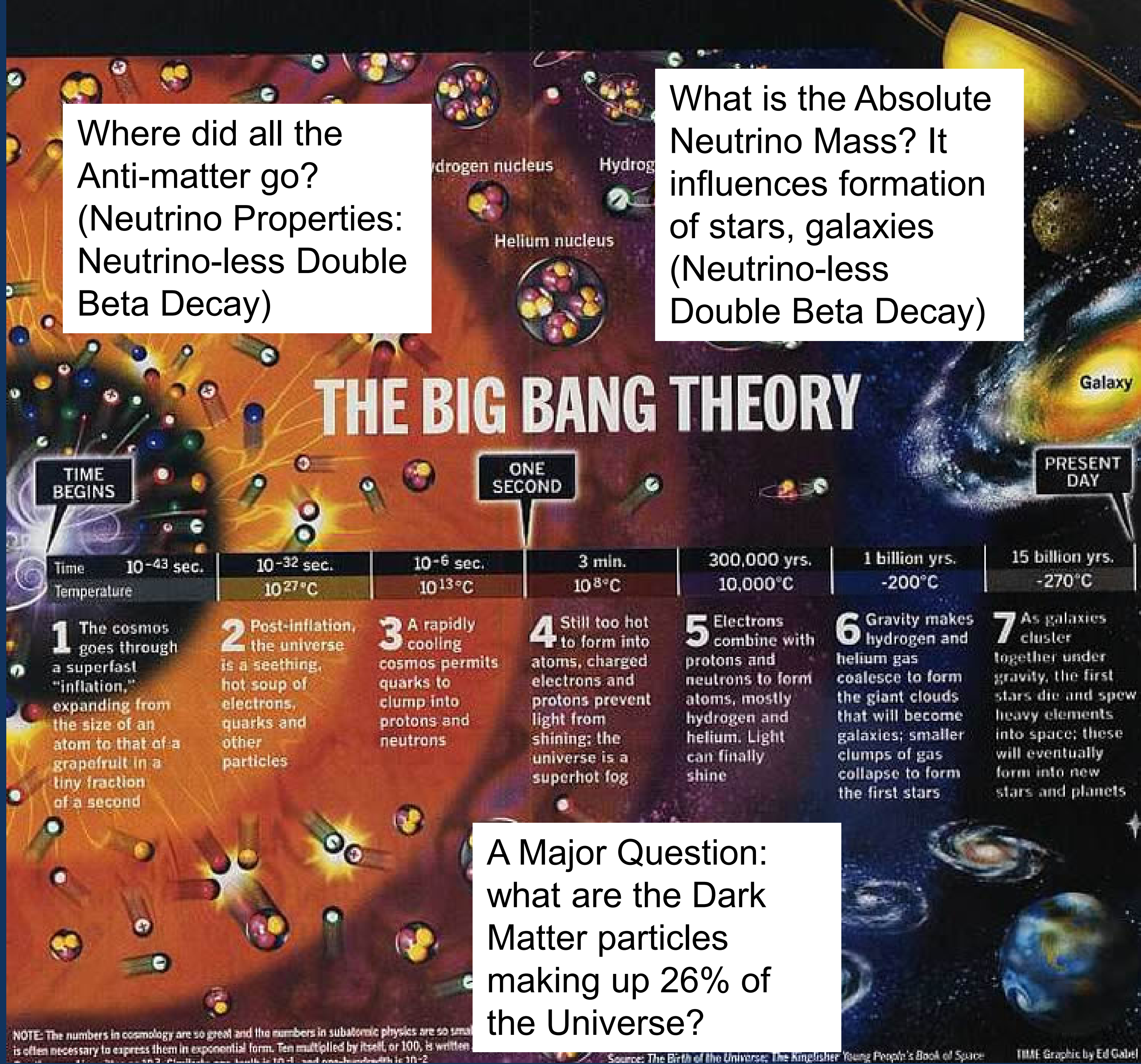
Particle Data Group



Future objectives: Majorana ν?, absolute mass, δ_{CP}, hierarchy, θ_{23} max? sterile ν?

DUNE

Impact of Future underground experiments



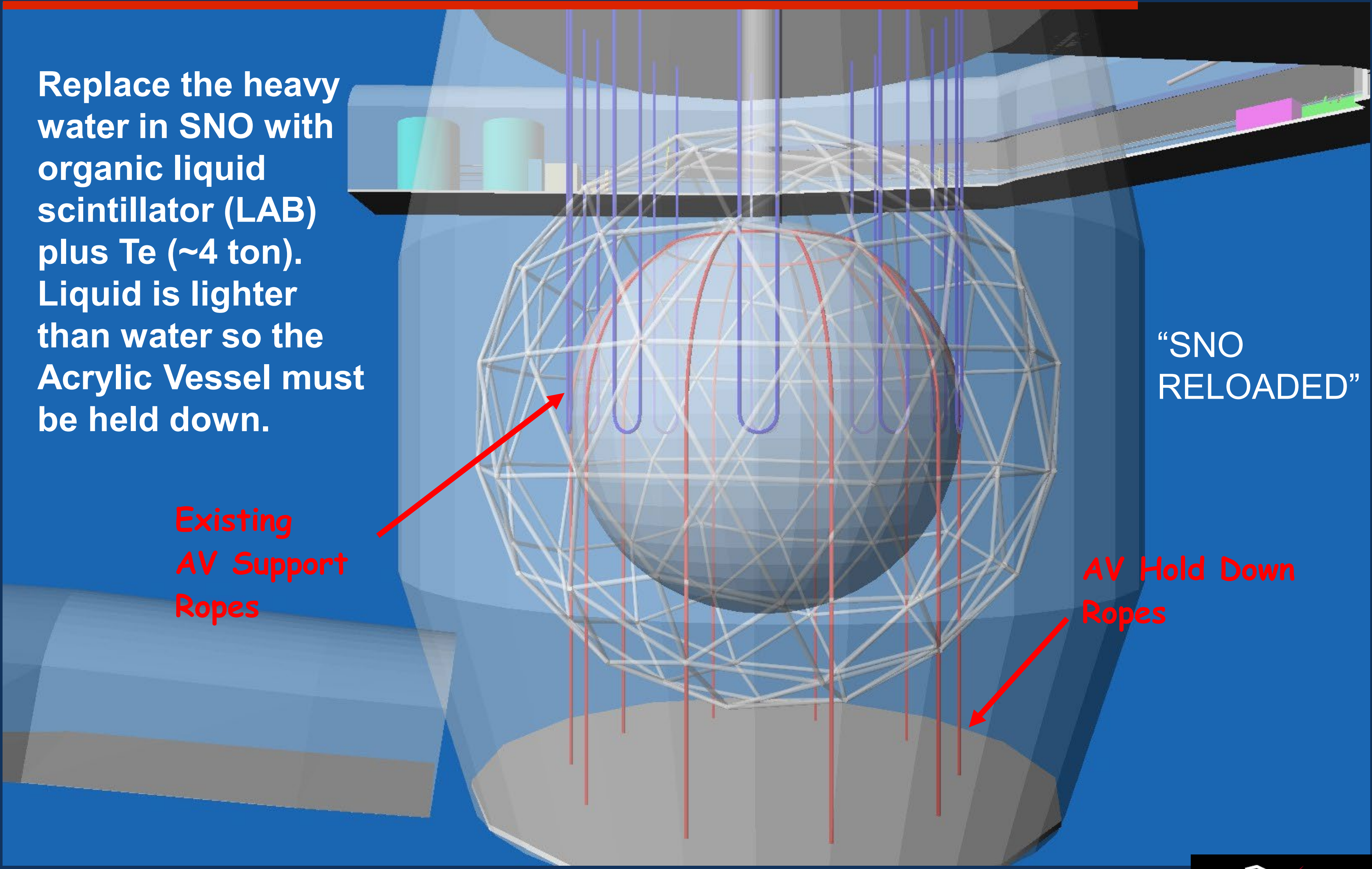
Where did all the Anti-matter go? (Neutrino Properties: Neutrino-less Double Beta Decay)

What is the Absolute Neutrino Mass? It influences formation of stars, galaxies (Neutrino-less Double Beta Decay)

A Major Question: what are the Dark Matter particles making up 26% of the Universe?

Neutrino-less Double Beta Decay: SNO+

Replace the heavy water in SNO with organic liquid scintillator (LAB) plus Te (~4 ton). Liquid is lighter than water so the Acrylic Vessel must be held down.



"SNO RELOADED"

1 year of data with pure water. Filling with LAB. Te (Diol) to be installed in 2020.

SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE

The SNO+ collaboration

U. Pennsylvania
U. Washington
Black Hills S.U.
U. Armstrong Atlantic
U. Chicago
U. North Carolina
U. C. Berkeley / LBNL
U. C. Davis
BNL

- U. Alberta
- Queen's University
- Laurentian University
- TRIUMF
- SNOLAB

LIP Lisboa

Universidad Nacional Autonoma de Mexico

Technical University Dresden

- Oxford University
- University of Sussex
- Liverpool University
- Lancaster University
- Queen Mary University of London

120 members of 23 institutions over 6 countries

ν-less Double Beta Decay: Measuring Effective ν Mass

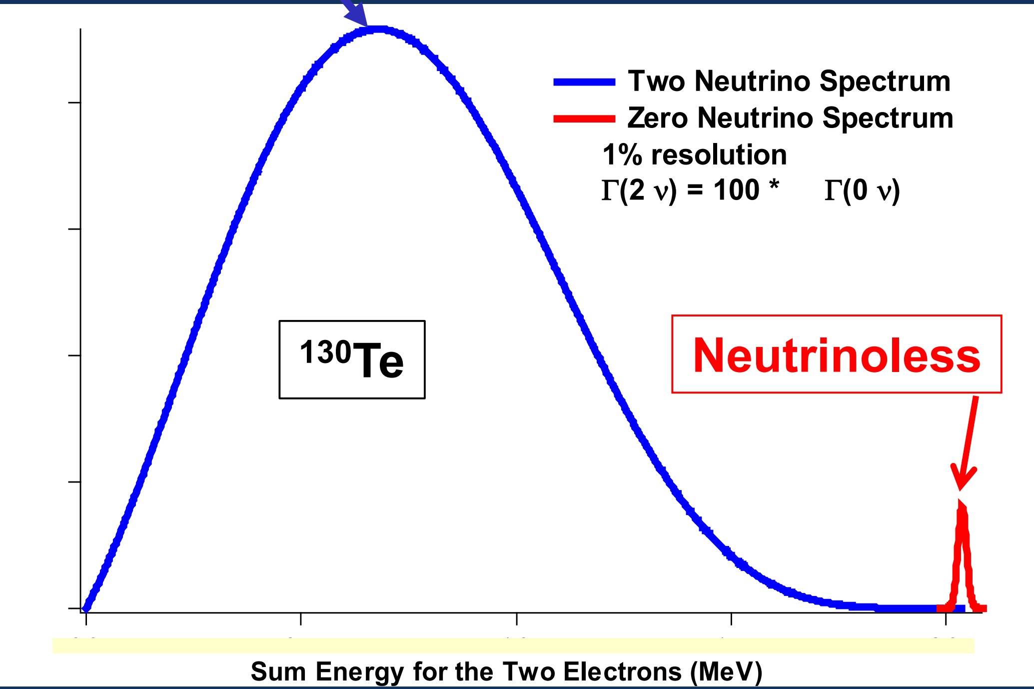
$$(T_{1/2})^{-1} = F(Q_{\beta\beta},Z)\,|M^{0\nu}|^2\,\langle m_{\nu\beta\beta}\rangle^2$$

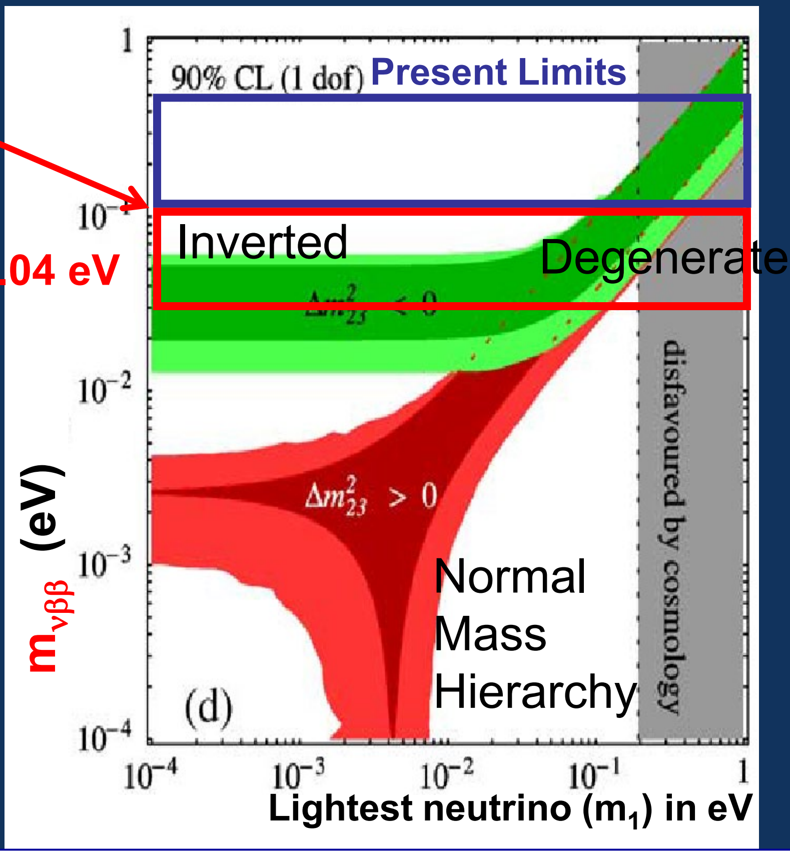
Additional phases

$$m_{\nu\beta\beta} = |m_1 \cos^2\theta_{13}\cos^2\theta_{12} + m_2\, e^{2i\alpha}\cos^2\theta_{13}\sin^2\theta_{12} + m_3\, e^{2i\beta}\sin^2\theta_{13}|$$

2 ν Emission

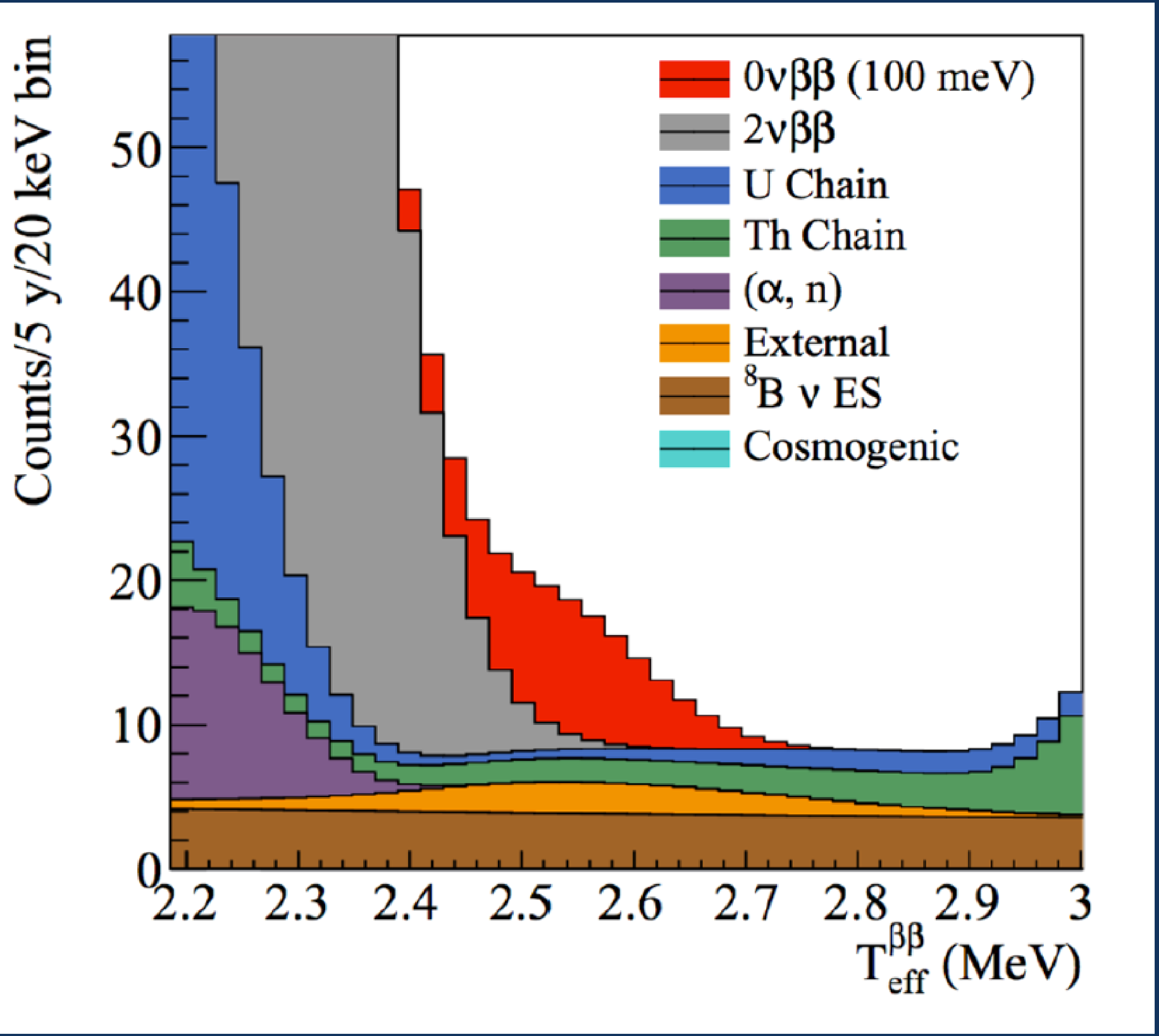
SNO+





Requires: Neutrinos to be their own antiparticle (Majorana particles)

- **Finite ν mass: Lifetimes > ~10^{26} years imply ν mass < 0.1 eV**



SNO+

5 years at 0.5% Te Loading: 1300 kg ^{130}Te

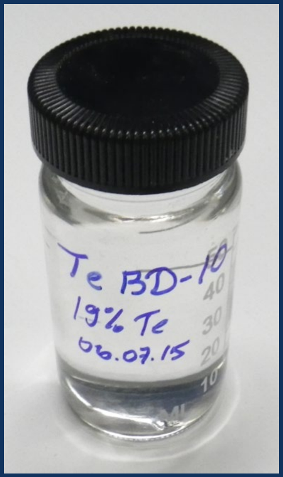
$T_{1/2} > 2 \times 10^{26}$ yr (90% CL)

$m_{\beta\beta} <$ 36-90 meV

Phase II ??

5.0% ^{130}Te

HQE PMT's



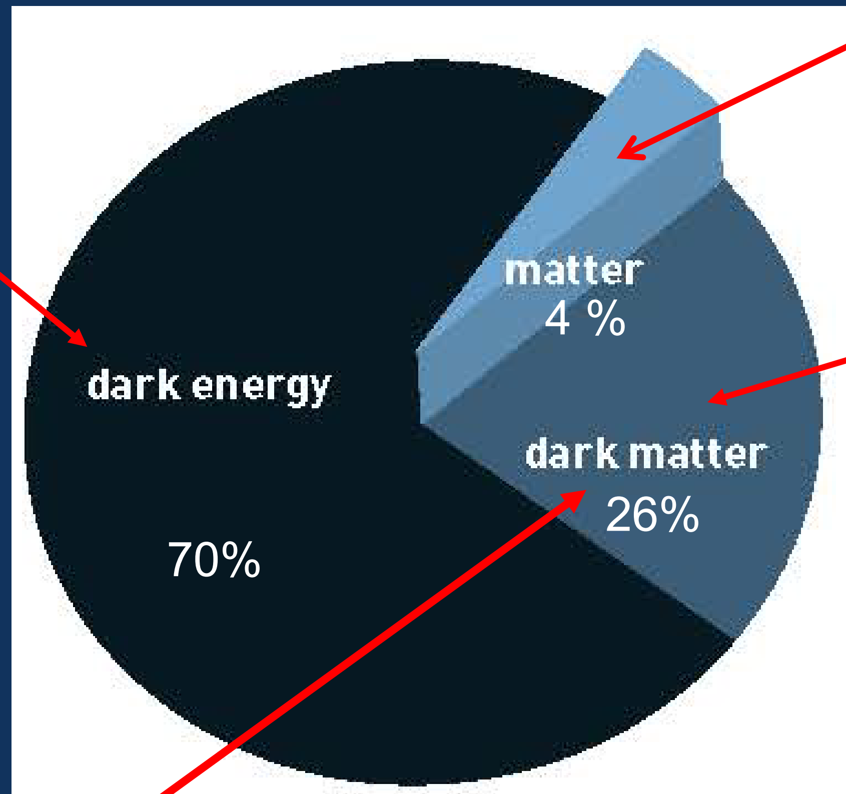
1 year of operation with pure water, looking for nucleon decay in oxygen. Now filling with liquid scintillator. Te projected for 2020.

Composition of the Universe as we understand it today

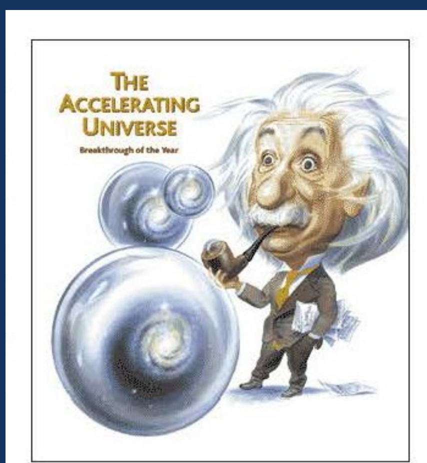
(Very different than 20 years ago thanks to very sensitive astronomical and astrophysical experiments such as measurements of the cosmic microwave background, large scale structure and distant supernovae.)

US!!!

Responsible for accelerating the Universe's expansion



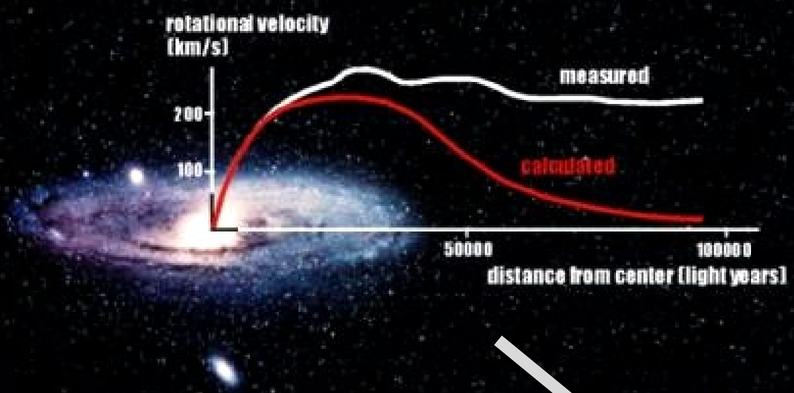
Neutrinos Are only a few %



With underground labs we look for Dark Matter particles left from the Big Bang, with ultra-low radioactive background.

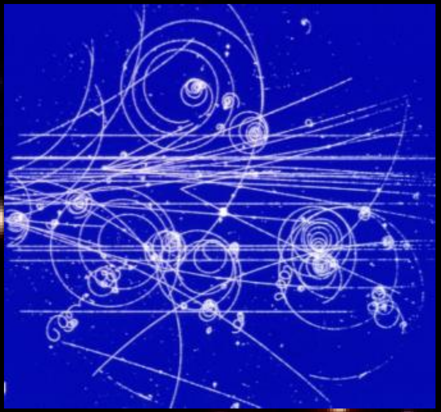
At CERN Accelerator: Try to create it for the first time since the Big Bang

Dark Matter



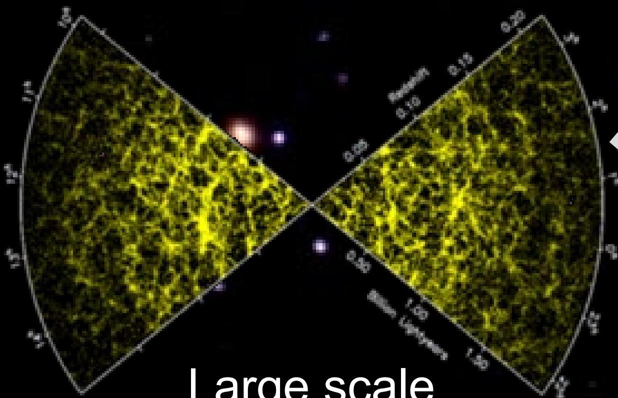
Here, but not yet observed directly in nature: **Weakly interacting**

Not observed in accelerator experiments:



WIMP

(Weakly Interacting Massive Particle)

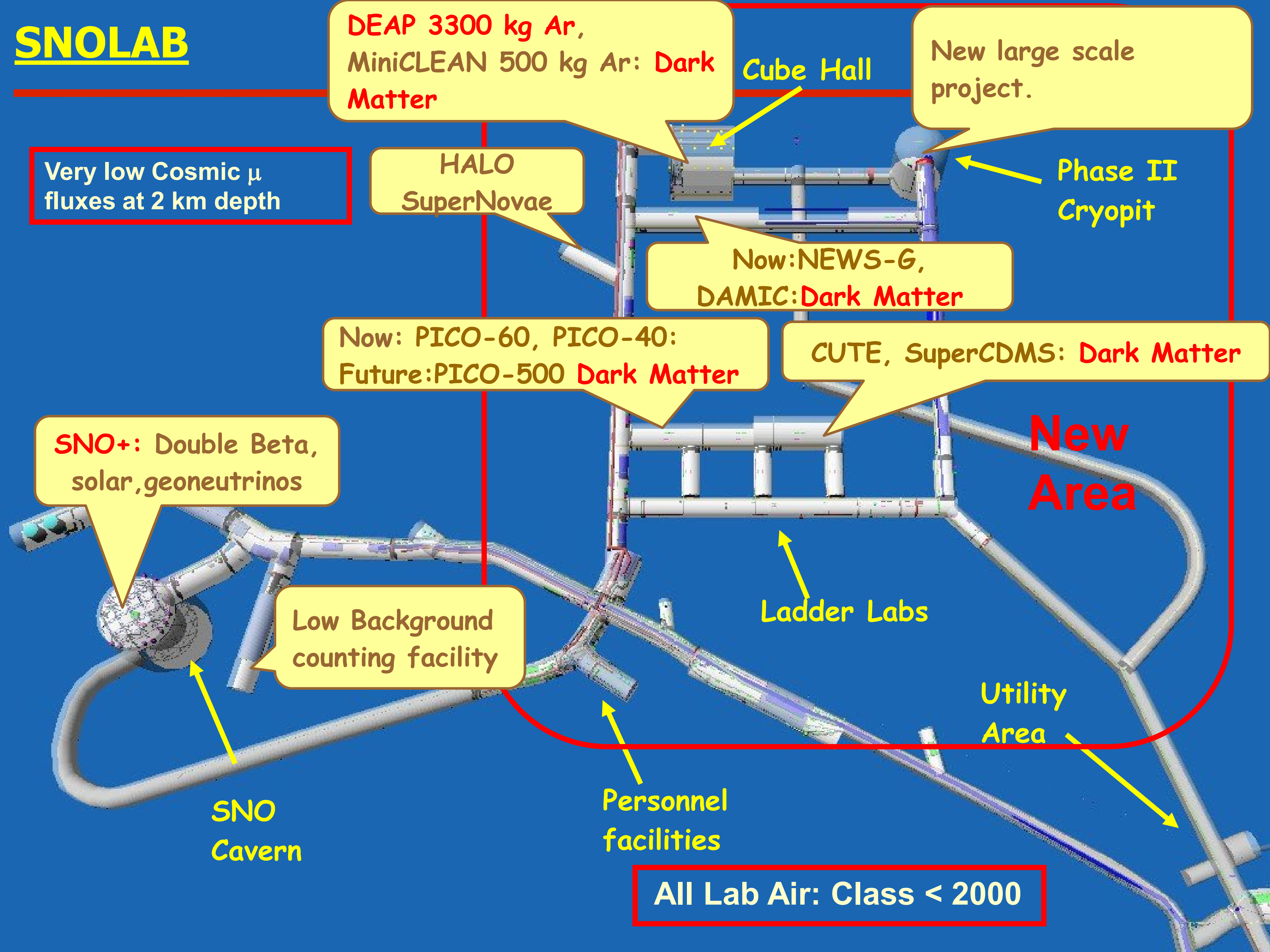


Large scale structure of the Universe: **Slowly moving ('cold')**

Interaction with ordinary matter: **Nuclear Recoils** (most backgrounds: electron recoils)

Predicted by SUSY: **Neutralino**
Universal extra dimensions: **Kaluza-Klein particles**

SNOLAB



DEAP 3300 kg Ar, MiniCLEAN 500 kg Ar: Dark Matter
Cube Hall
New large scale project.
Very low Cosmic μ fluxes at 2 km depth
HALO SuperNovae
Phase II Cryopit
Now:NEWS-G, DAMIC:Dark Matter
Now: PICO-60, PICO-40: Future:PICO-500 Dark Matter
CUTE, SuperCDMS: Dark Matter
SNO+: Double Beta, solar,geoneutrinos
New Area
Low Background counting facility
Ladder Labs
Utility Area
SNO Cavern
Personnel facilities
All Lab Air: Class < 2000

SNOLAB Experimental Area

Stephen Hawking and fans observing the CRYOPIT area in September 2012

DEAP-3600 Collaboration

DEAP Collaboration: 75 researchers in Canada, UK, Mexico and Germany

UNIVERSITY OF ALBERTA

Carleton UNIVERSITY

LaurentianUniversity UniversitéLaurentienne

TUM TECHNISCHE UNIVERSITÄT MÜNCHEN

Queen's UNIVERSITY

ROYAL HOLLOWAY UNIVERSITY OF LONDON

Particle Physics Rutherford Appleton Laboratory

SNOLAB MINING FOR KNOWLEDGE CREUSER POUR TROUVER... L'EXCELLENCE

US University of Sussex

Canadian Nuclear Laboratories Laboratoires Nucléaires Canadiens

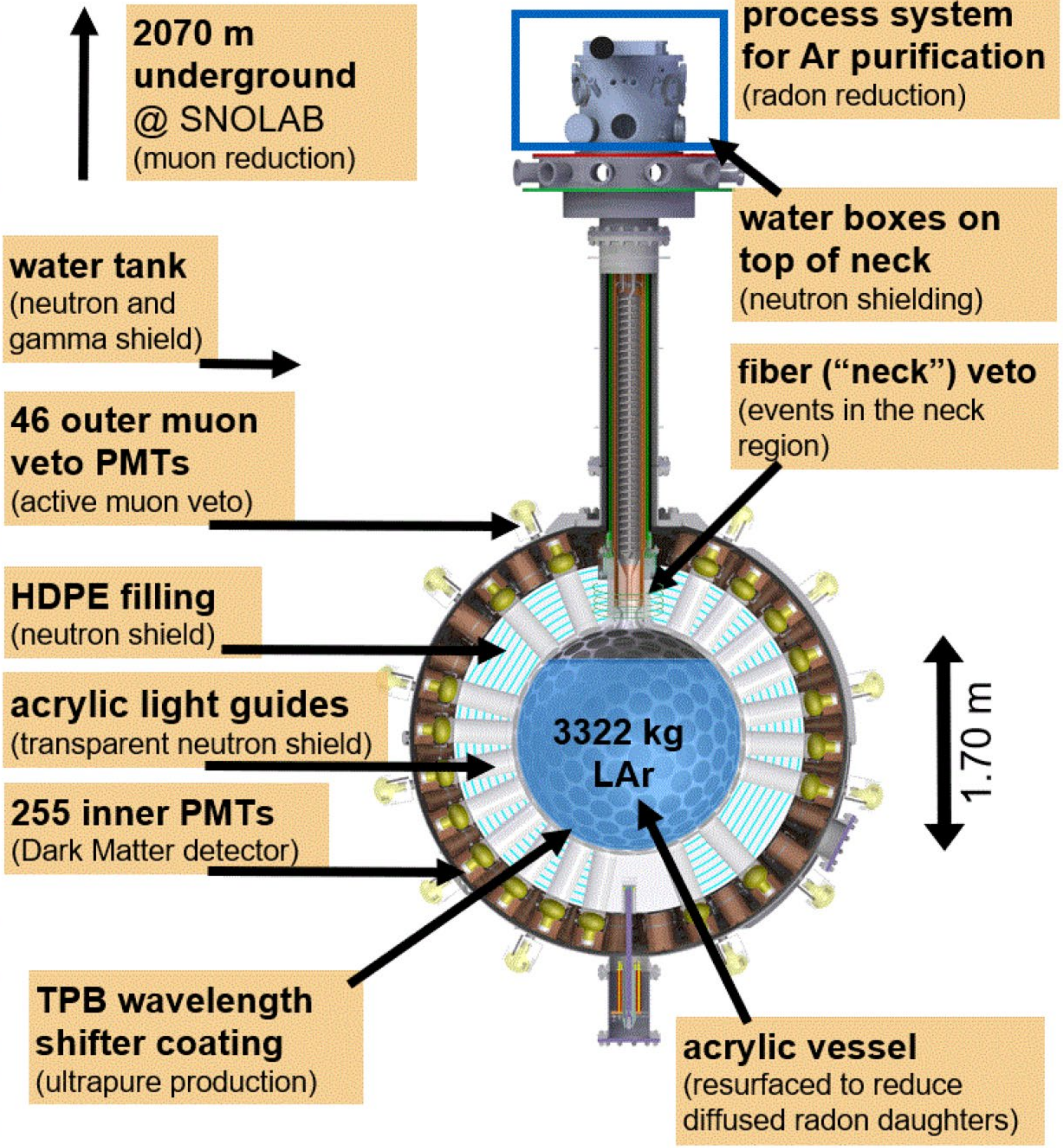
TRIUMF

iF Instituto de Fisica

Science & Technology Facilities Council

+ recent new DarkSide collaborators from 6 institutions

DEAP-3600



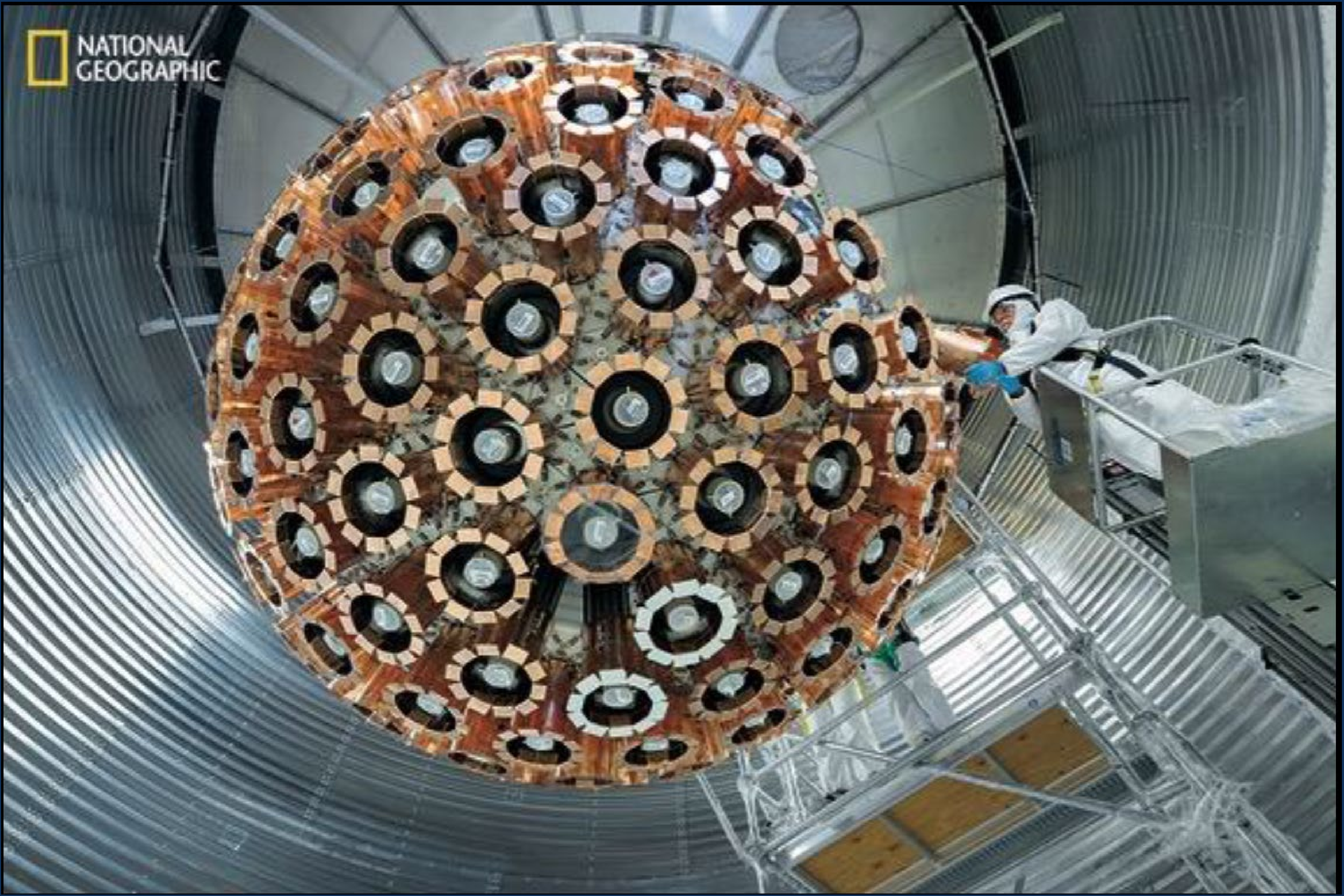
- **Single phase** liquid argon (**LAr**) target (new concept)
- Detection of **scintillation** light

- Goal: **< 1 background event** in 3000 kg x yr fiducial exposure

- Sensitivity for spin-independent WIMP-nucleon cross-selection: **10^{-46} cm^2** **(@100 GeV)**

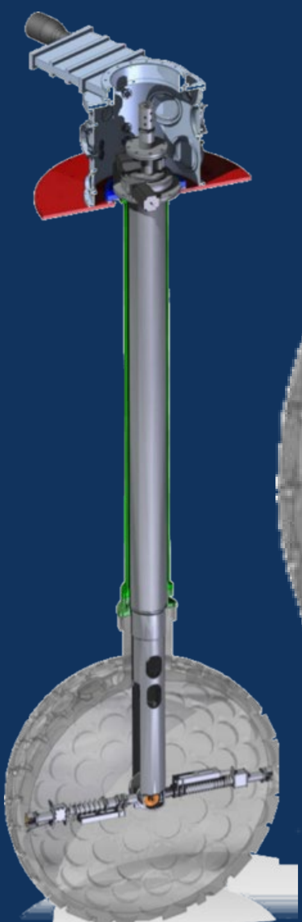
Hardware design concepts for background mitigation:

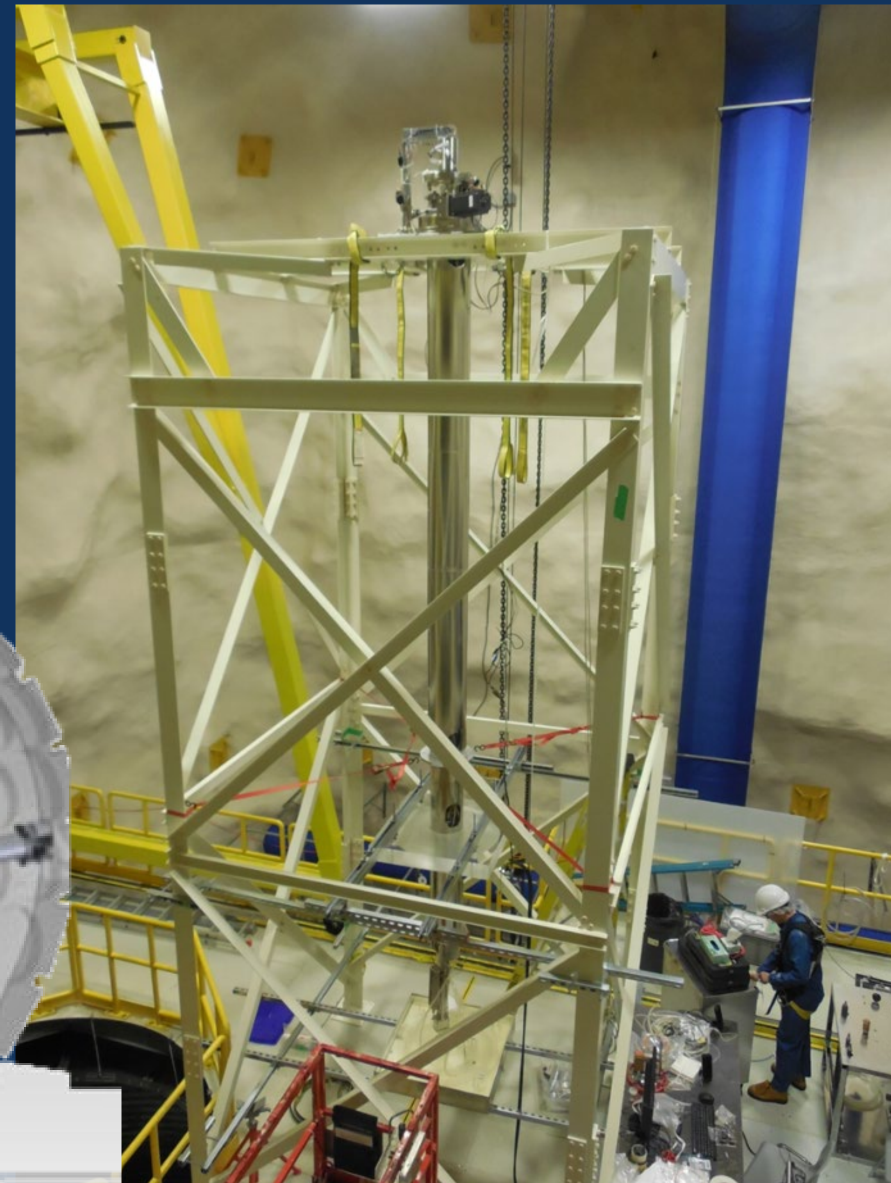
- Deep underground
- Active muon veto
- Onion-layer passive shielding
- Resurfacing of acrylic vessel to remove diffused radon
- Neutrons from PMTs shielded by long transparent acrylic light guides


NATIONAL
GEOGRAPHIC

Acrylic Vessel Resurfacer

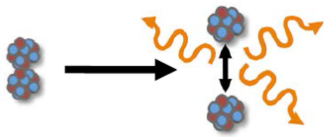
- Mechanical sander to clean inner surface
- Components selected for low radon emanation
- Remove 0.5-mm surface *in situ* with N_2 purge
- Cleans surface to bulk-level impurities
  (order 100,000 cleaner than SNO vessel)



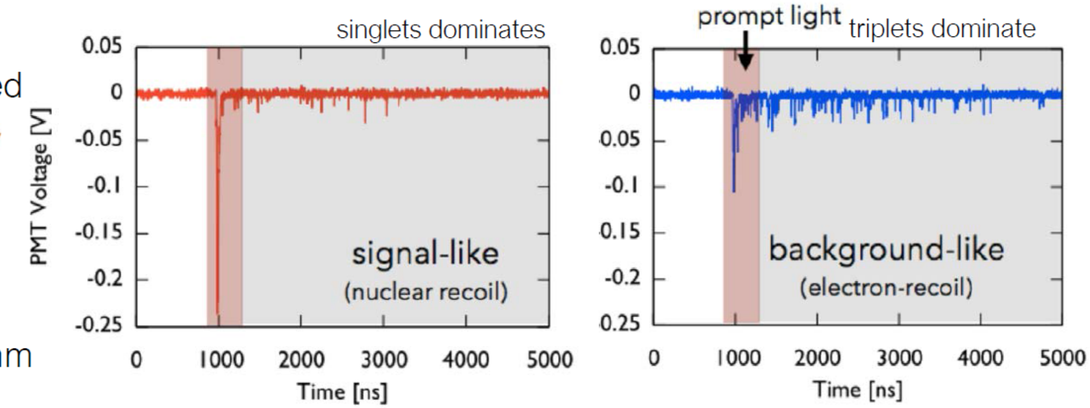


Experimental Signature: Pulse Shape Discrimination

Ar scintillation:
- excimers are created



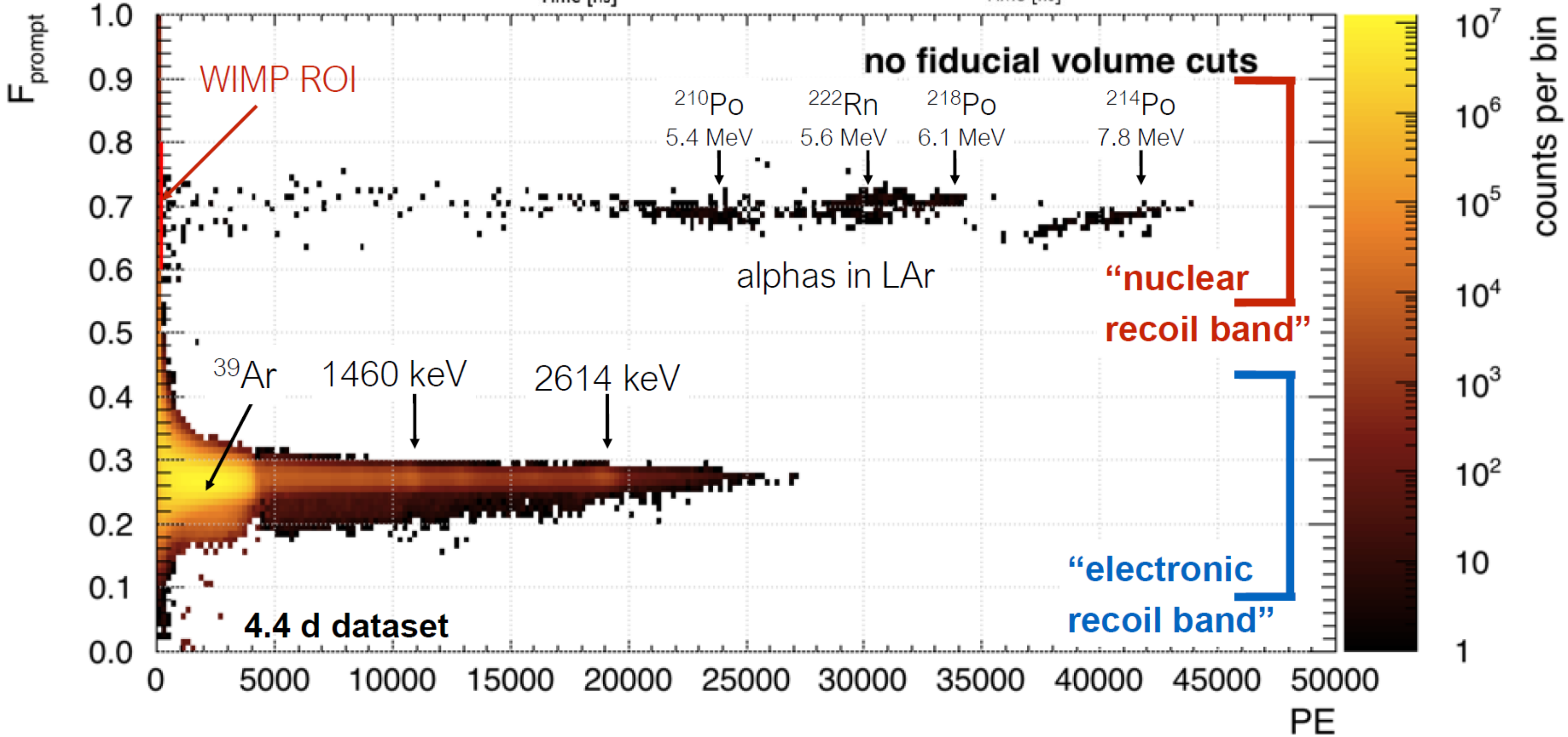
- singlet: 6 ns
- triplet: 1300 ns
- wavelength: 128 nm



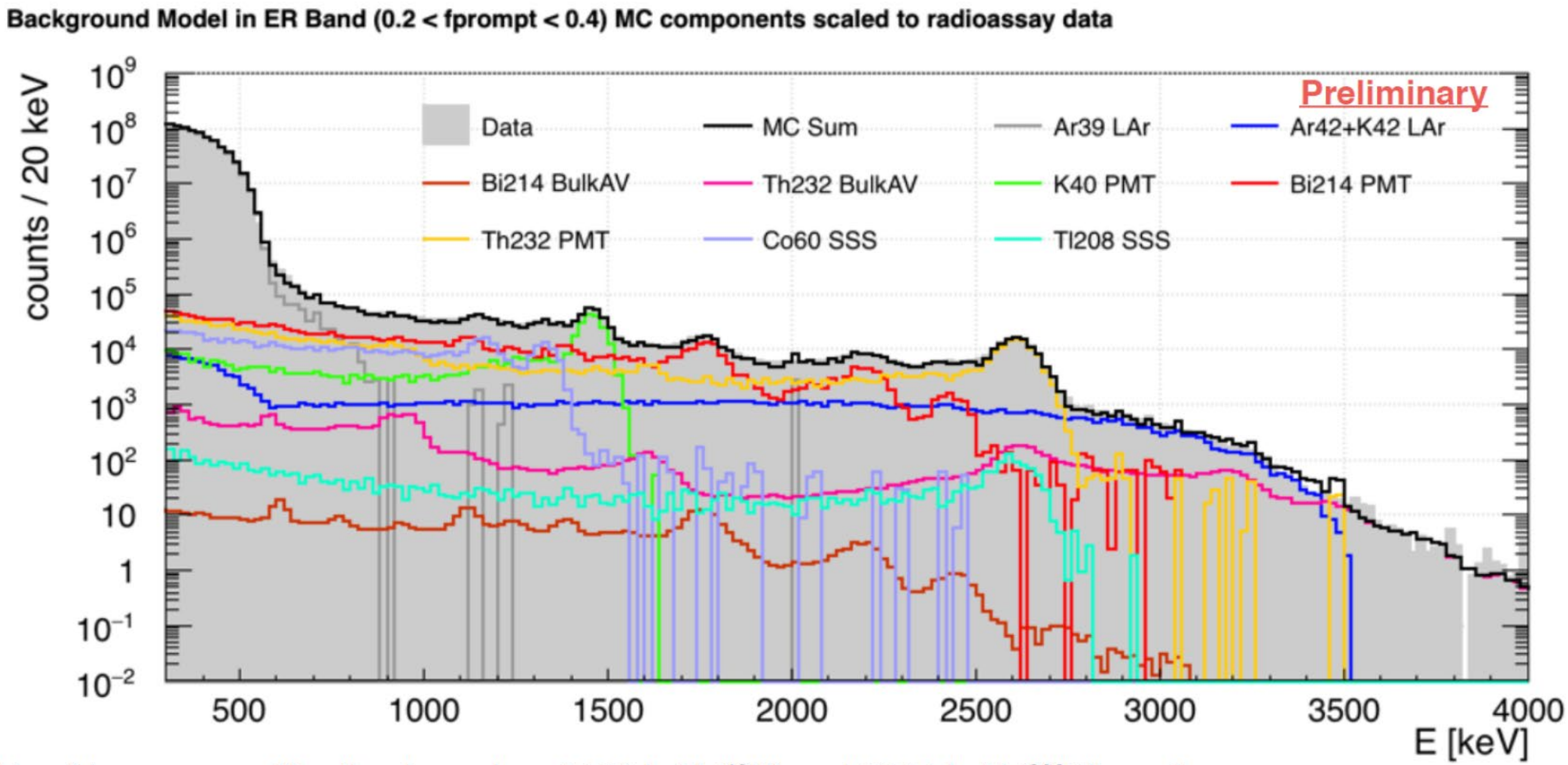
Pulse shape discrimination (PSD) parameter:

$$F_{prompt} = \frac{\textbf{prompt light (150 ns)}}{\textbf{total light (10000 ns)}}$$

factor 10^{10} separation



Gamma and Beta Background Model



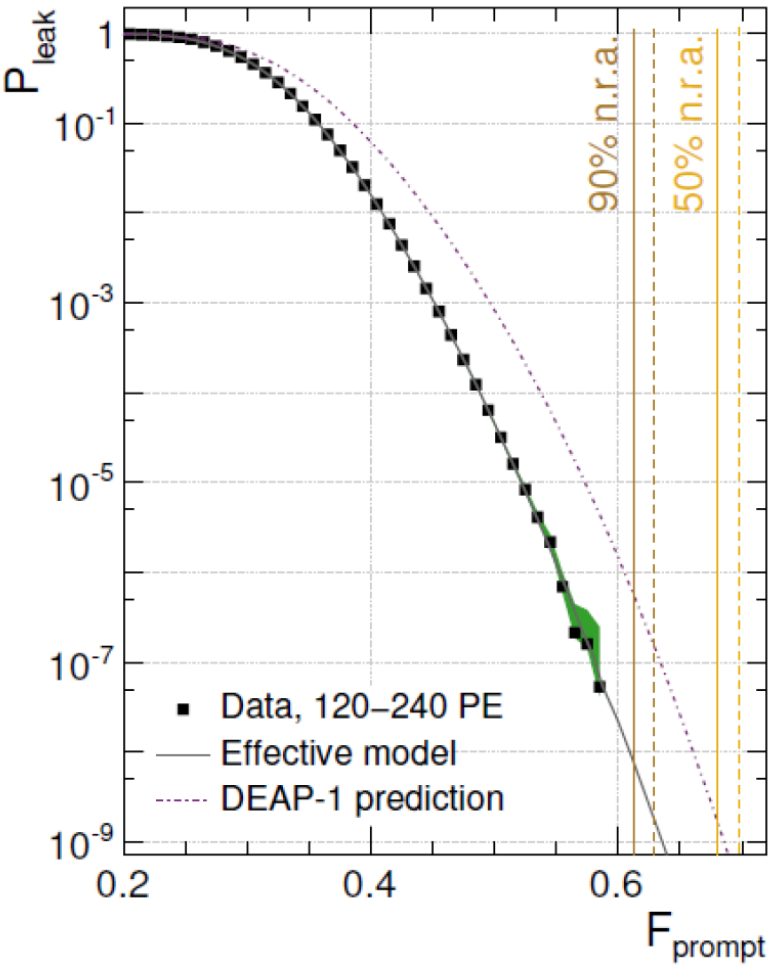
- Empiric energy calibration based on 1460 keV (^{40}K) and 2614 keV (^{208}Tl) peak
- Scaling of MC simulations to known screening / literature values (this is not a fit)
- Low energy region (< 0.5 MeV) dominated by ^{39}Ar
- Mid energy region (0.5 - 2.6 MeV) dominated by gammas from outside components (mainly PMT glass)
- High energy region (> 2.6 MeV) dominated by ^{42}K and by close ^{208}Tl sources

- **Gamma line measurements can be used to constrain (α,n) neutron production within a factor of 2**

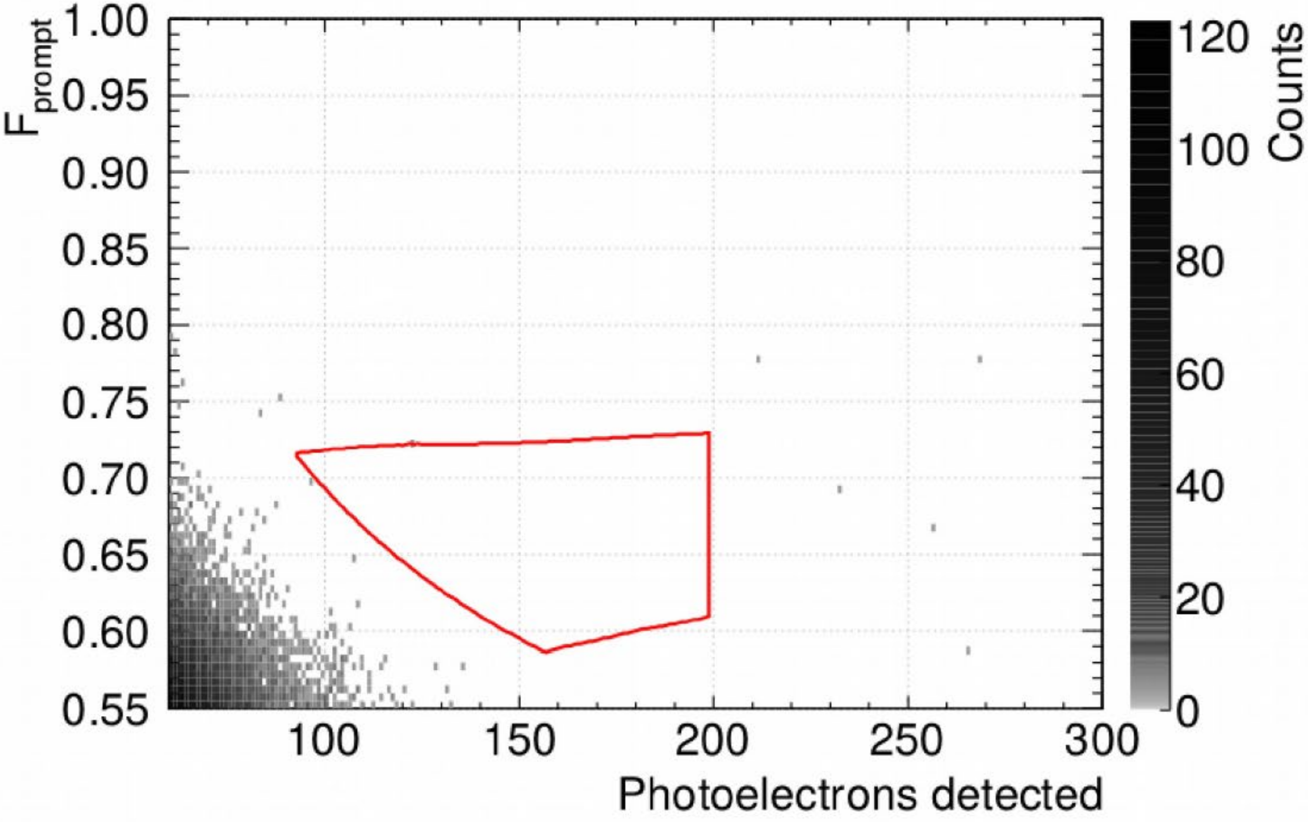
Pulse-Shape Discrimination in DEAP-3600

Fraction of the data leaking above a given value of F_{prompt}.

Vertical lines show 90% and 50 % acceptance for nuclear recoils



After all cuts, no WIMP-like signals

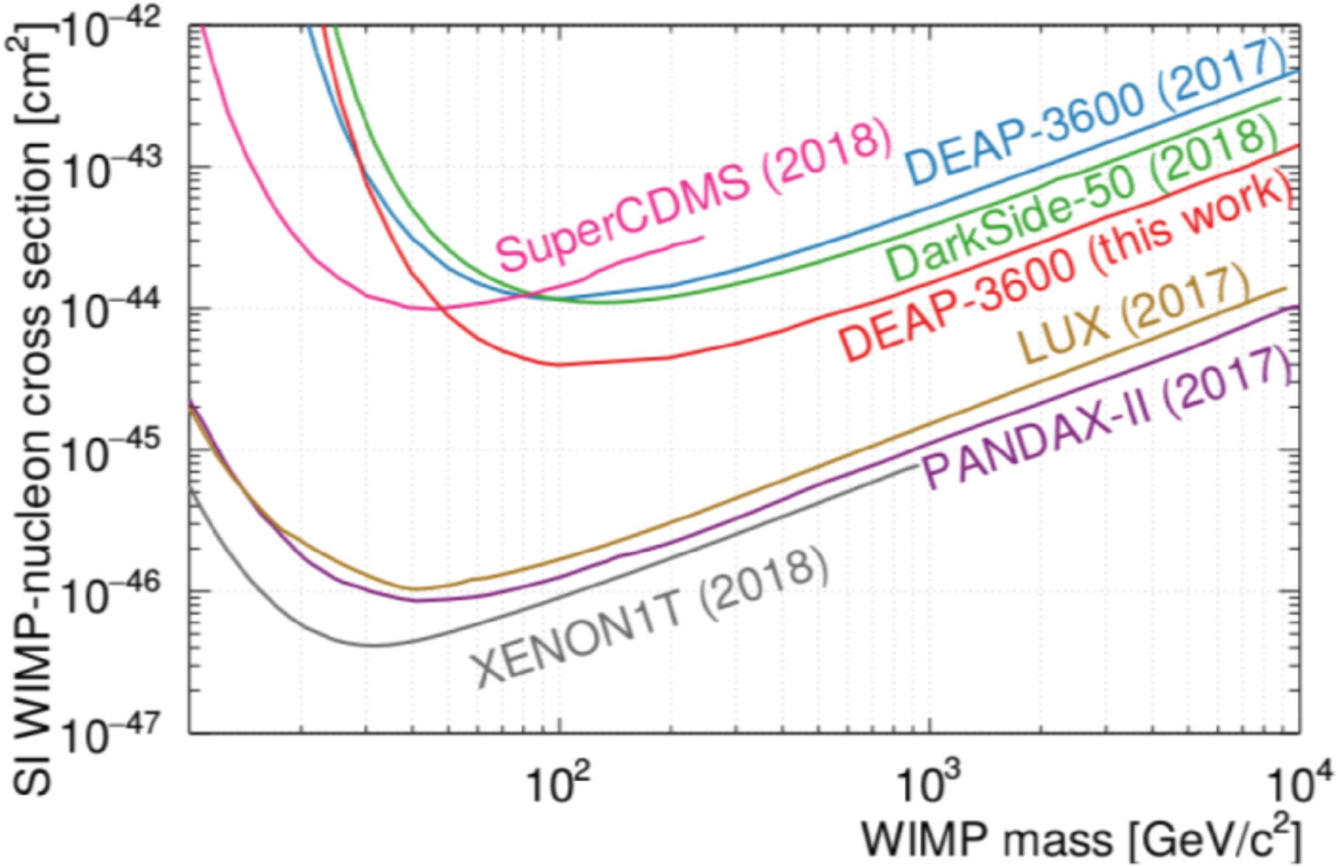


231 live days after run selection and deadtime corrections

824 kg fiducial mass

0 events in ROI

Most sensitive WIMP search to date with LAr target



231 live days after run selection and deadtime corrections

824 kg fiducial mass

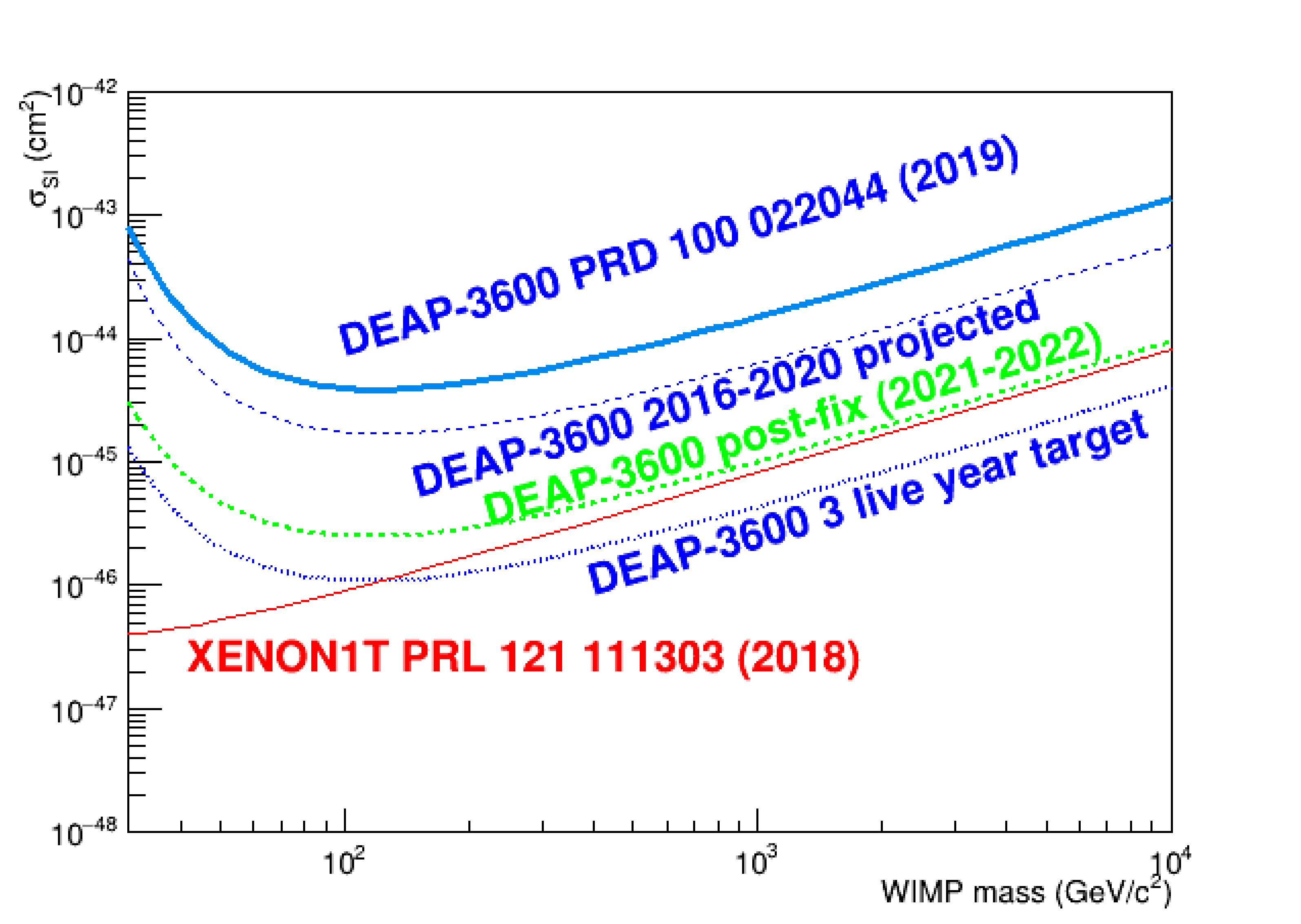
0 events in ROI

Exclude S.I. WIMP-nucleon cross sections above 3.9×10^{-45} cm^2 for 100 GeV/c^2 WIMP mass

arXiv:1902.0408

Run plan: continue counting until June 2020, upgrade the neck region and restore recirculation. Maximum Likelihood and Machine Learning analysis techniques are being developed that are improving the efficiency for WIMP detection with zero background.

DEAP Sensitivity after Planned Upgrade



Global Argon Dark Matter Collaboration

Towards global argon collaboration:
DarkSide, DEAP, miniCLEAN, ArDM > 350 researchers

- 68 institutes
- 416 researchers
- Strong assistance from CERN
- 14 nations:

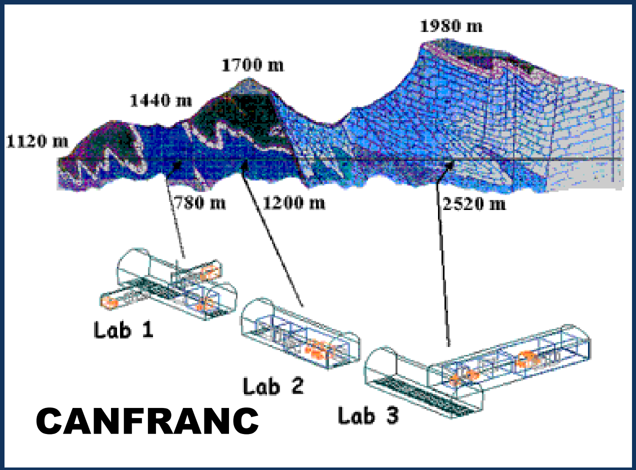
Brazil, Canada, China, France, Greece, Italy, Mexico, Poland, Romania, Russia, Spain, Switzerland, UK, USA

Sequence of experiments:

- SNOLAB: DEAP: 3 tonnes
- GranSasso: DarkSide 20K: 50 tonnes
- SNOLAB: Argo: 400 tonnes to reach the “Neutrino Floor”

Letter of support from Gran Sasso, SNOLAB, CanFranc Laboratory Directors

Support from International Underground Laboratories



Darkside – 50 (50 kg)
Darkside – 20k (50 tonnes: 20 tonne fiducial)

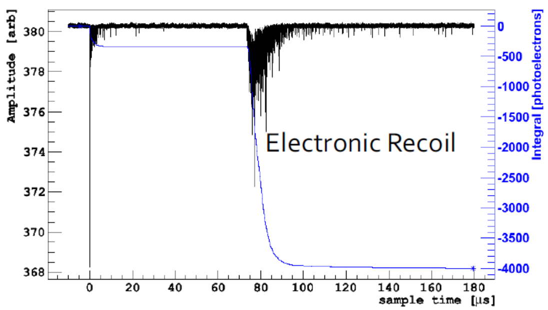
DART:
Use ARDM to measure depletion factor for ^{39}Ar

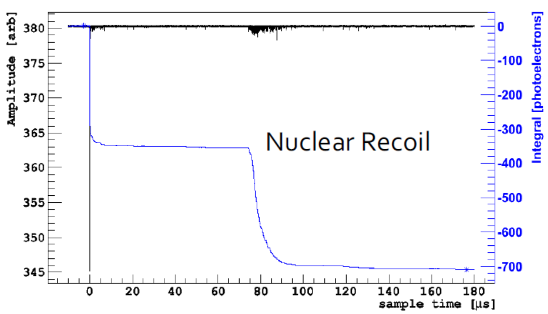
DEAP (3.3 tonne) (~1 tonne fiducial)

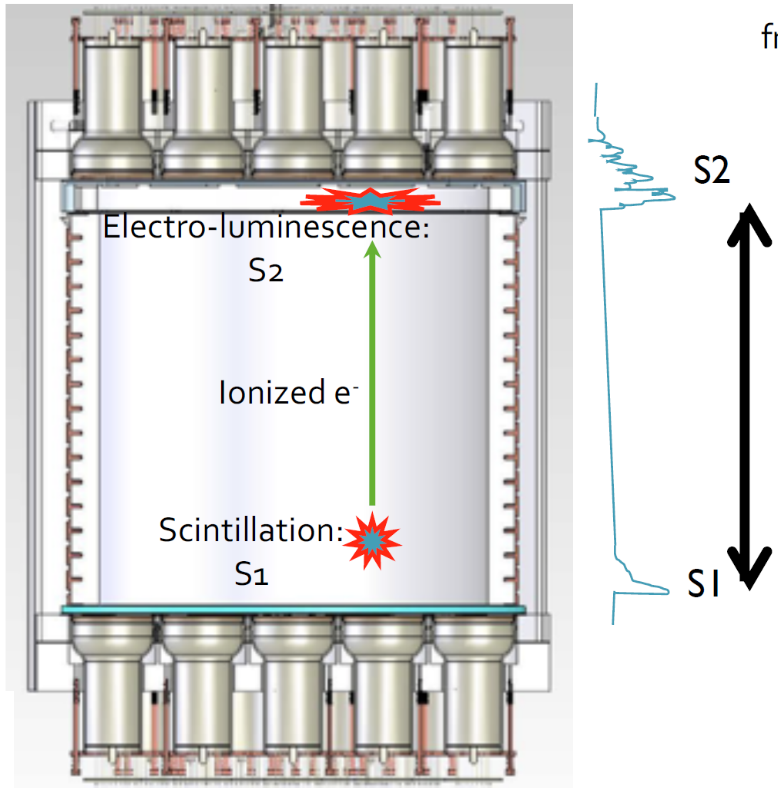
Argo: Future ~400 tonne

Darkside-50 and Future Darkside 20k

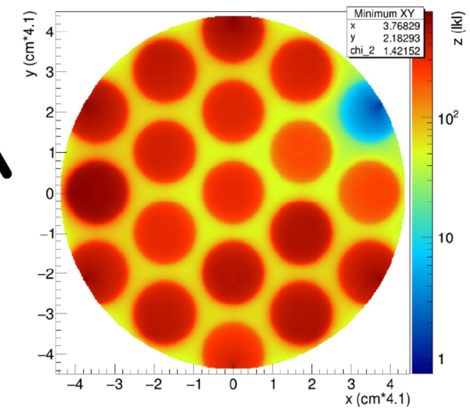
Two-Phase LAr Dark Matter Detectors





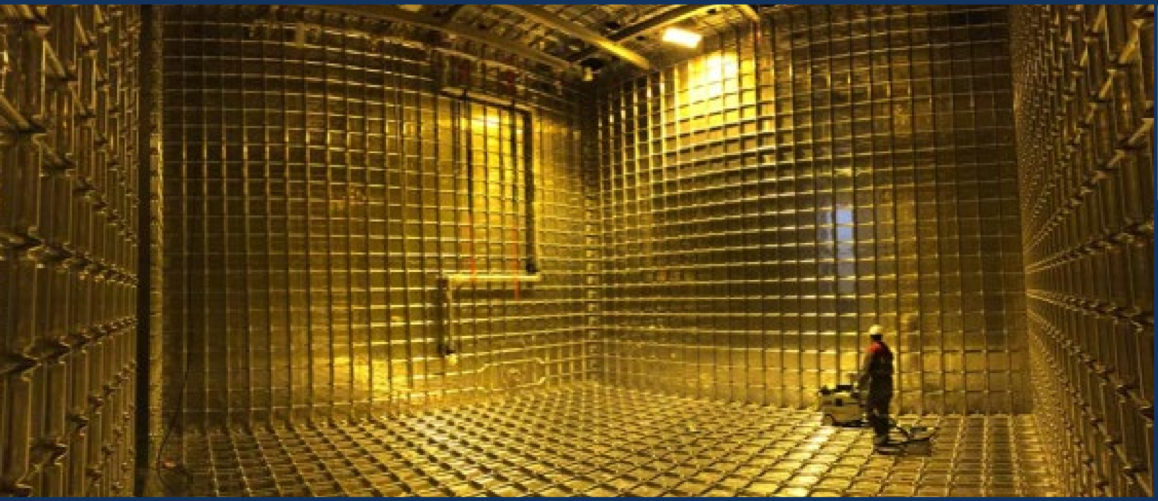


DS-50 Top Array PMT light fractions for S2 gives x,y location



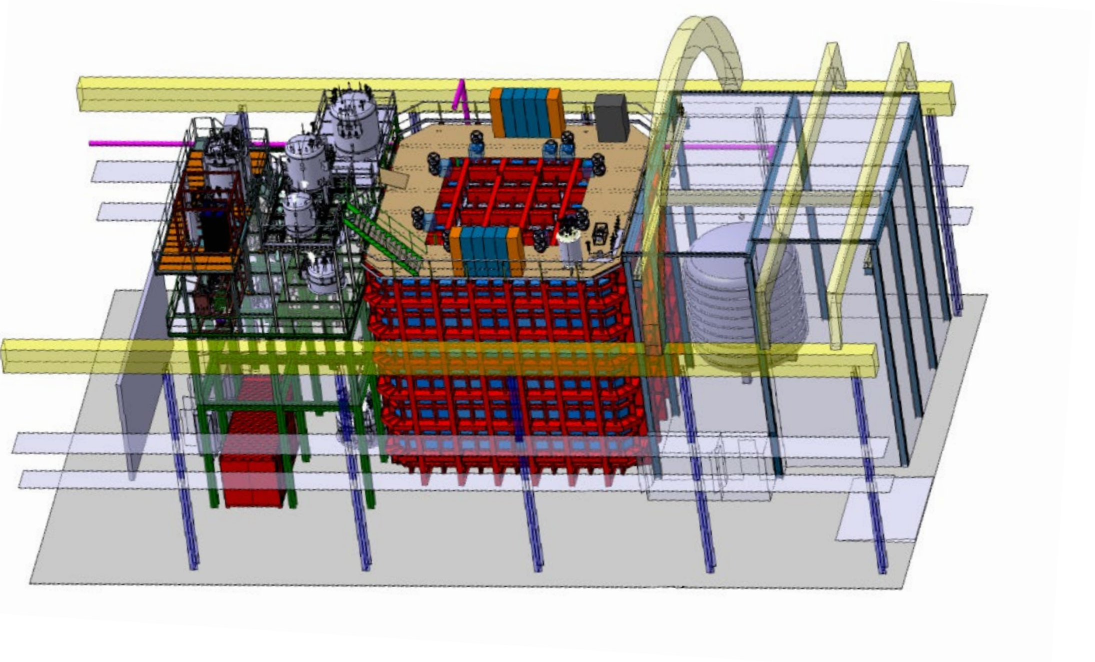
The drift time gives the z-position with mm precision

Proto Dune detector at CERN

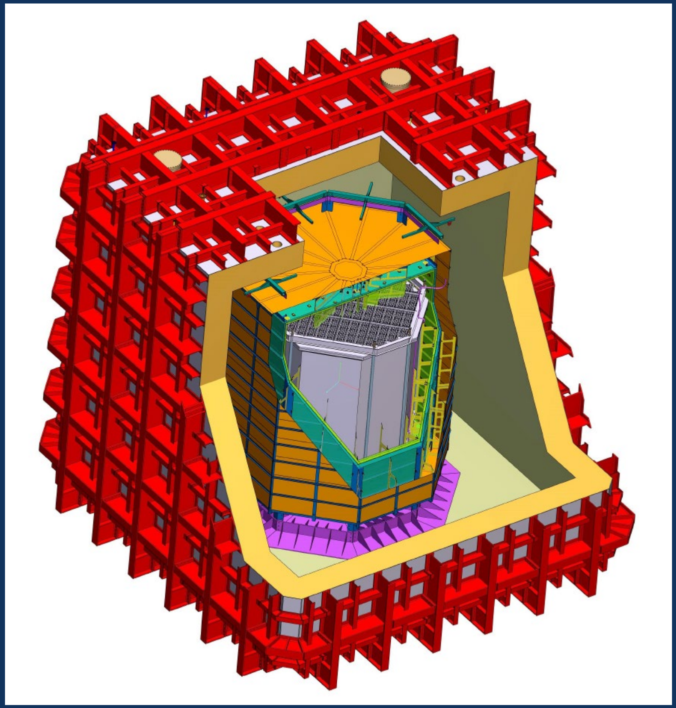


DarkSide-20k builds on the technology from the Proto-DUNE detector at CERN

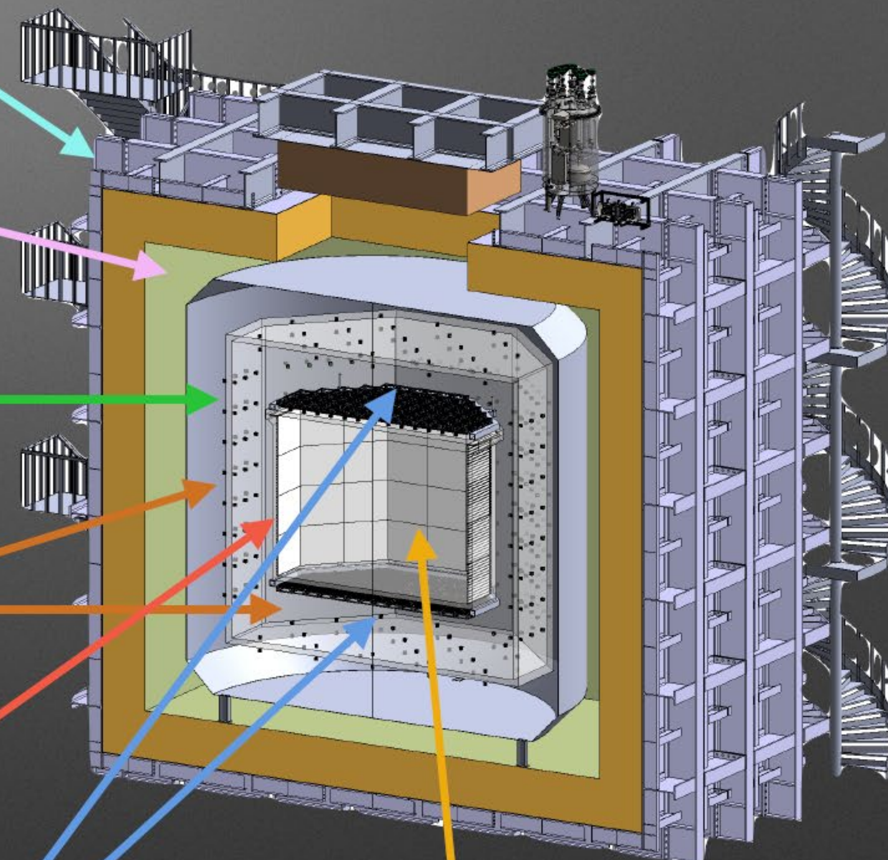
DarkSide-20k Full Layout at Gran Sasso



DarkSide-20k detector at Gran Sasso

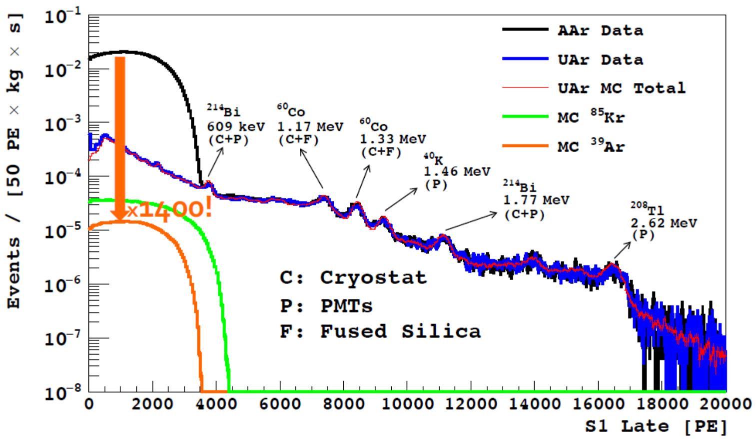


DarkSide-20k new design

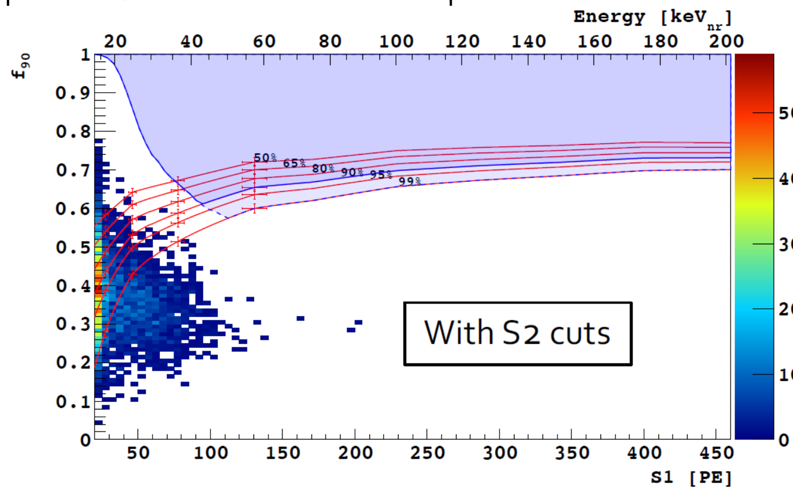


Underground Argon (UAr)

- $^{40}Ar(n,2n)^{39}Ar$ occurs in the atmosphere → 1 Bq/kg
- Argon that has remained underground can therefore have extremely low levels of ^{39}Ar



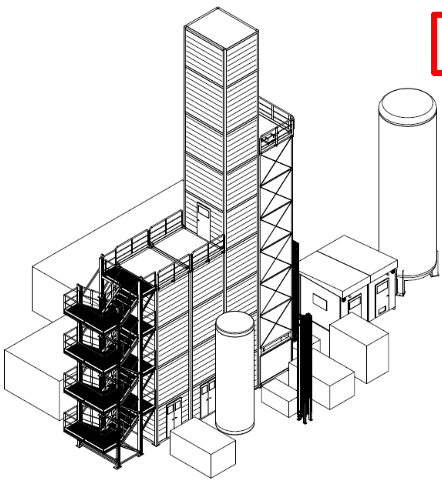
2616 kg day UAr exposure



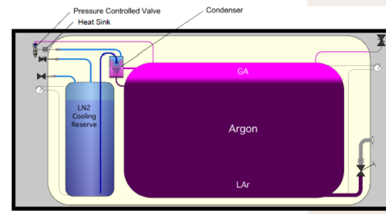
DarkSide 50 data

UAr for DS-20k

Extract Ar from Cortez, CO underground CO_2 flow.

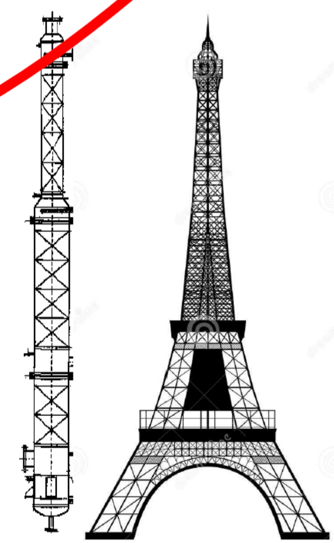


- Urania: procure 50 t of UAr
- Extract 260 kg/day
- UAr transported to Sardinia for final chemical purification at Aria



Extraction capacity of 90 Tonnes/year for the longer term.

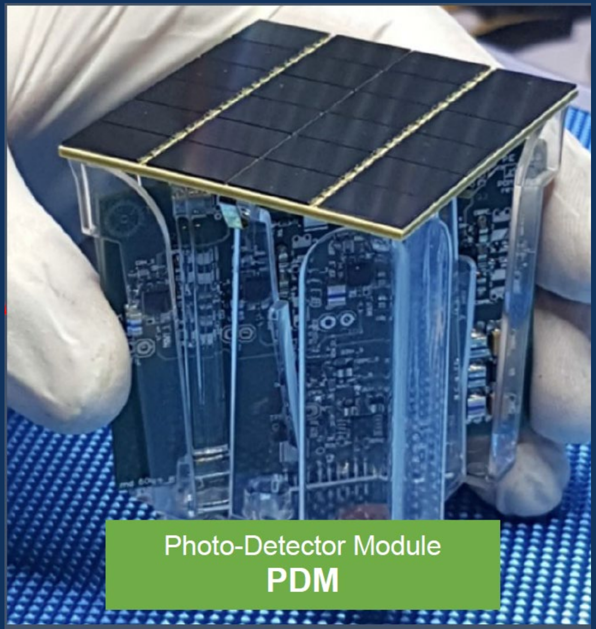
- Aria project: final chemical purification of the UAr
- Process O(1 t/day) with 10^3 reduction of all chemical impurities
- Ultimate goal - isotopically separate ^{39}Ar from ^{40}Ar
- At 10 kg/day: projected enrichment of factor of 10

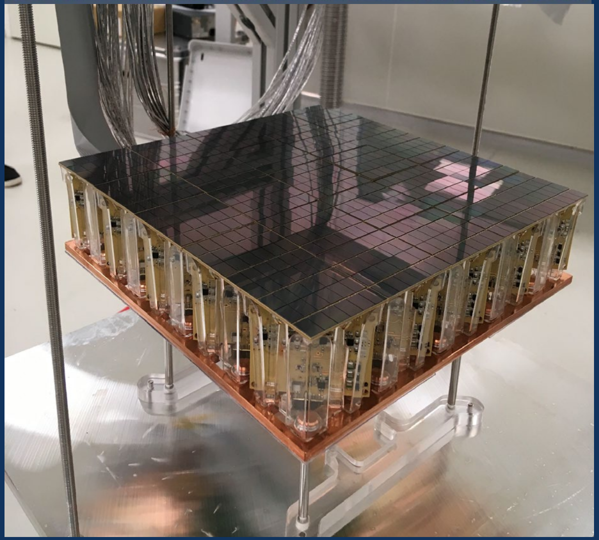


Tender let by INFN (Italy) for the Urania extraction equipment.

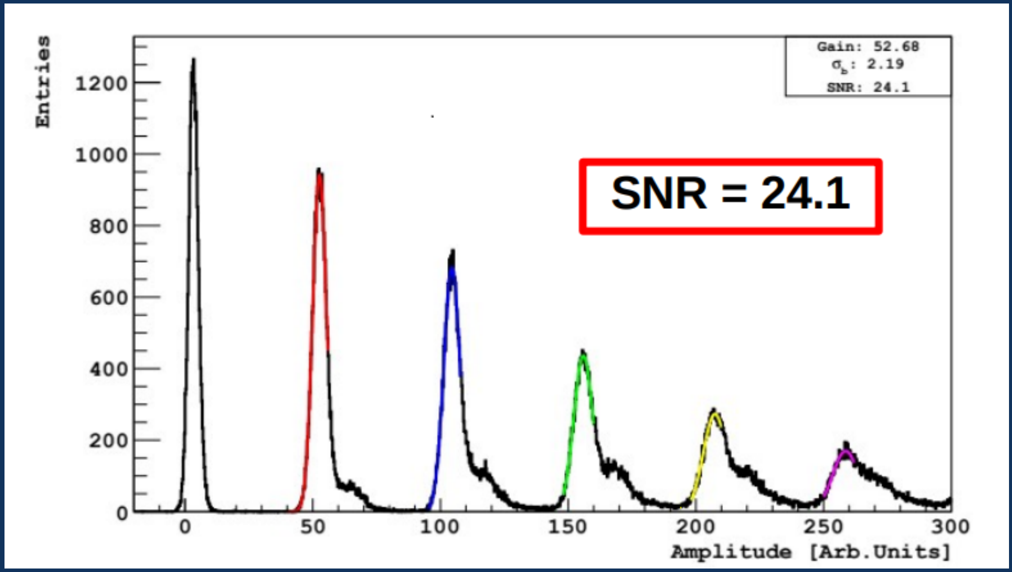
First sections of ARIA commissioned in Sardinia after vacuum tested at CERN. Specifications are met.

SPECIALIZED NEW SILICON PHOTOMULTIPLIERS (SiPM's) DEVELOPED IN ITALY FOR DARKSIDE-20K.

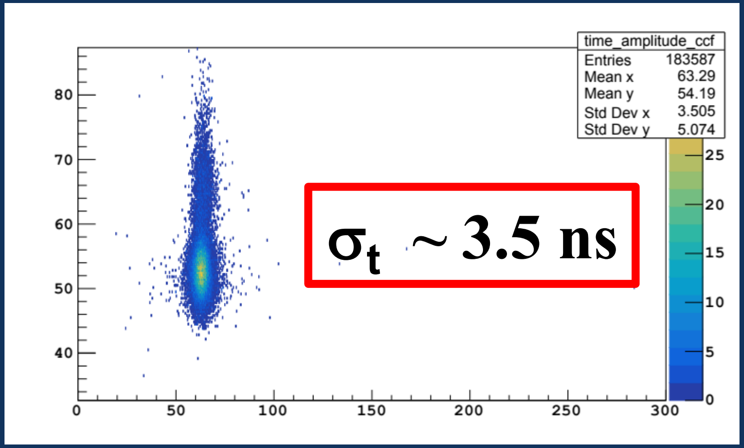


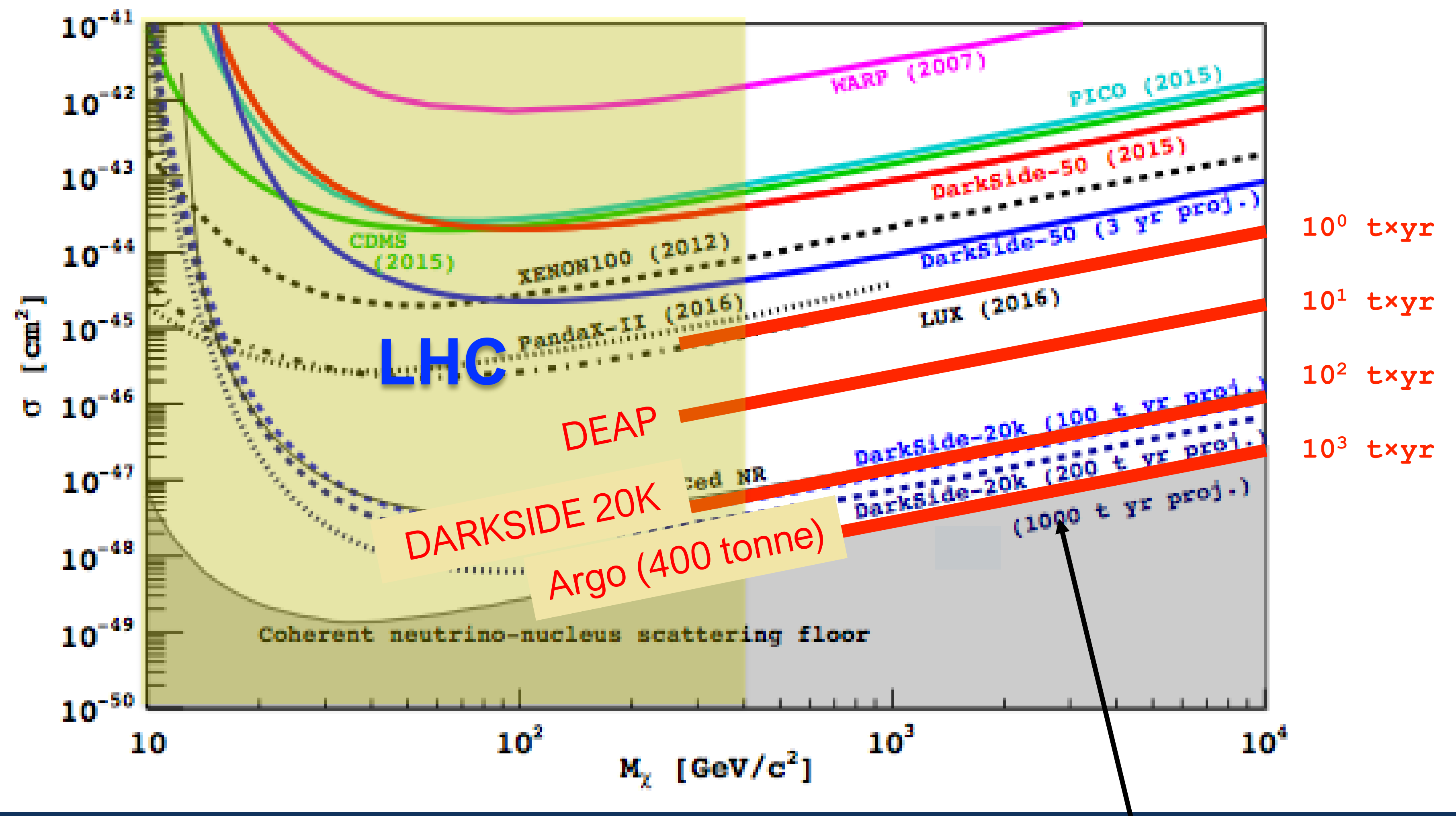


Motherboard being tested at CERN



Single **photo-electron** timing



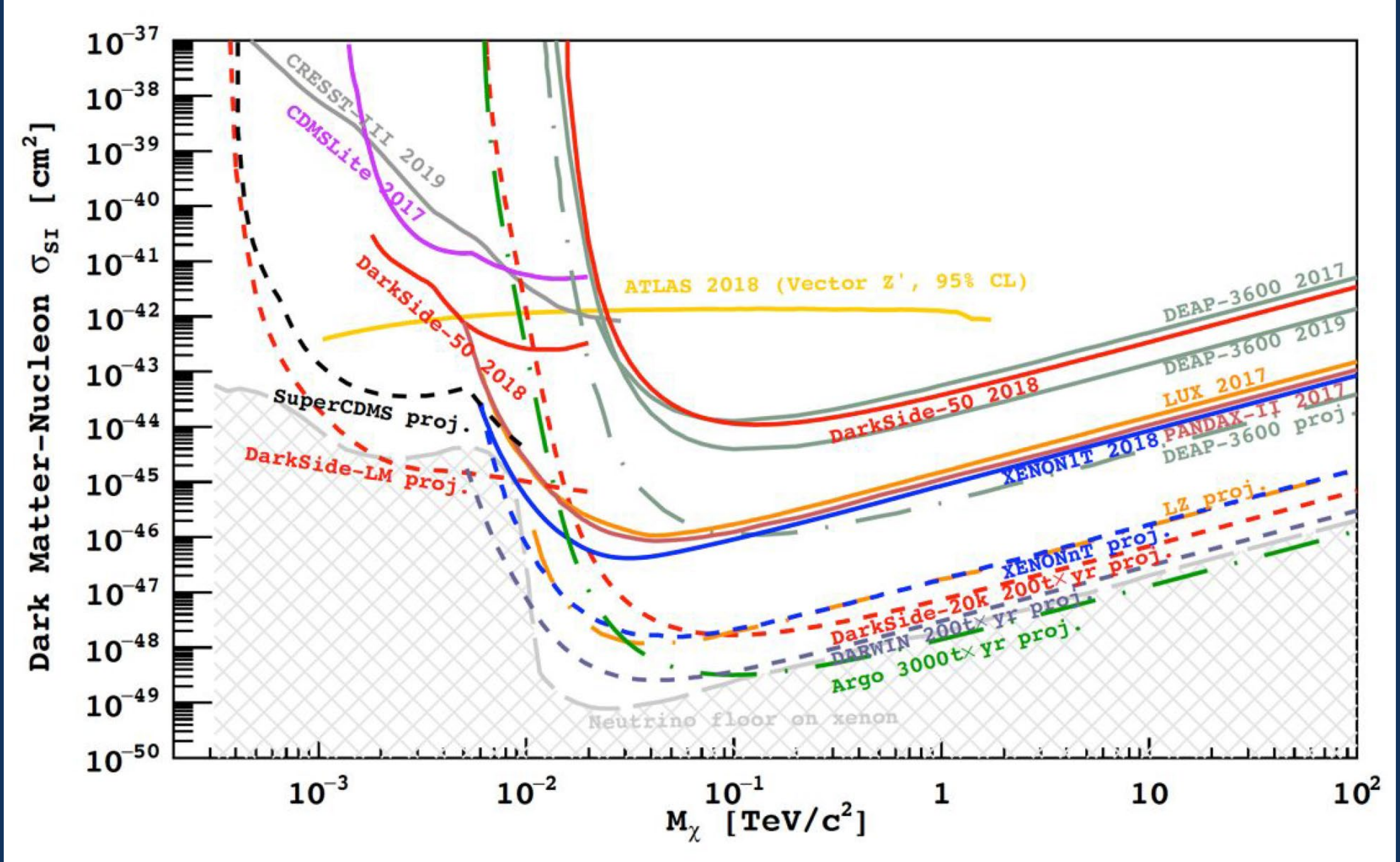


Future objective for the Global Argon Dark Matter Collaboration:

Argo: 400 ton Liquid Argon detector with optimum technology at SNOLAB.

Excellent sensitivity and electron discrimination at the neutrino floor.

Advantage: No interference from solar neutrinos for Dark Matter signals.



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Conclusions

- Particle Astrophysics is a thriving field of study with the potential for significant fundamental discoveries.

- Underground laboratories provide excellent conditions for studies of rare decays such as Neutrino-less double beta decay and detection of rare, weakly interacting particles such as neutrinos and Dark Matter.

- Noble Liquid detectors have the potential for a factor of 100 more sensitivity for WIMPs as Dark Matter candidates with excellent sensitivity in the region being studied with the LHC and for factors of 100 or more beyond in mass.

- Stay tuned!