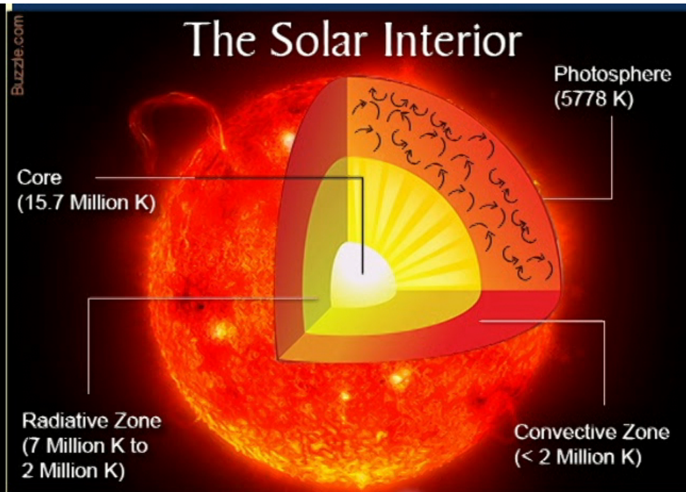
Title: Special Guest Talk - 'Science Opportunities Underground: Neutrinos and Dark Matter'

Speakers: Arthur McDonald

Collection: The Day of Discovery

Date: October 20, 2022 - 9:30 AM

URL: https://pirsa.org/22100064



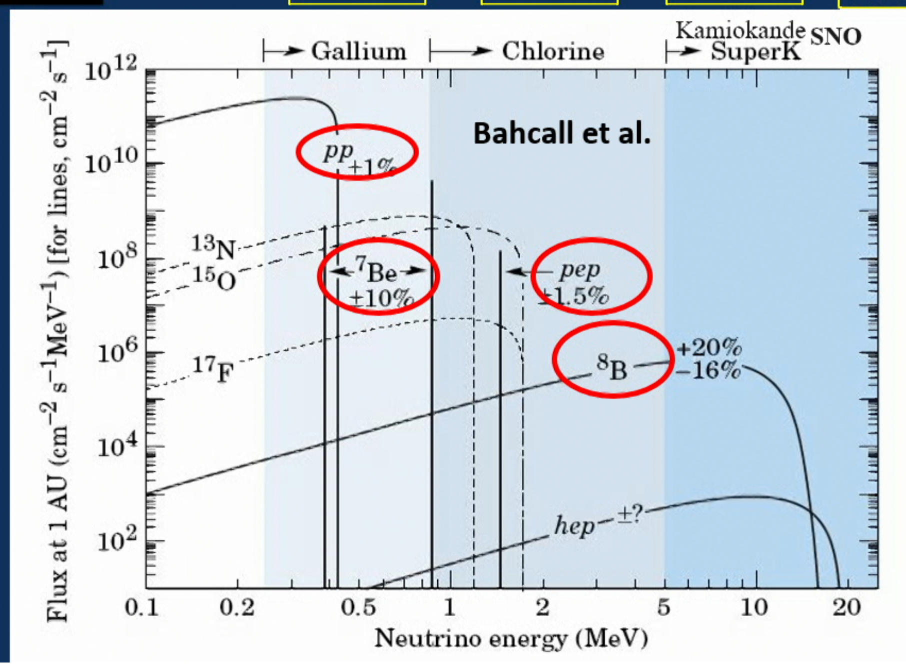
NEUTRINO FLUXES FROM THE SOLAR CORE

EXPERIMENTS

1992 on | 1968 on | 1989 on | 2001 on

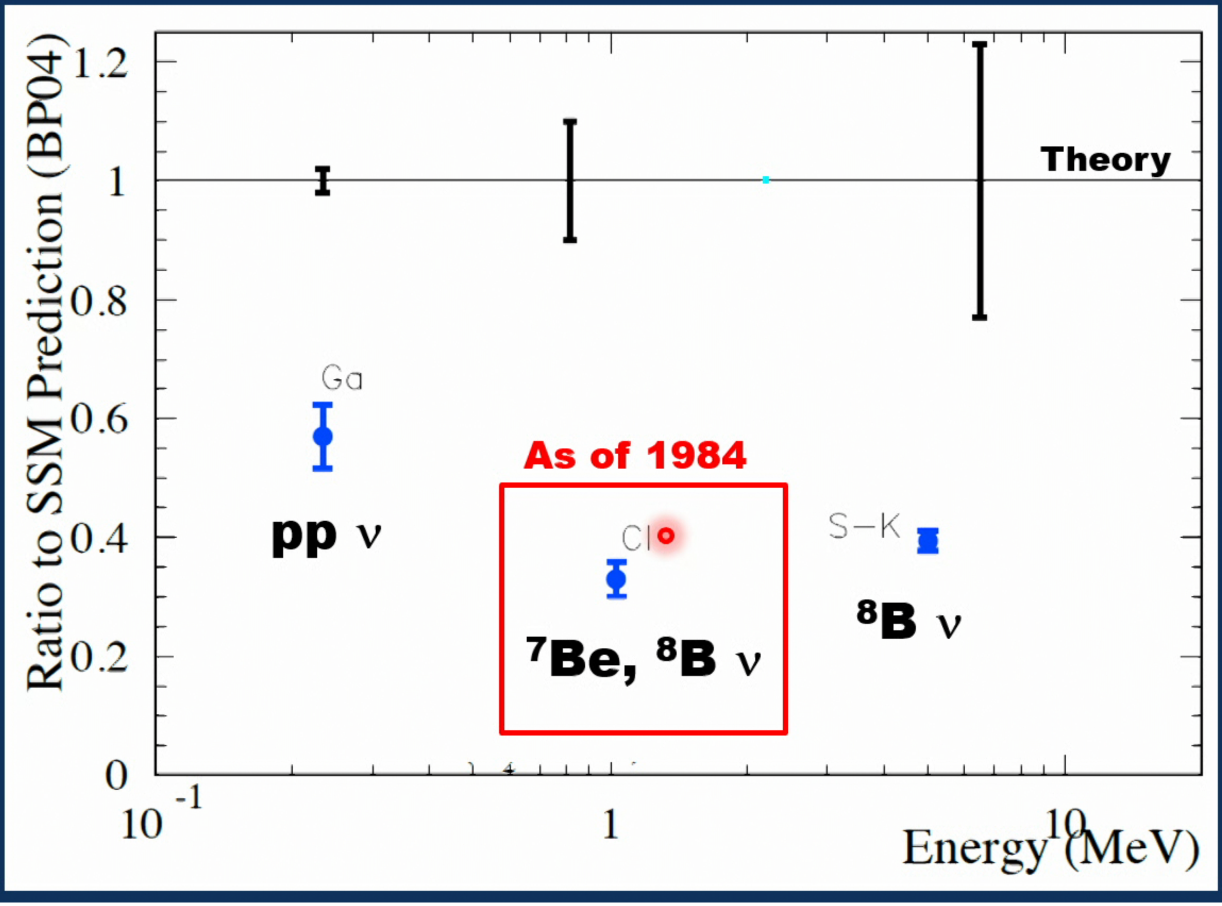
HOW DOES THE SUN BURN?

Nuclear fusion reactions produce enormous numbers of electron neutrinos



Solar Neutrino Problem

As of the year 2000: Experimental sensitivity: primarily or exclusively electron neutrinos



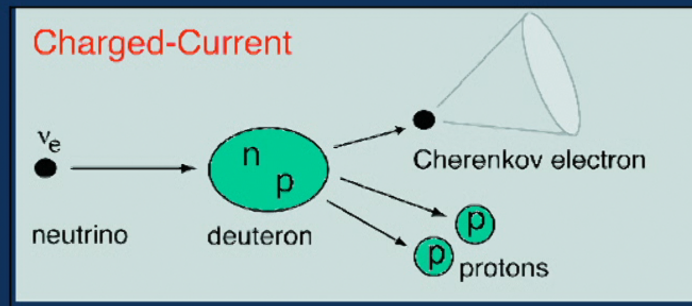
Unique Signatures in SNO (D_2O)

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

Electron Neutrinos (CC)

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

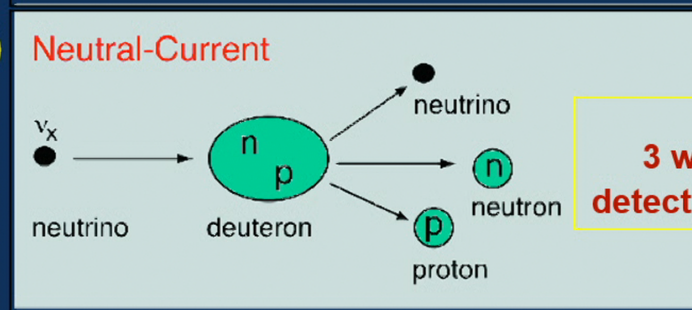
$E_{thresh} = 1.4$ MeV



Equal Sensitivity All Types (NC)

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

$E_{thresh} = 2.2$ MeV



3 ways to detect neutrons

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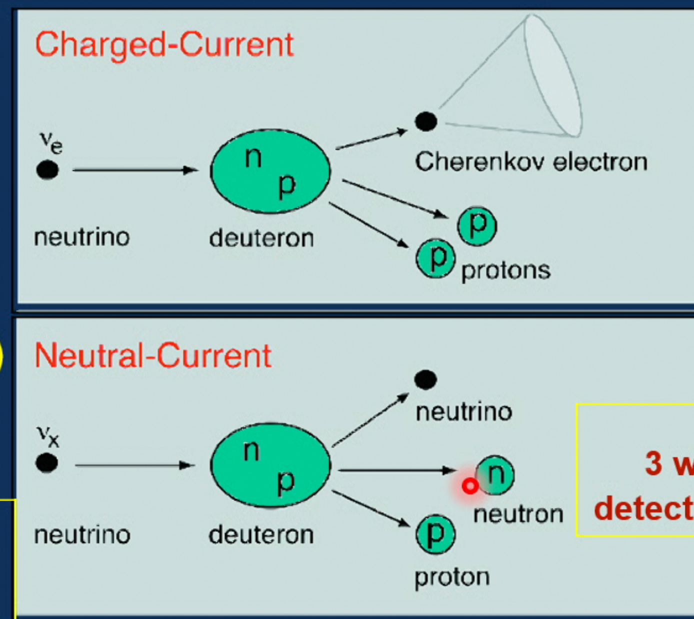
Comparing these two reactions tells if electron neutrinos have changed their type.



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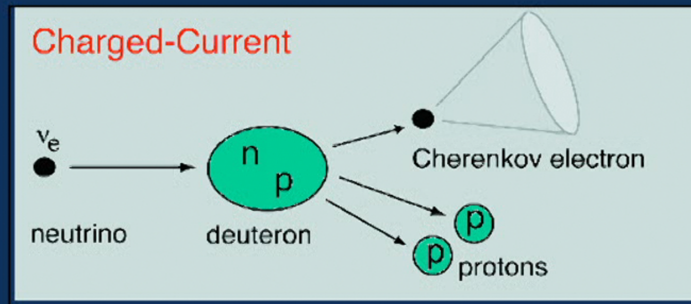

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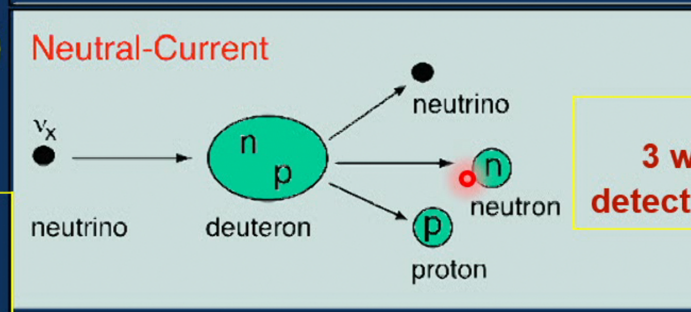
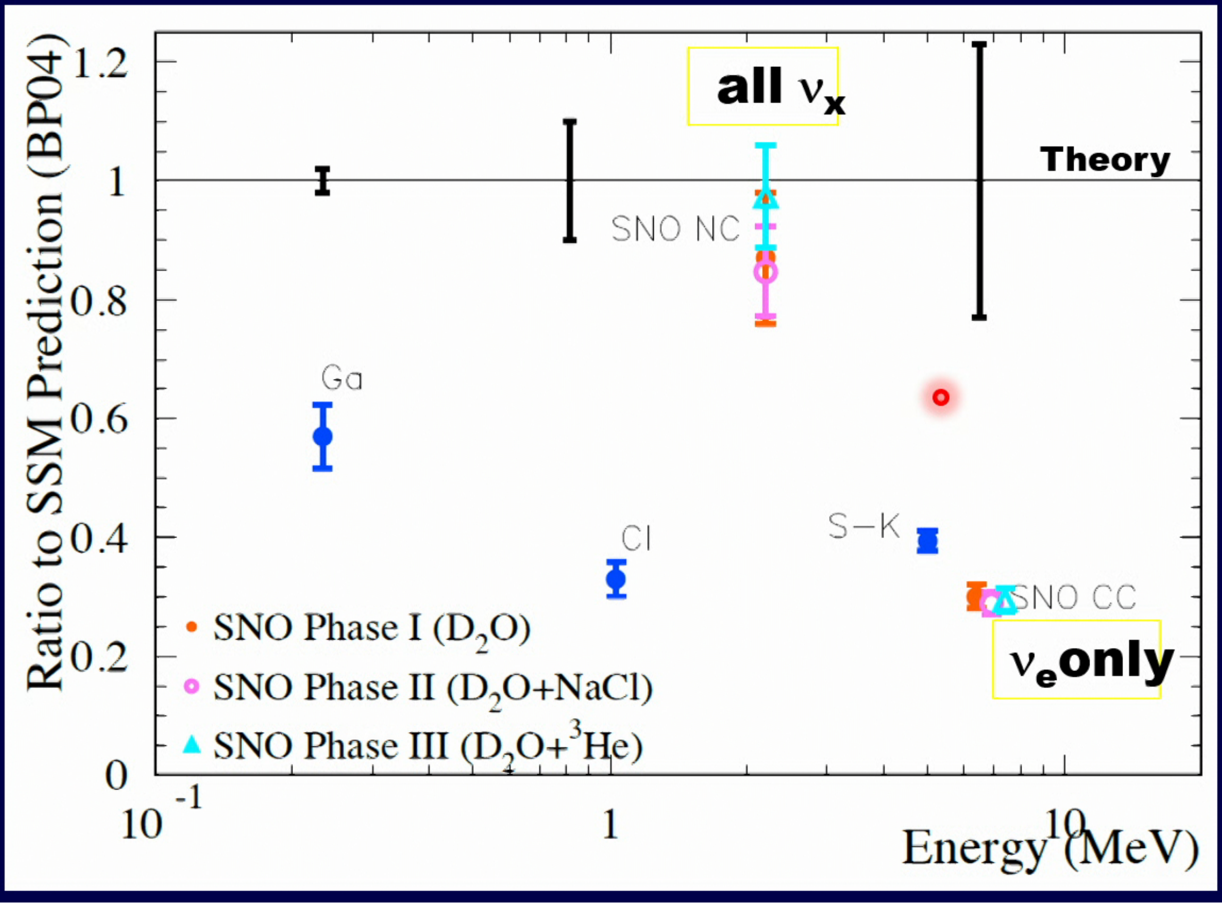


3 ways to detect neutrons

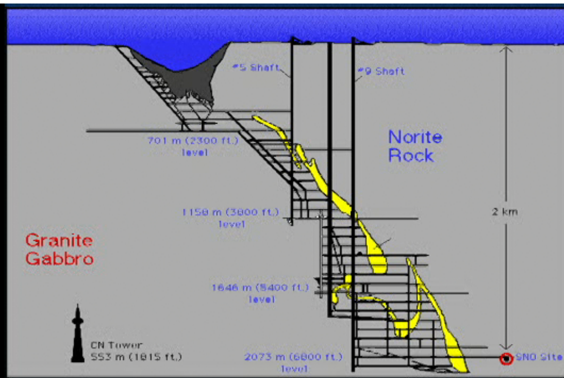
Comparing these two reactions tells if electron neutrinos have changed their type.

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.

Solar Neutrino Problem
Resolved: Neutrinos Change Flavour



Sudbury Neutrino Observatory (SNO)



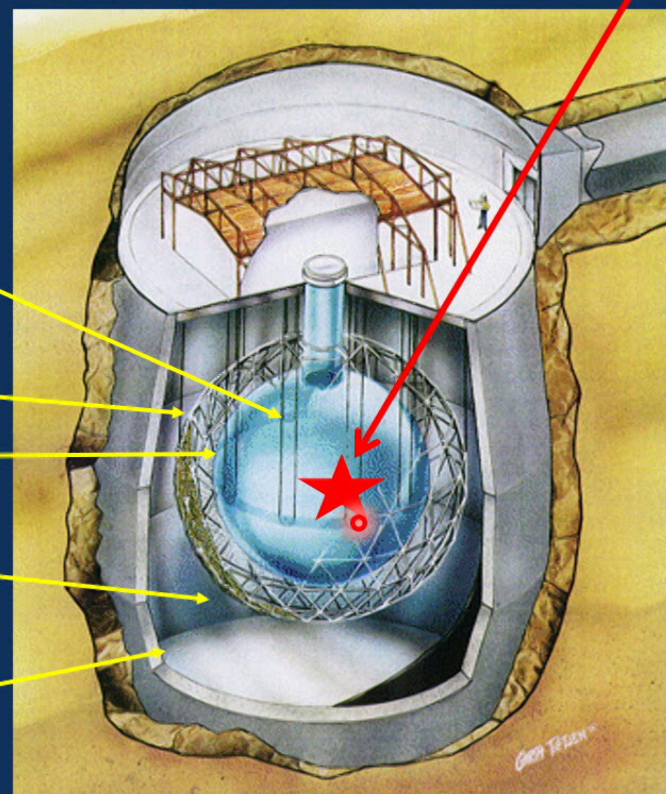
1000 tonnes of heavy water: D_2O
$ 300 million on Loan for $1.00

9500 light sensors

12 m Diameter Acrylic Container

Ultra-pure Water: H_2O.

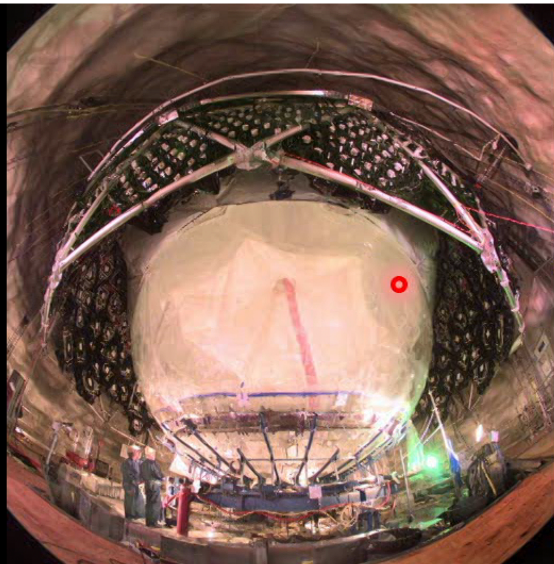
Urylon Liner and Radon Seal



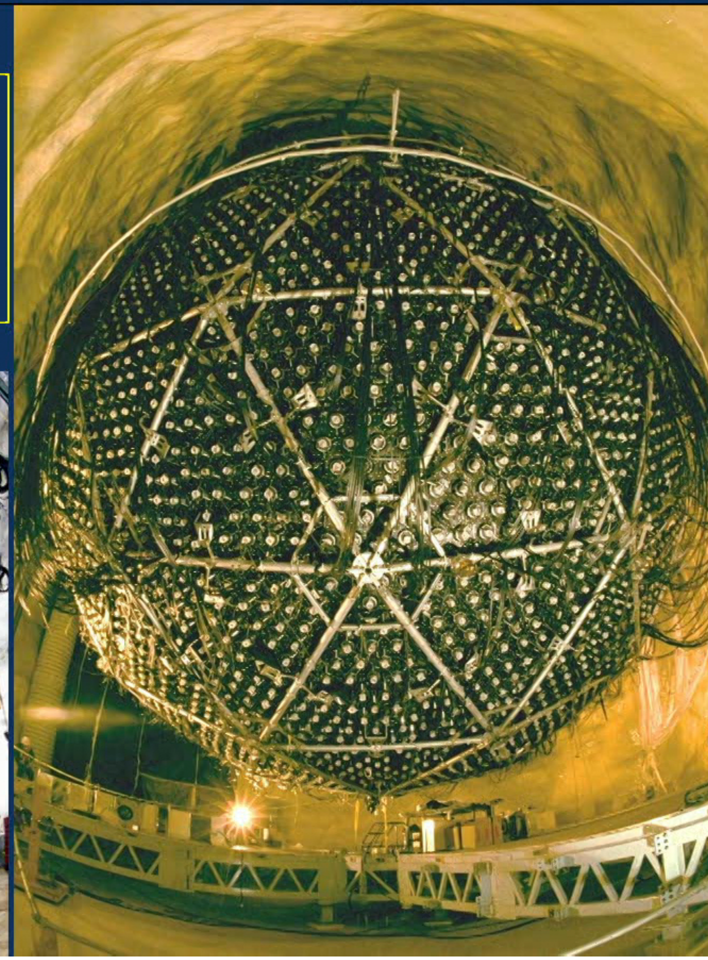
34 m or ~ Ten Stories High!

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



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.

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

Pontecorvo-Maki-Nakagawa-Sakata matrix

(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)

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

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

SUMMARY OF OSCILLATION RESULTS FOR THREE ACTIVE ν TYPES

Particle Data Group

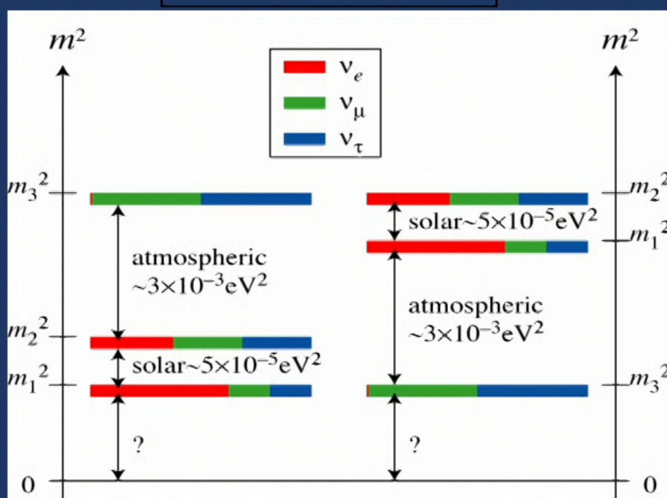
$\sin^2(\theta_{12}) = 0.307 \pm 0.013$
$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2$
$\sin^2(\theta_{23}) = 0.539 \pm 0.022$ $(S = 1.1)$ (Inverted order)
$\sin^2(\theta_{23}) = 0.546 \pm 0.021$ (Normal order)
$\Delta m^2_{32} = (-2.536 \pm 0.034) \times 10^{-3}\ \mathrm{eV}^2$ (Inverted order)
$\Delta m^2_{32} = (2.453 \pm 0.033) \times 10^{-3}\ \mathrm{eV}^2$ (Normal order)
$\sin^2(\theta_{13}) = (2.20 \pm 0.07) \times 10^{-2}$

} Solar, Reactor

} Atmospheric,Accelerator

} Reactor, Accelerator

Mass Hierarchies

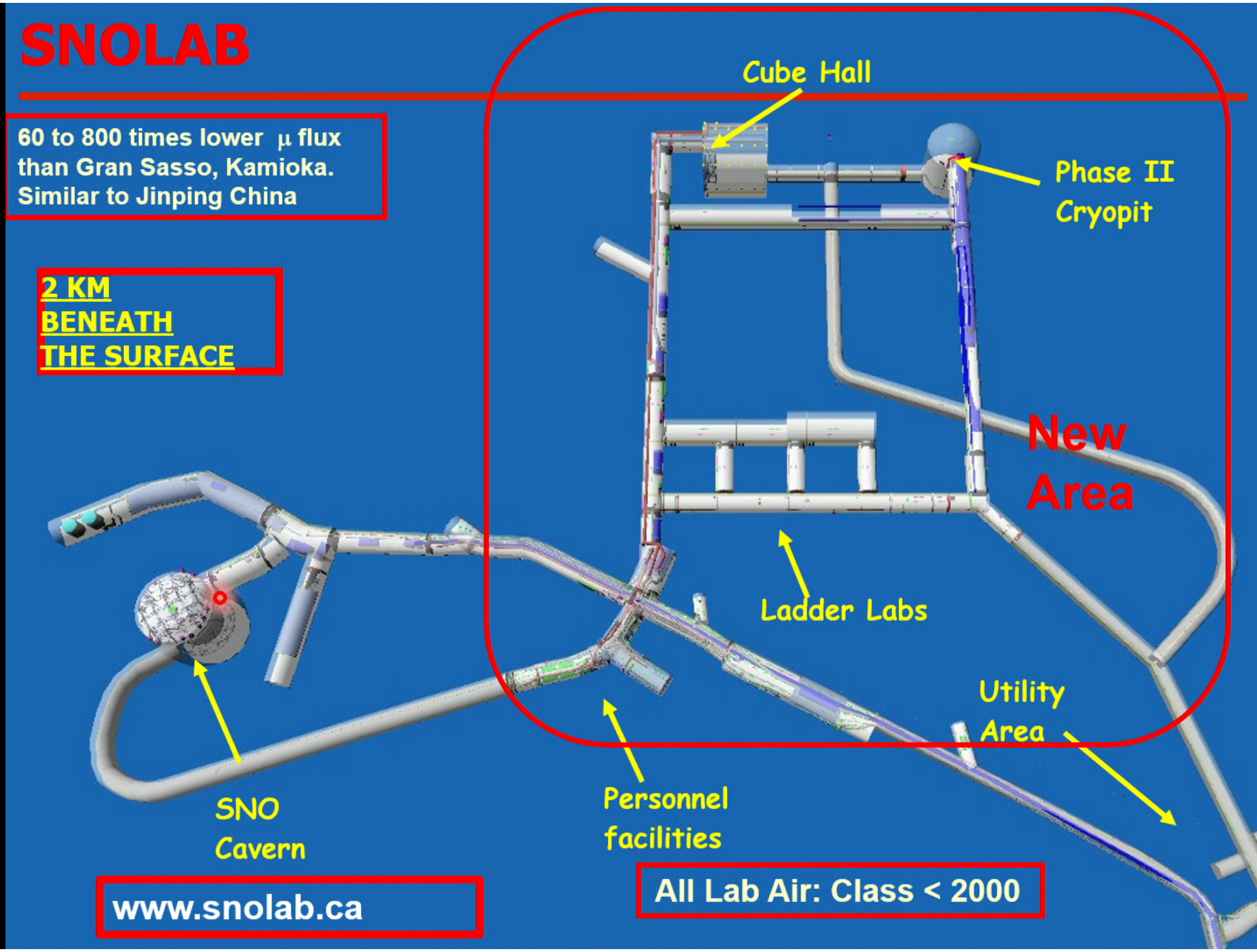


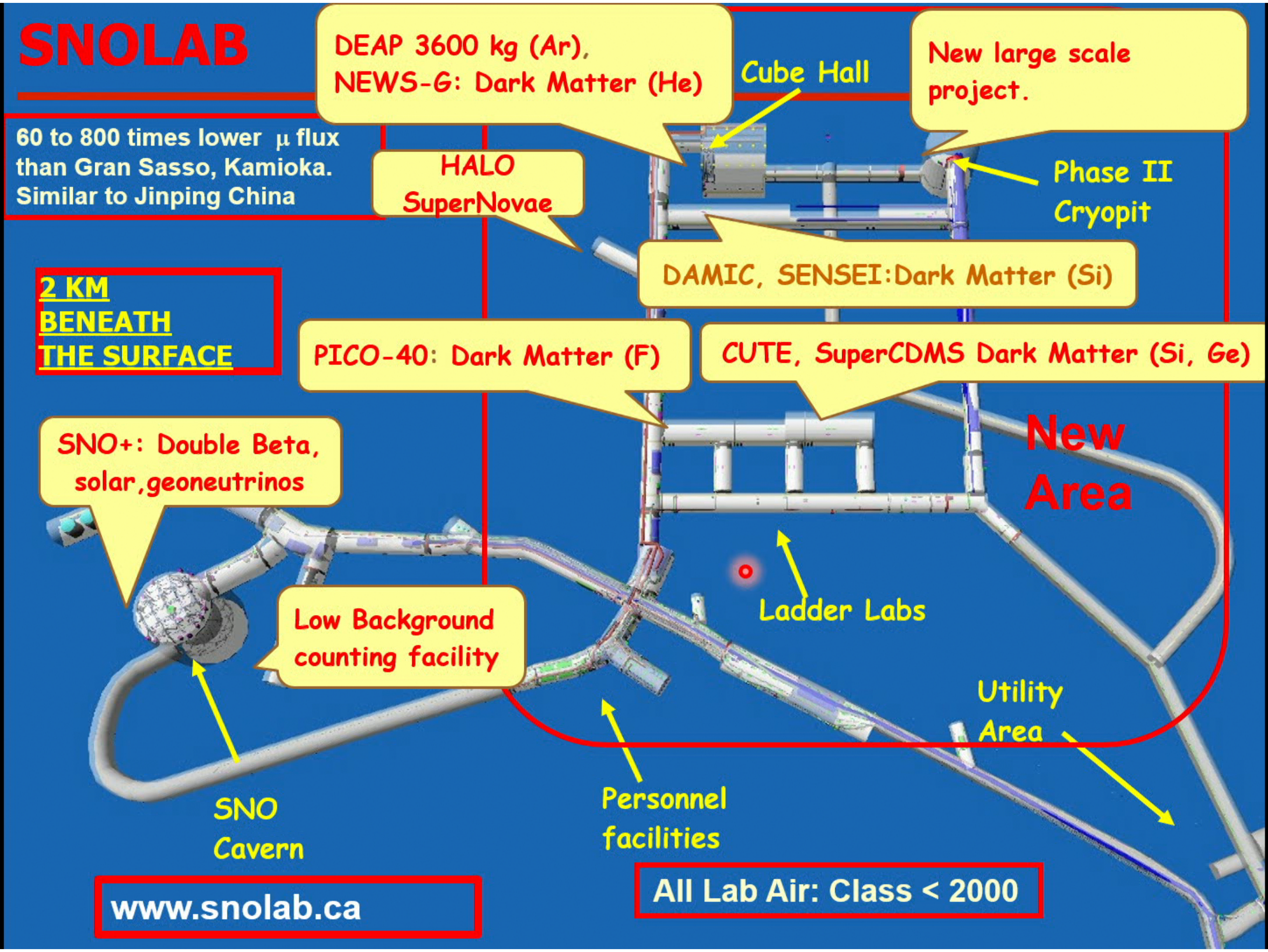
Normal Inverted

Future objectives:

- Majorana ν?
- Absolute mass
- Hierarchy?
- δ_{CP}
- θ_{23} max?
- Sterile ν?

} **Neutrinoless Double Beta Decay**


SNOLAB
60 to 800 times lower μ flux than Gran Sasso, Kamioka. Similar to Jinping China
2 KM BENEATH THE SURFACE
Cube Hall
Phase II Cryopit
New Area
Ladder Labs
Utility Area
SNO Cavern
Personnel facilities
www.snolab.ca
All Lab Air: Class < 2000

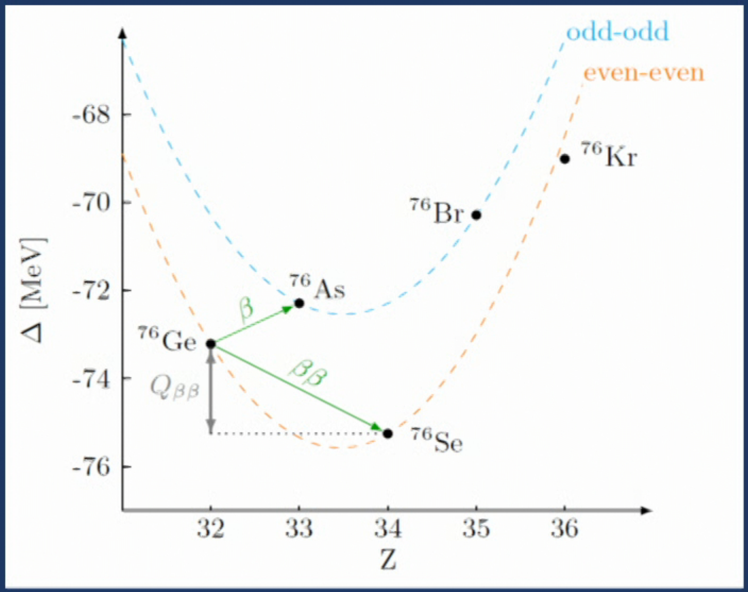


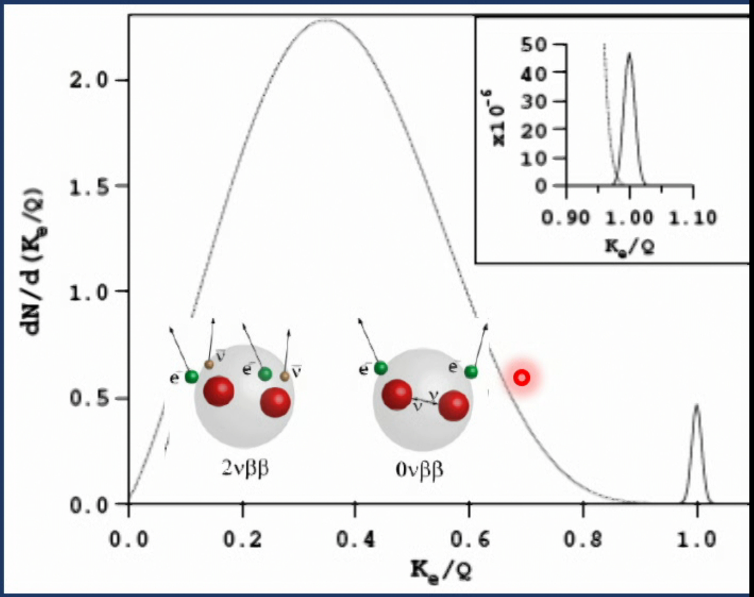
SNOLAB
60 to 800 times lower μ flux than Gran Sasso, Kamioka. Similar to Jinping China
DEAP 3600 kg (Ar), NEWS-G: Dark Matter (He)
Cube Hall
New large scale project.
HALO SuperNovae
Phase II Cryopit
DAMIC, SENSEI:Dark Matter (Si)
2 KM BENEATH THE SURFACE
PICO-40: Dark Matter (F)
CUTE, SuperCDMS Dark Matter (Si, Ge)
SNO+: Double Beta, solar,geoneutrinos
New Area
Ladder Labs
Low Background counting facility
Utility Area
Personnel facilities
SNO Cavern
www.snolab.ca
All Lab Air: Class < 2000

SNOLAB
Experimental Area

Stephen Hawking and fans observing the CRYOPIT area in September 2012

Neutrino-less Double Beta Decay



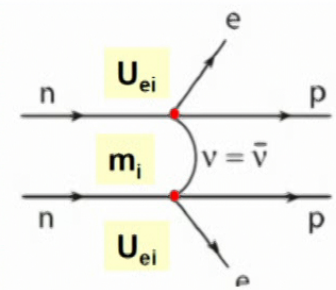


- For a select number of nuclei, single beta decay is energetically forbidden, but double beta decay is allowed.
- Emission of 2 β and 2 ν can occur and has been observed for most nuclei.
- If the neutrino is a massive Majorana particle neutrino-less double beta decay could occur, providing a monoenergetic peak for the sum of the 2 β total energy.

(A,Z) → (A,Z+2) + e⁻ + e⁻

0νββ-decay

(LNV at ≈ GUT scale, exchange of three light ν)



$$\left(T^{0\nu}_{1/2}\right)^{-1} = \left|\frac{m_{\beta\beta}}{m_e}\right|^2 g_A^4 \left|M^{0\nu}_{\nu}\right|^2 G^{0\nu}$$

?

Phase space factor well understood

NME must be evaluated using tools of nuclear theory

Effective Majorana mass can be evaluated. It depends on
$m_1, m_2, m_3, \theta_{12}, \theta_{13}, \alpha_1, \alpha_2$
(3 unknown parameters: m_1/m_3, α_1, α_2 and ν-mass hierarchy)

$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 e^{i\alpha_1} m_1 + c_{13}^2 s_{12}^2 e^{i\alpha_2} m_2 + s_{13}^2 m_3\right|$$

Neutrino Oscillations:

- **Provides differences in mass for three states**
- **Defines mixing angles {$c_{12} = \cos(\theta_{12})$}**
- **Eventually CP violating phase δ**

Flavor States $\quad |\nu_l\rangle = \sum U^{PMNS}_{li} |\nu_i\rangle \quad$ Mass States

0νββ phases

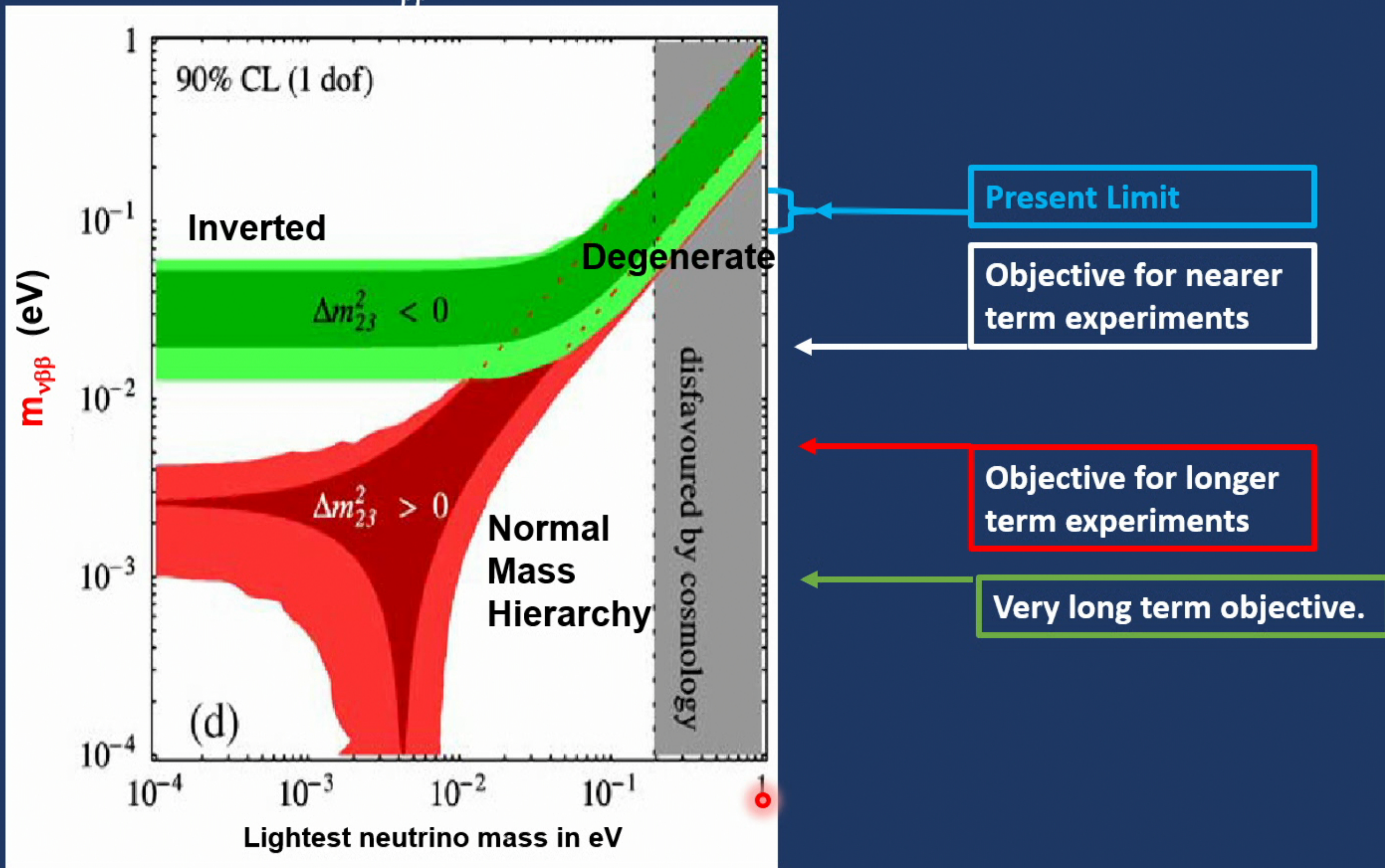
$$U^{PMNS} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & e^{-i\delta}s_{13} \\ -c_{23}s_{12} - e^{i\delta}c_{12}s_{13}s_{23} & c_{12}c_{23} - e^{i\delta}s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{12}s_{23} - e^{i\delta}c_{12}c_{23}s_{13} & -e^{i\delta}c_{23}s_{12}s_{13} - c_{12}s_{23} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Simcovic: Neutrino 2022

- **ν is its own anti-particle: Majorana ν**
- **ΔL = 2: Violation of B-L symmetry.**
- **Sensitive to the absolute mass of the neutrinos**

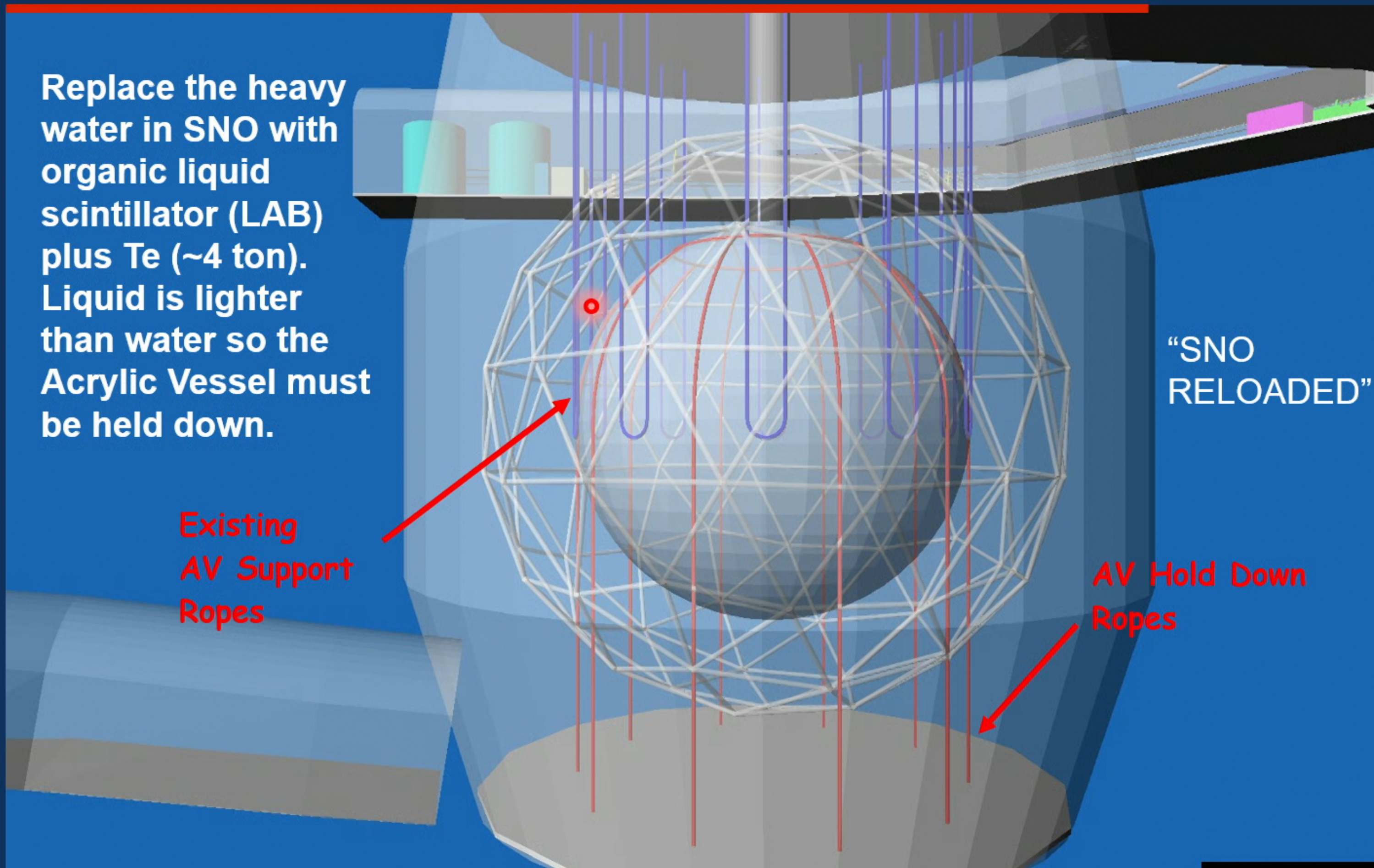
- **Note: Exchange of three light ν. Data can also be analyzed for exchange of a Heavy ν.**
- **The calculation of nuclear matrix elements is a very complex. Uncertainties factor of ~4.**

Variation of $m_{\beta\beta}$ vs Lightest ν mass

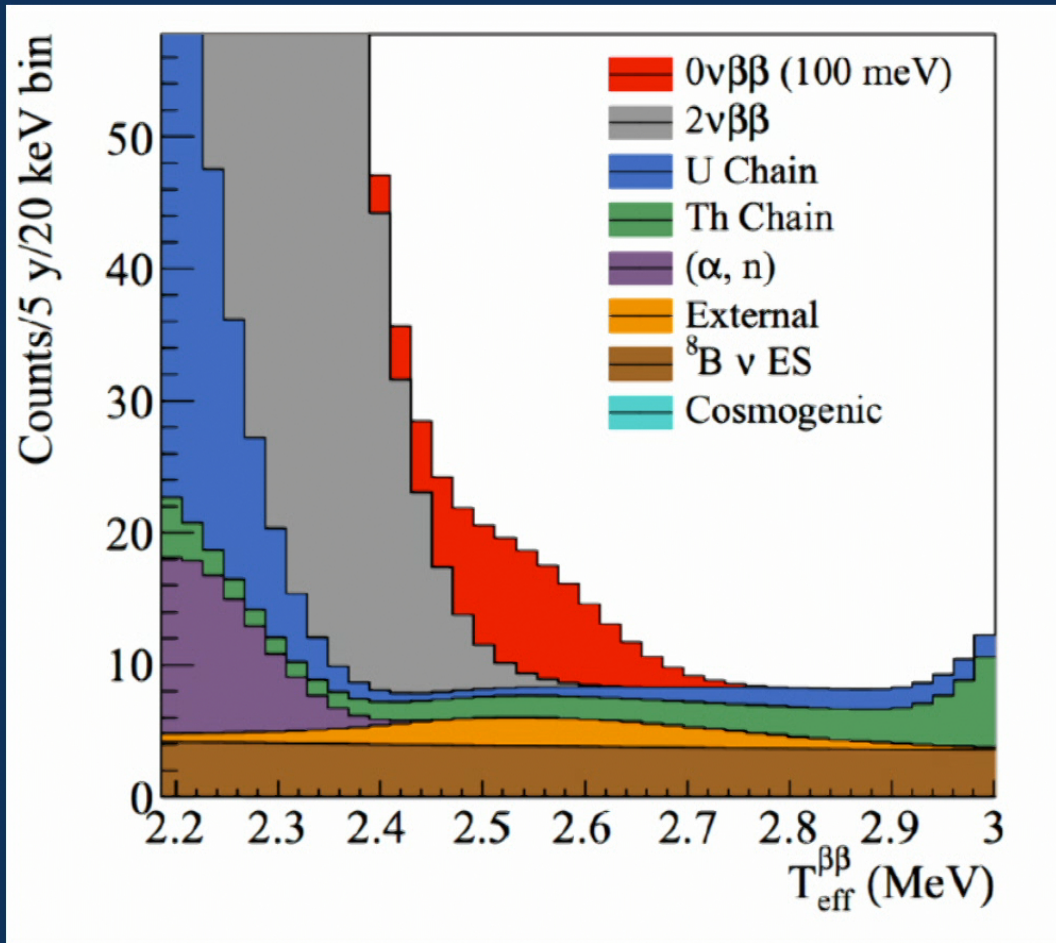


Neutrino-less Double Beta Decay: SNO+

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.



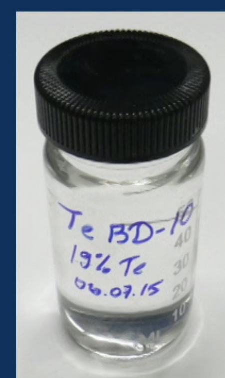
Now running with scintillator. Te installation starting in 2023.



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

$T_{1/2} > 2 \times 10^{26}$ yr
(90% CL)
$m_{\beta\beta} < 36$-110 meV

Phase II
3.0% ^{130}Te

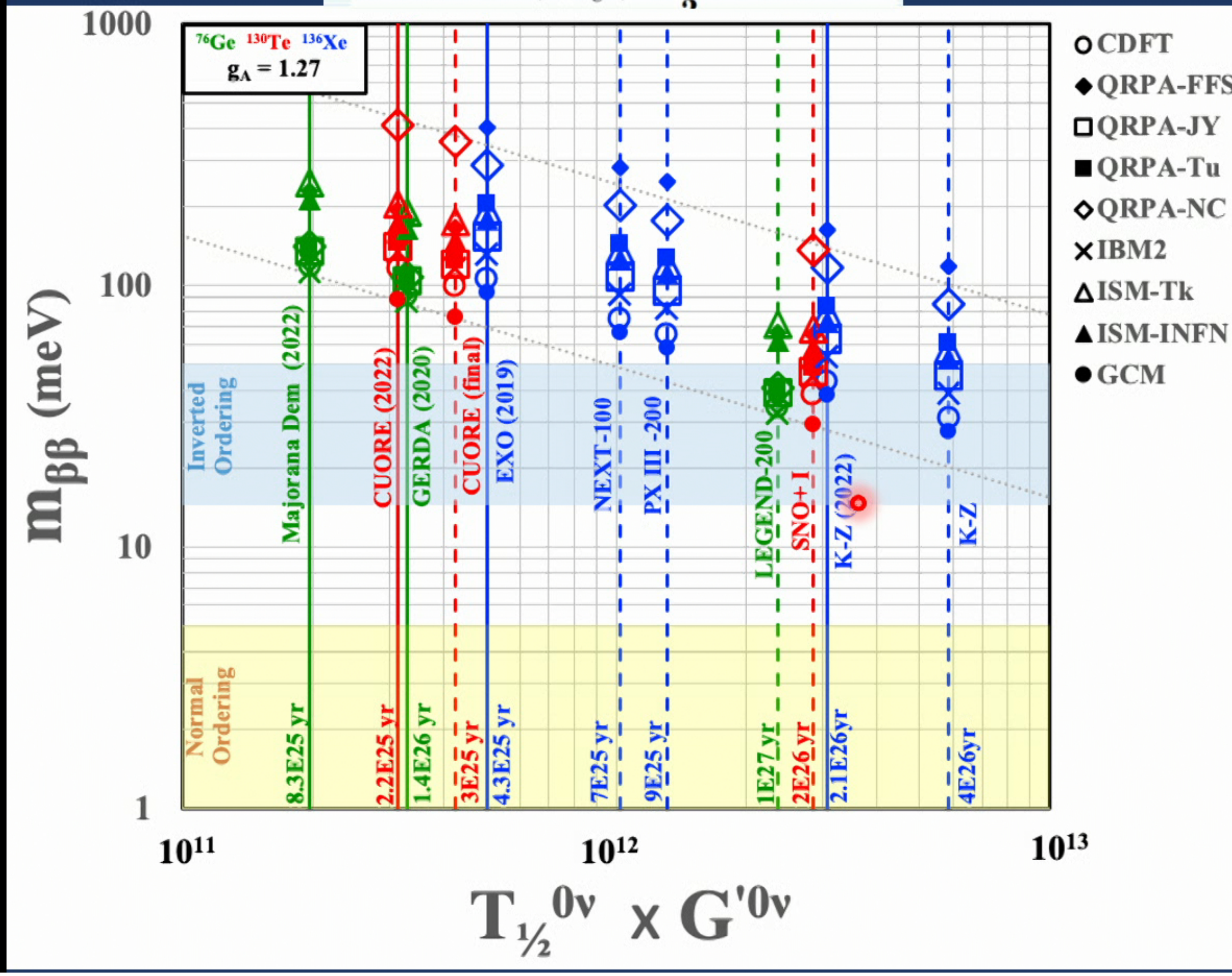


Te to be installed starting in 2023.

Near Term Experiments: Solid line: published, Dashed: Near Future

$$\left(T_{1/2}^{0\nu}\right)^{-1} = \left|\frac{m_{\beta\beta}}{m_e}\right|^2 g_A^4 \left|M_\nu^{0\nu}\right|^2 G^{0\nu}$$

$g_A = 1.27$



- Symbols: Nuclear Matrix Element Theoretical results

- Figure courtesy of Steve Biller. 90% Confidence Limits on lifetime from published info

Longer Term Experiments: Symbols: Nuclear Matrix Element Theory

$$\left(T_{1/2}^{0\nu}\right)^{-1} = \left|\frac{m_{\beta\beta}}{m_e}\right|^2 g_A^4 \left|M_\nu^{0\nu}\right|^2 G^{0\nu}$$

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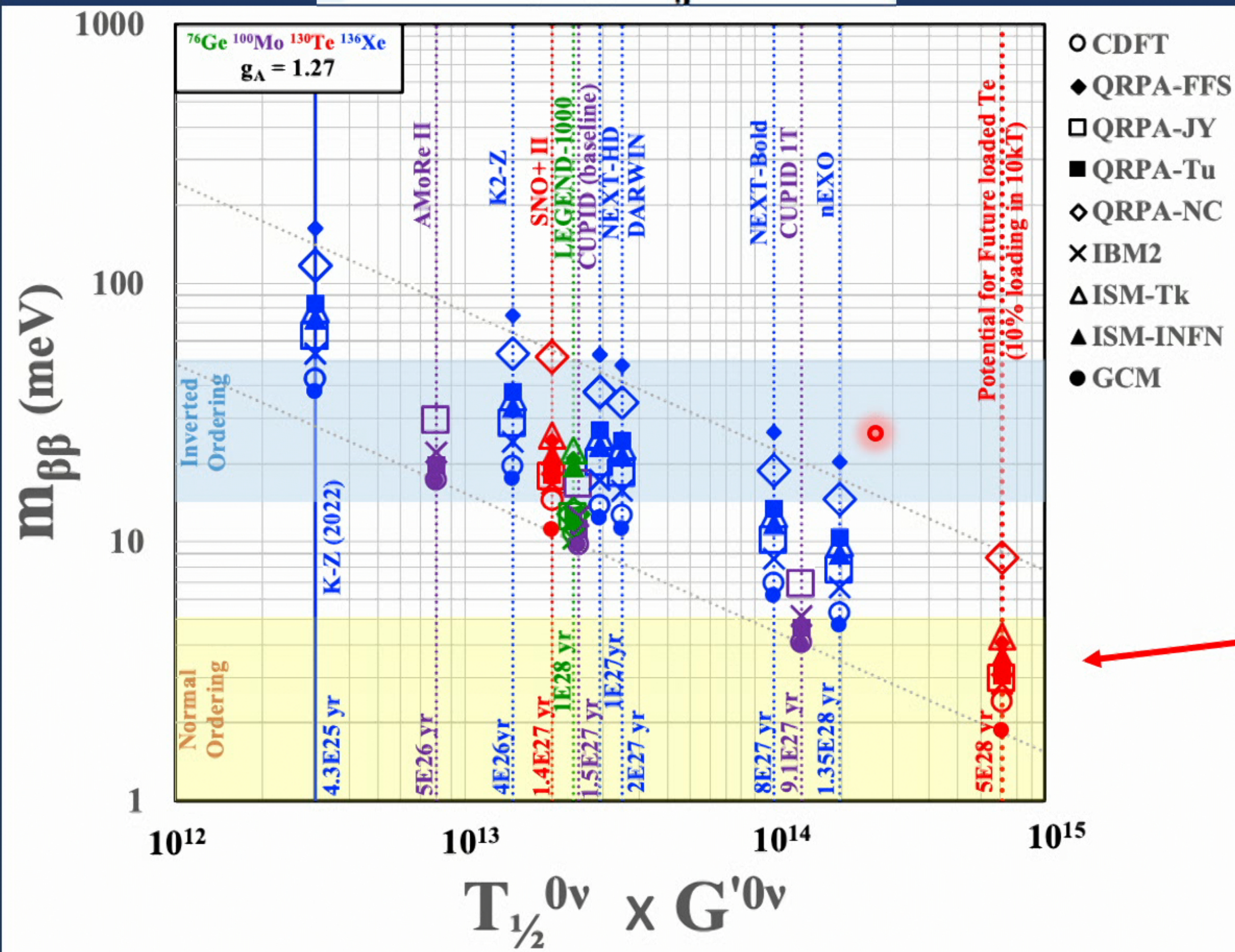
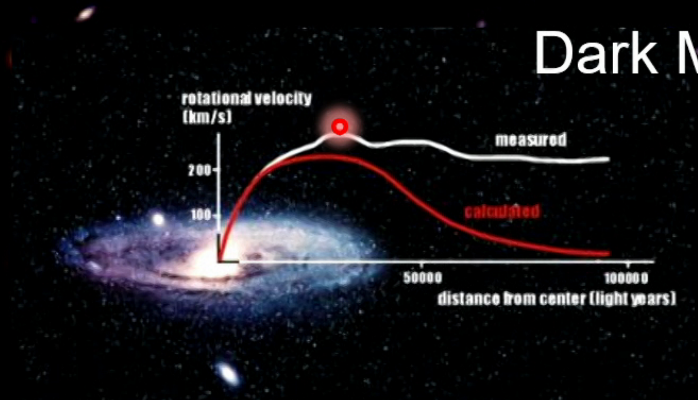


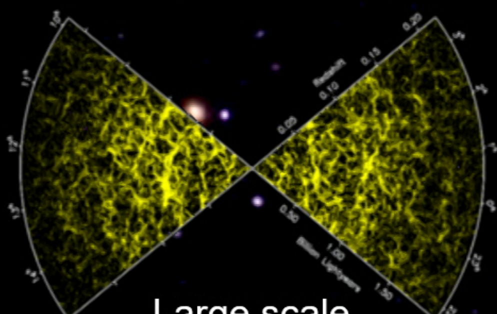
Figure courtesy of Steve Biller. 90% Confidence Limits on lifetime from published info

Very long term concept ~10x SNO+ (10kT LAB) and 10% Te loading. Biller: Lisbon Workshop Jul 7 2022

Dark Matter

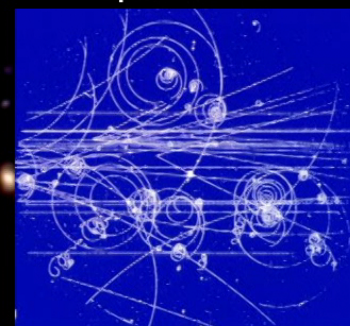


Here, but not yet observed directly in nature: **Weakly interacting**

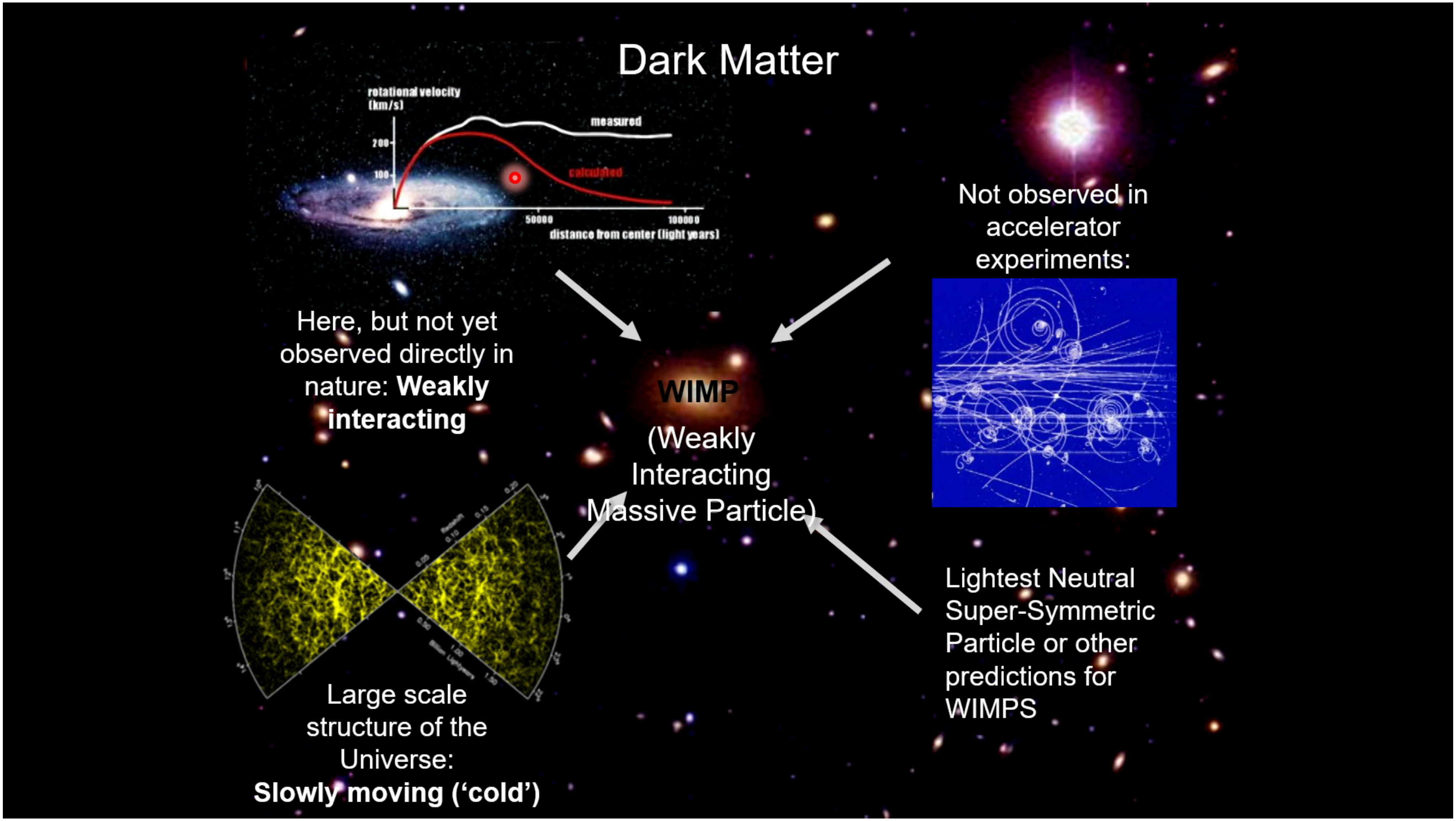


Large scale structure of the Universe:
Slowly moving ('cold')

Not observed in accelerator experiments:



Lightest Neutral Super-Symmetric Particle or other predictions for WIMPS


Dark Matter
rotational velocity (km/s)
200
100
measured
calculated
50000
100000
distance from center (light years)
Here, but not yet observed directly in nature: **Weakly interacting**
WIMP
(Weakly Interacting Massive Particle)
Not observed in accelerator experiments:
Large scale structure of the Universe: **Slowly moving ('cold')**
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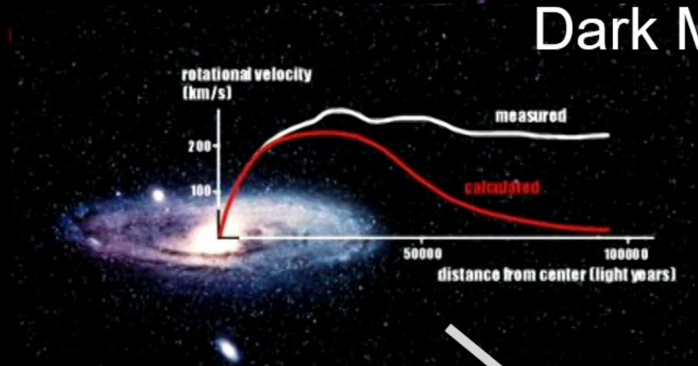
Dark Matter



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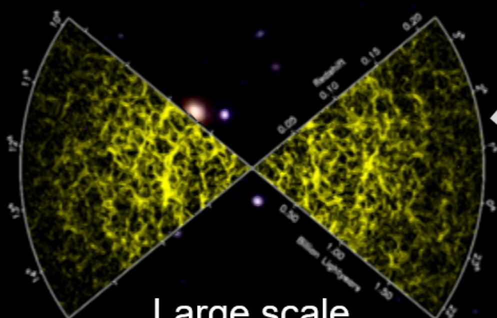
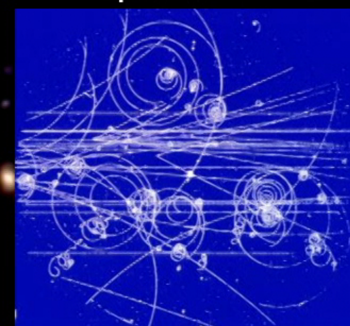


Large scale structure of the Universe:
Slowly moving ('cold')

WIMP
(Weakly Interacting Massive Particle)

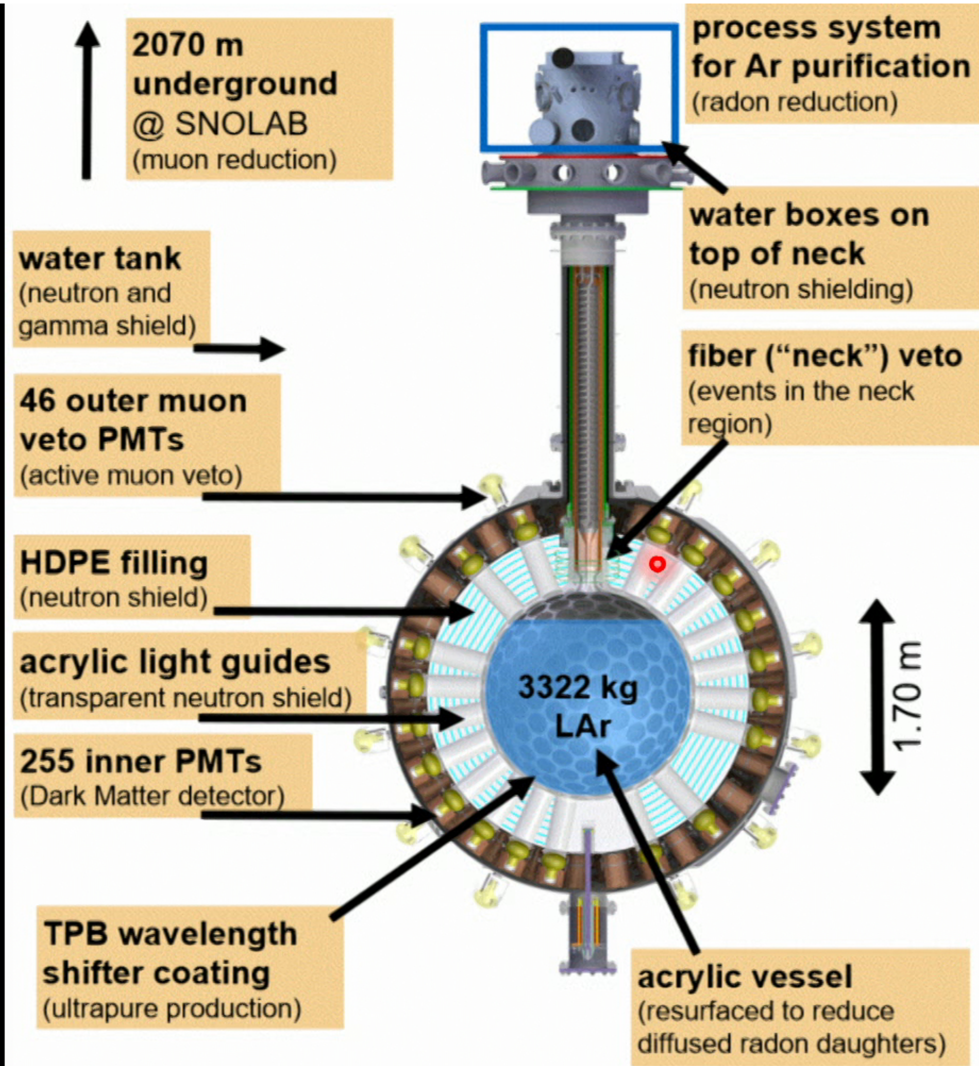
Interaction with ordinary matter:
Nuclear Recoils
(most backgrounds: electron recoils)

Not observed in accelerator experiments:



Lightest Neutral Super-Symmetric Particle or other predictions for WIMPS

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

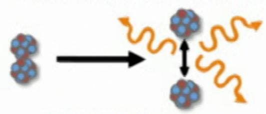
- Sensitivity for spin-independent WIMP-nucleon cross-selection: **10^{-46} cm^2 (@100 GeV)**

Hardware design concepts for background mitigation:

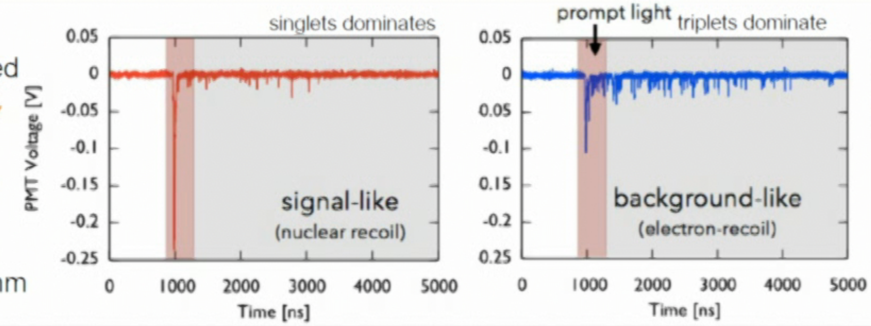
- Deep underground
- Active muon veto
- Onion-layer passive shielding
- Resurfacing of acrylic vessel to remove diffused radon
- Neutrons from PMTs shielded by long transparent acrylic light guides

Experimental Signature: Pulse Shape Discrimination

Ar scintillation:
- excimers are created



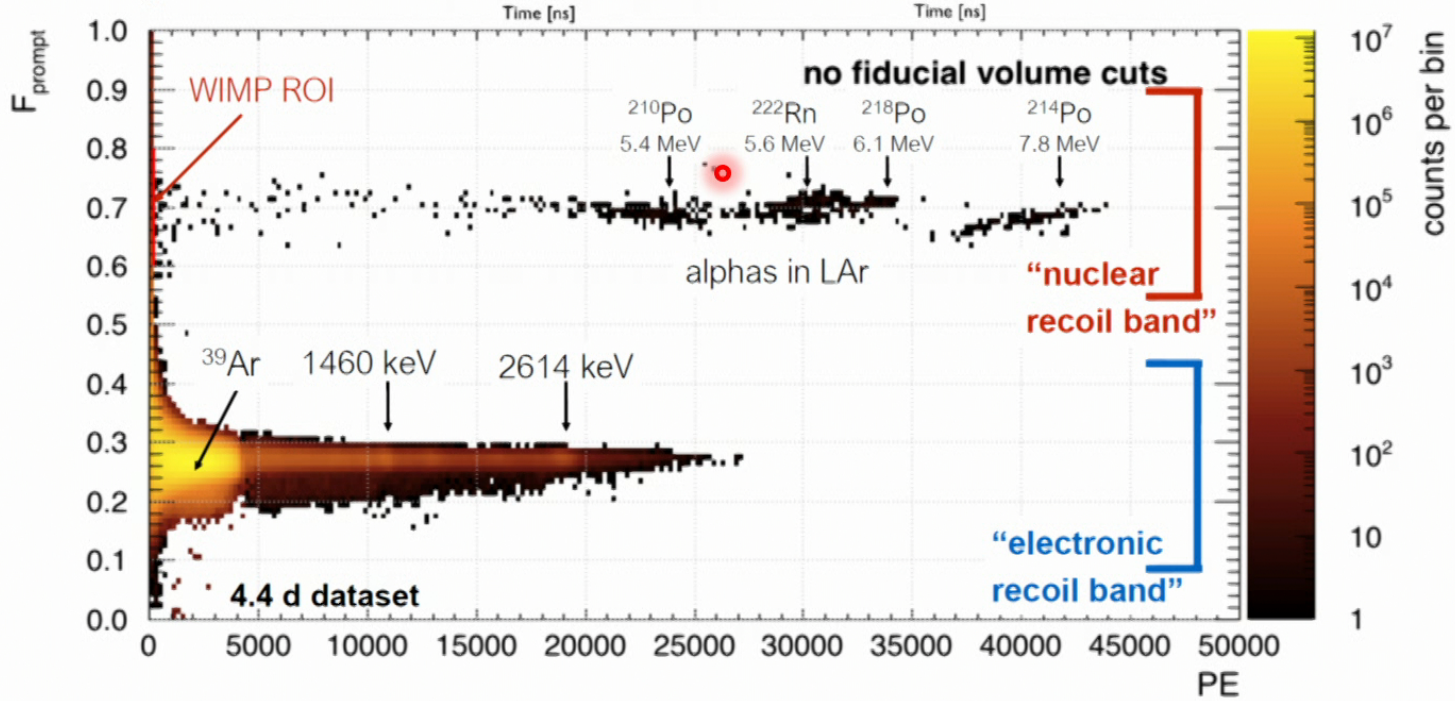
- singlet: 6 ns
- triplet: 1300 ns
- wavelength: 128 nm



Pulse shape discrimination (PSD) parameter:

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

Discrimination > 10^8



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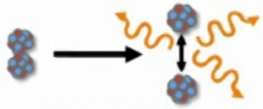

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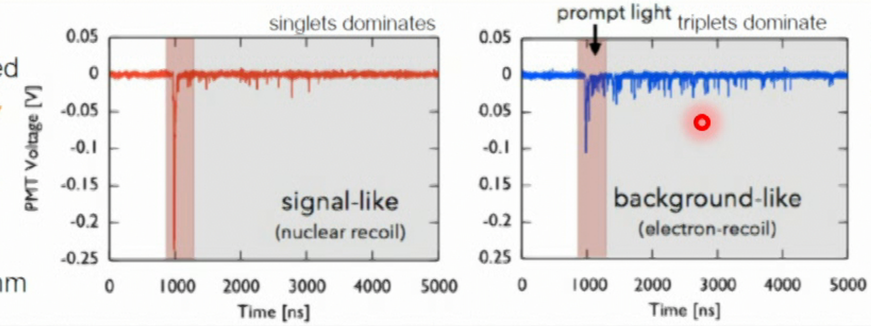

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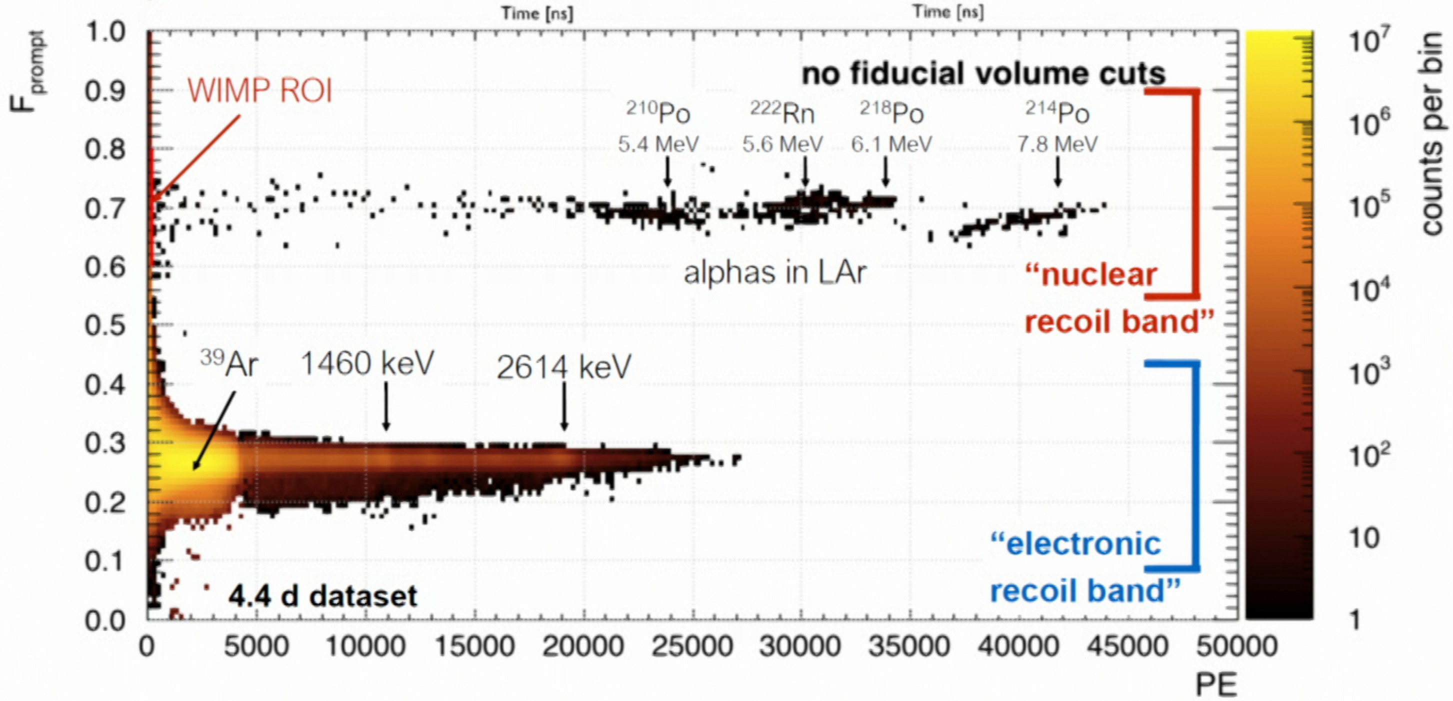


Over 400 scientists form the Global Liquid Argon Dark Matter Collaboration from 14 countries:

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

Sequence of Dark Matter experiments:

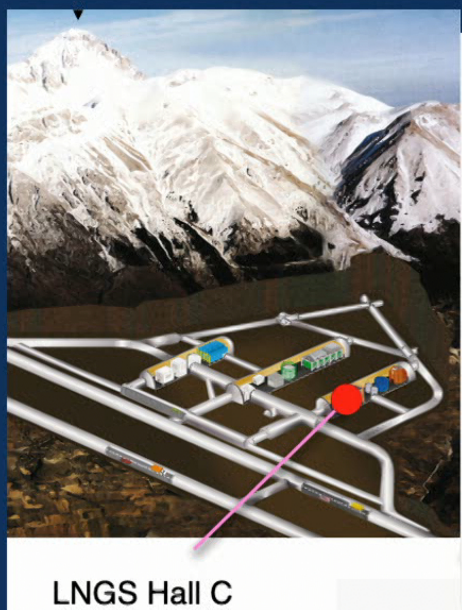
- DEAP: 3 tonnes (SNOLAB)
- DarkSide 20K: 100 tonnes (Italy)
- ARGO: 400 tons (SNOLAB) to reach down to the “Neutrino Fog” background

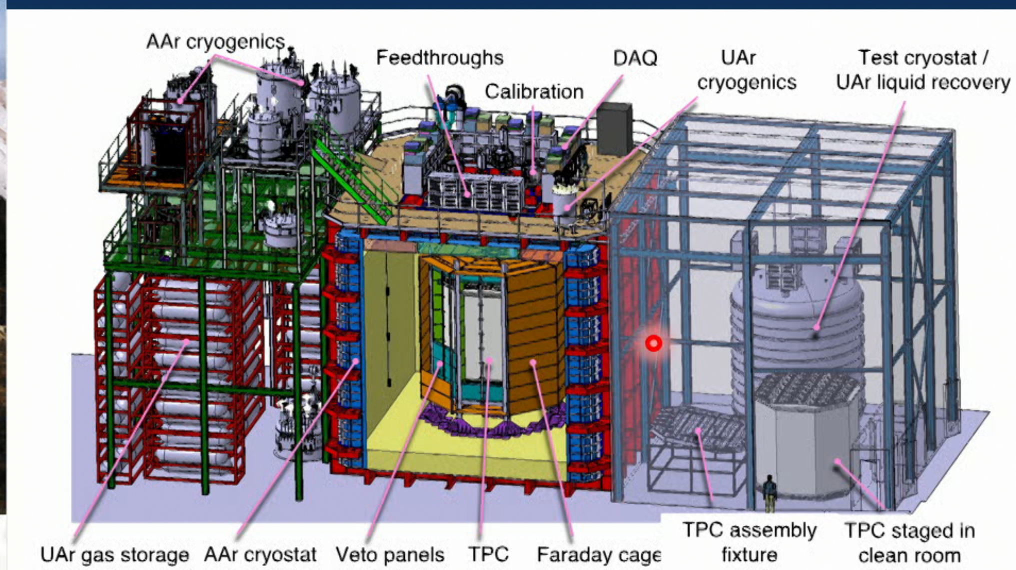
In DarkSide-20k we use the timing of the light signals to throw away radioactivity and also add an electric field to drift the electrons to the top of the detector where they produce a further signal in the gas above the liquid.

Proto Dune detector at CERN

This is a complicated experiment that builds on the technology from the Proto-DUNE detector at CERN

DarkSide-20k at Gran Sasso

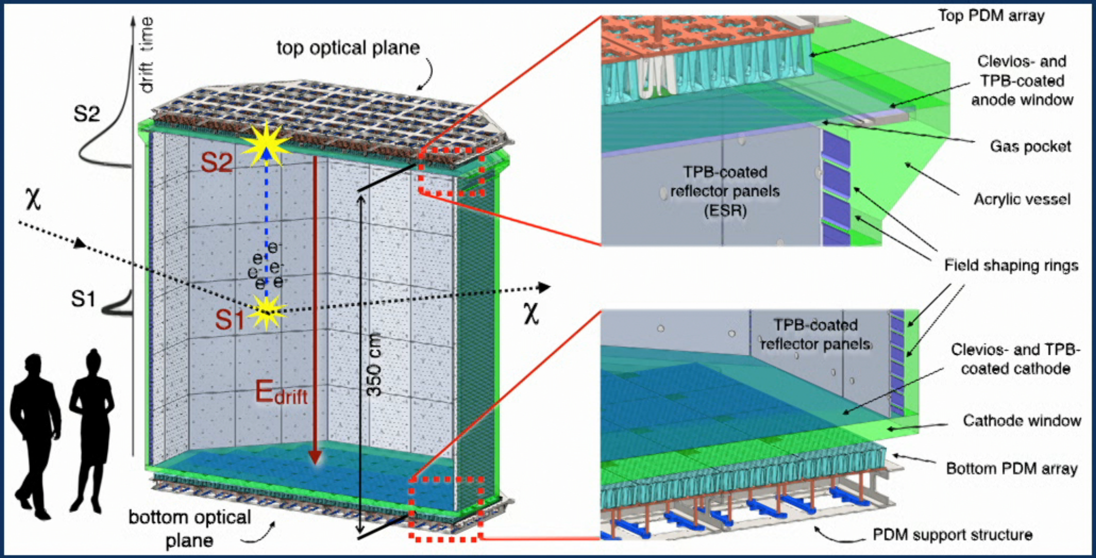




DarkSide-20k at Gran Sasso

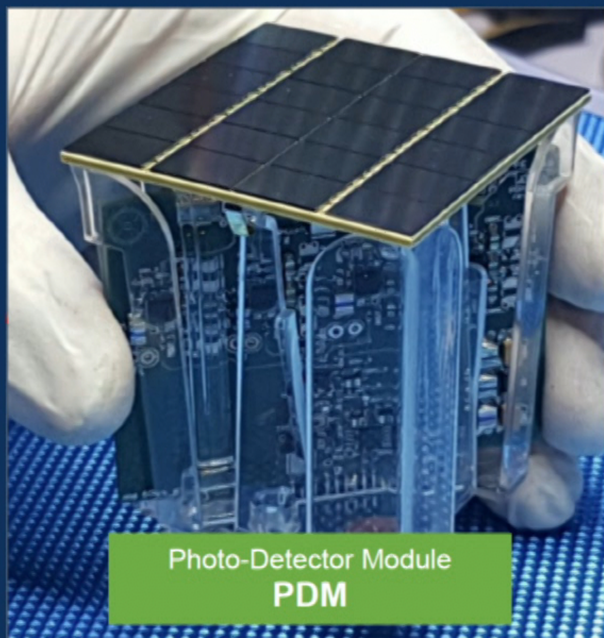
100-tonnes of underground argon with 20 tonnes fiducial volume

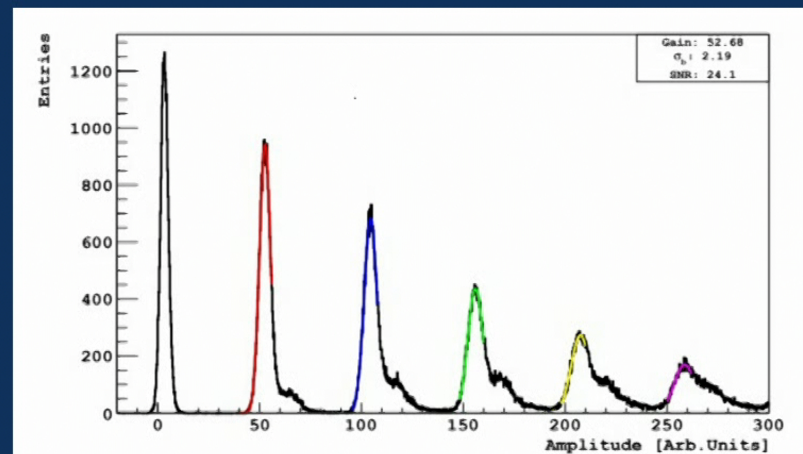
21 m^2 of Silicon PhotoMultipliers operating at Cryogenic Temperature



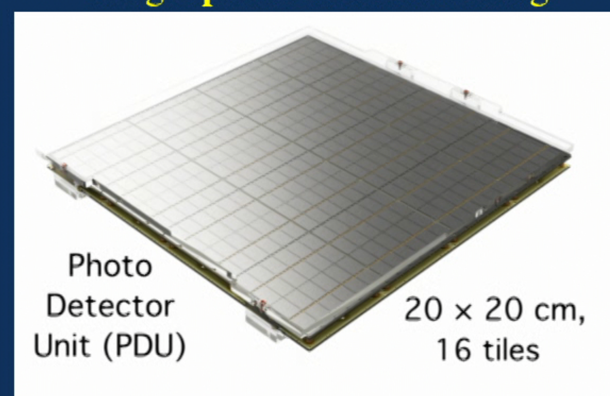
TPC acrylic vessel surrounded by Low radioactivity Ar + Gd-loaded acrylic shell and instrumented external region as a neutron veto

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





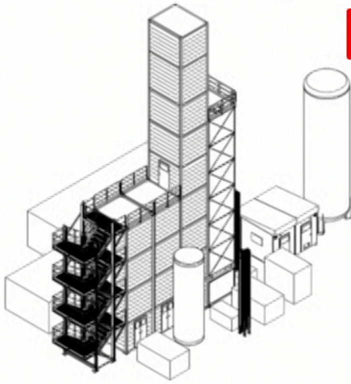
Single **photo-electron** timing

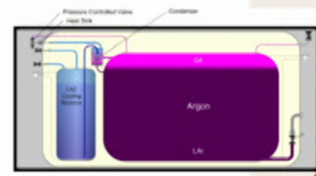


Preliminary version: SIMILAR TO 3 INCH DIAMETER PHOTOMULTIPLIER

UAr for DS-20k

Extract Ar from Cortez, CO underground CO_2 flow.

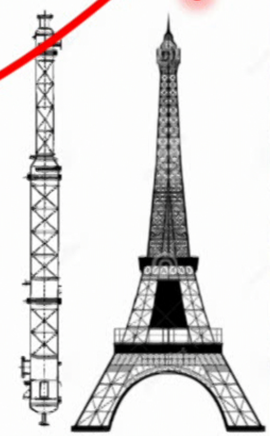




- Urania: procure 50 t of UAr
- Extract > 280 kg/day
- UAr transported to Sardinia for final chemical purification at Aria

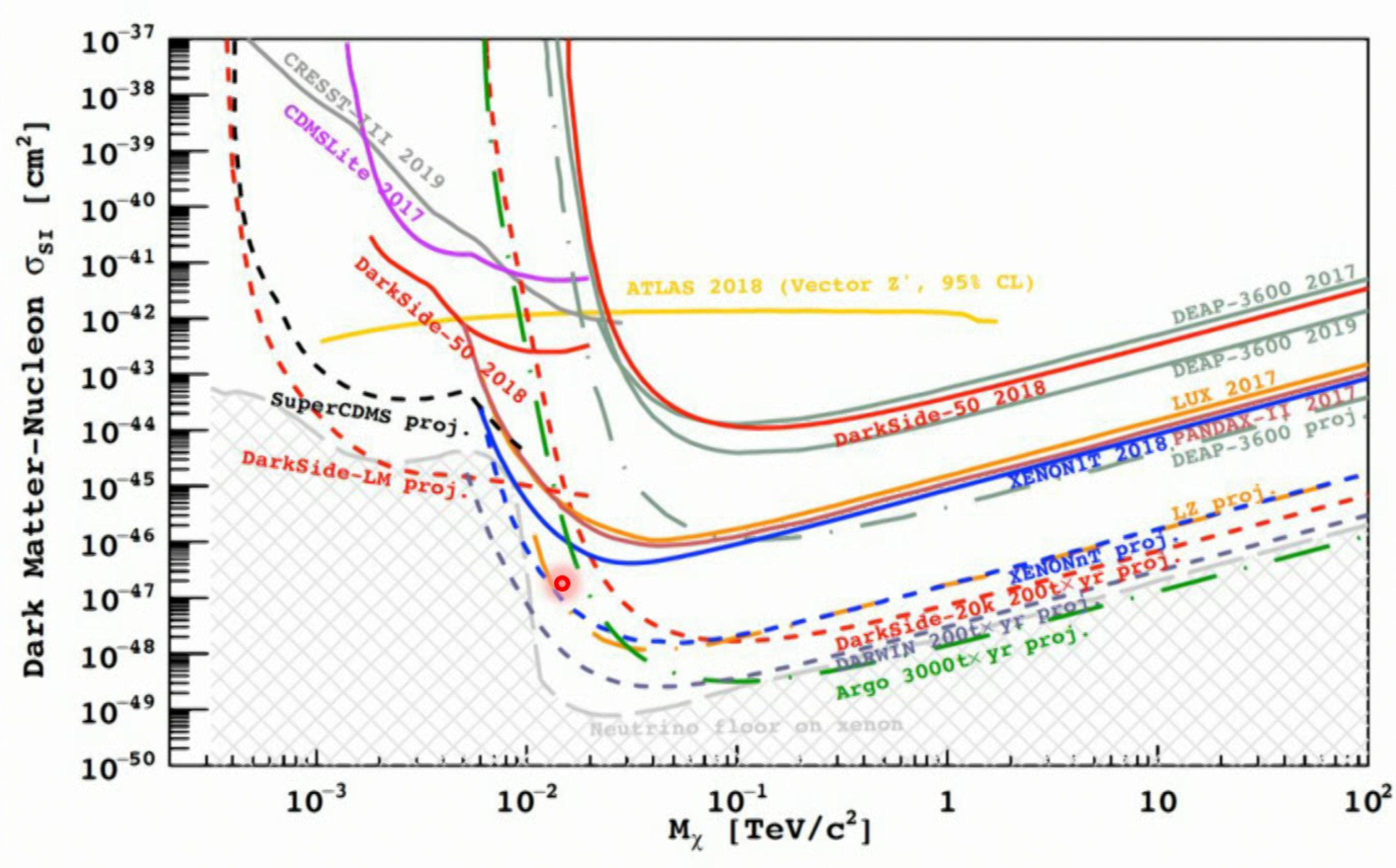
Extraction capacity of > 90 Tonnes per year for the longer term.

- 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 1 kg/day projected enrichment of factor of 10



Urania extraction equipment completed, ready for shipment to US.

First part of ARIA successfully operated in Sardinia after tests at CERN



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.

Conclusions

- Particle Astrophysics has become a major part of the field of particle physics
- Underground laboratories are making major progress with experiments that address:
  - Neutrino properties with measurements of Neutrino-less double beta decay (Majorana nature and absolute neutrino mass)
  - Neutrino properties with long and short baseline accelerator measurements (mass hierarchy, CP violation, sterile neutrinos)
  - Direct Dark Matter measurements
- All of these measurements have great significance in Particle Physics, Astrophysics and Cosmology and these fields are working well together to understand our Universe and its evolution.