Particle Astrophysics in Underground Laboratories

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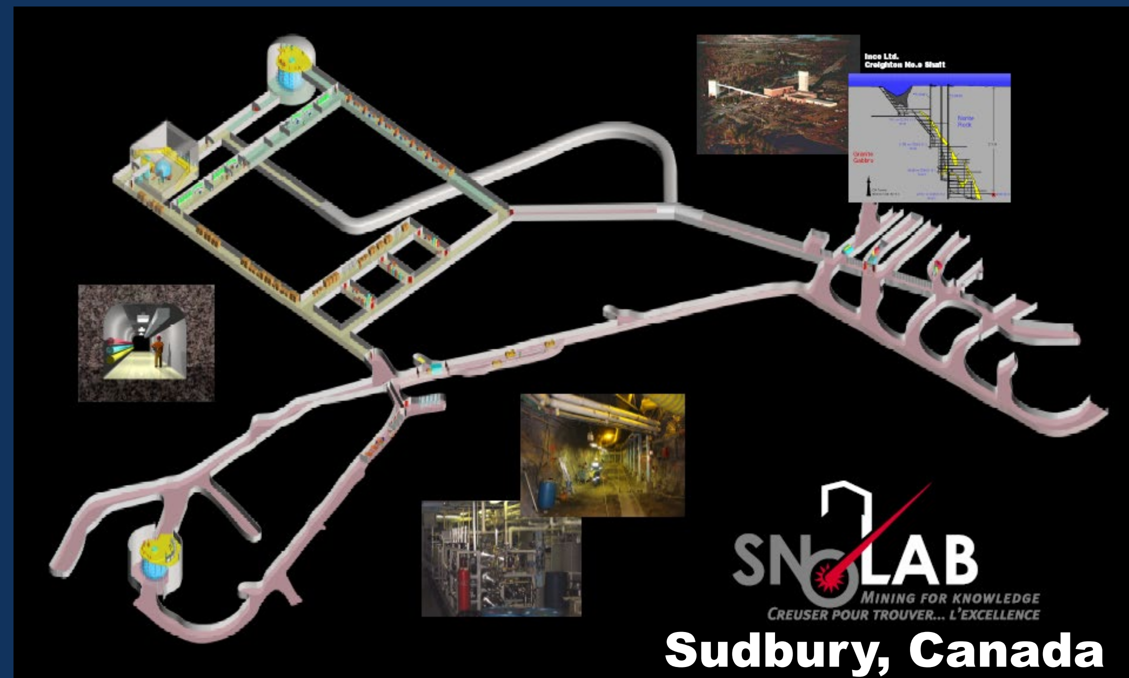


With our laboratories deep underground we have created one of the lowest radioactivity locations in the world where we study some of the most basic scientific questions:

- **How do stars like our Sun burn and create the elements from which we are made?**

- **What are the basic Laws of Physics for the smallest fundamental particles?**

- **What is the composition of our Universe and how has it evolved to the present ?**

How do you make measurements that can provide answers to enormous questions like these?

Answers:

1. **Measure elusive particles called NEUTRINOS that come from the deepest reaches of the Sun where the energy is generated.**

2. **Measure fundamental particles (DARK MATTER) that are left over from the original formation of the Universe.**

3. **Measure rare forms of radioactivity (DOUBLE BETA DECAY) that can tell us more about fundamental laws of physics.**

Neutrino facts:

• **Neutrinos, along with electrons and quarks, are basic particles of nature that we do not know how to sub-divide further.**

• **Neutrinos come in three "flavours" (electron, mu, tau) as described in The Standard Model of Elementary Particles, a fundamental theory of microscopic particle physics.**

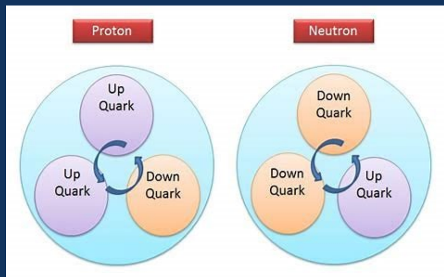
• **They only feel the Weak Force. Therefore, they only stop if they hit the nucleus of an atom or an electron head-on and can pass through a million billion kilometers of lead without stopping.**

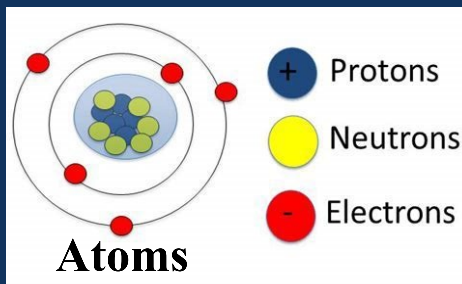
• **That makes them very difficult to detect and their properties have been the least known among the basic particles.**

• **The Standard Model said that they should not change their flavor or oscillate between flavors. If the do oscillate, it implies that they have a mass greater than zero.**

Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

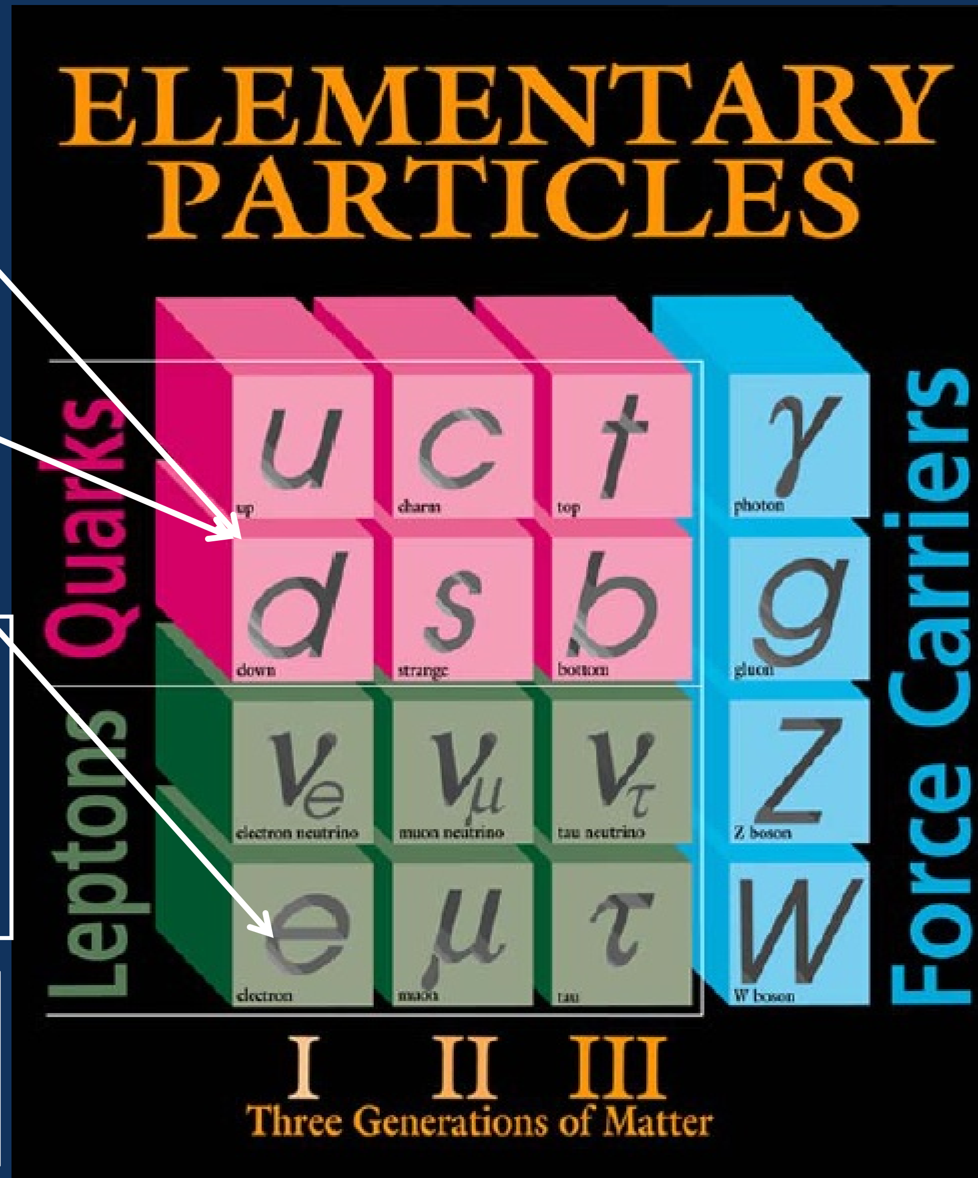
Standard Model for Elementary Particles





- Neutrinos feel only the weak force (and gravity). Produced in radioactive decay or in large numbers by nuclear fusion in the Sun

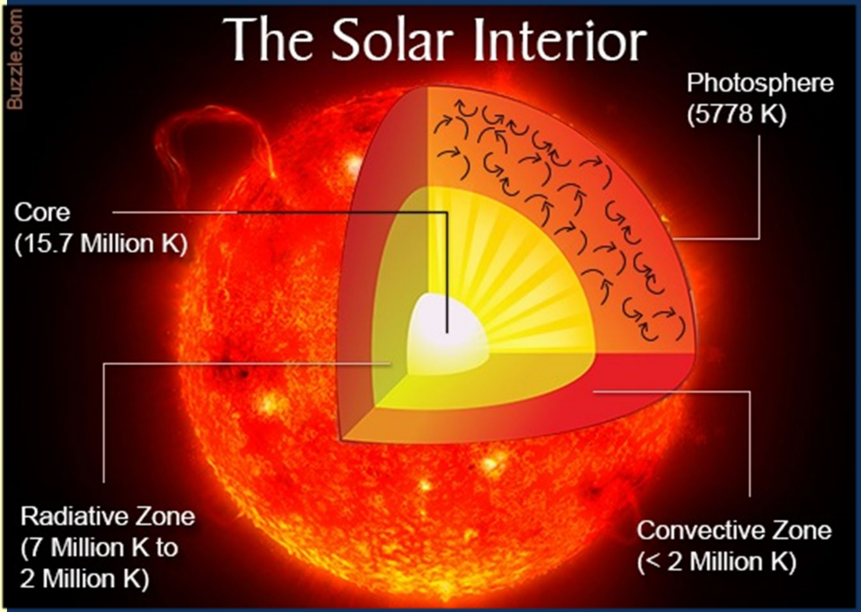
- Each particle has a matching particle made of anti-matter.



+ Higgs Boson

+ Anti-Matter Particles

The Standard Model provides a basis for the Electromagnetic, Weak and Strong forces, but does not yet include Gravity.



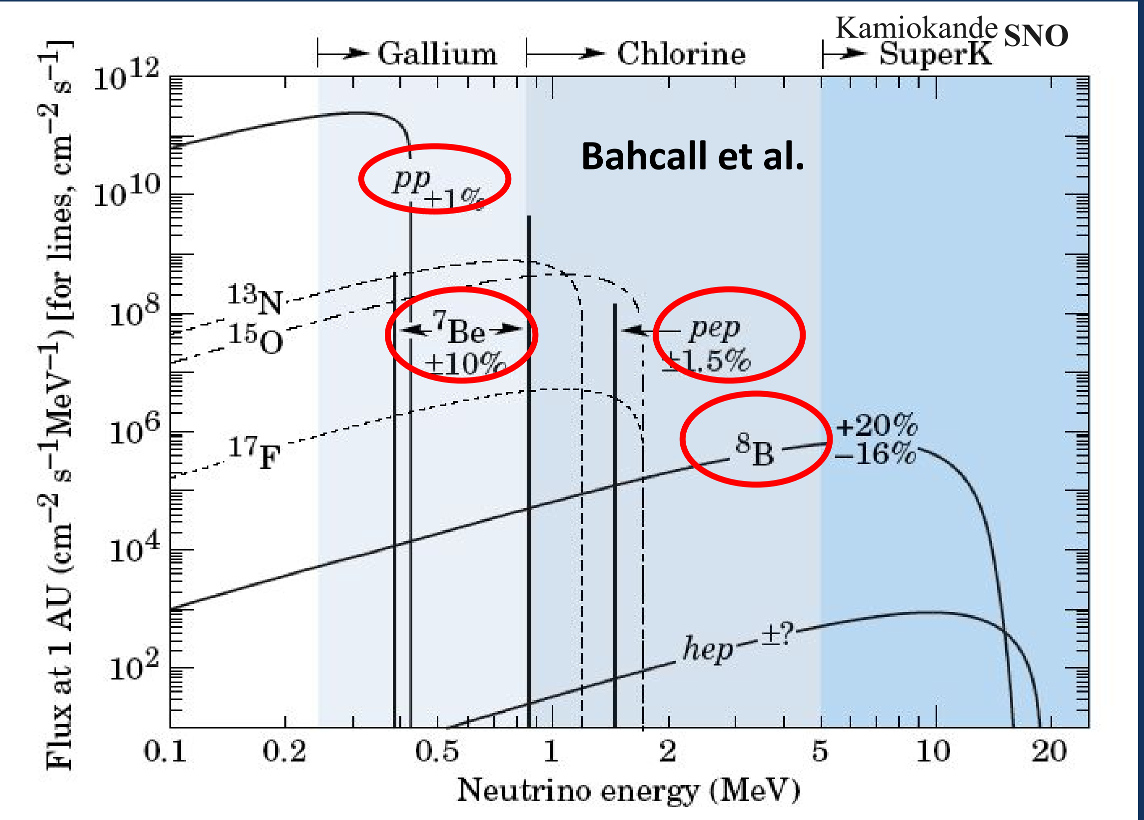
NEUTRINO FLUXES FROM THE SOLAR CORE

EXPERIMENTS

1992 on | 1968 on | 1989 on | 2001 on

HOW DOES THE SUN BURN?

Nuclear fusion reactions produce enormous numbers of electron neutrinos



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

- NEUTRINO MEASUREMENTS OBSERVED TOO FEW OF THE ELECTRON FLAVOUR NEUTRINOS PRODUCED IN THE SUN, COMPARED TO SOLAR MODEL CALCULATIONS

- 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.

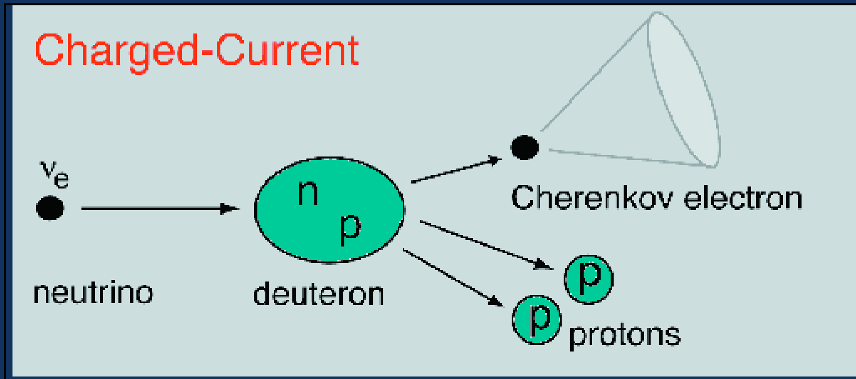
Unique Signatures in SNO (D_2O)

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

Electron Neutrinos (CC)

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

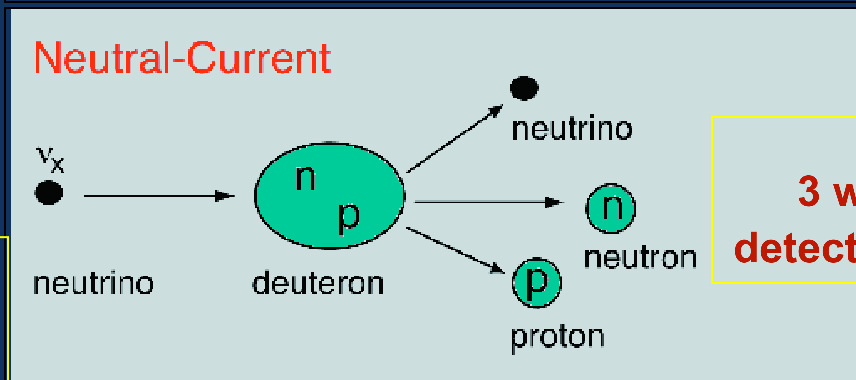
$E_{thresh} = 1.4$ MeV



Equal Sensitivity All Types (NC)

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

$E_{thresh} = 2.2$ MeV

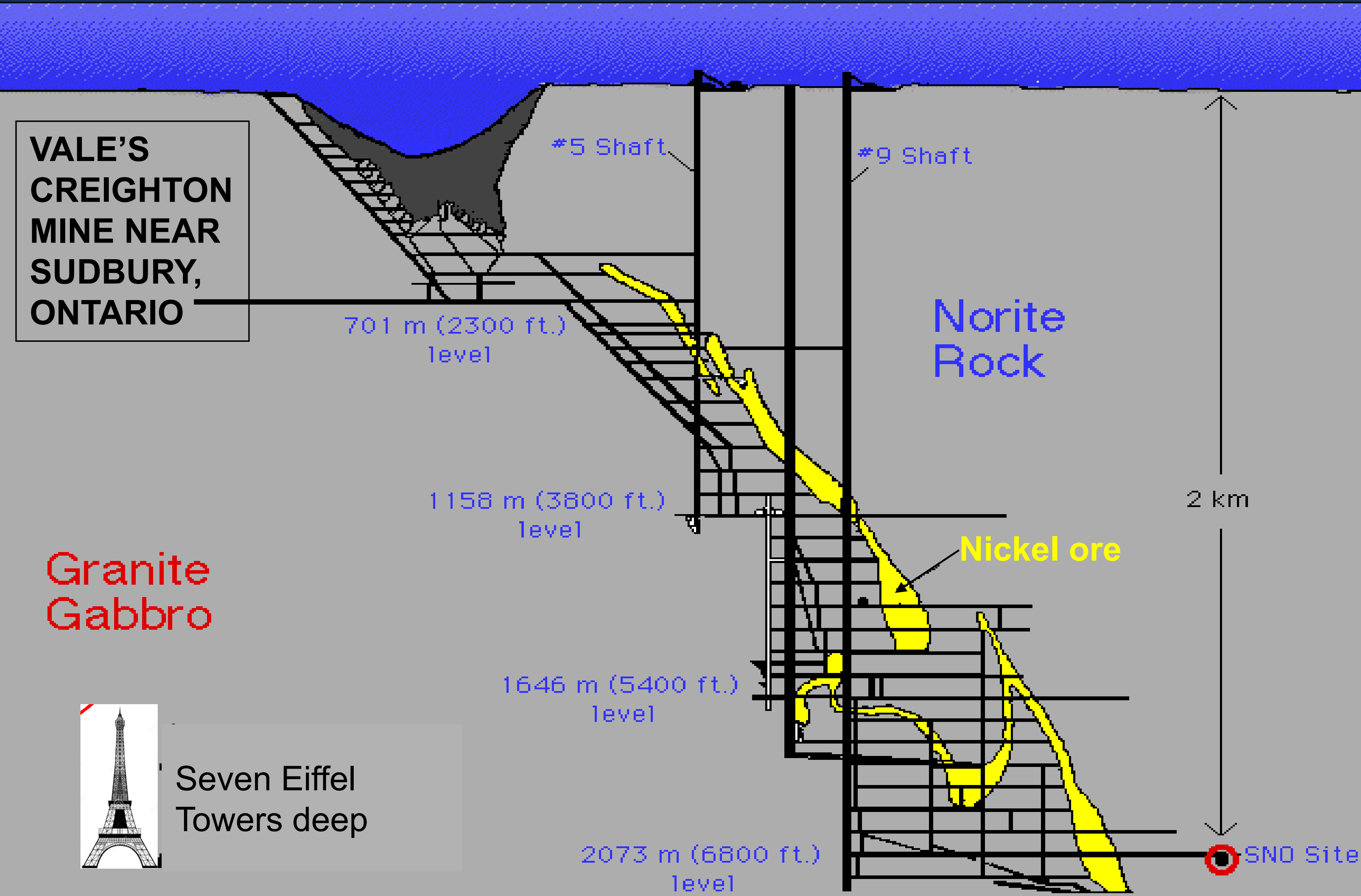


3 ways to detect neutrons

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.

To study Neutrinos with little radioactive background, we went 2 km underground to reduce cosmic rays and built an ultra-clean laboratory: SNOLAB



Sudbury Neutrino Observatory (SNO)

Neutrinos are very difficult to detect so our detector had to be very big with low radioactivity deep underground.

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

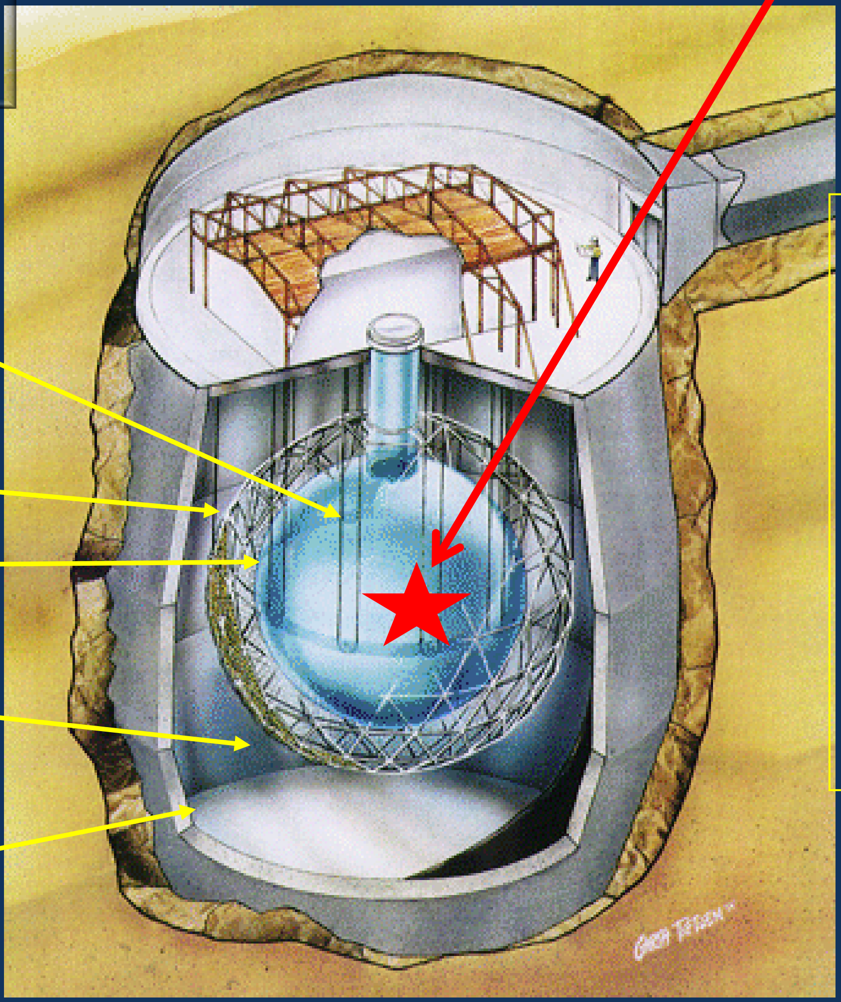
9500 light sensors

12 m Diameter Acrylic Container

Ultra-pure Water: H_2O.

Urylon Liner and Radon Seal

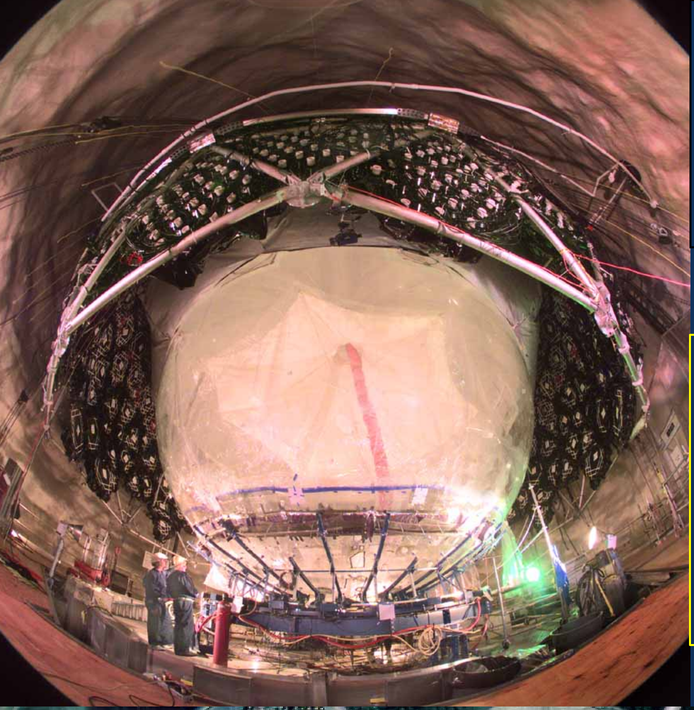
NEUTRINO



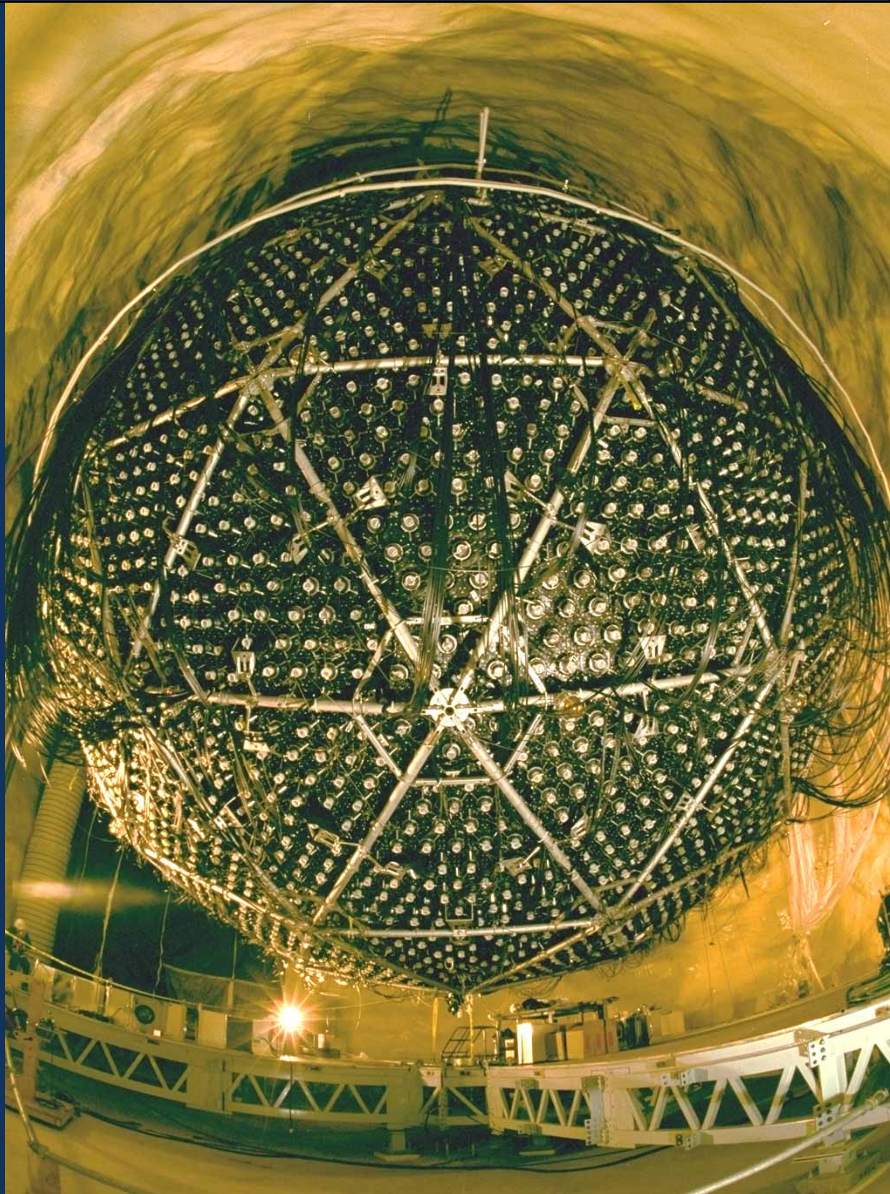
34 m or ~ Ten Stories High!

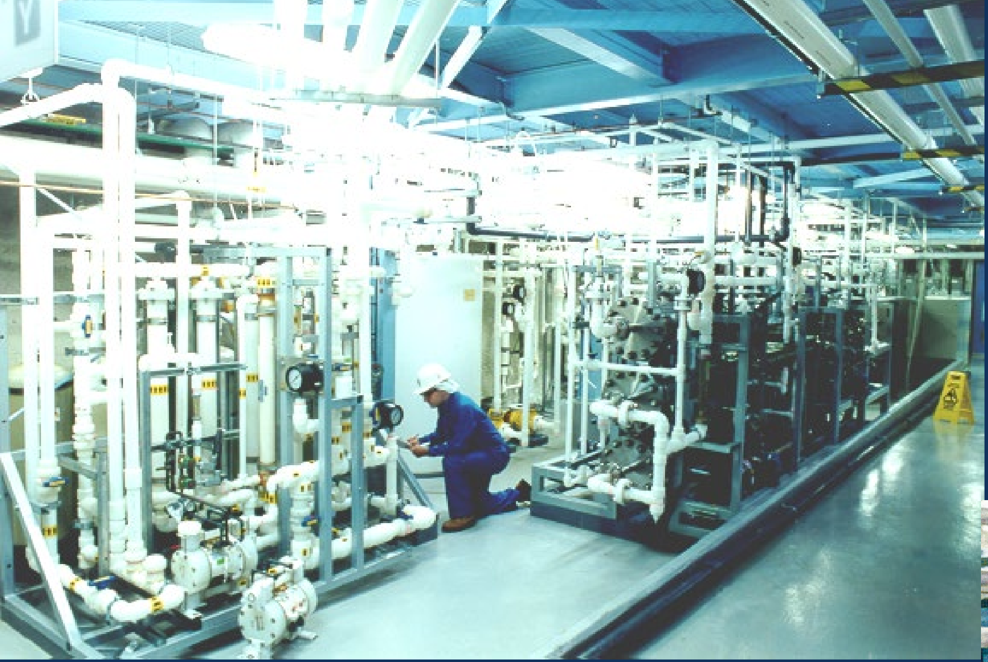
2 km below the ground

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

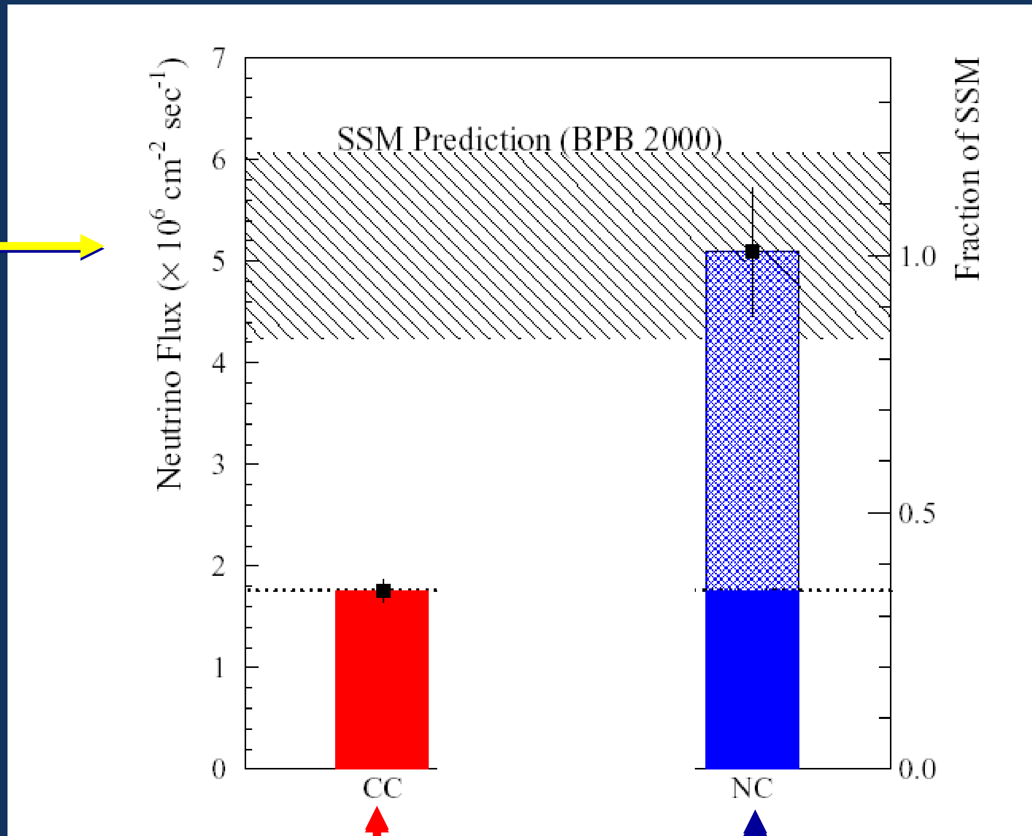




Water systems were developed to provide low radioactivity water and heavy water: 1 billion times better than tap water. Less than one radioactive decay per day per ton of water!!

Steven Hawking's Visit Posed some special Challenges – INCO Designed a special Rail car for him.

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.

Why is it important for us to know these details about the sun & neutrinos?

1. **Neutrinos**: Observation of flavor change and finite mass for neutrinos provide evidence for **physics beyond the Standard Model**

2. **Neutrinos** are produced extensively in the Big Bang and depending on their mass, can have a significant influence on **how the Universe evolved since the Big Bang**.

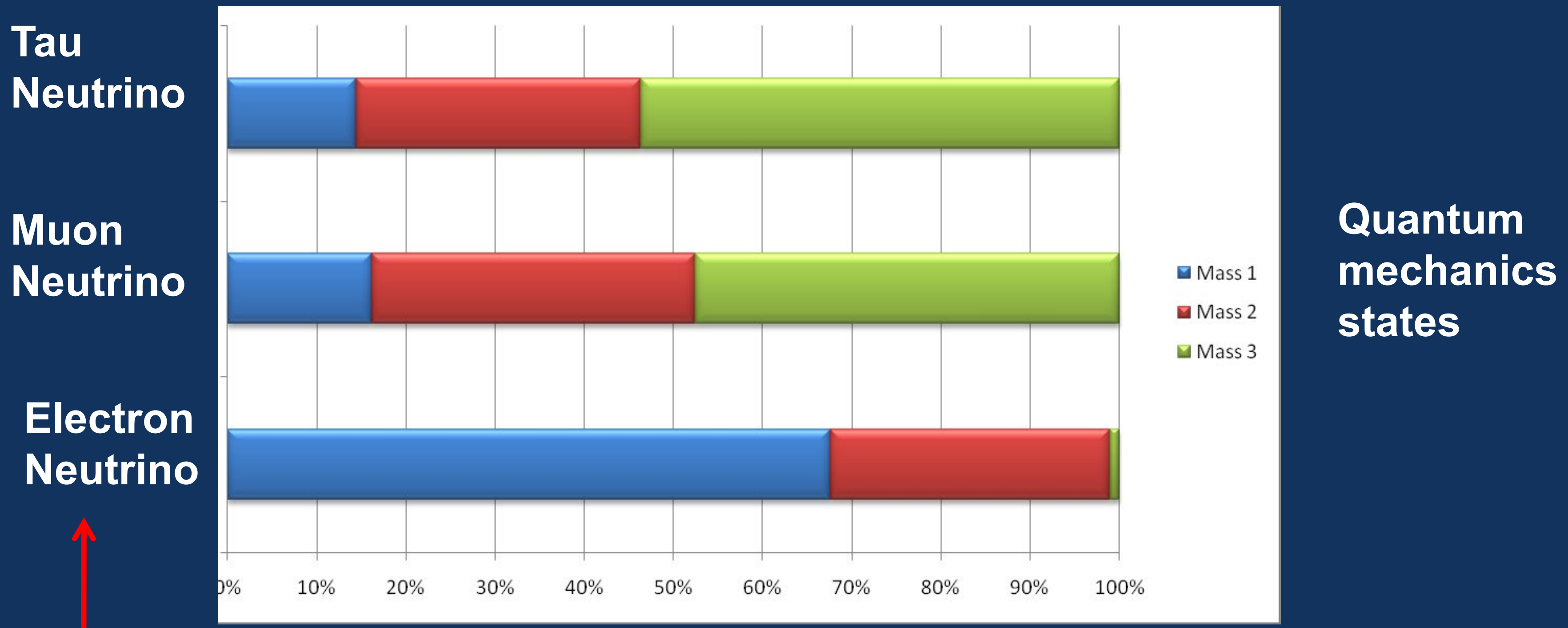
3. **Understanding The Sun**: Most of **the elements from which we are made (C, N, O)** were **produced** in the nuclear processes in the center of stars like the sun or in collapsing stars called supernovae.

4. **Understanding The Sun**: People are trying to reproduce the sun's energy generation here on earth, confined by magnetic fields instead of gravity. It is called a **fusion power source**. We have proven that calculations of sun are very accurate, and they are very similar to the calculations needed for **fusion power here on earth.**

So our measurements help with our understanding of the Universe large and small as well as providing practical information for new energy systems here on earth.

NEUTRINO OSCILLATIONS AND NEUTRINO MASS

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



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} ✓

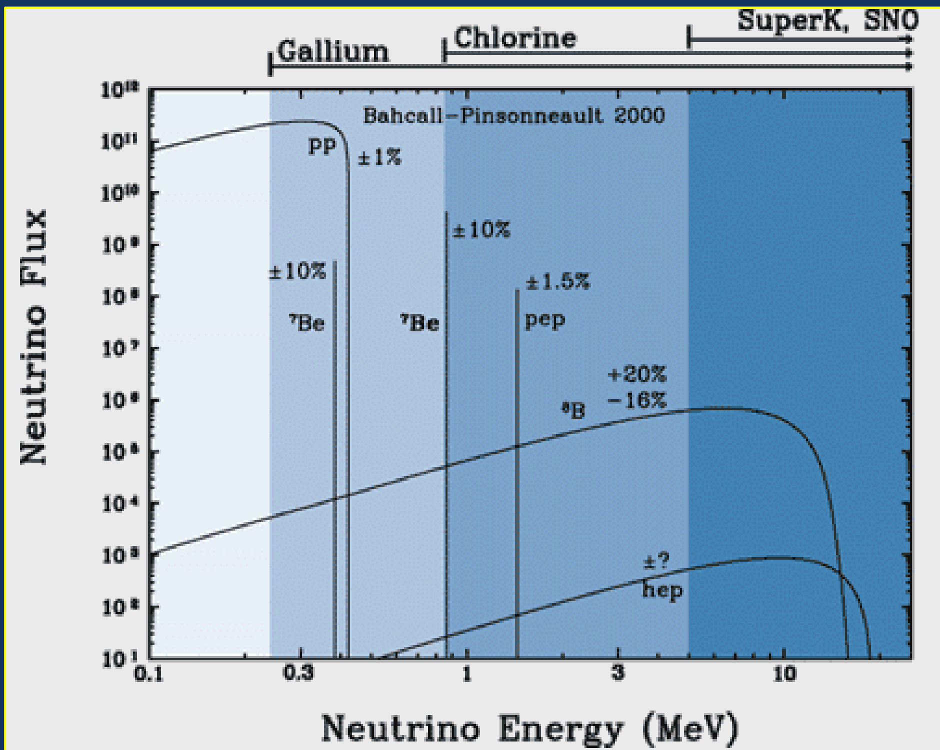
For two neutrino oscillation in a vacuum: (a valid approximation in many cases)

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

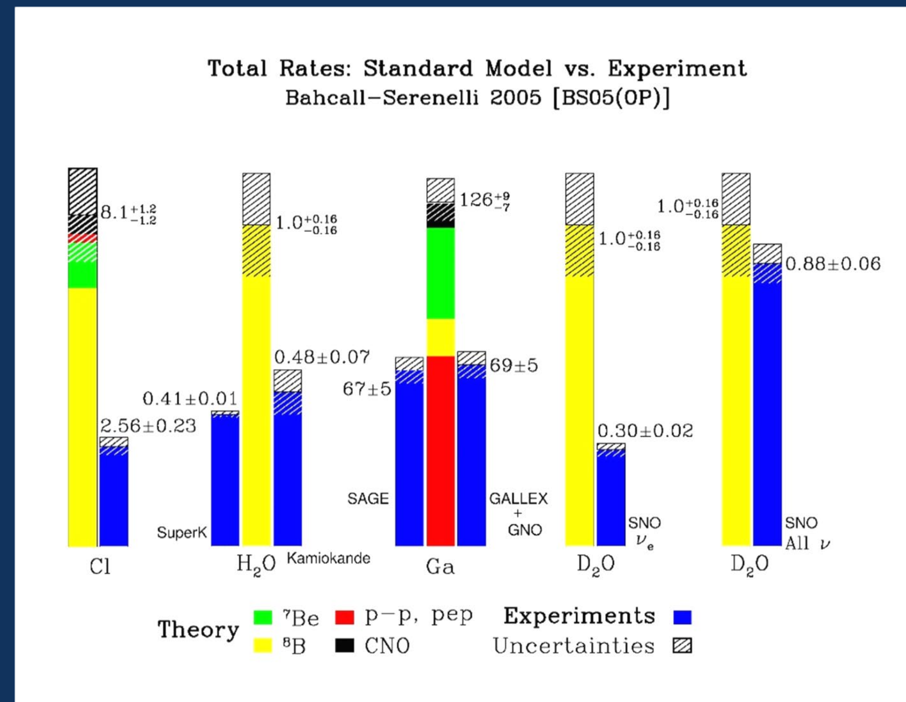
Interactions with high electron density can influence the process in the sun and the earth

Combining SNO with other solar measurements

Solar Fluxes: Bahcall et al

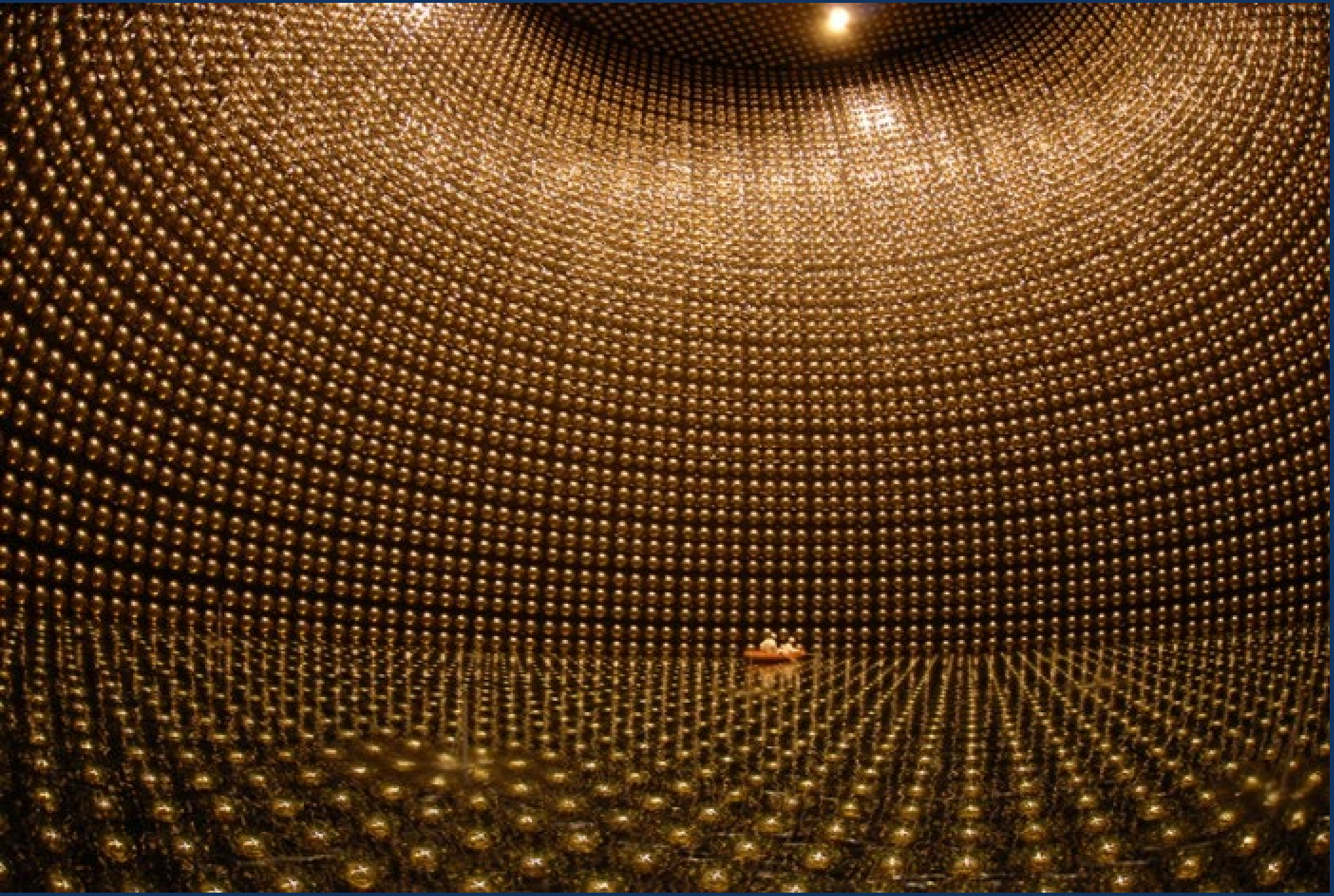


Experiment vs Solar Models



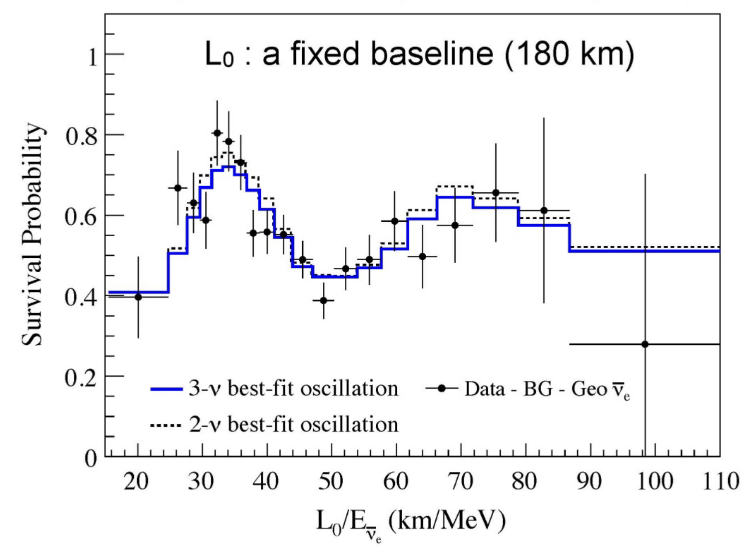
The analysis concludes that the ^{8}B electron neutrinos are converted to a pure Mass 2 state by interaction with the dense electrons in the sun via the Mikheyev-Smirnov-Wolfenstein (MSW) effect. This interaction determines that Mass 2 is greater than Mass 1 as well as determining Δm_{12}^2 and the mixing parameter θ_{12} .

SuperKamiokande Experiment under a mountain in western Japan Observation of oscillation for Atmospheric Neutrinos: Nobel Prize shared with Takaaki Kajita

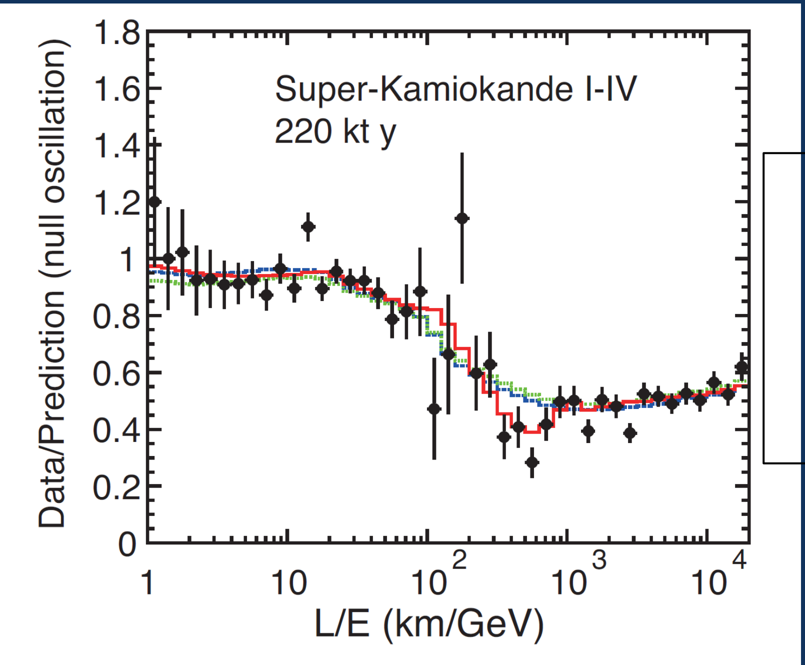


Oscillation Patterns (Various Neutrino Sources)

KamLAND Reactor Neutrinos



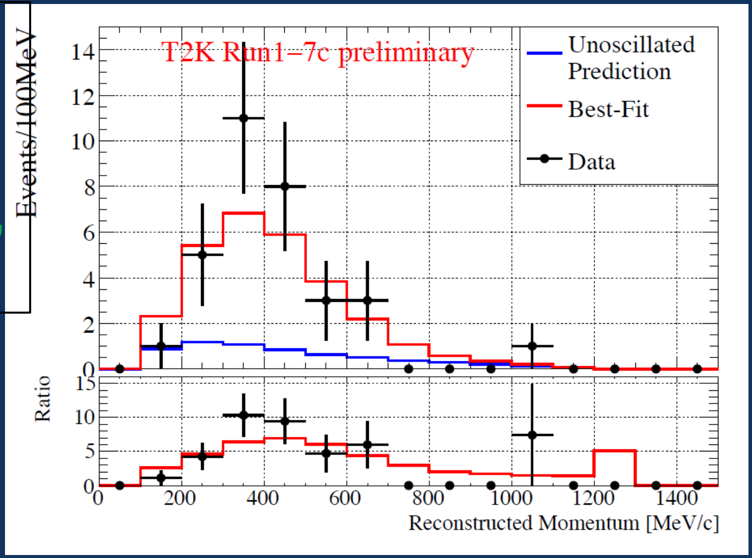
Atmospheric Neutrinos: SuperKamiokande, Oscillation reported 1998



ν_μ oscillation

Disfavored: Neutrino decay, Decoherence

Accelerator Neutrinos: T2K, MINOS, NOVA

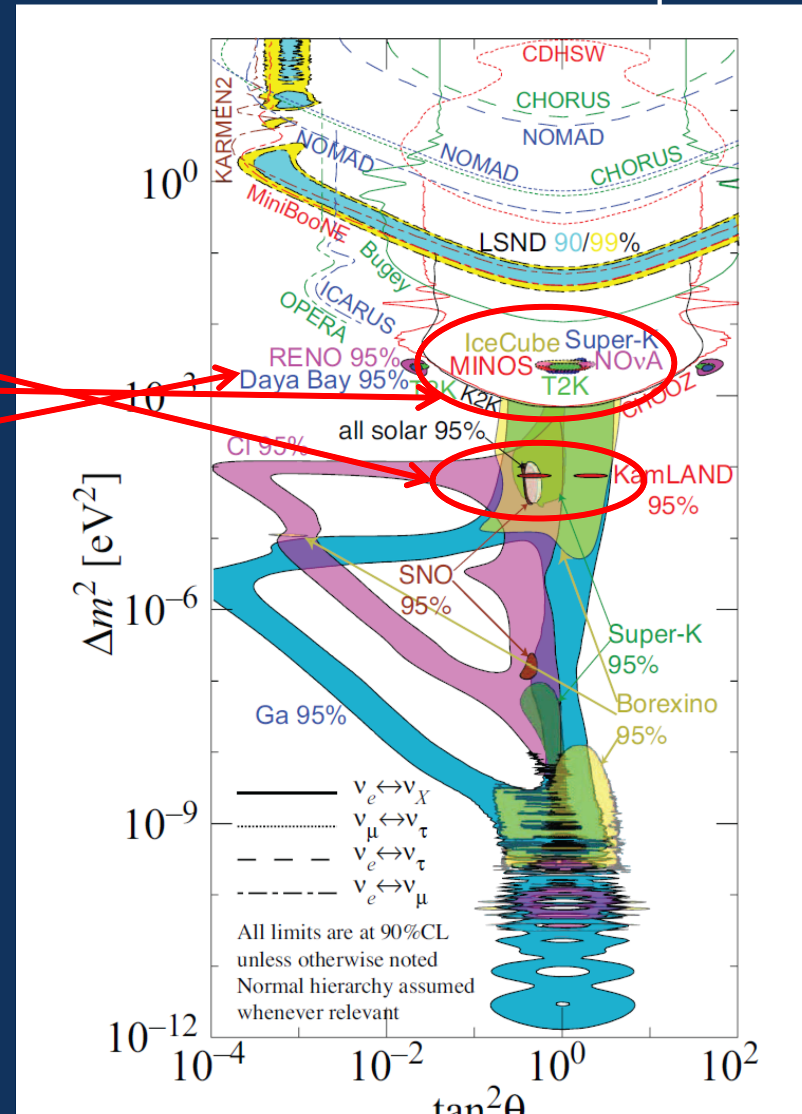


Such oscillations can only occur if neutrinos have the ability to "sense" elapsed time in their rest frame and change type as time evolves. If they can do that, Einstein's theory of relativity requires that they travel at slightly less than the speed of light and thus have a small finite rest mass.

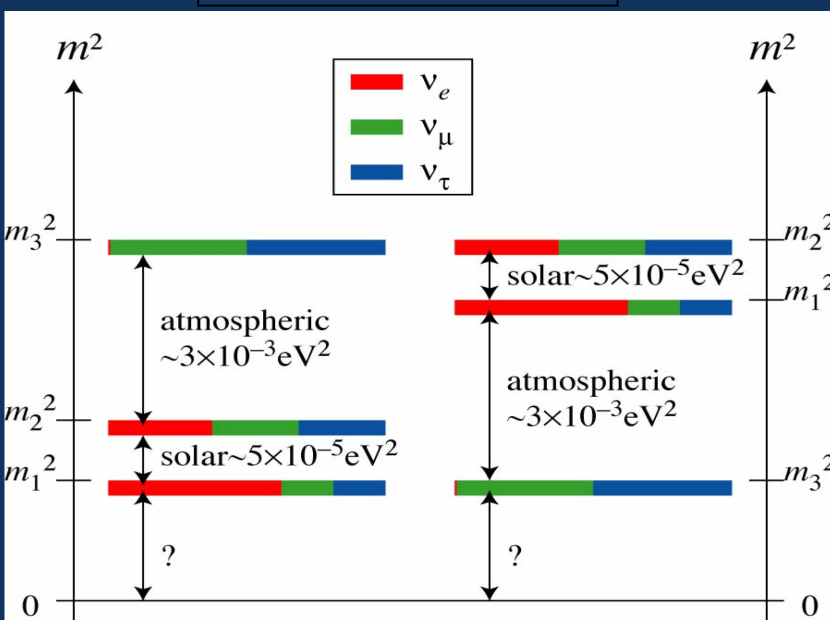
SUMMARY OF RESULTS FOR THREE ACTIVE ν TYPES

Parameter	best-fit	3σ
Δm^2_{21} [10^{-5} eV ^{2}]	7.37	6.93 – 7.97
$\vert\Delta m^2\vert$ [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))

Particle Data Group



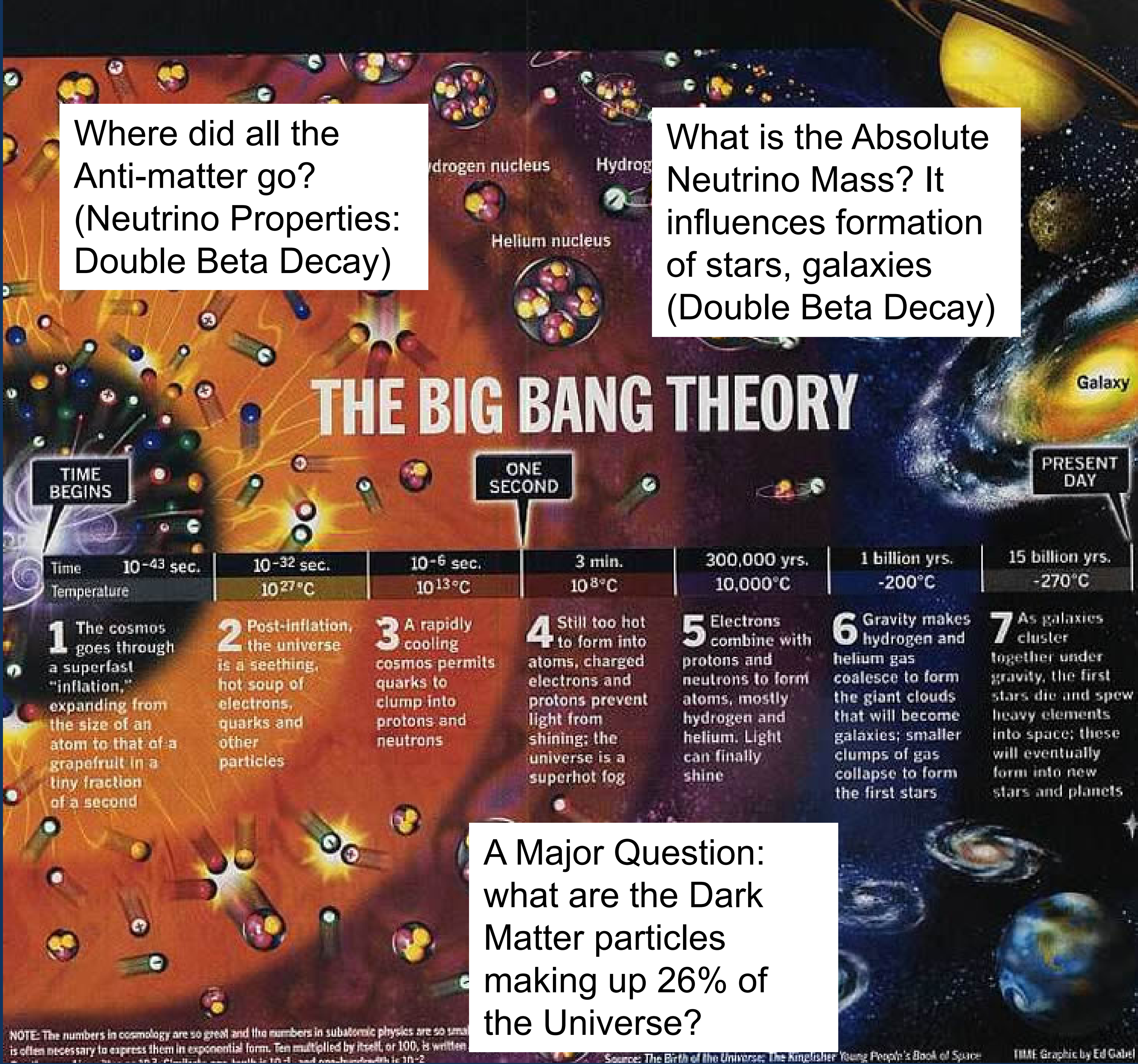
Mass Hierarchies



Normal Inverted

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

Impact of Future SNOLAB experiments



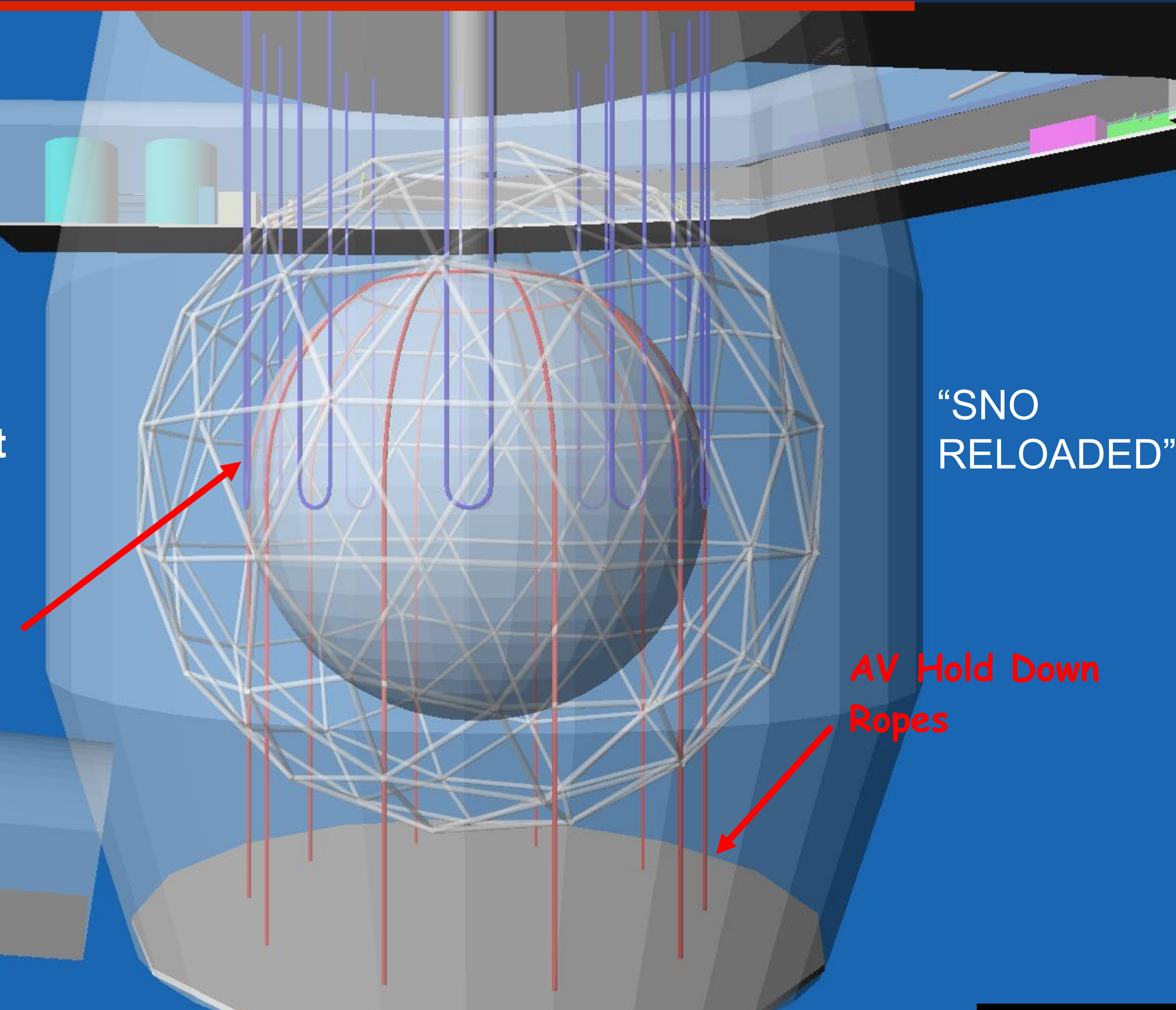
Where did all the Anti-matter go? (Neutrino Properties: Double Beta Decay)

What is the Absolute Neutrino Mass? It influences formation of stars, galaxies (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"

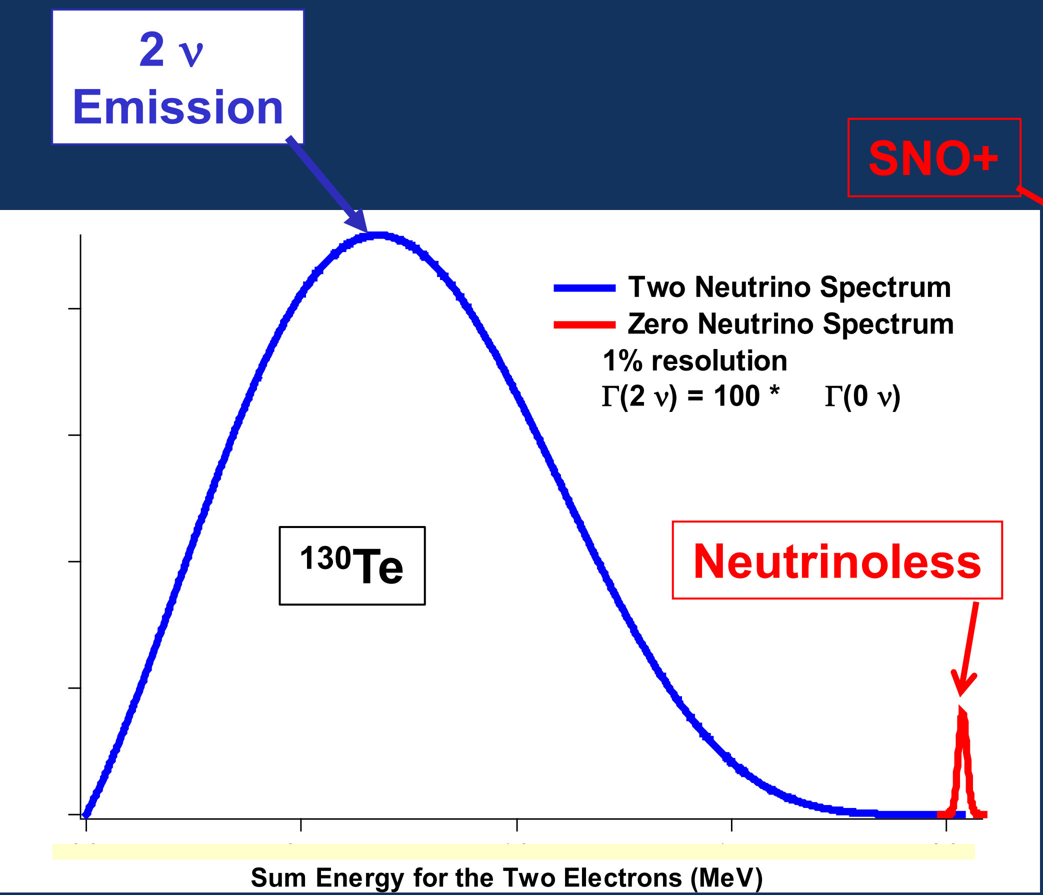
Scintillator now installed. Te installation in early 2021.

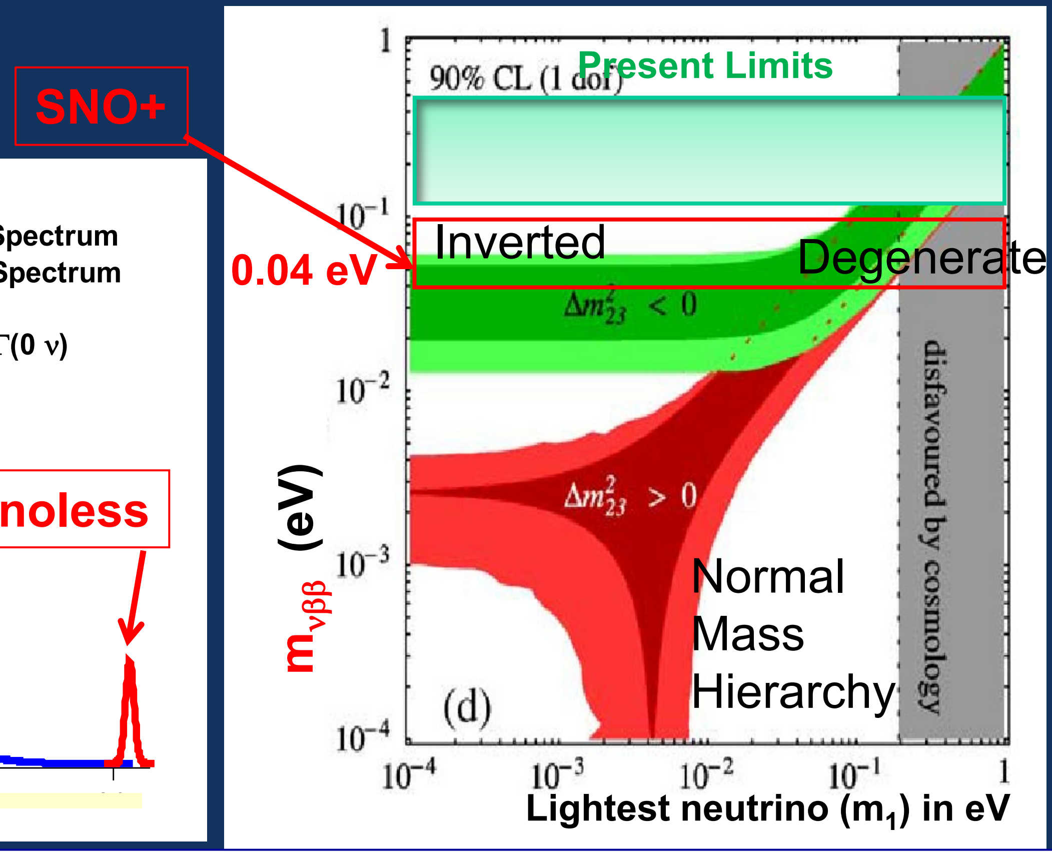
ν-less Double Beta Decay: Measuring Effective ν Mass

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

Additional phases

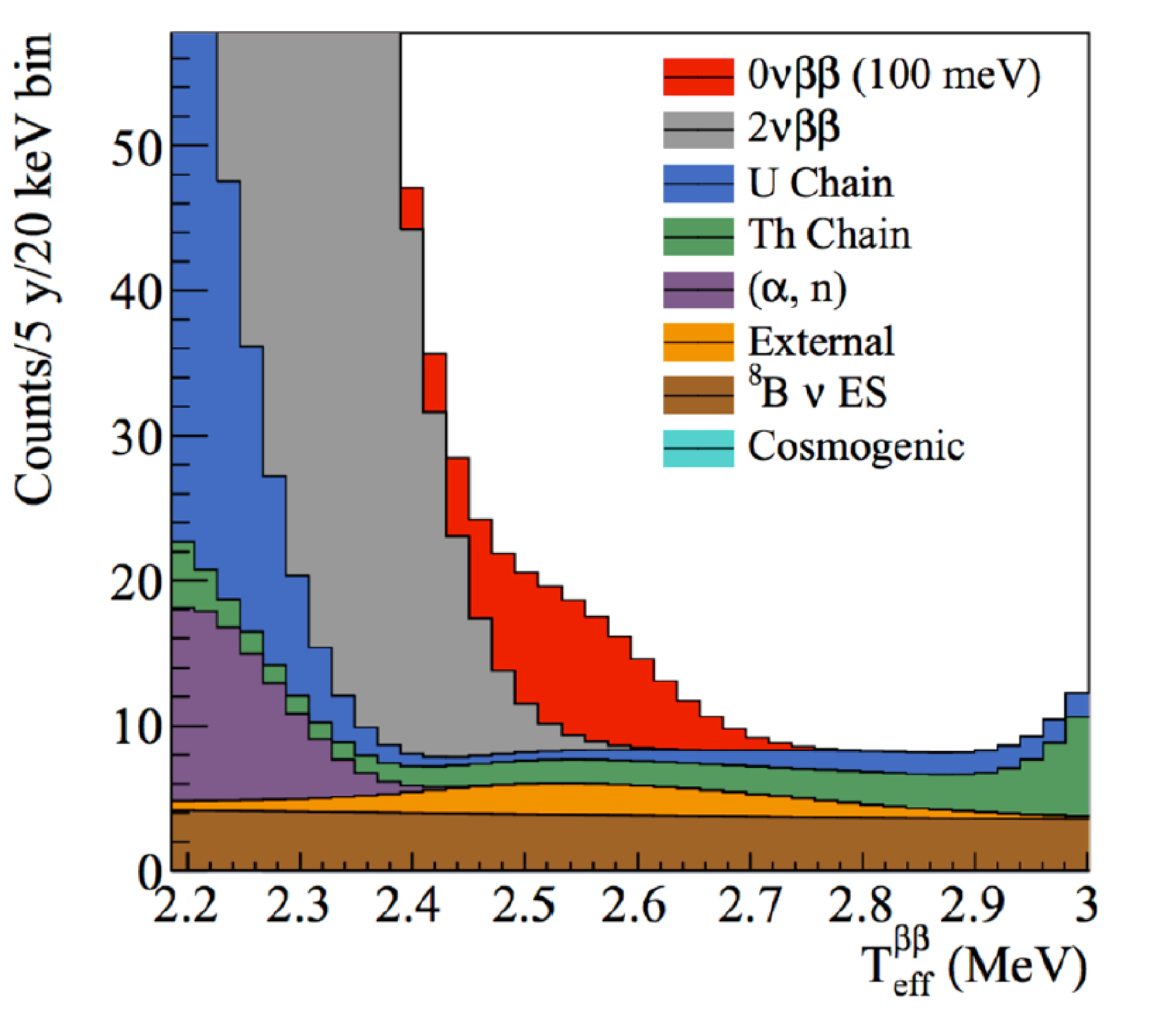
$$m_{\nu\beta\beta} = |m_1 \cos^2\theta_{13}\cos^2\theta_{12} + m_2\, e^{2i\alpha} \cos^2\theta_{13}\sin^2\theta_{12} + m_3\, e^{2i\beta} \sin^2\theta_{13}|$$





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

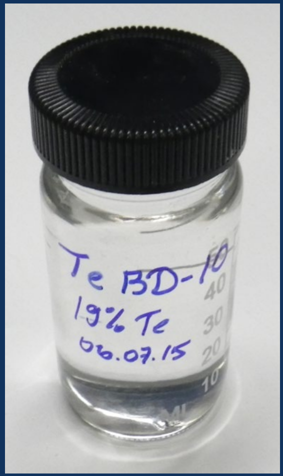
- **Finite ν mass: Lifetimes > ~10^{26} years imply ν mass < 0.1 eV**



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

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

Phase II ??
5.0% ^{130}Te
HQE PMT's

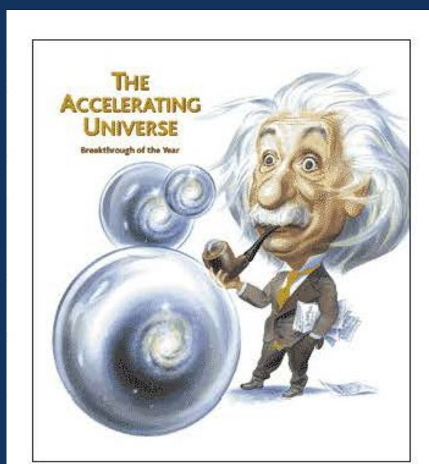


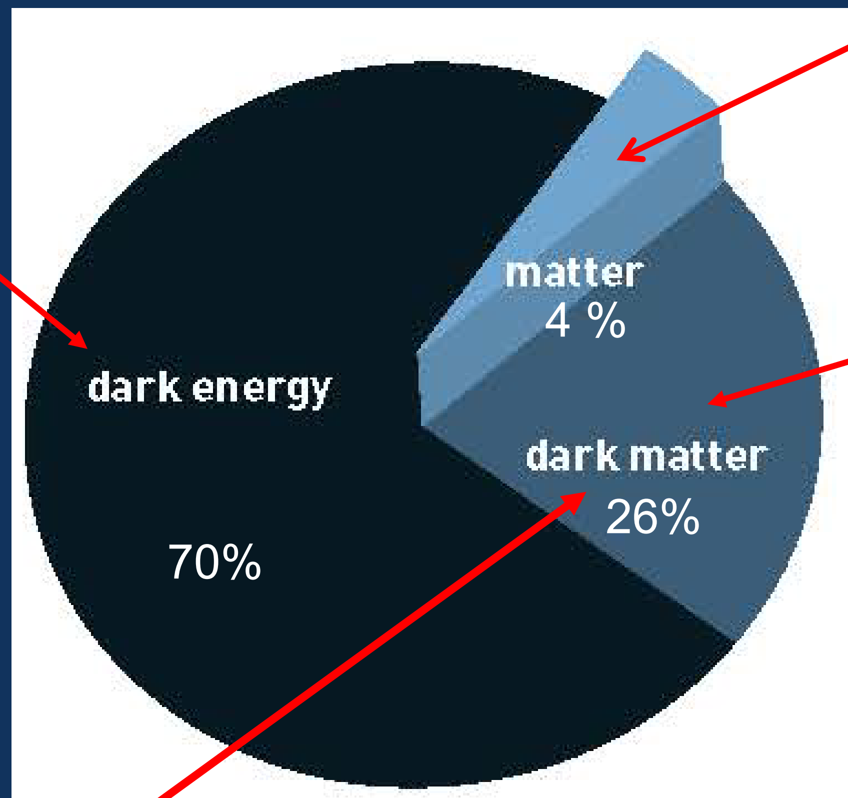
Te to be installed in 2020.

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.)

Responsible for accelerating the Universe's expansion





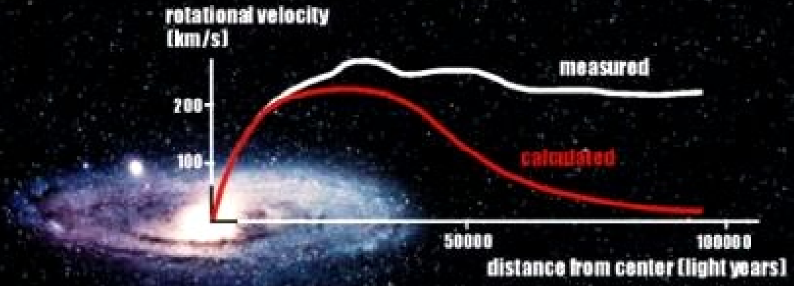
US!!!

Neutrinos Are only a few %

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

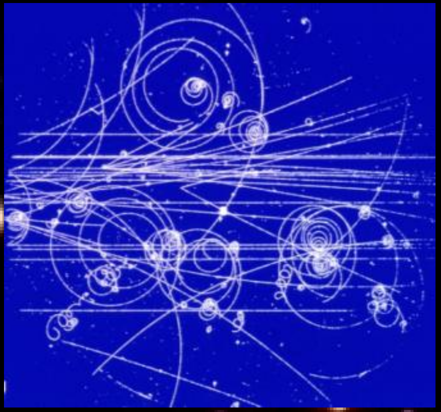
At CERN Accelerator: Try to create it again as occurred in the Big Bang

Dark Matter



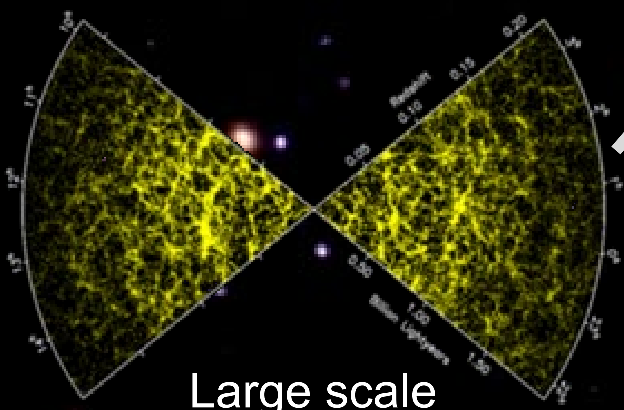
Here, but not yet observed directly in nature: **Weakly interacting**

Not observed in accelerator experiments:



WIMP

(Weakly Interacting Massive Particle)

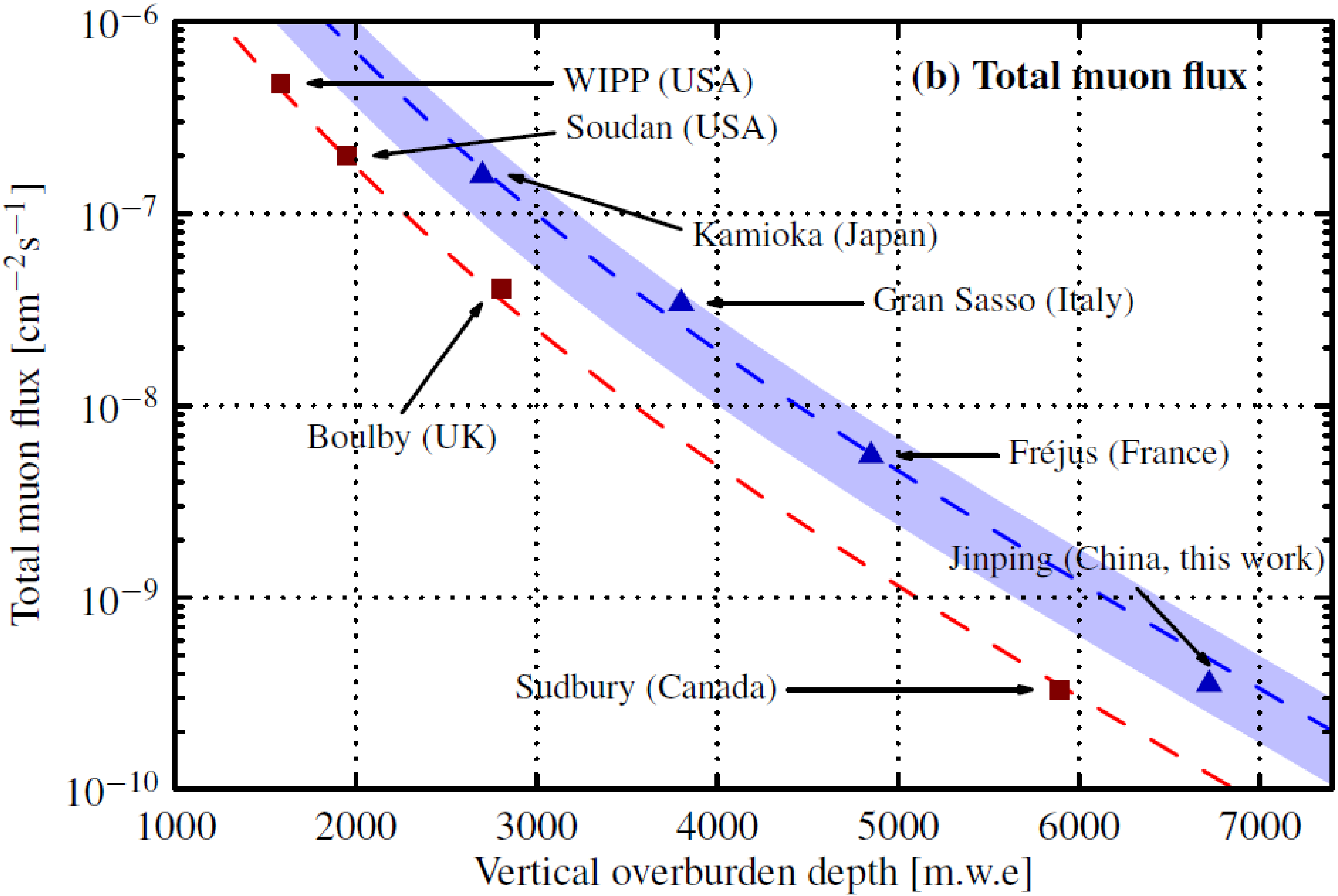


Large scale structure of the Universe: **Slowly moving ('cold')**

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

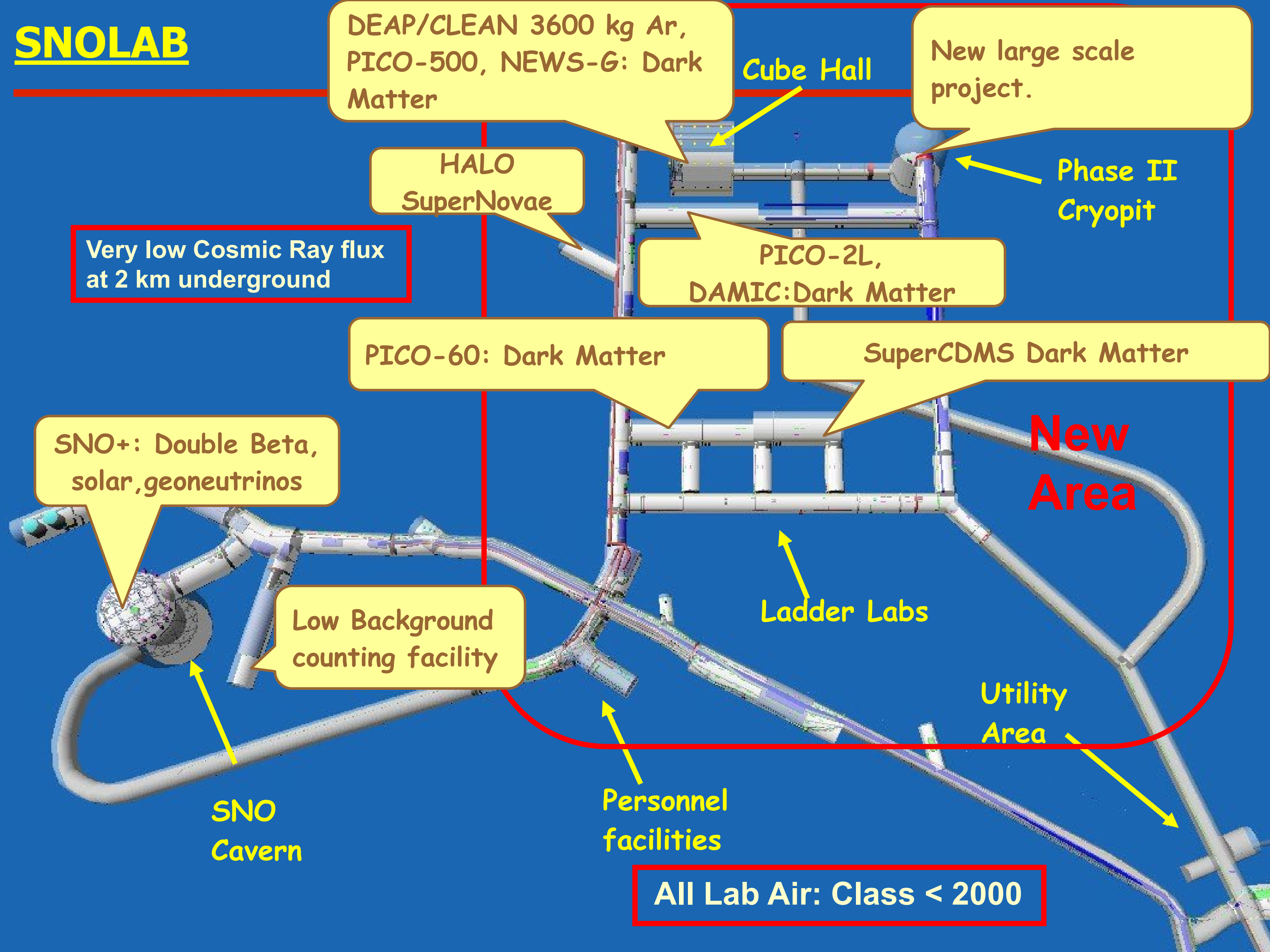
Predicted by SUSY: **Neutralino**
Universal extra dimensions: **Kaluza-Klein particles**

International Underground Laboratories (Dark Matter experiments)



arXiv:2007.15925v2 [physics.ins-det] 13 Oct 2020

SNOLAB



DEAP/CLEAN 3600 kg Ar, PICO-500, NEWS-G: Dark Matter
Cube Hall
New large scale project.
Phase II Cryopit
HALO SuperNovae
Very low Cosmic Ray flux at 2 km underground
PICO-2L, DAMIC:Dark Matter
PICO-60: Dark Matter
SuperCDMS Dark Matter
New Area
SNO+: Double Beta, solar,geoneutrinos
Low Background counting facility
Ladder Labs
Utility Area
SNO Cavern
Personnel facilities
All Lab Air: Class < 2000

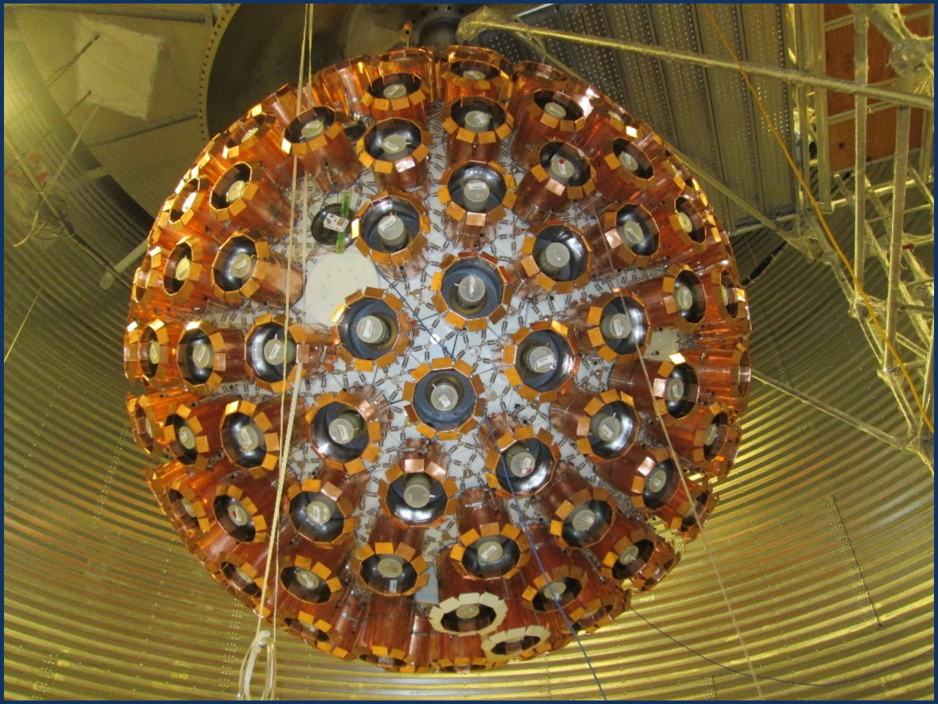
SNOLAB
Experimental Area

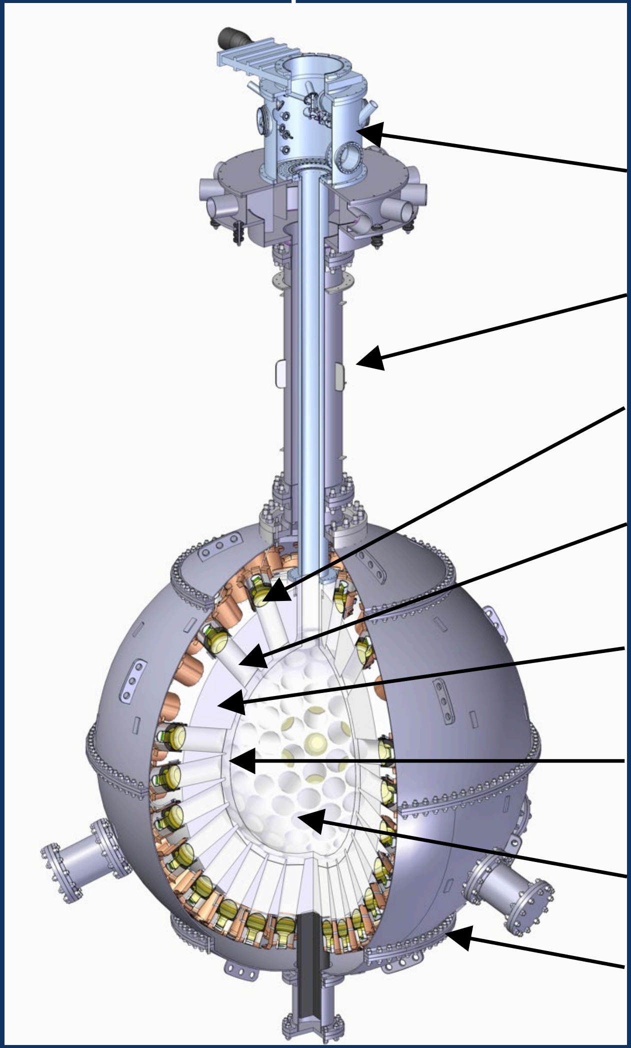
Stephen Hawking and fans observing the CRYOPIT area in September 2012

DEAP3600 detector

3.6 Tonnes of Liquid Argon: Dark Matter particles give very short bursts of light, gamma rays and electrons 200 times longer, enabling them to be separated.

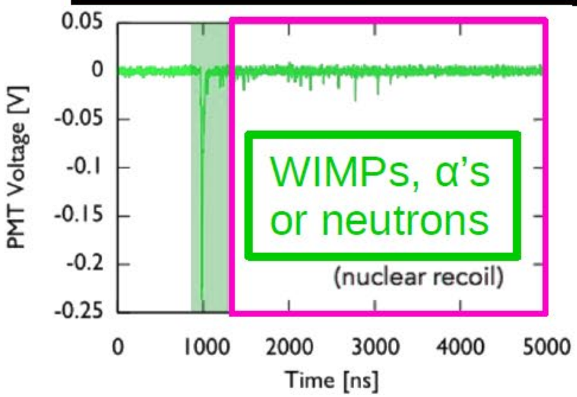
DEAP has very good sensitivity for high mass WIMPS.

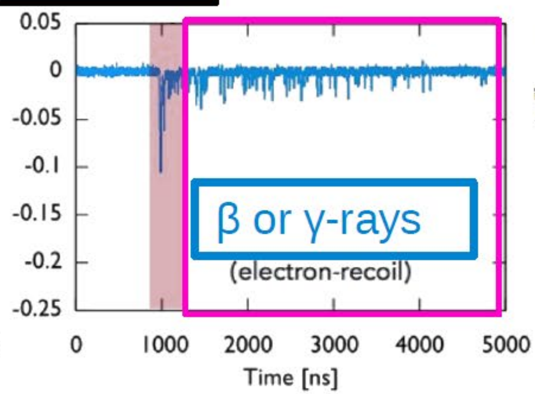


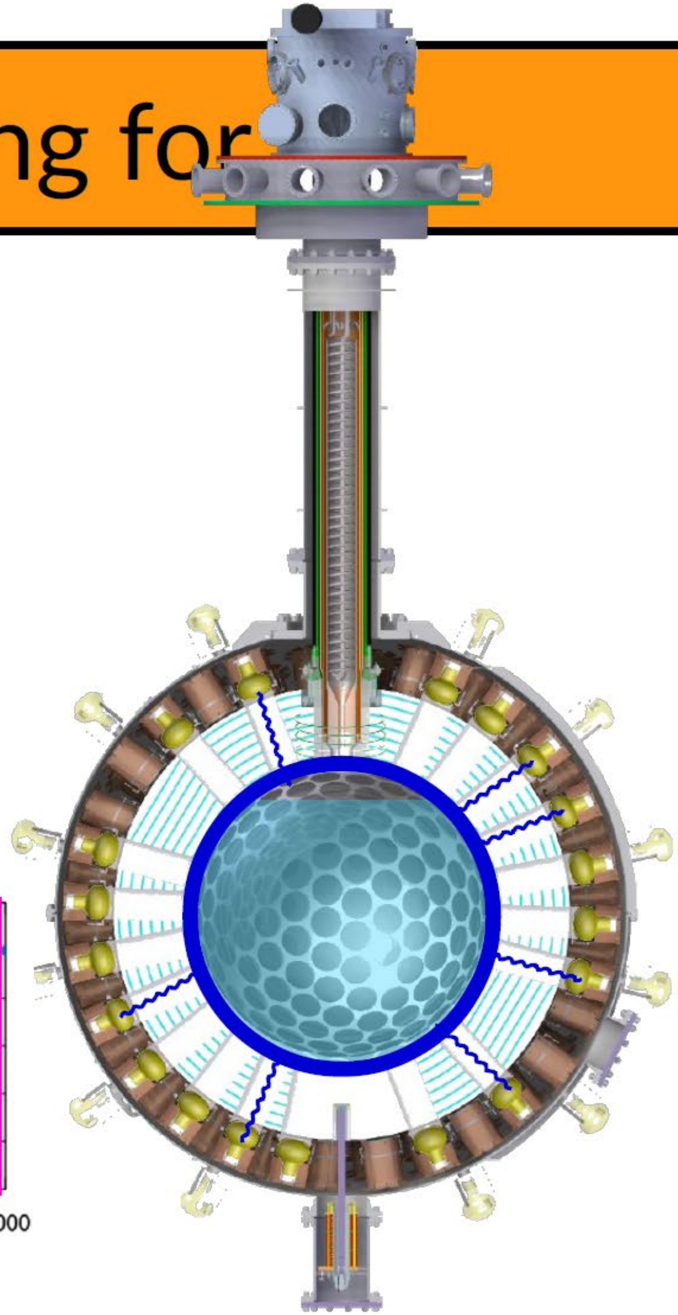


The signal we're looking for

- WIMP scatters on argon nucleus
- Singlet and triplet Ar dimers form
- Singlets decay (~6 ns), create 128 nm photons
- TPB shifts light to visible, detected by PMTs
- Triplets decay (~1.3 μs), create 128 nm photons
- TPB shifts light to visible, detected by PMTs

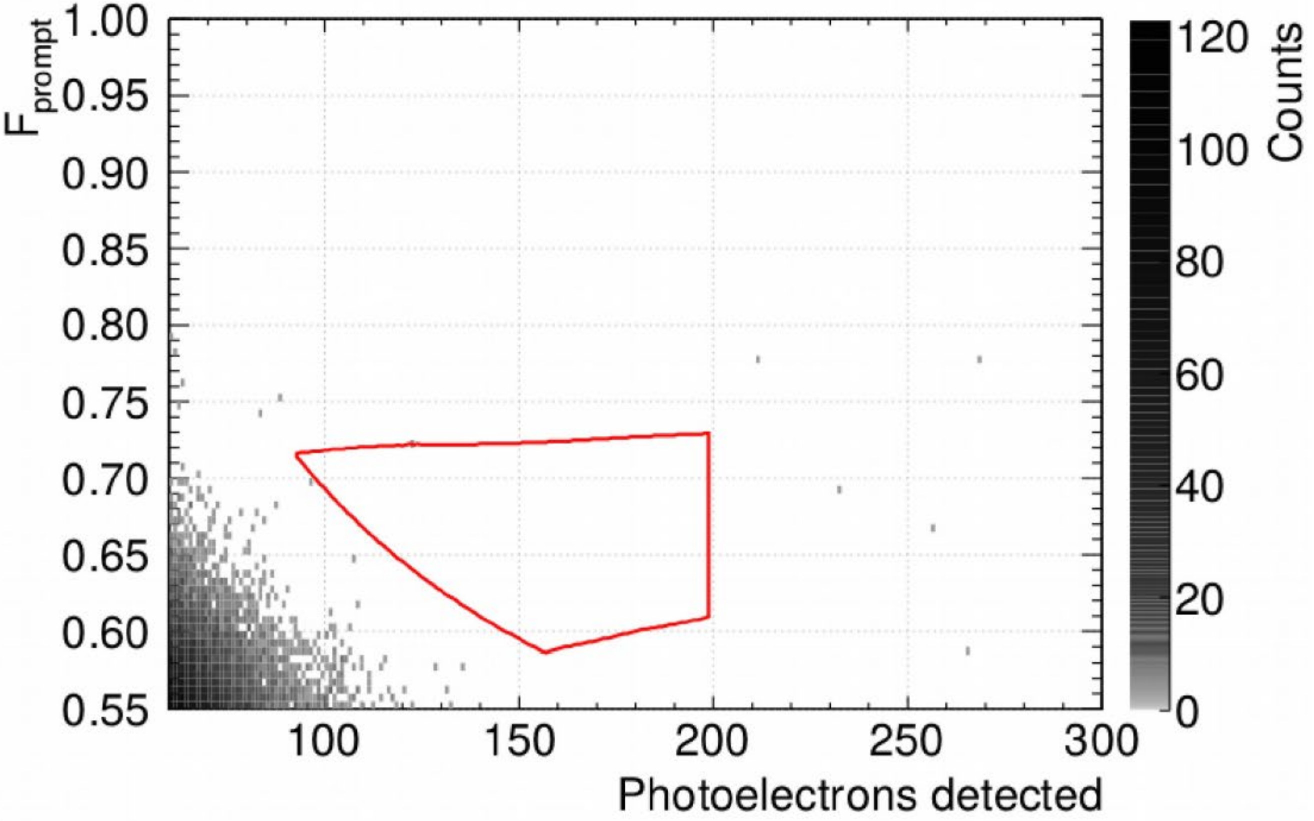






Define parameter F_{prompt} = Prompt Light(150 ns)/Total Light (10000 ns)

After all cuts, no WIMP-like signals

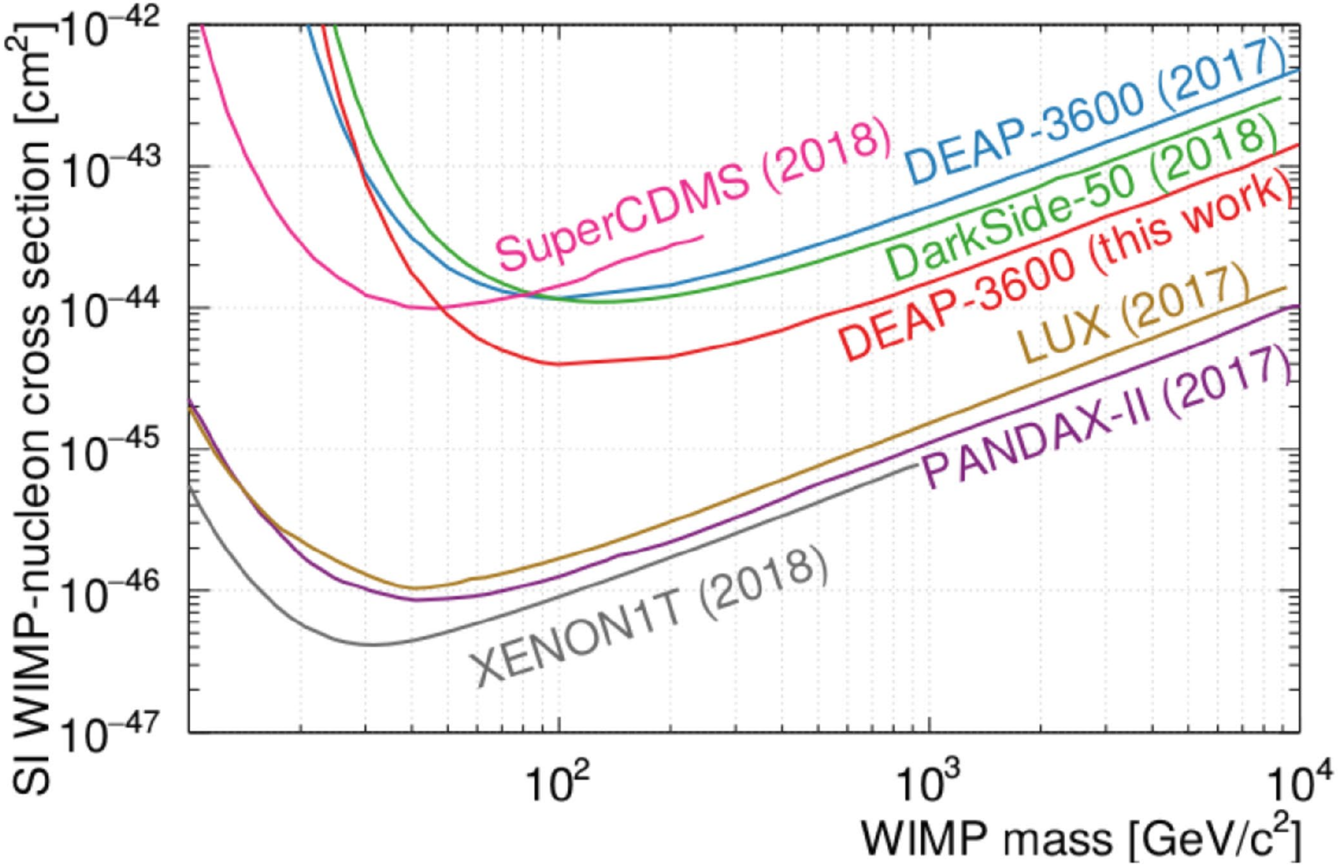


231 live days after run selection and deadtime corrections

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

See arXiv:1902.04048

DEAP has continued counting, for a total of three years of data. More sophisticated analysis techniques are being developed that are improving the efficiency

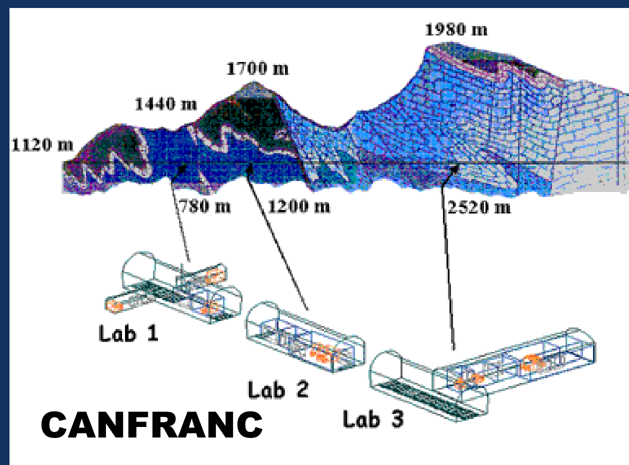
Global Argon Dark Matter Collaboration

- 76 institutes
- > 420 researchers
- Strong assistance from CERN
- 15 nations:

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

Sequence of experiments:
- DEAP: 3 tonnes
- DarkSide 20K: 50 tonnes
- Argo: 400 tonnes to reach the “Neutrino Floor”

Support from International Underground Laboratories



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

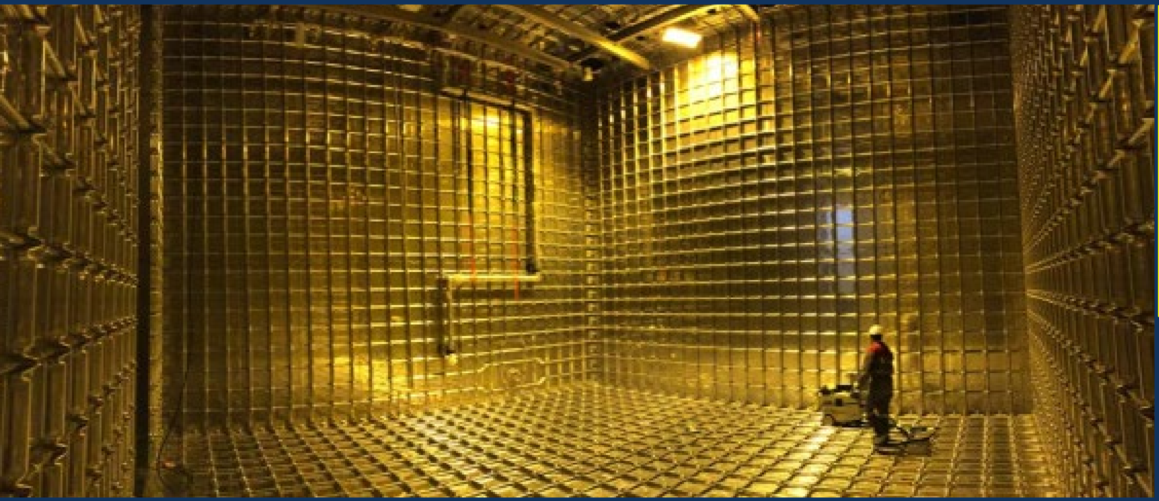
DART:
Use ARDM to measure depletion factor for ^{39}Ar

DEAP (3.3 tonne) (~1 tonne fiducial)

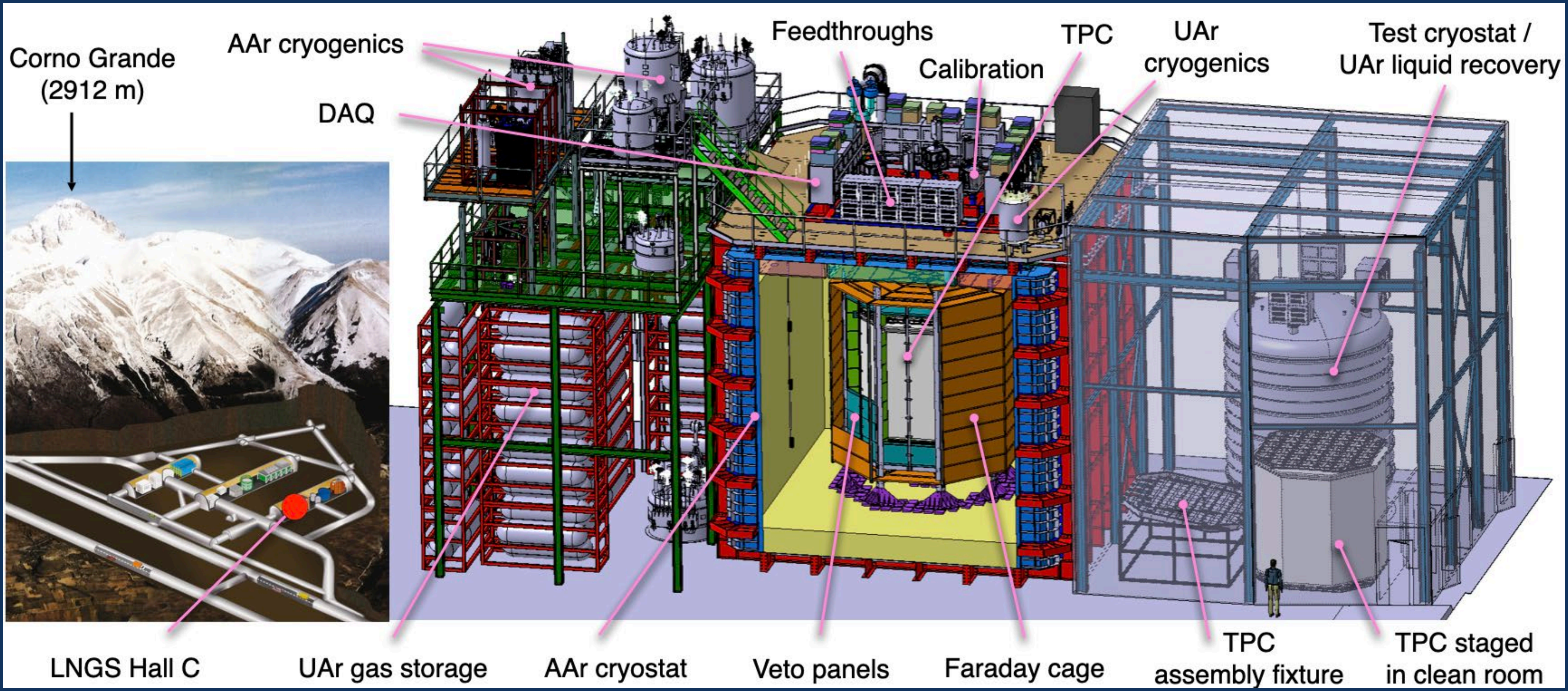
Plans for storage of ~400 tonnes of Underground Argon

ARGO: Future detector with ~300 tonnes fiducial

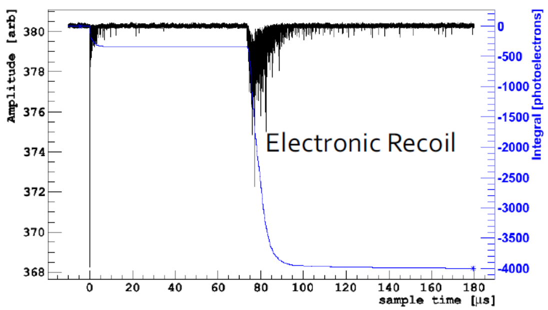
Proto Dune detector at CERN

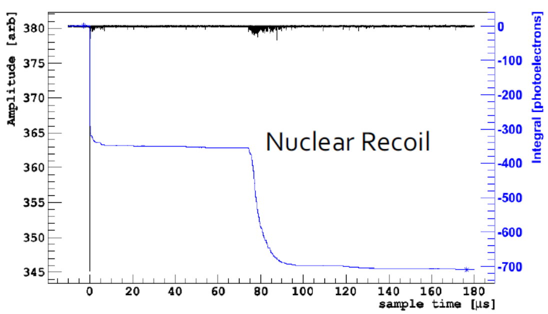


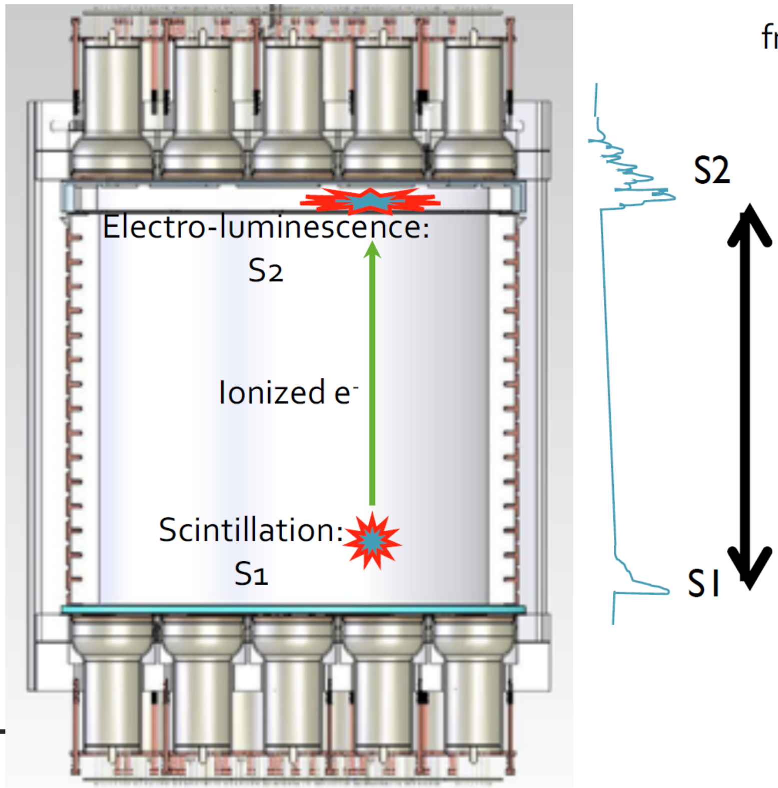
This is a complicated experiment that builds on the technology from the Proto-DUNE detector at CERN



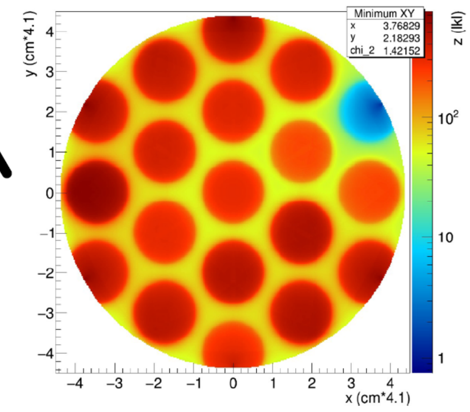
Two-Phase LAr Dark Matter Detectors







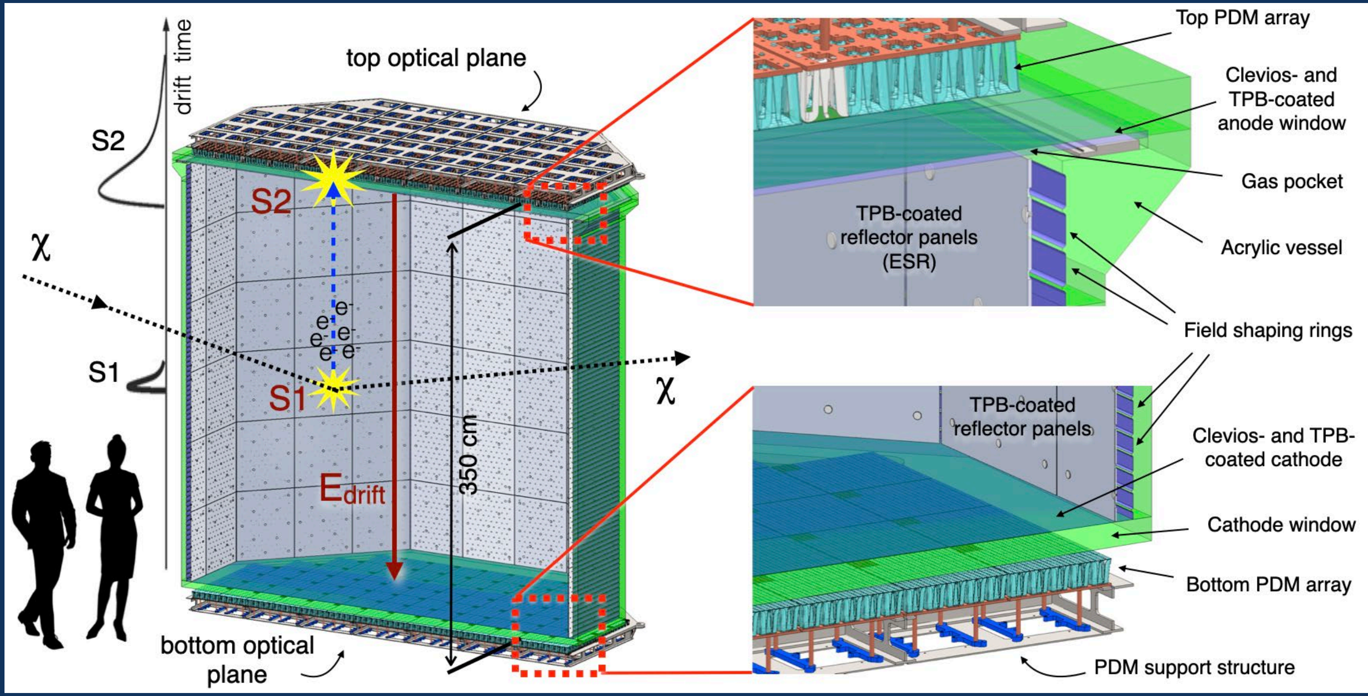
DS-50 Top Array PMT light fractions for S2 gives x,y location



The drift time gives the z-position with mm precision

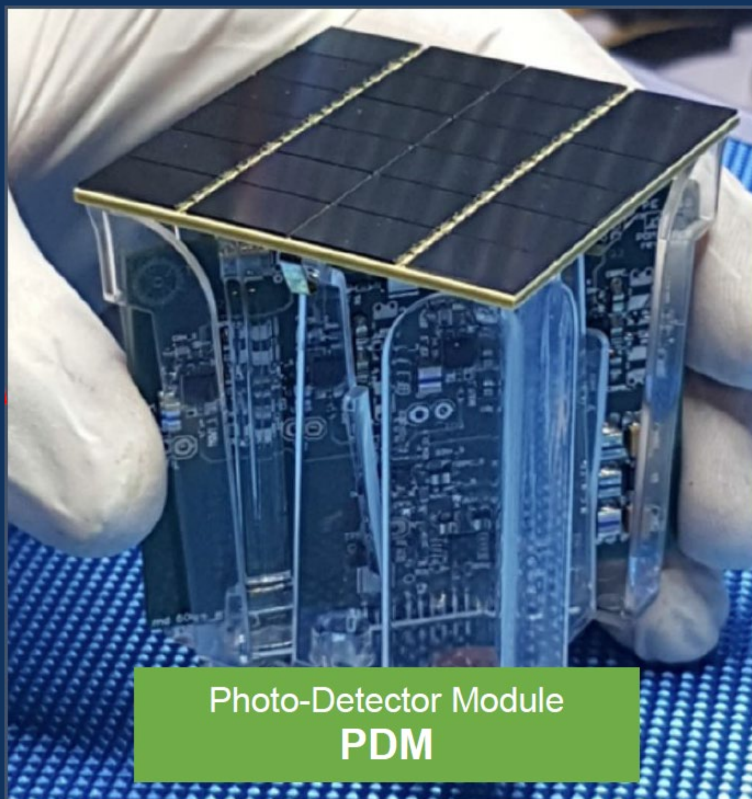
A 50-tonnes fiducial argon detector filled with underground argon

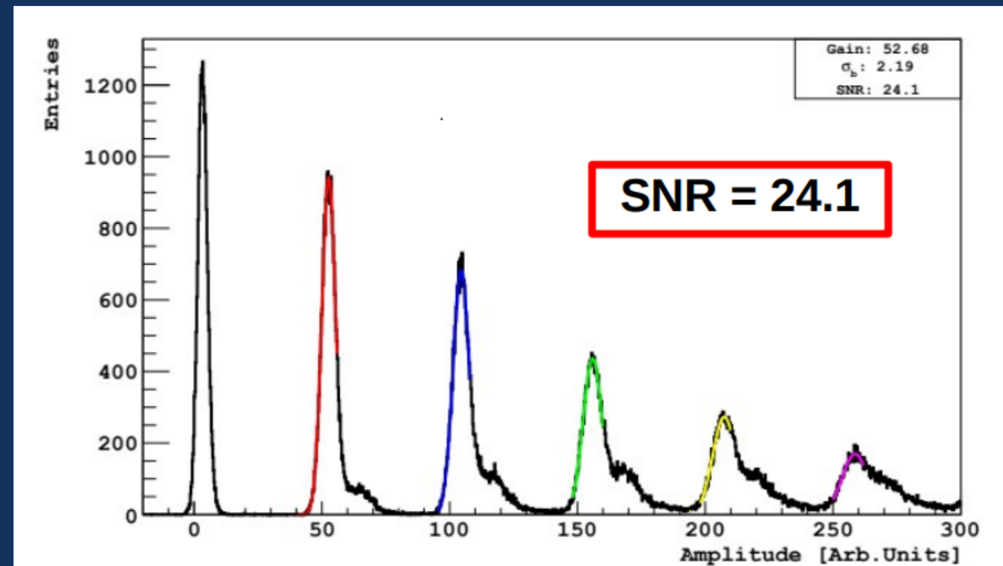
21 m^2 of Silicon PhotoMultipliers operating at Cryogenic Temperature



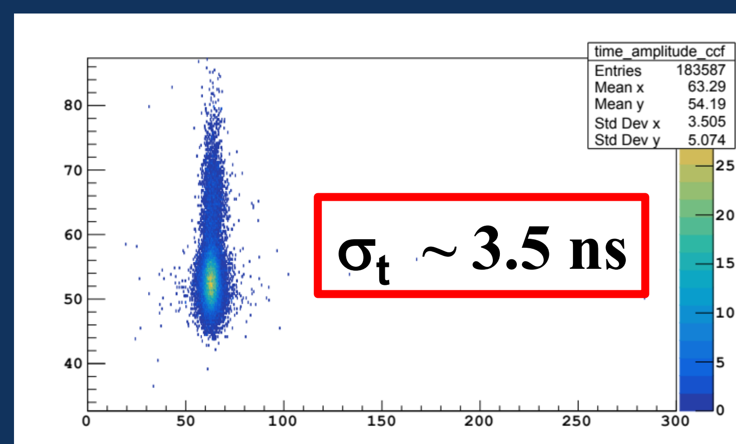
TPC acrylic vessel surrounded by AAr + Gd-loaded acrylic shell as a neutron veto

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





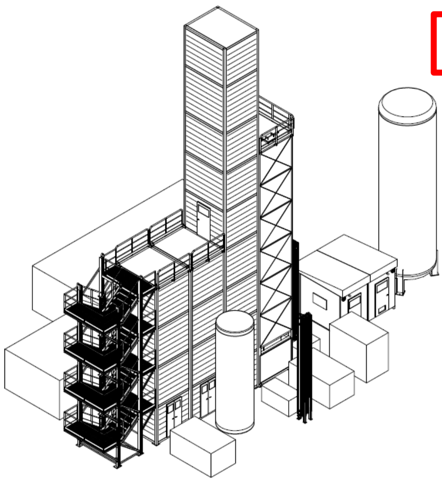
Single **photo-electron** timing

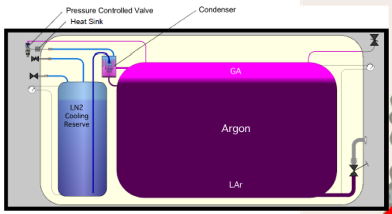


SIMILAR TO 3 INCH DIAMETER PHOTOMULTIPLIER

UAr for DS-20k

Extract Ar from Cortez, CO underground CO_2 flow.

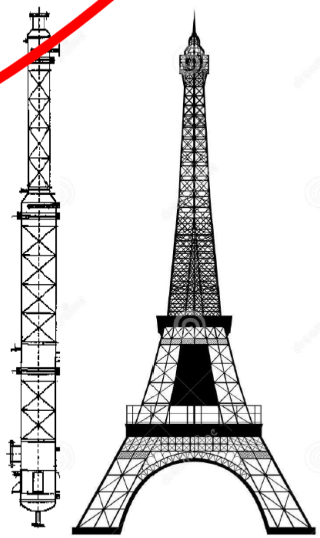




- Urania: procure 50 t of UAr
- Extract > 280 kg/day
- UAr transported to Sardinia for final chemical purification at Aria

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



Contract by INFN (Italy) for the Urania extraction equipment.

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

DART in ArDM

Insertion of active small chamber in ArDM.
Use ArDM target as VETO (single phase).

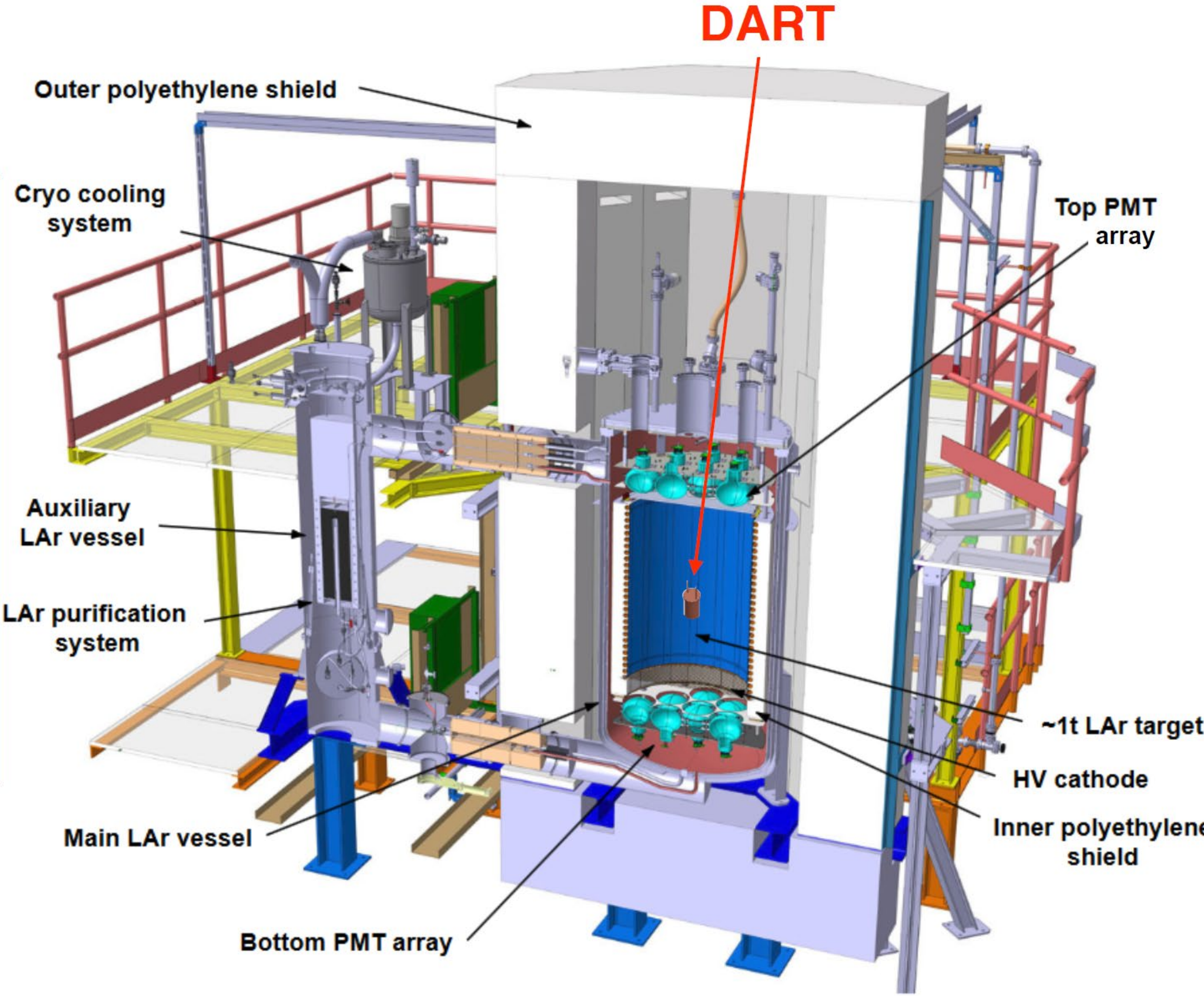
ArDM in single phase

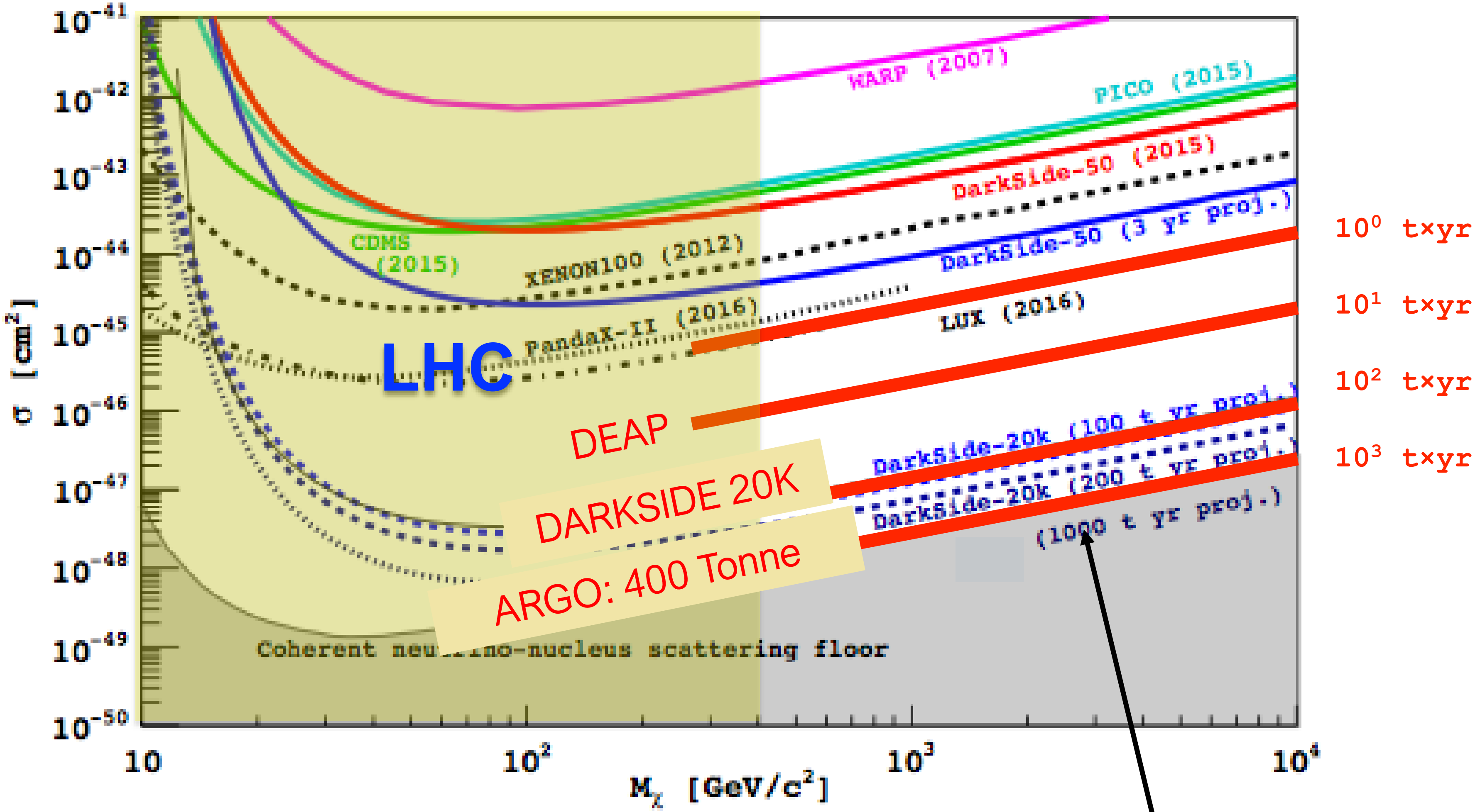
Use existing flanges on top

Use spare DAQ channels

Dissipated power and condensation heat to be absorbed by ArDM cryogenic system

Thermodynamic stability to be tested at CERN



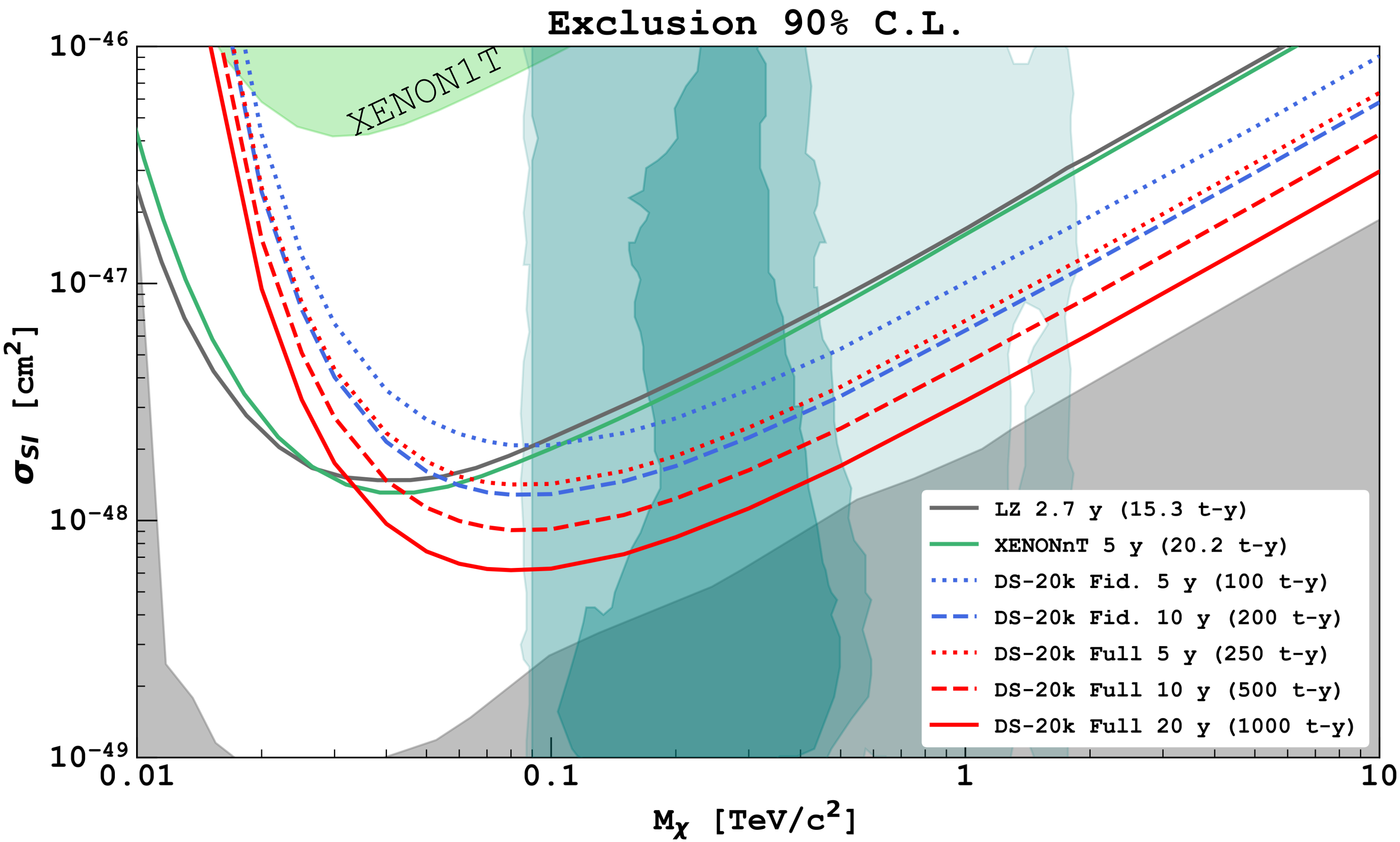


Future objective for the Global Argon Dark Matter Collaboration:

A ~400 ton Liquid Argon detector with optimum technology and site.

Excellent sensitivity and electron discrimination at the neutrino floor.

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



DarkSide-20k operation to start in 2025.

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.