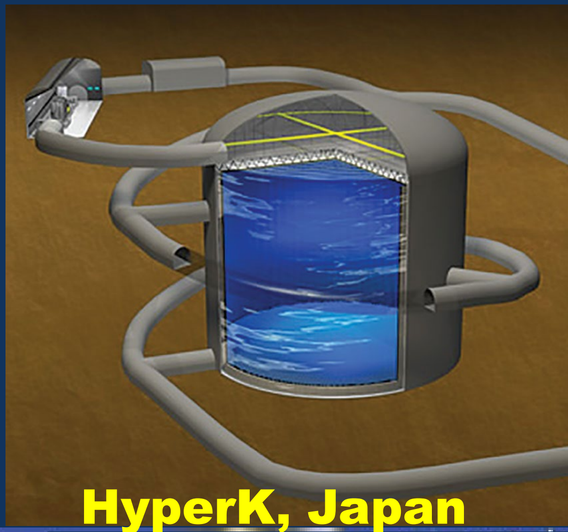
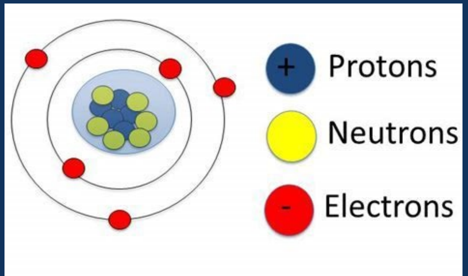
Understanding the Universe from Deep Underground



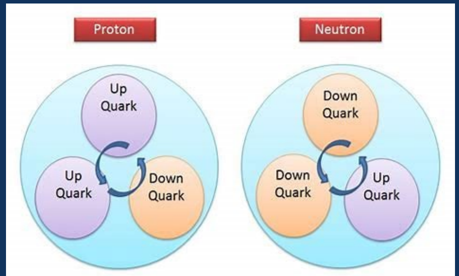
ATOMS

10^{-10} meters



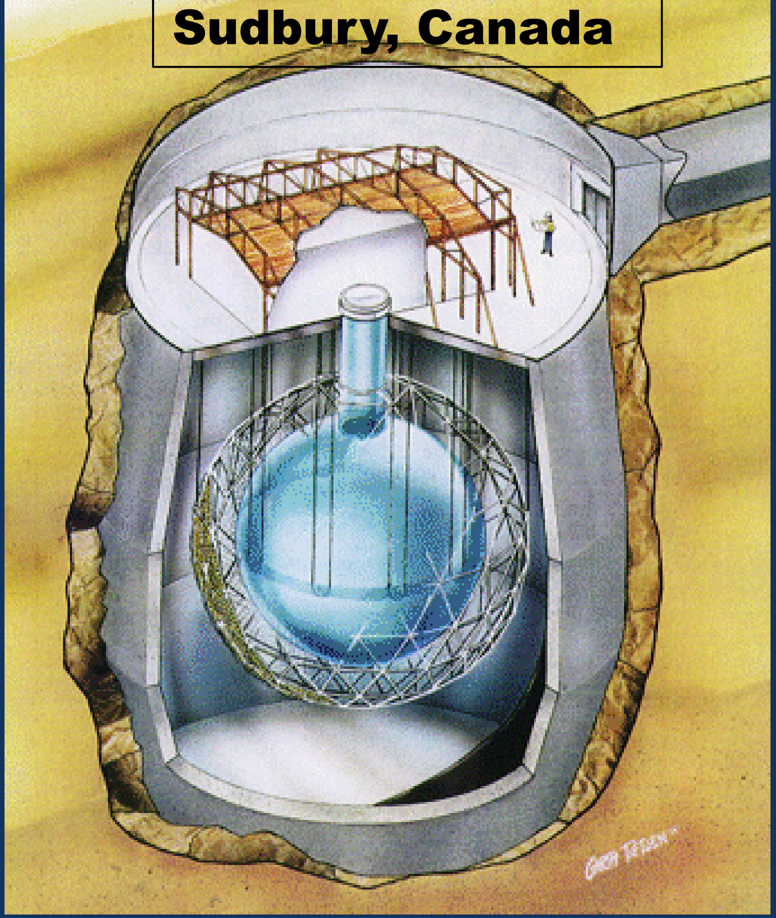
Quarks in Protons, Neutrons

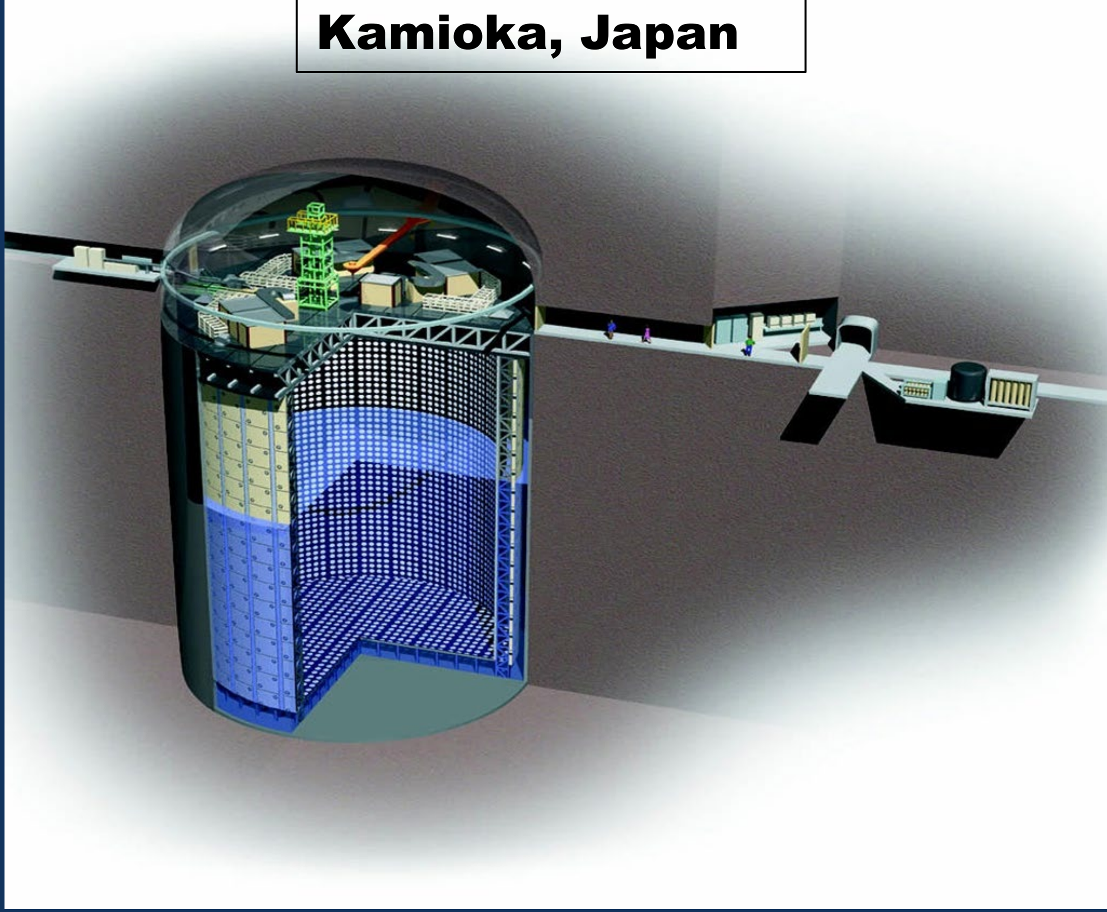
$< 10^{-15}$ meters



Neutrinos

$< 10^{-18}$ meters





Sudbury Neutrino Observatory (SNO)

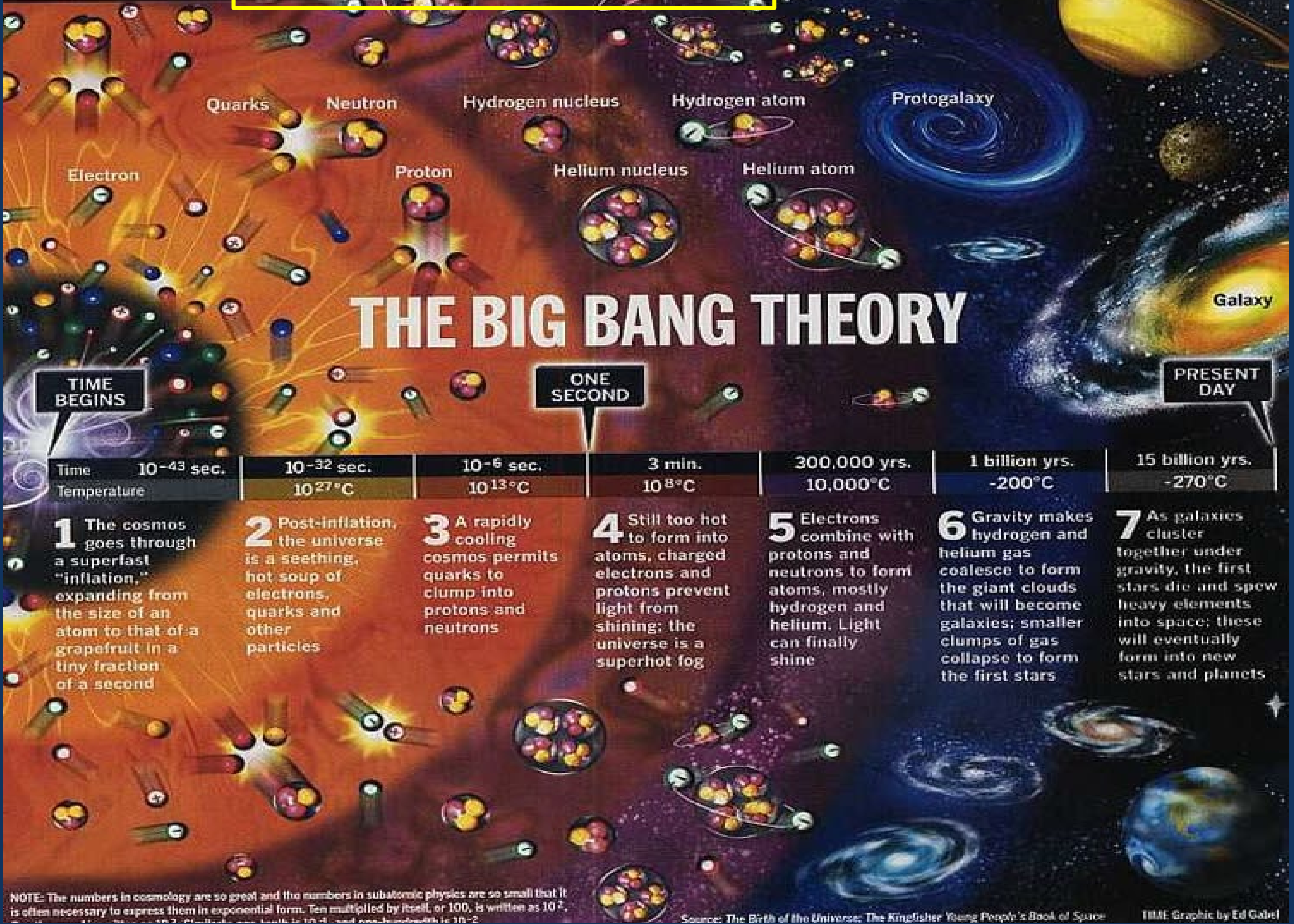
Observed Electron Neutrinos from the Sun to change Flavor while traversing the Sun. Also confirmed how the Sun burns.

SuperKamiokande

Observed Muon Neutrinos made in the Atmosphere to change Flavor while traversing the Earth

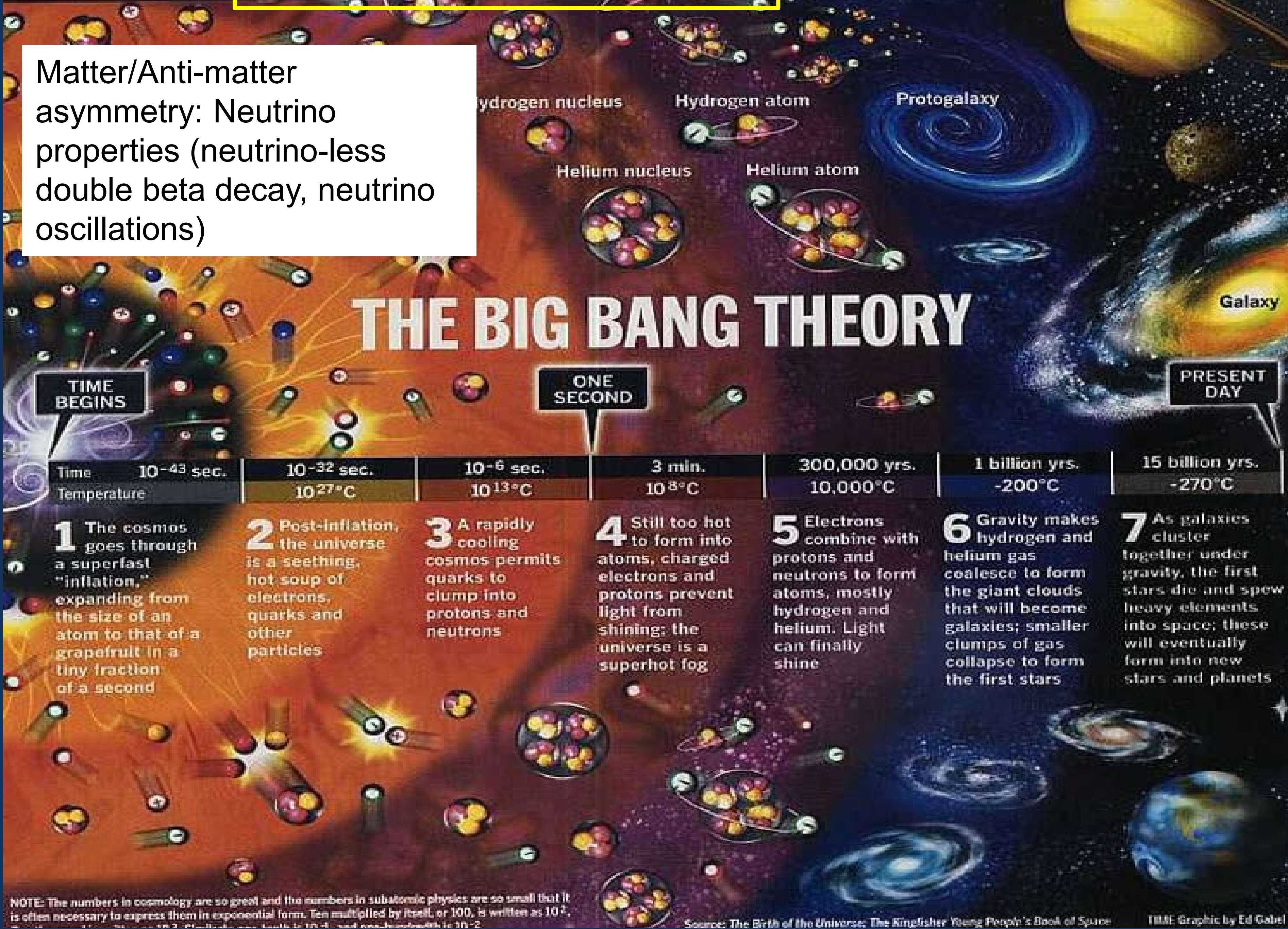
Shared the 2015 Nobel Prize for the observation of the oscillation of neutrinos between flavors, also implying that neutrinos have a finite mass

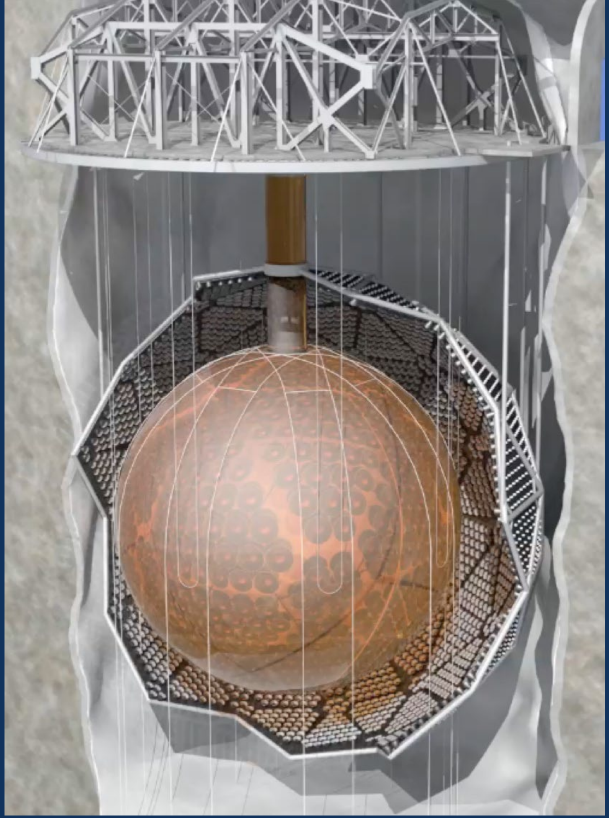
Current Theory of Cosmology



Current Theory of Cosmology

Matter/Anti-matter asymmetry: Neutrino properties (neutrino-less double beta decay, neutrino oscillations)





SNO+ : Former SNO detector filled with liquid scintillator plus dissolved Te to be added to study Neutrinoless Double Beta Decay.

- Neutrino properties relevant for theory of the early universe.
- Could determine the absolute mass of the neutrino

Many other major experiments.

HyperKamiokande: ~10 times bigger than SuperKamiokande. Look for differences in the oscillation of muon neutrinos and muon anti-neutrinos shot across Japan from an accelerator near Tokyo.

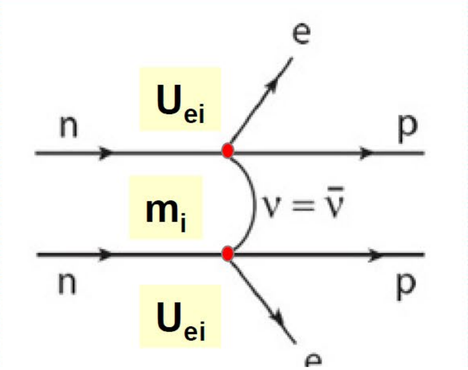
- Help to understand why most of the anti-particles in the Universe decayed after the Big Bang. AstroCent Poland is collaborating.

Another: **DUNE**, Fermilab to South Dakota

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

$0\nu\beta\beta$-decay

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



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

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, θ_{12}, θ_{13}, α_1, α_2

(3 unknown parameters: m_1/m_3, α_1, α_2 and ν-mass hierarchy)

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

Neutrino Oscillations:

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

Flavor States

$$|\nu_l\rangle = \sum U_{PMNS\,li}\,|\nu_i\rangle$$

Mass States

$0\nu\beta\beta$ 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

- **For Neutrinoless Double Beta Decay, Note: Exchange of three light ν is assumed. Data can also be analyzed for exchange of a Heavy ν.**
- **The calculation of nuclear matrix elements is a very complex topic and results range over a factor of 2 or more.**
- **For HyperK, DUNE, principal objective is the CP violating phase δ and the hierarchy.**

SUMMARY OF OSCILLATION RESULTS FOR THREE ACTIVE ν TYPES

Particle Data Group

$\sin^2(\theta_{12}) = 0.307 \pm 0.013$
$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \text{eV}^2$

Solar, Reactor

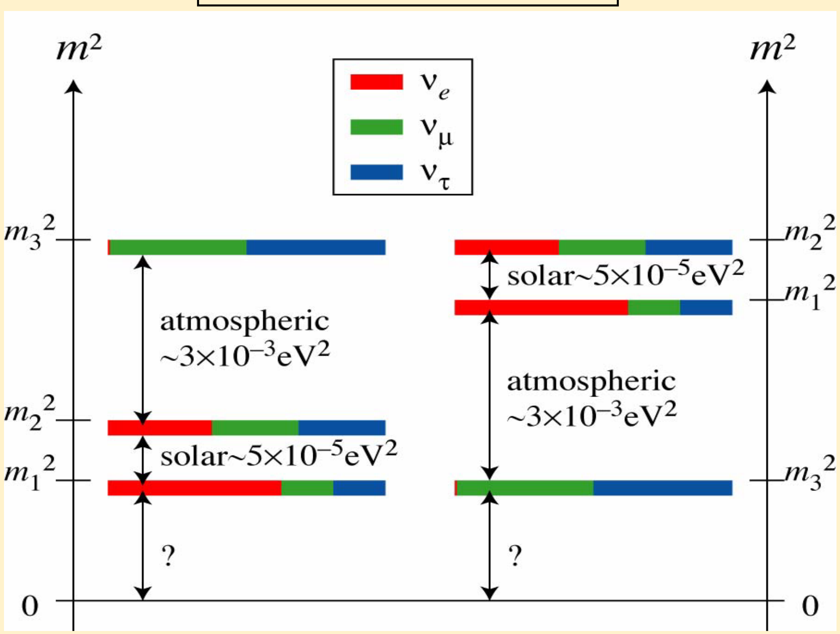
$\sin^2(\theta_{23}) = 0.539 \pm 0.022 \quad (S = 1.1) \quad$ (Inverted order)
$\sin^2(\theta_{23}) = 0.546 \pm 0.021 \quad$ (Normal order)
$\Delta m^2_{32} = (-2.536 \pm 0.034) \times 10^{-3}\ \text{eV}^2 \quad$ (Inverted order)
$\Delta m^2_{32} = (2.453 \pm 0.033) \times 10^{-3}\ \text{eV}^2 \quad$ (Normal order)

Atmospheric,Accelerator

$\sin^2(\theta_{13}) = (2.20 \pm 0.07) \times 10^{-2}$

Reactor, Accelerator

Mass Hierarchies



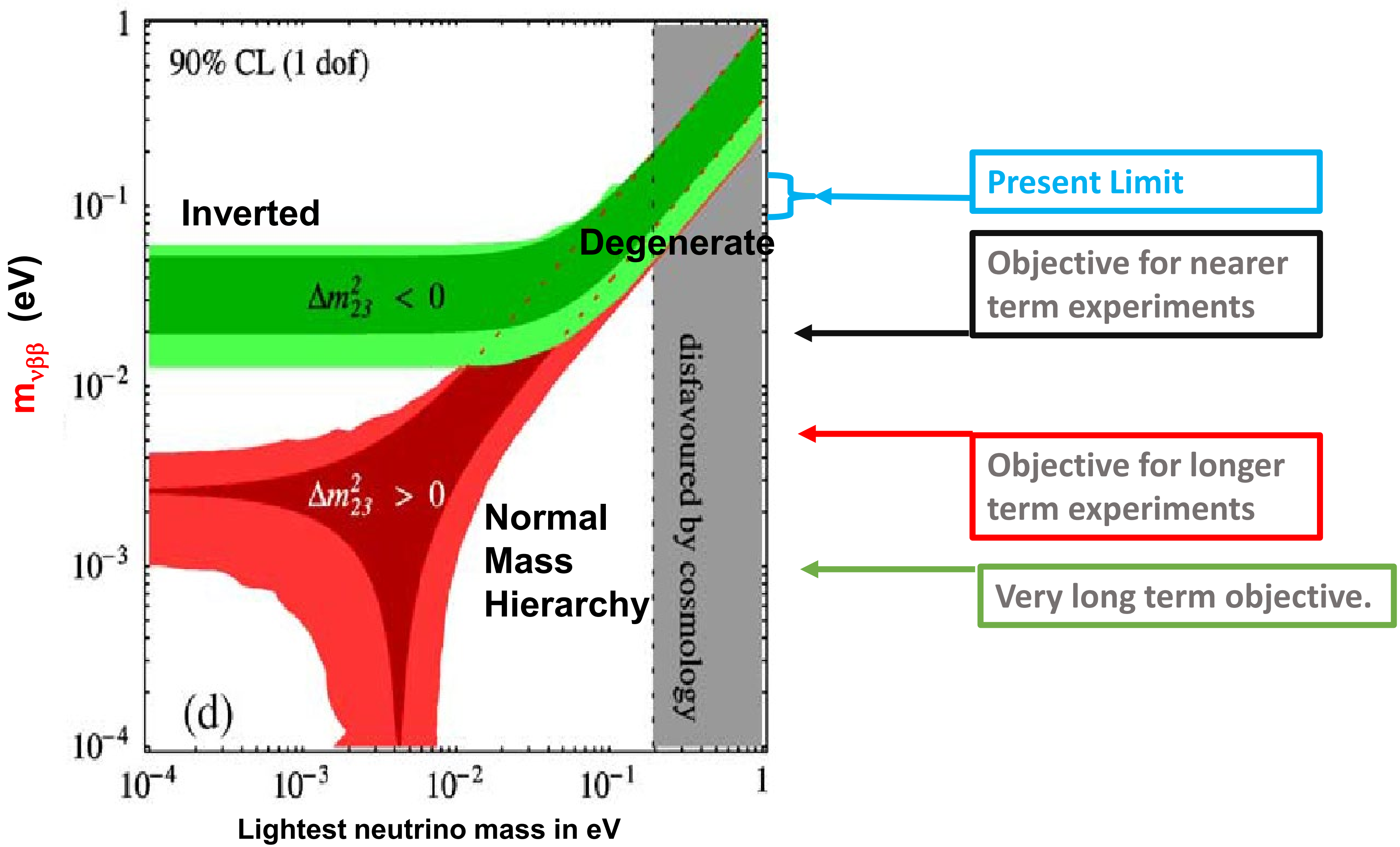
Normal | Inverted

Future objectives:

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

Neutrinoless Double Beta Decay

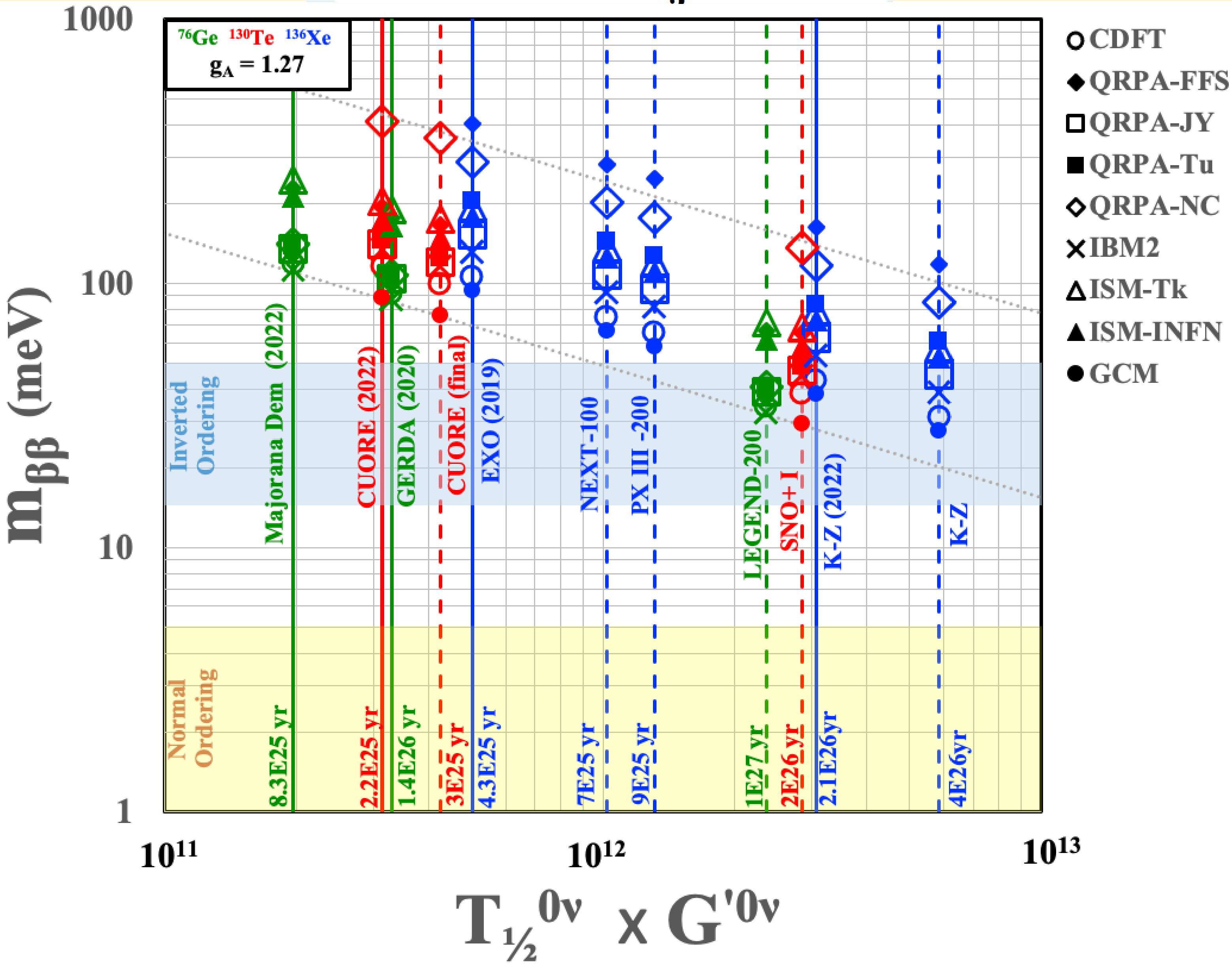
Variation of $m_{\beta\beta}$ vs Lightest ν mass



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

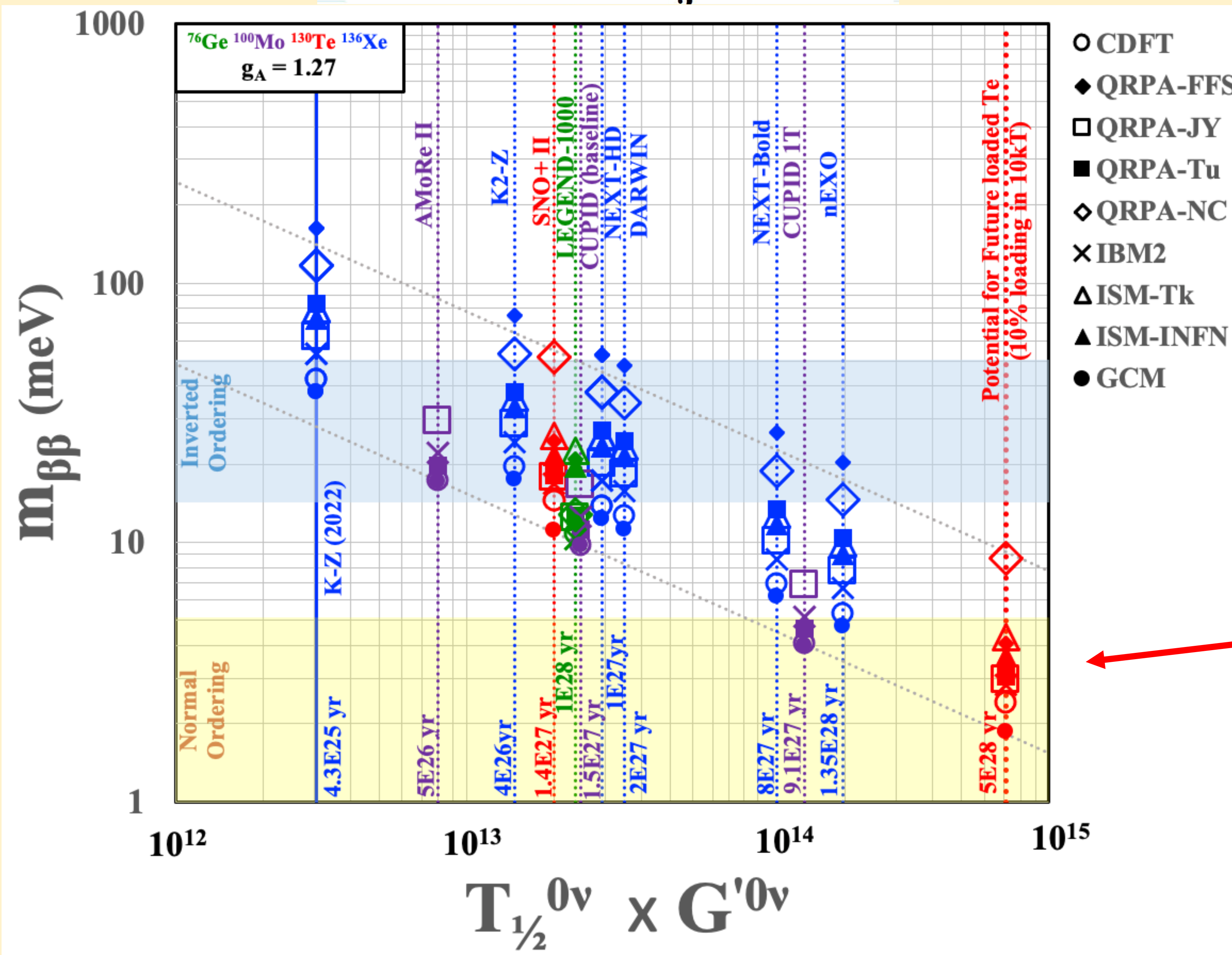
- Figure courtesy of Steve Biller. 90% Confidence Limits on lifetime from published info

Longer Term Experiments: Symbols: Nuclear Matrix Element Theory

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

$g_A = 1.27$

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

Hyper-Kamiokande

- **Far detector electronics (underwater)**
  - Development of Multi-PMT concentrator cards

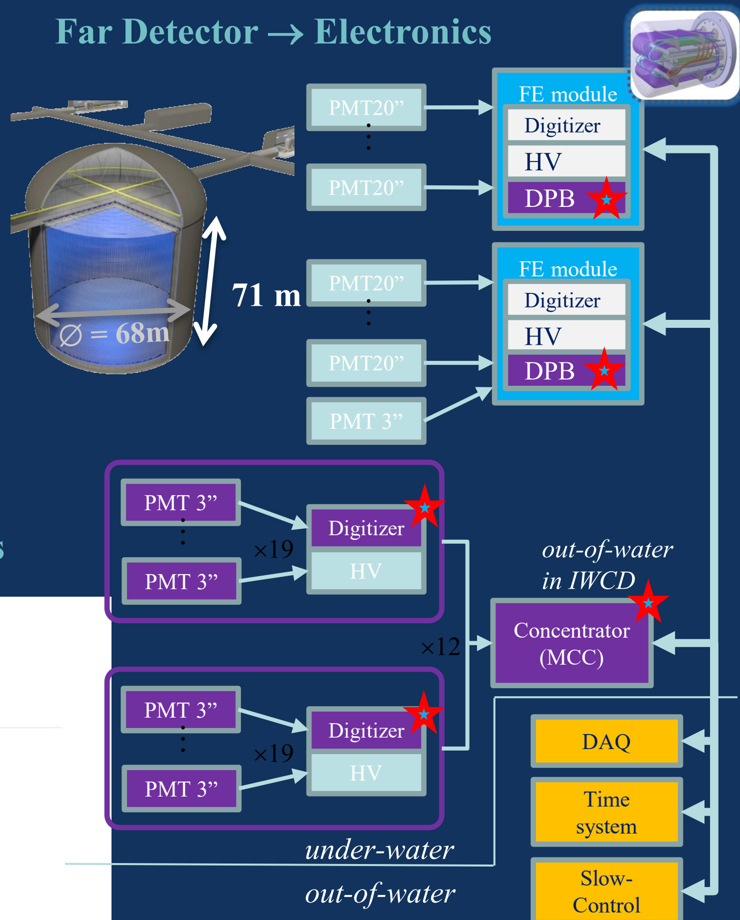
    Partnership with: Jagiellonian Univ., AGH
  - Development of data processing block

    Partnership with: Universitat Politècnica de València
- **Intermediate detector (IWCD) + test experiment at CERN (WCTE)**
  - Multi-PMT modules
  - Multi-PMT Concentrator cards
  - Digital signal processing algorithms for time & charge estimation
- **Reliability optimization**

In consortium with:

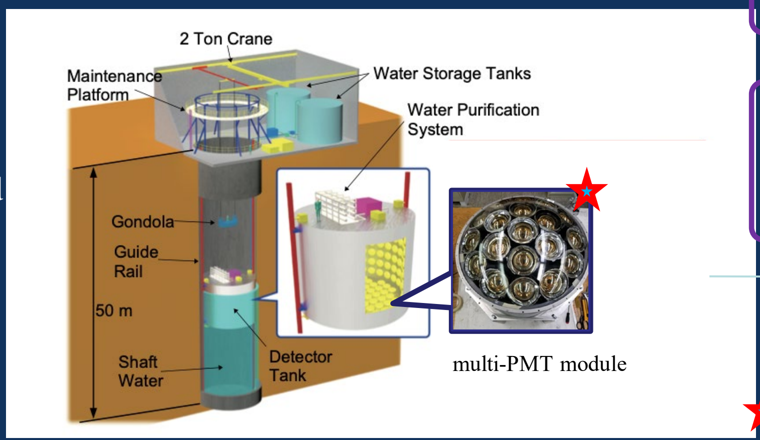
- National Center for Nuclear Research
- Warsaw University of Technology
- Jagiellonian University
- AGH University of Science and Technology
- Warsaw University
- University of Silesia
- University of Wroclaw
- Institute of Nuclear Physics, Polish Academy of Sciences

Far Detector → Electronics

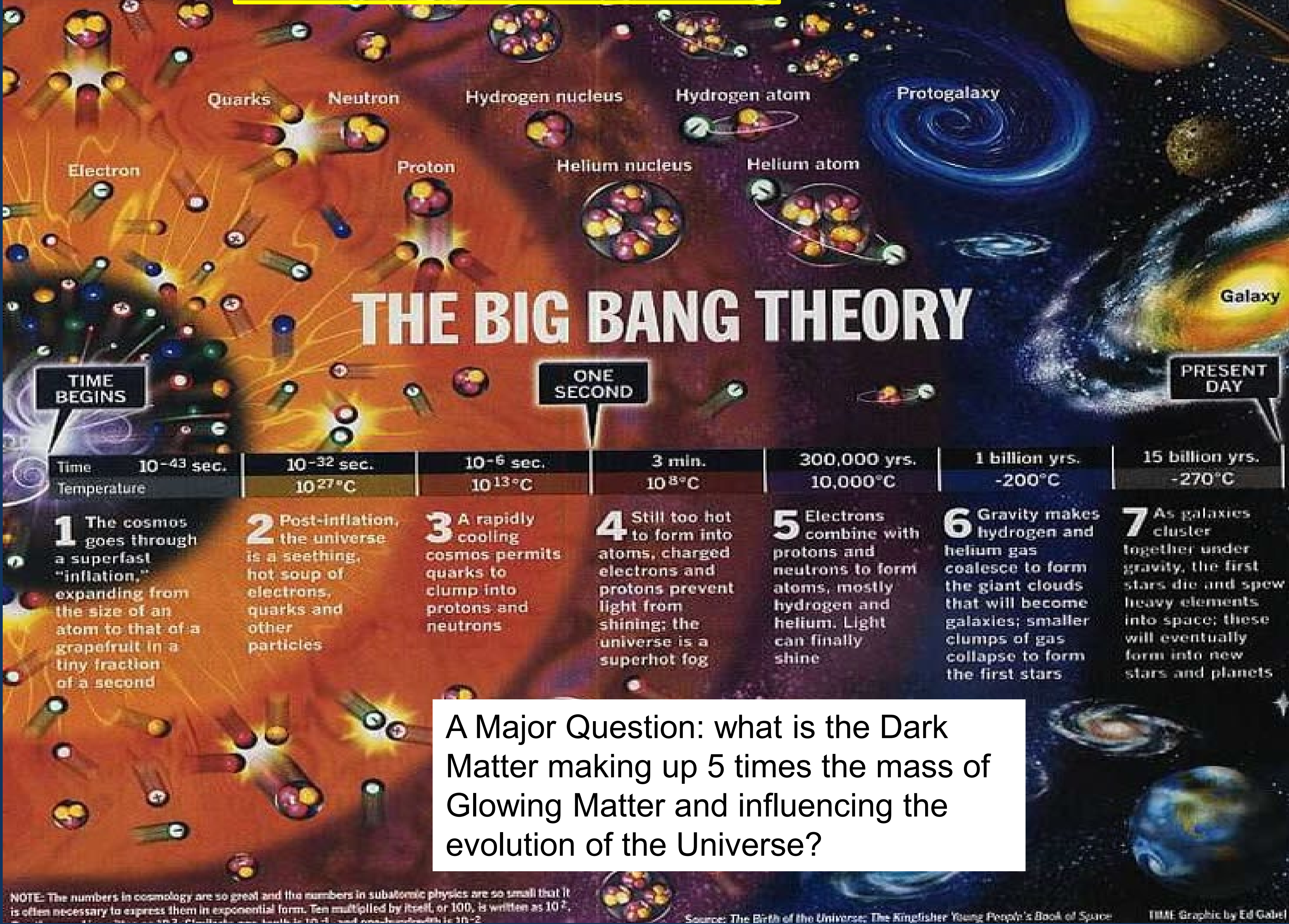


= AstroCeNT involvement

Intermediate detector → multi-PMT modules & electronics



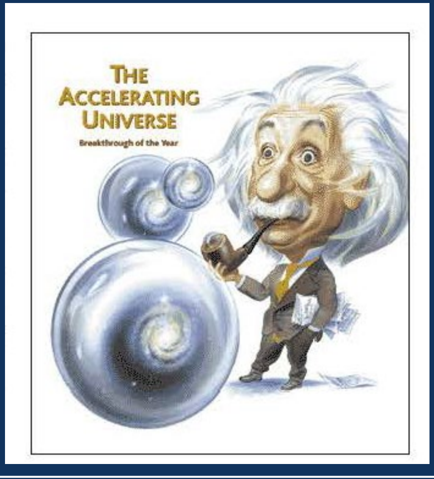
Current Theory of Cosmology

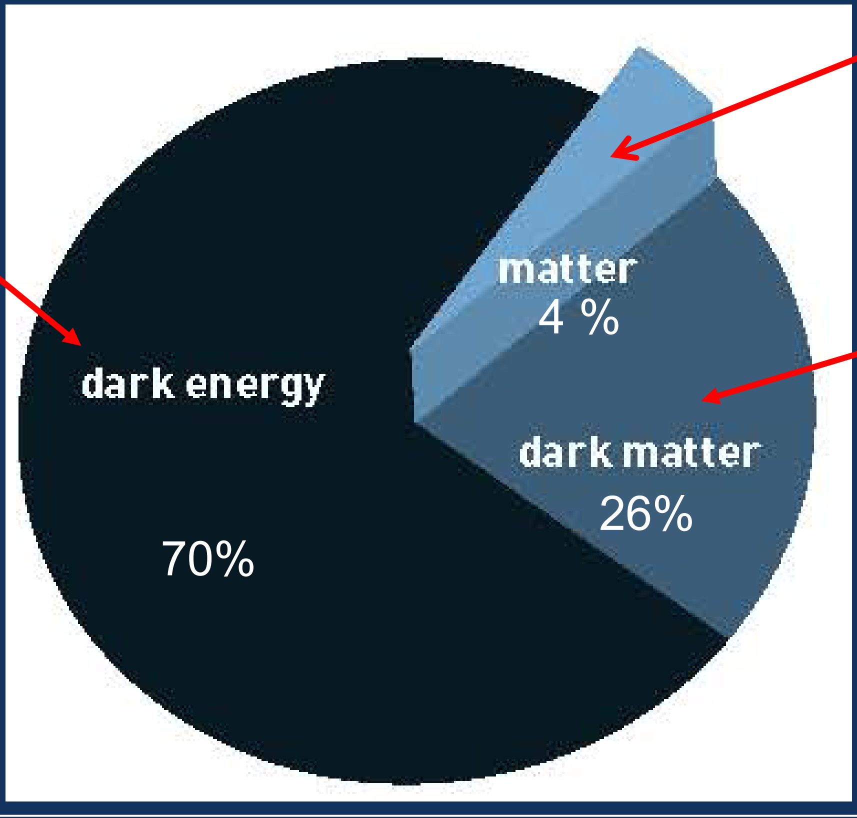


A Major Question: what is the Dark Matter making up 5 times the mass of Glowing Matter and influencing the evolution of the Universe?

Composition of the Universe as we understand it today

Responsible for accelerating the Universe's expansion





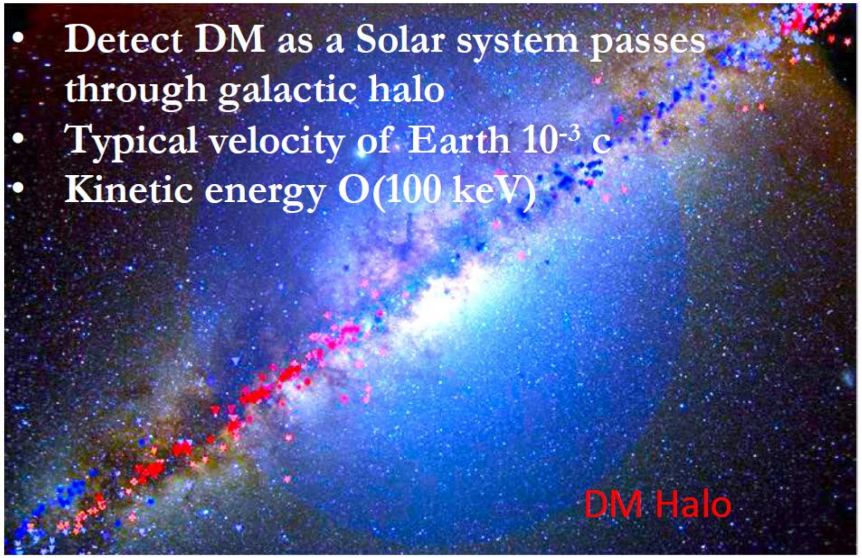
The Stars and US!!!

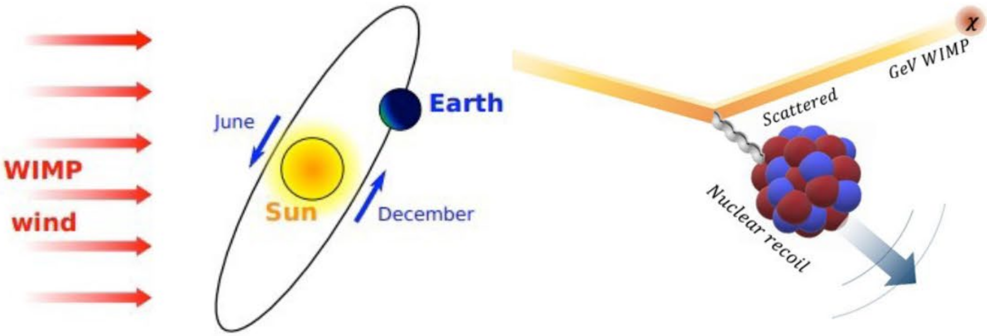
Neutrinos Are only a few %

- **Dark Energy** was observed by studying Supernovae at the farthest distances in the Universe and finding that they have accelerated more than expected.
- **Dark Matter** could be Weakly Interacting Massive Particles (WIMPS) that hit nuclei in our underground detectors. (Axions are a different possibility)
- At CERN they are trying to create **Dark Matter** particles by reproducing the energy in the Big Bang in proton/proton collisions.

The WIMP direct detection

WIMP (in mass range 1 GeV/c^2 – 1 TeV/c^2), existing in many theory beyond the Standard Model, is a possible candidate for dark matter





Detection signal: nuclear recoil (NR)

- Purely kinematical process

- **As we pass through the Dark Matter made in the Big Bang that is holding our Galaxy in its present form, WIMPs could hit atoms in our detector and they would recoil like a billard ball.**
- **In Argon, that creates very short pulses of light (~7 nanoseconds) whereas light from radioactivity is emitted over about 1.5 microseconds.**
- **We can throw away millions of pulses from radioactivity and look for the few pulses from Dark Matter.**

SNOLAB

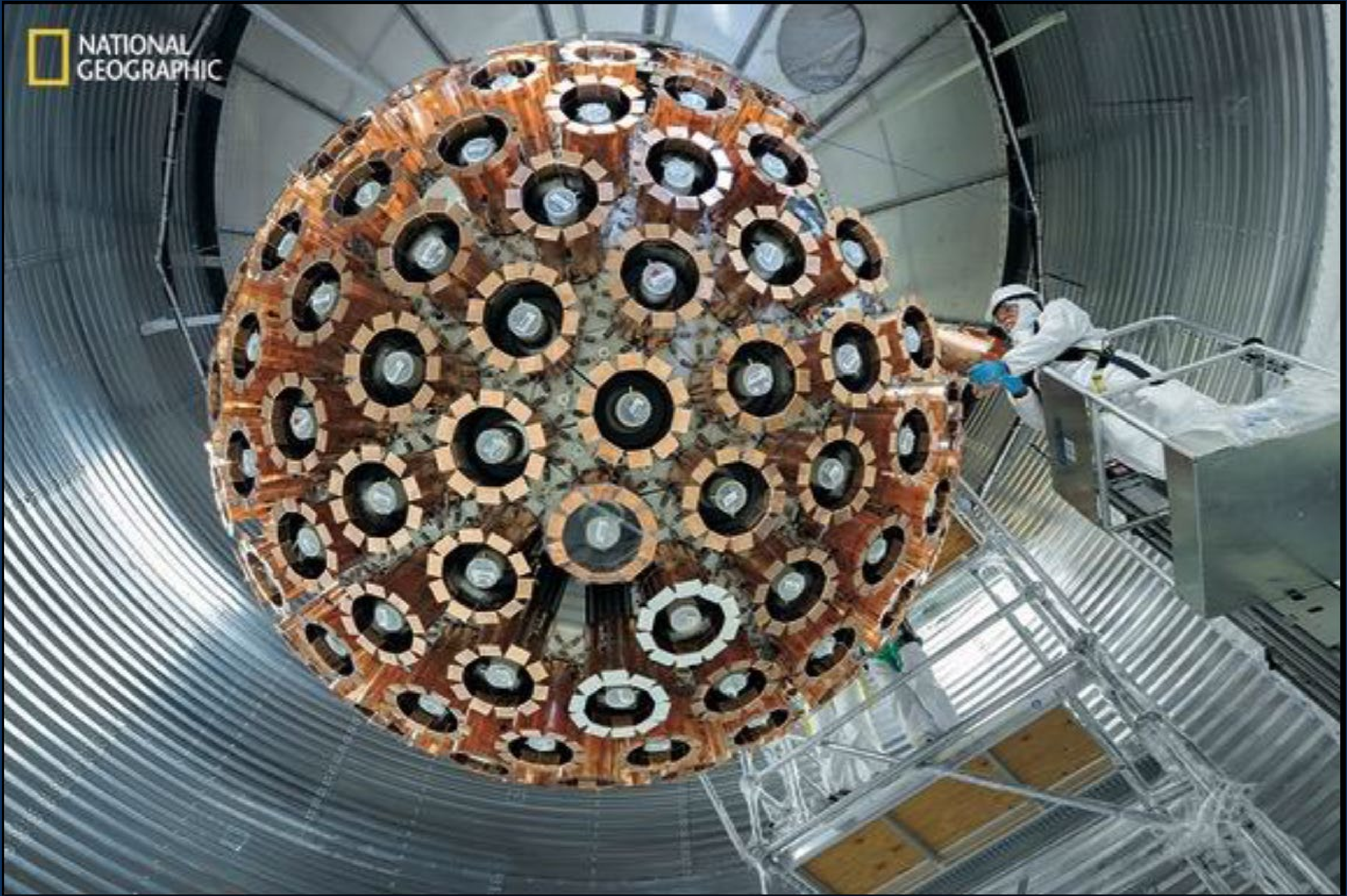
10 to 130 times lower muon fluxes than Sanford, Gran Sasso Labs, similar to China

2 KM BENEATH THE SURFACE

www.snolab.ca

All Lab Air: Class < 2000

DEAP EXPERIMENT – 3 Tonnes of Liquid Argon



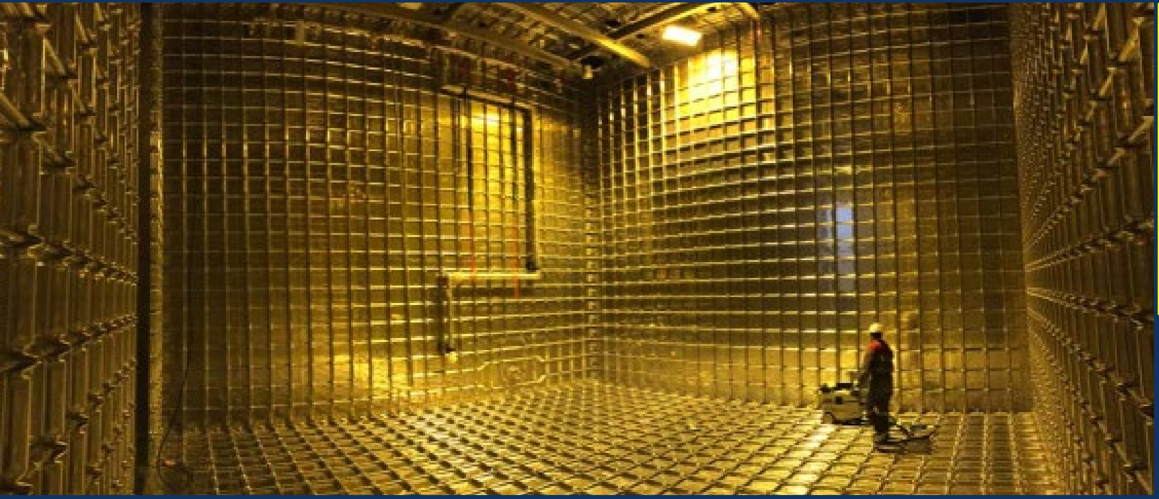
Over 400 scientists form the Global Liquid Argon Dark Matter Collaboration from over one hundred institutions in 13 countries

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.

Sequence of Dark Matter experiments:

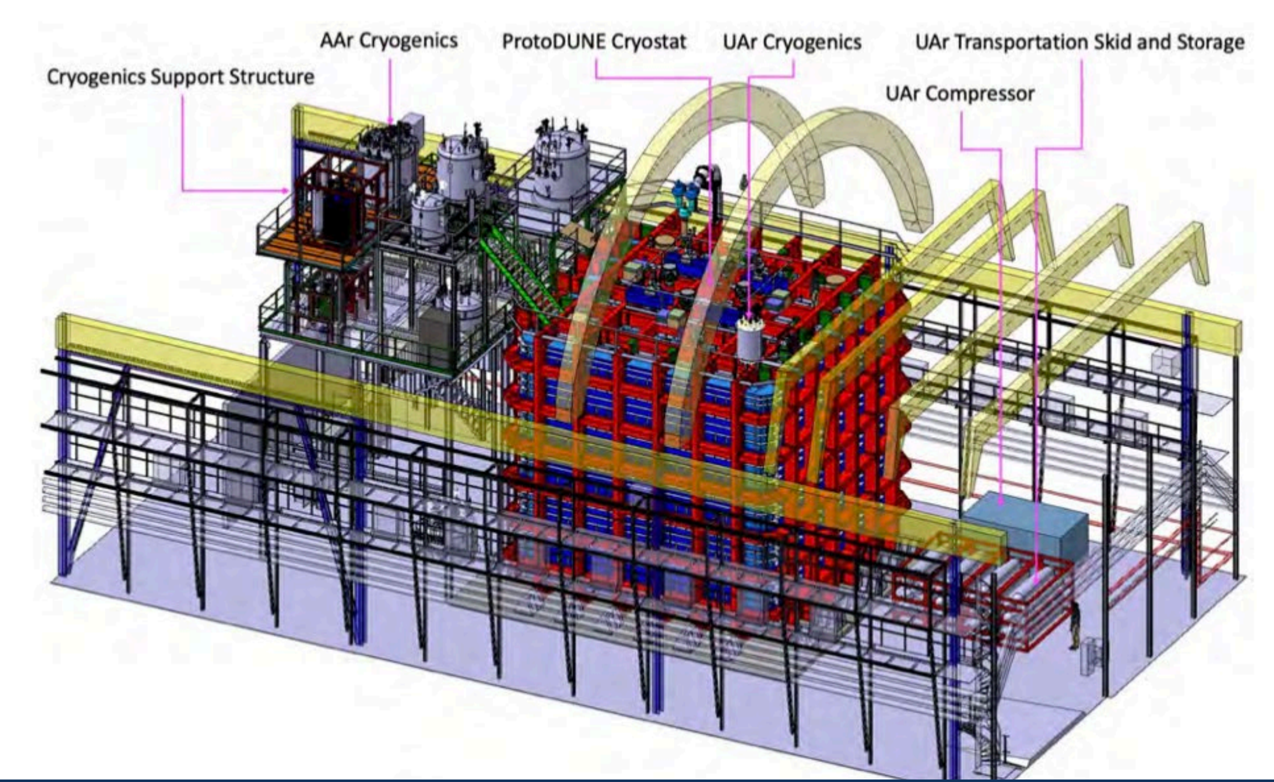
- DEAP: 3 tonnes (SNOLAB)
- DarkSide 20K: 100 tonnes (Italy)
- ARGO: 400 tons (SNOLAB) to reach down to the “Neutrino Fog”

Proto Dune detector at CERN



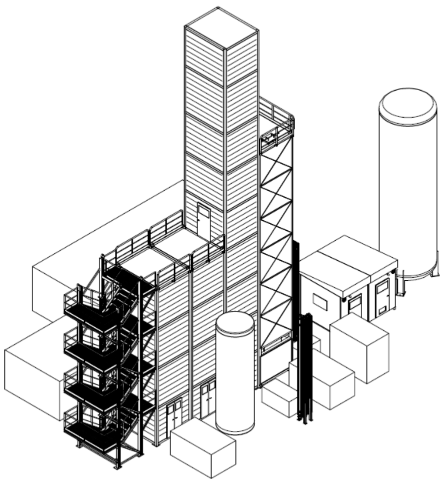
This is a complicated experiment that builds on the technology from the Proto-DUNE detector at CERN

DarkSide-20k at Gran Sasso

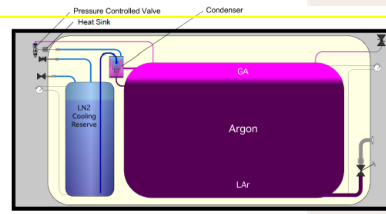


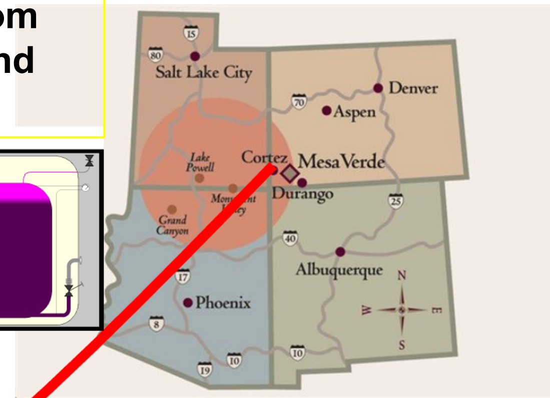
Argon in the atmosphere contains radioactive ^{39}Ar. Underground sources have been found with this reduced by more than 1400 times

UAr for DS-20k



URANIA: Extract Ar from Cortez, CO underground CO_2 flow.

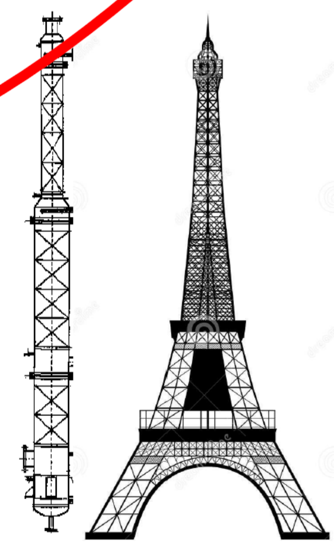




- Underground Argon (UAr) has 1400 times lower ^{39}Ar
- Extract > 280 kg/day
- UAr transported to Sardinia for final chemical purification at Aria

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

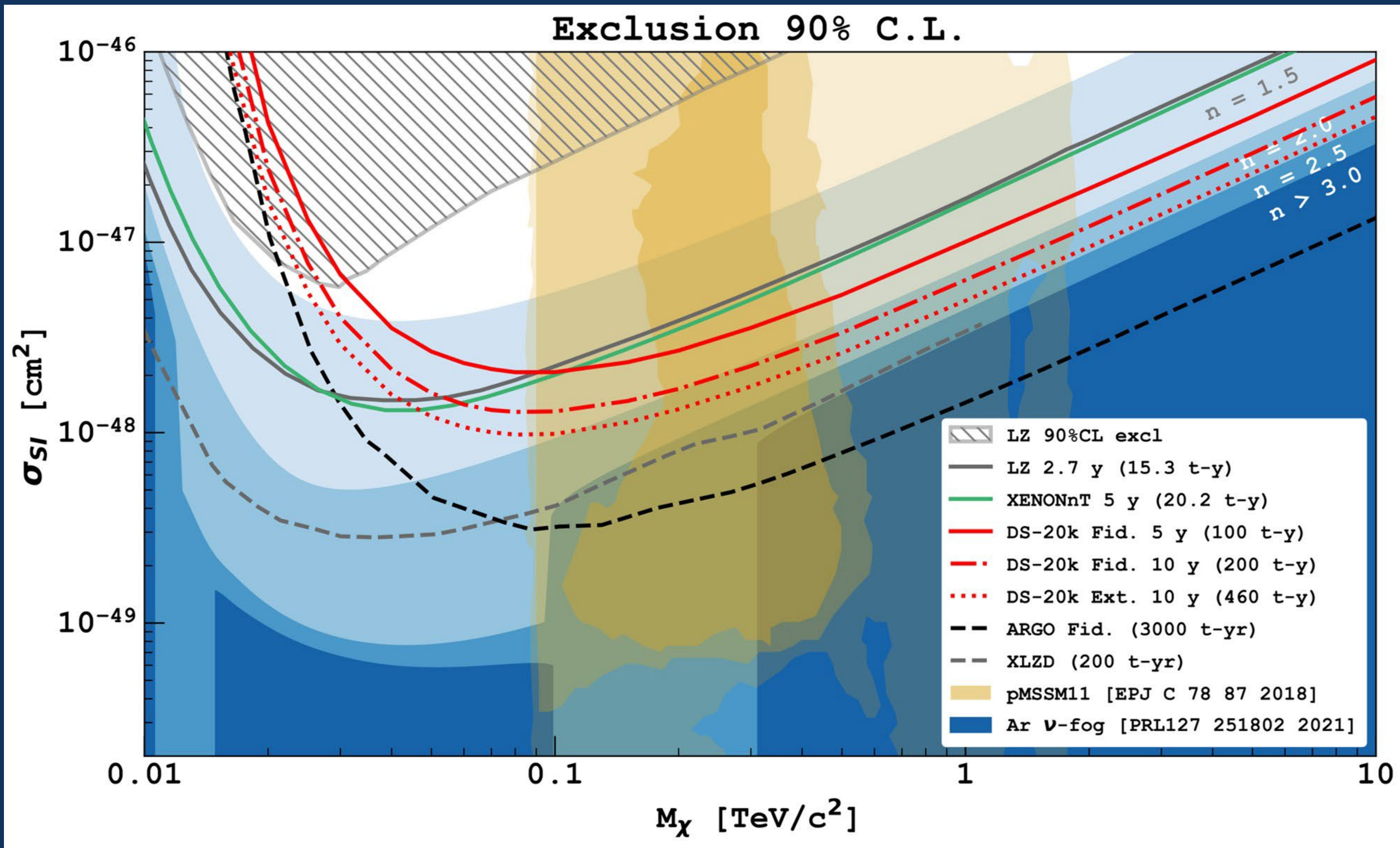


Extraction equipment shipped to US. Also interest: Legend, Coherent, Dune

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

With this set of detectors we can extend our sensitivity for Dark Matter particles striking Argon to the point where the background interfering with our signals comes from neutrinos produced in the atmosphere that cannot be removed by going deeper underground.

Sensitivity for interaction of Dark Matter



Mass of the Dark Matter Particle

DarkSide-20k: Wavelength Shifters, Coatings

- **AstroCeNT:**

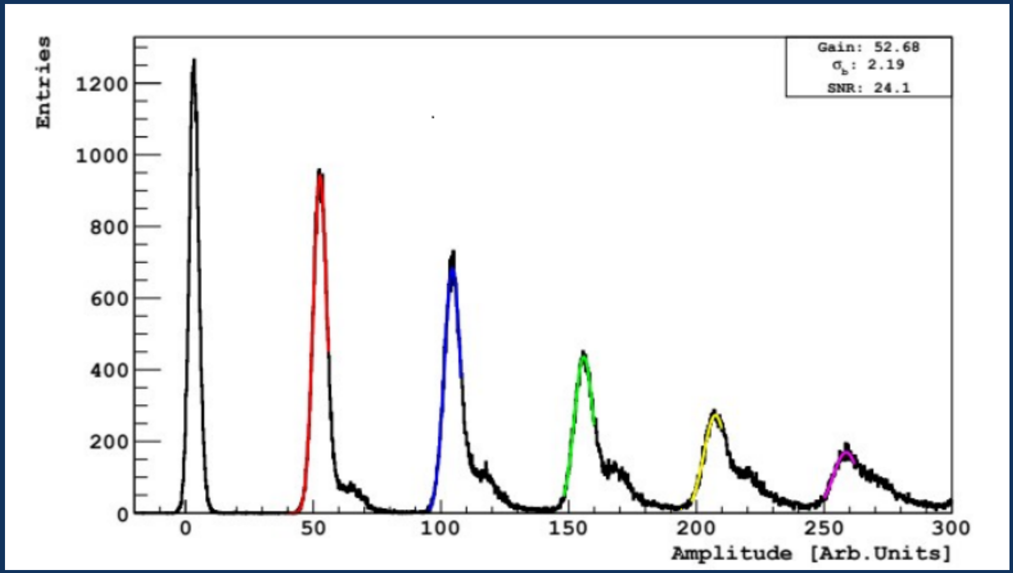
- **R&D on materials for conversion of UV light to visible**
  - **identified novel material for the future large dark matter and neutrino detectors**
  - **currently working with industry on further performance enhancement, and possible applications in photovoltaics**

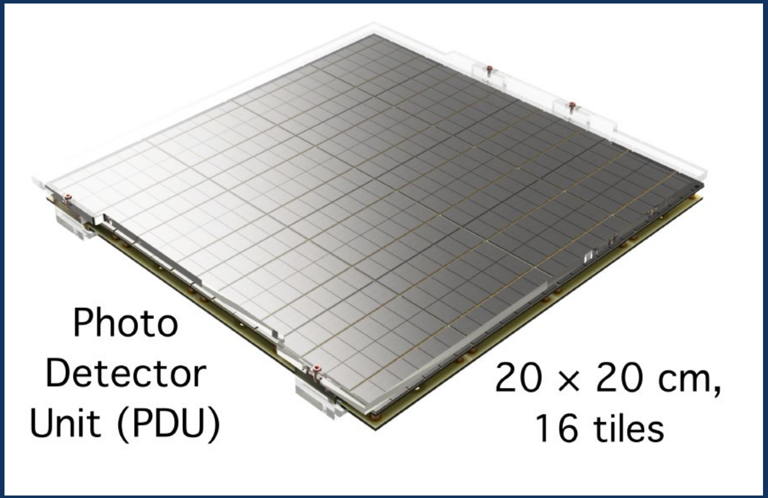
- **Development of UV-transparent polymeric electrodes**
  - **potential use in development of flexible organic sensors**
  - **proposed a new type of light and electric charge sensitive detector**

- **Other DarkSide-20k responsibilities:**
  - **300 m^2 of wavelength shifting reflector surface for the veto detector - in charge of selection and procurement**
  - **dedicated cryogenic test facility at AstroCeNT for silicon photomultiplier testing**
- **Jagiellonian University:**
  - **Strong Expertise in radioactivity control (Minister's Prize last night).**

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

Single and multiple photo-electron signals

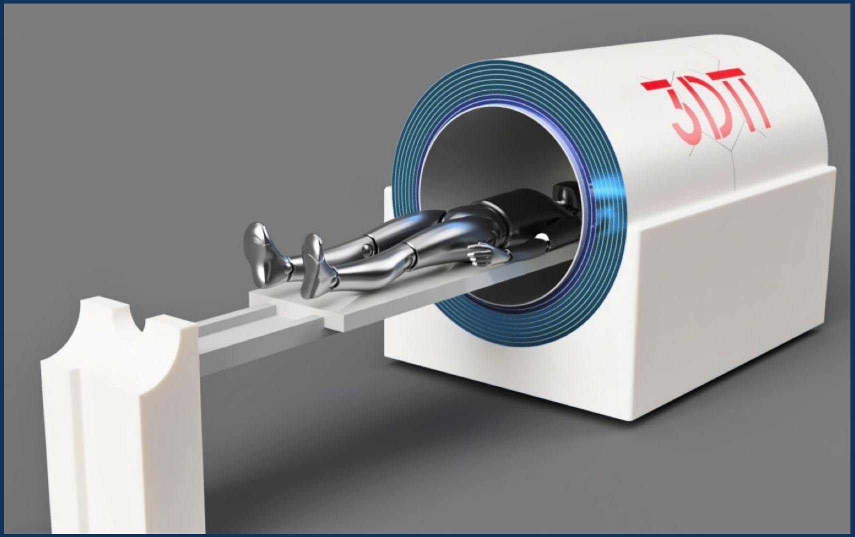




- **Superior light detection, low radioactivity.**
- **20 square meters of these in DarkSide experiment.**
- **Of value in medical and other applications.**

3Dπ: Liquid Argon PET Scanner

- **Positron emission tomography (PET) scanner measures physiological function of human body.**



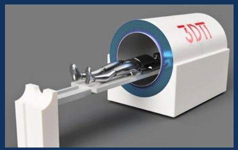
Features of 3Dπ

- Monolithic liquid argon (LAr) and xenon (Xe) scintillator (no resolution loss due to segmentation)
- Fast scintillation light (from xenon doping)
- Low SiPM dark counts due to low temperature
- Full body coverage (2 m)

Performance based on MC

- Based on computer simulation at AstroCent and collaborators, 3Dπ has **high peak-performance** with **low radioactive dose** due to high sensitivity and good time/position resolution.

- Could extend treatment to younger patients.



Scanner	Peak NECR [Mcps]	Activity concentration at peak [kBq/mL]	Sensitivity [kcps/MBq]	Timing resolution [ps]
3Dπ (MC) (Preliminary)	~8.75	~8	500	163
uEXPLORER TB-PET/CT	~1.5	17.3	174	412
J-PET-TB (MC)	0.63	30	38	500
GE SIGNA PET/CT	0.22	20.8	21.8	386
VRAIN PET	0.14	9.8	25	229

Conclusions

- Particle Astrophysics is a rapidly growing area of particle physics with strong relevance for Cosmology.
- Underground laboratories provide excellent locations for detecting rare penetrating particles (Neutrinos, Dark Matter) or long-lived (> 10^{26} year) radioactivities with little interference from cosmic rays.
- Poland is a very active participant with Astrocent, Warsaw and Jagiellonian University involved in a number of major international experiments.
- These experiments all involve pushing the frontier technologically, with strong industrial and societal opportunities.