Underground Physics
A way to look at the most elusive messengers of the Universe

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Outline

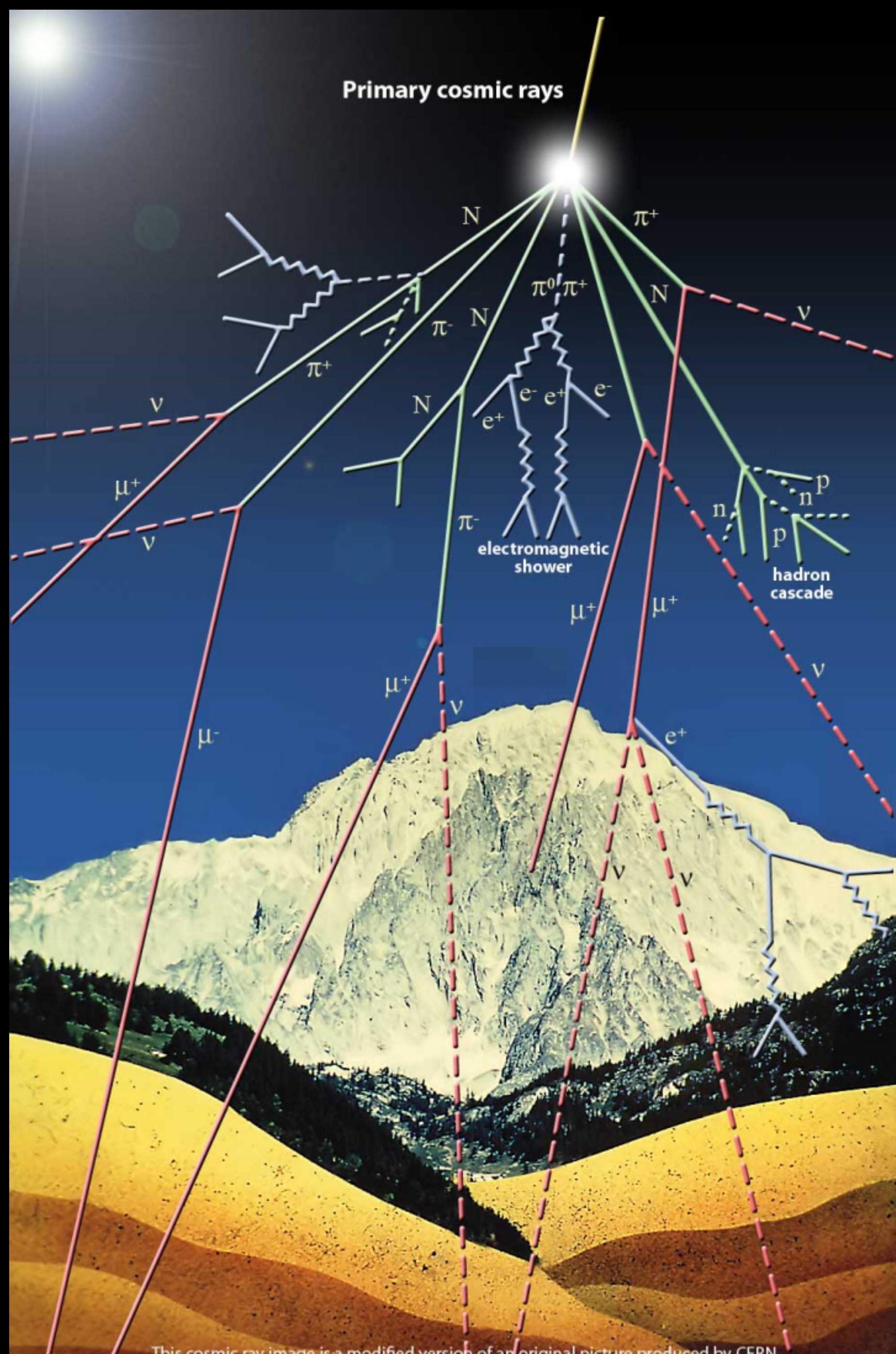
- Why underground ?
- The main physics line of research to pursue underground
- Existing laboratories
- Neutrinoless Double Beta Decay searches
- Dark Matter searches
- A bit of biology

Why can't we see the stars by day?

If we want to see a very small signal (e.g. starlight) we need to get rid of the strongest light sources (the sun)

To study rare nuclear events, we need an environment in which all the possible interferences are minimized.

So, why Underground ?

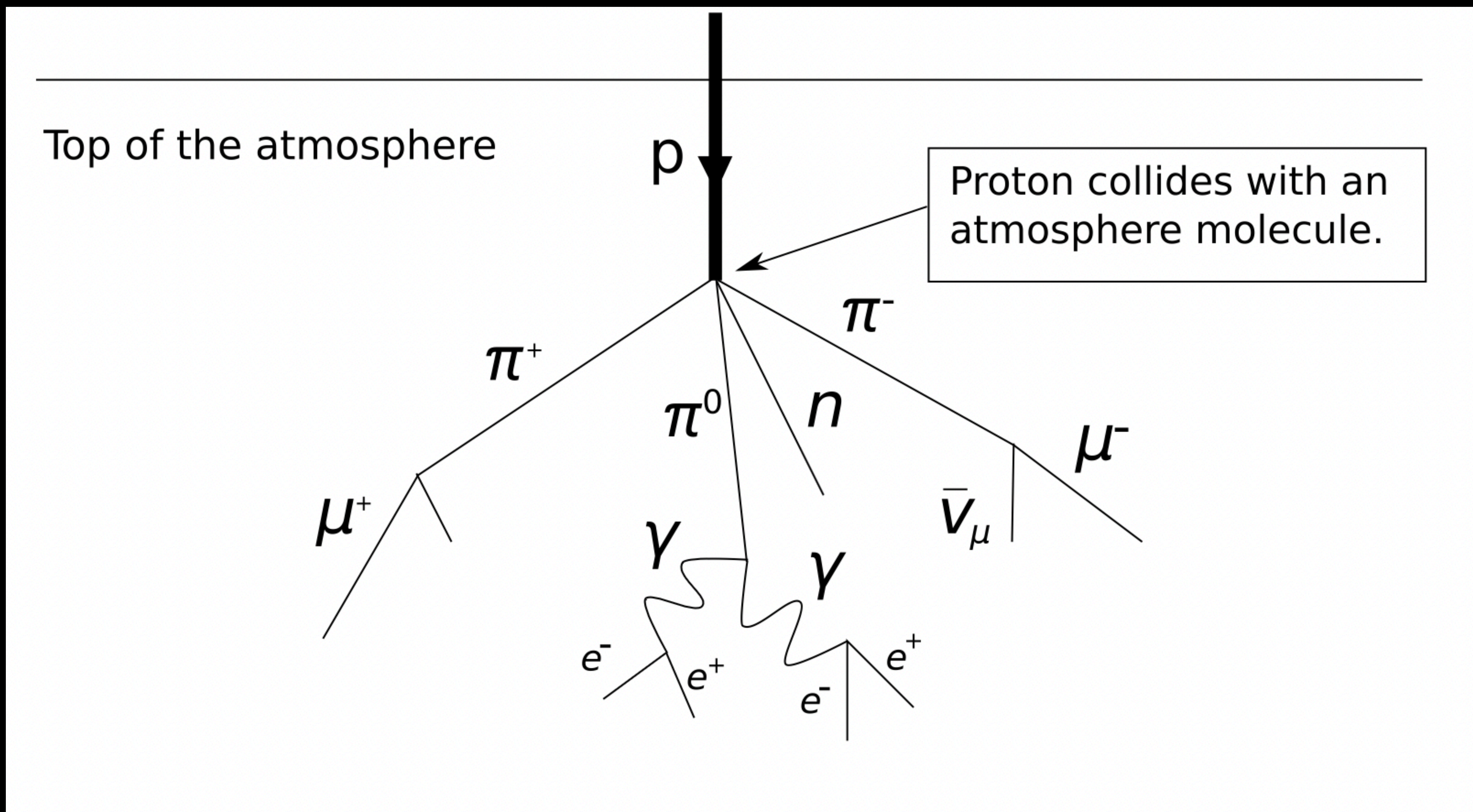


Earth is constantly bombarded by all kind of particles coming from space.

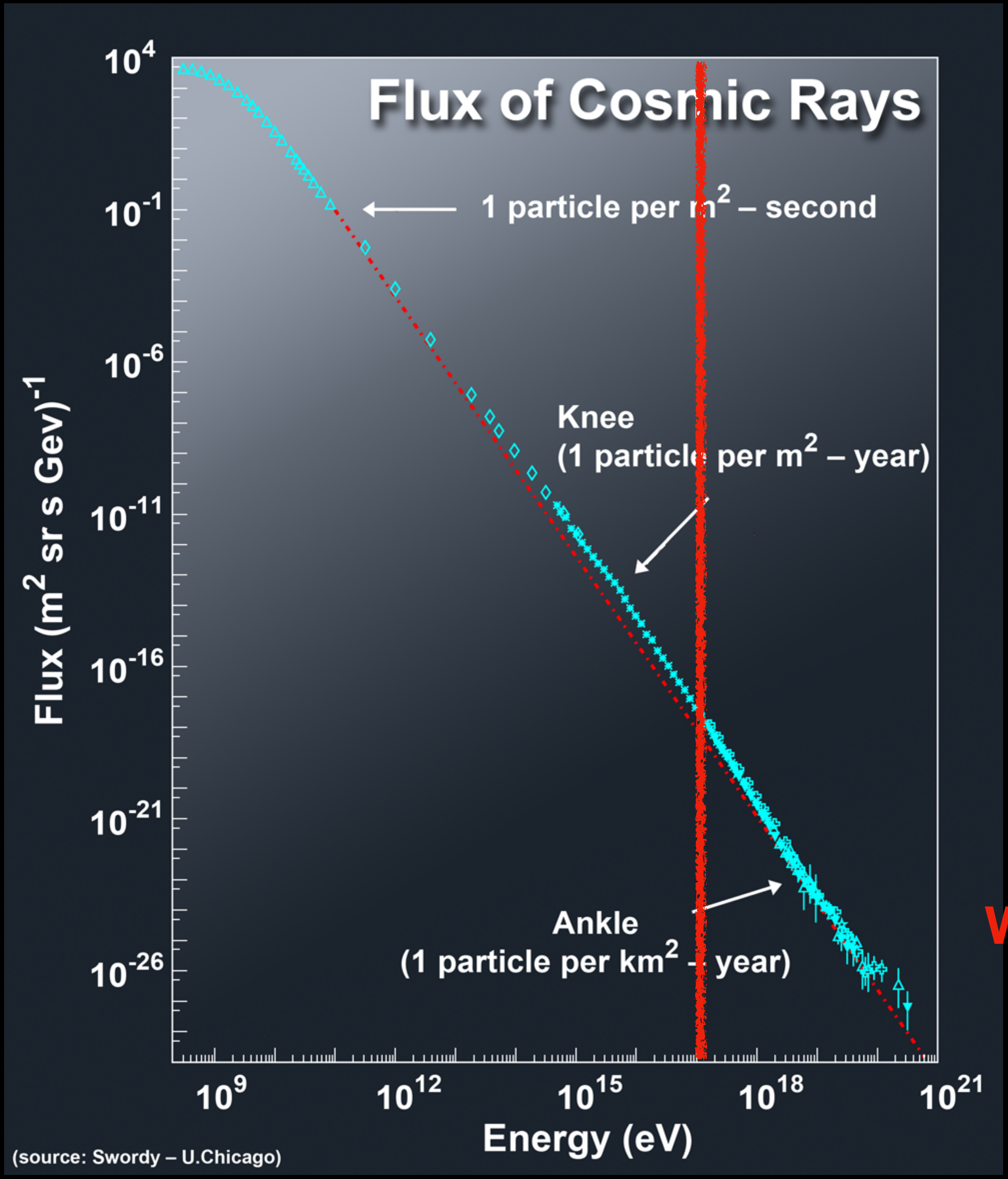
Many of them interact as soon as they feel our atmosphere and give rise to showers composed by hadronic (mainly pions) and electromagnetic particles (electrons, positrons, photons)

In the successive acts of production, absorption and decay the only survivors are muons and neutrinos

Hadronic showers



How many cosmic rays are there ?
How energetic are they ?



How does it compare to LHC energy ?

LHC CoM energy is 14 TeV (14×10^{12} eV)

The CoM energy in a fixed target process is $E_{CoM} = \sqrt{(2 \times M_p \times E_{inc}}$

Therefore if we equate

$$14 \times 10^{12} = \sqrt{2} \times 10^{9} \times x$$

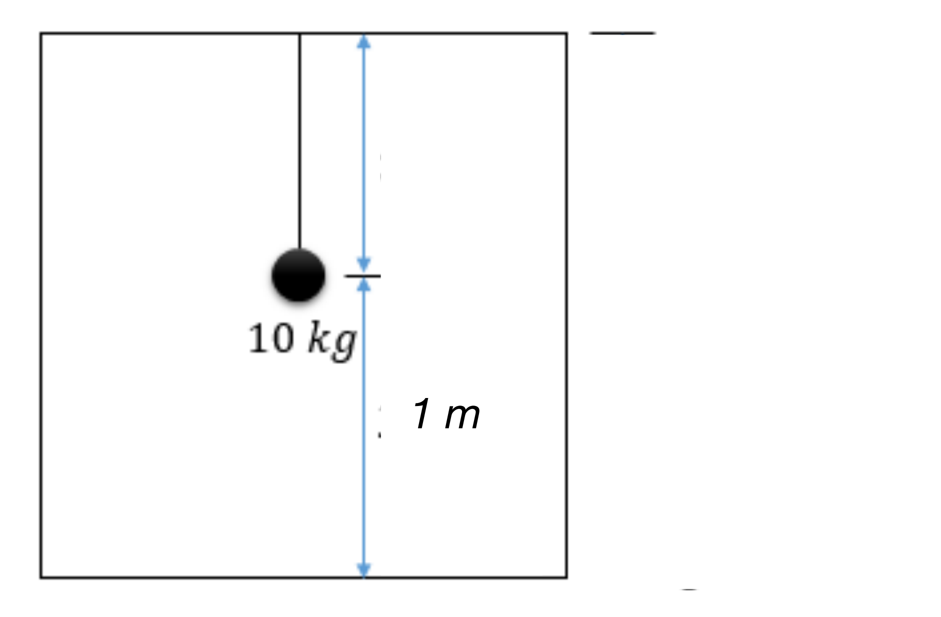
We find that the energy of a cosmic ray that will produce a collision with the same final energy as one at LHC is:

$$x \simeq 200 \times 10^{24}/(2 \times 10^{9}) \simeq 10^{17} eV$$

They can be very stiff

- The largest CR observed are in between 10^{20} and 10^{21} eV
- The conversion (eV/Joule) is $1eV \simeq 1.6 \times 10^{-19} J$
- Therefore our stiffest CR have an energy of ~ 100 J*
- Fortunately they interact in the upper atmosphere and get degraded !

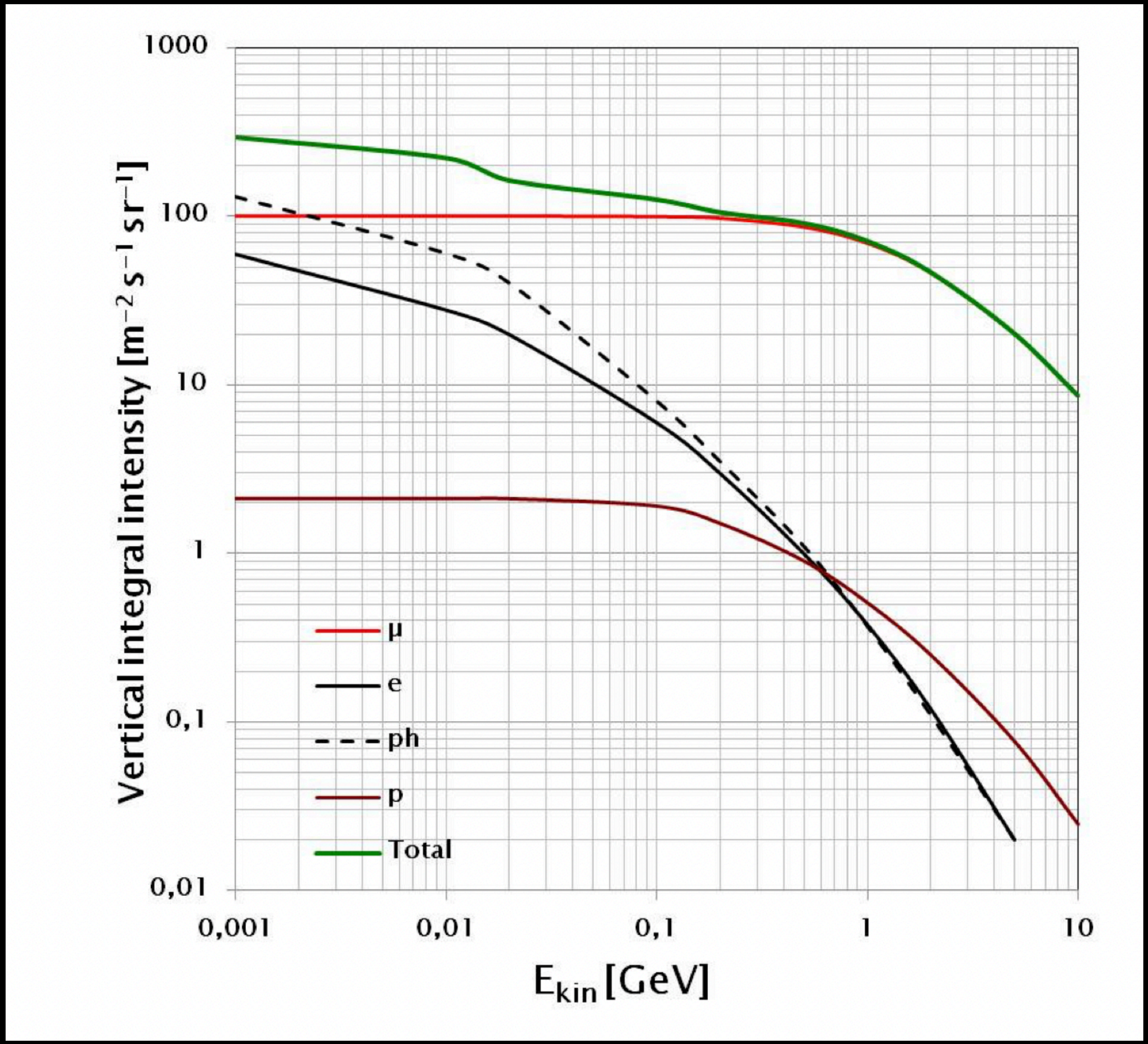
* 10Kg, 1m ……….mgh = 10x9.8x1= 98 J !)



The reason for degrading

The atmosphere of the Earth consists mainly of nitrogen and oxygen: the interaction target for the primary beam is half protons and half neutrons. Assuming an average atmospheric nucleus with A ~ 14.5, $\lambda_N \simeq 80$ g/cm^2. The total vertical atmospheric depth is about 1000 g/cm^2 and it corresponds to more than 11 interaction lengths.

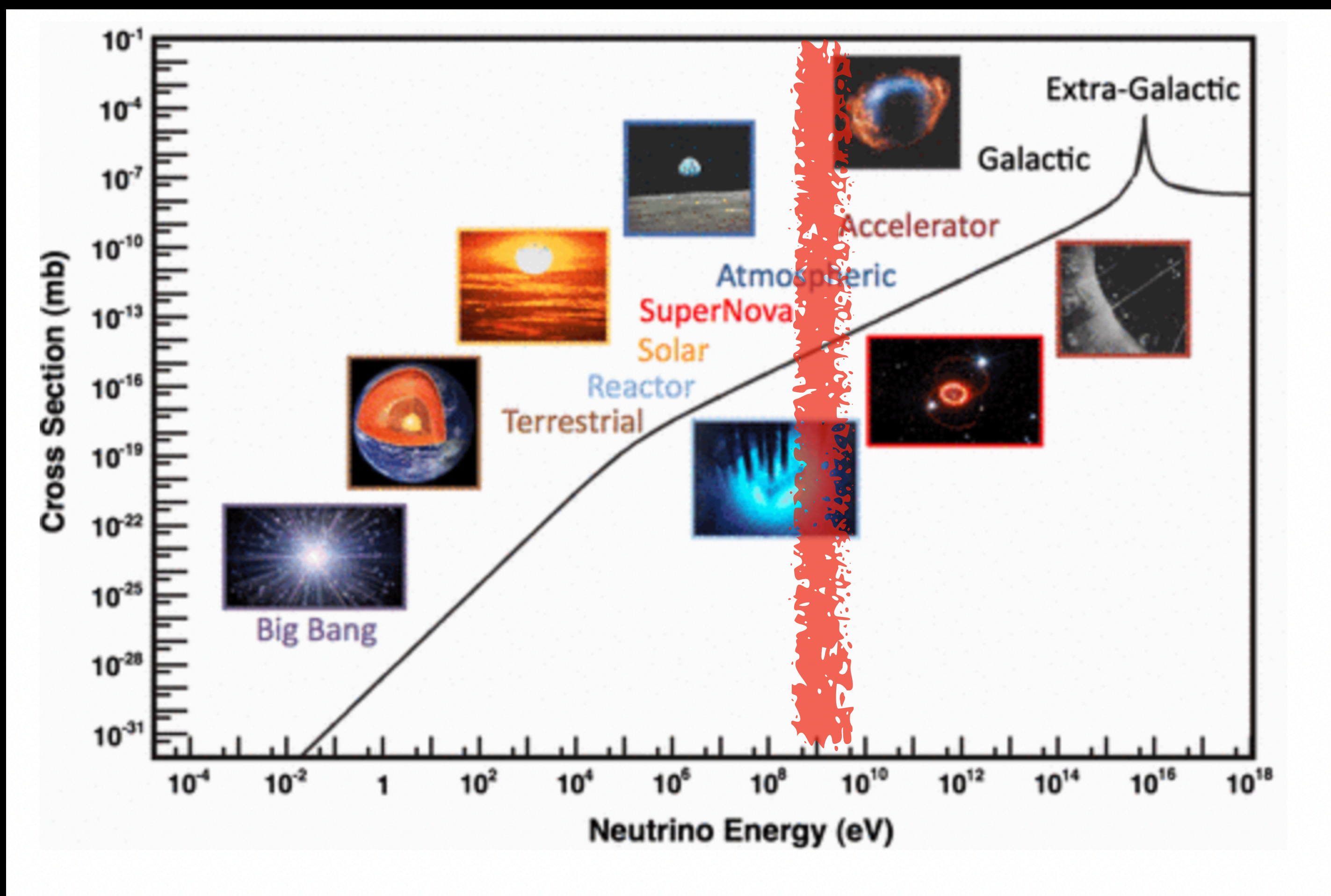
The radiation length in air is of the order of $X_0 \simeq 37.5$ g/cm^2, so that atmosphere is even more efficient in degrading electromagnetic showers



The message is that above few hundred MeV you get only muons (and neutrinos)

Neutrinos you can forget

(Well not completely, say by now !)



Cross section is in the 10^{-14} mb range

With a density to Earth crust of 2.2g/cm^3

You can calculate a mean free path $(\lambda = 1/(n\sigma\rho))$ of 10^{14} m

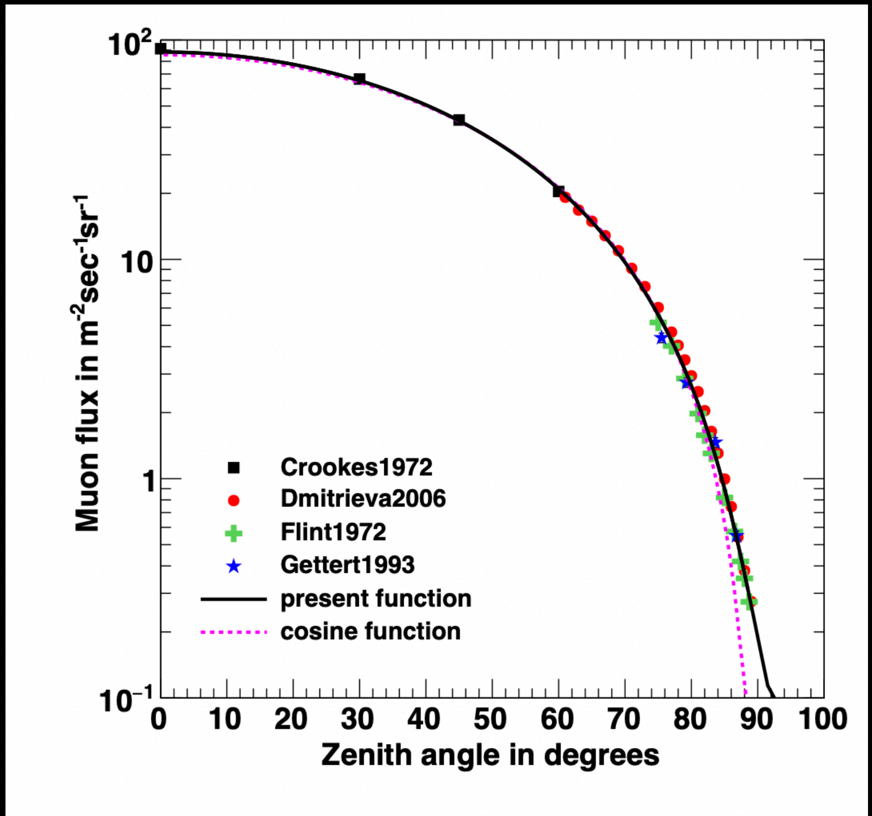
[$N_A \sim 6 \times 10^{23}$]

This is true for atmospheric neutrinos (~ 1 GeV) whose flux is determined by primary cosmic interactions (solar are a different story and also a different energy (~MeV))

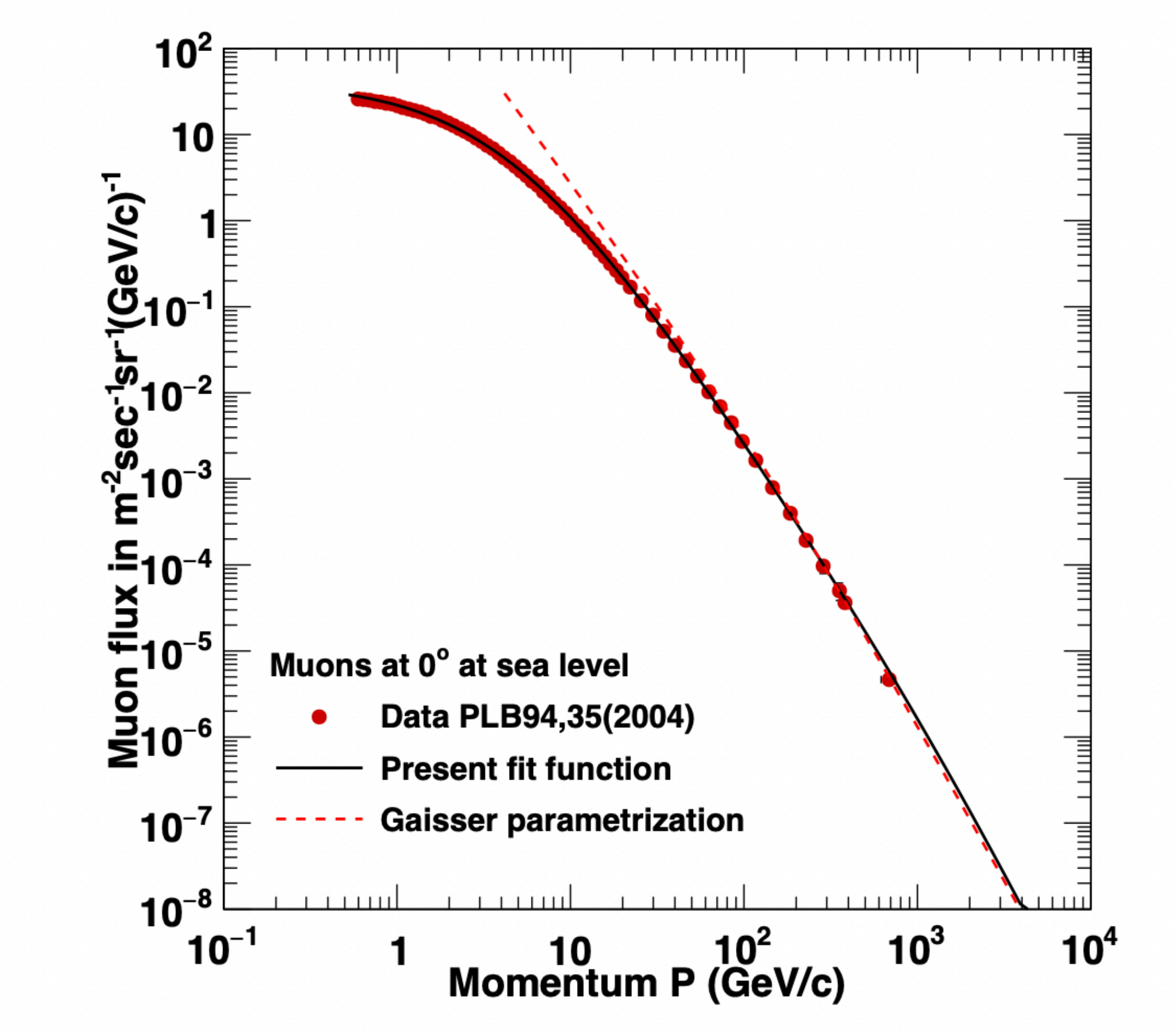
Muons you cannot forget

$$\pi^- \rightarrow \mu^- + \bar{\nu_\mu} \qquad \pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$K^- \rightarrow \mu^- + \bar{\nu_\mu} \qquad K^+ \rightarrow \mu^+ + \nu_\mu$$

$$\Phi(\theta) \simeq I_0 cos^2(\theta)$$



	I_0 (m^{-2} s^{-1} sr^{-1})
μ at 0° sea level (E>0.5 GeV)	70.7 ±0.2



Muons arrive at sea level with an average flux of about 1 muon per square centimeter per minute.

In the space of a single night, a million muons pass through the human body.

Effect on you and your experiment

- The palm of your hand is ~ 100 cm^2, therefore it is traversed by 100 muons per minute, 1.5 per second

- If your detector is a cube of one ton of water (1 m^3) it gets a rate of 150 Hz of muons….widely incompatible for searches of rare events

Muon attenuation

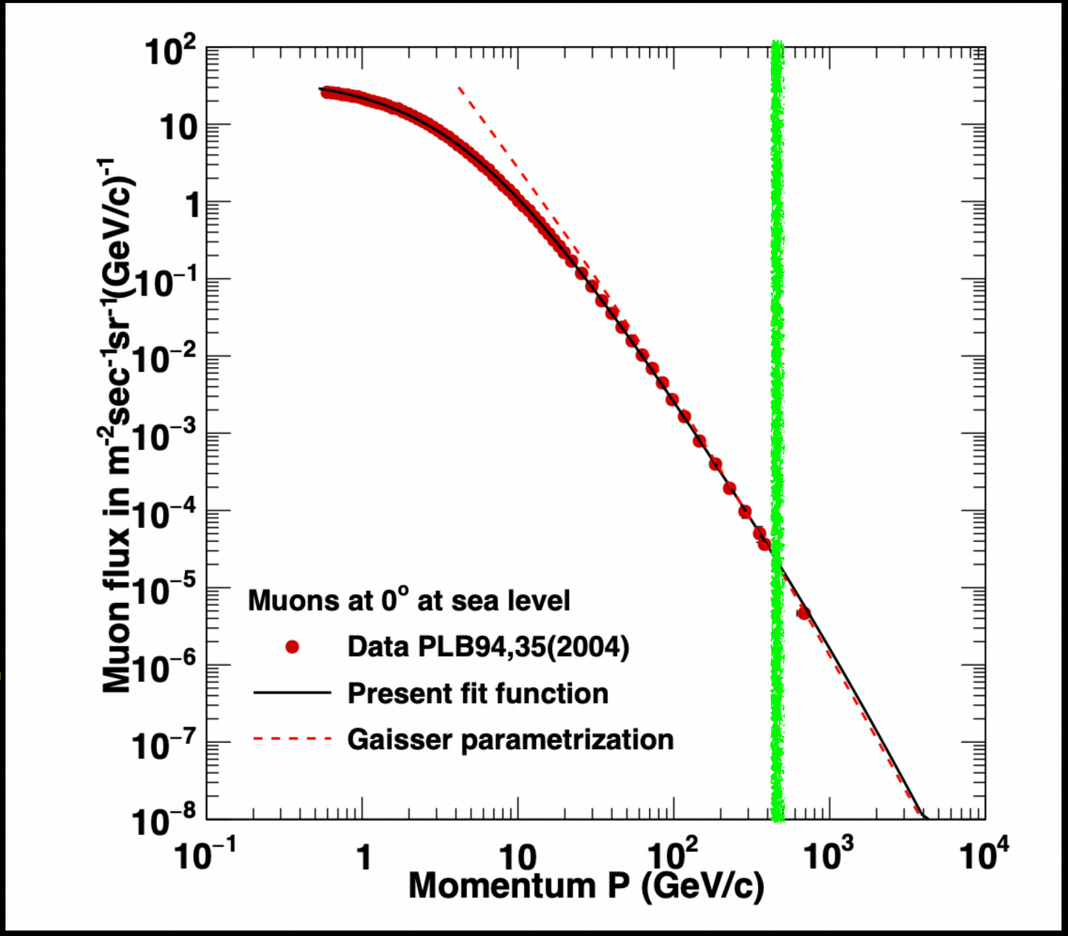
- Energy loss is $\simeq 2$ MeV /(g/cm²)
- Earth crust has a density of ~ 2.2 g/cm³
- So that a muon looses 4.5 MeV per cm
- 450 MeV per m, 450 GeV per km !!!!!
- So we know how to get rid of muons !

One km below ground muon flux decreases by a factor higher than 10^6

Remember the 150 Hz ? Now we have ~ 10^{-4} Hz

1 muon every few hours !

And you can go deeper !!!!



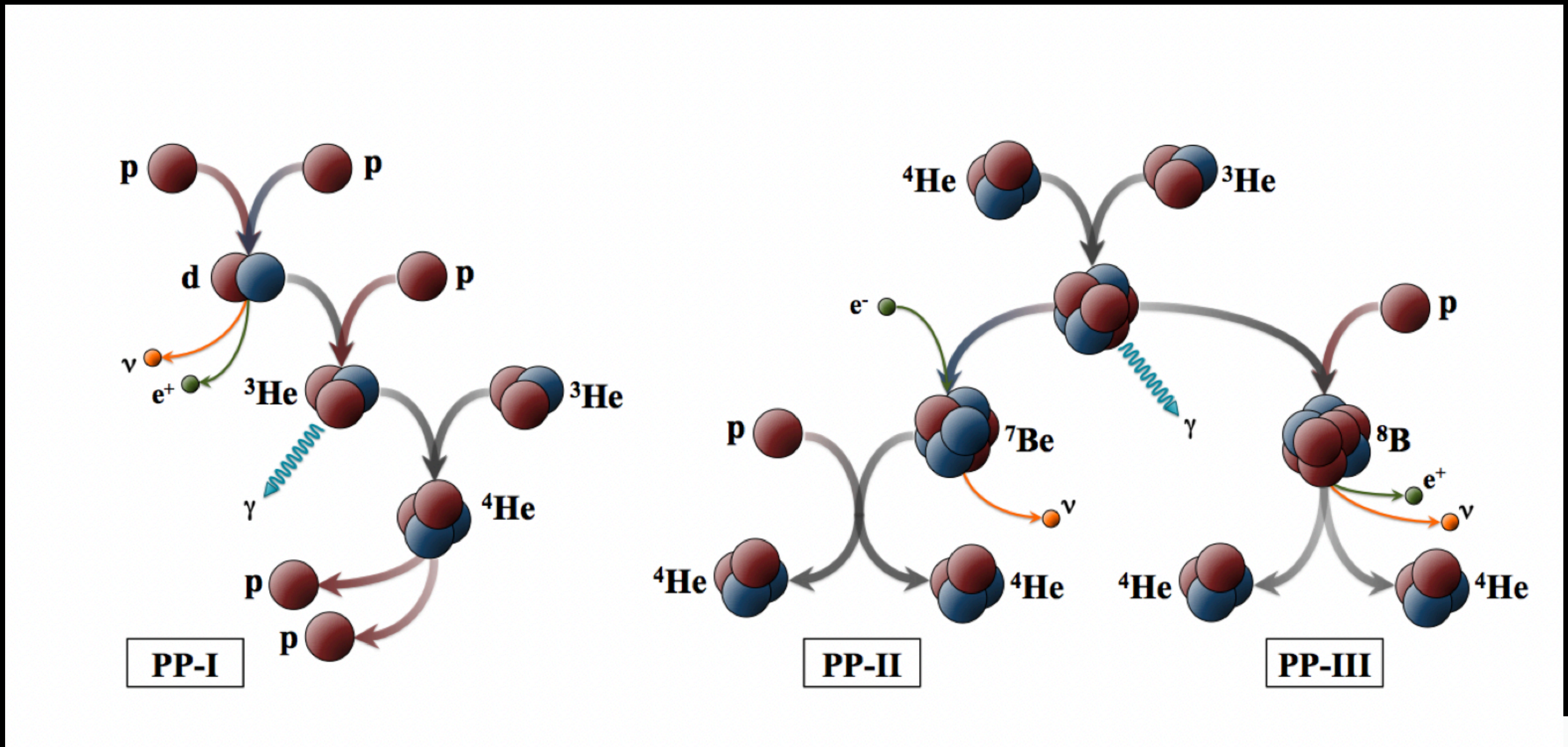
It happens because special relativity

- Mean energy of muons created in a shower $< E_\mu > \simeq 6$ GeV
- Muon lifetime at rest is $\tau \simeq 2.2 \mu$sec, range $c\tau \simeq 660$ m
- Dilation factor $E/m \simeq < E_\mu > /m_\mu \simeq 5/0.1 \simeq 50 \; [\gamma c\tau \simeq 33 km]$
- Hence an average muon can travel the entire atmosphere from the creation point (<15km>) down to ground
- Atmosphere vertical depth $\simeq 1000$ g/cm^2
- Ionization loss of a minimum ionising particle is $\simeq 2$ MeV /(g/cm^2)
- Energy loss $\simeq 2$ GeV, $< E_\mu >_{Earth} \simeq 4$ GeV

Rare ? How rare ?

- A few examples
  - Solar neutrinos
  - Double Beta Decay
  - Dark Matter search

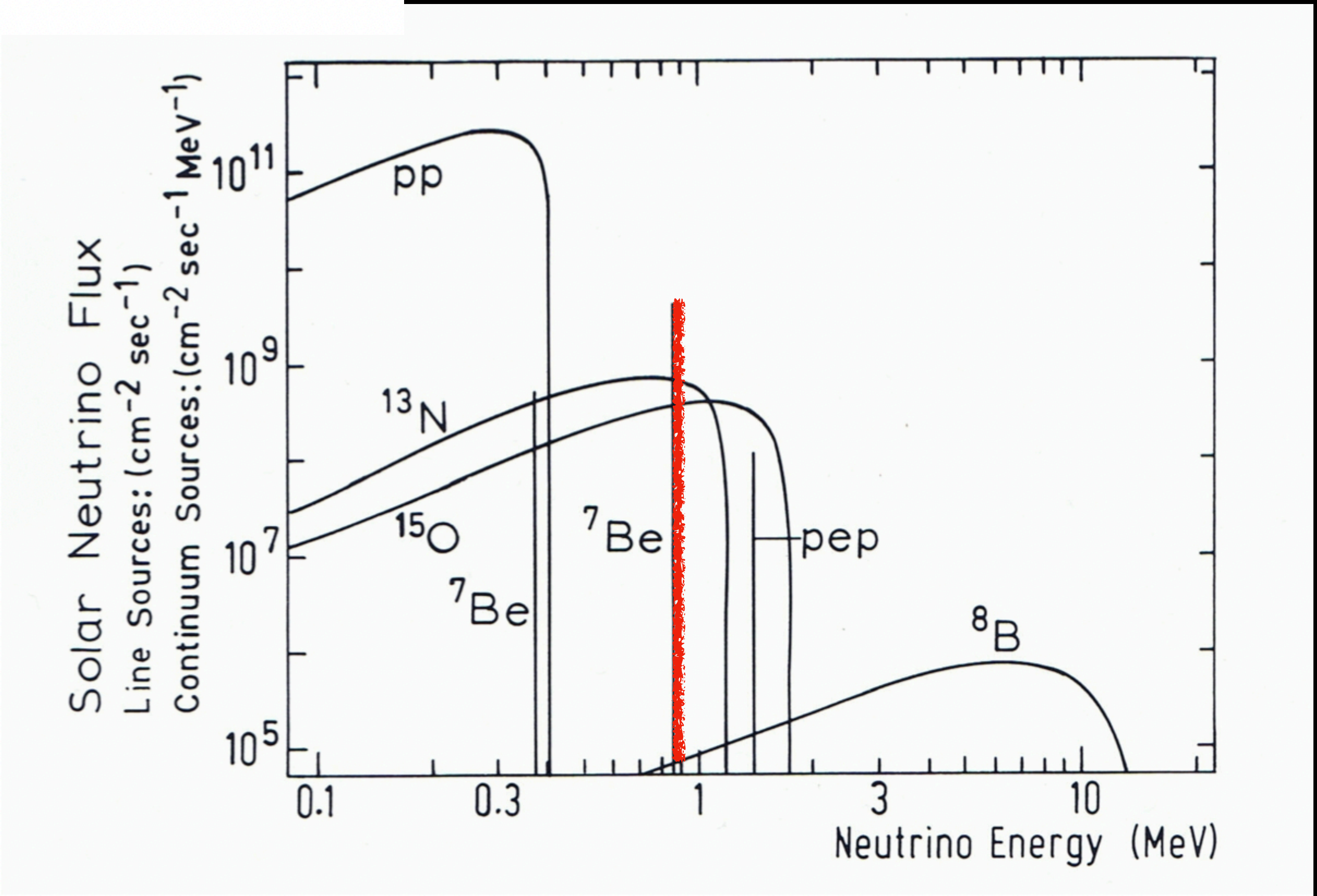
Solar Neutrinos



Just to give you an idea

The neutrinos from ^{7}Be are more than 10^9 per (cm^2 sec)

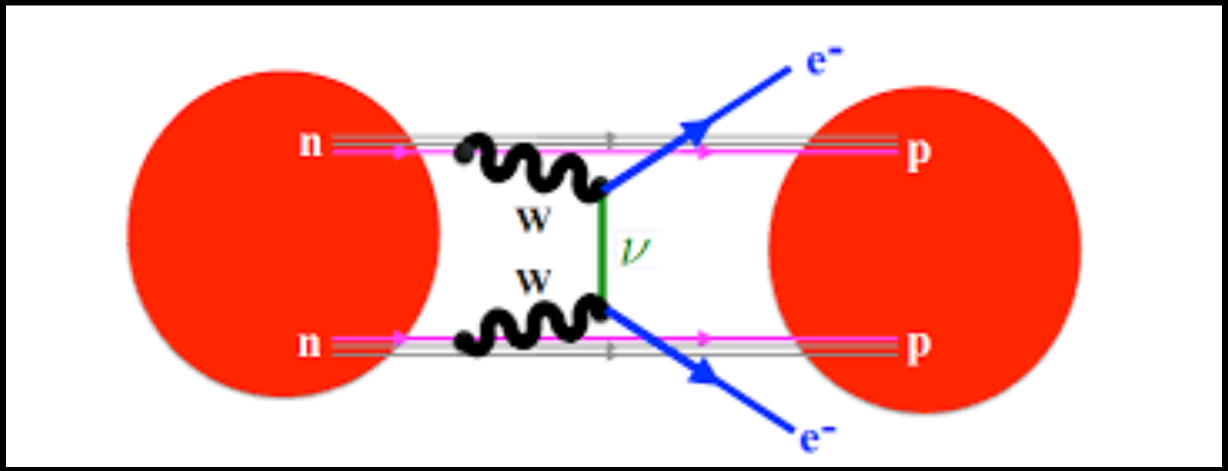
Borexino experiment has measured them. They have found a rate of:
49+/3(stat)+/4(cyst) events/ (day x 100tons)

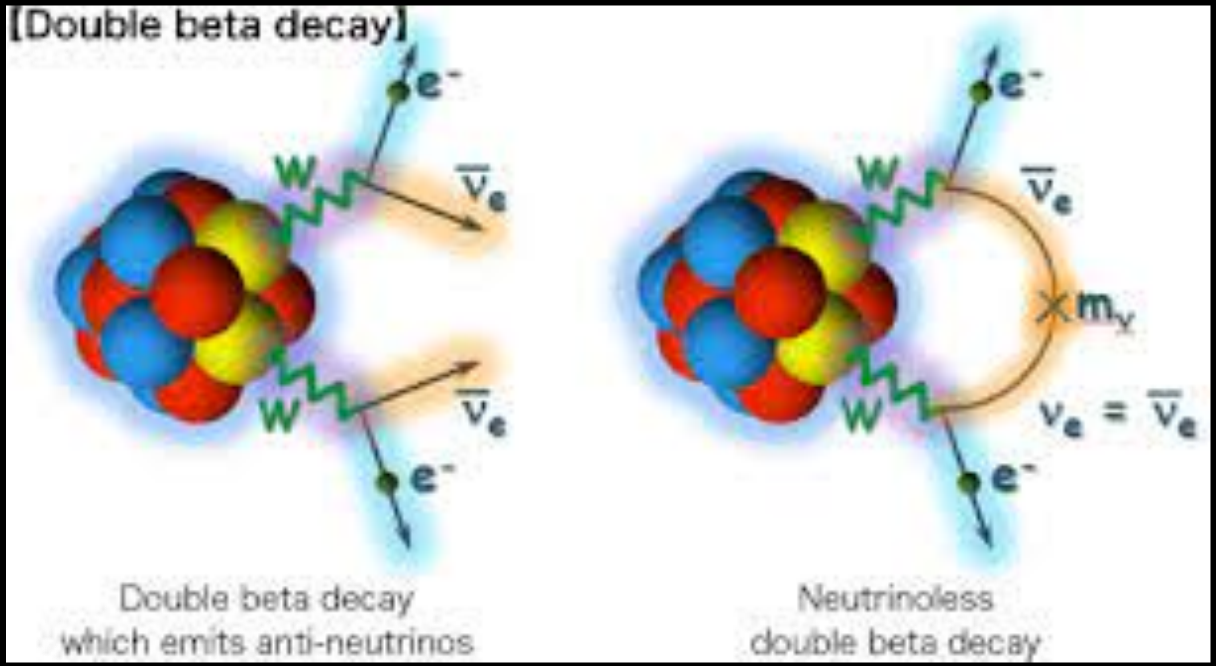


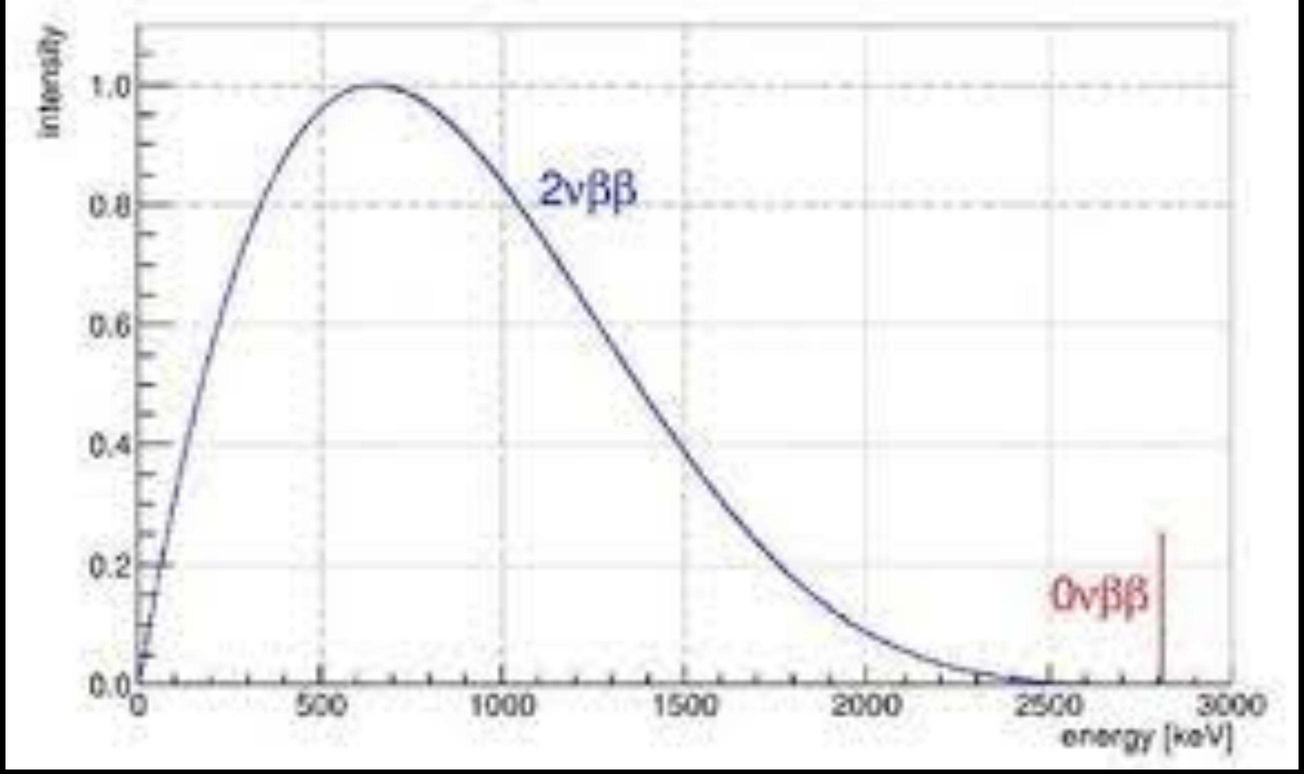
Pretty rare , isn't it ?

We'll come back to this experiment later

Double Beta Decay







Low energy again ~ MeV

Long half-lives

Half-life measurements of the two-neutrino double-β decay

The measured half-life values for the transitions $(Z,A) \to (Z+2,A) + 2e^- + 2\overline{\nu}_e$ to the 0^+ ground state of the final nucleus are listed. We also list the transitions to an excited state of the final nucleus (0^+_i, etc.). We report only the measuremetnts with the smallest (or comparable) uncertainty for each transition.

$t_{1/2}(10^{21}$ yr)			ISOTOPE	TRANSITION	METHOD	DOCUMENT ID	
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 0.87			^{134}Xe		EXO-200	[1] ALBERT	17C
0.82	±0.02	±0.06	^{130}Te		CUORE-0	[2] ALDUINO	17
0.00690	±0.00015	±0.00037	^{100}Mo		CUPID	[3] ARMENGAUD	17
0.0274	±0.0004	±0.0018	^{116}Cd		NEMO-3	[4] ARNOLD	17
0.064	$^{+0.007}_{-0.006}$	$^{+0.012}_{-0.009}$	^{48}Ca		NEMO-3	[5] ARNOLD	16
0.00934	±0.00022	$^{+0.00062}_{-0.00060}$	^{150}Nd		NEMO-3	[6] ARNOLD	16A
1.926	±0.094		^{76}Ge		GERDA	[7] AGOSTINI	15A
0.00693	±0.00004		^{100}Mo		NEMO-3	[8] ARNOLD	15
2.165	±0.016	±0.059	^{136}Xe		EXO-200	[9] ALBERT	14
9.2	$^{+5.5}_{-2.6}$	±1.3	^{78}Kr		BAKSAN	[10] GAVRILYAK	13
2.38	±0.02	±0.14	^{136}Xe		KamLAND-Zen	[11] GANDO	12A
0.7	±0.09	±0.11	^{130}Te		NEMO-3	[12] ARNOLD	11
0.0235	±0.0014	±0.0016	^{96}Zr		NEMO-3	[13] ARGYRIADES	10
0.69	$^{+0.10}_{-0.08}$	±0.07	^{100}Mo	$0^+ \to 0^+_1$	Ge coinc.	[14] BELLI	10
0.57	$^{+0.13}_{-0.09}$	±0.08	^{100}Mo	$0^+ \to 0^+_1$	NEMO-3	[15] ARNOLD	07
0.096	±0.003	±0.010	^{82}Se		NEMO-3	[16] ARNOLD	05A
0.029	$^{+0.004}_{-0.003}$		^{116}Cd		$^{116}CdWO_4$ scint.	[17] DANEVICH	03

pls. Note the unit :

10^{21} yr

$$N_A \simeq 6 \times 10^{23}$$

~ 600 decays /year per mole

Dark Matter

- As we do not know of what is made it is difficult to predict an interaction rate

- What we know is that if it would behave accordingly to the electroweak interactions we would have observed already

- We have not, meaning that (if any) it has a very low probability of interaction

At the end of the day

- If you want to search for rare processes you cannot do the experiment at ground level

- So the idea is to go underground with manifest advantages

The theory of an UL

- There are two options:
  - Find a mine , possibly still in operation, and see if you can equip it to the scope you need
  - While building an highway that cross a mountain chain convince the Ministry of Infrastructure to add a little money to dig a cavern orthogonal to the tunnel where traffic flows

Pro and cons
Mines

- Mines are usually pretty deep. The infrastructure to access the underground space exists (lifts…) . The reason to find a site in operation is because anything abandoned is almost impossible to bring back to operations (slides, water, technical services…..)

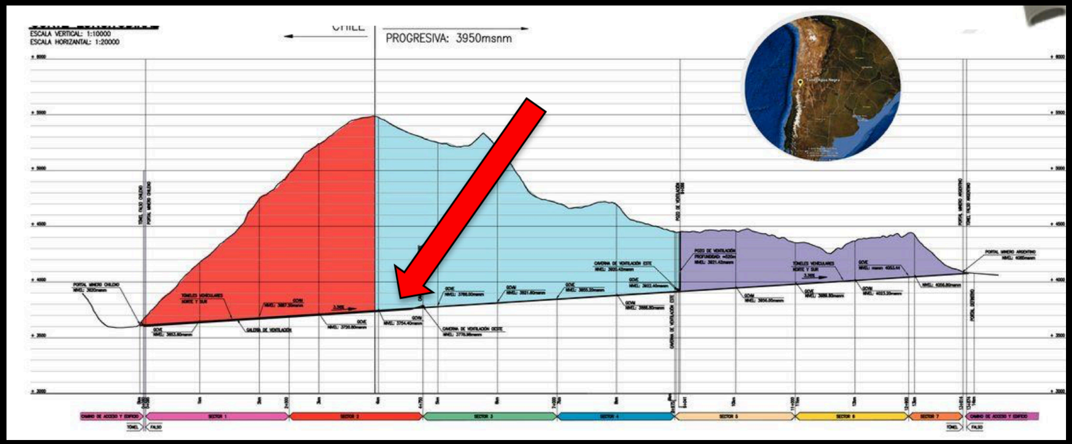
- It is very difficult to have very large spaces underground . The mines do not need to dig big tunnels to reach the ore.

- Mines are a dirty place. A lot of caution for you and your valuable equipment.

- You cannot bring an entire detector or large parts of it directly down. The lifts have a small volume capacity. You have to assemble everything down.

Pro and cons
Highway tunnels

- The tunnels under the mountains are not so deep. If you dig at the base the tunnel becomes financially unaffordable for its length
- You can get inside the laboratory by car and trucks. No problem in bringing in large detectors
- Clean environment

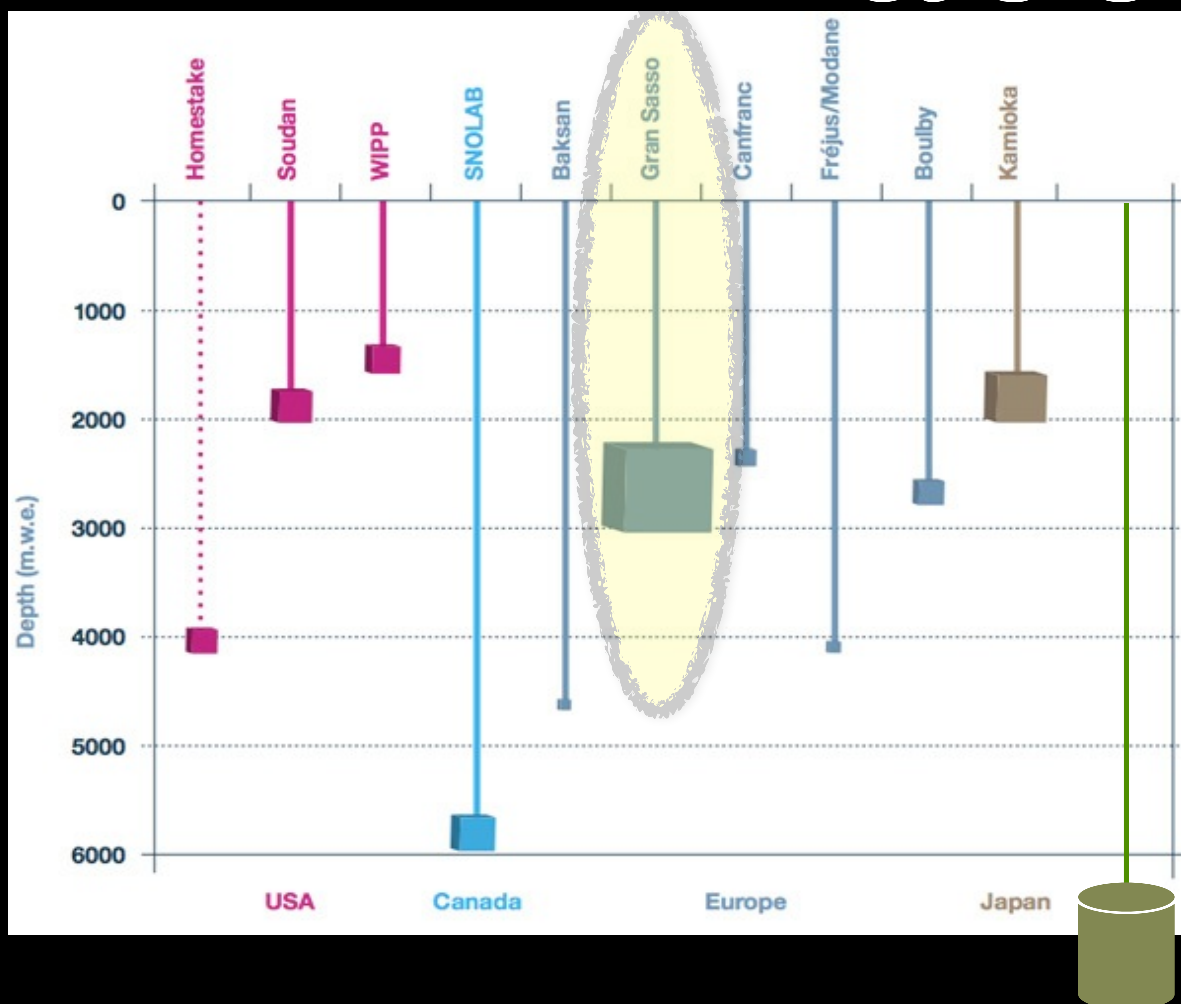


Existing laboratories

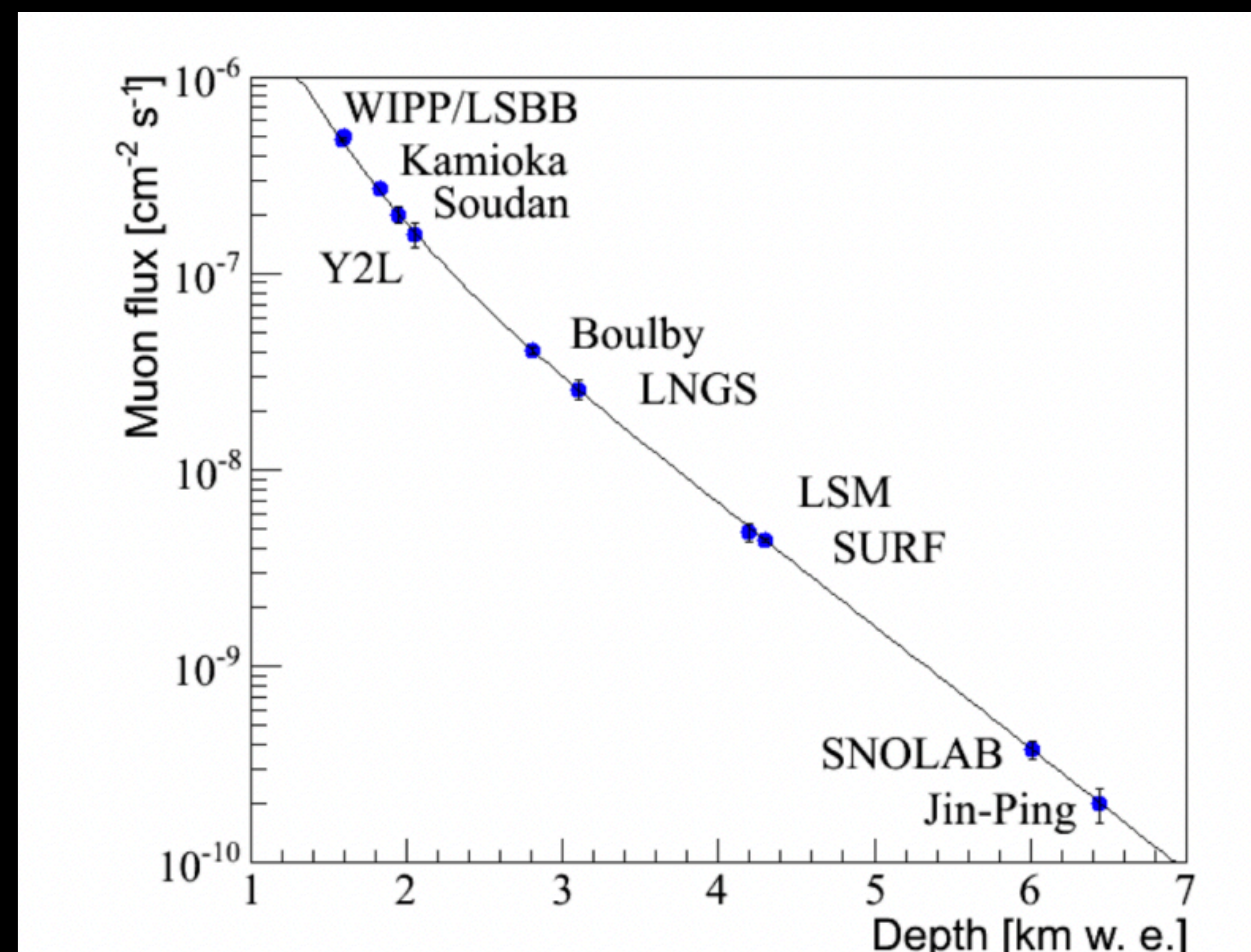
- LNGS (Italy)
- SNOLAB (Canada)
- Kamioka (Japan)
- SURF (USA)
- JINPING (China)
- Y2L. (S. Korea)
- A few others [Modane (F), Stawell (Aus), Boulby (UK)….]

None in operation in the Southern Hemisphere

Underground Science Laboratories



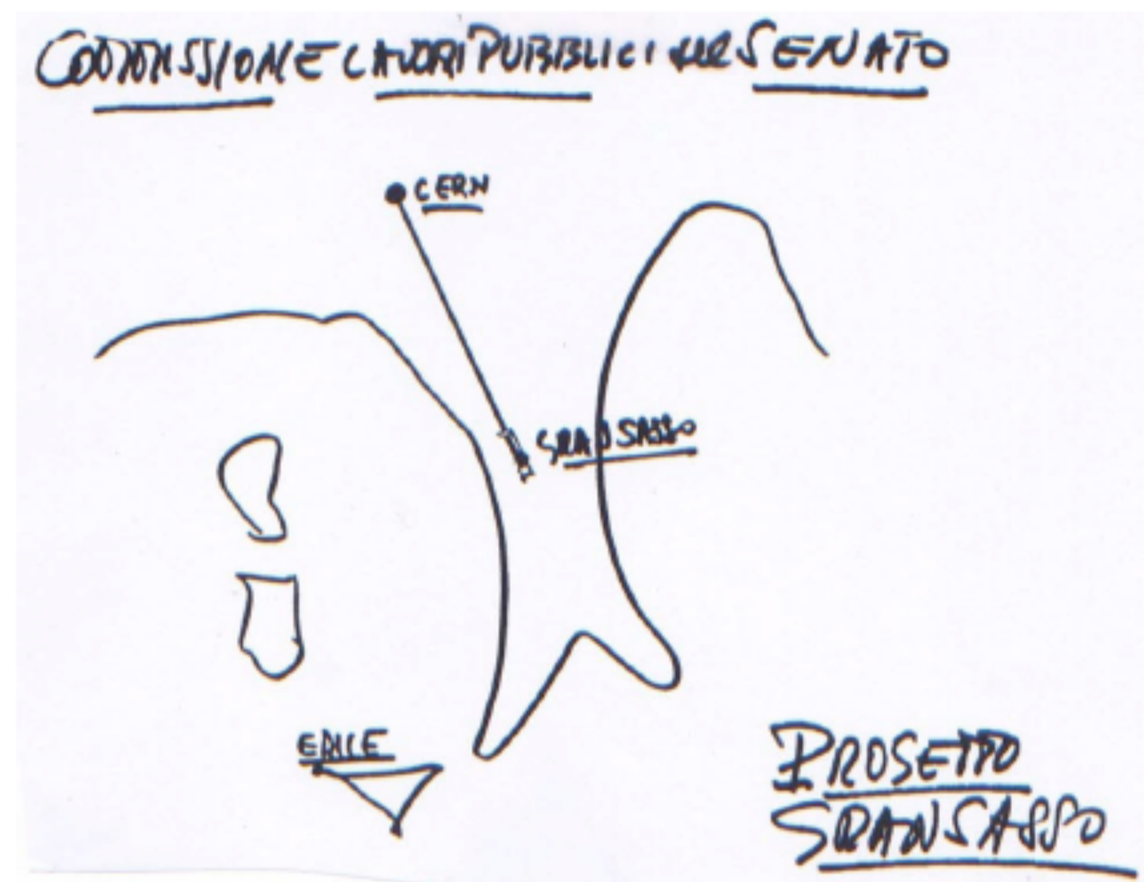
LNGS is (still) the largest, the easiest to access and deep enough



LNGS (Gran Sasso)

The idea of cosmic silence

from dream to reality !



Note manoscritte di A. Zichichi presentate nella Seduta della Commissione Lavori Pubblici del Senato convocata con urgenza dal Presidente del Senato per discutere la proposta del Progetto Gran Sasso (1979).

To summarize, the scientific aims of the "Gran Sasso" laboratory are the study of:

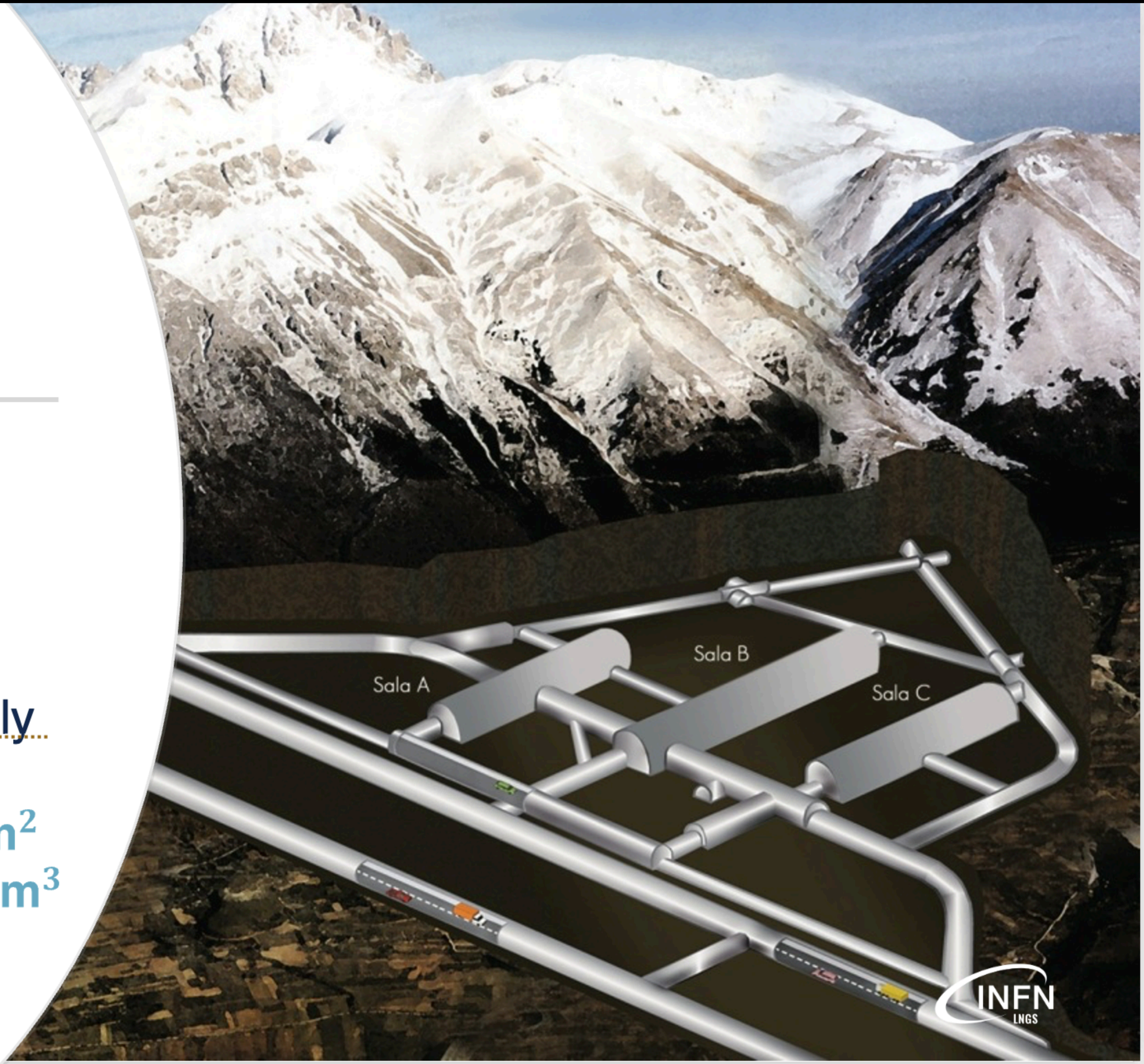
1) nuclear stability;
2) neutrino astrophysics;
3) new cosmic phenomenology;
4) neutrino oscillations;
5) biologically active matter;
6) ground stability.

NOT only $\tau_p \neq \infty$

Features of the underground laboratory

- **1400 m** of rock overhead
- Cosmic ray flux reduction: **1.000.000**
- The largest in the world actually running

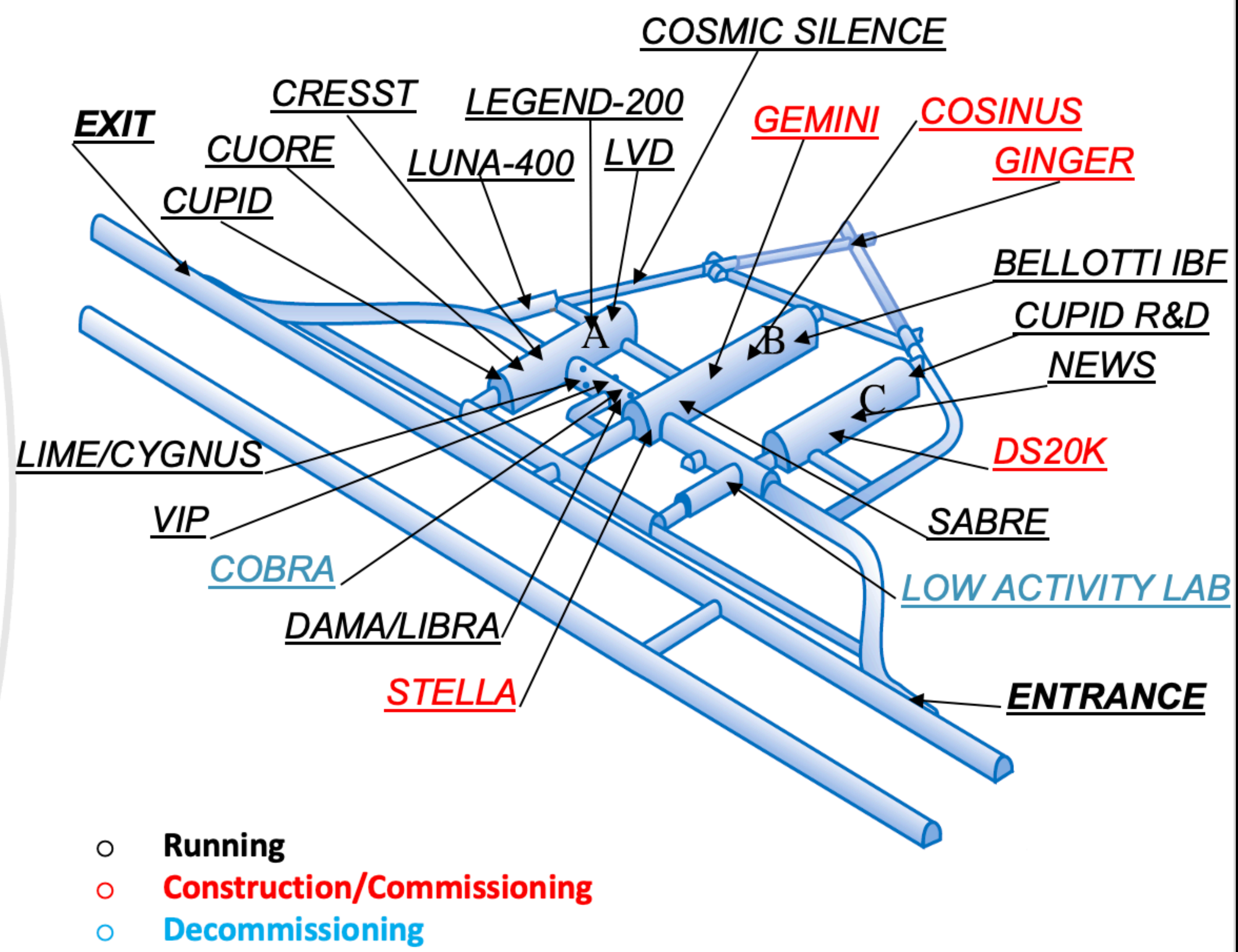
Underground Surface: 17800 m^2
Underground Volume: 180000 m^3



A look inside

A look inside

- The 3 experimental halls measure approximately 100 m in length, 20 m in width and 18 m in height
- About 22 experiments in data taking or under construction
- The most sensitive laboratory (LOW ACTIVITY LAB) dedicated to the measurement of contaminants in materials



Not only experiments

LNGS Users Support and Facilities

1. Ultra-low background techniques
2. Chemistry lab and service
3. Mechanics workshop
4. Mechanics design & 3D-lab
5. Electronics
6. IT
7. Clean Rooms

A virtual tour of LNGS

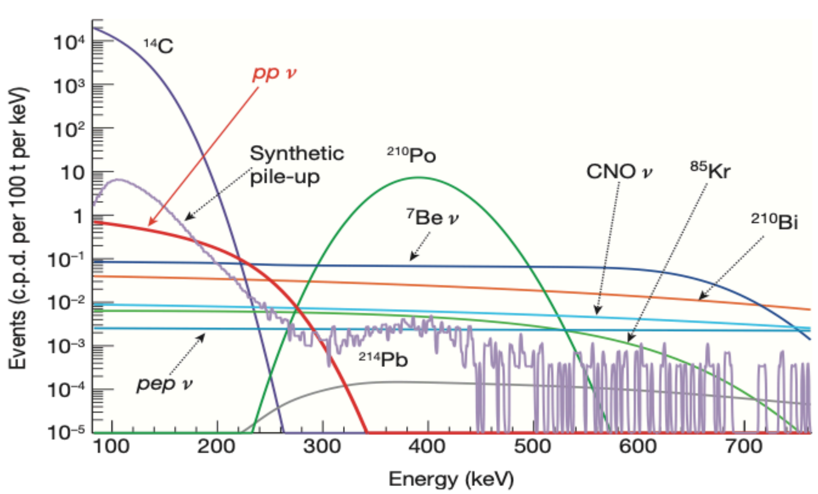
- https://www.google.it/maps/@42.4527666,13.5735482,2a,90y,202.68h,98.42t/data=!3m6!1e1!3m4!1sgoFKiyrwwLBaVtMQIStnEQ!2e0!7i13312!8i6656?hl=en

The flagship experiment

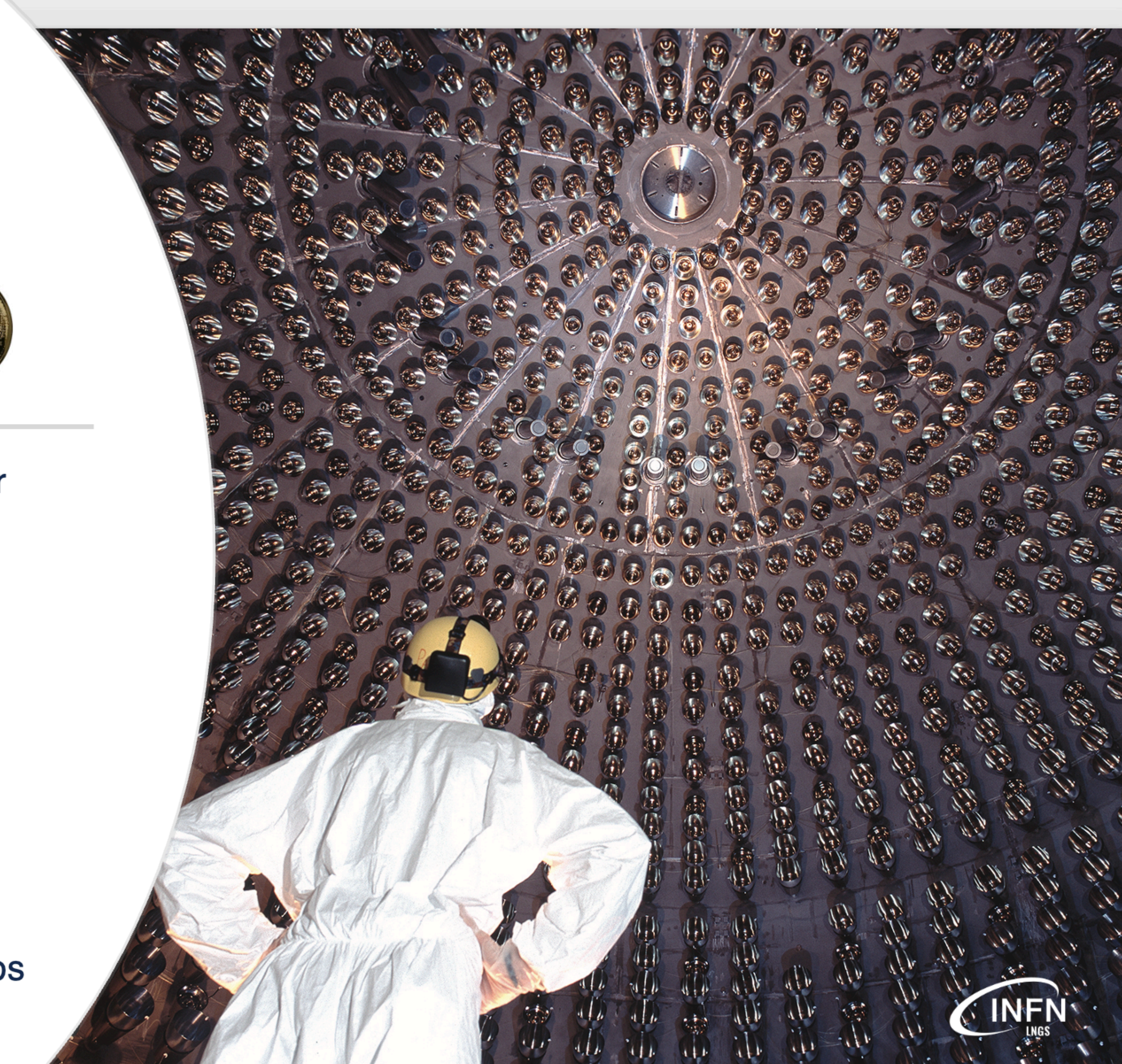
Borexino

Real time neutrino (all flavours) detector

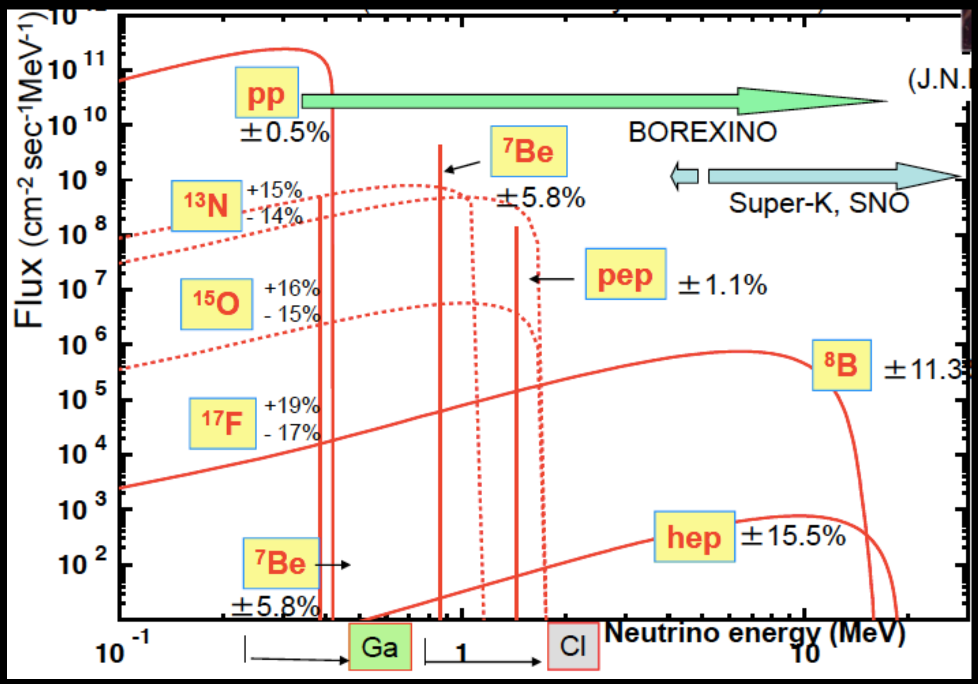
Real-time measurement of pp neutrino

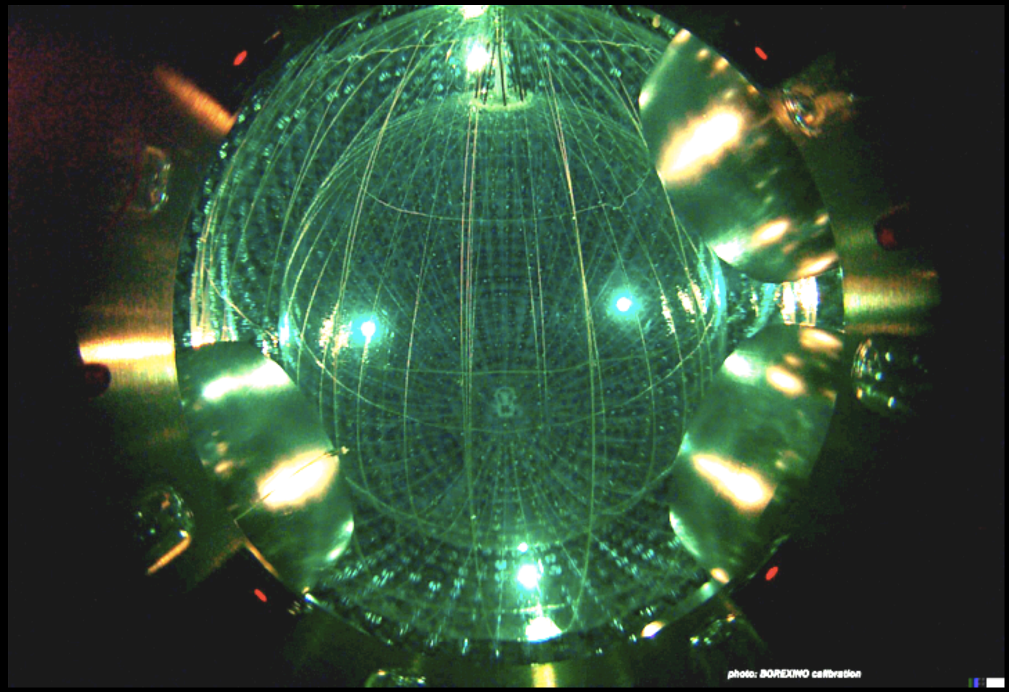


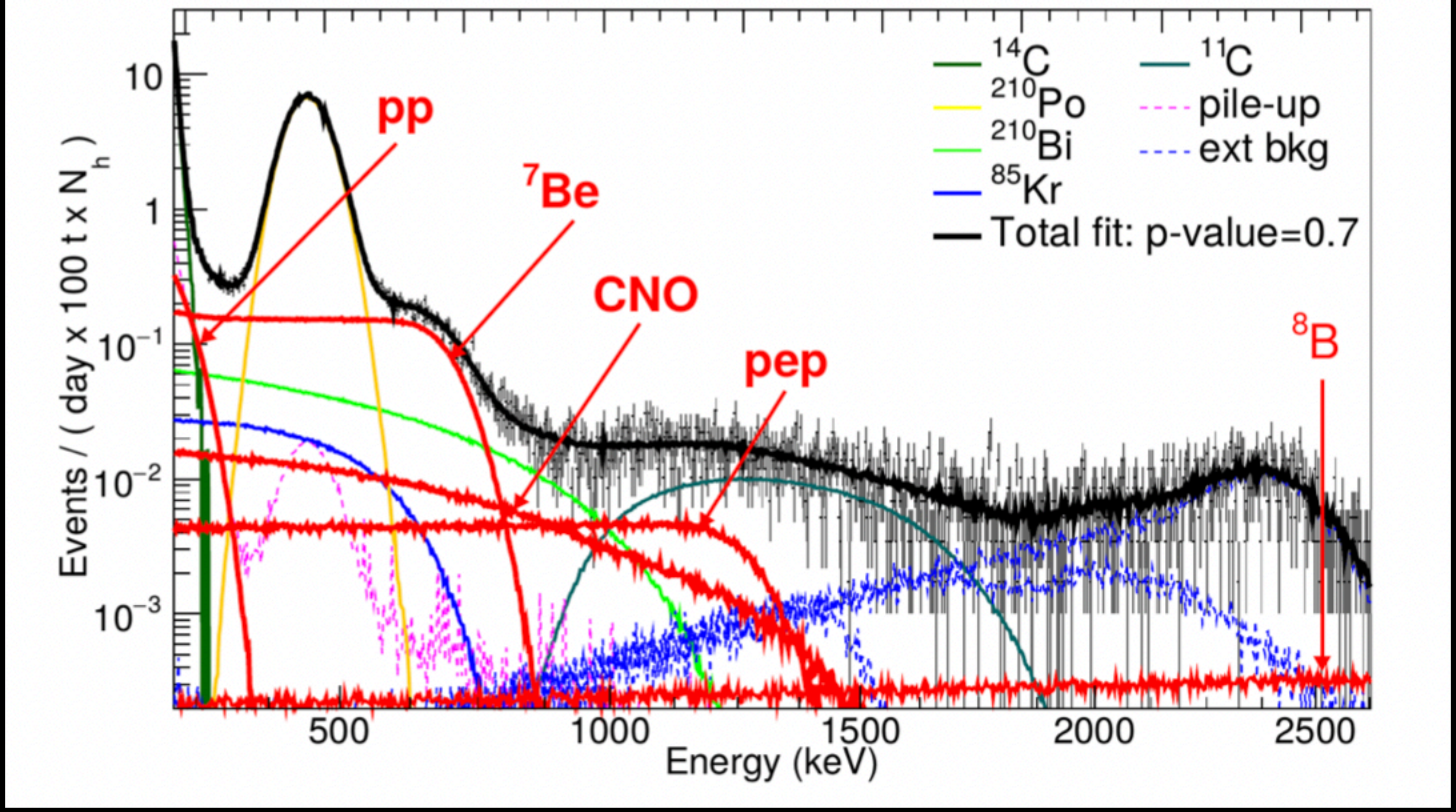
Real-time measurement of Geo-neutrinos

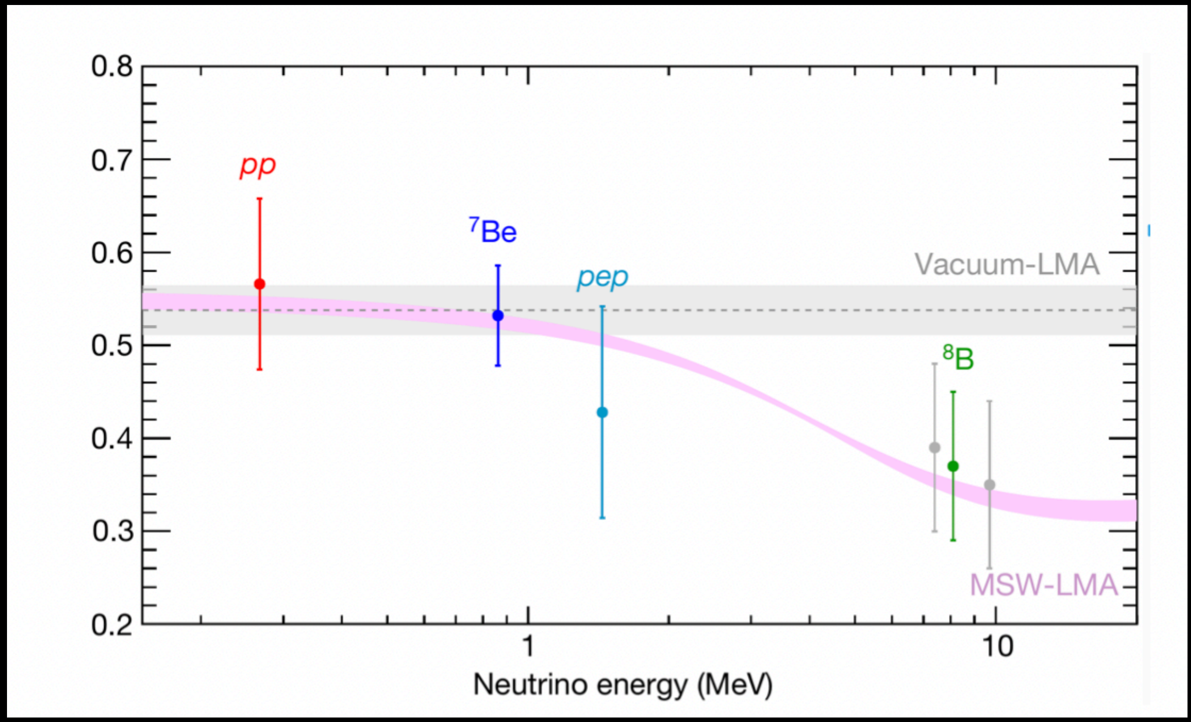


One key result (Borexino)

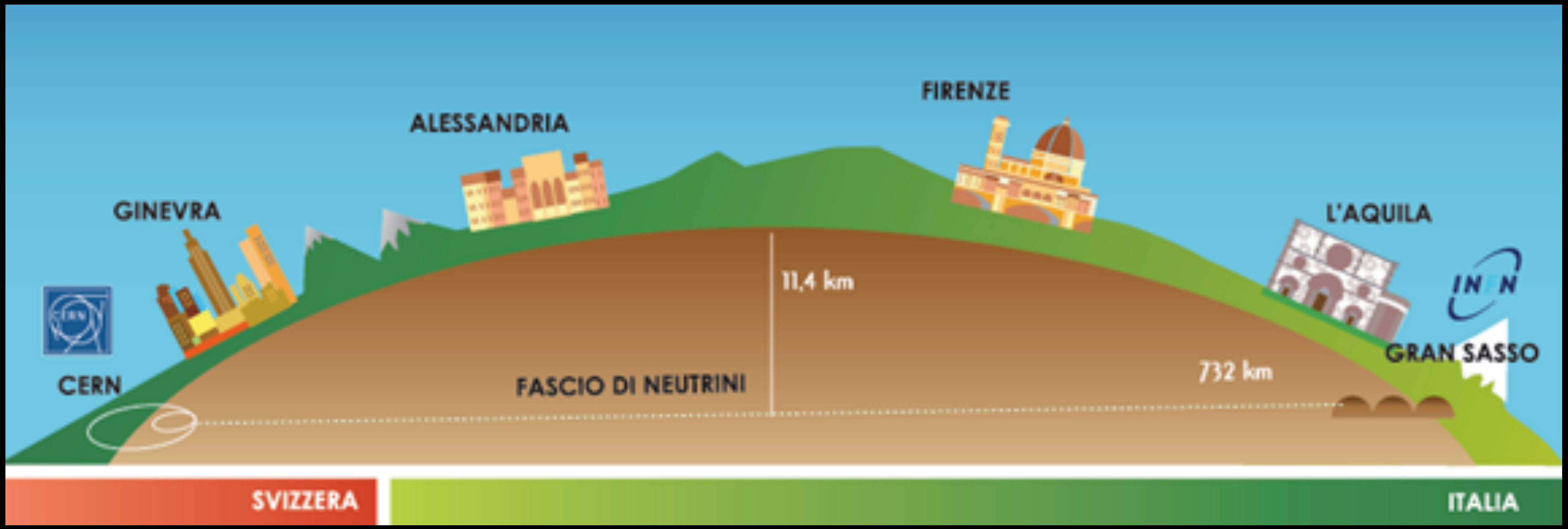




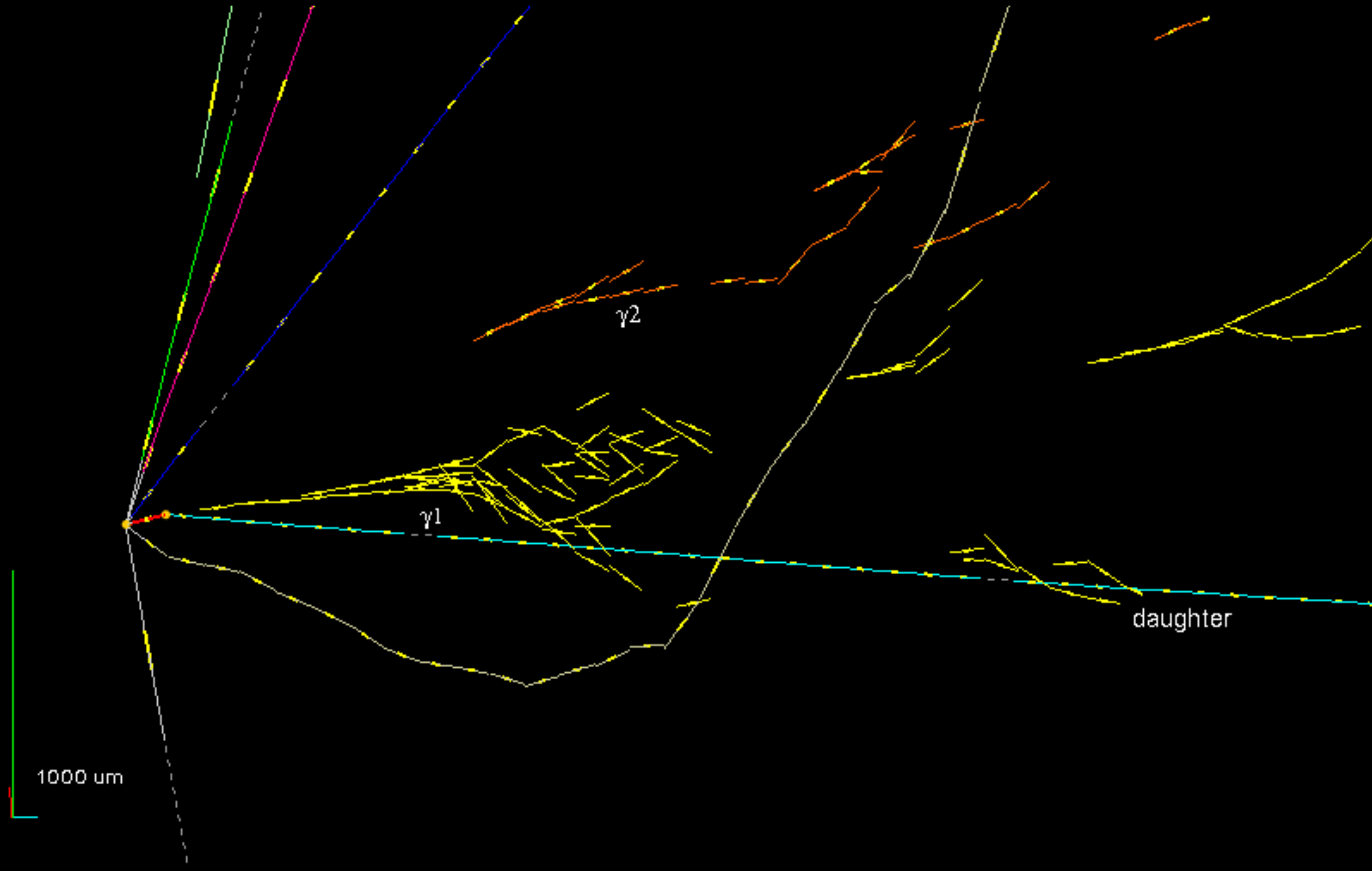




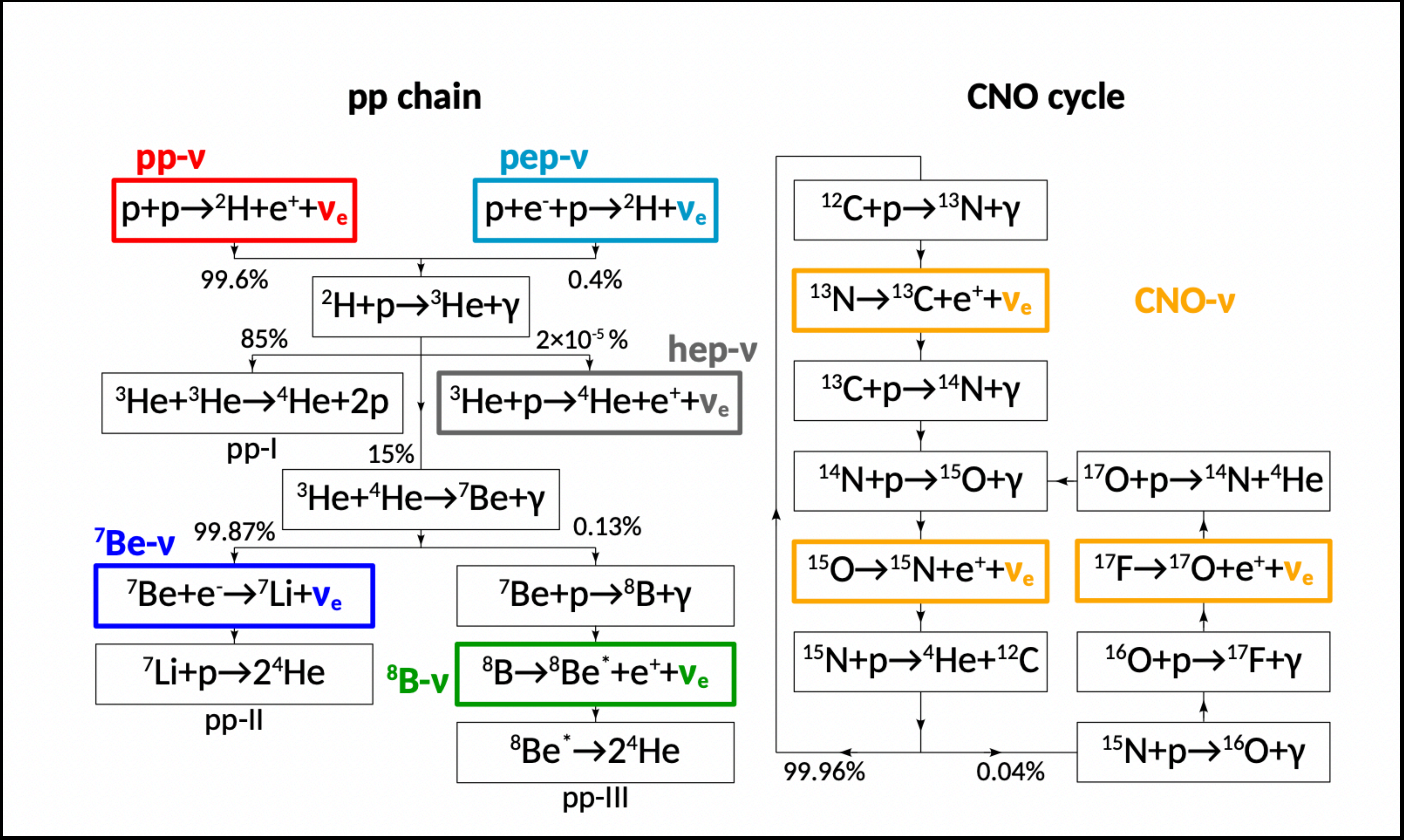
CERN to LNGS beam



$\nu_\mu \rightarrow \nu_\tau$

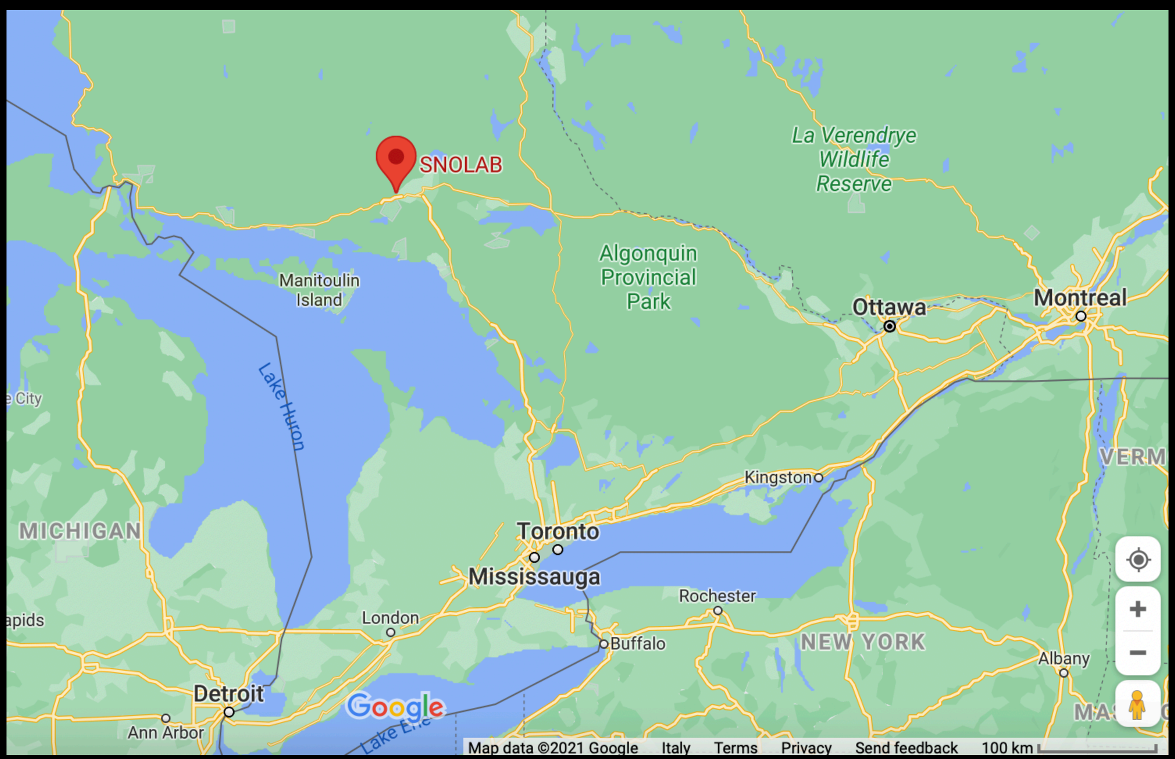


The Sun completely understood



SNOLAB

Sudbury neutrino observatory



Main features

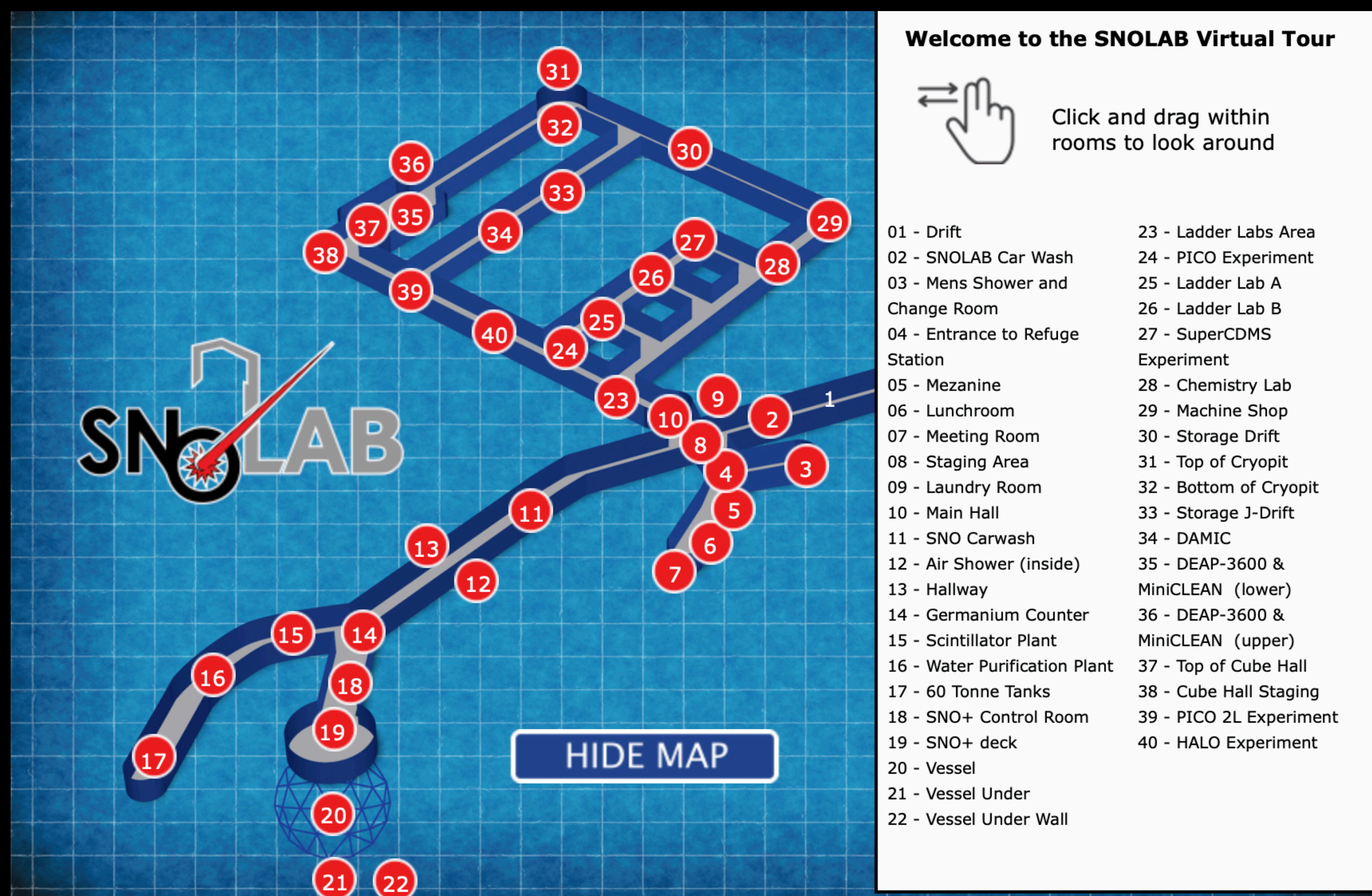
The SNOLAB underground laboratory has 5,000 m2 of clean space, of which 3,100 m2 is experimental cavern space. SNOLAB has an additional 2,600 m2 excavated outside the clean room used for the service infrastructure and material transportation and storage.

The ambient rock temperature on the 6800 level is 42C and there is a 2070 m granite rock overburden. SNOLAB was designed and operates as one large clean room

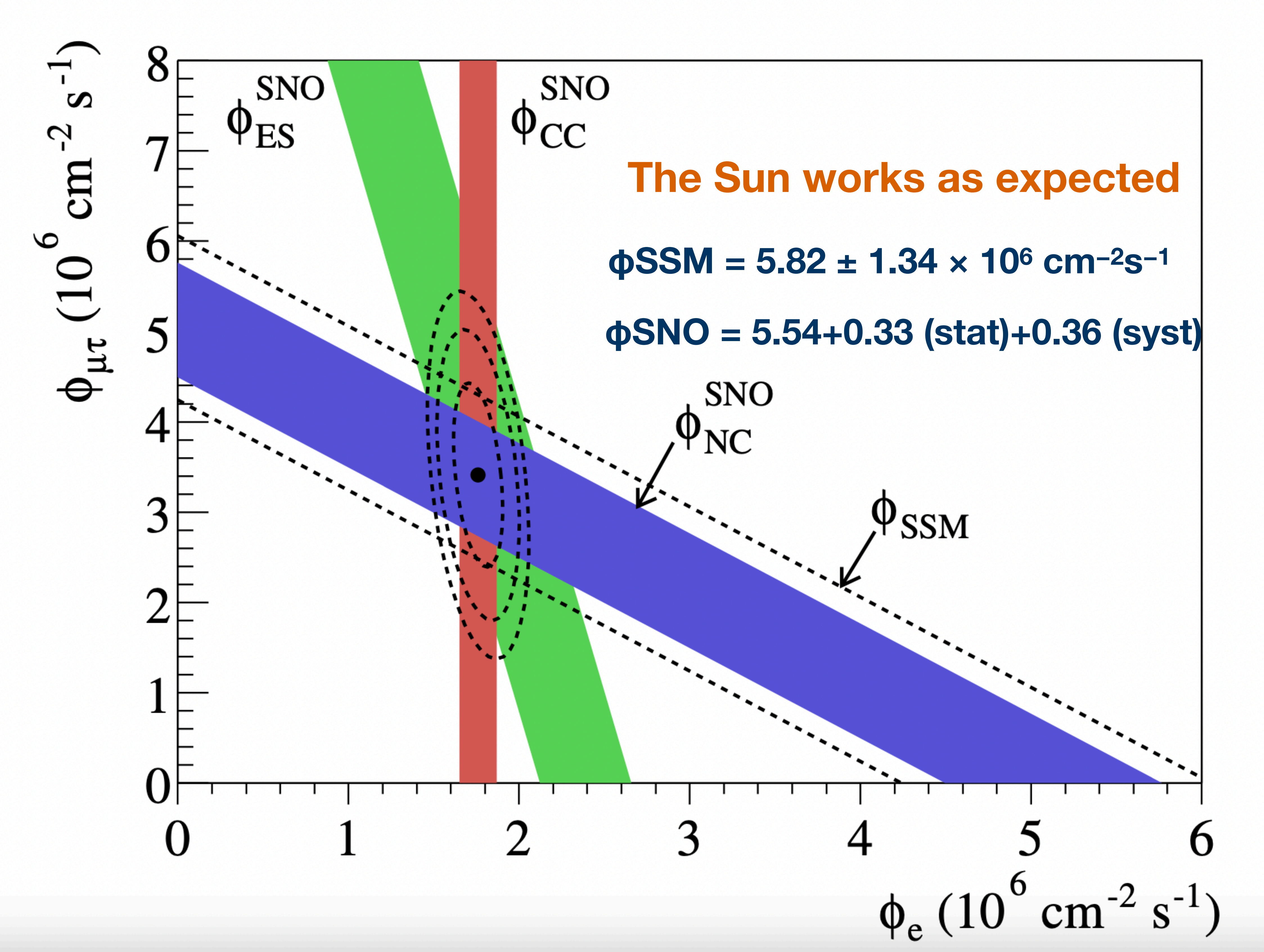
SNOLAB has four main experimental areas underground. The SNO cavern, Cryopit, and Cube Hall are experimental caverns for large experiments, and the Ladder Labs are drift areas for small and medium-sized experiments.

Virtual tour

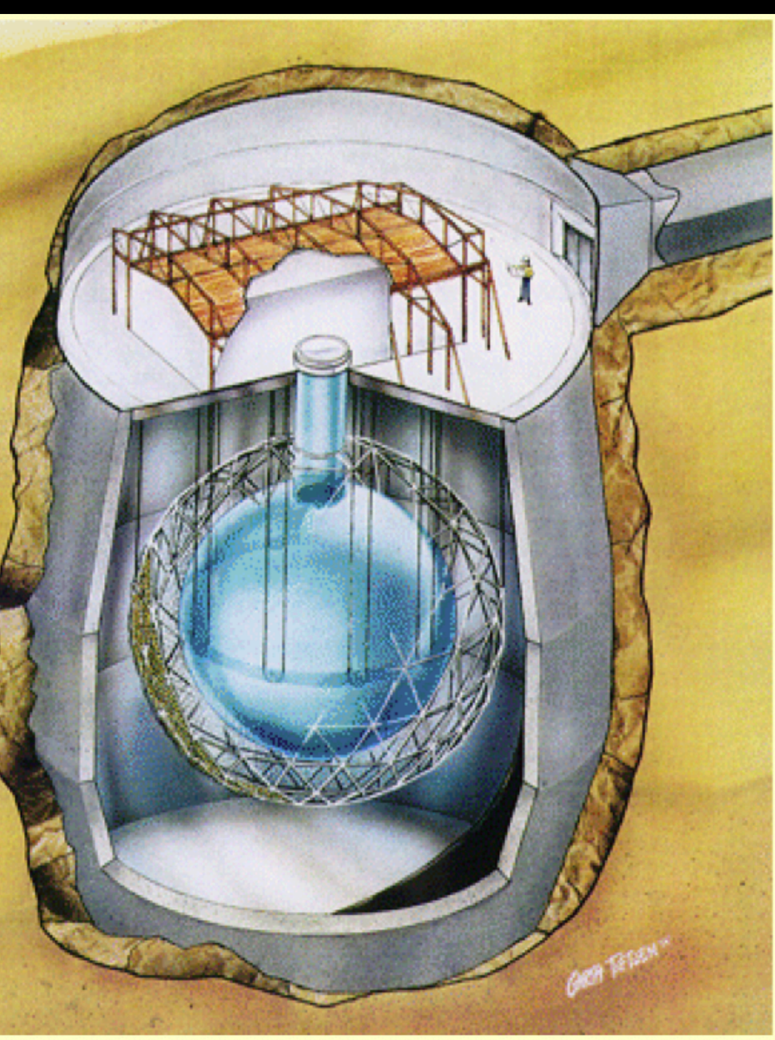
- https://www.snolab.ca/facility/virtual-tour/

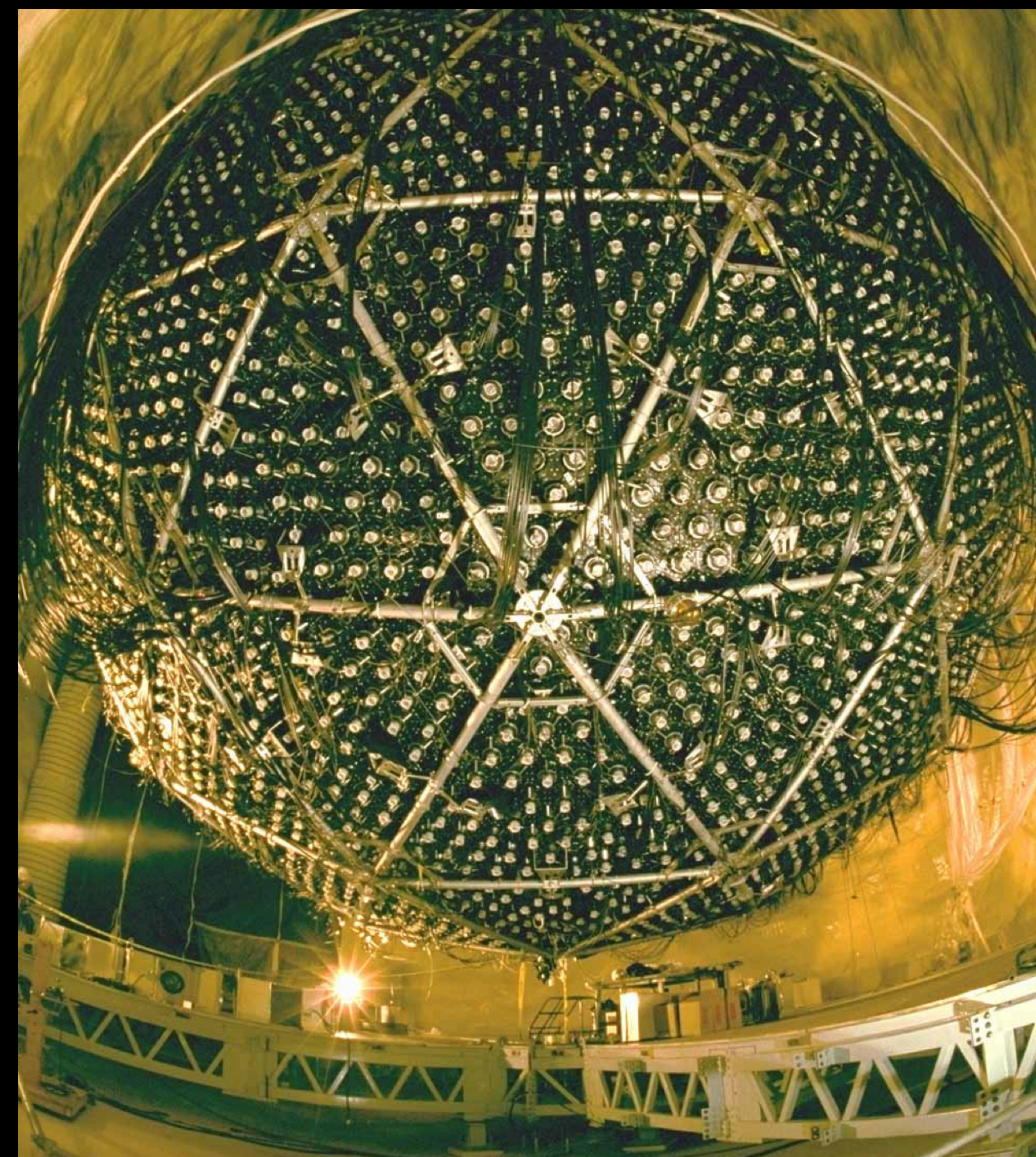


Main achievement

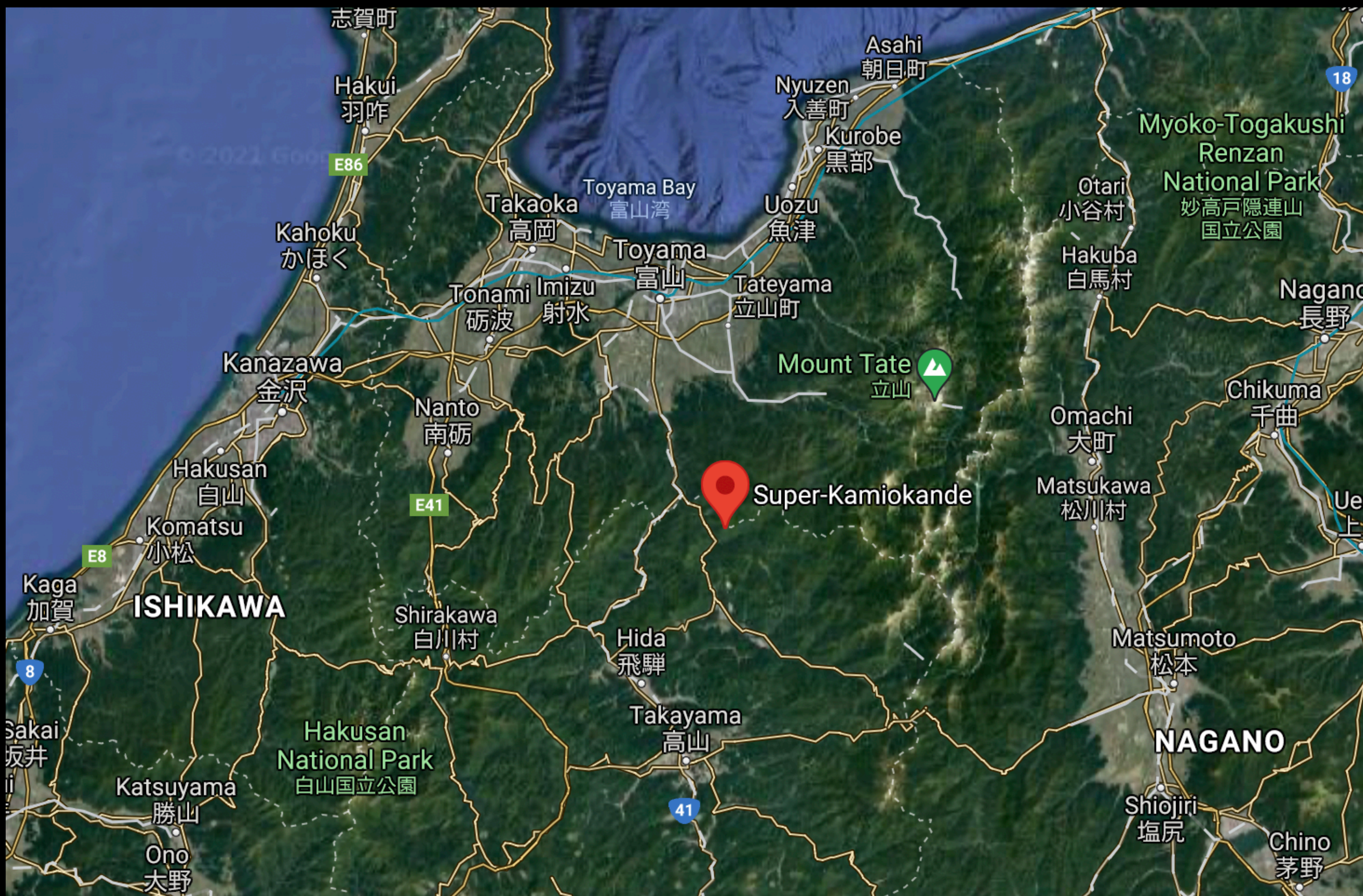


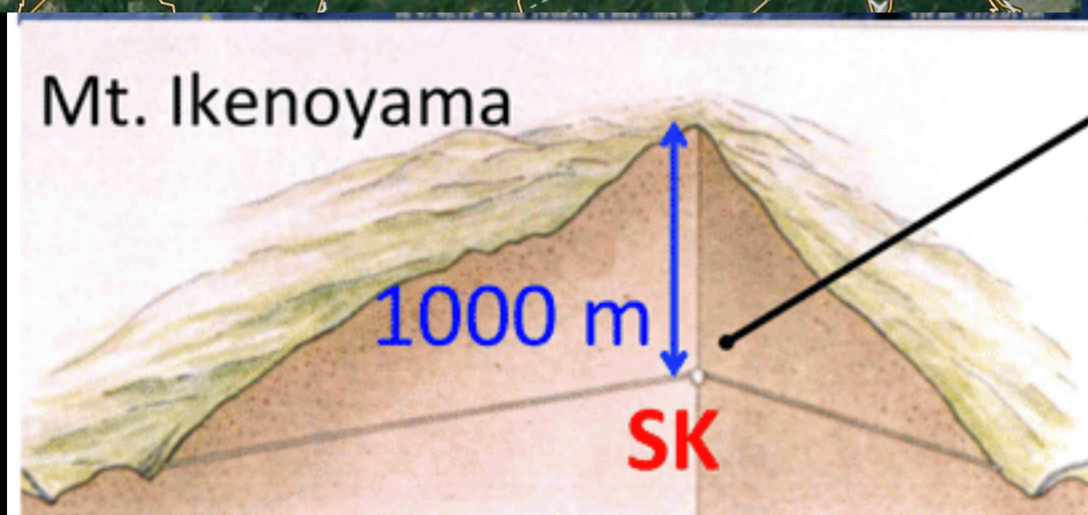
Obtained in SNO

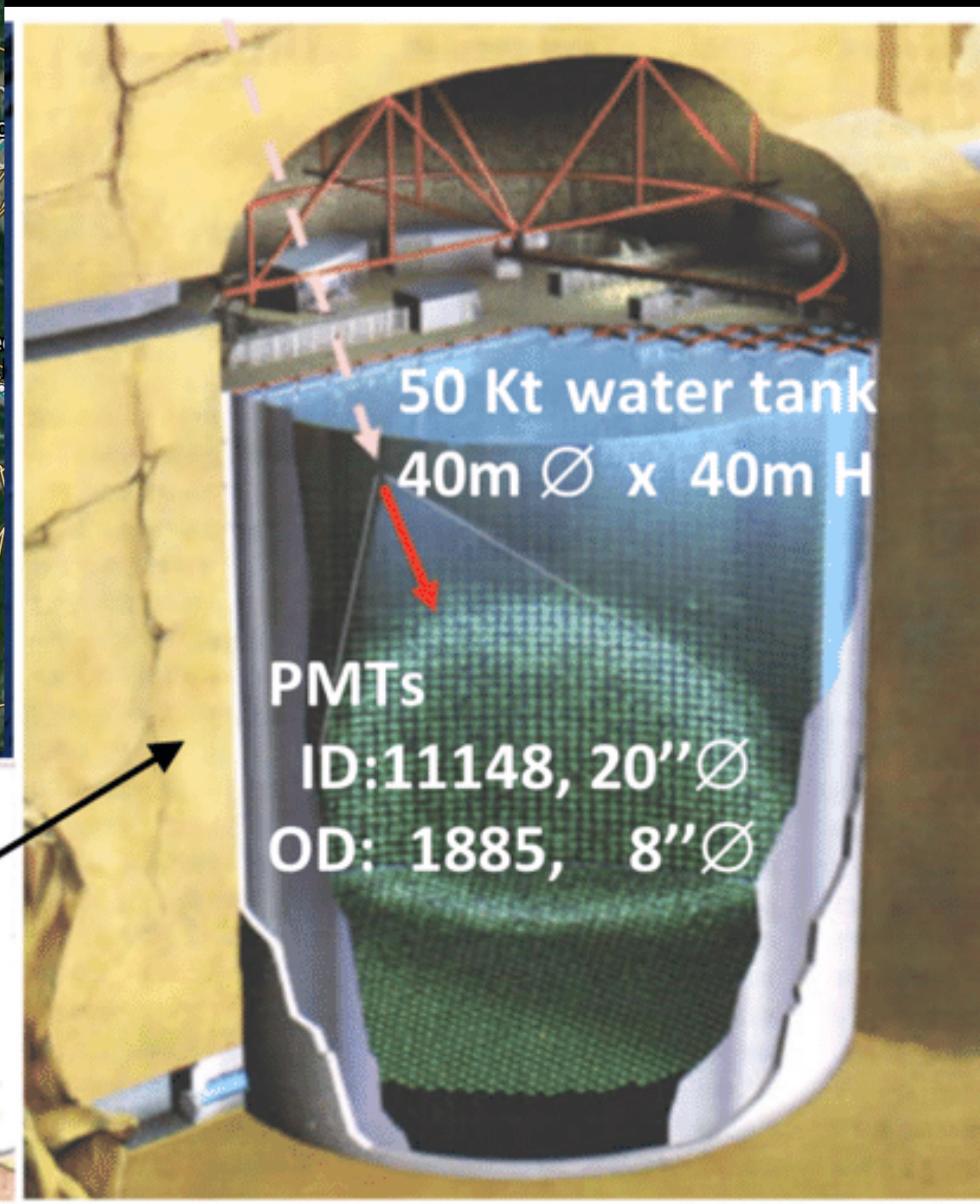




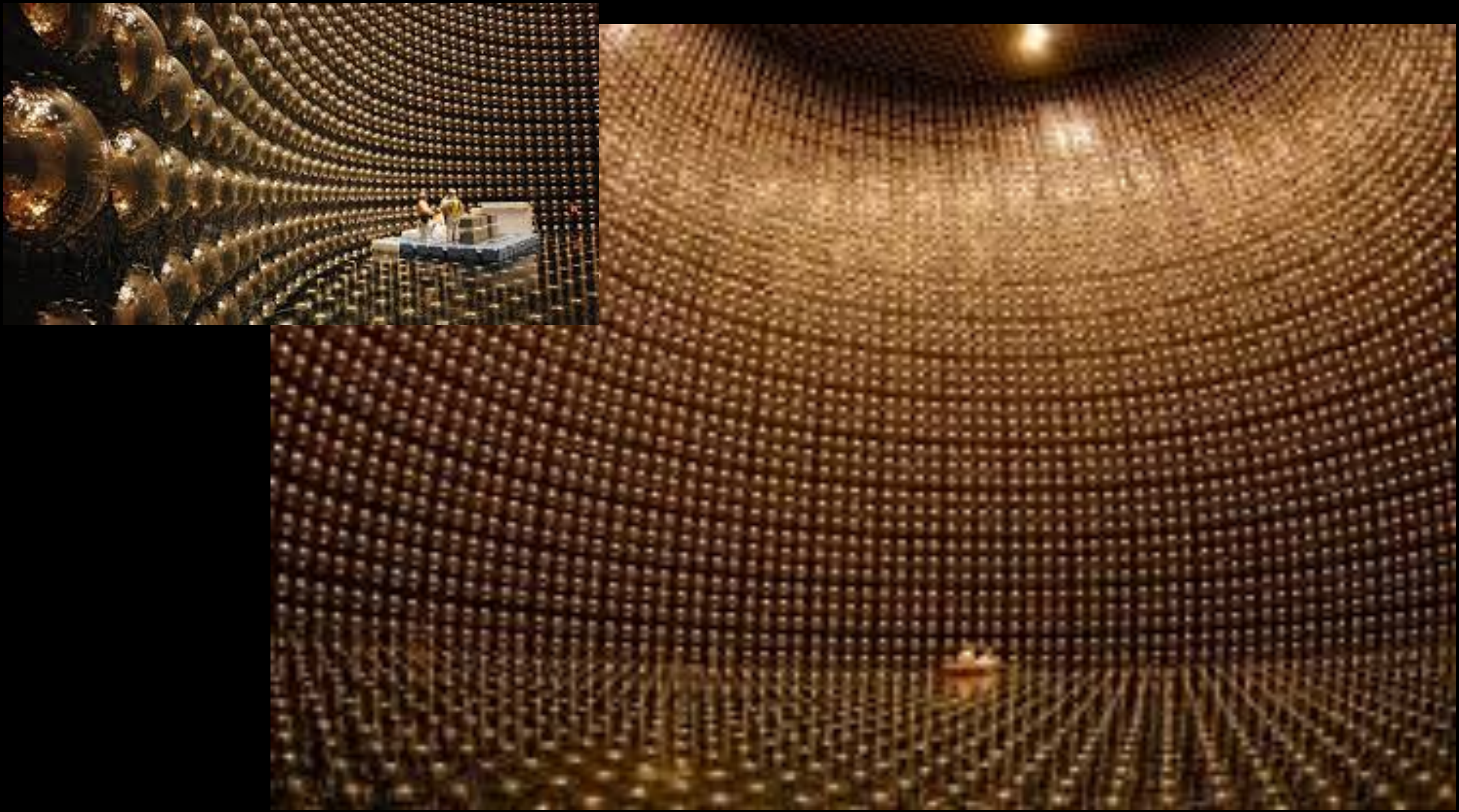
Kamioka


Super-Kamiokande
Toyama Bay
富山湾
Toyama
富山
Takaoka
高岡
Kanazawa
金沢
Mount Tate
立山
Hida
飛騨
Takayama
高山
Matsumoto
松本
NAGANO
ISHIKAWA
Hakusan
National Park
白山国立公園
Myoko-Togakushi
Renzan
National Park
妙高戸隠連山
国立公園

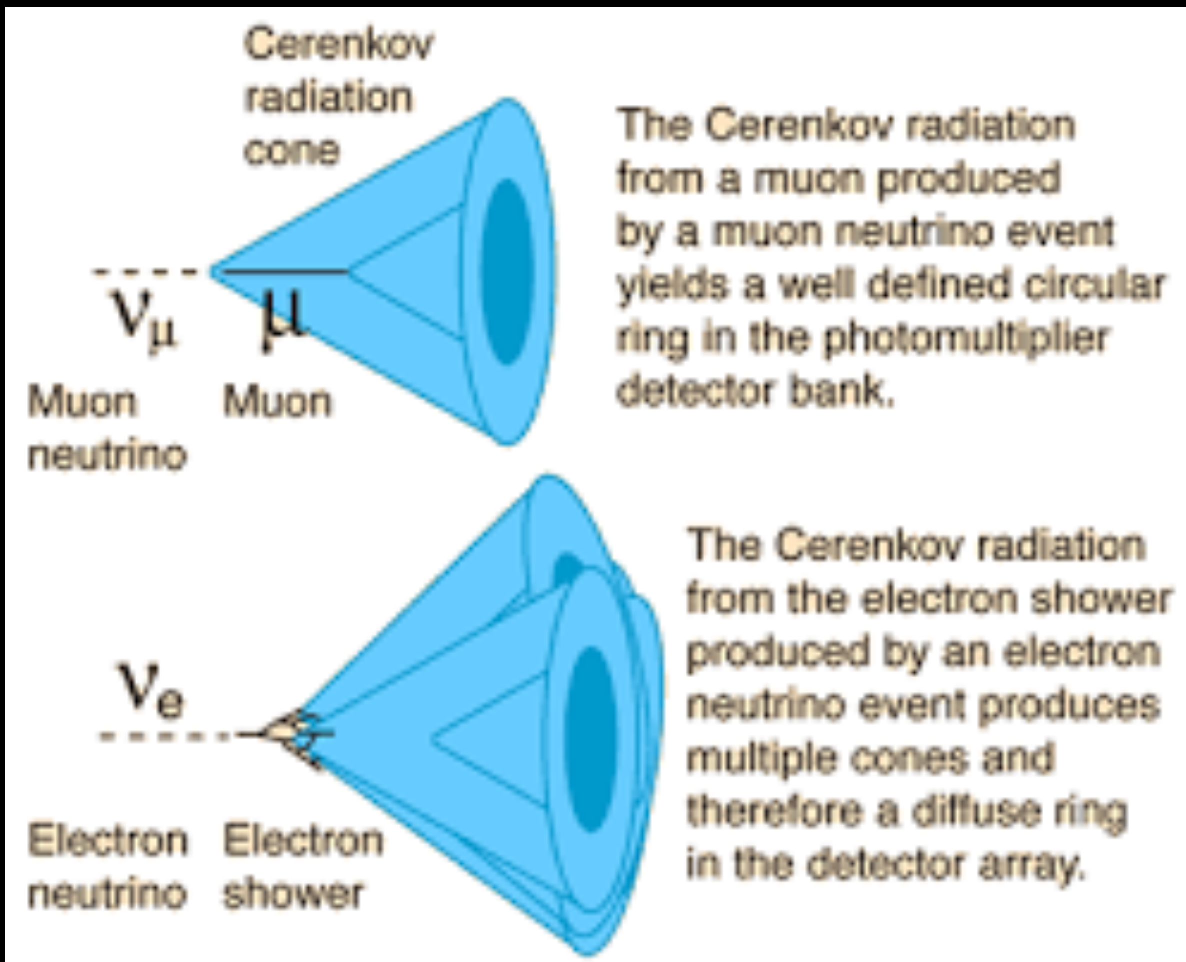

Mt. Ikenoyama
1000 m
SK

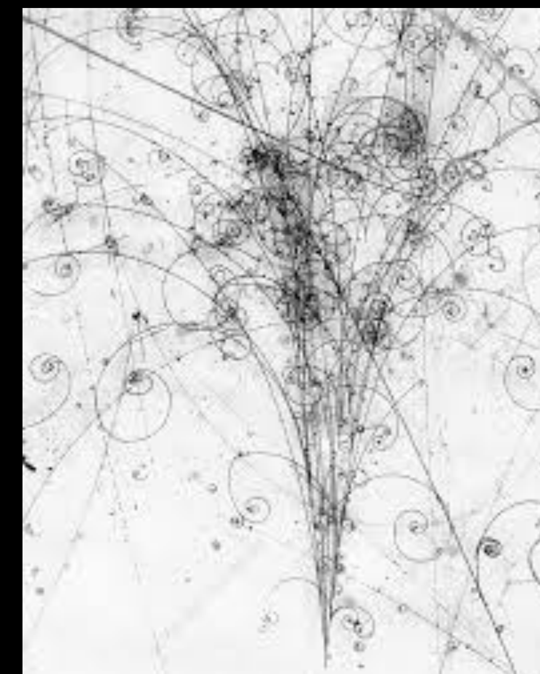

50 Kt water tank
40m ∅ x 40m H
PMTs
ID:11148, 20”∅
OD: 1885, 8”∅

Super Kamiokande

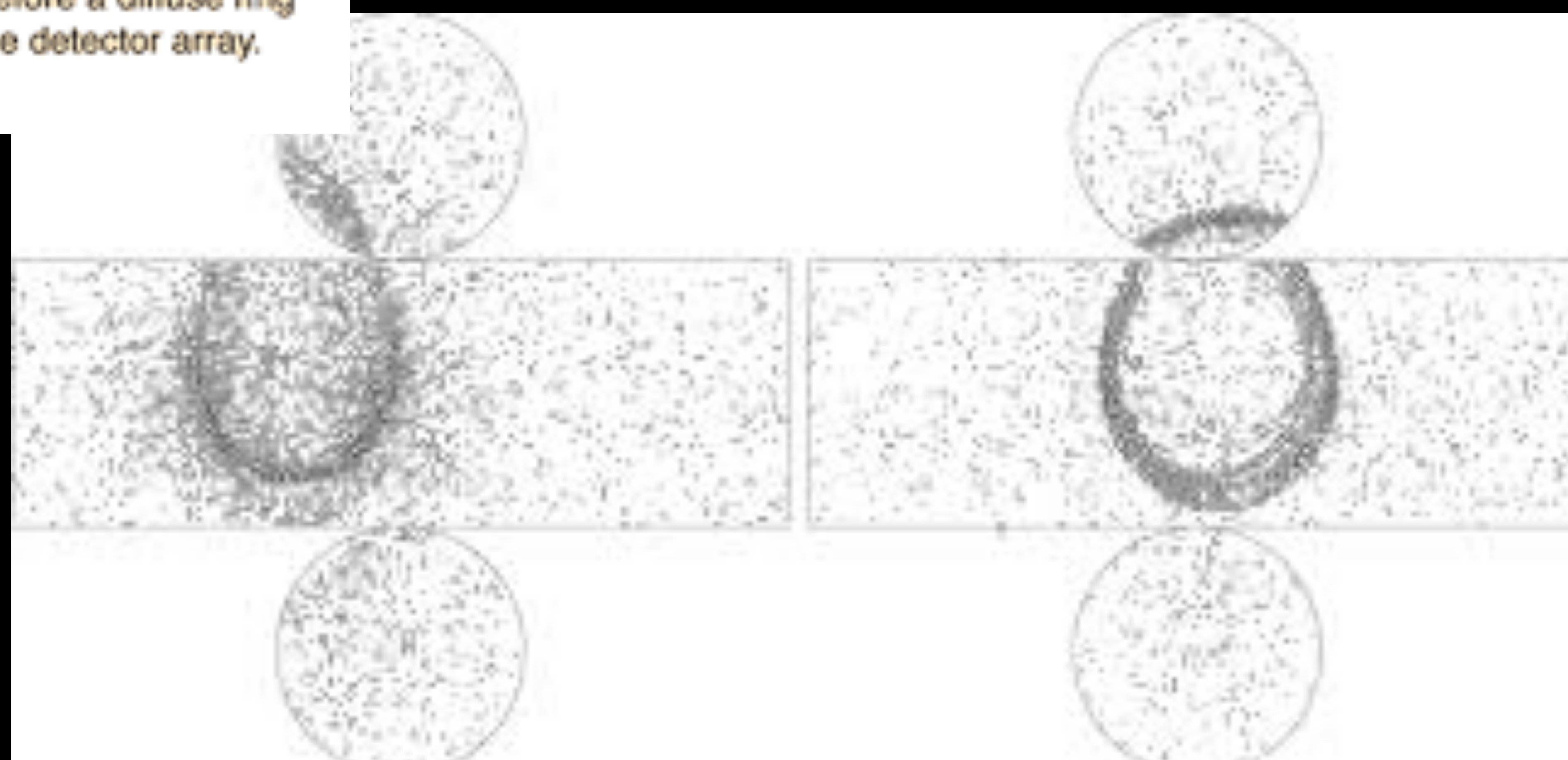


The Cherenkov magic !



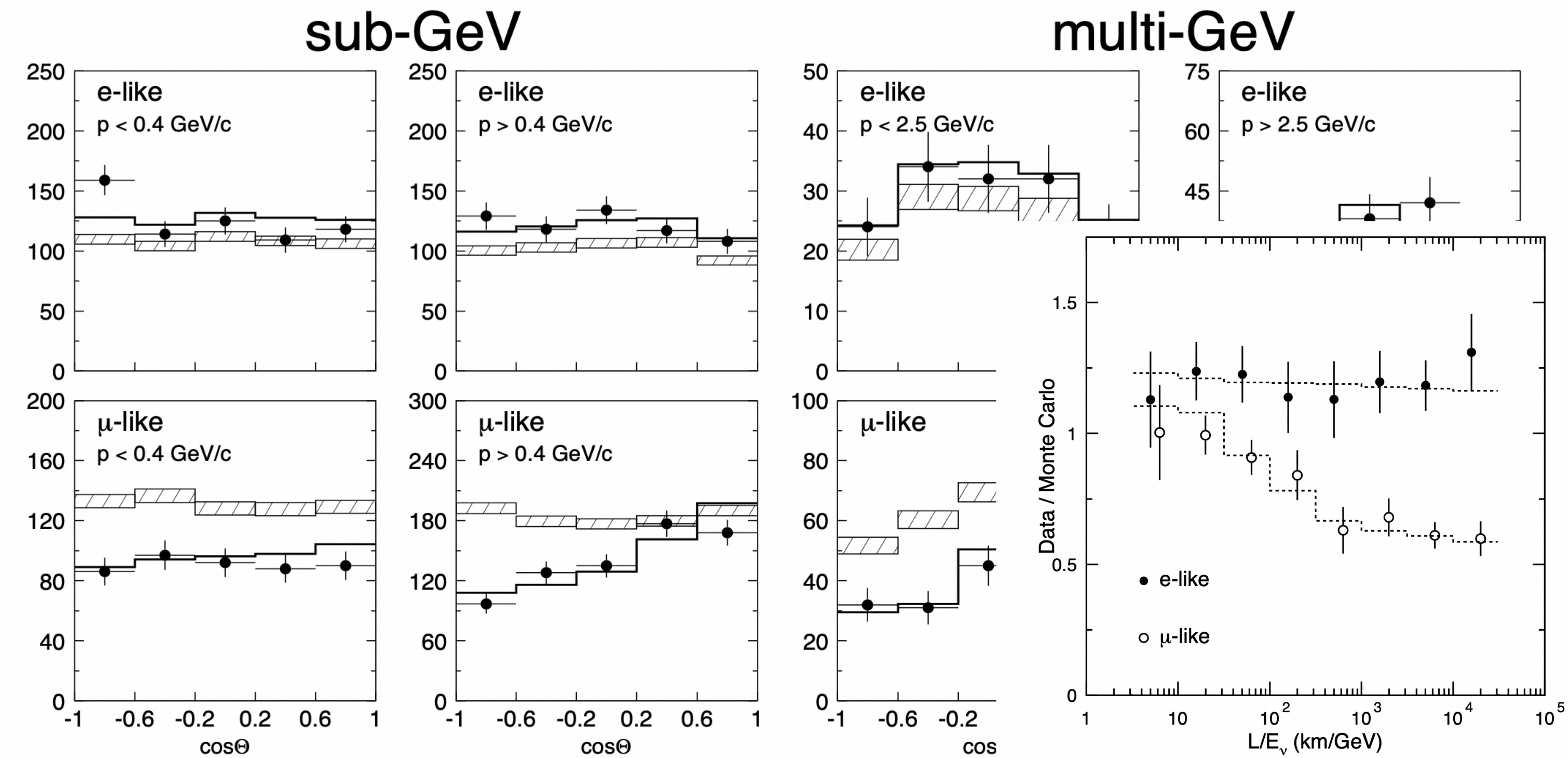


Visualisation of an electron shower

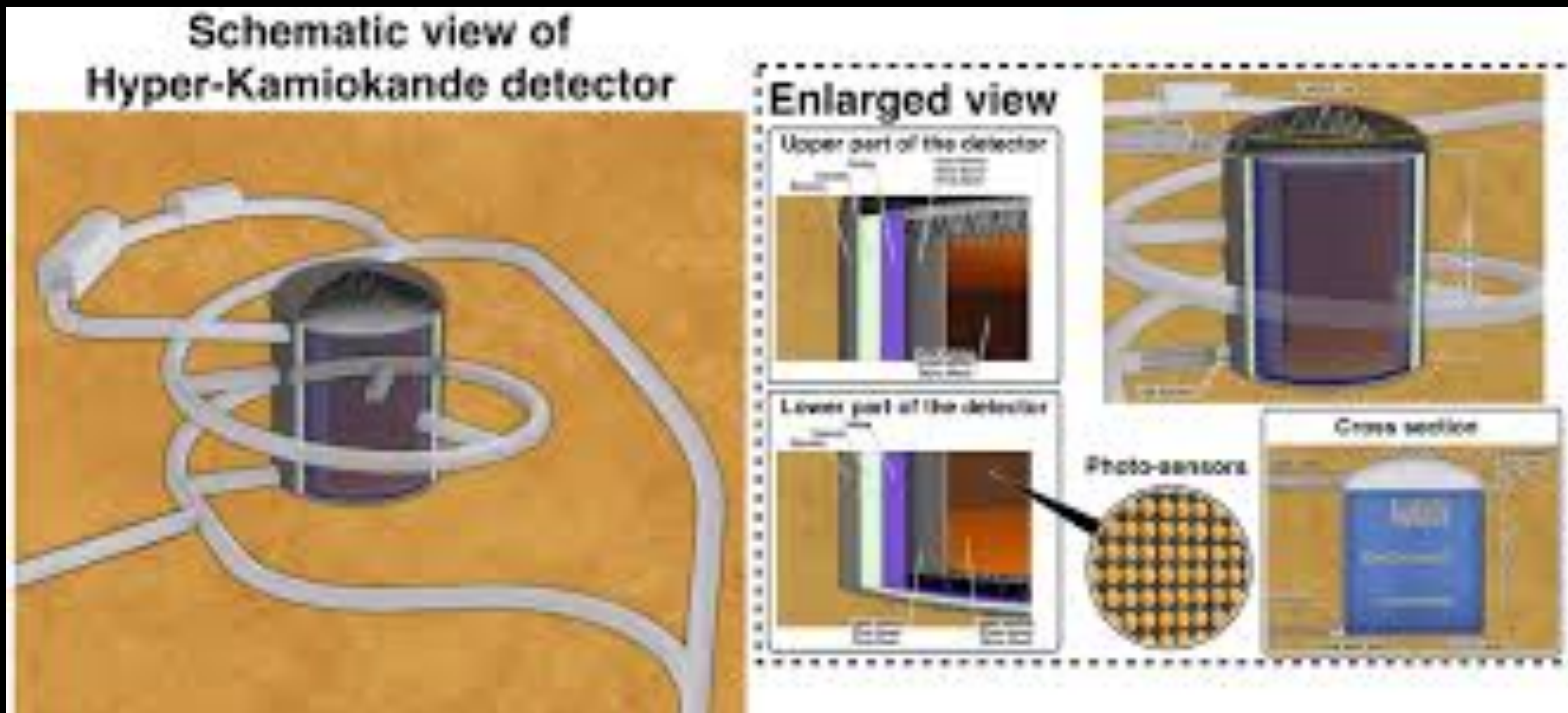


Cherenkov Ring in SuperK

Neutrinos oscillates
Neutrinos have a mass



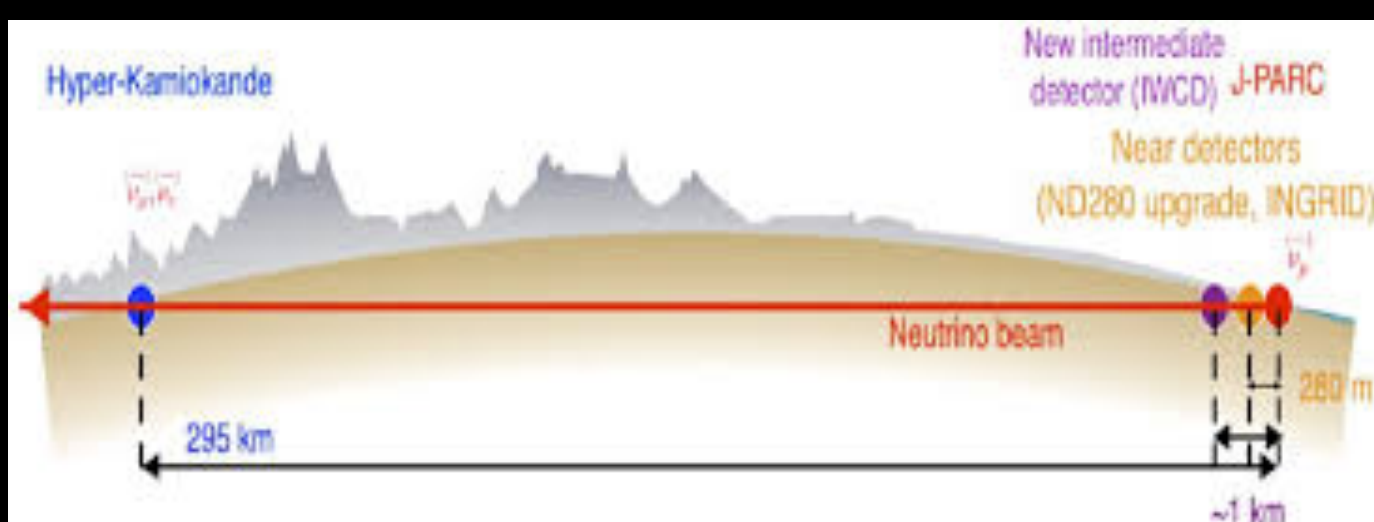
Next: Hyper-K



258 kTon of Water

(Super-K is 50kTon)

(Kamiokande was 3kTon)



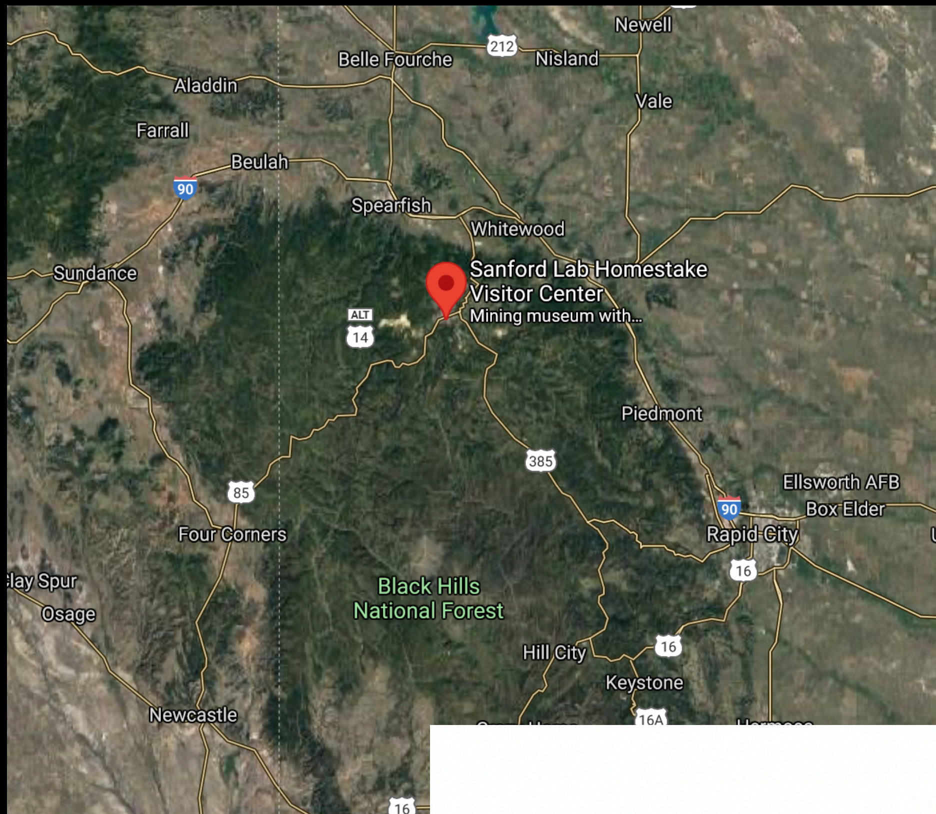
SURF

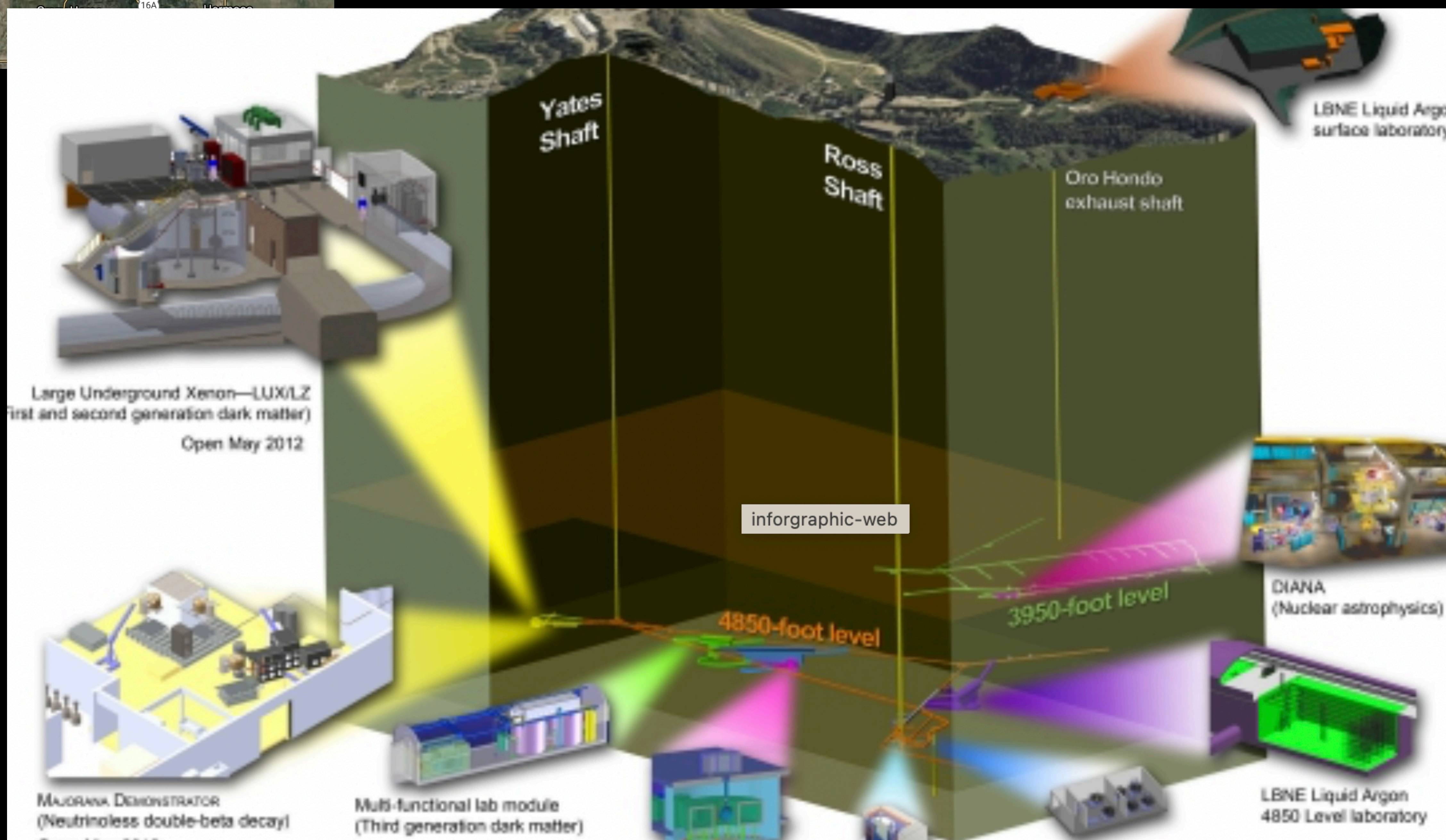
Sanford Underground research Facility

Where the R. Davis experiment was located

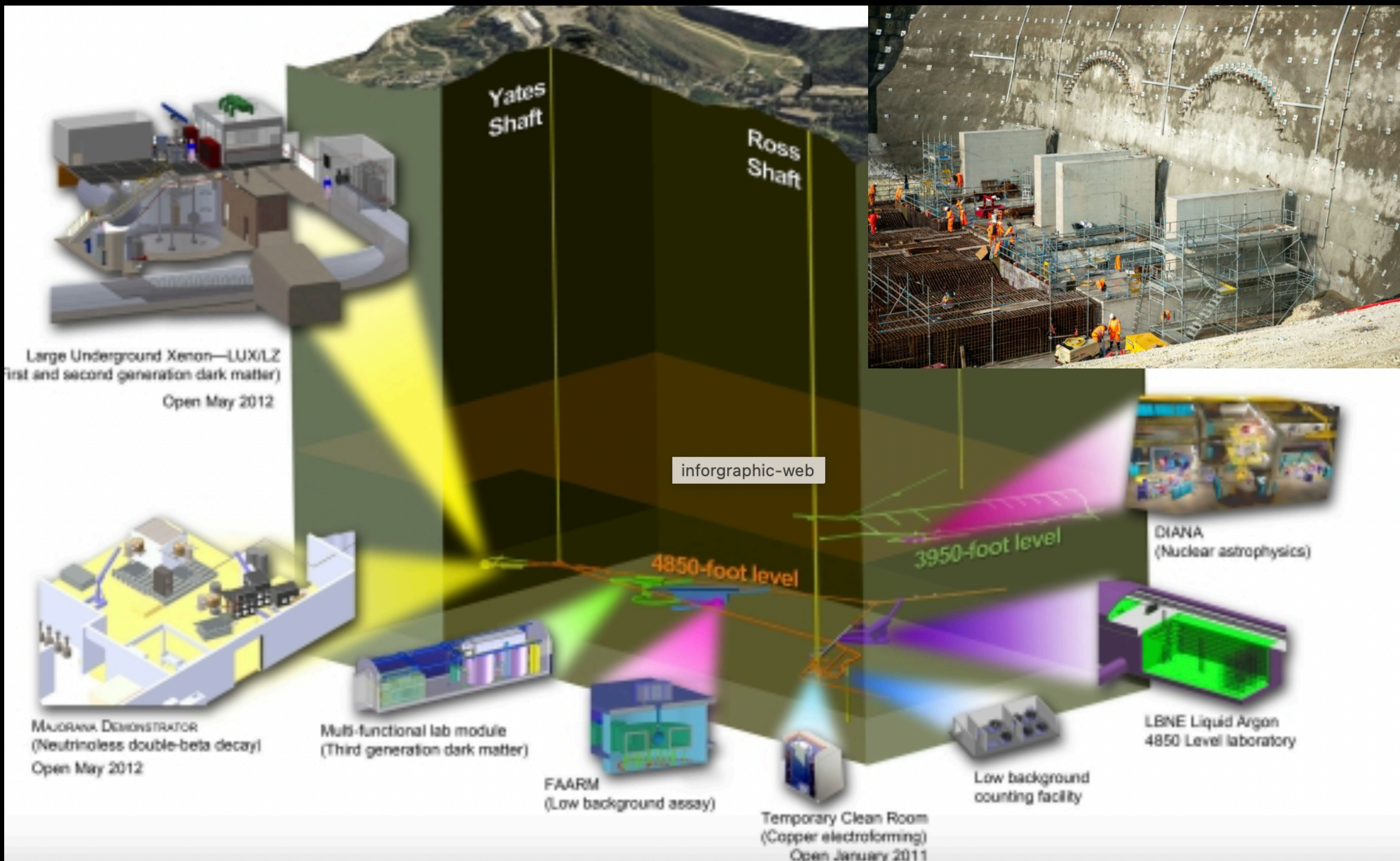
The origin of the solar neutrino puzzles

Somewhere in South Dakota

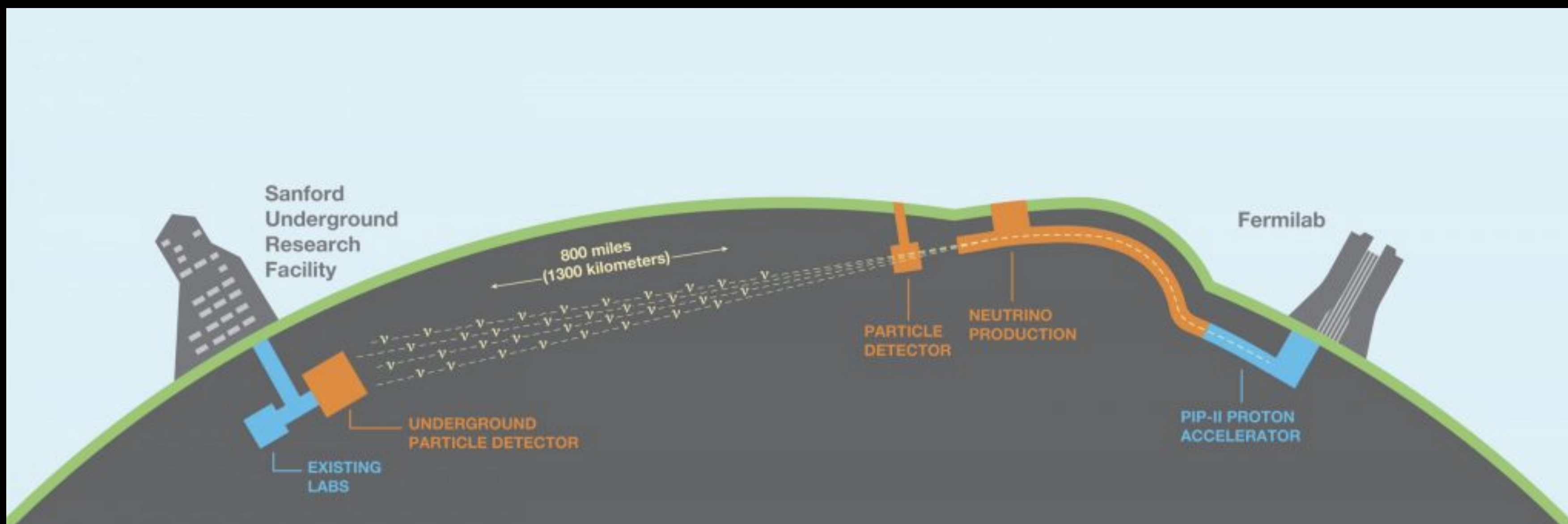


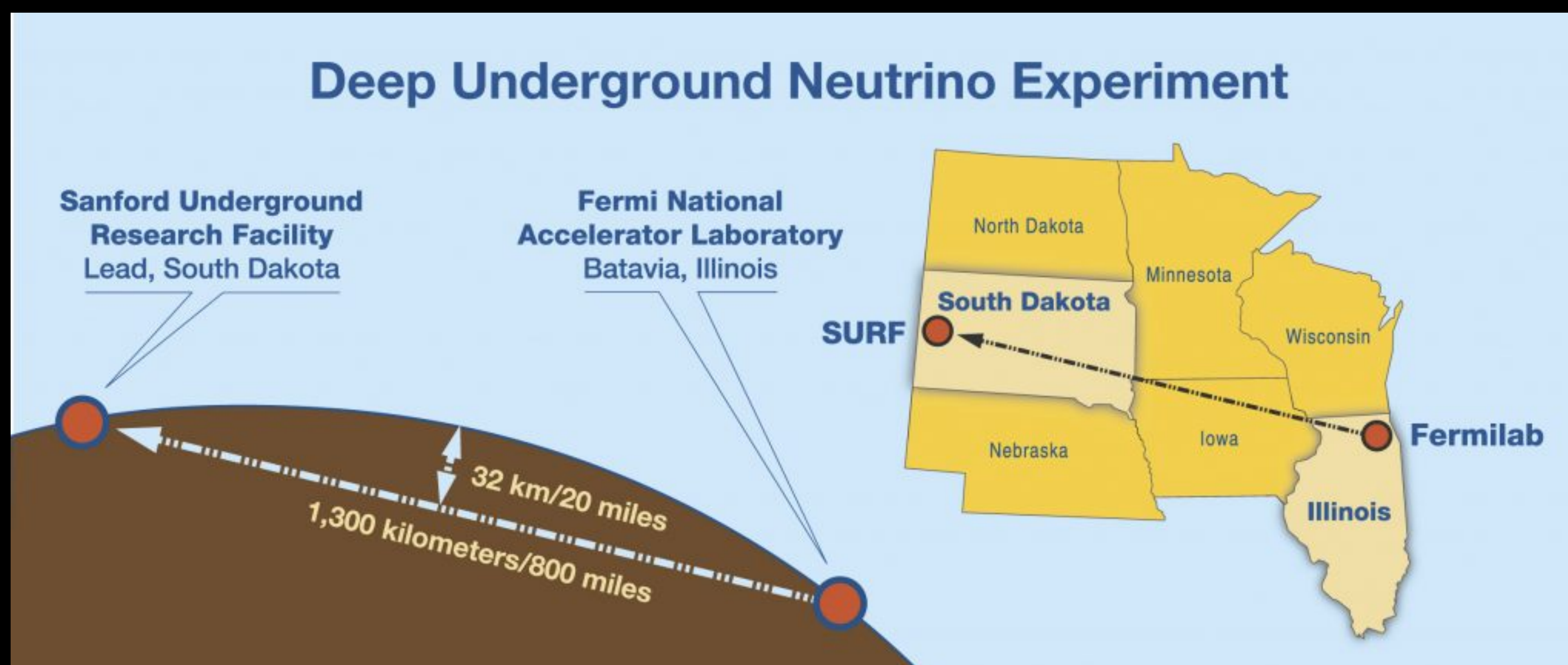


In preparation for DUNE

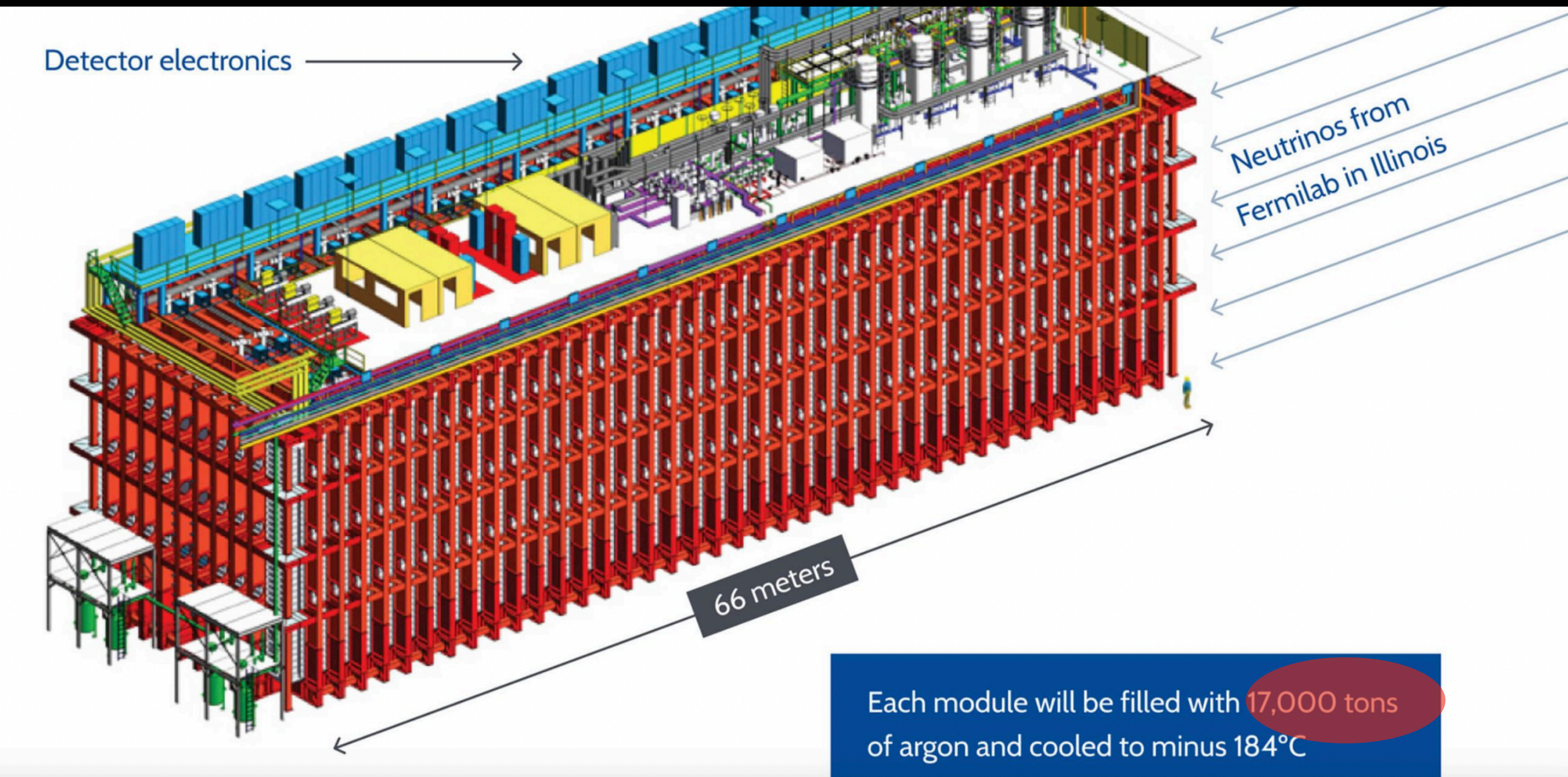


The LBL neutrino experiment: DUNE





DUNE: 4 LAr modules

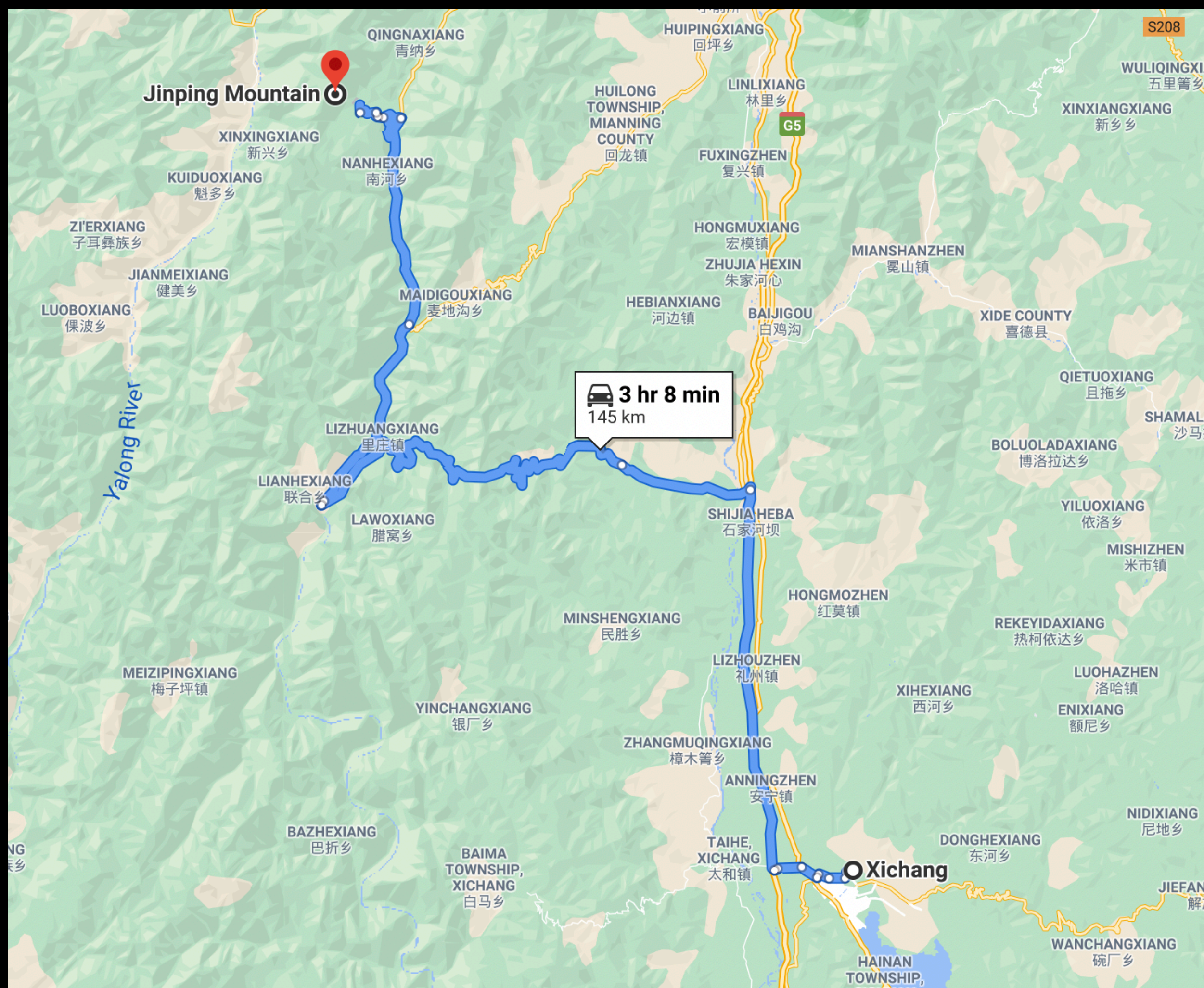


JINPING


Jinping Mountain
2400m
Yalongjiang
River
CJPL
At the middle
Traffic Tunnel
~8 km


양양양수발전소

Far… far…. away



The closest airport is in Xichang

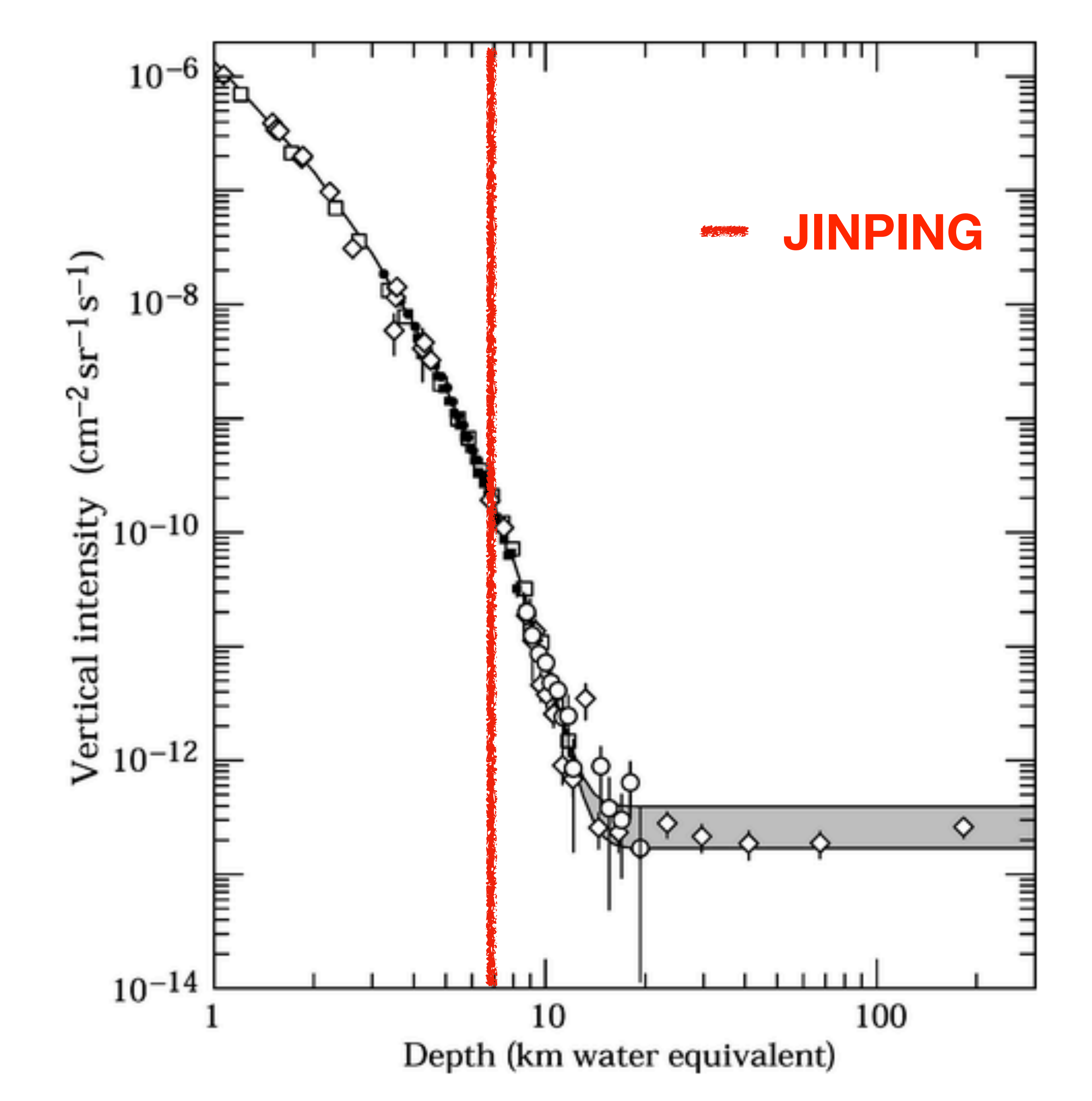
The road is rather tortuos

Very deep
(2400 m rock,
6720 m.w.e)

Muon flux ~ $0.2/m^{-2}$/day

BTW, if you go much deeper
you don't gain anymore with muons

Neutrinos will keep muon flux constant



Some more in operation

- Modane (France, under Alps, accessible from Frejus tunnel, pretty deep -4800 m.w.e but really small)
- CANFRANC(Spain, under Pyrenees , small and less deep than LNGS)
- Yangyang (South Korea, small and less deep than LNGS)
- Boulby (UK, in a salt mine, small)

An interesting question:
Underground Physics only in the Northern emisphere ?

- Two projects in preparation
  - Stawell (gold mine, Victoria state , Australia)
  - ANDES (like LNGS , under Andes between Argentina and Chile

Is this a relevant subject ? Absolutely yes
Be patient and you will discover why !

The main lines of research in UL

- The labs where we study (surprisingly for many) the life of the stars from birth to death
- Labs for Dark Matter searches
- Labs for testing Majorana neutrino hypothesis

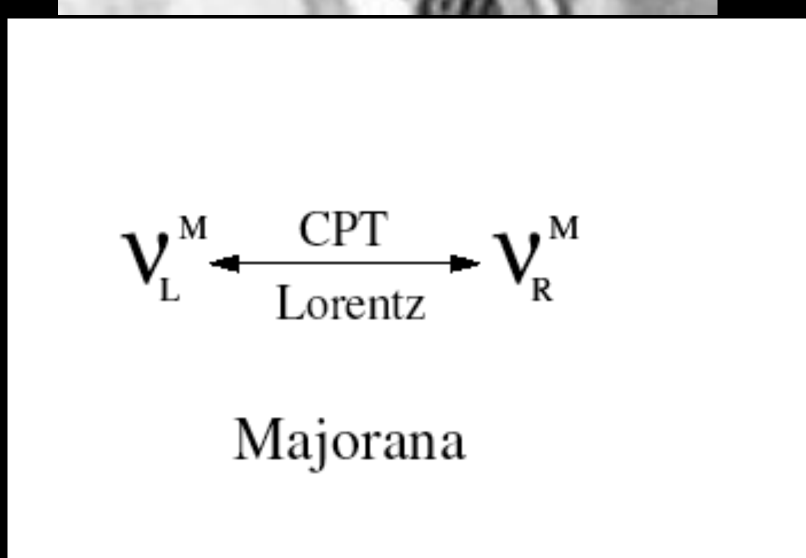
Neutrino Physics

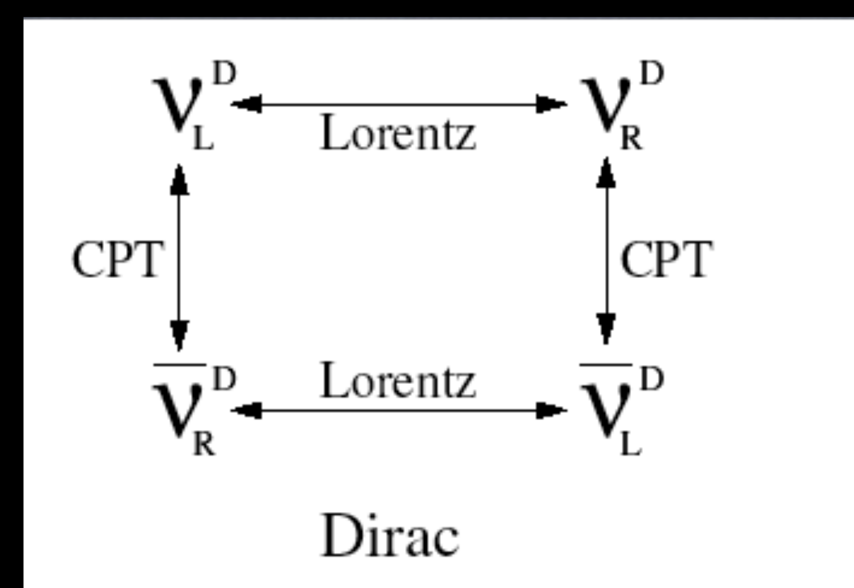
- Neutrinos might hold the key to both the mystery of the antimatter disappearance and the New Physics

Leptogenesis

Majorana mass

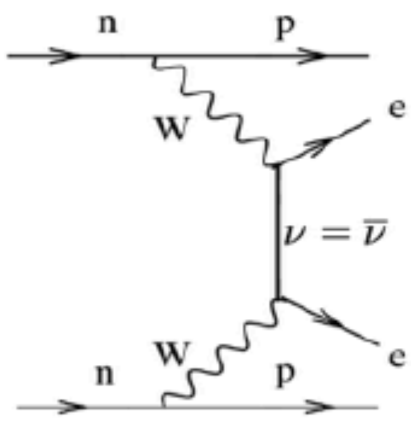
what is a neutrino ?





The DBD physics in short

- Rare nuclear process: $\mathbf{(A, Z) \rightarrow (A, Z+2) + 2e^-}$



If observed:
- Lepton number violation ΔL=2
- Majorana Nature of neutrinos

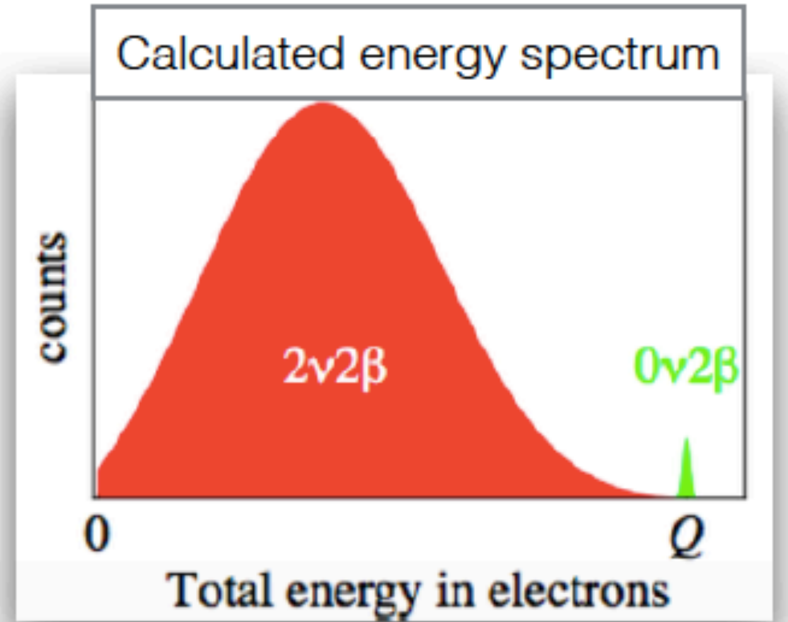
- It occurs only in few natural isotopes: ^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, ^{136}Xe (and not many others).

$$m_{\beta\beta} = \sum_{i=1}^{3} |U_{ei}^2| m_i$$

- We measure the decay half-life: $\tau_{1/2}^{0\nu} \propto 1/m_{\beta\beta}^2$

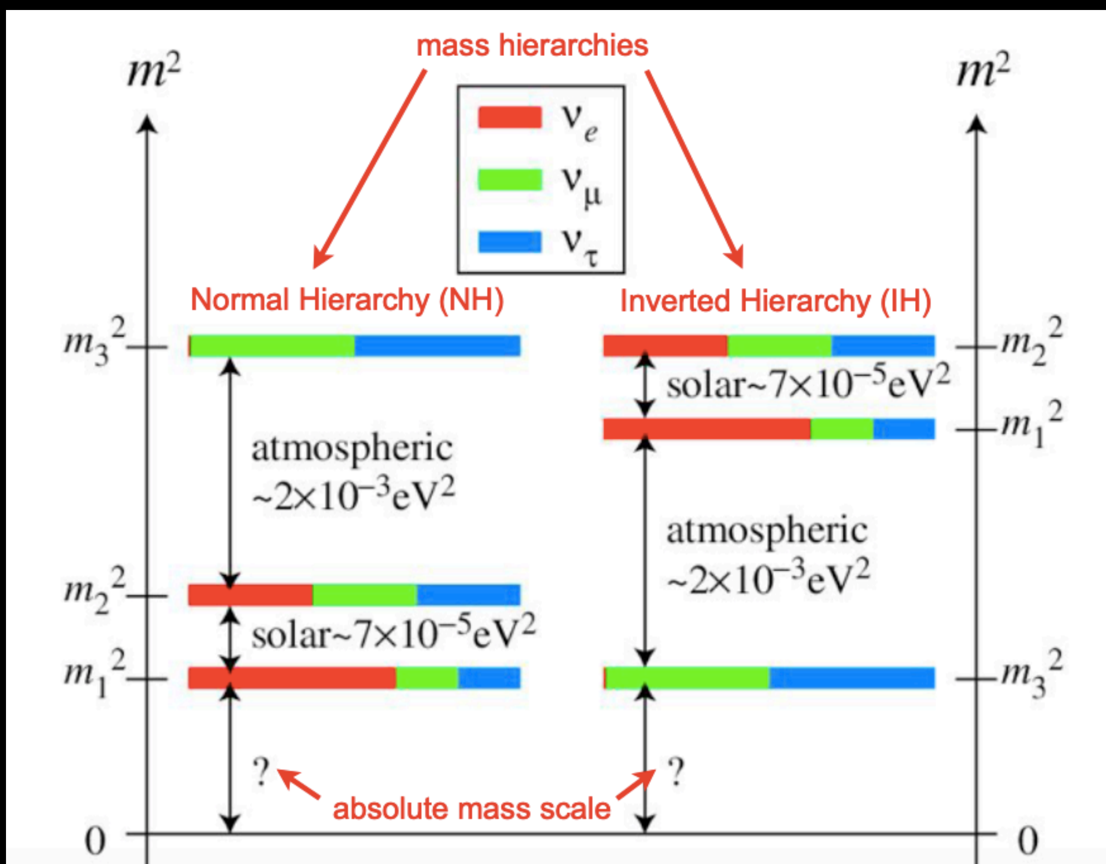
Current limits are of the order of 10^{24}-10^{25} years.

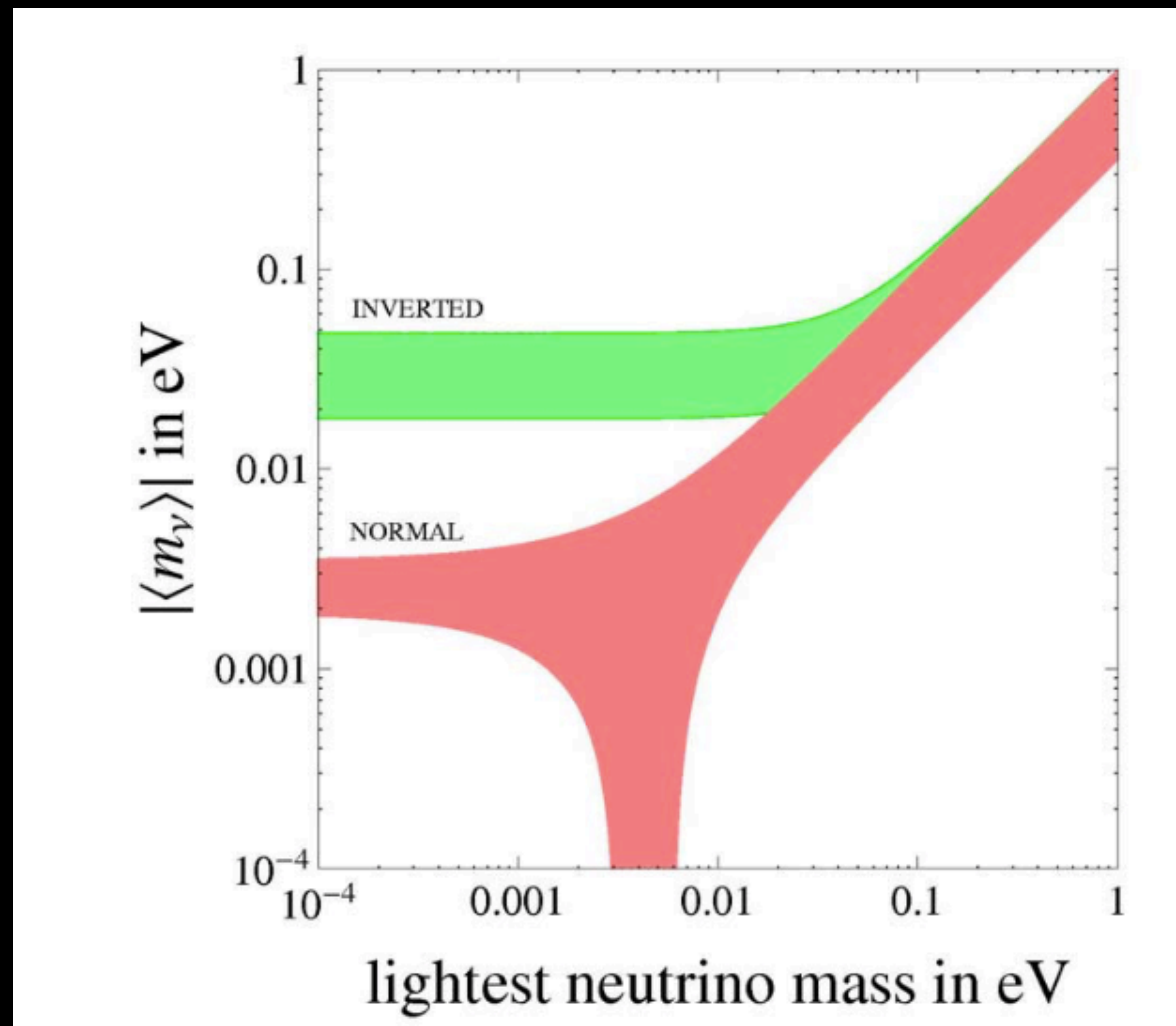
- Signature: peak at the sum-energy (Q) of the two electrons (2-3 MeV).



The name of the game

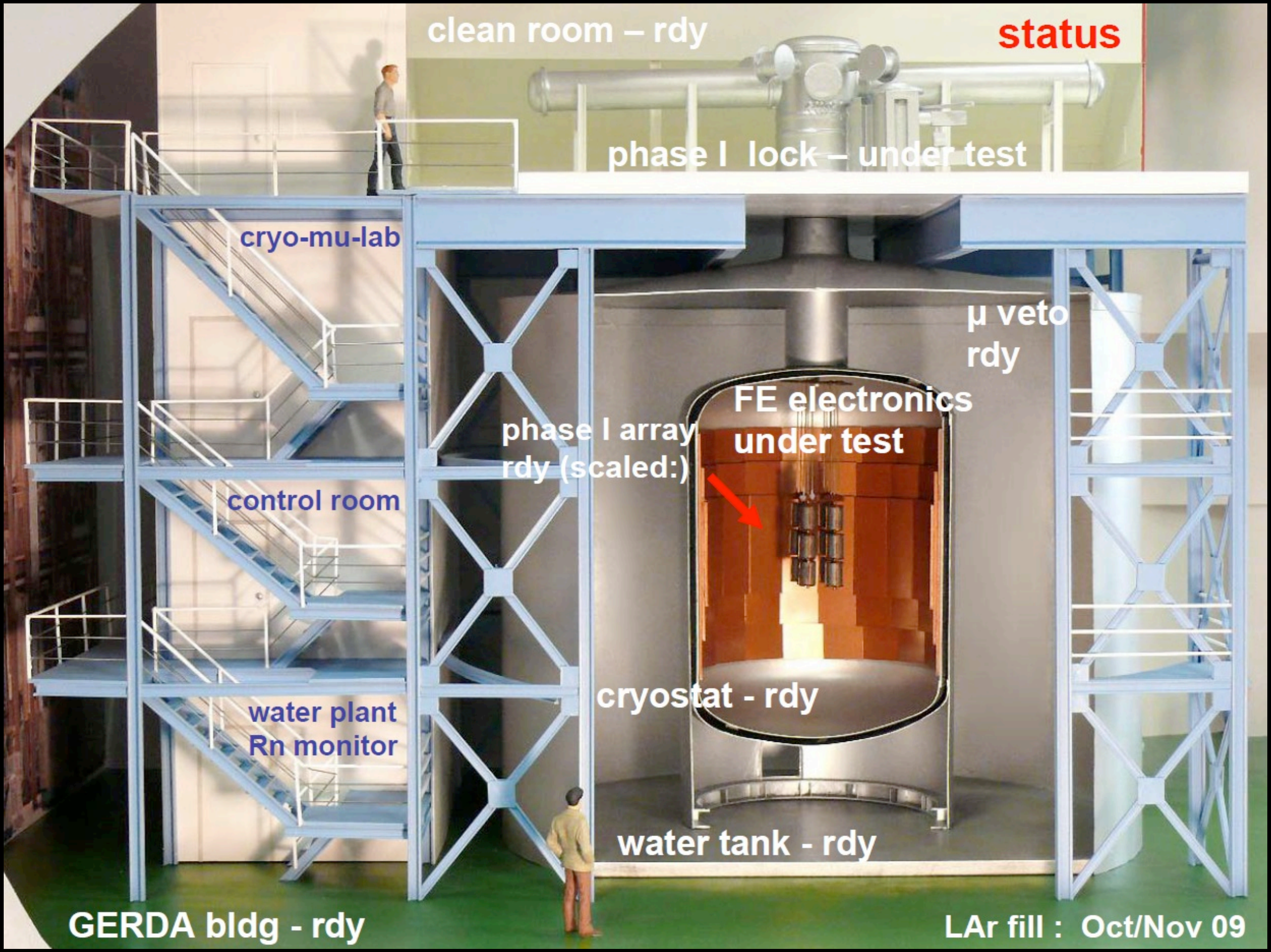
$$\Gamma^{0\nu} = \frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2 \frac{|m_{\beta\beta}|^2}{m_e^2}$$





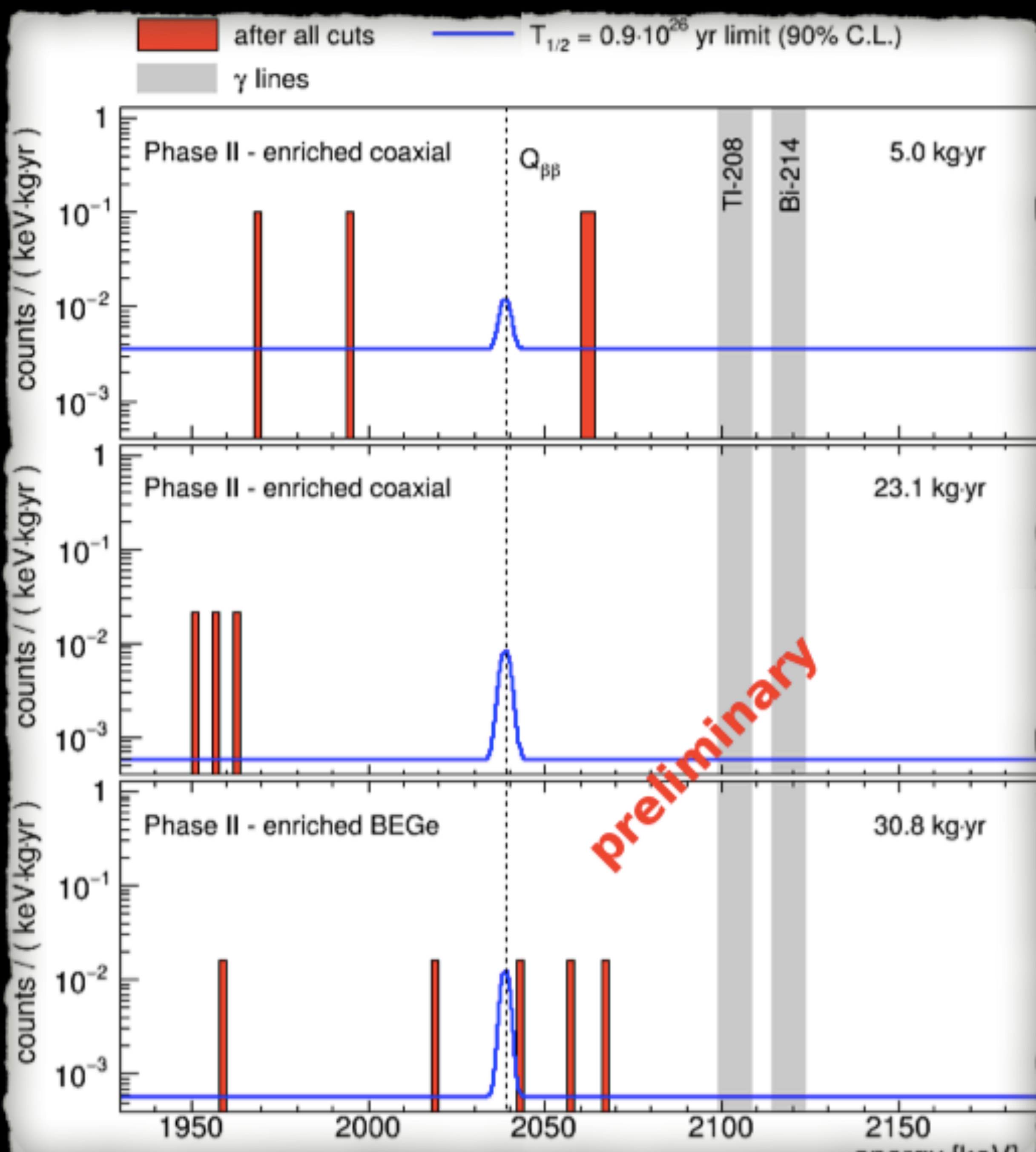
$$S_{0\nu} \propto \sqrt{\frac{M \times t}{n_B \times \Delta E}}$$

GERDA



clean room – rdy
status
phase I lock – under test
cryo-mu-lab
µ veto
rdy
FE electronics
under test
phase I array
rdy (scaled:)
control room
cryostat - rdy
water plant
Rn monitor
water tank - rdy
GERDA bldg - rdy
LAr fill : Oct/Nov 09

the best result in town



- Limit on $T^{0\nu}_{1/2} > 0.9 \cdot 10^{26}$ yr (90% CL)
- Median Sensitivity: $1.1 \cdot 10^{26}$ yr (*the best in the world!*)
- BI(^{enr}Coax): $0.6^{+0.4}_{-0.3} \cdot 10^{-3}$ cts/(keV· kg · yr)

  BI(^{enr}BEGe): $0.6^{+0.4}_{-0.3} \cdot 10^{-3}$ cts/(keV ·kg · yr)

Now and then: LEGEND

- 7 events surviving. Background index BI = 5.3 ± 2.2 · 10^{-4} cts / (keV kg yr)

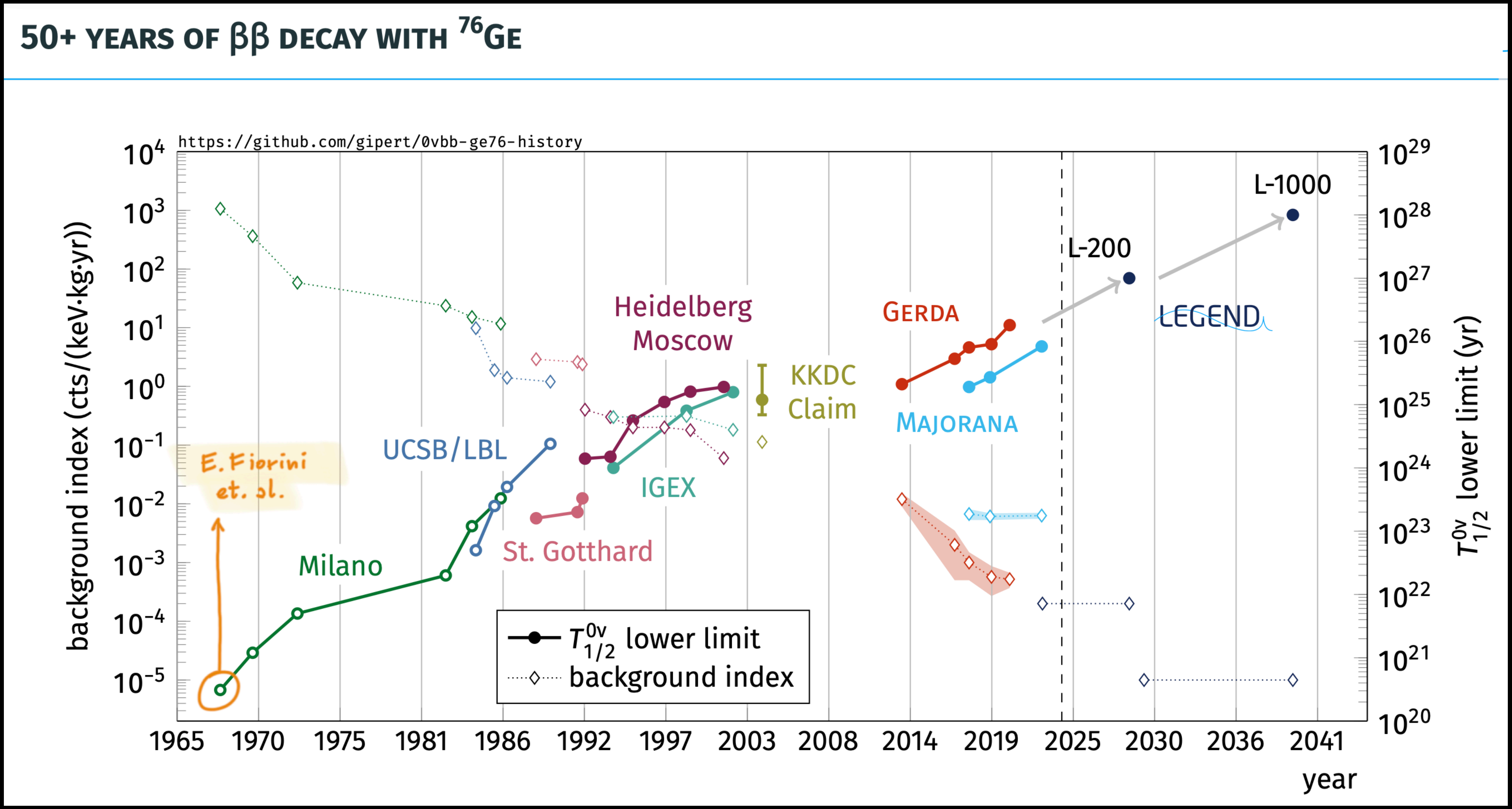
PRELIMINARY!

GERDA, MAJORANA and LEGEND combined fit

- *p*-value of background-only = 26%
- $T^{0\nu}_{1/2}$ lower limits (90% frequentist C.L.)

Observed	Sensitivity
> 1.9 · 10^{26} yr	2.8 · 10^{26} yr

The Ge Road

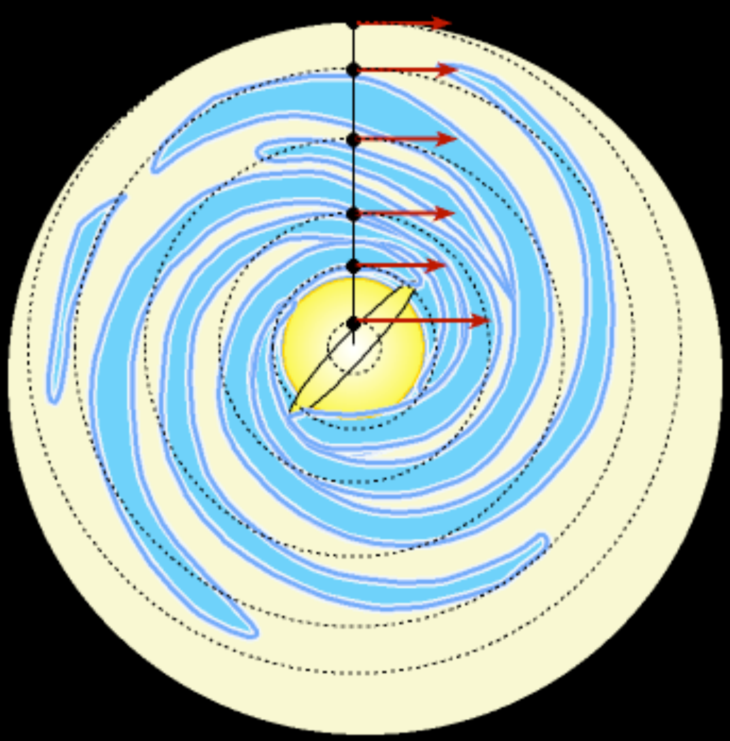


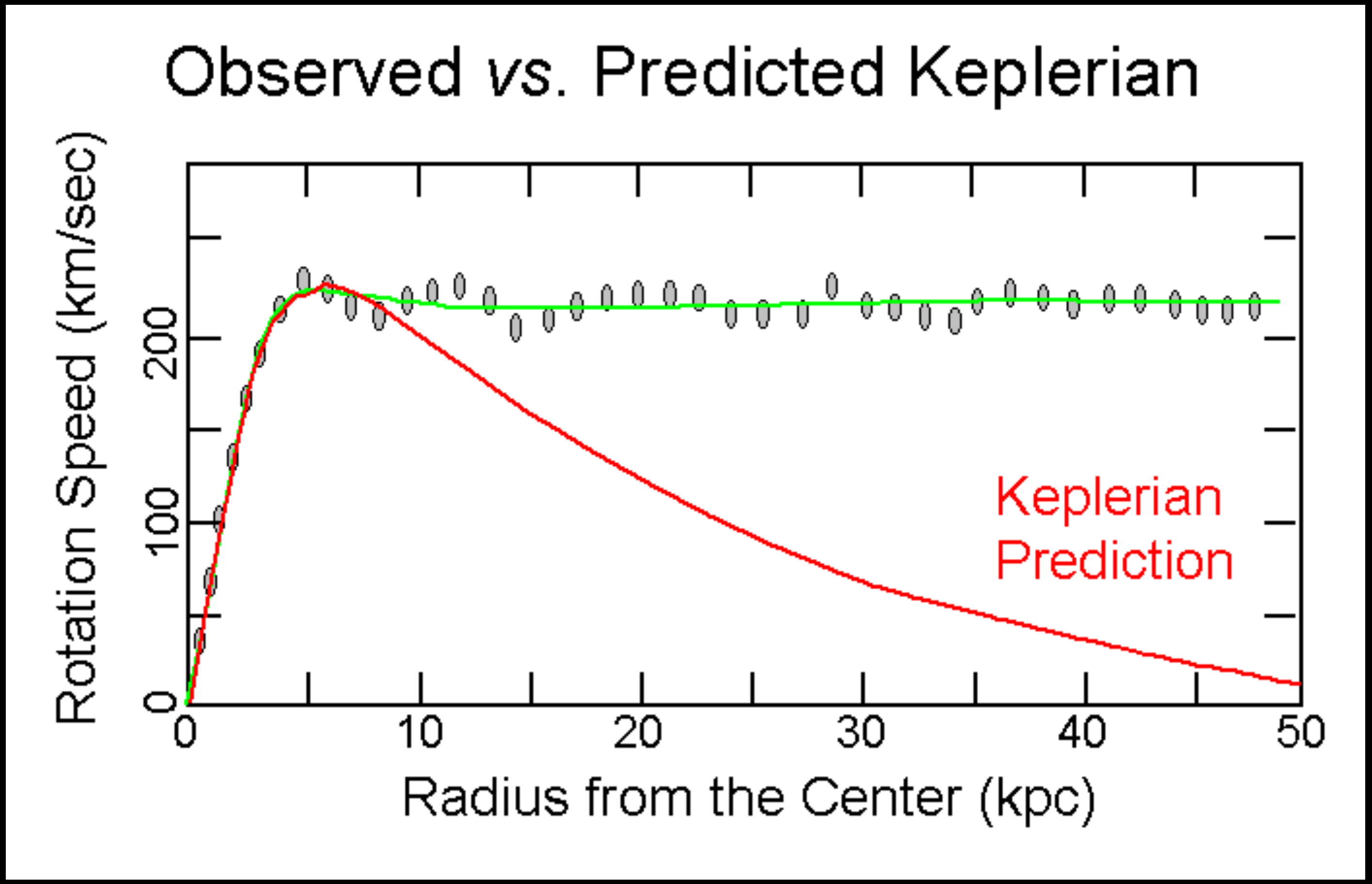
50+ YEARS OF ββ DECAY WITH 76GE
https://github.com/gipert/0vbb-ge76-history
background index (cts/(keV·kg·yr))
$T^{0\nu}_{1/2}$ lower limit (yr)
E. Fiorini et. al.
Milano
UCSB/LBL
St. Gotthard
Heidelberg Moscow
IGEX
KKDC Claim
GERDA
MAJORANA
L-200
L-1000
LEGEND
$T^{0\nu}_{1/2}$ lower limit
background index
year
1965
1970
1975
1981
1986
1992
1997
2003
2008
2014
2019
2025
2030
2036
2041

DARK MATTER SEARCHES

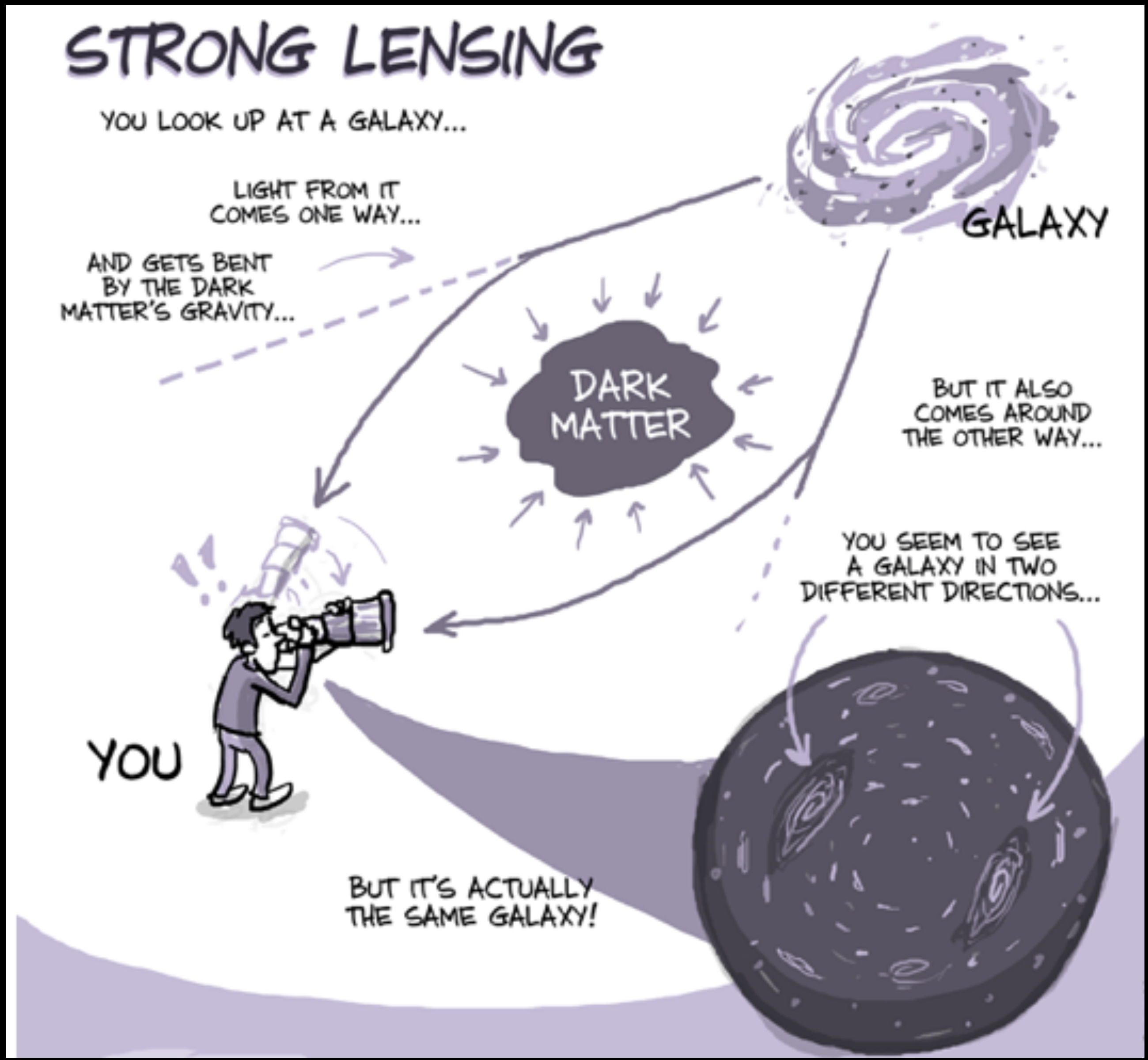
Why in this way ?

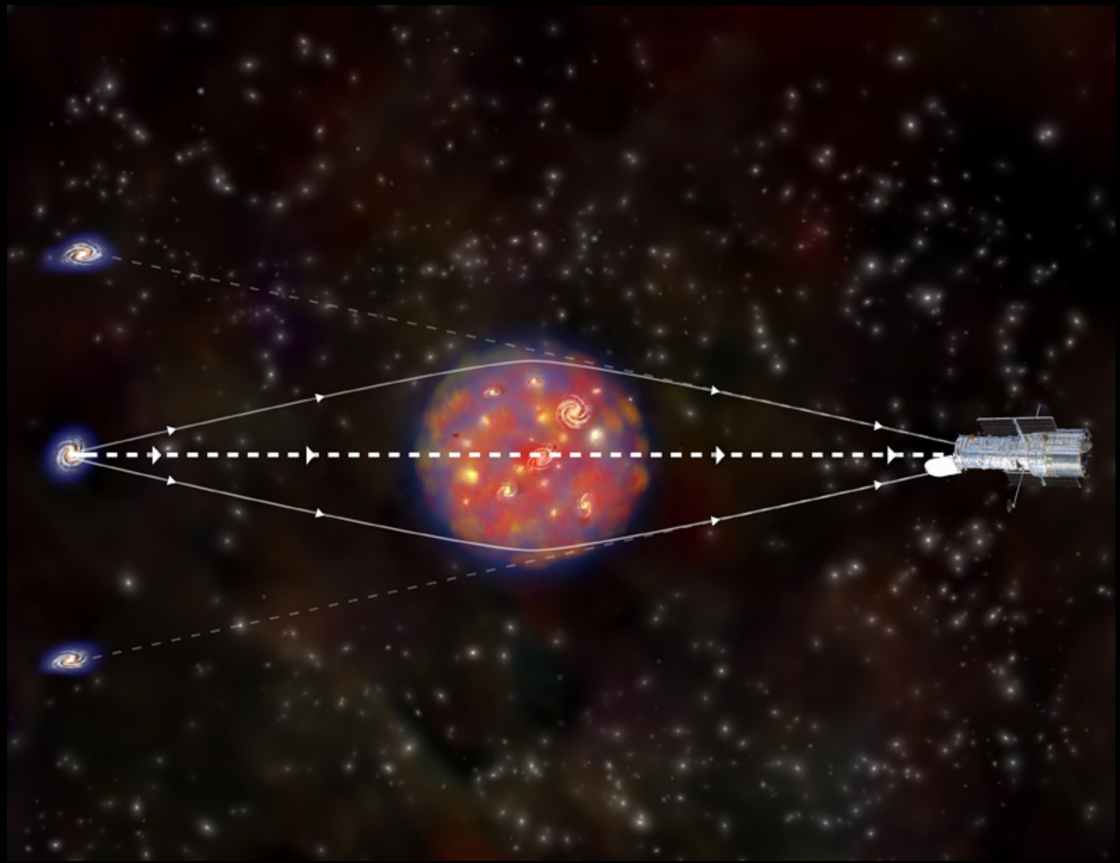
Rotation curves



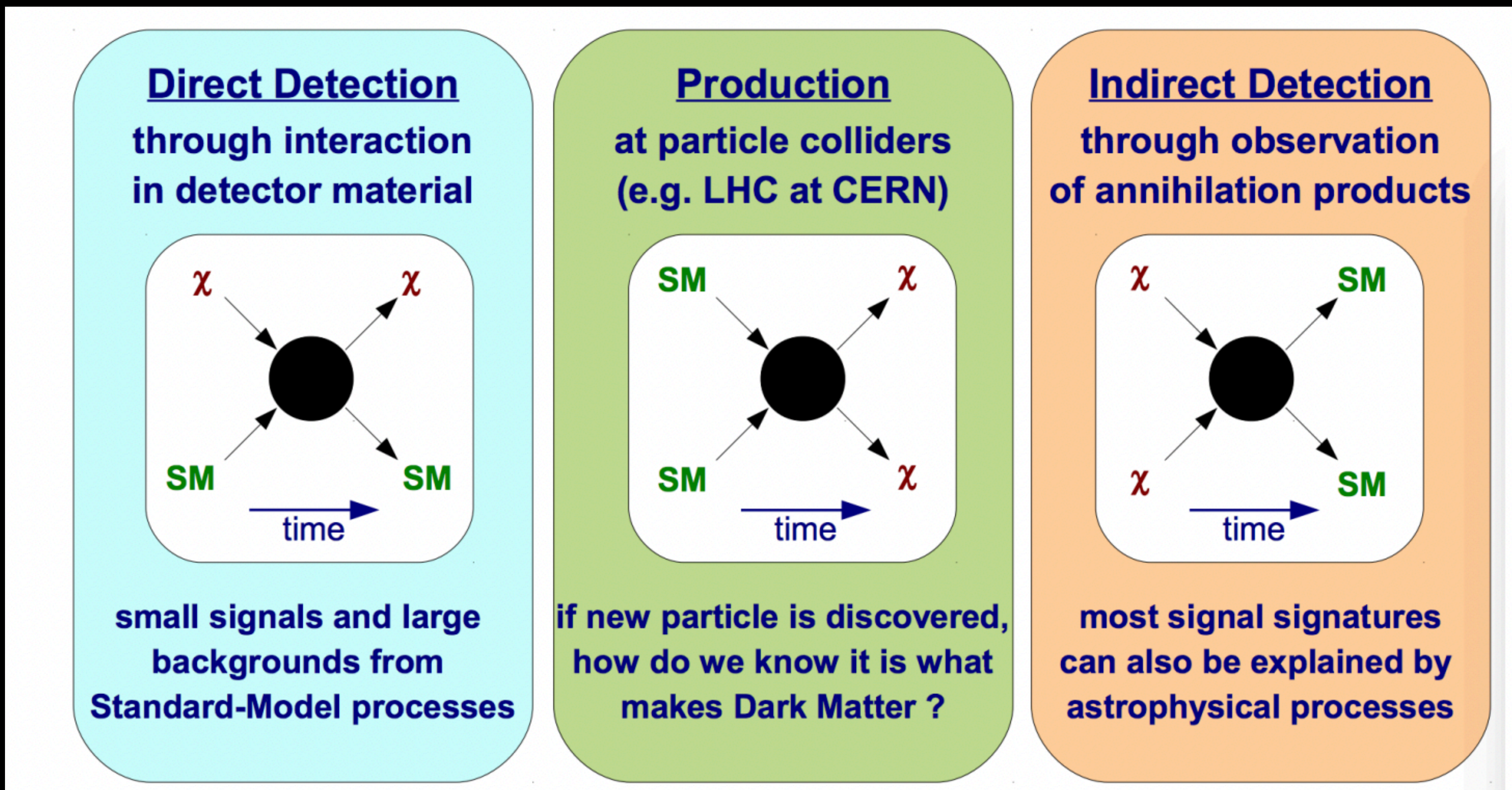


lensing

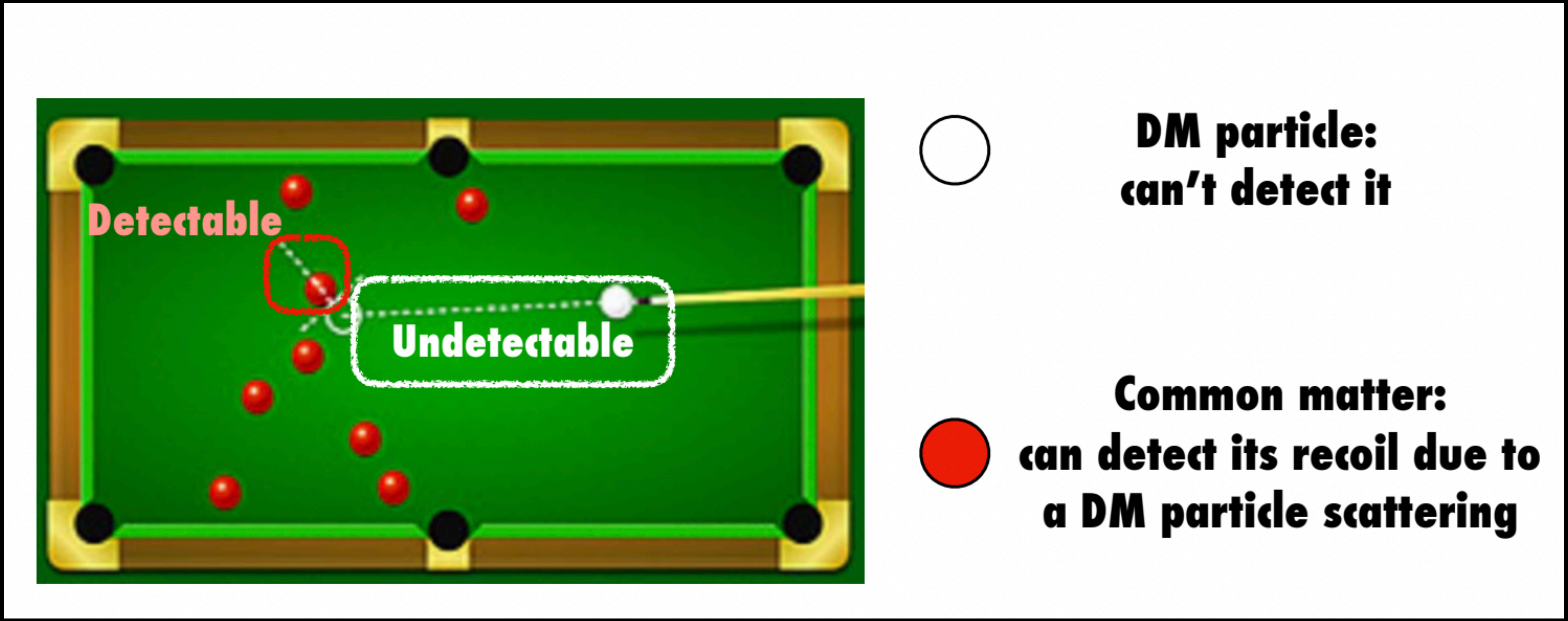

STRONG LENSING
YOU LOOK UP AT A GALAXY...
LIGHT FROM IT COMES ONE WAY...
AND GETS BENT BY THE DARK MATTER'S GRAVITY...
GALAXY
DARK MATTER
BUT IT ALSO COMES AROUND THE OTHER WAY...
YOU SEEM TO SEE A GALAXY IN TWO DIFFERENT DIRECTIONS...
YOU
BUT IT'S ACTUALLY THE SAME GALAXY!



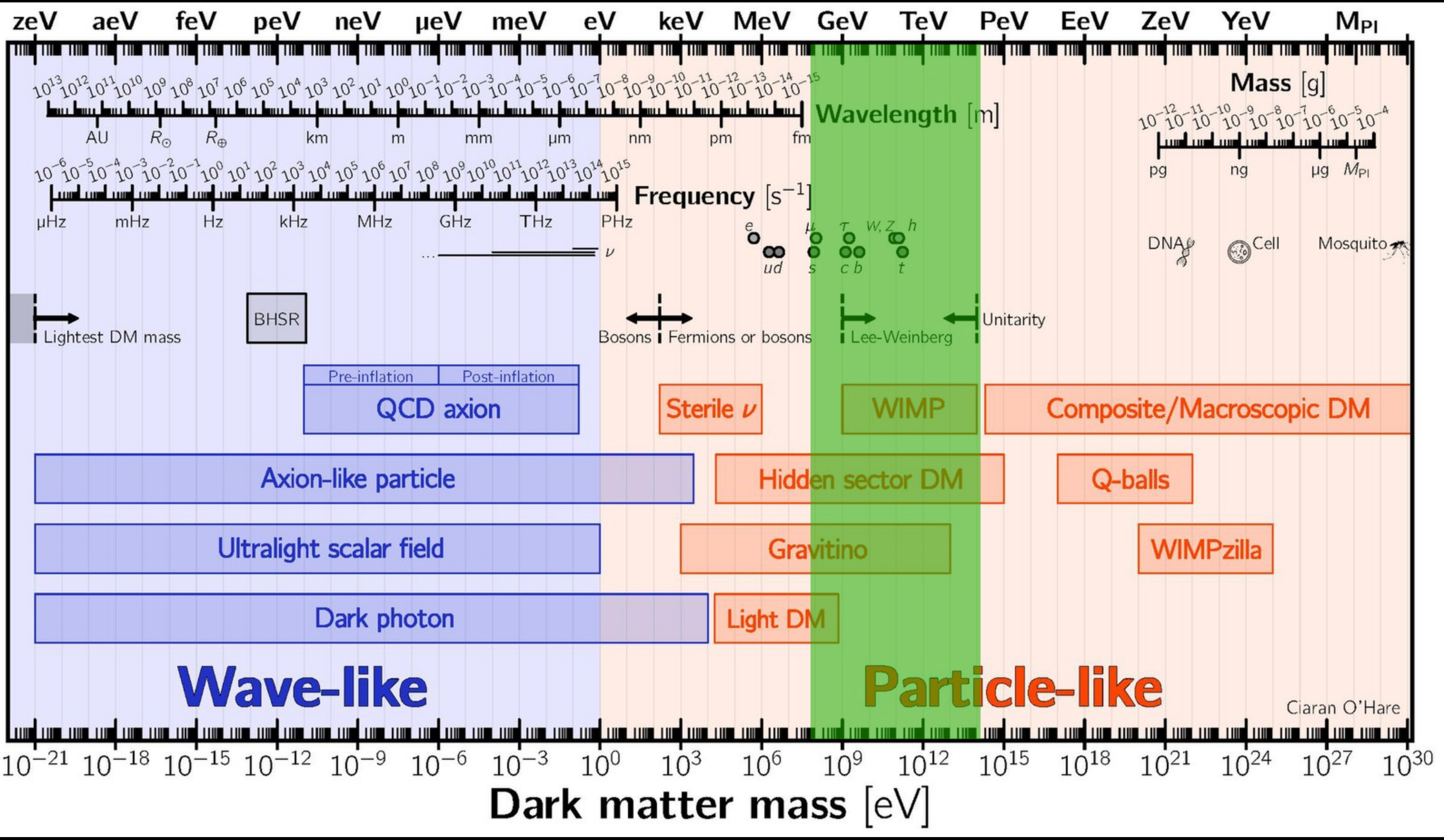
Try to find it



Detecting the undetectable



Betting on a specific model of Dark Matter:
Weakly Interacting Massive Particles



If WIMP then

How many WIMP scattering events per unit time can we expect?

$$R \sim N_N \times \phi_0 \times \sigma_{WN} = \frac{N_A}{A} \times \frac{\rho_0}{m_W} \times \langle v \rangle \times \sigma_{WN}$$

Local DM density

$\rho_0 = 0.3 \ \mathrm{GeV} \ \mathrm{cm}^{-3}$,

WIMP number density

$n_0 = \rho_0 / \mathrm{m}_W$,

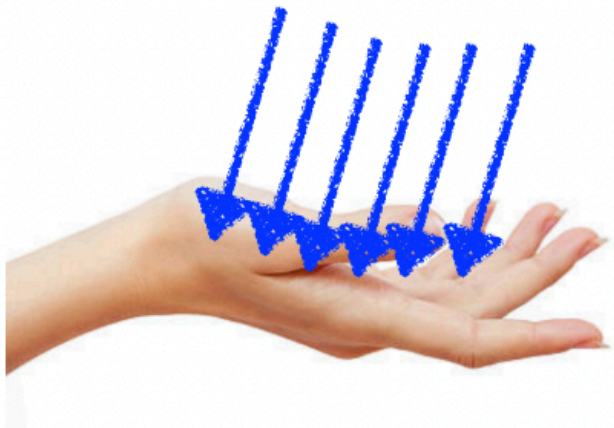
WIMP mean velocity w.r.t. the target nuclei

$\langle v \rangle = 220 \ \mathrm{km} \ \mathrm{s}^{-1} = 0.75 \times 10^{-3} \ \mathrm{c}$.

WIMP mass

$\mathrm{m}_W = 100 \ \mathrm{GeV/c}^2$,

Expected WIMP flux $\phi_0 = n_0 \times \langle v \rangle = \frac{\rho_0}{m_W} \times \langle v \rangle \sim$ **10^5 particle/cm²/s**

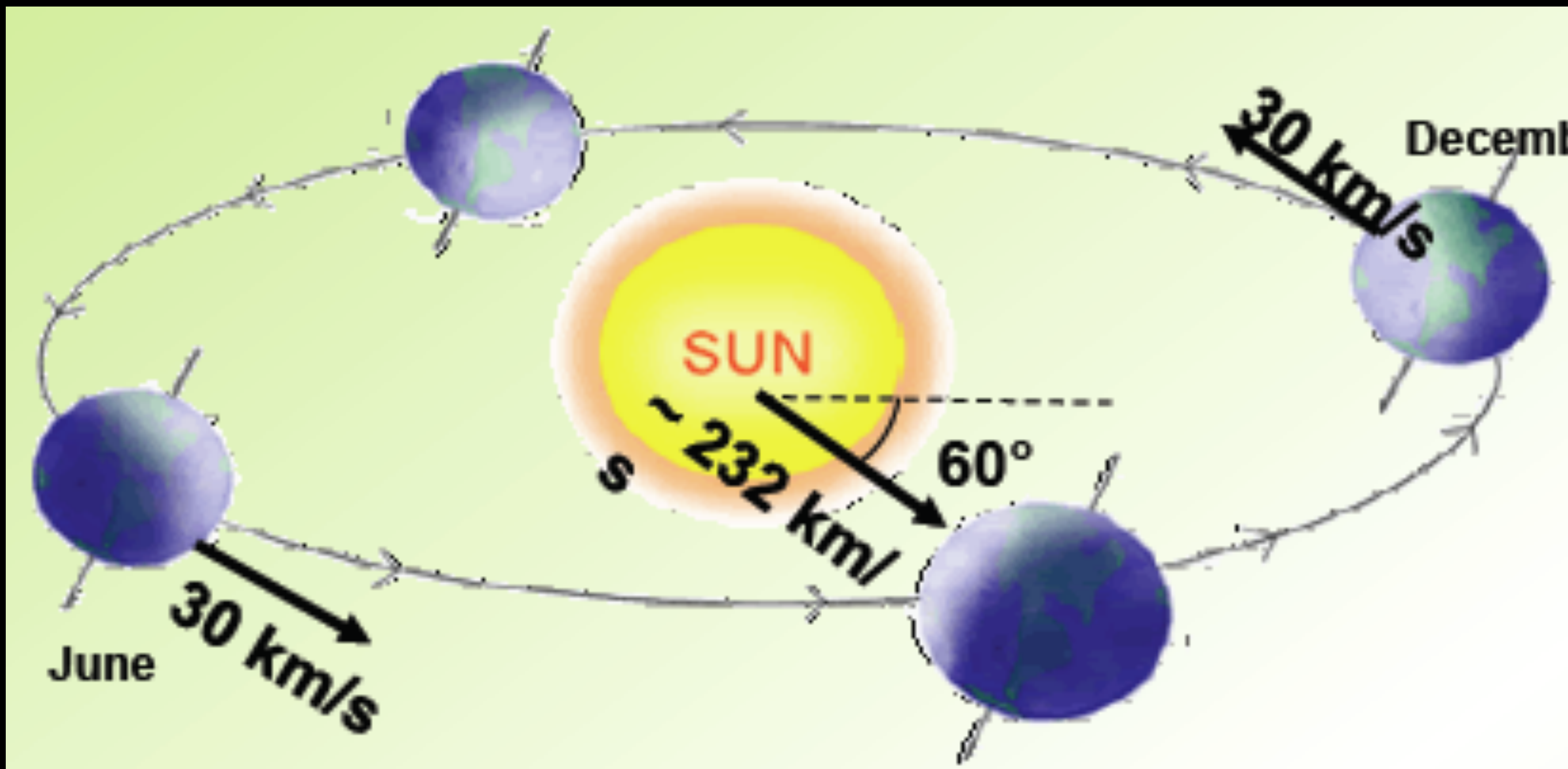


20 million particles/hand/s!

Not so small...but what is the expected rate?

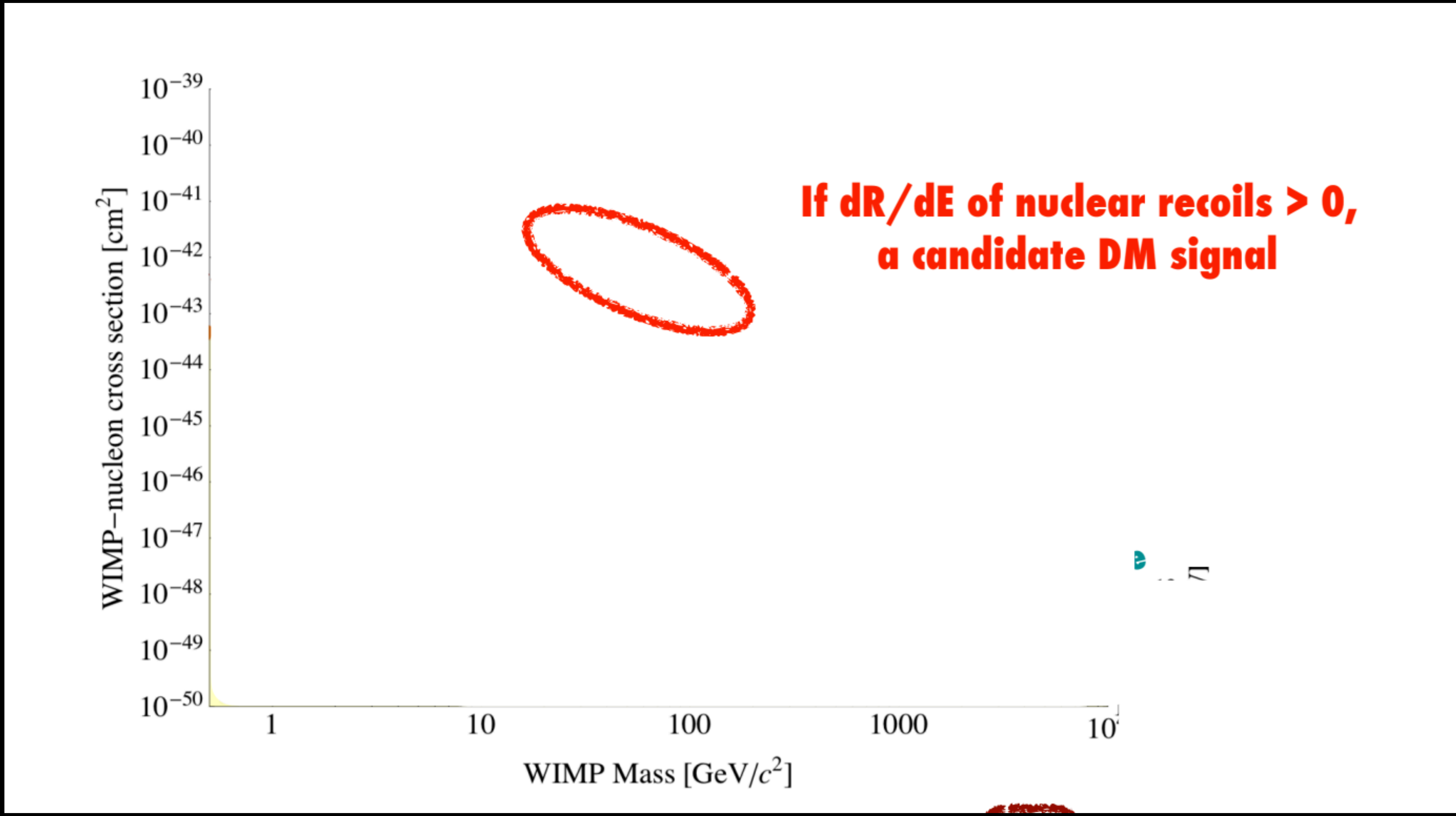
?

the basic concept

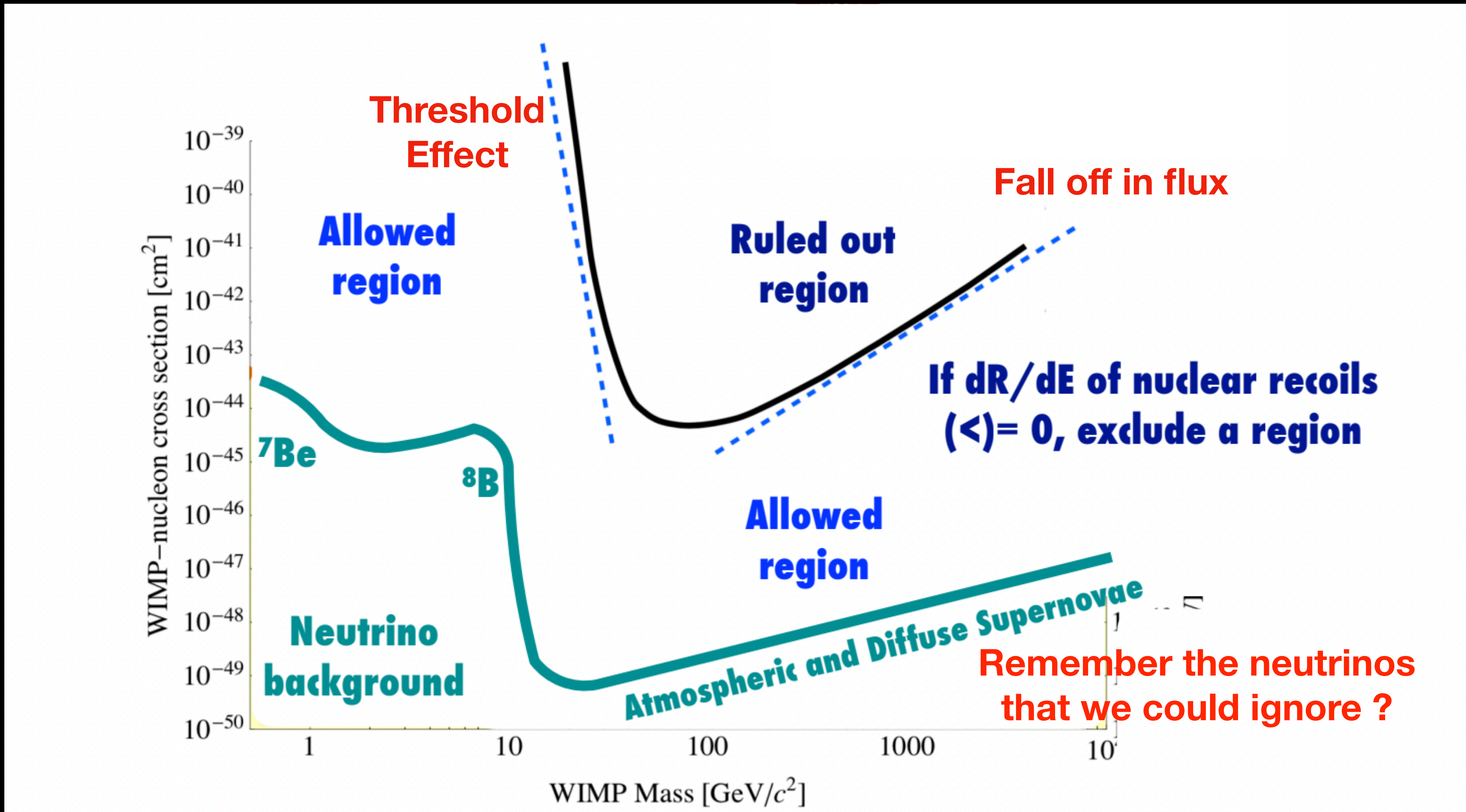


- v_{sun} ~ 232 km/s (Sun velocity in the halo)
- v_{orb} = 30 km/s (Earth velocity around the Sun)
- $\gamma = \pi/3$, $\omega = 2\pi/T$, $T = 1$ year
- t_0 = 2nd June (when $v_\oplus$ is maximum)

Basic phase space result

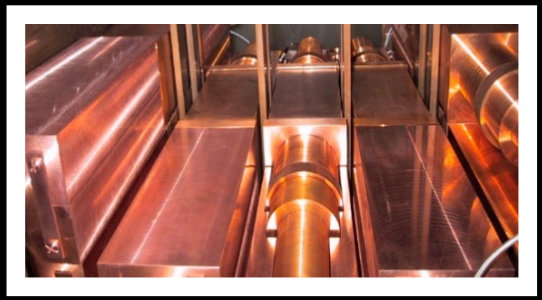


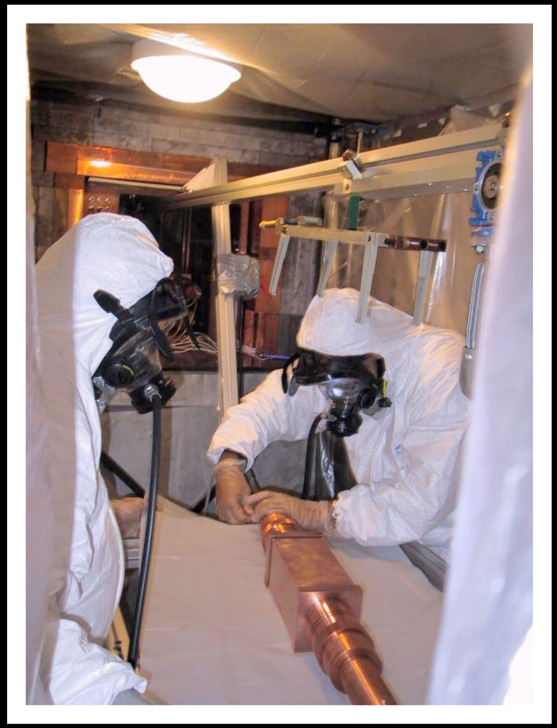
That in case of no event



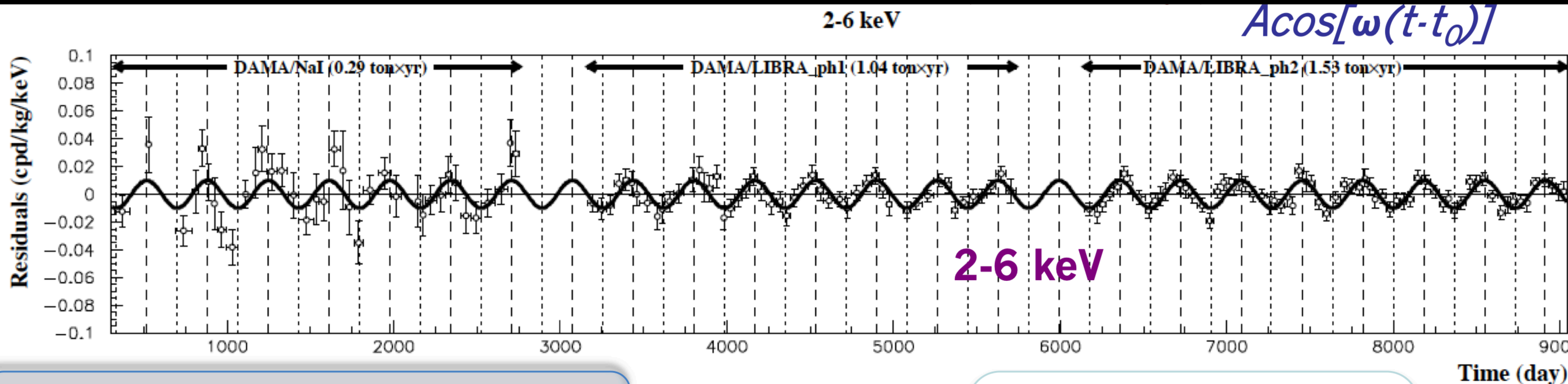
The DAMA/LIBRA mystery case

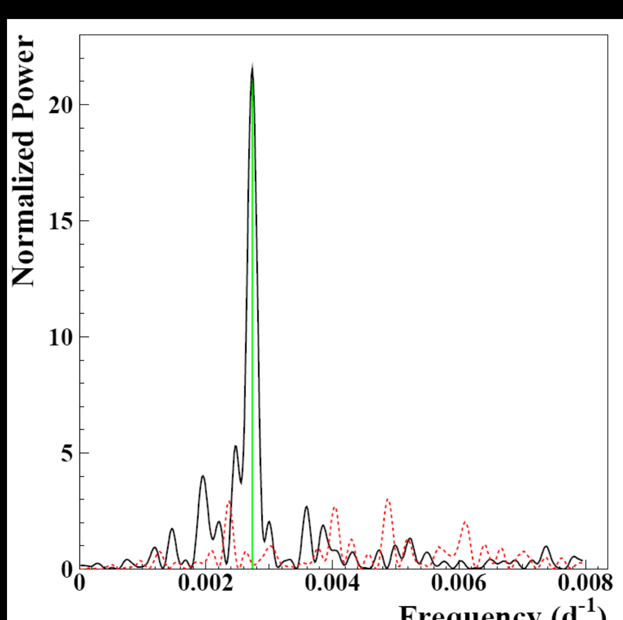
- Ultrapure Na(Tl)
  - residual contamination ^{232}Th, ^{238}U and ^{40}K at level of 10^{-12} g/g





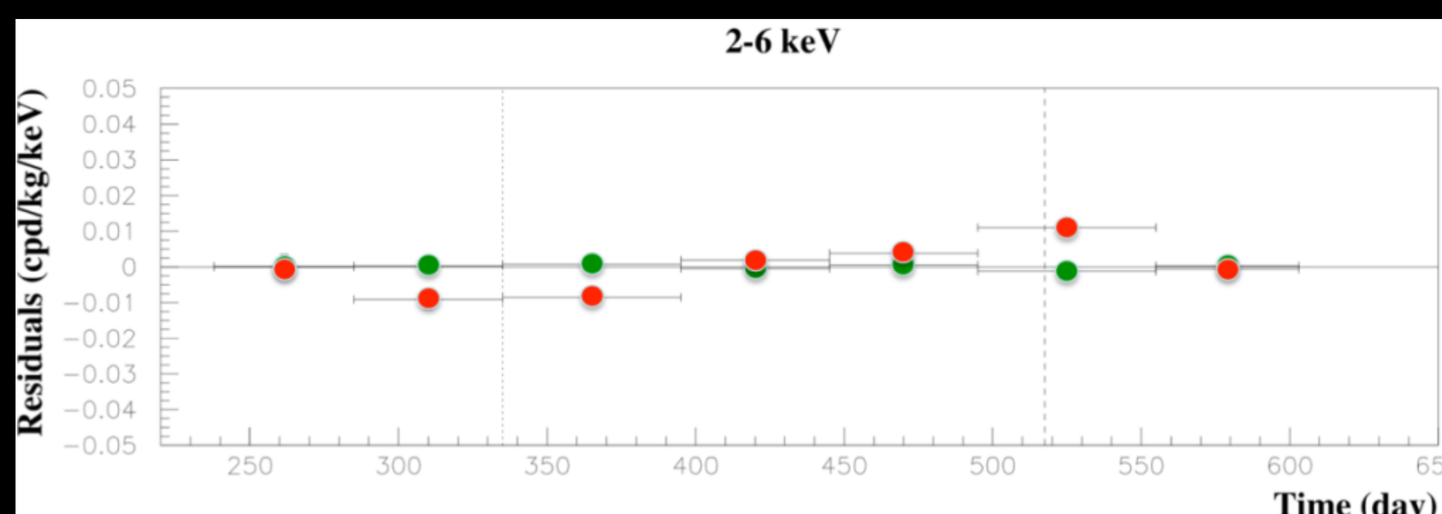
DAMA/LIBRA annual modulation



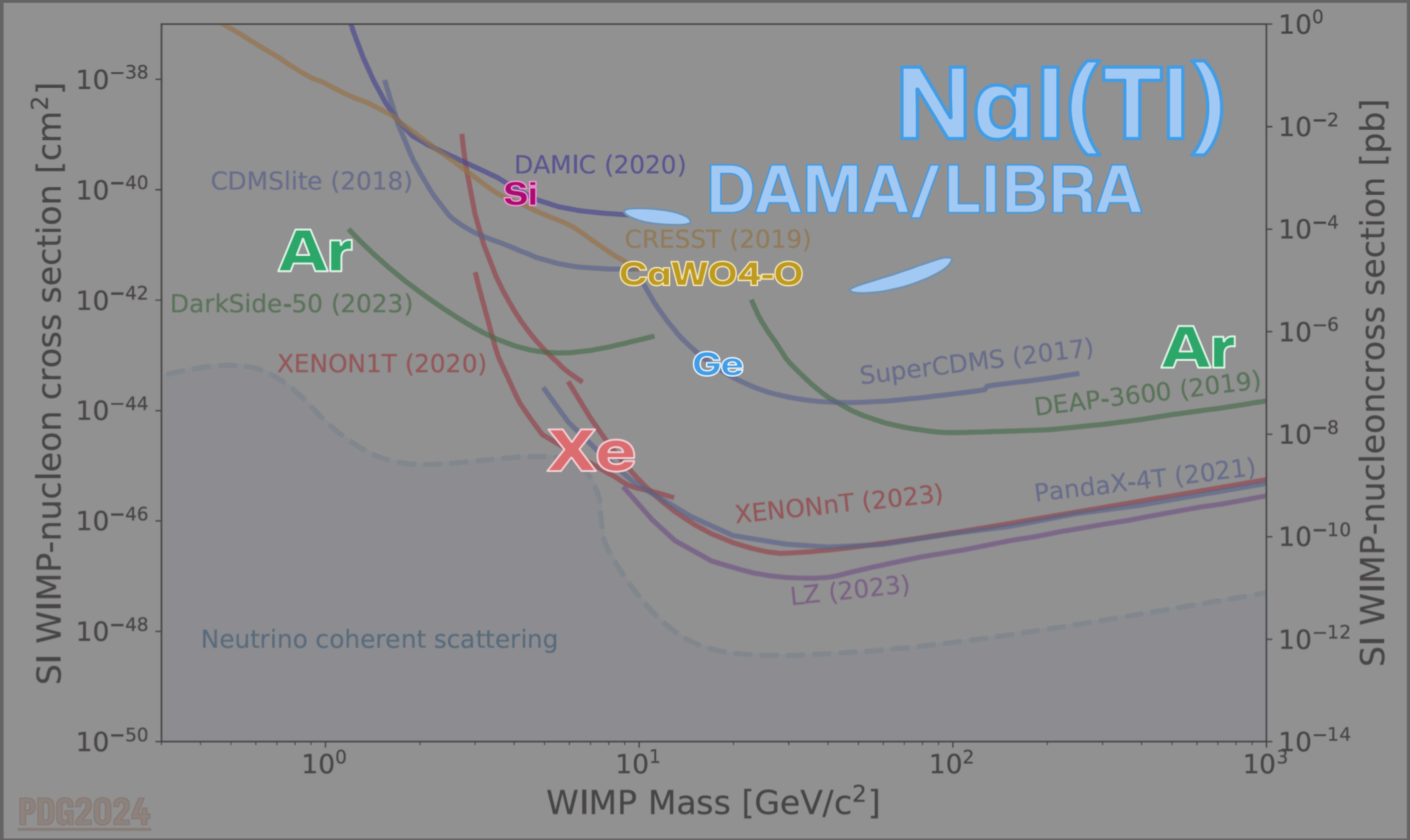


Comparison between single hit residual rate (red points) and multiple hit residual rate (green points); A=-(0.0006±0.0004) cpd/kg/keV

Multiple hits events = Dark Matter particle "switched off"



The translation is

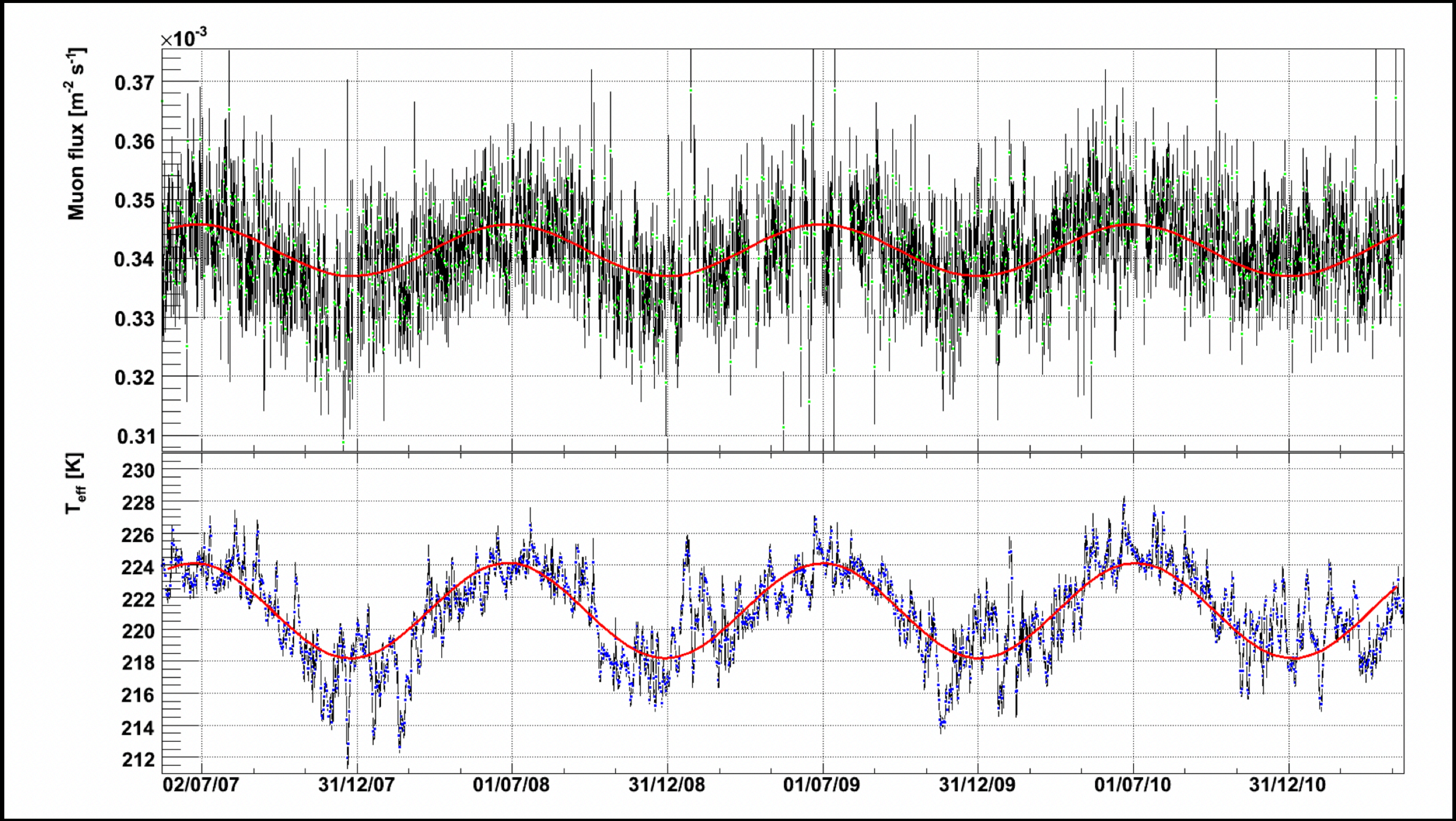


And the problem is:

- Many other experiments (not using modulation*, only event counting) do not confirm DAMA/LIBRA result
- They put limits significantly lower and exclude with high confidence that result
- But…..the significance of the signal is out of discussion
- No other experiment measuring modulation has so far produced a result that exclude/confirm DAMA

*** this situation is changing thanks to ANAIS & COSINE**

Which background could mimic a signal ?



Muon flux measured at LNGS by BOREXINO experiment

Of course

- DAMA/LIBRA says they know, are completely shielded and have an active veto……but

- There will be one way to resolve this issue

- Do the same experiment in the Southern Hemisphere, where:

  - The DM flux would not change

  - The muon flux would have a 180^0 shift of phase

Coiming....Stawell (Aus)

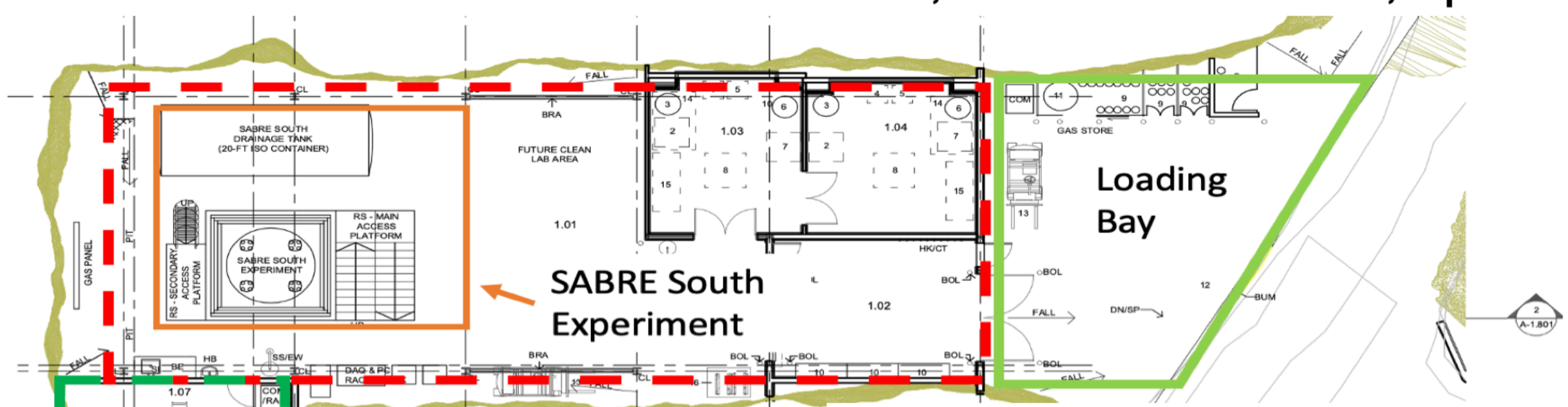
SUPL

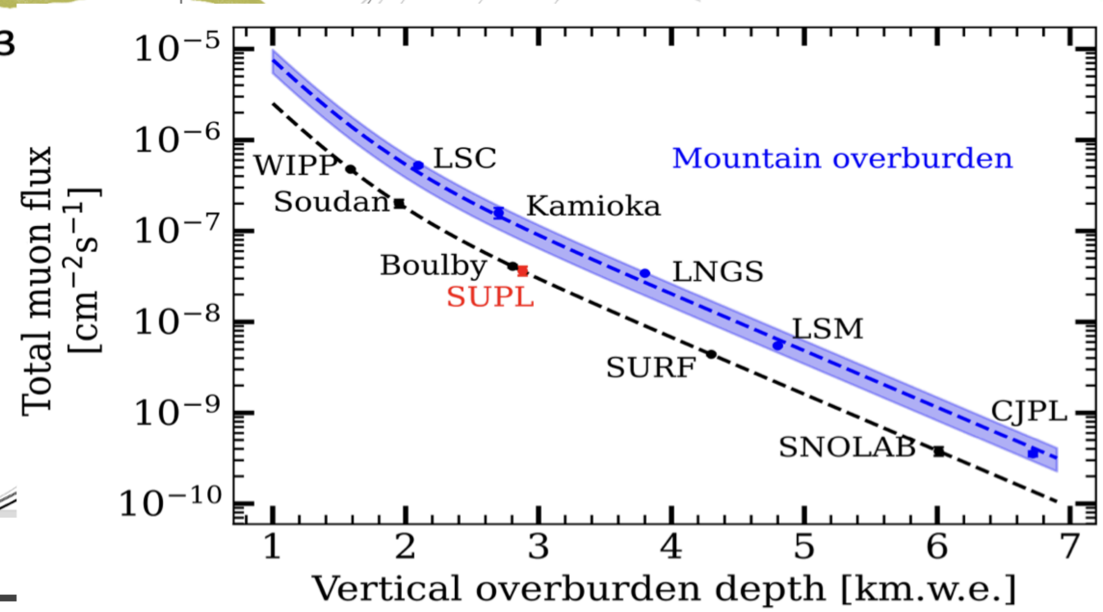
Operating since January 2024

STAWELL UNDERGROUND PHYSICS LAB

https://www.supl.org.au

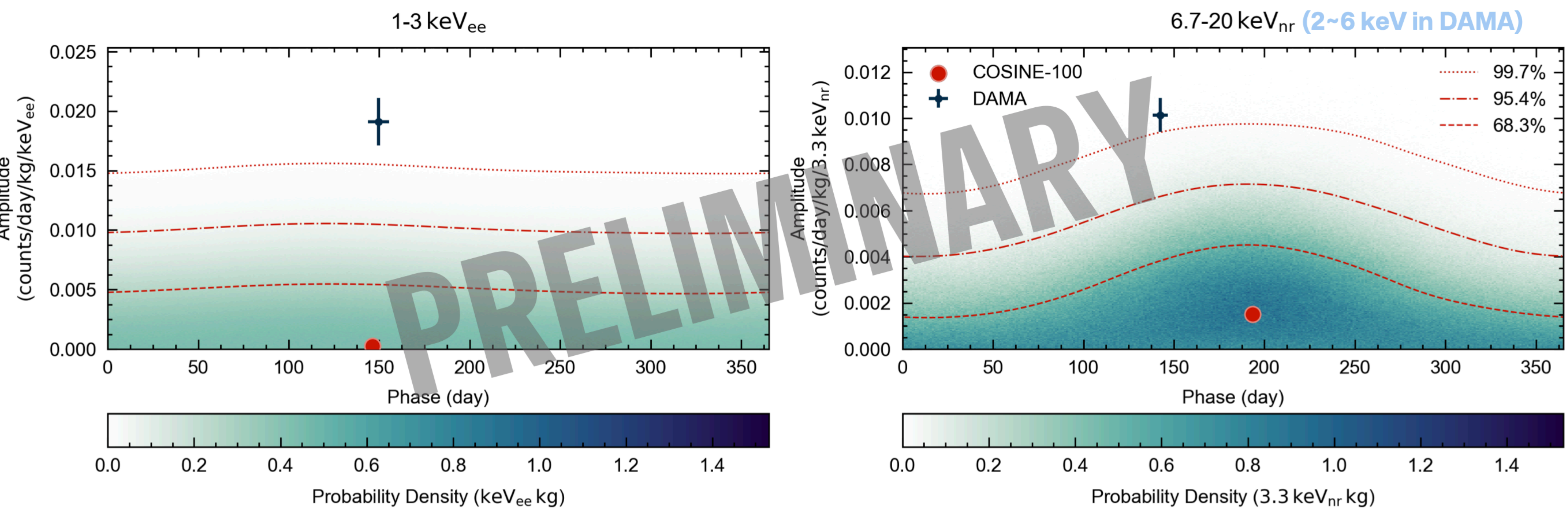
- First deep underground lab in the Southern Hemisphere
  - 1025 m deep (2900 m w.e.) in an active gold mine (SGM)
  - Flat overburden
  - Helical drive access: 10 km tunnel, max 5 m diameter, up to 10% slope



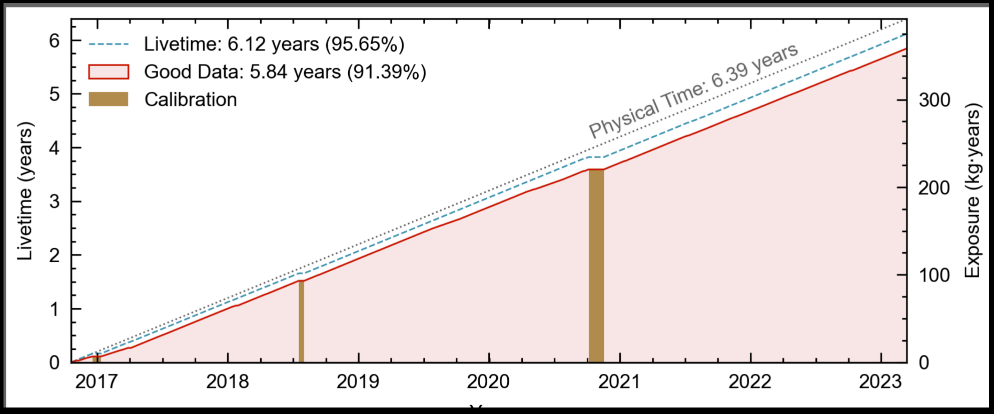


ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

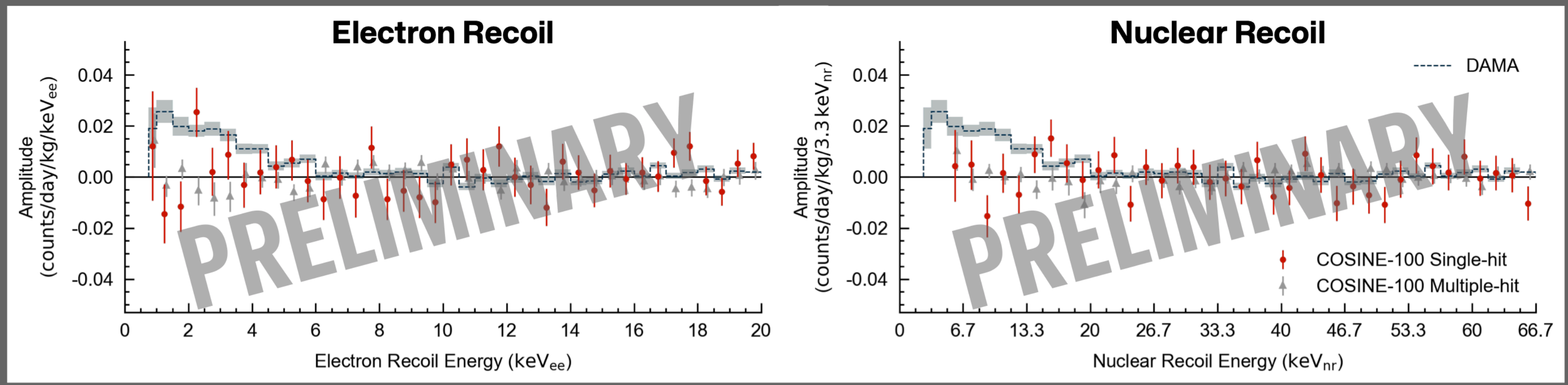
In the meanwhile



COSINE-100 at Y2L



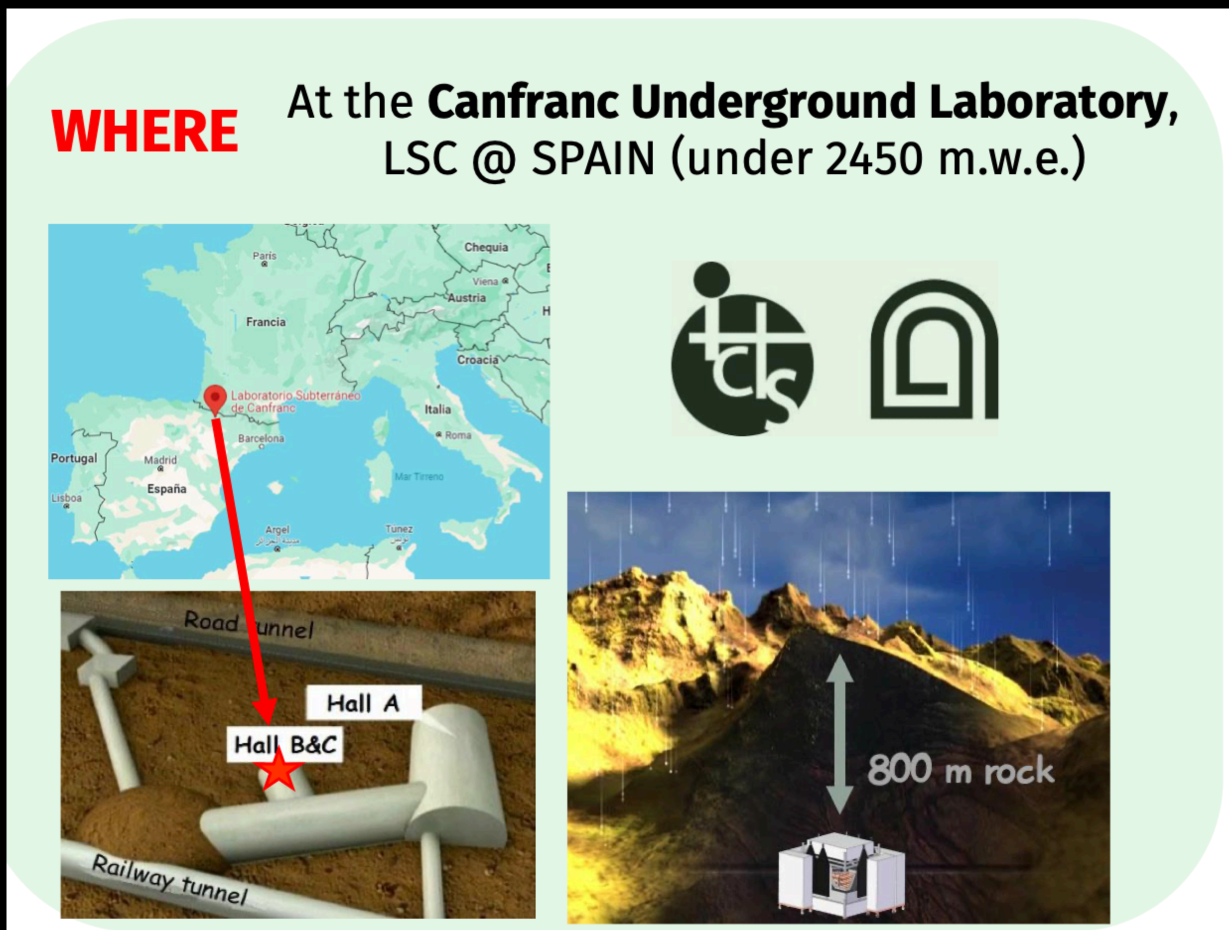
No Modulation Detected

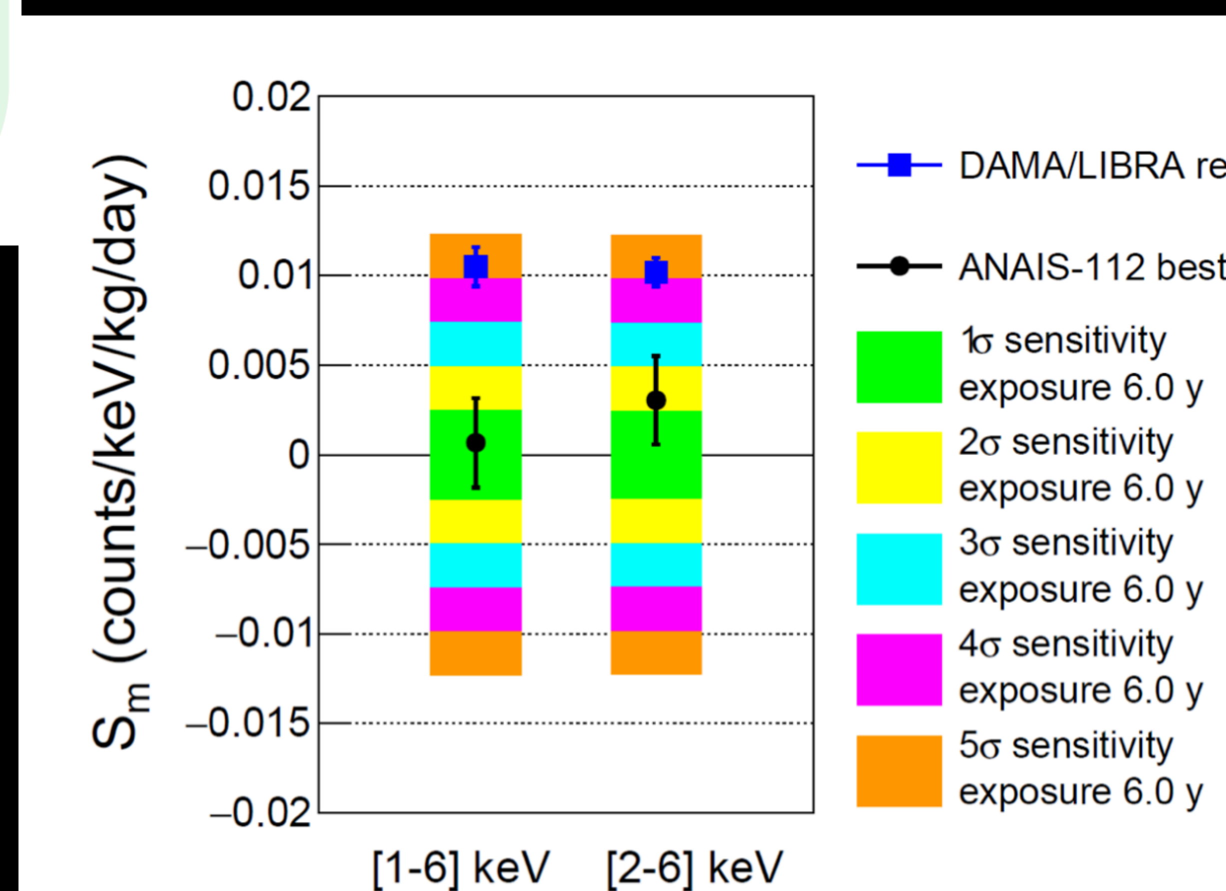


E (keV$_{ee}$)	A (counts/day/kg/keV$_{ee}$)	
	COSINE-100	DAMA/LIBRA
1~3	0.0004 ± 0.0050	0.0191 ± 0.0020
1~6	0.0017 ± 0.0029	0.01048 ± 0.00090
2~6	0.0053 ± 0.0031	0.00996 ± 0.00074

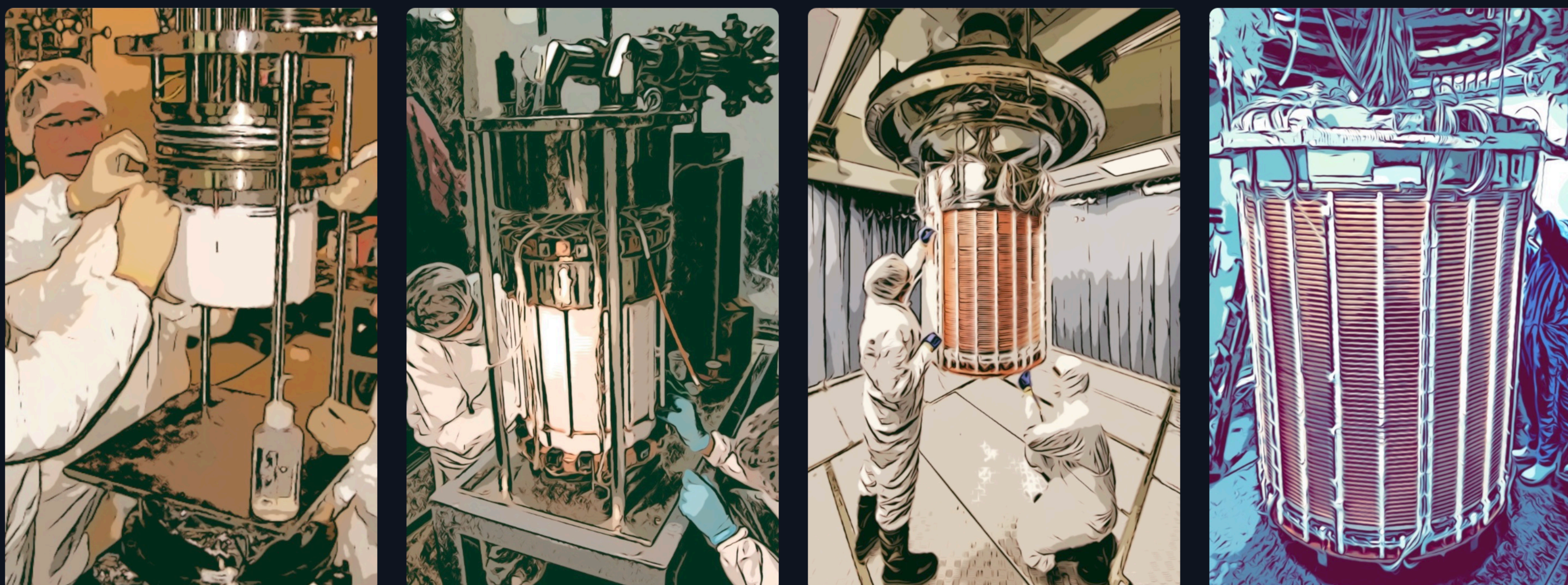
E (keV$_{nr}$)	A (counts/day/kg/3.3 keV$_{nr}$)	
	COSINE-100	DAMA/LIBRA
6.7~20	0.0013 ± 0.0027	0.00996 ± 0.00074

ANAIS at Canfranc (E)





The counting technique
The Xenon story



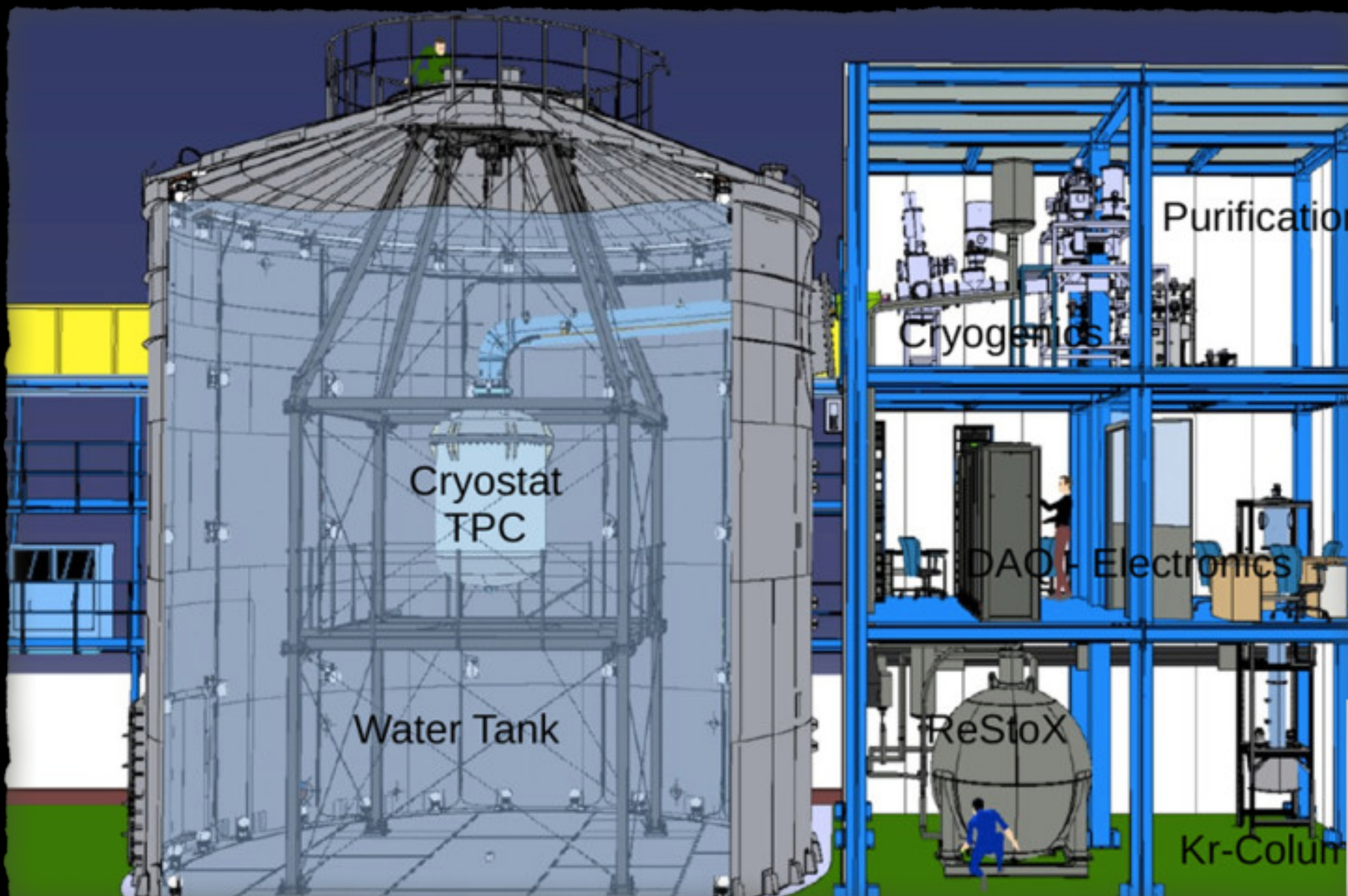
2006 Start	**15 cm** Drift Length	**600 [t d keV]$^{-1}$** Background
25 kg Total LXe Mass	**89** PMTs	**4.5×10^{-44} cm^2** Best Sensitivity

2008 Start	**30 cm** Drift Length	**5.3 [t d keV]$^{-1}$** Background
160 kg Total LXe Mass	**178** PMTs	**1.1×10^{-45} cm^2** Best Sensitivity

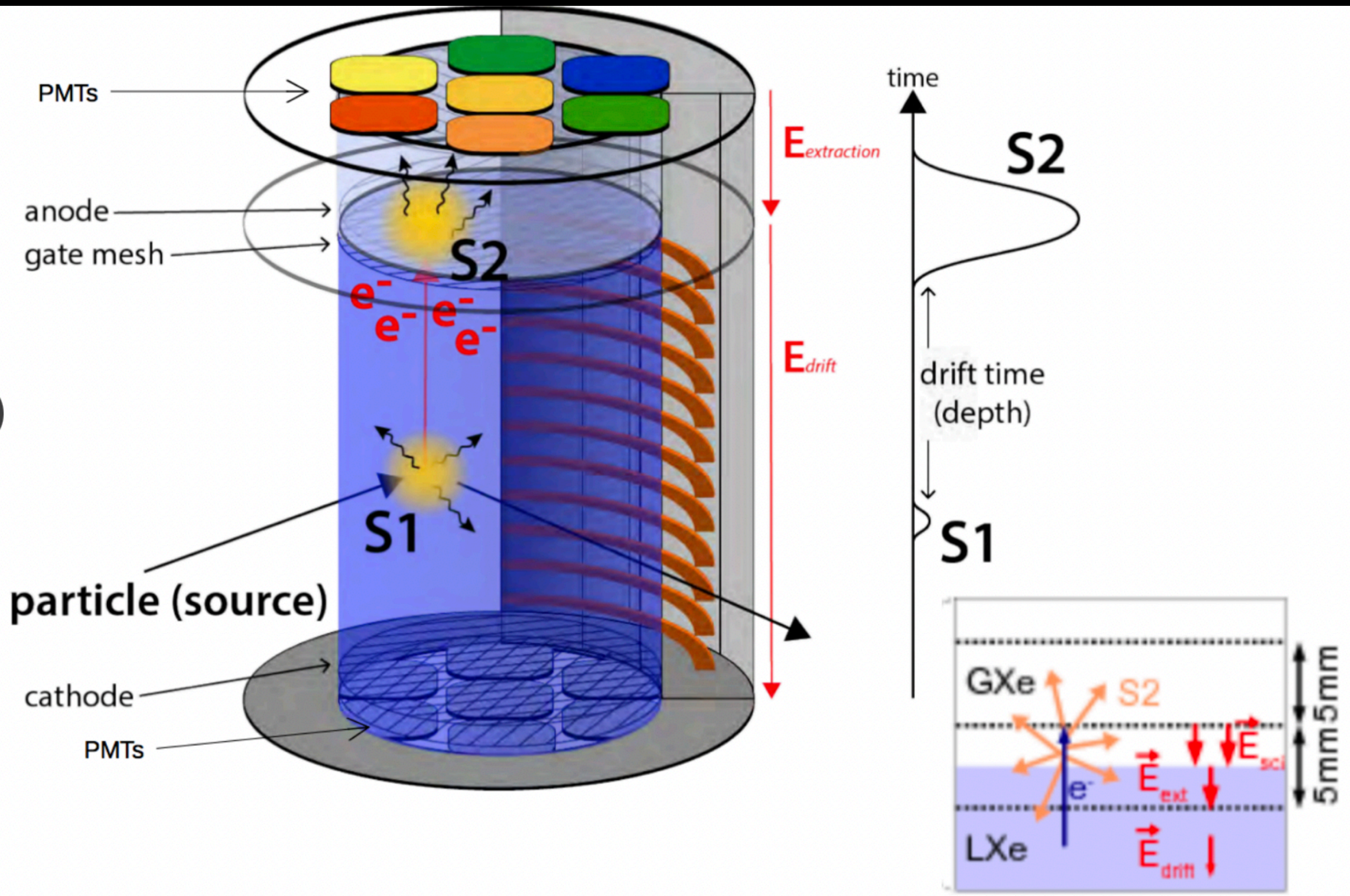
2015 Start	**100 cm** Drift Length	**0.2 [t d keV]$^{-1}$** Background
3,200 kg Total LXe Mass	**248** PMTs	**4.1×10^{-47} cm^2** Best Sensitivity

2020 Start	**148 cm** Drift Length	**0.04 [t d keV]$^{-1}$** Background
8,600 kg Total LXe Mass	**494** PMTs	**1.4×10^{-48} cm^2** Design Sensitivity

XENON 1T@LNGS



Working principle
(Dual phase noble liquid detector concept)



- Two electric fields between cathode, gate and anode
- Top and bottom PMTs detect light
- Signal generation:

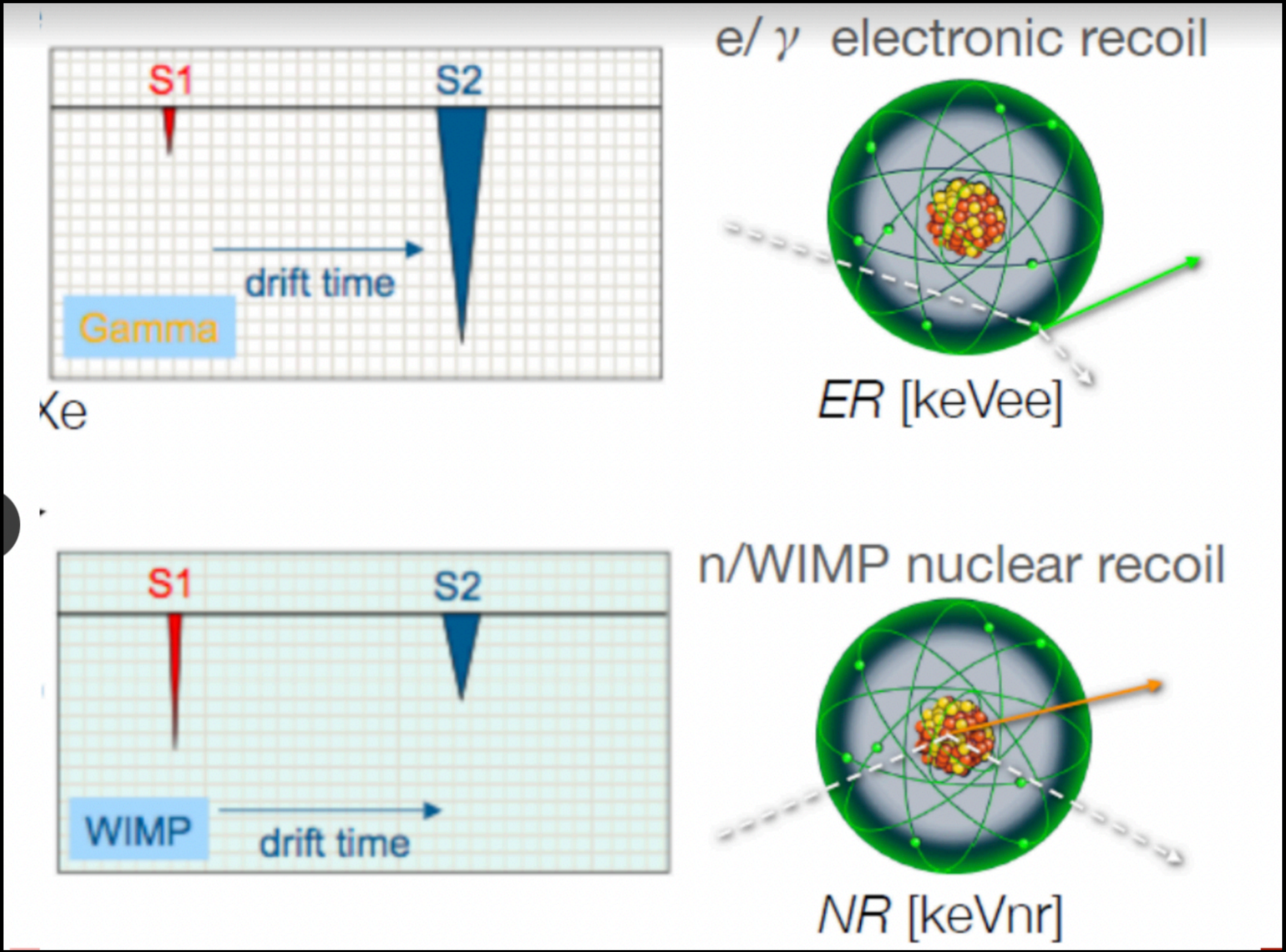
  → Incoming particle

  → S1 signal:
  Xe-dimers are created via **excitation and ionization → light emission**

  → S2 signal:
  Electrons are drifted to gate via E_{drift} and extracted via $E_{extraction}$ → **light emission via electrolumniscence**

Extraction of the charge from the liquid and amplification via electroluminescence in the gas region

S1/S2 discrimination

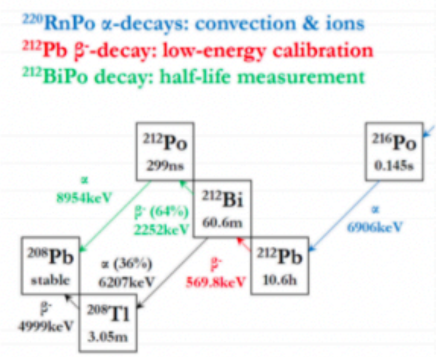


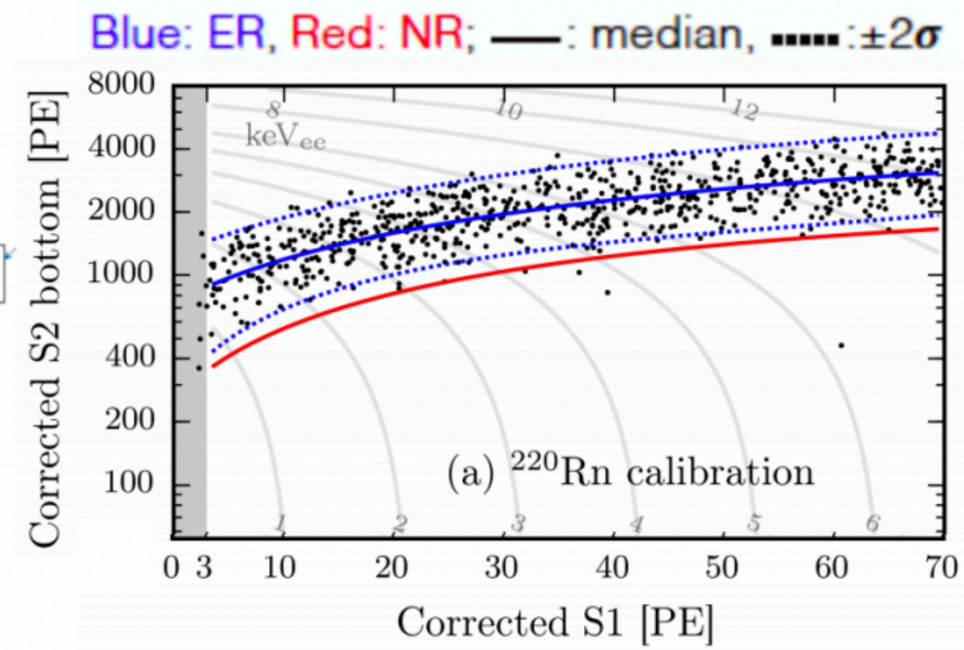
Painful calibration

Electronic Recoils (ER)

- ^{228}Th source emanates ^{220}Rn into LXe
- β-decay of ^{212}Pb to ^{212}Bi low energy events (2-20 keV)

Phys. Rev. D 95, 072008 (2017)

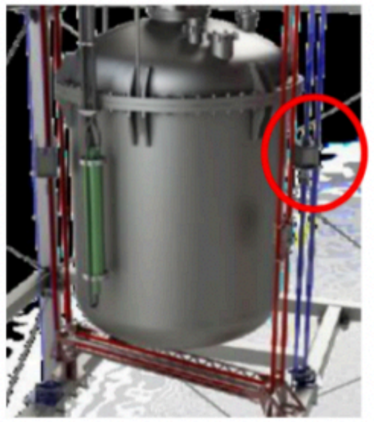


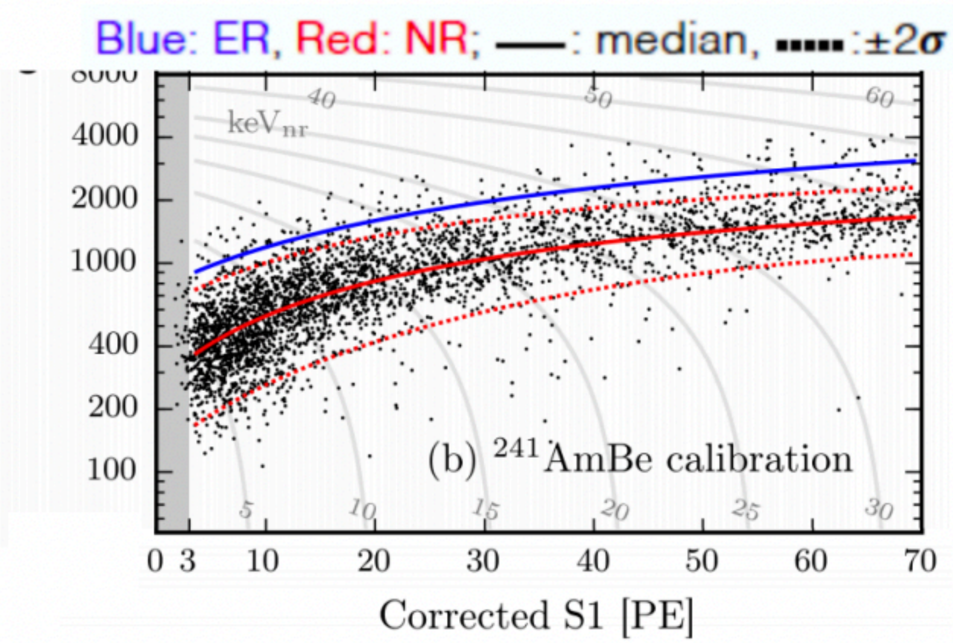


Nuclear Recoils (NR)

- external ^{241}AmBe source mounted on a belt
- α particles emitted by Am-decay collide with the light Be nuclei

➔ fast neutrons



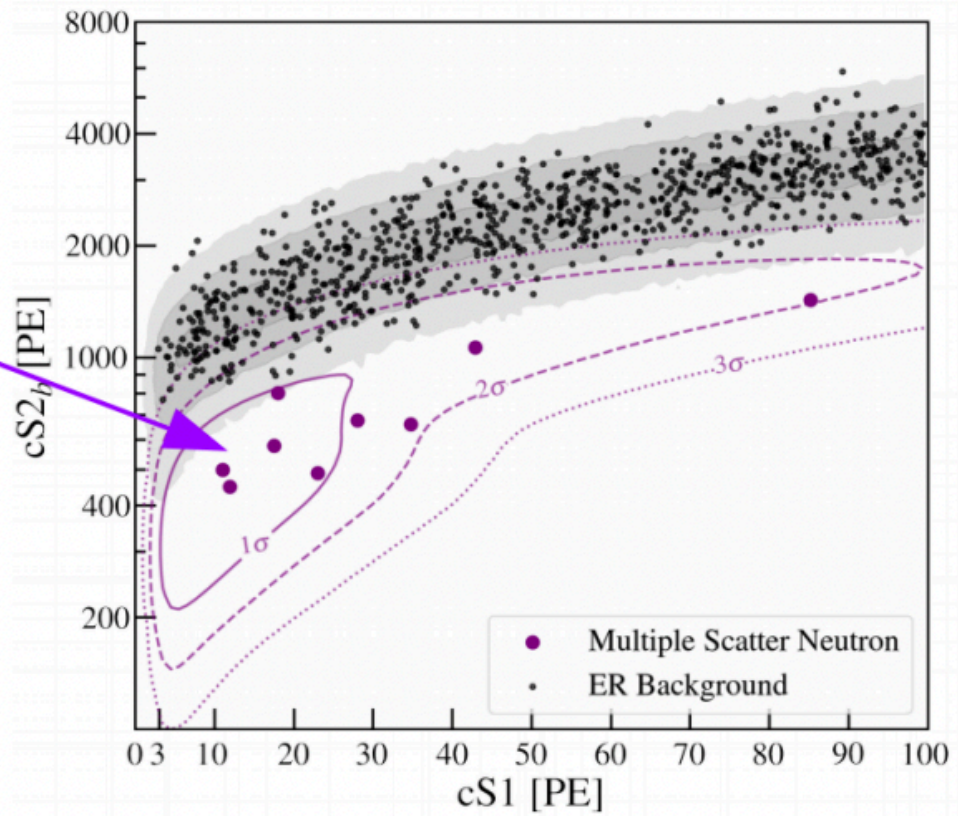


Photons out, neutrons ?

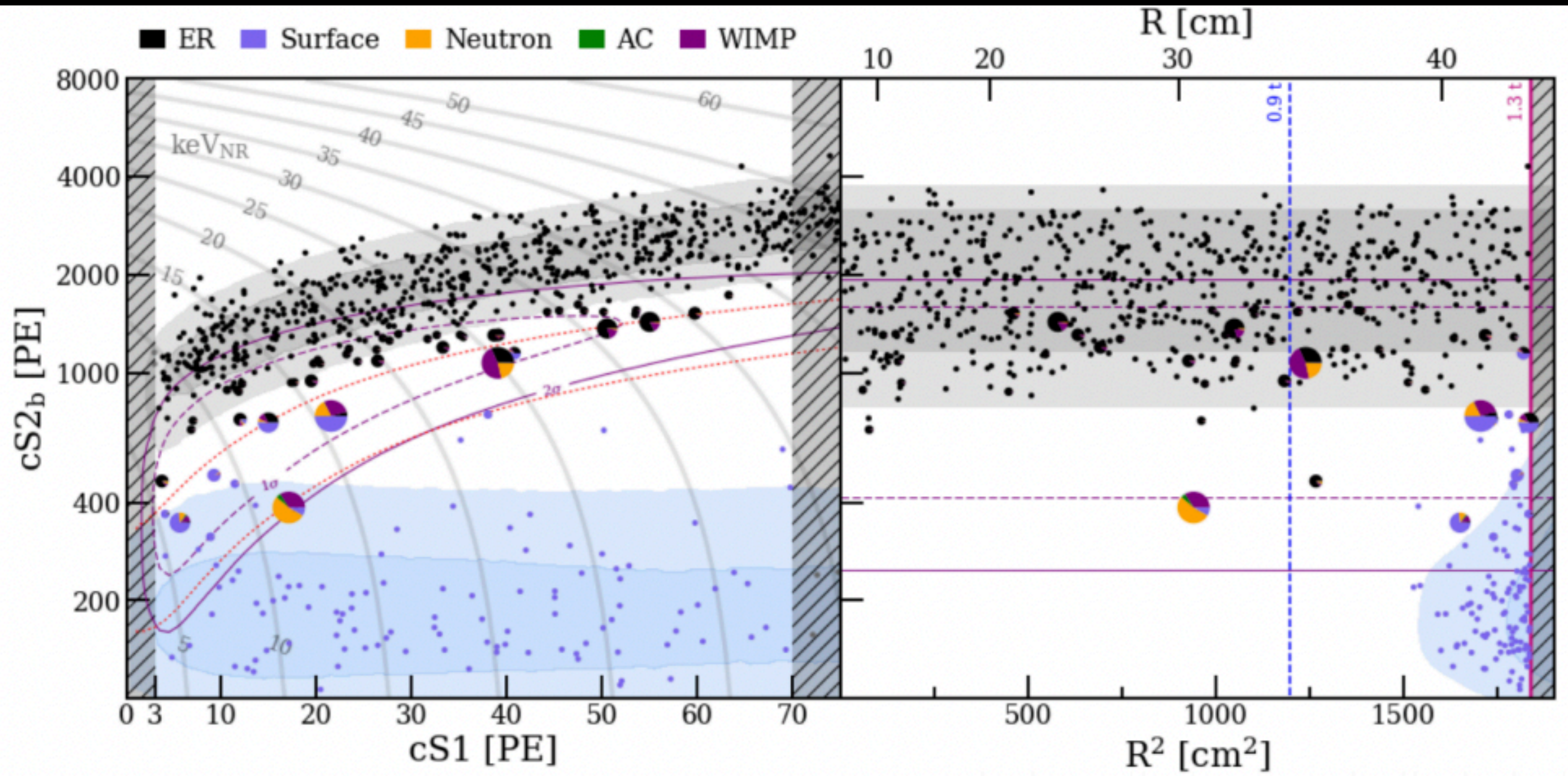
Source	Mitigation strategy
Radiogenic neutrons (from materials)	Material selection, reject multiple scatter, fiducializatio
CEνNS (mainly ^{8}B solar ν)	
Cosmogenic neutrons	Muon Veto, reject multiple scatter, fiducialization

Dedicated search for multiple scatter events found 9 candidates with (6.4±3.2) expected

Constrain the expected single-scatter neutron event rate

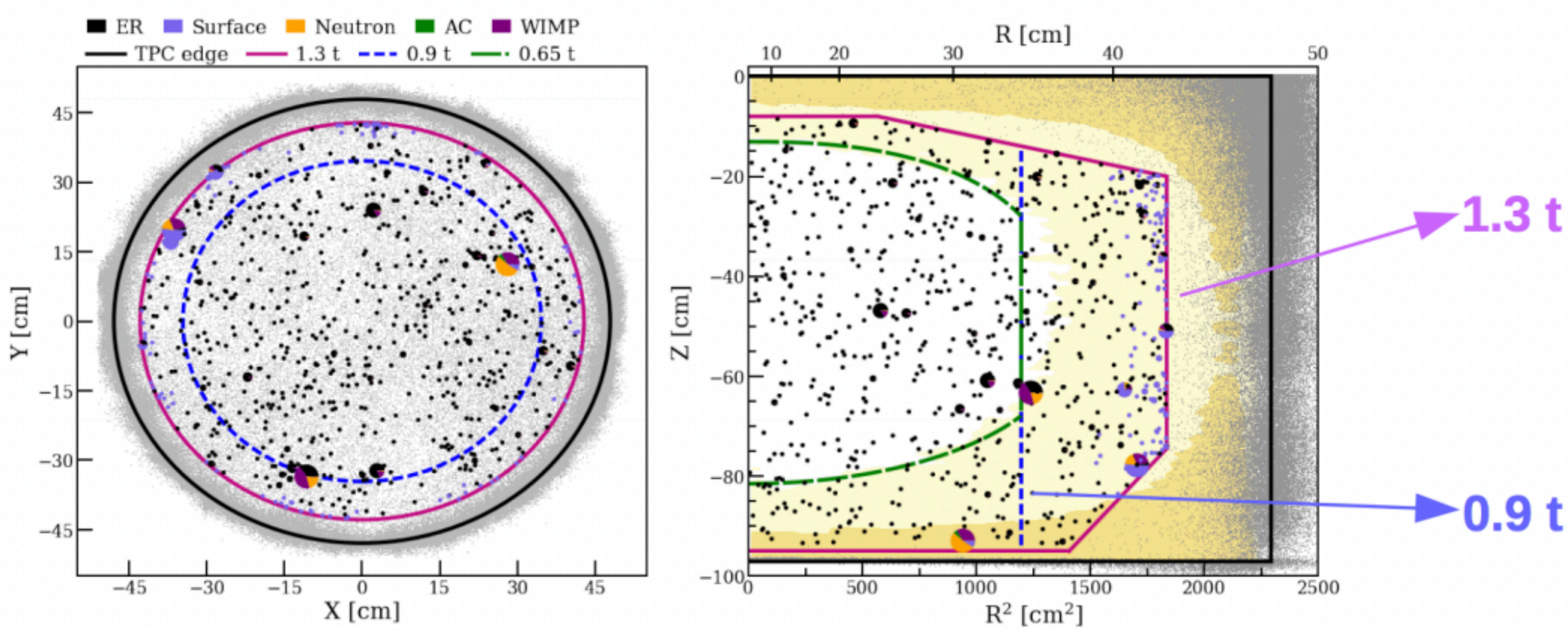


Complex result



Events that pass all cuts are shown

They are shown as pie charts representing the best-fit probabilities of the background and signal (200 GeV WIMP) components at each event

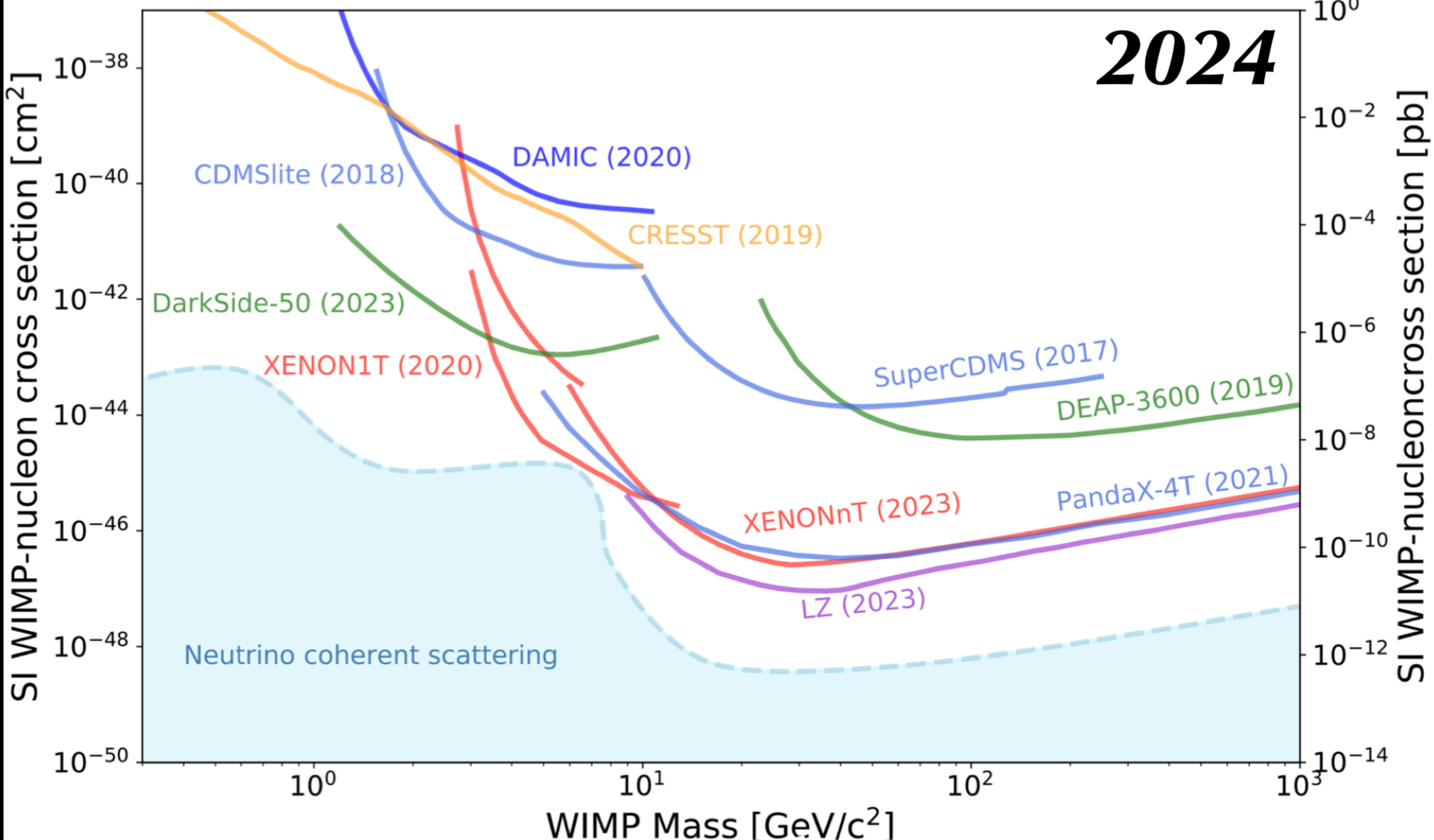


Performed unbinned profile likelihood, model uncertainties included as nuisance parameters

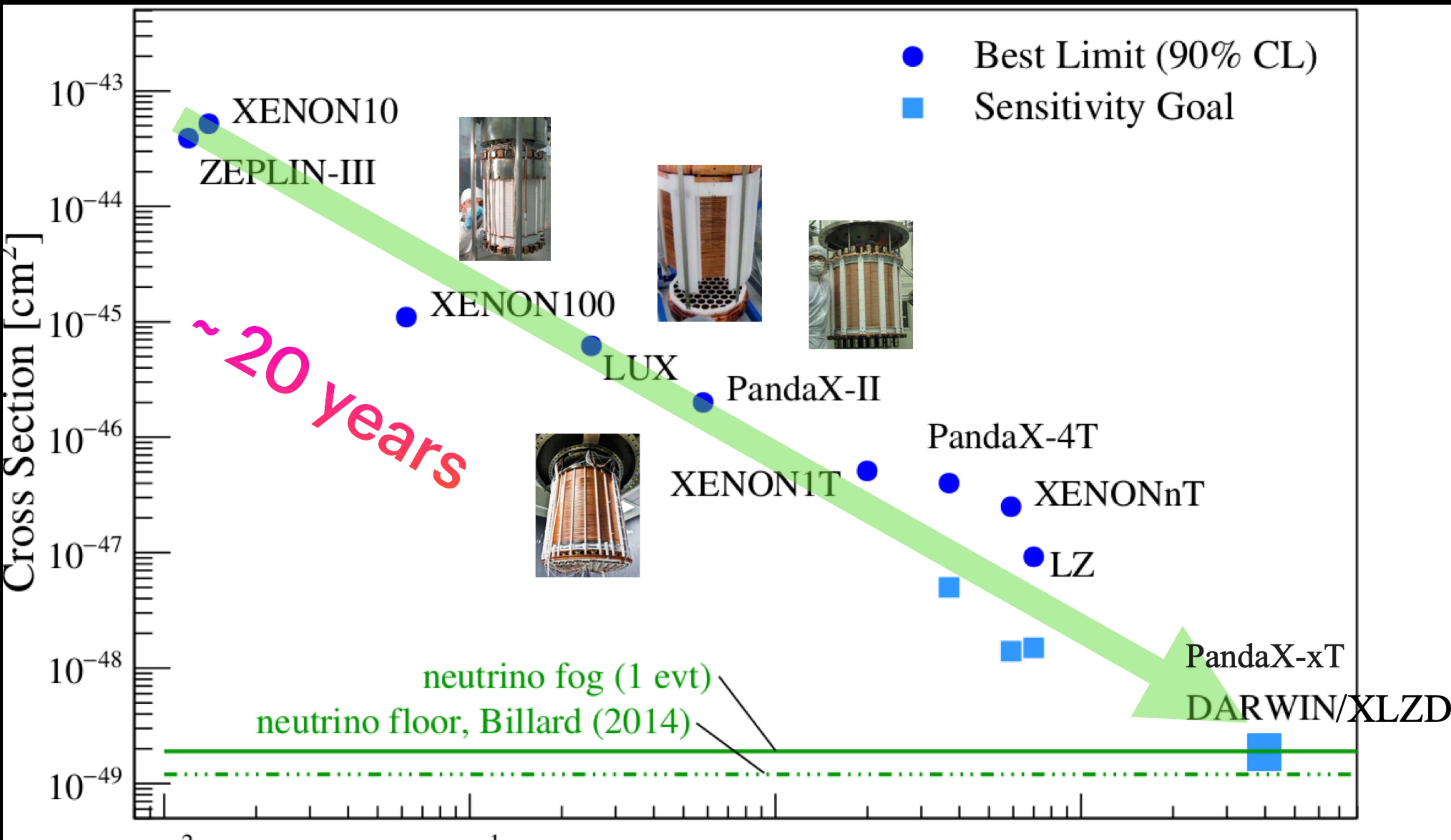
Maximum radius of 1.3 t fiducial volume set by surface event contribution.

Here we are

[Baudis & Profumo, PDG 2023]



And there we will go



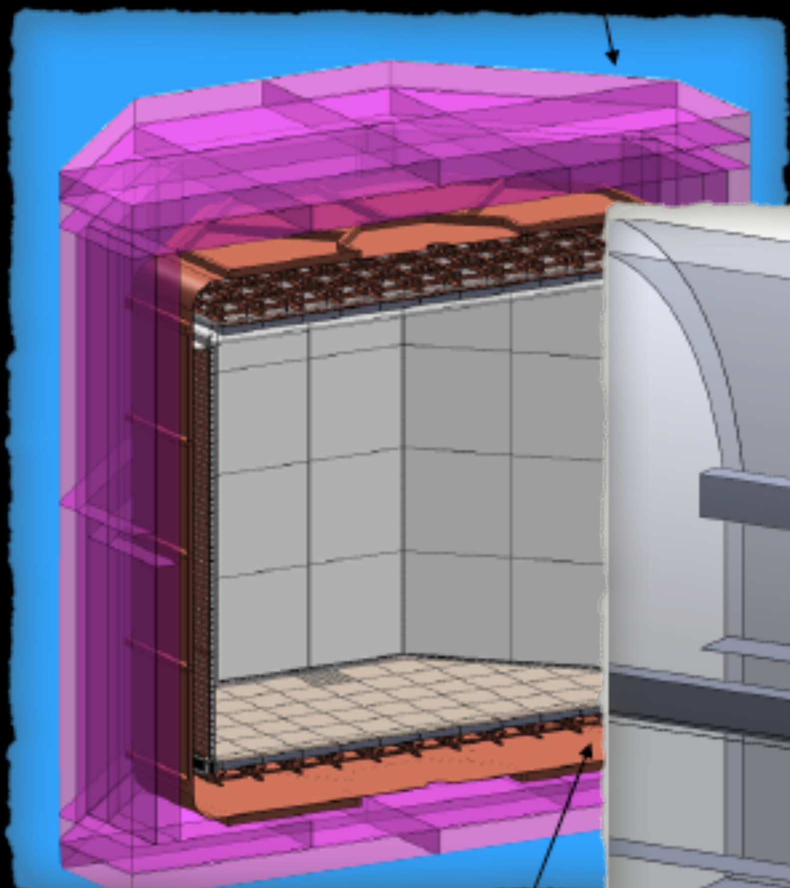
A word on comparison with modulation experiments

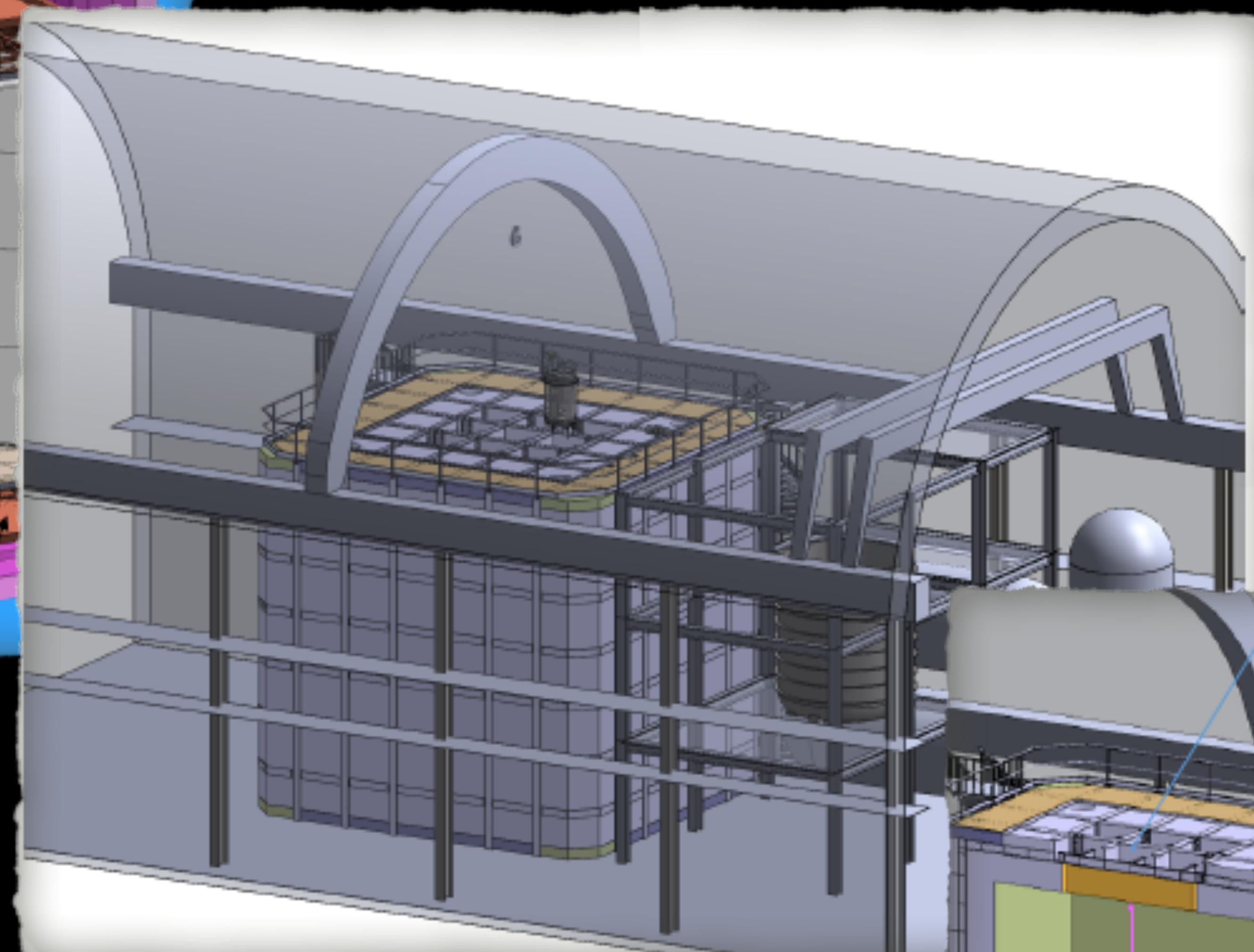
- DAMA/LIBRA works with a ~ 1keV threshold, so that ‘looks’ at a wide region of the scattering parameters phase space. A lot of events -> Modulation

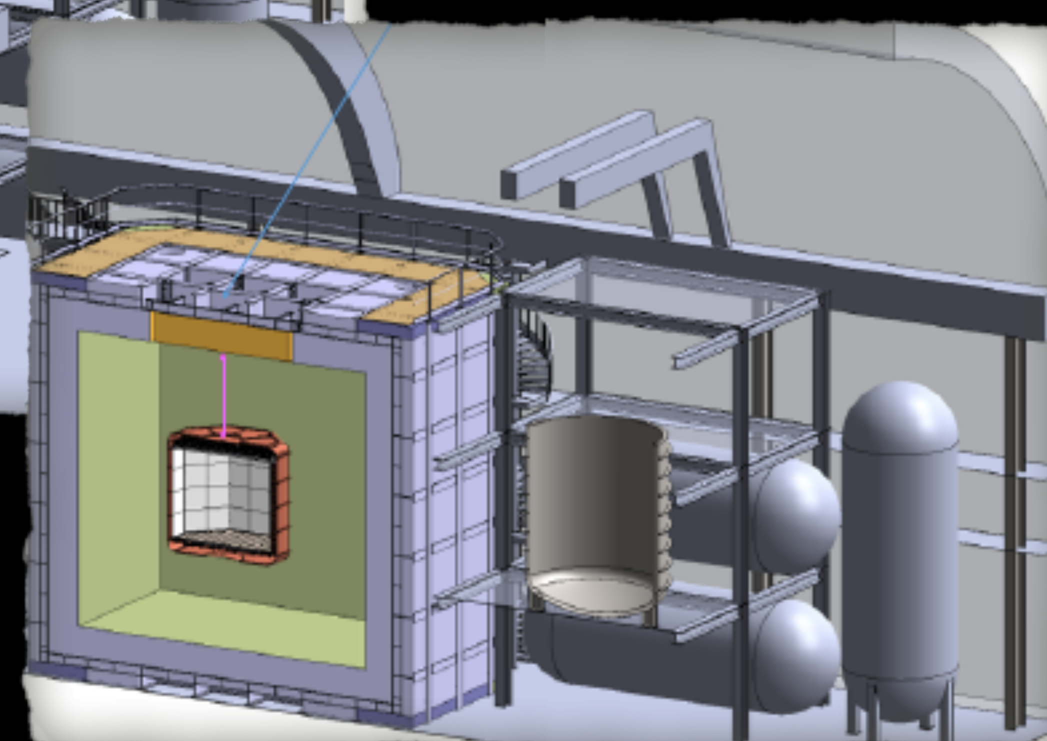
- Noble liquids have a threshold of dozens of KeV, on the exponentially falling recoil spectrum they are limited to observe a few events aiming at zero background

- Very different experiments

Future suggests Ar as liquid

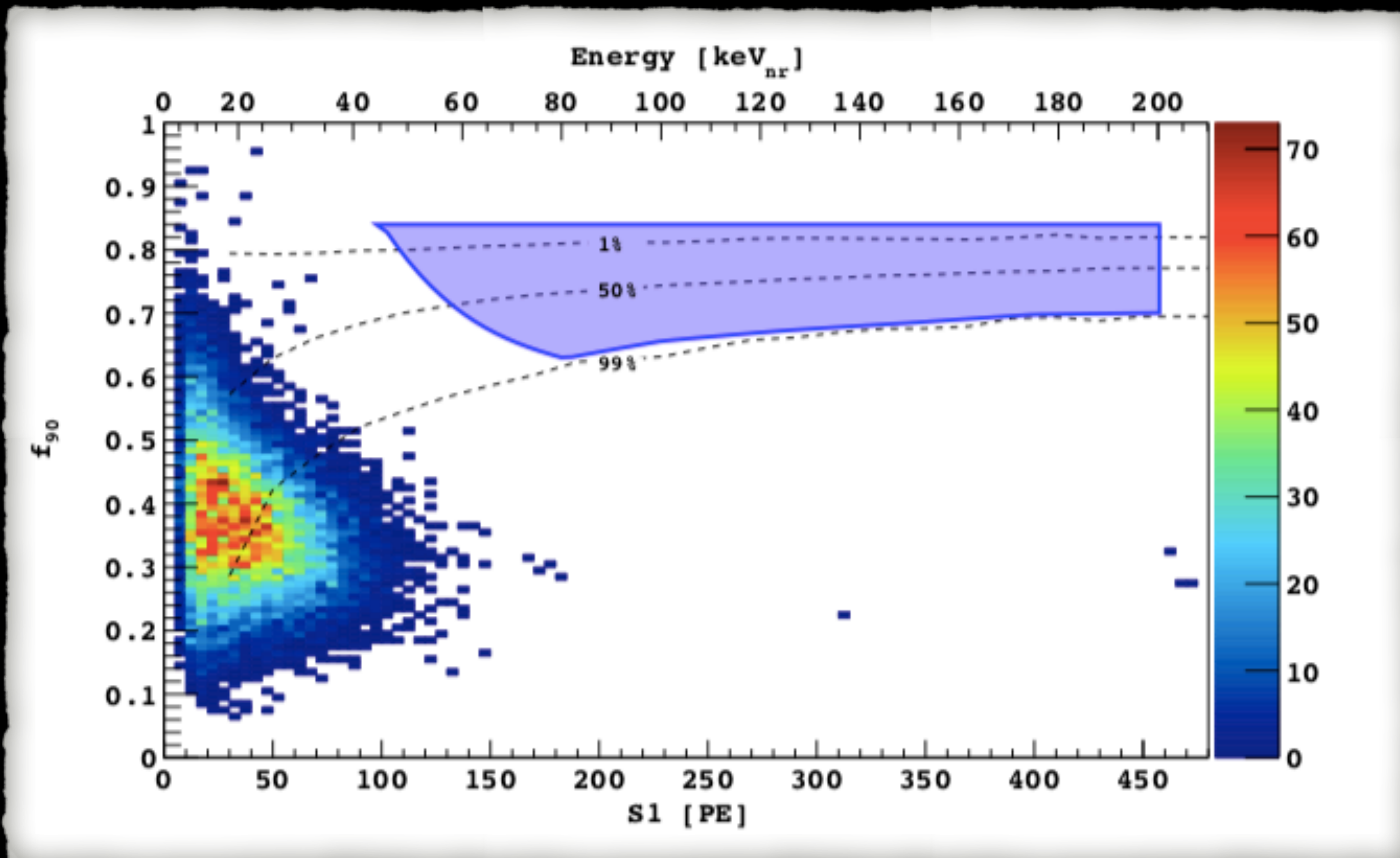






Dark Side@LNGS

Reason being :



S1/S2 works much better

But

iso	NA	half-life	DM	DE (MeV)	DP
^{36}Ar	0.337%	–	$(\beta^+\beta^+)$	0.4335	^{36}S
^{37}Ar	syn	35 d	ε	0.813	^{37}Cl
^{38}Ar	0.063%	^{38}Ar is stable with 20 neutrons			
^{39}Ar	trace	269 y	β^-	0.565	^{39}K
^{40}Ar	99.600%	^{40}Ar is stable with 22 neutrons			
^{41}Ar	syn	109.34 min	β^-	2.49	^{41}K
^{42}Ar	syn	32.9 y	β^-	0.600	^{42}K

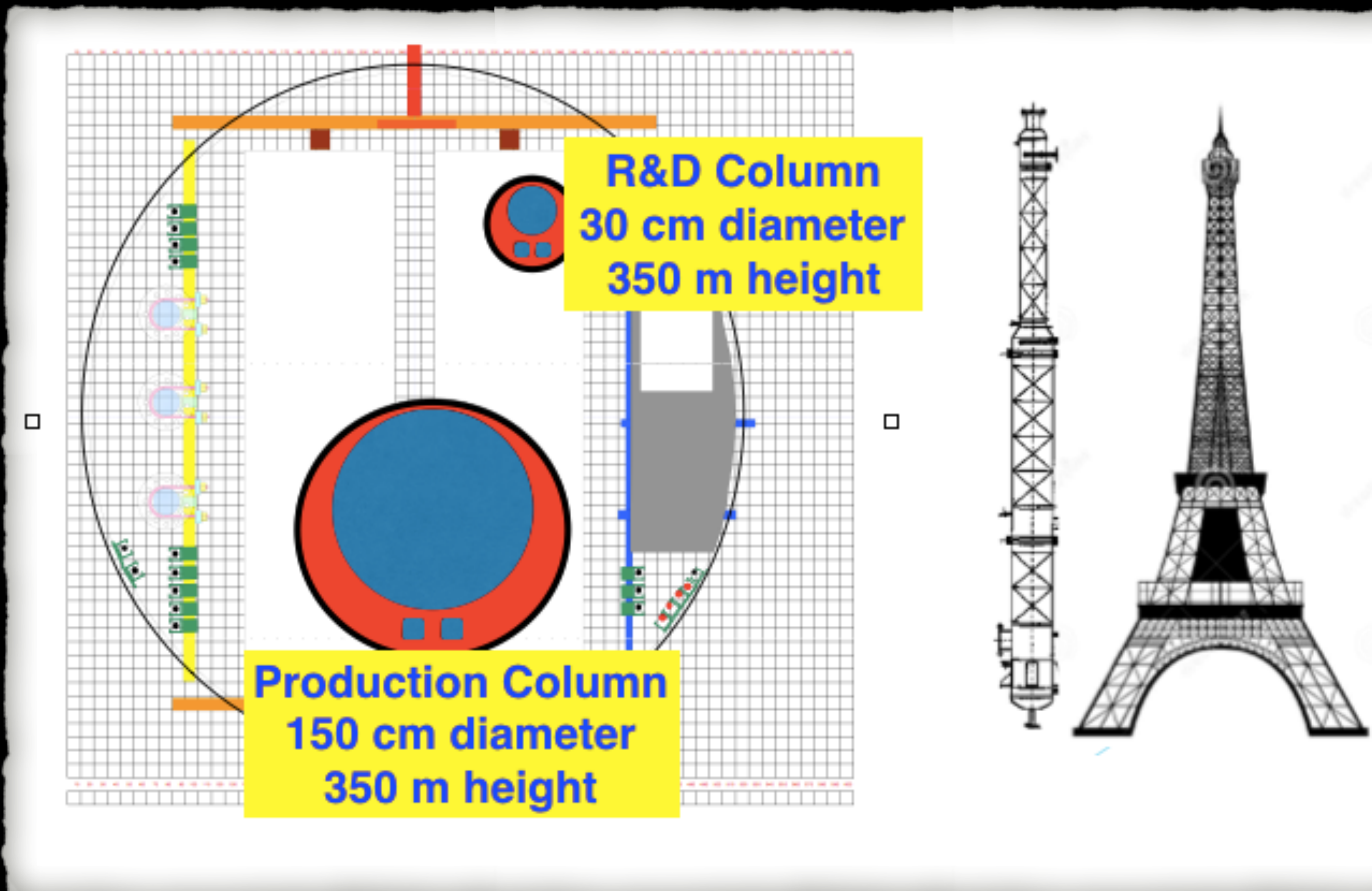
Ar is widely available at low cost

If you extract it From Air !

^{39}Ar is made in the atmosphere

Extract from deep in a mine In Colorado and

go by cryogenic distillation



It relies on different vapour tensions for the different isotopes of the same element

Thousands of equilibrium states are needed

Aria@Sulcis

The shaft of a coal mine that
is being shut down and
needs a reconversion
of its activity.

In Sardinia.

A bit of BIOLOGY

Low background radiation

- Test the "Linear No Threshold" model
    - No point in doubling the dose
    - Need to lower the dose

      Is the damage to cells (DNA) $\propto$ dose

        - at low dose

      or are low doses of radiation

      more damaging ….. or ….

      less damaging

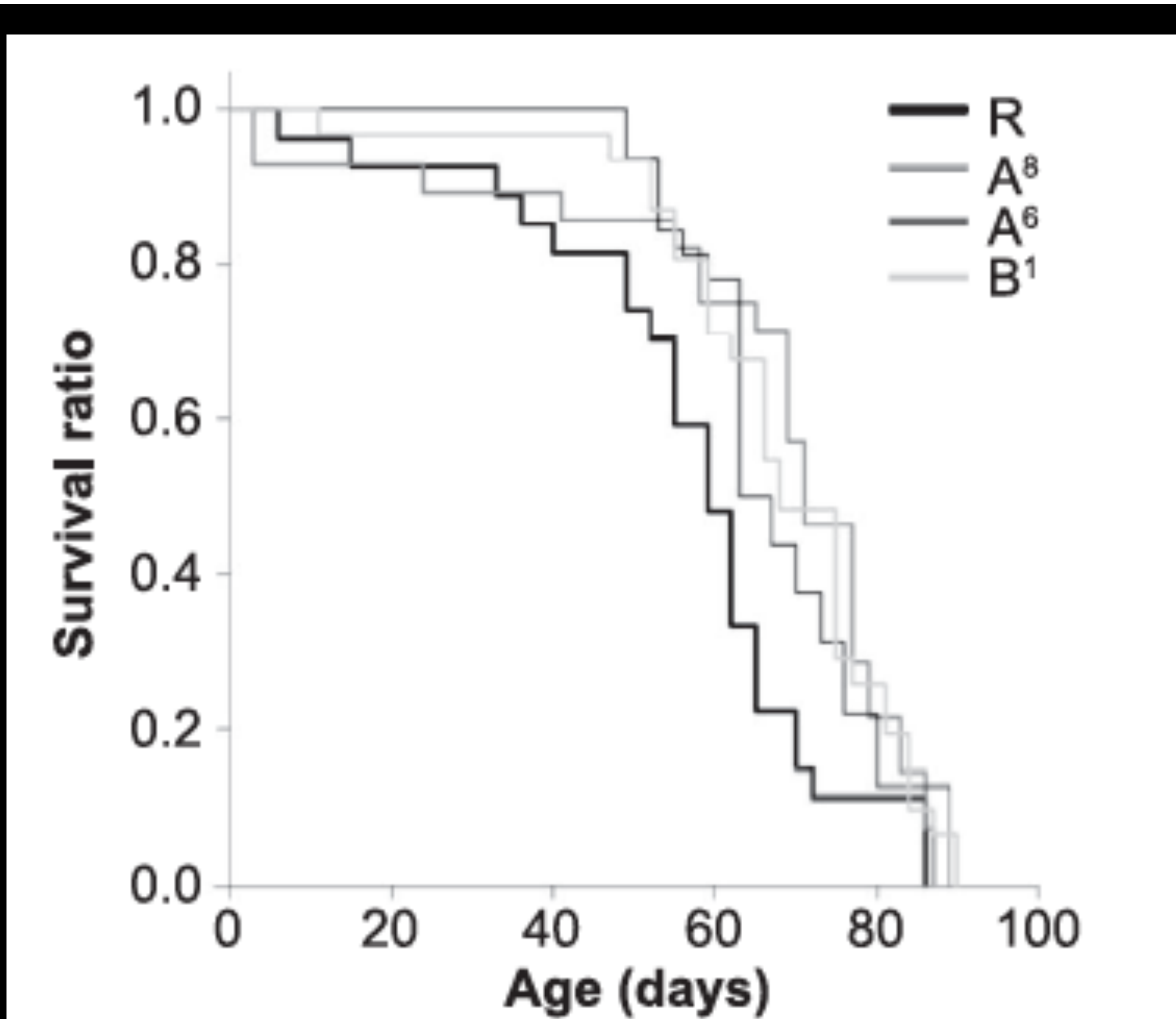
      than expected from the LNT model
    - *in vitro* studies done

      with tantalising results
    - *in vivo* (drosophilae)

The Cosmic Silence experiment: on the putative adaptive role of environmental ionizing radiation

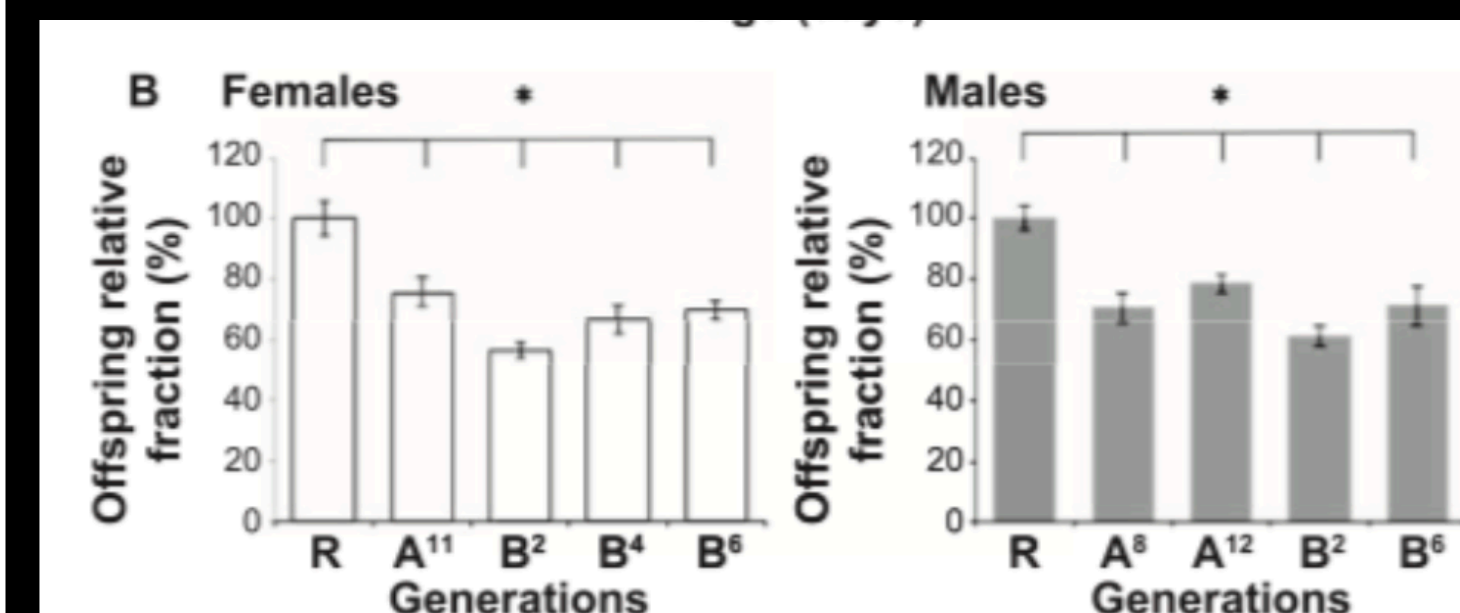
BioOne® RESEARCH EVOLVED

Fruit Flies Provide New Insights in Low-Radiation Background Biology at the INFN Underground Gran Sasso National Laboratory (LNGS)



live longer

procreate less



Summary

- Great physics at Underground Laboratories
- We have only touched a bit of it , with some emphasis on DM
- We have not talked of Supernova neutrinos, proton decay…. Studies of processes key in the Star formation in the Gamow window …need an accelerator underground (and there are two at LNGS)
- Other sciences, in particular biology
- A lot of fun