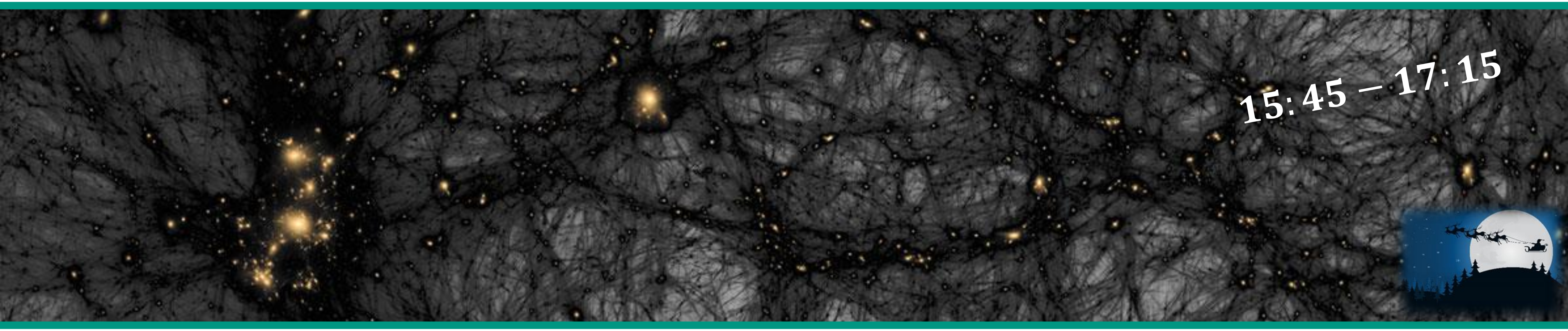
Astroparticle physics I – Dark Matter

Winter term 23/24 Lecture 10 Dec. 6, 2023



Recap of Lecture 9

- CTA & **rare event searches: on the look–out for $0\nu\beta\beta$ and $WIMPs$**

  - CTA: upcoming observatories (La Palma, Chile) for new $TeV-\gamma-$ sources

  - detector background: intrinsic & cosmic–induced

  - $DM-$ signals: experimental sensitivity down to $\sigma_{tot} \sim 10^{-48}\ cm^2$ $(yocto-barn)$

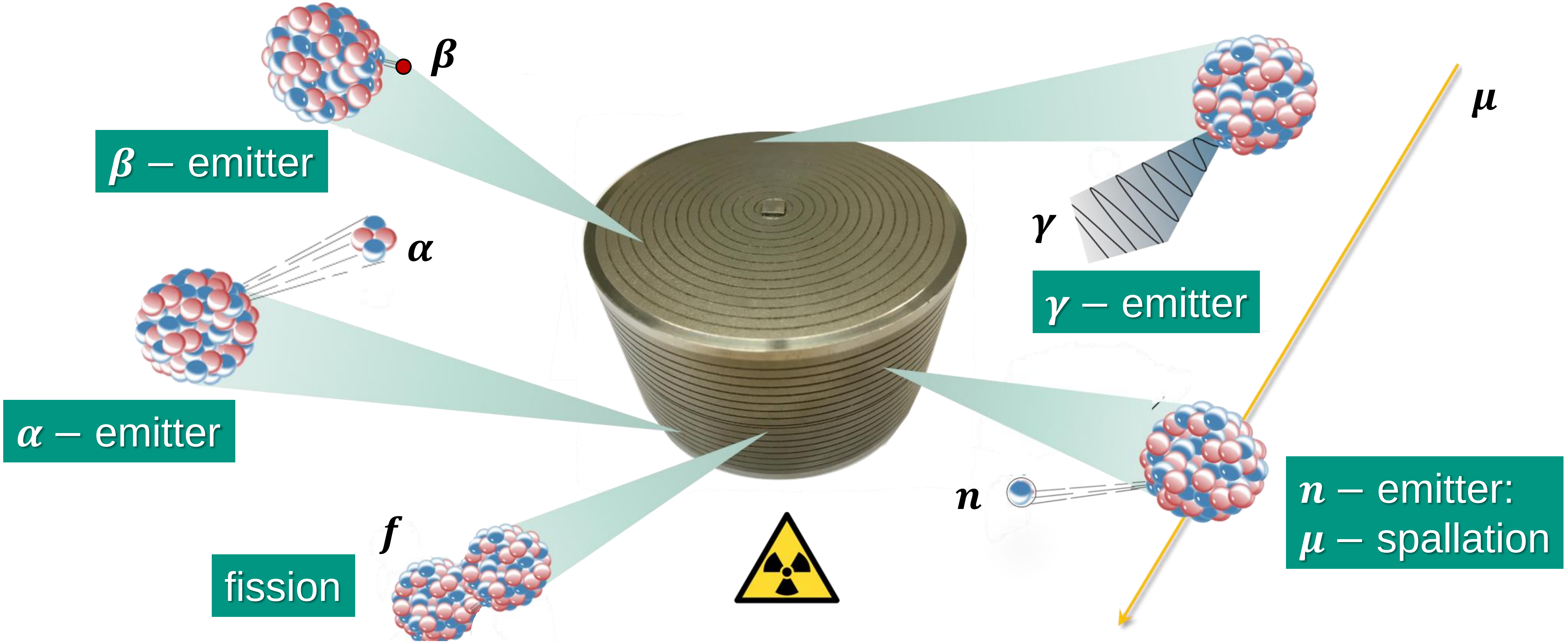
  - **activity A**: in $Bq\ (Ci)$, decreases exponentially (τ)

  - important natural isotopes: $^{14}C,\ ^{40}K$

  - calibration sources: an important tool for precision modelling of detectors

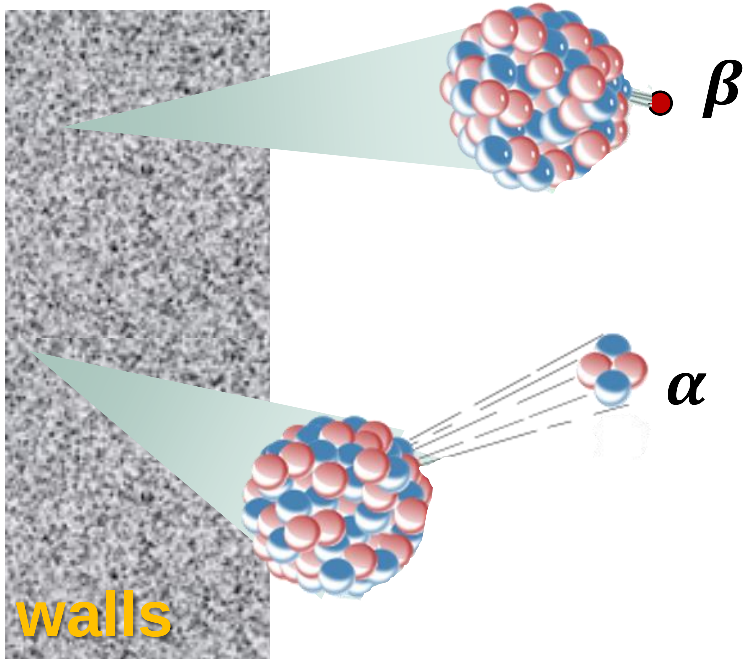
Decay processes – intrinsic detector activity

- **Intrinsic activity of detector: rigorous screening** & **material selection**



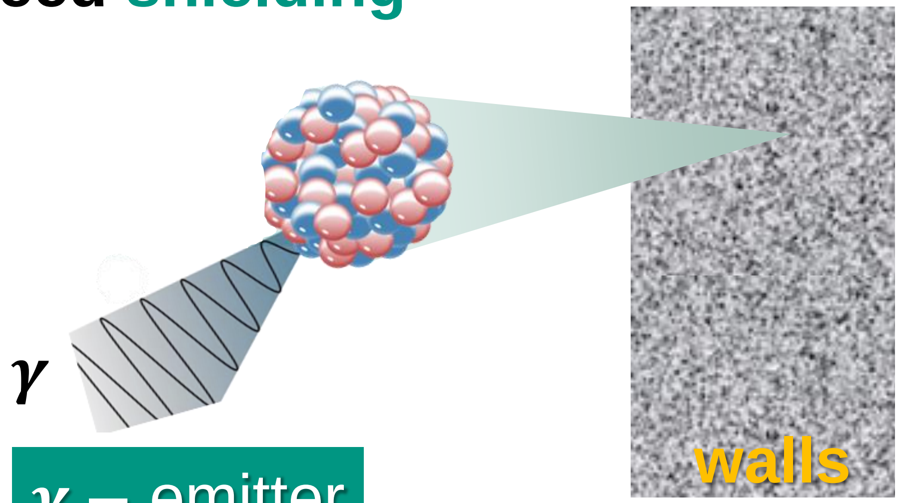
Decay processes – external activity in walls…

- **Intrinsic activity of surrounding materials: we need shielding**



surrounding
our detector:
$\alpha-, \beta-, \gamma-,$ … decays

range is important

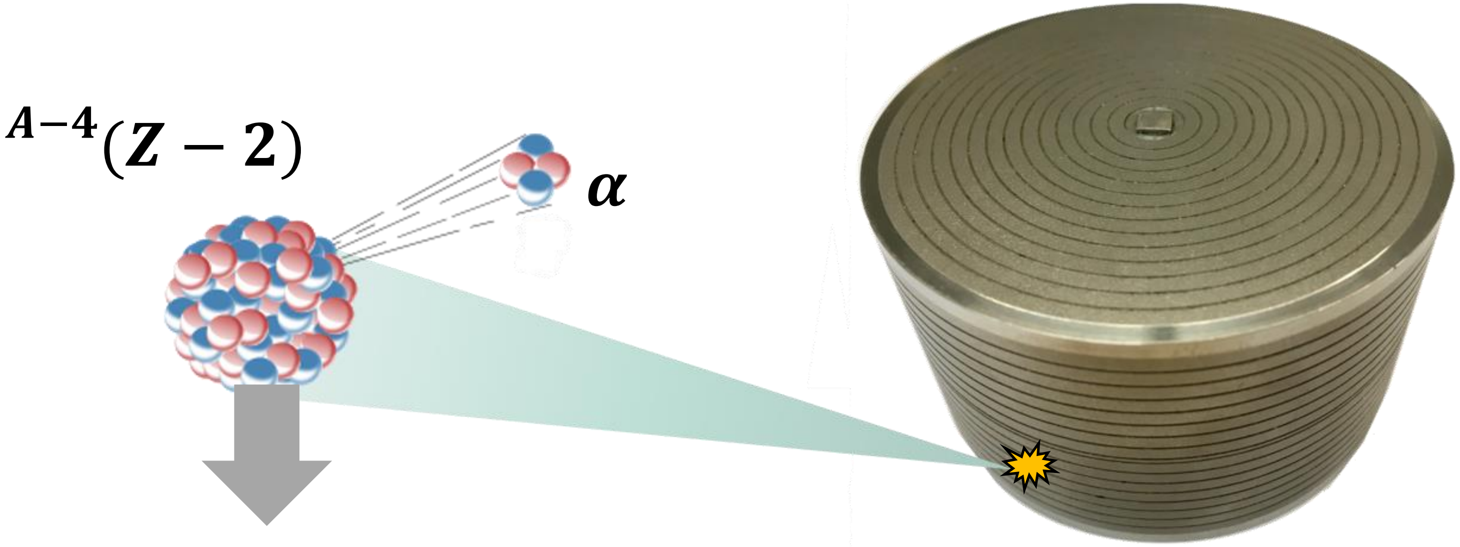


γ – emitter

RECAP: Decay processes – the α – decay

- Single α – decays often are part of a much larger (primordial) decay chain

- two monoenergetic particles: $\boldsymbol{\alpha}$ – particle ($\boldsymbol{E_{kin}} \sim \boldsymbol{MeV}$) & recoil ion ($\boldsymbol{E_{kin}} \sim \boldsymbol{keV}$)



- **$\boldsymbol{\alpha}$ – particle**:

  a) ***external*** decay in material surrounding detector:
  ⇨ $\boldsymbol{\alpha}$ is stopped close to surface

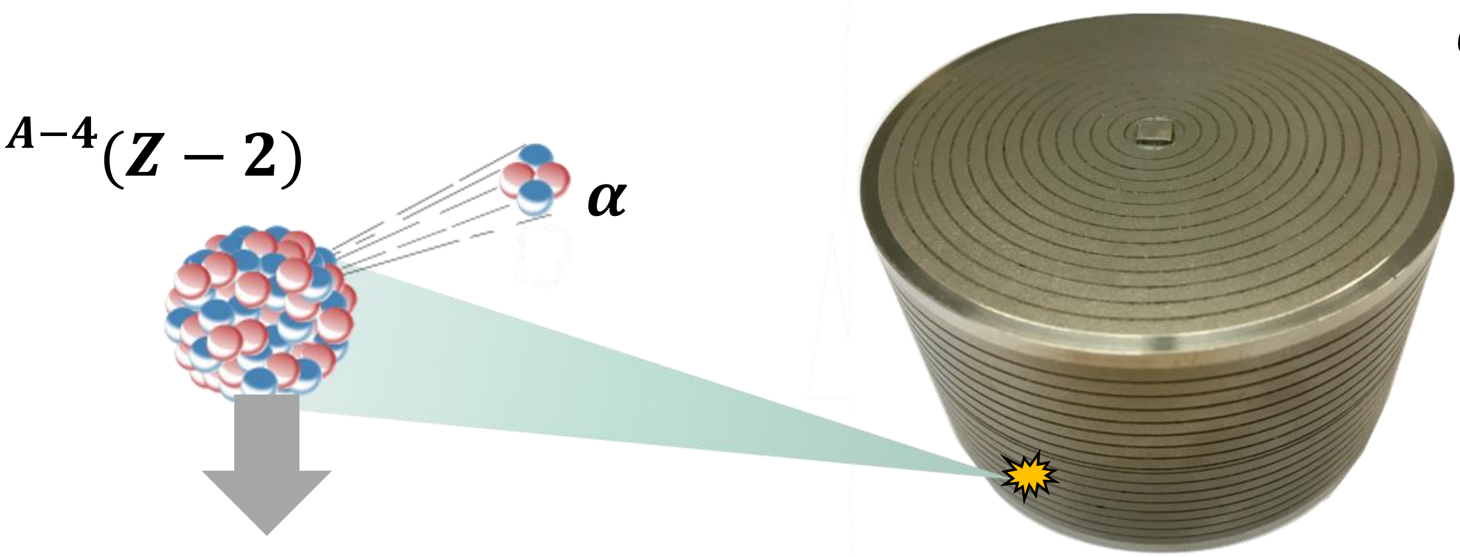
  b) ***internal*** decay in detector:
  ⇨ $\boldsymbol{\alpha}$ is stopped close decay
  ⇨ sucessive decays there

- **recoil ion**: extremely short ($\boldsymbol{\mu m}$) range due to strong ionization of detector material (remember Bethe formula for slow velocities: large $\boldsymbol{dE/dx}$ value)

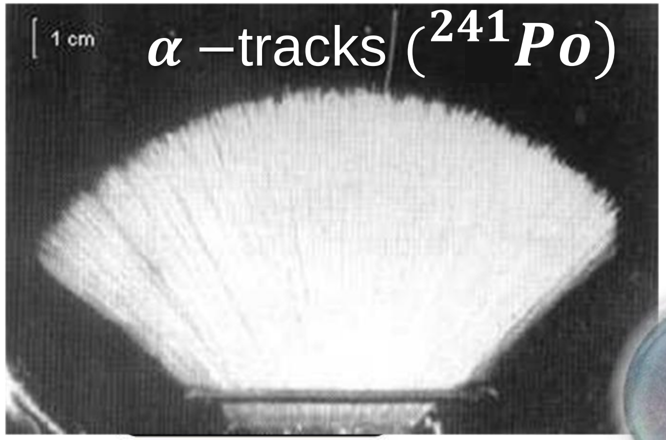
RECAP: Decay processes – the α – decay

- **Single α – decays often are part of a much larger (primordial) decay chain**

- huge variation in **half–lifes $t_{1/2}$** of α – decaying isoptopes (**Geiger–Nuttall law***)



α – particles are monoenergetic



Po – source

- slowest α –decay: $^{232}Th \rightarrow {}^{228}Ra + \alpha \quad t_{1/2} = 1.4 \cdot 10^{10}\ yr \Leftrightarrow E_\alpha = 3.9\ MeV$
- fastest α –decay: $^{212}Po \rightarrow {}^{208}Pb + \alpha \quad t_{1/2} = 3.5 \cdot 10^{-7}\ s \Leftrightarrow E_\alpha = 8.95\ MeV$

*see Mod. Ex. Phys III

Background processes: reduction & mitigation

- **How do I keep my detector (almost) free of intrinsic background ?**

  - very stringent selection of all **detector materials:** screening of each $\boldsymbol{PMT}$, each signal cable, everything ...

  - **clean room conditions** during assembly

  - active elements (electronics, $\boldsymbol{DAQ}$, cooling) have to be separated from detection volume

  - in case of **fluids**: **also active purification steps**

Background processes: reduction & mitigation

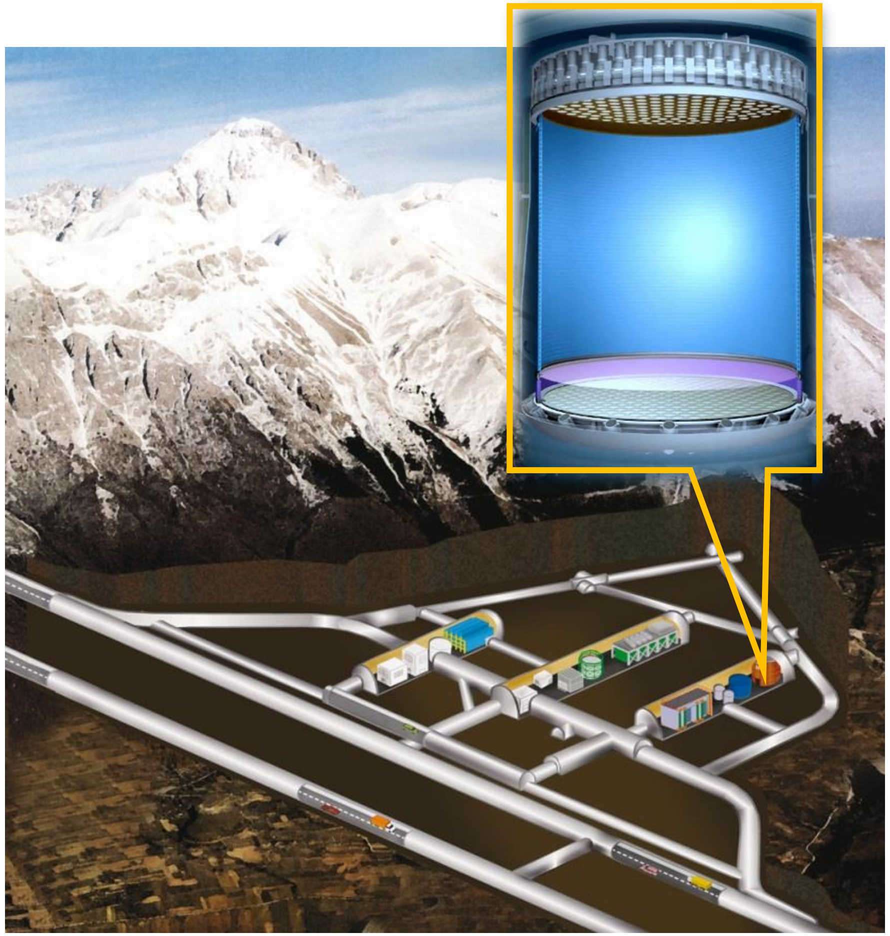
- **How do I keep my detector (almost) free of background processes?**

  - use of a very **deep underground laboratory**:
    strong reduction of μ – induced reactions

  - **active veto** against remaining muons
    $+$ passive shield near the detector ($\mu - veto$)

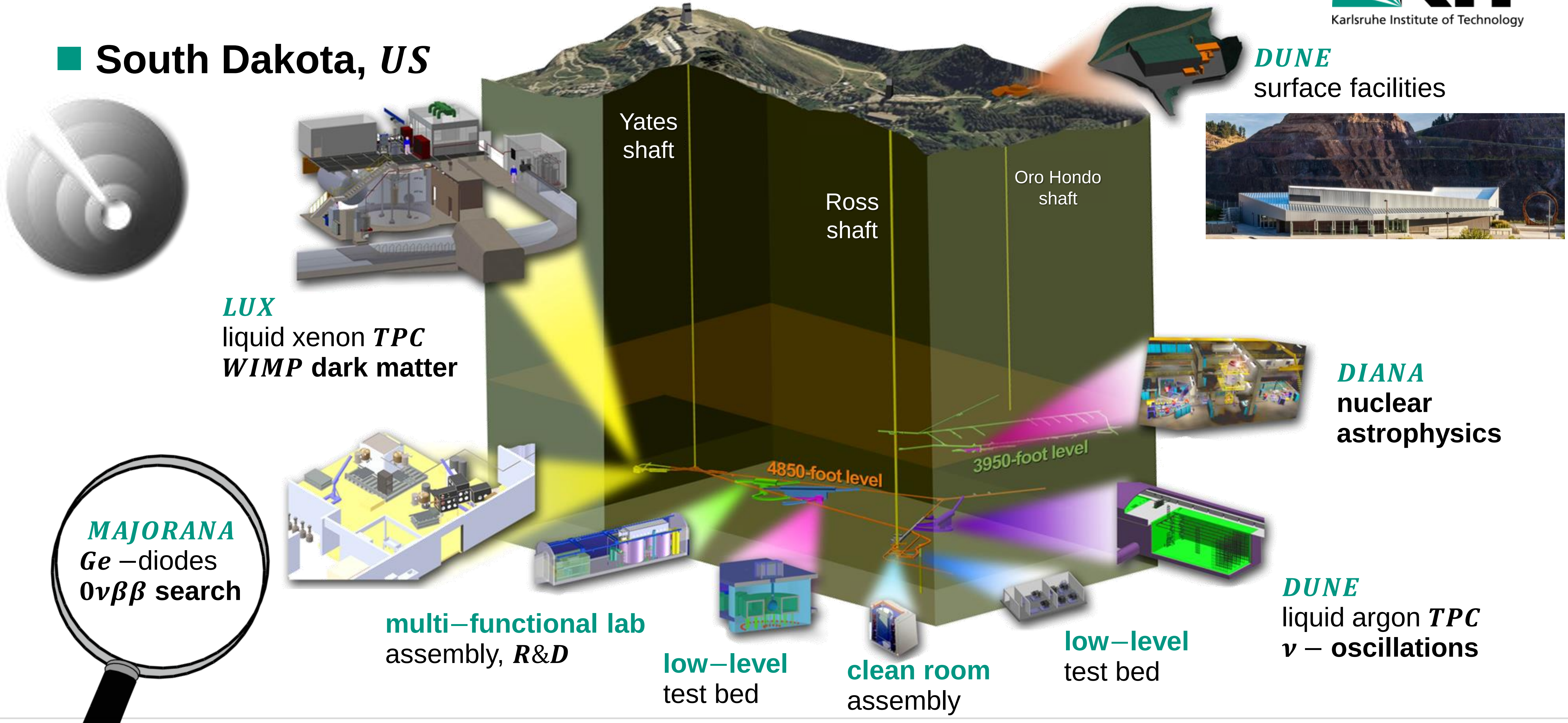
  - detailed MC **simulation** of background reactions
    (typically [Geant4 (cern.ch)](https://geant4.web.cern.ch)):
    ⇨ **optimized shielding concept**
    consisting of passive/active layers

  - data analysis cuts: fiducial volume, cuts, ...



Underground Laboratories – example Sanford Lab

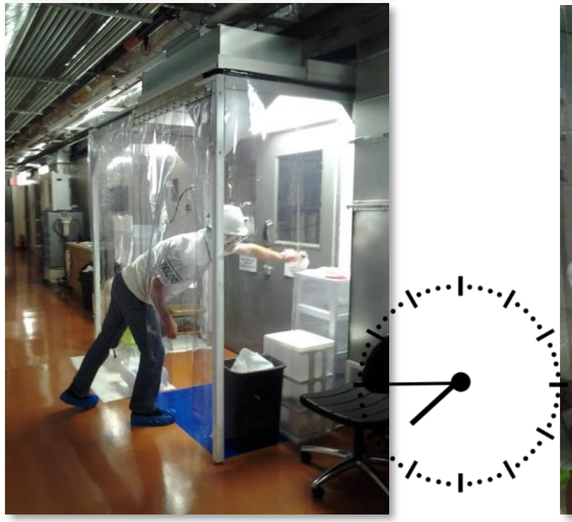
- **South Dakota, *US***



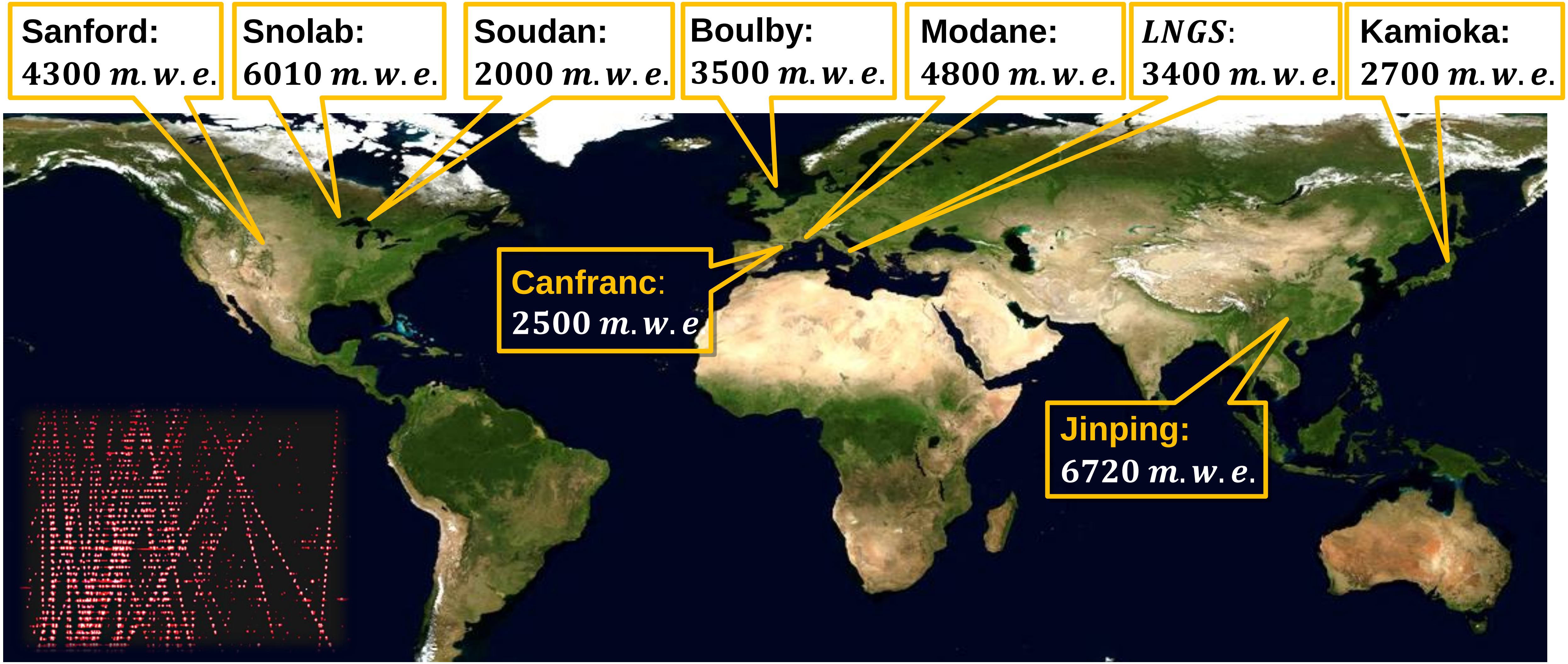
Underground Lab – daily routine of a researcher

- **Life as postdoc**

MAJORANA
$\boldsymbol{Ge}$ – diodes for $\mathbf{0\nu\beta\beta}$ **search**



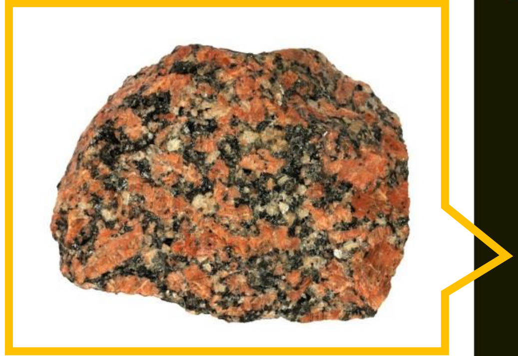
Underground laboratories – global overview



Underground laboratories – overburden & μ´s

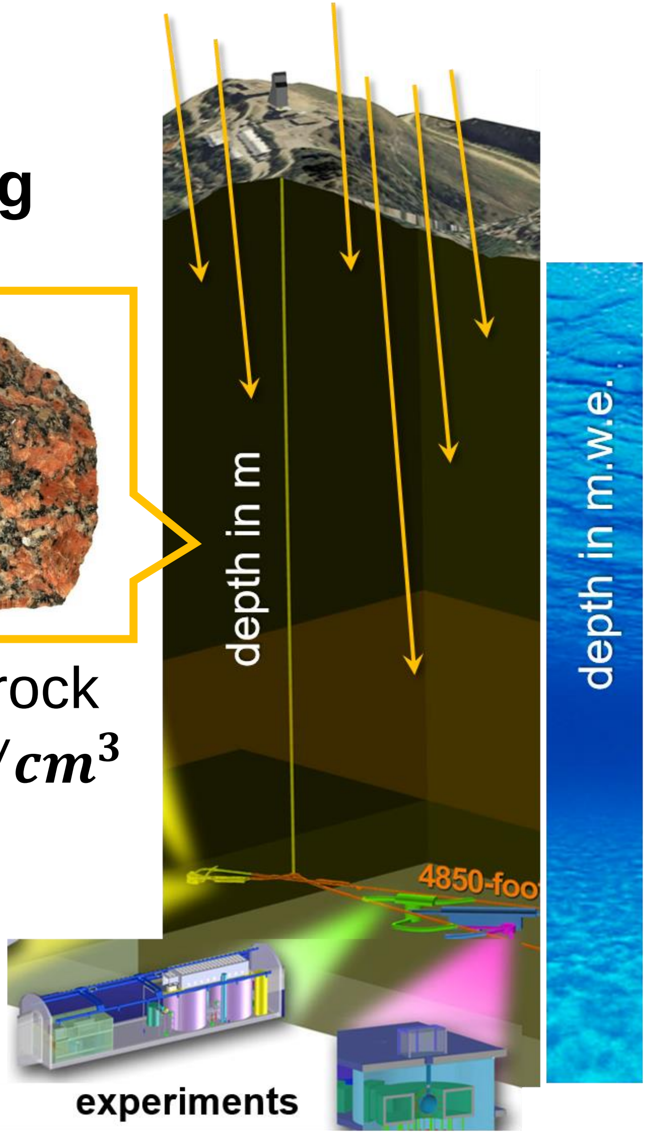
- **Overburden of under–ground labs & resulting muon rate**

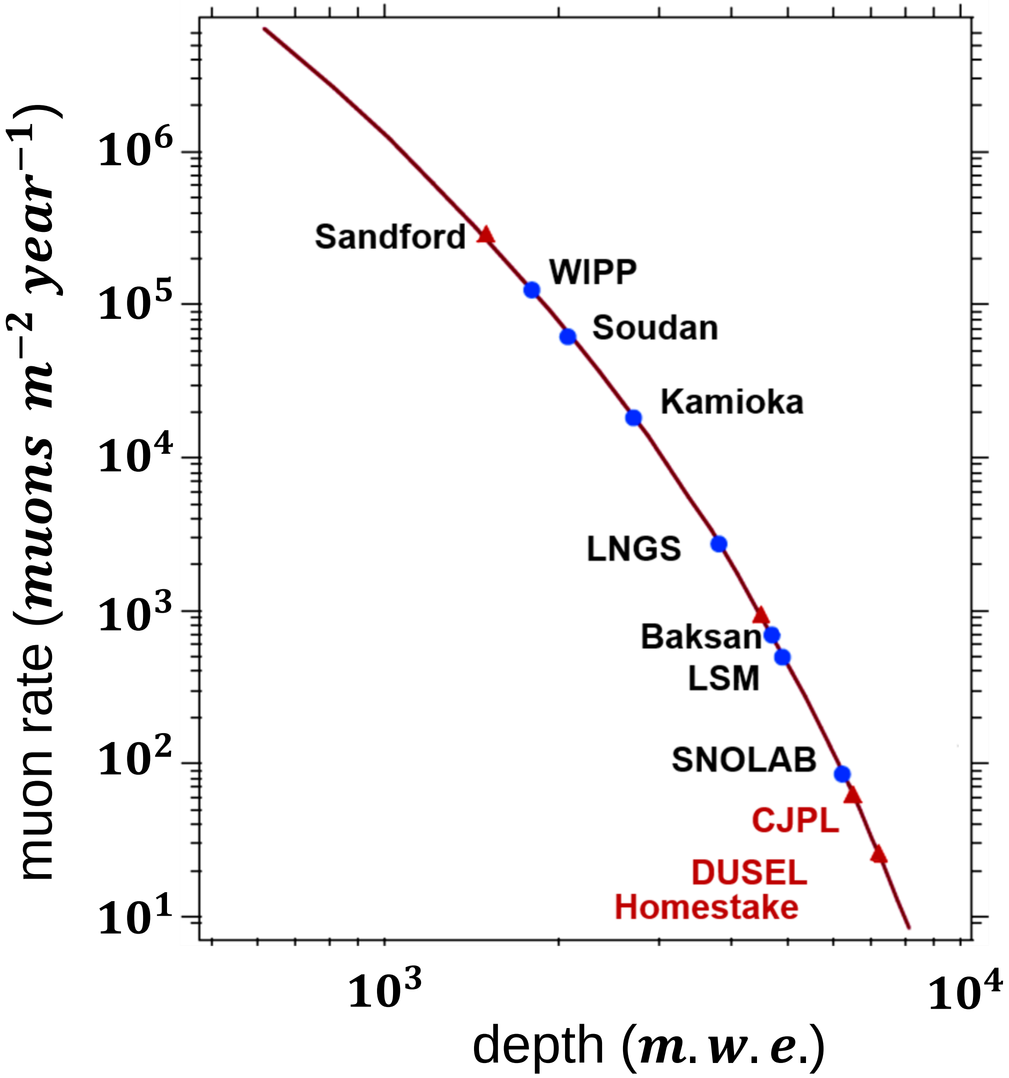
- unit $m.w.e.$ ($m$eter $w$ater $e$quivalent)



´standard´ rock
$\rho = 2.65\ g/cm^3$

a standard measure for the actual rock overburden



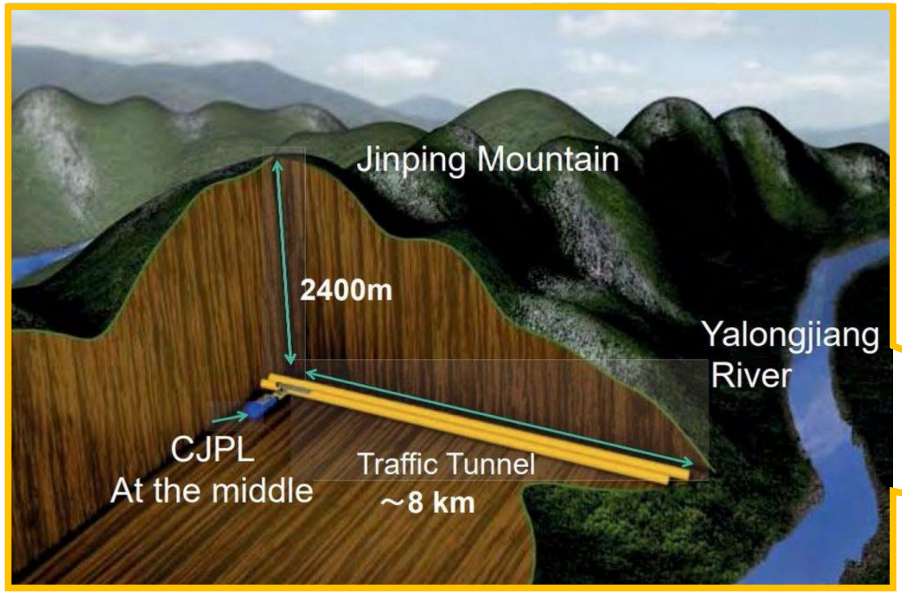


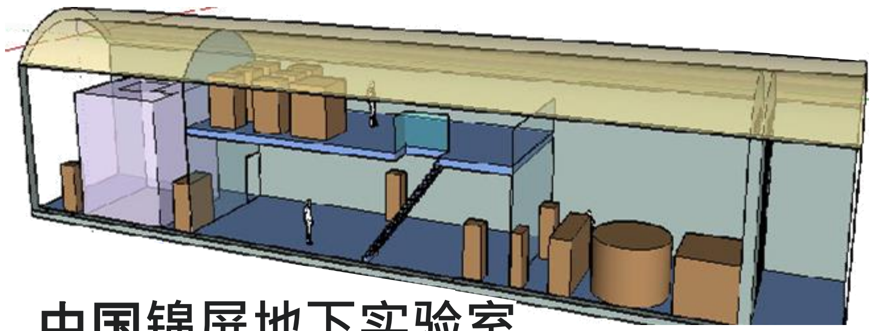
Underground laboratories – overburden & μ´s

■ $CJPL$ – China Jinping Underground Laboratory

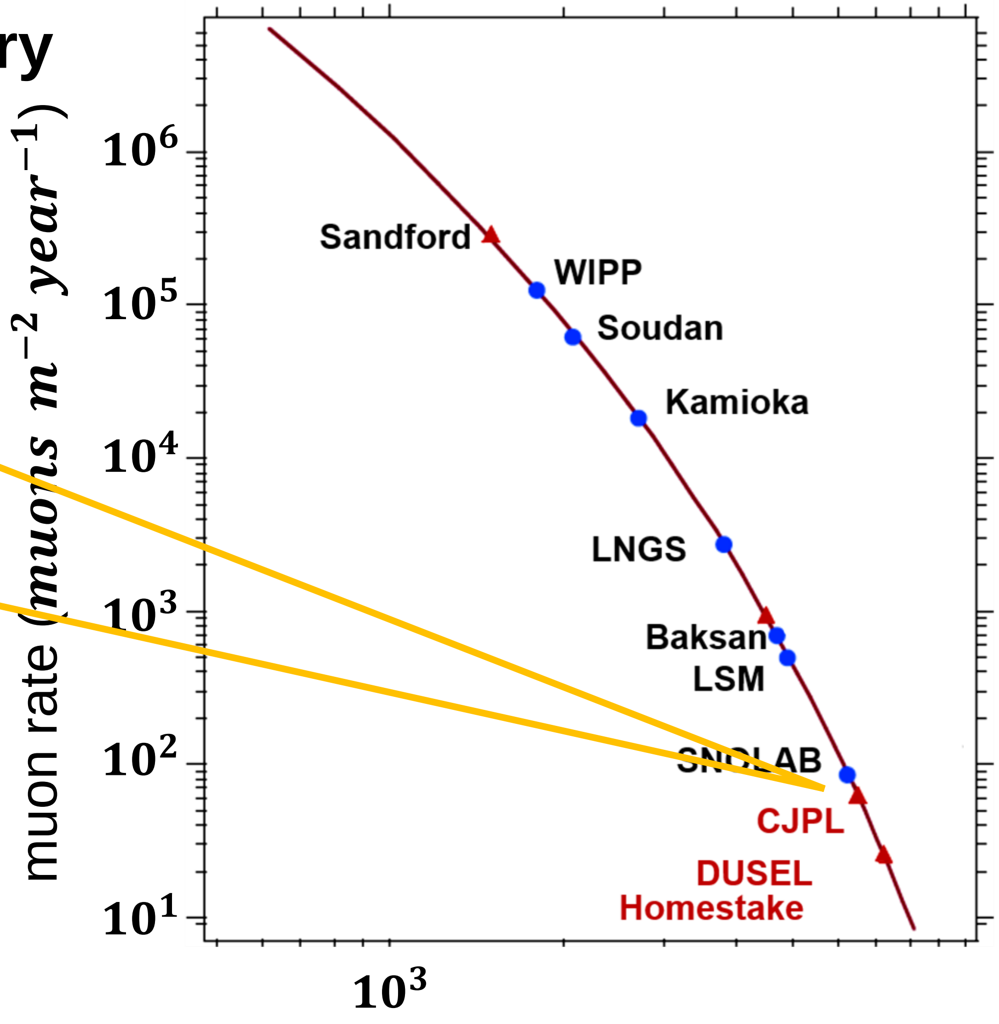
- deepest active underground lab in the world: $6720\ m.w.e.$

- extension to $CJPL-II$ (now the largest under–ground lab worldwide with $300.000\ m^3$)





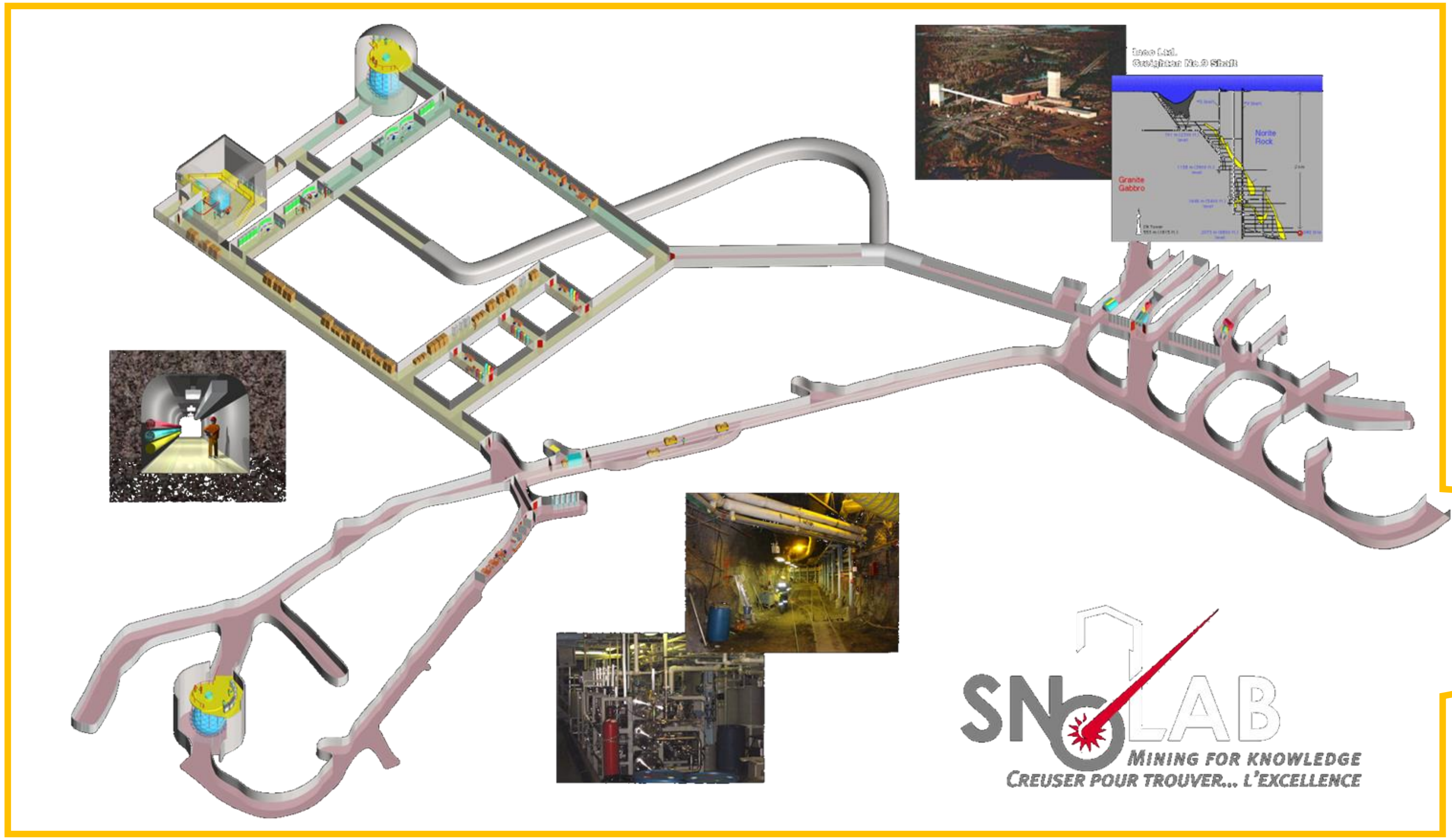
中国锦屏地下实验室

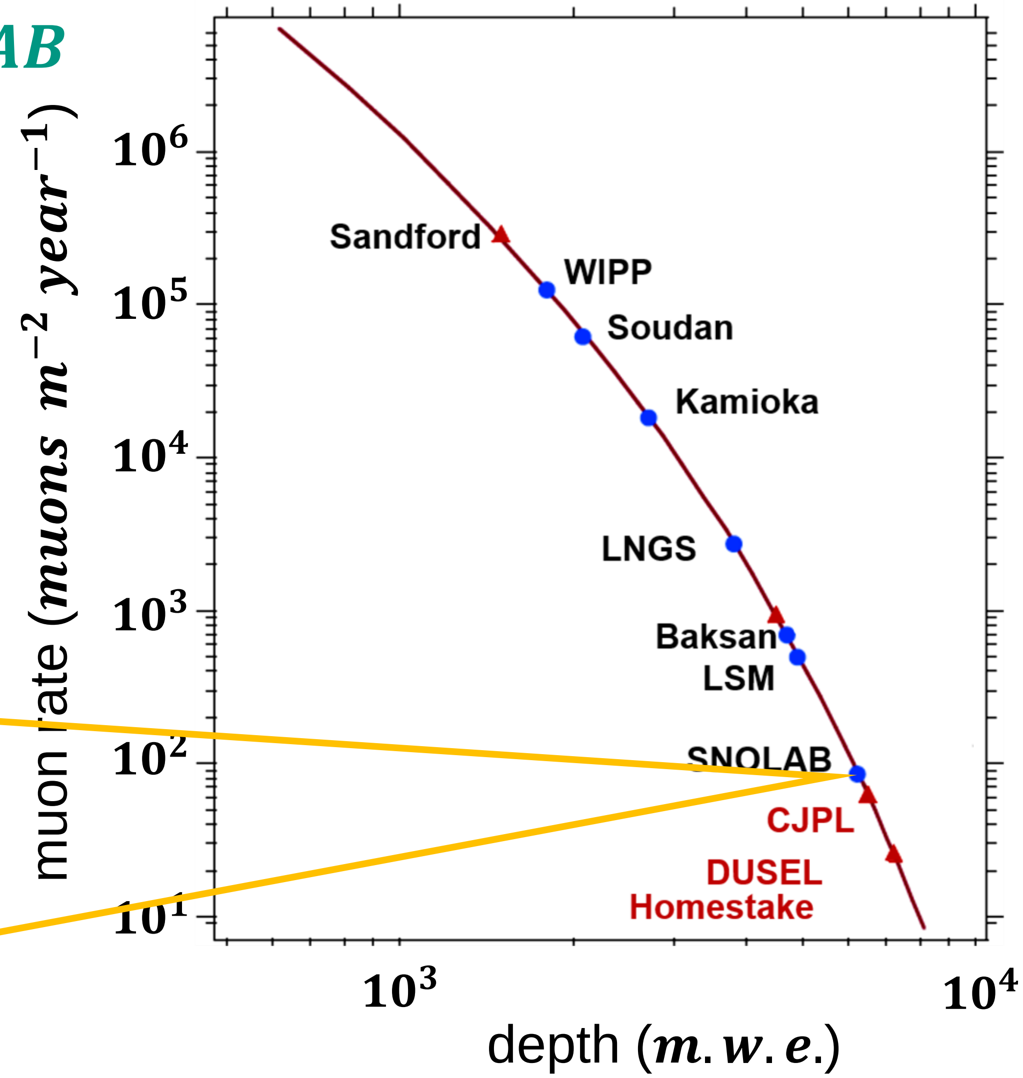


Underground laboratories – overburden & μ´s

- **SNOLAB – Sudbury Neutrino Observatory LAB**

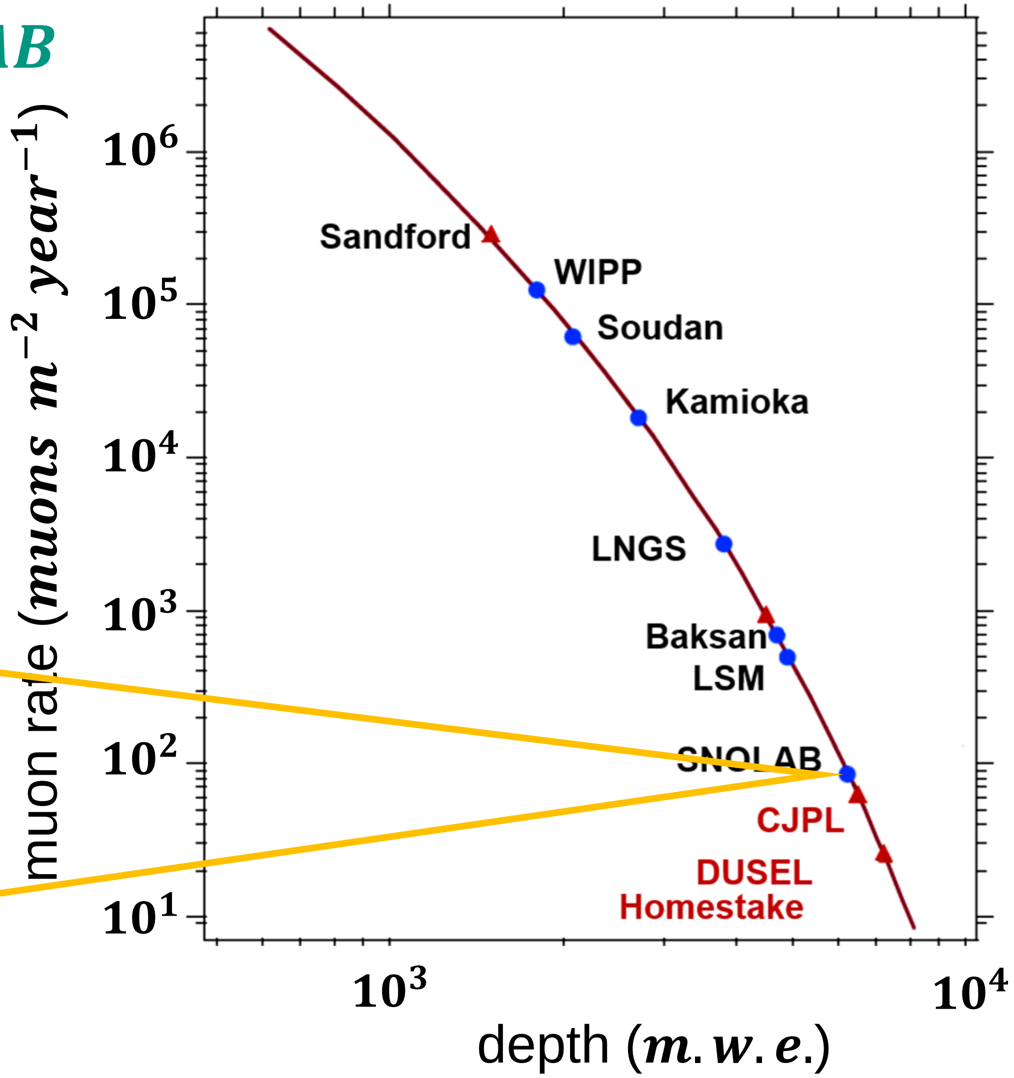
- underground lab in Ontario (CN): $6010\ m.w.e.$





Underground laboratories – overburden & μ´s

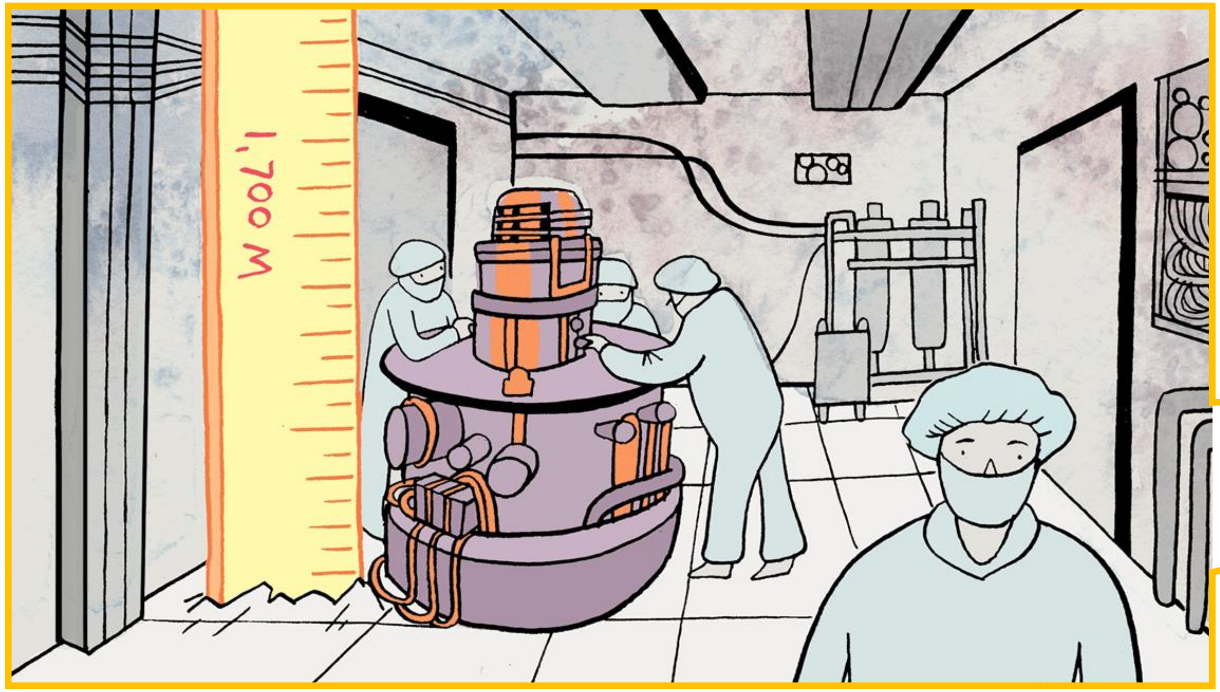
- ***SNOLAB*** – ***S***udbury ***N***eutrino ***O***bservatory ***LAB***



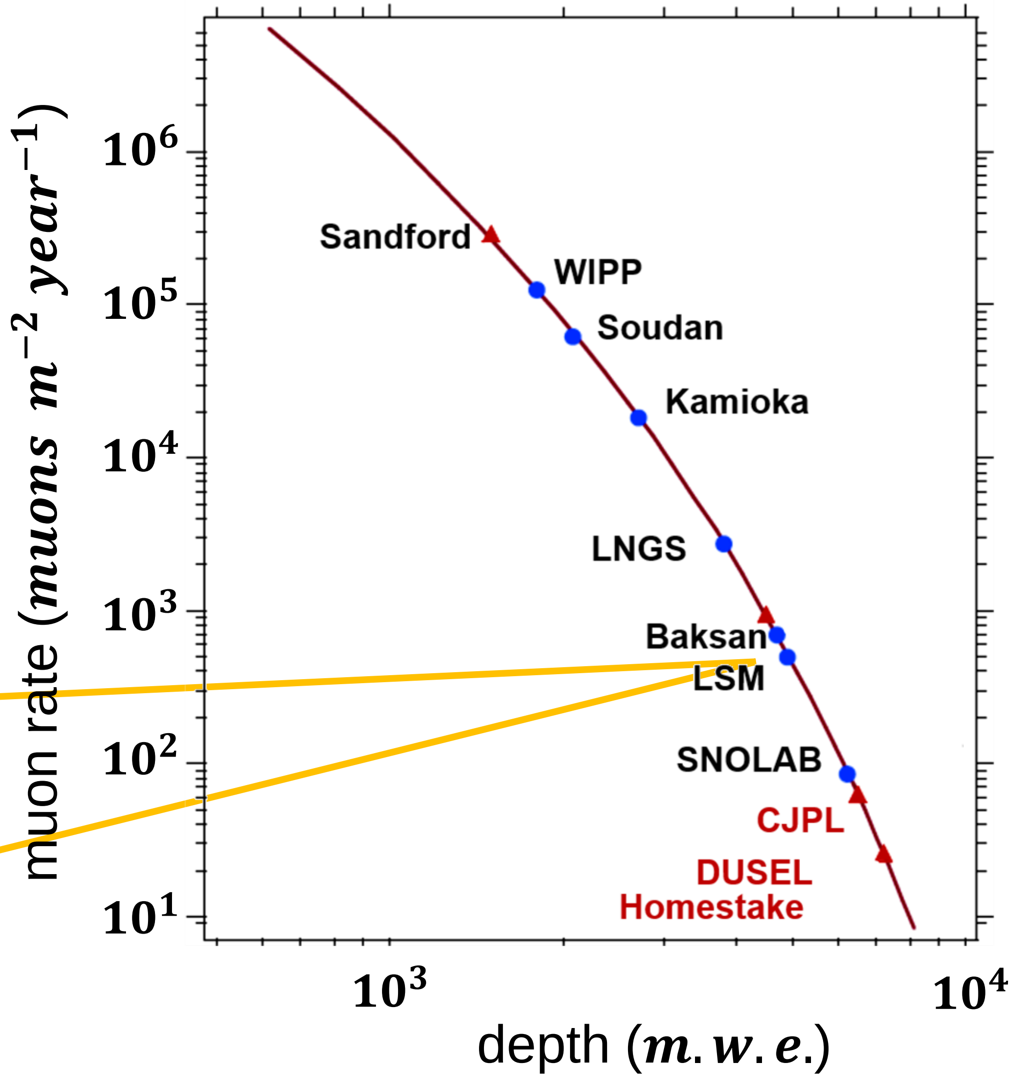
Underground laboratories – overburden & μ´s

- ***L***aboratoire ***S***outerrain de ***M***odane (***LSM***) – France

- overburden: $4800\ m.w.e.$



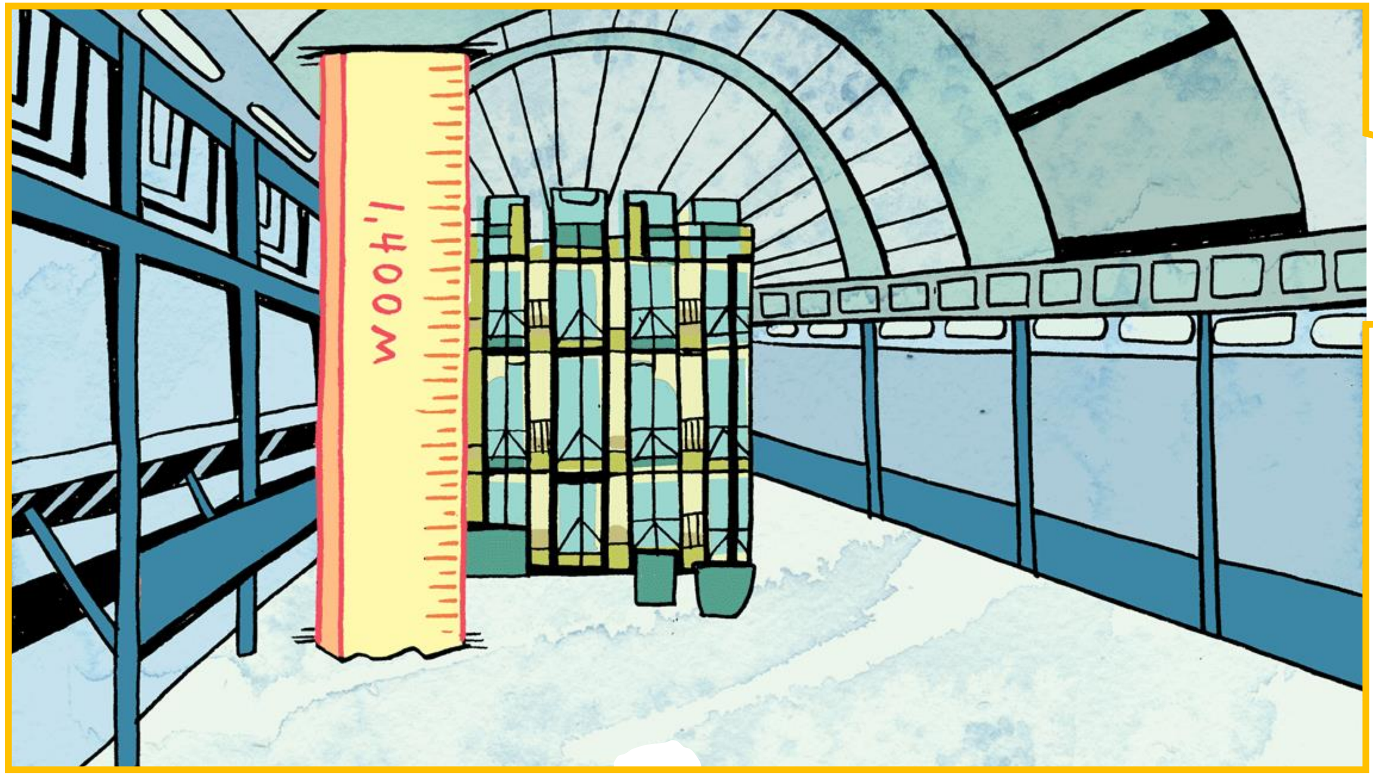
EDELWEISS experiment

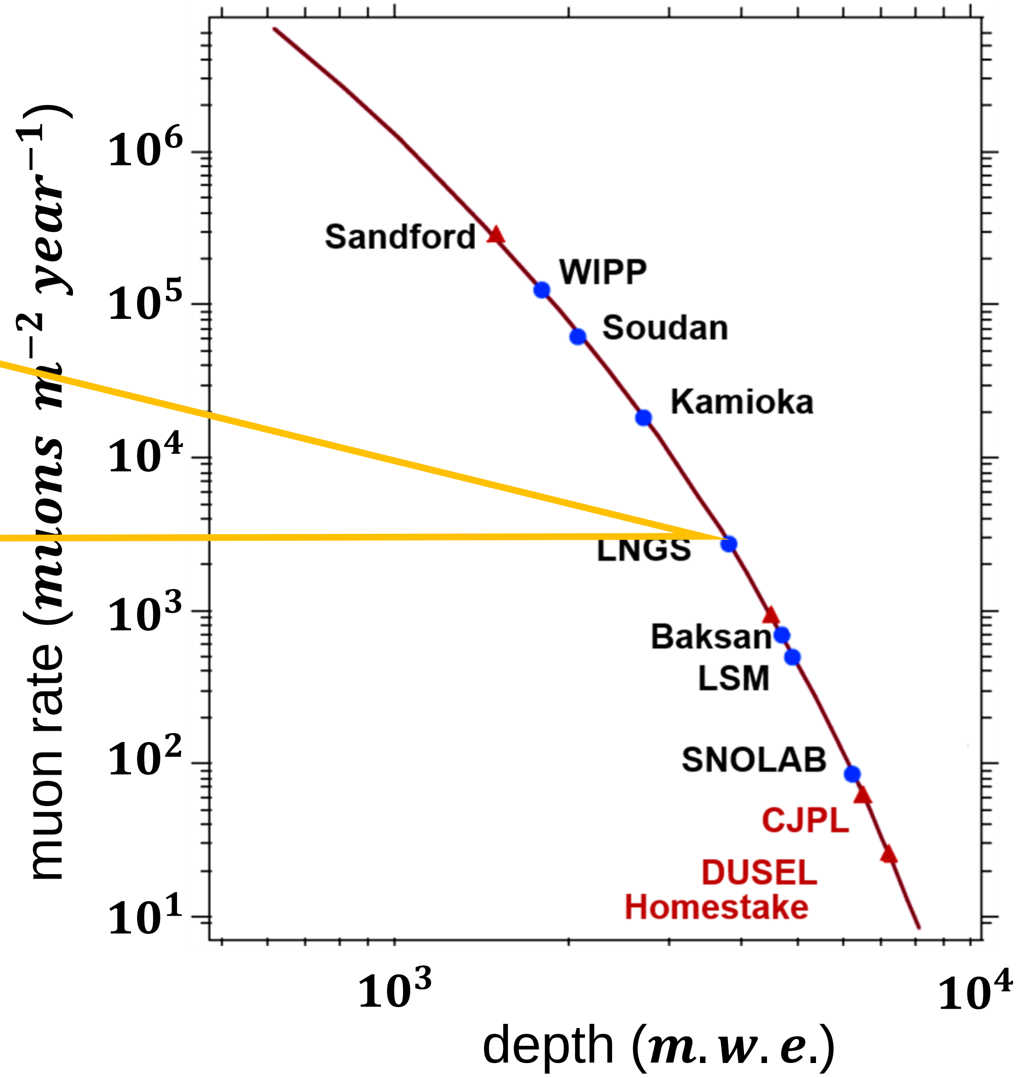


Underground laboratories – overburden & μ´s

- ***L***aboratori ***N***azionali del ***G***ran ***S***asso

  - the ´ideal´ underground laboratory in Europe





Underground laboratories – $LNGS$

- $LNGS$ – 3 experimental halls: $A/B/C$

Hall B: $XENONnT$ experiment

Underground laboratories – $LNGS$ virtual tour

https://www.google.it/maps/@42.4527214,13.5734979,3a,75y,157.46h,113.17t/data=!3m6!1e1!3m4!1sq6nrE6TmfIYpXqaACC7kGw!2e0!7i13312!8i6656?hl=en

© Google

Underground laboratories – $LNGS$

- $XENONnT$ – direct (world–leading) search for $WIMP$ dark matter

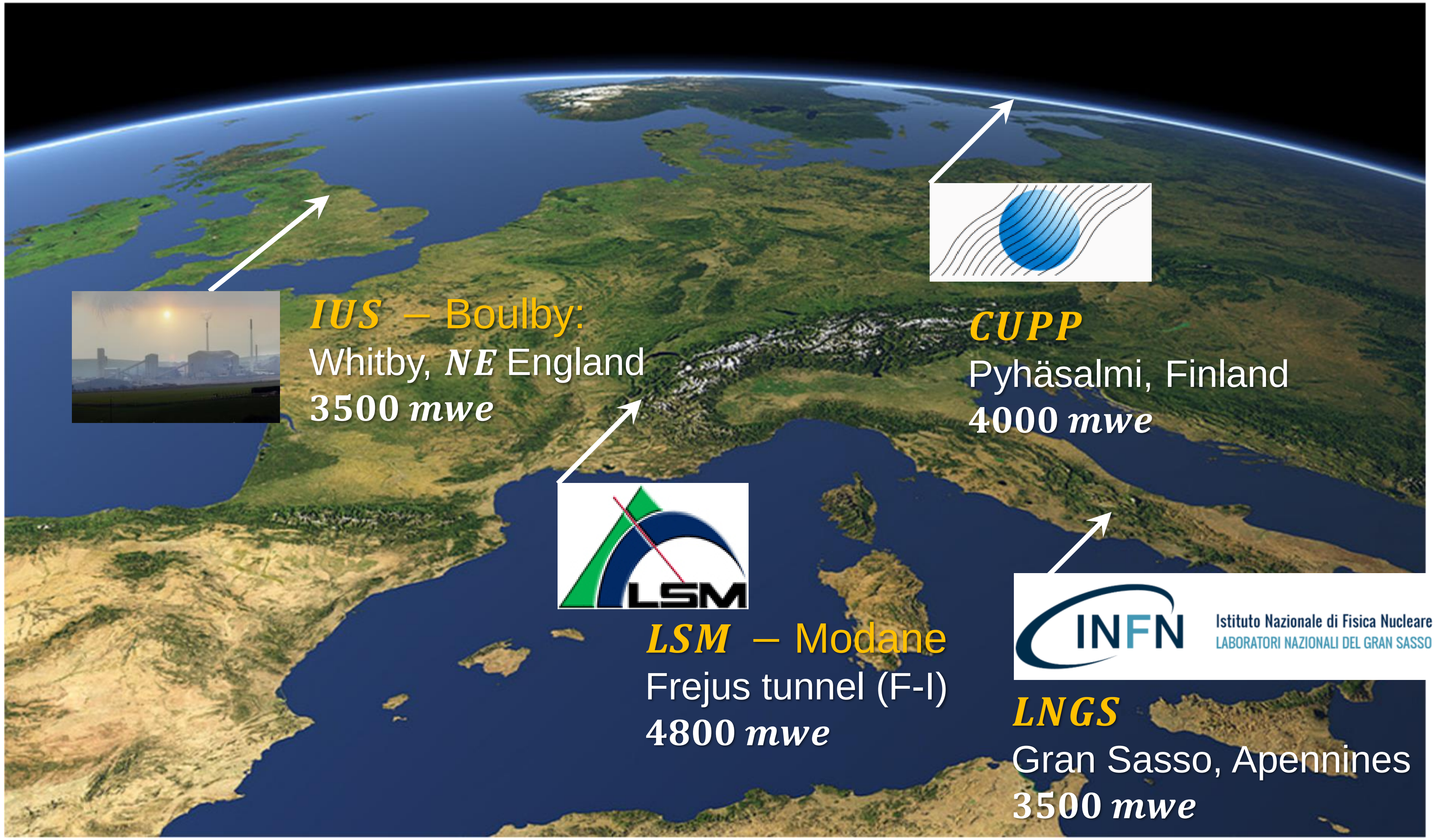
- $XENON - nT$: $8.3\ tons\ LXe$ TPC

(see ch. $4.5.3$)

Underground laboratories in Europe

- **Cooperation via** ***ILIAS********

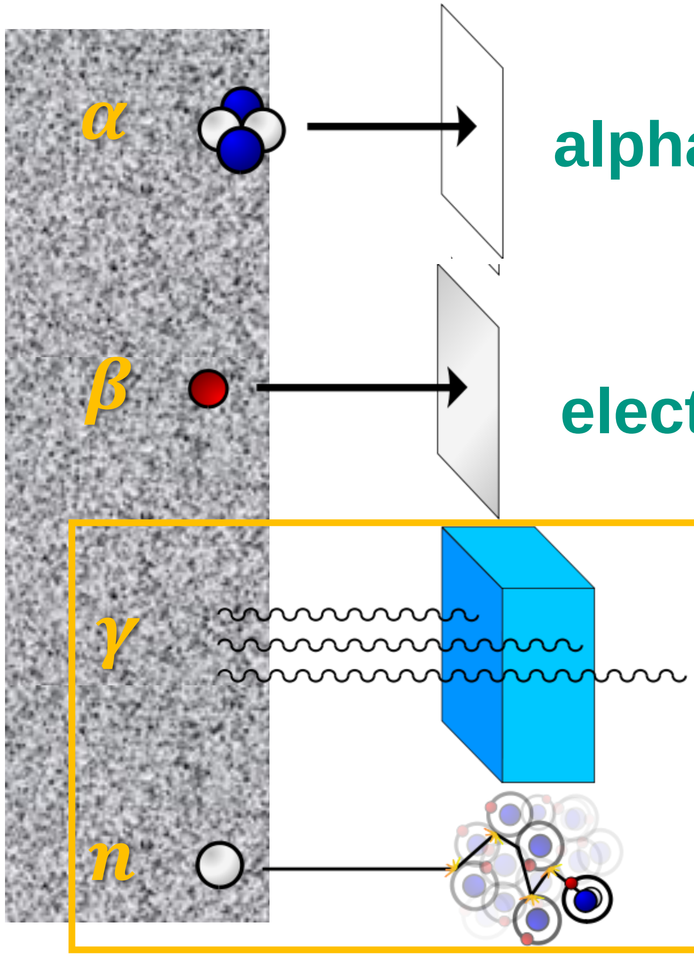
Integrated
Large
Infrastructures
for
AStroparticle
Physics



*do not confound with ILIAS

2. 2. 2 Shielding Methods

- How much shielding do I need in my underground lab against background?



alphas $(4 \dots 8\ MeV)$

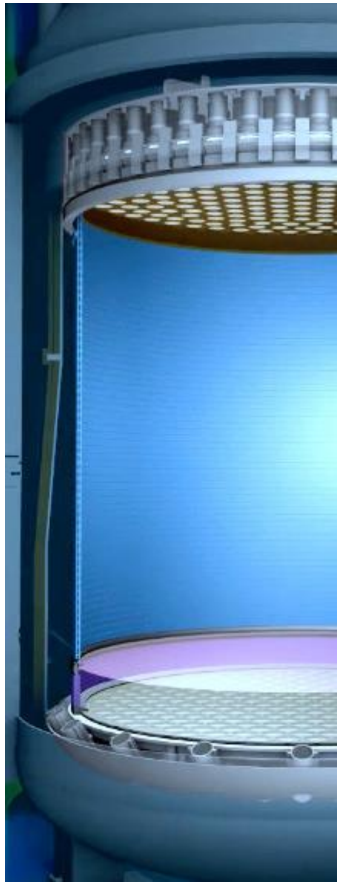
electrons $(0.02 \dots 2\ MeV)$

gammas
$(< 3.6\ MeV)$

neutrons
(MeV)

Cu

Pb

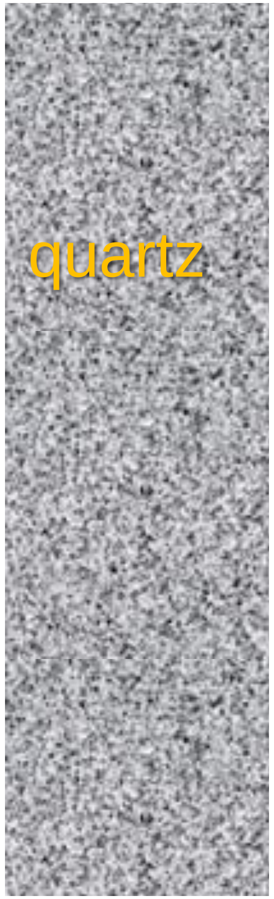


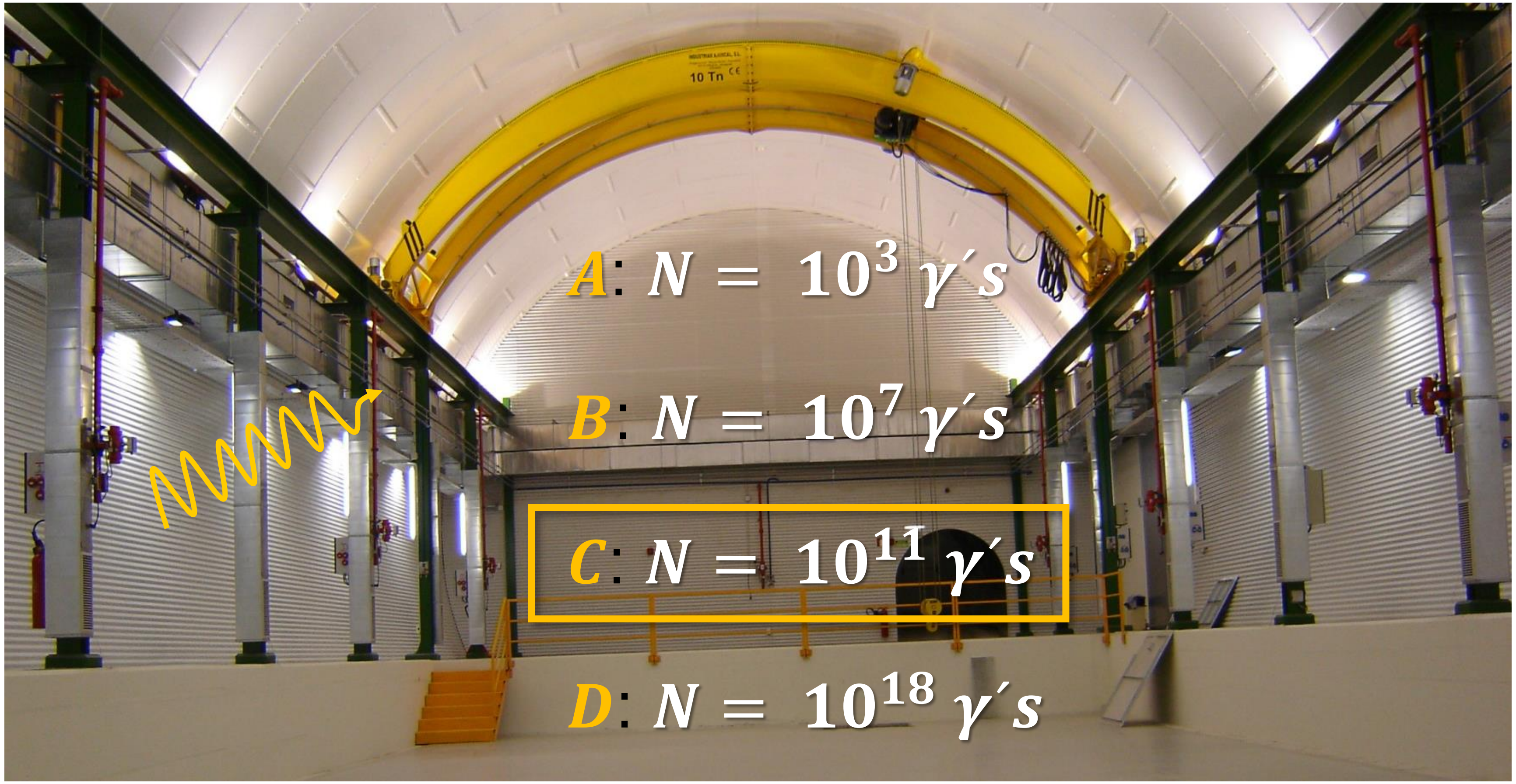
Shielding methods: external sources

- Particle radiation from rocks, lab walls: charged / neutral components

Shielding methods: external sources

- Quiz: how many **gammas** are emitted / year from a $600\ m^2$ lab surface?





A: $N = 10^3\ \gamma\text{´}s$

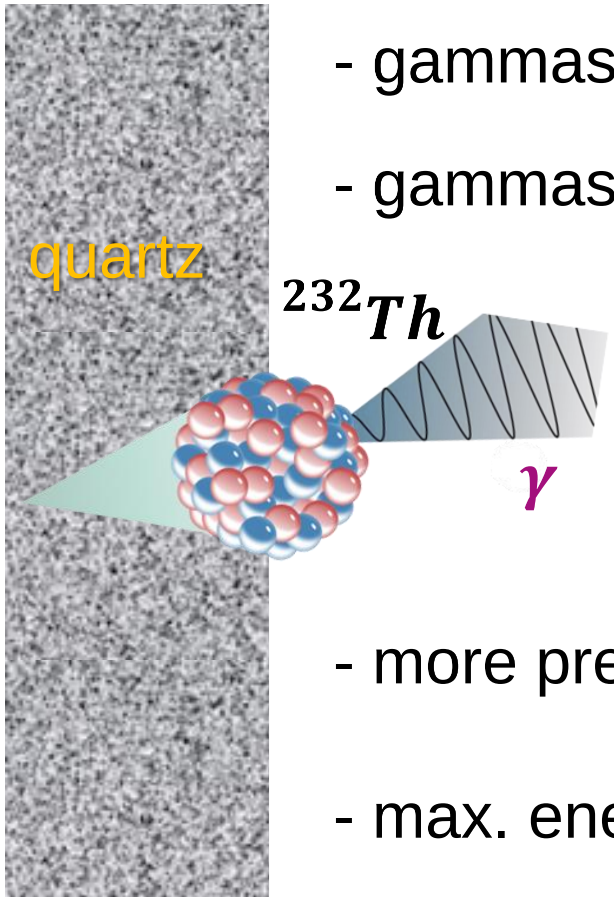
B: $N = 10^7\ \gamma\text{´}s$

$\boxed{C: N = 10^{11}\ \gamma\text{´}s}$

D: $N = 10^{18}\ \gamma\text{´}s$

Shielding methods: external sources

- **Answer to quiz: # of gammas / year from a $600\ m^2$ lab surface**



- gammas: only from top $\mathbf{5}\ cm$ surface ⇨ $V = 30\ m^3$ of rock contribute

- gammas: primarily from ^{232}Th with $10^{-6}\ g\ ^{232}Th/g = 100\ g\ ^{232}Th$

- half–life $t_{½}(^{232}Th) = 1.4 \cdot 10^{10} yr$ ⇨ $4 \cdot 10^{10}\ \gamma ́s\ /\ yr$

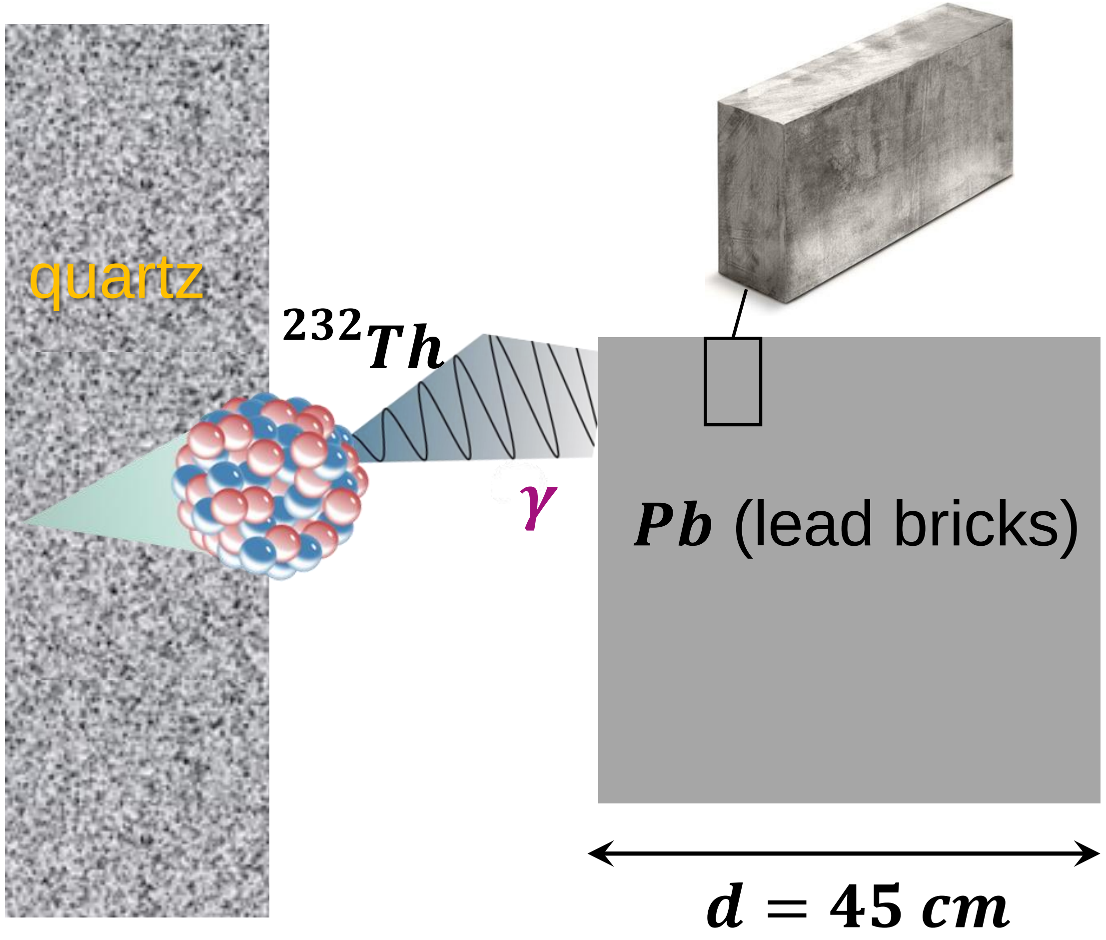
⇨ $1300\ \gamma ́s\ /\ s$

- more precise estimate, including self–shielding $10^{11}\ \gamma ́s\ /year$

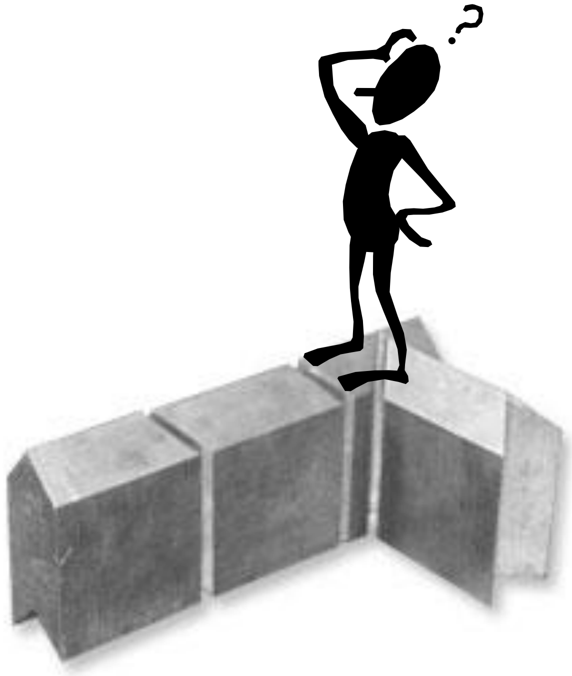
- max. energy $\gamma ́s$: $E_\gamma = 2.6\ MeV$ from ^{206}Tl, from $^{238}U - {}^{232}Th$ decay chain

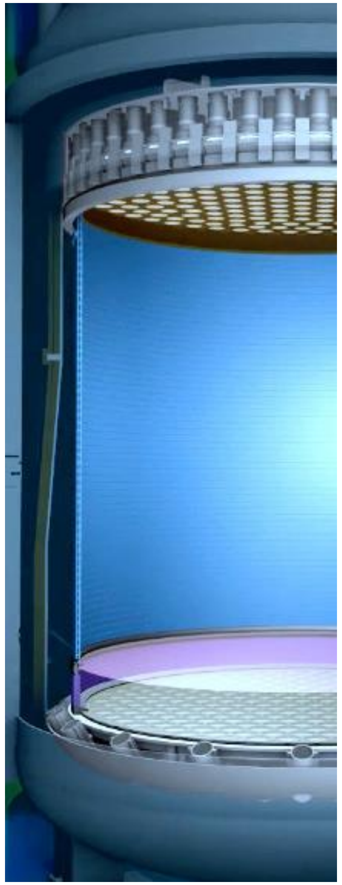
Classic shielding method: lead bricks

- **Required gamma shielding factor: massive absorber, minimum of $20\ X_0$**



shielding factor $\sim 10^9$

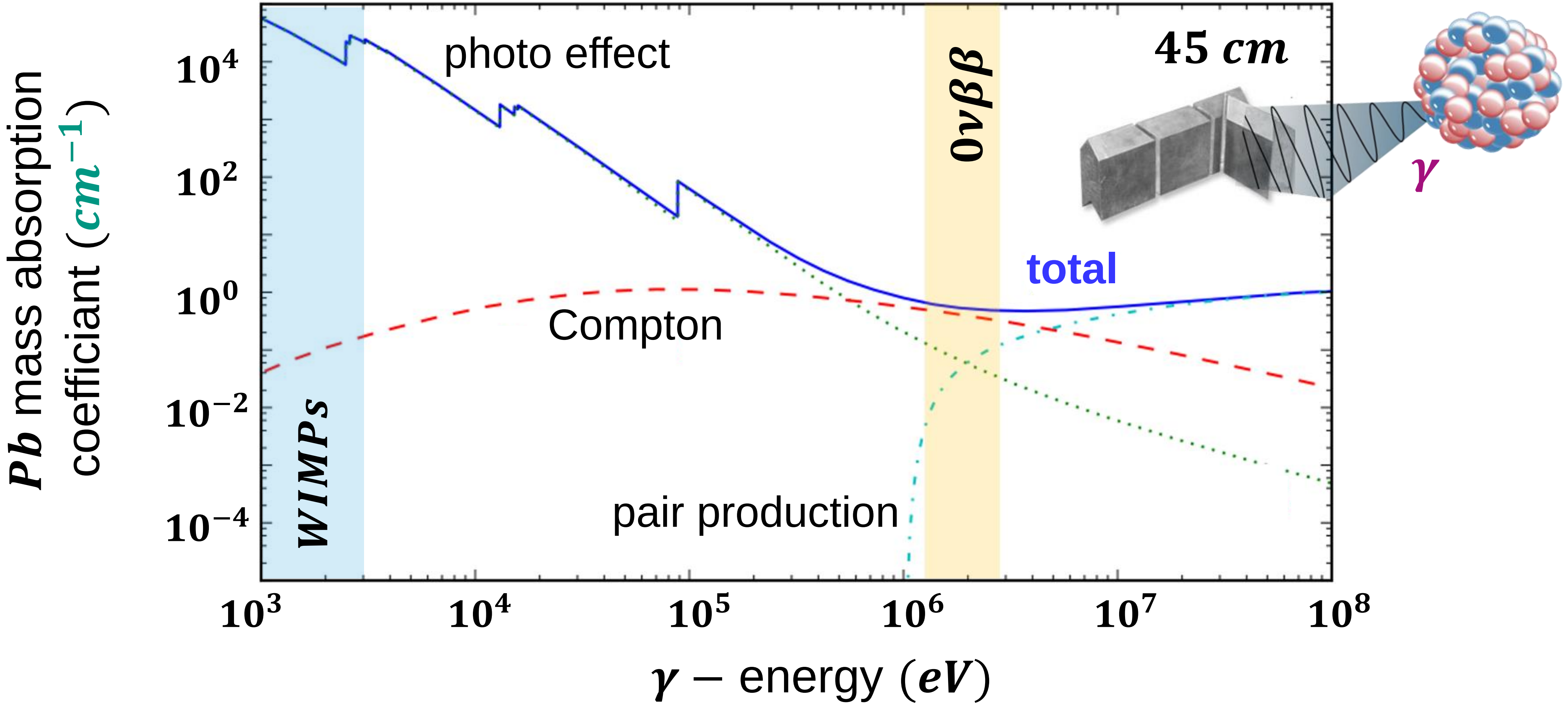




Shielding methods: lead as gamma–absorber

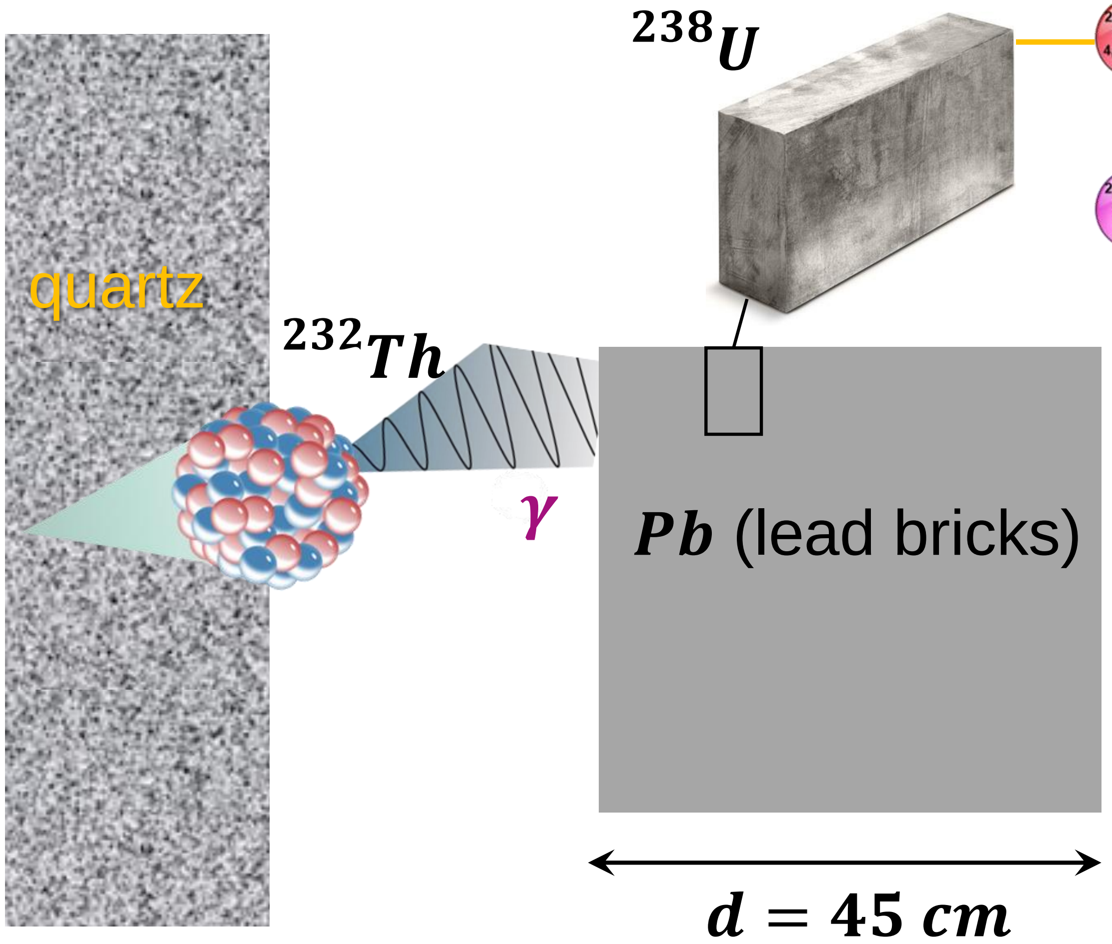
- **Linear mass absorption coefficient μ of Pb for γ´s from $1\ keV$ … $100\ MeV$**

$I(x) = I_0 \cdot e^{-\mu \cdot x}$



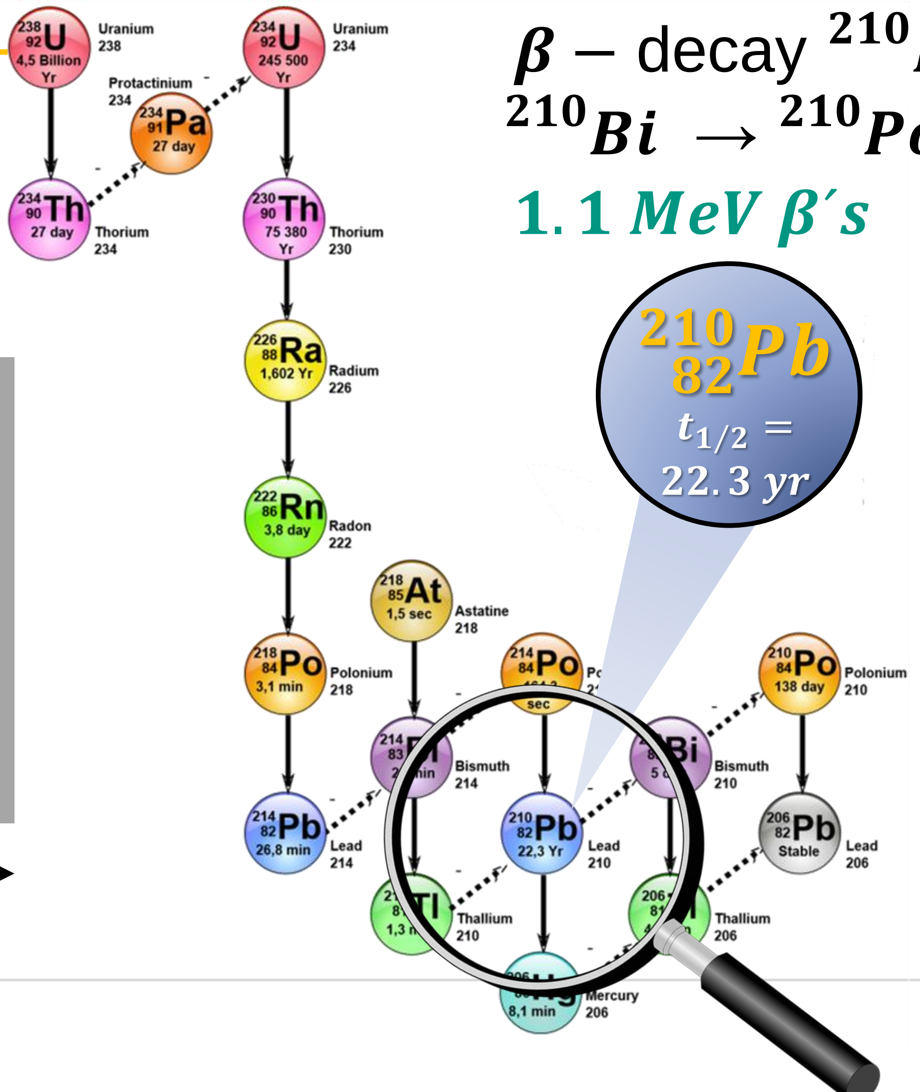
Shielding methods: lead bricks & their activity

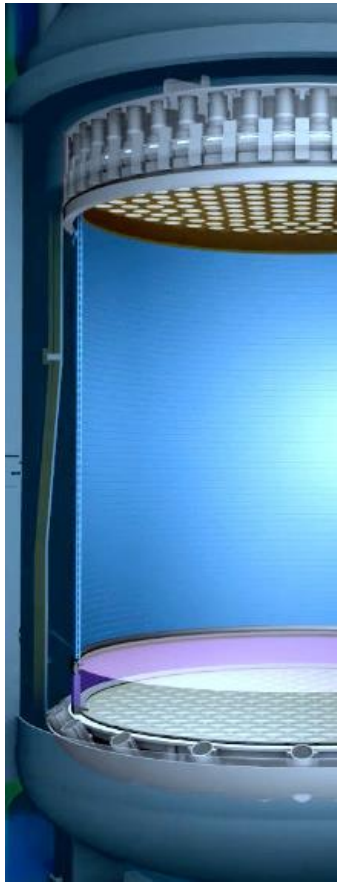
- What about the **intrinsic purity** of the new Pb wall? It contains isotope ^{210}Pb



β – decay $^{210}Pb \rightarrow$
$^{210}Bi \rightarrow {}^{210}Po$

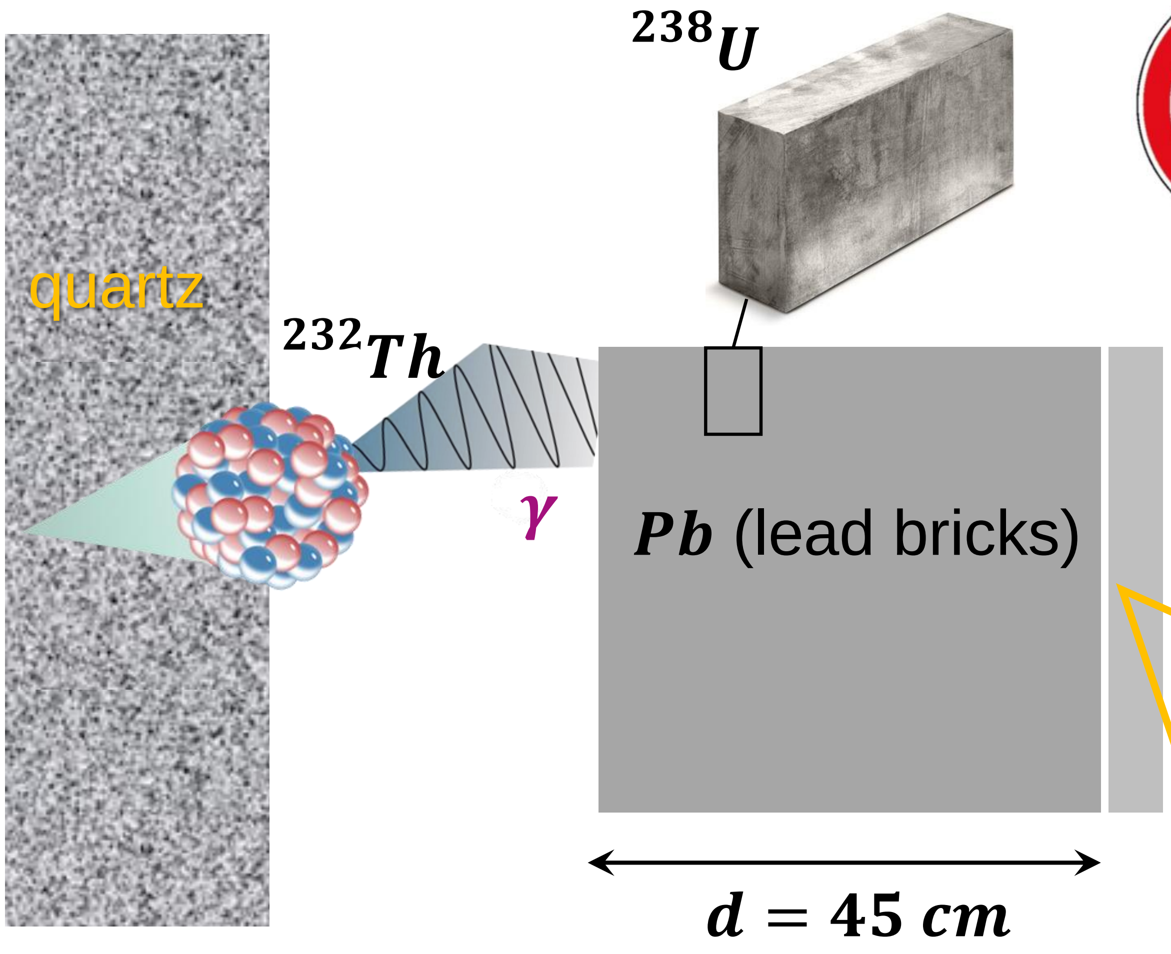
$1.1\ MeV\ \beta's$





Shielding methods: Roman lead from sea floor

- We need **very old lead**, where the activity of ^{210}Pb has decayed away



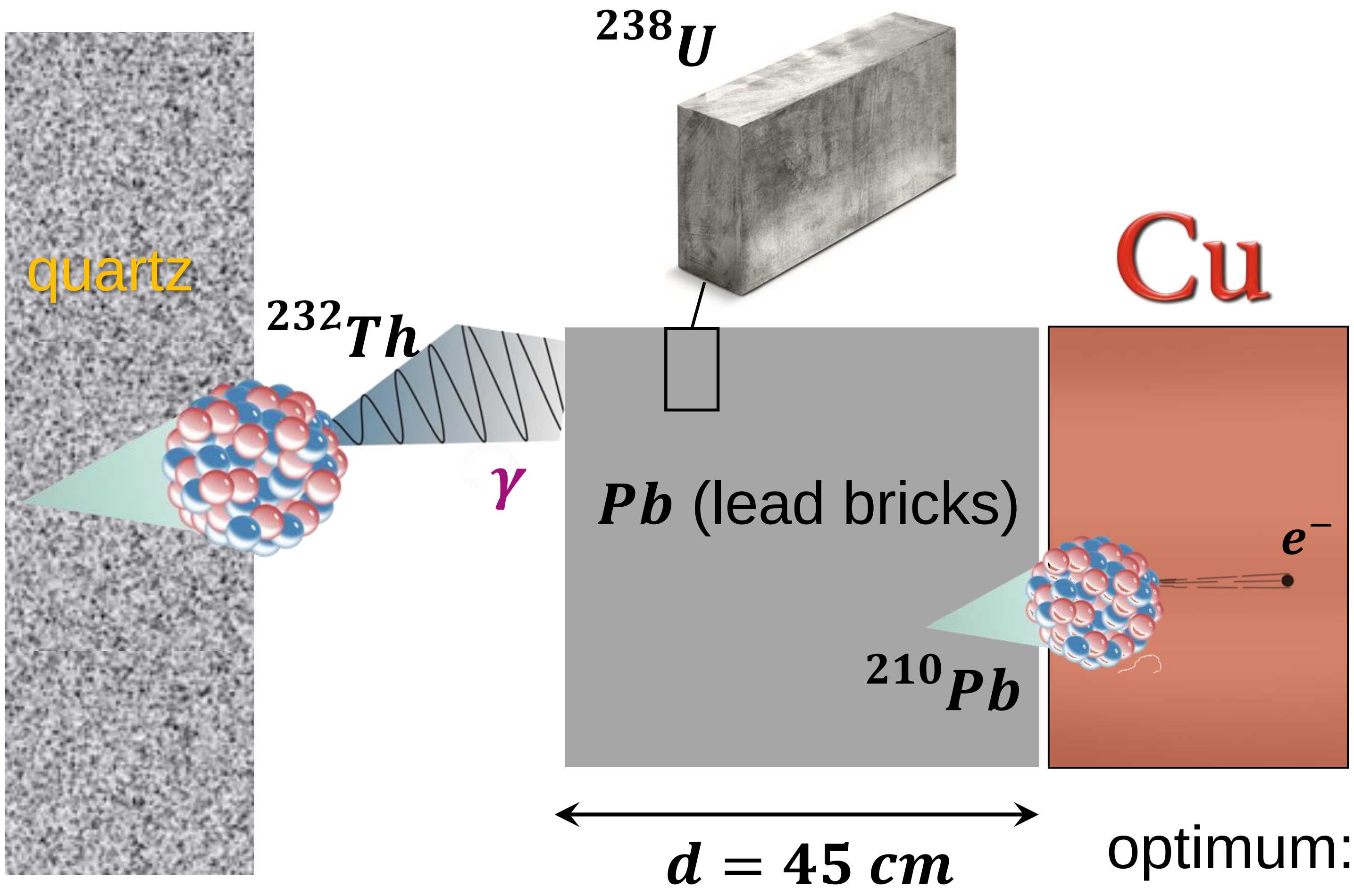
ROMAN LEAD

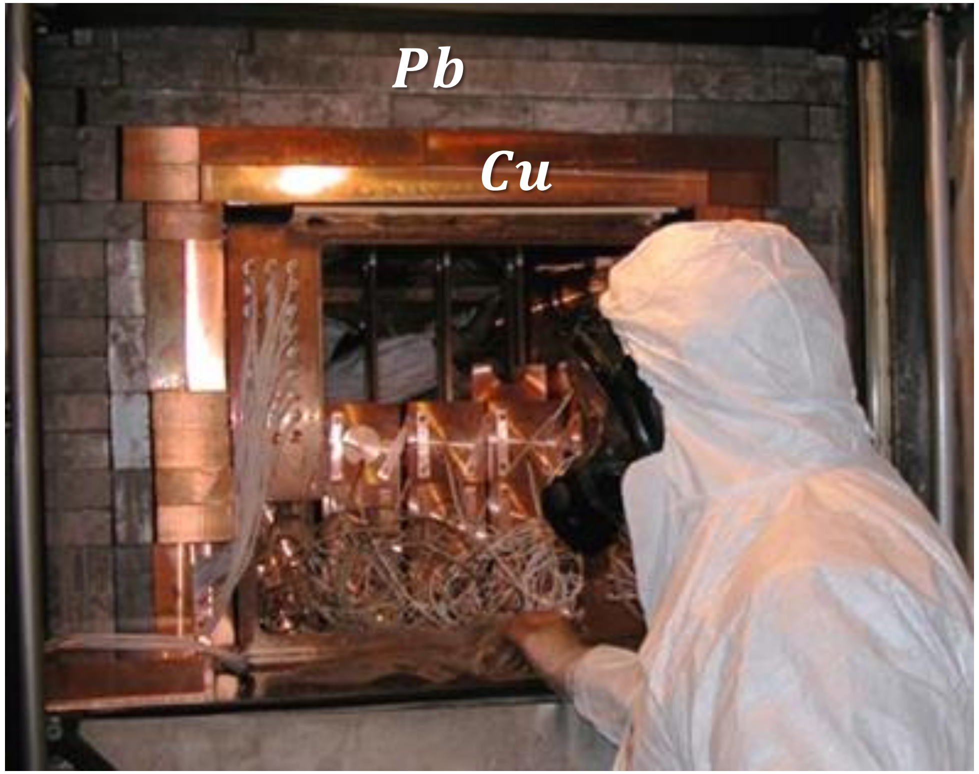
Italian groups only

- extracted from **sunken Roman galleys** (entire ^{210}Pb has decayed after $\Delta t \sim 2000\ yr$)

Shielding methods: extremely pure copper

- We need to install an inner copper shielding of ultra−pure Cu

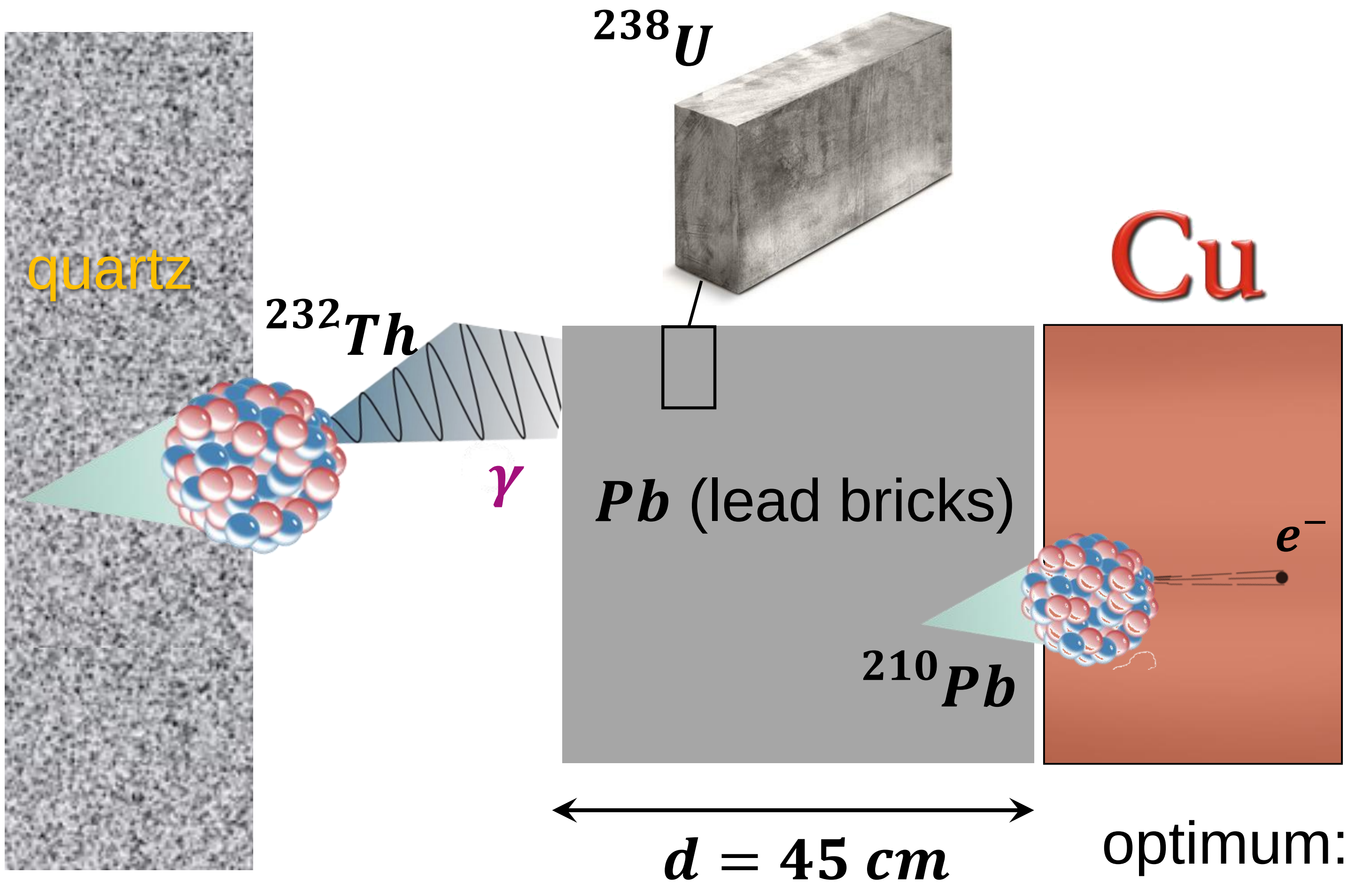


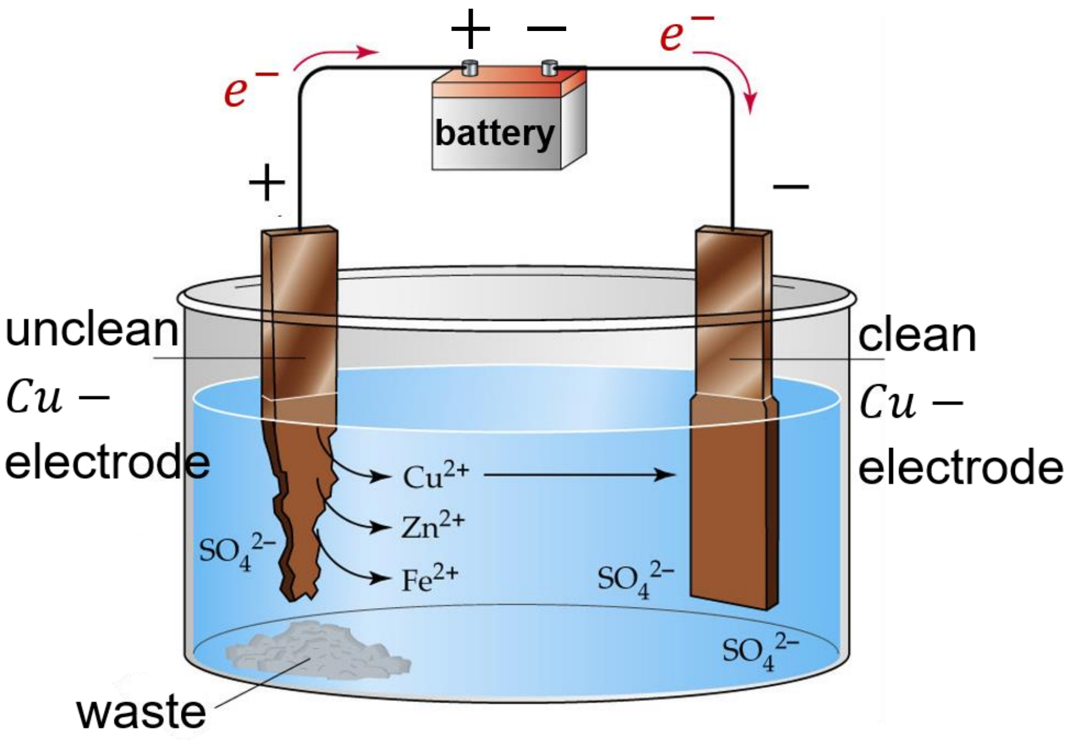


optimum: **electro−formed** Cu (no ^{238}U)

Shielding methods: extremely pure copper

- We need to install an inner copper shielding of ultra–pure Cu





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Shielding methods: extremely pure copper

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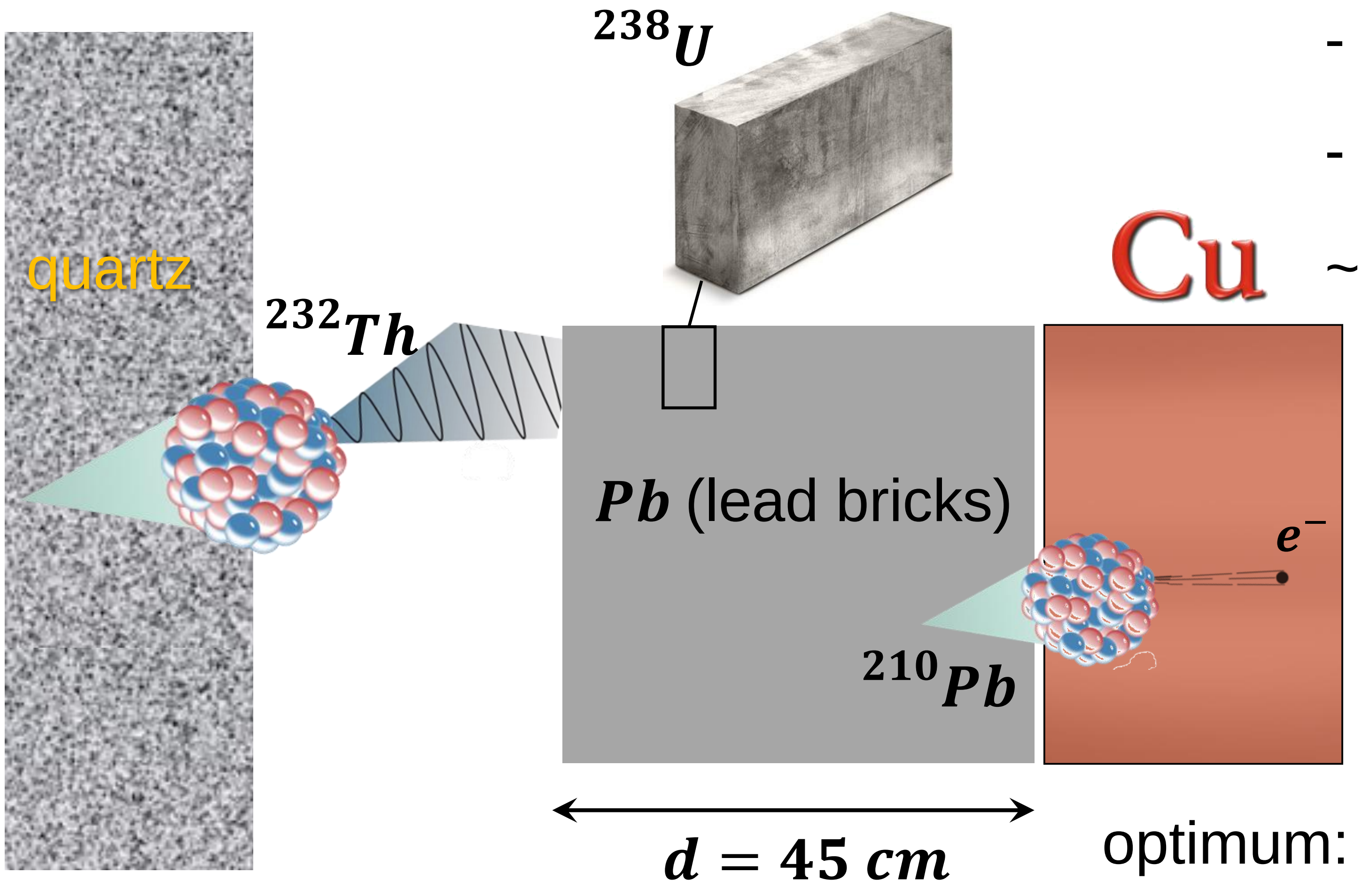


- direct production in underground lab

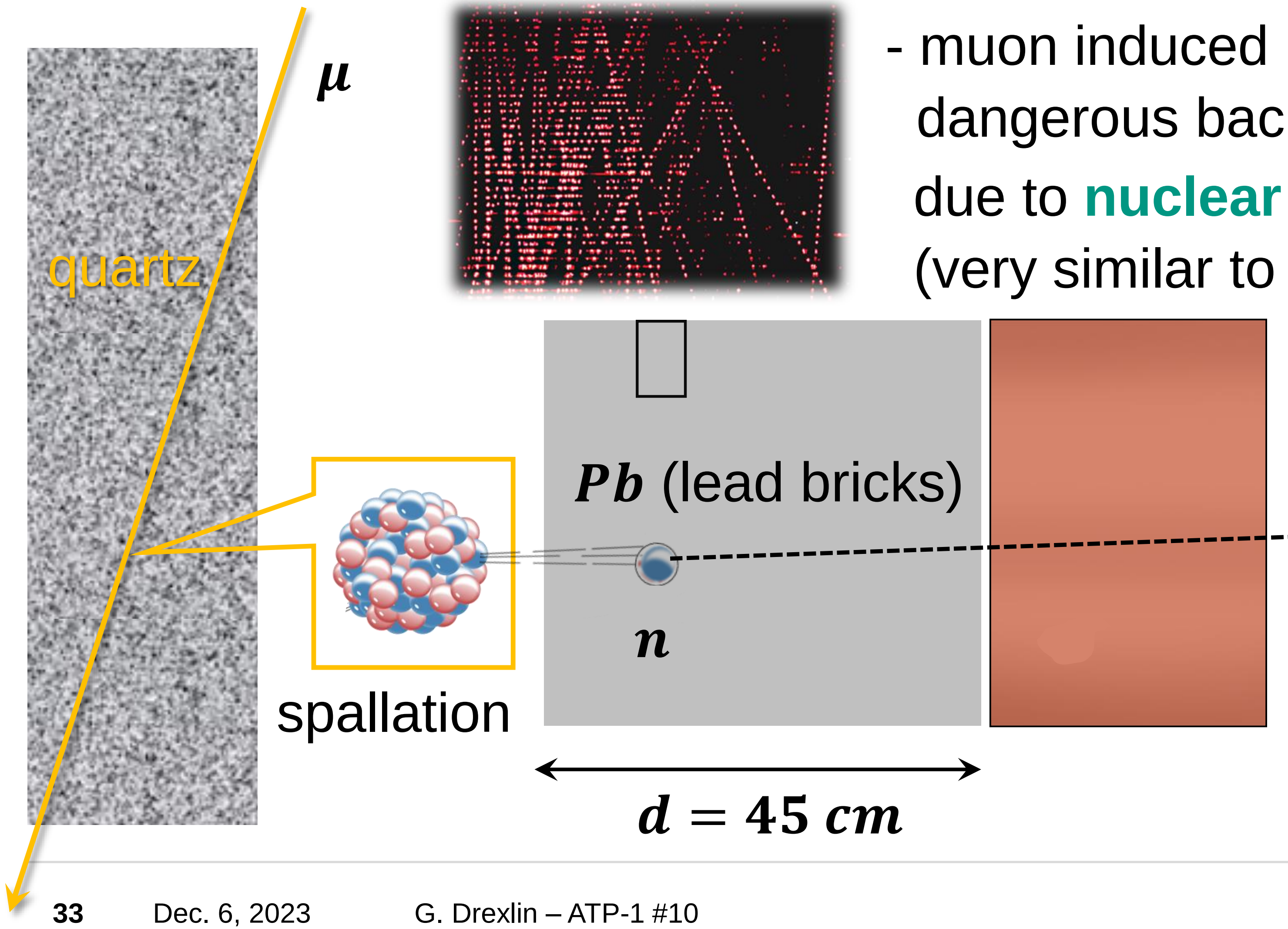
- growth: $10 \times$ slower than human hair

~ $100\, nBq/kg$ for rare event searches
dark matter, $0\nu\beta\beta$ – decay

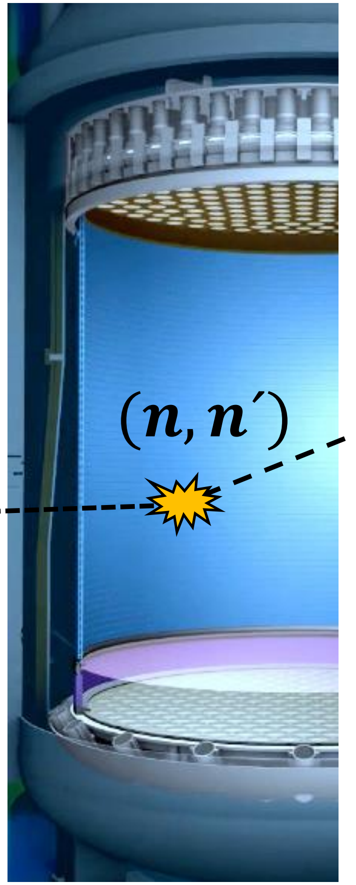
optimum: electro–formed Cu (no ^{238}U)

Shielding methods: muon−induced neutrons

- We need to shield against **neutrons from muon interactions** nearby



- muon induced neutrons can generate dangerous background signatures due to **nuclear recoil processes** (very similar to $WIMP$ – signals!)

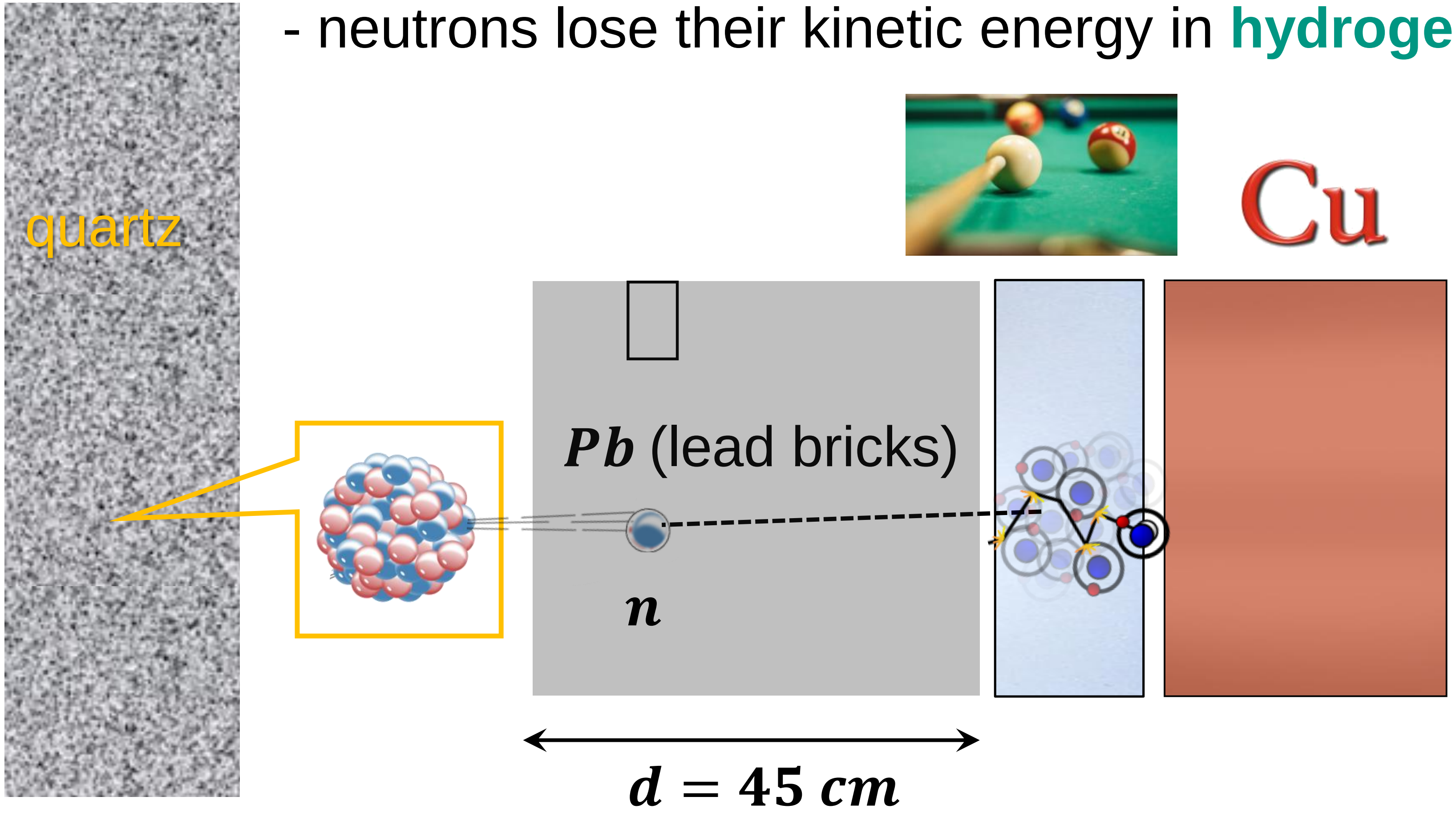


I need shielding against these neutrons!

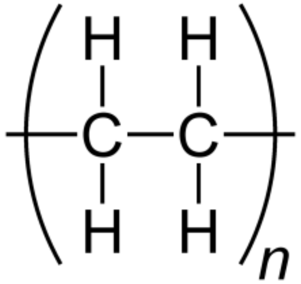
Shielding methods: muon–induced neutrons

- **Shielding against neutrons: polyethylene wall (CH_2) or water (H_2O)**

- neutrons lose their kinetic energy in **hydrogen–rich** materials

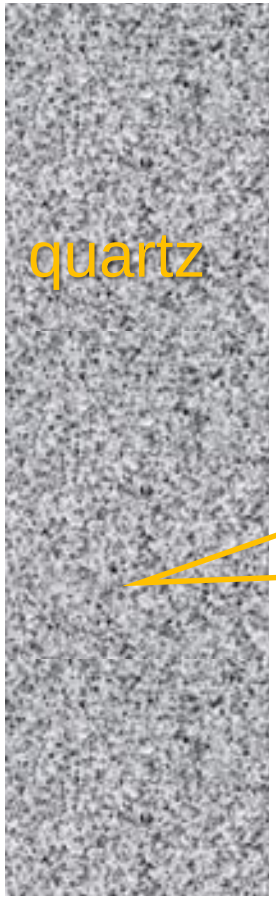


Polyethylene (PE)



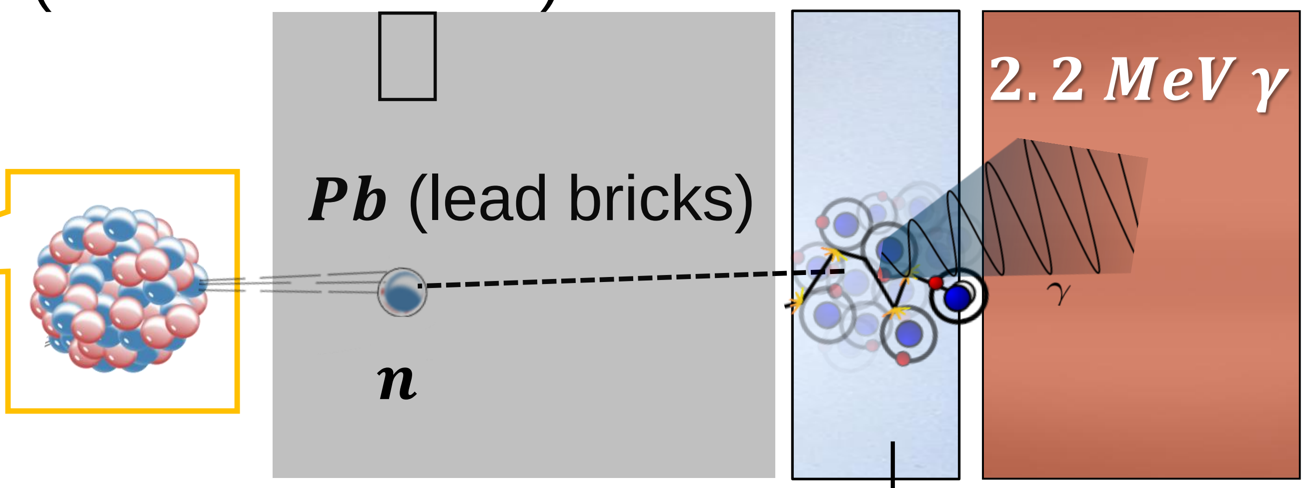
Shielding methods: muon–induced neutrons

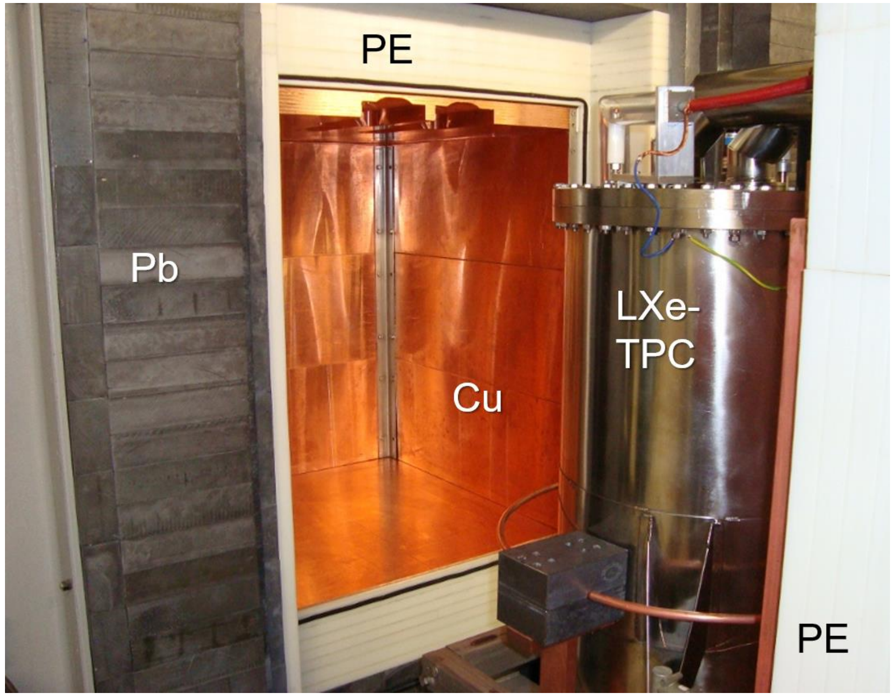
- **Shielding against neutrons: polyethylene wall (CH_2) or water (H_2O)**



- neutrons lose their kinetic energy in **hydrogen–rich** materials: but we need to shield the $2.2\ MeV$ $\gamma - ray$ with our ultra–pure Cu (PE surrounds Cu)

Cu





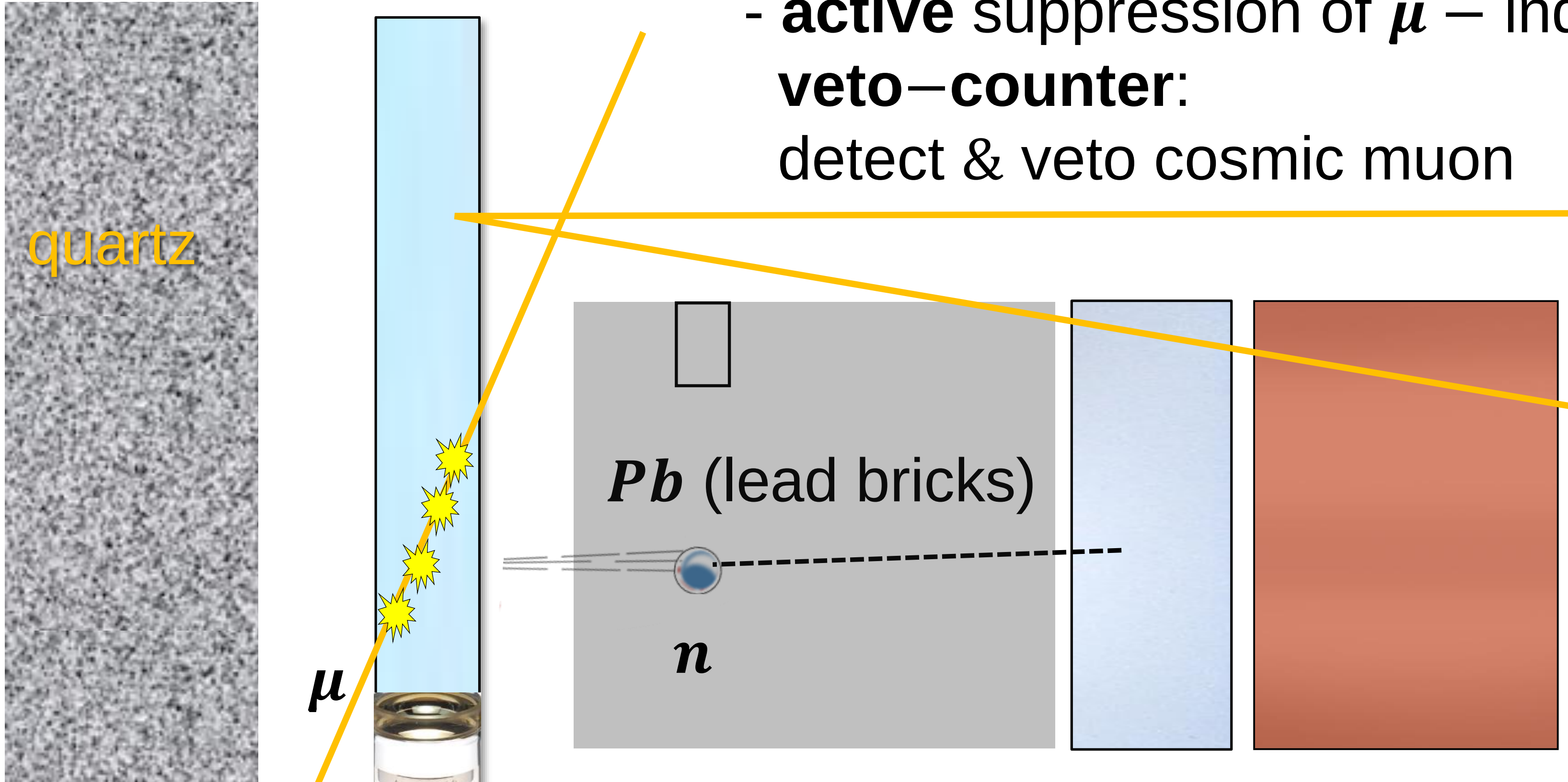
$d = 45\ cm$

$n + p \rightarrow d + 2.2\ MeV\ \gamma$

Shielding methods: one more thing…

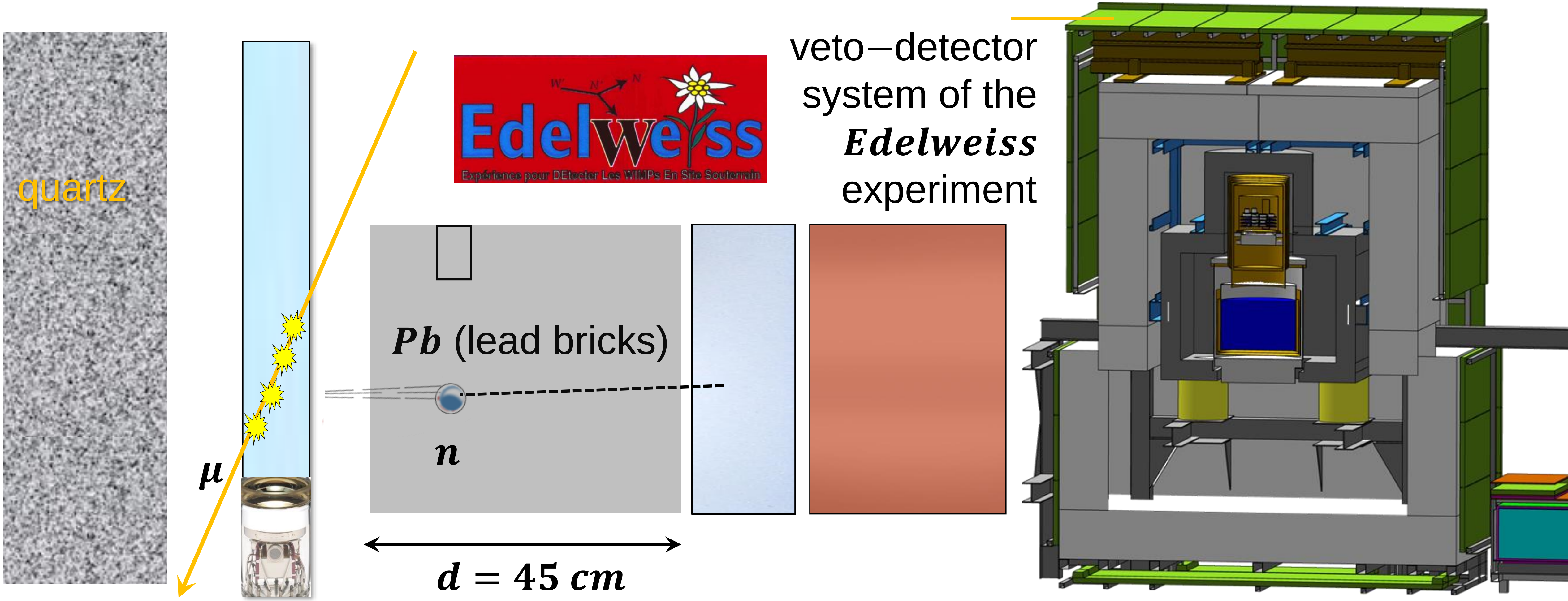
- **Veto against cosmic muons:** plastic scintillator **or** water Cherenkov detector

- **active** suppression of μ – induced neutrons via outer **veto–counter**: detect & veto cosmic muon



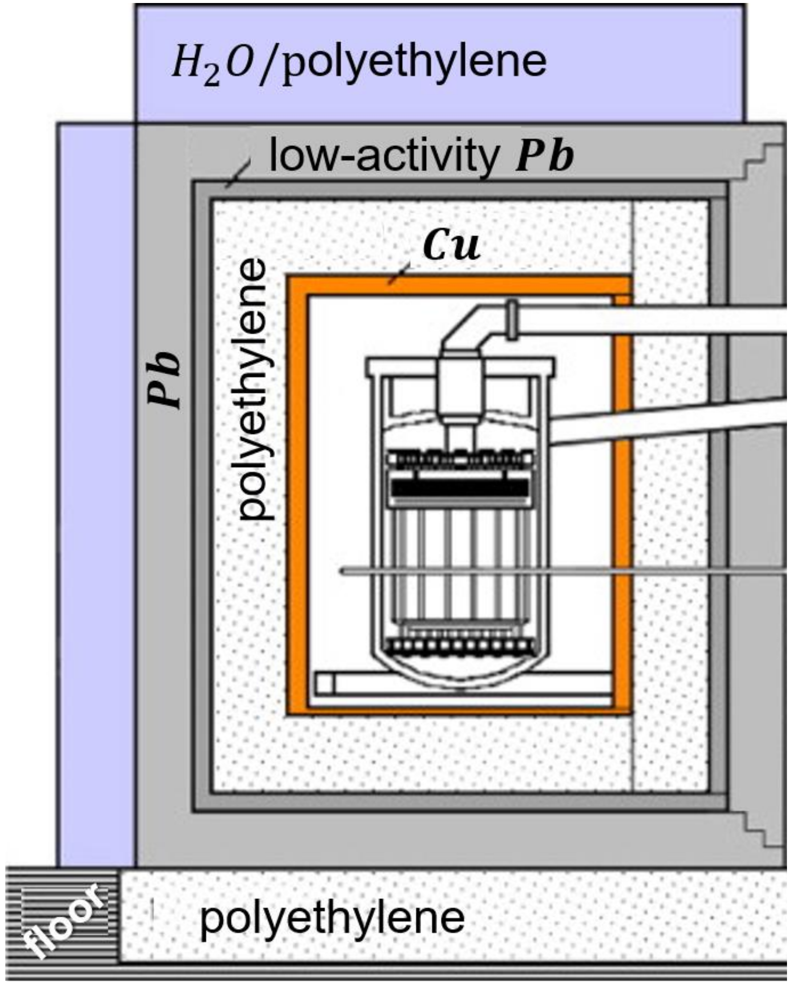
Shielding methods: one more thing…

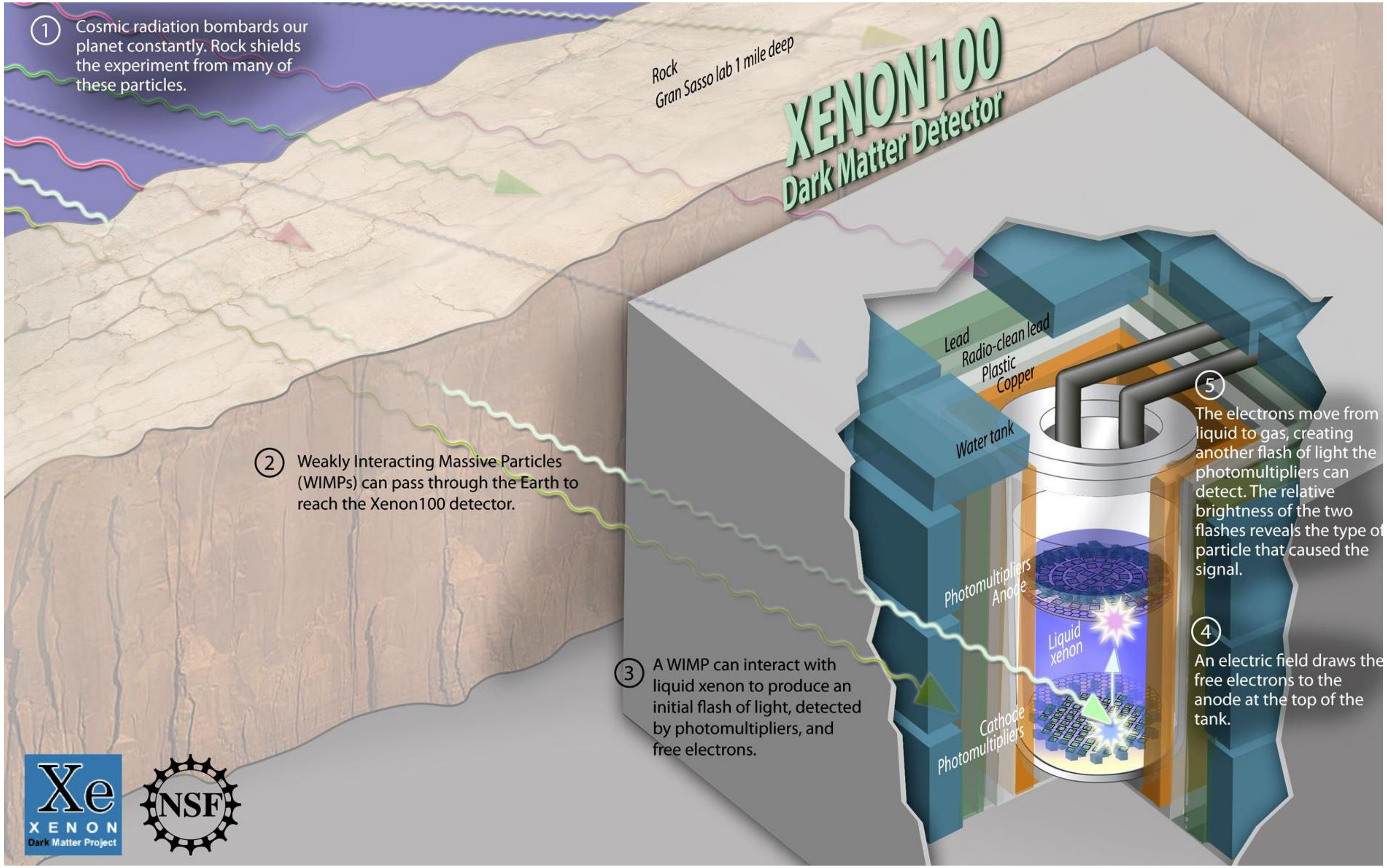
- Veto against cosmic muons: plastic scintillator or water Cherenkov detector



Shielding methods: example $XENON$

- $XENON100$ at $LNGS$





Shielding methods: final optimization ($DARWIN$)

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- $DARWIN$ proposal at $LNGS$

- very large **H_2O veto counter** &
  careful material screening / selection

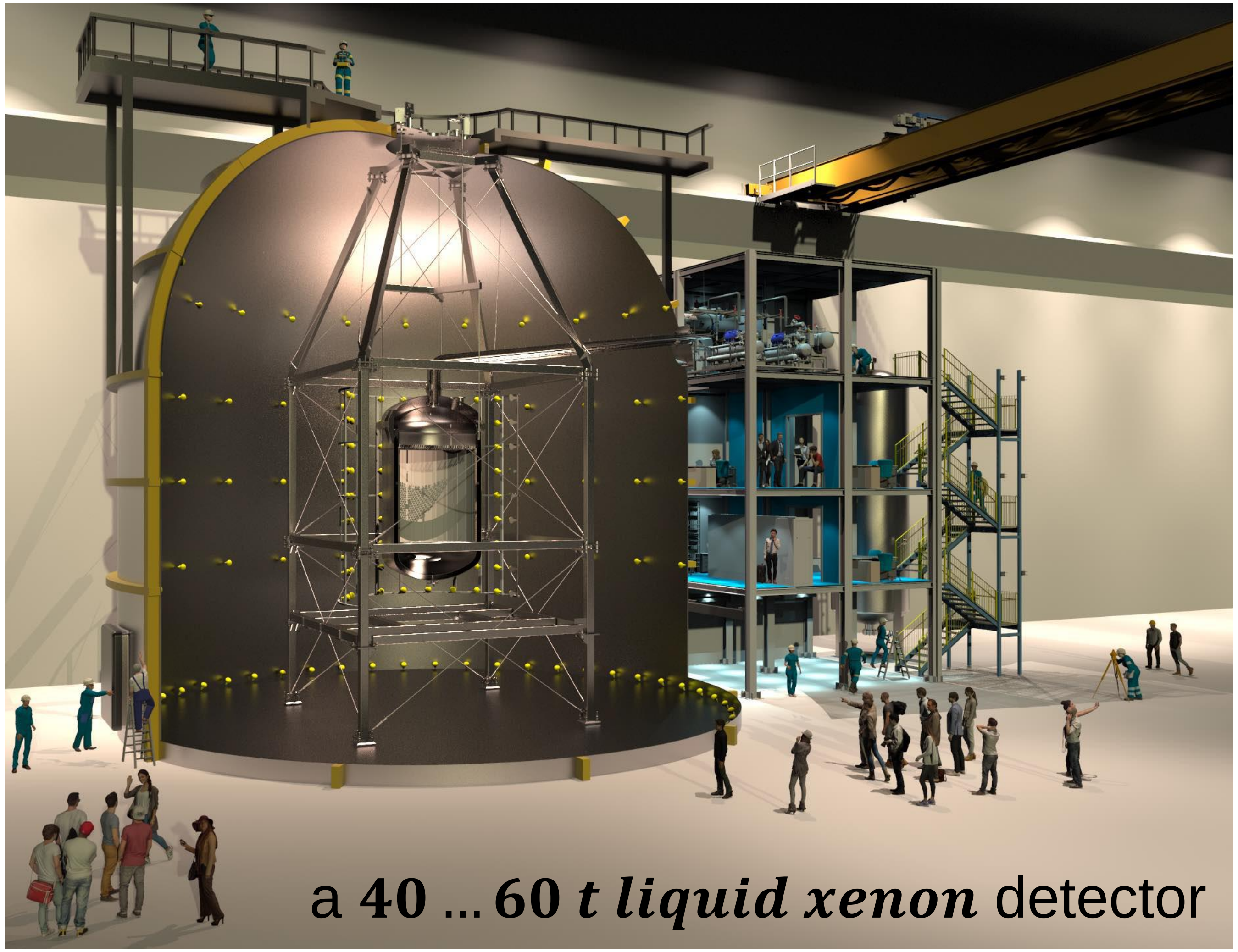
- continuous liquid xenon **purification**

- dominant background source:

  solar neutrinos
  atmospheric neutrinos
  diffuse SN neutrinos

  ν – floor

- the ´**ultimate**´ shielding frontier



a $40 \ldots 60\ t$ $liquid\ xenon$ detector

Shielding methods: final optimization $(DARWIN)$

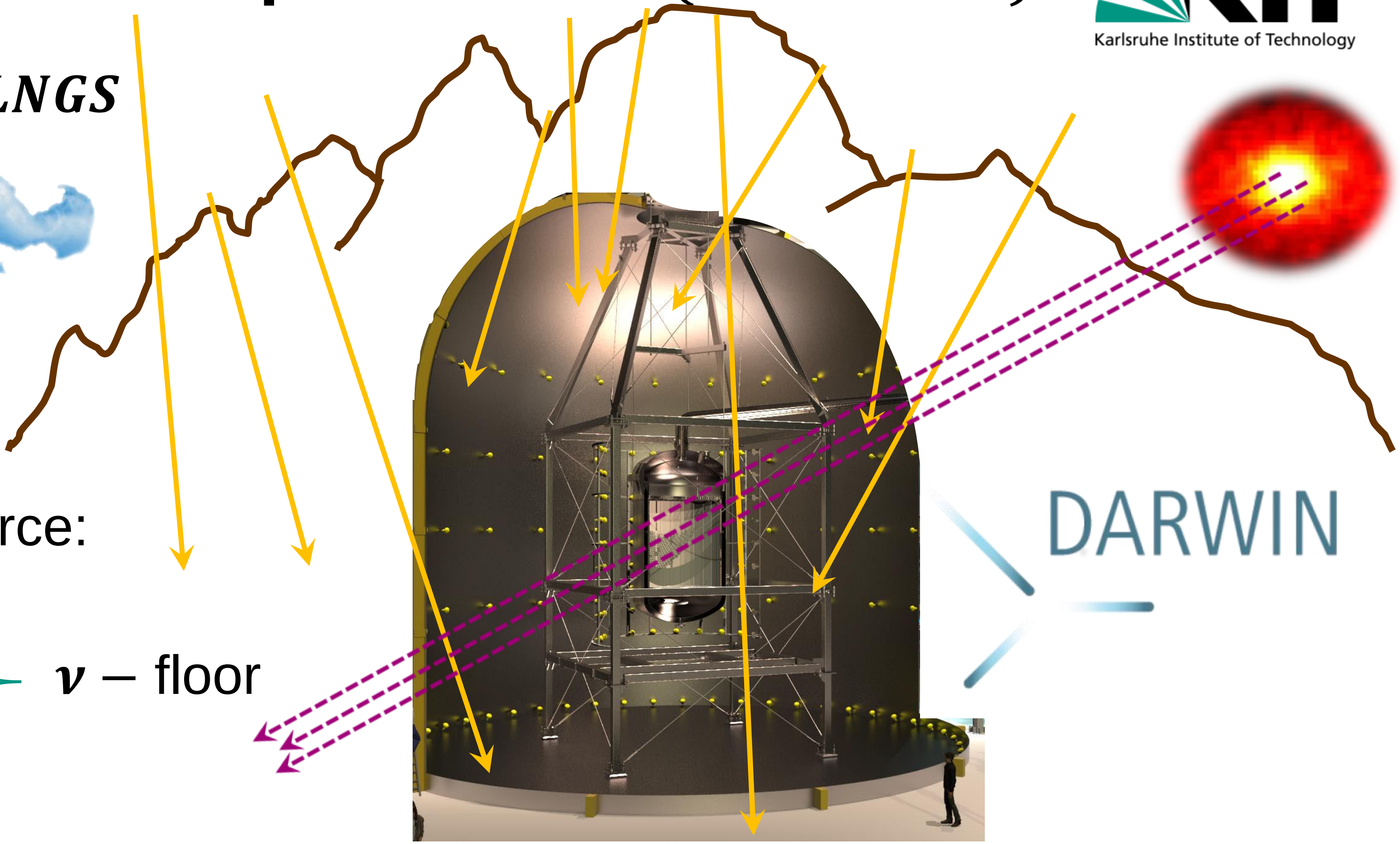
- $DARWIN$ **proposal at** $LNGS$

- dominant background source:

  solar neutrinos
  atmospheric neutrinos
  diffuse SN neutrinos

  ν – floor

- the ´**ultimate**´ shielding frontier



a $\mathbf{40 \dots 60\ \boldsymbol{t}\ \boldsymbol{liquid\ xenon}}$ detector

2.2.3 Primordial decay chains

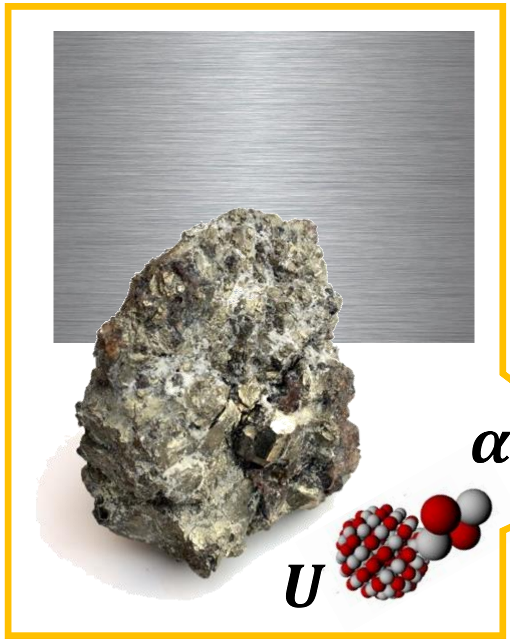
- **Origin of radioactive isotopes here on Earth**

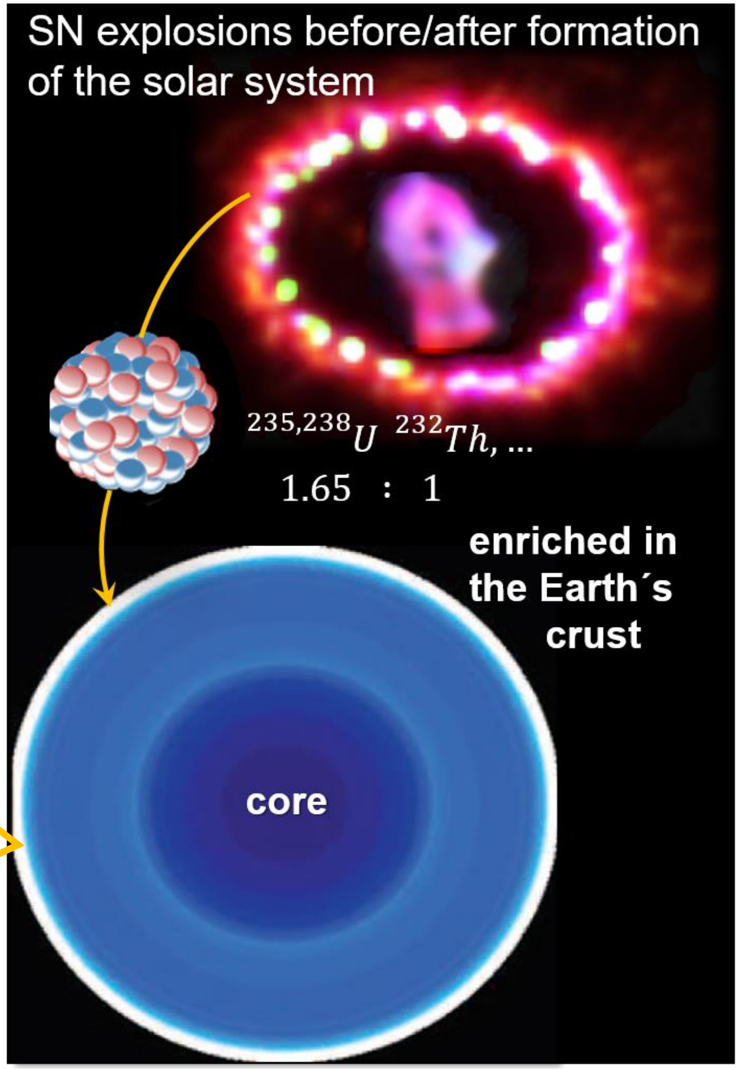
  - radioactive isotopes are forged in $\boldsymbol{SNae}$ explosions / $\boldsymbol{G}$amma $\boldsymbol{R}$ay $\boldsymbol{B}$ursts ($\boldsymbol{GRB}$s*) in our galaxy

  - after galactic voyage to Earth: enrichment in outer crust

  - important isotopes: $^{232}\boldsymbol{Th}, {}^{235}\boldsymbol{U}, {}^{238}\boldsymbol{U}$

  - there are **4 primordial decay chains**



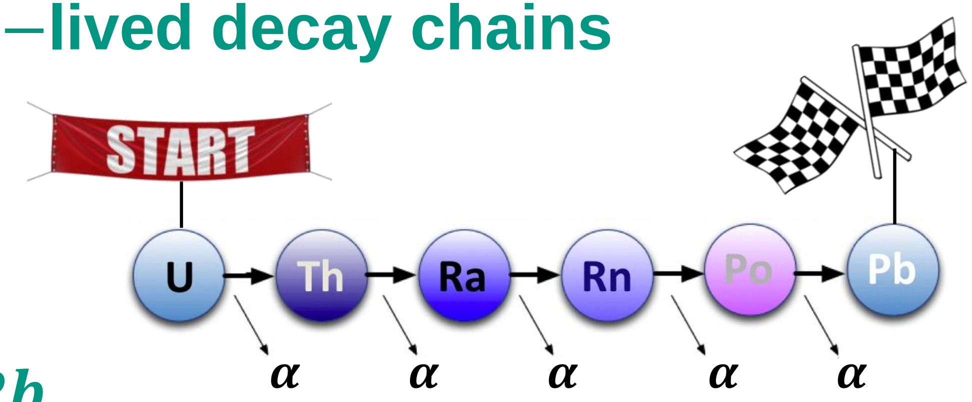


*see $\boldsymbol{ATP-2}$ summer term $\boldsymbol{2024}$

The four primordial decay chains

- natural radioactive isotopes are part of 4 long–lived decay chains

- the $\mathbf{4}$ primordial decay chains ($\mathbf{10^6} \ldots \mathbf{10^{10}}\ \boldsymbol{yr}$) are:



$^{232}Th - chain$: $A = 4 \cdot j + 0$ stable end: ^{208}Pb

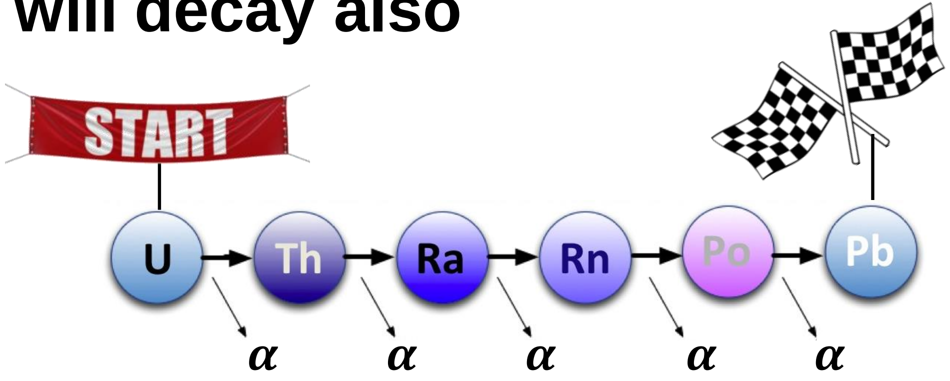
$^{237}Np - chain$: $A = 4 \cdot j + 1$ stable end: ^{209}Bi

$^{238}U - chain$: $A = 4 \cdot j + 2$ stable end: ^{206}Pb

$^{235}U - chain$: $A = 4 \cdot j + 3$ stable end: ^{207}Pb

The four primordial decay chains

- **natural radioactive isotope: daughter isotopes will decay also**



- differential equations for # **of nuclei**:

$$\frac{dN_1}{dt} = -\lambda_1 \cdot N_1$$ mother nuclide N_1: decay $(-\lambda_1)$

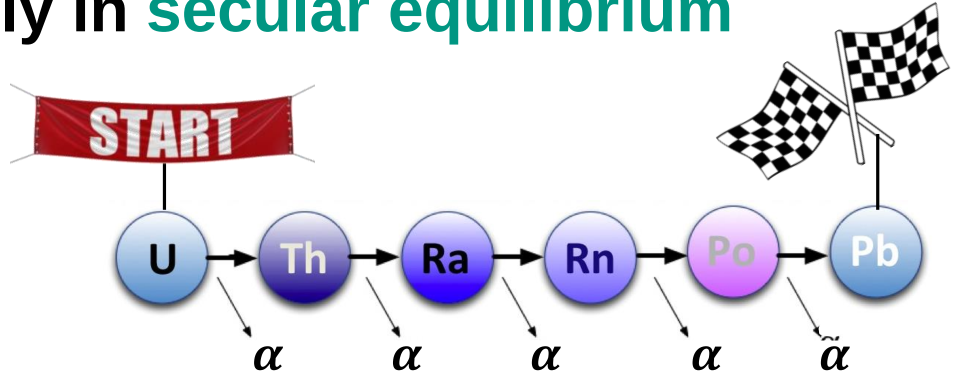
$$\frac{dN_2}{dt} = +\lambda_1 \cdot N_1 - \lambda_2 \cdot N_2$$ daughter nuclide N_2: generation $(+\lambda_1)$ & decay $(-\lambda_2)$

$$\frac{dN_3}{dt} = +\lambda_2 \cdot N_2 - \lambda_3 \cdot N_3$$ grand–daughter N_3: generation $(+\lambda_2)$ & decay $(-\lambda_3)$

$$\vdots \qquad\qquad \vdots$$

The four primordial decay chains

- **natural radioactive isotope within chain: usually in secular equilibrium**



- production & decay rates within a primordial decay chain are ***identical***:

$$\frac{dN_1}{dt} = \frac{dN_2}{dt} = \frac{dN_3}{dt}$$ **identical** decay rates of nuclides $N_1, N_2, N_3, \ldots$

$$A_1 = A_2 = A_3$$ **identical** activities $A_1, A_2, A_3, \ldots$

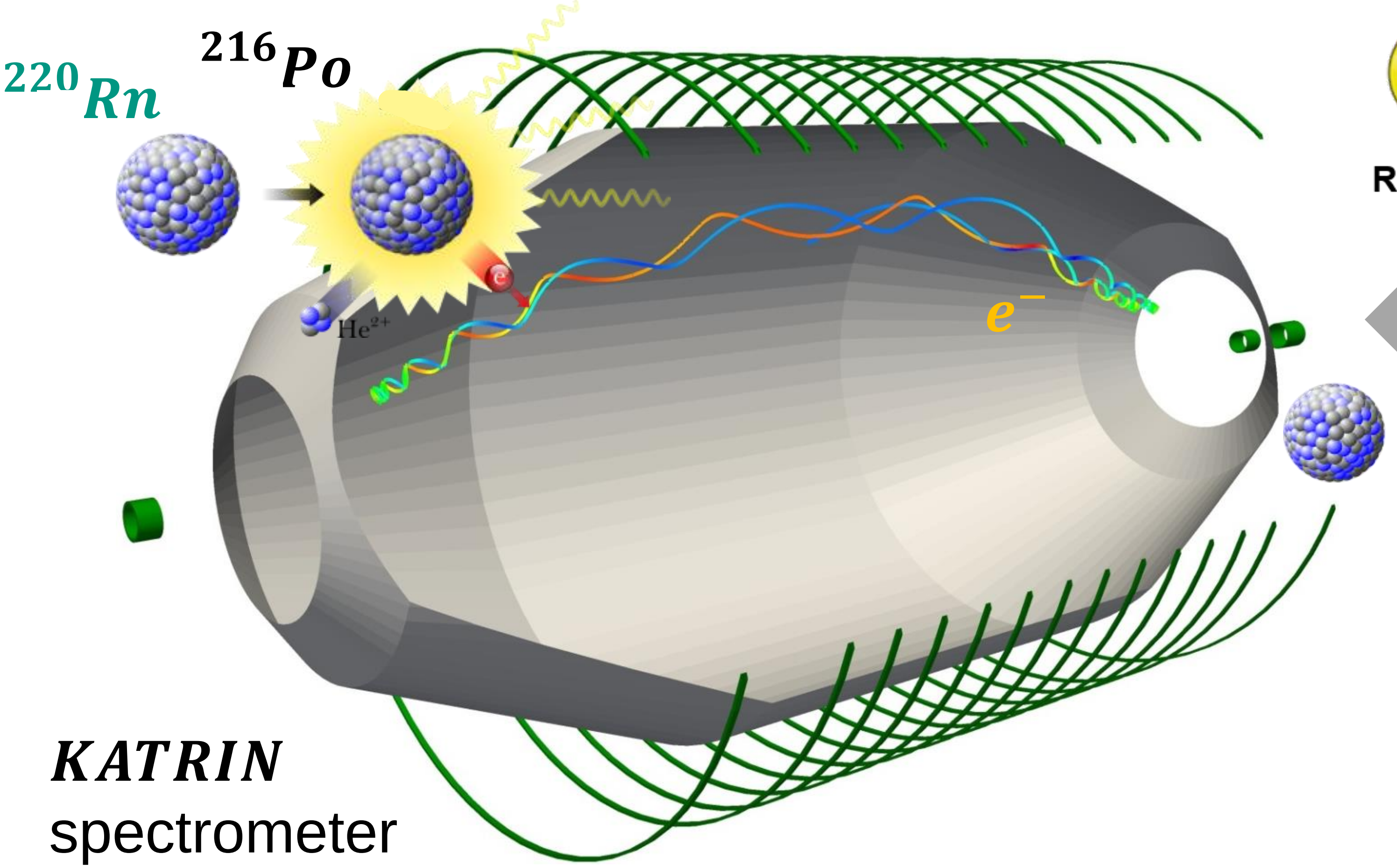
$$\lambda_1 \cdot N_1 = \lambda_2 \cdot N_2 = \lambda_3 \cdot N_3$$ **secular equilibrium*** is reached after some time

- for a specific decay chain, only activity A_j of one isotope J needs to be measured

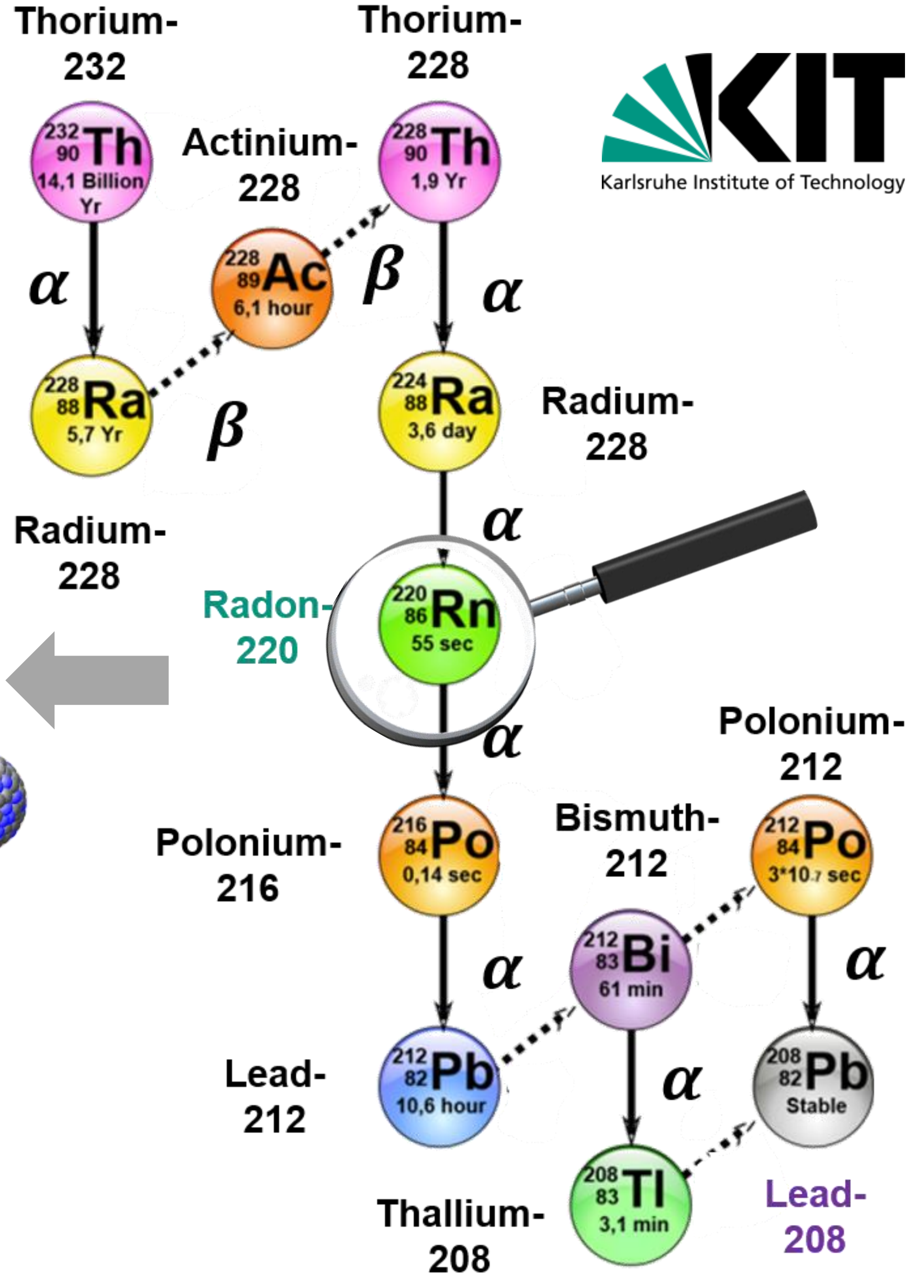
*implies that isotopes are not removed/added

Primordial decay chain of ^{232}Th

- Decay chain $^{232}Th \rightarrow {}^{208}Pb$



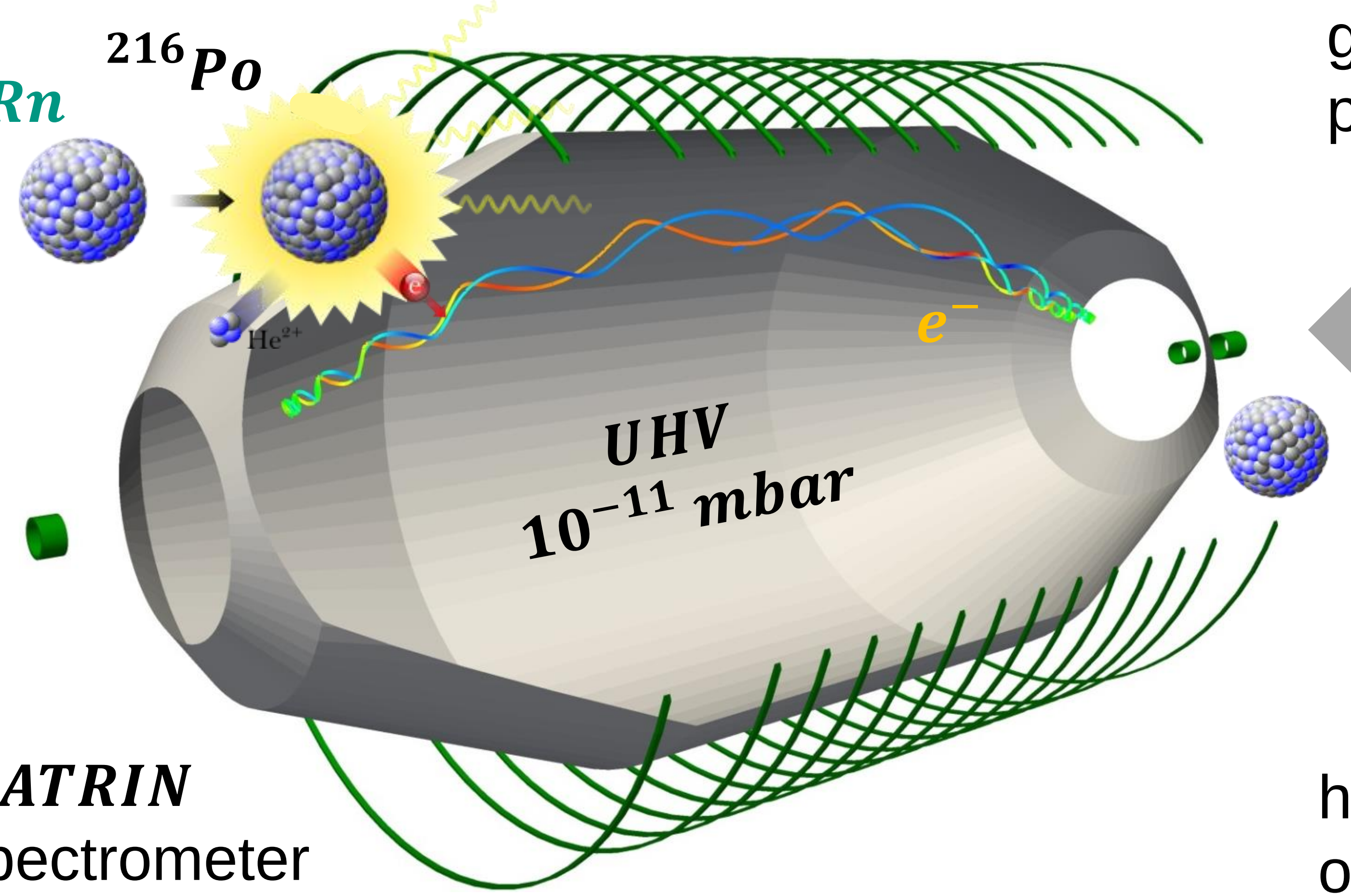
KATRIN
spectrometer



Primordial decay chain of ^{232}Th

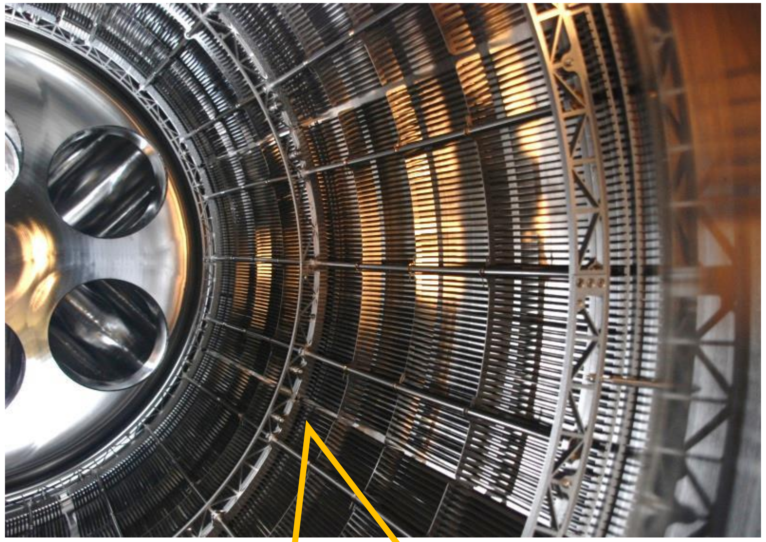
- **Decay chain $^{232}Th \rightarrow {}^{208}Pb$: emanation of gaseous ^{220}Rn generates e^-**

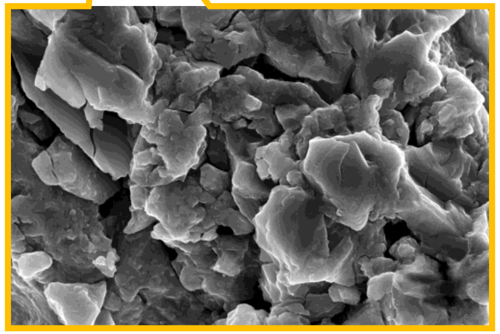
^{220}Rn ^{216}Po



$KATRIN$
spectrometer

getter
pump

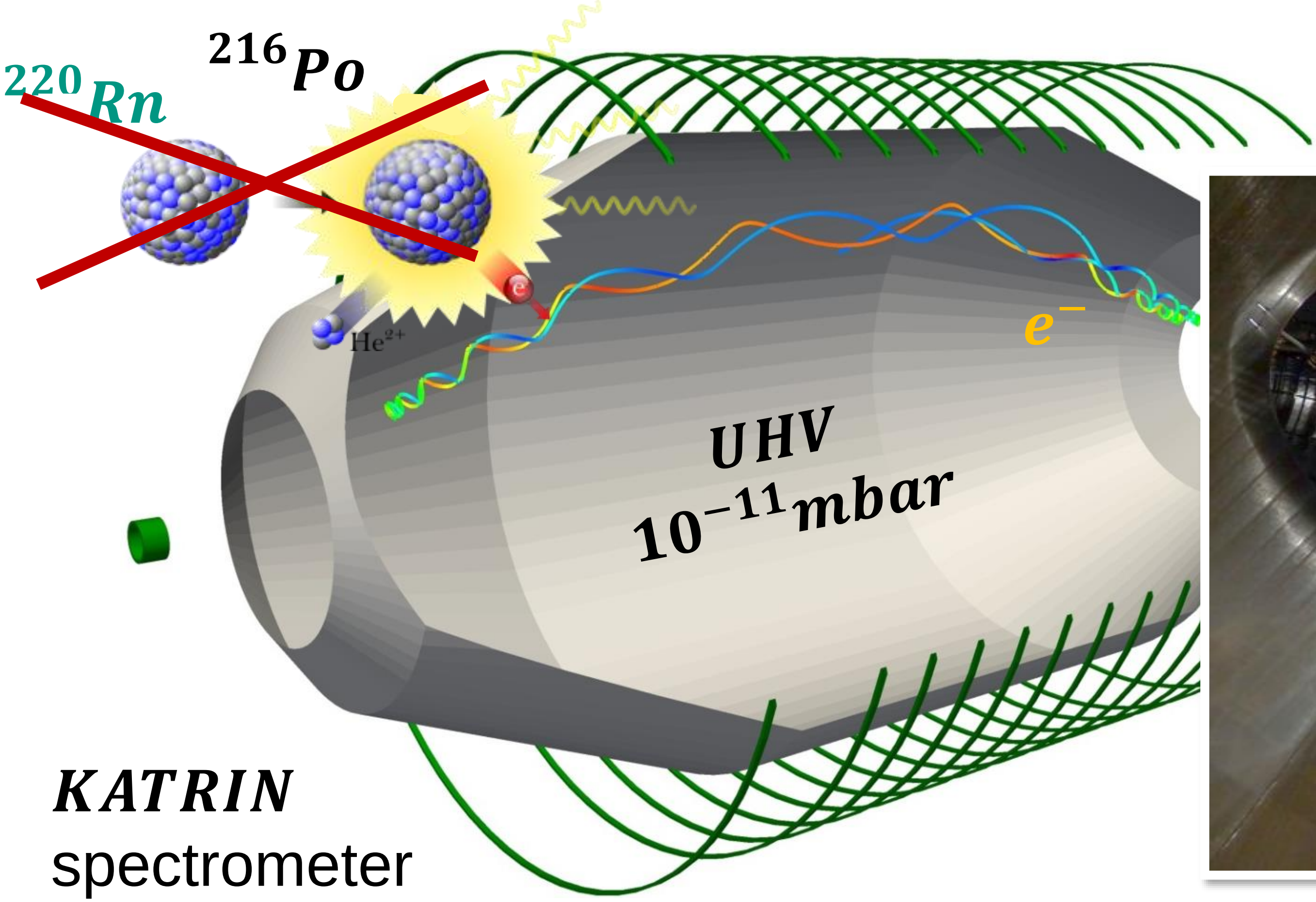




huge surface
of getter material

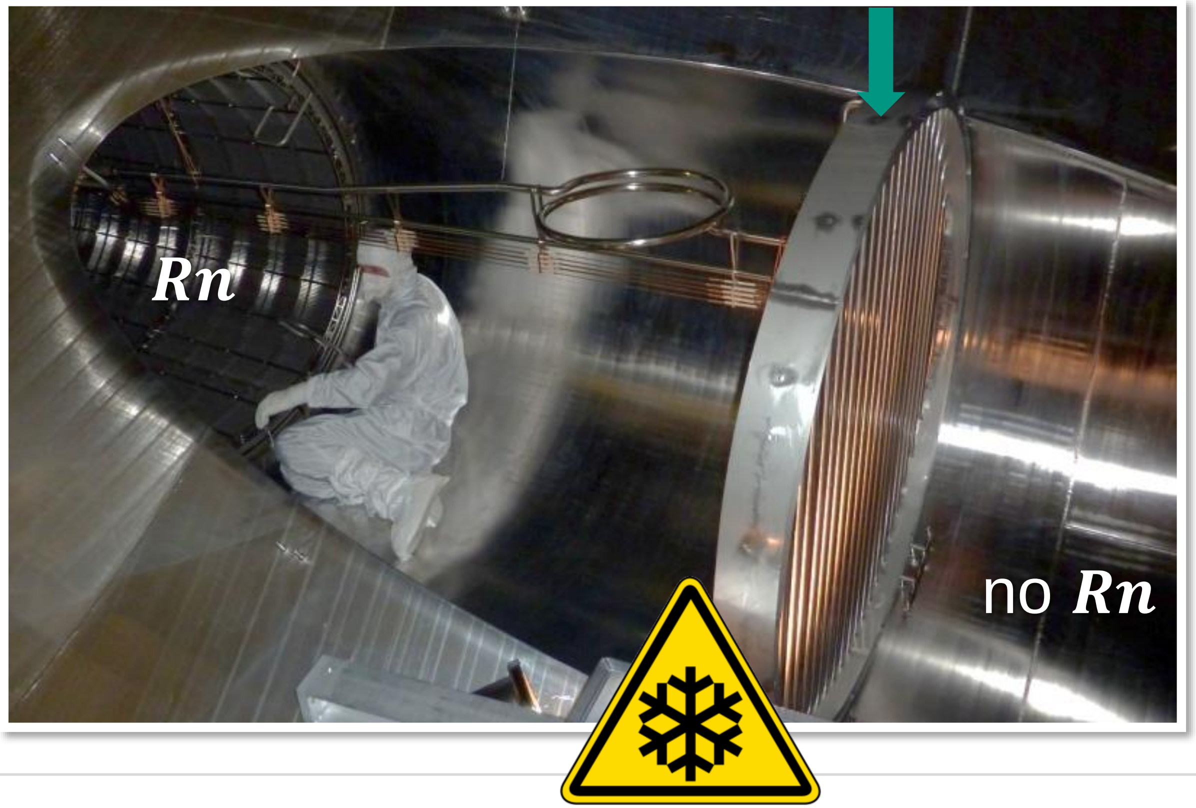
Primordial decay chain of ^{232}Th

- **Decay chain $^{232}Th \rightarrow {}^{208}Pb$: counter–meaures against gaseous ^{220}Rn atoms**



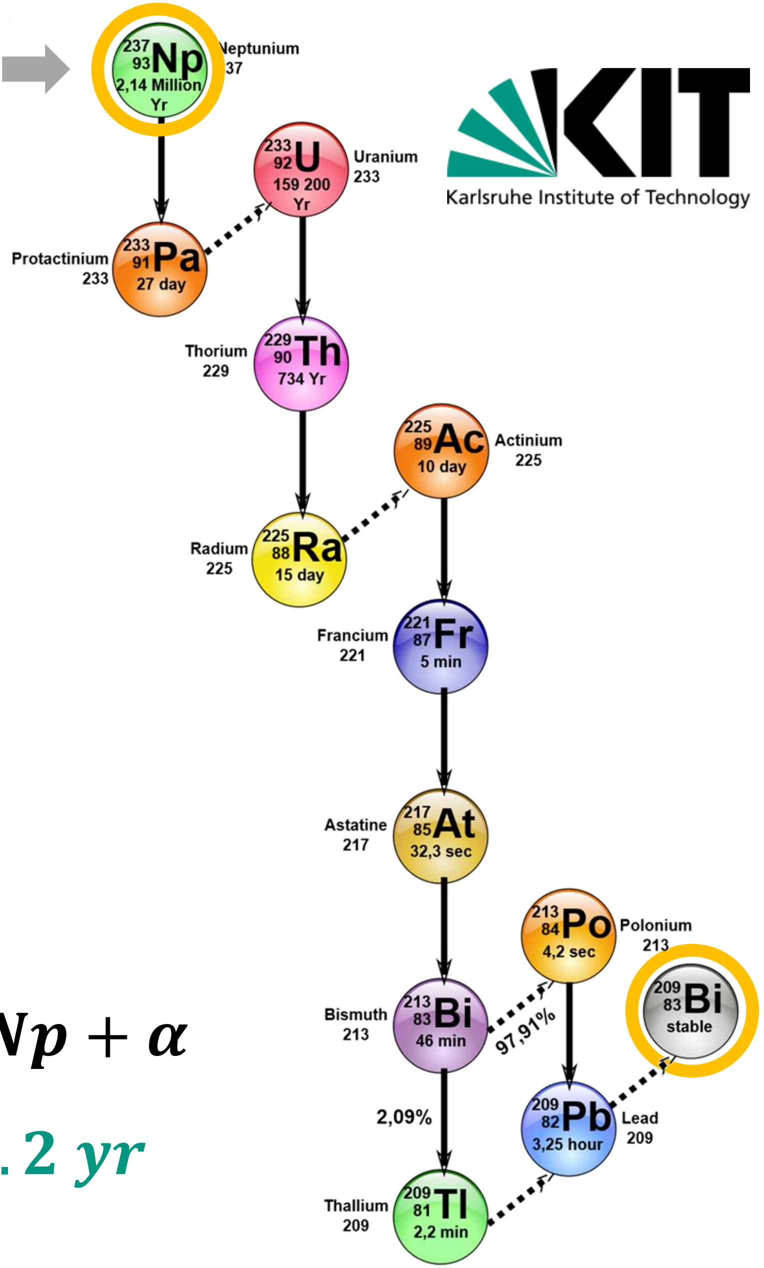
$KATRIN$
spectrometer

copper baffles at cryogenic temperature capture ^{220}Rn atoms



Primordial decay chain of ^{237}Np

^{241}Am →



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- **Decay chain** $^{237}Np \rightarrow {}^{209}Bi: t_{½} = 2.1 \cdot 10^{6}\ yr$

  artificial mother isotope ^{241}Am

  - smoke detectors sometimes contain isotope ^{241}Am

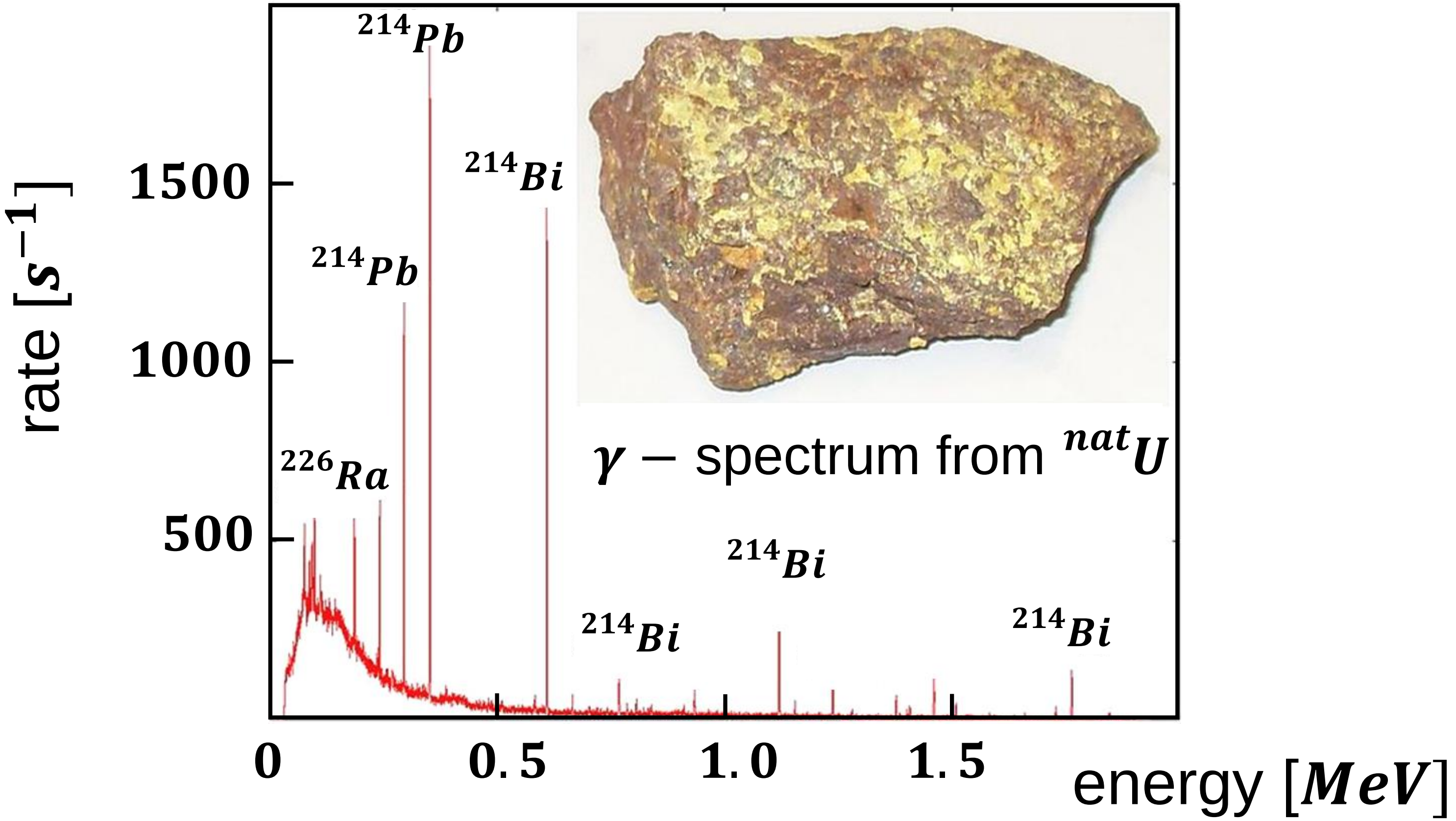
$$^{241}Am \rightarrow {}^{237}Np + \alpha$$

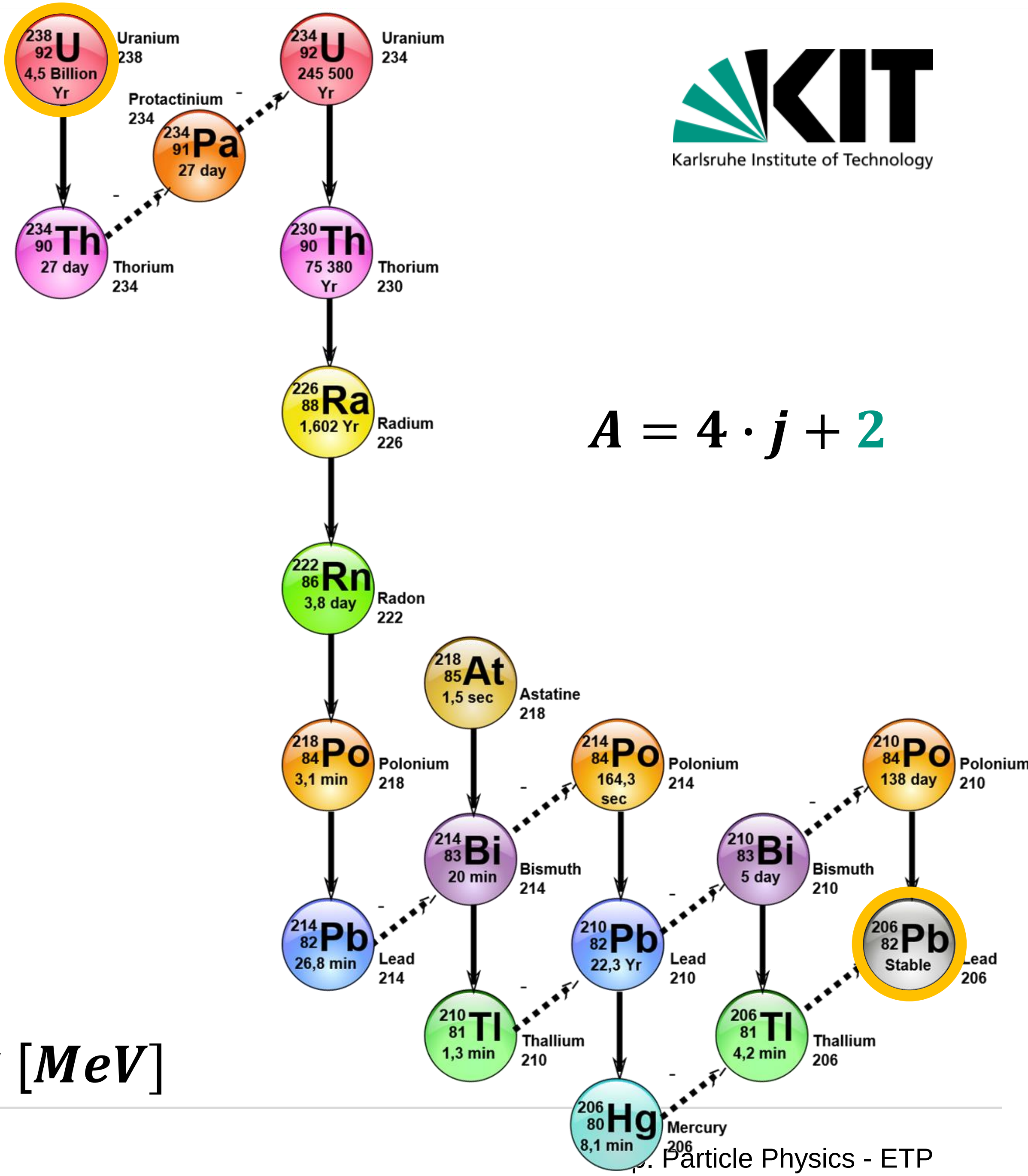
$$t_{½} = 432.2\ yr$$

Primordial decay chain of ^{238}U

- Decay chain $^{238}U \rightarrow {}^{206}Pb$

  $t_{½} = 4.5 \cdot 10^9\ yr$

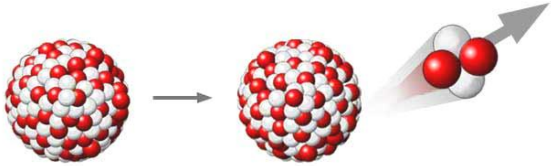




$A = 4 \cdot j + 2$

Primordial decay chain of ^{238}U

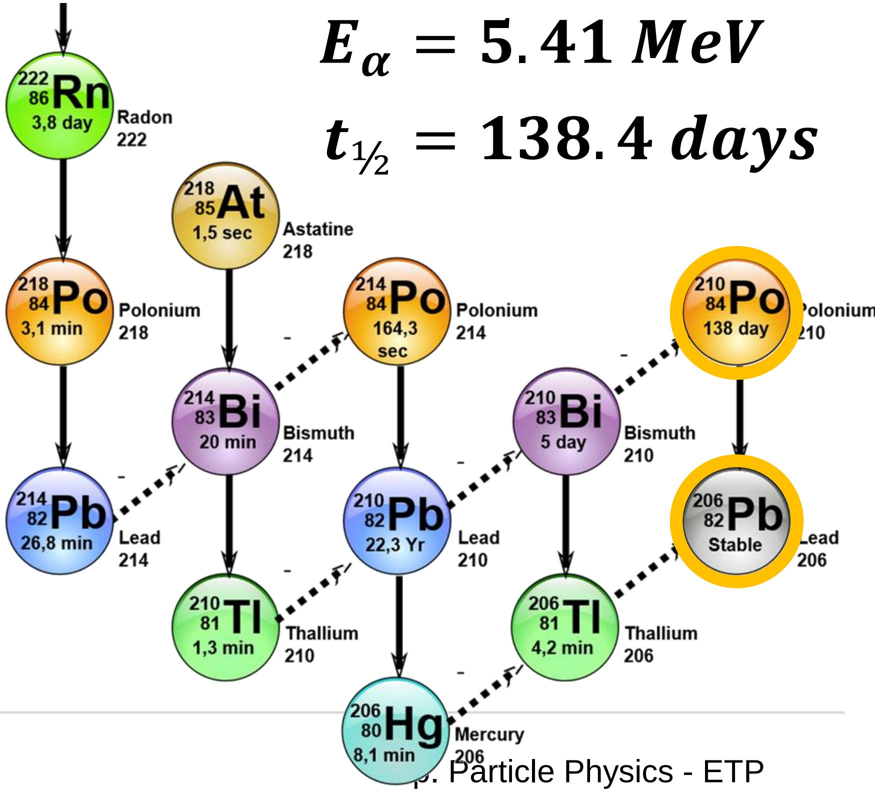
- Decay chain $^{238}U \rightarrow {}^{206}Pb$: α – decay of ^{210}Po
  - **1951**: Gilbert´s Atomic Energy Lab (**49.50 $**)
  - included were **2** α – sources: ^{210}Po & ^{210}Pb



^{210}Po – source

$E_\alpha = 5.41\ MeV$

$t_{1/2} = 138.4\ days$



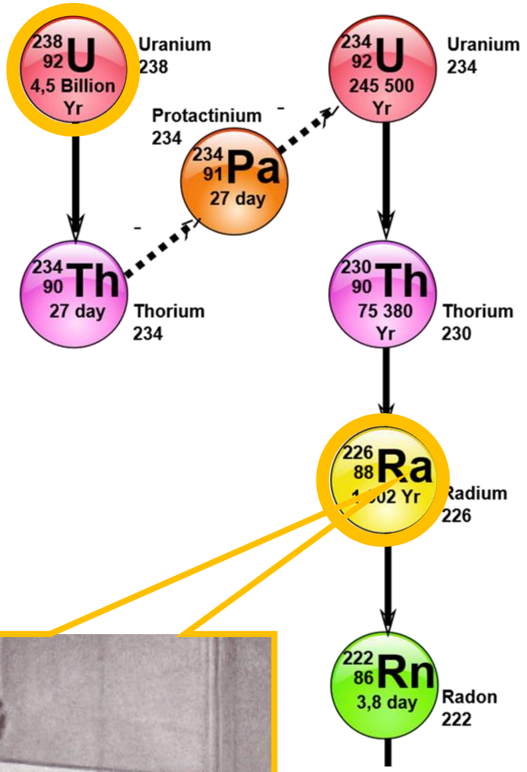
Primordial decay chain of ^{238}U

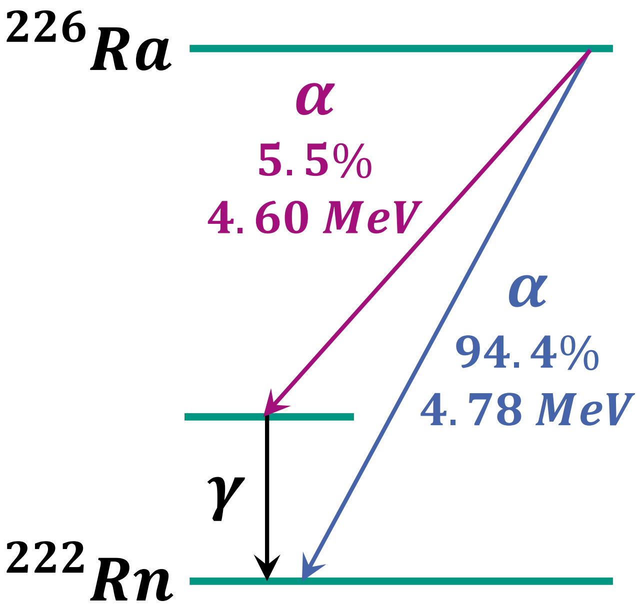
- **Decay chain $^{238}U \rightarrow {}^{206}Pb$**

  $\alpha -$ **decay of ^{226}Ra**

  $t_{½} = 1602\ yr$

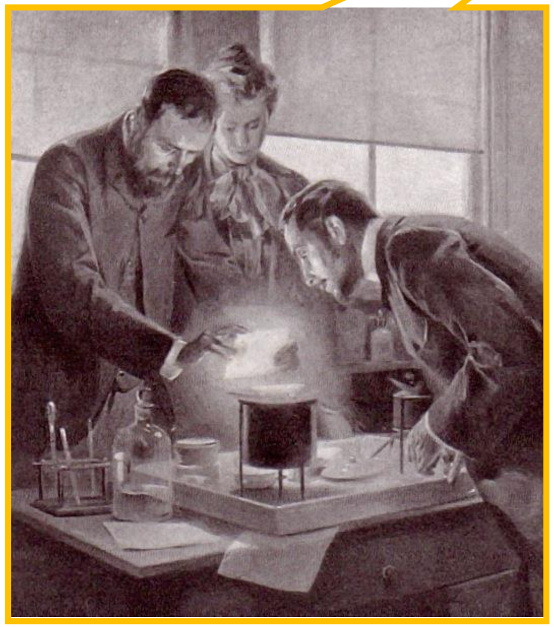
- discovery of ^{226}Ra
  by **Pierre** & **Marie Curie**





$1\ Curie\ = 3.7 \cdot 10^{10}$ decays / s

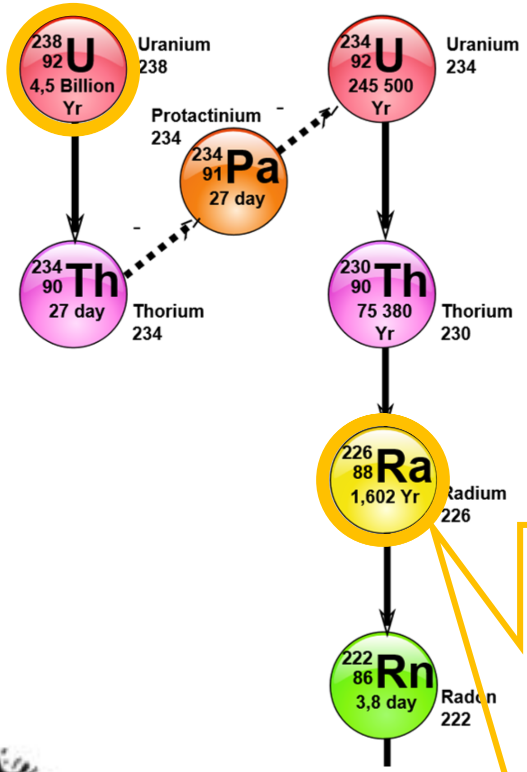
$1\ Ci \equiv$ **activity of $1\ g$ radium,**
more specifically ^{226}Ra

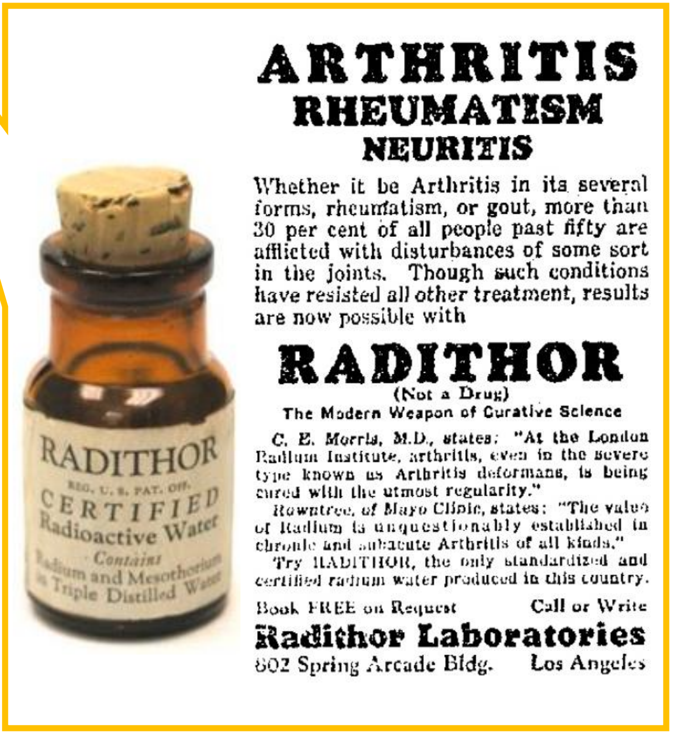


Nobel prize
in physics
1903 to both

Primordial decay chain of ^{238}U

- **Decay chain $^{238}U \rightarrow {}^{206}Pb$**
  - radium water (Radithor) / chocolate
  - radium was in use as ´convenient´ **illuminant for watches**



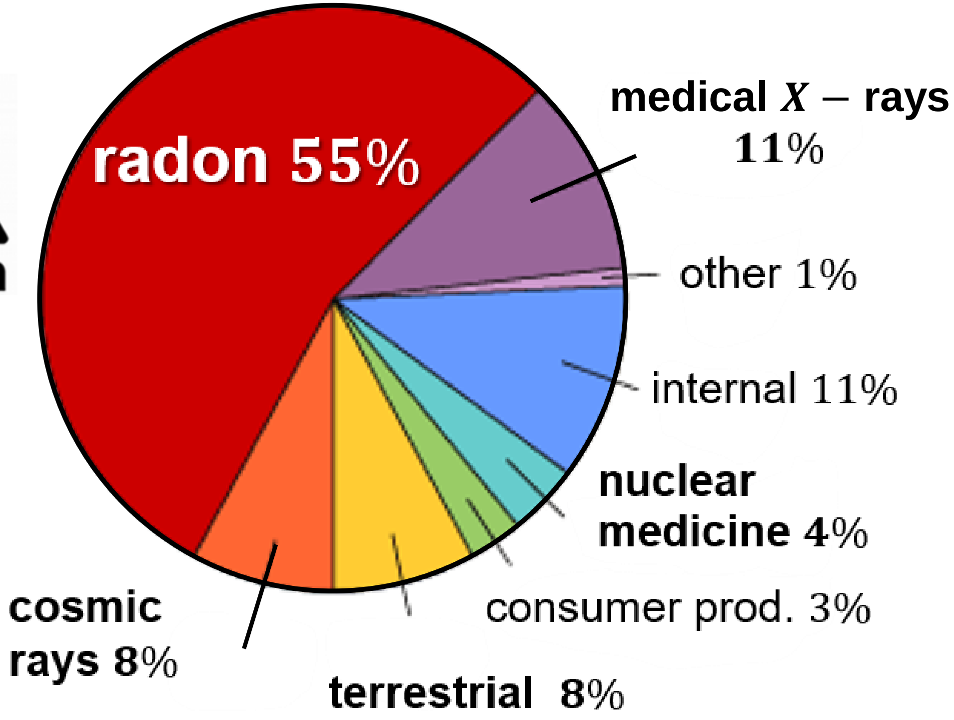


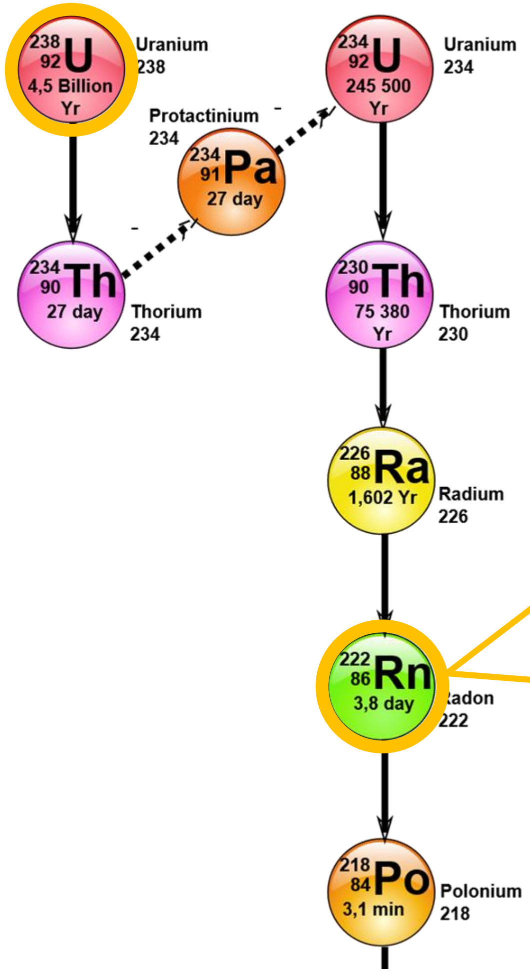
Primordial decay chain of ^{238}U

- Decay chain $^{238}U \rightarrow {}^{206}Pb$

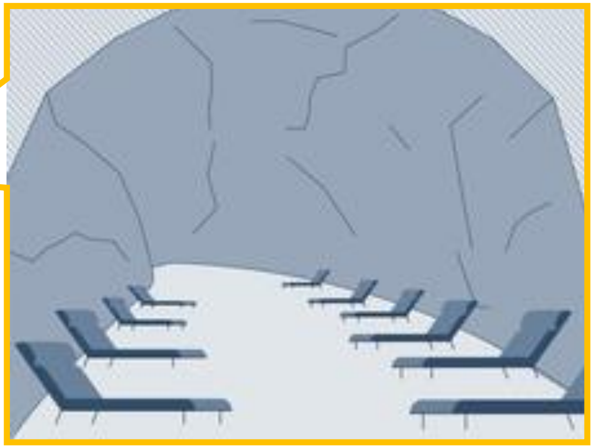
  $\alpha -$ decay of ^{222}Rn

  $t_{½} = 3.82$ days





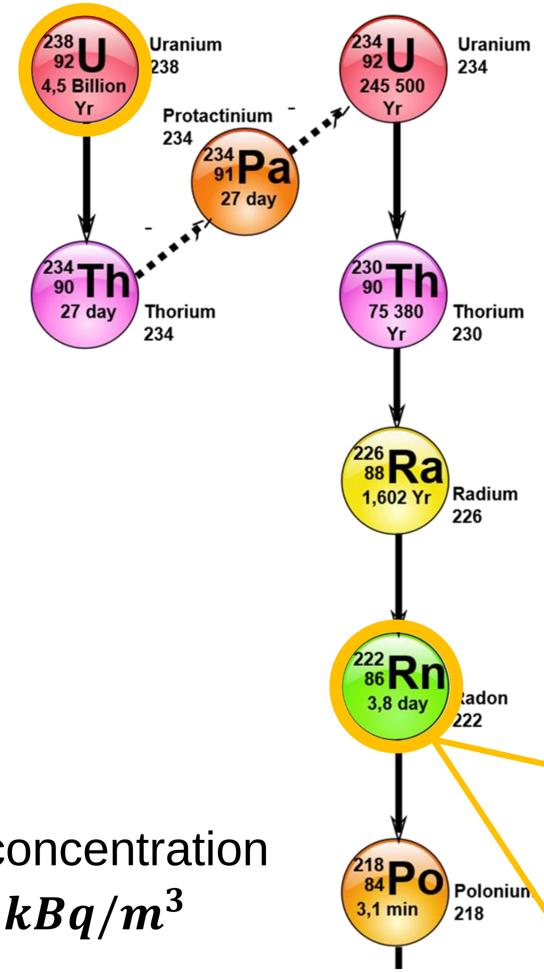
radon ´therapy´ in **underground** tunnels*



- radon emanation & average radiation exposure

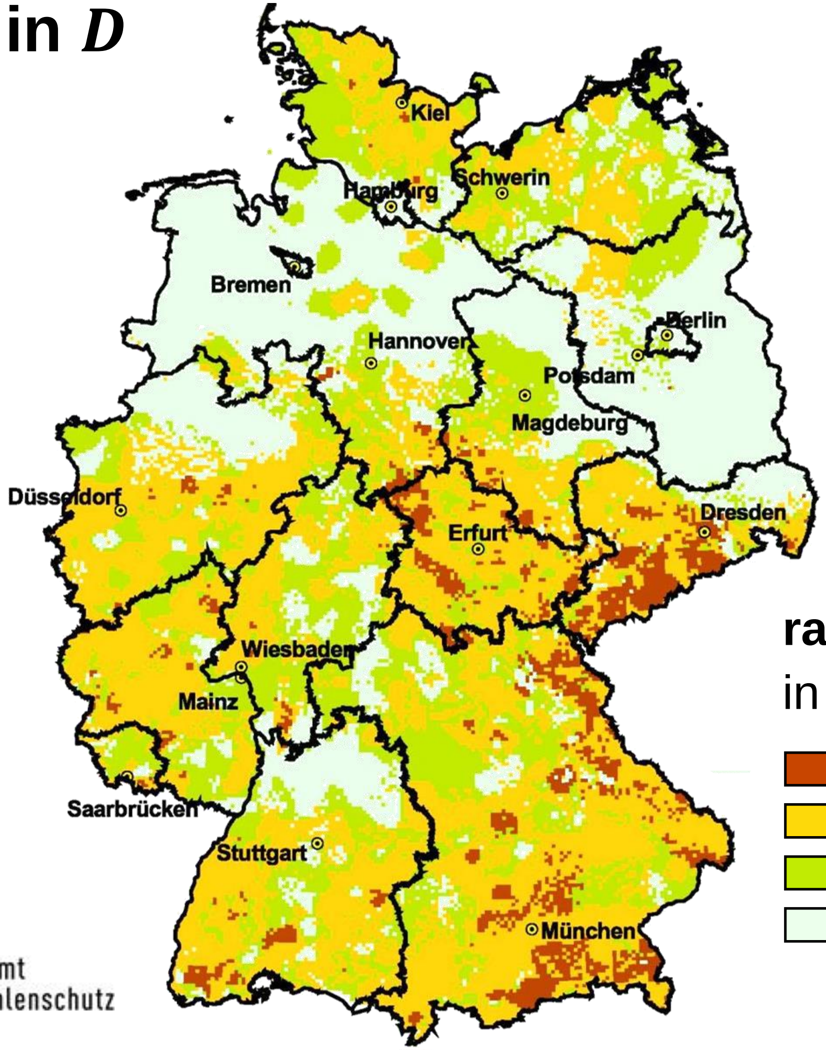
*see Bundesamt für Strahlenschutz

Primordial decay chain of ^{238}U



$\sim 50\ Bq/m^3$

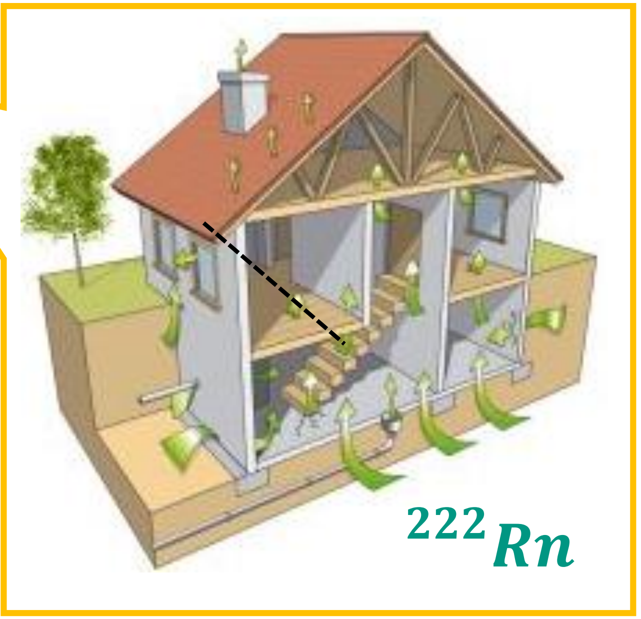
- Radon in D



radon concentration in air in kBq/m^3

- > 100
- $40 \ldots 100$
- $20 \ldots 40$
- < 20

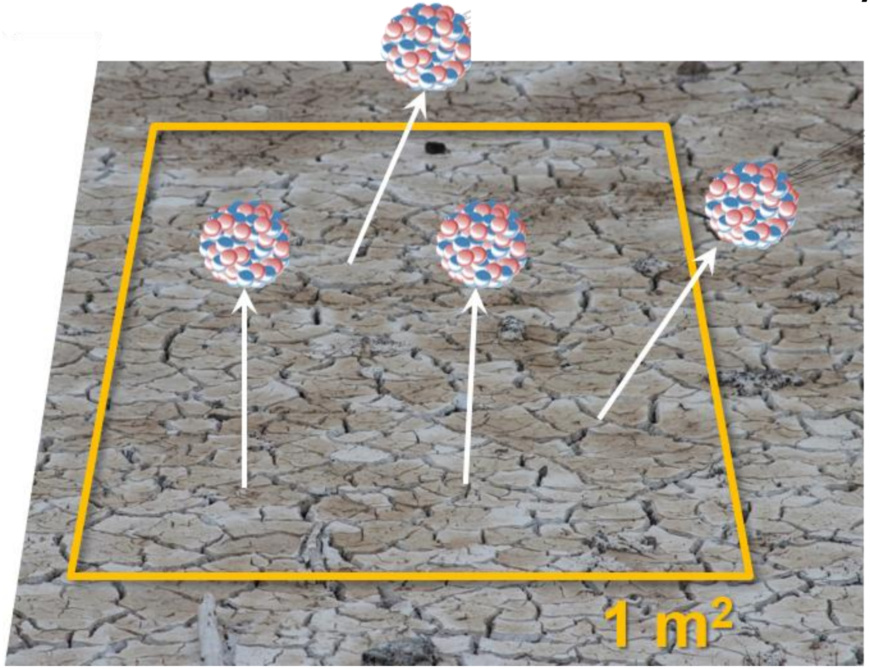
Bundesamt für Strahlenschutz



Primordial decay chain of ^{238}U

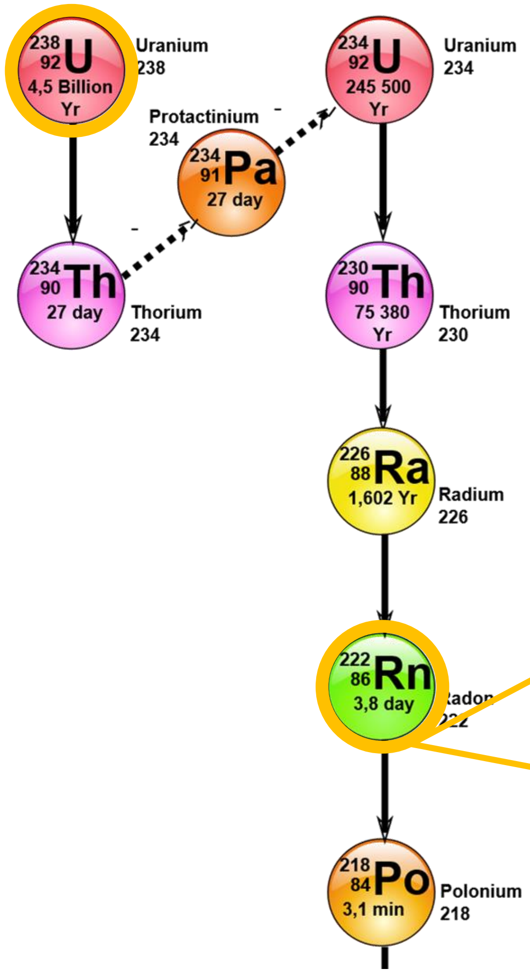
- Radon emanation per m^2 of soil

$\sim 7400\ {}^{222}Rn -$ atoms / s



$= 0.5\ pCi/s$
$= 1\ \mu Ci$ per ton

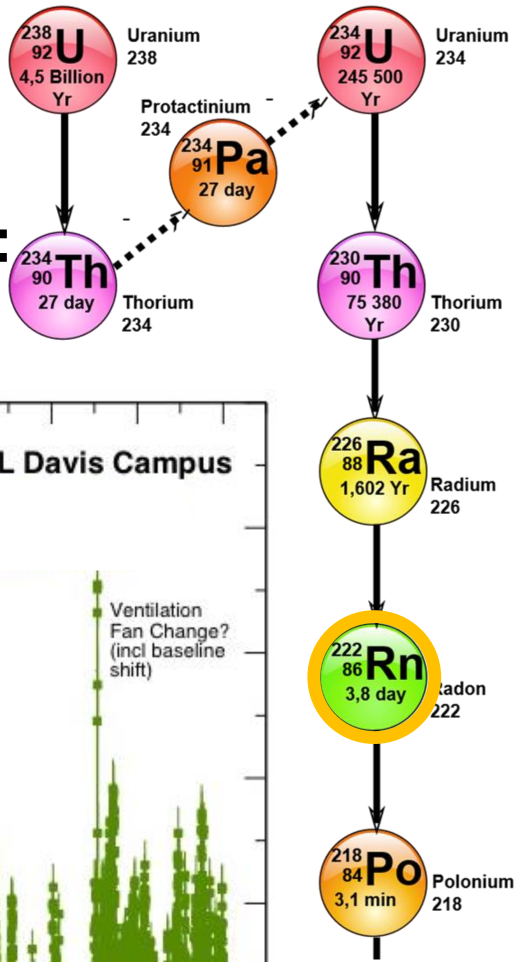
due to ^{222}Rn



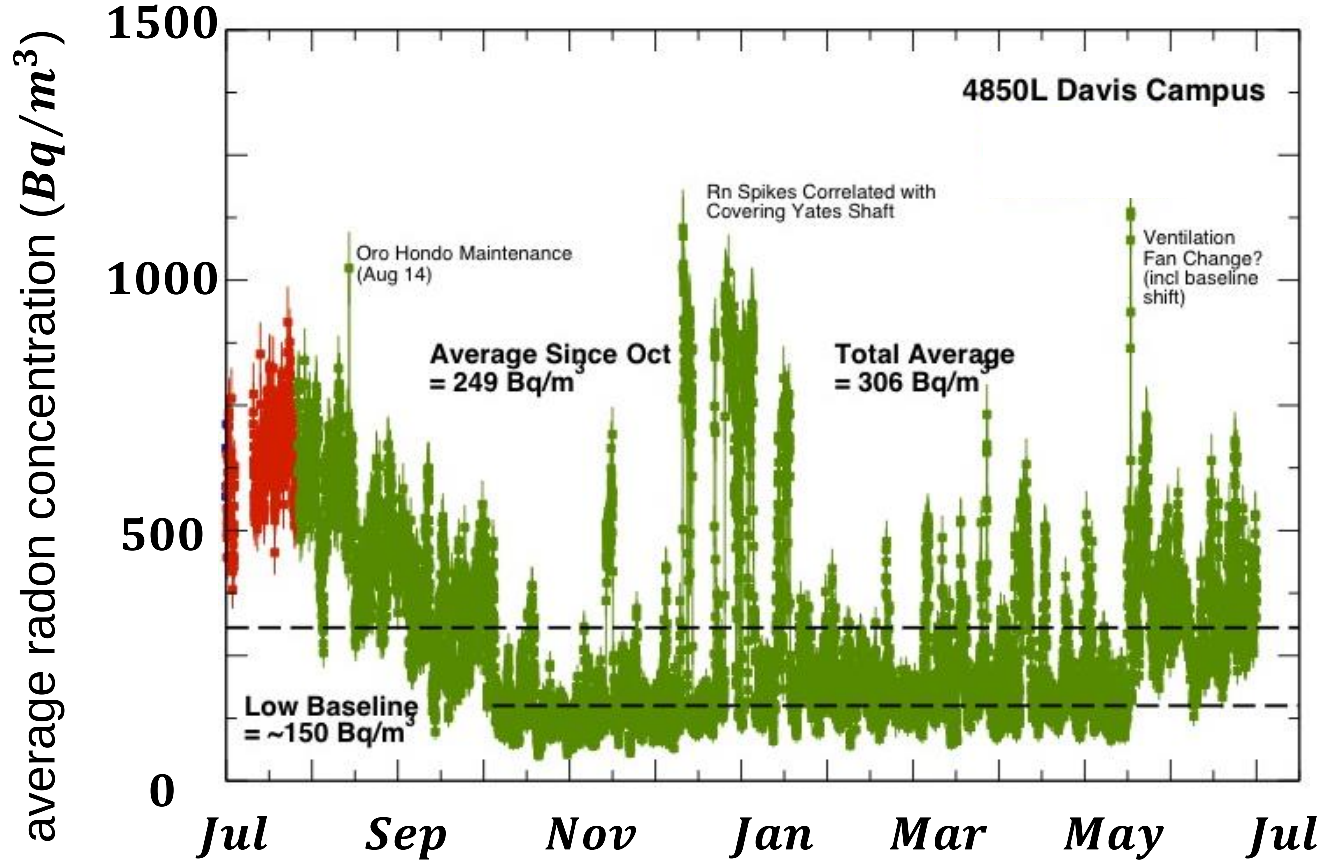
- yearly activity (over entire surface) from $^{222}Rn -$ emanation: **91 TBq**

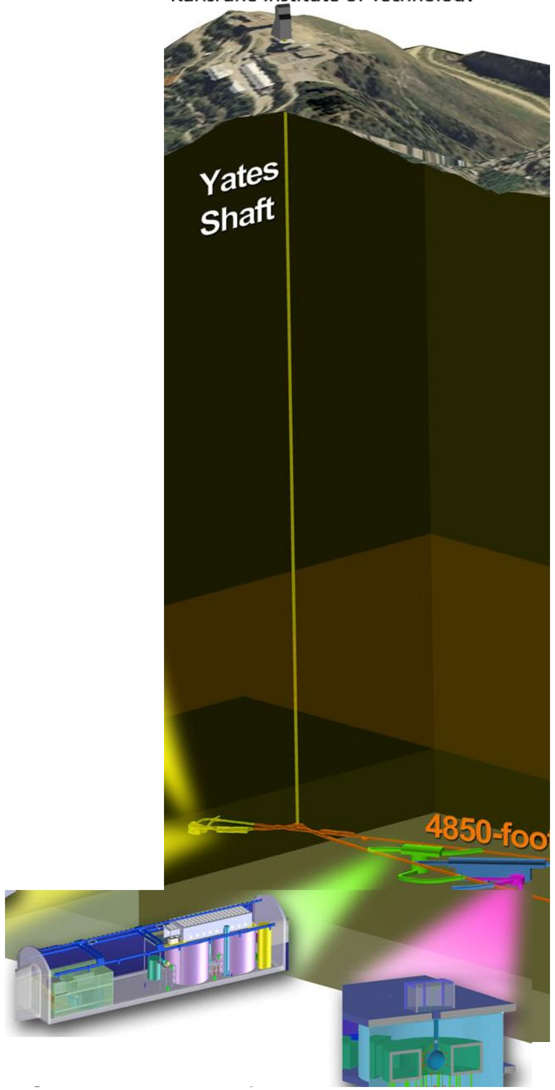
Primordial decay chain of ^{238}U

- Radon emanation in **underground labs**: permanent venting & monitoring



is a noble gas





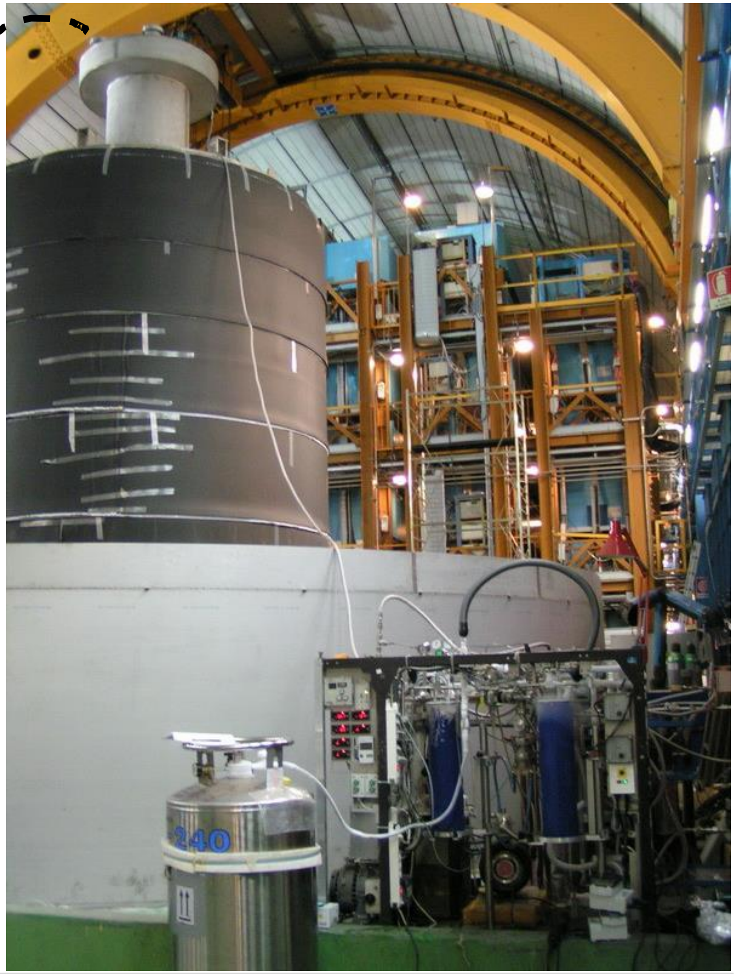
Primordial decay chain of ^{238}U

- **Radon emanation in underground experiments: example $GERDA$ $(0\nu\beta\beta)$**

  - requires careful **assessment of radon emanation** of all detector components

  - example in astroparticle physics: measurement of radon emanation in the $\boldsymbol{GERDA}$ cryostat at $\boldsymbol{LNGS}$

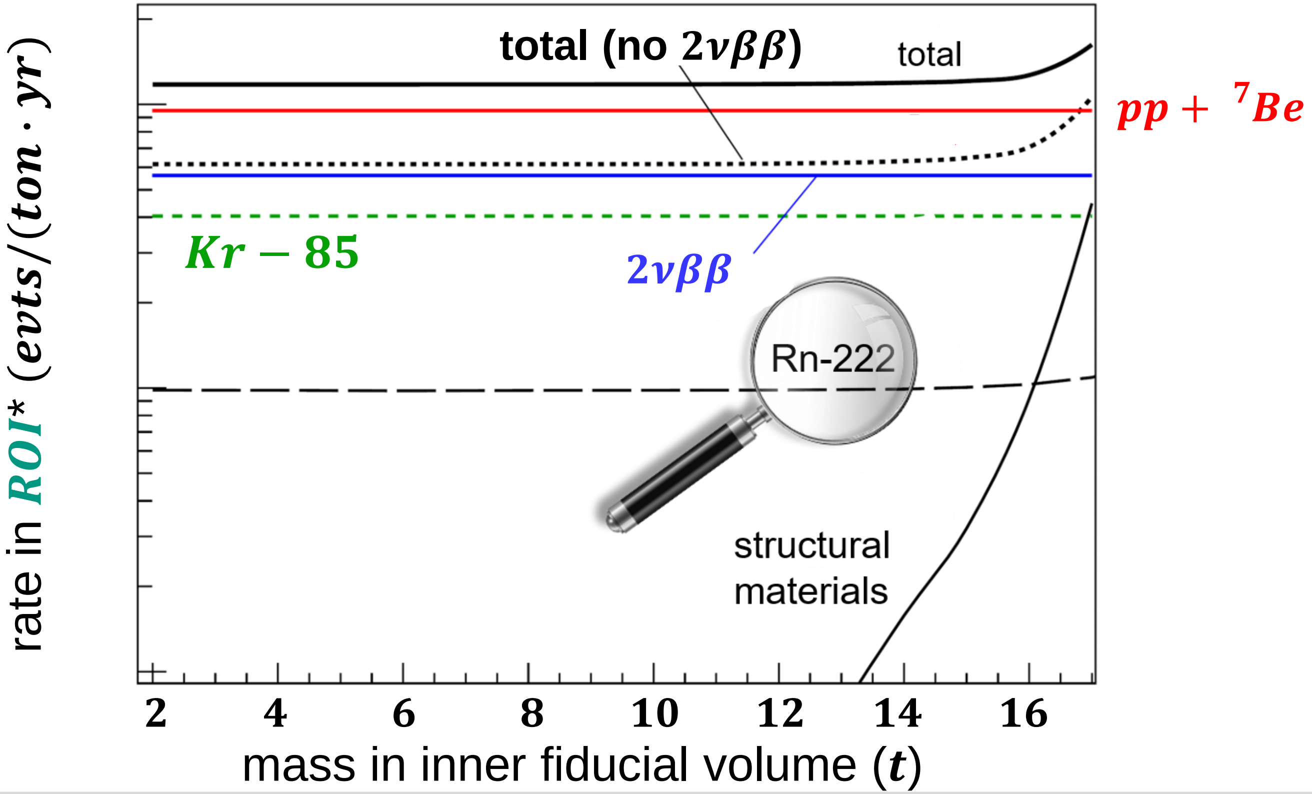
  - stringent material selection as to radon emanation („***screening***“)

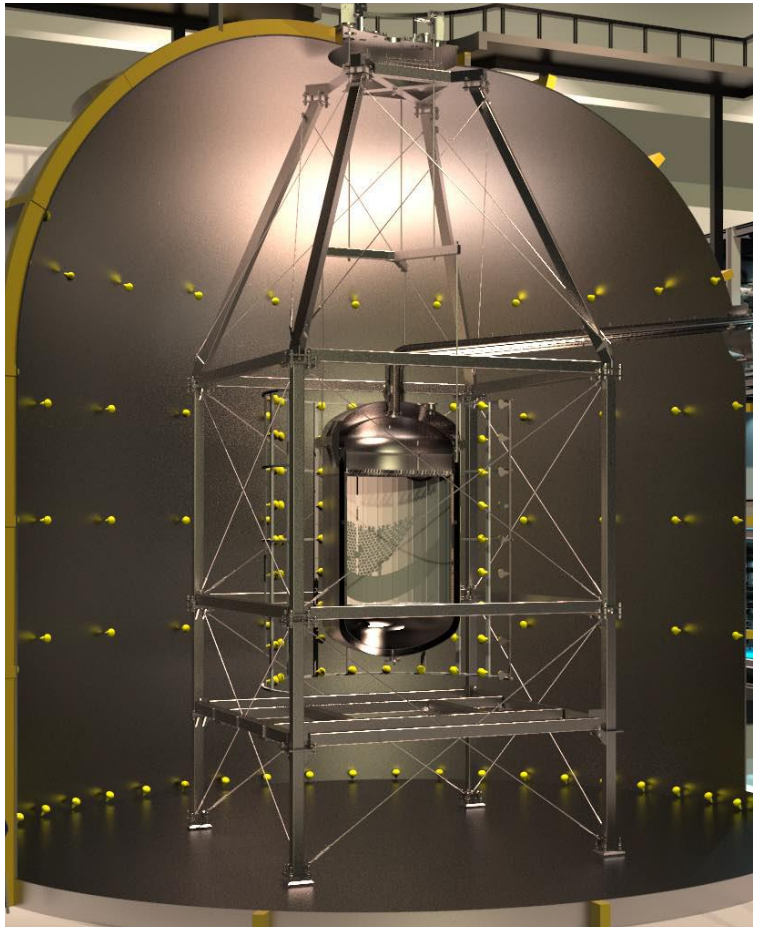


Primordial decay chain of ^{238}U

- **Radon emanation in underground experiments: example $DARWIN$**

  - $Xenon$ purification & coating of materials:
    $R\&D$ works for most sensitive DM search **ever**





$^*ROI$ = $r$egion–of–$i$nterest (signal energy)

evaluation period – Dec. 4 – 16, 2023

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- **Please evaluate the *ATP – I* lectures & exercises/tutorials**

lectures: QR – code & link

https://onlineumfrage.kit.edu/evasys/online.php?p=C7YNV

exercises & tutorials: QR – code & link

https://onlineumfrage.kit.edu/evasys/online.php?p=4H73K