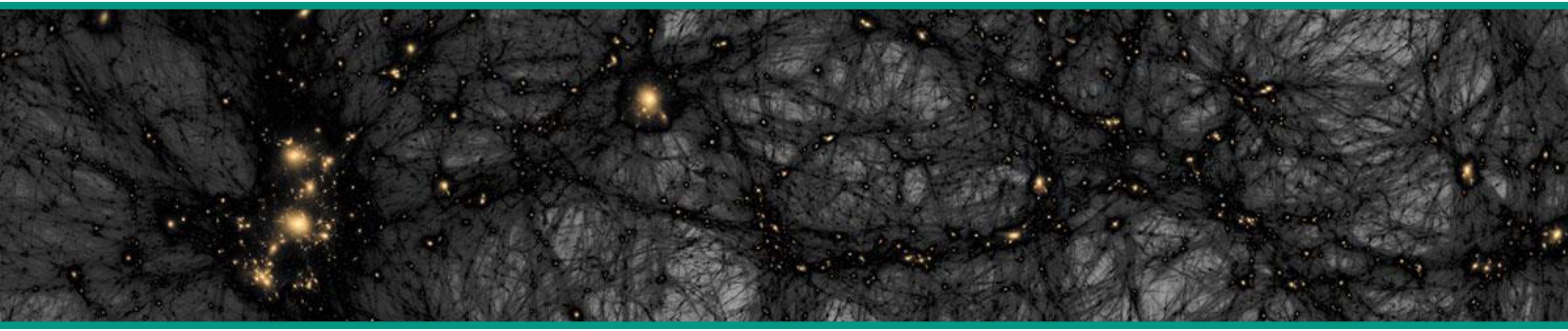
Astroparticle physics I – Dark Matter

WS22/23 Lecture 10 Dec. 7, 2022



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-γ –sources

  - detetector background: intrinsic & cosmic-induced

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

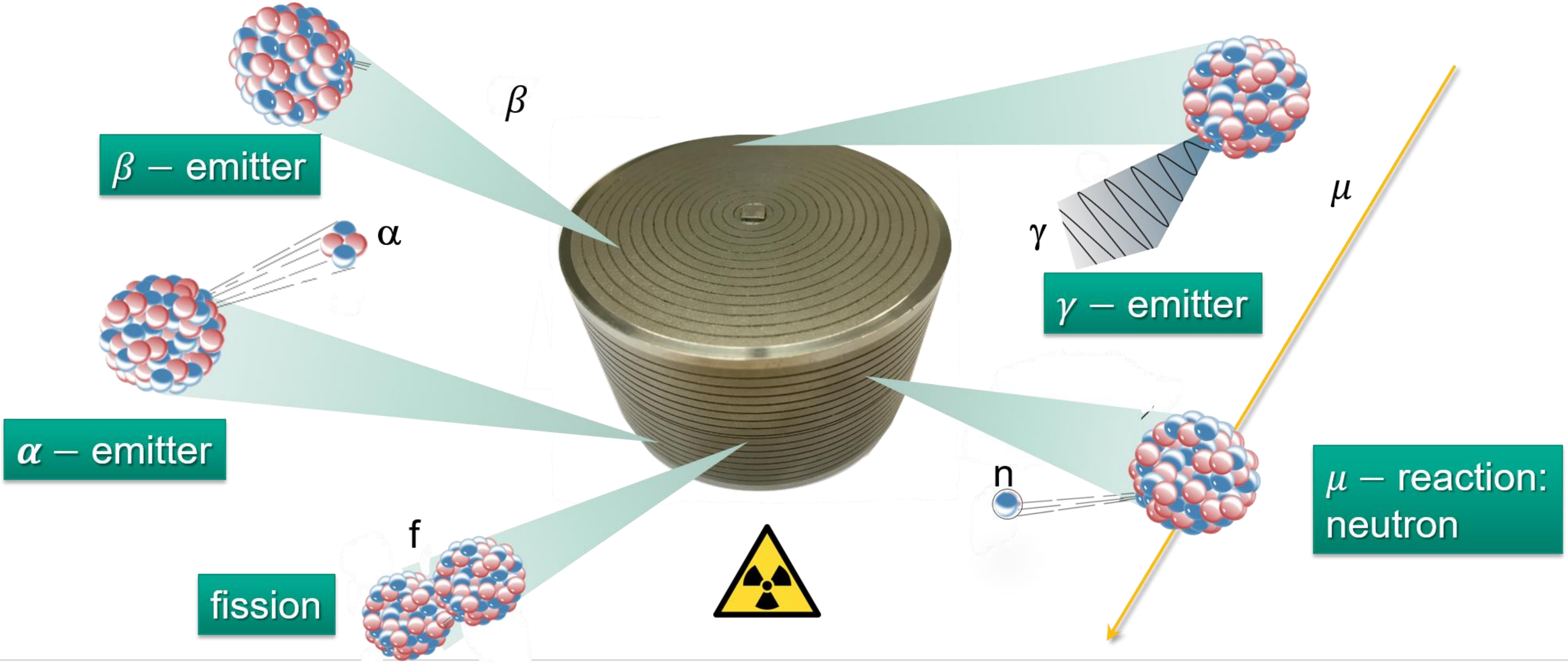
  - activity A: in Bq/Ci , decreases exponentially (τ)

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

  - calibration sources: an important tool in detector modelling

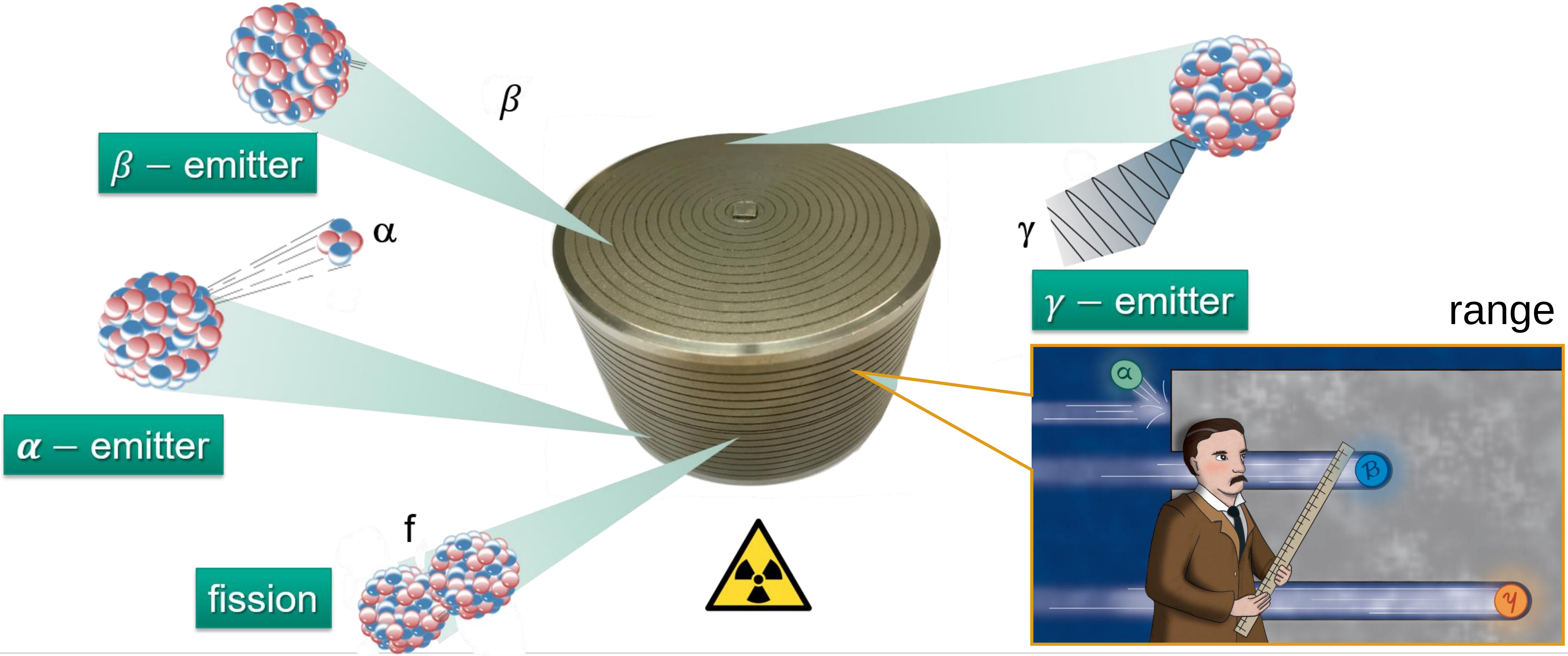
Decay processes – intrinsic detector activity

- Intrinsic activity of detector & surrounding materials is a major challenge



Decay processes – intrinsic detector activity

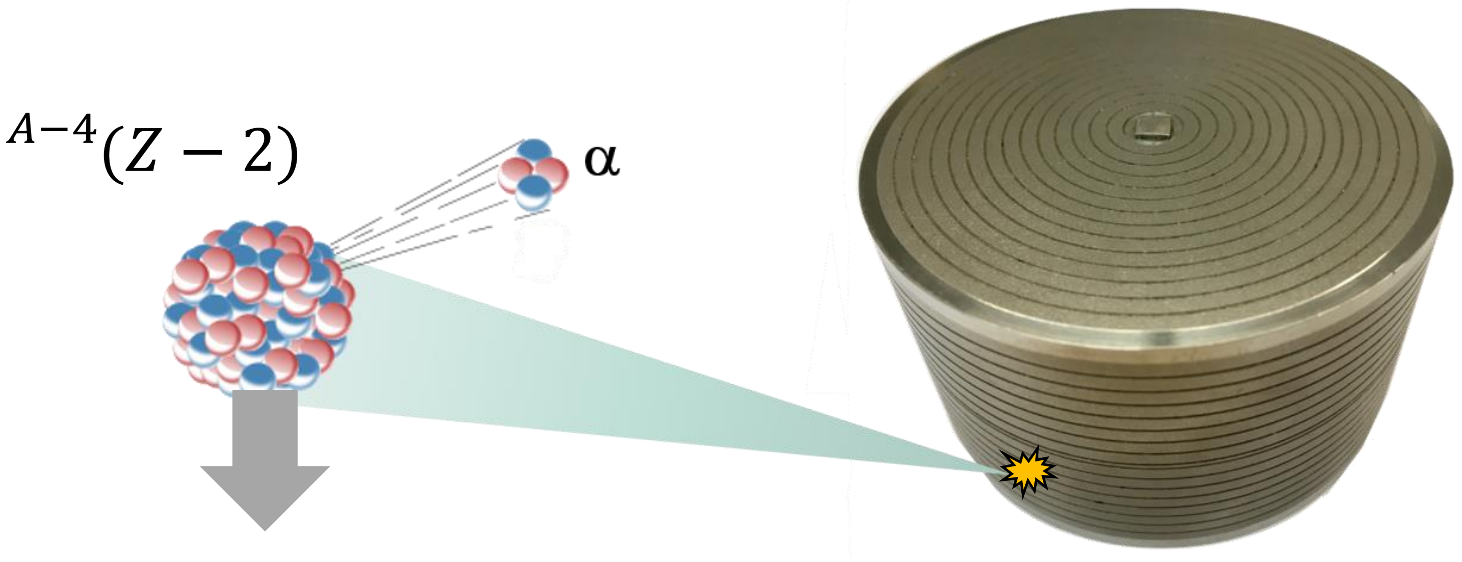
- Intrinsic activity of detector & surrounding materials is a major challenge



RECAP: Decay processes – the $\alpha-$decay

- **Single $\alpha-$decays often are part of a much larger (primordial) decay chain**

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



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

  a) *external* decay in material surrounding detector:
  ⇨ α is stopped close to surface

  b) *internal* decay in detector:
  ⇨ α is stopped close decay
  ⇨ sucessive decays there

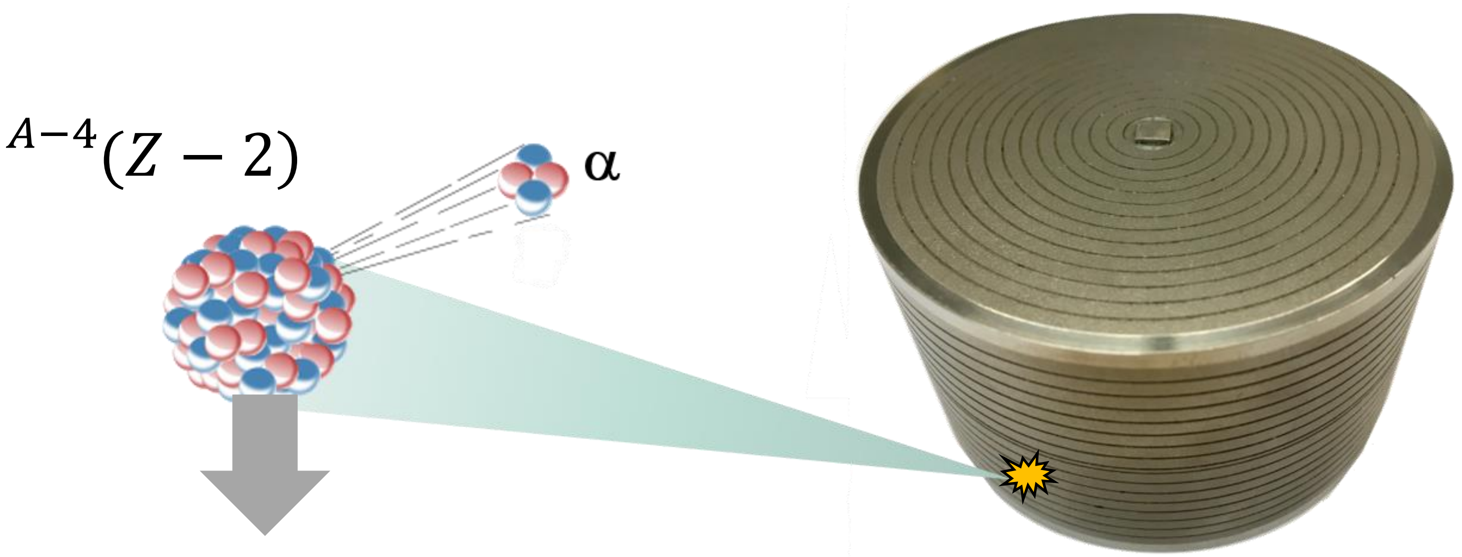
- **recoil ion**: extremely short (μm) range due to strong ionization of detector material (Bethe formula: large dE/dx value)

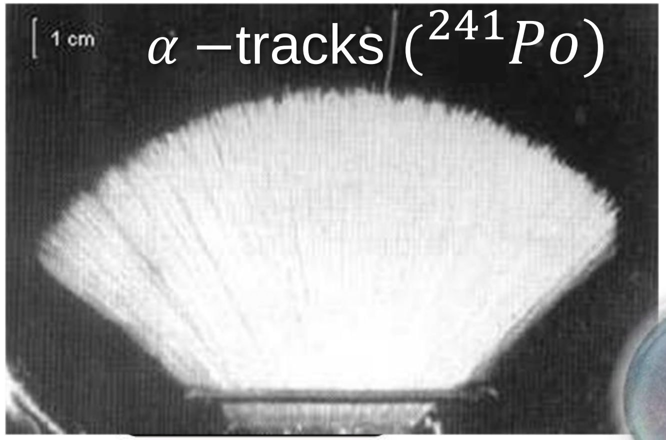
RECAP: Decay processes – the $\alpha -$ decay

- **Single $\alpha -$ decays often are part of a much larger (primordial) decay chain**

  - huge variation in half-lifes $t_{½}$ of $\alpha -$ decaying isoptopes (Geiger-Nuttall law*)

  - **$\alpha -$ particle (monoenergetic)**:





$Po -$ source

- slowest $\boldsymbol{\alpha}$ –decay: $^{232}Th \rightarrow {}^{228}Ra + \alpha \quad t_{½} = 1.4 \cdot 10^{10}\ yr \Leftrightarrow E_\alpha = 3.9\ MeV$
- fastest $\boldsymbol{\alpha}$ –decay: $^{212}Po \rightarrow {}^{208}Pb + \alpha \quad t_{½} = 3.5 \cdot 10^{-7}\ s \Leftrightarrow E_\alpha = 8.95\ MeV$

*see Mod Ex Phys III

Background processes: reduction & mitigation

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

  - very stringent selection of **detector materials:** screening of each PMT, each signal cable, everything…

  - **clean room conditions** during assembly

  - active elements (electronics, DAQ, cooling) have to be separated from detection volume

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

Background processes: reduction & mitigation

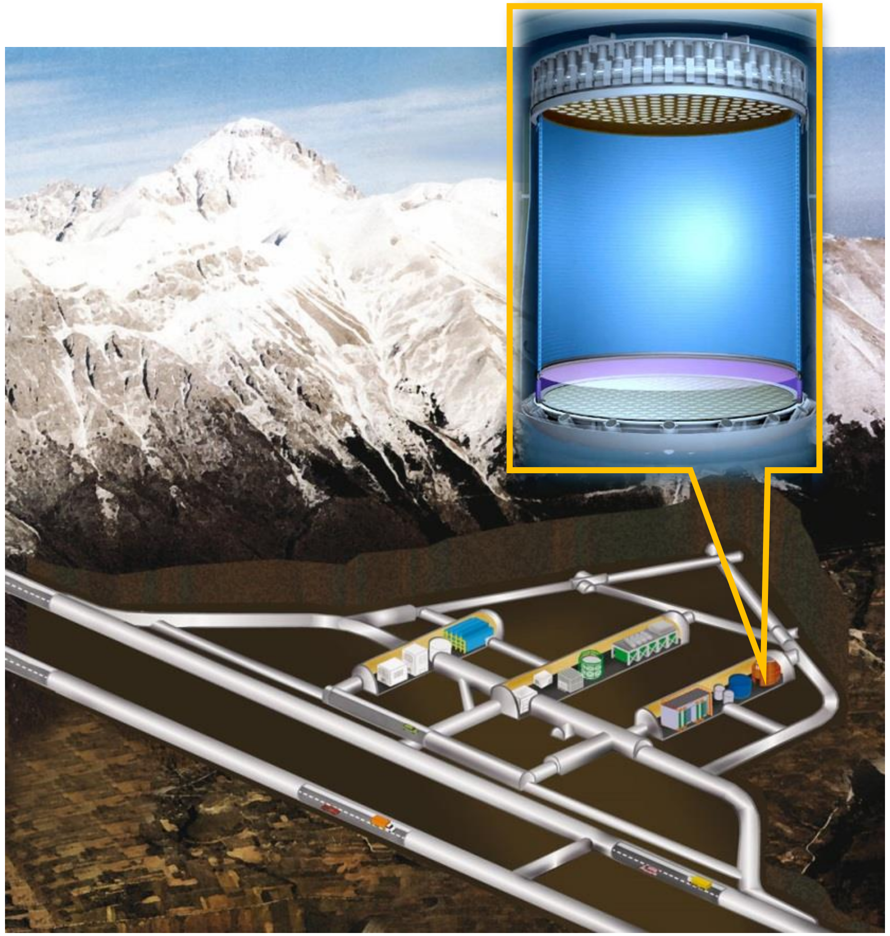
- **How do I keep my detector (almost) free of background processes?**

  - very deep underground laboratory: reduction of $\mu -$ induced reactions

  - active veto against remaining muons passing near the detector ($\boldsymbol{\mu - veto}$)

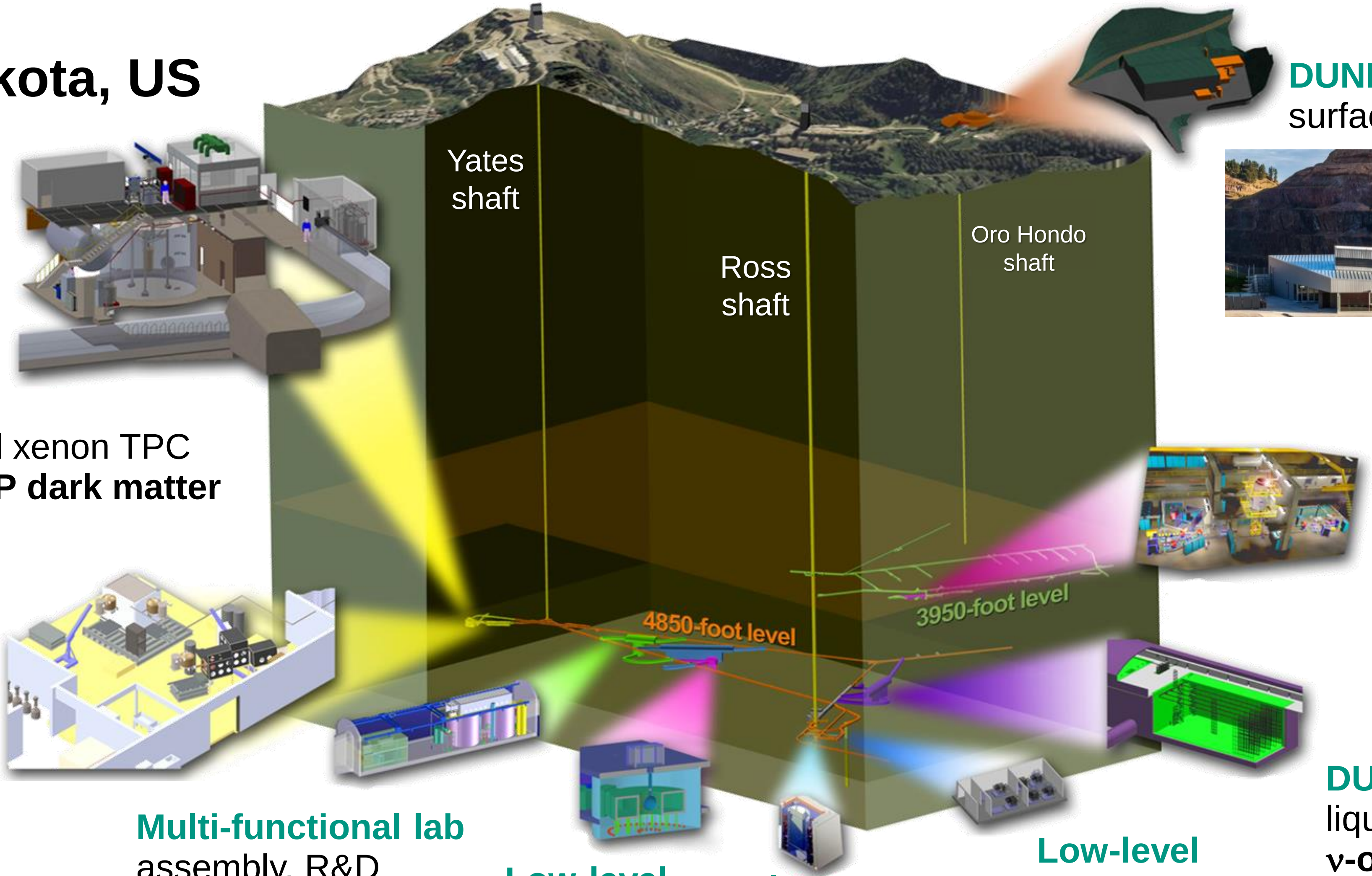
  - detailed simulation of background reactions (typically GEANT4): ⇨ **optimized shielding concept** consisting of passive/active layers

  - data analysis cuts: fiducial volume, cuts,…



Underground Laboratories – example Sanford Lab

- South Dakota, US



DUNE
surface facilities

LUX
liquid xenon TPC
WIMP dark matter

DIANA
nuclear astrophysics

MAJORANA
Ge-diodes
$0\nu\beta\beta$ search

Multi-functional lab
assembly, R&D

Low-level
test bed

clean room
assembly

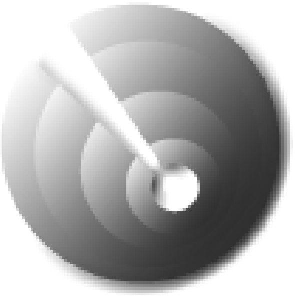
Low-level
test bed

DUNE
liquid argon TPC
ν-oscillations

Underground Lab – daily routine of a researcher

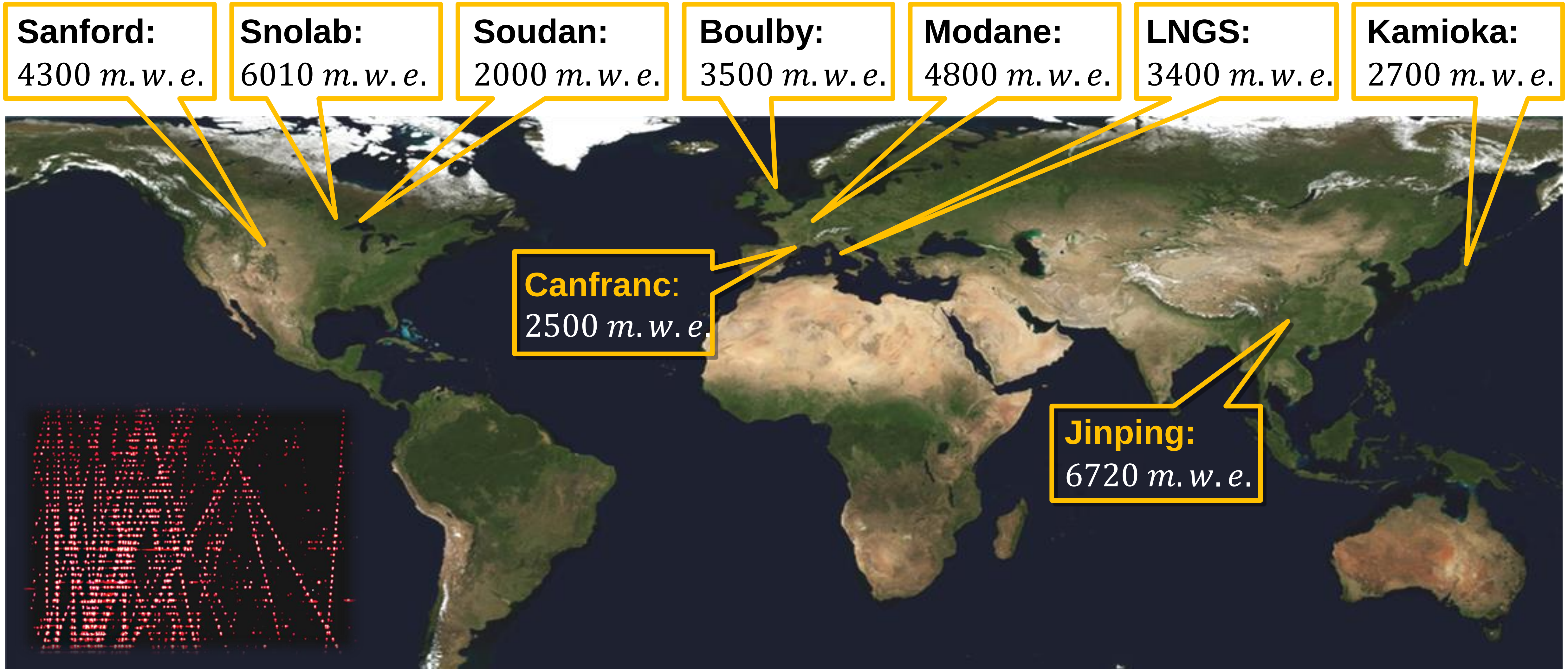
Karlsruhe Institute of Technology

- Life as postdoc



MAJORANA
Ge-diodes for $0\nu\beta\beta$ search

Underground laboratories – global overview

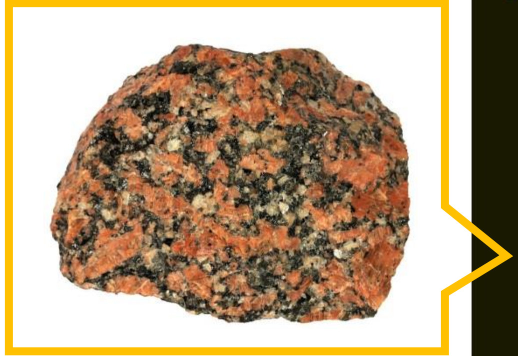


Underground laboratories – overburden & μ´s

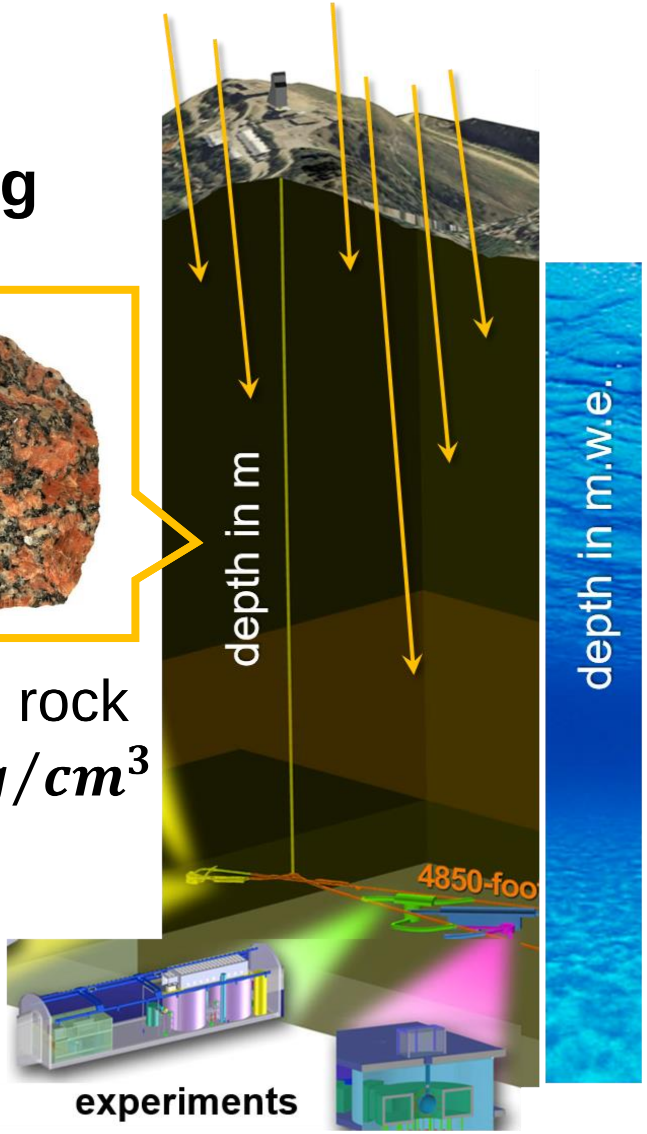
- **Overburden of underground labs & resulting muon rate**

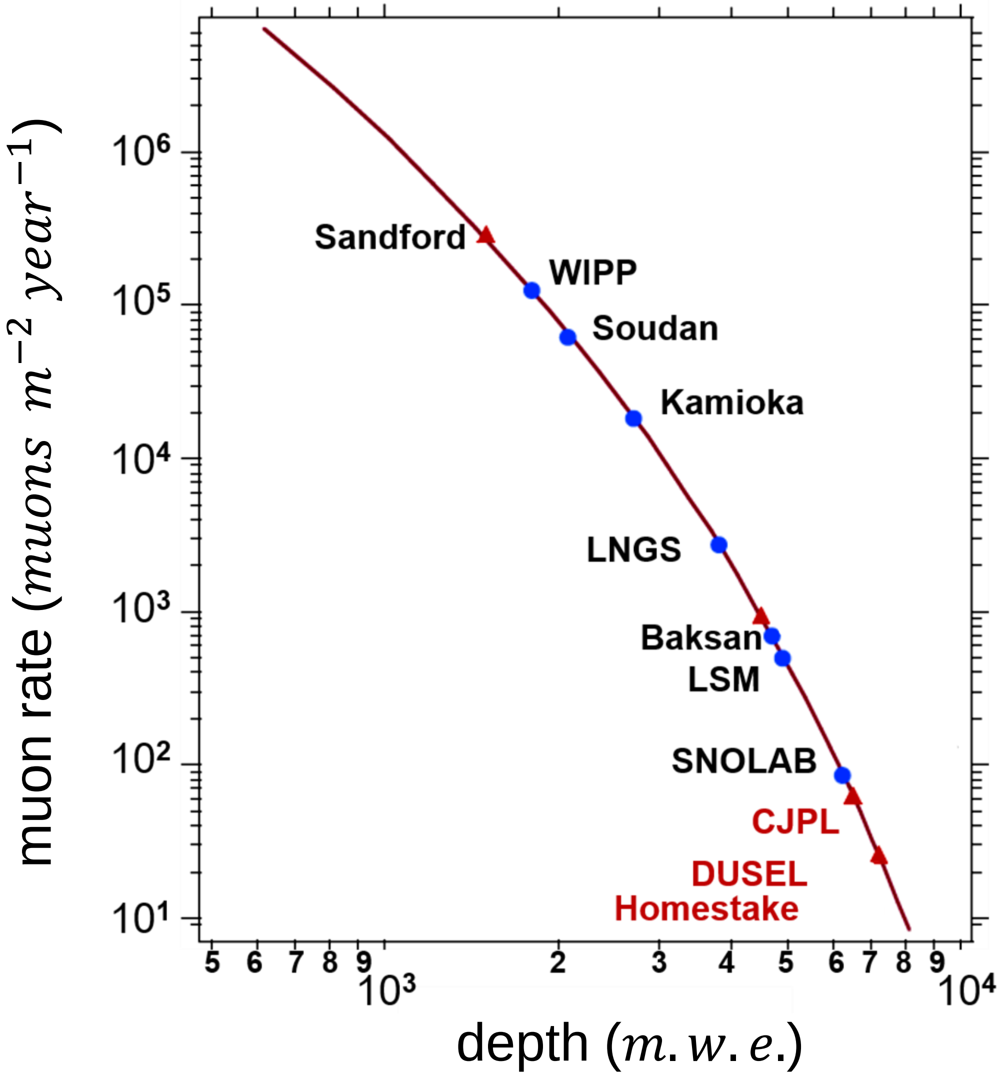
  - unit *m.w.e.* (*m*eter *w*ater *e*quivalent)

  a standard measure for the actual rock overburden



´standard´ rock
$\rho = 2.65\ g/cm^3$



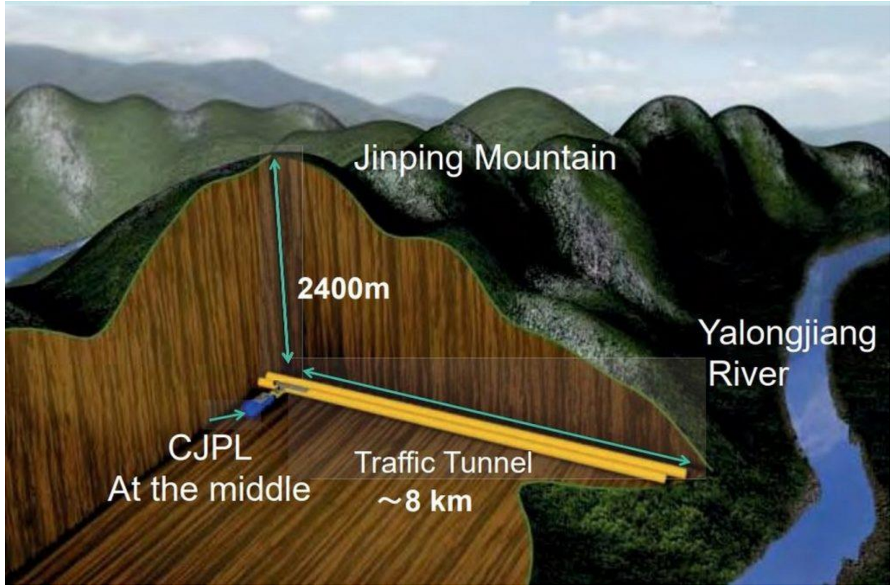


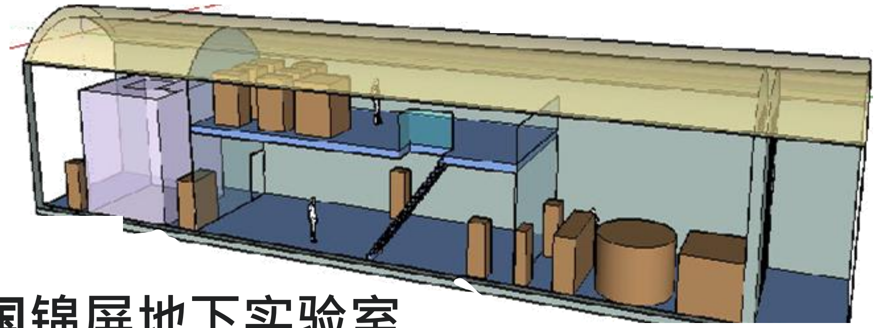
Underground laboratories – overburden & μ´s

■ CJPL – China Jinping Underground Laboratory

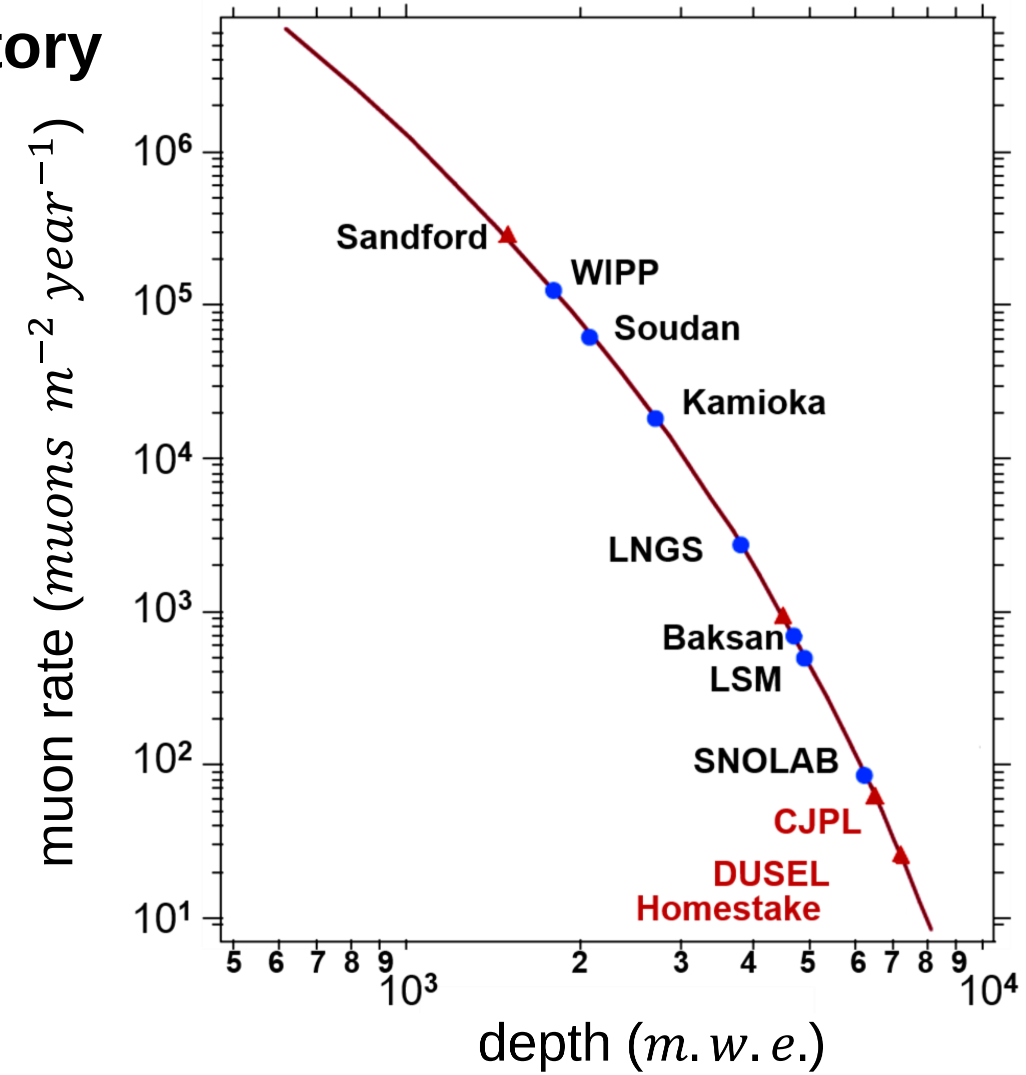
- deepest underground lab in the world: *6720 m.w.e.*

- currently extension to CJPL-II (then largest under-ground lab worldwide)





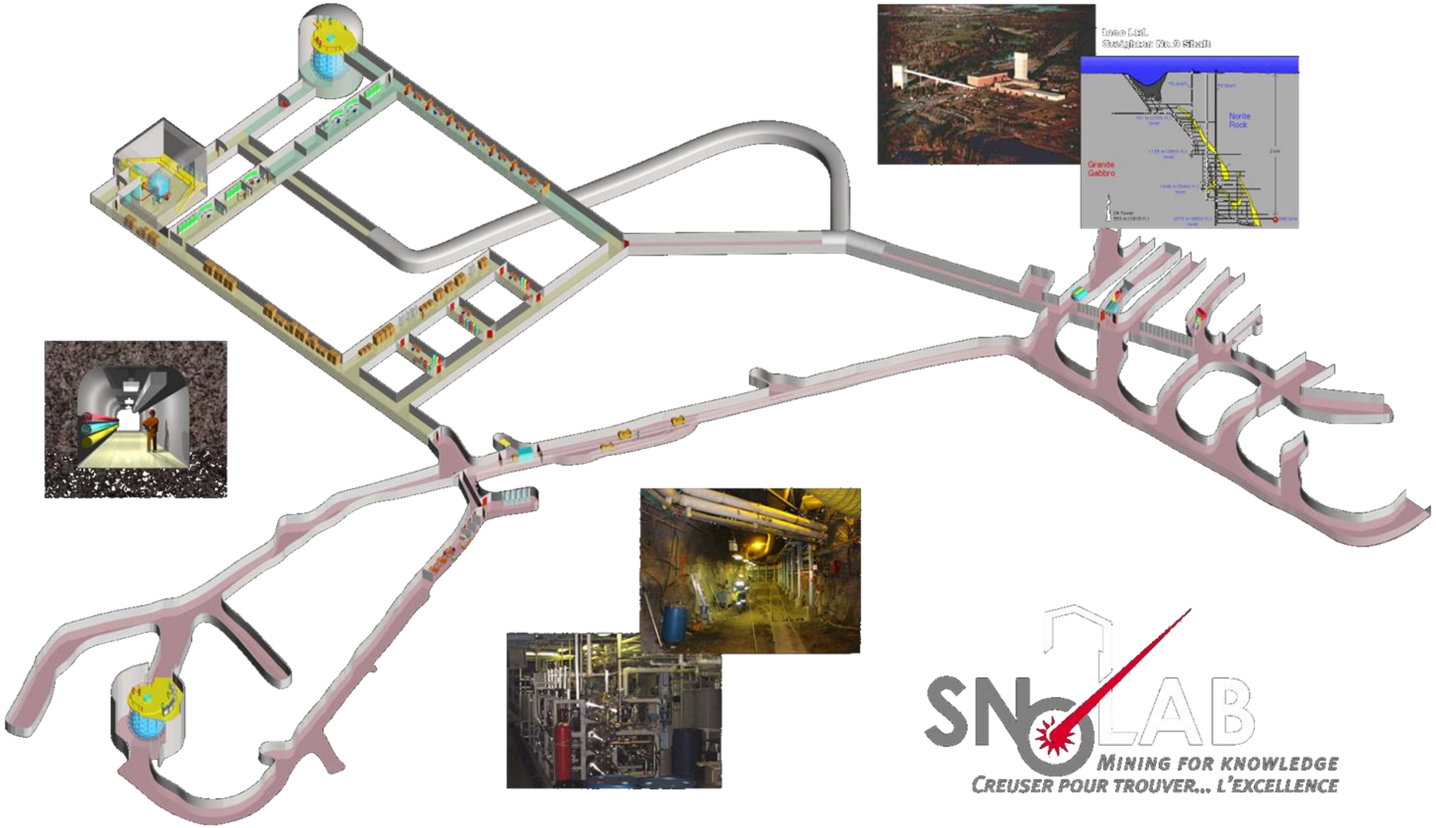
中国锦屏地下实验室

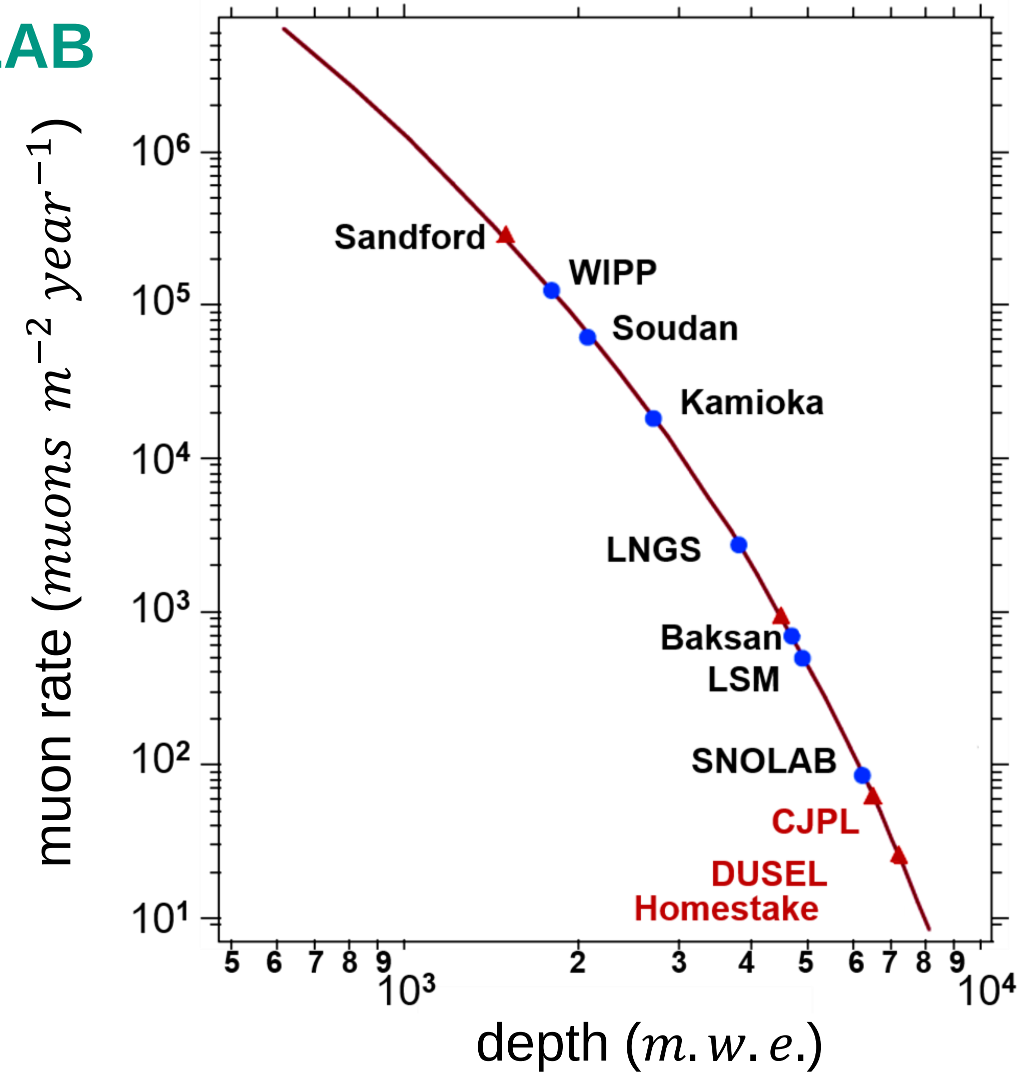


Underground laboratories – overburden & μ´s

- **SNOLAB – Sudbury Neutrino Observatory LAB**

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





Underground laboratories – overburden & μ´s

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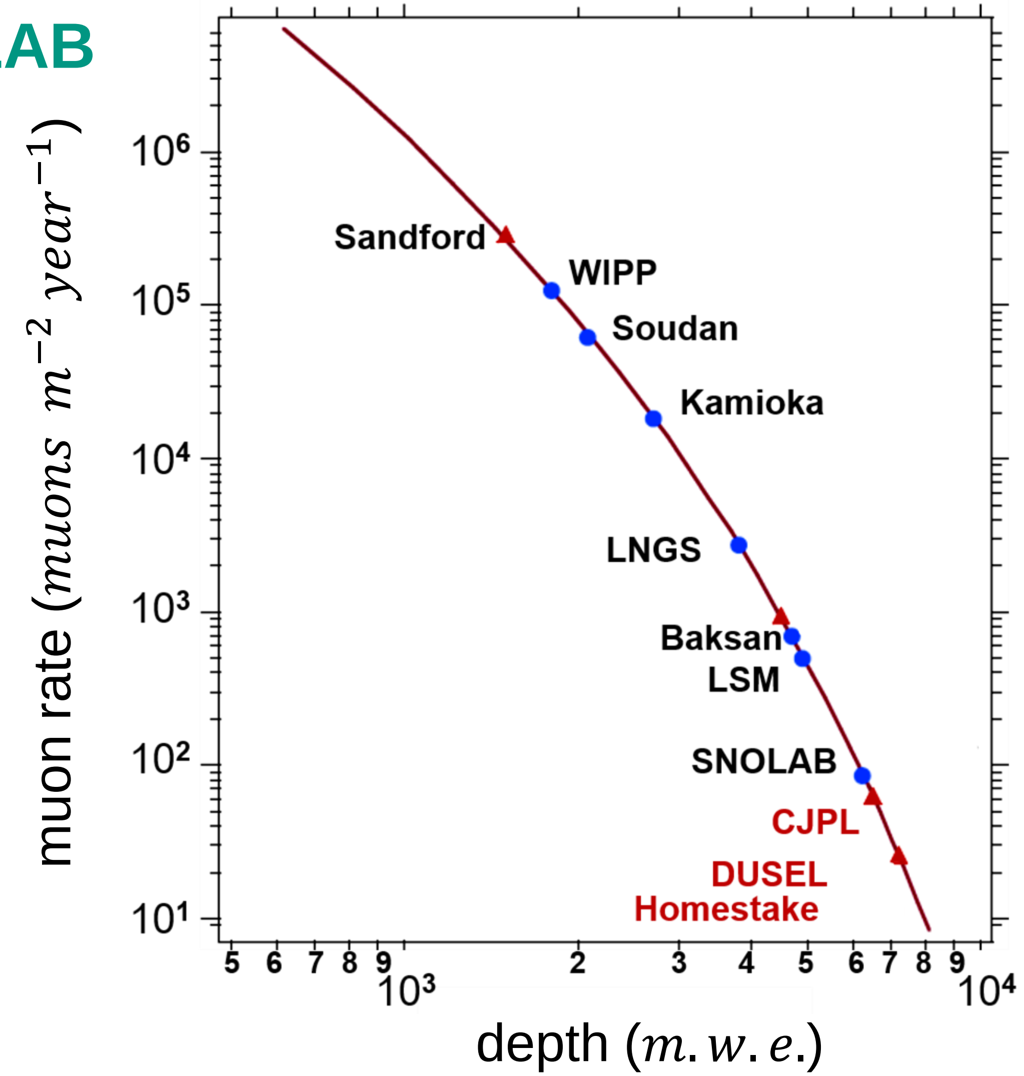
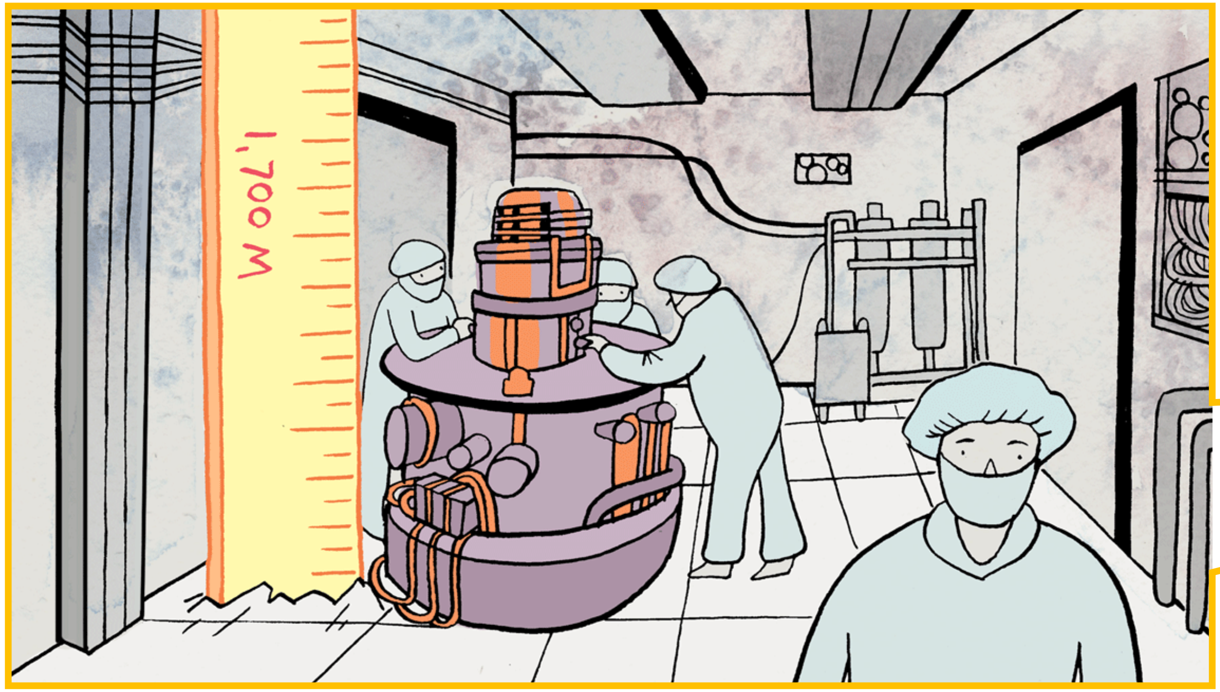


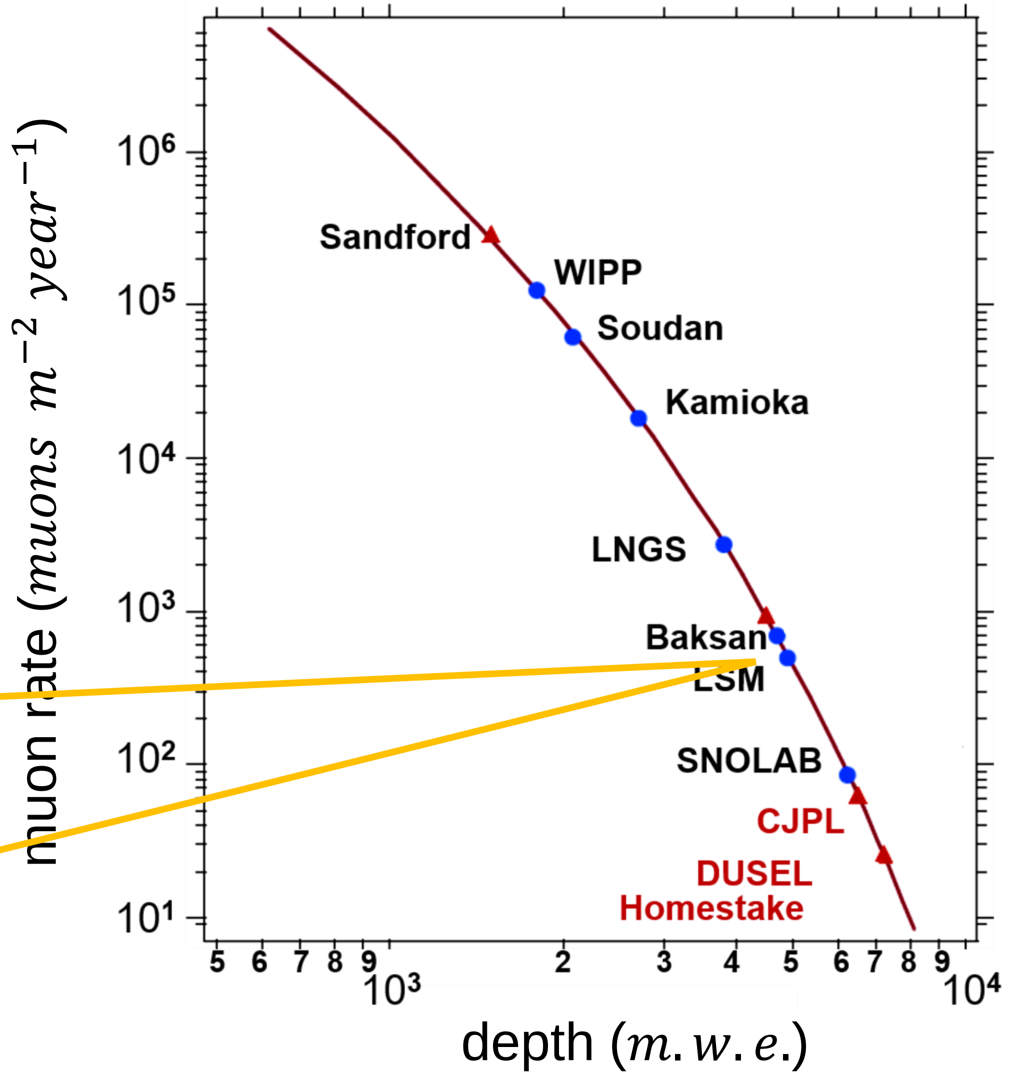
Underground laboratories – overburden & μ´s

- **Laboratoire Souterrain de Modane (LSM) - France**

- overburden: *4800 m.w.e.*



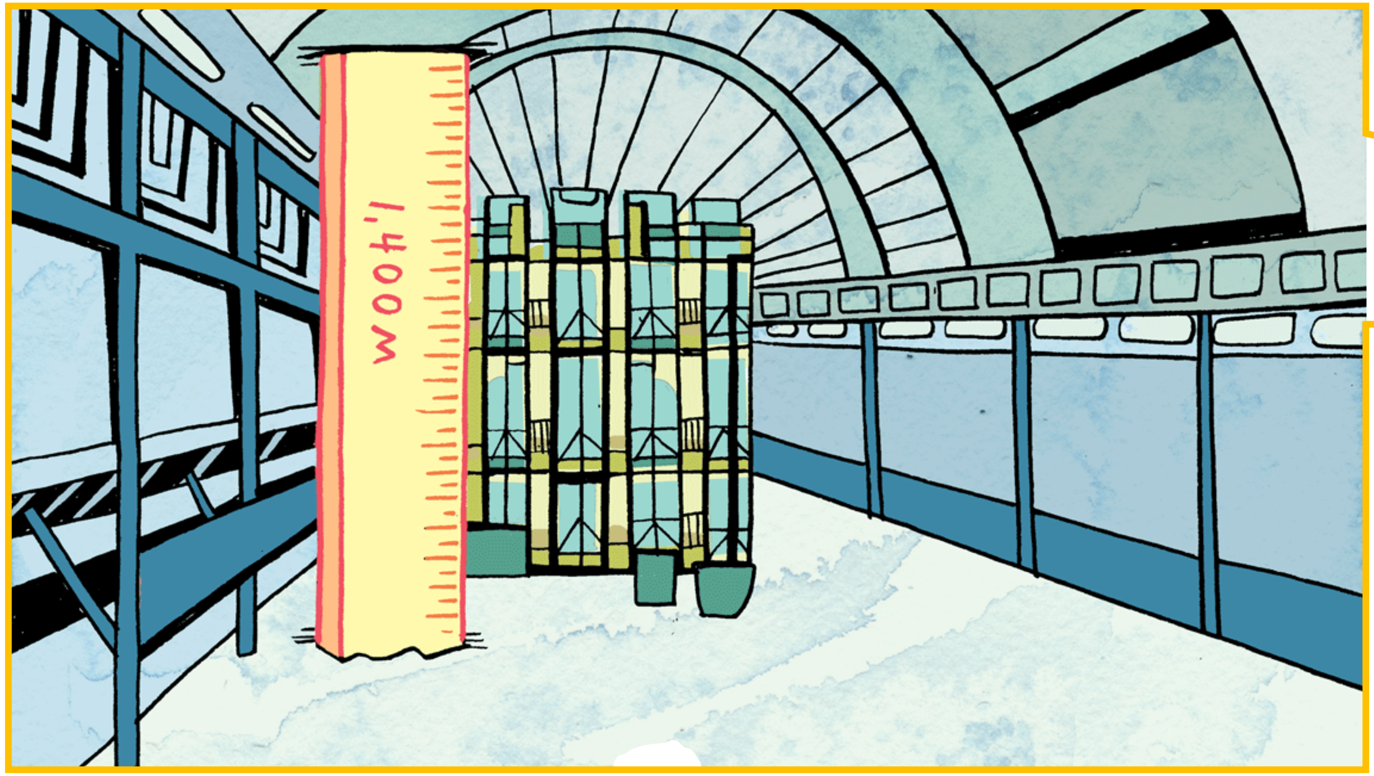
EDELWEISS experiment

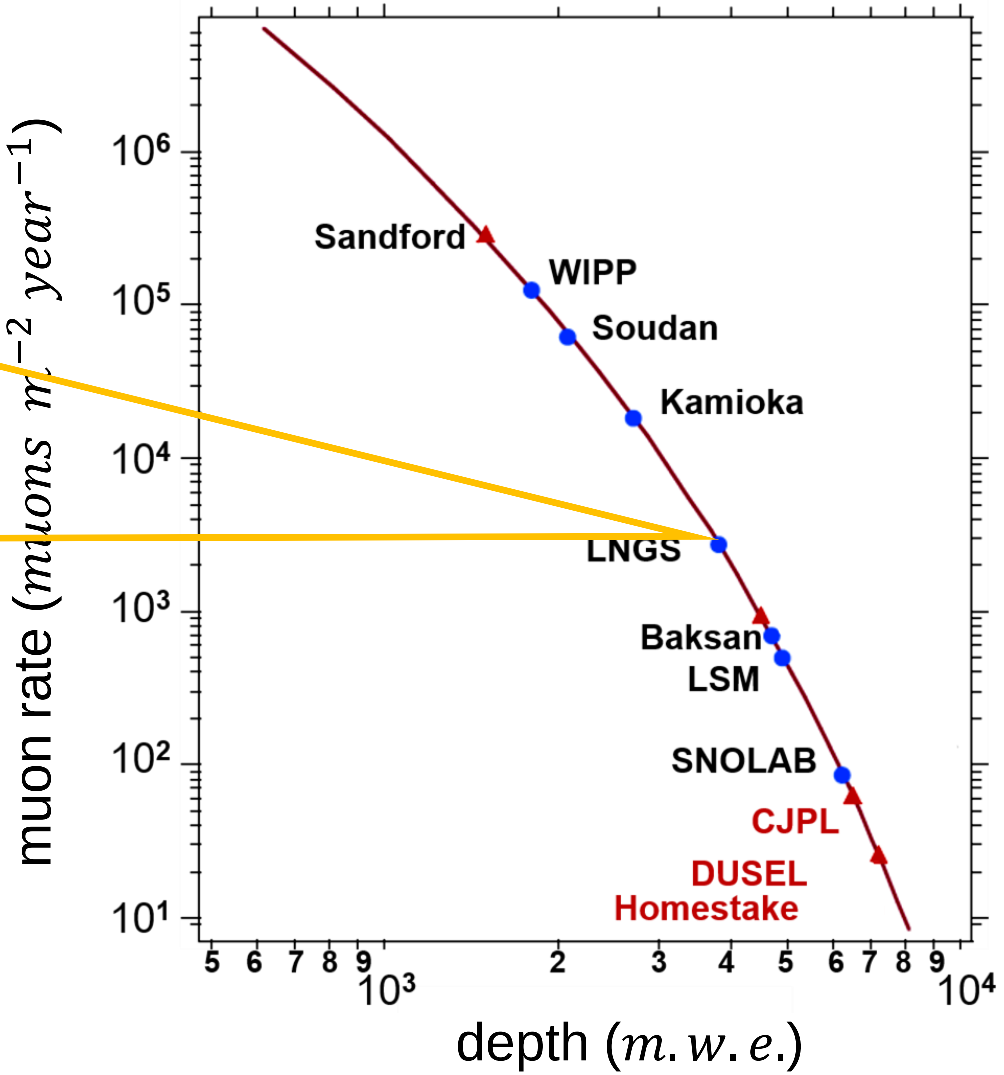


Underground laboratories – overburden & μ´s

- **Laboratori Nazionali del Gran Sasso**

  - the best 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!1sq6nrE6TmflYpXqaACC7kGw!2e0!7i13312!8i6656?hl=en

Underground laboratories – LNGS

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

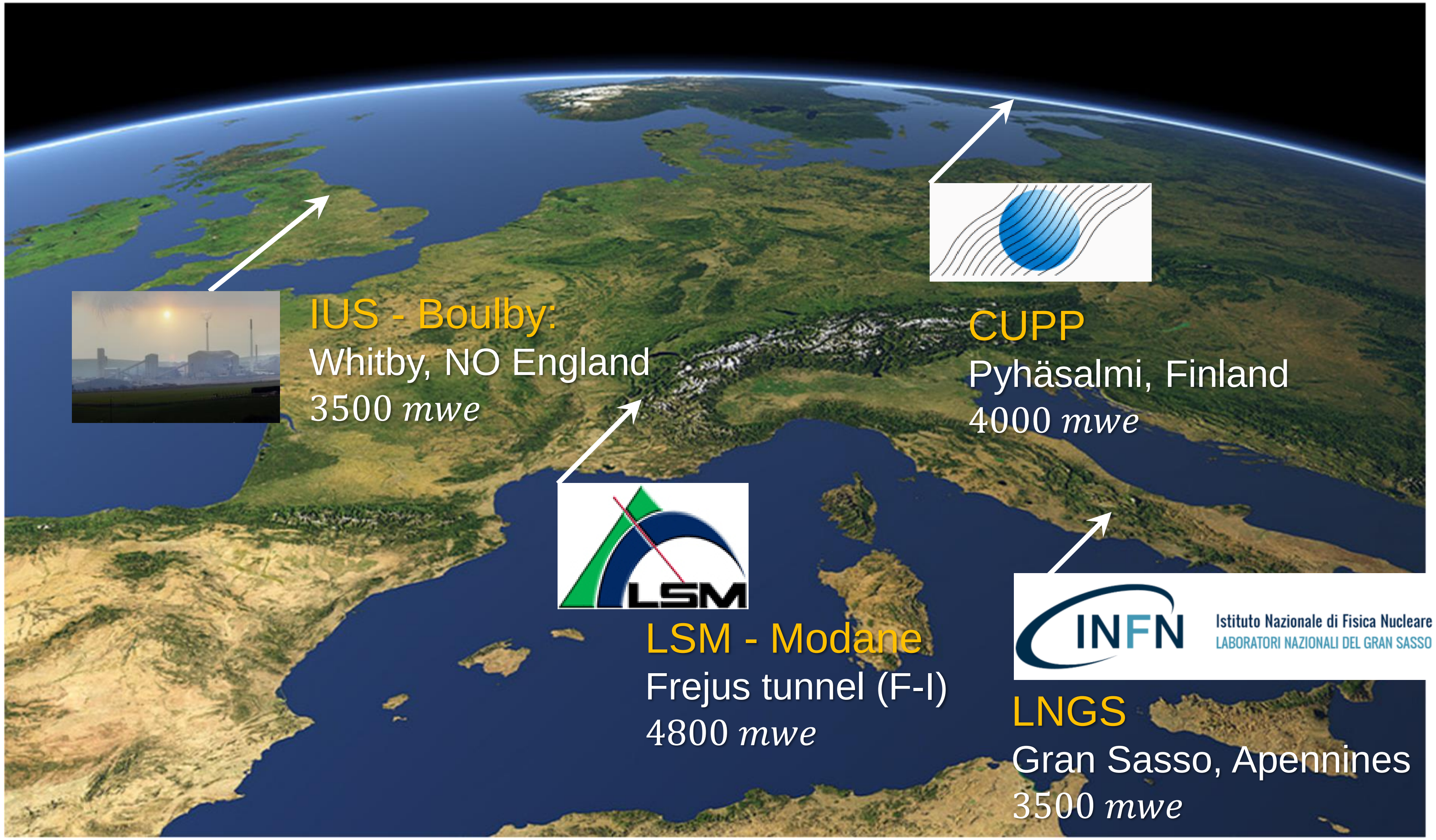
- **XENON-nT:**
  8.3 tons LXe
  TPC

(s. ch. 4.5.3)

Underground laboratories in Europe

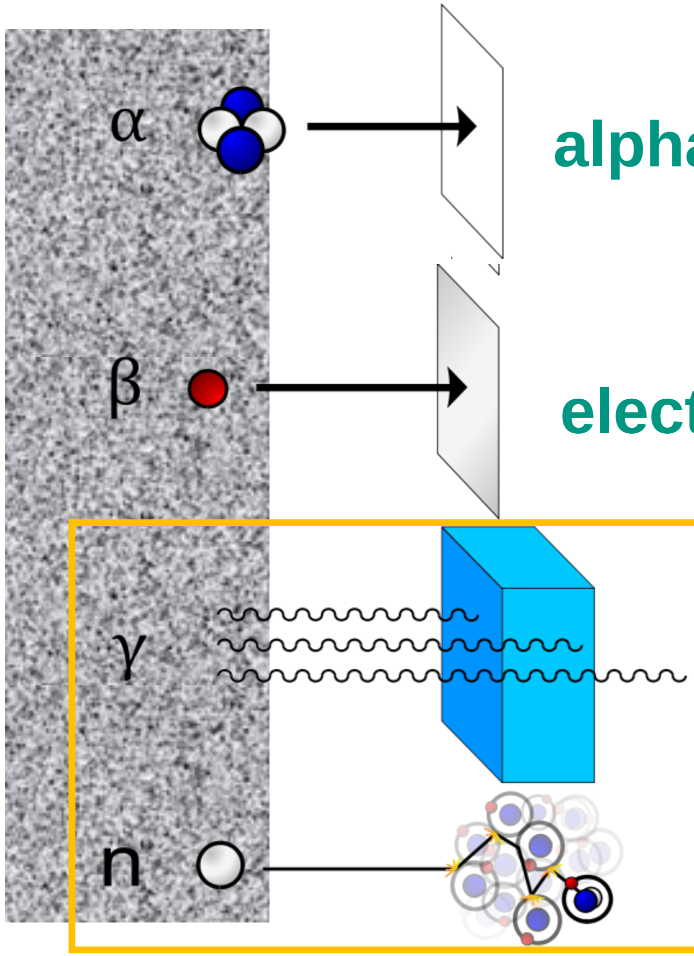
- **Cooperation via ILIAS**

Integrated
Large
Infrastructures
for
AStroparticle
Physics



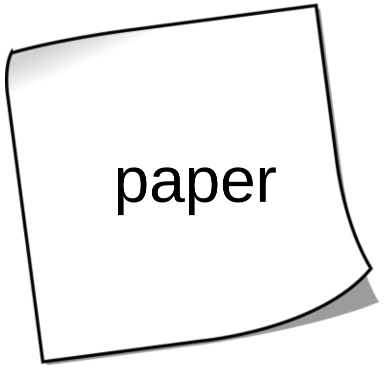
2.2.2 Shielding Methods

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



alphas $(4 - 8\ MeV)$

electrons $(0.02 - 2\ MeV)$

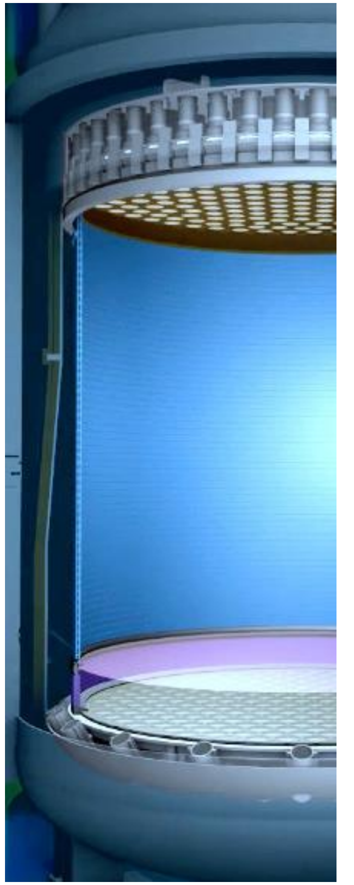


gammas $(< 3.6\ MeV)$

neutrons (MeV)

Cu

Pb

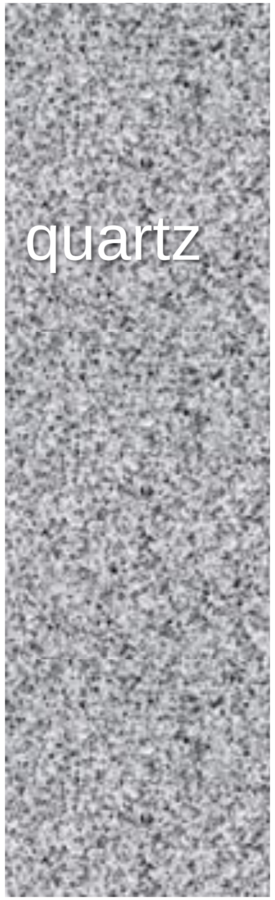


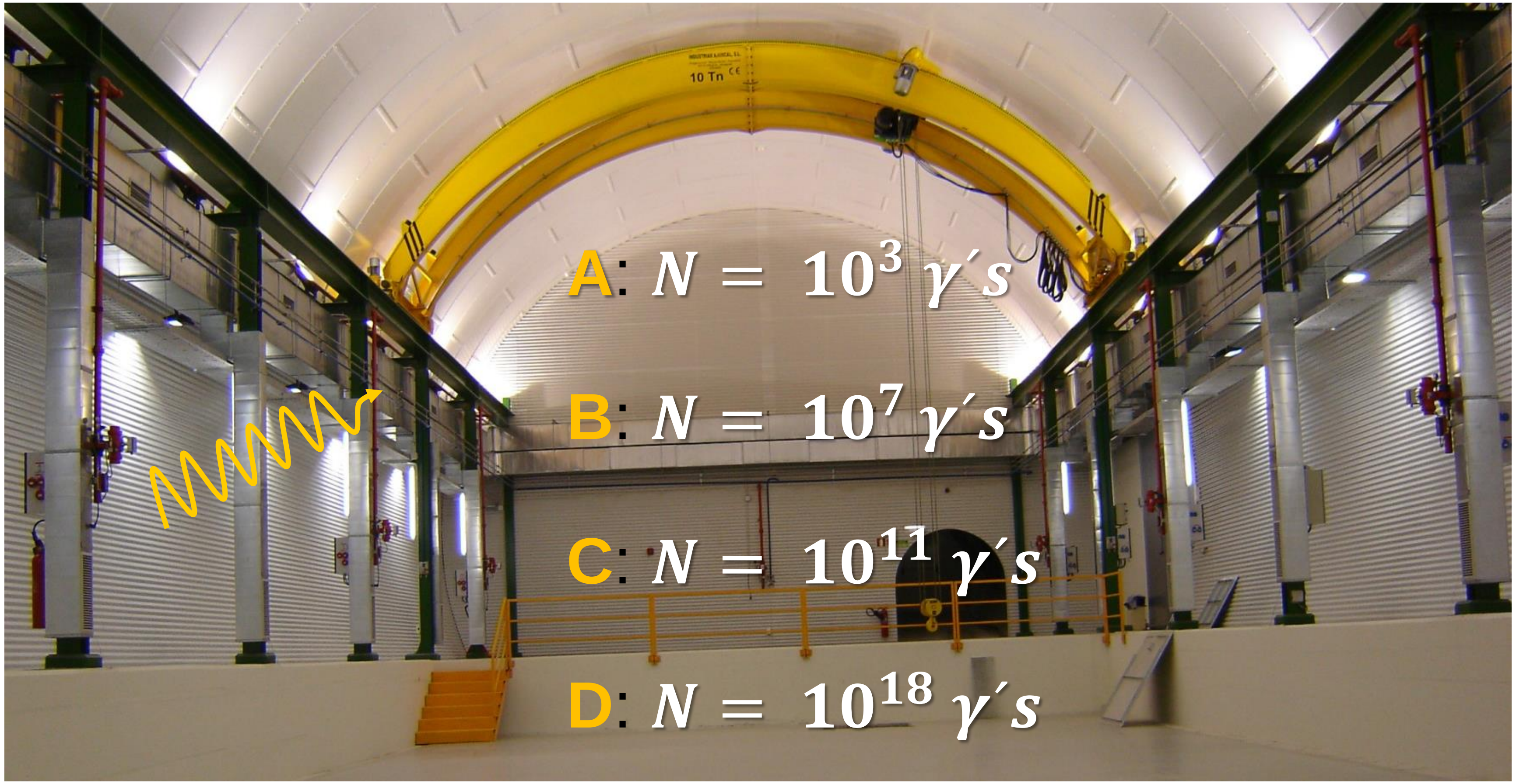
Shielding methods: external sources

- 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: $N = 10^3\ \gamma' s$

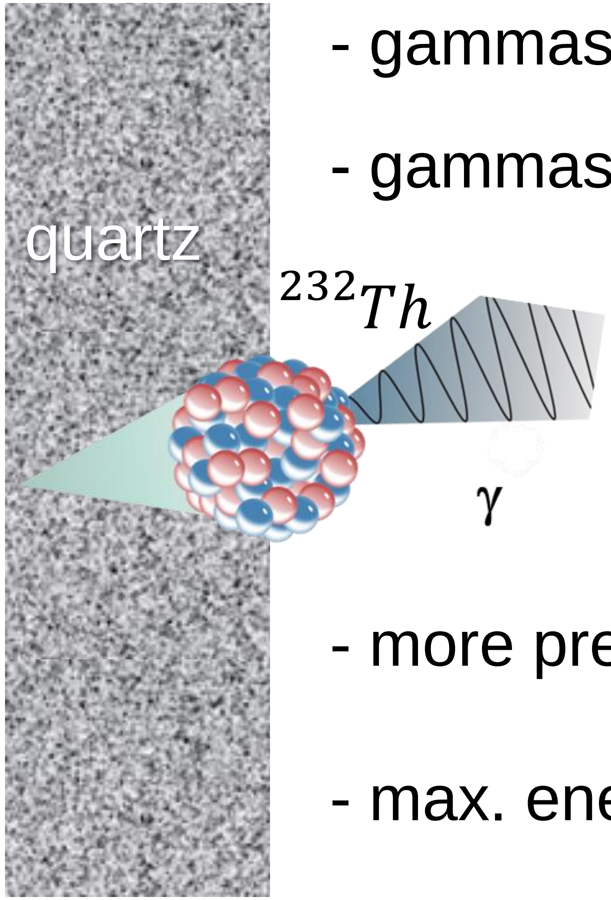
B: $N = 10^7\ \gamma' s$

C: $N = 10^{11}\ \gamma' s$

D: $N = 10^{18}\ \gamma' s$

Shielding methods: external sources

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



- gammas: only from top 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 $t_{½}(^{232}Th) = 1.4 \cdot 10^{10} yr$ ⇨ $4 \cdot 10^{10}\ \gamma' s/year$

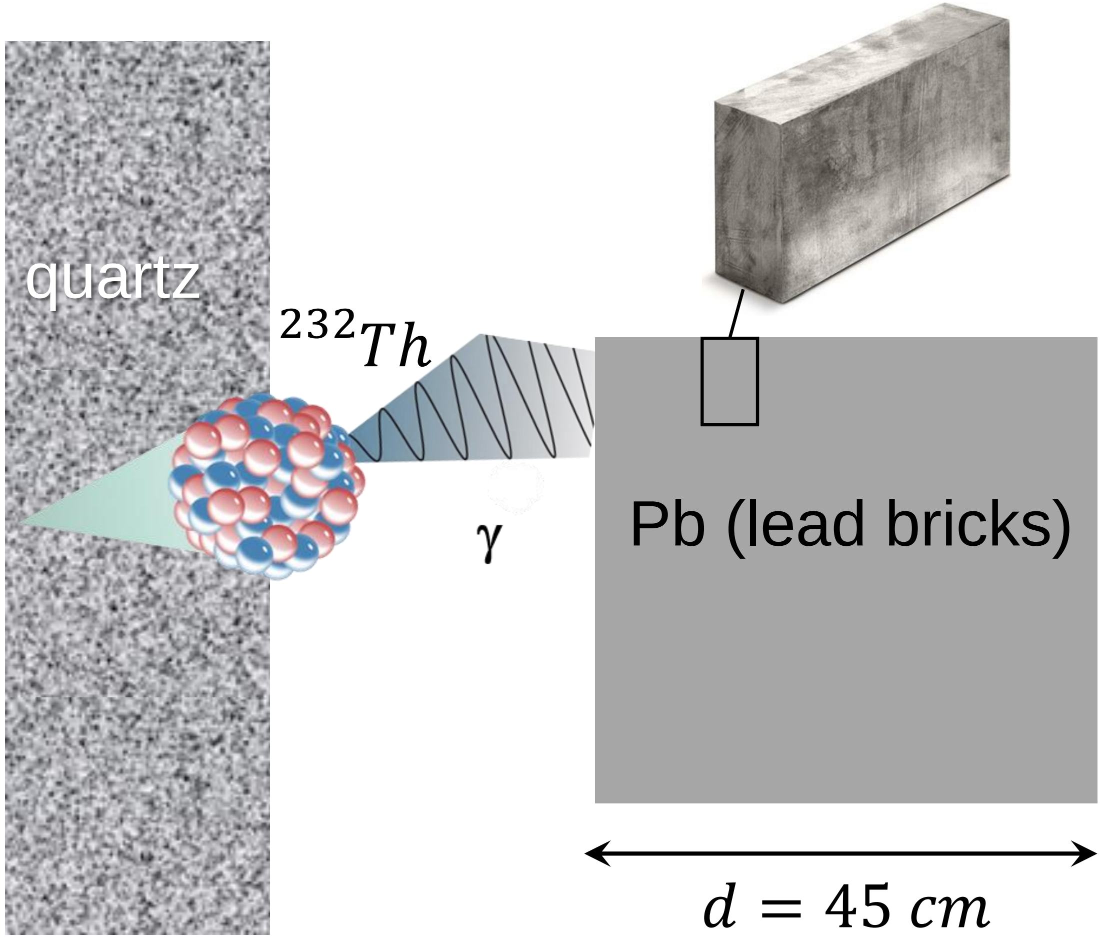
⇨ $1300\ \gamma' s/sec$

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

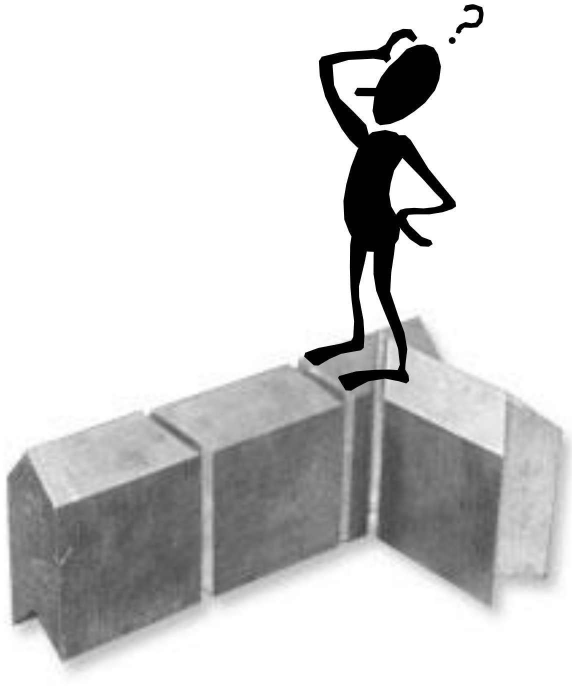
- max. energy $\gamma' s$: $E_\gamma = 2.6\ MeV$ from ^{206}Tl, part of $^{238}U - {}^{232}Th$ decay chain

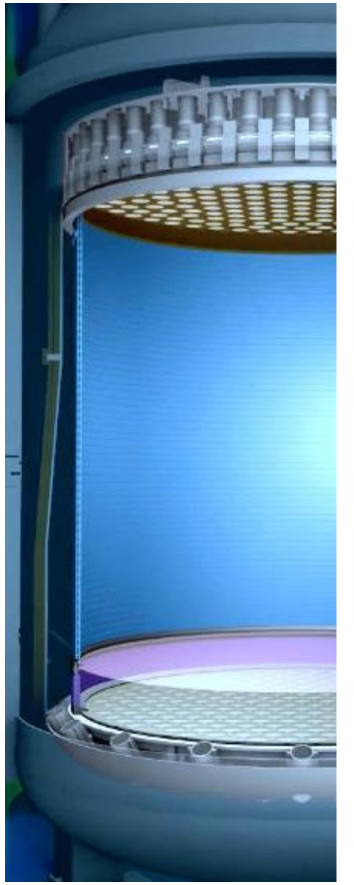
Shielding methods: lead bricks

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



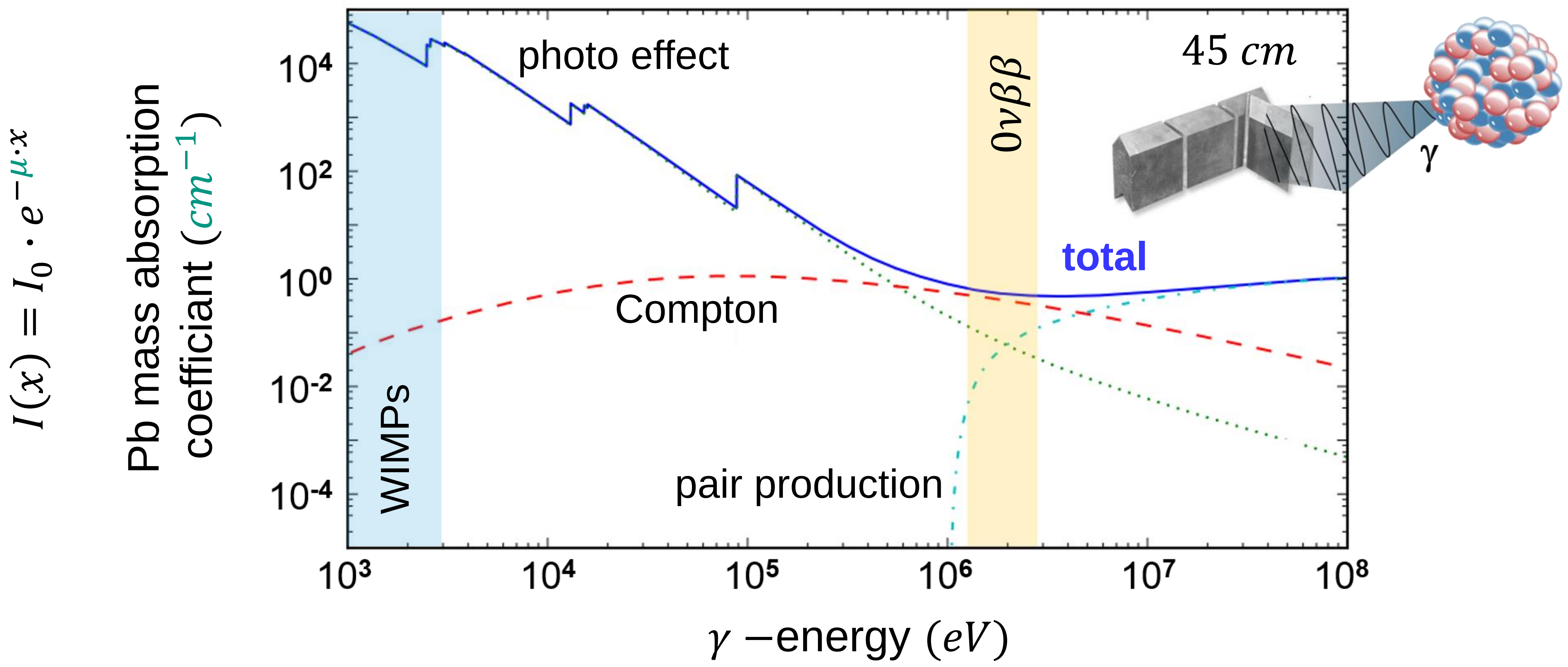
shielding factor $\sim 10^9$





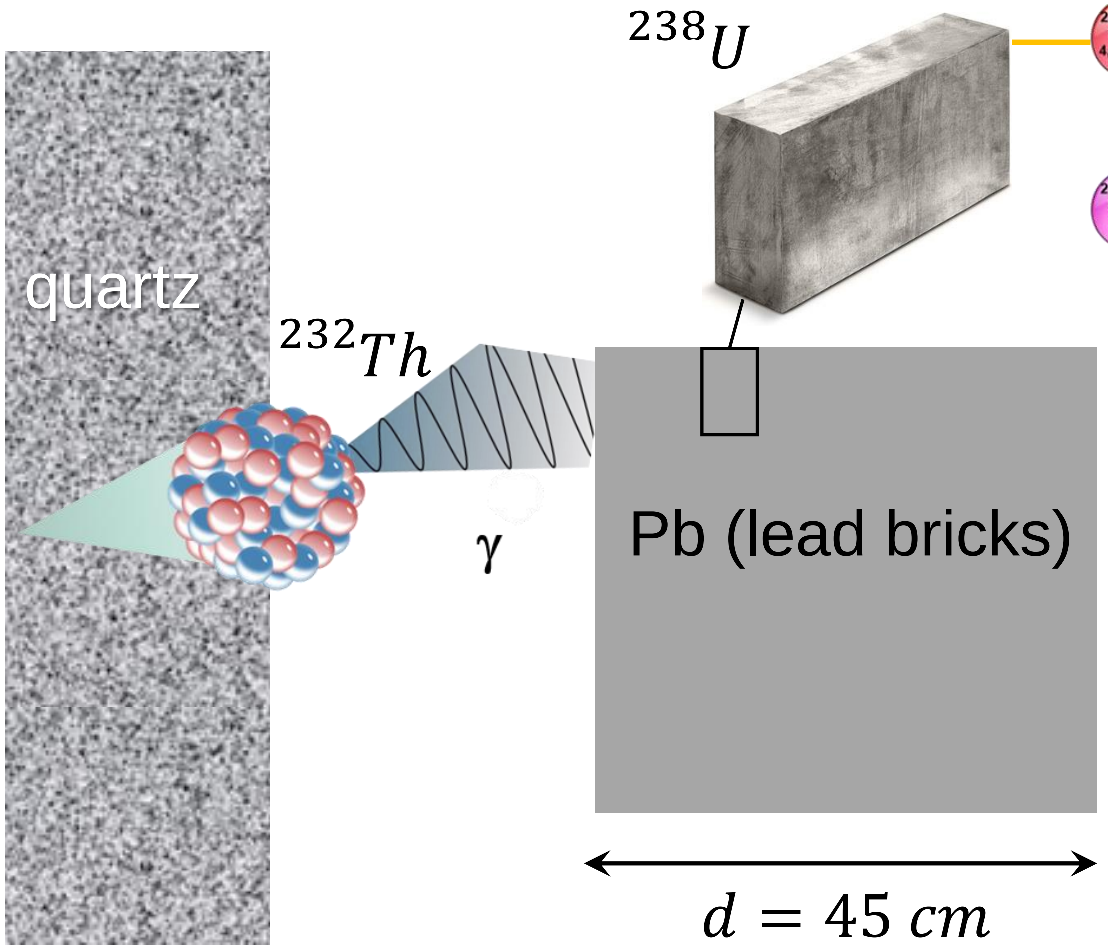
Shileding methods: lead as gamma-absorber

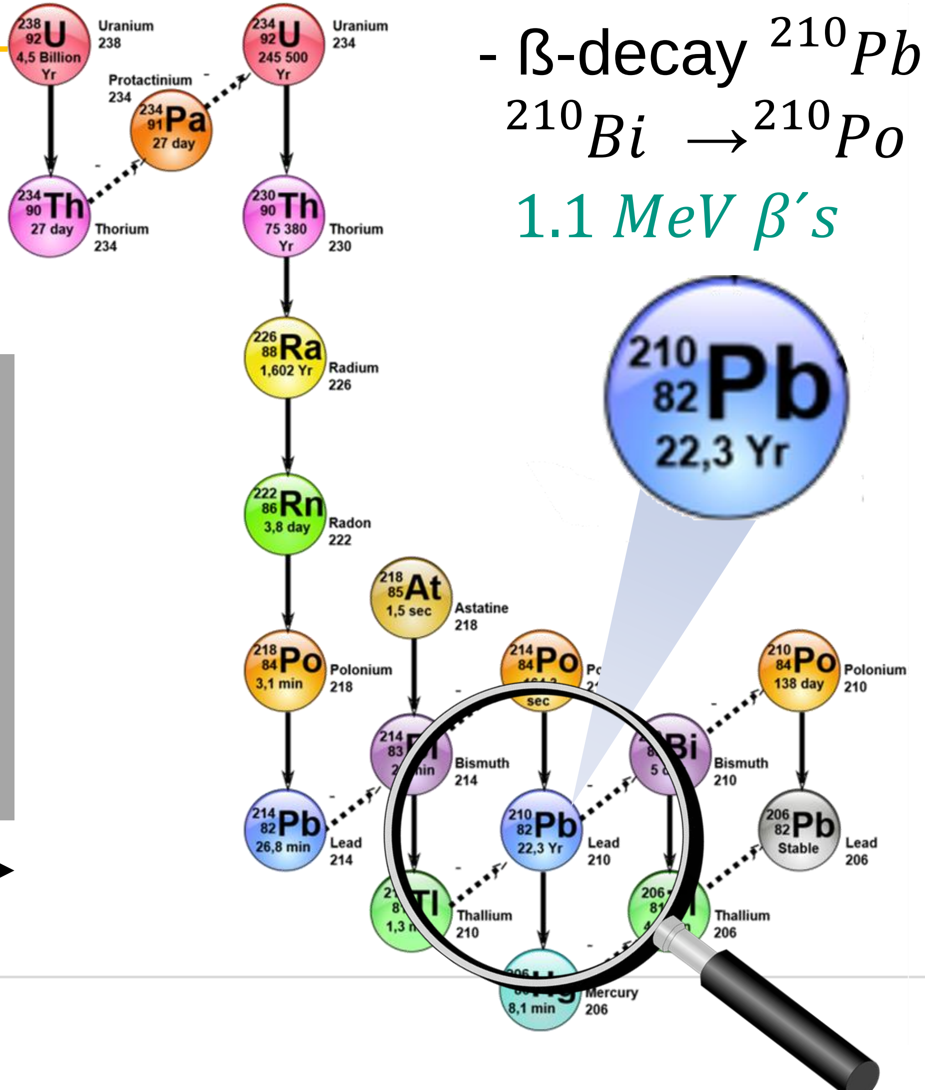
- **Linear mass absorption coefficient μ of Pb for γ´s from $0.1\ MeV$ … $100\ MeV$**



Shielding methods: lead bricks & their activity

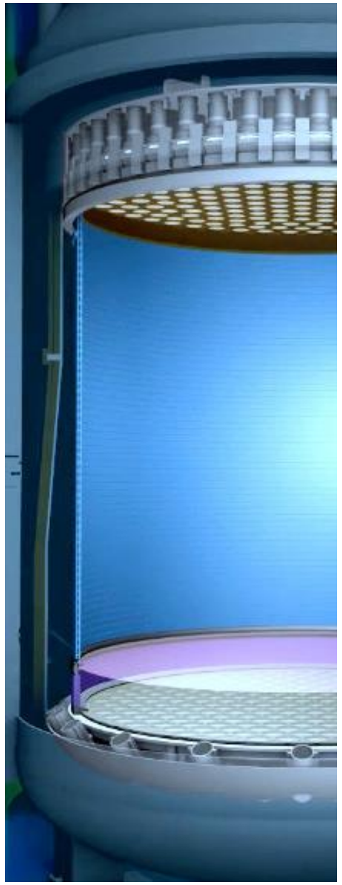
- What about the intrinsic purity of the new Pb wall? It contains isotope ^{210}Pb





- ß-decay $^{210}Pb \rightarrow$ $^{210}Bi \rightarrow {}^{210}Po$

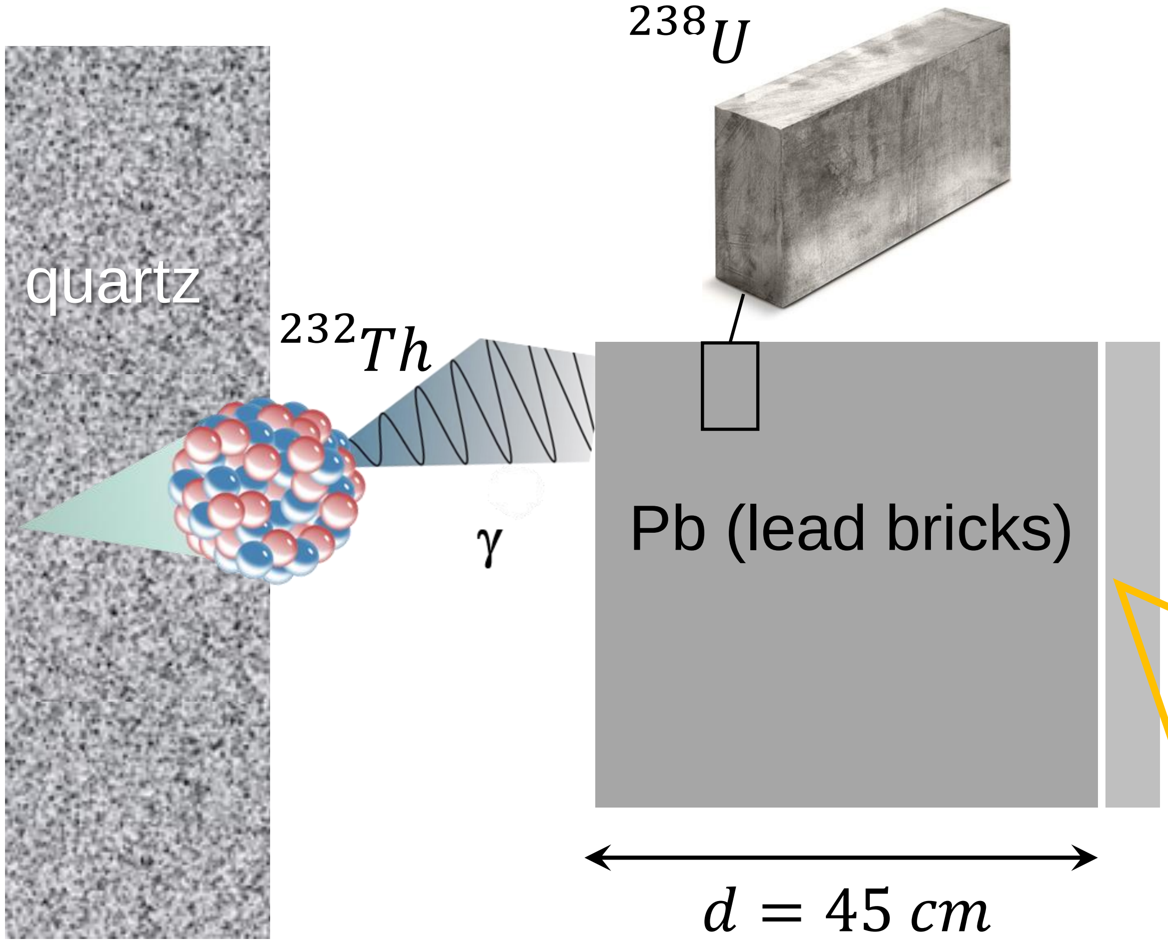
$1.1\ MeV\ \beta´s$



Shielding methods: Roman lead from sea floor

Karlsruhe Institute of Technology

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



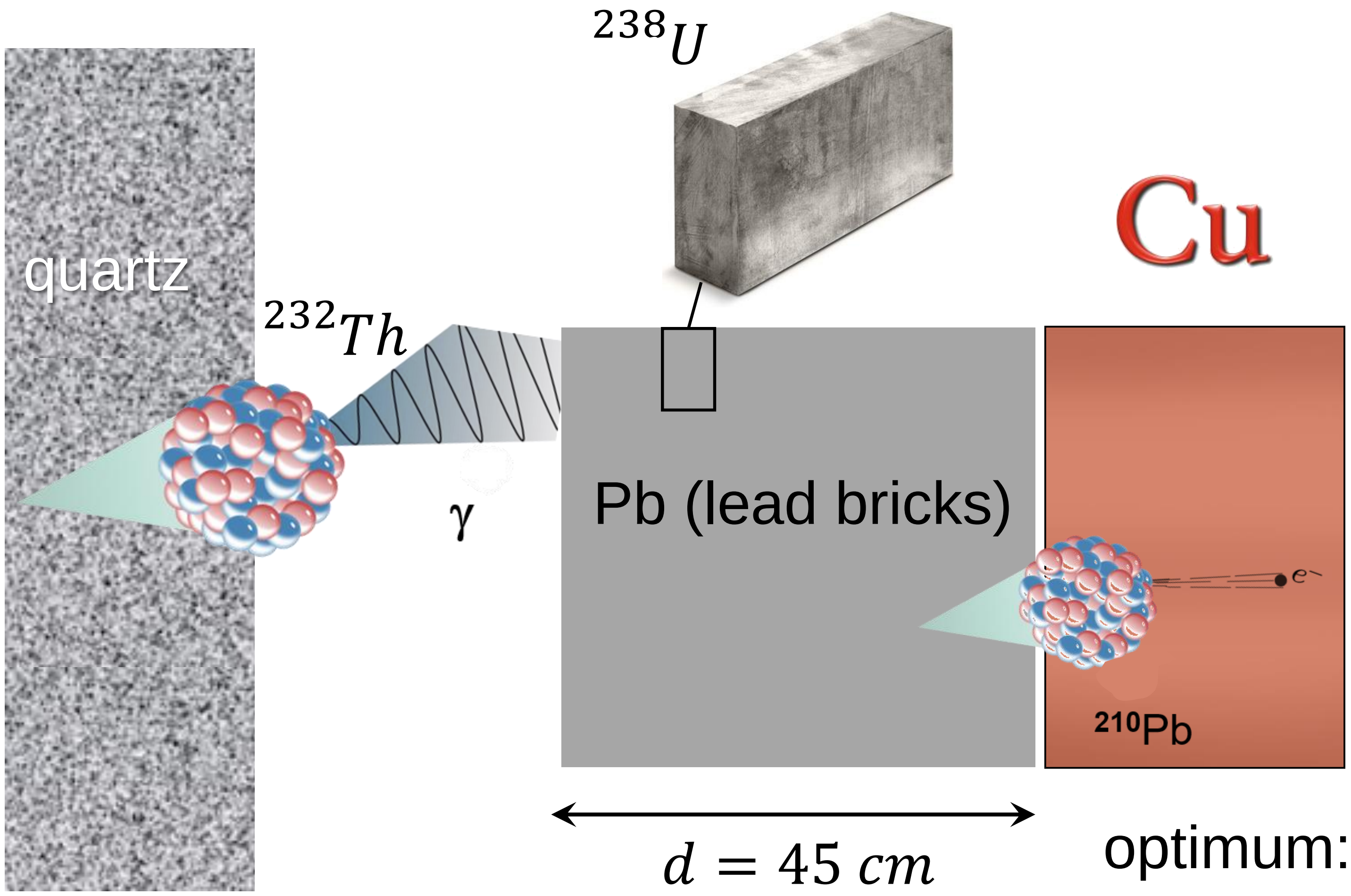
ROMAN LEAD

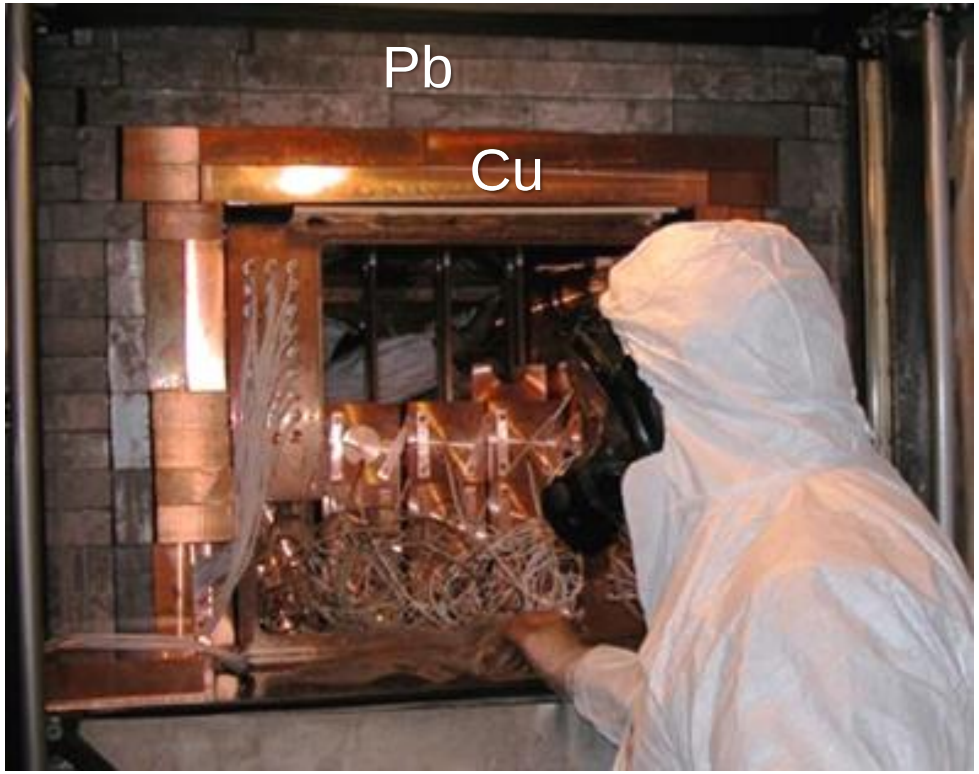
Italian groups only

- 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**

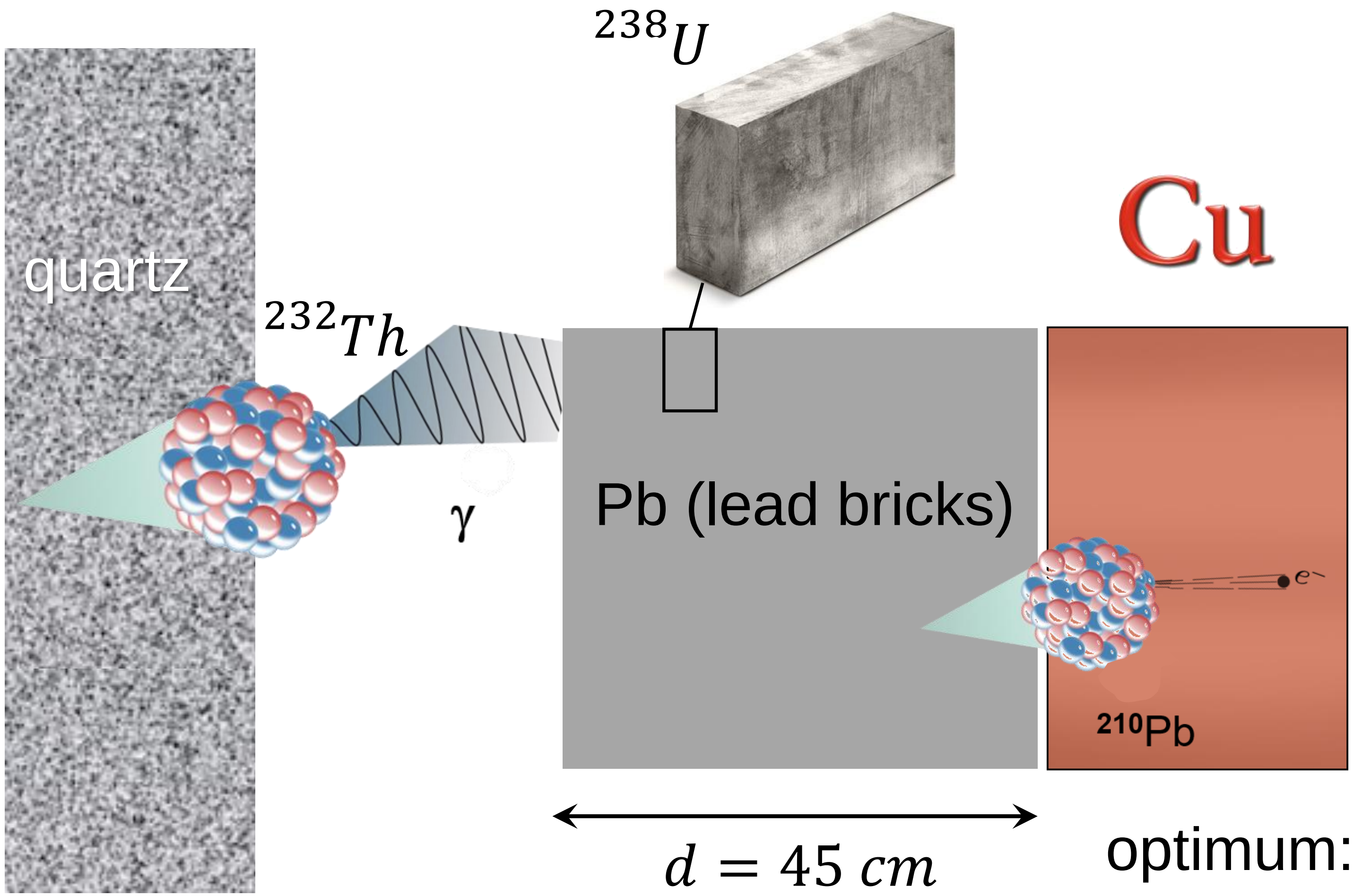


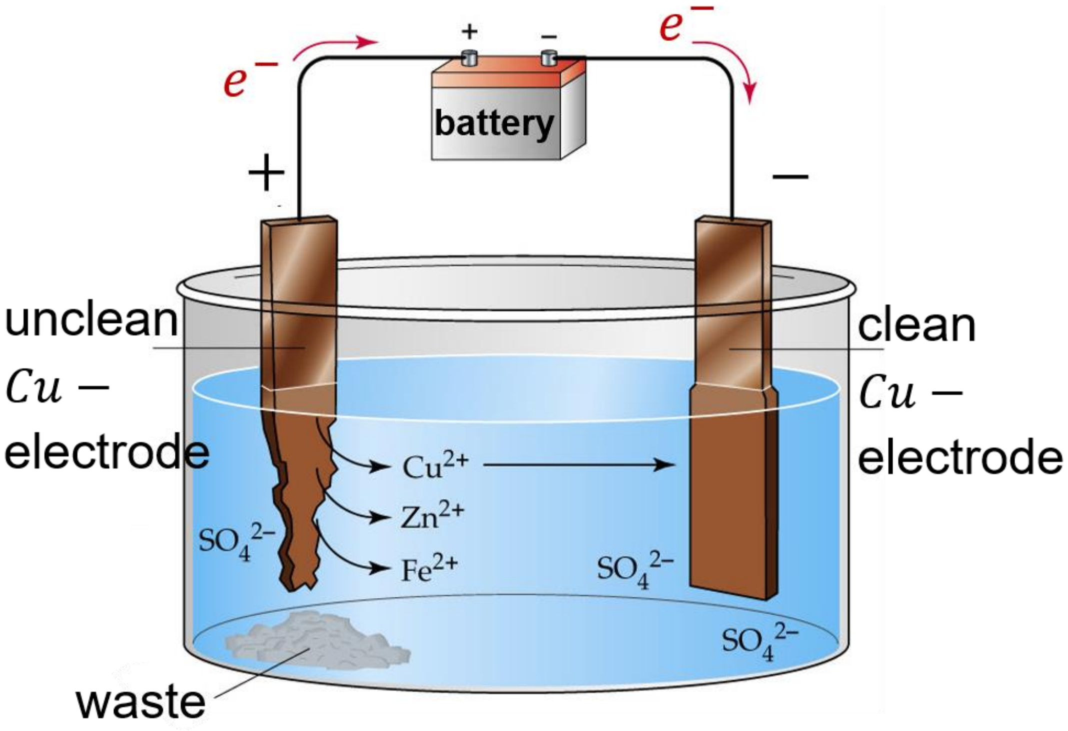


optimum: electro-formed Cu (no ^{238}U)

Shielding methods: extremely pure copper

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





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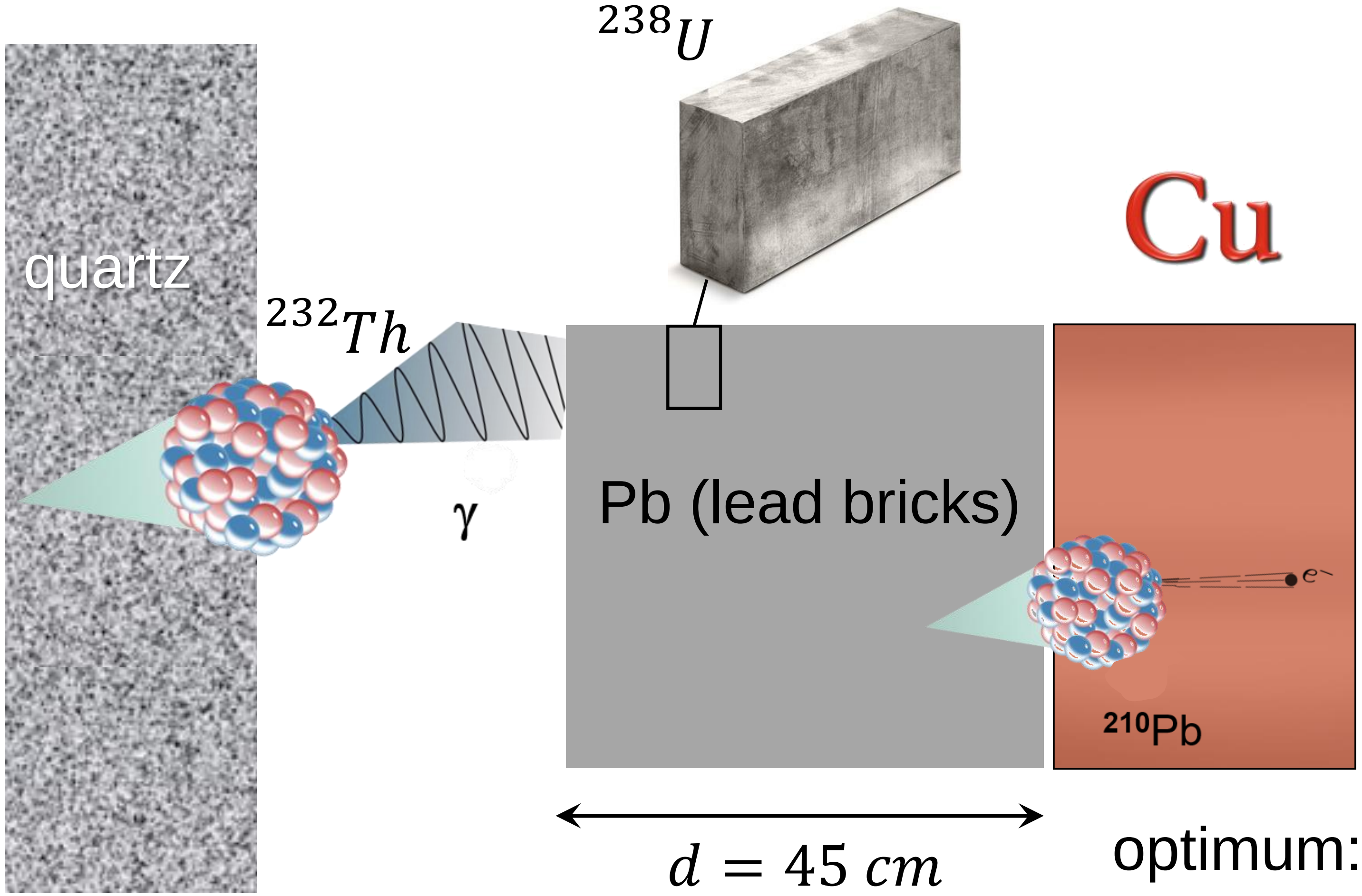


- production in underground lab
- growth: $10 \times$ slower than human hair

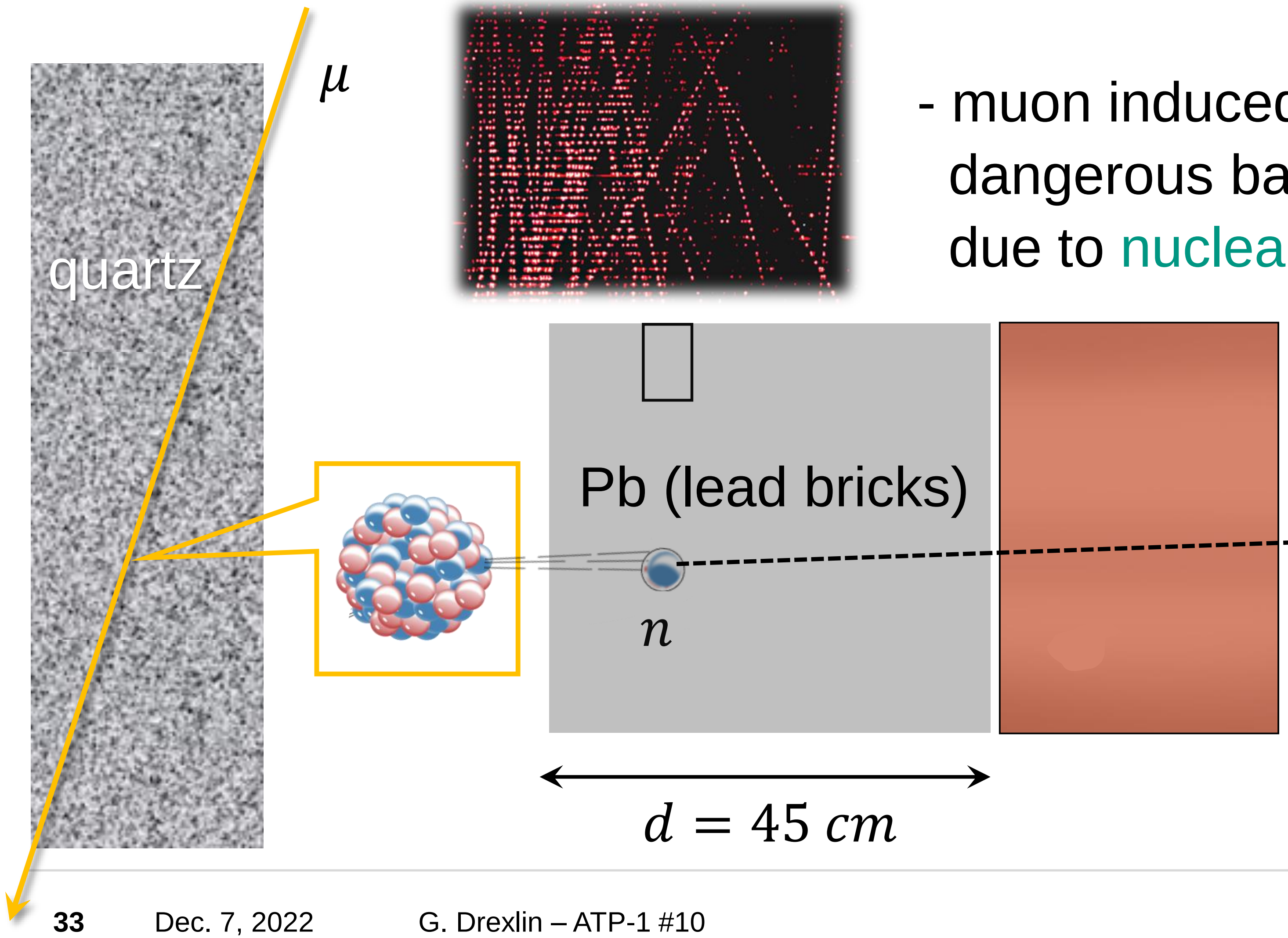
~ $100\, nBq/kg$ for rare event searches
dark matter, $0\nu\beta\beta$ –decay

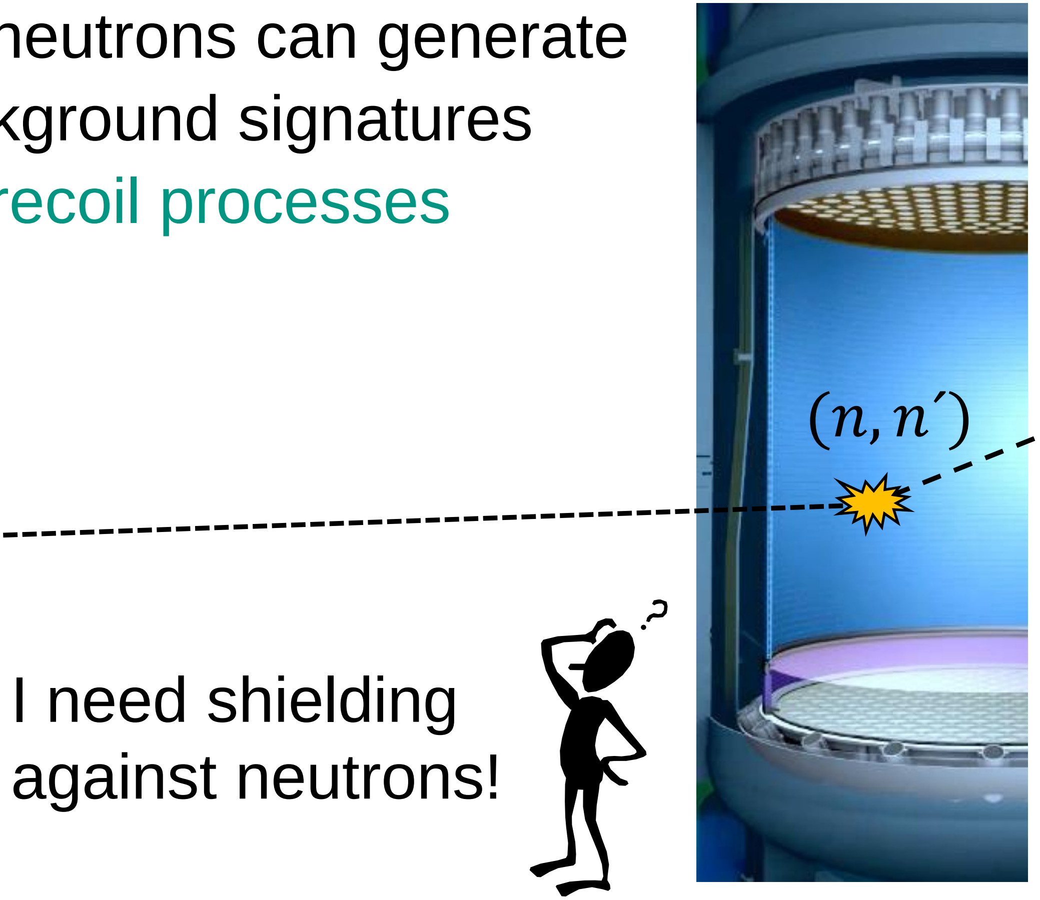
optimum: electro-formed Cu (no ^{238}U)

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

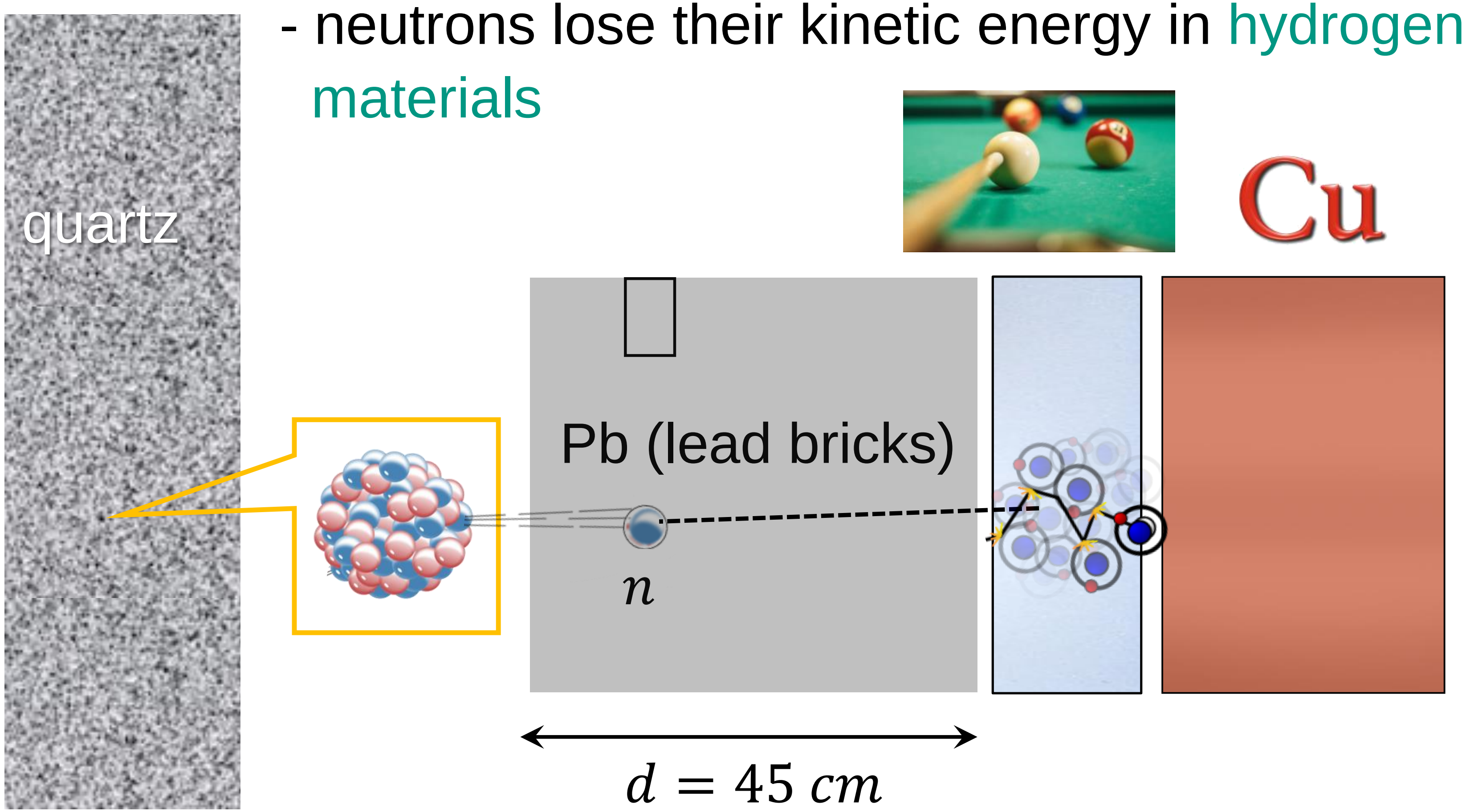




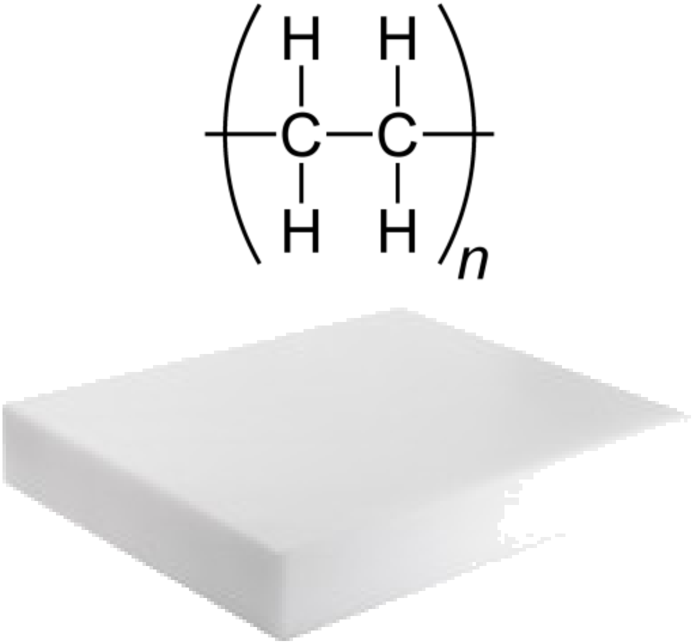
Shielding methods: muon-induced neutrons

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

- neutrons lose their kinetic energy in hydrogen-rich materials



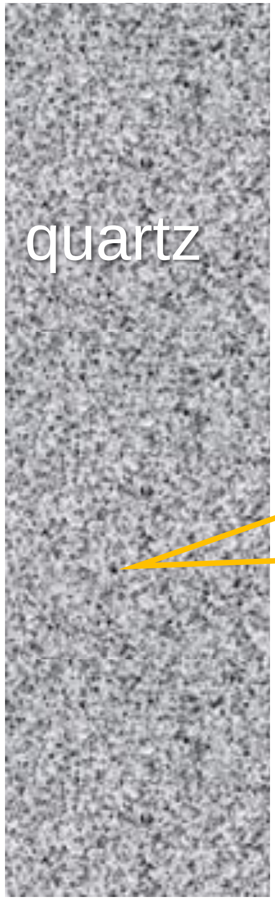
Polyethylene (PE)

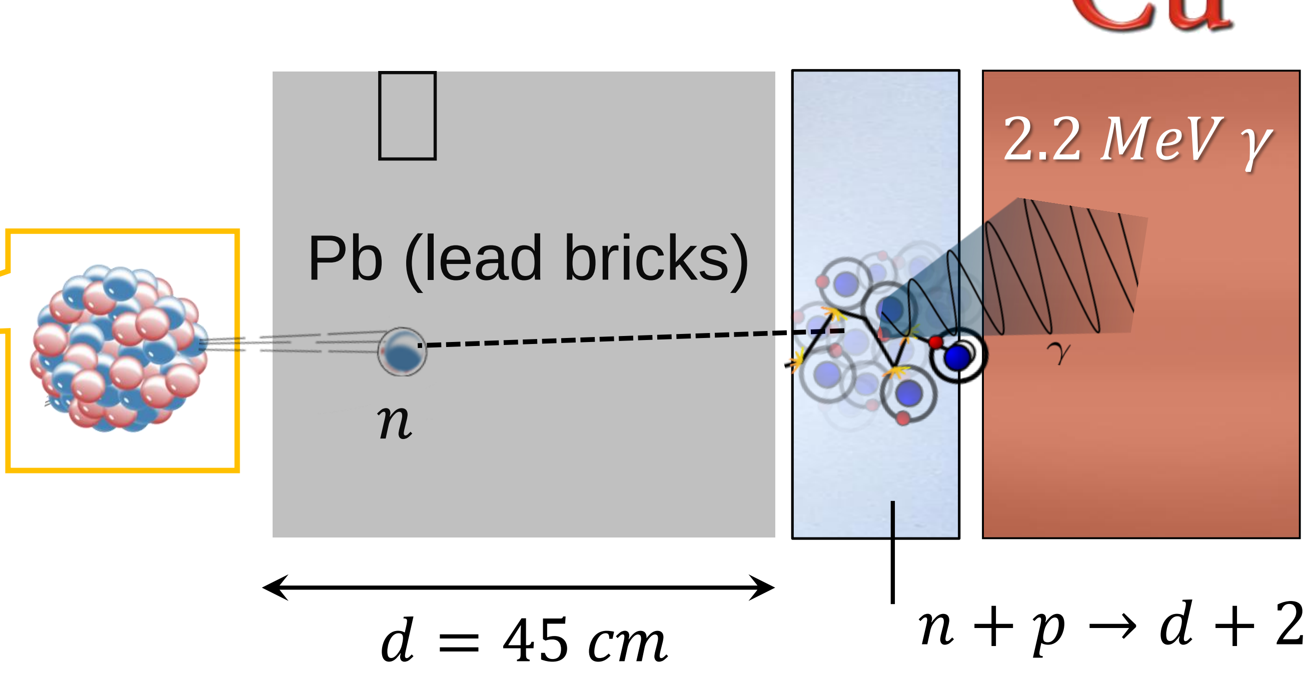


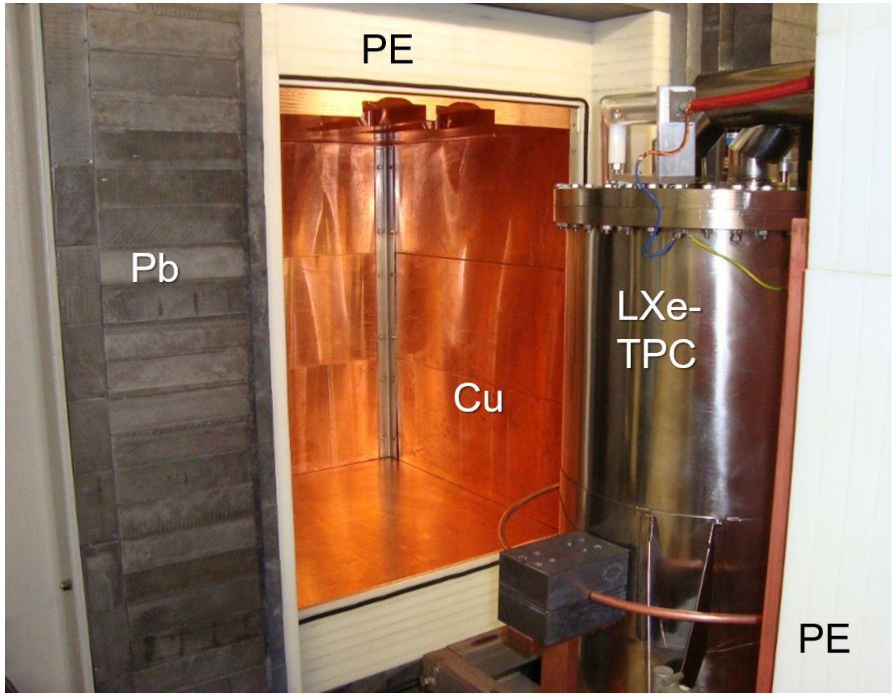
Shielding methods: muon-induced neutrons

- **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)



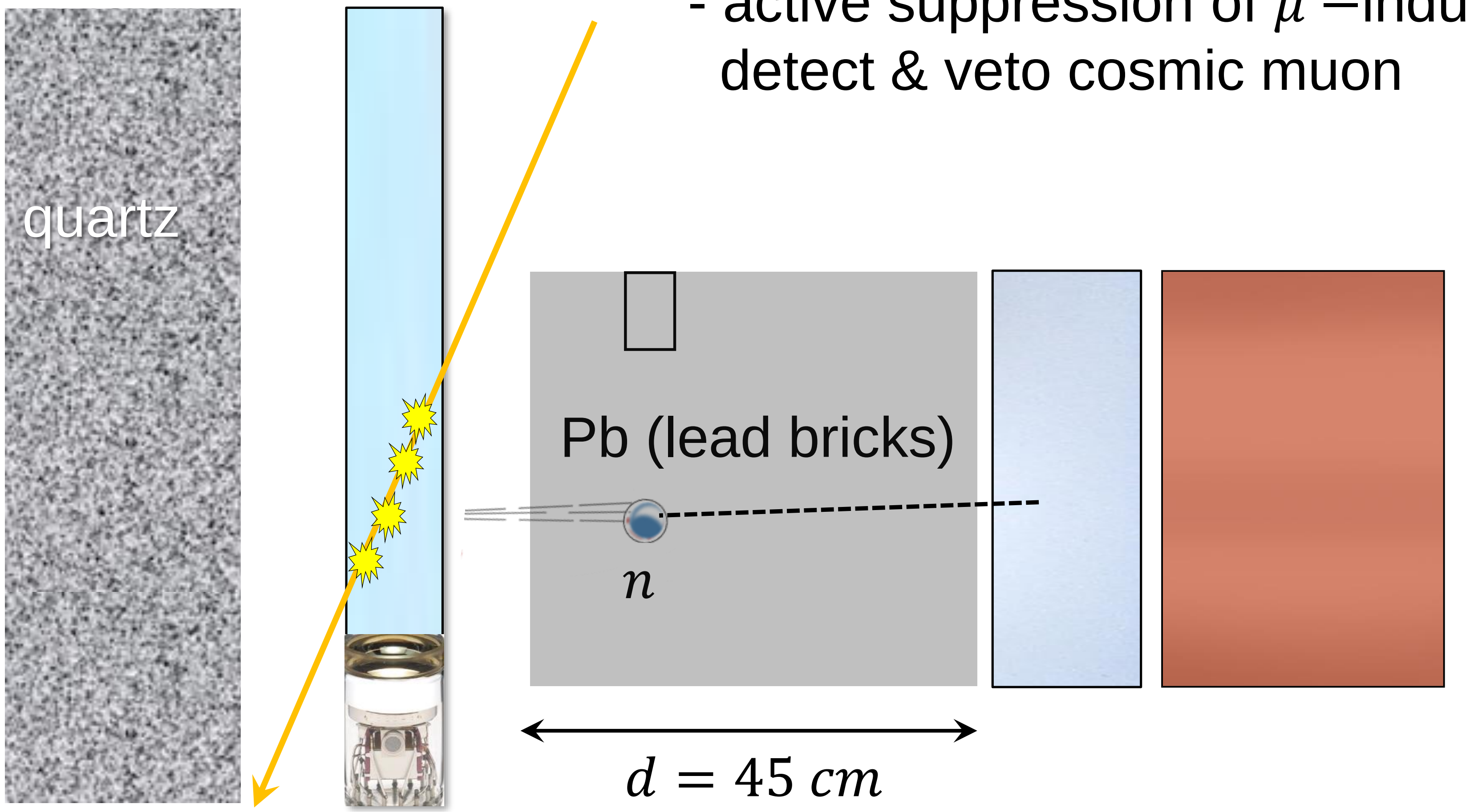




Shielding methods: one more thing…

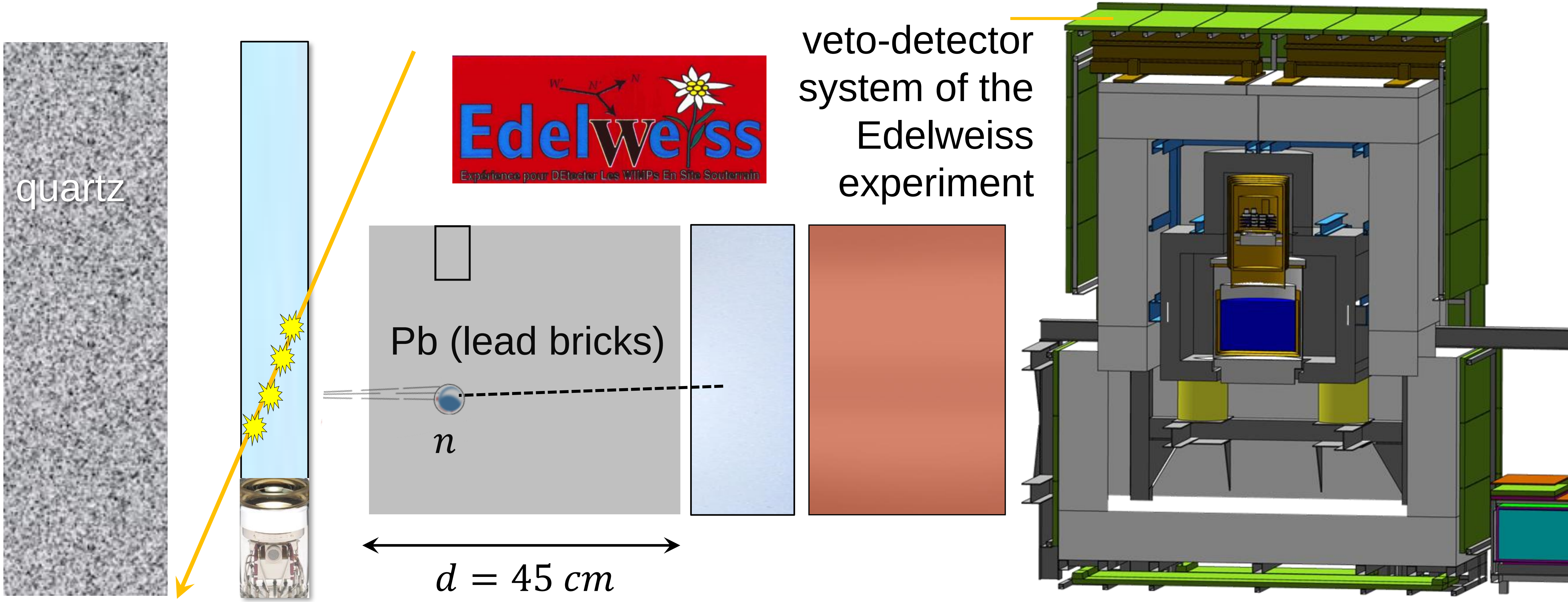
- **Veto against cosmic muons: plasic scintillator or water Cherenkov detector**

- active suppression of μ –induced neutrons via vetocounter: detect & veto cosmic muon



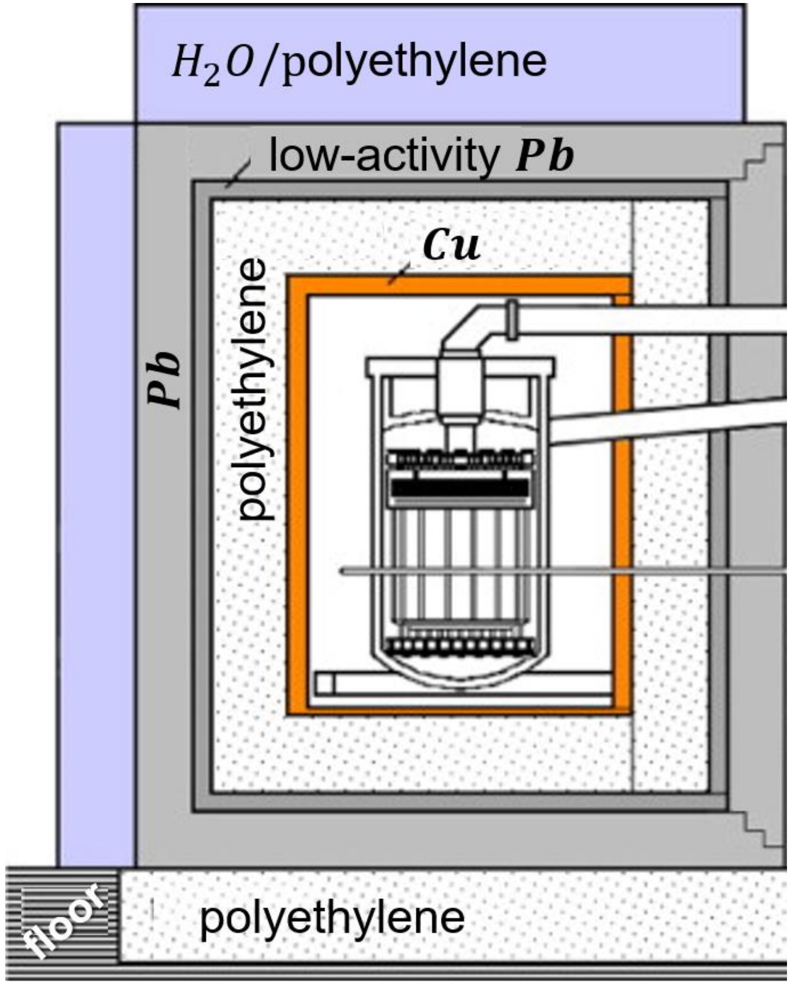
Shielding methods: one more thing…

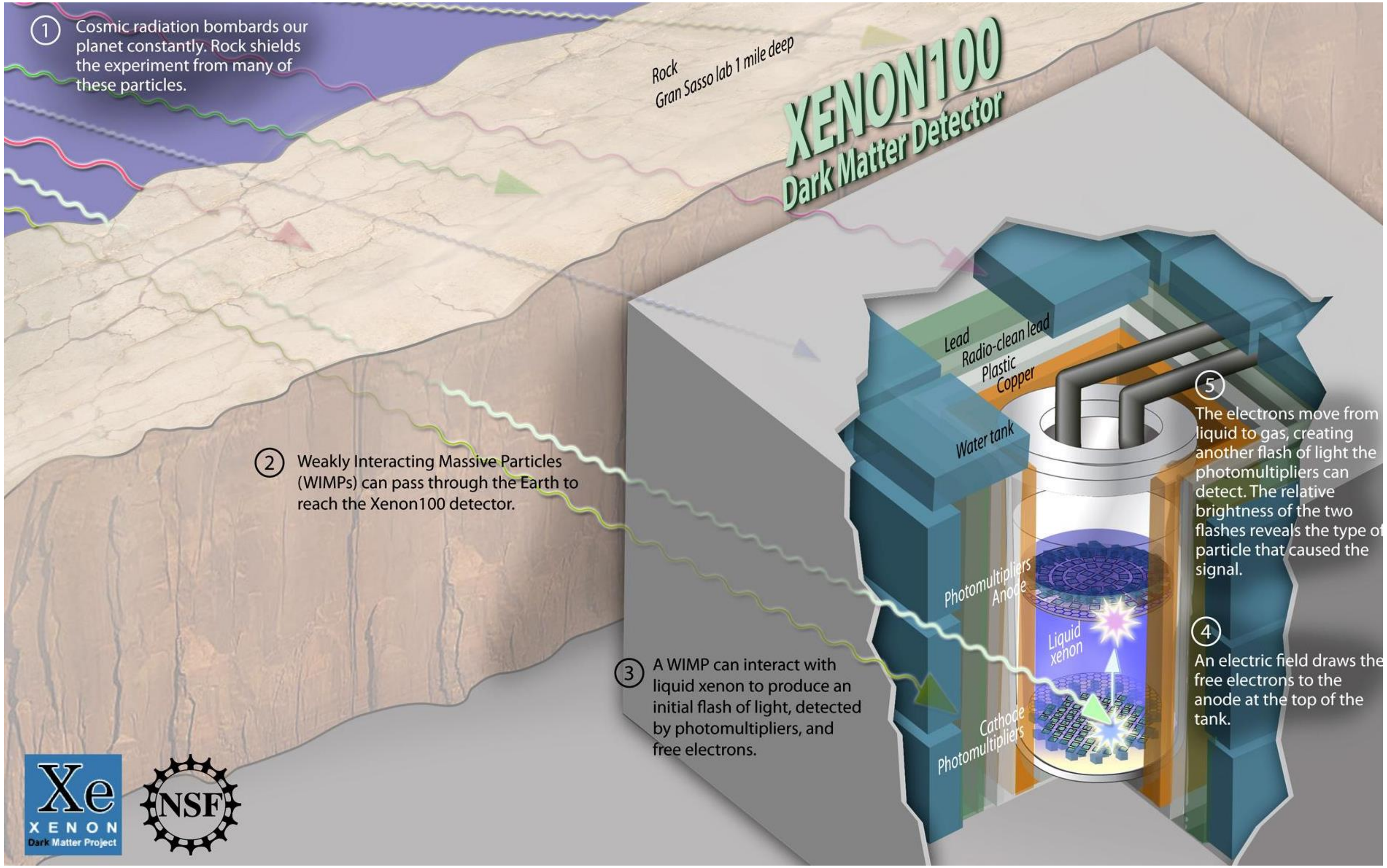
- Veto against cosmic muons: plasic scintillator or water Cherenkov detector



Shielding methods: example XENON

- XENON100 at LNGS





Shielding methods: further optimization (DARWIN)

- **DARWIN proposal at LNGS**

- very large H_2O veto counter & careful material screeing/selection

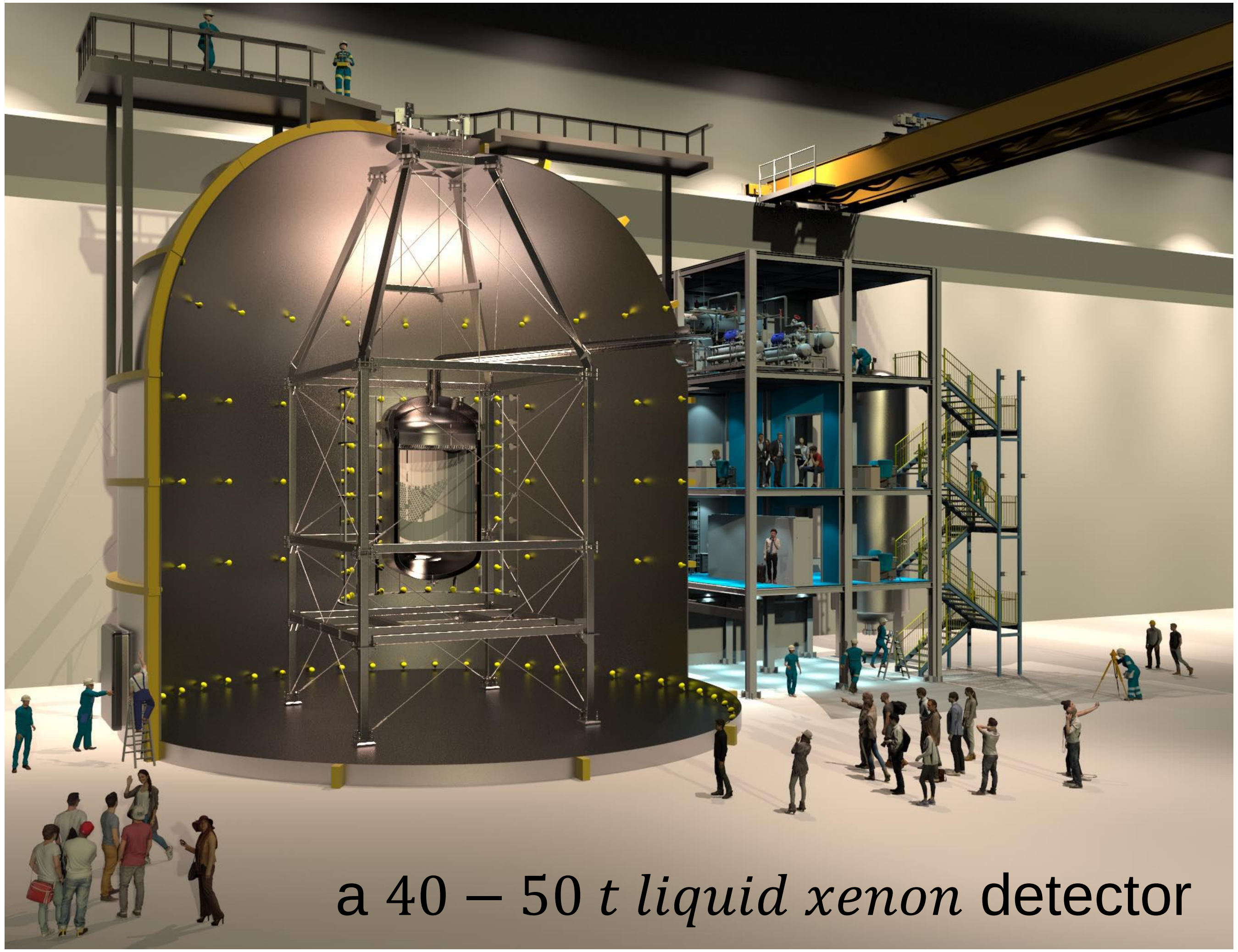
- continuous liquid xenon purification

- dominant background source:

solar neutrinos
atmospheric neutrinos
diffuse SN neutrinos

} ν –floor

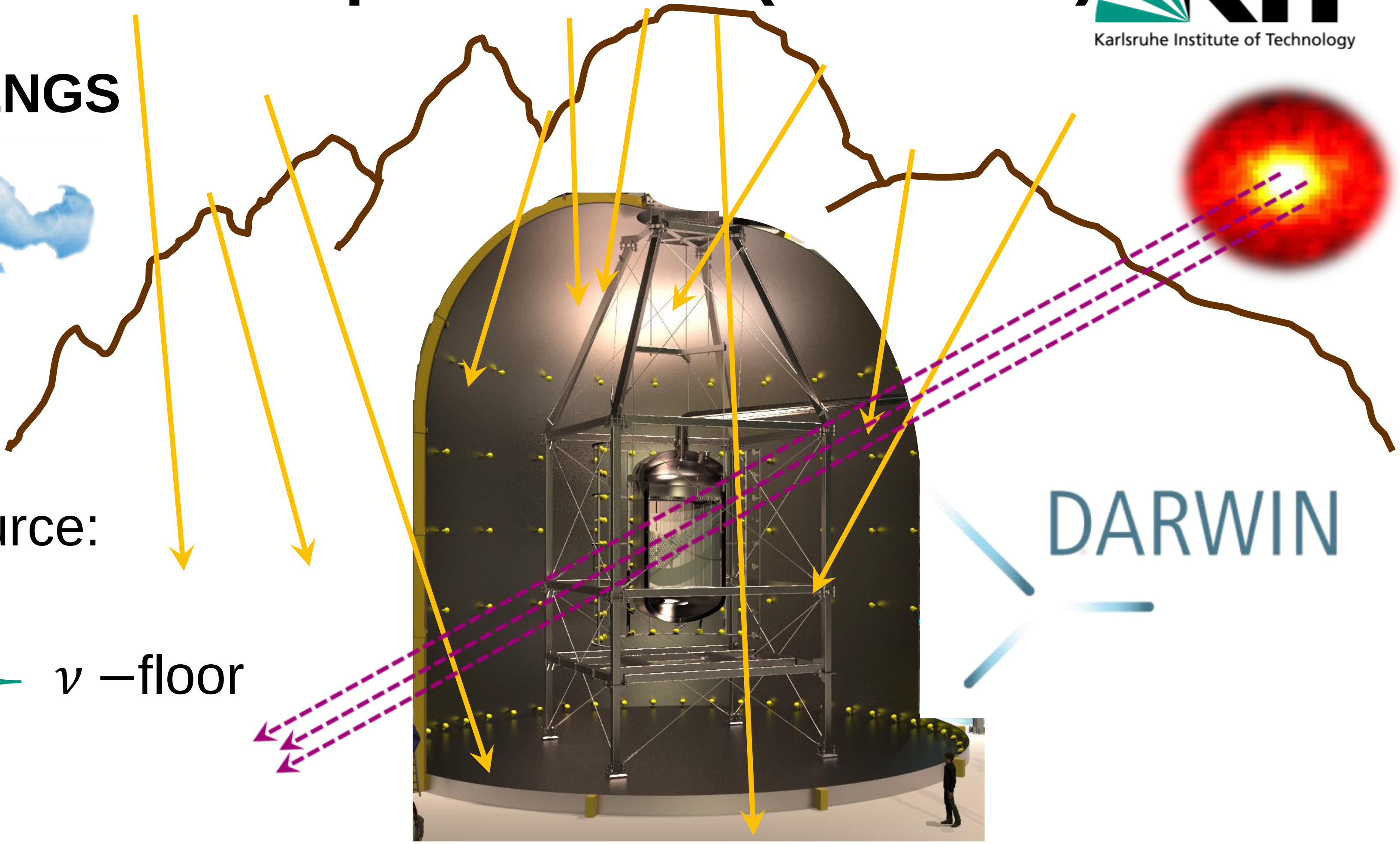
- the ´ultimate´ shielding frontier



a $40 - 50\,t$ *liquid xenon* detector

Shielding methods: further optimization (DARWIN)

- **DARWIN proposal at LNGS**



- dominant background source:

  solar neutrinos
  atmospheric neutrinos
  diffuse SN neutrinos

  } ν –floor

- the ´ultimate´ shielding frontier

a $40 - 50\ t\ liquid\ xenon$ detector

2.2.3 Primordial decay chains

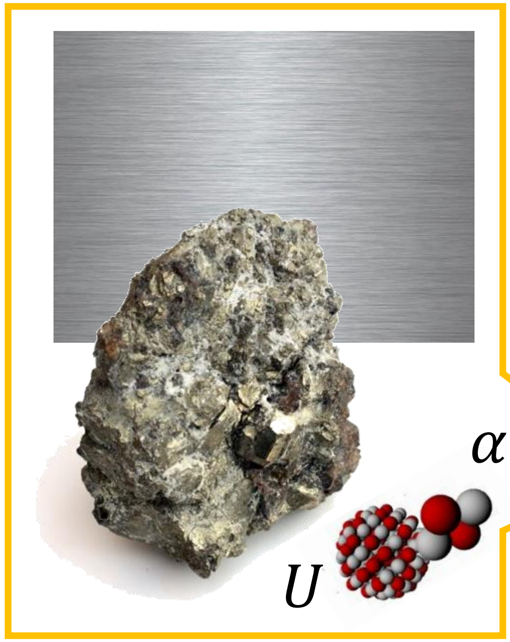
- **Origin of radioactive isotopes here on Earth**

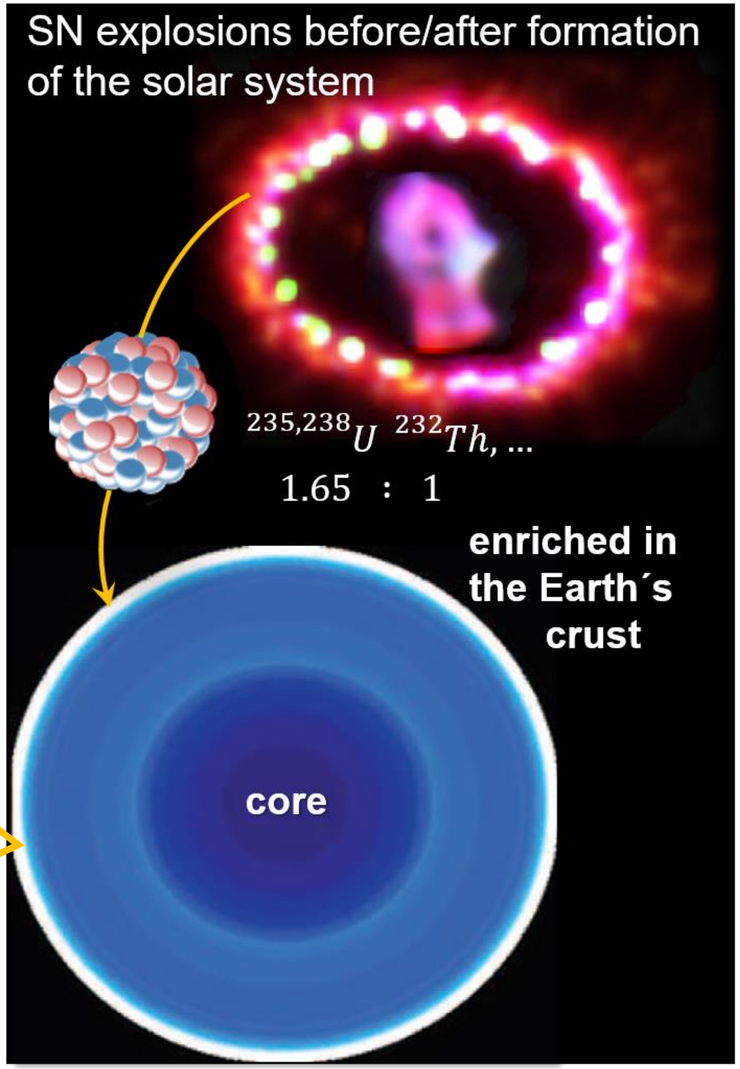
  - radioactive isotopes are forged in SNae explosions / Gamma Ray Bursts (GRBs*) in our galaxy

  - after galactic voyage to Earth: enrichment in outer crust

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

  - there are 4 primordial decay chains



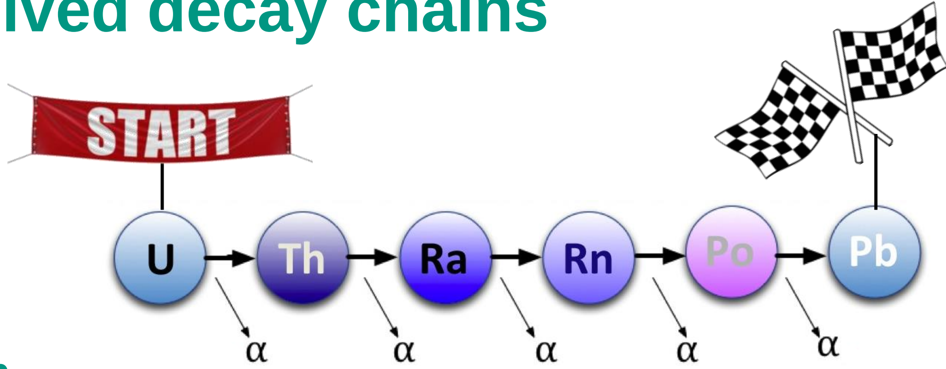


*see ATP-2 summer term 2023

The four primordial decay chains

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

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



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

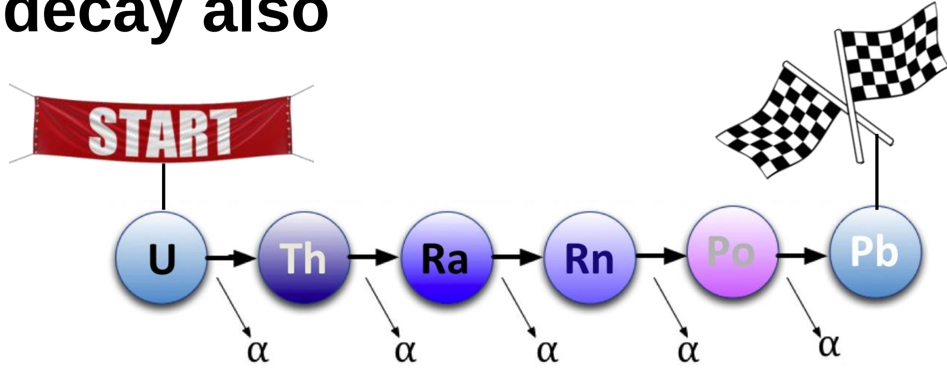
$^{237}Np - chain$: $A = 4 \cdot j + 1$ stable end: ^{209}Bi

$^{238}U - chain$: $A = 4 \cdot j + 2$ 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 decay also**



- differential equations for # of nuclei:

$$\frac{dN_1}{dt} = -\lambda_1 \cdot N_1$$ decay of mother nuclide N_1

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

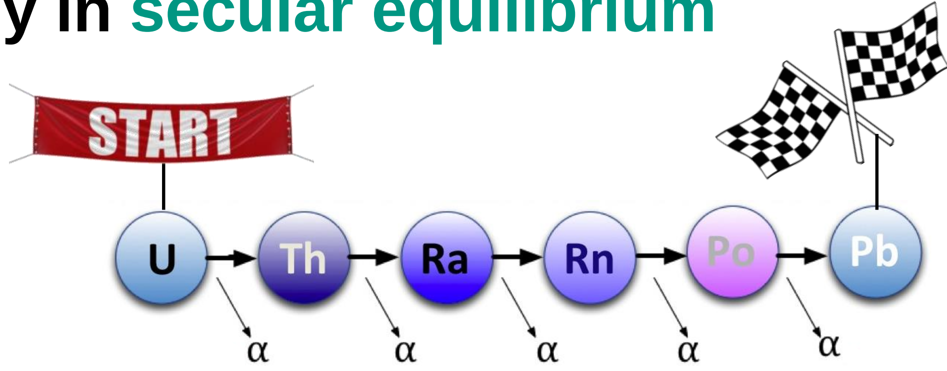
$$\frac{dN_3}{dt} = \lambda_2 \cdot N_2 - \lambda_3 \cdot N_3$$ generation ($+\lambda_2$) & decay ($-\lambda_3$) of grand-daughter N_3

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

The four primordial decay chains

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

  - production & decay rates are ***identical***:



$$\frac{dN_1}{dt} = \frac{dN_2}{dt} = \frac{dN_3}{dt}$$

idential decay rates of nuclides $N_1, N_2, N_3, \ldots$

$$A_1 = A_2 = A_3$$

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

$$\lambda_1 \cdot N_1 = \lambda_2 \cdot N_2 = \lambda_3 \cdot N_3$$

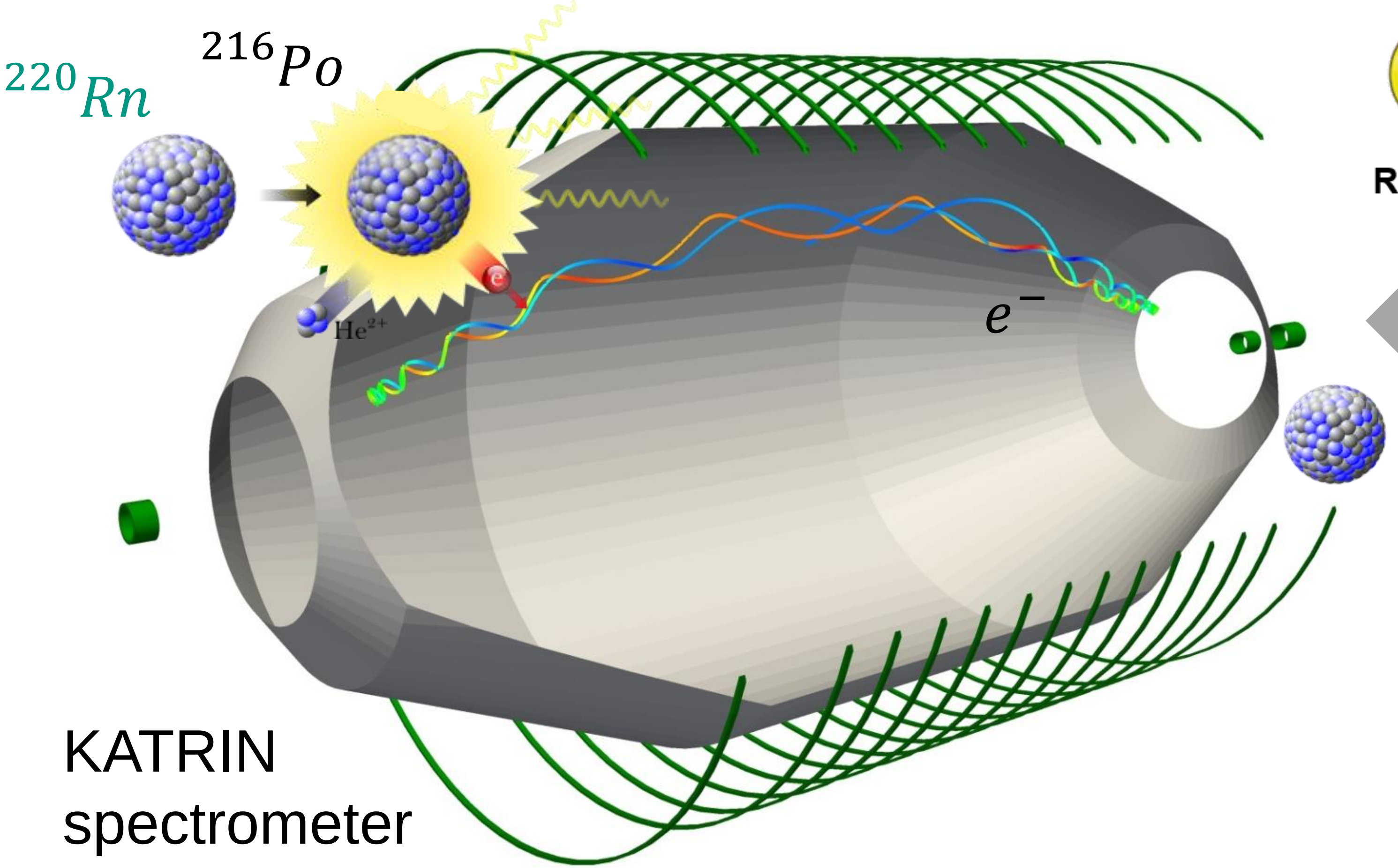
secular equilibrium* is reached after some time

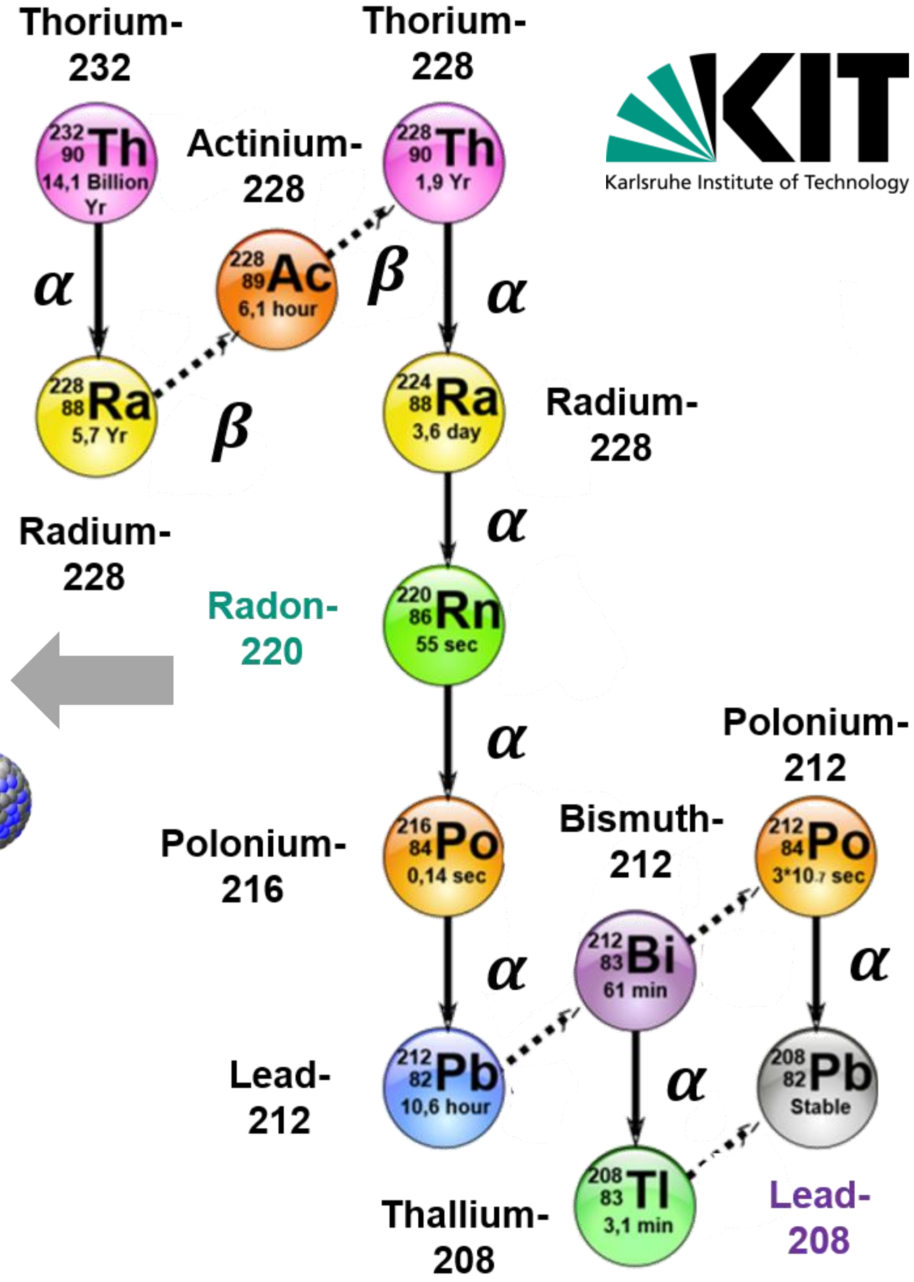
  - for a specific decay chain, only activity A_j of one isotope J needs to be measured

*implies that isotopes are not removed/added

Primordial decay chain of ^{232}Th

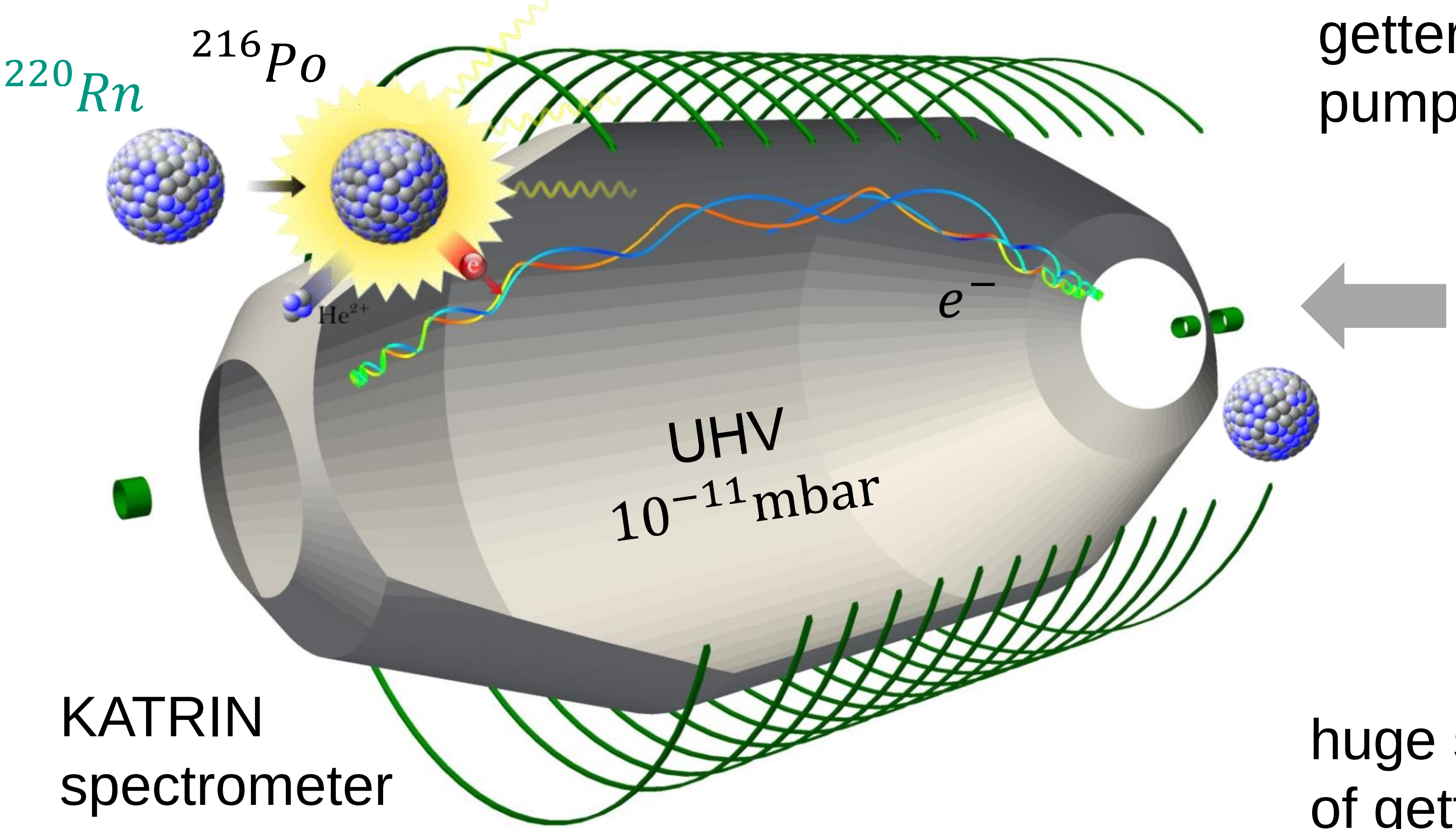
- Decay chain $^{232}Th \rightarrow {}^{208}Pb$





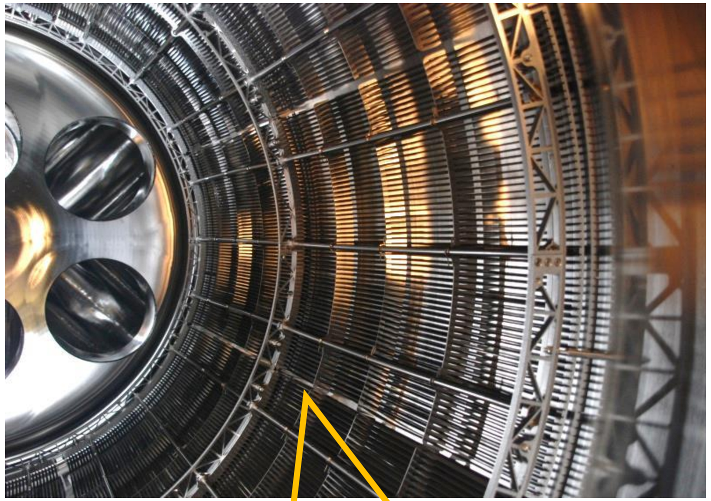
Primordial decay chain of ^{232}Th

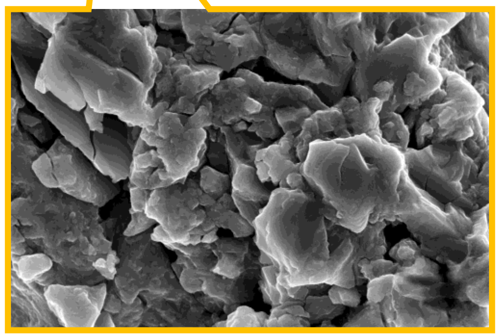
- **Decay chain $^{232}Th \rightarrow {}^{208}Pb$: emanation of gaseous ^{220}Rn generates e^-**



KATRIN
spectrometer

getter
pump

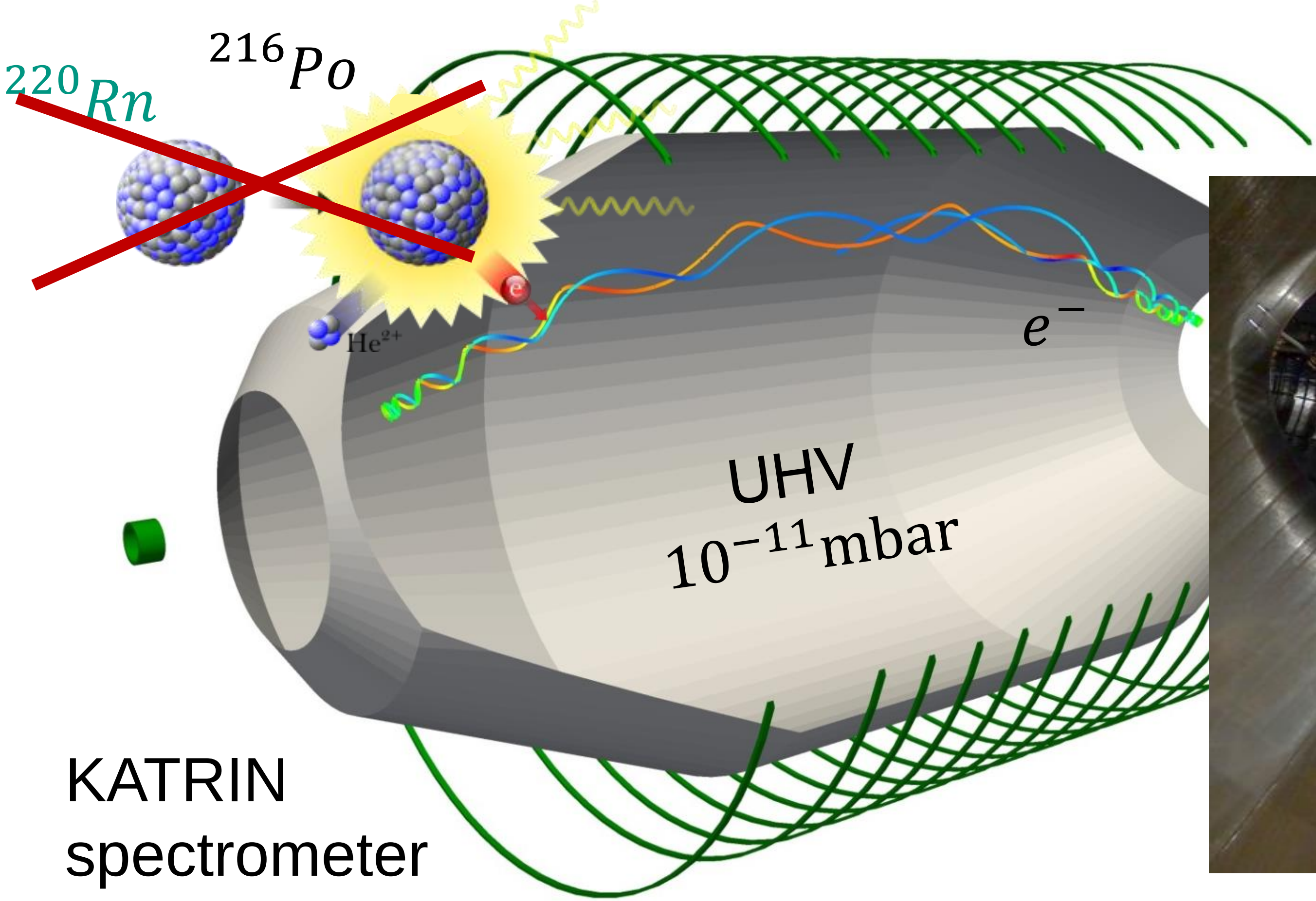




huge surface
of getter material

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

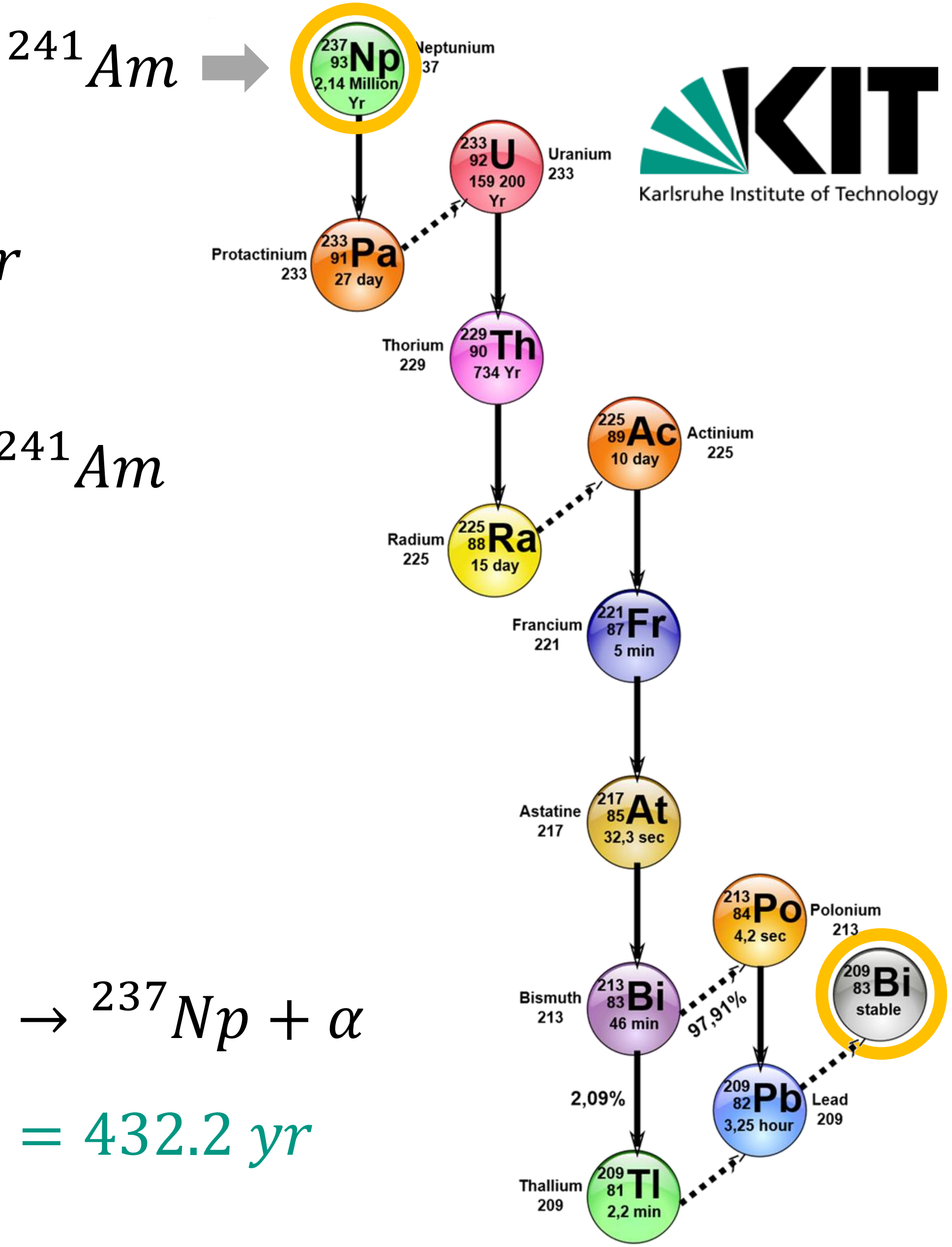
Primordial decay chain of ^{237}Np

- **Decay chain $^{237}Np \rightarrow {}^{209}Bi$: $t_{1/2} = 2.1 \cdot 10^6\ yr$**
  artificial mother isotope ^{241}Am

  - smoke detectors sometimes contain isotope ^{241}Am

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

$$t_{1/2} = 432.2\ yr$$

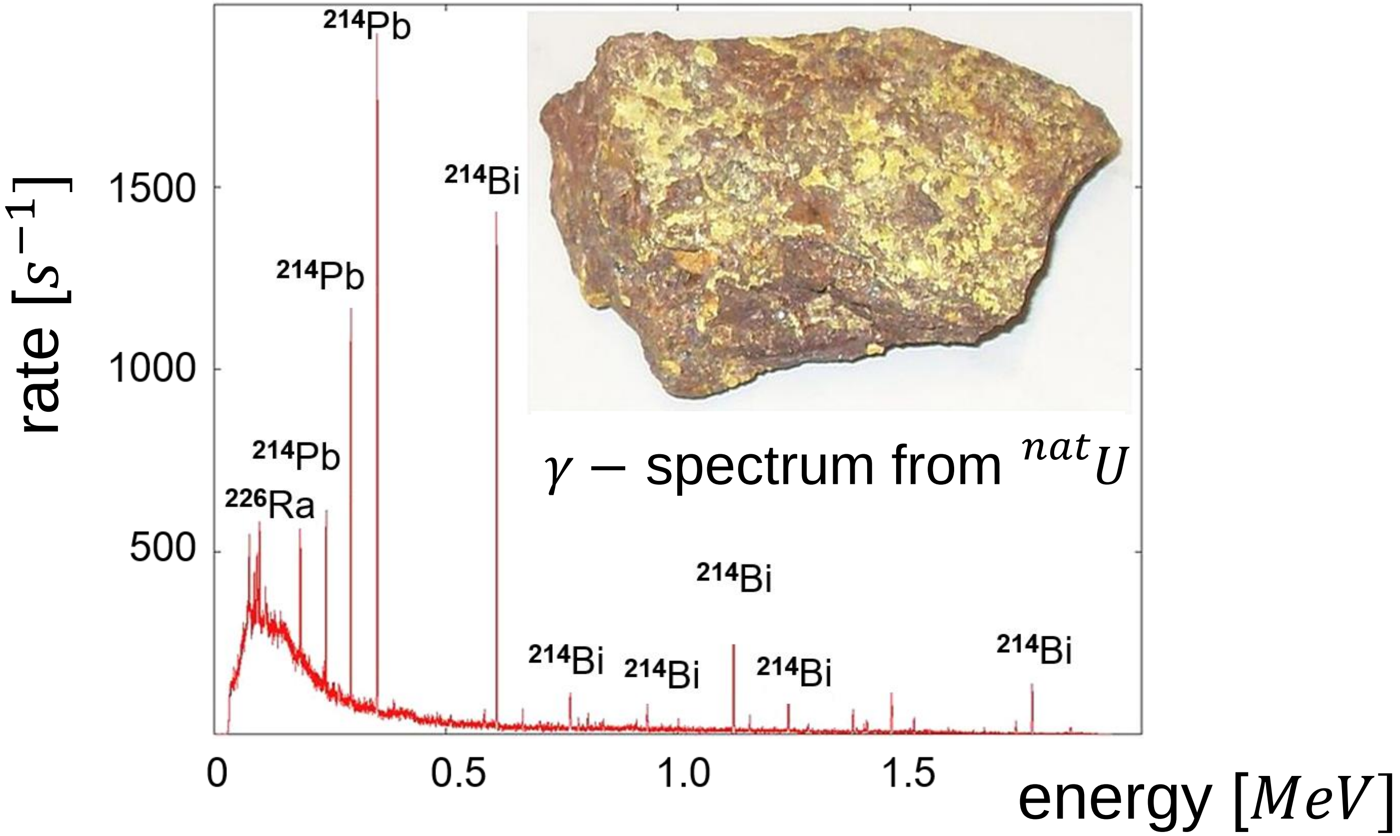


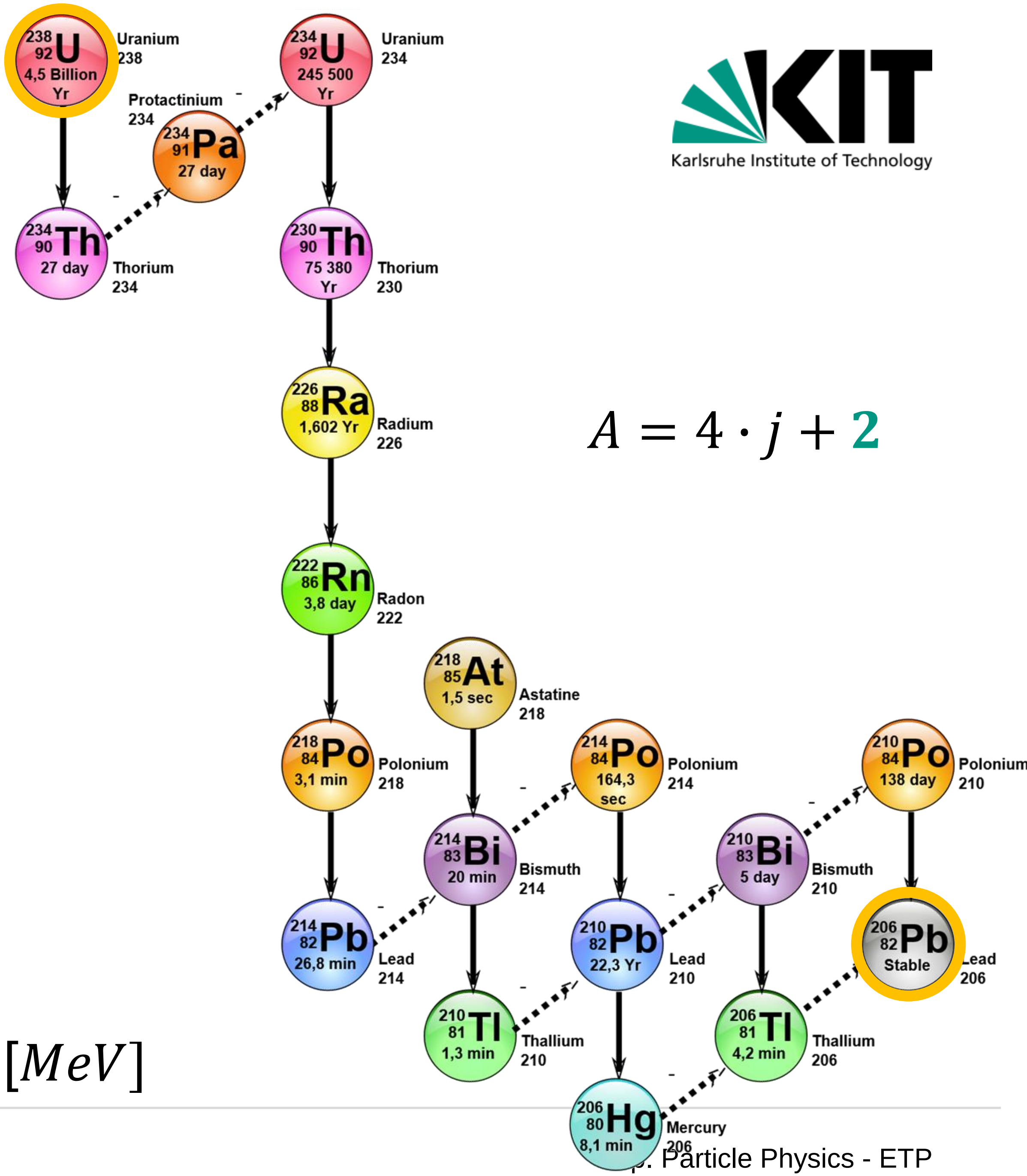
Karlsruhe Institute of Technology

Primordial decay chain of ^{238}U

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

$t_{½} = 4.5 \cdot 10^9 yr$

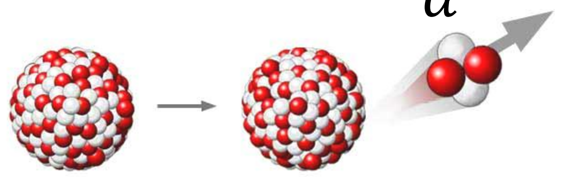




$A = 4 \cdot j + 2$

Primordial decay chain of ^{238}U

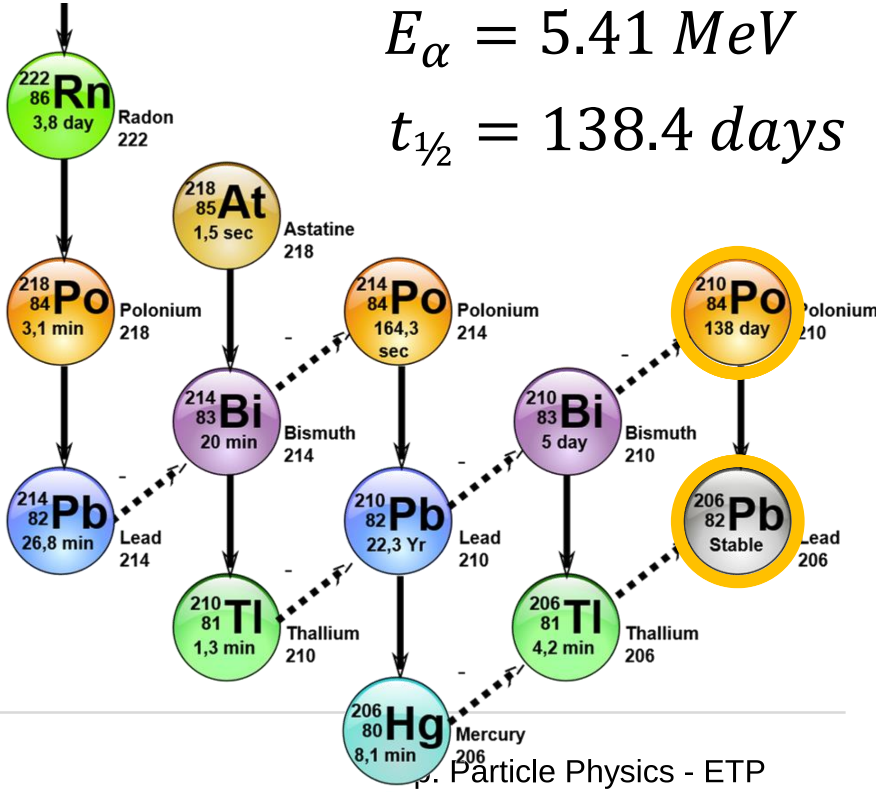
- **Decay chain $^{238}U \rightarrow {}^{206}Pb$: $\alpha -$ decay of ^{210}Po**
  - 1951: **Gilbert´s Atomic Energy Lab** (49.50 $)
  - included were 2 α –sources: ^{210}Po & ^{210}Pb



^{210}Po – source

$$E_\alpha = 5.41\ MeV$$

$$t_{½} = 138.4\ days$$

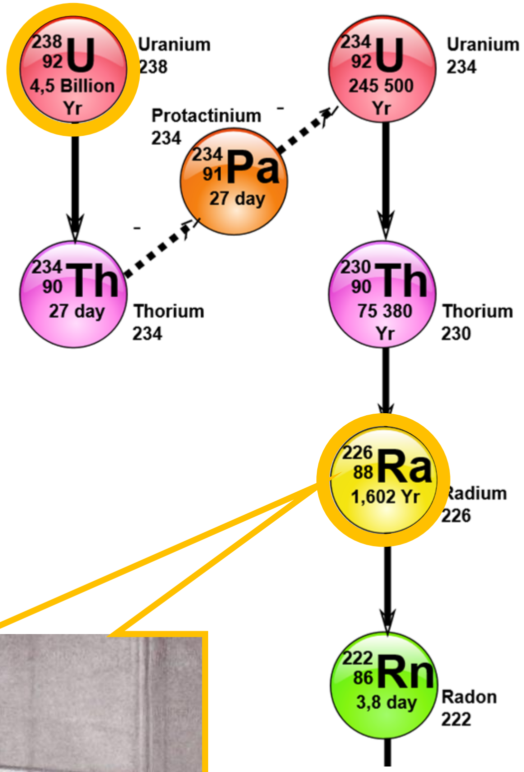


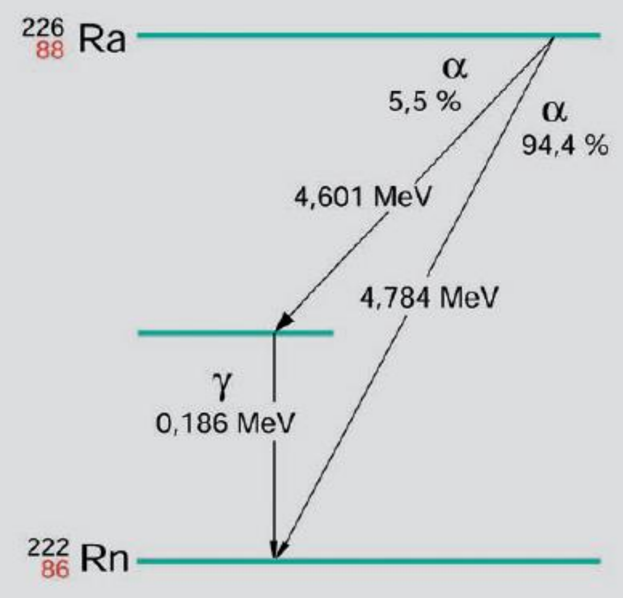
Primordial decay chain of ^{238}U

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

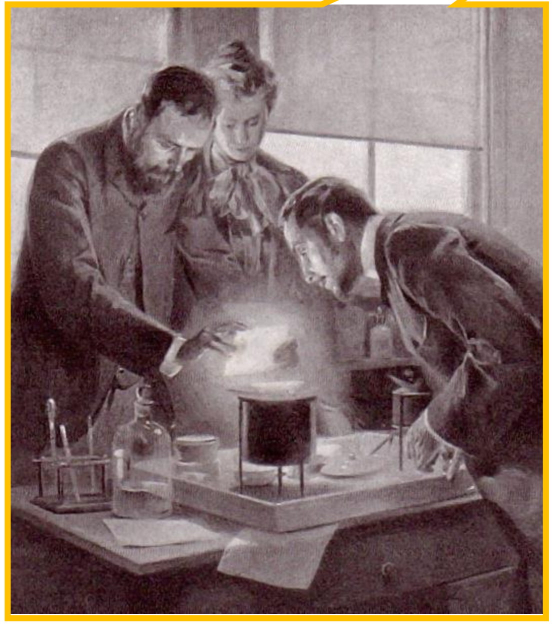
  α –decay of ^{226}Ra

  $t_{½} = 1602\ yr$





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

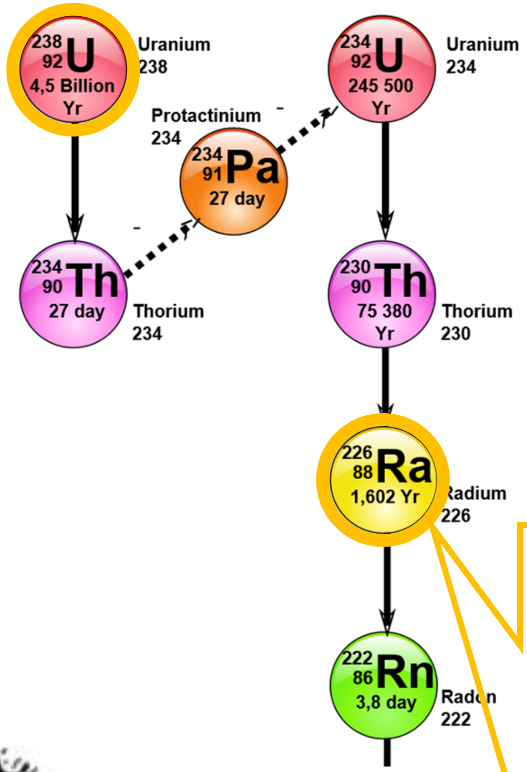


$$1\ Curie = 3.7 \cdot 10^{10}\ decays/s$$

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

Nobel prize in physics 1903 to both

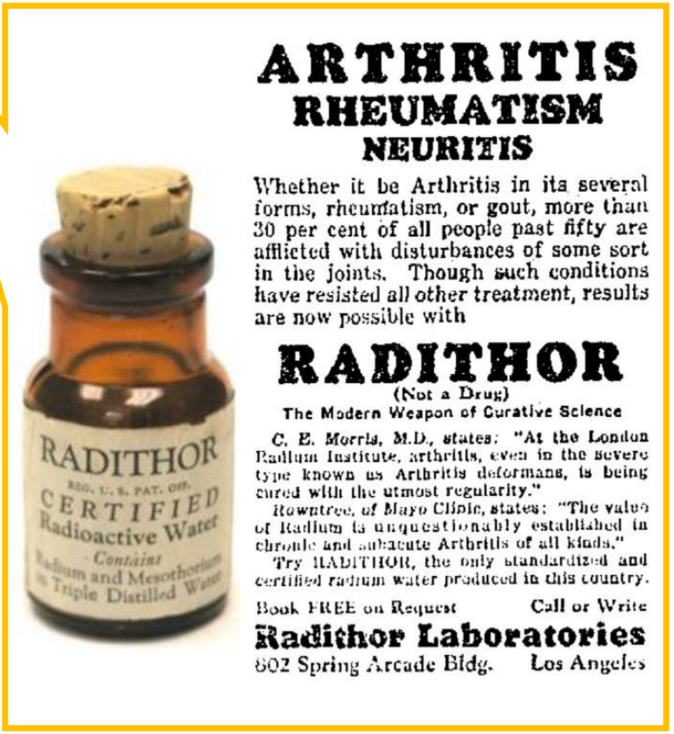
Primordial decay chain of ^{238}U



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

  - radium water (Radithor) / chocolate

  - radium was in use as ´convenient´ illuminant for watches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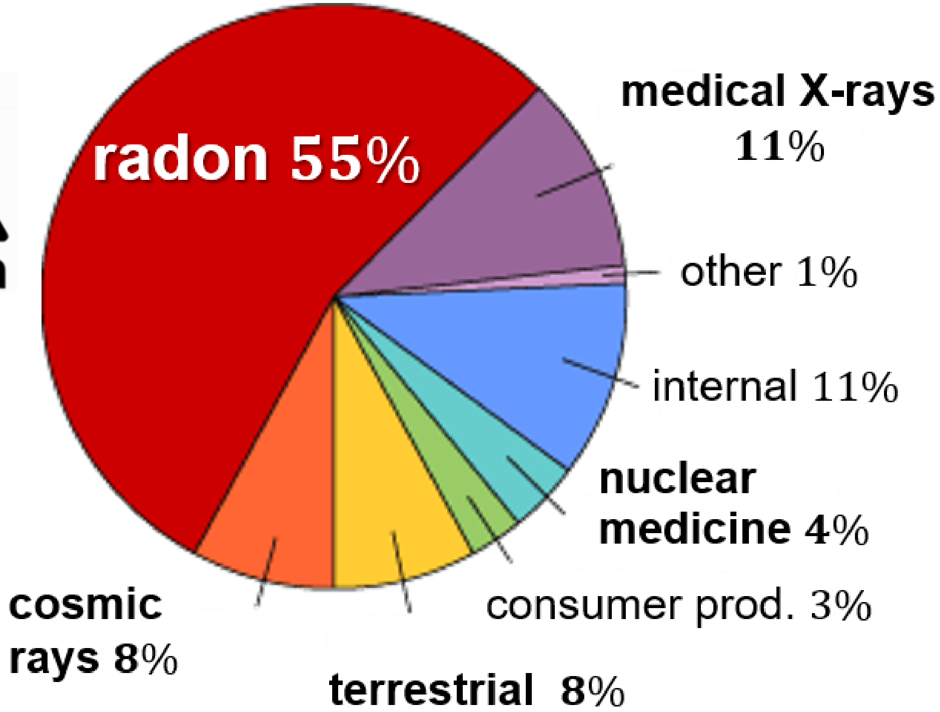
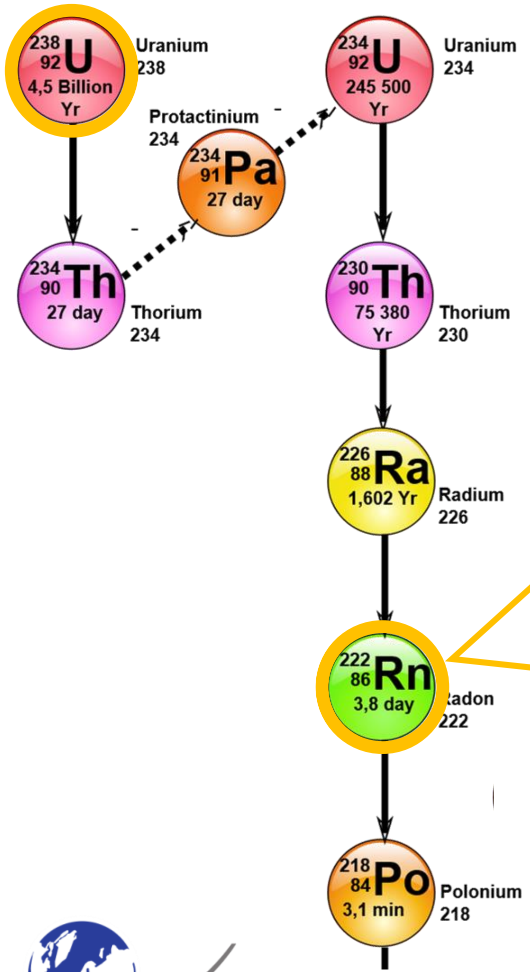
Primordial decay chain of ^{238}U

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

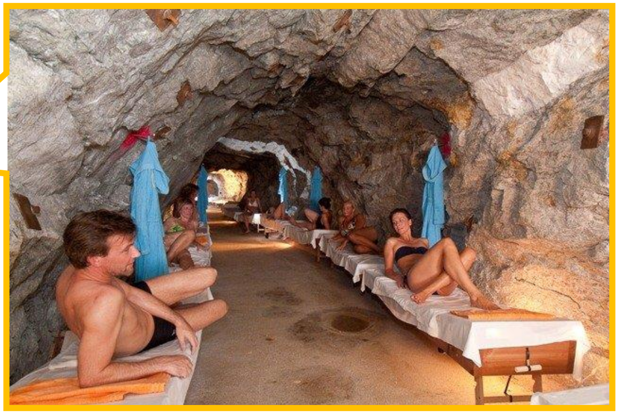
  α –decay of ^{222}Rn

  $t_{½} = 3.82$ days





radon ´therapy´ in underground tunnels

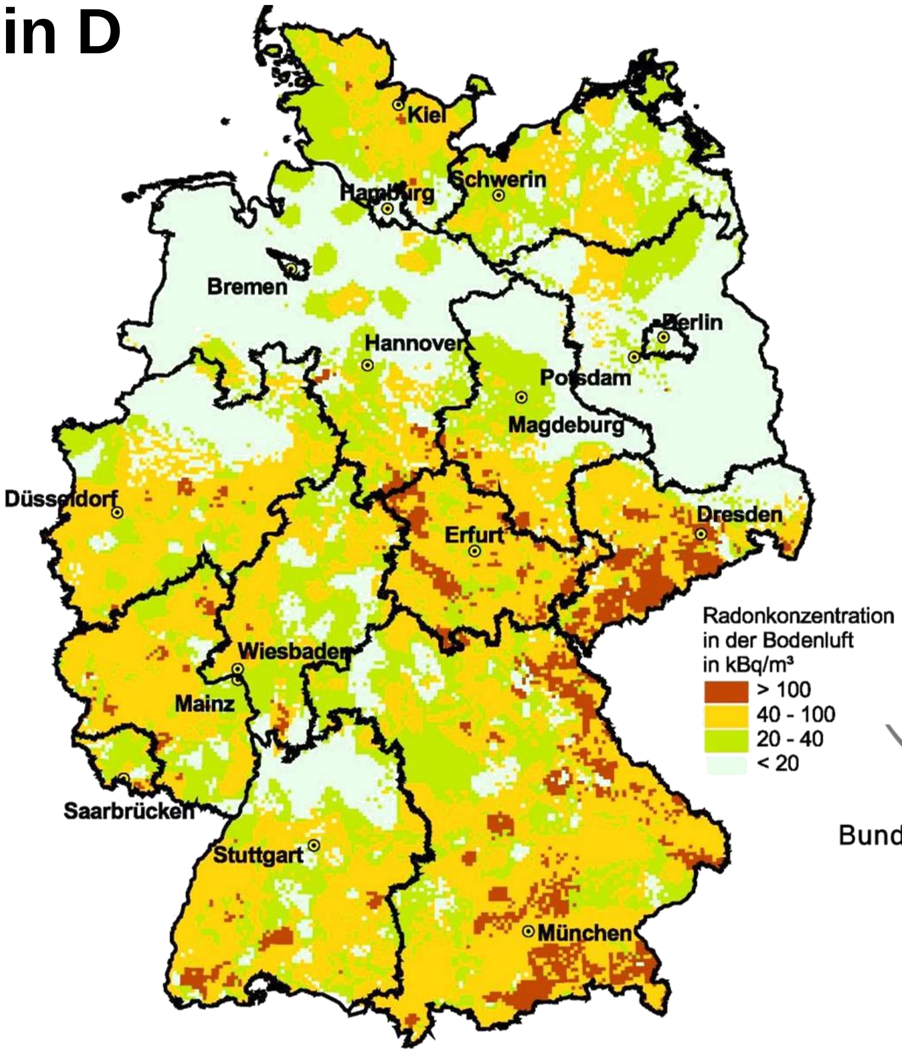


Bundesamt für Strahlenschutz

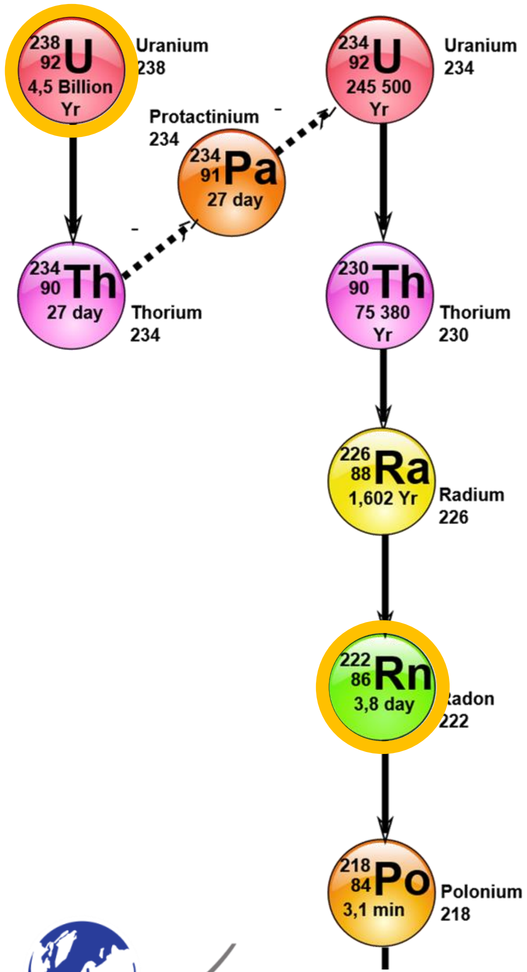
- radon emanation & average radiation exposure

Primordial decay chain of ^{238}U

- Radon in D



Bundesamt für Strahlenschutz



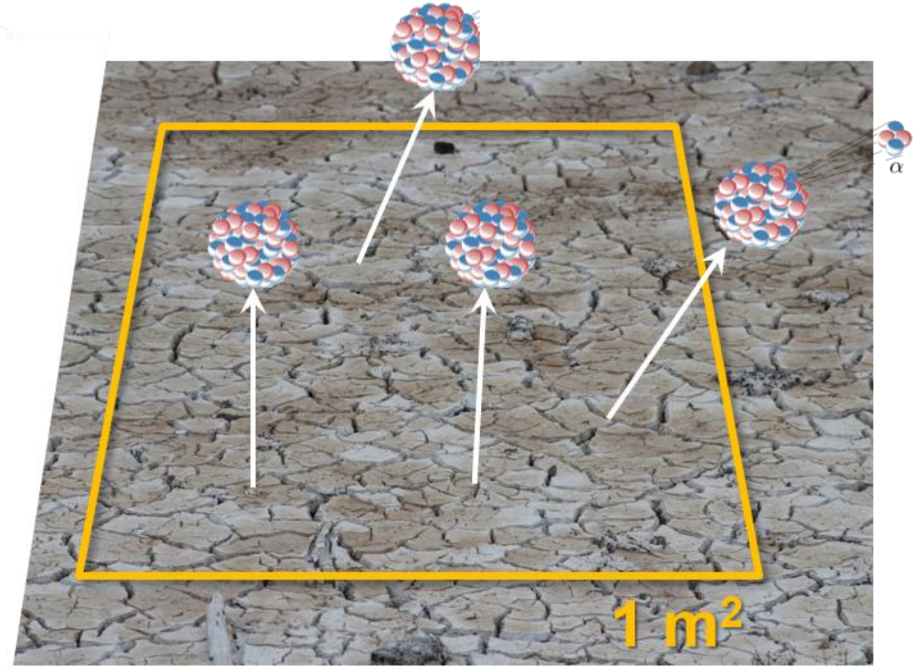
$\sim 50\ Bq/m^3$

^{222}Rn

Primordial decay chain of ^{238}U

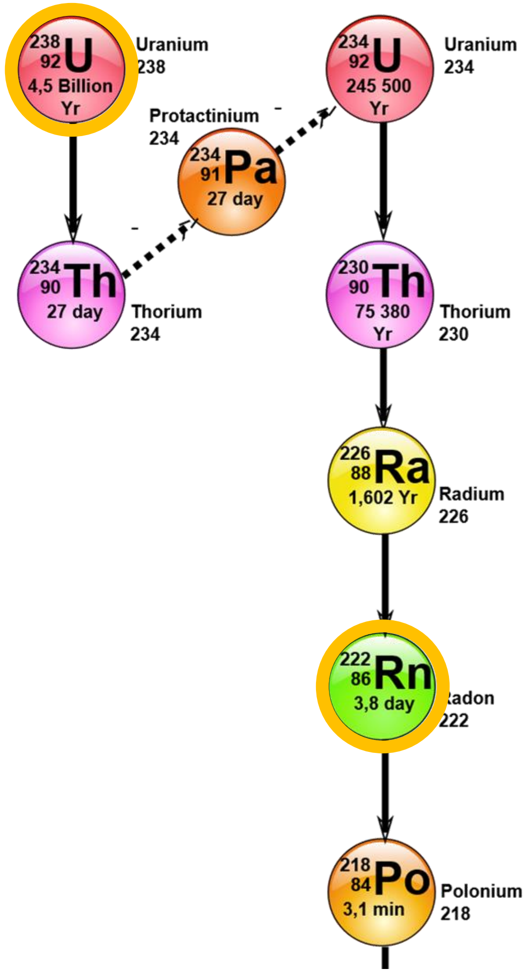
- **Radon emanation per m^2 of soil**

$\sim 7400\ ^{222}Rn$ –atoms / s



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

due to ^{222}Rn



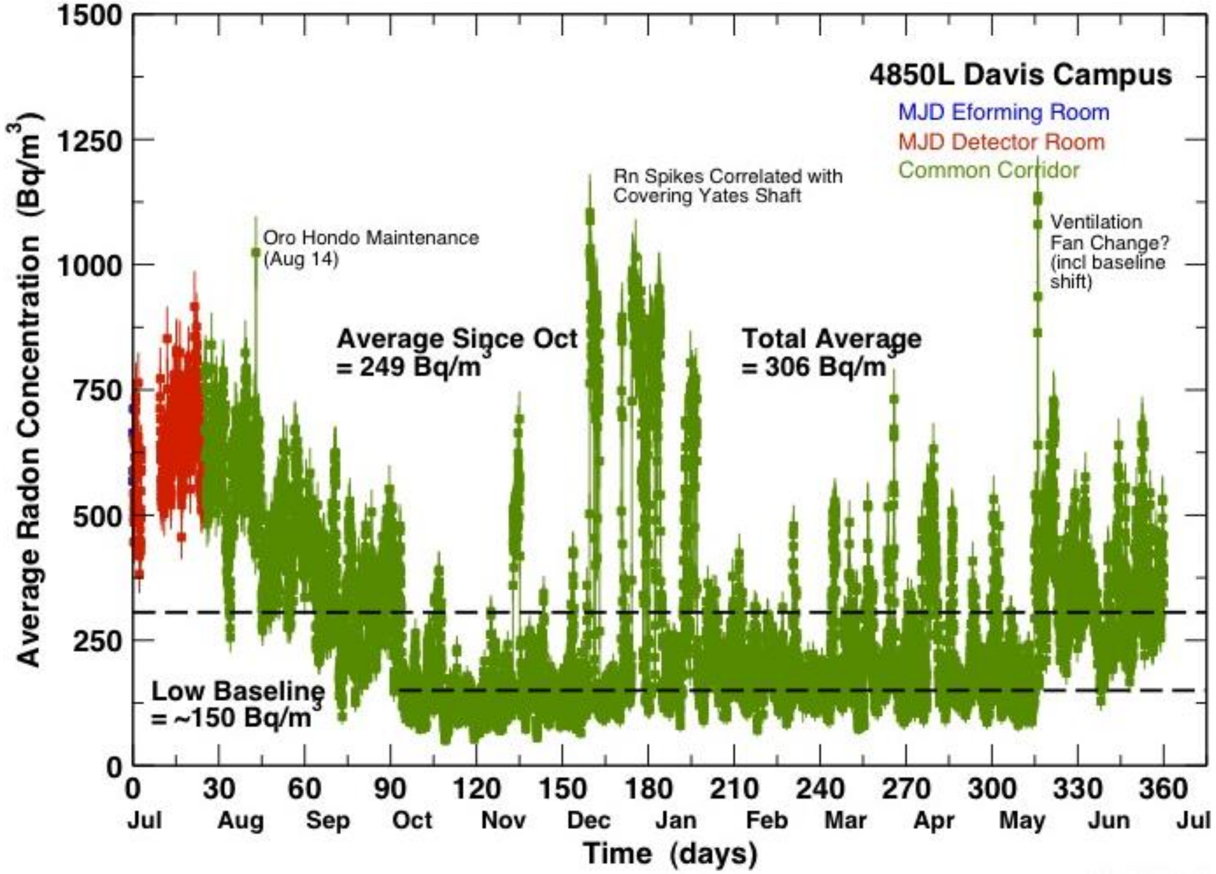
- yearly activity (over entire surface) from ^{222}Rn emanation: **$91\ TBq$**

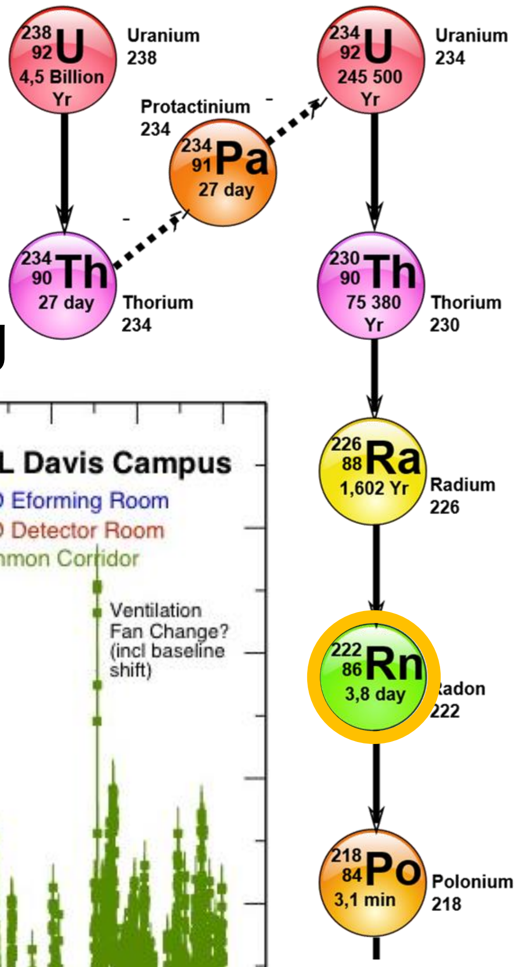
Primordial decay chain of ^{238}U

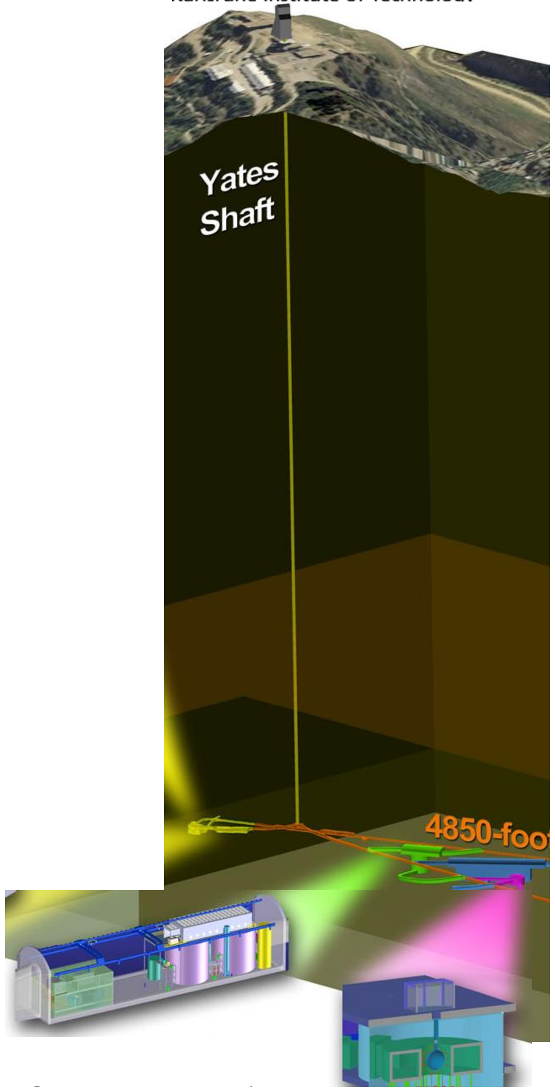
- **Radon emanation in underground labs**

- requires permanent ventilation & monitoring

is a noble gas







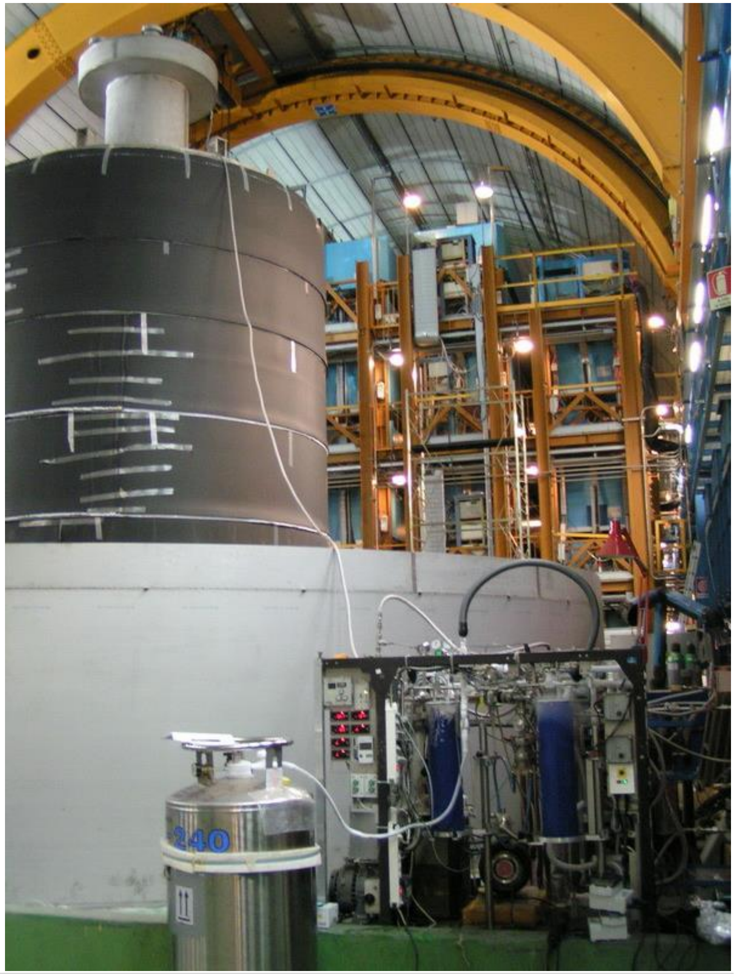
Primordial decay chain of ^{238}U

- **Radon emanation in underground experiments: example GERDA**

  - requires careful assessment of radon emanation of all detector components

  - measurement of radon emanation in the GERDA cryostat at LNGS

  - stringent material selection („***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