CYGNO-04 Monte Carlo

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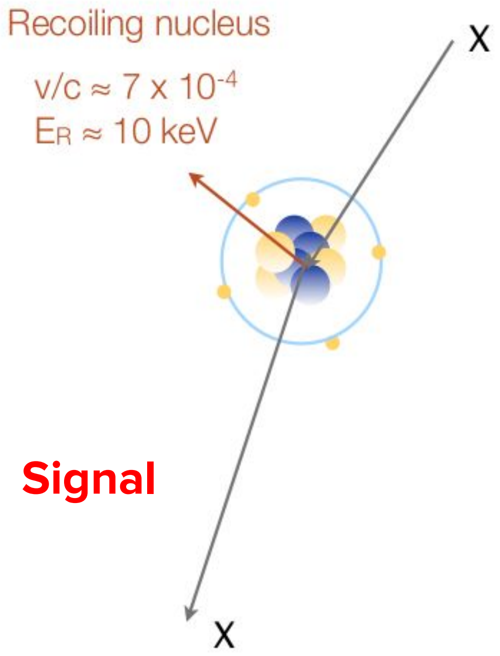
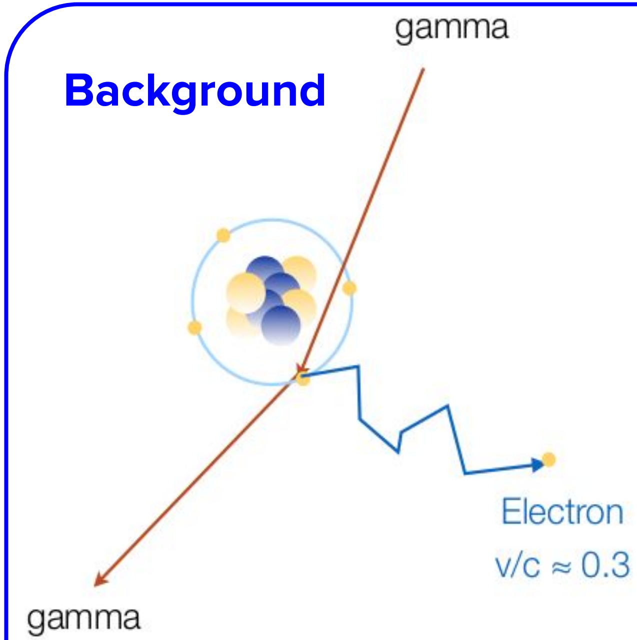
Signal and background events in dark matter search

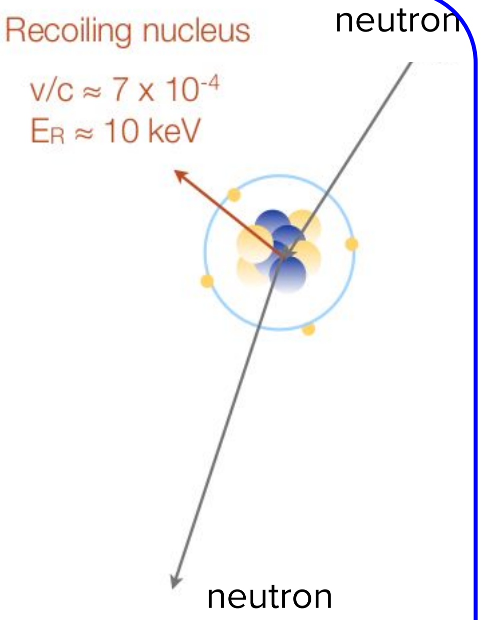


WIMPs produce
nuclear recoils (NR)

Background



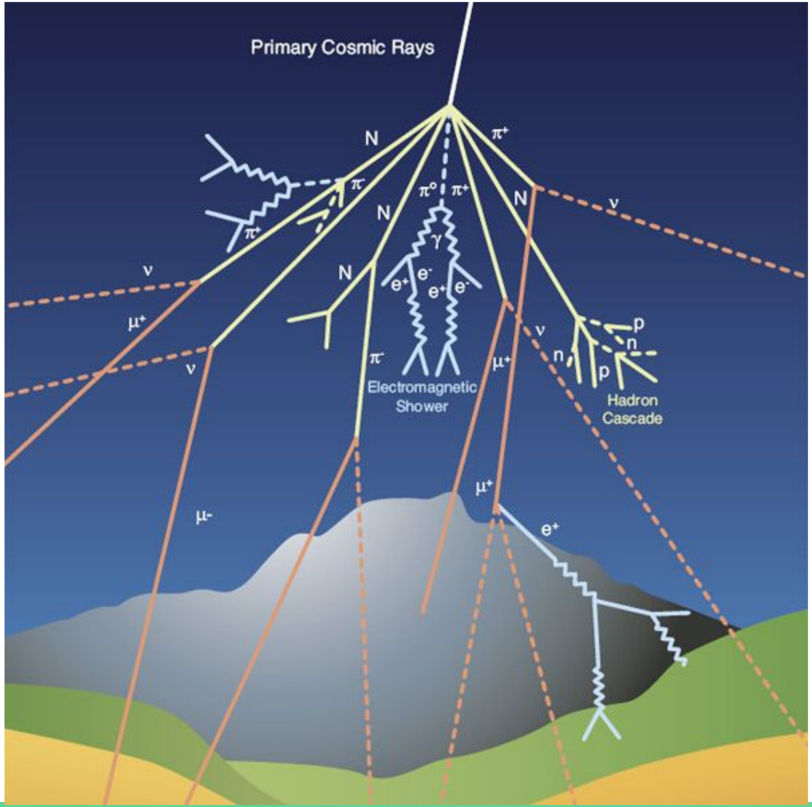
Most of the background from **electron recoils (ER)** caused by **β/γ events**



Neutrons produce
nuclear recoils (NR)
similar to WIMPs

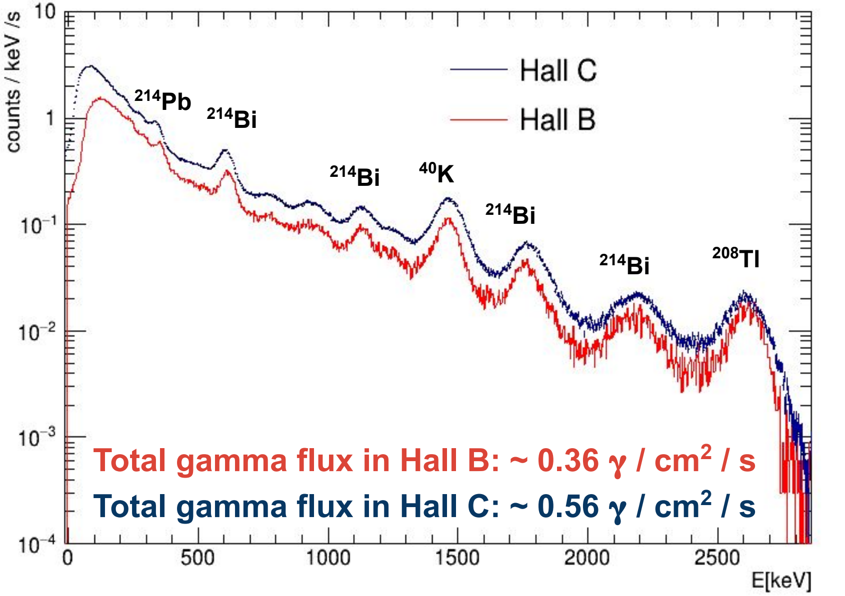
Background sources

1) Cosmic rays (+ cosmogenics)



2) Environmental radioactivity

Mainly potassium (K) uranium (U) and thorium (Th) and their daughters

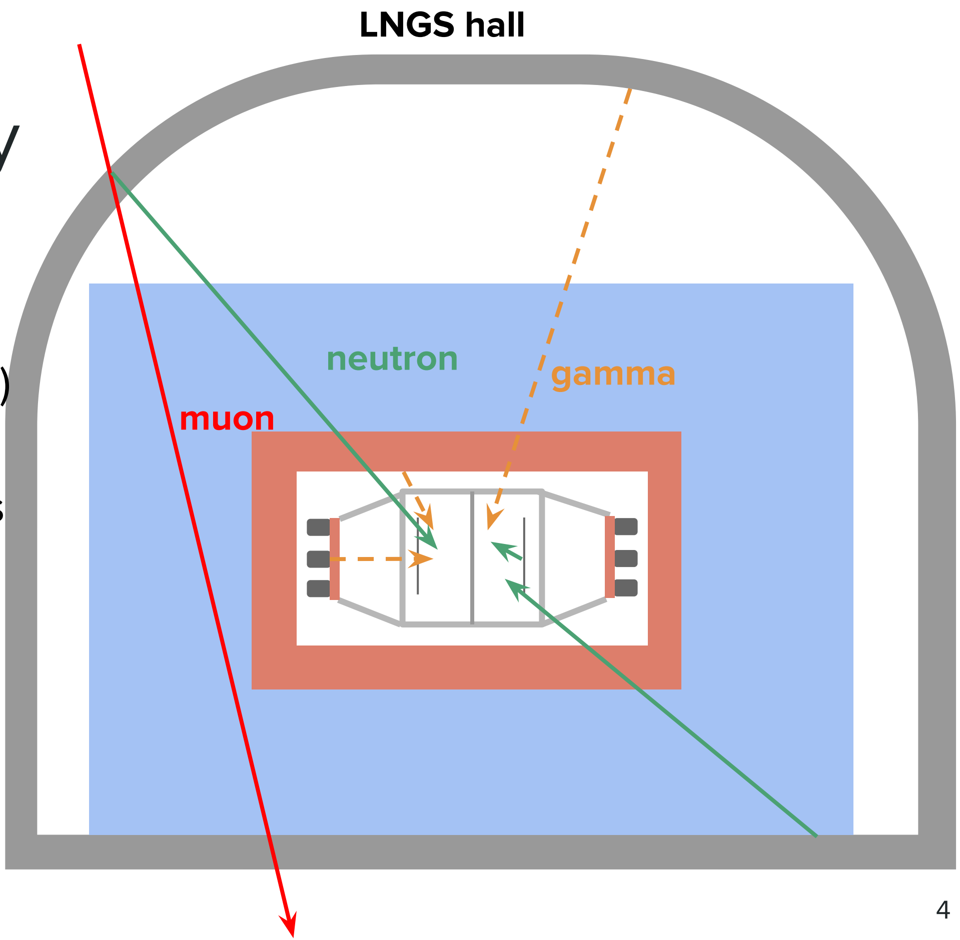


Background components in underground laboratory

- Internal neutrons/gammas
(origin: radioactivity of the materials in setup, including cosmogenic isotopes)

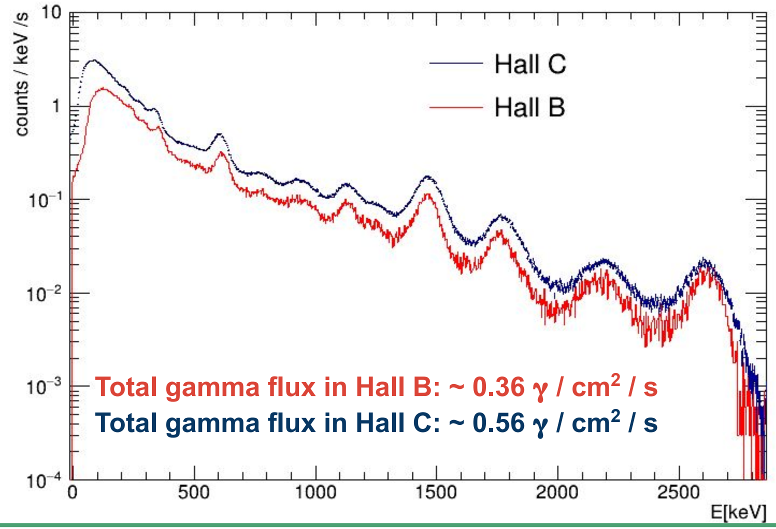
- External radiogenic neutrons/gammas
(origin: radioactivity of rocks and concrete of the lab)

- External cosmogenic neutrons
(origin: muon interactions)



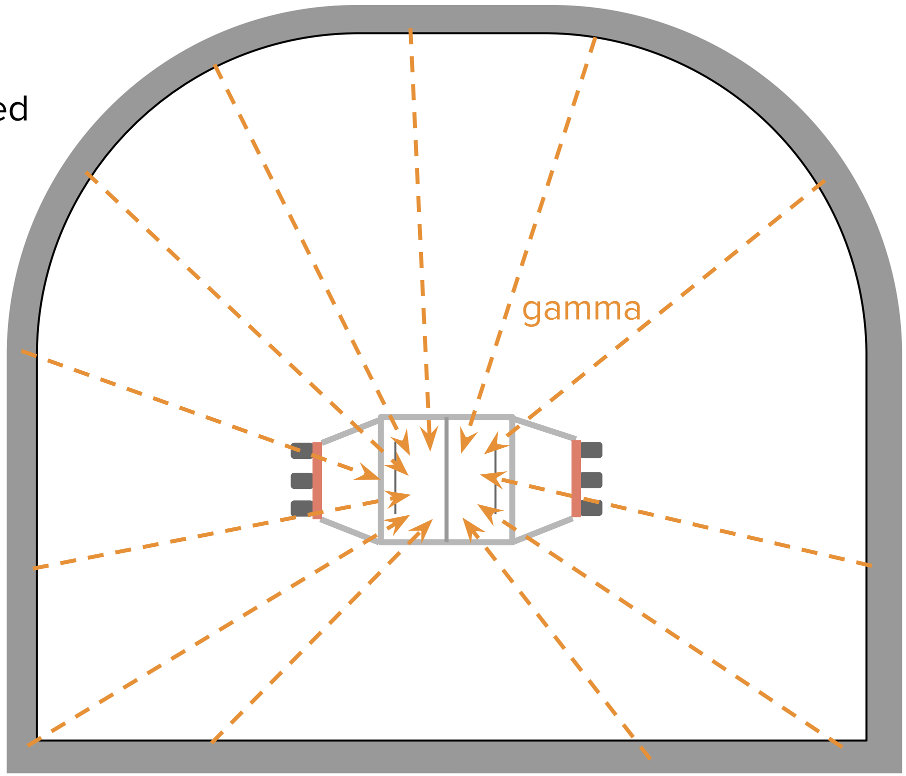
Ambient gammas

- Gammas mostly from **K, U** chain and **Th** chain
- Spectrum measured with NaI detector can be used as input for CYGNO-04 simulations



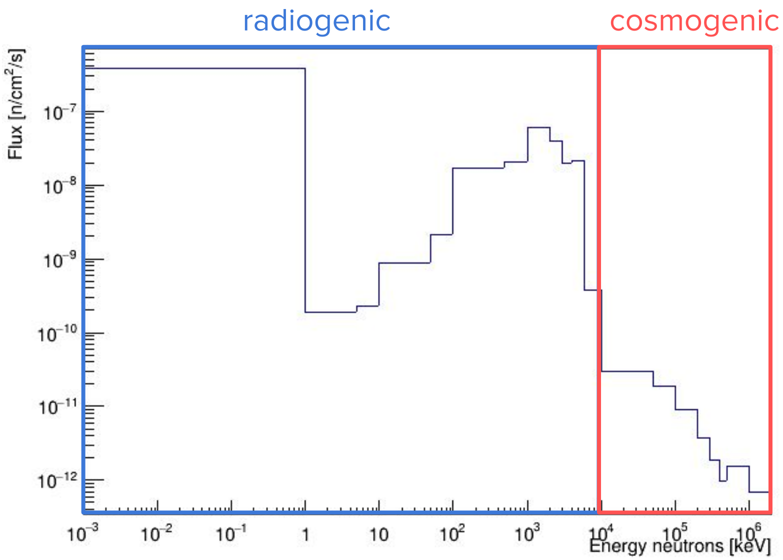
Without shield **O(10^8-10^9) evts/yr** in the CYGNO-04 detector → shielding with **attenuation power 10^{-5}-10^{-6}**

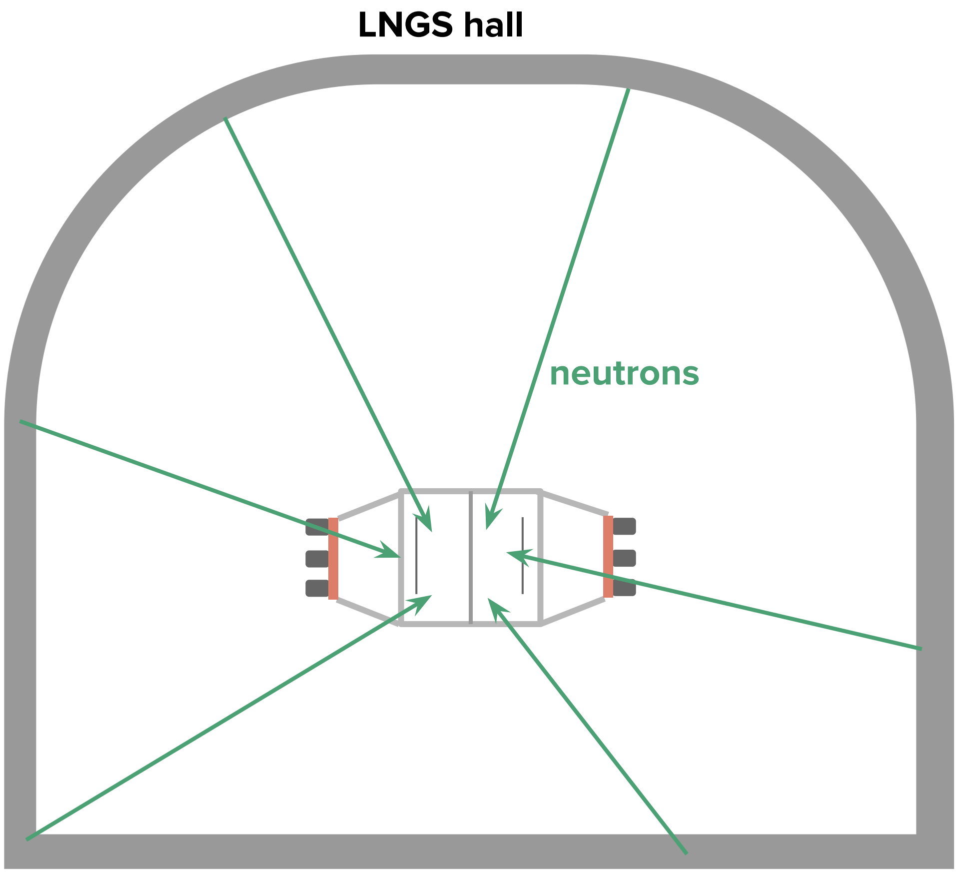
LNGS hall



Ambient neutrons

- Ambient neutrons from radioactivity in the rock
- Spectrum from CUORE MC
  ➜ measurements Belli/Arneodo (radiogenic, E<10 MeV) and Hime (cosmogenic E>10 MeV)



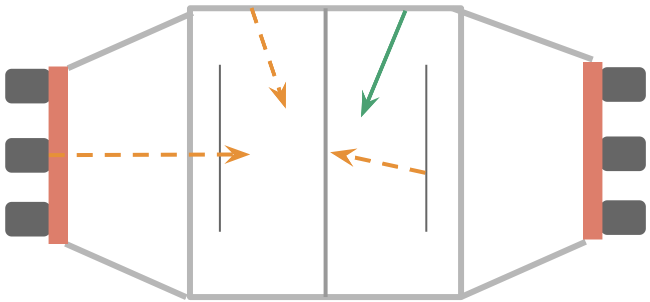


Radioactivity

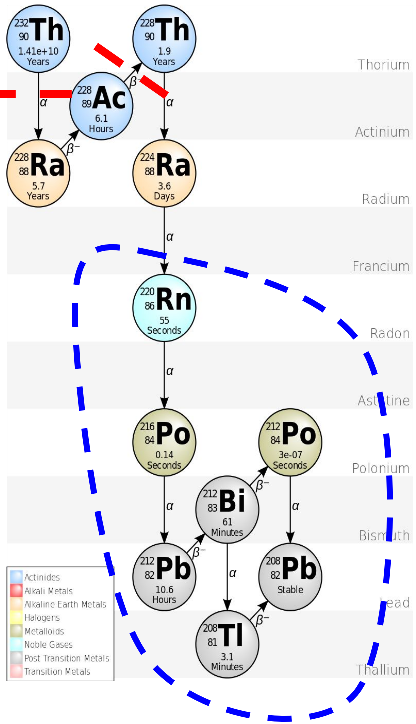
- natural radioactivity: ^{238}U, ^{235}U, ^{232}Th and ^{40}K
- anthropogenic: ^{137}Cs
- radon
- cosmogenically activated isotopes

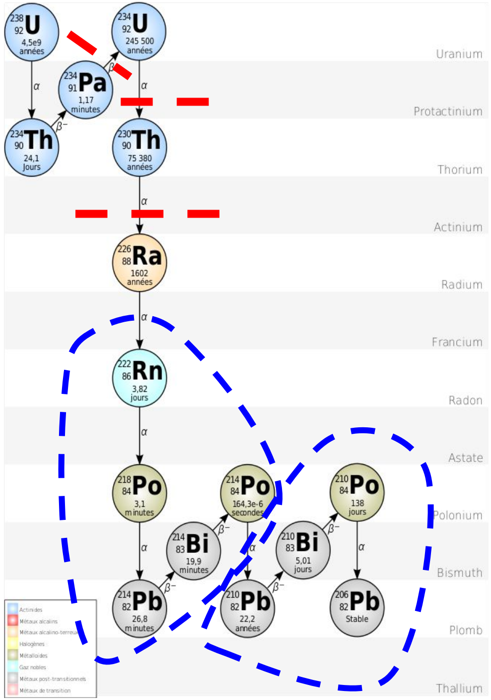
➜ usually the most worrisome backgrounds are internal (externals can be shielded)

➜ Careful evaluation of the material activities is important to predict the background



Radioactive chains and equilibrium

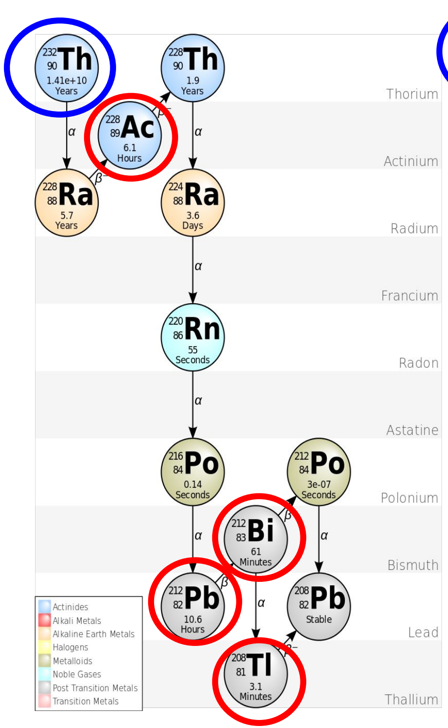


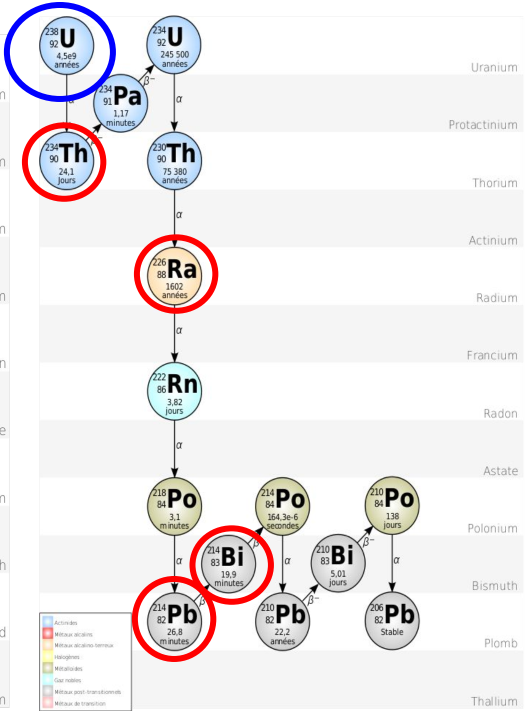


- Secular equilibrium may be broken (in principle) in correspondence to isotopes with long half-life

- Radon plate-out can also create sub-chains with different activities

Radioactive chains and screening techniques





- Gamma emitters can be measured with HPGe screening up to 10-100 µBq/kg precision (usually done in STELLA facility at LNGS)
- ICP-MS can measure the concentration of primordial nuclides U, Th at ppt level
  ➜ 1-10 µBq/kg precision
  (Chemistry lab service at LNGS)

Conversion factors:

```
1 Bq 238U/kg = 81 ppb U (81 x 10-9 gU/g)
1 Bq 232Th/kg = 246 ppb Th (246 x 10-9 gTh/g)
1 Bq 235U/kg = 1.76 ppm U (1.76 x 10-6 gU/g)
1 Bq 40K/kg = 32300 ppb K (32300 x 10-6 gK/g)
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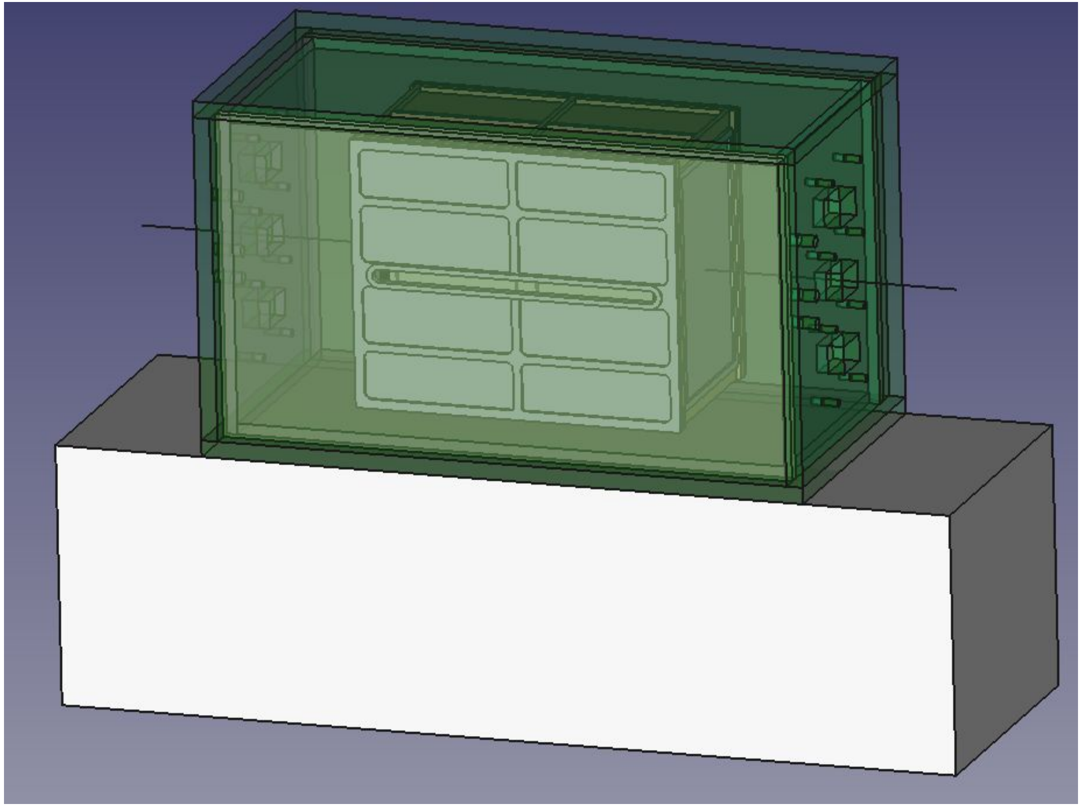
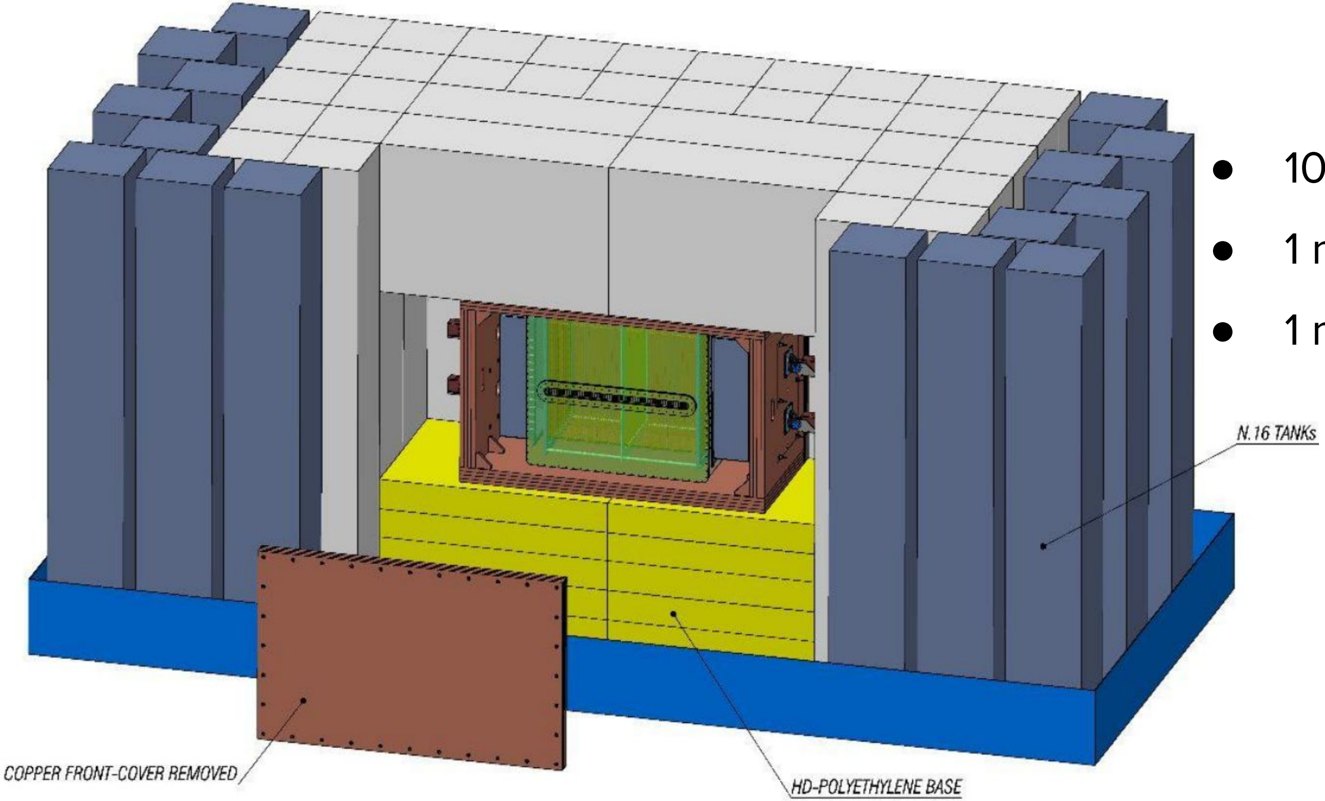
CYGNO-04 design



- $0.5 \times 0.8 \times 1$ m^3 sensitive volume (0.4 m^3)
- He:CF_4 gas mixture
- Central cathode
- 2 drift regions of 50 cm each
- 2 x triple-GEM stack
- 2 x 3 cameras on each side, framing 50 x 80 cm^2 area
- 2 x 8 PMTs

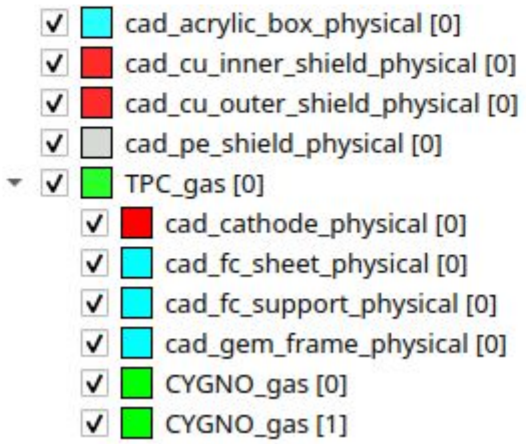
CYGNO-04 shielding design

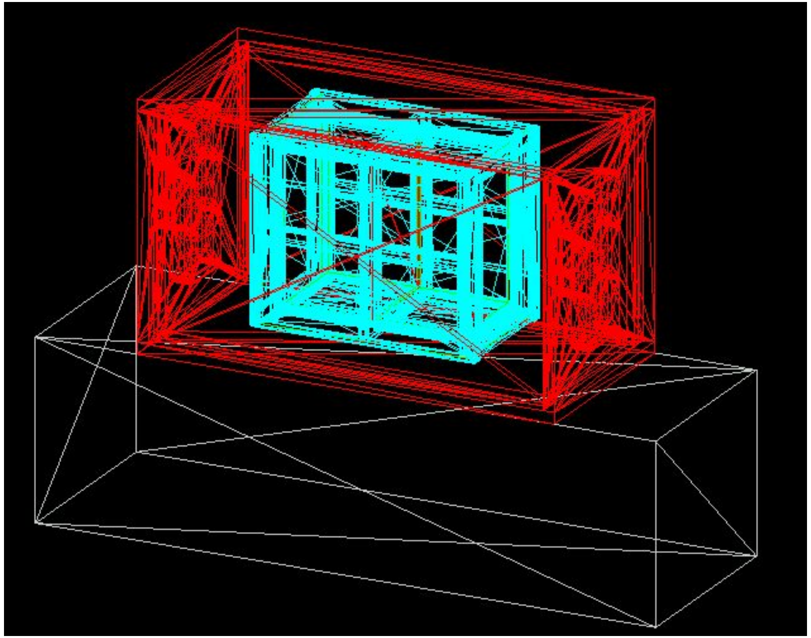


- 10 cm copper on all sides
- 1 m water on sides and top
- 1 m PE on the base

Geometry implemented in Geant4

- Github repository:
  - **Geometry (*):** https://github.com/CYGNUS-RD/geometry/tree/master/cygno_04_v3
  - **Geant4 code:** https://github.com/CYGNUS-RD/CYGNO-MC/tree/cygno_04

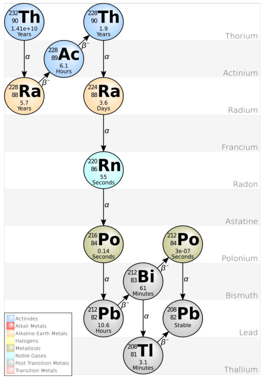


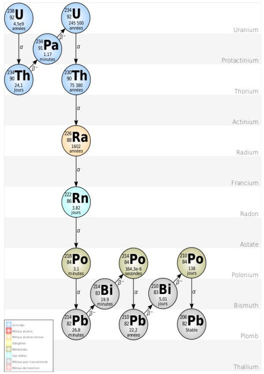


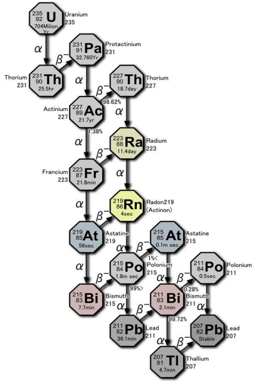
(*) Missing in this design:
water tanks, GEMs, cameras, PMTs

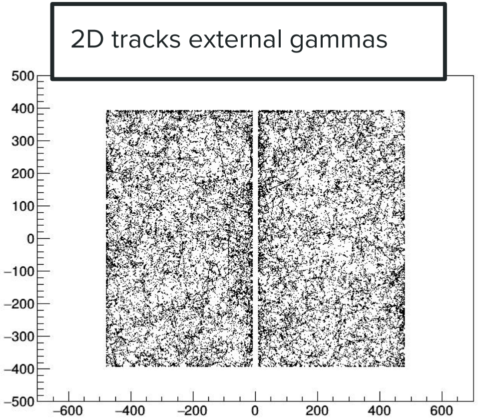
Geant4 radioactivity simulation

- Particles from radioactivity (α,β,γ,n) interact with all the materials in the setup (“passive” elements)
- Energy deposits in the active gas are stored in the output (x,y,z,dE)
- In each simulation: user defines the source of radioactivity
  - **external** ➔ γ,n from a surface containing the full setup
  - **internal**
    ➔ setup parts are simulated separately as “active” sources
    ➔ each isotope is simulated individually









Normalization and background spectrum

- Assuming N_{gen} events are generated, it corresponds to an equivalent time of simulation t_{sim} that depends from the activity (flux) for internal (external) backgrounds:
  - For internal background: $t_{sim} = N_{gen}/(A^{*}mass)$
  - For external background: $t_{sim} = N_{gen}/(\Phi \cdot S)$
  - Activities of CYGNO materials are saved in this database
  - γ and n fluxes at LNGS are known (but variability among LNGS halls, the best is a direct measurement with NaI in experimental site)
- We usually express background as a **rate** in units of **events/year** in a given energy range
  ➜ each simulation is normalized using t_{sim}
- Energy deposits from nuclei are saved in separate variable (QF *not* included)

The expected background spectrum is the sum of all background rates (normalized):
Σ_{setup_parts} ($\Sigma_{isotopes}$ (rate)) + rate (ext γ) + rate (ext n)

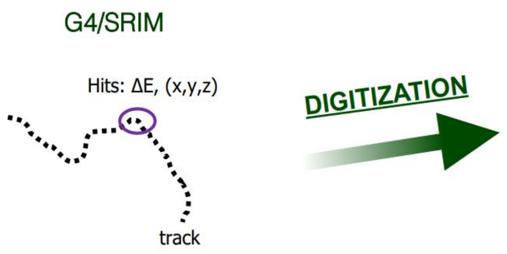
Simulation workflow

1. Interactions of ER/NR in the gas ➔ tracks (x,y,z,dE) **Geant4**

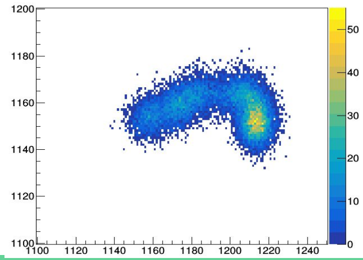
2. Electron diffusion in CYGNO gas **Garfield**

3. Simulation of primary electrons + transport to the GEMS
4. Simulation of GEM multiplication with saturation effect
5. Simulation of light production
6. Simulation of the cameras/PMTs

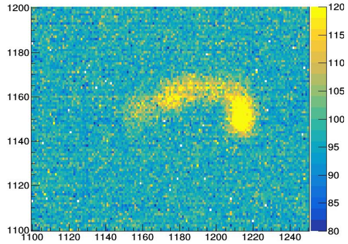
} **detector simulation (digitization)** see Pietro's talk



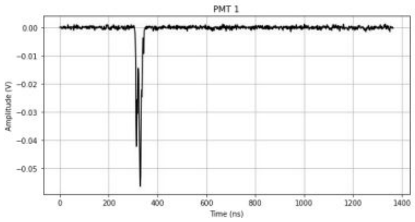
sCMOS signal



Signal + noise



PMT Signal + noise



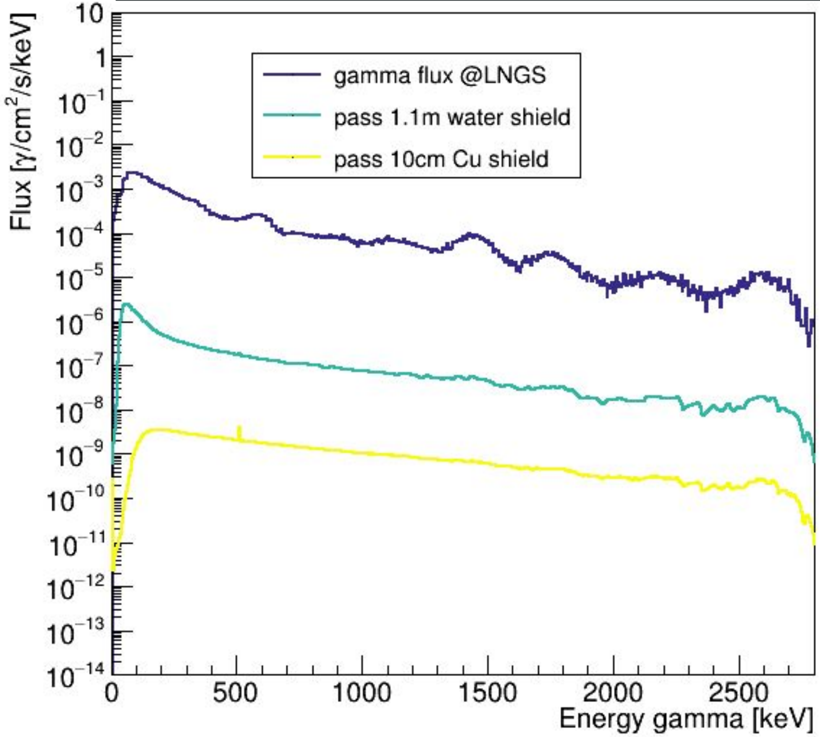
Summary and next steps

- Some CYGNO-04 backgrounds already calculated (see Melba's talk)
    - copper shielding simulation helped to fix the final configuration
    - acrylic simulations done
    - field cage simulations in progress (PET+Cu, kapton+Cu, glue/no glue)
- Still some details to fix in the CYGNO-04 design
    - calibration window dimensions and position
    - some volumes (GEMs, cameras, PMTs, water shield) still to be implemented in Geant4
- Next steps:
    - implement and simulate all setup parts, complete CYGNO-04 background simulation
    - most radioactivity measurements are in fact upper limits from HPGe screening
      ➔ check if we can have more precise measurements (e.g. ICP-MS)
    - ER/NR simulations for analysis training
    - ...discussion

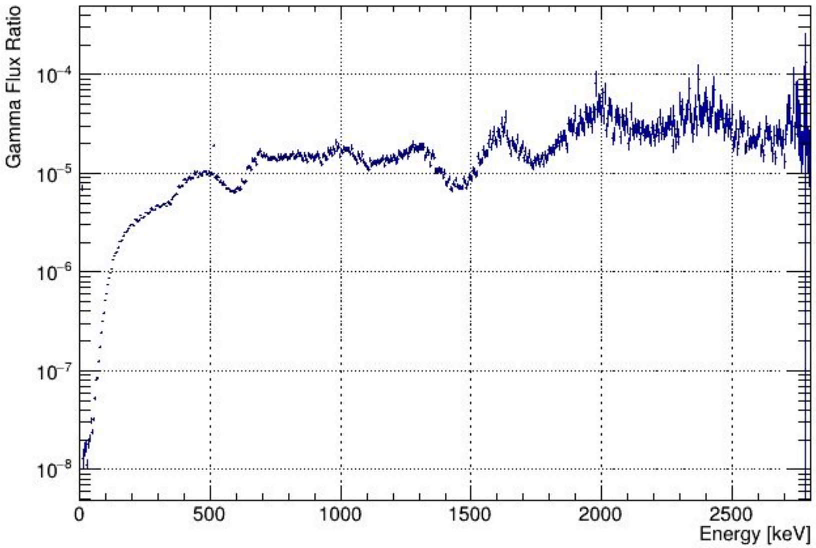
Extra slides

Gamma flux

gamma flux entering shield: 2.4×10^{-6} $cm^{-2}s^{-1}$

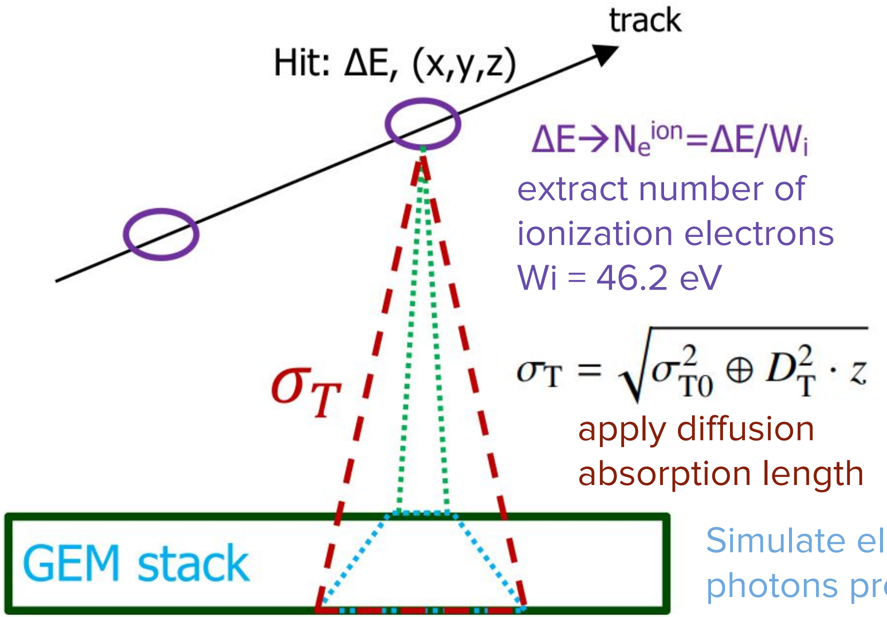


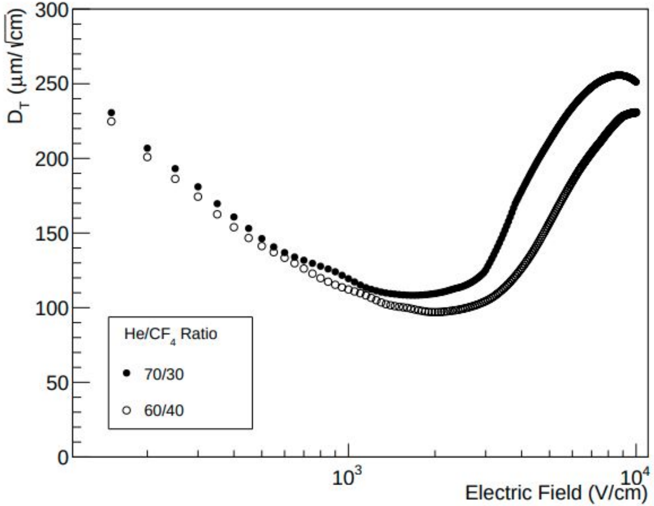
110 cm water shield
+ 10 cm copper shield



Detector simulation

See Pietro's talk.





Simulate electron multiplication, saturation & photons production in GEM stack

+ Digitization ➔ cameras: lens, quantization pixel, sensor noise
➔ PMTs: QE, gain, single photoelectrons, noise, quantization of the digitizer