Cosmogenic activation of xenon

PhD seminar

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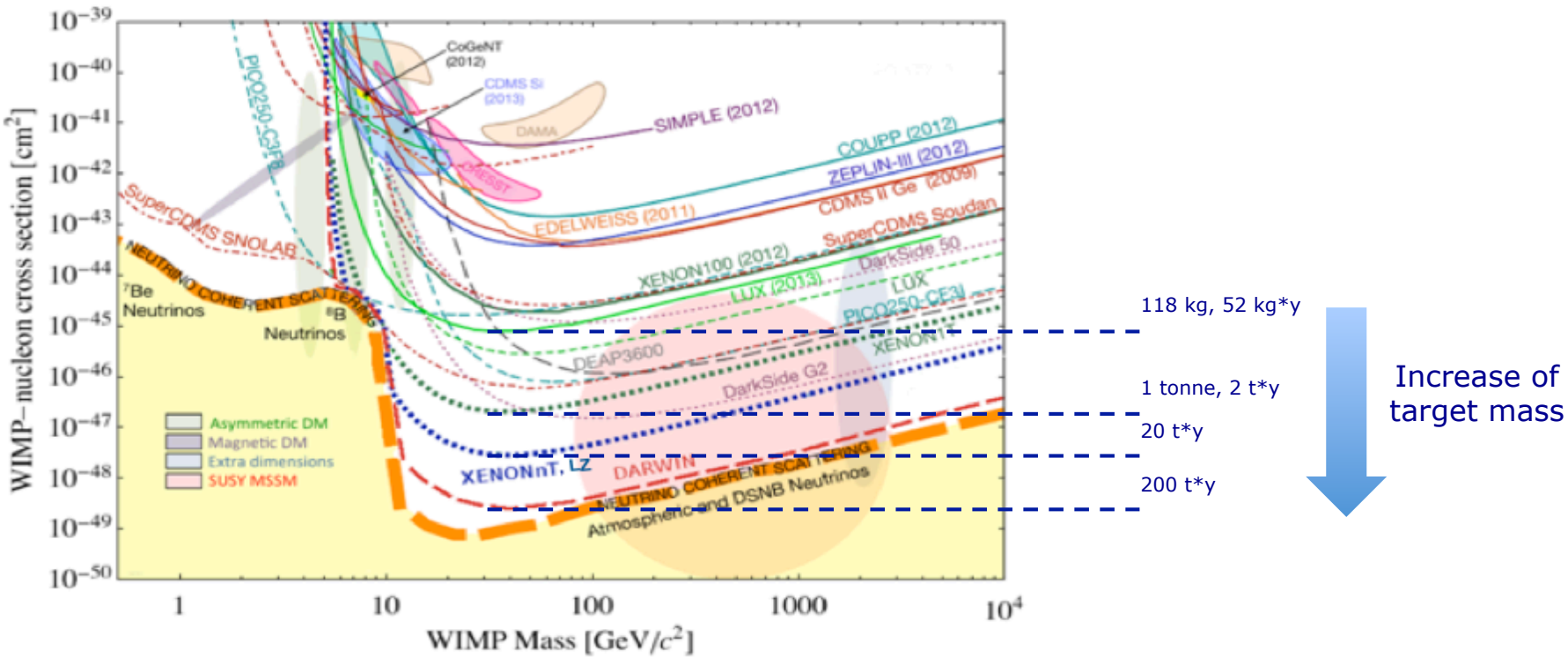
Motivations: direct dark matter future searches



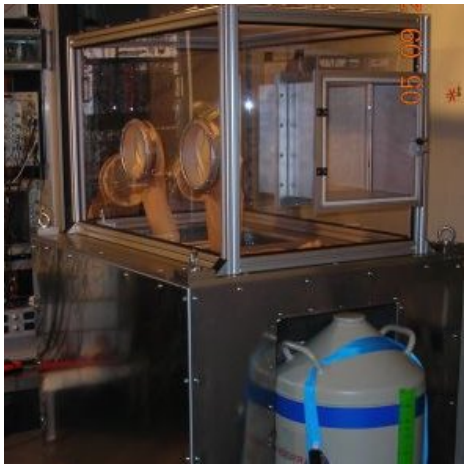
- Intrinsic sources dominate the electron recoil background in multi-ton scale detectors: ^{85}Kr, ^{222}Rn, solar neutrinos.
- Long and medium-lived cosmogenic products of Xe may contribute to the intrinsic background.
- No direct measures of cosmogenic activation studies of Xe are present in literature.
- Prediction codes for cosmogenic activation (ACTIVIA, COSMO, TALYS) have never been validated for xenon.

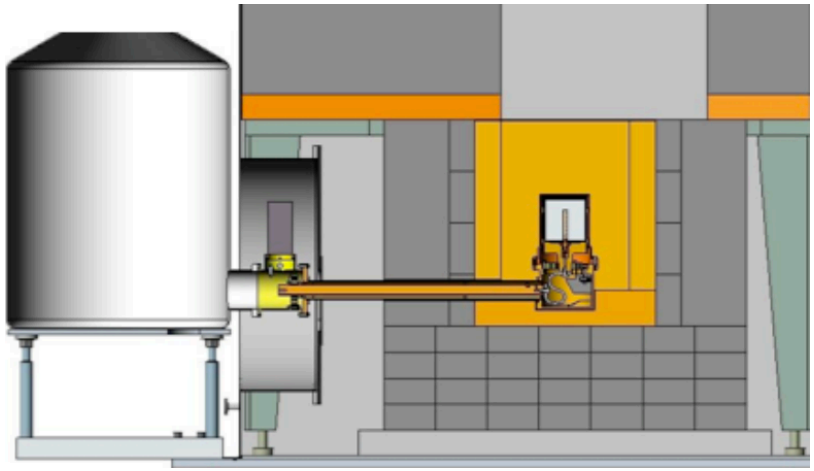
Cosmogenic activation

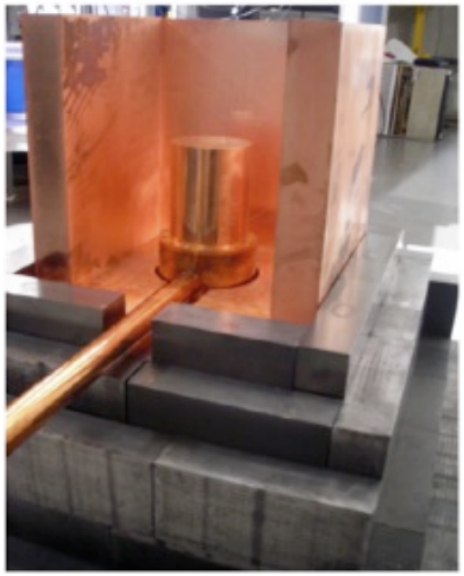
High Altitude Research Center Jungfraujoch [http://www.ifjungo.ch/jungfraujoch/]

- Measure the γ-ray spectra before and after the exposure of the samples to CR flux with HPGe spectrometer
- Xe gas sample:
  - 2.04 kg
  - Natural isotopic abundances
  - Impurities < 10 ppm
- OFHC Cu sample (as benchmark sample):
  - 10.35 kg
  - Natural isotopic aboundances
  - Impurities < 100 ppm
- Exposure:
  - 3470 m asl (728 g/m^2 atm depth)
  - 345 days
  - Cosmic ray flux 11.4 time than sea level
- Radio-nuclei produced by nuclear fragmentations by HE nucleons (>10 MeV).
- Atmospheric model: U.S. Standard Atmosphere 1976

Gator γ-ray spectrometer [JINST 6, P08010]



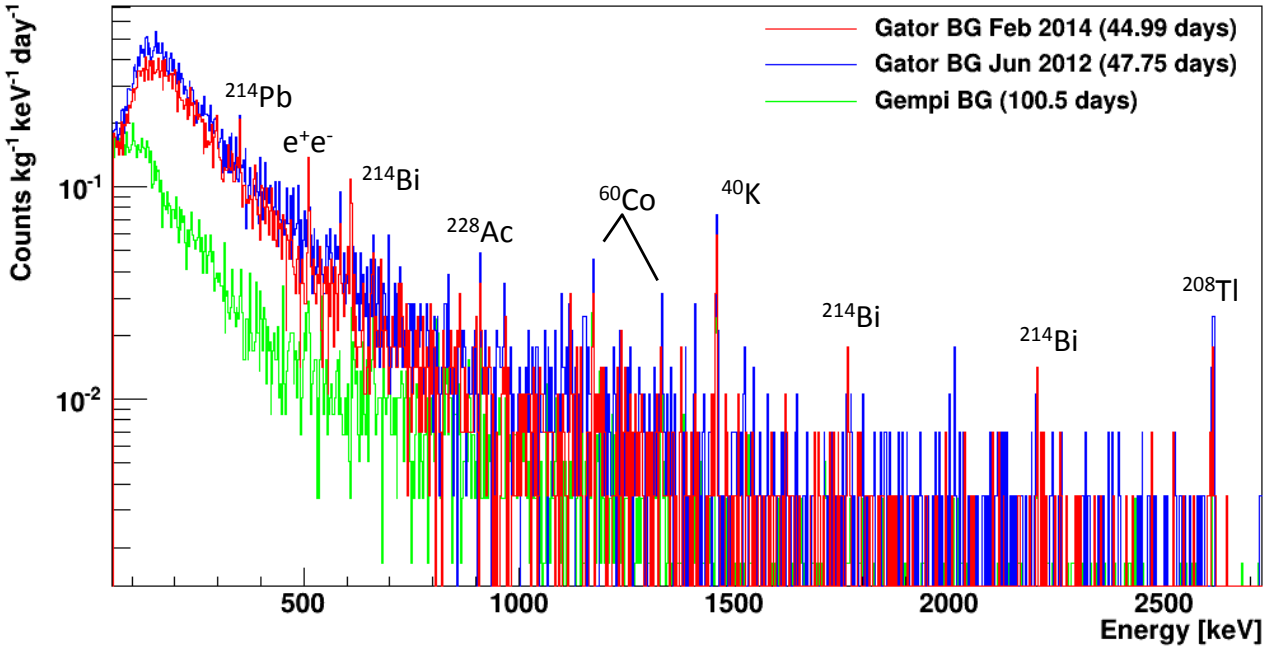




- 2.2 kg HPGe coaxial crystal (82 mm diameter, 81.5 mm height).
- Ultra low activity shielding materials for detector and shielding.
- Air tight encasing and glove box to prevent ^{222}Rn diffusion from outside.
- 21 liters samples cavity (25×25×33 cm^3) to allow the measurement of large and massive samples.
- Boil-off N_2 cavity purging to flush out the ^{222}Rn emanated from the detector's materials.

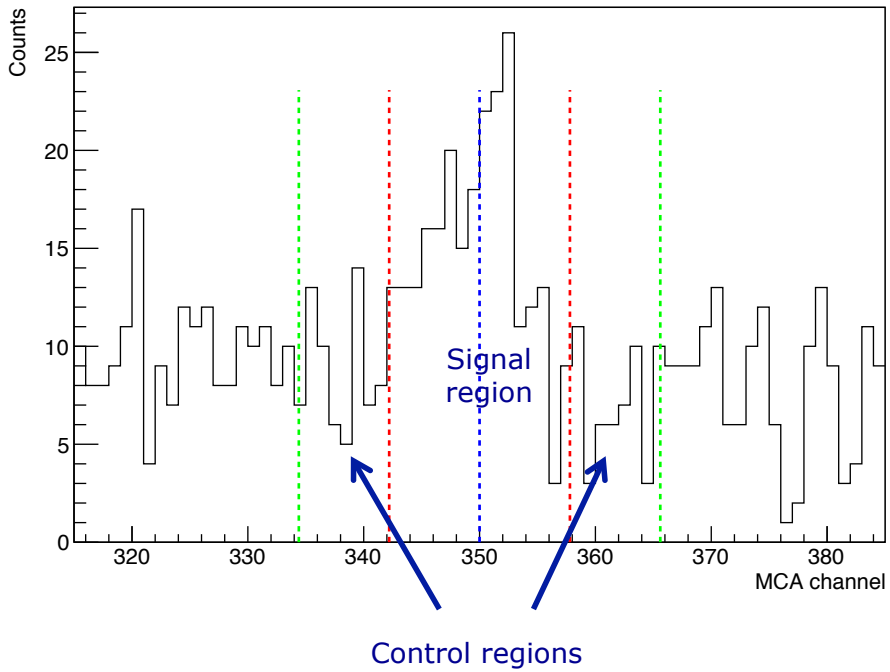
Gator performance

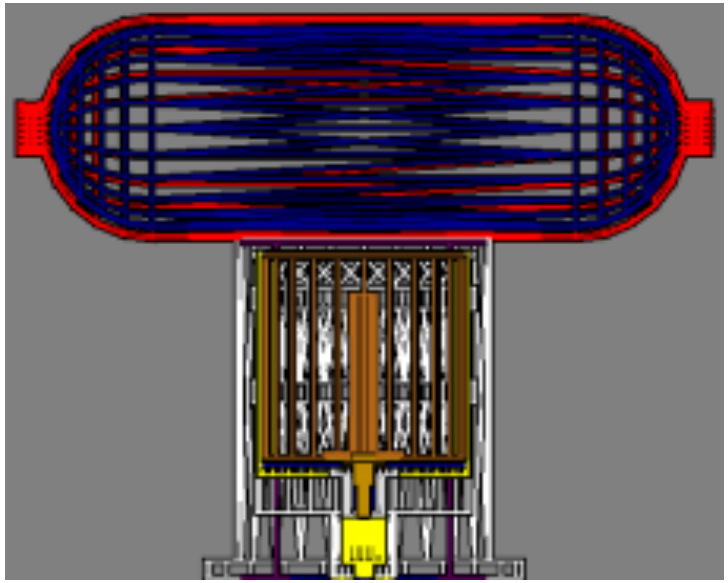
Background



- Energy threshold: ≈50 keV
- Ultra-low background: ≈270 counts/day in the 50 keV – 2650 keV energy range (≈0.1cnts/keV/d).
- High sensitivity over run time of 10 – 20 days:
  - ≲ 10 mBq/kg for high self-shielding materials (Cu, steel, Ti, Pb).
  - ≳ 1 mBq/kg for low self-shielding materials (plastics, PTFE, electronic components).
- Main contributions to the background: ^{40}K, ^{228}Th chain, ^{222}Rn in the cavity.

Bayesian data analysis





- Activities determined by the isotopes' most prominent γ-lines
- Signal region: $\pm 3\sigma$ interval around the line center (between red lines)
- Control region: $\pm 3\sigma$ outside the signal region (between red and green lines)
- Detailed Geant4 model of the detector's and samples' geometry used to evaluate the γ-lines full absorption efficiencies
- G4RadioactiveDecay class used to simulate isotopes decays: correct BR for γ-lines

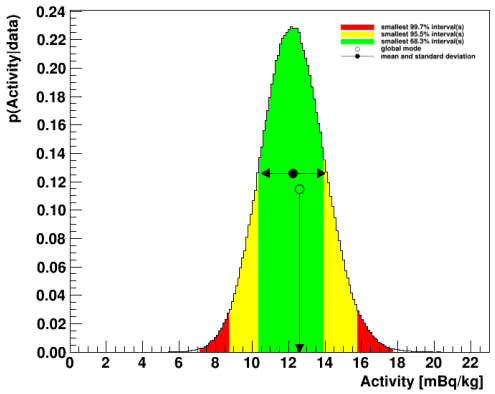
Bayesian data analysis

$$P(A|Data) \propto P(Data|A)\Pi(A)$$

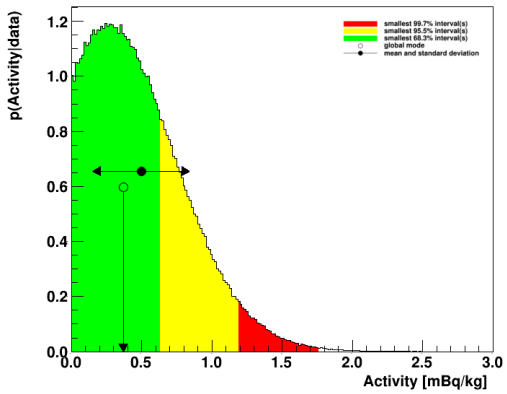
$$\mathcal{L} = \prod_{k=1}^{N_{\text{lines}}} \text{Poiss}\left(C_{\text{S}_k}|\gamma_{\text{S}_k}\right) \cdot \text{Poiss}\left(C_{\text{L}_k}|\beta_{\text{L}_k}\right) \cdot \text{Poiss}\left(C_{\text{R}_k}|\beta_{\text{R}_k}\right)$$

$$\gamma_{\text{S}} = (\varepsilon \cdot BR) \cdot m \cdot A + w_S \frac{\beta_{\text{L}}+\beta_{\text{R}}}{w_{\text{L}}+w_{\text{R}}}$$

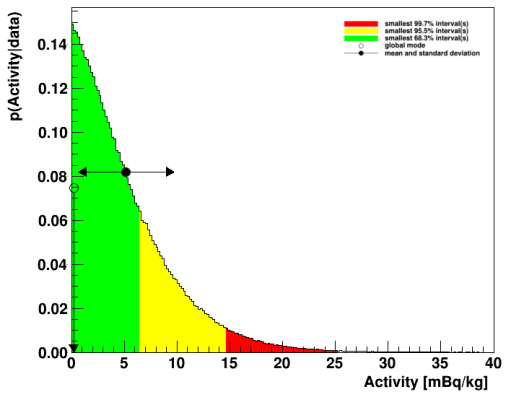
- Flat priors for background parameters and for activity parameter
- Posteriors produced with MCMC method (BAT toolkit) [Comp.Phys.Comm 180, 2197]



Presence of activity: report mode and the shortest 68.3% C.I.

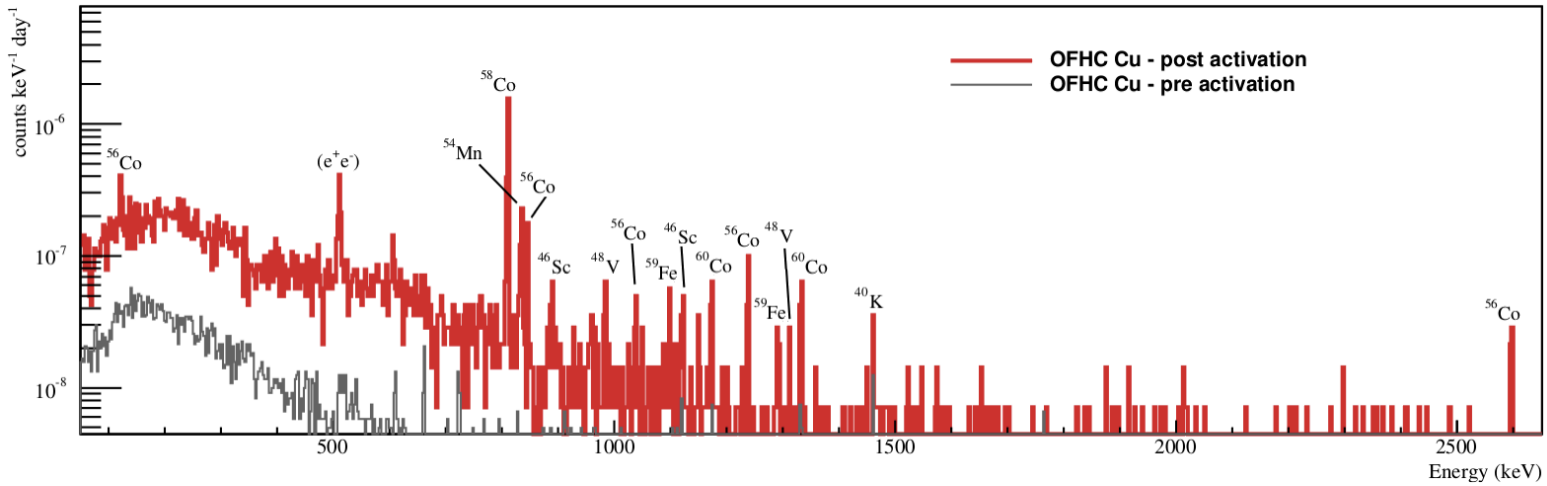


Presence of activity, but too weak: report the 95.5% upper limit



Activity not present: report the 95.5% upper limit

Results – OFHC Cu sample

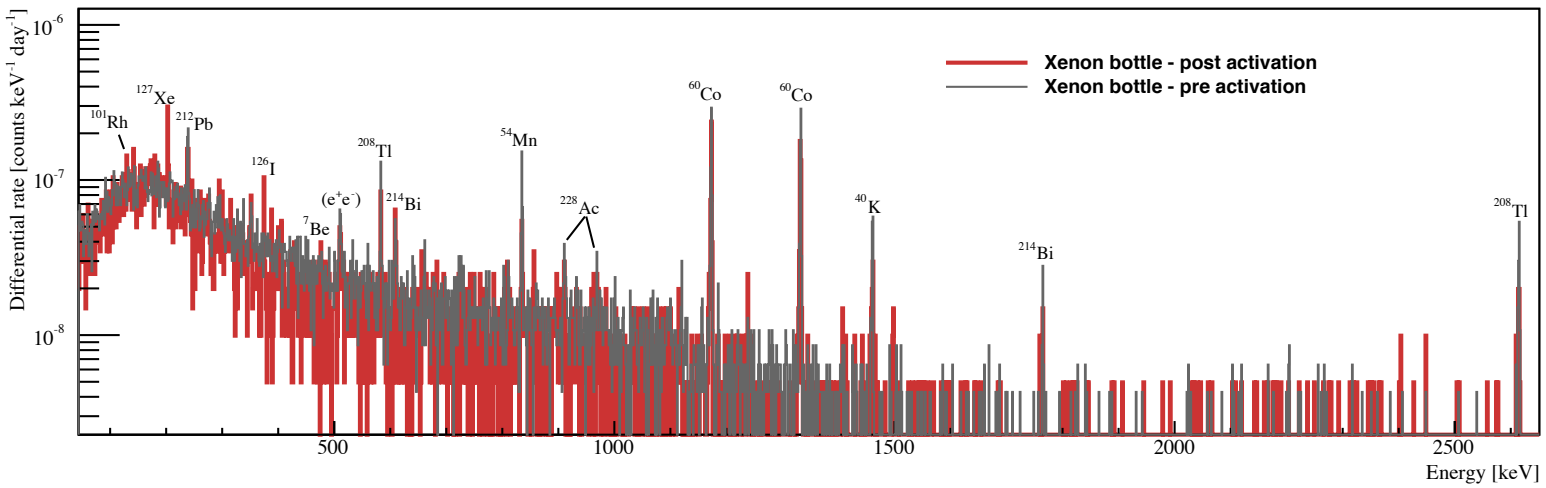


Saturation activities at sea level

Isotope	Half-life (d)	This work (μBq/kg)	Literature [App.Rad.Isot 67, 750] (μBq/kg)	ACTIVIA predictions (μBq/kg)
^{46}Sc	83.8	27 (10)	25.2 (8.6)	36
^{48}V	16.0	39 (17)	52 (19)	34
^{54}Mn	312	154 (35)	394 (39)	170
^{59}Fe	44.5	47 (15)	57 (14)	49
^{56}Co	77.2	108 (15)	110 (14)	100
^{57}Co	272	519 (100)	860 (190)	380
^{58}Co	70.9	798 (60)	786 (43)	660
^{60}Co	1925	340 (75)	1000 (90)	300

- General good agreement with predictions: deviations <30%
- Our understanding of the CR flux and it's modeling is satisfactory
- Very good agreement with literature.

Results – Xe sample

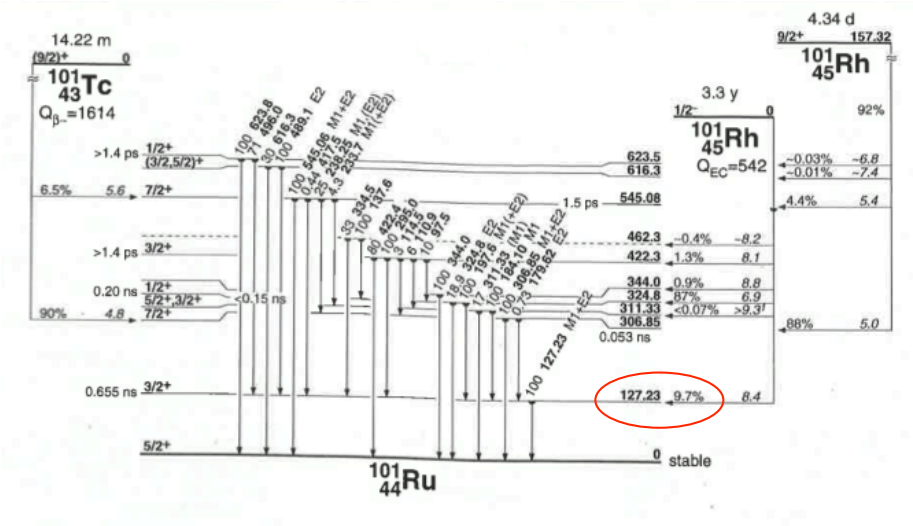


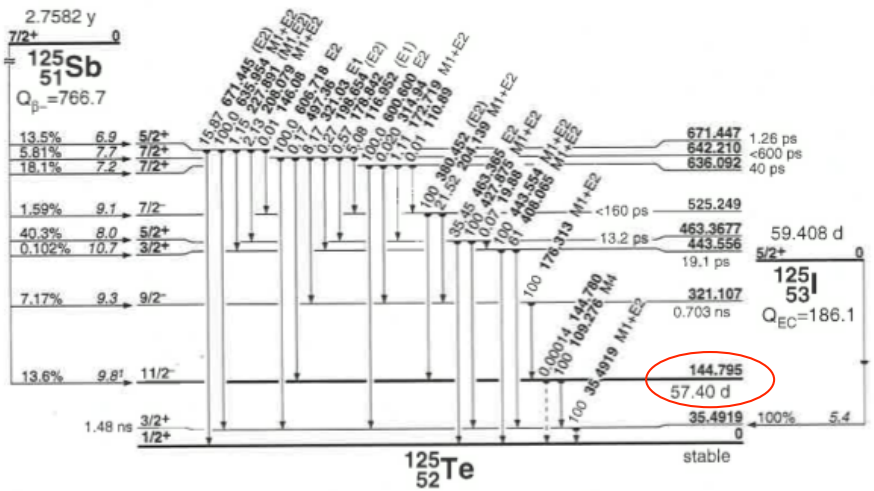
Saturation activities at sea level

Isotope	Half-life	This work (μBq/kg)	ACTIVIA predictions (μBq/kg)
^{7}Be	53.2 d	370 (240)	6.4
^{101}Rh	3.3 yr	1420 (900)	17
^{125}Sb	2.8 yr	590 (250)	0.2
^{126}I	12.9 d	175 (90)	250
^{127}Xe	36.3 d	1870 (280)	420

- Systematic underestimation of the production rates from predictions.
- ^{127}Xe activation observed also in LUX [Astropart.Phys. 62, 33] and in agreement with this dedicated measurement.
- ^{7}Be, ^{126}I and ^{127}Xe will decay out in few months after the end of activation.
- ^{101}Rh and ^{125}Sb are long lived and their impact in LXe targets must be evaluated.

Background impact in LXe target





^{101}Rh, $T_{1/2}$=3.3 y:

- Decays by EC, only γ-lines from the daughter isotope.
- The lowest energy γ-line is 127 keV, no background below this energy.
- All other low energy γ-lines sum up to higher energies by piling-up (time delays <1ns).
- No background contribution in the WIMP energy search region.

^{125}Sb, $T_{1/2}$=2.8 y:

- Decays by β emission, 13% end up in the 145 keV long-lived level of ^{125}Te ($T_{1/2}$=57.4d): event rejection not possible.
- Background for E<10keV not negligible: 3×10^{-2}ev/keV/kg/day (dru) for 1mBq/kg of contamination.
- Tension with the LUX low-energy background [Astropart.Phys. 62, 33].
- Xe purification systems might remove efficiently this element.

Conclusions and outlook

- First activation measurement of xenon useful for next generations LXe based detectors for very-rare events search [under review in EPJ-C, available at arXiv:1507.03729].

- Out of 5 detected radio-isotopes from Xe activation only ^{101}Rh and ^{125}Sb are potential issues.

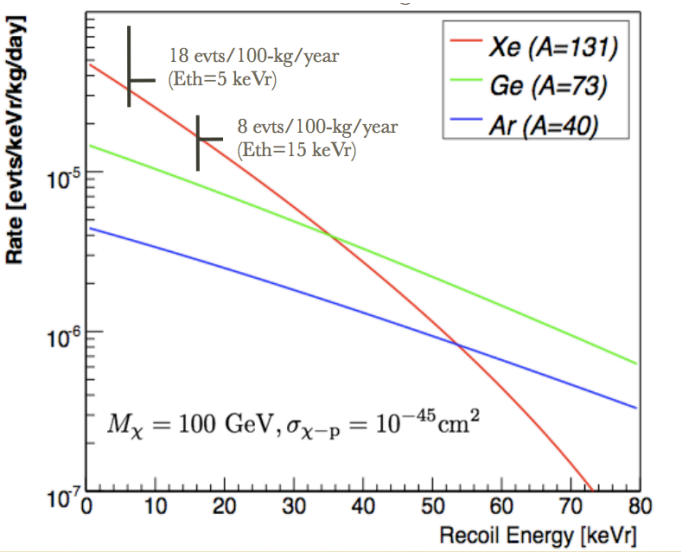
- Dedicated measurements of the Xe excitation functions are needed for more reliable predictions.

- Xe activation by residual HE muons in UG laboratories could be a background issue:
  - Muon capture cross sections
  - HE muon production cross sections (spallation/fragmentation)

Thank you for your attention!

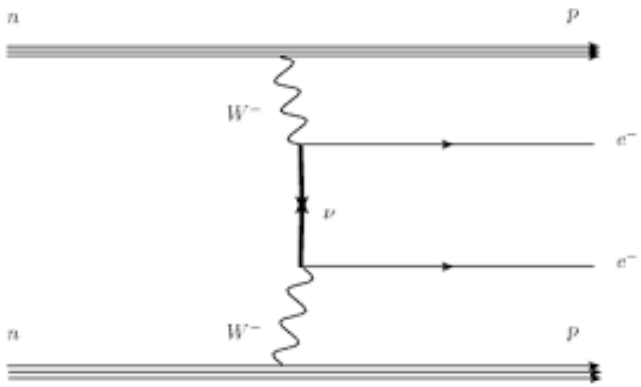
LXe based detectors for rare event searches

Dark matter direct searches



- High scintillation efficiency for 178 nm photons (~46 ph/keV)
- Expected higher WIMP nuclei scattering rate for low energy nuclear recoils: ~A^2
- No medium lived radioisotopes: no intrinsic background.
- Long lived double beta emitters (or potential) are negligible sources of background:
  - ^{124}Xe: $T_{1/2} > 1.4\times10^{14}$ y
  - ^{126}Xe: $T_{1/2} = (5\text{-}12)\times10^{25}$ y [J.Phys.G 34, 549]
  - ^{134}Xe: $T_{1/2} > 5.8\times10^{22}$ y
  - ^{136}Xe: $T_{1/2} = 2.17(6)\times10^{21}$ y [Phys.Rev. C 89, 015502]
- High atomic number (Z=54) + high density (~2.9 g/cm^3) provide good self shielding from γ-rays background (mostly from detector's materials)

$0\nu2\beta$ decay in ^{136}Xe



$$^{136}\mathrm{Xe} \rightarrow ^{136}\mathrm{Ba} + 2\mathrm{e}^-$$