Developments of radiopure $ZnWO_4$ anisotropic scintillators and improvements of their response at keV region

DAMA, INR-Kyiv
For the measurements with neutron beam: ENEA-Casaccia

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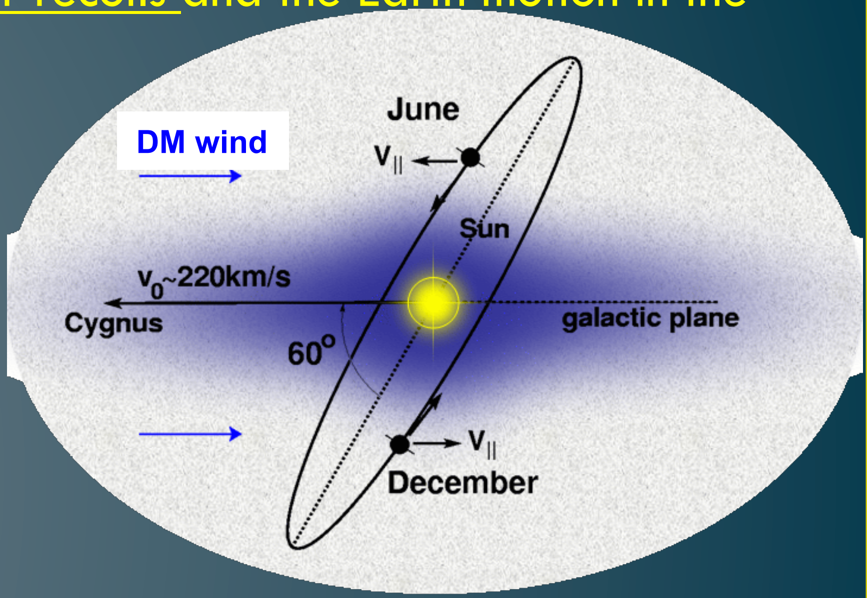
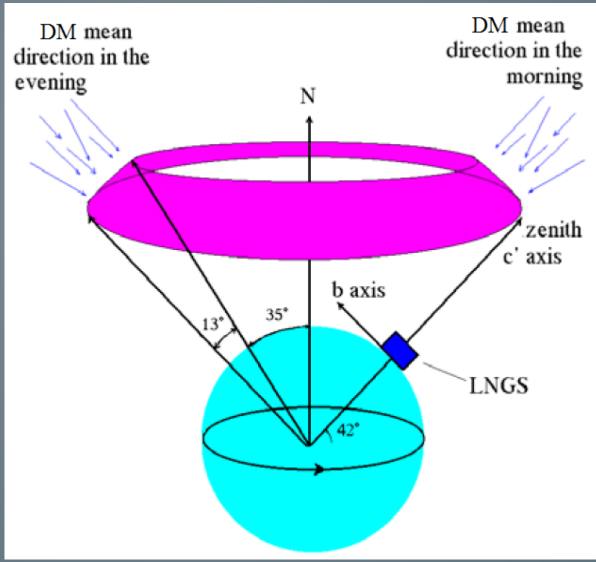
The directionality approach

Based on the study of the correlation between the arrival direction of those Dark Matter (DM) candidates inducing just nuclear recoils and the Earth motion in the galactic frame

Impinging direction of DM particle is (preferentially) opposite to the velocity of the Sun in the Galaxy…





… but because of the Earth's rotation around its axis, the DM particles average direction with respect to an observer on the Earth changes with a period of a sidereal day

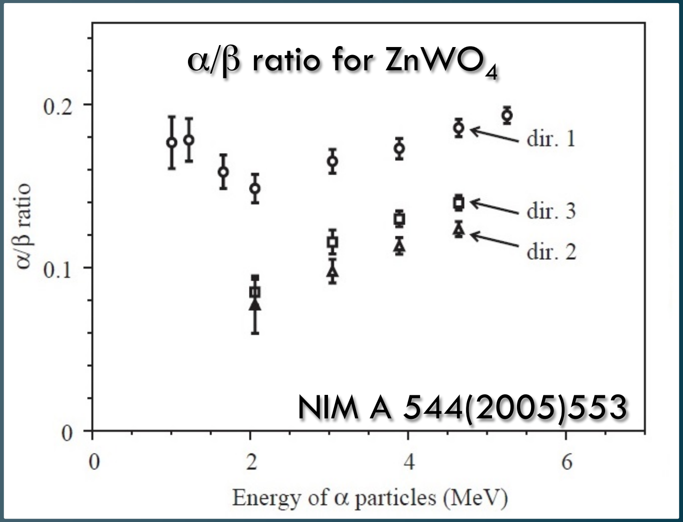
In the case of DM particles interacting with nuclei, the direction of the induced nuclear recoil is strongly correlated with that of the impinging DM particle. Therefore, the observation of an anisotropy in the distribution of nuclear recoil direction could give evidence for such candidates

direction-sensitive detector

Directionality sensitive detectors: anisotropic scintillators

- The use of anisotropic scintillators to study the directionality signature proposed for the first time in refs. [**P. Belli et al., Il Nuovo Cim. C 15 (1992) 475**], where the case of anthracene was analysed; some preliminary activities have been carried out [N.J.C. Spooner et al, IDM1997 Workshop; Y. Shimizu et al., NIMA496(2003)347]: the idea was revisited in [**R. Bernabei et al., EPJC28(2003)203**]

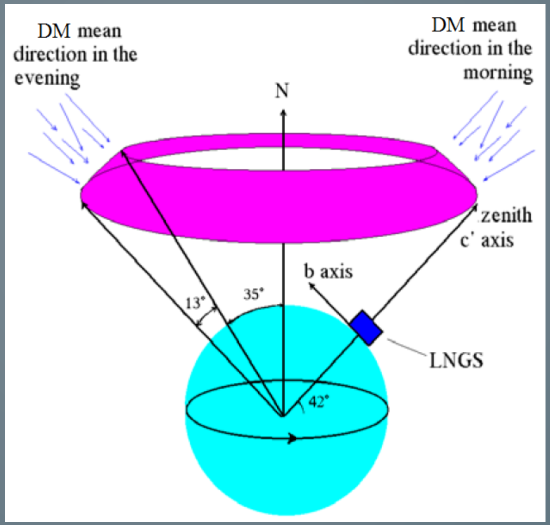
- Anisotropic Scintillator:
  - for heavy particles the light output and the pulse shape depends on the particle impinging direction with respect to the crystal axes
  - for γ/e the light output and the pulse shape are isotropic



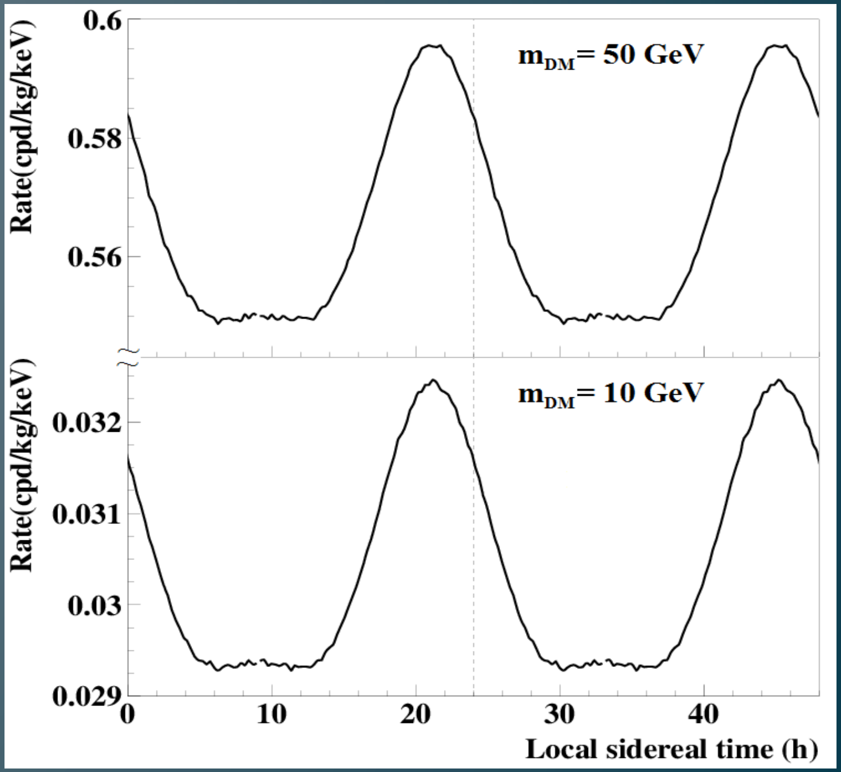
- **$ZnWO_4$ anisotropic scintillator:** a very promising detector (NIMA544(2005)553, Eur. Phys. J. C 73 (2013) 2276): i) very good anisotropic features; ii) high level of radiopurity; iii) high light output, that is low energy threshold feasible; iv) high stability in the running conditions; v) sensitivity to small and large mass DM candidate particles; vi) detectors with ~ kg masses

Directionality sensitive detectors: anisotropic scintillators

- The variation of the response of an **anisotropic scintillator** during sidereal day can allow to point out the presence of a DM signal due to candidate inducing just nuclear recoils



Example of expected signal rate for $ZnWO_4$ in a given scenario in (2-3) keV @ LNGS (see later)

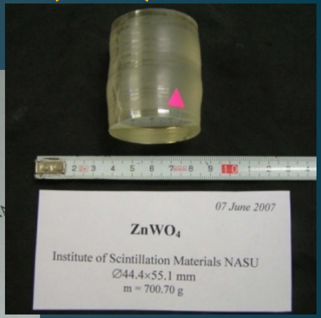


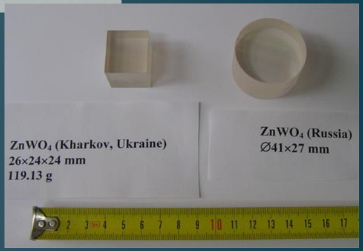
The signature is very distinctive and cannot be mimicked by background

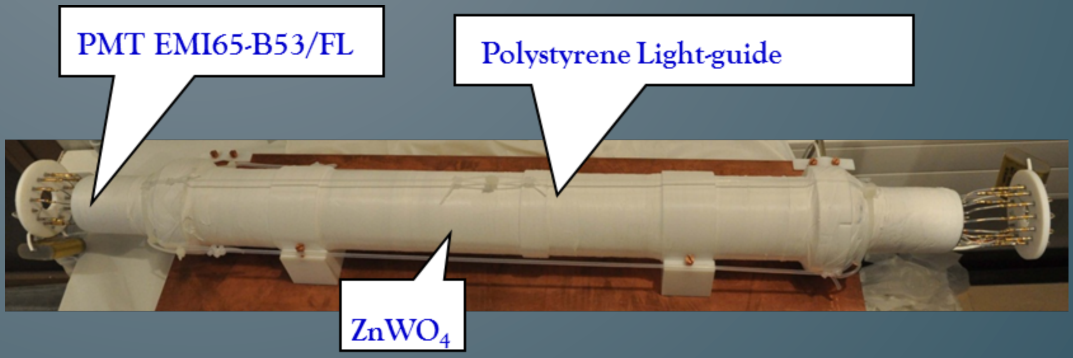
Developments of $ZnWO_4$ in DAMA, INR-Kyiv Coll.

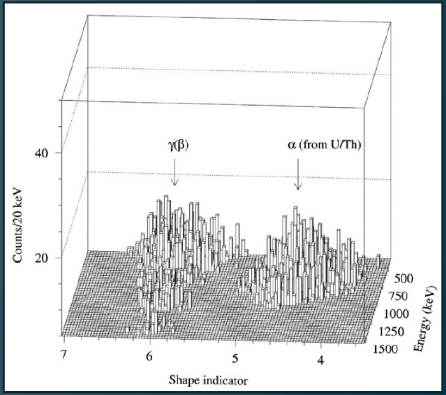
PLB658(2008)193
NPA826(2009)256
NIMA626-627(2011)3
JP38(2011)115107
NIMA935(2019)89

- Low background $ZnWO_4$ with large volume and good scintillation properties realized with mass **0.1-0.7 kg** by exploiting different materials and techniques
- Detectors measured in the low background DAMA facilities at LNGS
- Properties of $ZnWO_4$ have been estimated
- Results:
  - high level of radiopurity (≈ 0.1 cpd/kg/keV)
  - PSD capability for α/β have been proved
  - Very good light output (threshold at 10 keV, res 9% @ 662keV)
  - search for 2β in Z and W isotopes ($T_{1/2}$ ~10^{18} – 10^{21} yr)









Rooms for improvements ➔ Further developments are ongoing

Studying anisotropic features of $ZnWO_4$ crystal scintillator

- In summer 2018 a campaign of measurements using a dedicated $ZnWO_4$ crystal to study the anisotropic features of the detector for low energy nuclear recoils started

- Preliminary measurements with a collimated α source have been preformed

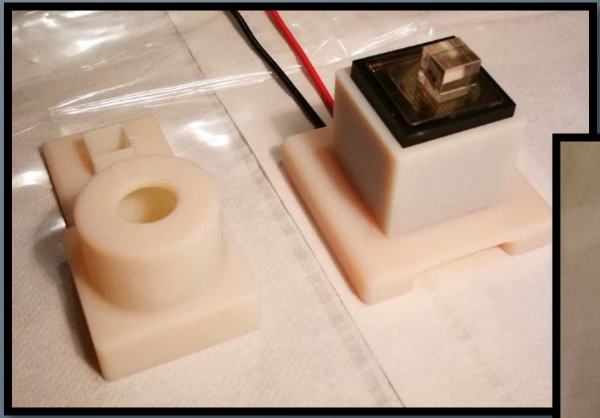
- After α calibrations a campaign of measurements at ENEA-Casaccia with a 14 MeV neutron beam has been carried out

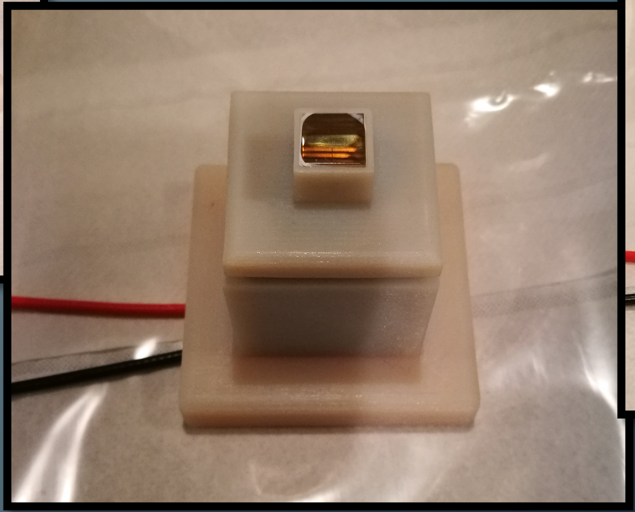
$ZnWO_4$ crystal = 10.20 x 10.20 x 10.20 mm^3 (detector of reduced dimensions to investigate neutron single-scattering)

Studying the response of the $ZnWO_4$ with ^{241}Am α source

Calibration set-up:

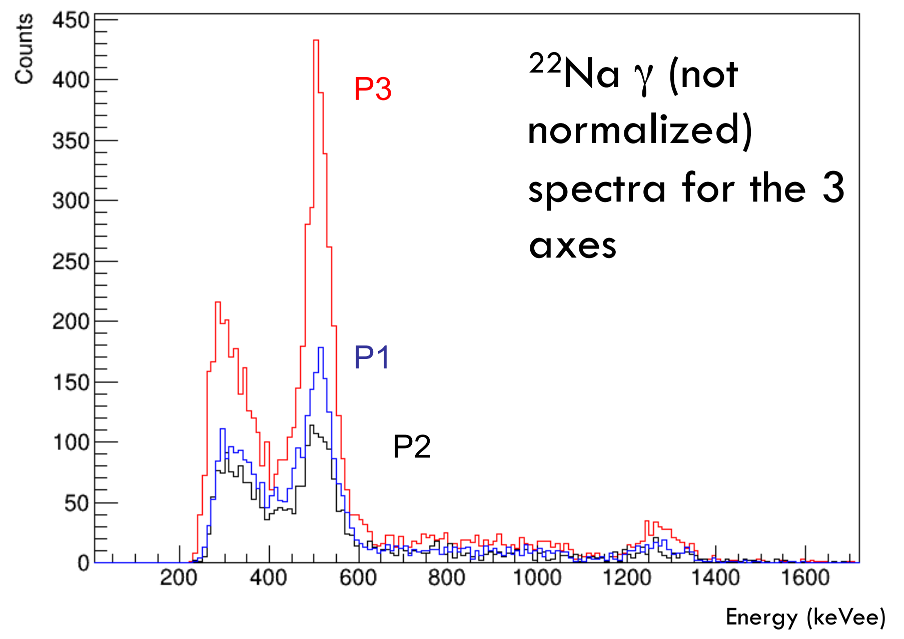
- PMT Hamamatsu H11934-200 (T.T. ≈ 5 ns) + $ZnWO_4$
- LeCroy Oscilloscope 24Xs-A, 2.5 Gs/s, 200MHz band width
- Metallic Box
- Pulse profiles acquired in a time window of 100 μs

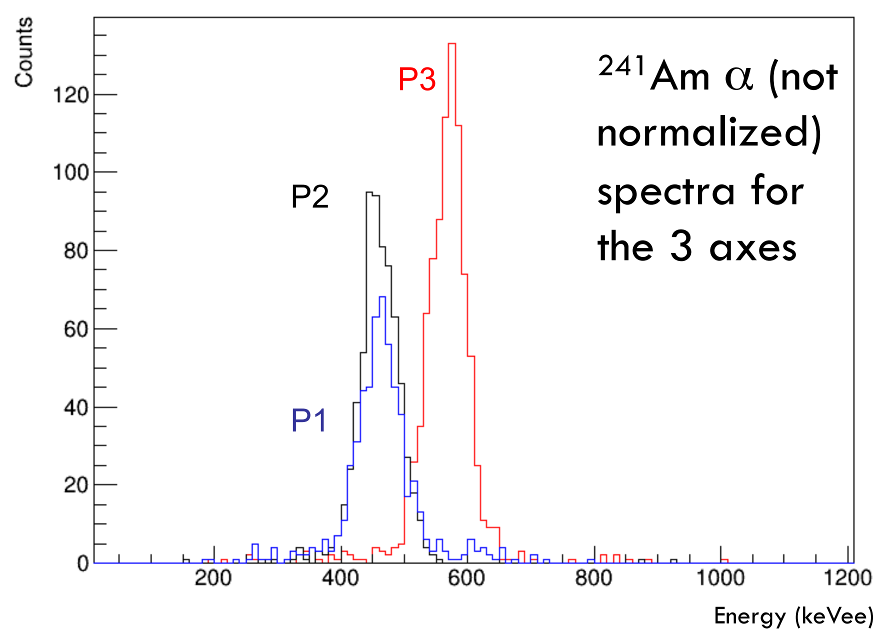




Studying the response of the $ZnWO_4$ with ^{241}Am α source

- We performed measurements irradiating contemporaneously the crystal with a γ source (^{22}Na) and a collimated α source (^{241}Am) along the three crystal axes (named P1, P2, P3)
- The energy of the α's have been measured with a Si detector

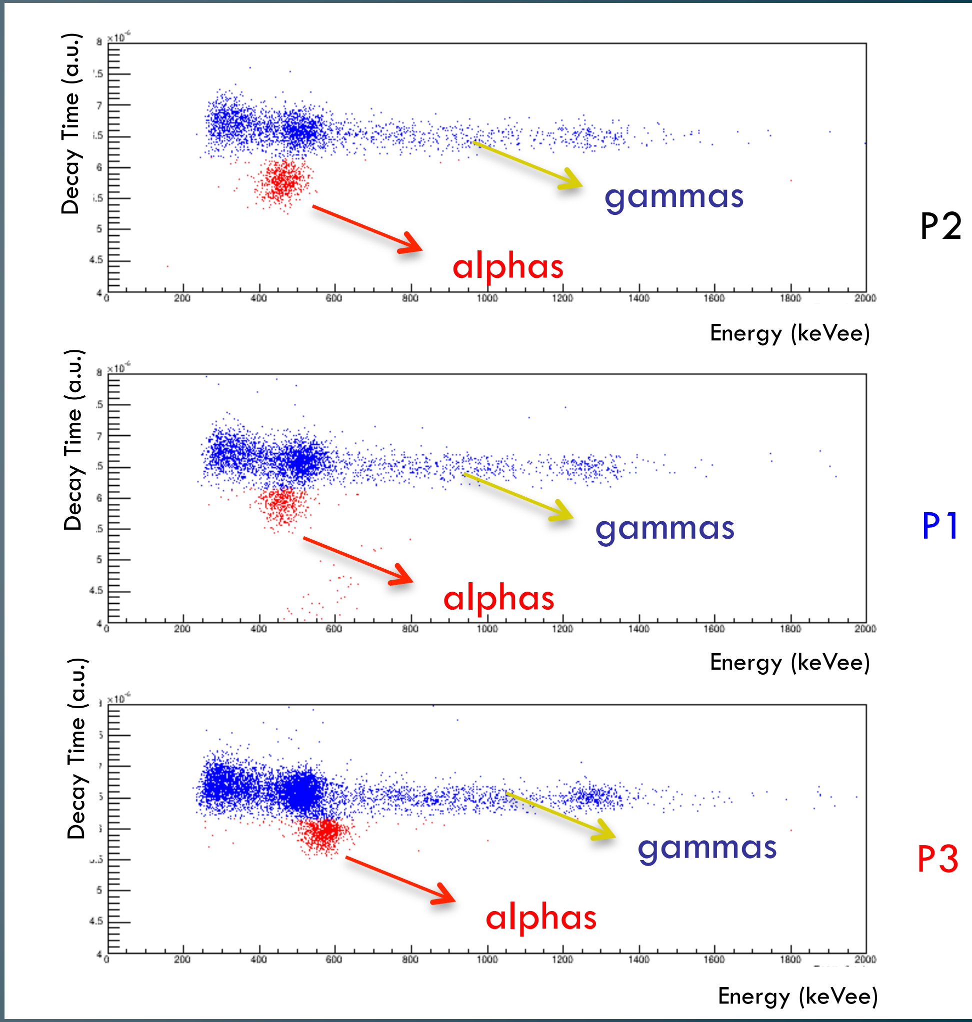




The axis with highest light response has been identified (P3)

Studying the response of the $ZnWO_4$ with ^{241}Am α source

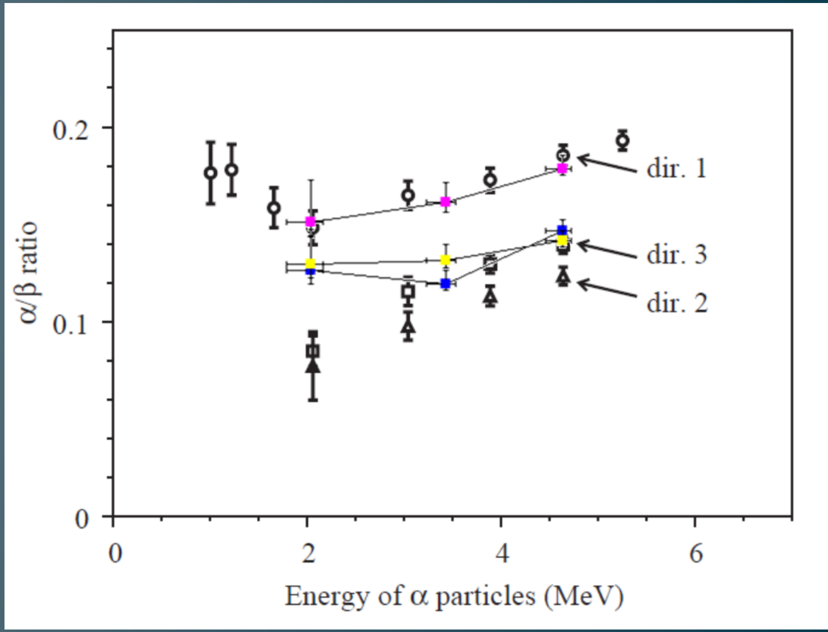
- Plot of decay time vs Energy for γ (^{22}Na) and collimated α along the three crystal axes (named P1, P2, P3)
- PSD capability to discriminate α/γ is evident
- The highest response to α's is along P3



Studying the response of the $ZnWO_4$ with ^{241}Am α source

- By using absorbers of different thickness, we perform measurements of α/β ratio as a function of the α energy
- The α energy after absorbers has been measured with a Si detector

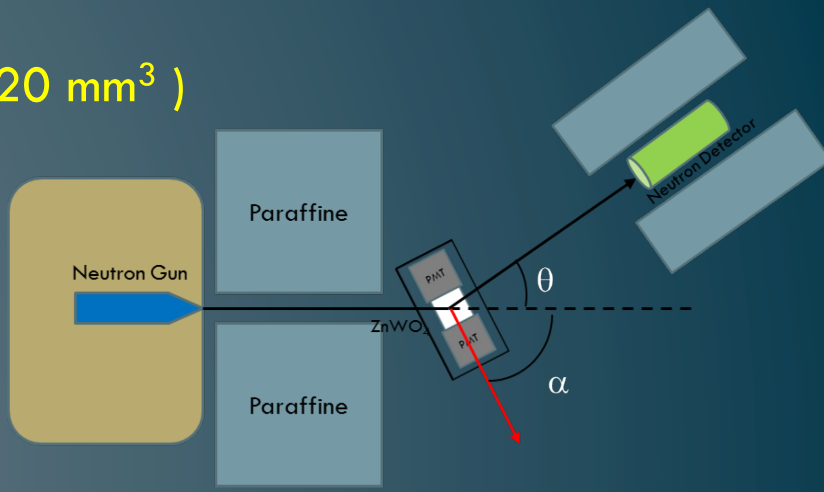
E_α (MeV)	Axes	α/β	Px/P3	P3/PX
2.04	P1	$0.126^{+0.018}_{-0.007}$	0.83	1.20
	P2	$0.129^{+0.018}_{-0.007}$	0.84	1.17
	P3	$0.151^{+0.021}_{-0.008}$	1.00	1.00
3.43	P1	$0.119^{+0.007}_{-0.003}$	0.74	1.35
	P2	$0.131^{+0.008}_{-0.004}$	0.81	1.23
	P3	$0.161^{+0.010}_{-0.004}$	1.00	1.00
4.63	P1	$0.146^{+0.006}_{-0.003}$	0.82	1.22
	P2	$0.141^{+0.005}_{-0.003}$	0.80	1.25
	P3	$0.177^{+0.007}_{-0.003}$	1.00	1.00



- At ≈ 2 MeV $(\alpha/\beta)_{P3} \approx 0.15$ $(\alpha/\beta)_{P1} \approx (\alpha/\beta)_{P2} \approx 0.13$
- In agreement with the results reported in literature

Studying the response of the $ZnWO_4$ with 14 MeV neutron source @ ENEA-Casaccia

- Set-up:
  - ✓ $ZnWO_4$ Crystal (10.20 x 10.20 x 10.20 mm^3)
  - ✓ PMT1 and 2: HAMA-H11934-200
  - ✓ 2 Neutron detectors (Scionix EJ-309)
  - ✓ Neutron Gun, Thermo Scientific MP320: 14 MeV neutrons

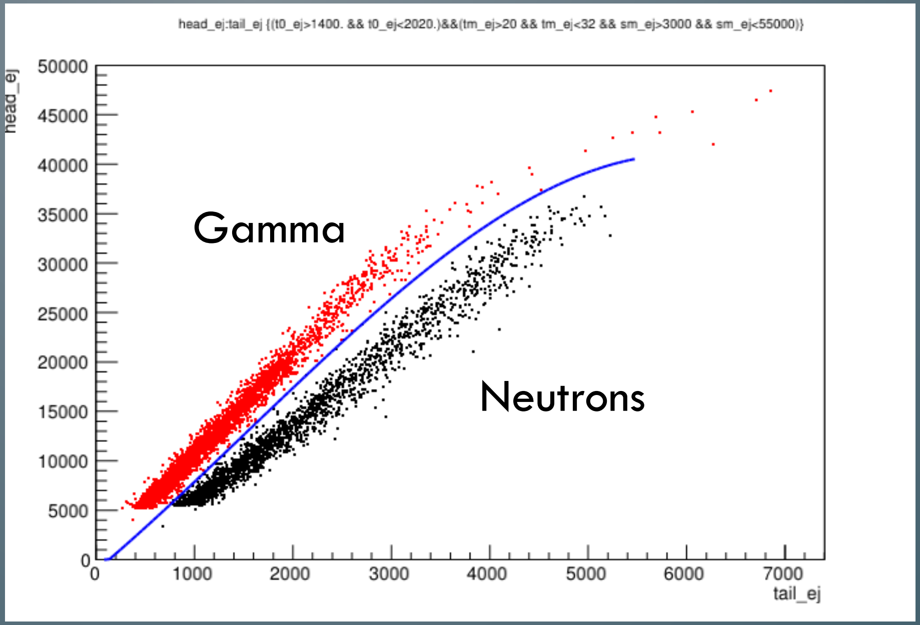


- Strategy: search for coincidence between a scattered neutron at a fixed angle and scintillation event in $ZnWO_4$ occurred in a well defined time window (ToF)
- Once fixed the θ angle, the recoil direction and energy are fixed
- Measurements performed at different θ angle

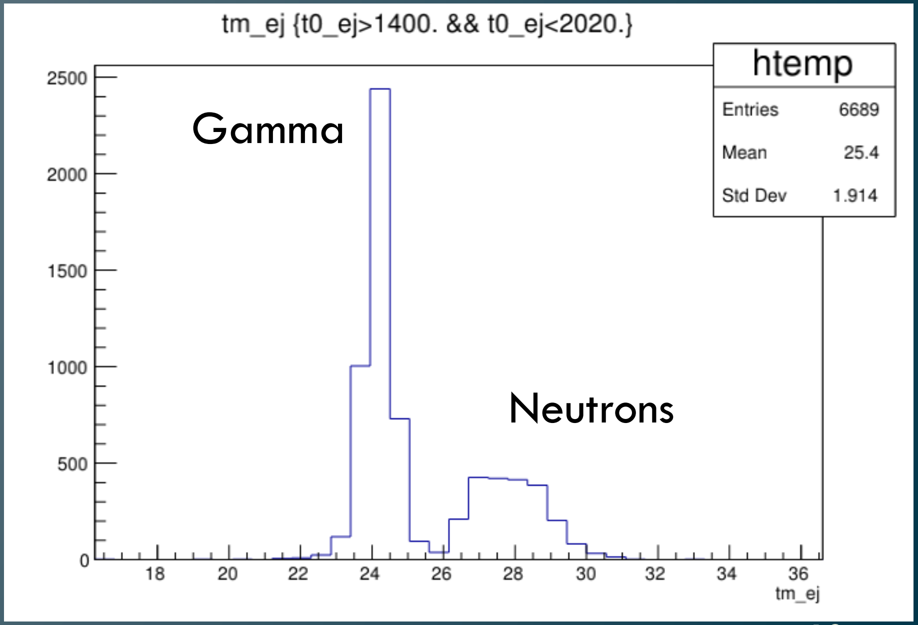
Gamma/Neutron discrimination in EJ-309

- PSD capability of EJ-309 to discriminate gamma from neutrons

Typical Head vs Tail Plot



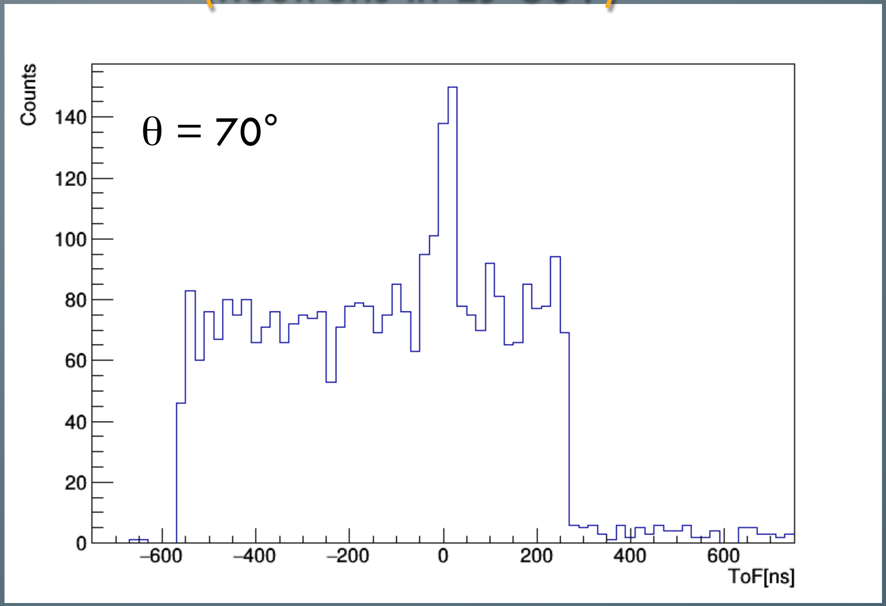
Typical Time Decay Distribution



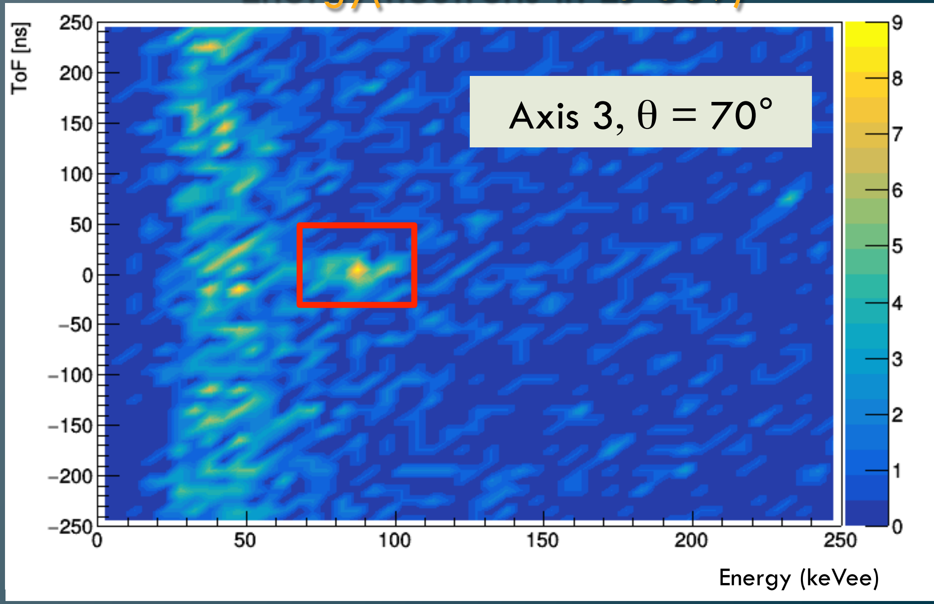
Event selection criteria

- Electronic chain selects events in coincidence between $ZnWO_4$ and EJ-309 in a large ToF ($=t0_{EJ} - T0_{ZWO}$) window
- Off-line analysis selection criteria:
  - ✓ Scattered neutrons in EJ-309
  - ✓ ToF in the time window [-20;+30] ns
  - ✓ Due to ph.e. structure of $ZnWO_4$ low energy pulses, the ToF has an exponential behaviour from ≈15.5 ns to below

Example of ToF distribution (neutrons in EJ-309)



Example of scatter plot ToF vs Energy(neutrons in EJ-309)



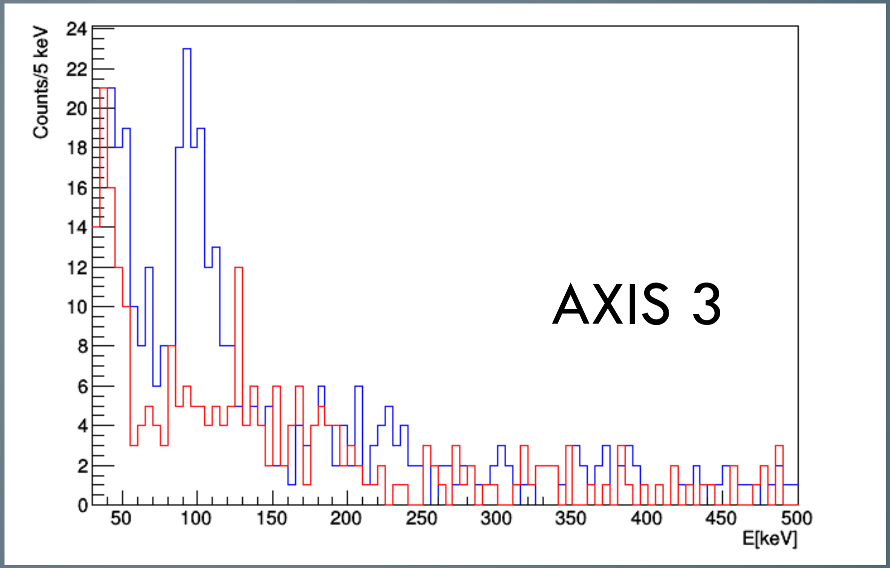
Excess observed in the region: E ≈100 keVee, ToF ≈ [-20;+30] ns

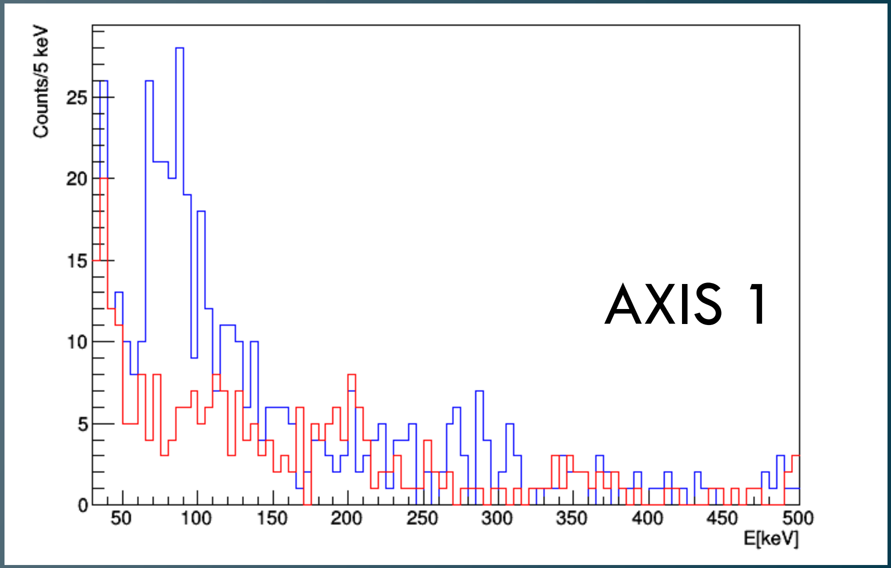
$ZnWO_4$ energy distribution

Energy distributions in $ZnWO_4$ for coincidence events when neutrons are identified in EJ-309 and two ToF window are considered (θ=80°):

- ✓ -20 ns < ToF < 30 ns (neutron induced recoils)
- ✓ 60 ns < ToF < 110 ns (random coincidences)

Preliminary





θ = 80°

- A clear peak is present for events with ToF ≈ [-20;+30] ns and E ≈100 keVee,
- No peak is present when random coincidences are selected

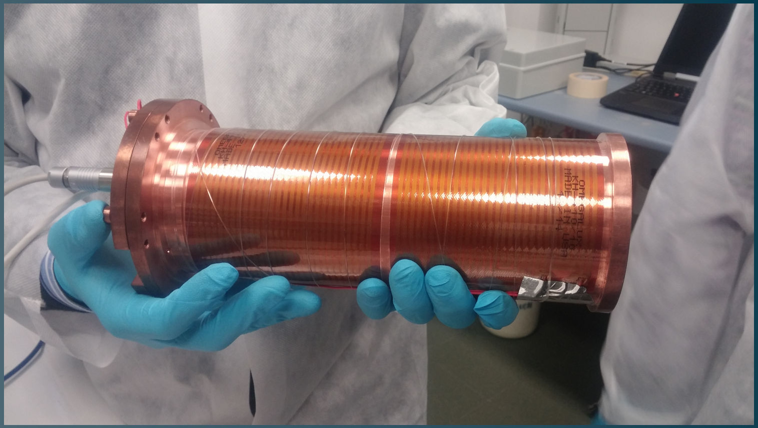
Evaluation of the Quenching Factor for O nucleus

Preliminary

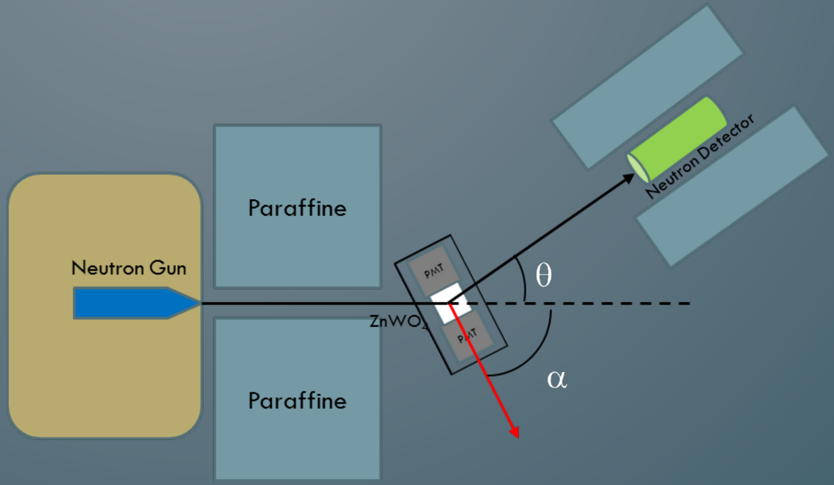
Angle	Axis	E_{peak} (keVee)	$E_{recoil,O}$ (keV)	Q	Q_{III} / Q_{I}
80°	3	99.2±2.5	1387	0.0715±0.0018	1.189±0.047
80°	1	83.4±2.5	1387	0.0601±0.0018	
70°	3	87.0±2.1	1116	0.0780±0.0019	1.227±0.063
70°	1	78.9±3.2	1116	0.0635±0.0029	
60°	3	to be completed	856		
60°	1	to be completed	856		

First evidence for anisotropy on the response of $ZnWO_4$ for nuclear recoils

$ZnWO_4$ – work in progress…



- Cryostat for low temperature measurement with scintillation detectors has been realized
- Test of the Cryostat is in progress
- Lowering the energy threshold (new PMT with higher QE, SiPM, APD, SDD, …)



- Measurements of anisotropy at low energy with MP320 Neutron Generator (E_n = 14 MeV) at ENEA-Casaccia is ongoing
- Development of electronics

Conclusions

- Anisotropic $ZnWO_4$ detectors are promising detectors to investigate the directionality for DM candidates inducing nuclear recoils
- First evidence of anisotropy in the response of $ZnWO_4$ crystal scintillator to low energy nuclear recoils reported
- These detectors could permit to reach - in some given scenarios and candidates - sensitivity comparable to that of the DAMA/LIBRA positive model independent results
- Such an experiment can obtain, with a completely different new approach, further evidence for the presence of some DM candidates in the galactic halo and provide complementary information on the nature and interaction type of the DM candidate