LEGEND

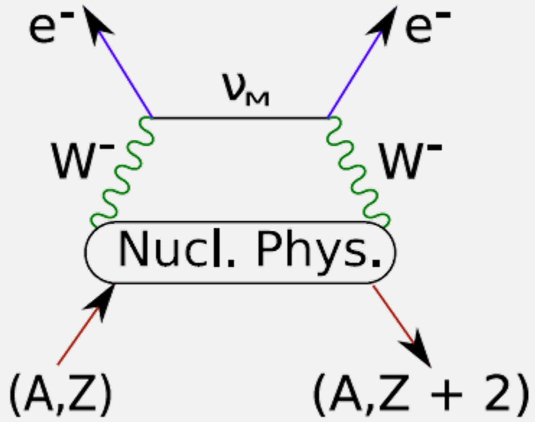
Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

PEN Scintillators for Low Background Experiments

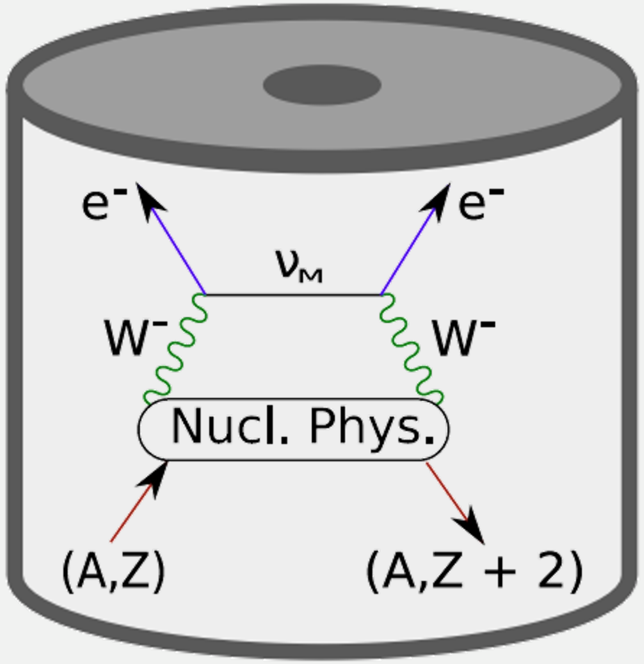
Brennan Hackett

MAX-PLANCK-INSTITUT
FÜR PHYSIK

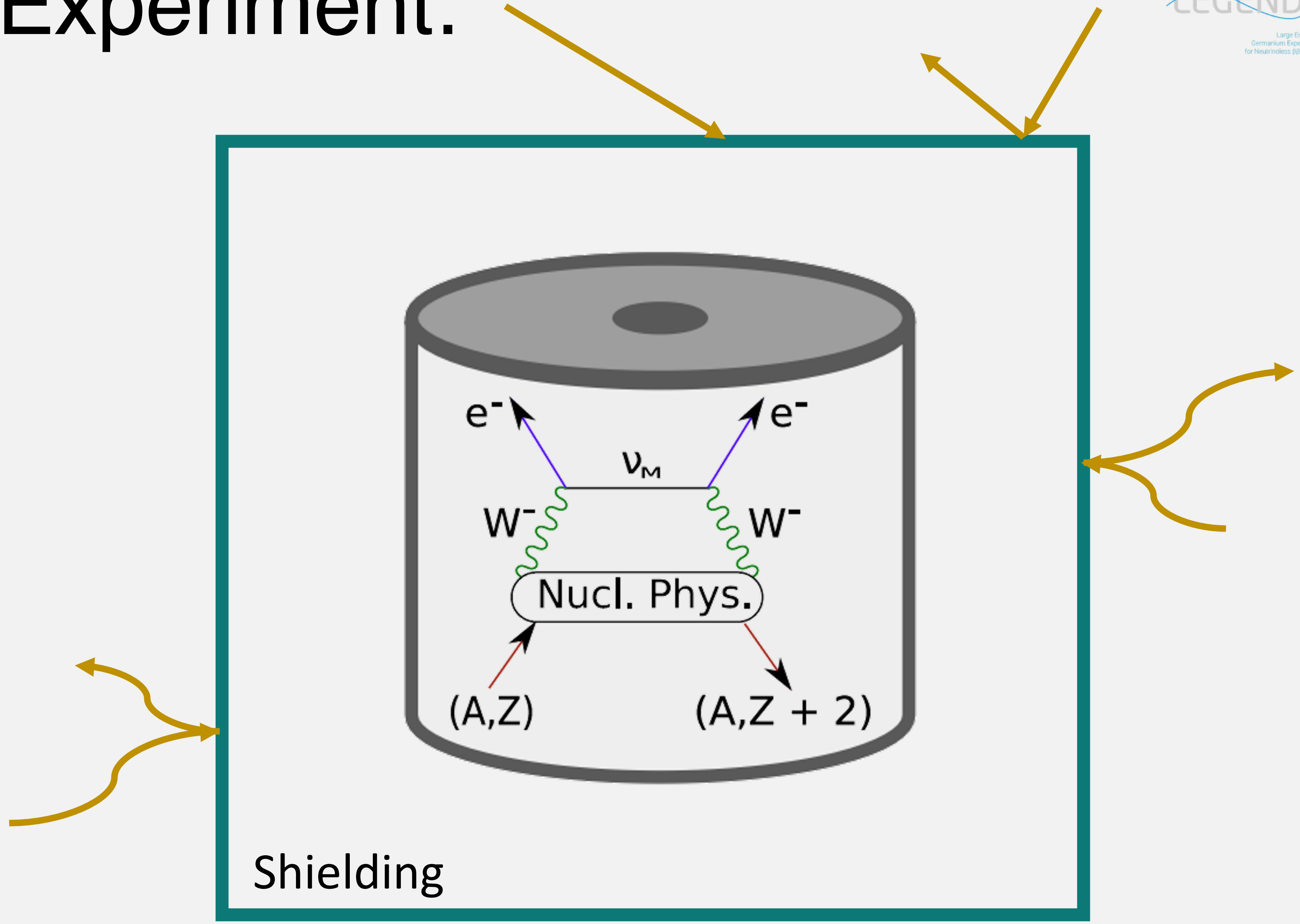
Low Background Experiment: LEGEND



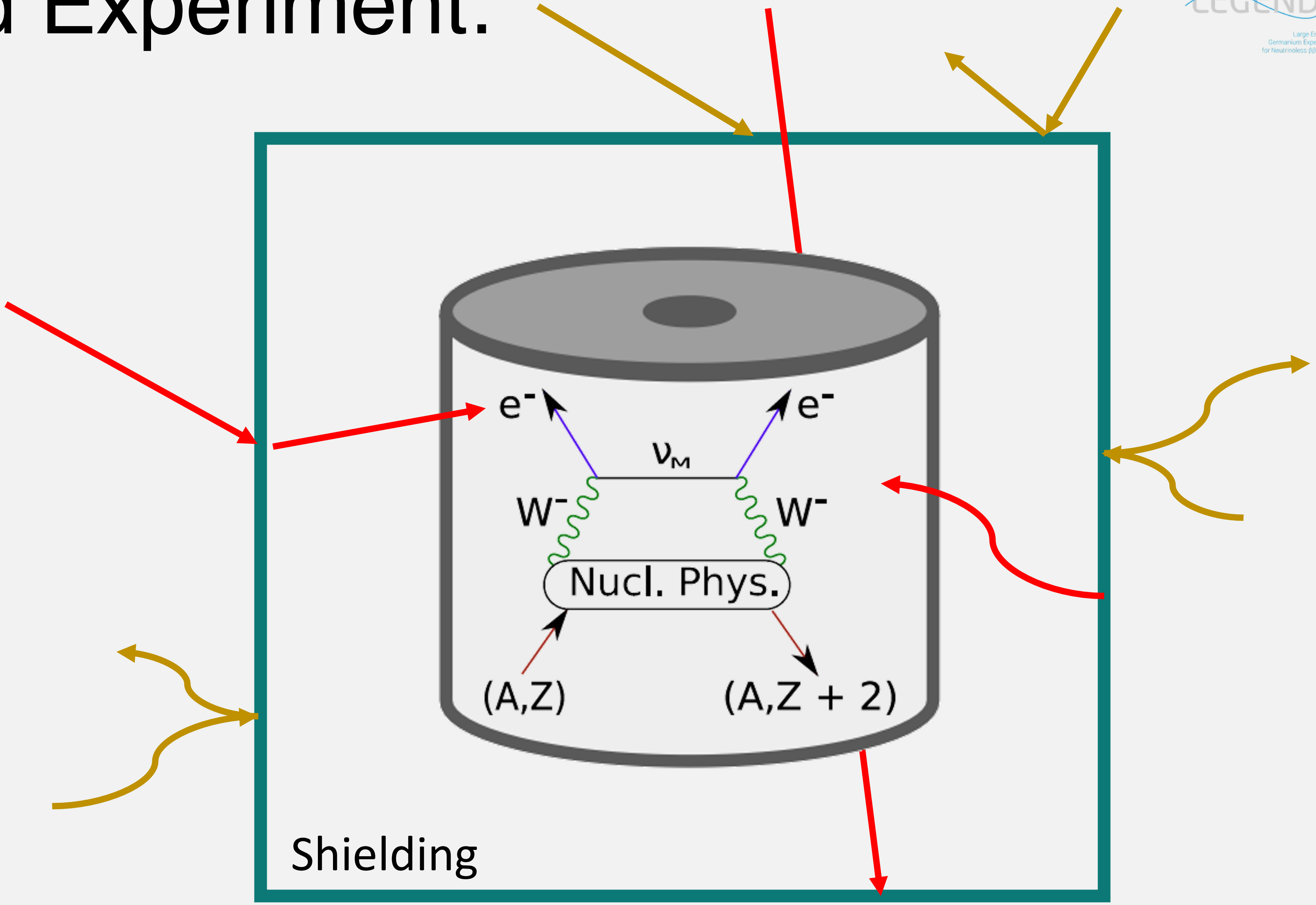
Low Background Experiment: LEGEND



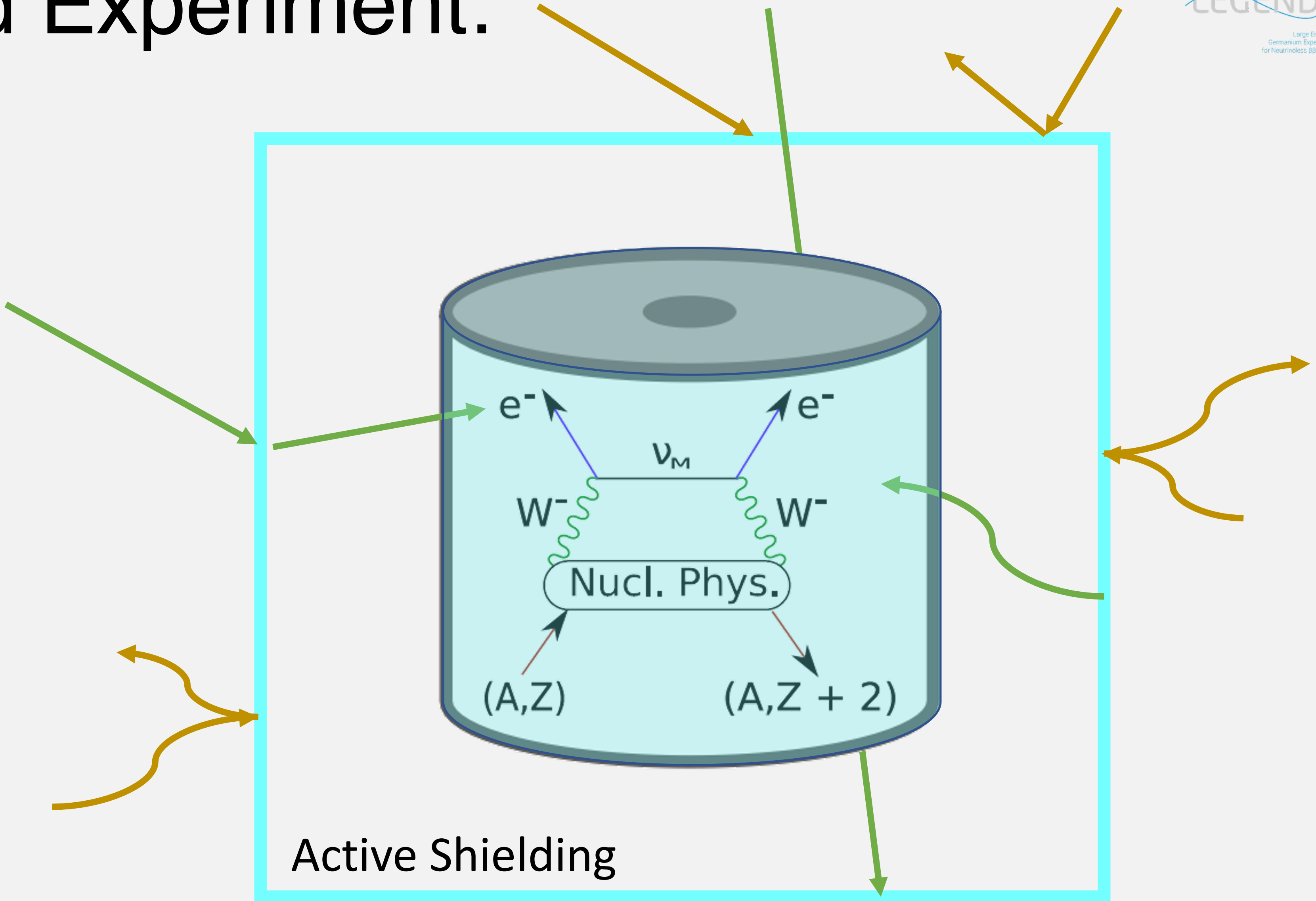
Low Background Experiment: LEGEND



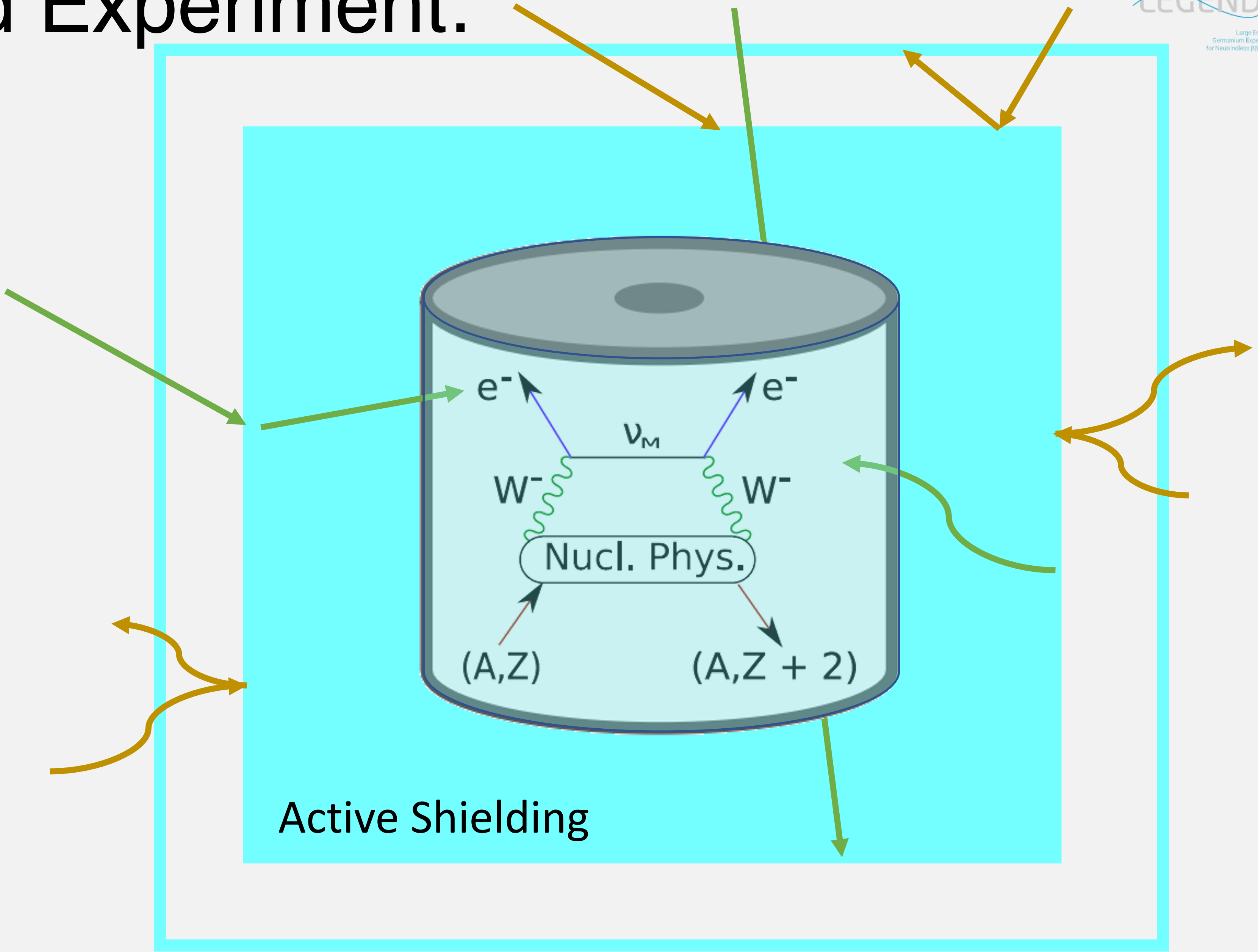
Low Background Experiment: LEGEND



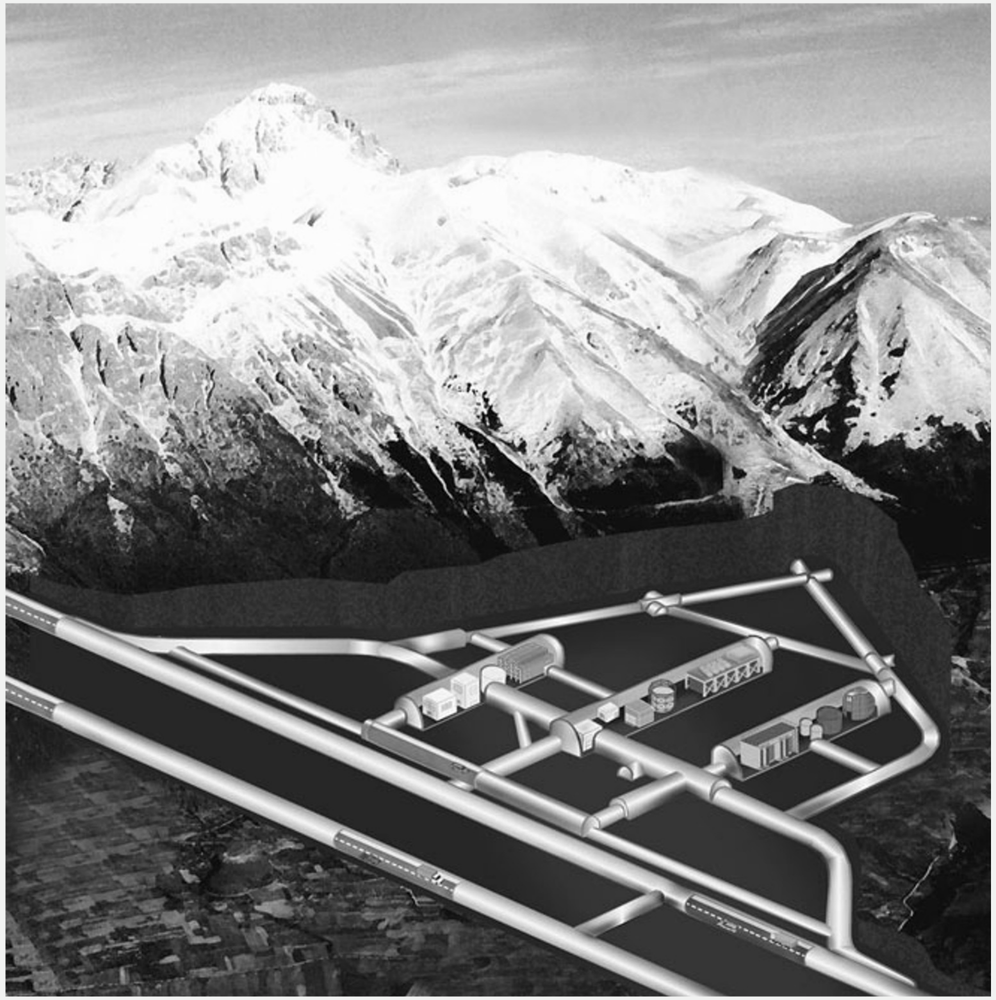
Low Background Experiment: LEGEND



Low Background Experiment: LEGEND

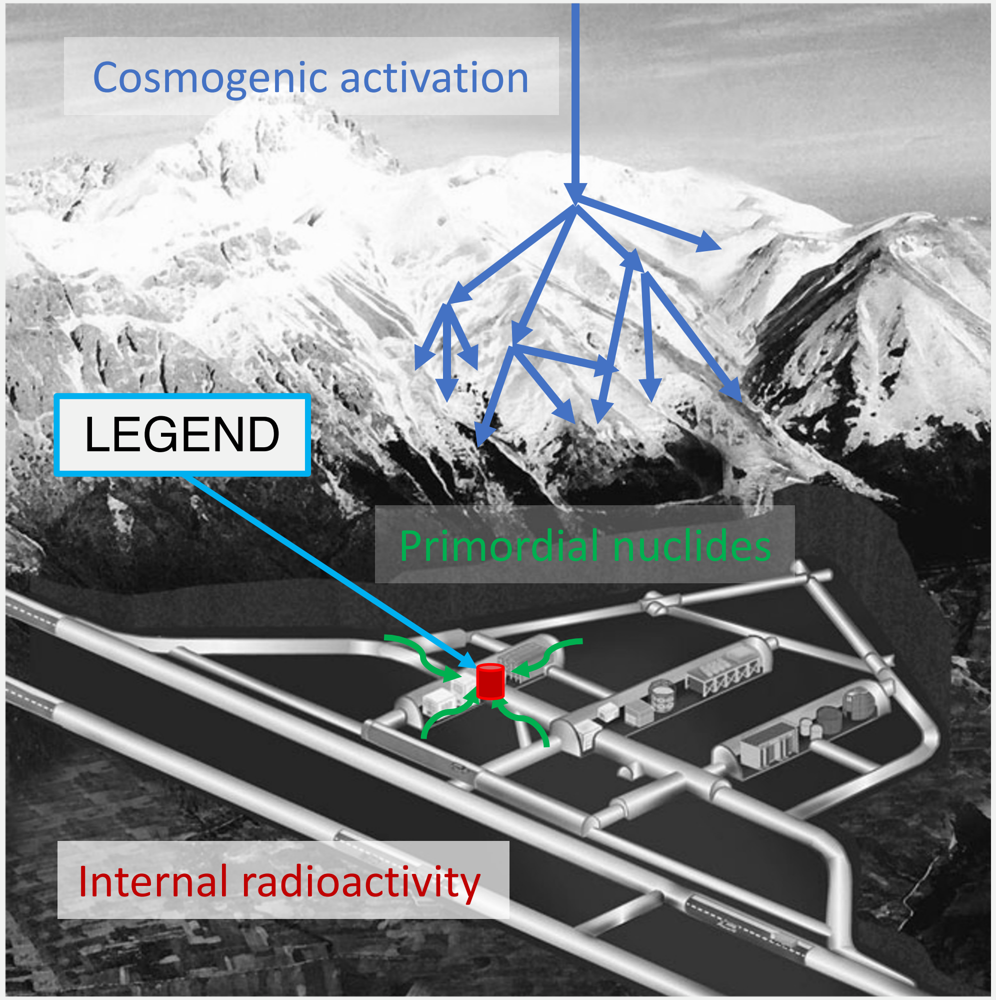


Background Reduction Strategy

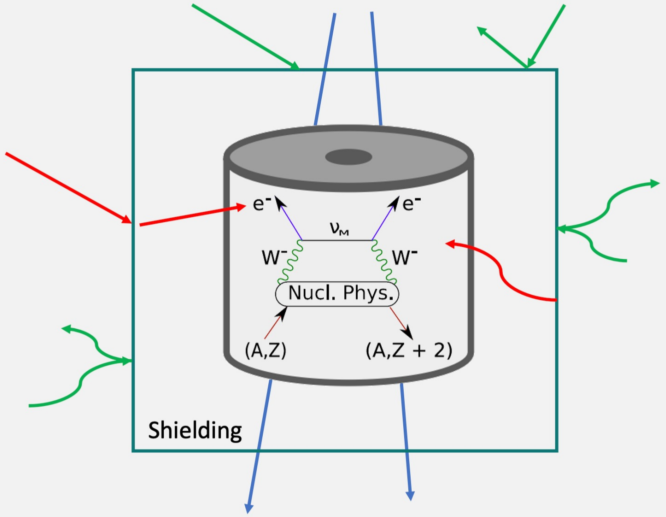


Gran Sasso National Laboratory (LNGS)

Background Reduction Strategy

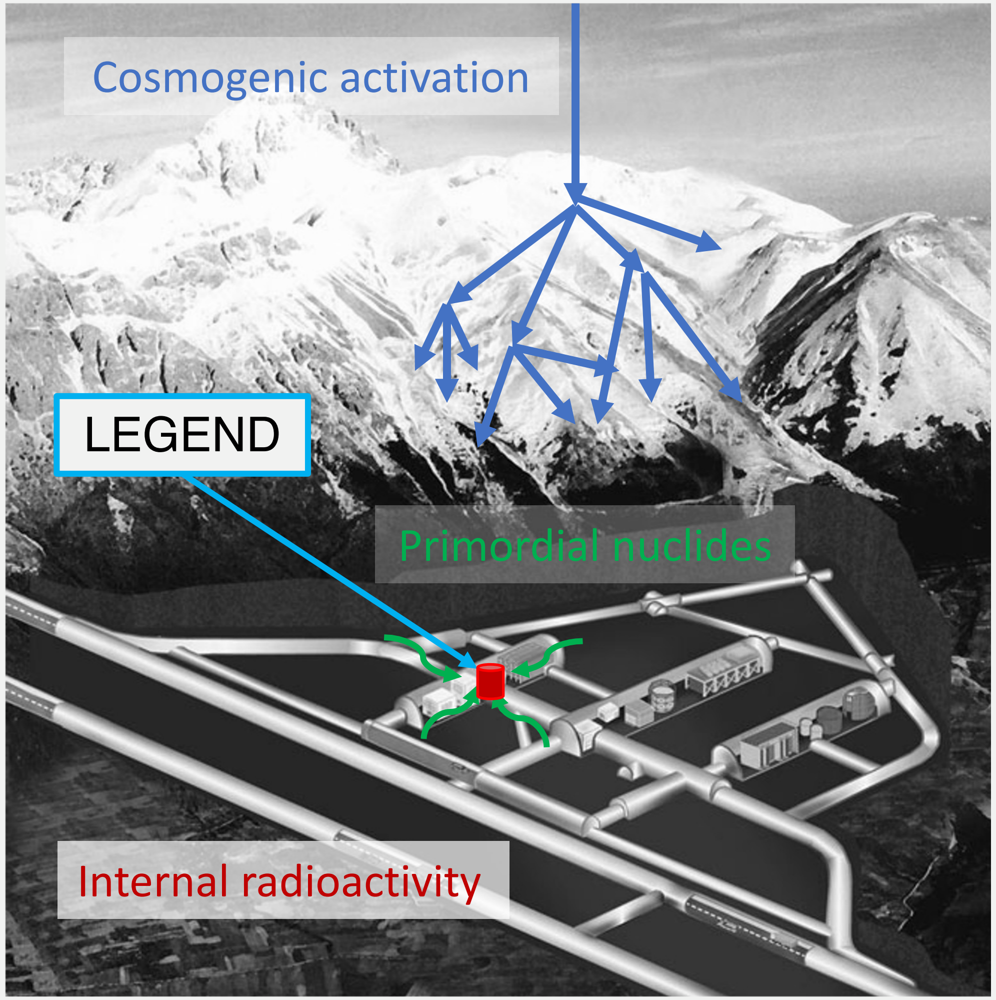


Gran Sasso National Laboratory (LNGS)

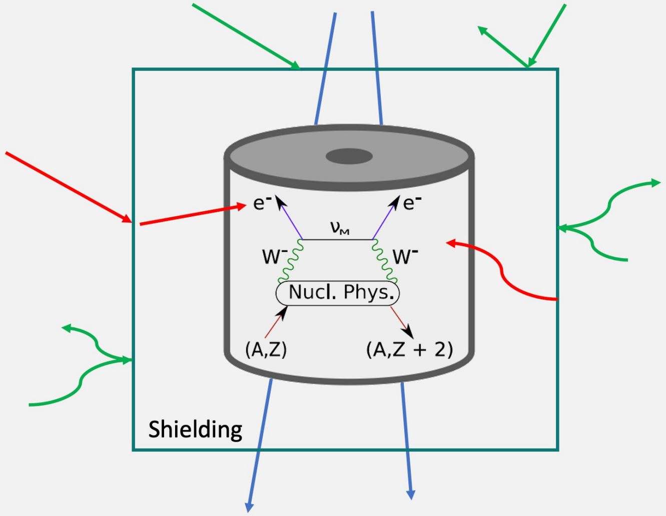


Background Reduction Strategy

- Shield
- Detect
- Minimize

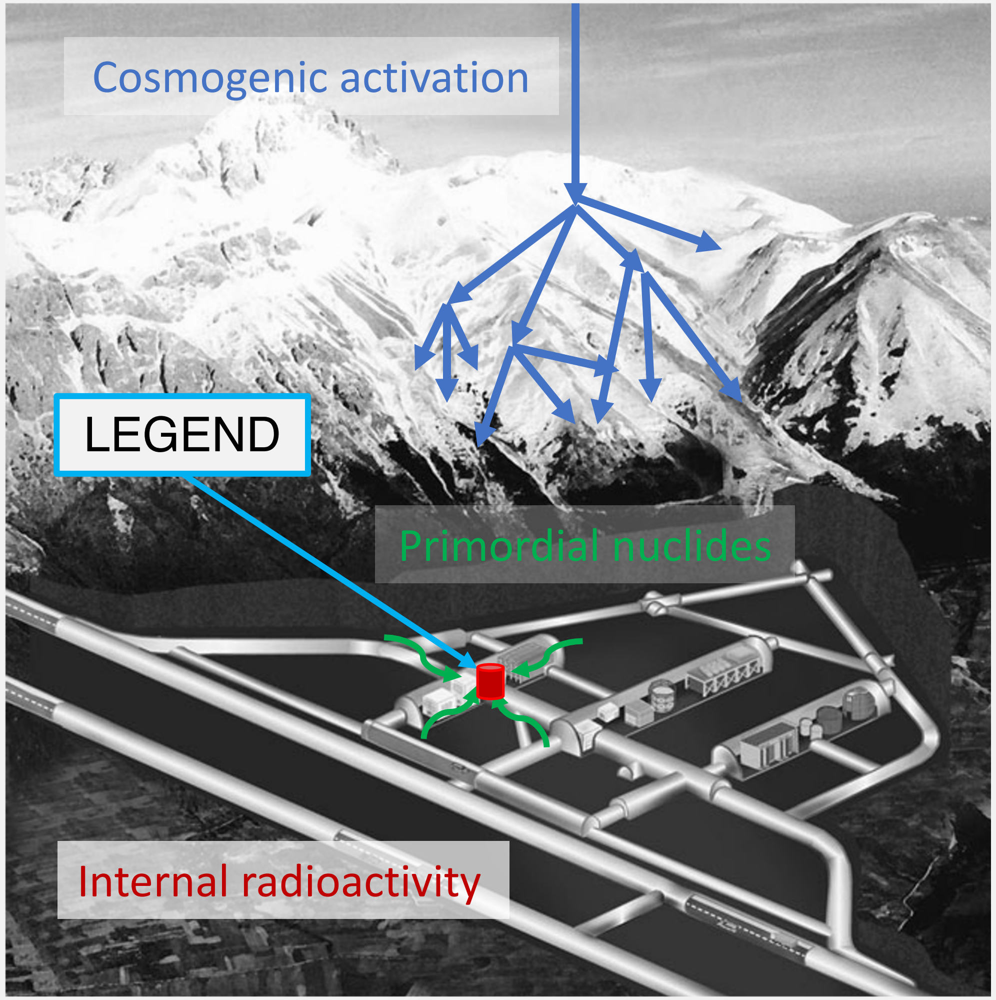


Gran Sasso National Laboratory (LNGS)

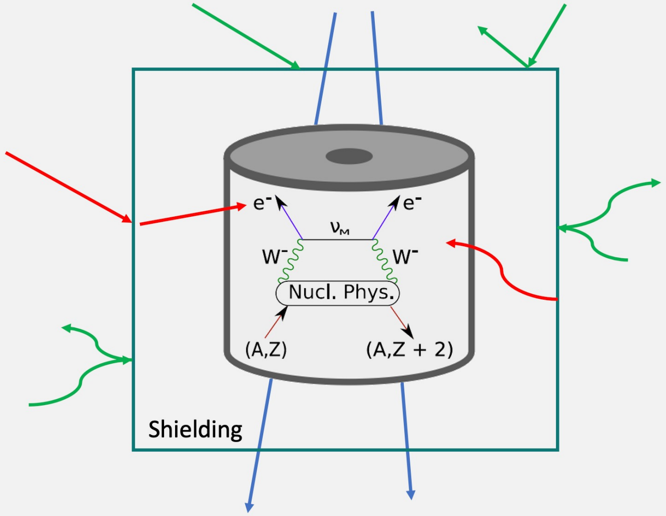


Background Reduction Strategy

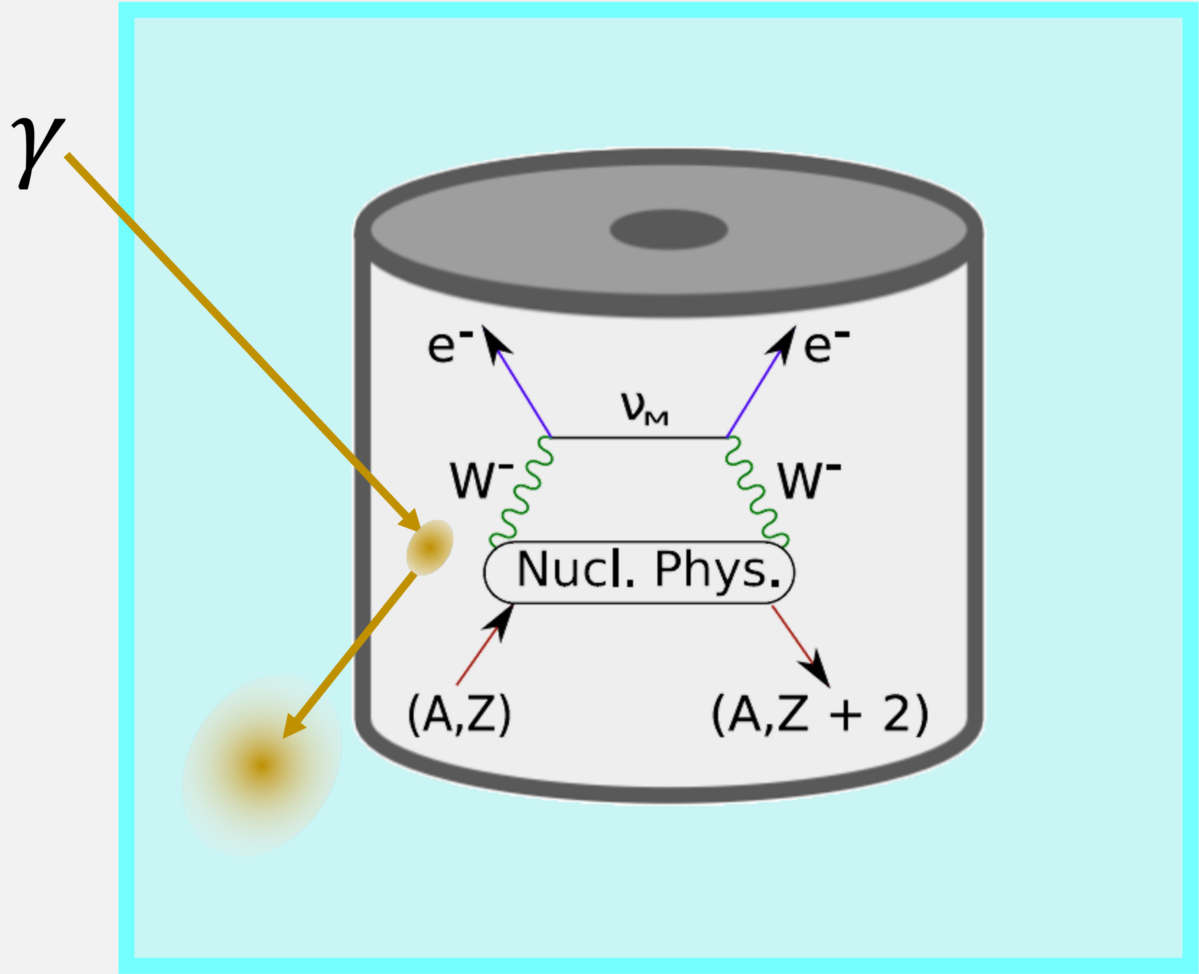
- Shield ✓
  - Underground
- **Detect**
- **Minimize**



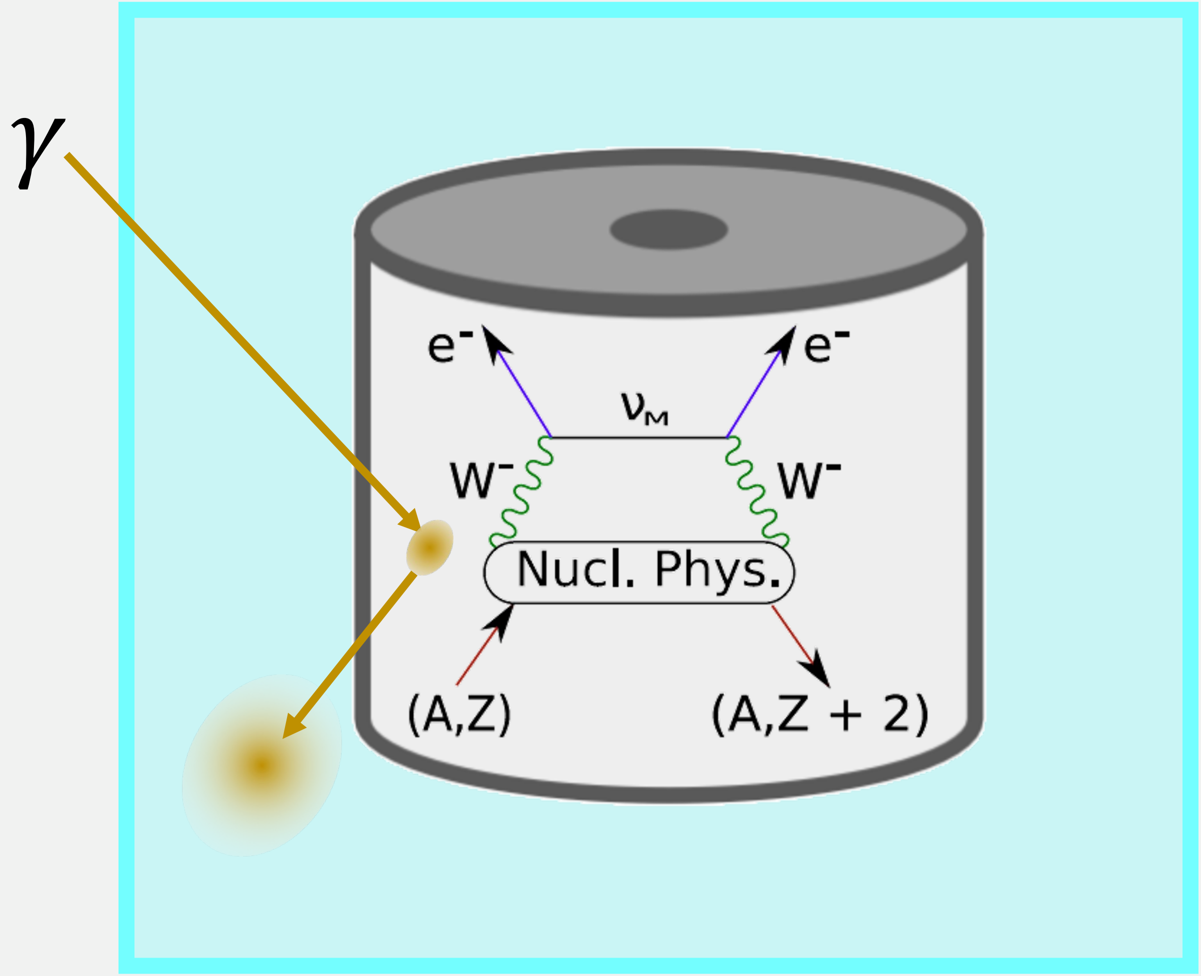
Gran Sasso National Laboratory (LNGS)



Detecting Background Radiation

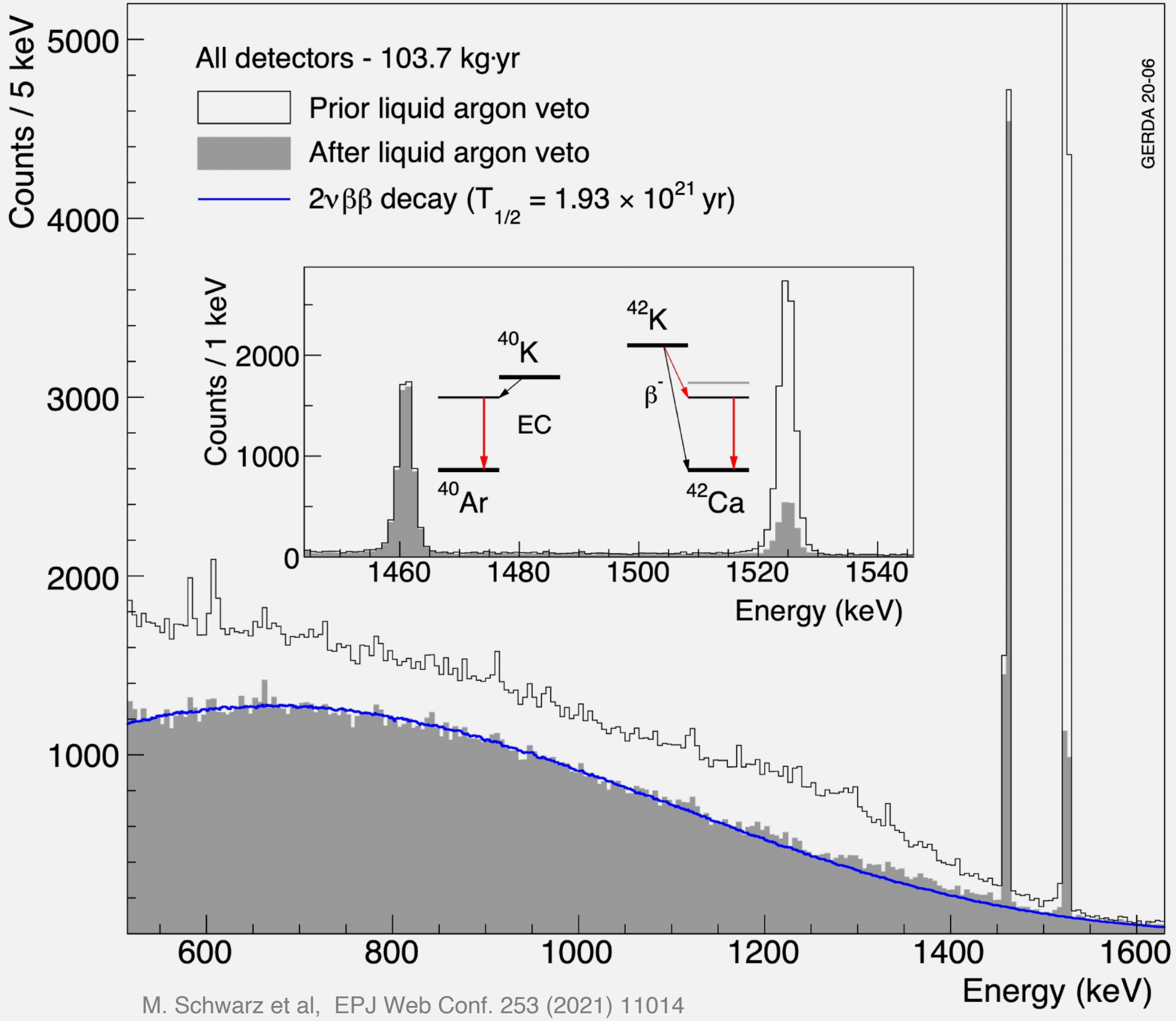


Detecting Background Radiation



- Active material → secondary detectors
- Events in coincidence
- Remove from data set

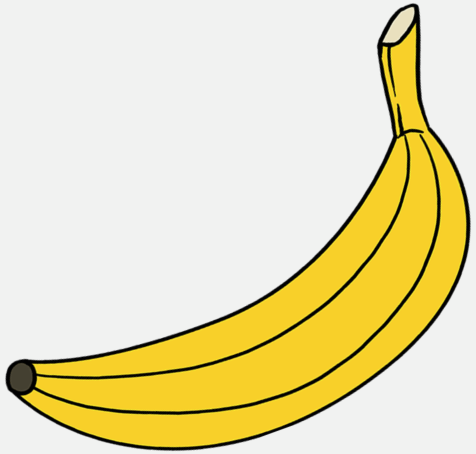
Detecting Background Radiation



M. Schwarz et al, EPJ Web Conf. 253 (2021) 11014

- Active material → secondary detectors
- Events in coincidence
- Remove from data set

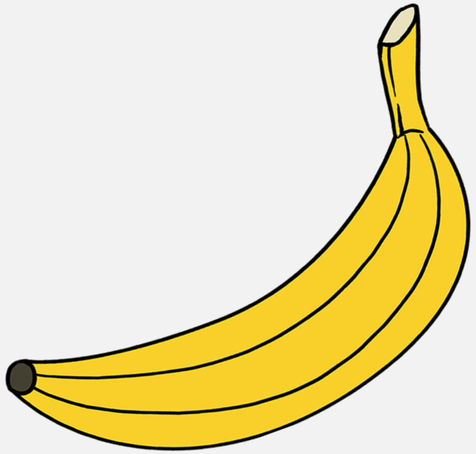
Minimizing Background Radiation



Banana

PEN Baseplate

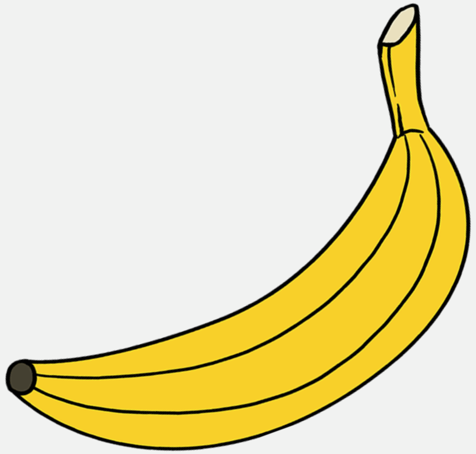
Minimizing Background Radiation



Banana
Activity:10 Bq

PEN Baseplate
Activity: 10^{-6} Bq

Minimizing Background Radiation



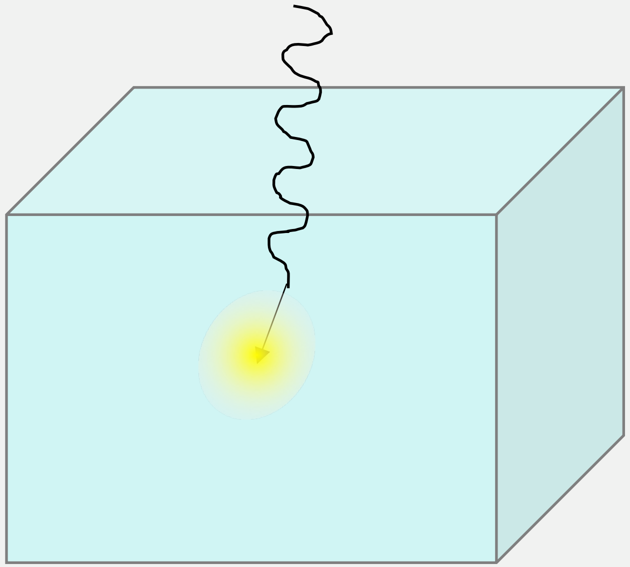
Banana
Activity:10 Bq

PEN Baseplate
Activity: 10^{-6} Bq

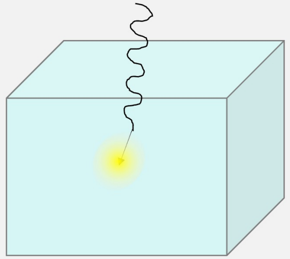
- Surface cleaning
- Careful handling
- Reduced natural activity

(Organic) Scintillators

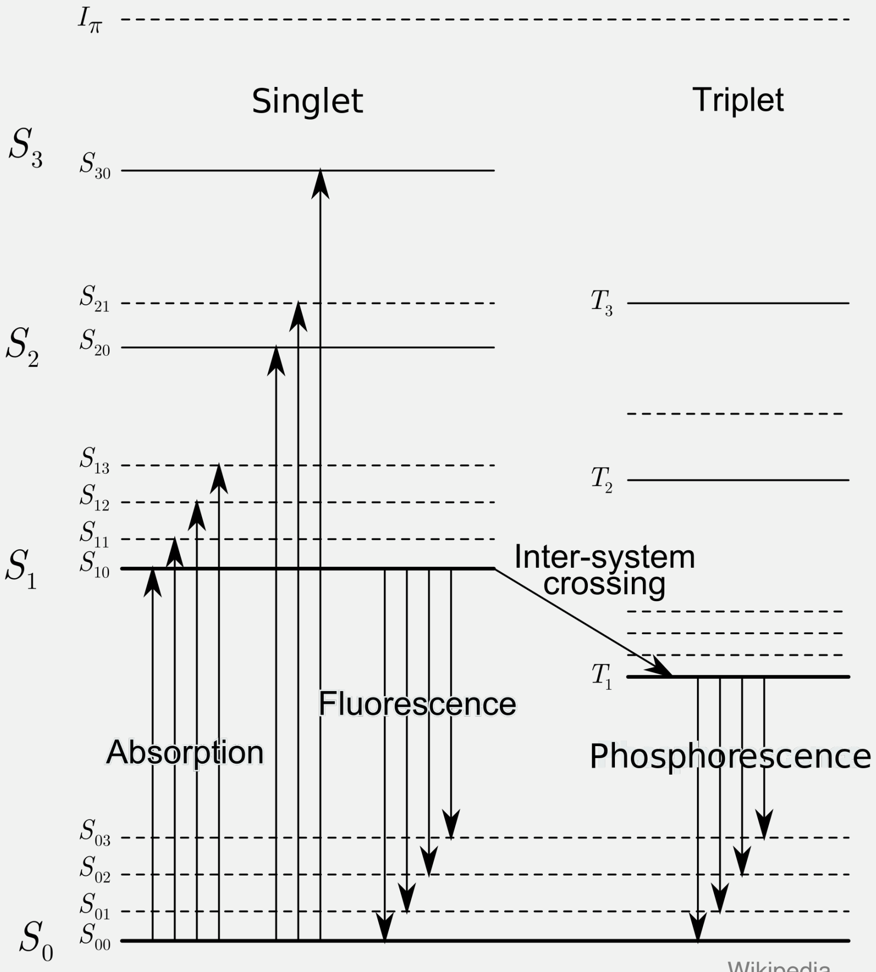
- Ionizing radiation excites molecules



(Organic) Scintillators

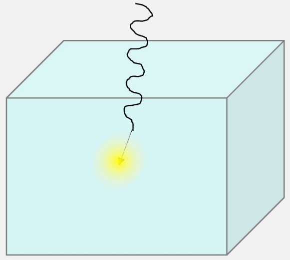


- Ionizing radiation excites molecules
- Molecules relax to first excited state
  - Fluorescence: emission of photon from singlet excited state
  - Phosphorescence: emission of photon from triplet excited state

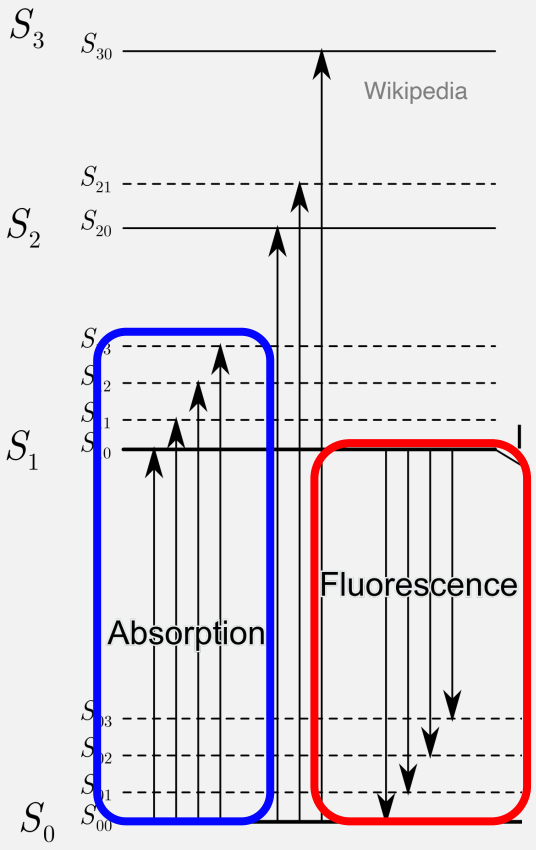


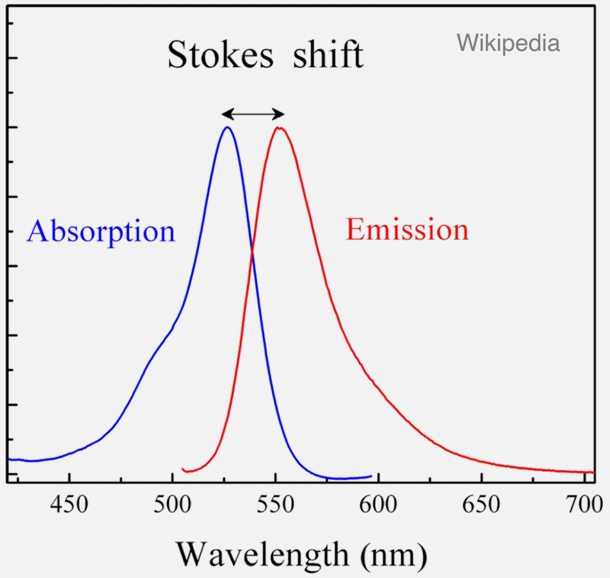
Wikipedia

(Organic) Scintillators

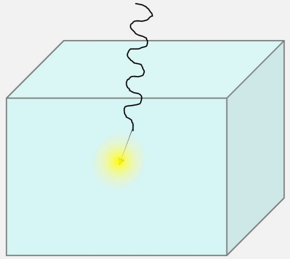


- Ionizing radiation excites molecules
- Molecules relax to first excited state
  - Fluorescence: emission of photon from singlet excited state
  - Phosphorescence: emission of photon from triplet excited state
- Stoke’s shift
  - Difference of maximum absorption λ to maximum emission λ

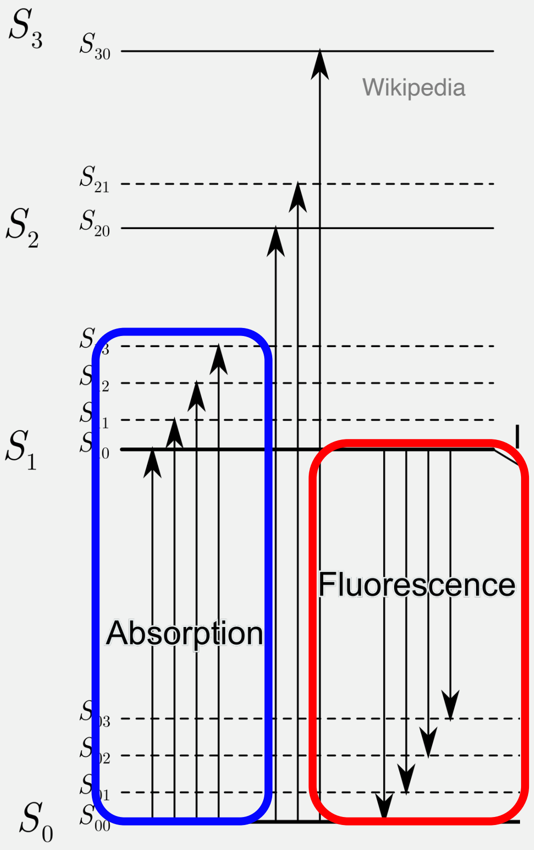


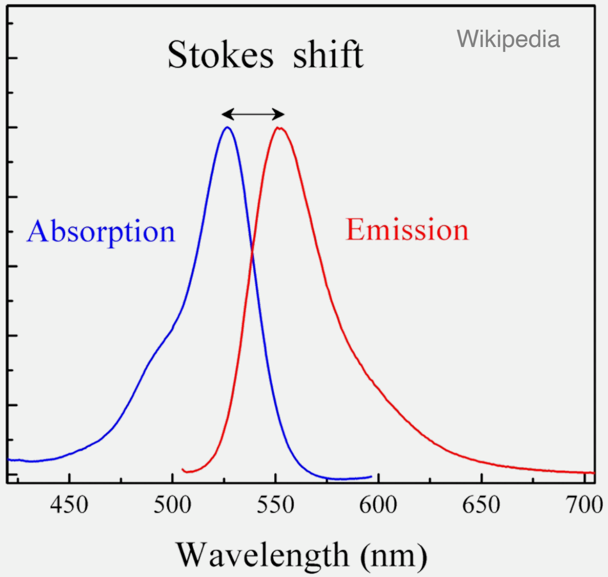


(Organic) Scintillators

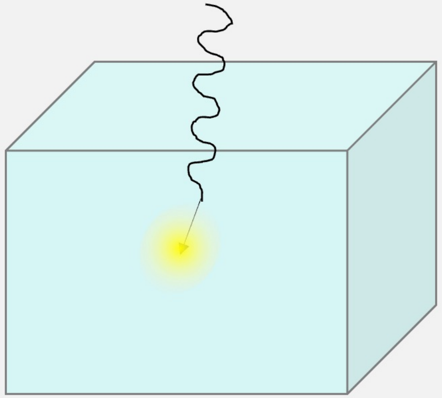


- Some Quick Definitions
  - Peak emission
    - Wavelength where emission intensity is maximal
  - Wavelength shifting (WLS)
    - Absorbing a shorter wavelength and re-emitting a photon in the emission spectrum
  - Photons per MeVee
    - # photons emitted for every MeV of energy deposited in the scintillator by electrons
  - Quantum efficiency (QE)
    - Ratio of photons emitted to photons absorbed

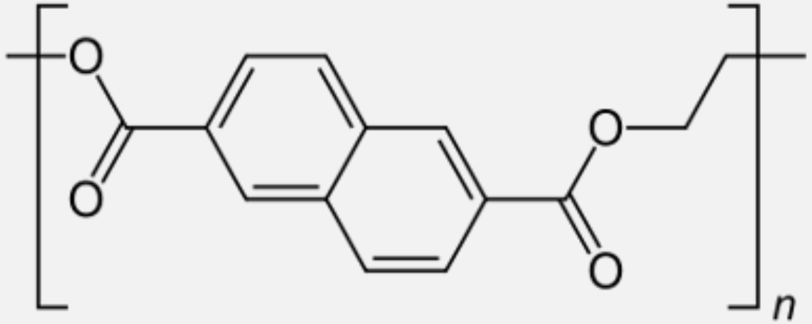




PEN as a Scintillator

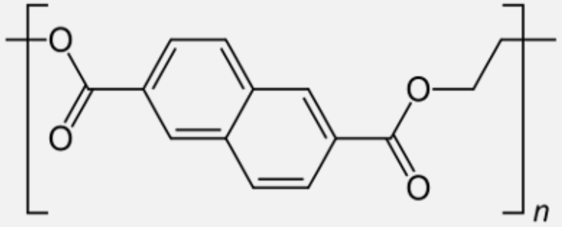


- Commercially available polyester



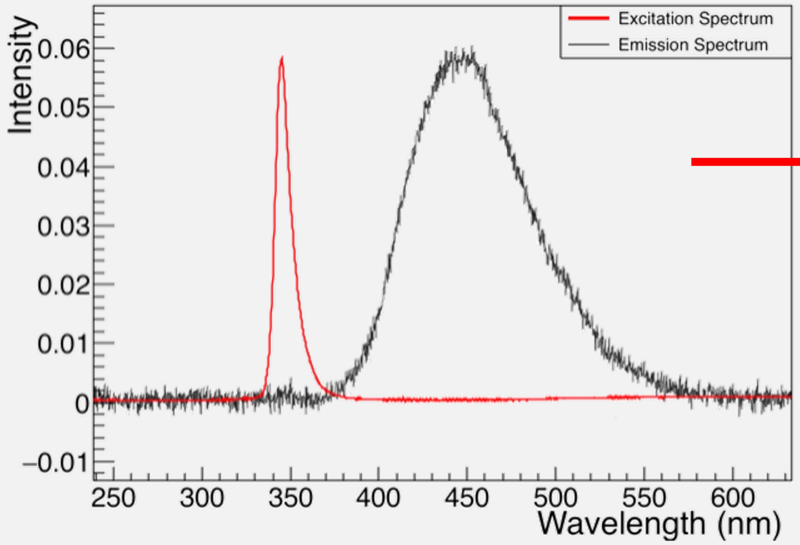
Poly(ethylene 2,6-naphthalate)
(PEN)

PEN as a Scintillator

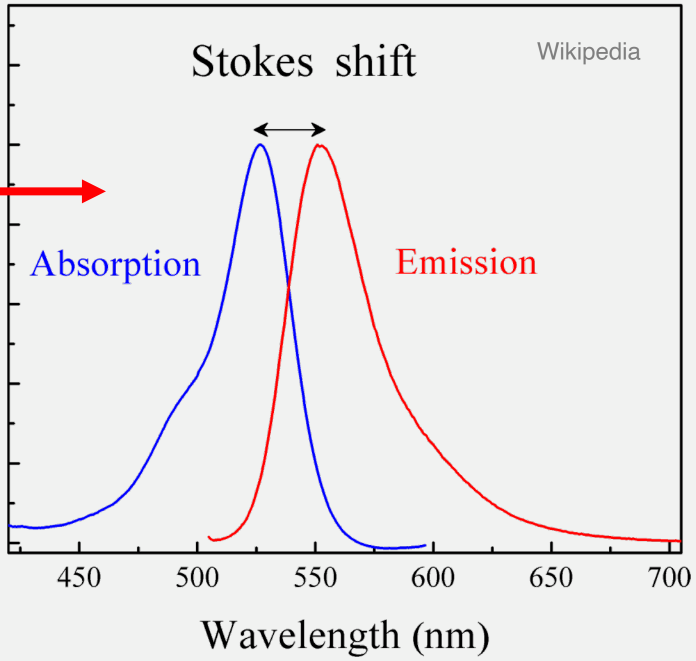


Poly(ethylene 2,6-naphthalate)
(PEN)

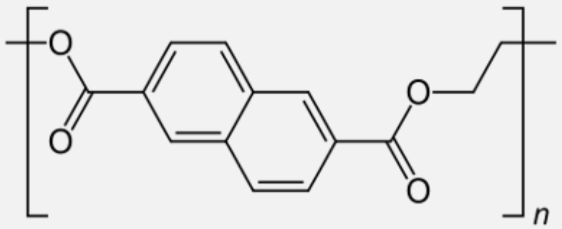
- Commercially available polyester
- Peak emission at λ ~ 425 nm
  - Best sensitivity for photon detectors

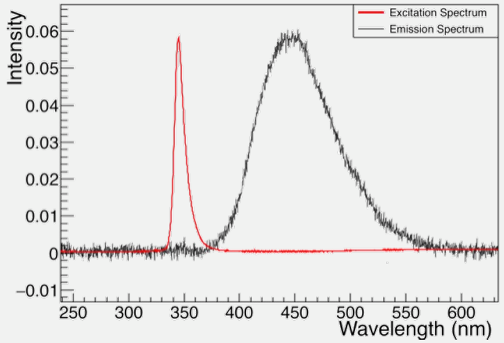


Wavelength shifting of PEN from
λ ~ 350 nm to λ ~ 425 nm



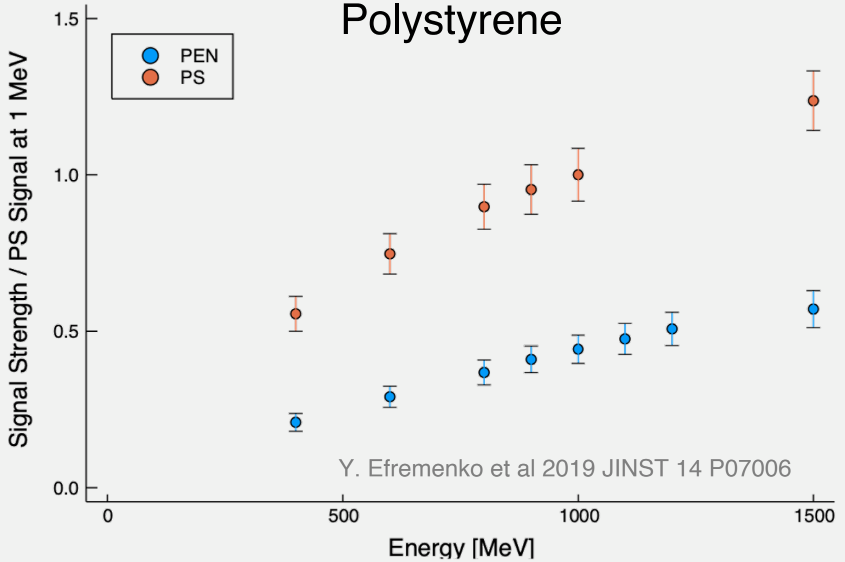
PEN as a Scintillator


Poly(ethylene 2,6-naphthalate) (PEN)



WLS λ ~350 nm to λ ~425 nm

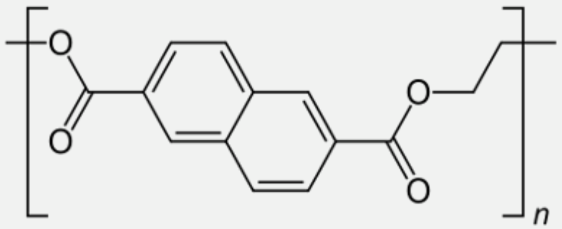
Light Emission from Electrons in PEN and Polystyrene



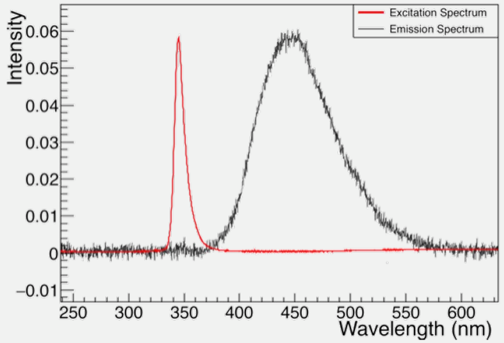
Y. Efremenko et al 2019 JINST 14 P07006

- Commercially available polyester
- Peak emission at λ ~ 425 nm
  - Best sensitivity for photon detectors
- Produces 5,000 photons per MeVee
  - ~50 % conventional scintillators

PEN as a Scintillator

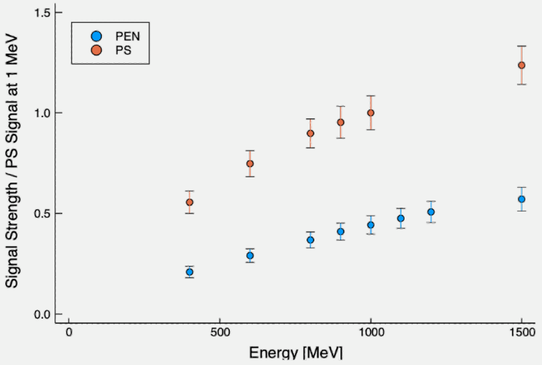


Poly(ethylene 2,6-naphthalate) (PEN)



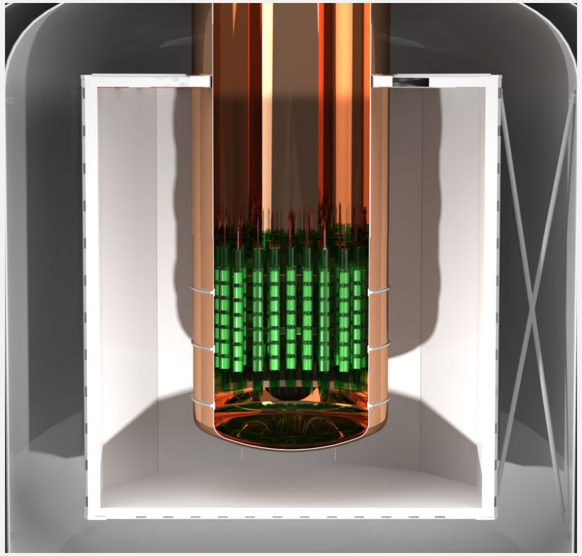
WLS λ ~350 nm to λ ~425 nm

Light Emission from Electrons



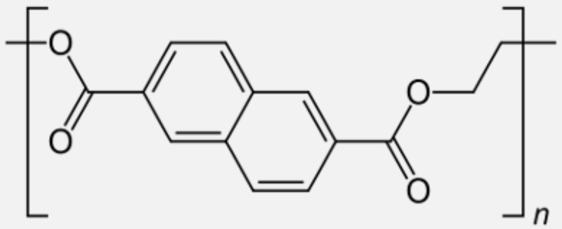
Y. Efremenko et al 2019 JINST 14 P07006

LEGEND-1000 Design

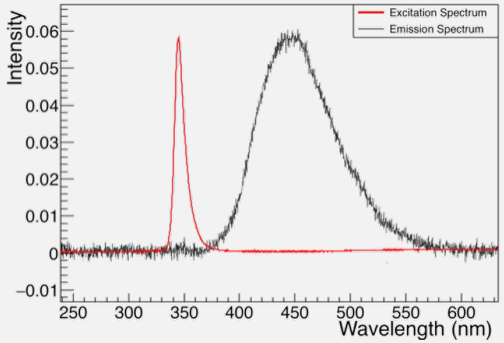


- Commercially available polyester
- Peak emission at λ ~ 425 nm
  - Best sensitivity for photon detectors
- Produces 5,000 photons per MeVee
  - ~50 % conventional scintillators
- ~60% QE at WLS LAr scintillation light (128 nm)
  - Improve sensitivity in active veto system

PEN as a Scintillator

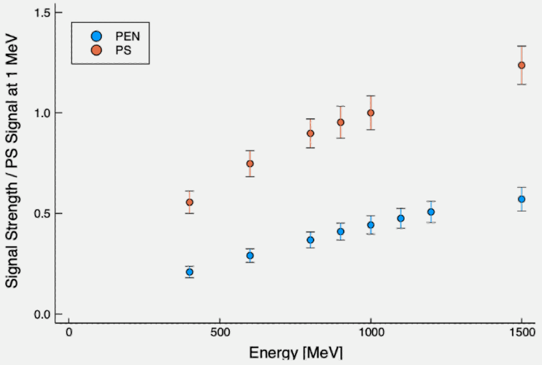


Poly(ethylene 2,6-naphthalate)
(PEN)



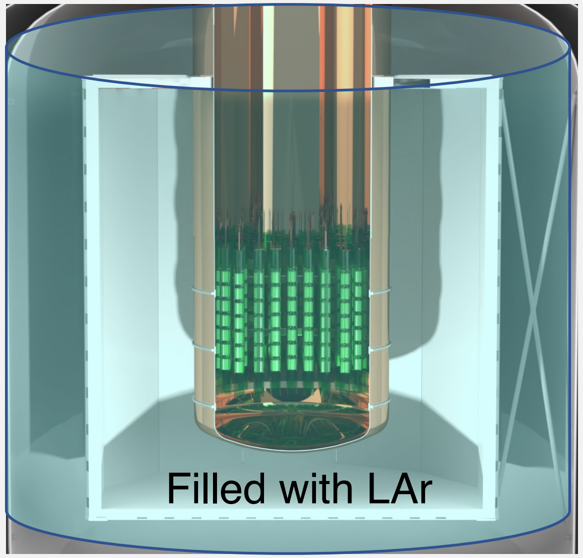
WLS λ ~350 nm to λ ~425 nm

Light Emission from Electrons



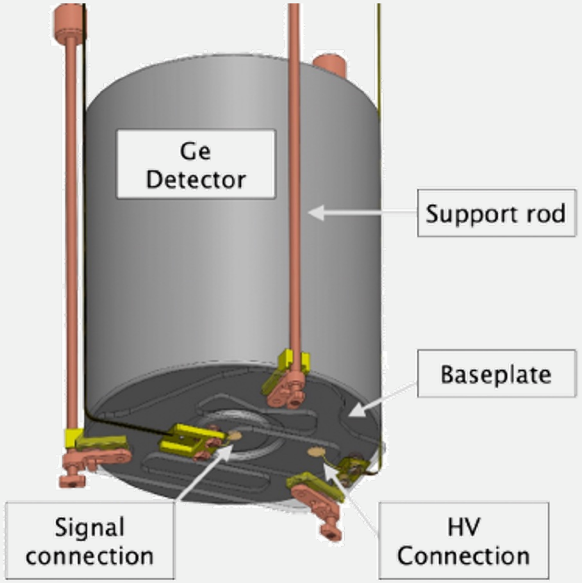
Y. Efremenko et al 2019 JINST 14 P07006

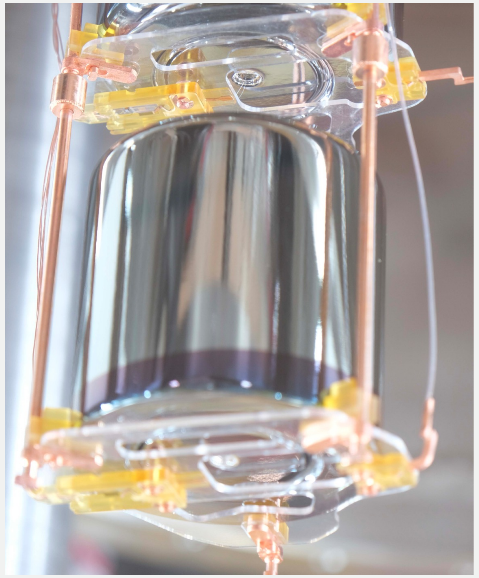
LEGEND-1000 Design

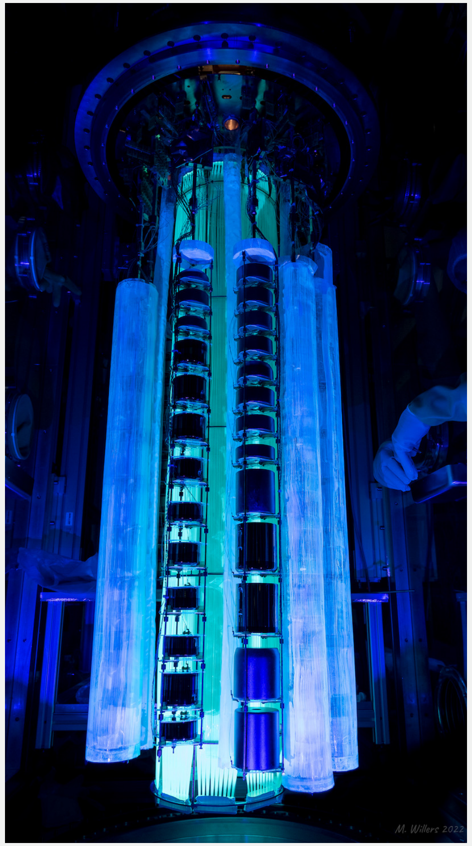


- Commercially available polyester
- Peak emission at λ ~ 425 nm
  - Best sensitivity for photon detectors
- Produces 5,000 photons per MeVee
  - ~50 % conventional scintillators
- ~60% QE at shifting LAr scintillation light (128 nm)
  - Improve sensitivity in active veto system

PEN in LEGEND-200







- PEN baseplates installed in LEGEND-200
  - LEGEND-200 – 0νββ detector with 200 kg of ^{76}Ge
  - Stabilizes and holds electronics for ^{76}Ge detector
  - Increases wls surface between detectors

Minimizing Background Radiation in PEN

PEN Baseplate
Activity: 10^{-6} Bq

- Surface cleaning
- Careful handling
- Reduced natural activity

Minimizing Background Radiation in PEN

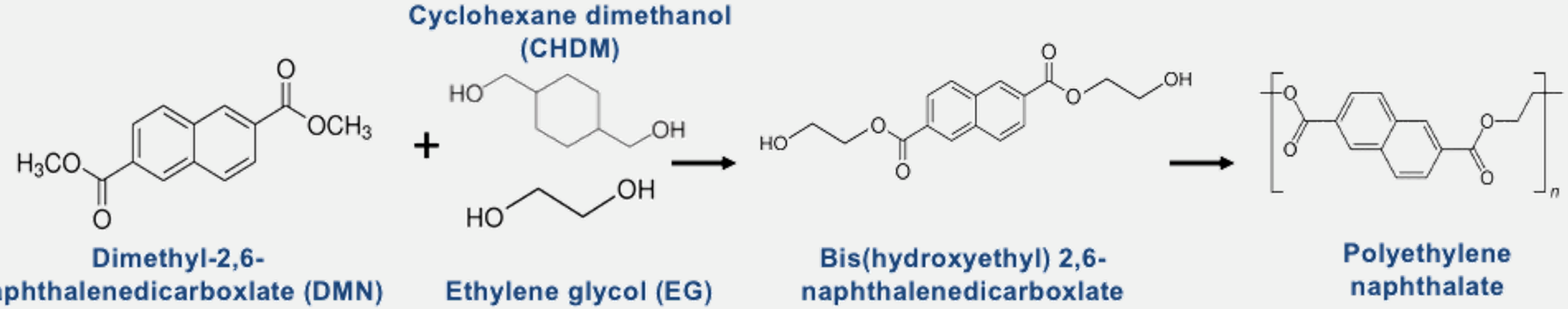
PEN Baseplate
Activity: 10^{-6} Bq

- **Reduced natural activity**
- Synthesized PEN:
  - Minimize additives
  - Purify ingredients
  - Optimize optical properties

Minimizing Background Radiation in PEN

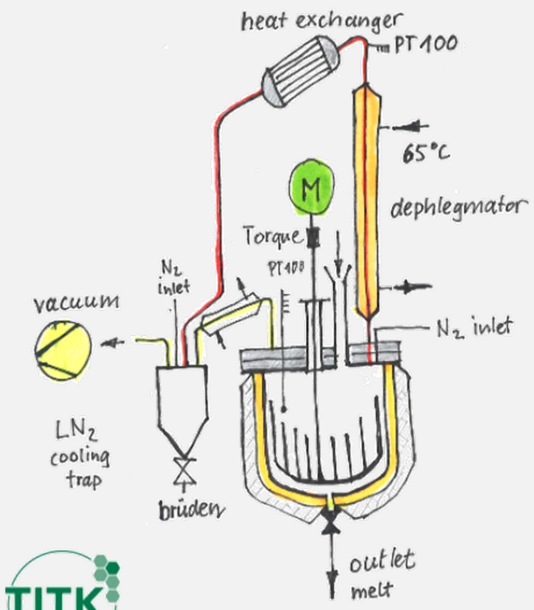
PEN Baseplate
Activity: 10^{-6} Bq

- **Reduced natural activity**
- Synthesized PEN:
  - Minimize additives
  - Purify ingredients
  - Optimize optical properties



PEN Synthesis at TITK

Polymer Reactor

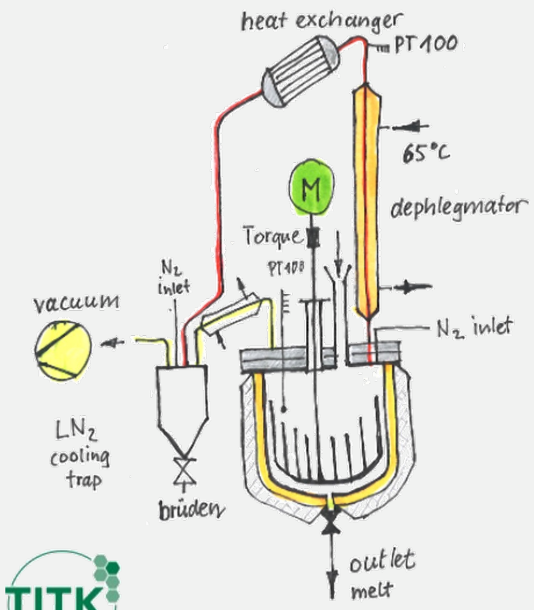


TITK DIVERSITY IN POLYMERS

Extrusion of PEN Material

PEN Synthesis at TITK

Polymer Reactor

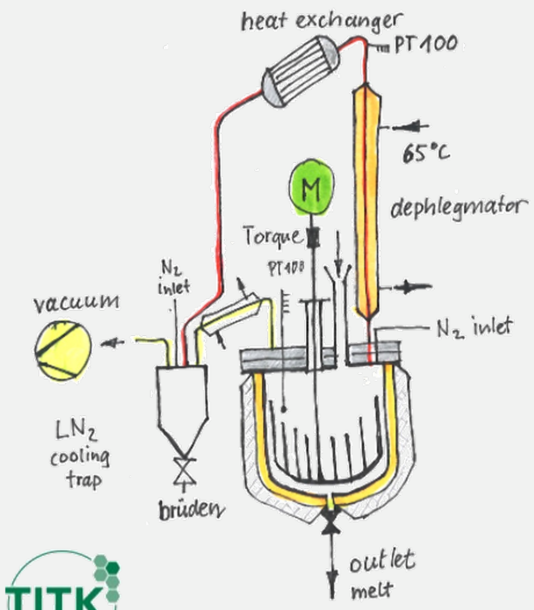


Extrusion of PEN Material

PEN pellets

PEN Synthesis at TITK

Polymer Reactor

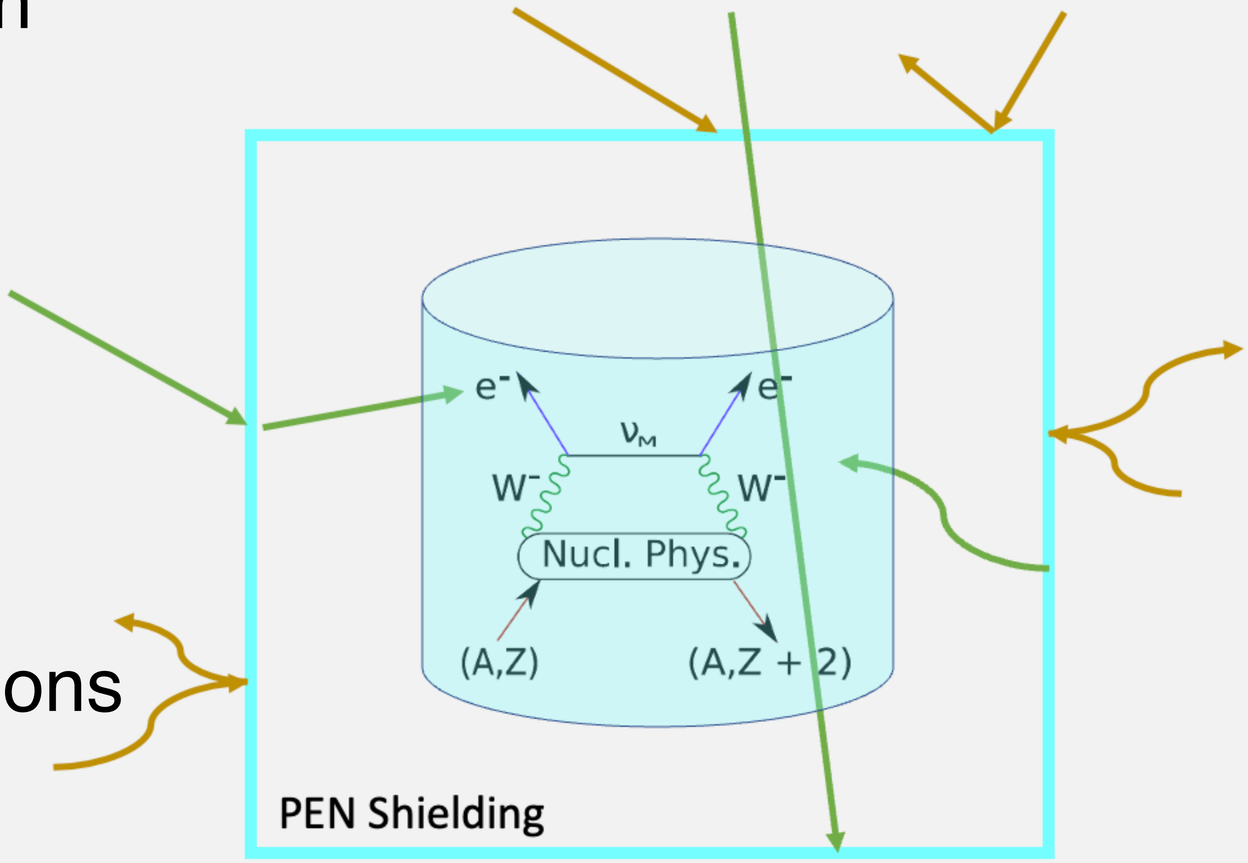


Extrusion of PEN Material

PEN pellets

Conclusions

- Background radiation mitigation
  - Shield
  - Detect
  - Minimize
- PEN as a scintillator
  - Active material
  - Low background
- Future work to extend applications
  - Synthesis

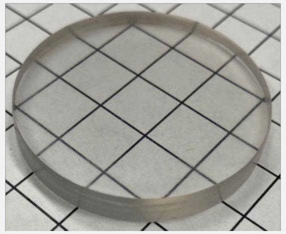


Backup

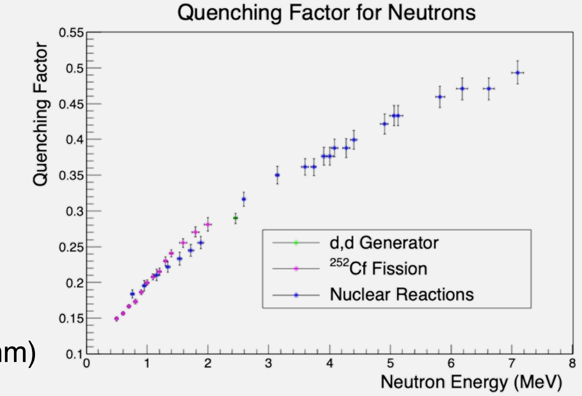
Measurement of PEN Quenching Factor

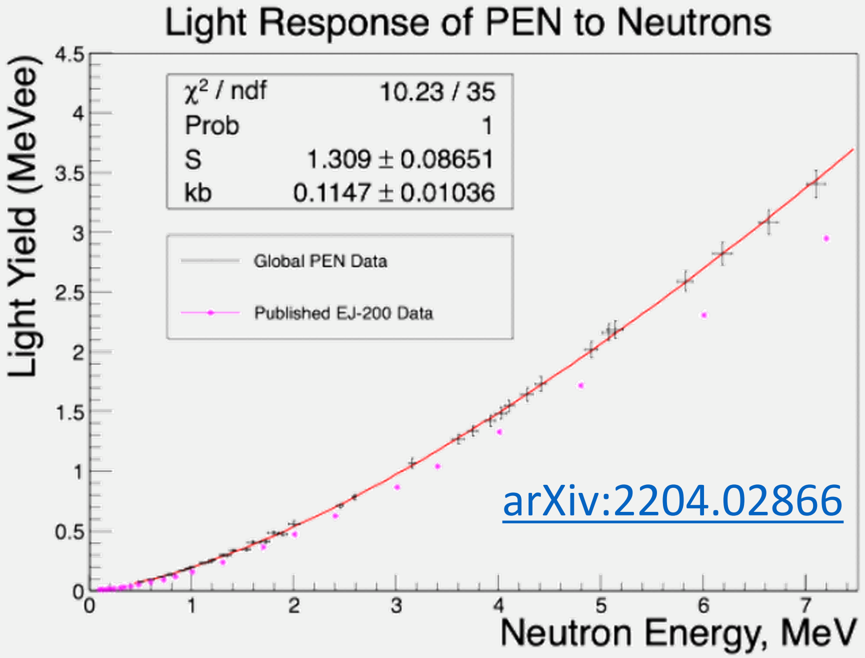
- Quenching factor (QF)
  - Fraction of light nuclear recoils (LY_n) produce relative to electronic recoils (LY_e)
- Measurement of neutron quenching factor
  - $E_n = 0.5 - 7.1$ MeV
- Birk's function
  - Qualitatively defines the non-linearity of light yield with energy for nuclear recoils
  - $\Delta L \propto \frac{\Delta E}{1+kB\frac{\Delta E}{\Delta x}}$
- Fit data to determine Birk's constant
  - $kB_{PEN} = 0.115 \pm 0.010$
  - $kB_{BC\text{-}408} = 0.155 \pm 0.005$ [4]

$$QF = {}^{LY_n}/_{LY_e}$$



PEN sample (50 mm x 5 mm)





arXiv:2204.02866

[4] https://doi.org/10.1016/j.nima.2020.164865

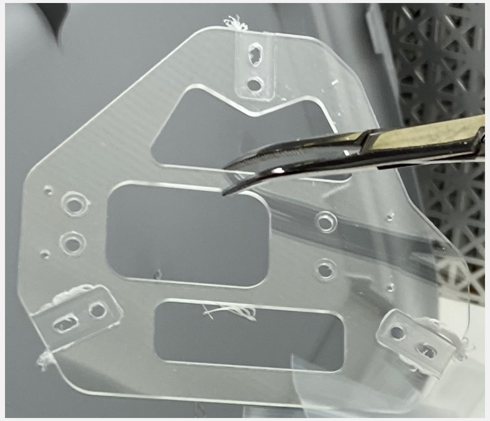
PEN Baseplate Production for LEGEND

- Low background molding method:
  - Pellets washed to remove surface impurities
  - Contact minimized during each step
    - Injection compression molding - electropolished flat plates for mold
    - Machine with acid-etched jig
  - PEN molded in a Class-1000 clean room
  - Baseplates machined in a laminar flow hood
- Final PEN baseplate material activity **< 10^{-3} Bq/kg**

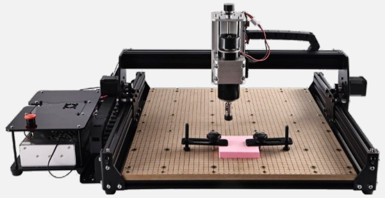
Commercial PEN pellets

Injection molding machine

PEN baseplate material



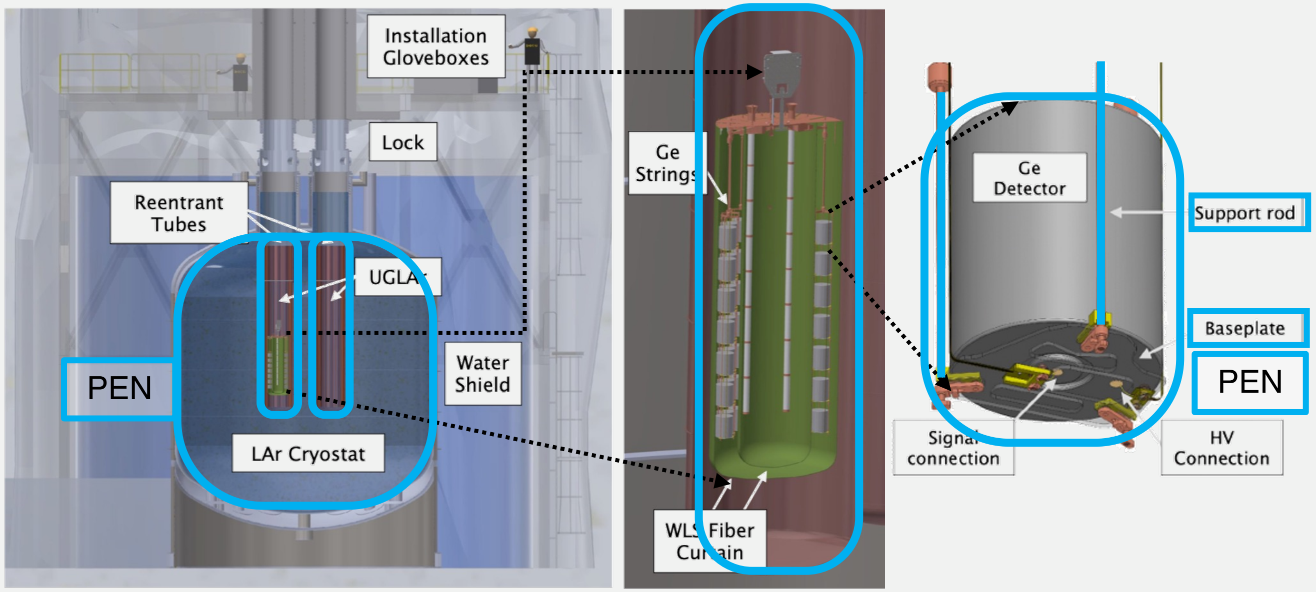
Final PEN baseplate for LEGEND-200



CNC machine

Future Prospects of PEN

- LEGEND-1000 will use PEN for
  - Detector baseplates
  - wls reflectors on LAr cryostat
- Potential expansion of applications in LEGEND-1000
  - Structural rods
  - Encapsulation
  - wls reflectors on UGLAr cryostat
- Radiopurity and optical quality of PEN will limit the applications
- PEN is being considered for other rare event physics experiments
  - DarkSide-20k



LEGEND-1000 detector geometry [1]

[1] https://arxiv.org/abs/2107.11462