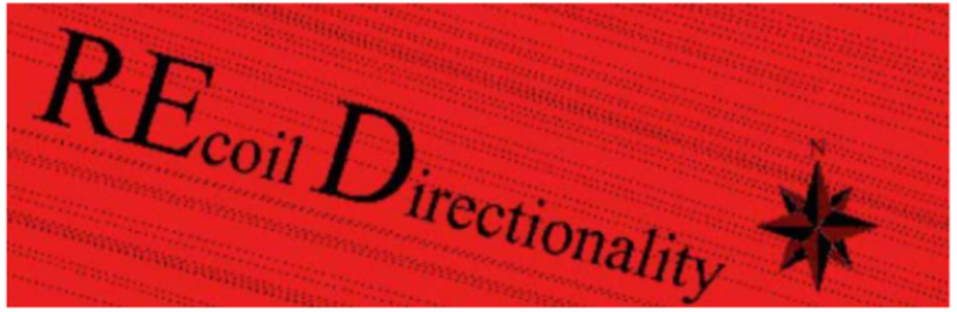


Directionality for nuclear recoils in a Liquid Argon Time Projection Chamber

Noemi Pino

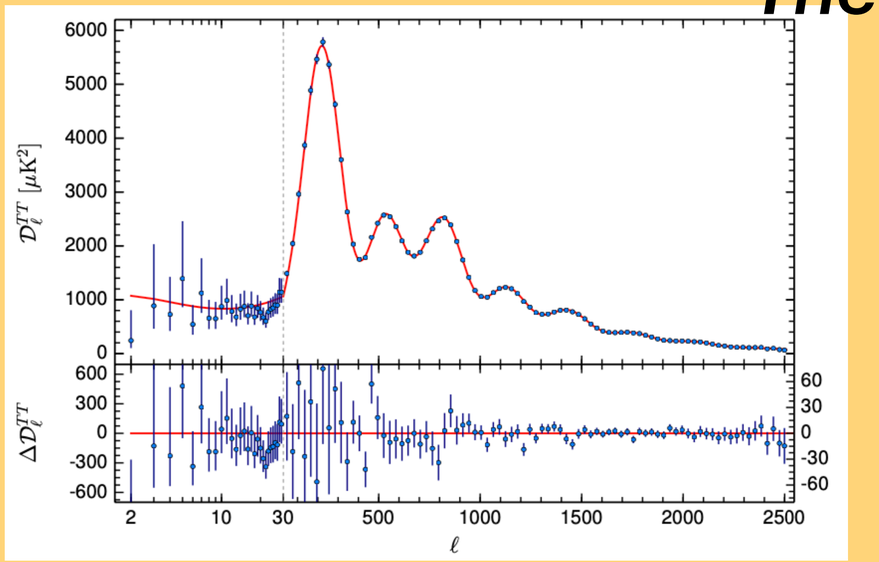
University and INFN of Catania

on the behalf of the ReD Working Group (Global Argon Dark Matter Collaboration)

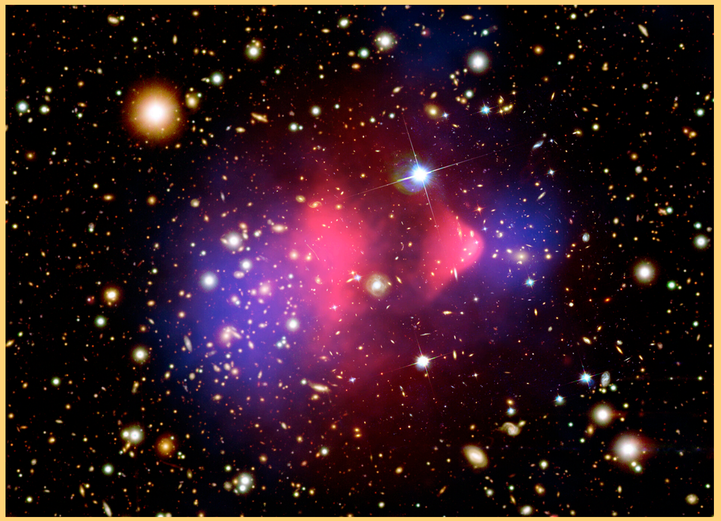
RICAP International Conference, Rome, 6th-9th September 2022

Dark Matter in a nutshell

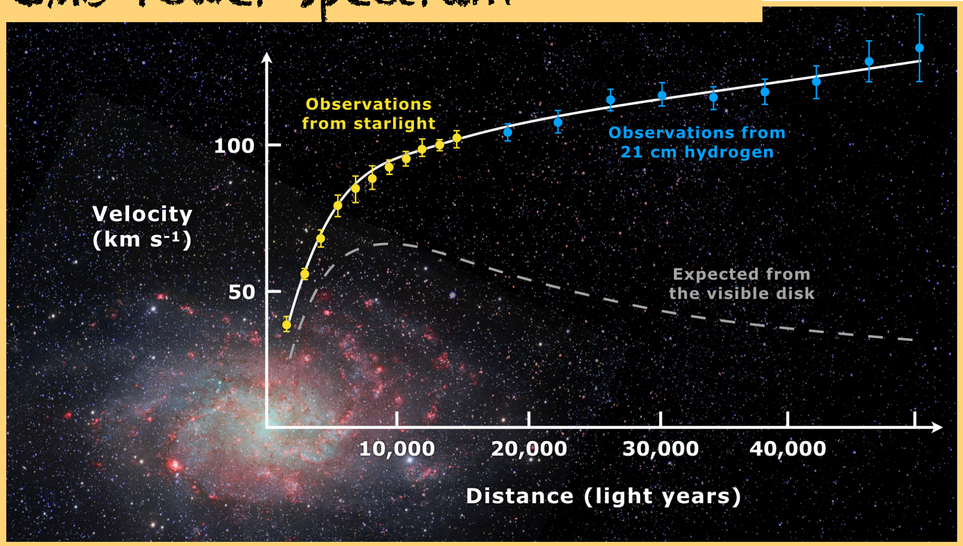
"The elephant in the Universe"



CMB Power Spectrum



Colliding Clusters (Bullet Cluster)



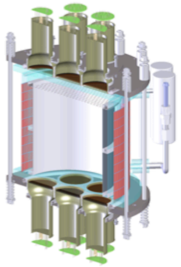
Rotation curves

Gravitational Lensing

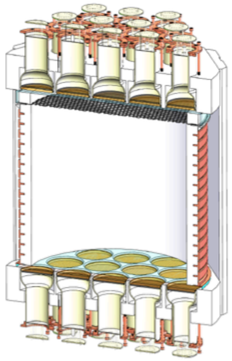
The Global Argon Dark Matter Collaboration program

The ***GADMC***

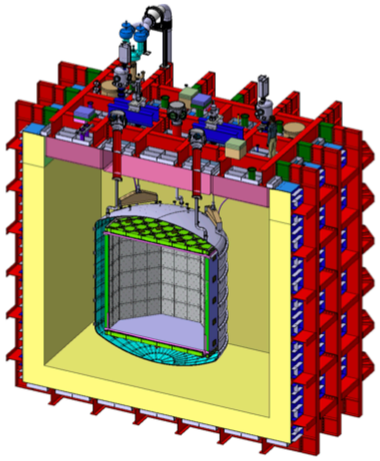
2012 | **2013 - 2018** | **2025 - 2035** | **2030s - ...**



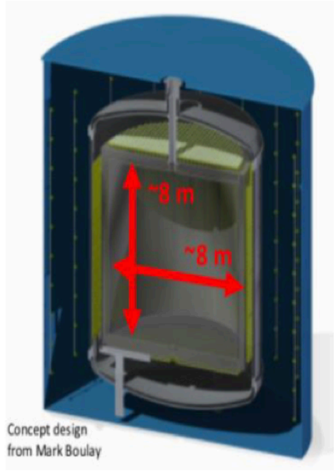
DarkSide-10



DarkSide-50



DarkSide-20k @LNGS

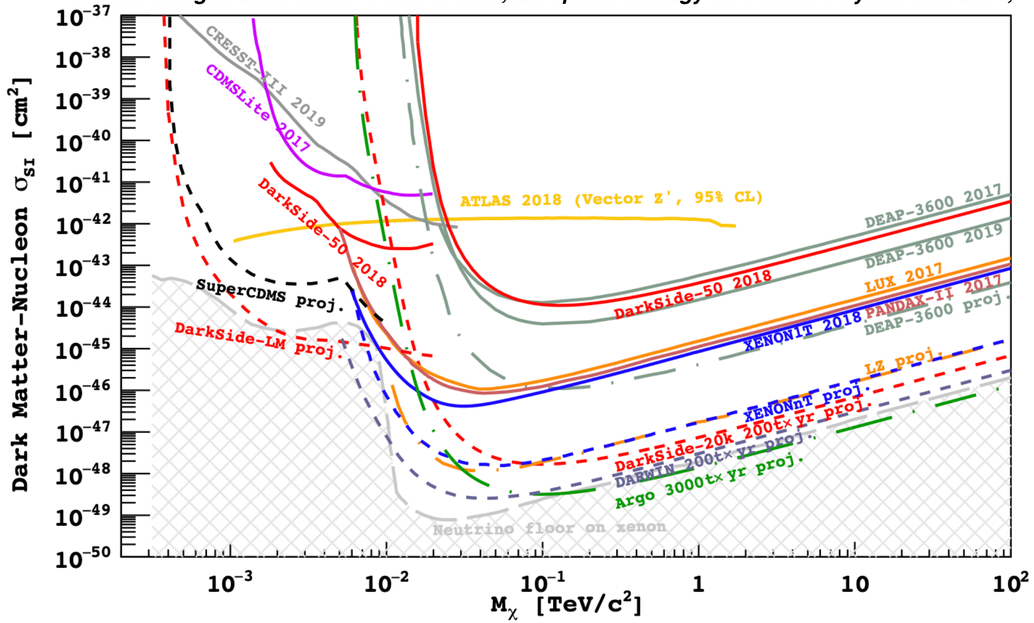


ARGO @SNOLAB

R&D phase → ***Readout technology*** and ***directional sensitivity***

REcoil Directionality

Global Argon Dark Matter Collaboration, European Strategy on Particle Physics Dec 2018;

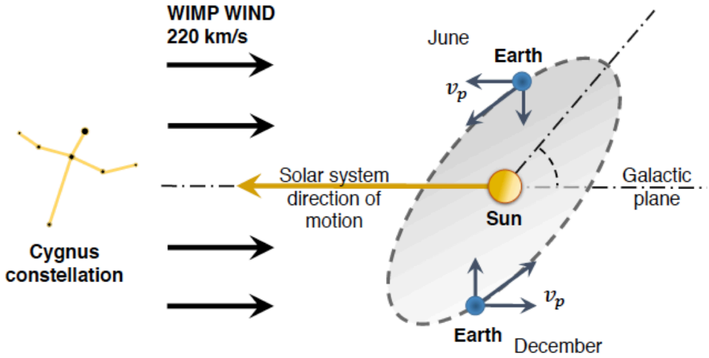


Directionality in Dark Matter searches

Unmistakable signature for WIMP Dark Matter

Apparent ***WIMP "wind"*** from the Cygnus Constellation

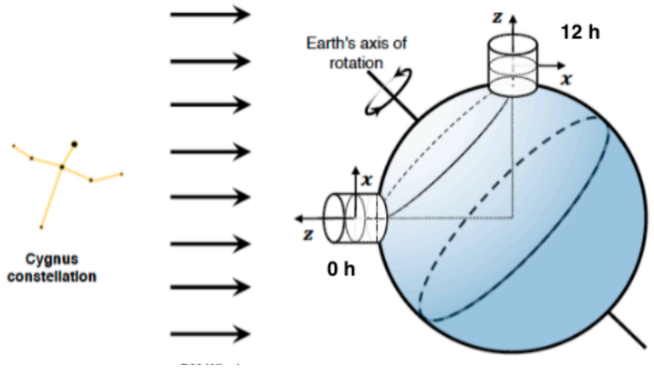
- motion of the Solar System in the Milky Way
- Earth's revolving motion → ***daily*** and ***seasonal modulations*** in the flux ***direction***

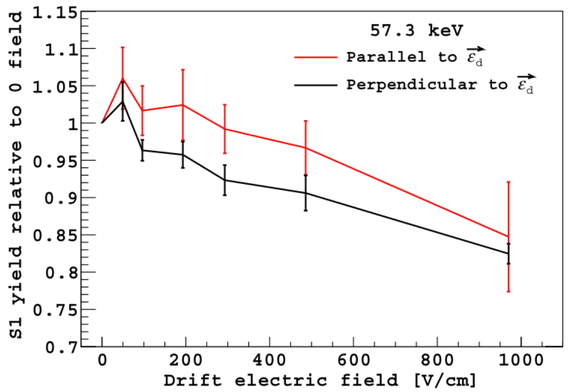


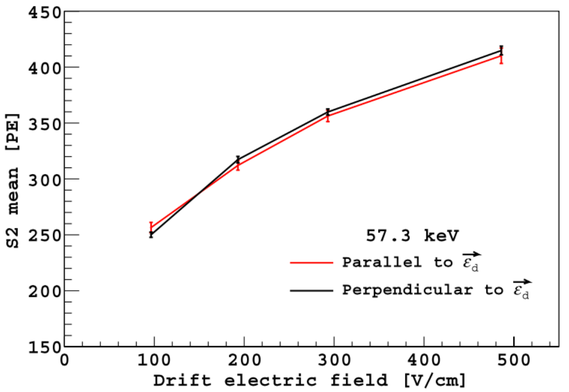
✦ Interest in ***angular distribution of Nuclear Recoils*** (NR) from WIMP elastic scattering

✦ ***It is hard for backgrounds to mimic this behavior***

✦ Directional information hinted by the SCENE experiment via the ***columnar recombination effect***





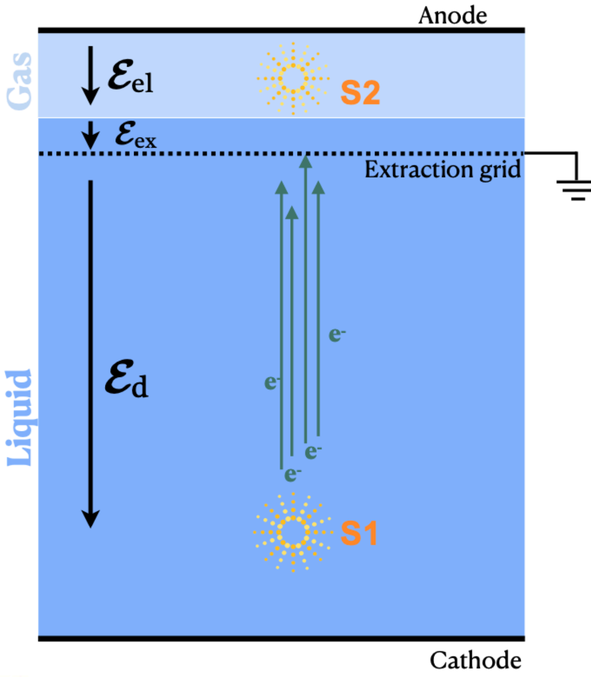


Cao H. et al. (The SCENE Collaboration)
Phys. Rev. D 91, 092007 (2015)

The Recoil Directionality (ReD) experiment

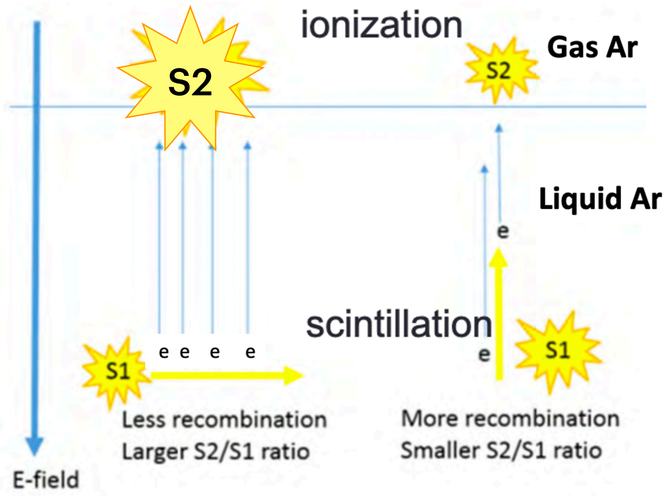
Directionality in a LAr Time Projection Chamber

- **Scintillation light** from the Ar dimers (Ar_2^*) or to the electron-ion recombination → **S1**
- Electrons from **ionization** can *escape recombination* (ε_d) and
  - Extracted in the gaseous phase (ε_{ex})
  - Light by electroluminescence (ε_{el}) → **S2**



NRs with ***tracks parallel*** to ε_d → ***enhanced S1*** and ***reduced S2***

A NR's kinetic energy of ***~70 keV*** falls in the ROI of WIMP search and has an anisotropic charge cloud (range > *Onsager radius*)



Experimental layout @LNS

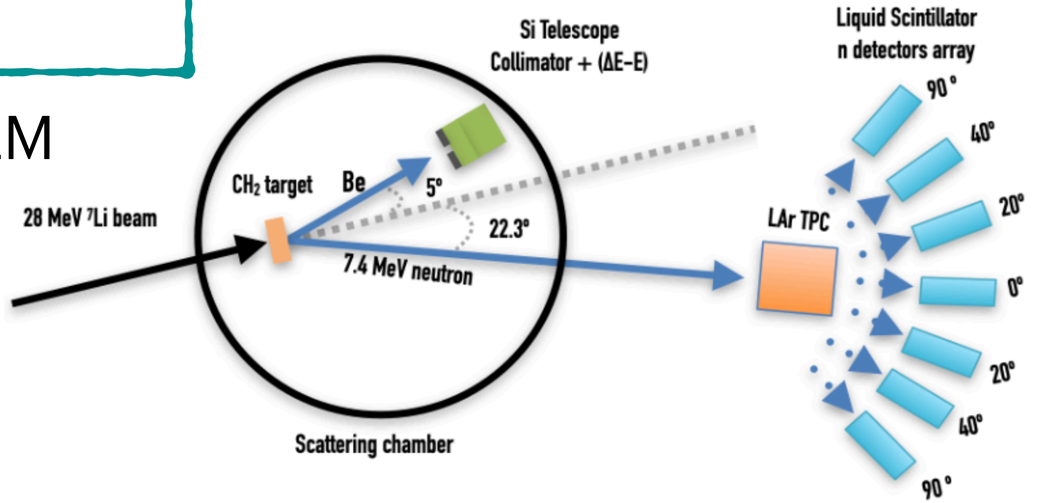
Our recipe for directional investigation

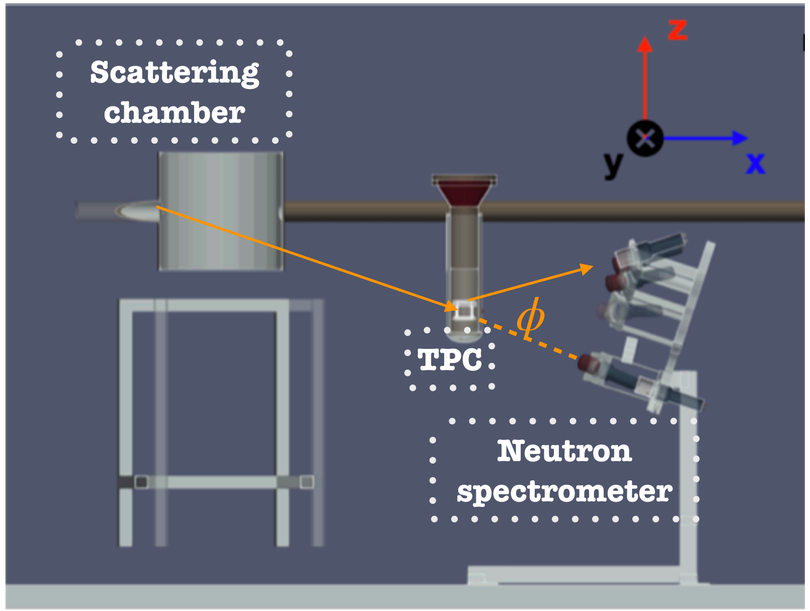
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud

Irradiate a miniaturized LAr TPC with mono-energetic neutrons to produce NRs with momenta at different angles wrt ε_d

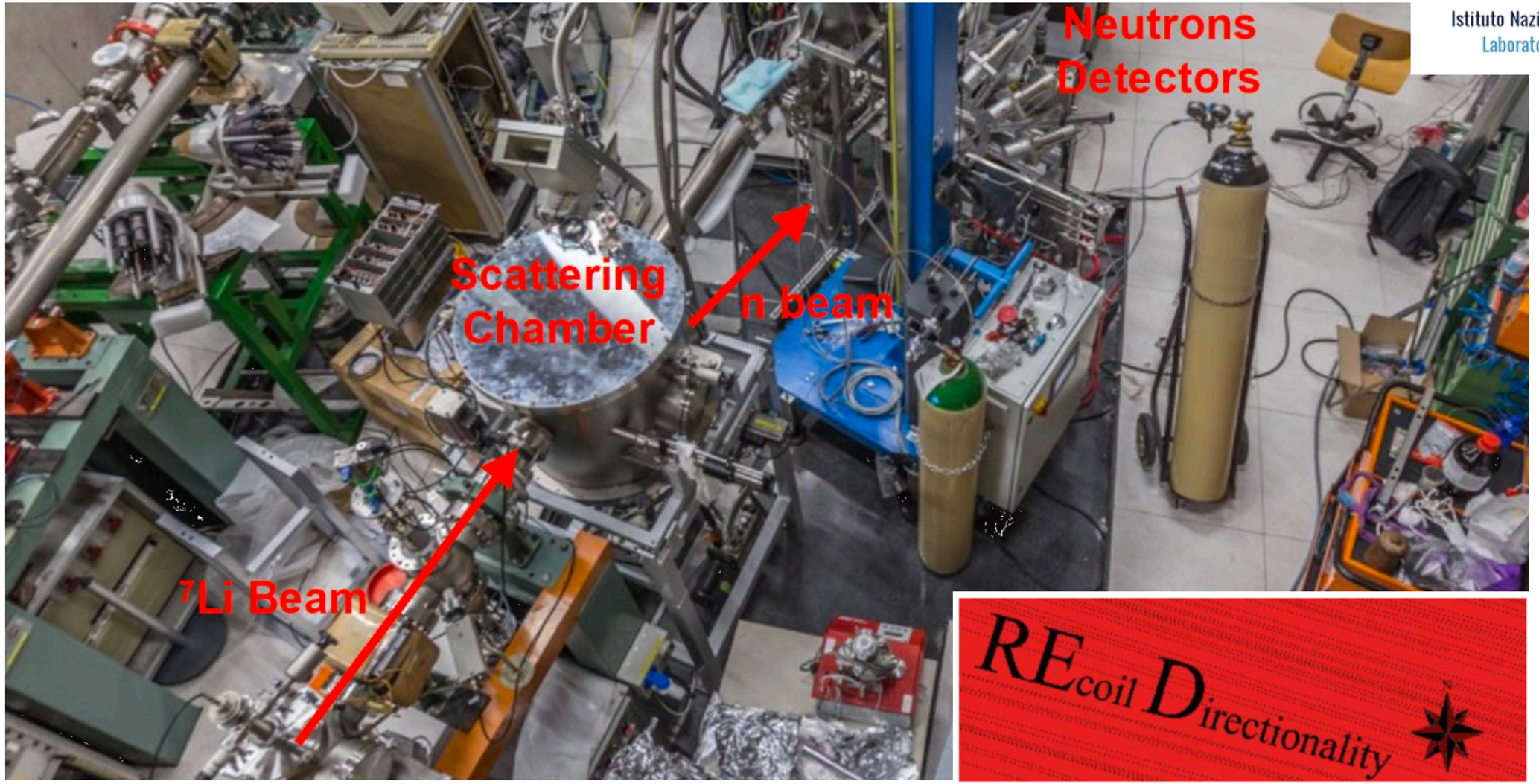
- Neutrons via the ***p(⁷Li,⁷Be)n*** reaction at the TANDEM accelerator. Beam: ^{7}Li (28 MeV)
- ***(n,n')*** with an Ar nucleus → Nuclear Recoil
  - Two-body kinematics constrain
- n' detected by an array of Liquid Scintillators (LScis)
- Every LSci detector determine the ***energy*** and ***direction*** of the recoiling Ar

→ NRs with the **same E_{recoil}** but **different azimuthal angle ϕ** (z-axis)





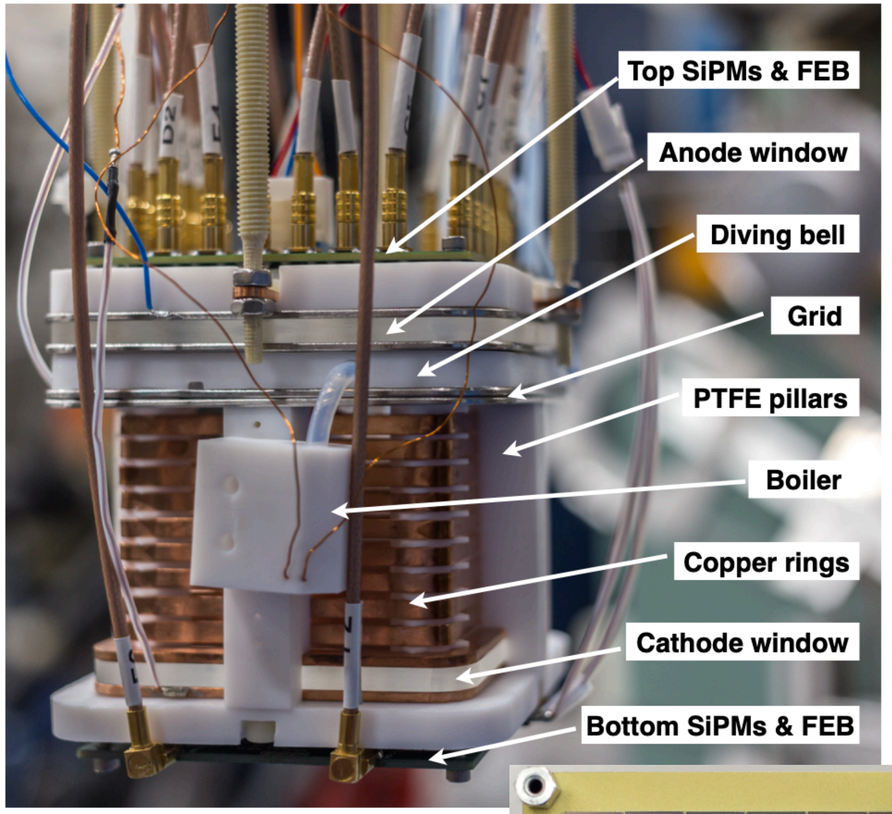
Experimental layout @LNS

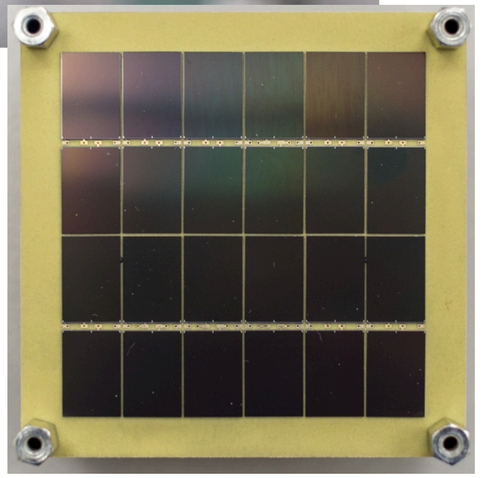


REcoil Directionality

The TPC

- Active volume of **5 (l) x 5 (w) x 6 (h)** cm^3
  - 7 mm gas pocket
- ***Cryogenic SiPM***: two 5x5 cm^2 tiles with 24 devices
  - ✓ *Tested for the **first time** on a LAr TPC for a 5-month-continuous period*
- 3D event reconstruction
  - ***x-y position*** from S2 signal on the top tile
  - ***z*** from ***drift time*** (up to ~60 μs)
- Ratio fast/total for Pulse Shape Discrimination (***PSD***) on S1 for ER/NR discrimination
- Technical description → ***P. Agnes et al., Eur. Phys. J. C 81, 1014 (2021)***

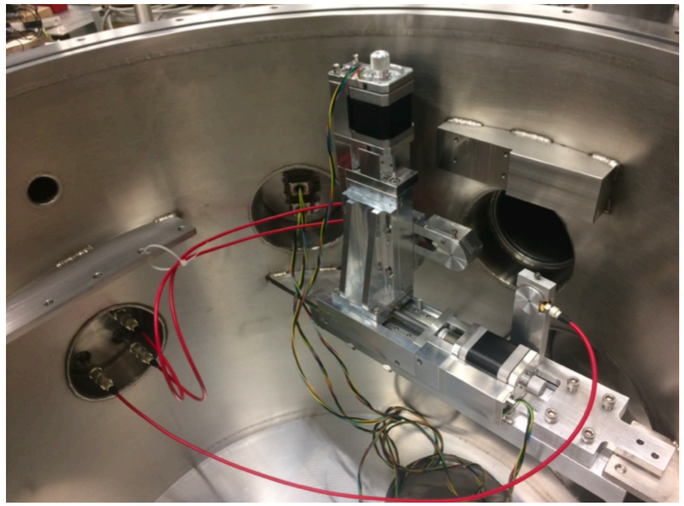




The tagger detectors

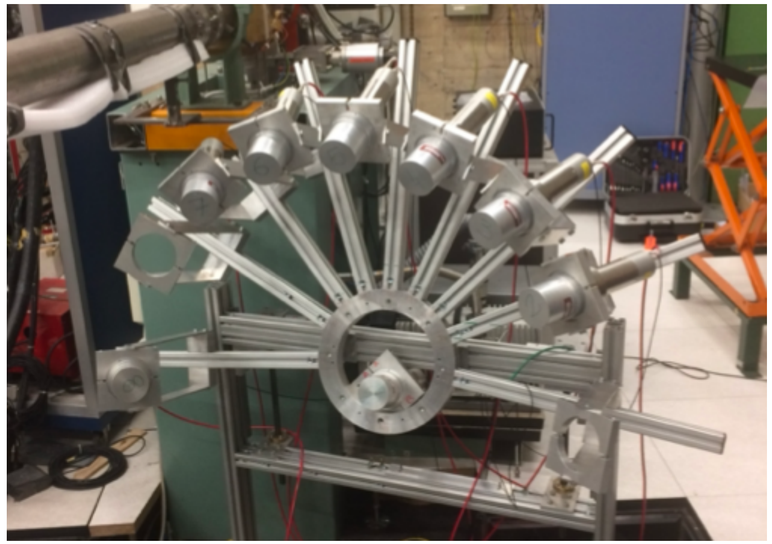
Si Telescope

- Measure the energy of the charged particle with ΔE/E telescope technique (20 μm & 1000 μm thickness)
- Tag ^{7}Be associated to ~ 7 MeV neutrons
  - Z separation (Li vs Be)



Neutron spectrometer

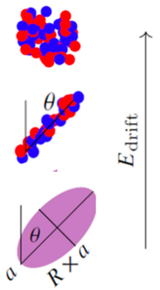
- "Wheel" structure holding 7 Liquid Scintillators cells (3-inch EJ-309) coupled with PMTs
- Allow PSD for n/γ discrimination
- Tag ^{40}Ar recoils in the TPC at different angles wrt ε_d : 0°, ± 20°, ± 40°, ±90°

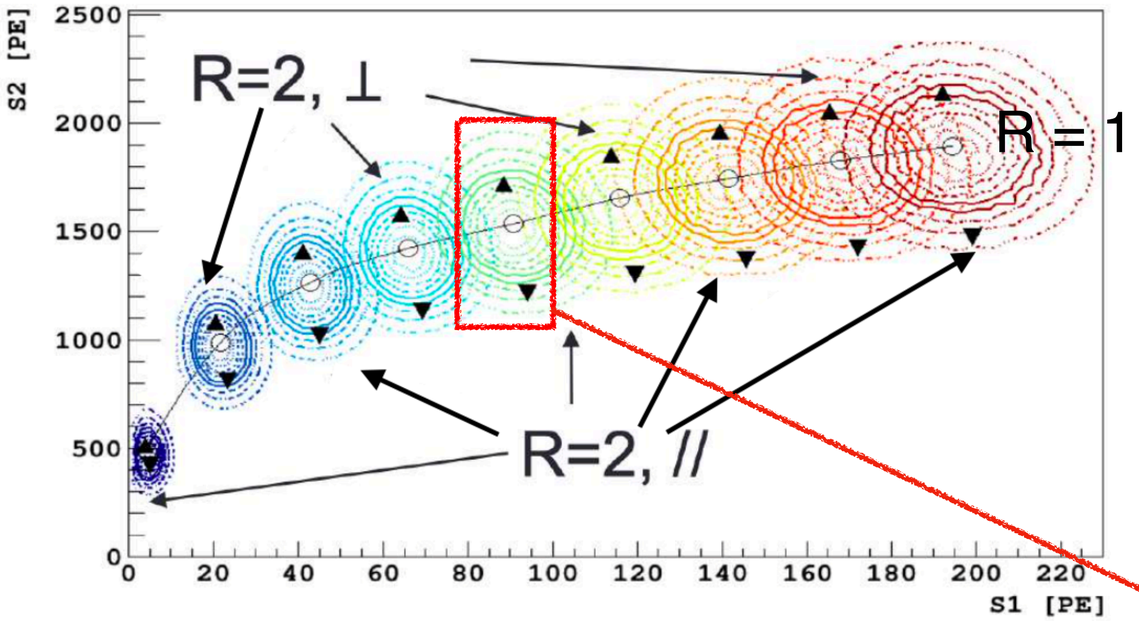


A novel model for directionality

The breakthrough of the elongated ellipsoid

Model	Directional dependence
Thomas-Imel, Box ("short track") Phys. Rev. A 36 (1987) 614	None
Jaffé-Birks ("infinitely long track") Ann Phys 347 (1913) 303	$[\sin\phi]^{-1}$
Cataudella et al. **JINST 12 (2017) P12002**	$\left[\sqrt{sin^2\,\phi + cos^2\,\phi\,/R^2}\right]^{-1}$





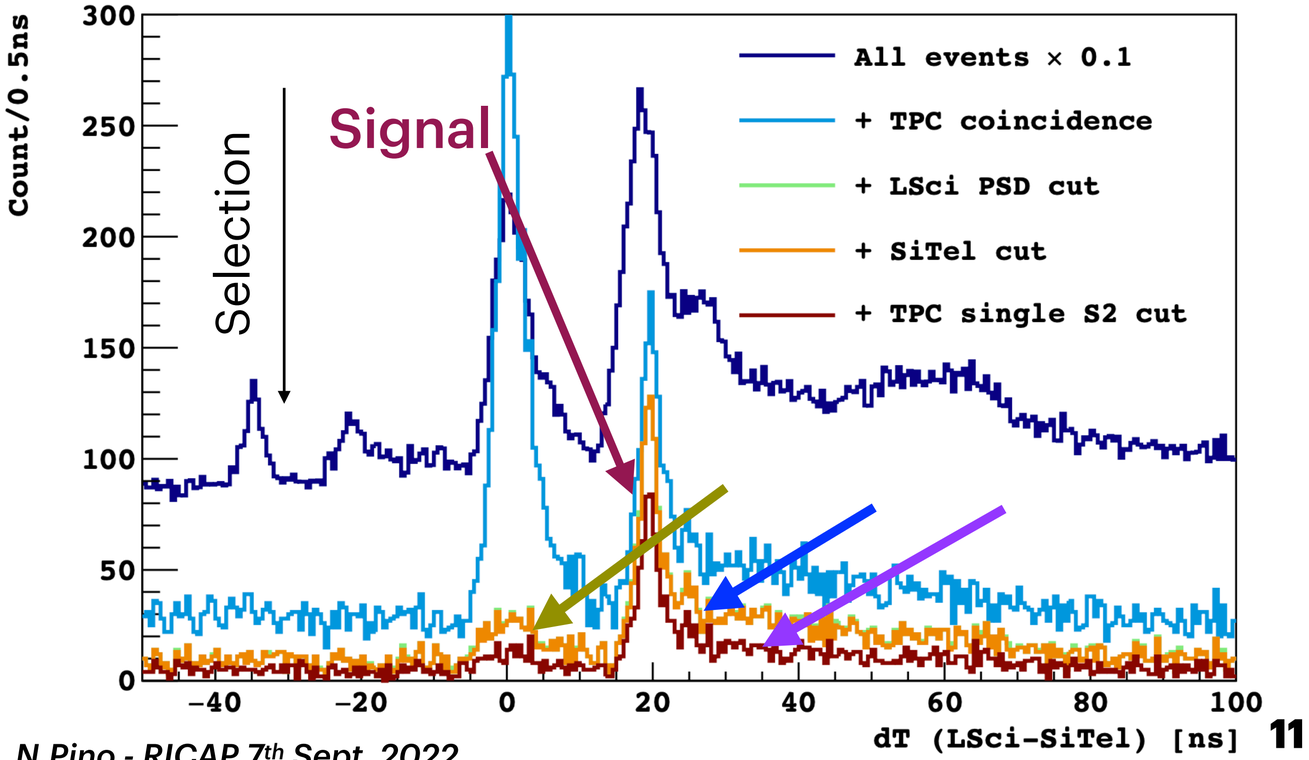
- Innovative model by **V. Cataudella et al., 2017 JINST 12 P12002**
- Relevant parameter ***R***, the ***non-sphericity*** of the initial electron cloud
  - If **R > 1** → net directional effect
  - If **R = 1** → no directional dependence (spherical symmetry, *Thomas-Imel*)
- ***Contours***: detector response from NRs (*simulated data*)
- Impact on detector response → change **S1-S2** balance

A directional effect would cause the ***shift of the centroid*** of the contours

Signals and Backgrounds

- The TPC was irradiated for 14 days in February 2020
- The events are the ***three-fold coincidences***: (1) Si-Tel → (2) TPC → (3) Neutron Spectrometer
- Further **cuts** and **cleaning**: *^{7}Be tagging, timing (**T**ime **o**f **F**light), PSD*

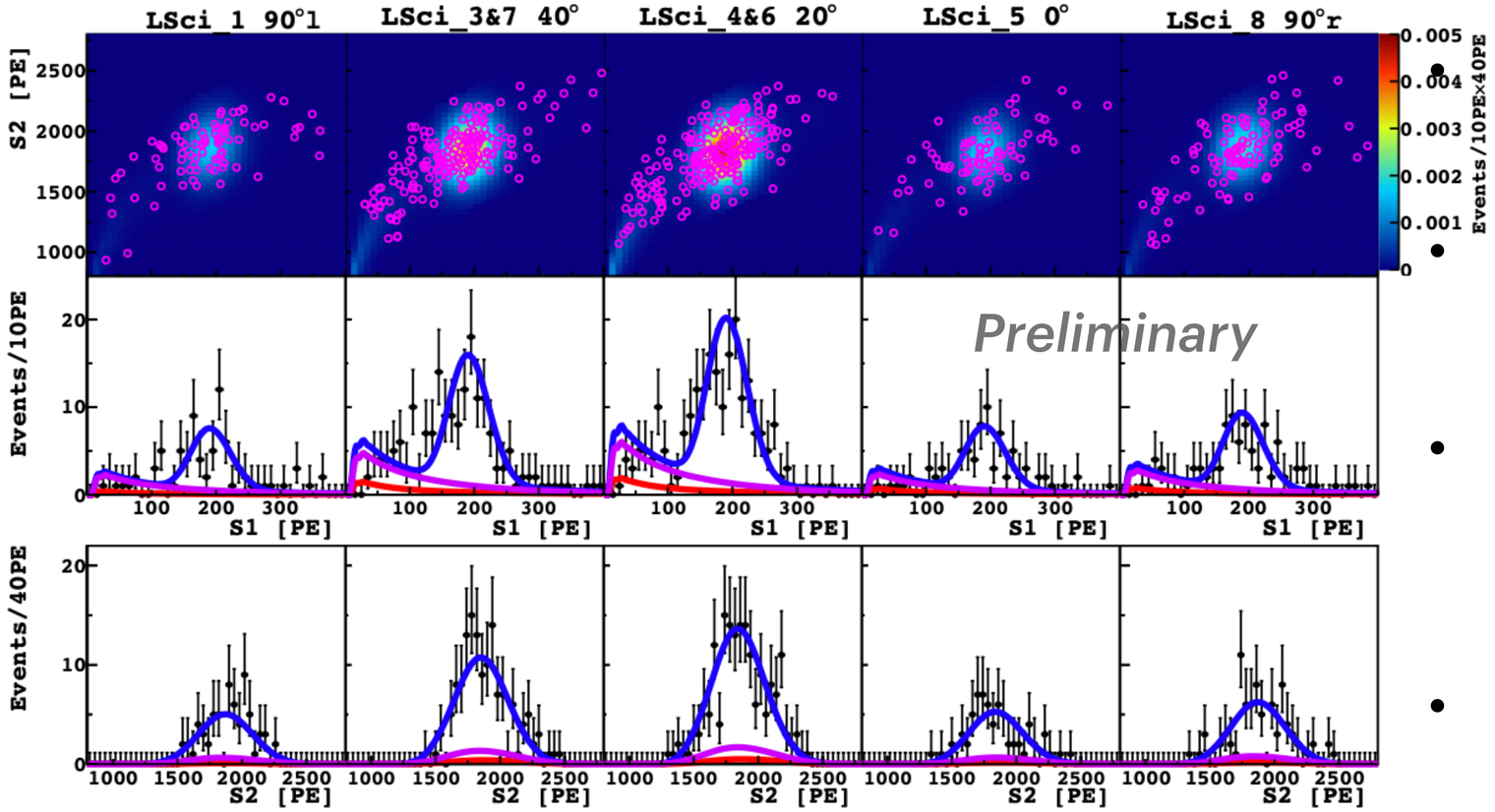
→ ~ 7000 events with proper energy (**70 keV$_{nr}$**) and timing , about 150 events/day



Residual **Backgrounds**:

- Accidentals
- **(n, n' γ)** events in the TPC
- Neutrons from **p(^{7}Li,^{7}Be*)n**
  - **63.5 keV** recoils in the TPC
- Neutrons with **multi-scattering**

Analysis and Results



- Statistical analysis consists in an ***unbinned maximum likelihood fit***
- **Three-fold coincidence** events + **Nuclear Recoil** (SiTel ∧ TPC) sample
- Components: **signal+background**, **multi scattering**, **accidental coincidences**
- PDF from Geant4 simulations and/or data-driven

→ ***R = 1.036 ± 0.024 ⇒ No effect***

(Preliminary)

- NR quenching in Ar → Lindhard + Mei models [***Phys Rev D. 91.092007***]
- Fitting region limited to 100-350 PE → ~ 30 - 100 keV_{nr}

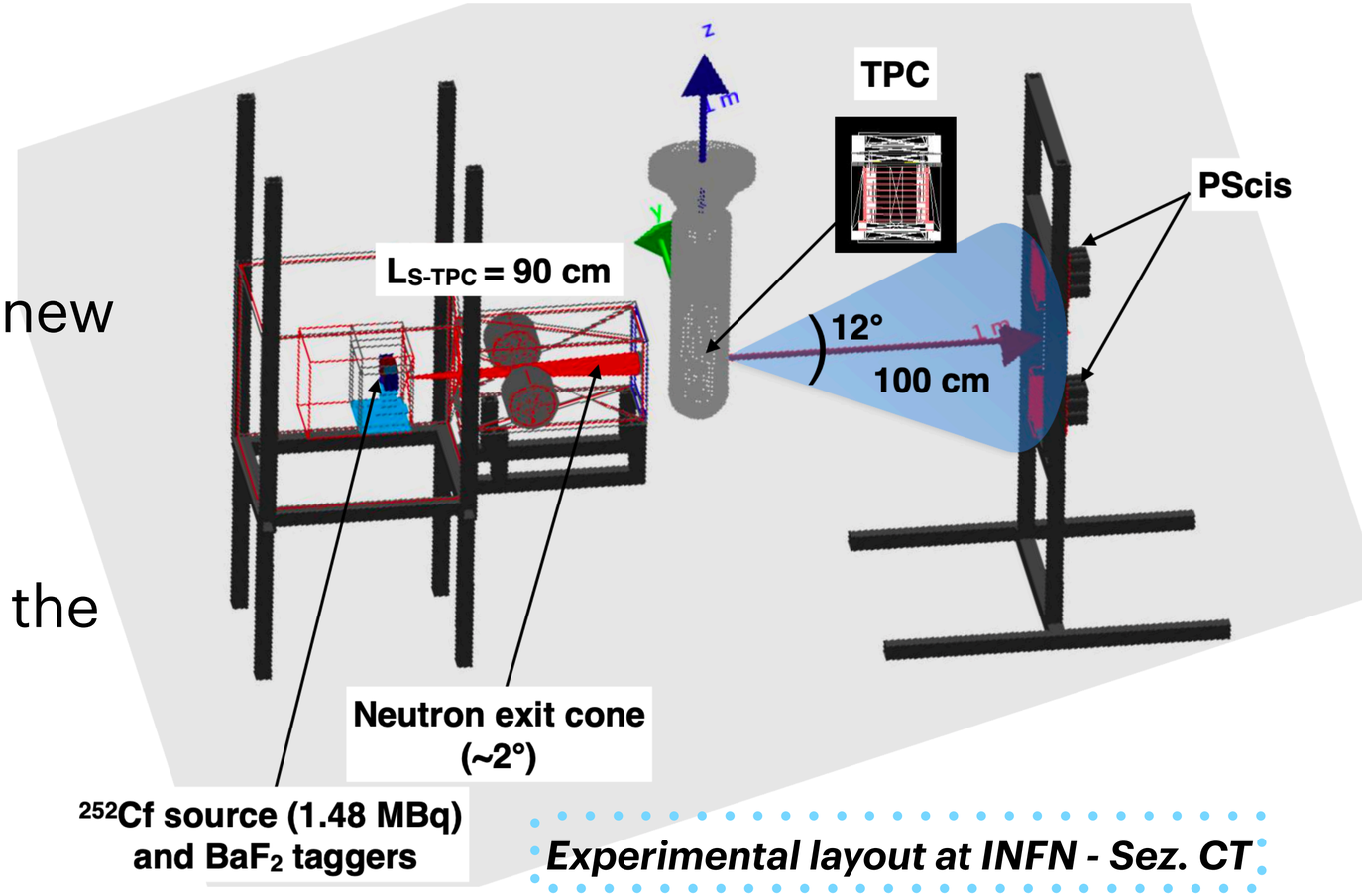
Low-energy perspective

ReD future steps

Use of an intense ^{252}**Cf neutron source** (1.48 MBq activity) **@*INFN-CT*** to study NR low energy response at **few keV**

Idea: Tag the fission events with BaF_2 detectors and the ToF in the “far” array of new Plastic Scintillators (PSci)

✓ First commissioning and calibration of the sub-systems

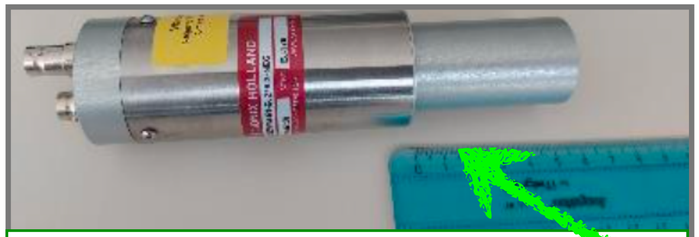


Experimental layout at INFN - Sez. CT

Experimental layout @INFN-CT

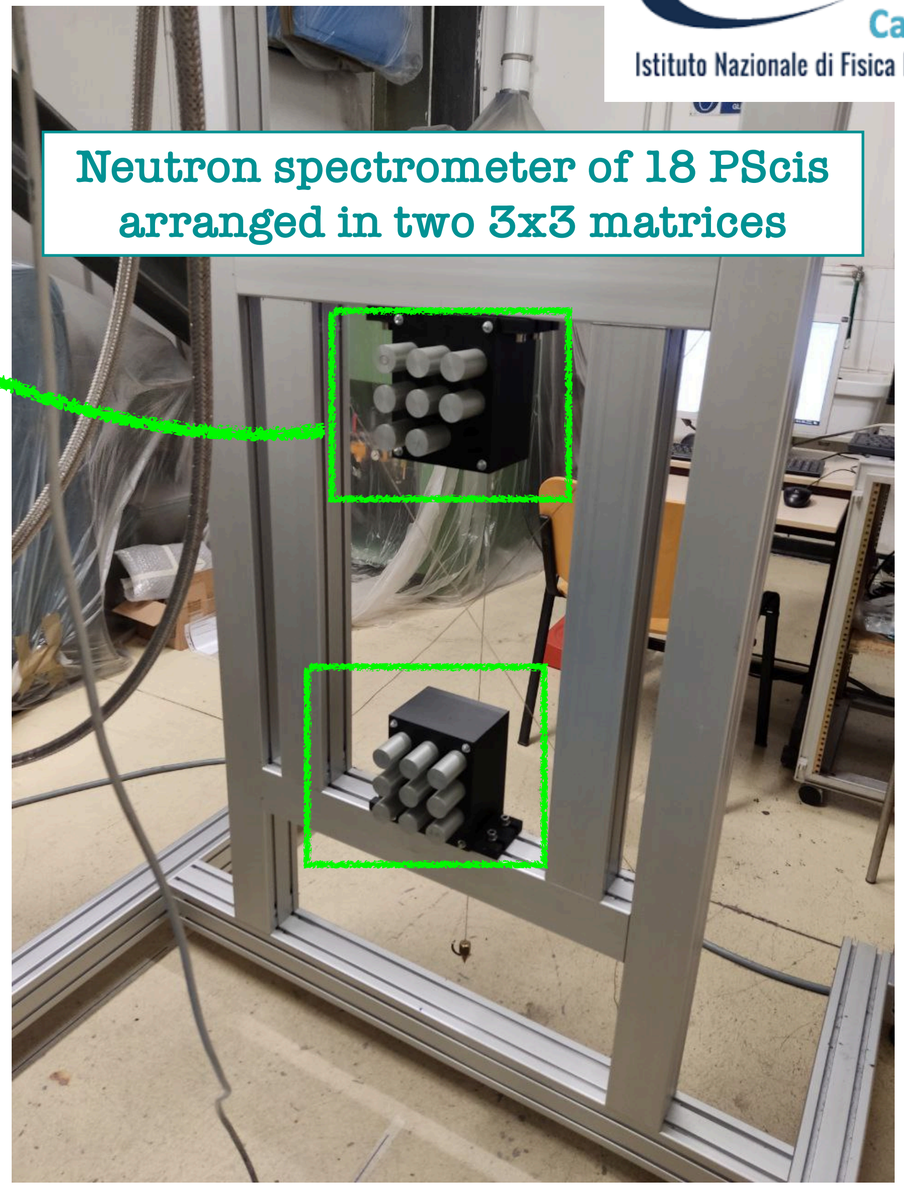
New setup elements

Shield and n collimator



1-inch EJ-276 + PMT

Neutron spectrometer of 18 PScis arranged in two 3x3 matrices



BaF_2 taggers and holding structure for the source

Conclusions

The ReD experiment aims to be a ***test bench*** for the DarkSide-20k new technology and a ***physics test*** for:

Directionality response of a LAr TPC

- Neutrons from ***p(⁷Li,⁷Be)n*** reaction
  → **7.4 MeV**
- Two-week run in Feb. 2020
- E_{recoil} **72 keV** (Ar)
- Data analysis according ***Cataudella et al. directional model***, evaluating the parameter **R** (aspect ratio of the charge cloud)
- No directional effect (preliminary result):

R = 1.036 ± 0.024

Low energy characterization

- Neutrons **O(2 MeV)** from spontaneous fission of ^{252}Cf
- E_{recoil} < **10 keV** (Ar)
- Preliminary test and commissioning of the new elements of the experimental setup

THANK YOU for your ATTENTION

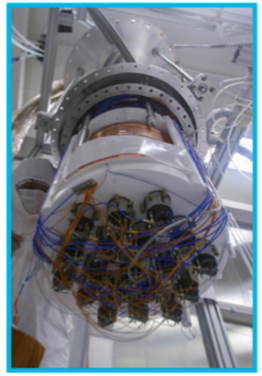
Contacts:
noemi.pino@ct.infn.it

Backup

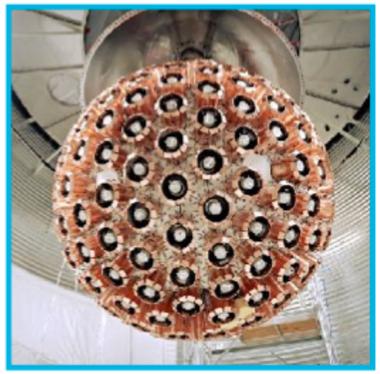
The Global Argon Dark Matter Collaboration

A multi-staged program of argon-based detectors

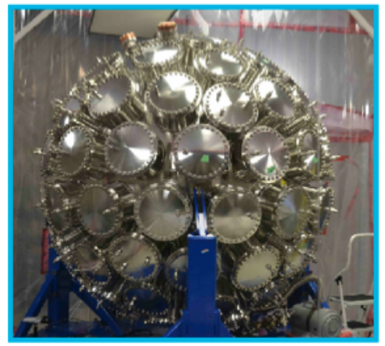
- The **Global Argon Dark Matter Collaboration (GADMC)**
  - ✦ improve the sensitivity to WIMPs by several orders of magnitude wrt the current generation of experiments
- ~500 collaborators from ~100 institutions
- Four argon experiments: DarkSide-50 @LNGS, DEAP 3600 @SNOLAB, MiniClean @SNOLAB and ArDM @LSC
- *Future goal*: **ARGO @SNOLAB**, a 300-tons fiducial mass detector filled with underground argon to ***reach the neutrino floor***



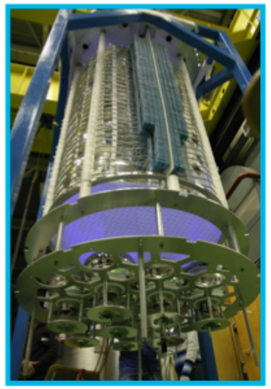
DarkSide-50



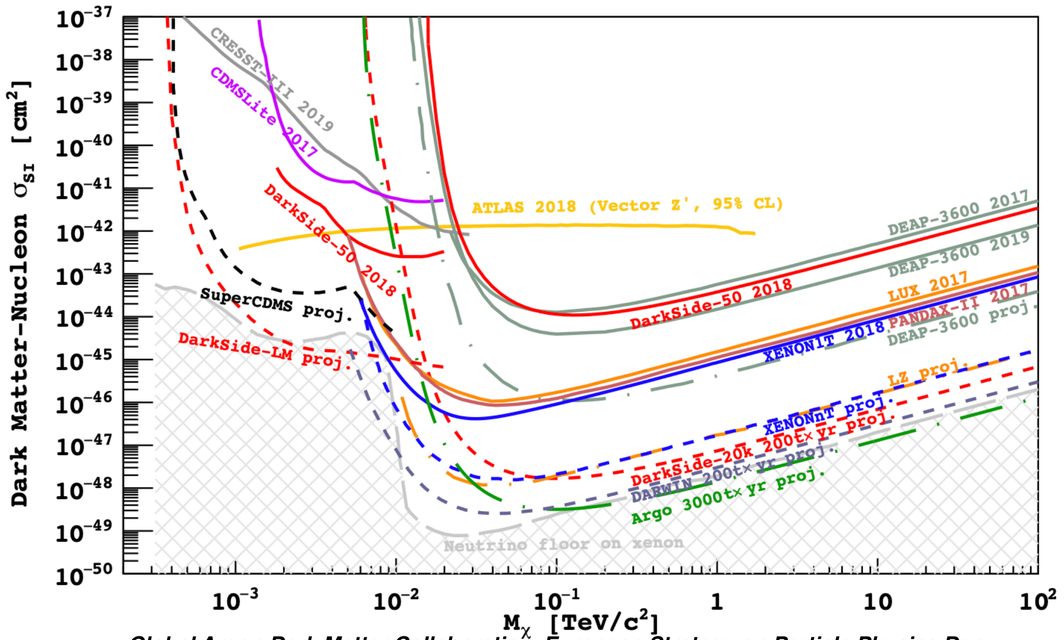
DEAP-3600



MiniCLEAN



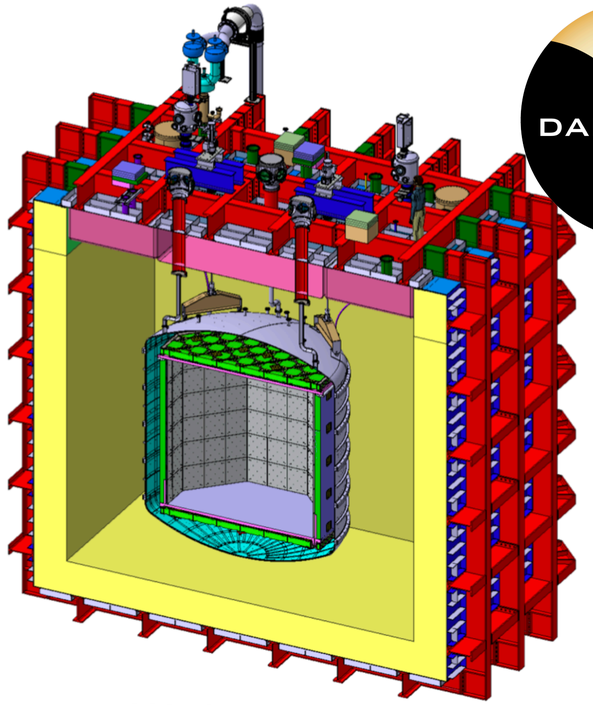
ArDM



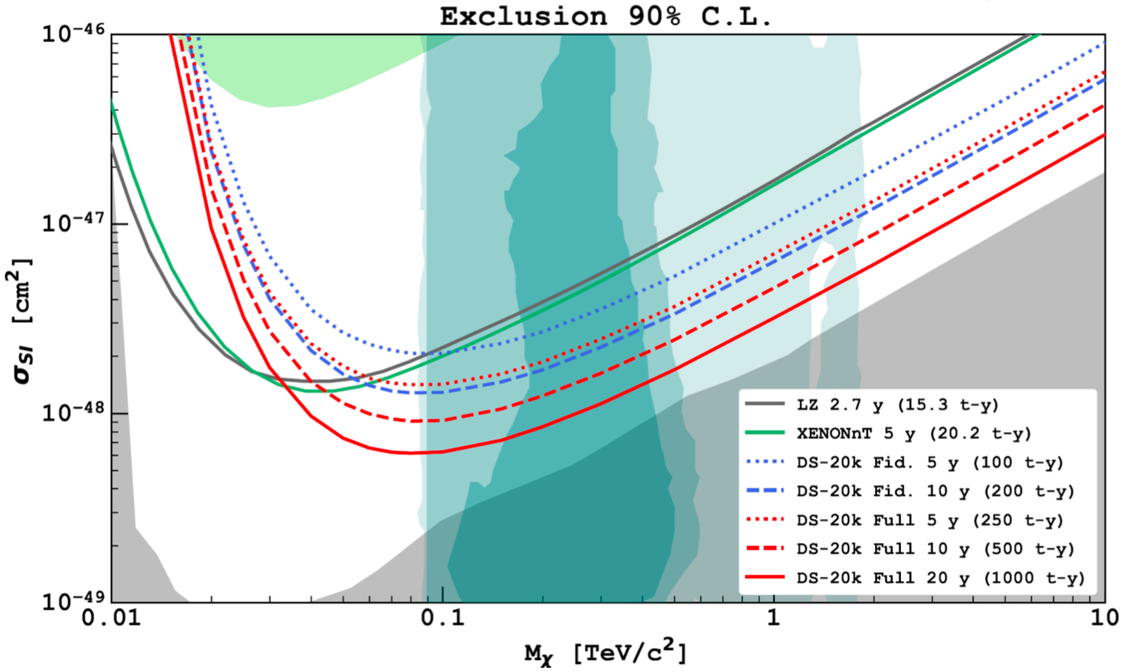
Global Argon Dark Matter Collaboration, European Strategy on Particle Physics Dec 2018;

DarkSide -20k

The near-future GADMC's goal



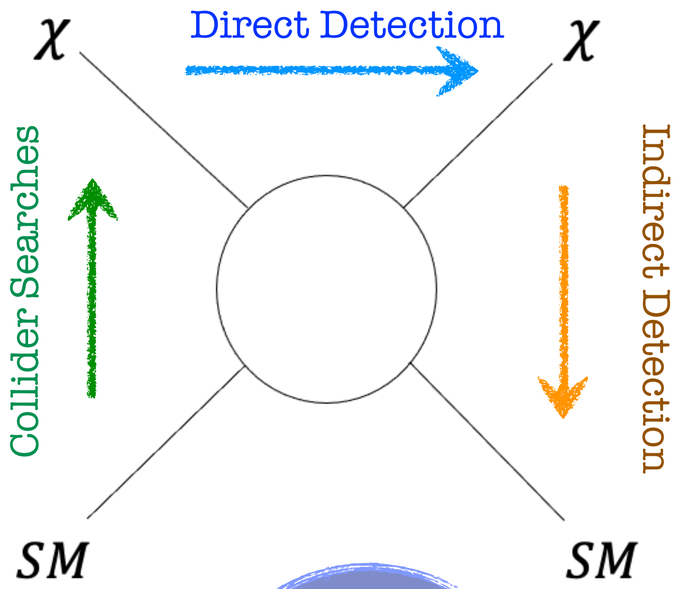
- DarkSide-20k @ the Gran Sasso Laboratory (LNGS) of INFN
  - 50 tonne **UAr** dual-phase TPC with **SiPM readouts**
- Approach the *"neutrino floor"*
- **Very low background levels** and **active suppression** for the background-free operation from both neutrons and $\beta/\gamma's$
- Present projection (10 yr run → fiducial volume 200 t-yr @ 1 TeV/c² WIMP):
  - ➡ 6.3 x 10^{-48} cm² (90% C.L.)
  - ➡ 2.1 x 10^{-47} cm² (5 σ discovery)

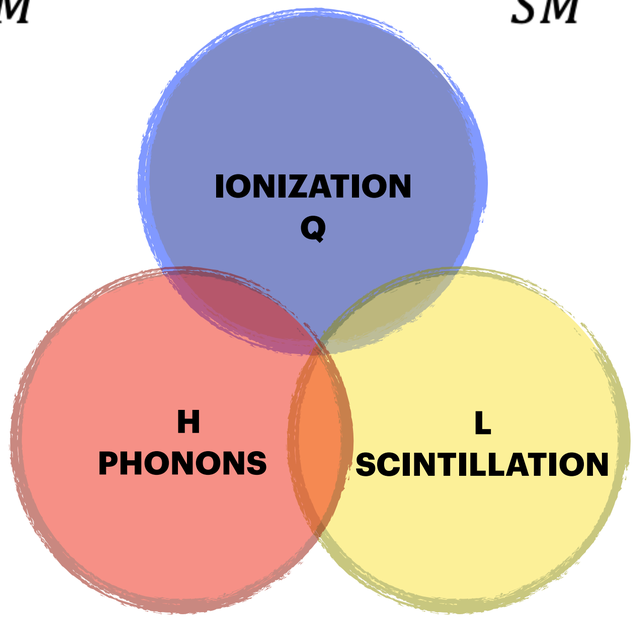


Turquoise filled contour is from pMSSM11 model (E. Bagnaschi et al., Eur. Phys. J. C 78, 87 (2018).

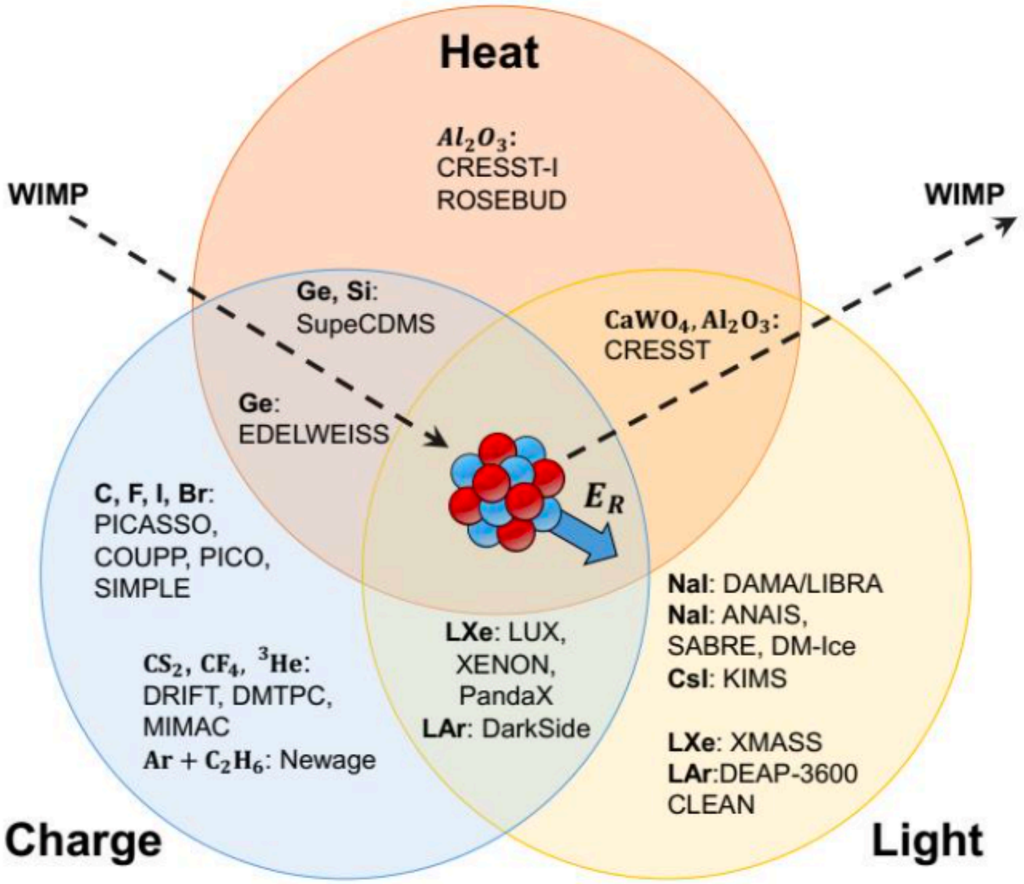
WIMP Direct Detection

- The most promising candidate for Dark Matter (DM) are the so-called **Weakly Interacting Massive Particles (WIMPs)** that can ***scatter elastically*** off a detector nuclei
- DM Direct Detection experiment looks for the signature of this ***low recoil energy (~ keV)*** of the nucleus due to the possible impact of a WIMP
- The ***low recoil energy*** makes it necessary a ***low background-controlled environment*** for the detector
- The energy lost by the recoiling nucleus is detected as
  - ❖ Ionization charge
  - ❖ Heat
  - ❖ Scintillation light



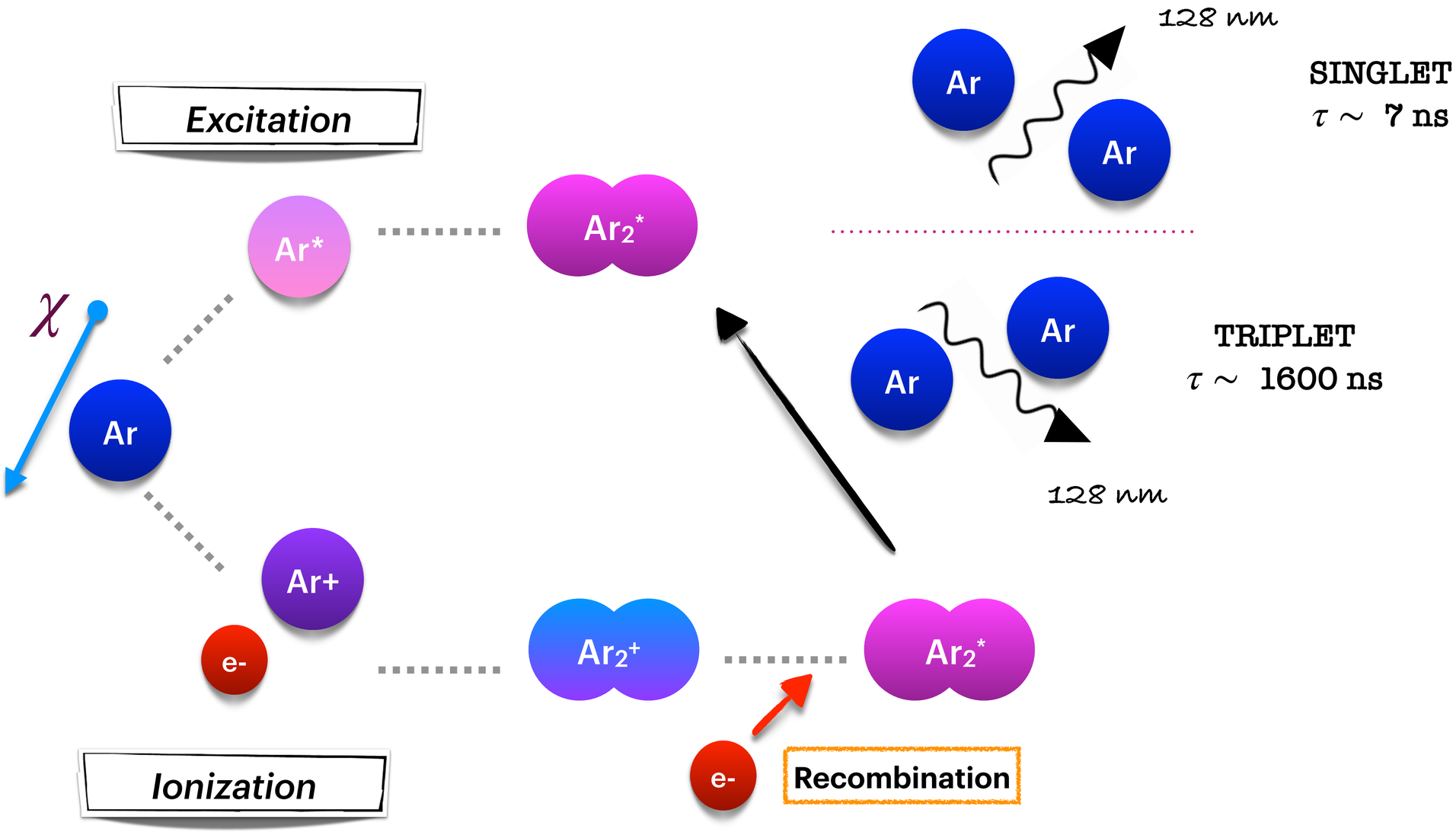


WIMP search technology zoo



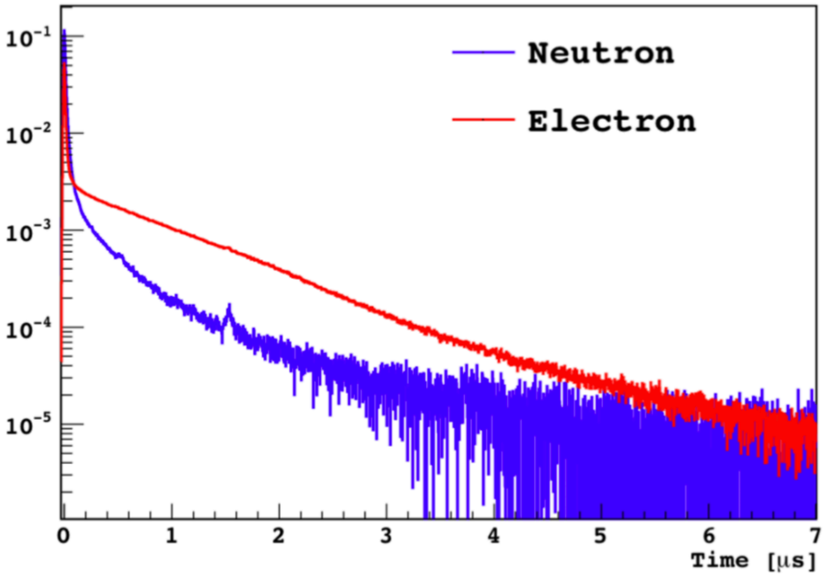
Signals in Ar

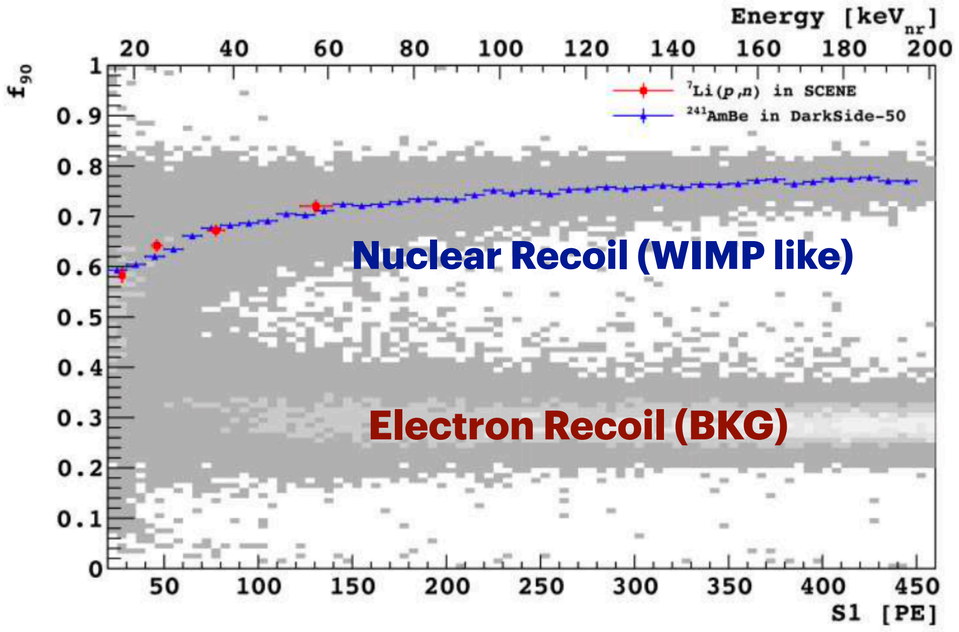
Scintillation + Ionization

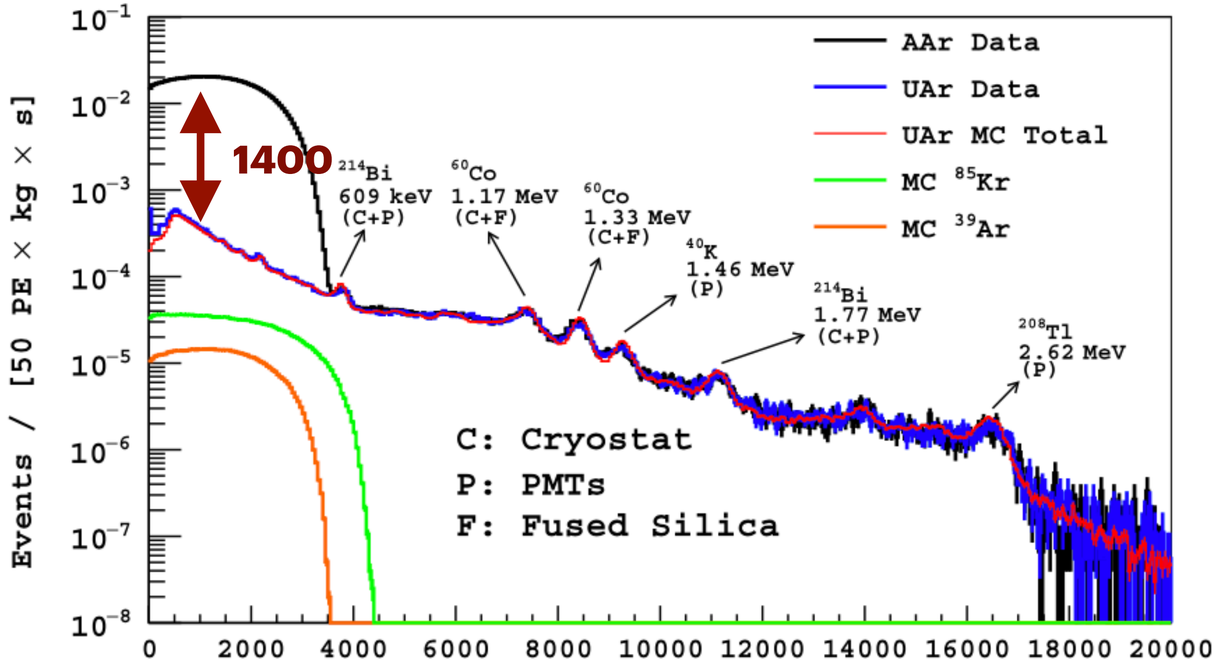


Direct searches with LAr Time Projection Chambers

- Efficient background rejection :
  - Pulse Shape Discrimination (PSD) for β/γ rejection → singlet vs triplet decay times
  - Low-radioactivity due to the underground extraction →suppression factor ~ 1400







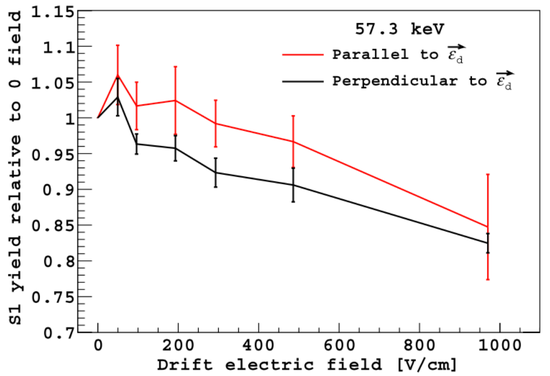
PHYS. REV. D 93, 081101(R) (2016)

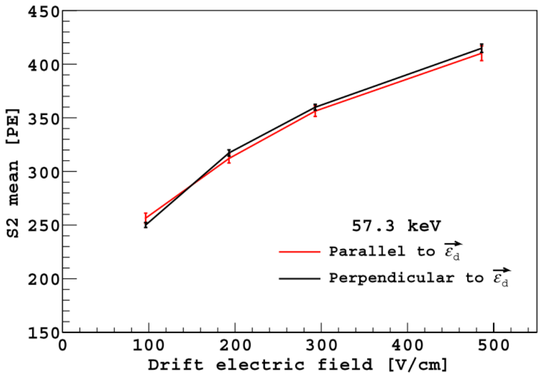
The Recoil Directionality (ReD) experiment

Our recipe for directional investigation

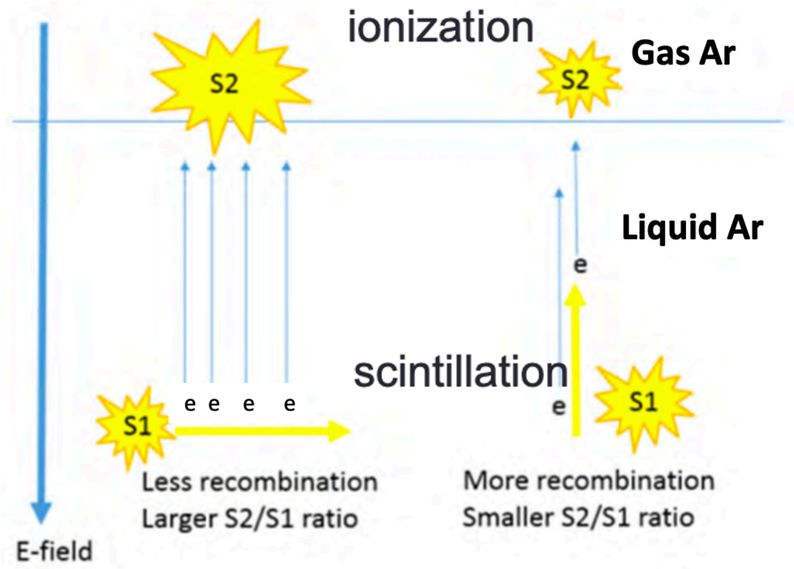
1. Direction information hinted by the SCENE experiment via the ***columnar recombination effect***
2. The directional dependance is revealed with anisotropic charge cloud → ionizing track longer than Osanger radius r_O
3. NR recoils with tracks parallel to ε_d are expected to have **enhanced S1** and reduced S2
4. A NR's kinetic energy of ~70 keV fails in the ROI of WIMP search and corresponds to a ion range larger than r_O

$\Longrightarrow$ Irradiate a miniaturized LAr TPC with mono-energetic neutrons to produce NRs with momenta at different angles wrt ε_d

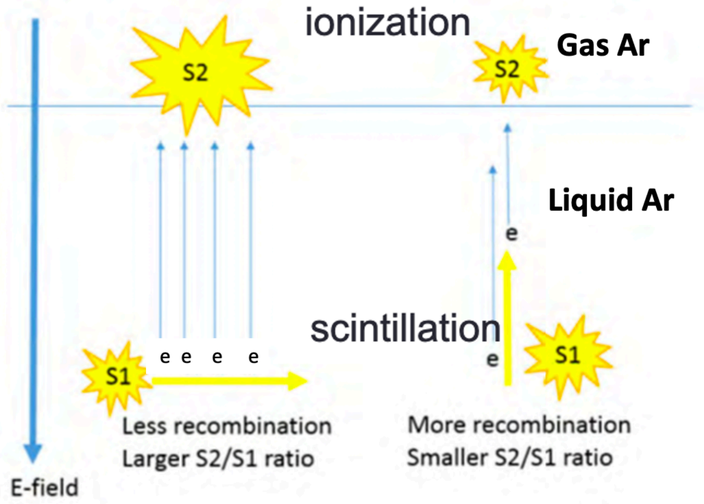




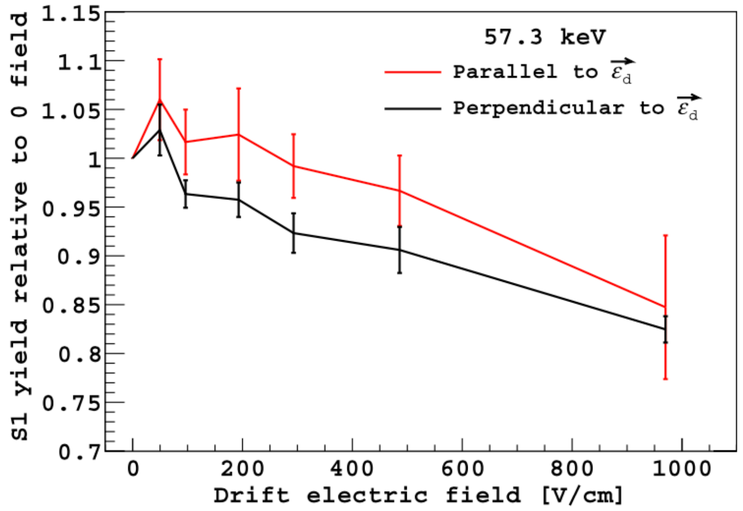
Cao H. et al. (The SCENE Collaboration)
Phys. Rev. D 91, 092007 (2015)

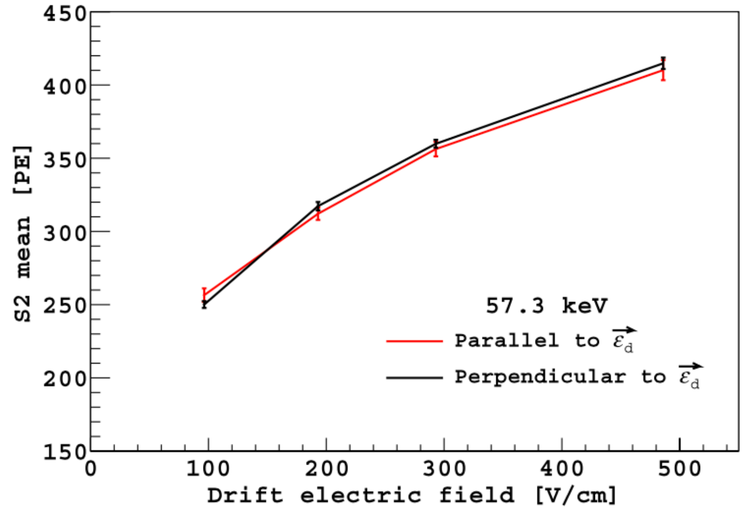


Columnar Recombination hint by SCENE



Cao H. et al. (The SCENE Collaboration), Phys. Rev. D 91, 092007 (2015)

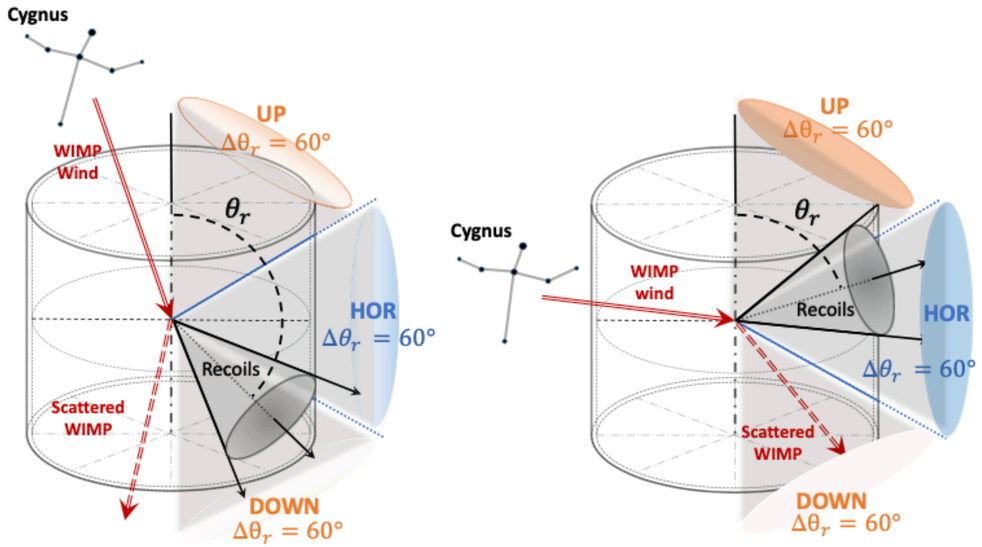




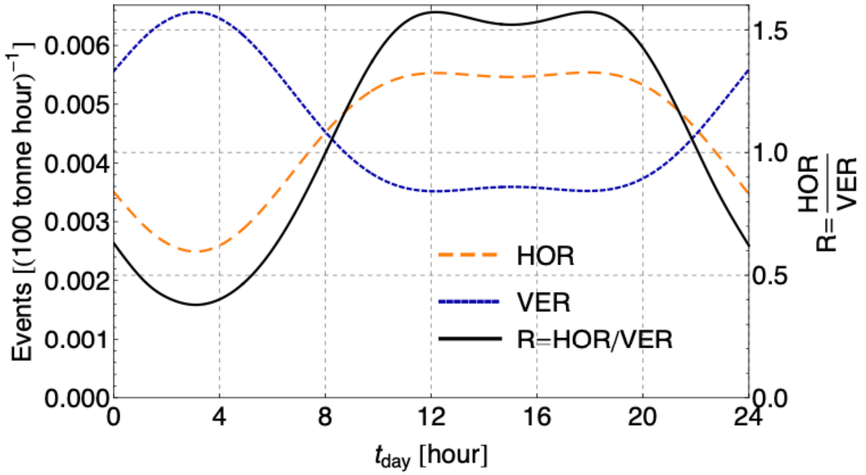
M. Cadeddu et al., JCAP01(2019)014

Using the angular information alone, 100 (250) events are sufficient to reject the isotropic hypothesis at 3 sigma level for a perfect (400 mrad) angular resolution

Directional Sensitivity for a LAr TPC @LNGS



- Angle between recoiling nucleus and vertical axis θ_r
- HOR : $|\cos\theta_r| < 0.5$
- VER : $|\cos\theta_r| > 0.5$



At LNGS's Latitude the time signature of an anisotropic WIMP wind should be evident also at this rude angular classification

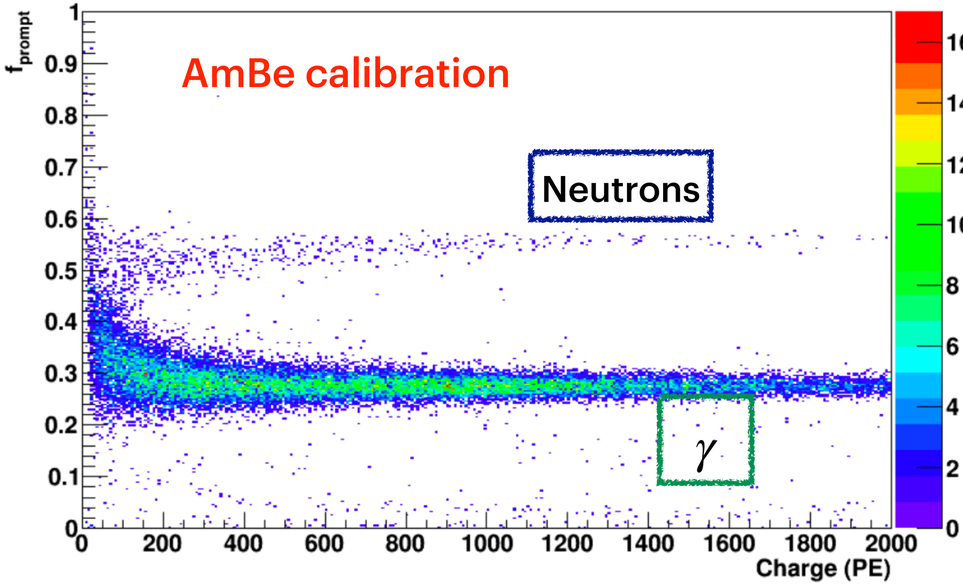
M. Cadeddu et al., JCAP01(2019)014

The TPC I

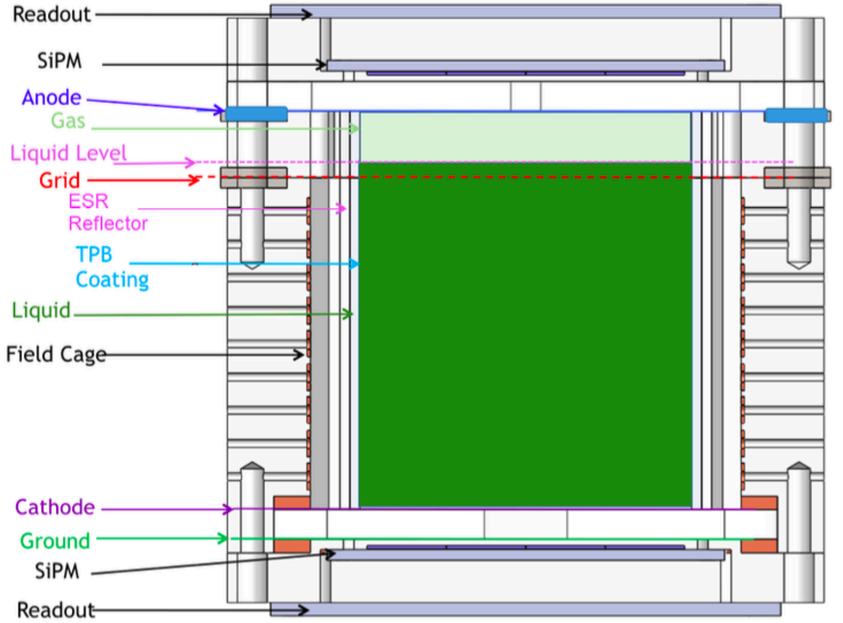
- Ratio fast/total for Pulse Shape Discrimination (PSD) on S1 for ER/NR discrimination

$$f_{prompt} = \frac{\int_0^{700ns} S1\ dt}{\int_0^{t} S1\ dt}$$

- Fields:
  - Drift field ε_d 152 V/cm
  - Extraction filed ε_{ex} 3.9 kV/cm
  - Electroluminescence field ε_{el} 5.9 kV/cm



- Top & bottom windows coated with ITO → *conductive layers*
- TPB as wavelength shifter



- **NUV-HD-Cryo SiPM** operated at ***+7 V of overvoltage wrt V_{bd}***
  - Power supply from custom made Front-End Boards (FEB)
- Extraction grid → stainless steel mesh 10 mm below the Anode window

The TPC II
Performance

- Characterization of the TPC performed @INFN-NA

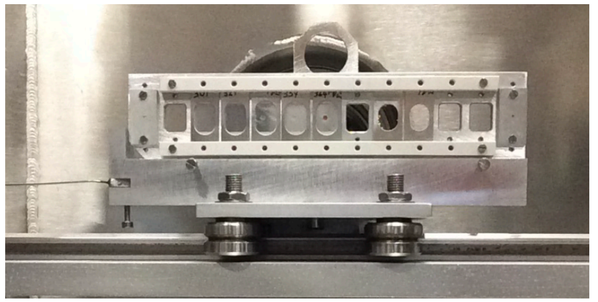
P. Agnes et al., Eur. Phys. J. C 81, 1014 (2021)

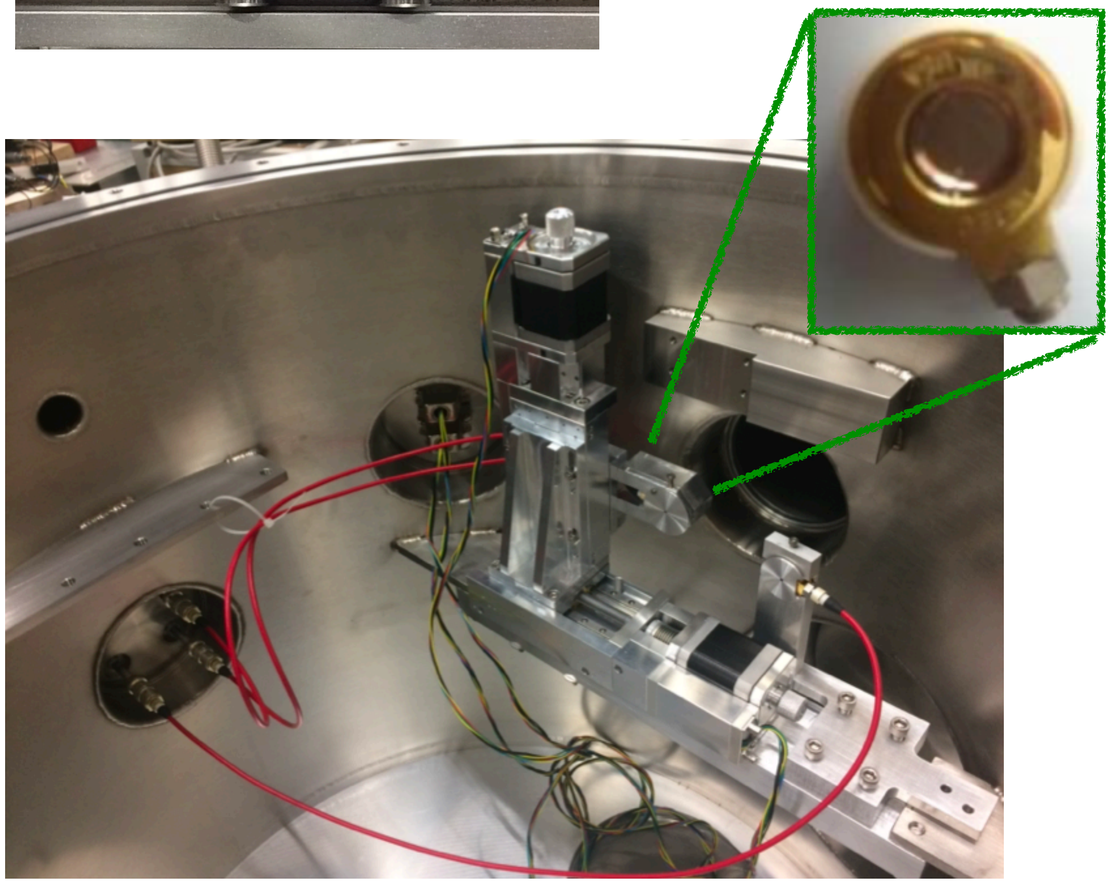
- Calibration of SiPMs with laser
  - Effect of **after-pulses** and **crosstalk** ~30%
  - System **stable at cold** for many months (**<1% rms in SER**)
- Scintillation gain g_1 = 0.194 PE/γ
- Ionization *a*mplification g_2 = 20 PE/e$^-$
- Total scintillation **light yield** at null field **9.80 PE/keV** at ^{241}Am→ stable (<2%)
- Power supply from custom made Front-End Boards (FEB)

⇒ TPC performance **appropriate** for the directionality searches ✔

^{7}Li Beam and Si Telescope

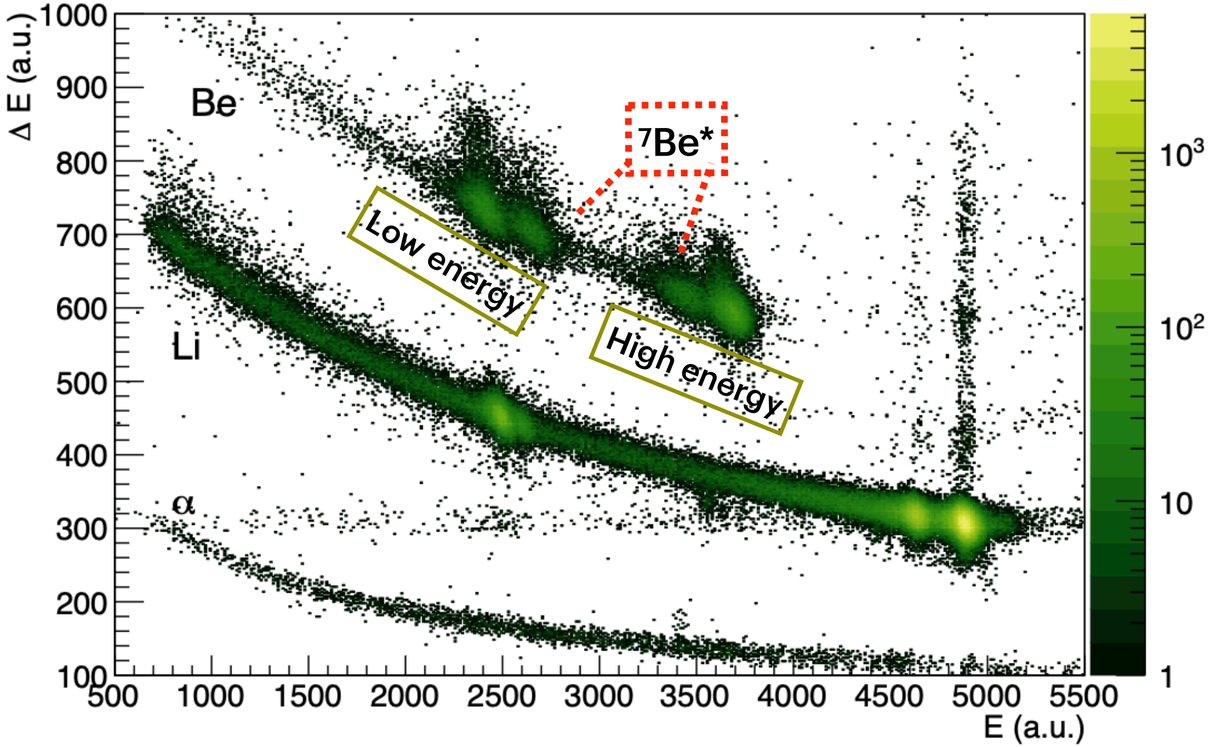
- ^{7}Li beam produced @LNS-TANDEM 15 MV accelerator
  → 28 MeV for ^{7}Li beam
- No pulsed accelerator ⇒ ^{7}Be tagging and inverse kinematics
- Inside the vacuum chamber:
  - **CH_2 target** → 150 - 350 μg/cm^2 thickness range, changed every 12 hours
  - **$\Delta E/E$ telescope** → 2 Si stages (ORTEC) to tag low energy ^{7}Be
    - ➡ 20 μm - 1000 μm (thickness), 7 mm diameter
    - ➡ Moved with a remotely-controlled stepper motor
    - ➡ Separation of ^{7}Be wrt ^{7}Li with **Z**





^{7}Li Beam and Si Telescope

Kinematical loci

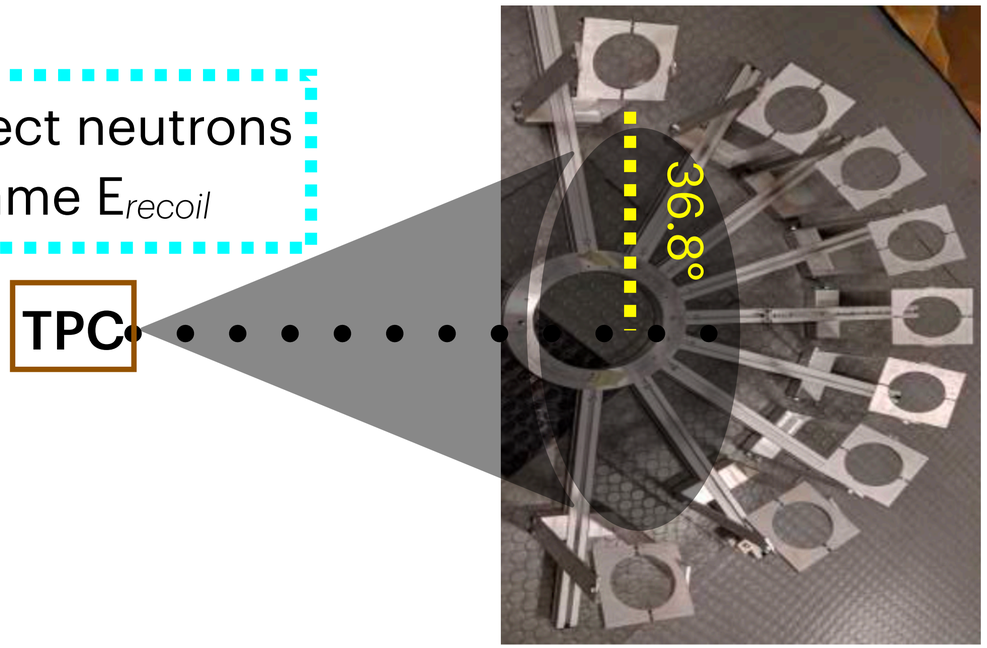


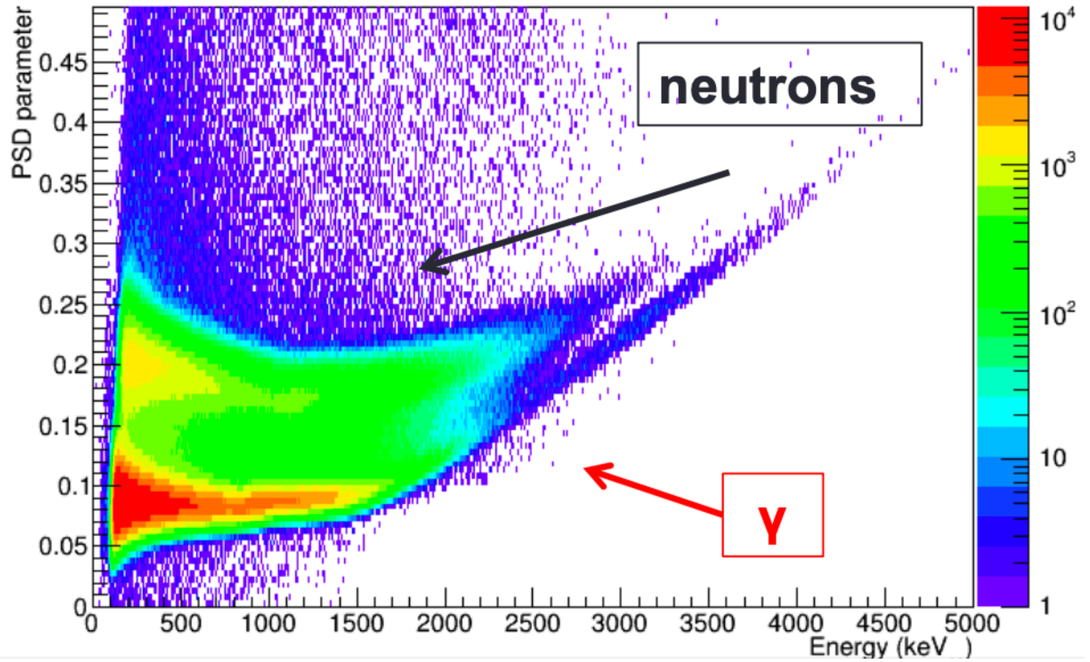
- ✓ ^{7}Be ***low energy*** (19 MeV) & neutrons 7.4 MeV @22.3° → **TPC**
- ^{7}Be ***high energy*** (20.4 MeV) & neutrons 2.7 MeV @44° → accidentals
- Population from **p(^{7}Li,^{7}Be*)n**

The Neutron Spectrometer

- 7 Liquid Scintillators cells (**3-inch EJ-309**) coupled with PMTs
- Tag ^{40}Ar recoils in the TPC at 4 ϕ angles wrt ε_d : 0°, ± 20°, ± 40°, ±90°
- Absolute calibration with ^{252}Cf → ϵ ~20-40% for 2-8 MeV n
- **Time resolution** ~0.5 ns rms
- Powerful PSD for n/γ

How to detect neutrons at the same E_{recoil}

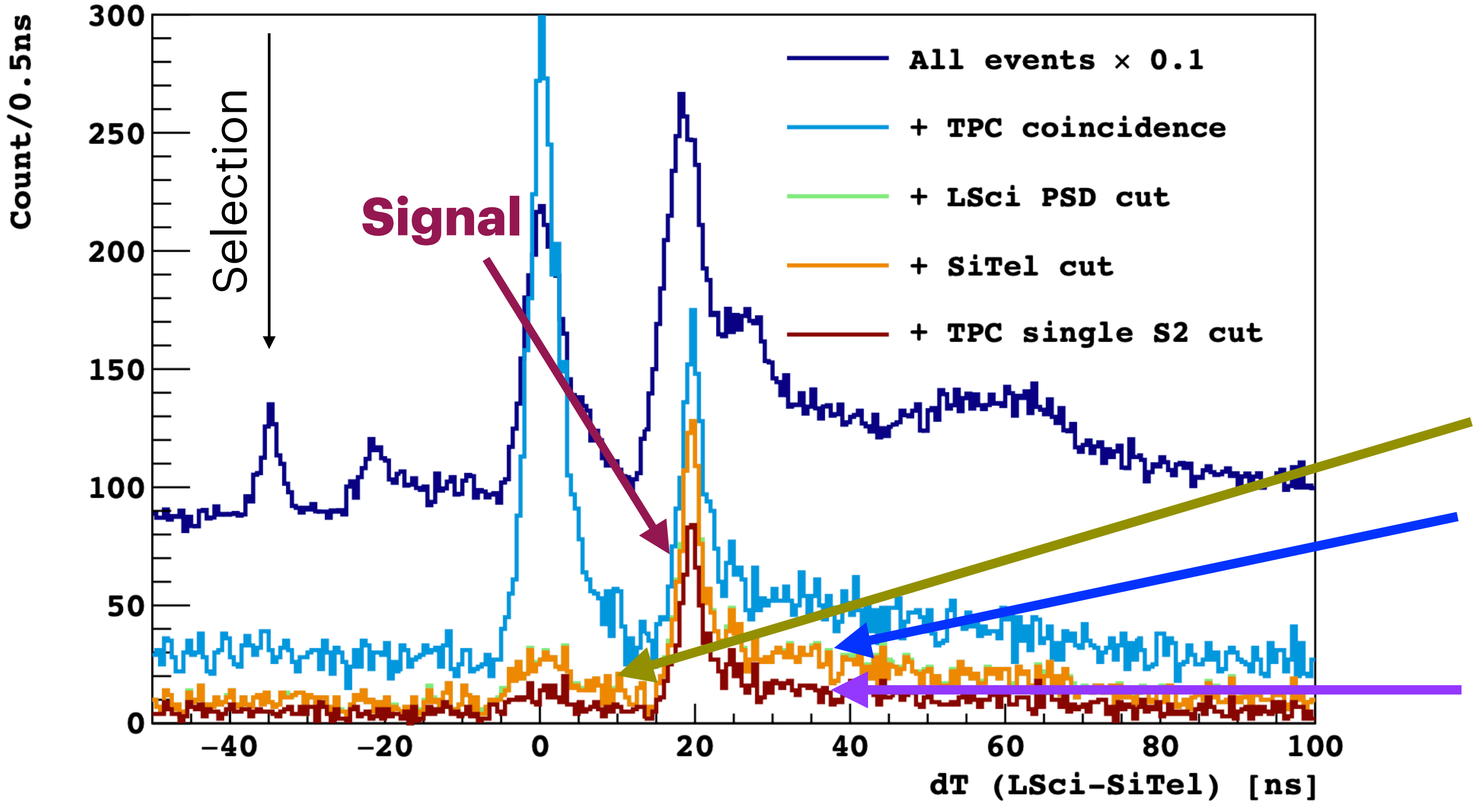


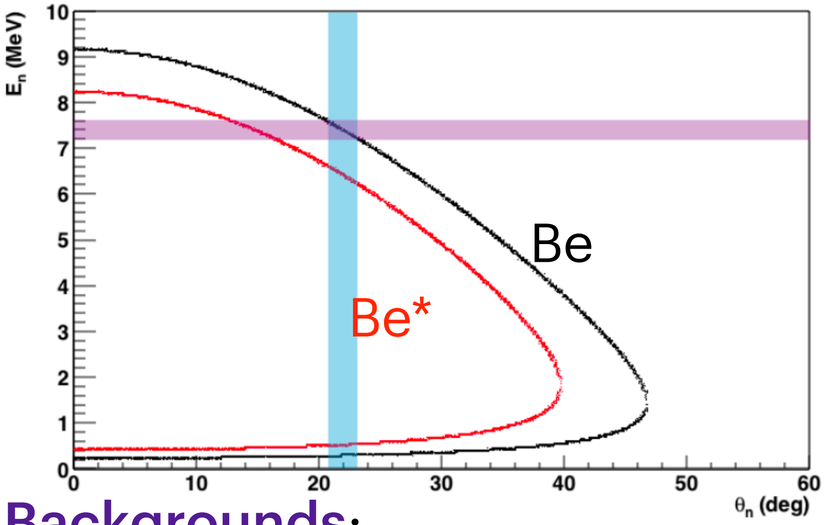


Signals and Backgrounds

Signal → single Ar recoils, same E_{recoil} but different ϕ

~ 7000 events with proper energy (70 keV_{nr}) and timing

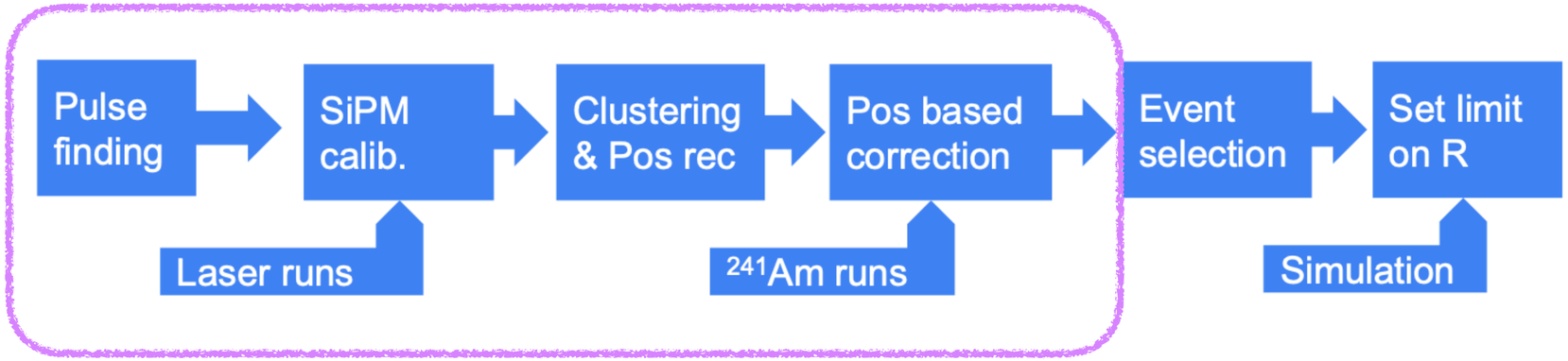




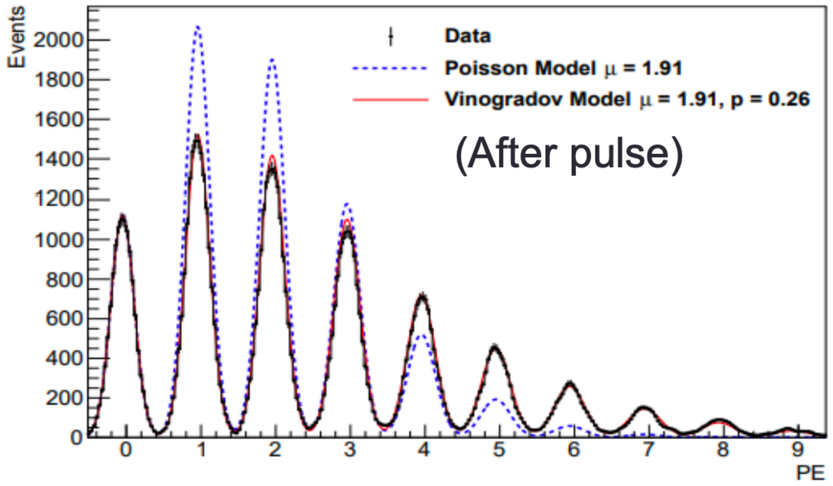
Residual **Backgrounds**:

- Accidentals
- (n, n′ γ) events in the TPC
- Neutrons from p(^{7}Li,^{7}Be*)n
  - 63.5 keV recoils in the TPC
- Neutrons with multi-scattering

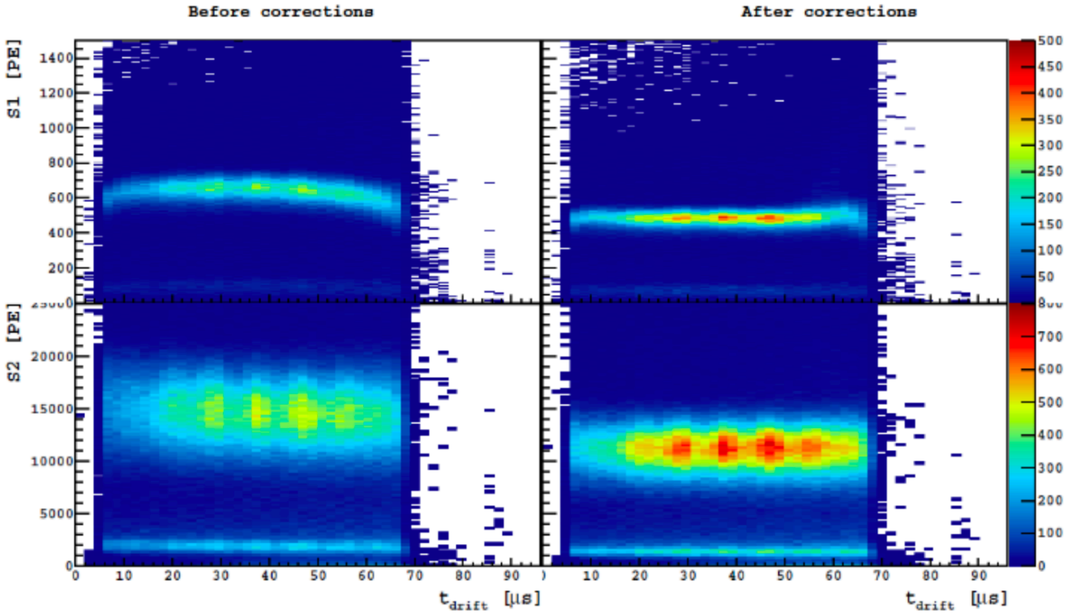
Analysis flow and event reconstruction



SiPM PE Response



3D position-based correction



Electron lifetime

Run ID	<= 1432	[1433, 1525]	[1526, 1627]	[1628, 1641]	>= 1642
τ_e [μs]	274	313	614	976	1095

Event Selection

"good things come in threes"

- The golden-plated events are the ***three-fold coincidences***:

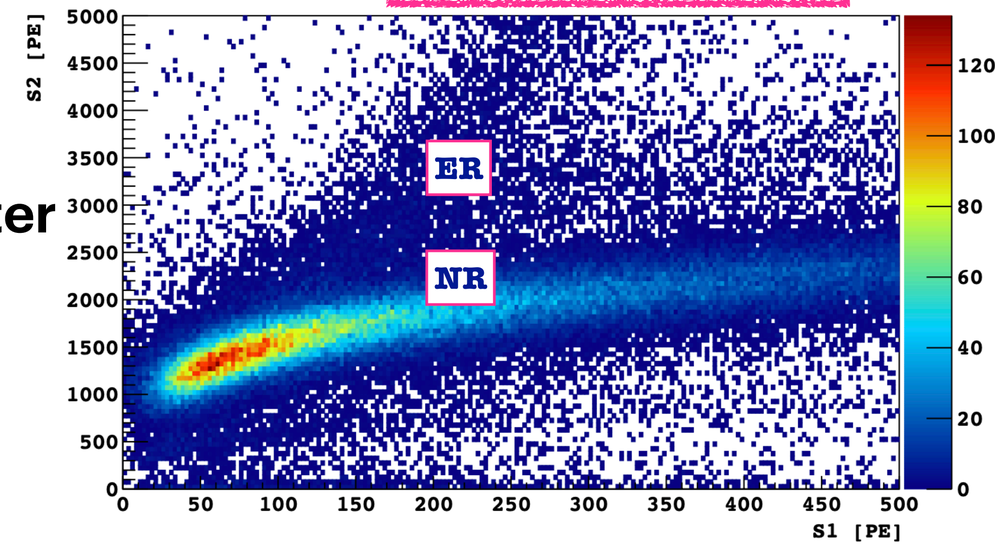
(1) Si-Telescope → (2) TPC → (3) Neutron spectrometer

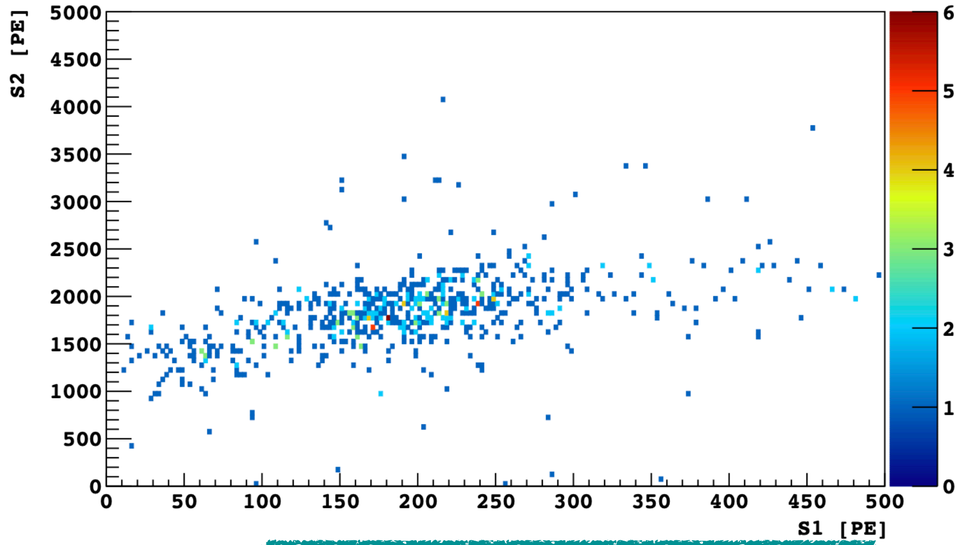
- Further **cuts** and **cleaning**:
  - "Good events" → **single pulses** S1 and S2
  - ^{7}Be tagging
  - ***Time of Flight*** (**ToF**) compatible with few-MeV neutron
  - **PSD** on the neutron spectrometer

→ ~ 7000 events with proper energy (**70 keV$_{nr}$**) and timing

About 150 events/day

SiTel ∧ TPC events





Triple coincidence events

Global likelihood fit

Unbinned maximum likelihood fit

$$\mathcal{L}(\boldsymbol{X} \mid \delta R, \boldsymbol{\nu}) = \prod_{i=0}^{5} \mathcal{L}_i(\boldsymbol{X}_i \mid \delta R, \theta_i, \boldsymbol{\nu}) \times \mathcal{L}_{\text{cali}}(\boldsymbol{X}_{\text{cali}} \mid \boldsymbol{\nu}) \times \mathcal{L}_{\text{prior}}(\boldsymbol{\nu})$$

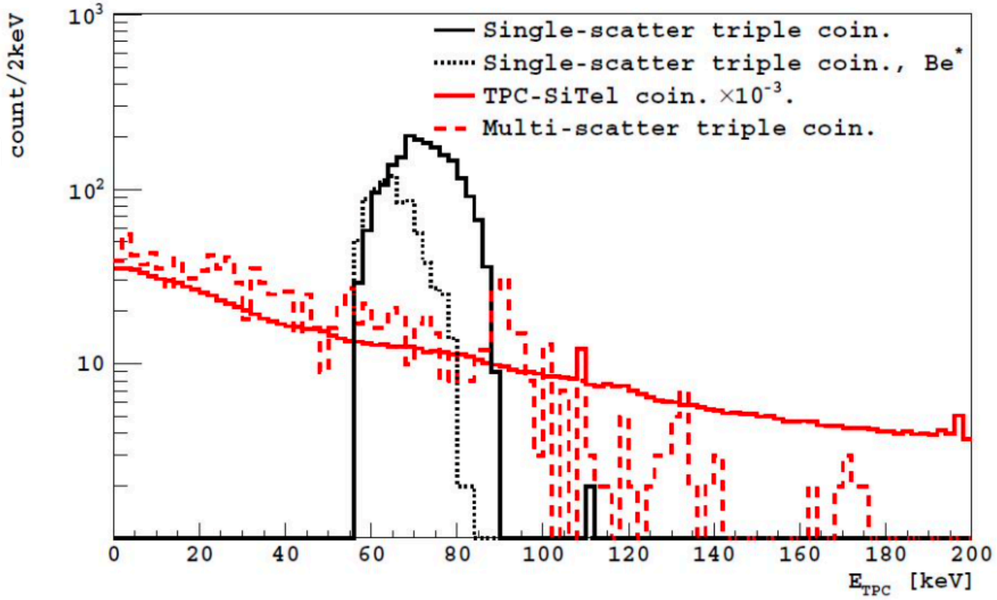
Pull term for the nuisance parameters

$\nu = \{C_{box}, g_1, g_2, \sigma_{S1}, \sigma_{S2}\}$

Calibrations (^{241}Am, Laser)

Signal + BKG samples at 5 different ϕ angles (0°, 20°, 40°, 90$_l$°, 90$_r$°)

- **PDF** for **signal** and **background** evaluated with Geant4-MC simulation and/or data
- Directional model + NR Ar response + detector response
- All parameters but **R** are taken as nuisance



Multi scattering background

Geant4 Simulations

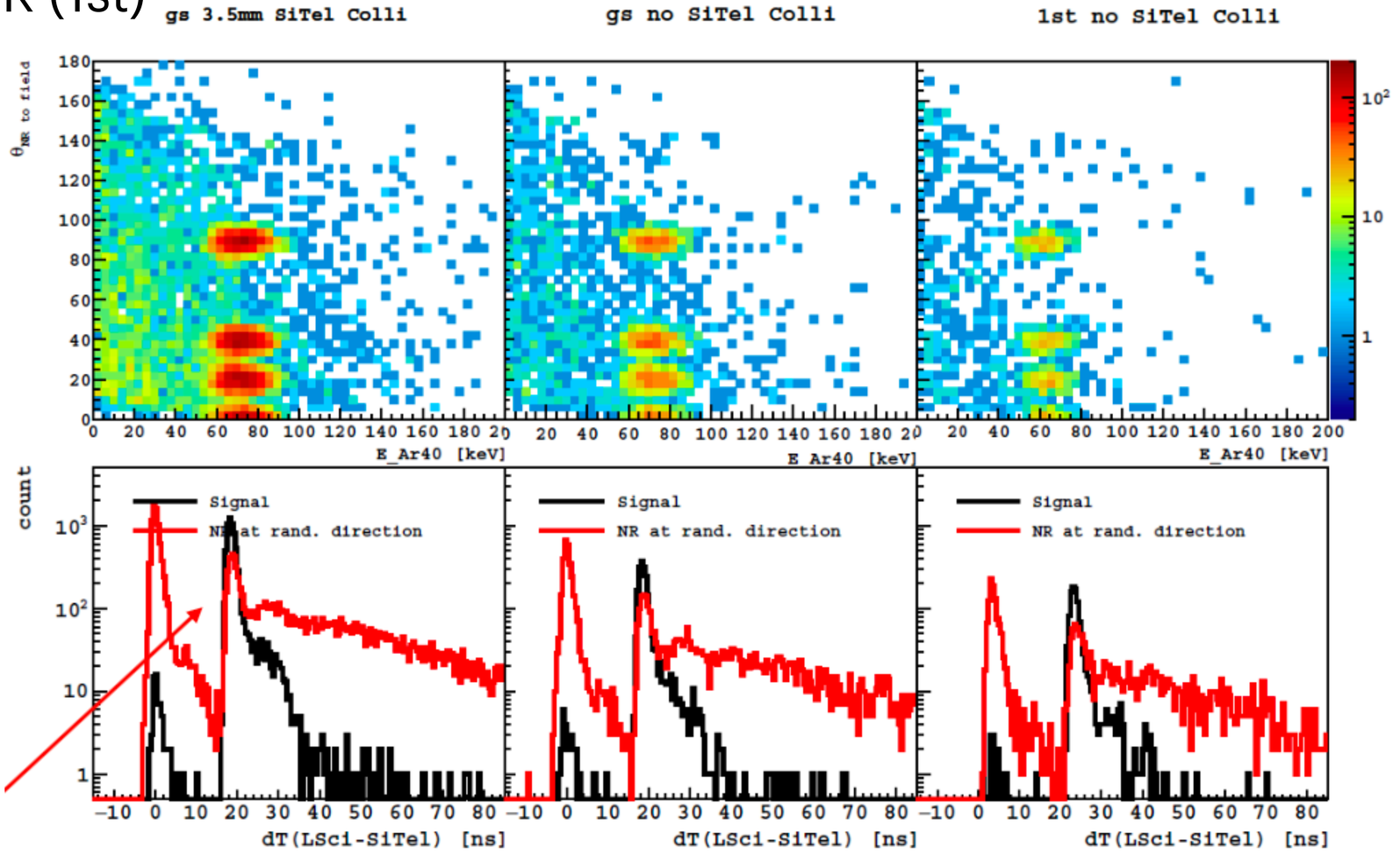
p(^{7}Li,^{7}Be)n → 72.5 keV NR (gs)

p(^{7}Li,^{7}Be*)n → 63.5 keV NR (1st)

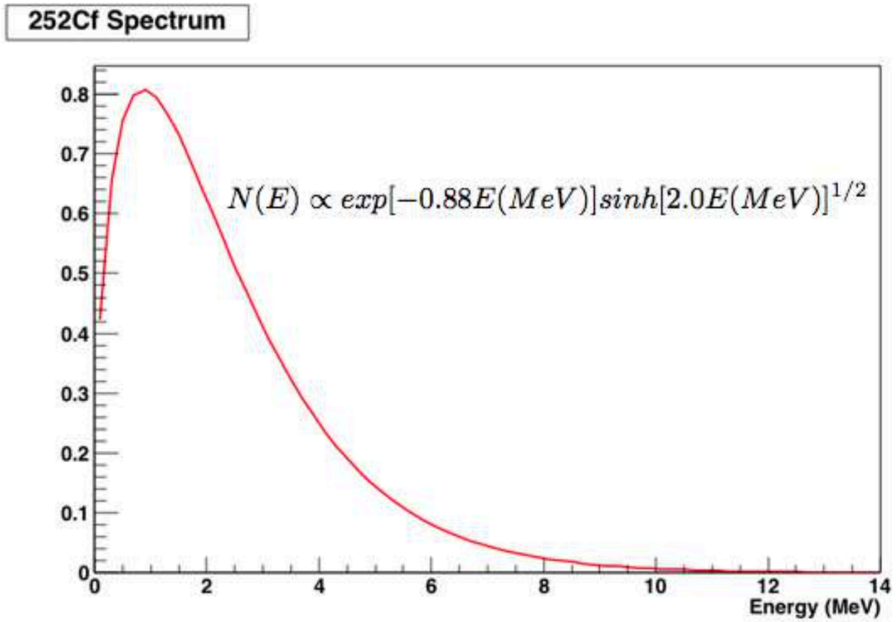
Recoil direction
vs
Ar energy recoil

Timing
Spectra

Irreducible



Expected signals for low energy characterization



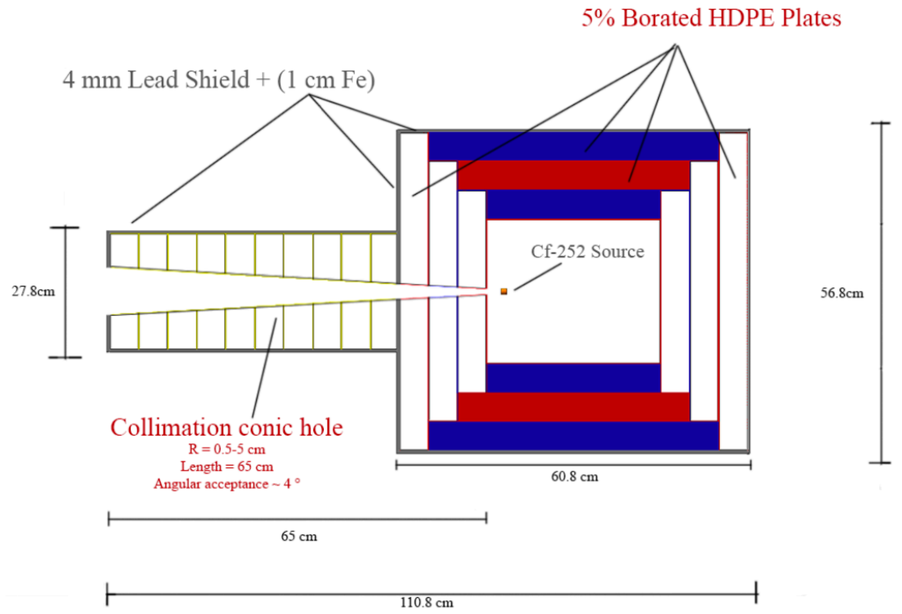
- Golden-plated events: neutrons from the ^{252}Cf source → TPC → trigger one PSci
- **Neutron energy** b/w ***1-10 MeV*** → **E_{recoil}** b/w ***1-5 keV$_{nr}$*** → scintillation signal in TPC *low* wrt the detection threshold

  ⇒ the trigger logic *does not include* the TPC, but only **BaF_2** + **PSci**
- Neutron Kinetic Energy KE_n from **ToF** measurements

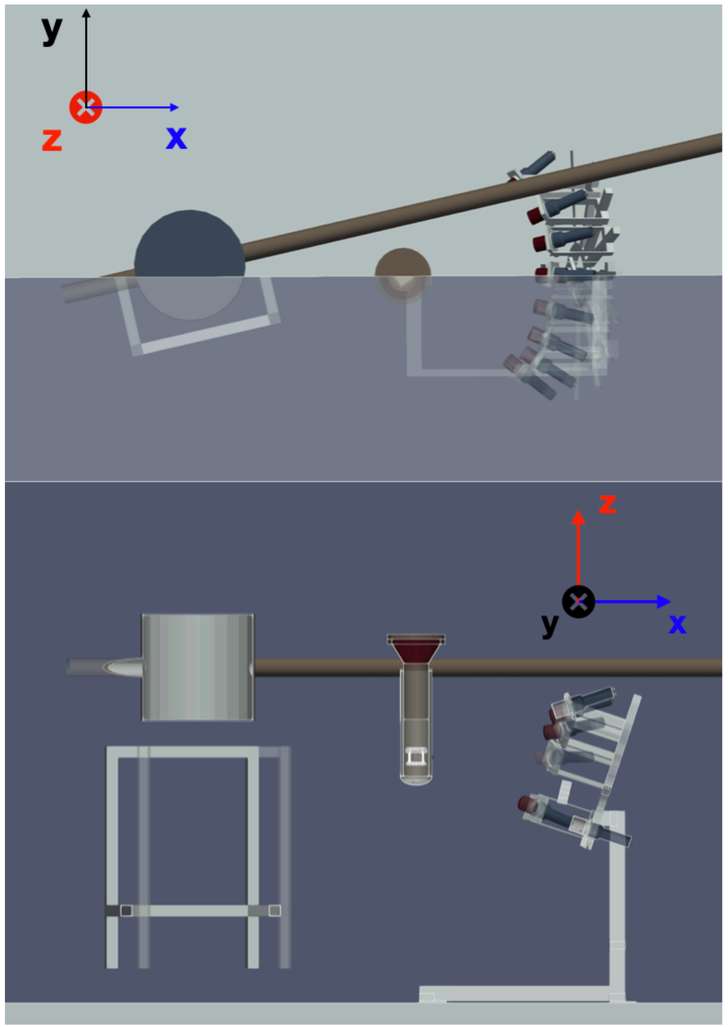
$$\Rightarrow E_{recoil} = 2KE_n \frac{m_n m_{Ar}}{\left(m_n + m_{Ar}\right)^2}\left(1 - \cos\theta_{scatt}\right)$$

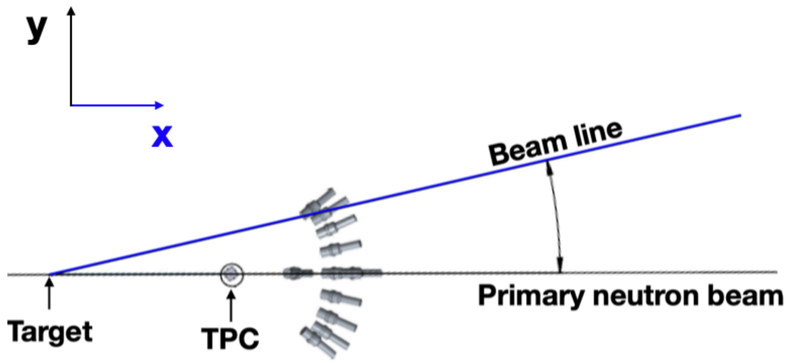
The source shield

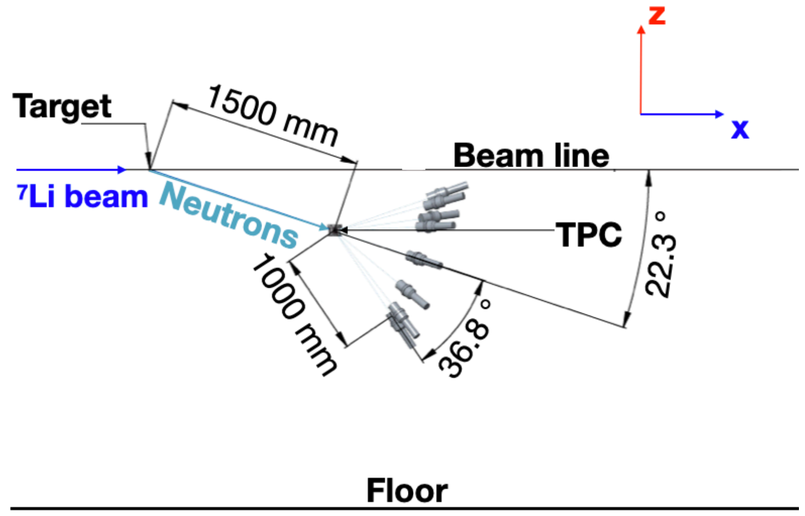
- 14 blocks of **B-loaded HDPE** 5 cm thick
  - 4 in the central box
  - 10 in the collimator “nose”
- Final coat made up by 4 mm thick **Pb** + 1 cm thick **Fe**
- **~ 2° opening angle** for exit neutrons



Experimental layout @LNS







TOP VIEW

SIDE VIEW