



DIRECTIONALITY FOR NUCLEAR RECOILS IN A LIQUID ARGON TPC

L. Pandola (LNS)

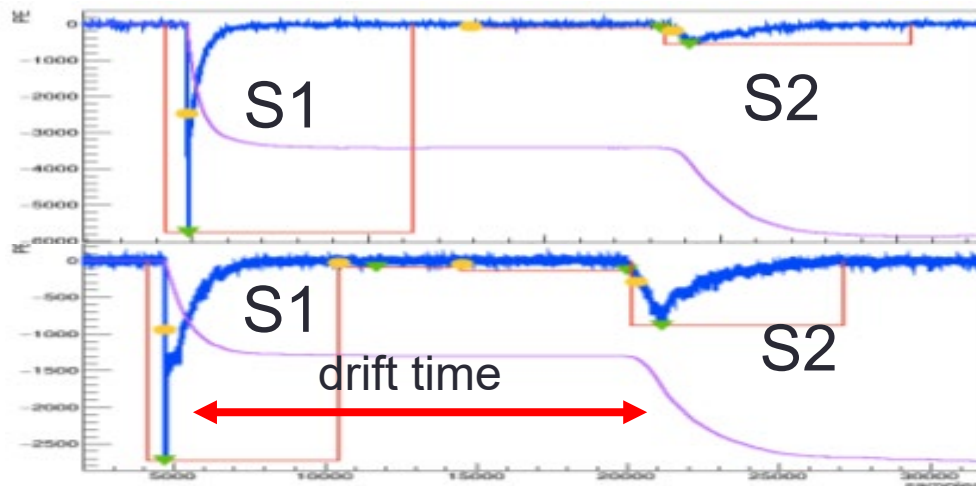
on behalf of the ReD Working Group
(GADM Collaboration)



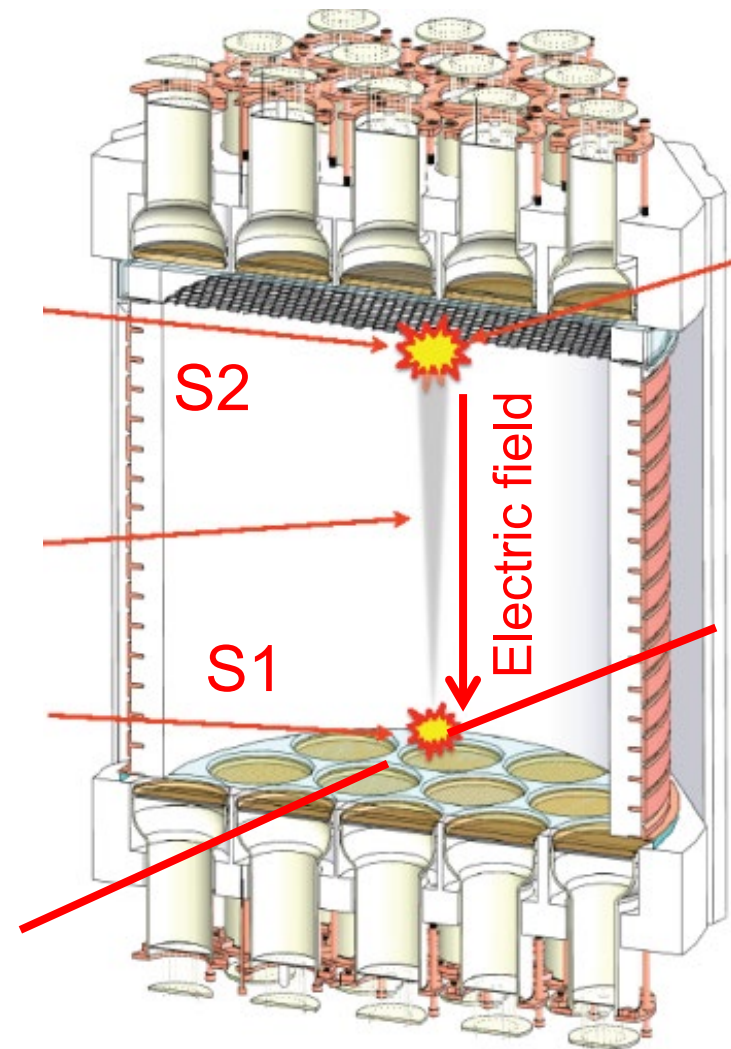
Physics background

- **DarkSide program** at Gran Sasso Laboratory, WIMPs search using **dual-phase Time Projection Chamber** with **low-radioactivity LAr**
- Operated a **50 kg TPC** (DS-50)
- In preparation: **50 ton TPC** (DS-20k)
 - Novel light **readout** with **SiPM**
- Pave way for next-generation (ARGO)

 See talk by G. Testera



darkside

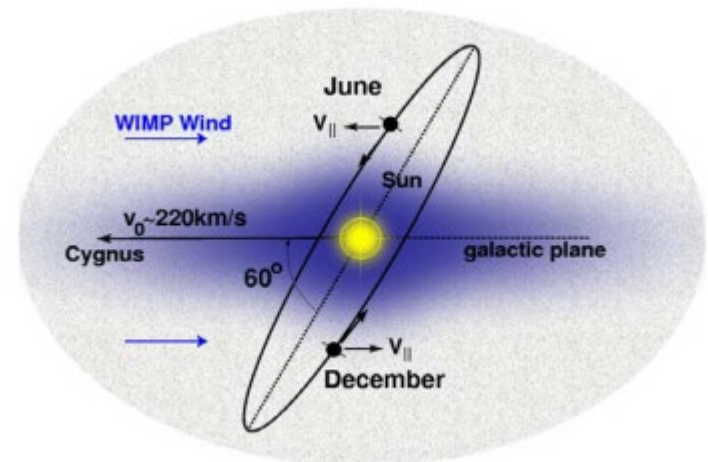


A smoking gun for dark matter discovery

- Correlation of **recoil direction** with the expected direction of the **WIMP galactic wind** would be a smoking gun
 - Much **more convincing** than a mere excess of recoil events
 - **Statistical** effect, but need only a **few 100's** of events

Cadeddu et al.

JCAP 01 (2019) 014

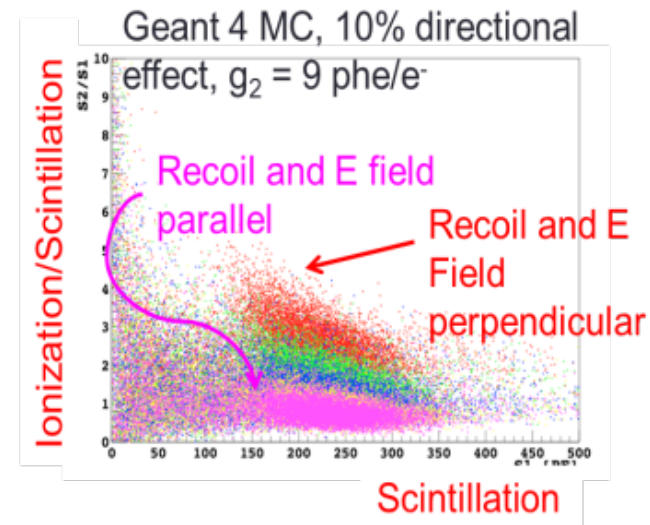
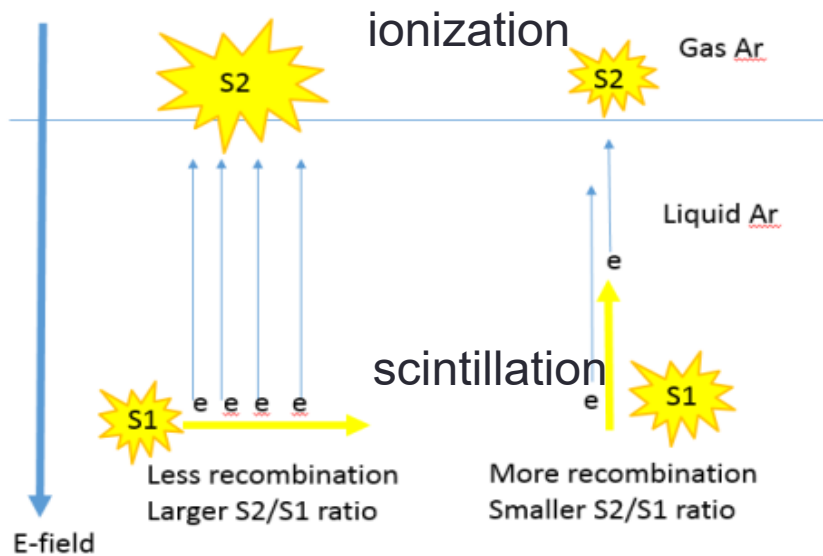


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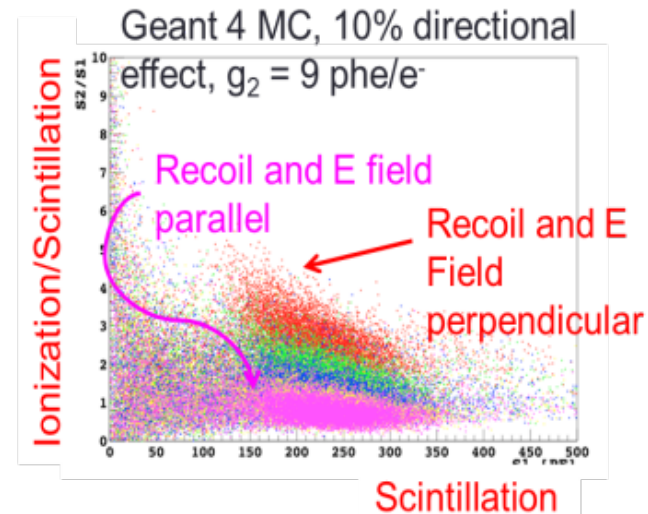
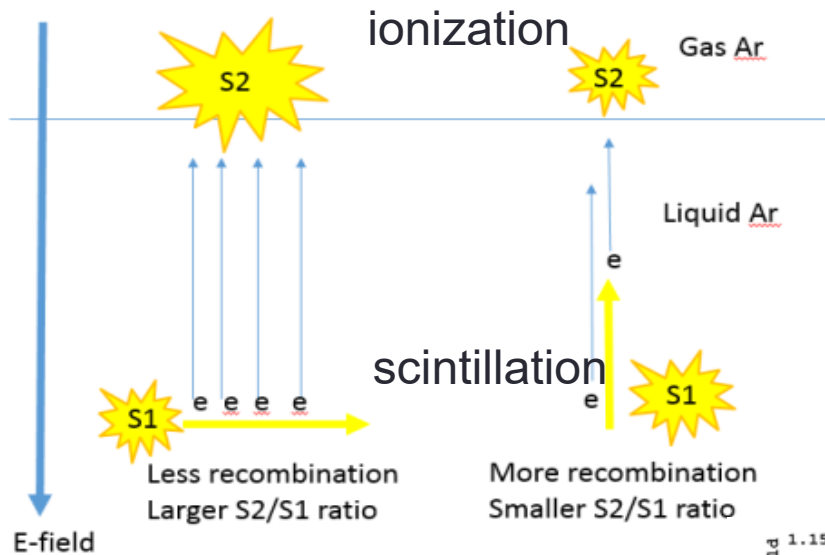
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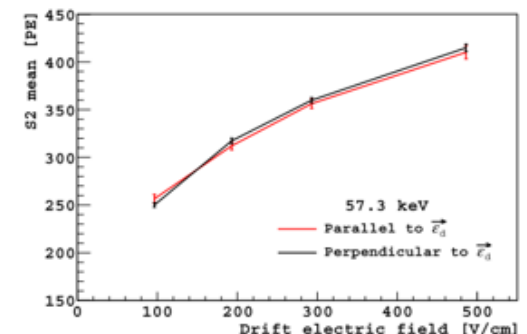
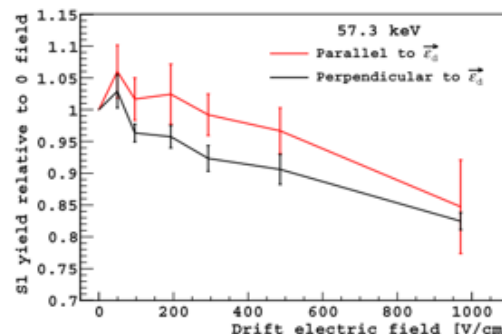
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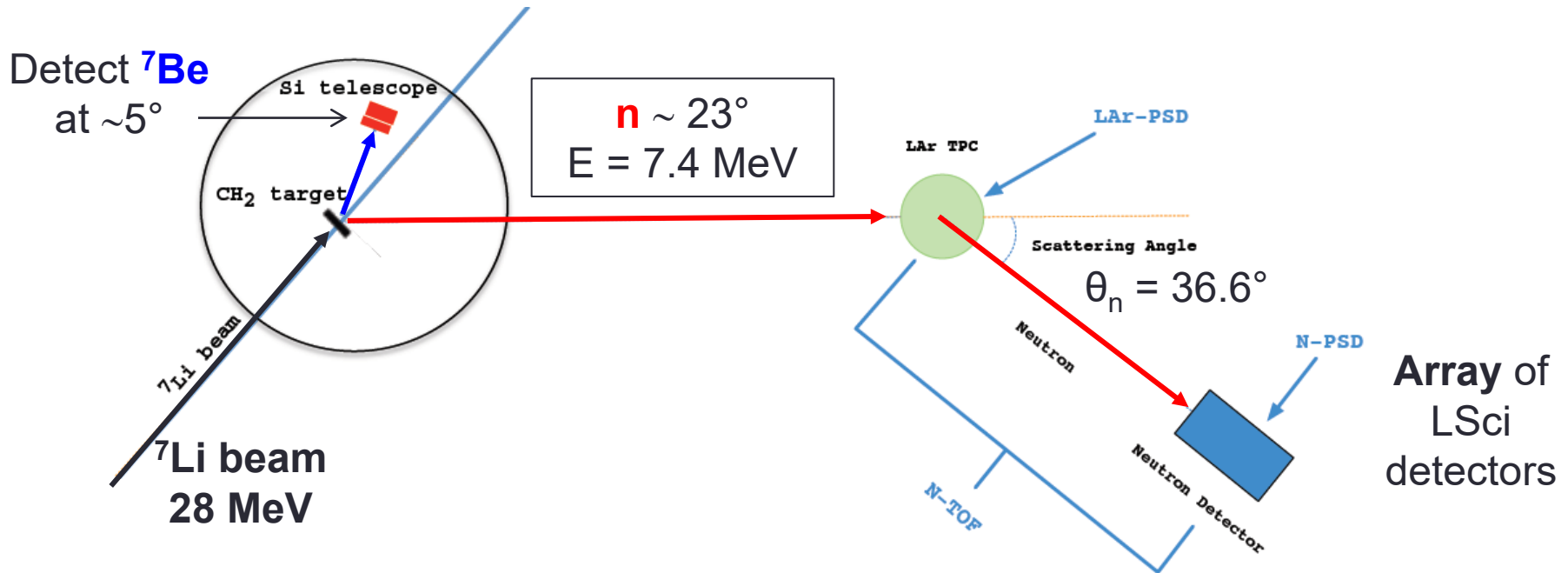
Further studies motivated by the **SCENE indication** →

SCENE, Cao et al, PRD **91** (2015) 092007

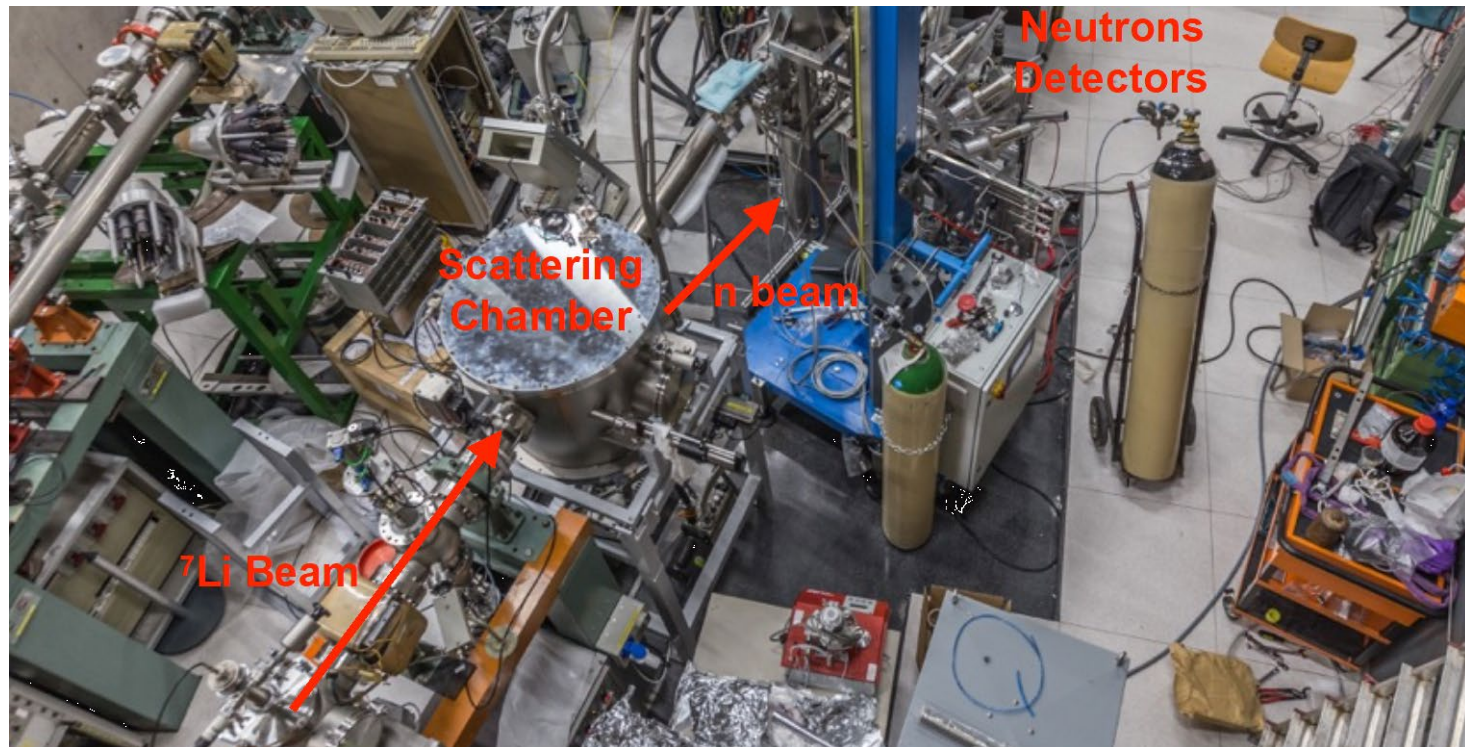
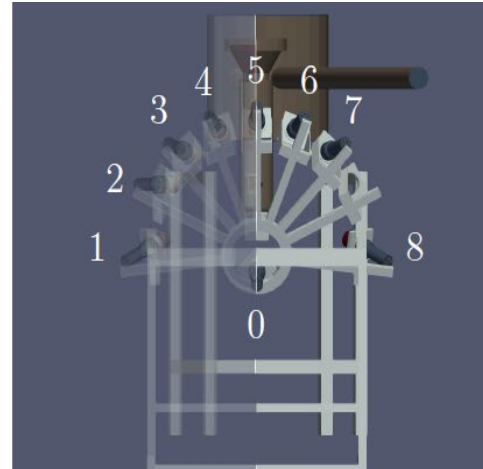
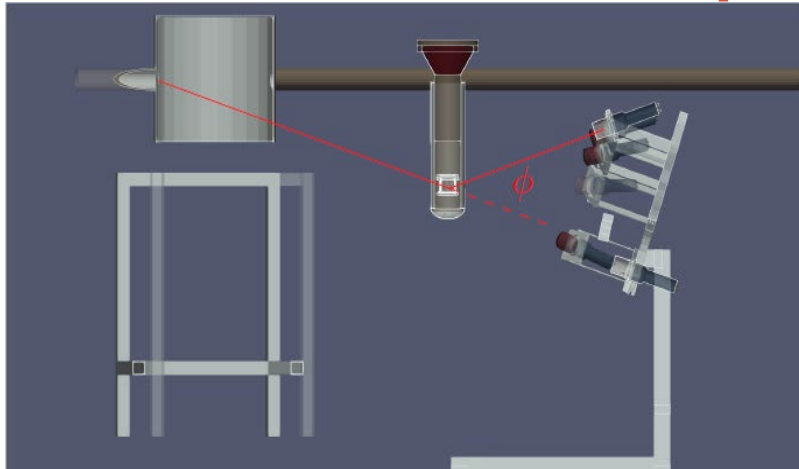


ReD conceptual design

- **ReD project** to address this issue!
- Produce **Ar recoils of known energy and direction** in a TPC by using a suitable **neutron beam**
 - Can be done via $p(^7\text{Li},^7\text{Be})n$
 - **^7Li beam** from the TANDEM accelerator of INFN-LNS (Catania)
 - Detect the **associate particle (^7Be)** to **tag neutron energy** event by event
- Detect neutrons **elastically scattered** off ^{40}Ar
 - Kinematics of (n,n') will fix **energy and direction** of the recoil



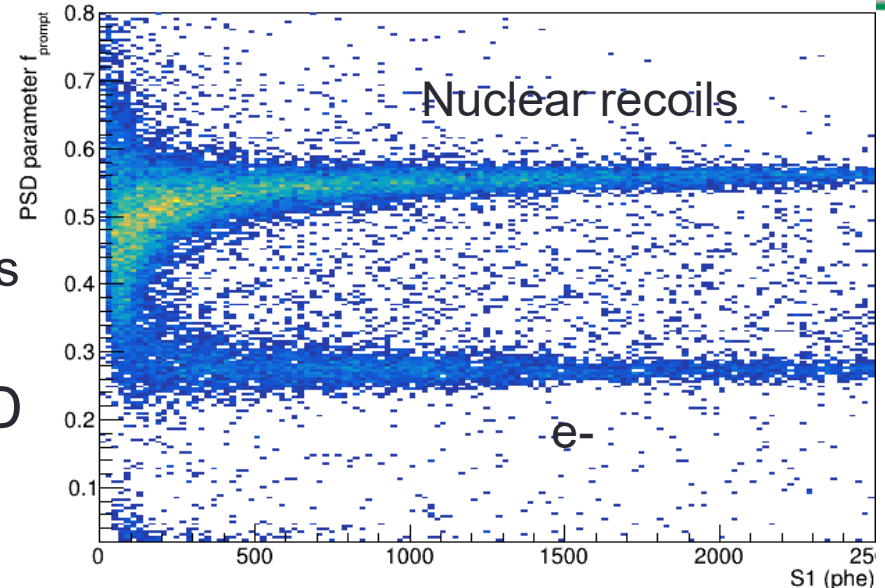
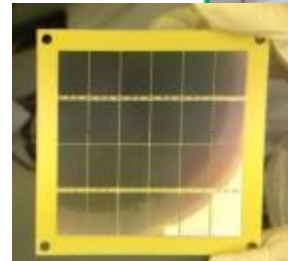
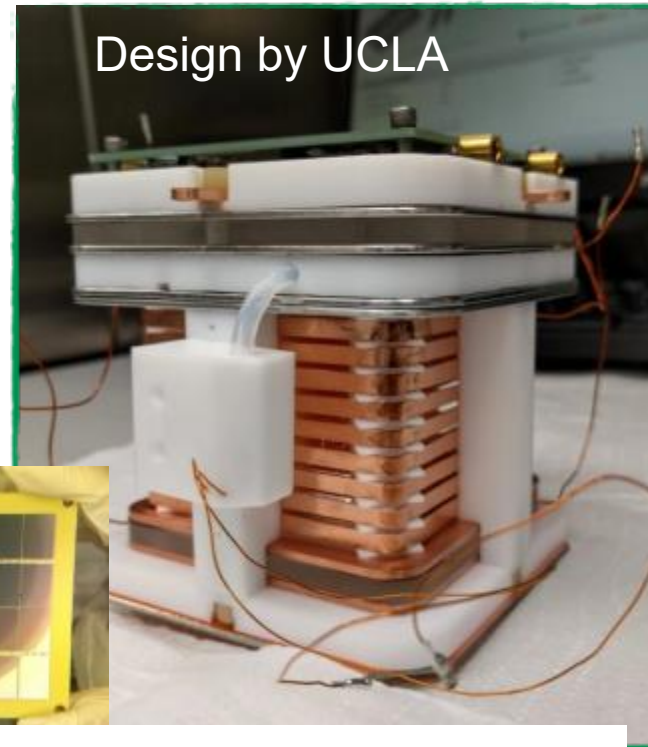
...and actual implementation at



THE INGREDIENTS

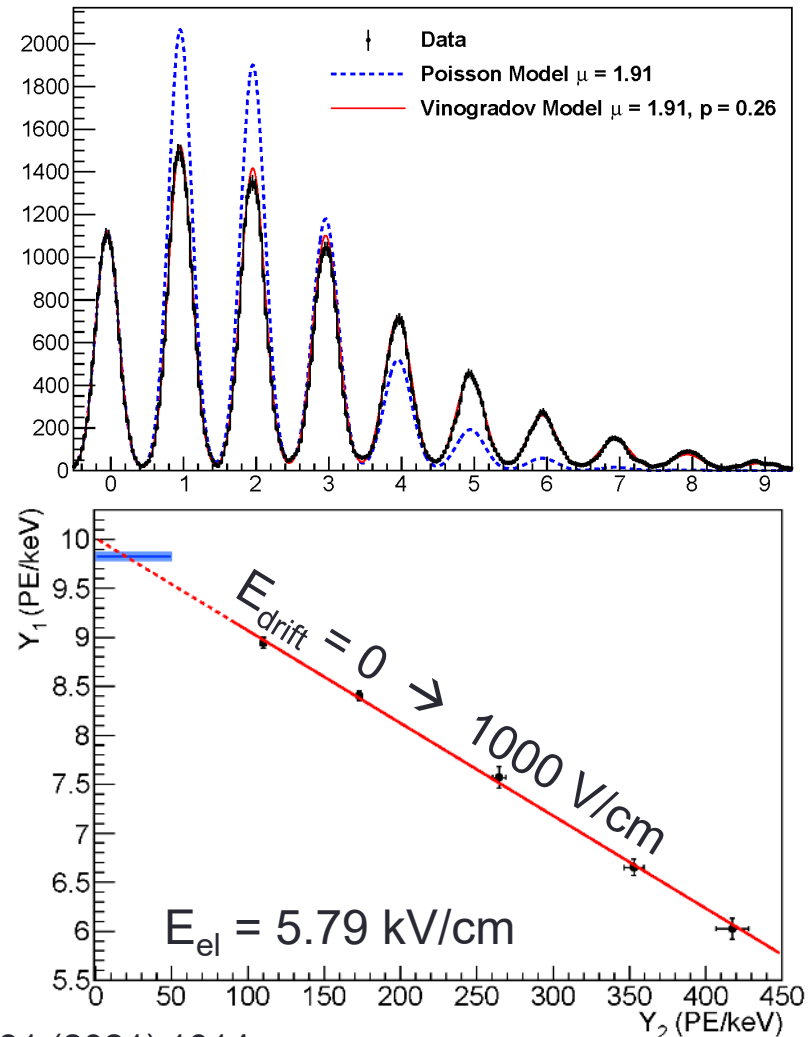
The TPC

- **Miniaturized version** of the DarkSide-20k TPC
 - Active volume: **5(L) x 5 (W) x 6 (H) cm**
 - Gas pocket: **7 mm** thick
 - **TPB coating** for wavelength shifting
- Light readout: **5x5 cm² SiPM** (as for DS-20k), 30% coverage
 - 24x1cm² SiPM **24 ch readout (top)**, for increased **(x,y) resolution**
 - 24x1cm² SiPM, **4 ch readout (bottom)**
- **Front End** from the DS-20k R&D
- **3D event reconstruction**:
 - **(x,y)** from S2 pattern on the top SiPMs
 - **z** from **drift time** (up to $\sim 60 \mu\text{s}$)
- **ER/NR discrimination** by using PSD parameter f_{prompt} on S1
 - Fast/total ratio



TPC Performance

- Detailed **characterization** of the **TPC**, prior to irradiation (Naples, 2019)
- Calibration of SiPMs with **laser**
 - Effect of **after-pulses** and **x-talk** $\sim 30\%$
 - System (w/ cold SiPM) **stable** for **many months** ($< 1\%$ rms in SER)
- Light response good **9.80(21) PE/keV** at ^{241}Am and **stable** ($< 2\%$)
 - Scintillation (S1) **anti-correlated** with charge (S2)

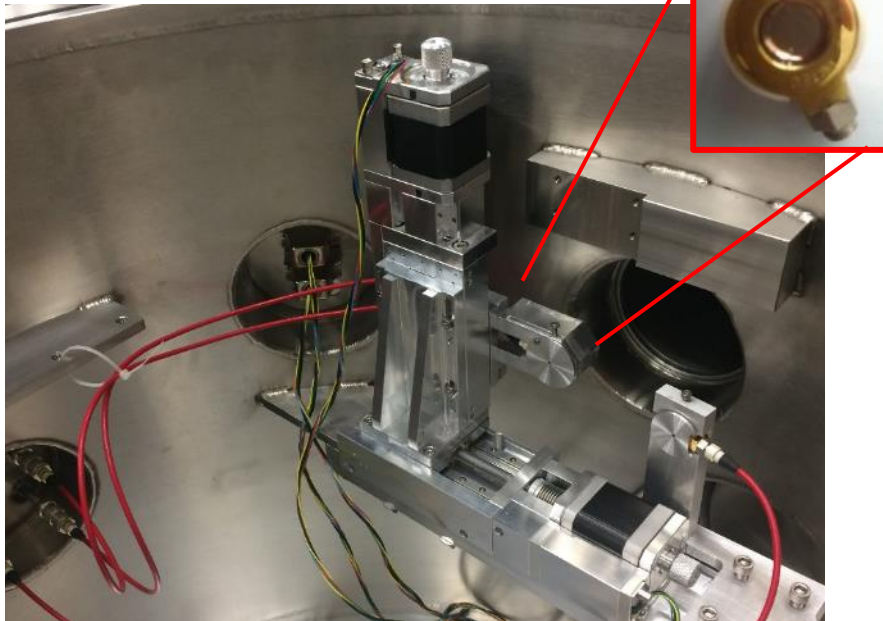


Agnes et al. EPJ C 81 (2021) 1014

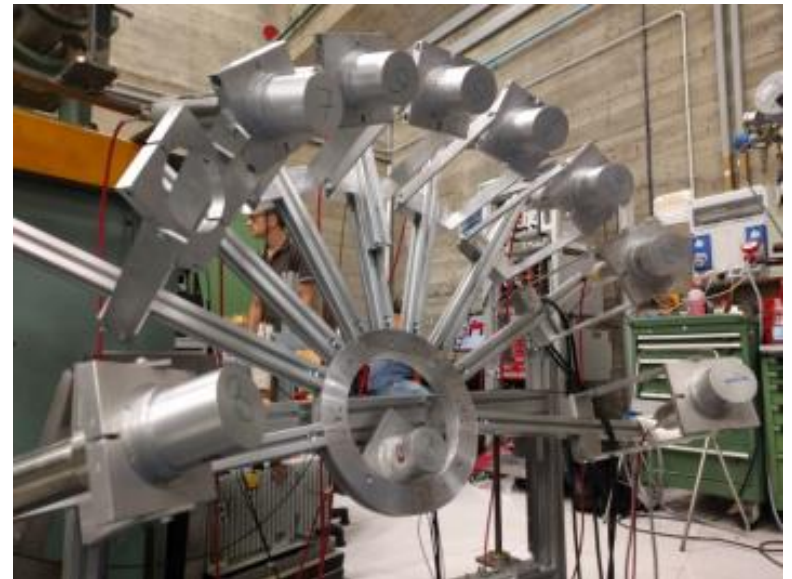
- **TPC performance appropriate** for the directionality search
 - $g_1 = 0.194 \text{ PE/ph}$, $g_2 = 20.0 \text{ PE/e-}$ ($E_{\text{drift}} = 183 \text{ V/cm}$, $E_{\text{el}} = 5.79 \text{ kV/cm}$)
 - $\sigma_{S2/S1}$ better than 12% for NR of $\sim 70 \text{ keV}$, electron lifetime $> 1 \text{ ms}$

Si detectors & neutron spectrometer

- ΔE -E telescope to tag ${}^7\text{Be}$ associated with neutrons
 - ΔE Si detector (25 μm), E Si detector (1000 μm)
 - Allows for Z separation (Li vs. Be)
 - Can be moved by a remotely-controlled stepper motor
- ${}^7\text{Li}$ beam on CH_2 target



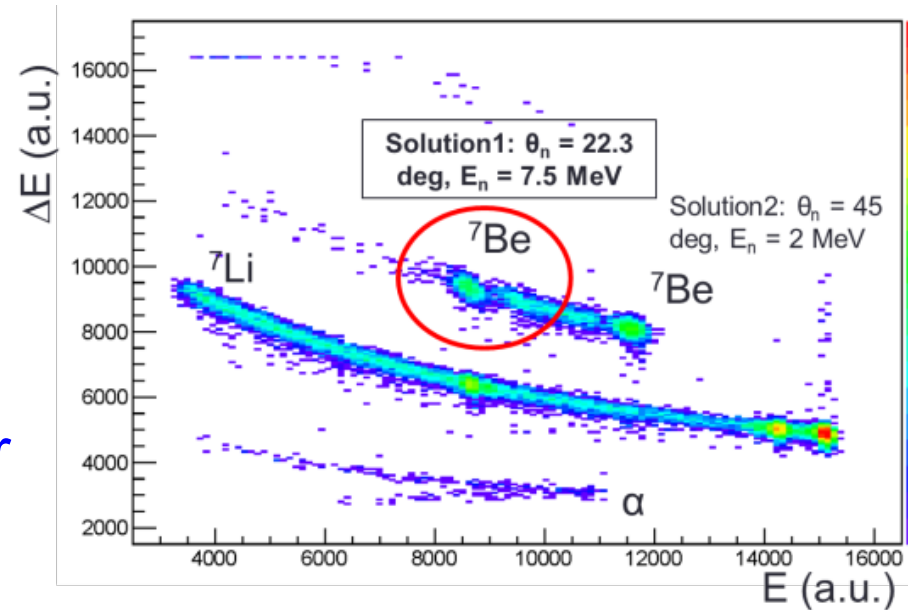
- 3-inch Liquid Scintillators cells (EJ-309), readout by PMTs
 - Featuring n/ γ discrimination
 - Absolute calibration with ${}^{252}\text{Cf}$, $\epsilon \sim 20\text{-}40\%$ for 2-8 MeV neutrons
 - Time resolution ~ 0.5 ns rms
- Arrangement within a "ring" structure
 - Tagging ${}^{40}\text{Ar}$ recoils in the TPC at $0^\circ, \pm 20^\circ, \pm 40^\circ, \pm 90^\circ$ wrt E_{drift}



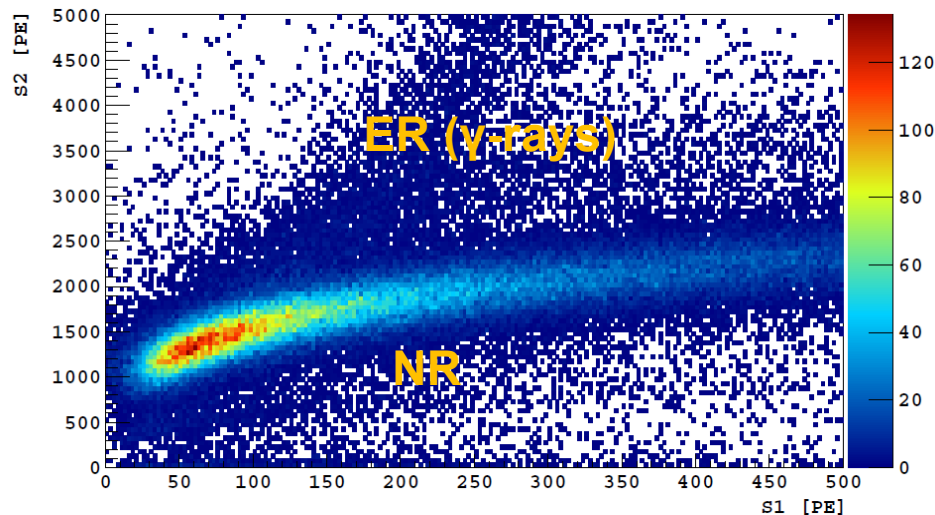
PUTTING ALL
TOGETHER

ReD run @ LNS

- Two-week beam time in **February 2020** (= 10.07 days live time)
- ${}^7\text{Li}$ beam delivered by LNS-TANDEM: **28 MeV**
 - $\theta_n = 22.3$ deg, $E_n = 7.4$ MeV \rightarrow TPC
- Energy/angles tuned to select ${}^{40}\text{Ar}$ recoils of **~ 70 keV** in the TPC
 - **Other** recoils energies selected by **changing the beam energy only**

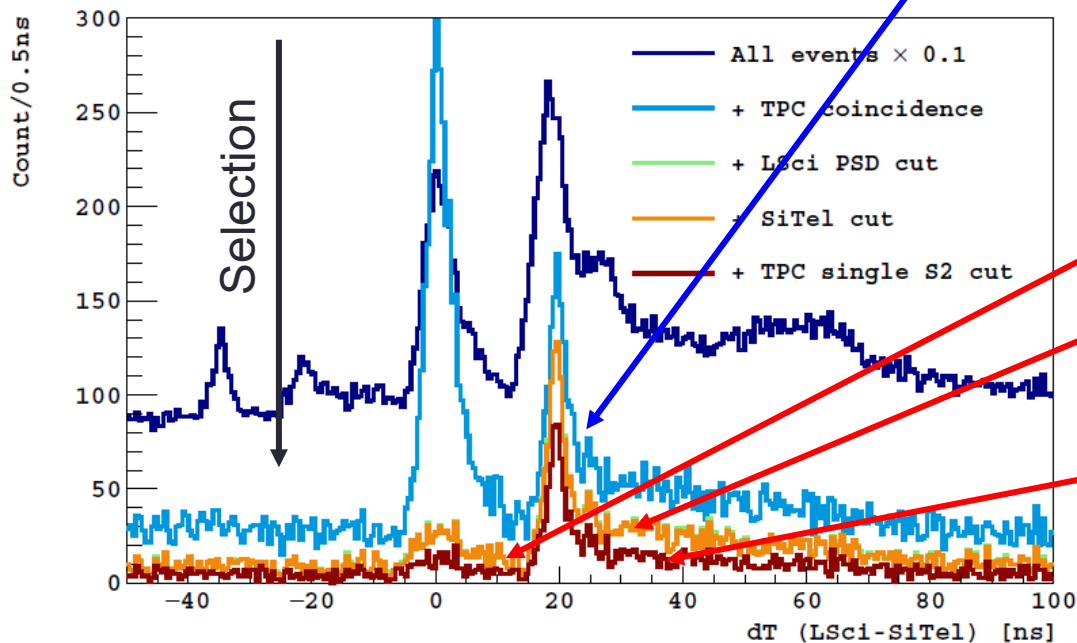
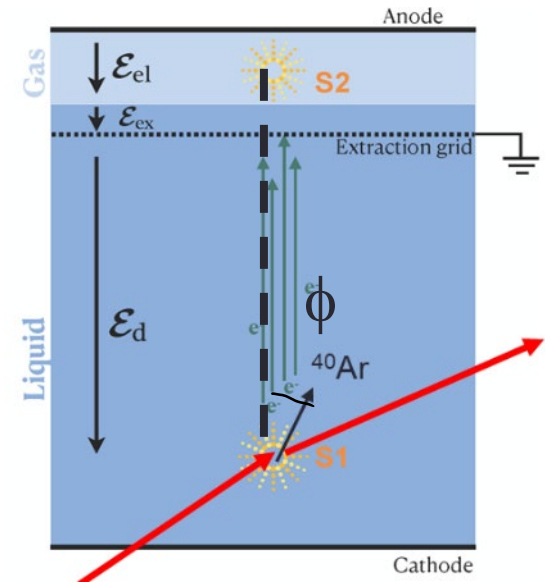


- Tagging of **neutron events** in the **TPC** by ${}^7\text{Be}$ in the Si telescope
 - Additional corrections: XY-Z, pile-up, leakage current
 - Large **sample of Ar recoil** events in TPC



Signal and backgrounds

- Signal: single Ar recoils, of same energy but different ϕ
- Full three-fold coincidences (Si \wedge TPC \wedge n-Spectrometer)
 - About **150 events/day**
- Very clean identification of events based on: ^7Be tagging, timing and PSD (TPC and LSci)
 - ToF resolution $\sim 1\text{-}2$ ns rms

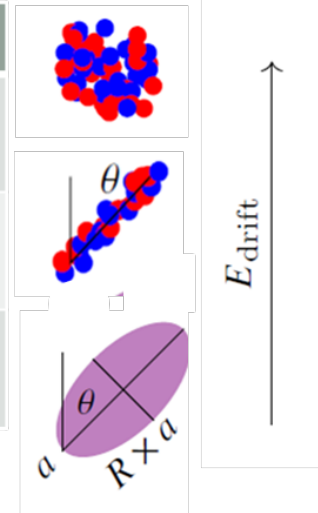


- Residual backgrounds:
 - Accidentals
 - $(n, n'\gamma)$ events in the TPC
 - Neutrons from $p(^7\text{Li}, ^7\text{Be}^*)n$
 - 63.5 keV recoils in the TPC
 - Neutrons with **multi-scattering**

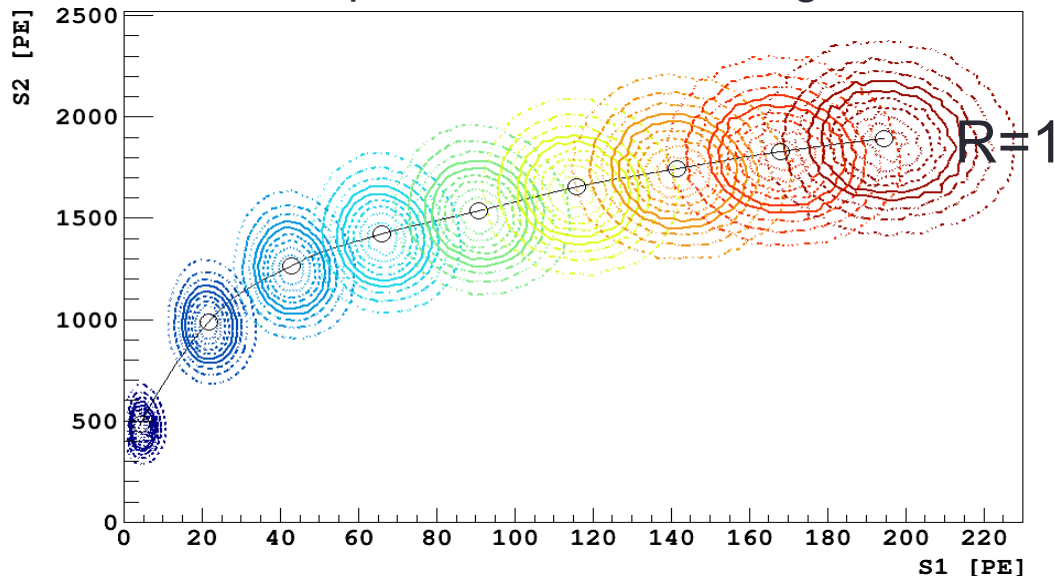
The directional model

- Data interpretation needs a **model** for the **directional effect**

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	$[\sqrt{\sin^2 \phi + \cos^2 \phi / R^2}]^{-1}$



Detector response for mono-energetic NRs

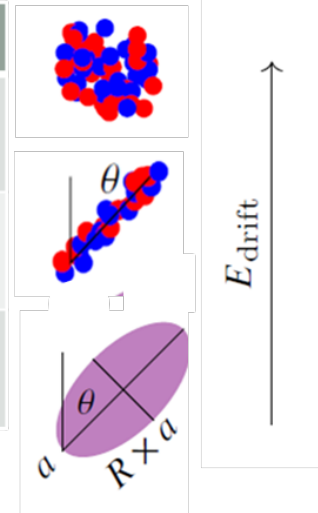


- Single parameter **R** \rightarrow **aspect ratio** of the **e-ion cloud**
 - R=1** \rightarrow **no directional effect** (Thomas-Imel)

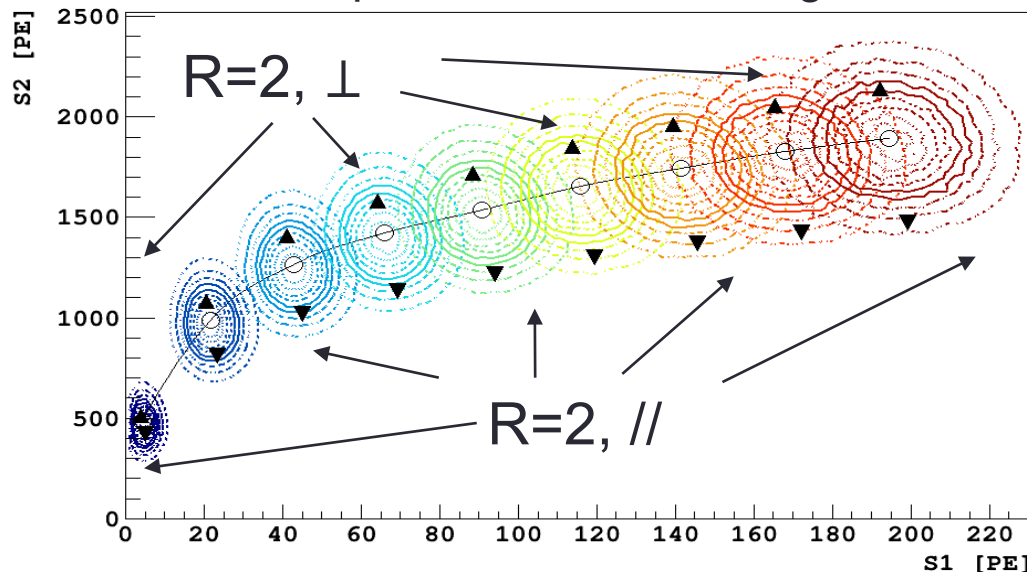
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Detector response for mono-energetic NRs



- Single parameter **R** \rightarrow **aspect ratio** of the **e-ion cloud**
 - R=1** \rightarrow **no directional effect** (Thomas-Imel)
- Impact on **detector response** \rightarrow change **S1 vs. S2 balance**

Analysis and results

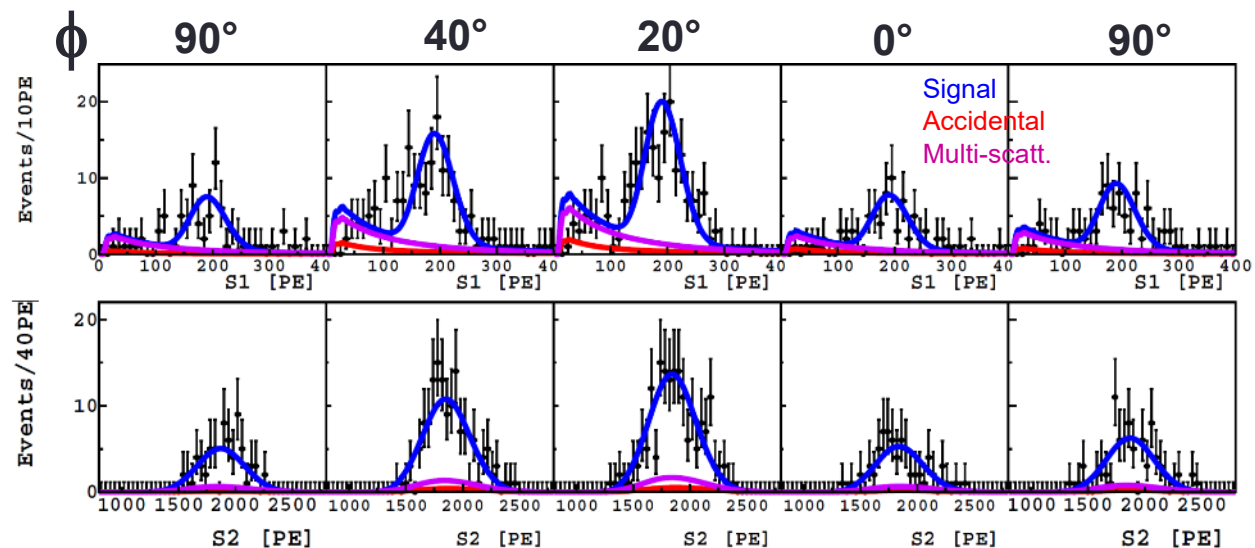


- Other ingredients:
 - NR **quenching** in Ar (Lindhard+Mei models) Phys Rev D. 91.092007
 - Fluctuations and correlations in the **detector response** (S1 & S2)
- Unbinned **maximum likelihood** fit
 - **Nuclear recoil** sample (Si \wedge TPC) and **triple coincidence** data
 - Components: **signal**, **multi-scattering**, **random coincidences**
 - **PDF** from **Geant4** simulations and/or **data-driven** (side bands)
 - **Nuisance** parameters (e.g. g_1, g_2) constrained with **pull terms**
- R is the **only** parameter of interest

$$R = 1.036 \pm 0.024$$

No effect

(Preliminary!)



Conclusions and outlook

- ReD has a two-fold value as a **physics experiment** (**directionality**, and possibly **low-energy characterization**) and as a **test bench** for the DarkSide-20k new technologies
- Produce **nuclear recoils** by neutron scattering
 - Neutrons from **$p(^7\text{Li}, ^7\text{Be})n$** with a **$^7\text{Li}$** beam of 18-30 MeV
- Two-week run in February 2020 at LNS, with **^7Li beam**
 - Run tailored to **directionality studies**, $E_{\text{Ar}} \sim 70$ keV ($E_n = 7.4$ MeV)
 - Data analysis according to the ***Cataudella et al.* directionality model** (parameter $R \rightarrow$ **aspect ratio** of the cloud)
- **No evidence** of **directional** effect at ~ 70 keV_{nr}
 $R = 1.036 \pm 0.024$ (Preliminary!)
- Information about directional sensitivity crucial for the **design** of the next-generation **experiment ARGO** by GADMC
- Future studies focused to **low-energy response** ($< \text{few keV}$)
 - Using **^{252}Cf neutron source**, currently **under preparation** at INFN Catania