Recent Low Mass Results with the Recoil Directionality (ReD) Experiment

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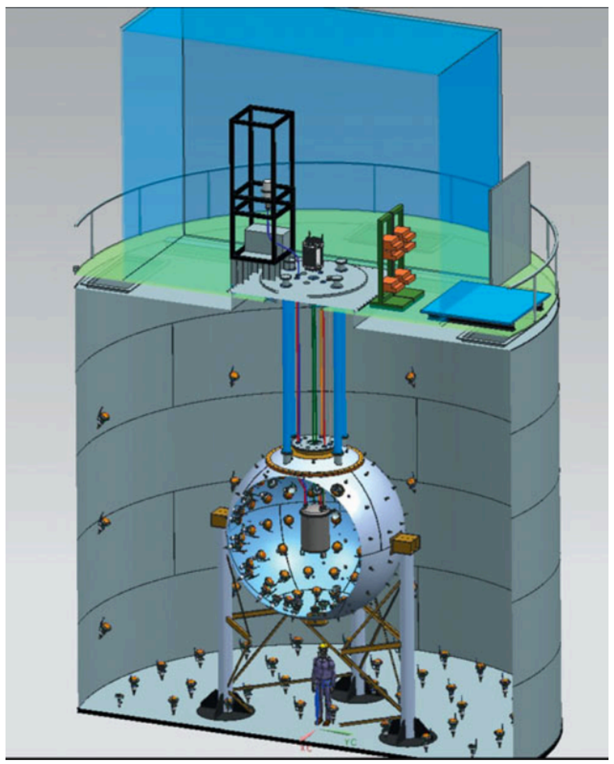
IFUSP

on behalf of the ReD Working Group (GADM Collaboration)

TeVPA Meeting

Napoli - 13th September 2023

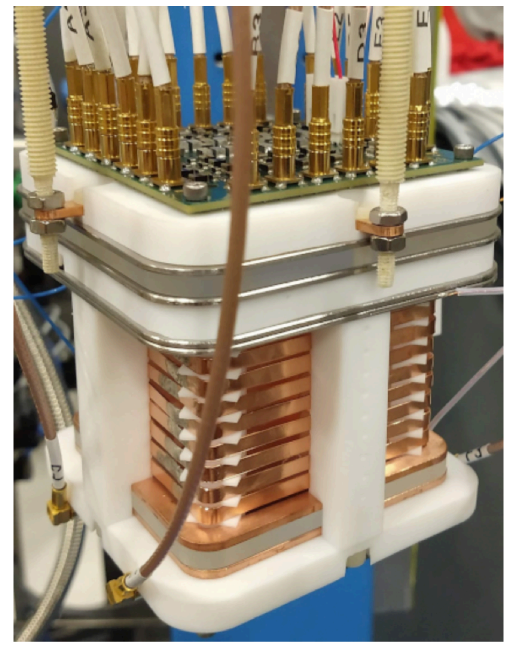
DarkSide LAr Detectors



DS-50

Oct 2013 - Feb 2018

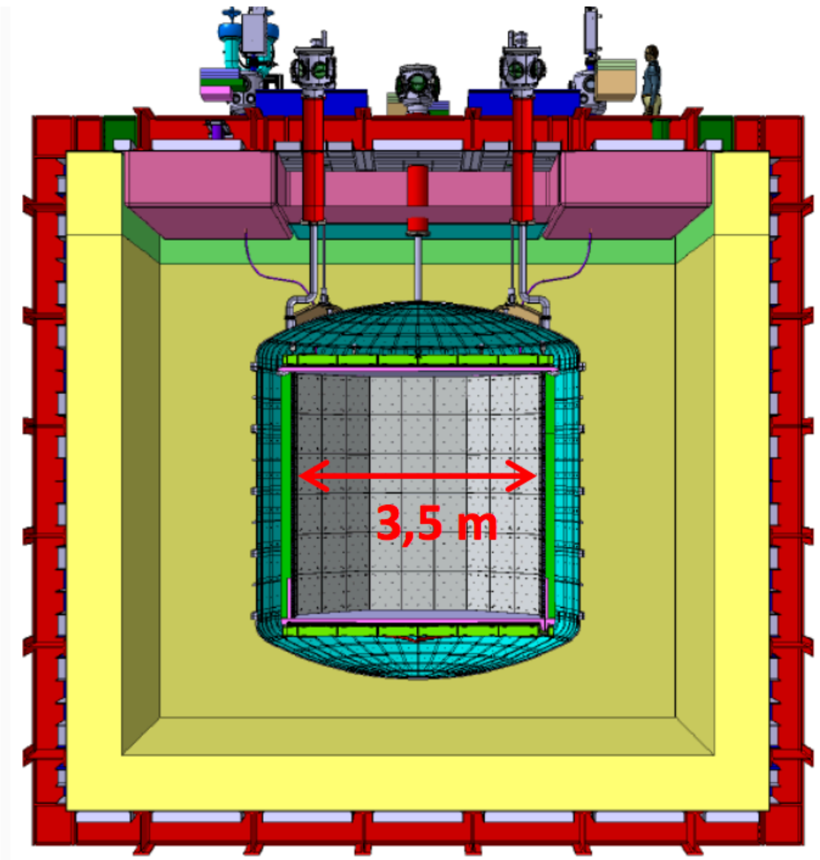
- **532 days Results: PRD 98 (2018)**
- **Low-mass DM: PRL 121(2018);**
  PRD 107(2023)
- **Migdal effect: PRL 130 (2023)**
- **Leptophilic DM: PRL 121 (2018);**
  PRL 130 (2023)
- **Low-mass Bayesian: EPJC 83 (2023)**



ReD

(185g)

at LNS - INFN
Catania

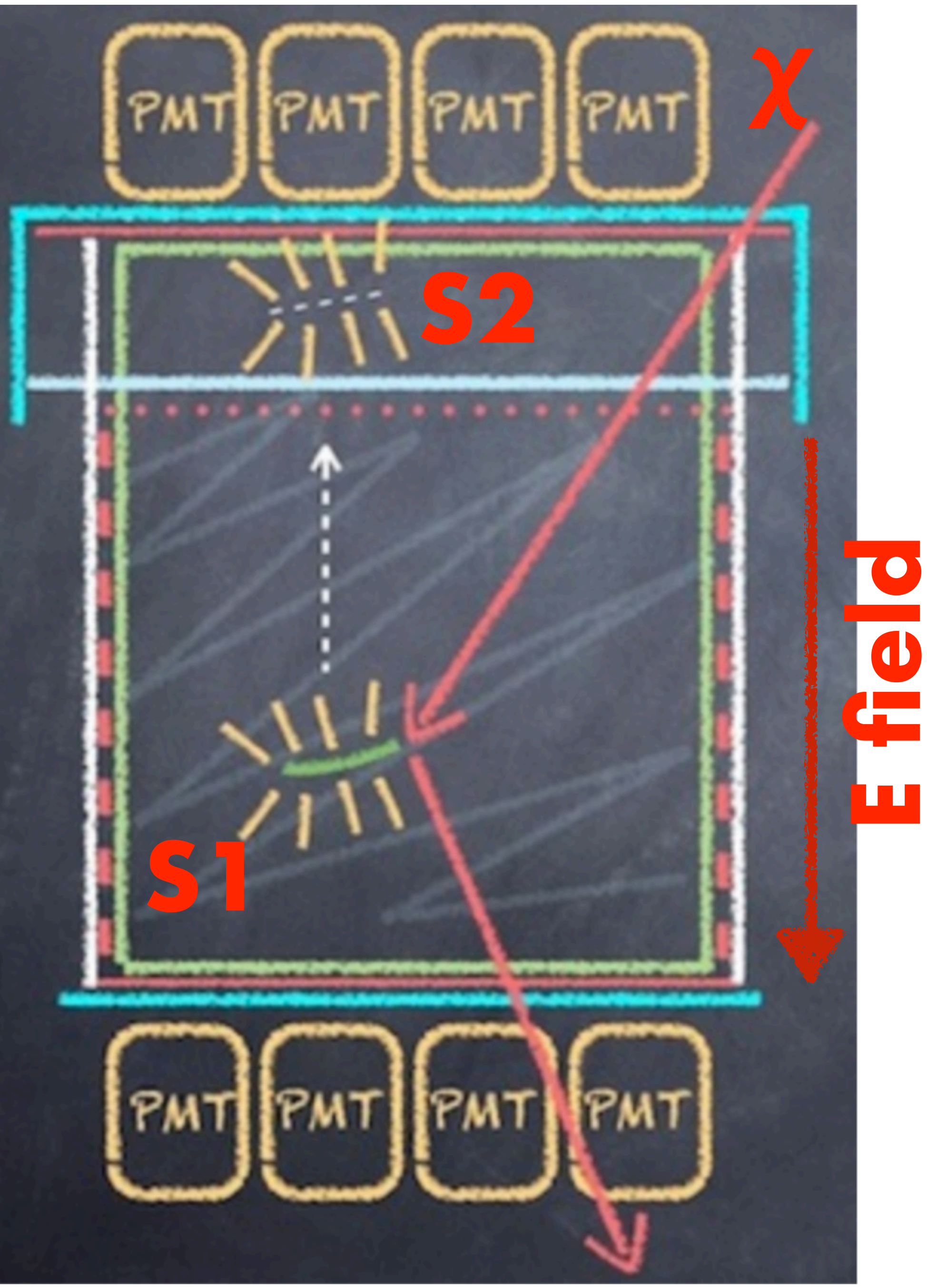


DS-20K

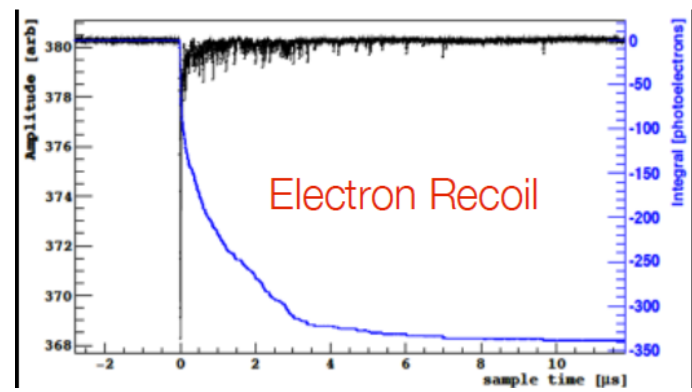
2026

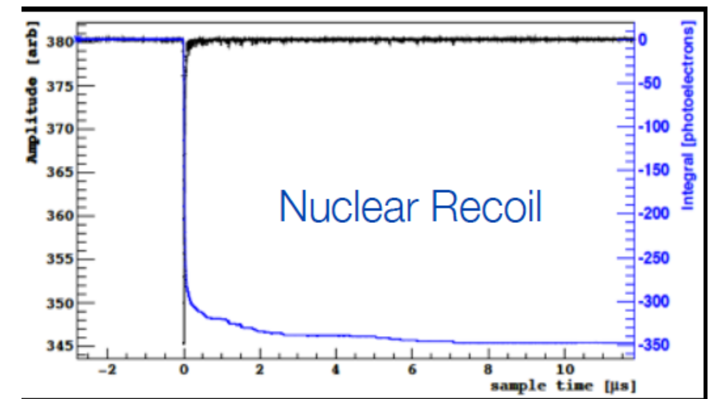
DS-LM...

Double Phase TPC's



LAr Pulse Shape Discrimination

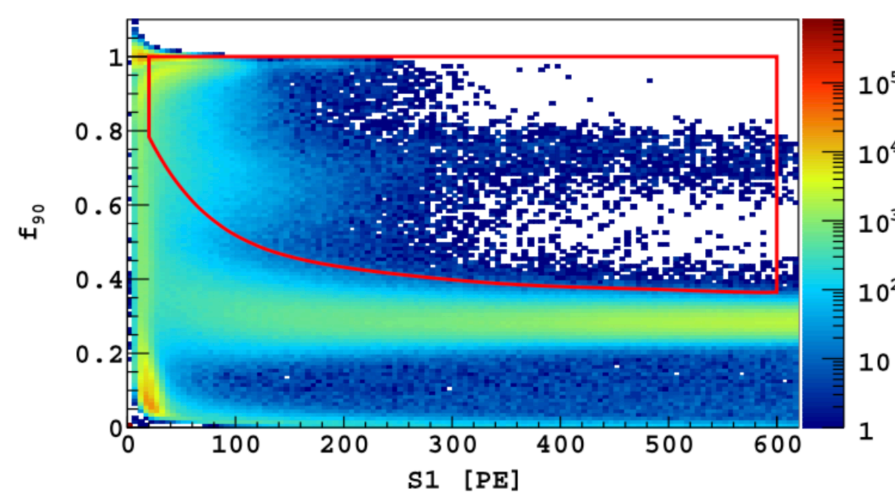




S1: prompt scintillation signal

DS50 PSD: f90

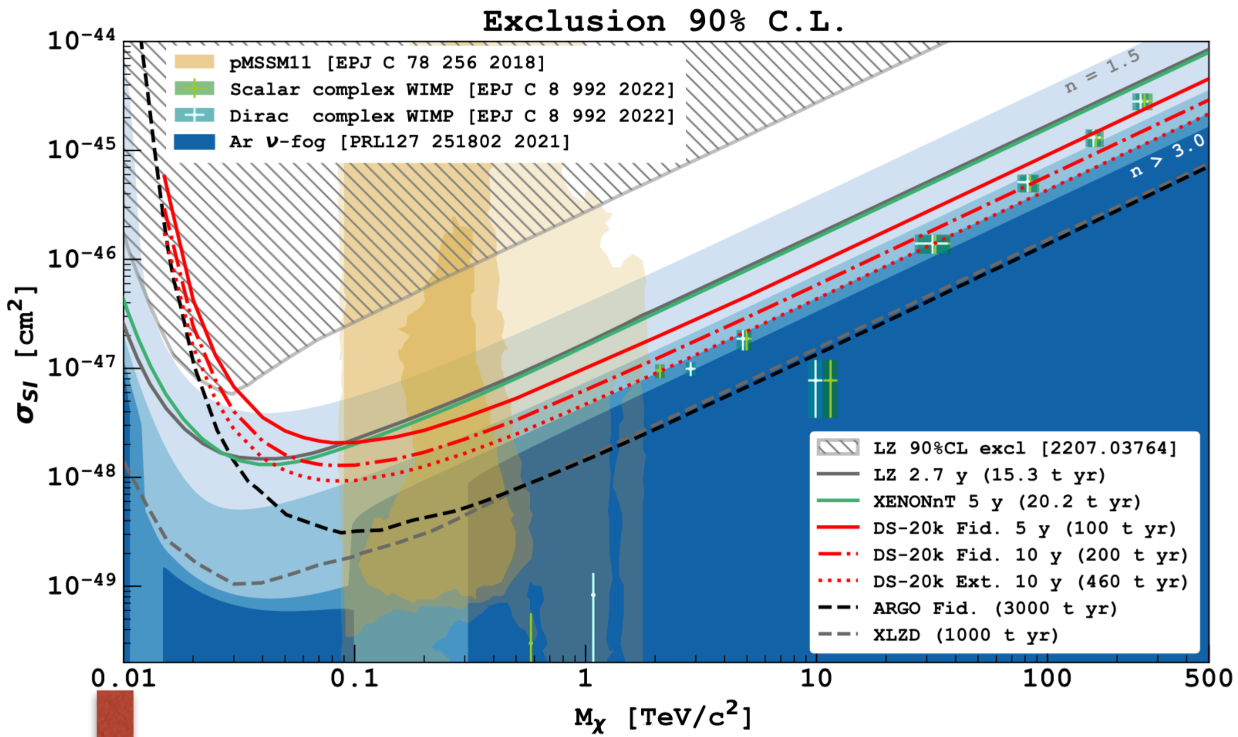
(fraction of S1 light collected within 90 ns)



Nuclear Recoils

Electron Recoils

DS-50 Low Mass Analysis



10 GeV/c²

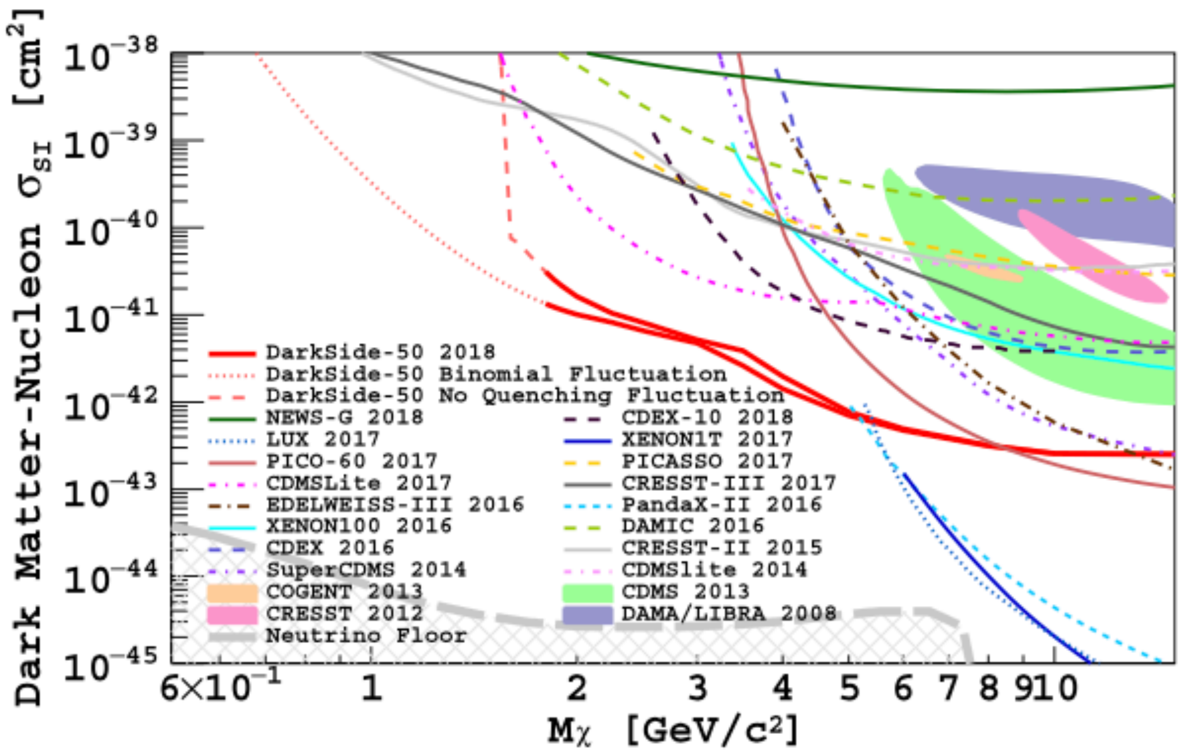
Dark Sector & Asymmetric DM

$$m_\chi \leq 10\ \mathrm{GeV/c^2}$$

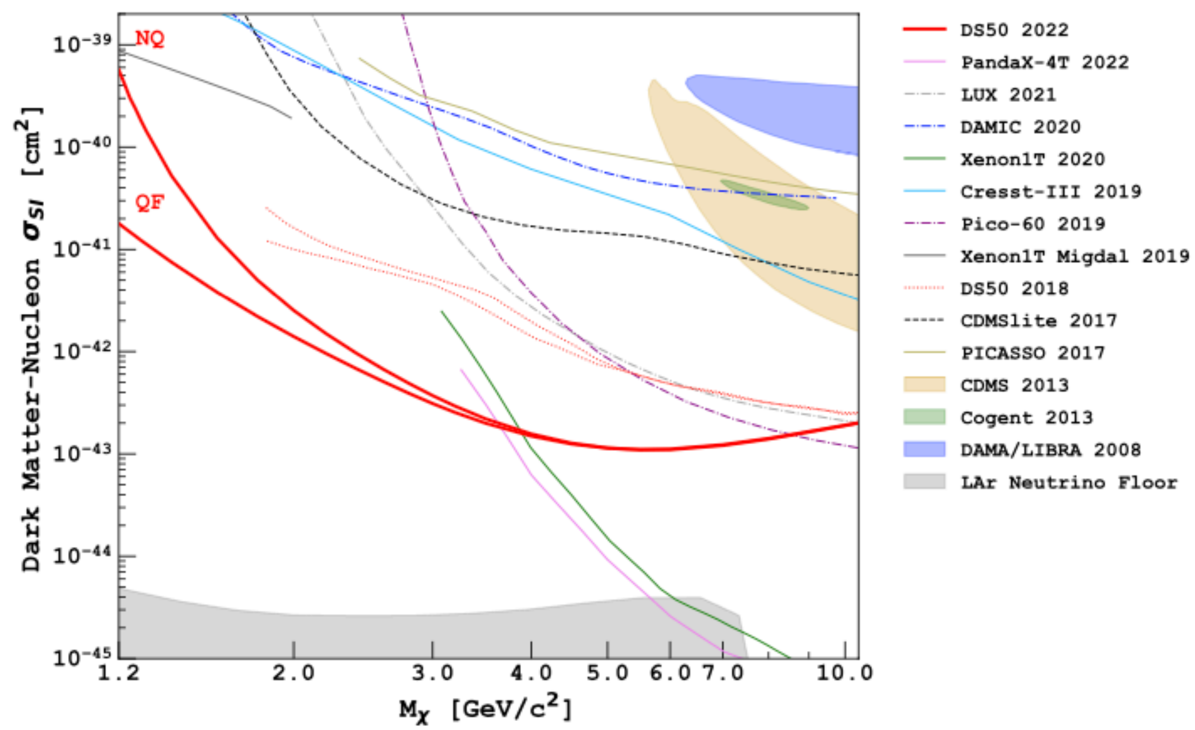
S2 only analysis

- Scintillation light (S1) is too low => not detectable
    - Give up Pulse Shape Discrimination

DS50 Low Mass Results



PRL 121 (2018)
DS50



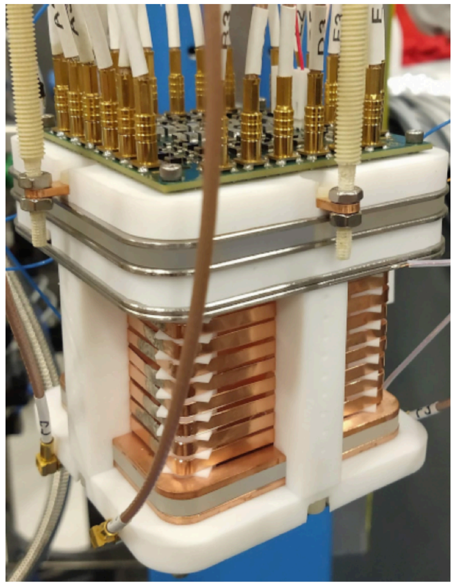
PRD 107(2023)
DS50

Better measurement of ionization yield at low energy is crucial

REcoil Directionality Experiment

Main goals:

- dark matter directionality (Agnes et al. arXiv:2307.15454)
- low recoil energy measurement
- test SiPM for DS-20K



ReD TPC:

- DS20K miniature (5x5x6) cm3
- Characterization and Commissioning here at UniNA

Eur. Phys. J. C, 81 (2021)

Low Energy Modes

GOAL: Measure ionization yield for keV NR in LAr

- Radioactive sources and Neutron Generator

[$\mathcal{O}$(2 MeV)] Neutrons

^{252}Cf neutron source (1.48 MBq)

at INFN - Catania

(2 - 5) keV detected energy range

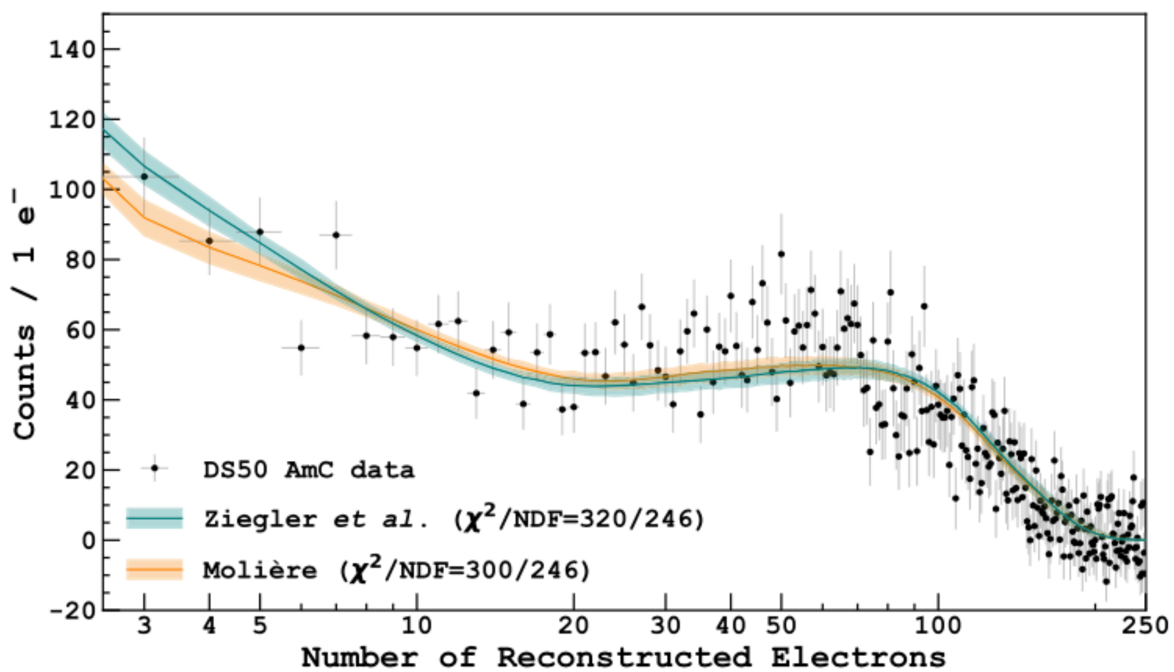
DD Neutron Generator

to be commissioned at USP - Brazil and to be taken to LNS

Down to 0.5 keV detected energy range

LAr Nuclear Recoil Ionization Yield

DS50 NR measurement: calibration with AmC and AmB neutron sources



$$E_{er} = w\left(\frac{S1}{g_1} + \frac{S2}{g_2}\right)$$

w = work function

g_i = S_i collection efficiency

$$N_{i.e.} = \frac{S_2}{g_2} - 1$$

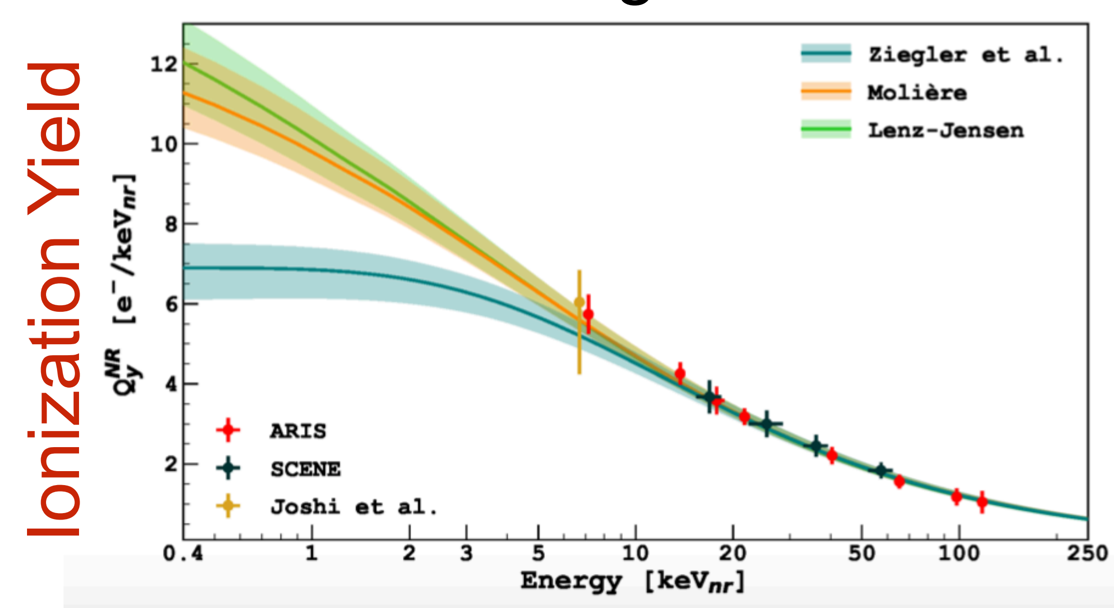
Assumes 2 free parameter model

Ionization Yield = $N_{ie}/E_{nr} = N_i(1 - r)/E_{nr}$

Number of produced e⁻ - ion pairs (1 free par)

Thomas-Imel (1 free par)

Different screening models at low energy

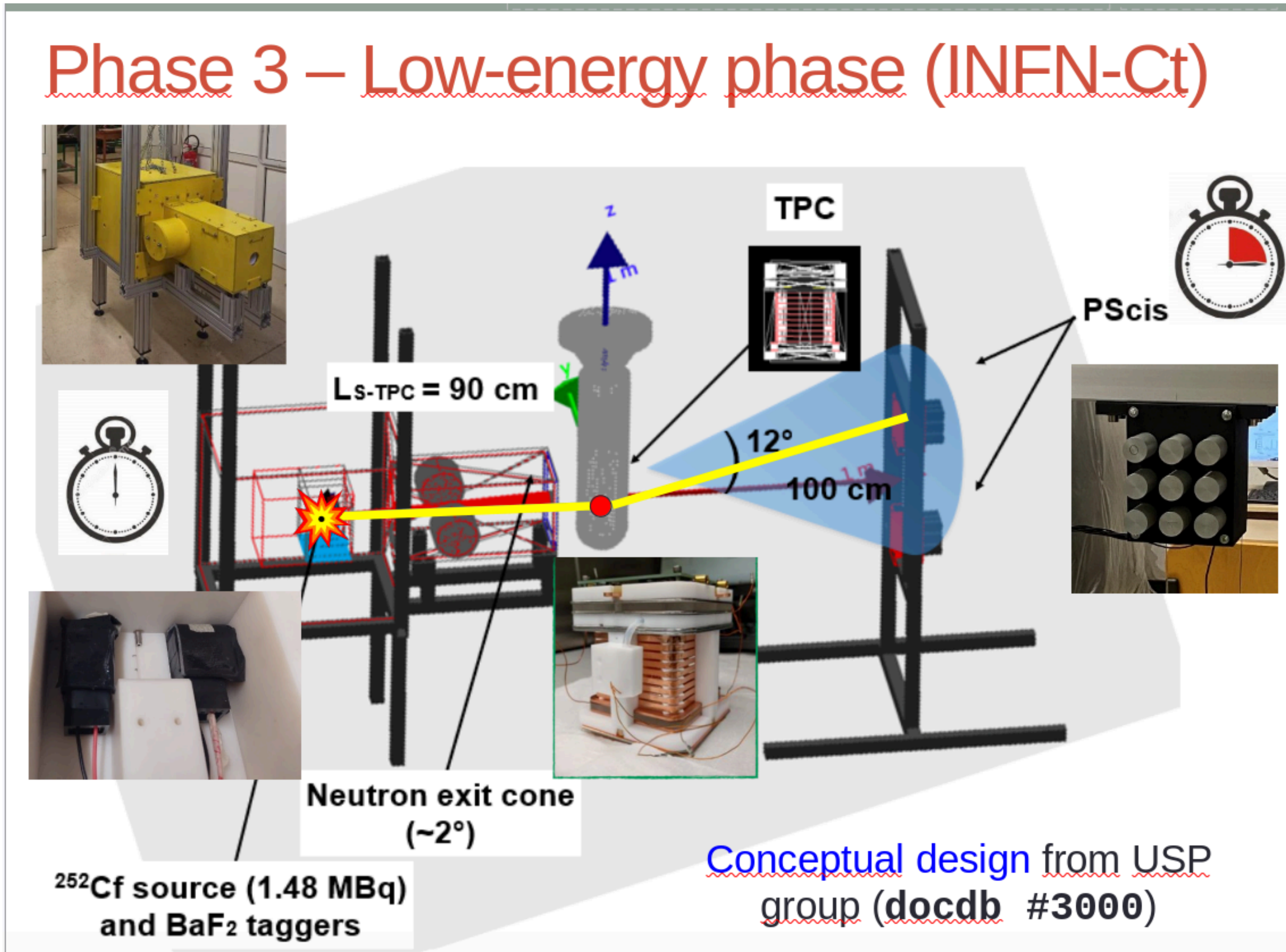


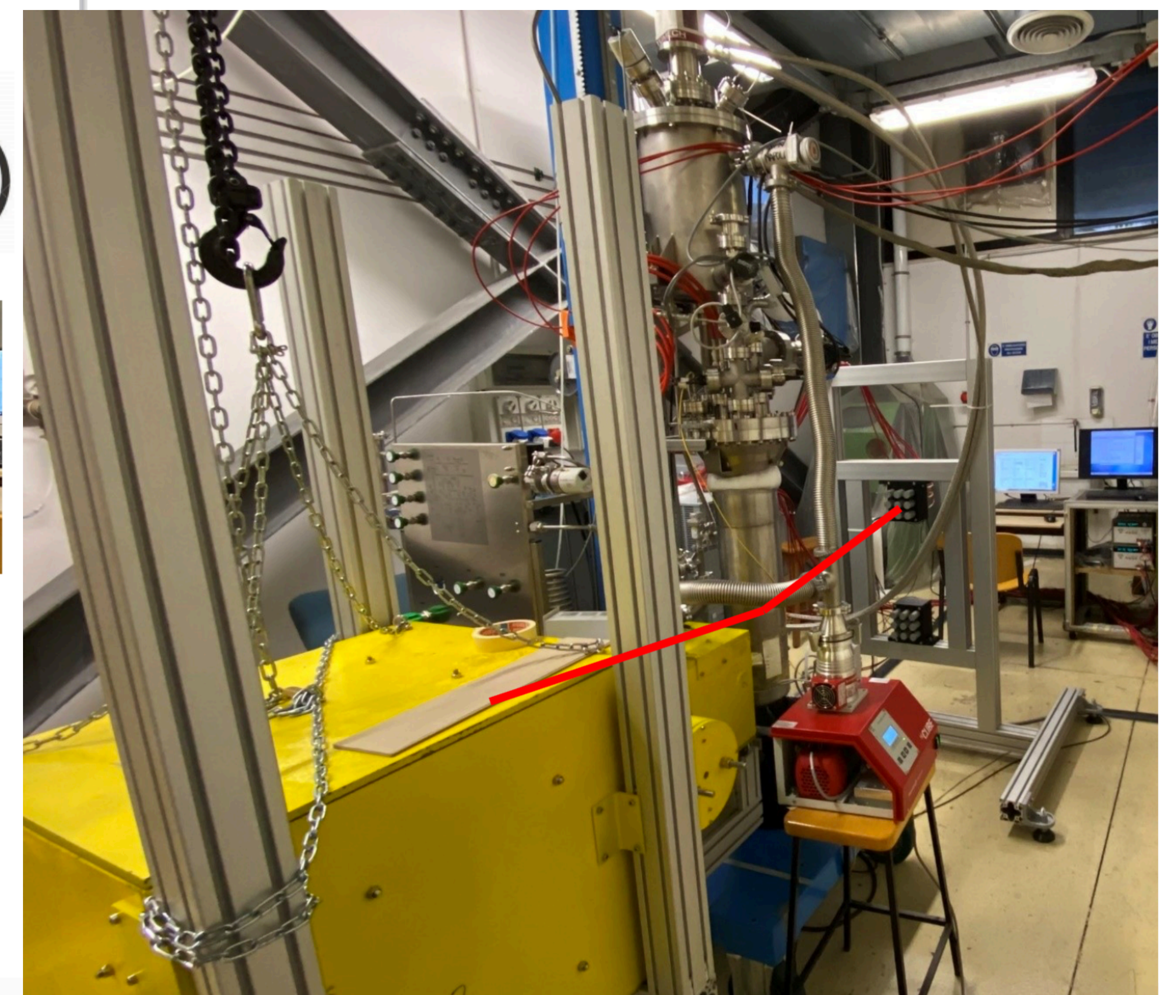
Constrained by DS50 AmC - MC based measurement

(no closed 2-body kinematics)

ReD can make direct measurement at 1-5keV NR

^{252}Cf as neutron source



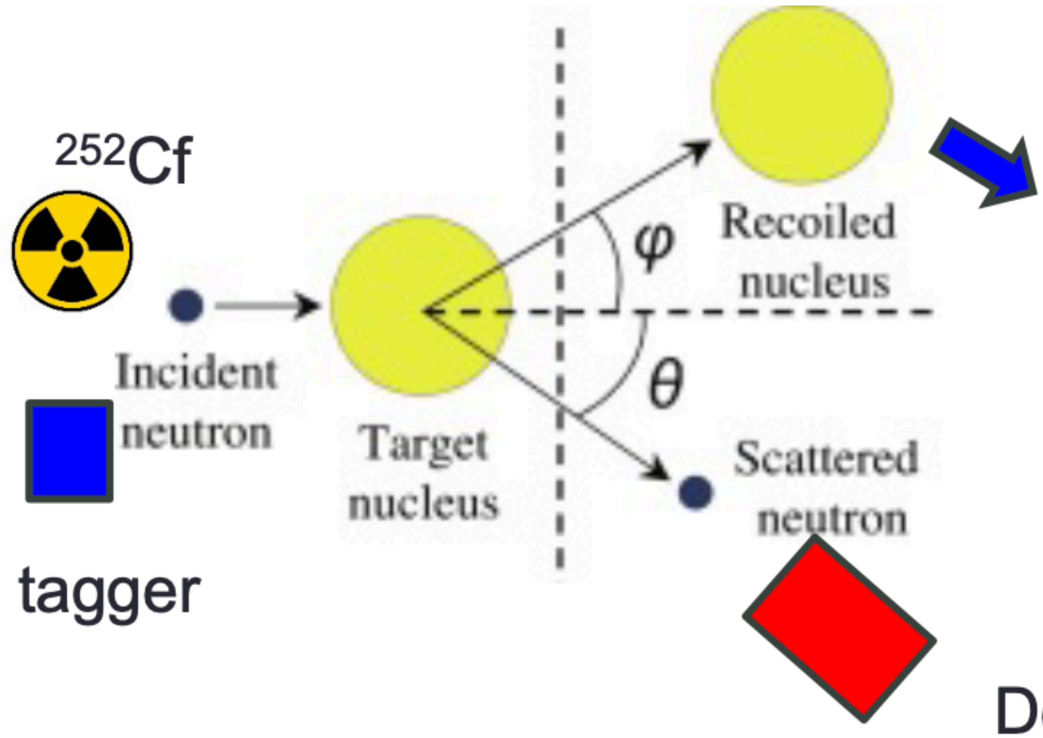


@ INFN-Catania

Credit: Luciano Pandola

- **Tag Neutron production (BaF2): ToF determines n energy**
- **TPC vertex + PSci position + $E_{neutron}$ => Recoil energy**
- **θ = 12^{o} => E_{NR} = 3 keV for 2.5 MeV neutrons**

2 Body Decay Kinematics



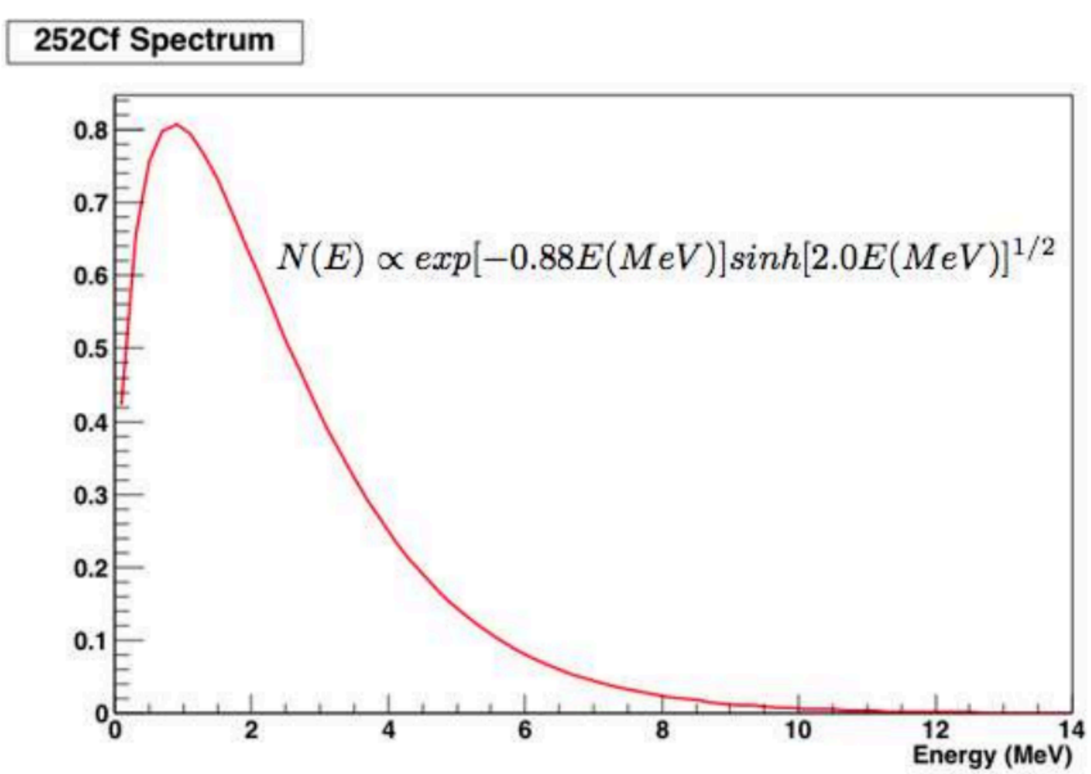
$$E_{NR} = 2KE_{neutron}\frac{m_n m_{Ar}}{(m_n + m_{Ar})^2}(1 - cos\theta_{scatt})$$

Time of flight

Fixed by geometry

Two-body kinematics!

(Credit: Luciano Pandola)

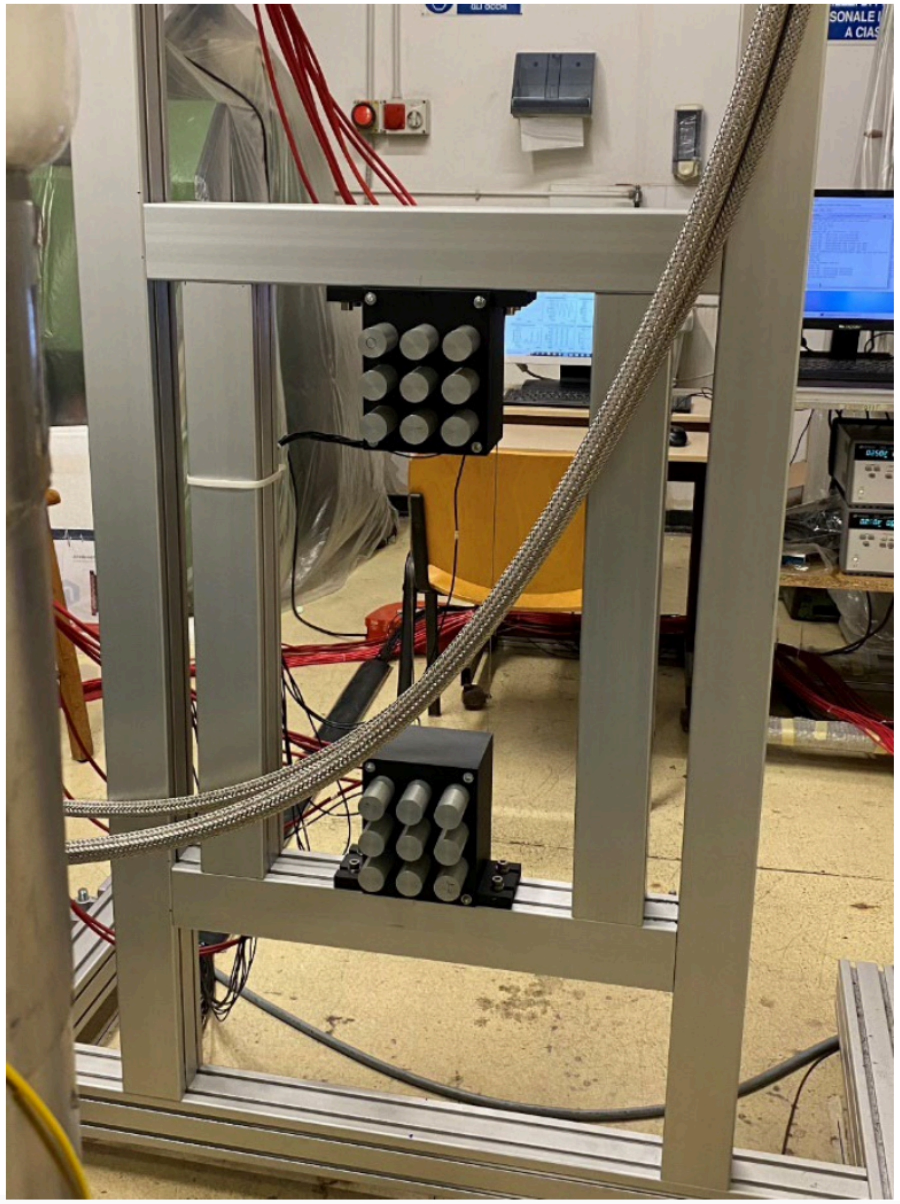


BR: 3% Spontaneous fission: neutron emission (3.76 multiplicity) + prompt gammas

97% alphas

Neutron Spectrometer

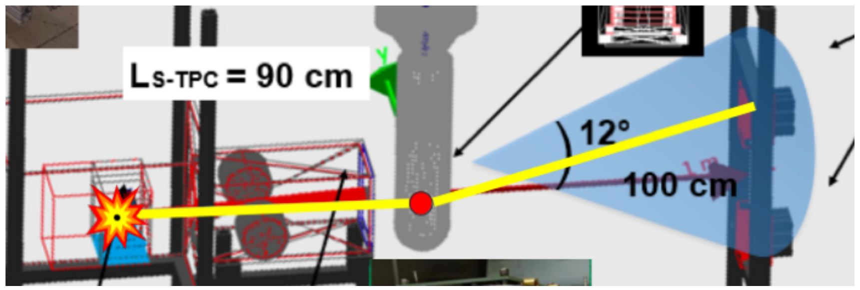
- 1" EJ276 **plastic scintillators**
  - Good timing (0.5 ns rms) → STOP for time of flight
  - Features n/γ discrimination capability
- Two **arrays** made by **3x3** detectors
  - Symmetric deployment to control systematics due to alignment
  - Placed about 1 m downstream the TPC
  - θ ~ 12°-17° in order to **avoid direct neutrons** from the source
  - Tag Ar recoils down to ~1-2 keV_{nr}



(Credit: Luciano Pandola)

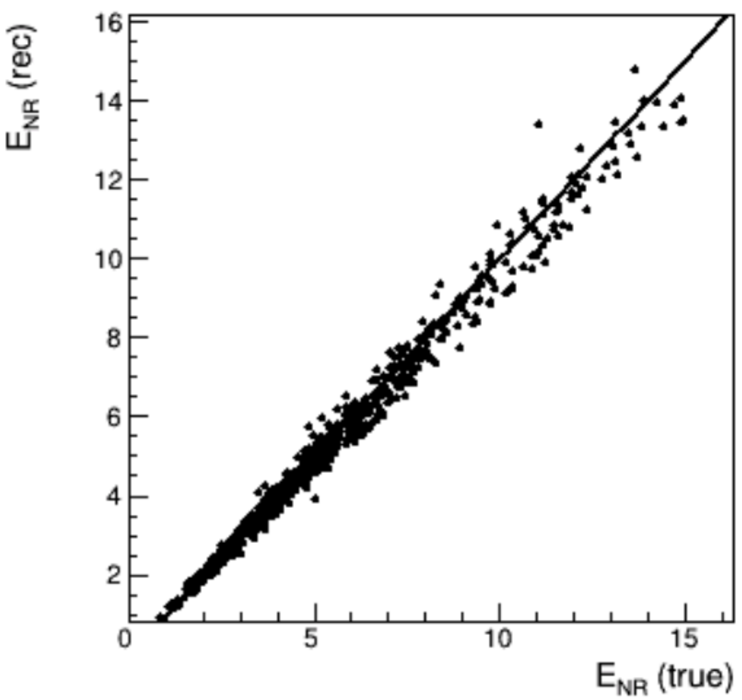
^{252}Cf Data Taking

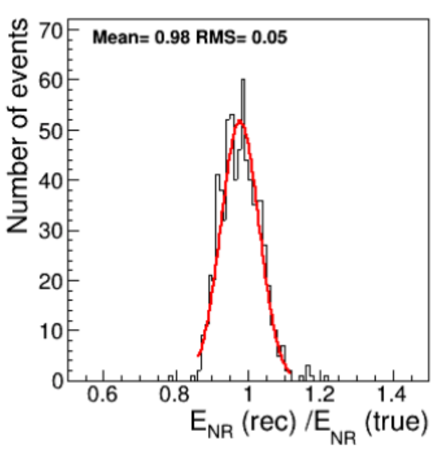
- **Jan 10 to March 16th: ~ 2.5 Hz**



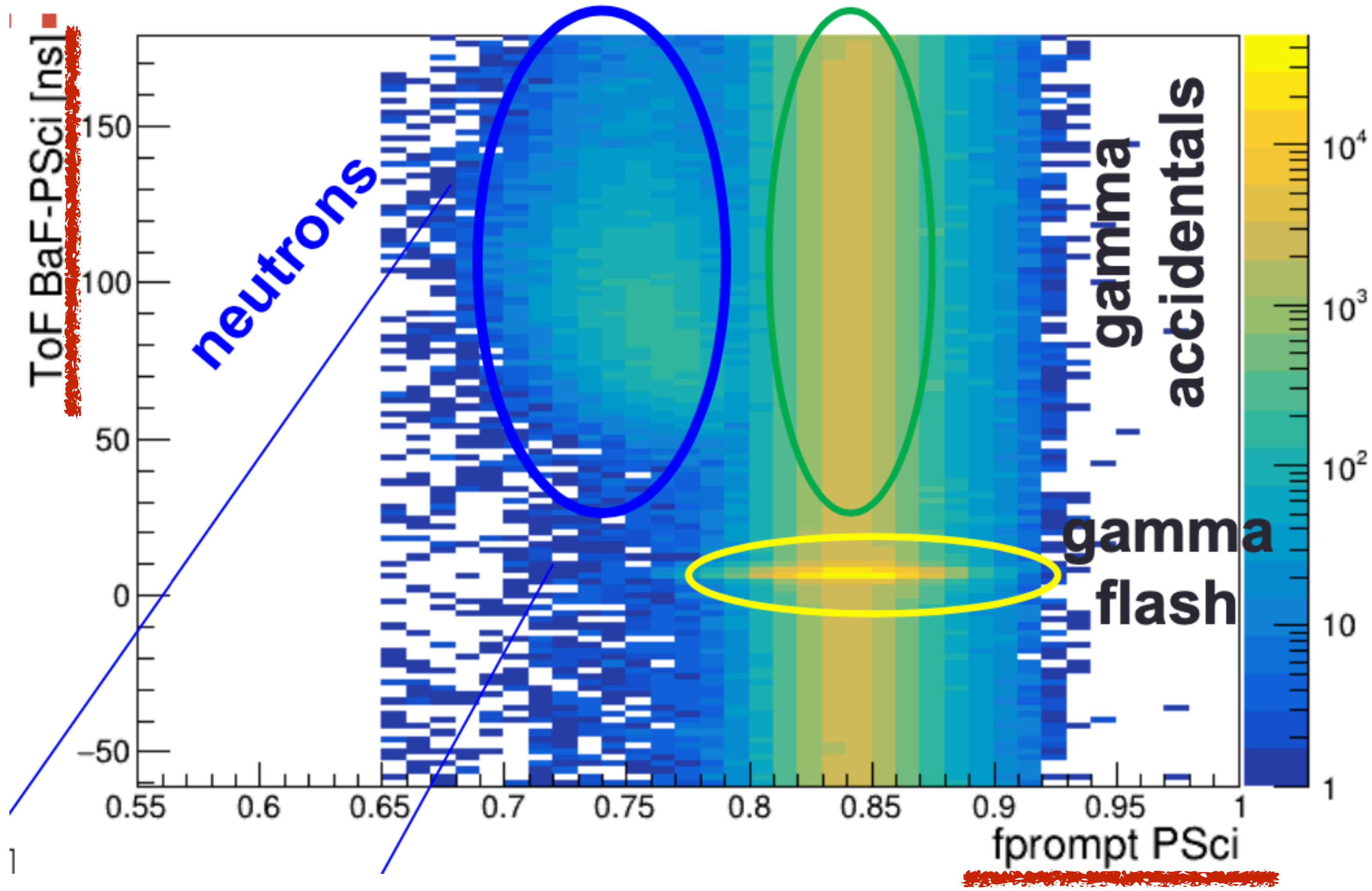
- Trigger: any BaF tagger AND any PSc (neutron detector)
- TPC does not require S1

- Weekly calibration with laser and ^{137}Cs/^{241}Am
  - determine and correct for non-homogeneity in the TPC response
- Detailed Monte Carlo data: same flow as real data
  - Tuned and validated with calibration data
- Essential to check reconstruction algorithms





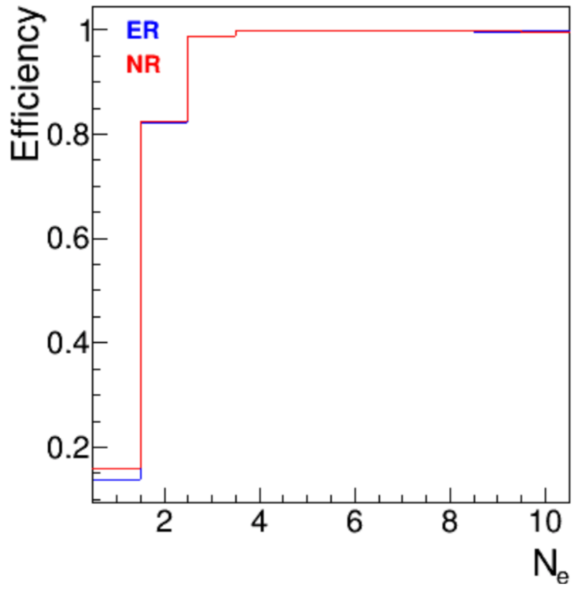
Neutron Candidates



- Events dominated by γ
- Neutrons selected by ToF + PSD in PSc (ToF res ~ 0.7 ns)
- ~28 events/h (0.3%)

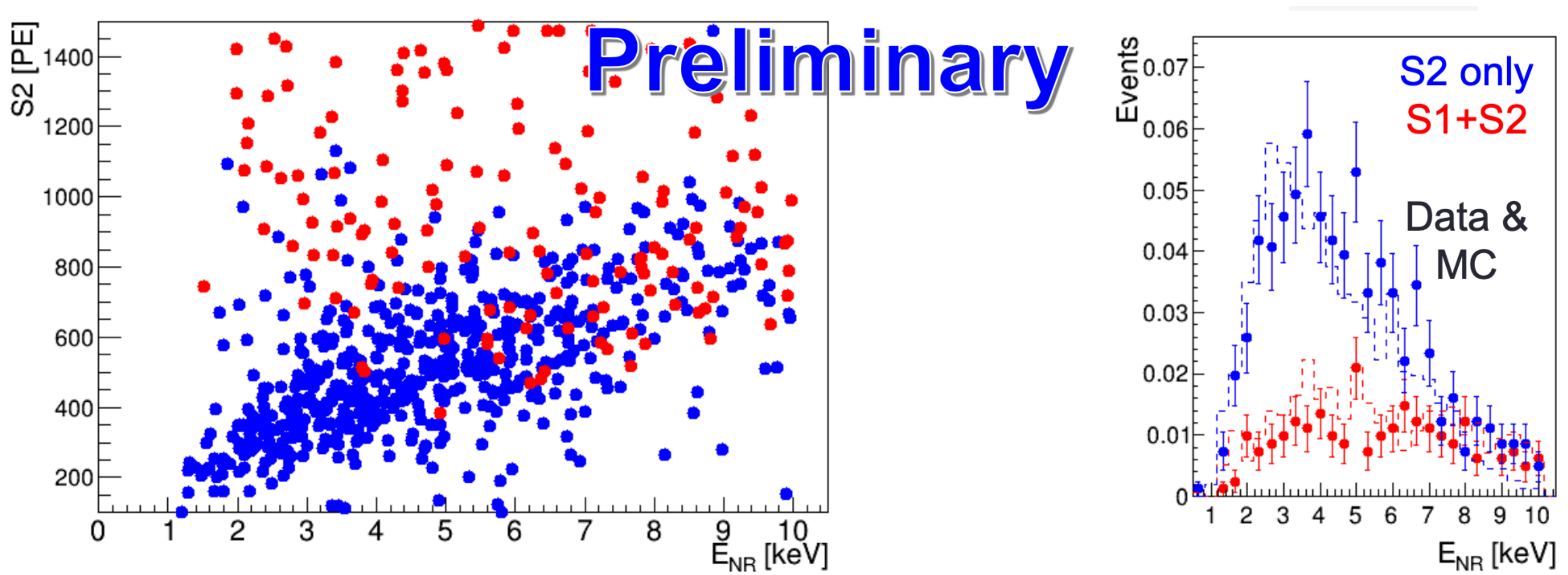
TPC Neutron Selection

- **TPC events are seen offline**
  - pulse finder (MC): fully efficient at S1 > 25 PE; S2 > 4 electrons



- **Requirements:**
  - Fiducialization: 4 cm x 4 cm
  - One S2 within 65 ns from BaF
    - and optionally an S1 with <100 PE with consistent ToF from BaF
  - No tails from previous S2 pulses

TPC Neutron Candidates

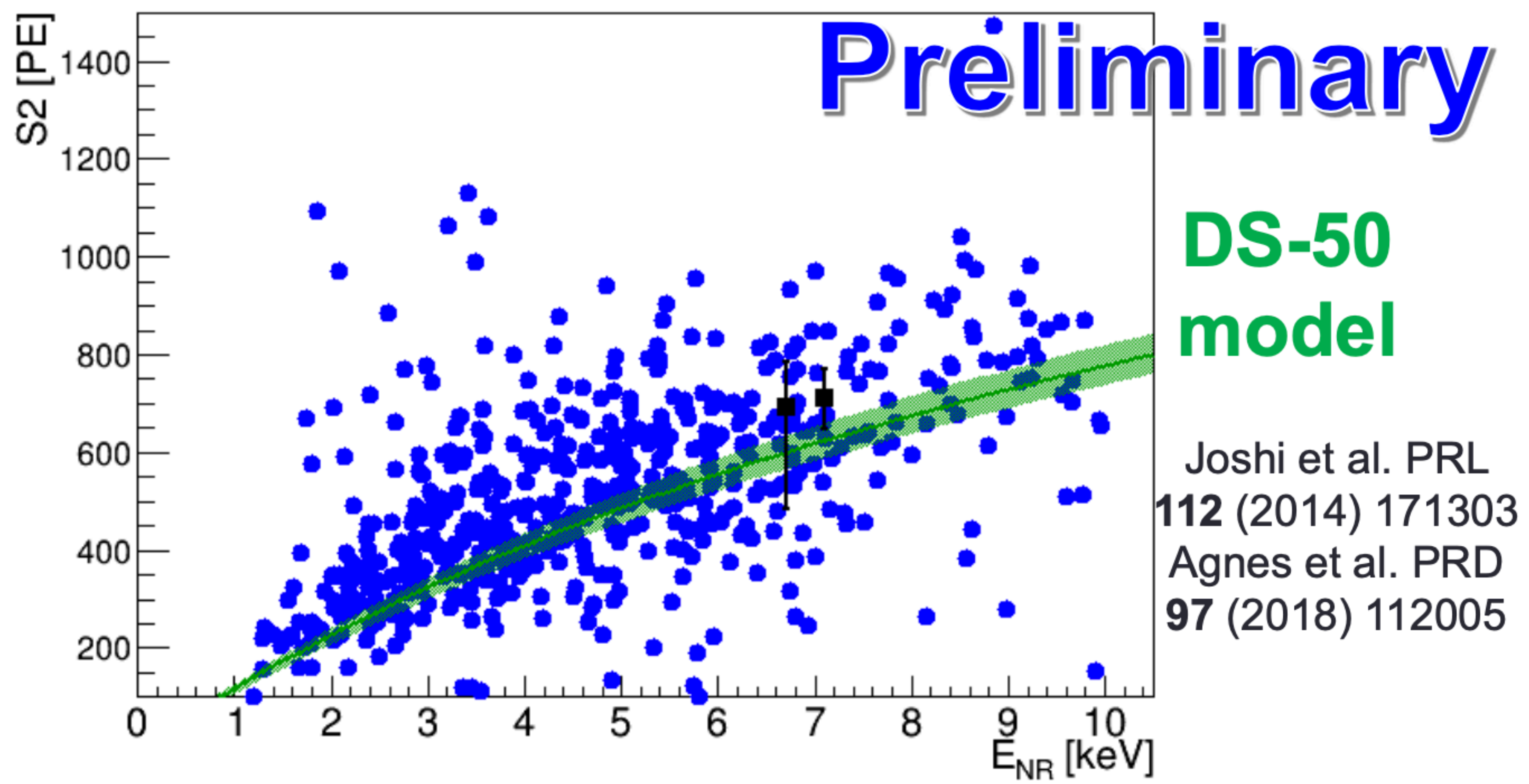


820 neutrons out of 3200 initial TPC sample

75% are S2 only (compatible with MC)

Most S1 + S2 are multiple scattering neutrons

ReD Low Mass Preliminary Results



- From S2-only: E_{NR} down to 1-2 KeV_{NR}
- Compare to prediction from DS50 + other models using g2 = 17.2 PE/e-
- NEXT: Infer g2 directly from ReD data

Conclusion and Prospects

- ReD has successfully measure the response of LAr down to 1-2 KeV_{NR}

Near Future - ReD+

- Extend ^{252}Cf measurements (Italian PRIN funding)
- Neutron Generator as source (Brazilian FAPESP funding)

Down to 0.5 keV detected energy range

Key Conclusion

ReD will measure LAr nuclear quenching down to 1/2 single KeV units

Crucial for Light Dark Matter Searches with LAr targets

DS20k Low Mass analysis can improve by a factor of 50 irt DS50

BACKUP SLIDES

Ionization Yield

- **kinetic energy:** $$E = w\left(\frac{S1}{g_1} + \frac{S2}{g_2}\right)$$ **w = <energy> to produce ion-e- pair**
g1(2) = S1(2) collection efficiency

- **ReD preliminary result: g2 = 17 PE/e- (@ E_{drift} = 200V/cm)**

- **DS50 ionization yield model:**

NR Ionization Yield = $N_{ie}/E_{nr} = N_i(1 - r)/E_{nr}$

Number of produced e-ion pairs (1 free par)

Thomas-Imel (1 free par)

$$1 - r = \frac{1}{\gamma N_i} \ln(1 + \gamma N_i)$$

$$N_i = \beta\, \kappa(\epsilon) = \beta \frac{\epsilon\, s_e(\epsilon)}{s_n(\epsilon) + s_e(\epsilon)}$$

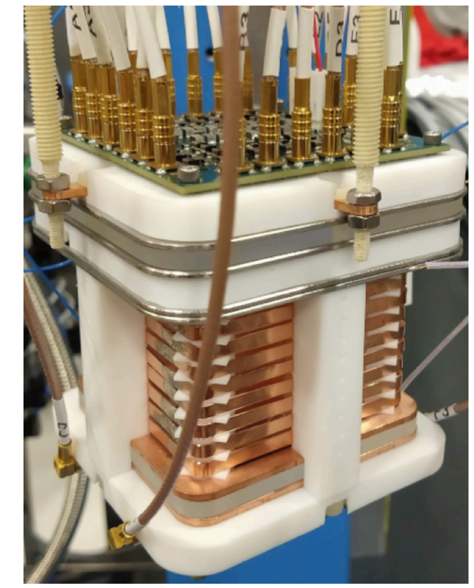
^{252}Cf vs NG

NG has an upper hand:

- **NG rate is 30 x ^{252}Cf setup**
- **Signal to Accidental: NG 13 x better**
- **Neutron energy: NG: given**
  ^{252}Cf: reconstructed
- **Neutron tagging: NG tagger defines neutron cone**
  Cf: 4 pi neutron beam; shield provides cone
- **NG can be used to measure n-LAr XS at 2.4 MeV**

However different systematics => use both

REcoil Directionality Experiment



Main goals:

- dark matter directionality
- low recoil energy measurement
- test SiPM for DS-20K

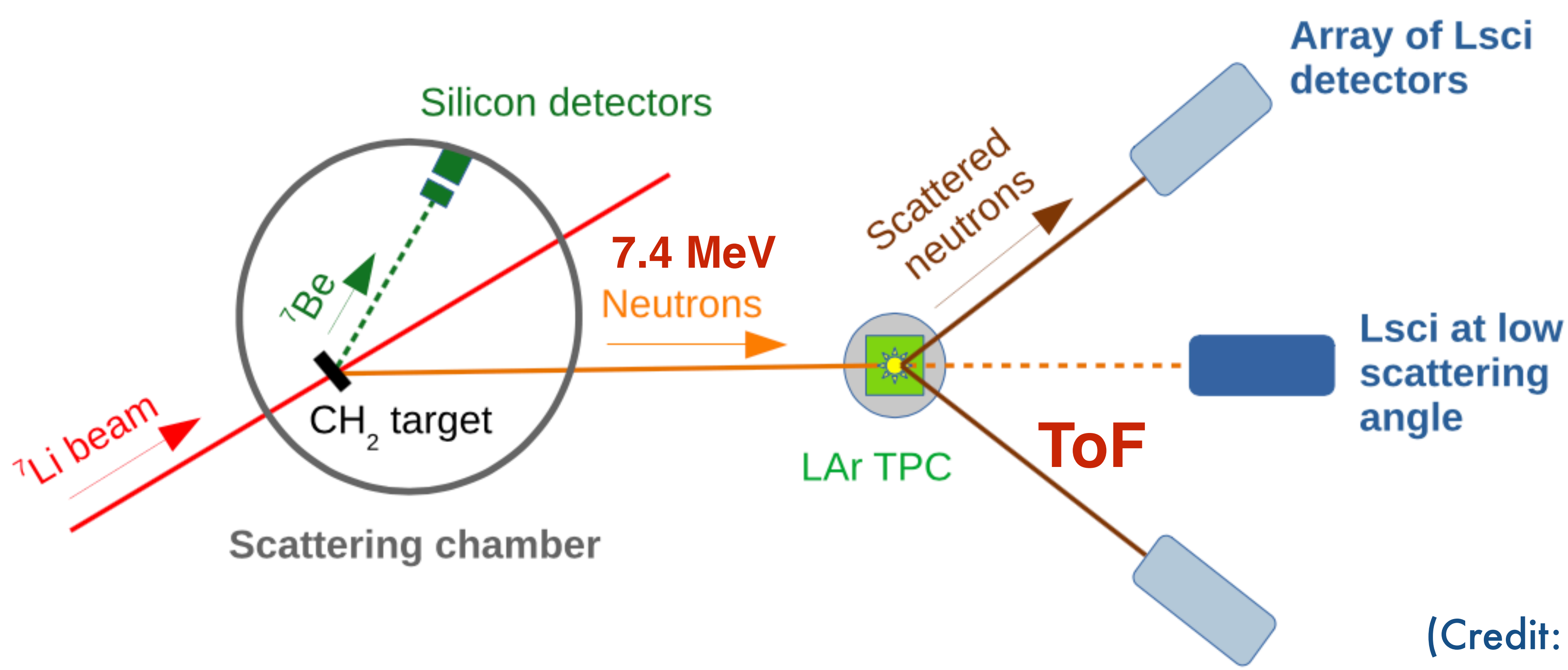
Directionality

Columnar Recombination Models

Jaffe (1940), D. Nygren (2013), Cautadella (2017)

- recombination effect depends on relative direction between drifting electrons and E field
- electron recombination is maximal when parallel to E field and minimal when perpendicular

ReD Initial Setup



(Credit: A. Sosa)

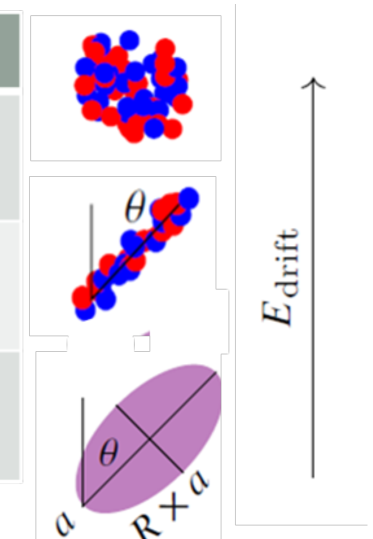
- ^{7}Li beam from the TANDEM accelerator of INFN-LNS (Catania)
- Neutron energy from ^{7}Be measurement
- Detect neutrons scattered at TPC

Preliminar => no directionality effect seen at 70 keVnr

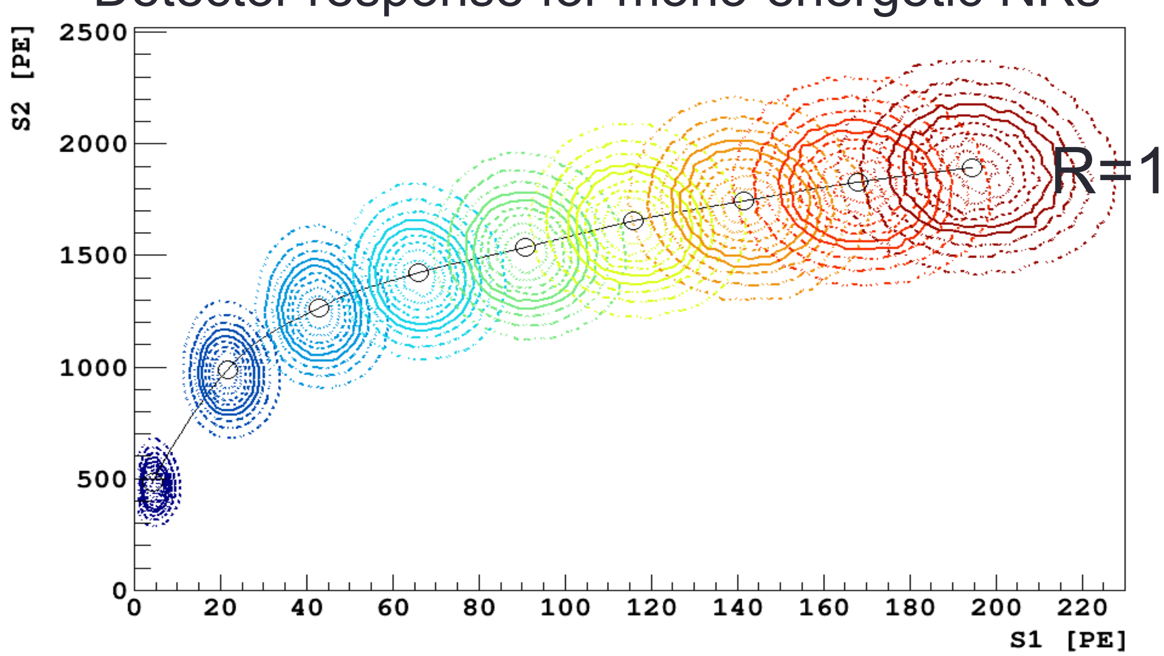
The directional model

- Data intepretation 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**	$\left[\sqrt{\sin^2\phi + \cos^2\phi / R^2}\right]^{-1}$



Detector response for mono-energetic NRs



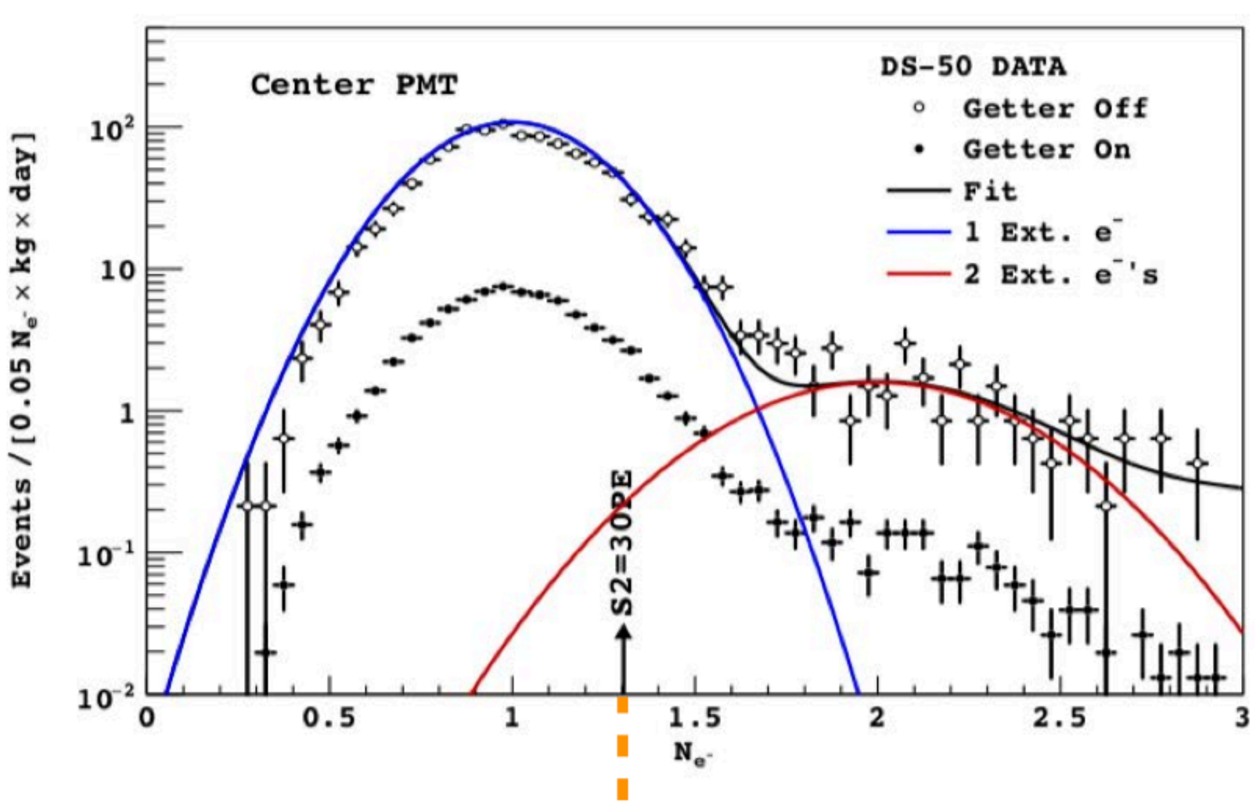
Agnes et al. arXiv:2307.15454

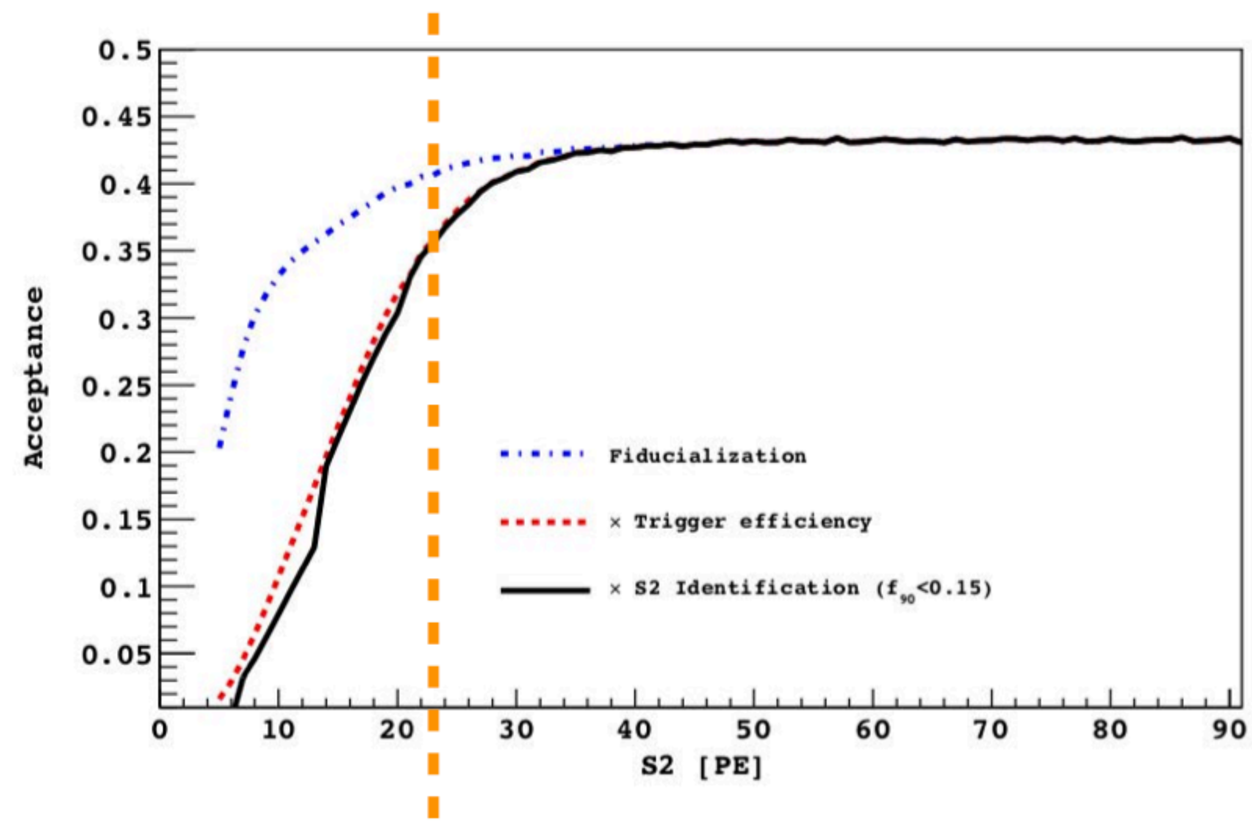
- Single parameter **R** → aspect ratio of the e⁻-ion cloud
  - R=1 → no directional effect (Thomas-Imel)

Changes S1 vs S2 detection Balance

Slide Credit: Luciano Pandola

Low Mass Calibration



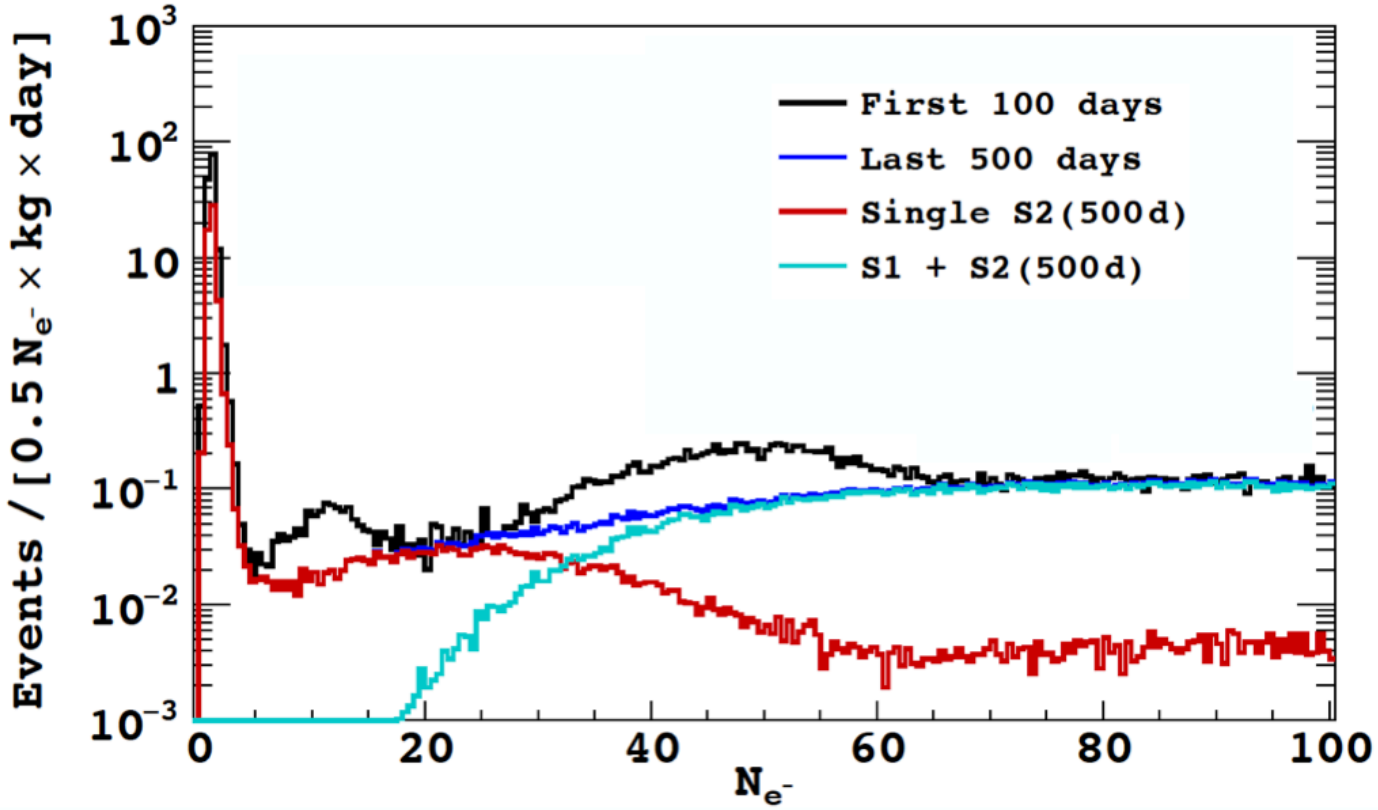


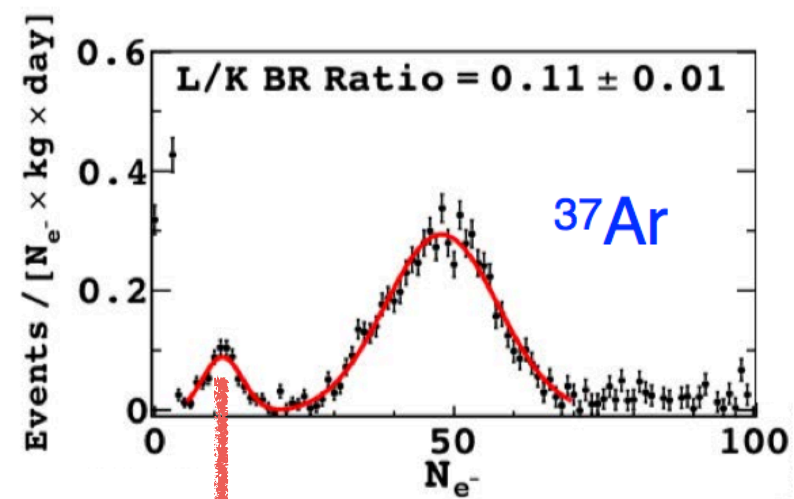
30 p.e.

single electron

- Signal down to single electron
  - 23 PE/e^- at detector axis

Low Mass Calibration - ^{37}Ar





τ = 34 days

100% e- capture

0.27

2.82 keV

L and K shells radiation after e- capture

direct N_e calibration for low energy electrons