Nuclear Recoil Energy at Low DM Mass
ReD's Radioactive and Neutron Gun Phase

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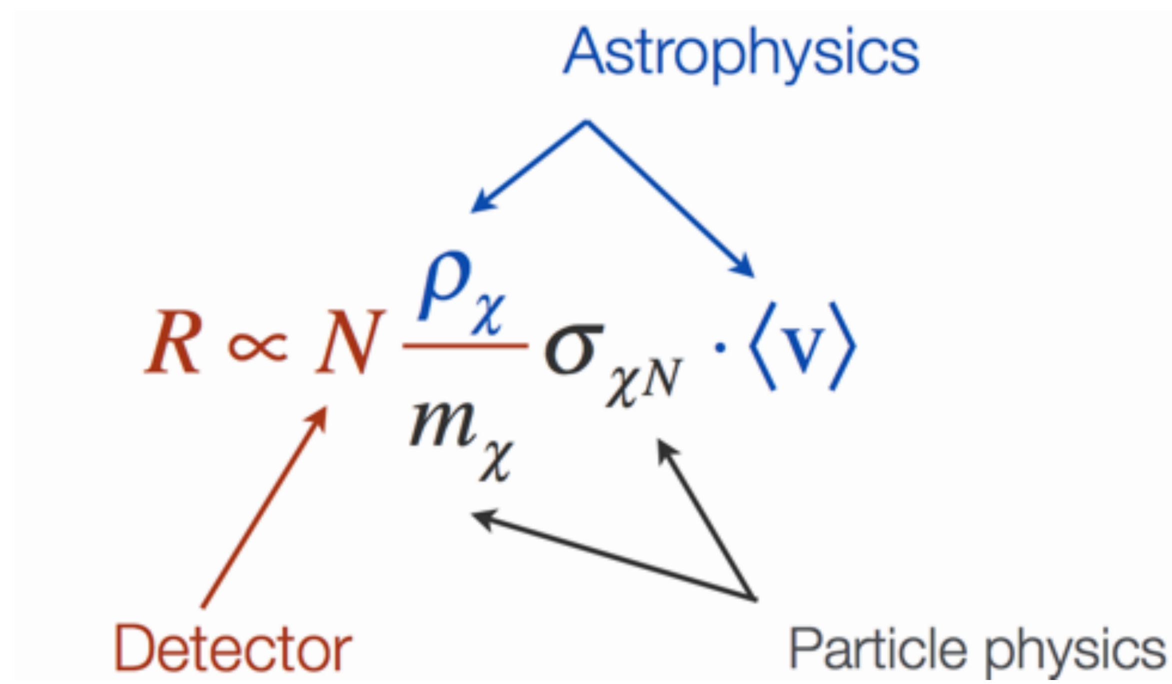
Dark Matter Direct Detection

- Elastic collisions with atomic nuclei

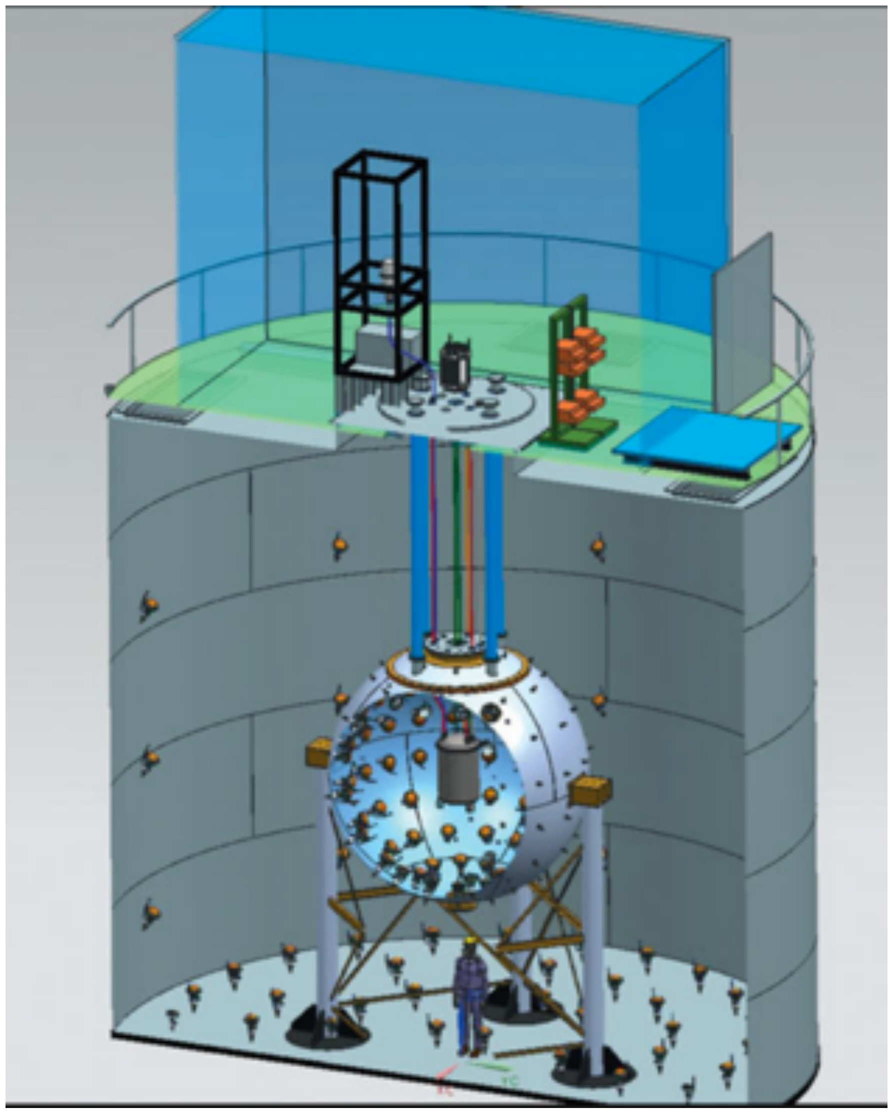
  → measure recoil energy

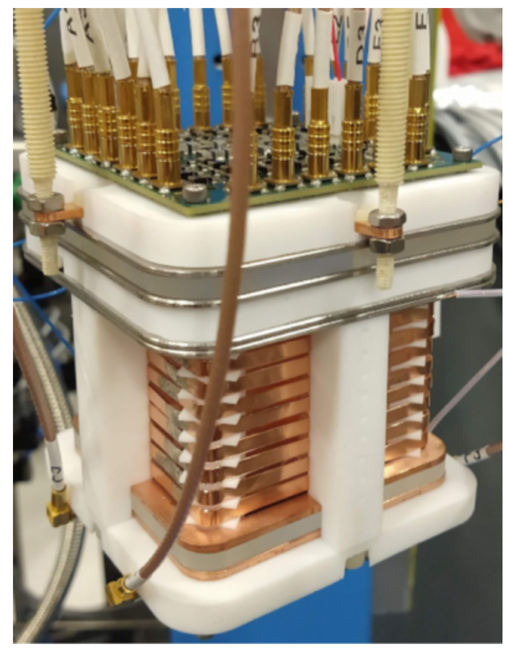
$\mathcal{O}$(10 KeV) recoils

- Expected rate:



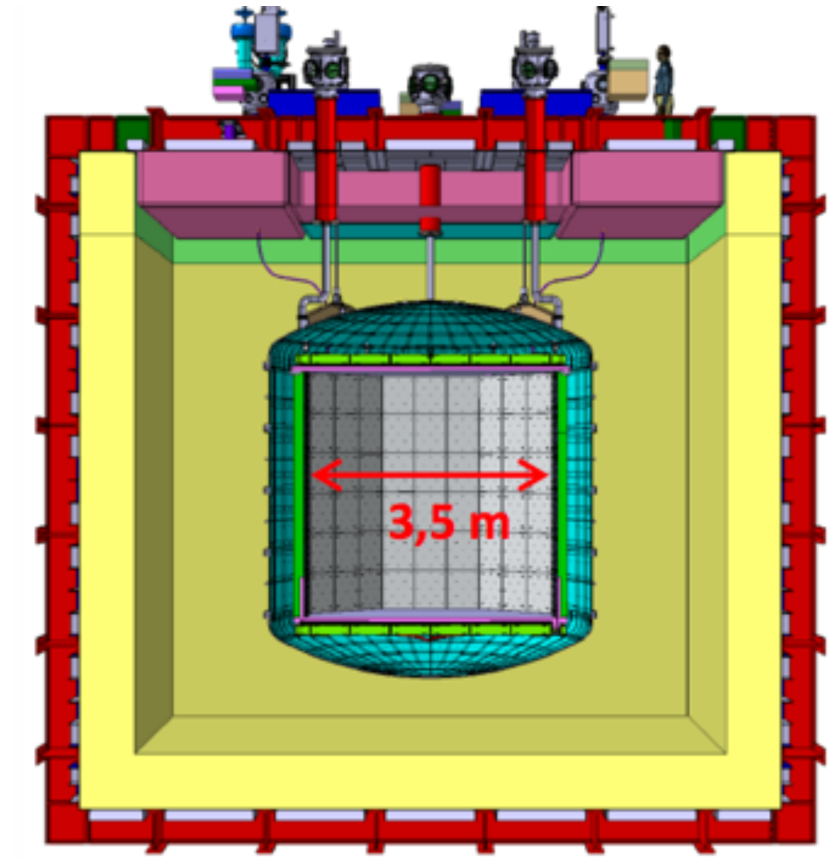
DarkSide LAr Detectors





ReD

2018...



DS-20K

2025...

DS-50

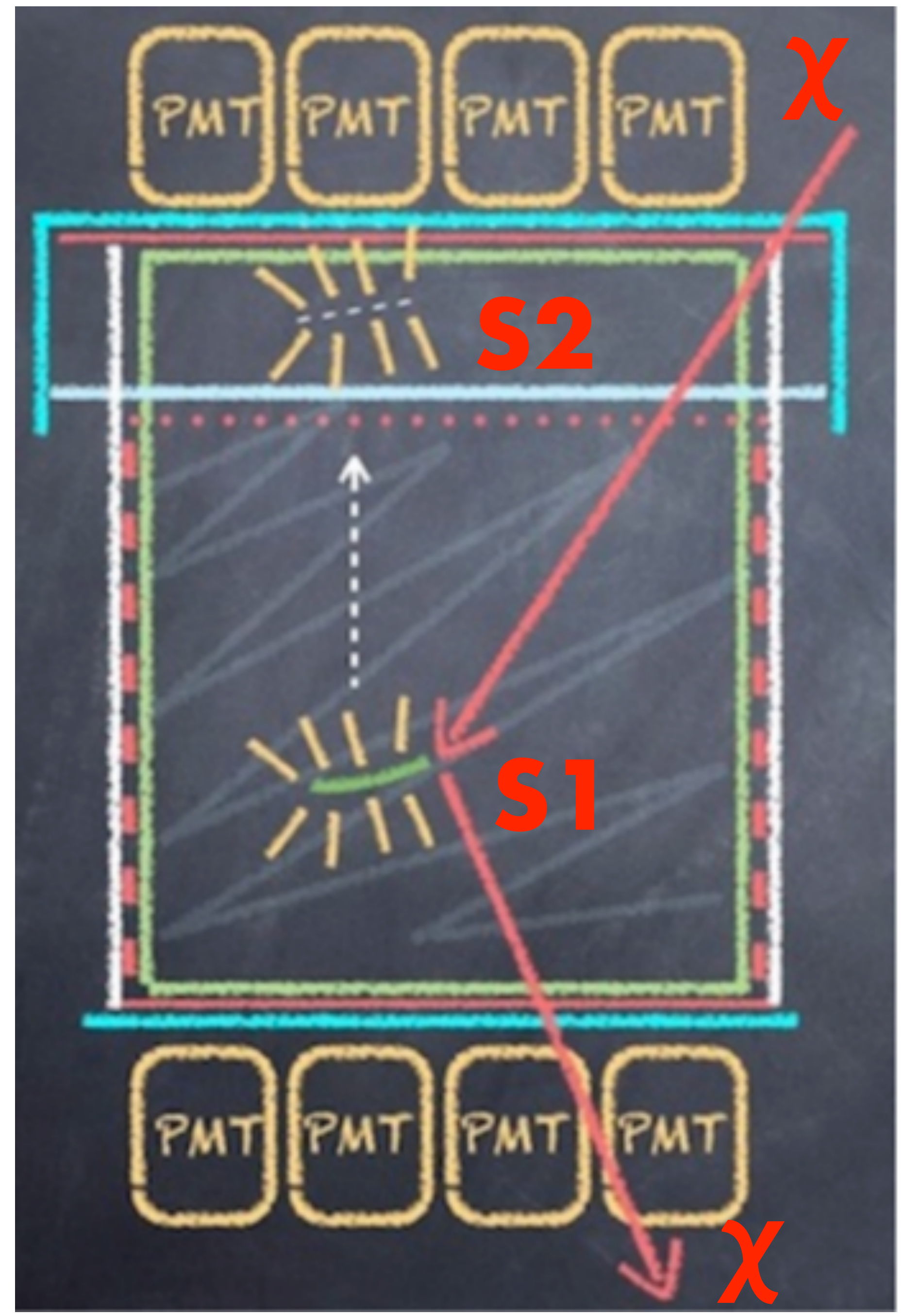
Oct 2013 - Feb 2018

DS-LM...

Double Phase Signals

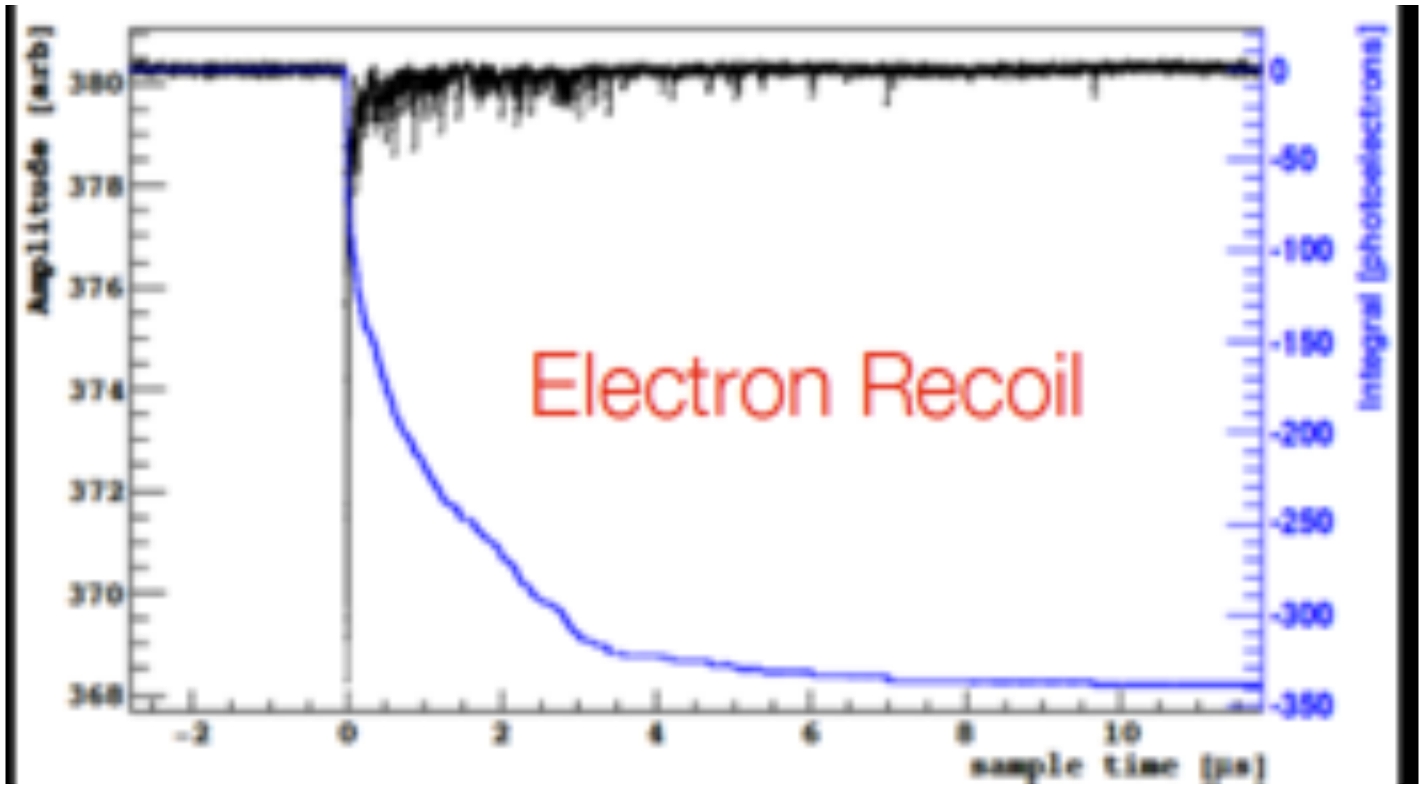
DS-50

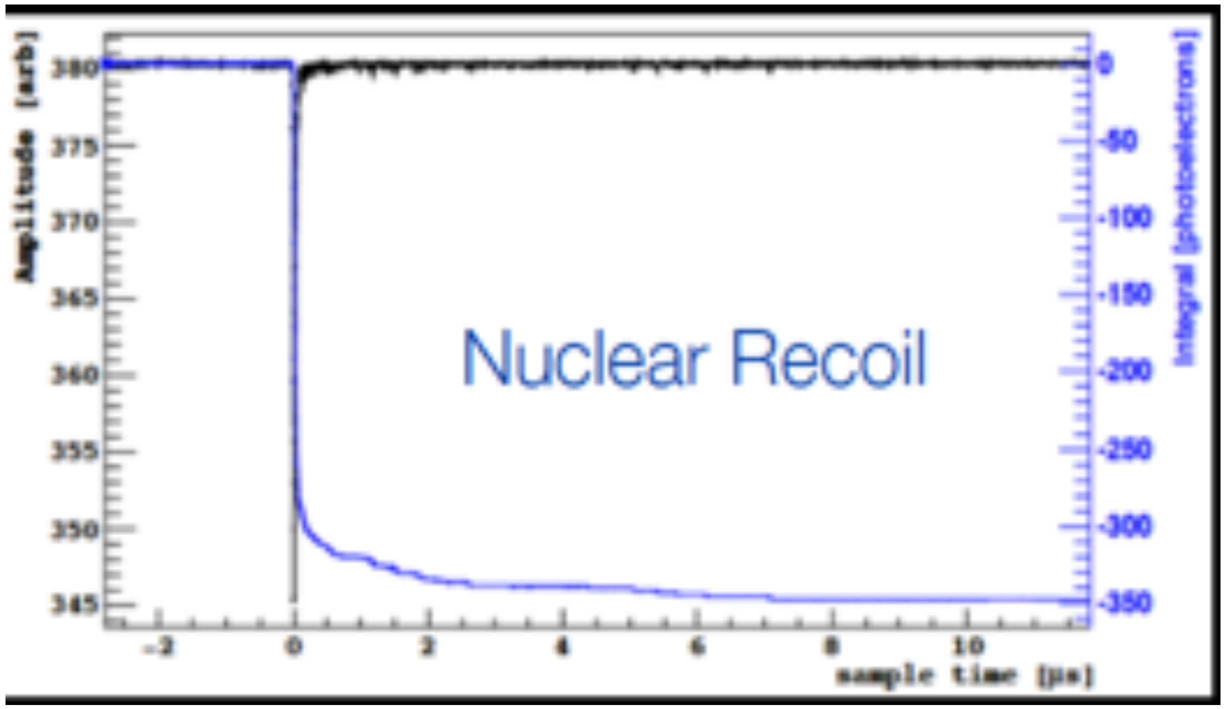
(46.4 +- 0.7) Kg
Fiducial volume:
(36.9 +- 0.6) Kg



(Credit: the Darkside collaboration)

LAr Pulse Shape Discrimination

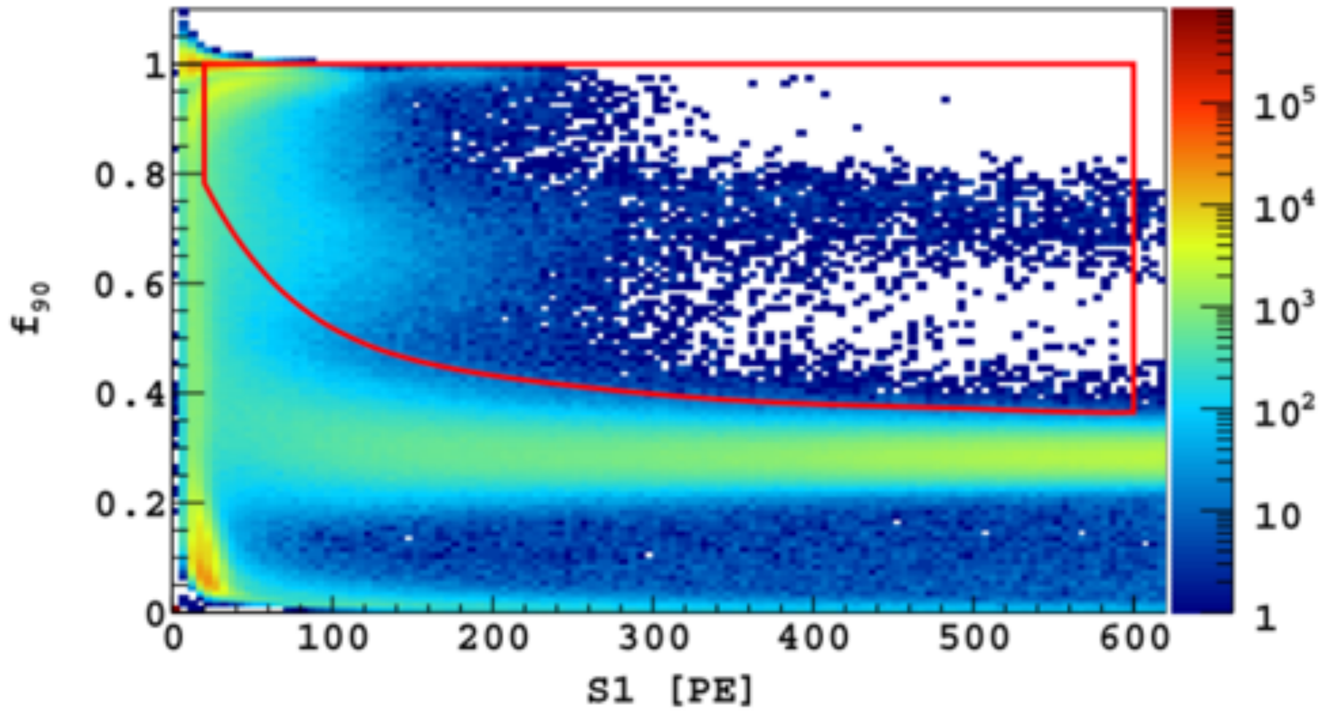




S1: prompt scintillation signal

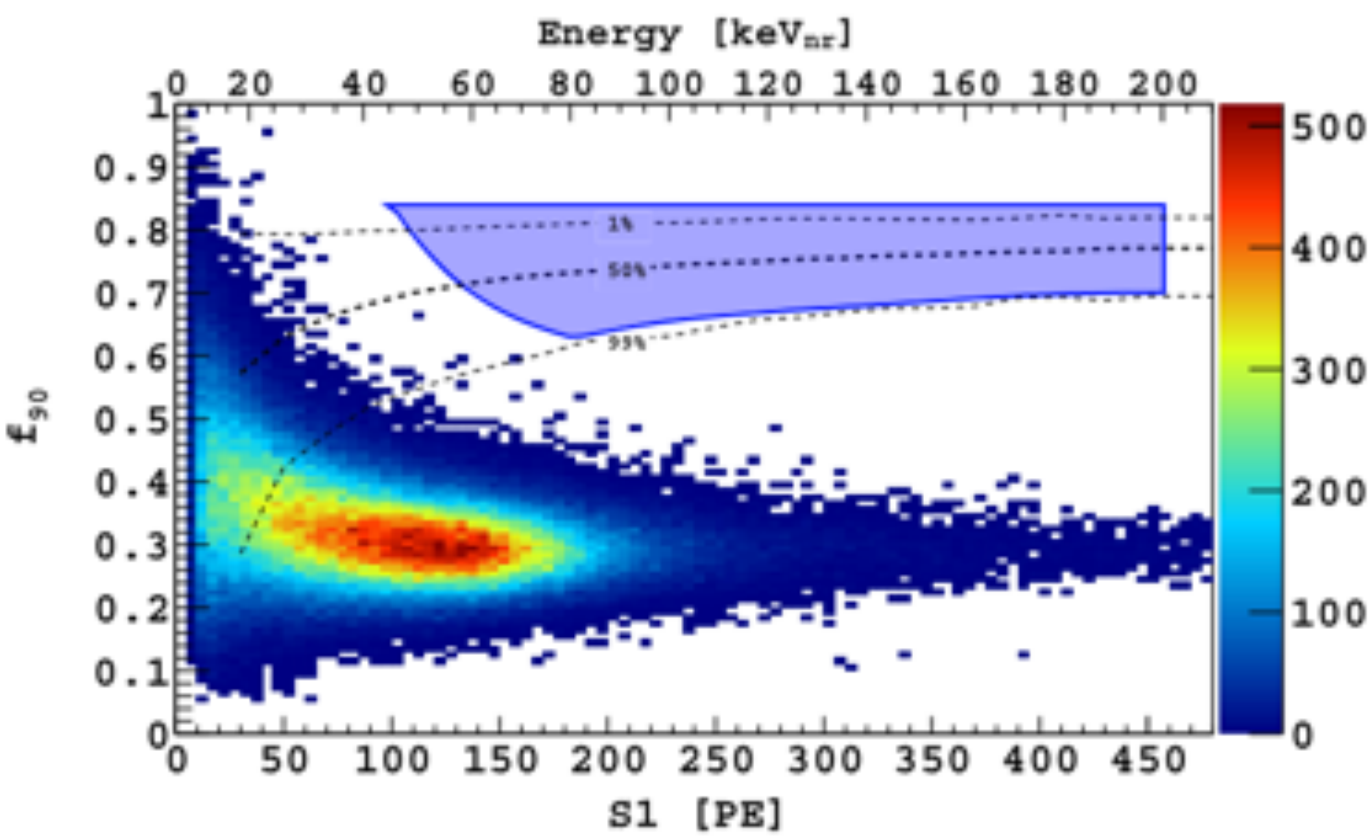
PSD: f90
(fraction of S1 light collected within 90 ns)

DS-50 PSD



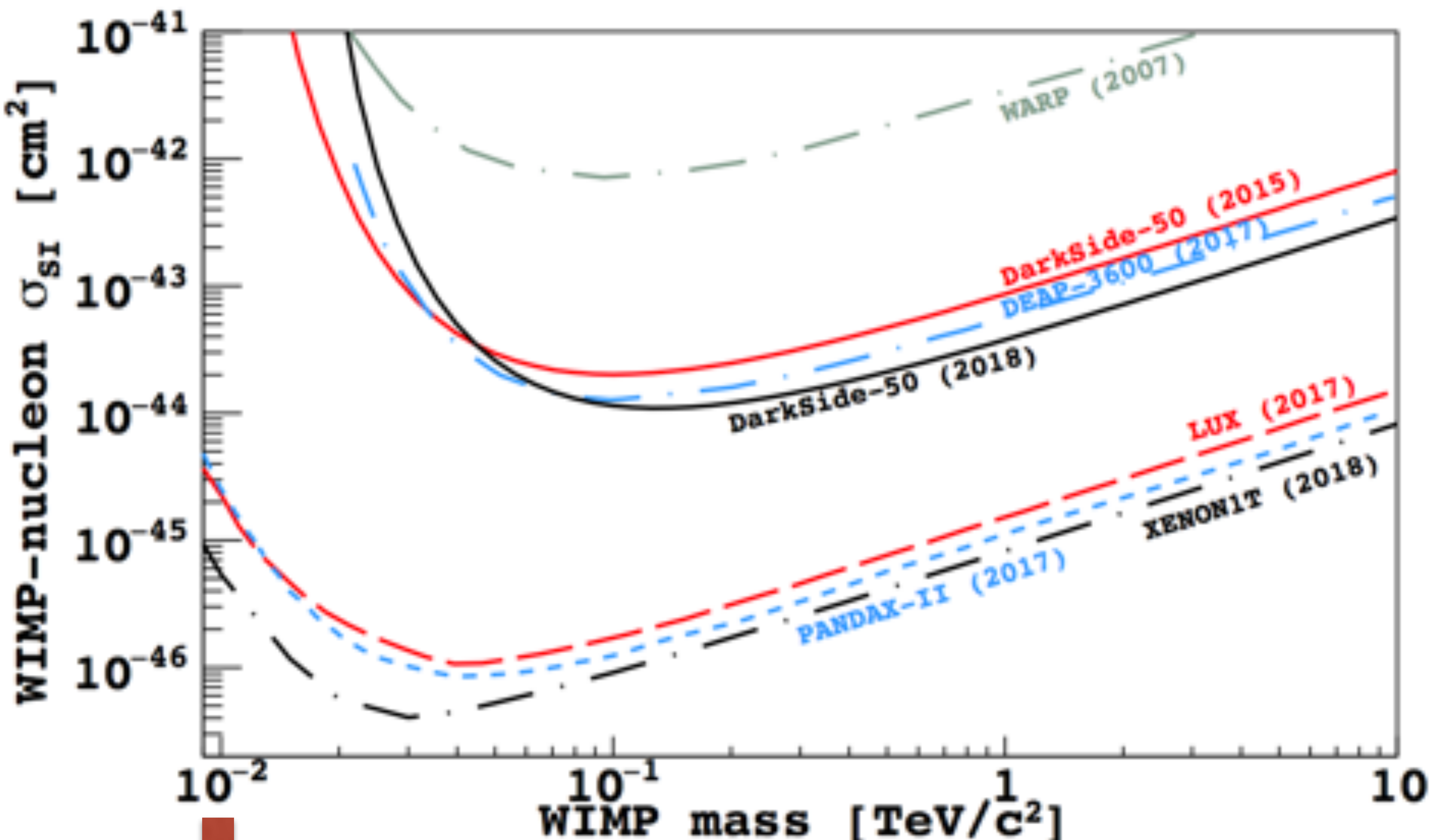
Nuclear recoils

Electron recoils



PRD **98, 2018** (Darkside Collaboration)

SI Exclusion Region



10 GeV/c²

DS50K Coll - PRD 98 (2018)

Low Mass Models

Asymmetric Dark Matter

$$\frac{\rho_{\mathrm{DM}}}{\rho_{\mathrm{Baryons}}} \sim \mathbf{5}$$

- No connection in standard WIMP scenario

  -- ρ_{DM} is set by freeze out temperature

- However a connection arises when $\frac{\rho_\chi}{\rho_{\overline{\chi}}} \neq 1$

$$(1 \leq m_\chi \leq 10)\ \mathrm{GeV/c^2}$$

Zurek
Phys. Reports 537, 2016

+ Dark Sector models

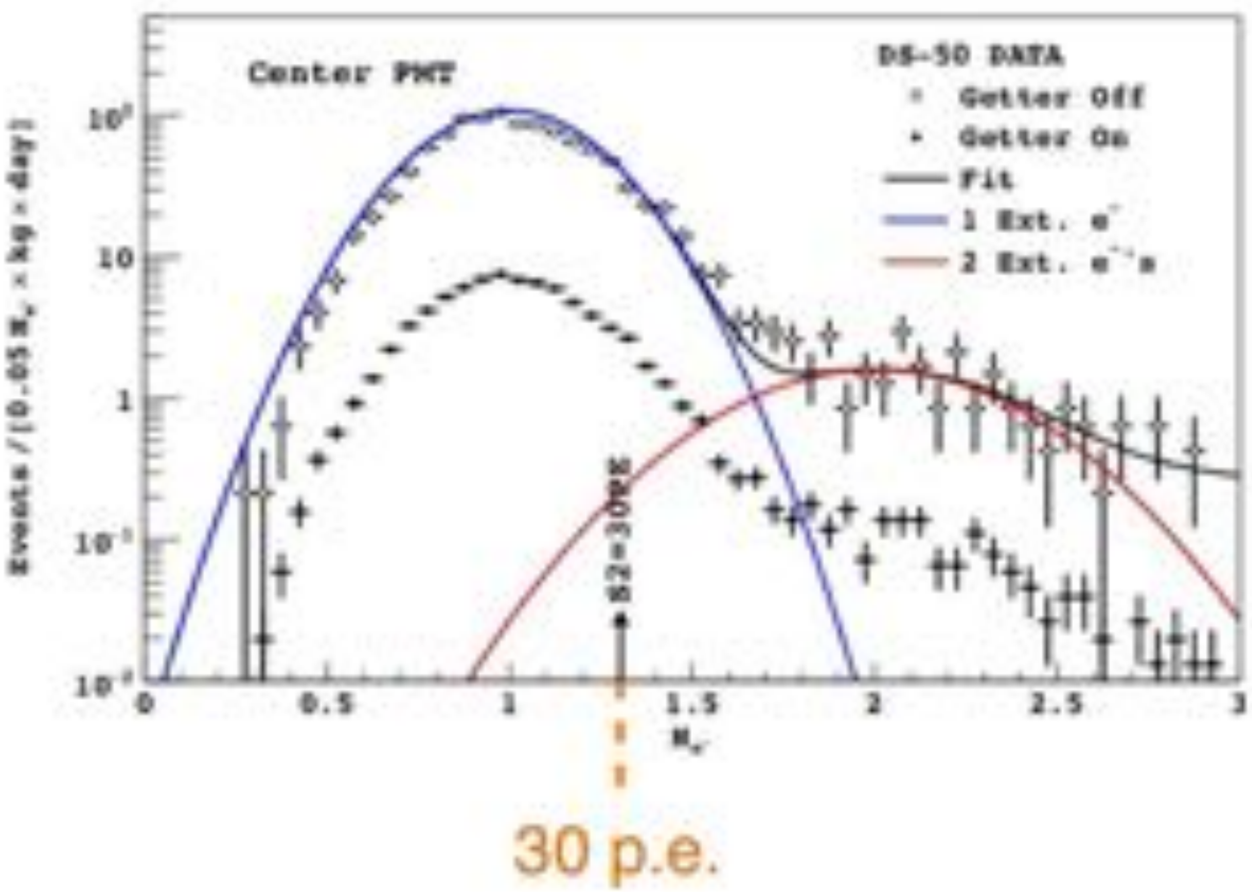
DS-50k Low Mass Analysis

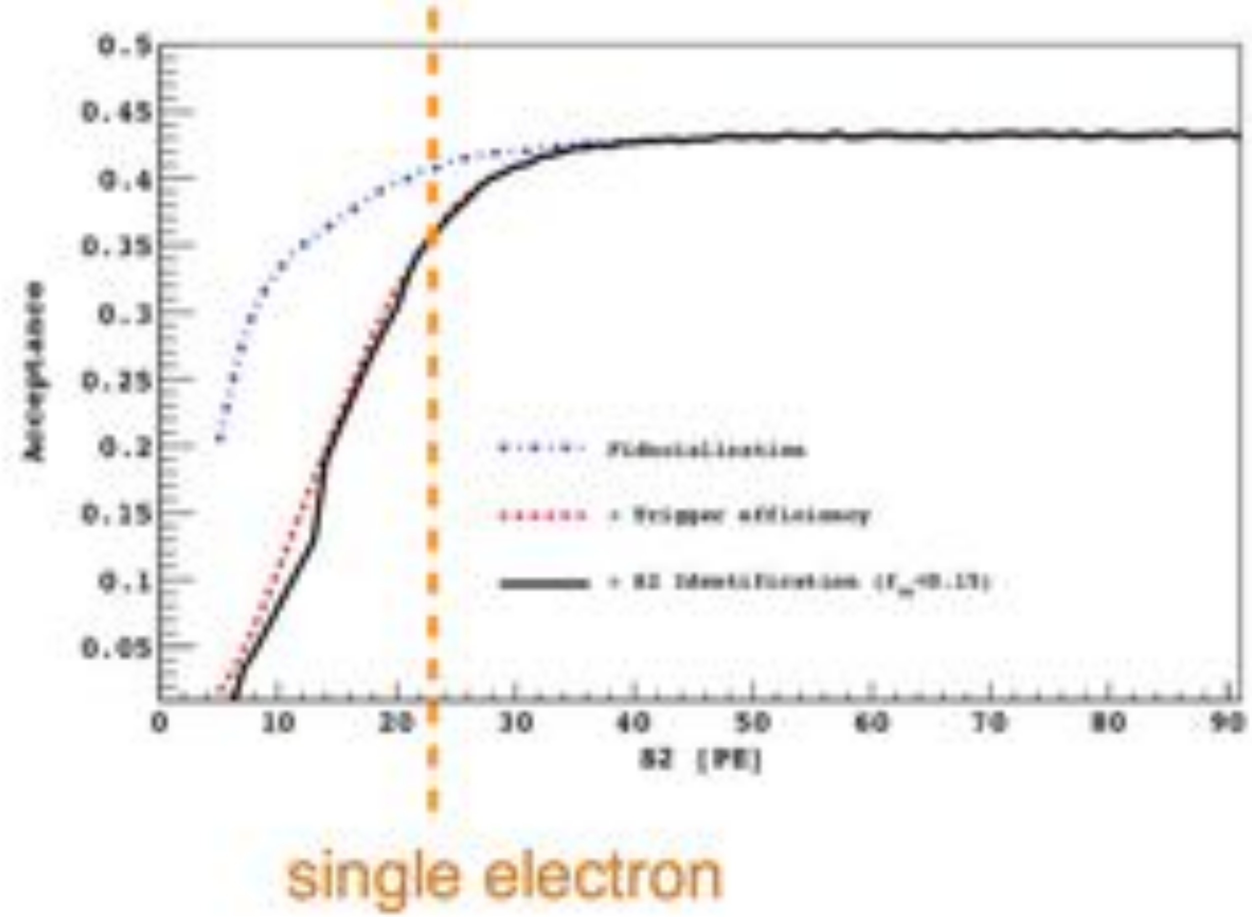
$$(1 \leq \mathbf{m}_\chi \leq 10)\ \mathbf{GeV/c^2}$$

S2 only analysis

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

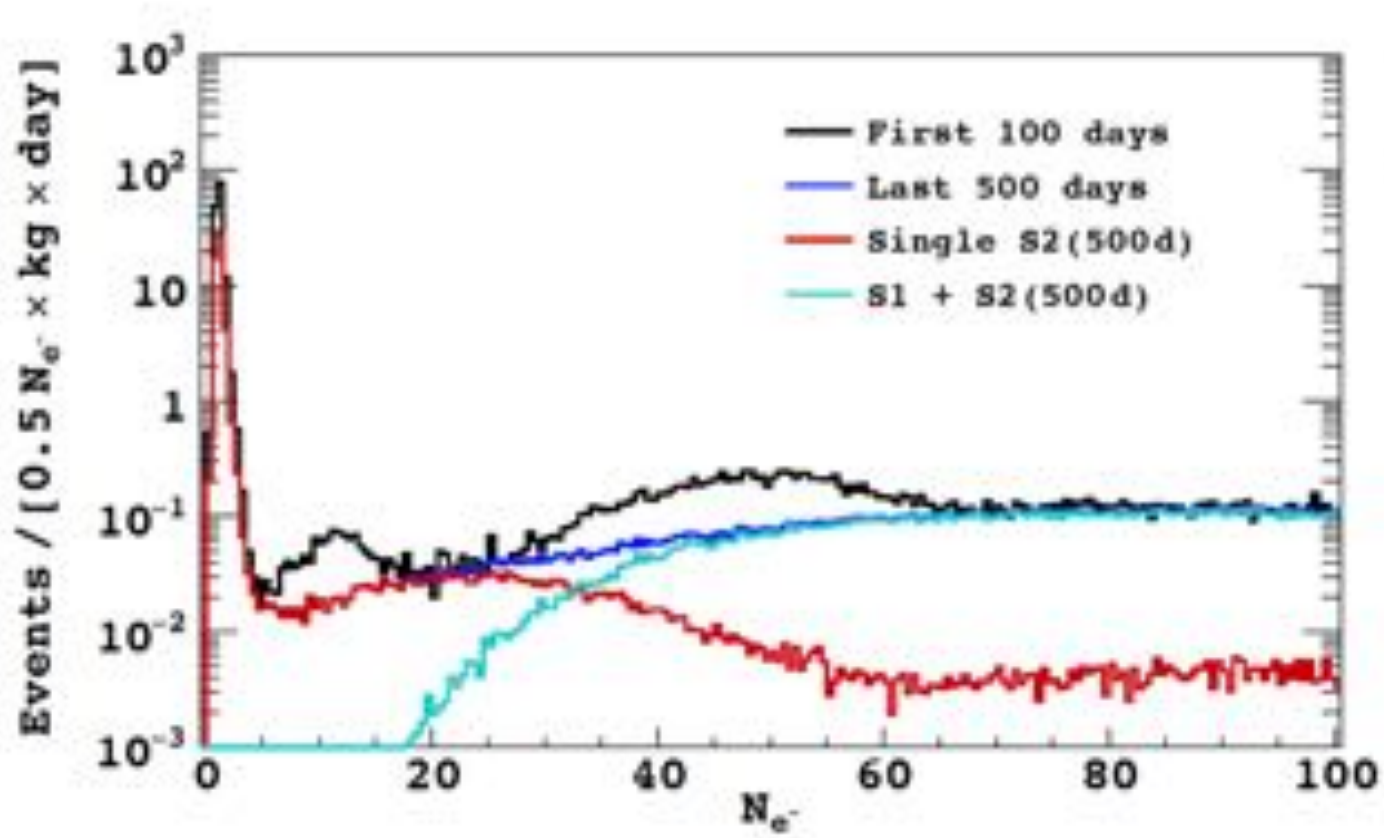
Low Mass Calibration

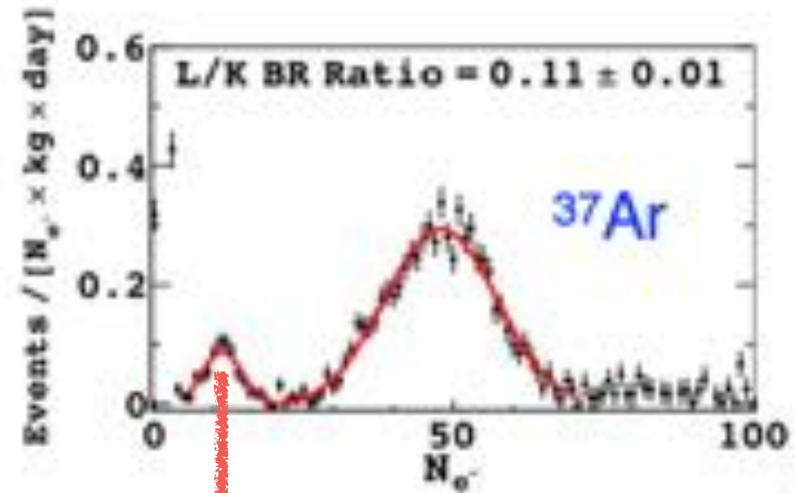




- Signal down to single electron
  - 23 PE/e⁻ at detector axis

Low Mass Calibration - ^{37}Ar





0.27

2.82 keV

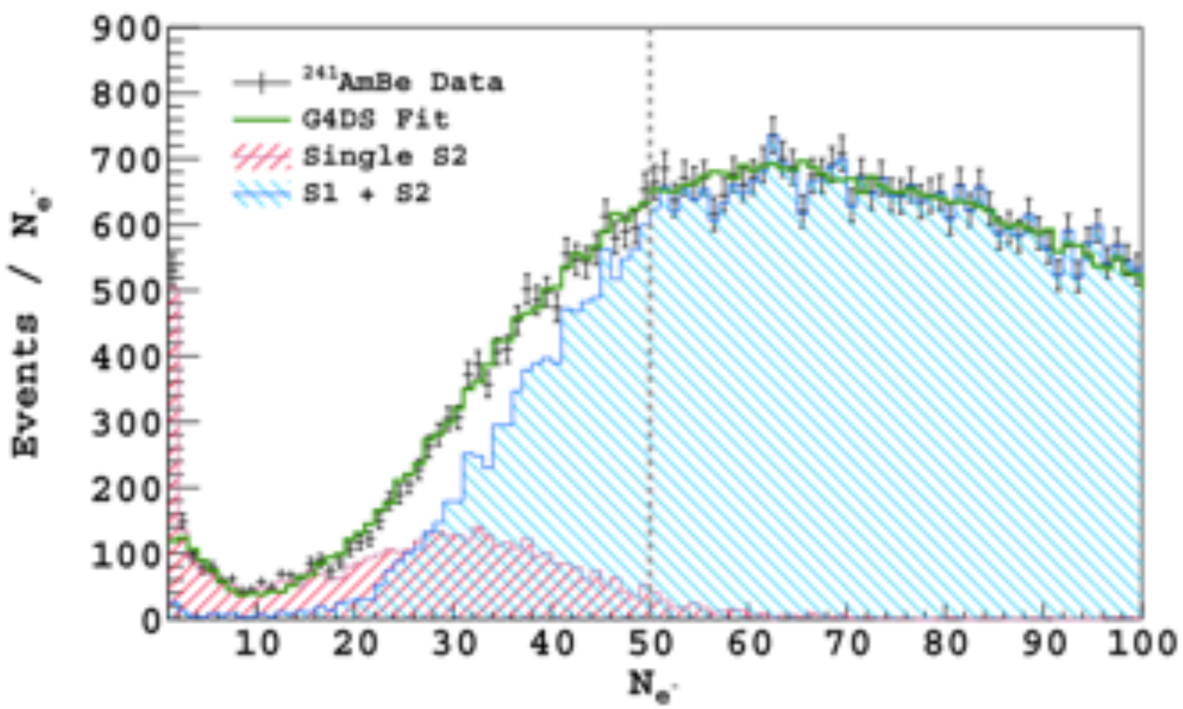
L and K shells radiation
after e- capture

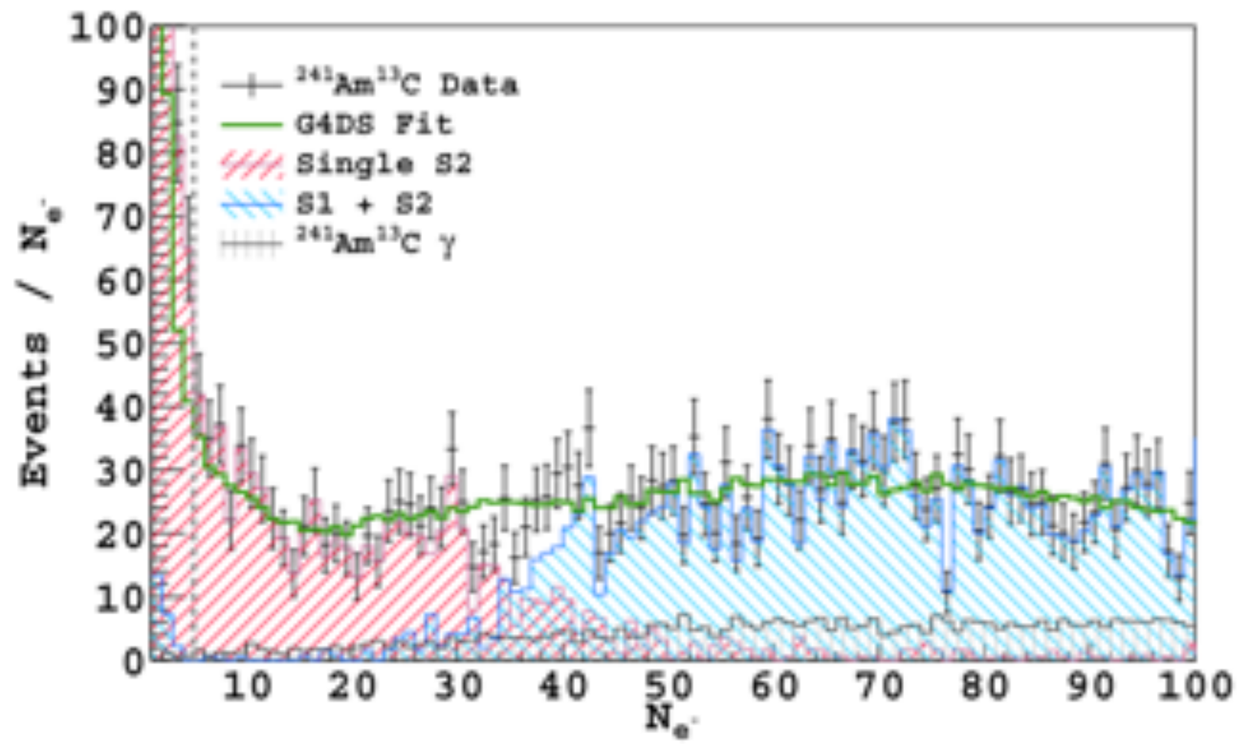
τ = 34 days
100% e- capture

direct N_e calibration for low energy electrons

Ionization Yield (Q_y) from Nuclear Recoils

Radioactive Neutron Sources





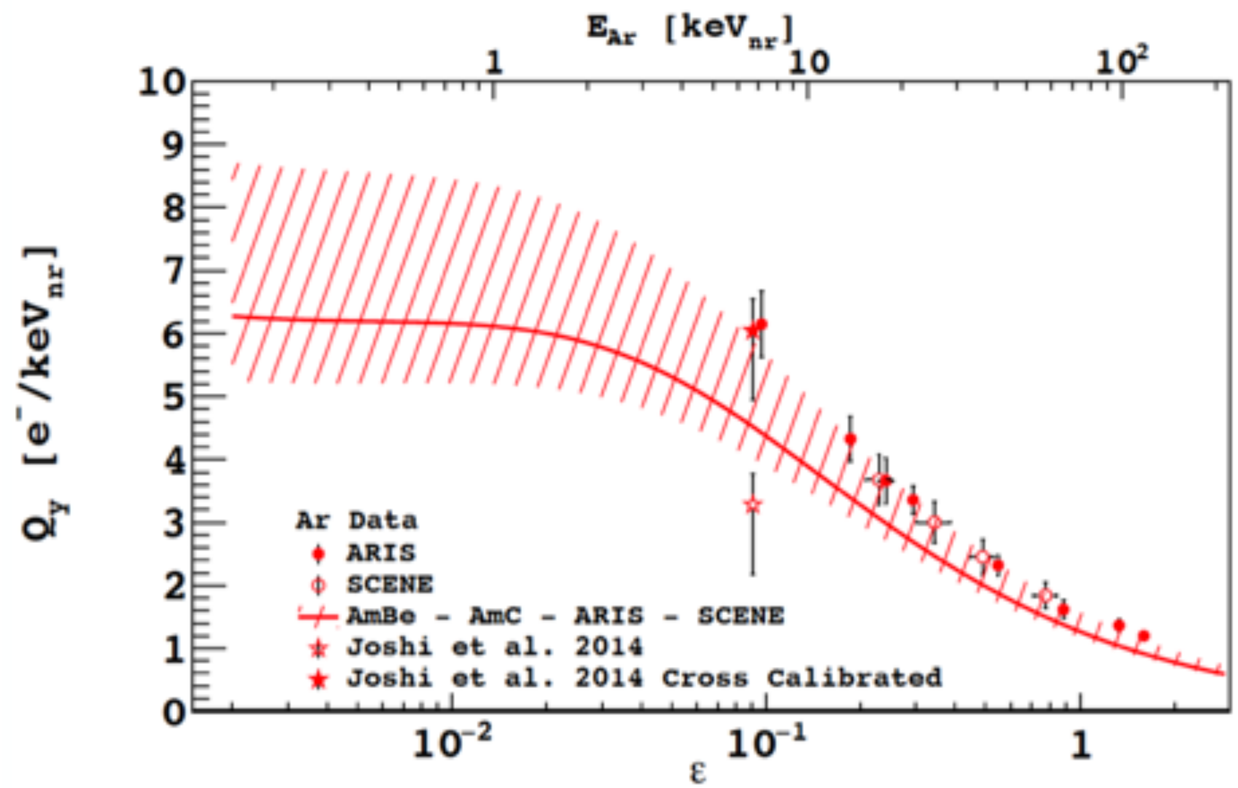
4.4 MeV γ signal in veto required
to validate TPC event

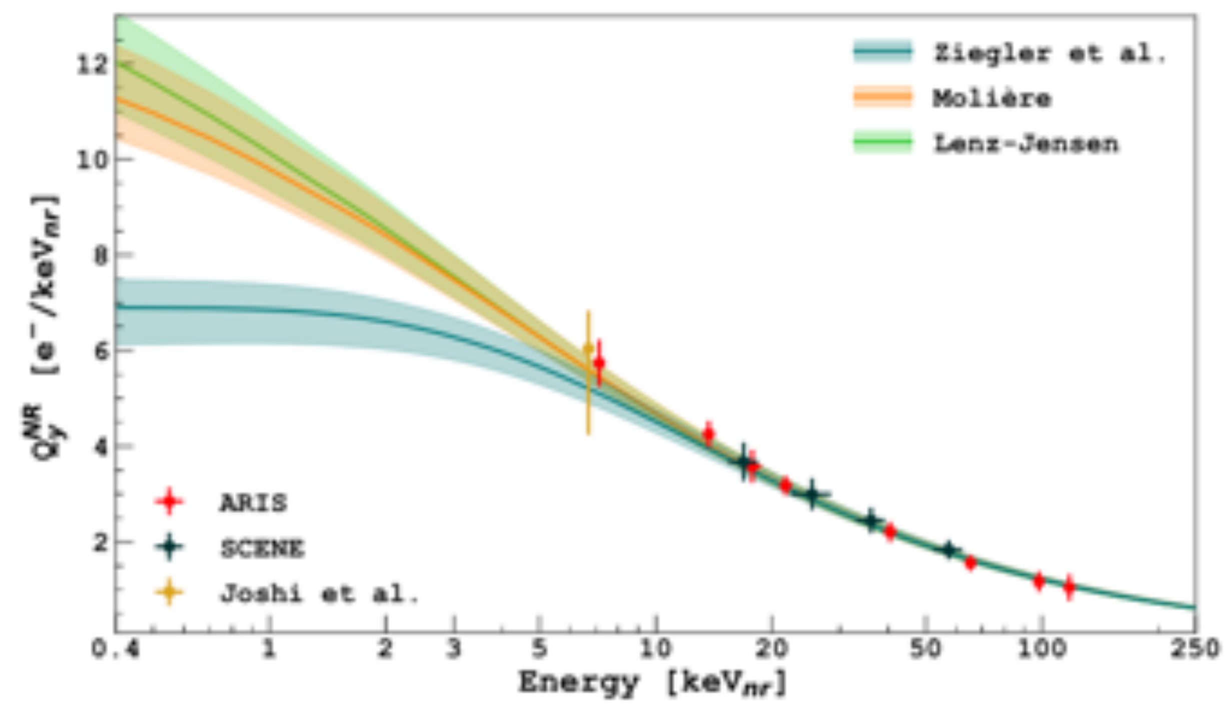
only 4 farthest PMTs
to reduce γ contamination

G4DS uses Bezrukov model

(Bezrukov et al., Astropart.Phys. 35 (2011)

Ionization Yield (Q_y) from Nuclear Recoils

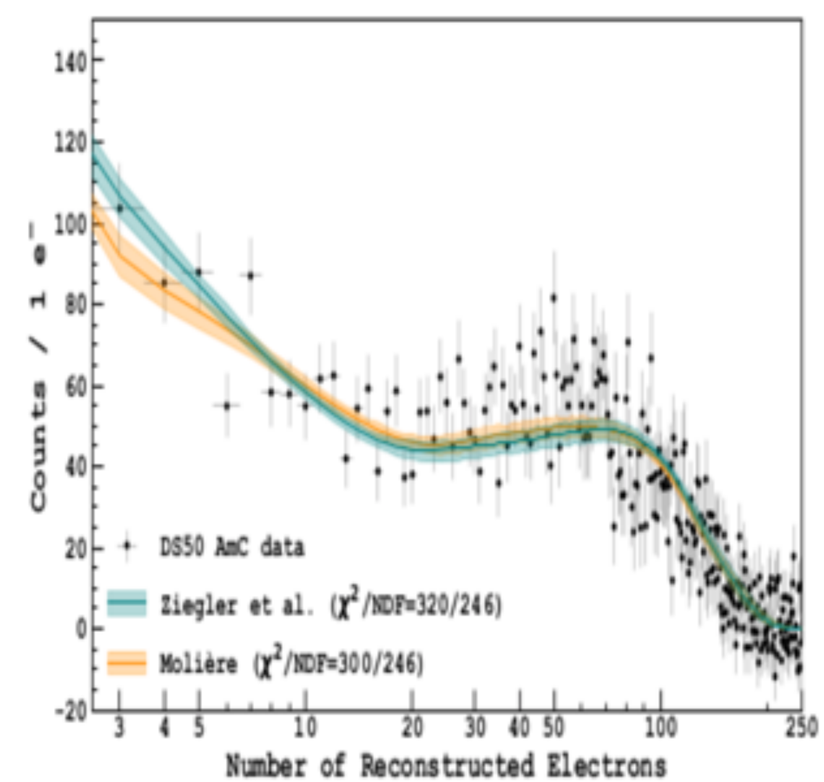




Q_y from AmBe + AmC + Bezrukov model

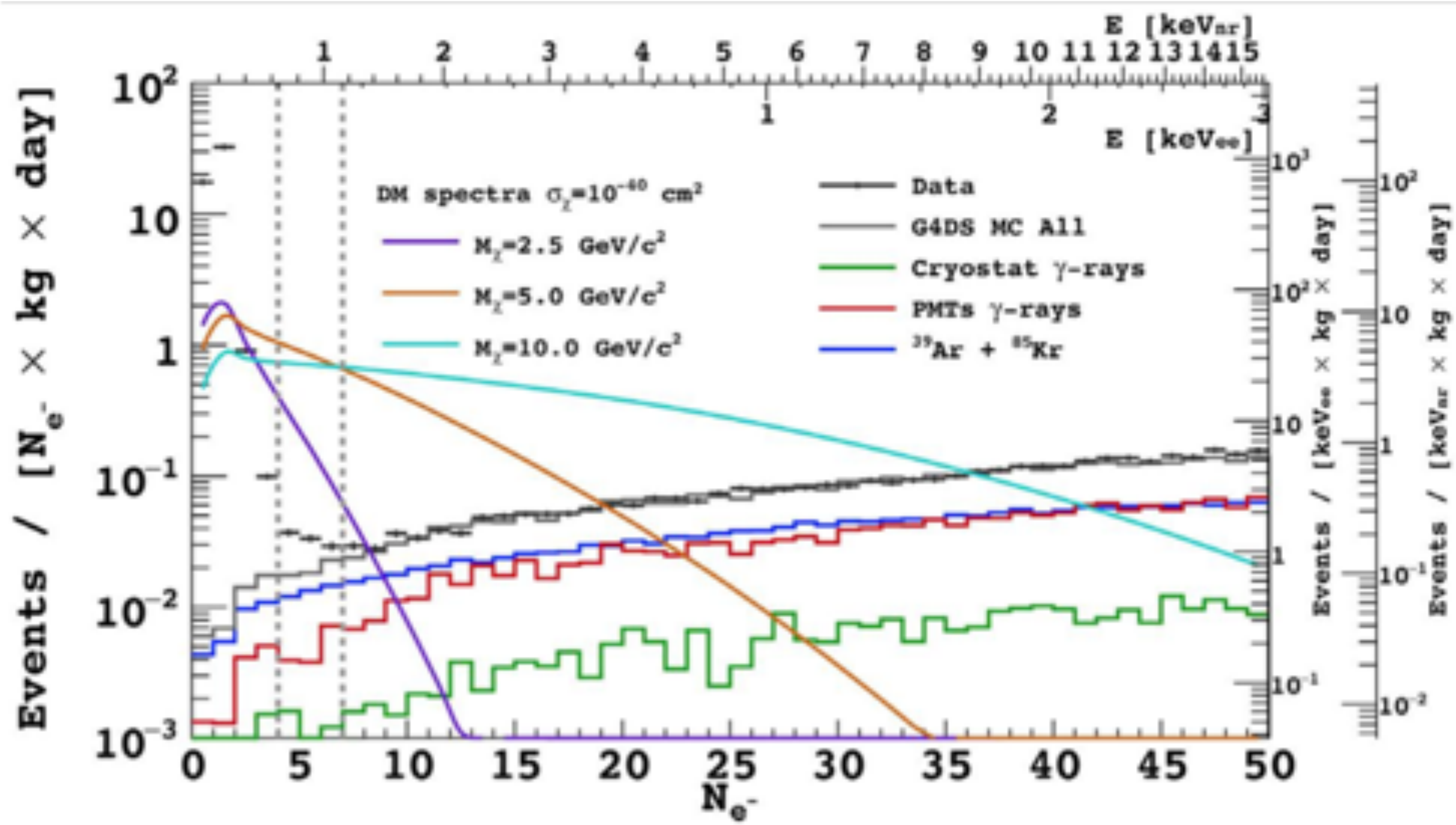
Agree within bounds with other data => systematics

Model dependency + extrapolation to lower energies



Phys. Rev. D 104, 082005 (2021)

Low Mass Wimps: Signal vs Backgrd



Expected signal assumes standard DM halo

Uncertainties in signal dominated by Q_y fluctuations

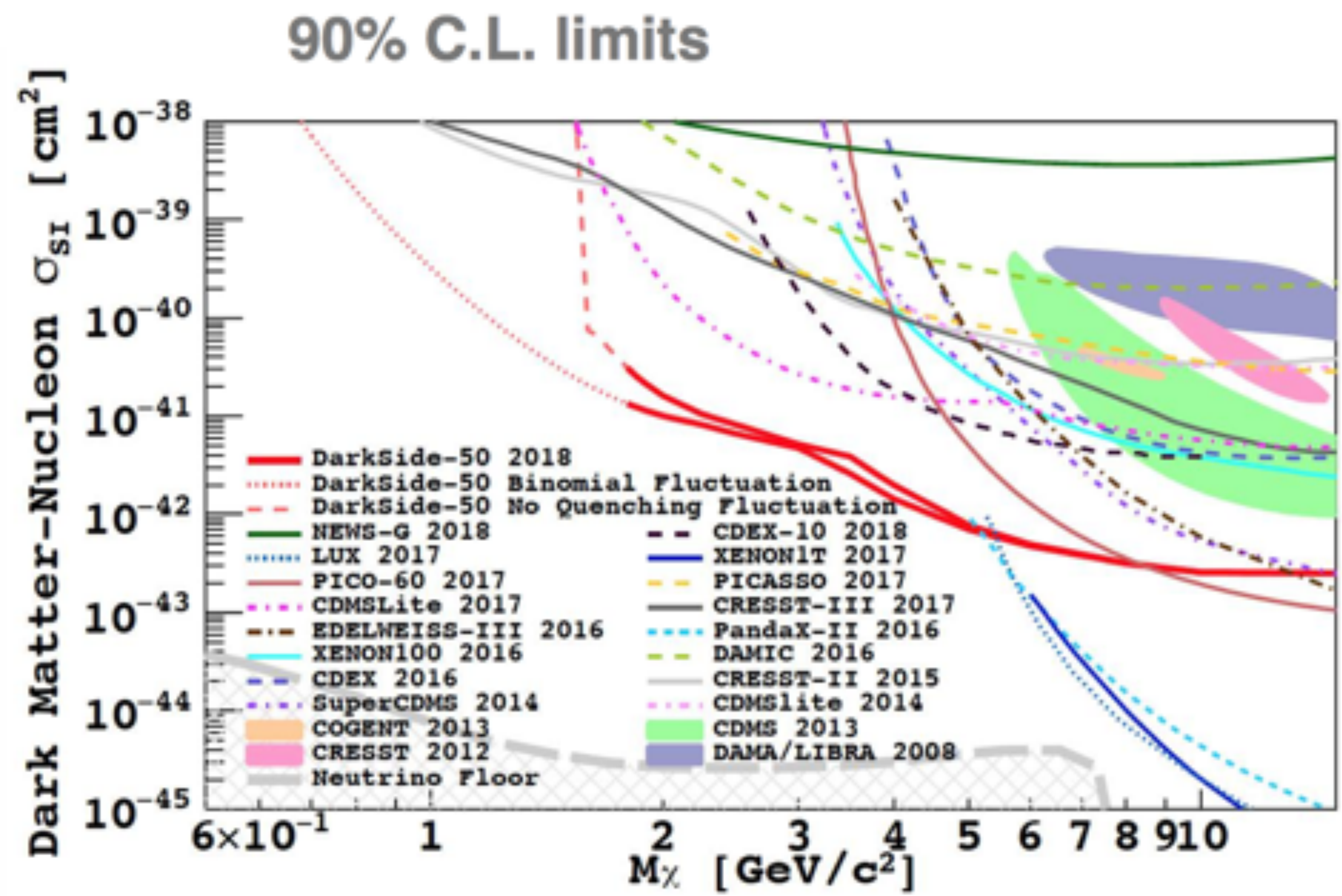
Low Mass Wimps: Signal vs Backgrd

- Cross Section limit => binned profile likelihood method

At low energy: average ionization dominates uncertainties

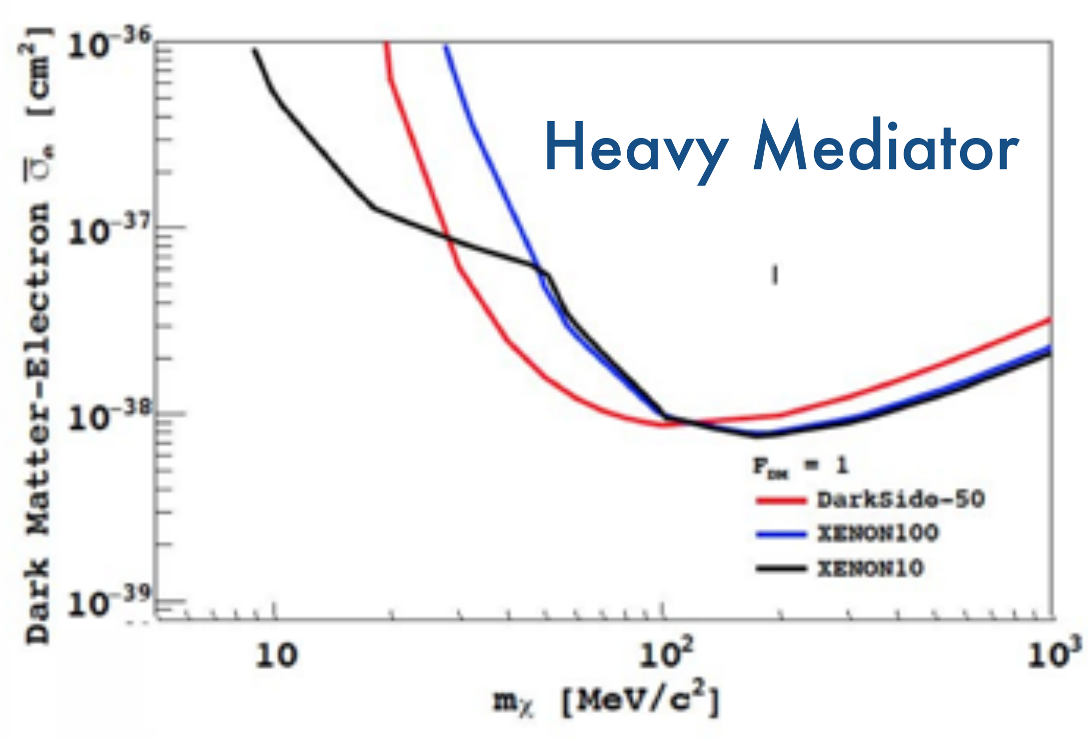
=> 2 assumptions on its fluctuations: binomial or no fluctuation

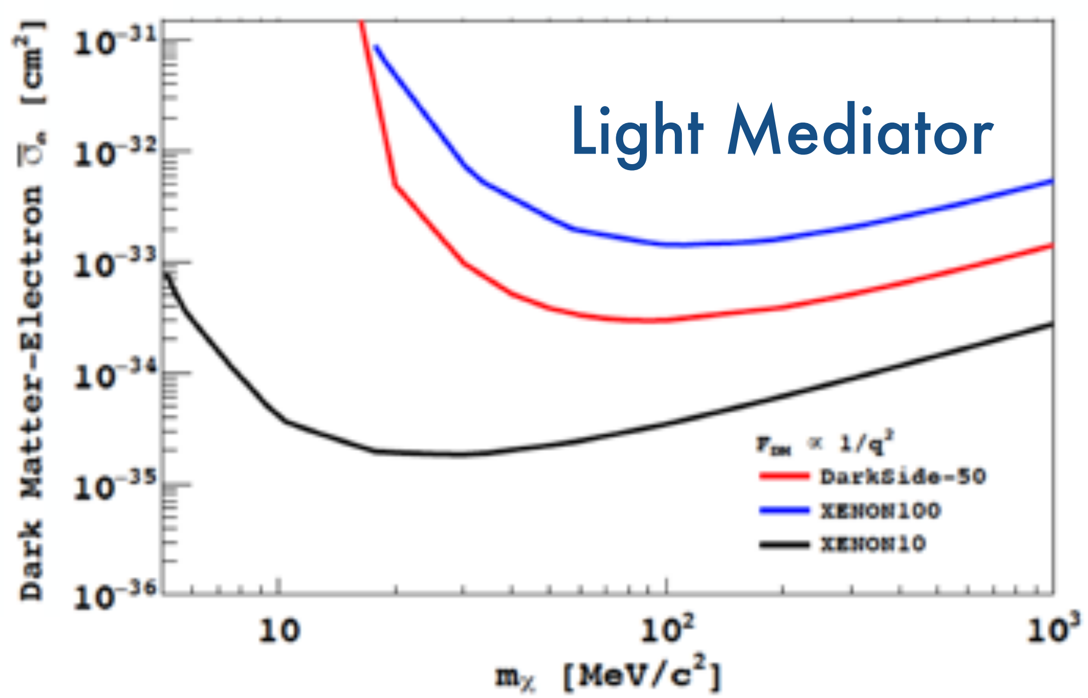
Low Mass Wimps: Limits



DS50K Coll - PRL 121 (2018)

DS-50k SubGeV Analysis





DS50K has best result
25 -100 MeV region

DS50K Coll - PRL 121 (2018)

Xe analysis
Essig, Volansky and Yu, PRD 96 (2017)

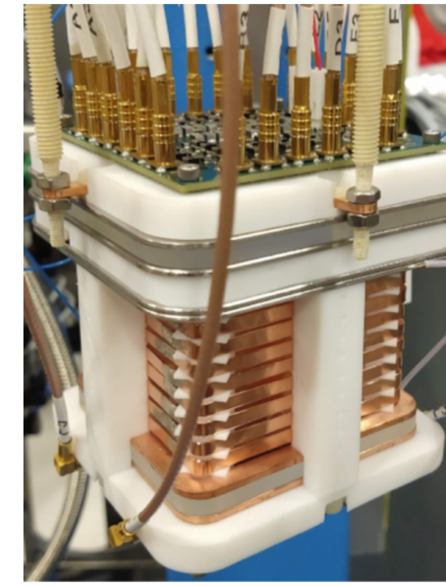
DS Low Mass Detector

- scaled down version of DS20K

- Aria cryogenic distillation tower is able to completely remove ^{85}Kr and greatly reduce ^{39}Ar

- Better understanding of ionization yield is needed => ReD's low mass effort

REcoil Directionality Experiment



Main goals:

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

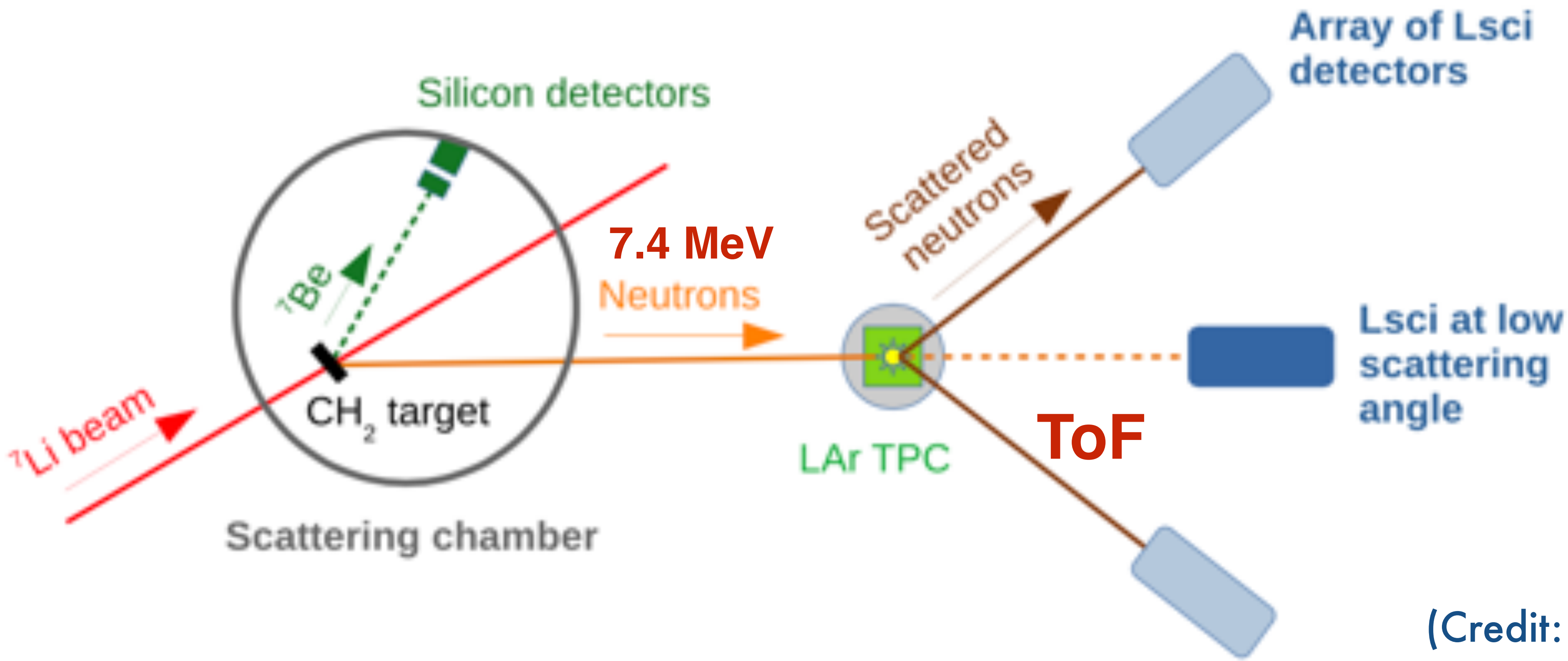
Directionality

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

Low Energy Modes

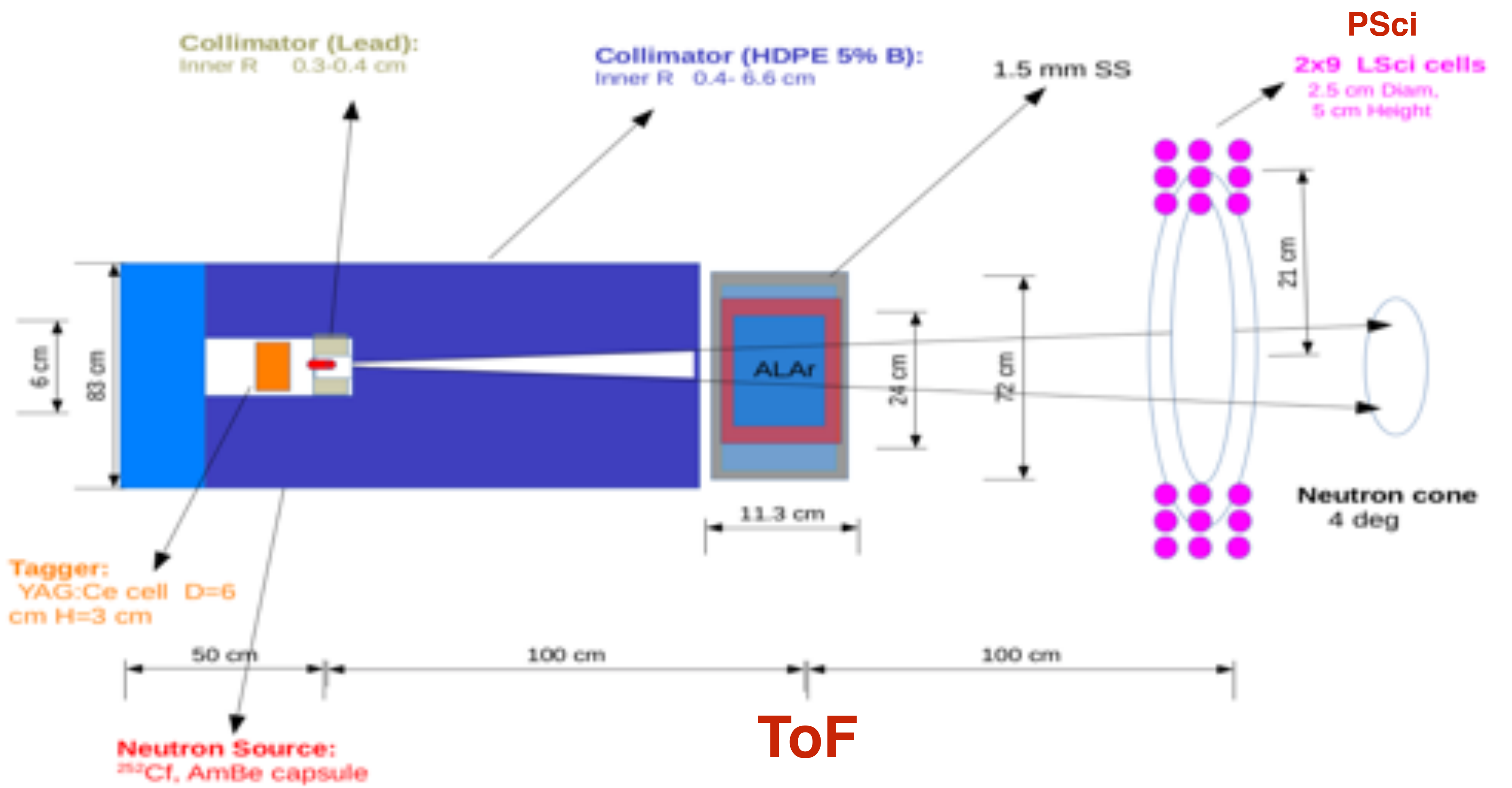
- Radioactive sources and Neutron Gun for low energy recoils

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

^{252}Cf neutron source (1.48 MBq)
currently being setup at INFN - LNS

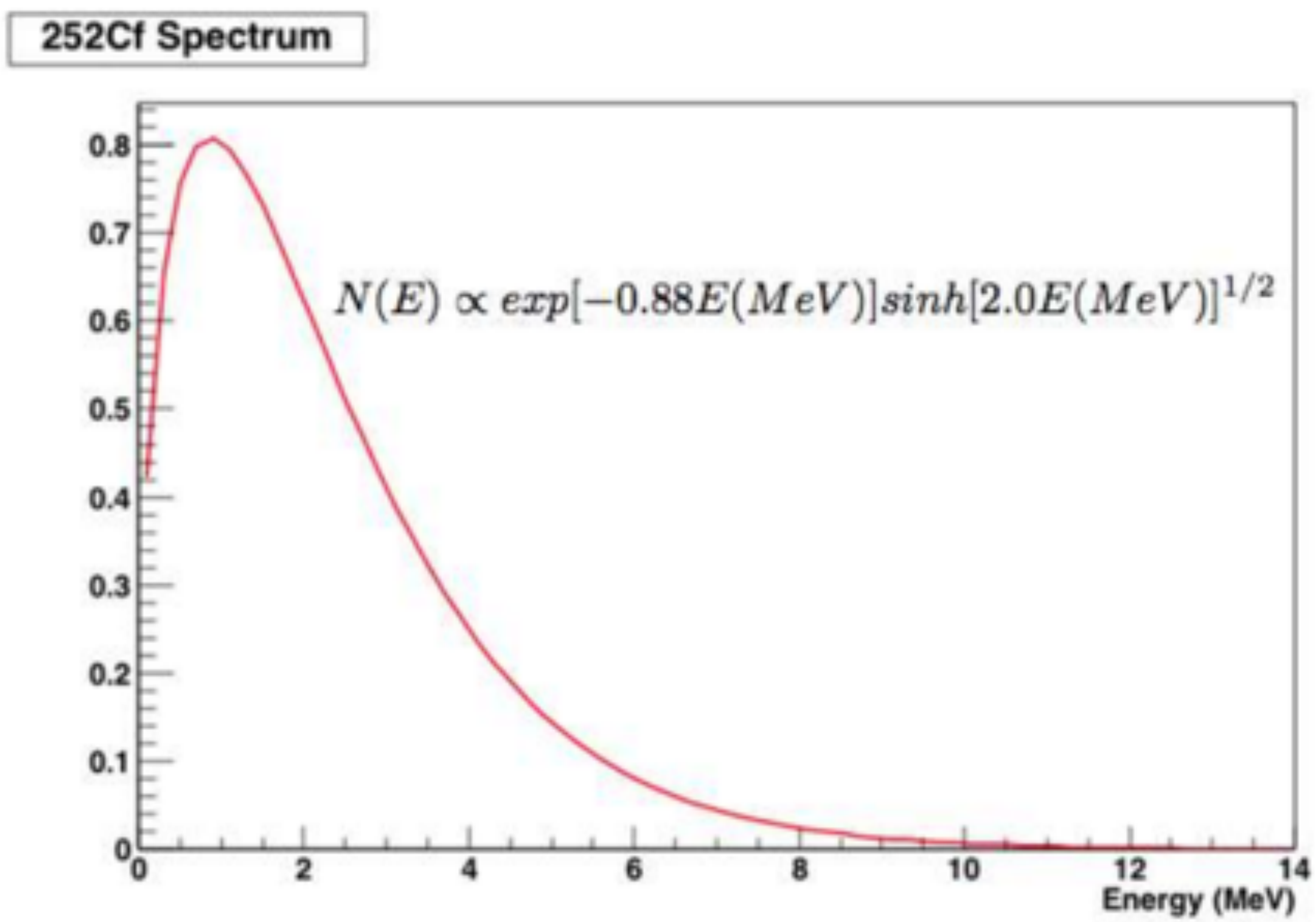
DD Neutron Gun
to be commissioned at USP - Brazil and to be taken to LNS

Nuclear Recoil with ^{252}Cf



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

^{252}Cf Energy Spectrum



BR: 3% Spontaneous fission;

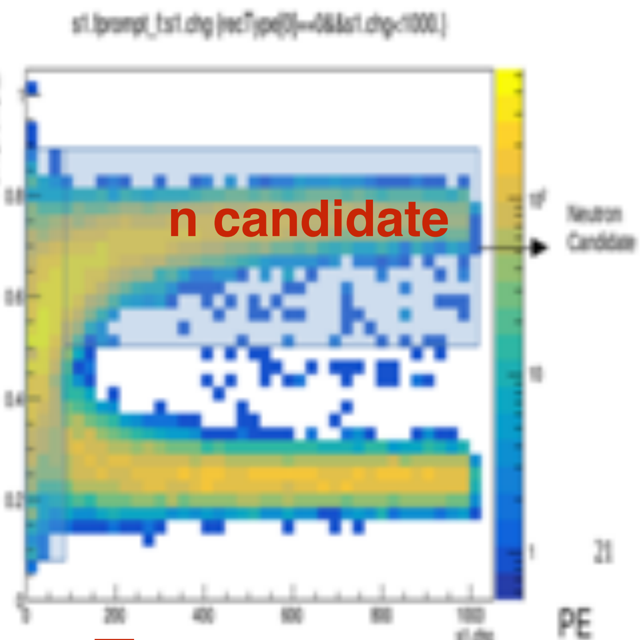
neutron emission (3.76 multiplicity) + prompt gammas

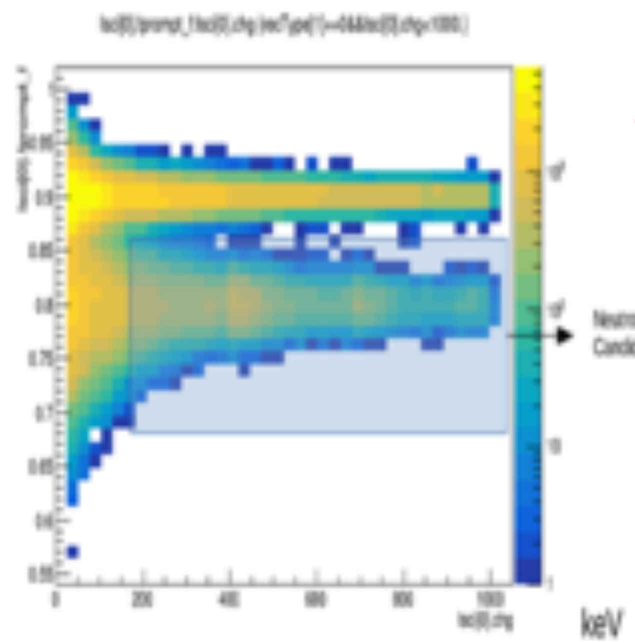
97% alphas

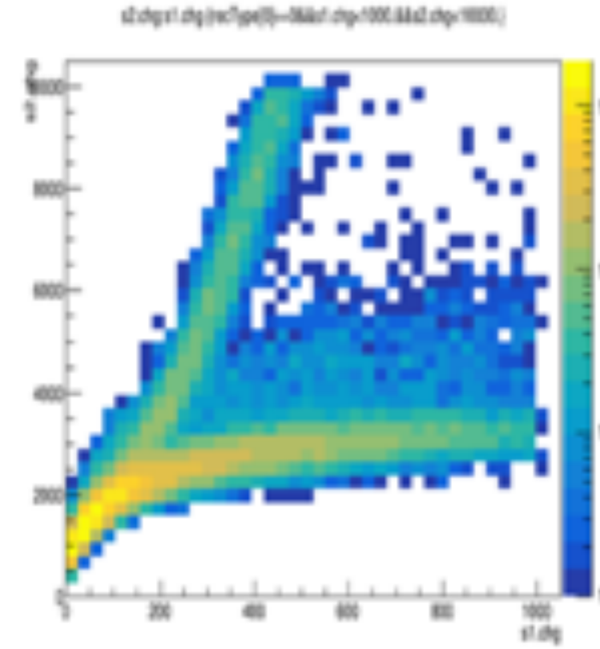
Tag the fission events (neutrons and γs) with BaF2 detector and use ToF + PSD

ReD ^{252}Cf at LNS

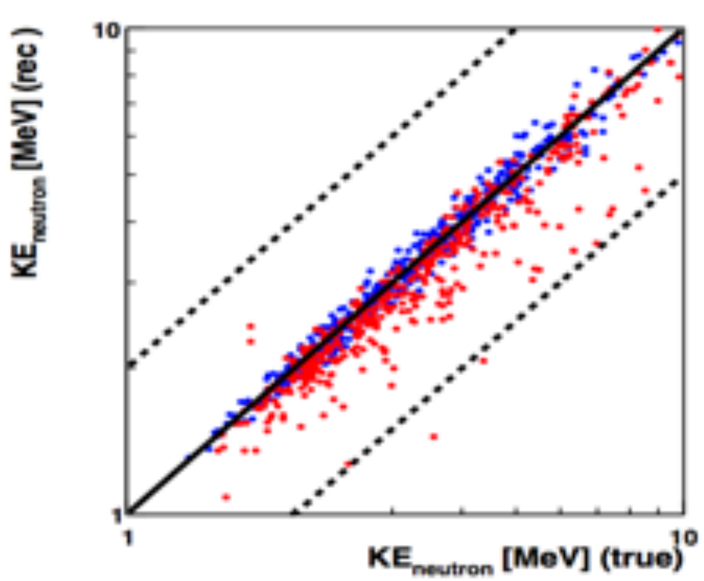
- **Commissioning now and measurements in early spring**

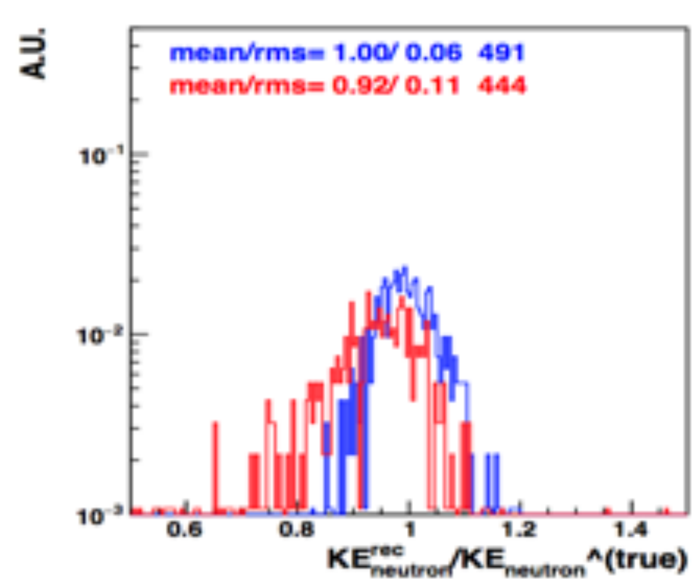






neutrons:
TPC: S1 < 100 pe OR
S1>100 and F_{prmt}>0.5
PSci: >200keV and
F_{prmt} < 0.85

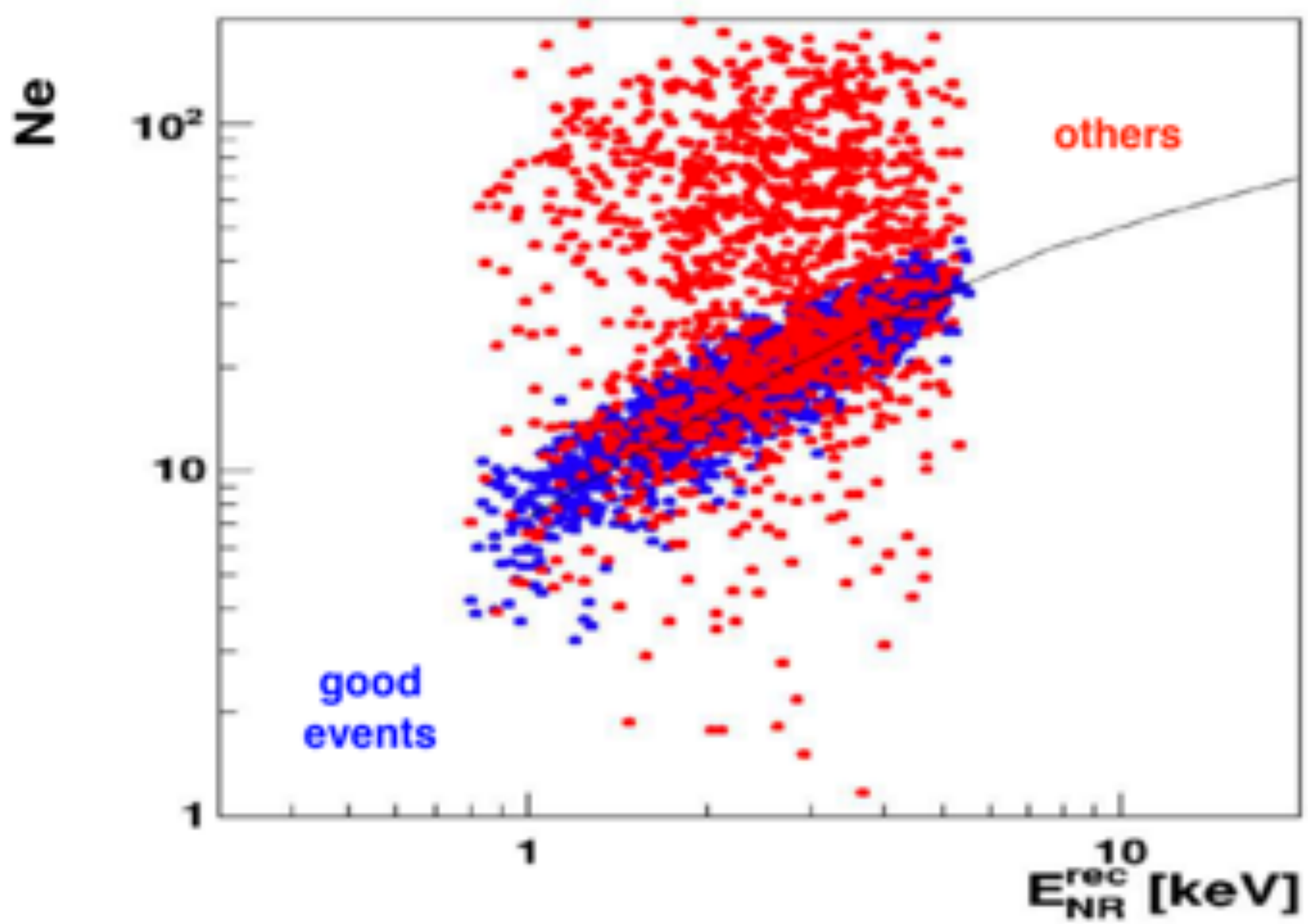




blue: good events
red: other (MS; no TPC)

good events: 1 n,
1 interaction in TPC
PSci triggers

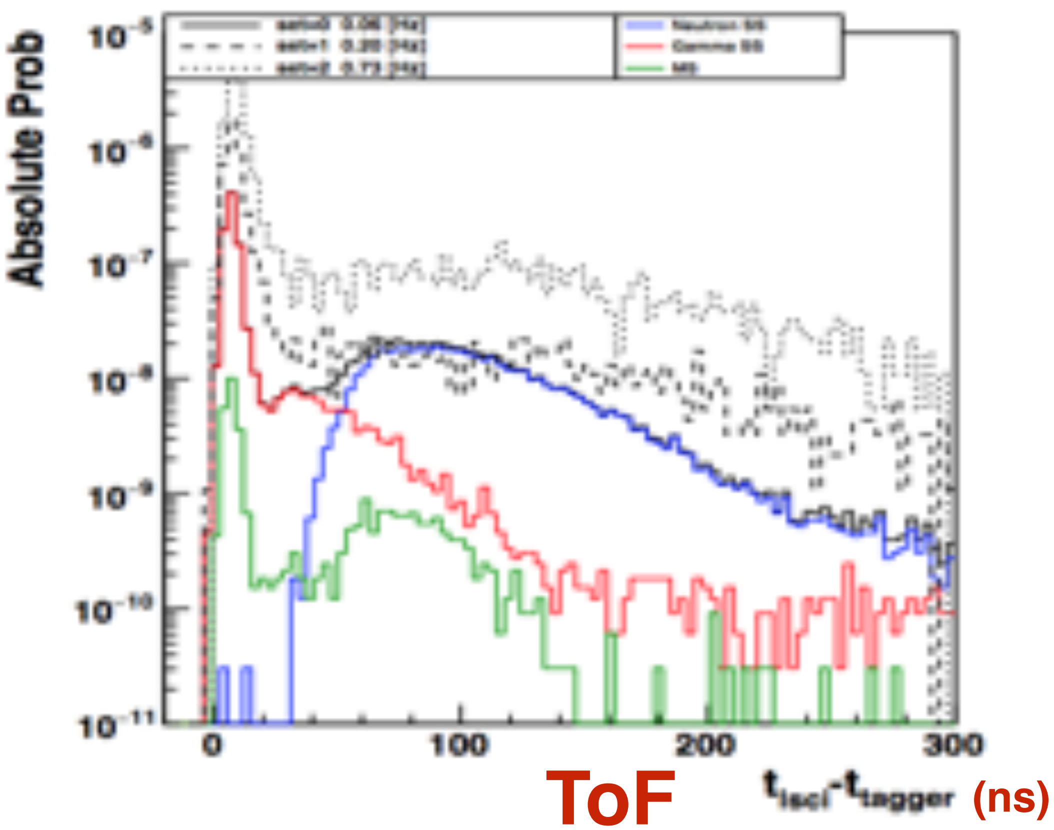
Energy Reconstruction

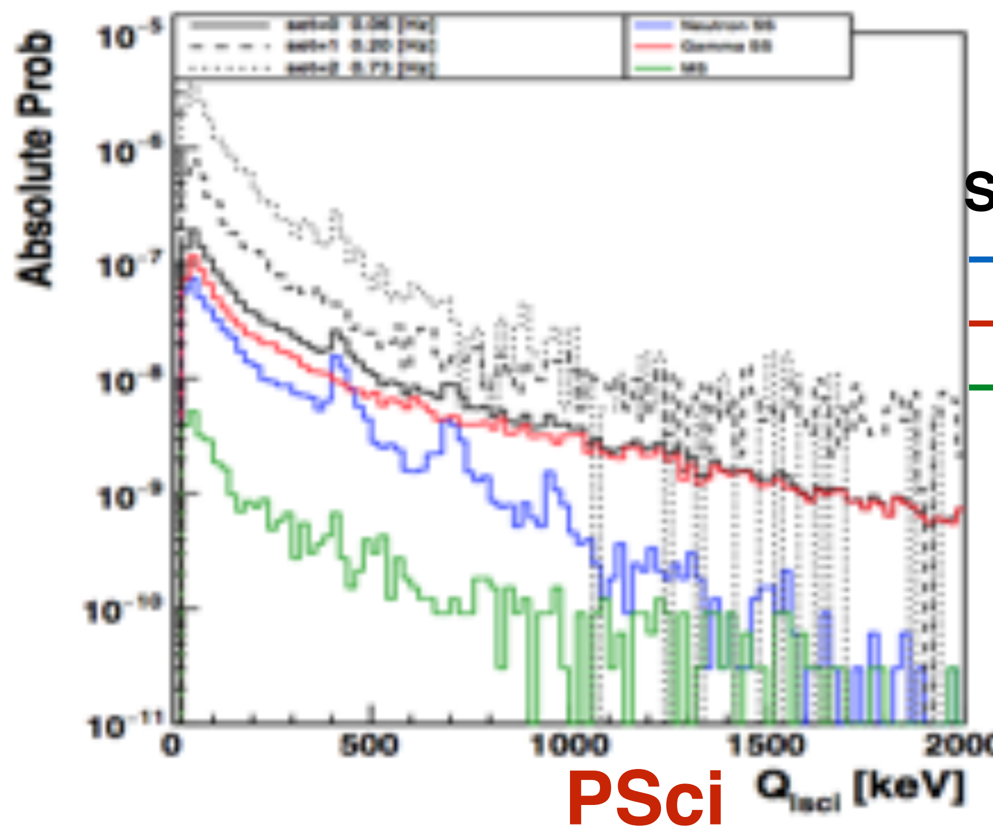


Energy Reconstruction Accuracy: 6% for neutrons; 10% NR

Systematics in NR energy < 10%
(change vertex reconstruction position)

ReD ^{252}Cf Prospects





Solid: forward neutrons
— **Single Scatter (SS)**
— **Gamma SS**
— **Neutron MS**

- **4 events / hour - 2 Good events / hour**

Accidentals: 165 counts / h * 100 μs (time window) * RateTPC

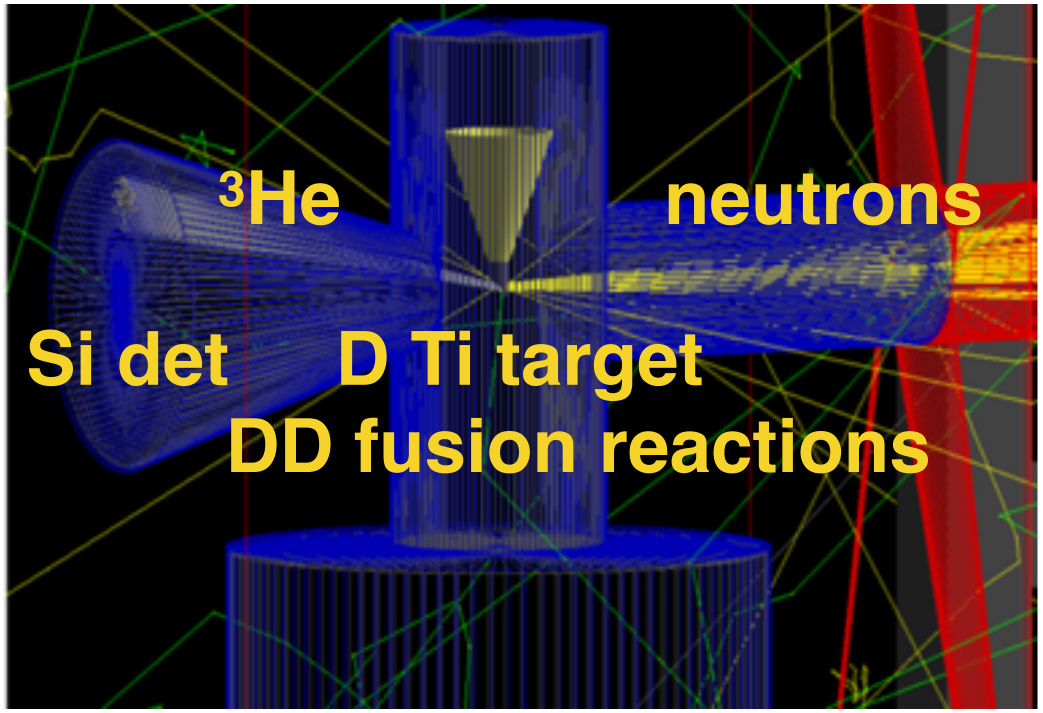
due to non forward neutrons that backscatter

Better shielding reduces it substantially

- **30 days of data taking should provide 1500 good events**

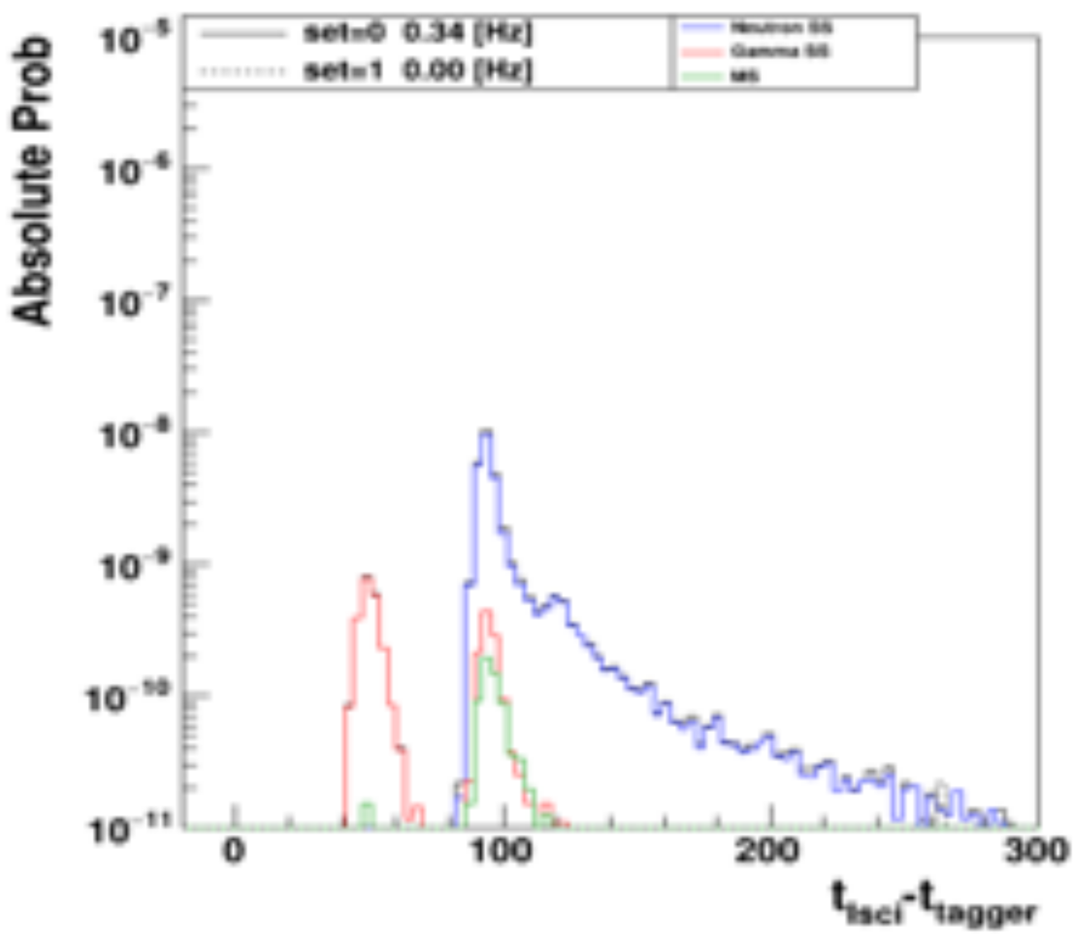
Neutron Gun Mode

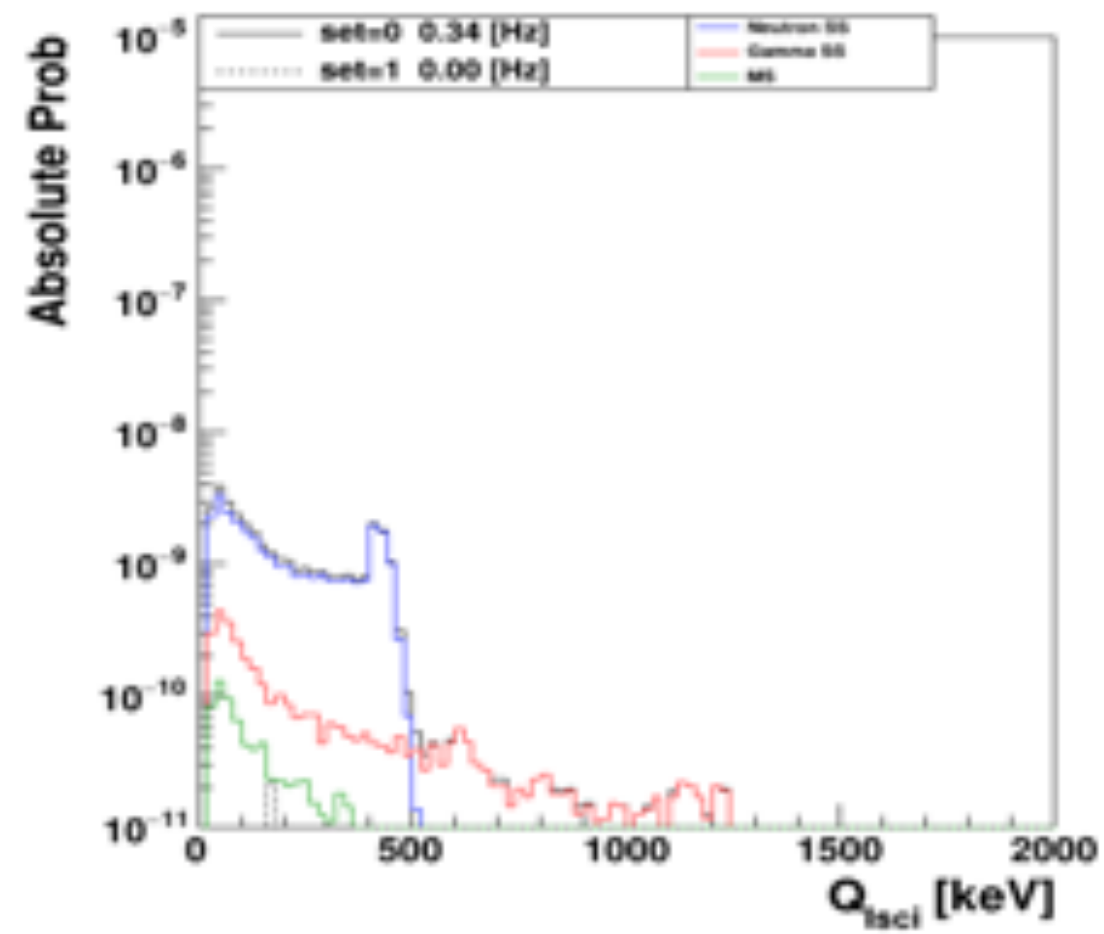
- **Neutron DD Gun Mono-energetic Beam: 2.5 MeV**
- **TPC vertex + PSci position + $E_{neutron}$ => Recoil energy**
- **Time tag the neutron with a Si detector inside NG**
- **10^7 neutrons/s and 50 keV Deuterons**



- **2.4 kHz trigger rate at Si Det**

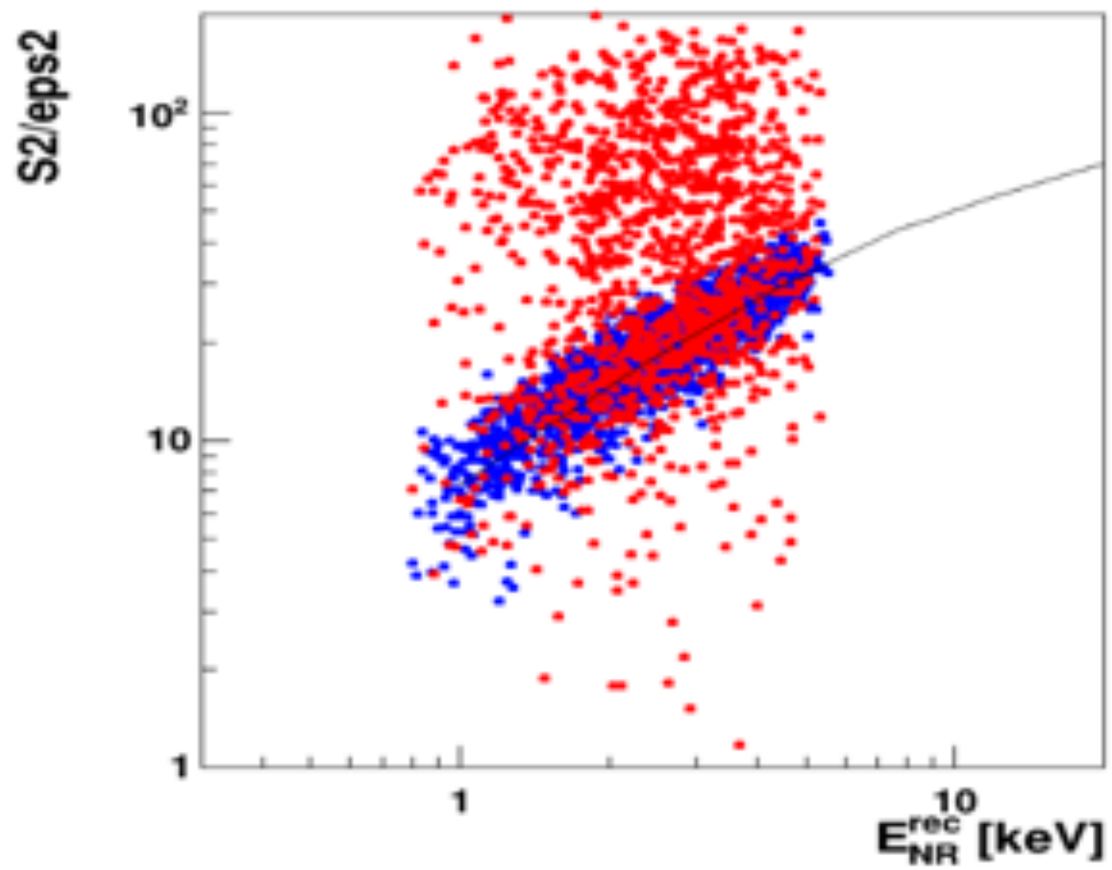
Neutron Gun Mode





— Neutrons (SS)
— Gamma SS (n scattering on TPC)
— Neutron MS

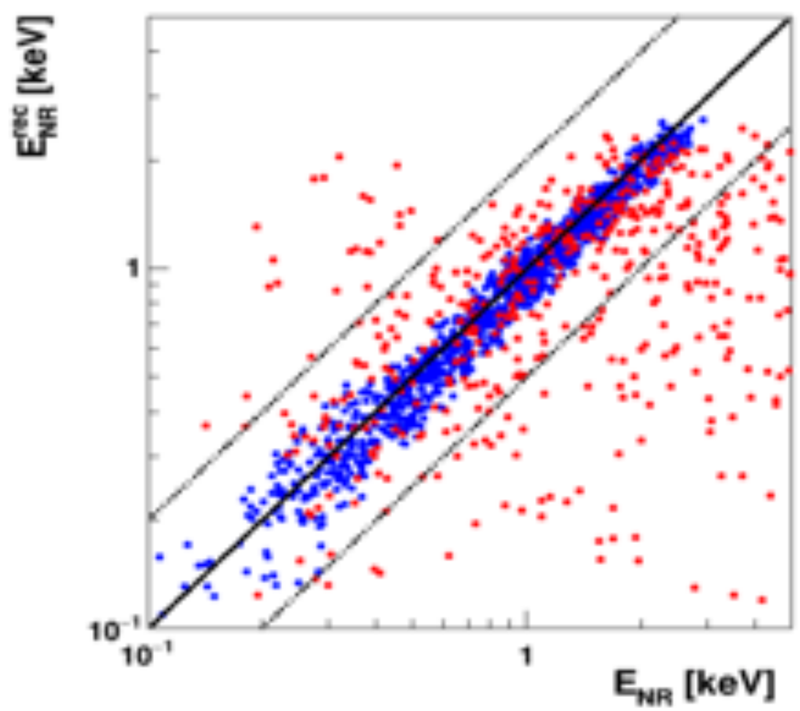
NG Energy Reconstruction

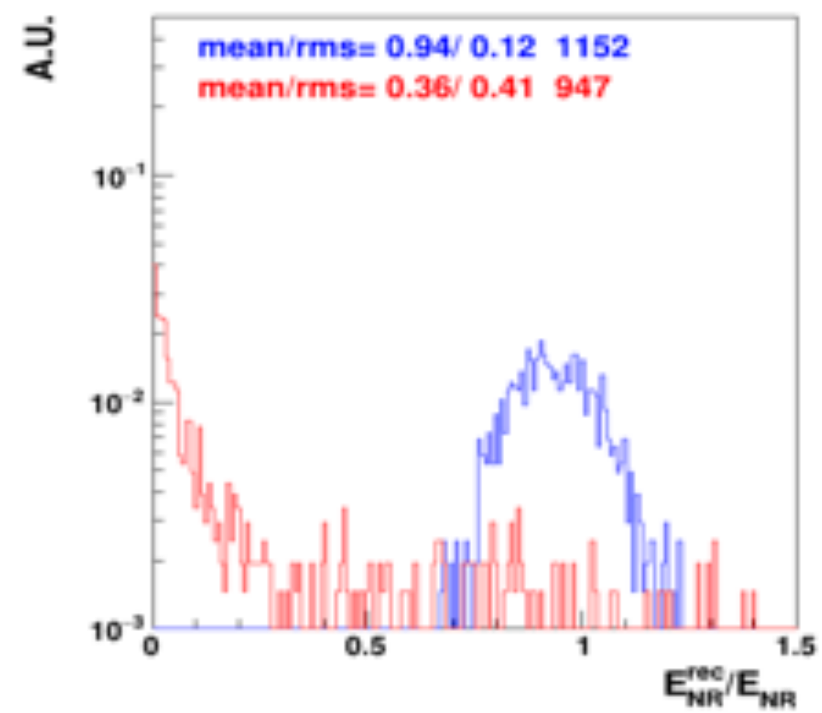


Energy Reconstruction Accuracy: 7% NR

Systematics in NR energy < 10%
(change vertex reconstruction position)

Neutron Gun Reconstruction





6 deg scattering angle

blue: good events
red: other (MS; no TPC)

- **111 events / hour; 60% are good events**
- **Accidentals: 360 events / hour * 100μs * TPCrate ~ 0.36ev/h; due to scattering on TPC inactive regions**
- **13 days of data taking should provide 1500 good events**

^{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

NG Schedule

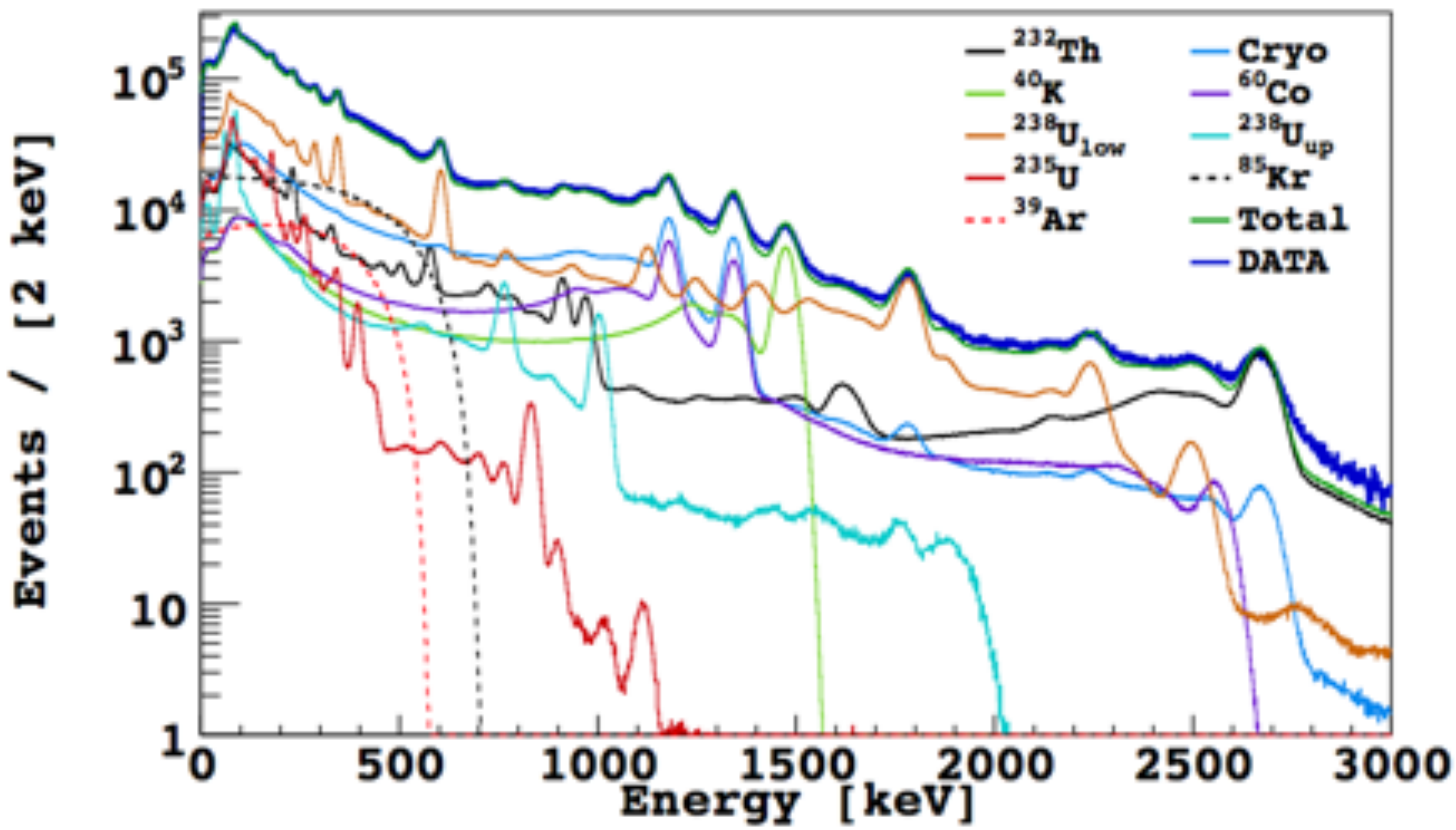
- IFUSP grant proposal to FAPESP under review
  - 2 years commissioning at IFUSP (no TPC): mid 22/mid 24
  - NG will be sent to LNS Catania
- Setup and data taking in LNS: 24/25

Conclusions

- Current WIMP exclusion region motivates lower mass (< 10 GeV) candidates

- DS-50k demonstrated that Liquid Noble dual phase detectors have good sensitivity at this mass region

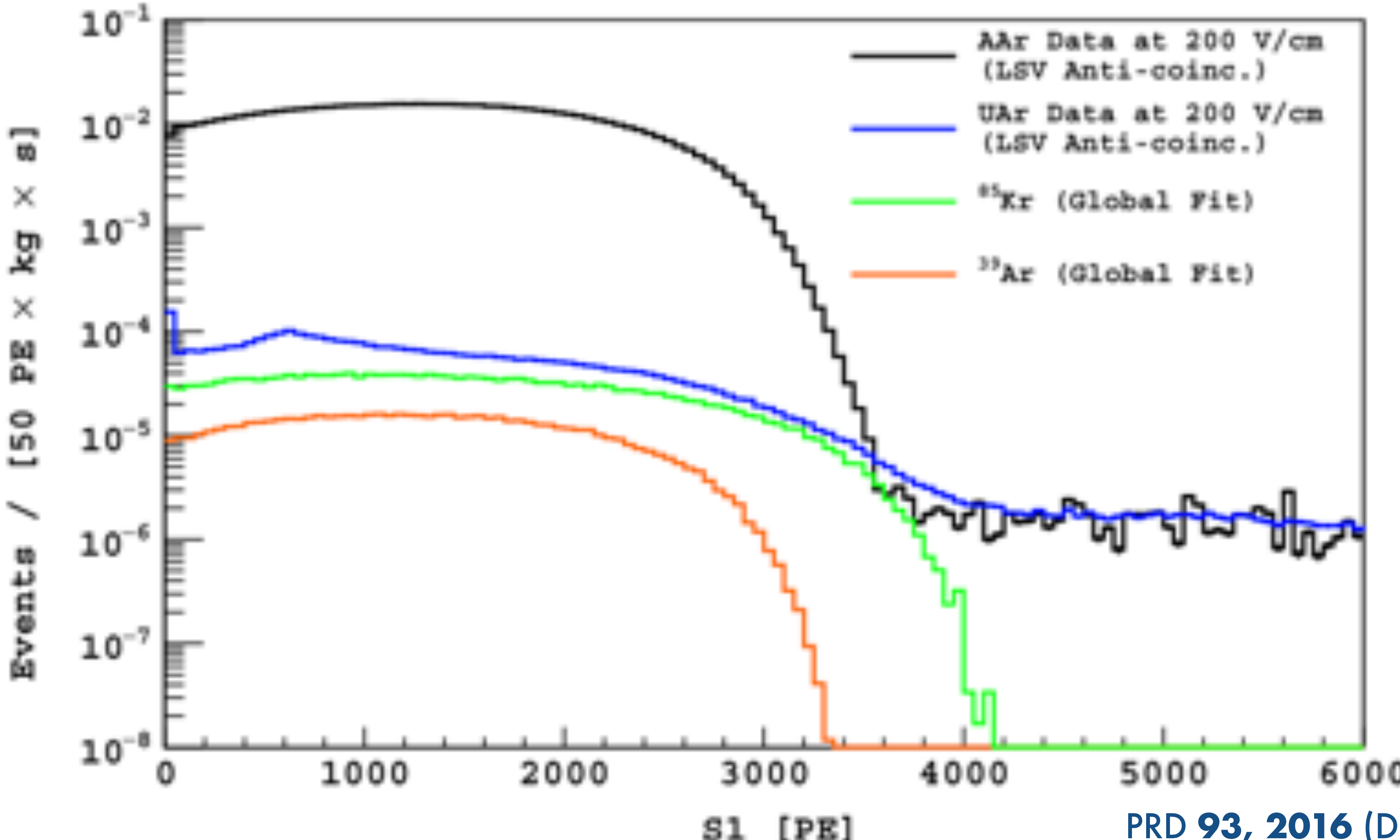
- Nuclear Recoil Energy at low energies can be better determined by ReD's ^{252}Cf and NG experimental setups



Background modeling: data/MC

JINST 12, P10015 (2017)

Backup



PRD **93, 2016** (Darkside Coll.)

Unexpected in UAr (~2 mBq/Kg)
from atm leaks or natural fission
can be effectively removed by cryogenic distillation

- High Scintillation Light Yields; transparent to their own light
- Good Nuclear versus Electron Recoil discrimination
- Large Detector Masses are possible

Ne	Ar	Xe
A = 20	A = 40	A = 131
30	1	400 cost unit/kg