

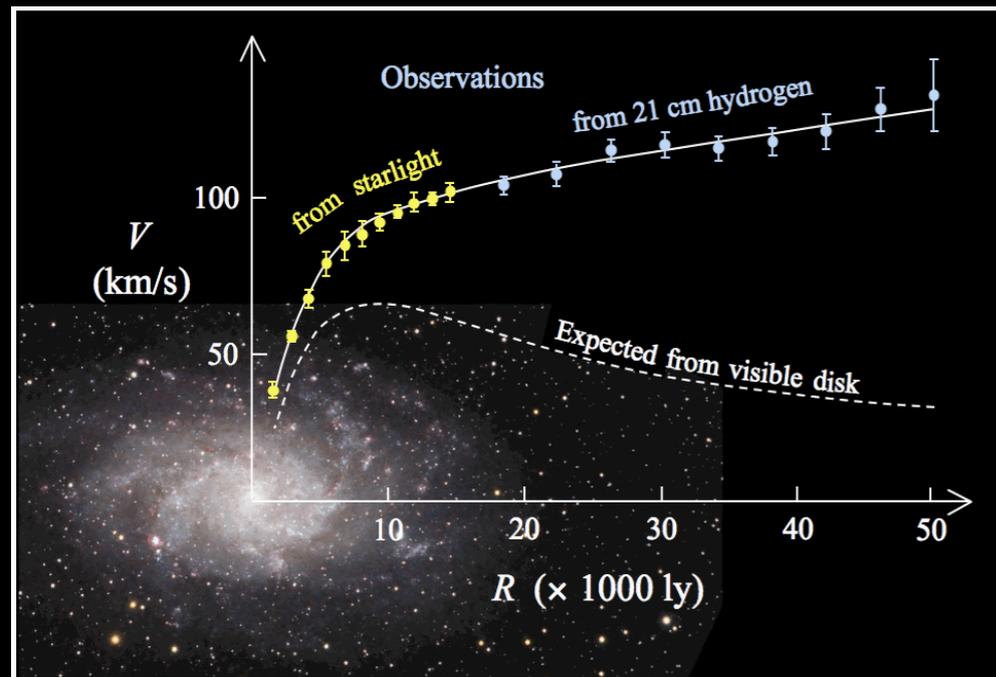
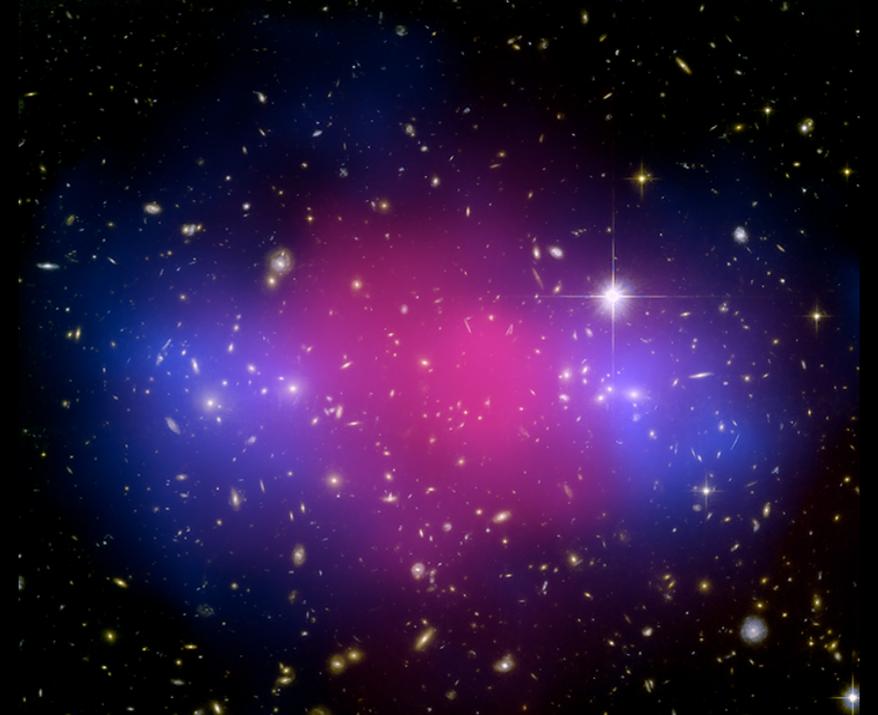
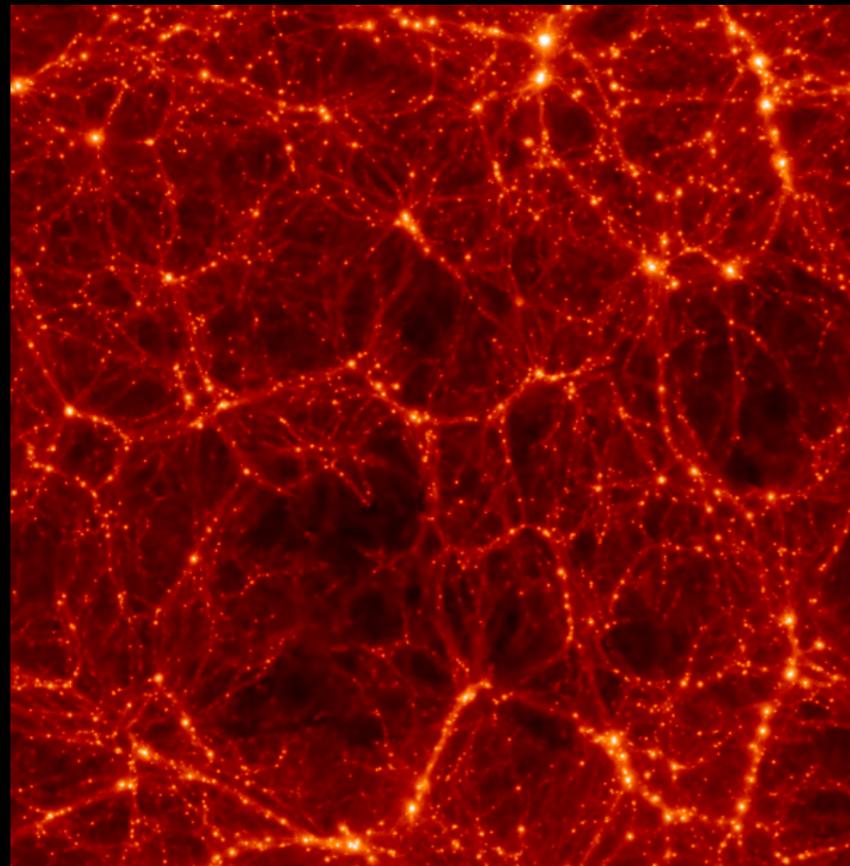
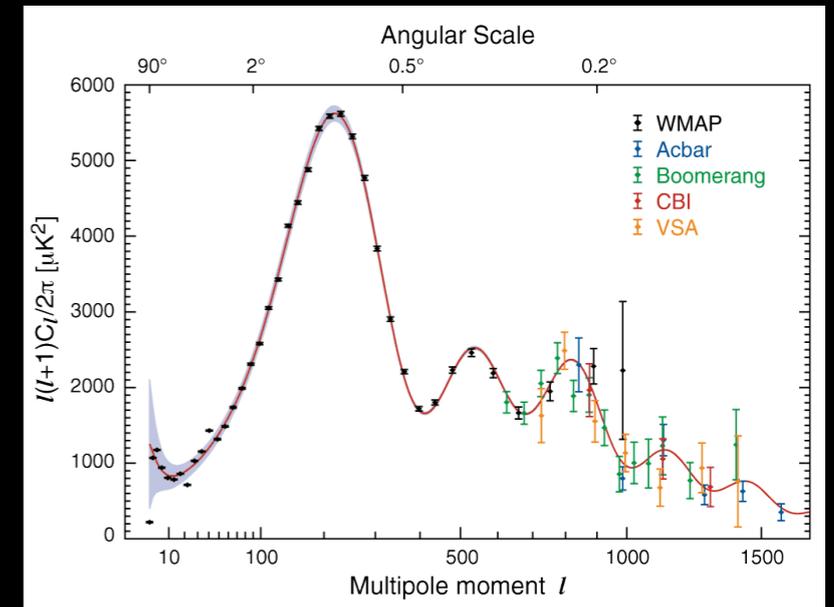
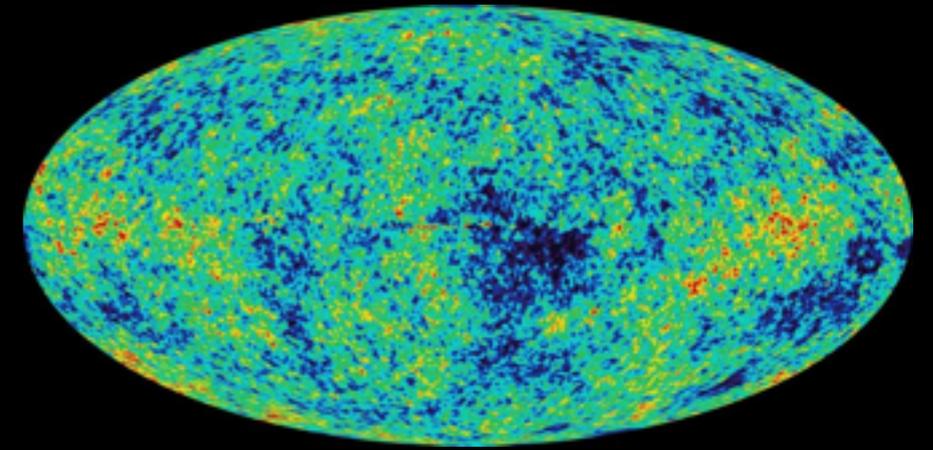
WIMP Search from the DarkSide

Masayuki Wada
Princeton University
03/03/2013

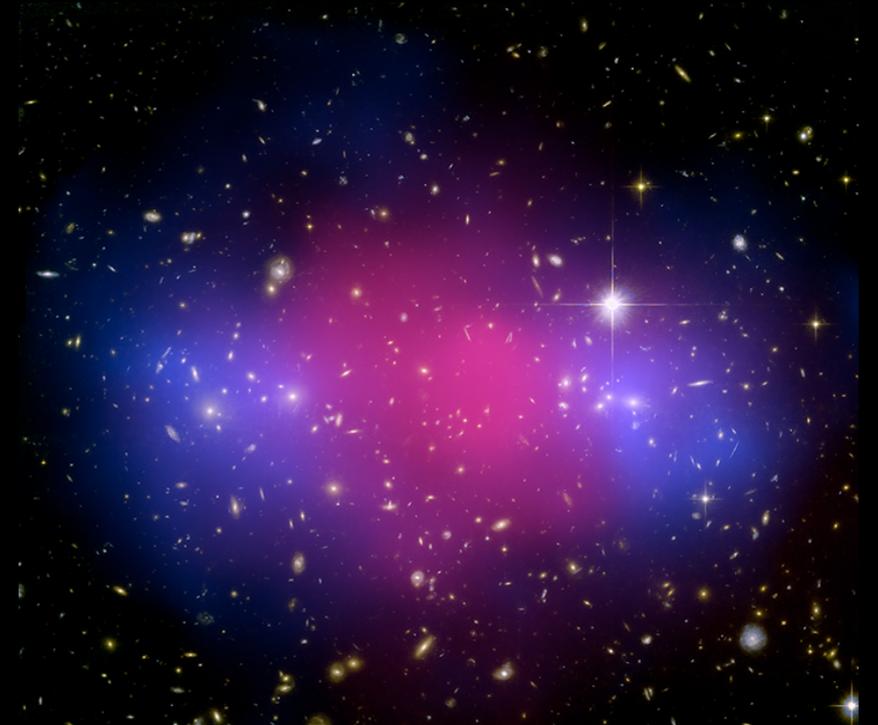
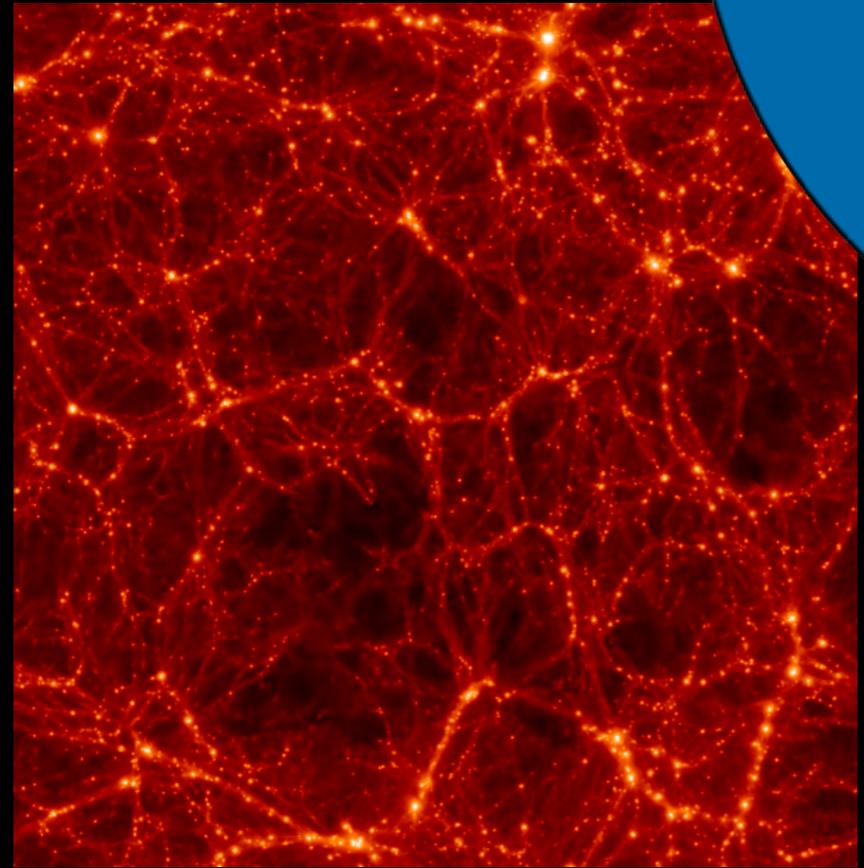
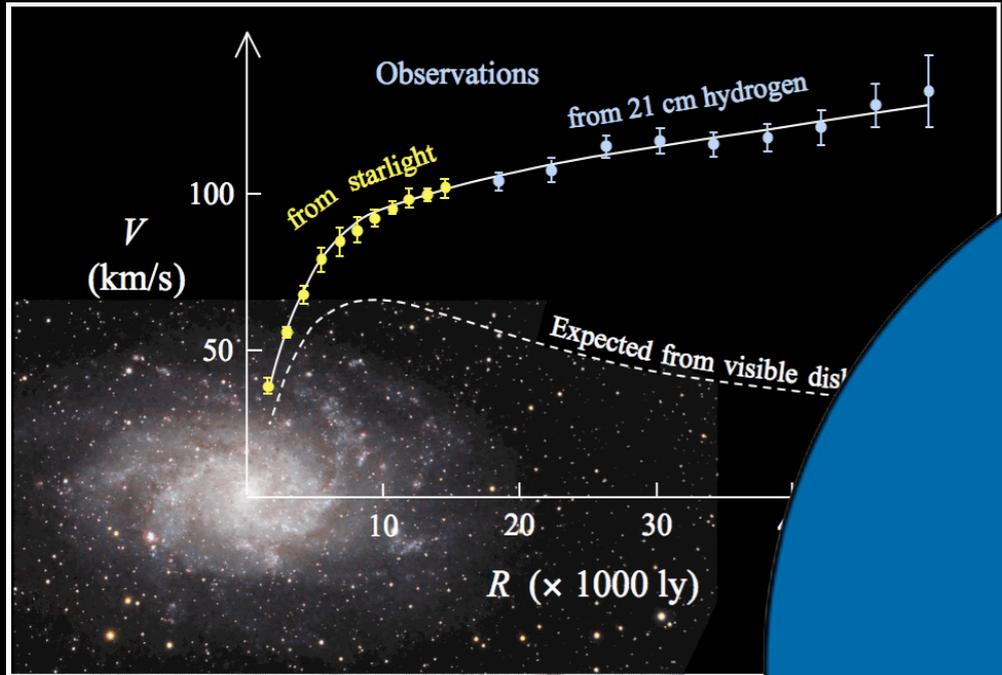
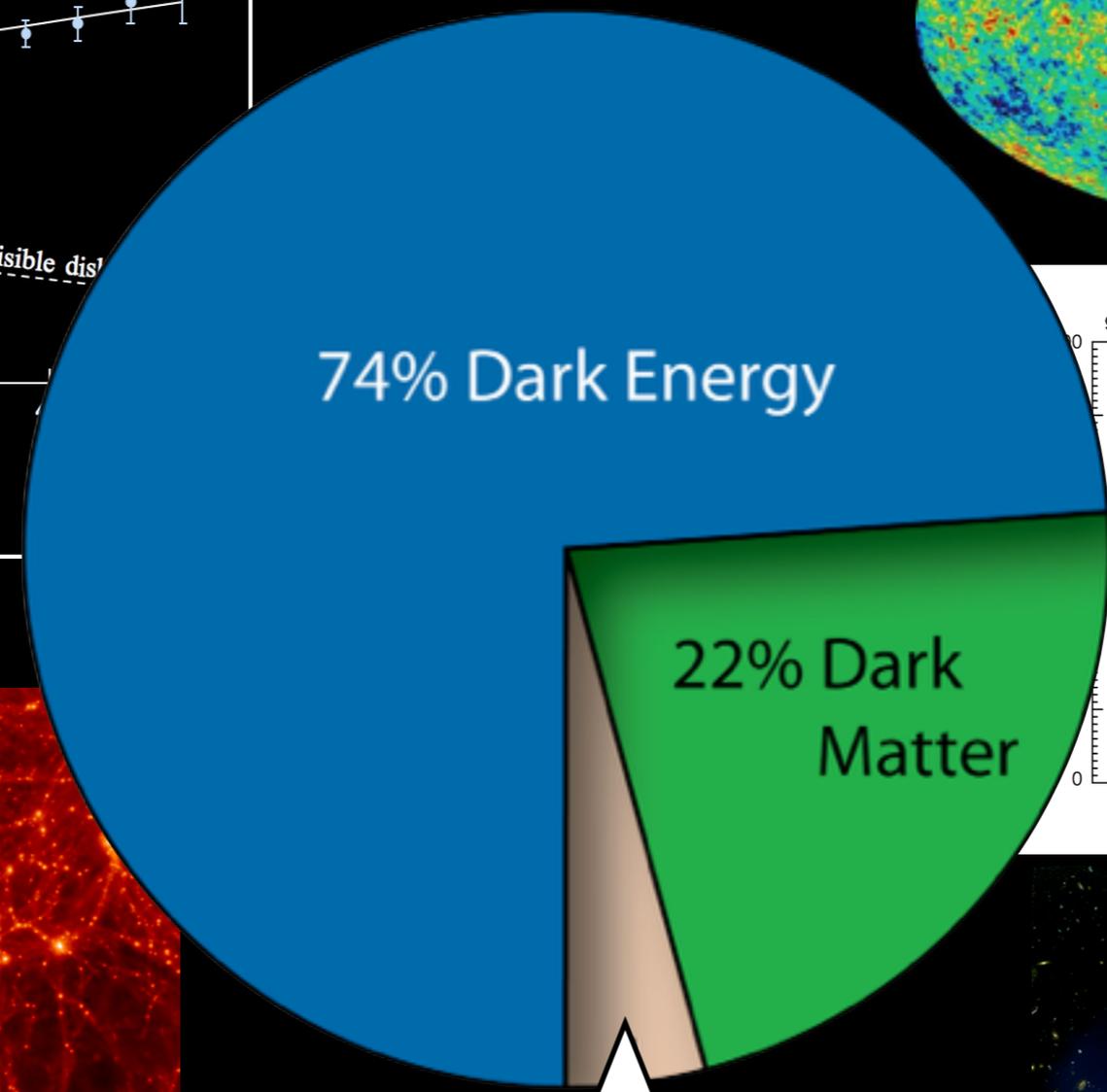
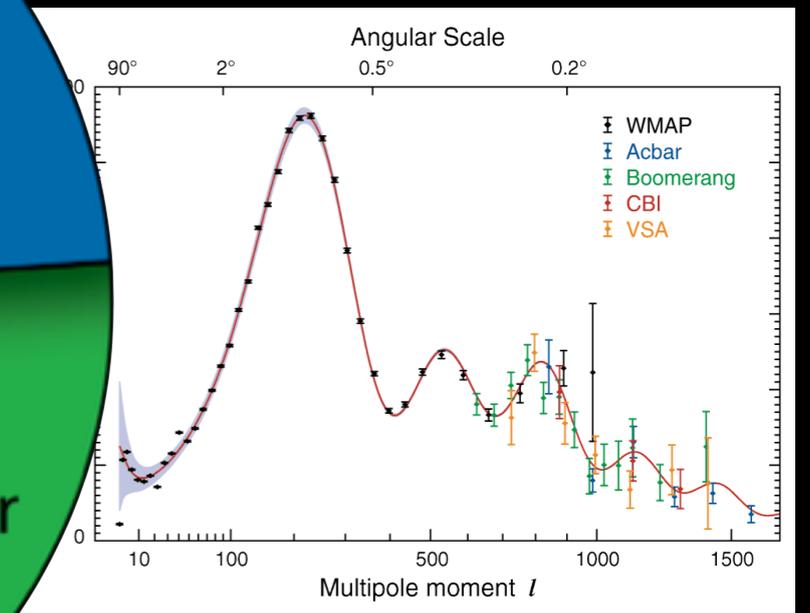
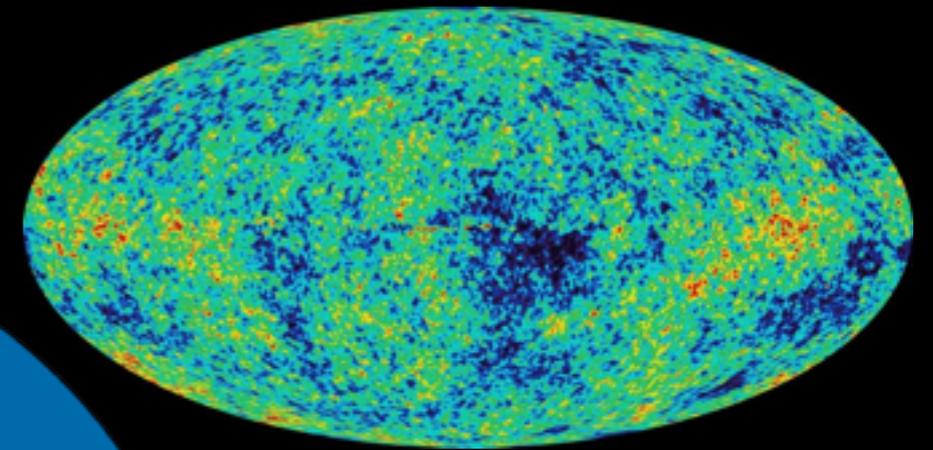
Outline

- Introduction to Direct Detection of Dark Matter
- DarkSide Program
- DarkSide-10 Prototype
- DarkSide-50
- BG run result

Evidence for Dark Matter

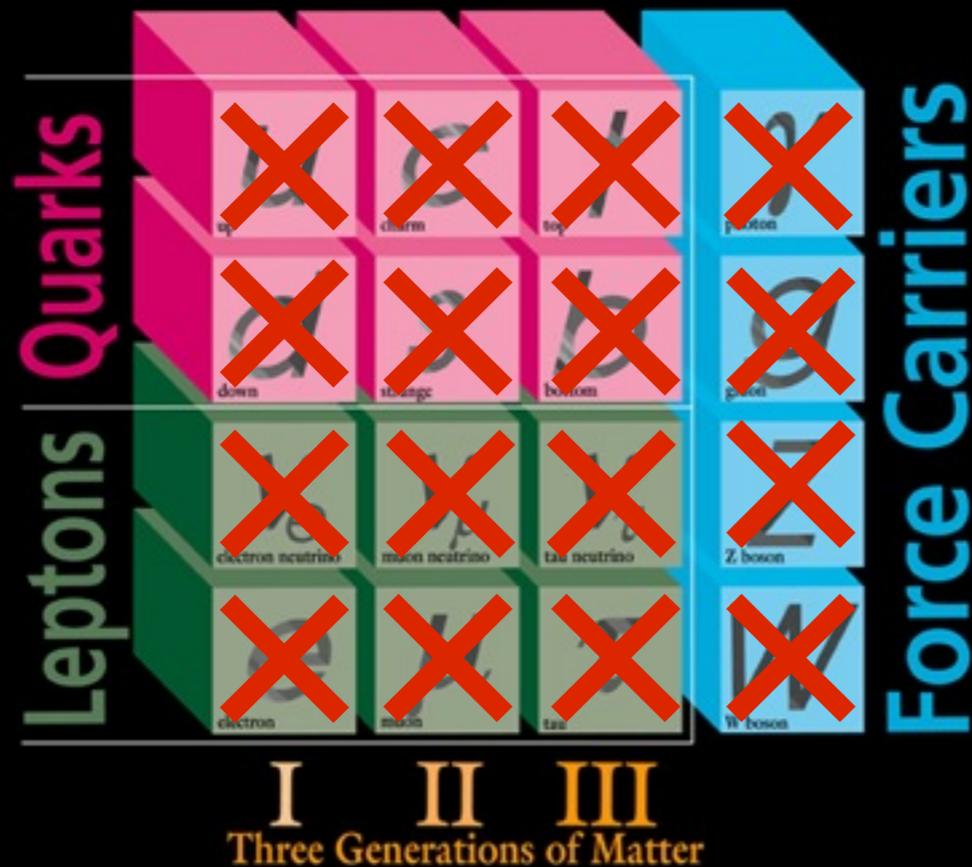


Evidence for Dark Matter



Dark Matter Properties

ELEMENTARY PARTICLES



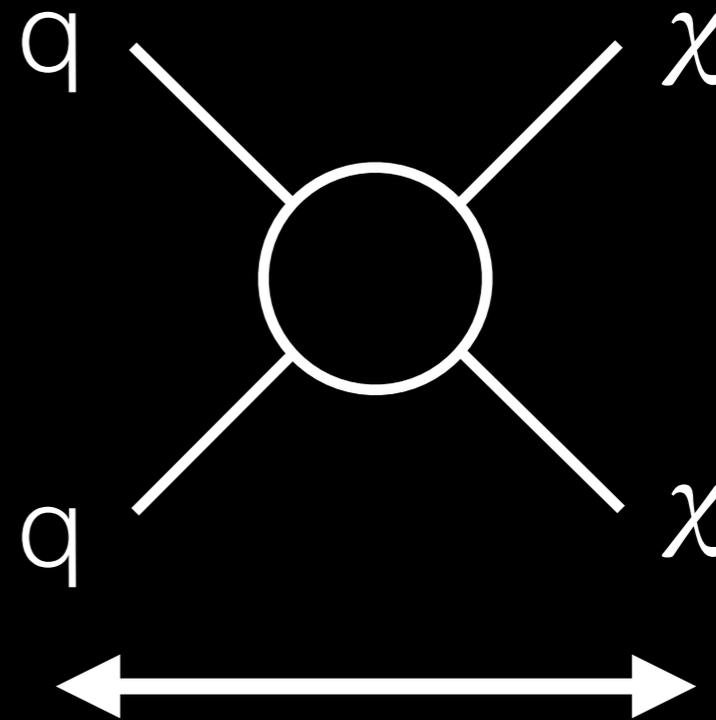
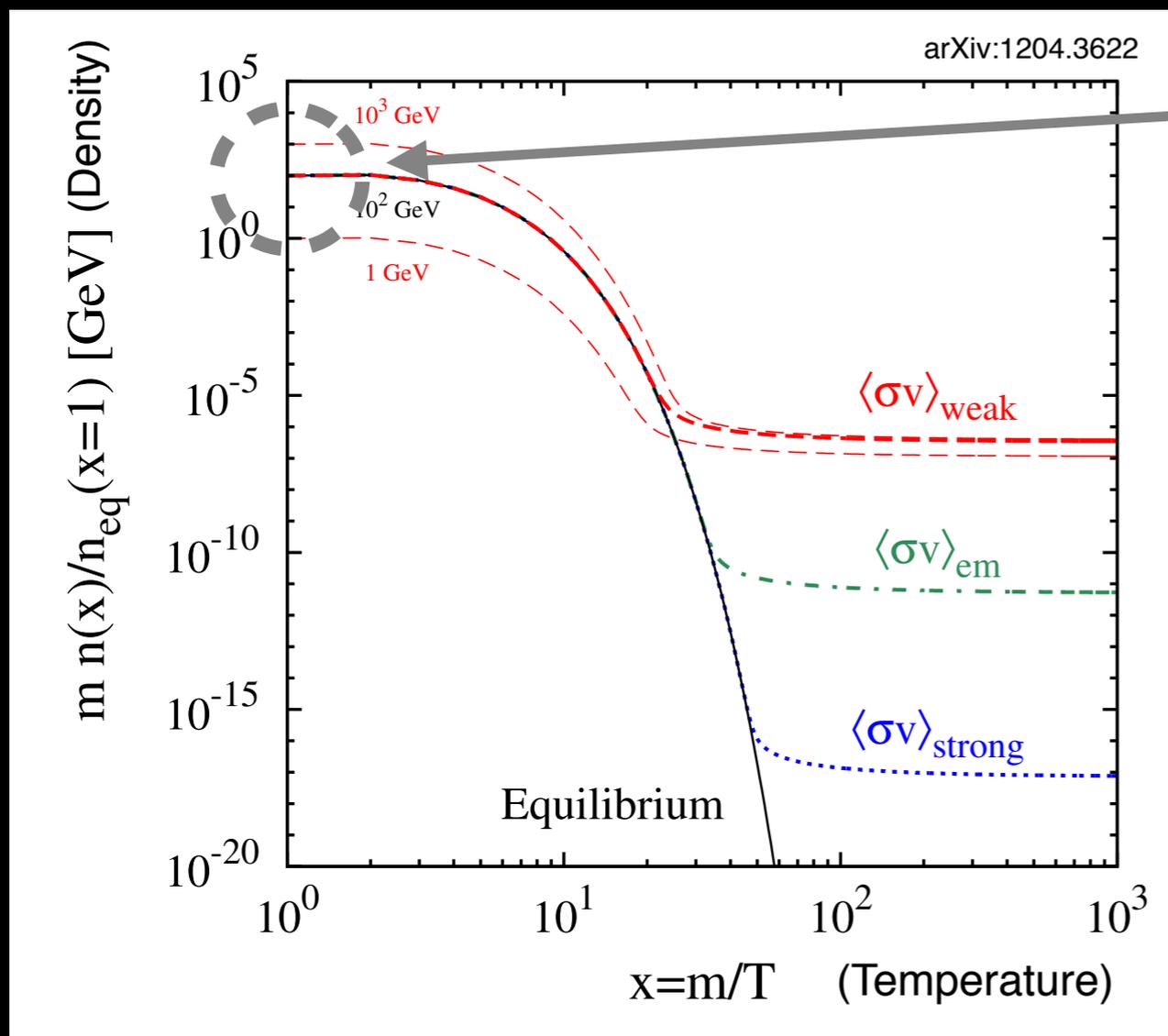
- Gravitationally interacting
- Stable particle
- Not Hot
- Not Baryon

Beyond Standard Model!!

One of the most physics motivated candidates is Weak Interacting Massive Particles (**WIMP**).

Why WIMP?

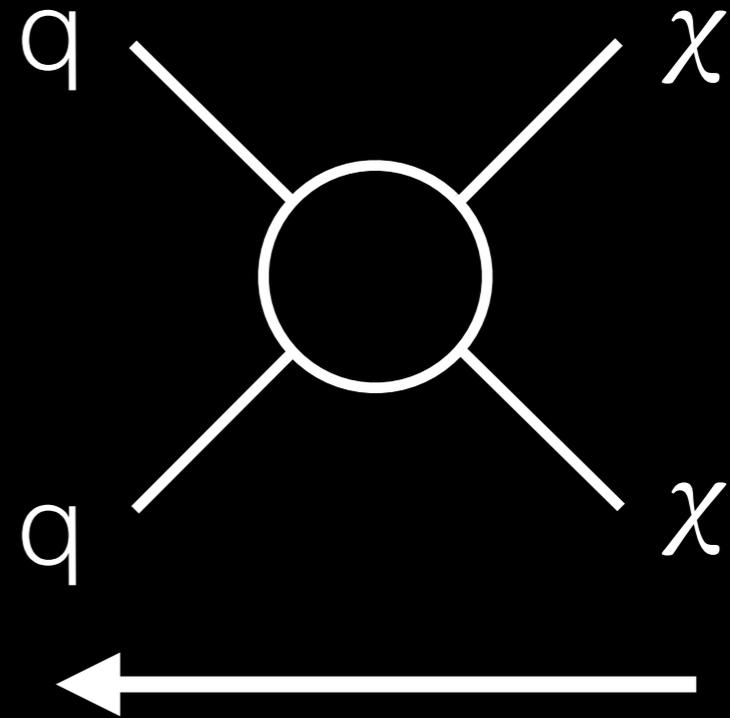
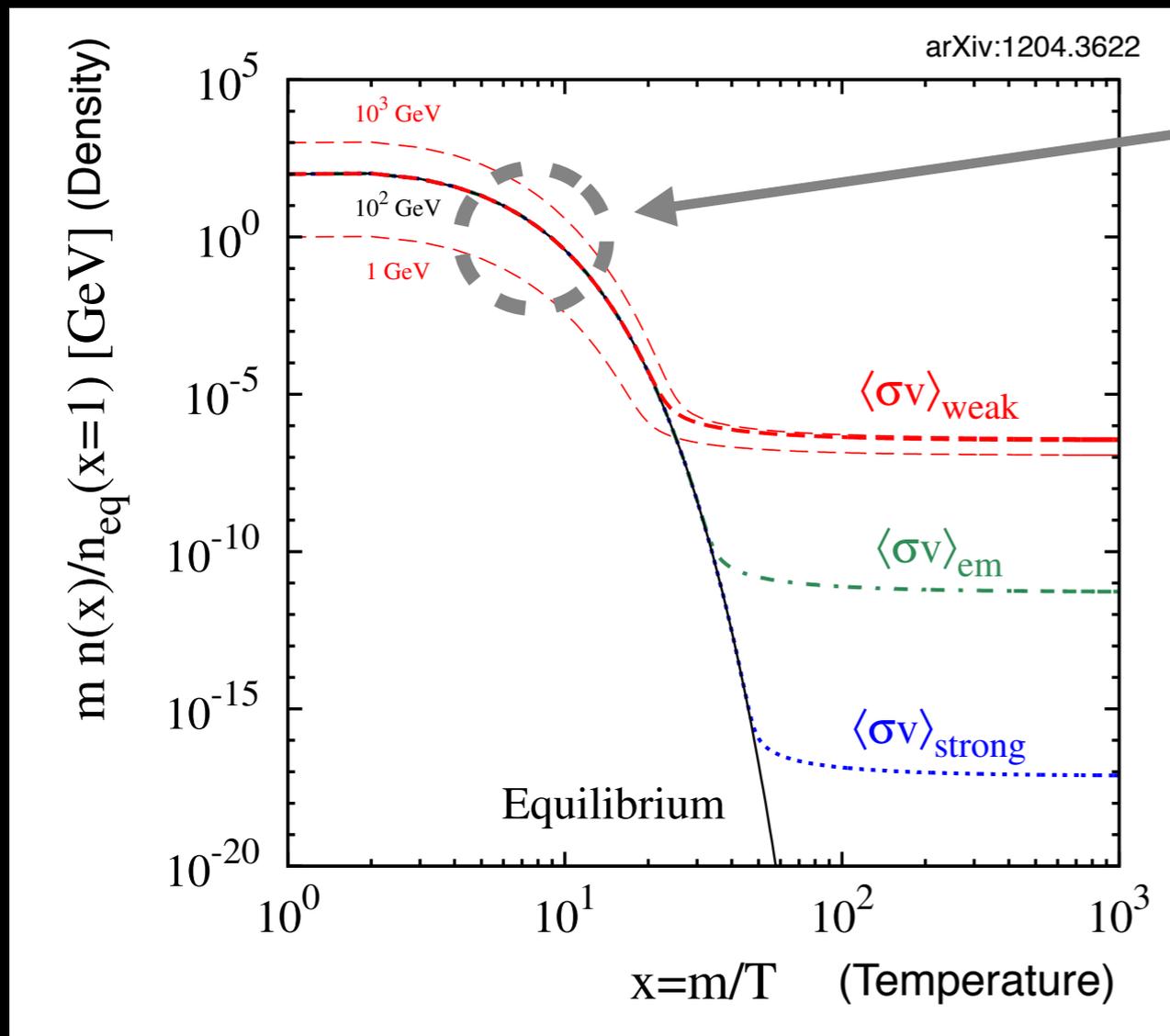
Thermal Relic (WIMP miracle)



When $T \gg m$, equilibrium

Time →

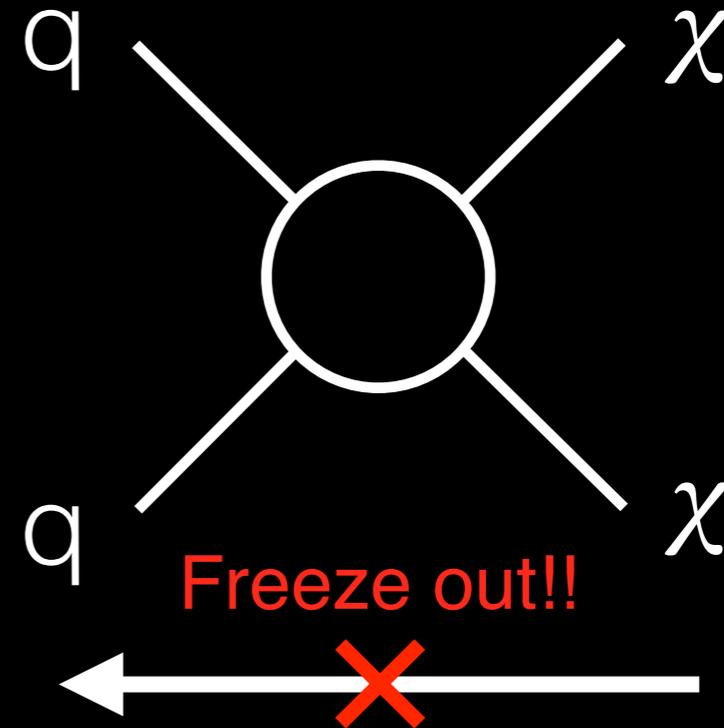
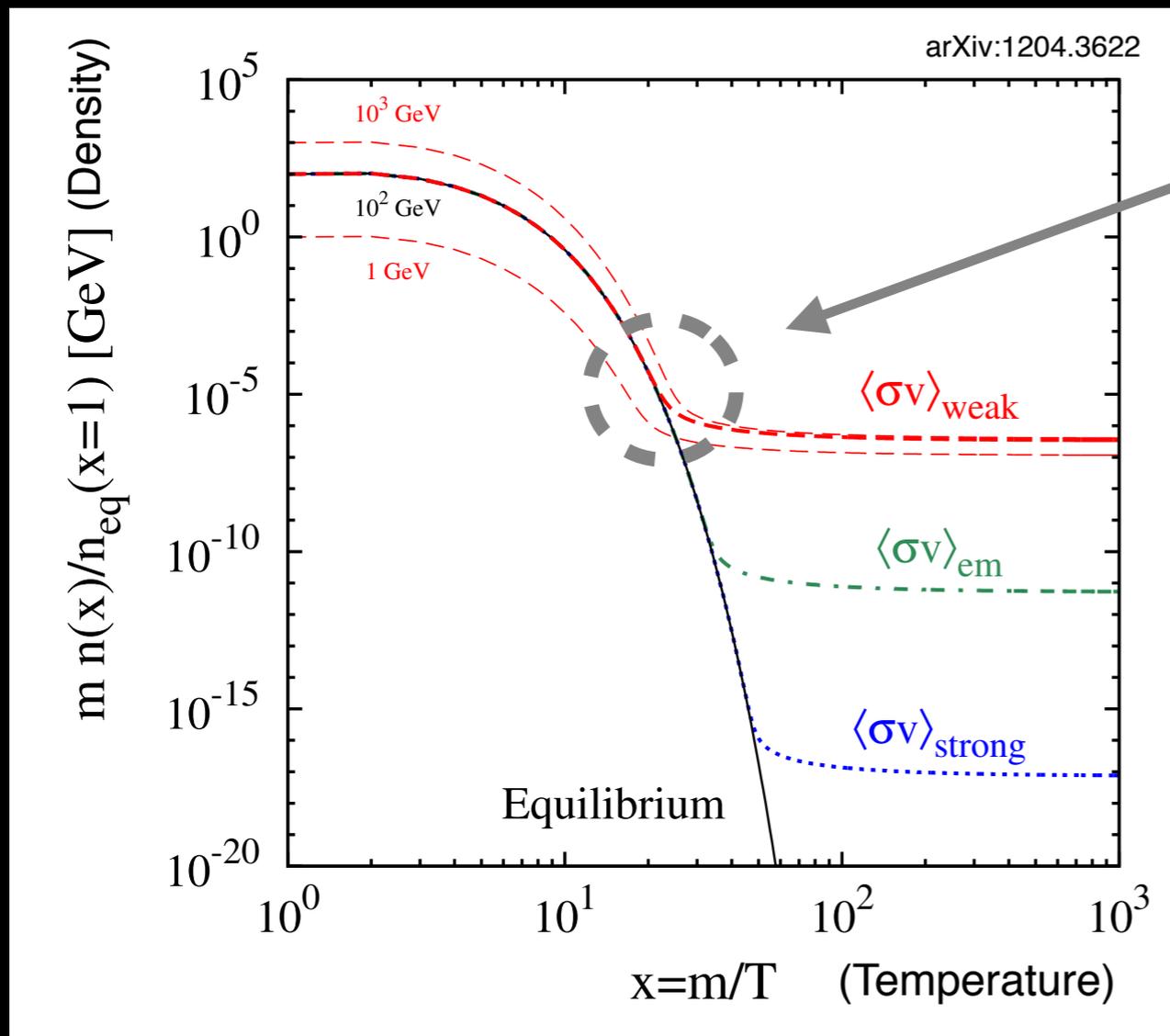
Thermal Relic



When $T < m$, χ decay exponentially.

Time →

Thermal Relic



When $\Gamma = H$, χ can not find each other.

$$\Gamma = n(x)\langle\sigma v\rangle \Rightarrow n_f(x) = H/\langle\sigma v\rangle$$

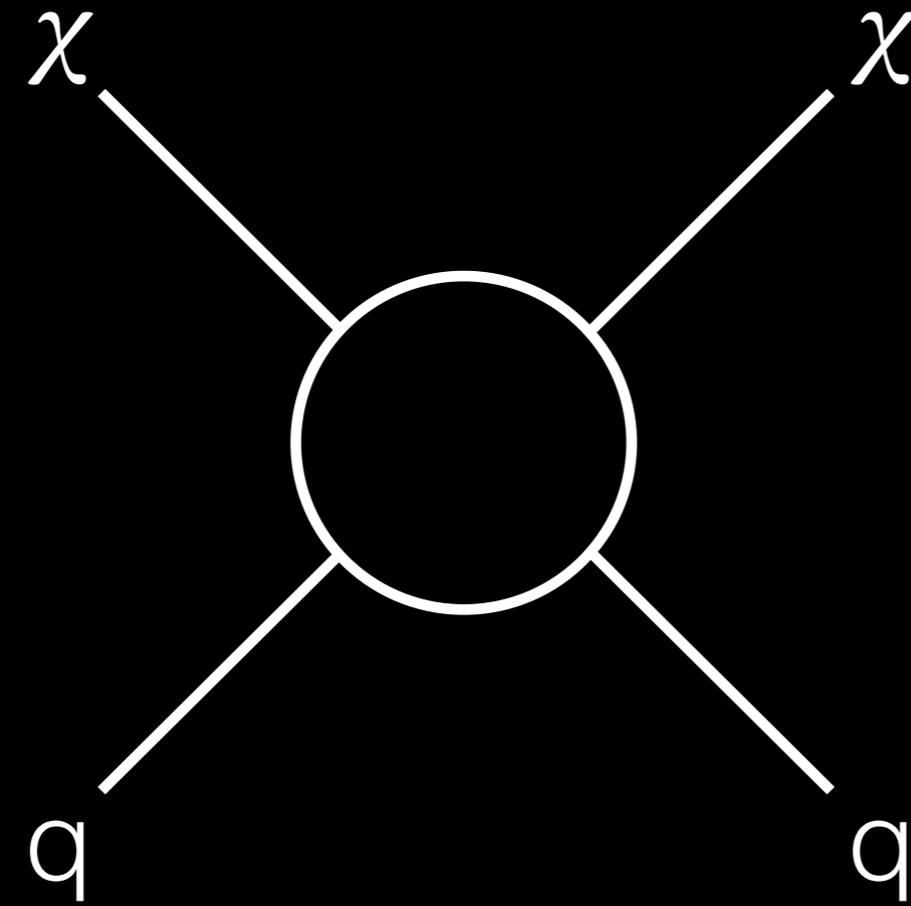
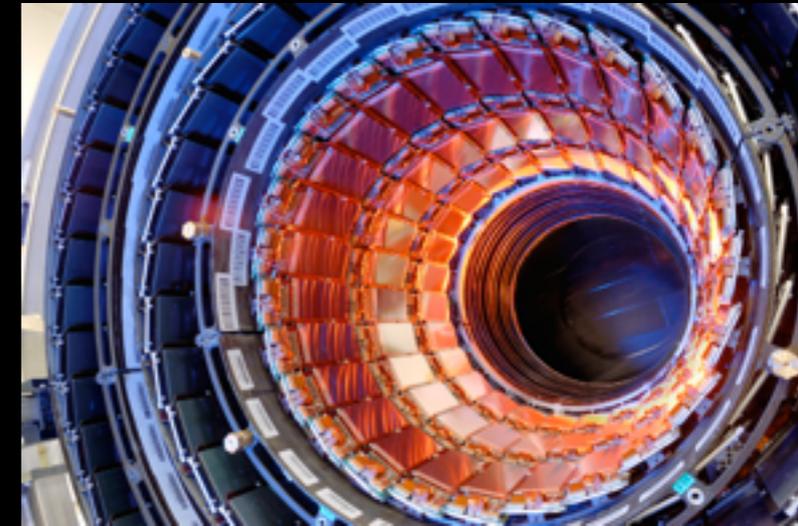
Weak-scale cross section reproduces the relic abundance of DM expected from Λ CDM.

Detecting WIMPs

Annihilation



Production



Indirect Detection

Colliders

Scattering



Direct
Detection

Direct Detection Rates

$$R \text{ (events/kg/yr)} = \langle \Phi_{\chi} \cdot \sigma_{\chi-N} \rangle \cdot n$$

Φ_{χ}

Flux of WIMPS

$\sigma_{\chi-N}$

WIMP-Nucleus Scattering Cross Section

n

Target Nuclei / kg

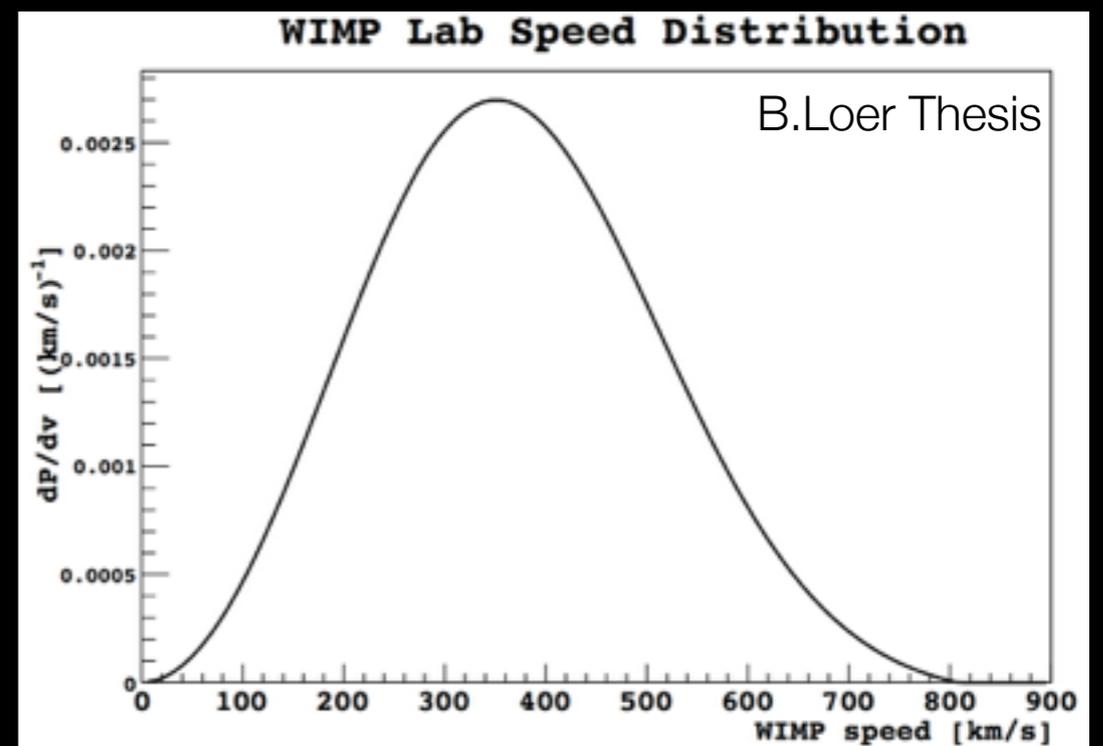
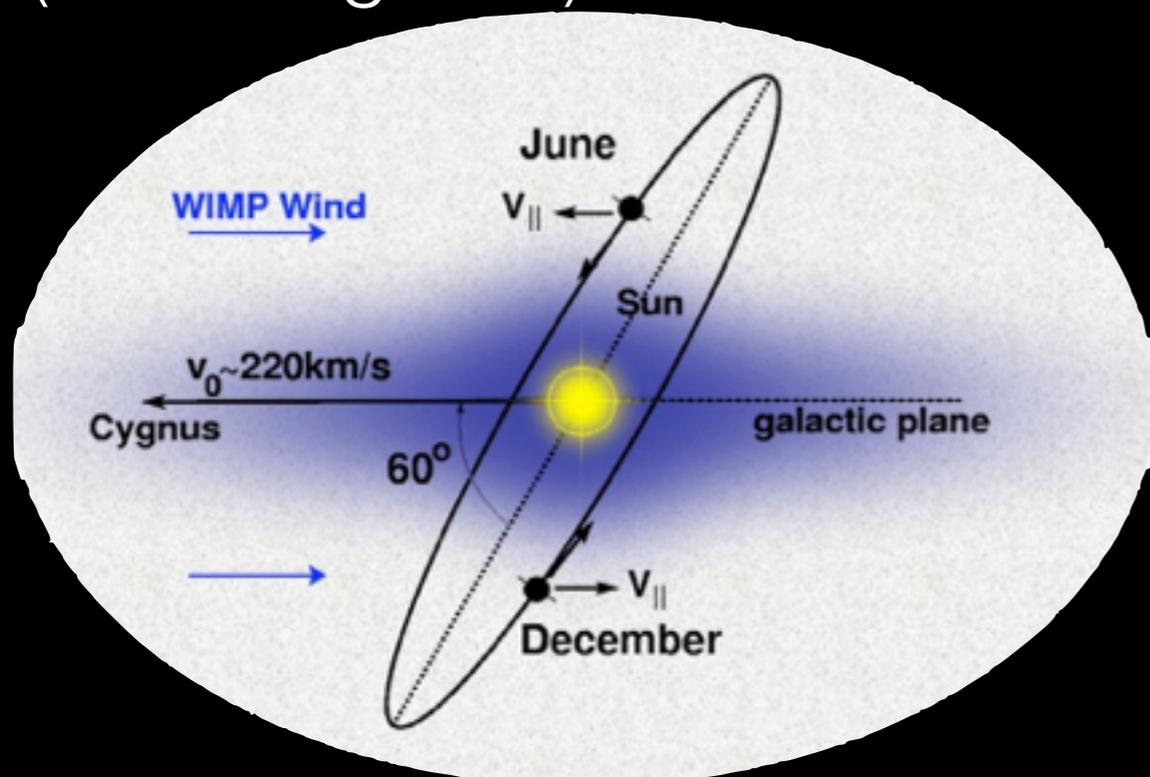
$$R \text{ (events/kg/yr)} = \langle \Phi \cdot \sigma \rangle \cdot n$$

Surrounded by a Dark Matter Halo

$$\Phi(v) = \frac{\rho_\chi}{m_\chi} v_\chi f(v_\chi, t)$$

Local density
 $\sim 0.3 \text{ GeV/cm}^3$
 $(5 \times 10^{-25} \text{ g/cm}^3)$

Maxwellian Velocity Distribution
 Local speed $\sim 220 \text{ km/s}$
 Escape Velocity $\sim 500 - 600 \text{ km/s}$



$$R \text{ (events/kg/yr)} = \langle \Phi \cdot \sigma \rangle \cdot n$$

WIMP - Nucleus SI Scattering Cross-Section

$$\sigma(v_\chi) \propto \frac{M_N}{\mu_n^2 v_\chi^2} \cdot \sigma_n \cdot A^2 \cdot F^2(q)$$

WIMP-Nucleon
Cross-Section

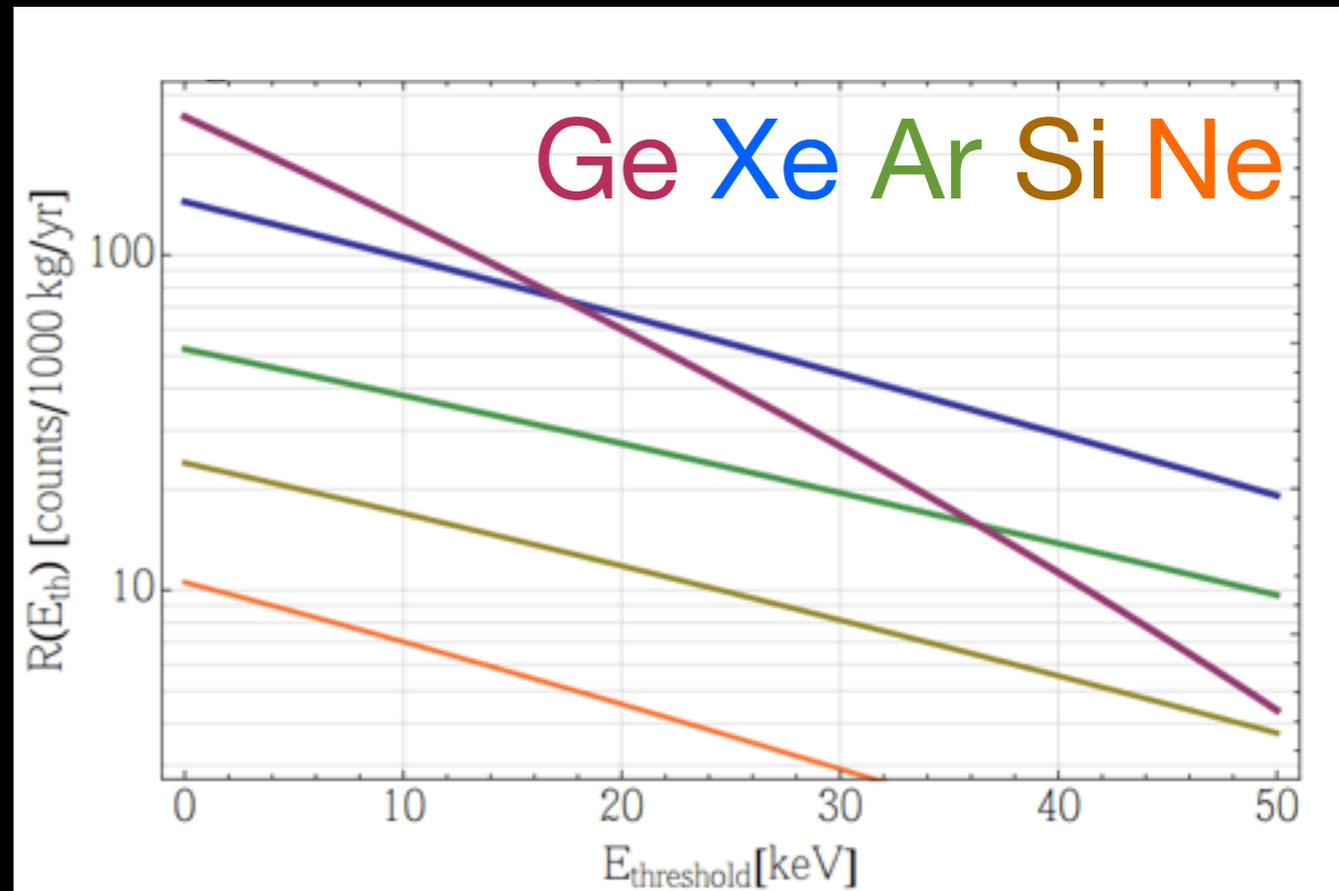
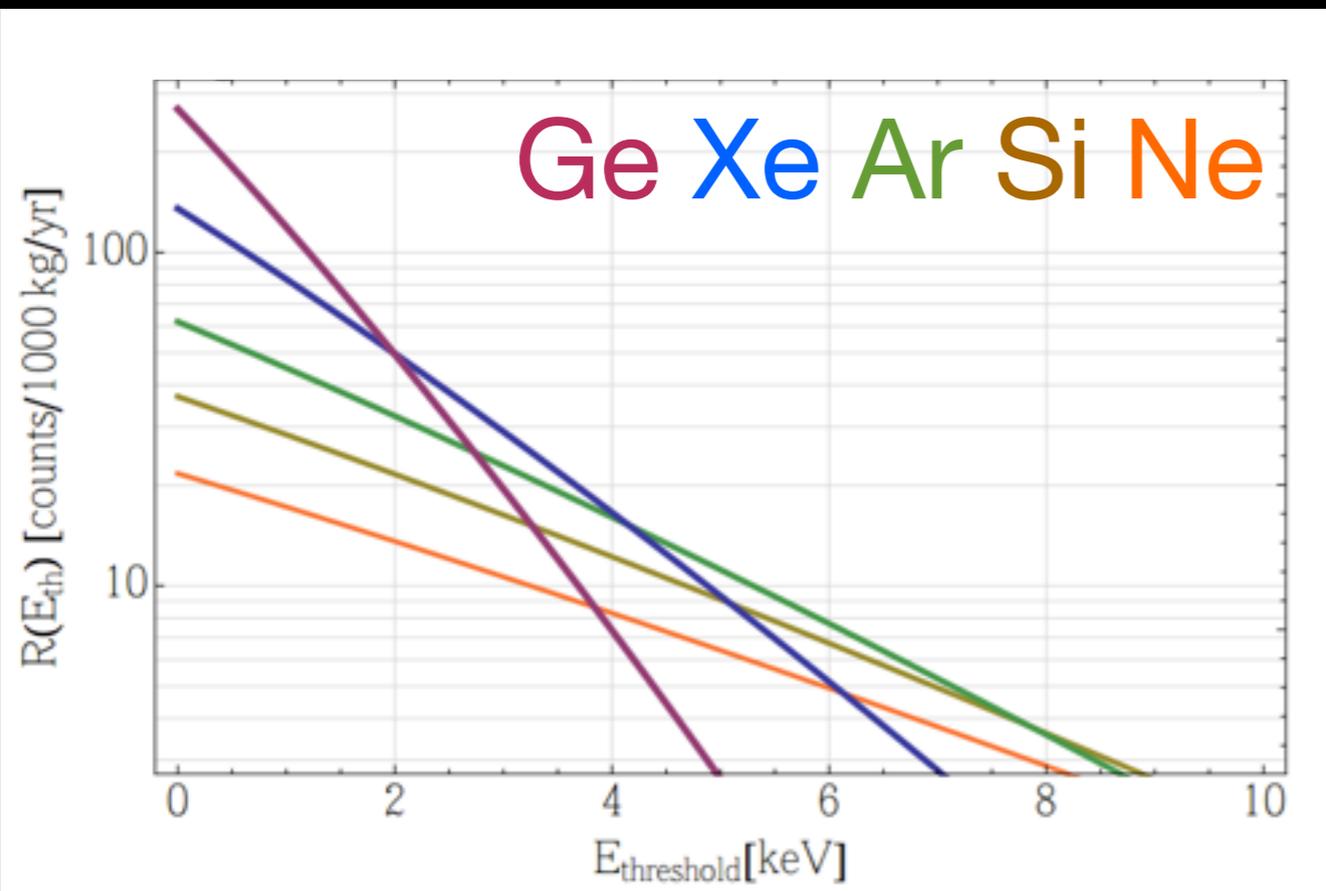
Mass number of nucleus
(assumes same interaction
for neutrons and protons)

Nuclear Form Factor
Correction for
decoherence at
non-zero
momentum transfer

Interaction Rates

$m_\chi: 10 \text{ GeV}, \sigma_{\chi-n}: 10^{-45} \text{ cm}^2$

$m_\chi: 100 \text{ GeV}, \sigma_{\chi-n}: 10^{-45} \text{ cm}^2$



arXiv:1310.8327v2 [hep-ex]

Total Interaction Rate for Ar $\sim 10^{-4} \text{ evt/kg/day}$
Rock Natural Radioactivity $\sim 10^7 \text{ evt/kg/day}$

DarkSide Program

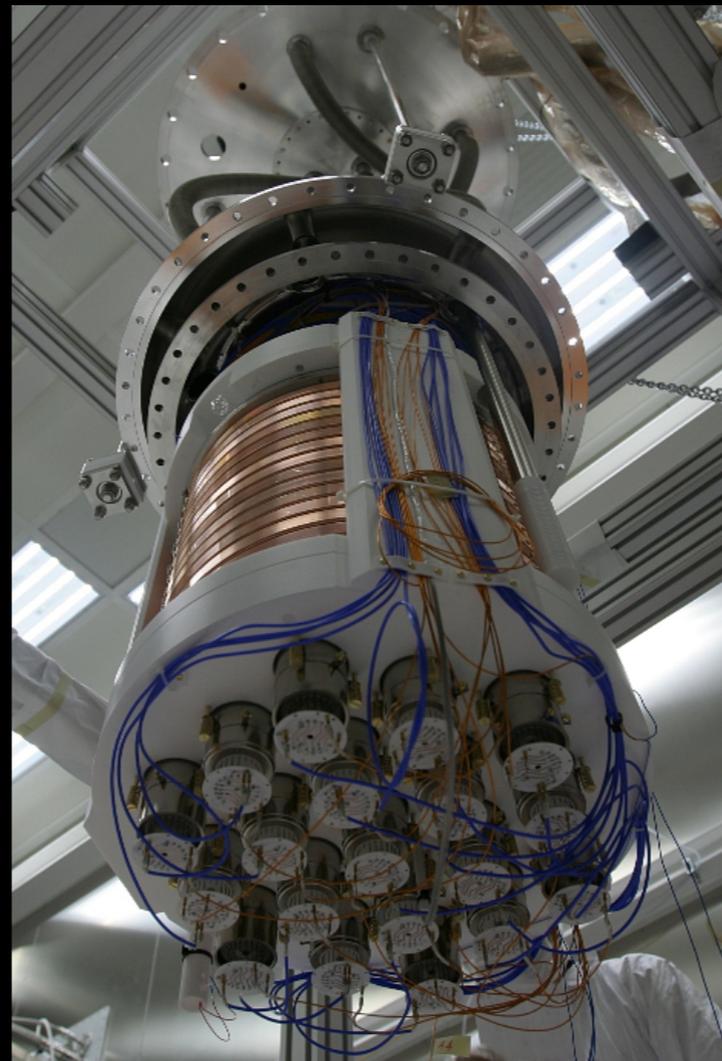
- Direct detection search for WIMP dark matter
- Based on a two-phase argon time projection chamber (TPC)
- Design philosophy based on having very low background levels that can be further reduced through **active** suppression, for background-free operation

DarkSide Program

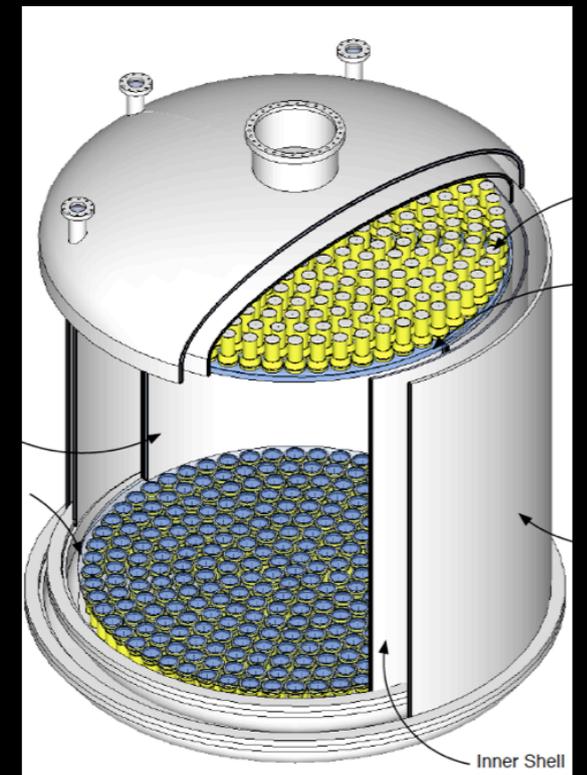
Multi-stage program at Gran Sasso National Laboratory



DarkSide 10
Prototype detector



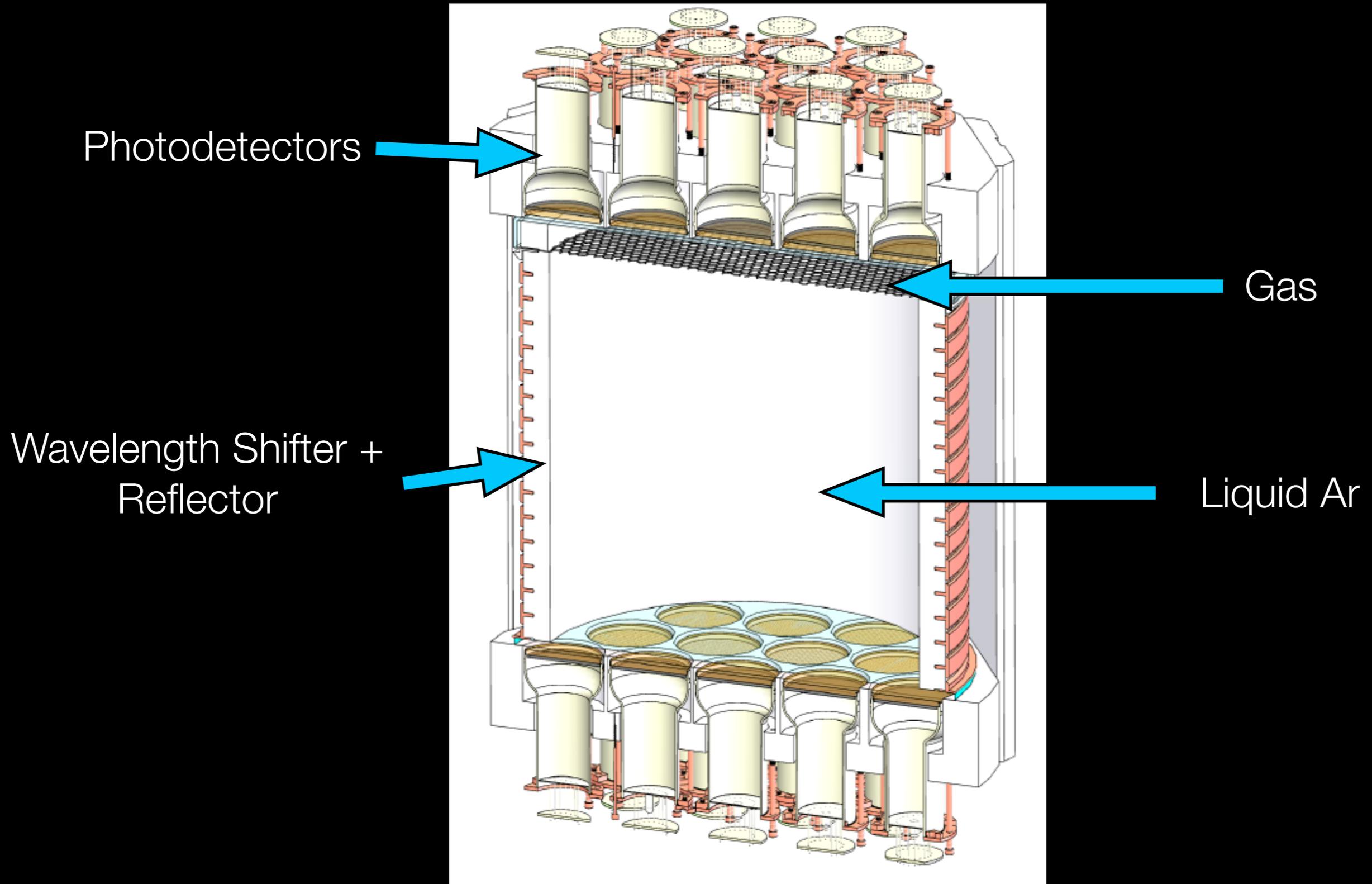
DarkSide 50
First physics detector
Recently commissioned



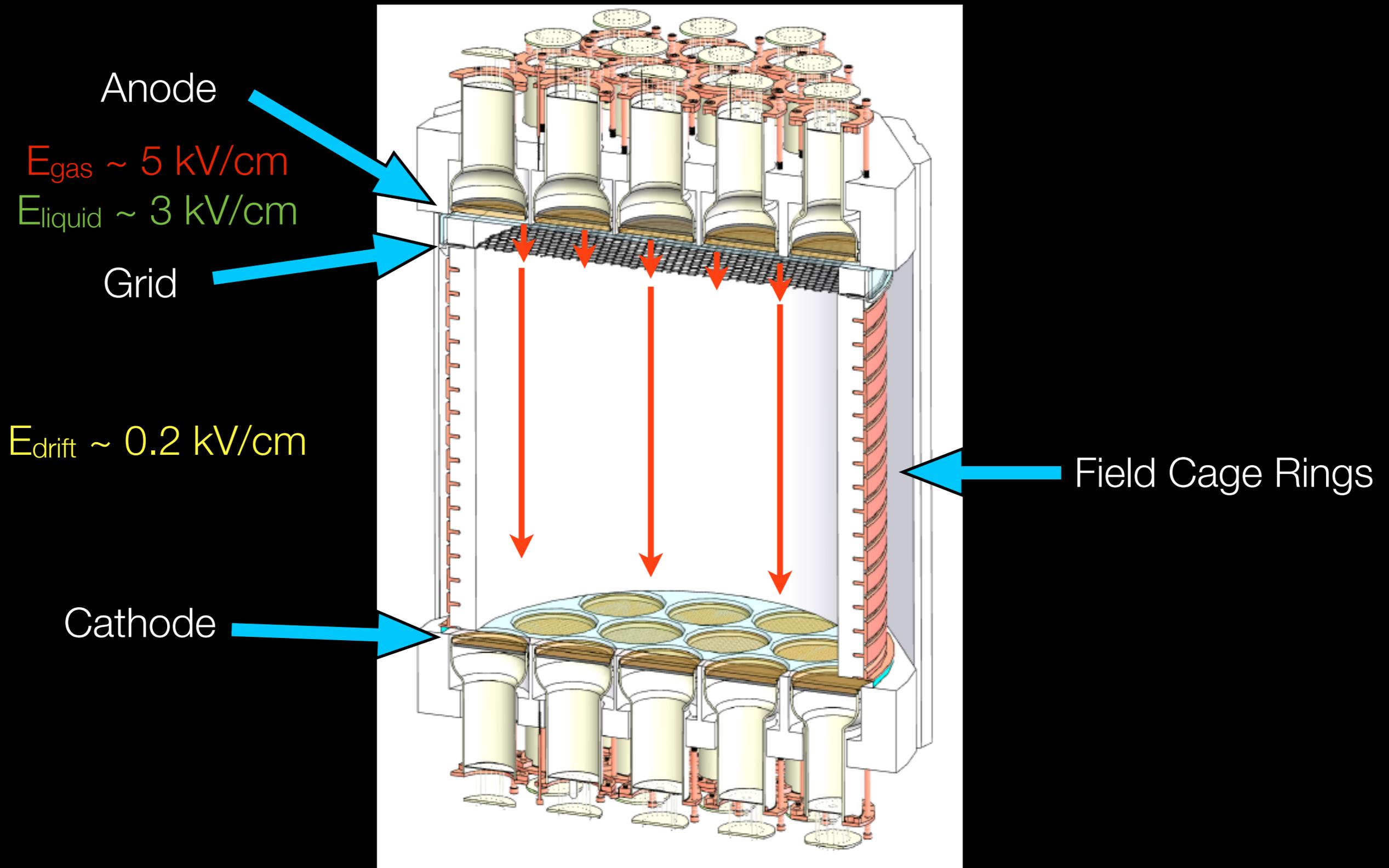
DarkSide G2
Future multi-ton detector

+ multiple smaller test setups and prototypes

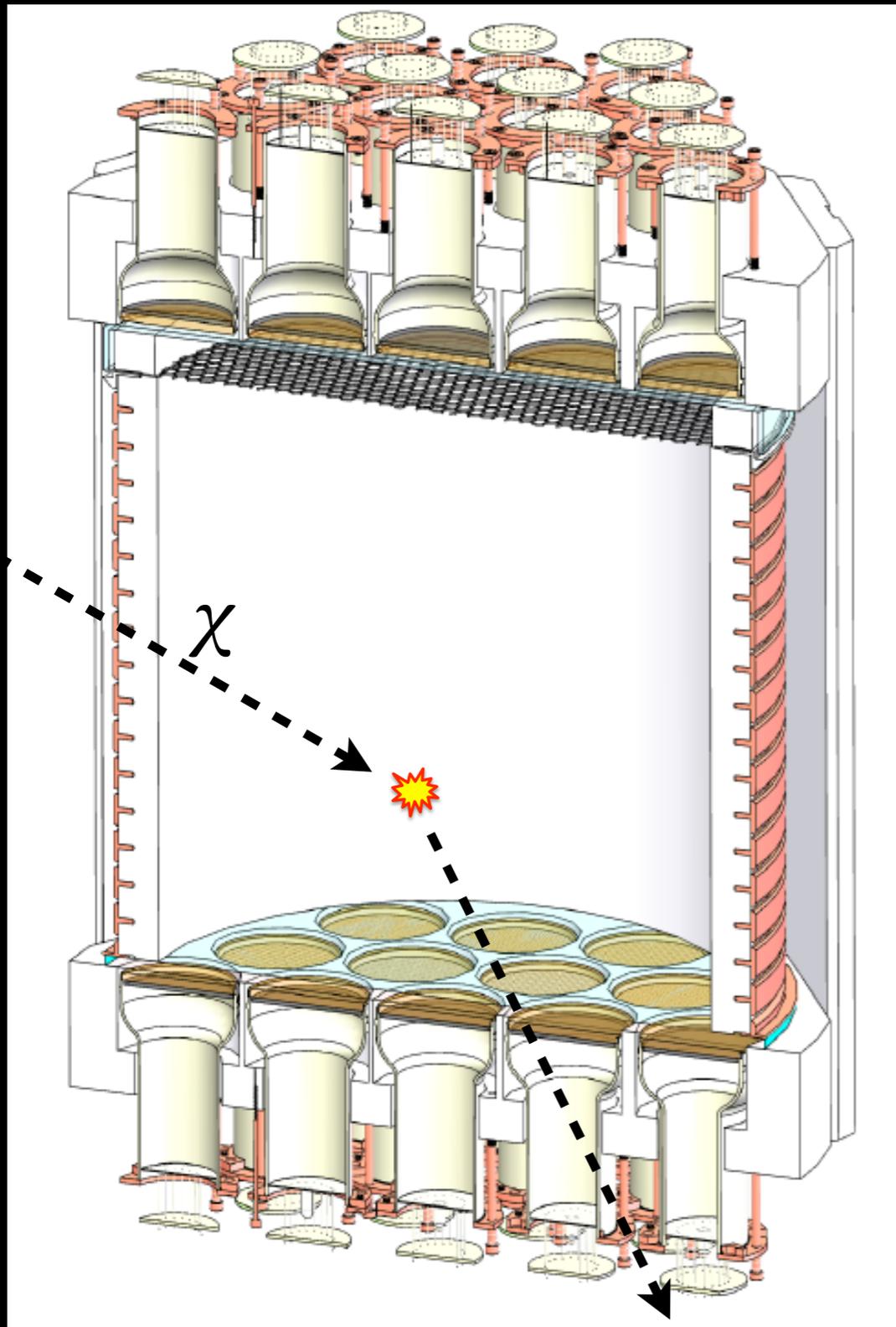
Two Phase Argon TPC



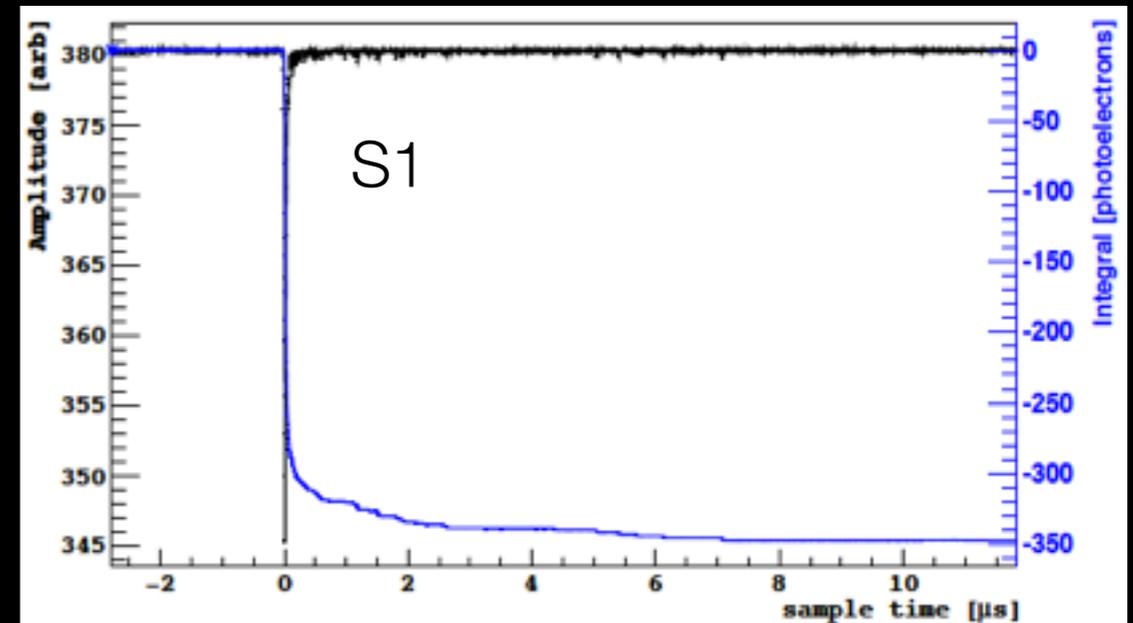
Two Phase Argon TPC



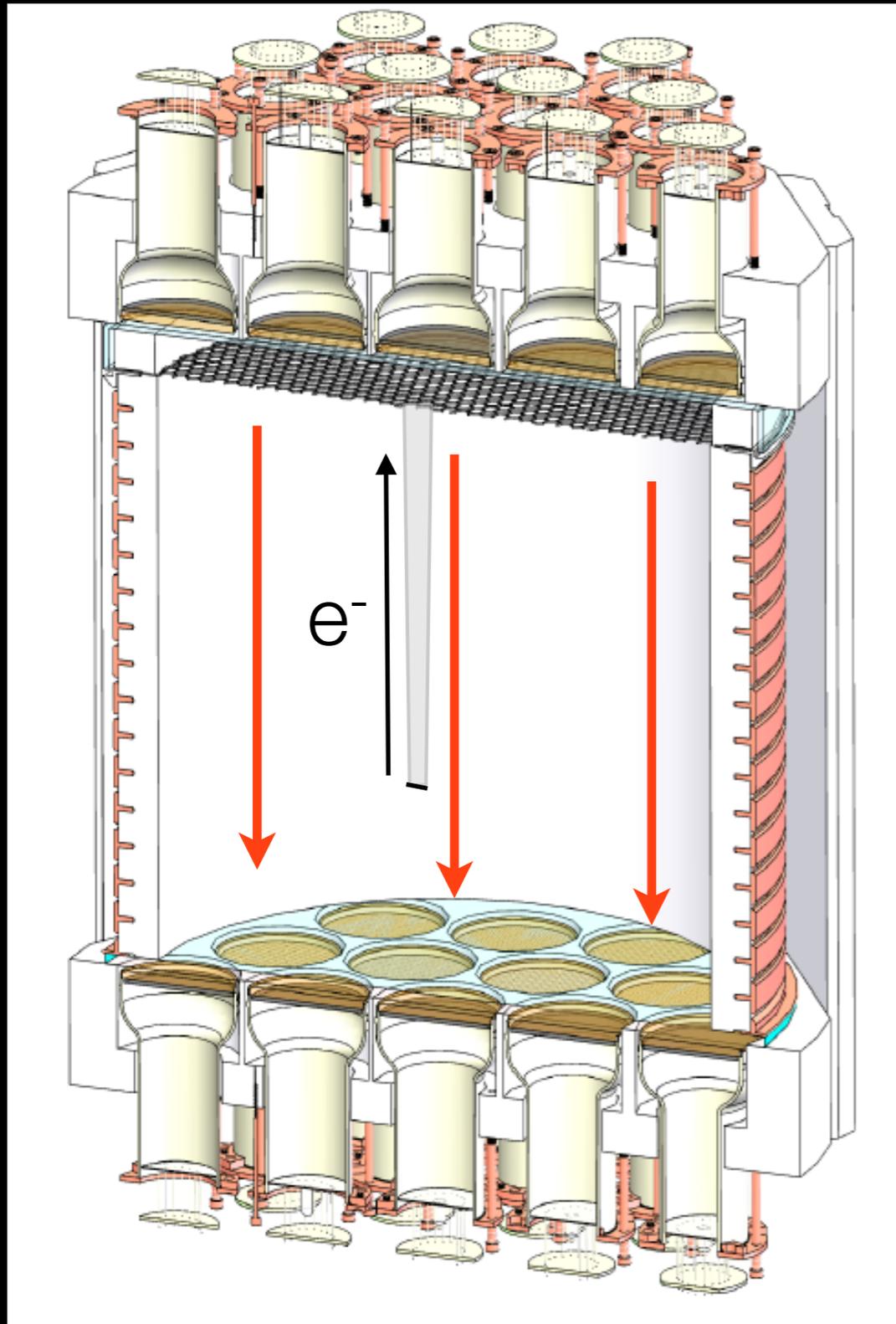
Detecting WIMPs



Nuclear Recoil excites and ionizes the liquid argon, producing scintillation light (S1) that is detected by the photomultipliers

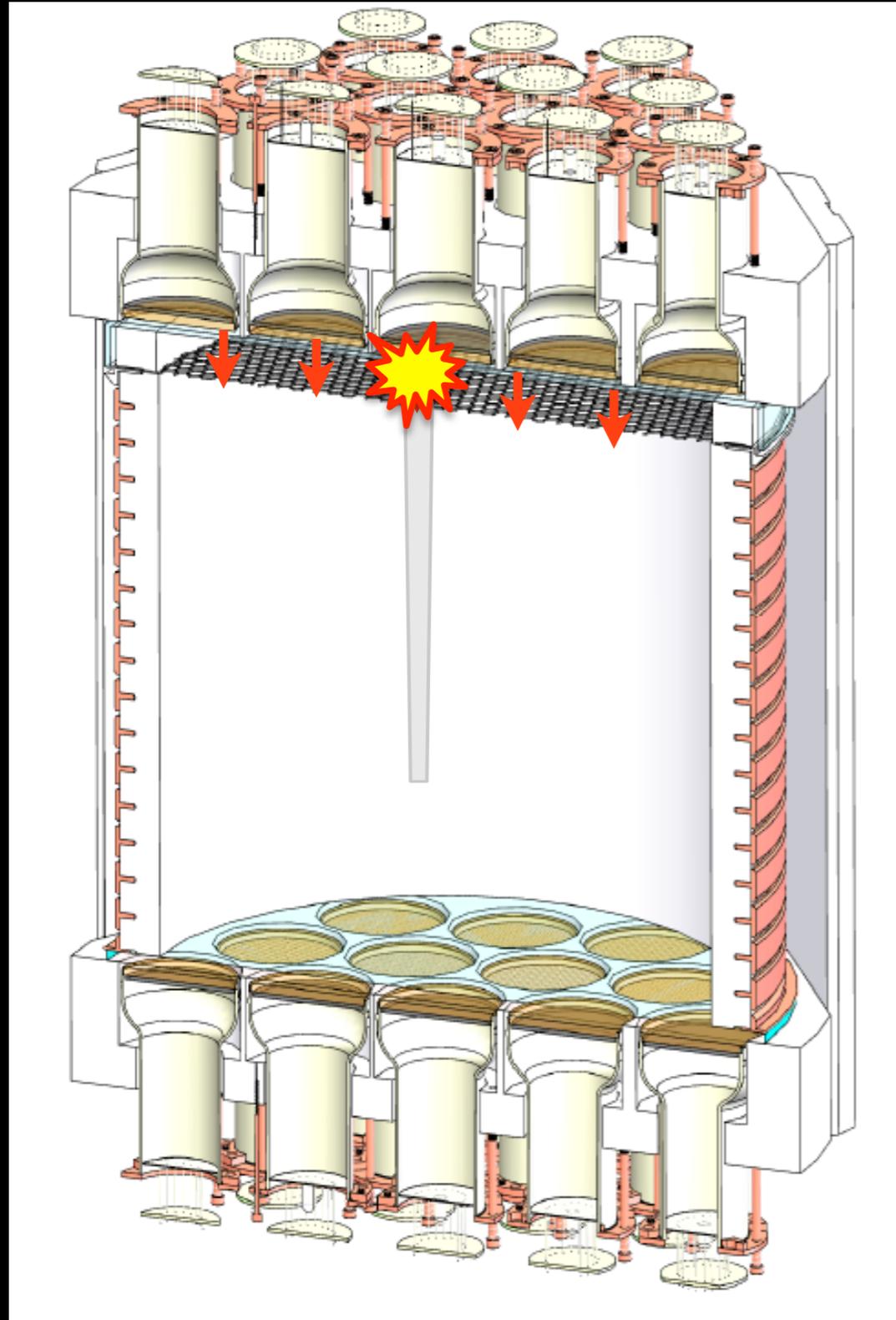


Detecting WIMPs

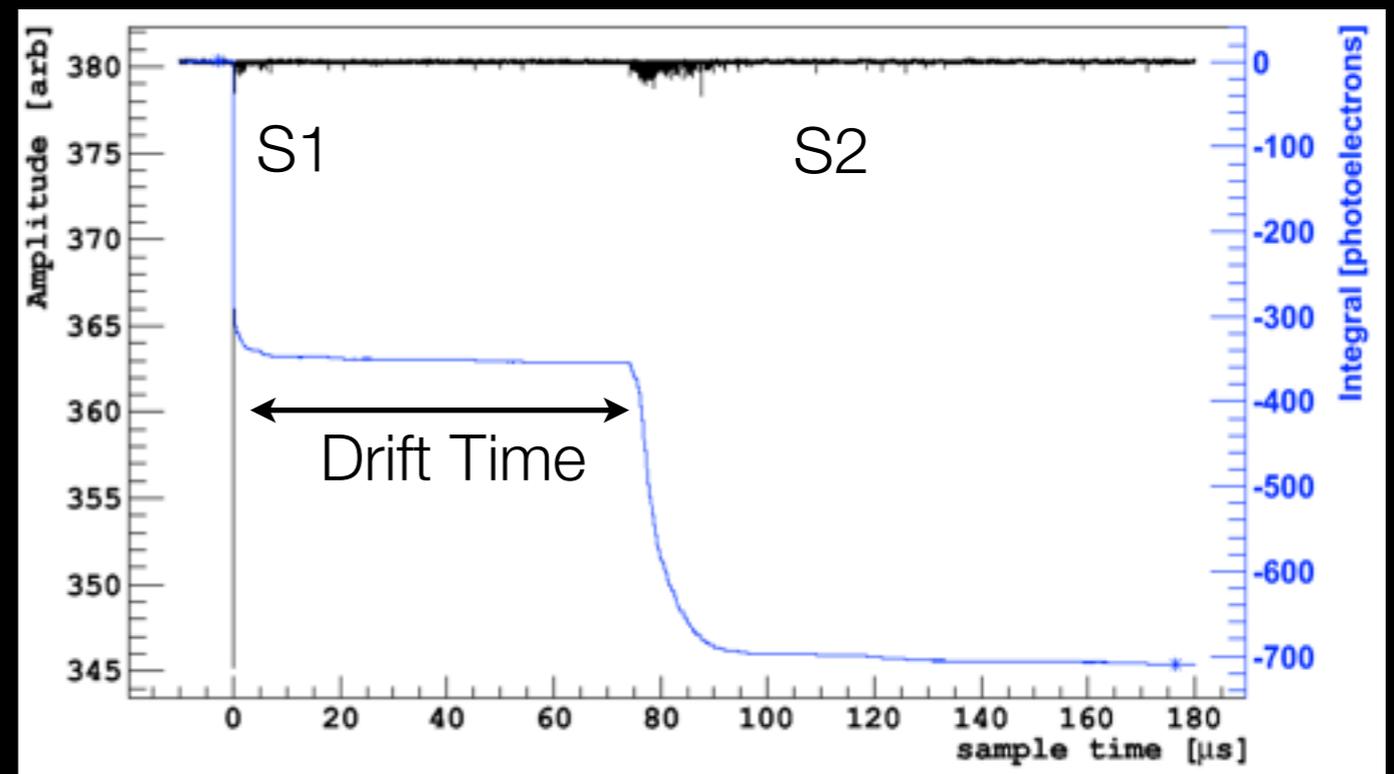


The ionized electrons that survive recombination are drifted towards the liquid-gas interface by the electric field

Detecting WIMPs



The electrons are extracted into the gas region, where they induce electroluminescence (S2)



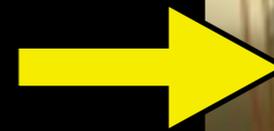
The time between the S1 and S2 signals gives the vertical position

DarkSide 10

7x 3" PMTs



TPB + ITO coated quartz window

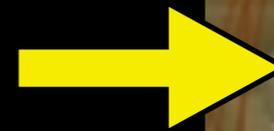


Acrylic cylinder
with TPB-coated reflector

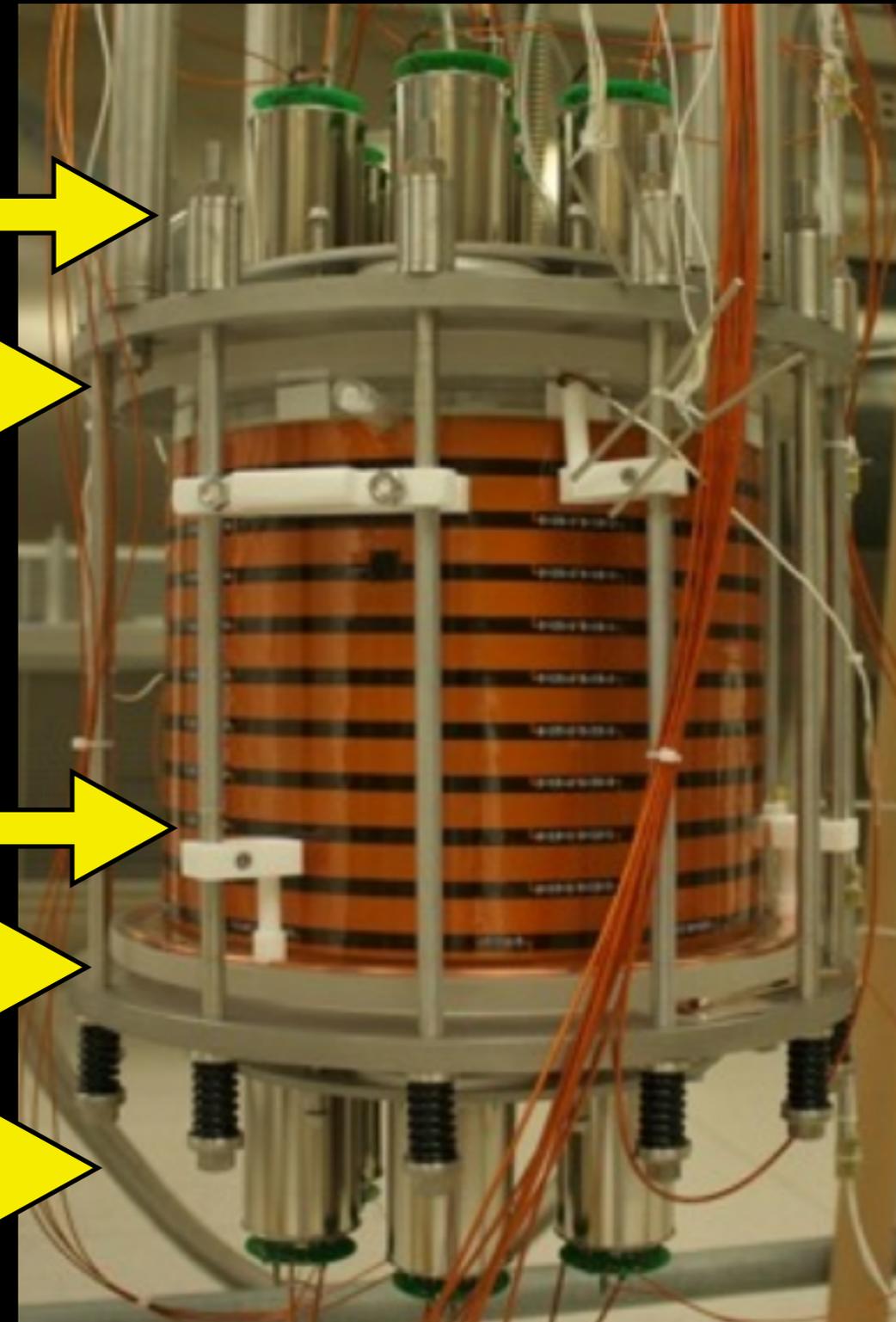
Flexible PCB field cage



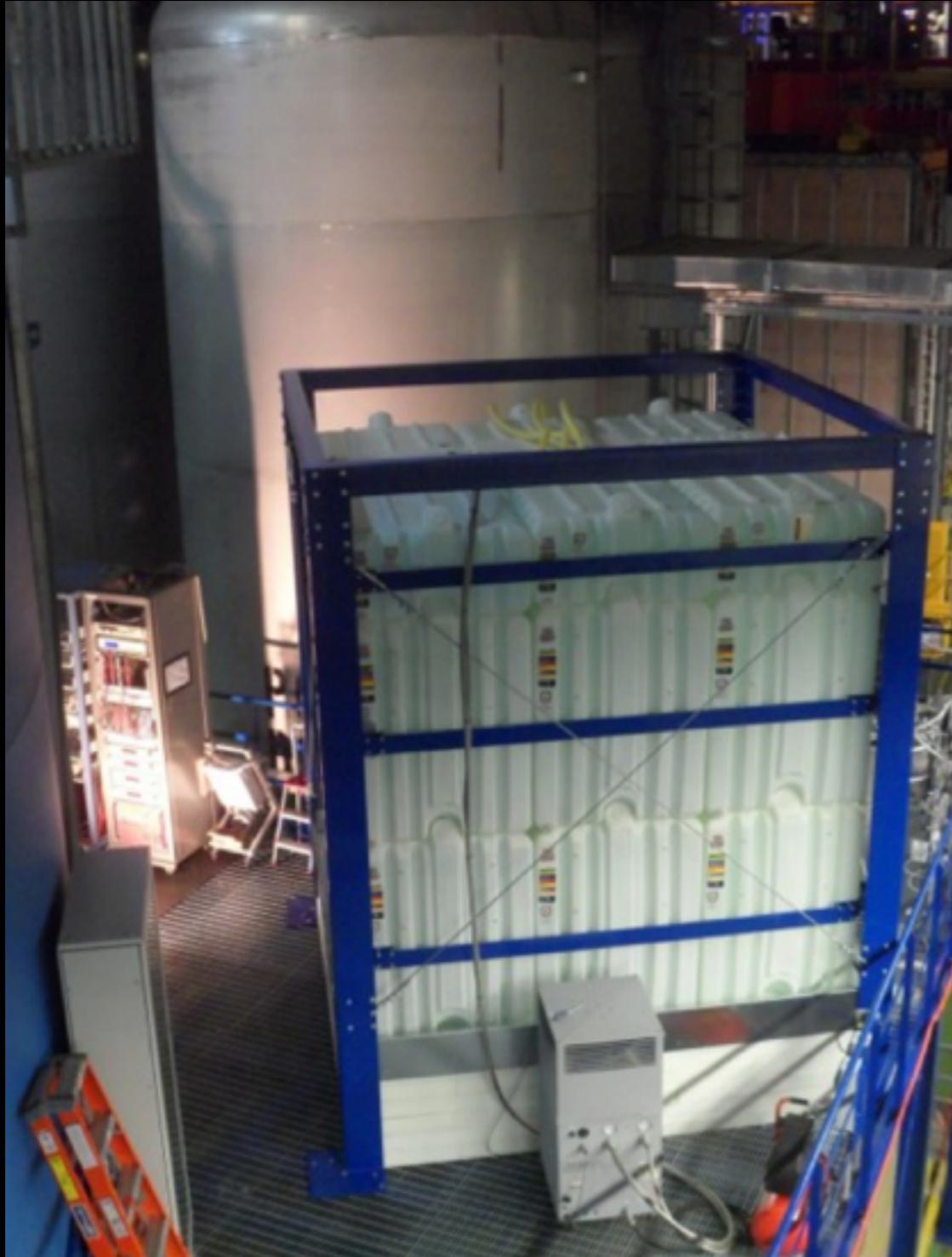
TPB + ITO coated quartz window



7x 3" PMTs



DarkSide 10



First designed, built and operated at Princeton University

Moved underground at Gran Sasso to operate in a low-background environment

Dedicated campaigns to test light collection, high voltage and other technical solutions for future detectors

DarkSide-50

(50 kg active mass)

- First physics-capable detector
- All components were chosen/designed to have the lowest possible radioactivity (including the active target !)
- Auxiliary detectors to identify and veto residual backgrounds

Backgrounds

[30-200]keVr

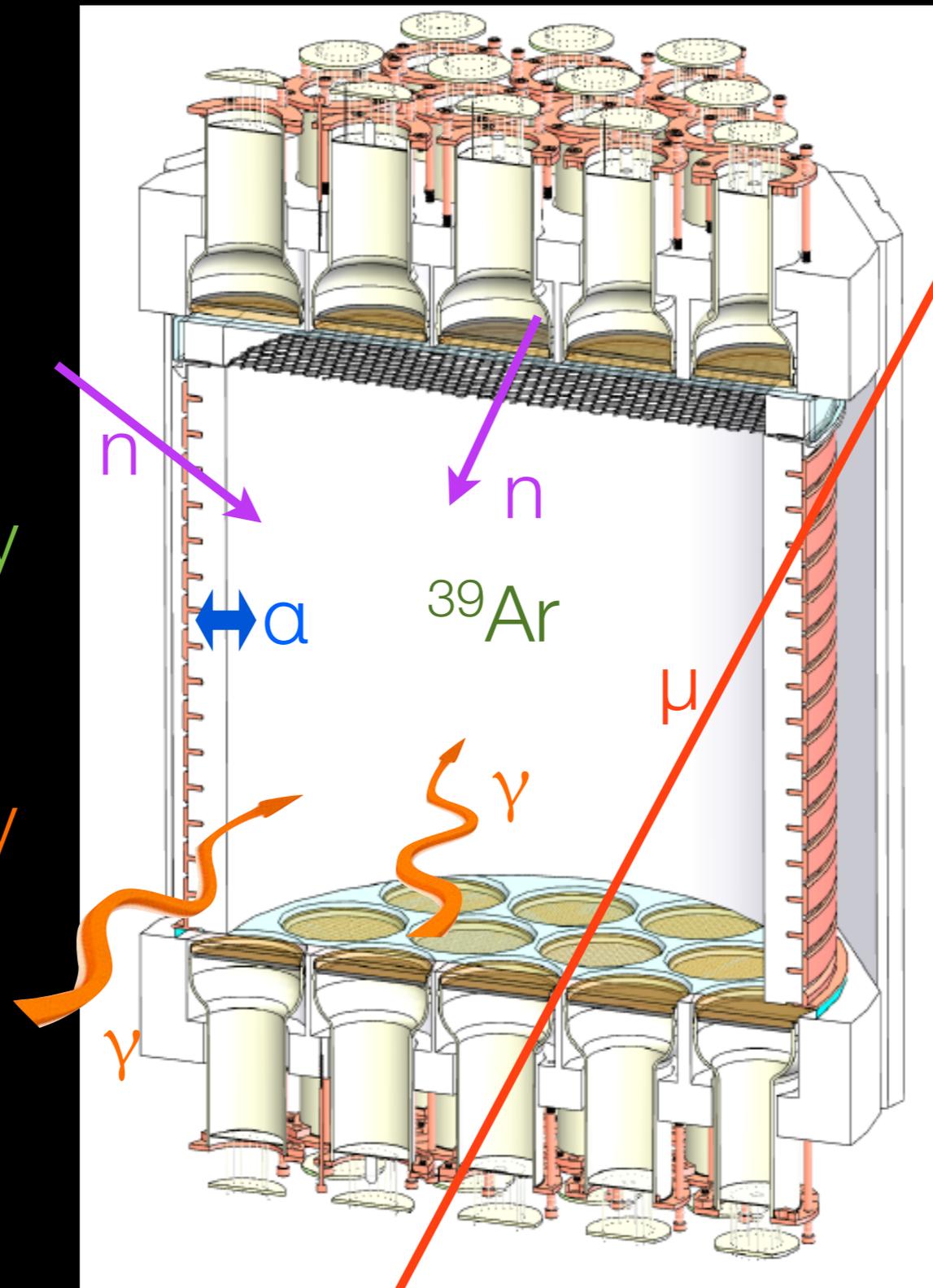
ELECTRON RECOILS

^{39}Ar

$\sim 1 \times 10^4$ evt/kg/day

γ

$\sim 1 \times 10^2$ evt/kg/day



NUCLEAR RECOILS

μ

~ 30 evt/m²/day

Radiogenic n

$\sim 6 \times 10^{-4}$ evt/kg/day

α

~ 10 evt/m²/day

100 GeV, 10^{-45} cm² WIMP Rate $\sim 10^{-4}$ evt/kg/day

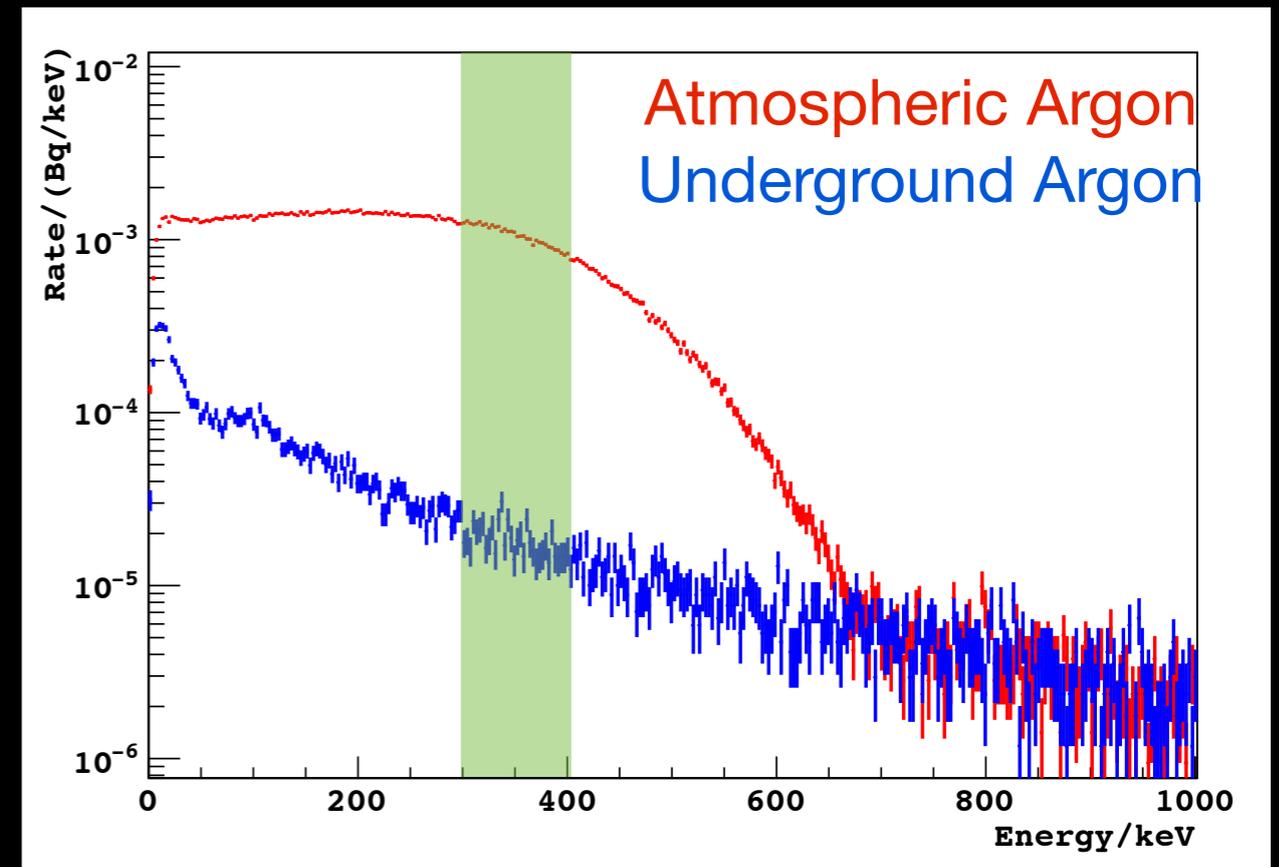
^{39}Ar

- Intrinsic ^{39}Ar radioactivity in **atmospheric** argon is the primary background for argon-based detectors
- ^{39}Ar activity sets the dark matter detection threshold at low energies (where pulse shape discrimination is ineffective)
- ^{39}Ar is a cosmogenic isotope, and the activity in argon from **underground** sources can be significantly reduced compared to **atmospheric** argon

Underground Argon Measurement

Low background LAr detector was operated underground at KURF with both atmospheric and underground argon

arXiv:1204.60111 [physics.ins-det]



	Total Rate [mBq/100 keV]	Estimated Background Rate [mBq/100 keV]	Background Subtracted Rate [mBq/100 keV]
Underground Argon (UAr)	1.87 +/- 0.06	1.5 +/- 0.2	0.32 +/- 0.23
Atmospheric Argon (AAr)	108.8 +/- 0.4		107.2 +/- 1.9*
³⁹ Factor	1.71 +/- 0.05 %		< 0.65 % (95 CL)

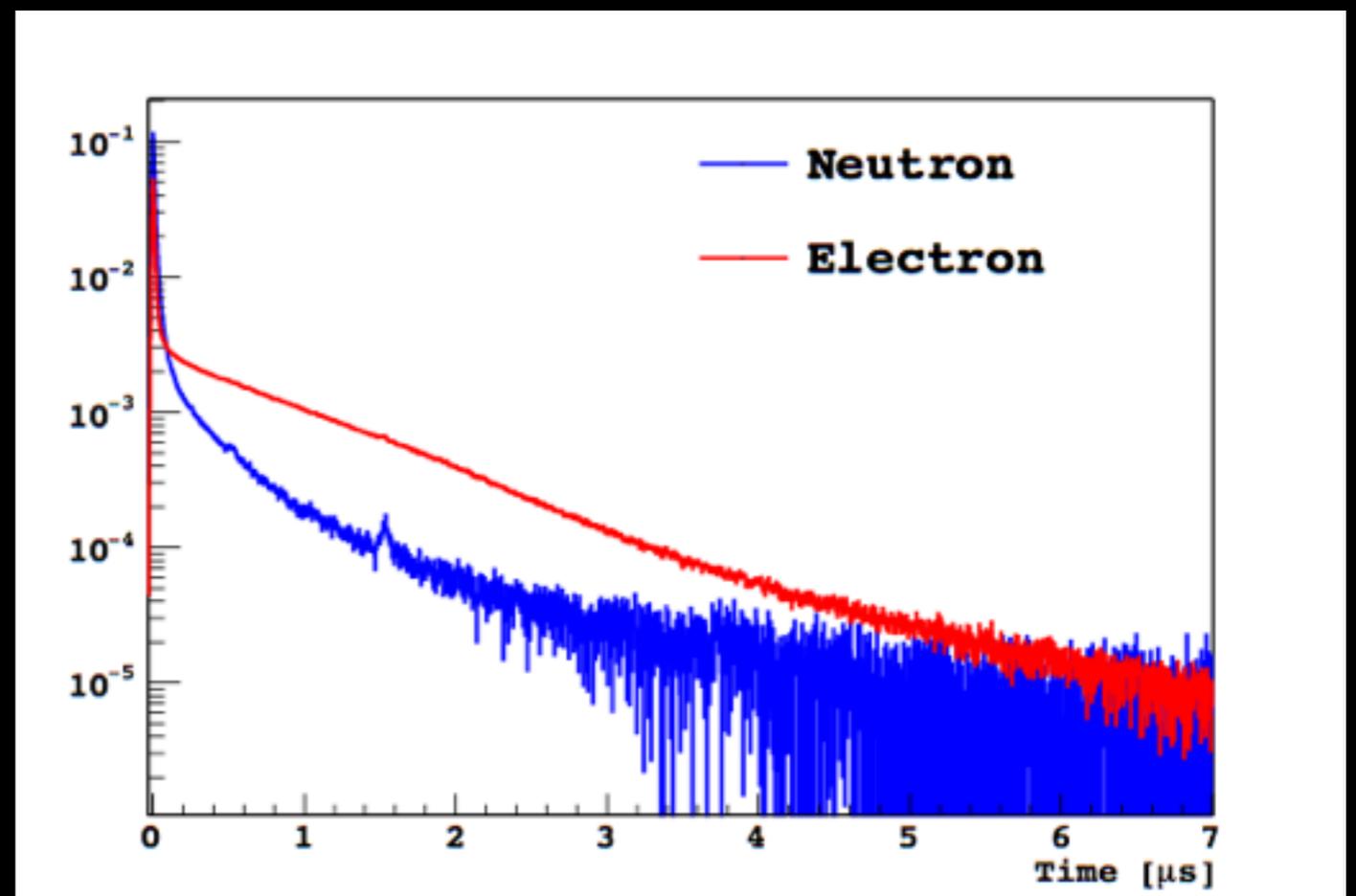
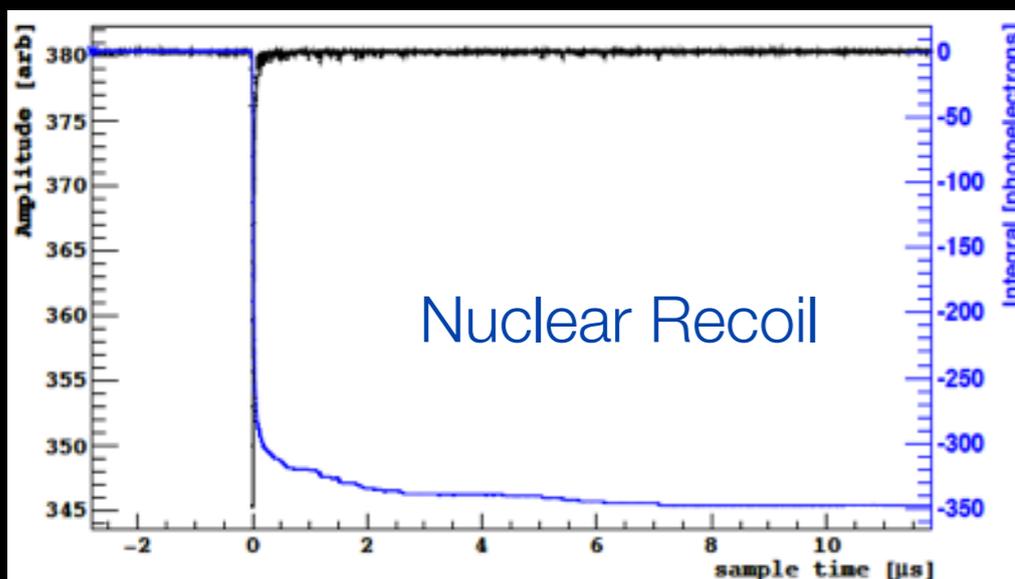
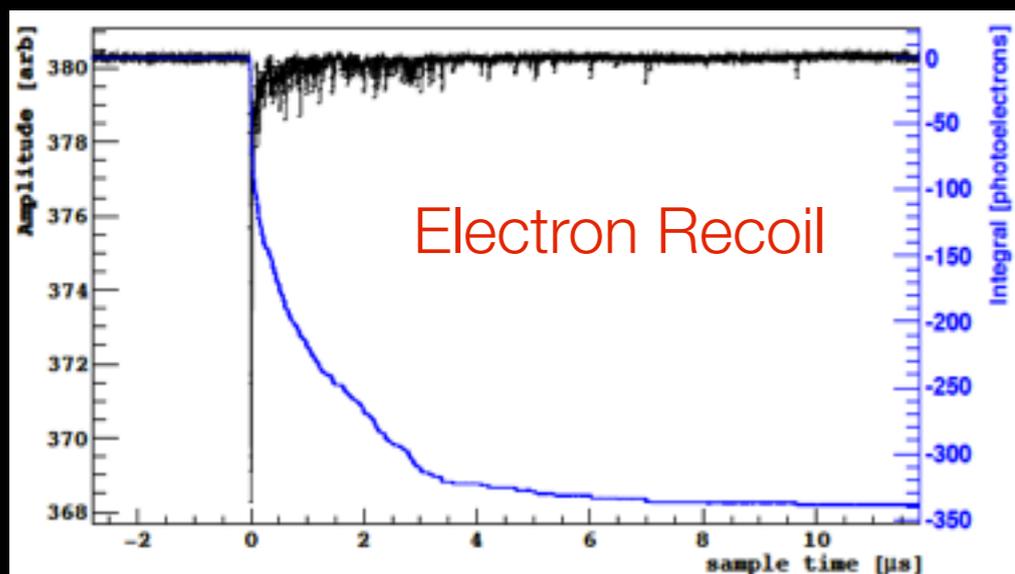
* Includes ⁸⁵Kr upper limit

Pulse Shape Discrimination

Electron and nuclear recoils produce different excitation densities in the argon, leading to different ratios of singlet and triplet excitation states

$$\tau_{\text{singlet}} \sim 7 \text{ ns}$$

$$\tau_{\text{triplet}} \sim 1600 \text{ ns}$$



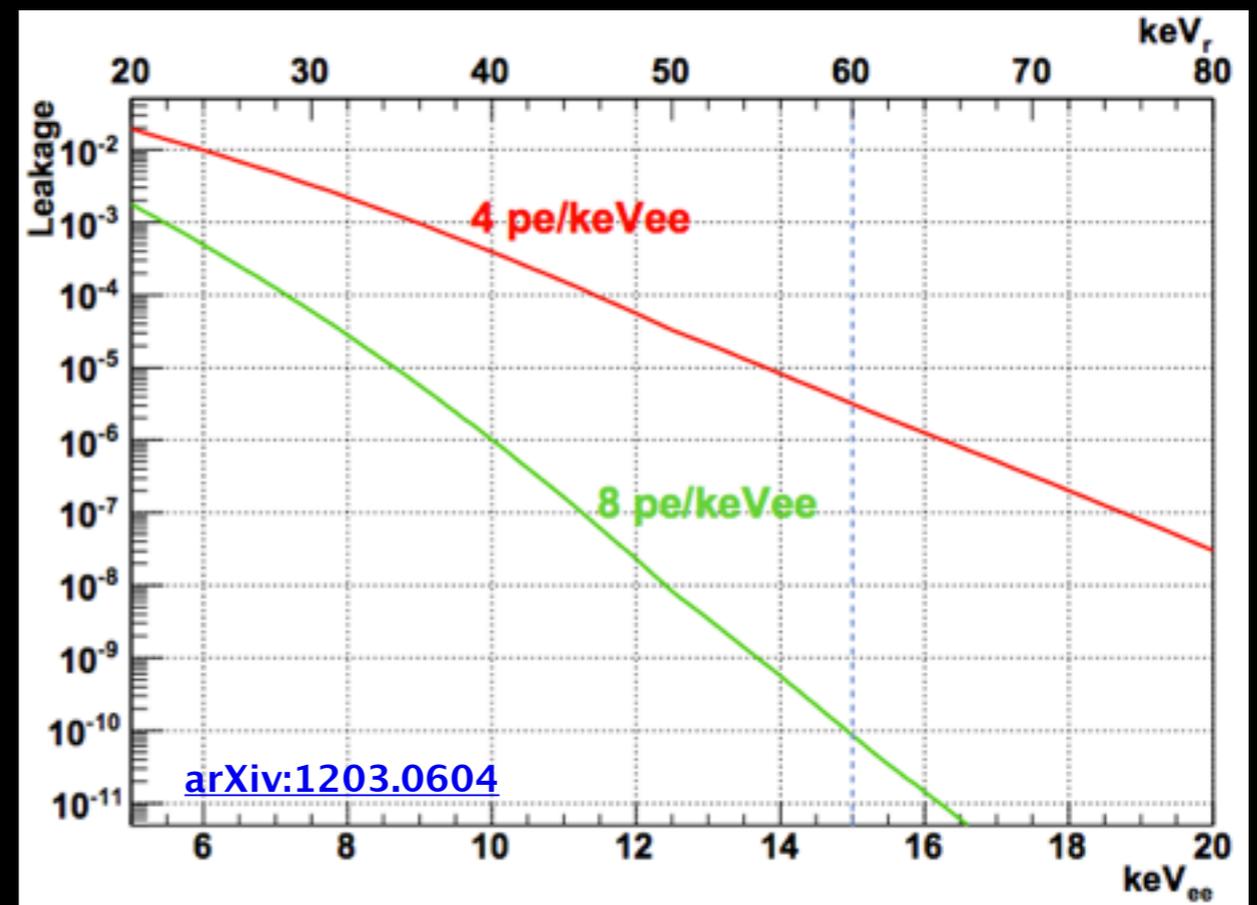
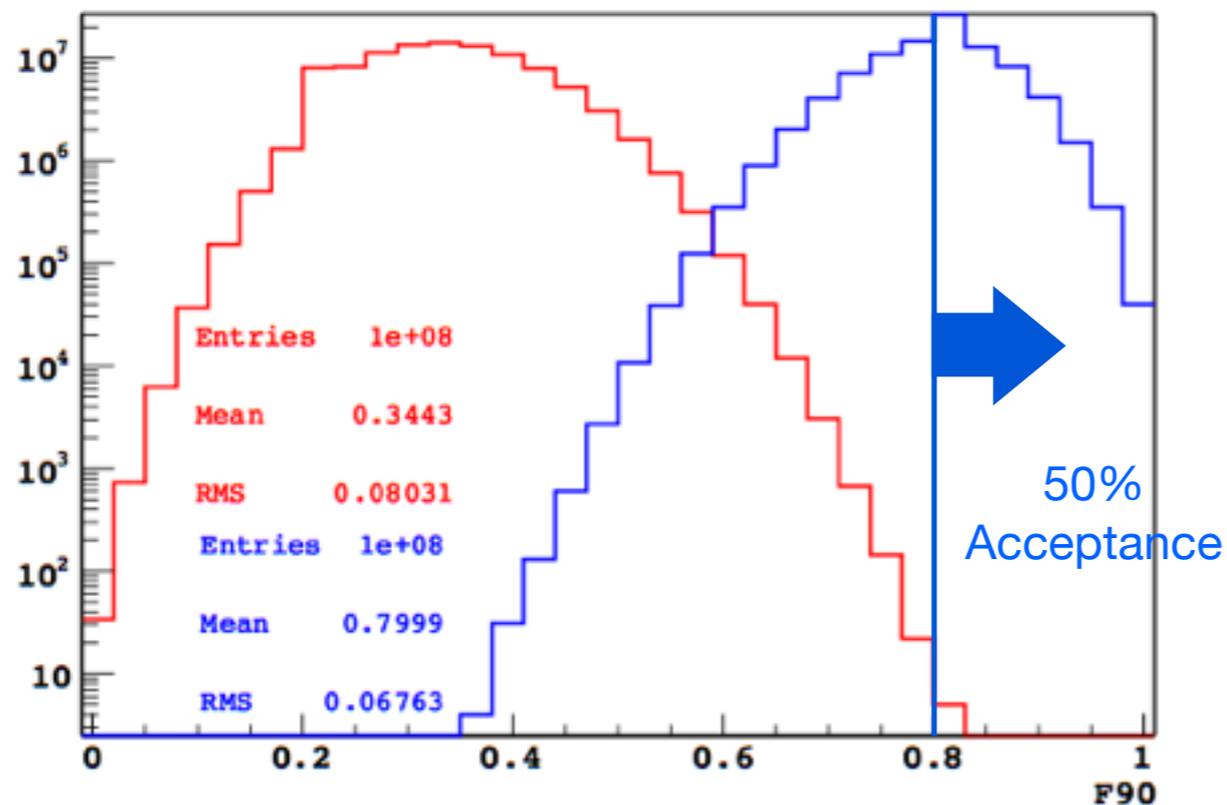
Pulse Shape Discrimination

F90: Ratio of detected light in the first 90 ns,
compared to the total signal

$\tau_{\text{singlet}} \sim 7 \text{ ns}$

$\tau_{\text{triplet}} \sim 1600 \text{ ns}$

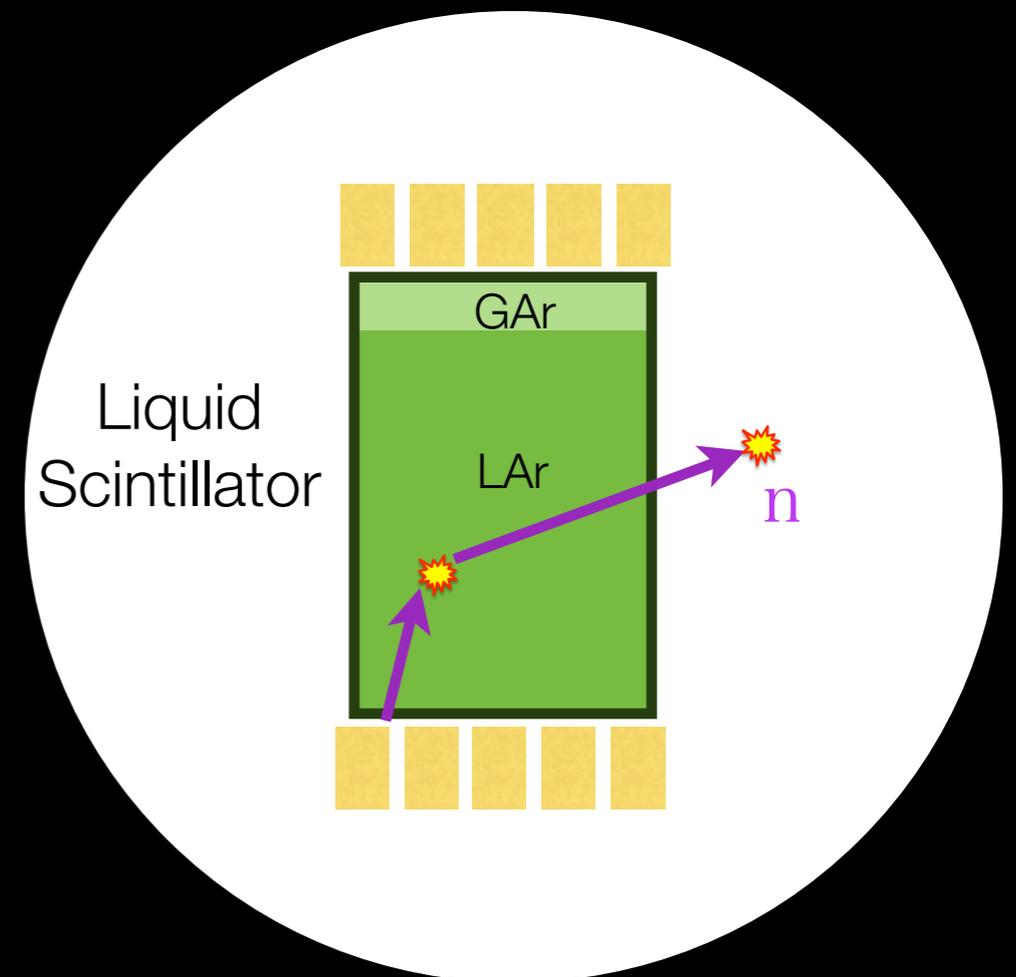
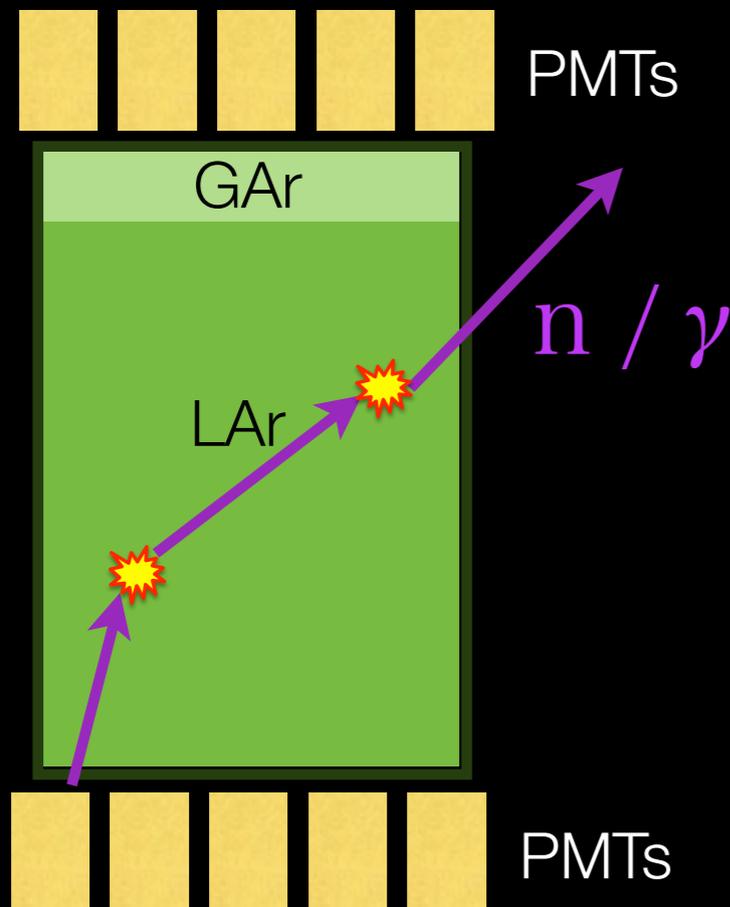
F90 \sim Fraction of singlet states



Discrimination power strongly dependent on light collection

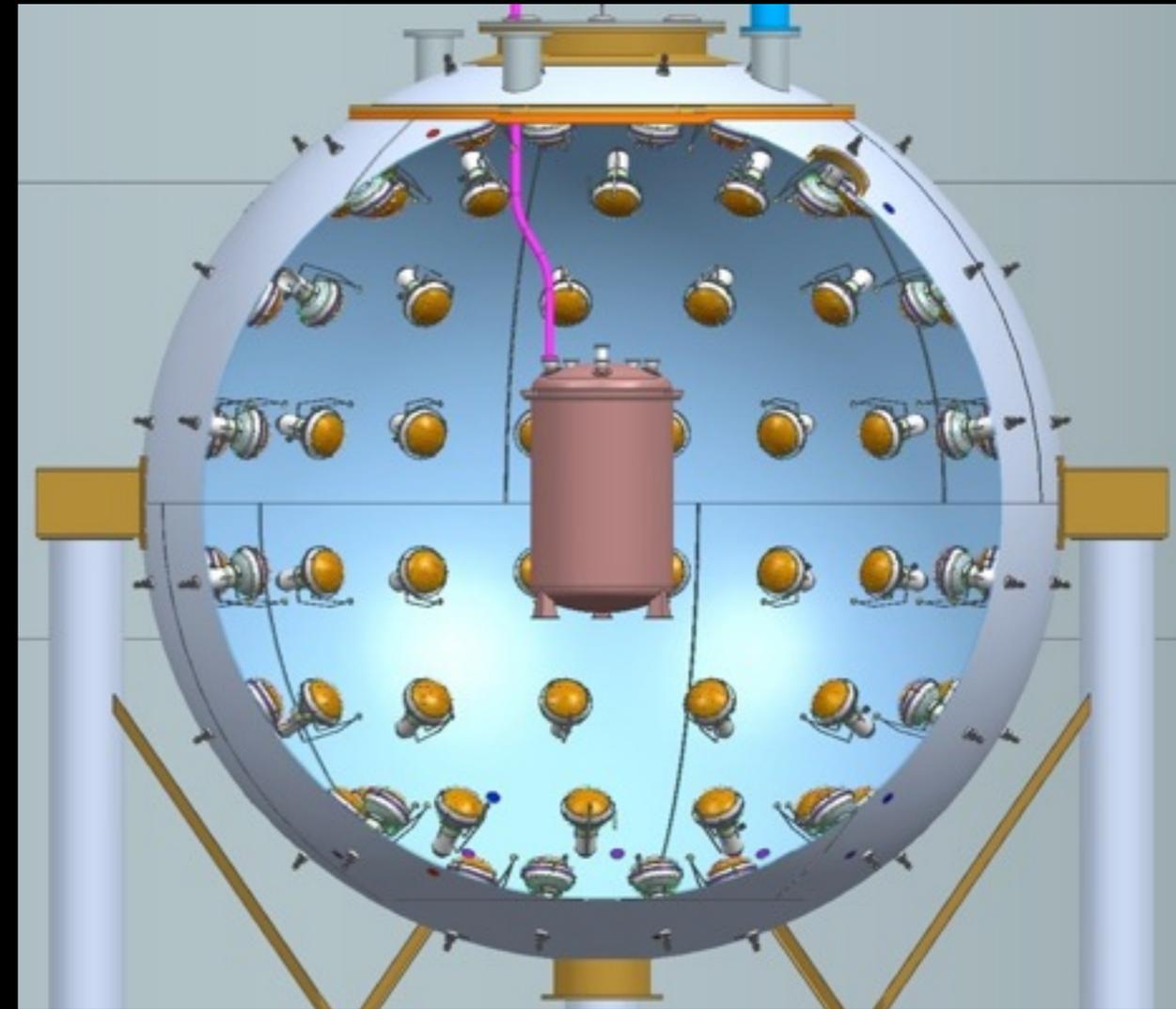
Multiple Interactions

Expected WIMP signal	Background Rejection Technique	Backgrounds Removed
Single Interaction	Multiple S2 Cut in TPC Liquid Scintillator Veto	Neutrons, Gamma rays



Liquid Scintillator Veto

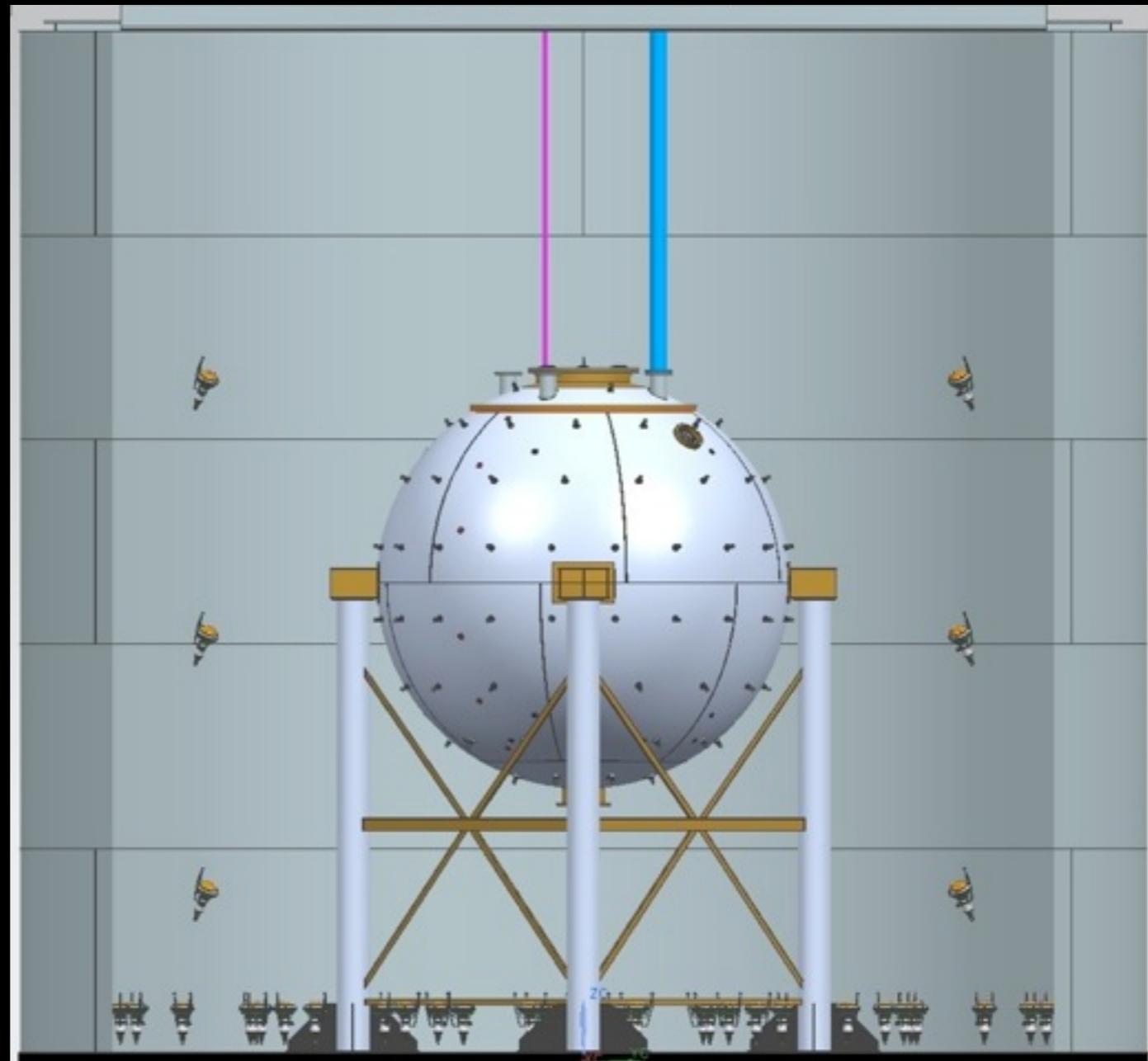
Liquid scintillator allows coincident veto of neutrons in the TPC and provides *in situ* measurement of the neutron background rate



- 4 m diameter sphere containing 1:1 PC + TMB scintillator
- Instrumented with 110 8" PMTs

External Water tank

- 80 PMTs within water tank (11m dia. x 10 m high)
- Acts as a muon and cosmogenic veto (~ 99% efficiency)
- Provides passive gamma and neutron shielding



Radon-Free Clean Rooms

Radon daughters plate out on surfaces of the detector causing dangerous alpha-induced nuclear recoils

Final preparation, cleaning, evaporation and assembly of all inner detector parts was carried out in radon-free clean rooms



Typical radon in air $\sim 30 \text{ Bq/m}^3$
Cleanroom radon levels $< 5 \text{ mBq/m}^3$



DarkSide 50

Radon-free clean room



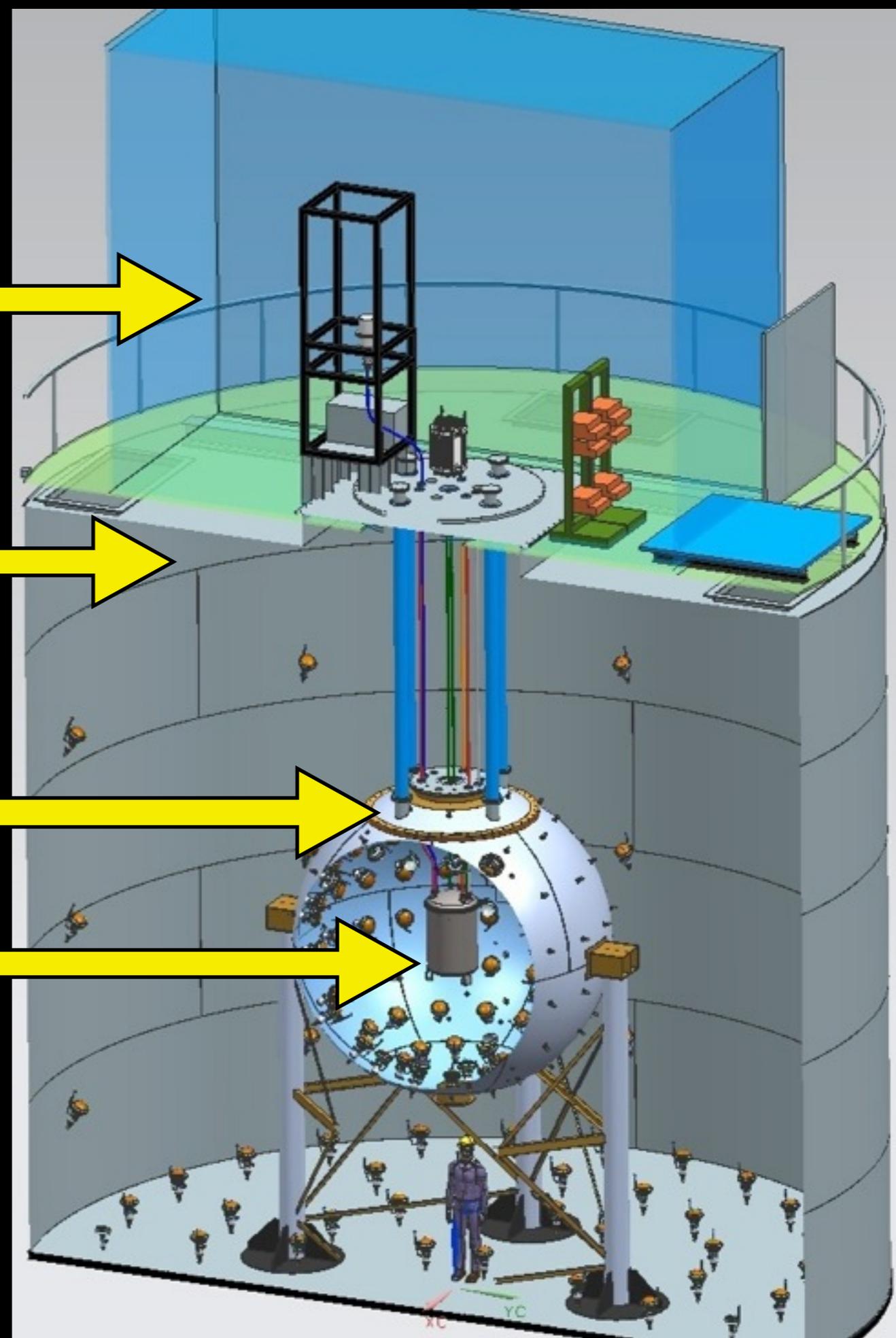
Instrumented water tank



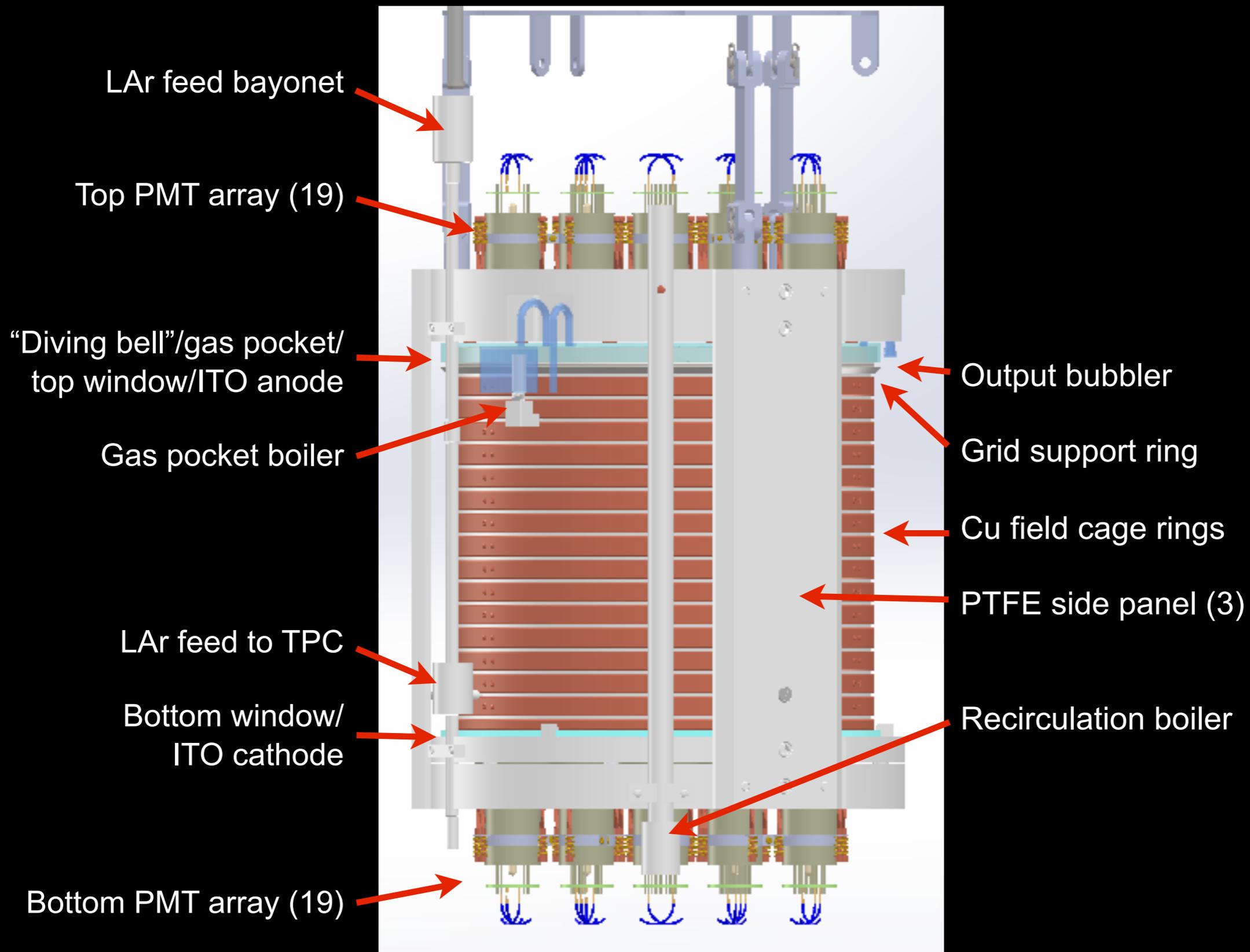
Liquid scintillator



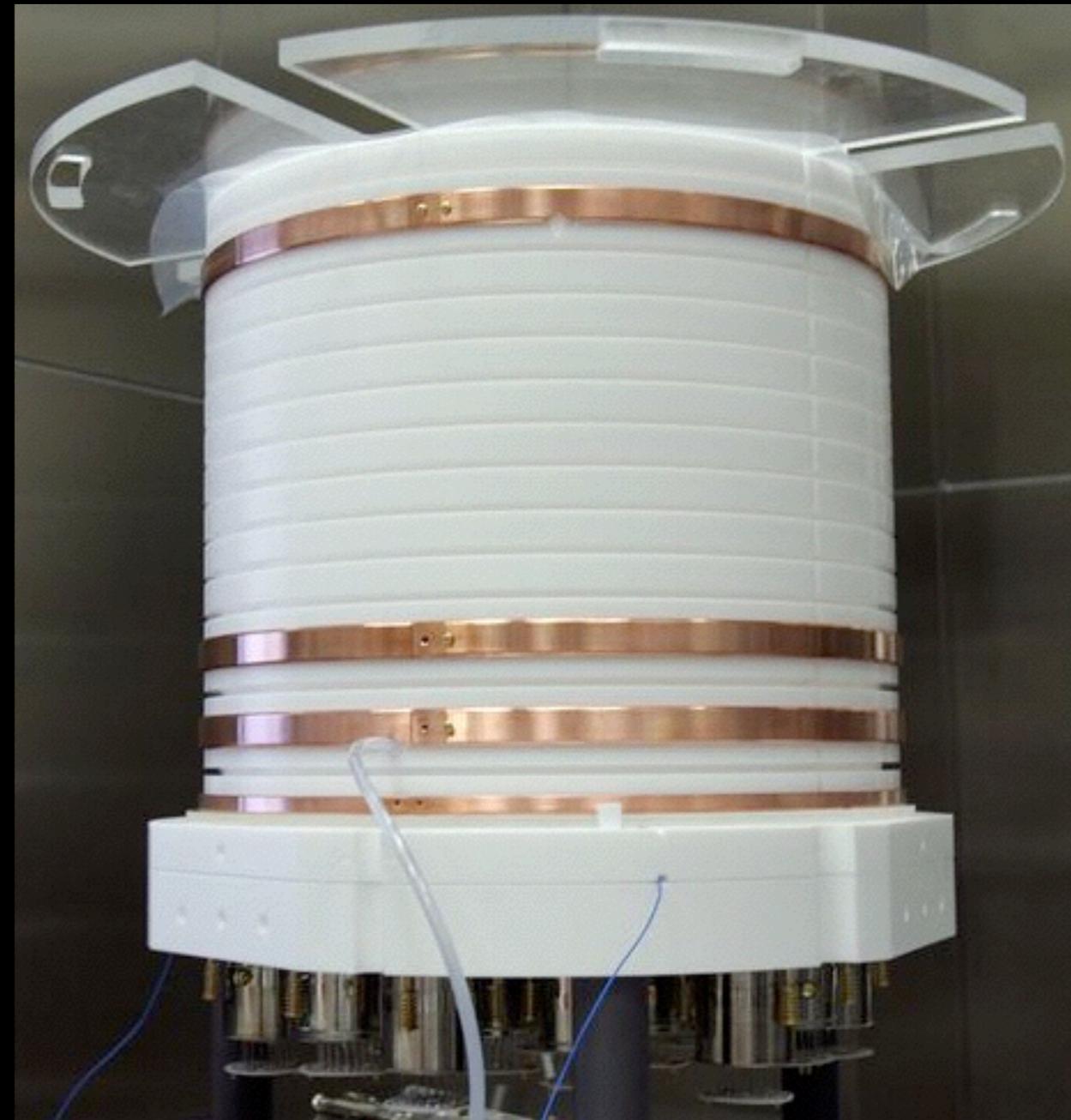
Inner detector TPC



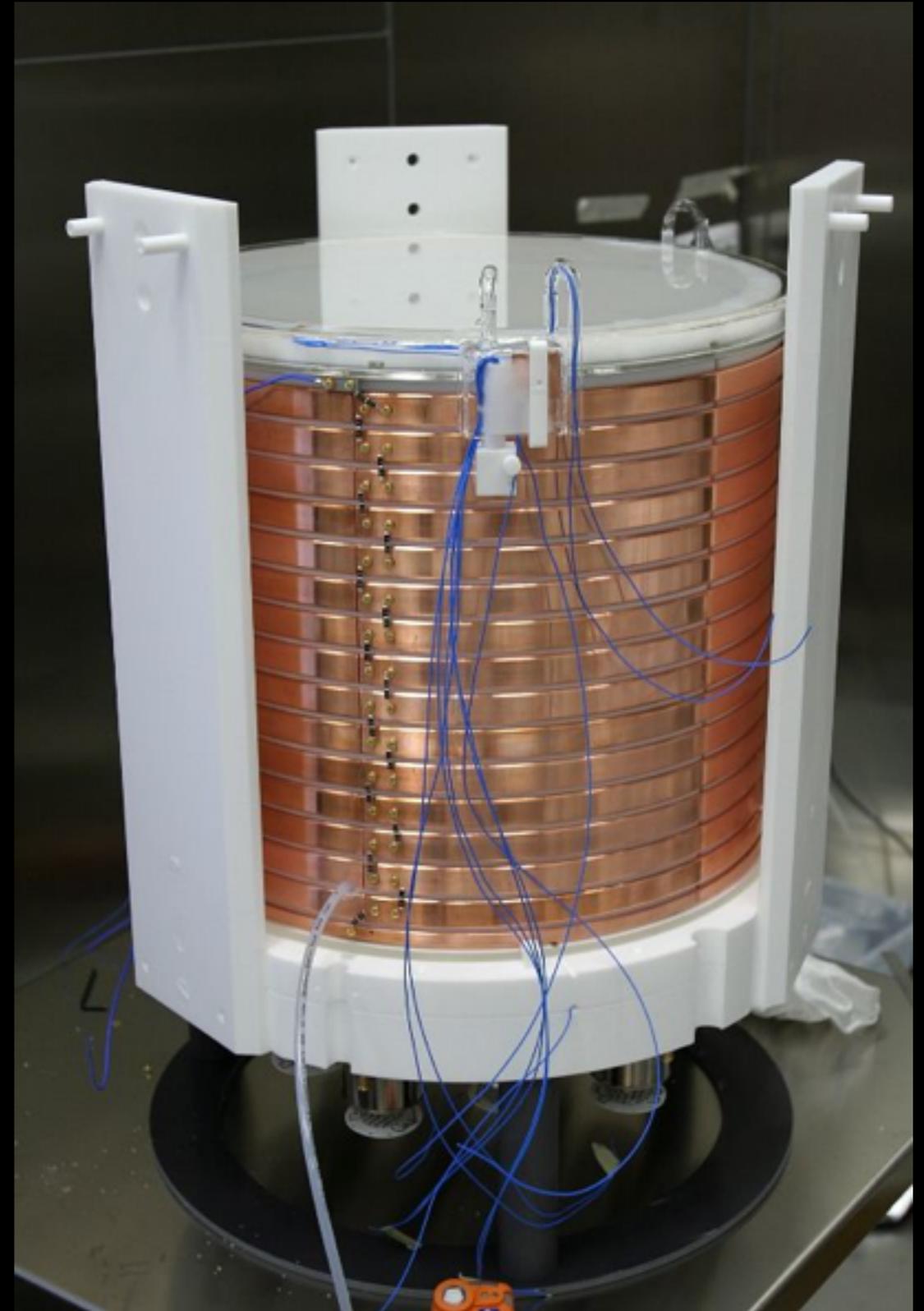
DarkSide 50 TPC



DS50 TPC assembly



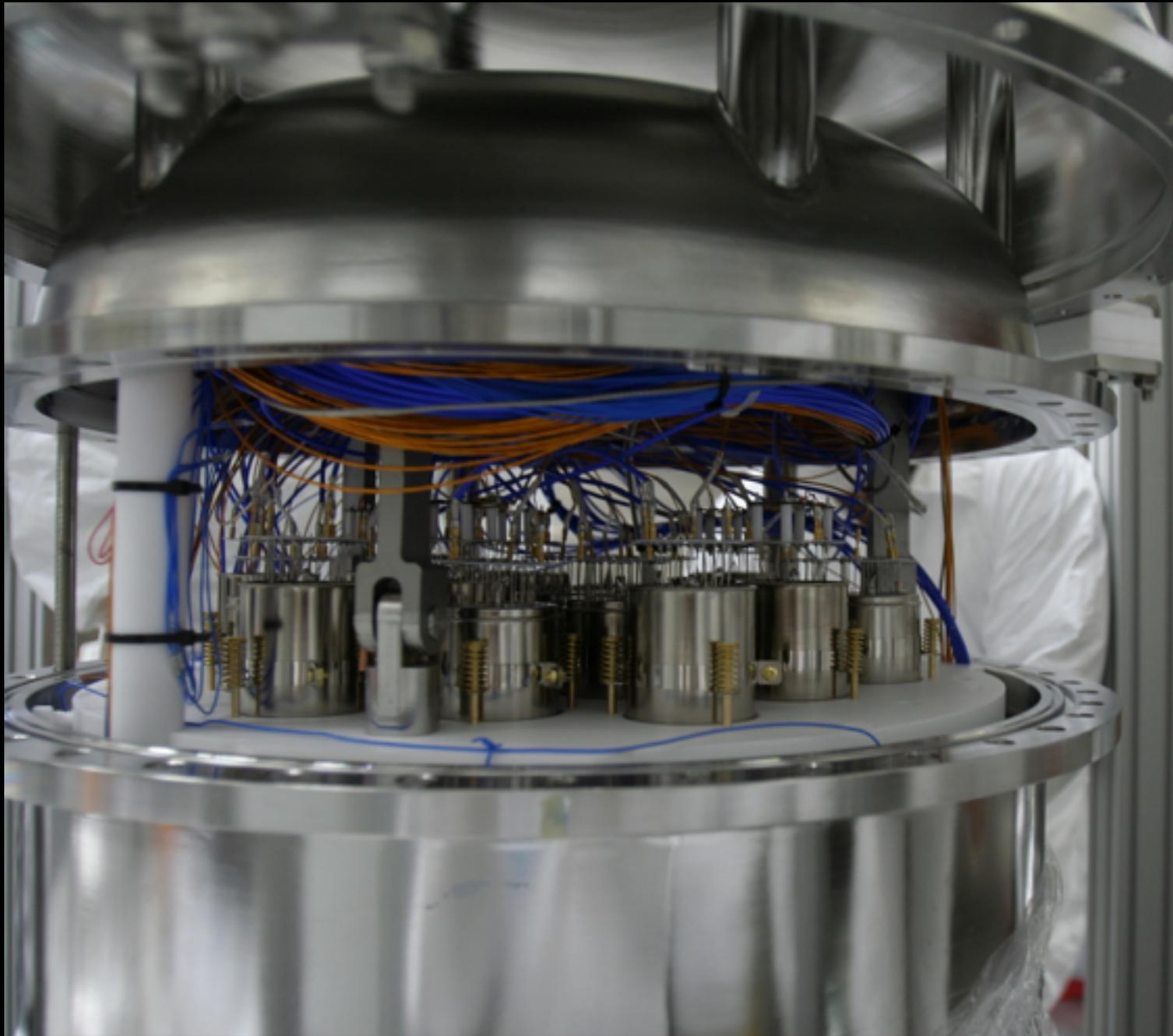
DS50 TPC assembly



DS50 TPC assembly



DS50 TPC deployment



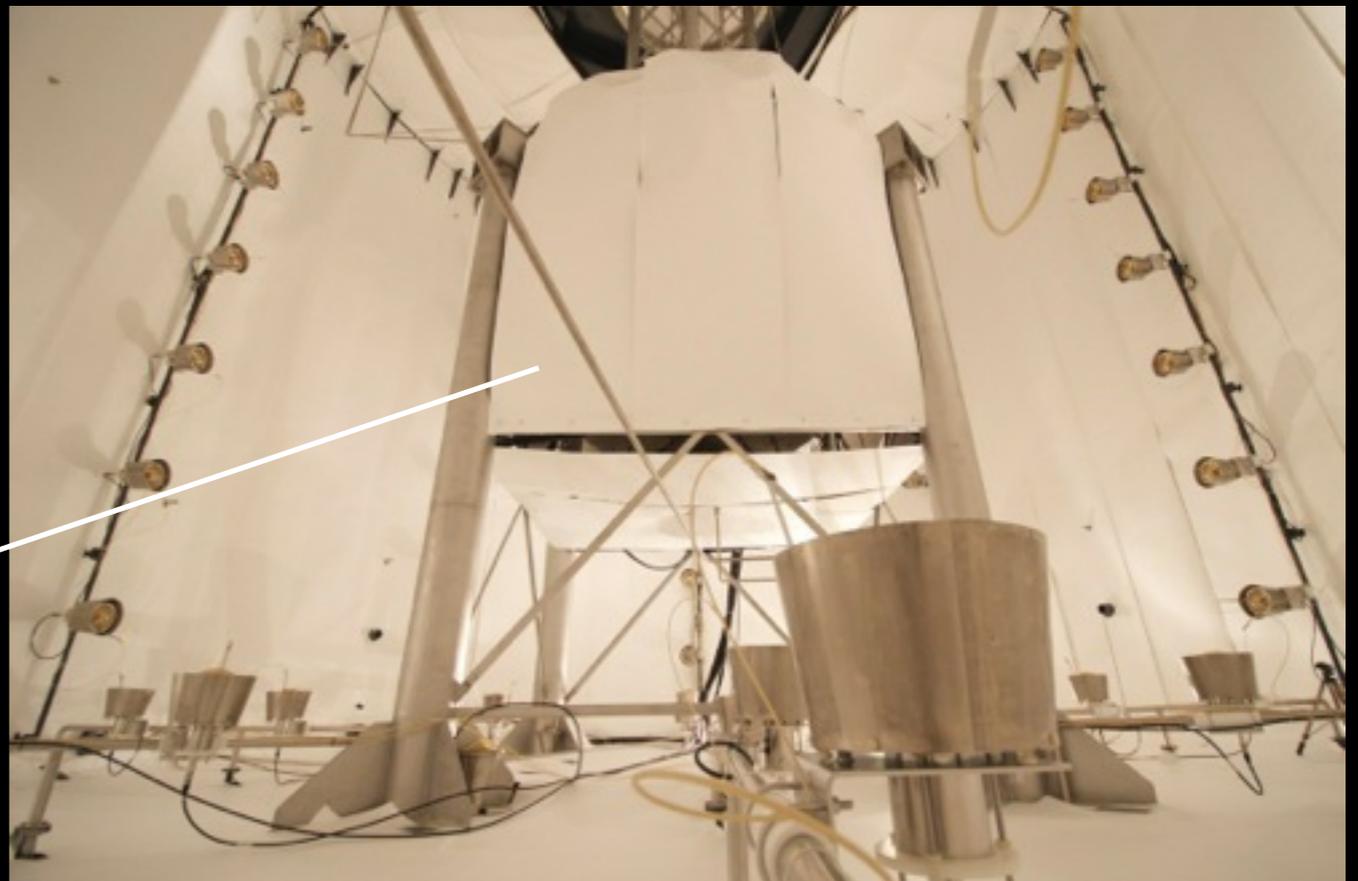


Inside of Liquid scintillator Veto
Neutron (BG) detection

TPC

Inside of Water Tank
muon (BG) detection

Liquid scintillator Veto



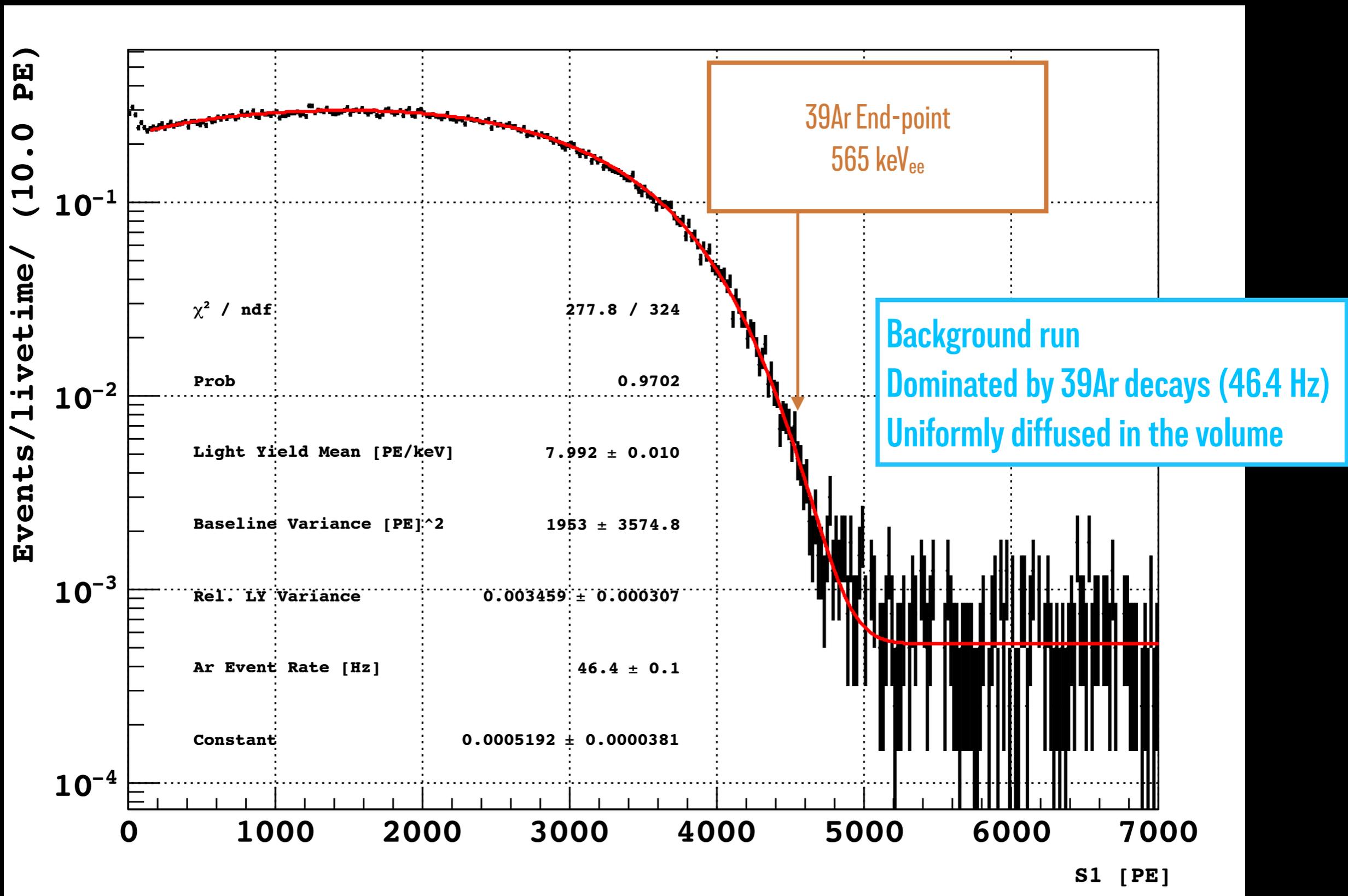
DS50 Timeline

- **Oct. 2013**: LArTPC, Neutron Veto and Muon Veto commissioned.
 - TPC filled with **atmospheric** argon (AAr).
- **Nov. - Jan. 2014**: large majority dedicated to improve DAQ, DATA HANDLING and PROCESSING.
- **Up to 20th of Feb. 2014**: collected 6.3 live days of AAr.
 - BG from **6.3 live days** (278 kg · day fiducial) of AAr corresponds to that expected in **2.6 year of UAr** DS-50 run.

All 3 detectors are filled and currently operating in the same mode of dark matter search

TPC Calibration

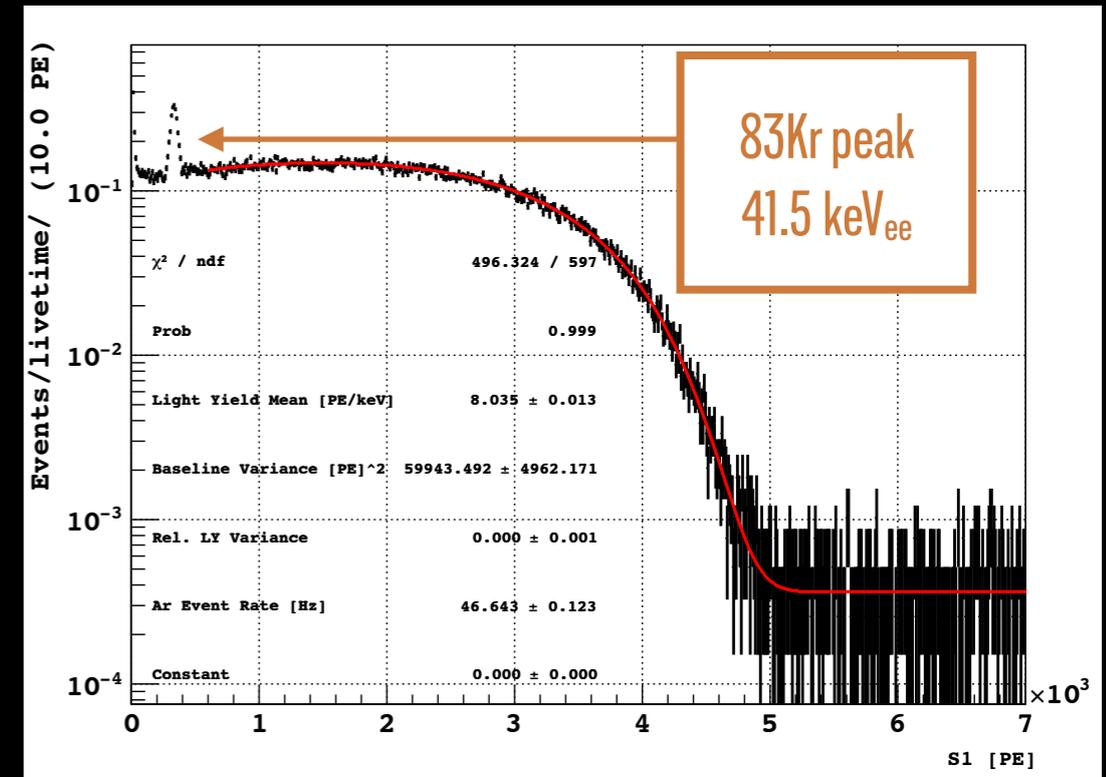
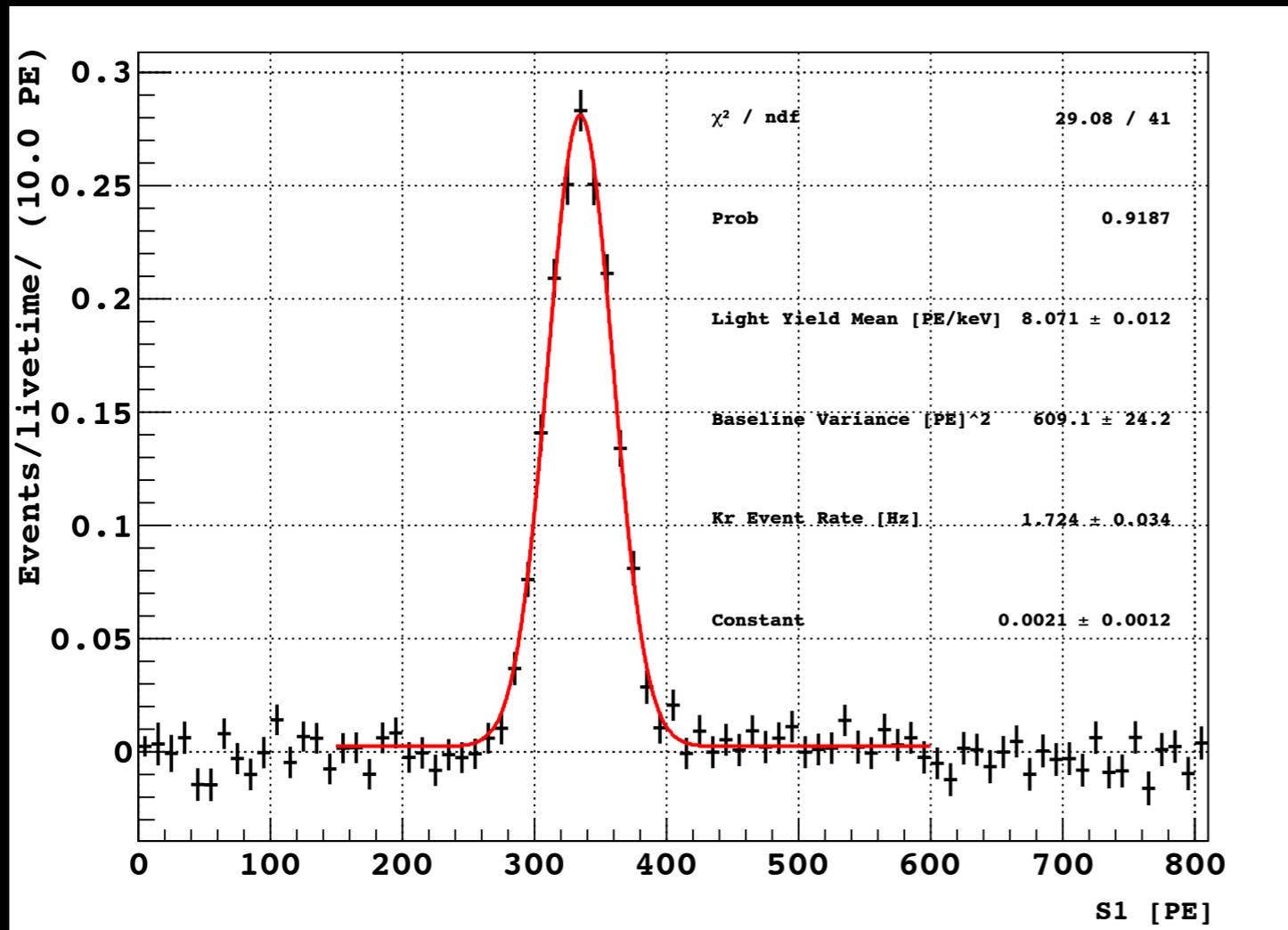
TPC: ER calibration @ null field



AVERAGE LIGHT YIELD: 8.040 ± 0.006 (stat) PE/keV_{ee}

TPC: ER calibration @ null field

Subtracted BG



$^{83\text{m}}\text{Kr}$ Half-life = 1.83 hours

$^{83\text{m}}\text{Kr}$ gas deployed into detector (41.5 keV_{ee})

Fits to ^{39}Ar and $^{83\text{m}}\text{Kr}$ spectrum indicate

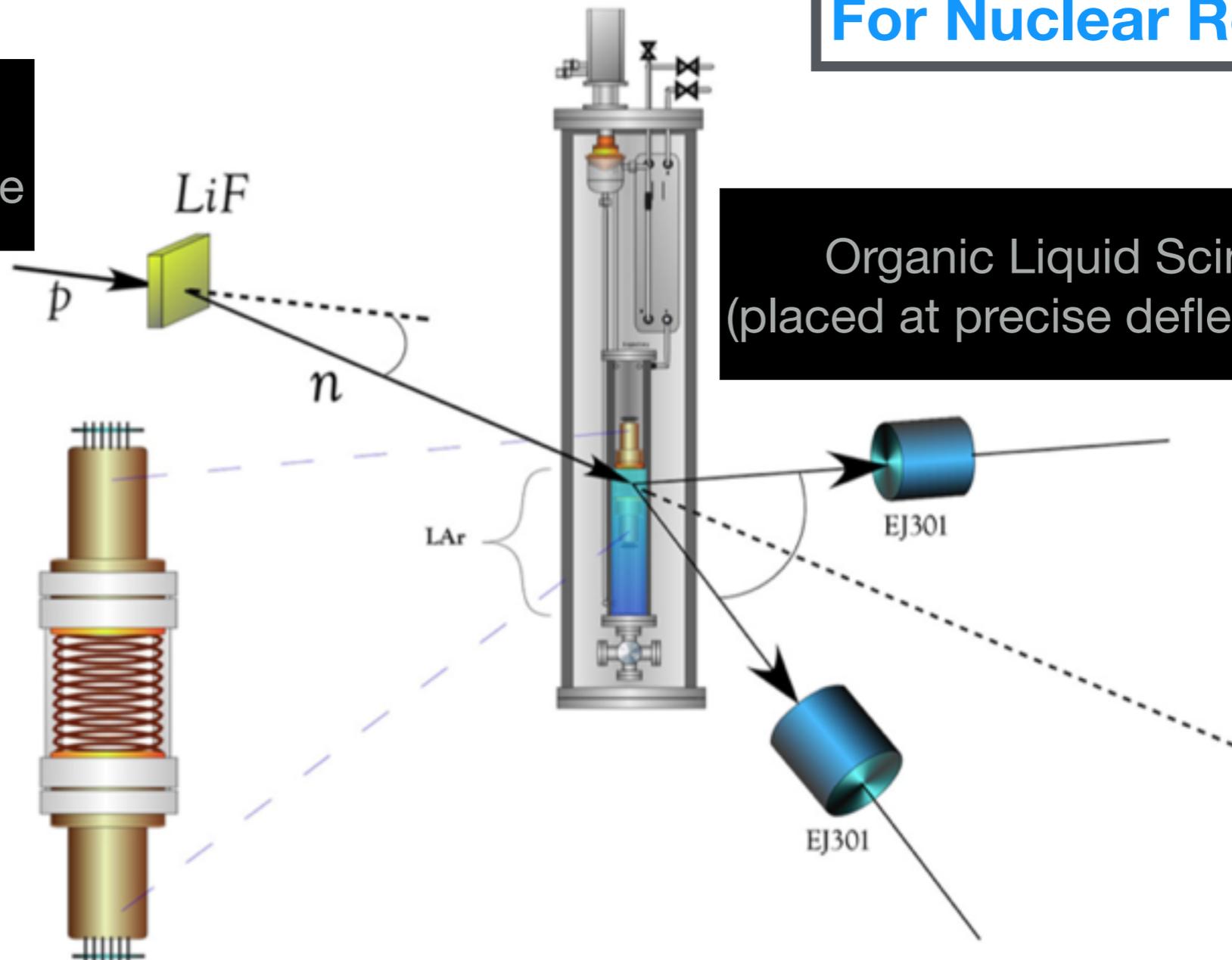
AVERAGE LIGHT YIELD: 8.071 ± 0.012 (stat) PE/keV_{ee}

SCENE

(Scintillation Efficiency of Nuclear Recoils in Noble Elements)

For Nuclear Recoils

Proton Beam at
University of Notre Dame



Organic Liquid Scintillators
(placed at precise deflection angles)

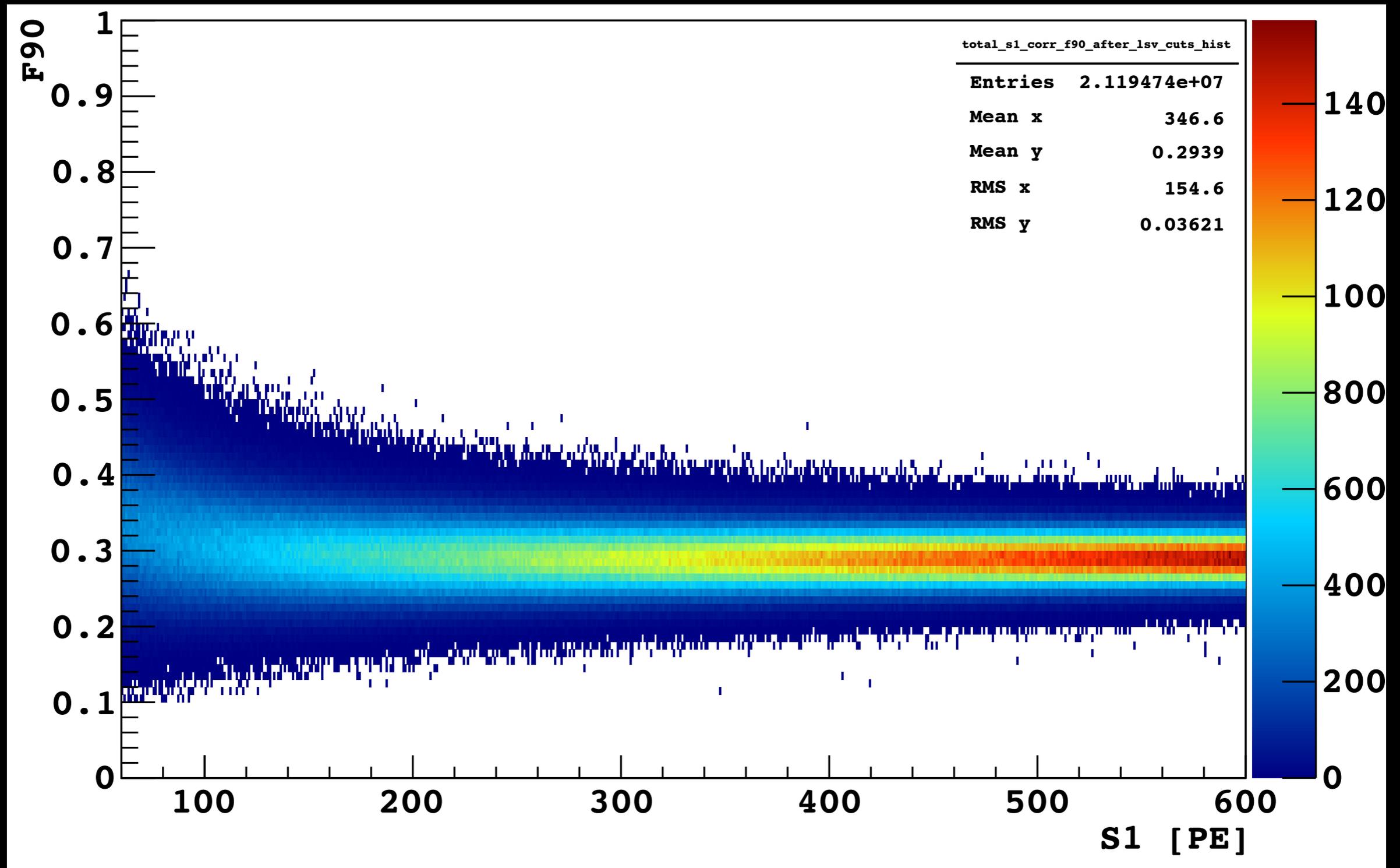
Liquid Argon TPC
(based on DarkSide
design)

${}^7Li(p, n){}^7Be$ reaction produces low energy monoenergetic neutrons
TOF measurement between target, LAr and organic scintillators allows
clean identification of elastic neutron interactions of known energy

BG Run Result

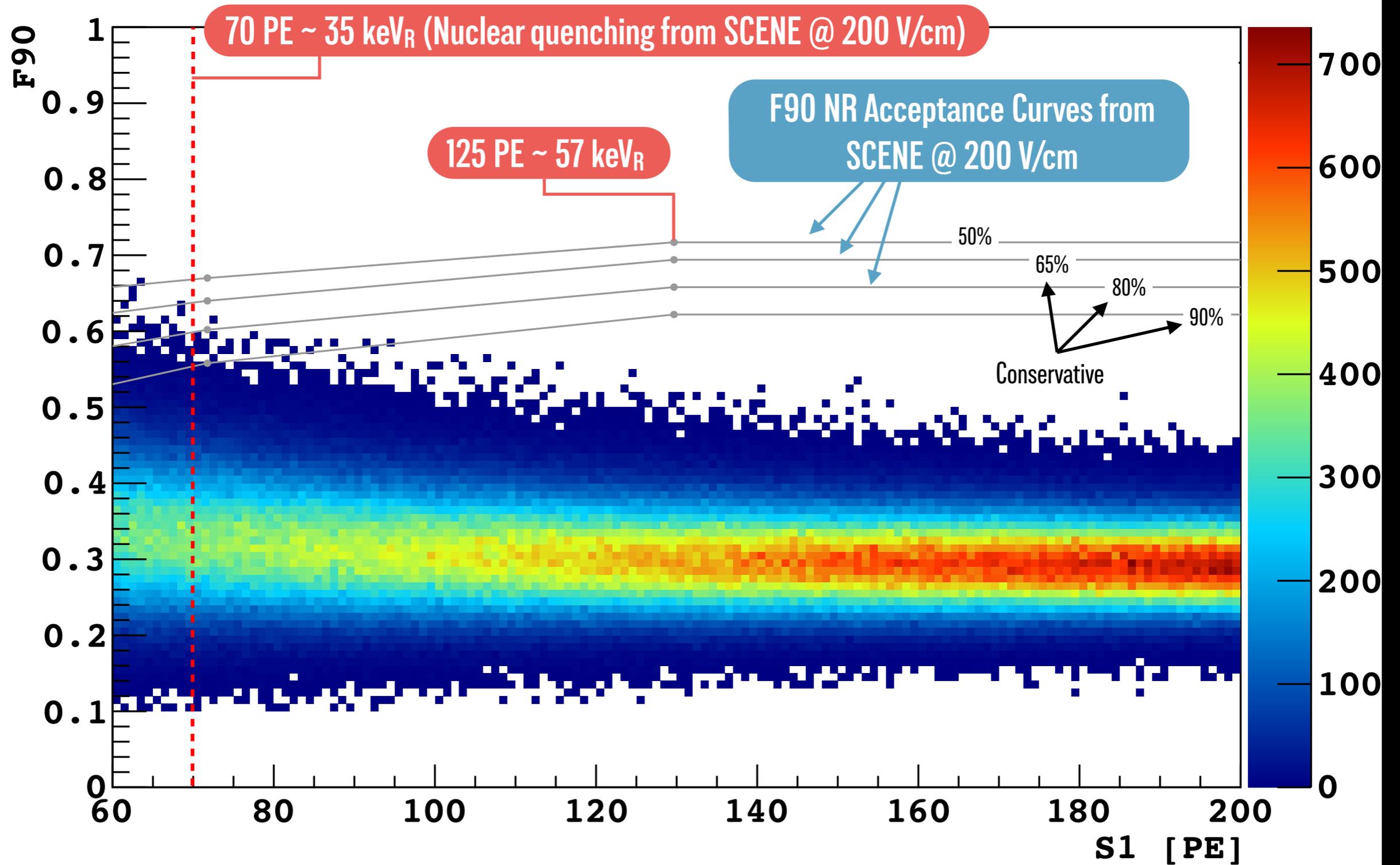
BG from **6.3 live days** (278 kg · day fiducial) of AAr corresponds to that expected in **2.6 year of UAr** DS-50 run (~planning physics run time).

Background (NR) free exposure of 280kg·day



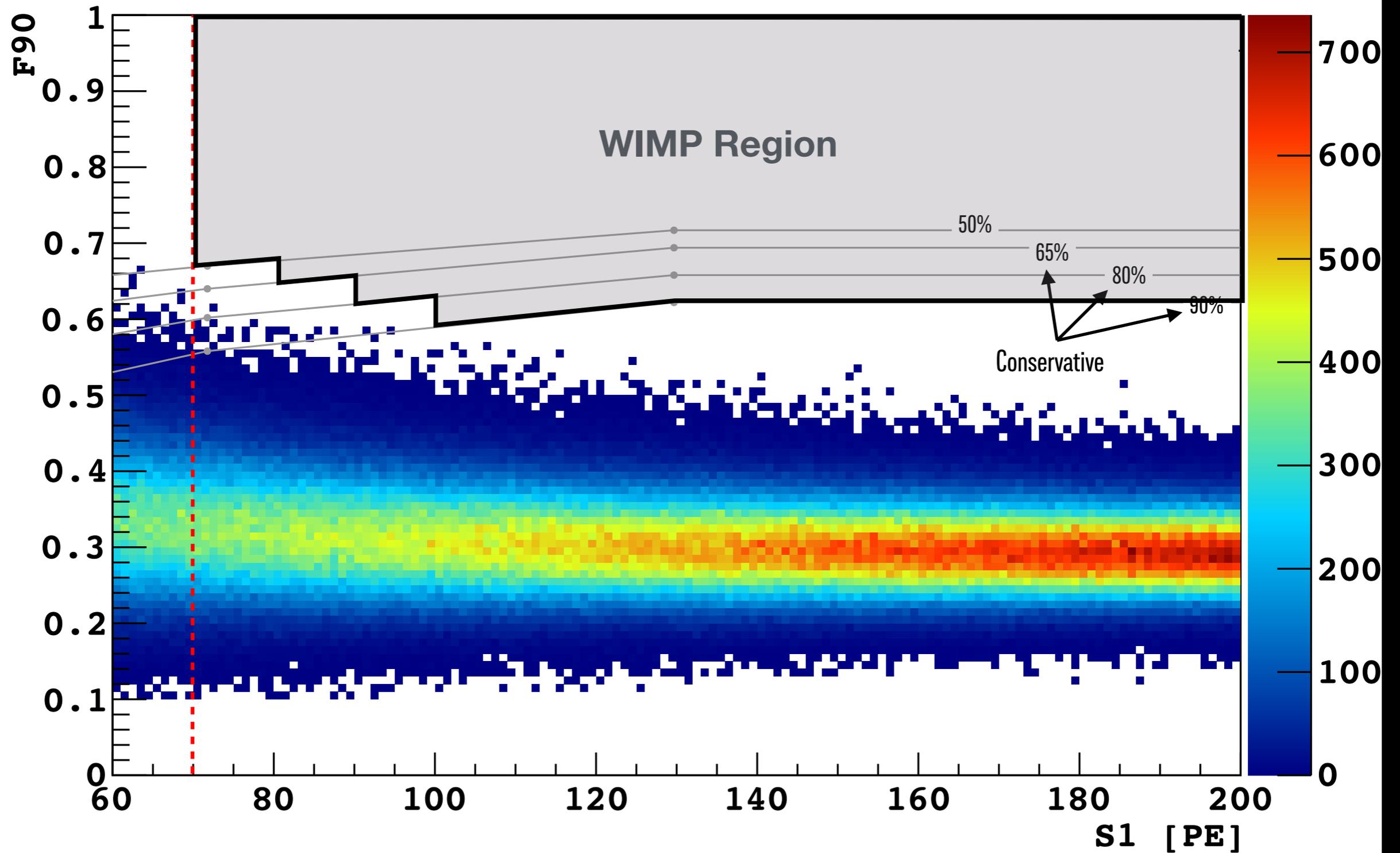
Selected only single-hit interactions in the TPC fiducial volume (44.1 kg) with no energy deposition in the veto

Background (NR) free exposure of 280kg·day

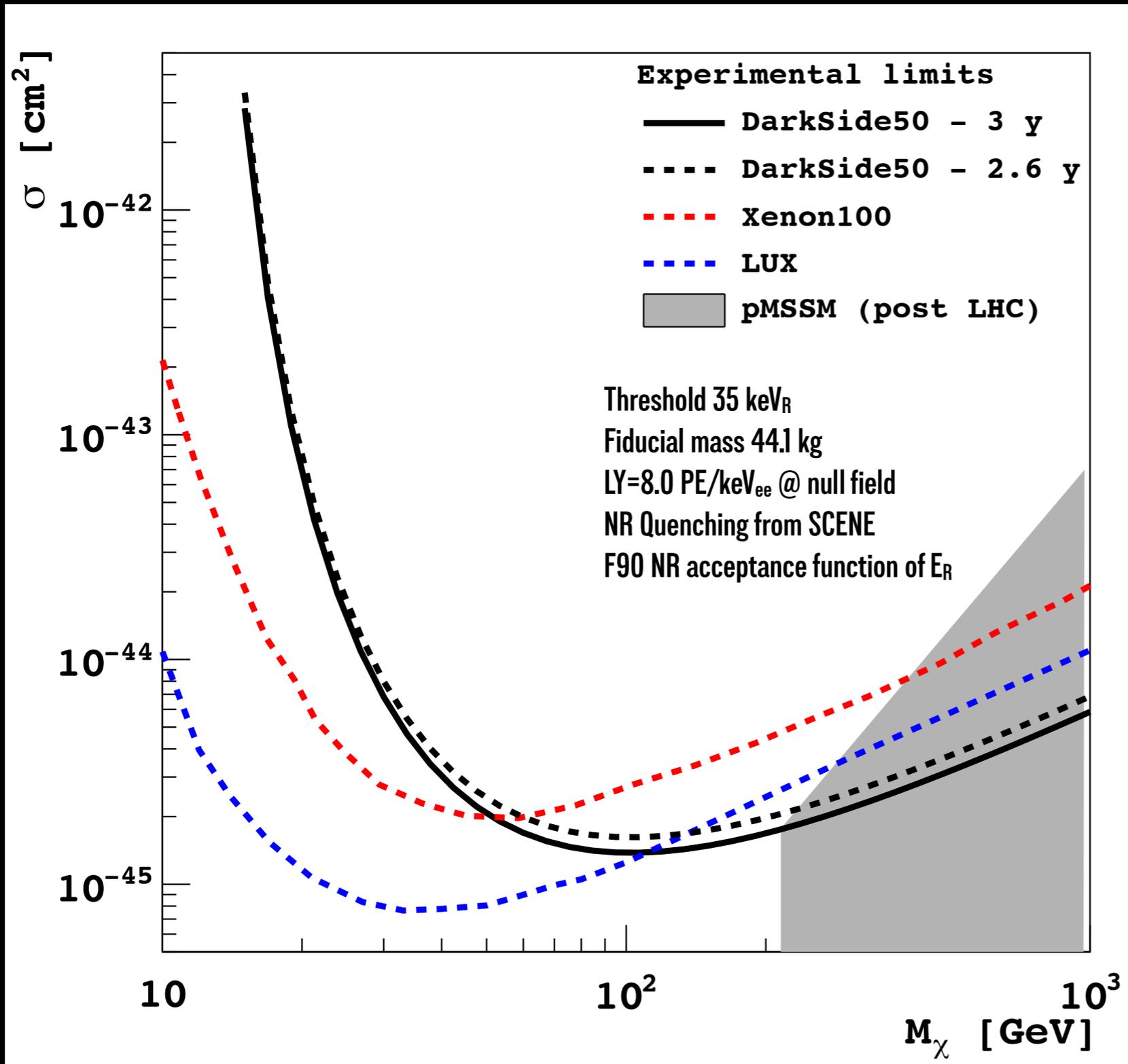


Background (NR) free exposure of 280kg·day

No background events in nuclear recoil (WIMP) region!



DS-50 projected sensitivity (90% C.L.)



Projected sensitivity evaluated assuming:

- the measured PSD performance;
- no rejection from S2/S1;
- fiducialization along z axis-only;
- zero neutron-induced events;
- NR quenching and F90 acceptance curves from SCENE @ 200V/cm

Present systematics on NR Quenching and F90 NR acceptance curves cause a ~10% variation of the projected sensitivity around 100 GeV/c².

Current Status

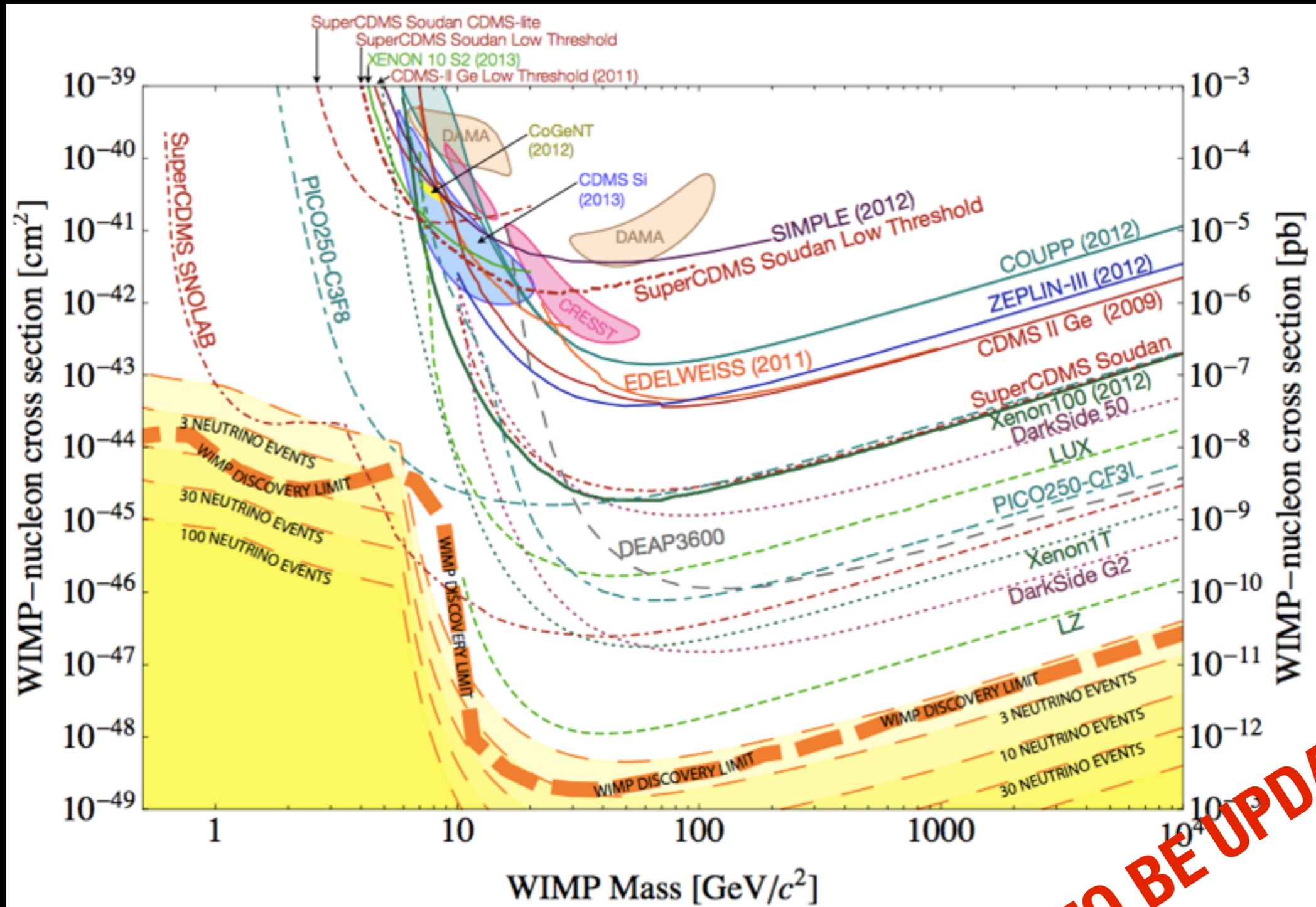
- **Collect Background Statistics**
about 1 week of running with atmospheric argon ~ 3 yrs
with underground argon

Future Plans

- **Increase ER statistics by injecting ^{39}Ar**
Improve ER pulse shape discrimination
- **Deploy calibration sources**
Calibrate both neutron veto and TPC using gamma and neutron sources
- **Refill with underground argon**
Fill TPC with underground argon around June 2014
- **Begin dark matter search**

THE END

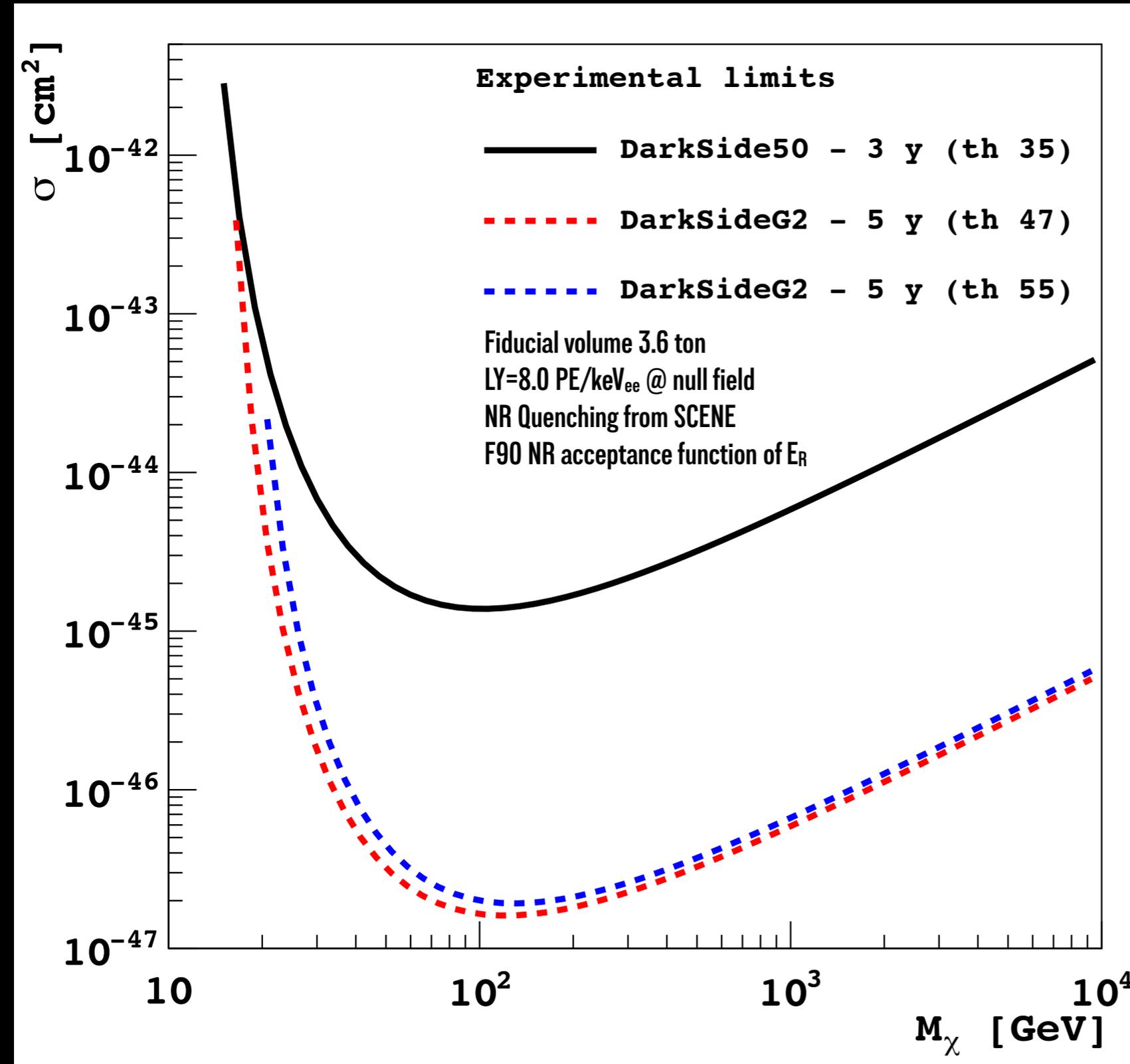
DS-50 & G2 Sensitivity



Sensitivity projection made on Nov. 2013.

TO BE UPDATED

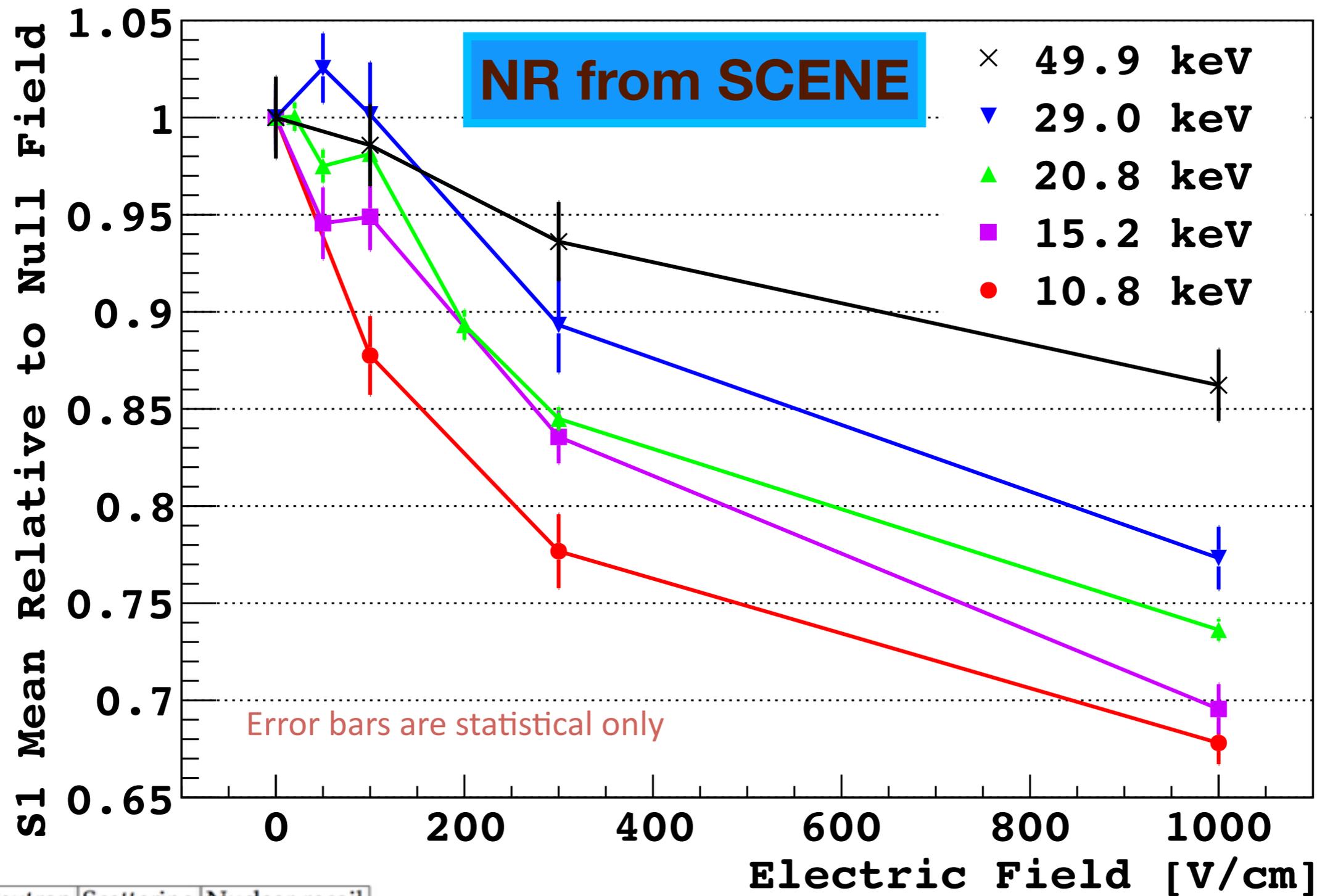
DS-50 projected sensitivity (90% C.L.)



Assumed:

- Same LY as in DS-50;
- PSD as per F90 model based on DS-50;
- no rejection from S2/S1;
- fiducialization along z axis-only;
- NR quenching and F90 acceptance curves from SCENE @ 200V/cm
- zero neutron-induced events according to present background MC study;

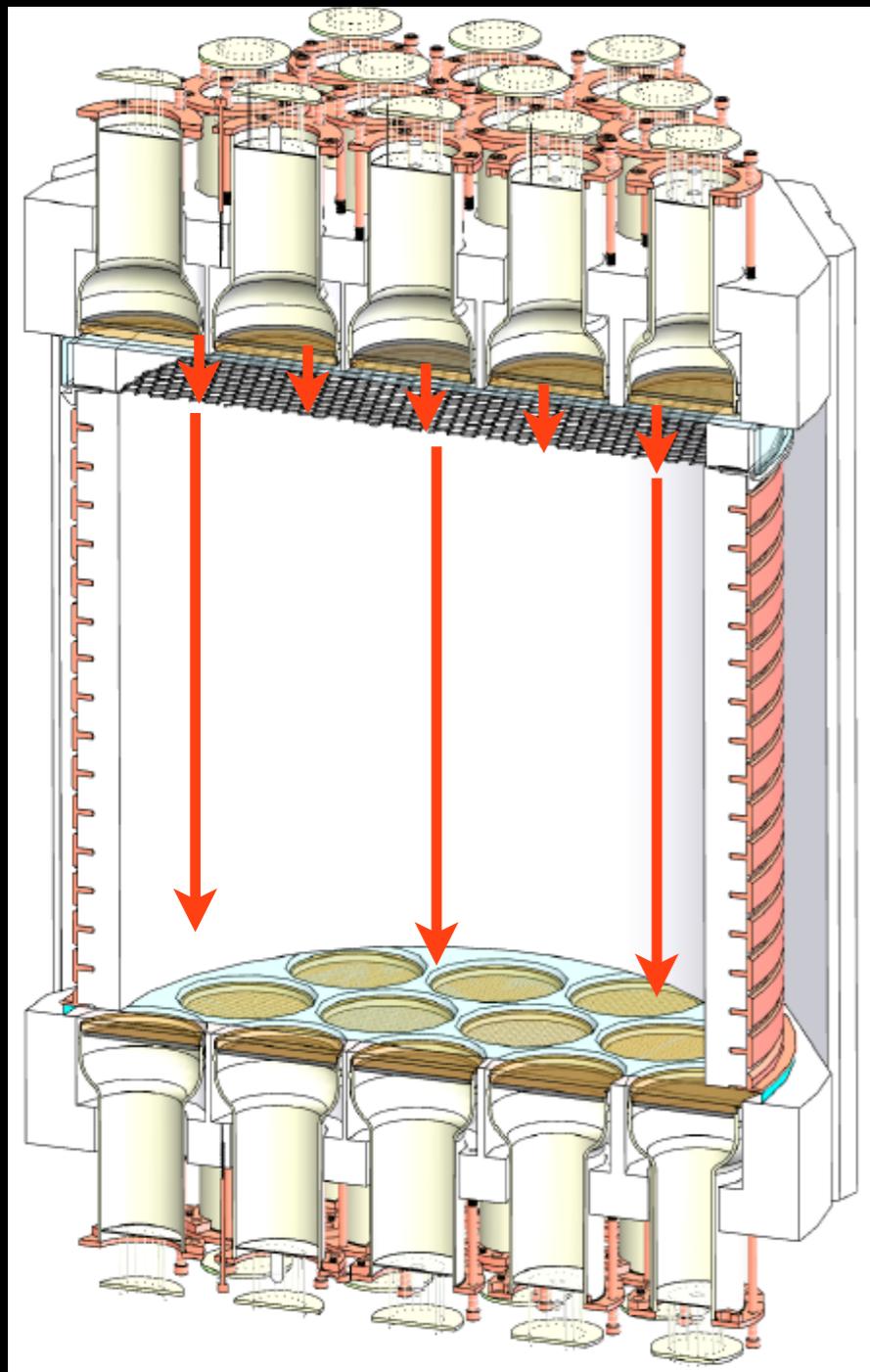
Scintillation yield as a function of applied field



Proton energy (MeV)	Neutron energy (MeV)	Scattering angle (°)	Nuclear recoil energy (keVr)
2.376	0.604	49.9	10.8
2.930	1.168	42.2	15.2
2.930	1.168	49.9	20.8
2.930	1.168	59.9	29.0
2.930	1.168	82.2	49.9

Drift Field

DS50 has been operating at a drift field of 200 V/cm
and an extraction field of 2.8 kV/cm



Anode: 0 V

$E_{\text{gas}} : 4200 \text{ V/cm}$

$E_{\text{ext}} : 2800 \text{ V/cm}$

Grid: -5600 kV

$E_{\text{drift}} : 200 \text{ V/cm}$

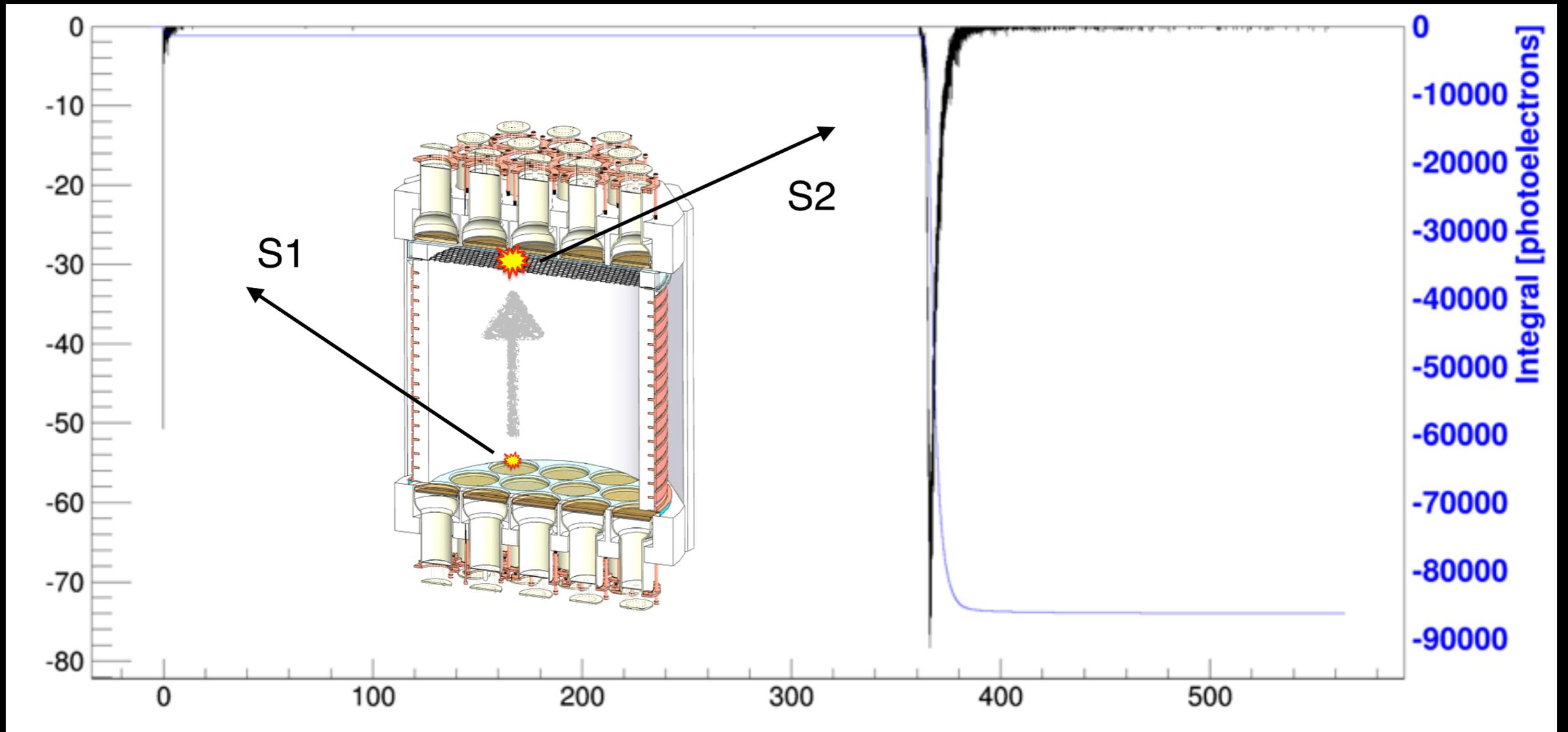
Cathode: -12700 V

Stable operation for several
months at -12700 V

Max Drift Time $\sim 370 \text{ us}$

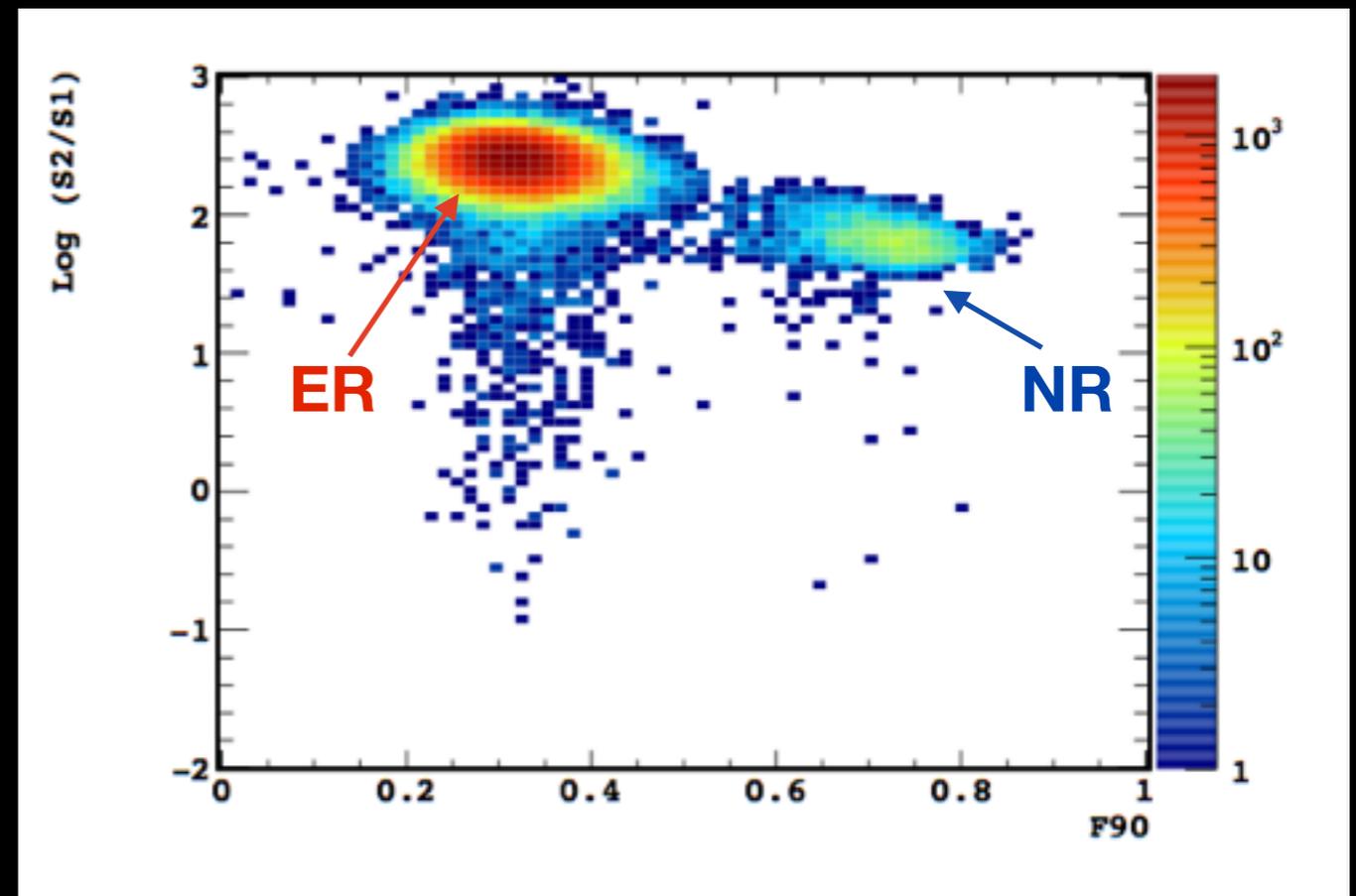
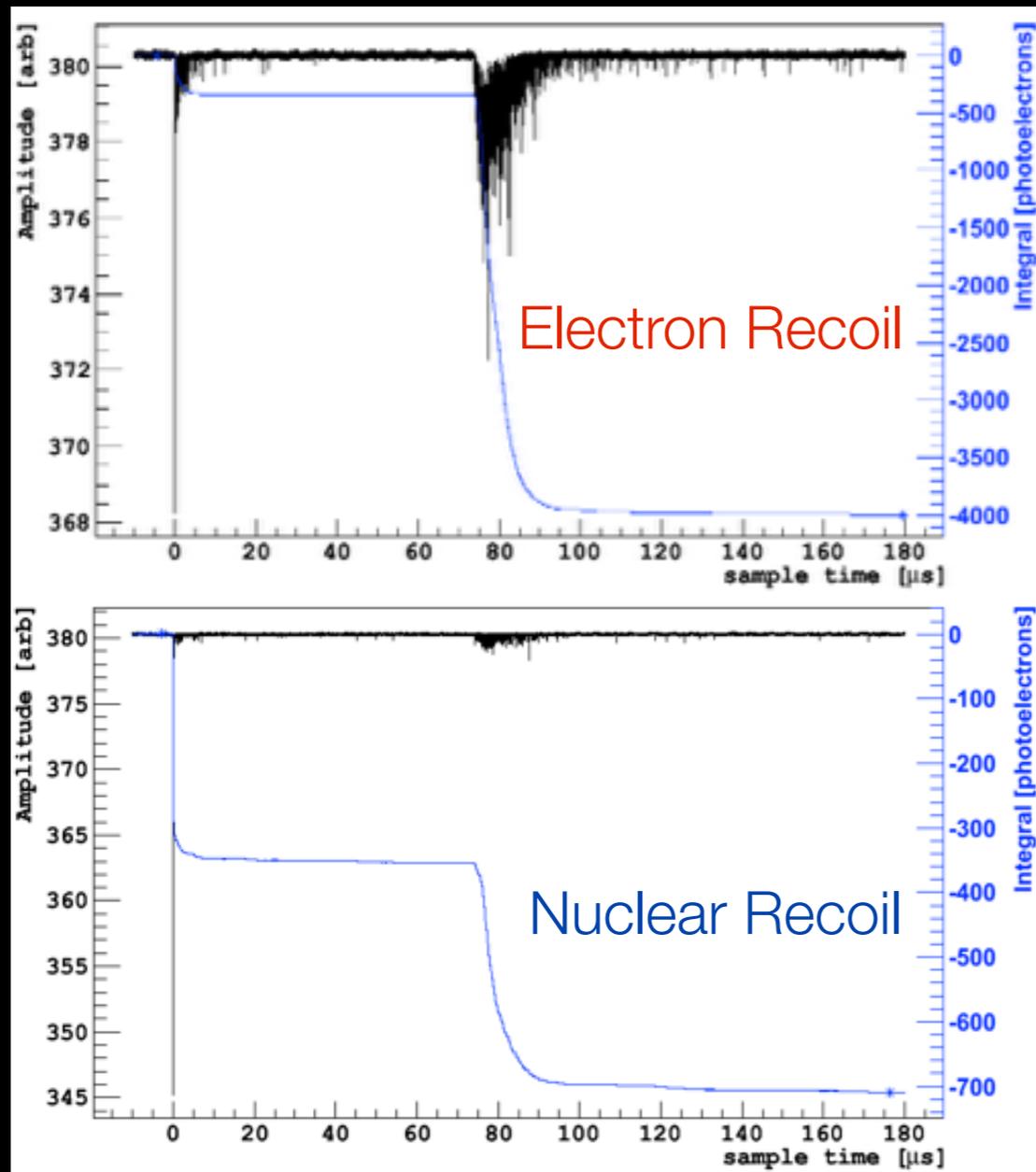
Electron Drift Lifetime $> 5\text{ms}$

S1 + S2 waveform



S2/S1

Electron and nuclear recoils produce different ionization densities that lead to different fractions of electrons that survive recombination

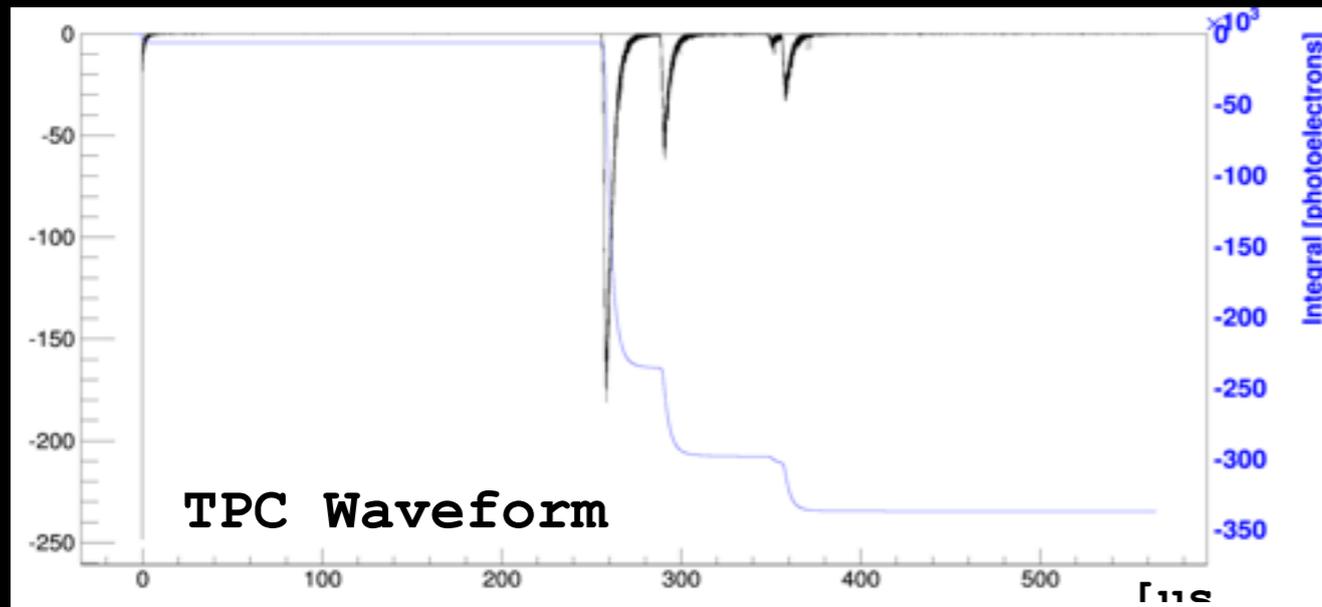


Am-Be Source

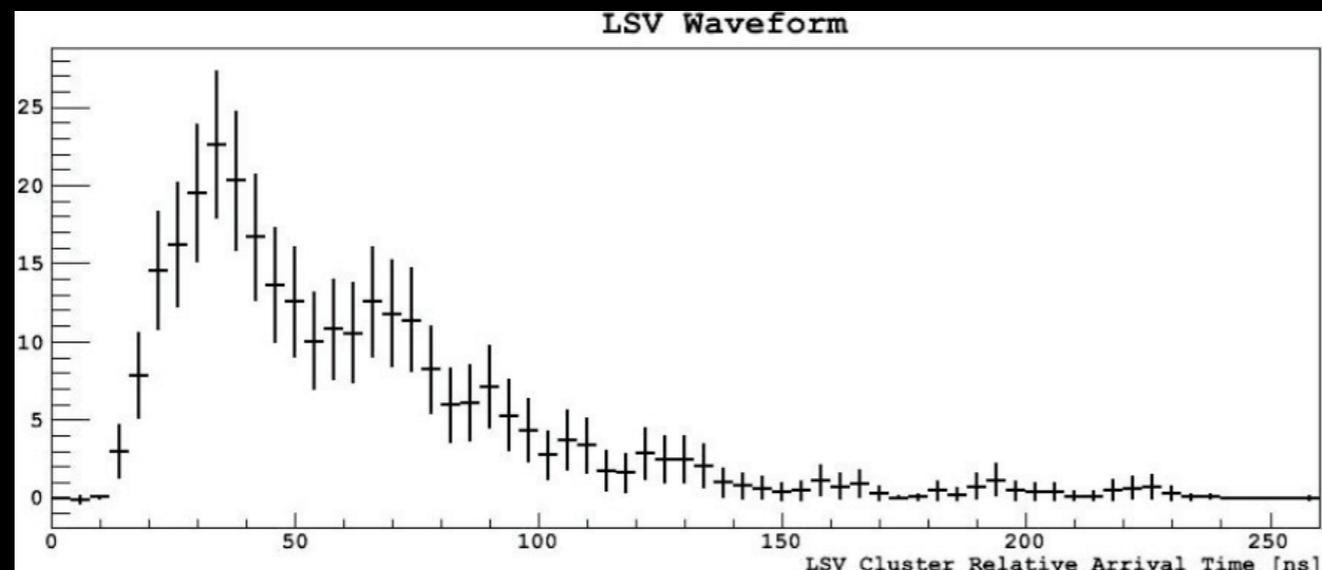
Ratio of ionization and scintillation signal (S2/S1) can be used to distinguish between the two populations

Neutron Veto Commissioning

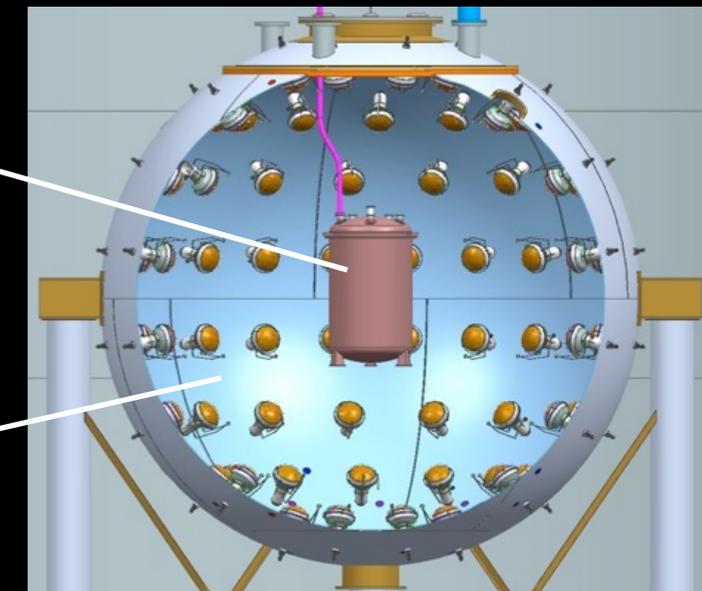
Coincident event in TPC and Neutron Veto



Electron recoil event with multiple S2 signals in TPC



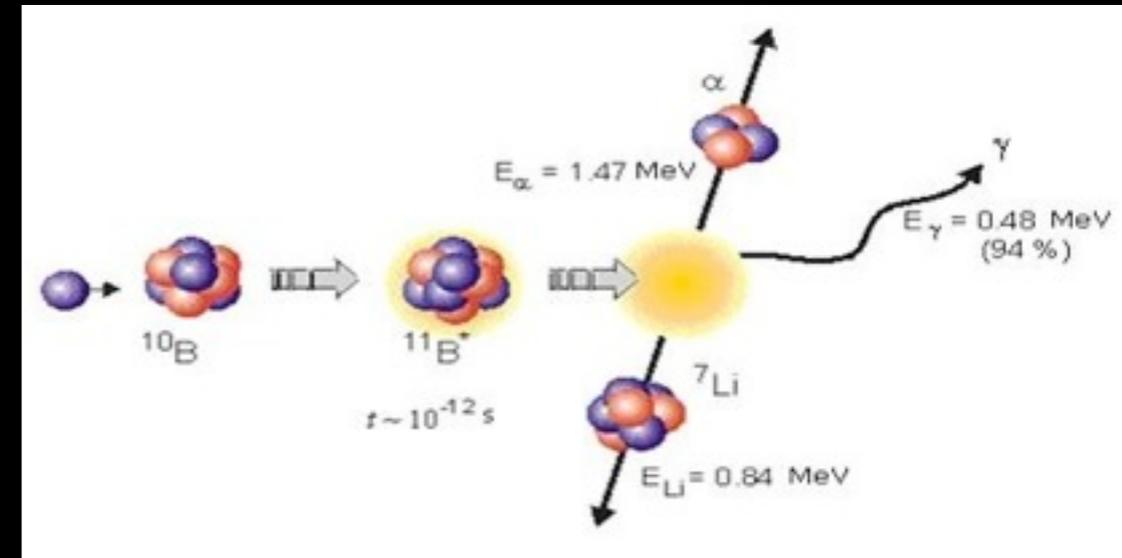
Coincident signal in liquid scintillator veto



Light Yield: liquid scintillator VETO LY of about 0.5 PE/keV_{ee}, satisfactory for VETO requirements.

Borated Liquid Scintillator

- High neutron capture cross section on boron allows for compact veto size
- Capture results in 1.47 MeV α particle - detected with high efficiency
- Short capture time ($2.3 \mu\text{s}$) reduces dead time loss



	Veto Efficiency (MC)
Radiogenic Neutrons	$> 99\%^*$
Cosmogenic Neutrons	$> 95\%$

Nuclear Instruments and Methods A 644, 18 (2011)