THE DARKSIDE EXPERIMENT – PRESENT STATUS AND FUTURE

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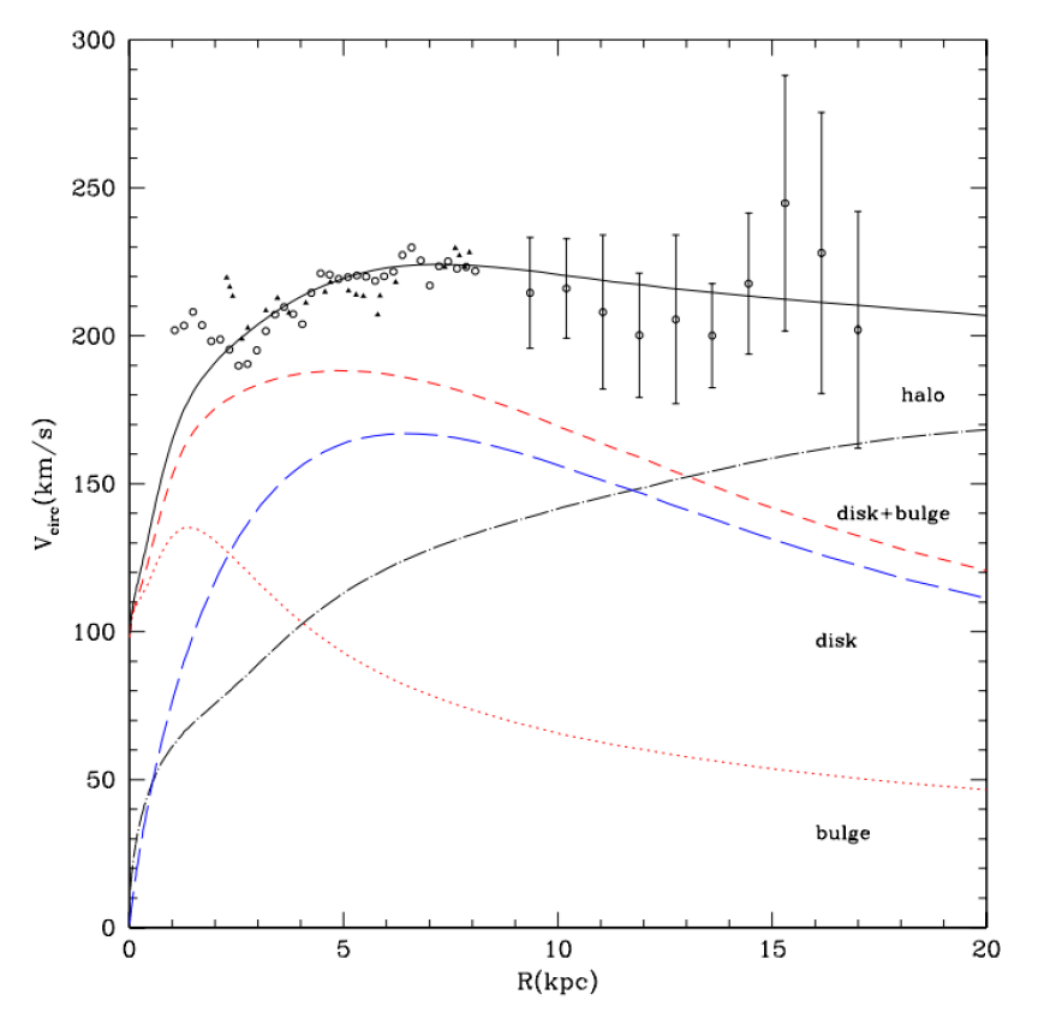
for the DARKSIDE Collaboration

Seminar of High Energy Physics, Faculty of Physics and Applied Computer Science AGH, 24.11.2017, Cracow

OUTLINE

- Introduction to Dark Matter
- The DARKSIDE program
- DARKSIDE-50 detector
- Physics results from DARKSIDE-50
- Future of DARKSIDE
- Summary

DARK MATTER EVIDENCES



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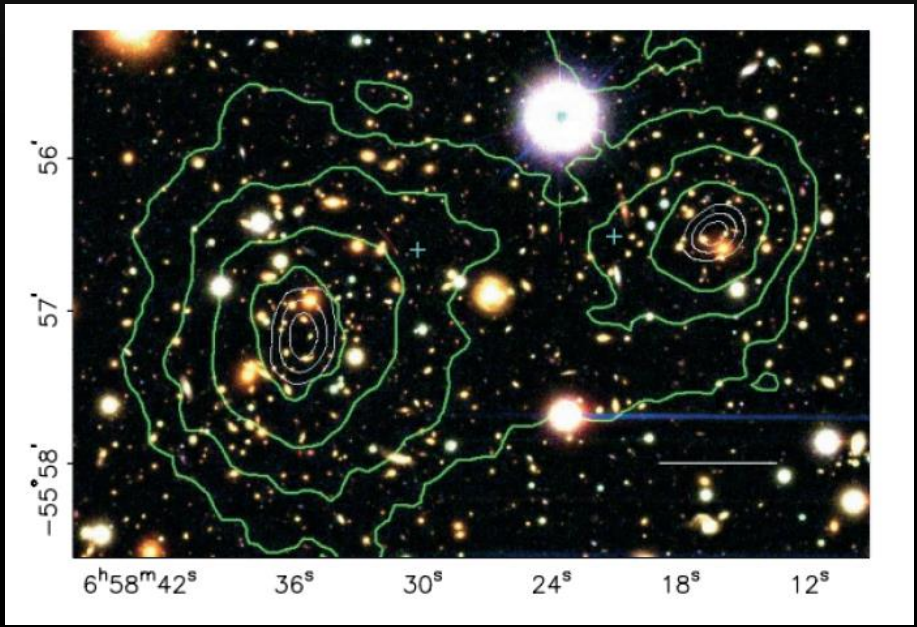
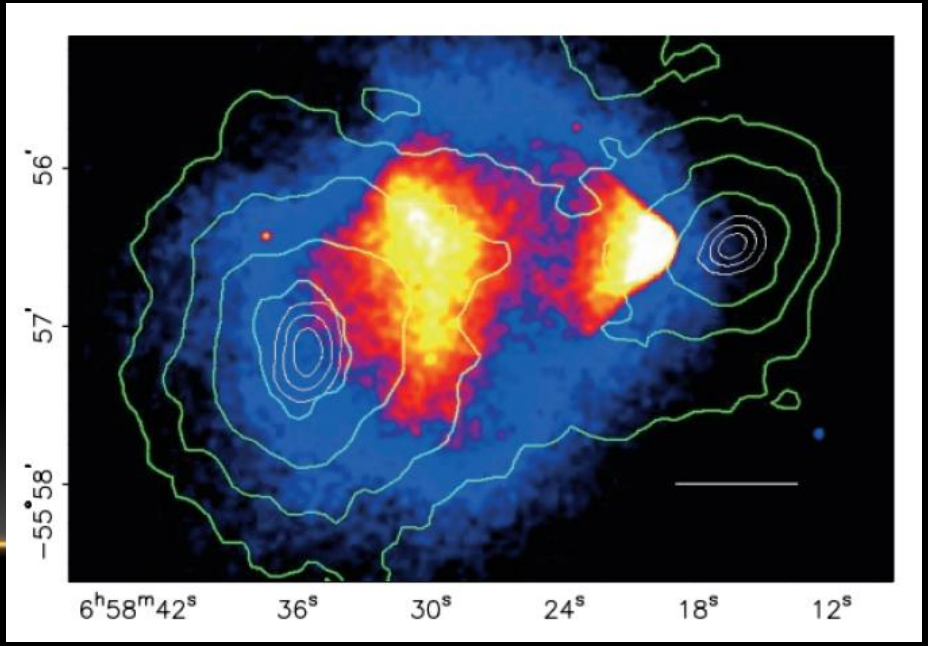
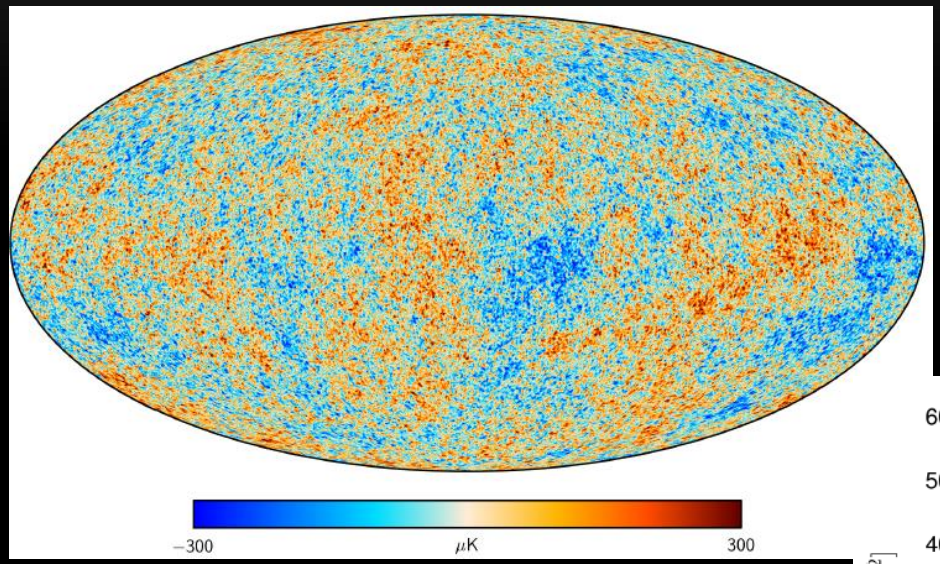


Magellan images of the Bullet Cluster, with weak lensing mass contours

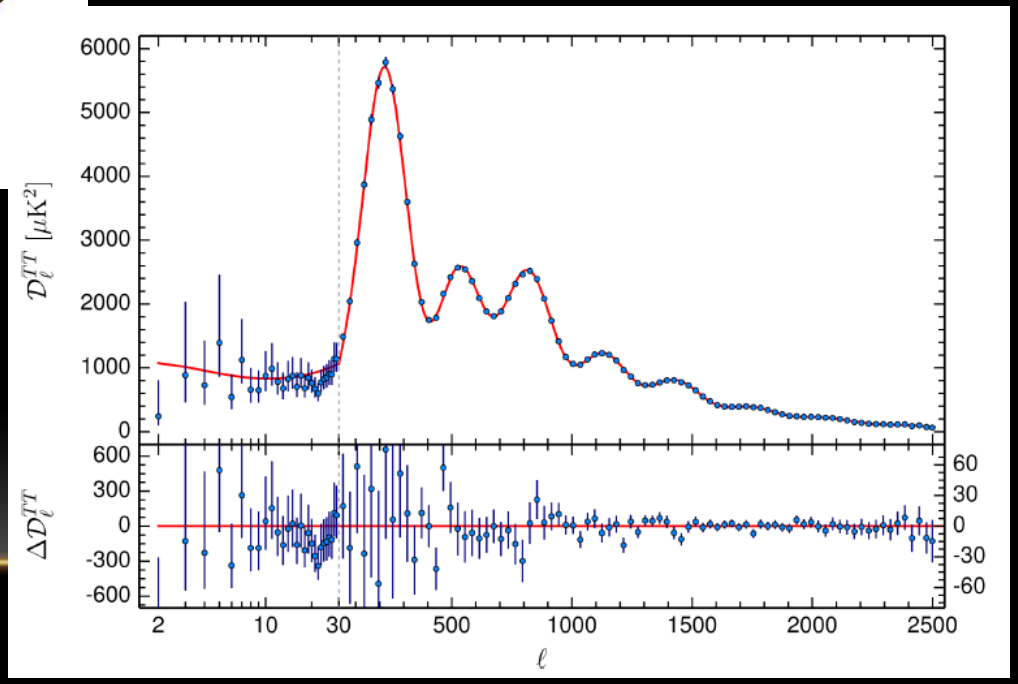


Bullet Cluster: Chandra observations of the X-ray emission from hot gas

DARK MATTER EVIDENCES

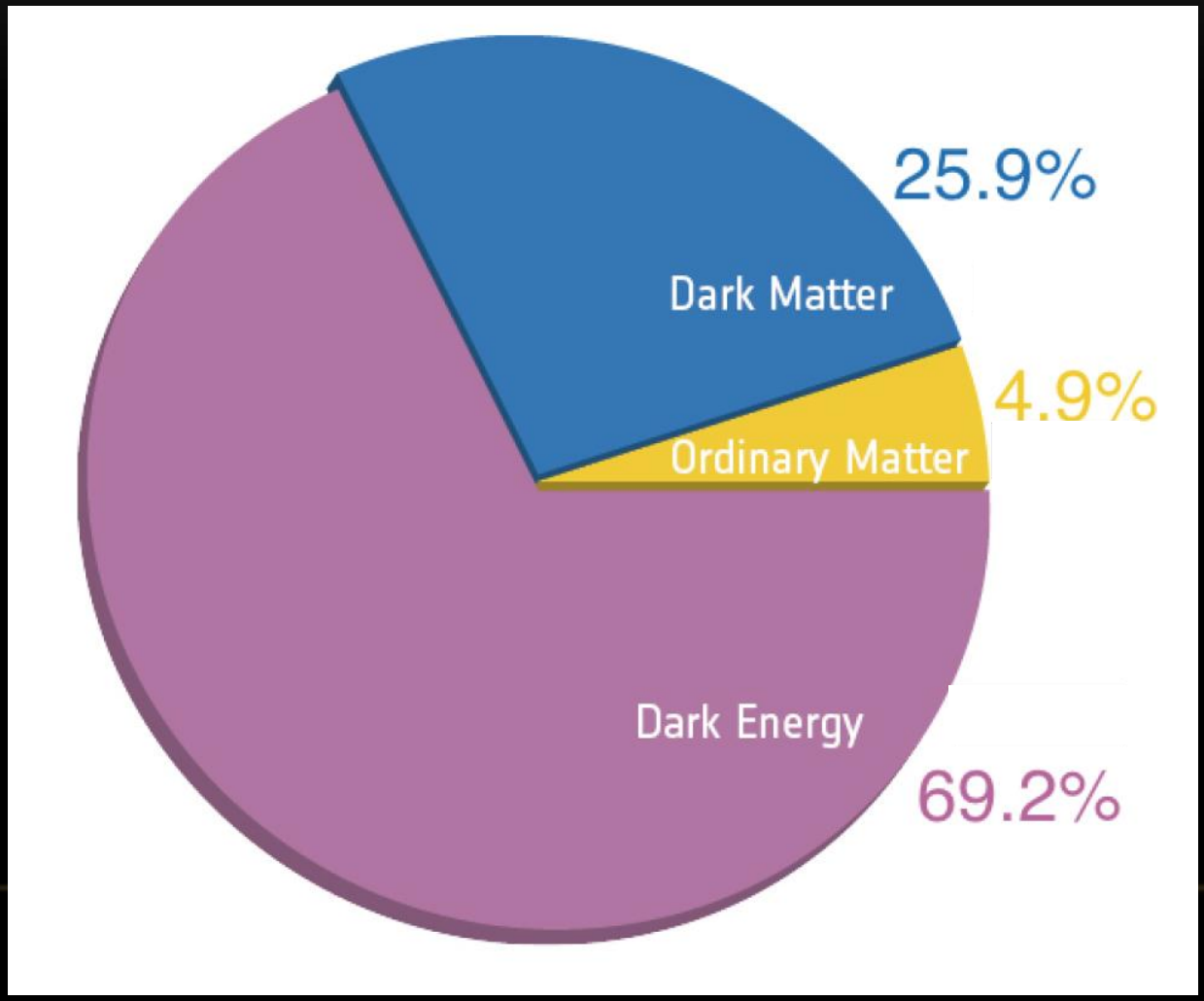


All-sky map of CMB temperature fluctuations produced by Planck



Power spectrum of CMB temperature as measured by Planck

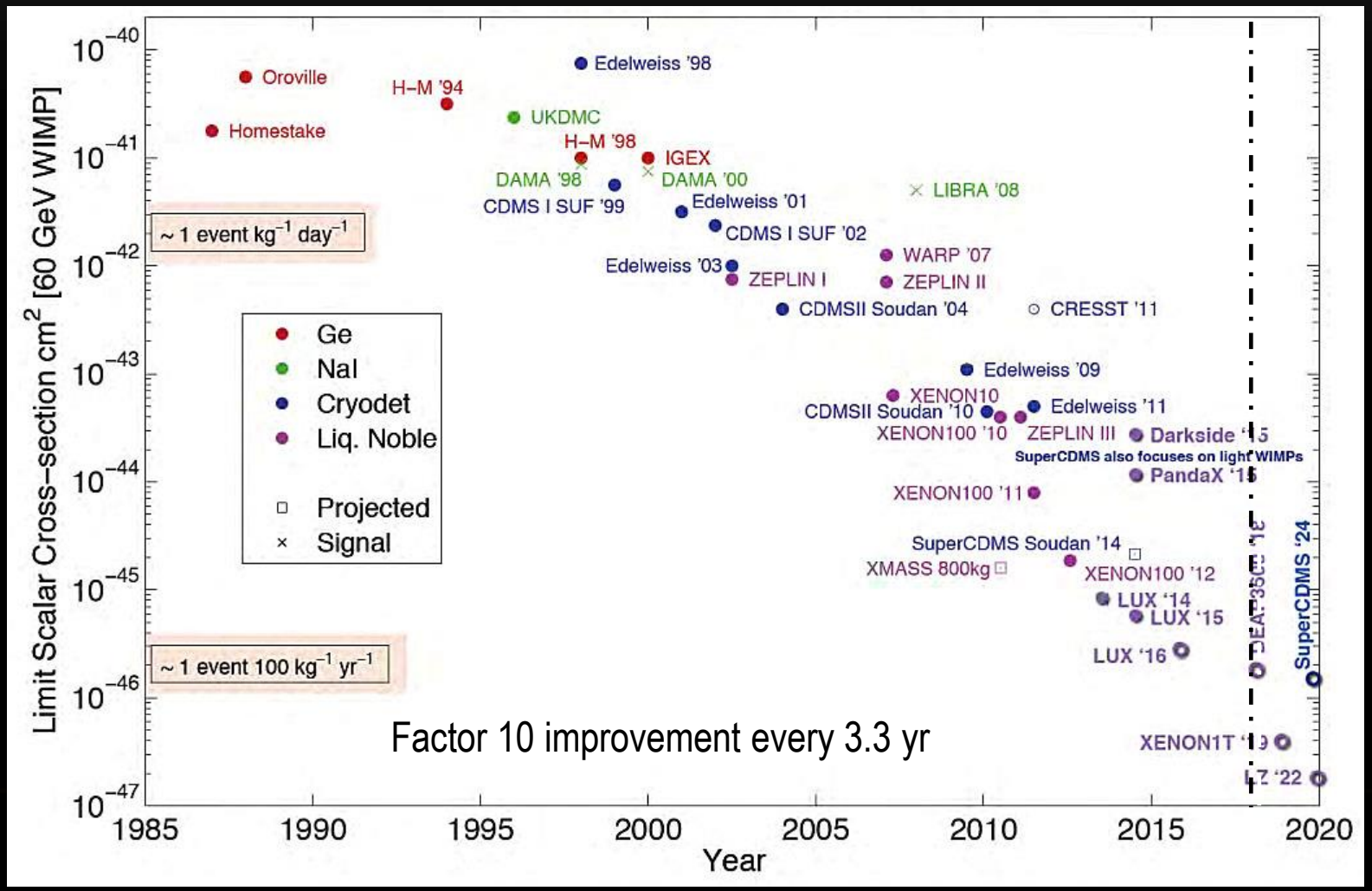
CONTENT OF THE UNIVERSE



SEARCHES FOR DARK MATTER

- Indirect (DM annihilation/decay products)
- Colliders (missing momentum/energy)
- Direct (DM particles interactions in terrestrial detectors)
  - WIMPs: produced in the early Universe, interacting weakly, no charge, heavy (10 – 1000 GeV/c^2)

DIRECT SEARCHES FOR DARK MATTER



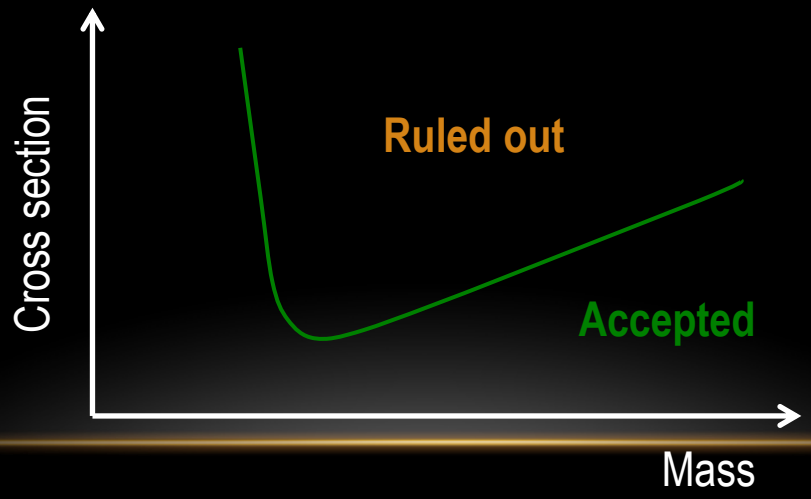
DARK MATTER – EXPECTED SIGNAL RATE

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{\sqrt{(m_N E_{th})/(2\mu^2)}}^{v_{max}} dv f(v) v \frac{d\sigma}{dE_R}$$

Detector physics N_N, E_{th}

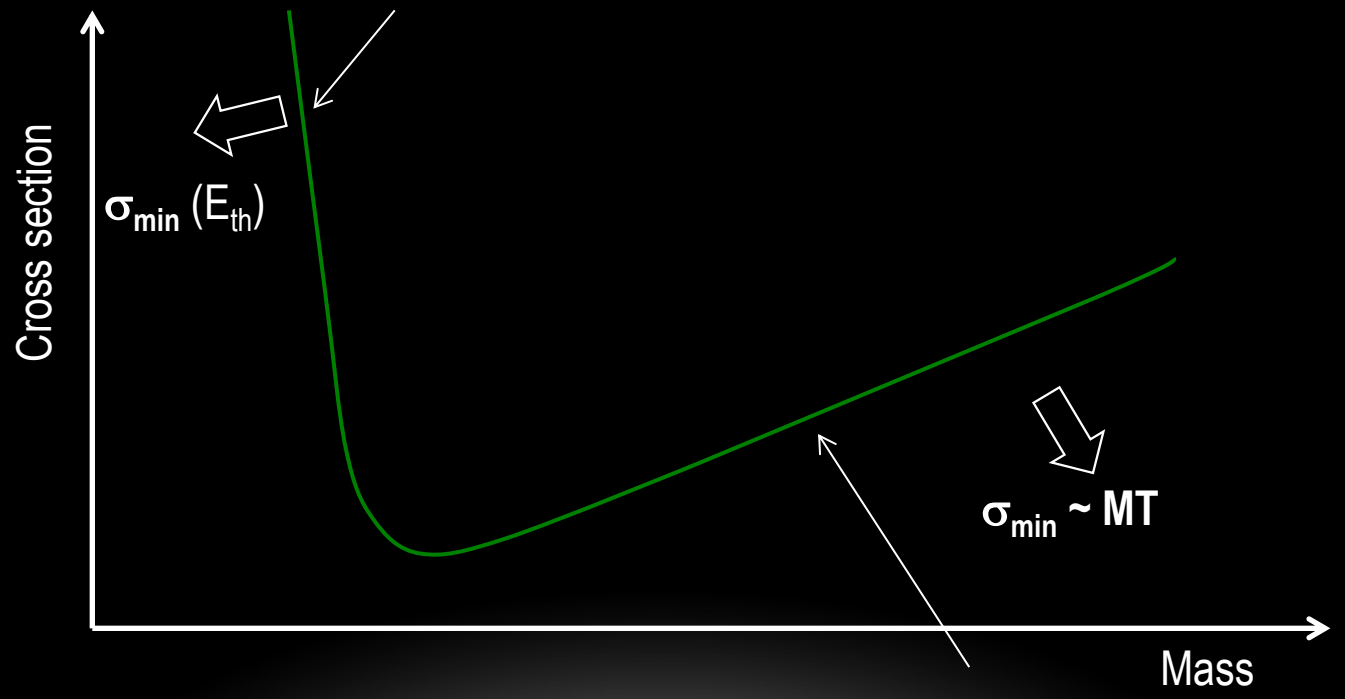
Particle/nuclear physics $m_W, d\sigma/dE_R$

Astrophysics $\rho_0, f(v)$



DARK MATTER – EXPECTED SIGNAL RATE

$$\frac{dR}{dE_r} \sim \frac{m_N}{m_\chi^3}\sigma_{SI}v_0^2 e^{-v_{min}^2/v_0^2} \Longrightarrow \sigma_{SI} \sim \frac{m_\chi^3}{m_N}\frac{dR}{dE_r}e^{E_r m_N/2m_\chi^2 v_0^2}$$



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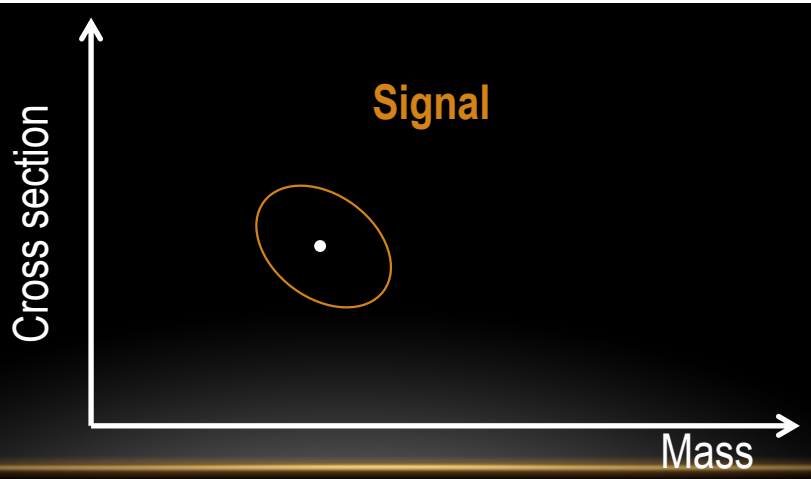
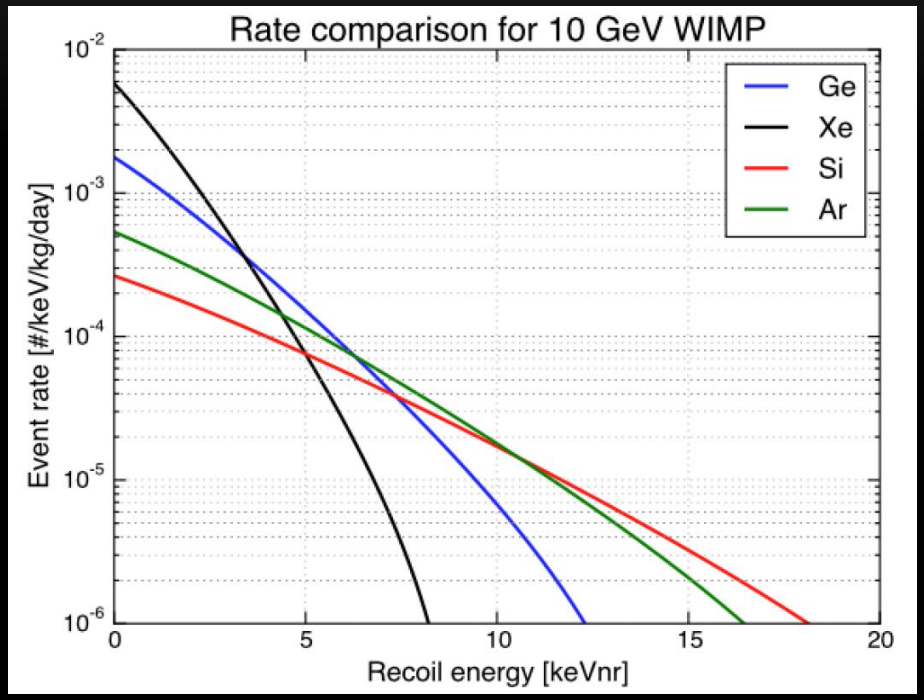


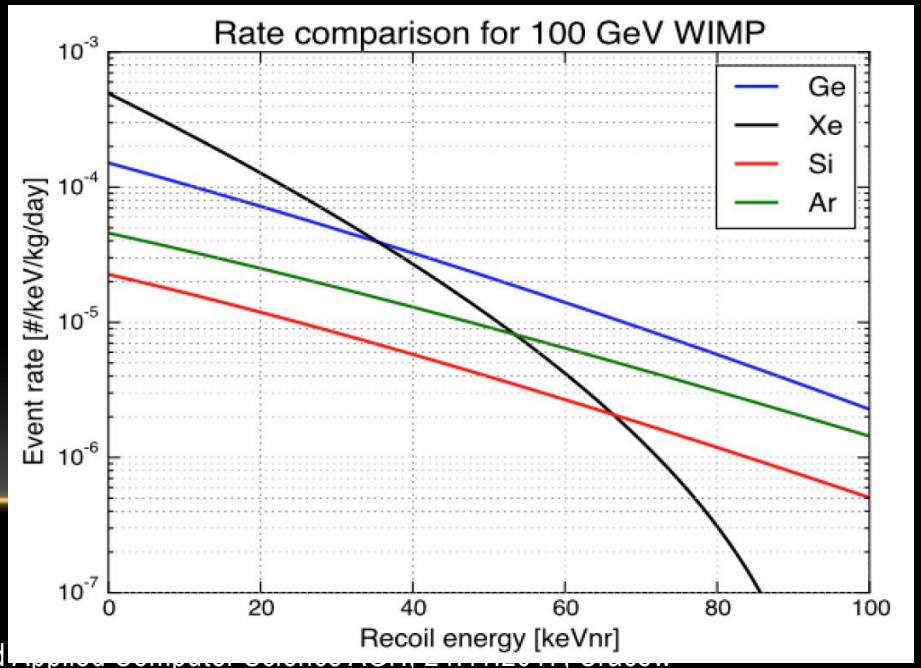
DARK MATTER SIGNAL SIGNATURES

- Rate and shape of the recoil spectrum depends on the target

DARK MATTER SIGNAL SIGNATURES



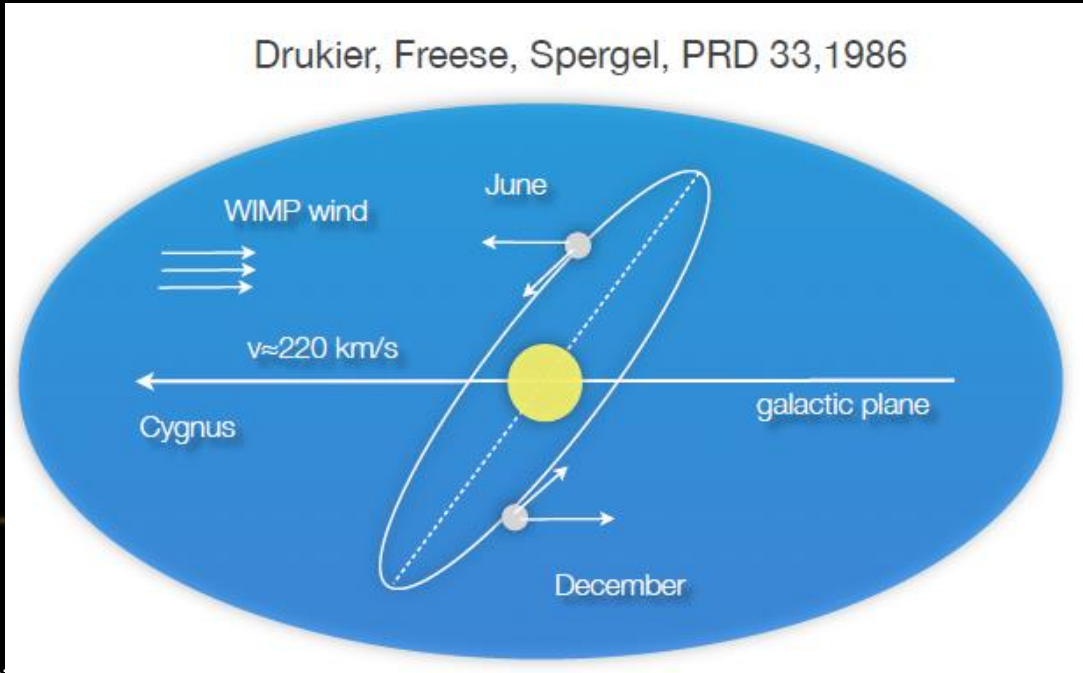
$\sigma_{SI} = 10^{-44}\ cm^2$
$\rho_0 = 0.3\ GeV/c^2/cm^3$
$v_{esc} = 544\ km/s$
$v_0 = 220\ km/s$
$v_e = 232\ km/s$



σ_{SI} – SI cross section
ρ_0 – WIMP density
v_{esc} = MB cut off/escape vel.
v_0 – halo RMS circular speed
v_e – target velocity

DARK MATTER SIGNAL SIGNATURES

- Rate and shape of the recoil spectrum depends on the target
- Annual variations of the signal rate (June-December asymmetry ~3 %)



DARK MATTER SIGNAL SIGNATURES

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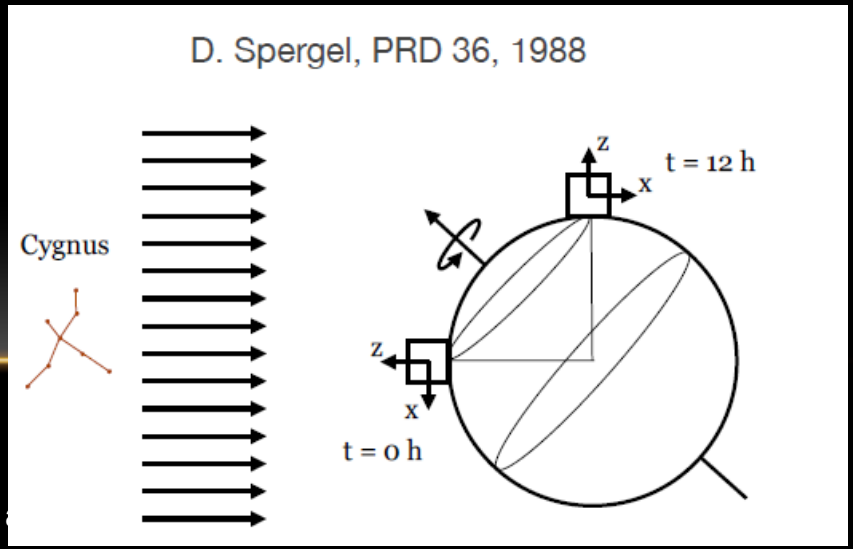
- Annual variations of the signal rate (June-December asymmetry ~3 %)
- Daily modulation of the recoil nuclei direction (directionality needs to be detectable)

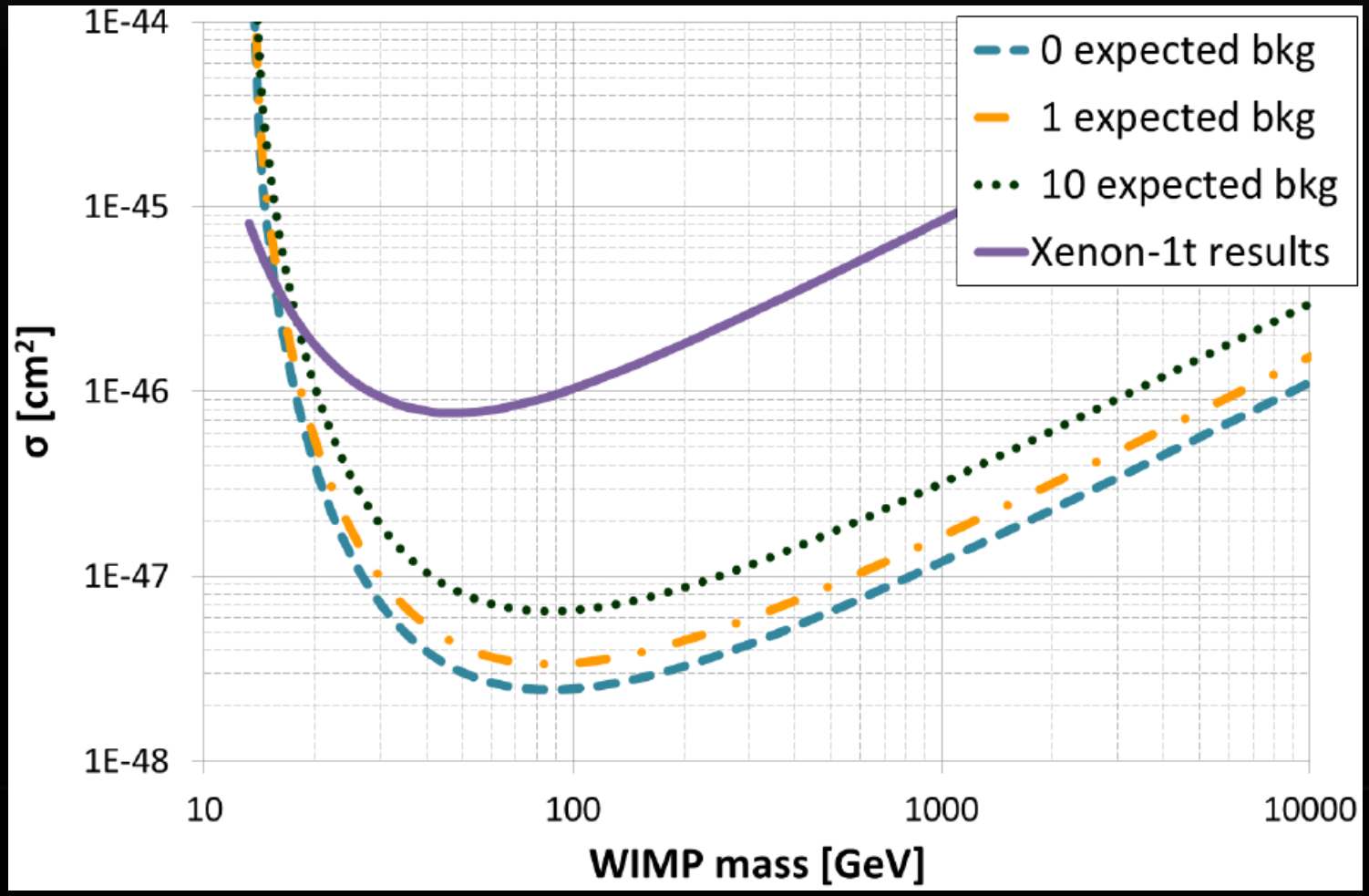


PERFECT EXPERIMENT

- **Background – free** (only DM contributes to the measured signal)
- Low energy threshold (probing interactions of low-mass DM particles)
- Large mass of the active volume to maximize the exposure
- Known detector response
- Easy/cheap scalability

SENSITIVITY CURVE WITH BACKGROUND

Argon: 100 t yr exposure



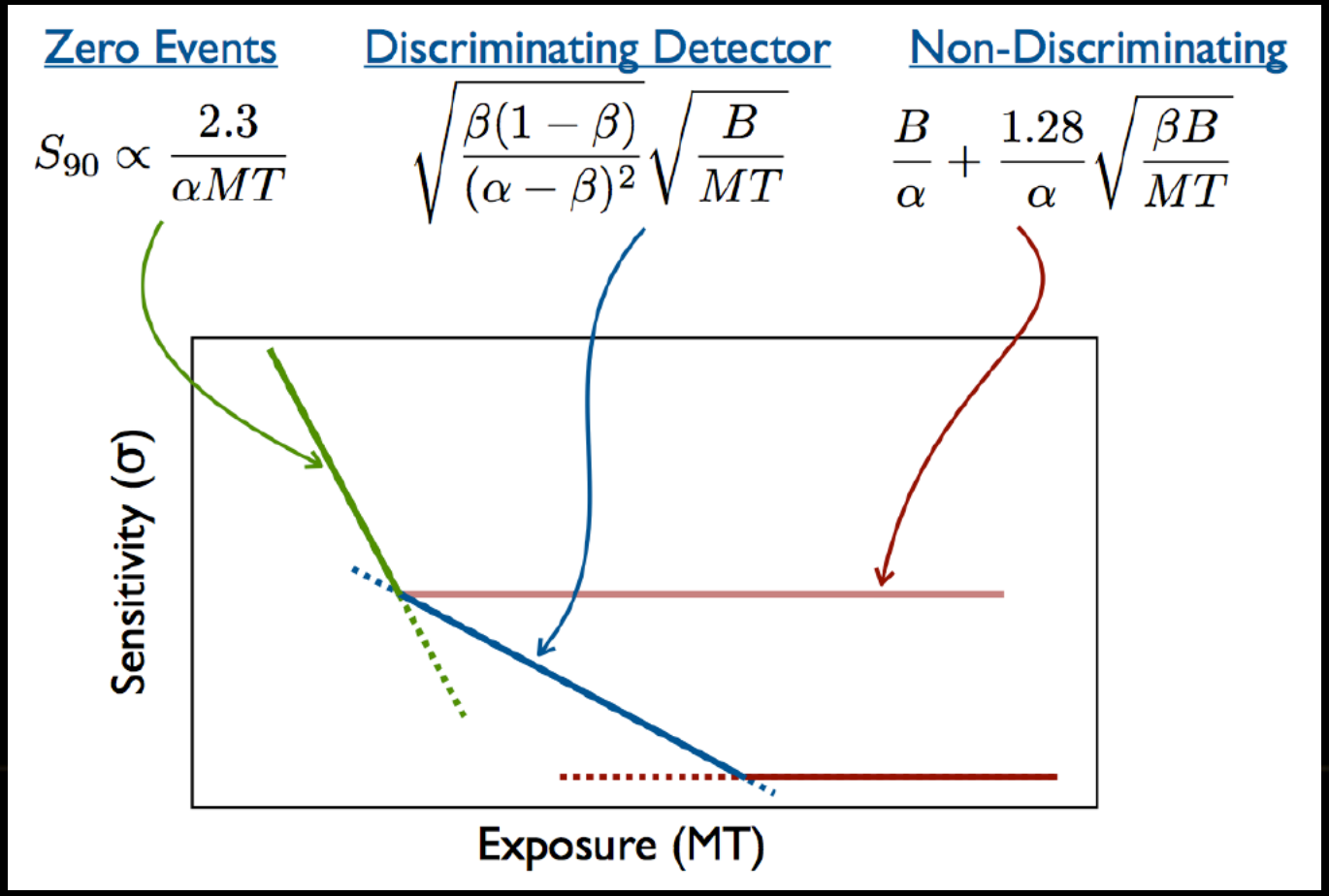
BACKGROUND SOURCES

- Radioactivity of the target material
  - ultra-pure target (real-time purification)
- Radioactivity of the detector installation and shield
  - selection of radio-pure construction materials
- Radioactivity of surroundings
  - effective shielding
- Cosmic rays and secondaries
  - detector location deep underground

BACKGROUND ISSUE

B – background
MT – exposure

β – background miss-identification
α – signal acceptance



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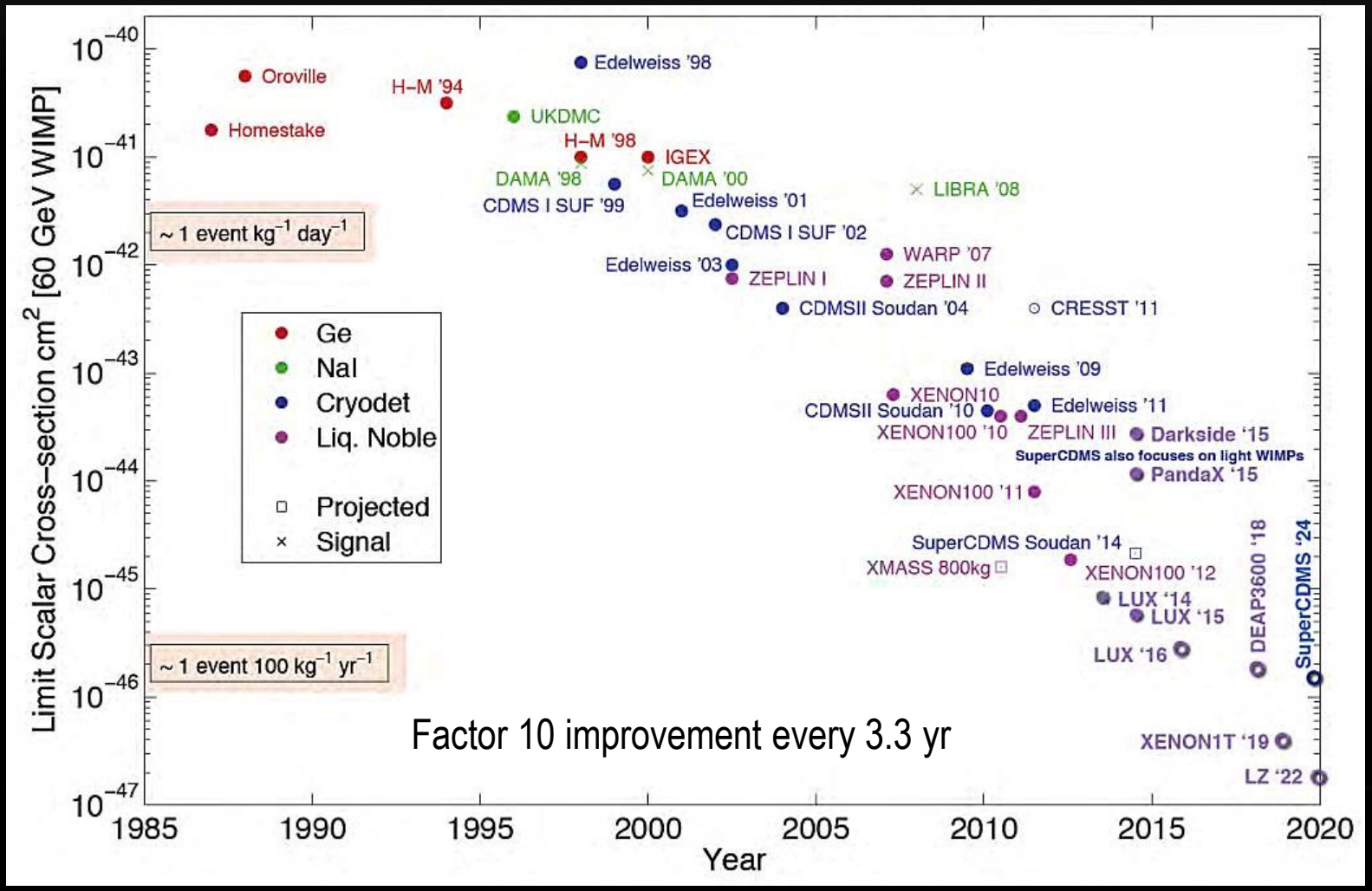

BACKGROUND ISSUE

σ_{SI} = ~10^{-46} cm^2 $\rightarrow$ R ~1 event/100 kg/year

$\downarrow$

S/B ~ 1 (very optimistic)

$\downarrow$

1 decay/100 kg/year ~ **3×10^{-10} Bq/kg**

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Mineral water: ~1 Bq/l

100 kg $\rightarrow$ 100 Bq

$\rightarrow$ 100 events/s

$\rightarrow$ **3×10^{10} events/year**

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100 kg $\rightarrow$ 100 Bq

$\rightarrow$ 100 events/s

$\rightarrow$ **3×10^{10} events/year**

Needed reduction factor: ~10^{10} !

BACKGROUND ISSUE

The most challenging task for DM experiments:

How to achieve and maintain required radio-purity of the detector target more than 10^{10} times below the environmental level (< 0.1 ev. for the assumed exposure)

For future experiments existing screening facilities may not be able to provide useful information for background predictions (required specific activities beyond detection limits).

$^{222}Rn \sim \mu Bq/kg \rightarrow \sim 2$ atoms/m^3 gas (STP)!

THE DARKSIDE PROGRAM

- Multi-stage program for searches of dark matter direct interactions in low-background detectors deployed at the Gran Sasso underground laboratory.
- Based on a two-phase low-radioactivity argon time projection chamber (TPC)
- Ultra-low background design
- Active suppression of residual backgrounds for true **background-free** operation

THE DARKSIDE PROGRAM

Why LAr?

- Relatively dense (1.4 g/cm^3)
- Easy to purify (^{222}Rn/^{85}Kr)
- Scales to large mass
- Exceptional discrimination power (PSD, S1/S2)

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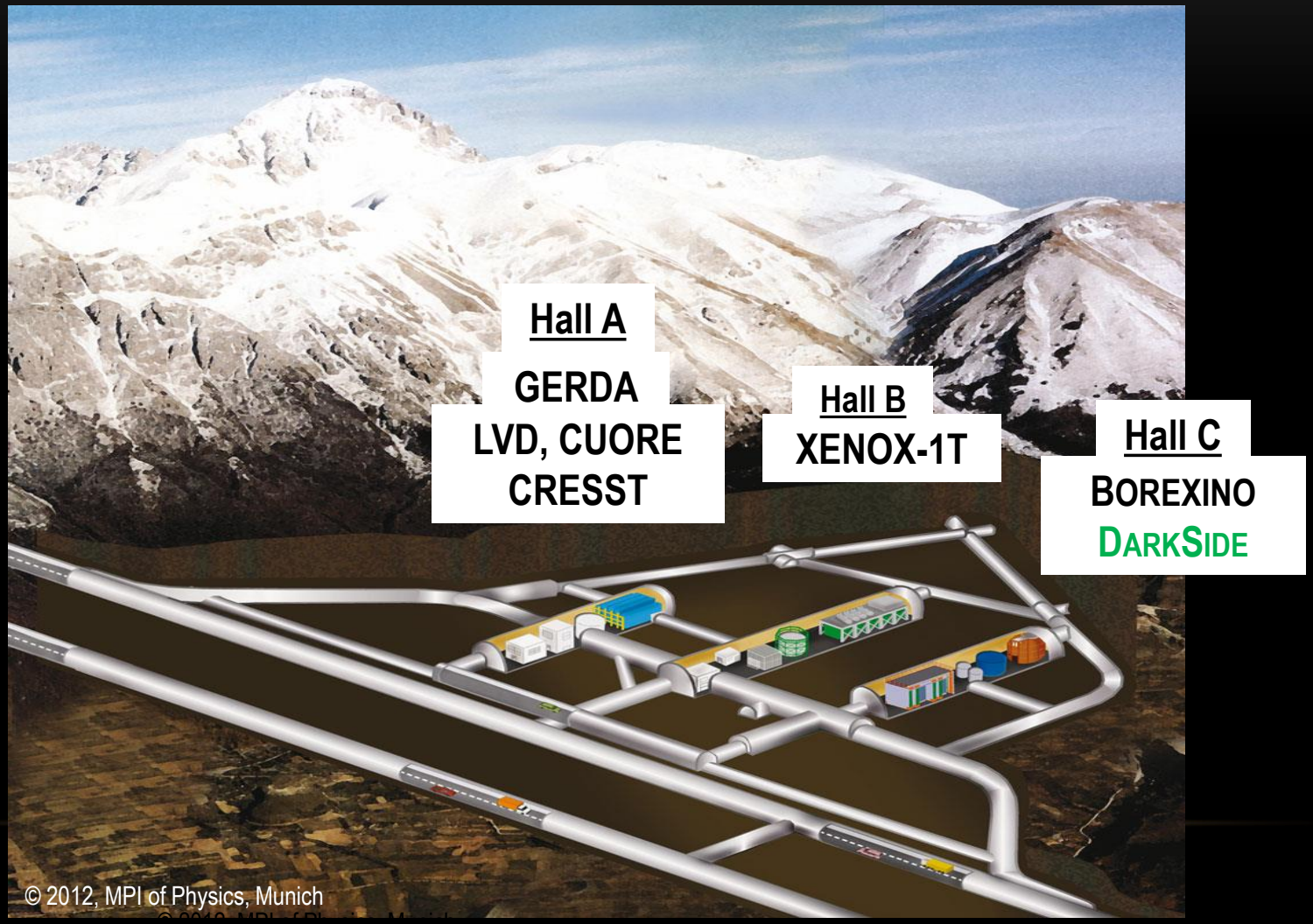
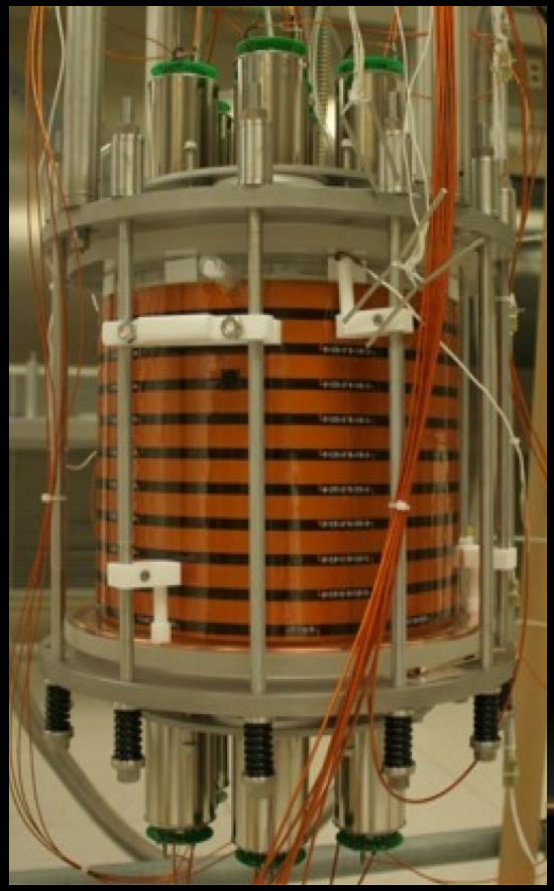
- ^{39}Ar at the level of 1 Bq/kg – dead time problem for a ton scale experiment ⟶ depletion needed

THE DARKSIDE PROGRAM



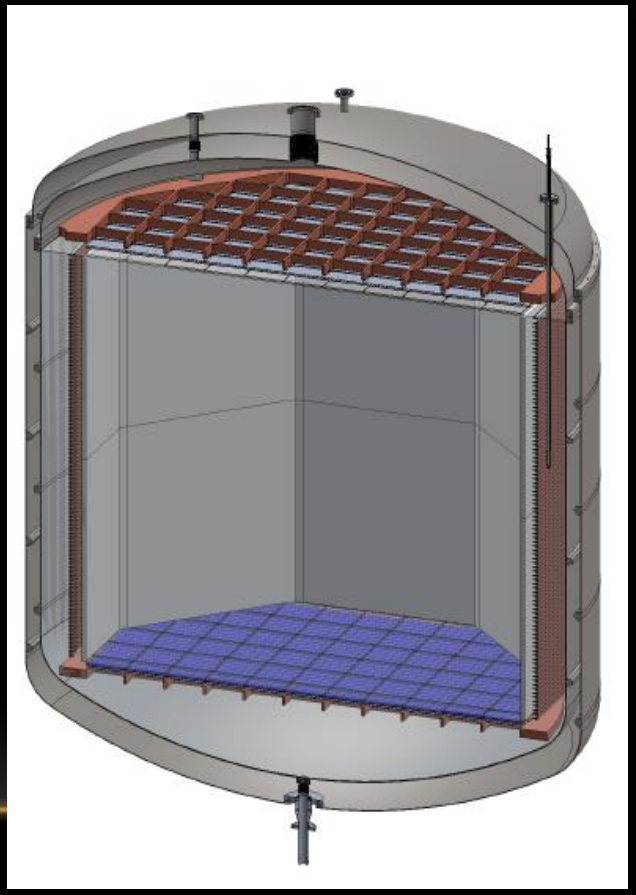
THE DARKSIDE PROGRAM

DS-10 prototype
(2011 - 2013)



DS-50 detector
(Since Oct. 2013)

DS-20k
(2020 –)



DS-50 DETECTOR

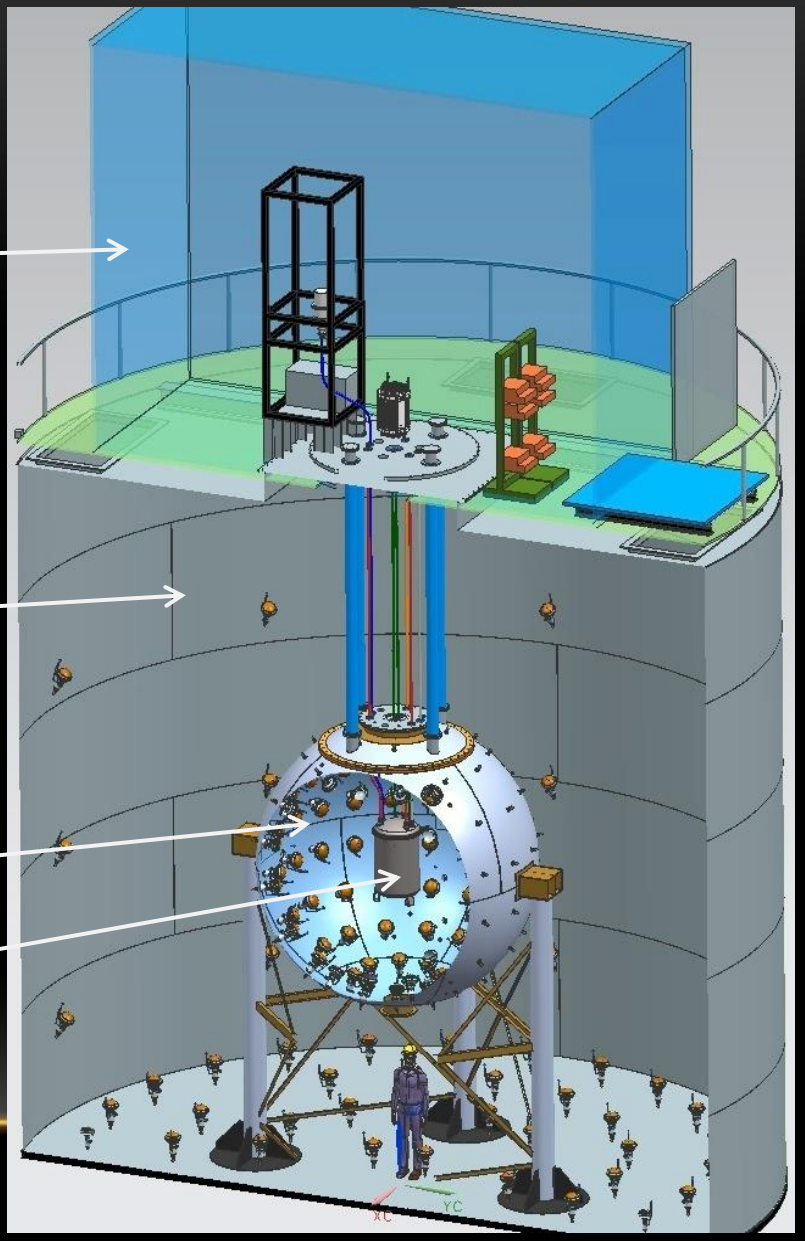
Clean room

Instrumented water tank (1 kton)

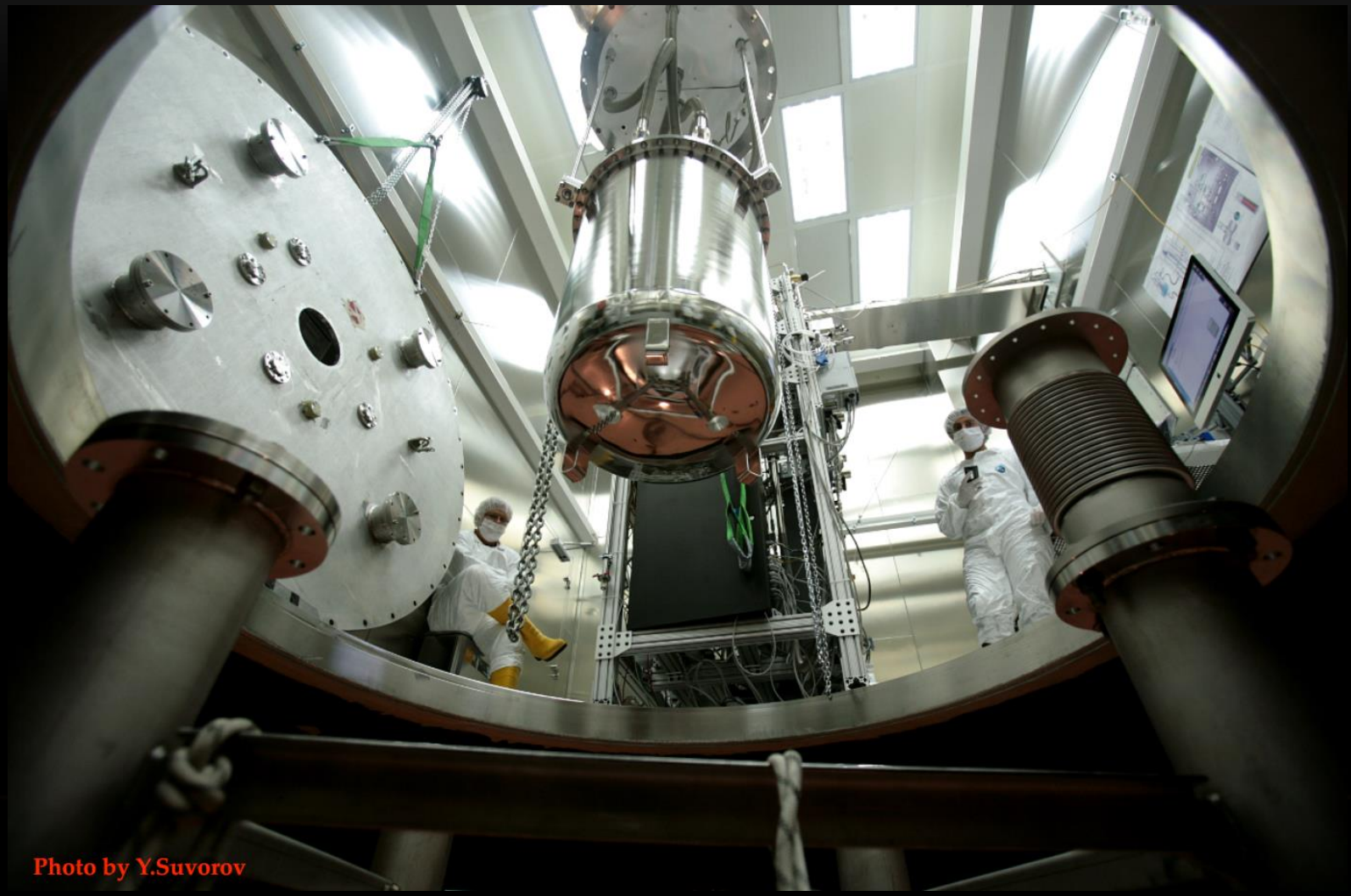
- 80 8” PMTs
- 11 m dia. x 10 m high
- Muon and cosmogenic veto (~ 99.5% efficiency)
- Passive γ/n shielding

Liquid scintillator detector

Inner detector: TPC



DS-50 DETECTOR



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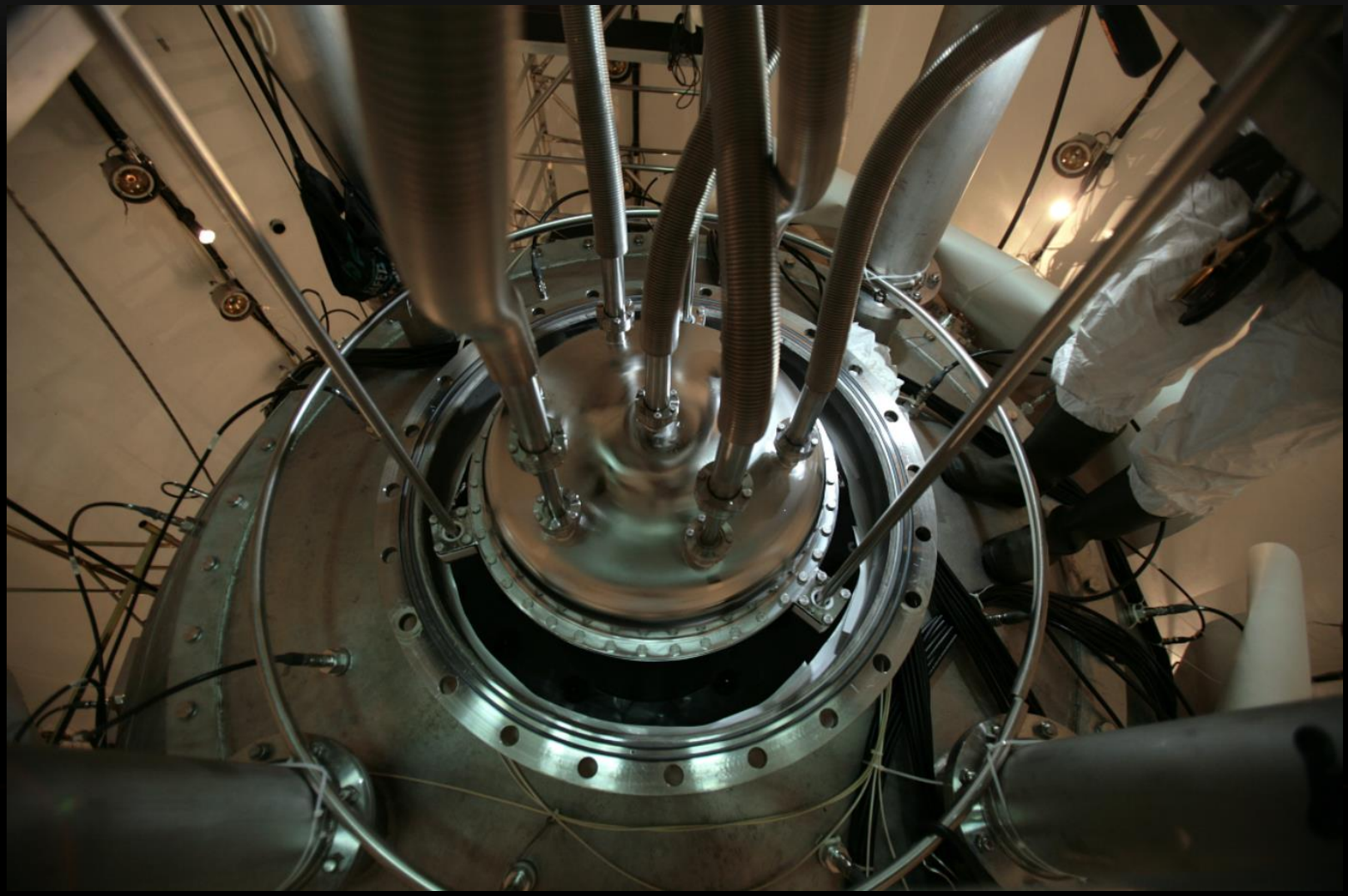


DS-50 DETECTOR

DS-50 TPC

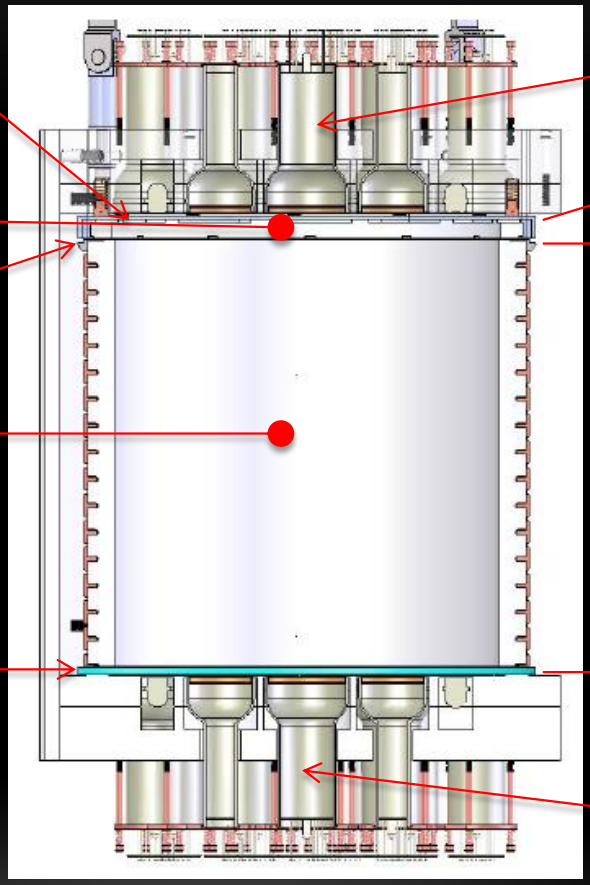
Anode (15 nm film ITO on silica fused window)

Gaseous Argon

Extraction grid

Liquid Argon

Cathode



PMTs (19 x 3” R11065)

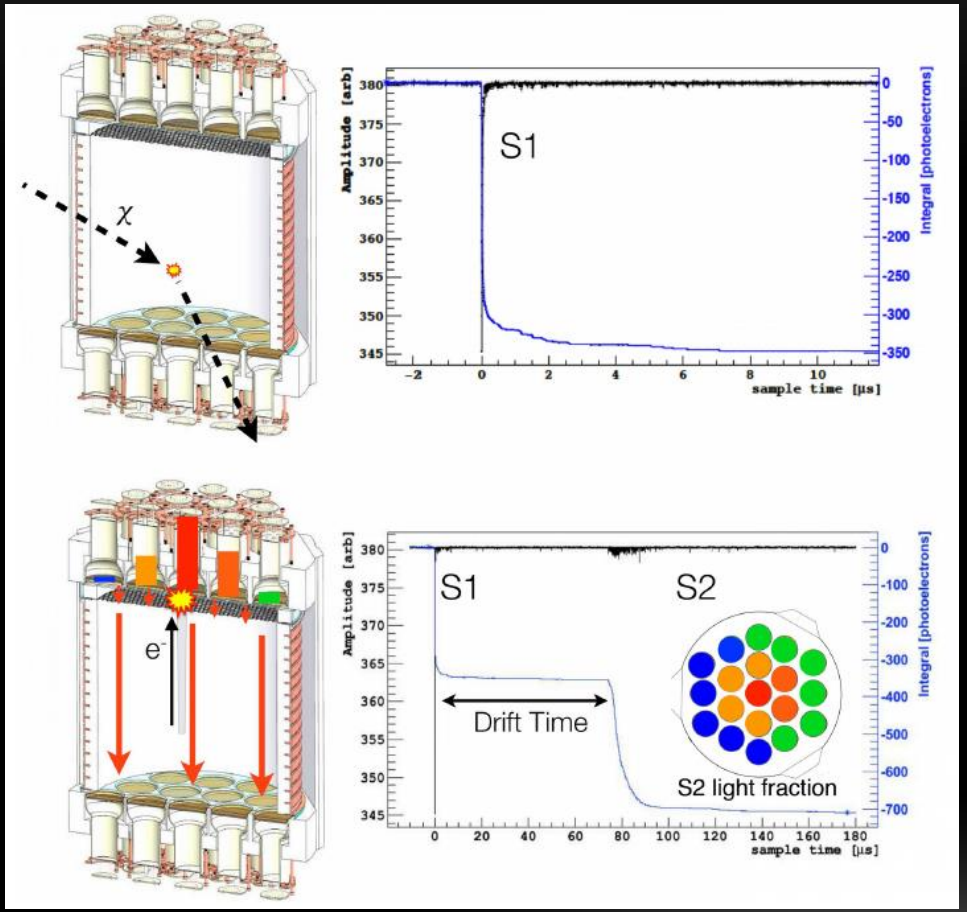
$\vec{E}_{extr.}$ (2.8 kV/cm)

$\vec{E}_{drift}$ (200 V/cm)

PMTs (19 x 3” R11065)

TPC: 36 cm φ × 36 cm high

DS-50 TPC

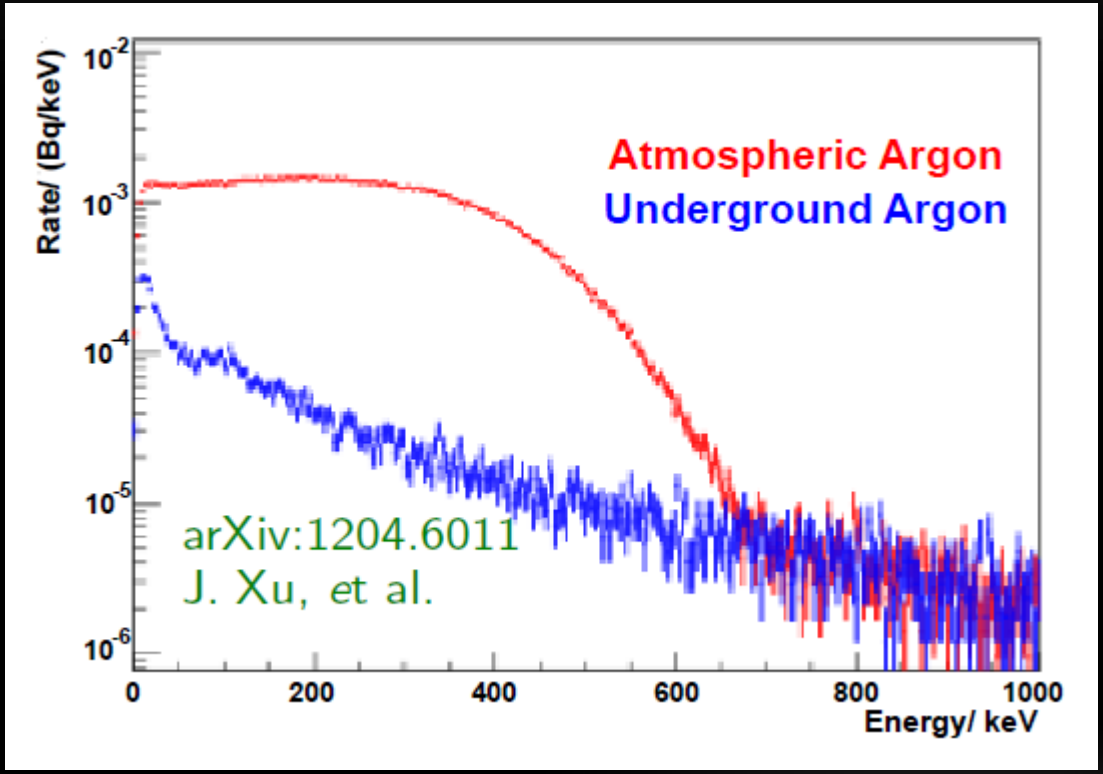


- Nuclear recoil produces primary scintillation light: S1
- Electrons that survive recombination are drifted towards the liquid-gas interface by the electric field
- The electrons are extracted into the gas region, where they induce electroluminescence: S2
- Time difference between S1 and S2 gives Z position, PMT hit pattern gives X-Y position
- Tools for backgrounds rejection:
  - PSD based on S1
  - S2/S1 ratio
  - Position reconstruction

UNIQUE FEATURES OF DARKSIDE

- Argon depleted in ^{39}Ar: underground argon (UAr)
- Liquid scintillator veto for neutrons
- Pulse shape discrimination for background rejection
- ^{222}Rn-free clean rooms

UNDERGROUND ARGON (UAr)



- ^{39}Ar radioactivity in atmospheric Ar (~1 Bq/kg) limits its usability as a WIMP target
- ^{39}Ar is of cosmogenic origin
- Source of underground argon (CO_2 well near Cortez, Colorado) measured to have > 150 times lower rate of ^{39}Ar (< 7 mBq/kg), compared to atmospheric argon
- Large-scale production possible (multi-ton Ar detectors)

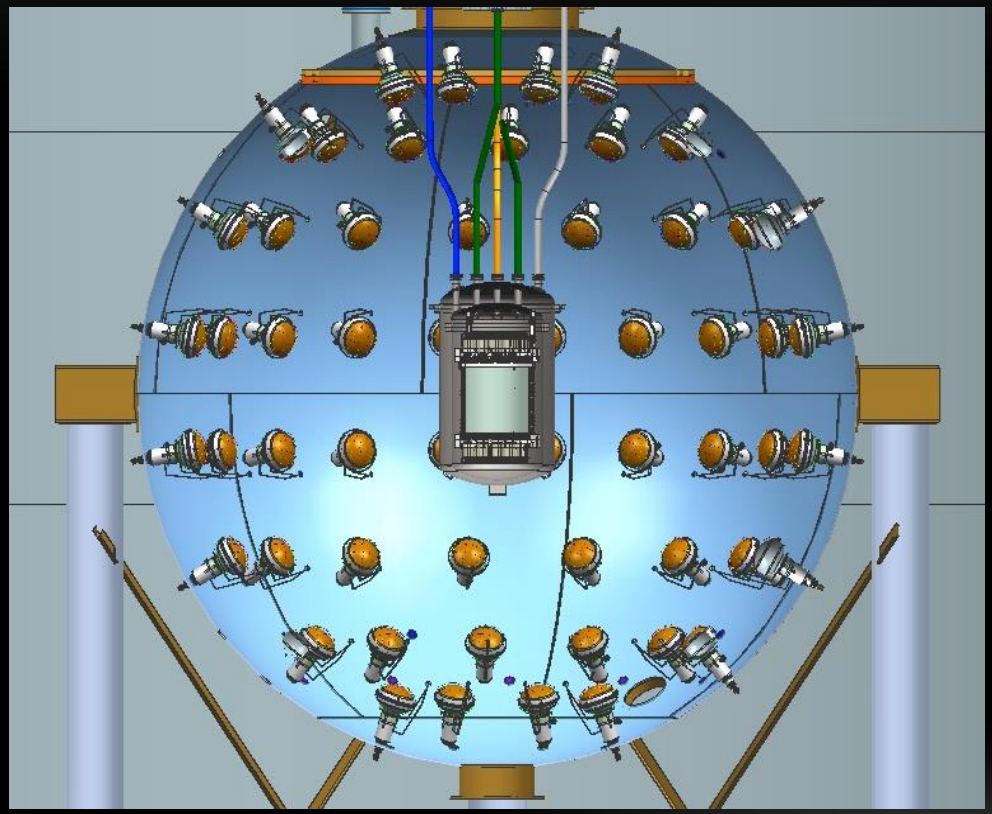
UNDERGROUND ARGON (UAr)

Extraction of UAr at Colorado.
Crude argon gas mixture (Ar, N_2 and He)

Distillation at Fermilab
Separate Ar from N_2 / He

UAr bottles (156 kg) at LNGS
Final purification with getters

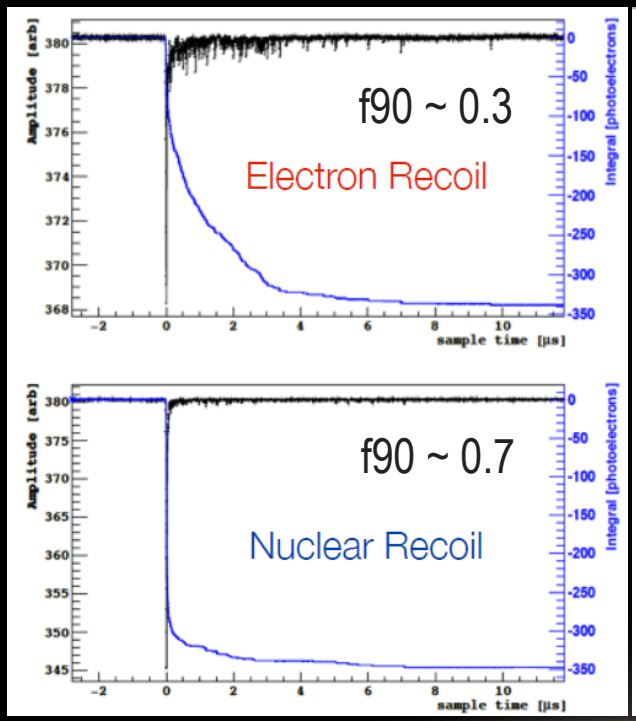
LIQUID SCINTILLATOR VETO

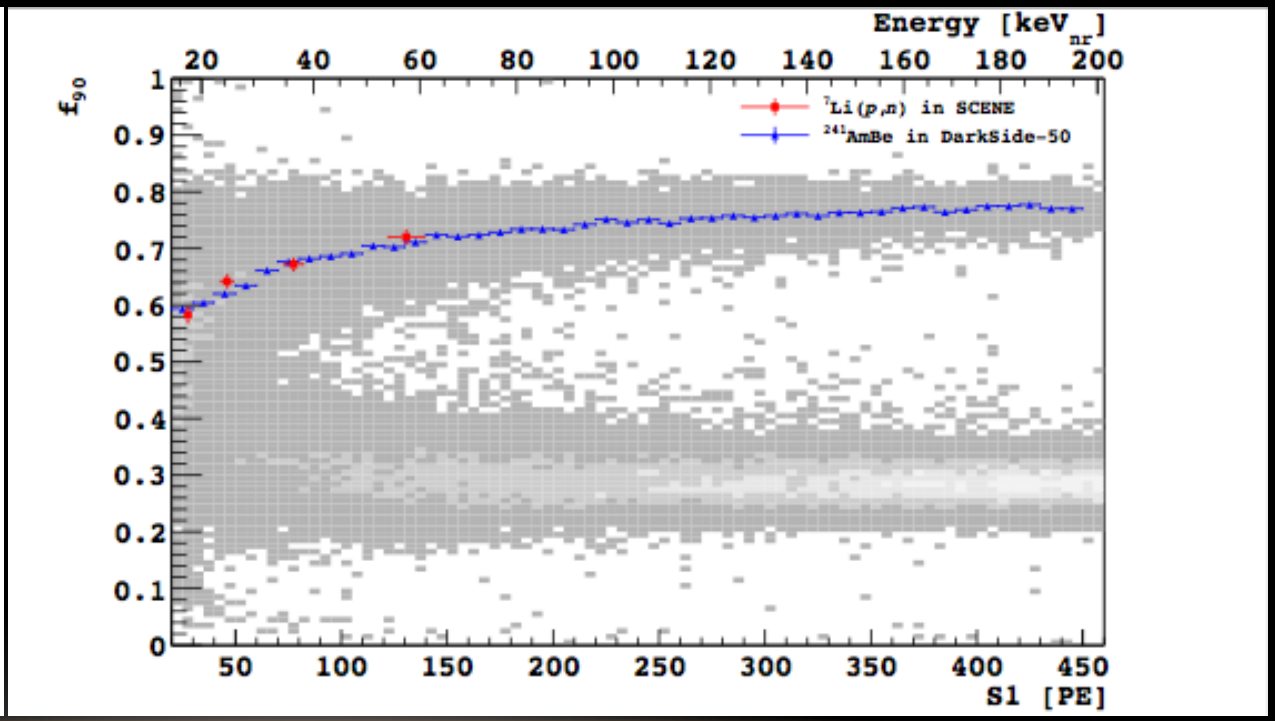


- 4 m diameter sphere containing PC + 5% trimethyl borate (TMB) scintillator (30 ton)
- Instrumented with 110 8” PMTs
- Veto of neutrons coincident in the TPC and provides in situ measurement of the neutron background rate
- Neutron capture results in 1.47 MeV α, capture time 23 μs
- Veto efficiency: >99.1% for neutrons detected via delayed capture on ^{10}B and ^{1}H (radiogenic) and >95% for cosmogenic neutrons

PULSE SHAPE DISCRIMINATION

Electron and nuclear recoils produce different excitation densities in the argon, leading to different **ratios of singlet and triplet excitation states → f90:** Ratio of detected light in the first 90 ns, compared to the total signal (~ single states fraction)





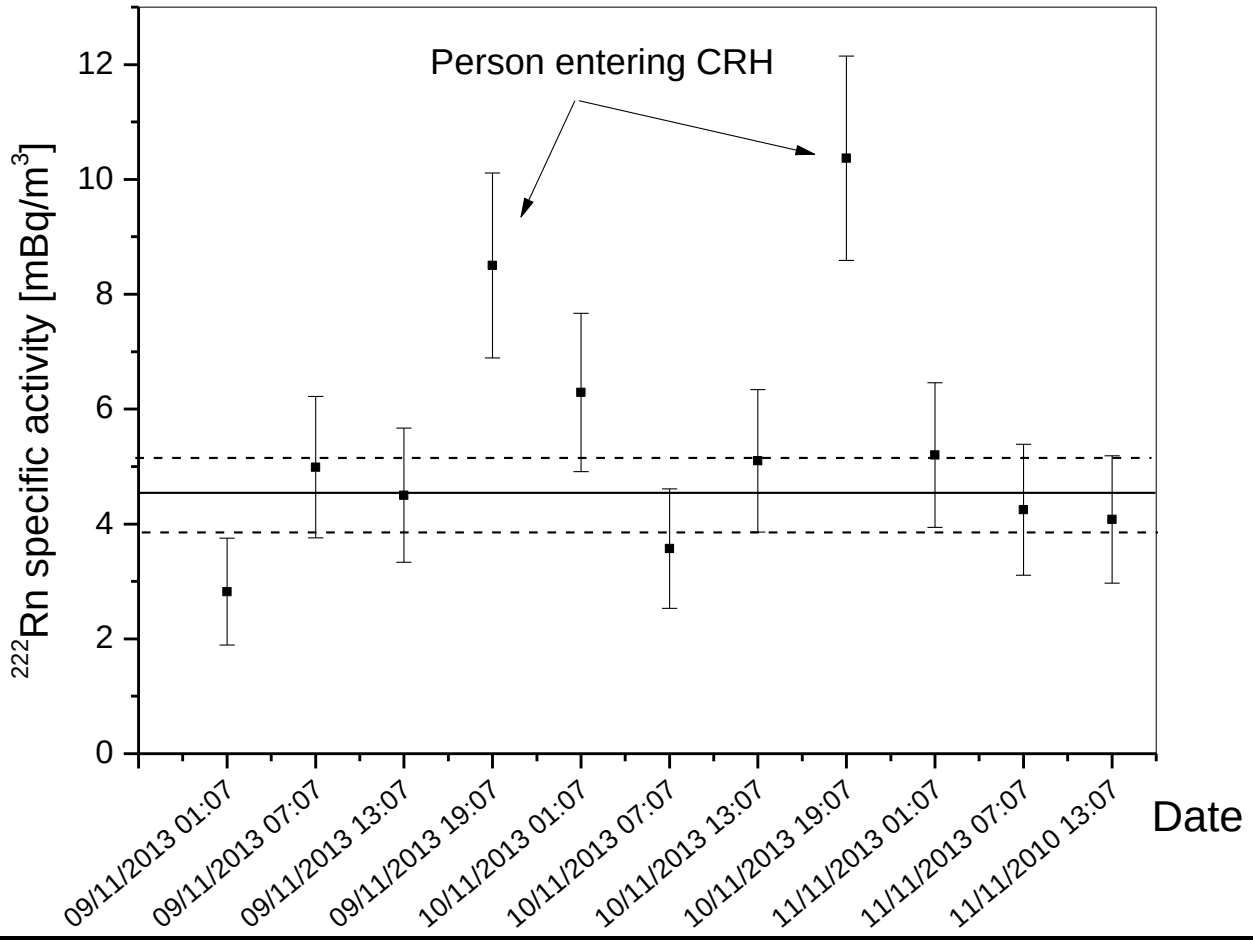
^{222}Rn-FREE CLEAN ROOMS

- Class 10 - 100
- Radon daughters plating out on surfaces of the detector may cause dangerous alpha-induced nuclear recoils
- Dedicated scrubbing system reducing ^{222}Rn concentration in the air down to ~1 mBq/m^3 has been implemented
- DARKSIDE clean rooms are supplied with the ^{222}Rn-free air
- ^{222}Rn content in the clean rooms is monitored online by a dedicated detector

Typical radon in hall C air ~ 30 Bq/m^3

Cleanroom radon levels 5 – 50 mBq/m^3

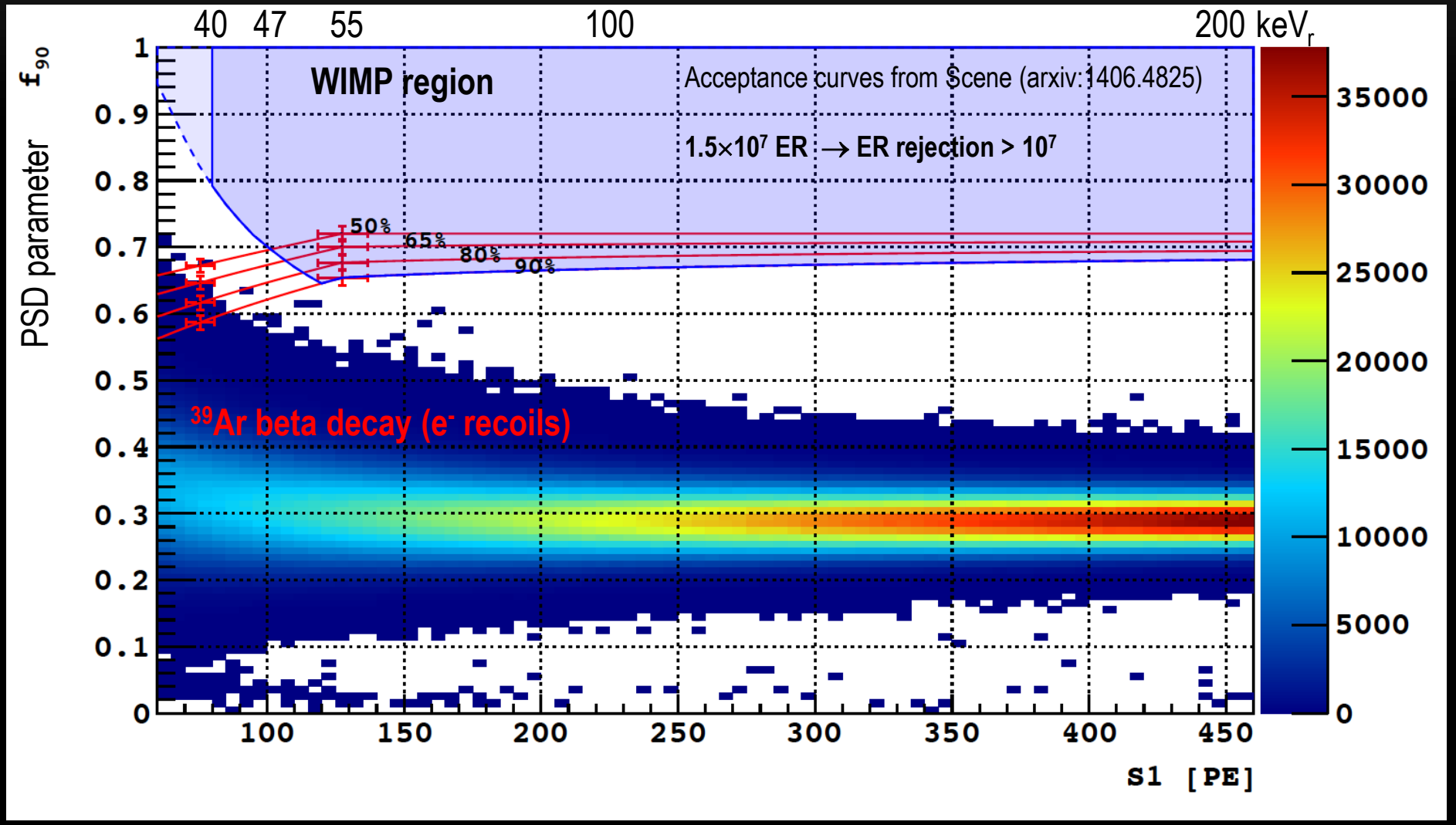
^{222}Rn-FREE CLEAN ROOMS



DS-50 RESULTS (AAr)

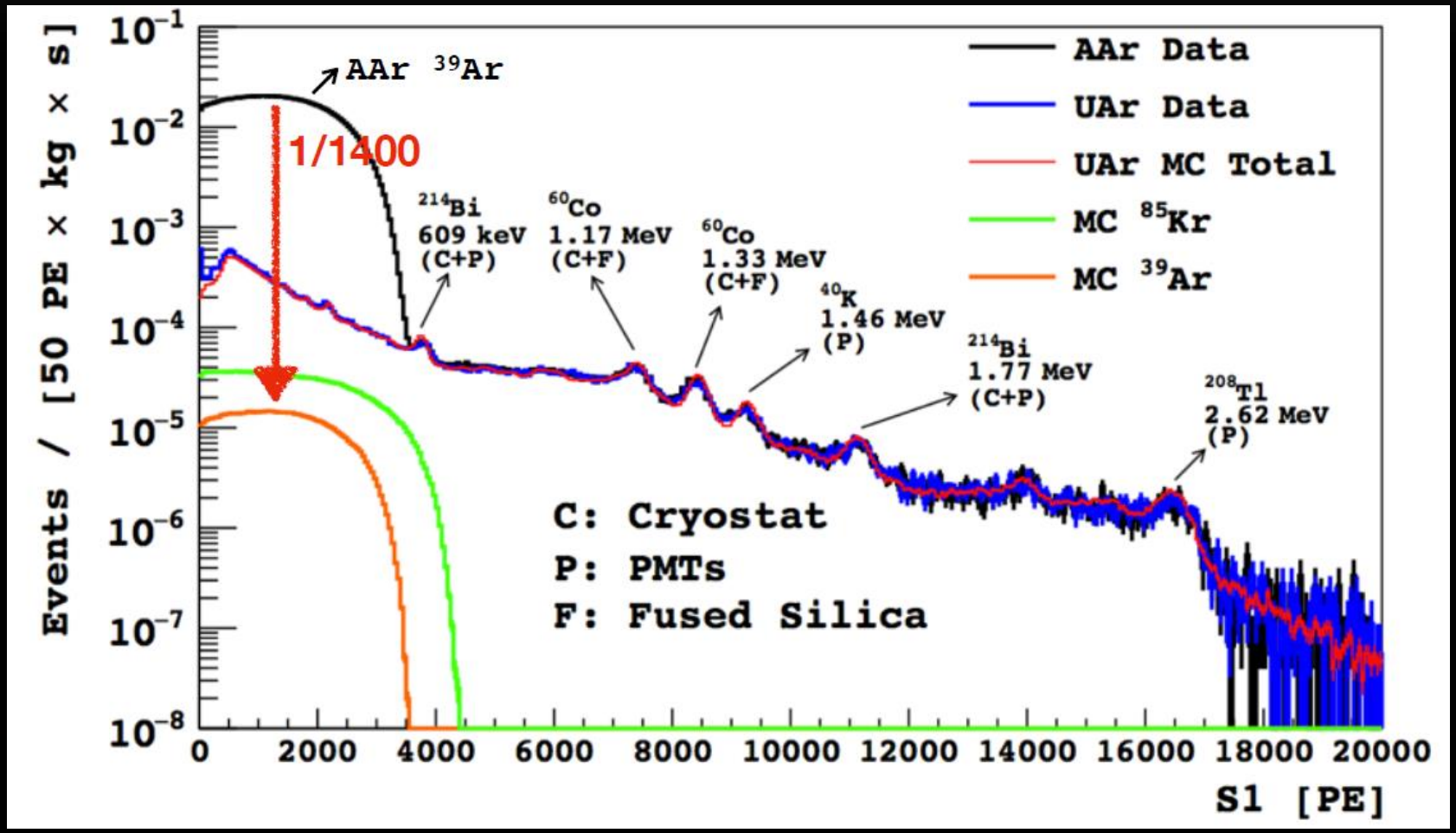
47.1 live-days after all cuts, (1422±67) kg day exposure.

Physics Letters. B, 2015 vol. 743, p. 456-466



DS-50 RESULTS (UAr)

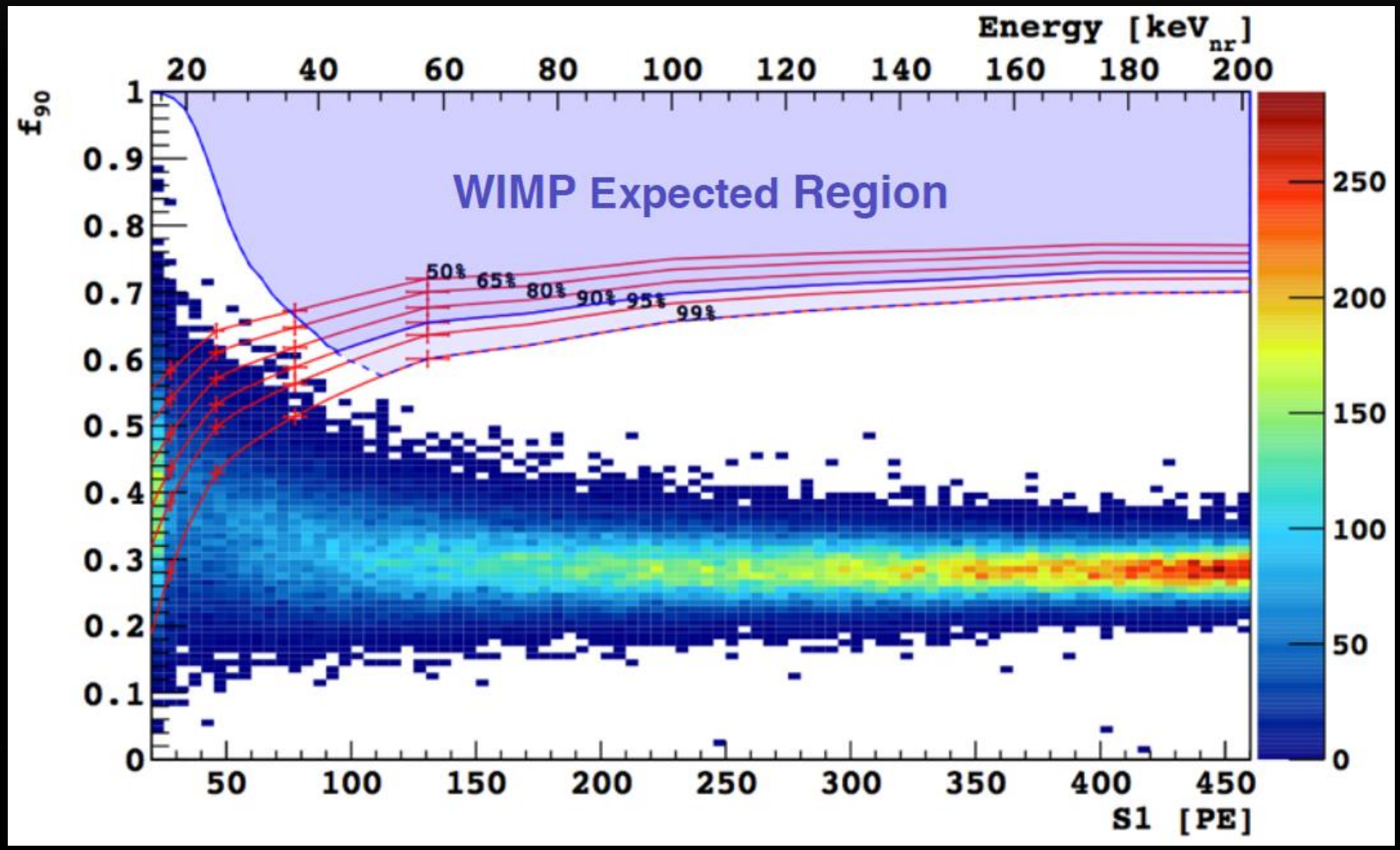
AAr vs UAr: ^{39}Ar depletion factor ~ 1400 ($C_{Ar\text{-}39}$ = 0.7 mBq/kg), $C_{Kr\text{-}85}$ = 2.1 mBq/kg
Low level of ^{39}Ar allows extension of DARKSIDE program to a ton-scale detector



DS-50 RESULTS (UAr)

Phys. Rev. D 93 (2016) 081101

70.9 live-days after all cuts, (2616±43) kg day exposure.
Single-hit interactions in the TPC → **No background events in the WIMP region**



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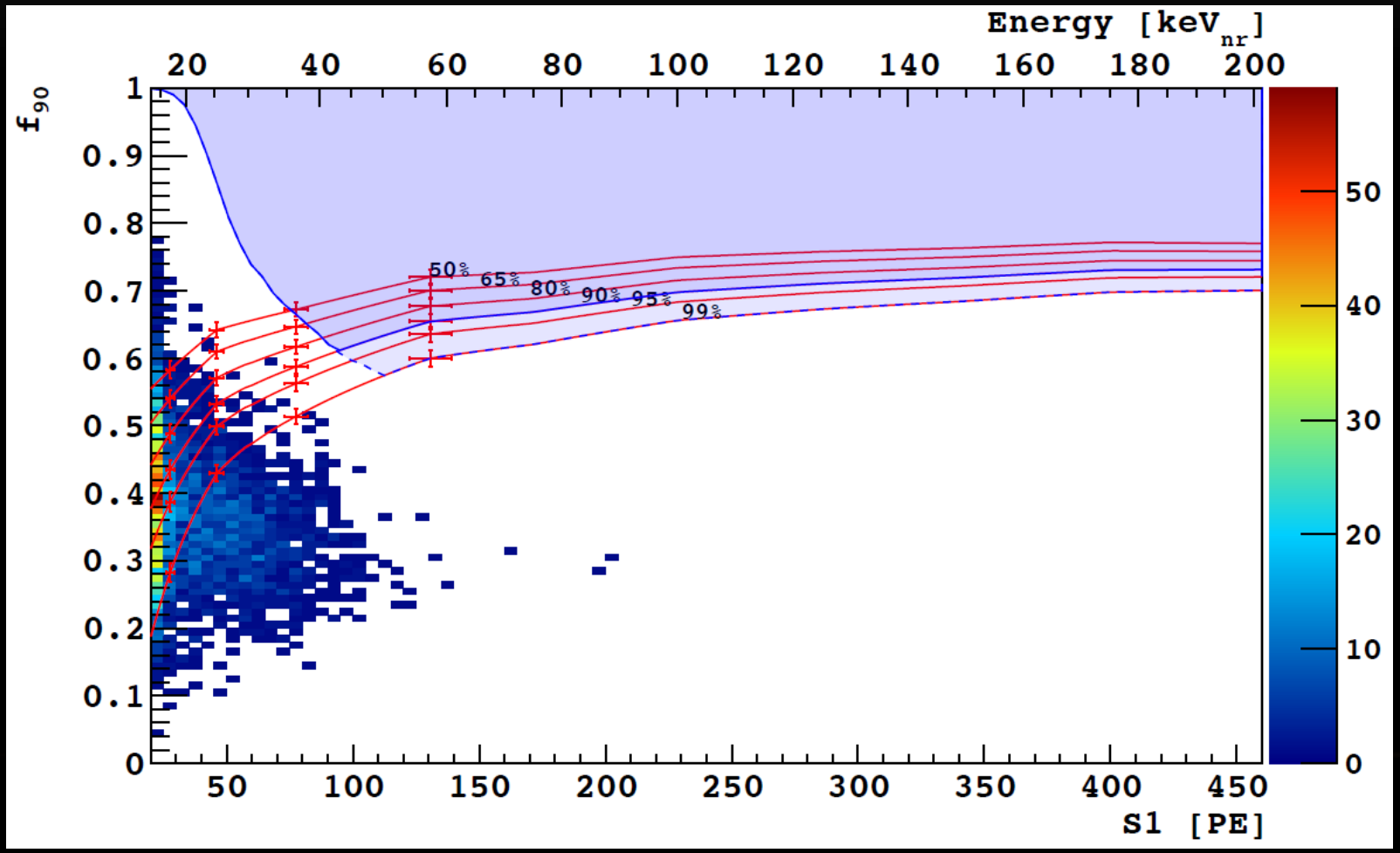
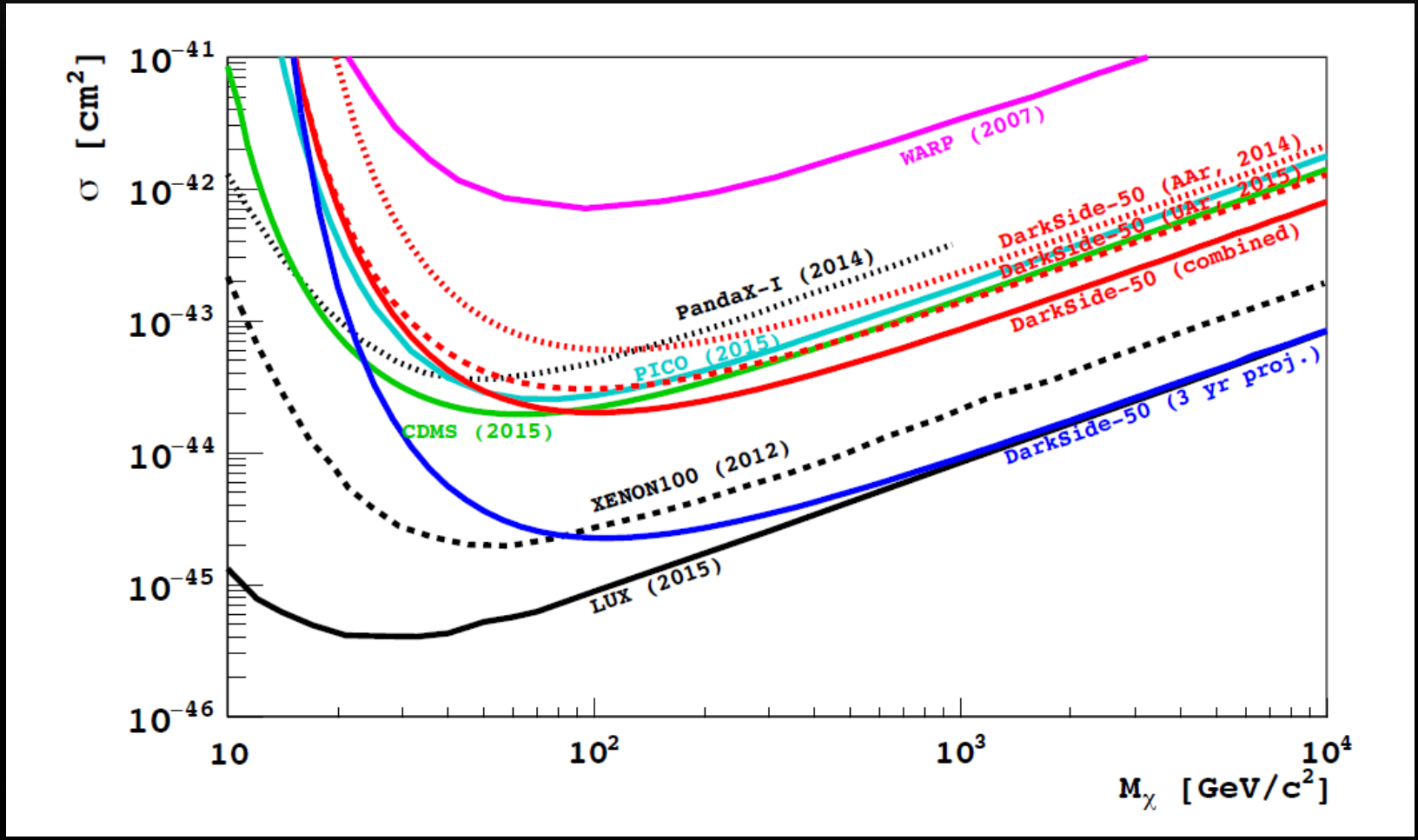
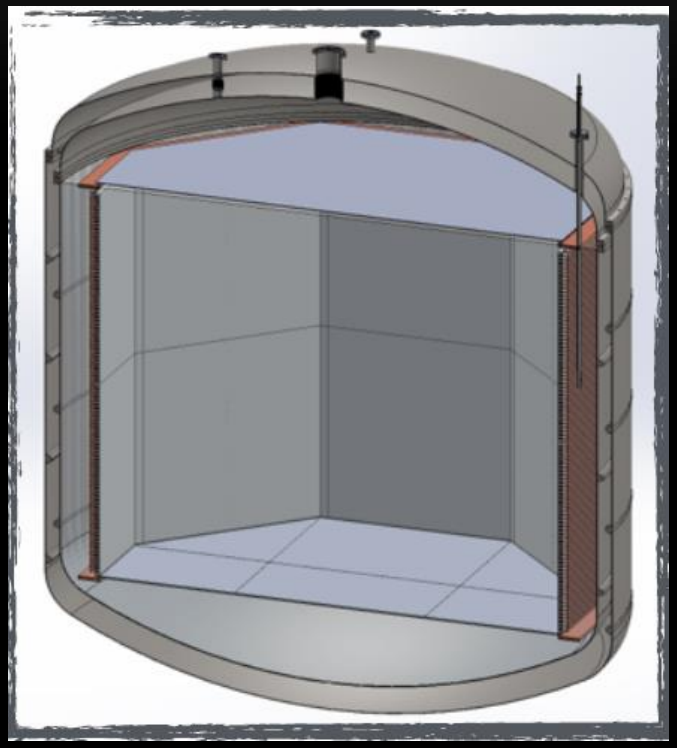


DS-50 RESULTS (UAr)

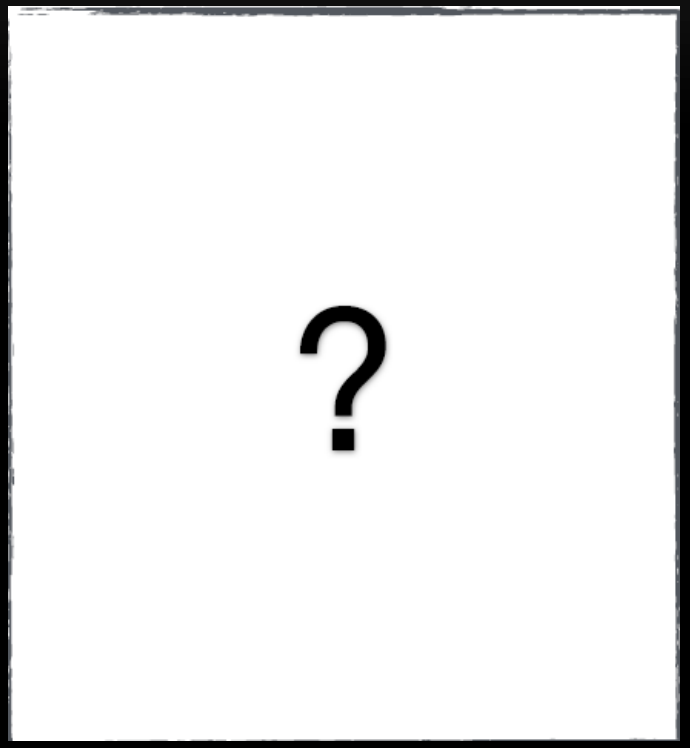
Combined result: $\sigma_{min} = 2\times10^{-44}$ cm^2 for 100 GeV/c^2



FUTURE DETECTORS



DS-20k
30 t (20 t fiducial) of UAr



ARGO
300 t (200 t fiducial) of UAr

FUTURE DETECTORS – NEW COLLABORATION

- DarkSide
- DEAP
- ArDM
- MiniCLEAN

→ DarkSide-20k → multi 100 t experiment

Global Argon Collaboration

Deep underground laboratory support for global collaboration towards discovery of dark matter utilising liquid argon detectors.

To whom it may concern;

As hosts of the existing operational liquid argon direct dark matter detectors, and as proponents and supporters of the Underground-GRI initiative, the LNGS, SNOLAB and LSC deep underground research facilities are pleased to recognize the collaborative developments within the global liquid argon dark matter community. The DarkSide project at LNGS, the DEAP project at SNOLAB and the ArDM project at LSC are all developing new technologies and capabilities to search for WIMP dark matter, and are beginning to coalesce into one collaboration to develop future, larger generations of liquid argon direct dark matter detectors. We encourage and

Letter of Intent

September 8, 2017

Rev B

Scientists at LNGS, LSC, and SNOLAB are joining in an international effort to mount a phased argon dark matter program with the goal of being sensitive to the neutrino floor. This effort will include a broad collaboration of scientists and will represent the global community for dark matter searches with argon. This letter is an update of a previous communication dating June 2017, which detailed the first conception of the program; this letter was expanded to capture the intent of all institutions and scientists participating in the program.

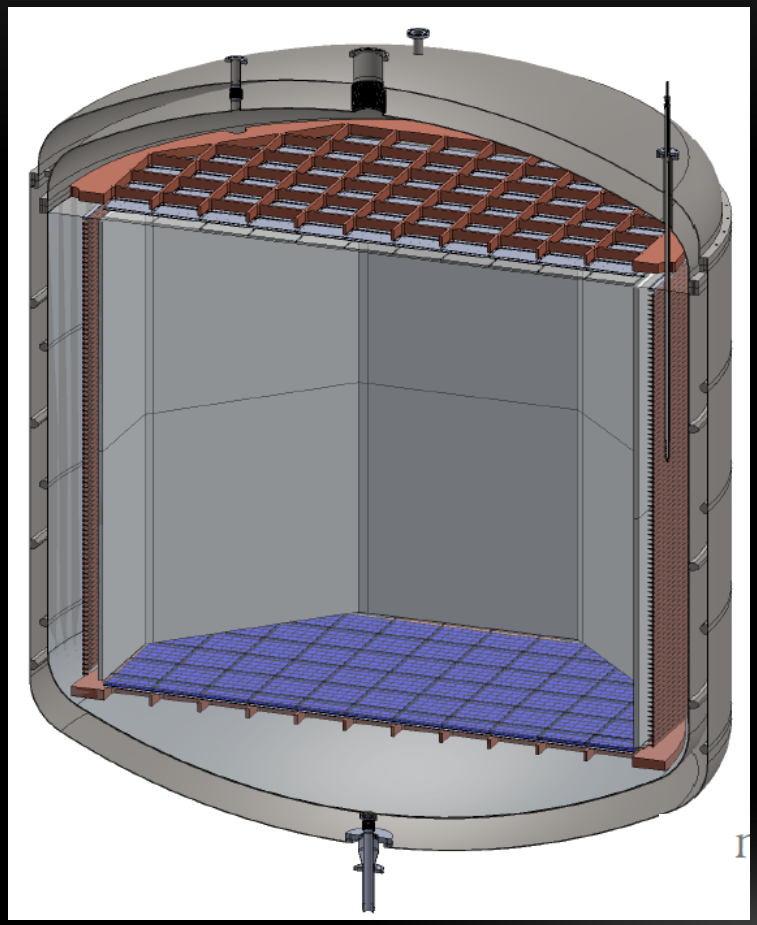
In this document, the undersigned representatives of groups working on argon dark matter searches, including Brazilian, Canadian, Chinese, French, German, Greek, Italian, Mexican, Polish, Romanian, Russian, Spanish, Swiss, US, and UK groups among others, memorialize their intent to form a Global Argon Dark Matter Collaboration to carry out a program for direct dark matter searches, consisting of two main elements.

AMBITIOUS DISCOVERY PROGRAM

- Complementary to LHC
- Raising the bar: from 1 t yr $\longrightarrow$ 1000 t yr
- “Zero Background” necessary for a discovery program
- Two crucial technologies

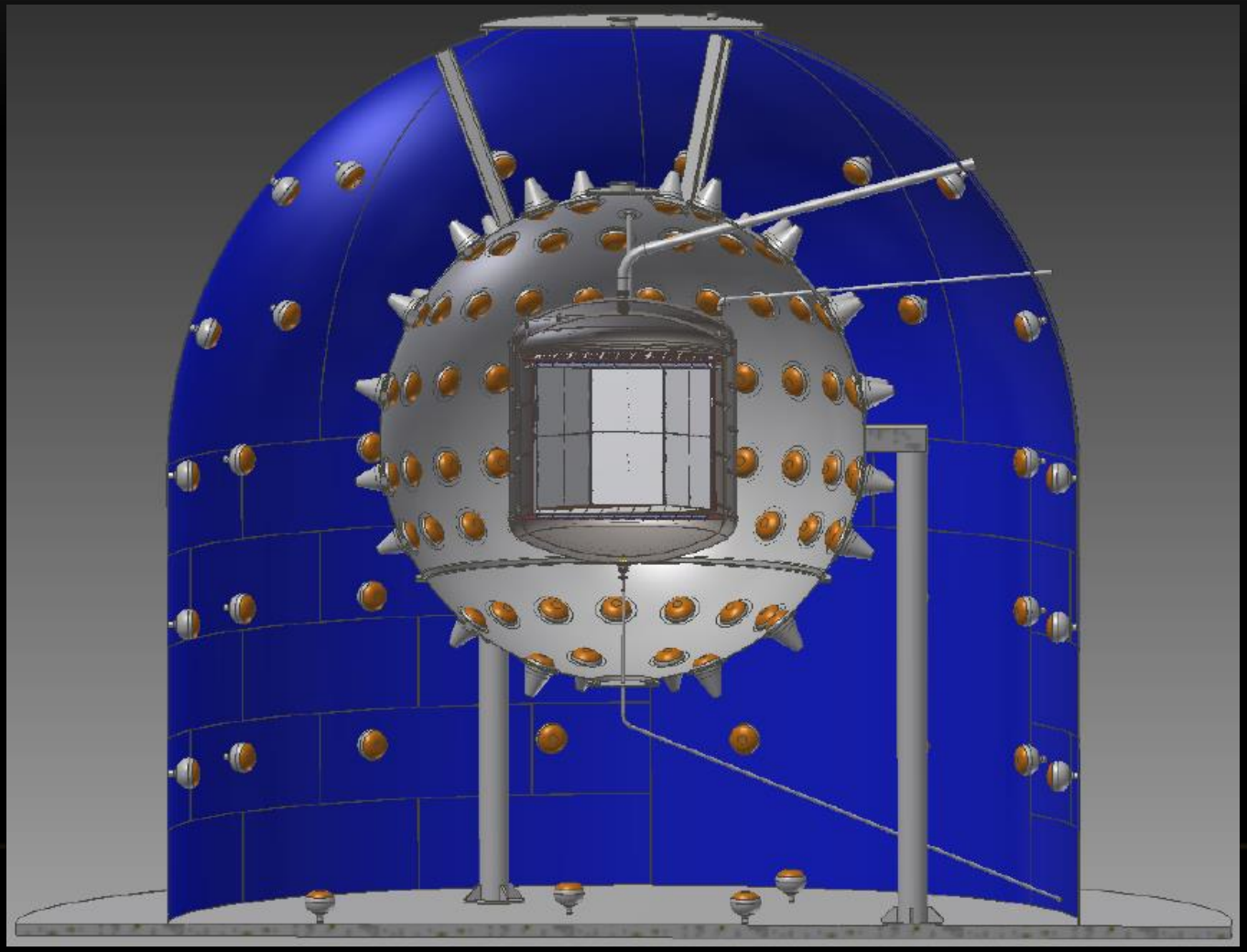
  - Liquid argon target depleted in the radioactive ^{39}Ar
  - SiPMs replacing cryogenic PMTs

DS-20k

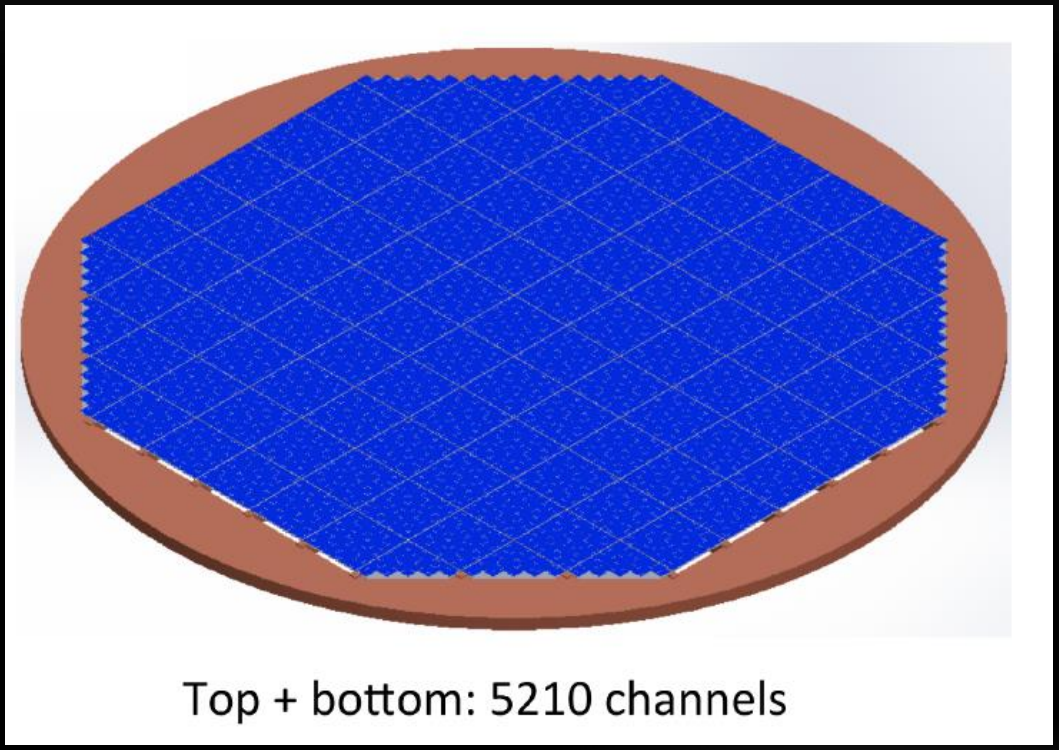


- Octagonal TPC filled with UAr/DAr
- 20 t Fiducial Volume (MT = 100 t yr)
- Radio-pure construction materials (ULR Ti/Stainless Steel)
- 15 m^2 of SiPMs (5210 modules 5×5 cm, lower radioactivity compared to PMTs, custom development by FBK, production in Abruzzo)
- DS-50-like veto design
- Time-line: 2020 – 202x

DS-20k DETECTOR

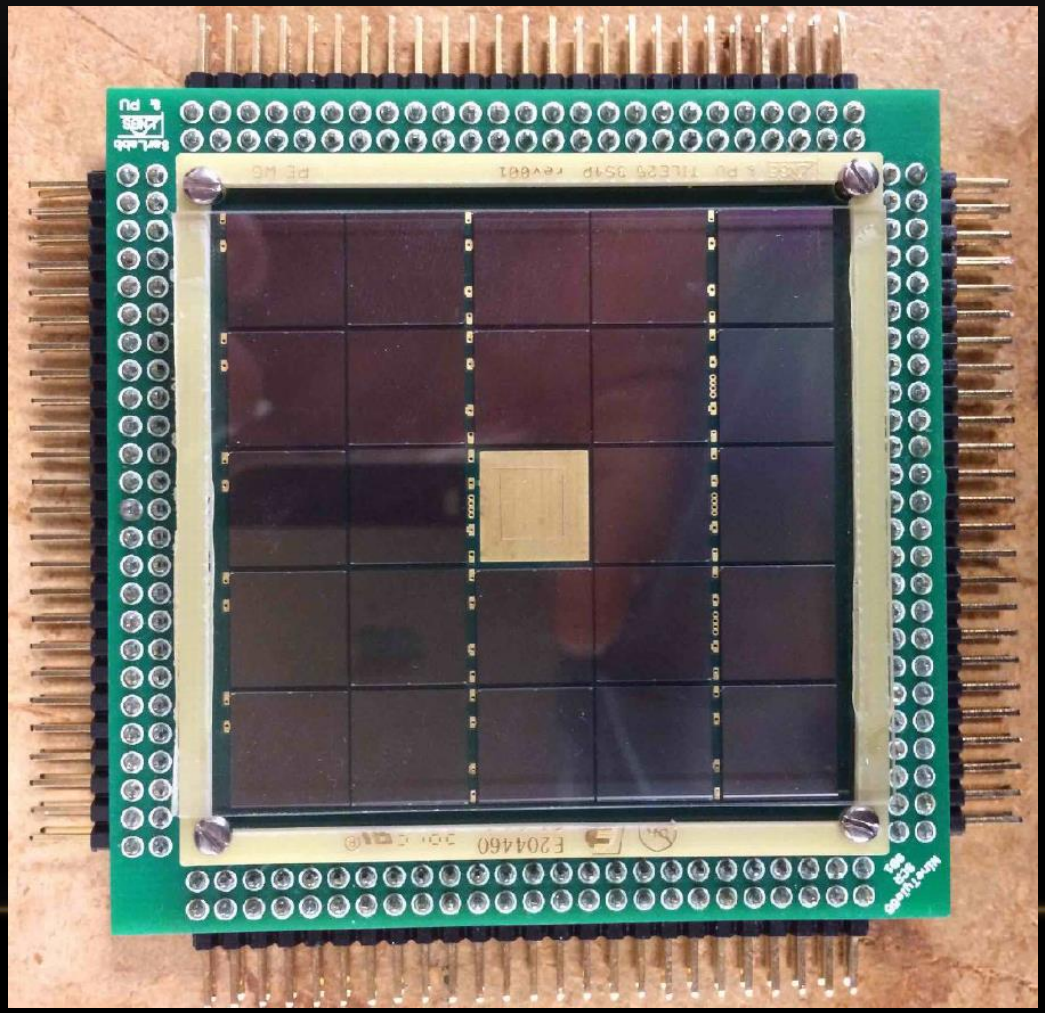


DS-20k SiPM

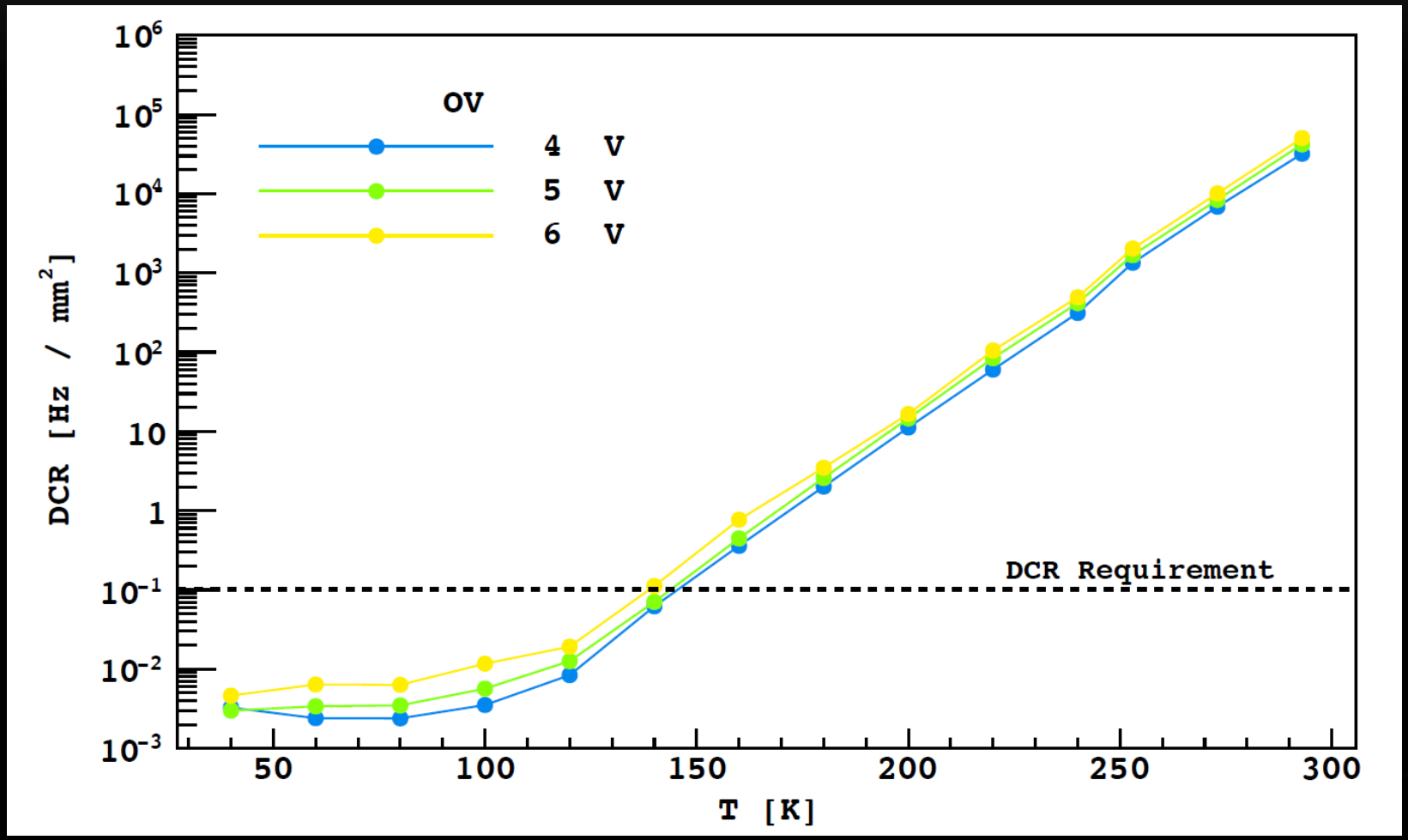


- Effective QE ~ 40%
- Geiger-mode gain >10^6
- Fast, sub-nanosecond timing
- No HV
- Large area arrays > 90% coverage commercially available
- Very compact, very low radioactivity

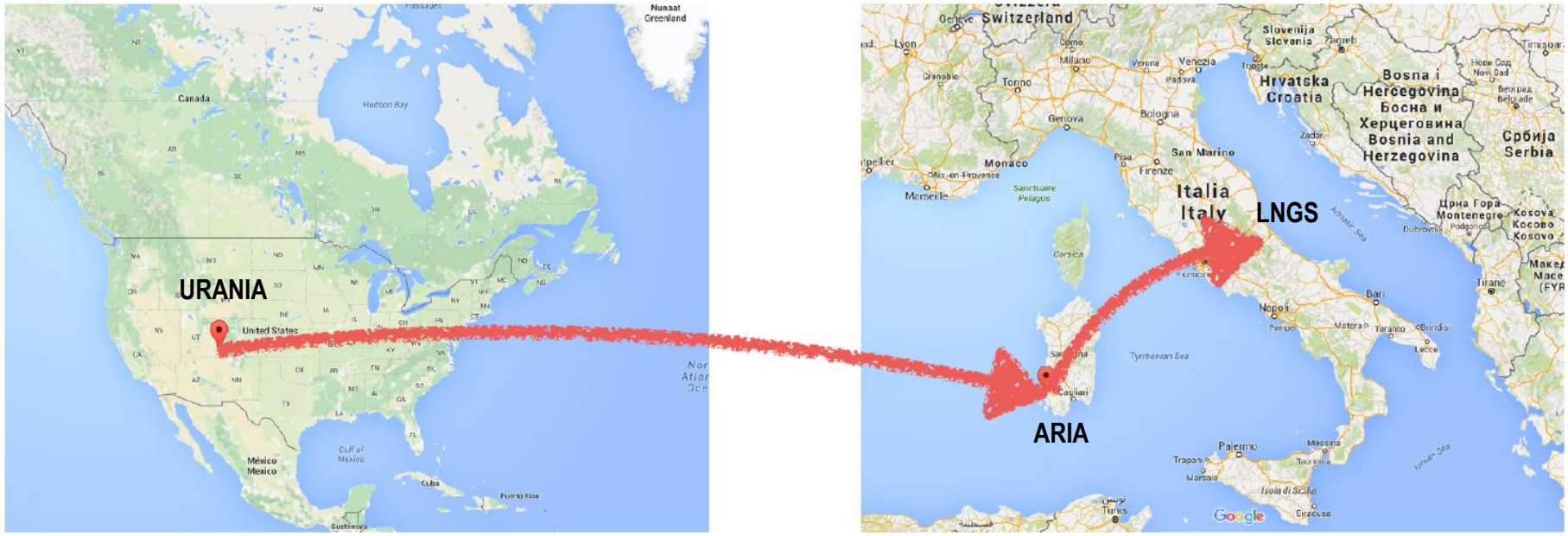
DS-20k SiPM



DS-20k SiPM

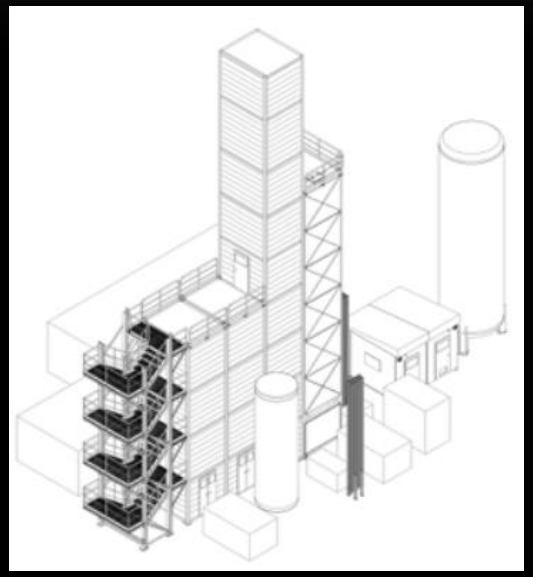

OV
4 V
5 V
6 V
DCR Requirement
DCR [Hz / mm^2]
T [K]
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
50
100
150
200
250
300

URANIA TO ARIA TO LNGS



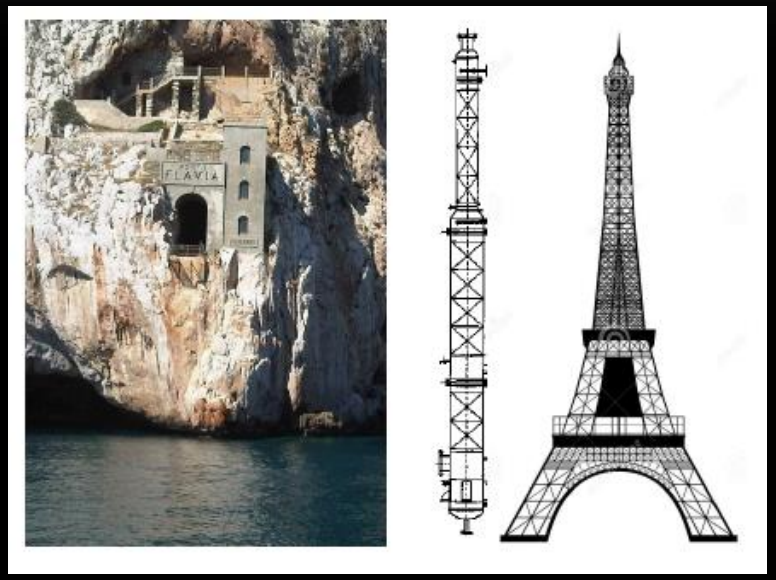
PRODUCTION / DEPLETION OF UAr

URANIA



Expansion of the argon extraction plant in Cortez to reach capacity of **100 kg/day** of Underground Argon

ARIA

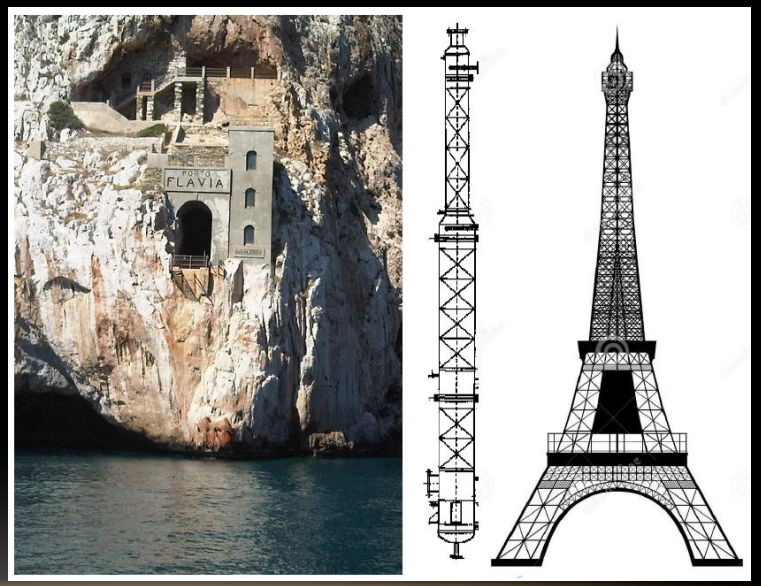


Additional purification and depletion of UAr at 150 kg/day: 350 m distillation column in the Seruci mine in Sardinia.

ARIA

- 350 m tall distillation column in the mine in Sardinia for chemical and isotopic purification of UAr
- Exploits finite vapor pressure difference between $^{39}Ar/^{40}Ar$ (^{39}Ar reduction factor of 10 per pass at the rate of 100 kg/day)
- Protocollo di Intesa between INFN and Regione Sardegna

  - Cost: 12.5 M€
  - INFN (4 M€)
  - NSF + other US sources (1.3 M€)
  - CARBOSULCIS (4.5 M€)
  - Regione Autonoma Sardegna (2.7 M€)

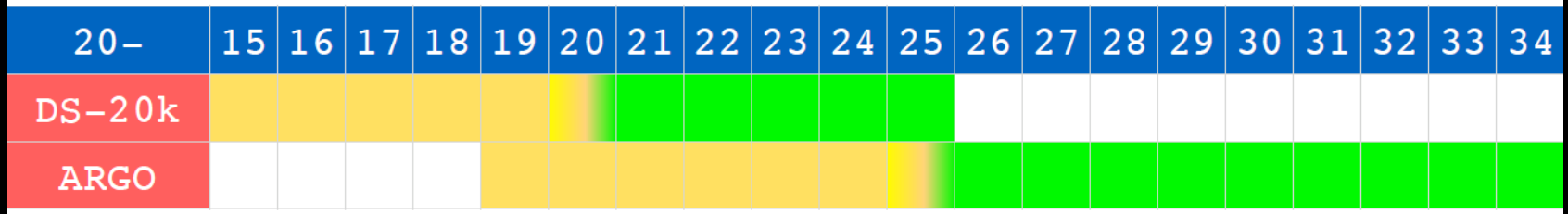


ARIA

DS-20k / ARGO TIME LINE

DarkSide-20k

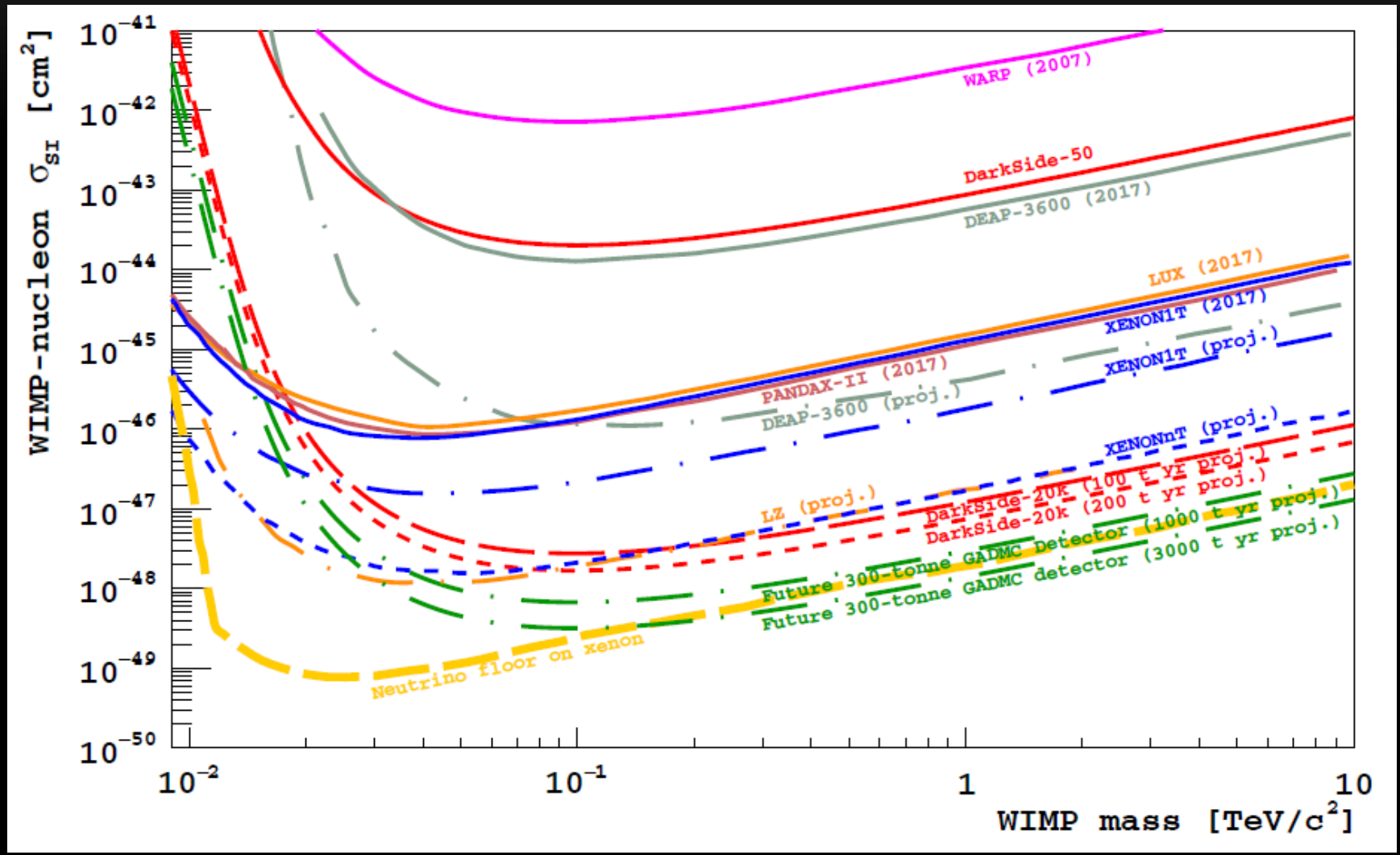
20-tonnes fiducial dark matter detector
start of operations at LNGS within 2020
100 tonne×year background-free search for dark matter



Argo

300-tonnes depleted argon detector
start of operations at LNGS within 2025
1,000 tonne×year background-free search for dark matter
precision measurement of solar neutrinos

PROJECTED SENSITIVITY

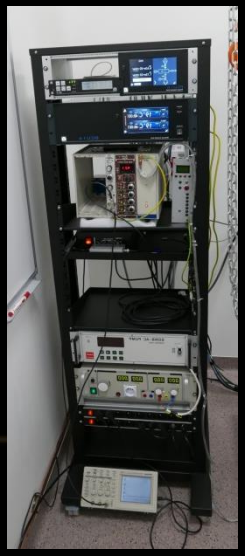


SUMMARY

- 1422 kg×day of truly background-free exposure has been demonstrated with AAr (> 20 yr of ^{39}Ar-free operation of DS-50 with UAr)
- So far 2616 kg×day of truly background-free exposure has been demonstrated with UAr, data taking continues
- Concentration of ^{39}Ar in DS-50 UAr is 1400 times lower than in AAr
- Within DS-50 the strongest WIMP limit among Ar target experiments has been obtained
- DS-20k detector (along with URANIA / ARIA) is under development
- Background-free exploration of DM signal down to the neutrino flor for $M\chi > 100$ GeV/c^2 feasible

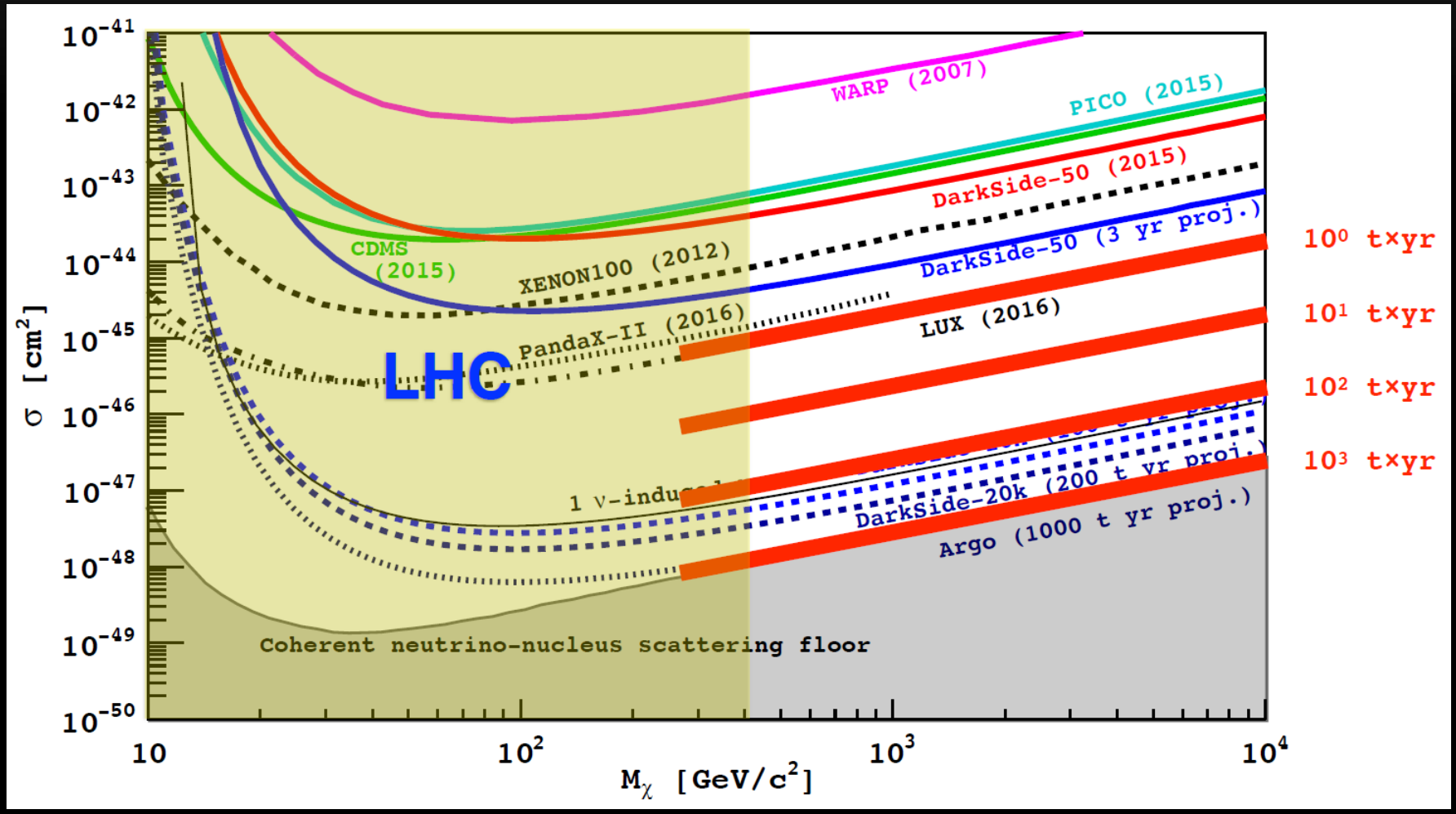
IF UJ CONTRIBUTION TO DARKSIDE

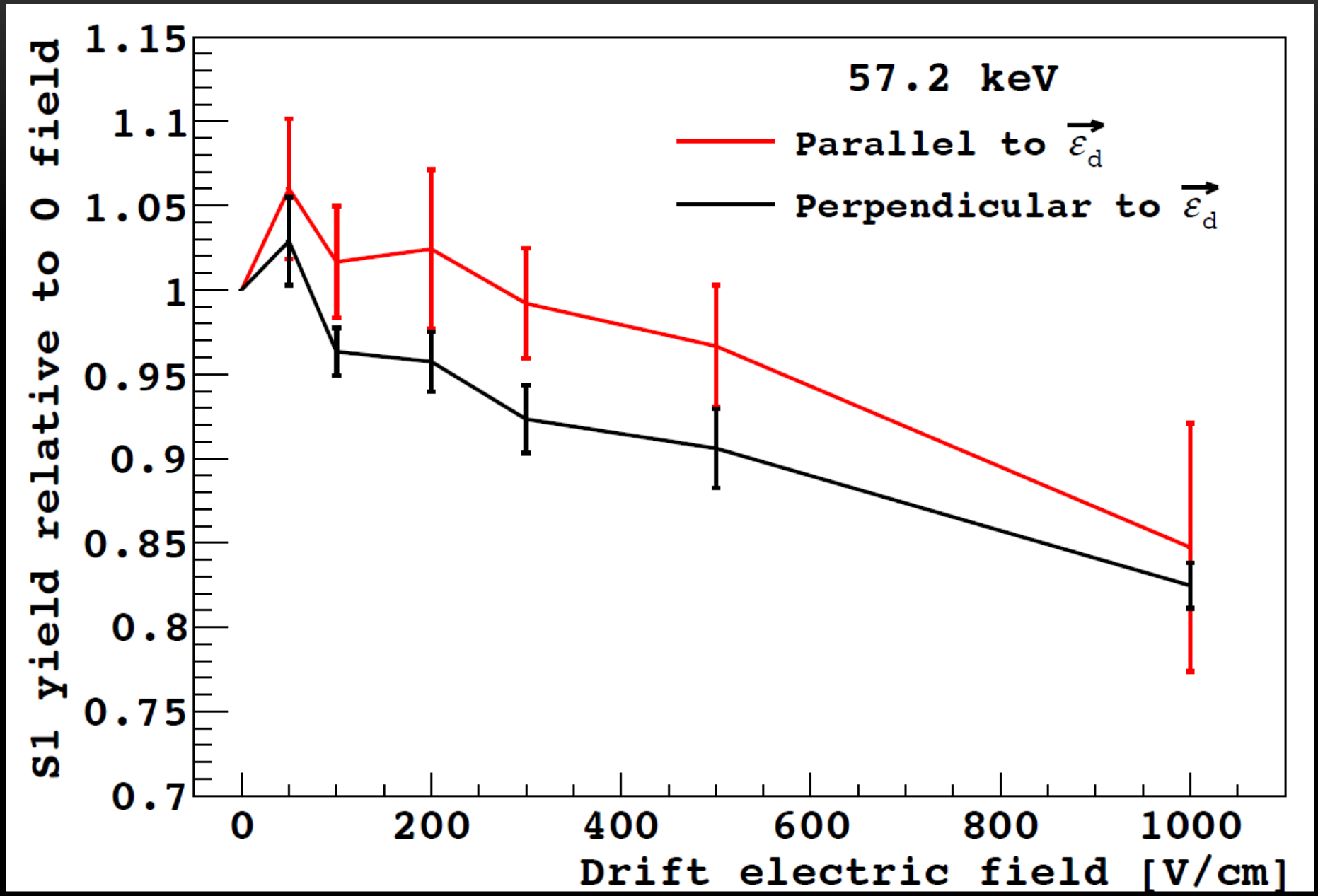
- Development and implementation of gas purification techniques (Borexino/GERDA)
- Development of counting techniques down to single atoms
- Ultra sensitive bulk and surface assay, Rn emanation and diffusion tests at a single atom level
- Development of software procedures for background identification/rejection
- Operating very unique apparatus (custom design/construction) for ultra-low level counting

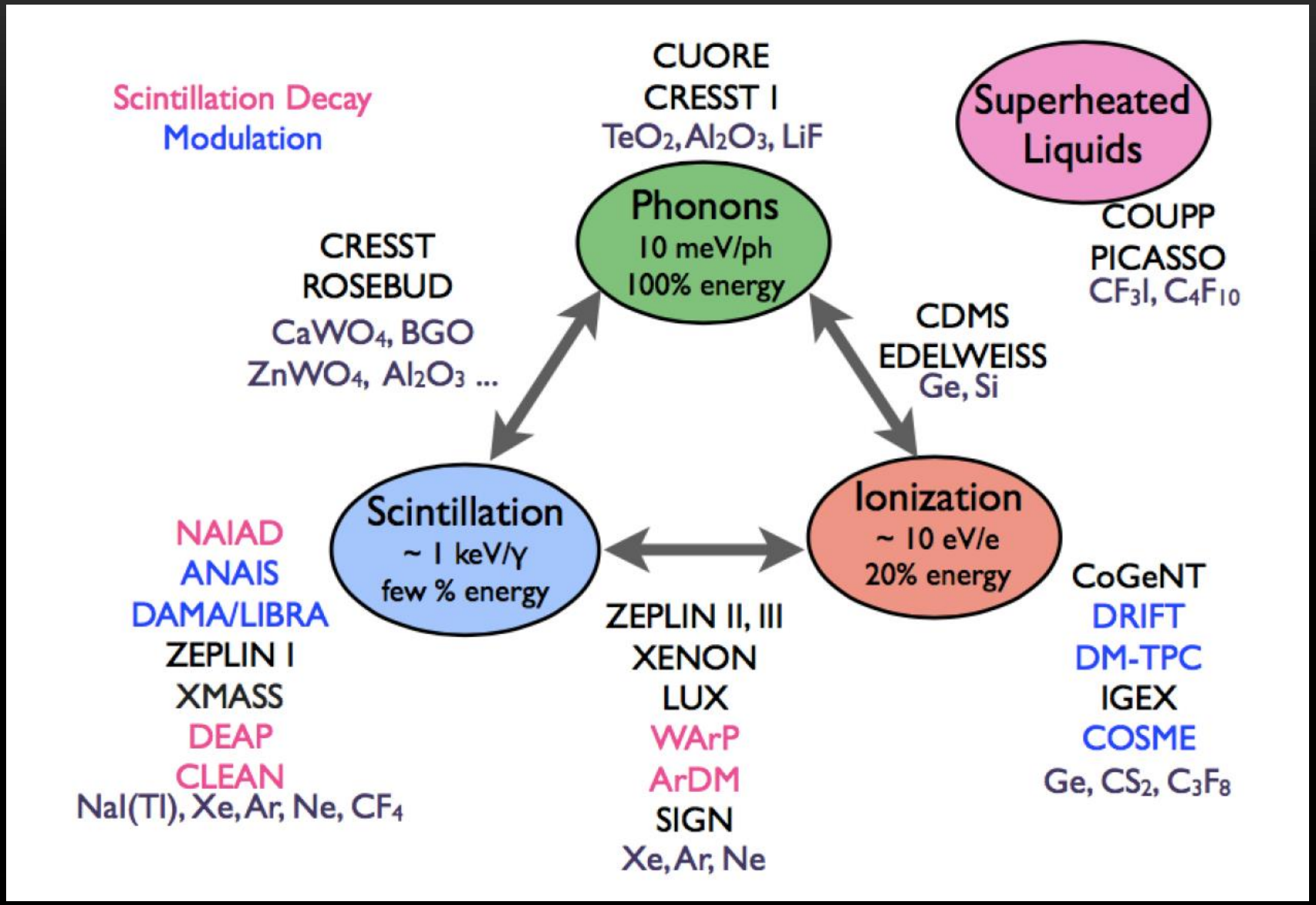


BACKUP SLIDES

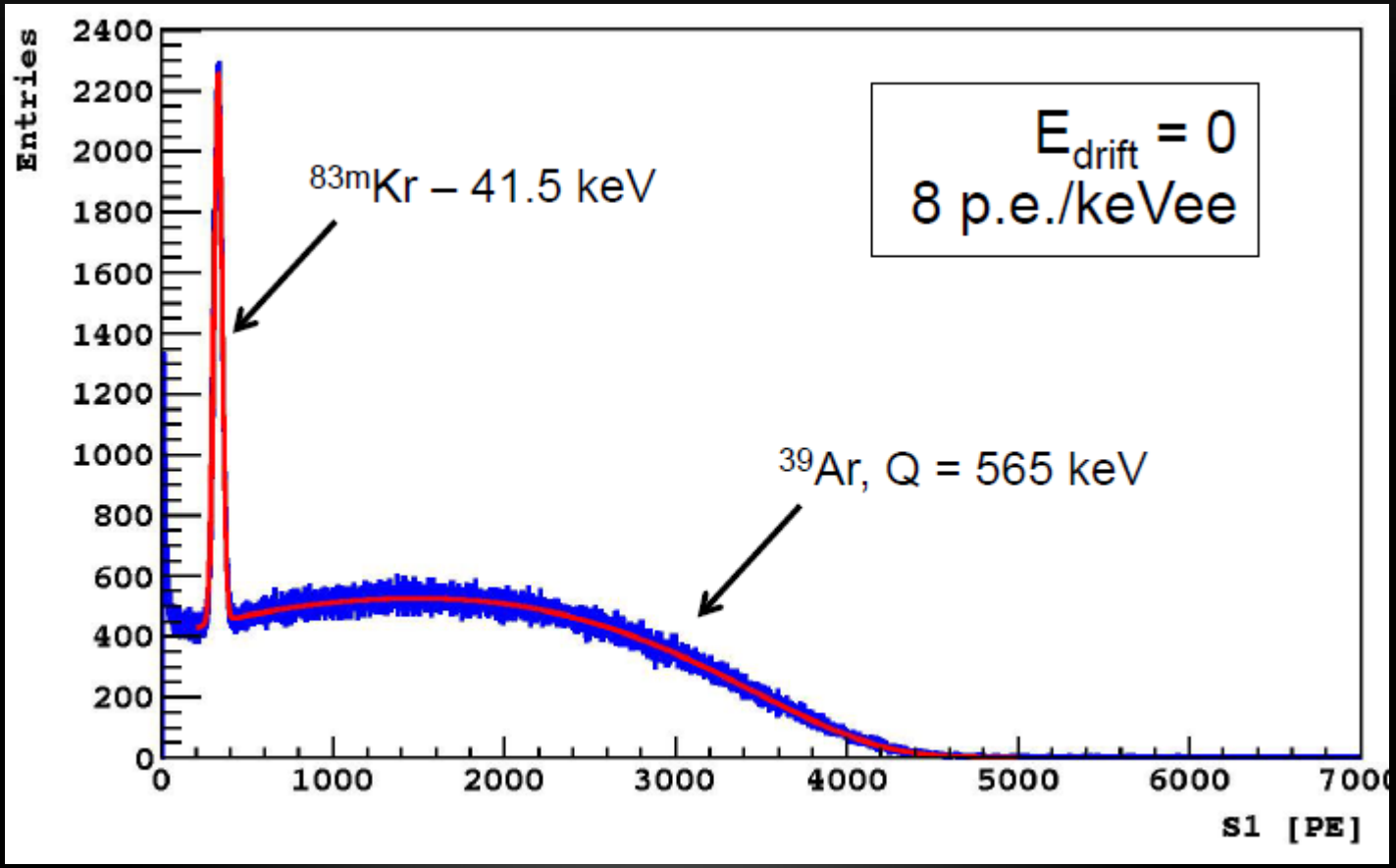
SEARCHES FOR DARK MATTER



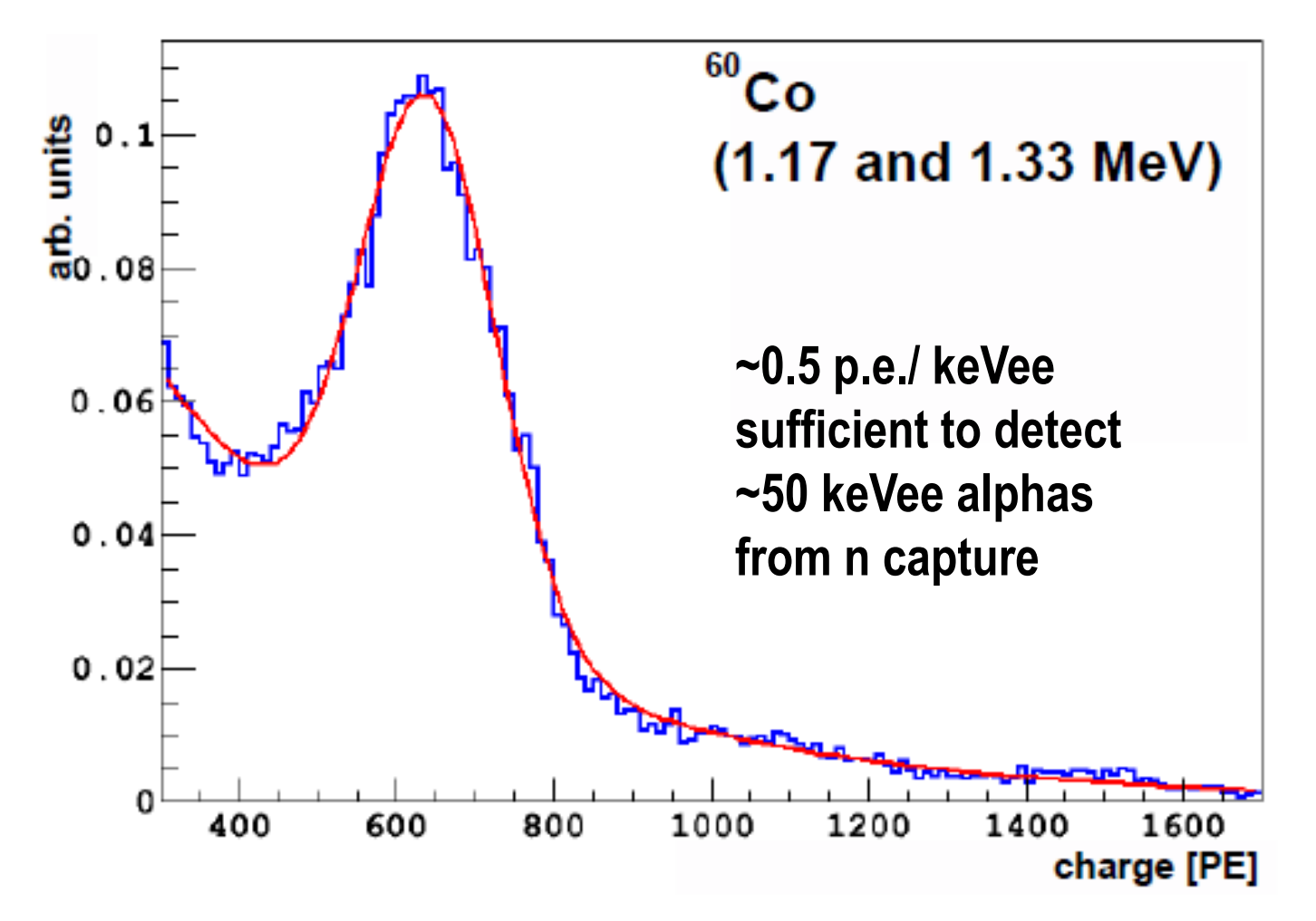

57.2 keV
Parallel to $\vec{\varepsilon}_d$
Perpendicular to $\vec{\varepsilon}_d$
S1 yield relative to 0 field
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
0.7
0
200
400
600
800
1000
Drift electric field [V/cm]


Scintillation Decay
Modulation
CUORE
CRESST I
TeO2, Al2O3, LiF
Superheated Liquids
COUPP
PICASSO
CF3I, C4F10
Phonons
10 meV/ph
100% energy
CRESST
ROSEBUD
CaWO4, BGO
ZnWO4, Al2O3 ...
CDMS
EDELWEISS
Ge, Si
Scintillation
~ 1 keV/γ
few % energy
Ionization
~ 10 eV/e
20% energy
NAIAD
ANAIS
DAMA/LIBRA
ZEPLIN I
XMASS
DEAP
CLEAN
NaI(Tl), Xe, Ar, Ne, CF4
ZEPLIN II, III
XENON
LUX
WArP
ArDM
SIGN
Xe, Ar, Ne
CoGeNT
DRIFT
DM-TPC
IGEX
COSME
Ge, CS2, C3F8

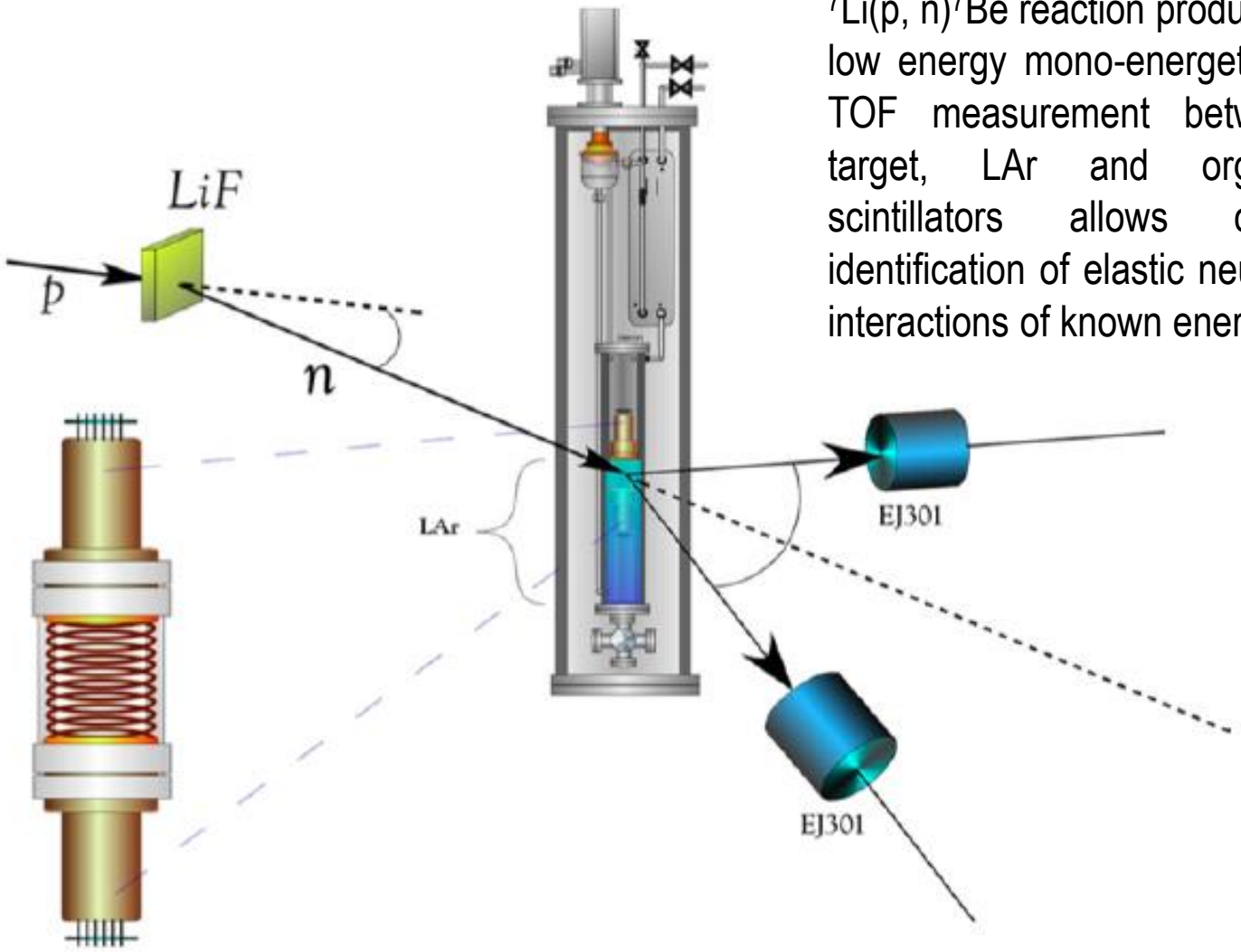
TPC CALIBRATION



LSV CALIBRATION



SCENE



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