Status and perspectives of the DarkSide experimental program

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on behalf of the DarkSide-20k Collaboration

Princeton University

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Overview

1. **Direct detection trivia**
2. **DarkSide status and perspectives**
    - The experimental program
    - DarkSide-20k overview
    - Detector design
    - Argon target procurement
3. **Detecting CCSN neutrinos with LAr detectors**
    - CCSN signal in LAr TPCs
    - Backgrounds
    - Discovery

Dark Matter and direct detection trivia

The physics case

CMB

Galactic clusters

Galaxies

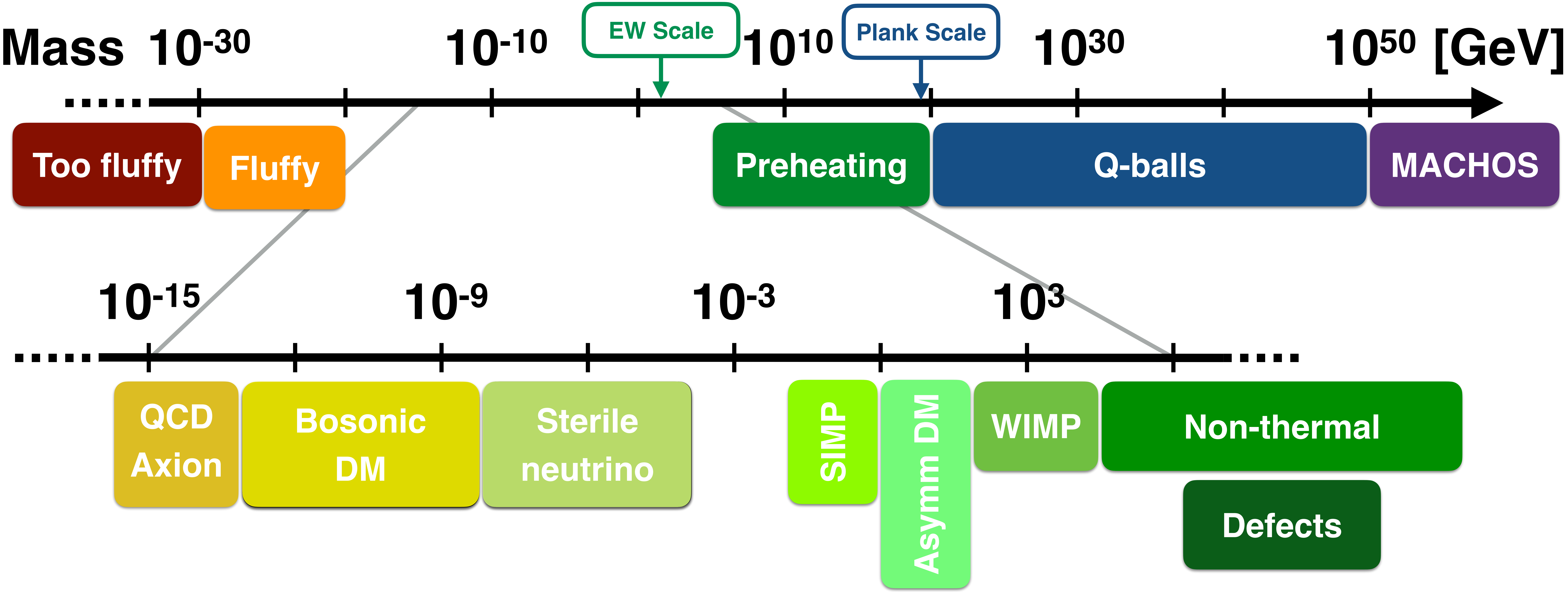
Thermal anisotropies
multipole expansion

Galaxy velocities
Gravitational lensing (Bullet)

Rotation curves
Gravitational lensing

Convincing evidence at all scales

Where should we look?



Mass 10^{-30} 10^{-10} 10^{10} 10^{30} 10^{50} [GeV]

EW Scale

Plank Scale

Too fluffy

Fluffy

Preheating

Q-balls

MACHOS

10^{-15} 10^{-9} 10^{-3} 10^{3}

QCD Axion

Bosonic DM

Sterile neutrino

SIMP

Asymm DM

WIMP

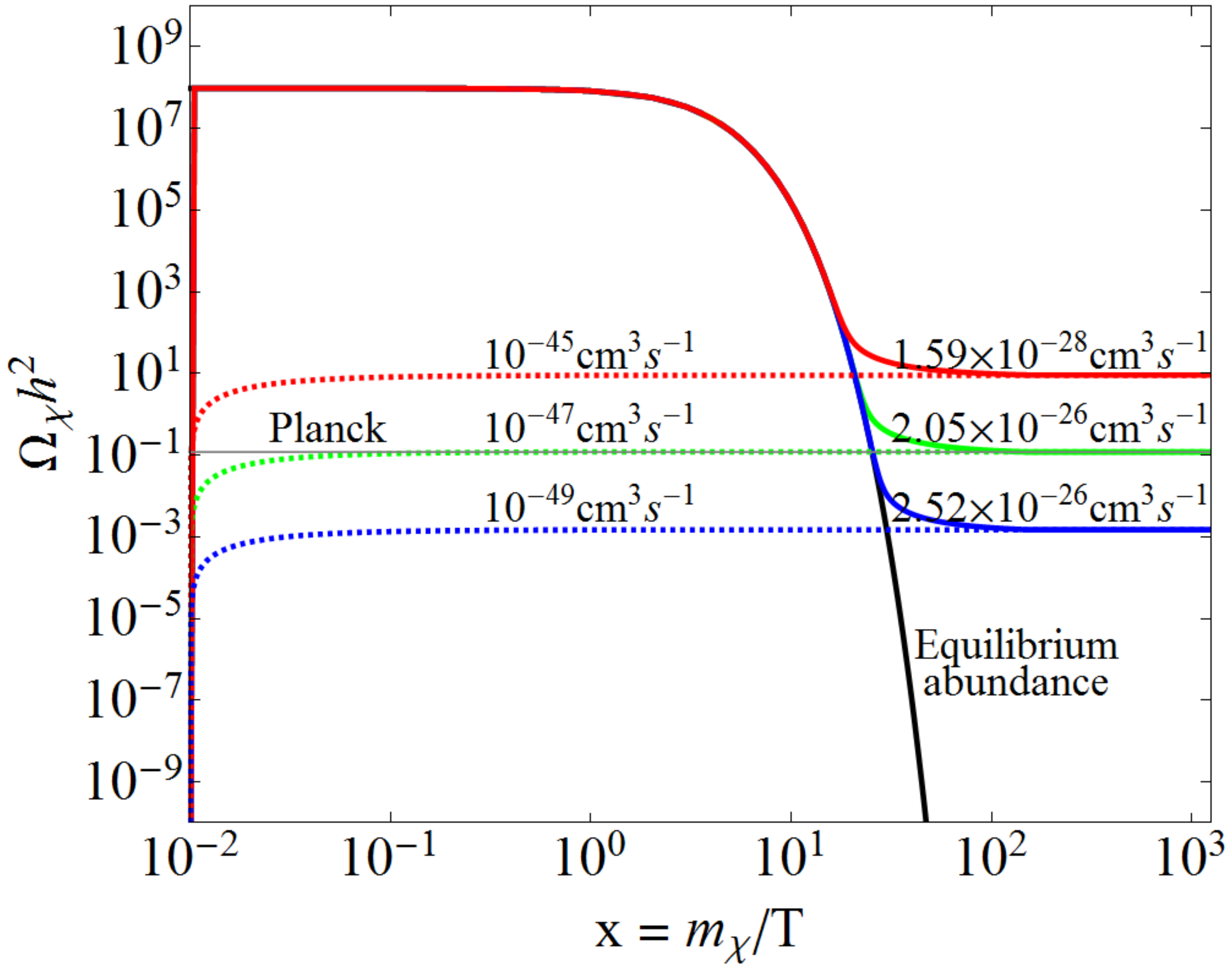
Non-thermal

Defects

~70 orders of magnitude and a zoo of theoretical models!

The WIMP realm

The WIMP miracle

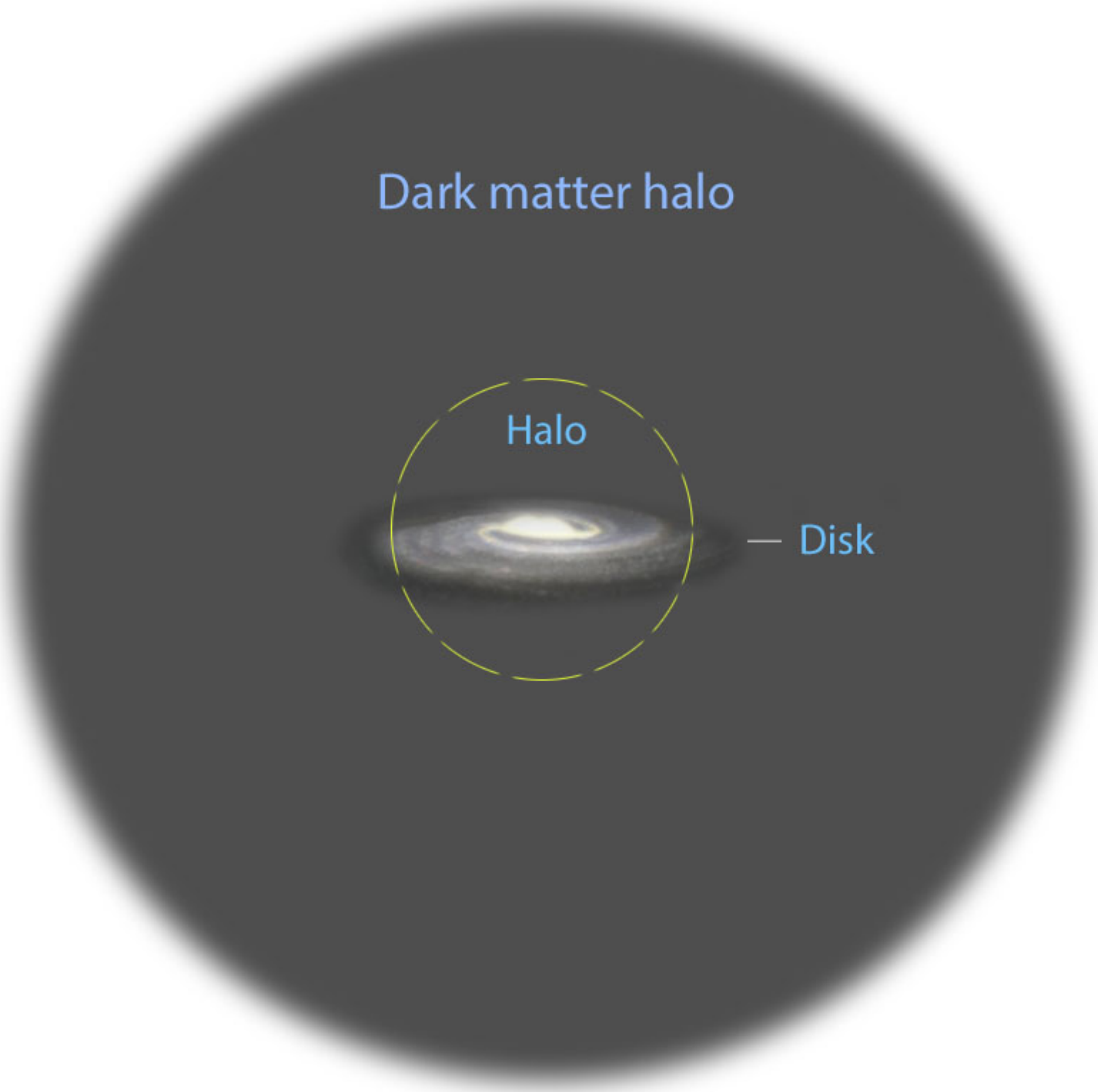


Weak X-section

Mass at EW scale

Observed DM abundance

CDM

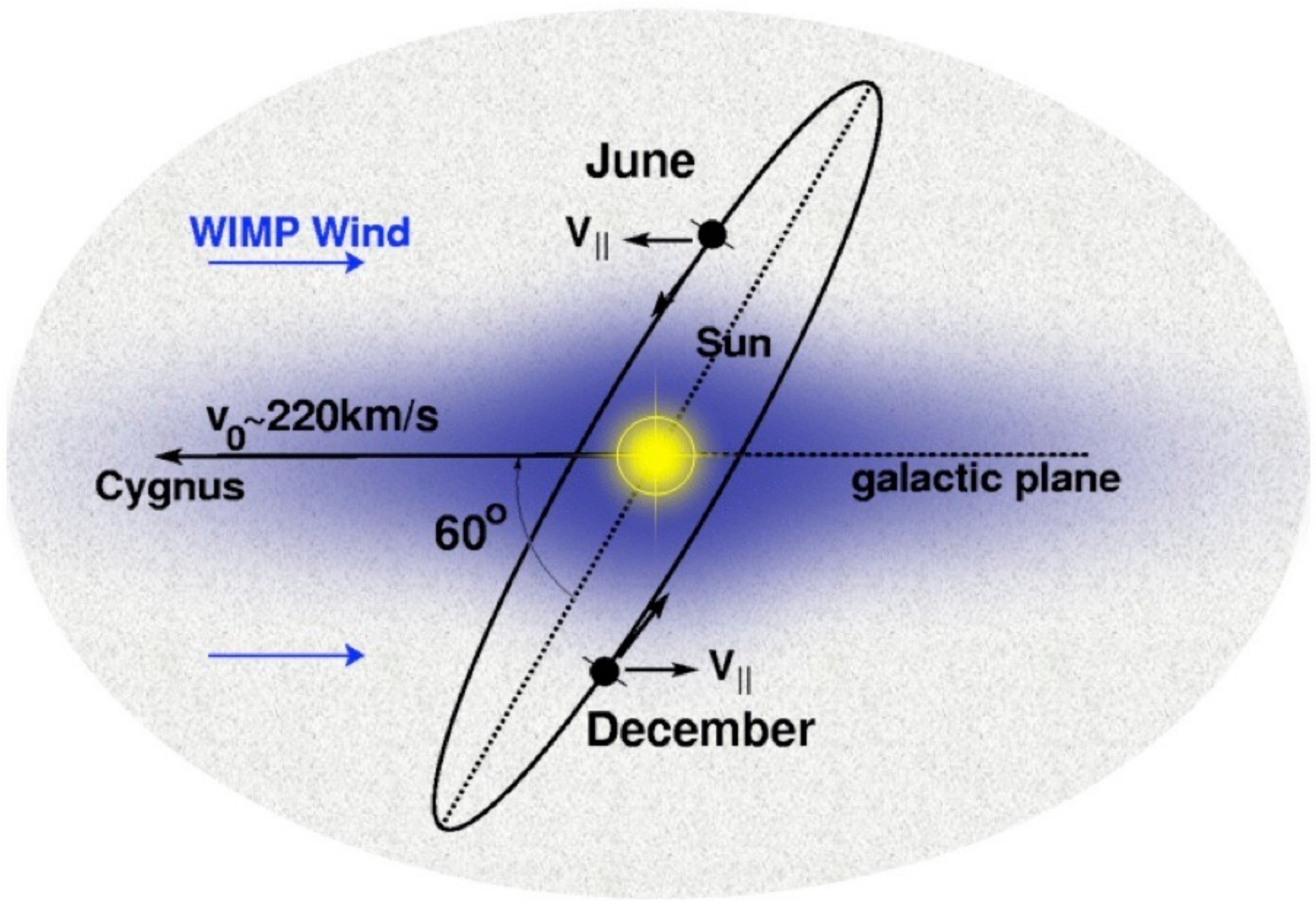


Milky Way model

CDM preferred by halo simulations

Maxwell velocity distribution

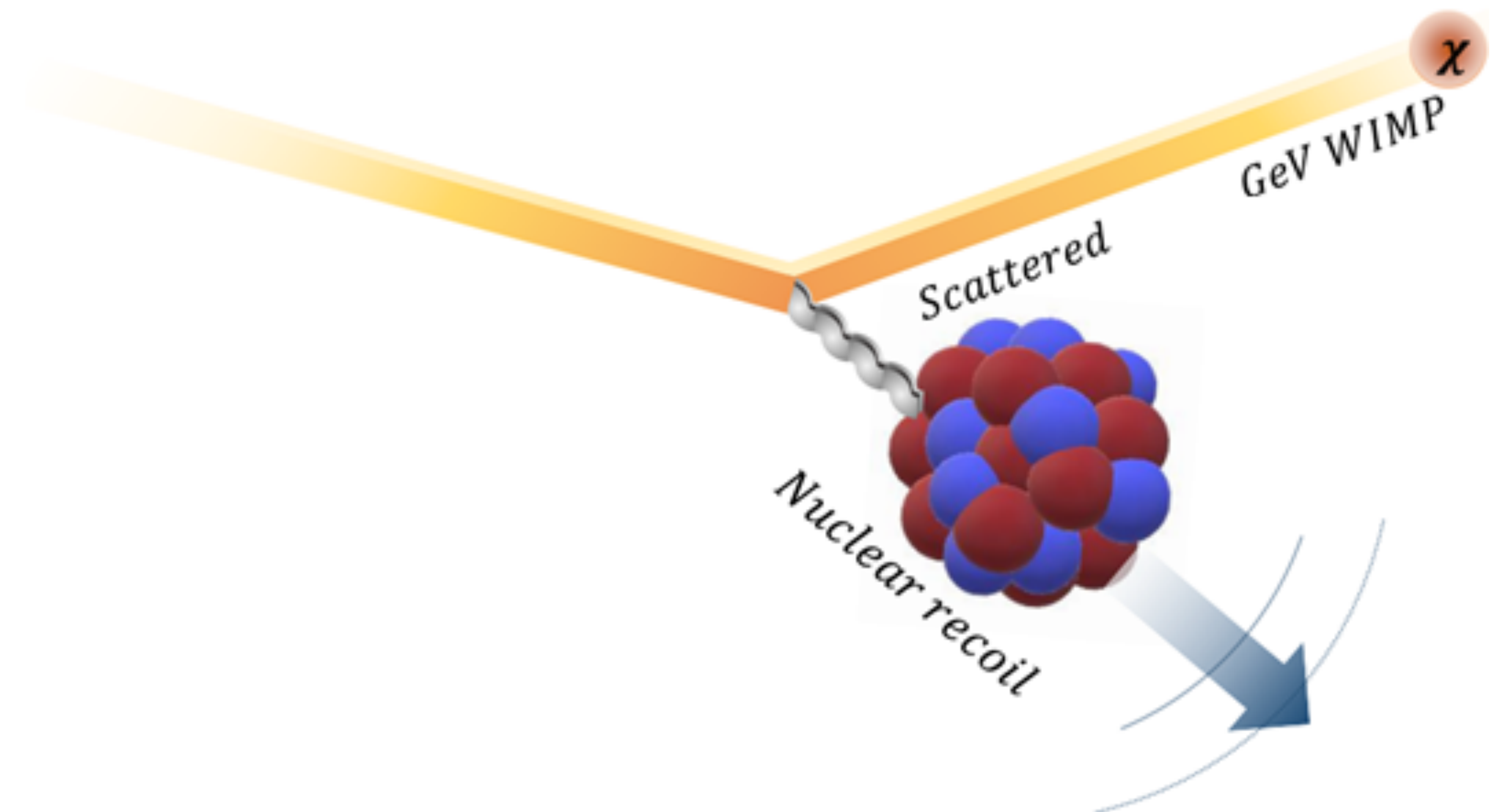
WIMP Wind



Sun motion ⇒ directional signature

Earth orbit ⇒ annual modulation

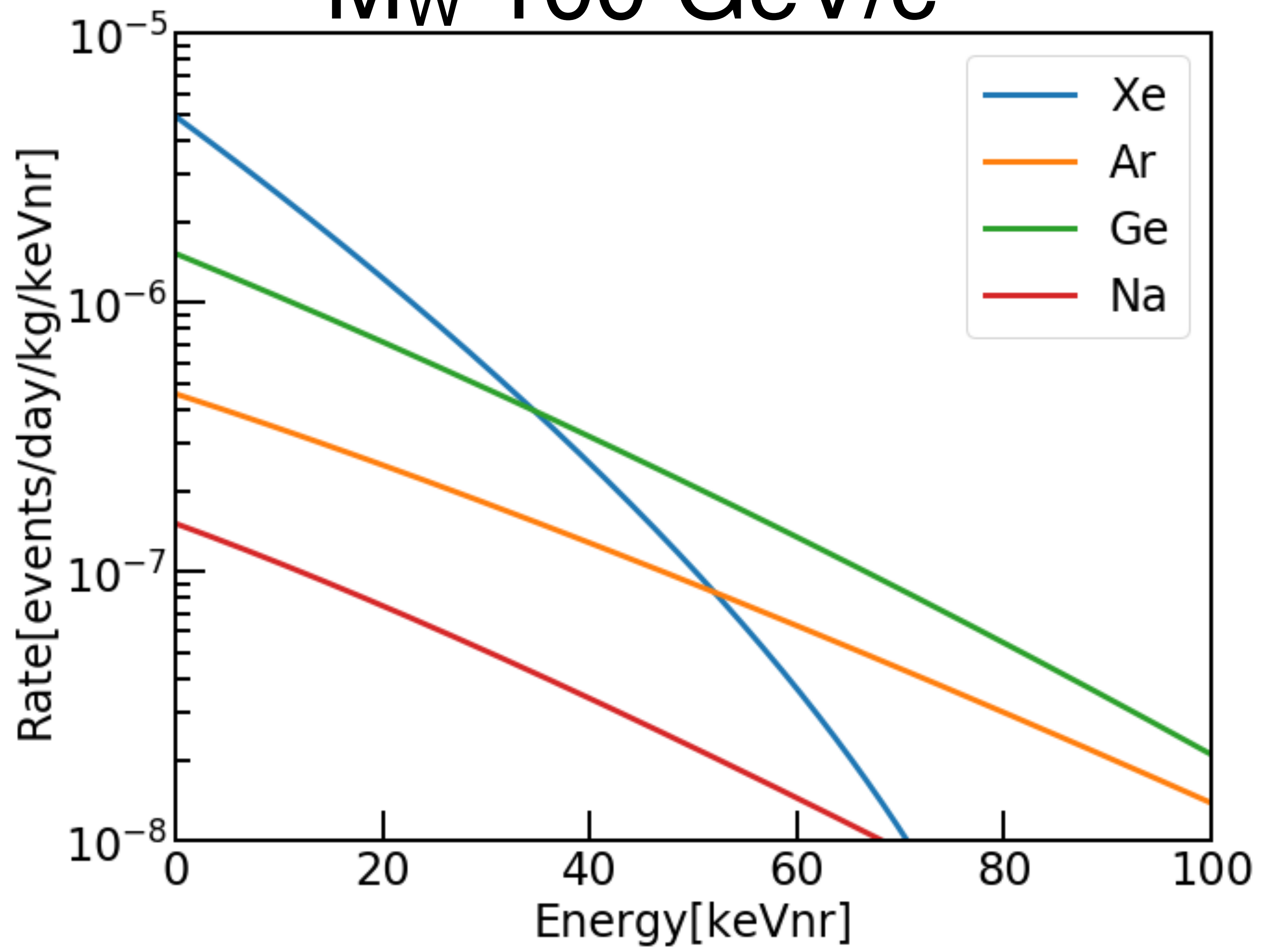
WIMP spectra



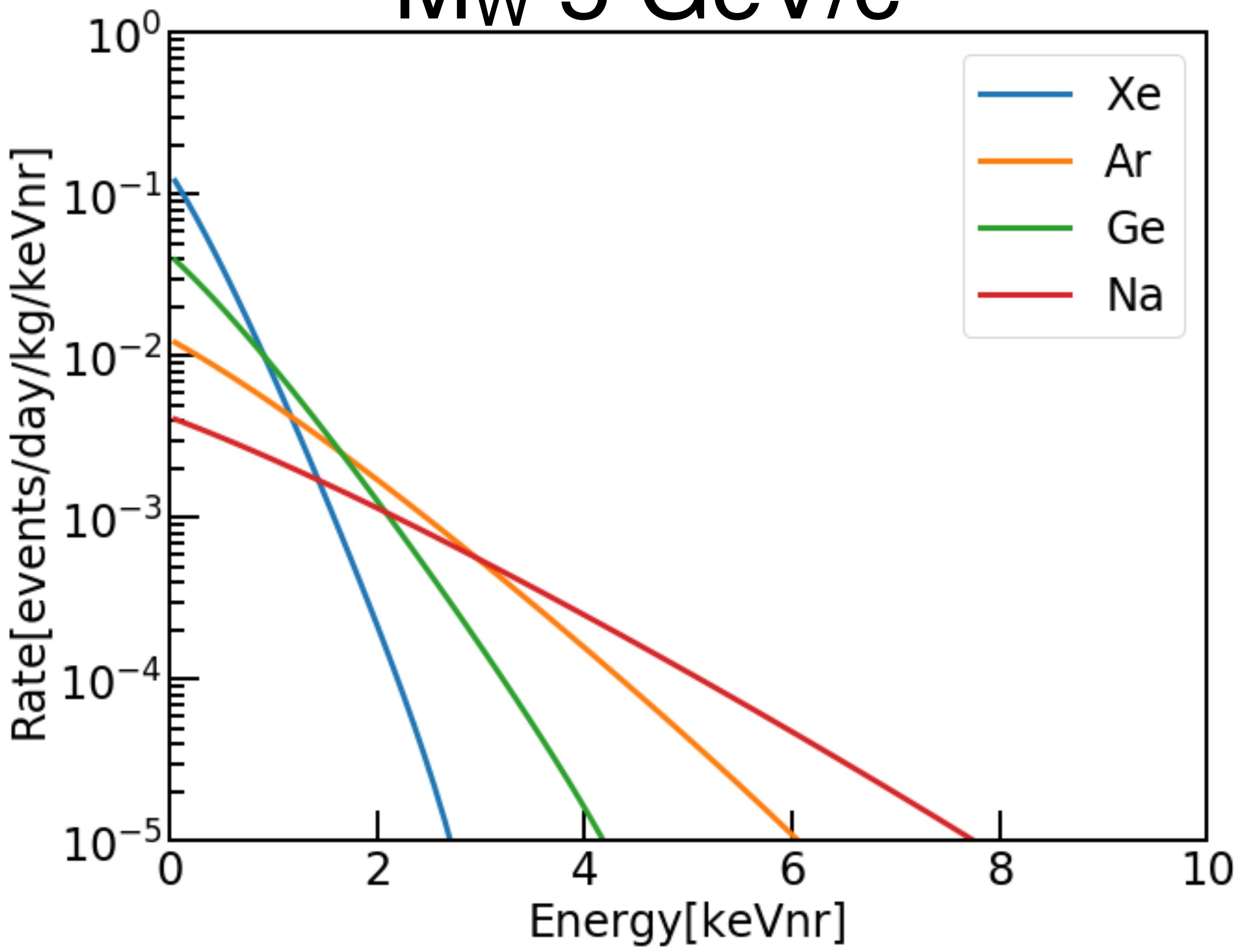
$$\frac{dR}{dE_r} = \frac{MT}{2m_W\mu_N^2} \times \underset{\text{Particle physics}}{\underset{\downarrow}{\boxed{\sigma_{Wn}}}} \times \frac{\mu_N^2}{\mu_p} A^2 \times \underset{\text{Nuclear physics}}{\underset{\downarrow}{\boxed{F^2(E_r)}}} \times \underset{\text{Astrophysics}}{\underset{\downarrow}{\boxed{\rho_0 \times \int_{v_{min}}^{v_{max}} \frac{f(\vec{v})}{v} d^3v}}}$$

- Non relativistic regime (v << c)
- **Signal: nuclear recoils (NR)**
- Coherent scattering enhancement (A^2)
- High energy suppression (F^2)
- Rate exponential in obs. energy
- σ_{WN} and ρ_{DM} degenerate

M_W 100 GeV/c²



M_W 5 GeV/c²

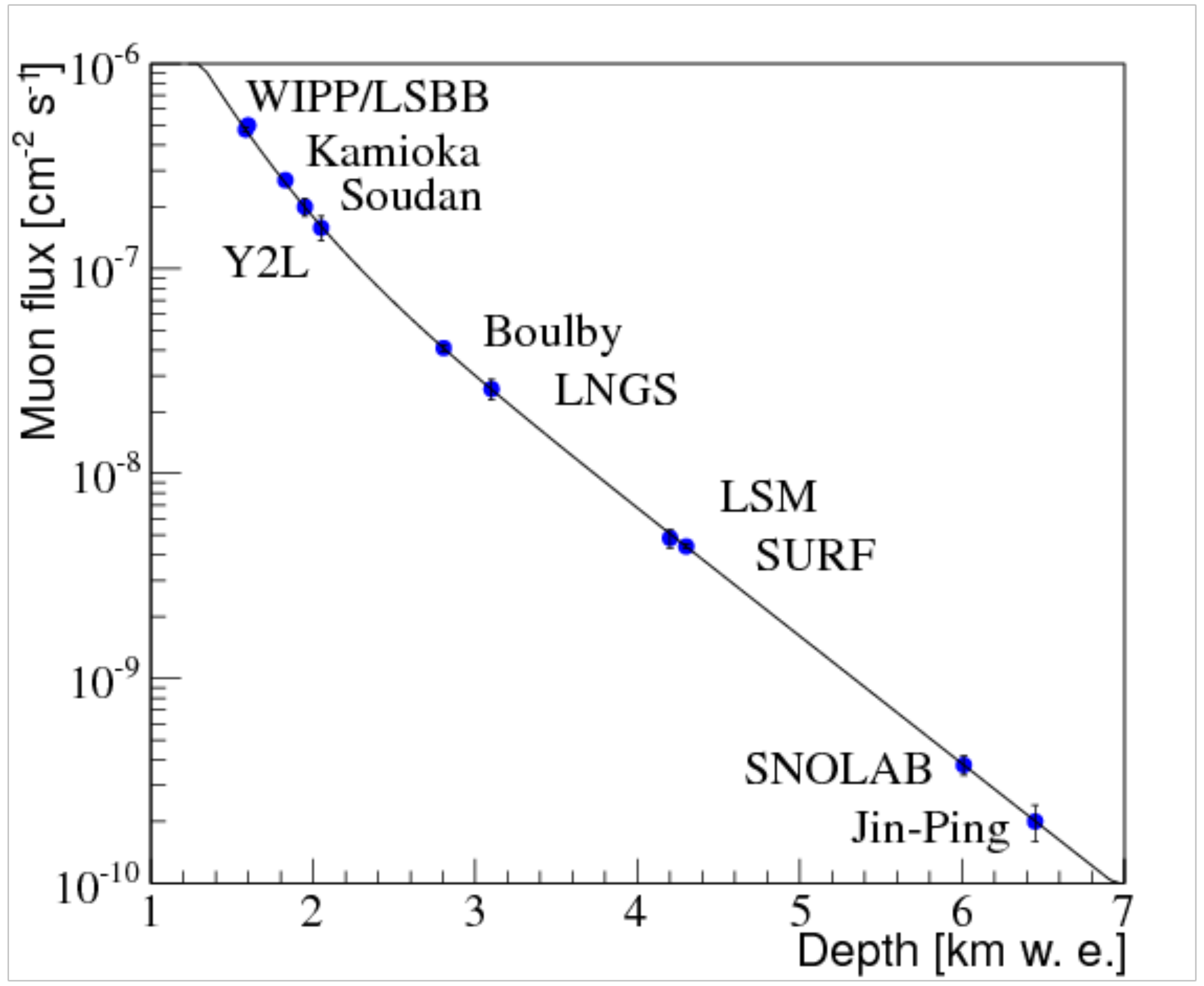


High M_W →
- Low number density ✗
- High recoil energies ✓
- High A target ✓

Low M_W →
- High number density ✓
- Low recoil energies ✗
- Low A target ✗

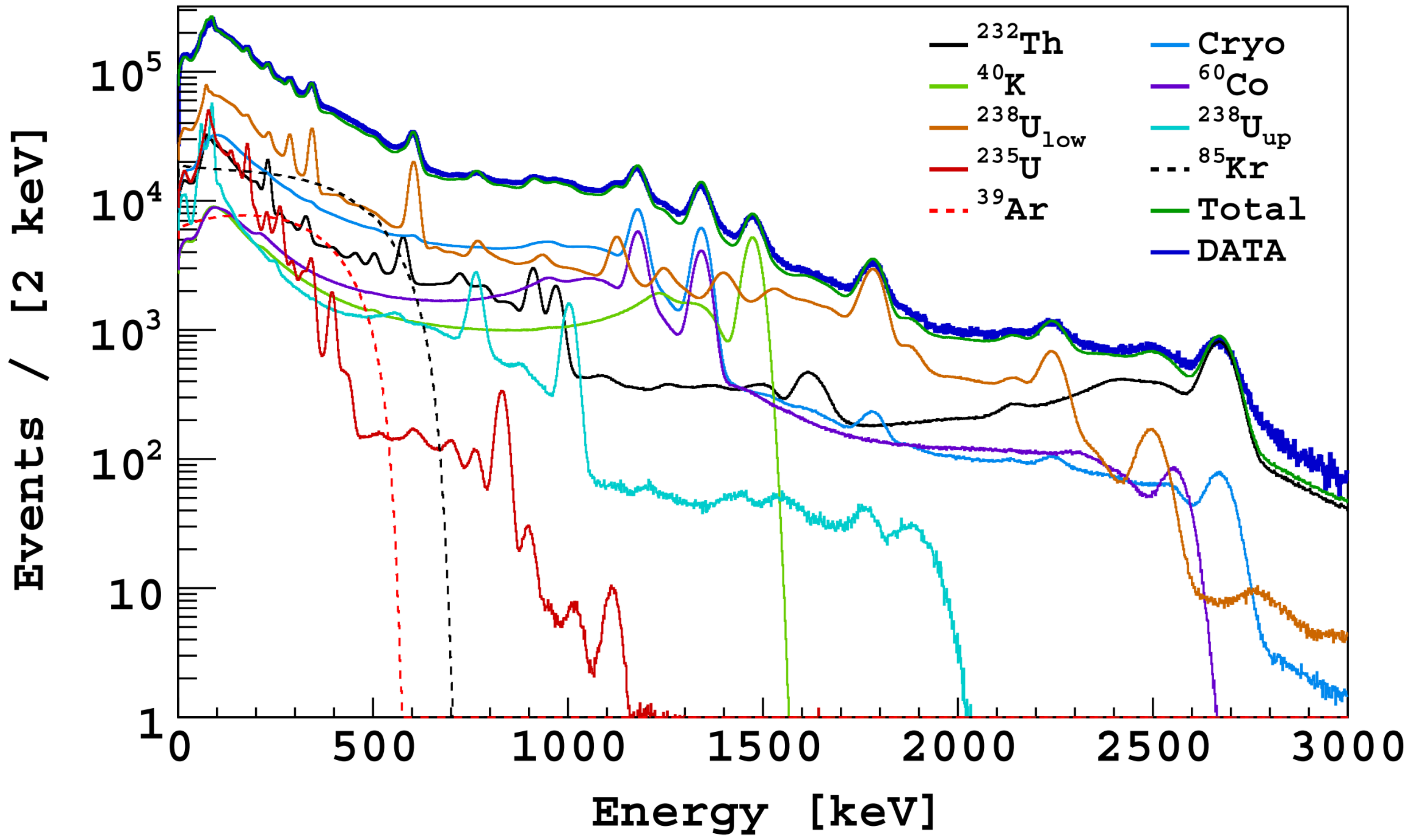
Radiogenic and cosmogenic backgrounds

From above



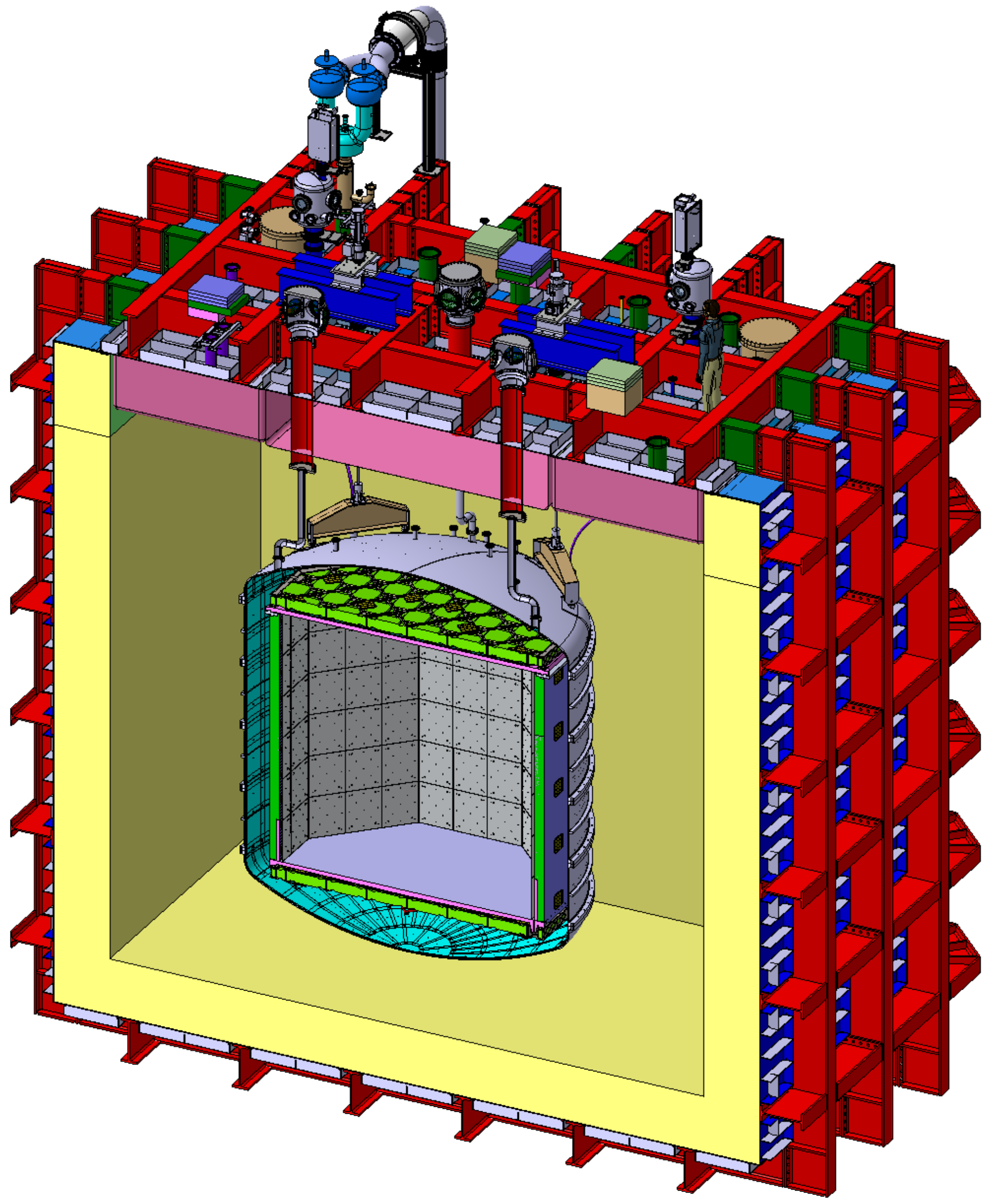
- Excessive muon rate at surface
- Radioactive isotopes activated
- Neutron generation
- Go underground!

From below



- Natural radioactive isotopes:
U and Th chains, non-actinides
- Material assay and selection
- Particle identification: ER/NR
- Fiducialization: surface events

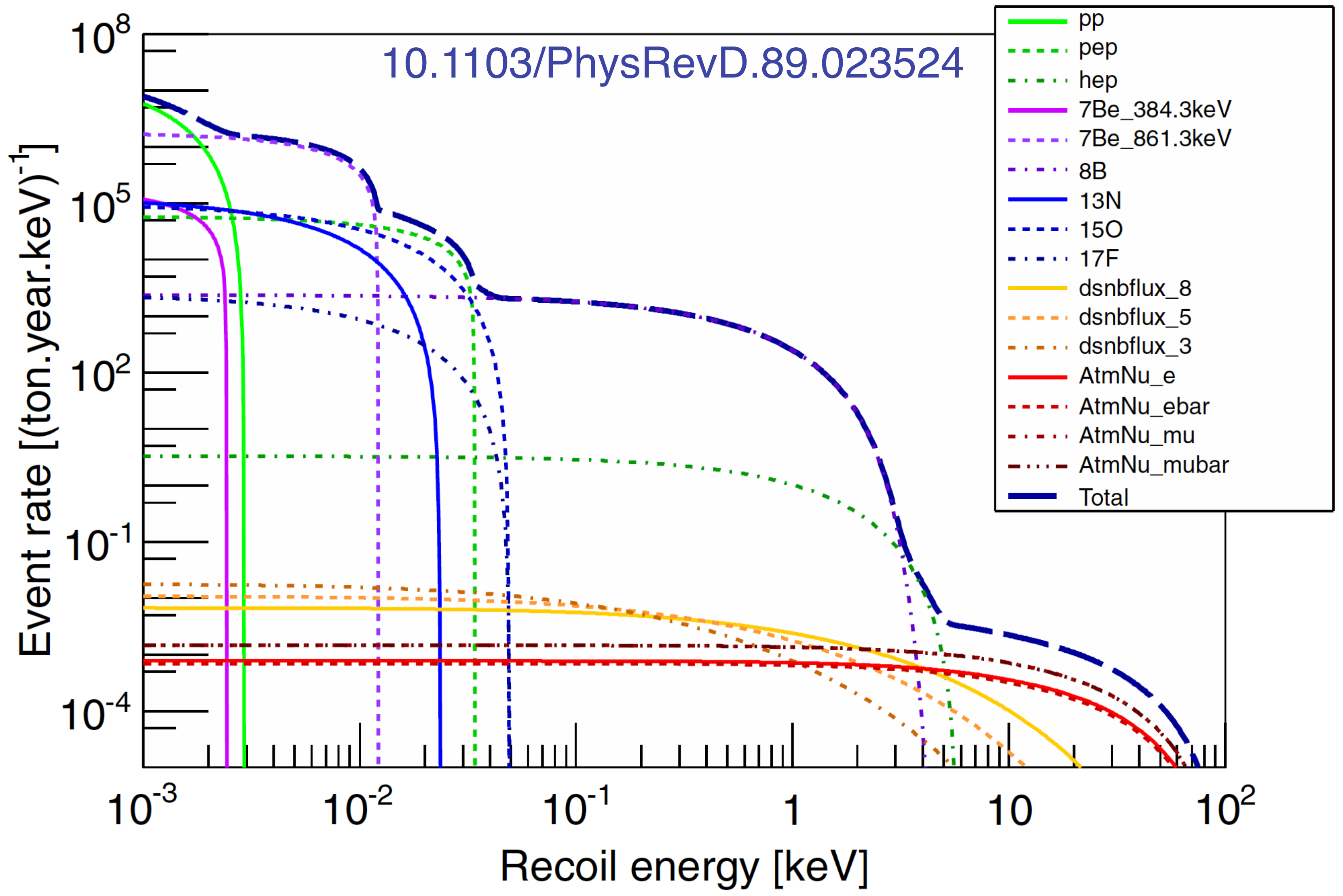
Solution



- Onion-like structure:
  1. Muon veto
  2. Neutron veto
  3. WIMP detector

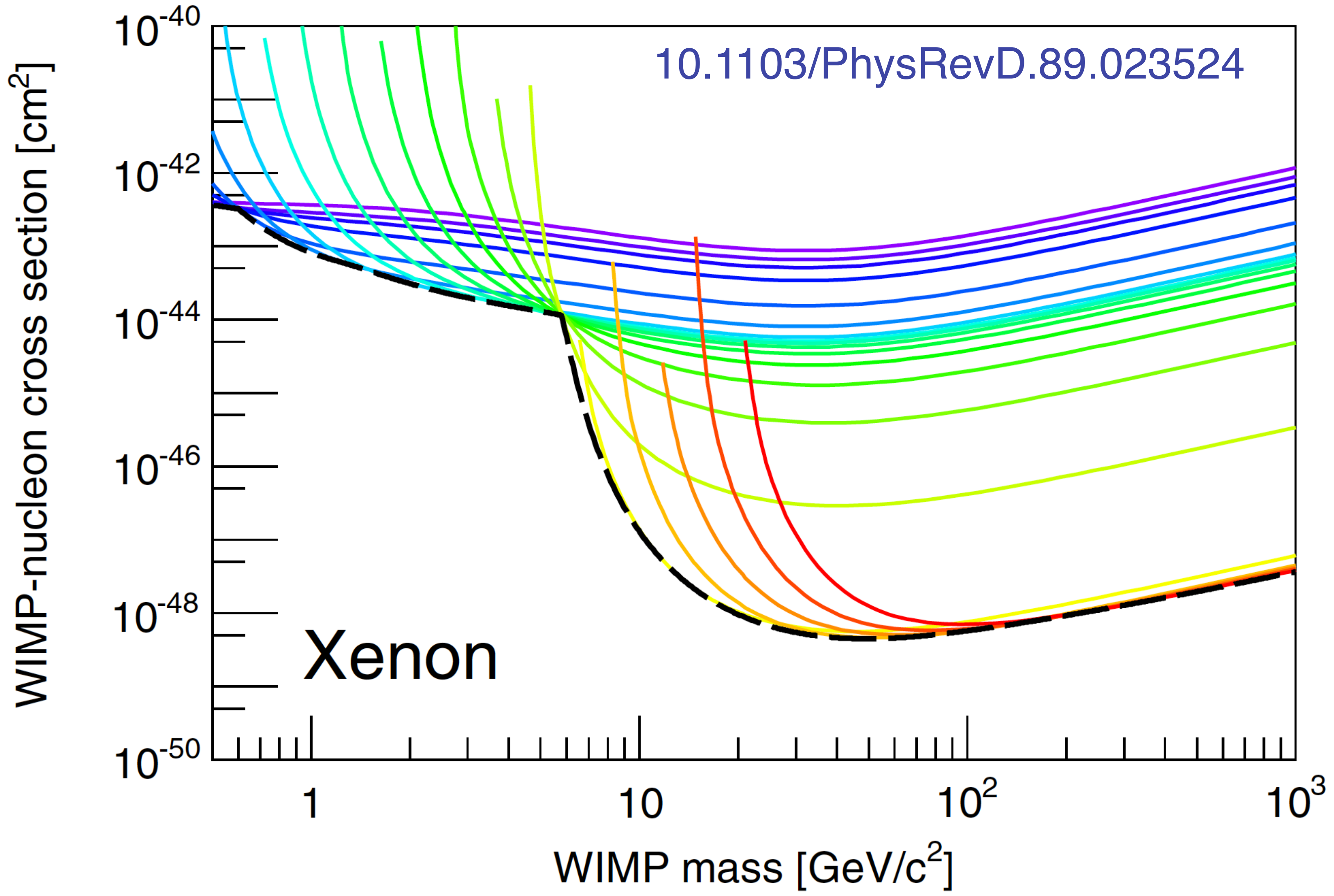
Neutrinos

Solar and atmospheric



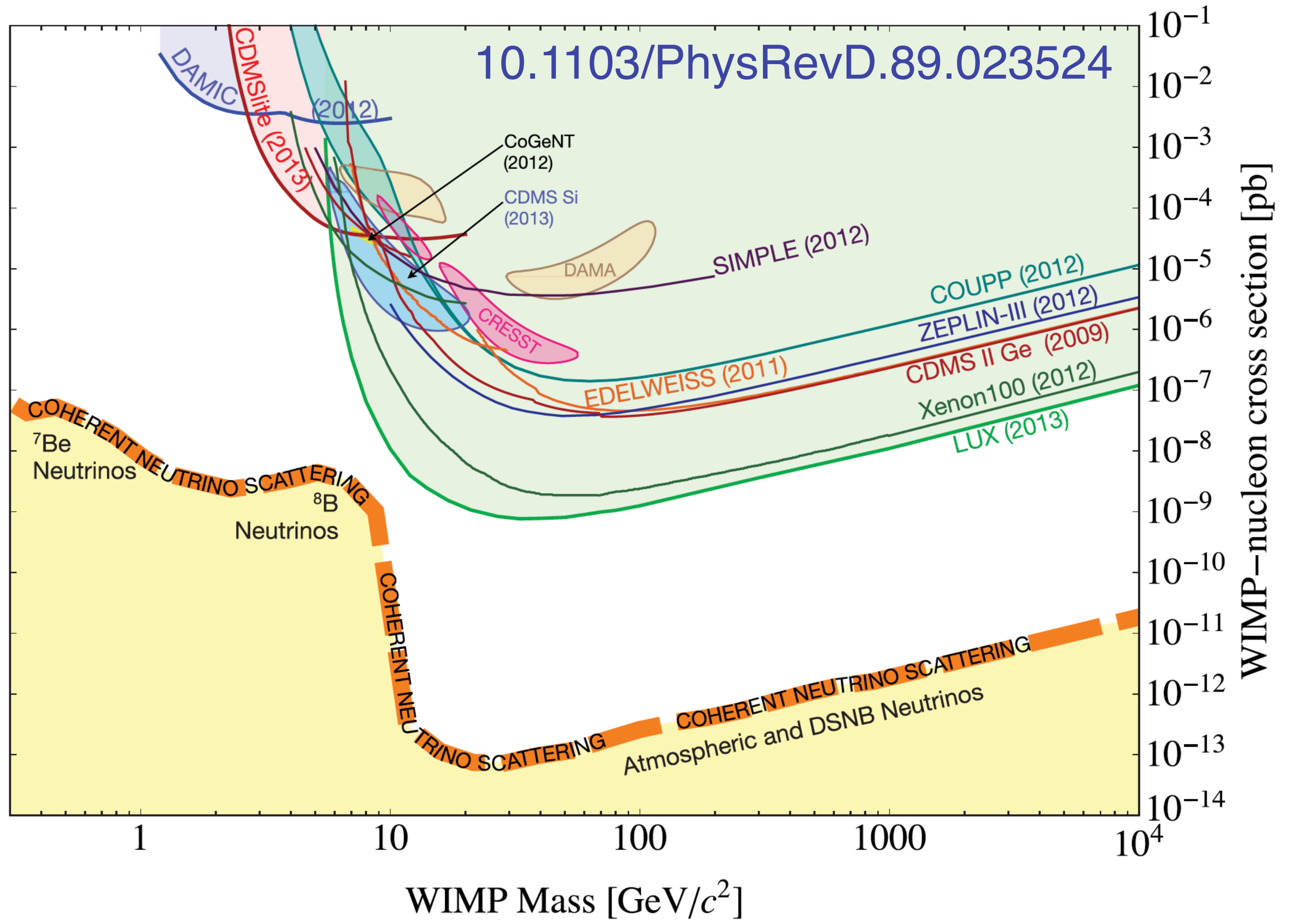
- Solar ^{8}B at low energies
- Coherent scattering on nuclei
- Atmospheric ν at high energies
- CC interactions with ^{40}Ar

Sensitivity vs E_{th}



- Background-free sensitivity for exposures reaching 1 event
- Different energy thresholds
- Envelope forms the neutrino floor

Neutrino floor/fog



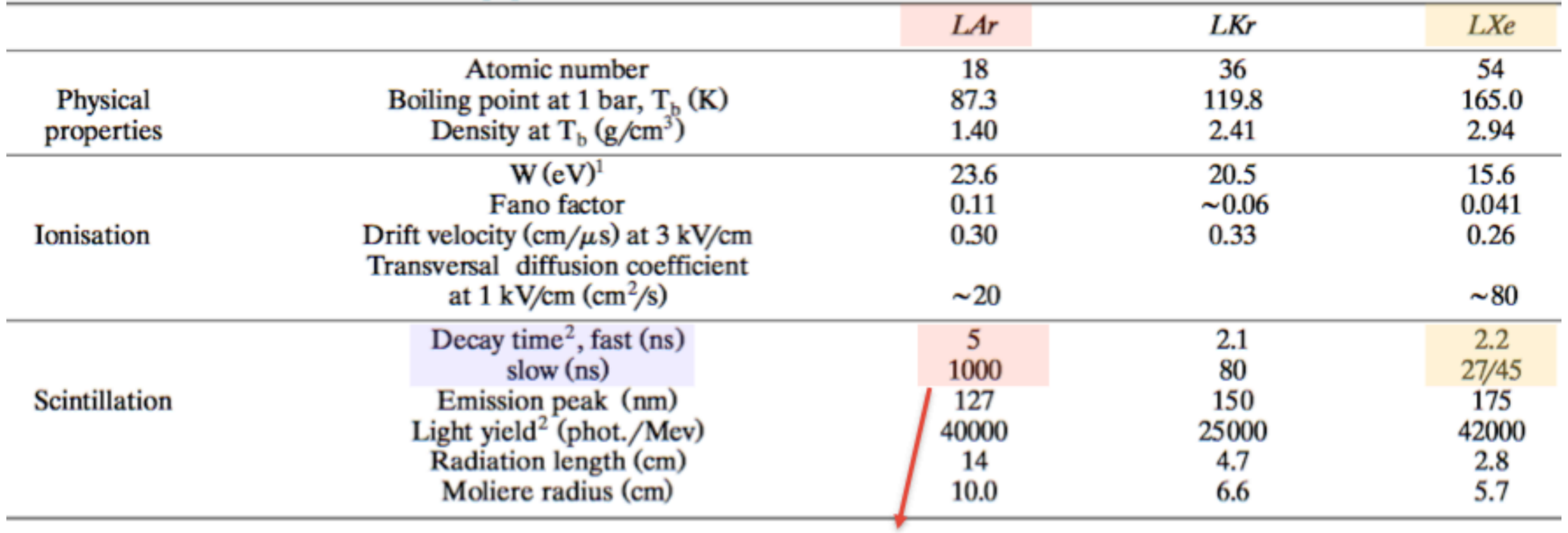
- Limit on experimental sensitivity for any detector
- How to go beyond?
  - Modulation
  - Directionality

Search with liquefied noble elements

- High density ✓

  Self screening

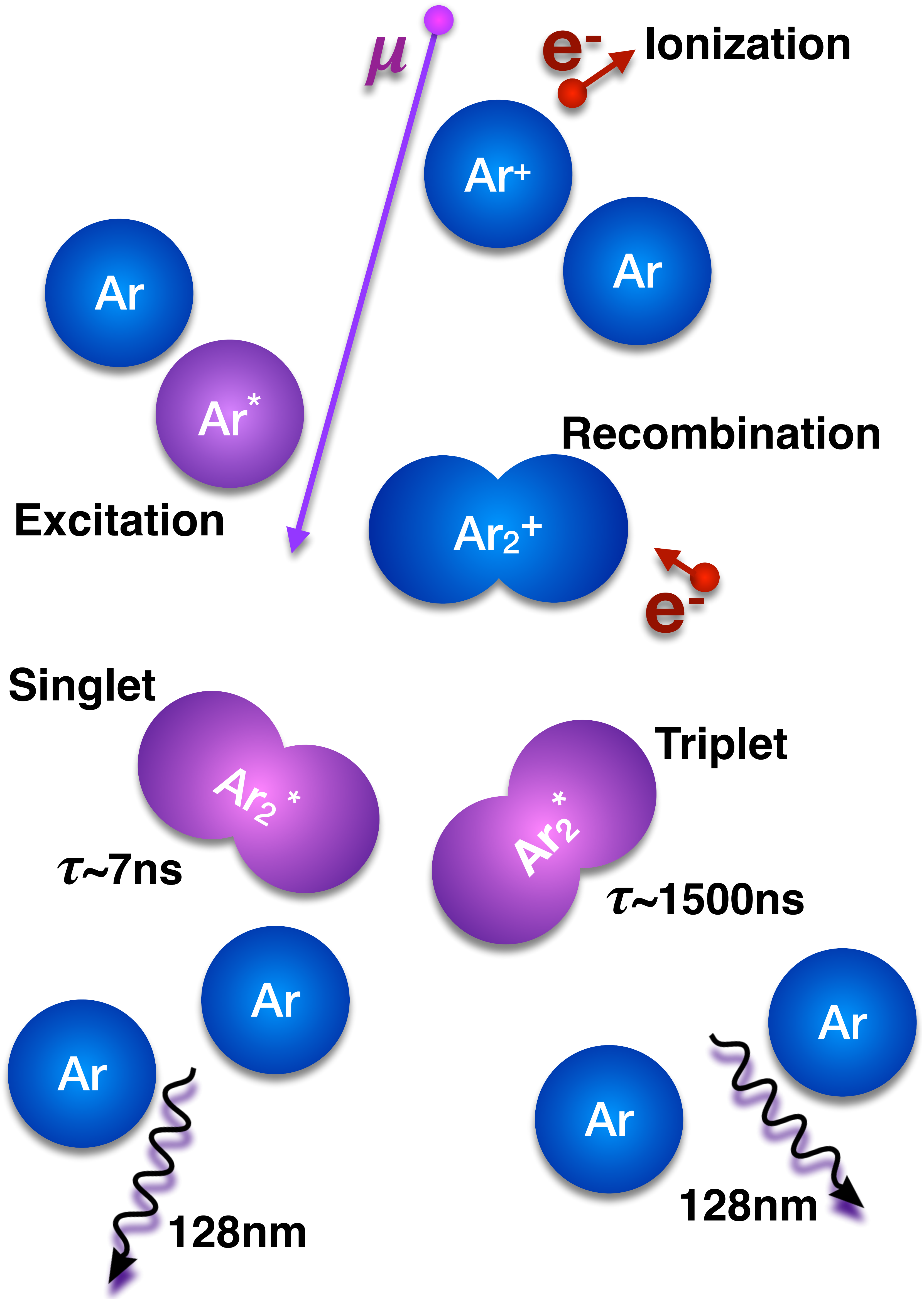
  Good scalability
- Easy(-ish) purification, also online ✓
- Scintillation: good light yield ✓
- Ionisation ✓
- ER rejection ✓
- NR quenching at low energies ✗

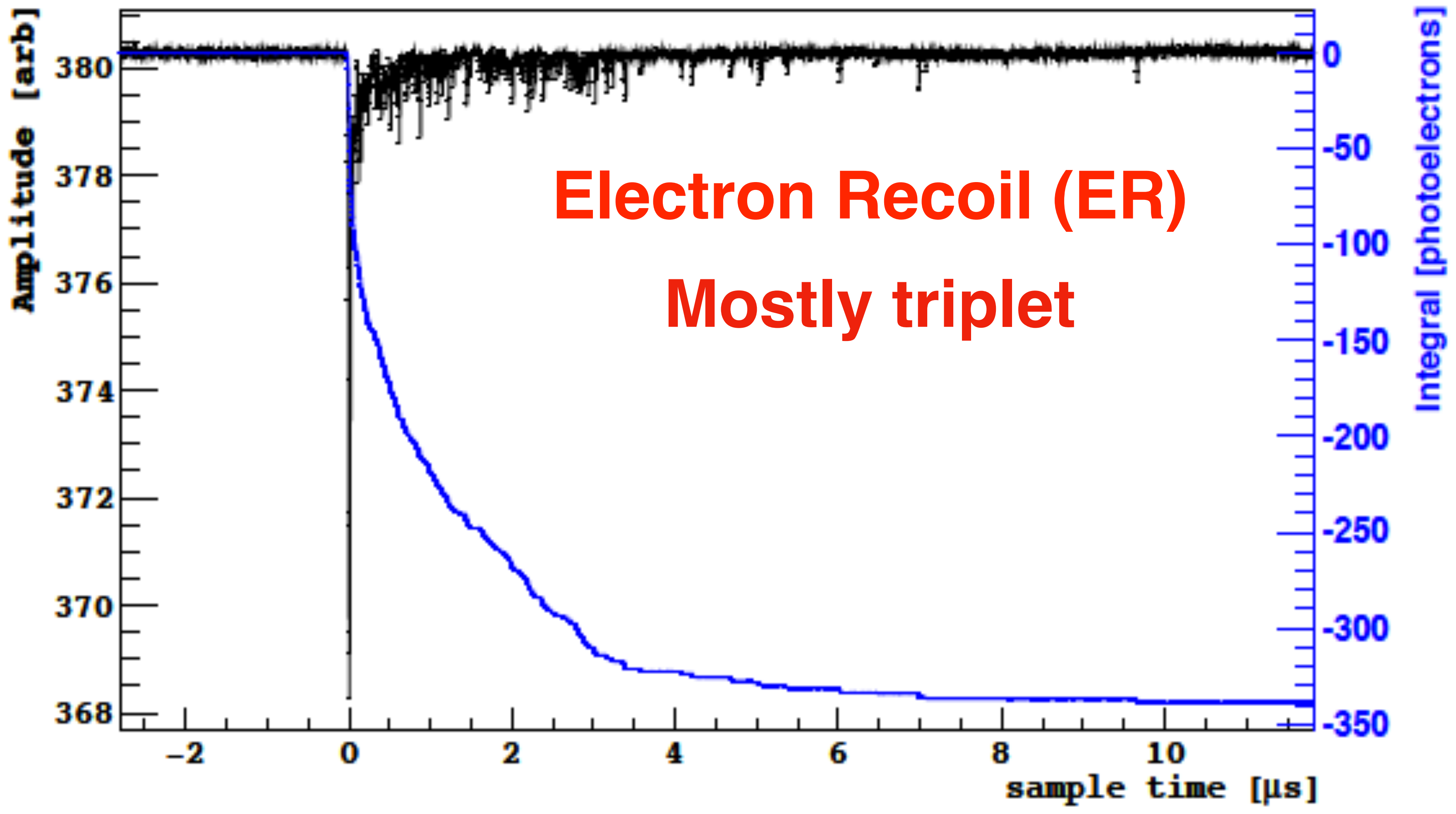


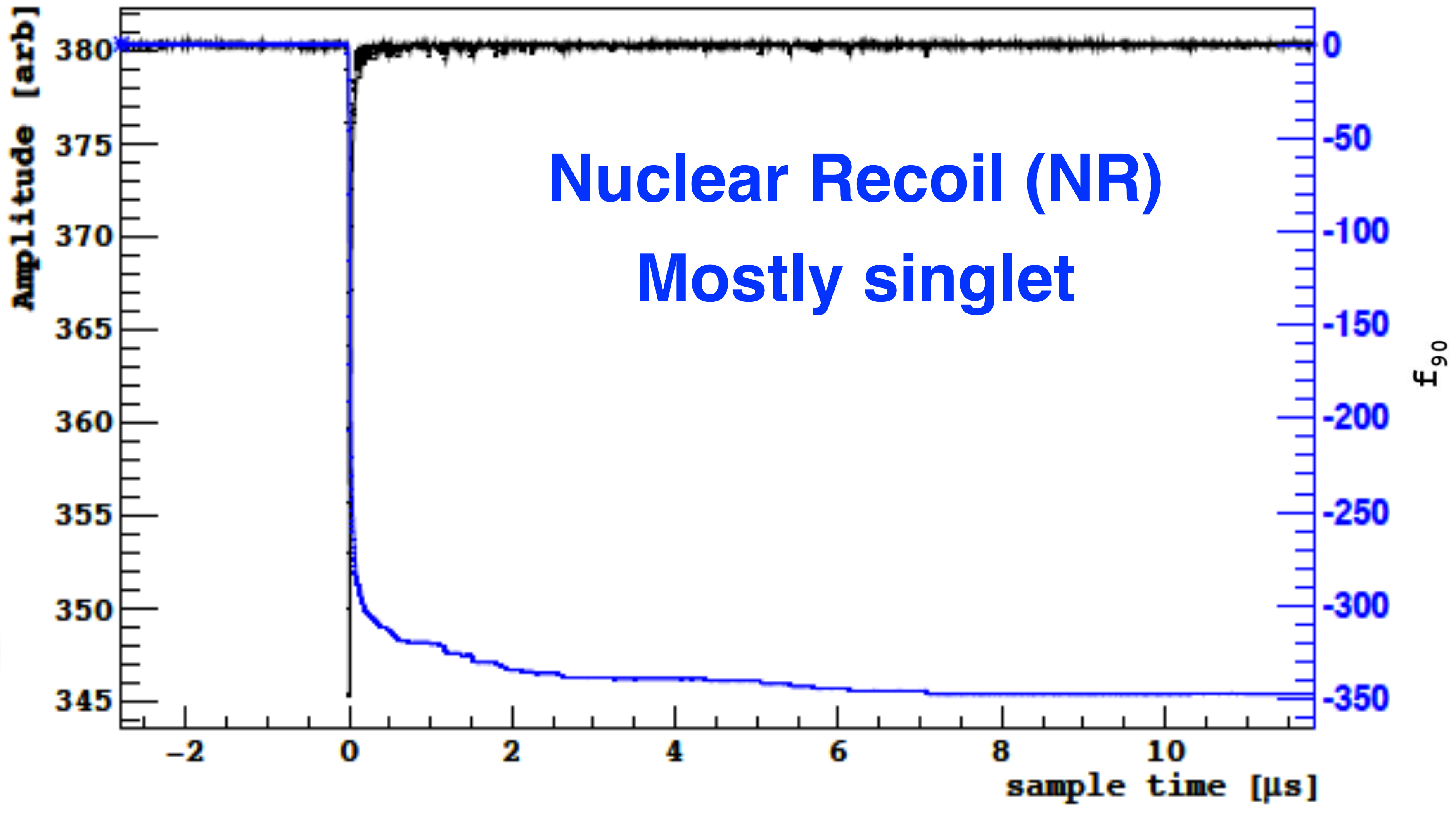
		LAr	*LKr*	*LXe*
Physical properties	Atomic number	18	36	54
	Boiling point at 1 bar, T_b (K)	87.3	119.8	165.0
	Density at T_b (g/cm^3)	1.40	2.41	2.94
Ionisation	W (eV)[1]	23.6	20.5	15.6
	Fano factor	0.11	~0.06	0.041
	Drift velocity ($cm/\mu s$) at 3 kV/cm	0.30	0.33	0.26
	Transversal diffusion coefficient at 1 kV/cm (cm^2/s)	~20		~80
Scintillation	Decay time[2], fast (ns)	5	2.1	2.2
	slow (ns)	1000	80	27/45
	Emission peak (nm)	127	150	175
	Light yield[2] (phot./Mev)	40000	25000	42000
	Radiation length (cm)	14	4.7	2.8
	Moliere radius (cm)	10.0	6.6	5.7

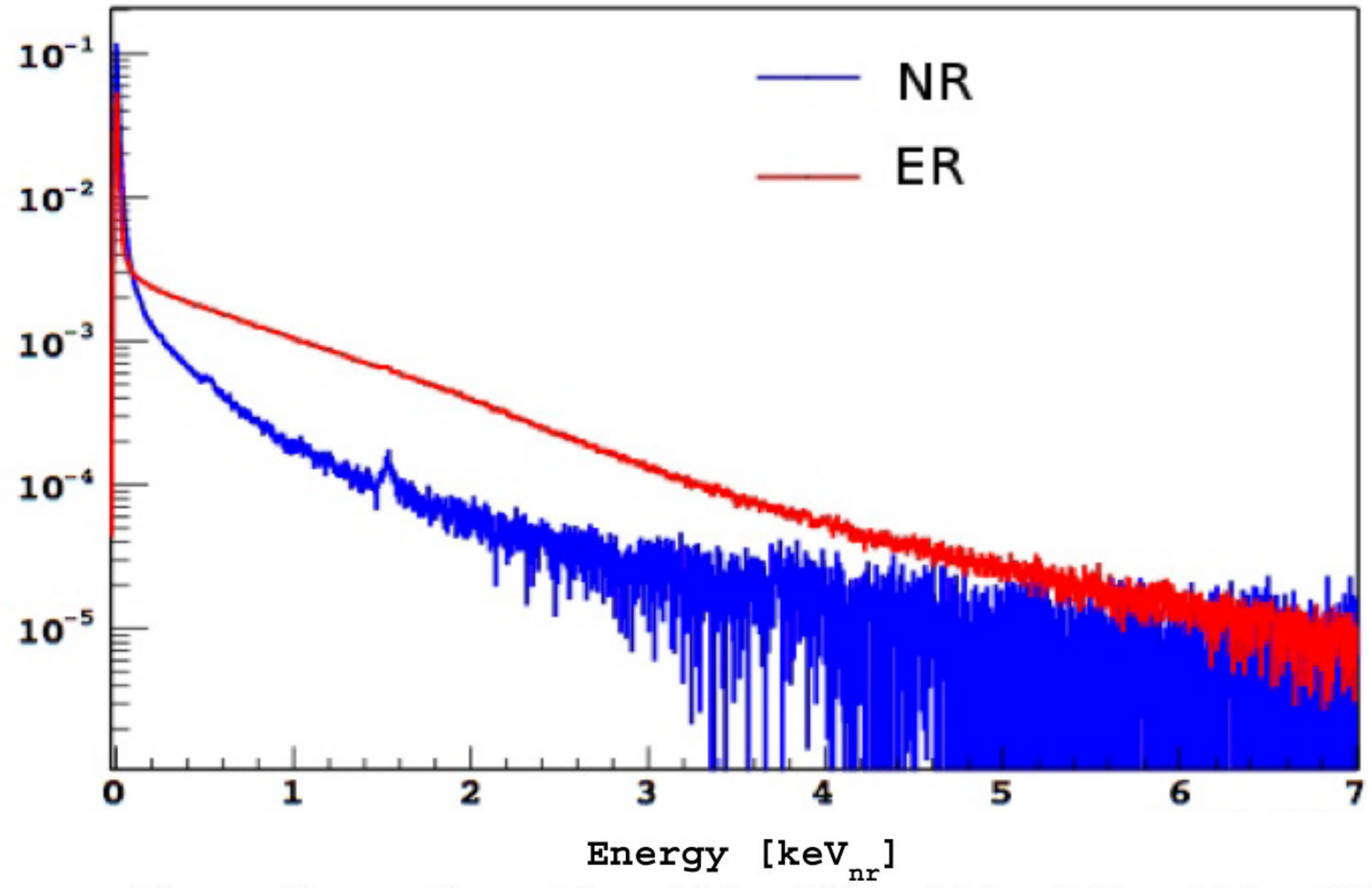
Excellent discrimination power!

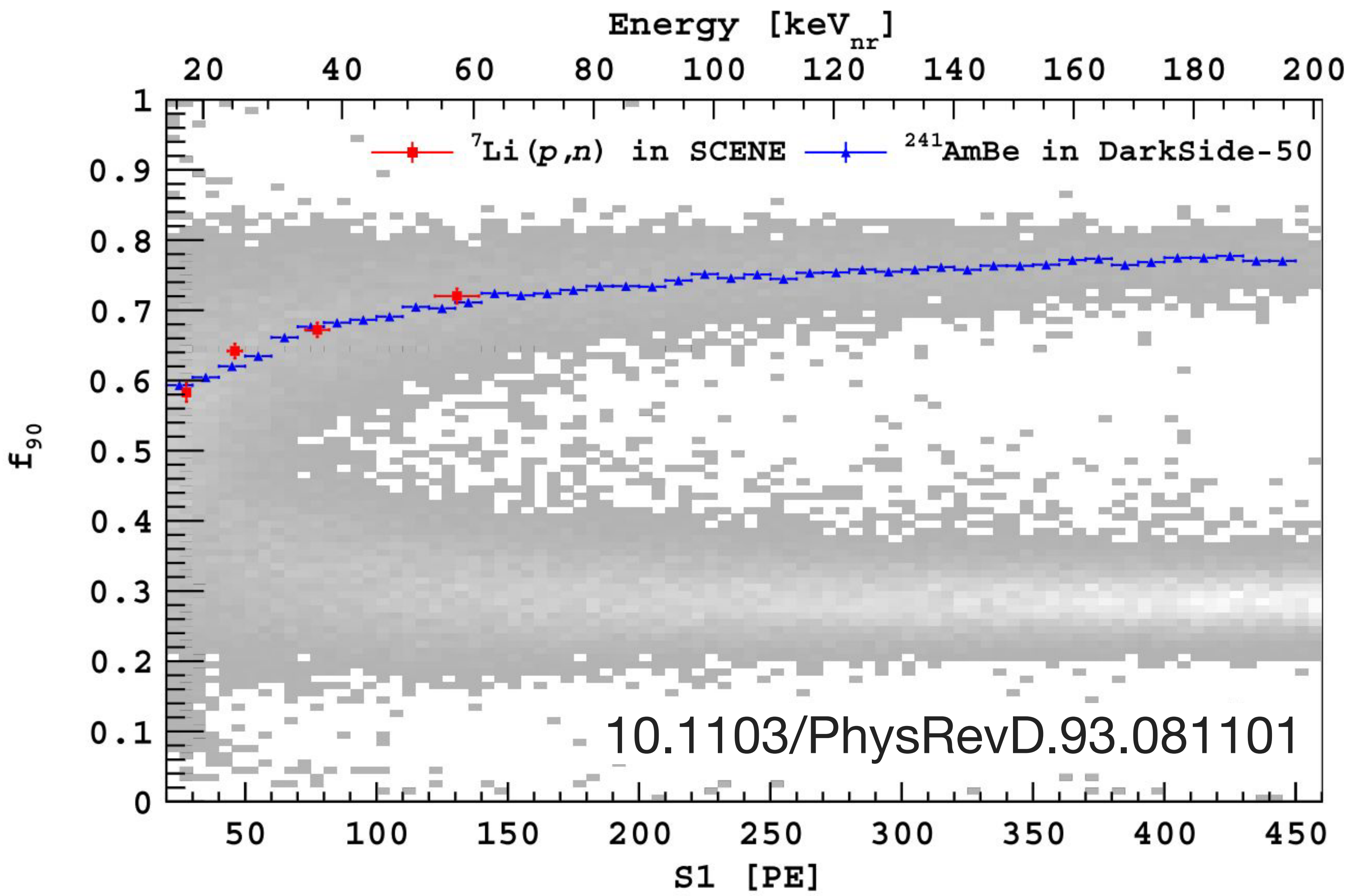
ER rejection in LAr











10.1103/PhysRevD.93.081101

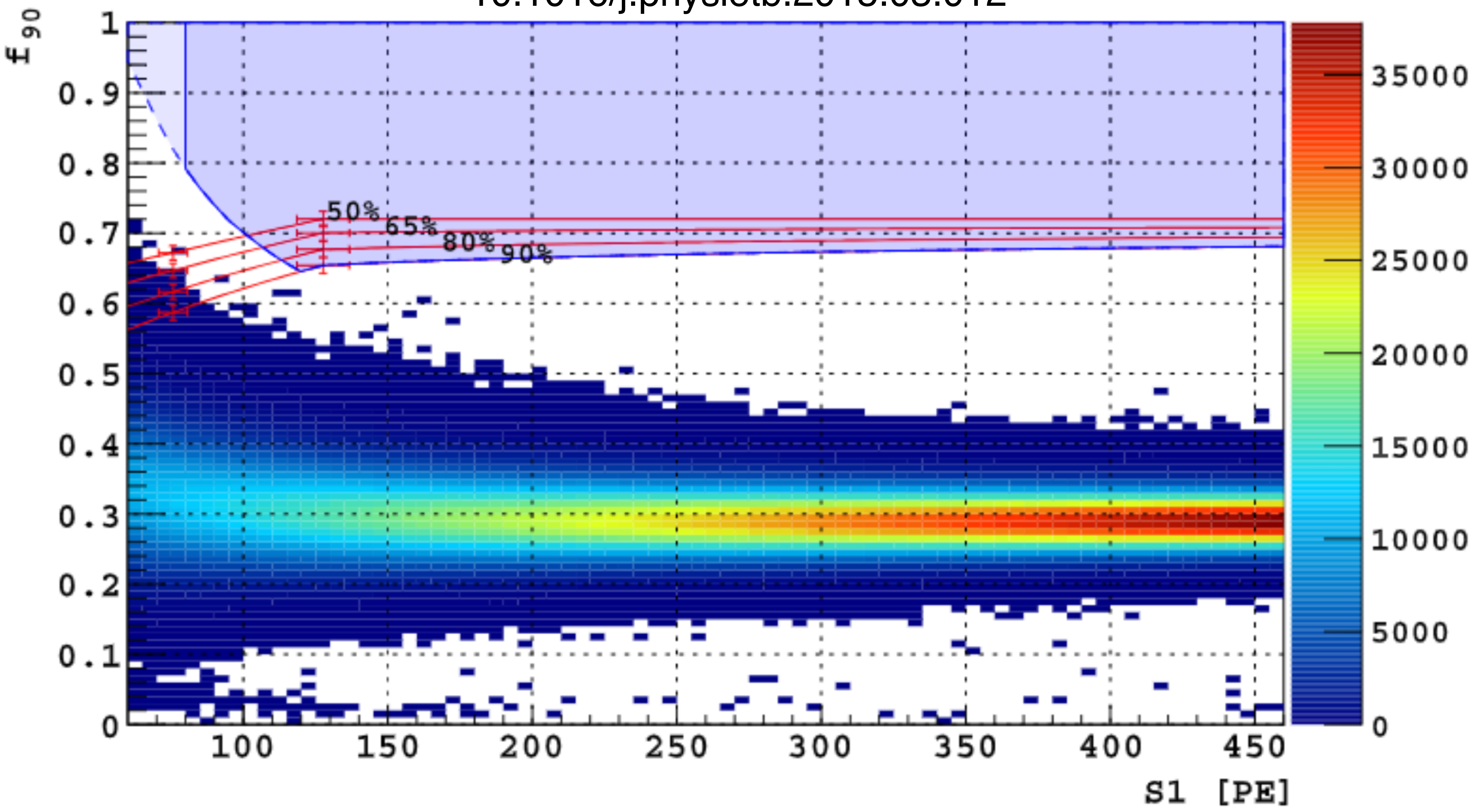
β,γ → ER ν, n, WIMPs → NR

$$f_{\text{prompt}} = \frac{\text{prompt light}}{\text{total light}}$$

ER rejection in LAr

DarkSide-50

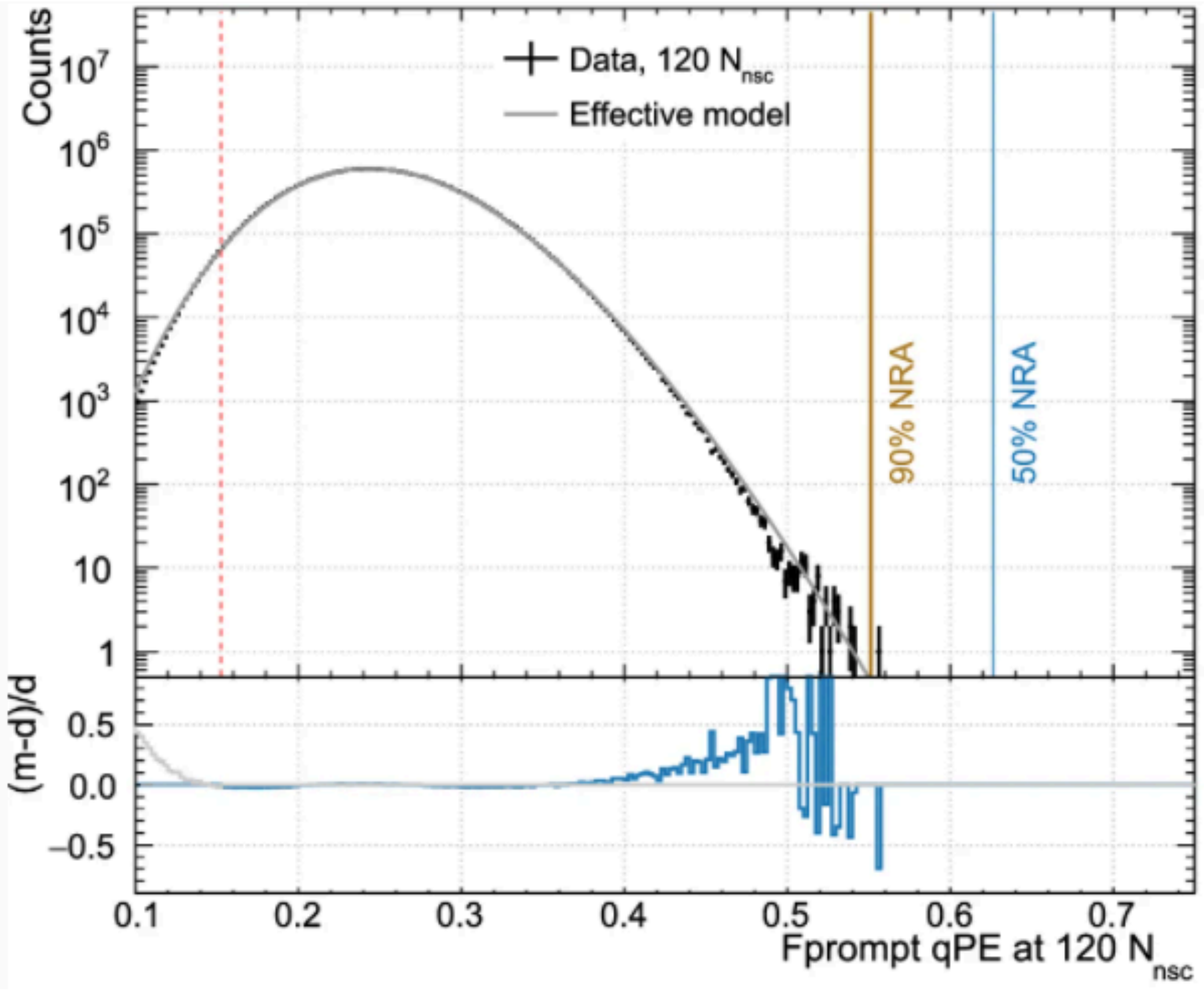
10.1016/j.physletb.2015.03.012



β,γ rejection better than 1.5x10^7

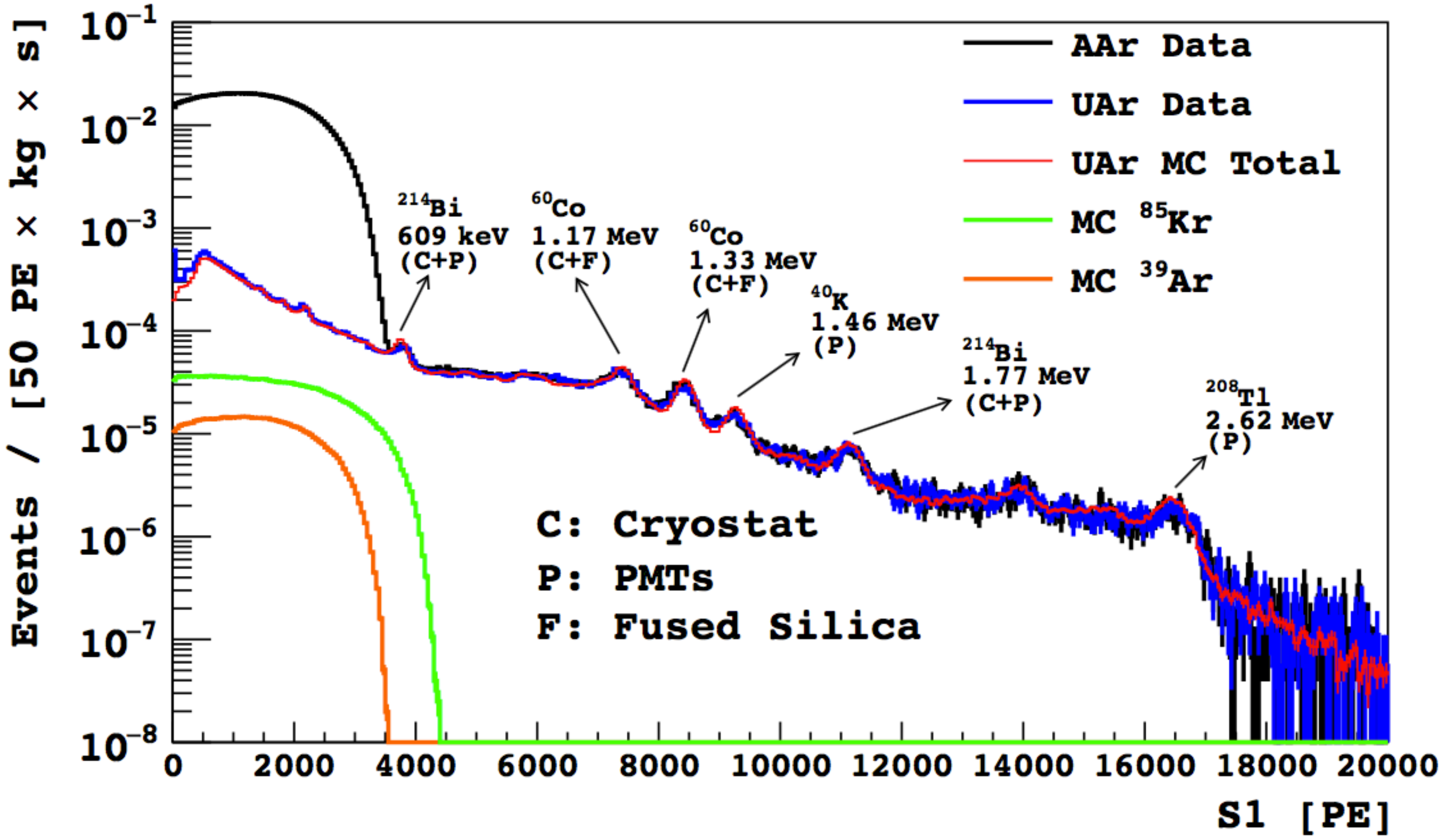
DEAP-3600

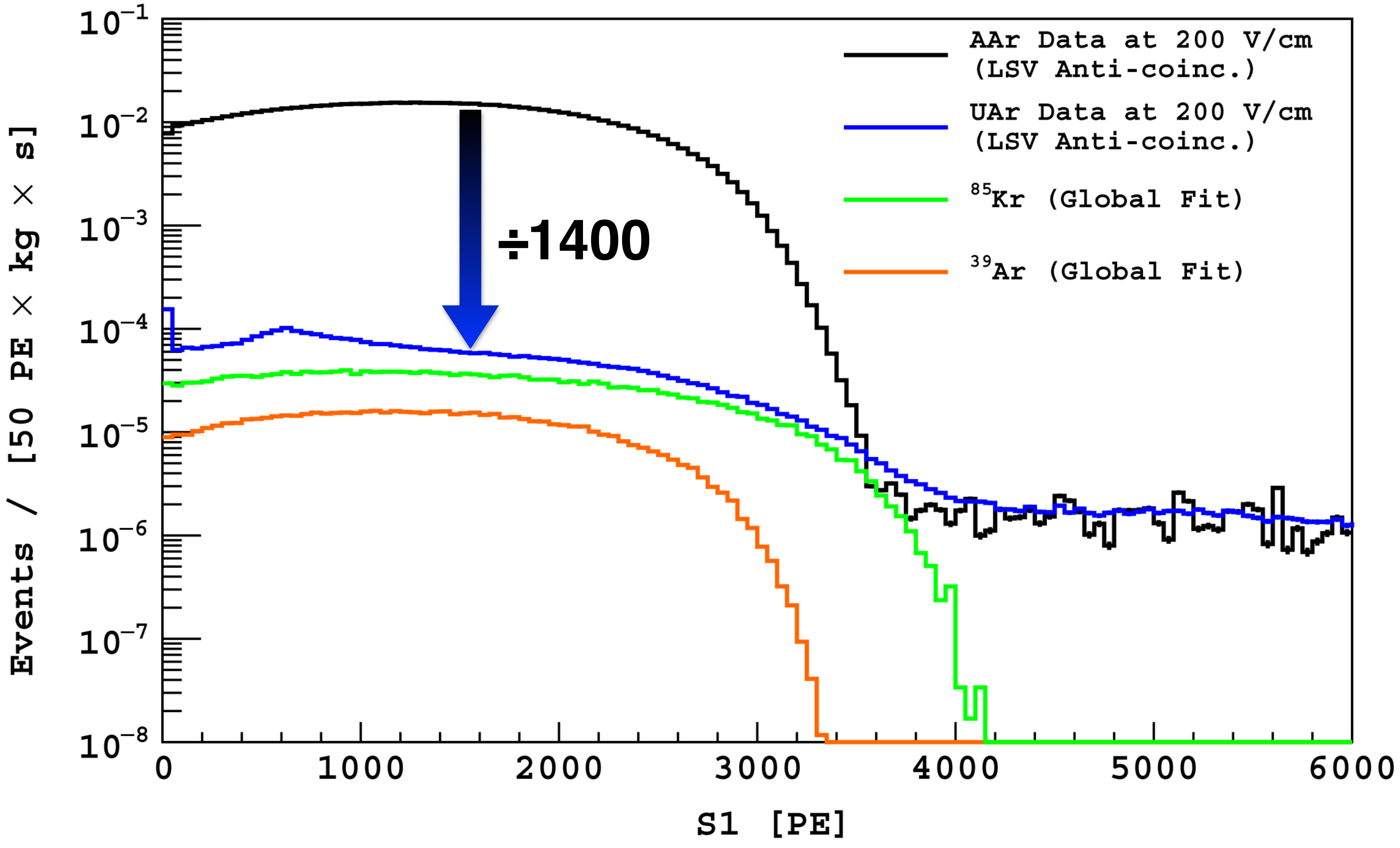
Eur. Phys. J. C 81,823 (2021)



β,γ rejection better than 10^8

LAr challenges: ^{39}Ar

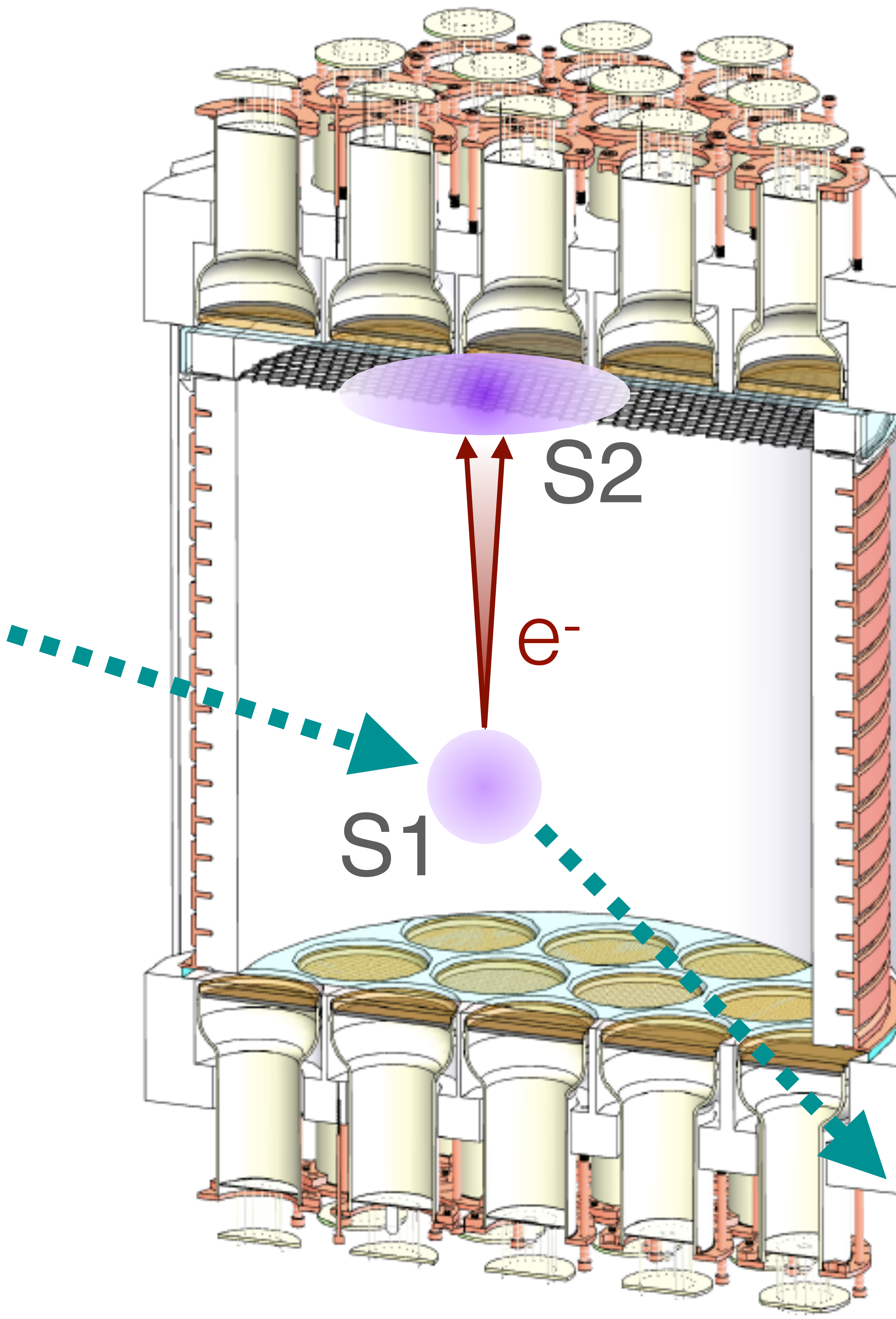




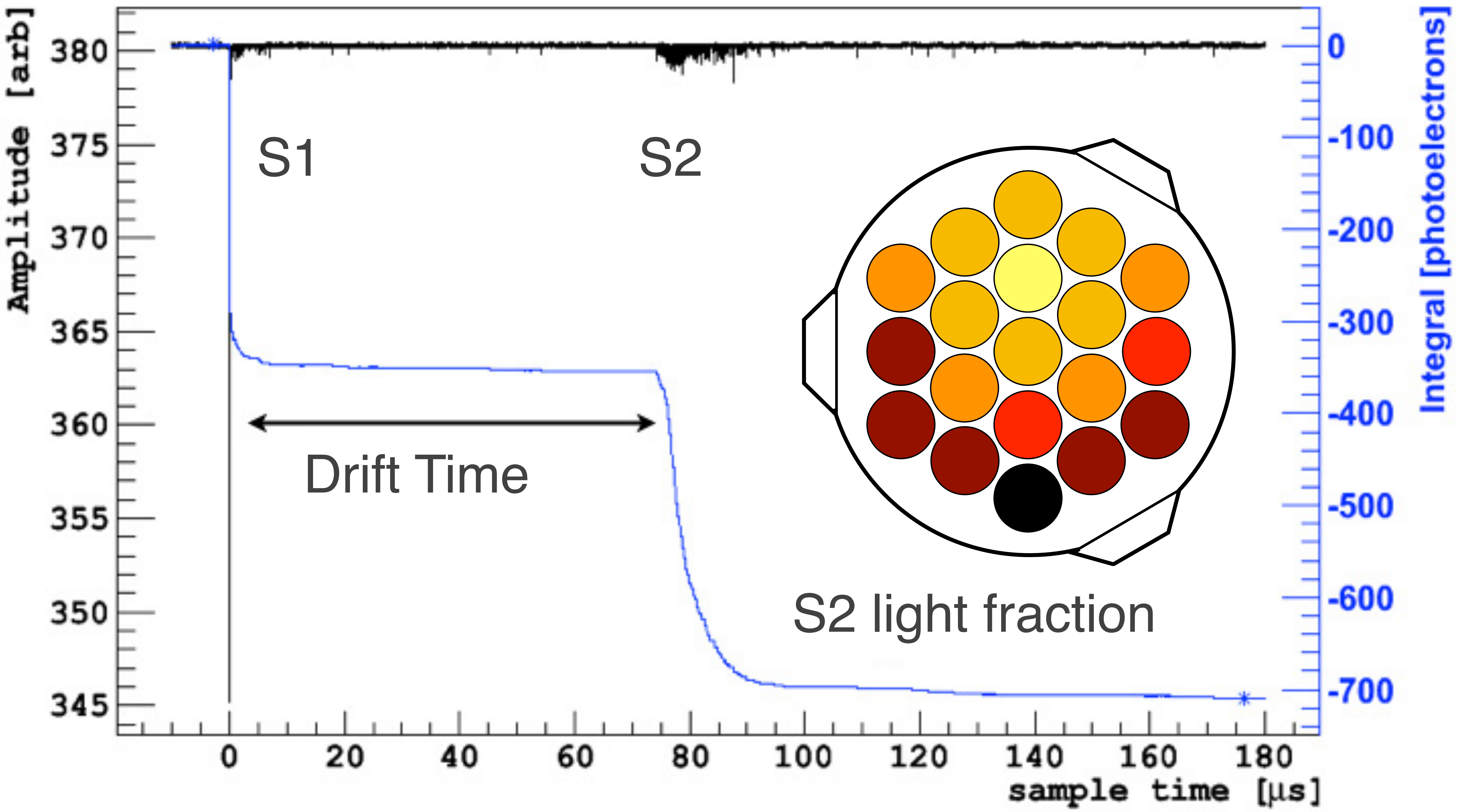
- ^{39}Ar is a cosmogenic isotope
- β-decay with 565 keV endpoint and ~269y of half life
- ~1Bq/kg in atmospheric Ar
- Rejection possible with PSD, but there's pile-up!

- No activation in Ar from deep gas reservoirs (UAr)
- Suppression factor ~1400 demonstrated in DS-50
- Possibly higher depletion factor

Dual-phase TPCs



3D position reconstruction



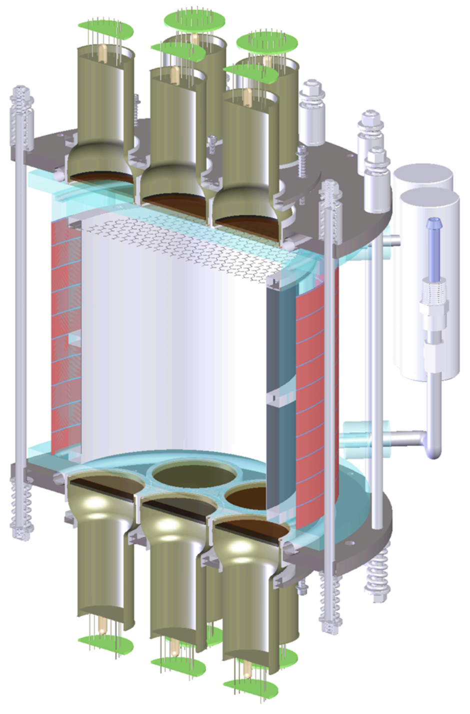
- Z from S1-S2 time difference
- XY from S2 light distribution

- Reliable fiducialization
- Multiple scattering rejection

The DarkSide program

A multi-stage approach

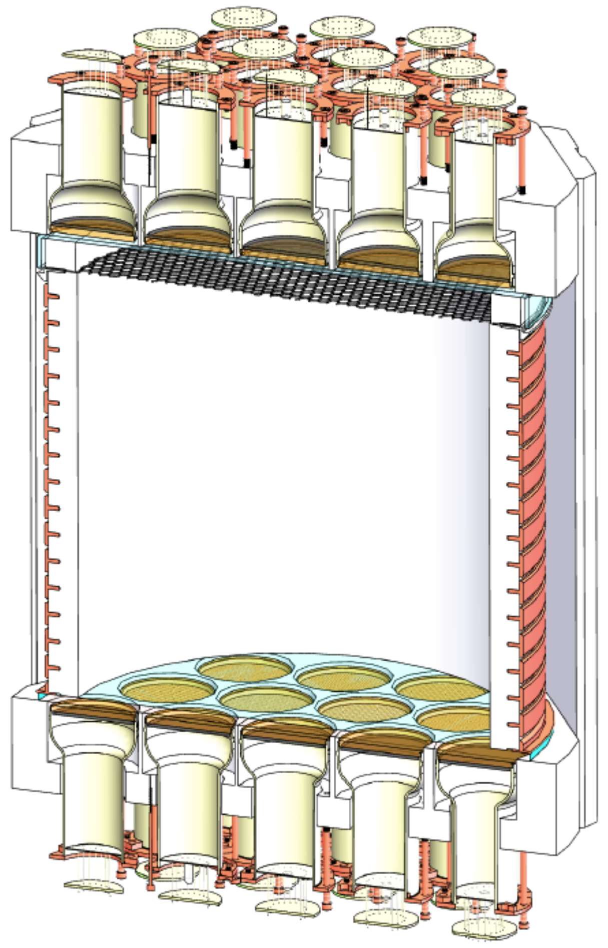
2012



DarkSide-10

- First prototype
- Helped to refine TPC design
- Demonstrated a light yield >9PE/keV$_{ee}$

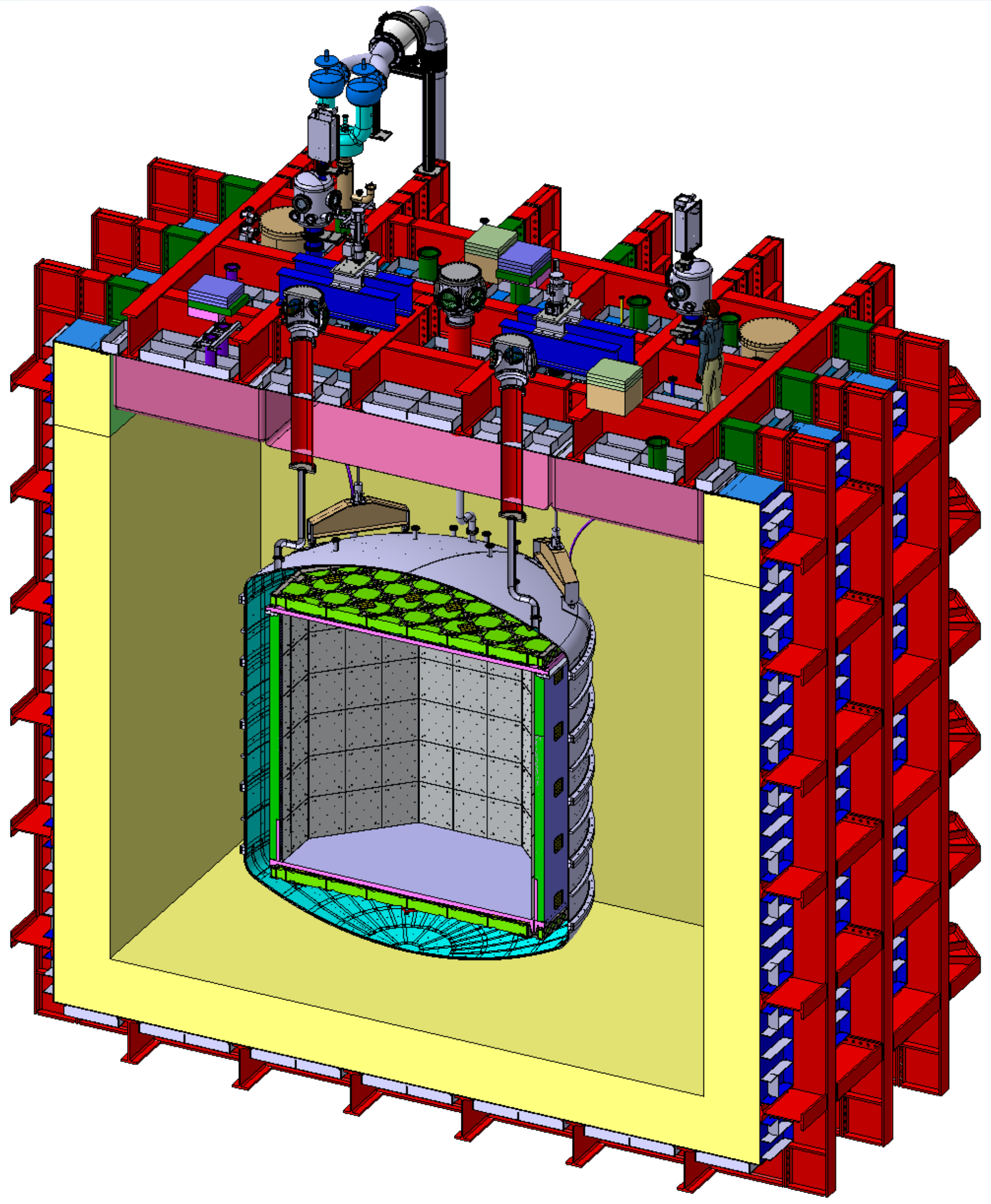
2013 - 2018



DarkSide-50

- Science detector
- Demonstrated the use of UAr
- First background-free results
- Best limits for low mass WIMP searches

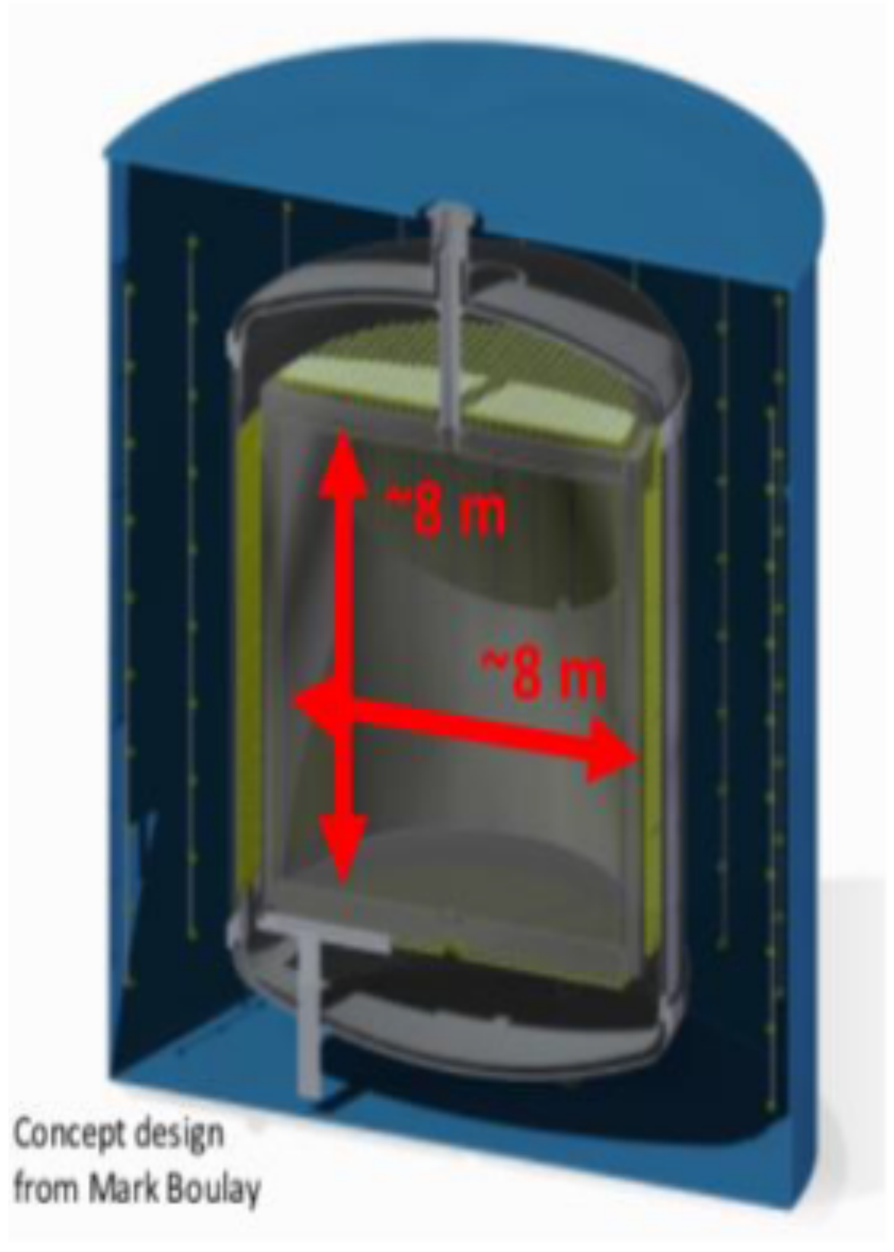
2025 - 2035



DarkSide-20k @ LNGS

- Novel technologies
- First peek into the neutrino fog
- Nominal exposure: 200 t y

2030s - ...



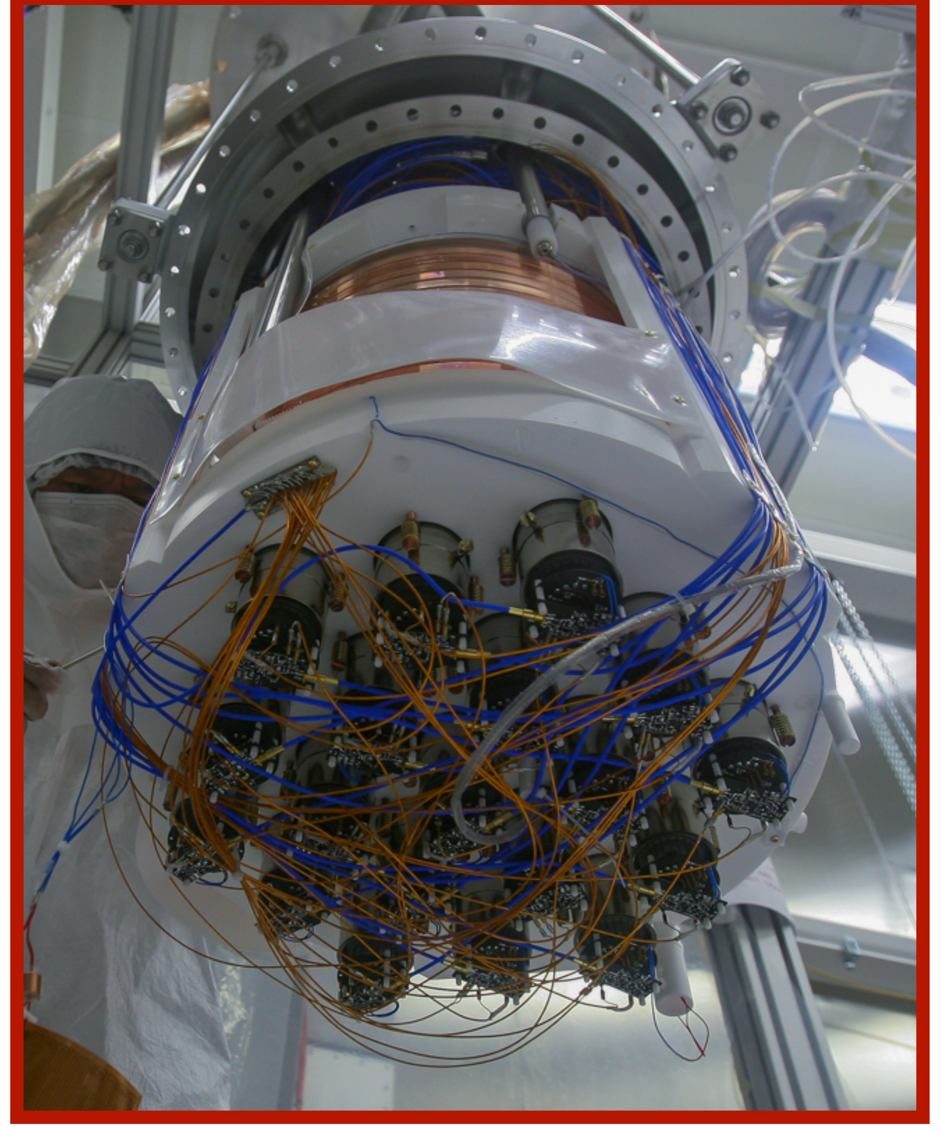
Concept design from Mark Boulay

Argo @ SNOLAB

- Ultimate LAr DM detector
- Push well into the neutrino fog
- Nominal exposure: 3000 t y

The GADMC

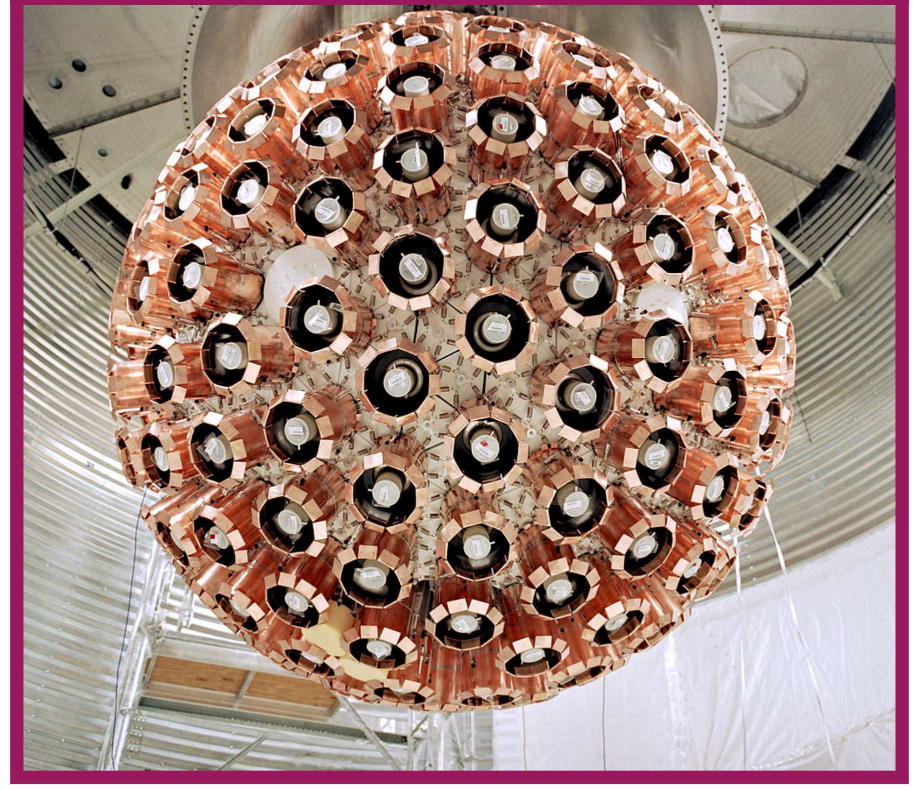
DarkSide-50 @ LNGS



ArDM @ Canfranc

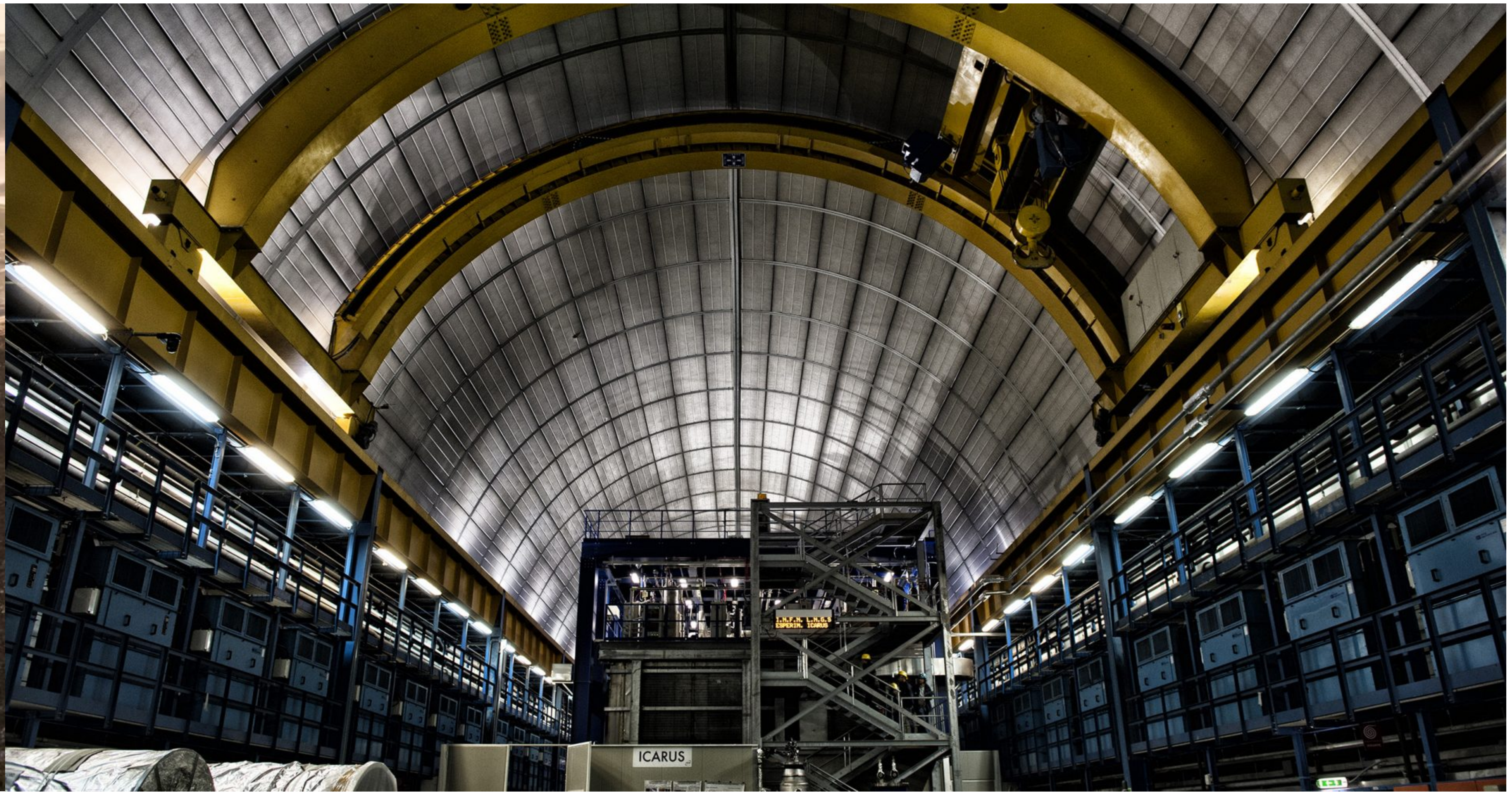
MiniClean @ Snolab

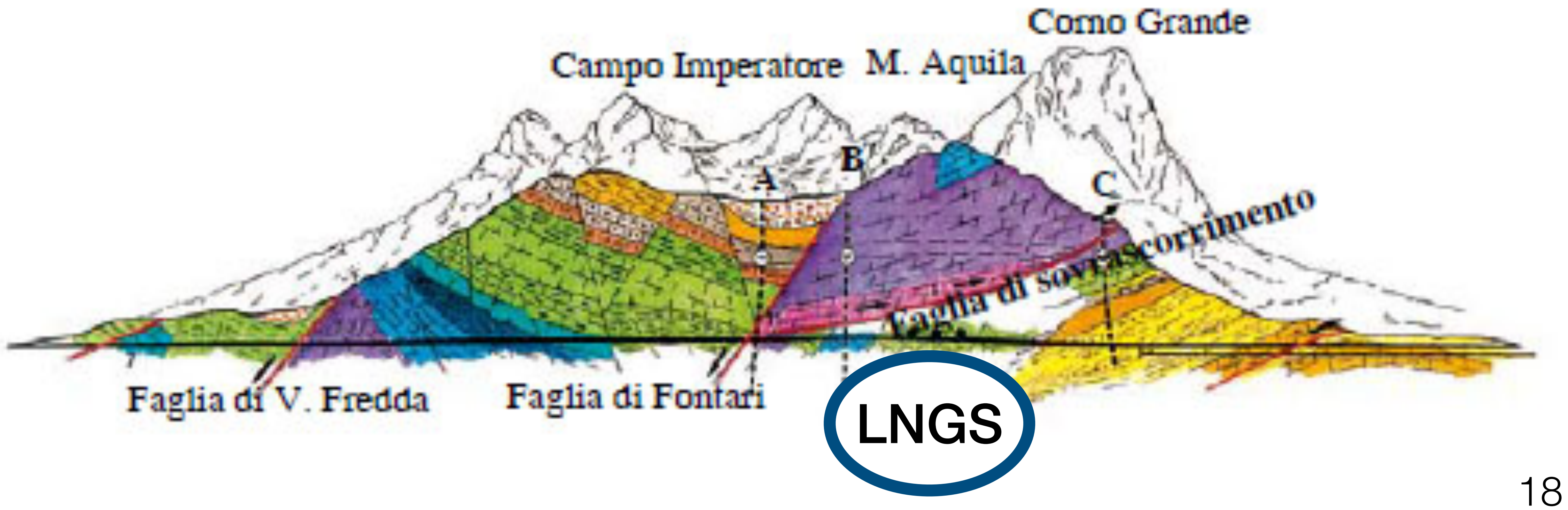
DEAP @ Snolab



>400 scientists, >100 institutions distributed across 13 countries

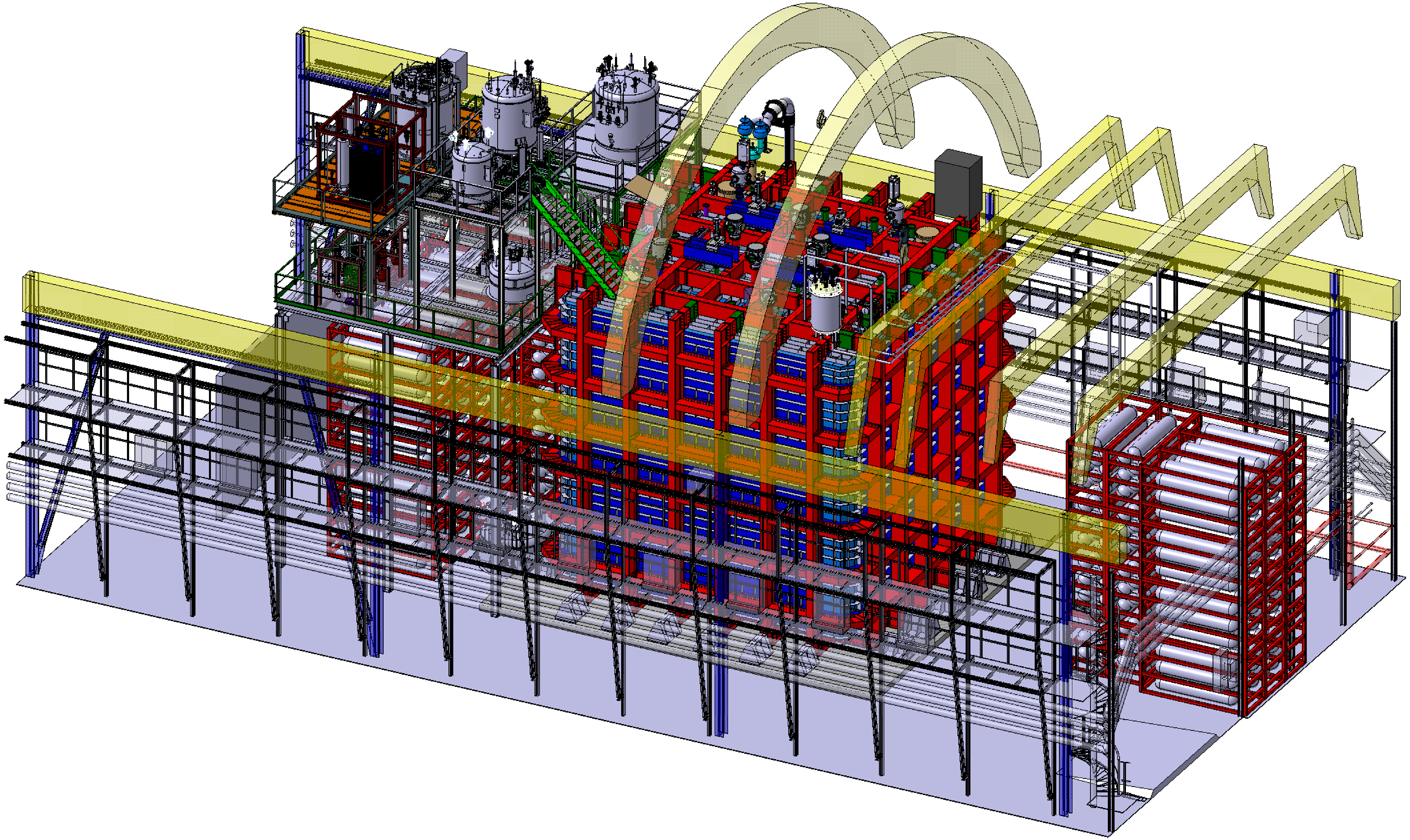
Host laboratory: LNGS



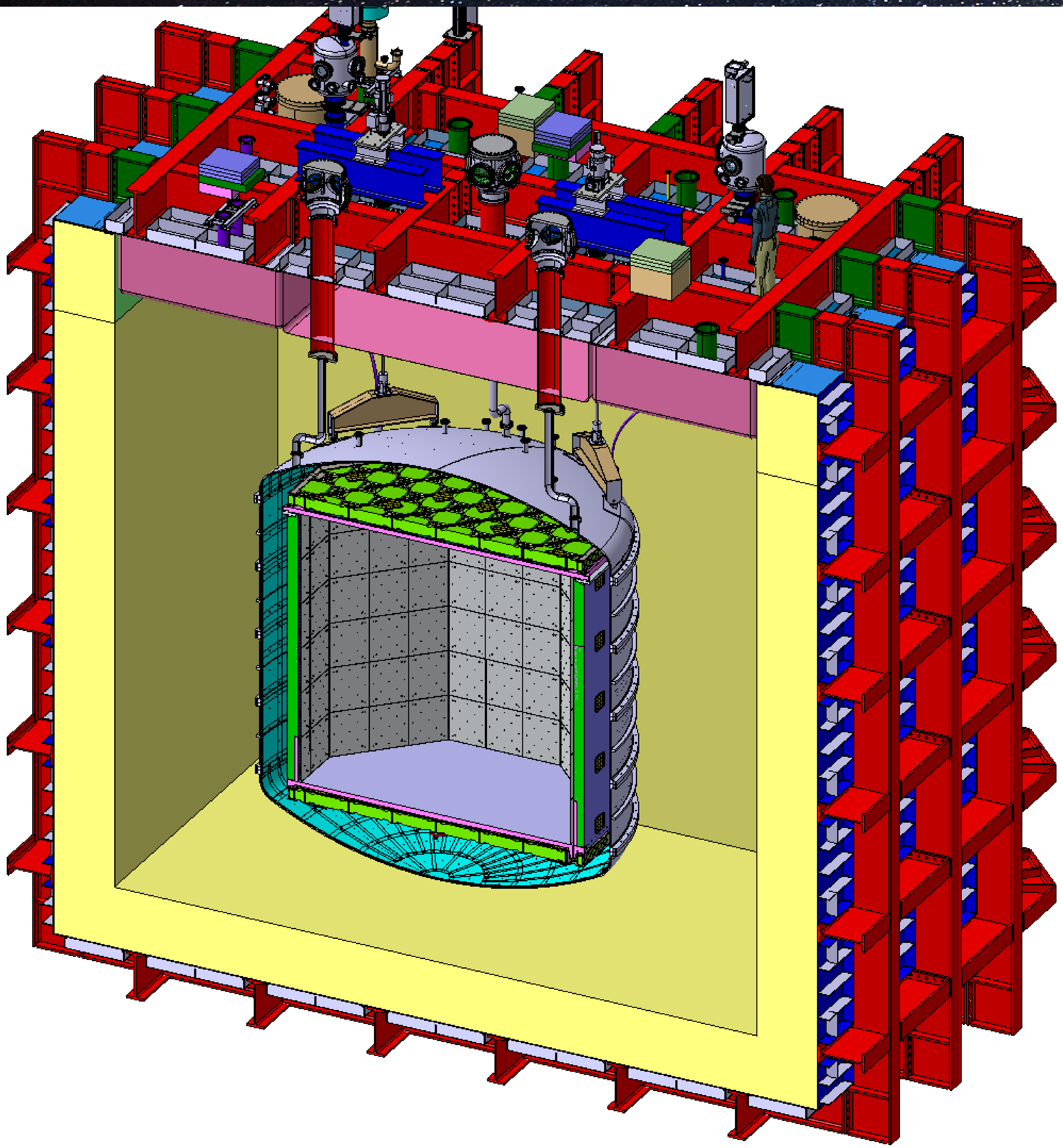


- Below ~1400m of rock (3400 m.w.e)
- Muon flux reduction factor ~10^6
- 3 main experimental halls (20x100x18 m^3)

DarkSide-20k in Hall C @ LNGS



DarkSide-20k overview



Nested detectors structure:

ProtoDUNE-like cryostat (8x8x8m³) - Muon veto

Ti vessel separating AAr from underground UAr.

Neutrons and γ veto

WIMP detector: dual-phase TPC hosting 50t of LAr

Fiducial mass: 20 tonnes

Multiple detection channels for bkg supression:

Neutron after cuts: < 0.1 in 10 y

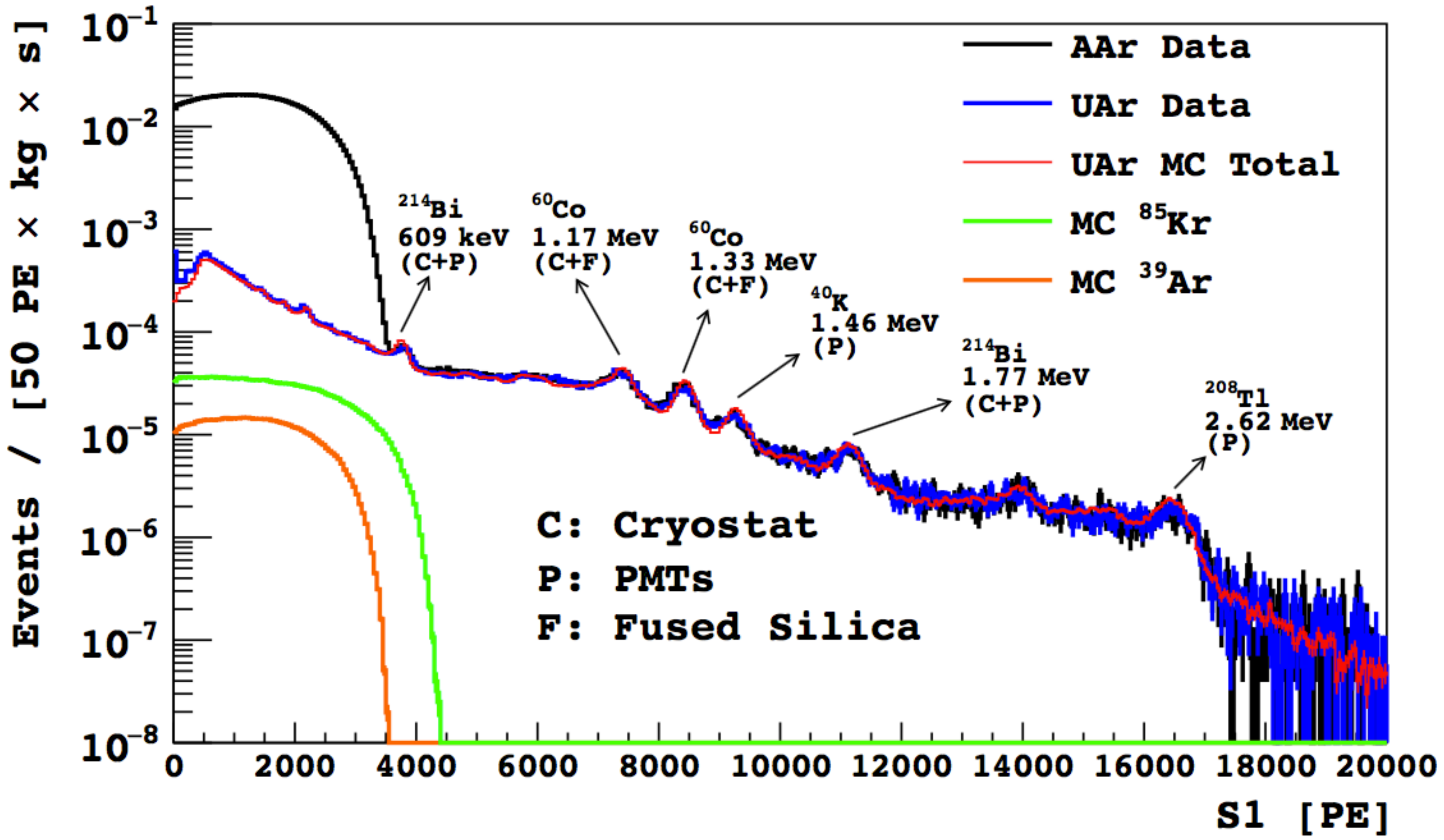
β and γ after cuts: < 0.1 in 10 y

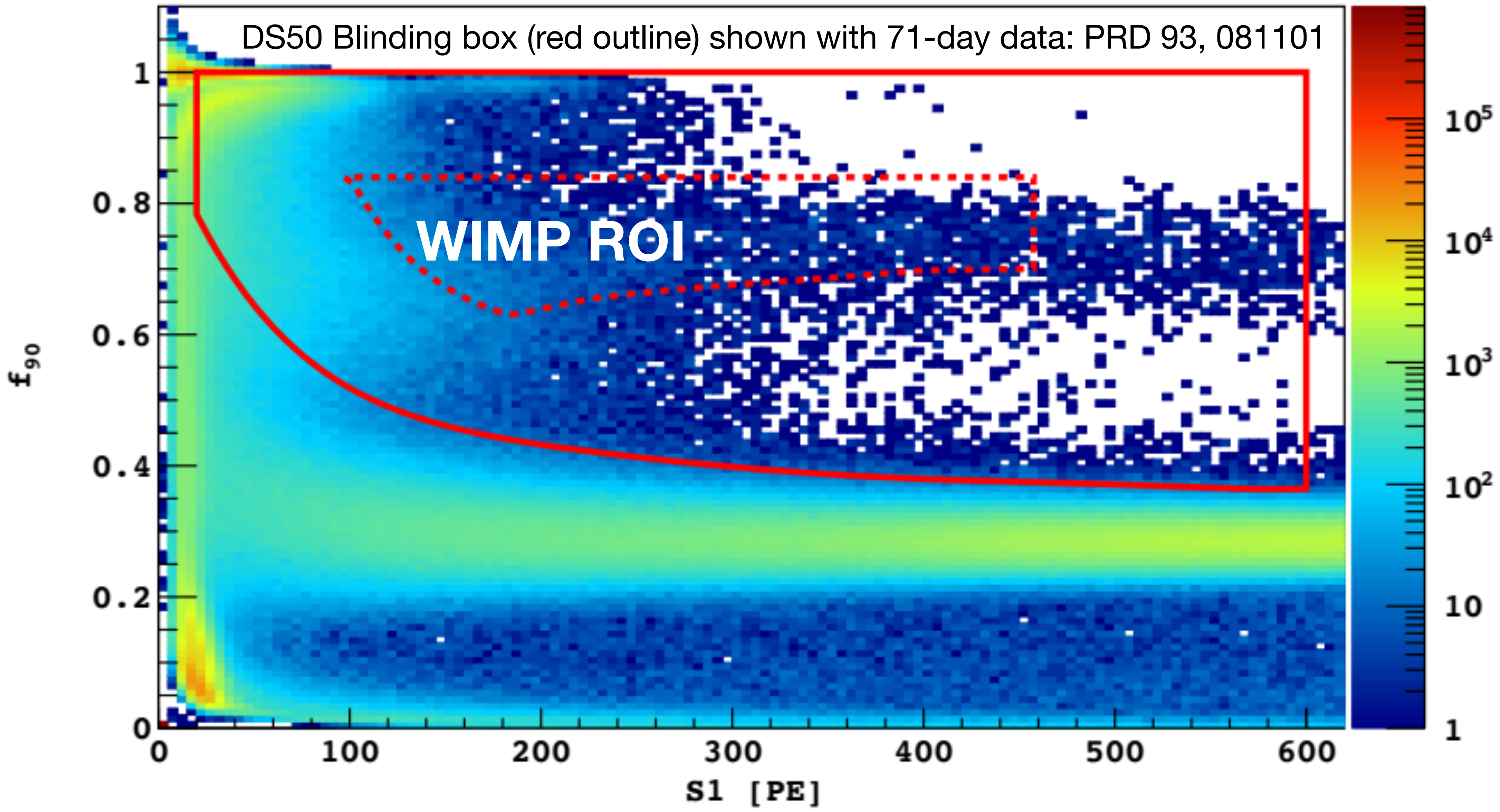
Position reconstruction resolution:

~ 1 cm in XY

~ 1 mm in Z

Backgrounds and Mitigation Strategies




DS50 Blinding box (red outline) shown with 71-day data: PRD 93, 081101

Electron Recoils (ER)

^{39}Ar β decays → Use of UAr, PSD

γ decays from U,Th chains + non actinides (^{40}K, ^{60}Co, ^{137}Cs) → Material selection, PSD

Surface events

Position reconstruction

Radon progeny → Surface cleaning

Rn abatement

Nuclear Recoils (NR)

Radiogenic neutrons, mainly from (α,n) reactions.

→ Material selection, Neutron Veto

Cosmogenic neutrons, from materials activation due to residual muon flux → Muon Veto

Atmospheric neutrinos → Irreducible

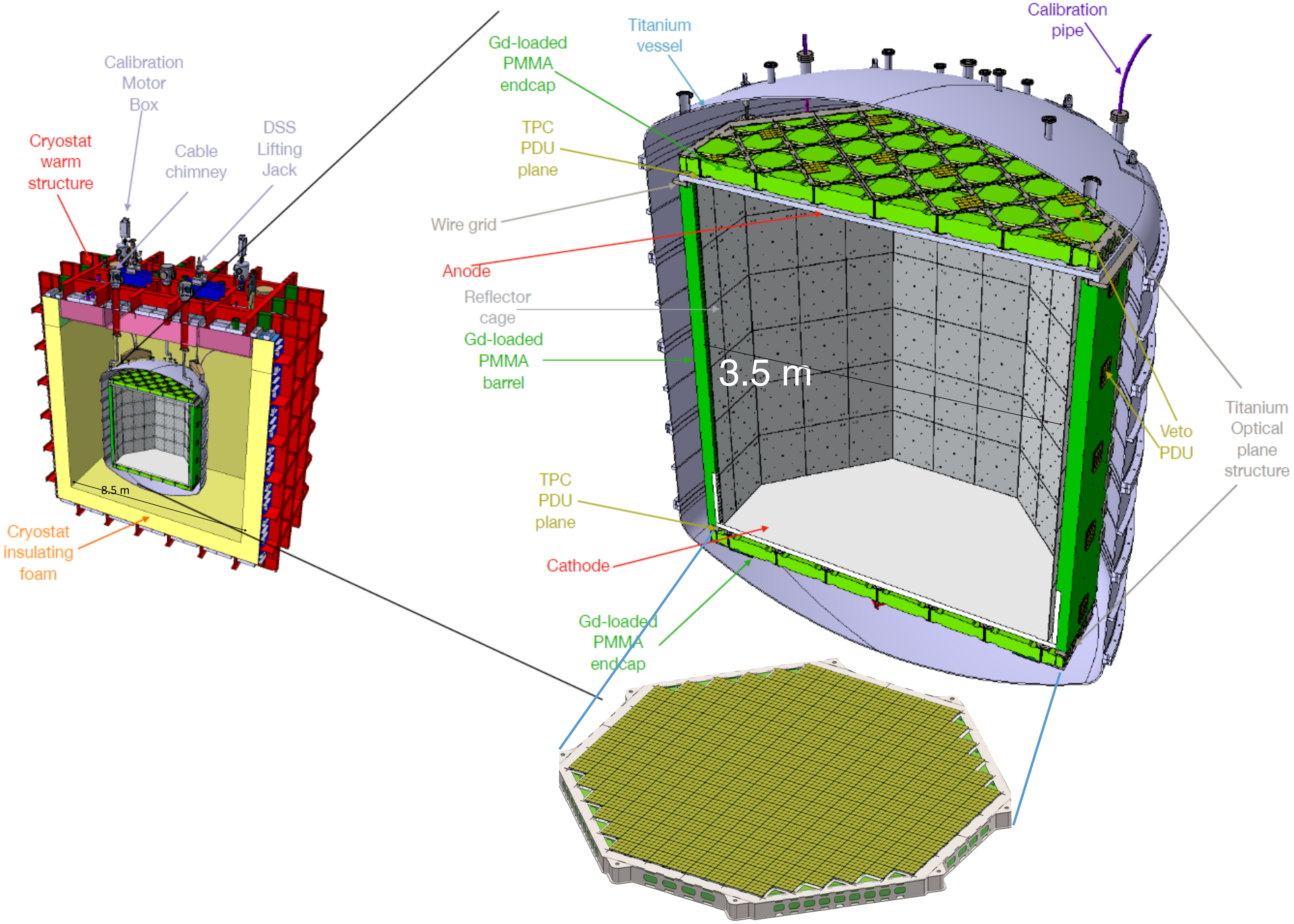
Inner detector

- Integration of **TPC** and **VETO** in a single object

- **TPC Vessel:**
  - top and bottom: transparent pure acrylic
  - lateral walls: Gd-loaded acrylic + reflector + WLS
  - anode, cathode and field cage made with conductive paint (Clevios)
- **TPC readout:** 21m^2 cryogenic SiPMs

- **Veto:**
- TPC surrounded by a single phase (S1 only) detector in UAr
- TPC lateral walls + additional top&bottom planes in Gd loaded acrylic (PMMA)
  - ○ to thermalize n (acrylic is rich in Hydrogen)
  - ○ neutron capture releases high energy γ
- **Veto readout:** 5 m^2 cryogenic SiPMs

99 t UAr held in Ti vessel



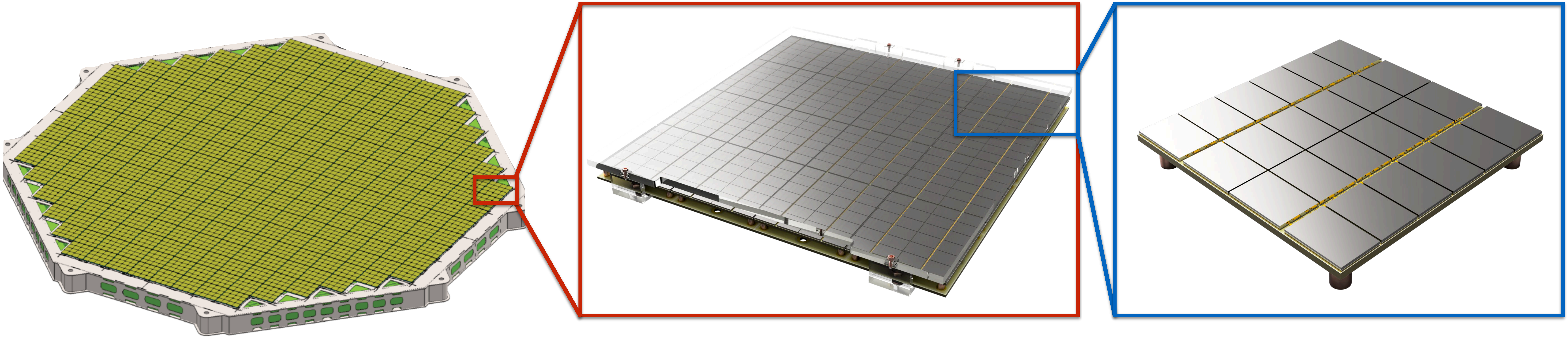
TPC photo-detection system

Photo-detection system

TPC optical plane

Photo-Detection Unit

Tile



TPC planes area: ~21m^2

Organized in 525 PDUs

100% coverage of TPC top and bottom

16 tiles arranged in 4 readout channels

SiPM bias distribution

cryogenic pre-amplifiers bias

Signal transmission

Channels switch-on/off

Photosensor

Array of 24 SiPMs

Signal pre-amplification

The journey of UAr: extraction

Picture of the extraction plant used to procure DS50 UAr target (<0.5kg/d)

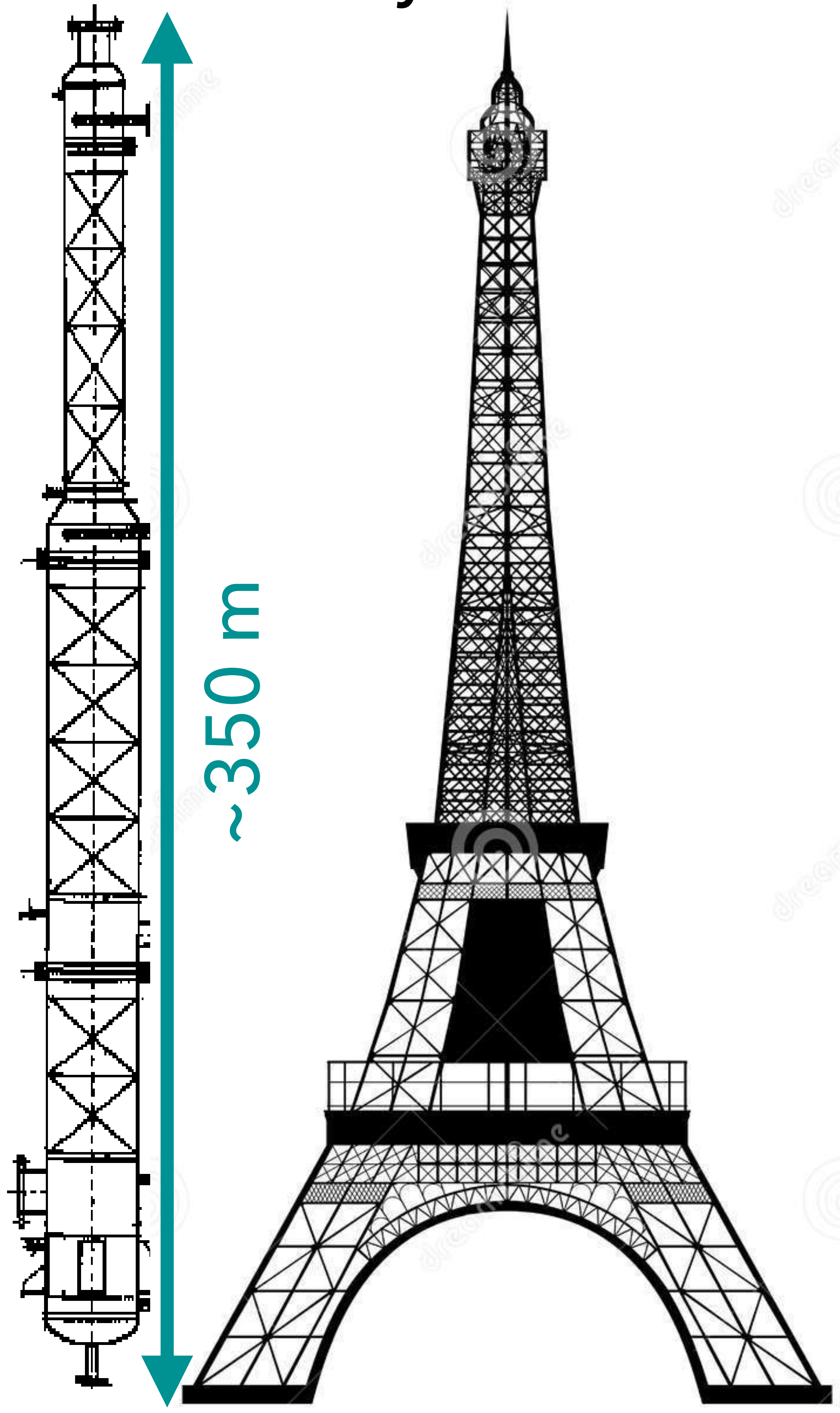
- CO_2 well in Cortez, CO, USA;
- Industrial scale extraction plant;
- Plant ready to be shipped;
- Civil work ongoing;
- Expected argon purity at outlet: 99.99%;
- UAr extraction rate: 250-330 kg/day;

The journey of UAr: purification

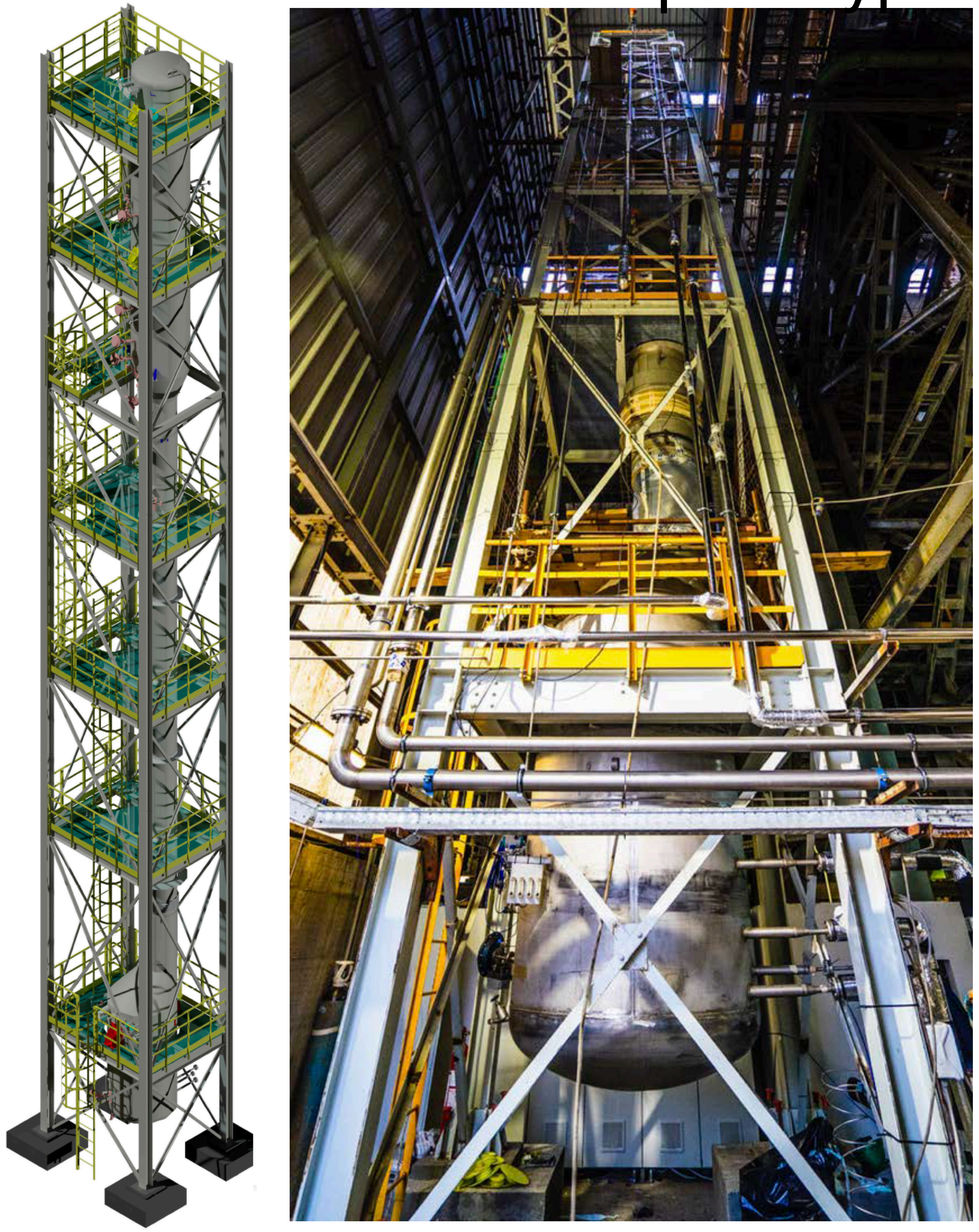
ARIA: UAr distillation plant

- Cryogenic distillation column in Sardinia (Italy).
- Installed in the shaft of a coal mine
- Three sections: bottom reboiler, 28 central modules (12 m each), top condenser
- Chemical purification rate: 1 t/day
- First module operated according to specs with nitrogen in 2019 (Eur. Phys. J. C (2021) 81:359)
- Run completed with Ar at the end of 2020: results to be published soon.
- Full assembly to start within 2022

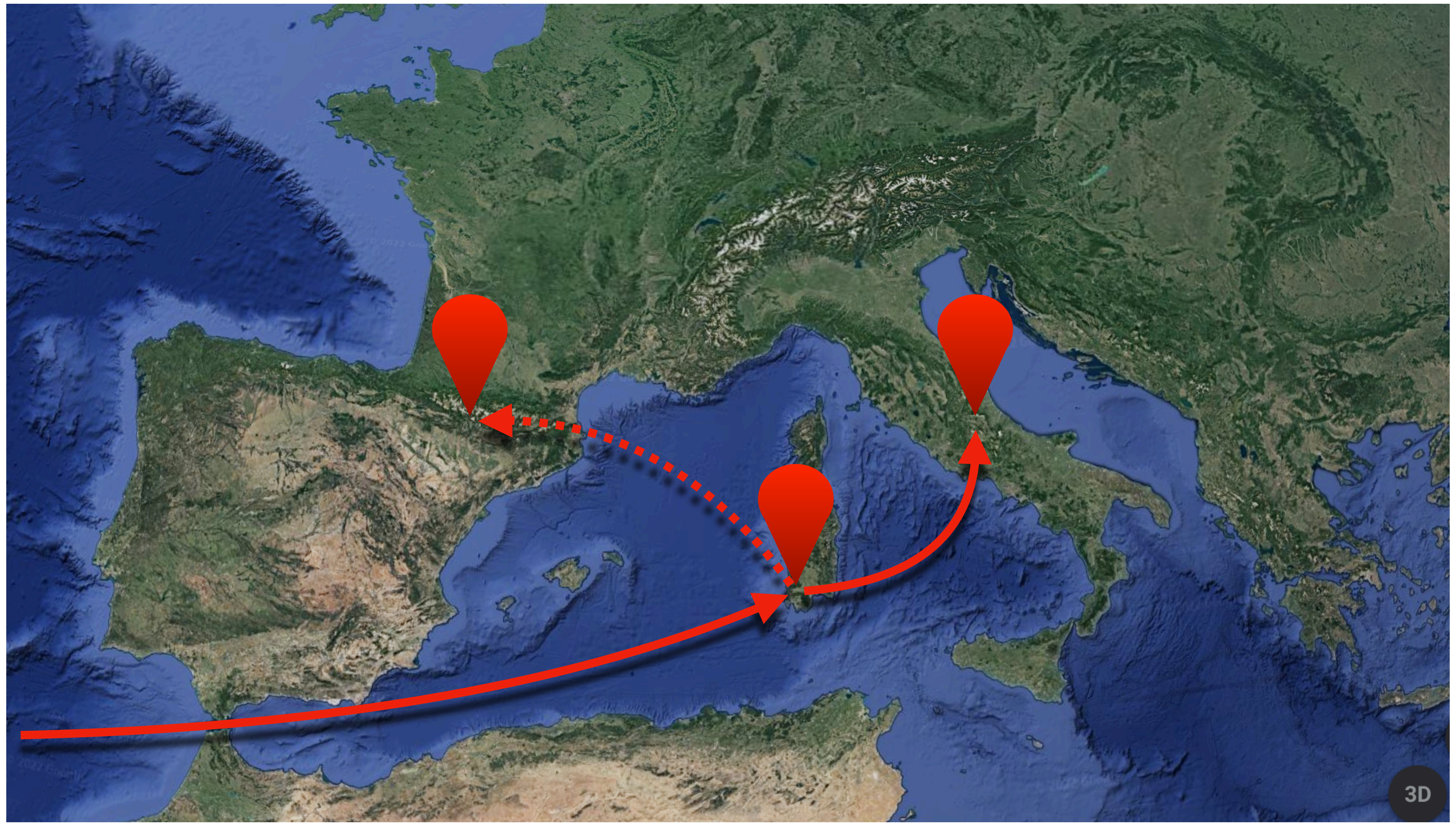
Sketch of ARIA when fully assembled

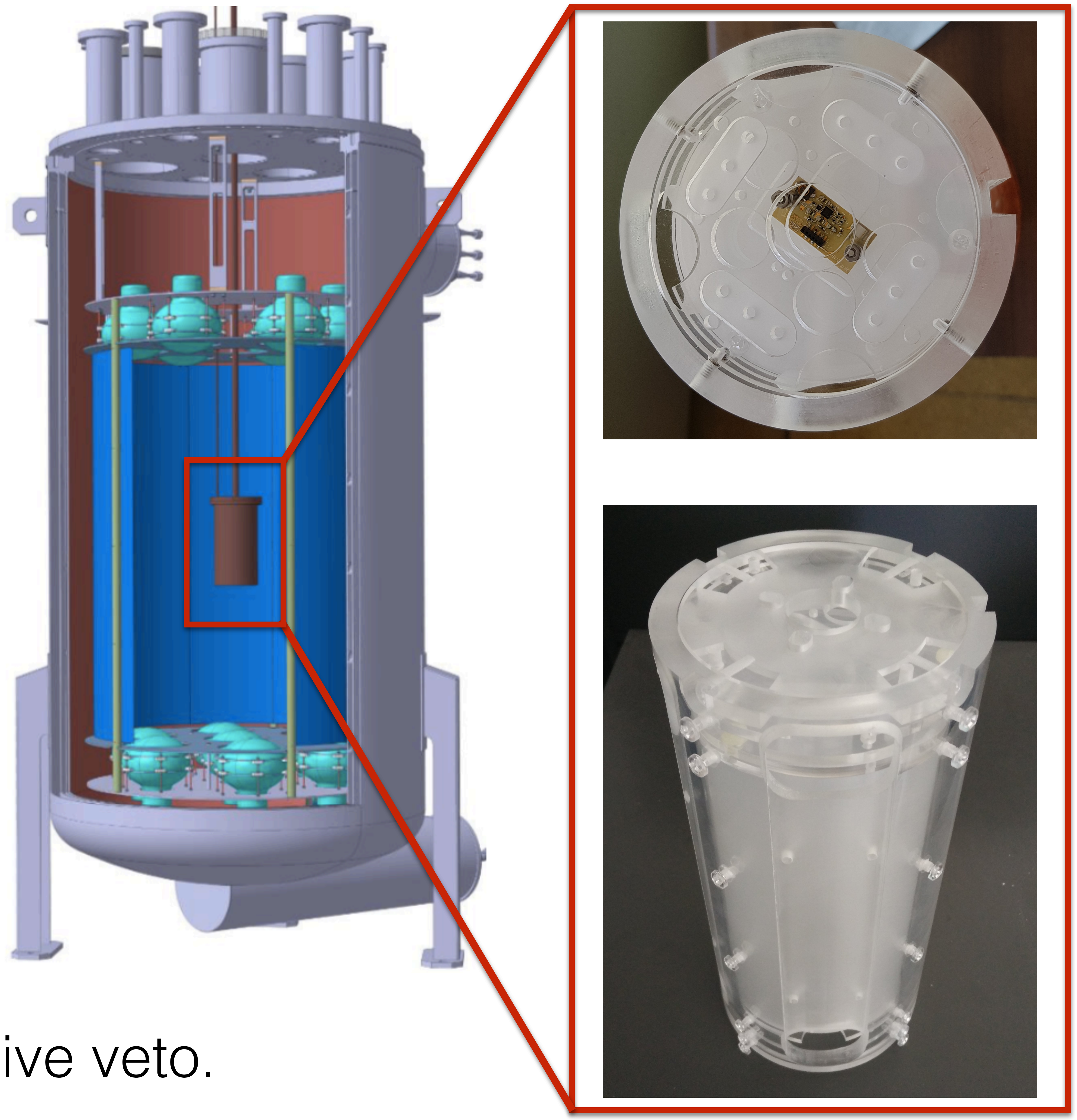


Drawing and picture of ARIA distillation column prototype



The journey of UAr: assaying



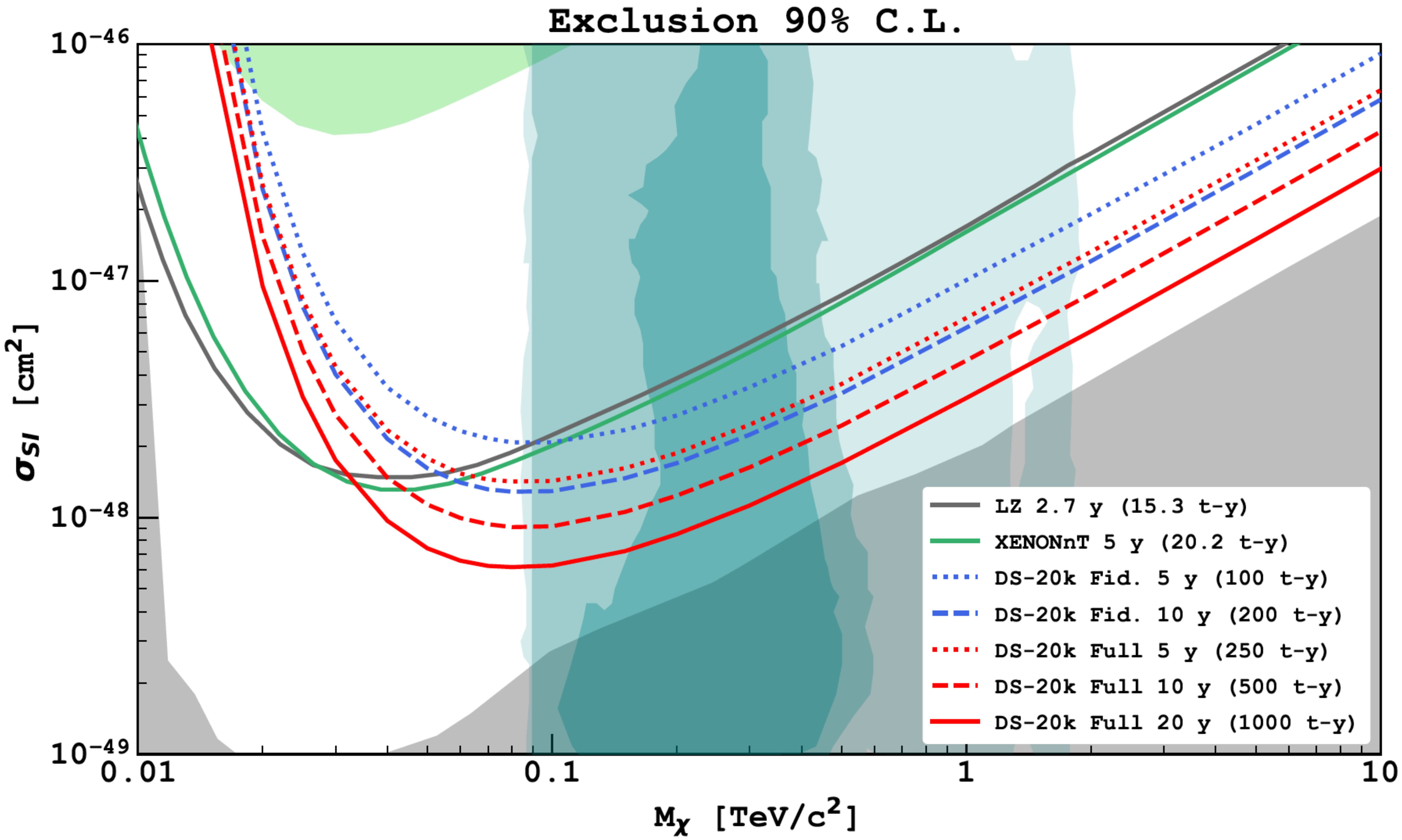


DArT : Measurement of the activity of the ^{39}Ar

- LSC, Canfranc, Spain
- Single-phase inner detector for 1.42 kg of liquid UAr
- Will be installed inside ArDM detector, acting as an active veto.
- ^{39}Ar depletion factor sensitivity: U.L. 90% CL. 6×10^4 (2020 JINST 15 P02024).

DarkSide-20k physics reach

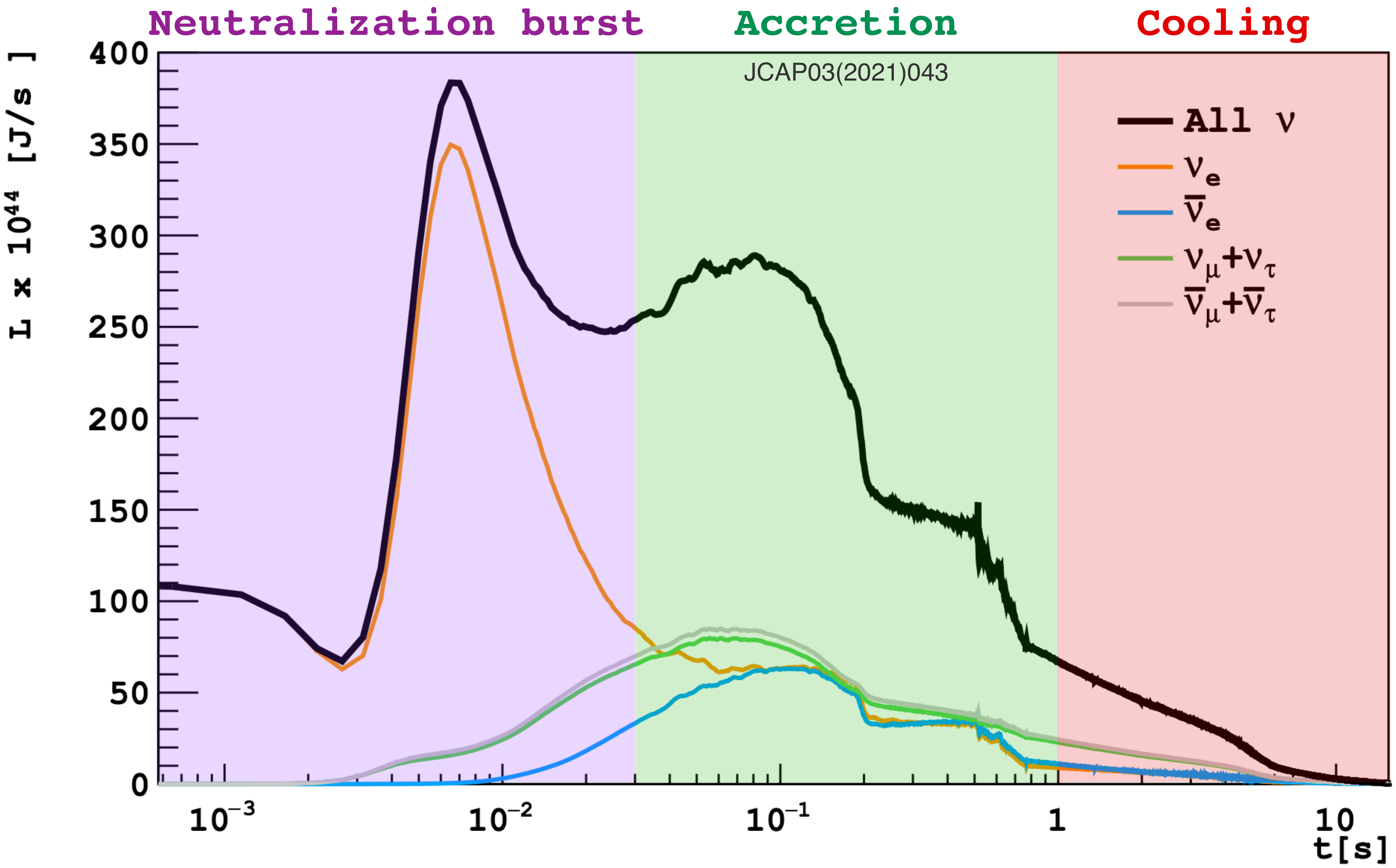
- Sensitivity: 6.3×10^{-48} cm^2 for a 1 TeV/c^2 WIMP (90% C.L.)
- (5σ) discovery: 2.1×10^{-47} cm^2
- Nominal exposure: (20×10) t yr
- Instrumental Background: 0.1 events in 200 t yr
- Expected neutrinos: 3.2 events in 200 t yr



SuperNova neutrinos in DS-20k and Argo

JCAP03(2021)043

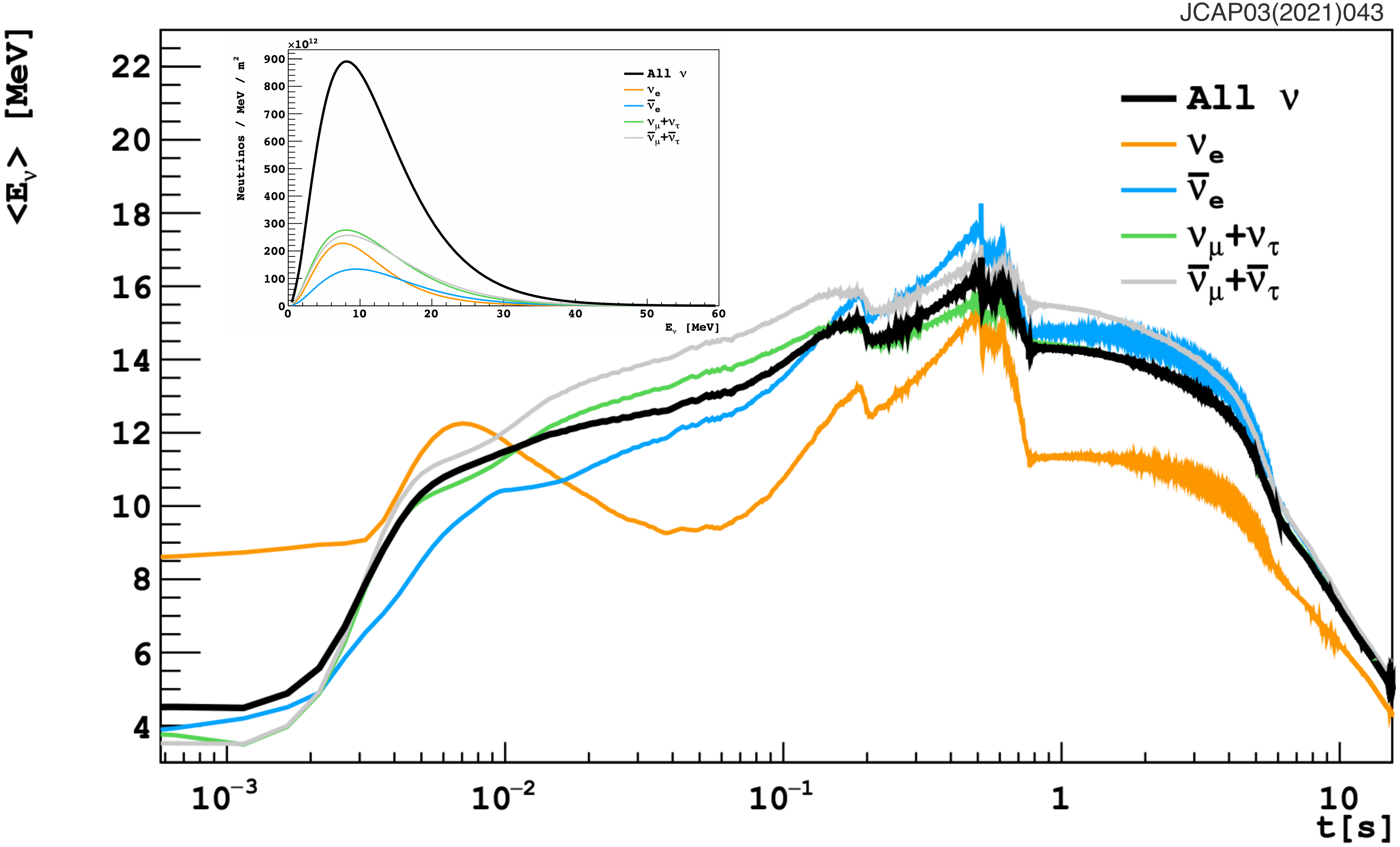
Core Collapse SN neutrinos



- Hydrodynamical spherically symmetric simulations by Garching group. Two progenitors are simulated: 11M⊙ and 27M⊙ (here shown) at 10kpc.

- Core Collapse Supernova phases:
  1. neutronization burst (~30ms),
  2. accretion phase (~0.02-1s),
  3. cooling (~1-10s).

Core Collapse SN neutrinos


JCAP03(2021)043

- 99% of the total energy of a core collapse SN (~10^{53} erg) is emitted through the neutrino channel.
- $\langle E_\nu \rangle$ maxes out in the accretion phase (15MeV) and drops to ~5MeV after ~10s.

What could we measure/learn?

- Total energy of the explosion
- Observe a second collapse due to a nuclear matter phase transition
- Observe a black-hole formation during the first 10s
- Observe the shock stall and the duration of the accretion phase
- Observe Standing Accretion Shock Instability (SASI)
- Probe BSM physics from deviations of the neutrino spectra from SM physics
- Observe motion of shock through the progenitor mantle
- Determine the sphericity of the core collapse
- Determine the angular momentum of the Proto-Neutron-Star (PNS)
- Determine neutrino mass ordering — How? Survival probability for neutralization burst ν_e:

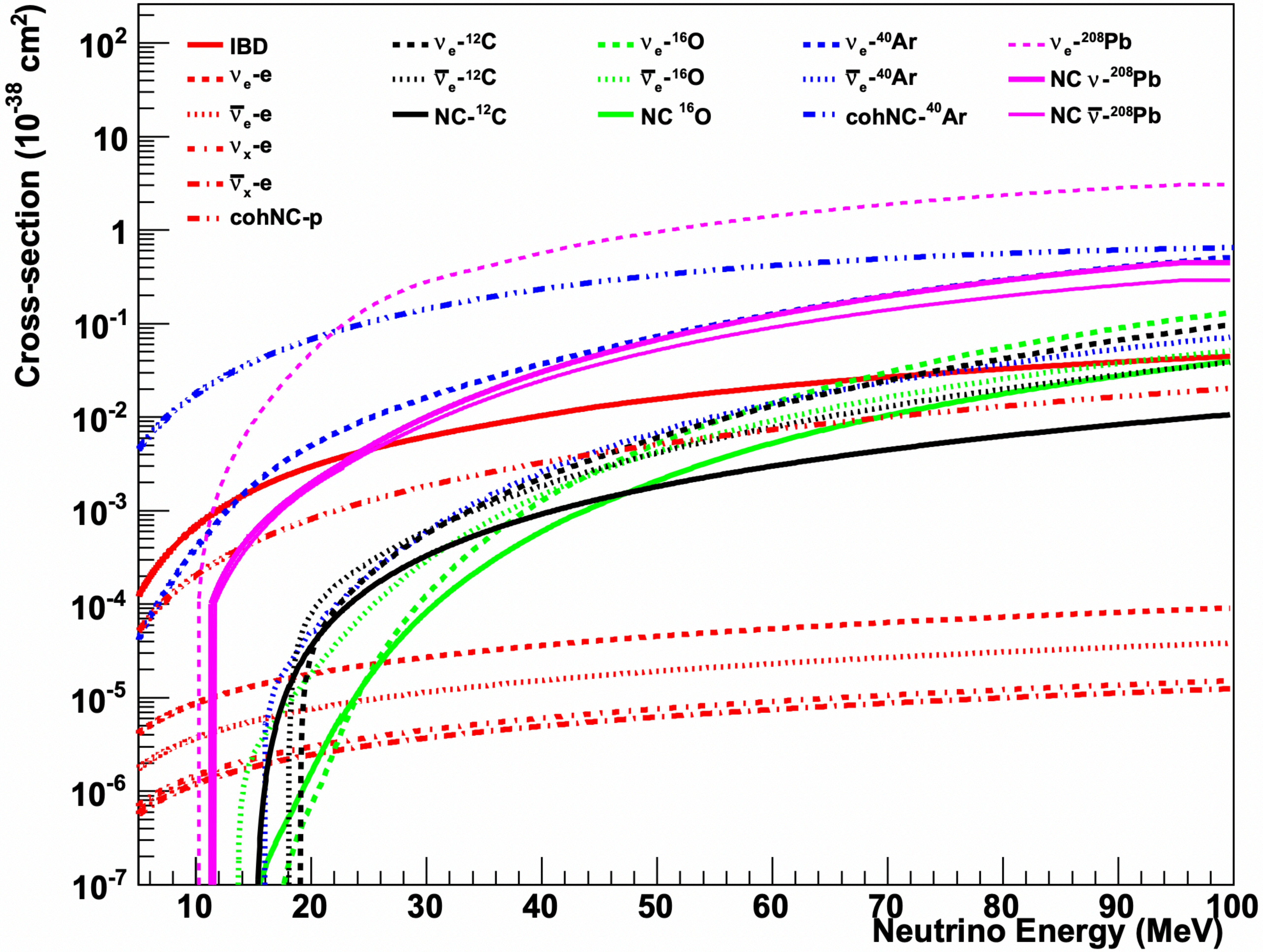
$p = \sin^2\theta_{13} = 0.02$ for NMO, $p = \sin^2\theta_{12}\cos^2\theta_{13} = 0.30$ for IMO

CCSN detectors

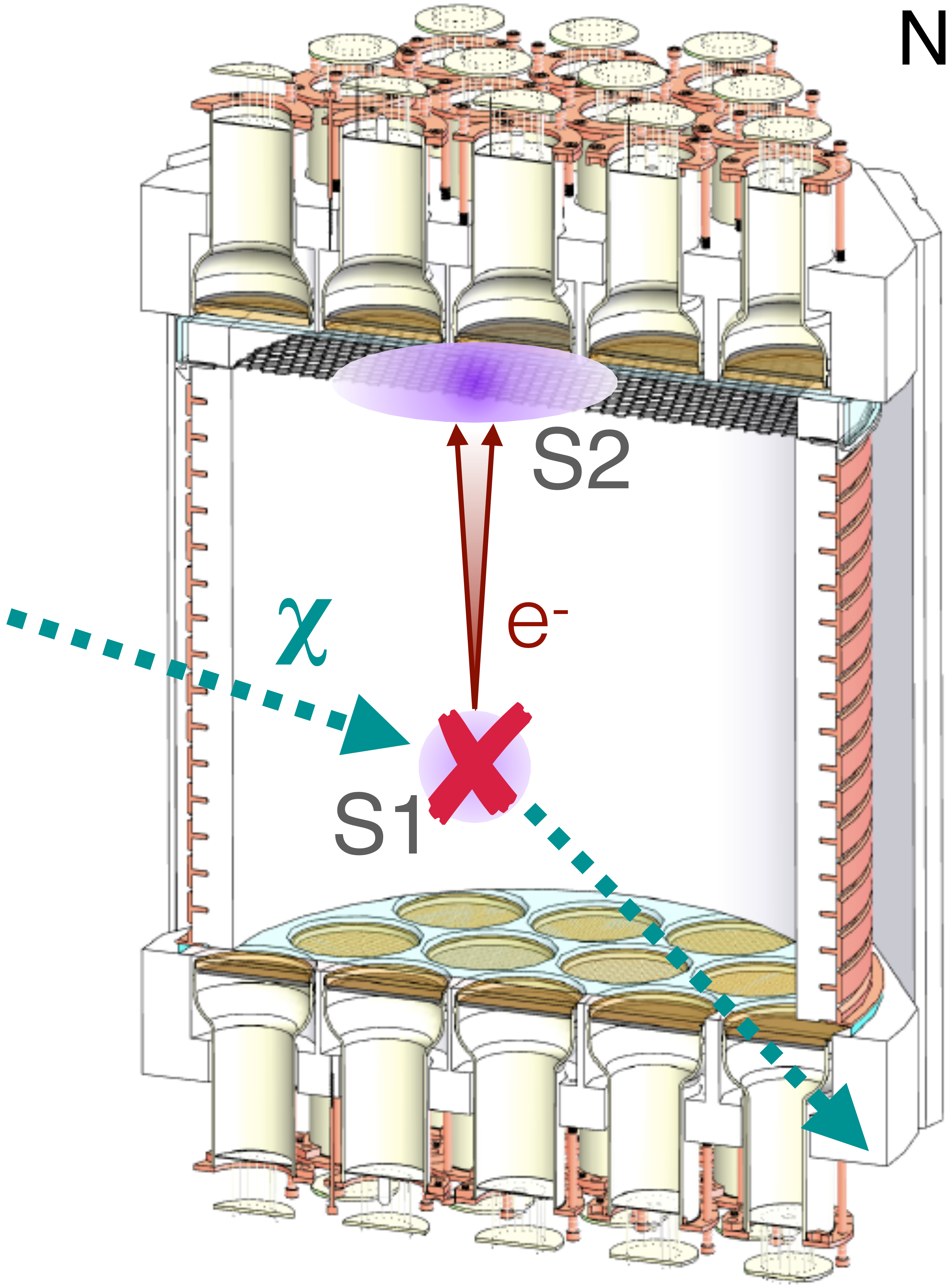
- Water Cherenkov - IBD $\bar{\nu}_e + p \rightarrow e^+ + n$: SuperK (32 kton) and HyperK (374 kton)
- Liquid Scintillators - IBD: KamLAND (1 kton), LVD (1 kton) and JUNO (20 kton)
- LAr: CC $\bar{\nu}_e$ + ^{40}Ar $\rightarrow e^- +$ ^{40}K*:DUNE (40 kton)
- LAr: CEvNS $\nu +$ ^{40}Ar $\rightarrow \nu +$ ^{40}Ar: DarkSide-20k (47.1 tonnes) and Argo (362.7 tonnes)

CEvNS high cross section (~x50σ_{CC}) compensates for the “low” target mass.

https://arxiv.org/pdf/1205.6003.pdf



CEvNS with S2-only analysis



Need to lower the energy threshold ⇒ Look at the S2 only events

S2 >> S1 (23ph/e^- in DS50)

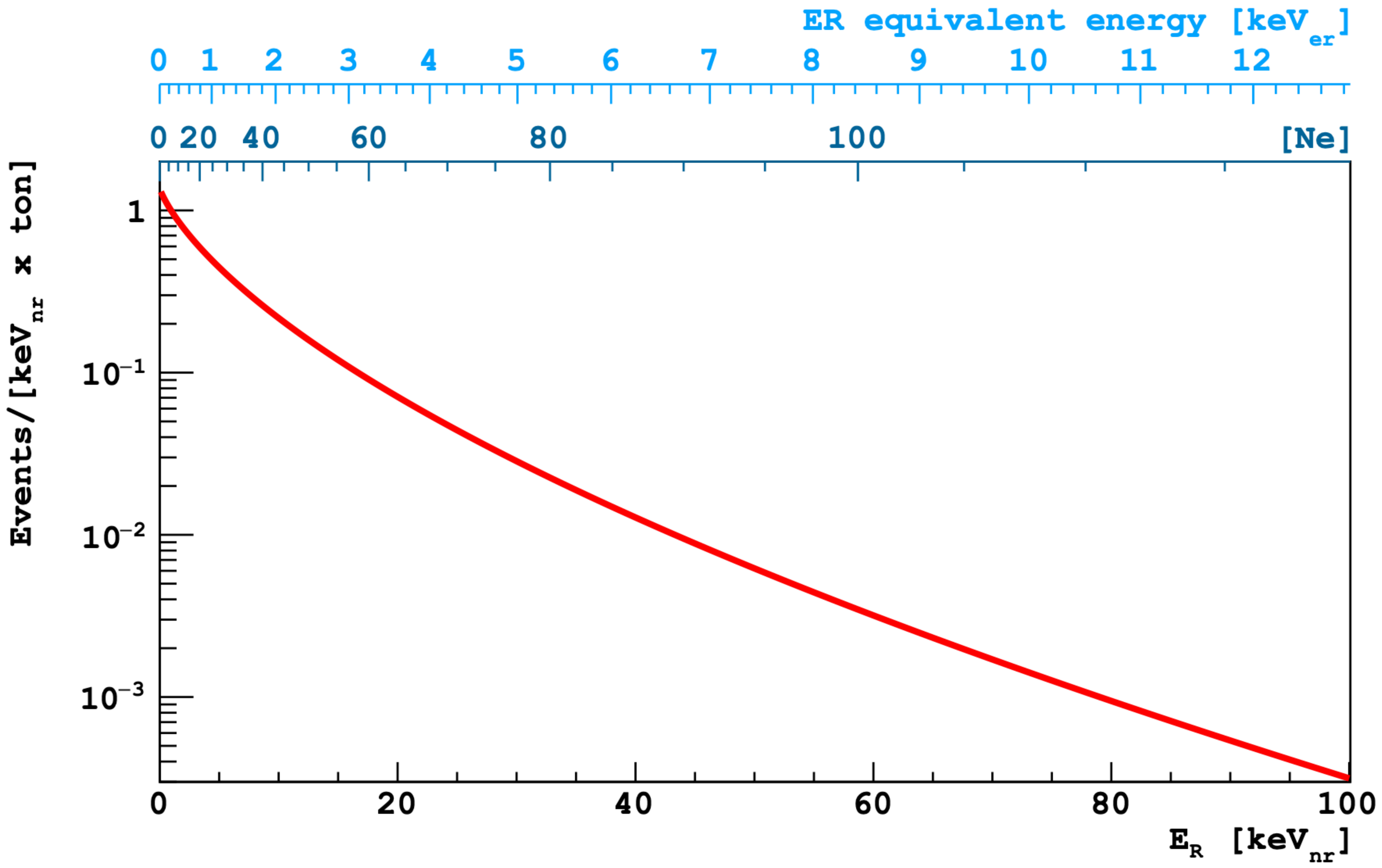
Pros:

- Low energy threshold:
- 100% Trigger eff. > ~30PE

Cons: No S1

- No position reconstruction in z
- No PSD ⇒ No ER rejection
- Poor timing reconstruction, limited to the TPC drift time

Detector response to CEνNS



- Window of observation: up to 100keV$_{nr}$.
- 70% (50%) of the recoils is <10keV$_{nr}$ (5keV$_{nr}$).

- DS50 performance:
  - S2 identification: 100% >30PE
  - Trigger efficiency: ~100% >30-40PE
  - NR deposits detection is 100% >0.46keV$_{nr}$.

86% of SN CE***ν***NS would be detected

From DS50 low-mass analysis

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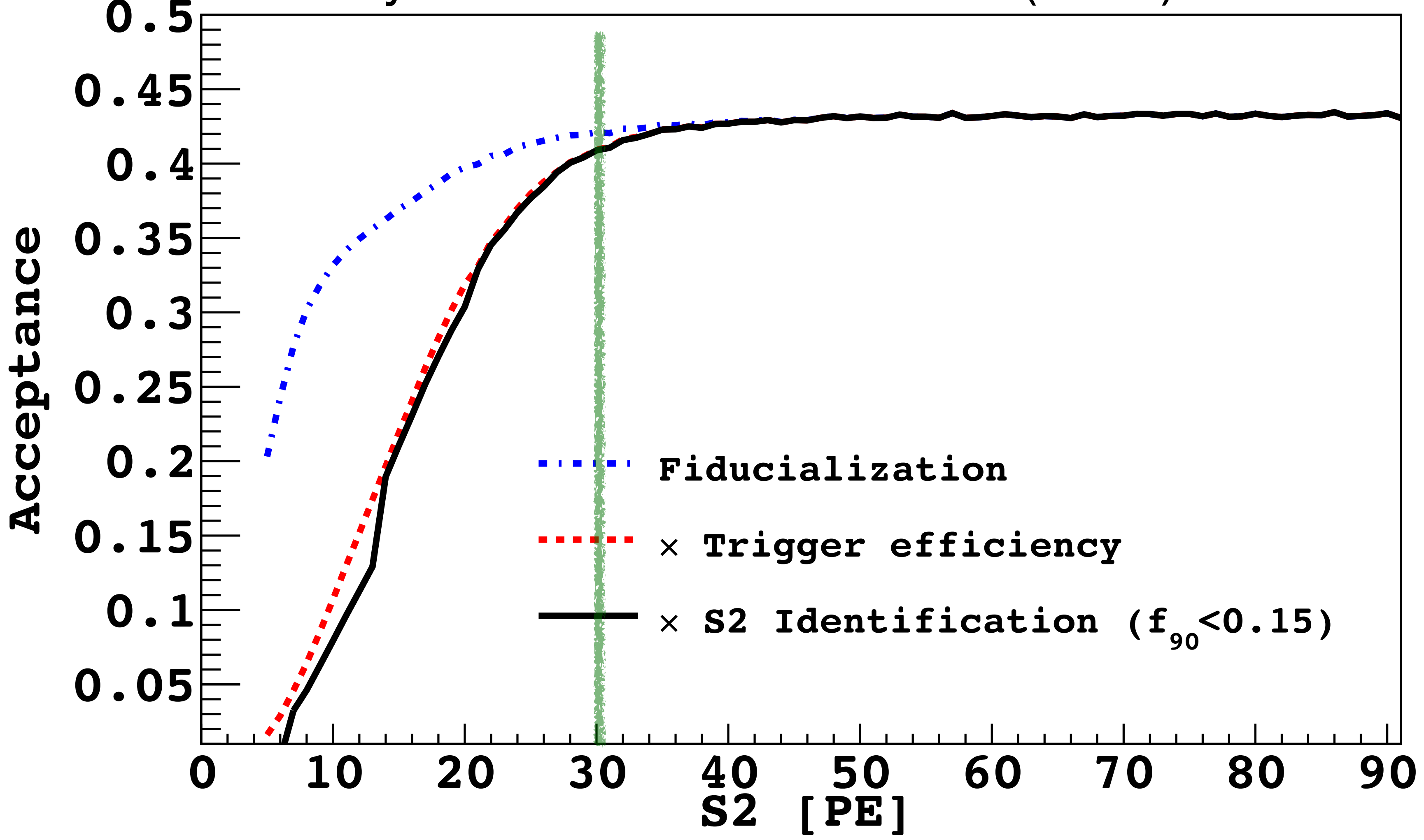
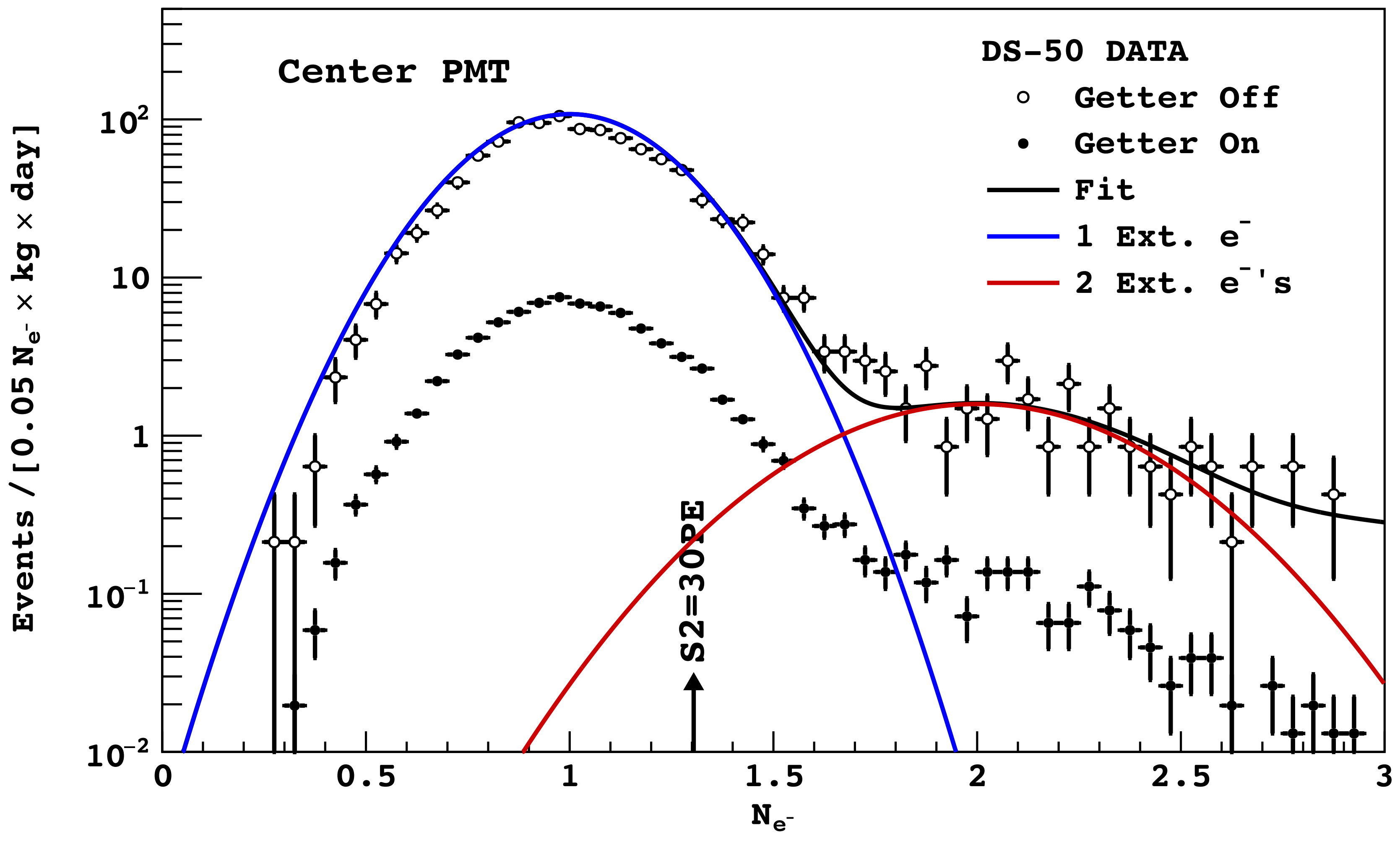
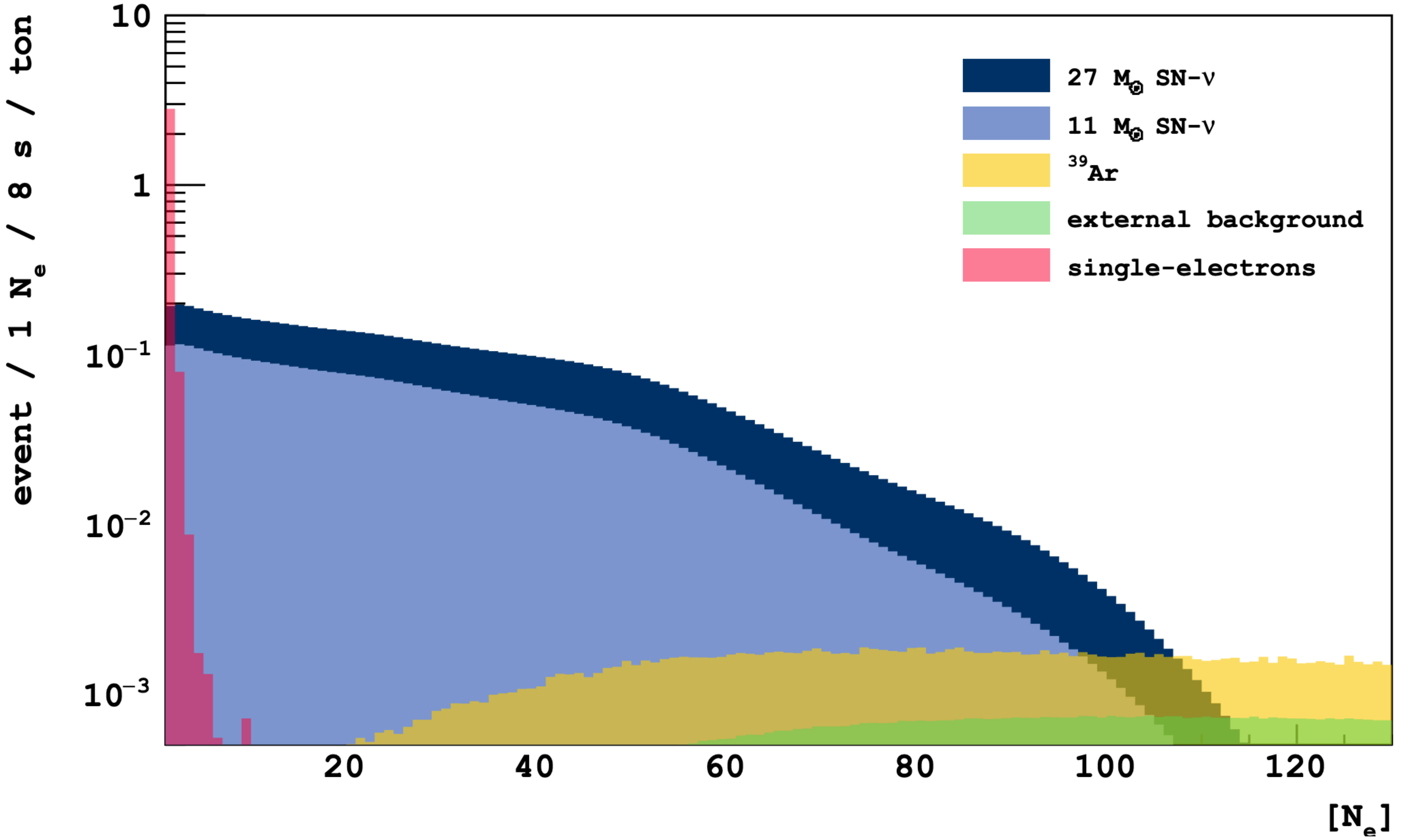
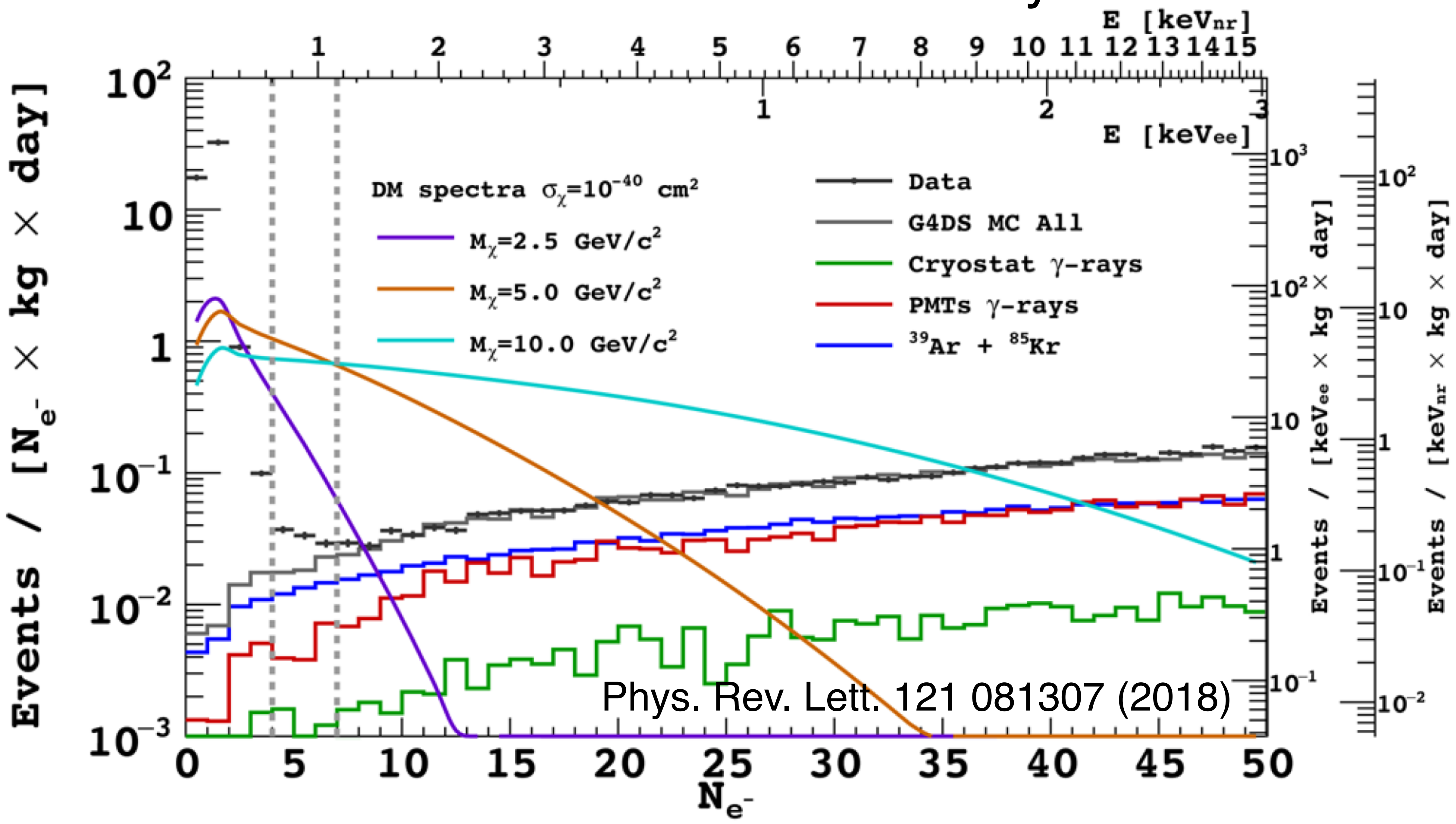




Backgrounds



From DS50 low-mass analysis



Phys. Rev. Lett. 121 081307 (2018)

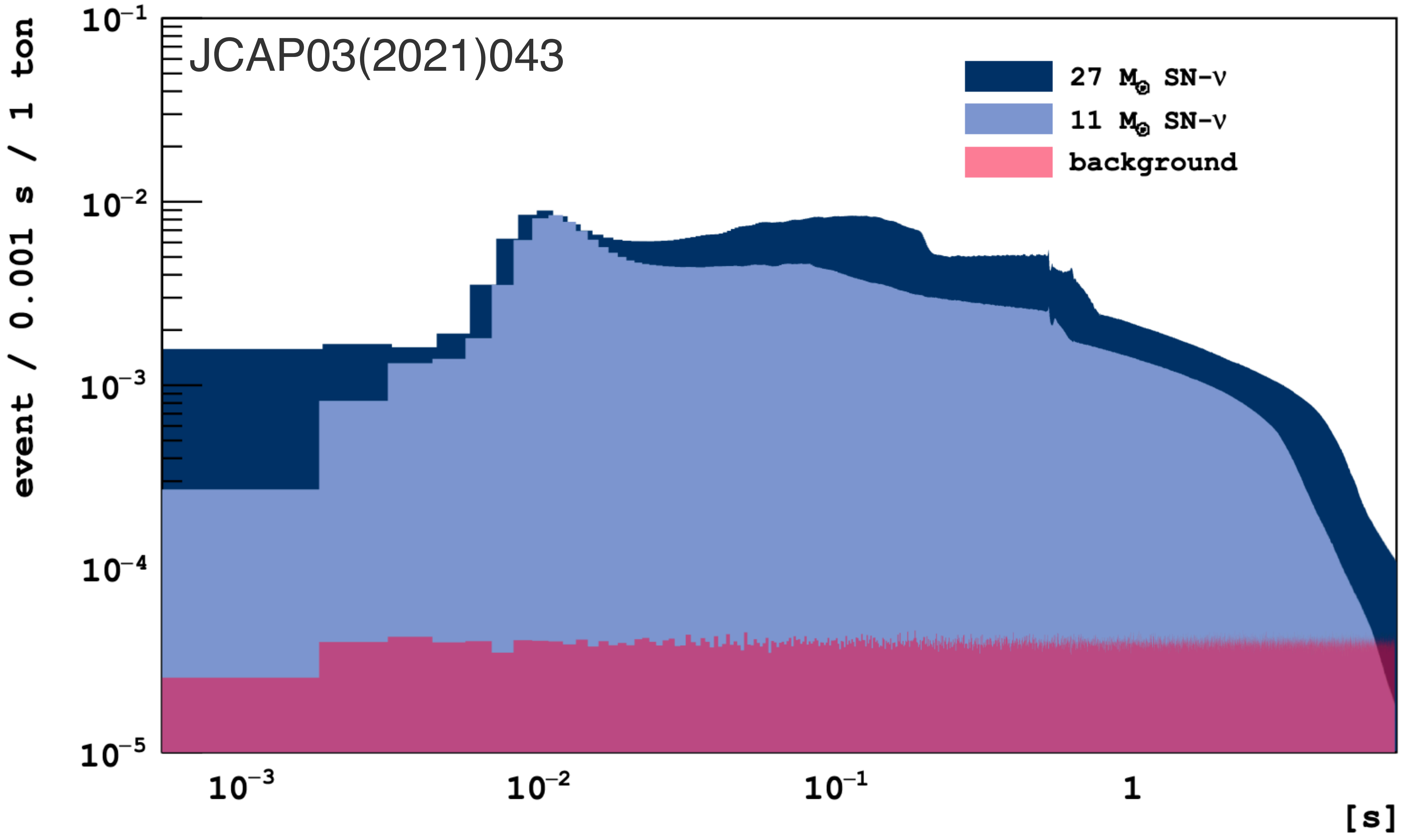
- **Internal background:** ^{39}Ar, dominant > 1keV$_{nr}$. Expected rate for N$_e$<100: 0.5Hz (DS20k) and 4.2Hz (Argo). ^{85}Kr will be removed by ARIA distillation column.
- **External background:** γ from SiPMs and cryostat. Expected rate for N$_e$<100: 0.3Hz (DS20k) and 1.3Hz (Argo). After fiducial cut: 0.2Hz (DS20k) and 1.1Hz (Argo).
- **Single electron background:** unknown origin, part due to impurities (observed time correlation with S2 events). Scaled rate from DS-50 for N$_e$>3: 1.8mHz/tonne, 0.085Hz (DS20k) and 0.65Hz (Argo).

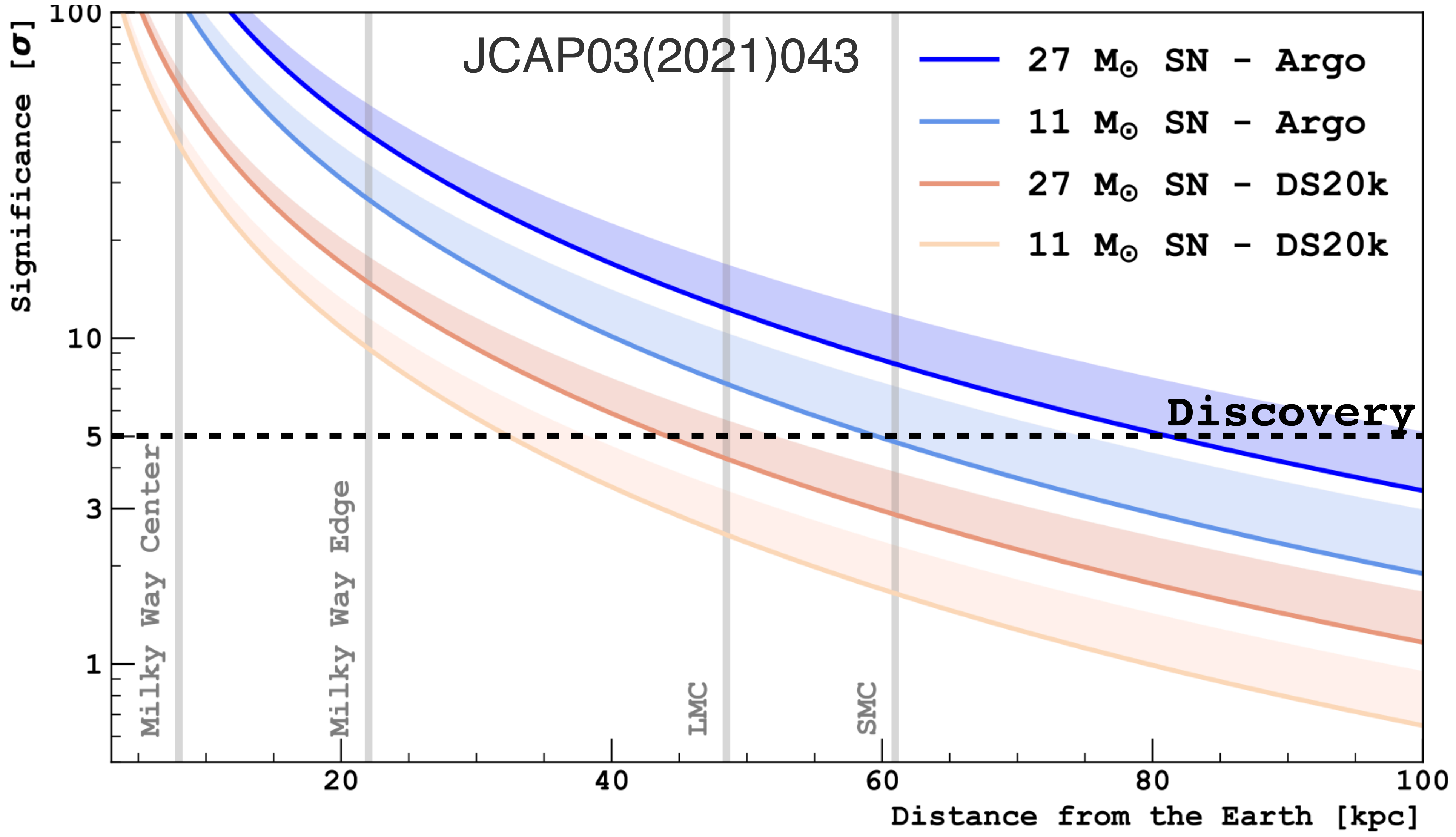
Sensitivity to CCSN

Expected signal and background in 8s
for a SN burst at a distance of 10kpc

	DarkSide-20k	Argo
11-$M_\odot$ SN-νs	181.4	1396.6
27-$M_\odot$ SN-νs	336.5	2591.6
^{39}Ar	4.3	33.8
external background	1.8	8.8
single-electrons	0.7	5.1

- SNR~10^2 during neutronization and accretion (1s). SNR~10 during cooling (>1s)
- Overall SNR~24(45) for 11$M_\odot$ (27$M_\odot$)
- Sensitivity >5**σ** up to the Milky Way edge for DS-20k and the Small Magellanic Cloud for Argo.





Not only a counting experiment

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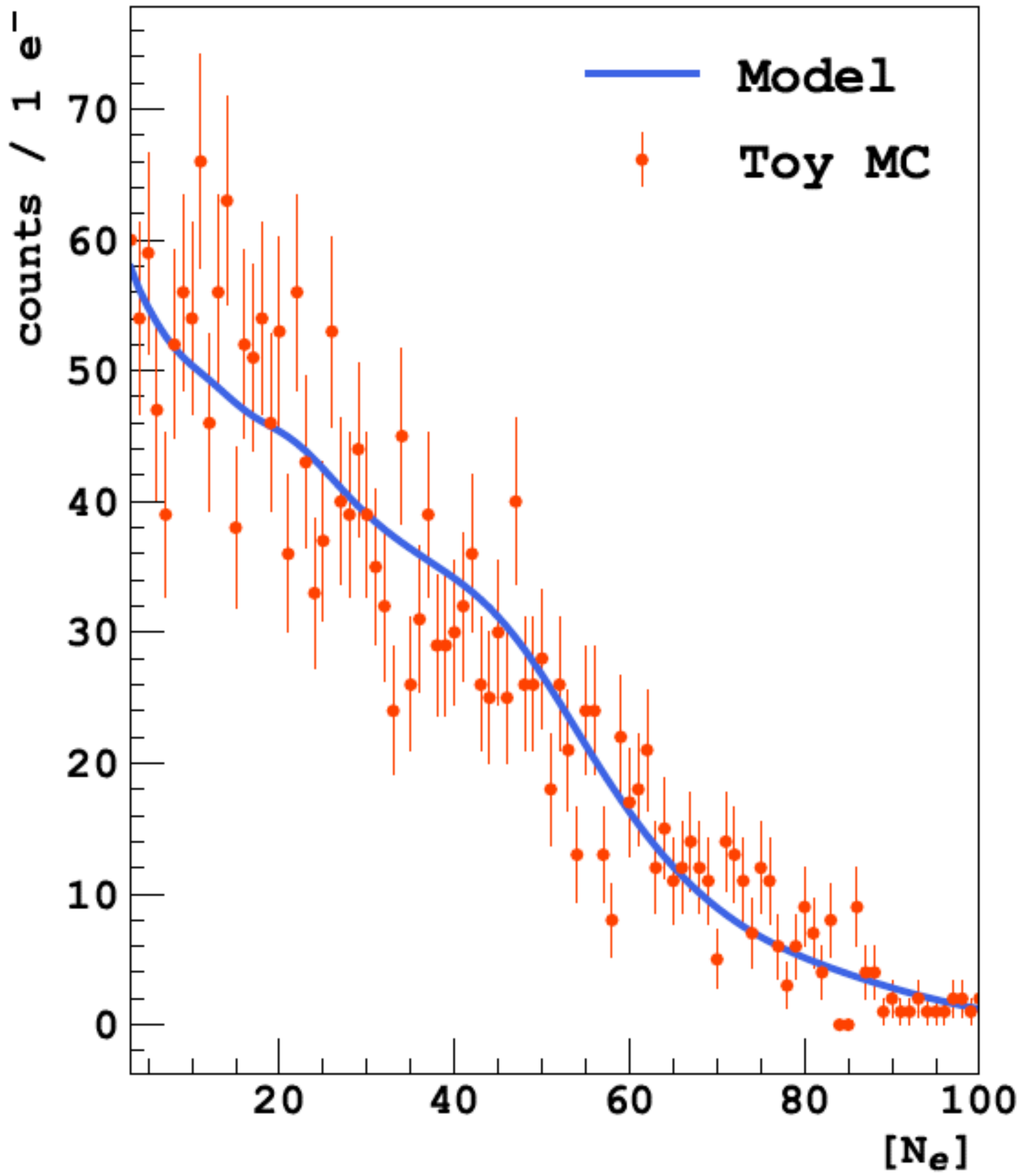

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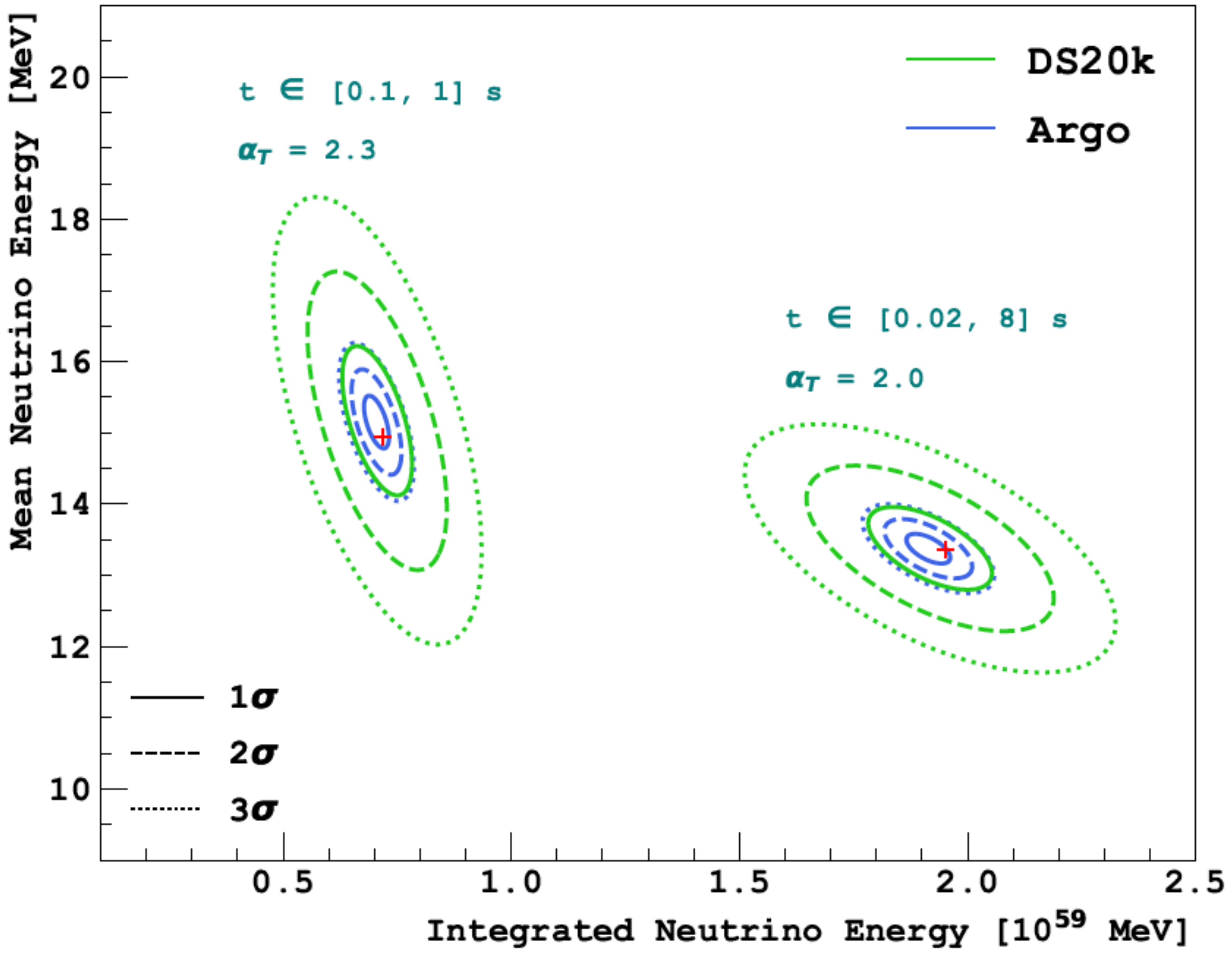

- DS-20k and Argo energy and time resolution allow to reconstruct the mean and total energy of neutrinos from a SN burst. Spectra are fitted excluding the neutronization burst.

- Total neutrino energy reconstruction at 3**σ** level with 11% (32%) accuracy in Argo (DS-20k).
- Mean neutrino energy reconstruction at 3**σ** level with 5% (13%) accuracy in Argo (DS-20k)

Thanks!

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