Status and perspectives of the DarkSide experimental program

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on behalf of the DarkSide-20k Collaboration

Princeton University

Dark Pollica
Pollica, Italy - 09/06/2022

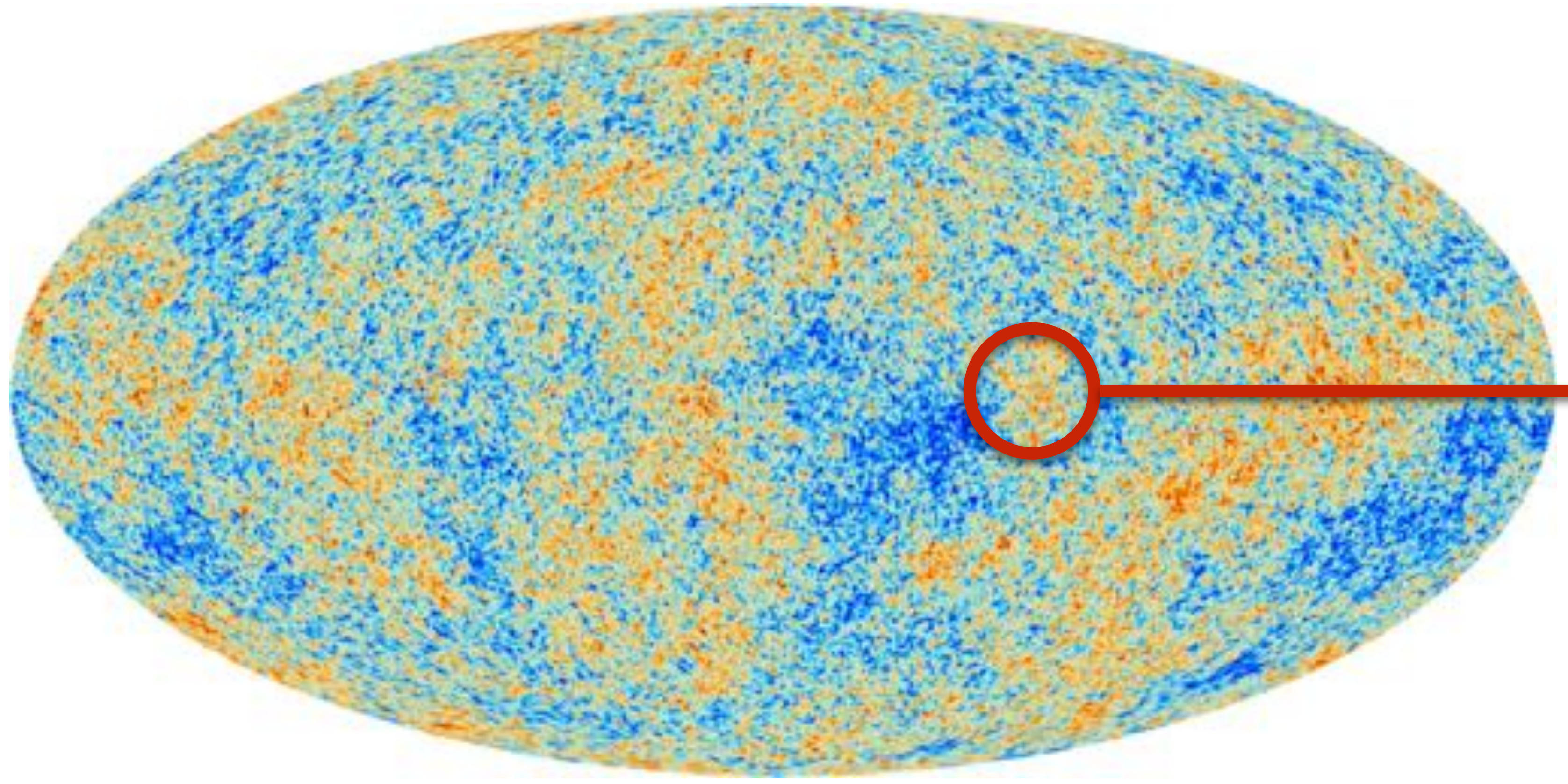
Overview

1. **Direct detection trivia**
2. **DarkSide status and perspectives**
    - The experimental program
    - DarkSide-20k overview
    - Detector design
    - Photo-detection system
    - Argon target procurement

Dark Matter and direct detection trivia

The physics case

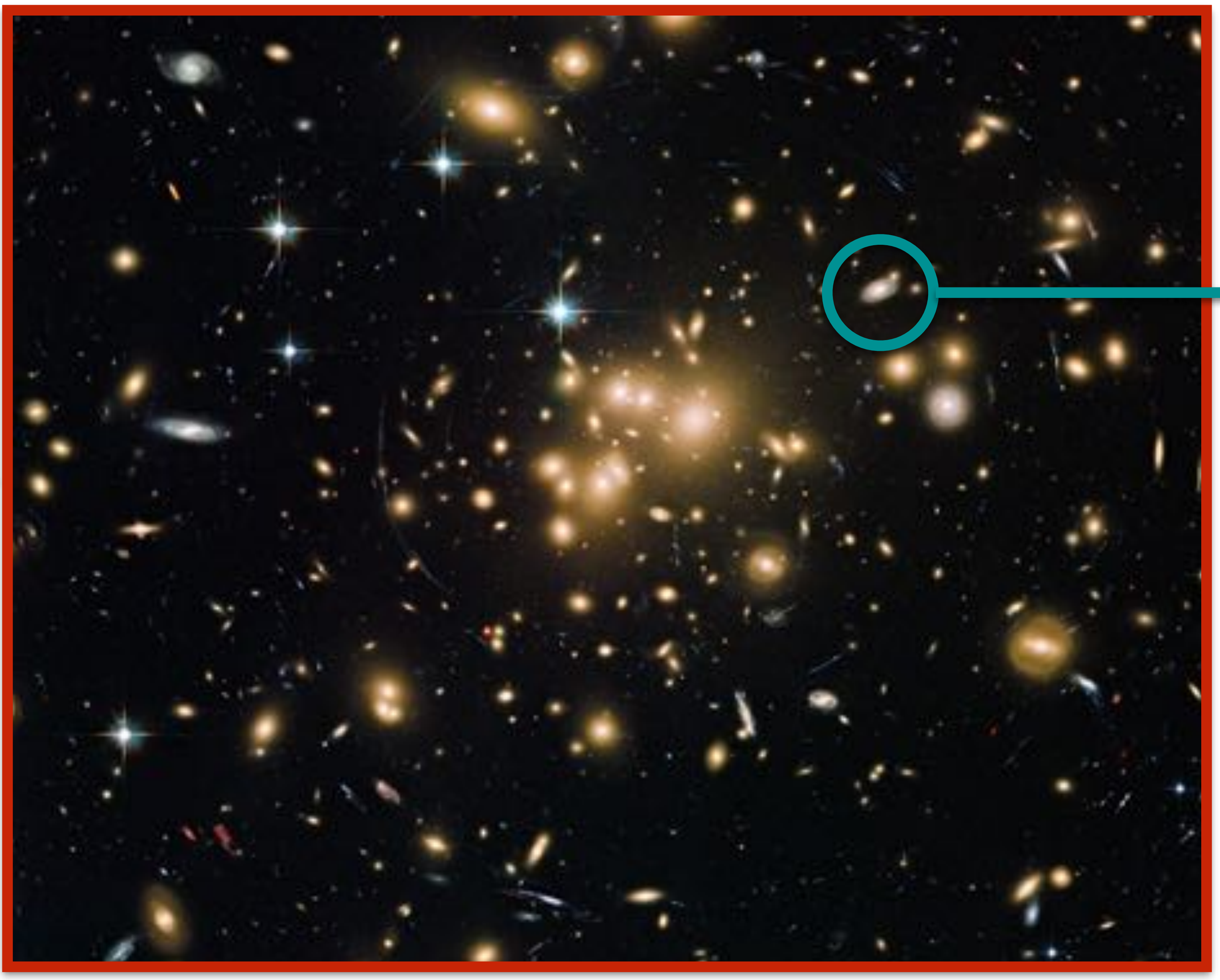
CMB



Thermal anisotropies

multipole expansion

Galactic clusters



Galaxy velocities

Gravitational lensing (Bullet)

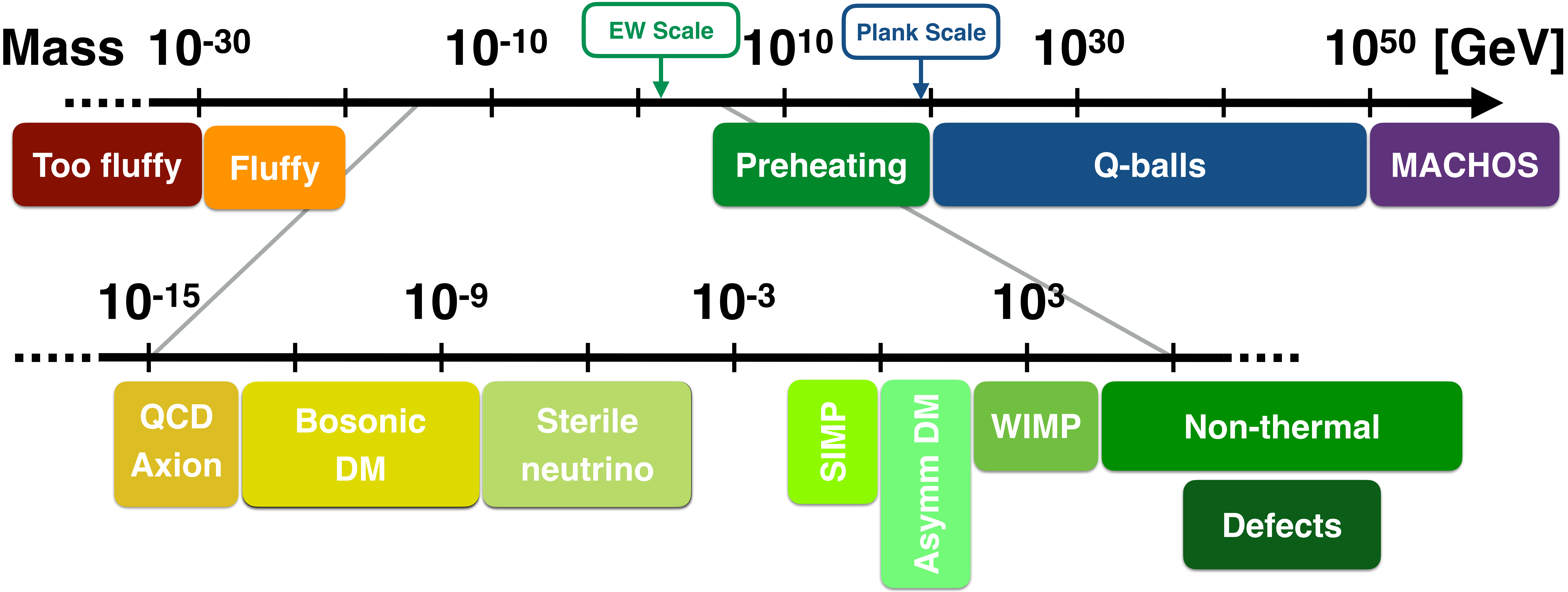
Galaxies

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

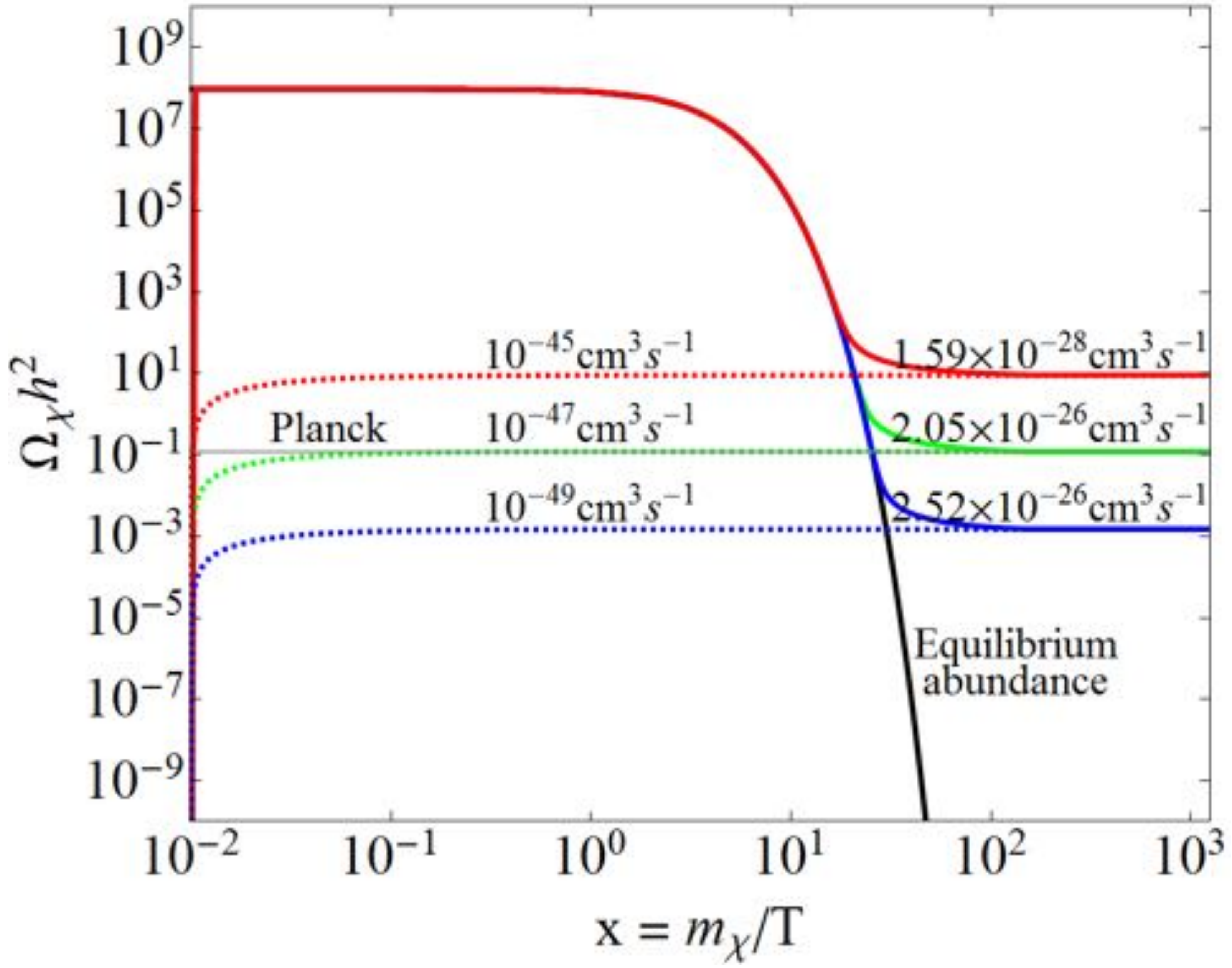
Non-thermal

Defects

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

The WIMP realm

The WIMP miracle

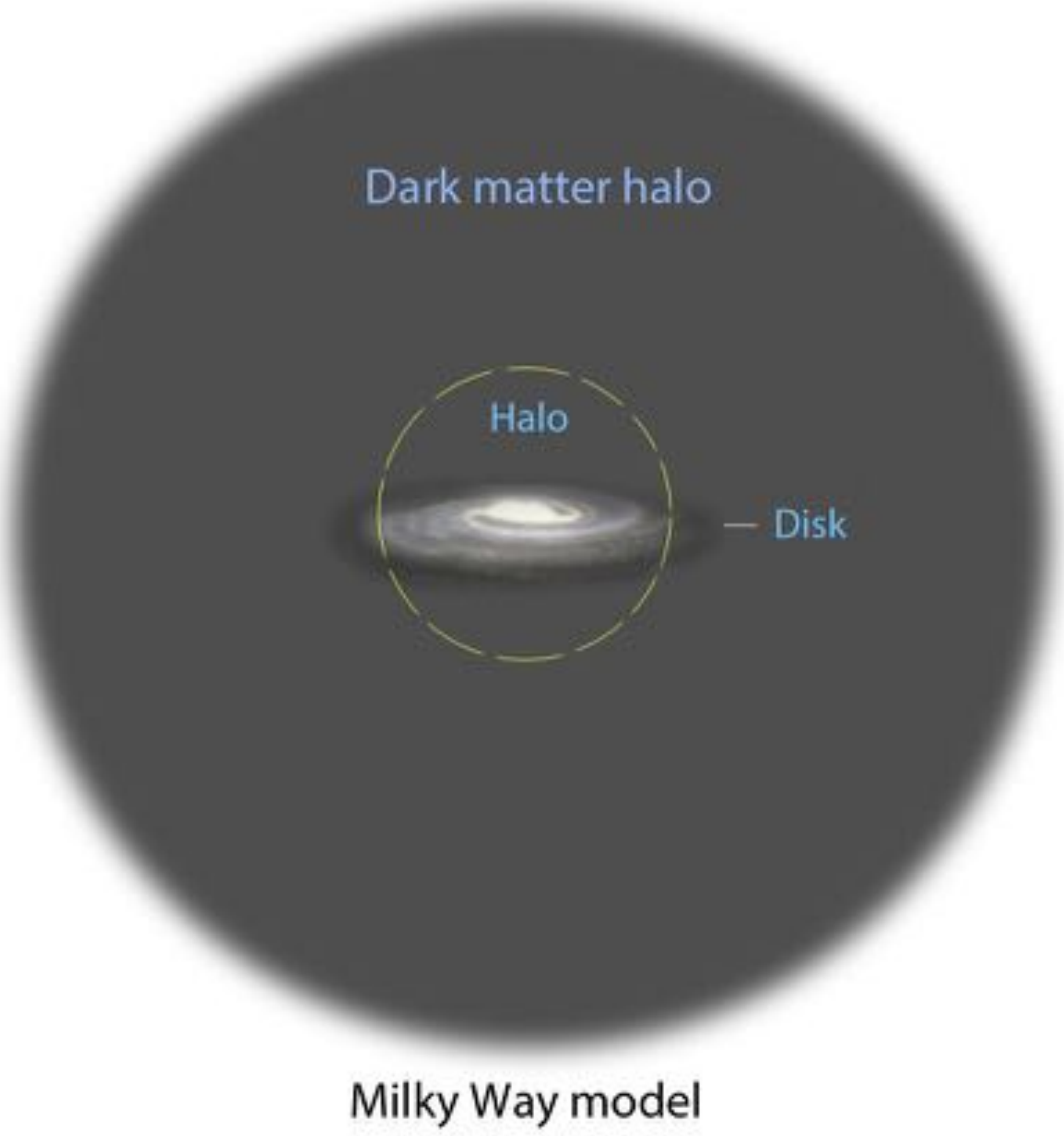


Weak X-section

Mass at EW scale

Observed DM abundance

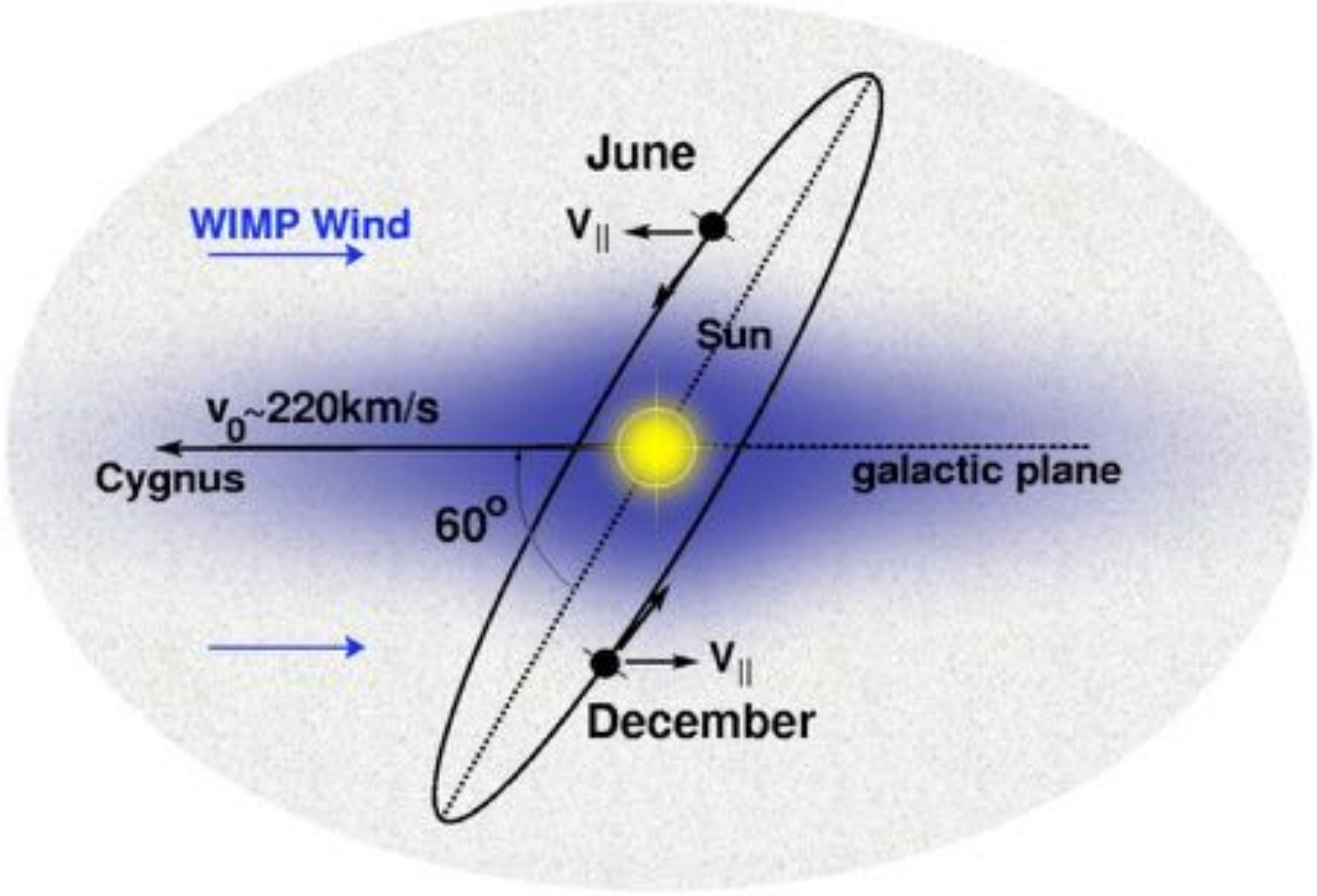
CDM



CDM preferred by halo simulations

Maxwell velocity distribution

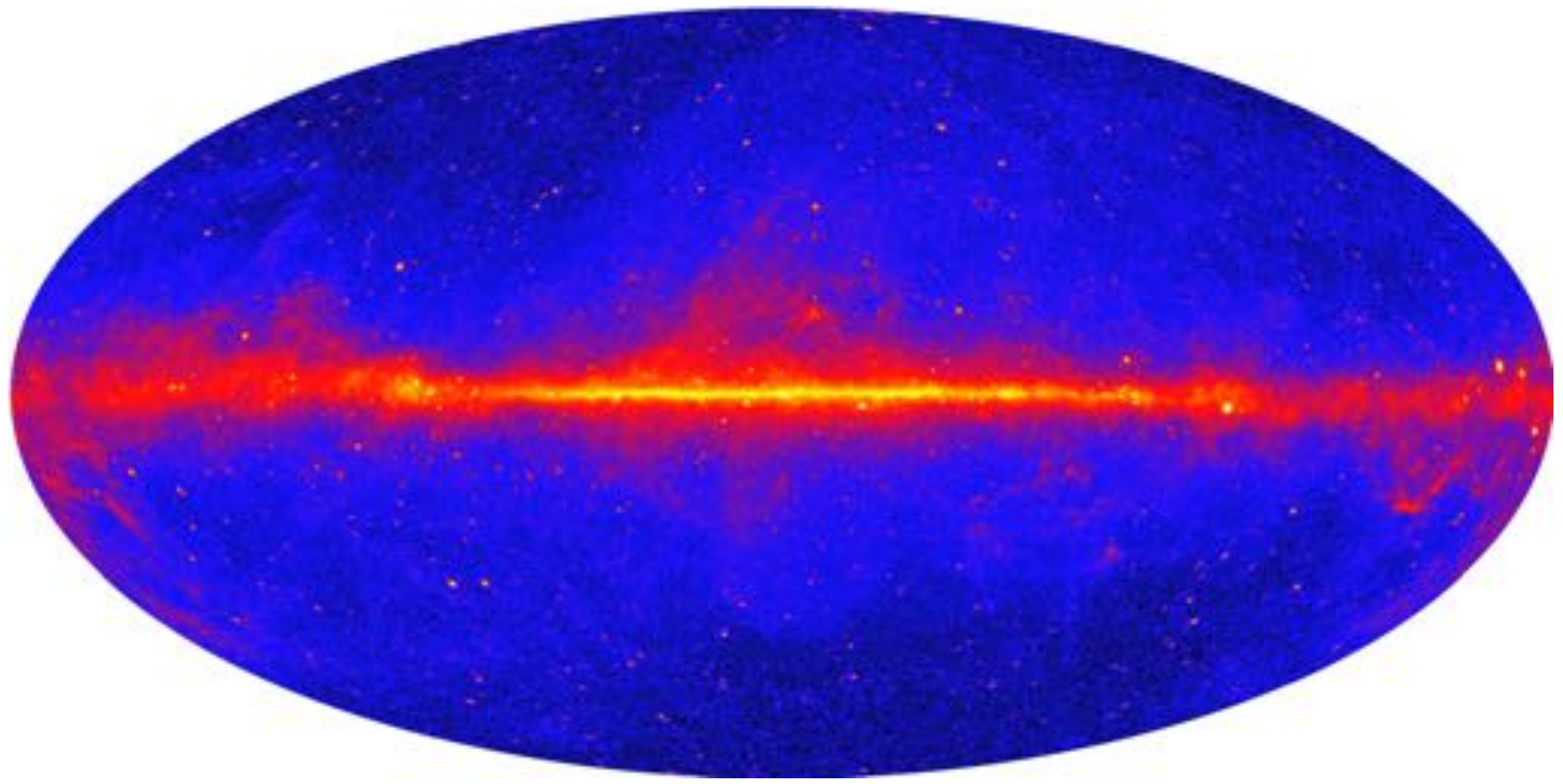
WIMP Wind



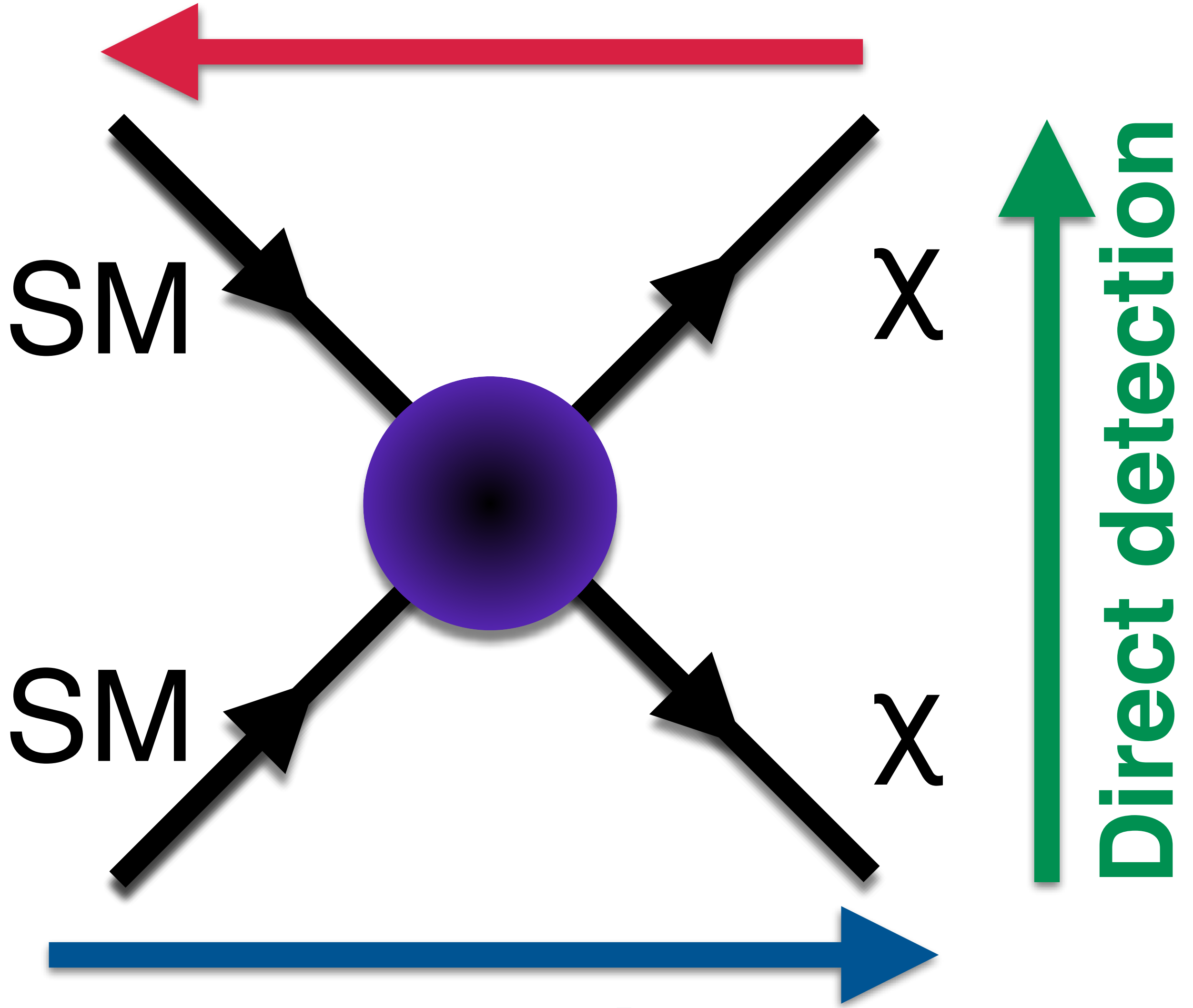
Sun motion ⇒ directional signature

Earth orbit ⇒ annual modulation

Hunt it down!



- Annihilation in SM particles
- Universe is our lab! ✔
- Mostly space-based detectors ✘
- Background fluxes difficult to predict ✘



Indirect detection

SM

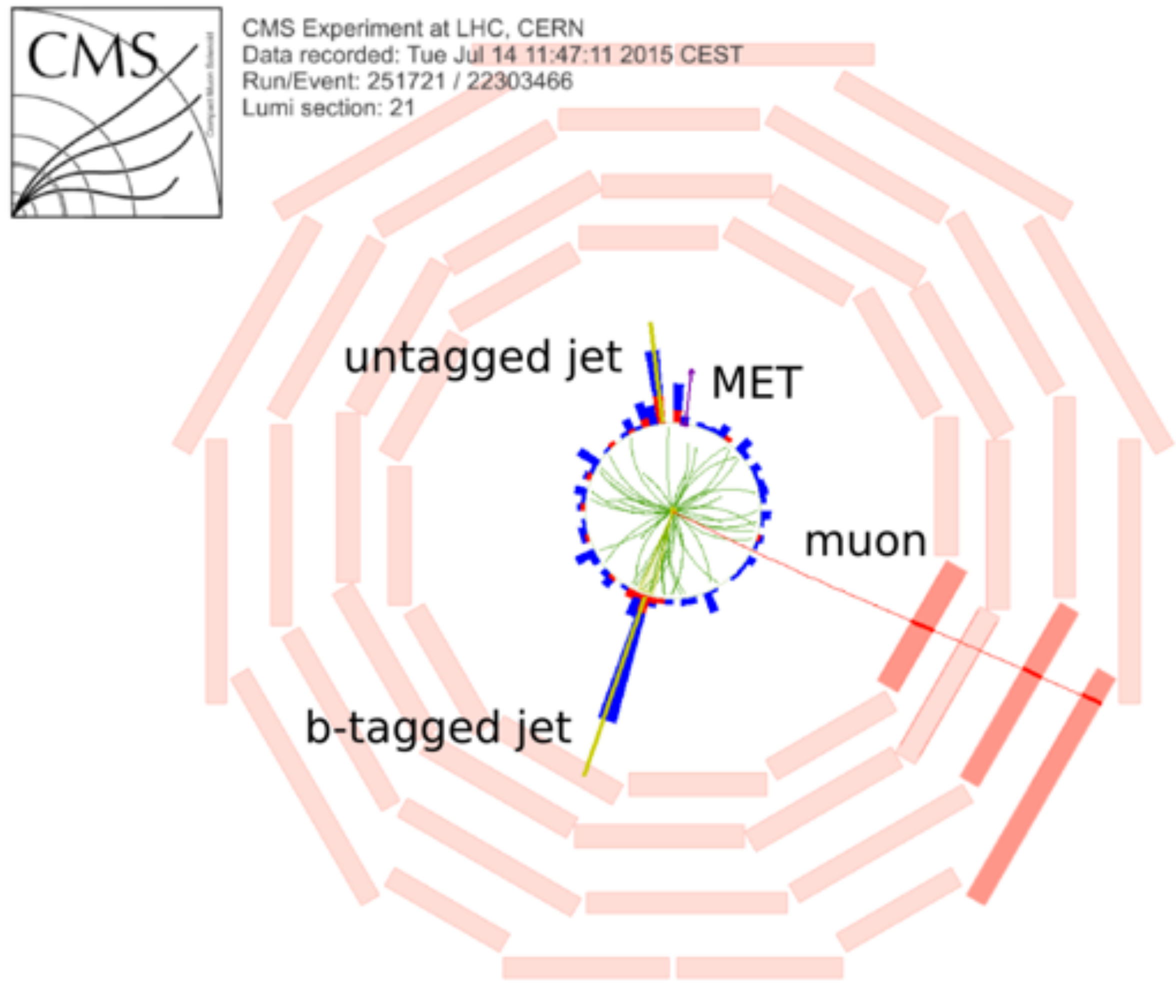
SM

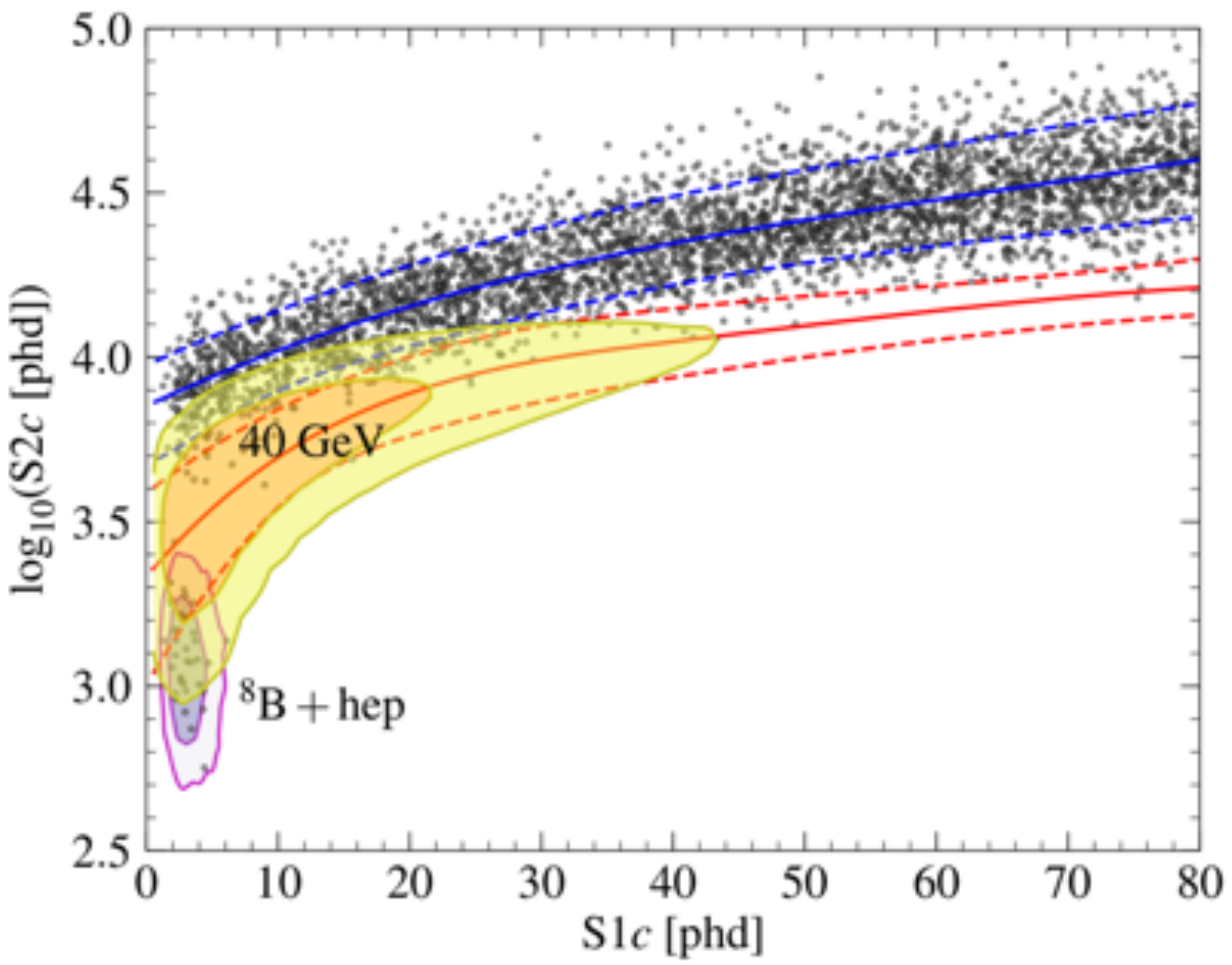
χ

χ

Direct detection

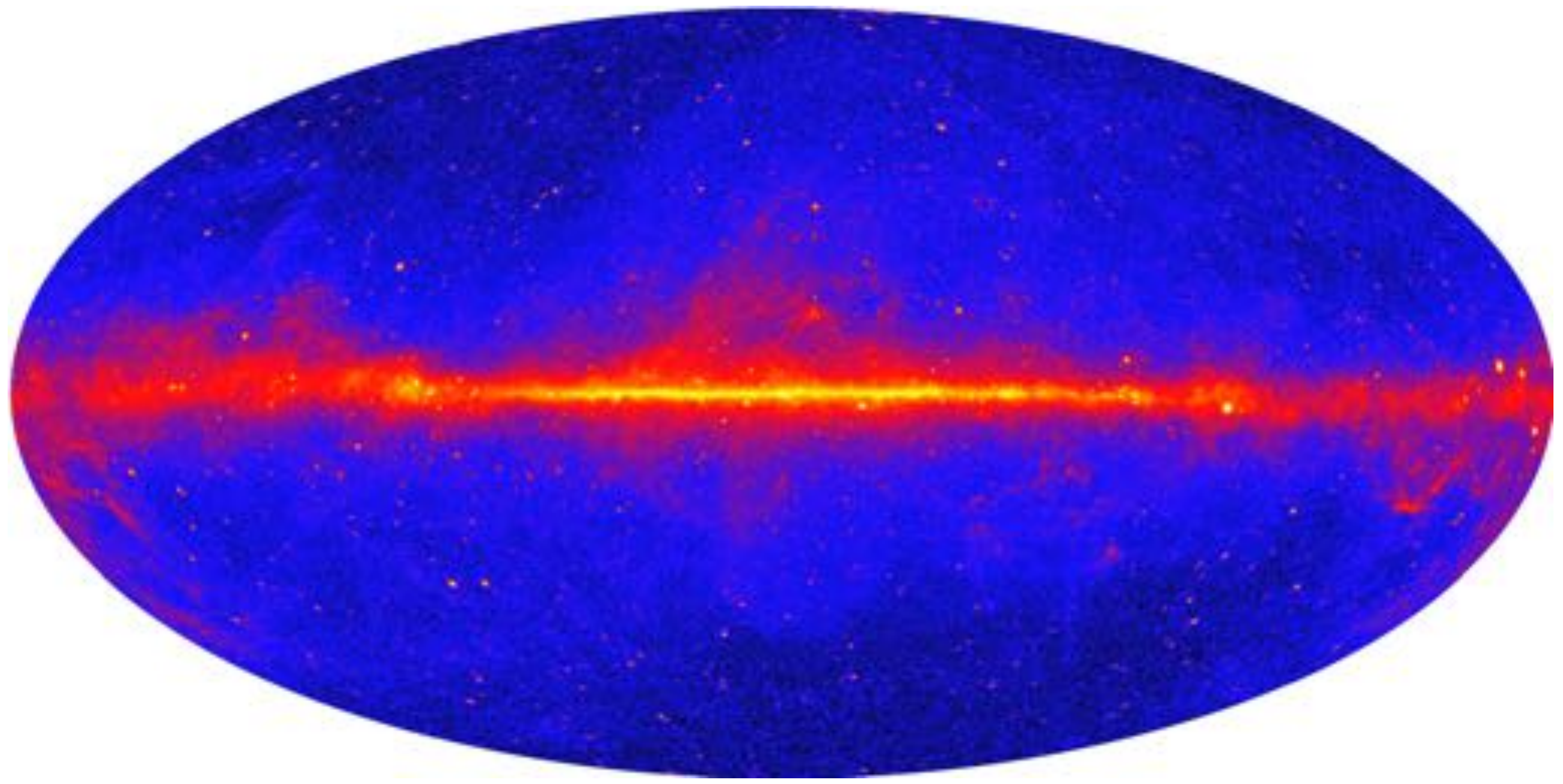
Production





- Scattering with SM particles
- Spans over many orders of magnitude in mass ✔
- Depends on local ρ_{DM} ✘
- Rare events and huge bkg ✘

Hunt it down!



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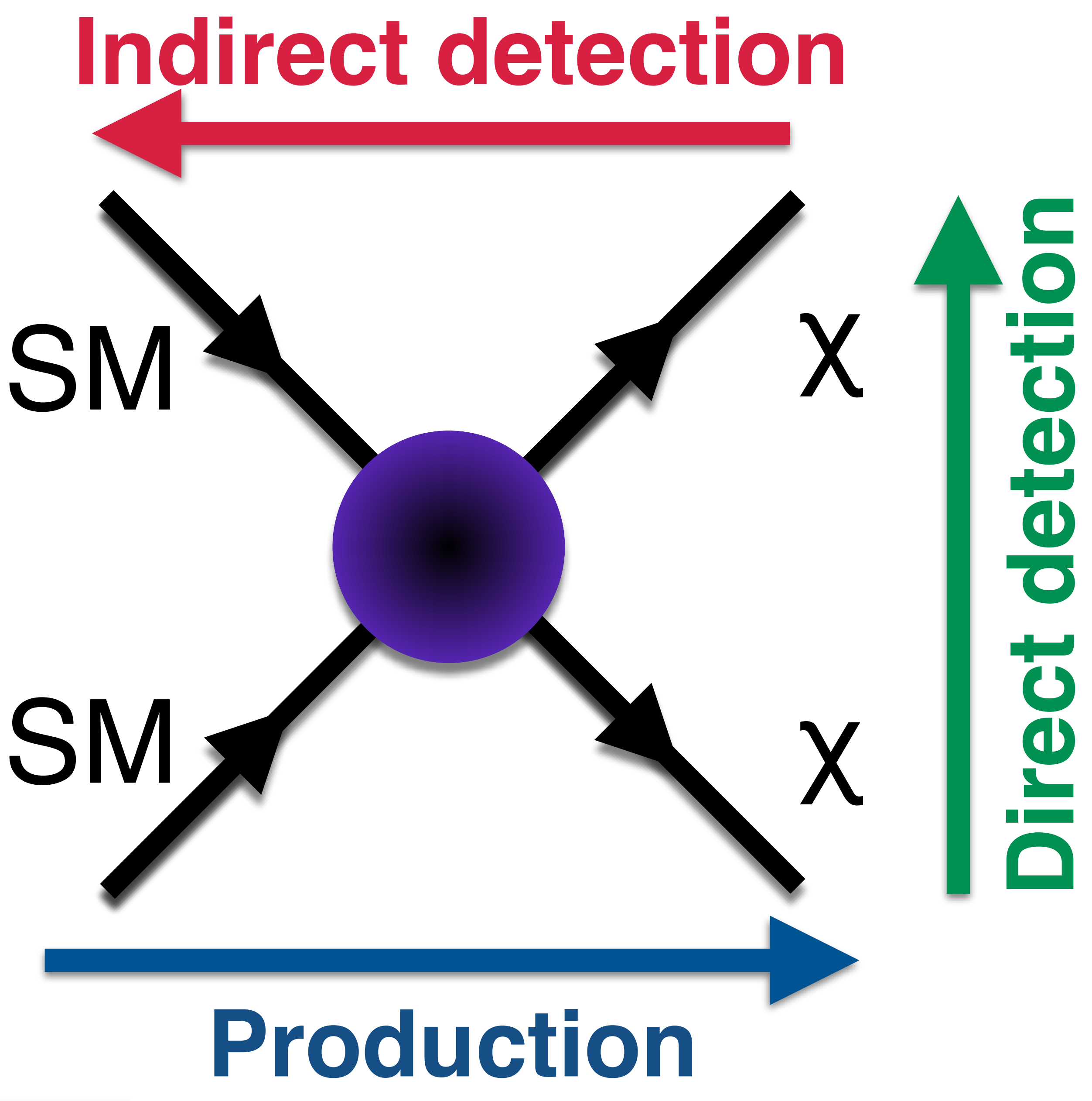

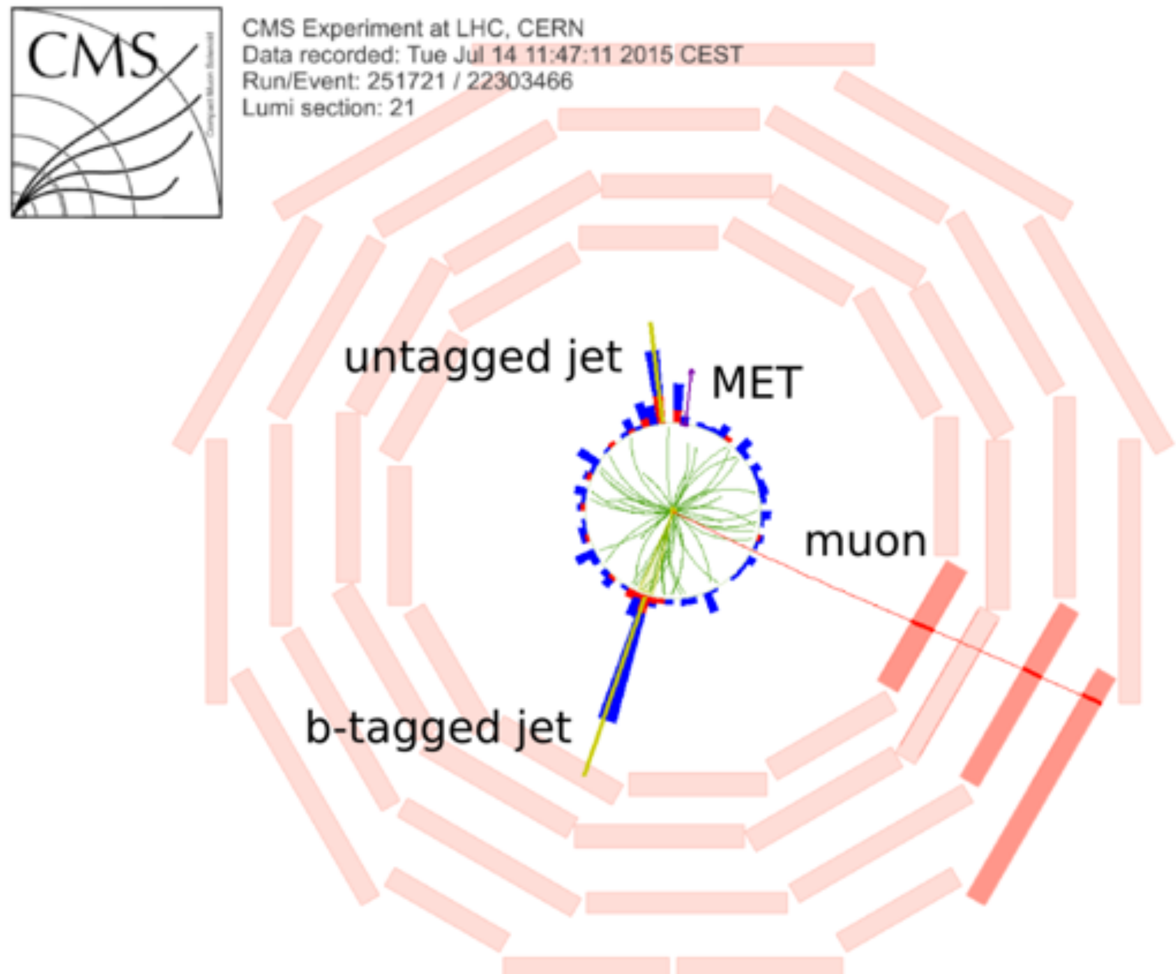

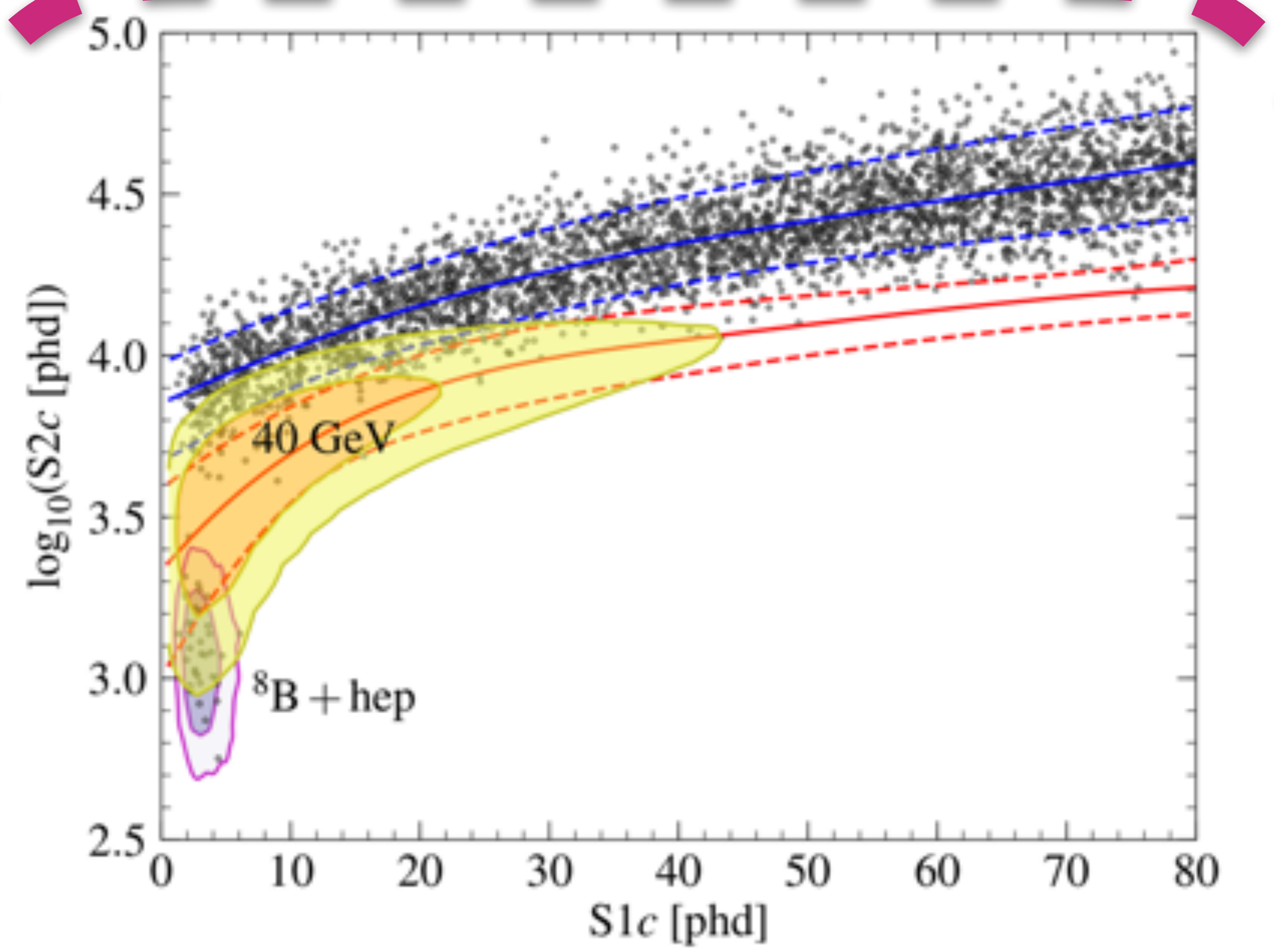

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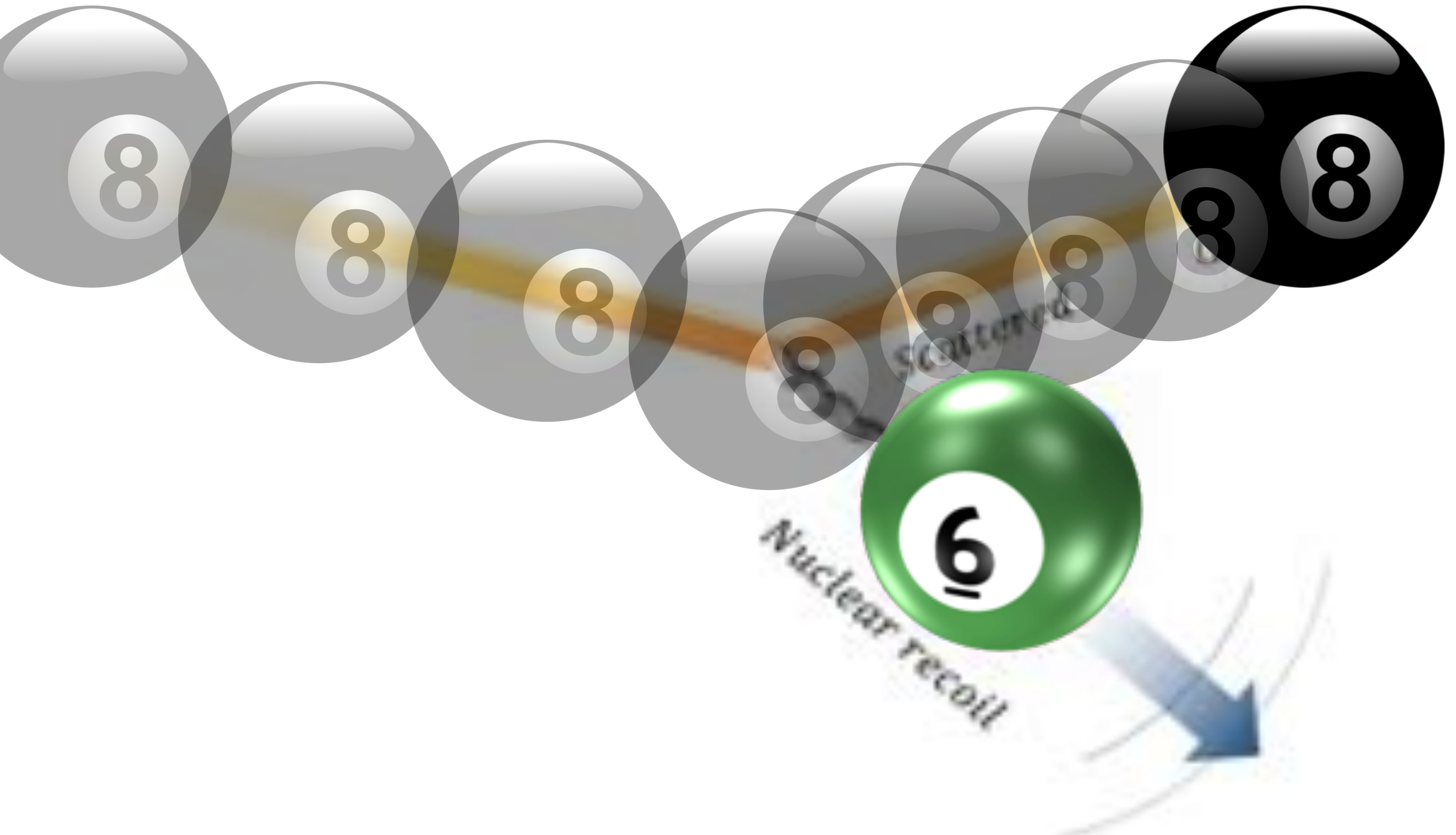
WIMP spectra

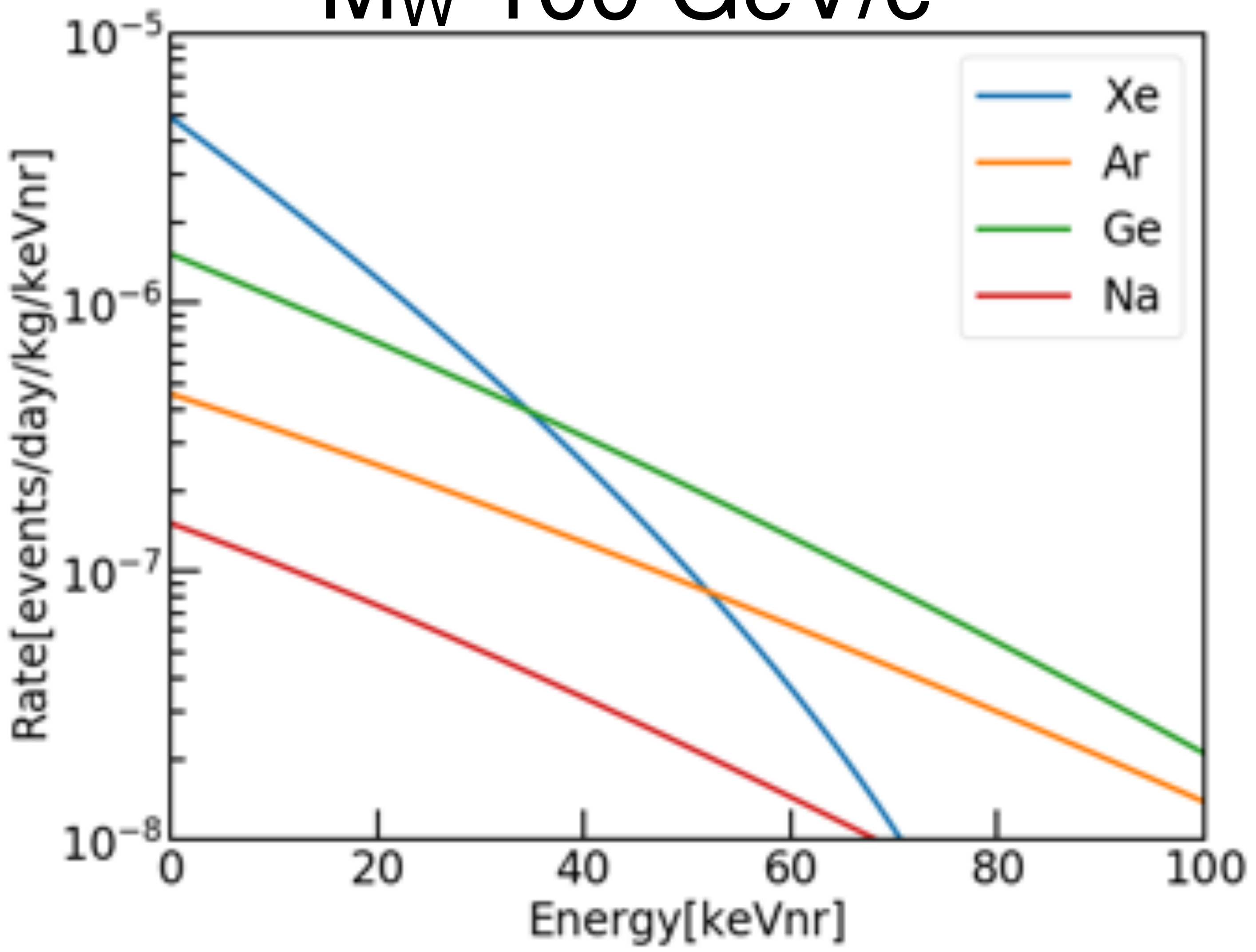


- Non relativistic regime (v << c)
- Signal: nuclear recoils (NR)
- Coherent scattering enhancement (A^2)
- High energy suppression (F^2)
- Rate exponential in obs. energy
- σ_{WN} and ρ_{DM} degenerate

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

Particle physics **Nuclear physics** **Astrophysics**

M_W 100 GeV/c²



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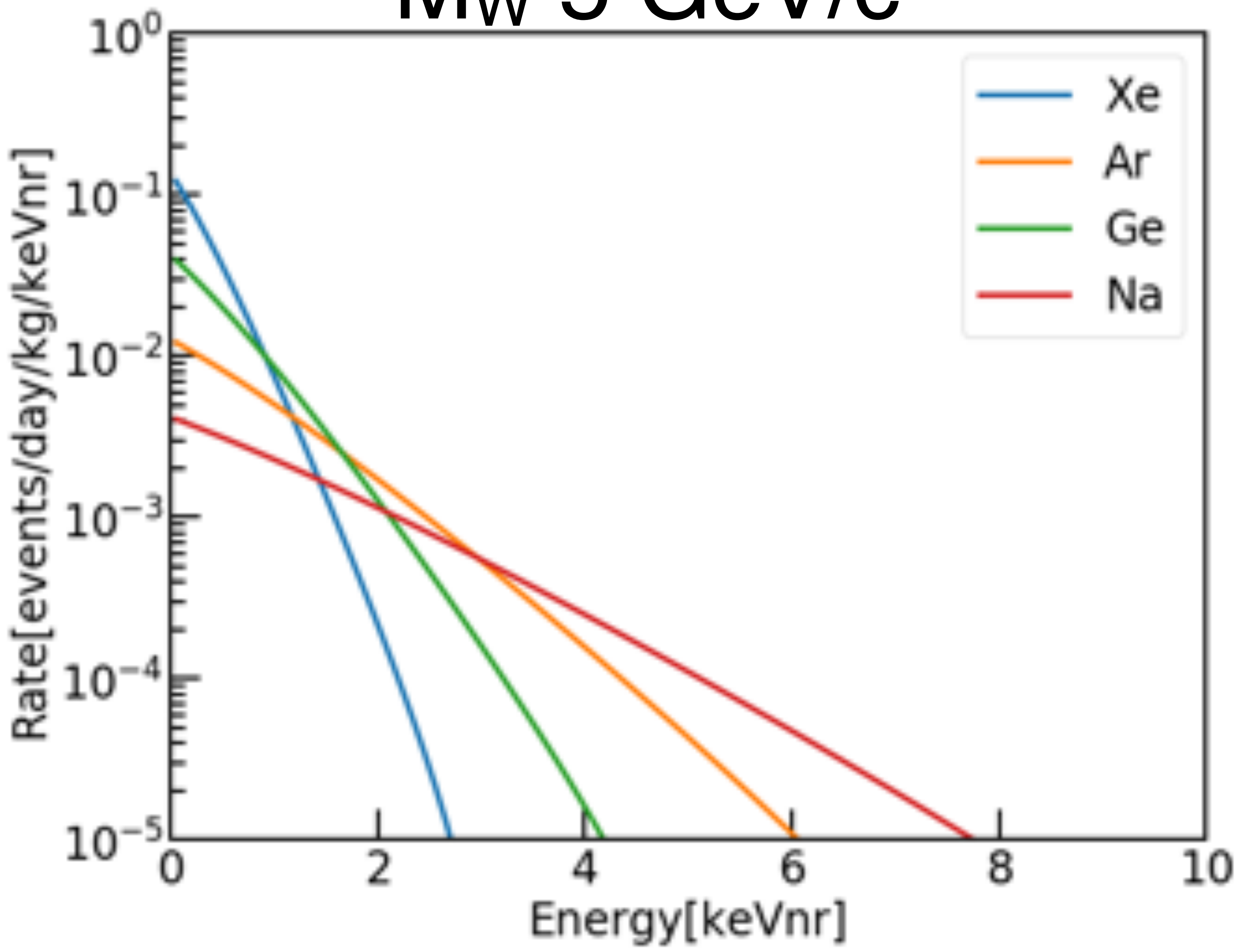
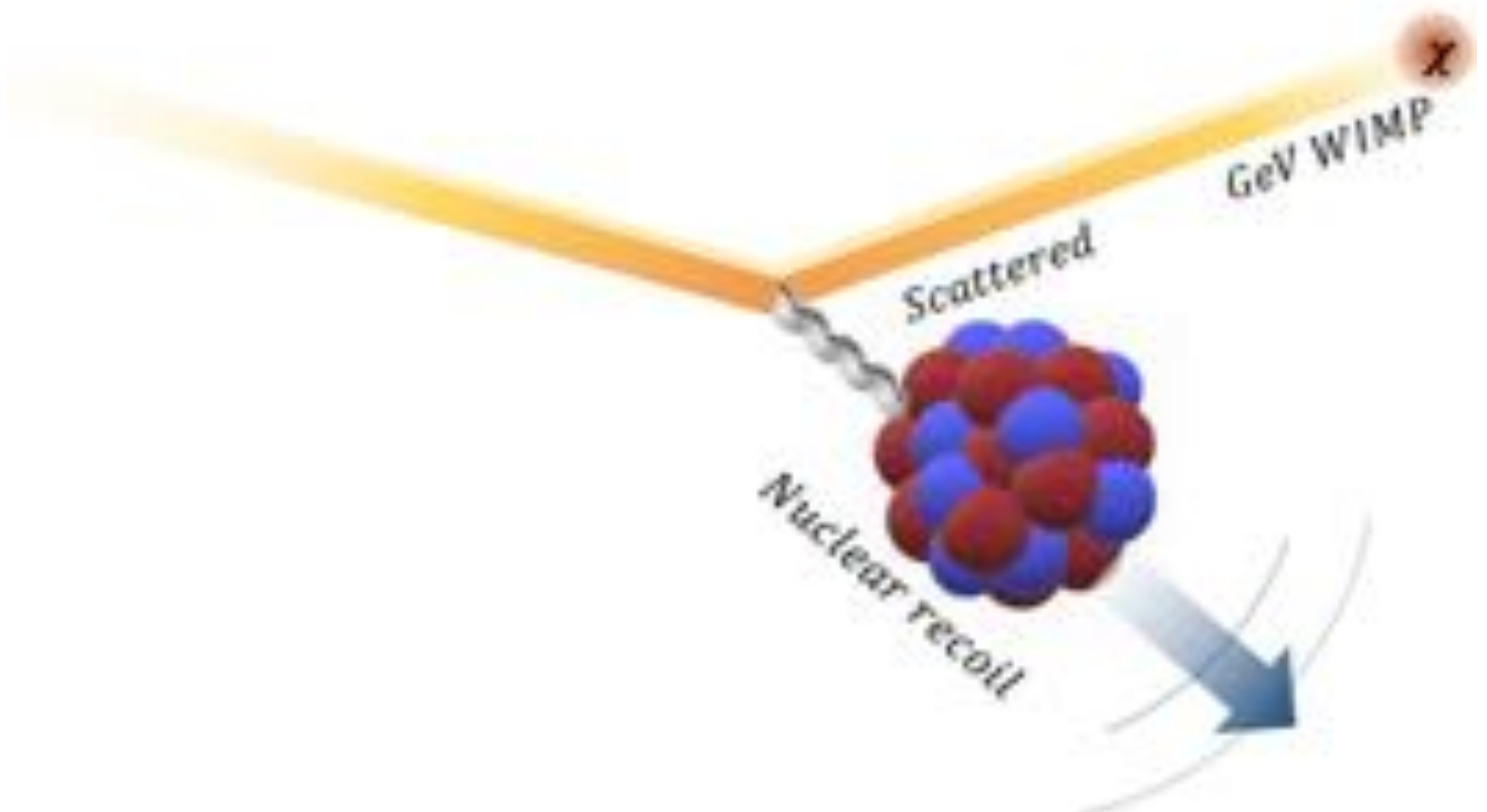


High M_W →
- Low number density ✘
- High recoil energies ✔
- High A target ✔

Low M_W →
- High number density ✔
- Low recoil energies ✘
- Low A target ✘

WIMP spectra



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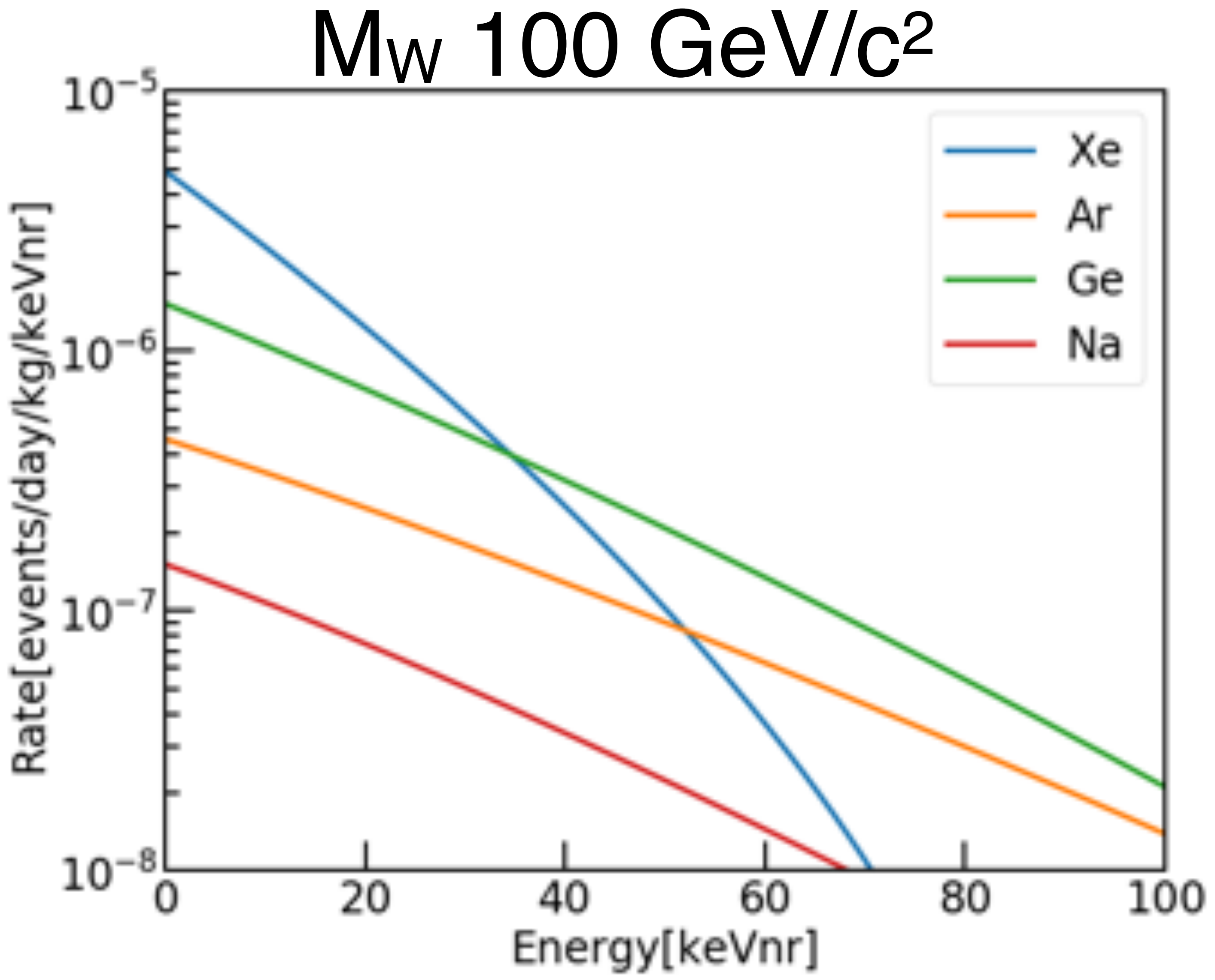
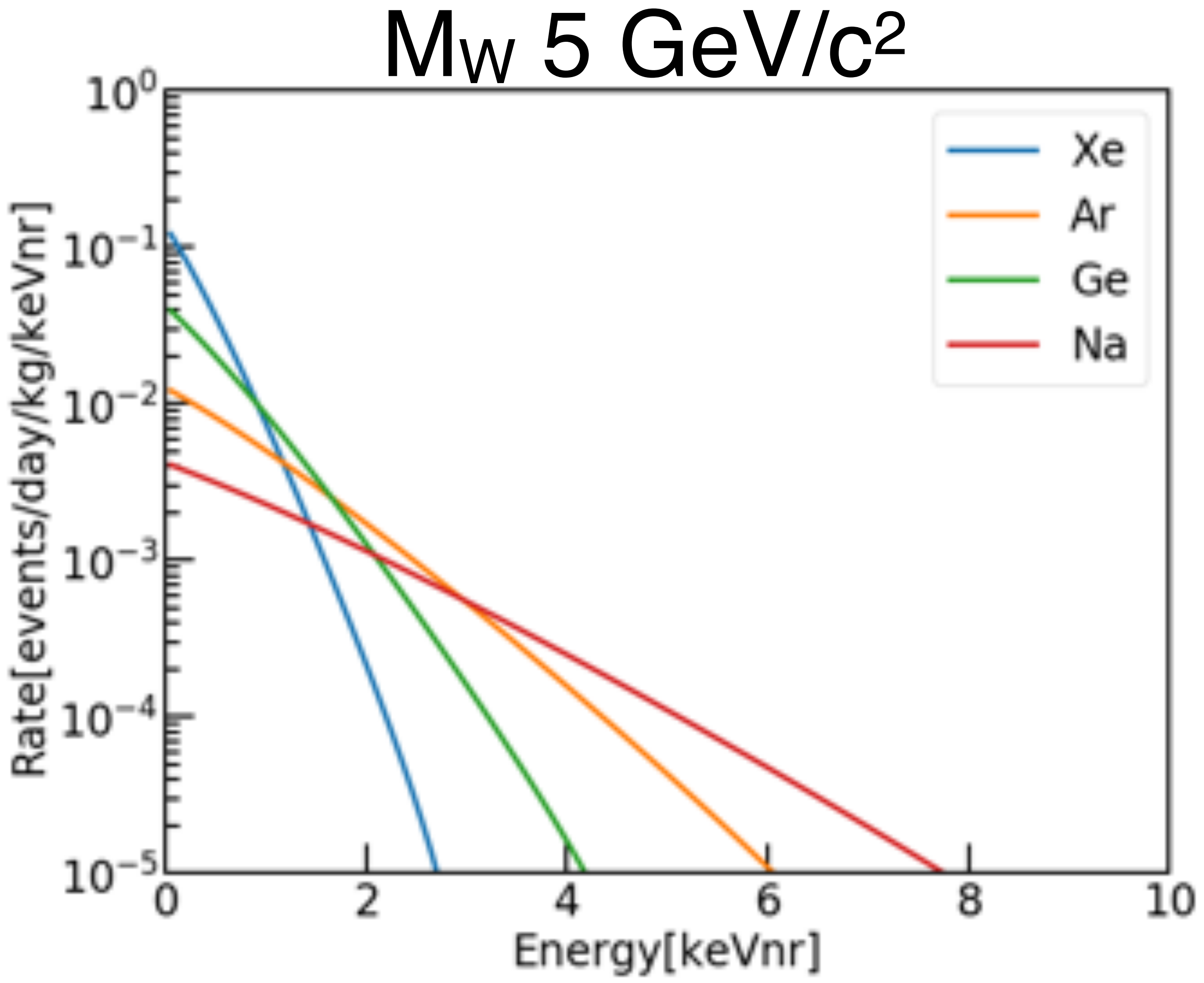
Particle physics **Nuclear physics** **Astrophysics**



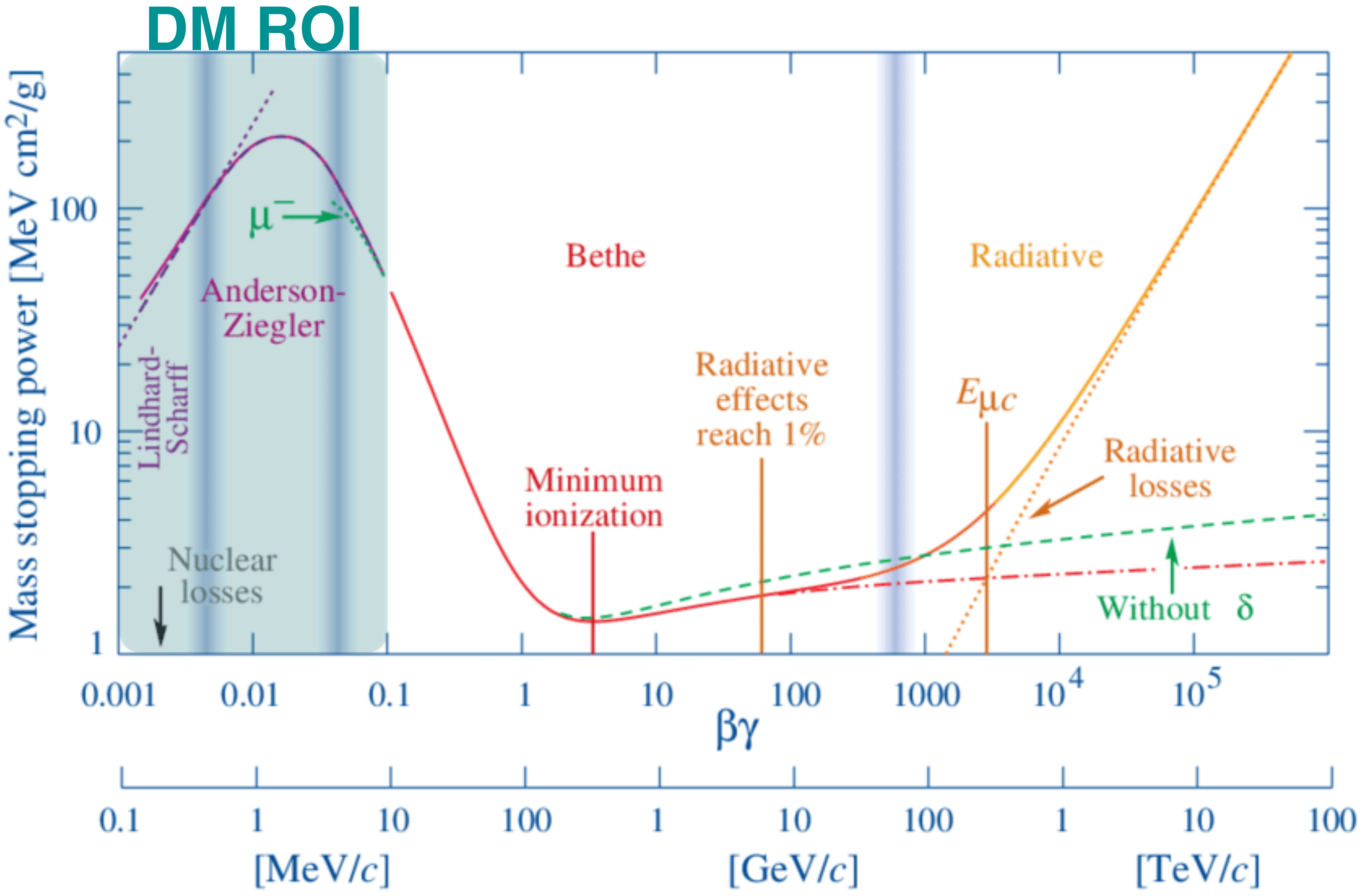


High M_W
- Low number density ✗
- High recoil energies ✓
- High A target ✓

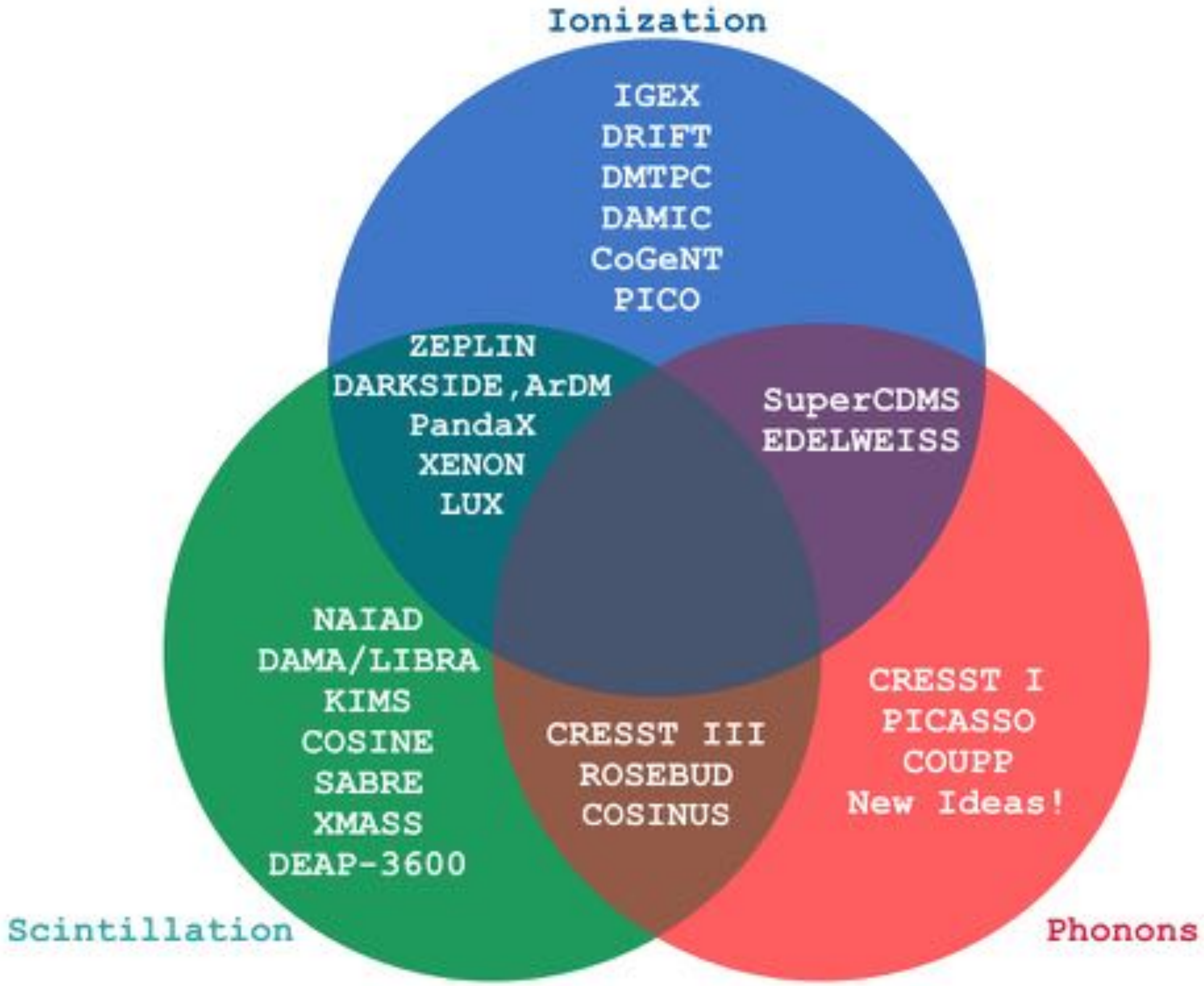
Low M_W
- High number density ✓
- Low recoil energies ✗
- Low A target ✗

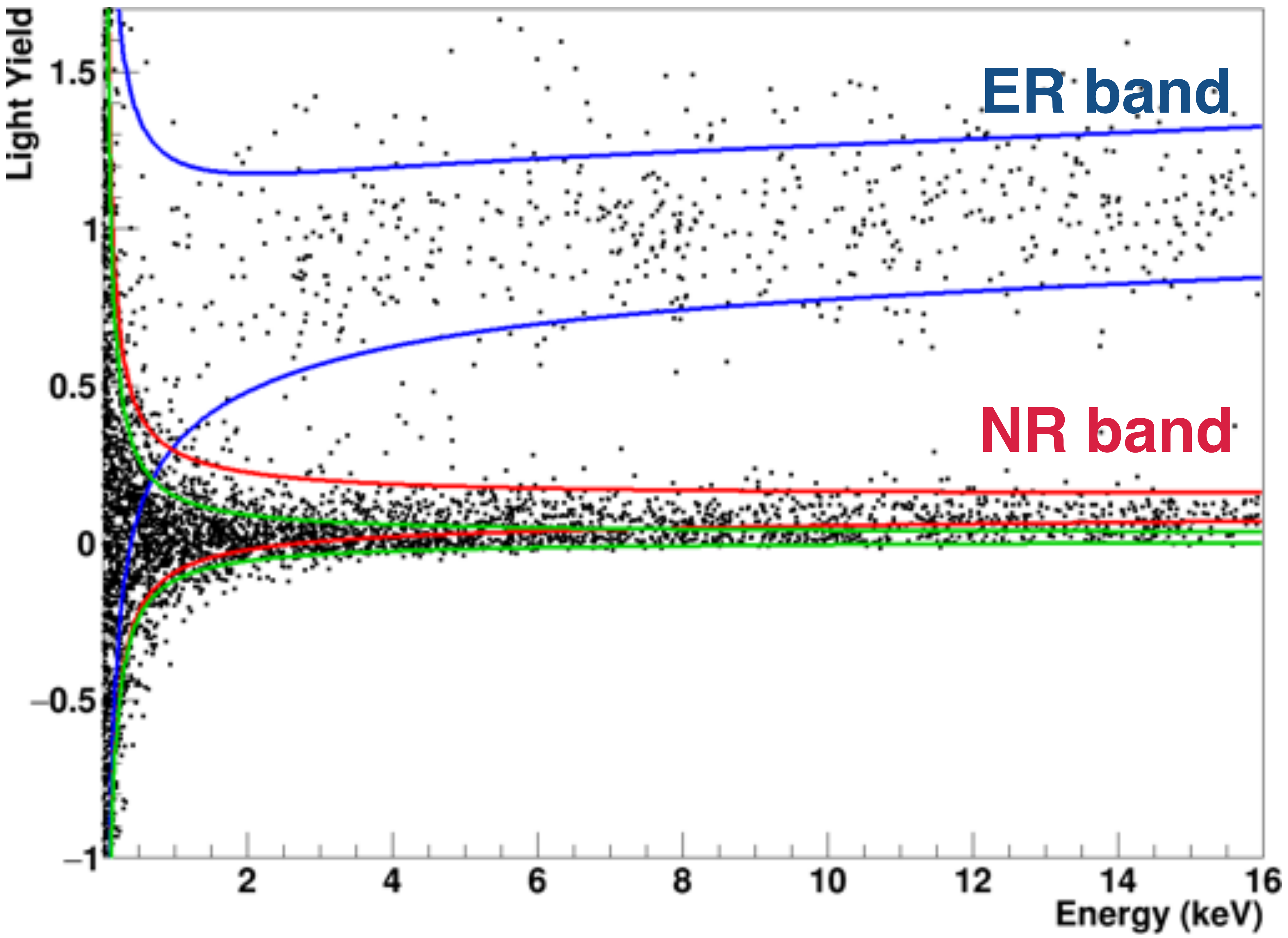
Experimental techniques

- Energy loss mechanisms in matter depend on energy scale
- ROI for DM direct search < 100 keV
- Lindhard regime: adiabatic overlap of electron shells
- Energy losses as HEAT (nuclear quenching)



Experimental techniques



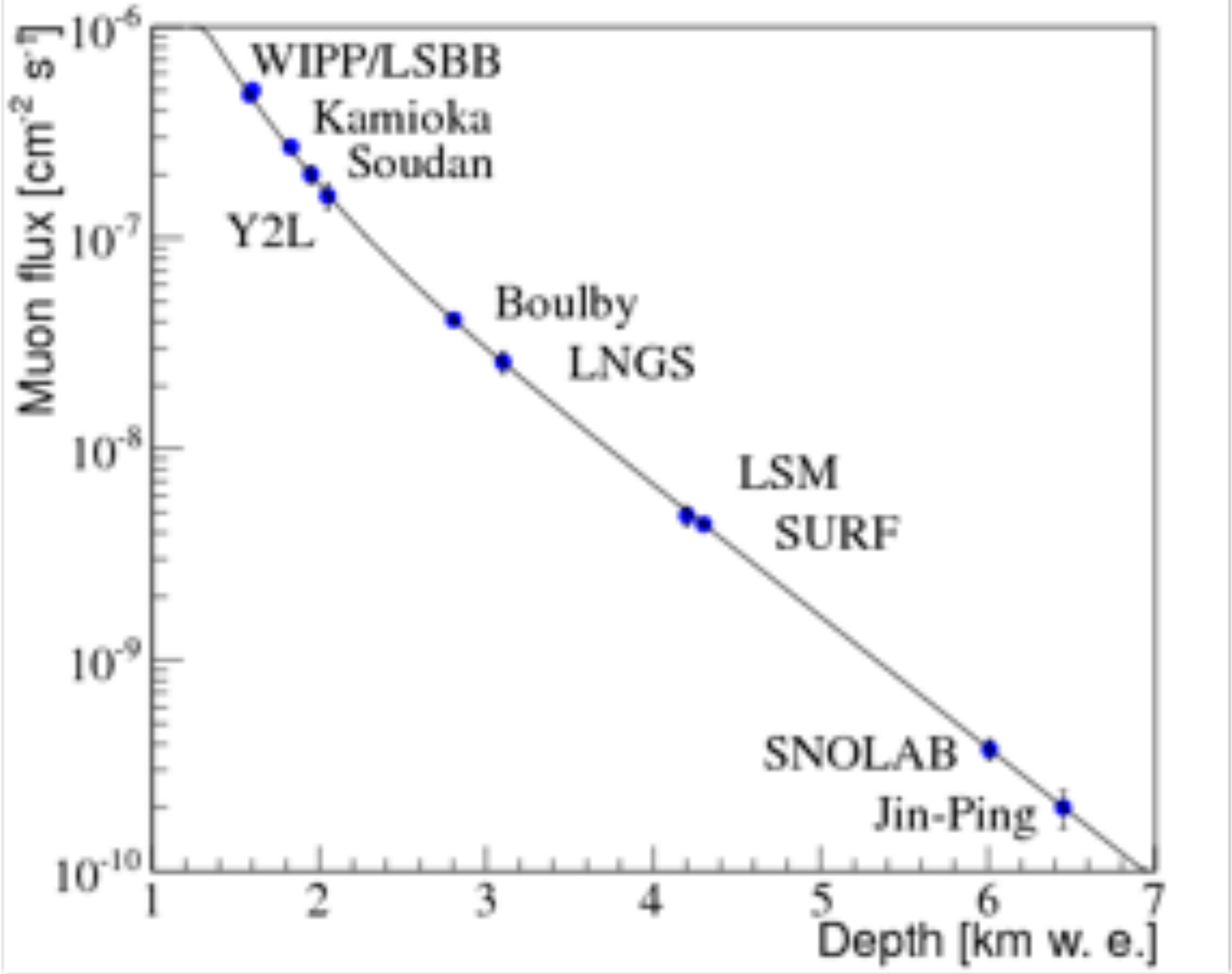


- Variety of experiments exploiting all channels
- Phonon observation requires cryogenics

- Sensitivity to 2 excitation channels
- ER/NR discrimination ⇒ background rejection

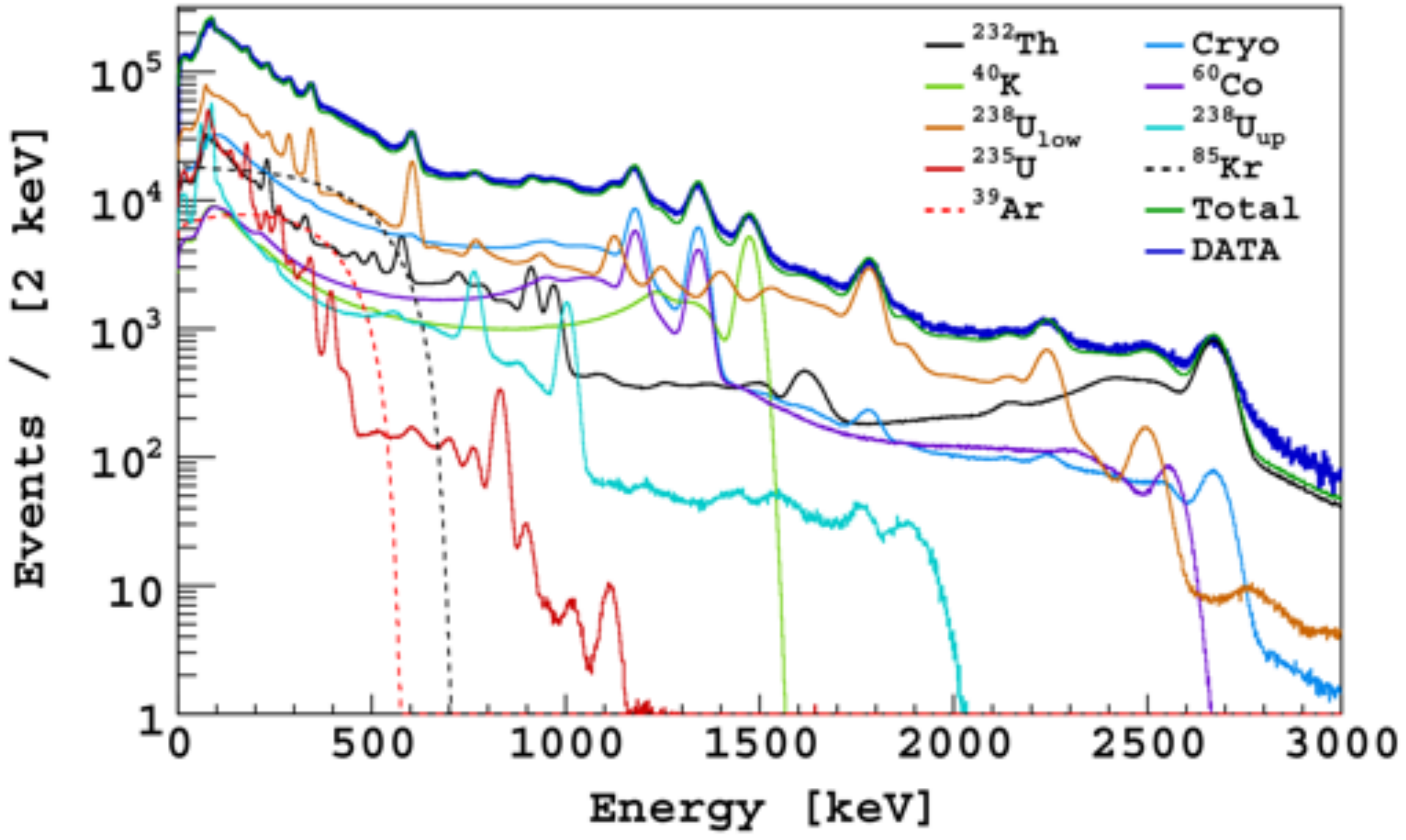
Radiogenic and cosmogenic backgrounds

From above



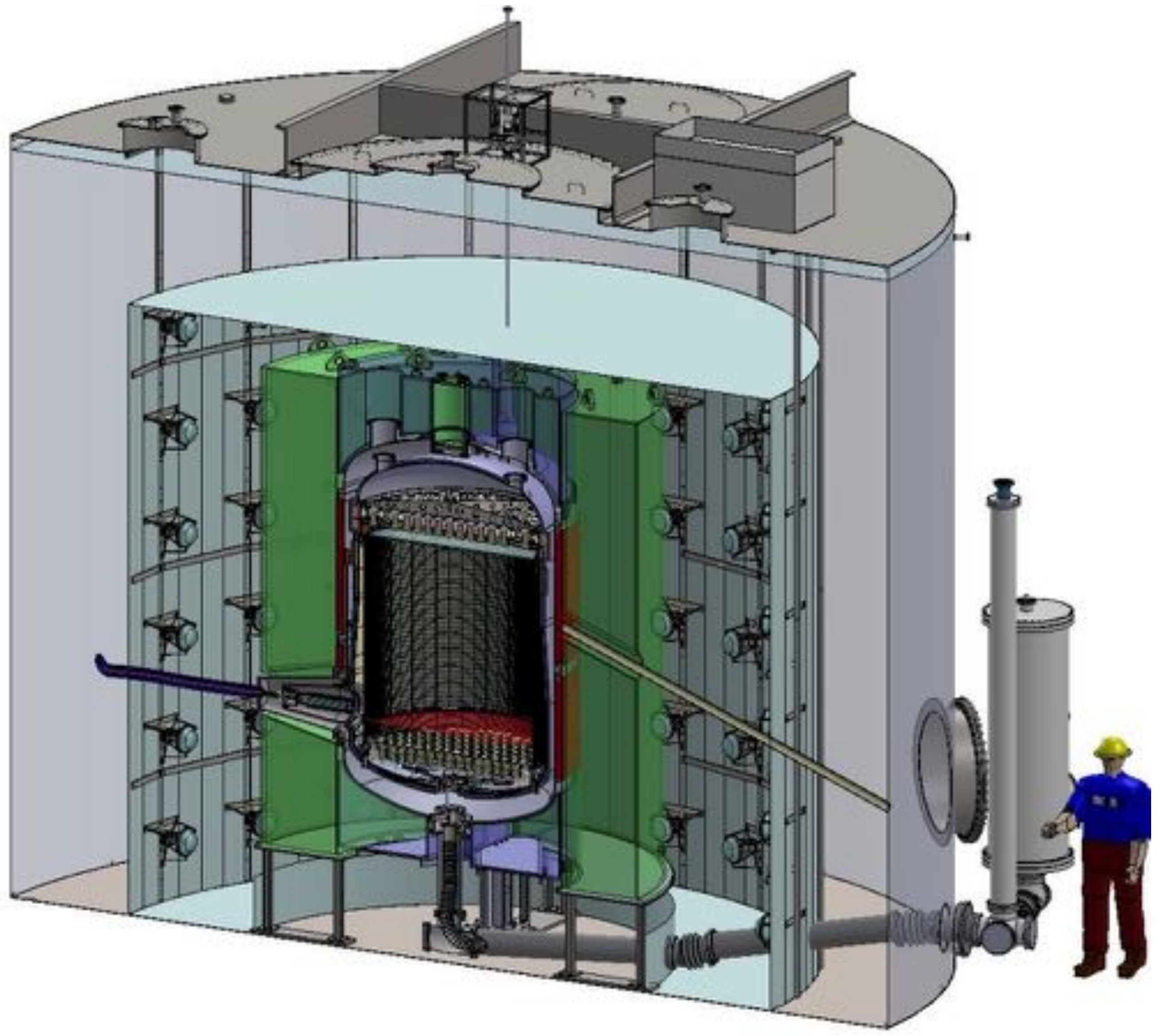
- Excessive muon rate at surface
- Radioactive isotopes activated
- Neutron generation
- Go underground!

From below



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

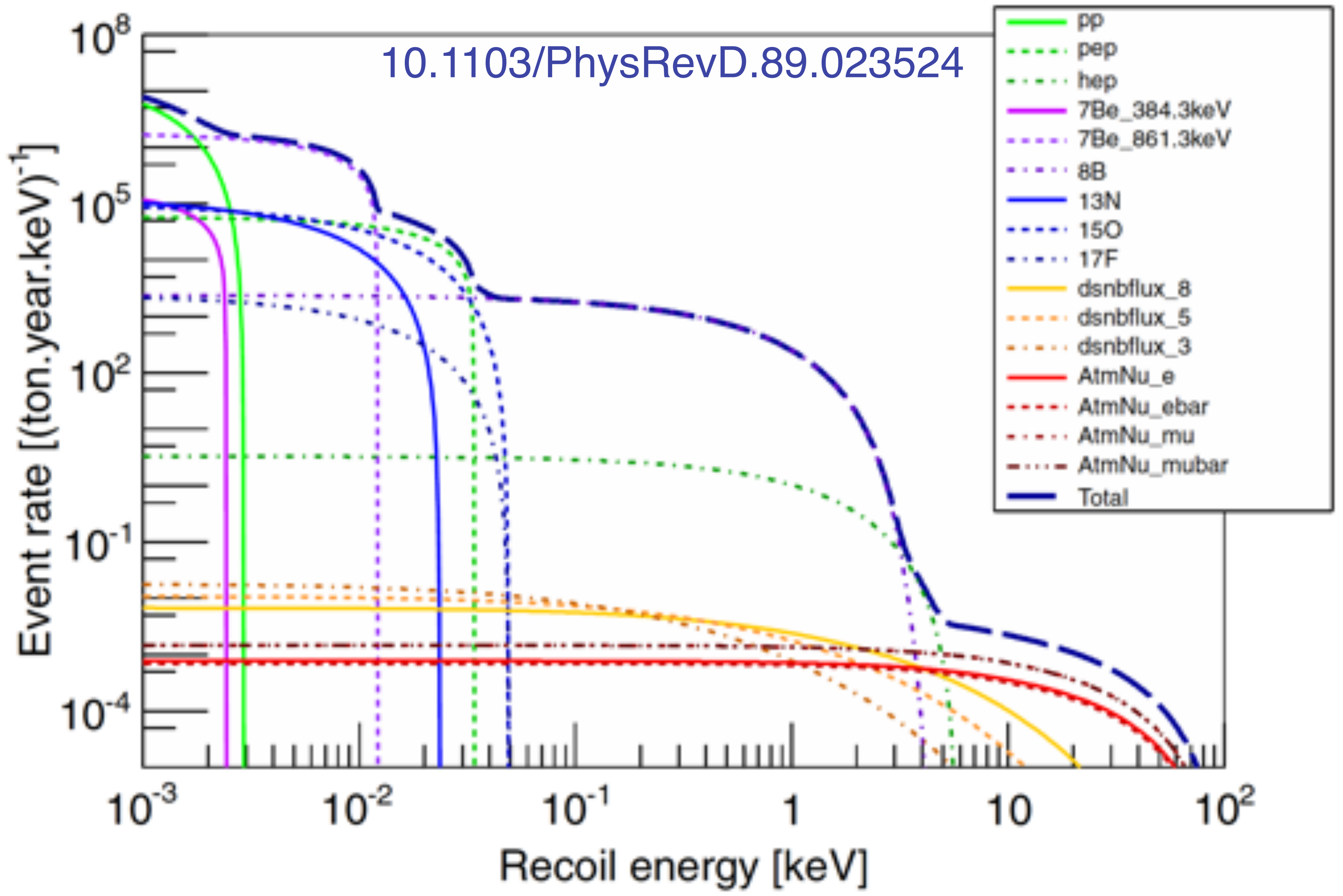
Solution



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

Neutrinos

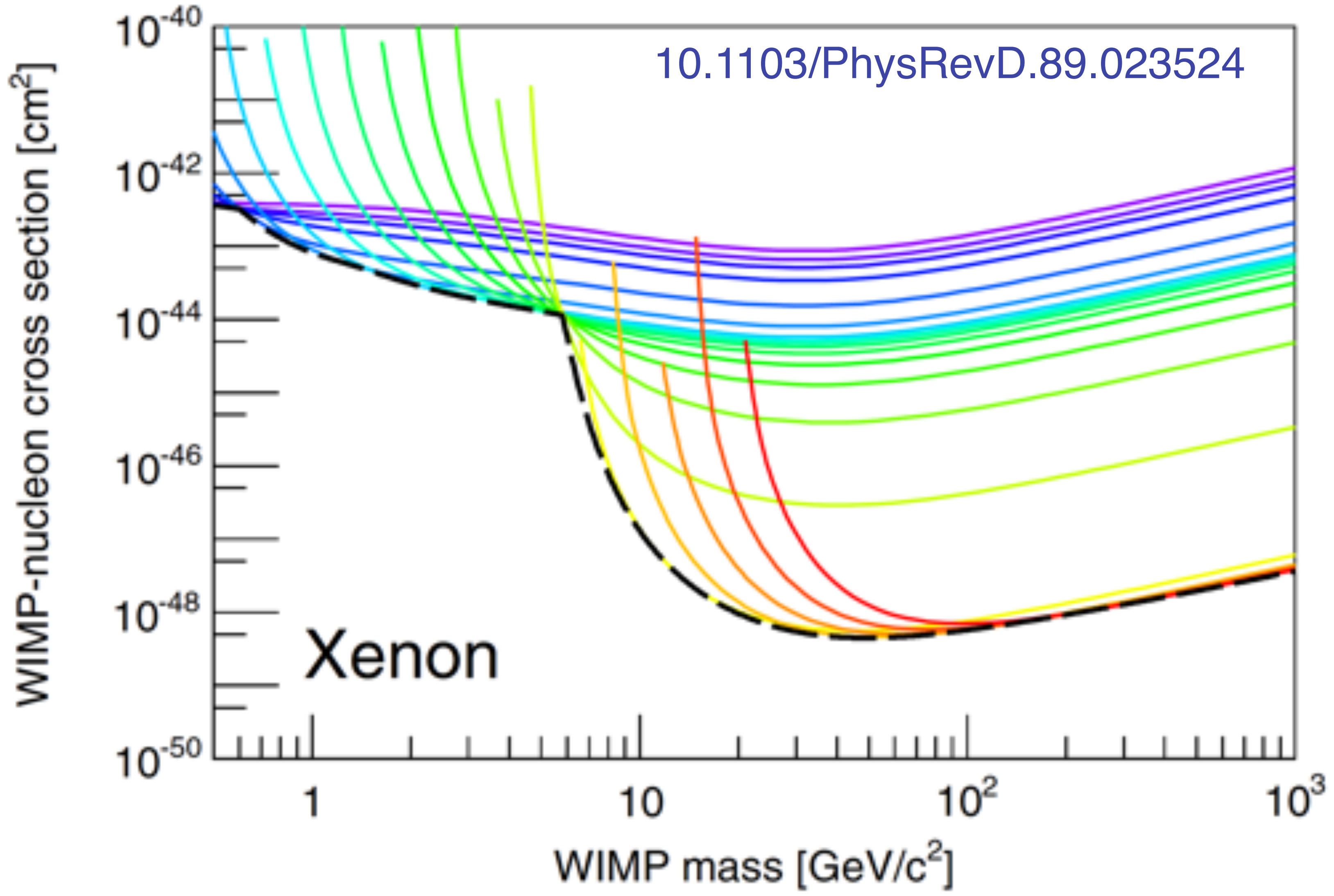
CEvNS



10.1103/PhysRevD.89.023524

- Neutrinos neutral current
- Coherent scattering on nuclei
- ^{8}B at low energies
- Atmospheric v at high energies

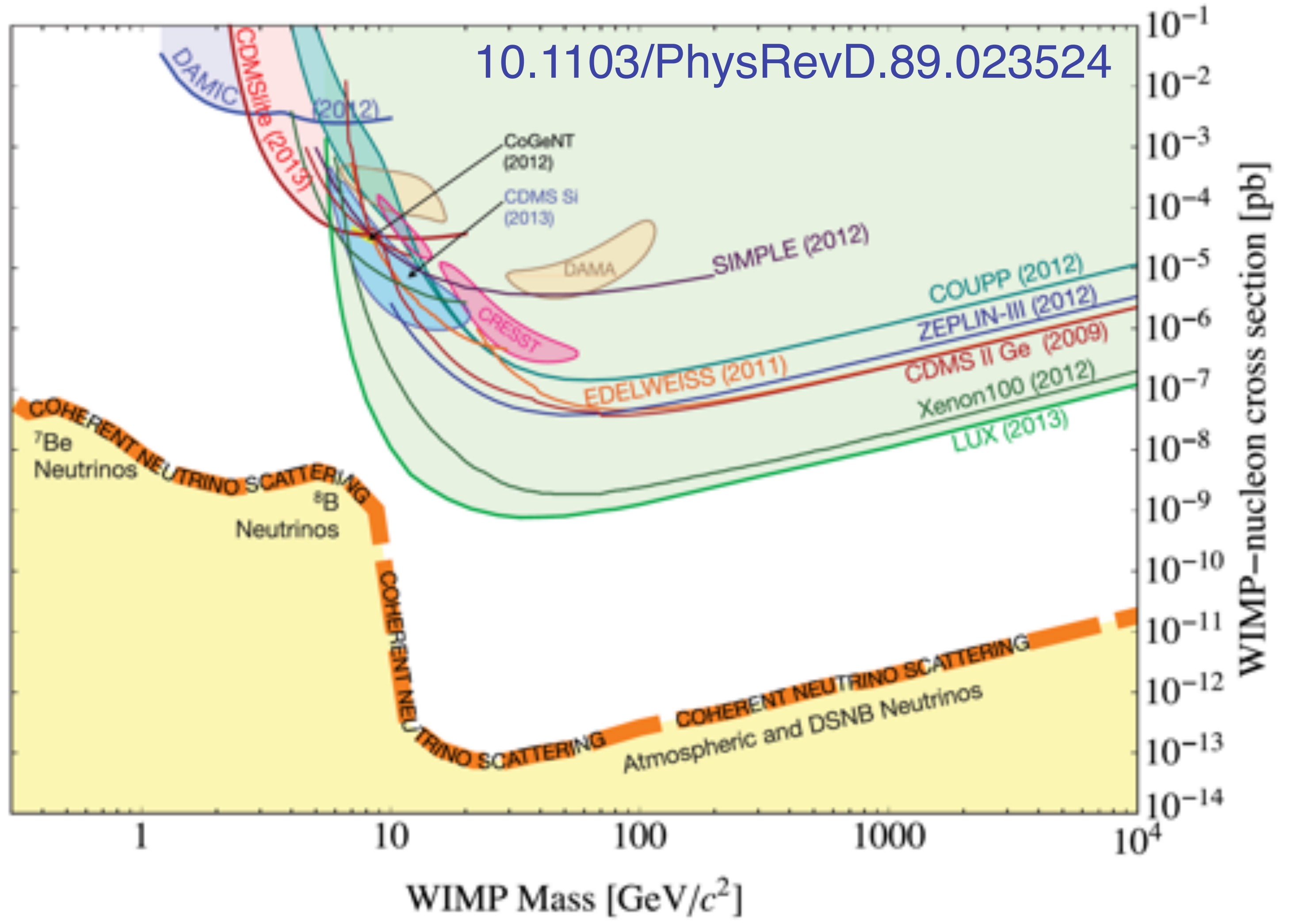
Sensitivity vs E$_{th}$



10.1103/PhysRevD.89.023524

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

Neutrino floor

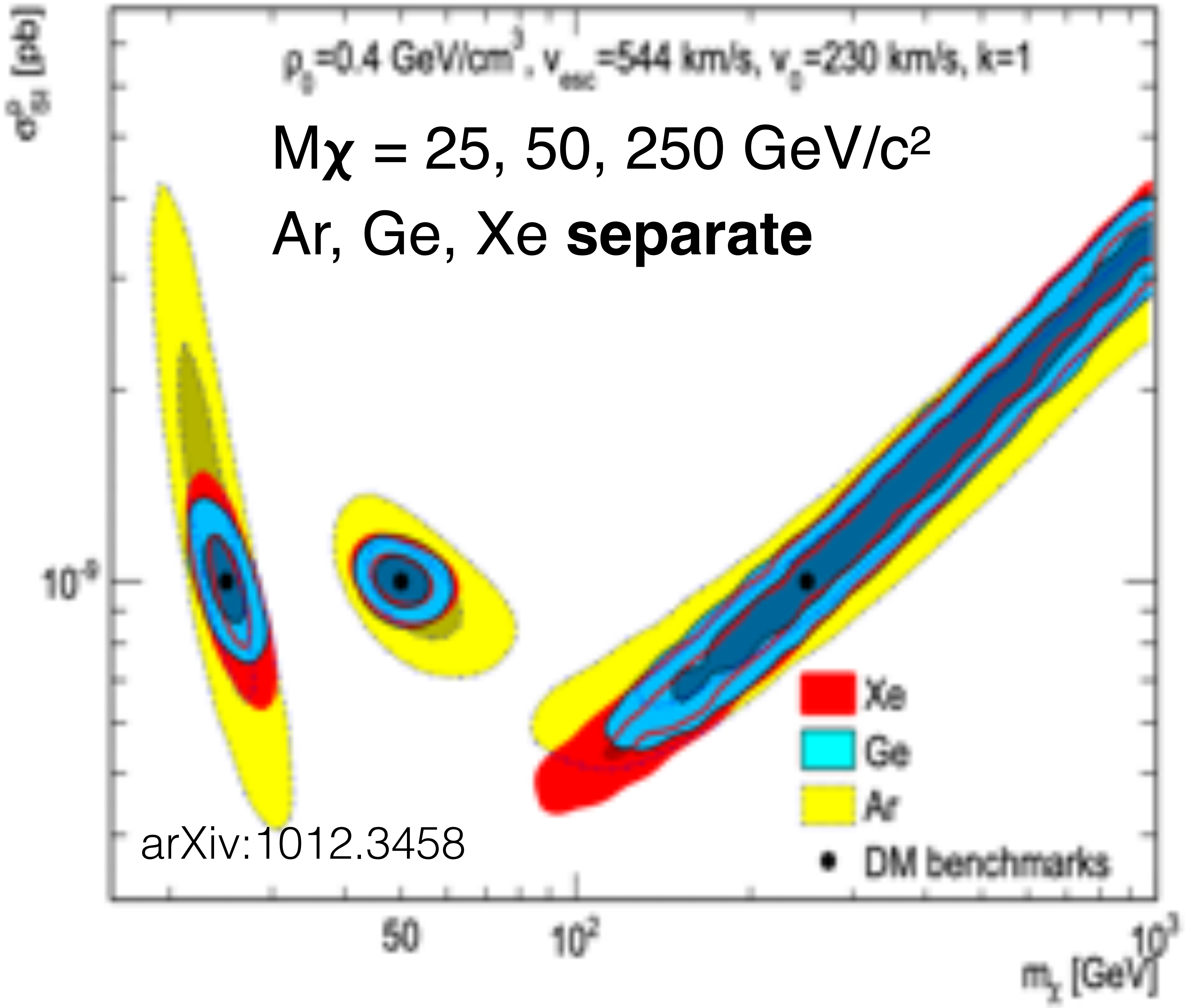


10.1103/PhysRevD.89.023524

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

Target complementarity

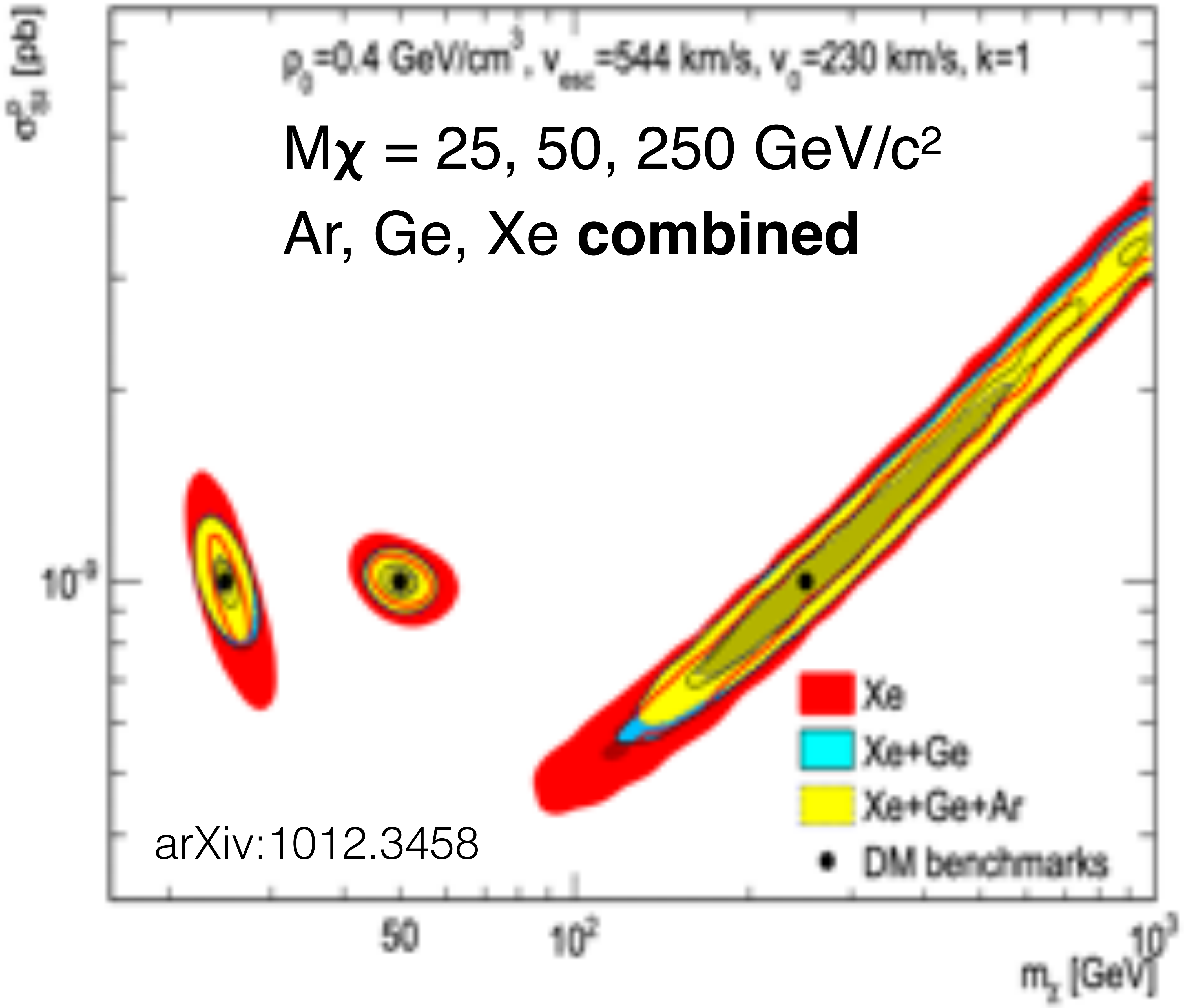
What if we actually observe something?



M**χ** = 25, 50, 250 GeV/c^2

Ar, Ge, Xe **separate**

arXiv:1012.3458



M**χ** = 25, 50, 250 GeV/c^2

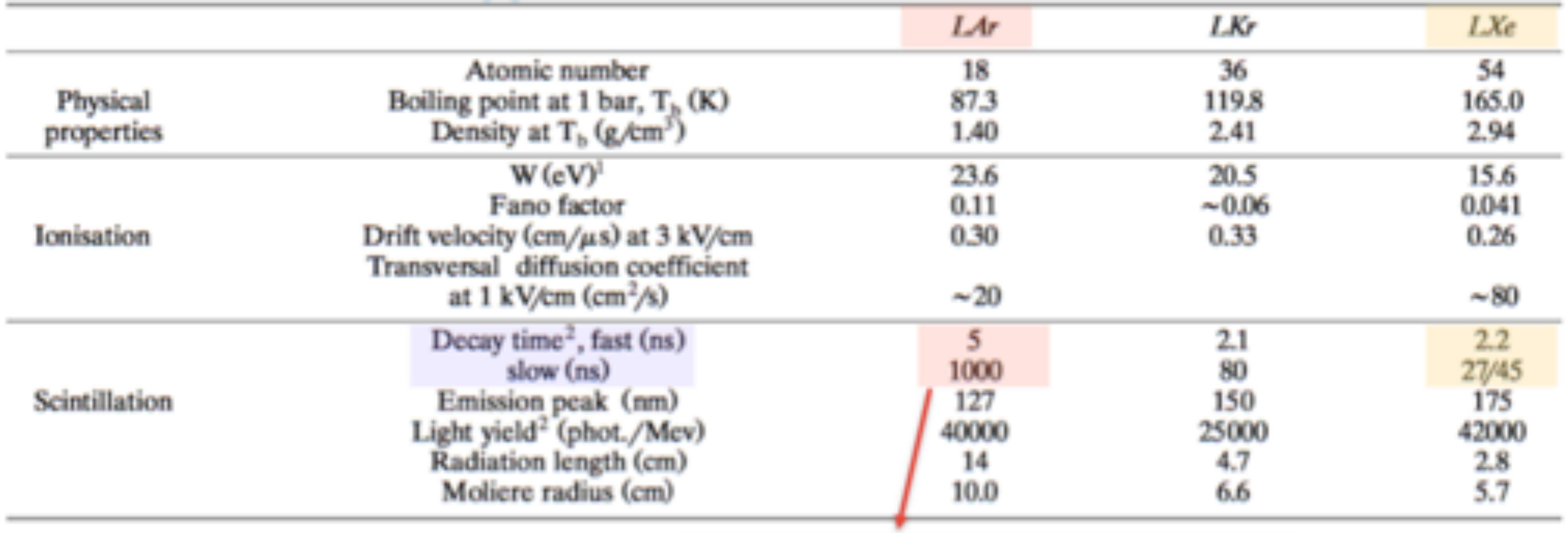
Ar, Ge, Xe **combined**

arXiv:1012.3458

A positive observation with more than one target will help constraining M**χ** and σ

Search with liquified noble elements

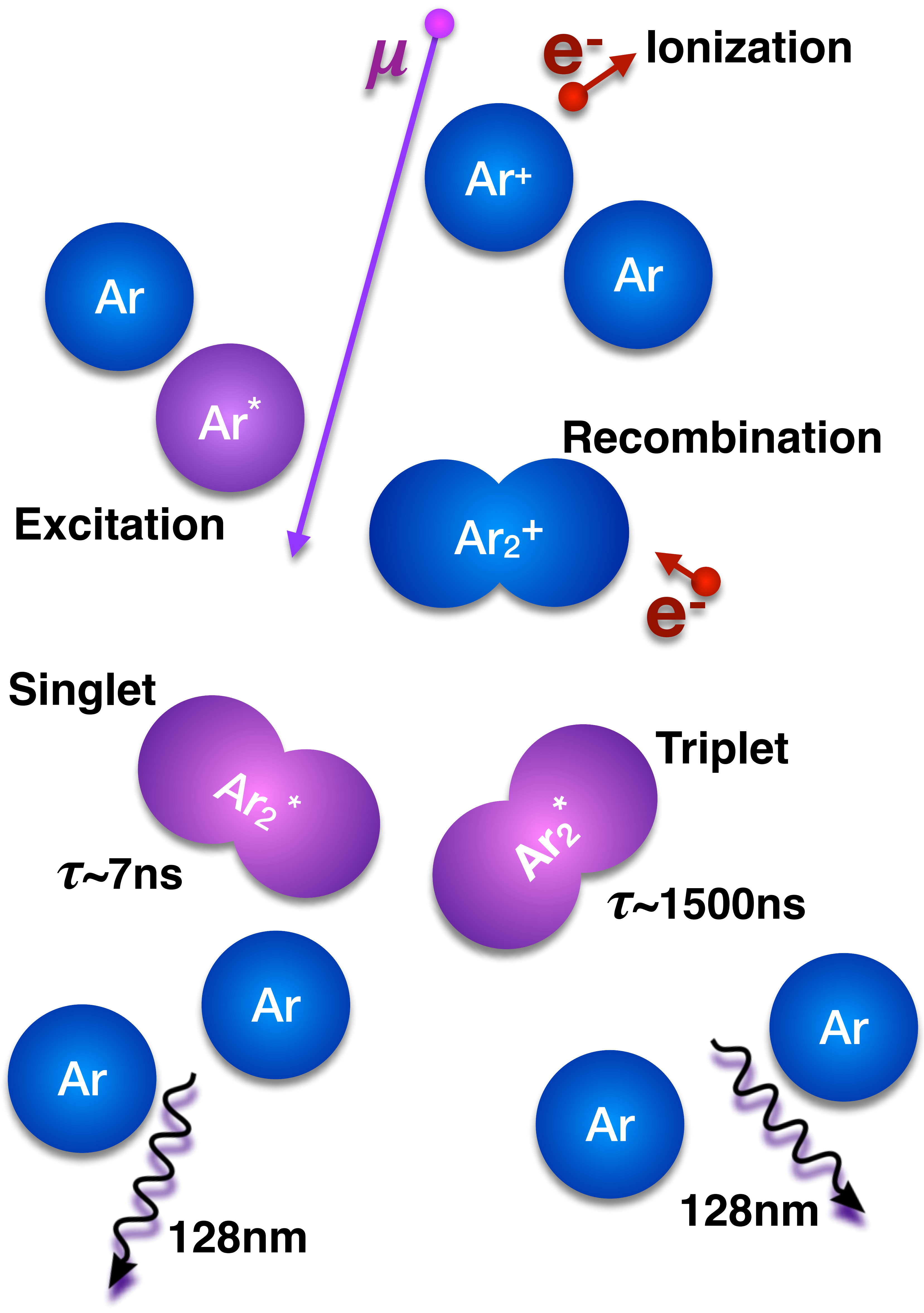
- High density ✔
  - Self screening
  - Good scalability
- Easy(-ish) purification, also online ✔
- Scintillation: good light yield ✔
- Ionisation ✔
- ER rejection ✔
- NR quenching at low energies ✘

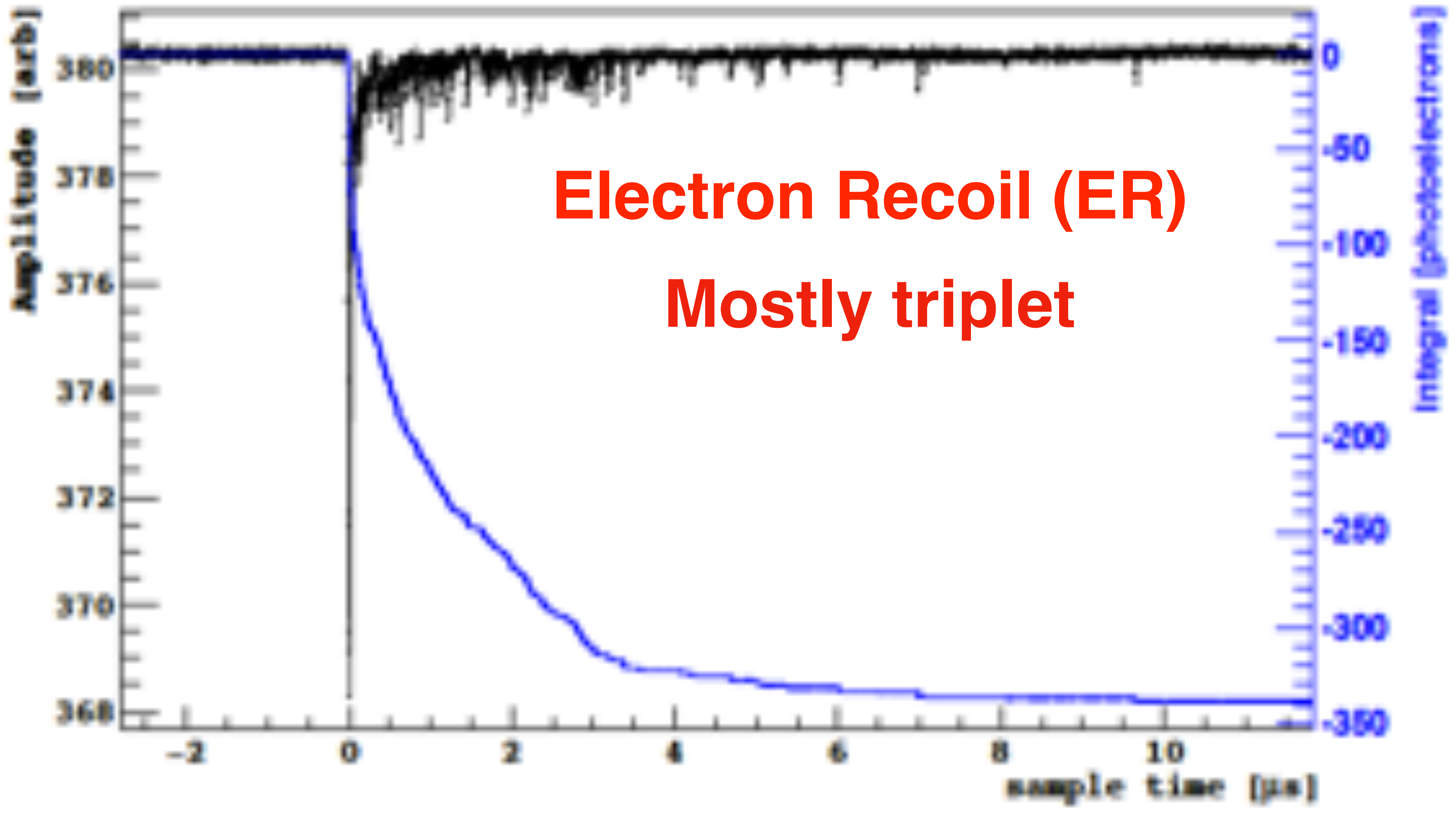


		LAr	*LKr*	*LXe*
Physical properties	Atomic number	18	36	54
	Boiling point at 1 bar, T_b (K)	87.3	119.8	165.0
	Density at T_b (g/cm^3)	1.40	2.41	2.94
Ionisation	W (eV)^1	23.6	20.5	15.6
	Fano factor	0.11	~0.06	0.041
	Drift velocity (cm/μs) at 3 kV/cm	0.30	0.33	0.26
	Transversal diffusion coefficient at 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

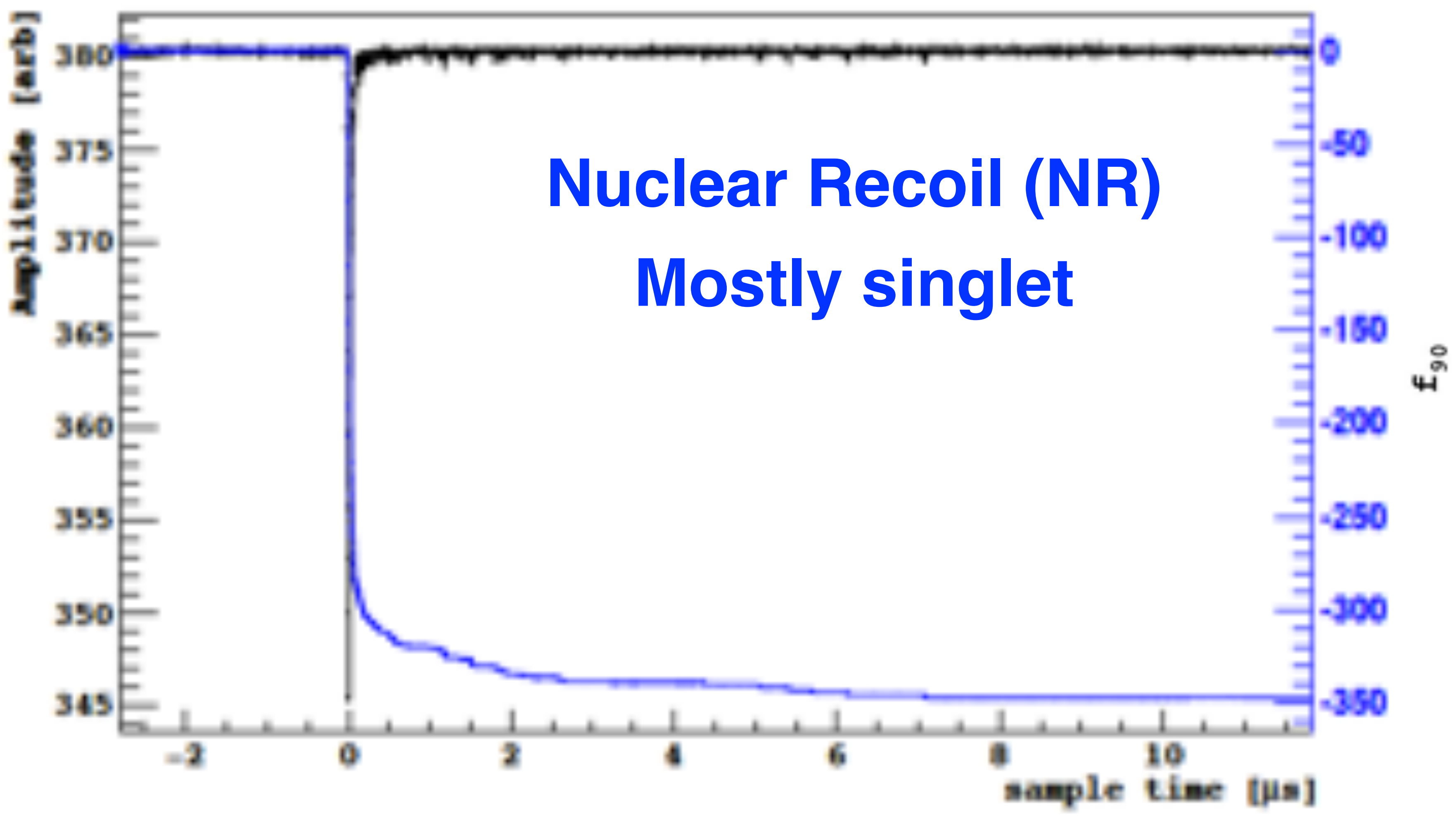
Excellent discrimination power!

ER rejection in LAr

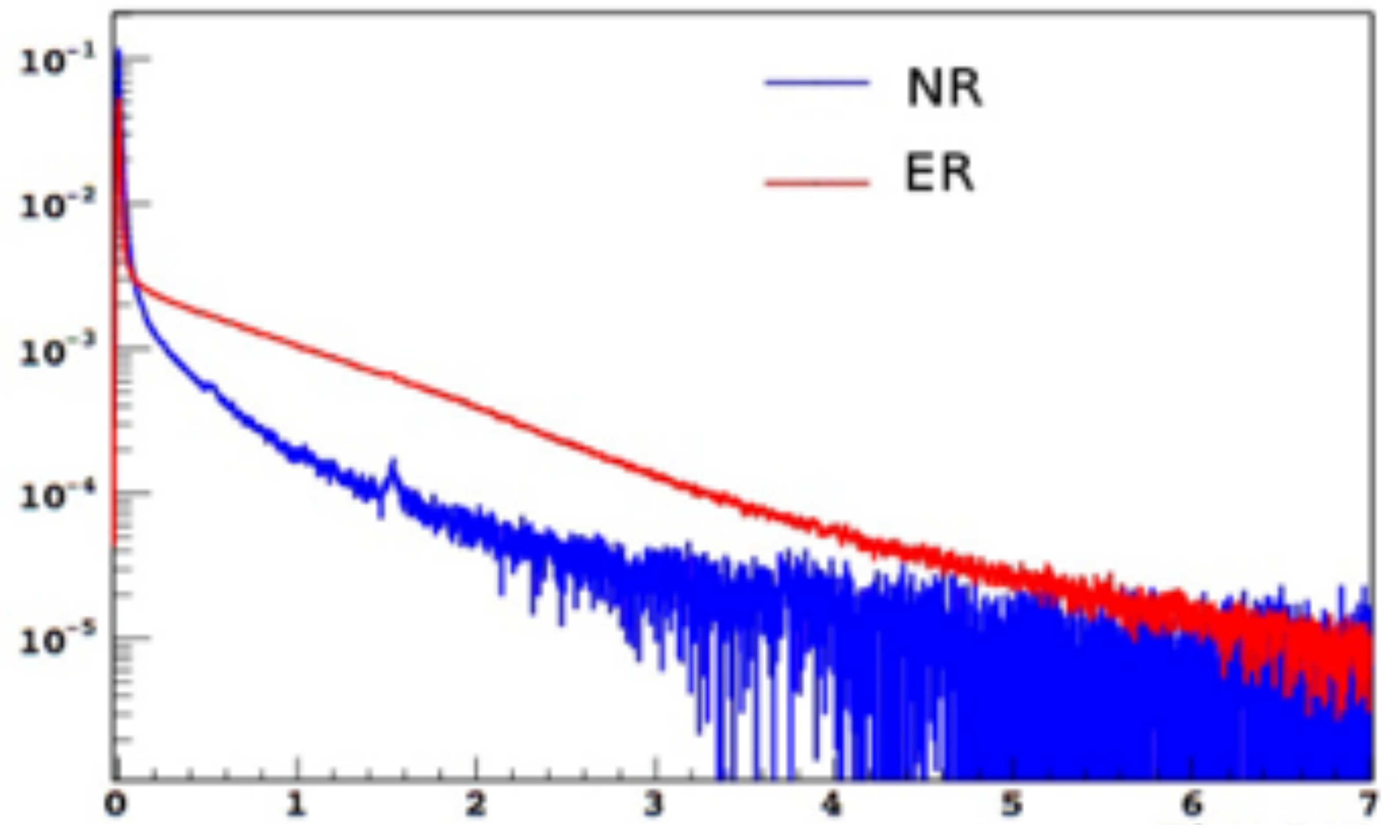


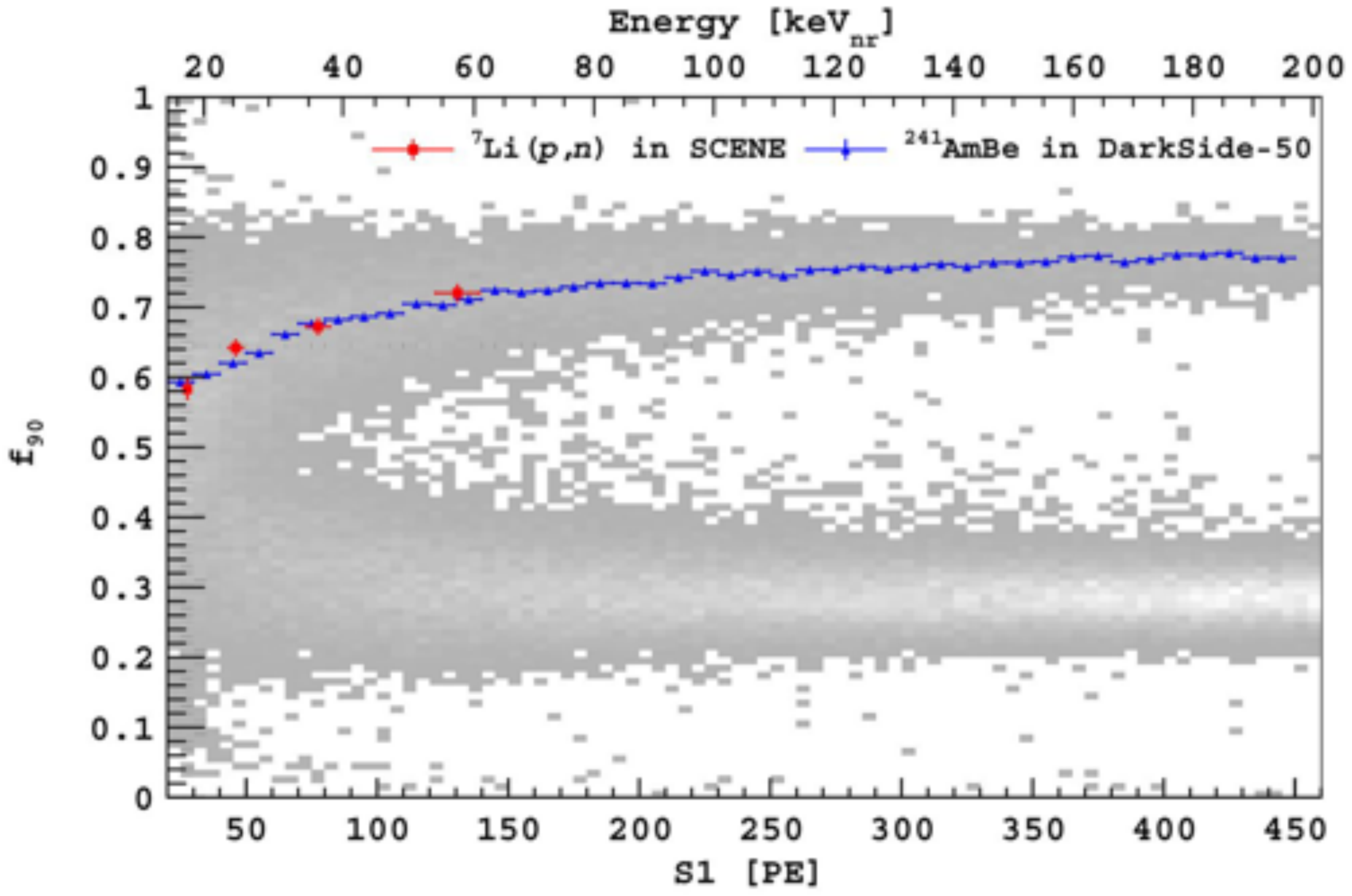


Electron Recoil (ER)
Mostly triplet



Nuclear Recoil (NR)
Mostly singlet





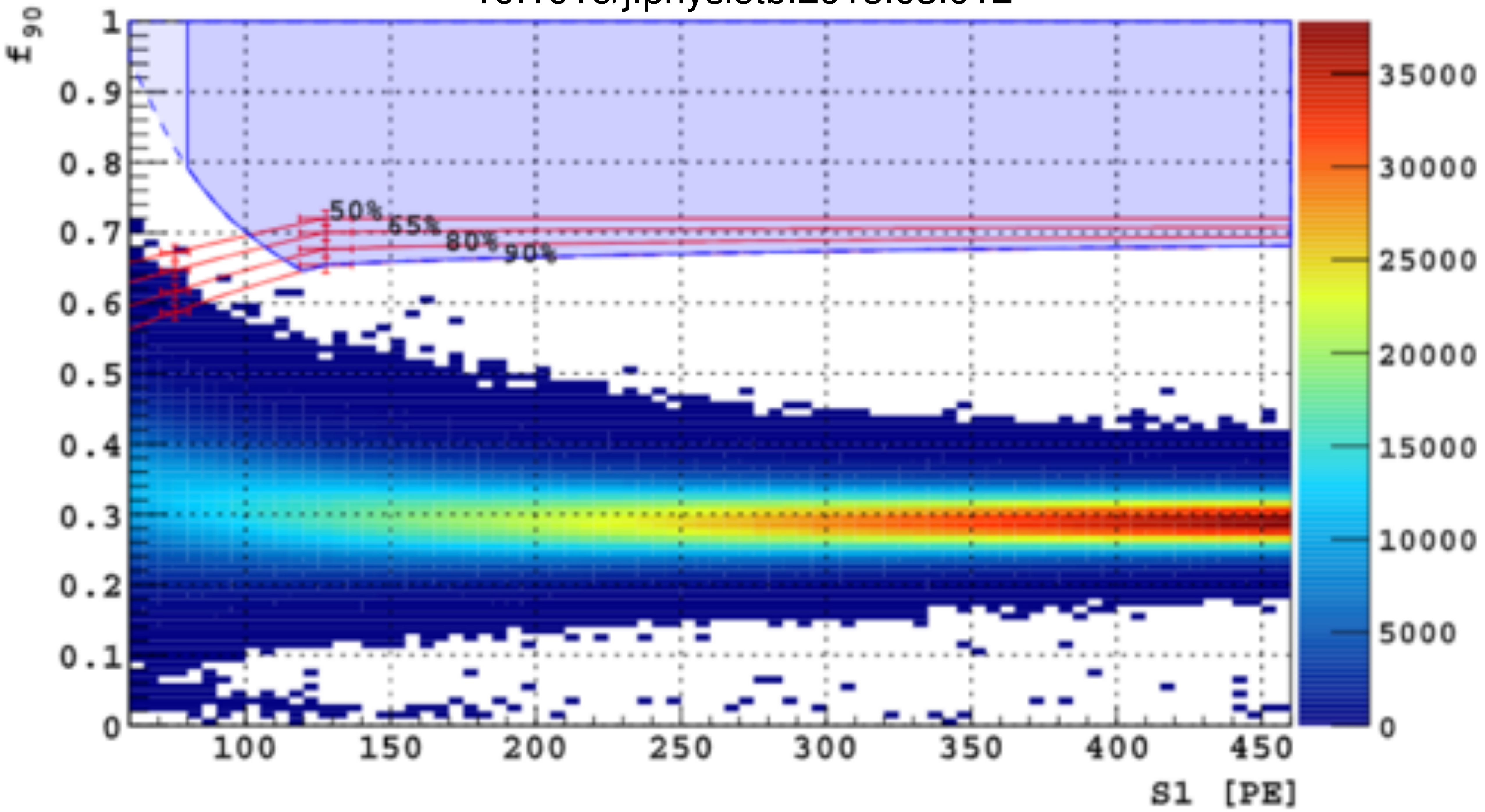
$\boldsymbol{\beta},\boldsymbol{\gamma}$ → ER $\boldsymbol{\nu}$, n, WIMPs → NR

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

ER rejection in LAr

DarkSide-50

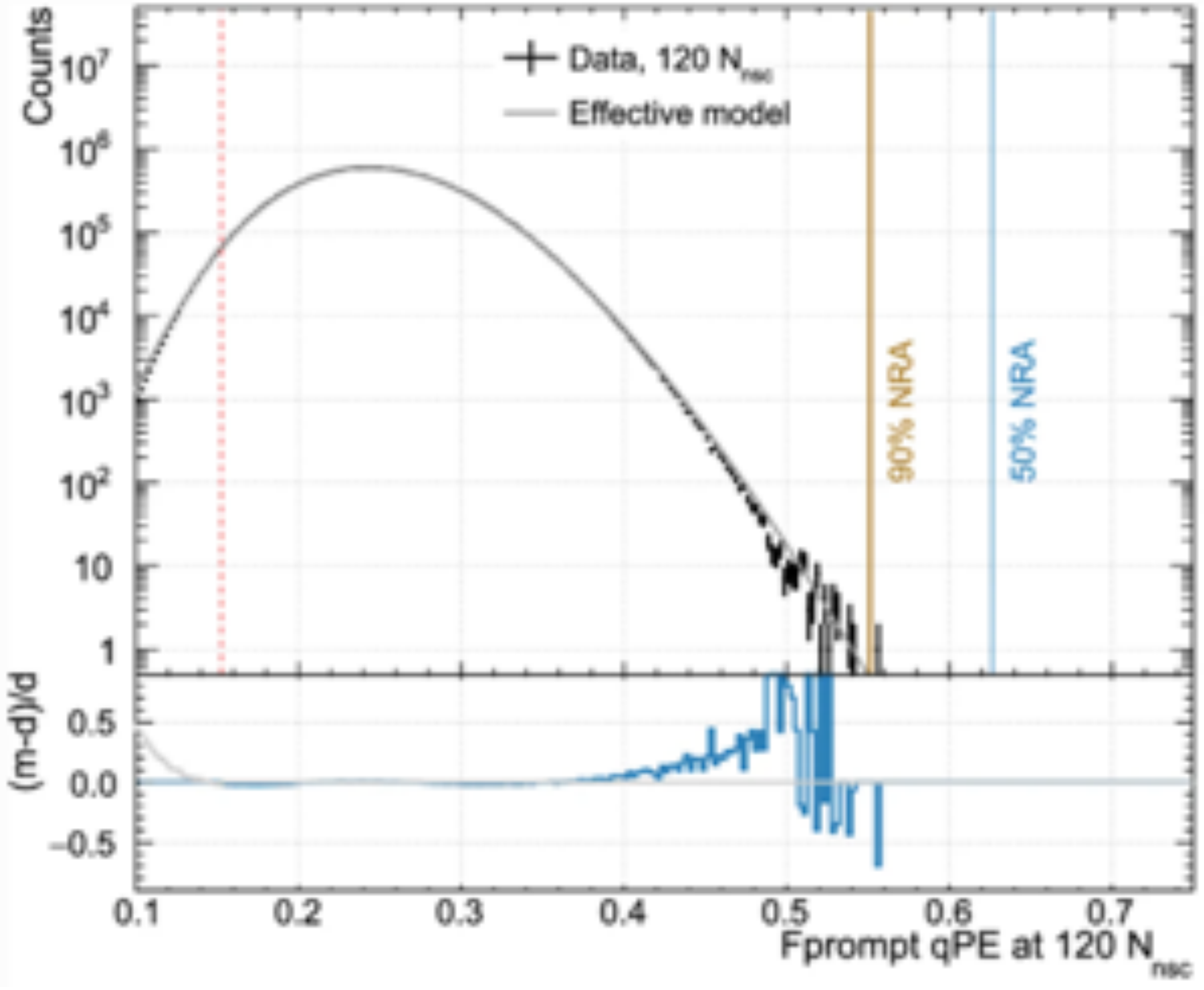
10.1016/j.physletb.2015.03.012



β,γ rejection better than 1.5x10^7

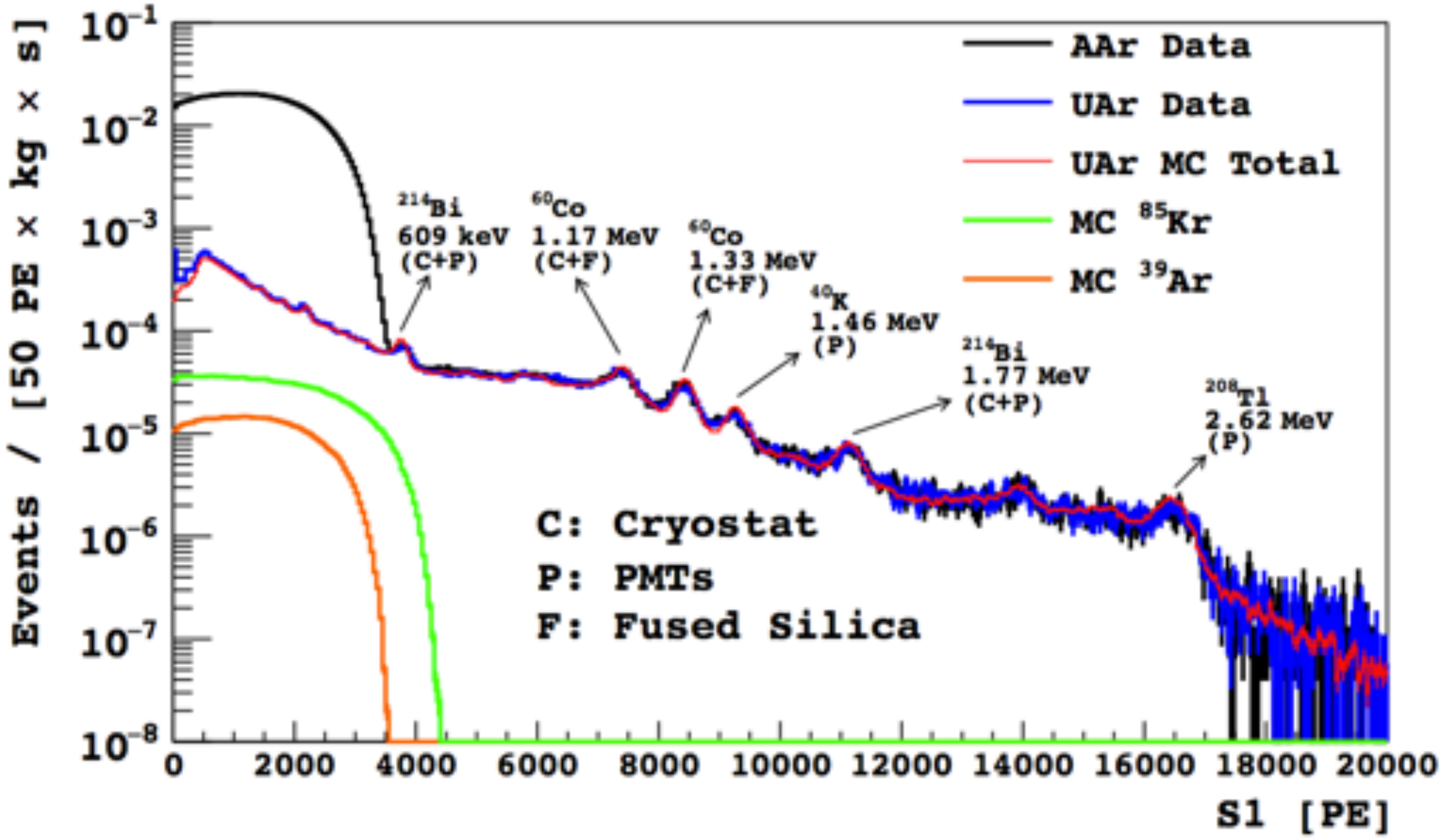
DEAP-3600

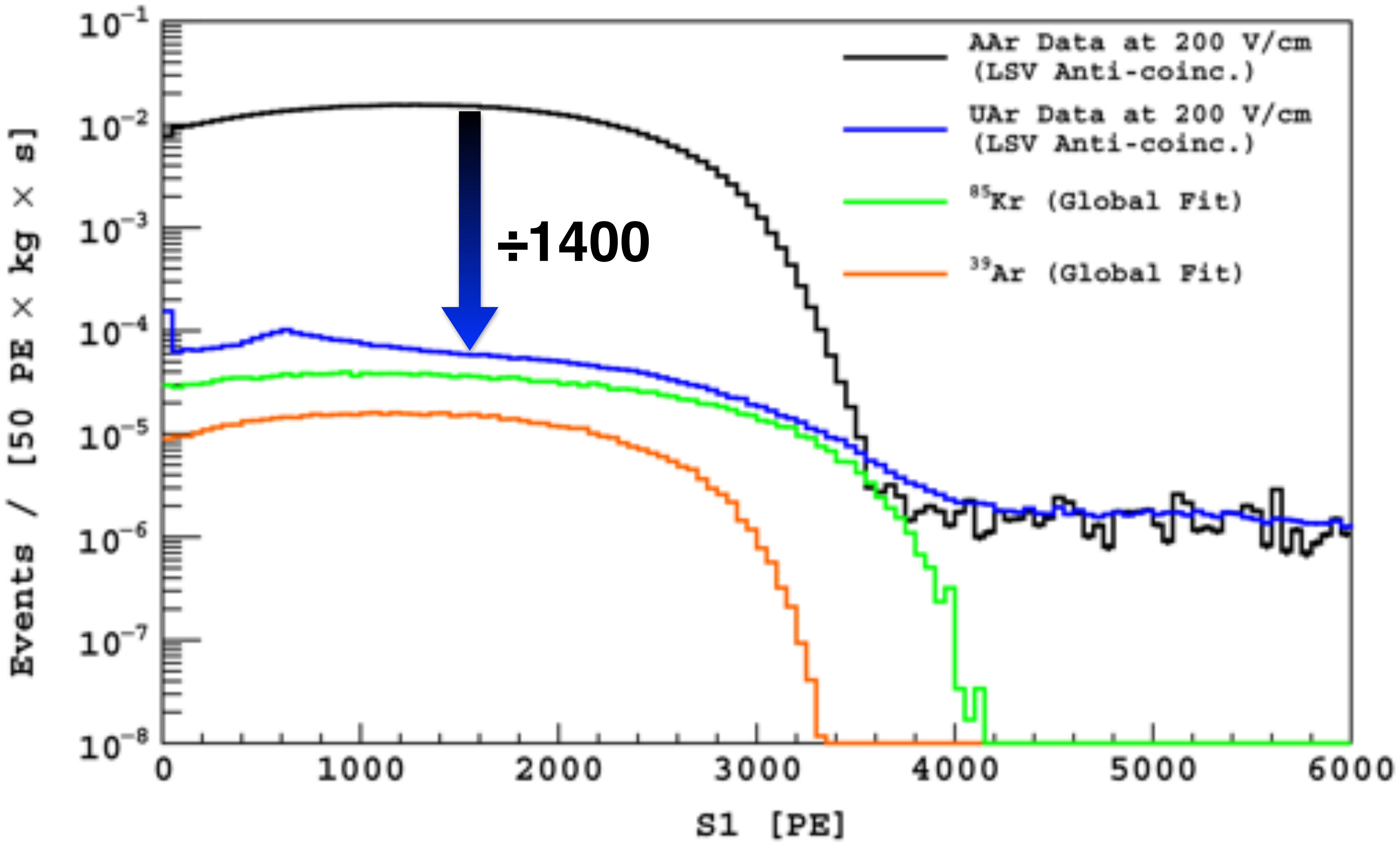
Eur. Phys. J. C 81,823 (2021)



β,γ rejection better than 10^8

LAr challenges: ^{39}Ar

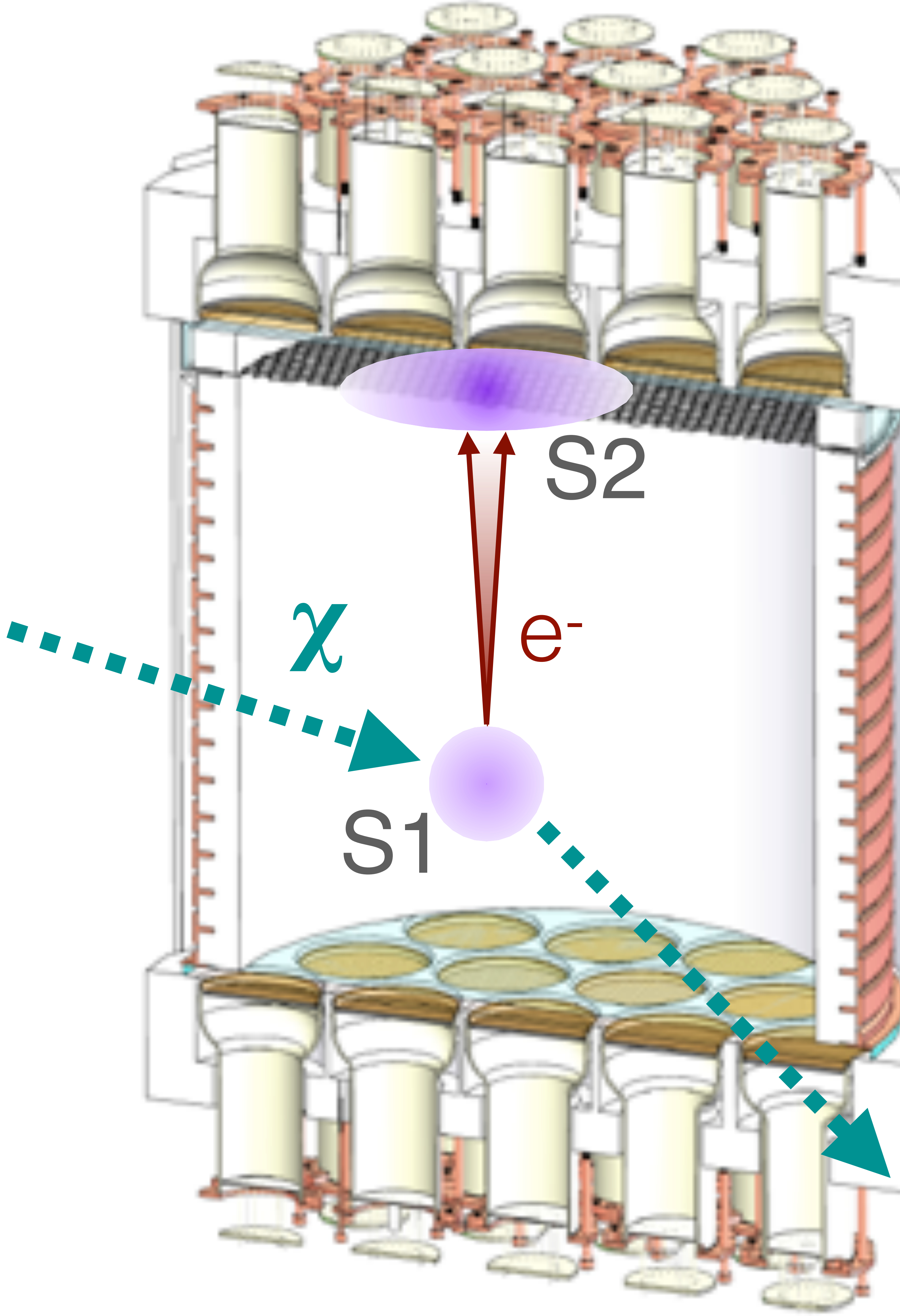




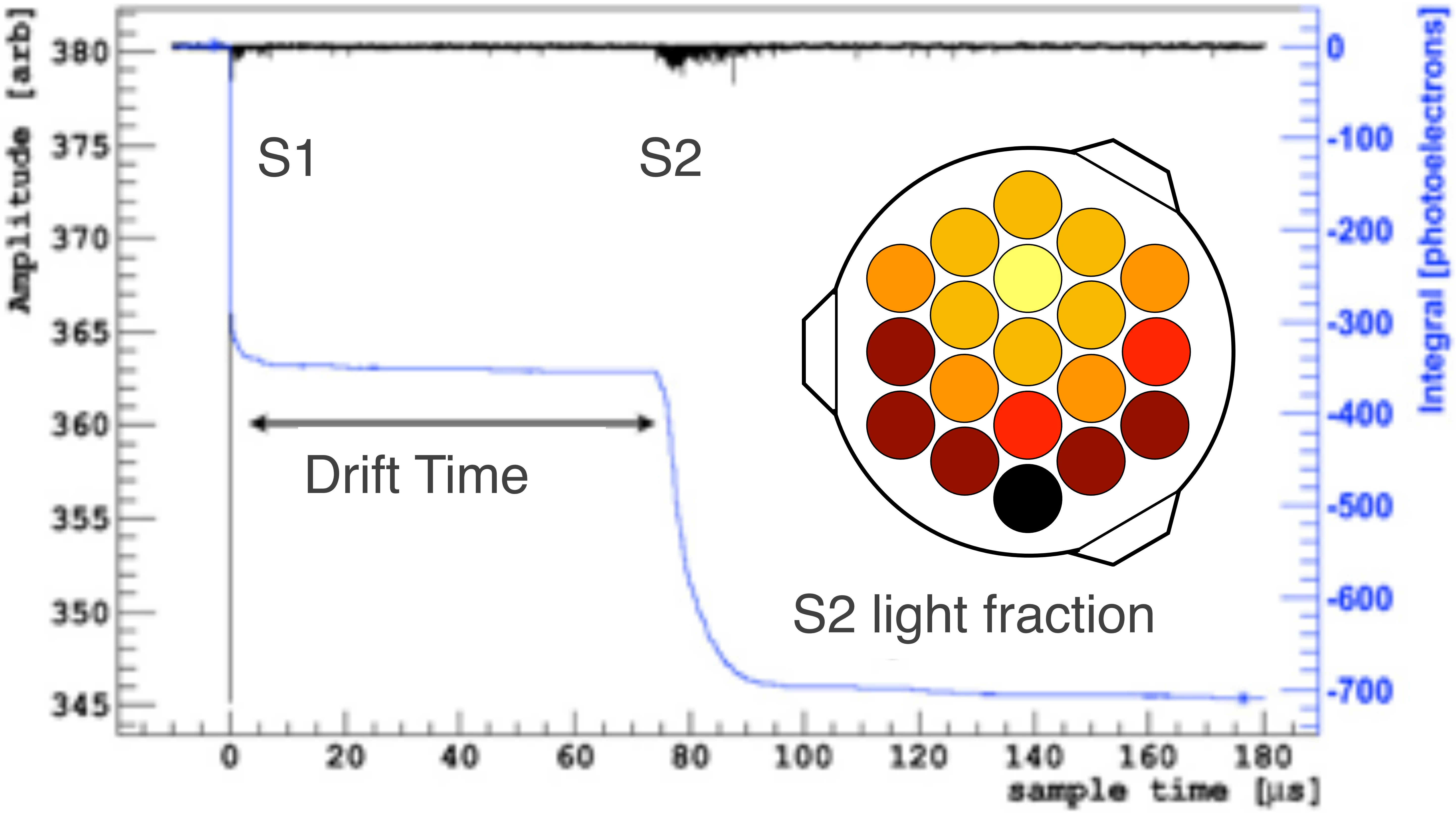
- ^{39}Ar is a cosmogenic isotope
- β-decay with 565 keV endpoint and ~269y of half life
- ~1Bq/kg in atmospheric Ar
- Rejection possible with PSD, but there's pile-up!

- 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



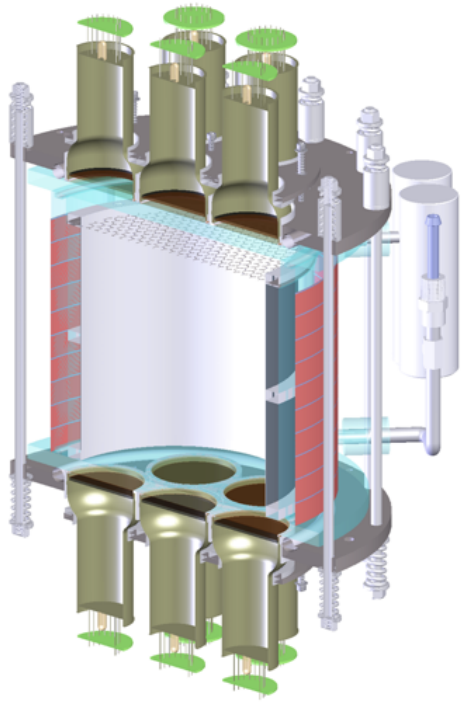
- Z from S1-S2 time difference
- XY from S2 light distribution

- Reliable fiducialization
- Multiple scattering rejection

The DarkSide program

A multi-stage approach

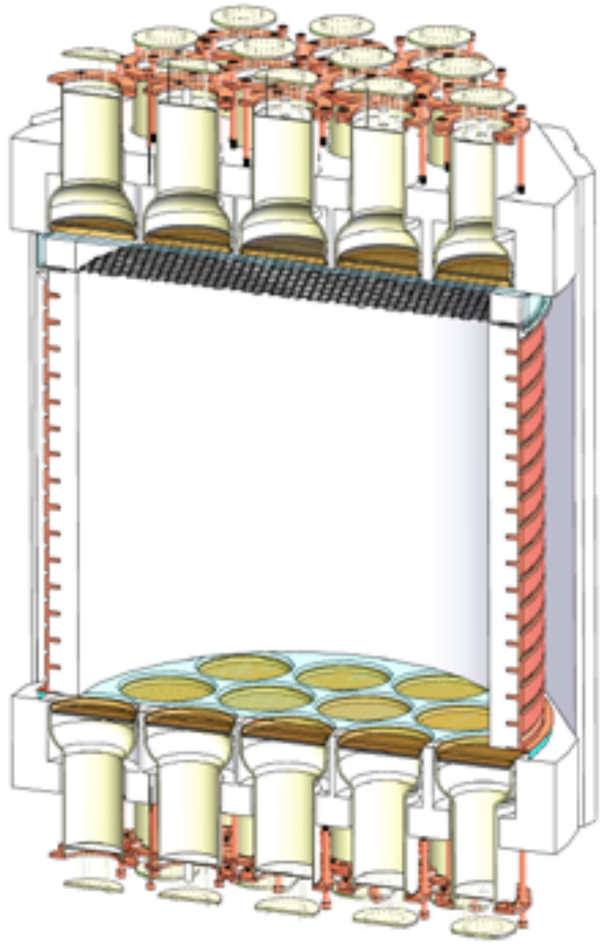
2012



DarkSide-10

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

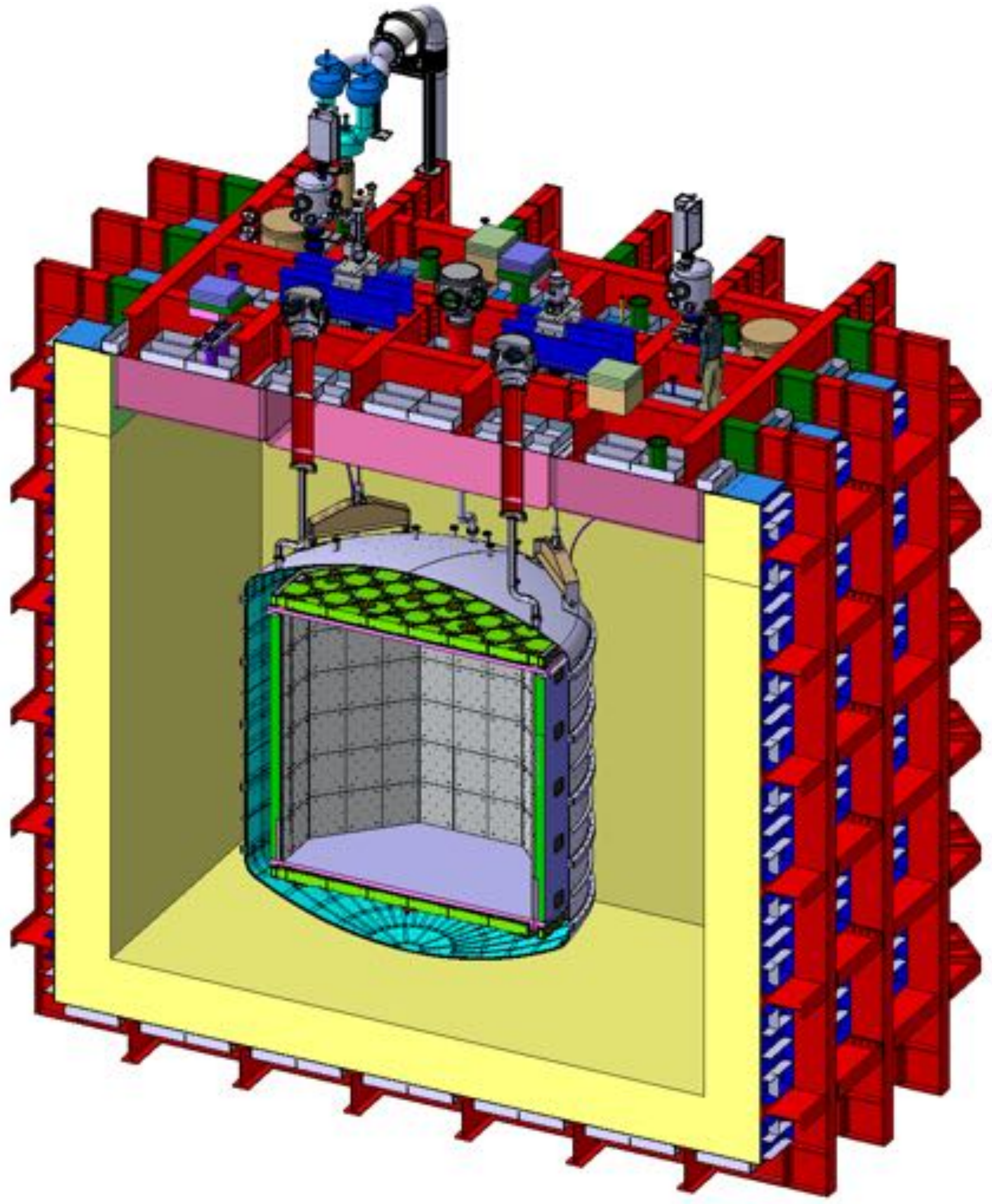
2013 - 2018



DarkSide-50

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

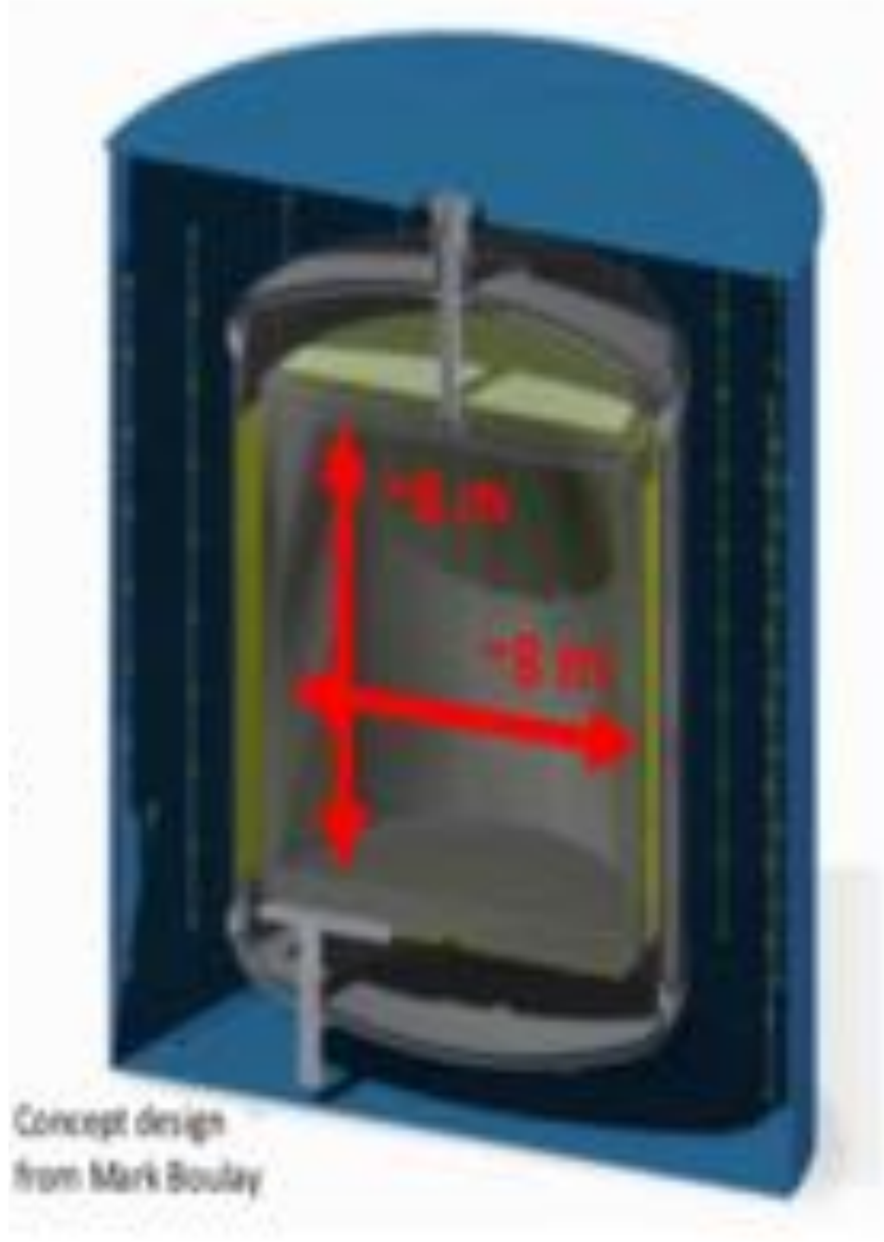
2025 - 2035



DarkSide-20k @ LNGS

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

2030s - ...



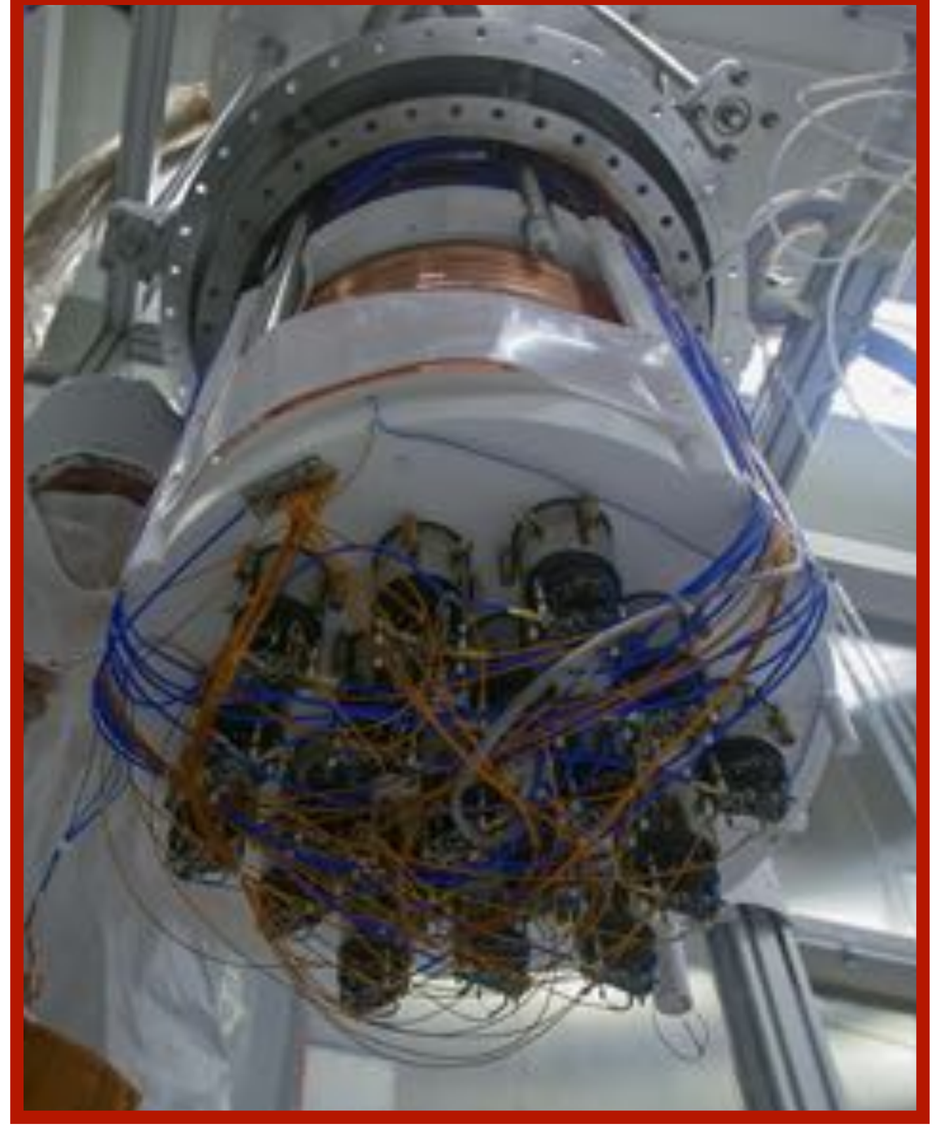
Concept design
from Mark Boulay

Argo @ SNOLAB

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

The GADMC

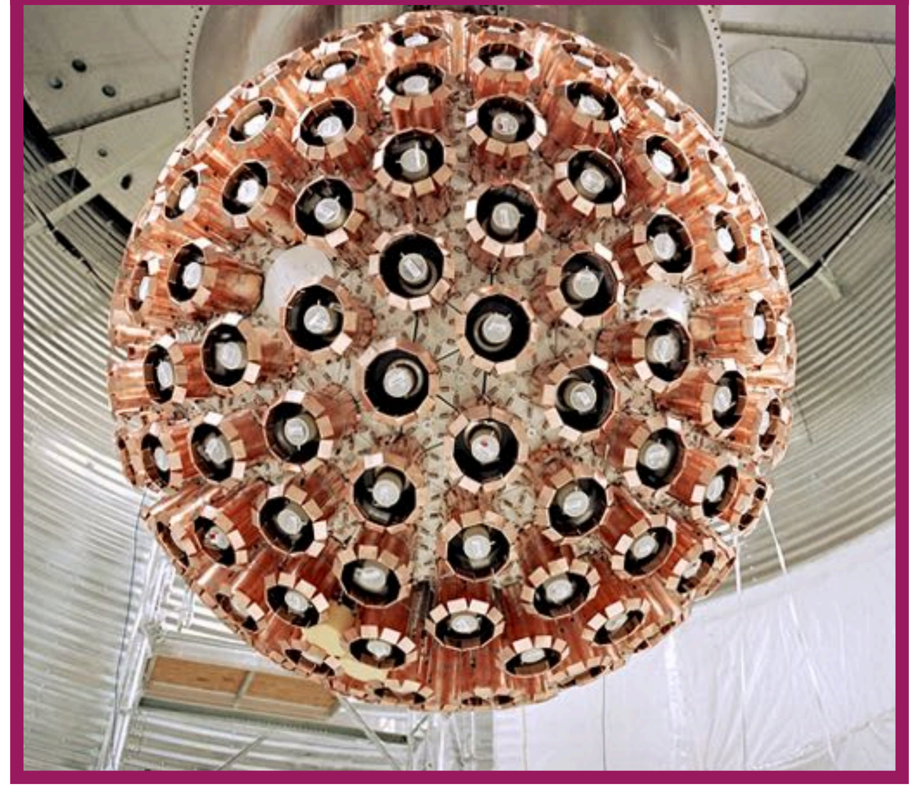
DarkSide-50 @ LNGS



ArDM @ Canfranc

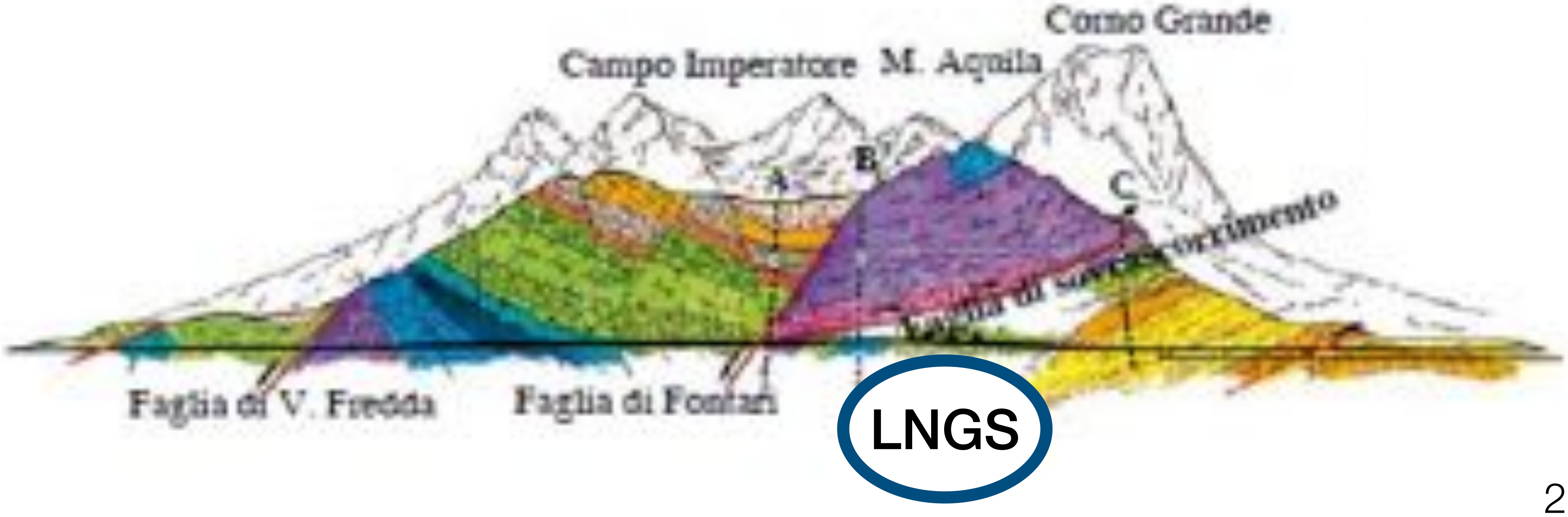
MiniClean @ Snolab

DEAP @ Snolab



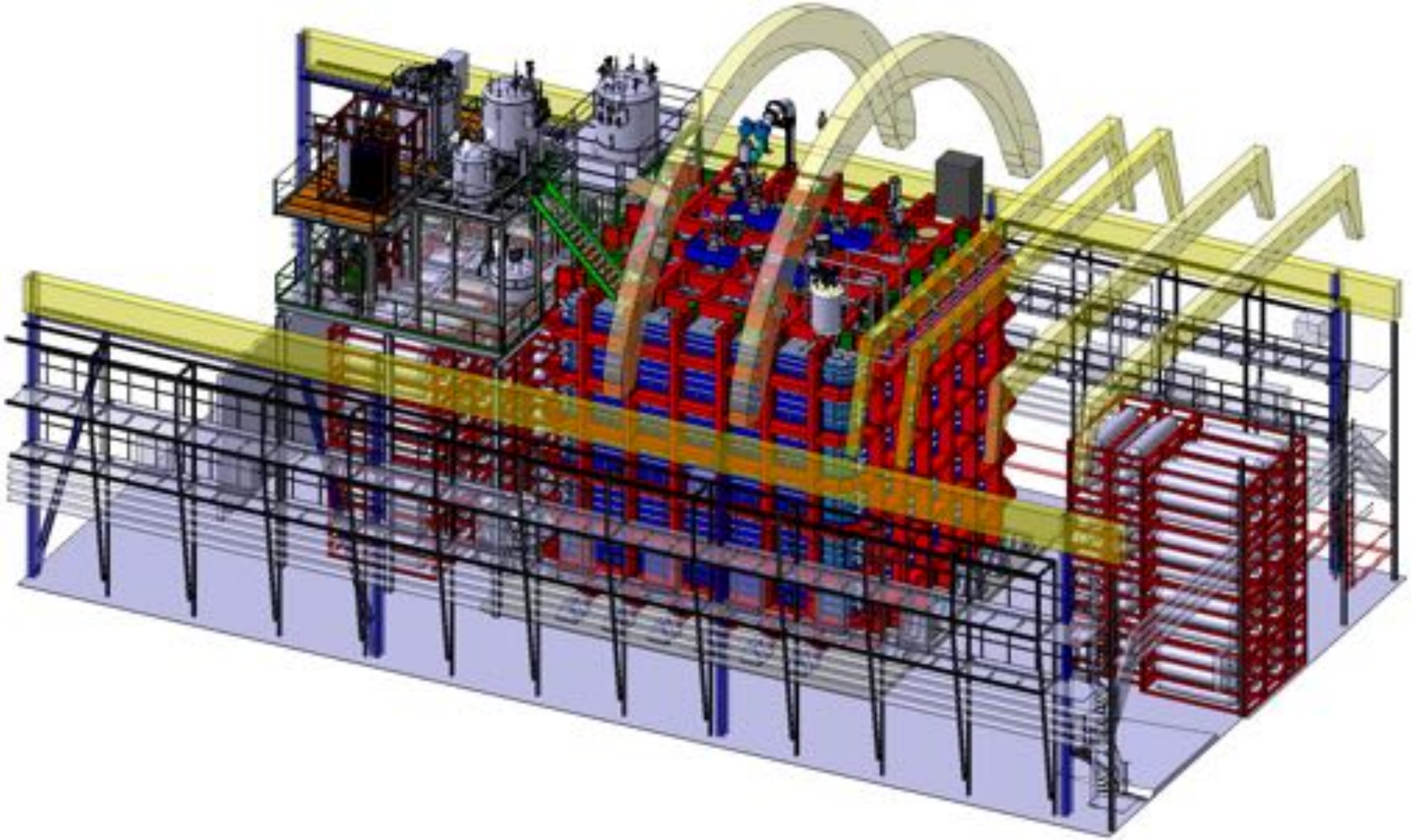
>400 scientists, >100 institutions distributed across 13 countries

Host laboratory: LNGS

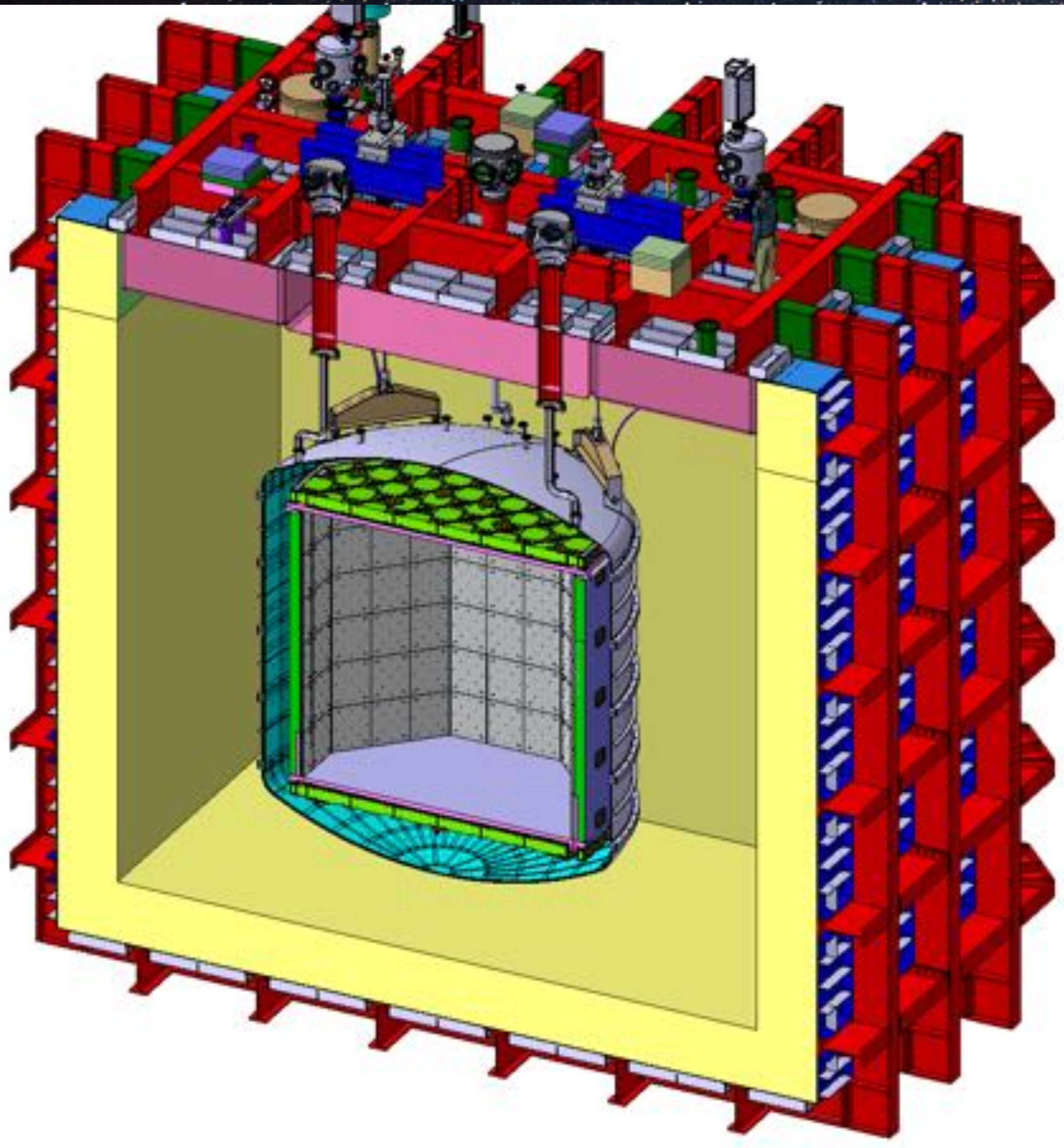


- Below ~1400m of rock (3400 m.w.e)
- Muon flux reduction factor ~10^6
- 3 main experimental halls (20x100x18 m^3)

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

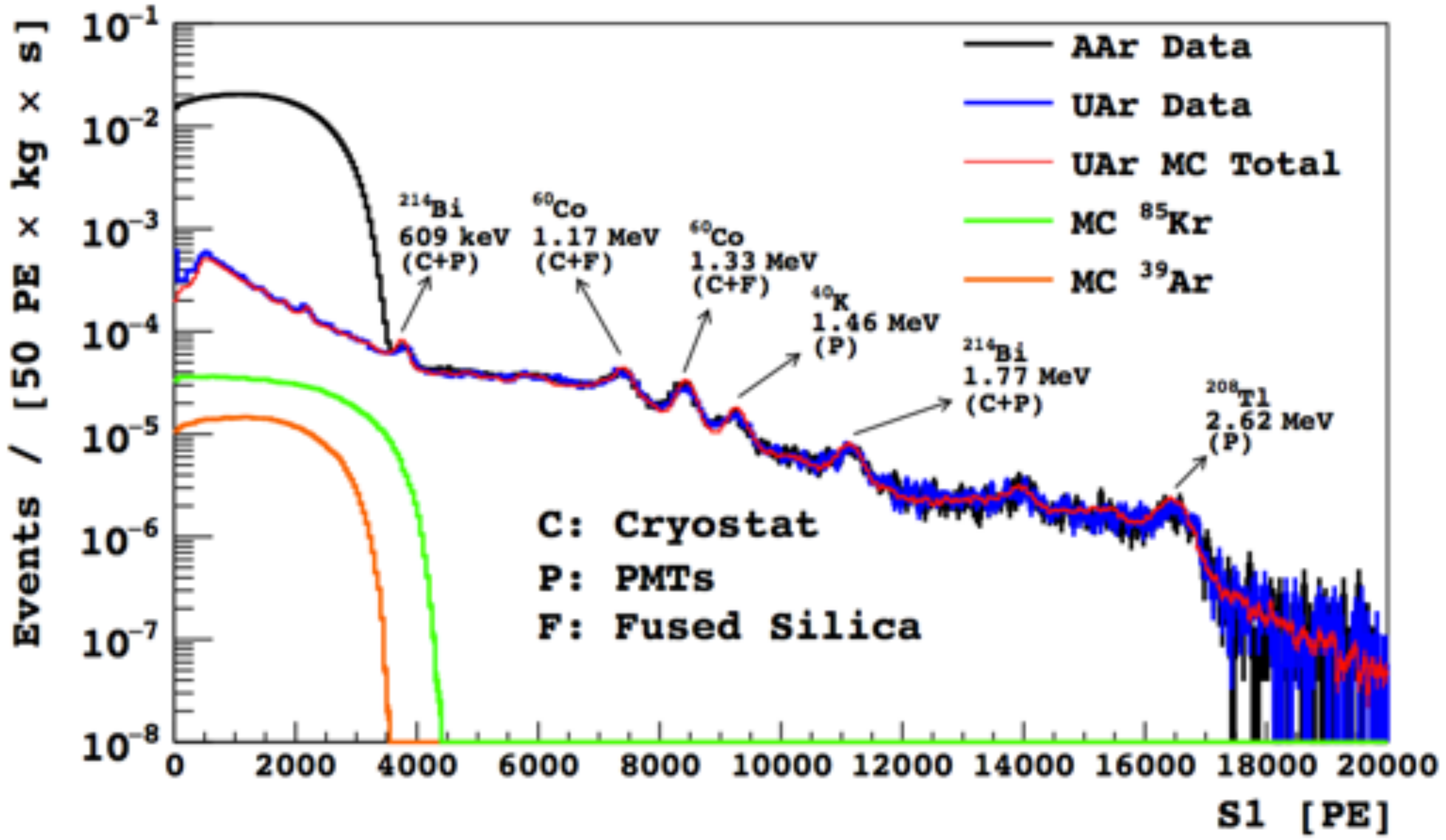
β and γ after cuts: < 0.1 in 10 y

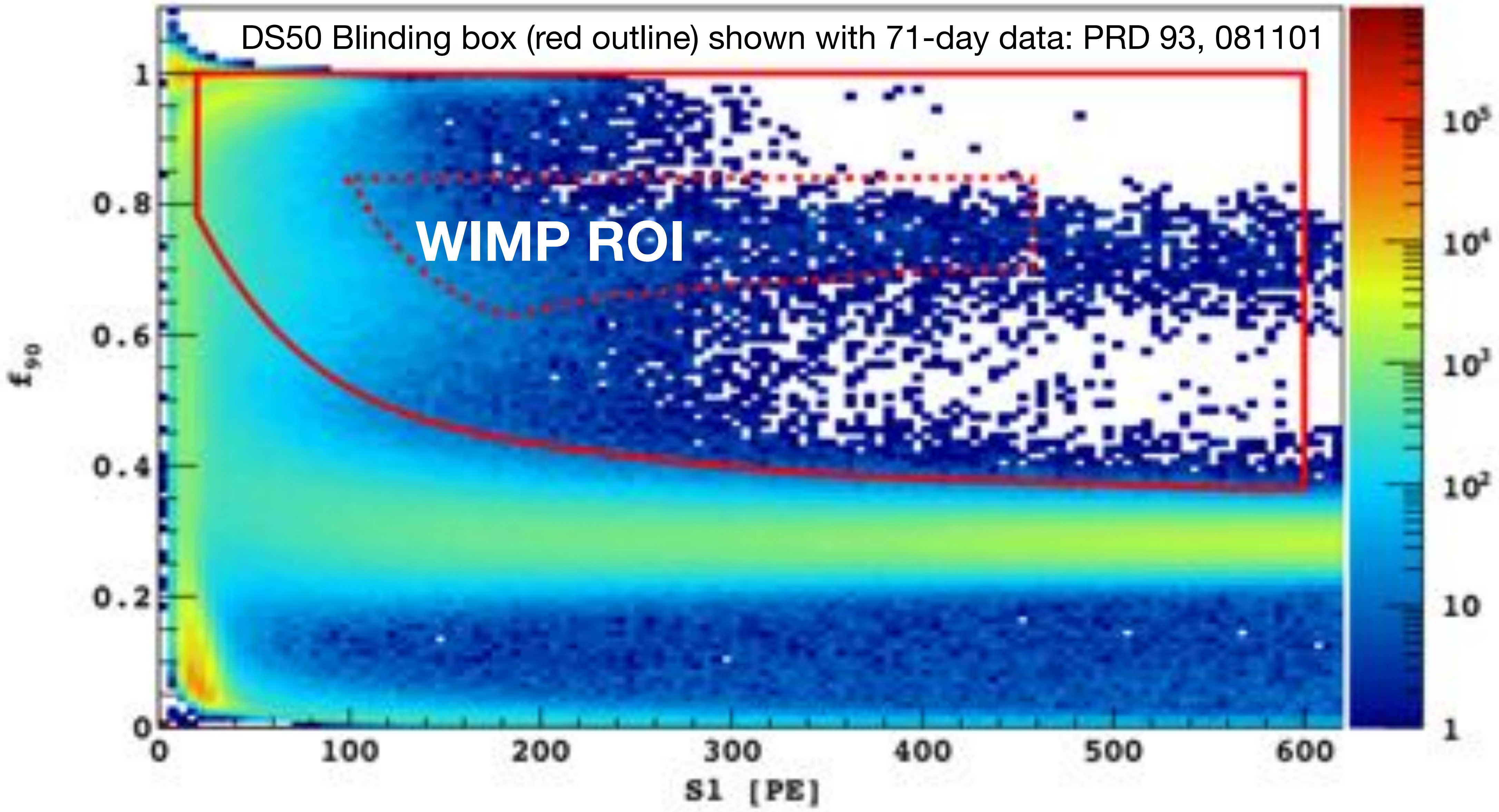
Position reconstruction resolution:

~ 1 cm in XY

~ 1 mm in Z

Backgrounds





Electron Recoils (ER)

^{39}Ar β decays

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

Surface events

Radon progeny

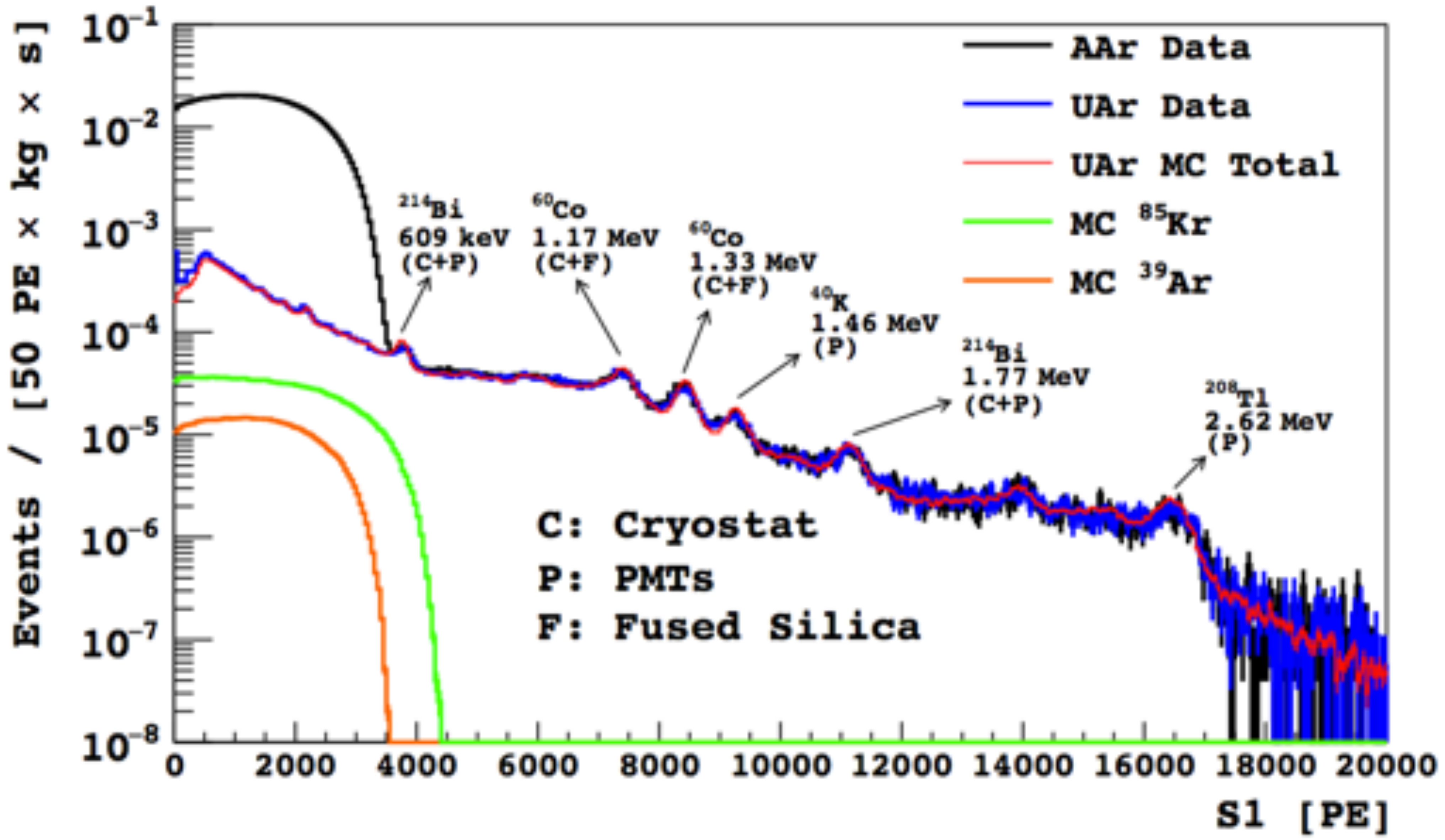
Nuclear Recoils (NR)

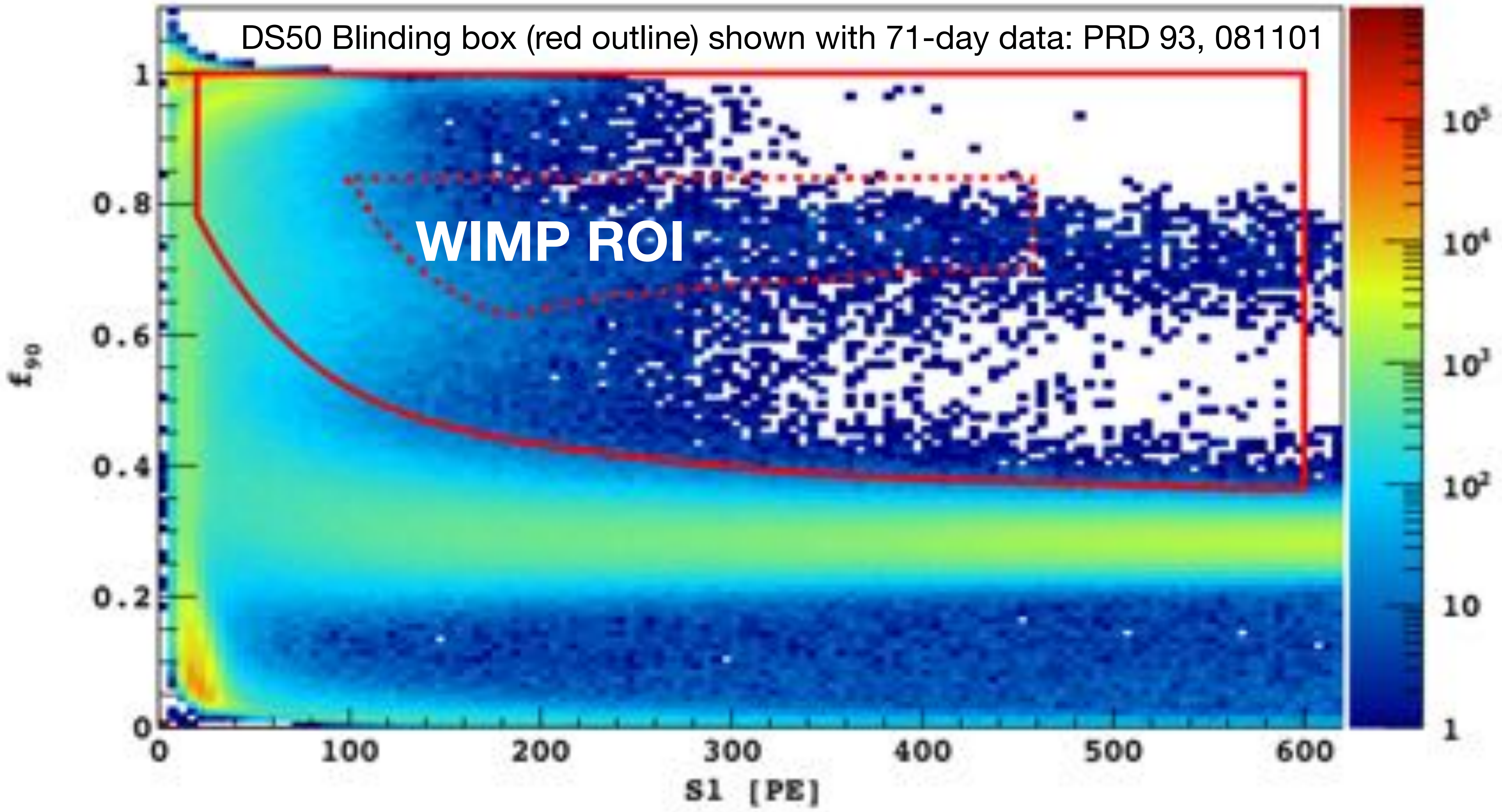
Radiogenic neutrons, mainly from (α,n) reactions.

Cosmogenic neutrons, from materials activation due to residual muon flux

Atmospheric neutrinos

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

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

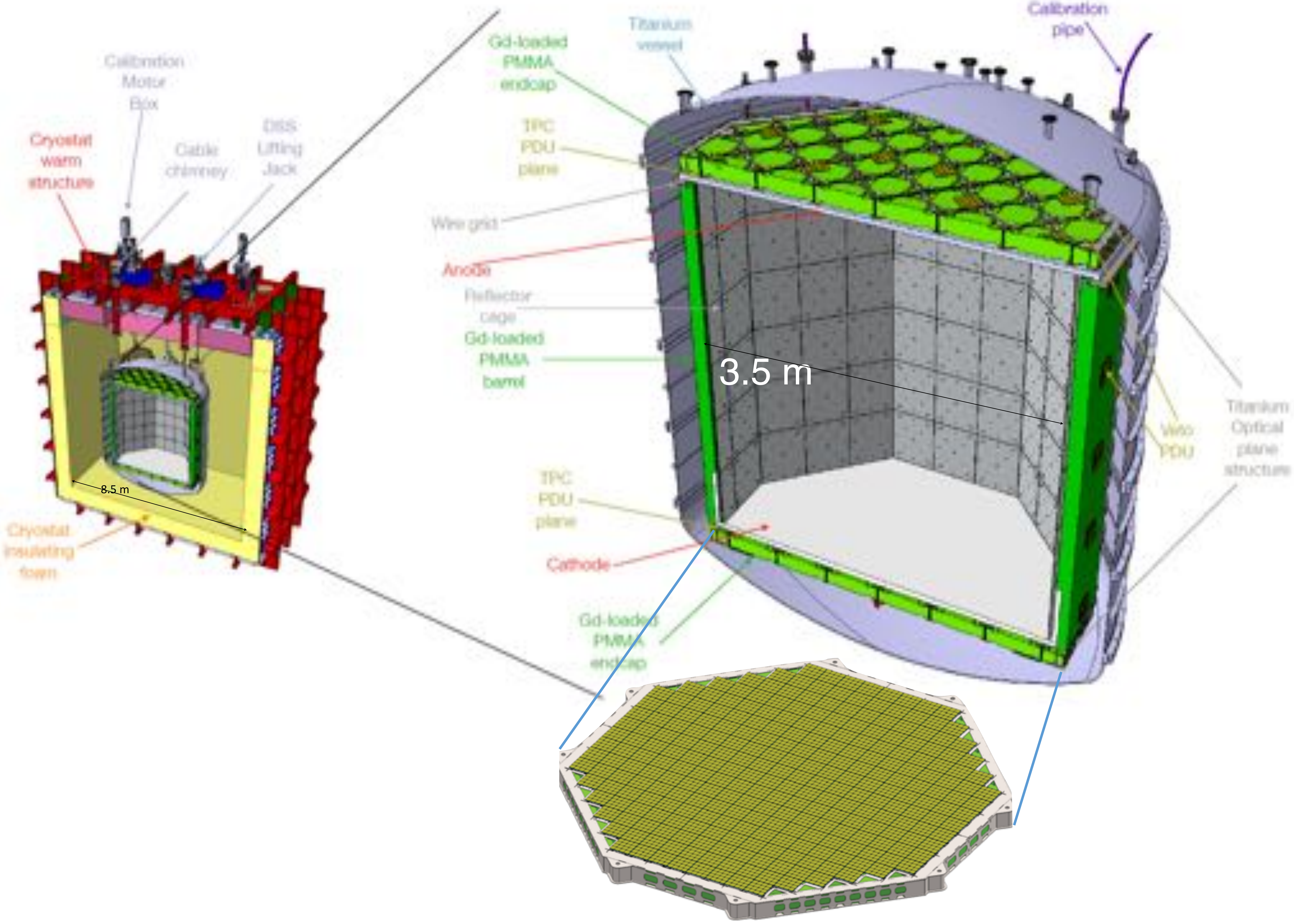
Inner detector

- 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

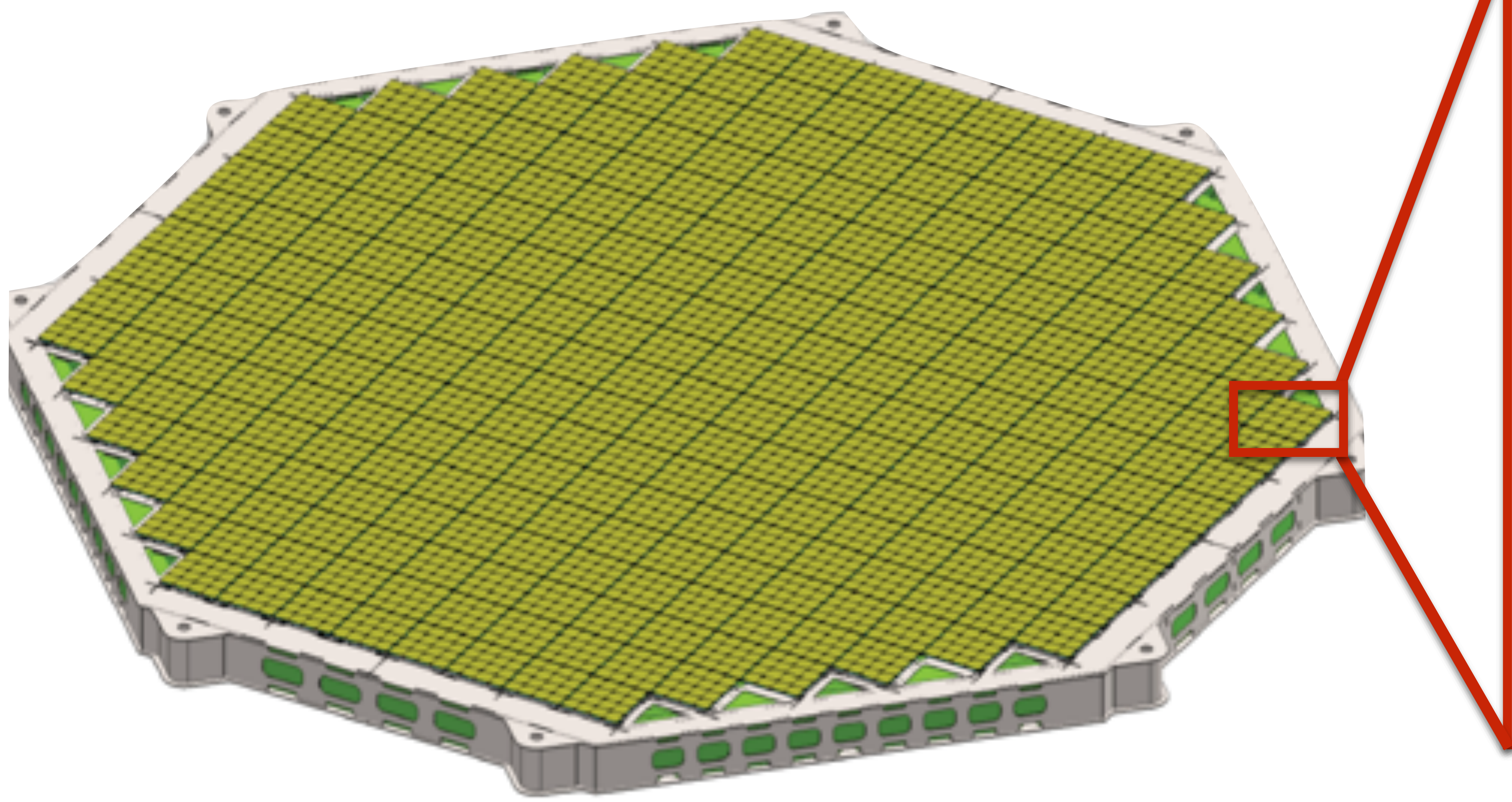
99 t UAr held in Ti vessel



TPC photo-detection system

Photo-detection system

TPC optical plane

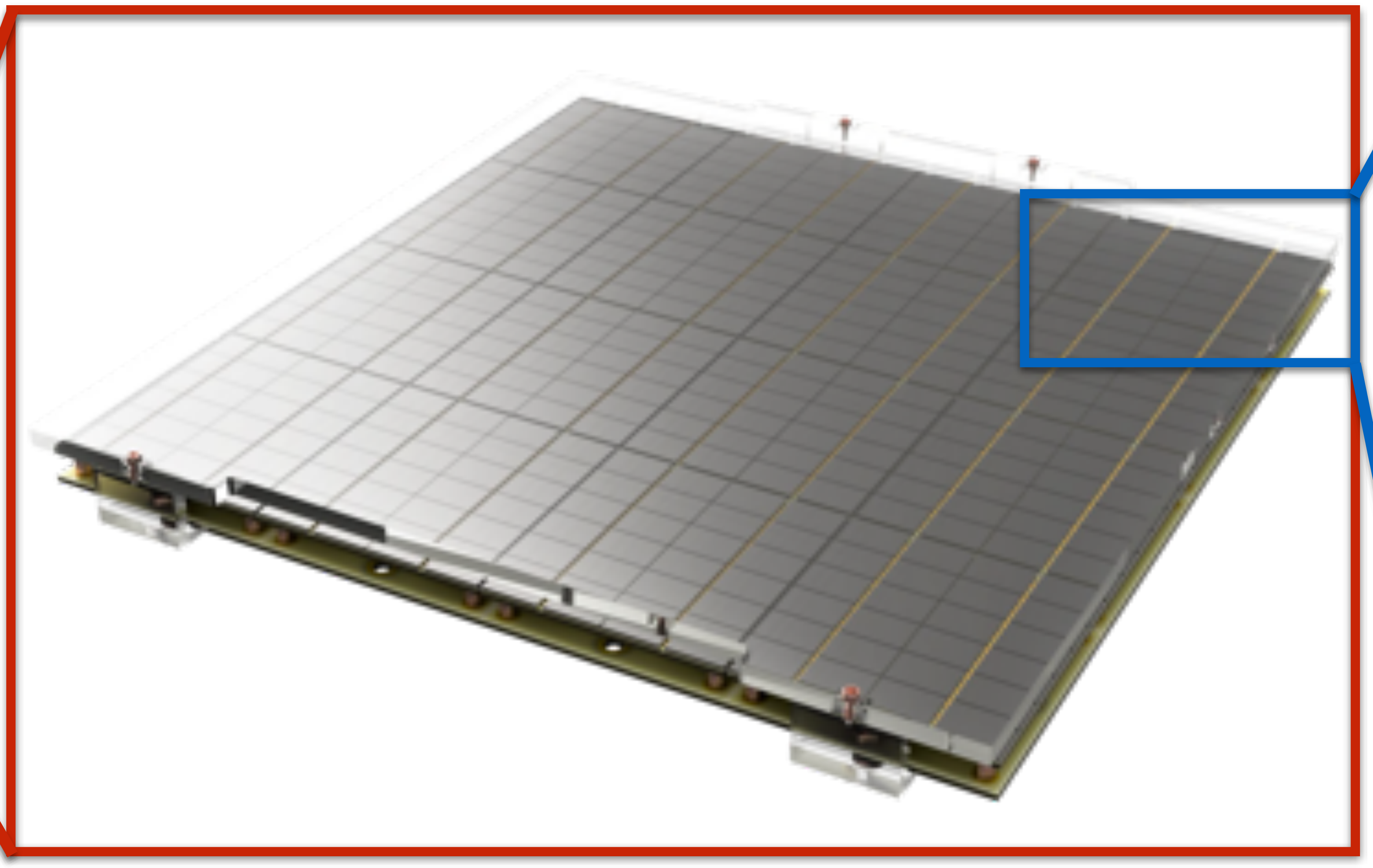


TPC planes area: ~21m^2

Organized in 525 PDUs

100% coverage of TPC top and bottom

Photo-Detection Unit



16 tiles arranged in 4 readout channels

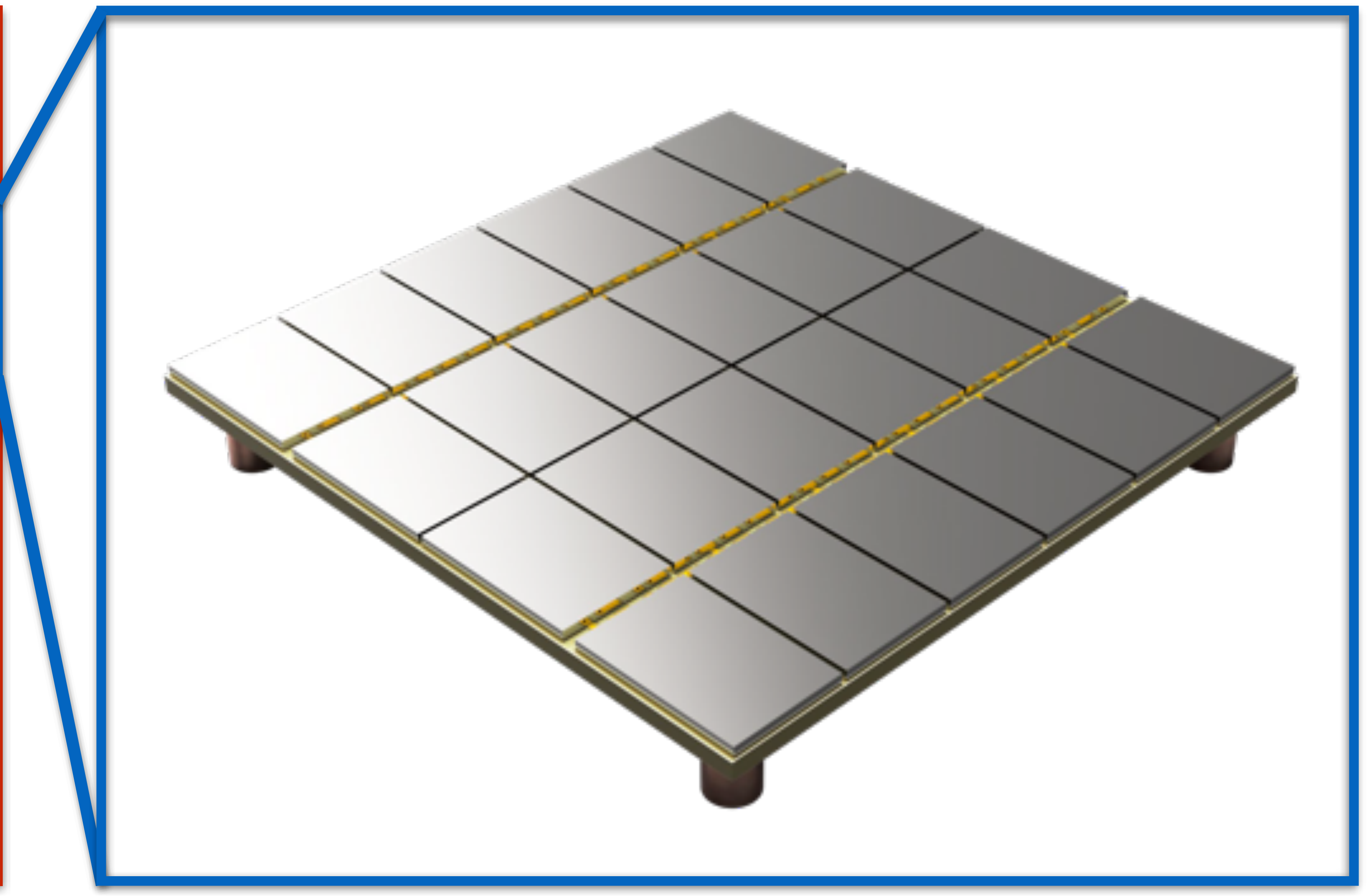
SiPM bias distribution

cryogenic pre-amplifiers bias

Signal transmission

Channels switch-on/off

Tile



Photosensor

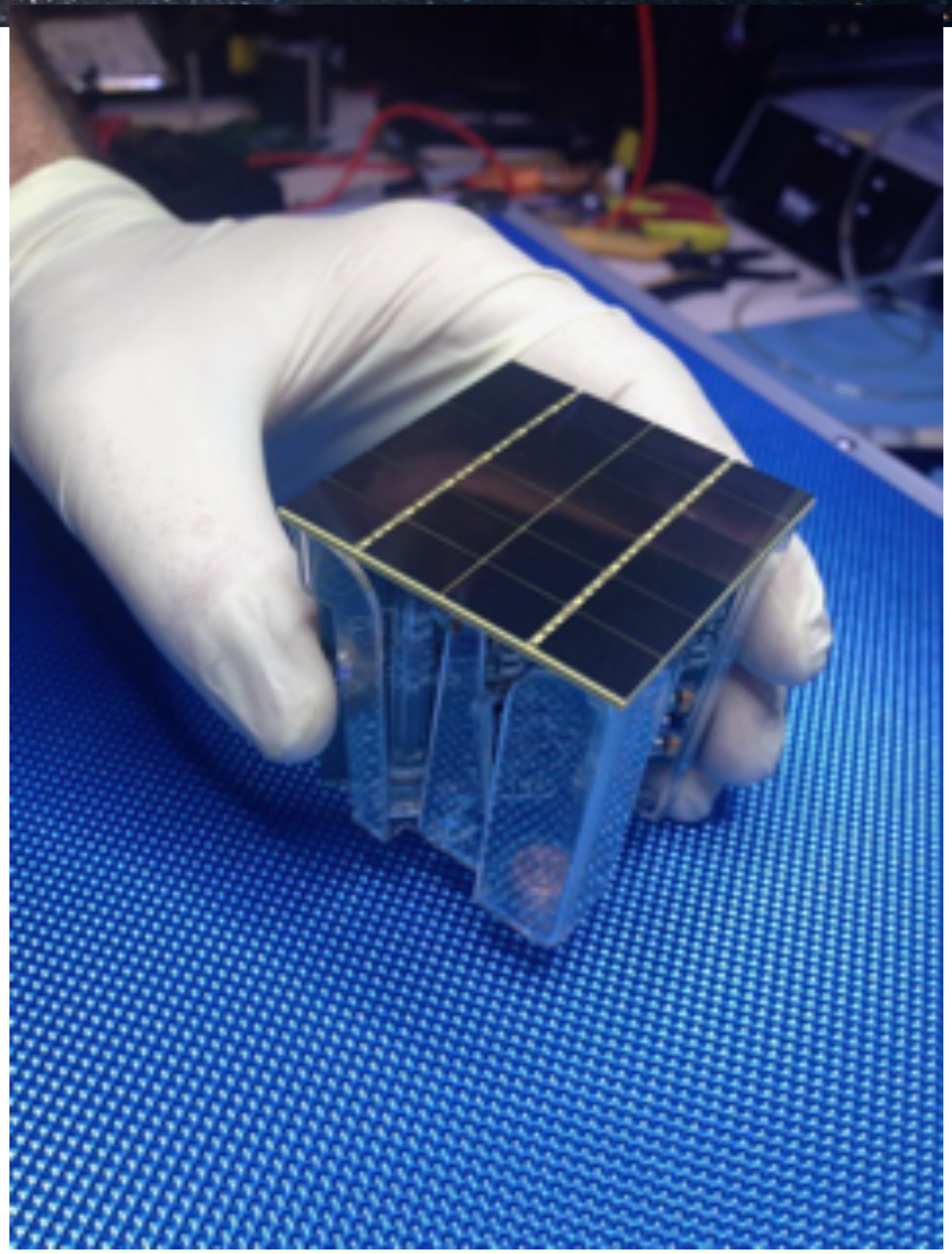
Array of 24 SiPMs

Signal pre-amplification

Transitioning to a new technology

Why?

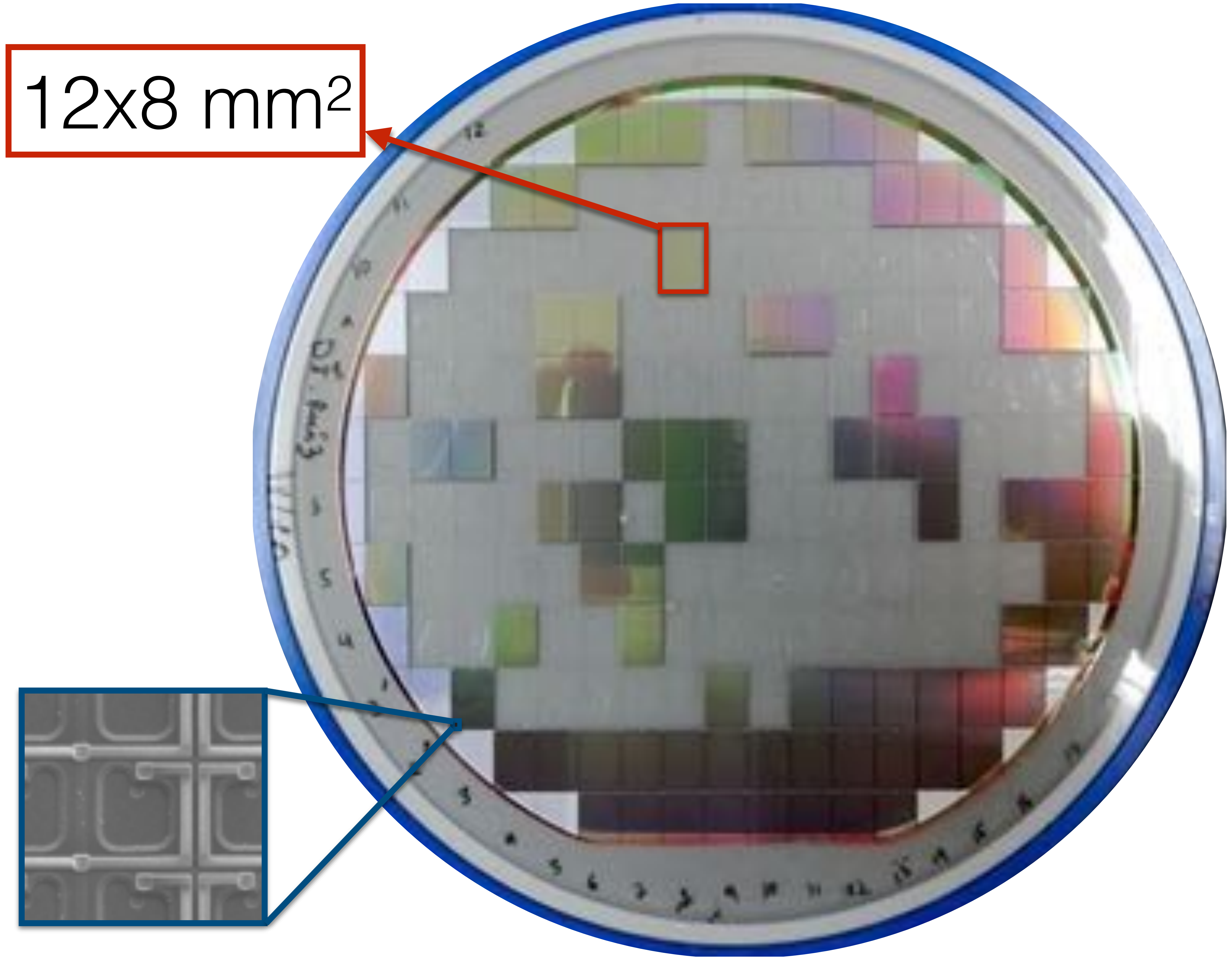
- Lower radioactivity
- Higher Photon Detection Efficiency
- Higher active area
- Operated with low bias
- Lower cost



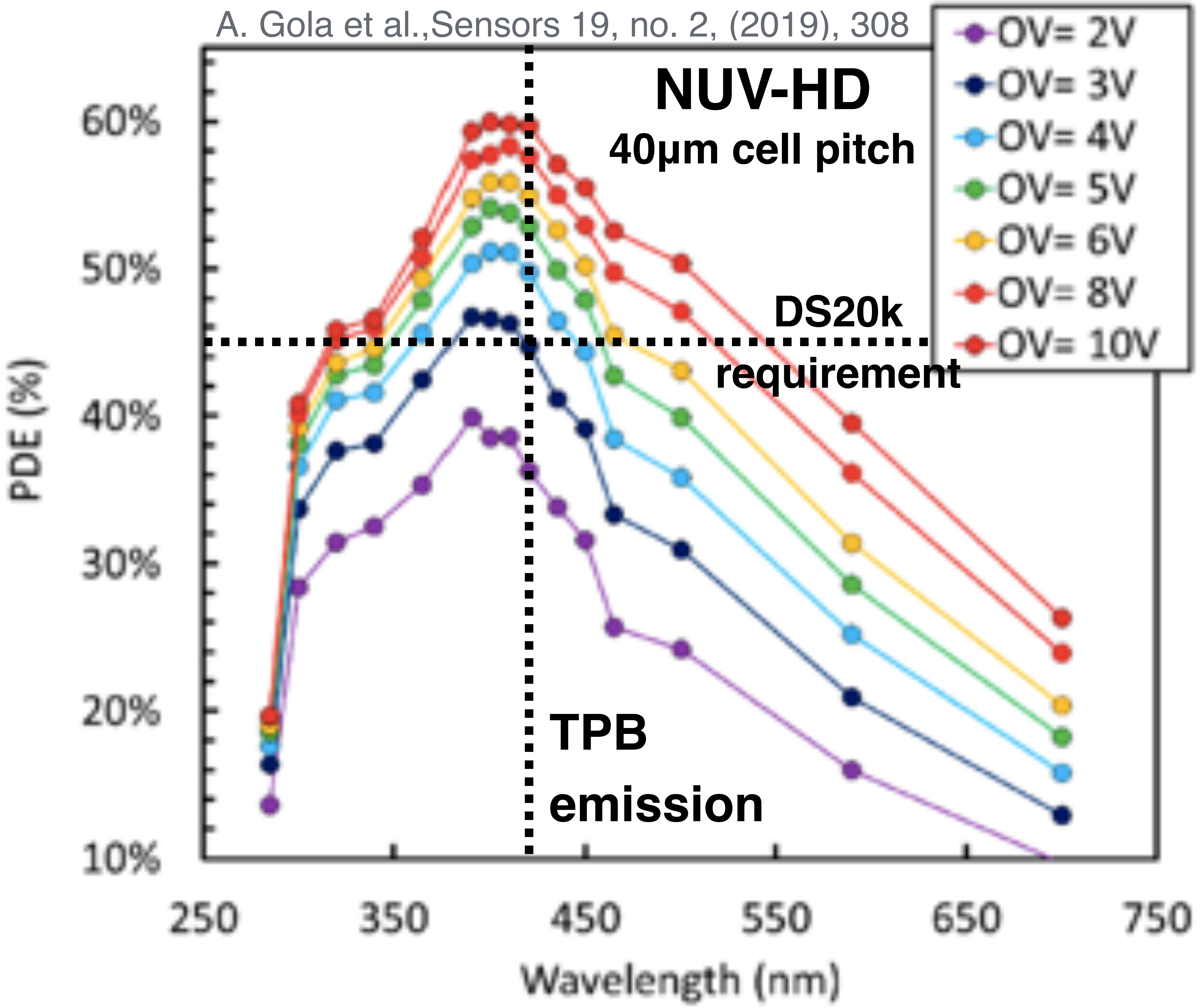
But...there's no such thing as a free meal!

- Higher dark rate and correlated noises (after-pulse, cross-talk)
- Small area (many channels)
- High output capacitance (high electronic noise, low bandwidth)

Step 1: SiPMs development



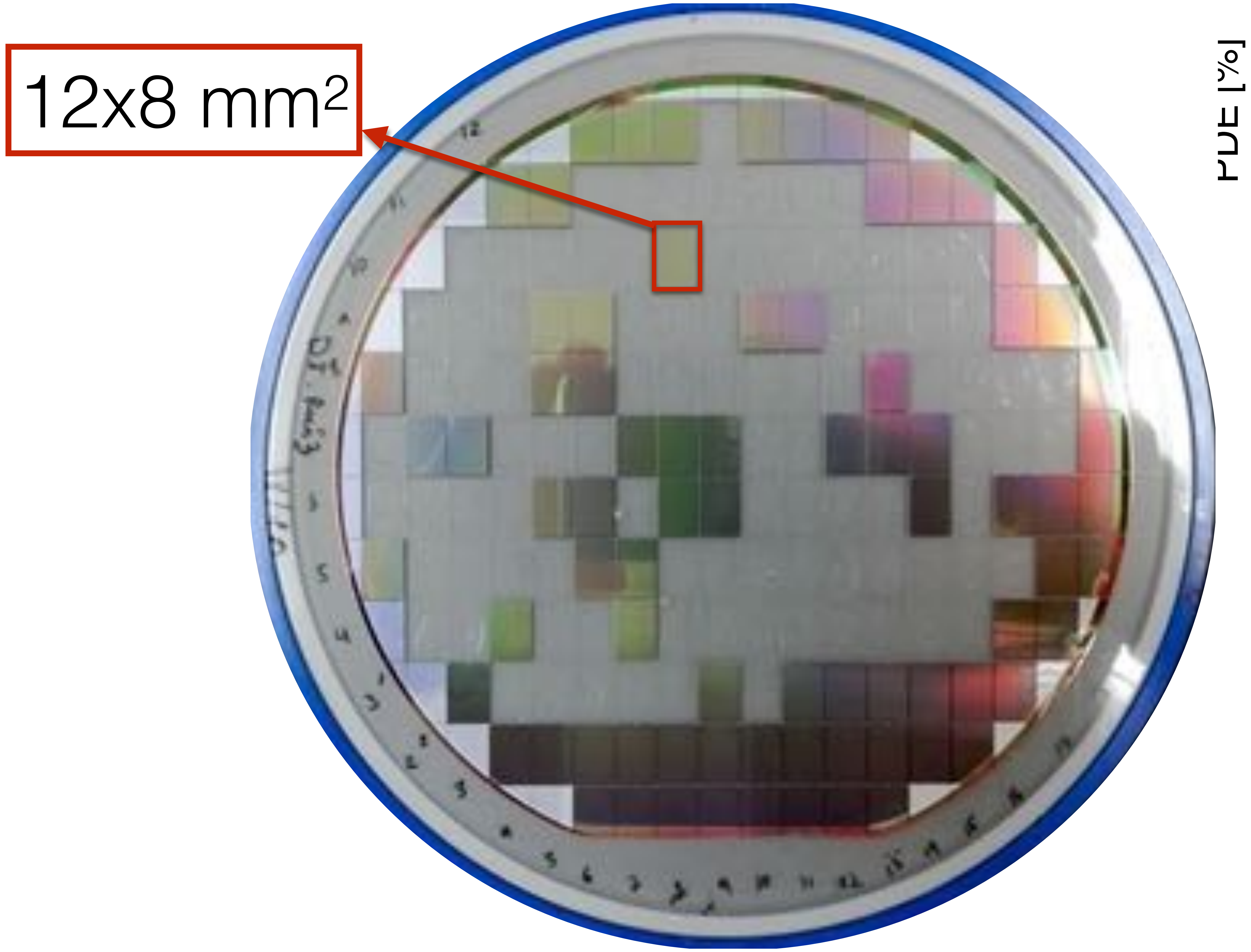
- NUV vs RGB choice (P_{01})
- Cell pitch and fill factor (FF) optimization
- **E** field profile ⇒ DCR+CN reduction

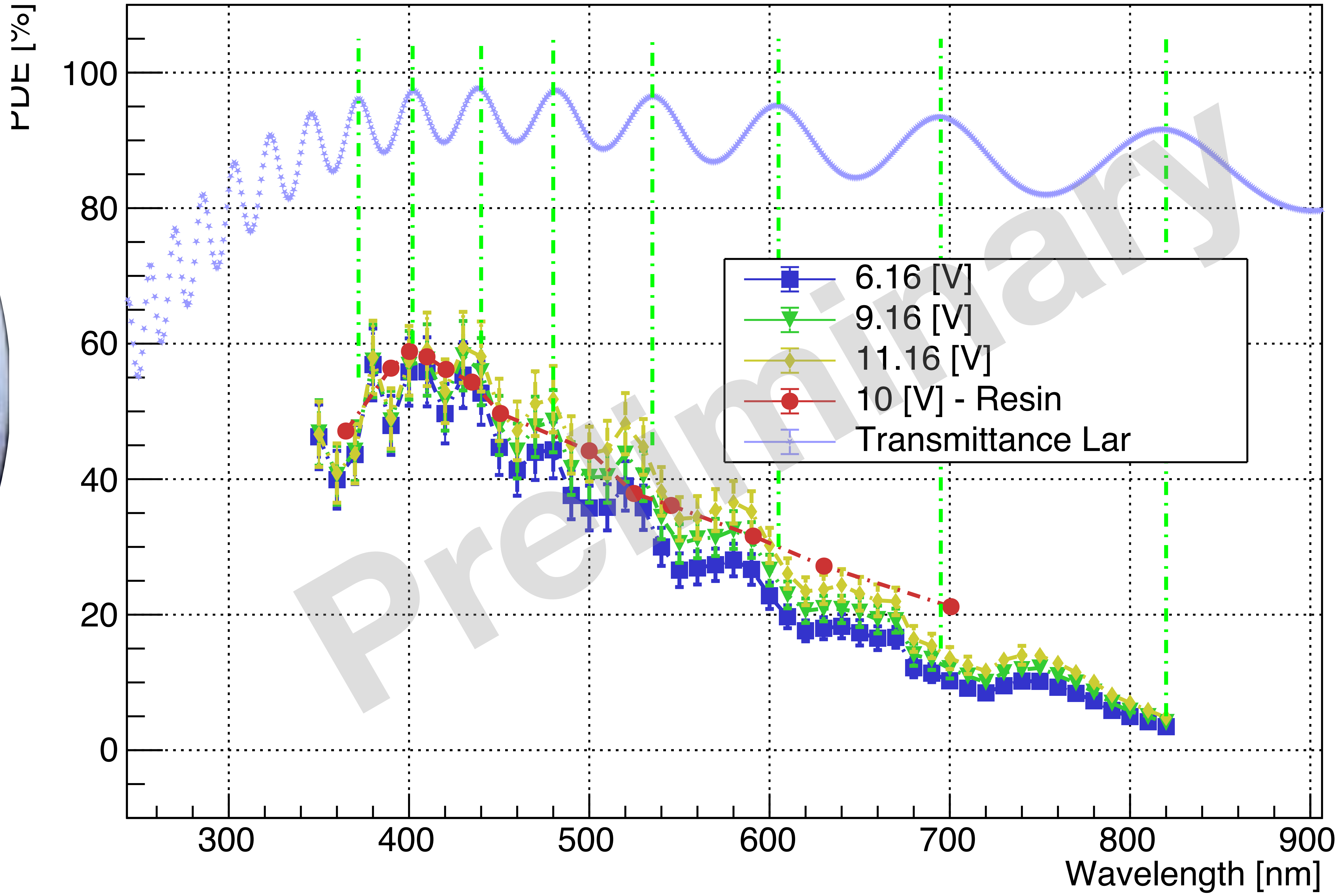

A. Gola et al.,Sensors 19, no. 2, (2019), 308

$$PDE = QE \times P_{01} \times FF$$

PDE > 55% @ 290K

Step 1: SiPMs development



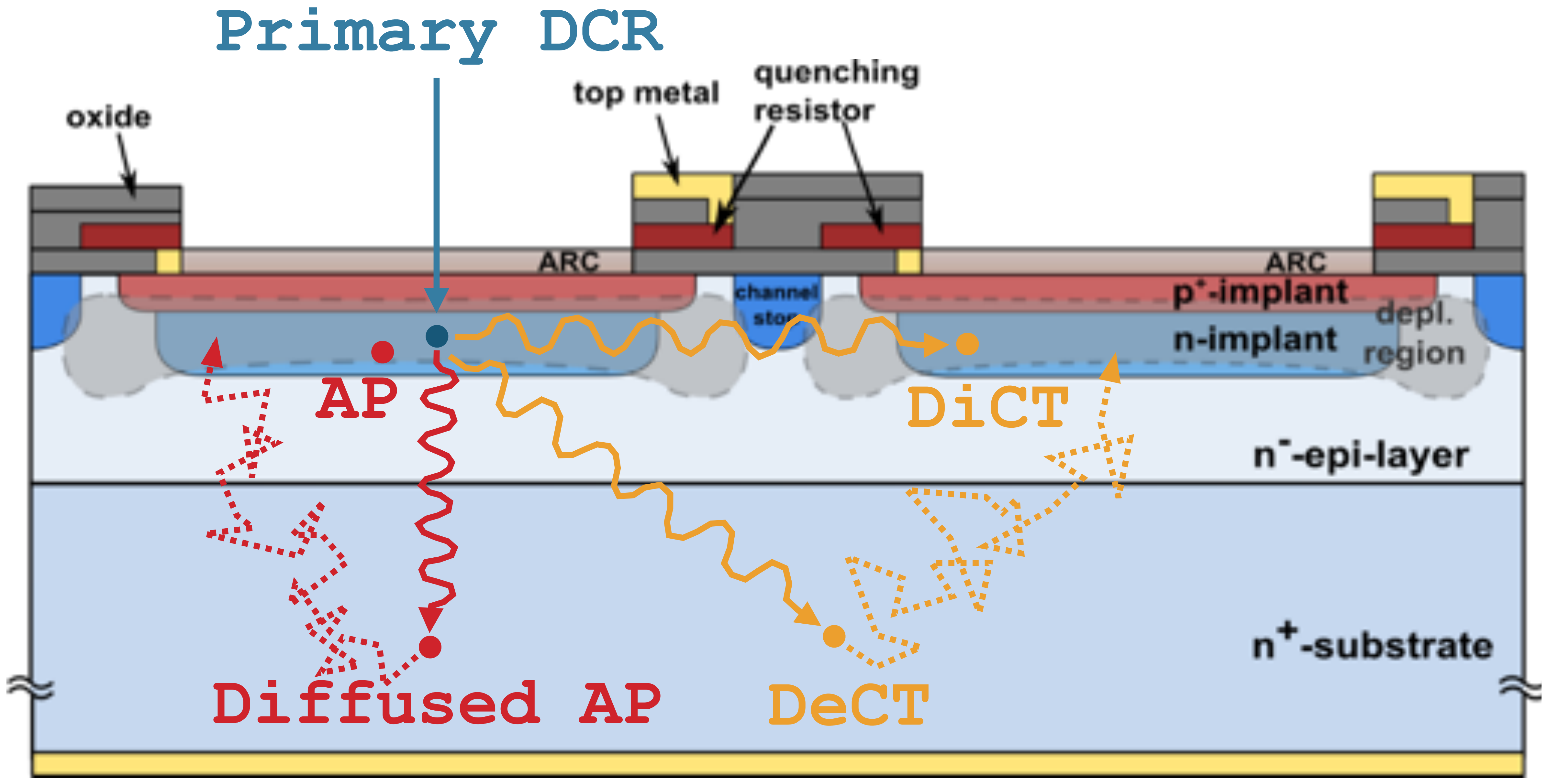


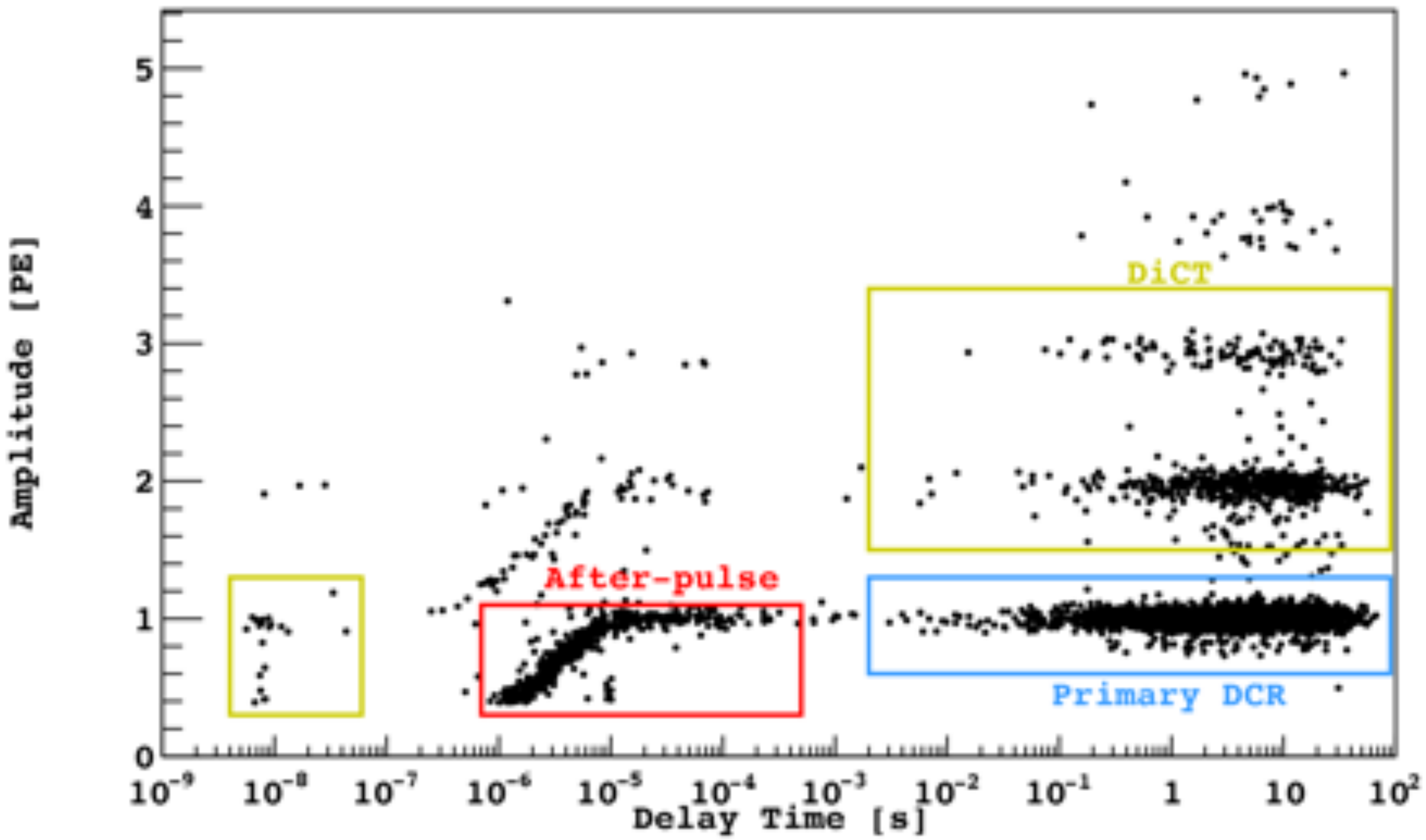
- NUV vs RGB choice (P_{01})
- Cell pitch and fill factor (FF) optimization
- **E** field profile ⇒ DCR+CN reduction

PDE = QE × P_{01} × FF

PDE ~50% in LAr

Step 1: SiPMs development

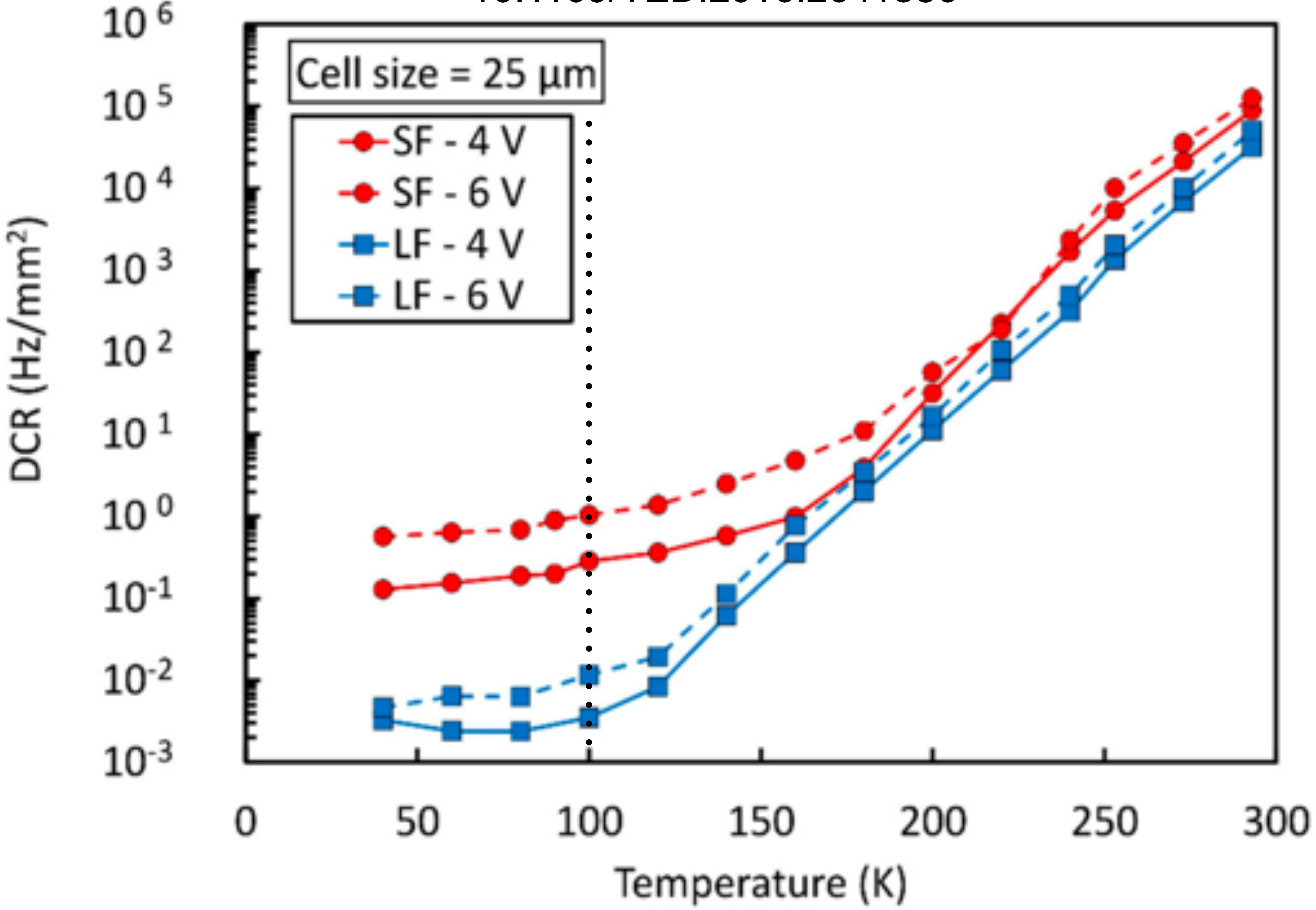




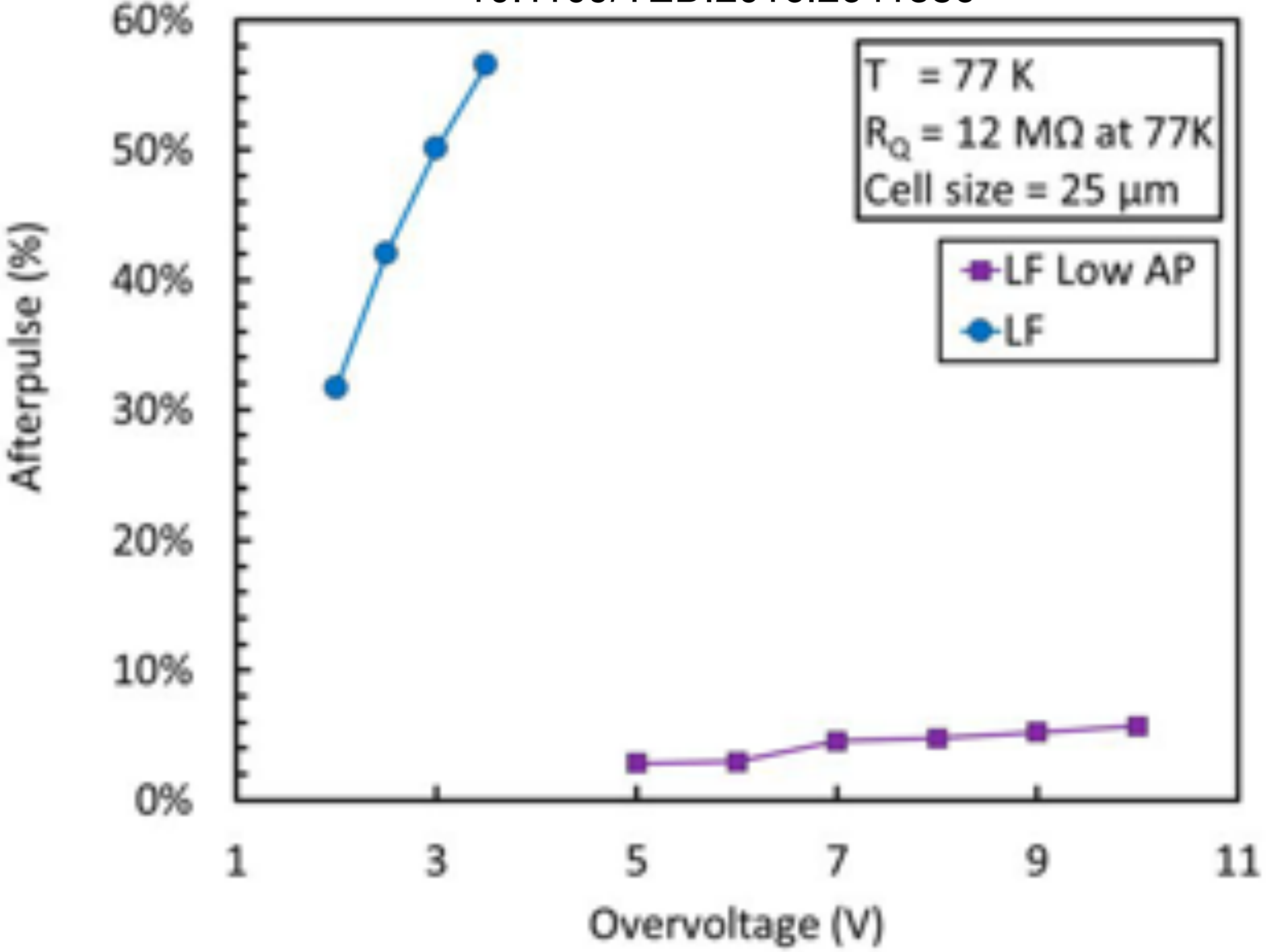
- Noises can be primary or correlated
- Primary: DCR
- Correlated: AP, DiCT, DeCT

- Different generation mechanism
- Different behavior

Step 1: SiPMs development



10.1109/TED.2016.2641586

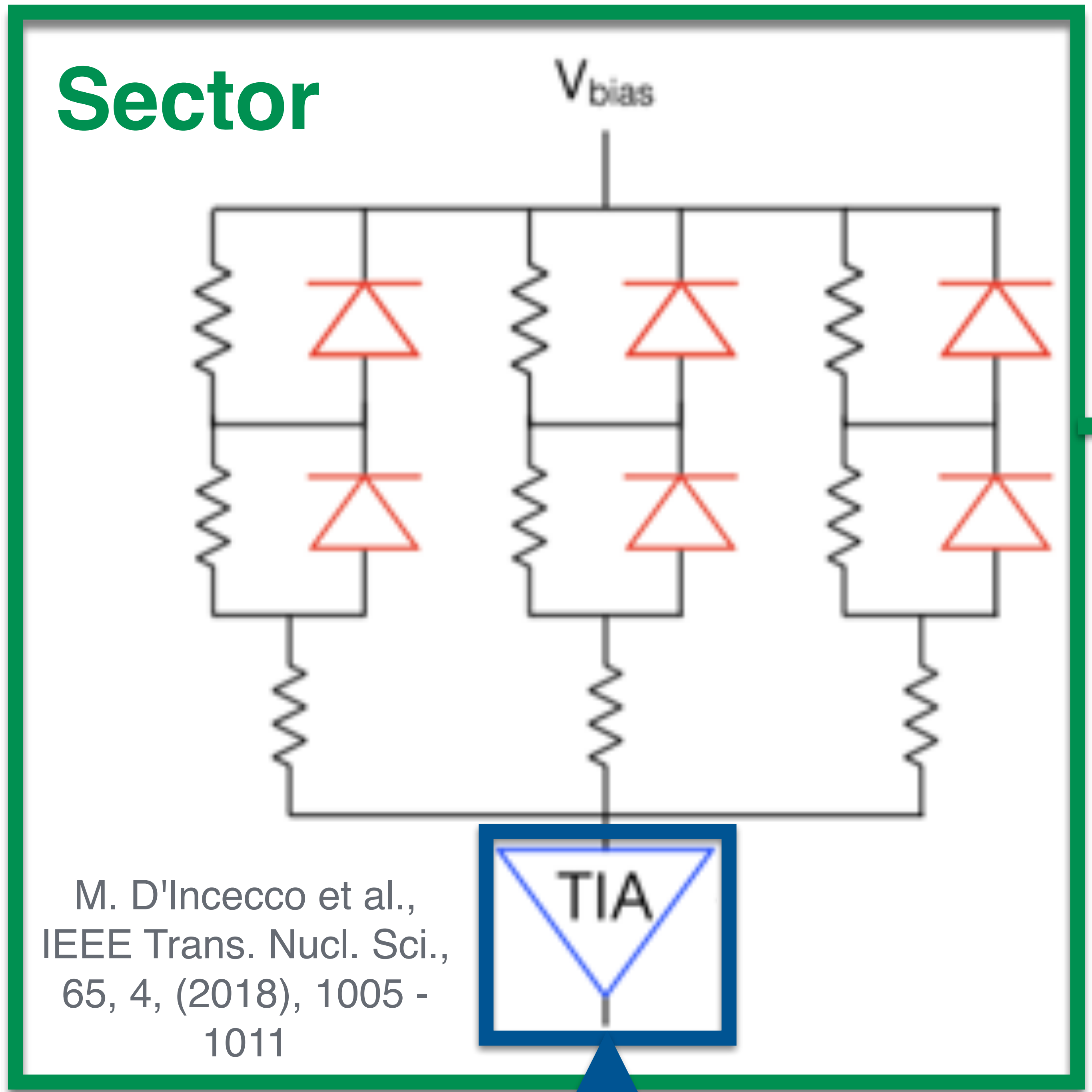


10.1109/TED.2016.2641586

- DCR has 2 generation mechanisms
- Thermal agitation dominant @T>100K
- Field-assisted tunneling @T<100K
- **E** field profile engineered to suppress tunneling.

- AP dangerous to PSD
- Suppressed by introducing a dopant into the SPAD junctions.
- DiCT suppressed by the low **E** field

Step 2: readout electronics design…

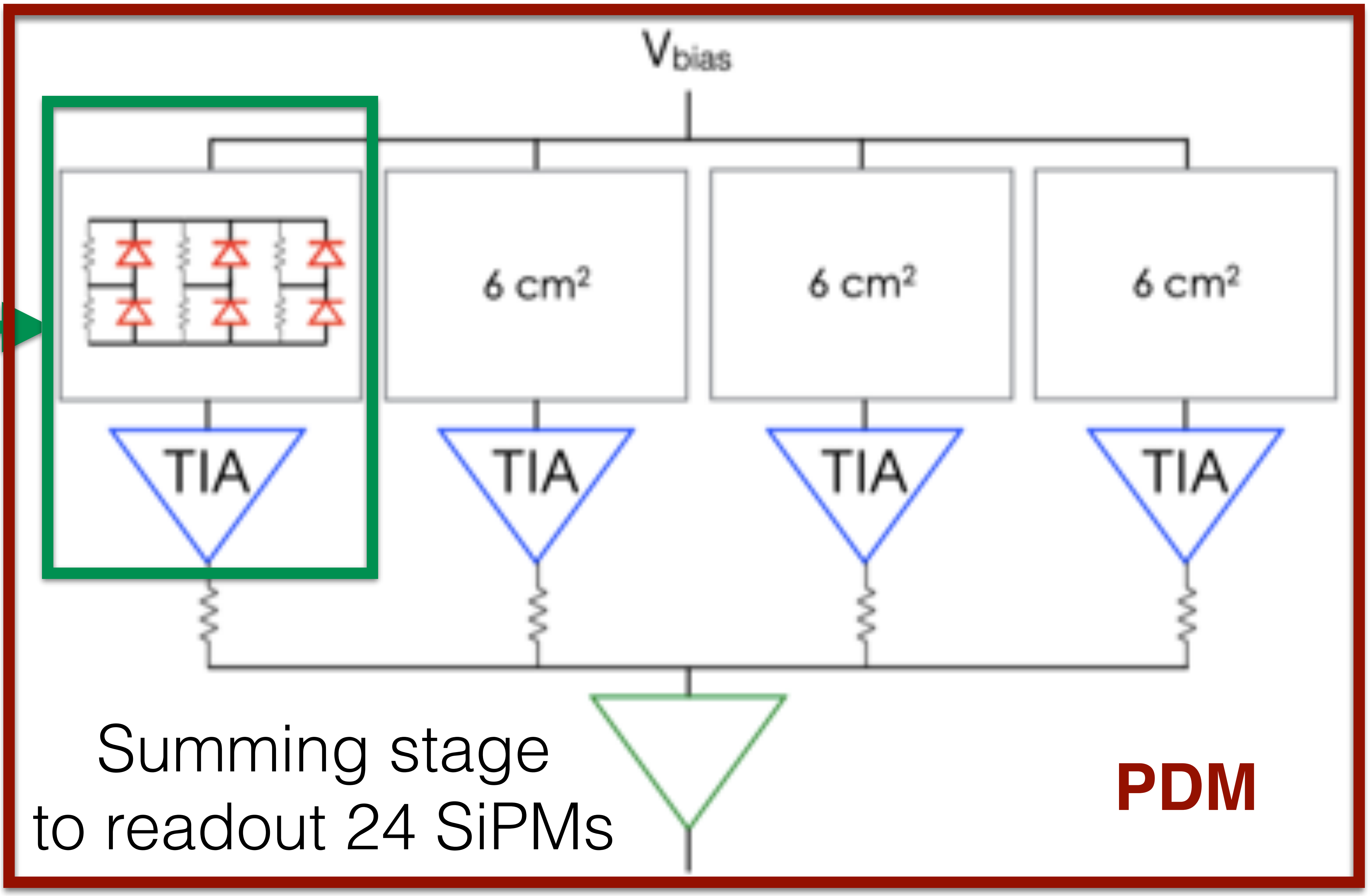


M. D'Incecco et al., IEEE Trans. Nucl. Sci., 65, 4, (2018), 1005 - 1011

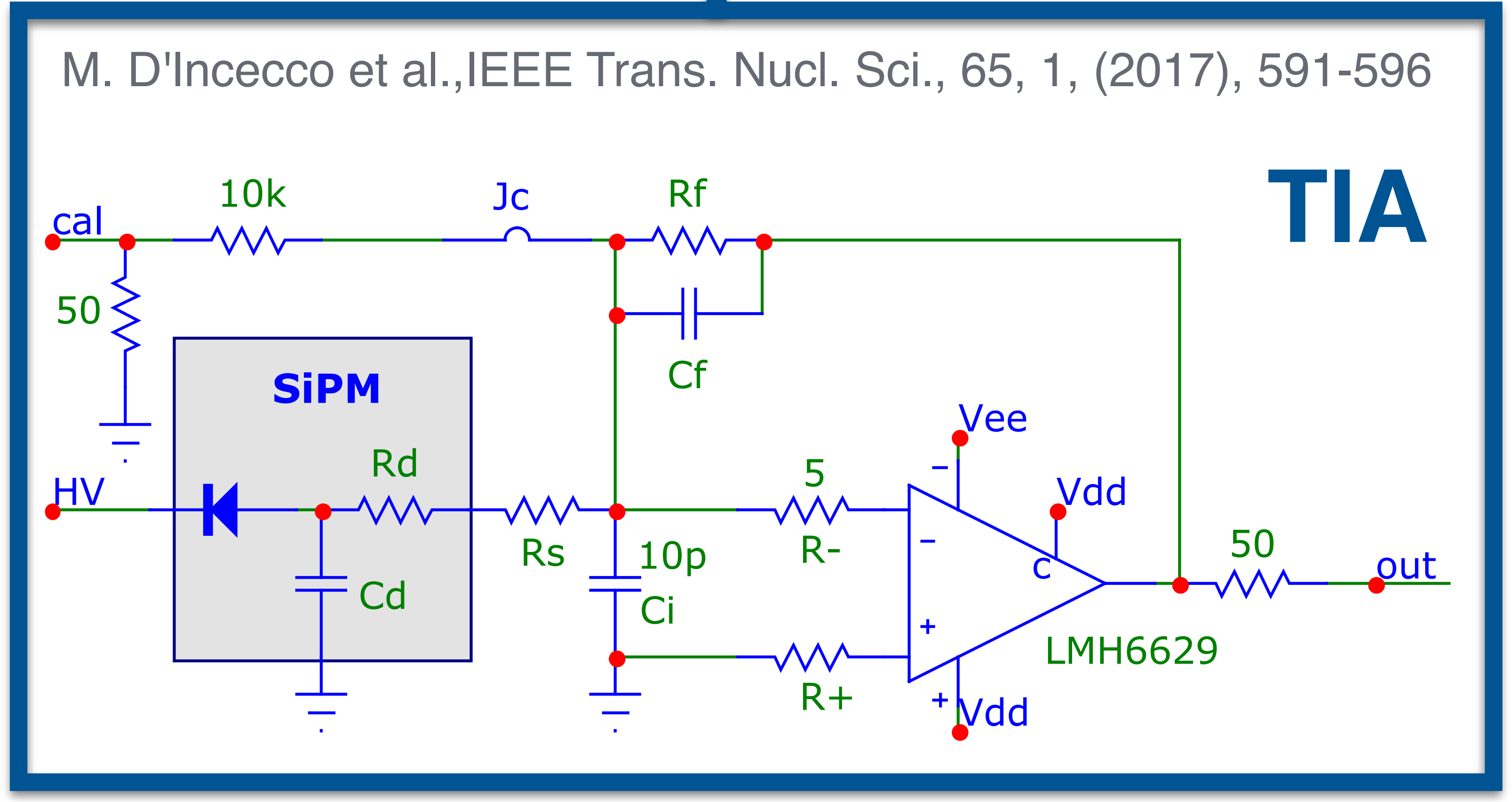
Mixed series/parallel configuration

Reduce C_{in}@TIA

Preserve BW



Summing stage
to readout 24 SiPMs



M. D'Incecco et al.,IEEE Trans. Nucl. Sci., 65, 1, (2017), 591-596

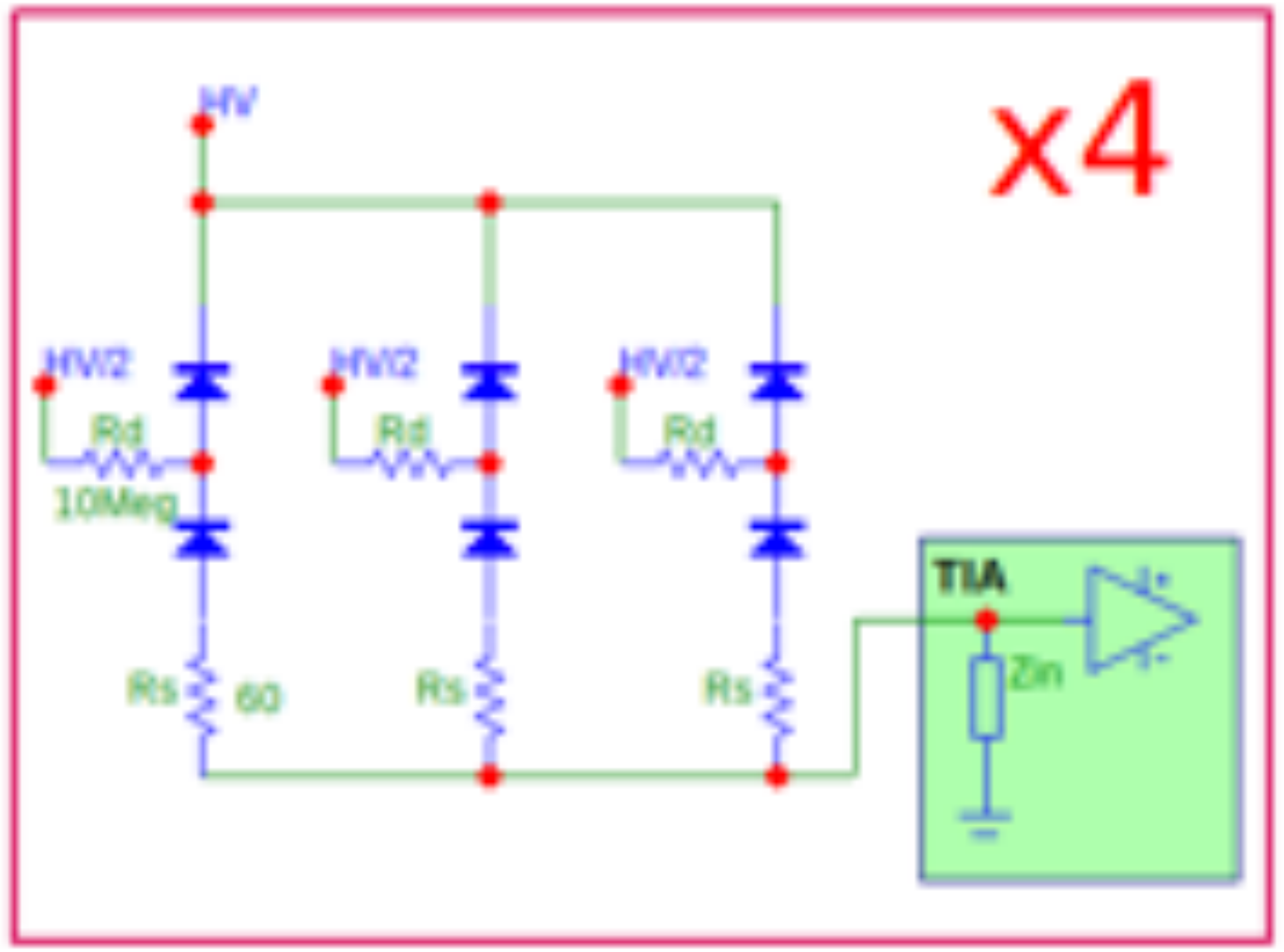
SiPM = current generators + huge output capacitance (~50pF/mm^2)

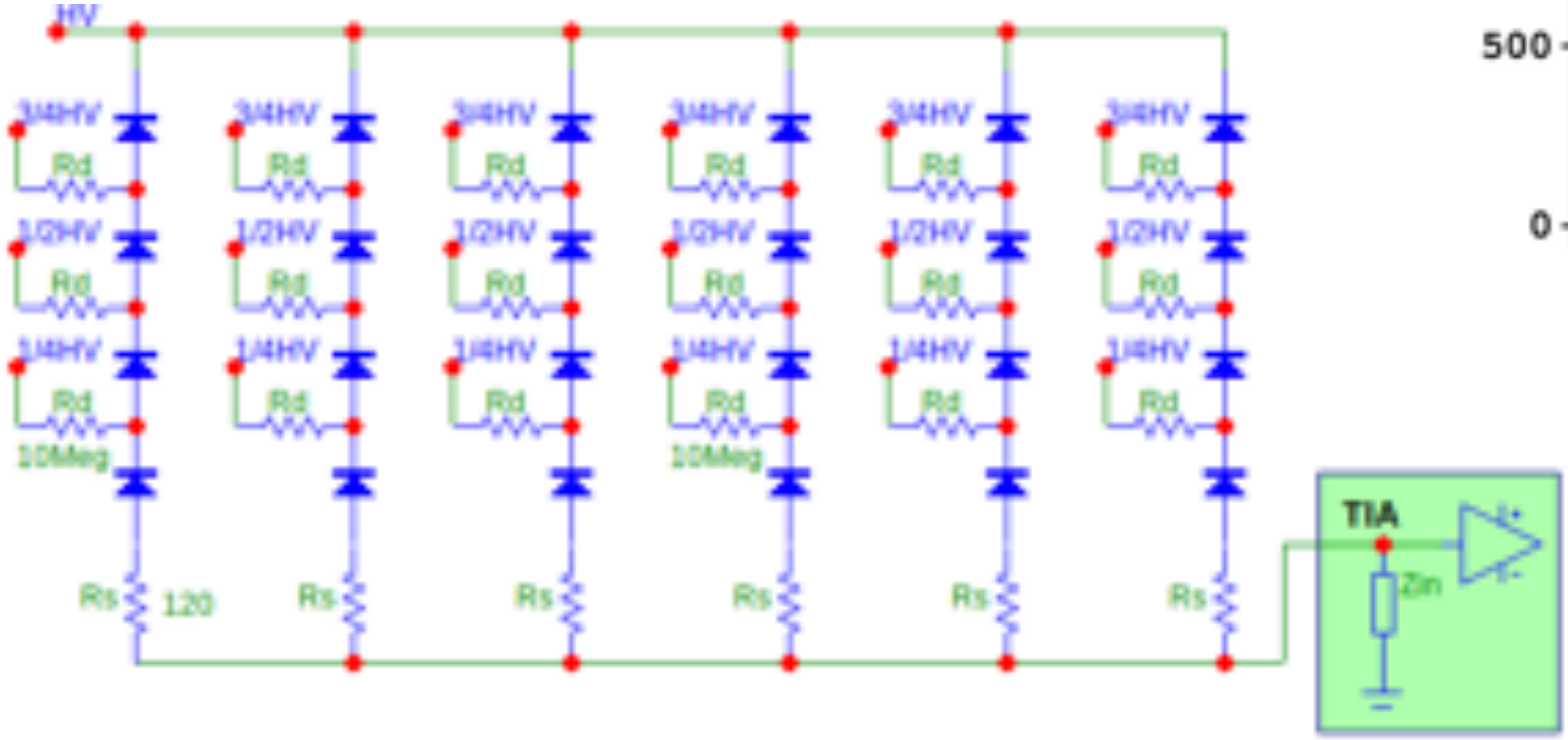
Transimpedance amplifier (TIA) High Bandwidth and Low Noise

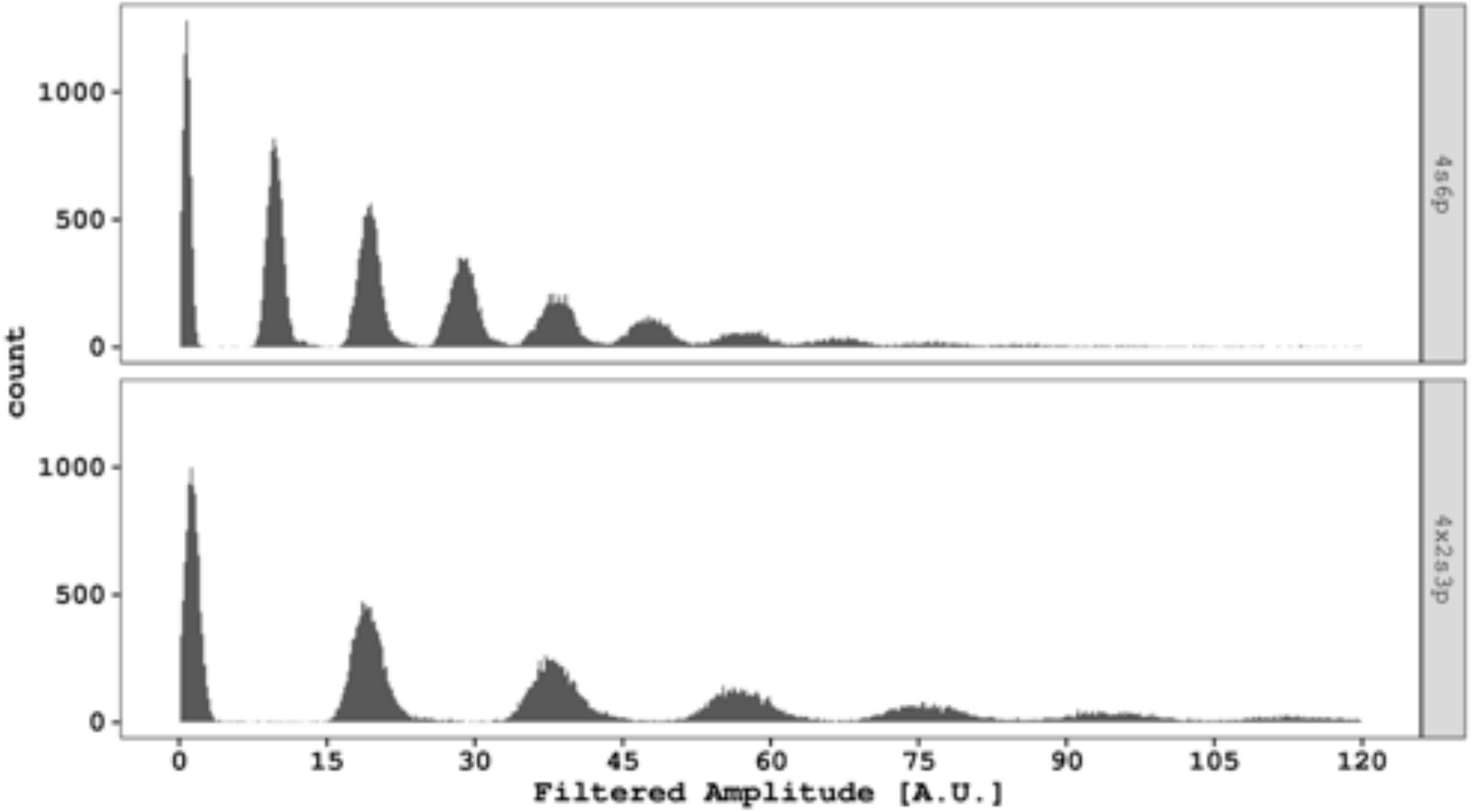
SNR is reduced wrt a single SiPM, but still very high

Power dissipation is < 250mW per PDM

Step 2: ...and upgrades



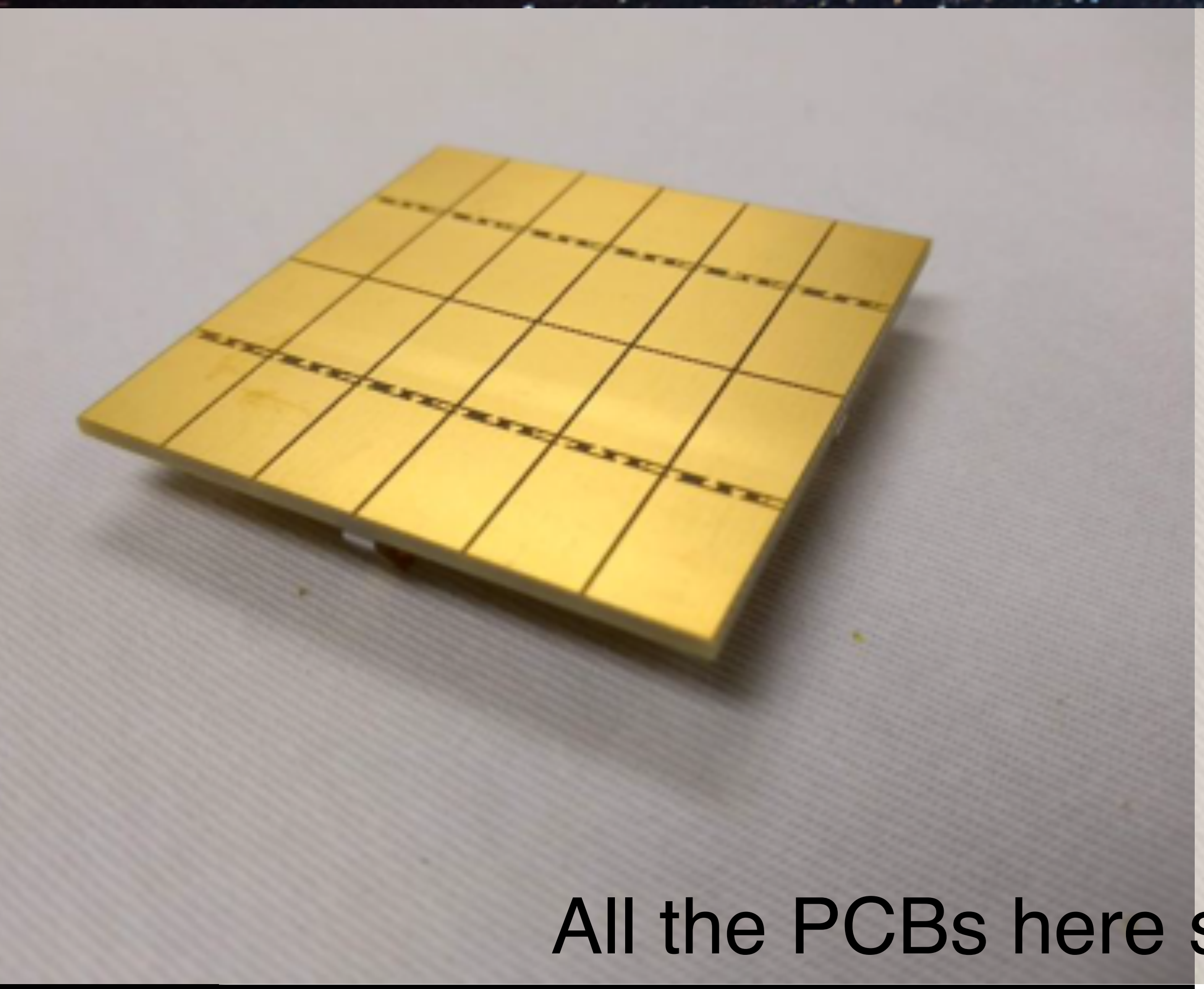


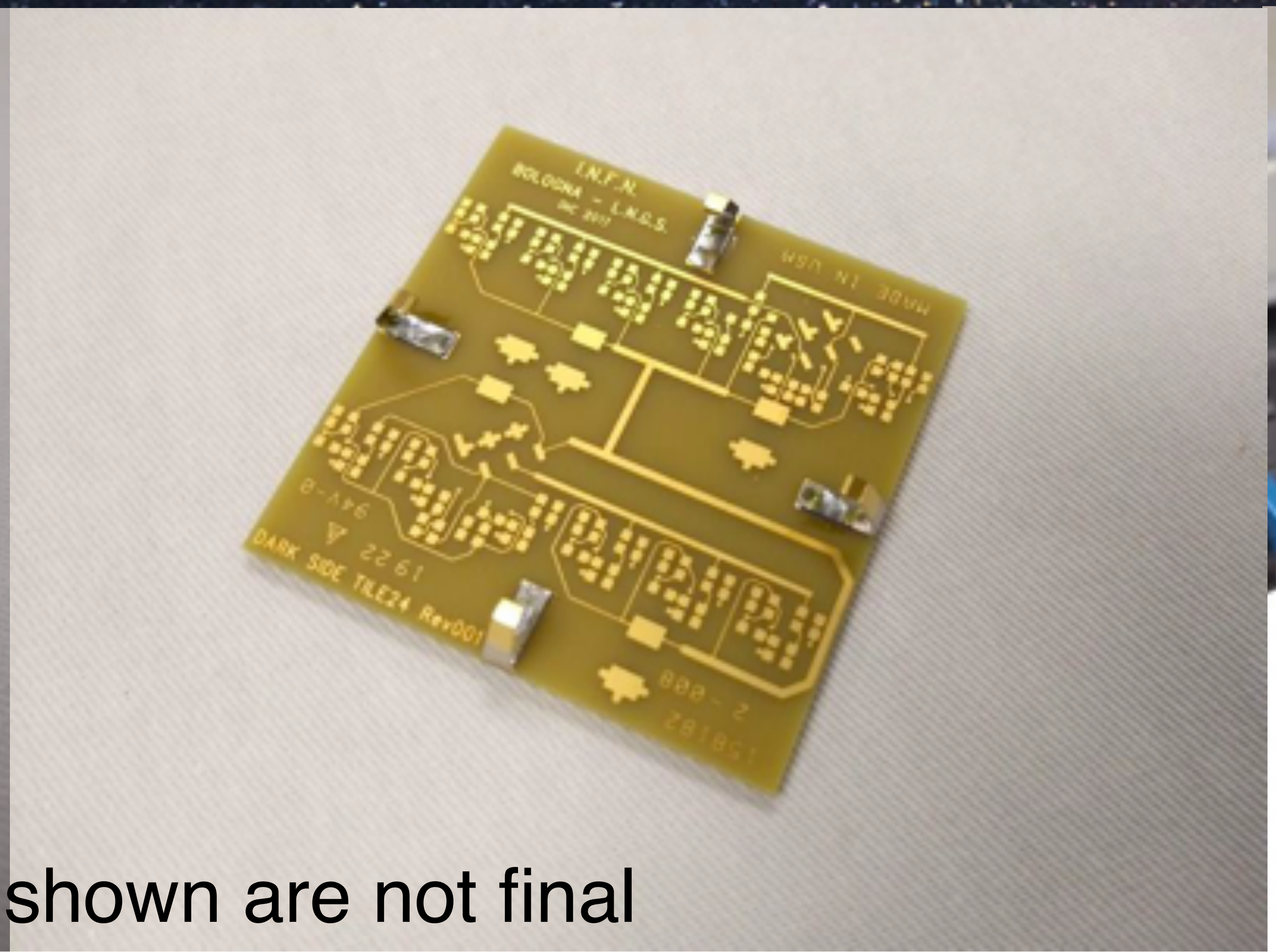


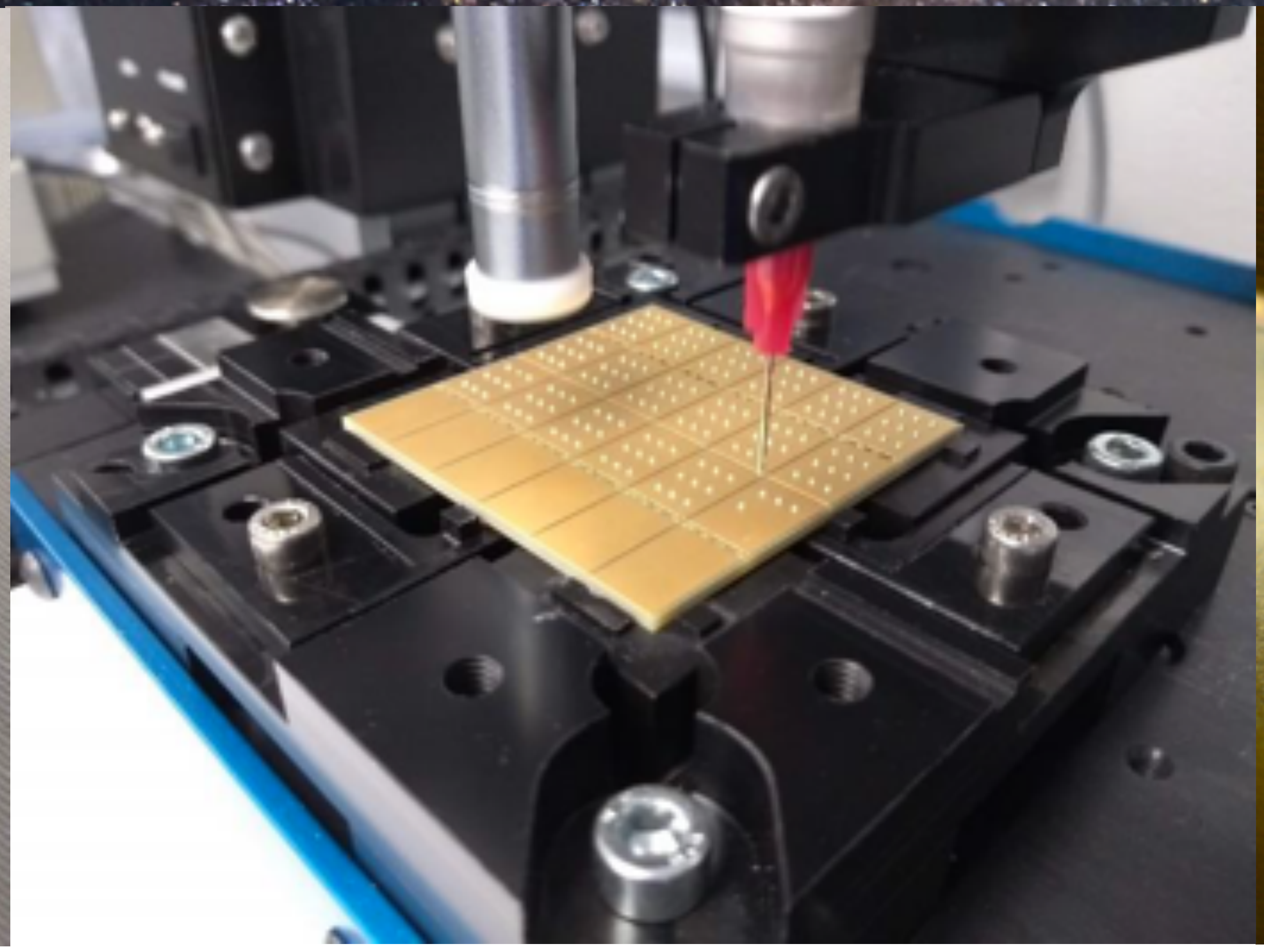
Switch from 4 sectors (6cm^2) to 1 single 24cm^2 unit

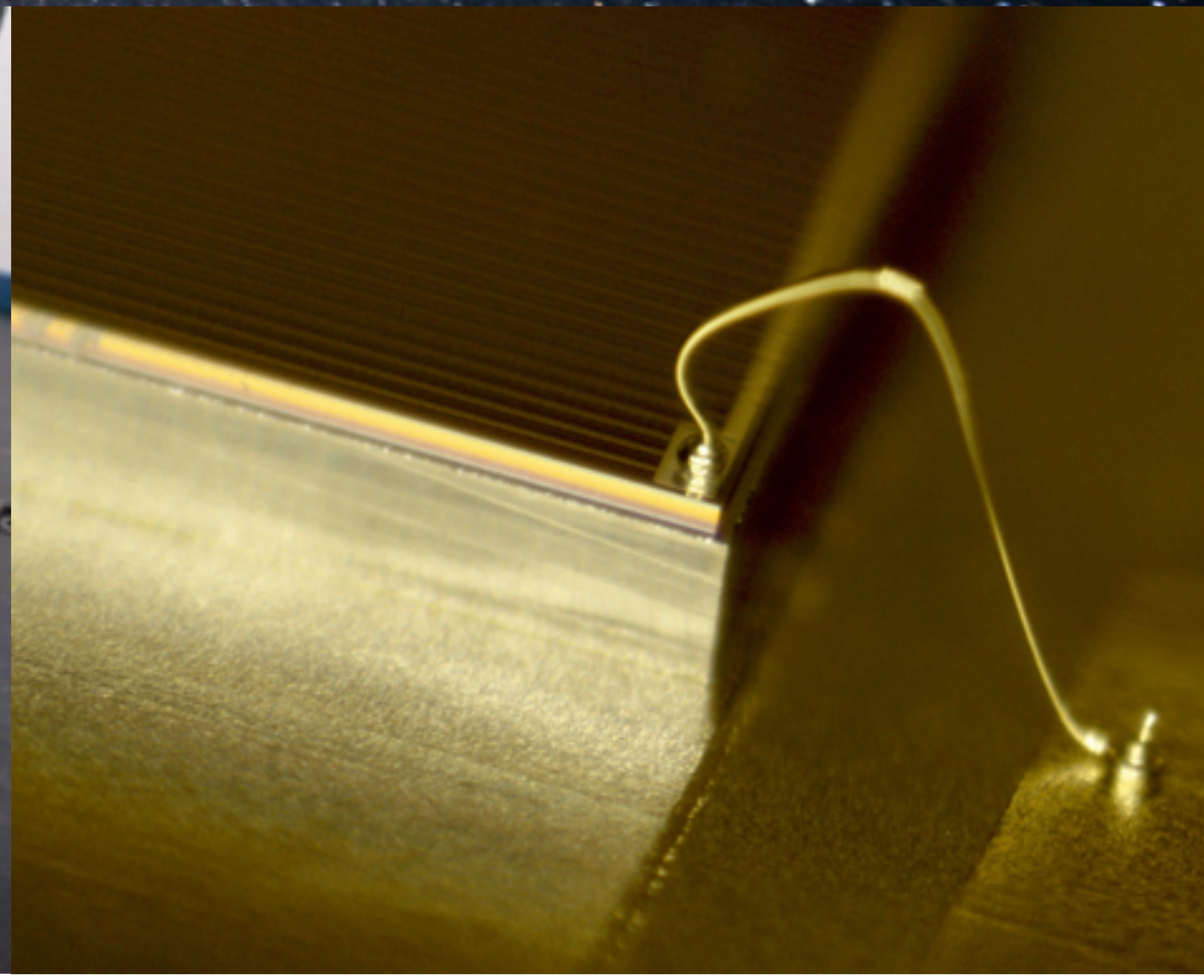
Power dissipation < 50mW per tile

Step 3: packaging and production

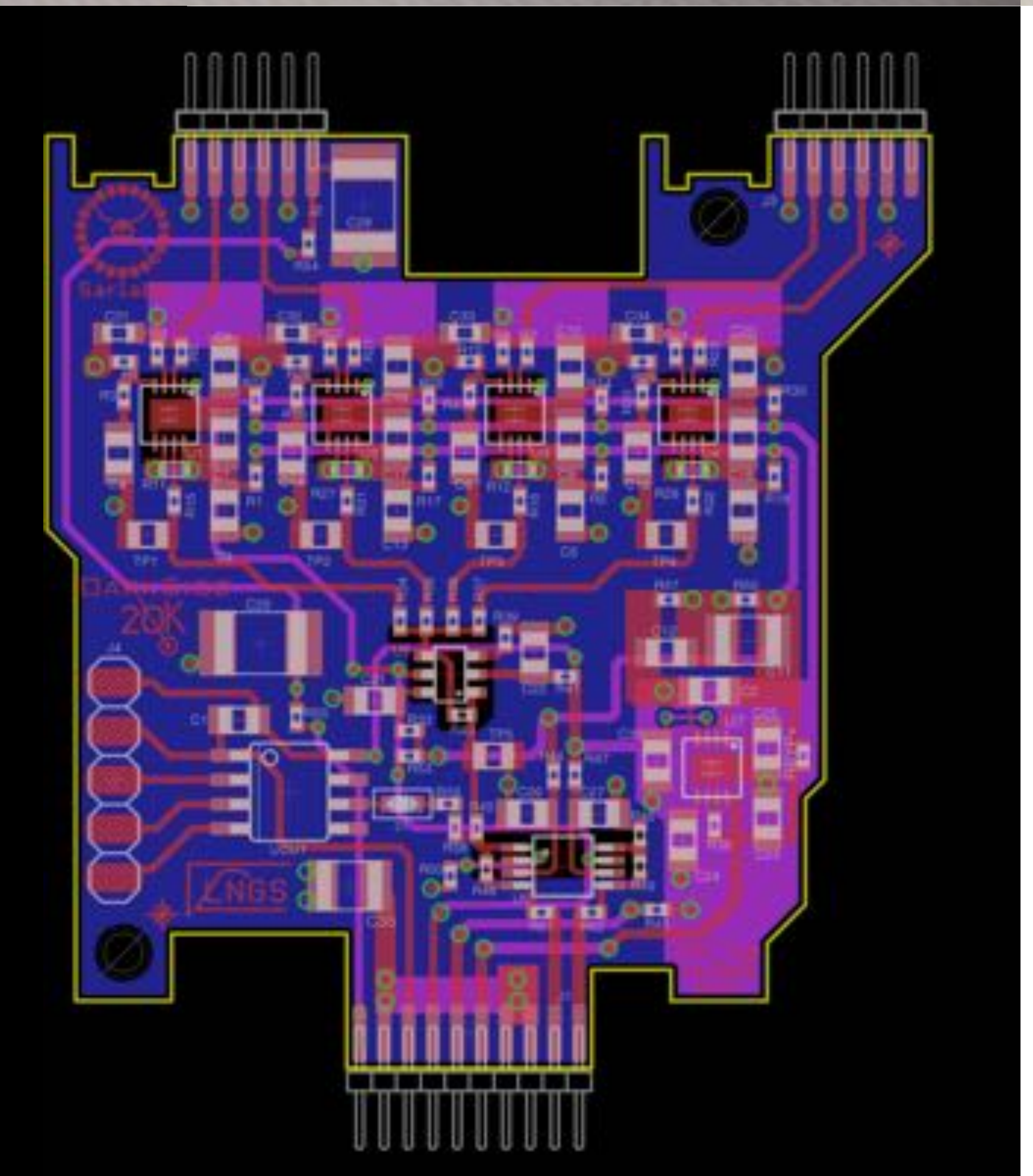






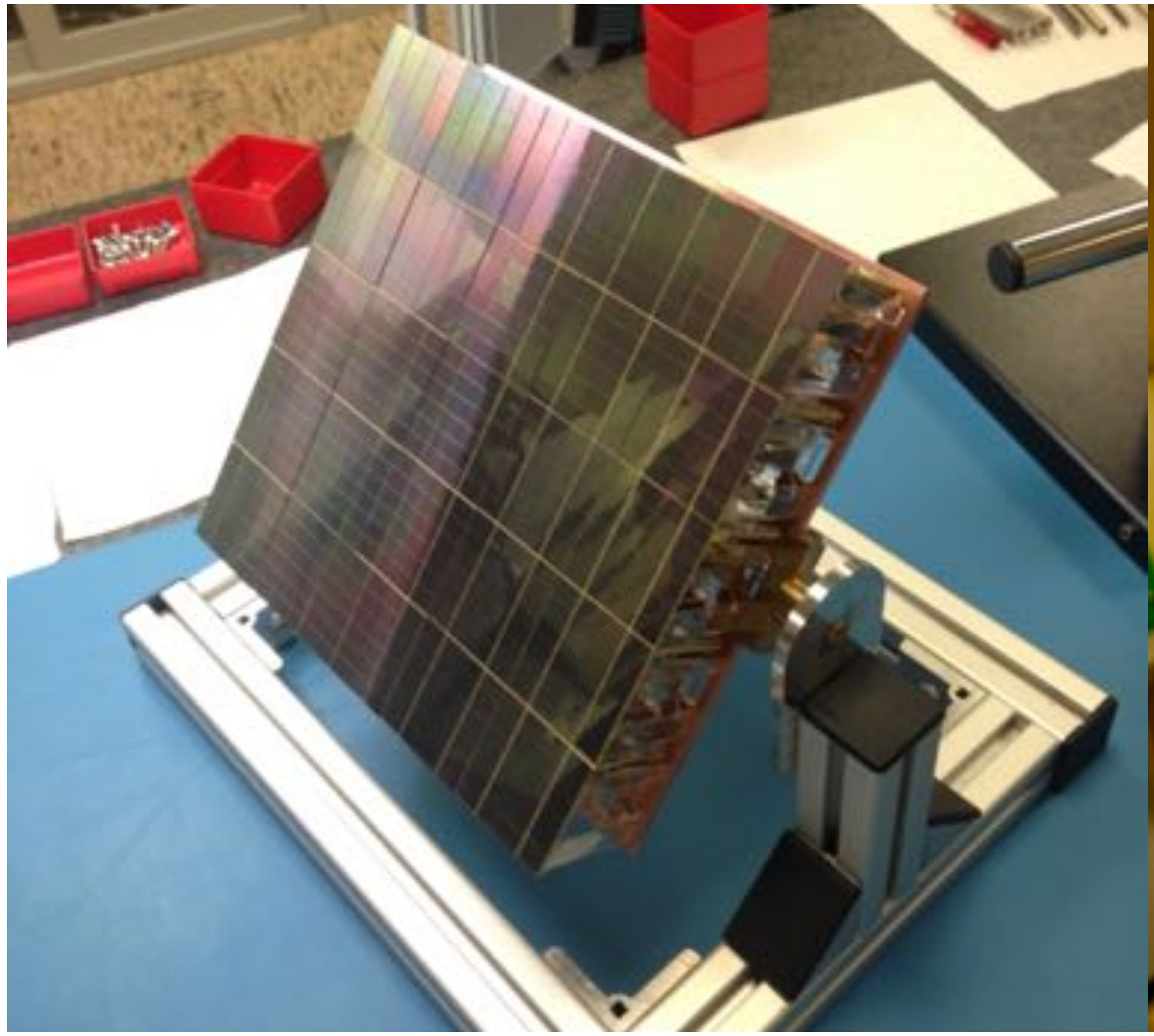


All the PCBs here shown are not final

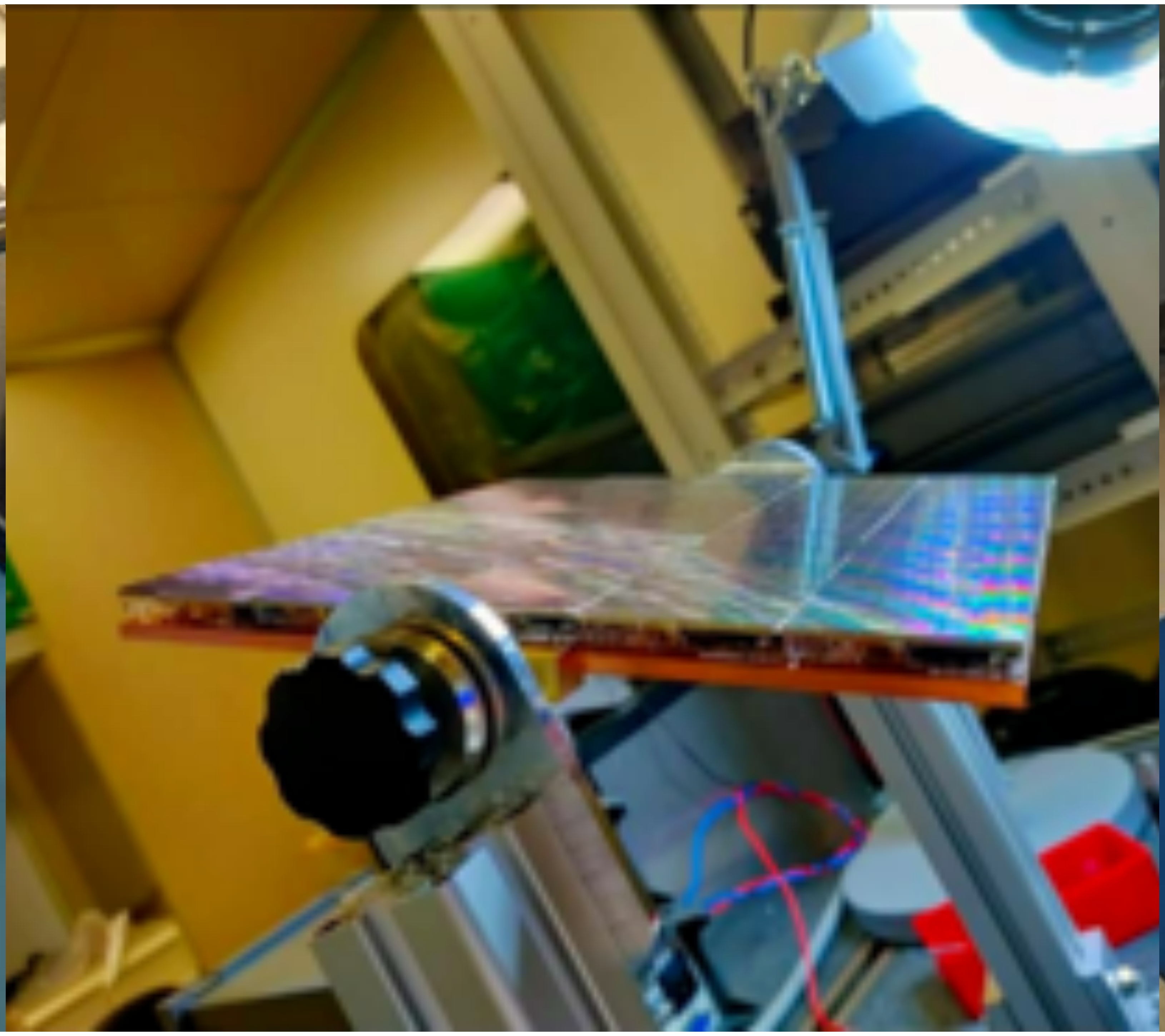


- SiPM development and readout electronics design are only the beginning of the journey!
- Wire-bonding and die-bonding procedures finalized.
- Materials and components are continuously being assayed and selected to ensure the fulfillment of radio-purity requirements.
- Final assembly to happen at the NOA packaging facility (in LNGS, Italy).

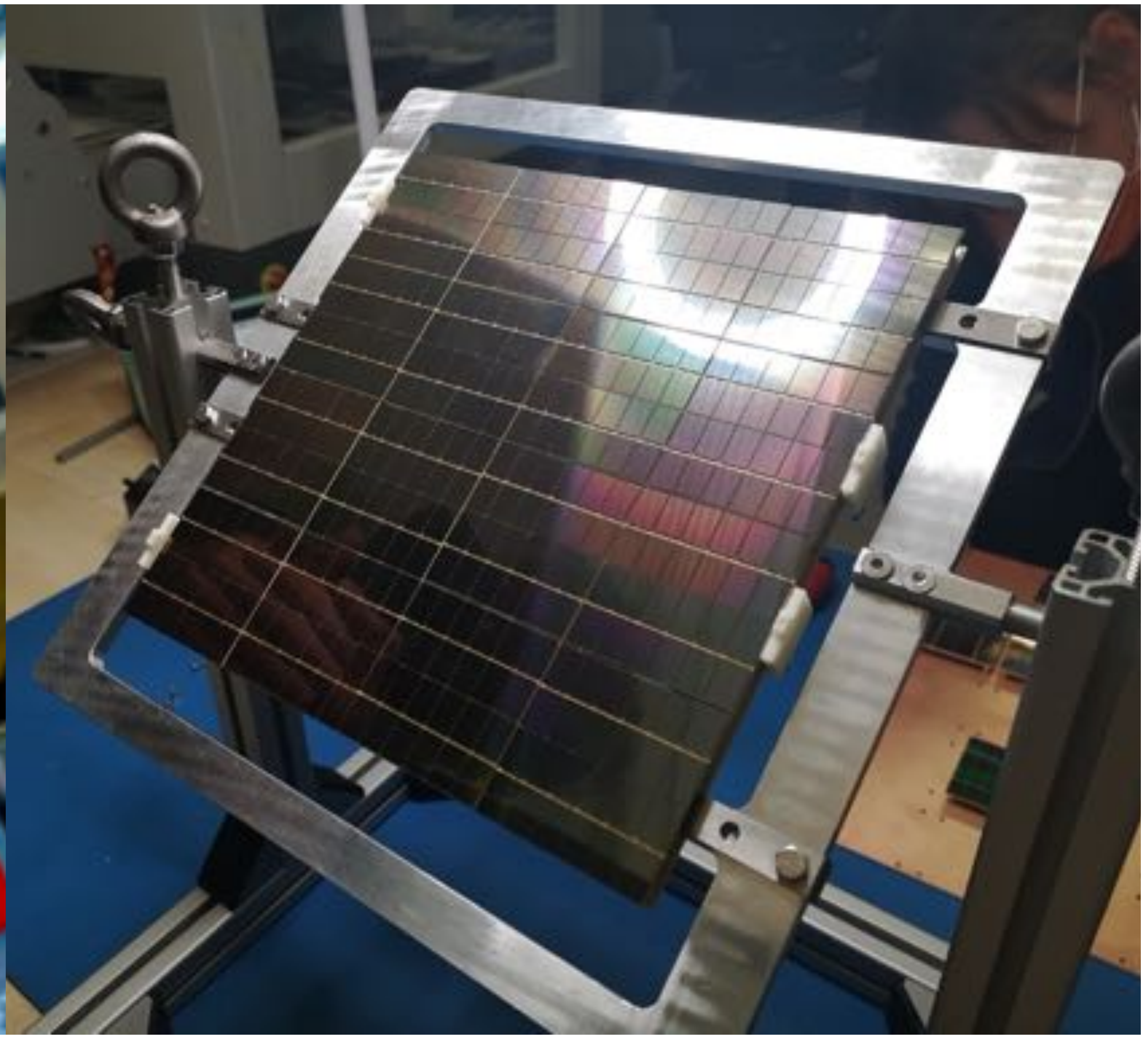
Status of photo-detection systems



First PDU prototype with 25 channels



PDU with 25 channels, less material



Final PDU: 16 tiles grouped in 4 or 8 readout channels

- Several prototypes of Photo-Detection Units (PDU) have been produced and tested in LN and LAr.
- All the requirements on gain, SiPM noises, SNR and timing resolution are met or exceeded.
- Mass production soon to start in a dedicated facility (NOA).

The journey of UAr: extraction

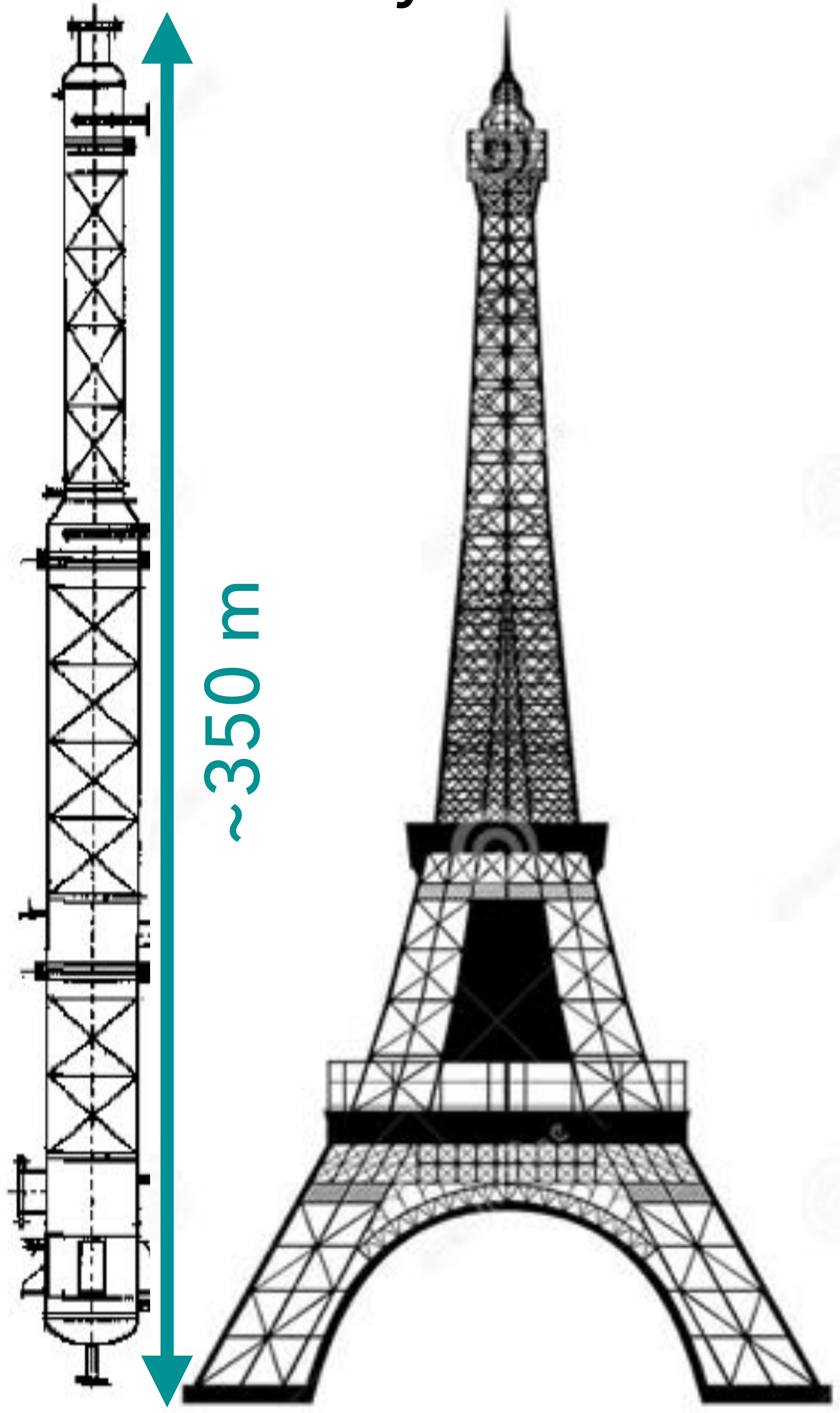
- CO_2 well in Cortez, CO, USA;
- Industrial scale extraction plant;
- Plant ready to be shipped;
- Civil work ongoing;
- Expected argon purity at outlet: 99.99%;
- UAr extraction rate: 250-330 kg/day;

The journey of UAr: purification

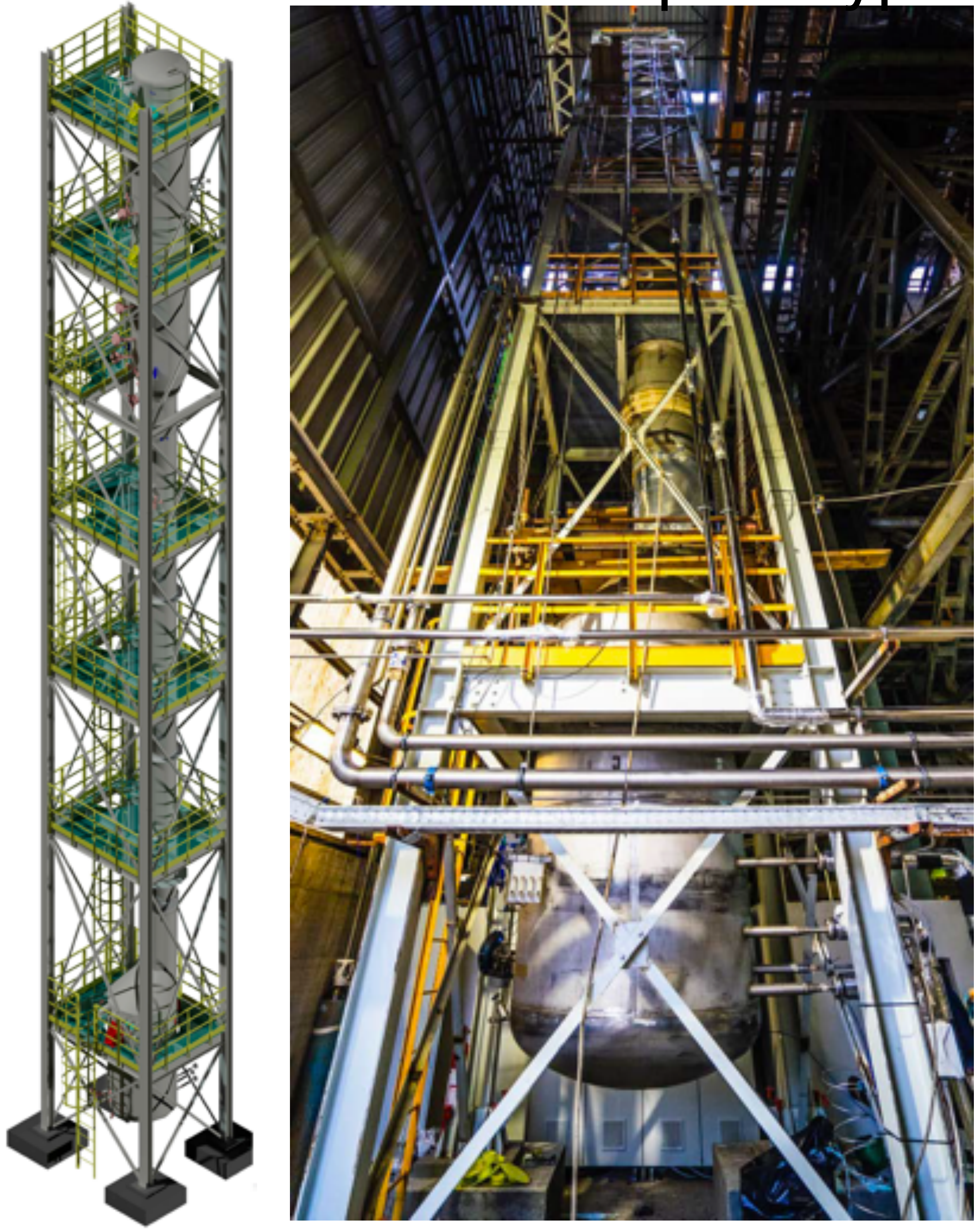
ARIA: UAr distillation plant

- 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

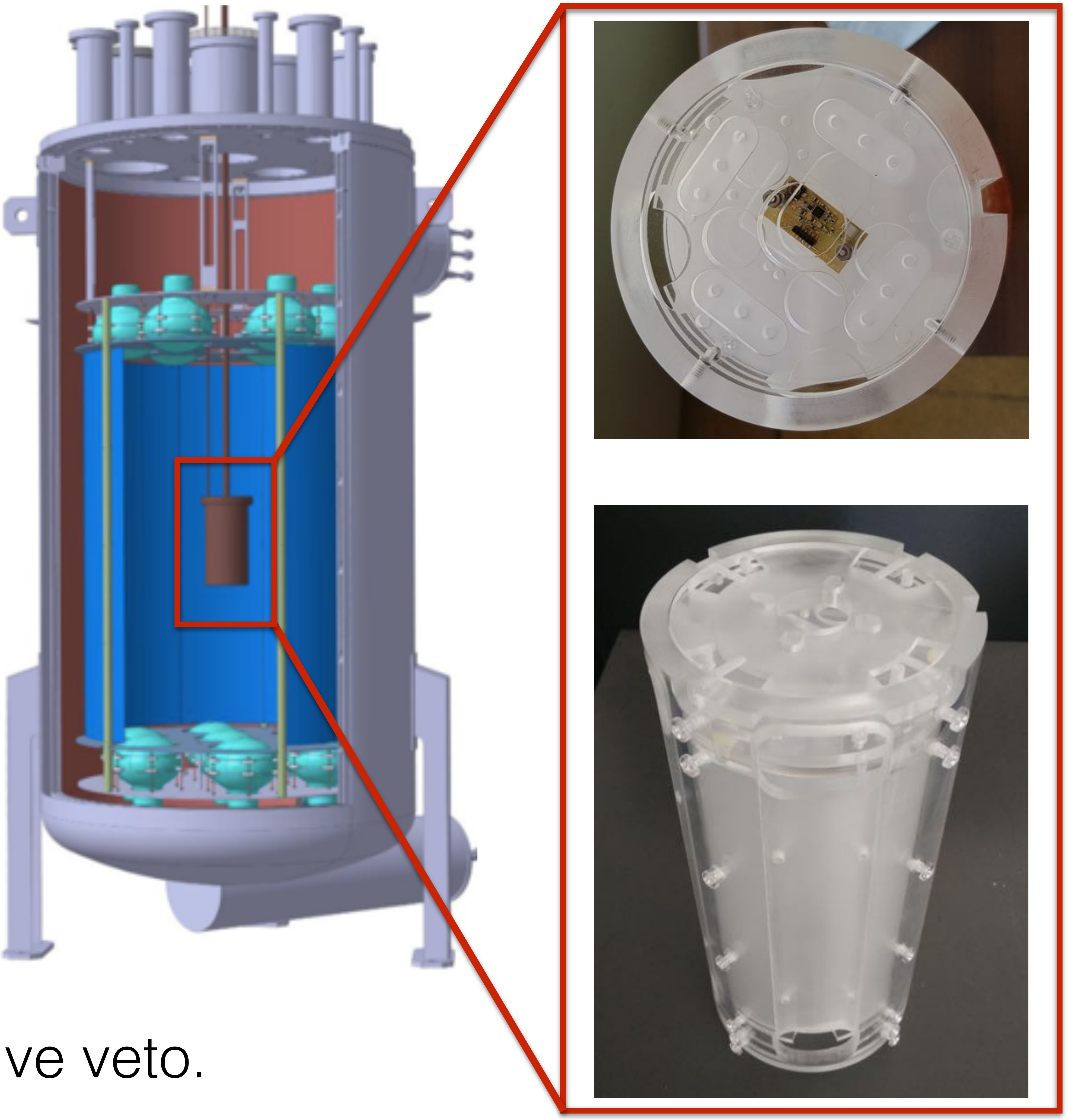
Sketch of ARIA when fully assembled



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).

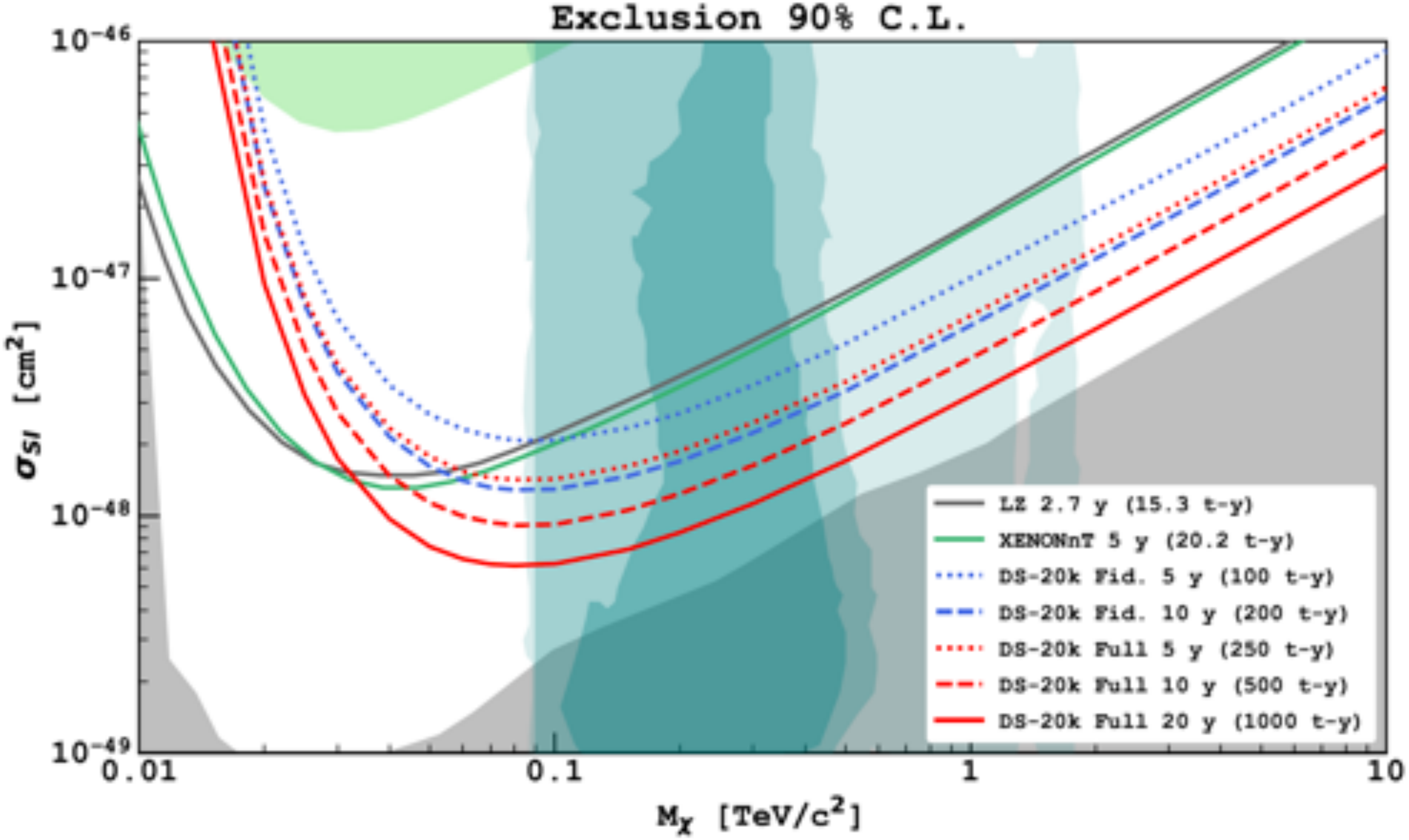
DarkSide-20k physics reach

- 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

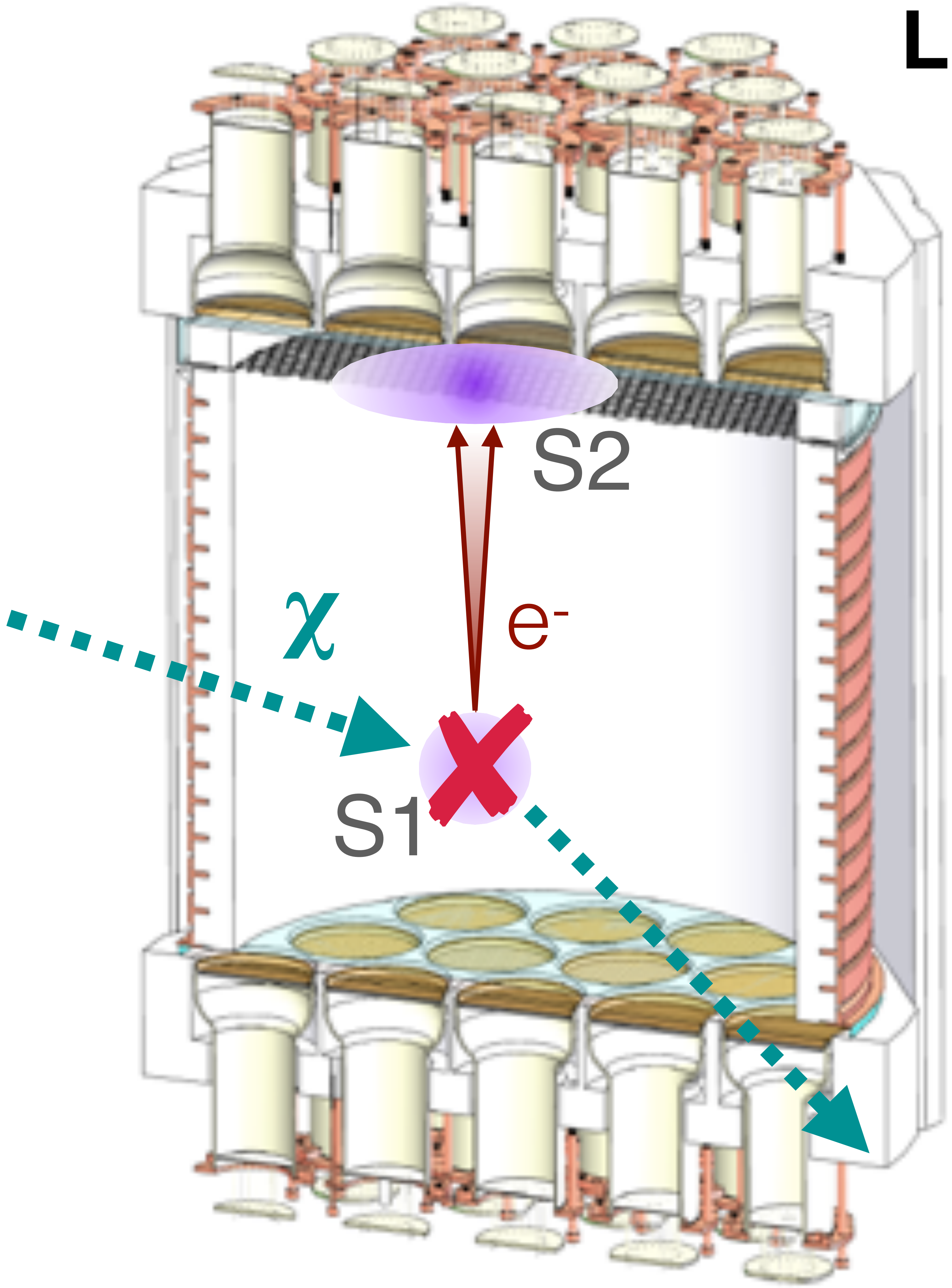
- Nominal exposure: (20×10) t yr

- Instrumental Background: 0.1 events in 200 t yr



Bonus content

S2-only analysis



Low Mass WIMP search ⇒ search with“low” energy events

Lower the energy threshold ⇒ Look at the S2 only events

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

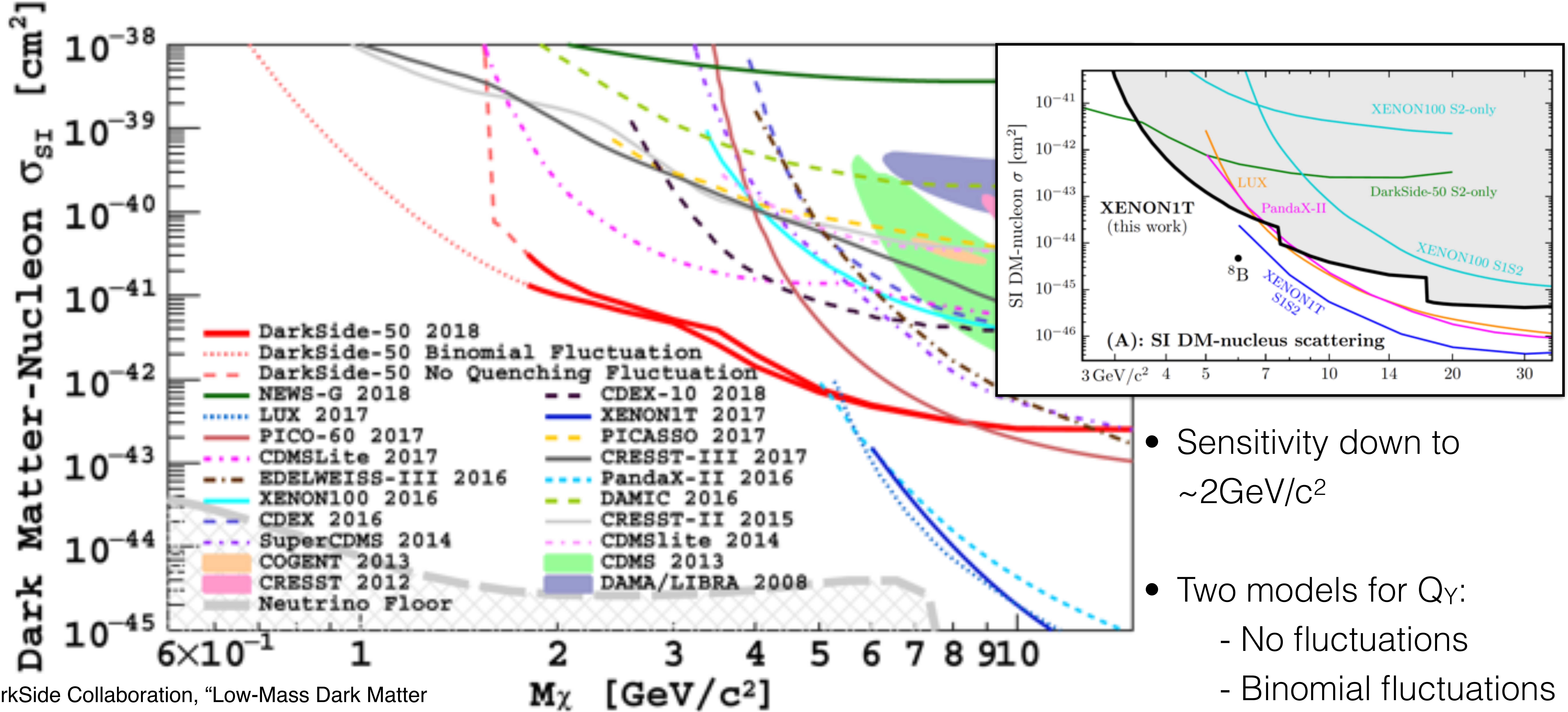
Pros:

- 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

LM exclusion limits

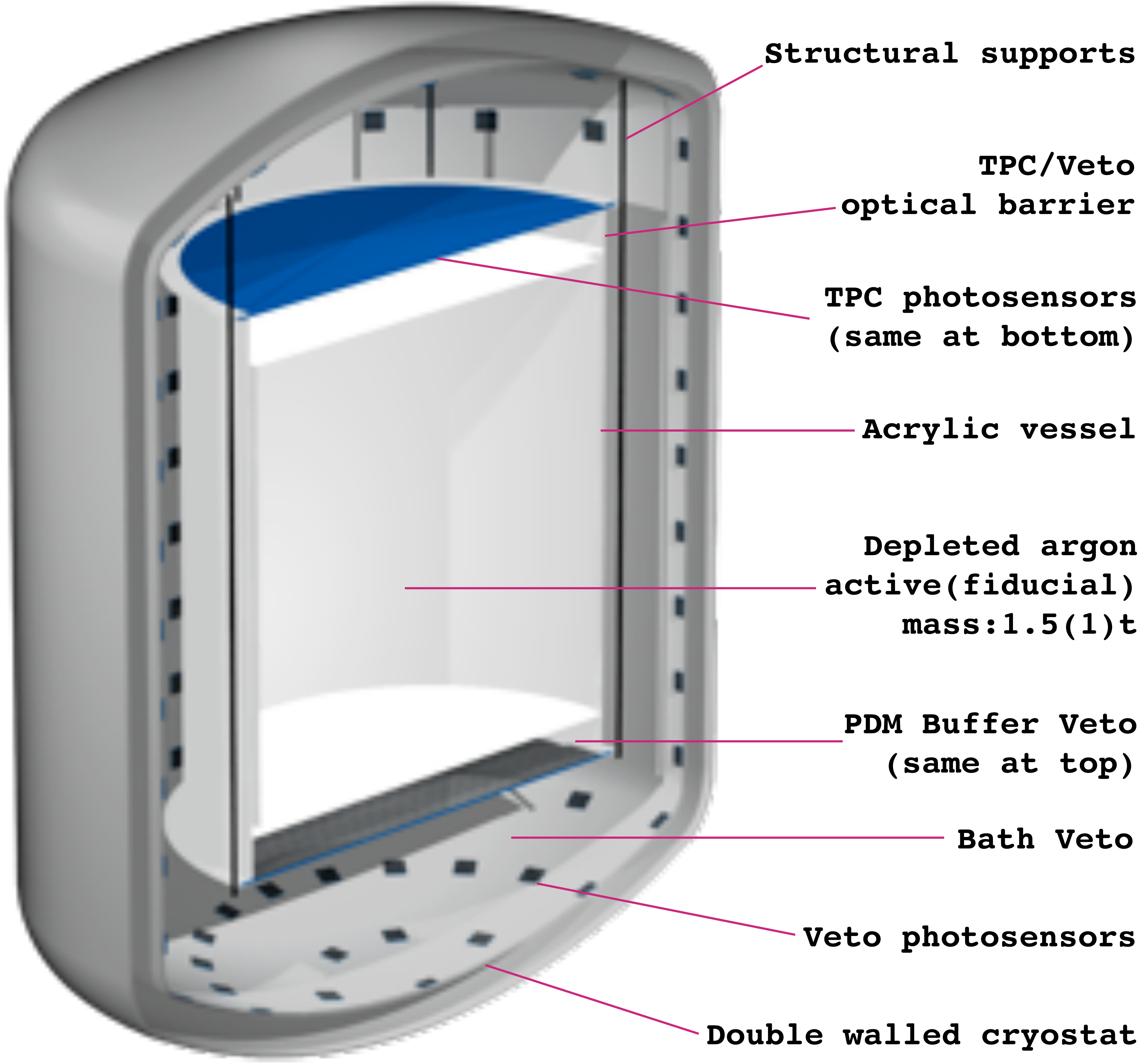


- Sensitivity down to ~2GeV/c^2

- Two models for Q_Y:
  - No fluctuations
  - Binomial fluctuations

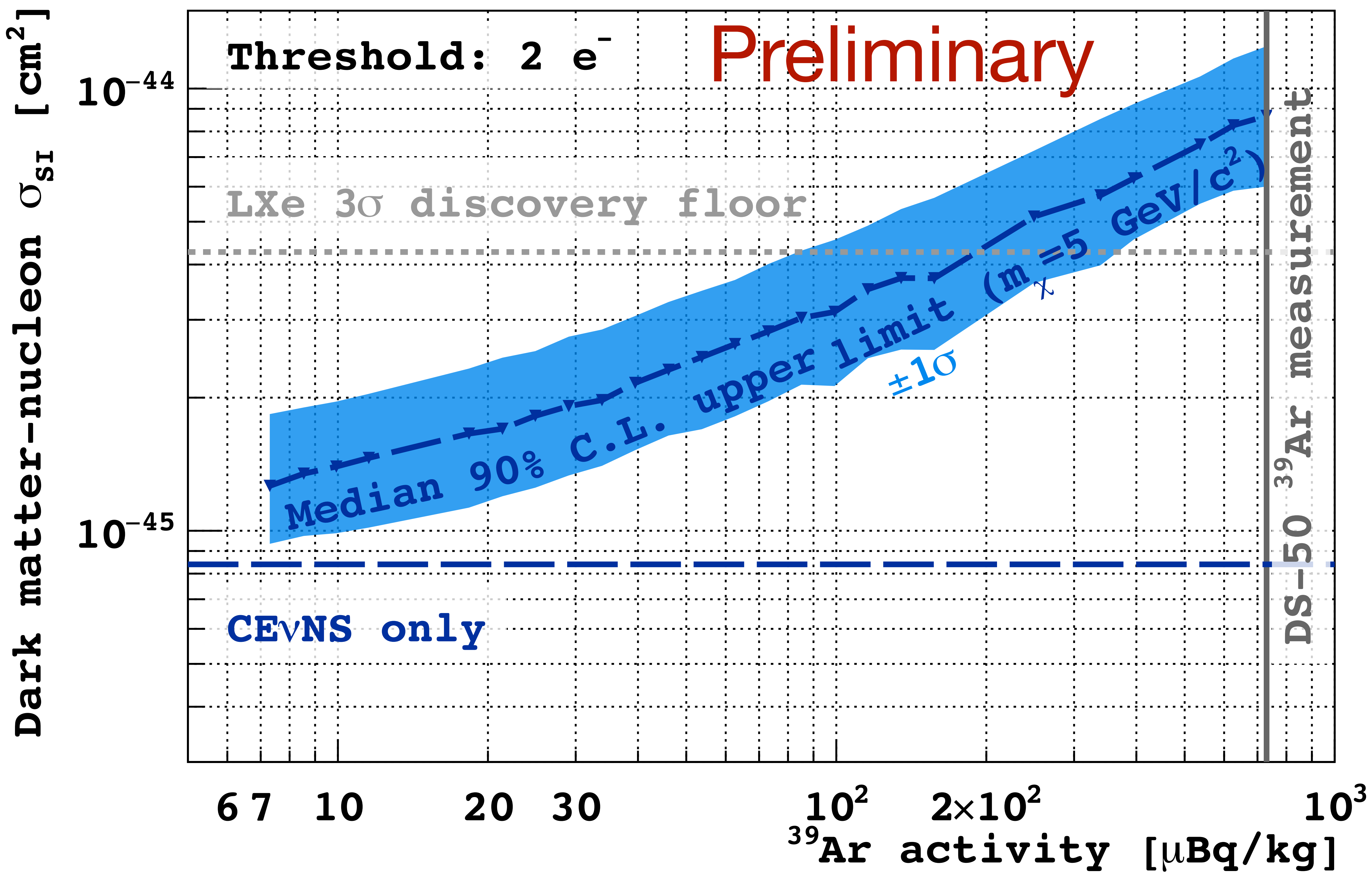
DarkSide Collaboration, “Low-Mass Dark Matter Search with the DarkSide50 Experiment” Phys. Rev. Lett. 121 081307 (2018)

Conceptual sketch of DS-LM

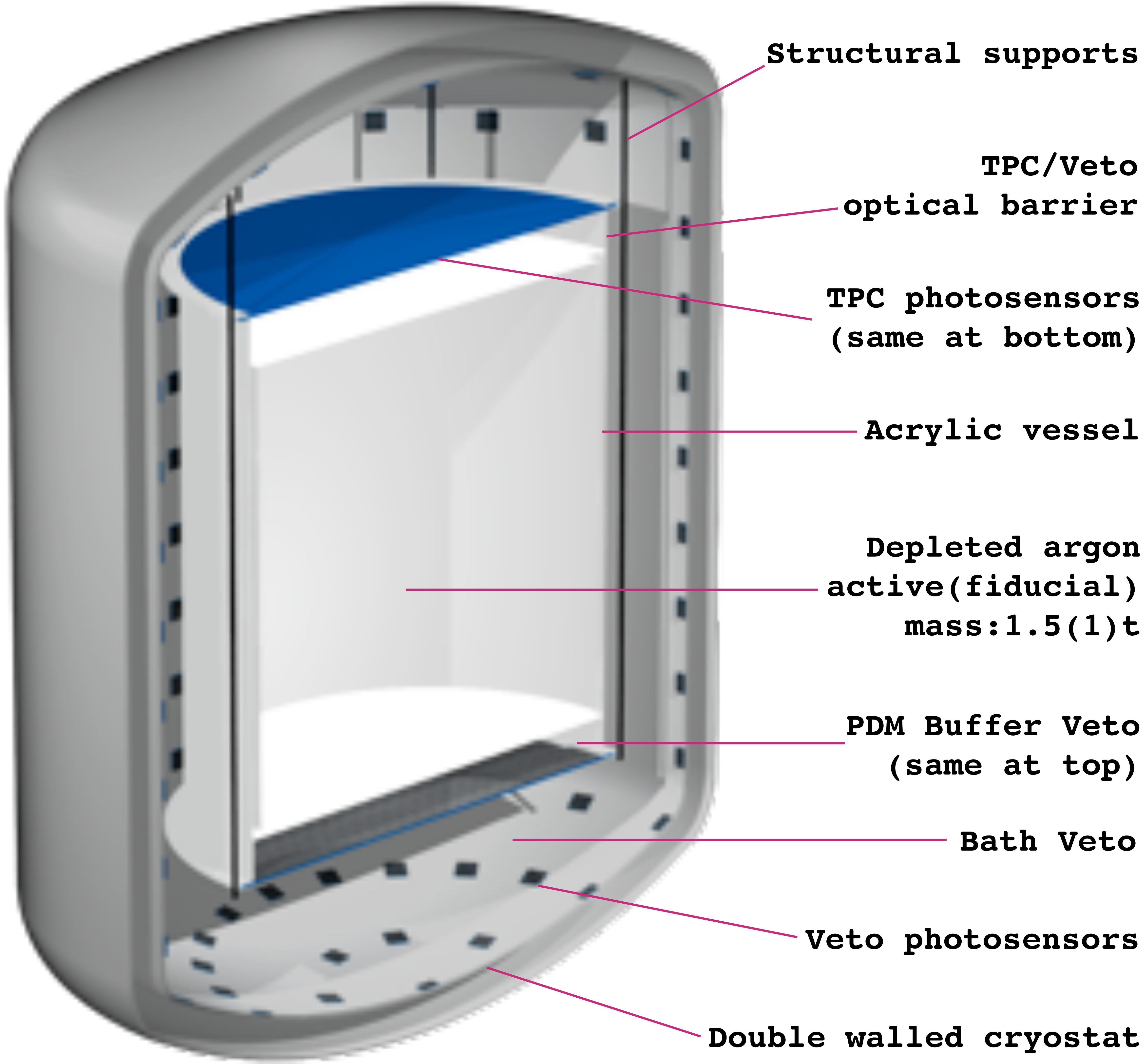


To reduce the beta bkg:

- chemical purification of UAr in ARIA to remove ^{85}Kr.
- isotopic separation of ^{39}Ar in ARIA.



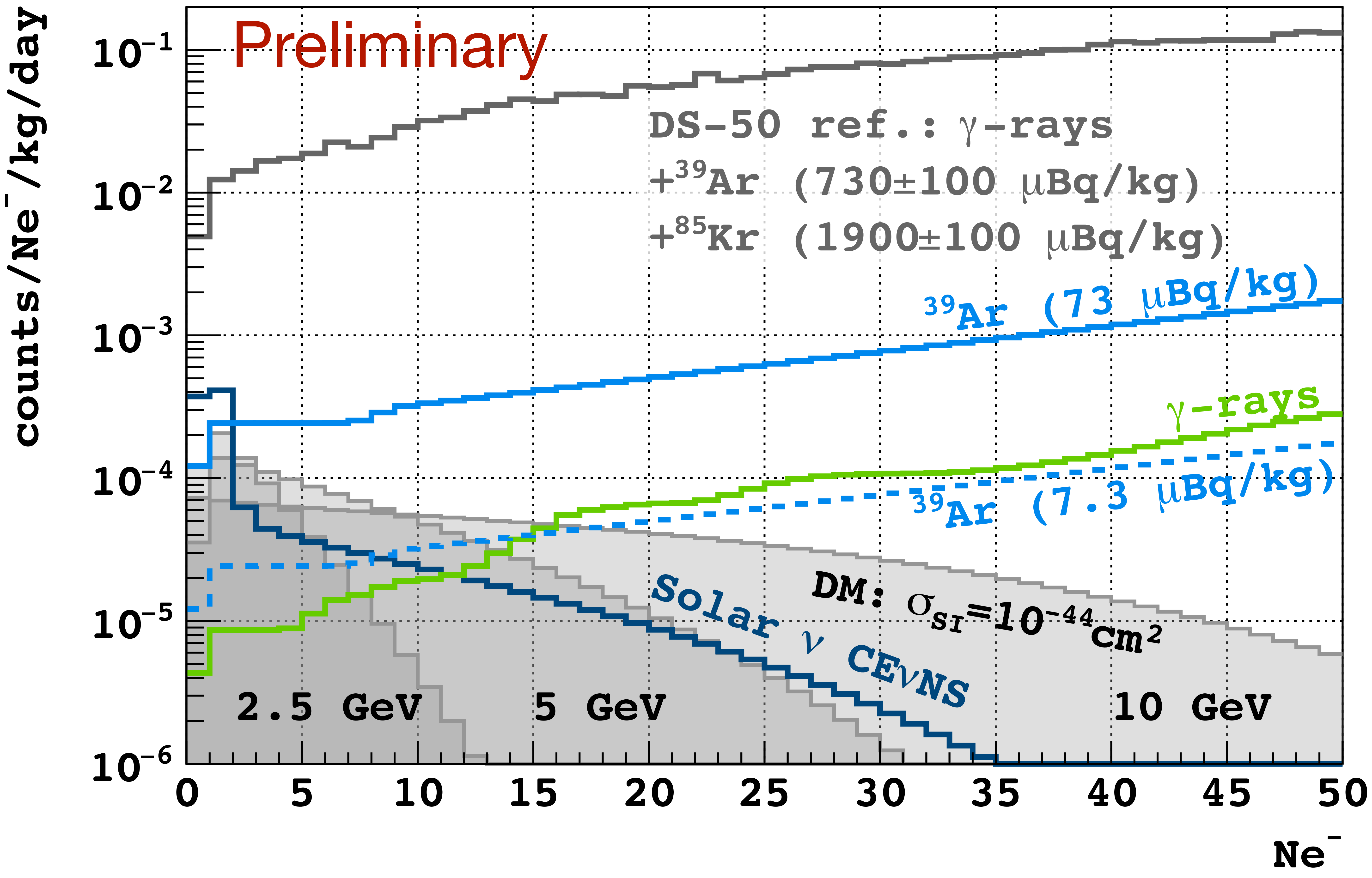
Conceptual sketch of DS-LM



To reduce the gamma bkg:

- very pure acrylic vessel
- very pure SiPM-based photosensors with ASIC readout
- low radioactivity SS cryostat
- XY fiducialization cut (10cm)
- Offset between TPC and optical planes
- Instrumented LAr volume outside TPC to act as an active gamma veto.

Expected backgrounds

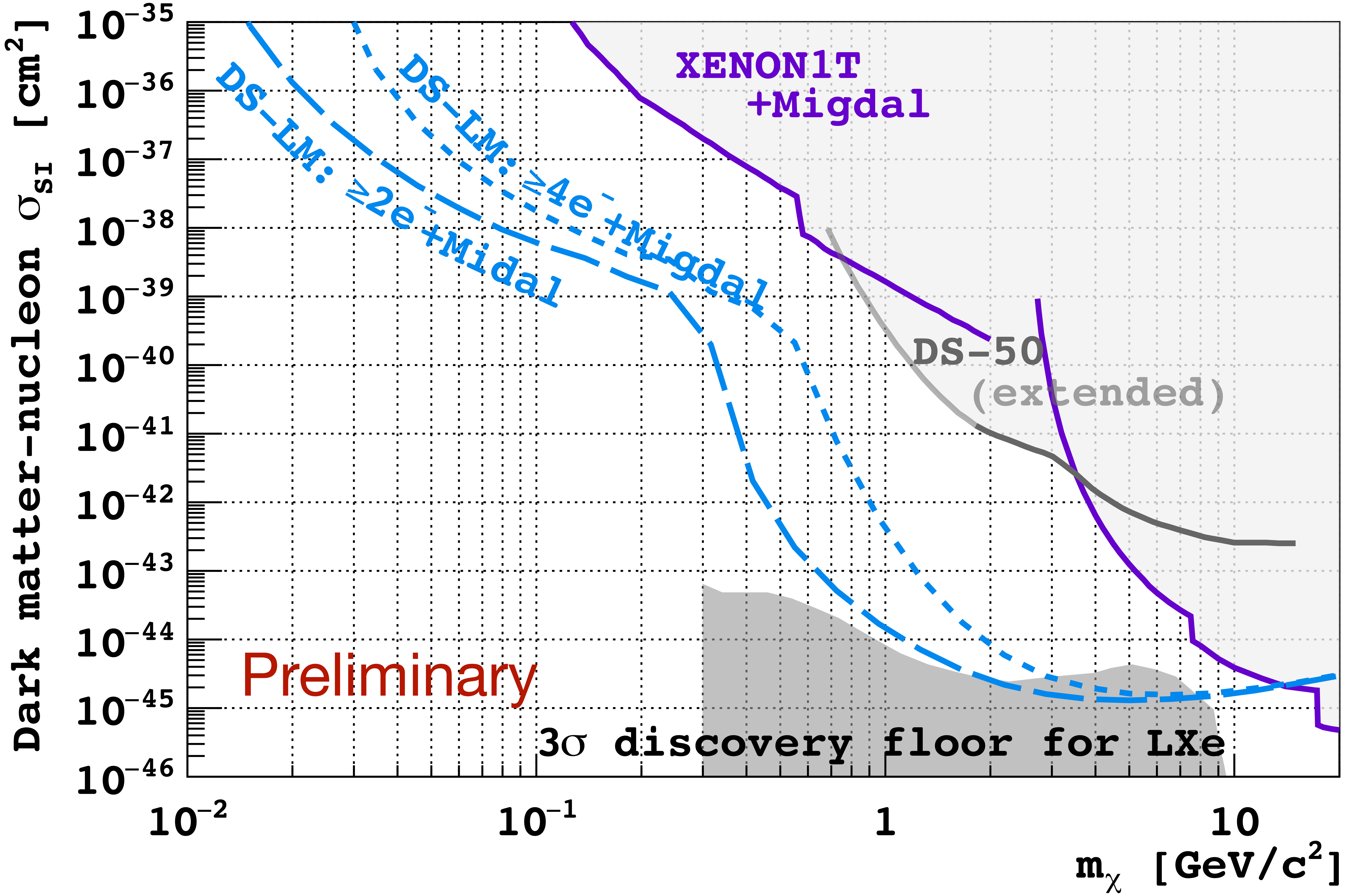


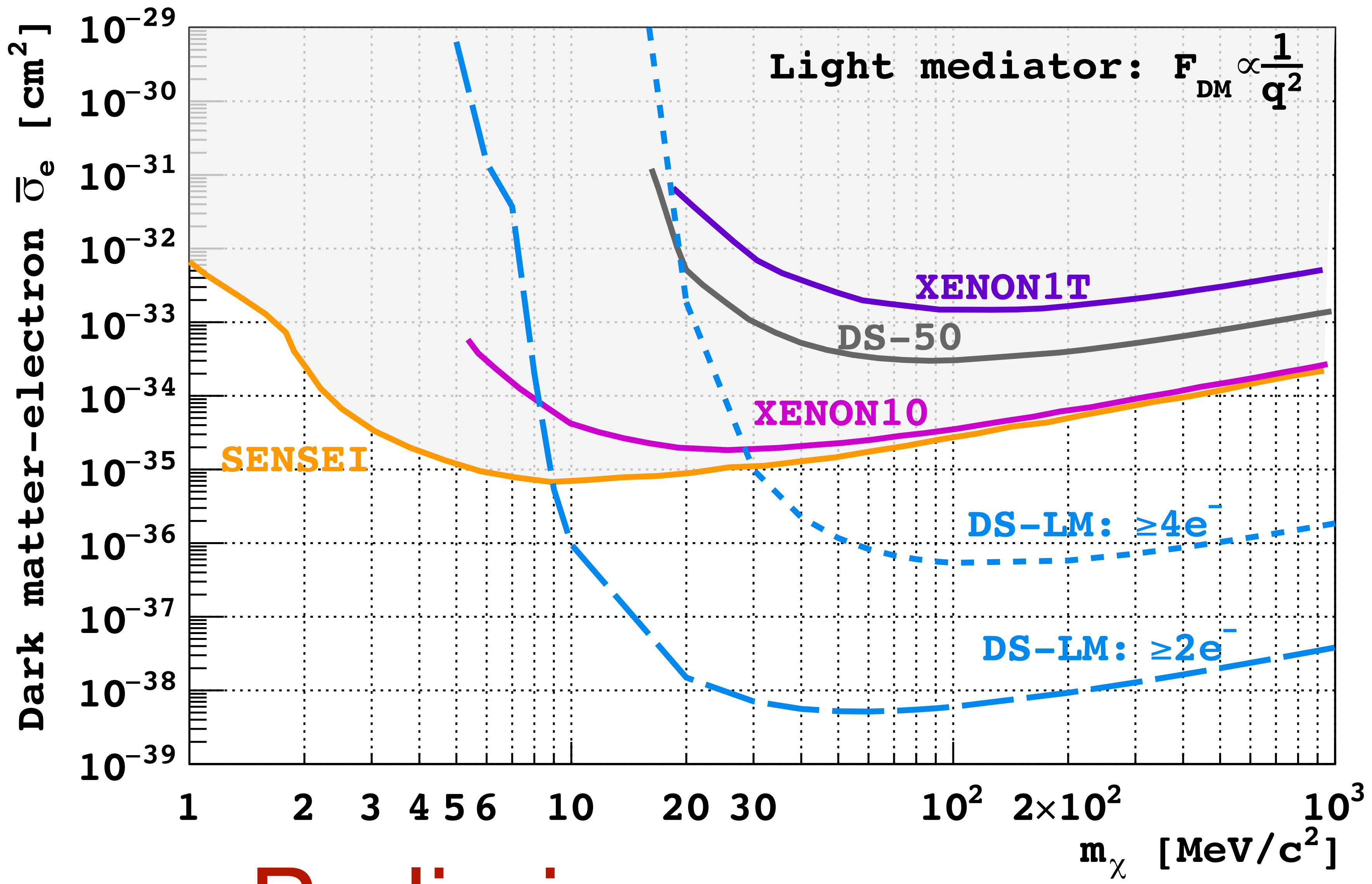
- The combination of pure materials and active veto reduces the gamma bkg of 3 orders of magnitude.

- The beta spectrum reduction here assumes:
  - Complete removal of ^{85}Kr
  - a x10 reduction thanks to improvement in the extraction techniques of UAr
  - a x10 reduction with isotopic distillation in ARIA

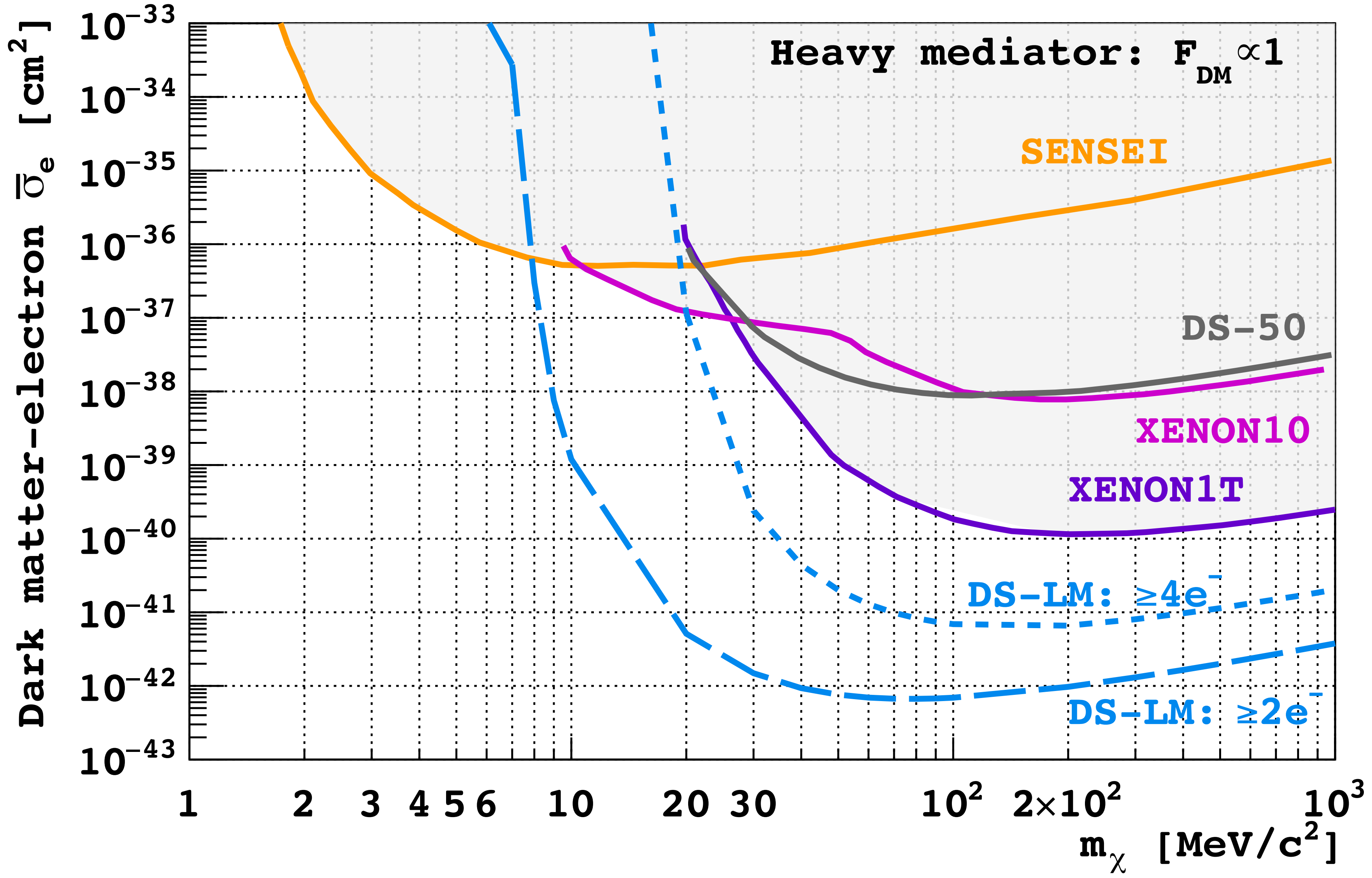
- The rate of SE is not yet understood, nor predictable with the current knowledge. Used to set an energy threshold.

Sensitivity projections





Preliminary



Thanks!

Contacts:
claudios@princeton.edu
Physics Department, 373 Jadwin Hall
(609) 933-8160

Backup slides

Single phase detectors

- High active mass
- Simple design
- 4π coverage, high light yield
- Bonus (for LAr): ER rejection via PSD on scintillation light
- No claim of observation

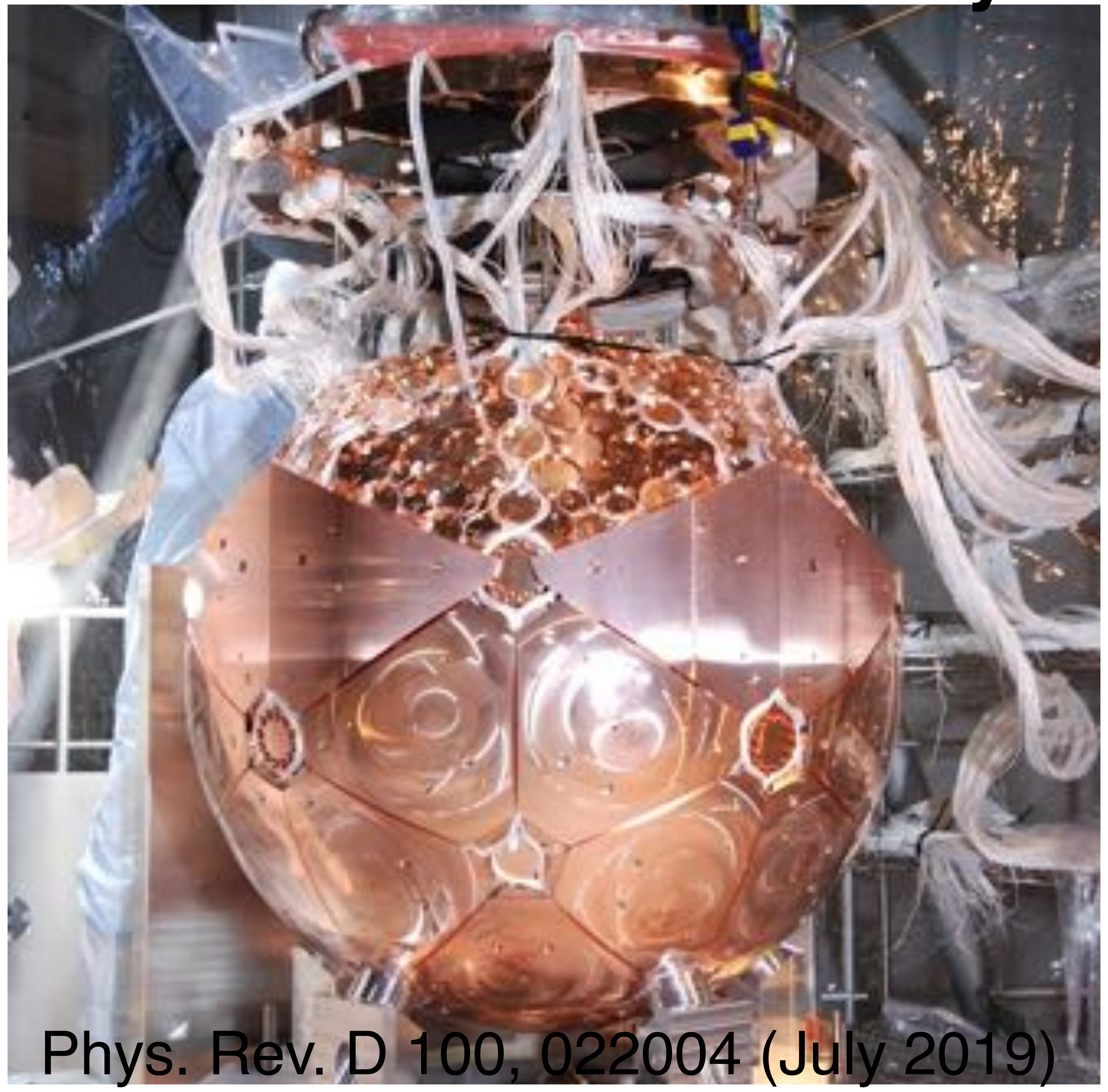
@SNOLAB

Phys. Rev. D 100, 022004 (July 2019)

DEAP-3600

- 3279 (824) kg of active (fid.) mass
- 5 cm acrylic vessel, 255 PMTs
- Cherenkov muon veto (300t H_2O)

@Kamioka Observatory

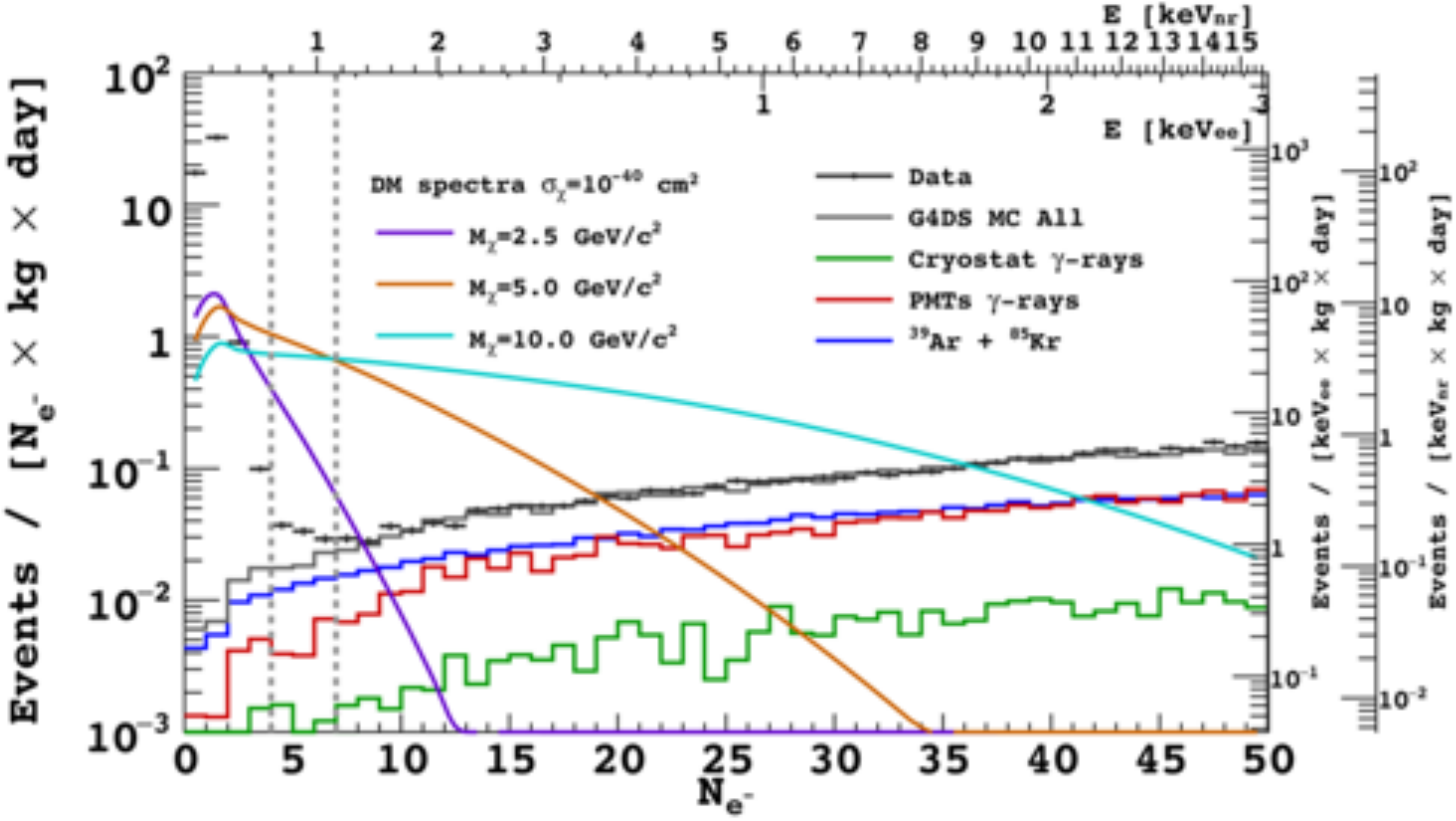


Phys. Rev. D 100, 022004 (July 2019)

XMASS-I

- 832 (97) kg of active (fid.) mass
- 642 2”-PMTs
- Cherenkov muon veto

Backgrounds in DS50



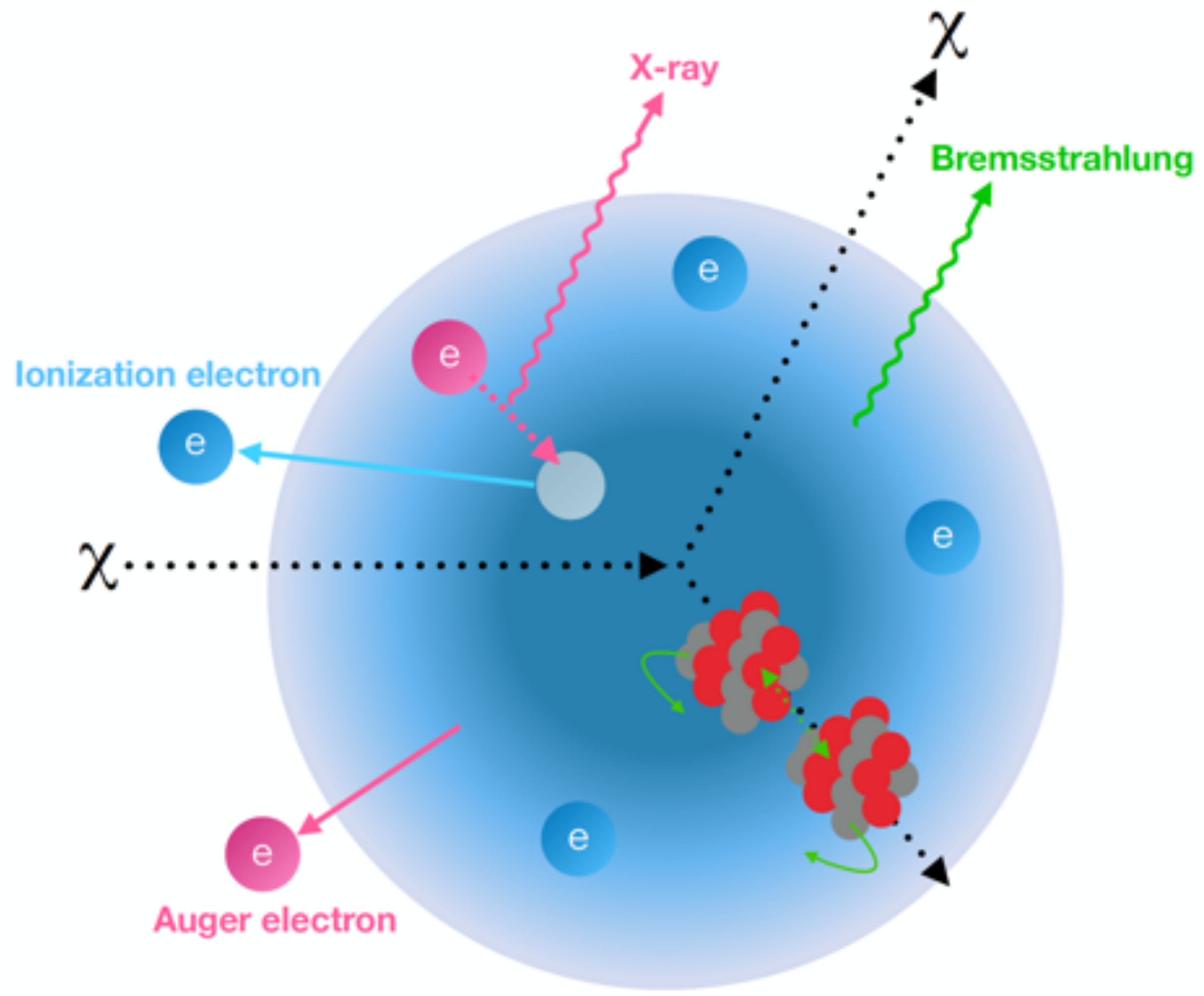
Expected BKGs

- ^{39}Ar + ^{85}Kr β spectra
- Compton continuum (PMTs + Cryostat)

Unexpected BKGs

- 1-2-3e$^-$ event rate. Energy threshold set by spurious electron background.
- Likely due to trace impurities in LAr capturing drifting electrons.

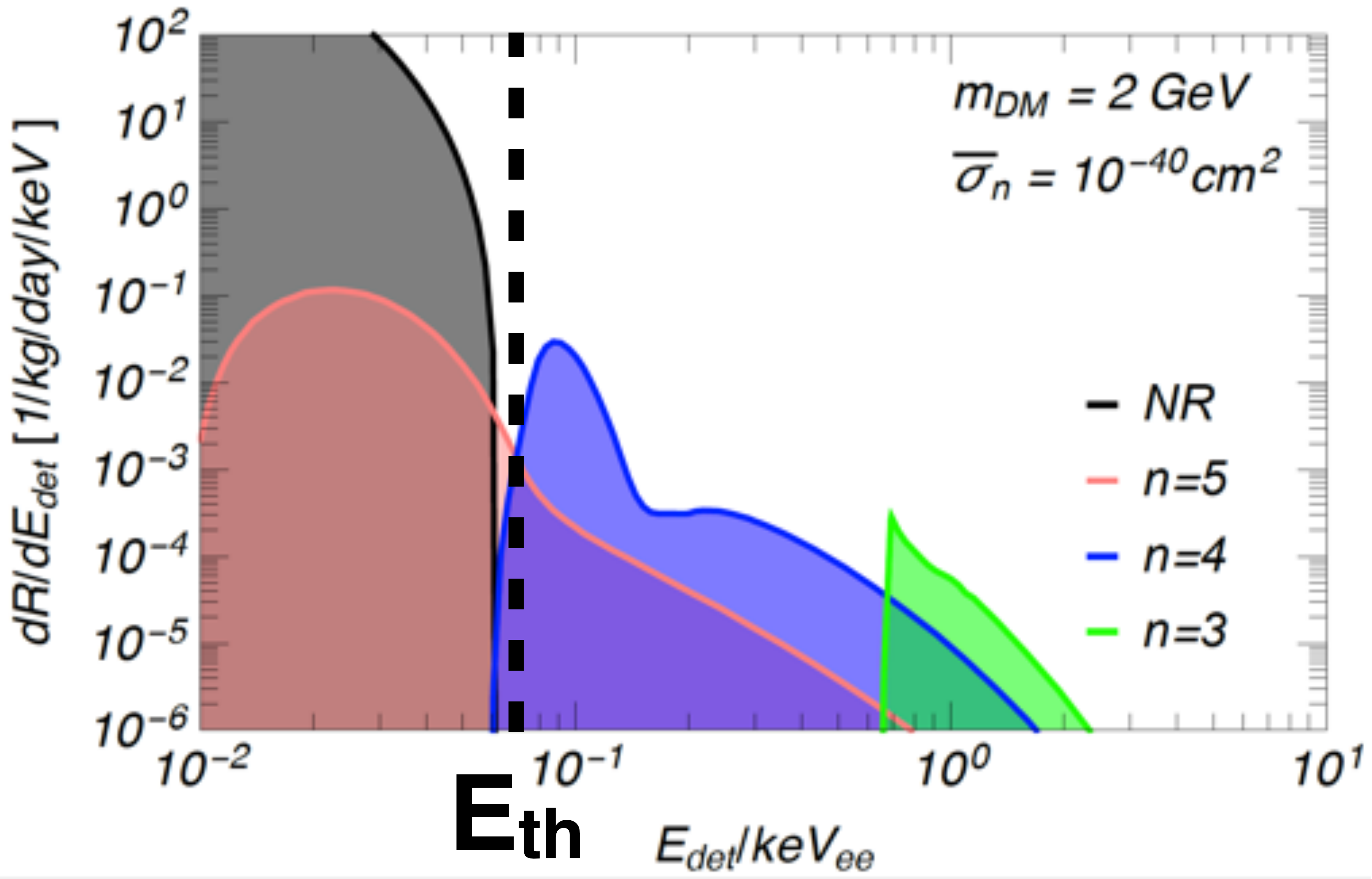
The Migdal Effect



- Different approach

- A recoiling nucleus (at low E) can produce excitation or ionisation of the electrons of its own atom

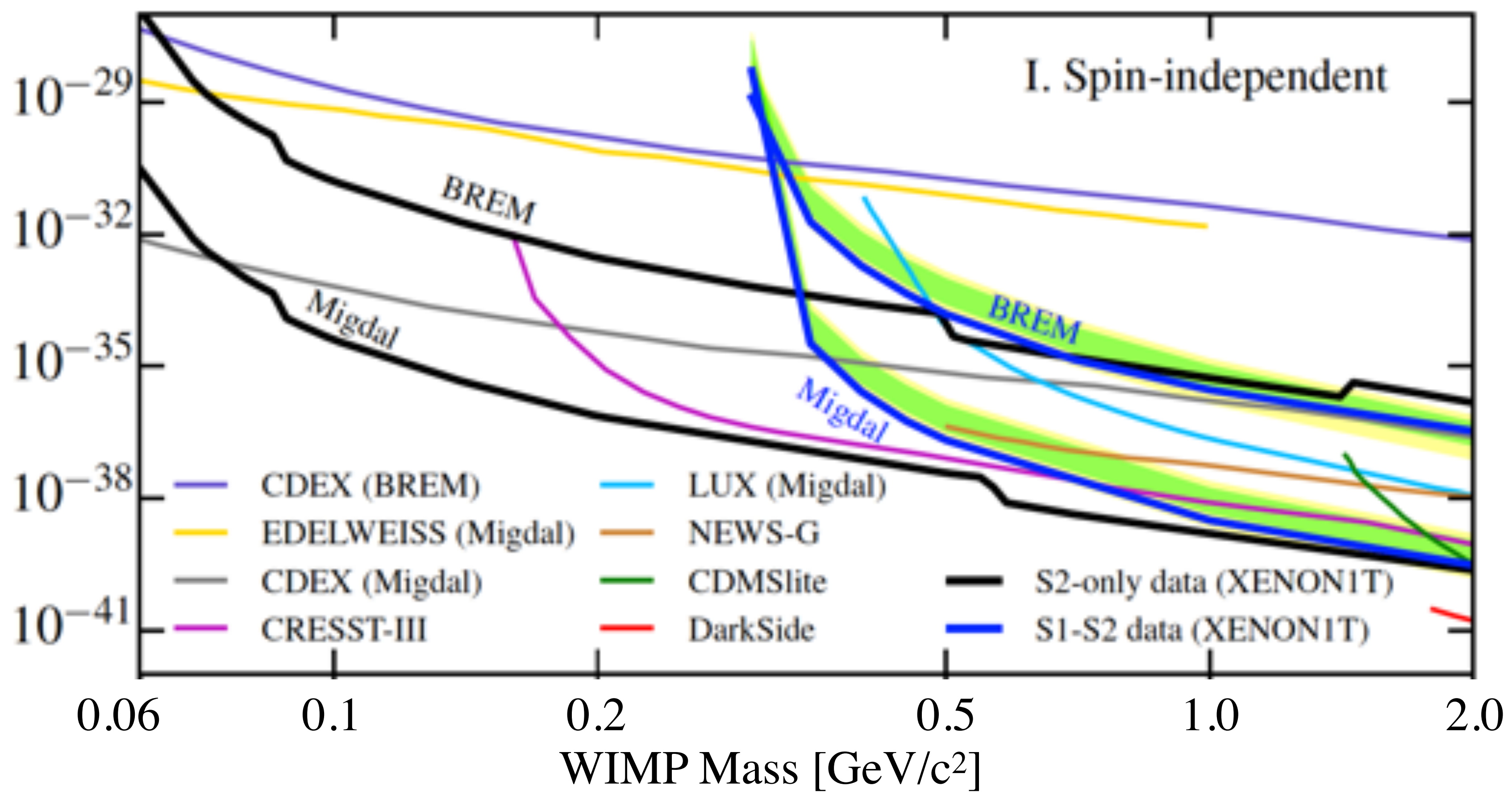
- New theoretical approach to an old prediction



- Small probability wrt normal NR

- ER events with higher observable energy

- Events that would be under threshold are detectable



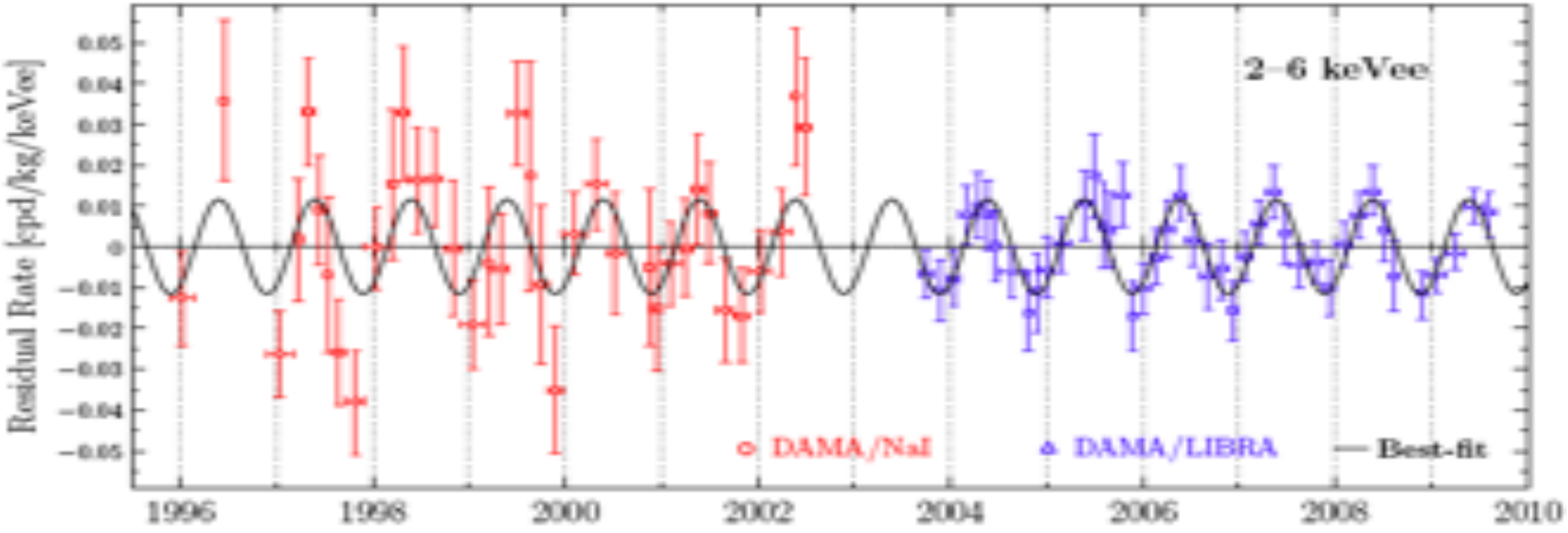
- New way of probing very low WIMP masses

- Sensitivities down to 60 MeV/c²

- Several collaborations published this analysis. Strongest limit up to date from Xenon-1T

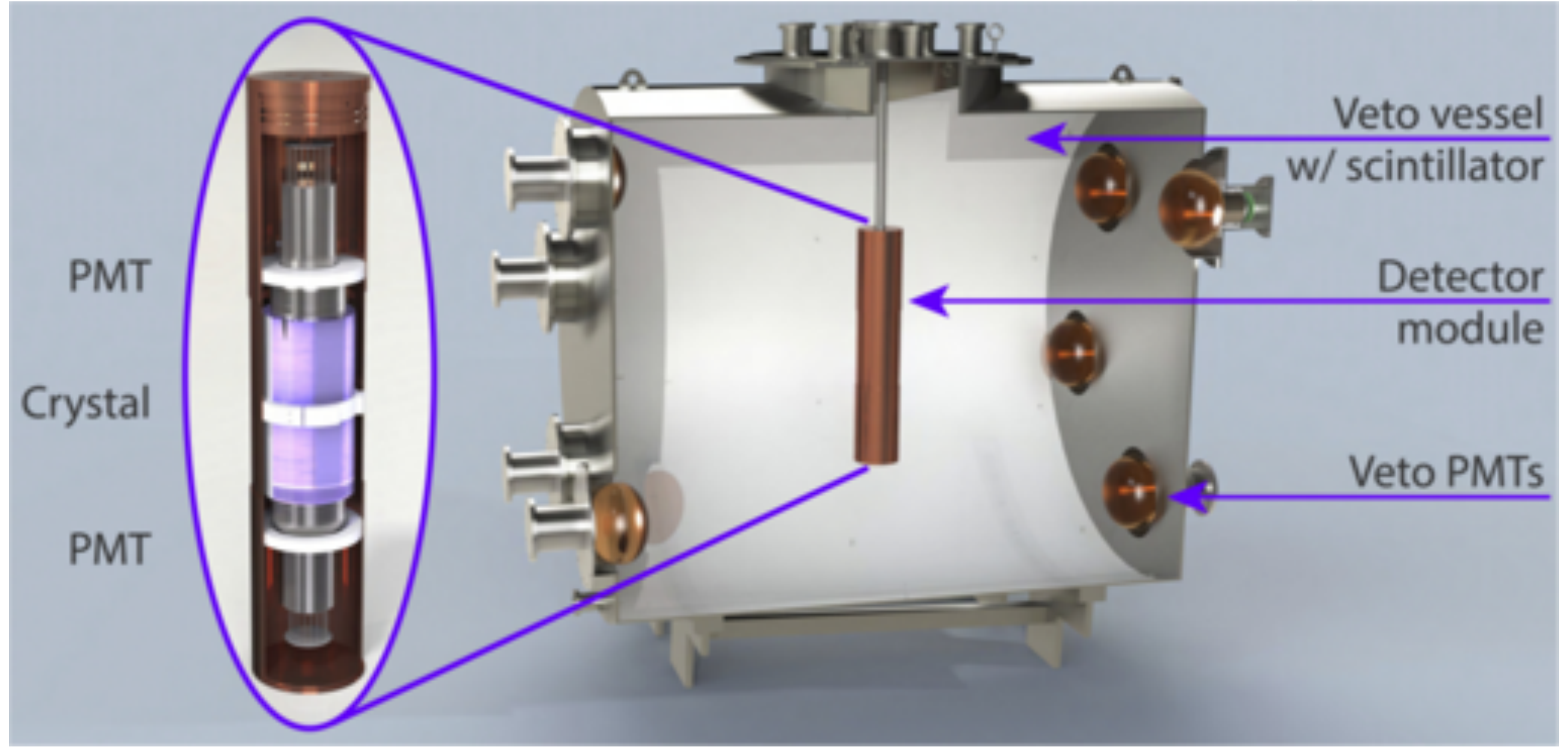
Modulation with SABRE

The long standing modulation: DAMA/LIBRA

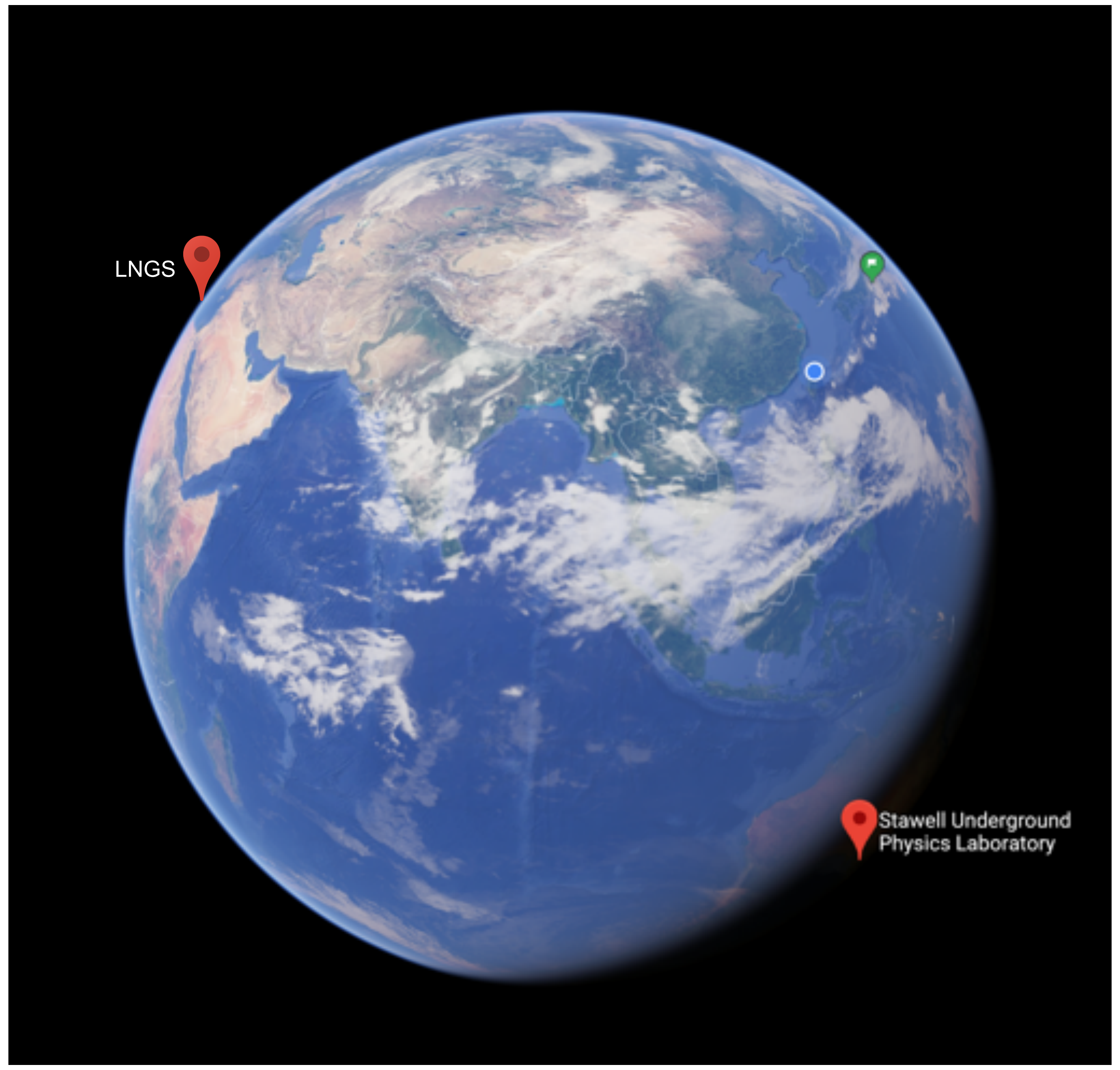


- Exposure: 1.13 ton × year (6y)
- Sensitive mass: about 250 kg of radio-pure NaI(Tl) crystals
- Statistical significance: 9.5σ in (1 - 6)keV and 12.9σ in (2 - 6)keV

SABRE Proof of Principle



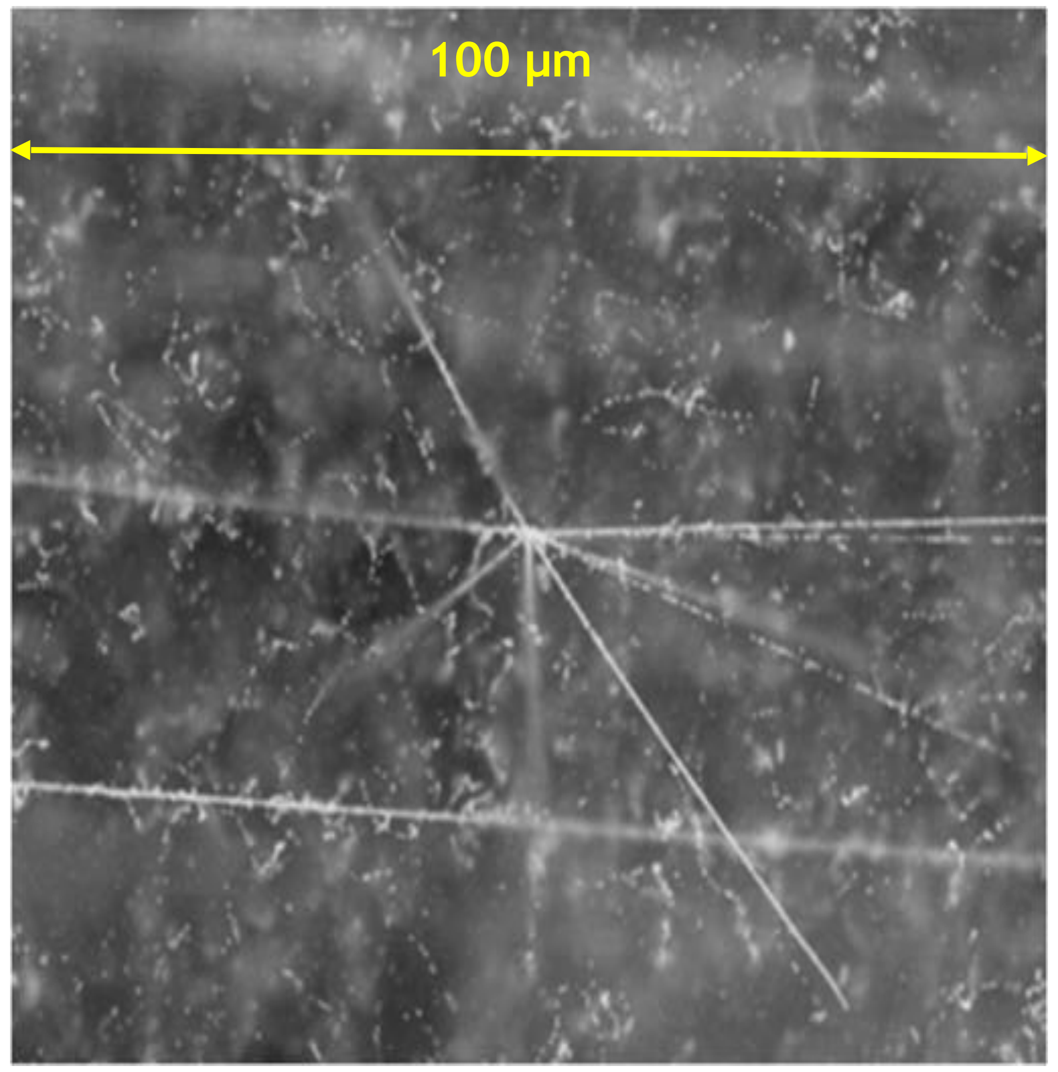
SABRE



- Active background rejection
- Low energy threshold
- Hemispheres: seasonal effects
- High purity crystals

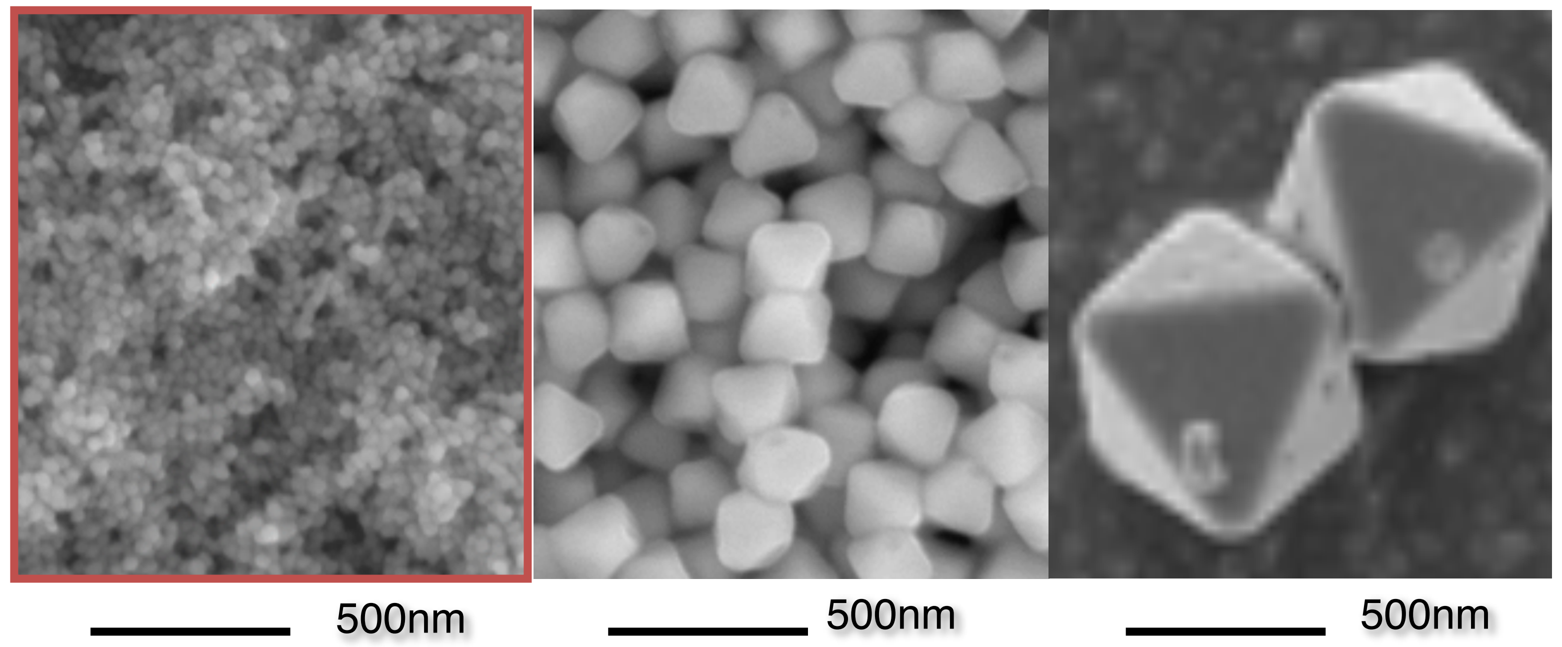
Directionality with NEWSdm

Nuclear emulsion



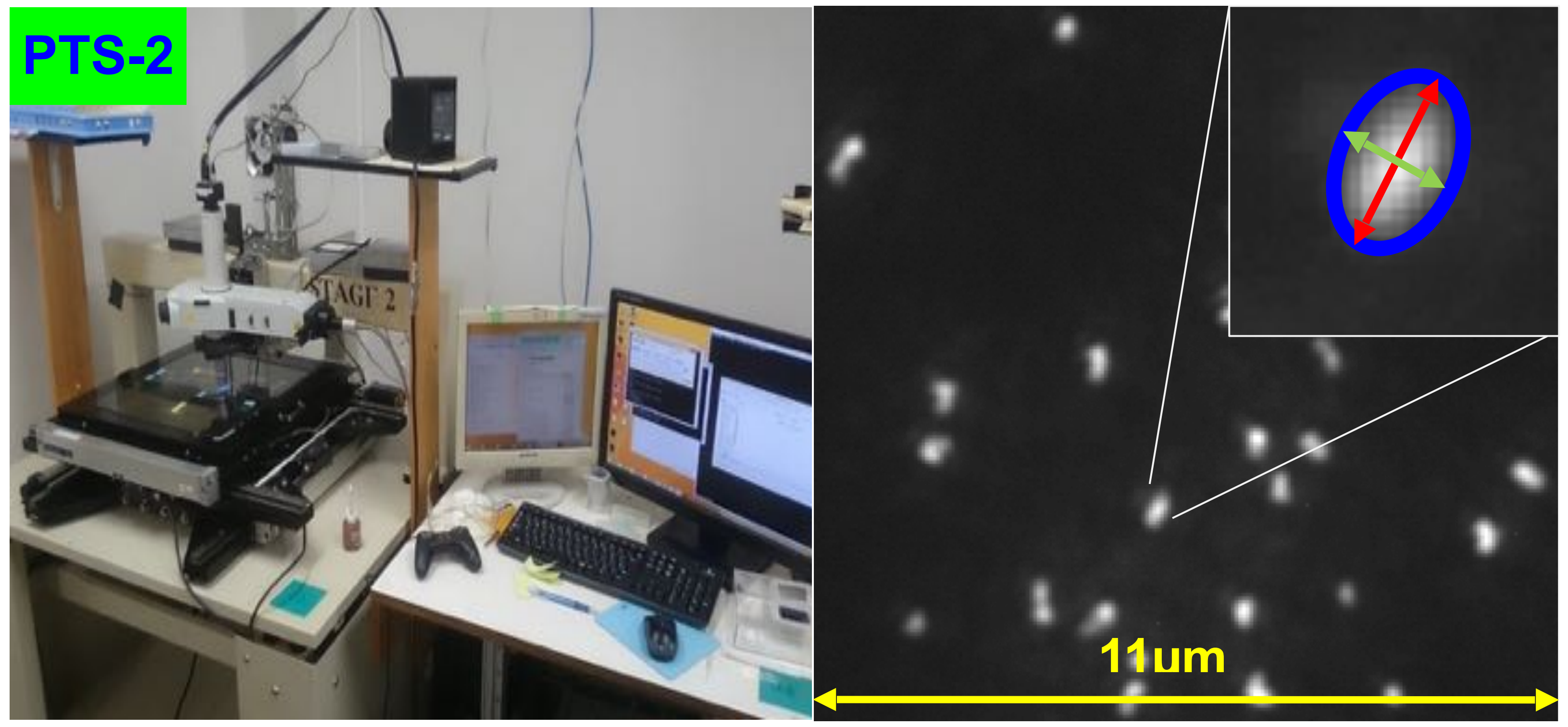
- Solid state detector ~3g/cm³
- Target: C, N, O, Ag, Br
- High spatial resolution
- 4π tracking
- Large scalability: OPERA (20t)

Crystal growth



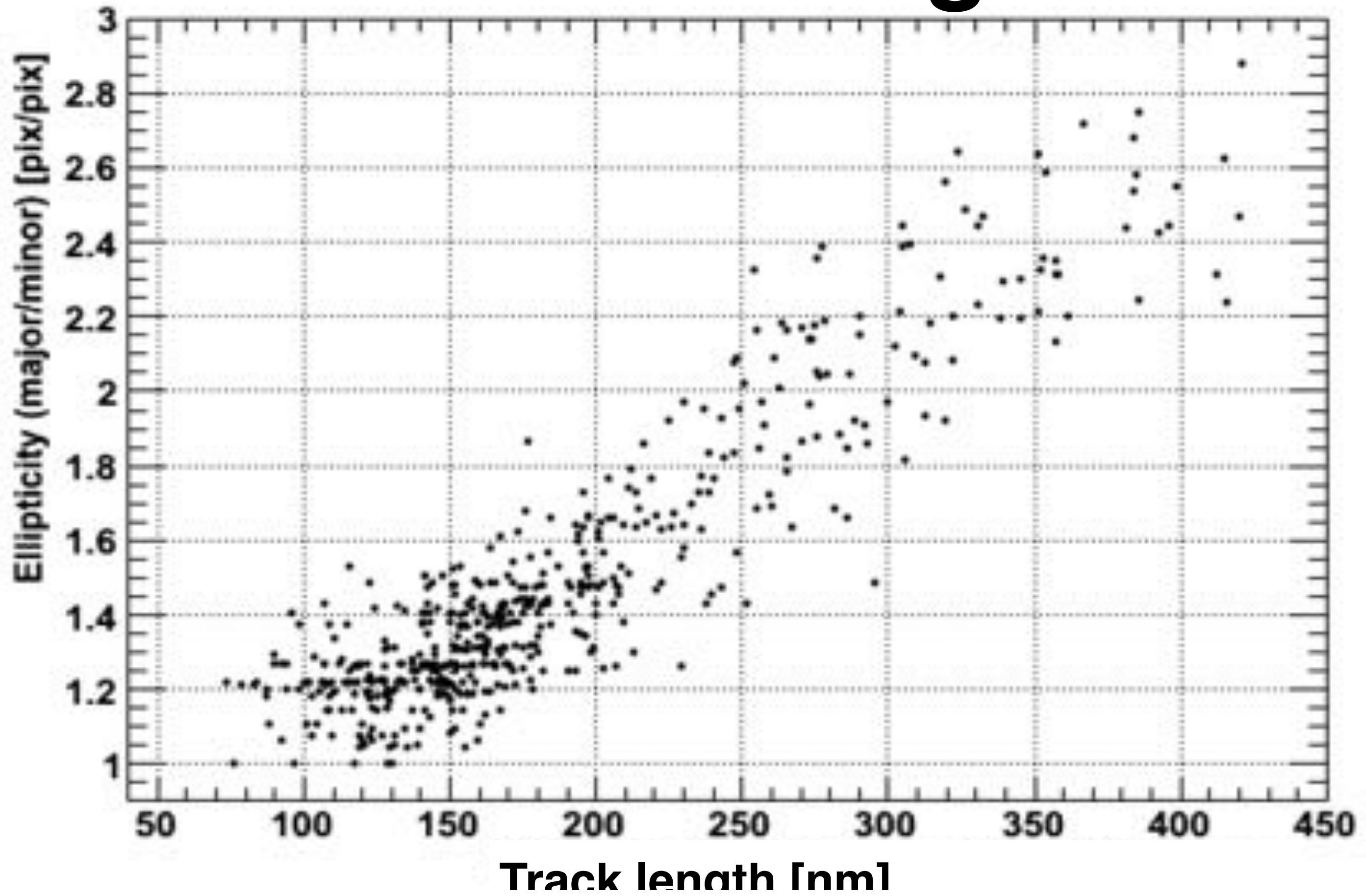
M_W~10GeV/c² NR track≪200nm

Tracks scanning with optical microscopes

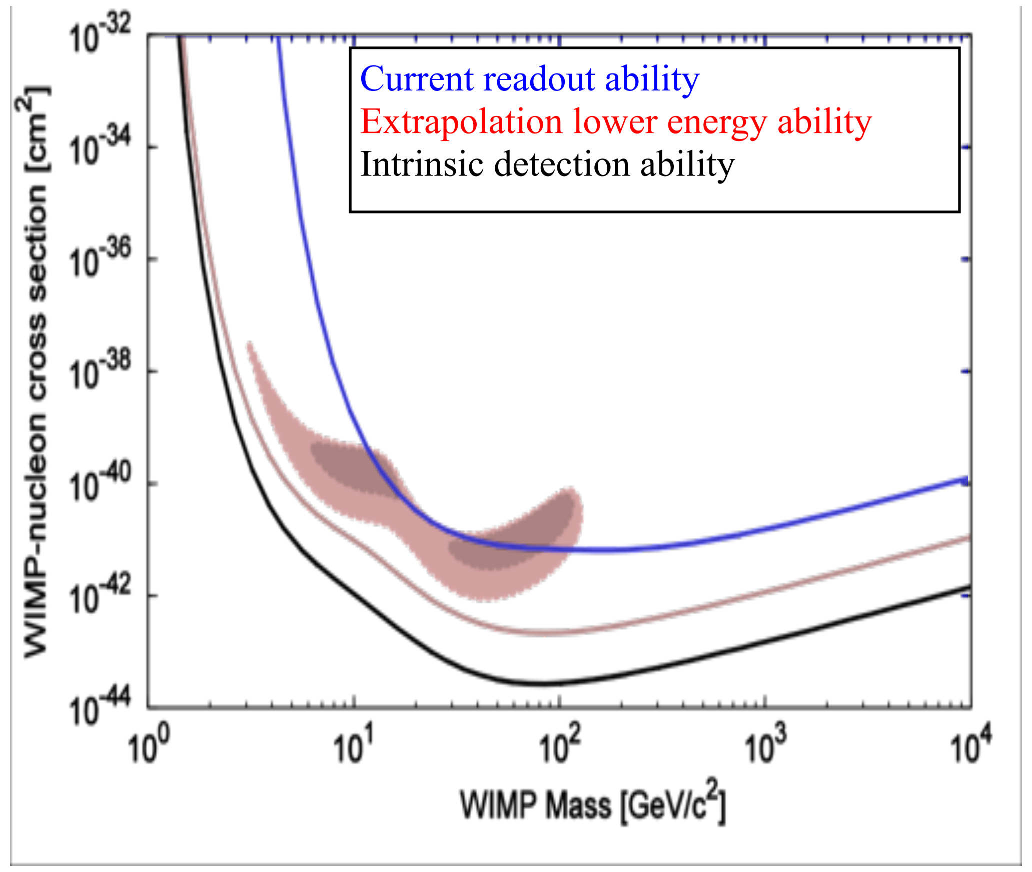


Current scan speed: 30g/y

Current microscope could select >100 nm length tracks



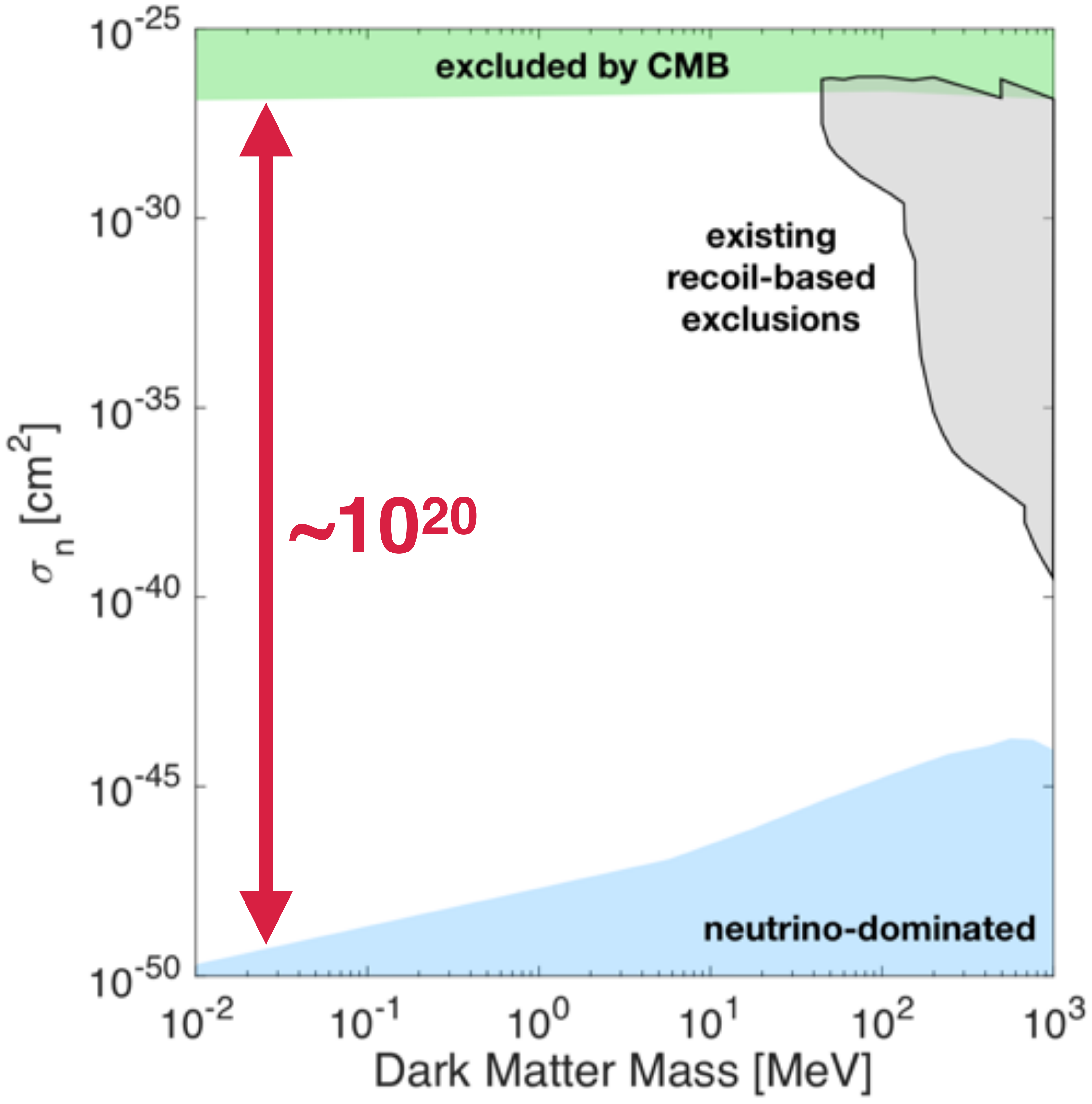
10 kg y sensitivity (No bkg)



What lies below

My impression: experimentalist community is willing to explore the low mass range

- ✓ Terra incognita: DM could lie at any cross-section between CMB limits and neutrino floor
- ✓ No need for giant detectors: Rate ~ number density ~ $1/M_{DM}$
- ✗ Need to lower the energy threshold
- ✗ Backgrounds at this energy scale are completely unknown



General strategy

- Identify a material with suitable excitation modes (maximize energy deposition)
- Select excitation producing maximal signal at given energy (and efficient transport mechanism)
- Design sensors with low E_{th} and low dark noise

Kinematics

- Transfer of kinetic energy to nuclei becomes inefficient at high mass mismatch
- Changing target (Xe to He) helps only of a factor 10 in mass
- Electrons as target
- Collective excitations with low effective mass