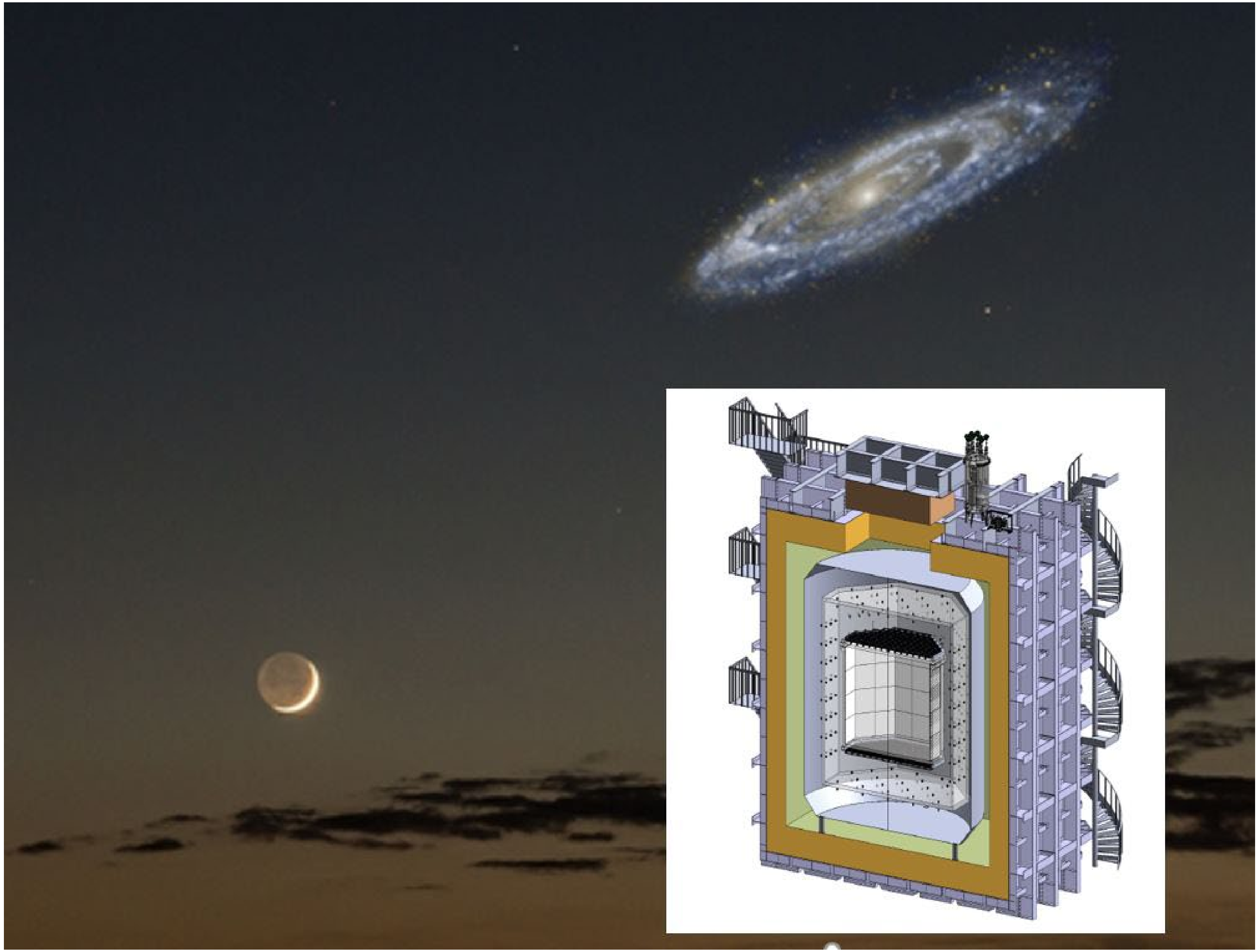
The DarkSide of the Universe

Finding the dark matter we observe through its gravitational pull.

Bruce Vogelaar
Camillo Mariani
Tommy O'Donnell
Tristan Wright

Andromeda and moon as seen from Earth.



Observational evidence of Dark Matter abounds…

Rotation curves Rubin & Ford; Freeman;…

arXiv:0812.4005

Stars and neutral hydrogen gas in spiral galaxies, move in circular orbits due to the force of gravity.

Speed measured from Doppler shift of hydrogen 21cm line.

NASA

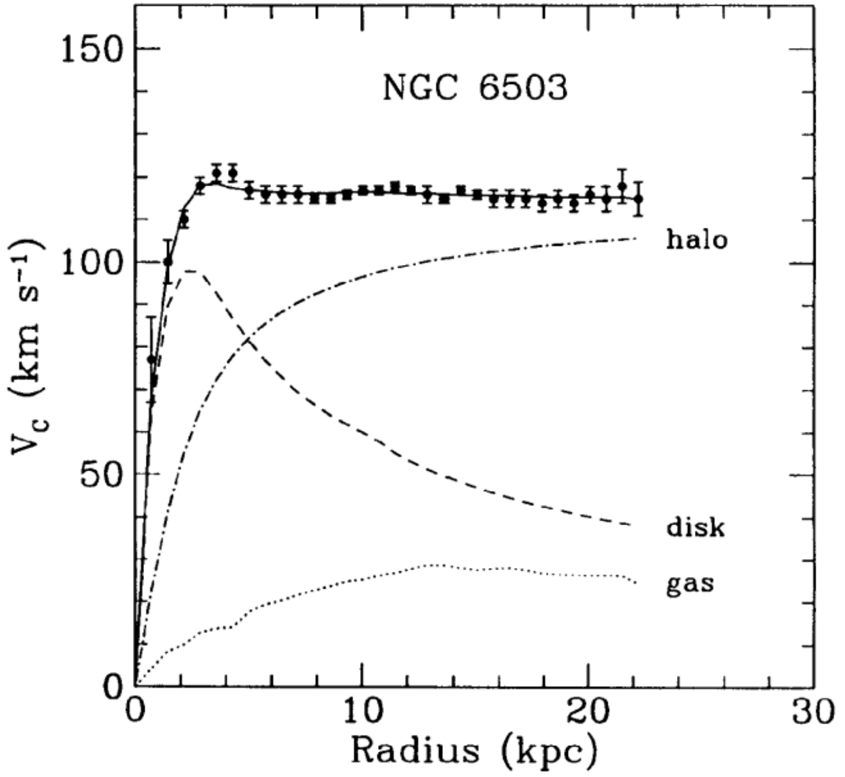


Fig. 1. Galactic rotation curve for NGC 6503 showing disk and gas contribution plus the dark matter halo contribution needed to match the data.

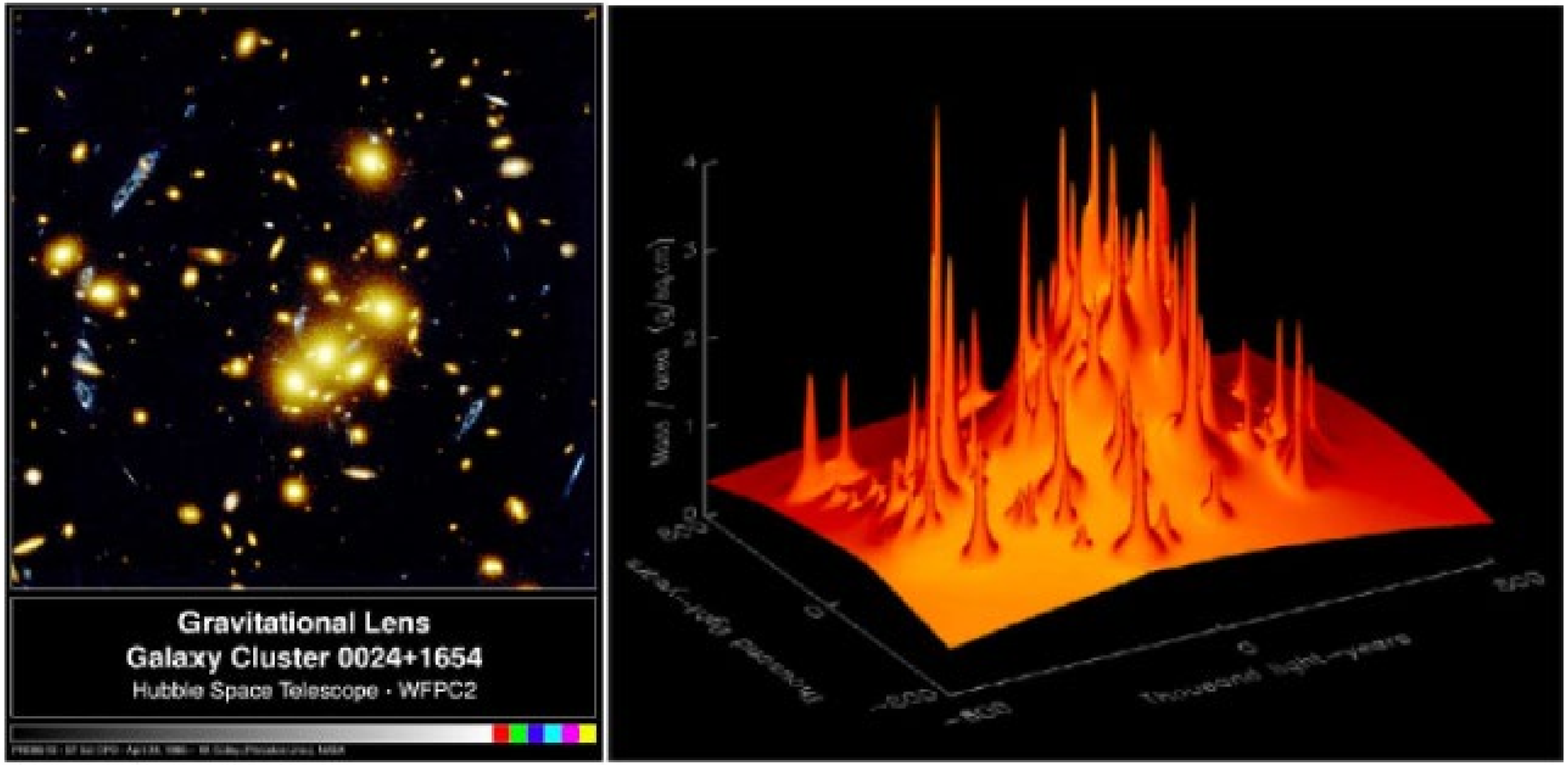


Fig. 2. Left: The foreground cluster of galaxies gravitationally lenses the blue background galaxy into multiple images. Right: A computer reconstruction of the lens shows a smooth background component not accounted for by the mass of the luminous objects.

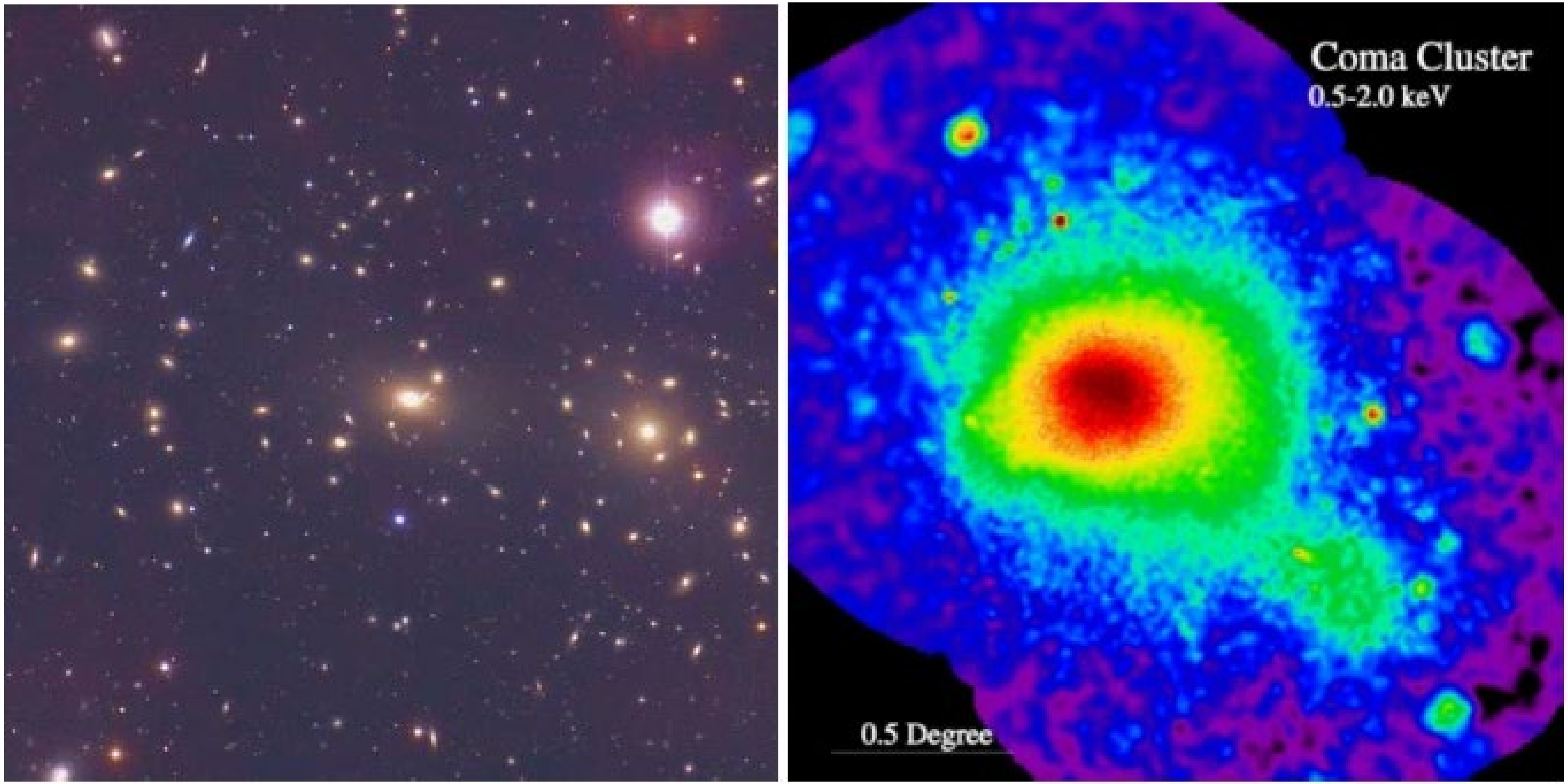
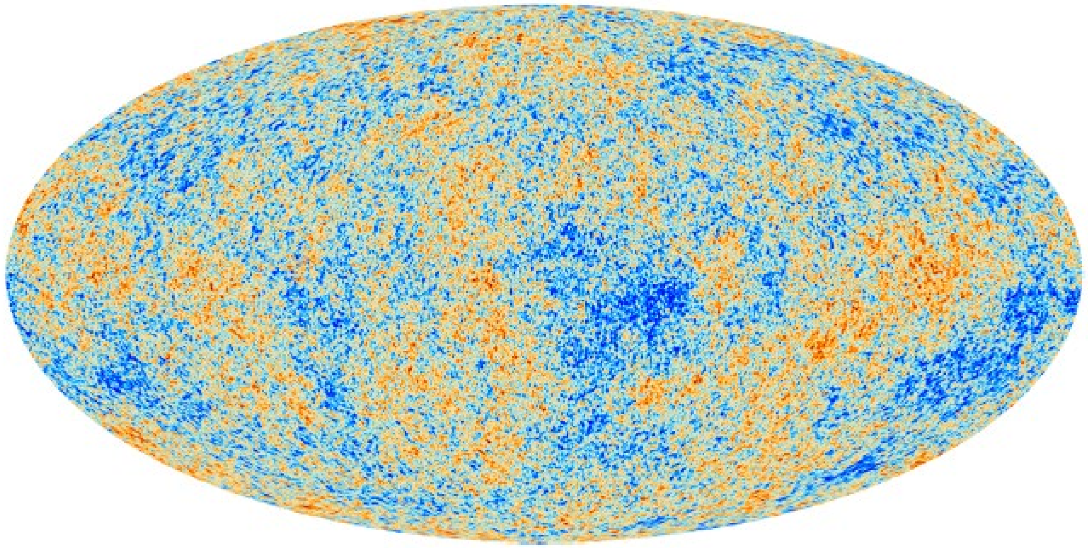
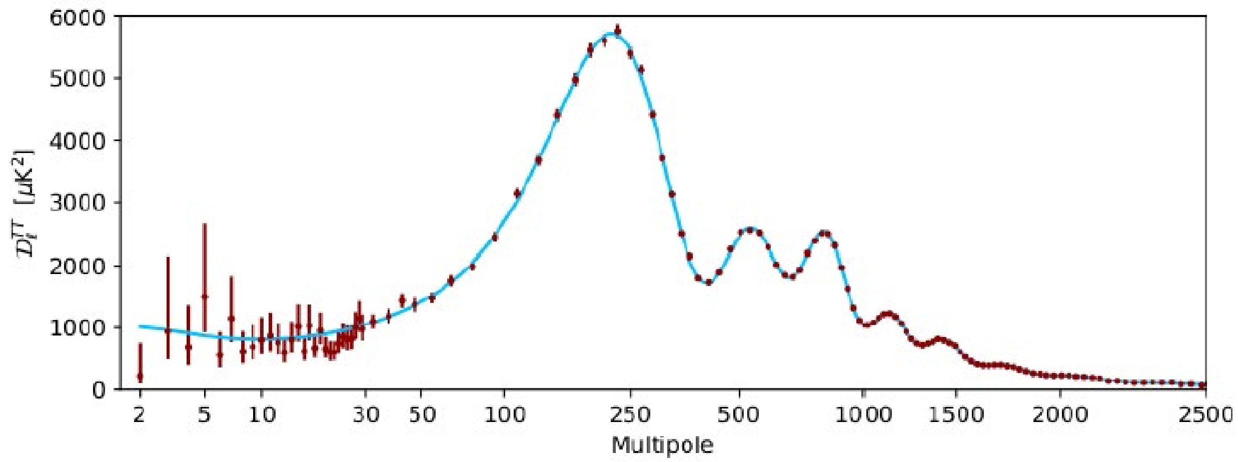


Fig. 3. COMA Cluster: without dark matter, the hot gas would evaporate. Left panel: optical image. Right panel: X-ray image from ROSAT satellite.

Characteristic angular scale (in particular position of first peak):

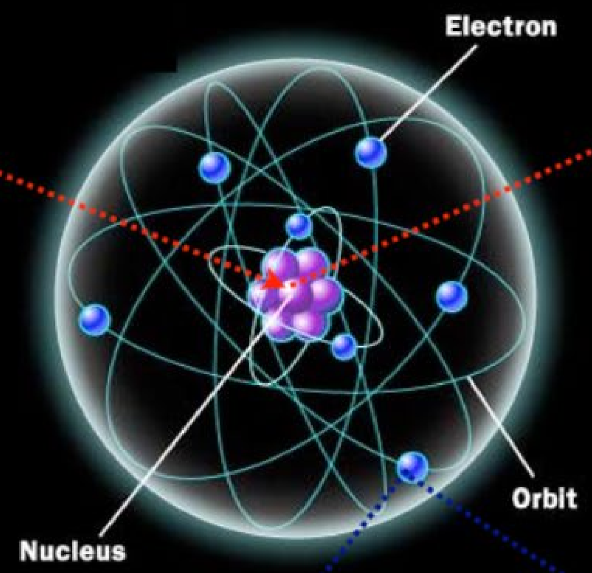
…if the light travels in a straight line (as would be the case for a flat geometry), then the angular scale of the first Doppler peak was expected to be found at 1 degree; indeed this is found to be correct. Thus the geometry is flat, corresponding to an energy density of the universe of $\sim 10^{-29}$gm/cm^3. The height of the second peak implies that 4% of the total is ordinary atoms, while matching all the peaks implies that 23% of the total is DM.





Planck 2018

Dark Matter Direct Detection

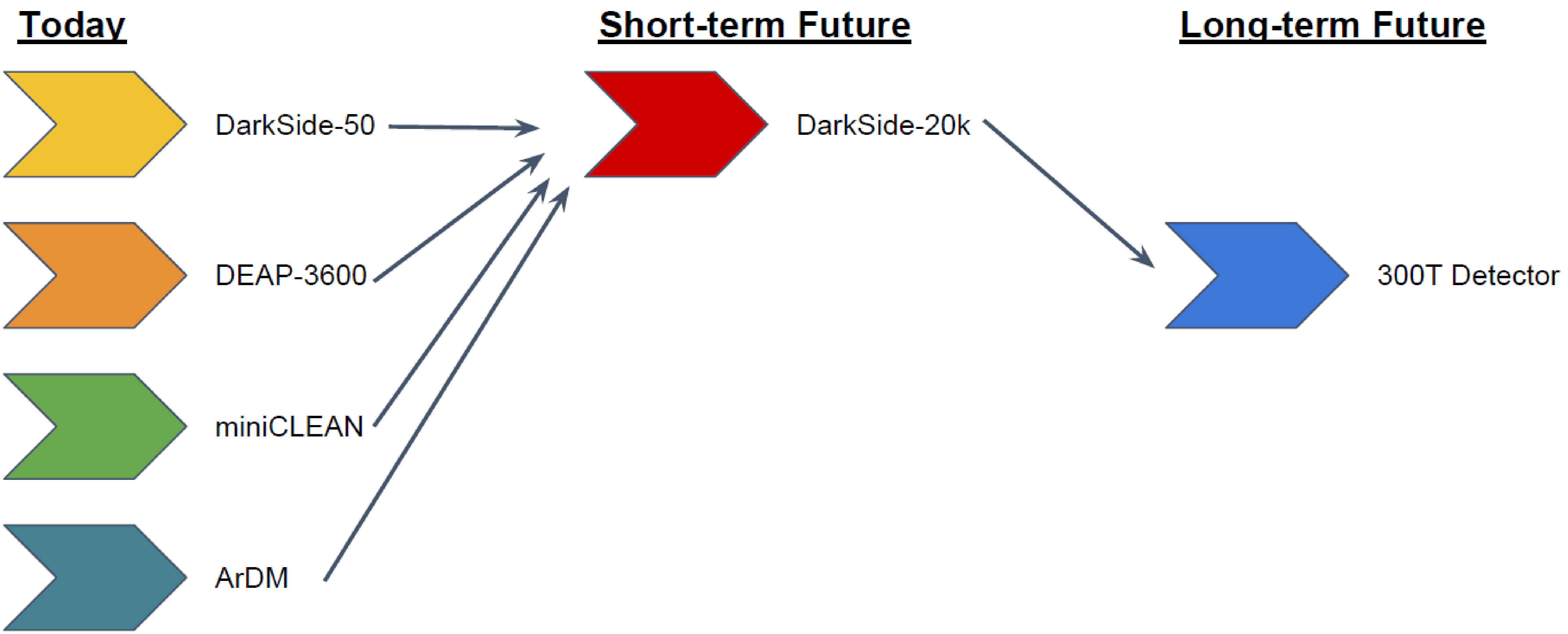


Nuclear recoils:
- ^{238}U and ^{232}Th in detector materials
- Cosmogenics
- (α,n) reactions
- Coherent neutrino scattering (irreducible)

Electron recoils:
- ^{238}U and ^{232}Th decay chains
- Beta decays in TPC and cryostat

experimental requirements: particle ID for recoil N, e-, alpha, n (multiple) final states

Global Argon Dark Matter Program



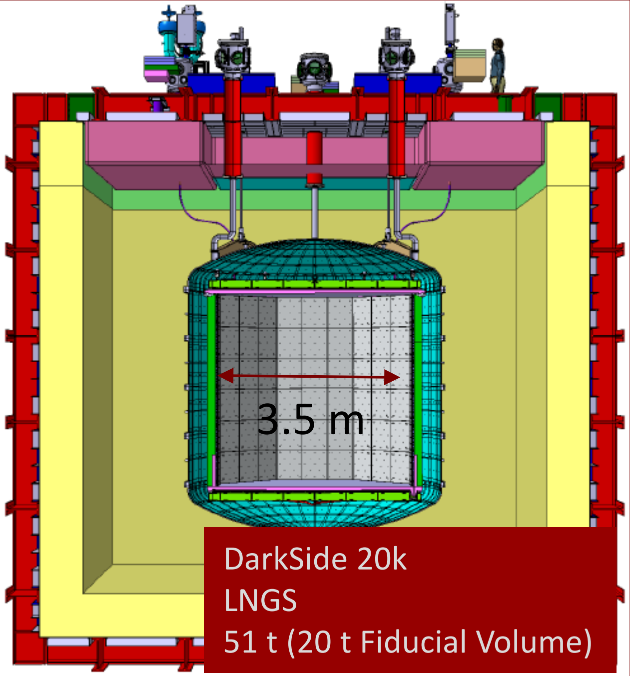
Direct search of Dark Matter with liquid Argon: GADMC Global Argon Dark Mater Collaboration

>500 people, about 100 Institutions
Join the expertise about low background liquid Argon based detectors
Multi step program towards WIMP dark matter detection

- Gained experience

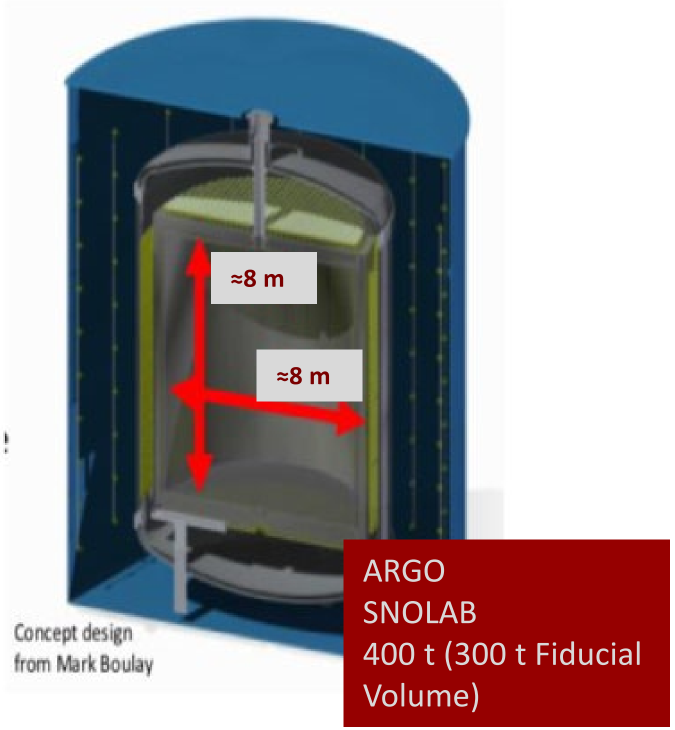
- **Present goal: DarkSide 20k @LNGS**

(+ ReD, Prototypes, R&D towards Low Mass WIMP sensitivity)



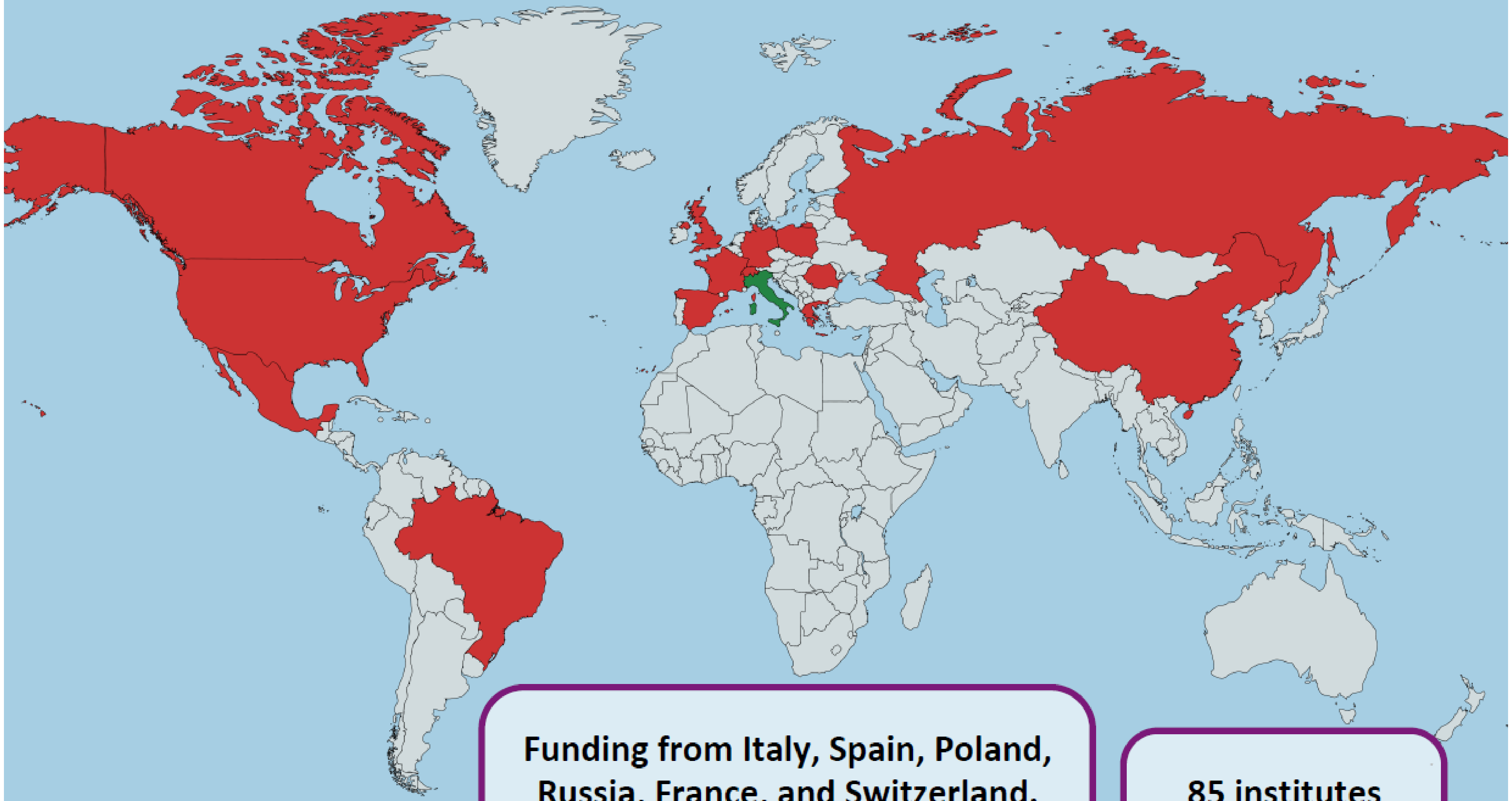
Construction starts in 2022
Data taking from 2025
Nominal run time: 10 years

- Future goal: ARGO@SNOLAB



Conceptual studies in progress
Nominal run time: 10 years (3 kt x year)

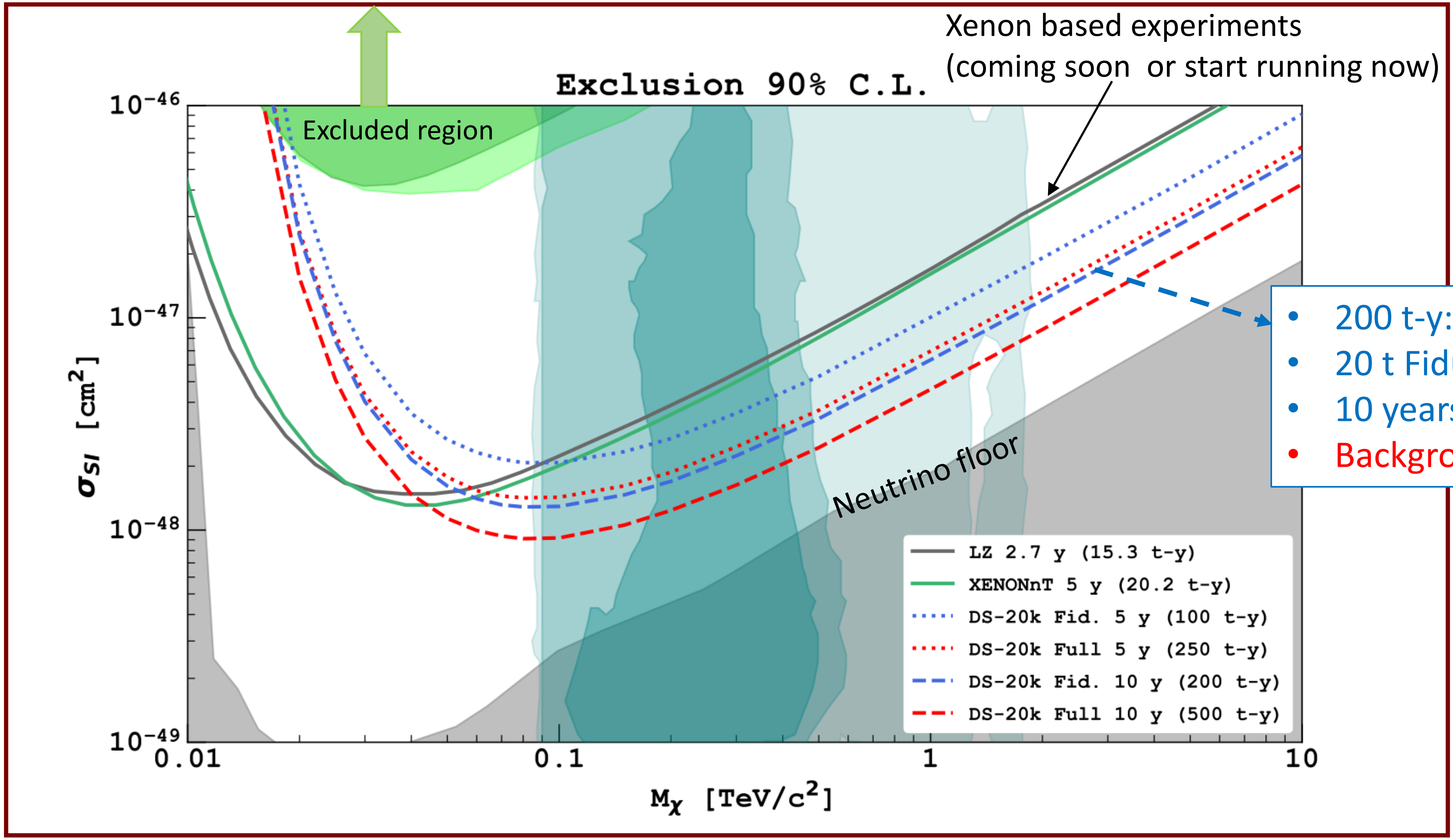
The DarkSide Collaboration

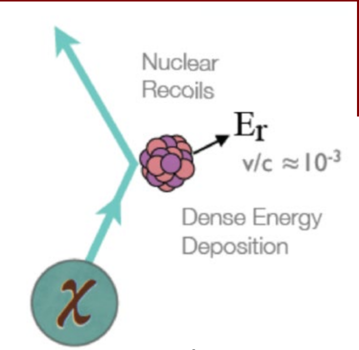


Funding from Italy, Spain, Poland, Russia, France, and Switzerland. Capital contributions from Canada, US, China, Brazil and Argentina.

85 institutes
15 countries
O(350) people

Expected DS20k sensitivity





WIMP signal:
Nuclear Recoil (NR)
(≈1 to ≈100 keV)

- 200 t-y: nominal exposure
- 20 t Fiducial Mass
- 10 years
- Background: 0.1 events!!!

Turquoise filled contours are from pMSSM11 model, E. Bagnaschi et al., Eur. Phys. J. C 78, 87 (2018).

Dual Phase TPC (Time Projection Chamber) and unique Ar pulse shape discrimination

1

Scintillation (S1)

Formation of excited molecular states Ar^{2*} and decay

Singlet τ= 6.7 ns

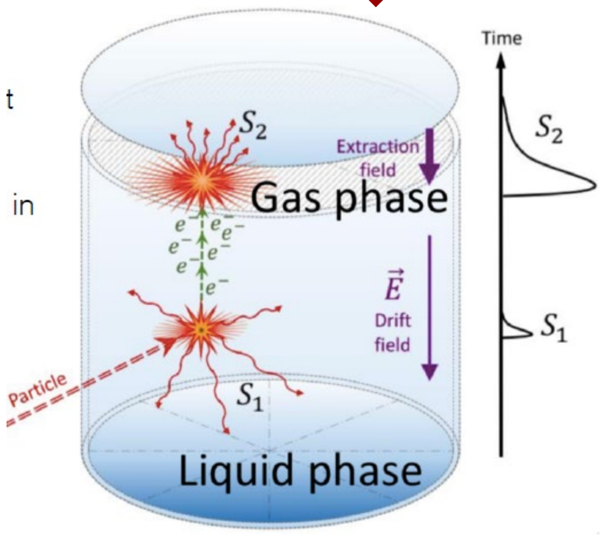
Triplet τ =1600 ns

Ionization (S2)

Drift of ionization e- (E field in the liquid)

Extraction in gas

Scintillation signal S2



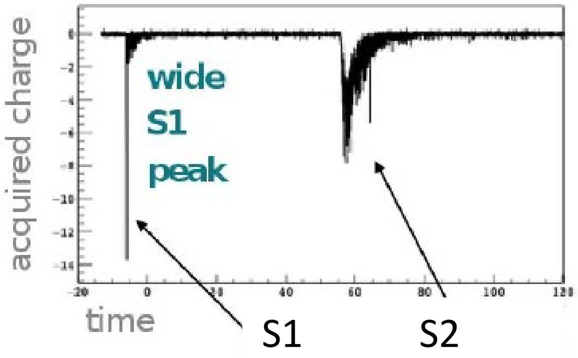
Dual Phase TPC: 3D space reconstruction

2

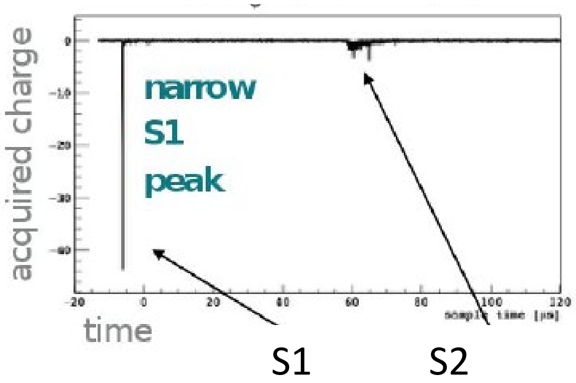
Nuclear recoils (NR) vs e-, γ (ER) signal discrimination

Fraction of prompt (F_{prompt}, f_{90}) and delayed light + S1/S2 ratio

Electron recoils:
Small prompt S1 light
Large late S2 light

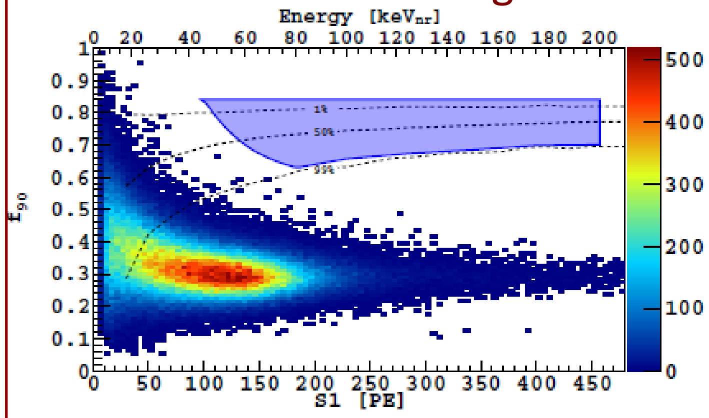


Nuclear recoils
Large prompt S1 light
Small late S2 light

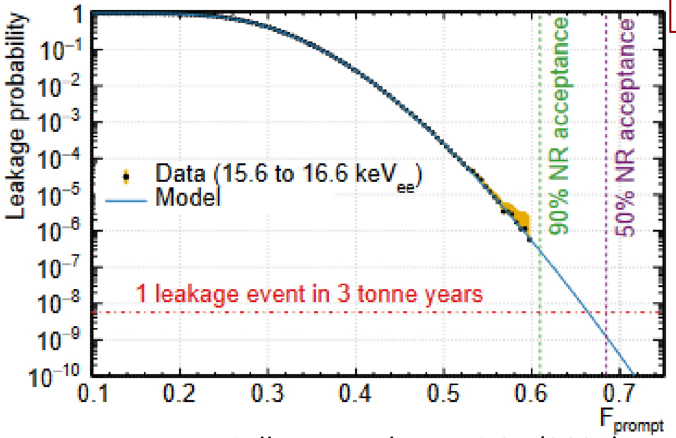


3

Signal discrimination results



DS50 Coll., Phys. Rev. D 98 102006 (2018)



DEAP Coll., Euro. Phys. J. C 81 (2021)

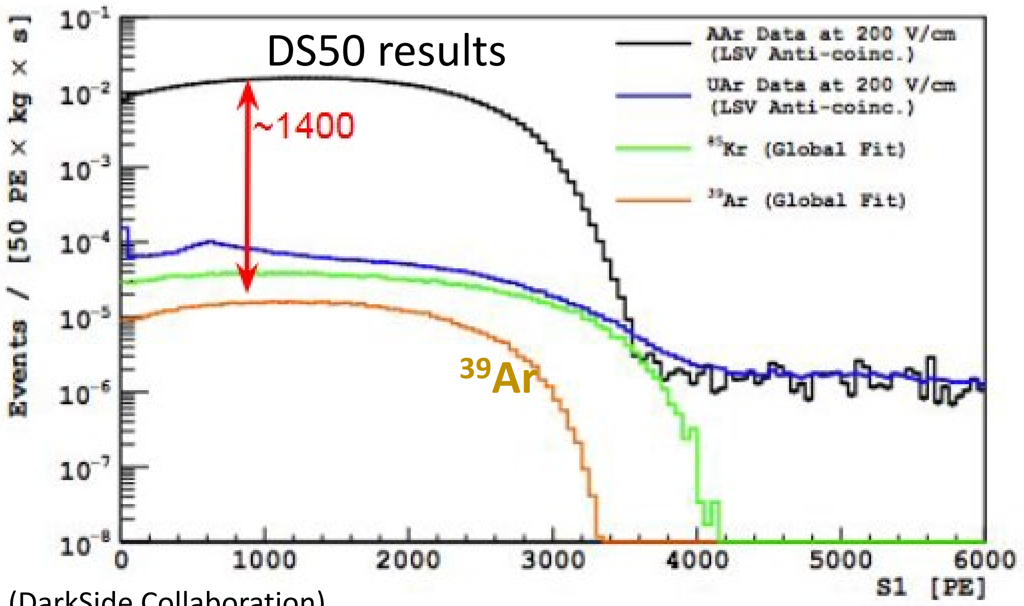
Radiopure Ar from underground sources

- ^{39}Ar β decay, $t_{1/2}$= 269 y
- End point: 570 keV
- Produced in the atmosphere $^{40}Ar(n,2n)$
- ≈1 Bq/kg in Argon from atmospheric origin

DS50: extraction of Ar of underground origin (UAr)

^{39}Ar depletion factor: 1400+- 200

Extraction of 157 Kg of UAr (50 Kg fiducial mass)



P. Agnes et al. (DarkSide Collaboration)
Phys. Rev. D 93, 081101(R) (2016)

DS20k filled with UAr
+ excellent Ar Pulse Shape Discrimination

< 0.1 events /(200 t year)
of residual
background due to Electron recoil (ER)

Early work on Ar back in KURF days...

Current KURF *Users*

A. mini-LENS (Low Energy Neutrino Spectroscopy)
   Virginia Tech, Louisiana State University, BNL (Vogelaar)
B. Neutron Spectrometer
   University of Maryland, NIST (Nico)
C. ββ Decay to Excited States
   Duke University (Turnow)
D. HPGe Low-Bkgd Screening
   North Carolina State University (Henning), University of North Carolina, Virginia Tech
E. MALBEK (Majorana 0νββ)
   University of North Carolina (Wilkerson)
F. ^{39}Ar Depleted Argon
   Princeton University (Calaprice)
G. Watchman
   LLNL (on 2nd level - Bernstein)
H. Proposals
   Berkeley (Bolometry - Kolomensky)
   FNAL (CENNS - Yoo)

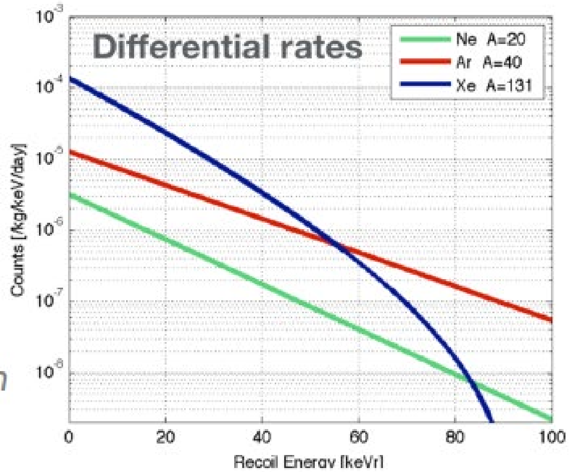
Sub-set of about 60 trained users for biannual refresher

Direct DM detection: why Argon?

What does Argon bring to direct DM detection?

- High ionisation yield (S2/S1) – ×500 LXe
- Powerful PSD for background rejection > 10^8 in LAr
- Efficient scintillator (128 nm): self-transparent
- Potential to achieve zero-background in full exposure
- Easily purified: long electron lifetime
- Availability & low cost: future scalability

- Nuclear form factor: better performance in Ar at high mass for non-standard DM
- DM signals on multiple media beneficial to resolve DM properties
- Different recoil spectra to Xe for same DM scatter



Natural radioactive isotopes not present in Xe need to be controlled: underground Argon!

URANIA: 90 T / yr long term with 99.9% purity

ARIA: distillation column processing 1 T / day with 10^3 impurity reduction

The path towards radiopure Ar: URANIA +ARIA+DArT

Scale up the UAr extraction from ≈100 Kg to ≈100 t

See the poster of L. Luzzi

URANIA: UAr extraction **1**

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

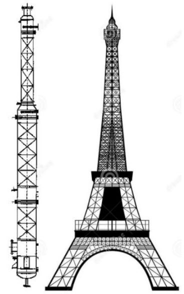
ARIA: UAr distillation **2**

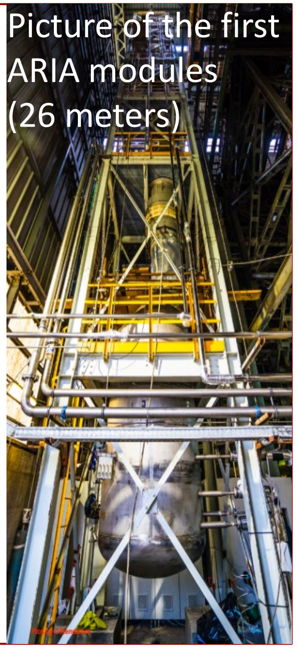
- Cryogenic distillation column in Sardinia (Italy)
  bottom reboiler
  + 28 central modules (12 m each) 350 m in total
  + top condenser
- Chemical purification rate: 1 t/day
- First module operated according to specs with Nitrogen in 2019

Eur. Phys. J. C (2021) 81:359

- Run completed with Ar at the end of 2020:

results to be published soon

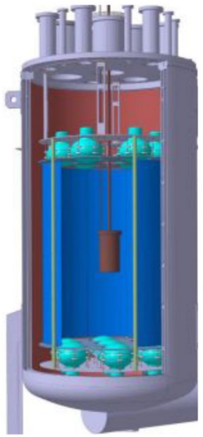




DArT : Measurement of the activity of the ^{39}Ar **3**

- LSC, Canfranc Spain
- Single-phase inner detector for 1.42 kg of liquid UAr
- Inside 1 tonne ArDM detector acting as an active veto for background radiation
- ^{39}Ar depletion factor sensitivity: U.L 90% CL. 6×10^4

2020 JINST 15 P02024.

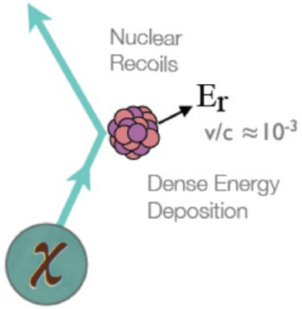


Signal and Background

Signal

- Nuclear recoil (NR): 1 to 100 keV
- Single scattering

Shape of the recoil spectrum
Annual modulation
Directionality (see previous talk of L. Pandola)



Background source	Mitigation strategy
^{39}Ar β decay	Use Ar from Underground source (UAr) + Pulse Shape Discimination (PSD)
γ from rocks and γ, e- from materials	Pulse Shape Discimination (PSD) Selection of materials & procedures
Neutrons **Radiogenic n (α,n) with a from material contaminants**	Material screening. Definition of Fiducial Volume in the TPC + active VETO to reject n signal.
Surface contamination due to Rn progeny	Surface cleaning Reduce the number of surfaces Installation in Rn abated air
Neutrino coherent scattering	irriducible

The design of the DS20k detector

- **Two-phase TPC LAr (WIMP target & detector)**
  filled with 50 t (20 t FV) low-radioactivity Ar from underground source (UAr)
- 21 m^2 cryogenic SiPMs (top and botton readout)

- TPC surrounded by **a single phase (S1 only) detector (Veto) in UAr**
  to identify and veto neutron signals
- 5 m^2 cryogenic SiPMs (Veto readout)

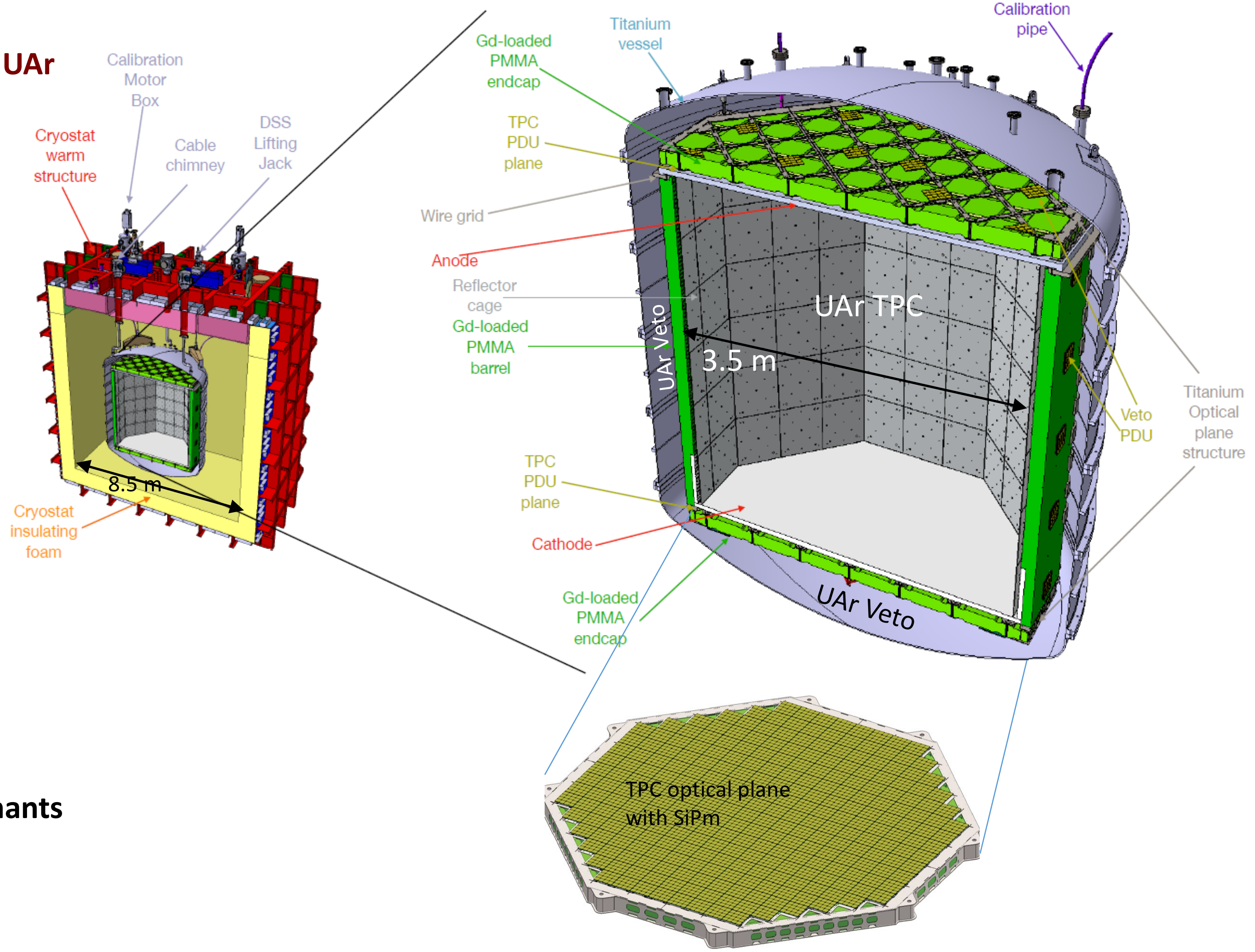
- Integration of TPC and VETO in a single object

- 99 t UAr in total contained in a hermetic Ti vessel

- TPC anode&cathode: transparent pure acrylic
- TPC lateral walls + additional top&bottom planes
  in Gd loaded acrylic (PMMA)
  - to thermalize n (acrylic is H rich)
  - high energy γ emitted by Gd after neutron capture
  - minimize the amount of material

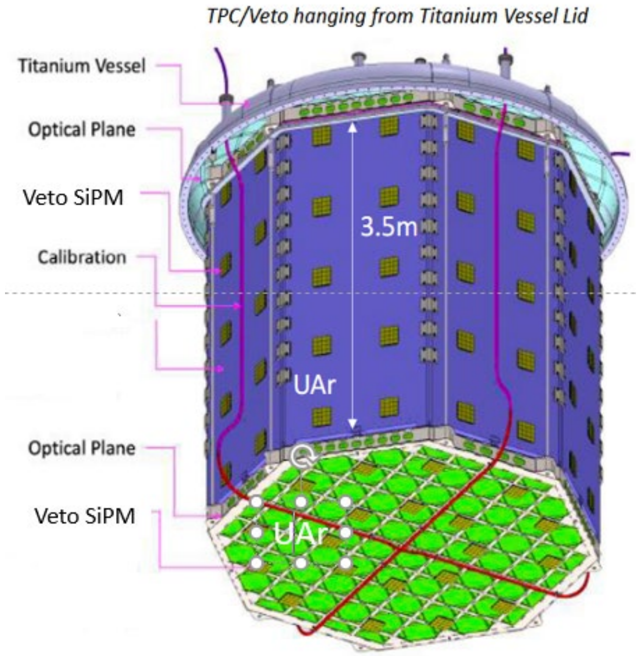
- ≈650 t AAr in a membrane cryostat, proto-DUNE like
- 2 independent cryogenics purification loops

- Selection and screening of all the materials
- Dominant n background: **(α,n) with α from material contaminants**

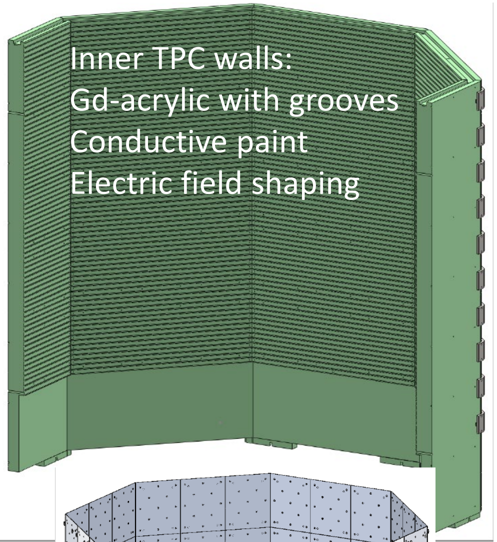


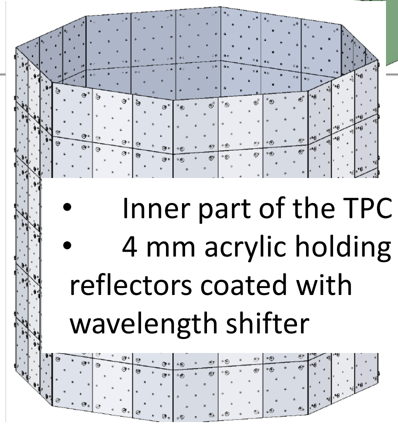
The design of the DS20k detector: more details

- Reflectors and wavelengh shifters
  - inner TPC walls (TPC light)
  - outer TPC walls (Veto light)
  - inner Ti walls (Veto light)
- Cathode and anode coated with new transparent conductor (Clevios) and wavelength shifter
- TPC lateral walls: grooves with Clevios for shaping the field cage (no copper rings)



- Gas pocket 7.0±0.5 mm
- Drift field 200 V/cm
- Cathode -73.38 kV
- Extraction grid -3.78 kV
- >10 phe/keV in the TPC
- 2 phe/keV in the Veto





Veto working principle

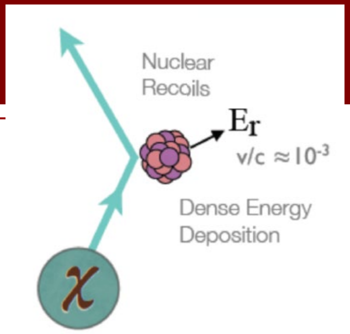
n identification:

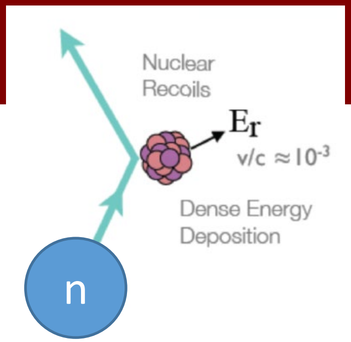
WIMP like event in the TPC (single cluster, PSD as Nuclear recoil 7.5 - 50 keV, r-z cut)

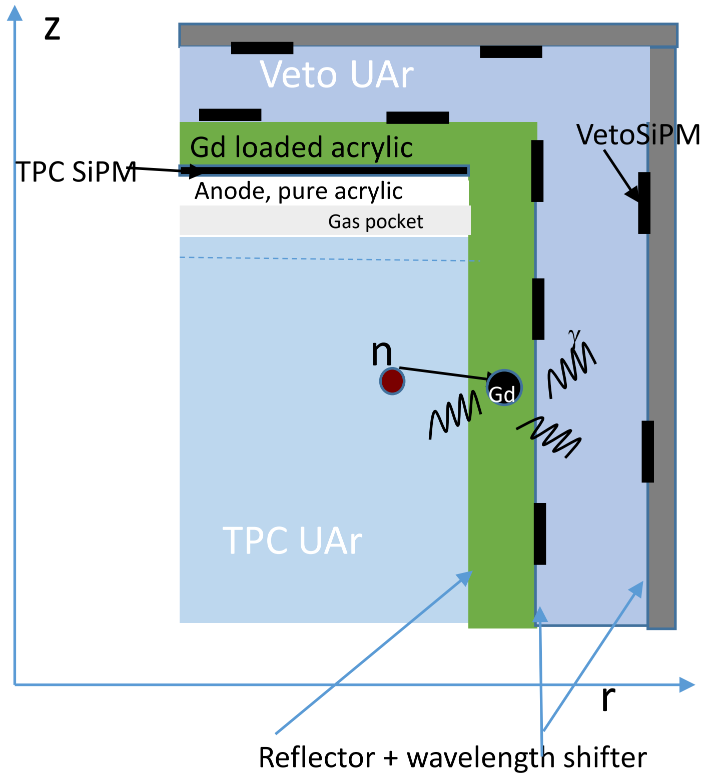
AND

event in the VETO with $E>E_{th1}$ and /or electron recoil event in the TPC with $E>E_{th2}$

within 800 μs







2 recipes to produce a new material: Gd loaded PMMA

- **Gd_2O_3: nanoparticle dispersion,**
  Gd_2O_3 commercially available
- **$Gd(acac)_3$ solution**
- R&D in progress to setup the production of $Gd(acac)_3$

Both are

- working at laboratory scale
- satisfying the radiopurity requirements
- under test with industry

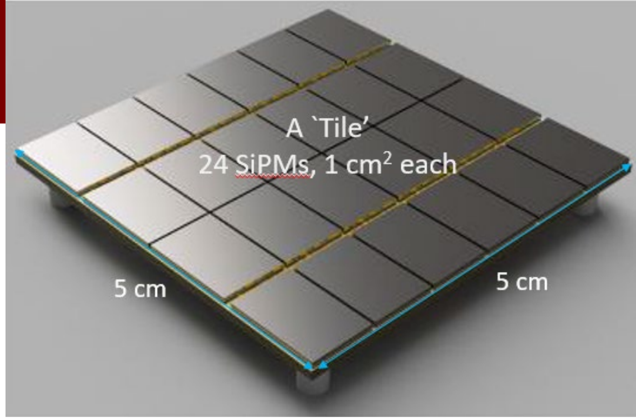
Efficient suppression of the most dangerous n background: radiogenic neutrons

- Selection of materials
- Monte Carlo simulations
- Analysis cuts (TPC+Veto)
- 1% Gd by weight in acrylic
- Very low ineff.
  $2.2\ 10^{-6}$ for n coming from TPC SiPM,
  smaller for other n sources

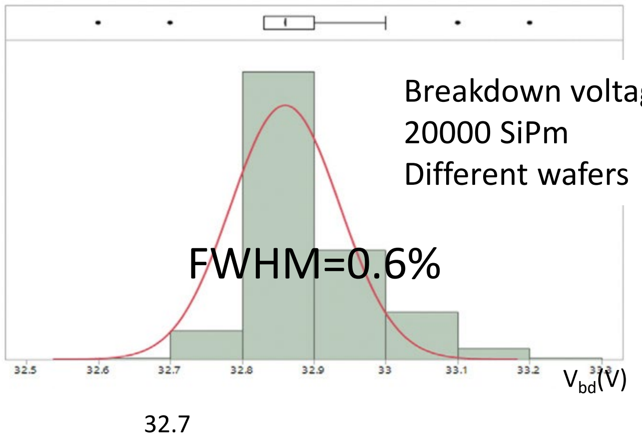
→ **≈0.1 n/200 t y from (α,n) reactions**

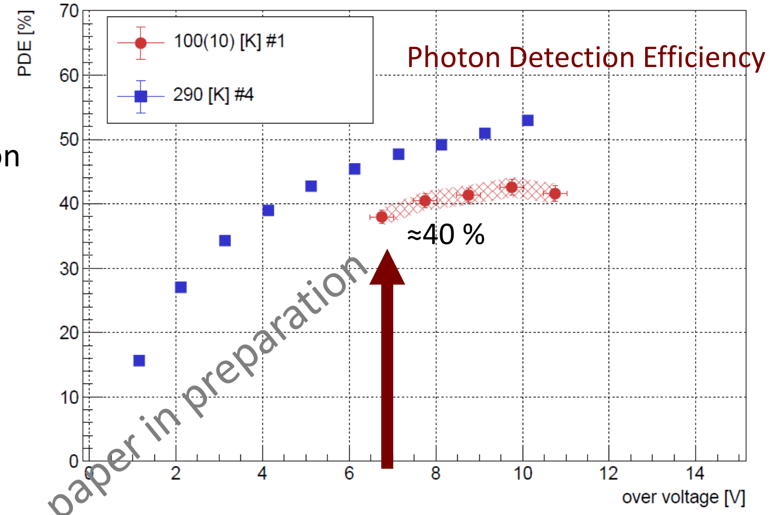
12 cm tall,
acrylic loaded with Gd_2O_3 ,
2% Gd by weight

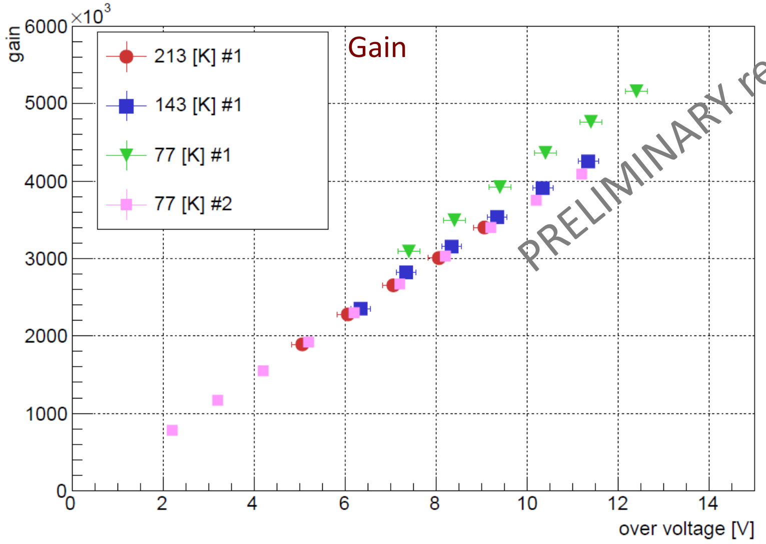
Photosensors: development of large area cryogenic SiPMs



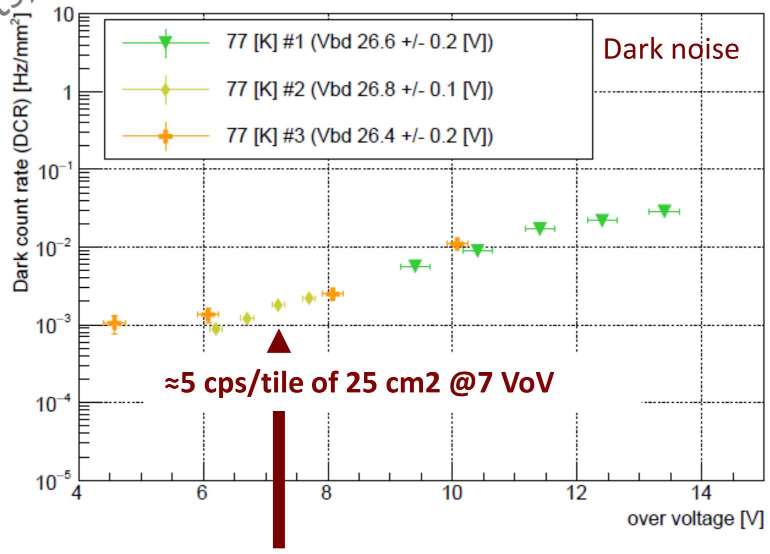
- Very high uniformity of the breakdown voltage (crucial for tiles of 24 SiPms and single Vbias)







PRELIMINARY results, paper in preparation



+ measurements of
Correlated Avalanche
Direct Cross Talk
.....

and inclusion of the data in the detector Monte Carlo

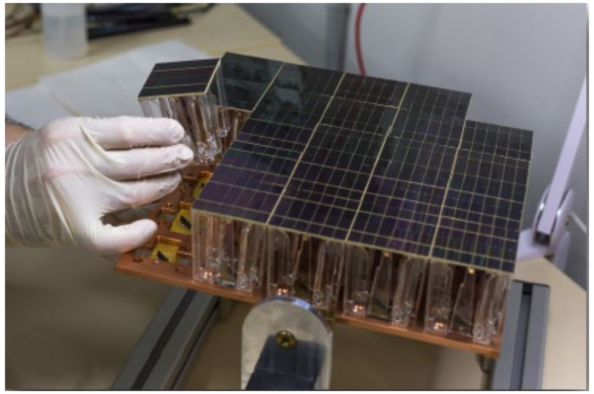
- R&D concluded
- Full SiPM procurement in progress
- Delivery during the first months of 2022

Photosensors: grouping SiPMs into a large matrix

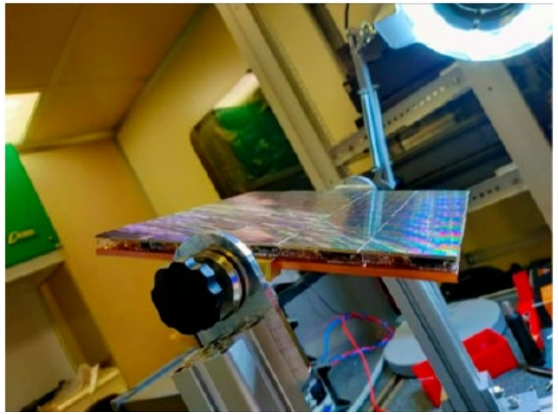
Development of cryogenic amplifiers (Trans Impedance Amplifier (TIA) scheme)

- Discrete elements
- ASIC

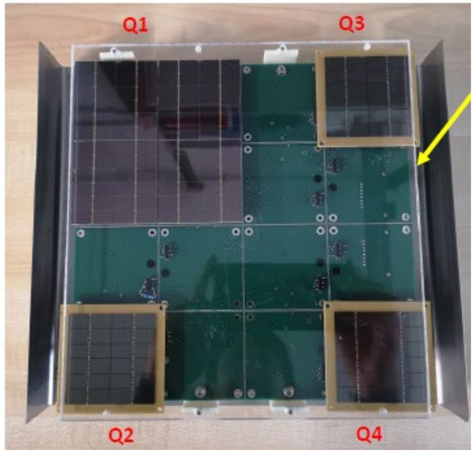
- Tested different solutions for assembling tiles into a large matrix, distribute power and control signals, route the output

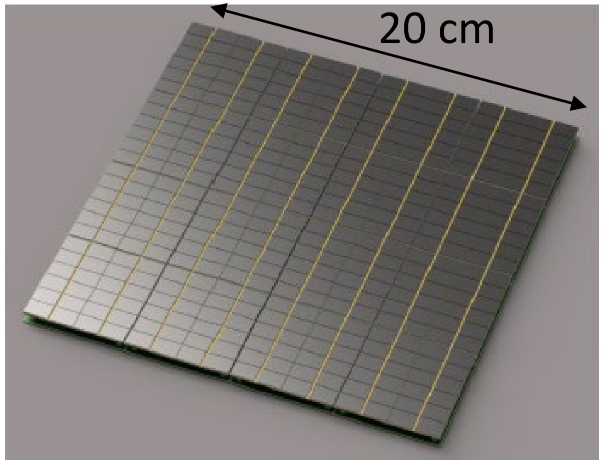


- The first prototype
- 25 Tiles
- Separate PCBs for various functions
- Thick structure (15 cm thick)
- Discrete elements amplifiers
- 25 outputs

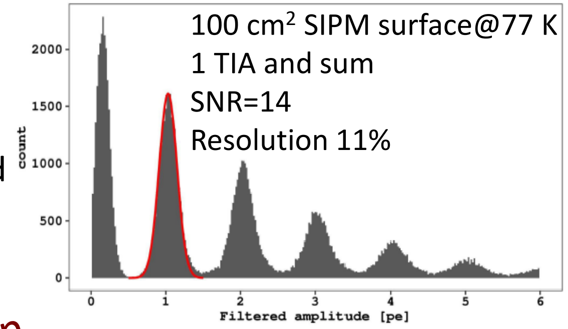


- 25 Tiles
- Separate PCBs for various functions
- Thin structure
- ASIC amplifier
- Sum of two amplified tile signals





- 16 Tiles
- Single PCB for Tile & amplifier+
- 1 large PCB for control signals
- Thin structure
- Discrete elements (for TPC) and ASIC (for Veto) amplifier
- Sum of 4 amplified tile signals
- 4 outputs

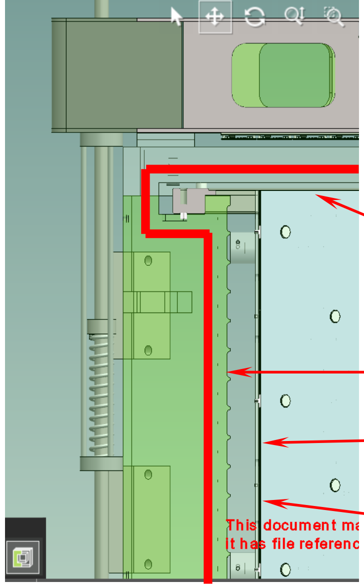


Baseline solution

Virginia Tech Roles

- there are OTHER background though!
- proposed redesign of central TPC acrylic vessel
- Dust mitigation and monitoring during construction of TPC
- TPC handling and transport
- Monitoring and Calibration
- Slow-Controls

Baseline TDR Design



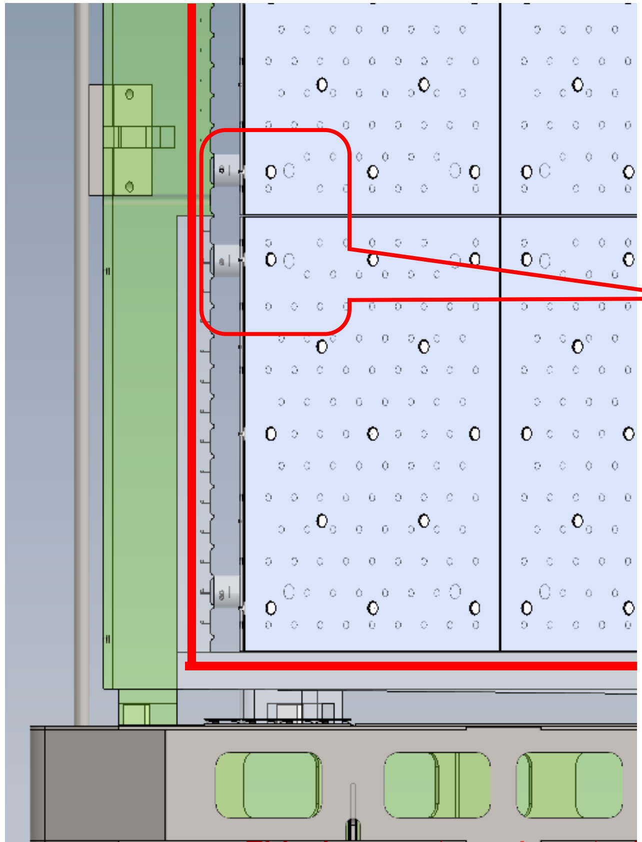
Effective Seal Boundary

Clevios & TPB layer

Field Cage (Clevios coated groove)

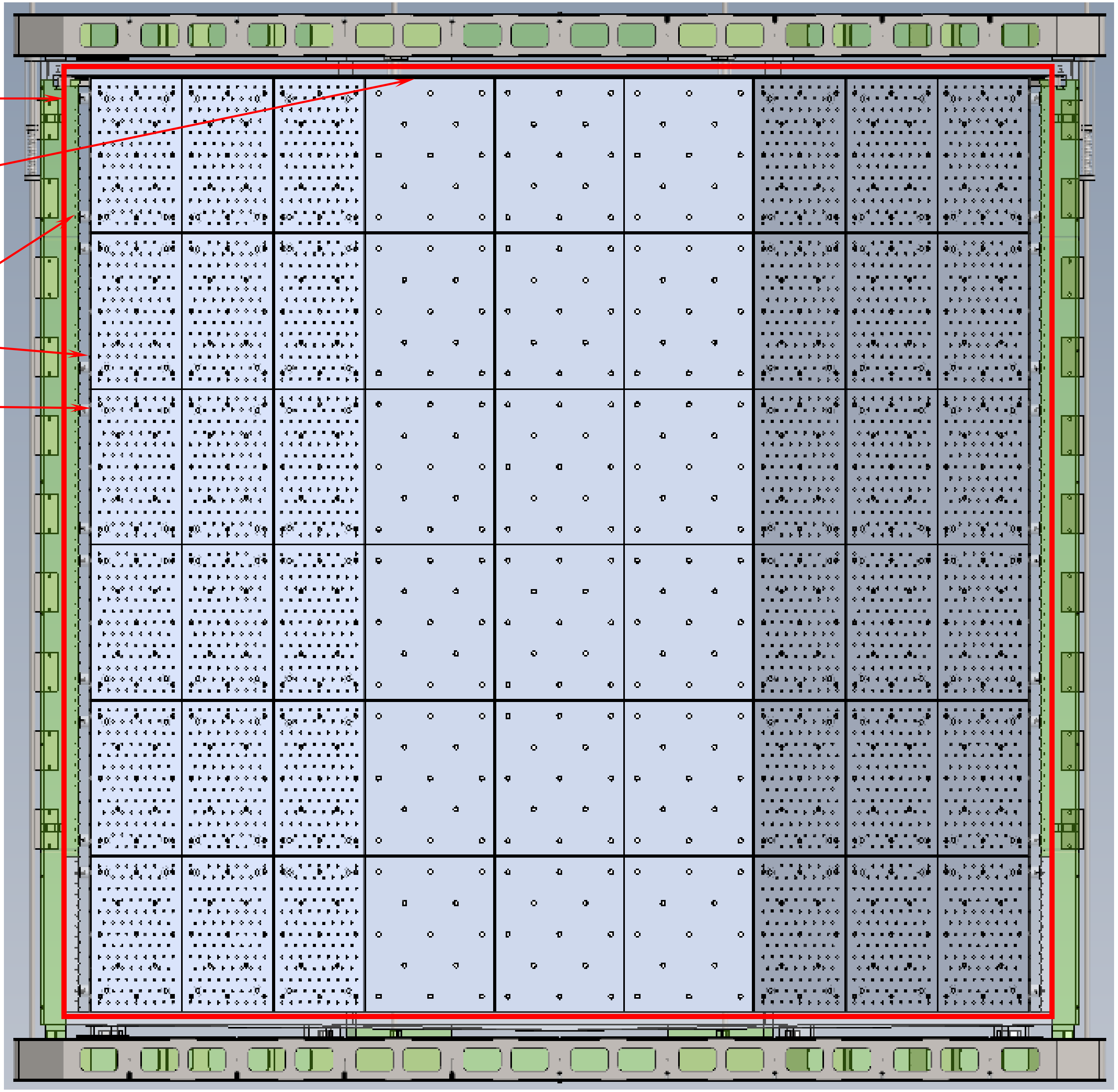
ESR film

TPB layer



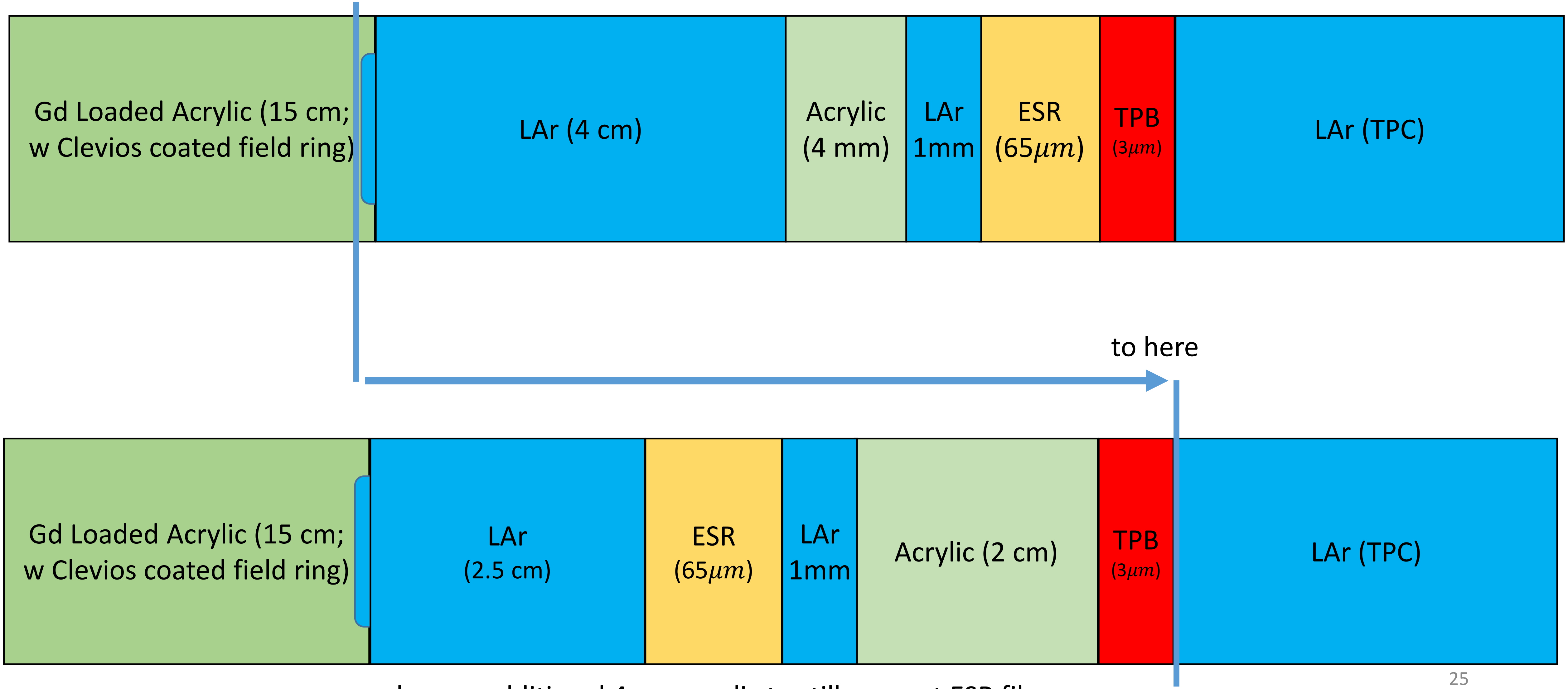
stand-offs,
acrylic support,
push-pins

UAr ports and HV feedthroughs not shown



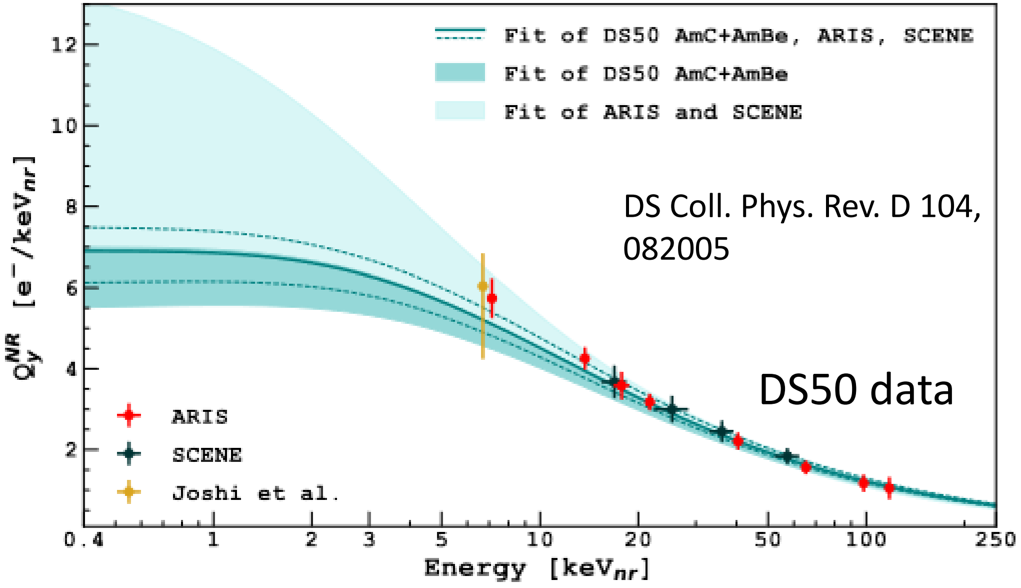
Fortify the separation of TPC and Veto UAr, and reduce the potential for spurious S1 light sources.

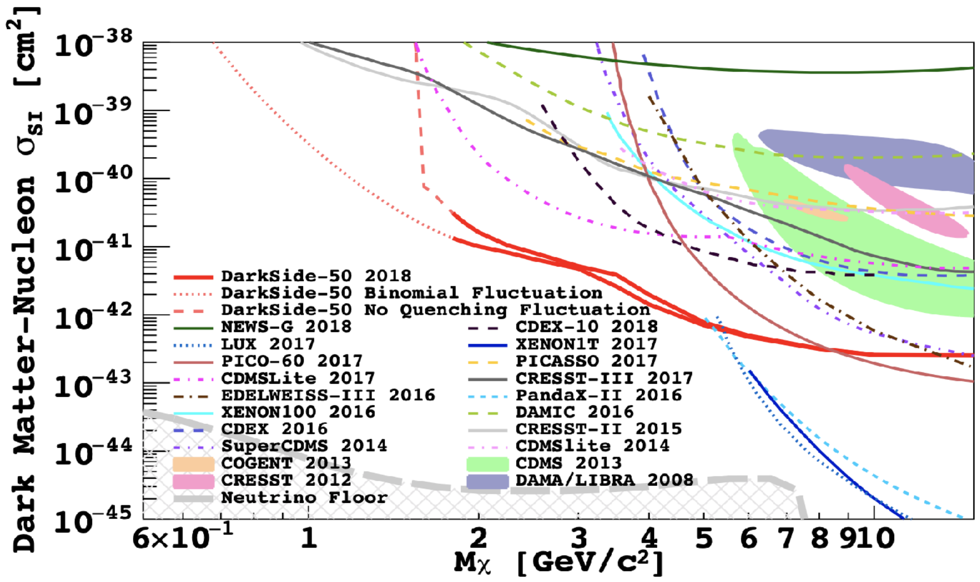
by moving the boundary from here



maybe use additional 4mm acrylic to still support ESR film

Sensitivity to light dark matter candidates





High potential of Dual Phase TPC
S2 signal larger than S1
S2 only events allow to identify nuclear recoil with keV and sub keV energy
Sensitivity to low WIMP mass values (few GeV)

- DarkSide-50 ionization-only analysis
  - world-best limit below 5 GeV/c2
  - recent new calibration of ionization response down to ~0.5 keVnr
  - soon new limits on WIMP-nucleon with/without Migdal, WIMP-electrons, solar and galactic axions, sterile neutrinos
- DarkSide-20k sensitivity evaluation in progress

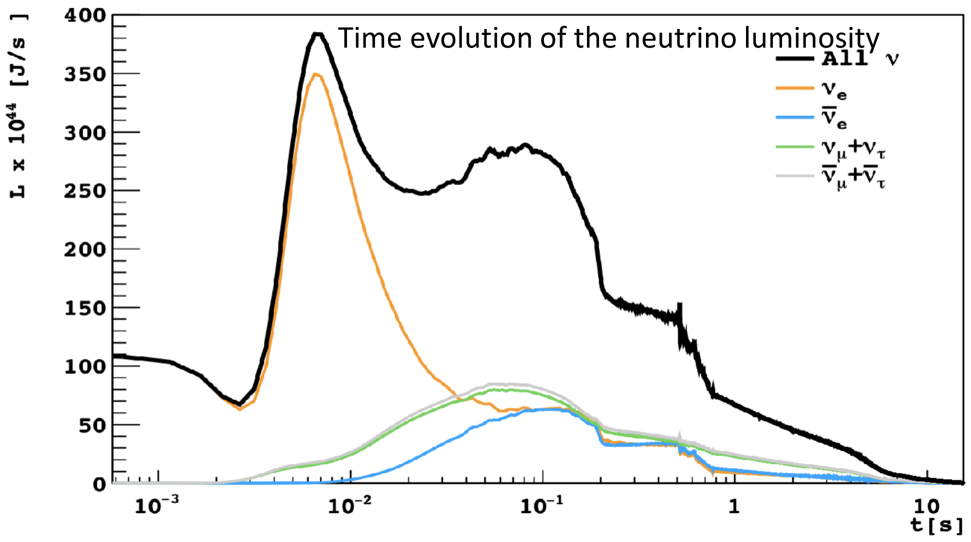
(with high statistics simulations, new observables under definition)

DS Coll. PRL 121 (2018) 081307, DS50 results

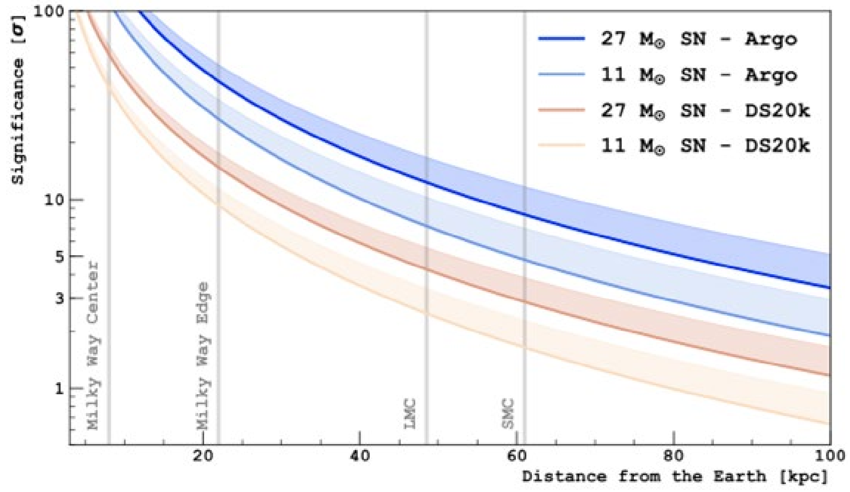
Sensitivity to core collapse supernova via CENνS

DS20k Coll, JCAP 2021 (2021)

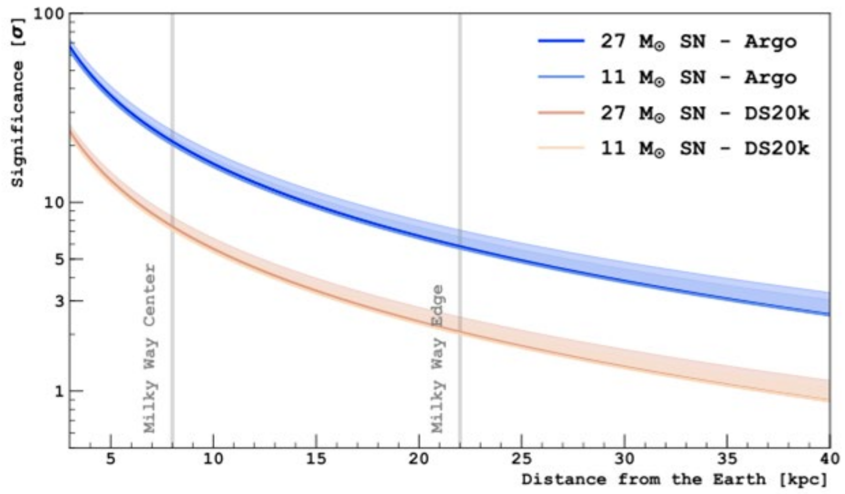
- Detection based on the ionization signal only (S2)
- Threshold down to 0.4 keV_{nr}
- Coherent scattering:
  - neutrino flavor insensitive
  - highest neutrino cross section
- Advantages of CENνS in LAr TPC:
  - Sensitive to the entire unoscillated neutrino flux
  - Sensitive to the neutronization burst (the electron flavor is highly suppressed by oscillations)



Sensitivity to the entire SN neutrino flux



Sensitivity to neutrinos from SN neutronization burst



In Brief

- GADMC has completed the R&D phase for the DS20k detector (Technical Design Report went to INFN on Dec 1, 2021
- Construction of the cryostat will start in 2022
- Full production of SiPMs already started
- URANIA & ARIA ongoing
- Several new technologies have been developed :
  - procurement of large amount (≈100 t) UAr
  - acrylic TPC vessels
  - conductive polymers
  - wavelength-shifters
  - reflectors
  - Gd-doped acrylic
  - cryogenics SiPMs
  - cryogenics low noise amplifiers
  - selection of low background materials

- Data taking expected in 2025
- it is a great time to join