Перспективы использования двухфазных эмиссионных детекторов в Баксанской нейтринной обсерватории ИЯИ РАН

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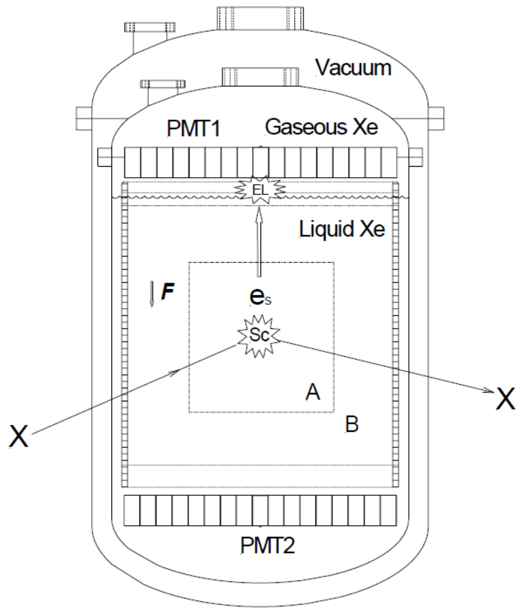
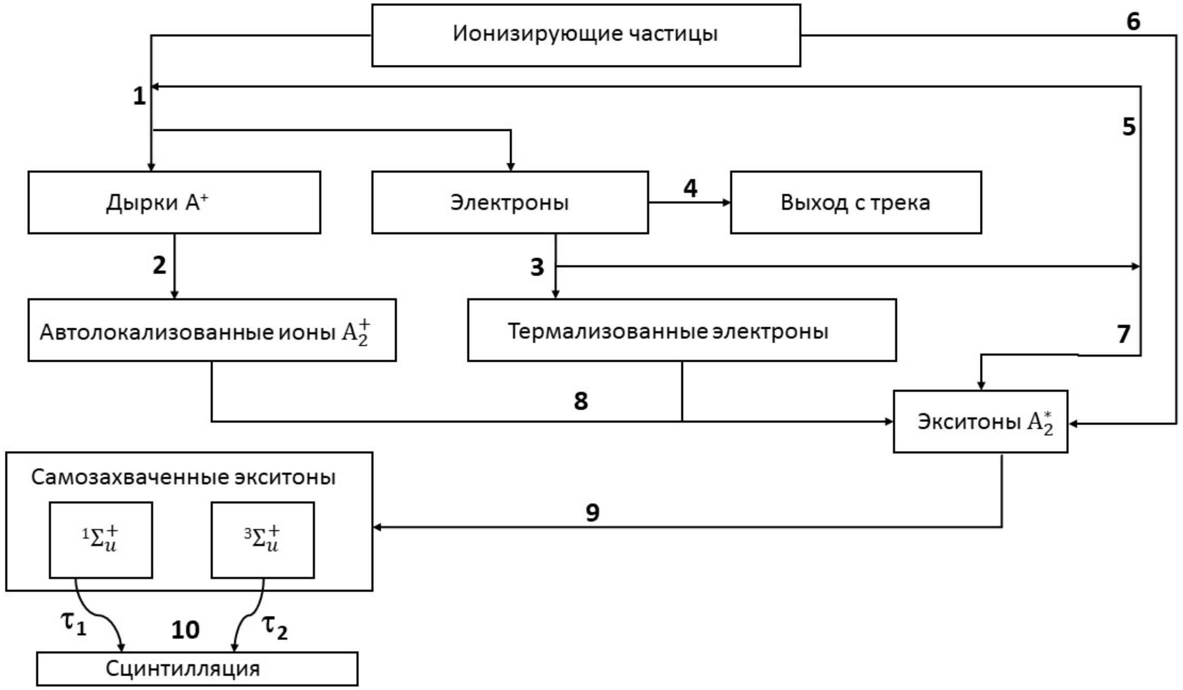
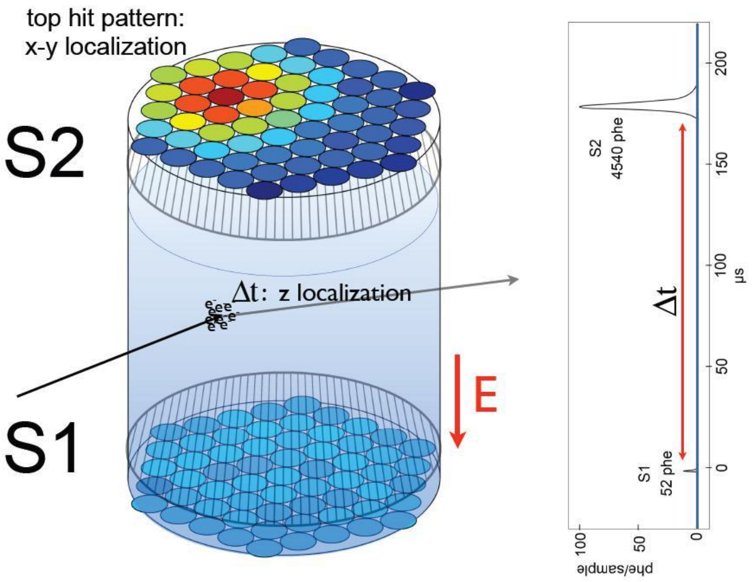


Принцип действия

Совмещает в себе многие преимущества газовых детекторов:

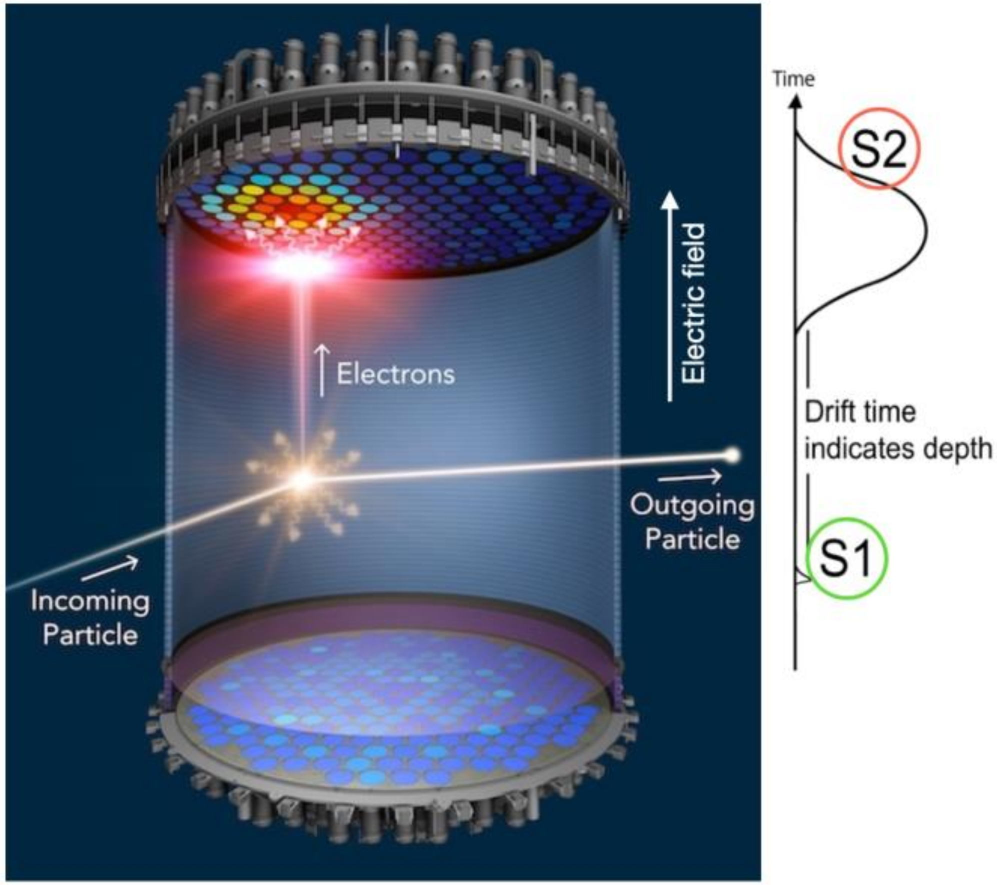
наличие пропорционального или электролюминесцентного усиления, XYZ – позиционирование событий, возможность легко нарастить большую массу (жидкость), в случае применения Xe детектор может быть бесстеночным, идентификация частиц (particle identification)





1 - генерация электронно-дырочных пар и экситонов. 2 - автолокализация дырок. 3 - термализация горячих электронов. 4 - выход горячих электронов за пределы поля ионов. 5 - генерация вторичных электронно-дырочных пар вторичными электронами. 6 - генерация экситонов ионизирующей частицей. 7 - генерация экситонов вторичными электронами. 8 - рекомбинация квазисвободных термализованных электронов с автолокализованными дырками. 9 - самозахваченные экситоны, образующие возбужденные молекулярные состояния. 10 - девозбуждение молекулярных состояний.

- Scintillation photons
  - High light yield (~40,000/MeV)
  - Little self absorption
- Ionization electrons
  - Similar yield to that of photons
  - Low electron affinity, long drift distances
  - Amplification of ionization signals possible
- Particle identification
  - Energy partition between photon/electron
  - Time profile of scintillation
- Position reconstruction
  - Accurate 3D position possible

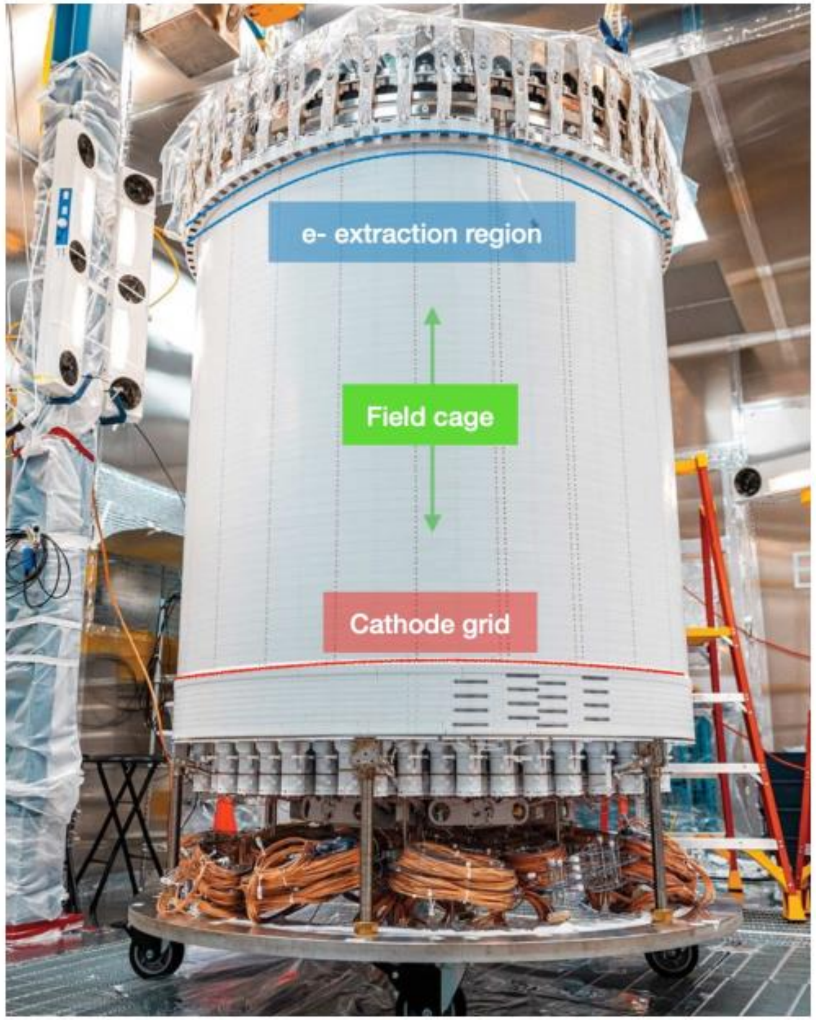


An illustration of signal generation in a dual-phase xenon TPC detector.

Advantages of a liquid target:

- Easy to purify
  - Fluid nature
  - Chemically inert
- Scalable
  - Little light/electron attenuation
  - Rapid size expansion possible
- Self shielding
  - Low intrinsic radioactivity
  - Monolithic target volume
- Little radiation damage

XENON10 detector 15cmx15cm, 2005



LUX-ZEPLIN detector 150cmx150cm, 2021

What makes LXe the most favorable target?

Rich Physics Goals

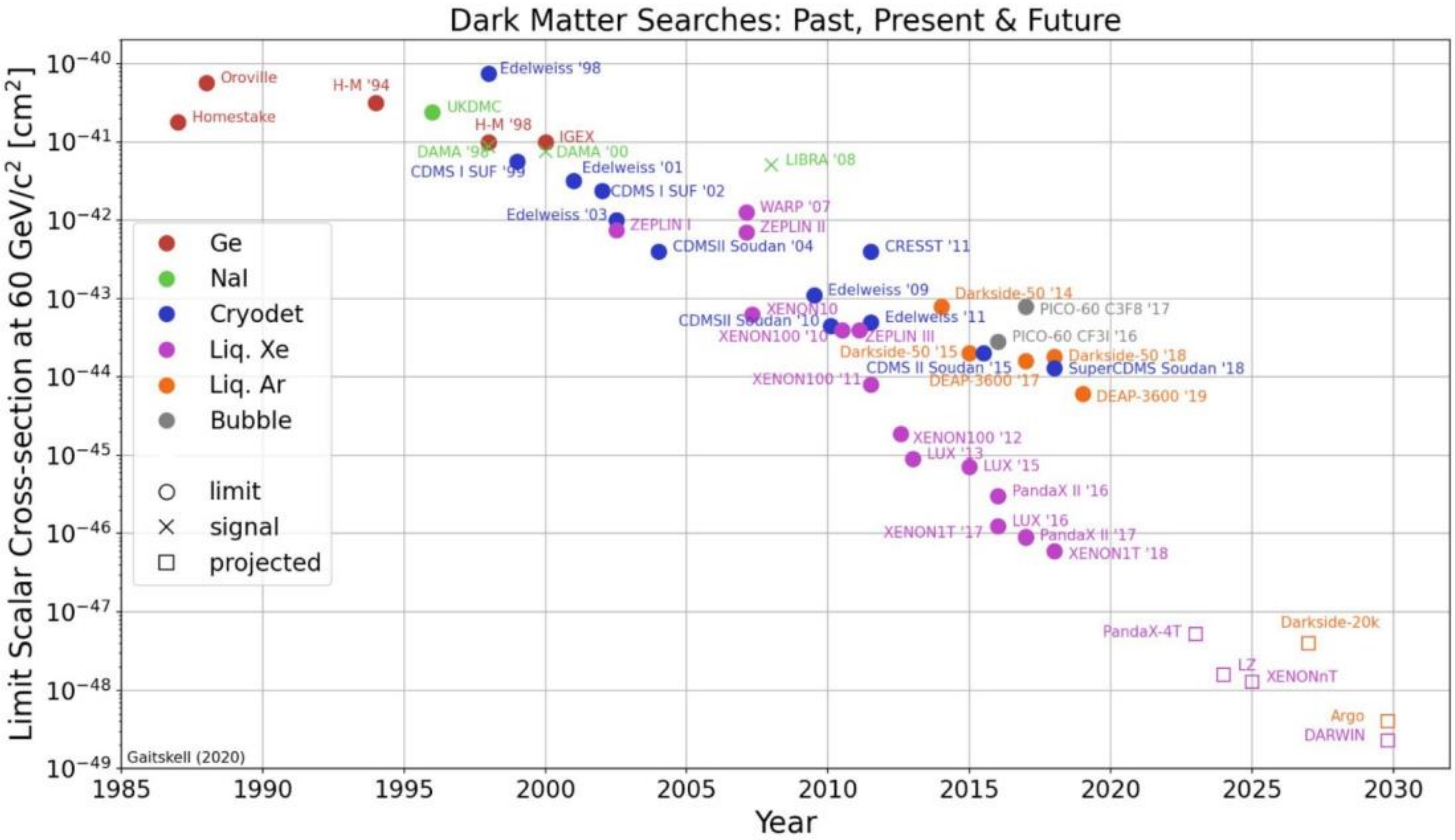
- Probe many DM models
  - SI & SD & EFT
  - Inelastic etc.
  - Heavy or sub-GeV
  - ALPs, dark photon
  - etc.
- Neutrino astrophysics
  - Elastic scattering of solar neutrinos (pp)
  - CEvNS of B8 neutrinos
  - Supernova neutrinos
- Neutrino physics
  - 0vbb with Xe-136
  - DEC with Xe-124

Mature Technology

- Large target
  - online purification of the liquid/gas target
  - multi-ton target demonstrated
  - Next generation: 50~100 ton
- Low background
  - Intrinsically pure and purifiable
  - self-shielding
  - 3D localization
  - ER/NR discrimination
- Low threshold
  - keV threshold with both charge and light
  - O(10) eV threshold with charge only

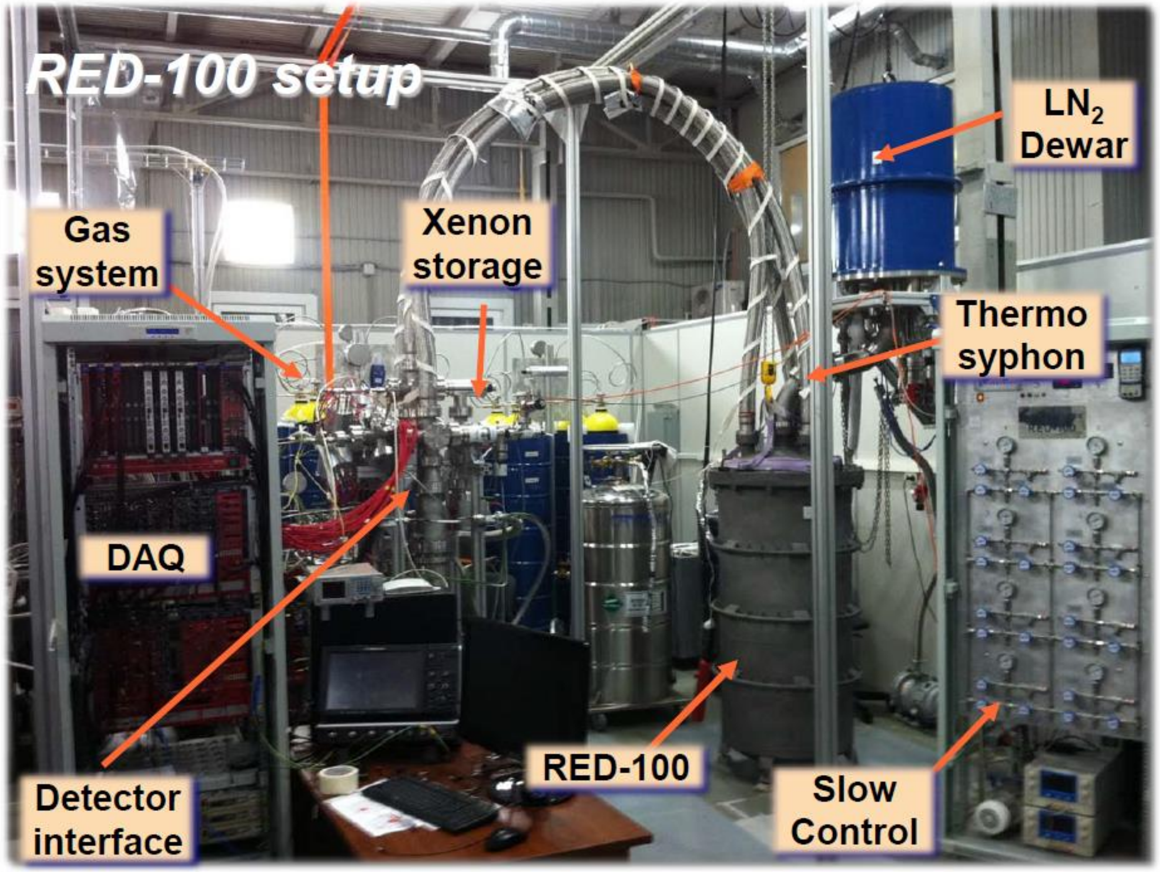
Rapid progress in 10 yrs

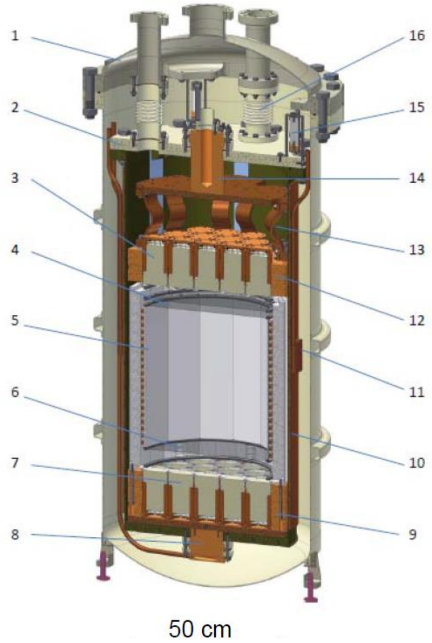
- XENON10
- DarkSide10
- XENON100
- ZEPLIN
- LUX
- DarkSide50
- DEAP3600
- XENON1T
- PandaX-II
- PandaX-4T
- XENONnT
- LZ
- *DarkSide-20K*
- *DARWIN/G3?*



Детекторы с рабочей средой – Xe, LXe

Россия: RED-100 (Xe, Ar) - CE?NS





Устройство детектора РЭД-100:

1 – внешний (тёплый) сосуд криостата,
2 – внутренний (холодный) сосуд криостата,
3 – верхняя матрица из девятнадцати ФЭУ типа HAMAMATSU R11410-20,
4 – сетчатый анод и вытягивающая сетка,
5 – рабочий объем, окруженный тефлоновым отражателем со встроенными полезадающими электродами,
6 – сетчатый катод,
7 – нижняя матрица из девятнадцати ФЭУ,
8 – нижний центральный теплосъемник с термосифоном,
9 – медная обойма для нижней матрицы ФЭУ,
10 – медный кожух холодного сосуда криостата,
11 – один из двух боковых теплосъемников с термосифонами,
12 – медная обойма верхней матрицы ФЭУ,
13 – гибкий тепловой мост,
14 – верхний центральный теплосъемник с медным диском, на котором конденсируется ксенон,
15 – теплоизолирующий подвес на основе материала Vespel,
16 – сильфонная тепловая развязка на трубопроводе для вывода кабелей.

RED-100 is a two-phase noble gas emission detector. Contains ~250 kg of LXe, ~100 kg in FV.

The sensitive volume ~ 45 cm in diam ~ 45 cm in height, is defined by the top and bottom optically transparent mesh electrodes and field-shaping rings.

PMTs are Hamamatsu R11410-20 (low-background); 38 in total (2 x 19)

Drift field is ~ 0.5 ÷ 1 kV/cm;

Field in EL region is ~ 7 ÷ 10 kV/cm (in the gas phase).

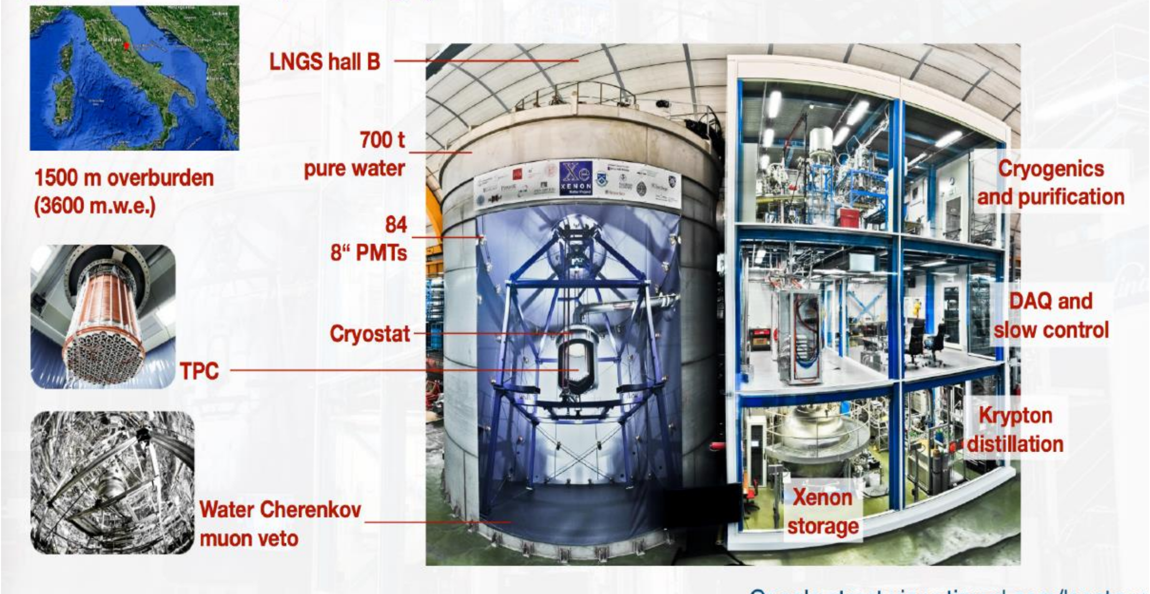
Size of the EL region – 1 cm. The expected *number of photoelectrons per one electron* extracted to the gas phase ~ 80.

Детекторы с рабочей средой – Xe, LXe

EU: XENONnT (Xe) – темная материя, аксионы, 0□□□ Xe-136 , солнечные нейтрино

The XENON1T experiment @ LNGS (Italy)

Università degli Studi dell'Aquila XENON



Google street view: tinyurl.com/lngstour

TPC inside the Water Tank + Ancillary systems: purification, Krypt distillation, cryogenics, DAQ, slow control, Xenon storage

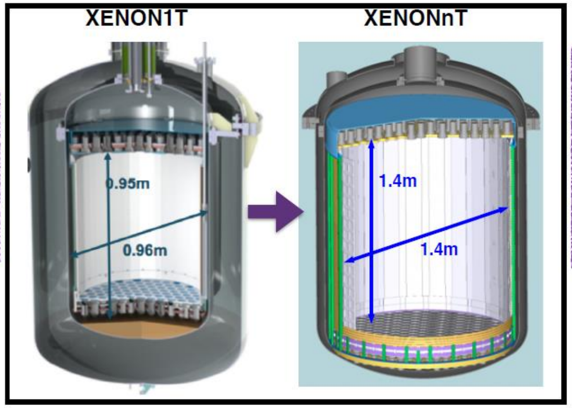
XENONnT: the next detector

Università degli Studi dell'Aquila XENON

5.9 t liquid Xe (3x XENON1T)

494 PMTs

Liquid Xe purification system (~1500 slpm)



Background reduction:
- Material selection and screening
- Radon distillation column
- Radon-free purification pump

Active neutron veto with Gd loaded water

High energy readout

- Cryostat filled with ~8.6 t of LXe
  - 6 wks for cool down and filling through gas purifiers (high temperature getters)
  - Started LXe circulation and electron lifetime measurements with dedicated purity monitor
- Initial purification of LXe volume with GXe purification system @ 60 slpm
- Cryogenic LXe purification
  - Started with a high-efficiency O_2 filter (copper on alumina support)
  - Electron lifetime went from 100 us to 5 ms in 5 days!
  - Continuous improvement with decrease in outgassing
  - Reached >10 ms after ~1 month of operation

Детекторы с рабочей средой – Xe, LXe

USA: LZ(LUX+ZEPLIN) – (Xe) - темная материя, аксионы, 0νββ Xe-136 , солнечные нейтрино

LZ overview

Liquid Xenon TPC:

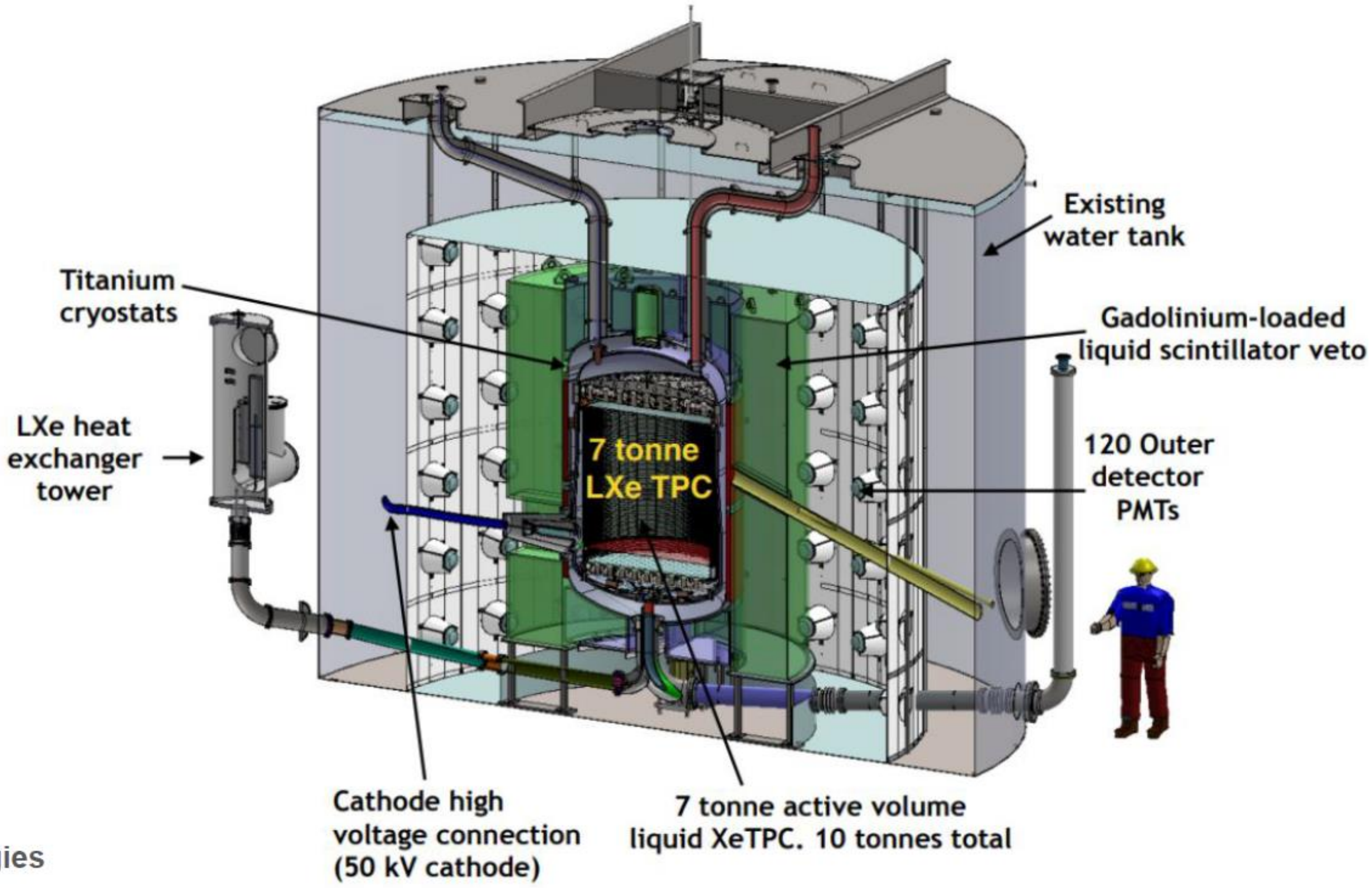
- 1.5 m diameter by 1.5 m height
- Active Mass: 7 t
  - 623 kg of ^{136}Xe
  - 741 kg of ^{134}Xe
- Fiducial: 5.6 t
- 494×3" PMTs

3 components veto detector:

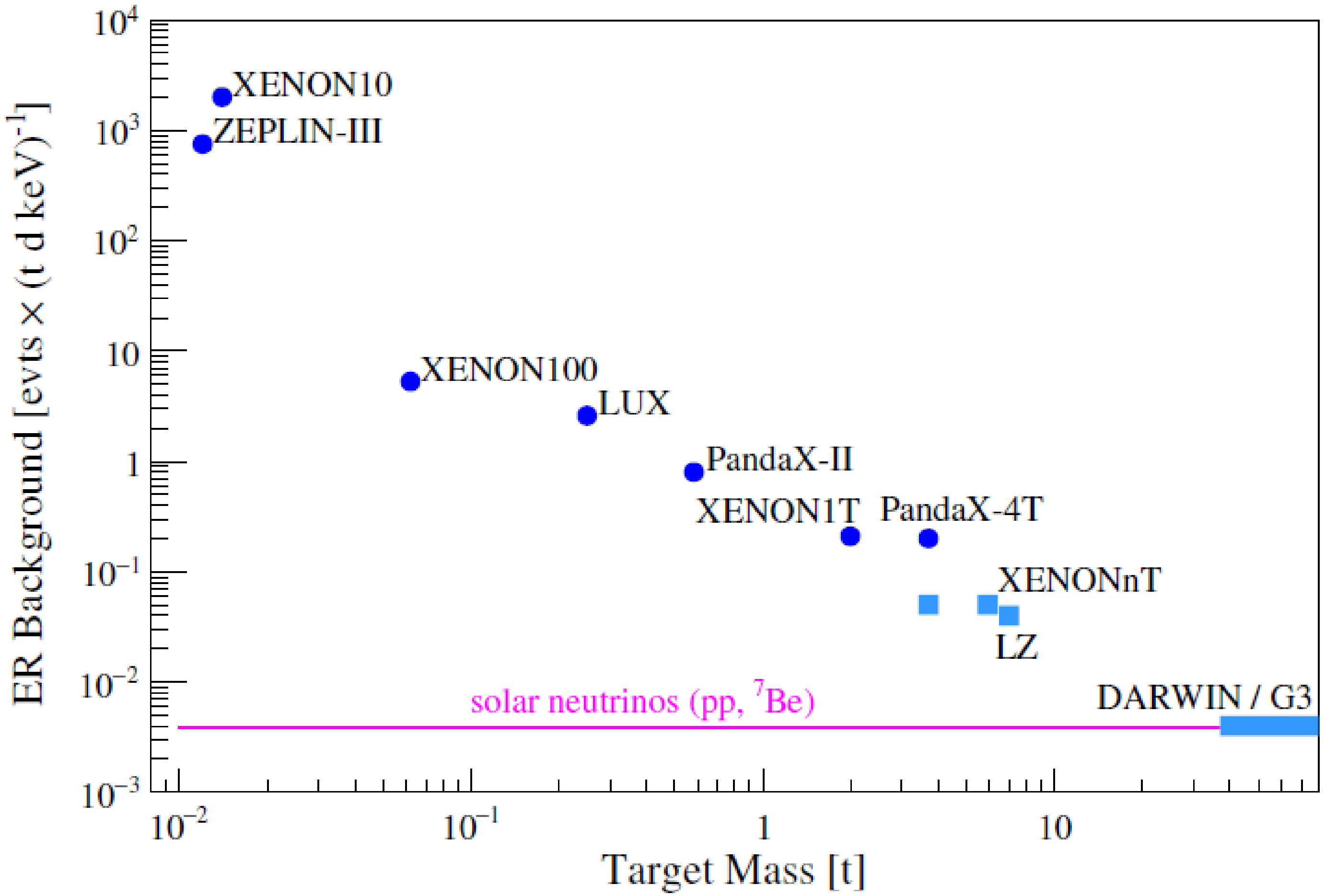
- Water Tank + Gadolinium-loaded scintillator
- Liquid Xe skin

Scientific program

1. WIMP search
2. Neutrino physics searches
   - 2ν2β – $Q_{\beta\beta}$= 826 keV (^{134}Xe)
   - 0ν2β – $Q_{\beta\beta}$= 2458 keV (^{136}Xe)
     - **Requires good energy resolution for high energies**



A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics



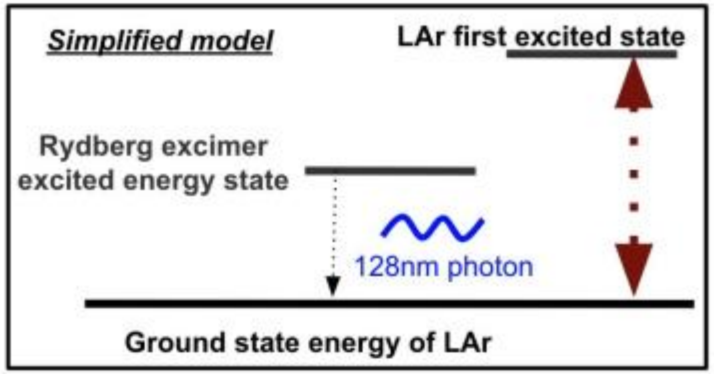
Kiloton-scale xenon detectors for neutrinoless double beta decay and other new physics searches
arXiv:2110.01537v2

A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics
arXiv:2203.02309v1

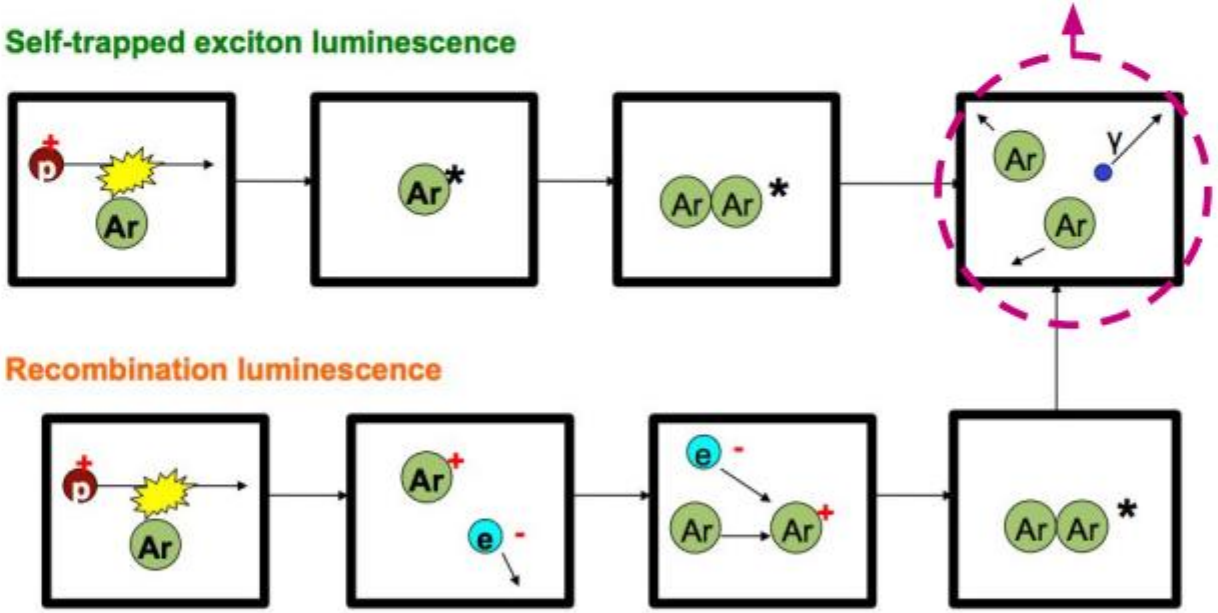
Для достижения чувствительности ~ 10^{30} лет 0[illegible] Xe-136, предполагается создание килотонных детекторов, н-р 3 кт Xe-nat (~ 300 т Xe-136)

Why Argon? And Why Liquid?

Dense 40% more dense than water → many nuclear centers for interaction
Abundant 1% of the atmosphere → “cheap”, we can build big detectors!
Ionizes easily 55,000 electrons / cm
High e^- lifetime Noble liquid!
Lots of scintillation light Transparent to light produced (128 nm)



Two detection mechanisms:
Ionization Charge and
Scintillation Light

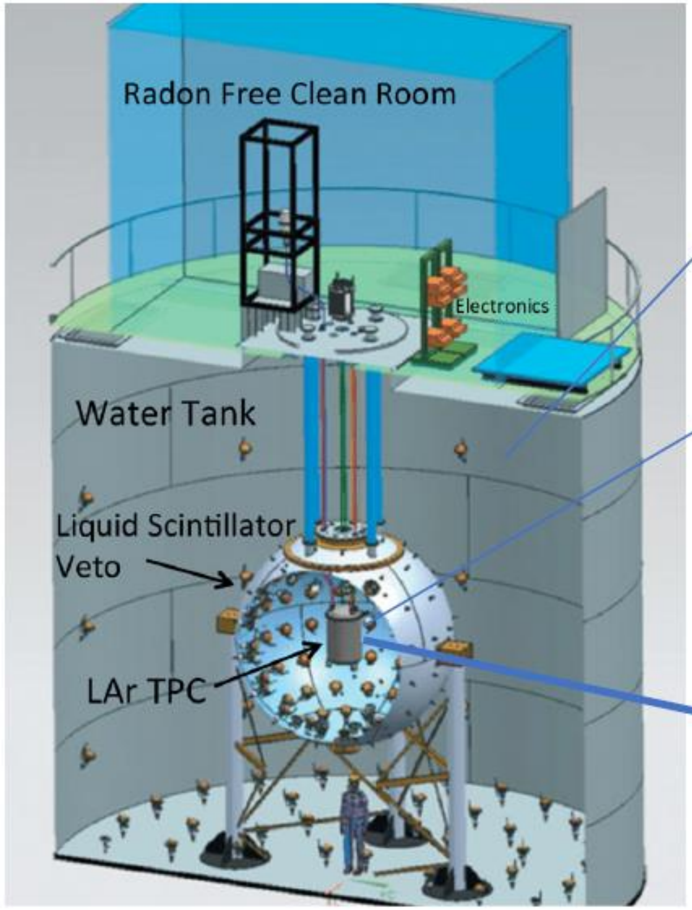


Детекторы с рабочей средой – Ar, LAr

- DarkSide-20k and ARGO
  - WIMP Dark Matter search
  - Argon is primary WIMP target
  - Argon related background: ^{39}Ar decay
  - Masses required:
    - ✓ DarkSide-20k – 50 tons
    - ✓ ARGO – 300-500 tons
- COHERENT
  - Coherent elastic ν-nucleus scattering
  - Argon is primary neutrino target
  - Argon related background: ^{39}Ar
  - Masses required:
    - ✓ SNS/COHERENT – 1 ton
    - ✓ CAPTAIN-MILLS – 10 tons
- LEGEND
  - Neutrinoless double beta decay
  - Argon shield surrounding HPGe detectors
  - Argon related background: ^{42}K decay (^{42}Ar daughter)
  - Mass required:
    - ✓ $\mathcal{O}$(10 tons)
- DUNE
  - Low-energy neutrino program
  - Argon is primary neutrino target
  - Ar related backgrounds: ^{42}Ar, ^{39}Ar, and ^{42}K
  - Mass potentially needed:
    - ✓ 17 ktons/module

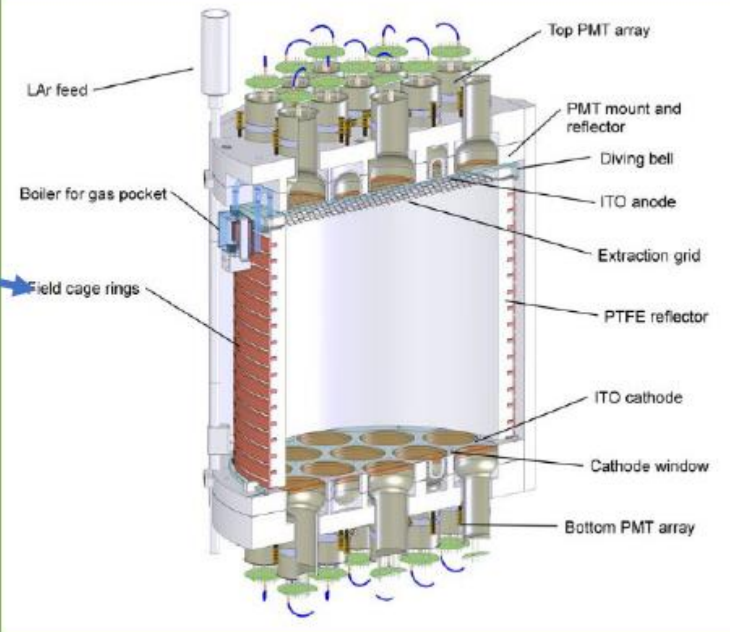
Детекторы с рабочей средой – Ar, LAr

EU: DarkSide50 – (UAr) - темная материя



Water Cherenkov detector (passive shield and μVETO)
Stainless steel vessel filled with **1kt** of **ultra pure water**.
80 8” PMTs.

Liquid scintillator detector (γ,nVETO)
30t Boron loaded scintillator.
110 8” PMTs



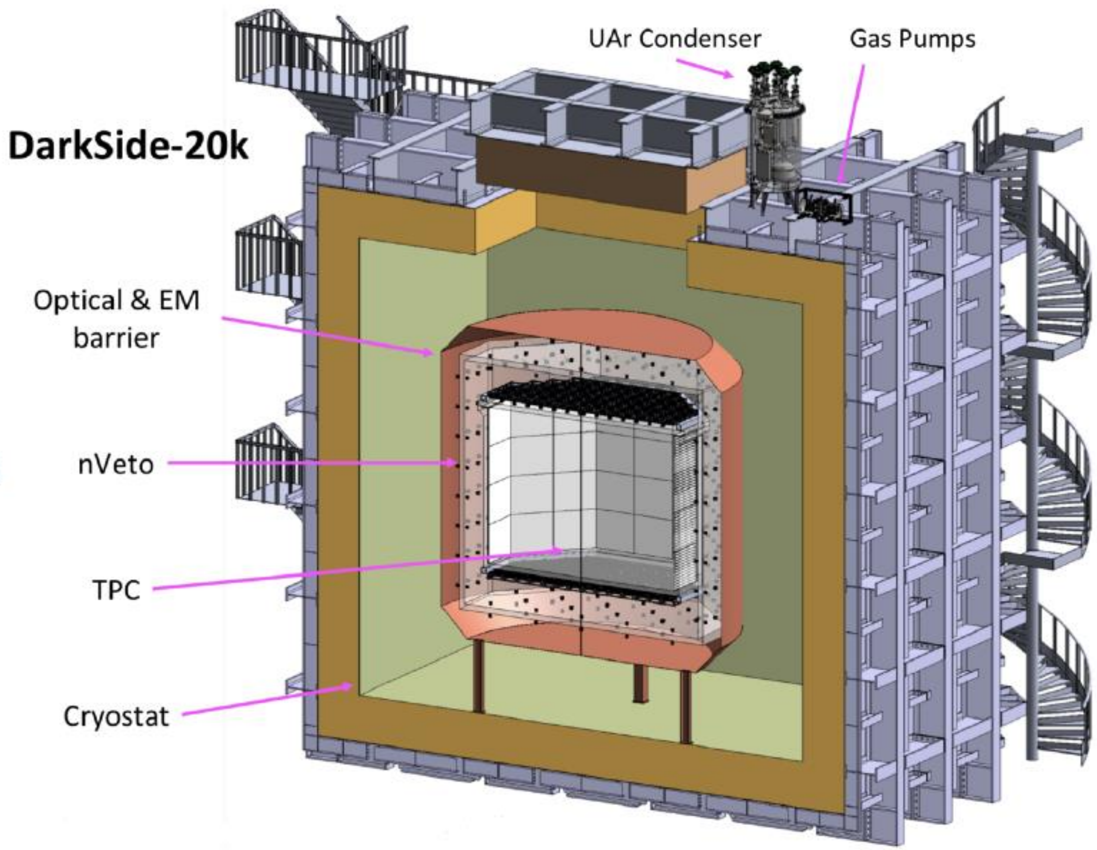
TPC housed in stainless steel cryostat
PTFE cylinder ⌀ **36.5 cm x 36.5 cm**
with the inner surfaces **coated** with
TPB (128nm to 420nm).
38 3” Hamamatsu R11065 PMTs (**19** on **top** and **19** on **bottom**).
Filled with **46kg** of **Underground Argon (UAr)**.

Детекторы с рабочей средой – Ar, LAr

EU: DarkSide20K – (UAr) - темная материя, аксионы, солнечные нейтрино

DarkSide-20k

- Sealed acrylic TPC filled with Underground Argon (UAr): 50 tonnes in total
- Membrane cryostat filled with Atmospheric Argon (AAr): based on the ProtoDUNE cryostat
- 2% Gd doped acrylic panels as neutron veto
- SiPMs as photosensors: 8280 channels in TPC, ~3000 channels in Veto



Детекторы с рабочей средой – Ar, LAr

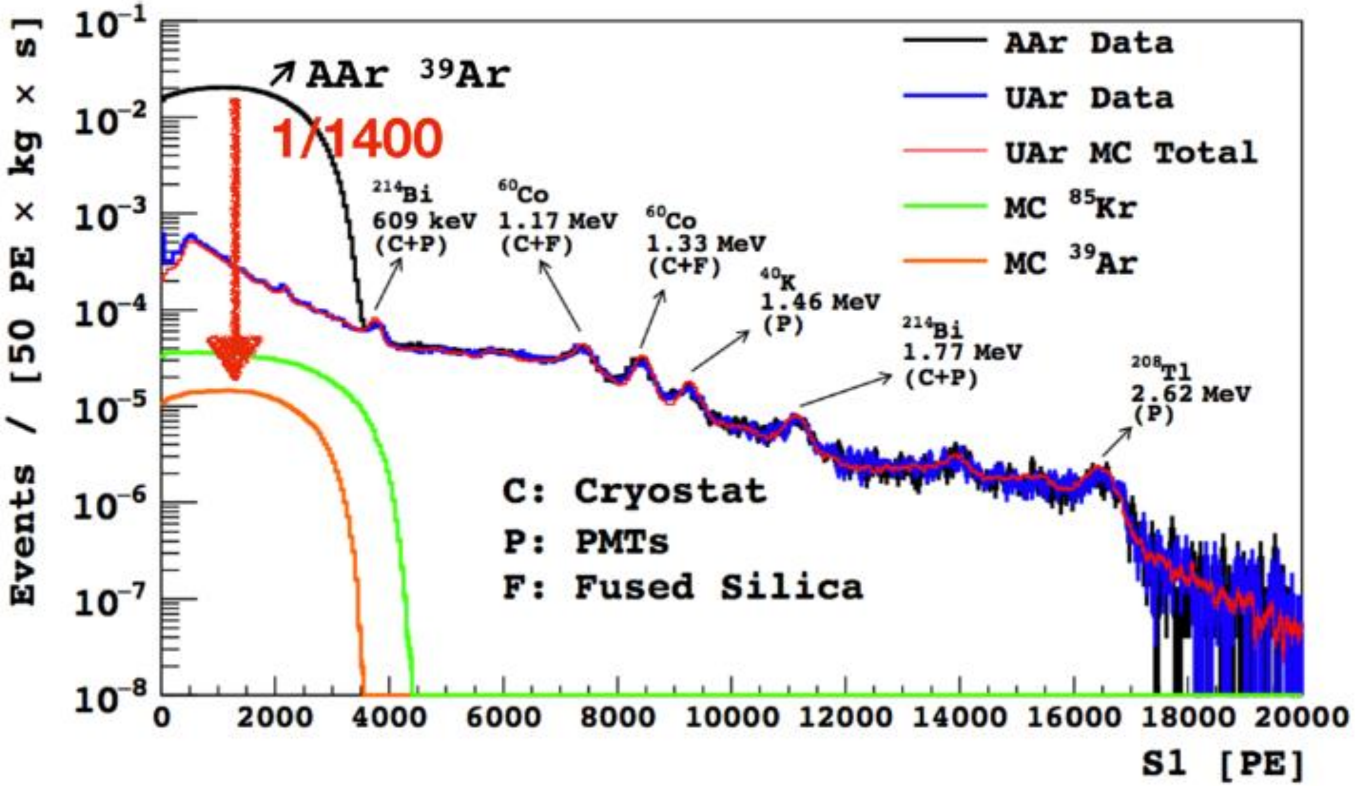
Pacific Northwest NATIONAL LABORATORY

DarkSide-50 Underground Argon

in the atmosphere: ^{39}Ar activity of 1 Bq/kg

DS-50 measured ^{39}Ar specific activity of 0.73 ± 0.10 mBq/kg

residual ^{39}Ar likely from air infiltration during extraction



UAr: ^{39}Ar < 0.07% of AAr

Научная программа

The XENON science program

Università degli Studi dell'Aquila — XENON

WIMP search

- -Spin independent
- -Spin dependent
- -Low-E (sub GeV) DM
- -Dark photons
- -Axion-like particles

Neutrino properties

- -Neutrinoless double-beta decay of ^{136}Xe
- -Double-electron capture in ^{124}Xe
- -Neutrino magnetic moment

SuperNovae

- -Supernova neutrinos
- -Multi-messenger information for DM experiments

From the Sun

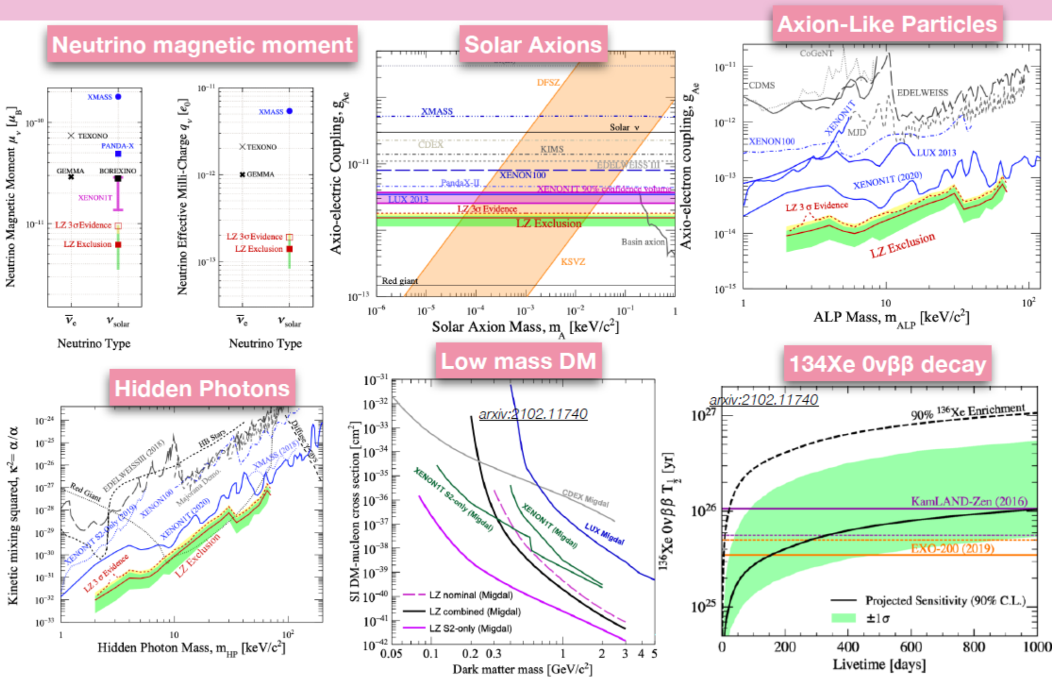
- -Solar axions
- -^{8}B solar neutrinos
- -pp neutrinos

LZ Physics Reach

LZ physics reach extends beyond vanilla WIMPs:

- Solar axions
- Axion-like particles (ALPs)
- 2νββ of ^{134}Xe with competitive sensitivity to 0νββ
- Enhanced sensitivity to low mass DM through Migdal effect
- Leptophilic dark matter
- Neutrino magnetic moment
- Mirror dark matter

arxiv:2102.11740
arxiv:2104.13374

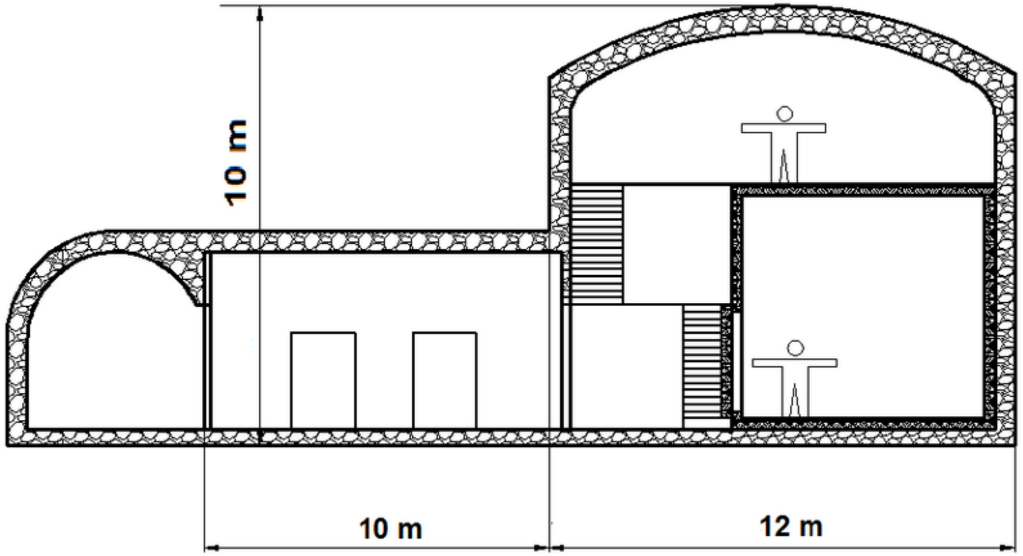


- WIMP dark matter detection
  - — Darkside-20K & GADMC
  - — Especially important for extending the reach of ionization-only analysis
- Neutrino physics via the CEνNS channel*
  - — Sterile neutrino searches
  - — Neutrino magnetic moment searches
  - — Non-standard interactions and new light mediators
  - — Flavor-blind observation of supernovae, including potential insight into the mass hierarchy**
- Anti-proliferation technology
  - — Reactor fuel cycle monitoring with antineutrino CEνNS***

Перспективы использования двухфазных детекторов в БНО

Новая подземная лаборатория,
в уже существующей выработке

Photo of the cavity at 2620 m depth



Предполагаемый план работ:

1) Проведение R&D исследований: a) возможна установка детектора (копии) RED-100 в подземной лаборатории ЛНФИ БНО, цель подготовка инфраструктуры БНО. Создание рабочей группы (коллаборции) ИЯИ-МИФИ-МГУ-ОИЯИ(?).
2) Разработка детектора с рабочим объемом 7 т, строительство новой подземной лаборатории.
3) При наличии новой подземной лаборатории, оценка возможности создания детектора объемом 20-50 тонн рабочего вещества.

A summary list of the 0νββ ongoing and proposed experiments

Experiment	Isotope	Mass	Technique	Present Status	Location
CANDLES-III [68]	^{48}Ca	305 kg	$^{nat}CaF_2$ scint. crystals	Operating	Kamioka
CDEX-1 [69]	^{76}Ge	1 kg	^{enr}Ge semicond. det.	Prototype	CJPL
CDEX-300ν [69]	^{76}Ge	225 kg	^{enr}Ge semicond. det.	Construction	CJPL
LEGEND-200 [16]	^{76}Ge	200 kg	^{enr}Ge semicond. det.	Commissioning	LNGS
LEGEND-1000 [16]	^{76}Ge	1 ton	^{enr}Ge semicond. det.	Proposal	
CUPID-0 [19]	^{82}Se	10 kg	Zn^{enr}Se scint. bolometers	Prototype	LNGS
SuperNEMO-Dem [70]	^{82}Se	7 kg	^{enr}Se foils/tracking	Operation	Modane
SuperNEMO [70]	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal	Modane
Selena [71]	^{82}Se		^{enr}Se, CMOS	Development	
IFC [72]	^{82}Se		ion drift SeF_6 TPC	Development	
CUPID-Mo [17]	^{100}Mo	4 kg	Li$^{enr}MoO_4$,scint. bolom.	Prototype	LNGS
AMoRE-I [73]	^{100}Mo	6 kg	$^{40}Ca^{100}MoO_4$ bolometers	Operation	YangYang
AMoRE-II [73]	^{100}Mo	200 kg	$^{40}Ca^{100}MoO_4$ bolometers	Construction	Yemilab
CROSS [74]	^{100}Mo	5 kg	$Li_2{}^{100}MoO_4$, surf. coat bolom.	Prototype	Canfranc
BINGO [75]	^{100}Mo		Li$^{enr}MoO_4$	Development	LNGS
CUPID [28]	^{100}Mo	450 kg	Li$^{enr}MoO_4$,scint. bolom.	Proposal	LNGS
China-Europe [76]	^{116}Cd		$^{enr}CdWO_4$ scint. crystals	Development	CJPL
COBRA-XDEM [77]	^{116}Cd	0.32 kg	^{nat}Cd CZT semicond. det.	Operation	LNGS
Nano-Tracking [78]	^{116}Cd		^{nat}Cd CdTe. det.	Development	
TIN.TIN [79]	^{124}Sn		Tin bolometers	Development	INO
CUORE [10]	^{130}Te	1 ton	TeO_2 bolometers	Operating	LNGS
SNO+ [80]	^{130}Te	3.9 t	0.5-3% ^{nat}Te loaded liq. scint.	Commissioning	SNOLab
nEXO [29]	^{136}Xe	5 t	Liq. ^{enr}Xe TPC/scint.	Proposal	
NEXT-100 [81]	^{136}Xe	100 kg	gas TPC	Construction	Canfranc
NEXT-HD [81]	^{136}Xe	1 ton	gas TPC	Proposal	Canfranc
AXEL [82]	^{136}Xe		gas TPC	Prototype	
KamLAND-Zen-800 [13]	^{136}Xe	745 kg	^{enr}Xe disolved in liq. scint.	Operating	Kamioka
KamLAND2-Zen [41]	^{136}Xe		^{enr}Xe disolved in liq. scint.	Development	Kamioka
LZ [83]	^{136}Xe	600 kg	Dual phase Xe TPC, nat./enr. Xe	Operation	SURF
PandaX-4T [63]	^{136}Xe	3.7 ton	Dual phase nat. Xe TPC	Operation	CJPL
XENONnT [84]	^{136}Xe	5.9 ton	Dual phase Xe TPC	Operating	LNGS
DARWIN [85]	^{136}Xe	50 ton	Dual phase Xe TPC	Proposal	LNGS
R2D2 [86]	^{136}Xe		Spherical Xe TPC	Development	
LAr TPC [87]	^{136}Xe	kton	Xe-doped LR TPC	Development	
NuDot [88]	Various		Cherenkov and scint. in liq. scint.	Development	
Theia [89]	Xe or Te		Cherenkov and scint. in liq. scint.	Development	
Slow-Fluor [90]	Xe or Te		Slow Fluor Scint.	Development	

Перспективы использования двухфазных детекторов в БНО

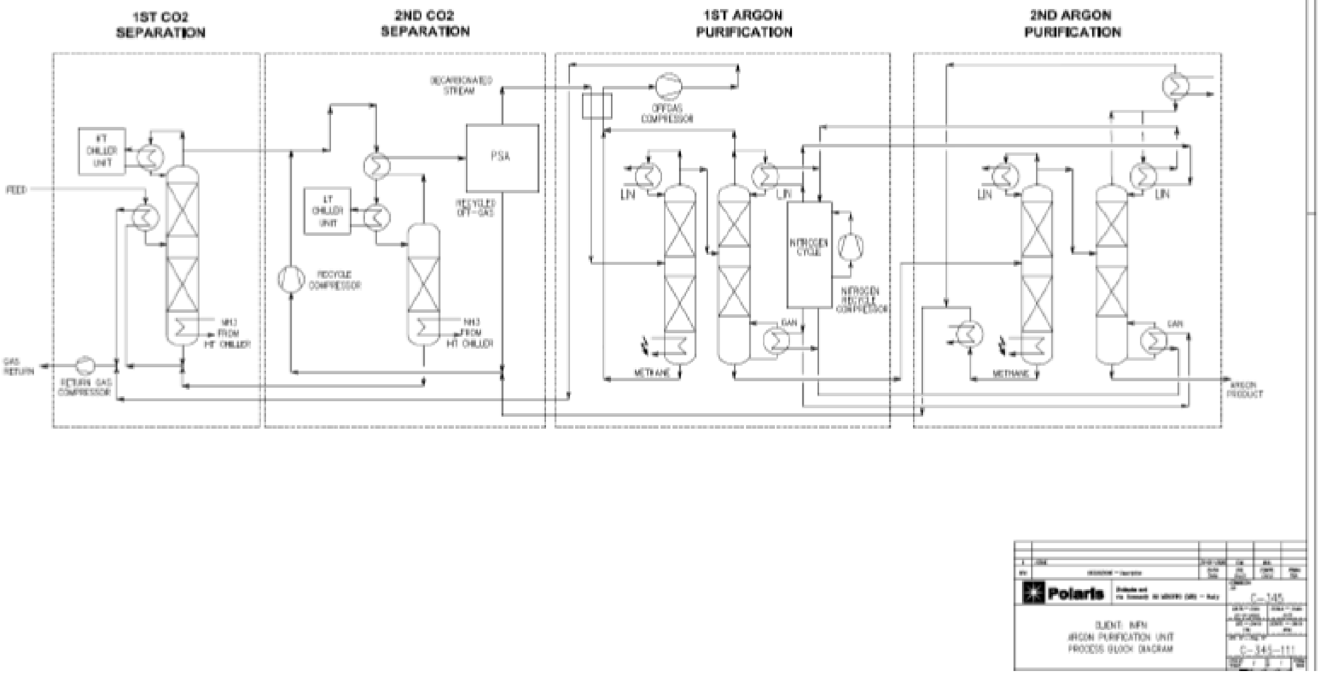
Проведение R&D работ

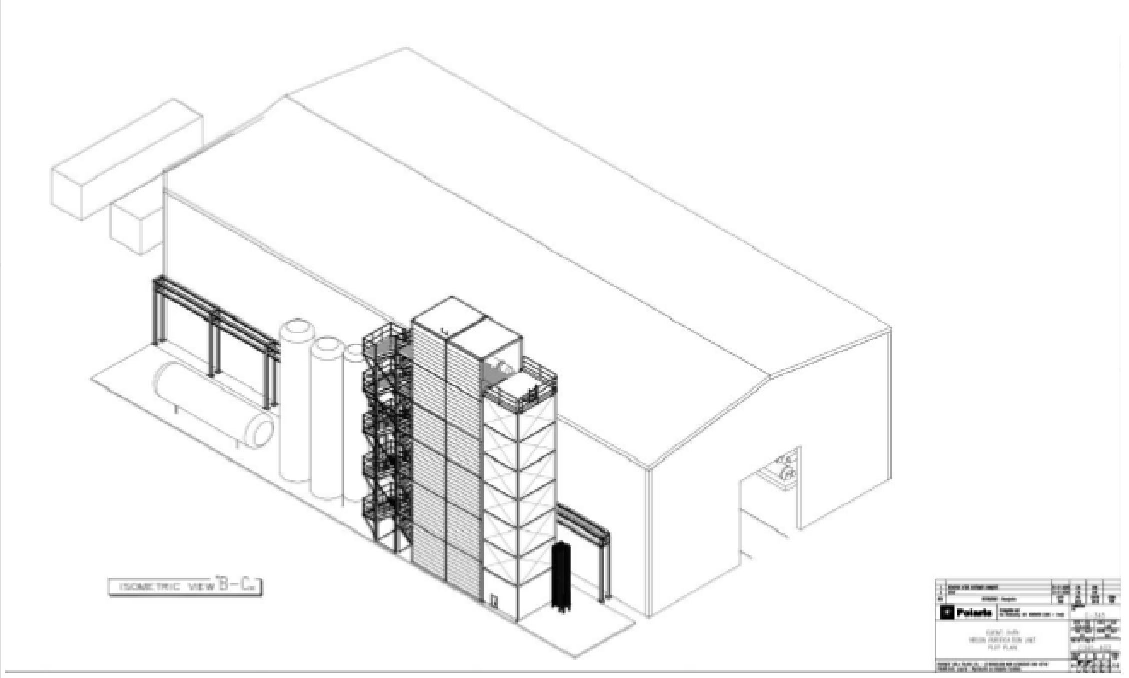
1. Изучение фона: тип защиты, конструкционные материалы (титан/нержавеющая сталь)
2. Разработка «новых» фотосенсоров (отечественное производство ФЭУ, SiPM)
3. Разработка системы очистки Xe, для больших объемом благородных газов (Kr-85 H-3, O_2, N_2 и т.д.)
4. Разработка технологии добычи подземного аргона, или производство «обедненного» аргона (без Ar-39 и Ar-41)
5. Изучение одноэлектроных шумов, снижение порога детектора
6. Обогащенный ксенон по Xe-136 для поиска БДБР, масса > 5 тонн
7. Синтез «шифтера» 1,1,4,4-тетрафинил-1,3-бутадиен (TPB), «смещение» VUV Lar с 128 нм в область 420 нм (если не использовать) чувствительные к VUV фотосенсоры

Запасные слайды

Urania

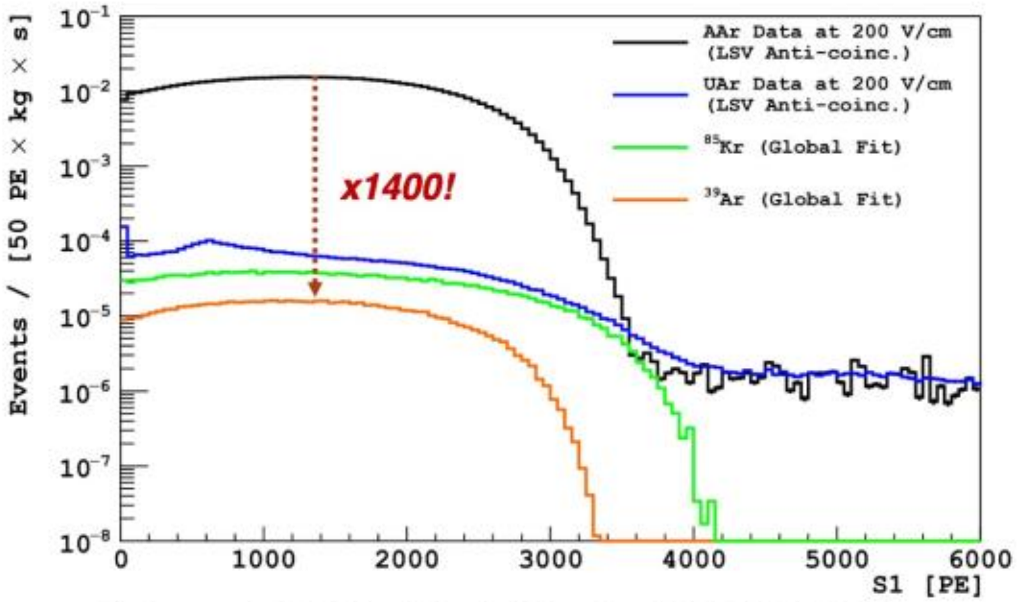
- will be located next to the previous location in Colorado, USA
- will extract UAr from same source as DS-50
- extraction and chemical purification plant to be built by Polaris
- capable of extracting UAr at rate of 300 kg/day with 99.99% purity



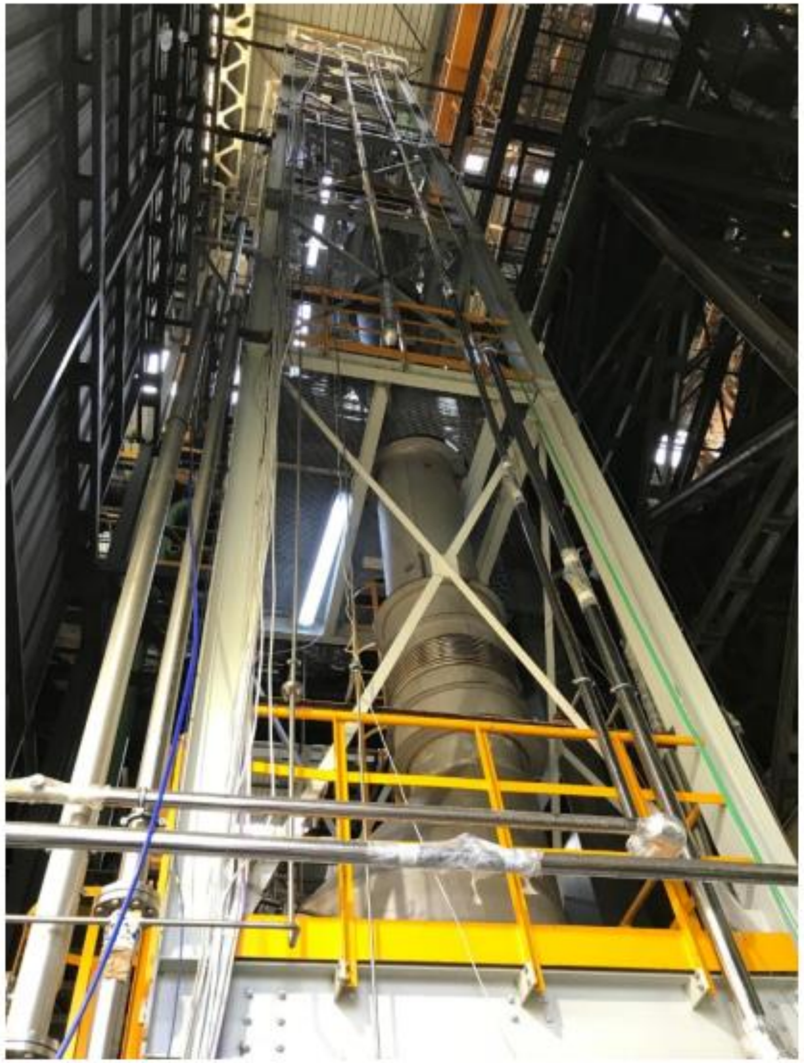


Dealing with radio contaminant in argon

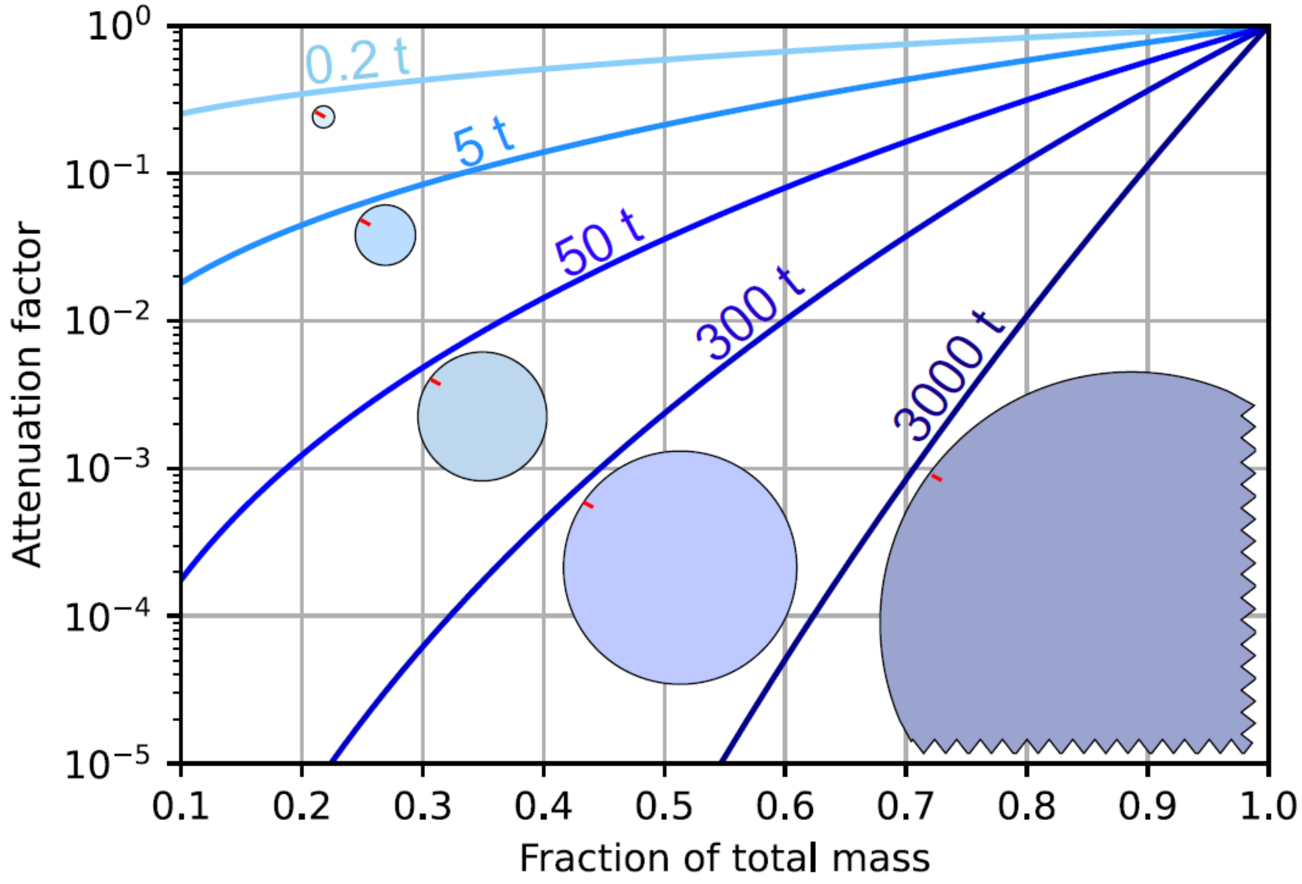
- ^{39}Ar is a cosmogenic background in argon from the atmosphere (~1 Bq/kg)
- Argon from certain underground sources are depleted of ^{39}Ar
- Further isotopic purification through cryogenic distillation is possible



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

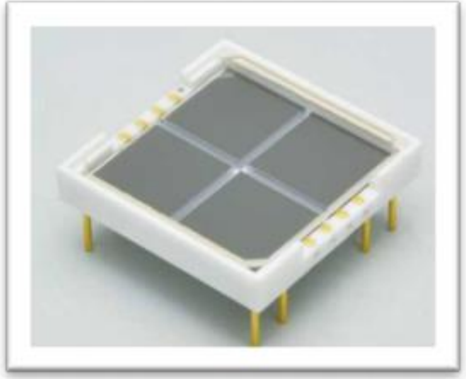


Длина пробега гамма-кванта с энергией 2,5 МэВ (~ 8,5 см), в зависимости от размера детектора

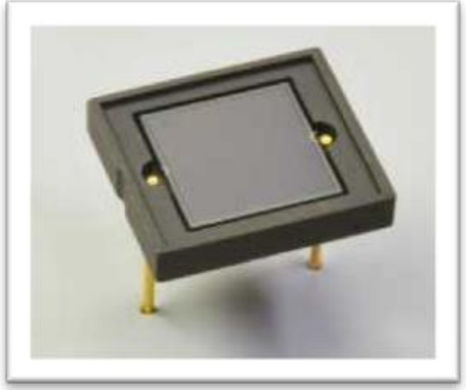


- Hamamatsu has developed a generation of VUV-sensitive Silicon PhotoMultipliers (SiPMs)
  - Appreciable Photon Detection Efficiency (PDE) down to argon scintillation wavelengths
- Main goal: quantify the performance of Hamamatsu's VUV4 SiPMs for:
  - Direct argon scintillation light detection
  - General operation in liquid argon

Hamamatsu VUV4 units to be utilized

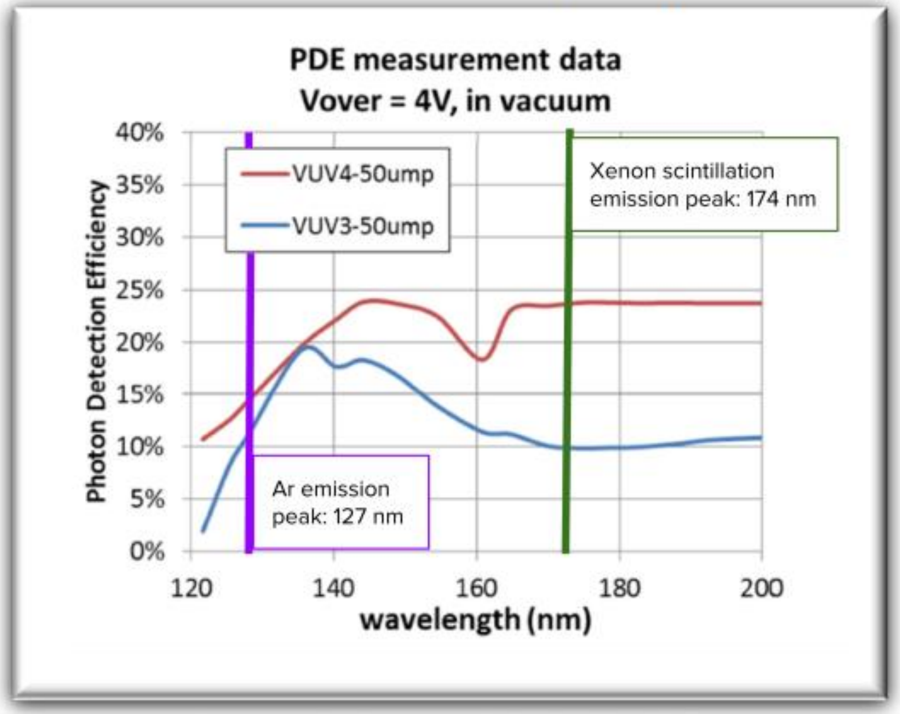


S13371 series

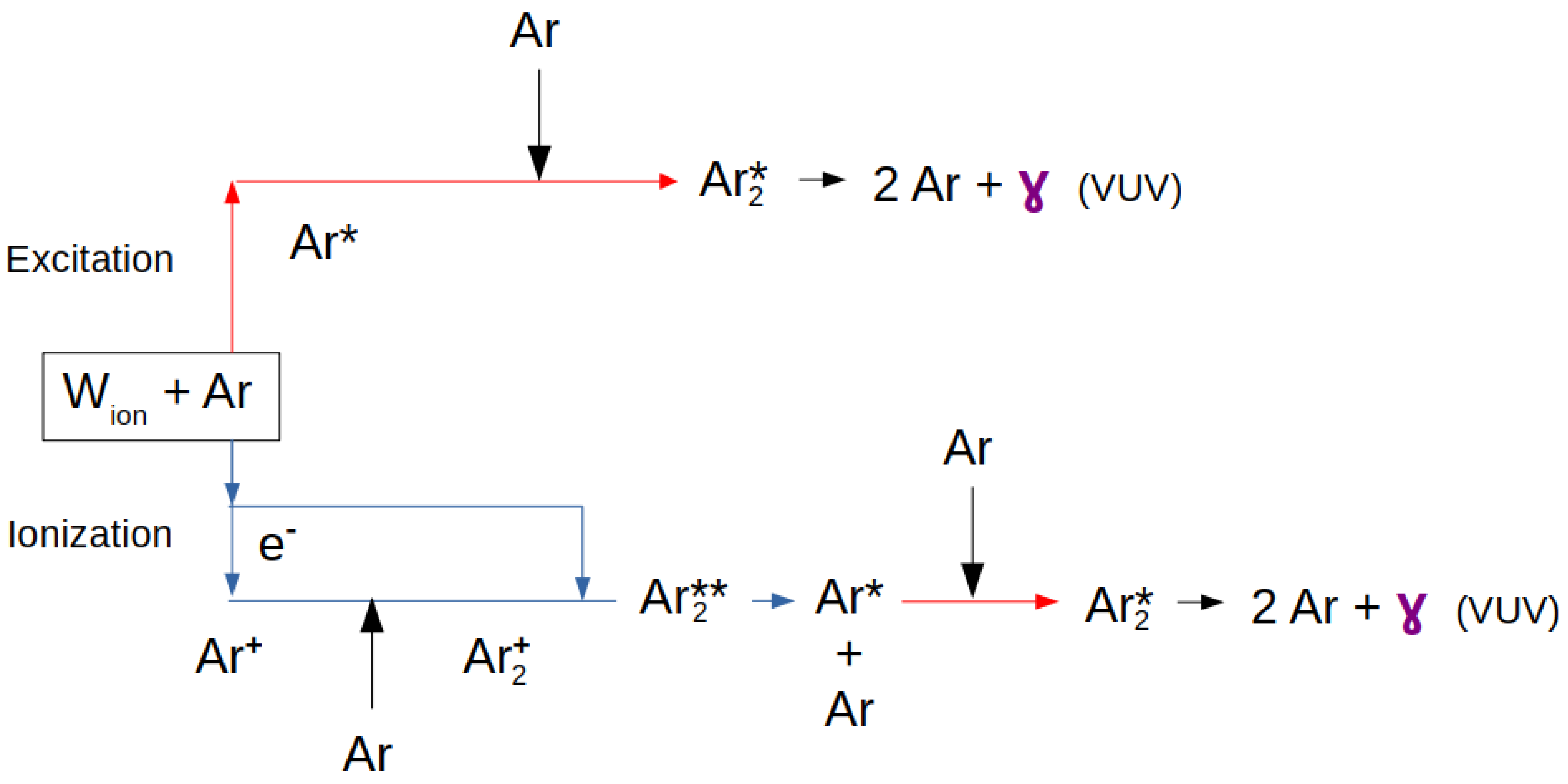


S13370 series

Quoted PDEs for VUV4 and prev. generation



Scintillation light production

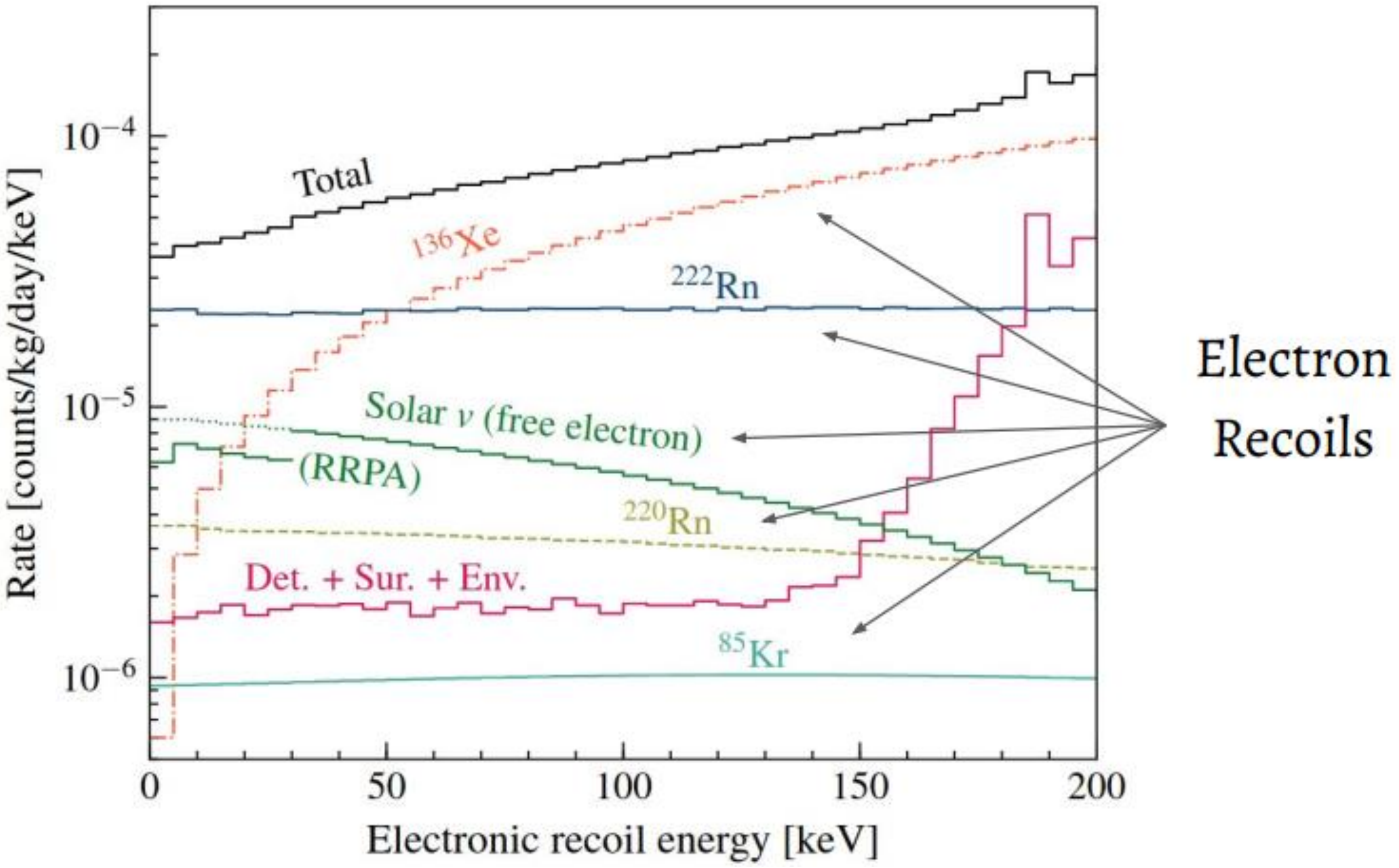


Backgrounds for Nuclear Recoil Searches

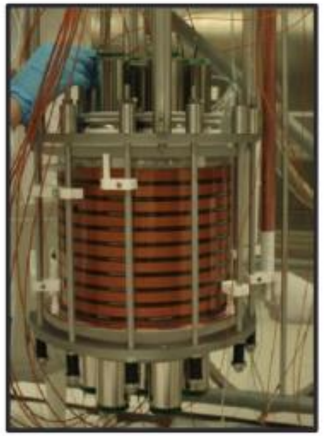
Dominant backgrounds for WIMP dark matter nuclear recoil (NR) searches are electron recoils (ER). Upcoming experiments will face challenging backgrounds that cannot be eliminated by shielding and fiducialization.

LUX-ZEPLIN Projections

Phys. Rev. D 101, 052002



The DarkSide Program



21 cm

2011 – 2013

DS-10

10 kg LAr

Gran Sasso, IT

First functional prototype in program

36 cm

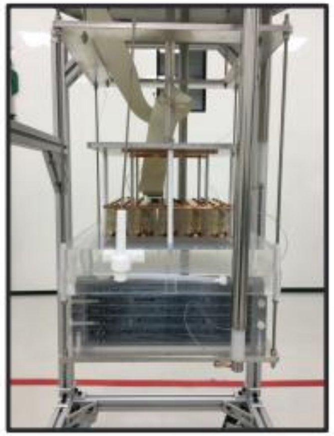
2013 – 2020

DS-50

46 kg LAr

Gran Sasso, IT

$3.78 \cdot 10^{-44}$ cm^2 @ 1 TeV (1.4 yr exposure)



36 cm

2019 – 2020

DS-Proto0

10 kg LAr

CERN, CH

Test bench for new DS-20k technologies

58 cm

2022

DS-Proto1

175 kg LAr

CERN, CH

Validation of detector and PDM components

360 cm

2025 –

DS-20k

20 t LAr

Gran Sasso, IT

$7.4 \cdot 10^{-48}$ cm^2 @ 1 TeV (10 yr exposure)

loading...

Proposed

ARGO & DS-LowMass

Proposed detectors to push below neutrino floor and expand mass sensitivity

Property	Gas scintillation wavelength	Gas scintillation lifetime	Liquid phase ionization energy	Ease of purification	Kinetic match to light particles
Argon	128 nm	~ 3.2 μs	14.3 eV	Easier	A = 39.95
Xenon	178 nm	~ 22 ns	12.13 eV	Difficult	A = 131.29

XENONnT TPC photosensor

3" R11410-21 photomultiplier tubes

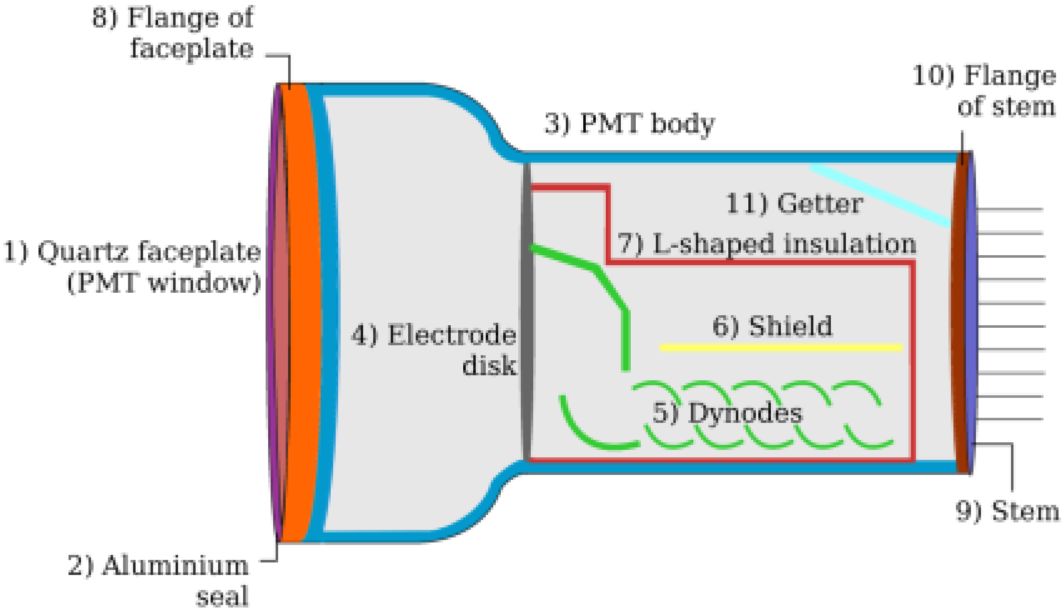
Low radioactivity components

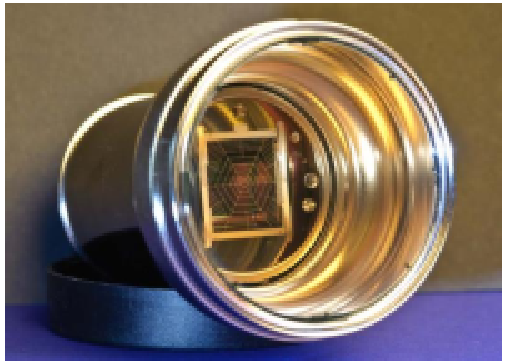
Reliable at liquid xenon temperature

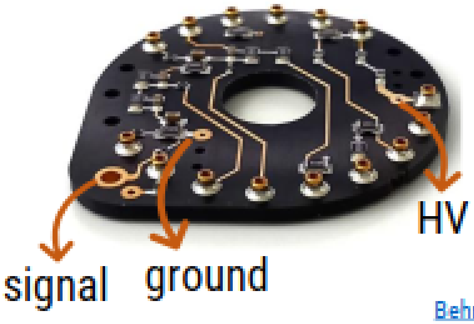
High performances at xenon scintillation light ($\overline{QE}|_{175\ nm} = 34\%$)

Linearity conserved up to 1 MeV

Low power dissipation into the detector[1]







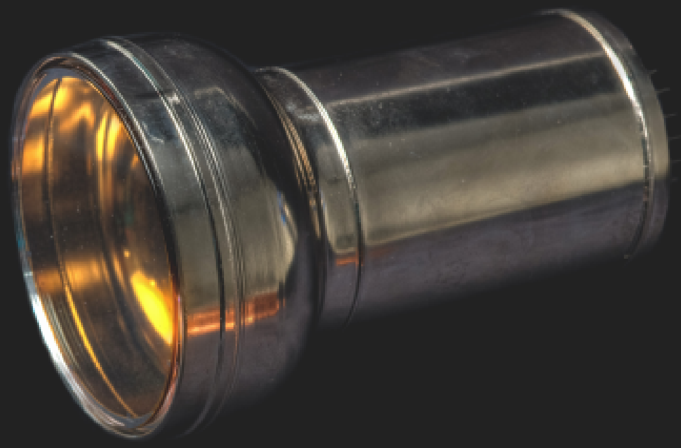
(1) 0.024 W at -1500 V with total resistance of 92.5 MΩ

Behrens A. (PhD thesis, UZH)
Mayani D. (PhD thesis, UZH)

THE HAMAMATSU R11410 PHOTOMULTIPLIER TUBE

THE PHOTOSENSOR OF CHOICE FOR LXE TPCS (XENON, LZ, PANDAX, NEXT, RED, …)

- 3″ window, VUV-transparent silica
- Low-temperature bi-alkali photocathode: QE 30% - 40% at 175 nm
- Low dark count rate: O(10) Hz at -100°C
- Low intrinsic radioactivity: < 13 mBq/PMT in ^{238}U and 0.4 +- 0.1 mBq/PMT in ^{228}Th EPJC 75, 546 (2015)



LARGE SCALE PMT TESTING

- Known issues: Light emission and imperfect leak tightness
- Developed new and improved old PMT testing strategies to detect these issues
- Tested in total 368 new R11410-21 PMTs for the XENONnT experiment over several years
- Results are published: V.C. Antochi et al 2021 JINST 16 P08033, (arxiv)