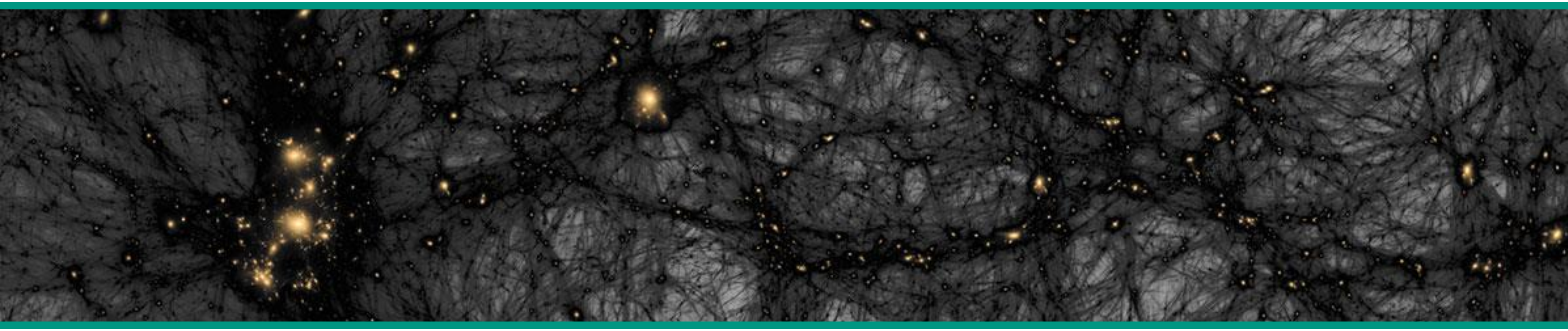
Karlsruhe Institute of Technology

Karlsruhe Institute of Technology

Astroparticle physics I – Dark Matter

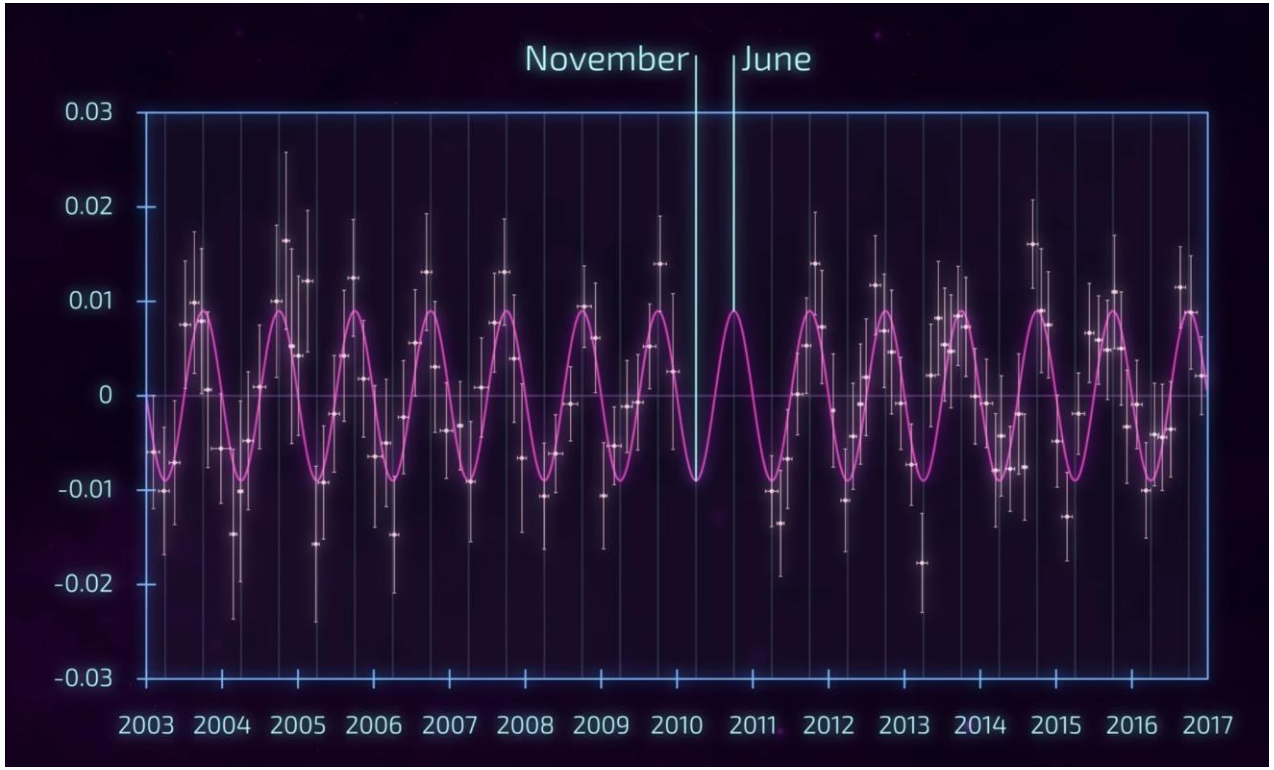
WS22/23 Lecture 18 Feb. 1, 2023



Recap of Lecture 17

- **Evidences & upper limits: DAMA & 1-phase Liquid Noble gas experiments**

  - DAMA-Libra: $\mathbf{250\ kg\ NaJ}$ scintillator crystals at $LNGS$ (low background) seasonal variation of rate over many years– is this a WIMP or systematics?



Recap of Lecture 17

- **Evidences & upper limits: DAMA & 1-phase Liquid Noble gas experiments**

  - DAMA-Libra: $\boldsymbol{250\ kg\ NaJ}$ scintillator crystals at $LNGS$ (low background) seasonal variation of rate over many years– is this a WIMP or systematics?

  - other $\boldsymbol{NaJ}$ experiments (and $\boldsymbol{LXe/LAr}$ detectors) exclude WIMP interpretation

  - scintillation process of liquid noble gases: formation of excimers & subsequent decay lead to emission of $\boldsymbol{VUV}$ light ($\boldsymbol{LAr}$ requires $\boldsymbol{WLS}$)

  - **argon** detectors: intrinsic background from β –decay of $\boldsymbol{^{39}Ar}$ (⇨ **UAr**) big advantage: pulse shape allows to suppress background (´WIMP sprinter´)

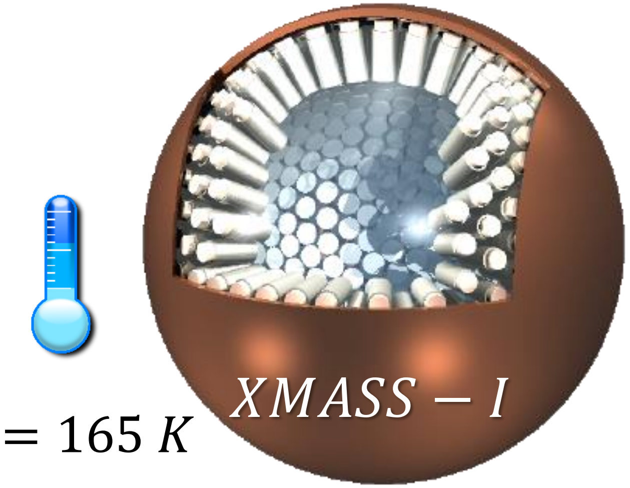
  - **xenon** detectors: cryodistillation of $\boldsymbol{^{85}Kr}$ - very pure target in fiducial volume

Liquid Xenon experiments: XMASS

- **XMASS* - a** single-phase LXe –detector **at the Kamioka mine in Japan**

  - XMASS-I exposure: $\boldsymbol{M \cdot t = 832\ kg \cdot 16\ months}$

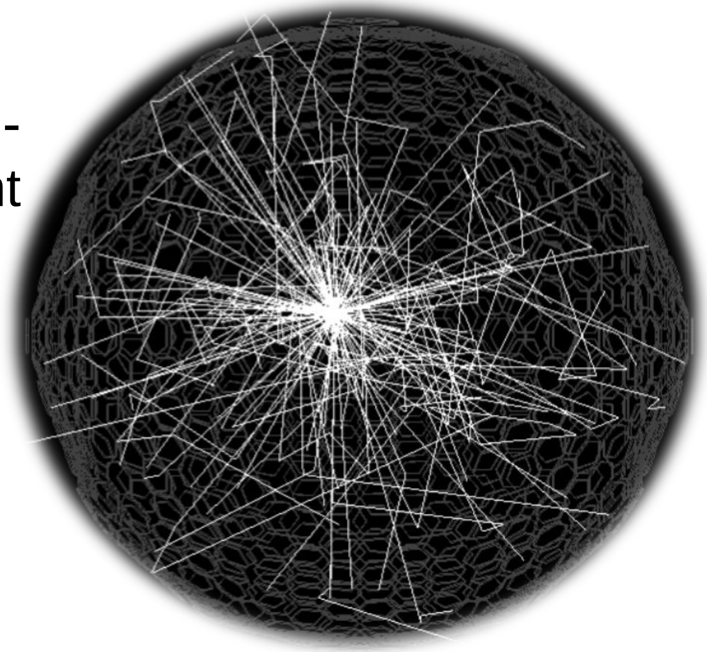
  - search for yearly modulation in data: no signal!

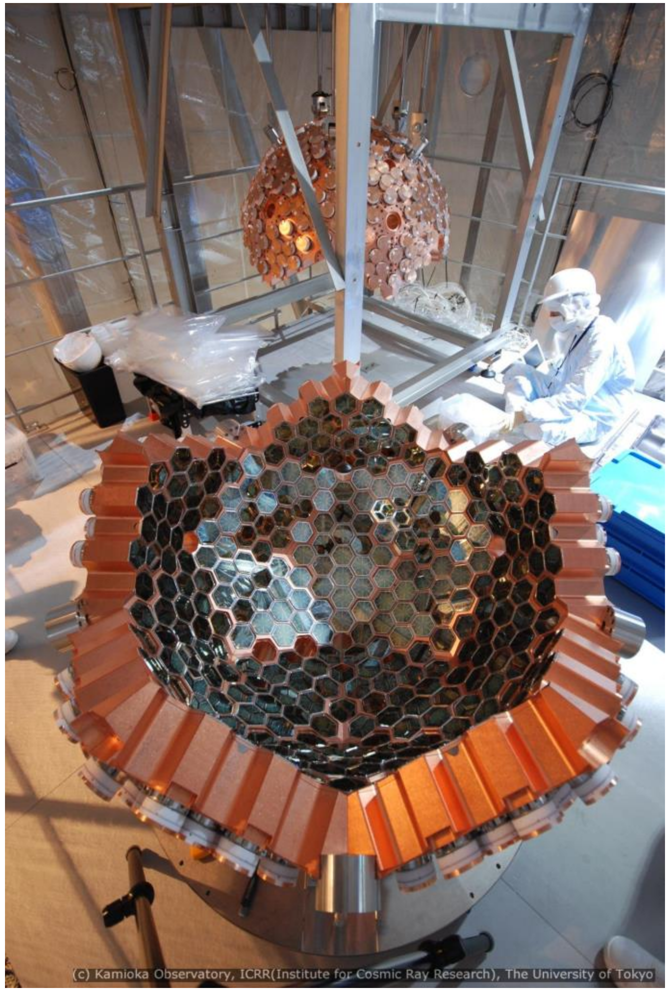


$T = 165\ K$

$\boldsymbol{M = 800\ kg\ (100\ kg\ fiducial)}$

scintillation-
light





*Xenon detector for Weakly Interacting **MASS**ive Particles

Liquid Xenon experiments: XMASS

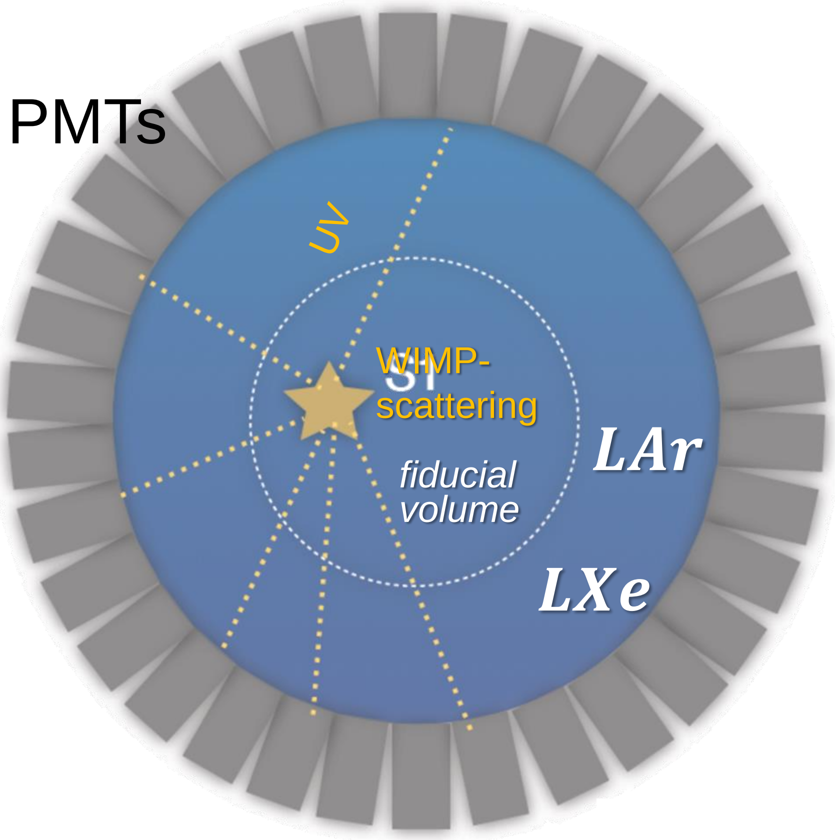
- **Projected increase in single-phase target mass by factor 30**

  - single-phase detector lacks $\boldsymbol{PID}$ provided by scintillation + ionization

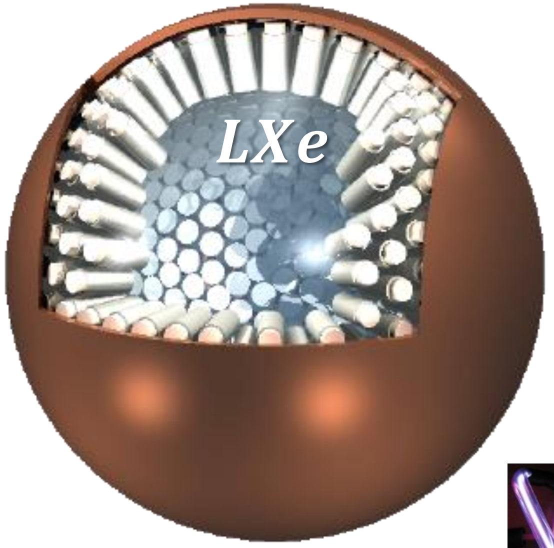
  - 2017: joining XENON (**2-phase-detector**)

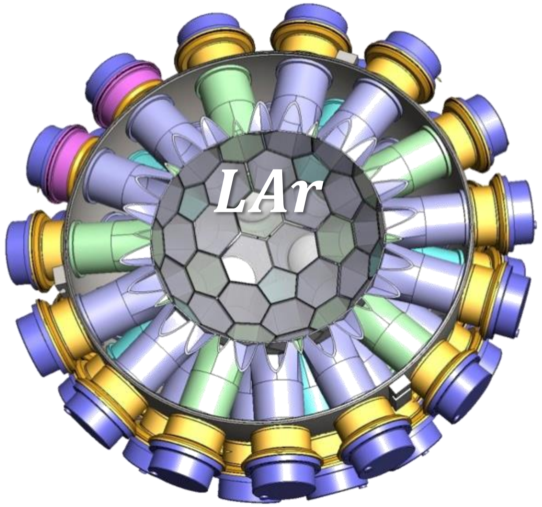
Liquid noble gas experiments: 2-phase detectors

- **Read-out of scintillation light + ionization: much better PID**



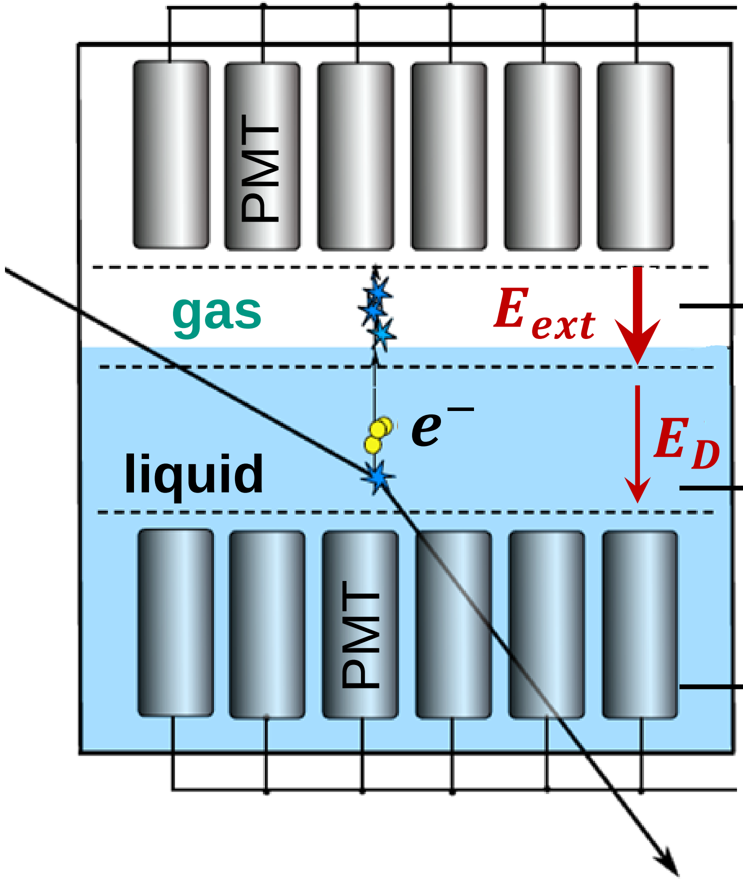
- all single-phase-projects with LAr & LXe (read-out of scintillation light only) were cancelled!





Liquid noble gas experiments: 2-phase detectors

- **Read-out of scintillation light + ionization: much better PID**



2-phase-noble gas detectors: the ultimate in DM

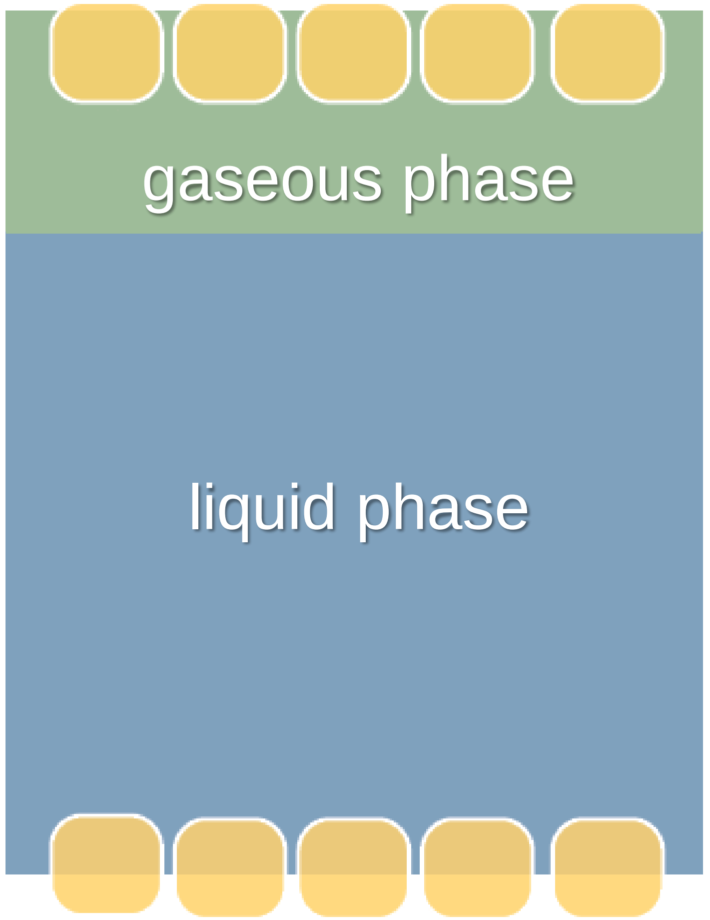
gaseous noble gas: read-out of ionisation signal via process of **electroluminescence (EL)**

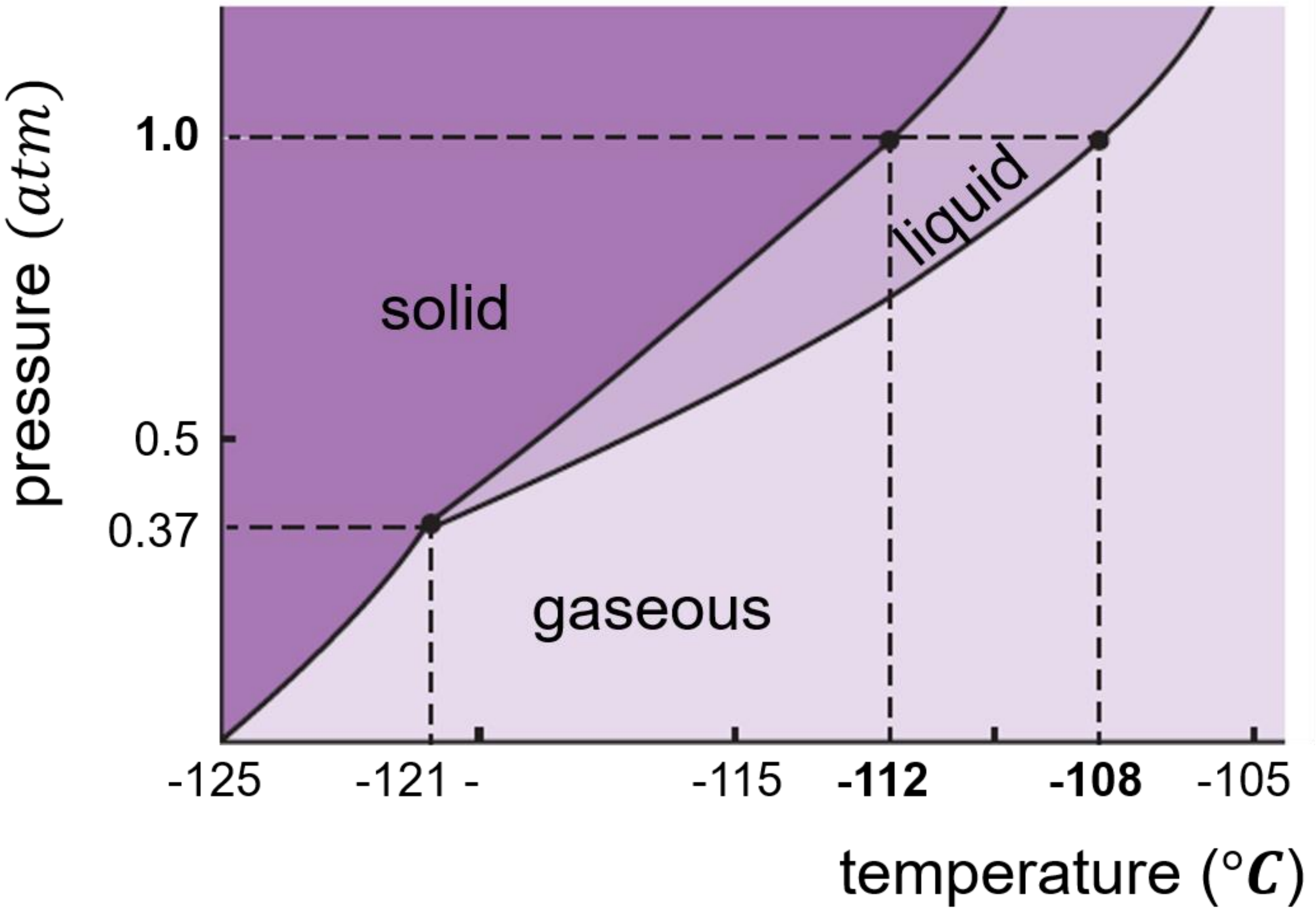
liquid noble gas: transport of the ionisation signal via electric field - constant **drift of e^-** to gas phase

top- & bottom PMT array: read-out of both the scintillation- & electroluminescence- light signal Ar (Xe) as detector medium with (without) WLS

Liquid noble gas experiments: 2-phase detectors

- **Operating temperature: thermodynamics of the liquid & gaseous phase**





Liquid noble gas experiments: 2-phase detectors

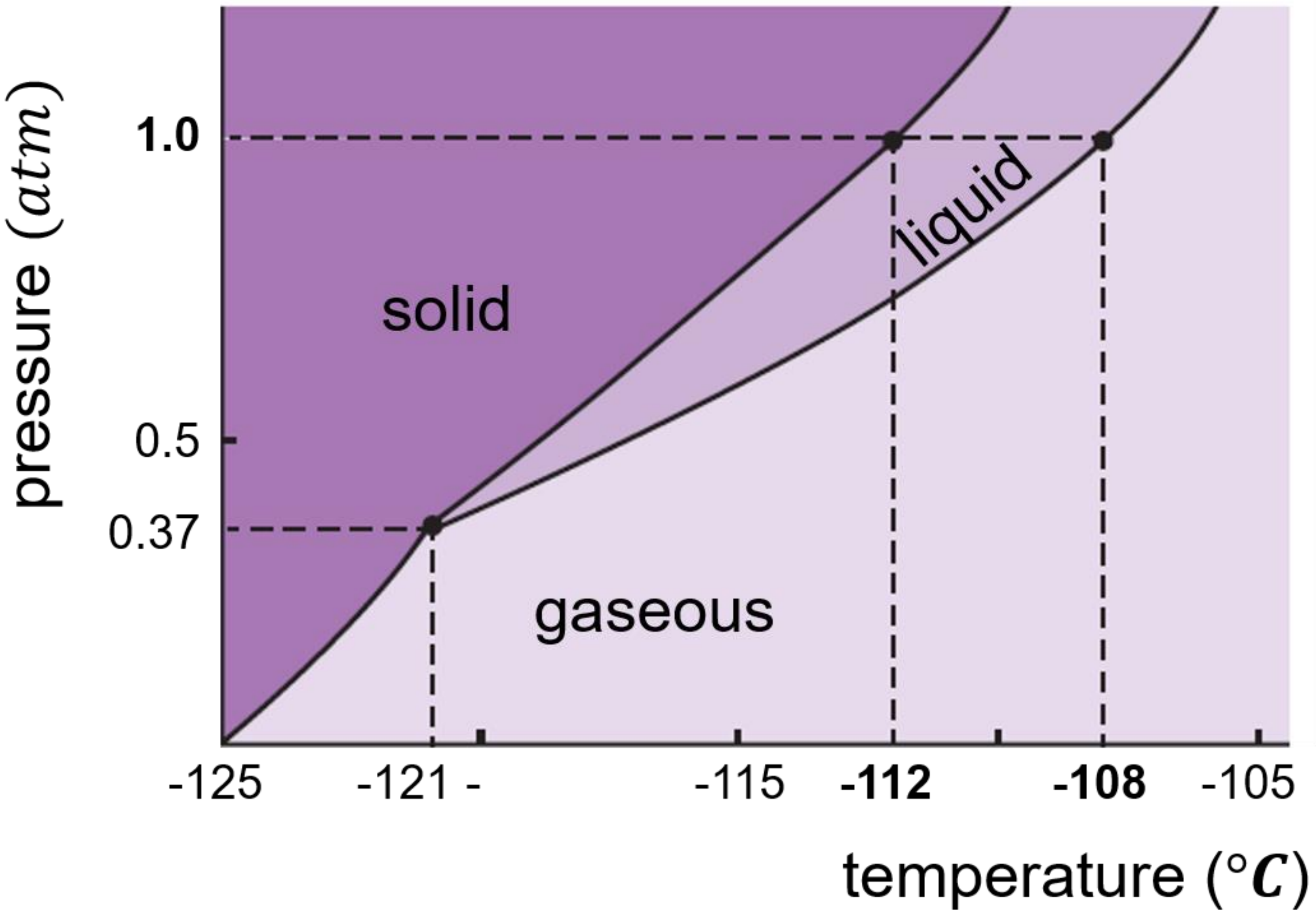
Karlsruhe Institute of Technology

- **Operating temperature: thermodynamics of the liquid & gaseous phase**

- operation of **Xe**-vessel at a **pressure p $\approx 1\ atm$**

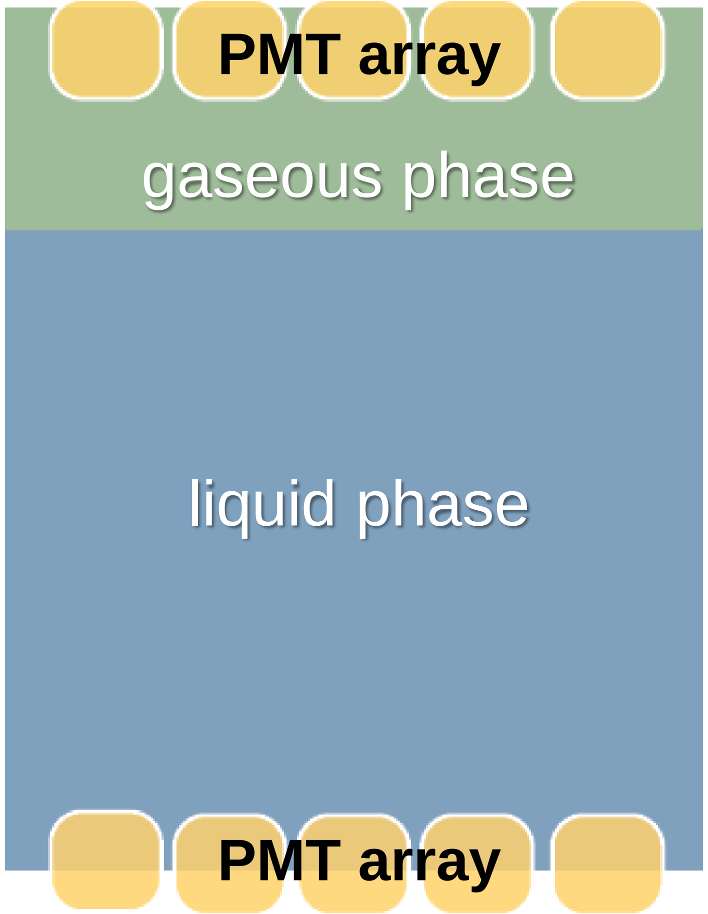
- cryo-cooling has to ensure $T = -108 \ldots -112\ °C$ to maintain the liquid state

- fine-tuning of temperature in the above range allows to adjust the pressure level of the gaseous phase above the liquid level



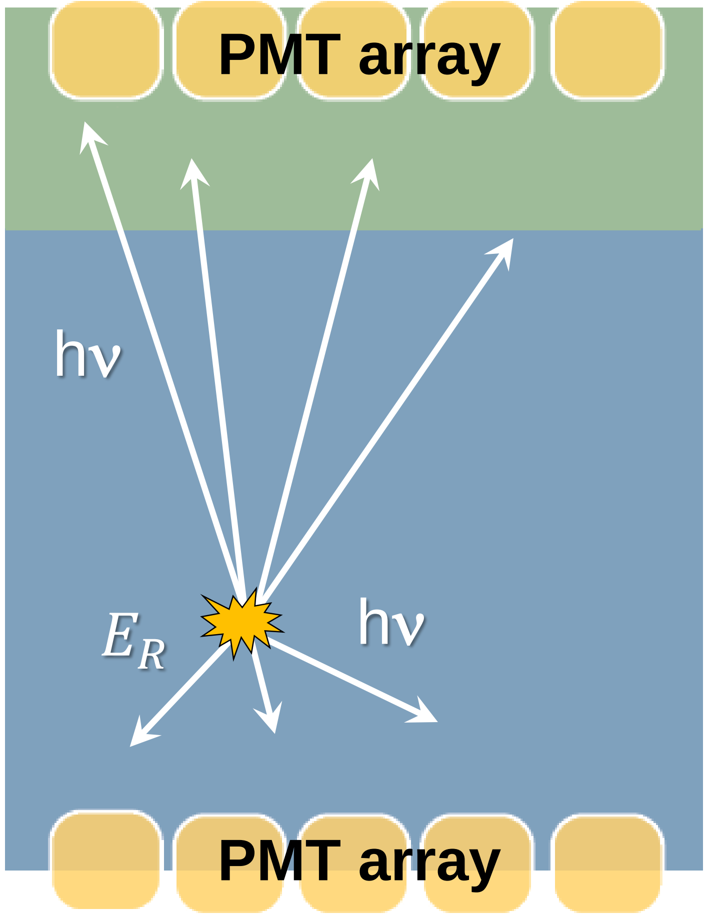
Liquid noble gas experiments: light detection

- **Top and bottom PMT arrays to detect VUV scintillation & light from EL**

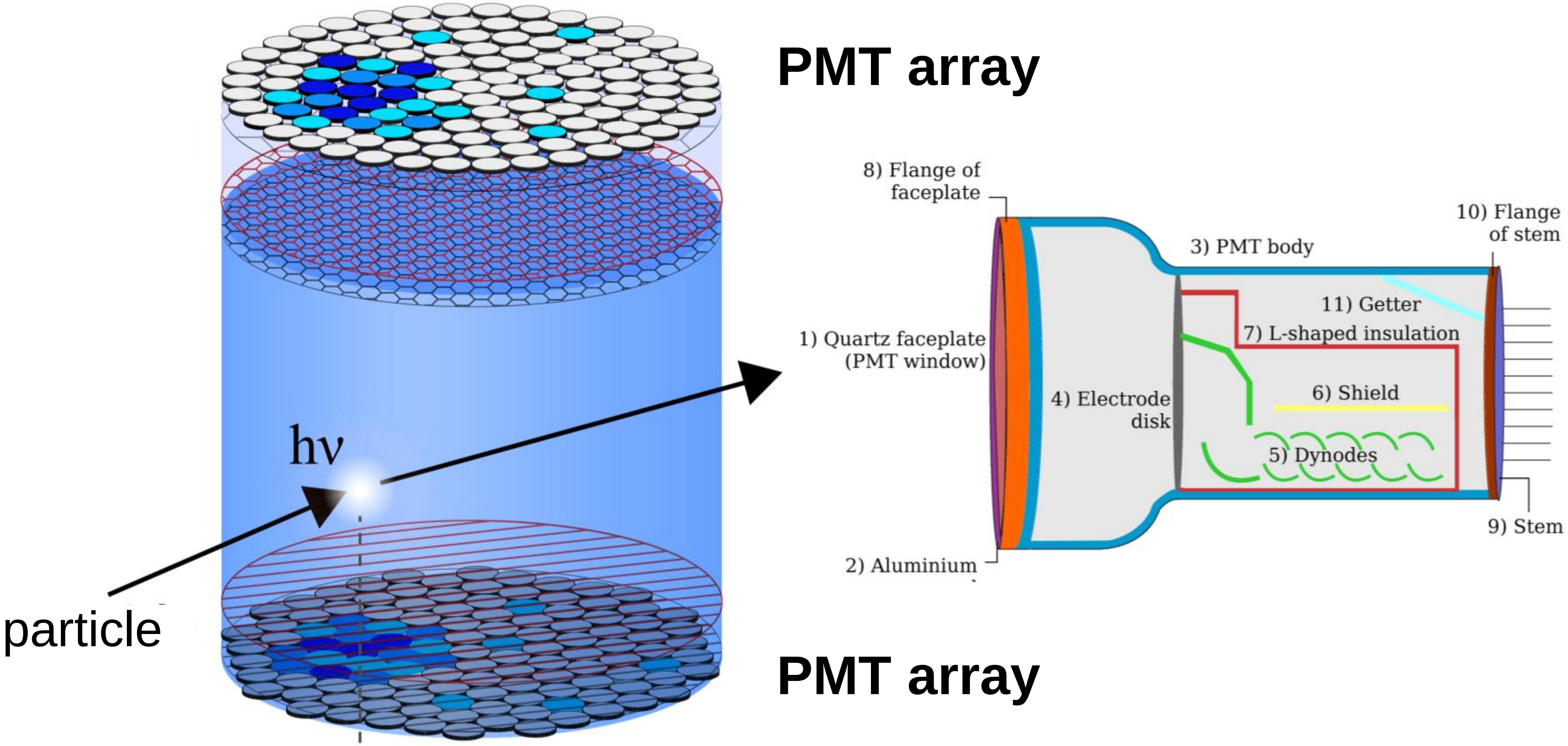


Liquid noble gas experiments: light detection

- Top and bottom PMT arrays to detect VUV scintillation & light from EL

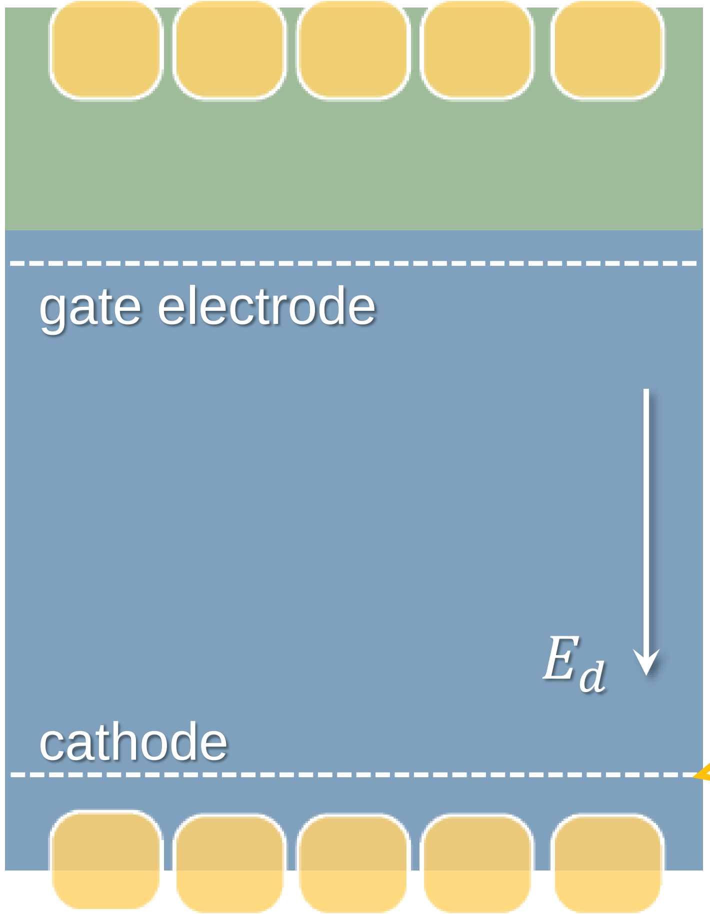


- detection of prompt scintillation light in the VUV range

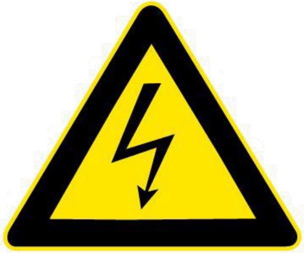


Liquid noble gas experiments: drifting of e^-

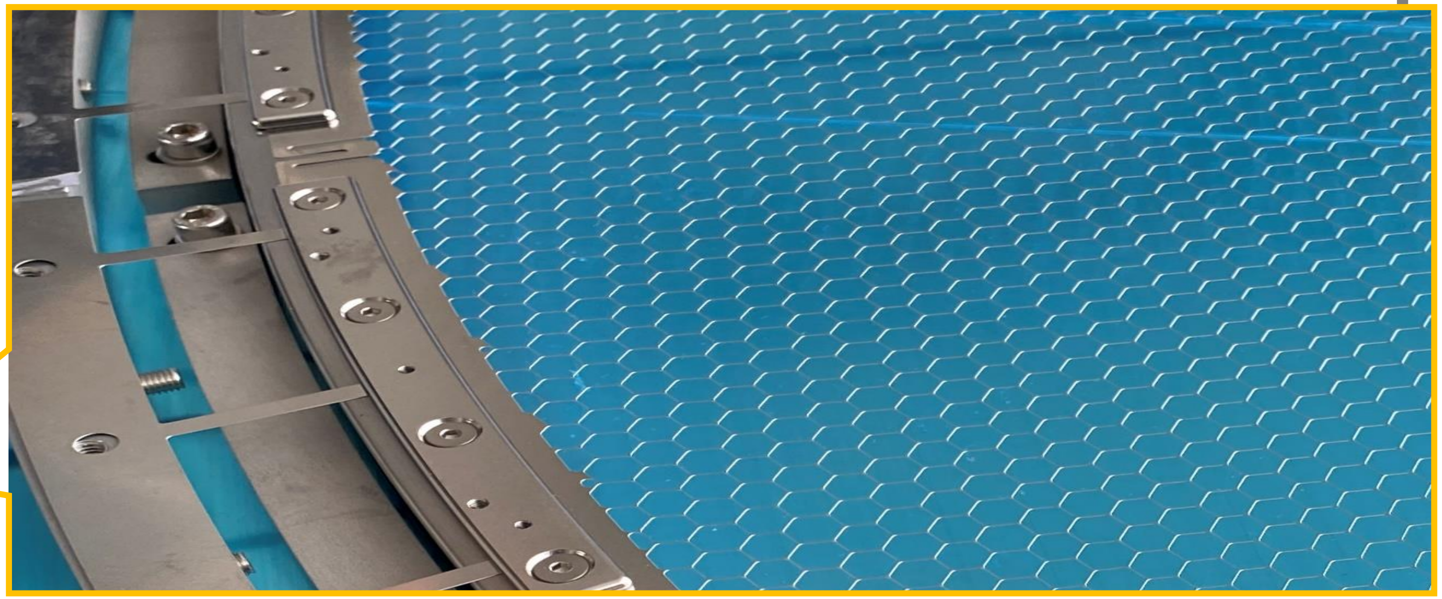
- Operated as Time Projection Chamber (TPC) to obtain 3D information



- generation of a homogeneous drift field $\boldsymbol{E_D}$ by applying HV to gate electrode

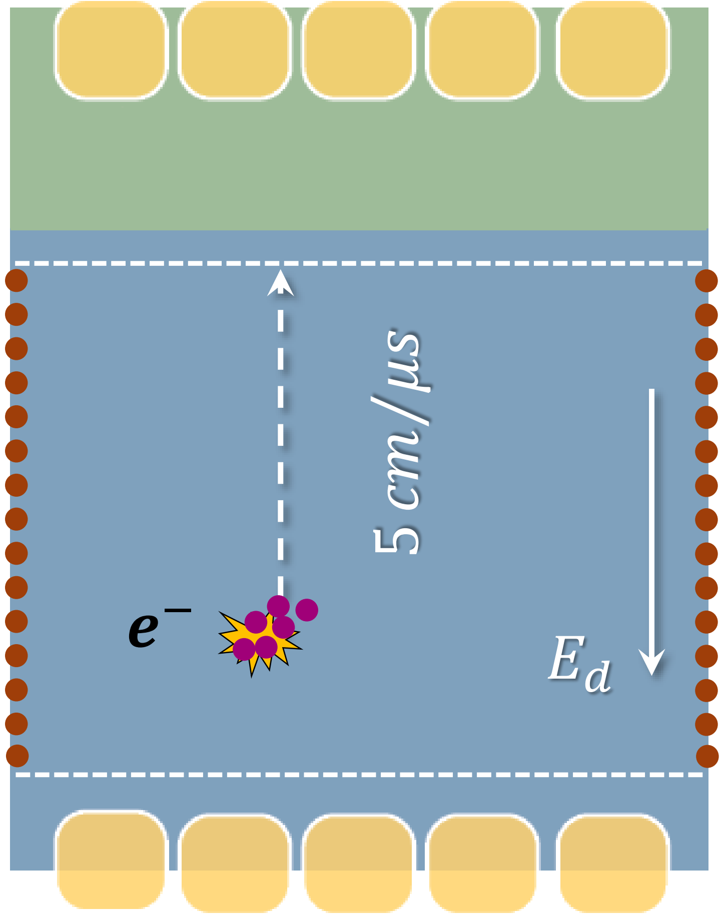


electrodes with $\varnothing = \mathbf{1.5}\ \boldsymbol{m}$ as mesh structure

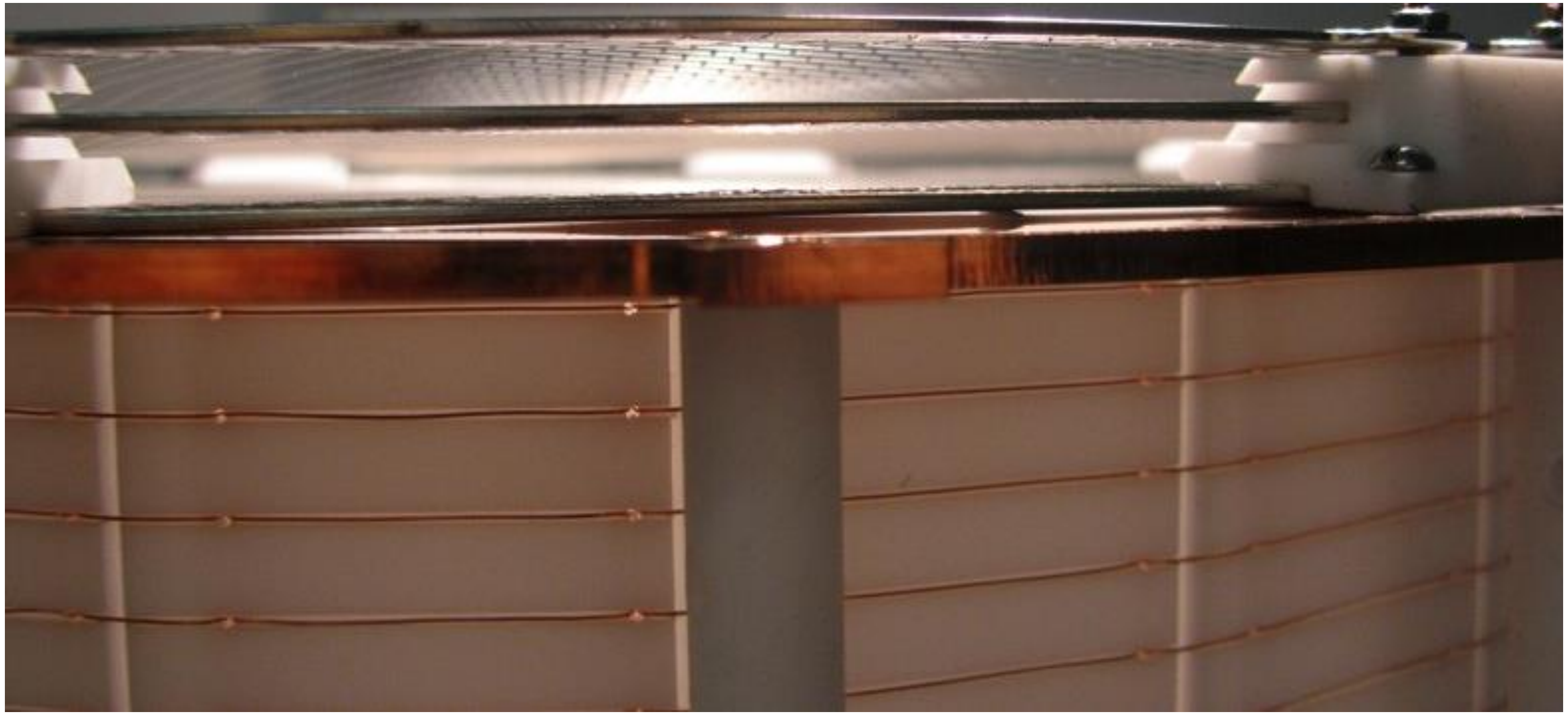


Liquid noble gas experiments: drifting of e^-

- **Operated as Time Projection Chamber (TPC) to obtain 3D information**

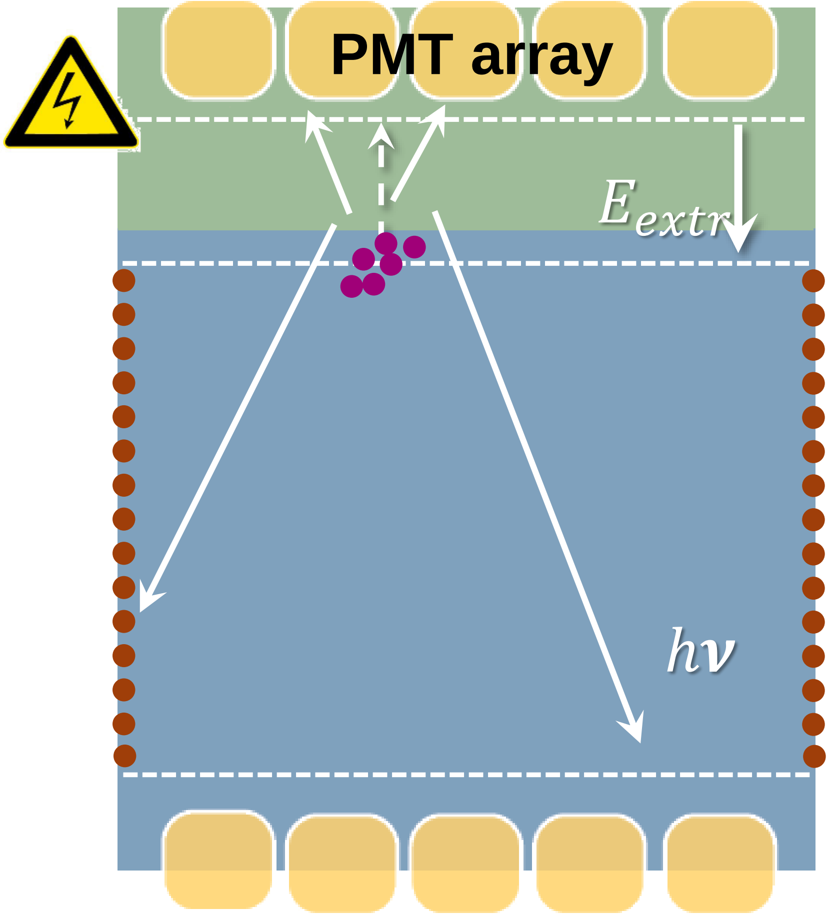


- field cage by ´**guard rings**´ to ensure homogeneity of E_D

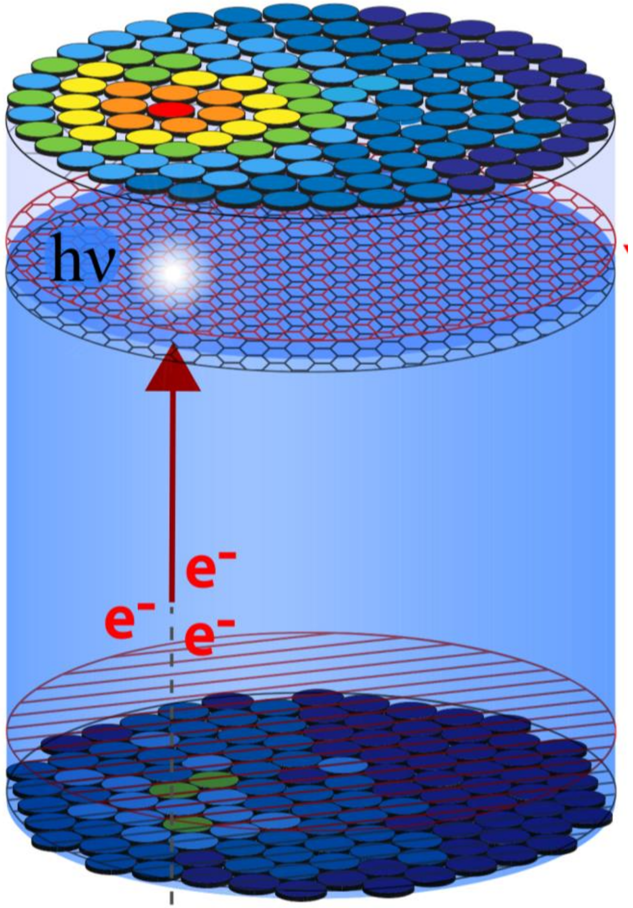


Redout of delayed light (EL) after drifting of e^-

- Applying a strong field to ´extract´ e^- into gaseous phase to induce EL



anode:
$+HV$

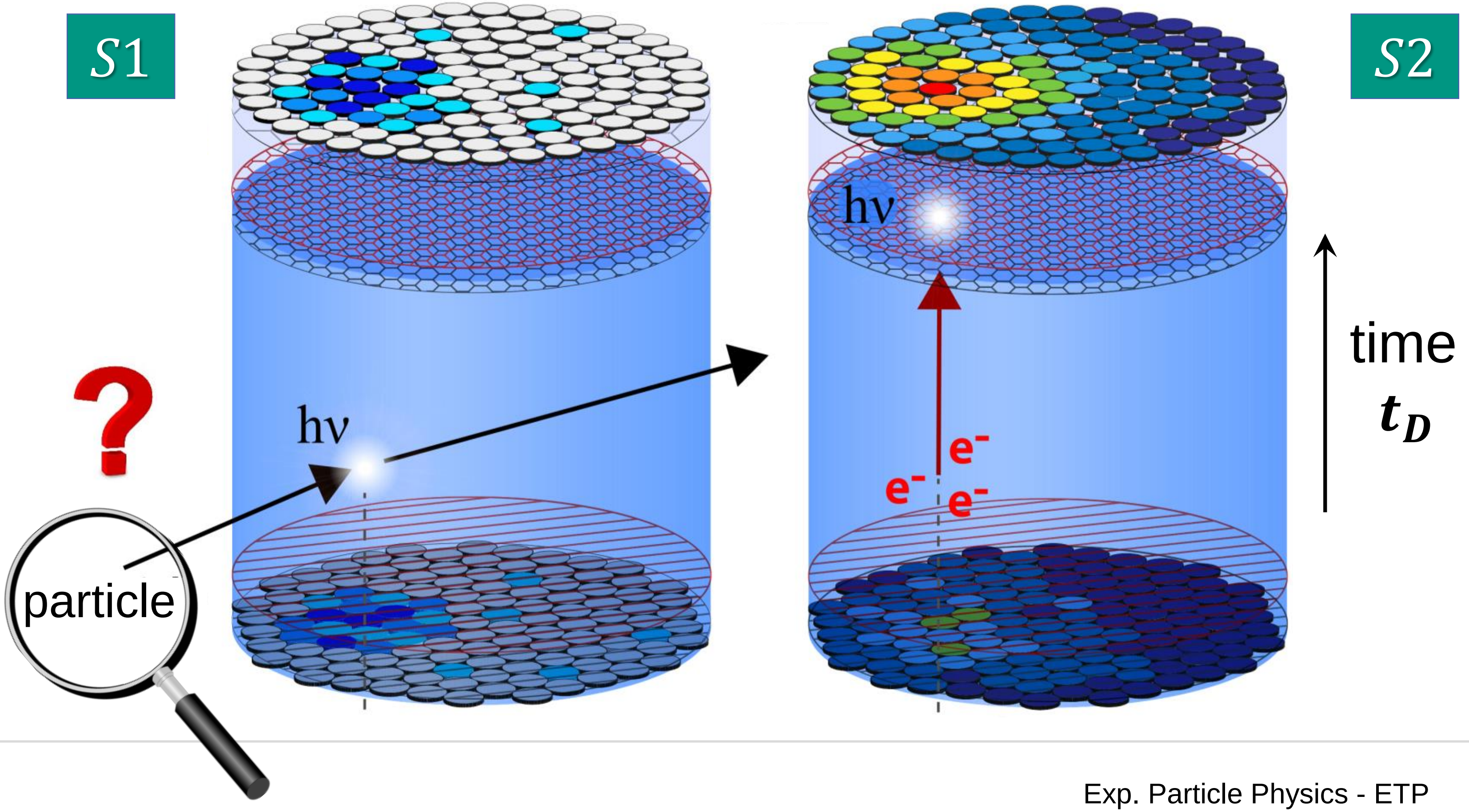


- electrons are being accelerated by a strong field $\boldsymbol{E_{extr}}$ towards the anode in the gas phase
- electrons collide with gas atoms, this causes **electroluminescence**
- electrons detected by $\boldsymbol{EL}$ light via PMT arrays

Liquid noble gas experiments: signals $S1$ and $S2$

- TPC principle: PMT hit pattern for (x,y) position, drift time t_D for z position

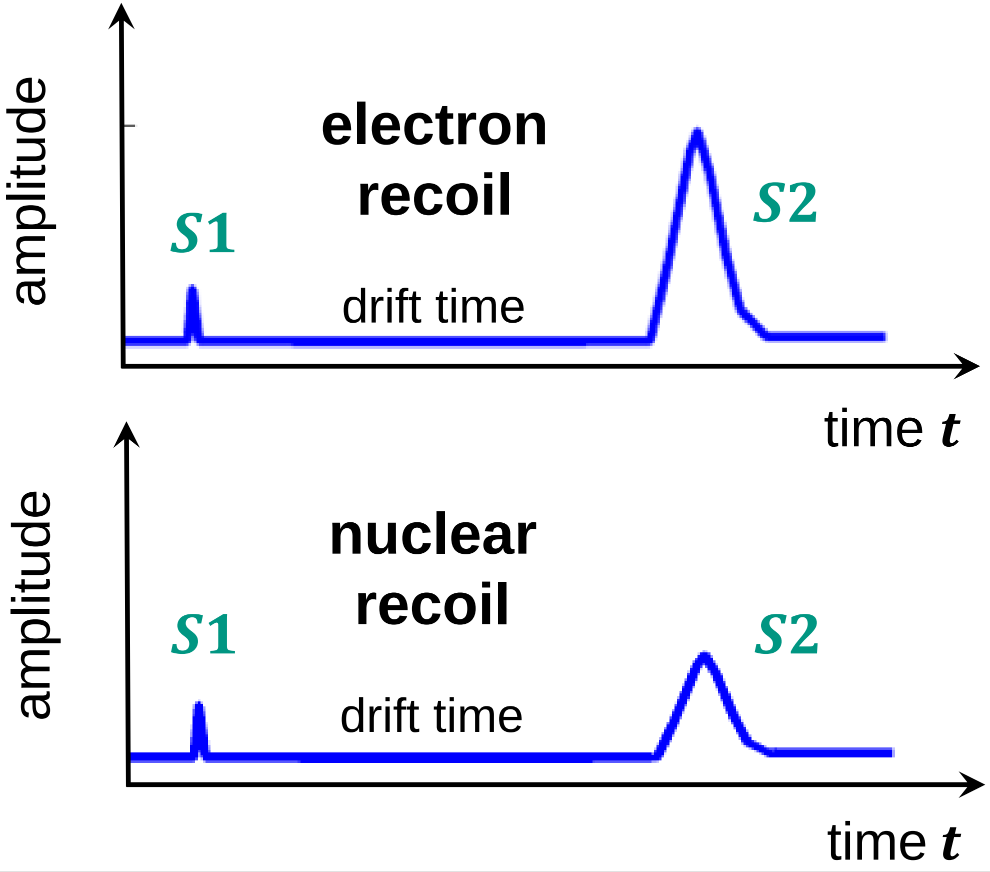
- scintillation light $S1$ & ionisation signal $S2$: perform **background discrimination**



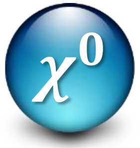
Liquid noble gas experiments: quenching of S2

- **Particle Identification via ratio $S2$ / $S1$ (ratio of delayed / prompt light)**

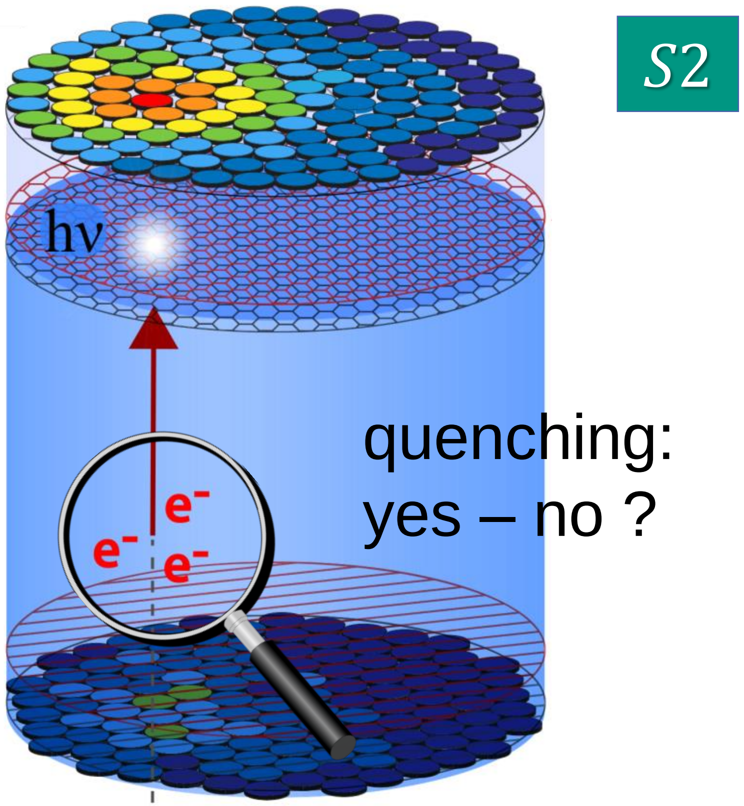
- ionization signal $S2$: **strong quenching in case of nuclear recoils**



$S2$ / $S1$ = large



$S2$ / $S1$ = small



Liquid noble gas experiments: quenching of S2

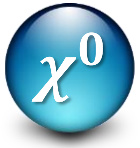
- **Particle Identification via ratio $S2$ / $S1$ (ratio of delayed / prompt light)**

- particle discrimination due to quenching of $S2$ for nuclear recoils

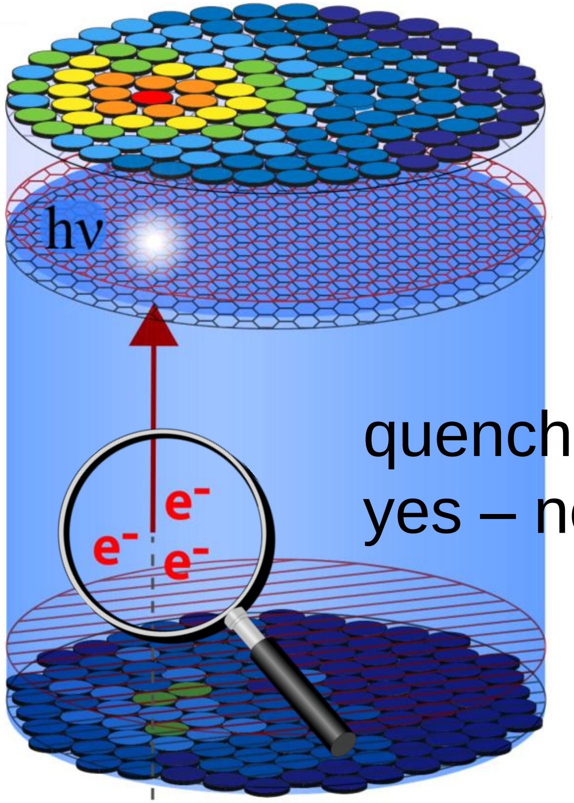
- very helpful for PID:
  signal $S2$ is ´amplified´ by
  electroluminescence

- recoil energy E_R
  signal $S1$ is independent of
  particle type (no quenching)
  ⇨ $S1$ determines energy
  of primary interaction
  ⇨ we aim for a very (very)
  low threshold for $S1$!

$S2$ / $S1$ = large



$S2$ / $S1$ = small



$S2$

quenching:
yes – no ?

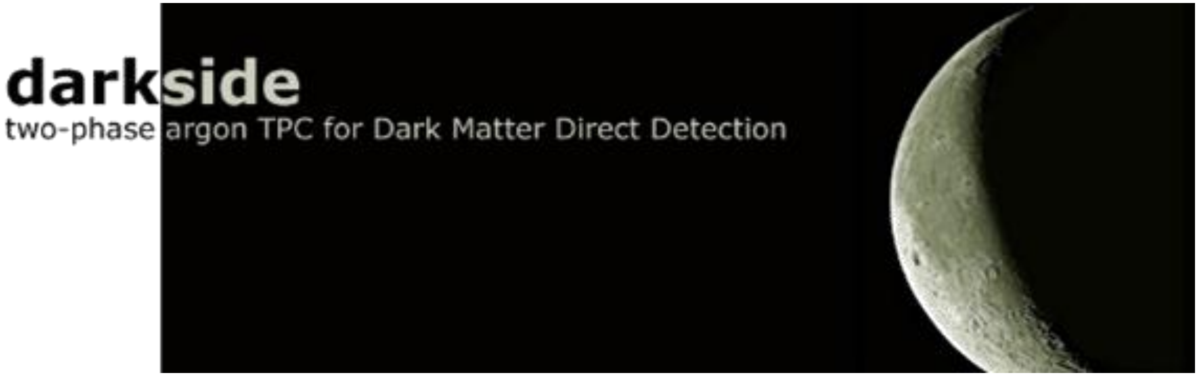
2-phase-experiments with argon: DarkSide 50

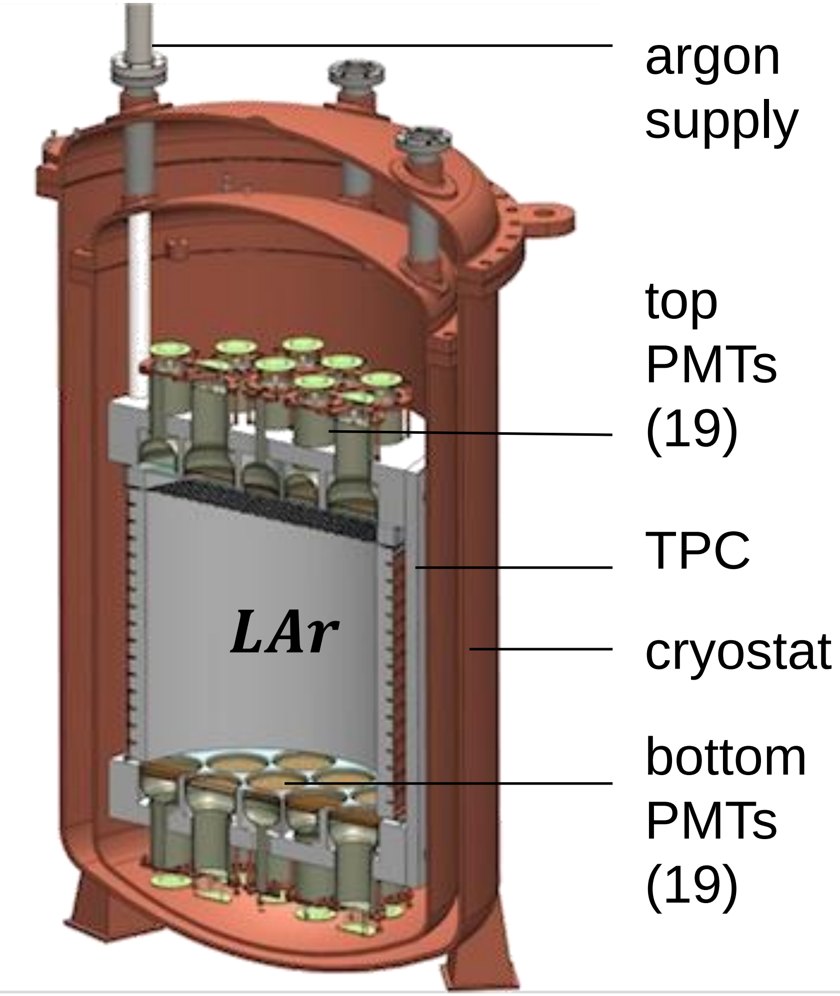
- **DarkSide 50: the first TPC in a series of experiments of increasing size**

  - location: hall C at $\boldsymbol{LNGS}$

  - total active mass: $\boldsymbol{m = 50\ kg}$

  - depleted $\boldsymbol{^{39}Ar}$ – fraction from an ´underground argon´ source in the US





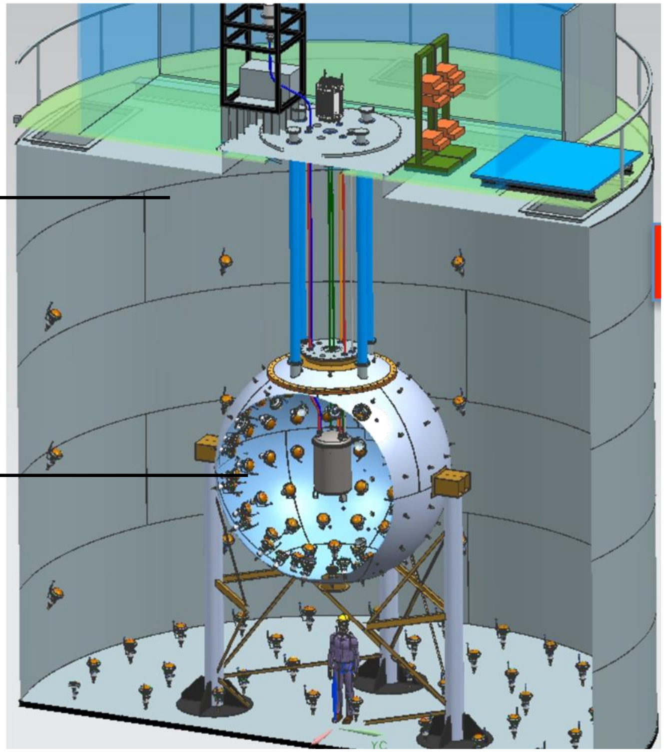
2-phase-experiments with argon: DarkSide 50

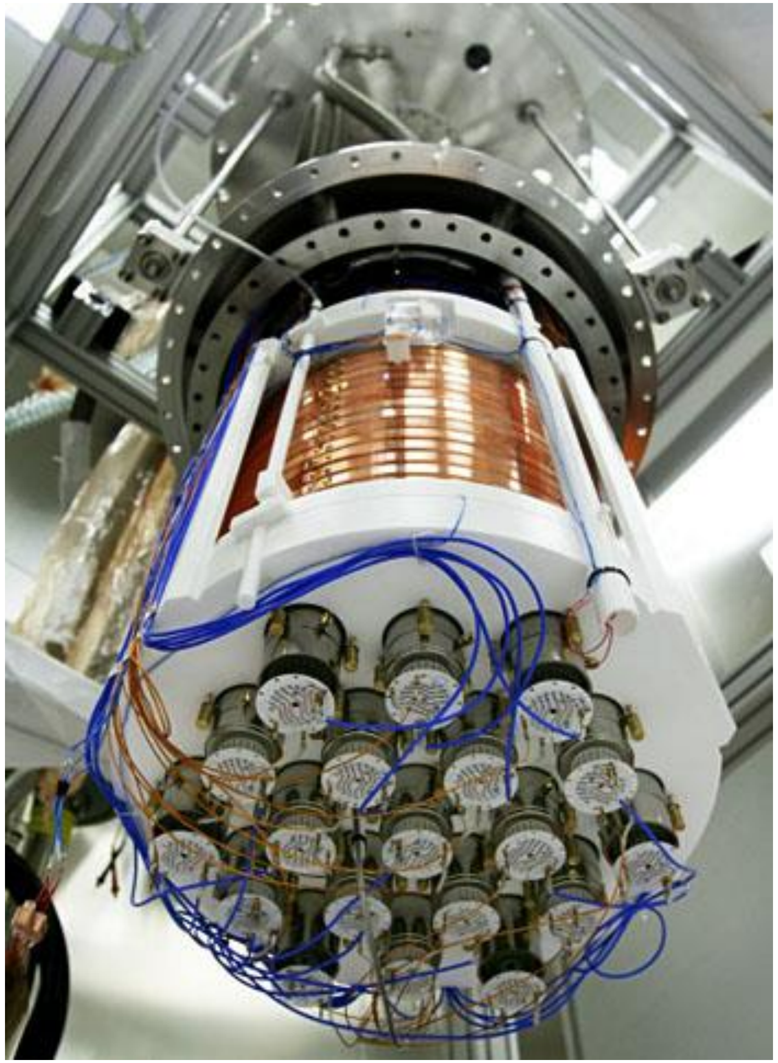
- **Setup: TPC surrouned by an inner & outer veto detector against external background**

- outer veto: using the former Counting Test Facility CTF of Borexino solar ν – experiment

outer H_2O Cherenkov-veto for μ – identification

inner liquid scintillator veto aginst μ – induced neutrons





DarkSide 50 – TPC setup in more detail

- **A prototype for todays much larger DM-detectors…**

anode (grounded) in gas-phase: $\boldsymbol{E_{extr} = 2.8\ kV/cm}$

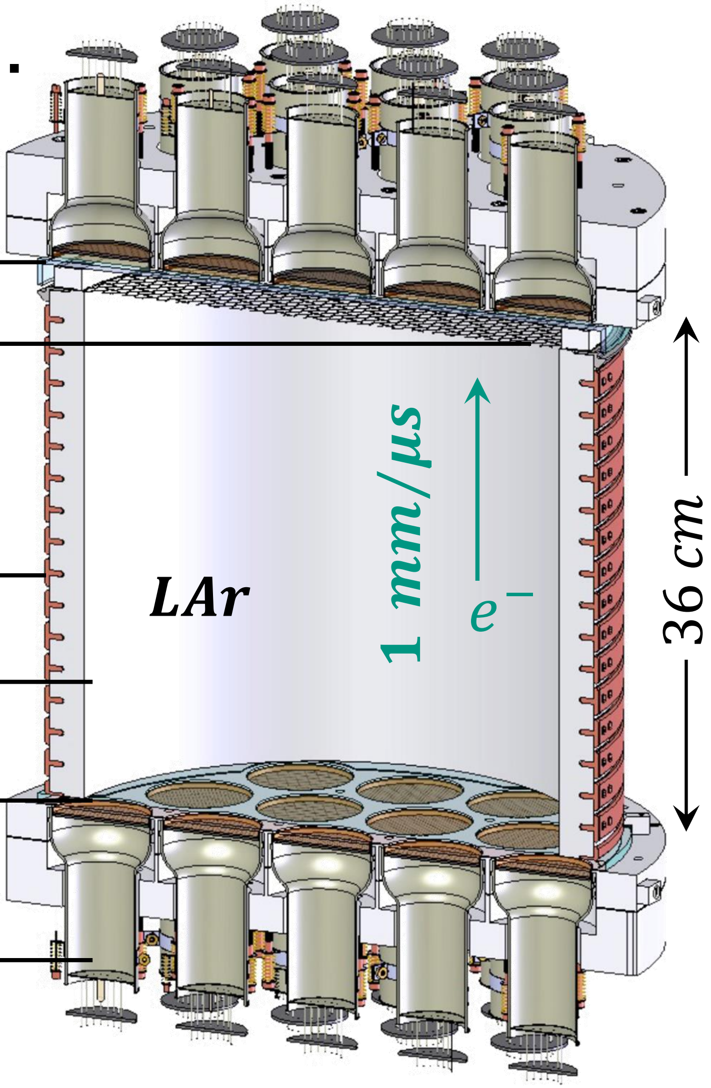
extraction grid for drifted $\boldsymbol{e^-}$
for transition liquid → gas

$\vec{\boldsymbol{E}}$ – field forming $\boldsymbol{Cu}$ – rings: $\boldsymbol{E_D = 200\ V/cm}$

PTFE (teflon) – reflector + WLS (TPB*)

cathode (up to $\boldsymbol{-60\ kV}$)

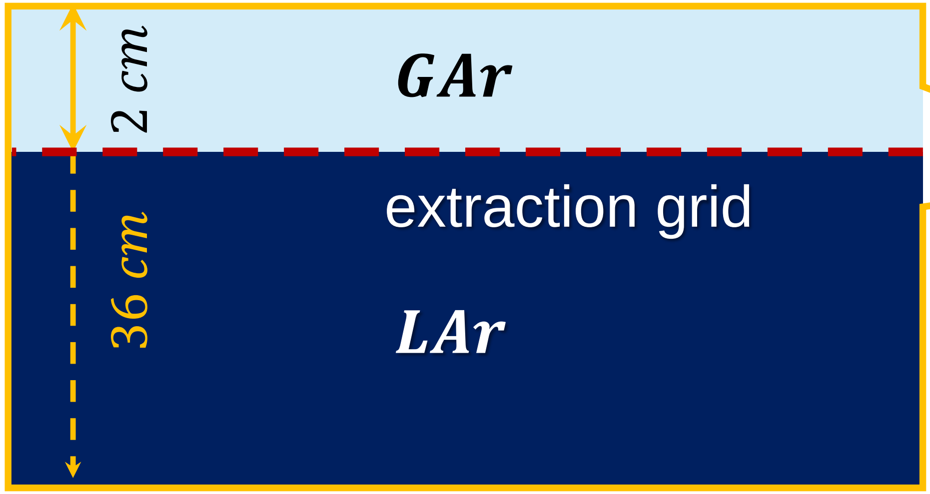
$3 - inch$ PMTs (Hamamatsu R11065)

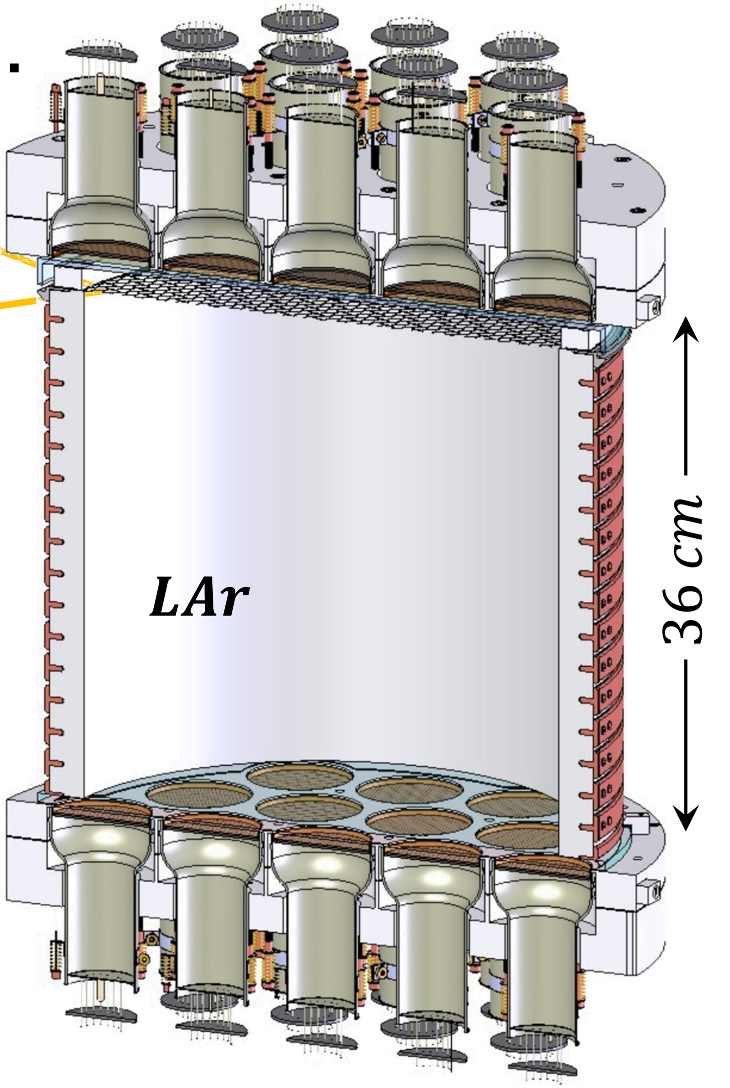


*Tetra-Phenyl-Butadiene

DarkSide 50 – TPC setup in more detail

- **A prototype for todays much larger DM-detectors…**





- first measurements with atmospheric argon were unsuccessful due to a very high ^{39}Ar background

DarkSide 50 – background overview

- **A prototype as proof-of-principle of ^{UG}Ar**

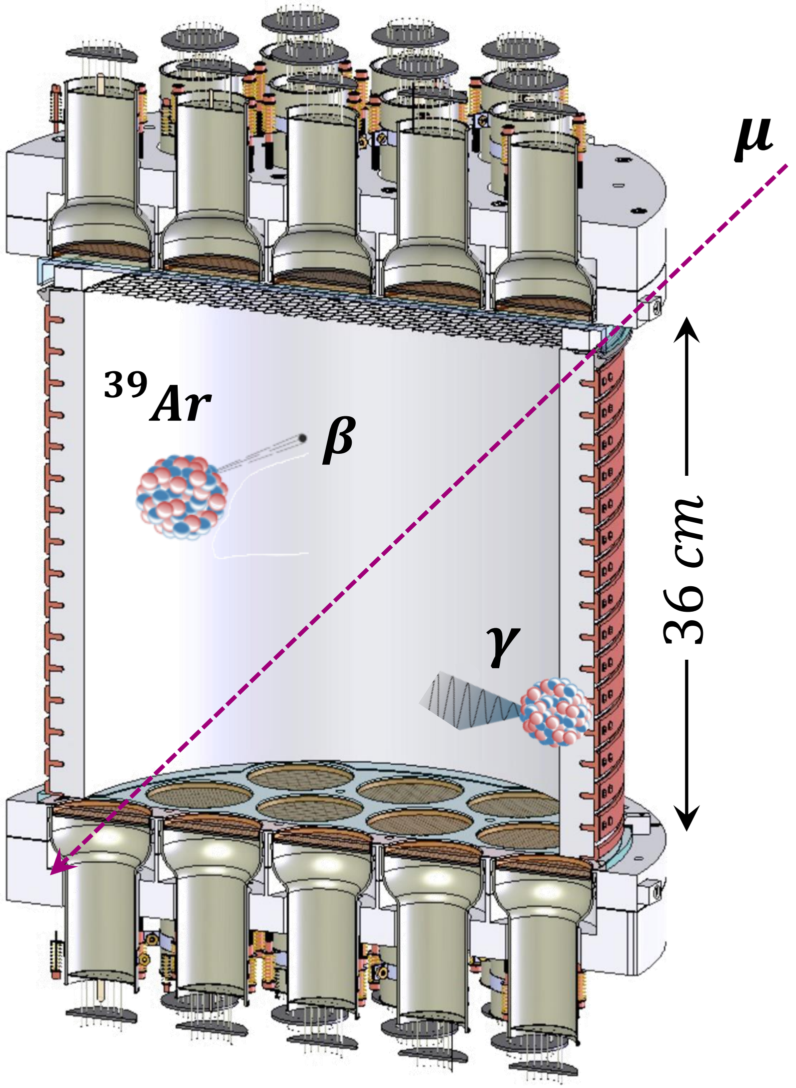
  - then: measurements with **u**nder**g**round **ar**gon (^{UG}Ar)
    ⇨ reduction of β – decay rate by factor ~ 300

  - **background contributions:**

    - β´s (^{39}Ar) : $\sim$ **90000** events / kg / day
    - gammas (e^-): $\sim$ **100** events / kg / day
    - muons: $\sim$ **30** events / m^2/ day
    - alphas: $\sim$ **10** events / m^2/ day

  - **$WIMP$ signal*:**

    - Ar – recoils: $\sim$ 10^{-4} events / kg / day

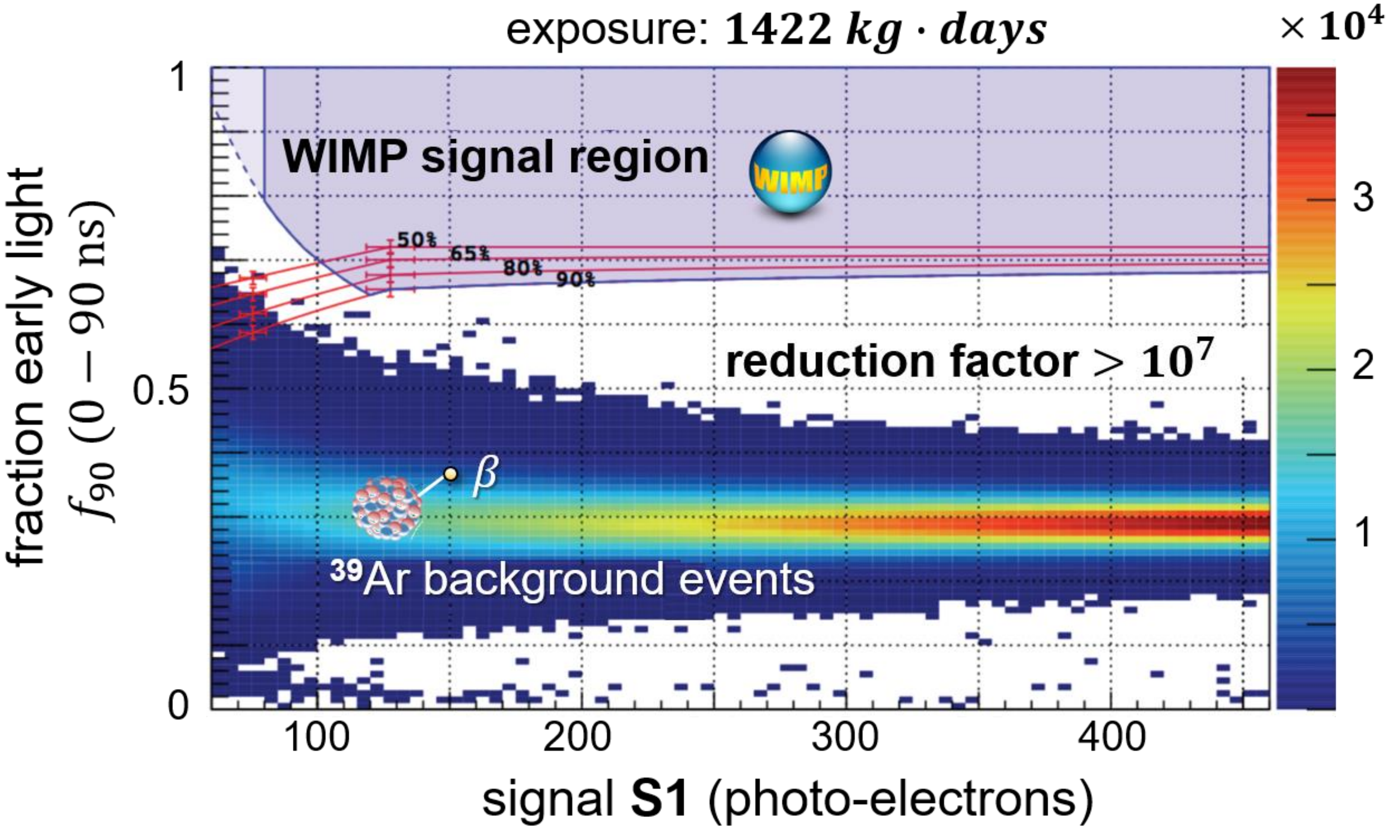


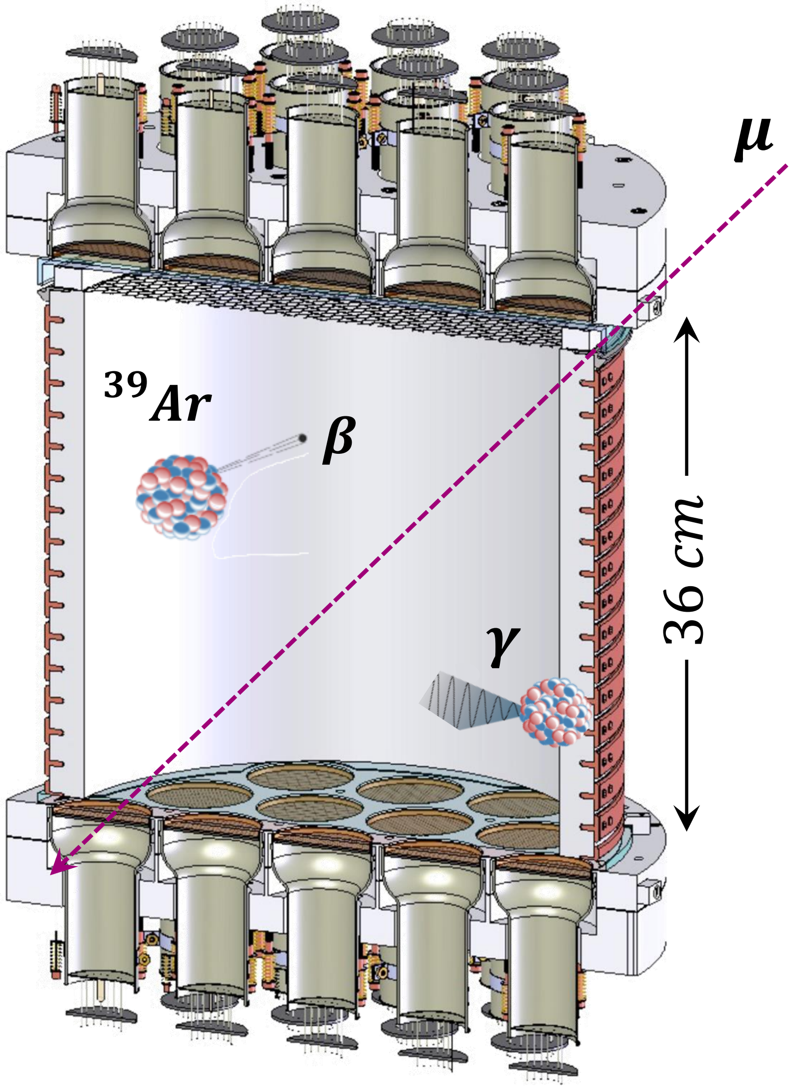
 *for $\sigma_{SI} = 10^{-45}\ cm^2$ & $M_{WIMP} = 100\ GeV$

DarkSide 50 – PID performance

- **background rejection verified by PSD**

  - excellent performance of the TPC in DM search





DarkSide 50 – PID performance

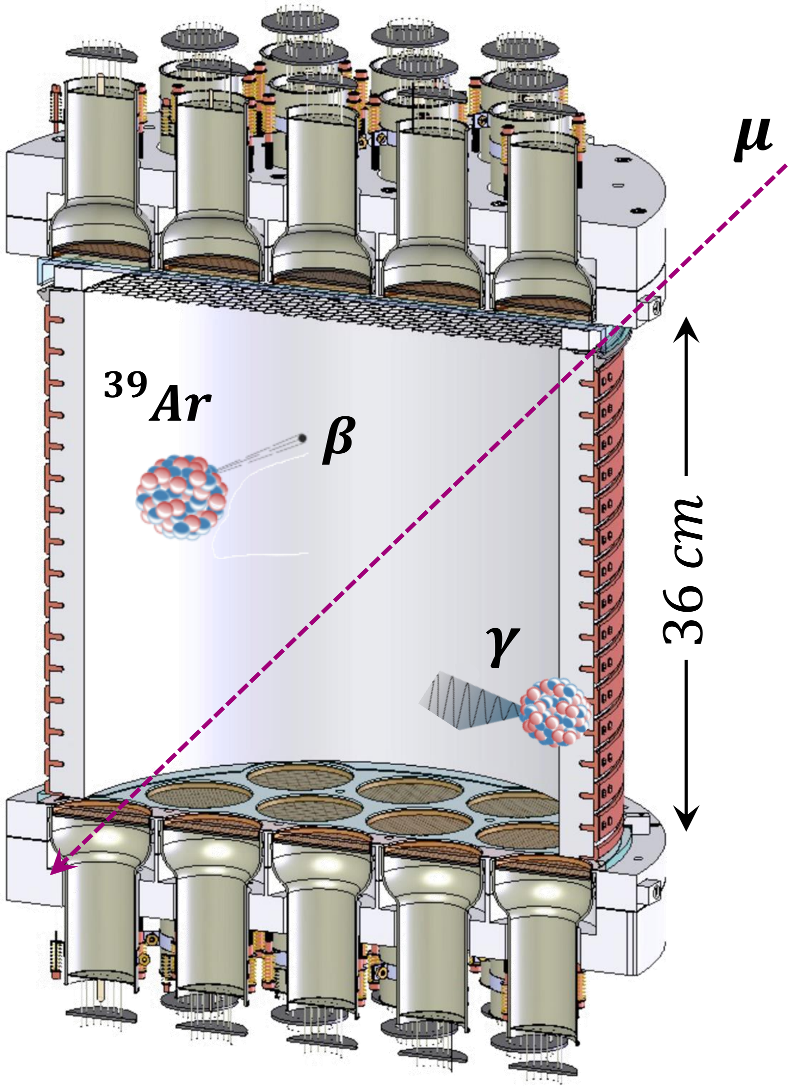
- **background rejection verified by PSD**

  - long exposure using untergground argon:
    532 days from 8/2015 – 10/2017
    $M \cdot t = 16600\ kg \cdot days$

  - ´blind´ analysis with predefined signal box:
    0 WIMP-events after ´***unblinding***´

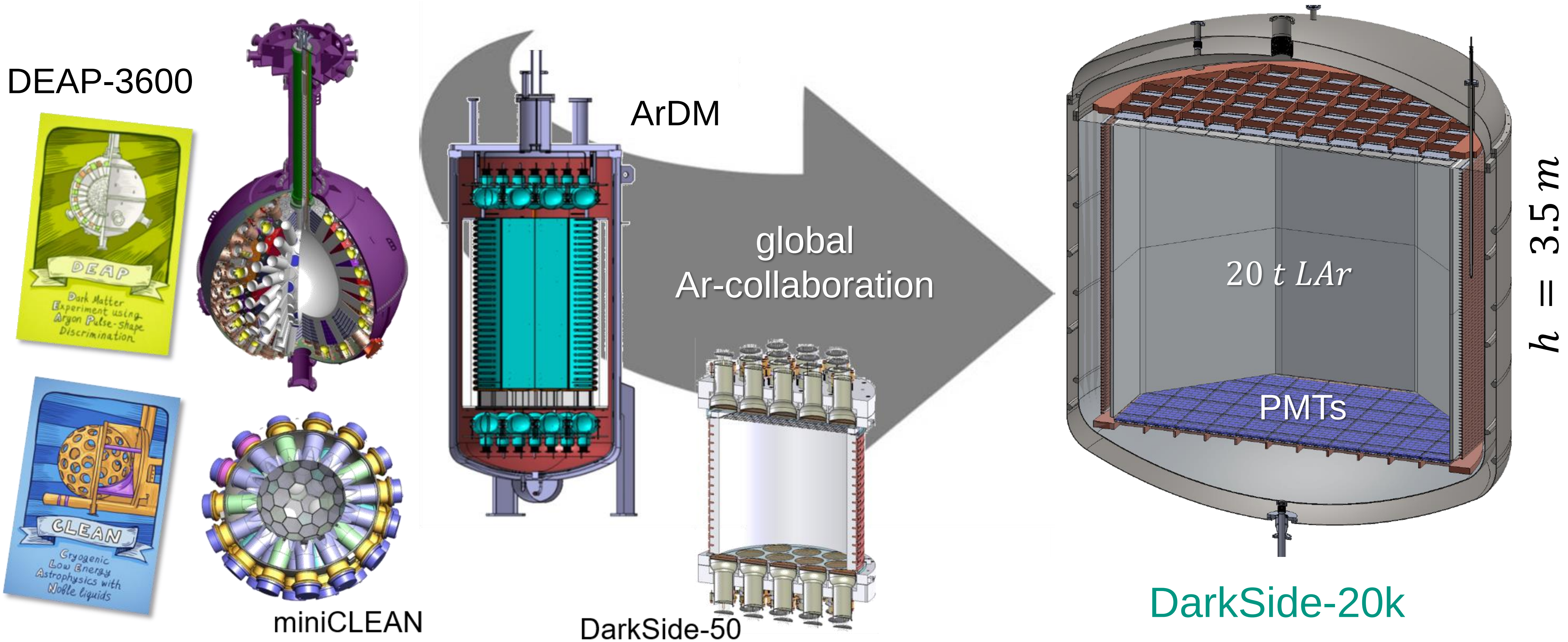
  - present DarkSide 50 exclusion limit:
    $\sigma_{SI} < 1.14 \times 10^{-44}\ cm^2$
    (for 100 GeV-WIMP)

  - **breakthrough result for 2-phase-Ar-detectors**



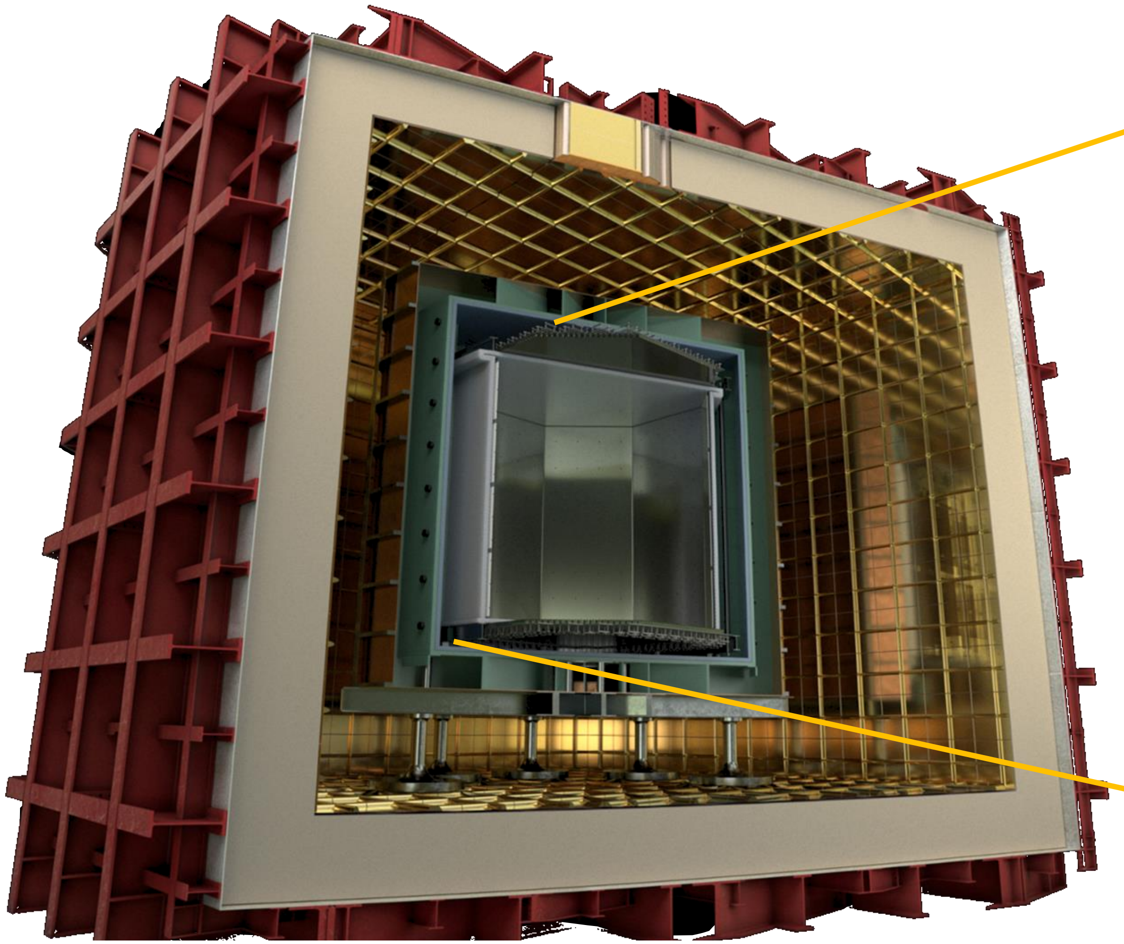
Darkside 20k: towards a global argon DM-detector

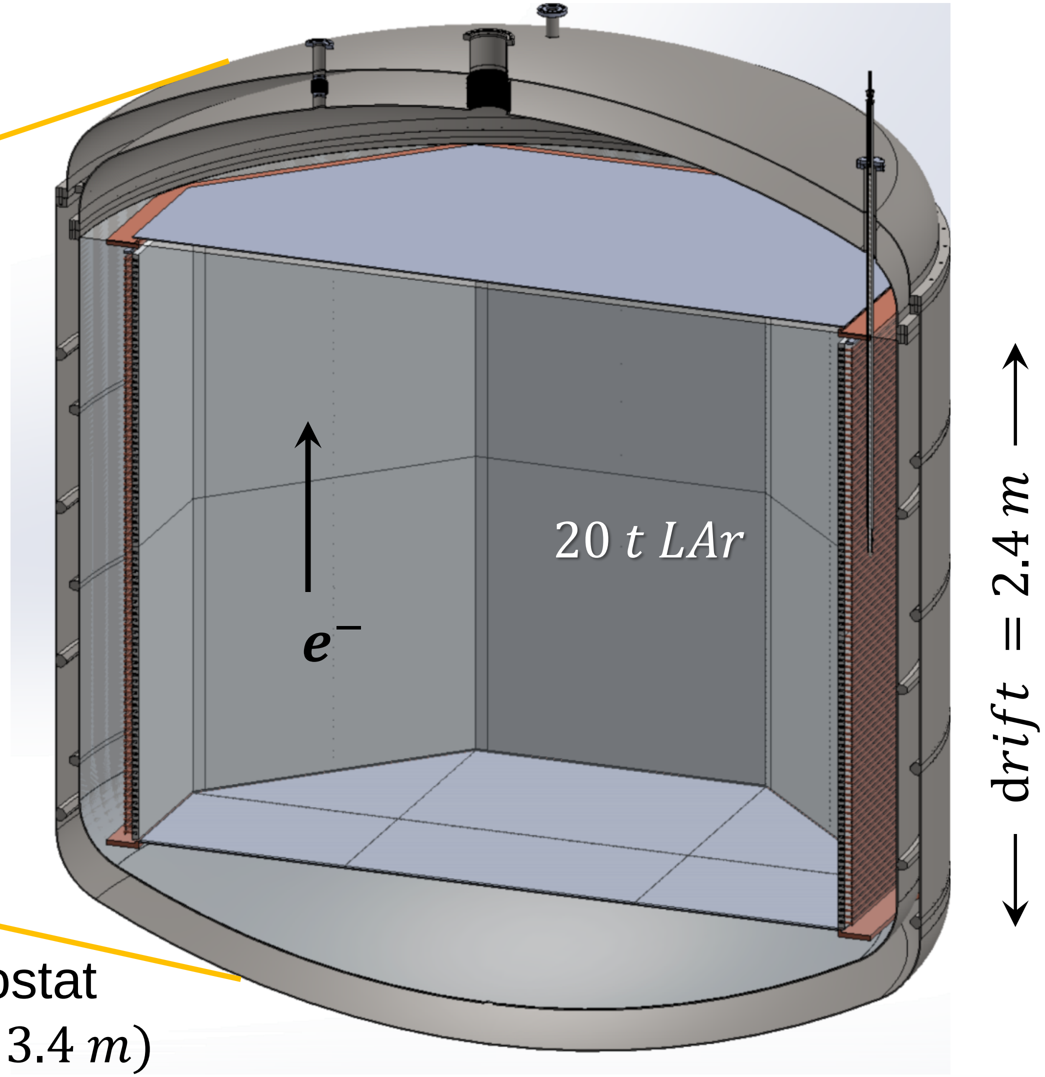
- Uniting all previous argon-based project in a **global argon collaboration**



Darkside 20k: towards a global argon DM-detector

- Veto-detector & TPC for DarkSide 20k

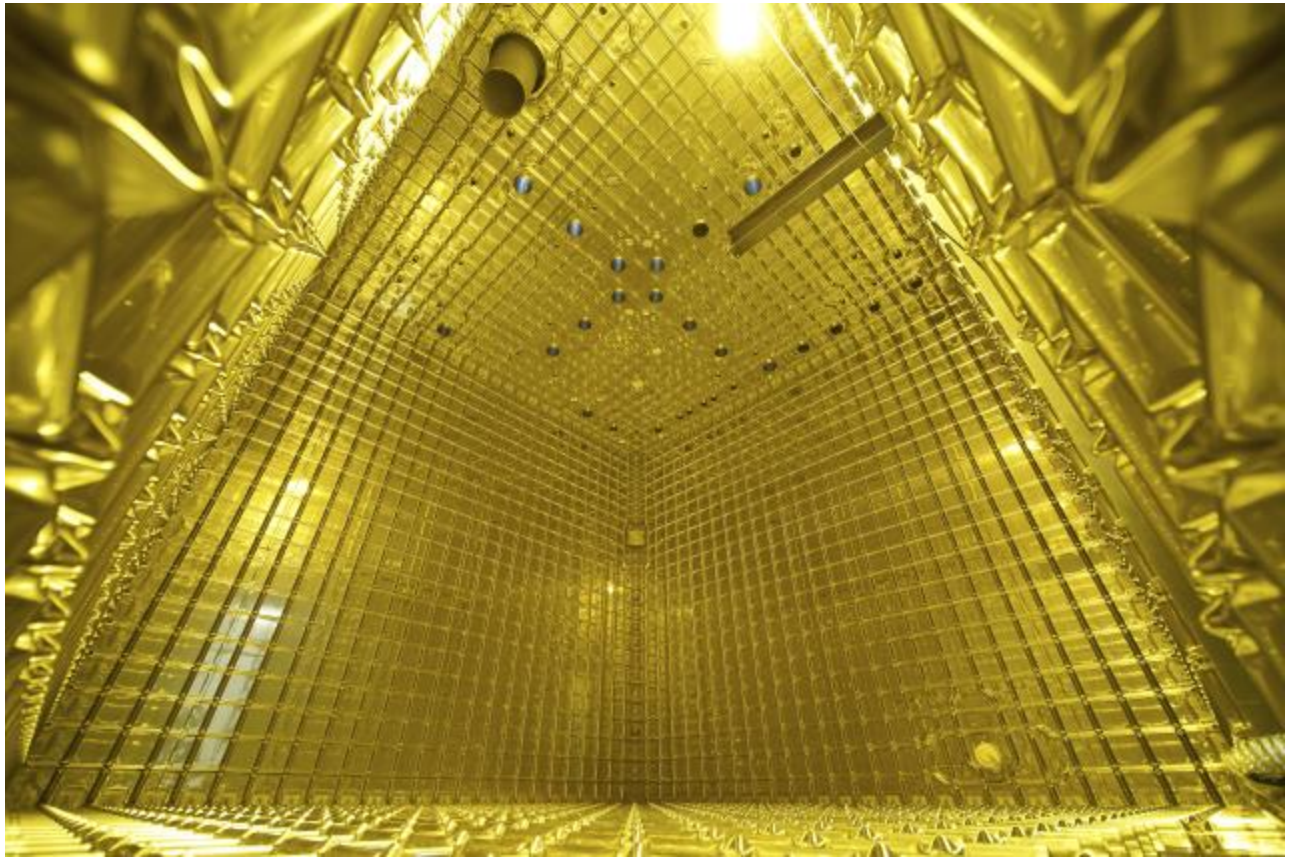




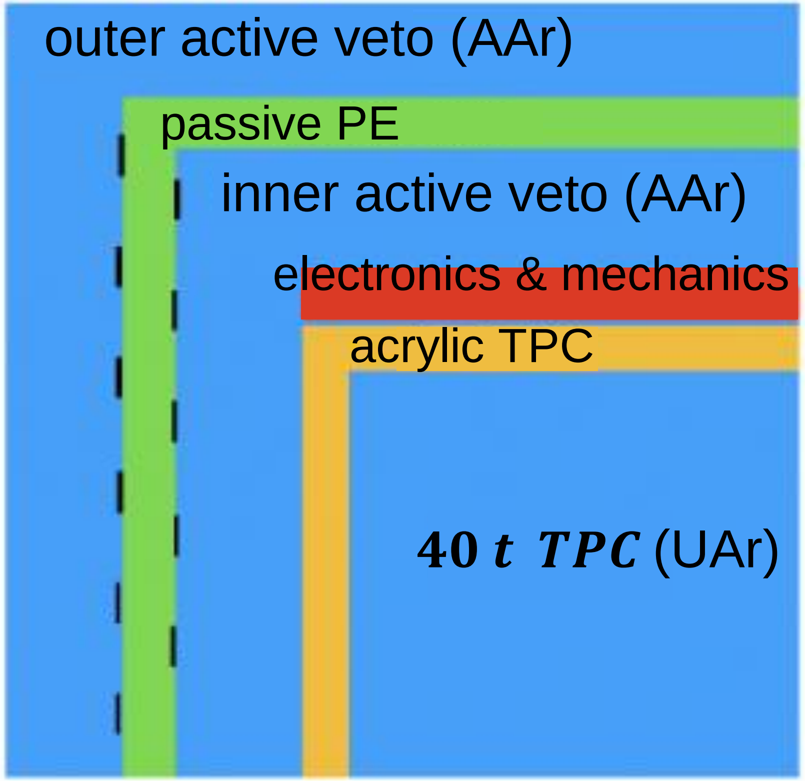
cryostat
$(\text{Ø} = 3.4\ m)$

Darkside 20k: towards a global argon DM-detector

- **Veto concept & TPC for DarkSide 20k**



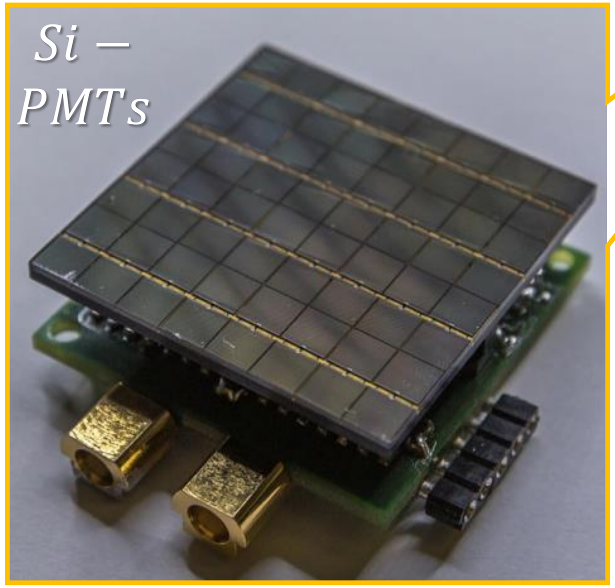
total argon mass: $\mathbf{50\ t}$



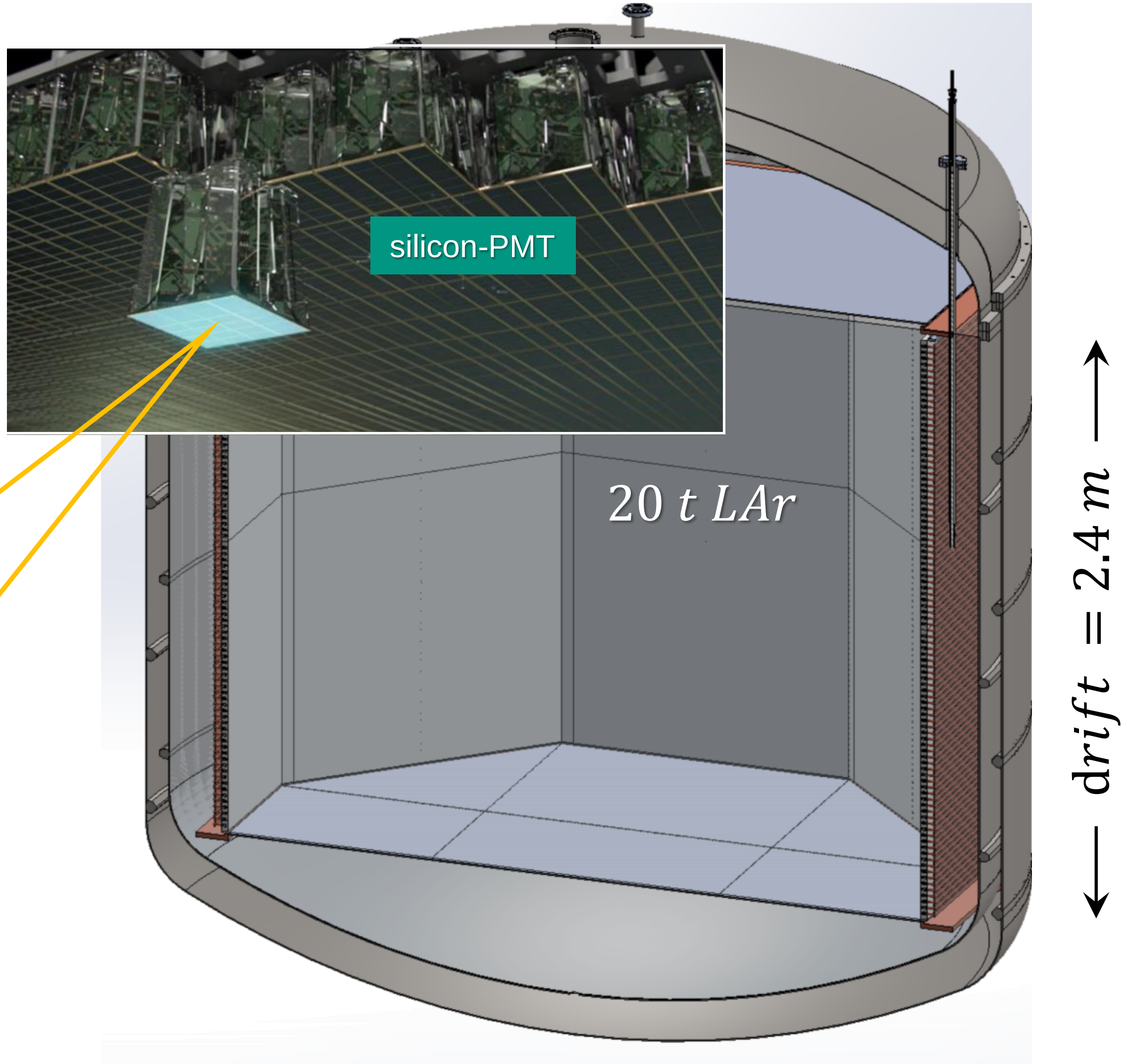
Darkside 20k: set-up of 50 t argon TPC

- **Design parameters of DarkSide 20k**

  - fiducial volume: $\mathbf{20\ t}$
  - octagonal PTFE* (teflon) panels & $\boldsymbol{Cu}$ – elements for forming of $\vec{\boldsymbol{E}}$ – field



8280 photosensors:
$\boldsymbol{Si}$-PMT-panels
$\boldsymbol{A = 5 \times 5\ cm^2}$



*Polytetrafluoroethylene

Darkside 20k: ongoing & future timeline

Karlsruhe Institute of Technology

Timeline & goals of DarkSide 20k

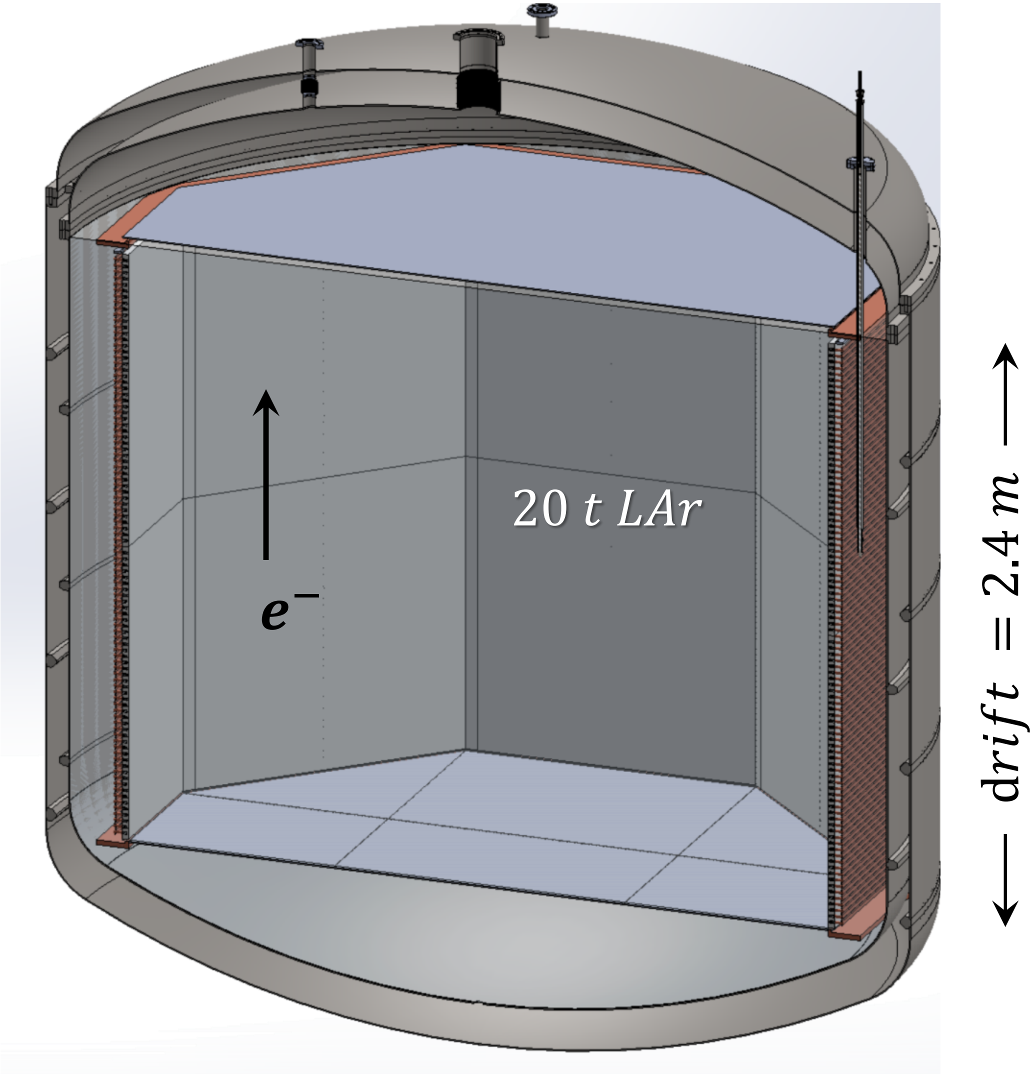
2022: ongoing installation works at $\boldsymbol{LNGS}$

2023: expected start of measurements

2023…28: planned time period for data taking, expecting a result **free of background**

exposure: $\boldsymbol{M \cdot t = 200\, t \cdot yr}$

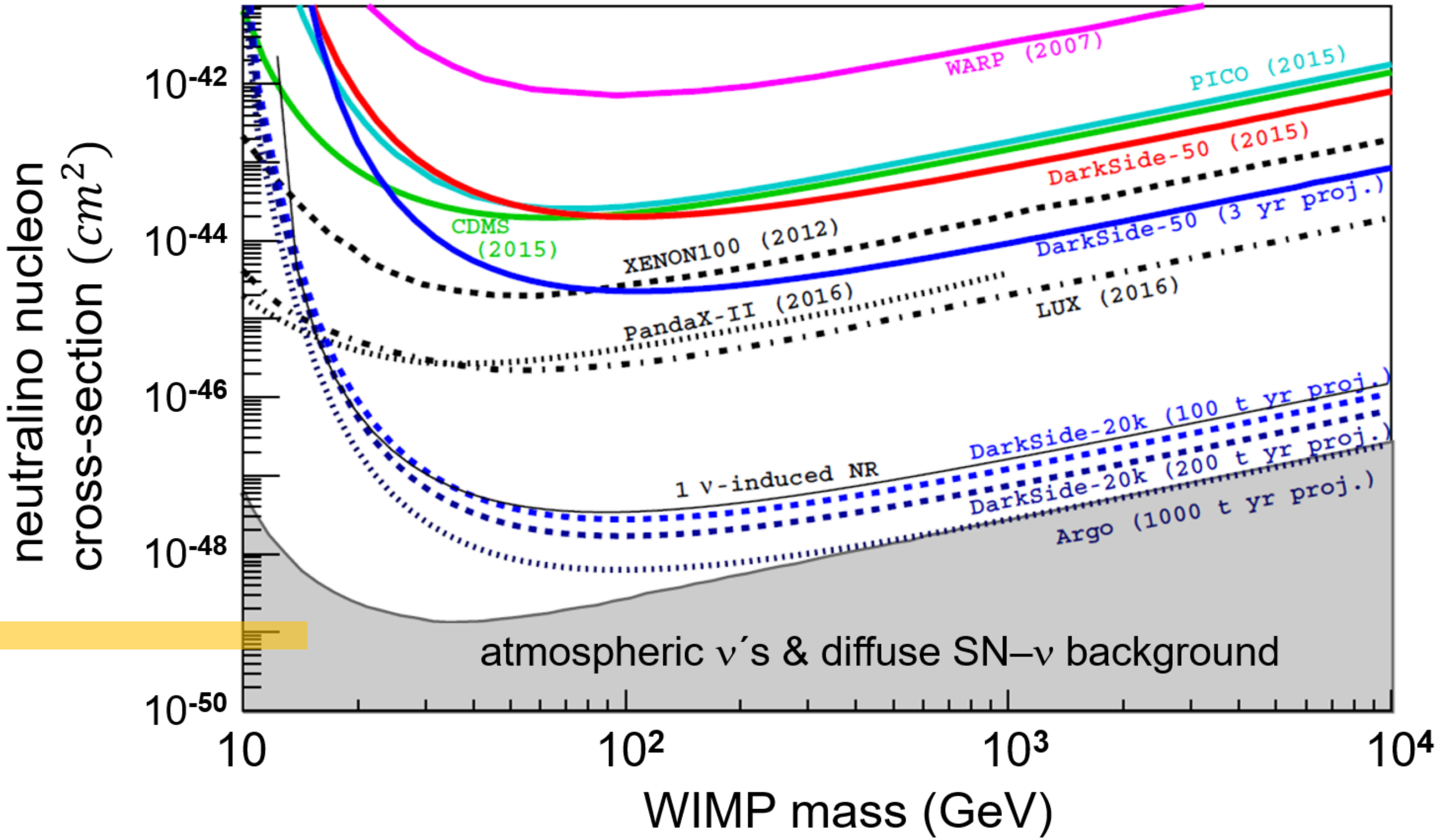
combination of $\boldsymbol{PSD}$ (**P**ulse **S**hape **D**iscrimination) & $\boldsymbol{S1 - S2}$ ratio



Darkside 20k: expected sensitivity & comparison

- **All scales with exposure in case of no background**

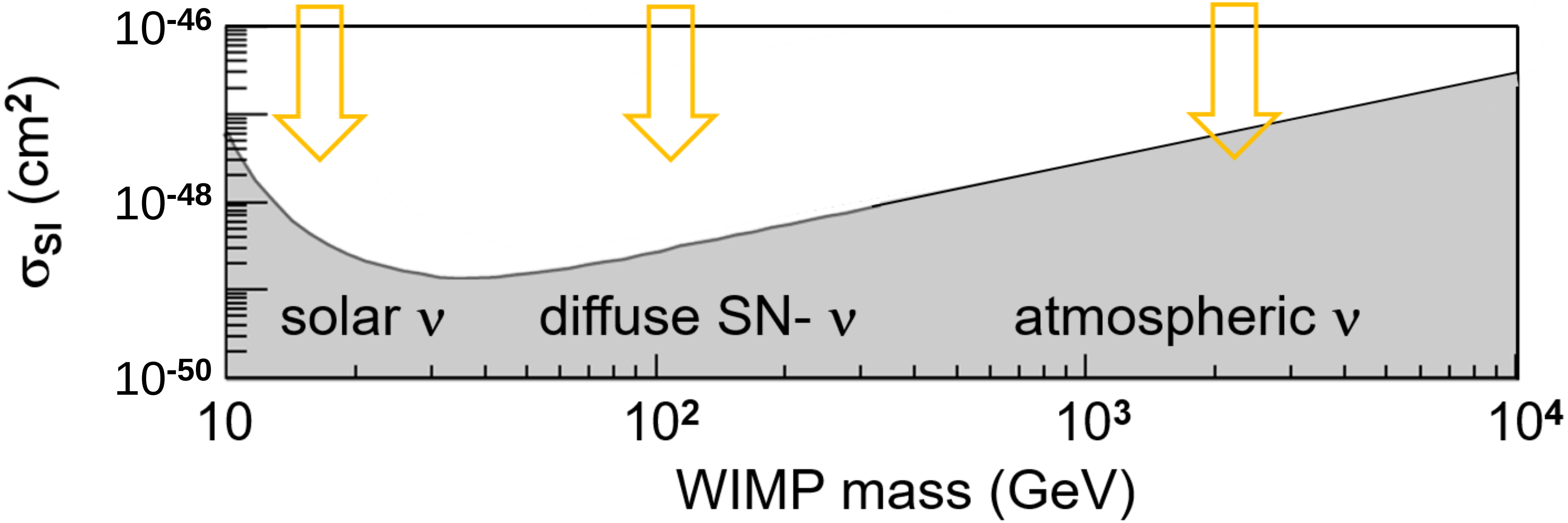
- potential of 2-phase argon experiments to push forward to **neutrino floor**



Neutrino floor – the ultimate limit for DM-searches

- **Coherent scattering of astrophysical neutrinos off target nuclei**

- $\boldsymbol{\nu}$´$\boldsymbol{s}$ from the Sun, all previous $\boldsymbol{SN}$´$\boldsymbol{s}$ & from the Earth´s atmosphere: no shielding is possible



Neutrino floor – kinematics of the scattering

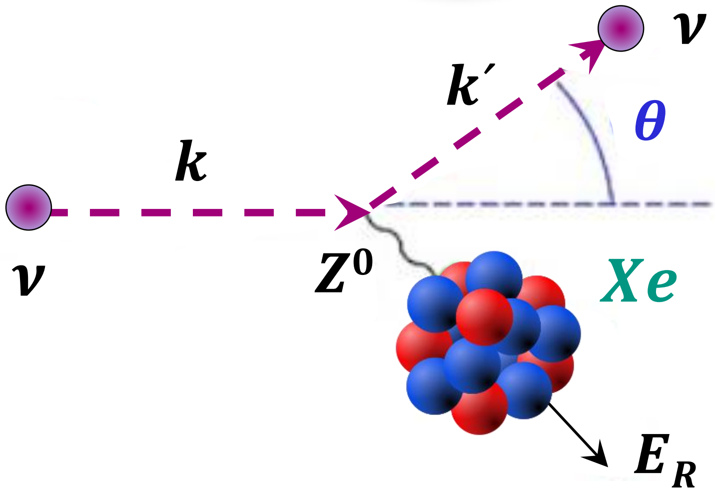
- **Coherent scattering of astrophysical neutrinos: from the $MeV \dots GeV$ – scale**

- primary interaction:
  NC – process via Z^0

- **coherent** interaction:
  with all neutrons within
  a target nucleus

$$\boxed{\sigma_\nu \sim E_\nu^2 \cdot N^2}$$

N: number of neutrons
in a nucleus



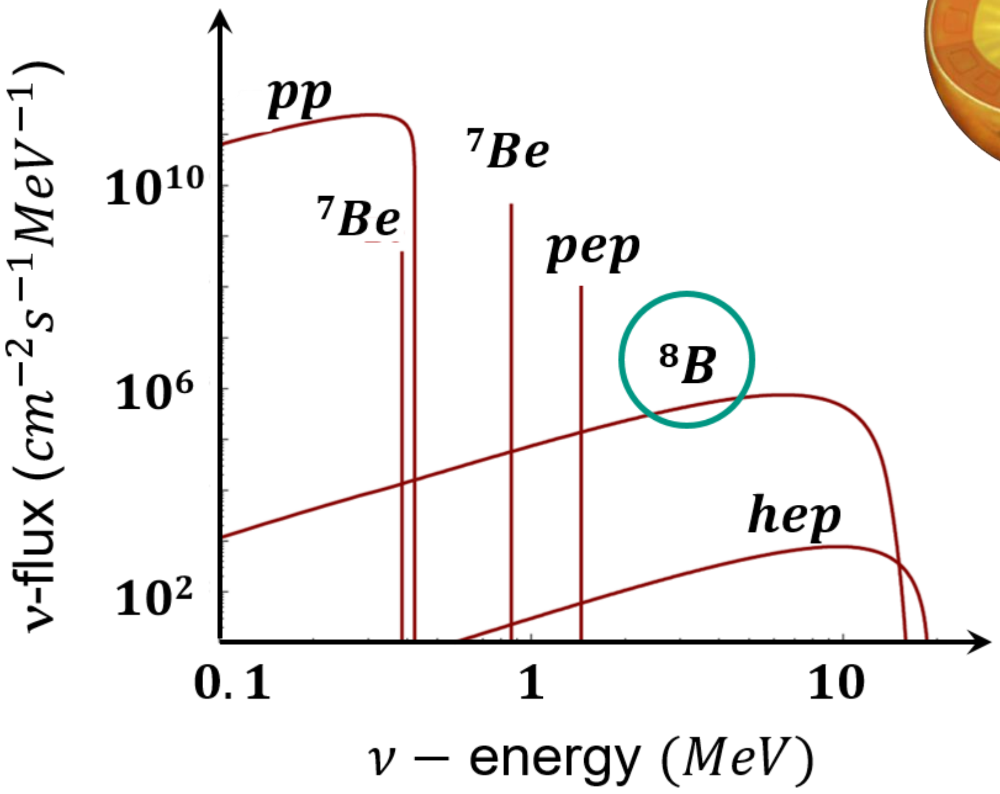
- kinematics:
  recoil of target nucleus

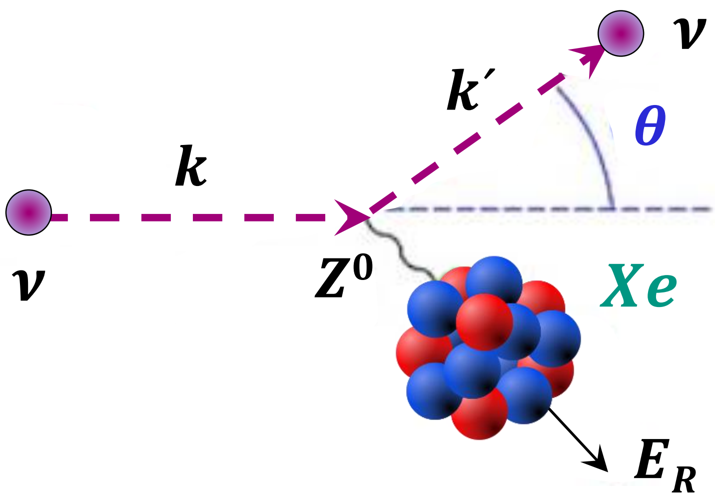
$$\boxed{E_{R,max} \sim (E_\nu)^2 / A}$$

Neutrino floor – scattering of solar neutrinos

Coherent scattering of solar neutrinos: MeV – scale

- energy spectrum:





- example:
  ^8B neutrino*
  scatters off a Xe – nucleus

- kinematics for a solar ν ($E = 3\ MeV$)
  $E_{R,max} \sim 150\ eV$

- cross section for a solar ν ($E = 10\ MeV$)
  $\sigma_{\nu-Xe} \sim 2 \cdot 10^{-39}\ cm^2$

2-phase-experiments with xenon: overview

XENON-10-100-1T-NT

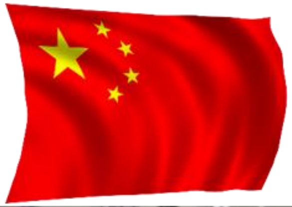
active mass:
$\mathbf{8.3}\ \boldsymbol{t}$

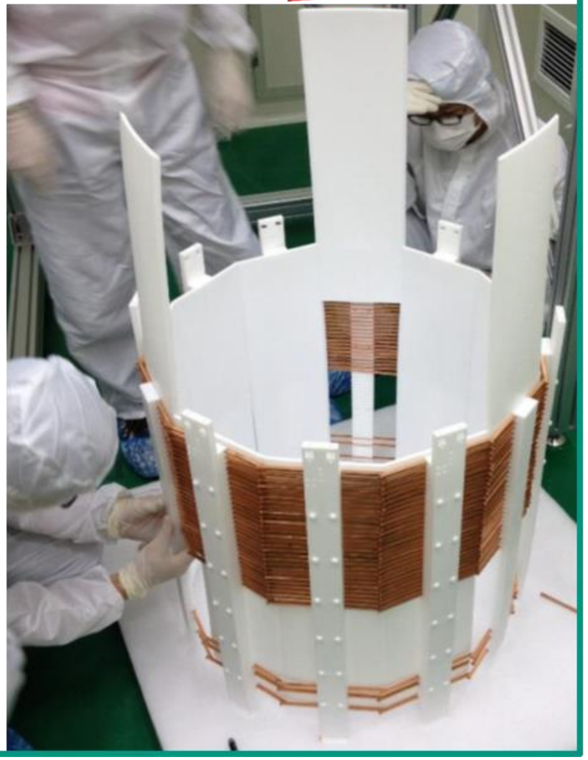
ZEPLIN-LUX-LZ

active mass:
$\mathbf{7}\ \boldsymbol{t}$

PANDA-X

active mass:
$\mathbf{4}\ \boldsymbol{t}$

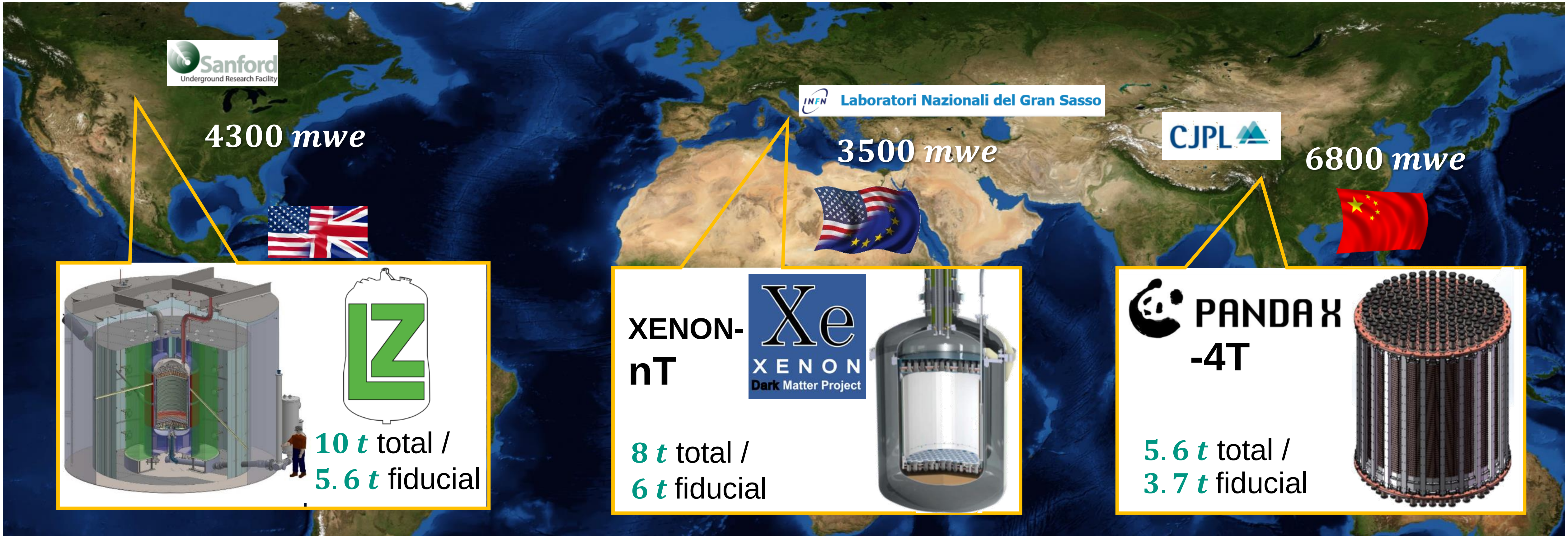




2-phase-experiments with xenon: overview

- **All three regions (US, Europe, China) operate multi$-ton\ Xe-$ targets**

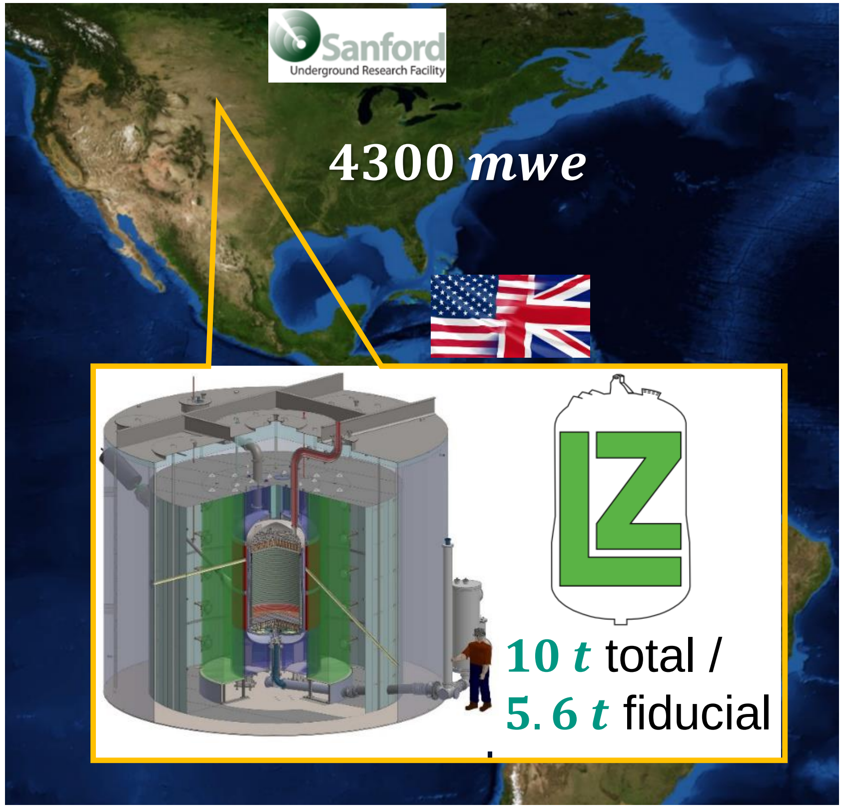
- which continent will win the race to provide the best WIMP sensitivity with xenon?

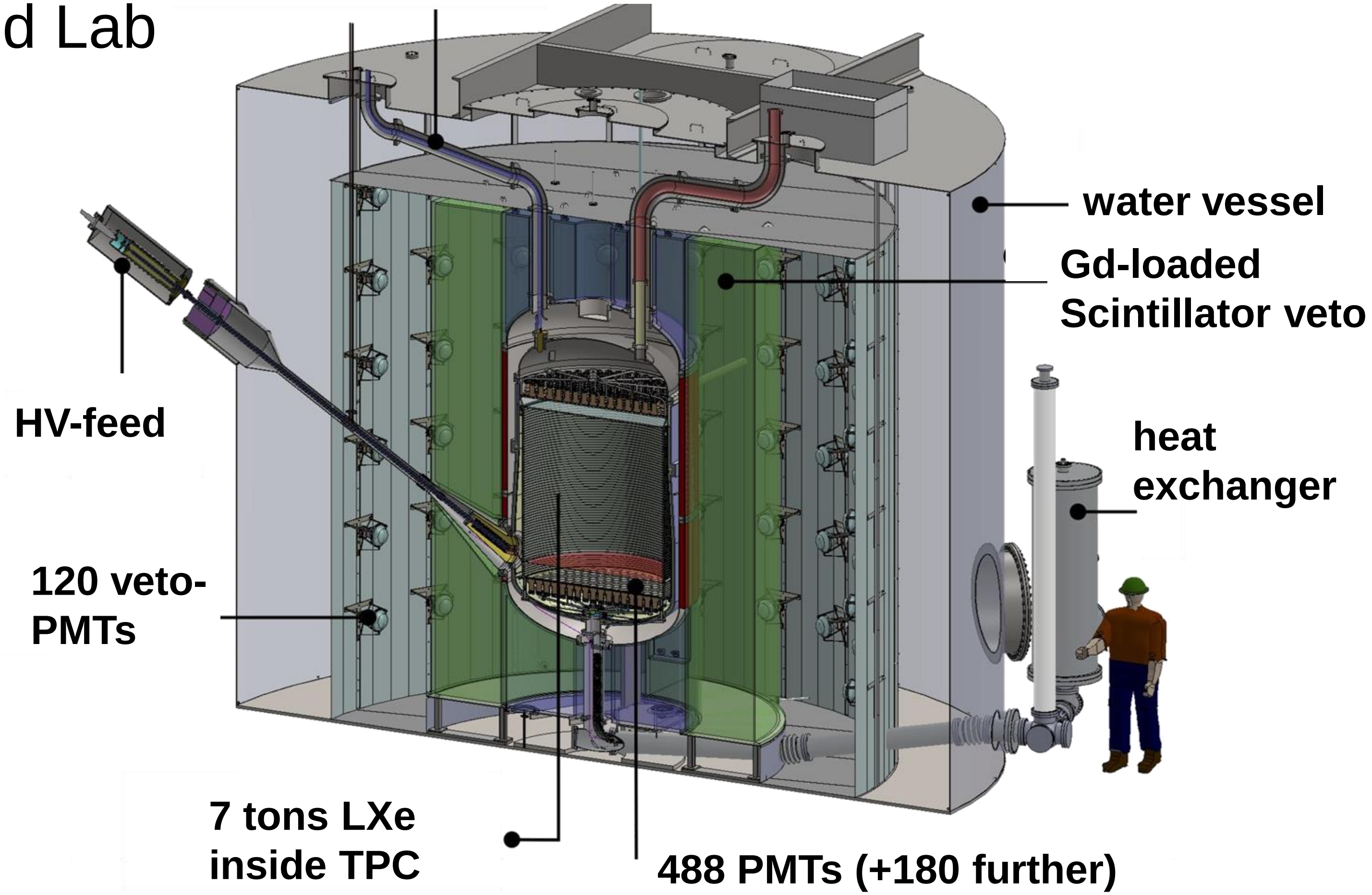


Lux-Zeplin (LZ) experiment in the US

- LZ is the successor from the merger of LUX (US) and $ZEPLIN$ (GB)

- operated at Sanford Underground Lab



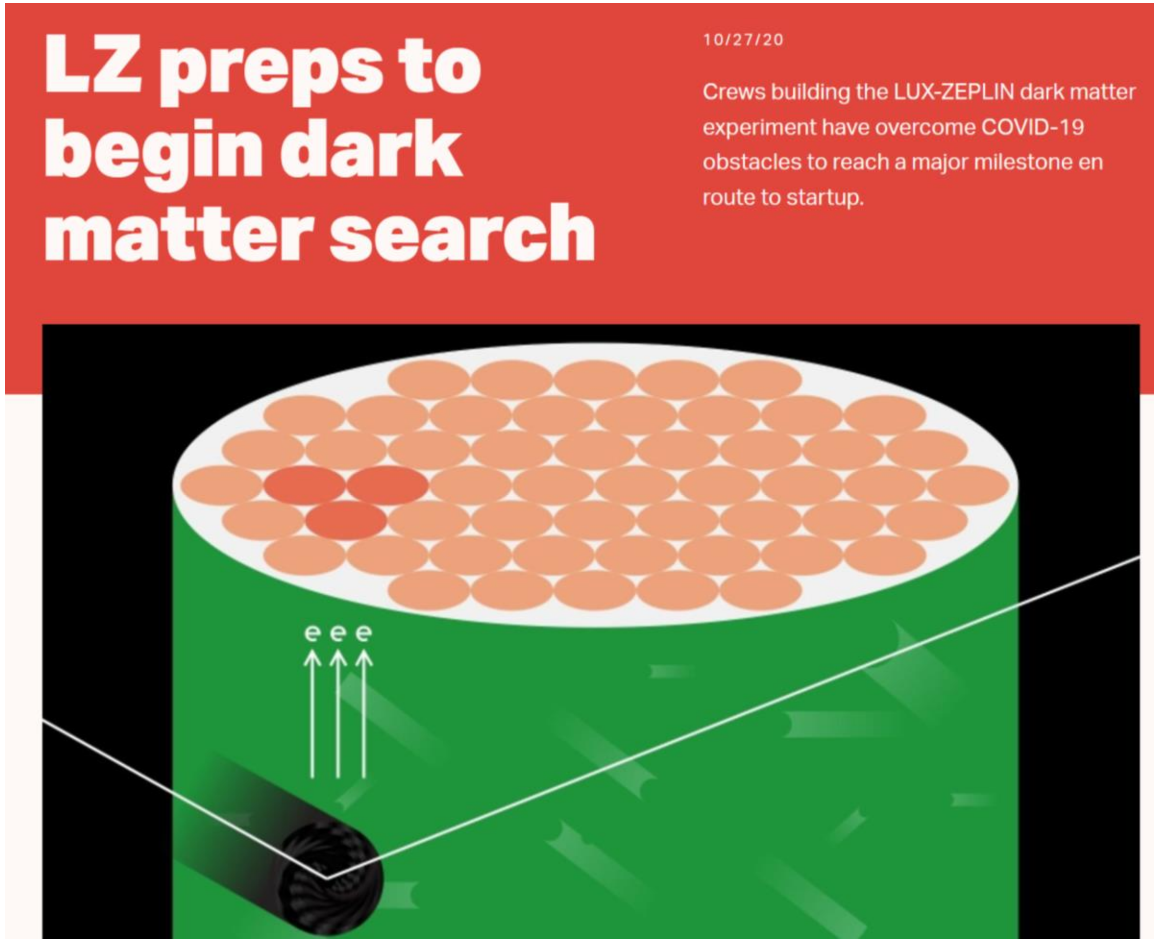


The LZ Dark Matter Experiment | The status and science of the LZ dark matter experiment. (lbl.gov)

Lux-Zeplin (LZ) experiment in the US

- LZ is taking data since 2021, first (initial) data published in July 2022

- careful final investigations of the integrity of the xenon-TPC by LZ-collaborators



Lux-Zeplin (LZ) experiment: first results

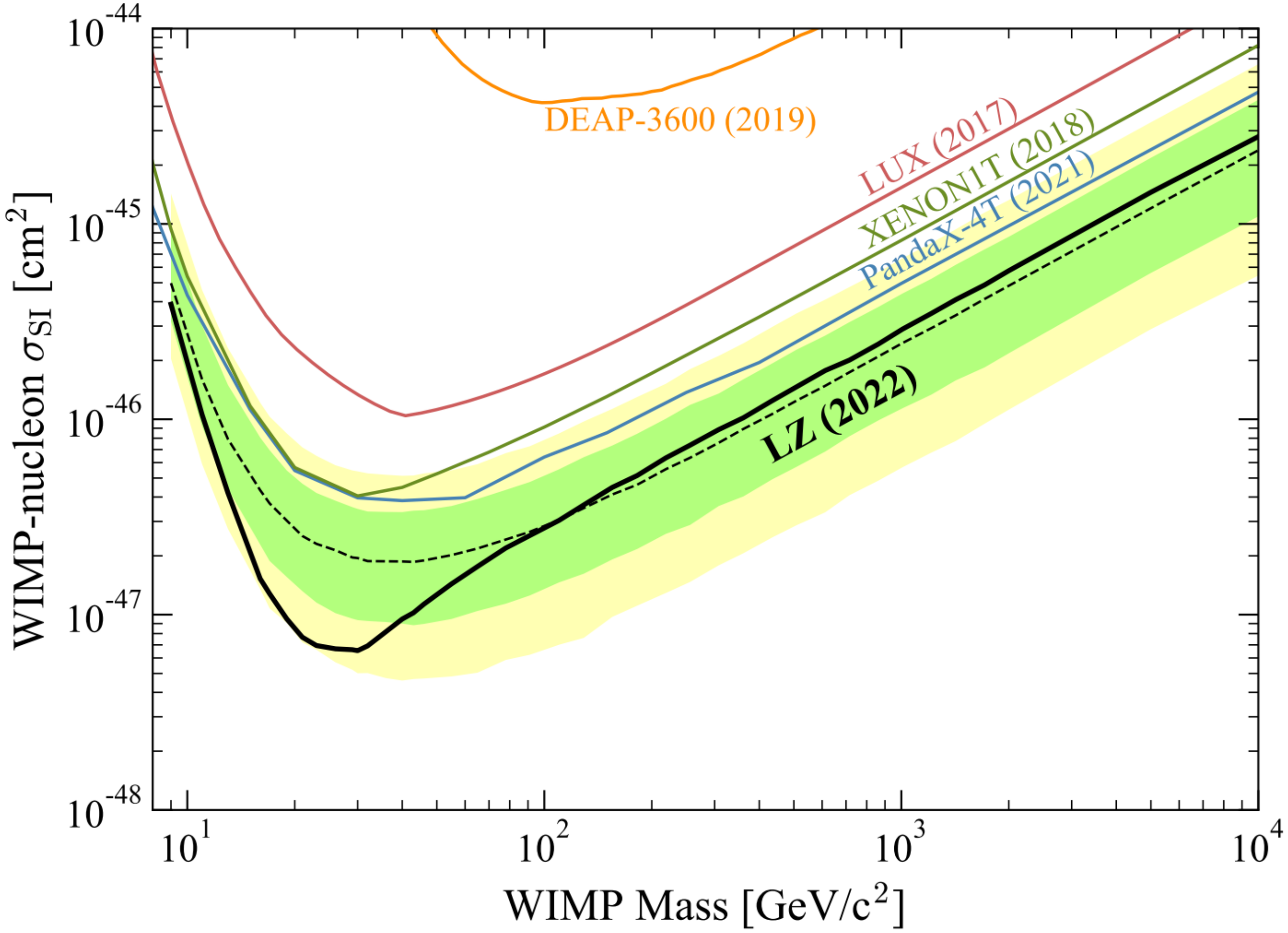
- **Data collected from Dec 2021 … May 2022 (60 days)**

- data fully consistent with a background-only hypothesis (p – value: 0.96)

- world-leading sensitivity (at present) for masses > 9 GeV

- WIMP-sensitivity at 30 GeV

$$\boldsymbol{\sigma_{SI} < 6.5 \times 10^{-48}\ cm^2}$$



Panda X-4T experiment in Jinping Lab, China

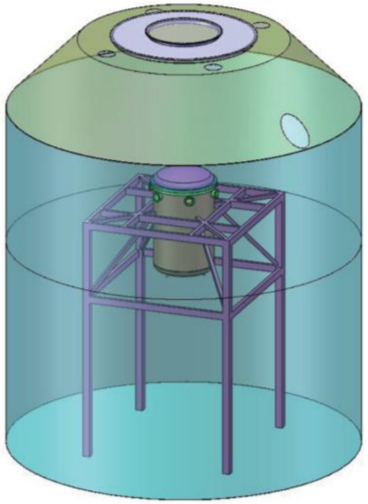
- **Panda X – Particle and Astrophysical Xenon detector: multiple generations**

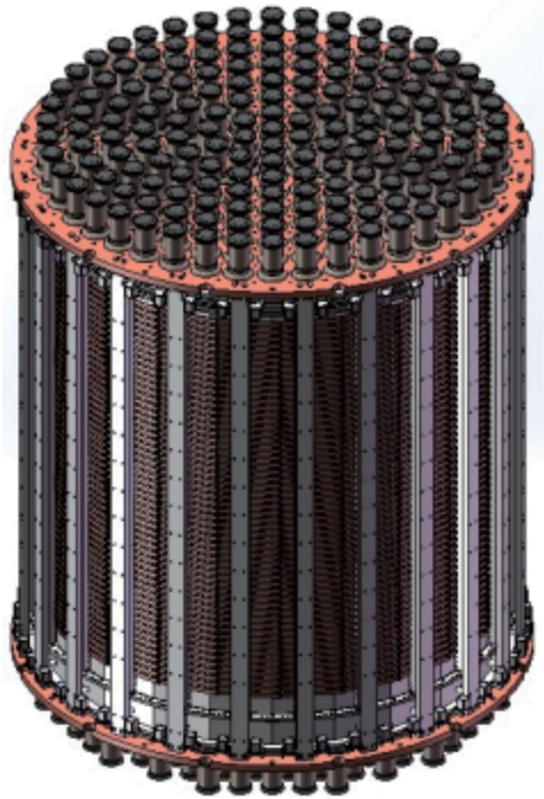
  - presently: $5.6\ t\ LXe$ (total mass), $3.7\ t\ LXe$ (sensitive target mass in TPC)

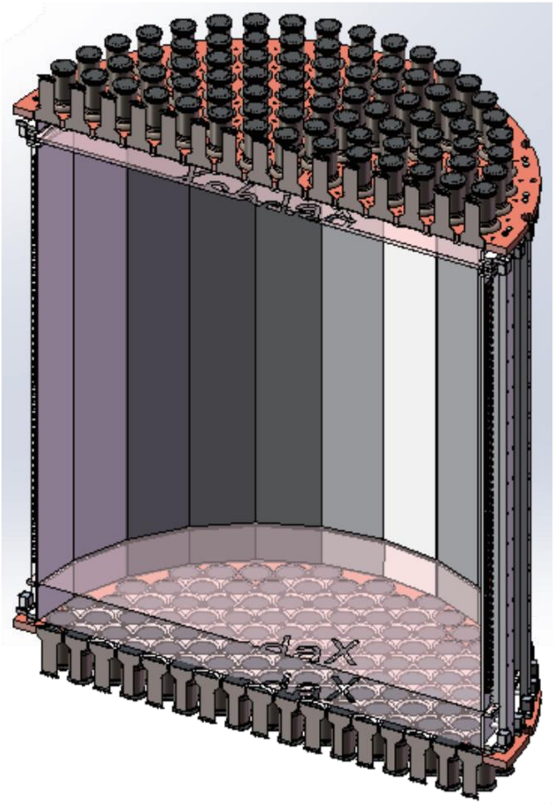
  - TPC surrounded by H_2O –veto-detector

  - TPC- dimensions: $\varnothing\ =\ 1.2\ m\ , h = 1.3\ m$

  - optical read-out via 3-inch PMT-arrays Hamamatsu R11410-23







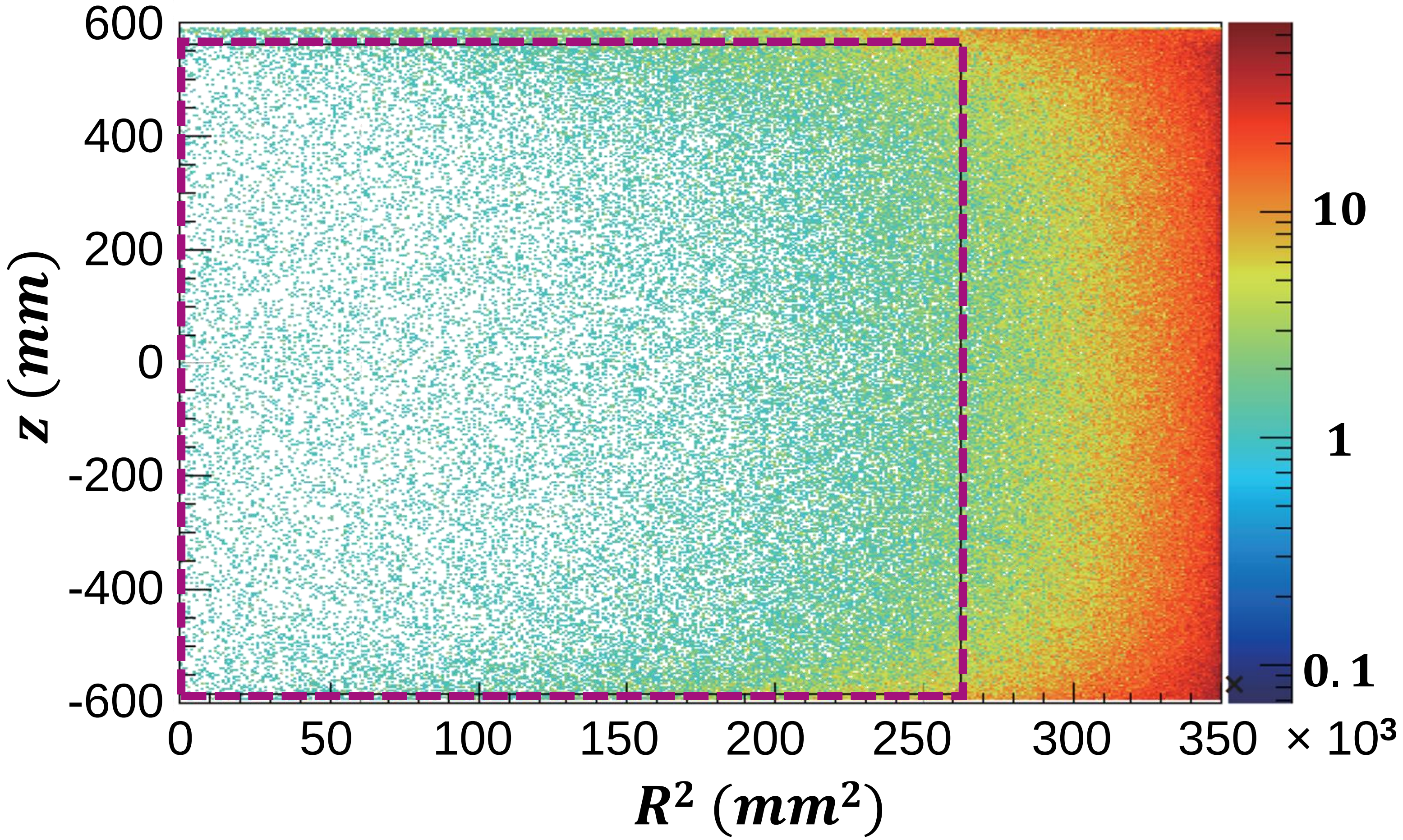
Panda X-4T: illustration of a fiducial volume

- Distribution of background events in the LXe volume in a side view

- background dominated by detector materials

- software cuts define ***fiducial volume***

inner region with lowest background level



Panda X-4T: first results published 12/2021

- **Data analysis based on an exposure of $M \cdot t = 0.63\ t \cdot yr$**

- no WIMP excess observed

- best WIMP sensitivity achieved for $M = 40\ GeV$

- WIMP-limit ($90\ \%\ CL$) for $40\ GeV$

$$\sigma_{SI} < 3.8 \times 10^{-47}\ cm^2$$

- limit is less stringent than LZ

XENON-1T experiment at the LNGS

- **European experiment (+ US groups): long-term leader of the field**

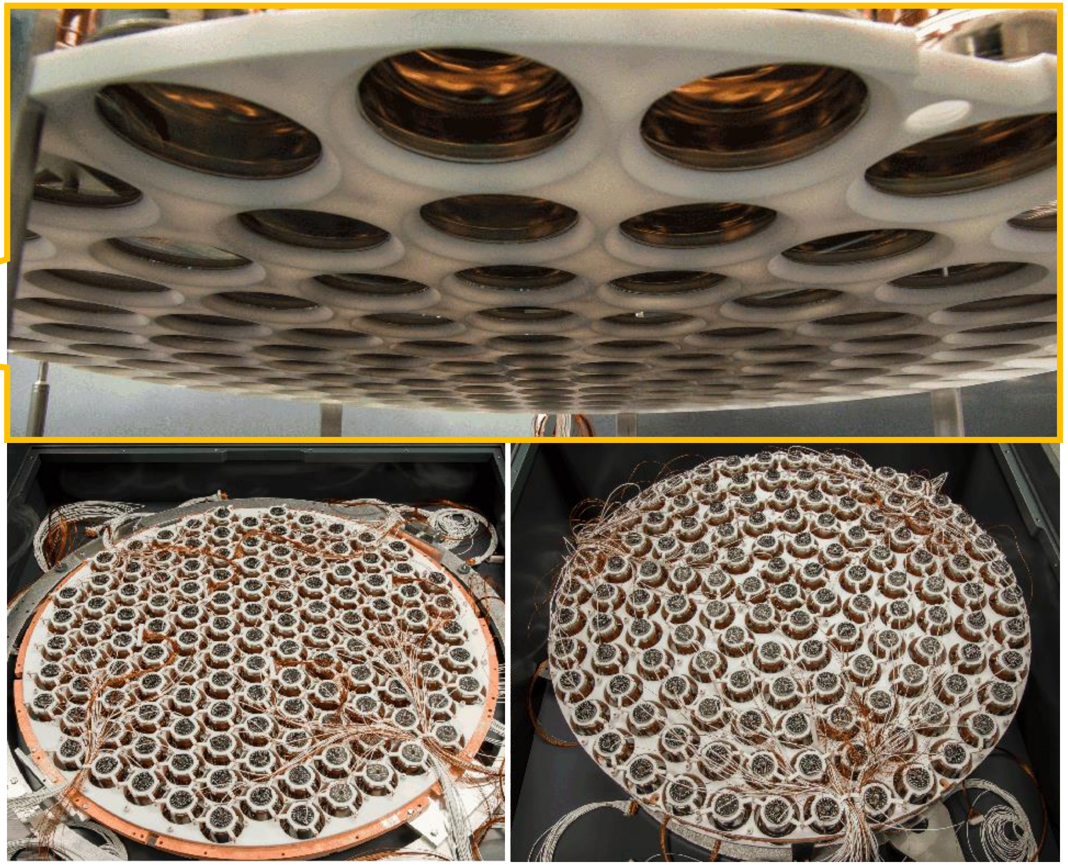
- successor to earlier XENON10-XENON100
- **construction period**: autumn 2013 up to autumn 2015 (2 years)
- total (active) LXe mass: $\mathbf{3.3}\ t$ ($\mathbf{2.0}\ t$)
- measurement phase from autumn 2016 – end of 2018

XENON-1T experiment – TPC design

- Special focus on an extremely low level of background of all TPC parts

drift rings (field cage)

cryostat



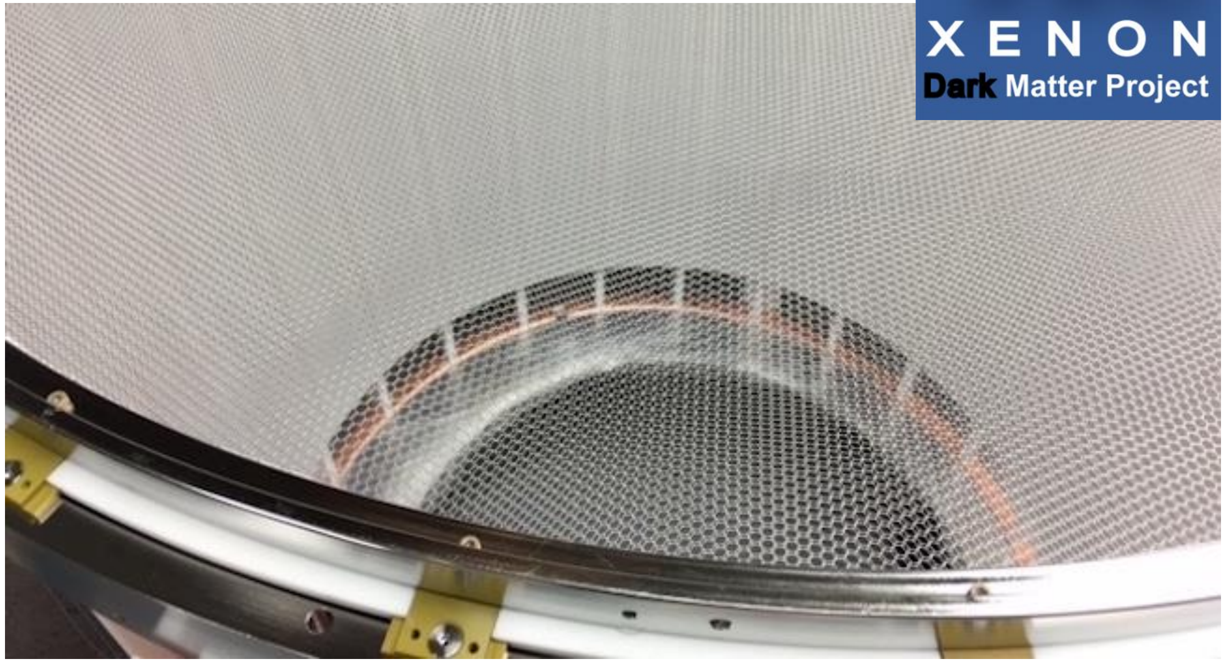
PMT-arrays

XENON-1T experiment – TPC construction

- **Special focus on an extremely low level of background of all TPC parts**

- assembly in clean room

- materials: selection/screening



extraction electrode

XENON-1T experiment – final results

- **2018: publication of then world-leading DM-results from 270 days of data**

- fiducial mass of –1T

  $m = 1.3\ t$

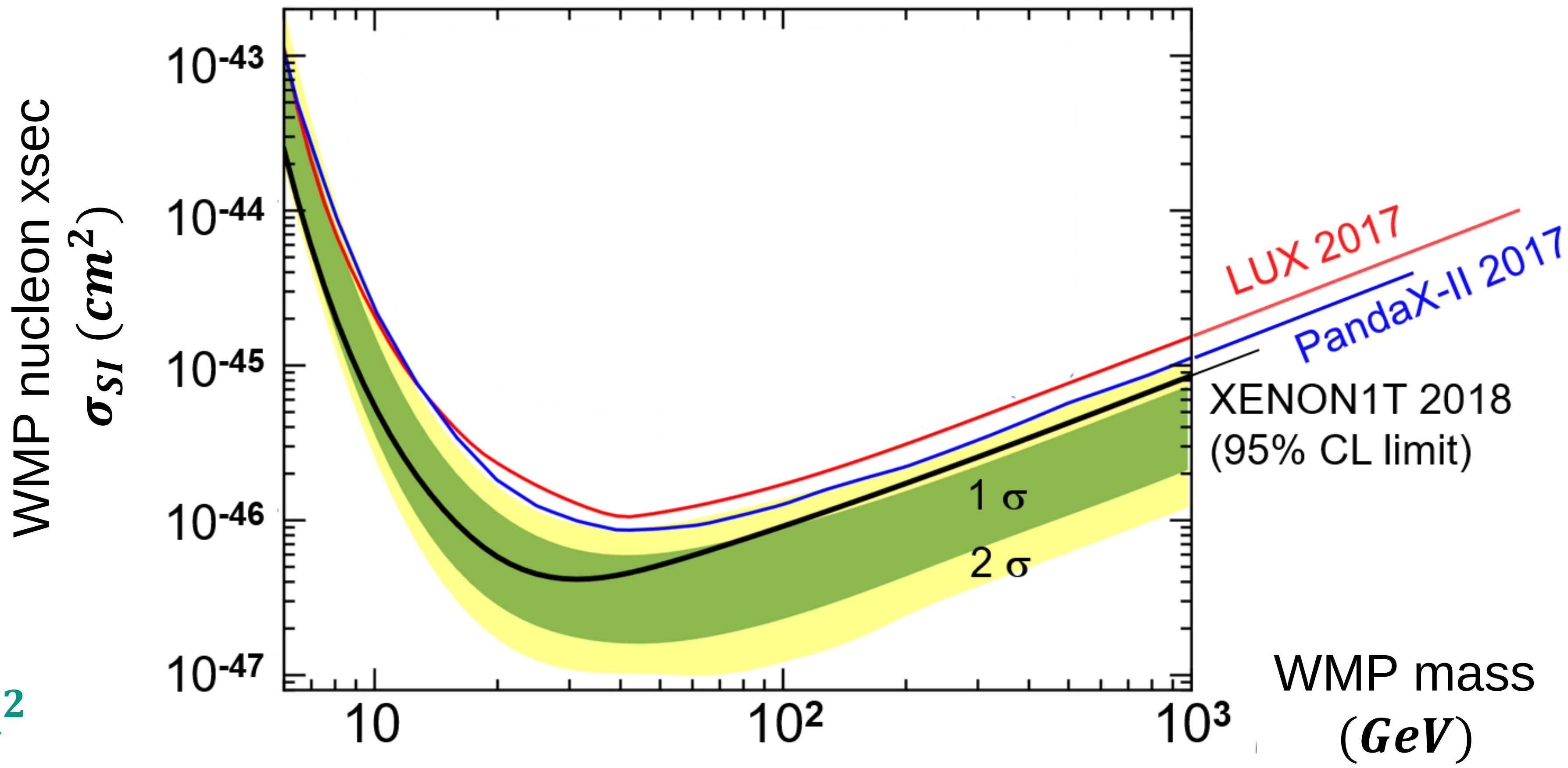
- exposure

  $m \cdot t = 1.0\ t \cdot yr$

- no WIMP signal in predefined box

- $\mathbf{90\%}$ $\boldsymbol{CL}$ upper limit for 30 GeV WIMPs:

  $\sigma_{SI} < 4.1 \times 10^{-47}\ cm^2$

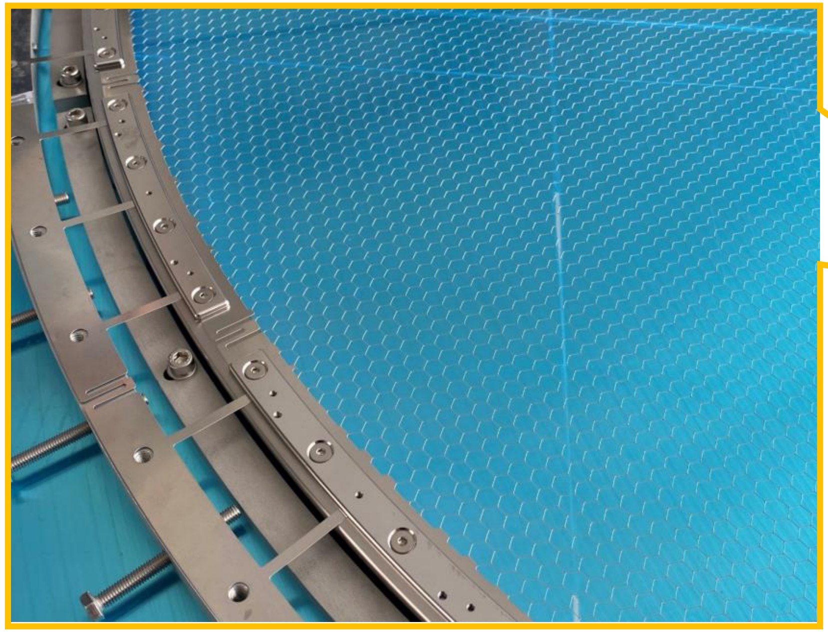


XENONnT experiment – a much larger TPC joins

- 2022: the hunt for WIMPs at LNGS with $8.3\ tons$ of xenon starts

  - special focus on very low-activity materials

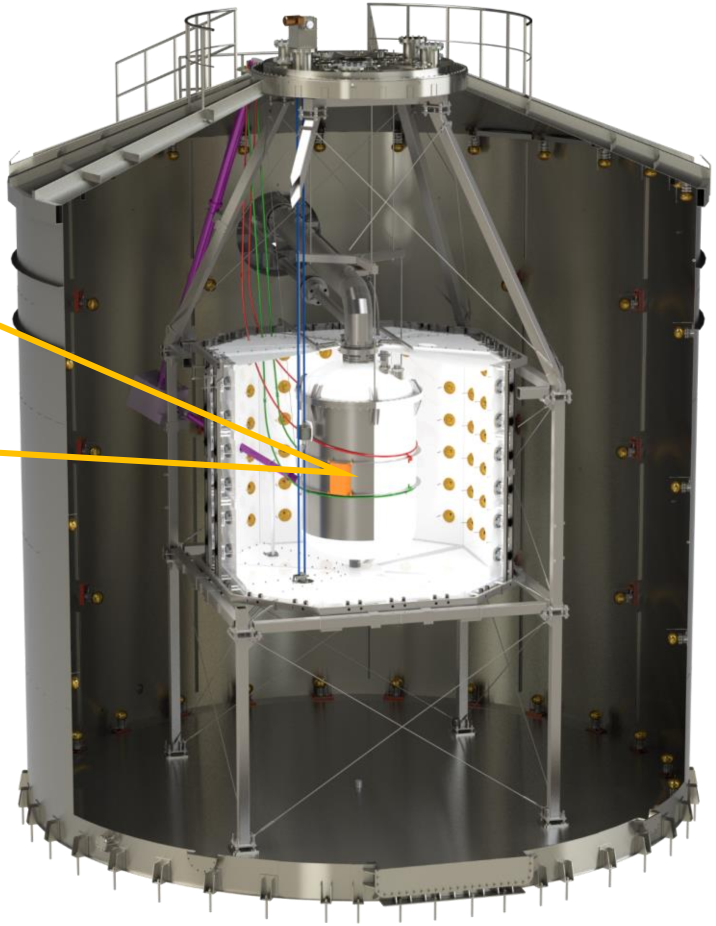
test of electrodes @ KIT



XENONnT experiment – a much larger TPC joins

- 2022: the hunt for WIMPs at LNGS with $8.3\ tons$ of xenon starts

the central $\boldsymbol{TPC}$ is ready…



during assembly work…

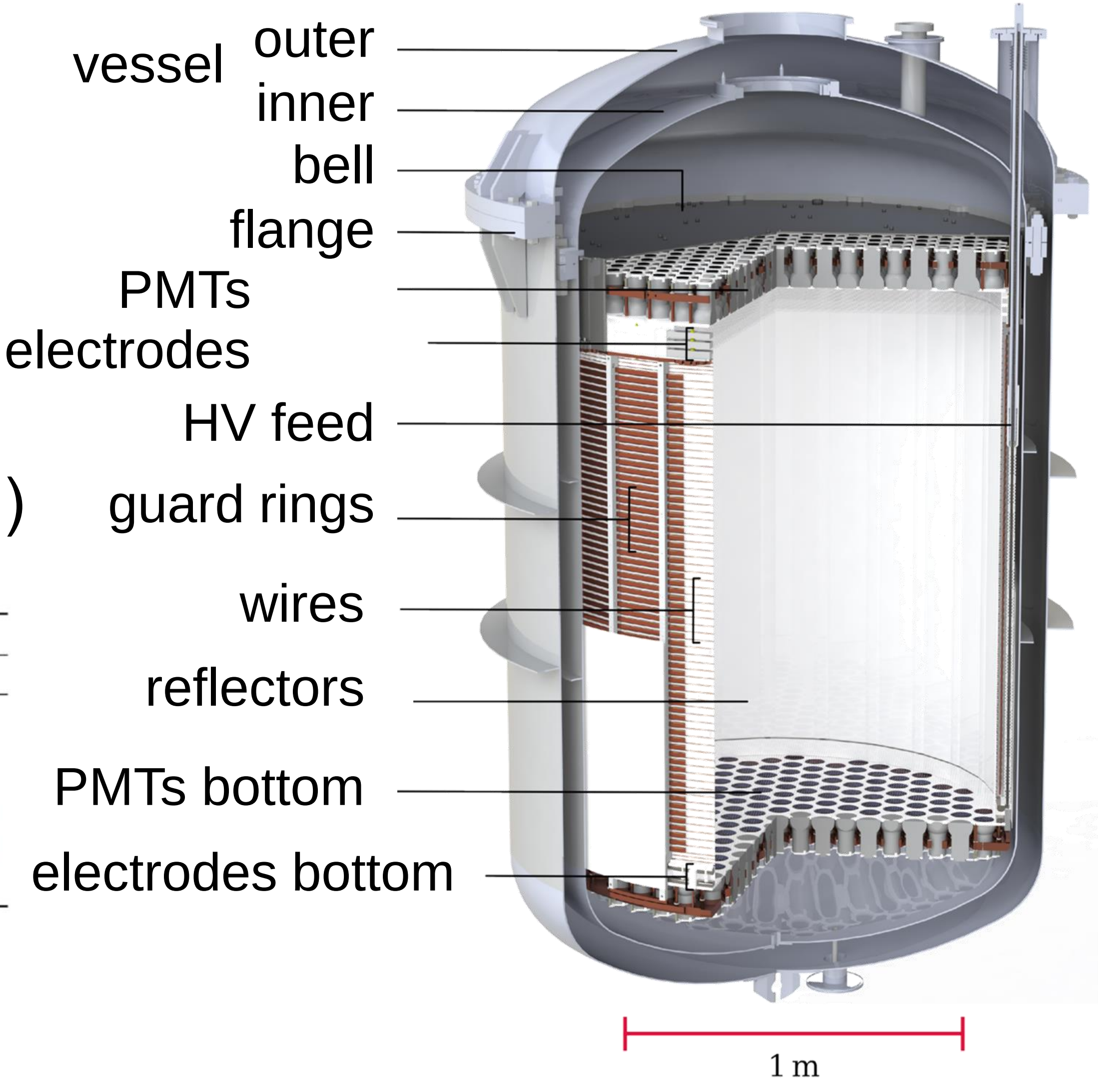
XENONnT experiment – a much larger TPC joins

- **2022/23: everything works perfectly**

  - drift field: $200\ V/cm$

  - all materials were screened & measured very carefully (see table below to see what this means…)

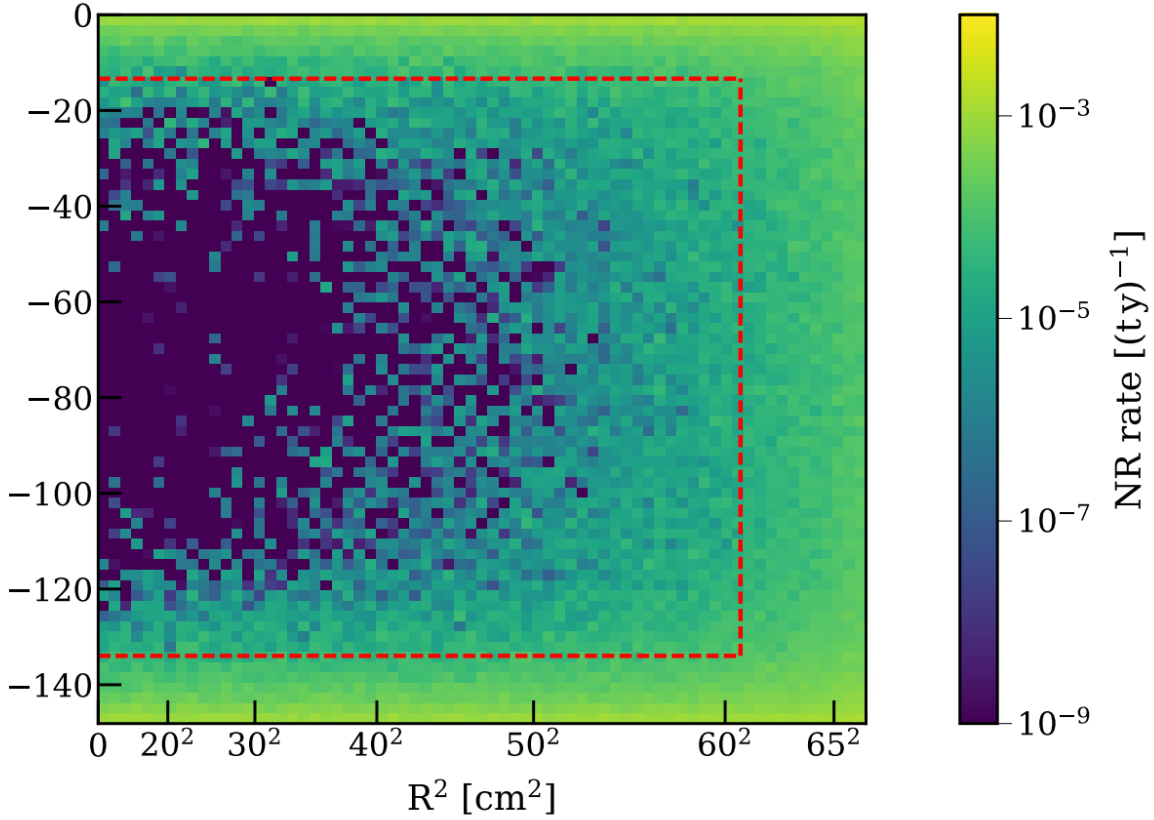
Component	Mass [kg]	Activity [mBq/kg] ^{238}U	^{235}U	^{226}Ra	^{232}Th	^{228}Th	^{60}Co	^{40}K	^{137}Cs
Cryostat vessels	1120	3.2 (9)	0.37 (13)	0.37 (5)	0.29 (7)	0.45 (5)	2.5 (5)	2.1 (3)	< 0.41
Cryostat flanges	730	1.4 (4)	0.06 (2)	< 4	0.21 (6)	4.5 (6)	14.1 (9)	< 5.6	< 1.5
Bell and electrodes[1]	190	3.2 (7)	0.57 (10)	0.62 (10)	0.36 (14)	0.46 (9)	0.78 (11)	1.6 (6)	< 0.17
PTFE[2]	128	0.12 (5)	< 0.06	0.10 (2)	0.11 (5)	< 0.06	< 0.053	2.4 (3)	< 0.038
Copper[3]	355	< 0.69	< 0.28	0.033 (5)	< 0.027	< 0.023	0.11 (2)	< 0.29	< 0.016
PMTs and bases[4]	98	53 (15)	2.2 (7)	4.6 (10)	3.5 (12)	4.2 (8)	7.1 (9)	73 (18)	0.9 (3)

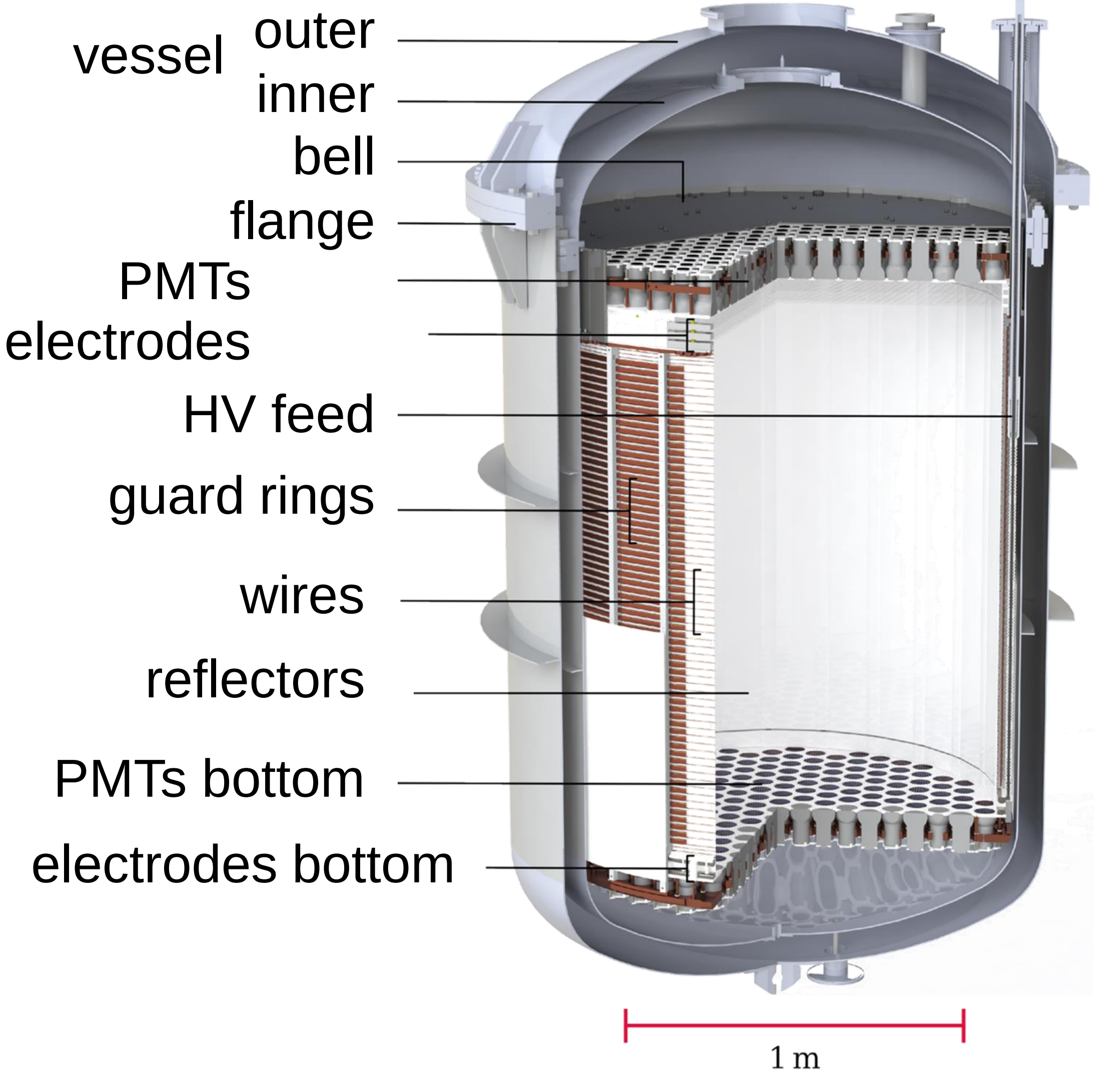


XENONnT experiment – a much larger TPC joins

- **2022/23: everything works perfectly**

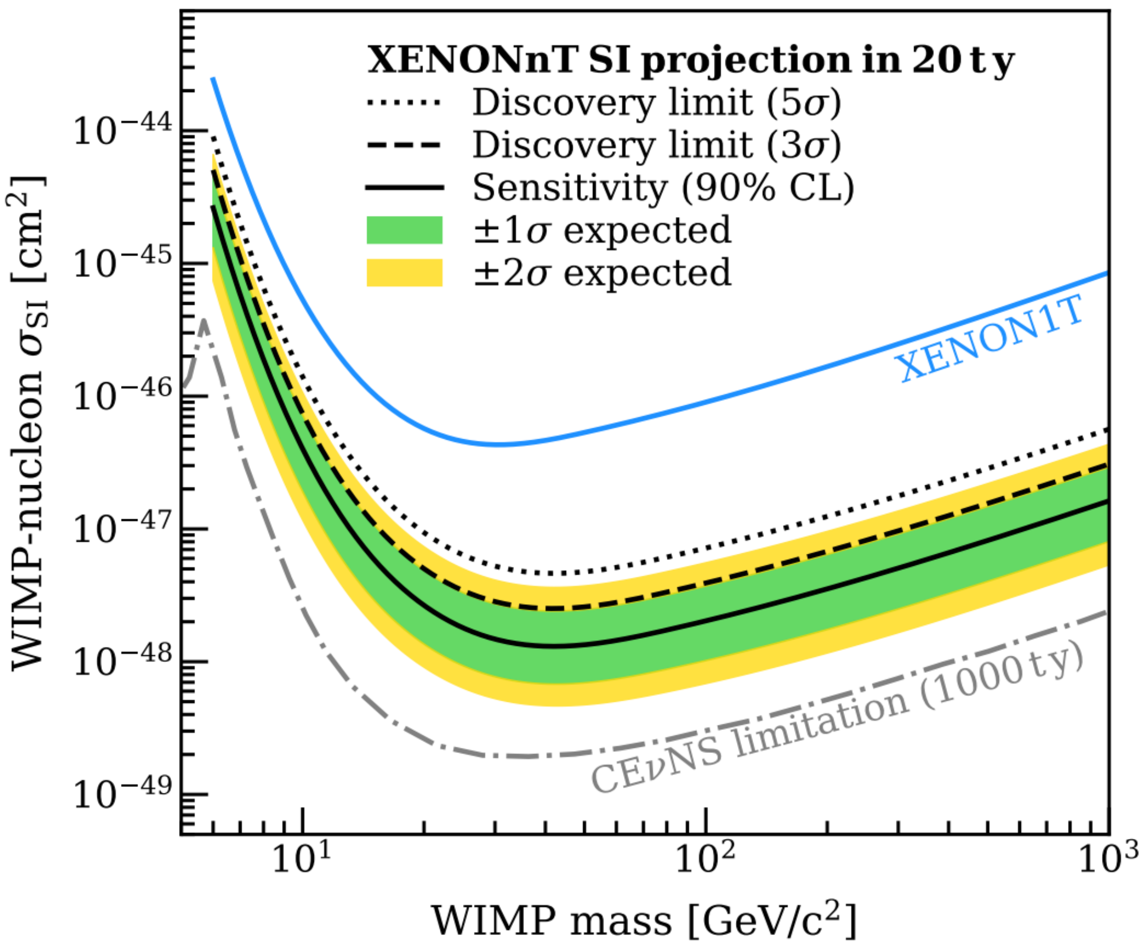
  - extremely low background from ***n´s***

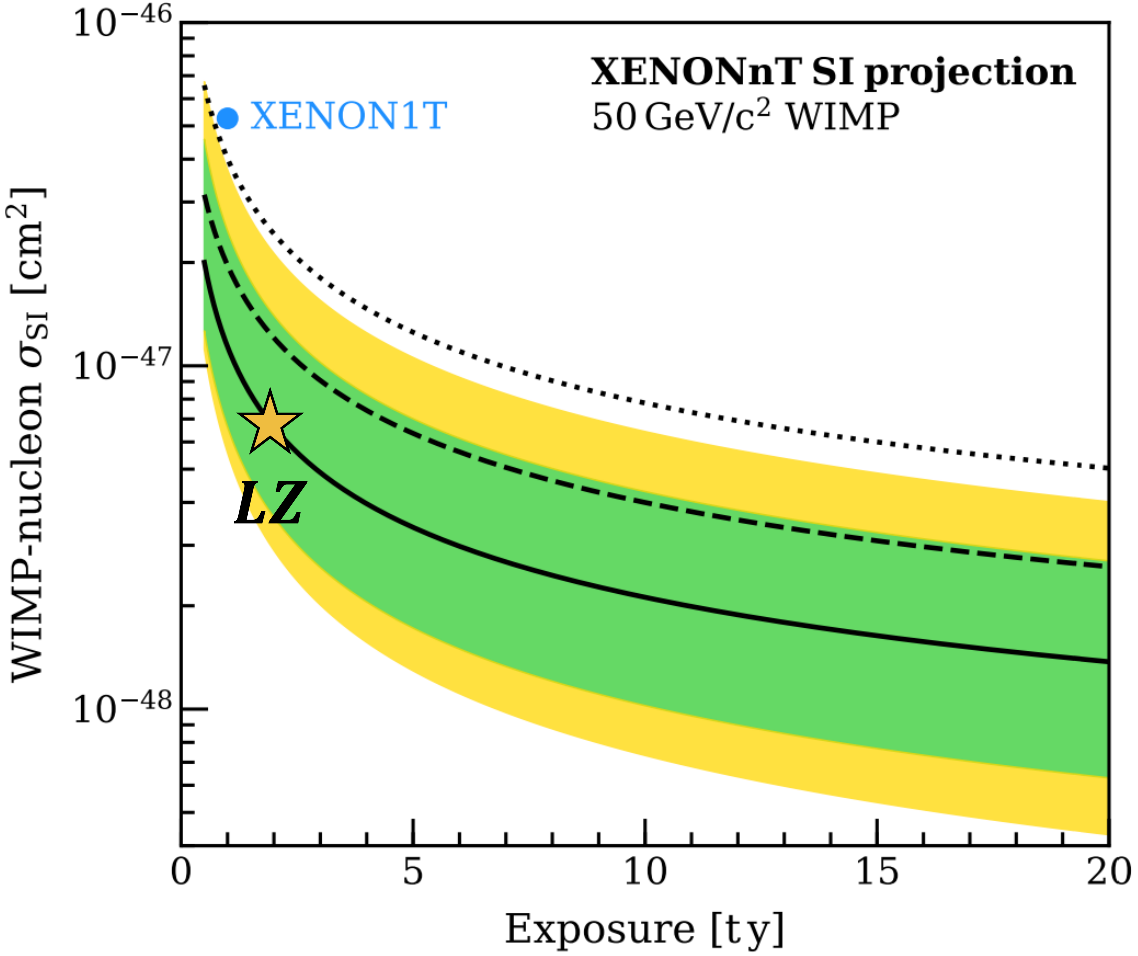




XENONnT experiment – projected sensitivity

- Expected signal sensitivity / exclusion limit as function of exposure $m \cdot t$





DARWIN* experiment – the ´ultimate´ DM-search

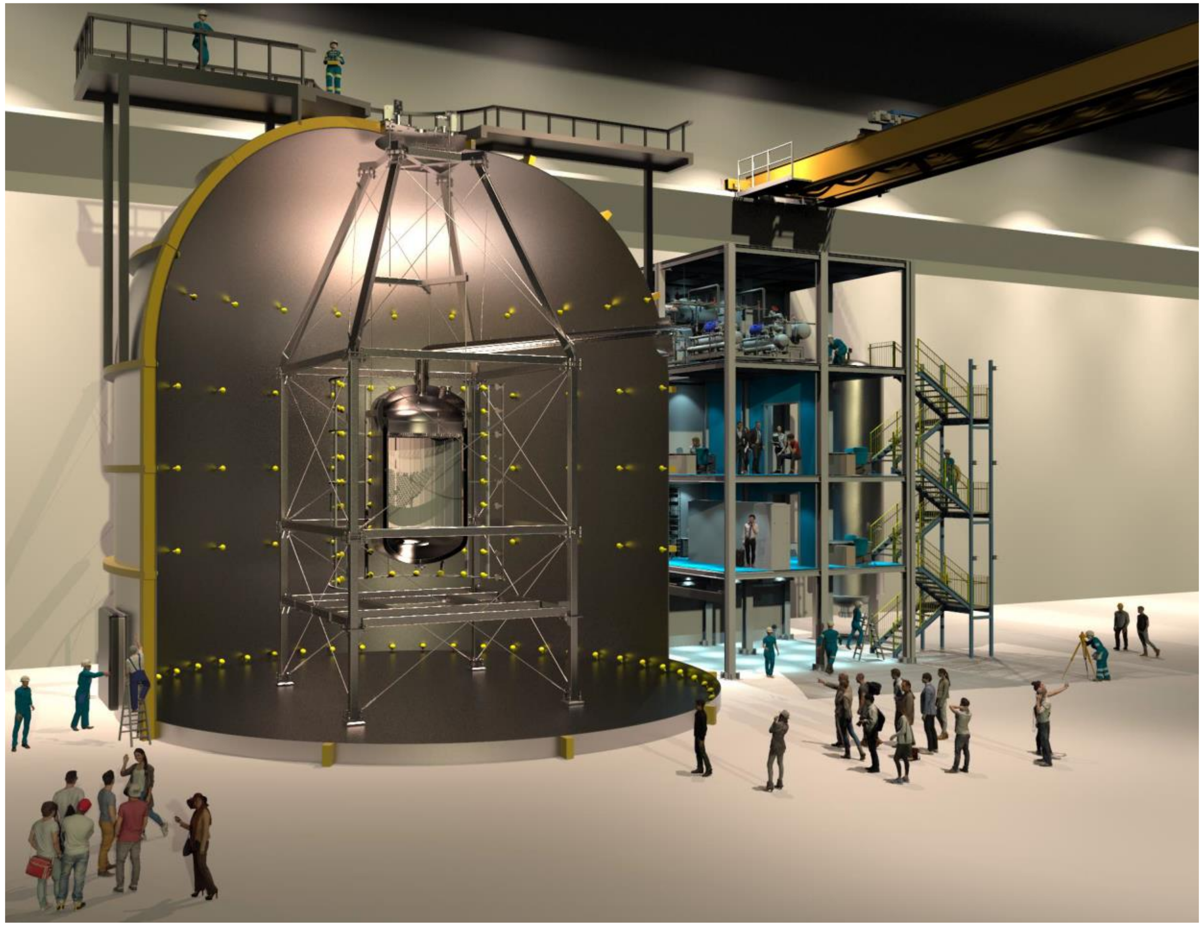
- **Mission: going down into the neutrino floor with a TPC of 50 t target mass**

- low-energy threshold $E_{thres,NR} = 4\ keV$

- **focus: extremely low background level** from intrinsic & external sources

- remaining: equal contributions from **solar ν´s** & ^{222}Rn

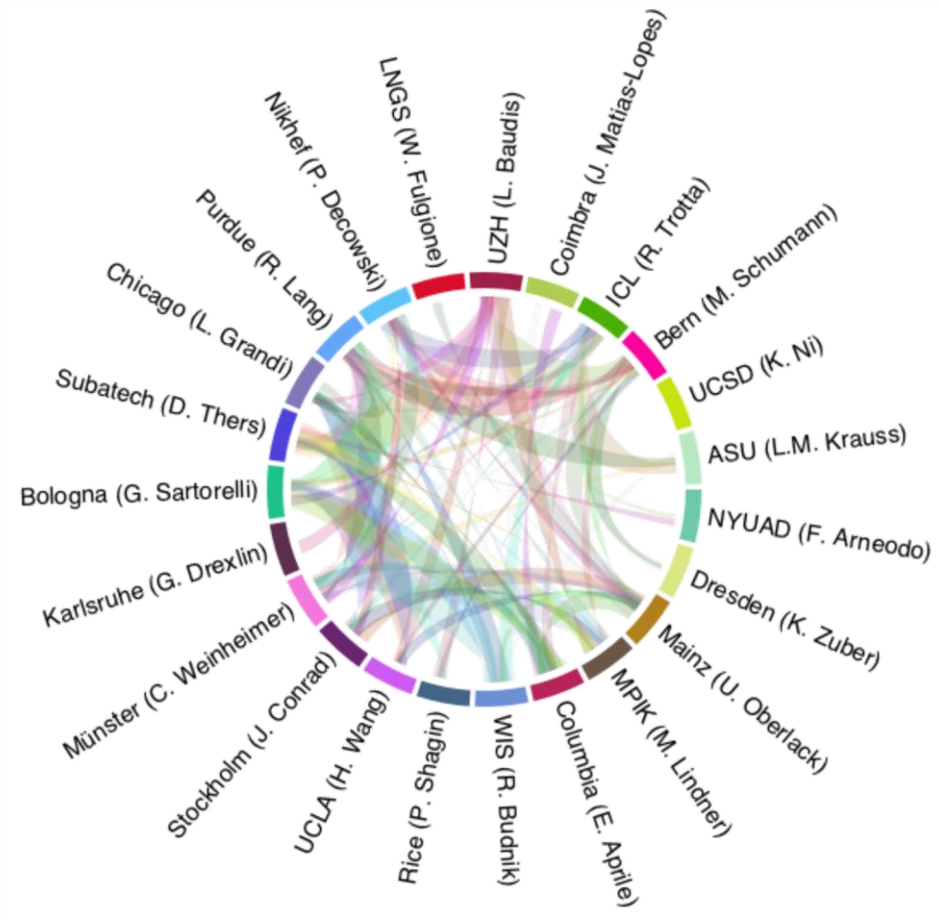
- many other physics channels:
    - search for $0\nu\beta\beta$
    - astrophysical ν´s
    - ...



*DARk matter WImp search with liquid xenoN

DARWIN – site at LNGS & internat. collaboration

- A strong team at the ideal underground laboratory



CERN Courier March 2017

Dark-matter searches

L.Baudis

Testing WIMPs to destruction

A surface building at Gran Sasso National Laboratory in Italy, below which lies a network of caverns shielded from cosmic radiation.

The DARWIN observatory to be built at Gran Sasso in the mid-2020s promises to be the ultimate dark-matter detector, probing the WIMP paradigm to its limit.

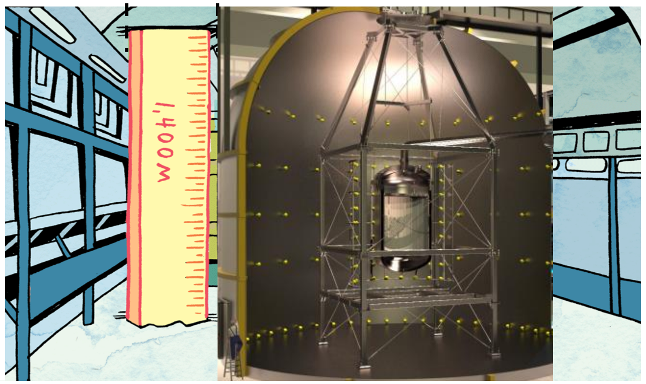
Dark matter is one of the greatest mysteries of our cosmos. More than 80 years after its postulation in modern form by the Swiss–American astronomer Fritz Zwicky, the existence of a new unseen form of matter in our universe is established beyond doubt. Dark matter is not just the gravitational glue that holds together galaxies, galaxy clusters and structures on the largest cosmological scales. Over the past few decades it has become clear that dark matter is also vital to explain the observed fluctuations in cosmic-microwave-background radiation and the growth of structures that began from these primordial density fluctuations in the early universe. Yet despite overwhelming evidence, its existence is inferred only indirectly via its gravitational pull on luminous matter. As of today, we lack the answer to the most fundamental questions: what is dark matter made of and what is its true nature?

DARWIN, the ultimate dark-matter detector using the noble element xenon in liquid form, will be in a unique position to address these fundamental questions. Currently in the design and R&D phase, DARWIN will be constructed at the Gran Sasso National Laboratory (LNGS) in Italy and is scheduled to carry out its first physics runs from 2024. The DARWIN consortium is growing, and currently consists of about 150 scientists from 26 institutions in 11 countries.

Worldwide search

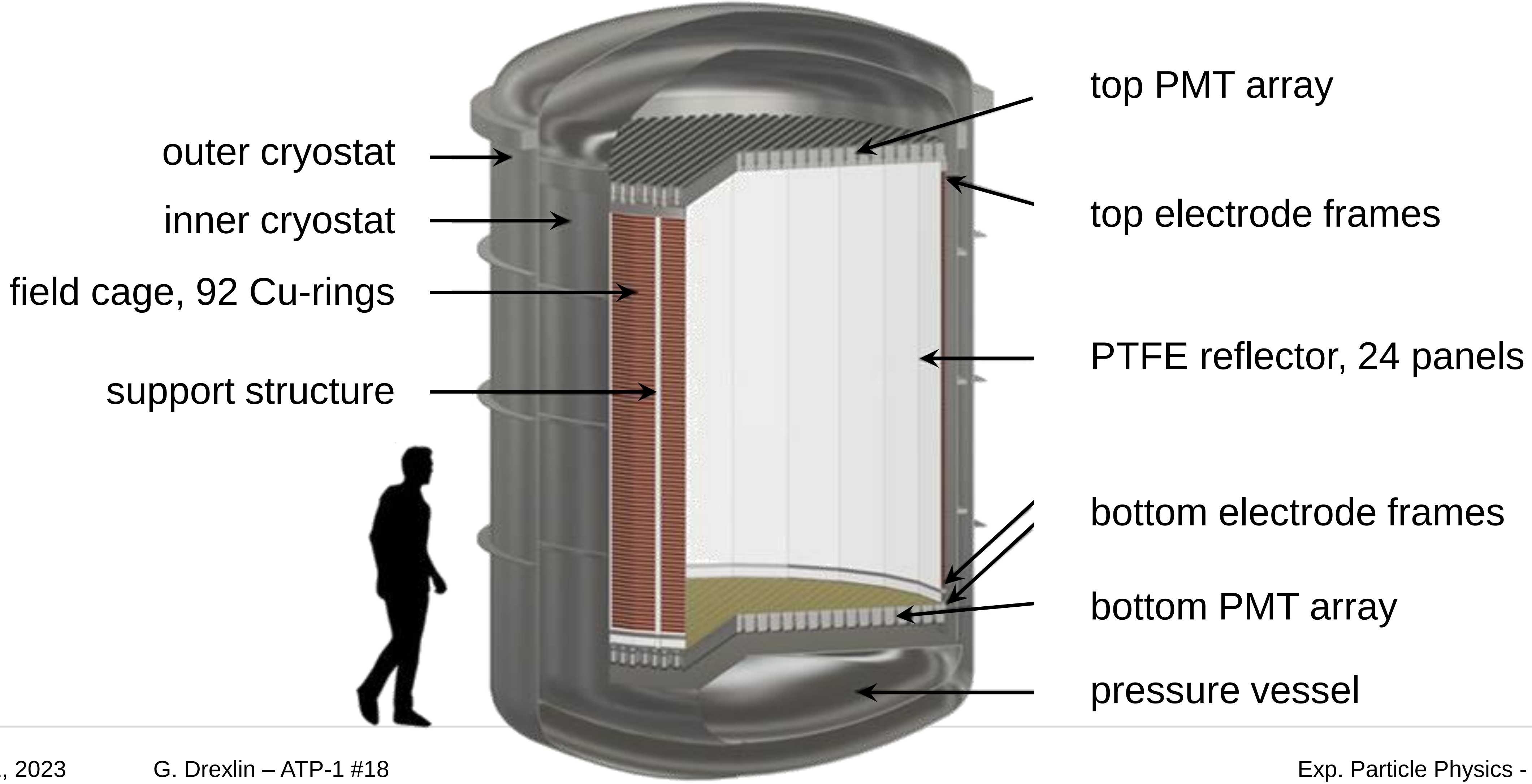
The particles described by the Standard Model of particle physics are unable to account for dark matter. Although neutrinos, the only elementary particles that do not interact with photons, would be ideal candidates, they are much too light and do not form the observed large-scale structures. Dark matter could, however, be made of new elementary particles that were born in the young and energetic universe. Such particles would carry no electric or colour charge, would be either stable or very long-lived and, similar to neutrinos, would interact only feebly (if at all) with known matter via new fundamental forces. Theories beyond the Standard Model predict a wealth of viable dark-matter candidates. The most ▷

1



DARWIN – design of the xenon TPC

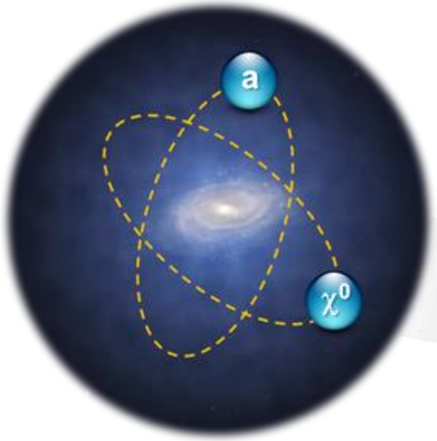
- **Total xenon inventory: $50\ t$ – inside the TPC: $40\ t$**



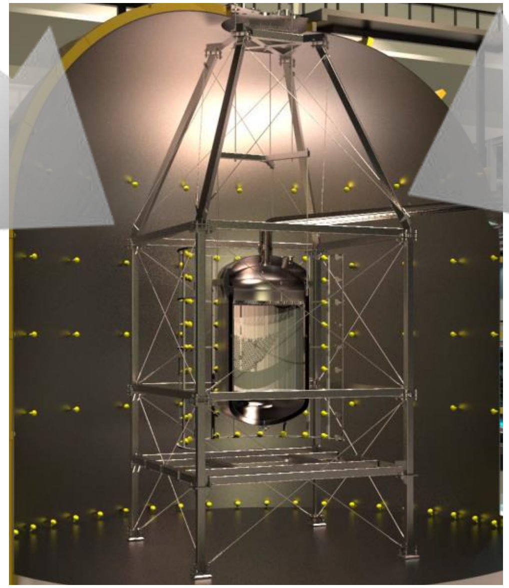
DARWIN experiment – a broad mission portfolio

- **Searching for WIMPs and other rare processes in astrophysics**

WIMPs & ALPs
(galactic halo)

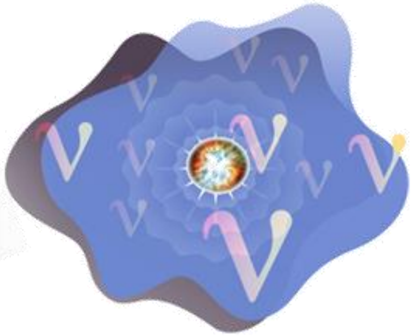


search for $\mathbf{0\nu\beta\beta}$



solar $\boldsymbol{pp - \nu\acute{}s}$
axions

supernova $\boldsymbol{\nu\acute{}s}$



planned DARWIN exposure: $\boldsymbol{M \cdot t = 200\, t \cdot yr}$

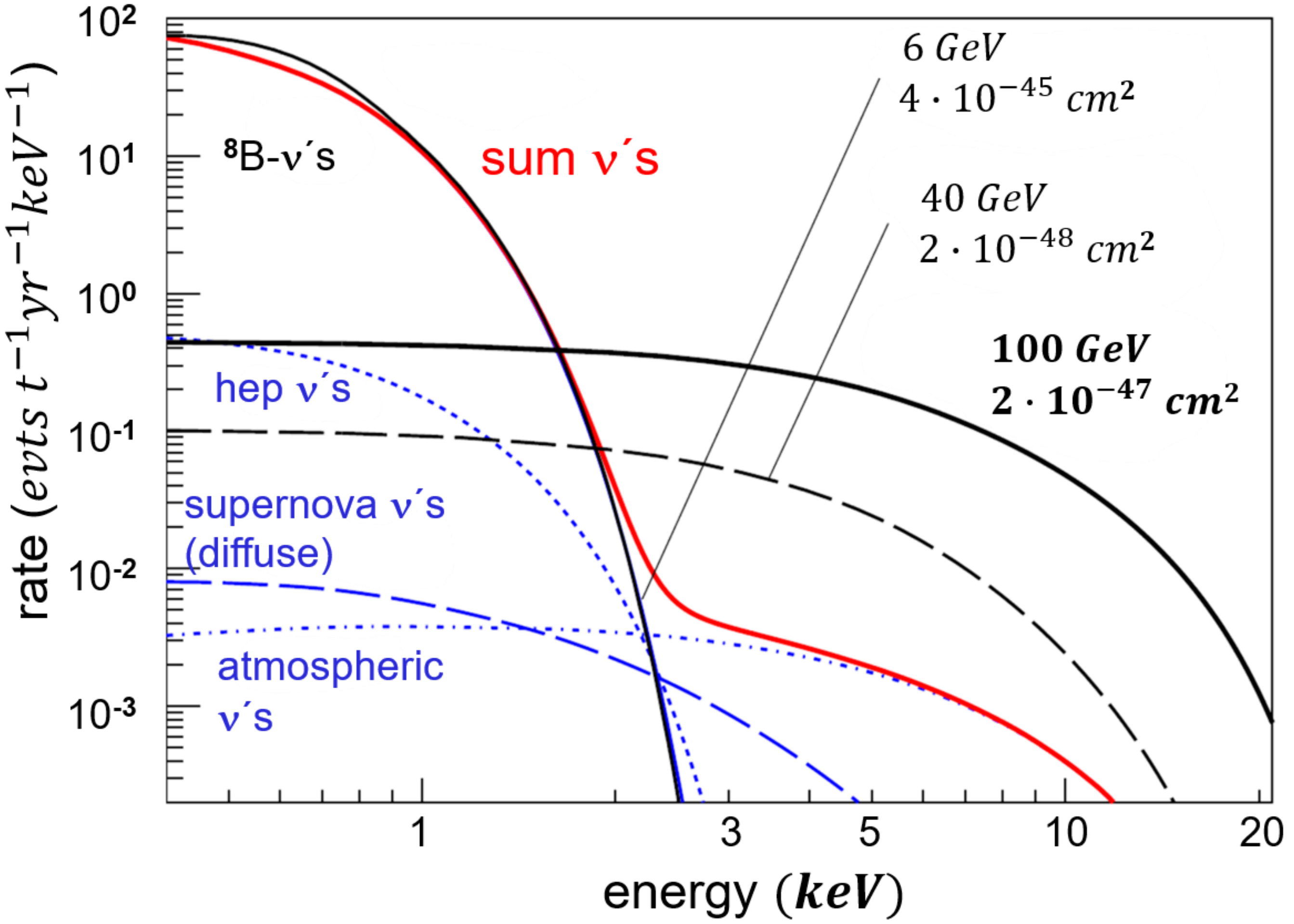
DARWIN – expected nuclear recoil spectra

■ Comparison of WIMP spectra to astrophysical neutrinos

- compare a low mass WIMP with solar neutrinos ($^{8}\boldsymbol{B}$) : identical recoil spectra

- compare a $\mathbf{100}\ \boldsymbol{GeV}$ WIMP with atmospheric neutrinos: identical recoil spectra

- **neutrino floor as the ultimate barrier in direct DM searches**



DARWIN – expected WIMP sensitivity

- **Comparison of previous, present & future direct searches for WIMPs**

- larger masses: sensitivity to very low WIMP cross-sections $\boldsymbol{\sigma_{SI}}$

- lower thresholds: sensitivity to very low WIMP masses