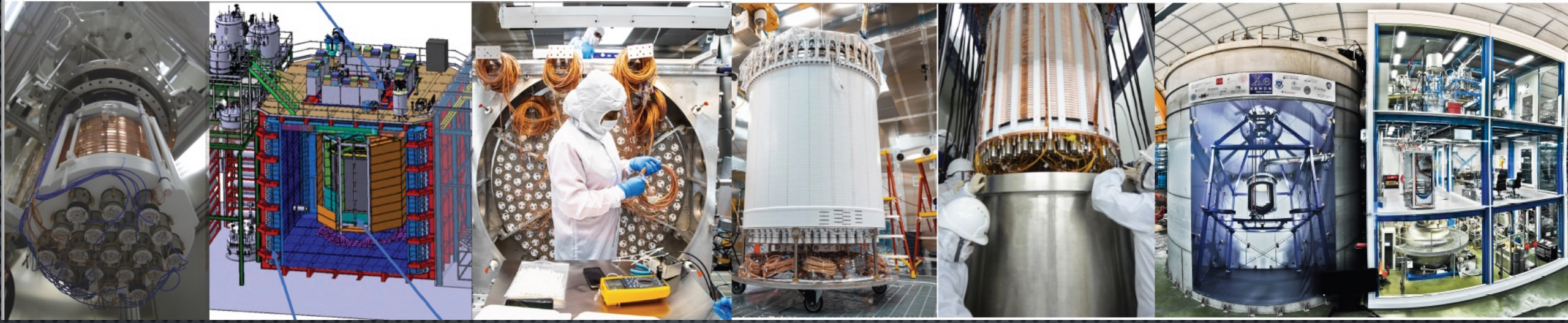
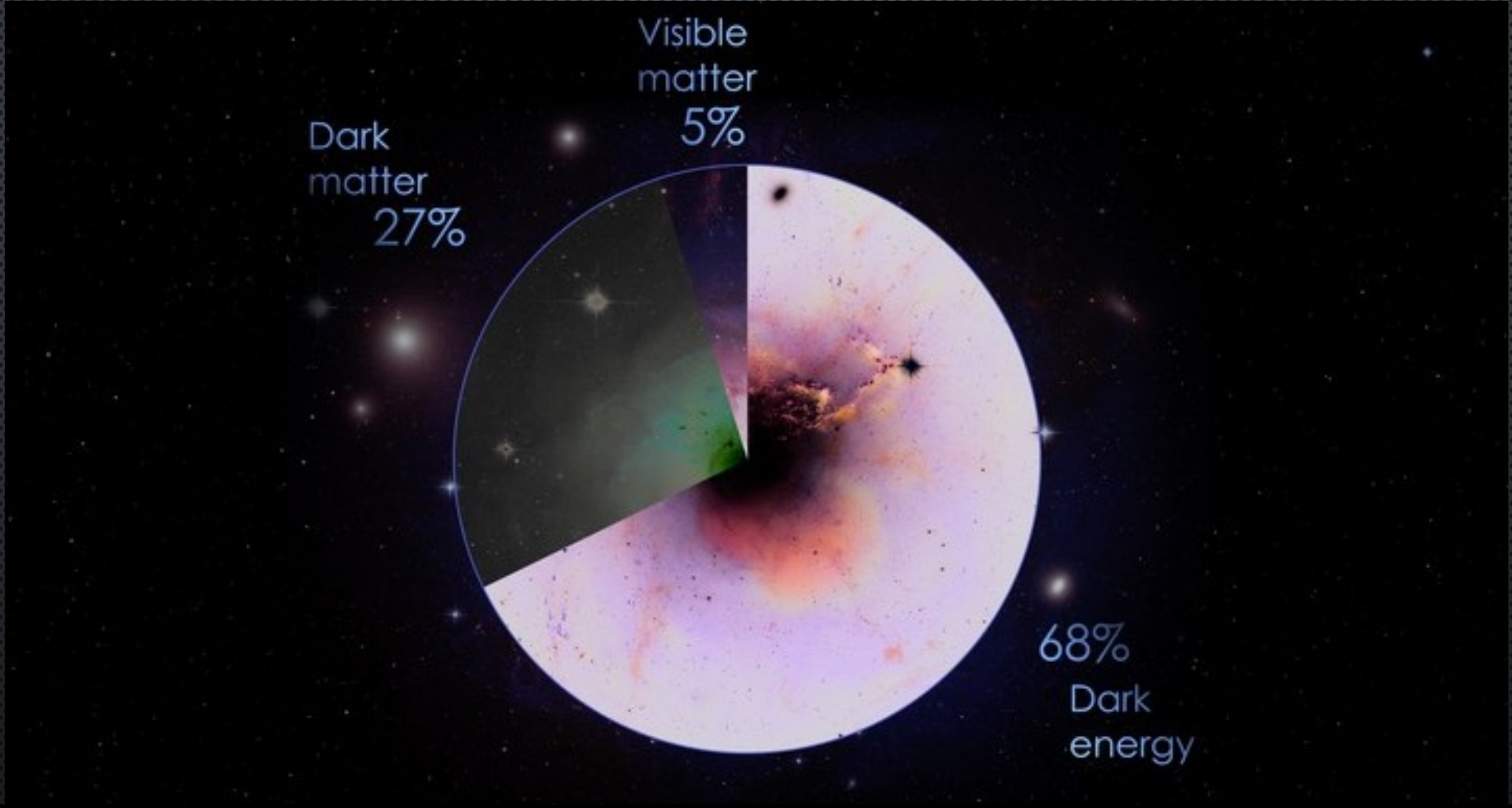


STATUS & PROSPECTS ON NOBLE GAS EXPERIMENTS

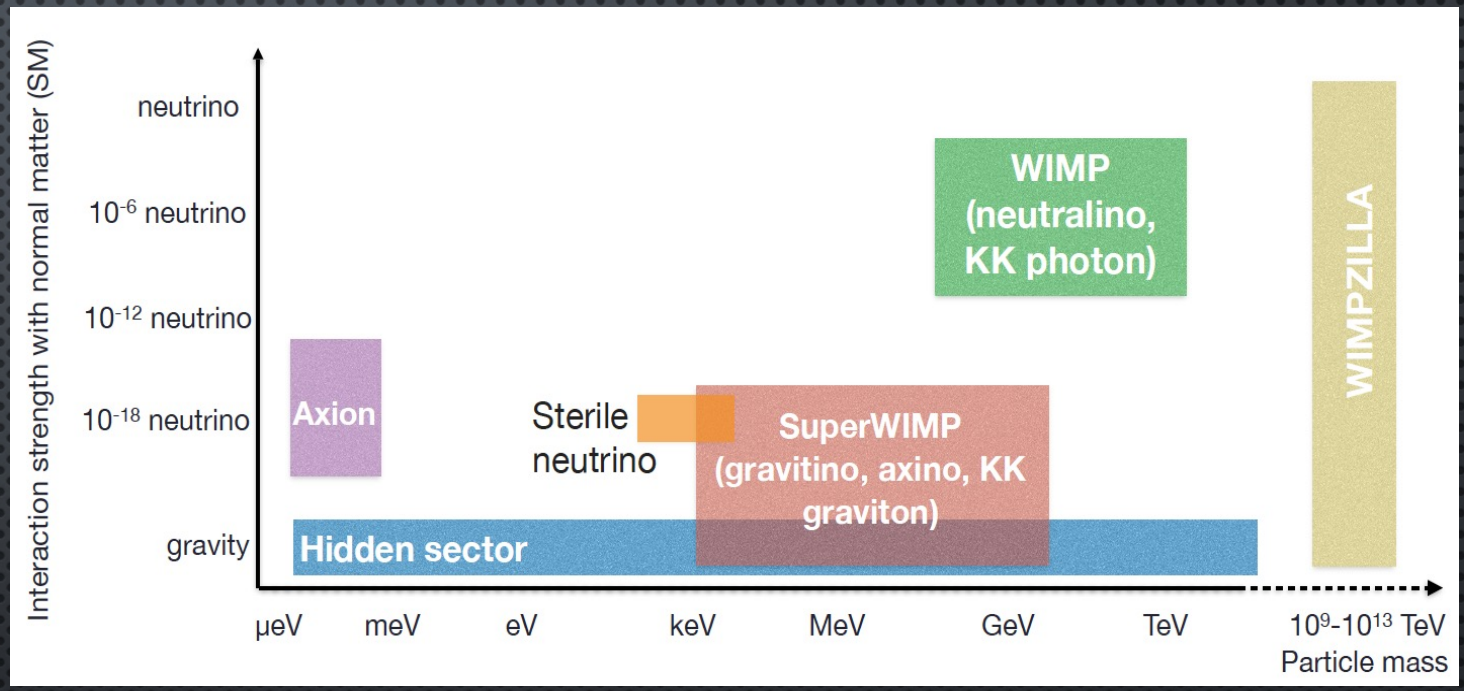
SARA DIGLIO, SUBATECH-NANTES

CDM Annual Meeting,23-25 Nov 2022, Geelong


Visible
matter
5%
Dark
matter
27%
68%
Dark
energy

DARK MATTER PARTICLE CANDIDATES

- Plenty of models
  - Weakly Interactive Massive Particles
  - Axions
  - …
- The mass and interaction strengths span many order of magnitude



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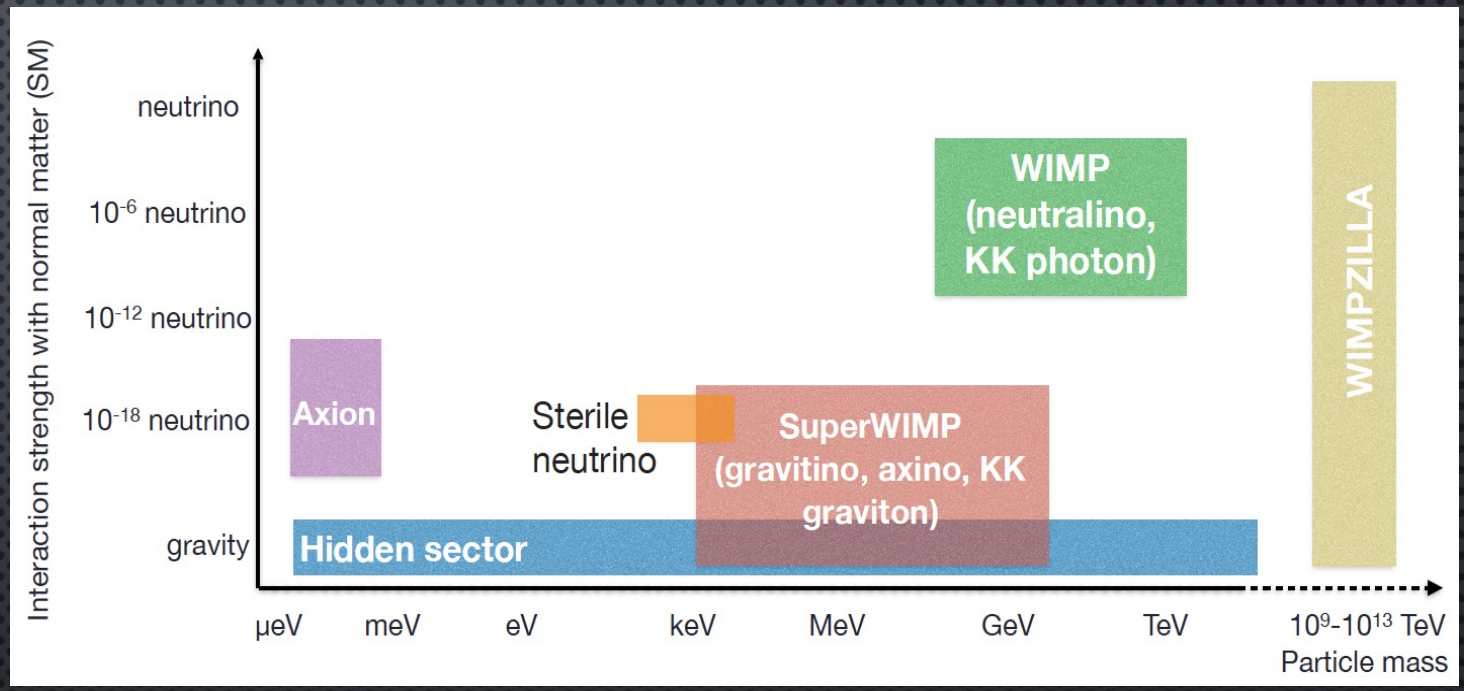
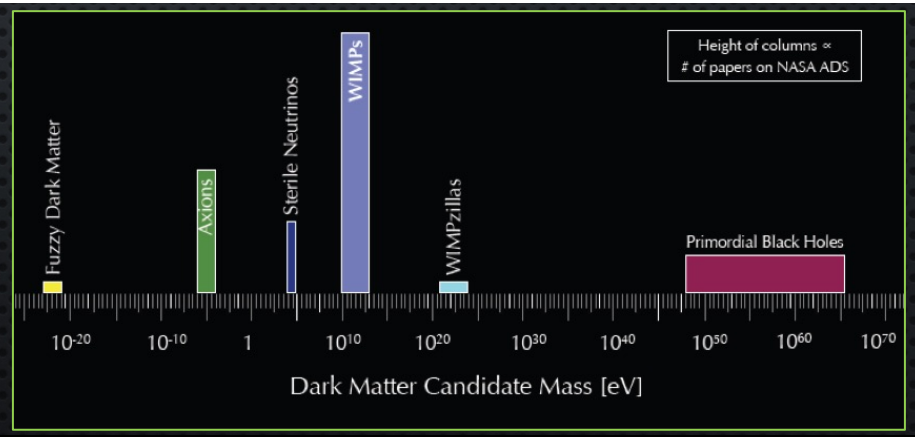
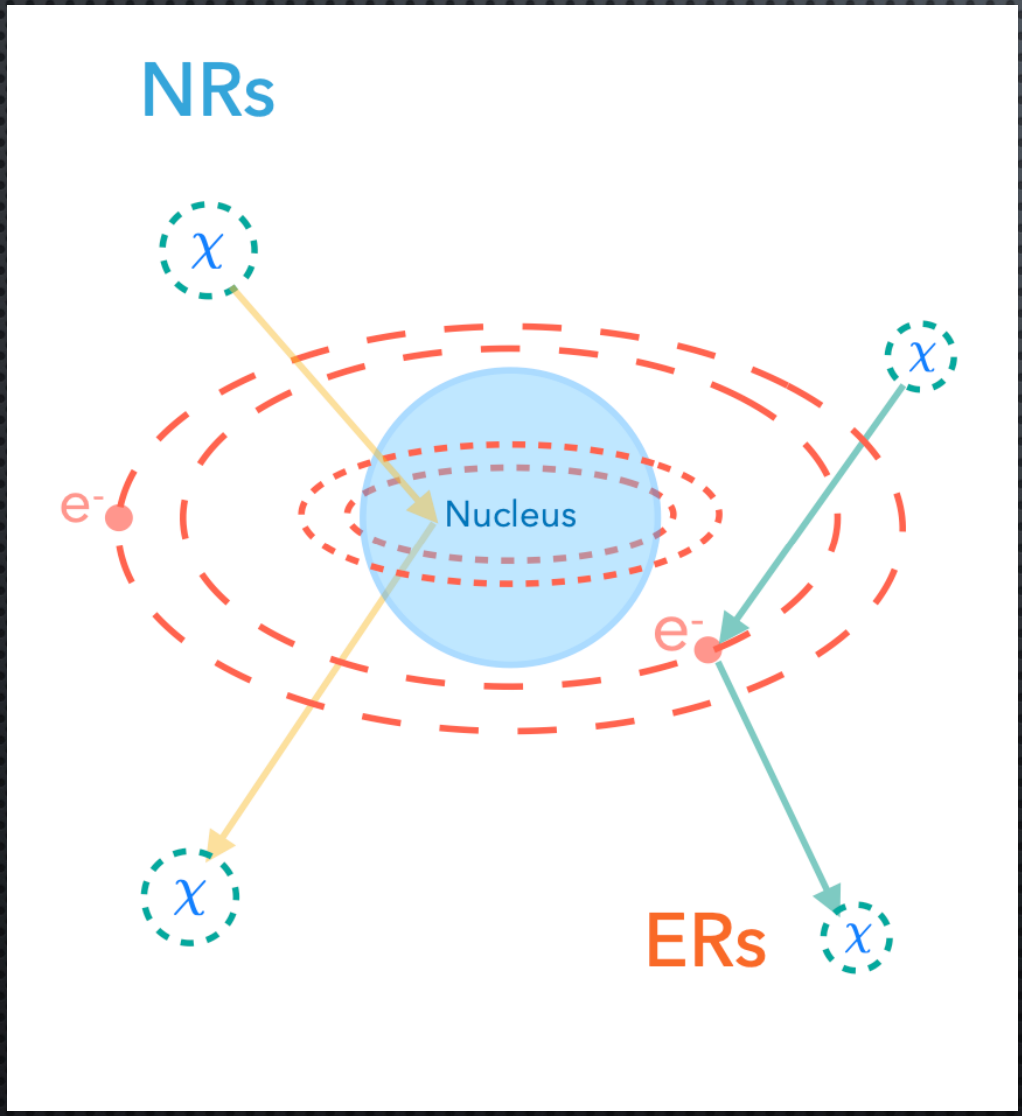




DARK MATTER DIRECT DETECTION

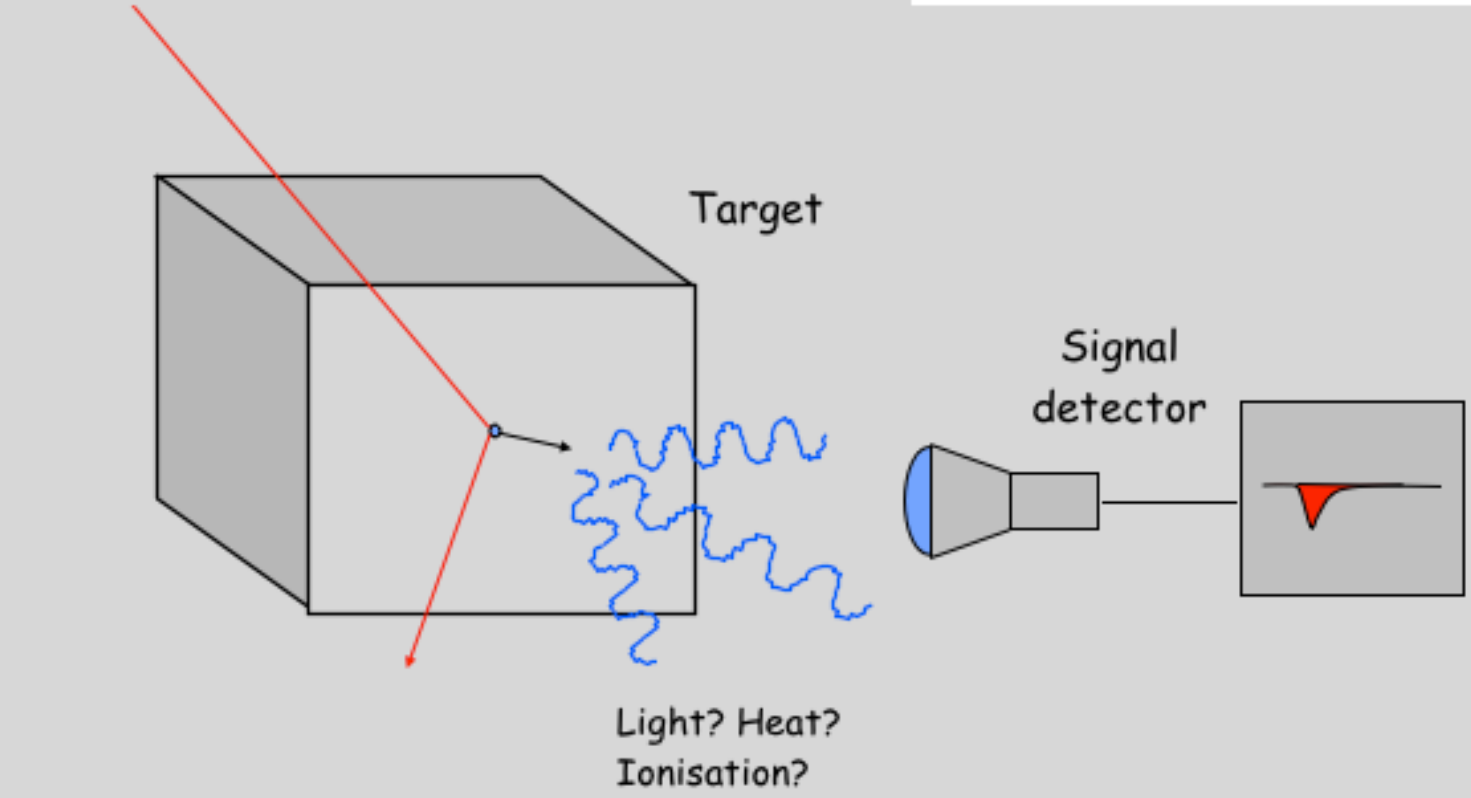


- DEPENDING ON THE DM CANDIDATE, COLLISIONS MIGHT HAPPEN
  - WITH NUCLEI → NUCLEAR RECOILS (NRS) (EX. WIMPS)

  OR
  - WITH ELECTRONS IN THE ATOMIC SHELL → ELECTRONIC RECOILS (ERS) (EX. AXIONS)

HOW TO DETECT A DM CANDIDATE ?

A simple particle detector...



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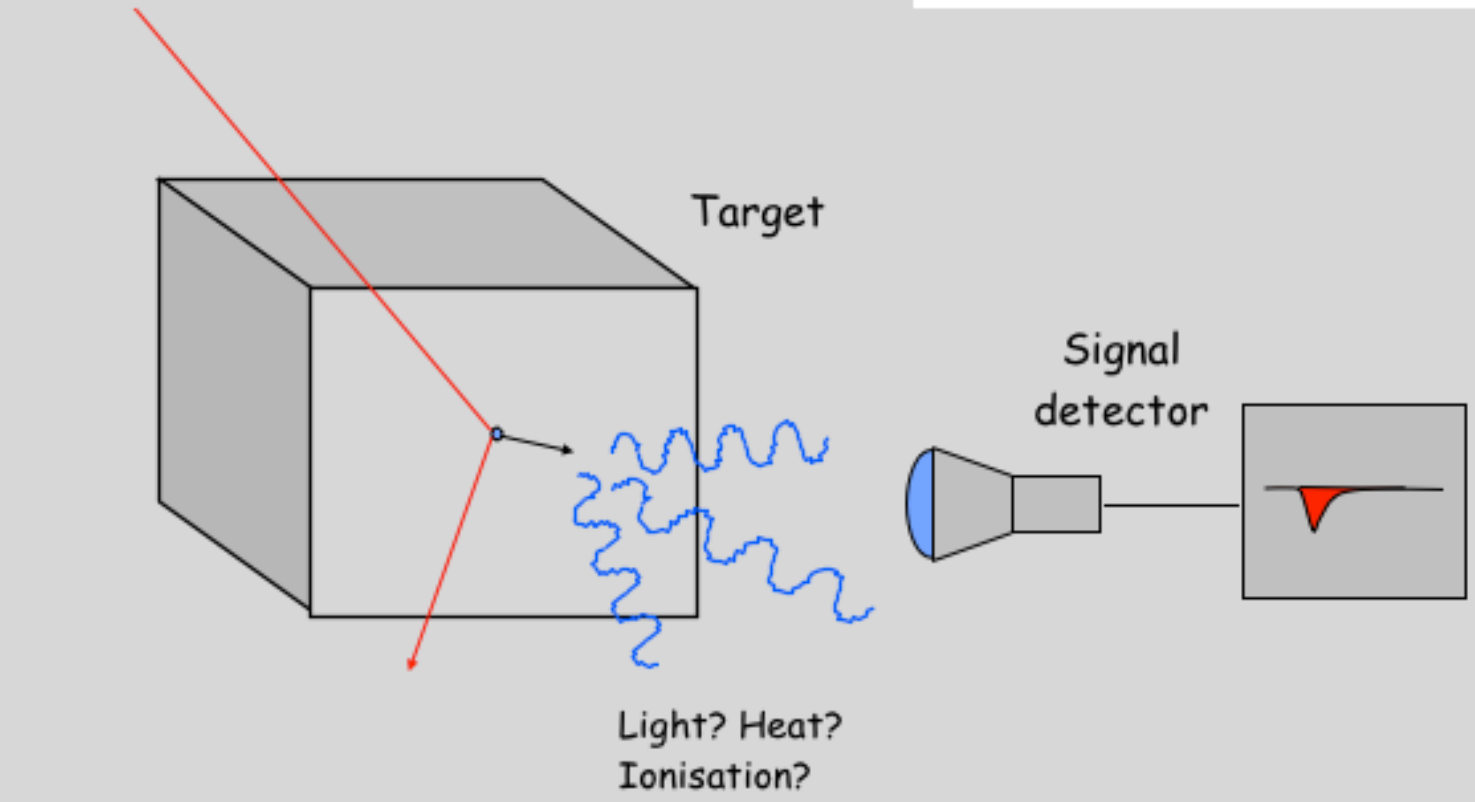
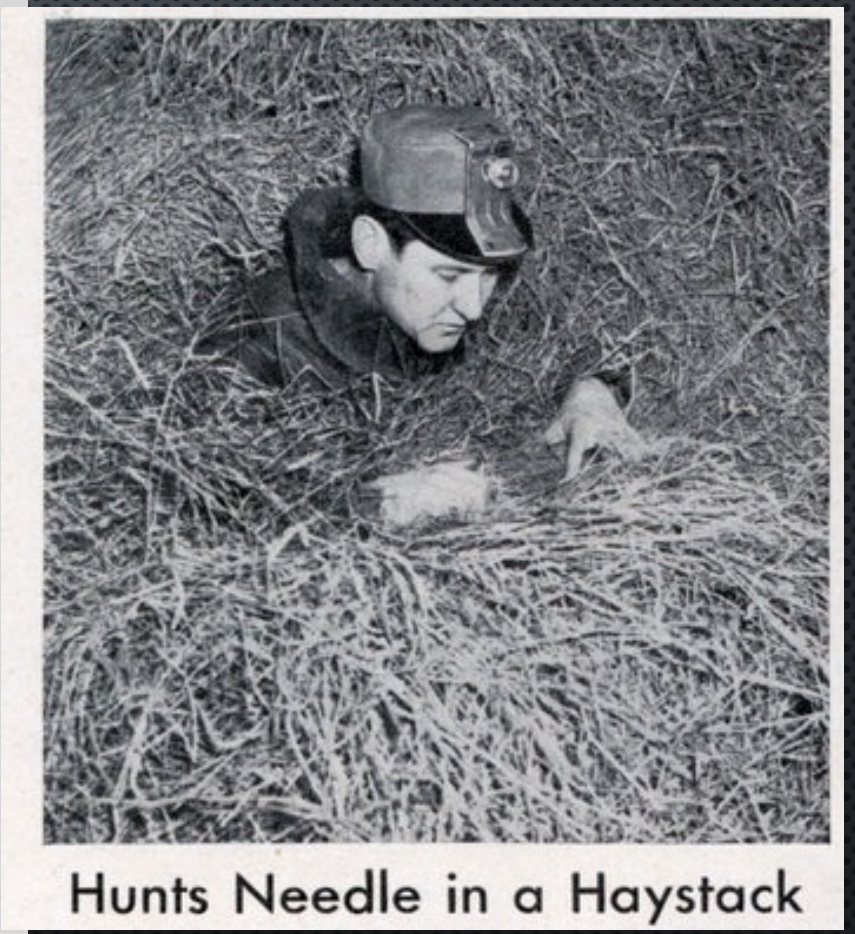
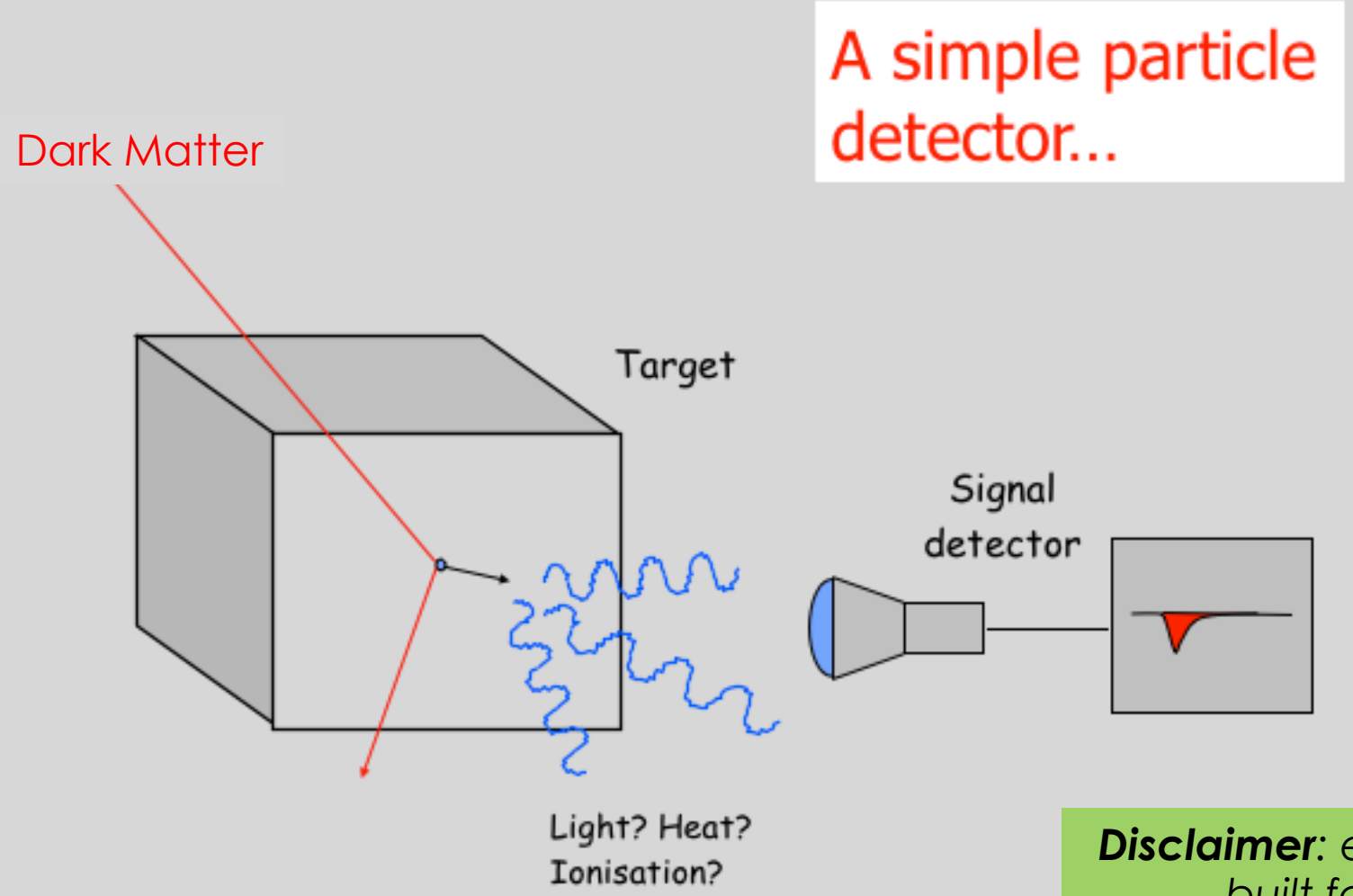




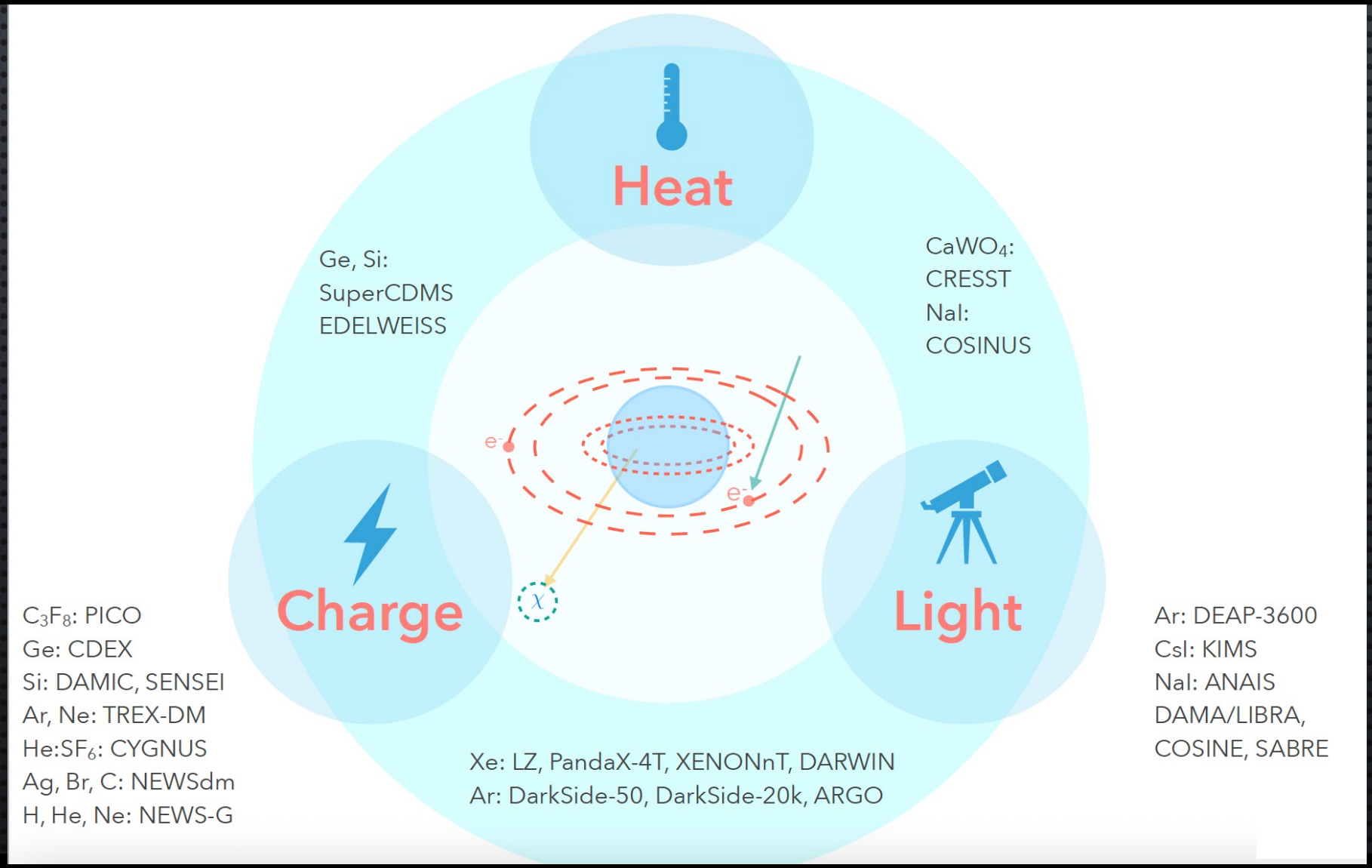
HOW TO DETECT A DM CANDIDATE ?



- ULTRA-LOW BACKGROUND EXPERIMENTAL ENVIRONMENT
- LOW ENERGY THRESHOLD TO DETECT SMALL RECOIL ENERGY SIGNALS
- GOOD DISCRIMINATION POWER AGAINST BACKGROUND
- LARGE DETECTOR MASS TO ENHANCE THE INTERACTION PROBABILITY INSIDE THE TARGET

***Disclaimer**: experiments I will present, are primarily built for **WIMPs searches** → E_R ~ 30 keV*

DIRECT DETECTION TECHNIQUES



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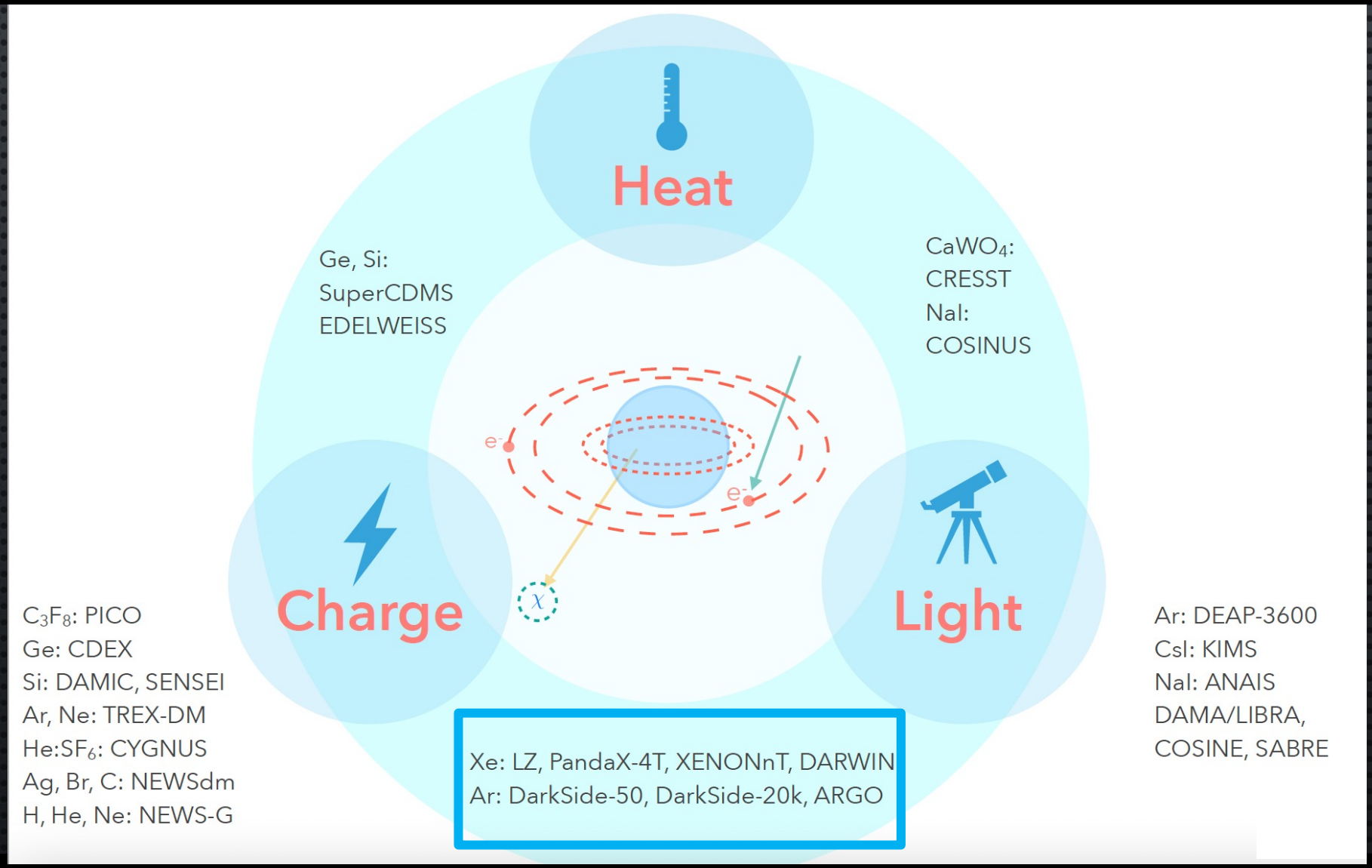
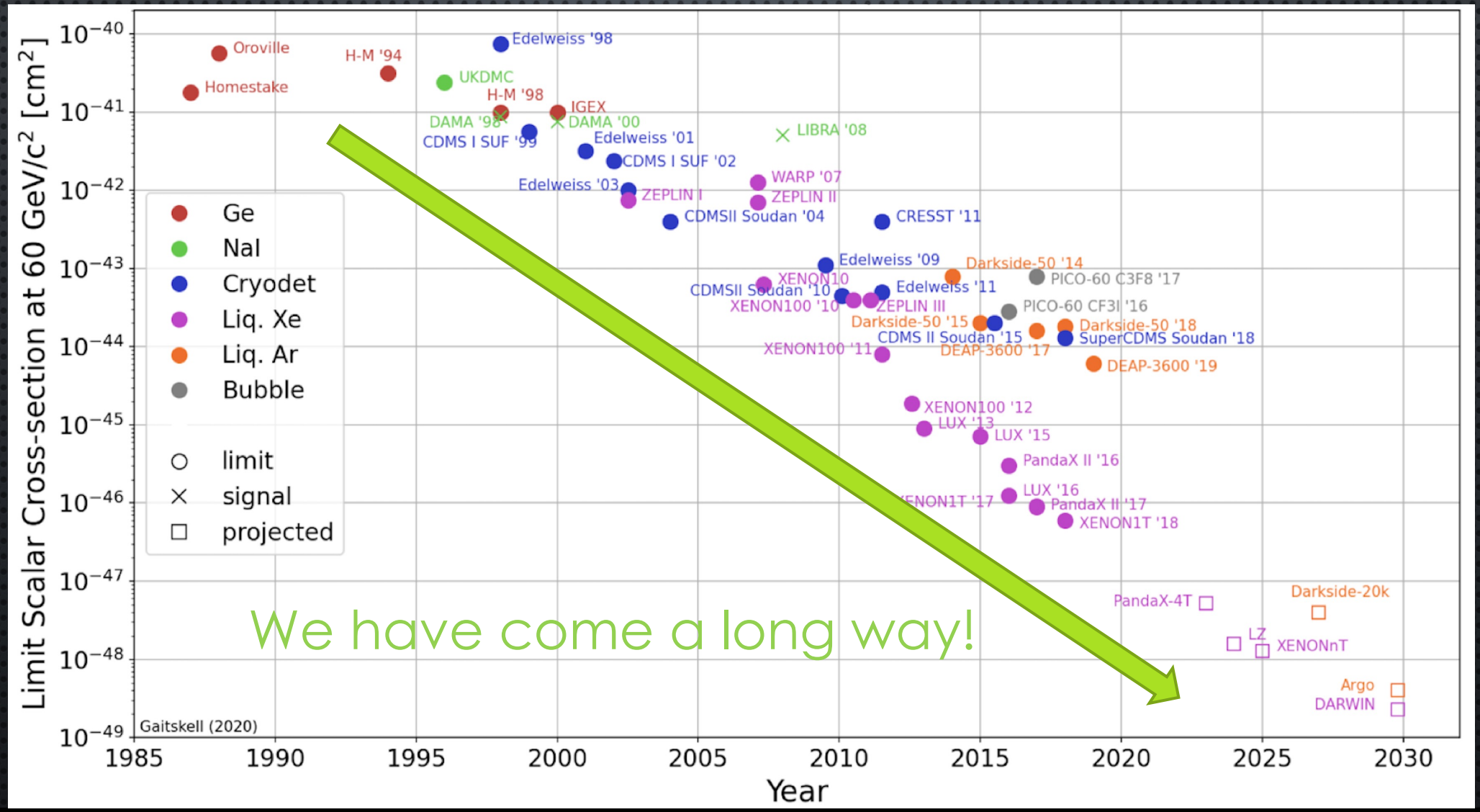
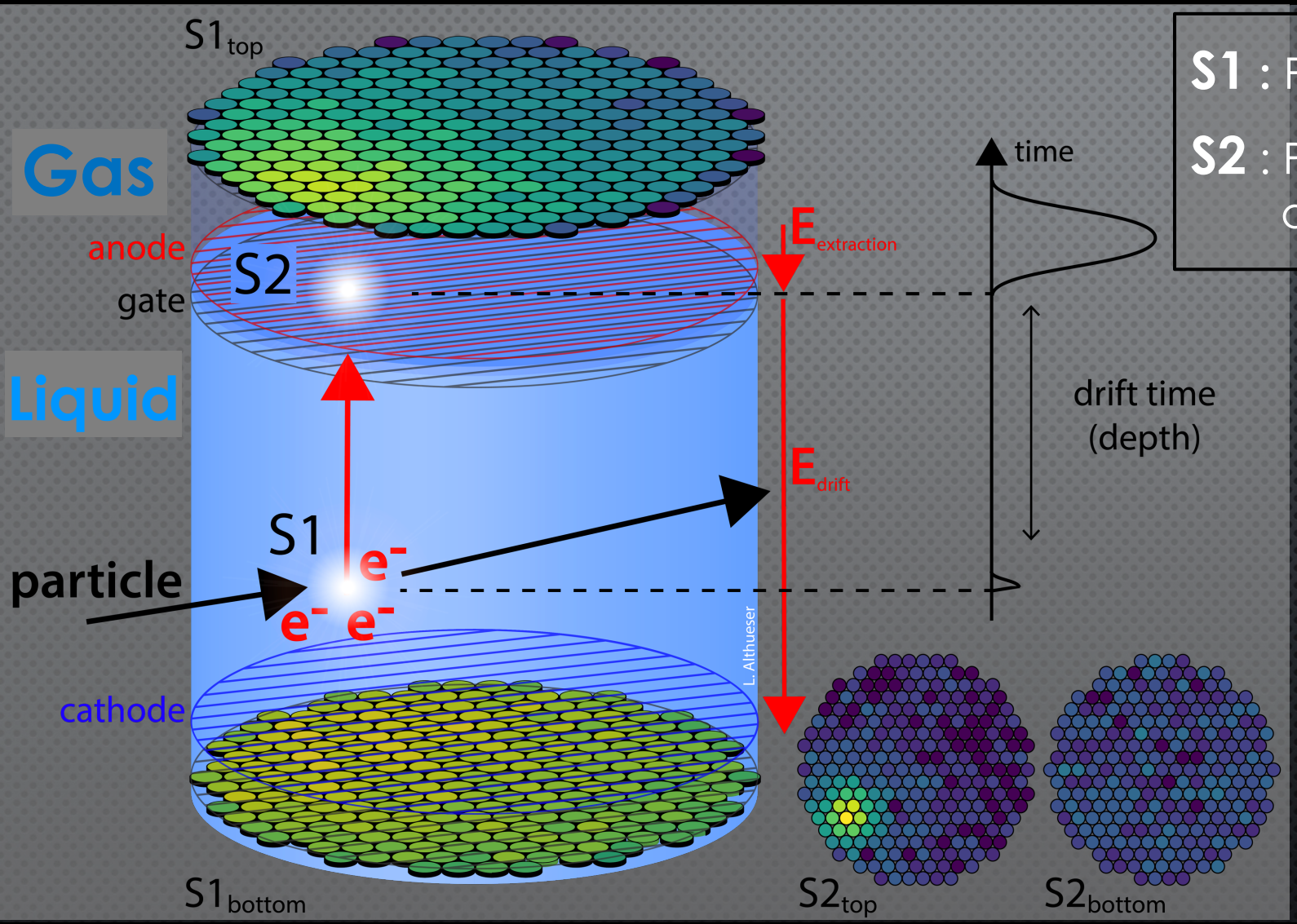


CURRENT STATUS OF WIMP SEARCH



DUAL PHASE TIME PROJECTION CHAMBERS



S1 : Prompt Scintillation (light)

S2 : Proportional scintillation following e^- drift and extraction into gas (charge)

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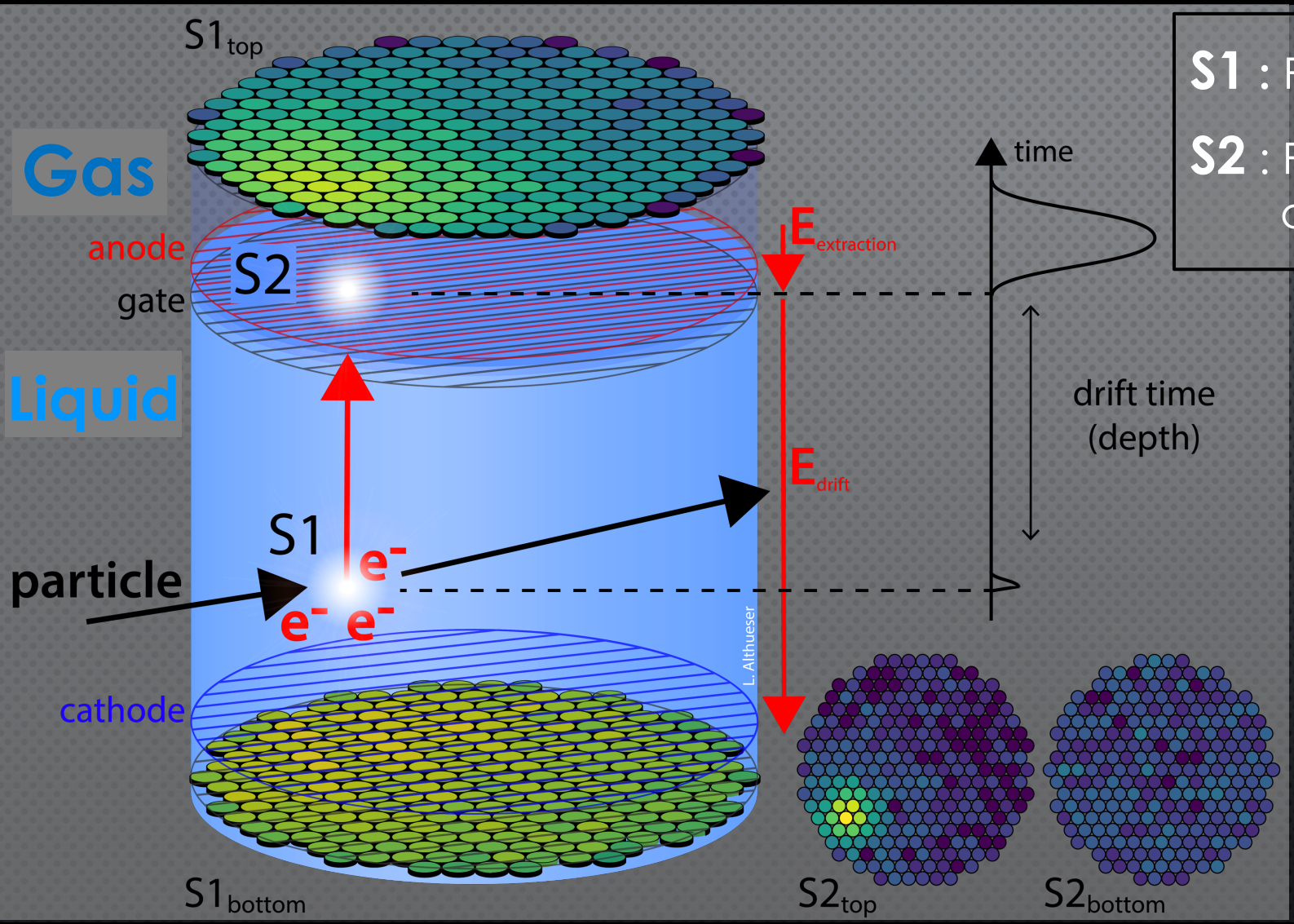

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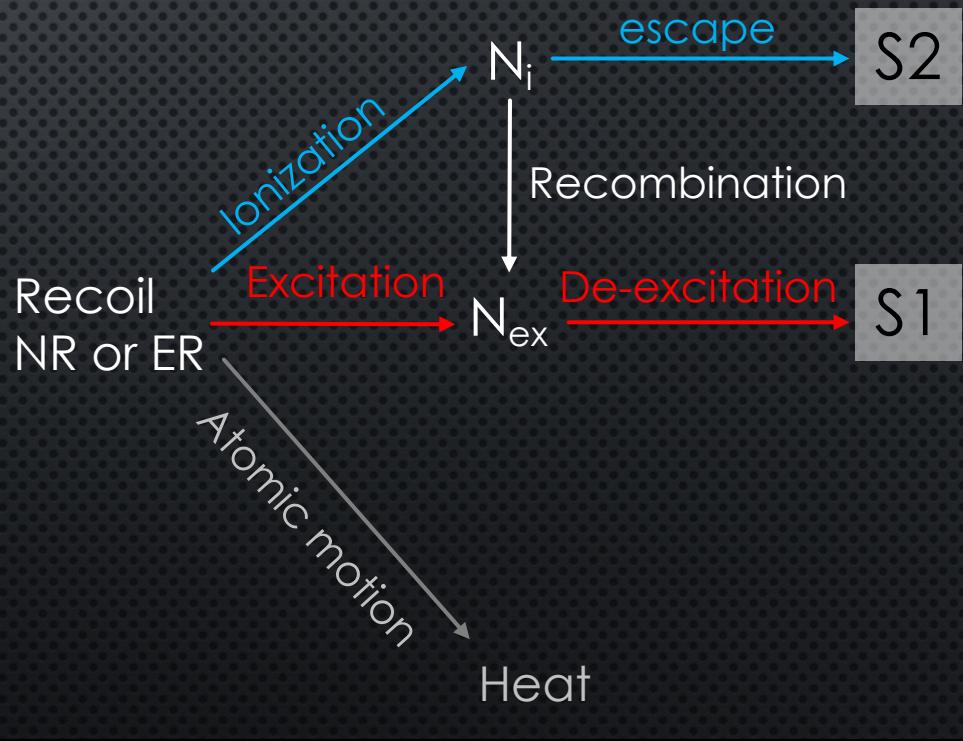

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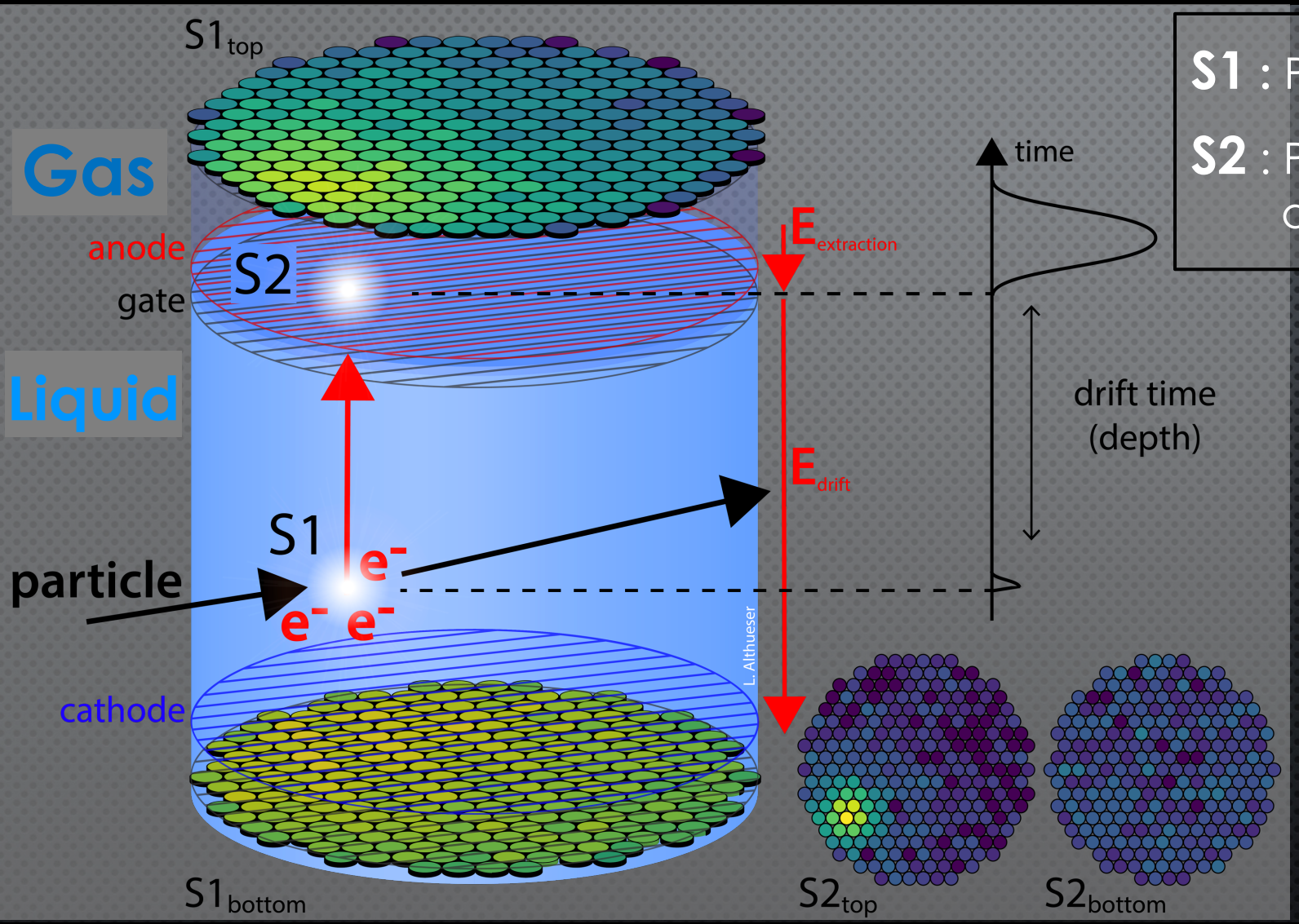

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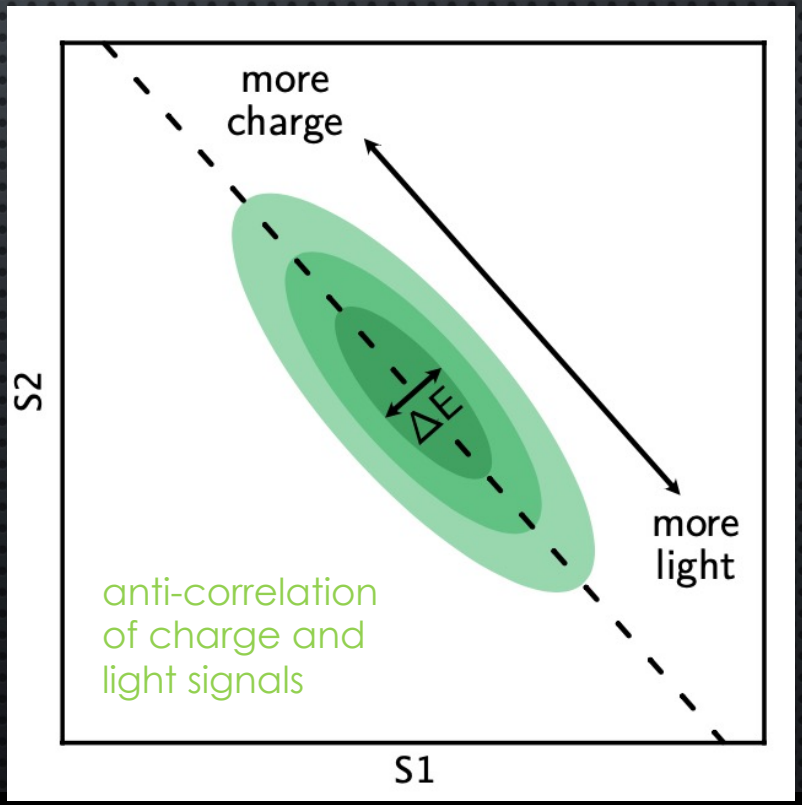

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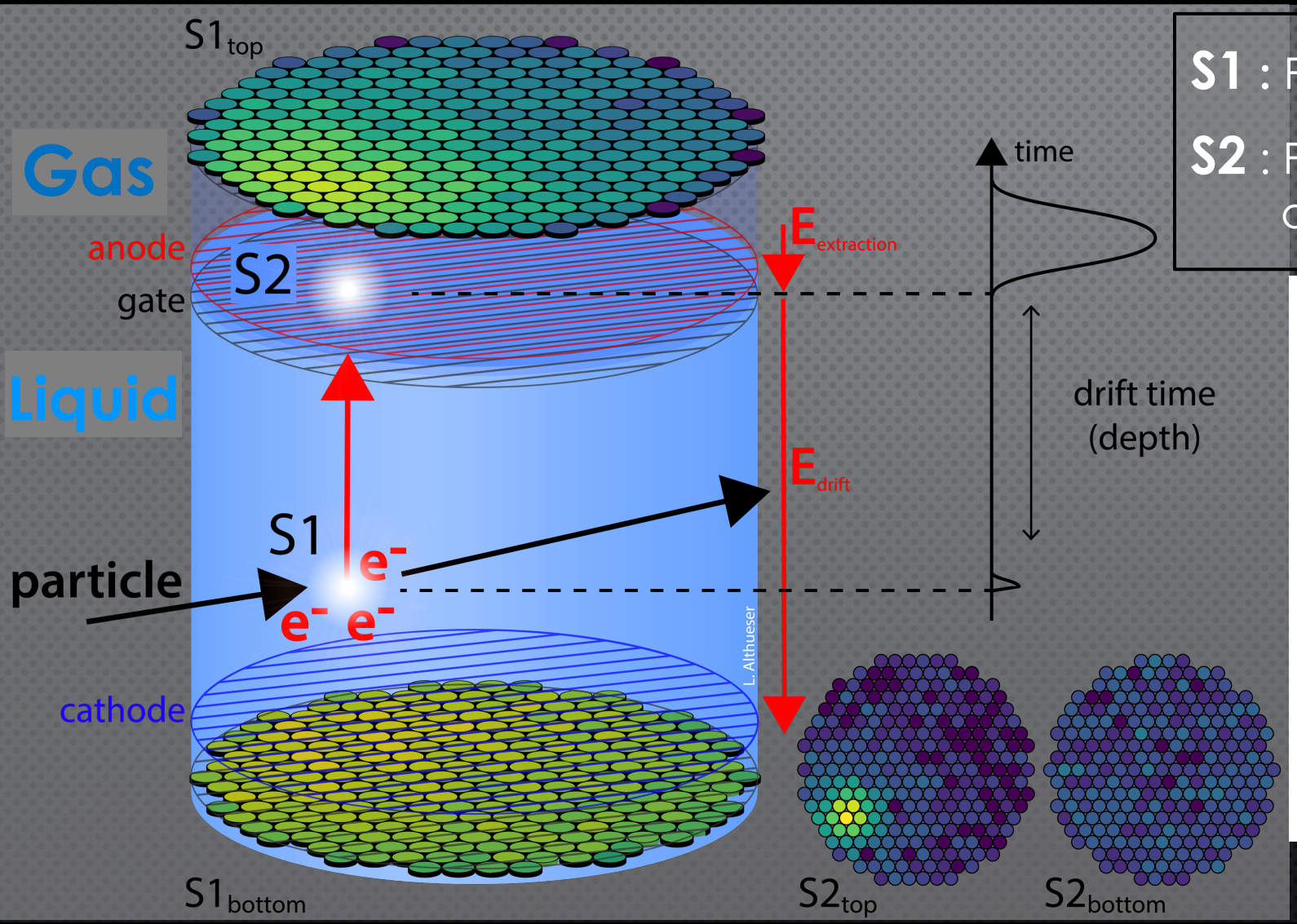

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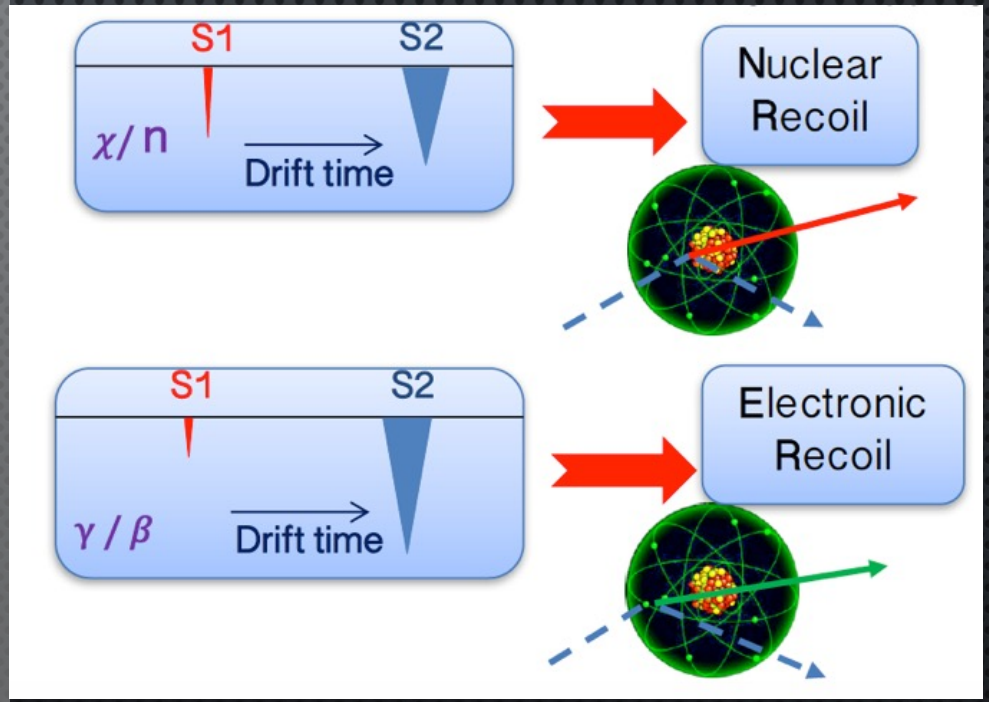
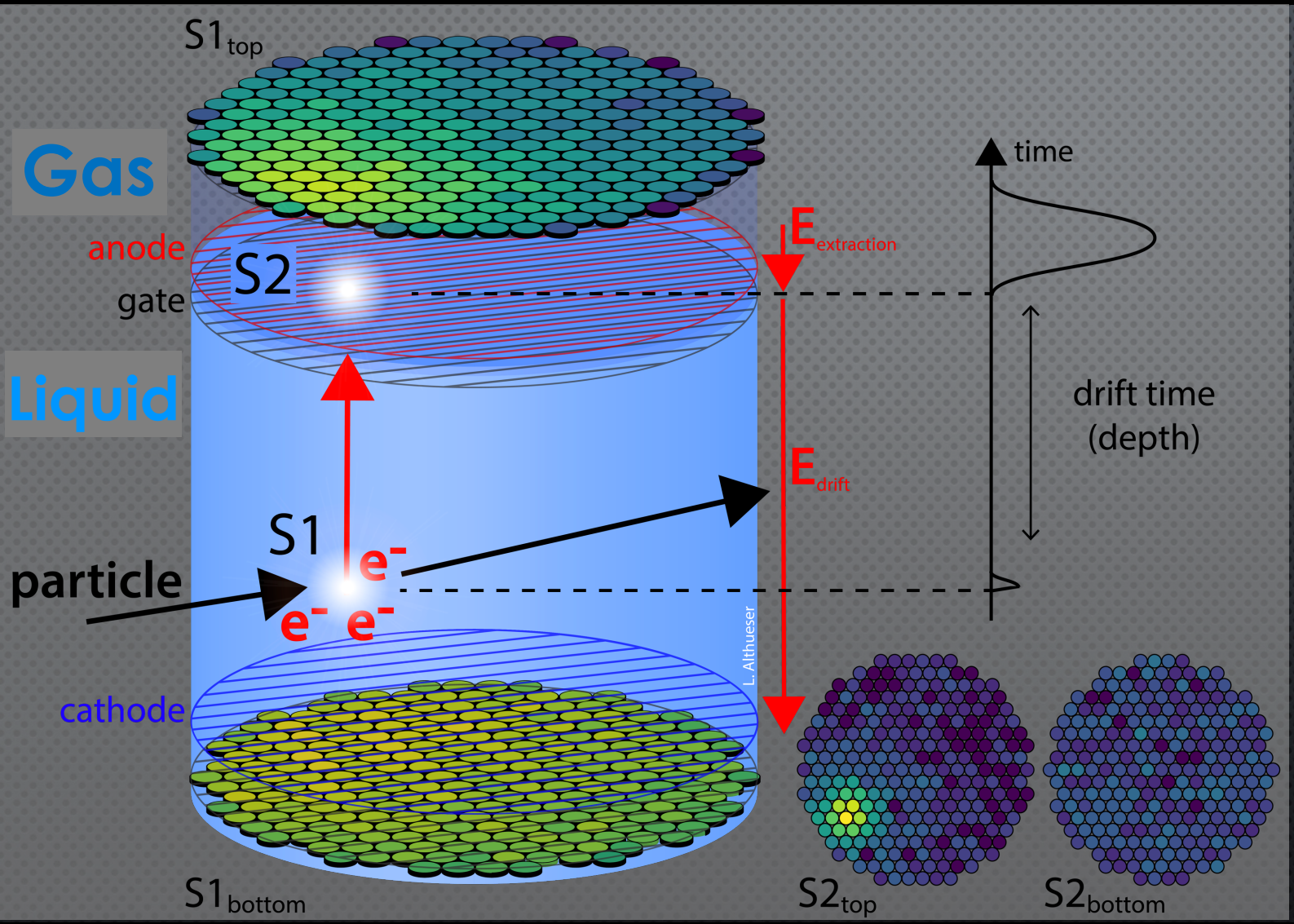
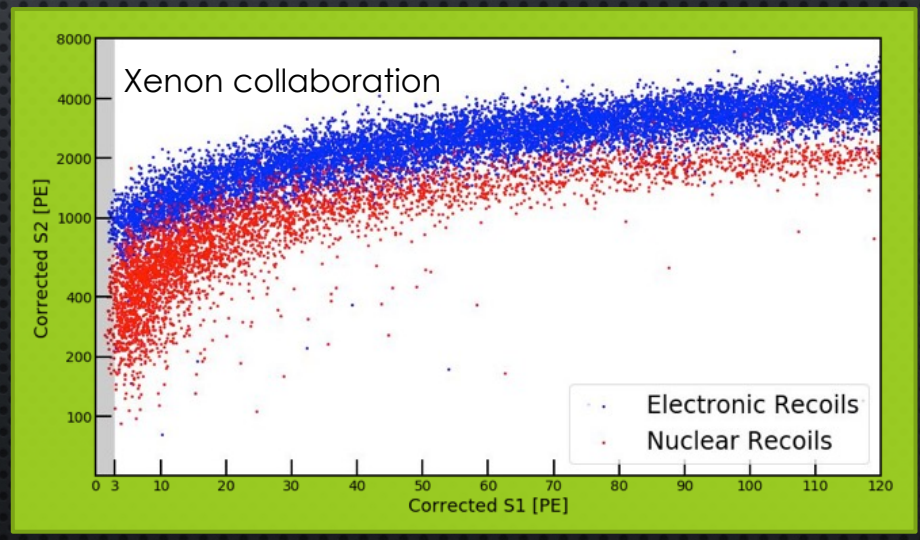


$(S2/S1)_{NR} < (S2/S1)_{ER}$

DUAL PHASE TIME PROJECTION CHAMBERS



- Energy from S1 and S2
- 3D event reconstruction:
  - X , Y from S2 hit pattern on top PMTs
  - Z from electrons drift time



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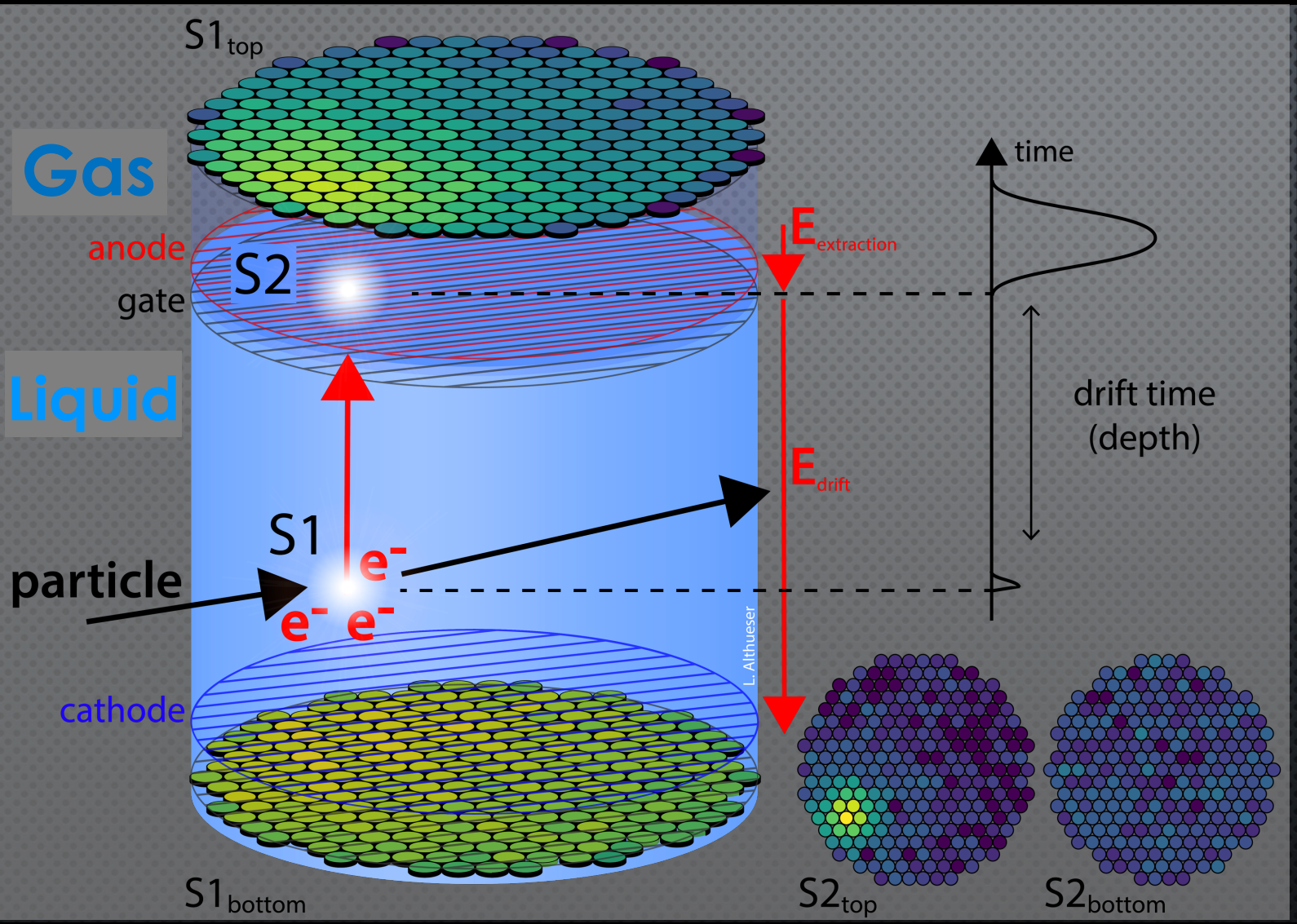
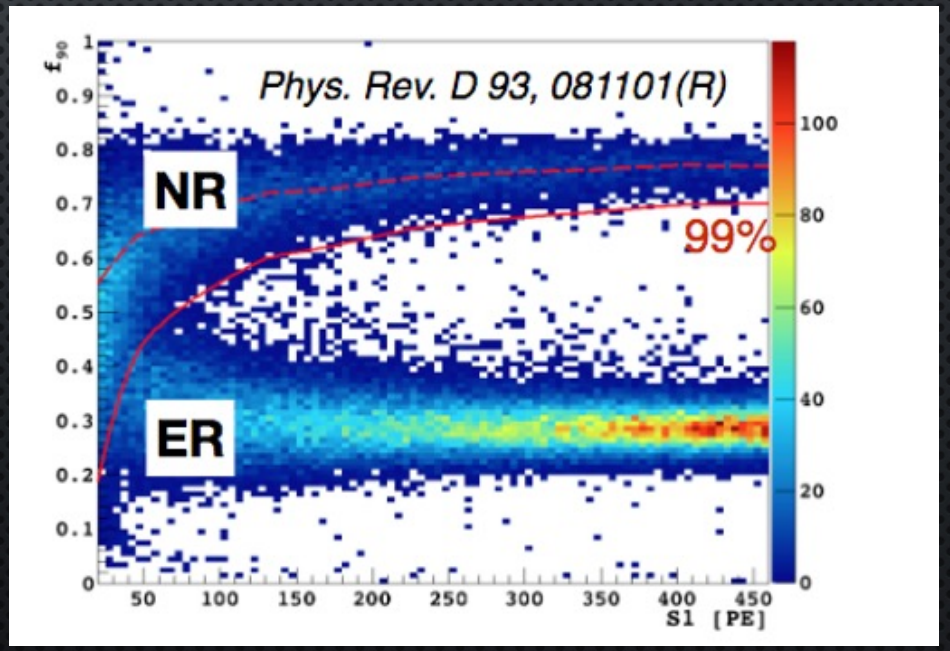


Additional ER/NR discrimination in LAr TPCs

- Pulse Shape Discrimination(PSD) parameter f_{90} : fraction of light seen in the first 90 sec



NOBLE LIQUIDS FOR DARK MATTER DIRECT DETECTION

- Scalability : compact detectors, scalable to larger dimension
- Easy cryogenic : 170 K (LXe), 87 K (LAr)
- Self shielding : very effective (expecially for LXe) for external bkg reduction
- Low threshold : high scintillation yield (similar to NAI(Tl) but much faster timing)
- NR vs ER discrimination by charge to light ratio and PSD (for LAr)
- Xe nucleus (A~131) good for SI and SD sensitivity (~50% odd isotopes)
- For Xe : no long lived radioactive isotopes (^{85}Kr can be removed)
- For Ar : radioactive ^{39}Ar can be reduced

PROPERTIES OF NOBLE GASES

Liquefied noble gases allow for:

- dense, homogeneous targets for ionising radiation
- detectors with self-shielding and fiducialisation
- large detector masses with ultra-low levels of radioactivity

Noble Gas	LXe	LAr
Atomic mass [g/mol]	131.3	39.95
Density [g/cm^3]	3.06	1.40
Wavelenght [nm]	178	128
Average ionization energy W [eV]	15.6	23.3
Ionization Yield [e^-/keV]	64	42
Scintillation Yield [photon/keV]	46	40

LAR TPC CURRENT EXPERIMENTS

Status

- DarkSide50
  - Target: 37 kg liquid argon (depleted in Ar39)
  - Exposure: 532 live-days
  - Decommissioned in 2019
- DEAP 3600
  - Target : 3.3 ton (fiducial 1 t)
  - Exposure: 231 live-days (2019)
  - Data taking finished in 2020
  - upgrading detector for background reduction to restart in 2023

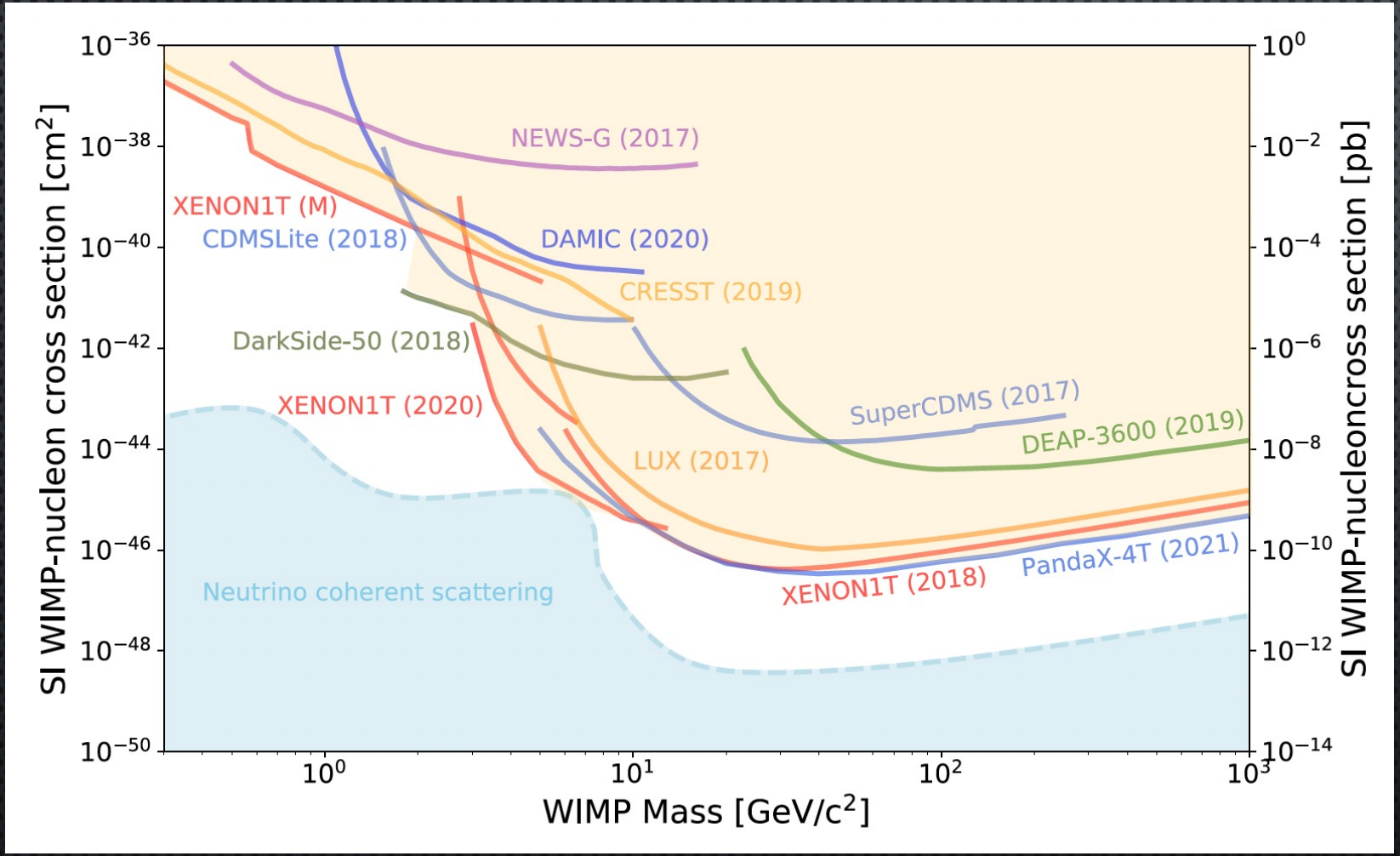
DarkSide50 @LNGS
Dual phase

DEAP3600 @Snolab
Single phase

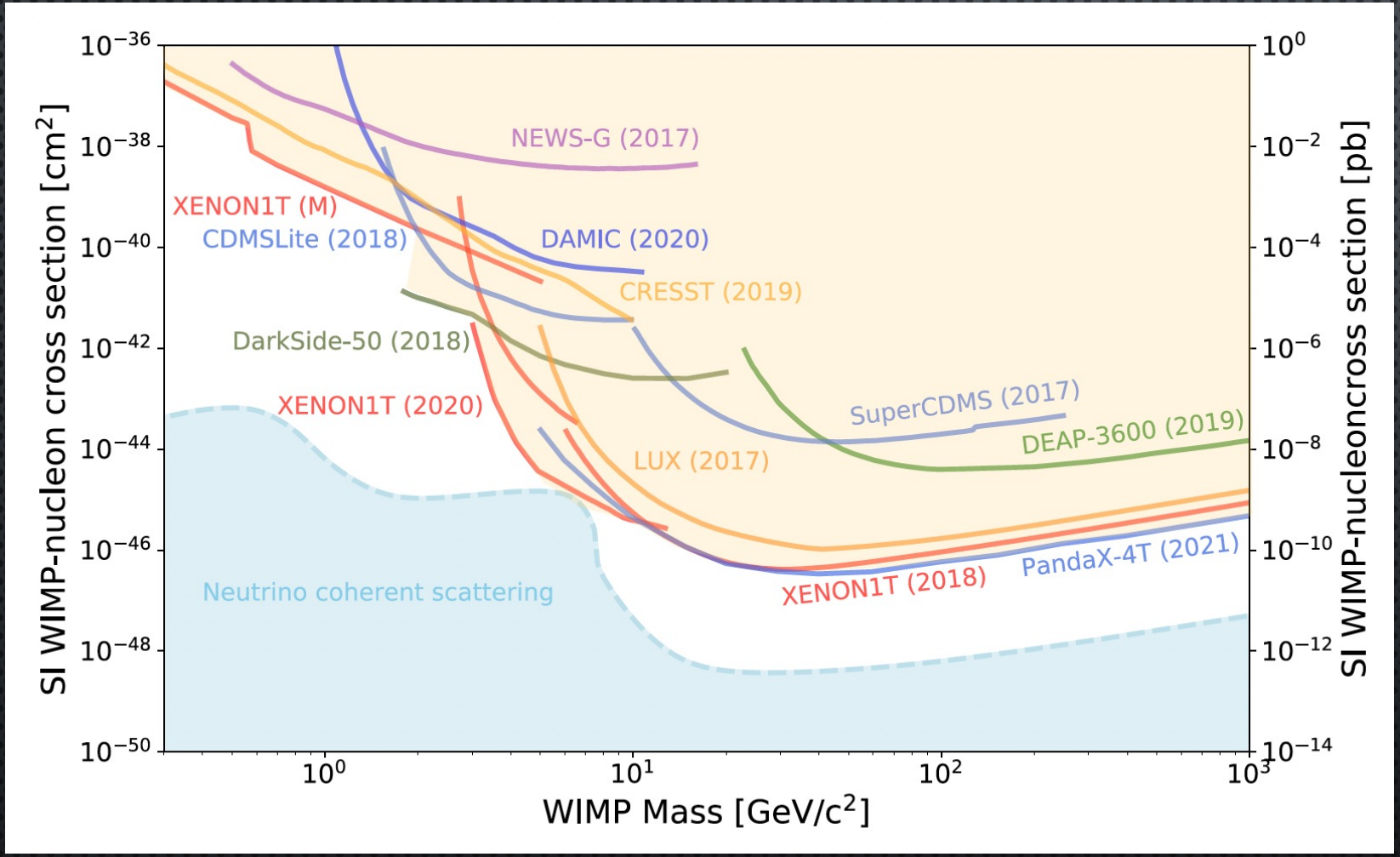
LXE TPC CURRENT EXPERIMENTS

Experiments	Location	Sensitive Mass [t]	Fiducial mass [t]	Radon reduction	Neutron veto	Data taking	First Results
PandaX-4T	CJPL (China)	4.0	2.8	Y	N	2021	2021
XENONnT	LNGS (Italy)	5.9	4.9?	Y	Y	2021	2022
LZ	SURF (US)	7.0	5.5	Y	Y	2022	2022

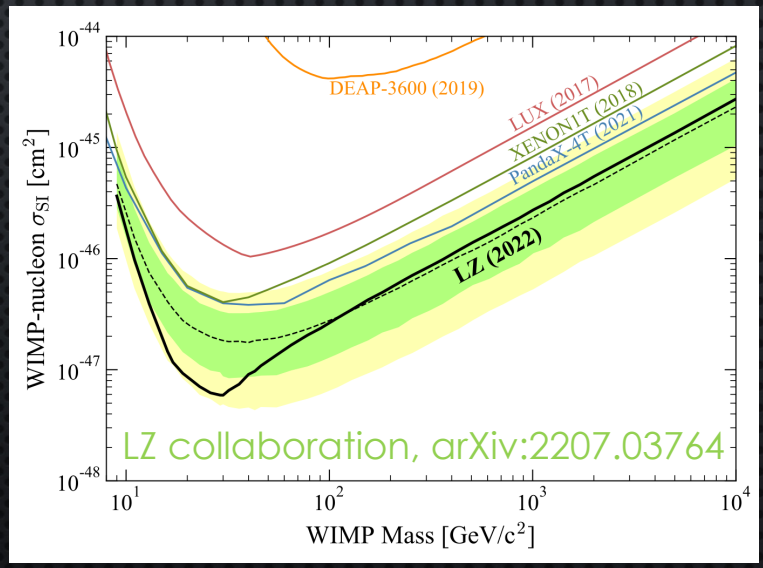
WIMP SEARCH RESULTS IN EARLY 2022



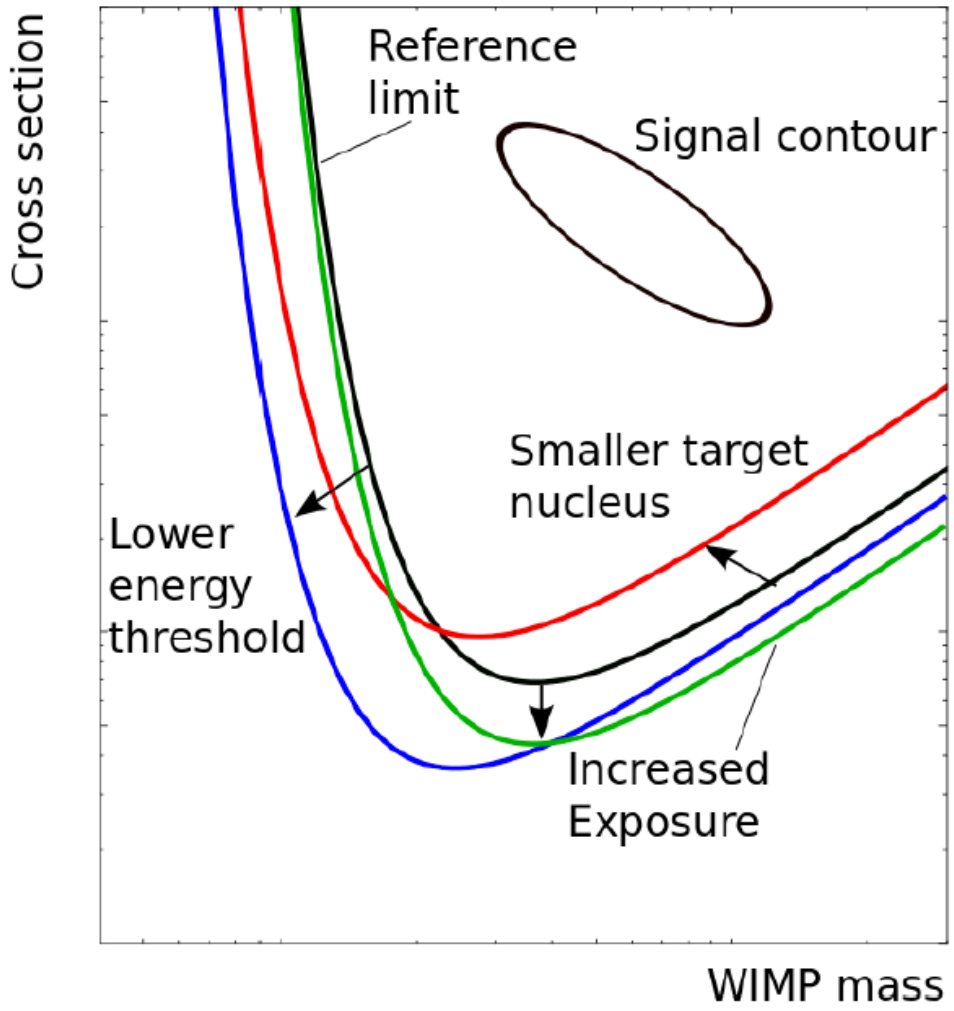
WIMP SEARCH RESULTS IN ~~EARLY~~ 2022

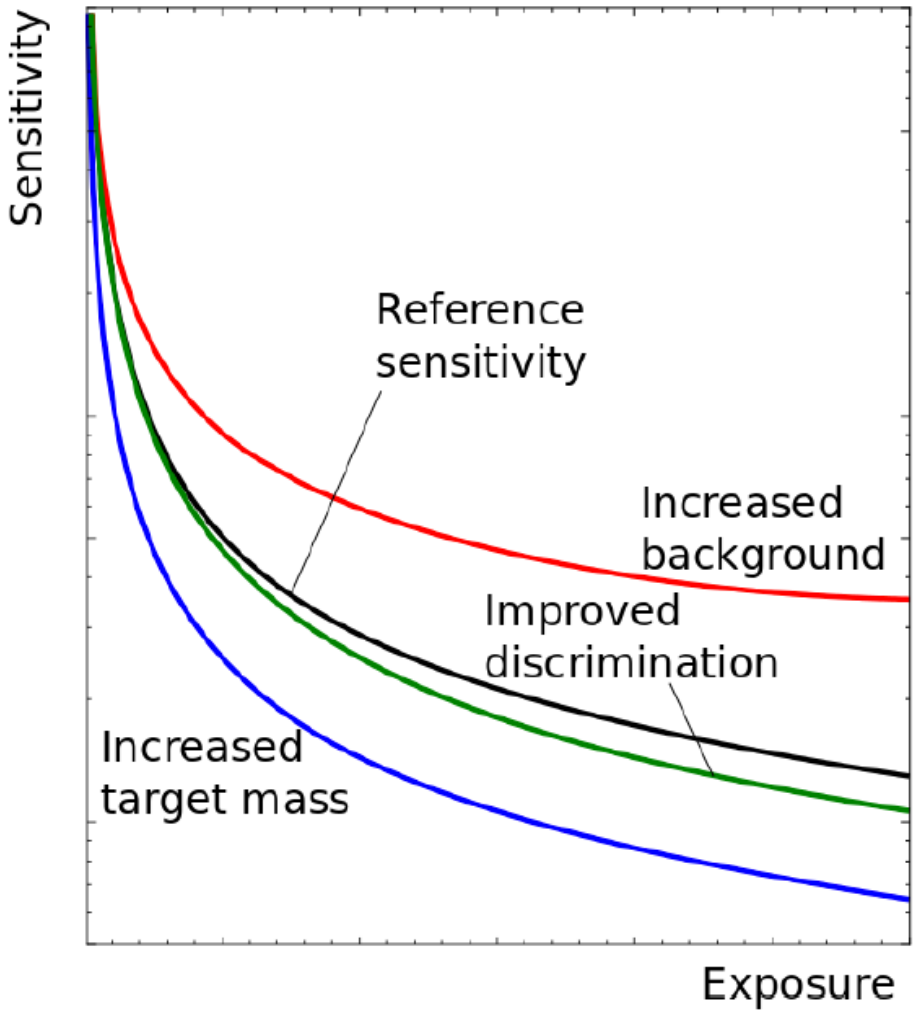


Liquid Noble gas dual phase time projection chambers are leading the field of WIMPs searches form masses above few GeV



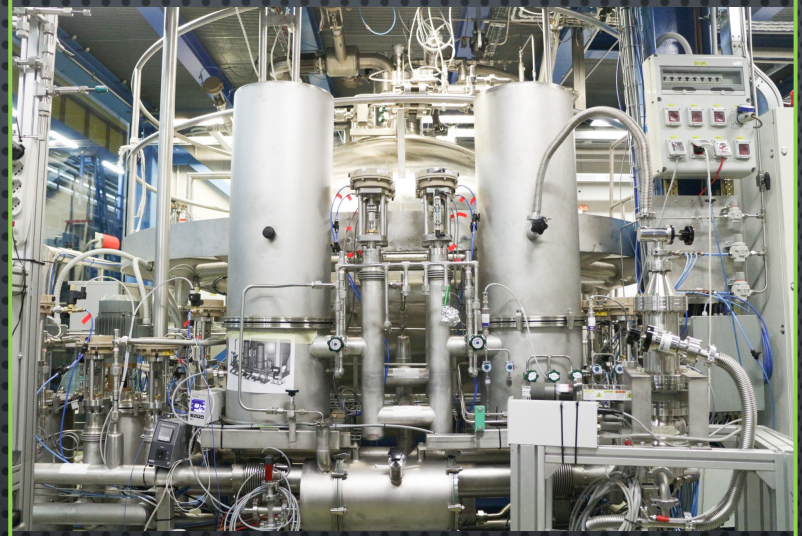
HOW TO IMPROVE WIMPS SENSITIVITY?



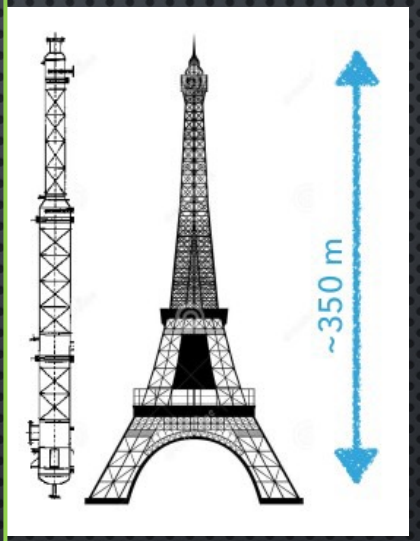


BACKGROUND MITIGATION STRATEGIES

- SHIELDING
  - DEEP UNDERGROUND LOCATION
  - LARGE SHIELD (PB, WATER, POLY)
  - ACTIVE VETO
  - SELF SHIELDING → FIDUCIALIZATION
- USE OF RADIOPURE MATERIALS
  - SCREENING CAMPAIGNS
- CLEANLINESS
  - (RN222 ABATED) CLEANROOMS
- PURIFICATION OF TARGET MATERIAL
  - DURING PRODUCTION
  - AT PROCUREMENT LEVEL
  - DURING DATA TAKING



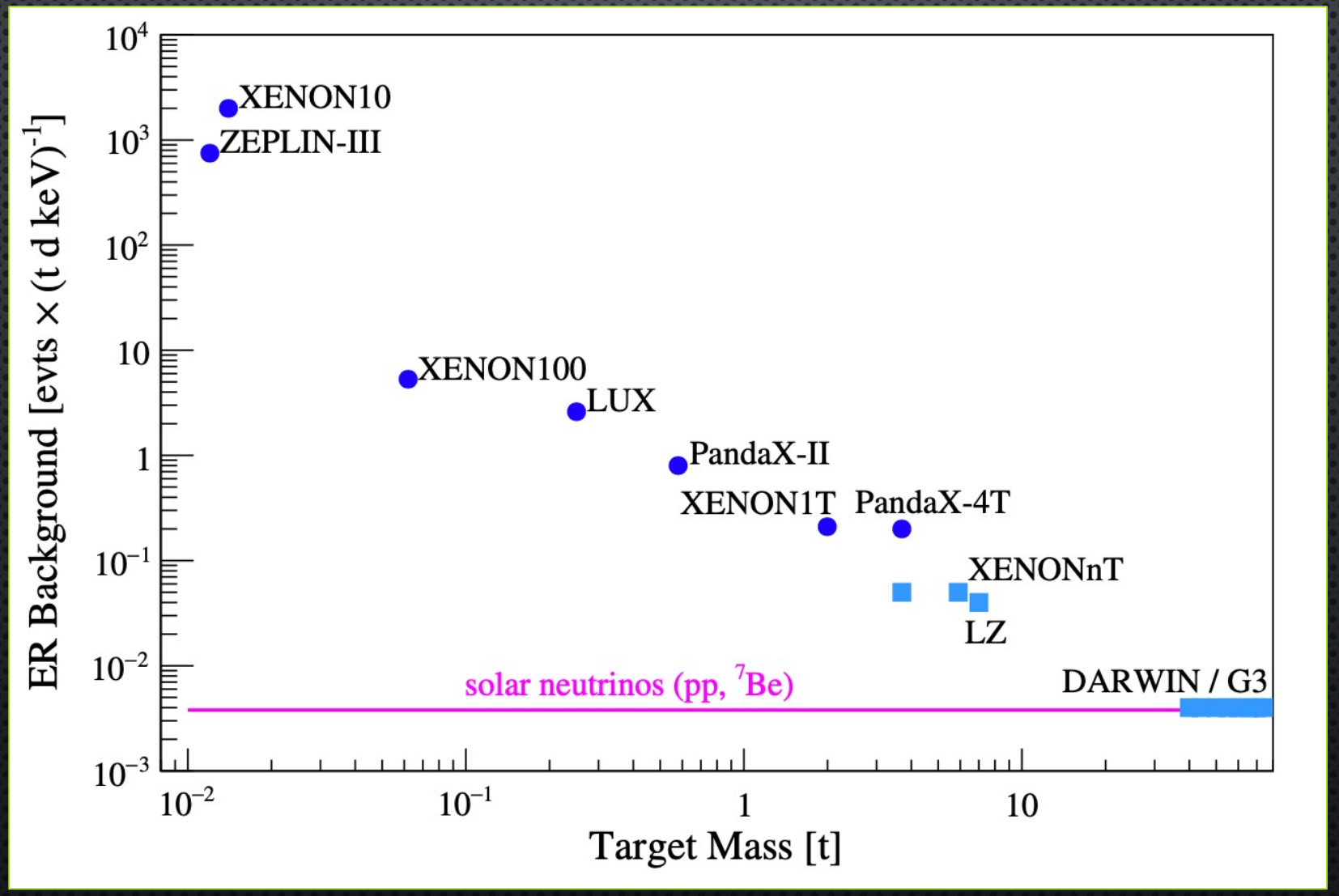
LXe purification system (5 L/min LXe, faster cleaning; 2500 slpm)



ARIA: Perform chemical and isotopic purification of UAr

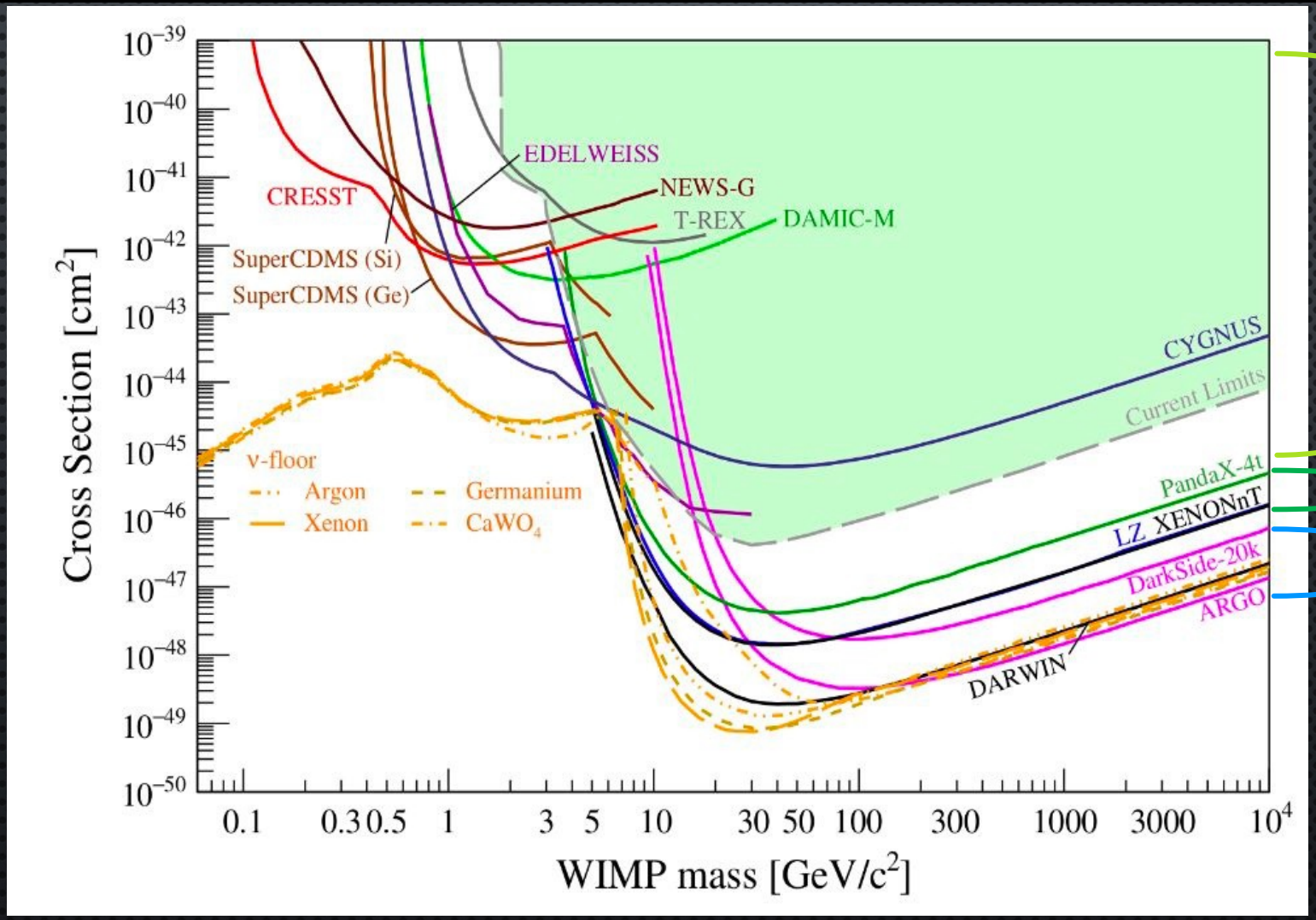
- IMPROVE DISCRIMINATION AT ANALYSIS LEVEL
  - SINGLE SCATTER WIMPS EVENTS
  - WIMPS INTERACT VIA NR → PSD & CHARGE/LIGHT RATIO

REDUCING THE BKG AND INCREASING THE TARGET MASS



ULTIMATE WIMP SENSITIVITY

Ultimate sensitivity dominated by neutrino interactions



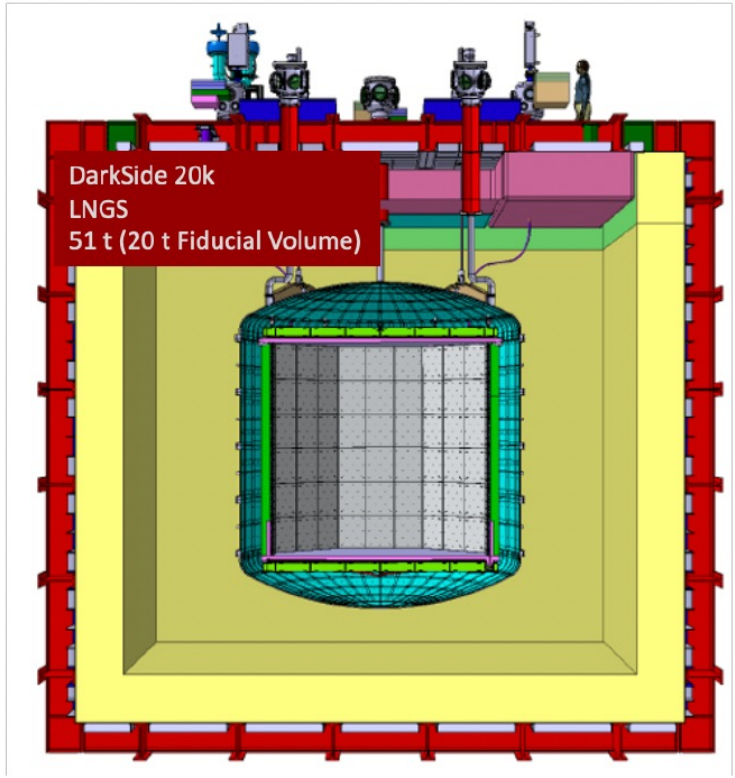
Past

Present

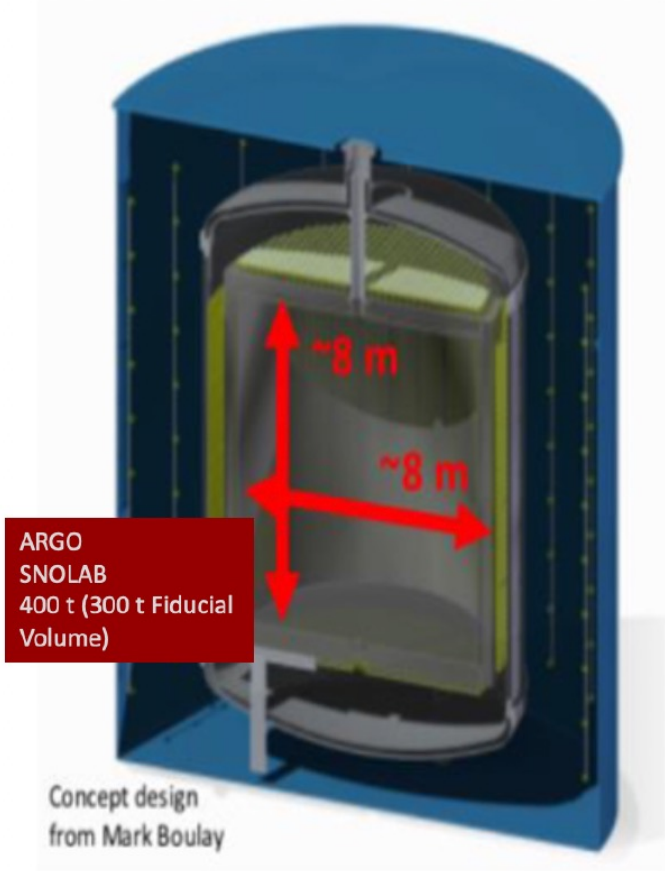
Future:
Darkside 20k
ARGO
DARWIN

THE GLOBAL ARGON DARK MATTER COLLABORATION - GADMC

GADMC includes over 400 researchers from 69 institutions in 14 countries

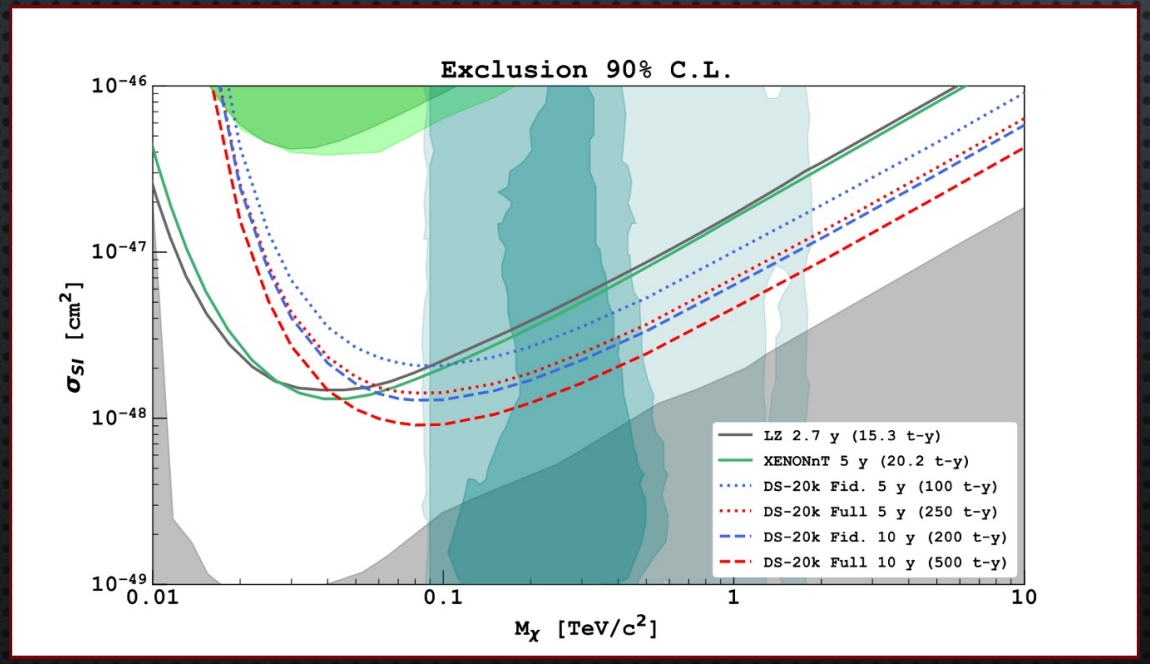


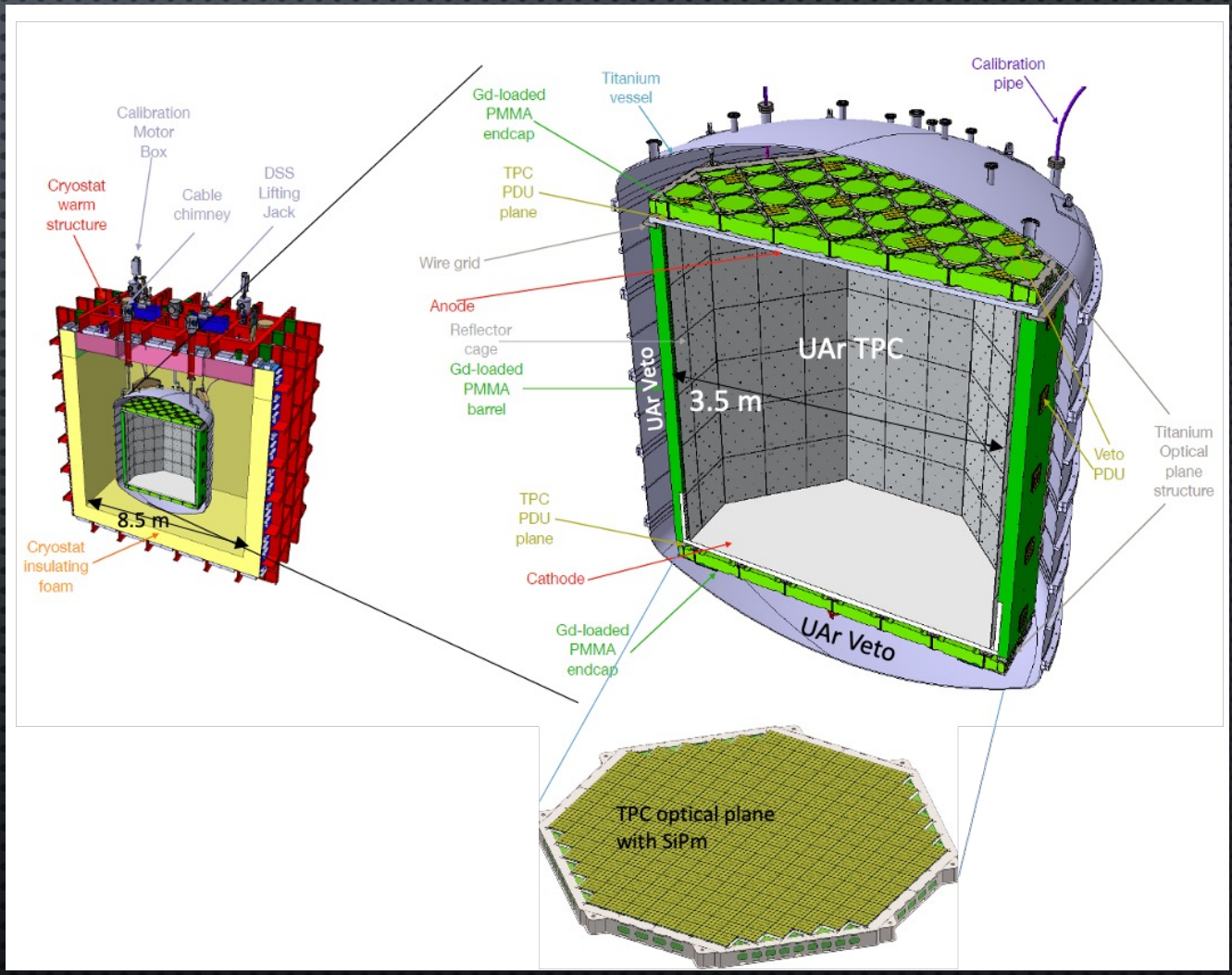
construction starts in 2022
data taking in 2025
nominal run time 10 years



DARKSIDE 20K

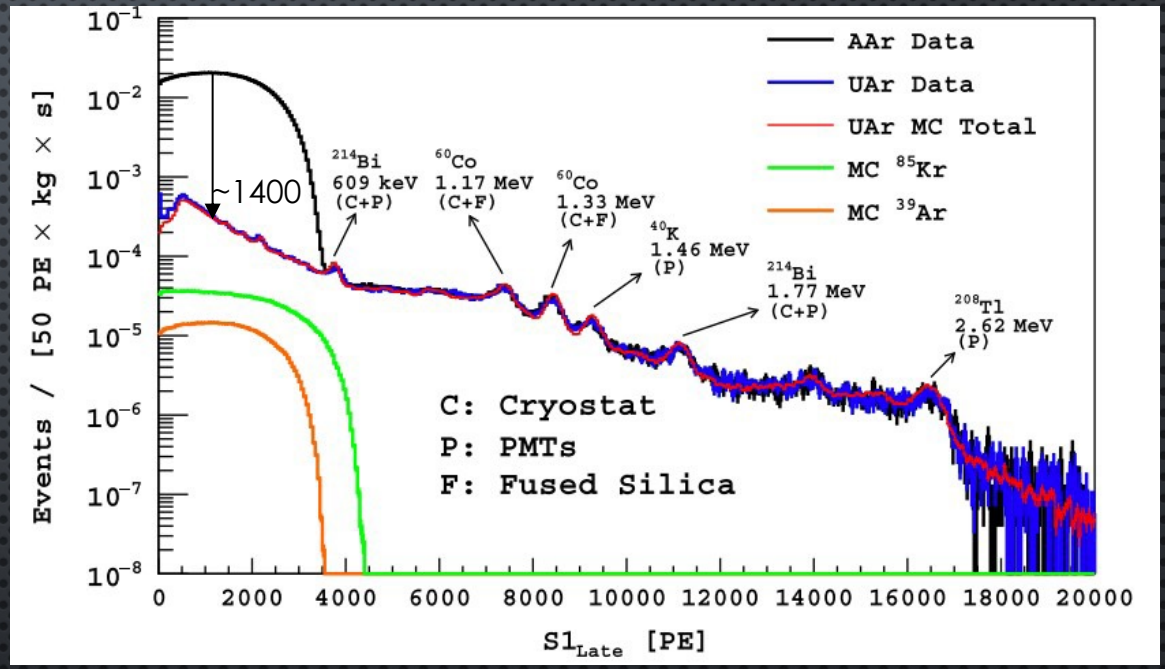
- Dual phase LAr TPC
- 21 m^2 cryogenic SiPMs
- Inner TPC surrounded by a single phase LAr neutron Veto detector
- Integration of inner TPC + veto in a single object





UNDERGROUND ARGON (UAR)

- ^{39}Ar radioactivity in **atmospheric** argon:
  - β-emitter with an endpoint of 565 keV
  - activity ~ 1Bq/kg
- ^{39}Ar **cosmogenic** isotope
  - → Lower ^{39}Ar production rate in UAr

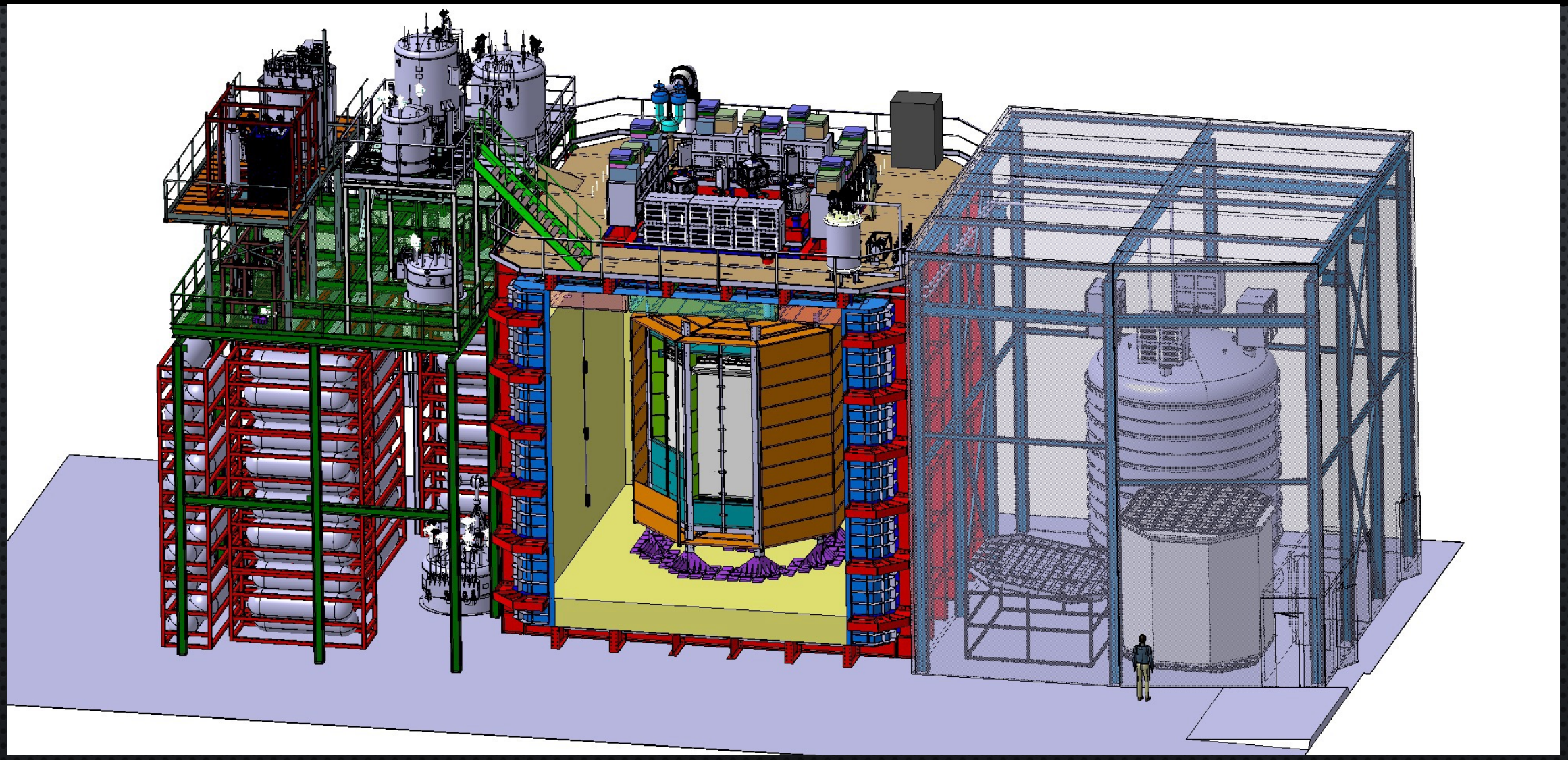


Extraction of Ar from **underground** sources, where such processes are suppressed

DS50 used 157kg of **UAr**

Depletion factor in ^{39}Ar : 1400 +/- 200

DARKSIDE 20K IN HALL C @LNGS



XLZD CONSORTIUM

XLZD consortium (xlzd.org) to design and build a common multi-ton xenon experiment

- currently 104 group-leaders in 16 countries : MoU signed in July 2021
- joint "white paper" on physics reach : 600 authors, 141 institutions
- Already official and active:
  - first in-person meeting at KIT in June 2022
  - second in person meeting in US in Spring 2023w
  - Weakly calls to discuss working group progress and status

XENON

DARWIN

LZD

PHYSICS REACH

Dark Matter
- Dark photons
- Axion-like particles
- Planck mass

WIMPs
- Spin-independent
- Spin-dependent
- Sub-GeV

Sun
- Solar pp neutrinos
- Solar Boron-8 neutrinos

Big Bang
- Neutrinoless double beta decay
- Double electron capture

Supernova
- Supernova neutrinos
- Multi-messenger

Cosmic Rays
- Atmospheric neutrinos

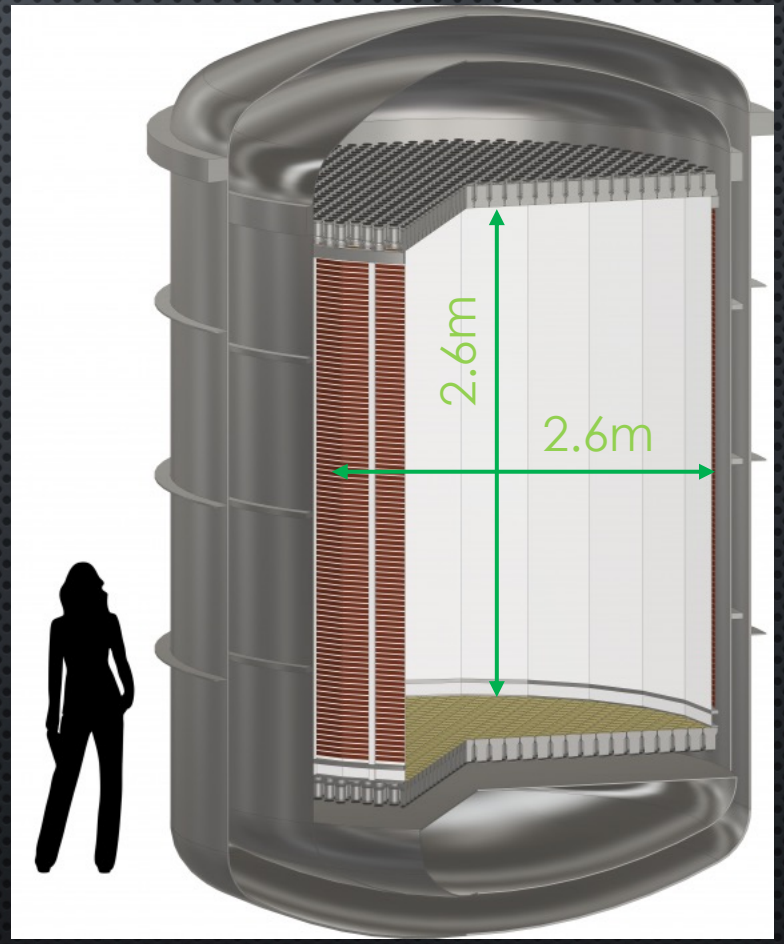
XENON LZ DARWIN

LZD

DARWIN BASELINE DESIGN & CHALLENGES

BASELINE DESIGN

- Dual-phase TPC: 2.6 m ø and 2.6 m height
- 50 t (40 t) LXe in total (in TPC)
- Top & bottom arrays of photosensors (e.g., 1800 3-inch PMTs)
- PTFE reflectors and Cu field shaping rings
- Low-background Ti cryostat
- Gd-doped water as n- and μ-vetos



DARWIN Collaboration, JCAP 1611 (2016) 017

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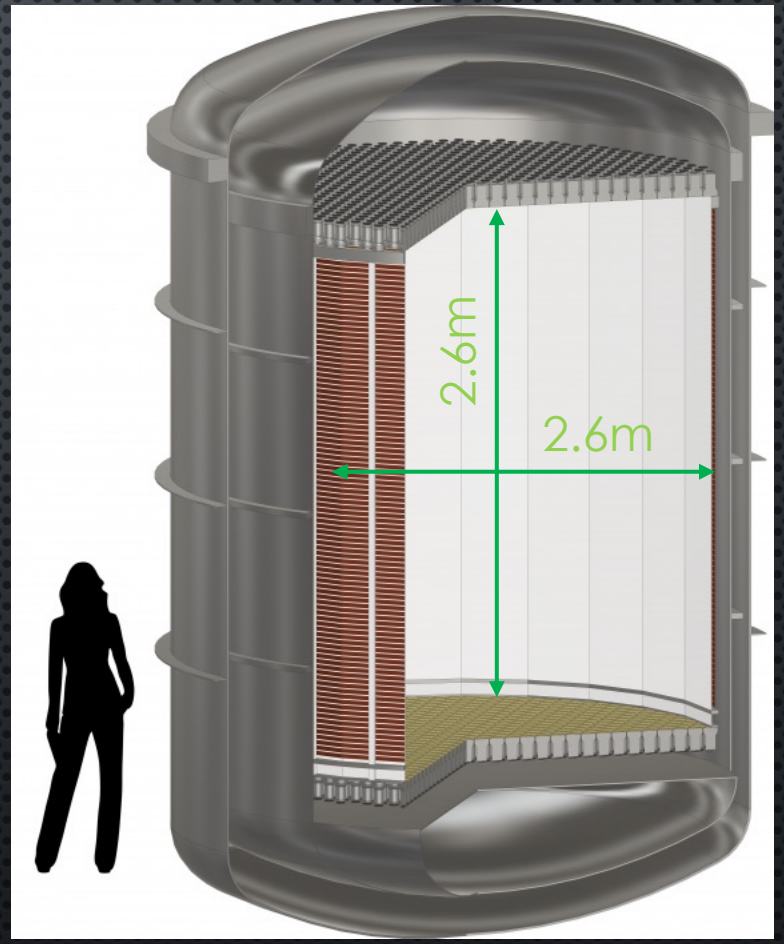
alternative designs and photosensors under consideration
→ various R&D ongoing in several institutions



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alternative designs and photosensors under consideration
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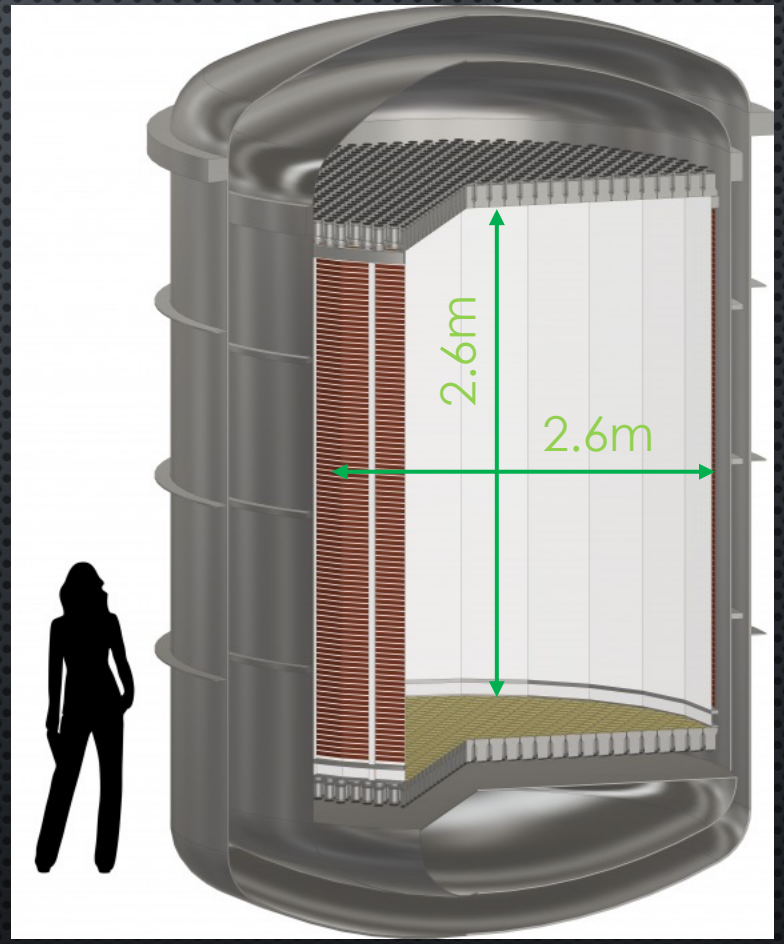
CHALLENGES

- Design of electrodes: robustness (minimal sagging/deflection), maximal transparency, reduced e- emission
- Xenon procurement & storage
- High voltage supply
- Liquid level control
- Significant staging space and UG fabrication capabilities
- …



DARWIN Collaboration, JCAP 1611 (2016) 017

DARWIN R&D : DEMONSTRATORS

Horizontal demonstrator Pancake in Freiburg:

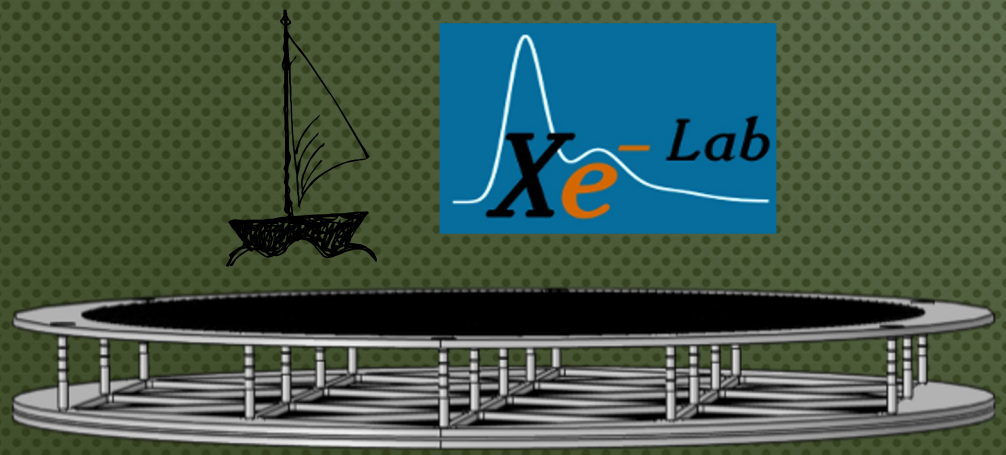
- 2.7 m diameter, 5 cm LXe height
- test horizontal components – real scale frames, electrodes etc.

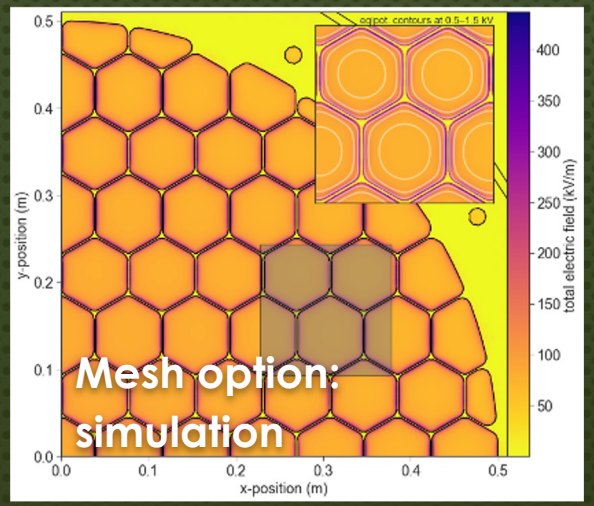
Vertical demonstrator Xenoscope in Zurich:

- 16 cm inner diameter, up to 2.6 m LXe height
- Full scale electron drift demonstration – high voltage, drift field properties, purity etc

DARWIN R&D : ELECTRODES & XENON RECOVERY

R&D on electrodes



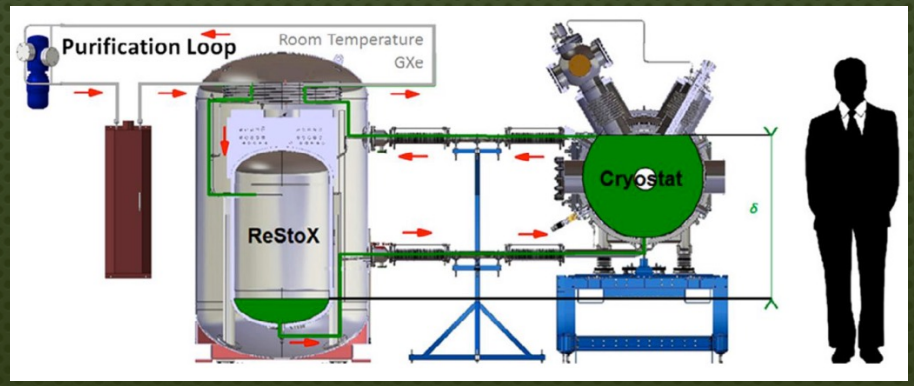


French laboratories:

SUBATECH-Nantes
LPNHE - Paris

Recovery & Storage of Xenon

- Just increasing the storage size is not reasonable → towards a modular approach
- Evaluating and testing the new concept of the LXe fast recovery by gravity

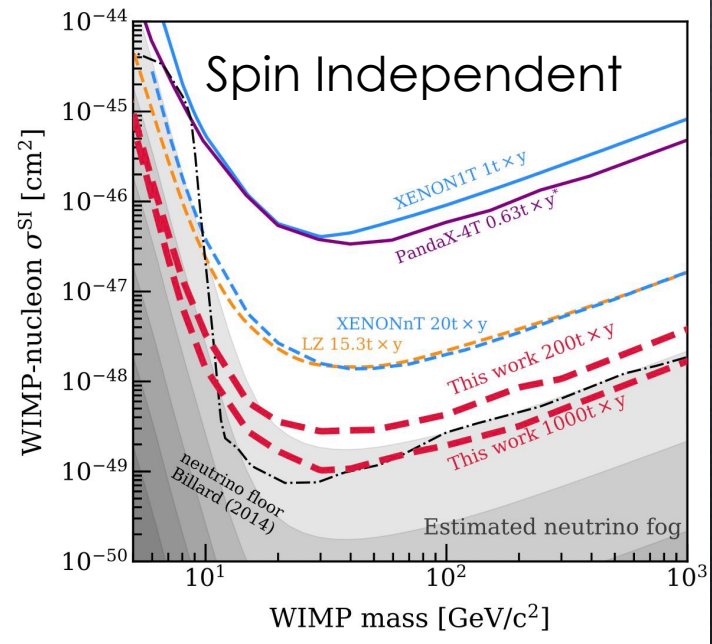


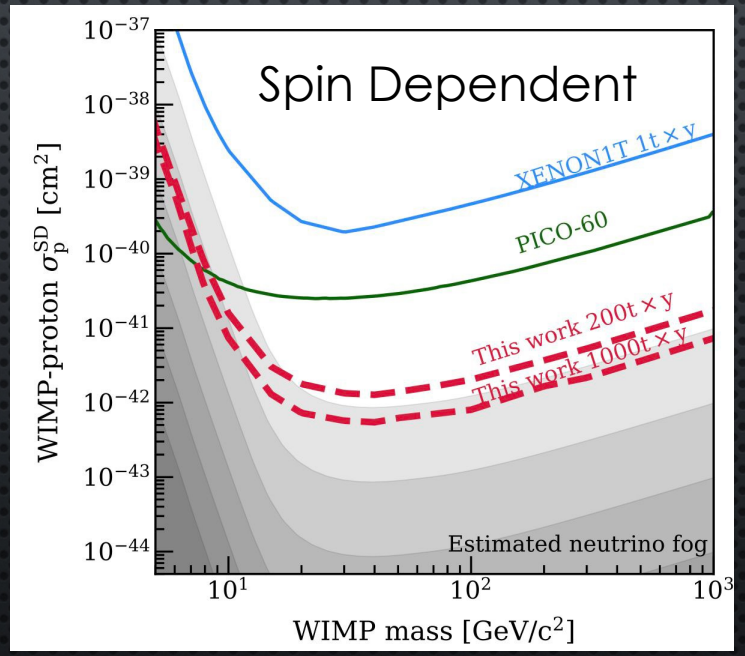
DARWIN : WIMPS SEARCHES

Arxiv : 2203.02309

WIMP SENSITIVITY

- Will probe entire parameter region for $m_\chi \sim 2$ GeV/c^2 until neutrino fog
- 99.8% ER rejection @30% NR acceptance

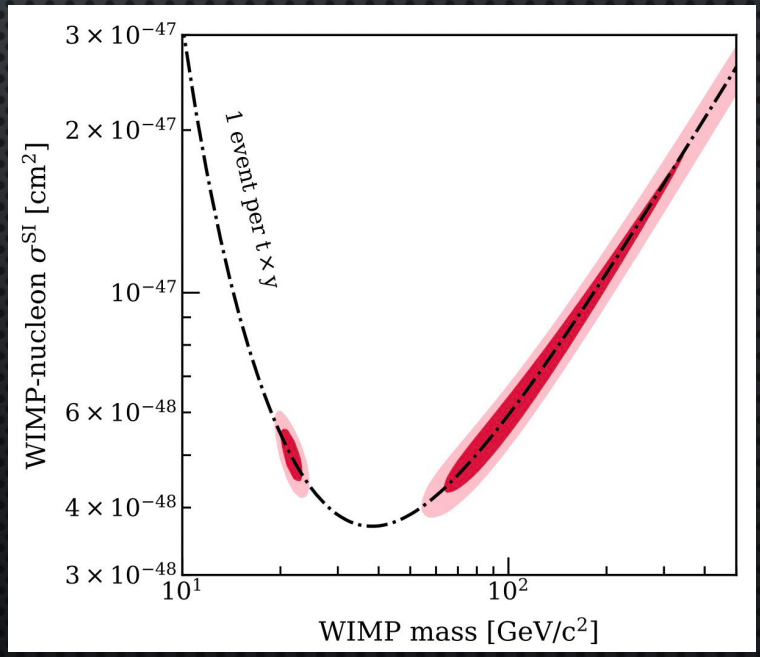




WIMP SPECTROSCOPY

Capability to reconstruct WIMP mass & cross section (SI) forvarious masses below 500 GeV/c^2

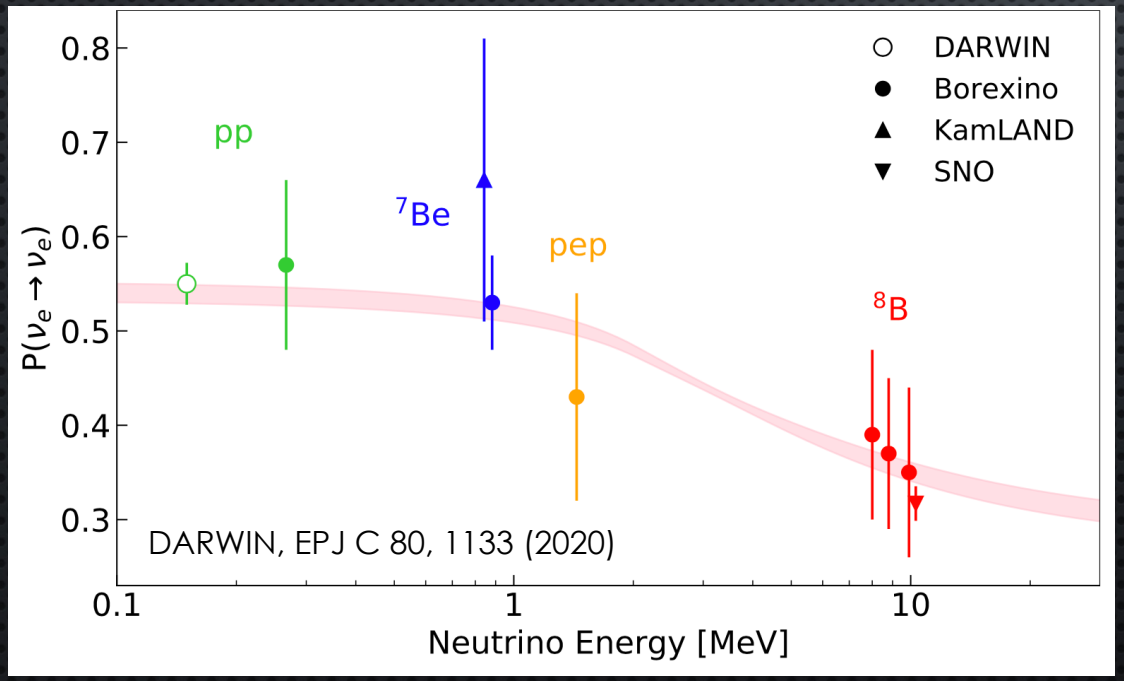
Exposure : 1000 t x y
Reconstruction m_χ = 20, 100 GeV/c^2

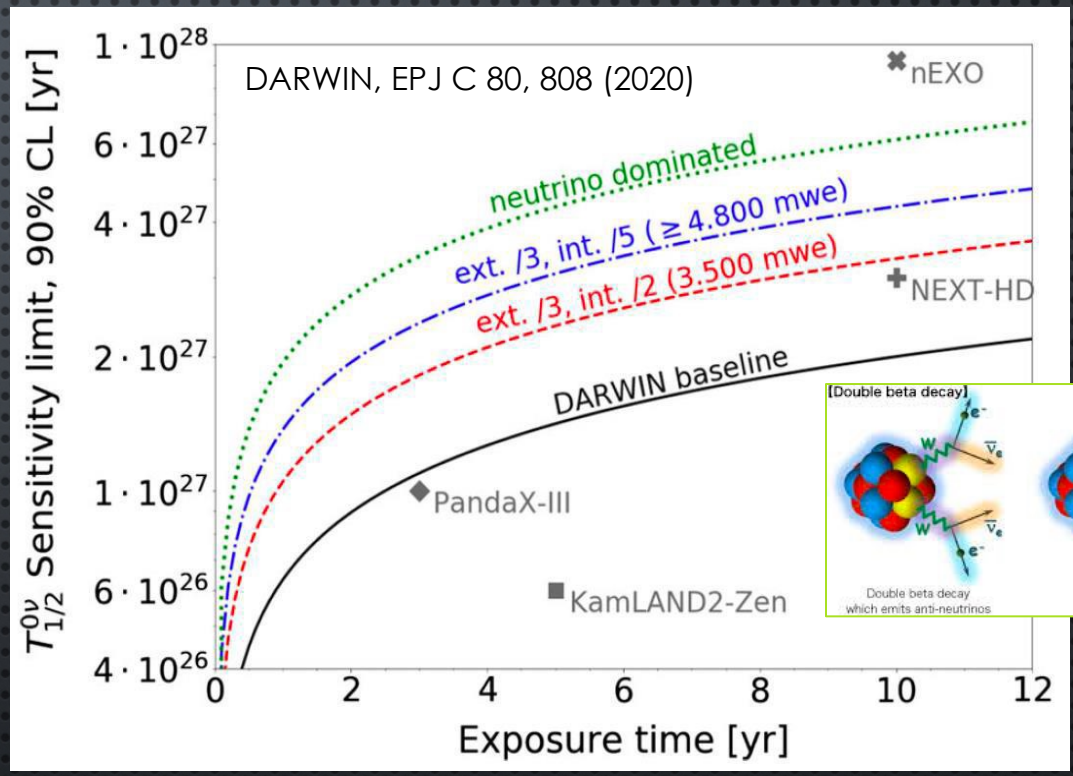


DARWIN : NEUTRINO PHYSICS

SOLAR NEUTRINOS

- elastic electron-neutrino scattering
- Flux at 0.15% with 300 ty exposure
- Measurement of electron neutrino survival probability (and weak mixing angle)
- Event rate 365 pp neutrino / t y





0vbb in ^{136}Xe

- Abundance 8.9% ⇒3.5 t in DARWIN
- Resolution 0.8% achieved by XENON1T
- 2.4 .10^{27}yr sensitivity with 50 t x10 yr exposure

CONCLUSION & OUTLOOK

- LXe and LAr TPCs have demonstrated to be the leading technologies to exploit WIMPs searches at masses > 3 GeV / c^2
- Current generation of noble liquid TPCs recently presented first results and continue to take data over the coming years
- They proved to be sensitive to additional rare events too
- An effort is in place in both Xe and Ar communities towards big consortia (GADMC & XLZD) to build giant detectors aiming to explore the WIMP parameter space up to the neutrino fog + other rare events channels
- R&D and design of these next-generation detectors is ongoing

CONCLUSION & OUTLOOK

- LXe and LAr TPCs have demonstrated to be the leading technologies to exploit WIMPs searches at masses > 3 GeV / c^2
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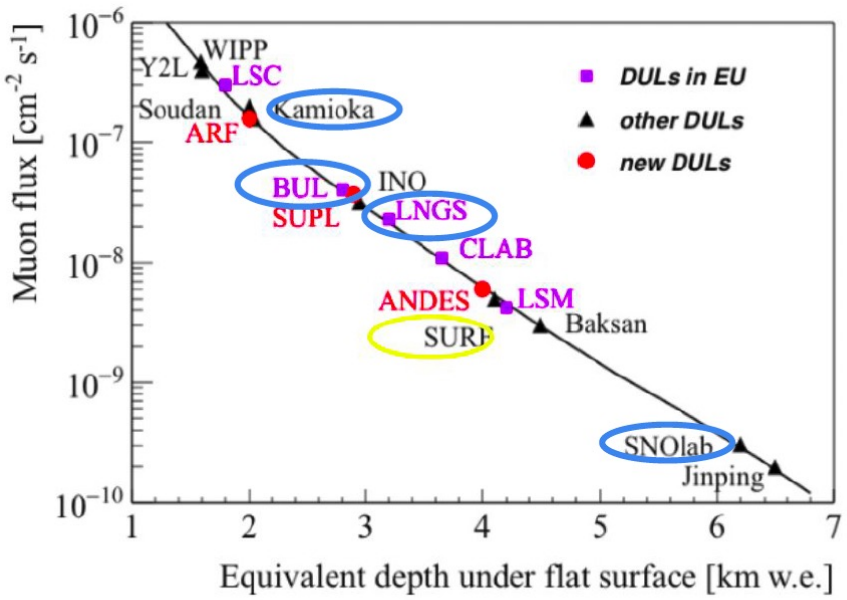
GOOD TIME TO JUMP ON BOARD!

BACKUP

DARWIN / XLZD SITING



Sanford Underground Research Facility
South Dakota Science and Technology Authority

SNOLAB

UKRI Science and Technology Facilities Council
Boulby Underground Laboratory

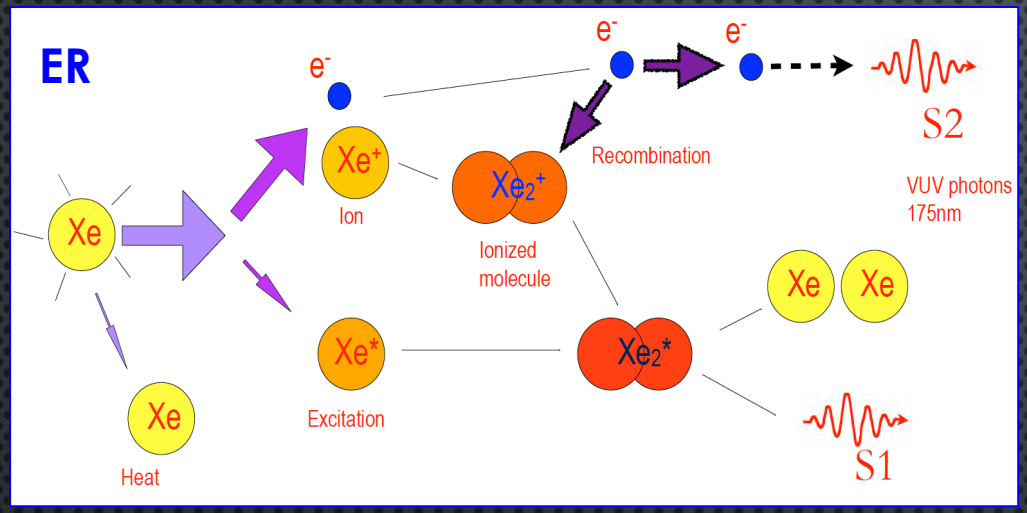
KAMIOKA OBSERVATORY

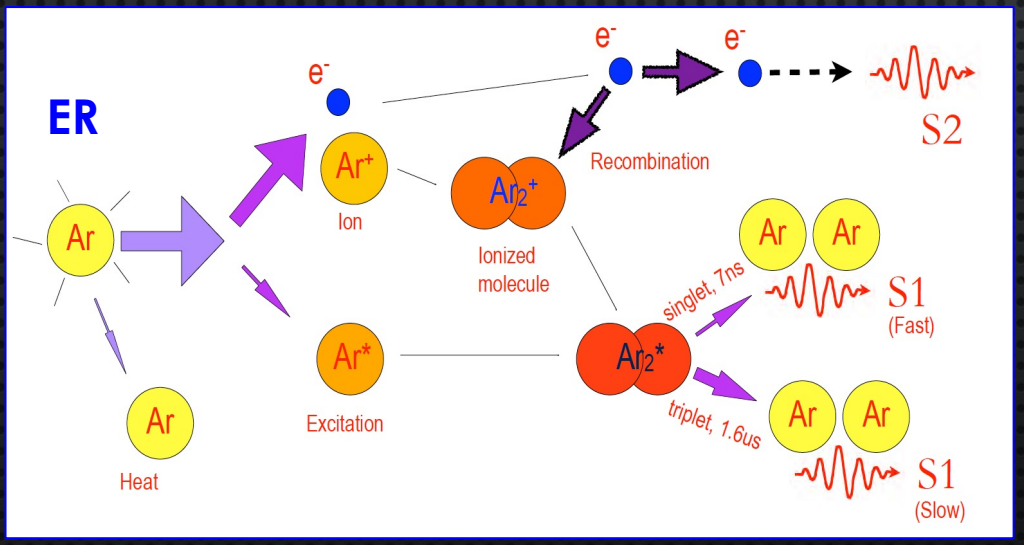
INFN LABORATORI NAZIONALI DEL GRAN SASSO

- 5 sites are being evaluated for XLZD (SURF, KAMIOKA, BOULBY, SNOLAB & LNGS)
  - Well known sites which demonstrated good supporting capabilities (SC) to carry out the science goals of state-of-the-art rare event search experiments.
- A next generation G3 detector like XLZD (~**3 meter** scale) will require **additional SC**: significant staging space and underground fabrication capabilities (e.g. larger and lower RRCR) than what currently exist in most of these facilities.
  - Required **cavity ~20 to 25 meters in diameter:** Gran Sasso (exist), Boulby (new construction), SURF (new construction or shared with LBNF)
  - UG access is generally a challenge and should be carefully planned

From
Alvine Kamaha (UCLA)

SIGNAL PRODUCTION IN NOBLE LIQUIDS





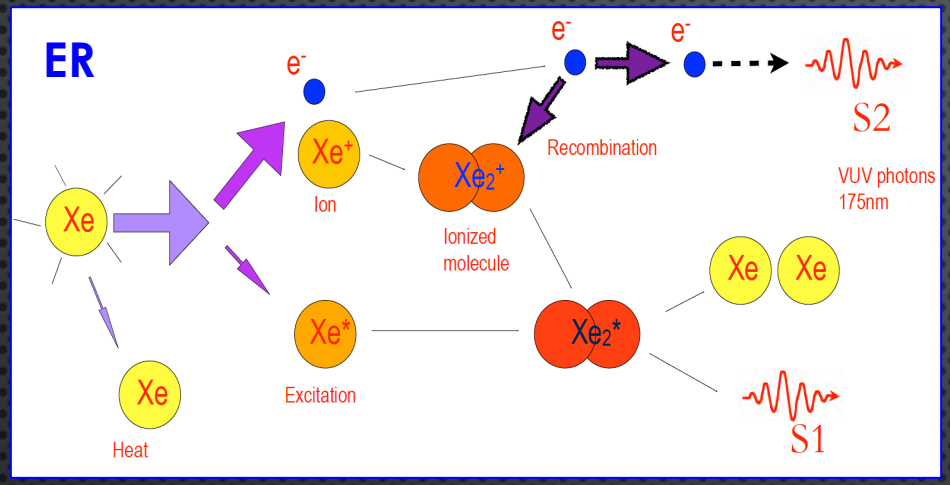
PULSE SHAPE DISCRIMINATION (PSD)

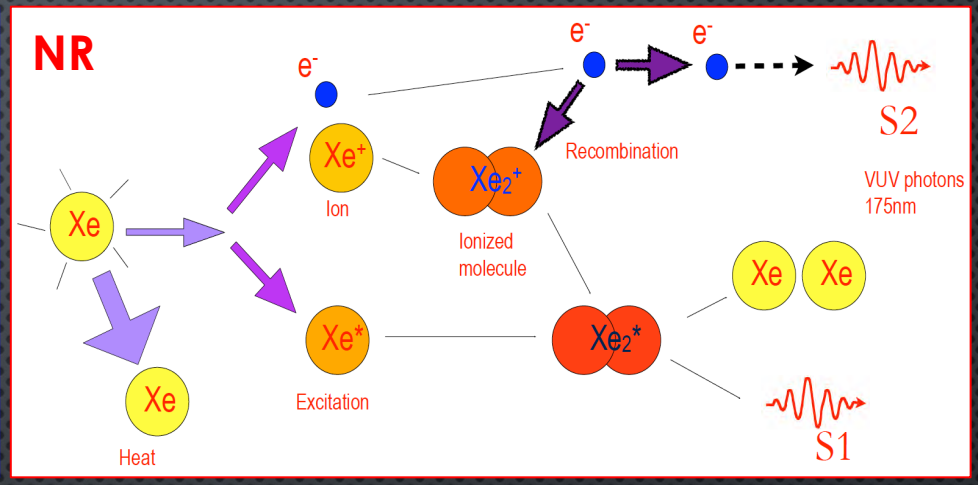
- WHEN THE RECOILING PARTICLE EXCITES THE ENCOUNTERED ATOMS, THE LATTER WILL COMBINE ITSELF WITH ANOTHER ATOM, CREATING AN **EXCITED DIMER**
- TWO DIFFERENT ENERGETIC STATES OF THE DIMER CAN OCCUR: THE SHORT- (SINGLET) AND LONG-LIVED (TRIPLET) STATES
- THE ASSOCIATED RELAXATION TIMES ARE DIFFERENT DEPENDING ON THE PARTICLE TYPE

→ **PSD TECHNIQUE IS VERY POWERFUL IF THE TWO COMPONENTS HAVE VERY DIFFERENT LIFETIME AND ARE THUS EASILY SEPARABLE**

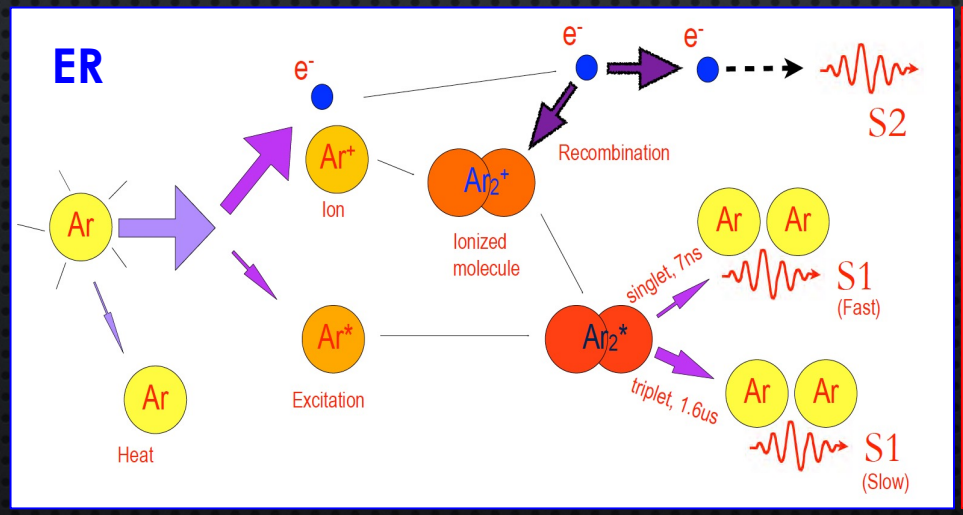
Noble gas	Singlet (Fast) lifetime [ns]	Triplet (Slow) lifetime [ns]
Xenon	4.3 ± 0.6	22.0 ± 2.0
Argon	7.0 ± 1.0	1600 ± 100

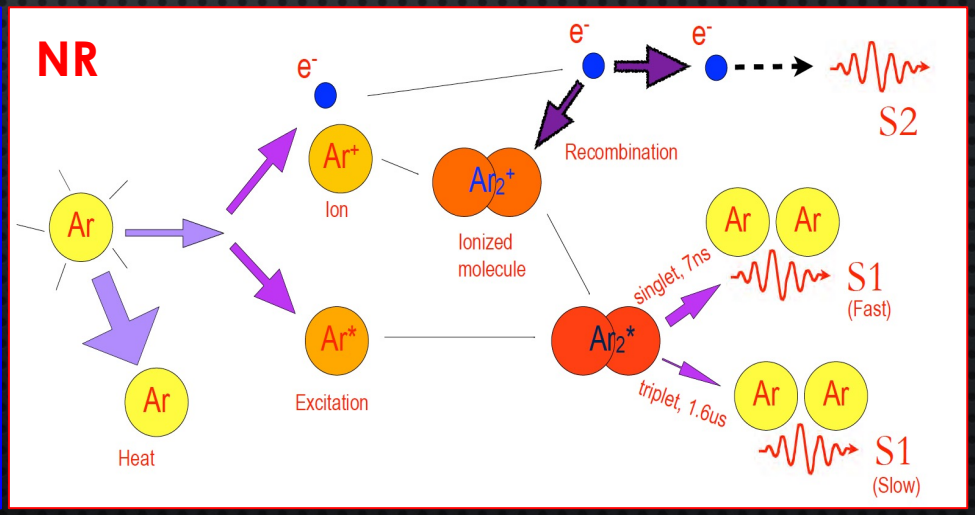
SIGNAL PRODUCTION IN NOBLE LIQUIDS





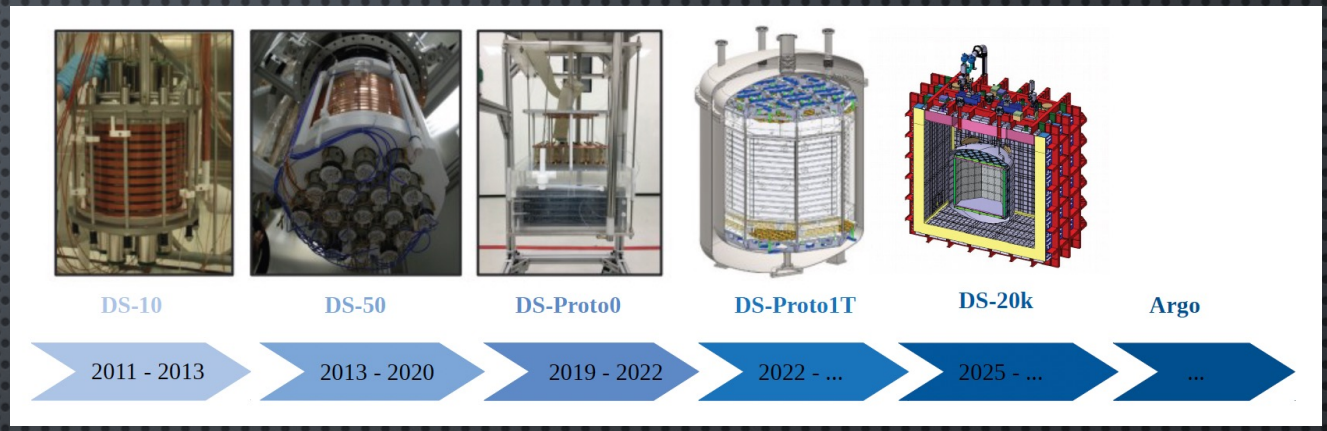
PSD is used in LAr experiment to improve the ER/NR discrimination

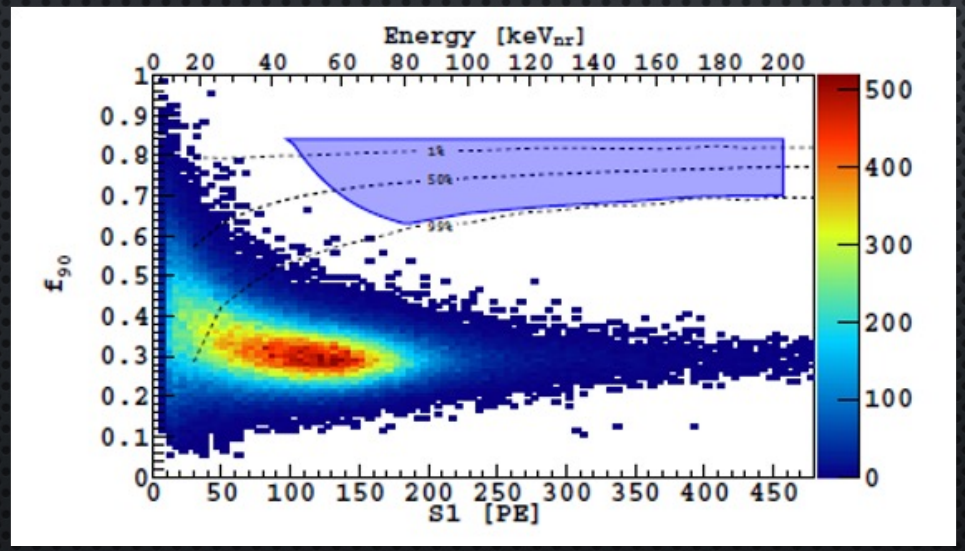




DARKSIDE EXPERIMENTS

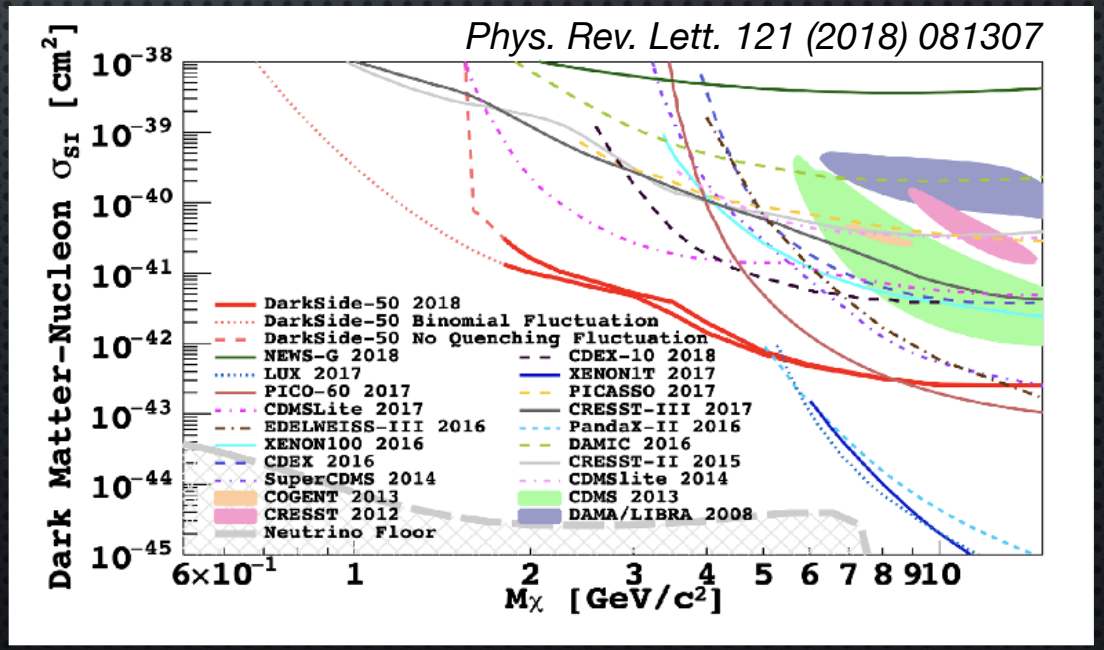
- Argon dual-phase TPCs
- Direct detection by NR & ER
- Background free at high WIMPs masses (Pulse Shape Discrimination)
- Modelled background for low DM masses studies (< 10 GeV/c2)





DarkSide50 Collaboration,
Phys Rev D 98 (2018) 102006

Phys. Rev. Lett. 121 (2018) 081307

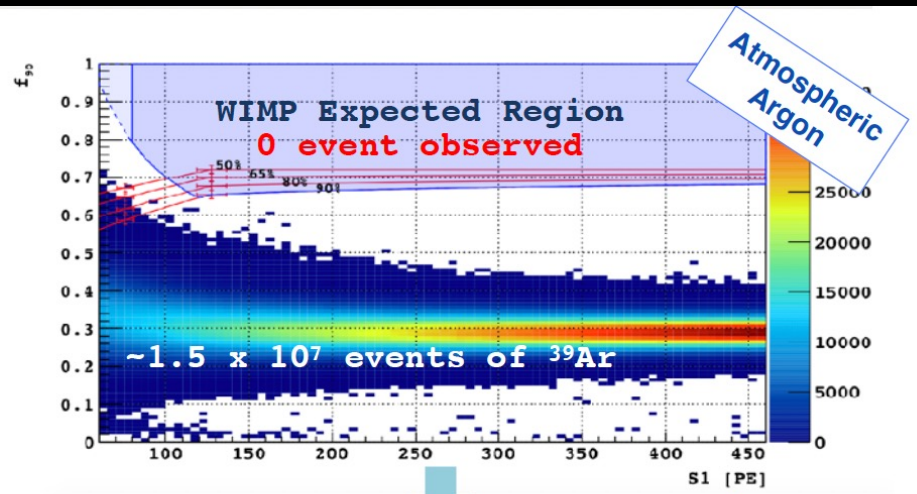


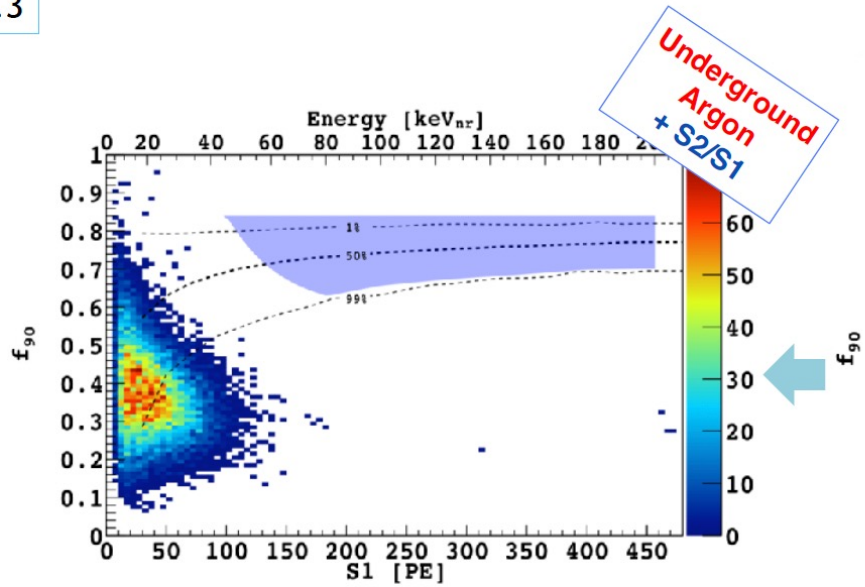
LIQUID ARGON : DARKSIDE 50

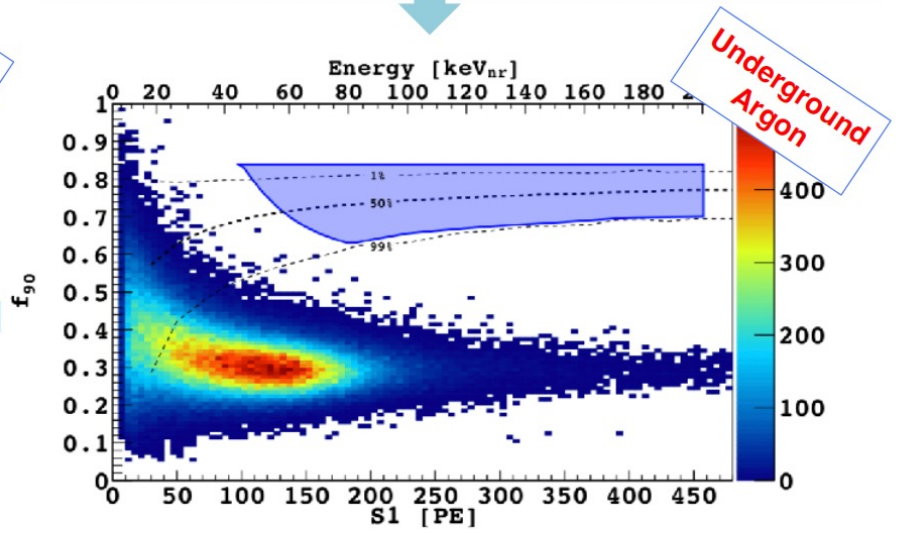
LAr scintillation times:
- singlet ~ 6 ns
- Triplet ~ 1600 ns

Singlet-to-triplet ratios:
- Nuclear recoils ~ 0.7
- Electron recoils ~ 0.3

Very distinctive (and unique) signatures to separate electron recoils from nuclear recoils



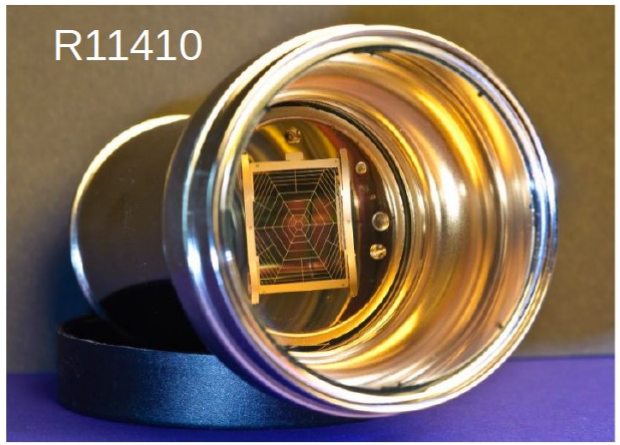




Background-free over more than 530 days!

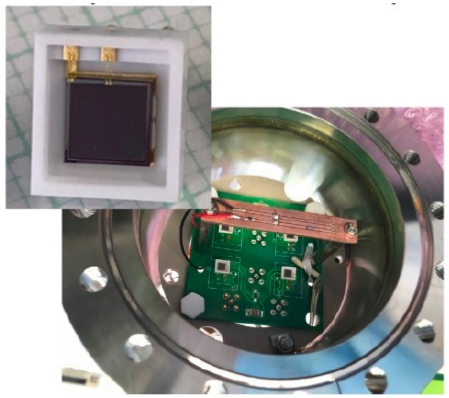
DARWIN R&D : PHOTOMULTIPLIERS

- "Baseline" design with PMTs
  - 3" PMTs R11410 (XENONnT, LZ)
  - reliable well-tested solution
  - But: relatively "dirty"

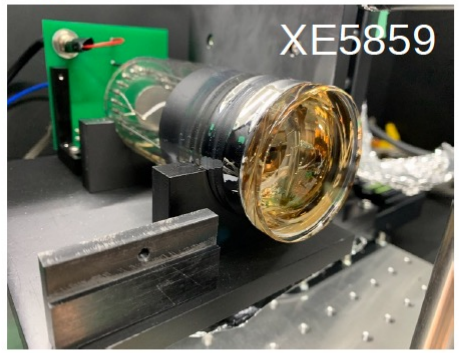


- Clean PMT alternative?

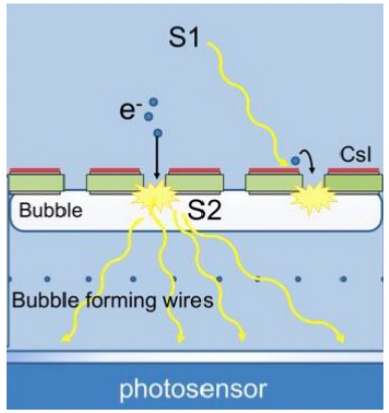
- Silicon PMs



- Hybrid sensors?



- Liquid hole multipliers?



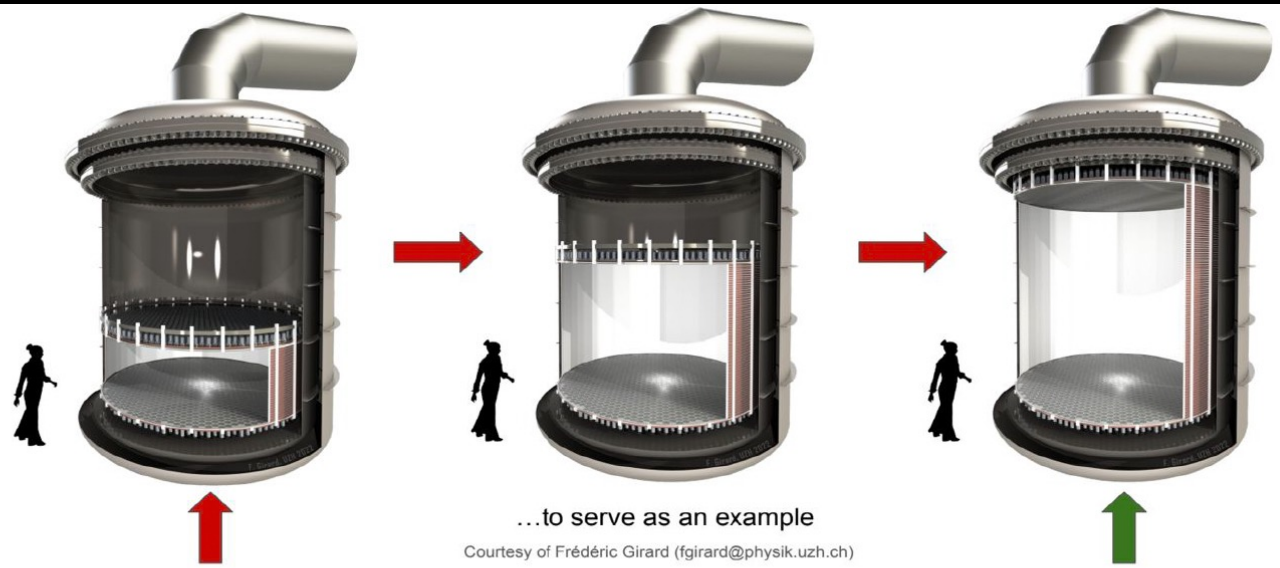
- Current R&D on quantum efficiency, dark count rates, radioactivity, operations…

DARWIN R&D : DETECTOR CONCEPTUAL DESIGN & SIZE

Stage approach

vs

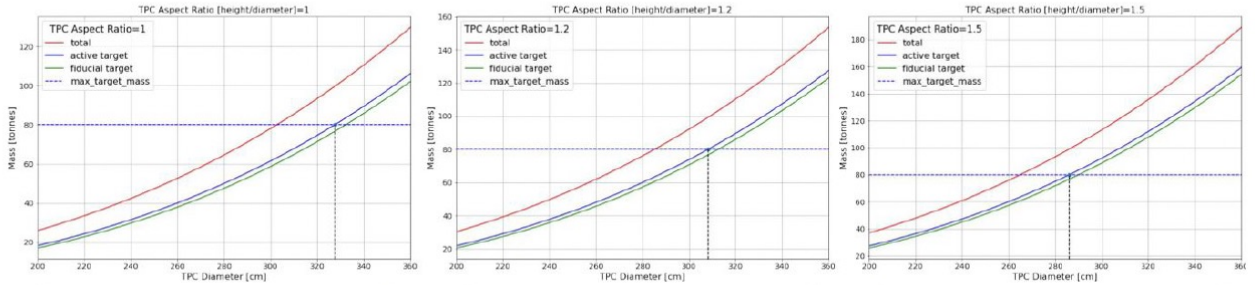
Monolithic approach



…to serve as an example

Courtesy of Frédéric Girard (fgirard@physik.uzh.ch)

In either approach, optimum size is **~ 100 tones** in volume (linear dimensions **~3 meter**) → *huge detector!*



AR =1
- TPC Act. Mass = **40 tonnes**: → TPC ∅=259 cm & drift=259 cm
- TPC Act. Mass = **60 tonnes**: → TPC ∅=297 cm & drift=297 cm
- TPC Act. Mass = **80 tonnes**: → TPC ∅=327 cm & drift=327 cm

AR =1.2
- TPC Act. Mass = **40 tonnes**: → TPC ∅=244 cm & drift=292 cm
- TPC Act. Mass = **60 tonnes**: → TPC ∅=280 cm & drift=336 cm
- TPC Act. Mass = **80 tonnes**: → TPC ∅=308 cm & drift=369 cm

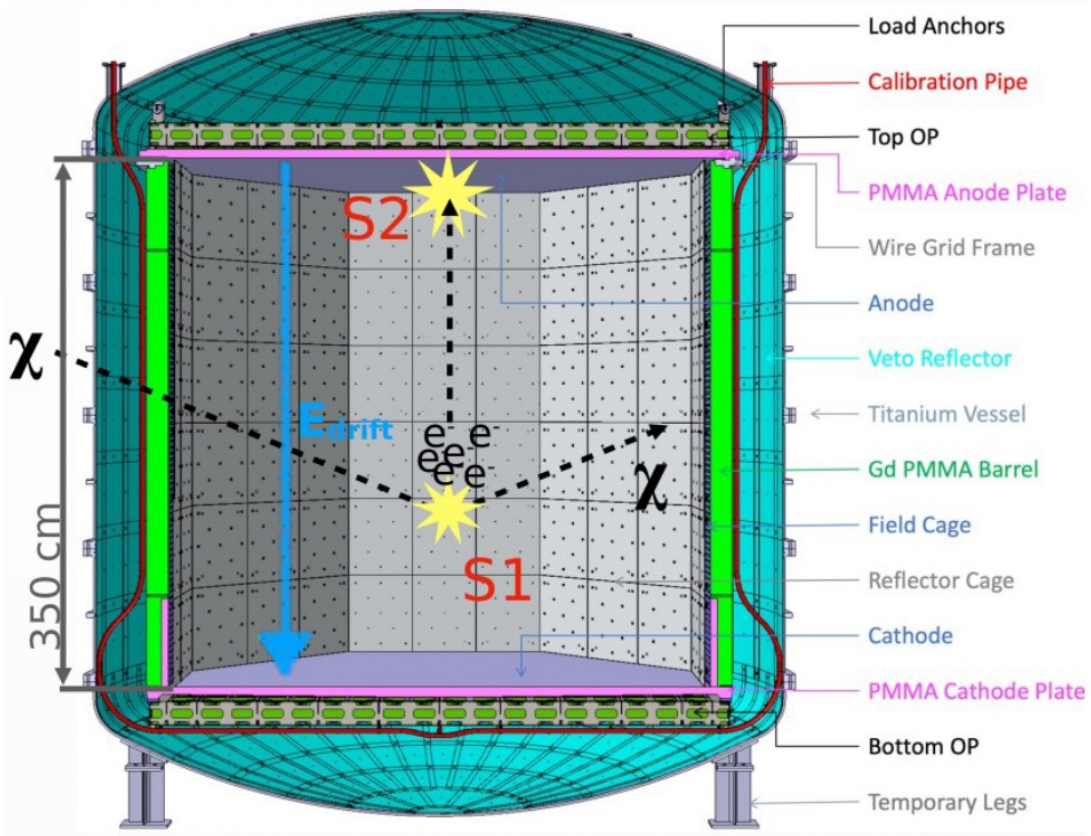
AR =1.5
- TPC Act. Mass = **40 tonnes**: → TPC ∅=227 cm & drift=340 cm
- TPC Act. Mass = **60 tonnes**: → TPC ∅=259 cm & drift=388 cm
- TPC Act. Mass = **80 tonnes**: → TPC ∅=286 cm & drift=429 cm

AR: Aspect Ratio

Pancake (AR <1) vs Oval (AR>1)

DARKSIDE 20K TPC

Design inside the Titanium Vessel:



Features:

Maximum drift length: 348 cm
Octagonal inscribed circle diameter: 350 cm
Gas pocket width: 7.0±0.5 mm
S1 Light Yield: 10 pe/keV
S2 Yield: > 20pe/e-

Drift field: 200 V/cm
Extraction field: 2.8kV/cm
Luminescence field: 4.2kV/cm

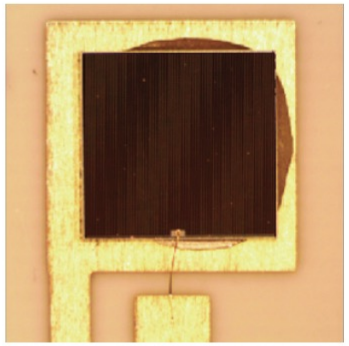
XY resolution: < 5cm
Z resolution: 1 mm

UAr mass in TPC: 51.1t
Vertical fiducial cut: 70 cm
Radial fiducial cut: 30 cm
Fiducial UAr mass: 20.2t

DARKSIDE 20 K PHOTODETECTION

Development of large area cryogenic radiopure SiPMs

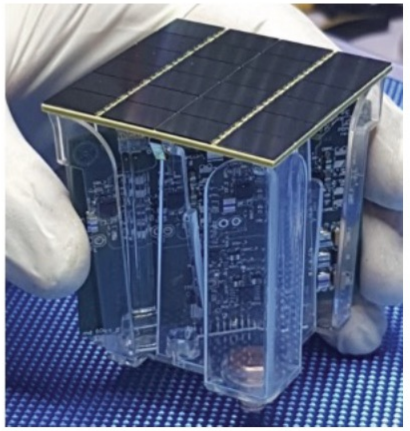
Single SPAD
~25 μm²



Single SiPM ~1 cm²

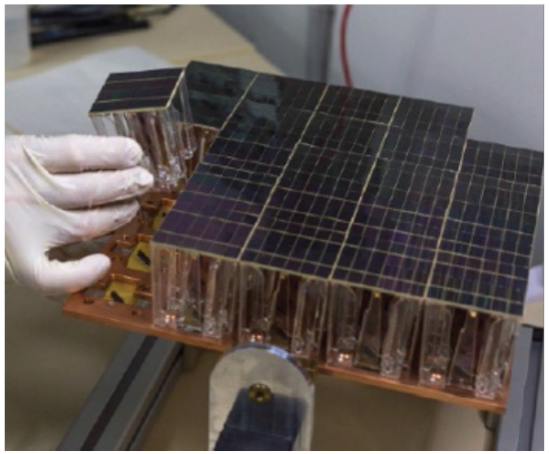
> 8000 PDMs (+2000 in the veto)
21 m² (inner TPC) + 5 m² (veto)
Mass production of the raw **wafers** at **LFoundry** (Italy)
Assembling facility **NOA** at **LNGS**
Other assembling facility for veto in UK
Testing facility in **Napoli**

Radiopure ~2mBq/PDM dominated by substrate and PCB
High **PDE** (~45%) >90% fill factor
Gain ~ 10^6
Dark Count rate at 87 K < 5 cps/PDM
Time **resolution** (sigma) ~10 ns
Low power consumption < 100 μW/mm2



Photodetector module (PDM)
matrix of 16-24 SiPMs
~5x5 cm²

Photodetector Unit
matrix of 16-25 PDMs



UNDERGROUND ARGON (UAR)

Urania

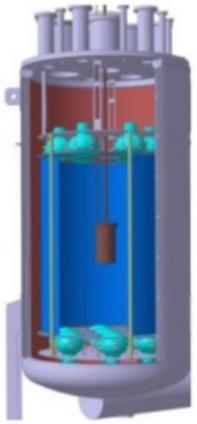
Extraction of UAr from CO2 wells

- Plant in Cortez, Colorado, US
- Can extract 330 kg/day
- Purity 99.99%

DArT

Measures 39Ar depletion factor

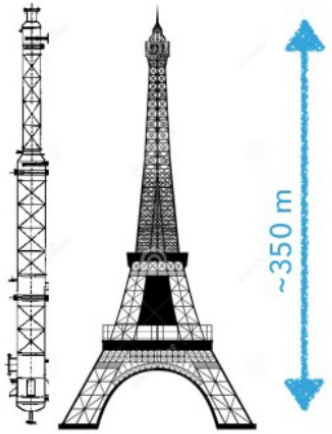
- At LSC, Canfranc, Spain
- Radiopure single phase LAr inner detector (1.42 kg LAr)
- -Veto: Inside ArDM detector (1t LAr)



Aria

Perform chemical and isotopic purification of UAr

- At Seruci mine in Sardinia, Italy
- Distillation Column, rate 1t/day
- A 39Ar reduction factor 10 expected per pass
- Medical applications (oxygen isotope separation for instance)
- Assembly of the final column will be finish this year

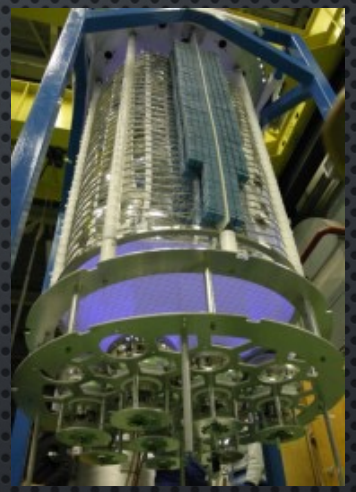


8

GADMC CONSORTIUM

- Detectors:
  - DarkSide50 and ArDM : dual phase
  - MiniClean and DEAP : single phase
- Status:
  - DarkSide50
    - Target: 37 kg liquid argon (depleted in Ar39)
    - Exposure: 532 live-days
  - ArDM
    - Target : 1 ton
    - Decommissioned in 2019 → DArT project
  - MiniClean
    - Target : 500 kg liquid argon
    - Decommissioned in 2019
  - DEAP 3600
    - Target : 3.3 ton (fiducial 1 t)
    - Exposure: 231 live-days (2019)
    - Data taking finished in 2020
    - upgrading detector for background reduction to restart in 2023

DarkSide50 @LNGS



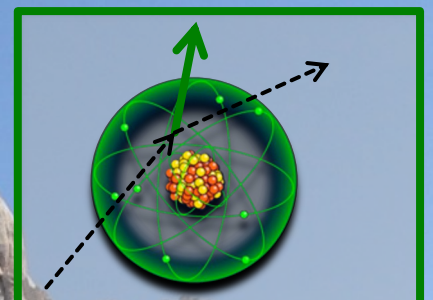
ArDM @Canfranc

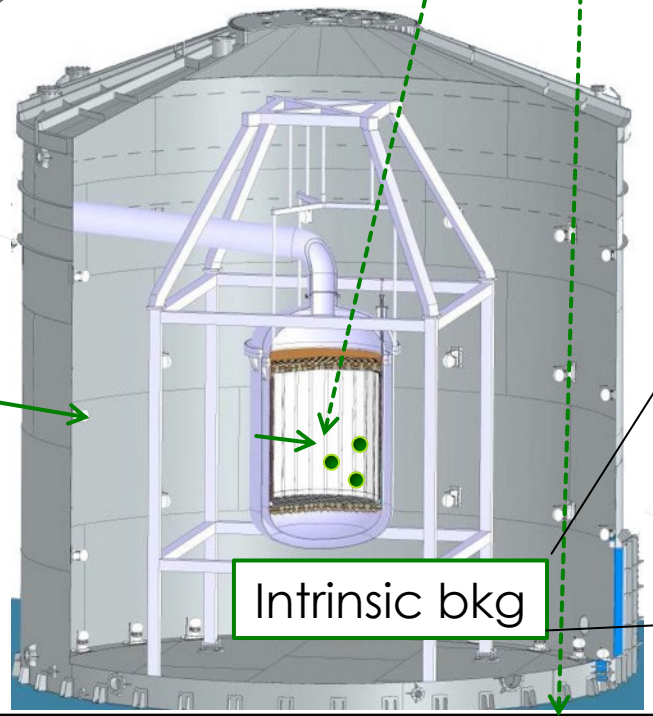
MiniClean @Snolab

DEAP3600 @Snolab

BACKGROUND SOURCES

Solar
pp + ^{7}Be ν





natural
γ bkg

Intrinsic bkg

Intrinsic bkgs

- **Rn222**
- **Kr85**
- **In Xenon detector**
  - Xe136
- **In Argon detectors**
  - **Ar39**

Cryogenic distillation column for Rn removal & surface cleaning

Using Kr distillation column allows to reduce the contamination to negligible level

Using Underground Argon (UAr) allows to have a reduction factor of background ~1400

BACKGROUND SOURCES

high energy n (CEvNS)

Solar pp + ^{7}Be ν

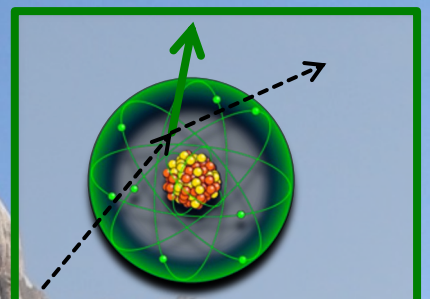
muons

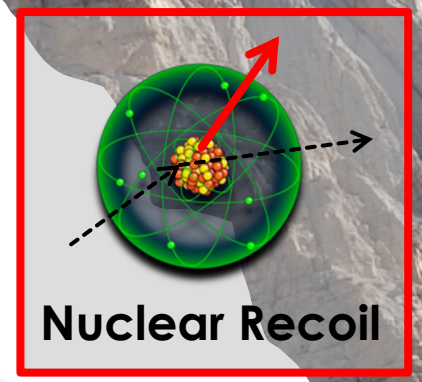
muon-induced neutrons

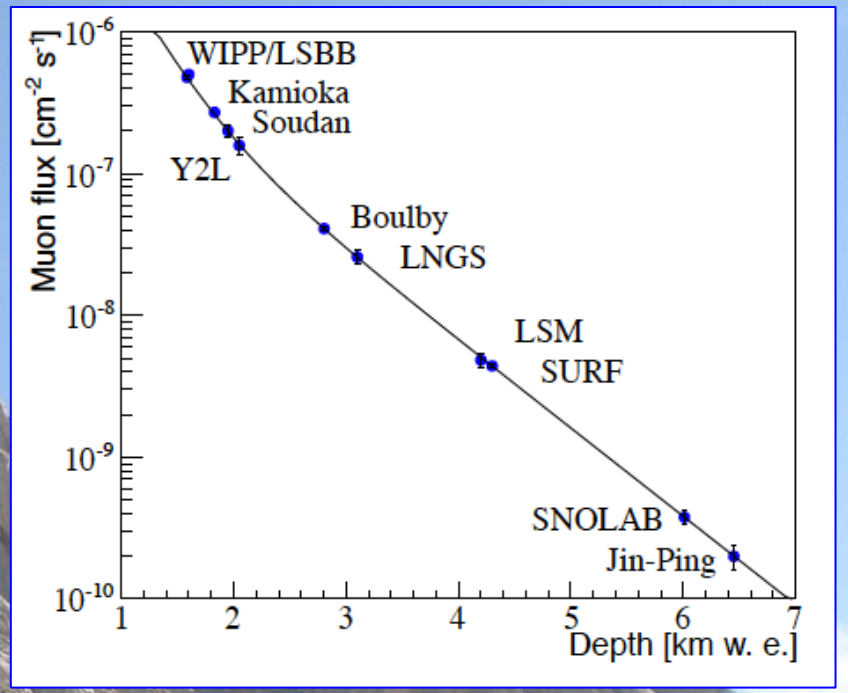
natural γ bkg

neutrons from (α,n), spontaneous fission

Intrinsic bkg







BACKGROUND SOURCES

high energy ν (CNNS)

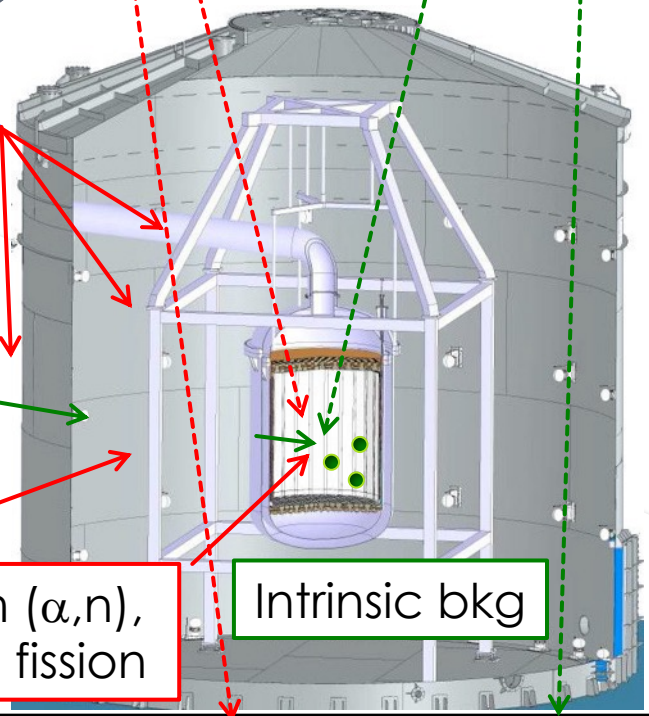
Solar pp + ^{7}Be ν

muons

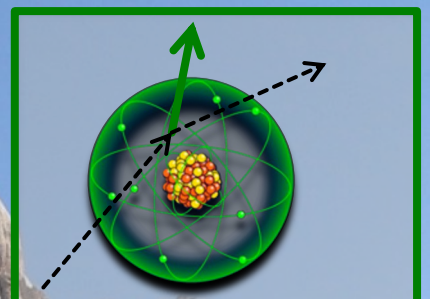
muon-induced neutrons

natural γ bkg

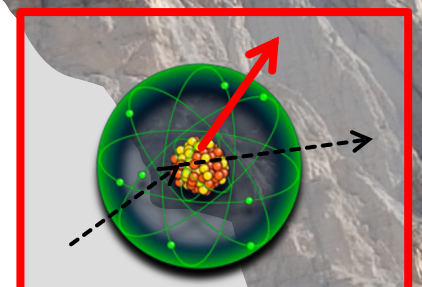
neutrons from (α,n), spontaneous fission



Intrinsic bkg



Electronic Recoil



Nuclear Recoil

Exxpected bkg on WIMPs searches in a 50 t LXe detector

Source	Rate [events/(t·y·keVxx)]
γ-rays materials	0.054
neutrons*	3.8×10^{-5}
intrinsic ^{85}Kr	1.44
intrinsic ^{222}Rn	0.35
$2\nu\beta\beta$ of ^{136}Xe	0.73
pp- and ^{7}Be ν	3.25
CNNS*	0.0022

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