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European School of Instrumentation in Particle & Astroparticle Physics

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European Scientific Institute

Enigmass

Noble liquid detectors

Slides are available here : http://lpsc.in2p3.fr/images/collot/Noble-Liquid-Detectors.pdf

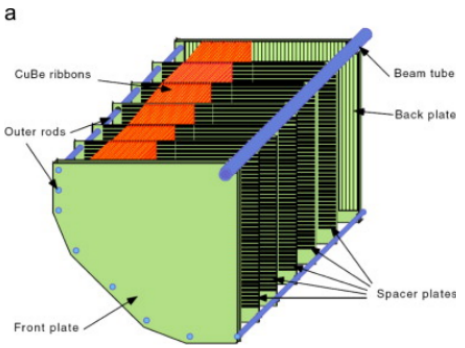
Introduction

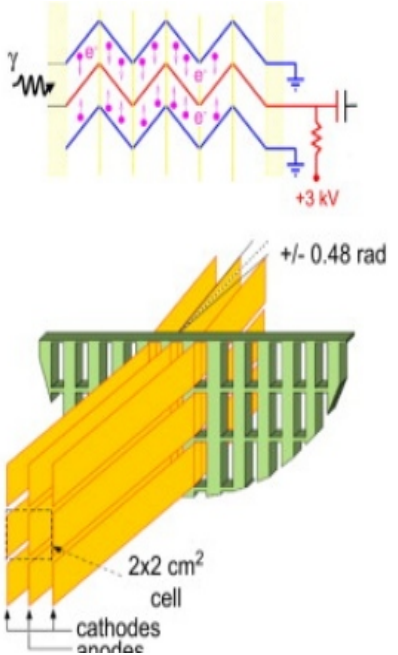
The growing success of noble-liquid particle detectors results from the following facts :

- they are chemically inert ; (long-term operation)
- they are radiation resistant ; (high-radiation environment, LHC , FCC-pp)
- they can be utilized in ionization or/and scintillation modes ; (auto-triggering)
- their signal yield is relatively high ; (good resolution)
- their industrial availability is good (Xe world prod. is 27 t/y) ; (large-size detectors)
- they can be easily purified ; (very long drift distance)
- they can be used to build complex-geometry detectors of increasing size ; (granularity)
- low temperature usually helps in reducing the electronic noise ; (good S/N)
- they constitute homogeneous media with homogeneous response. (good resolution)

A few emblematic examples

NA48 liquid krypton calorimeter (built in the 90's)



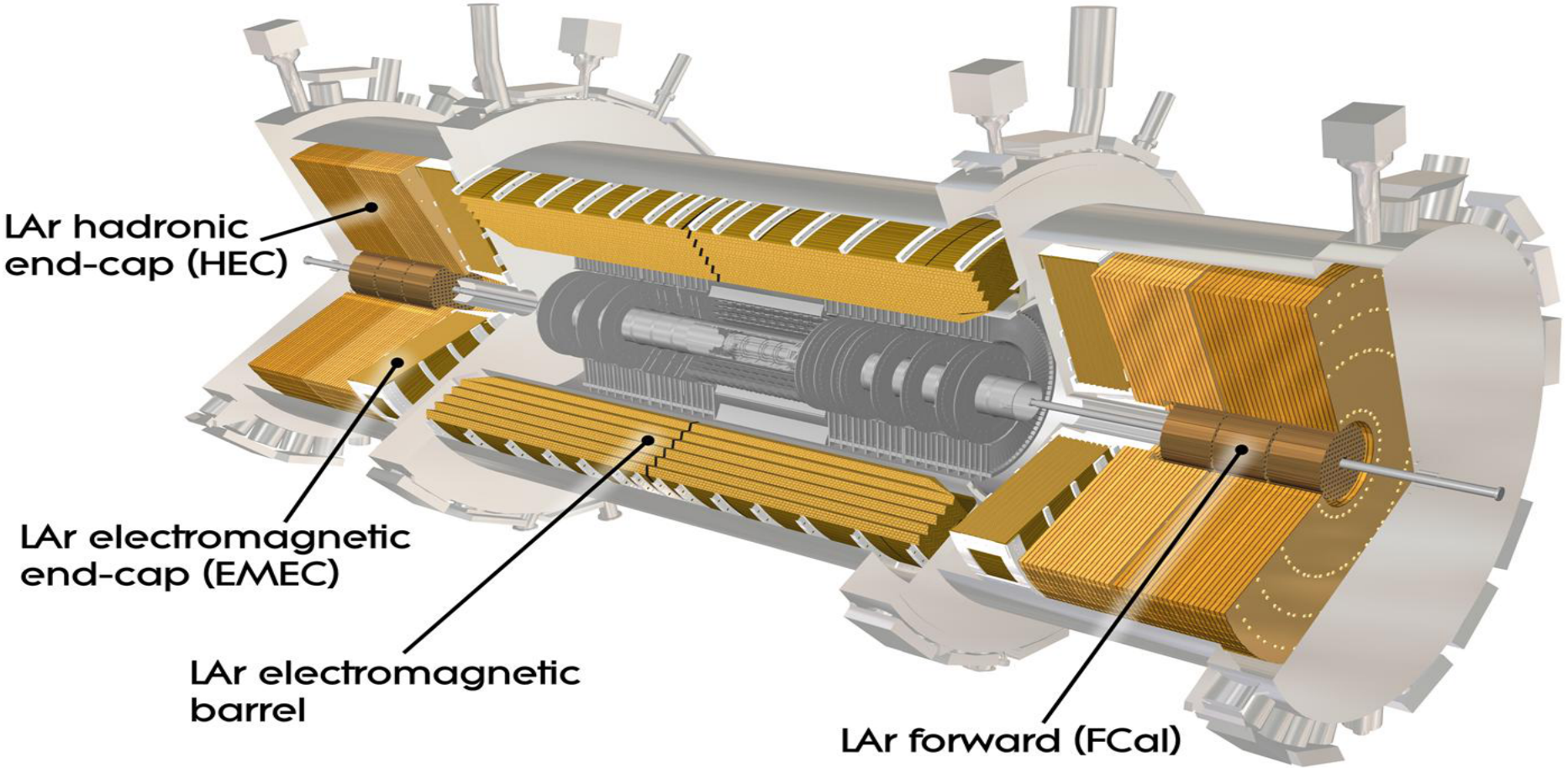


$$\frac{\sigma(E)}{E} = \frac{3.2\%}{\sqrt{E(\mathrm{GeV})}} \oplus 9\%/E(\mathrm{GeV}) \oplus 0.4\%$$

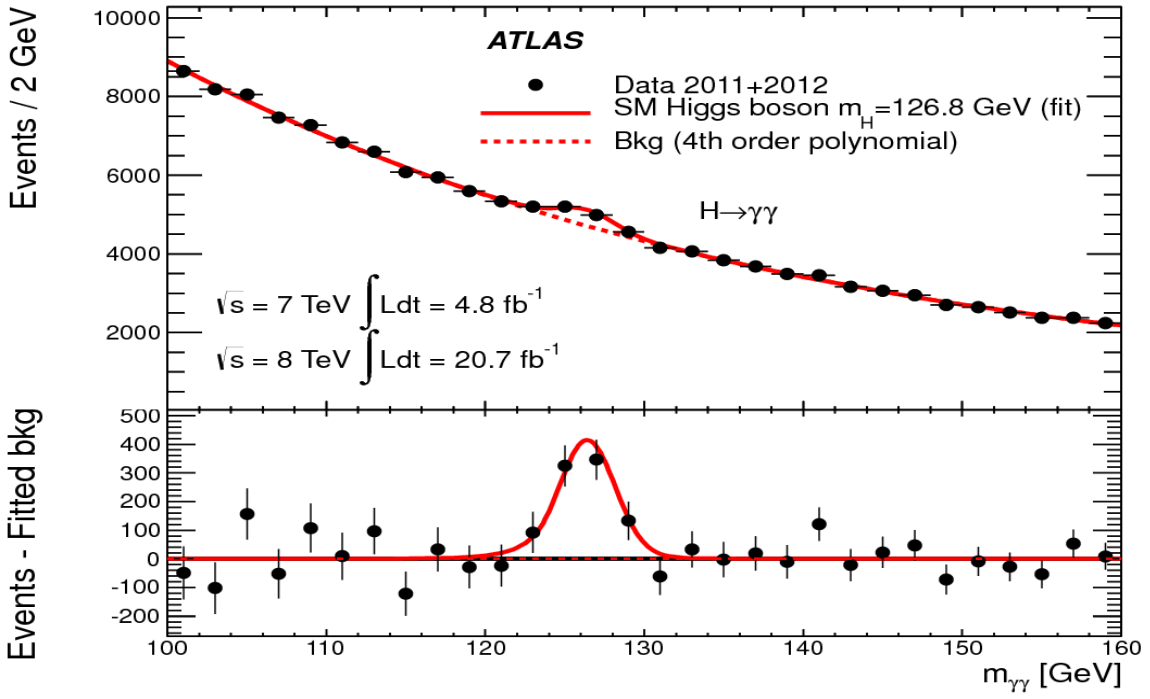
Homogeneous LKr calorimeter

Nucl. Instr. & Meth. A , vol. 370, p. 413, 1996

ATLAS liquid argon calorimeter (designed at the beginning of the 90's)

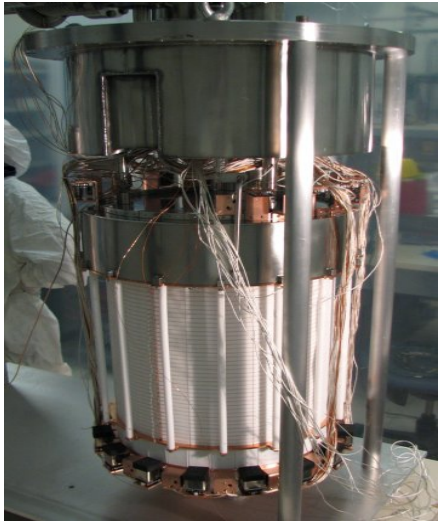


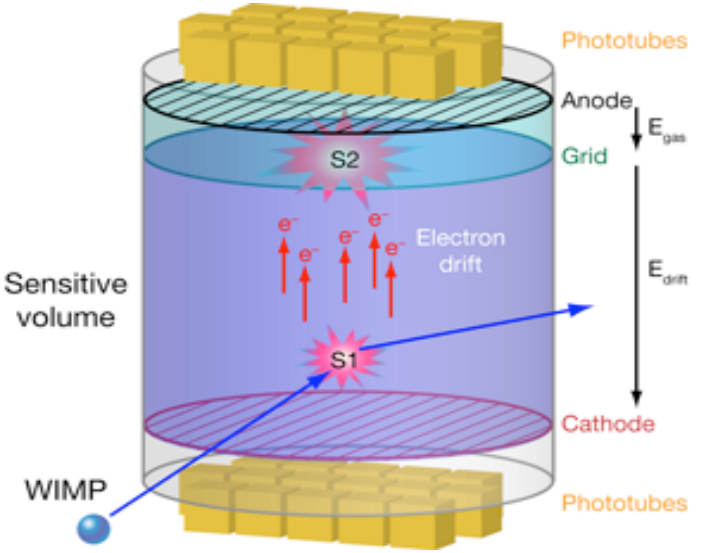
That strongly contributed to discover the Higgs boson decaying into two photons



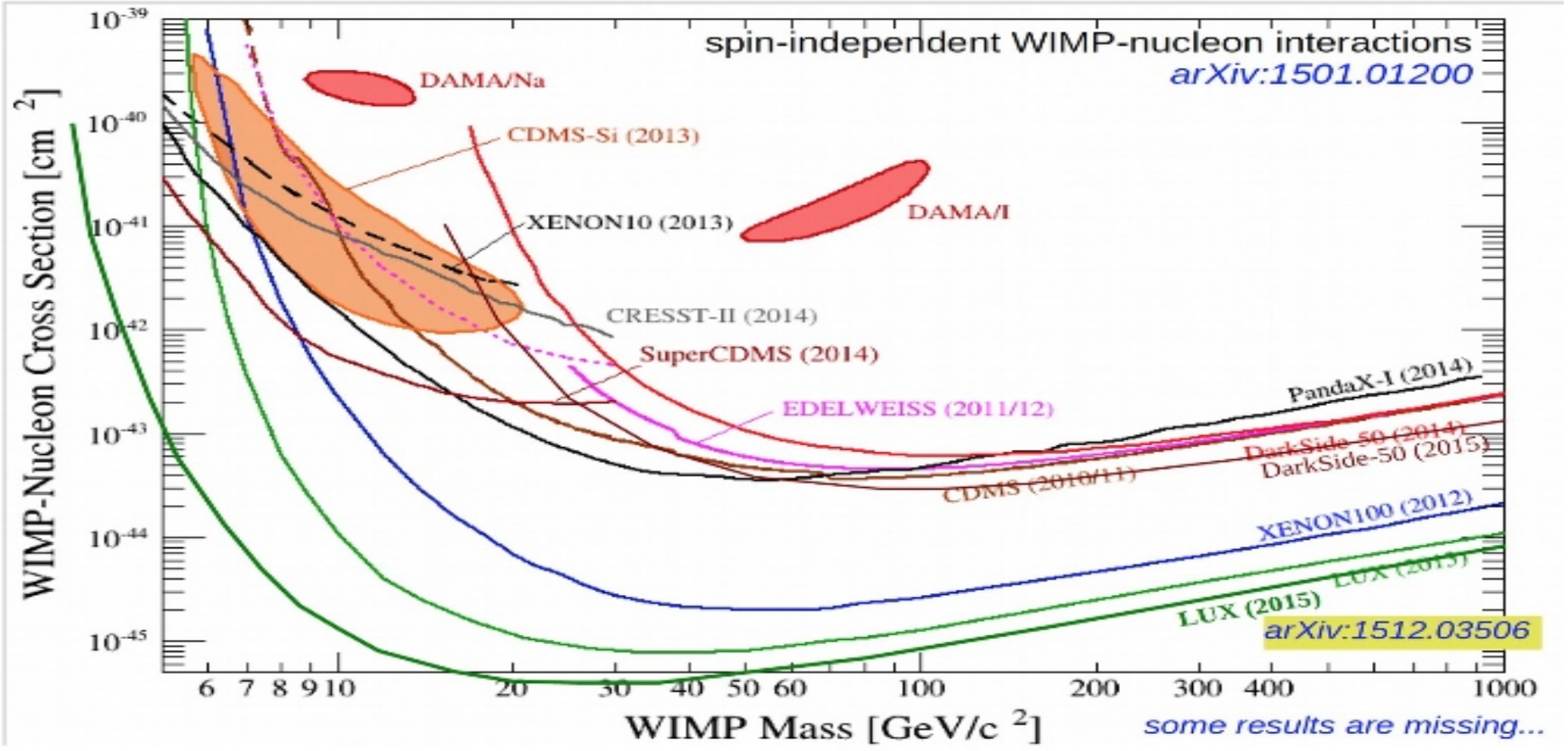
XENON100

100 kg LXe dual-phase TPC



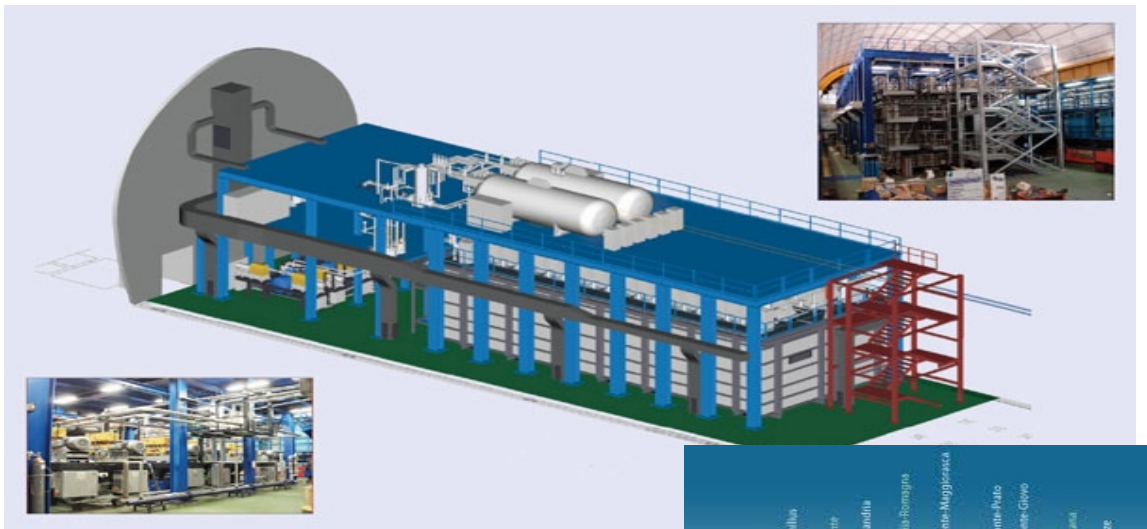


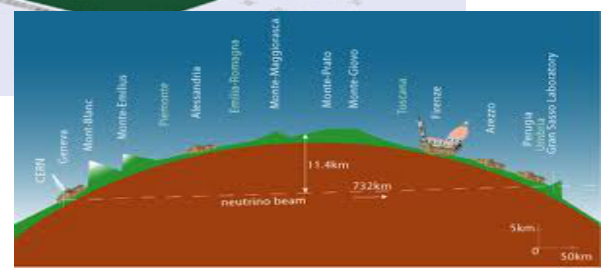
Produced with LUX the most constraining limits to the existence of Wimps

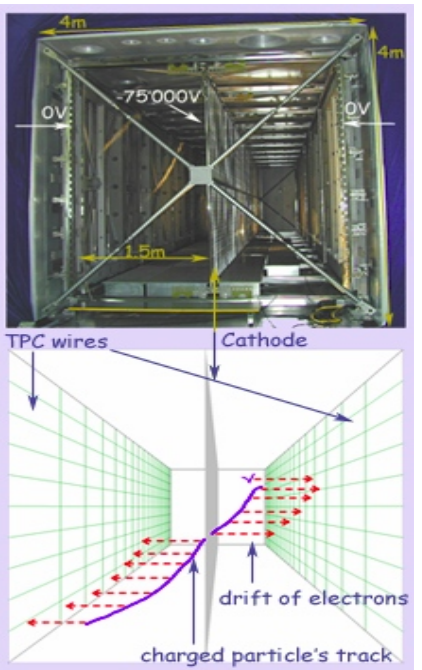


ICARUS

LAr 600 m^3 Time Projection Chamber that was installed in Gran Sasso National laboratory







Physical properties

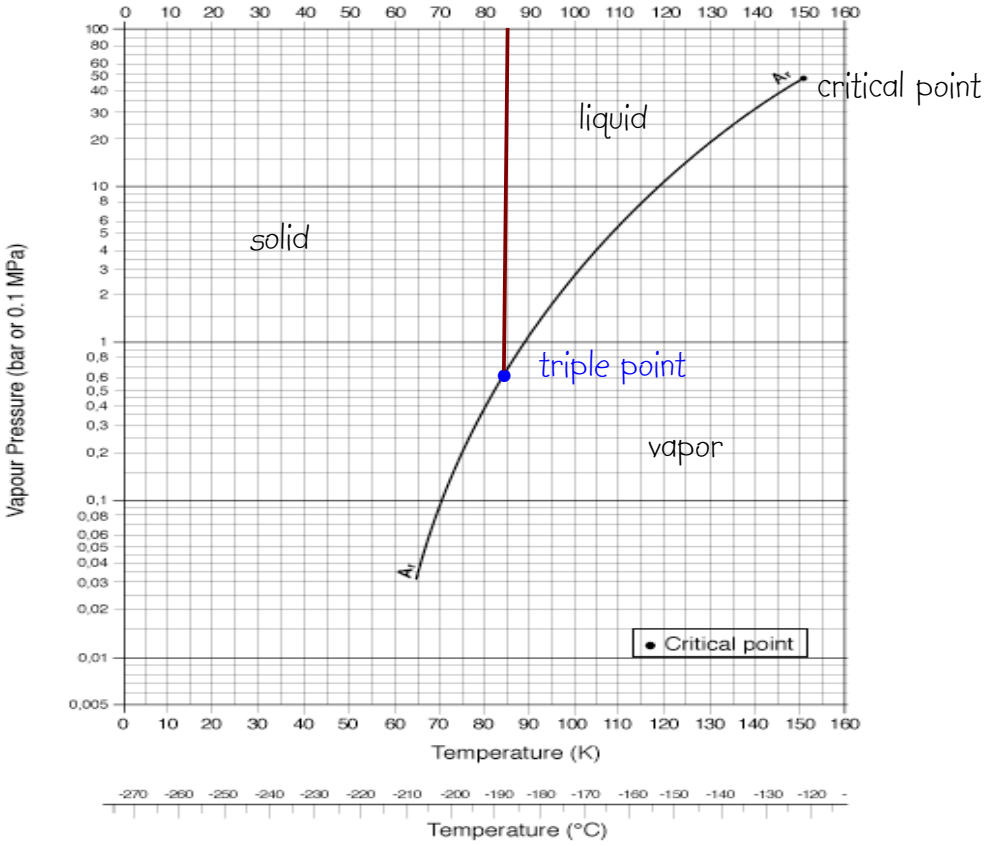
Table of main physical properties

	He	Ne	Ar	Kr	Xe
mol. mass (g mol^{-1})	4.0026	20.183	39.948	83.80	131.3
T_B : boil. temperature at 1 atm. (K)	4.22	27.102	87.26	119.74	169
specific mass at T_b (g cm^{-3})	0.13	1.2	1.399	2.413	3.1
T_s : fusion temperature at 1 atm. (K)		24.55	83.78	115.78	161.36
latent heat at T_B (J kg^{-1})		87.2	163.2	107.7	96.29
Triple point :					
temperature (K)		24.56	83.78	115.76	161.31
pressure (0.1 MPa)		0.43	0.6876	0.734	0.8
Critical point :					
temperature (K)	5.25	44.39	150.86	209.38	289.74
pressure (0.1 MPa)	2.26	26.86	48.9	54.27	57.64
Thermal conductivity at T_B (W $m^{-1}K^{-1}$)	1.6 10^{-5}	0.113	0.125	0.09	0.071

Easy to liquify given the fact
that T_B > LN_2 temperature (77.3 K)

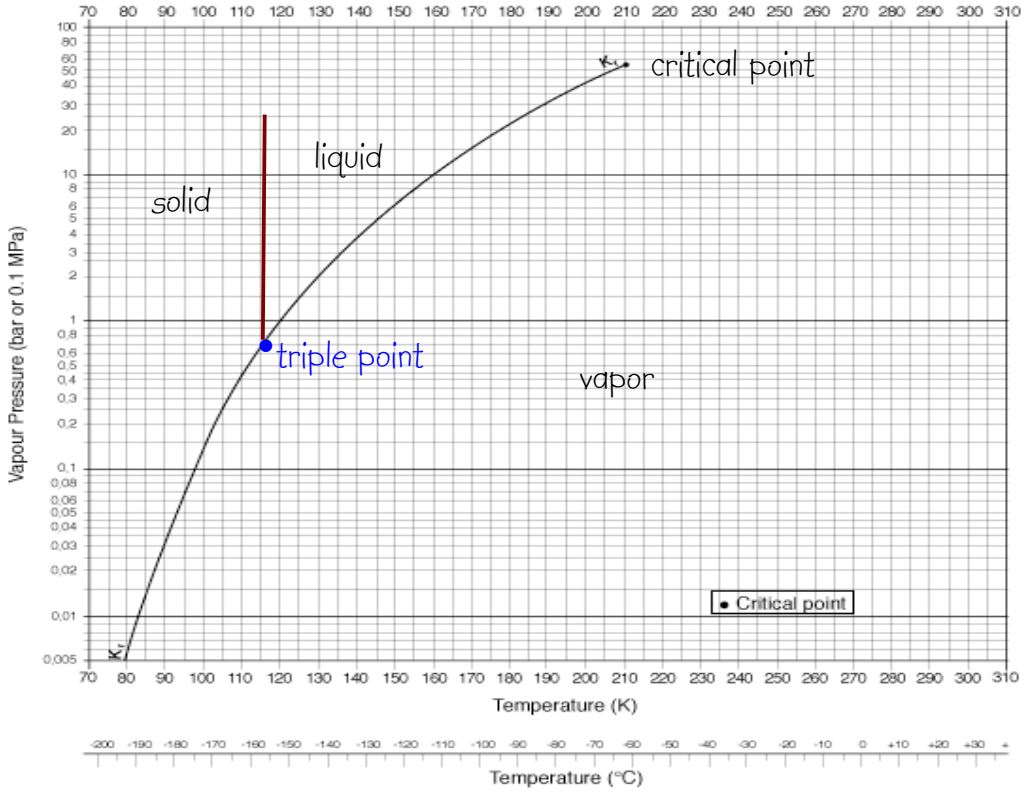
Vapour pressure curve of argon

Triple point :
83.78 K
0.6876 MPa



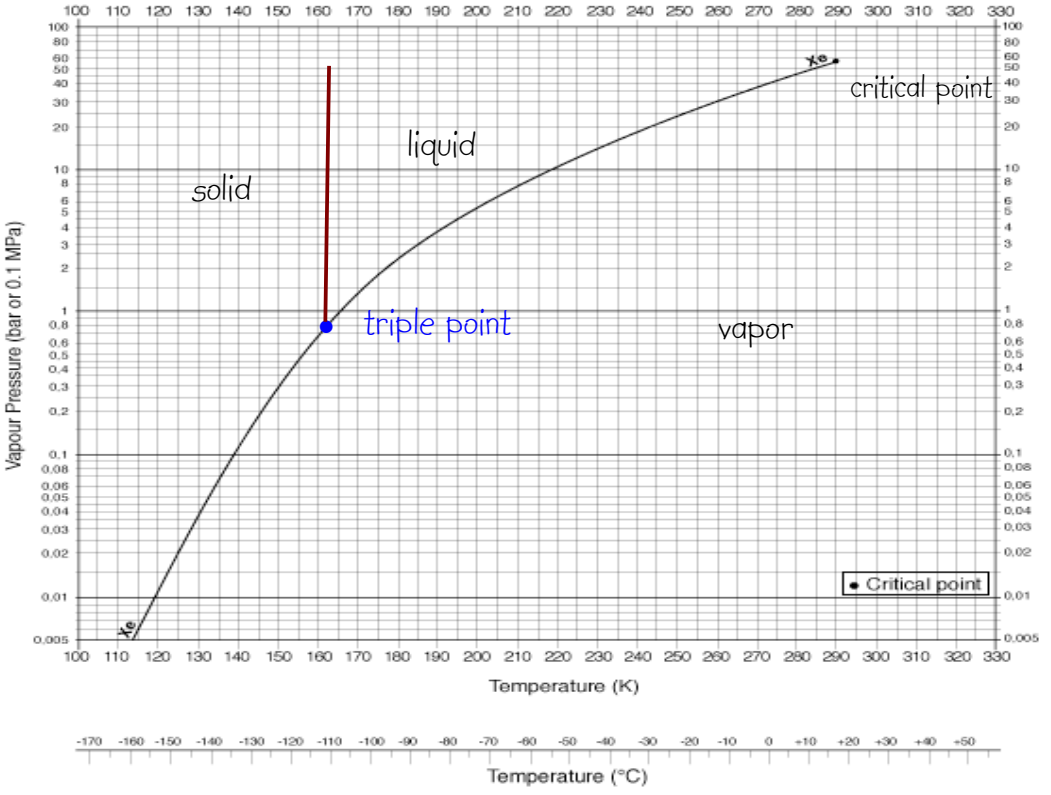
Vapor pressure curve of krypton

Triple point :
115.76 K
0.734 MPa

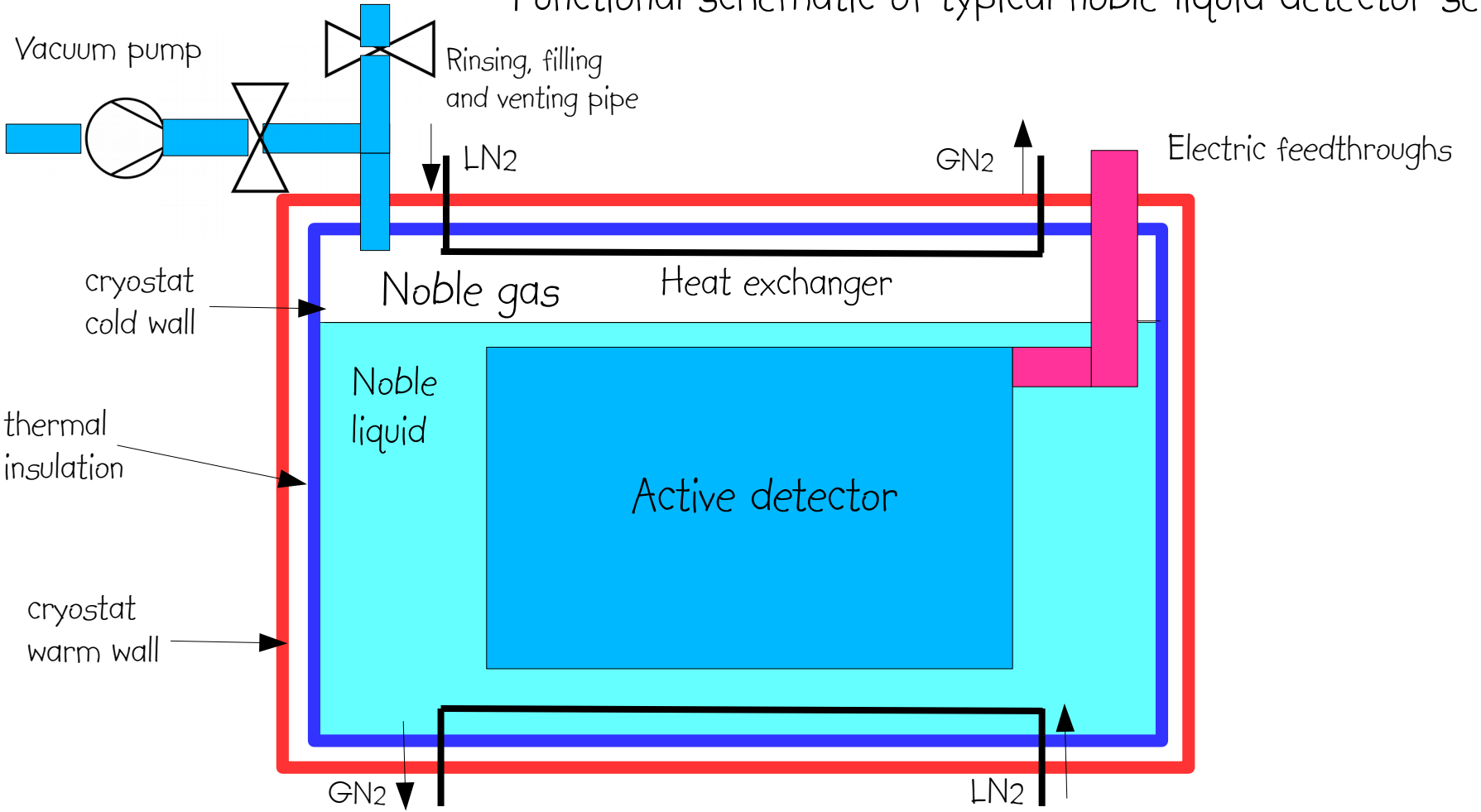


vapor pressure of xenon

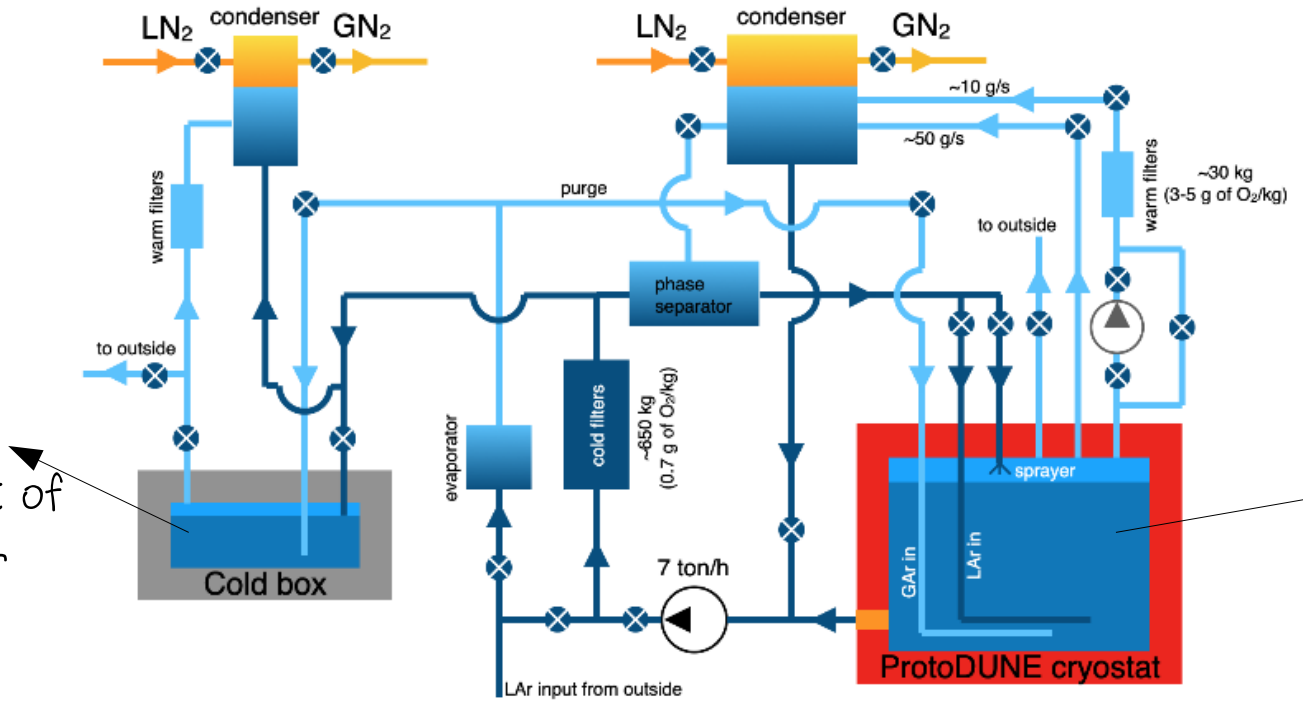
Triple point :
161.31 K
0.8 MPa



Functional schematic of typical noble liquid detector setup



Simplified cryogenics diagram of CERN LAr Neutrino Plateform

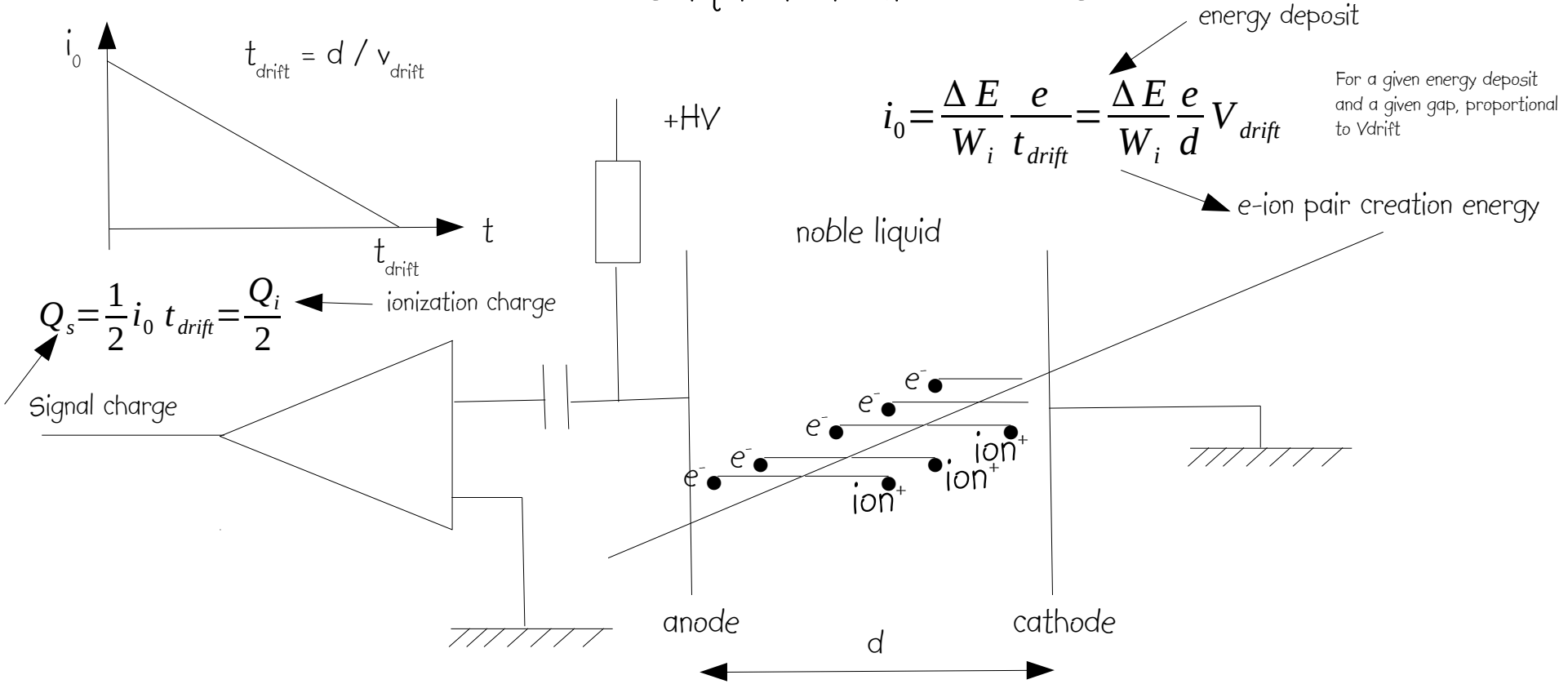


13 t of LAr

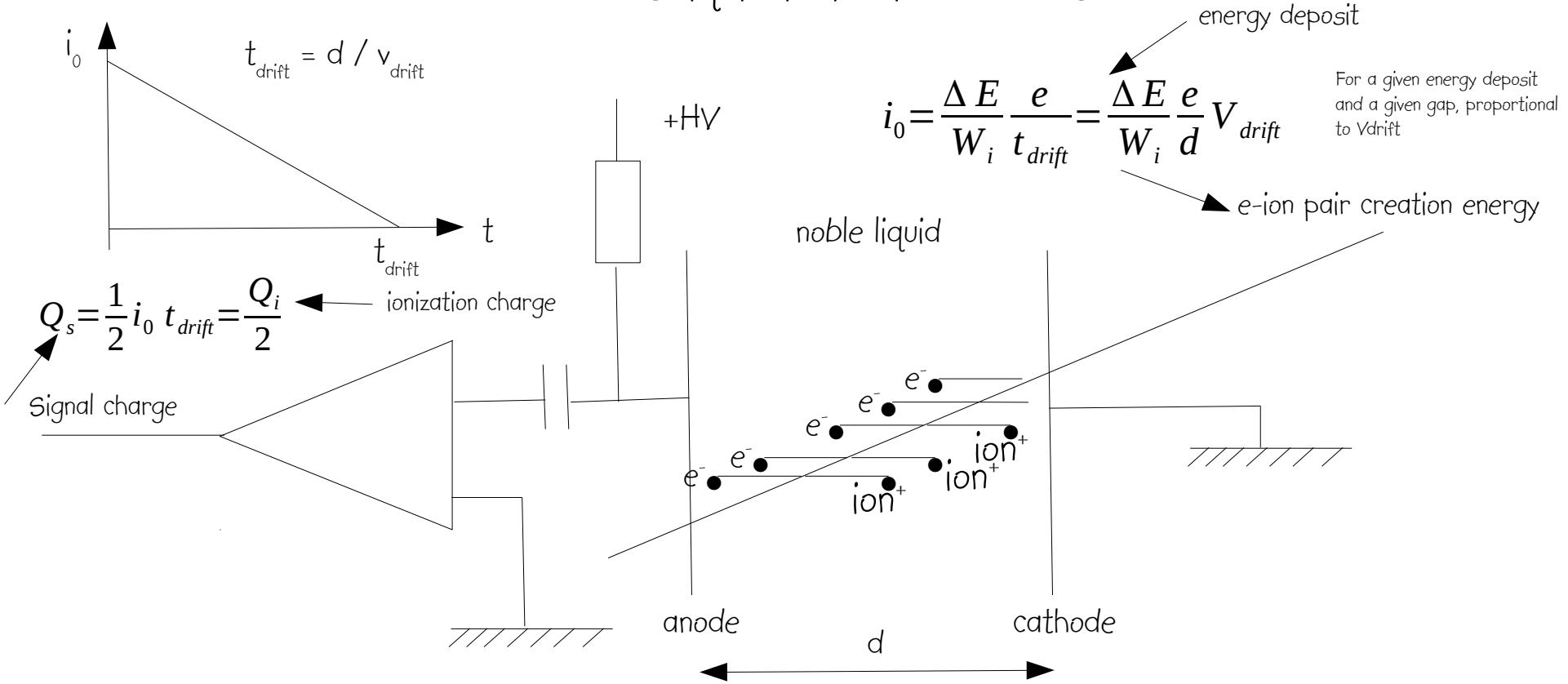
800 t of LAr purified to 1 ppb level

Ionization mode

Noble liquid ionization chamber



Noble liquid ionization chamber



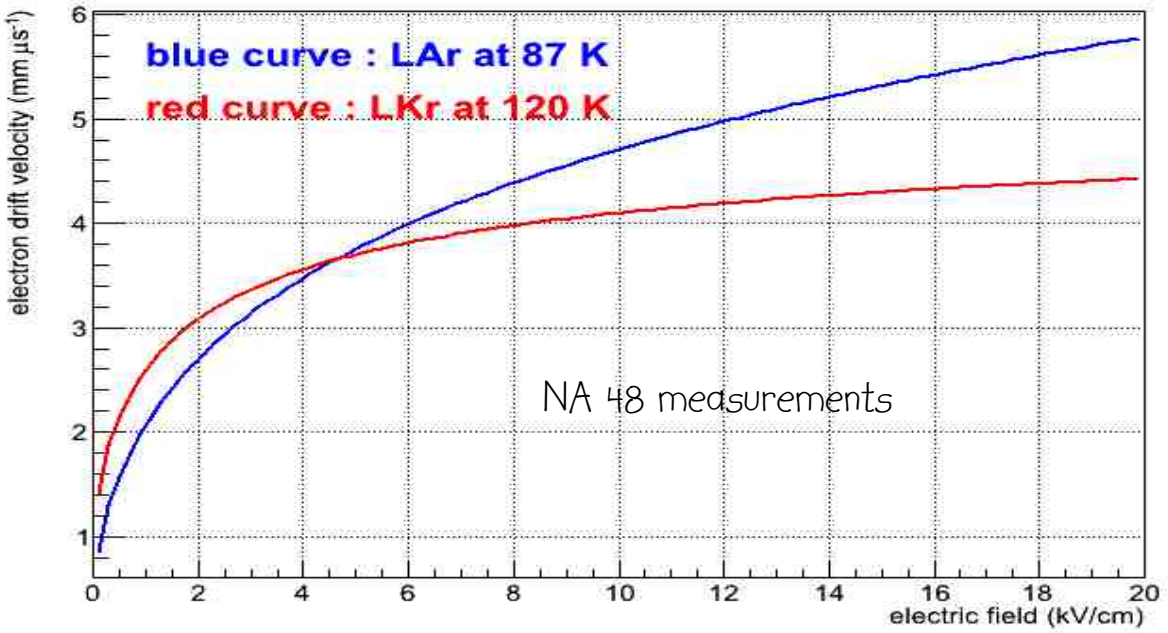
Ionization properties

	LAr	LKr	LXe
dE/dx for a MIP ($\beta\gamma$=3.5) in MeV/cm	2.2	3.5	4
W_i (eV)	23.6 +/- 0.3	18.4 +/- 0.3	15.6 +/- 0.3
V_{drift} at E=10 kV/cm and T_B (mm/µs)	4.75	4.1	2.6
relative dielectric constant	1.6	1.63	1.96

W_i is the energy needed to produce an electron-ion pair in the liquid.

T_B is the boiling temperature.

Electron drift velocity



Note that electron drift velocity decreases when T increases : $1/V\ dV/dT \approx -1.5\%\ K^{-1}$

Ion drift velocity is several orders of magnitude smaller. Ion contribution to signal can be neglected.

However ions may contribute to charge build-up if ionization load is too big.

Temperature variation of specific mass

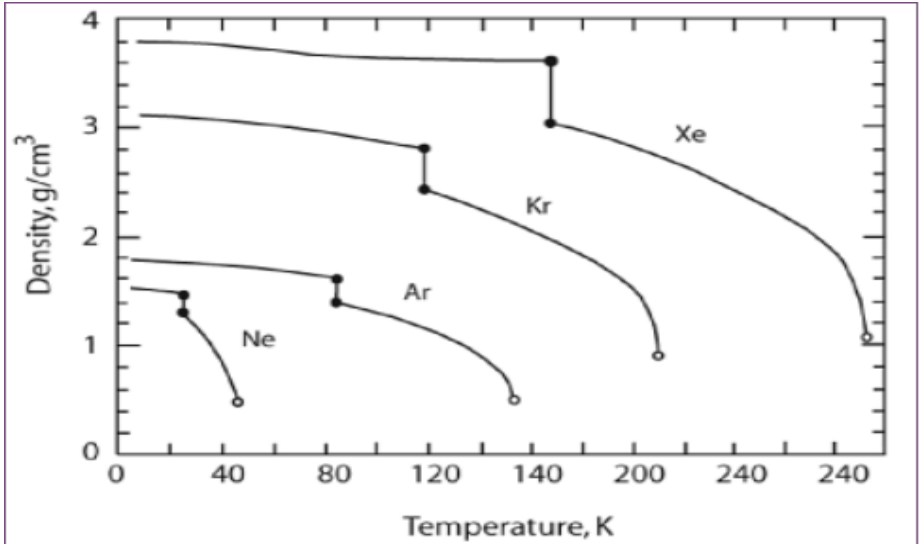


Fig. 2.1 Density of condensed noble gases dependence on temperature (open circles mark critical points, closed circles mark triple points). Redrawn from [18].

ρ diminishes when T increases, hence signal decreases : -0.5% K^{-1}

Recombination of e-ion pairs

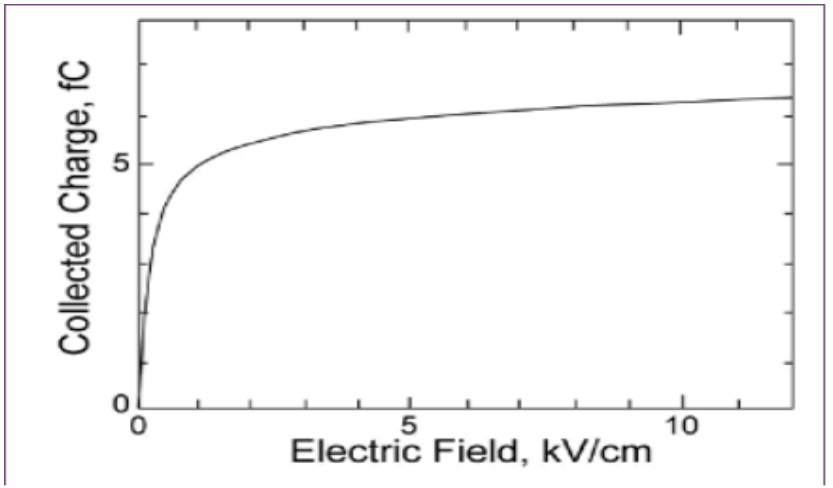
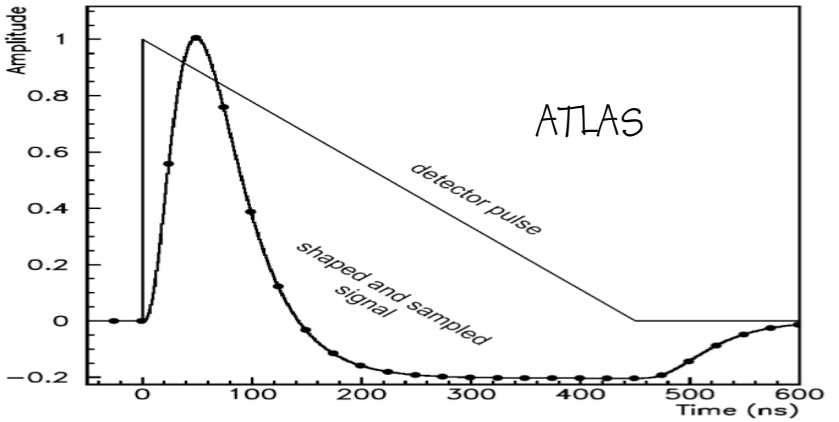


Fig. 2.9 Field dependence of the charge collected from liquid argon ionization chamber irradiated with 976 keV electrons. Redrawn from [60].

If no electric field is applied, all e-ion pairs recombine ! The collected charge progressively rises as a function of electric field and comes to a saturation.

Ionization readout modes

Initial current mode : readout of initial ionization current.
Differentiation of triangle pulse (time constant = 25 ns).
-high-rate capability (LHC)
- but higher electronic noise
-and increased dependence to temperature : -2% K^{-1}
requires temperature control over big volume : $\Delta T < 0.1$ K !



Fast charge mode : integration of current pulse (time constant =1.6 µs).
-lower-rate capability (LAr TPC)
-but better noise performance
-and reduced dependence to temperature : -0.5% K^{-1}
-non-destructive readout on several induction wire planes (anode)

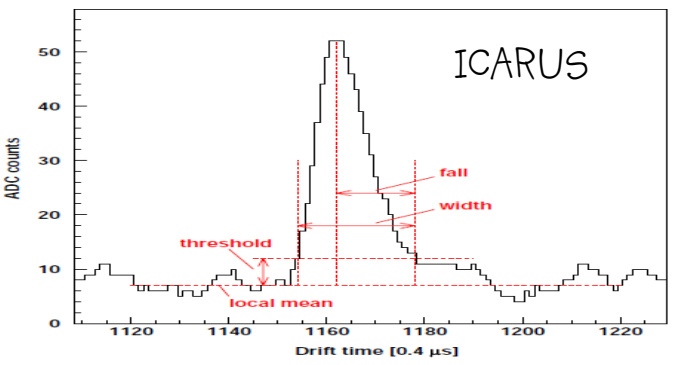
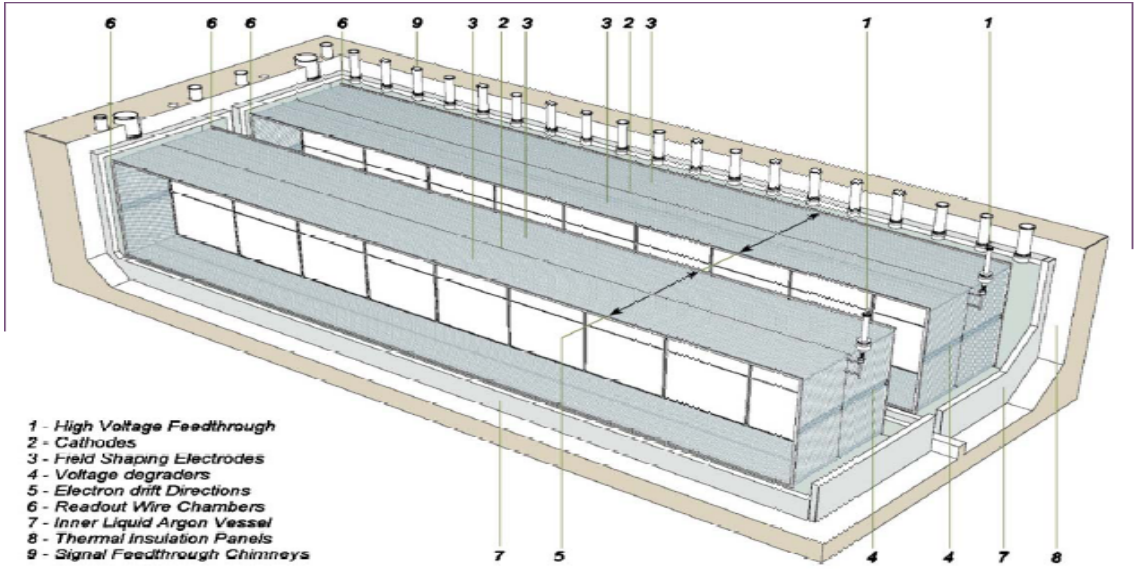
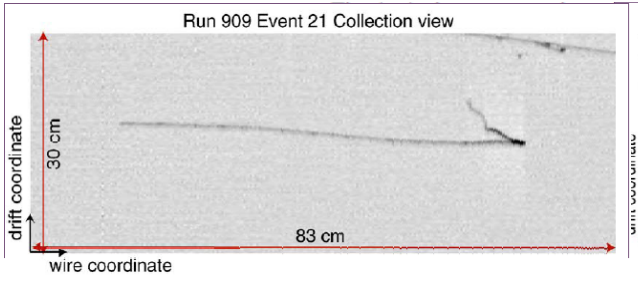


Fig. 68. Example of a hit produced by a minimum ionizing particle on a Collection wire. Marked are the parameters used in the hit search. The output signal has been passed through the low frequency filter.

ICARUS LAr TPC





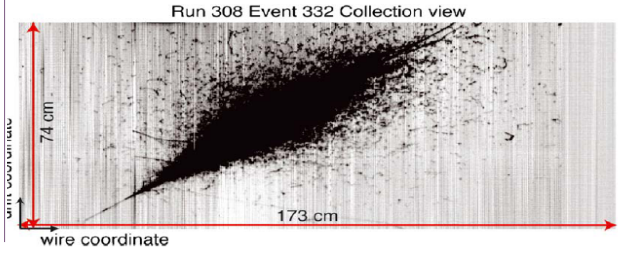
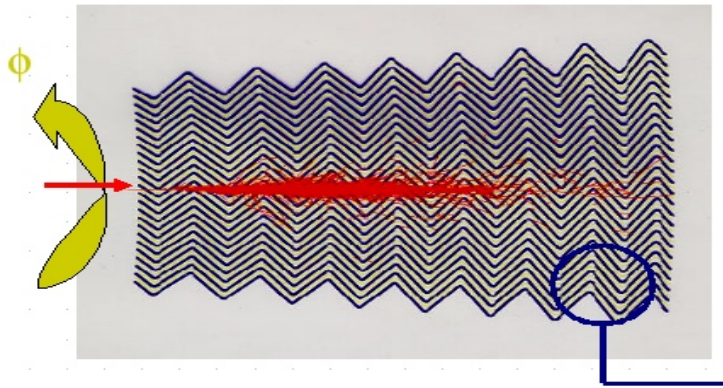
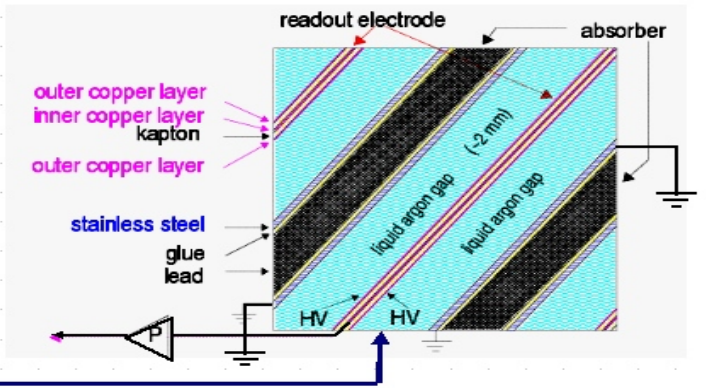
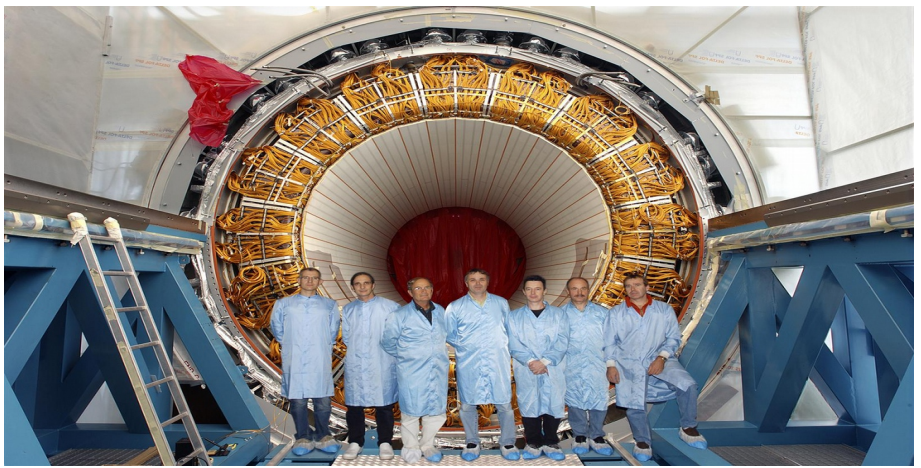


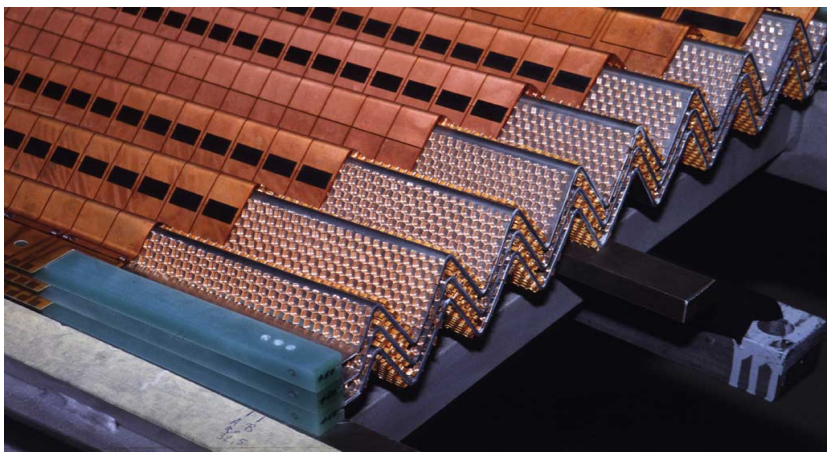
Fig. 66. Run 308, Event 332, Collection view. Electromagnetic shower.

ATLAS LAr electromagnetic calorimeter



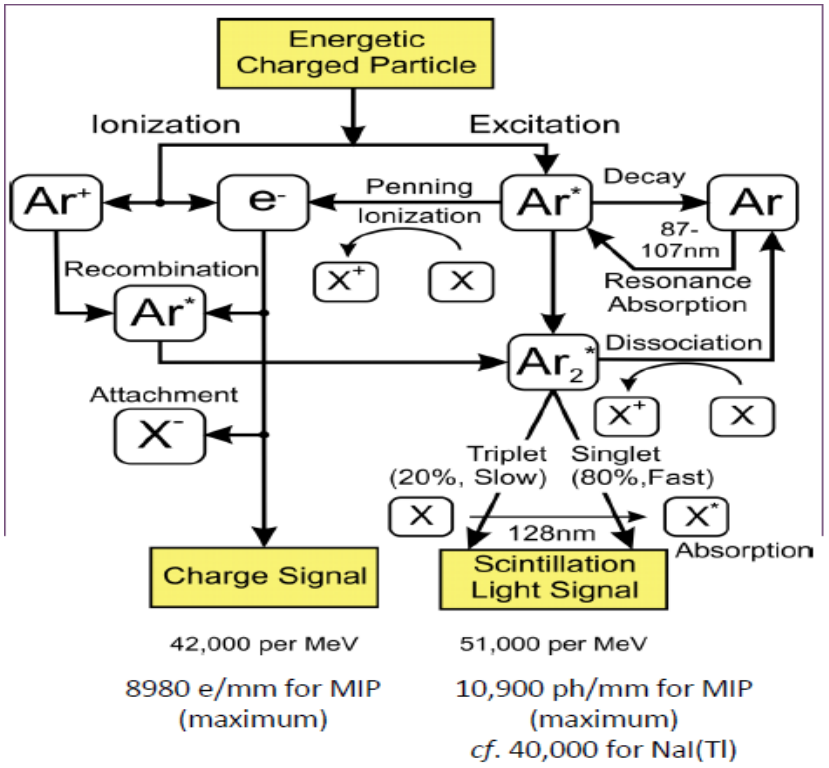


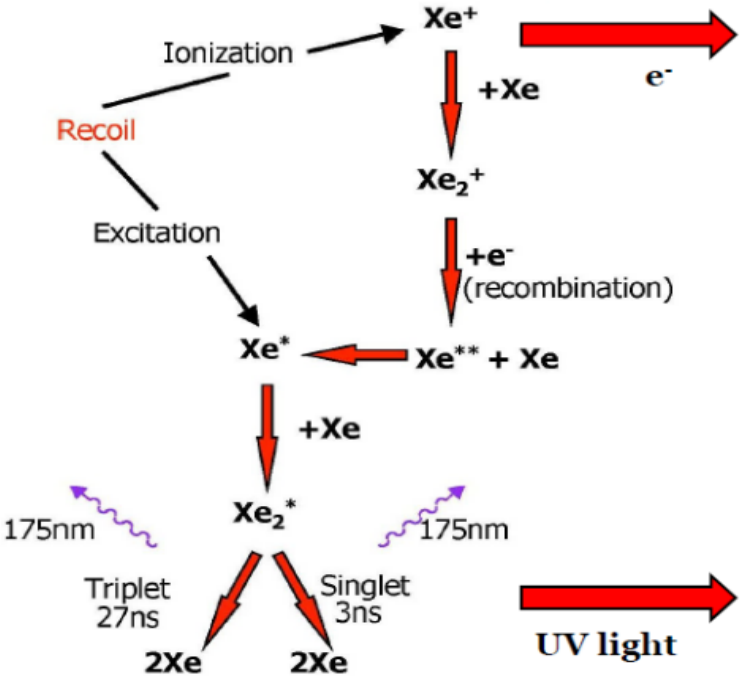




Scintillation mode

Scintillation in LAr and LXe





light curves in blue

charge curves in red

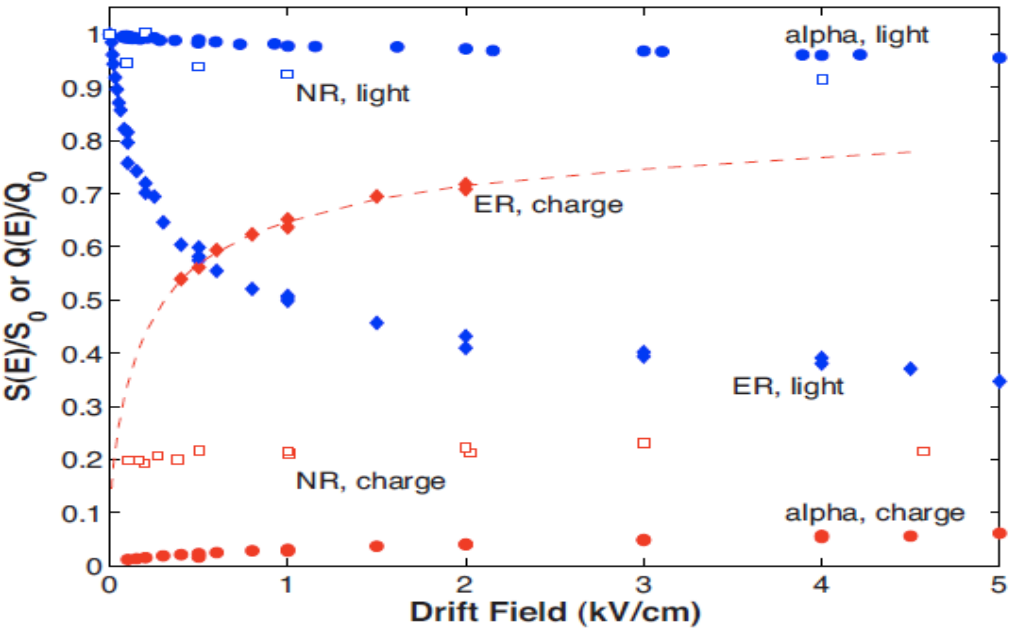


FIG. 6. (Color online) Field dependence of scintillation and ionization yield in LXe for 122 keV electron recoils (ERs), 56.5 keV$_r$ nuclear recoils (NRs) and 5.5 MeV alphas, relative to the yield with no drift field (Aprile *et al.*, 2006).

Light signal diminishes while charge signal increases with electric field

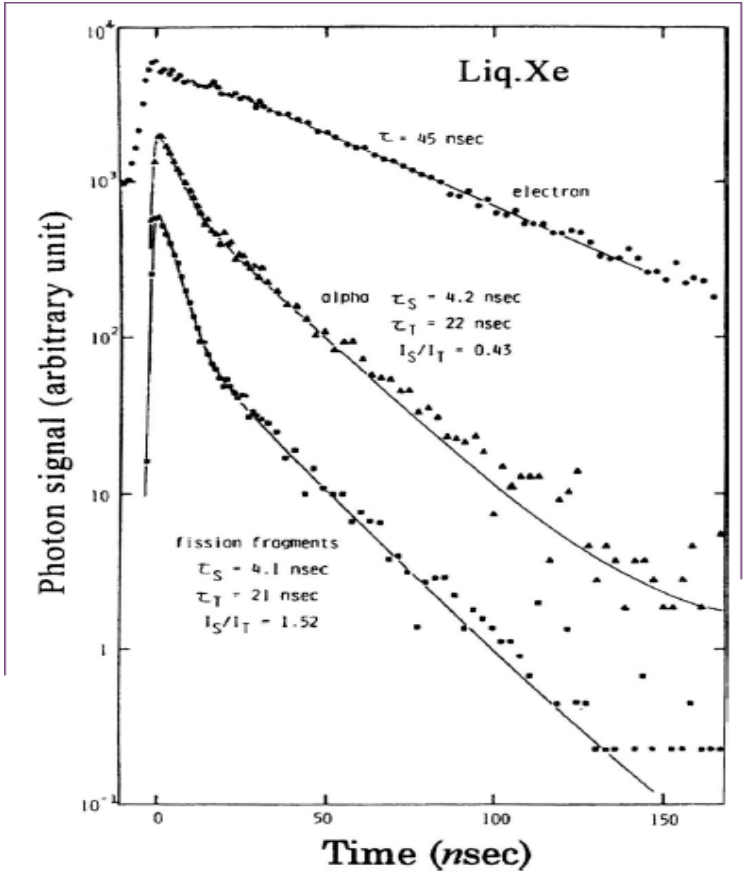


FIG. 19. Decay curves of scintillation from liquid xenon excited by electrons, α particles, and fission fragments, without an applied electric field (Kubota, Hishida, and Ruan, 1978; Hitachi *et al.*, 1983).

scintillation properties

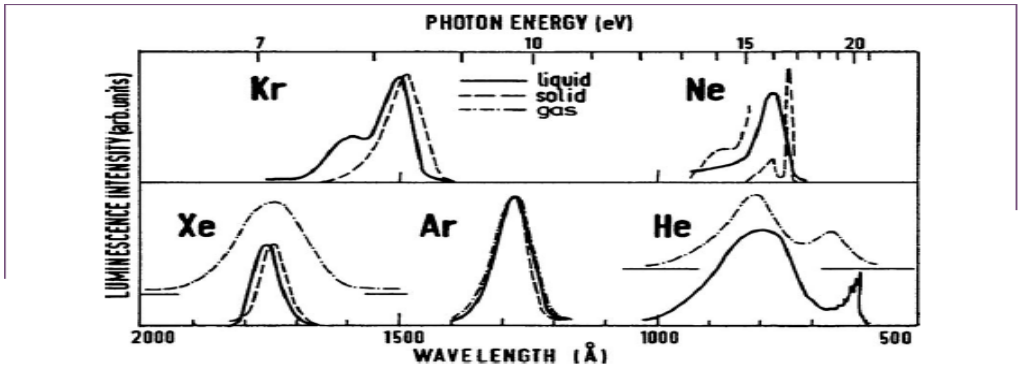


FIG. 18. Emission bands in liquid rare gases, together with solid- and gas-phase spectra (Jortner *et al.*, 1965; Schwenter, Kock, and Jortner, 1985).

	W_{ph} (at zero E field) in eV
LAr	19.5 +/- 1
LKr	15
LXe	13.8 +/- 0.9

W_{ph} is the energy needed to create a UV photon. Note that W_{ph} increases when the electric field is increased.

dual-phase LXe TPC

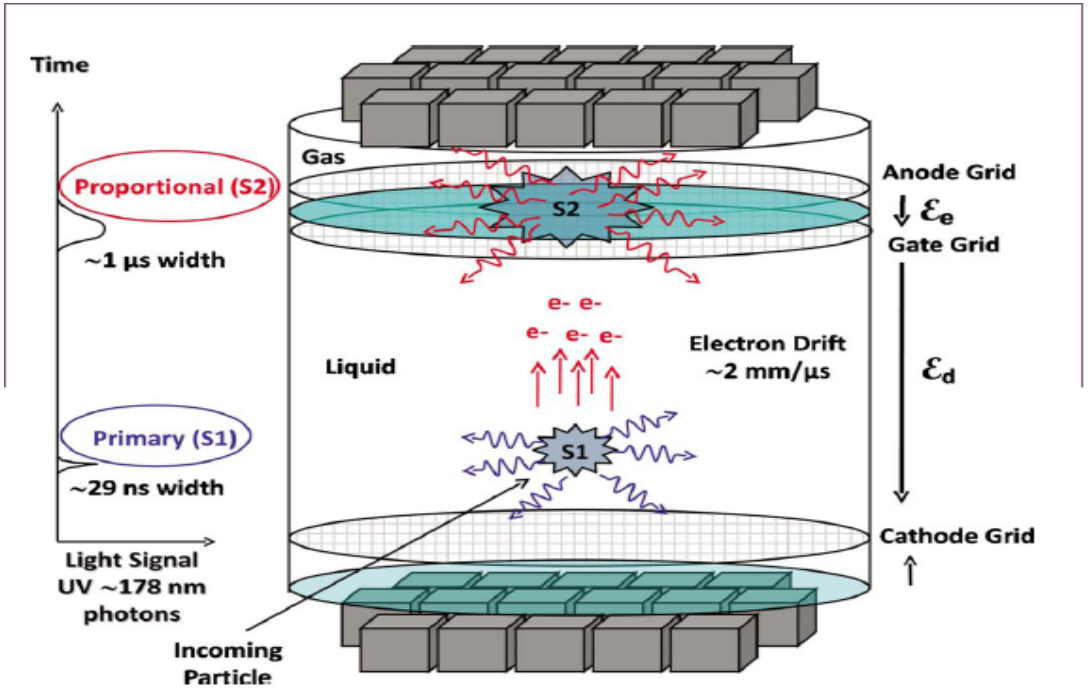
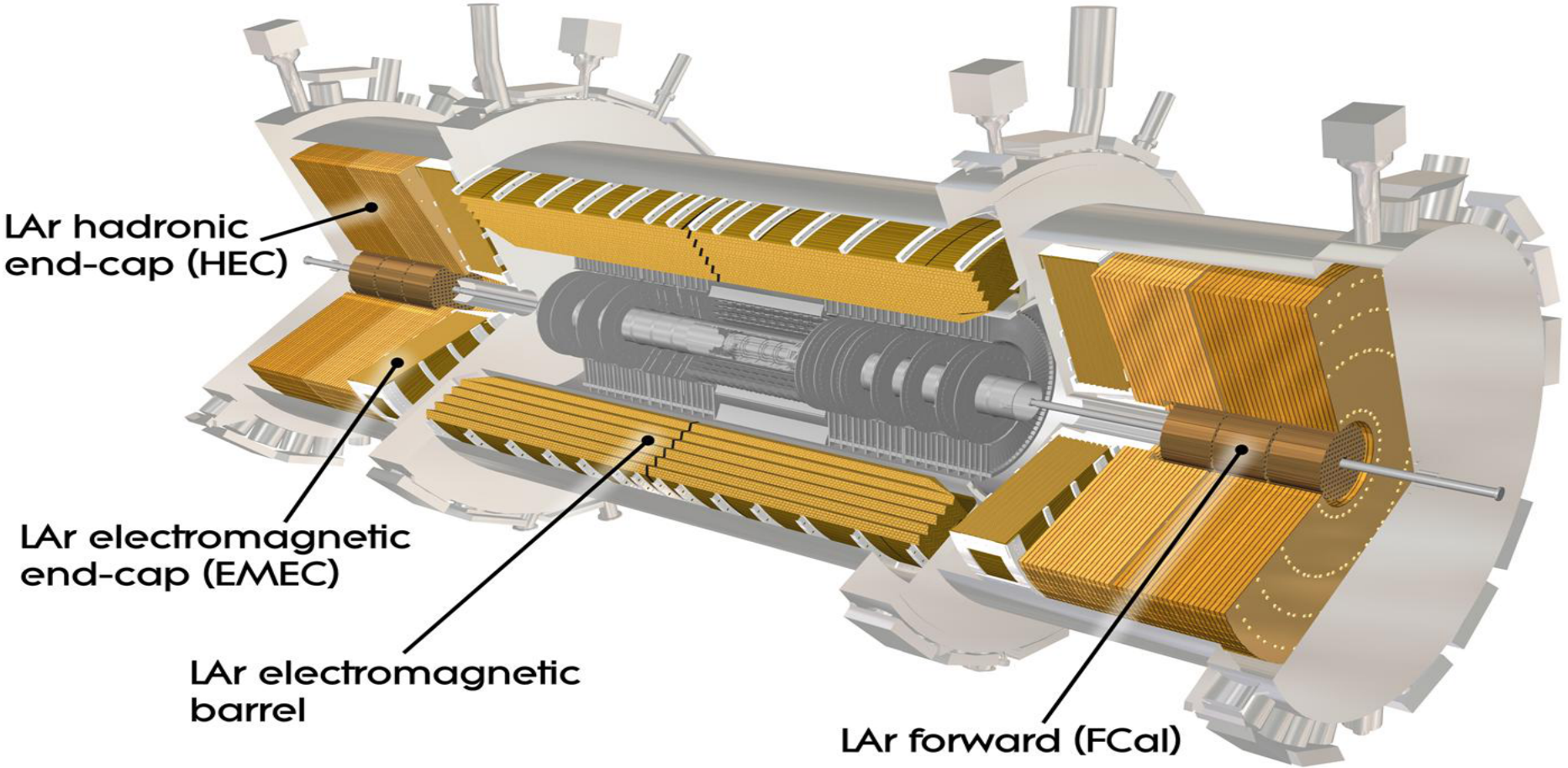
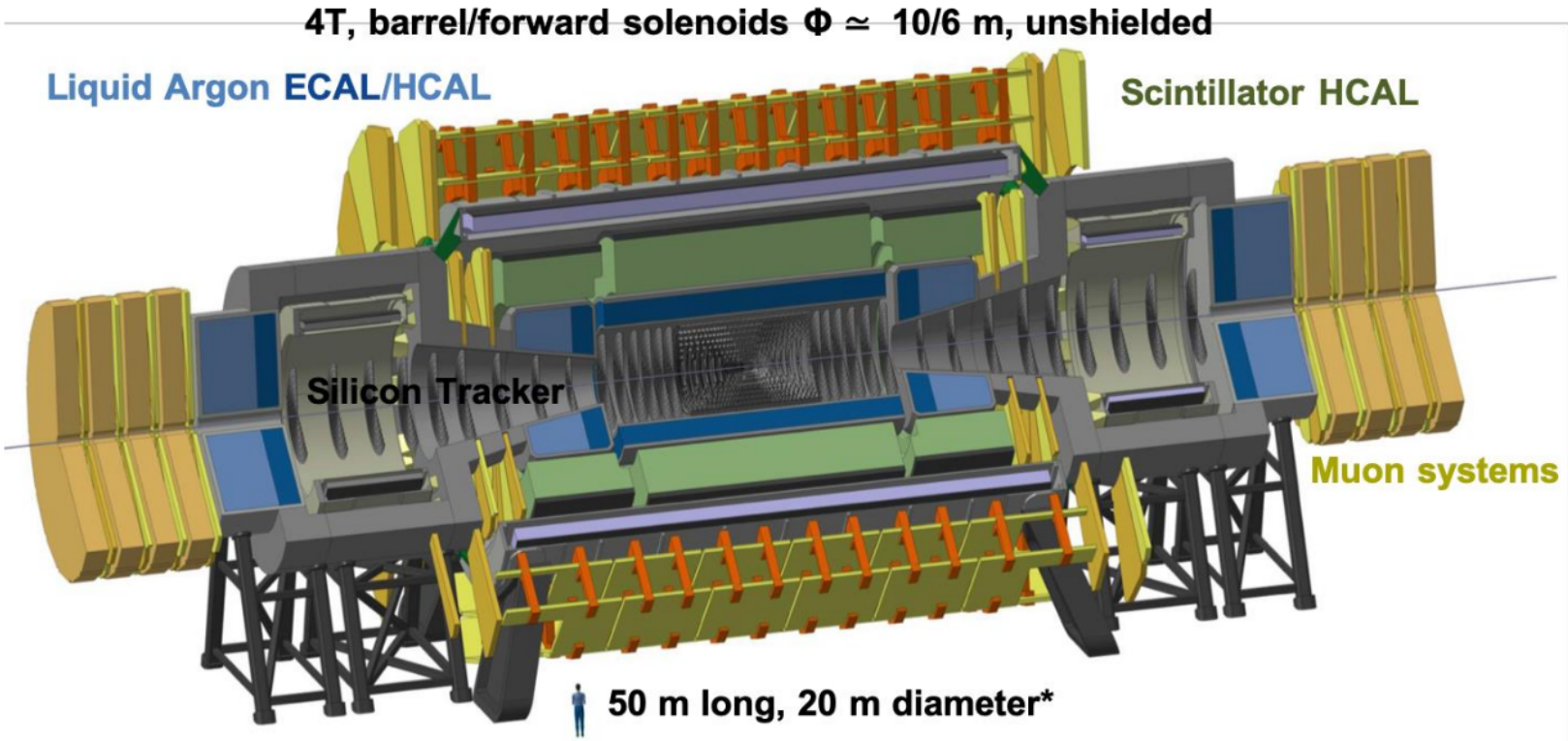


FIG. 44. (Color online) Schematic of a two-phase xenon TPC.

ATLAS liquid argon calorimeter (designed at the beginning of the 90's)



FCC-pp detectors (conceptual design report)



Xenon100

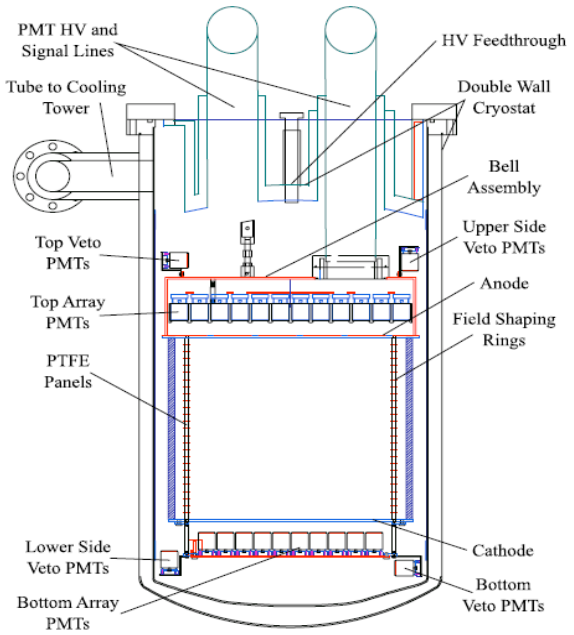


FIG. 56. (Color online) Schematic of the XENON100 detector (Aprile and Baudis, 2008).

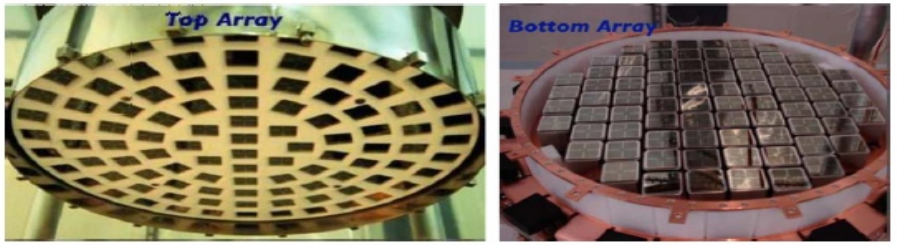


FIG. 57. (Color online) Photos of the top and bottom PMT arrays of the XENON100 detector.

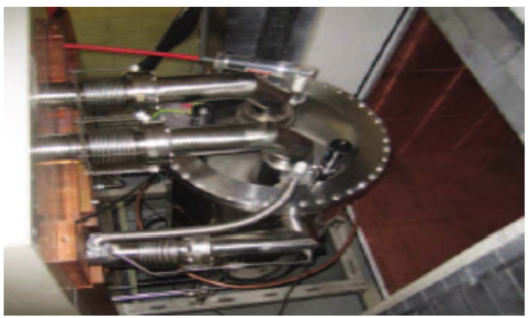
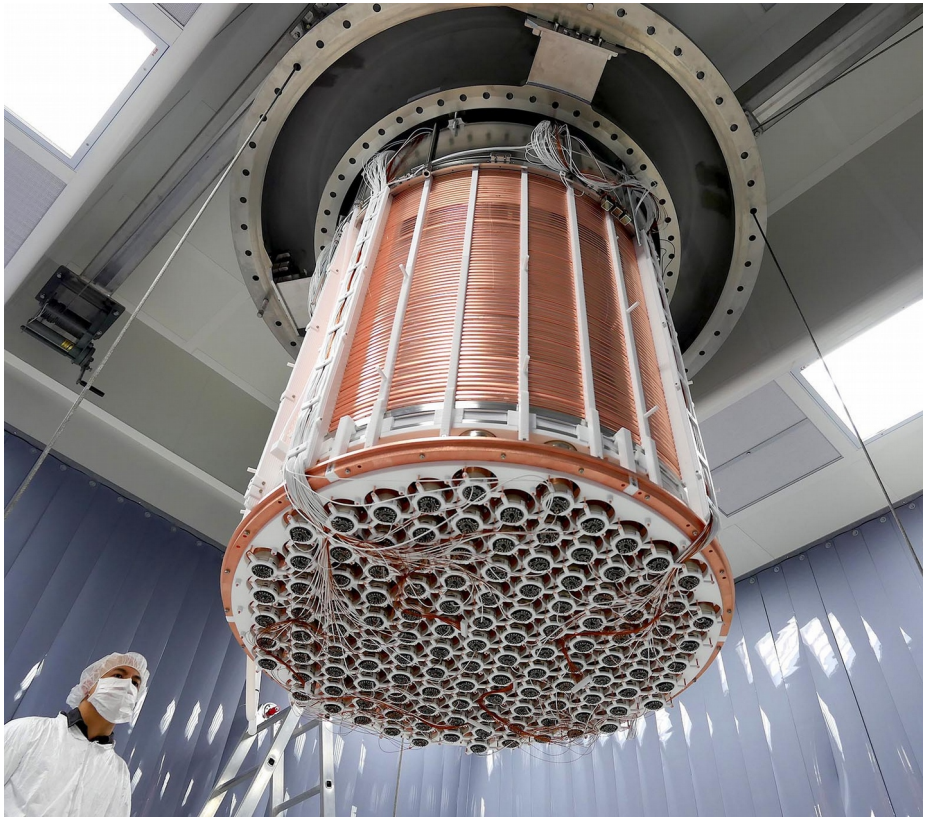


FIG. 58. (Color online) Photo of the XENON100 detector installed in its shield (Aprile, 2008).

https://doi.org/10.1016/j.astropartphys.2012.01.003

XenonIT



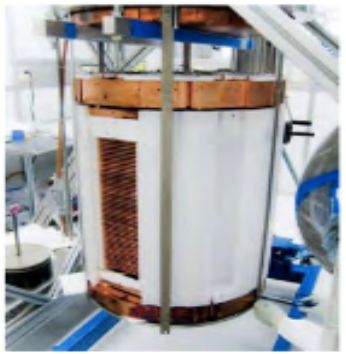
dual-phase noble liquid TPCs

LXe

XENON100

161 kg
≥34 kg

LUX



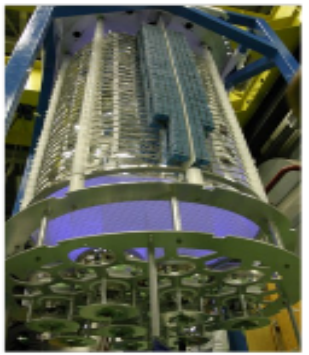
370 kg
≥118 kg

Panda-X

125 kg
≥25 kg

LAr

ArDM

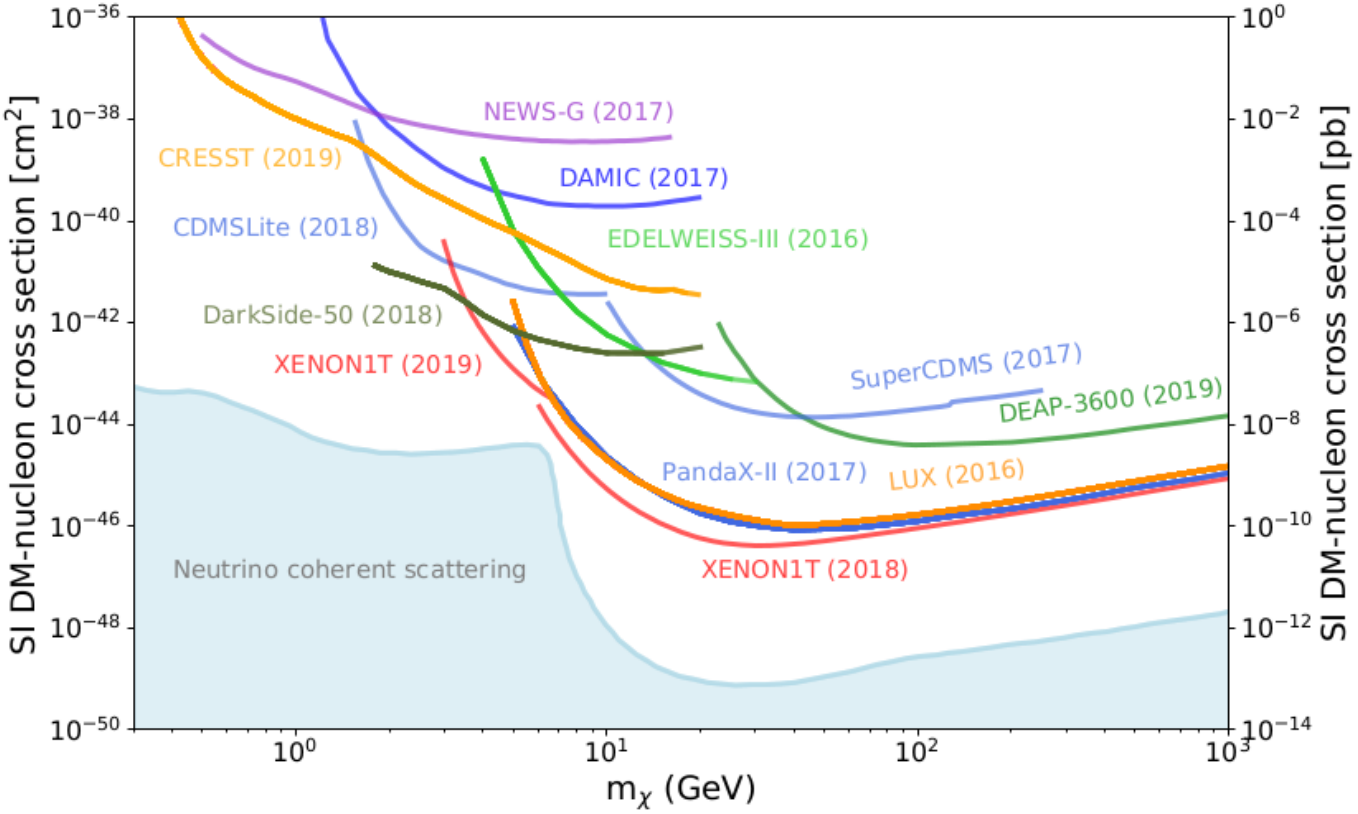


850 kg
~several
100 kg

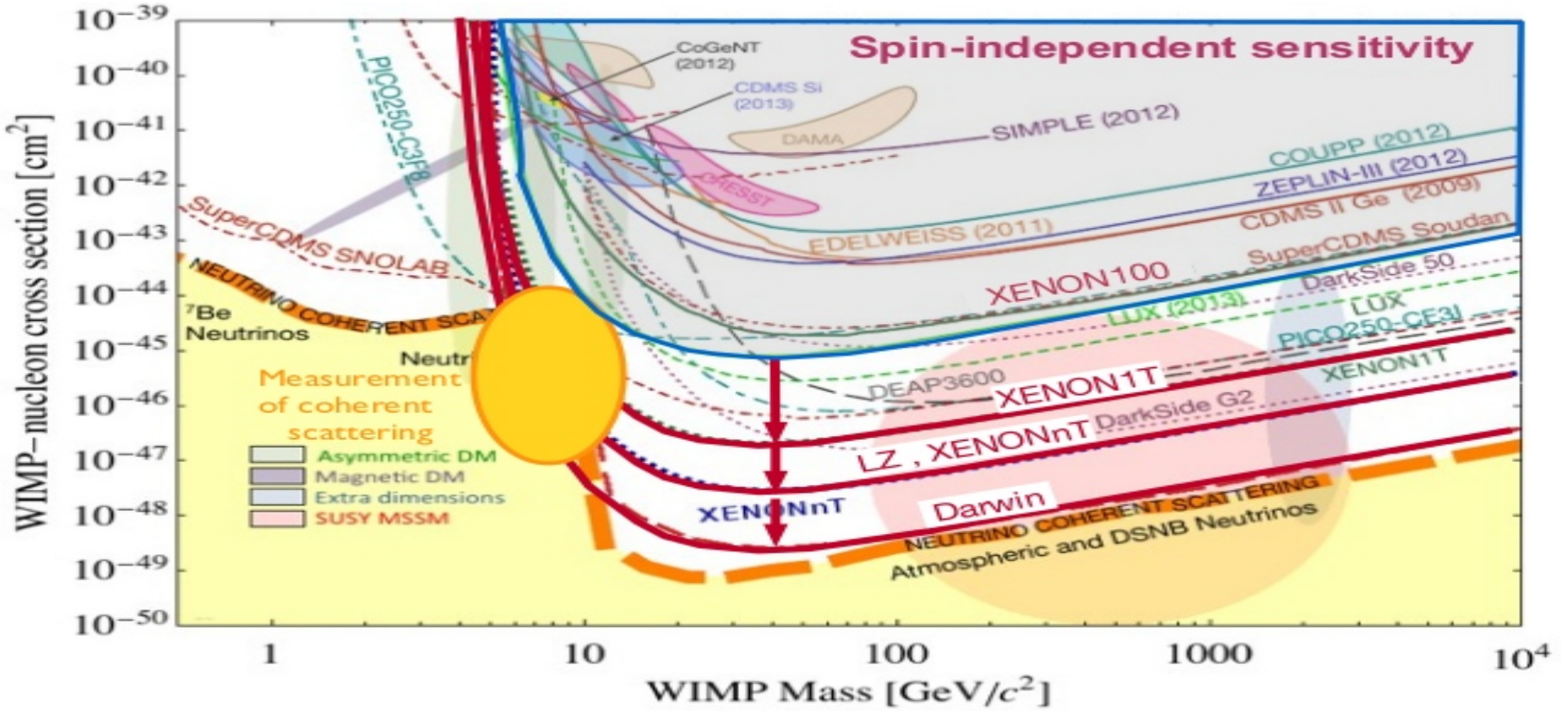
DarkSide-50

46 kg
≥37 kg

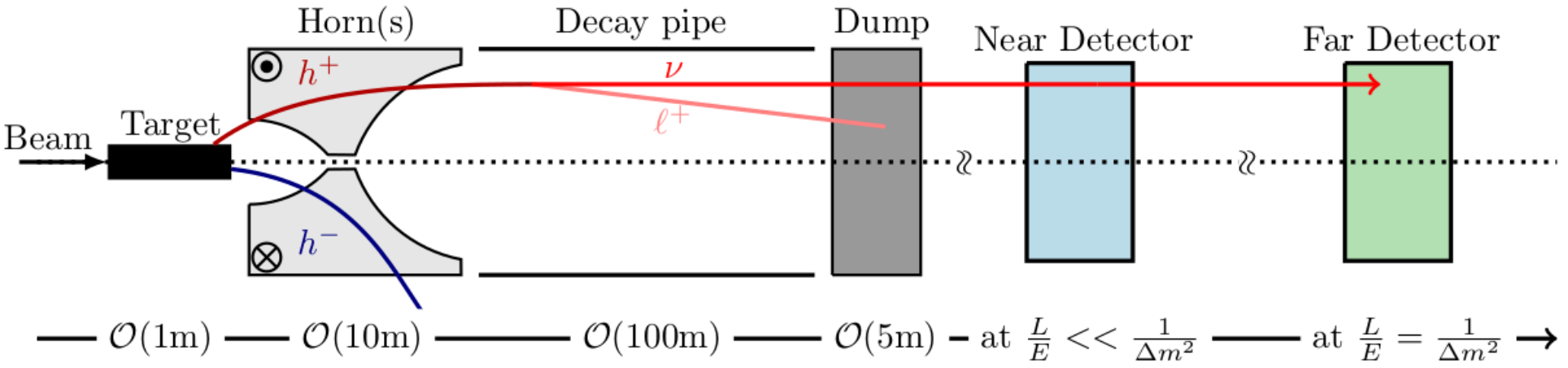
Current Status

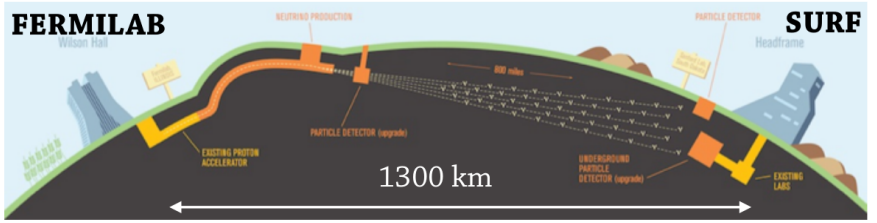


Current Status and future goals



DUNE : Deep Underground Neutrino Experiment

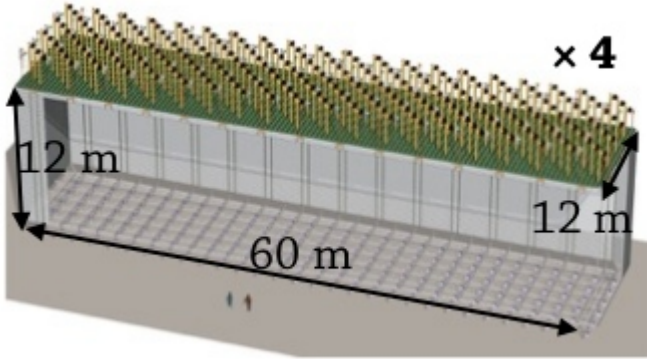




ν_μ and $\bar{\nu}_\mu$ beams

search for CP violation in neutrino oscillations

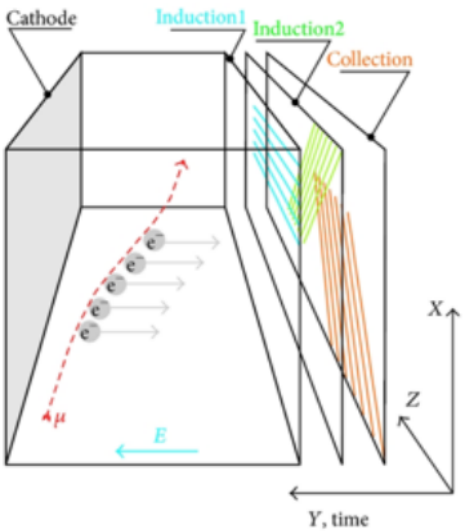
DUNE Far detector



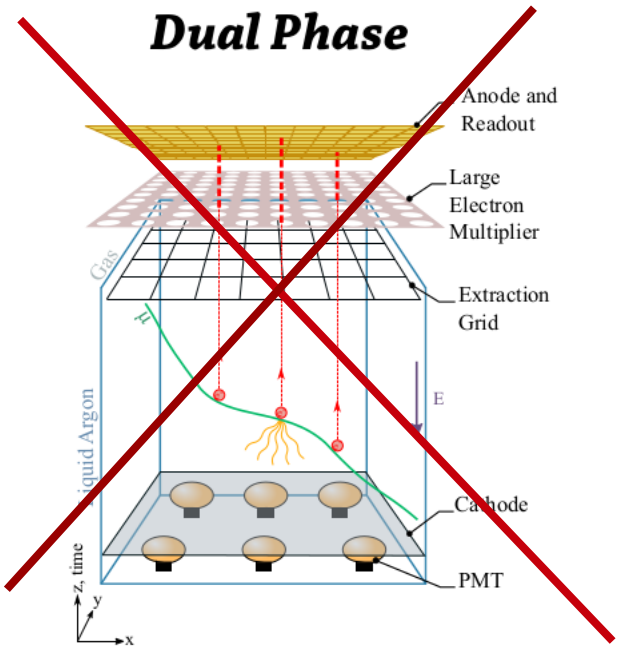
4 modules of 16 kt of LAr each.

First neutrinos in 2030

Single Phase



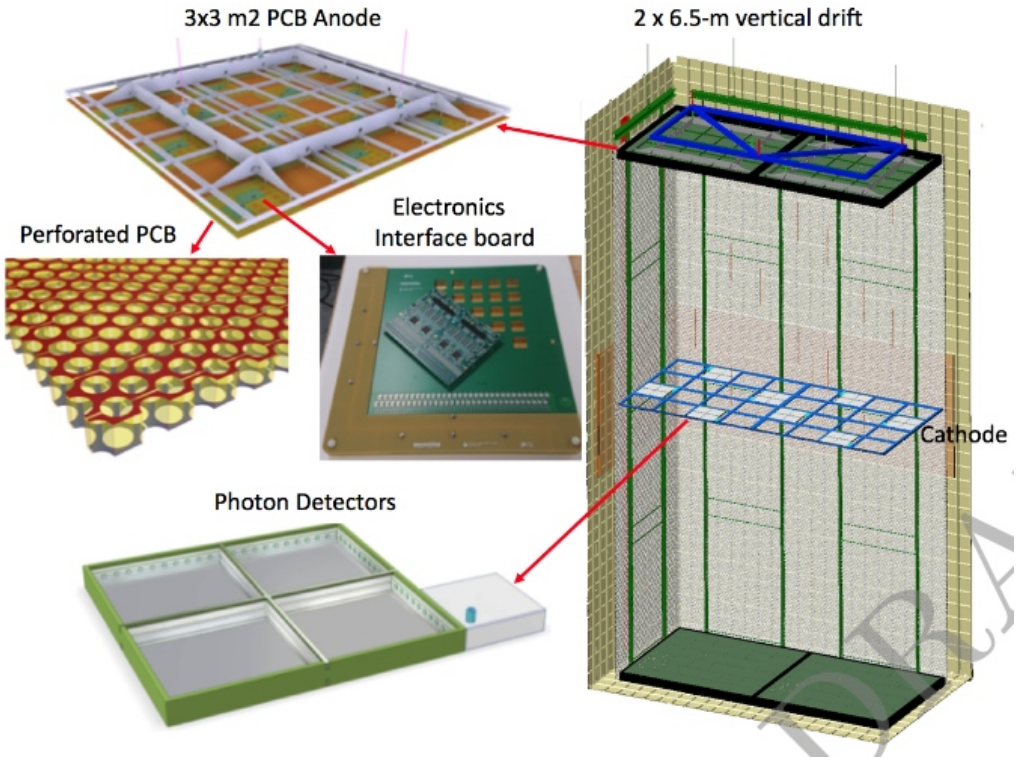
Dual Phase



DUNE Far detector

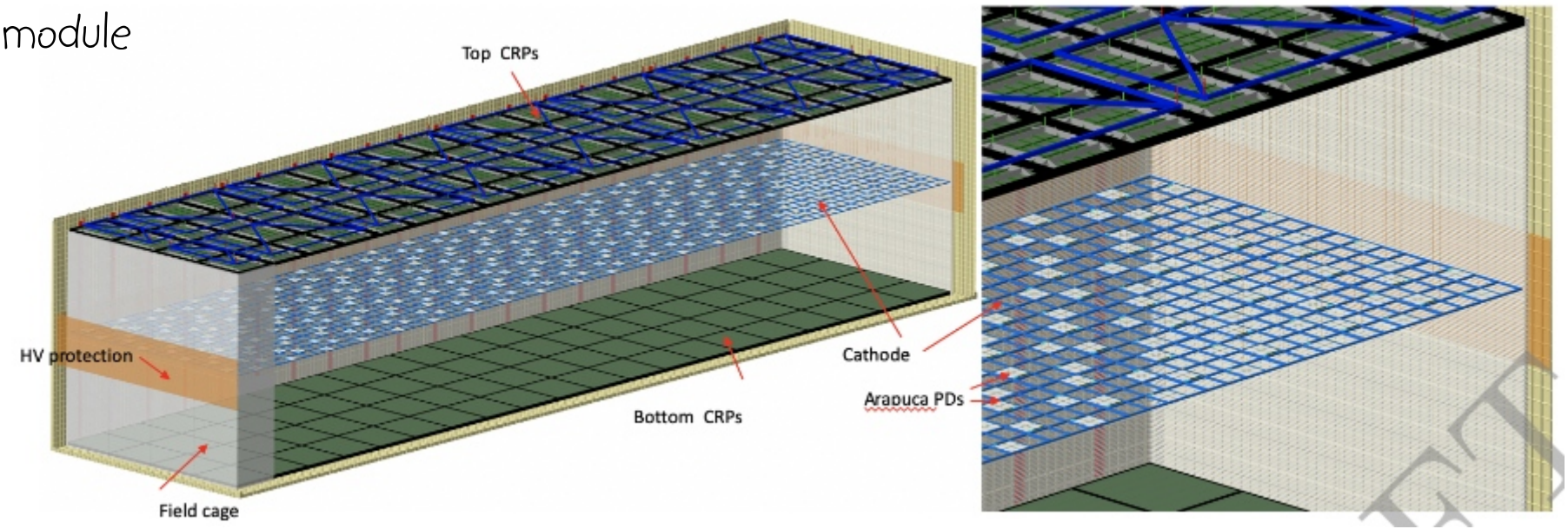
Merge of single phase and vertical drift :

Single phase vertical drift concept for second module

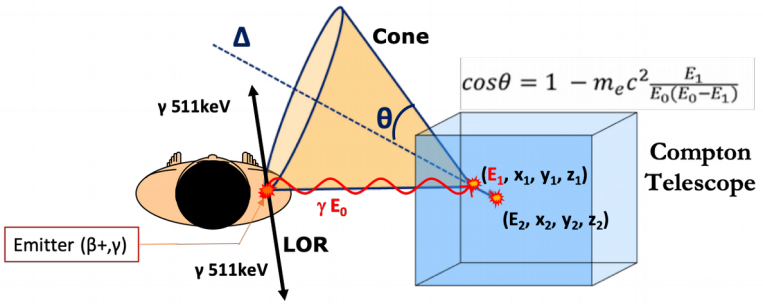


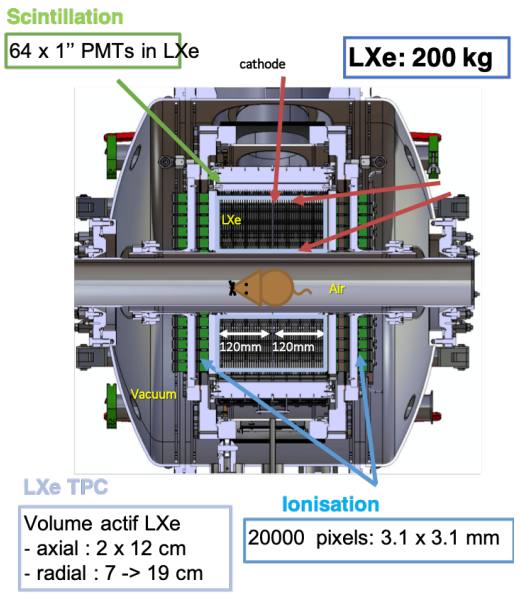
DUNE Far detector

Single phase vertical drift concept for second module



LXe detectors for medical imaging





XEMIS2 project in Nantes Subatech

https://hal.archives-ouvertes.fr/hal-02317373

To learn more :

- Noble gas detectors, E. Aprile, A.E. Bolotnikov, A.I, Bolozdynya, T. Doke

- Particle Detectors, Claus Grupen, Cambridge monographs on particle physics

-Particle Detectors : fundamental and applications, H. Kolanoski & N. Wermes, Oxford University Press

- Liquid xenon detectors for particle physics and astrophysics, E. Aprile and T. Doke, Rev. Mod. Phys., Vol 82, No 3, , 2010, 2053

- S. Amerio et al, Design, construction and tests of the ICARUS T600 detector, Nucl. Instrum. and Meth. in physics, A 527 (2004) 329

-DUNE conceptual design report : https://doi.org/10.2172/1250878

Short questions

- What are the benefits of using liquid argon as an active medium on a pp collider ?
- Why noble liquids are of interest in the search for dark matter particles ?
- Which noble liquid(s) could have an interest for medical imaging and why ?
- What are the noble gases that condense at a temperature above LN2 ?
- Which detection mode is used on a pp collider ?
- Explain briefly how a dual-phase noble liquid TPC works ?
- Do we collect ionized charges in noble liquid at zero electric field ?
- Do we collect scintillation light at zero electric field ?
- Compute the initial current induced by a MIP traversing a LAr ionization chamber of a 2 mm gap electrically biased at 10 KV/cm
- What is the scintillation mean wavelength of LXe.
- How many scintillation photons are produced in LXe by a 511 keV gamma undergoing photoelectric effect ?
- Compute the max drift time of free electrons in DUNE , knowing that the anode-to-cathode distance will be 6.5 m and that the electric field is 500 V/cm.
- What is a $\beta^+\gamma$ emitter ? and what benefit may it bring to medical imaging ?
- Is purification of the liquid argon needed for DUNE ? to which level ?
- What are the chemical species that emit UV light in noble liquids ?