Liquid Noble Gas Dual Phase Detectors for Dark Matter Direct Searches

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UCLA / Princeton / CERN

Outline of the Presentation

- Brief Historic R&D Review
- The ZEPLIN II Detector
- TPC Design Field Related
- TPC High Voltage Related
- Cryogenics and Purification Related
- Current Work – DarkSide-20k

Working history since 1982 after B.S

H.I.T. Harbin Institute of Technology, P. R China 1982 after B.S. at H.I.T

OPAL on LEP at CERN 1986-1988 (UC Riverside, Prof. B. Shen)

ICARUS at CERN & LNGS 1989- (Frascati, Prof. Pio Picchi, C. Rubbia)

Thanks to Prof. Sau Lan Wu of Wisconsin whom introduced me to Prof. Picchi

UCLA, 1992-present, Ph.D 1998, Postdoc, Researcher, Adjunct, (David B Cline)

ZEPLIN (II) 1997 – 2011 (UKDMC, PF Smith, N. Spooner, N Smith, T Sumner)

Initially with DOE fund for construction, then in 2002, NSF support for operation

LUX, 2006 – 2008 (with R Gaitskell, T Shutt, JT White…)

XENON100, XENON1T, XENONnT, 2008 – 2019 (E Aprile,…)

SIGN, (with James White, NEXT TPC, JJ Gomez-Cadenas, D Nygren)

DarkSide, 2008 – Present (with Prof. C Galbiati, Prof. G Fiorillo, …)

MAX- Multi-ton Argon and Xenon TPCs 2009-2013 (Prof. C Galbiati,…)

Darwin 2009 – 2019 (with Prof. L Baudies,…)

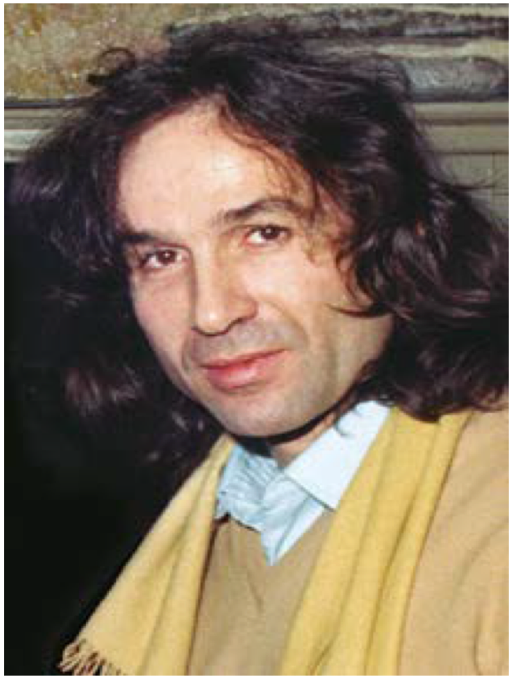
And some small R&D projects: SCENE, ARIS, ReD, SiGHT…

CAPTAIN (HV voltage and Cryogenic)

LBNE, Modular TPC design for LBNE, 35 ton HV system,

DUNE, protoDune, HV system (FF Pietropaol, Bo Yu)

Pio Picchi
1942–2019



LAr TPC (ICARUS3t)
2-phase TPC (Xe and LAr)

David B Cline
1933 – 2015

Ph.D 1965 Wisconsin,
1967 Faculty Wisconsin
1986 – 2015 UCLA

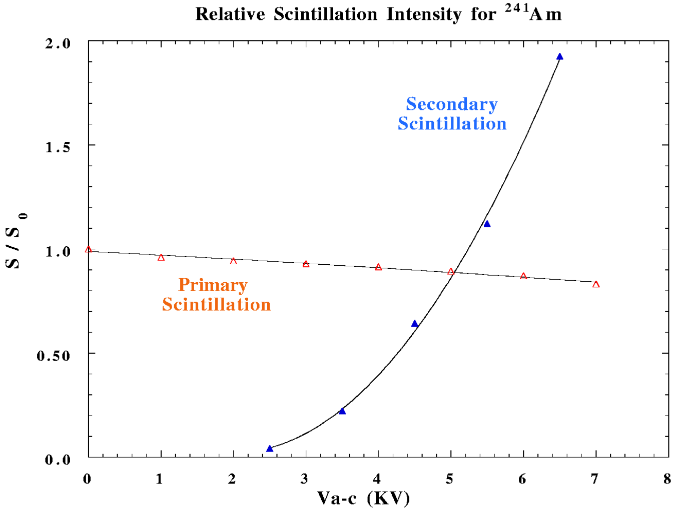
James T. White
1953 – 2013

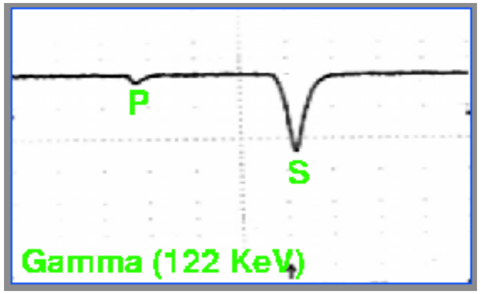
ZEPLIN II, LUX,
SIGN, NEXT
TAMU

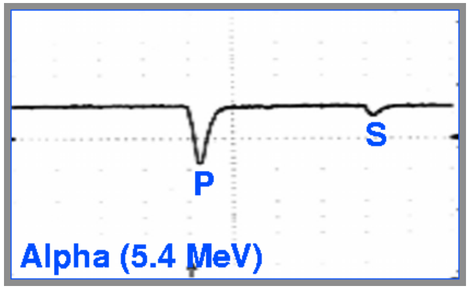
Pio Picchi first asked to measure e-recoil and nuclear recoil in LXe

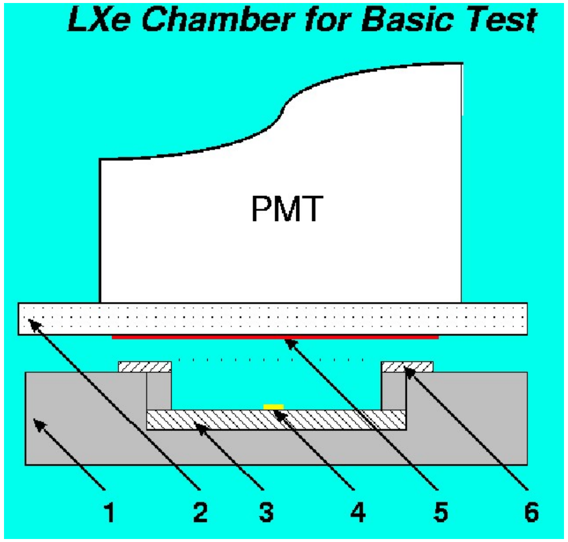
NIM A327 (1993) 203

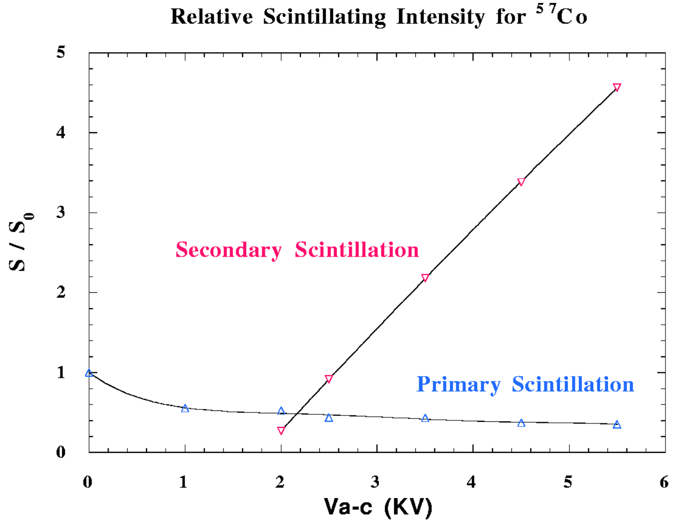
P. Picchi, F.F. Pietropaolo, S. Suzuki, H. Wang

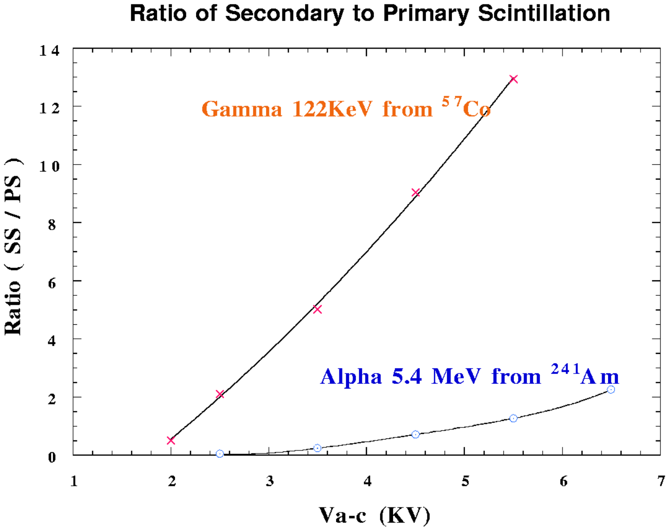

Relative Scintillation Intensity for ^{241}Am








Relative Scintillating Intensity for ^{57}Co


Ratio of Secondary to Primary Scintillation

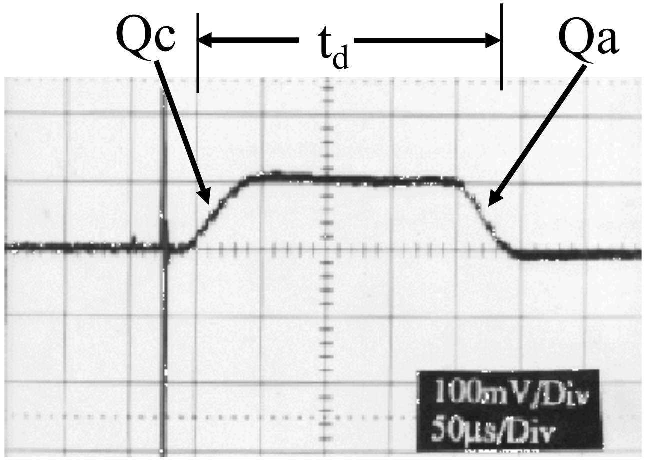
1. Ceramic.
2. Quartz Window,
3. Stainless Steel Cathode.
4. Source.
5. Grounded Grid.
6. Anode 3μ wire frame

proportional
Single phase TPC

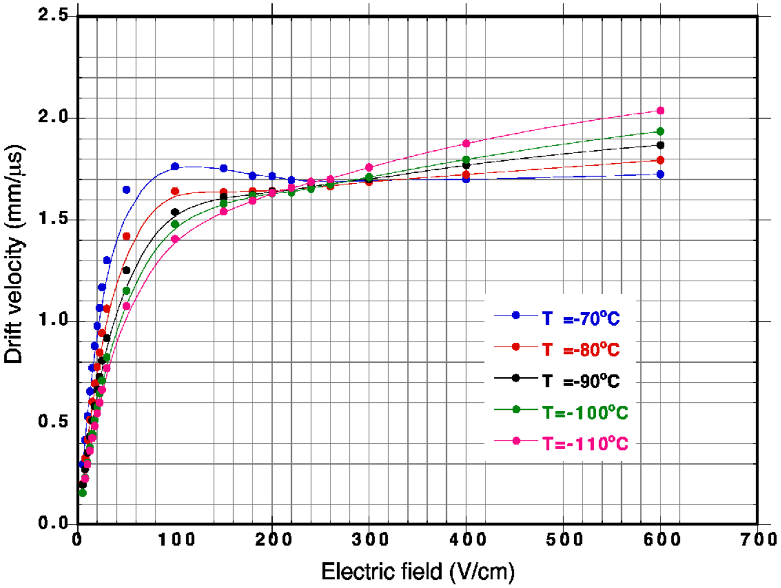
S2/S1

Electron lifetime and drift velocity in LXe: **the Purity Monitor**

Electron drift velocity were measured at all interested drift-field and temperature



Under 10V/cm drift field e-life-time > 5ms



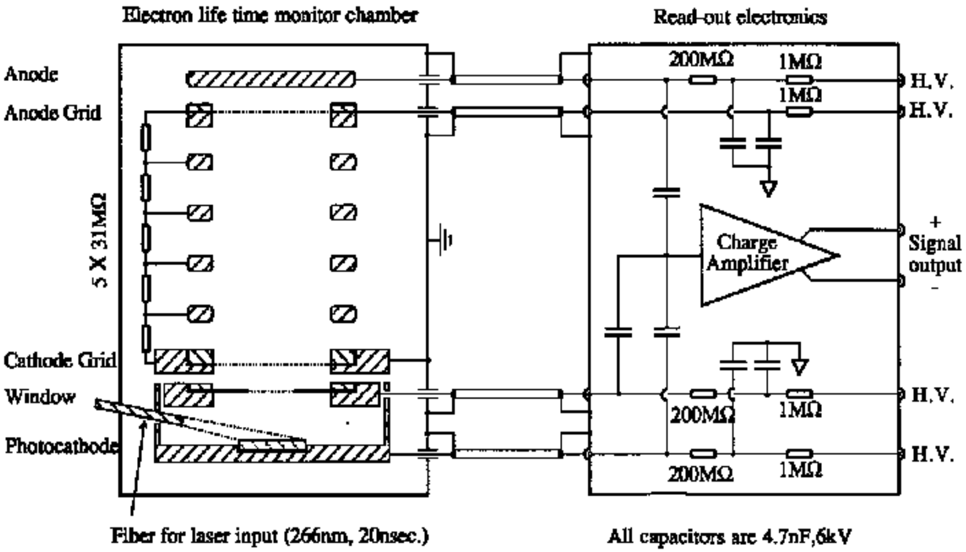
Nucl. Instrum. Meth. A 329 361 (1993).

Life time measurement:

Measure both injected charge Q_c and collected charge Q_a after drift

$$Q_a = Q_c \bullet e^{-t_d/\tau} \qquad \tau = \frac{t_d}{\ln\left(\frac{Q_c}{Q_a}\right)}$$

Lifetime measurement setup
And readout electronics



Old Slide

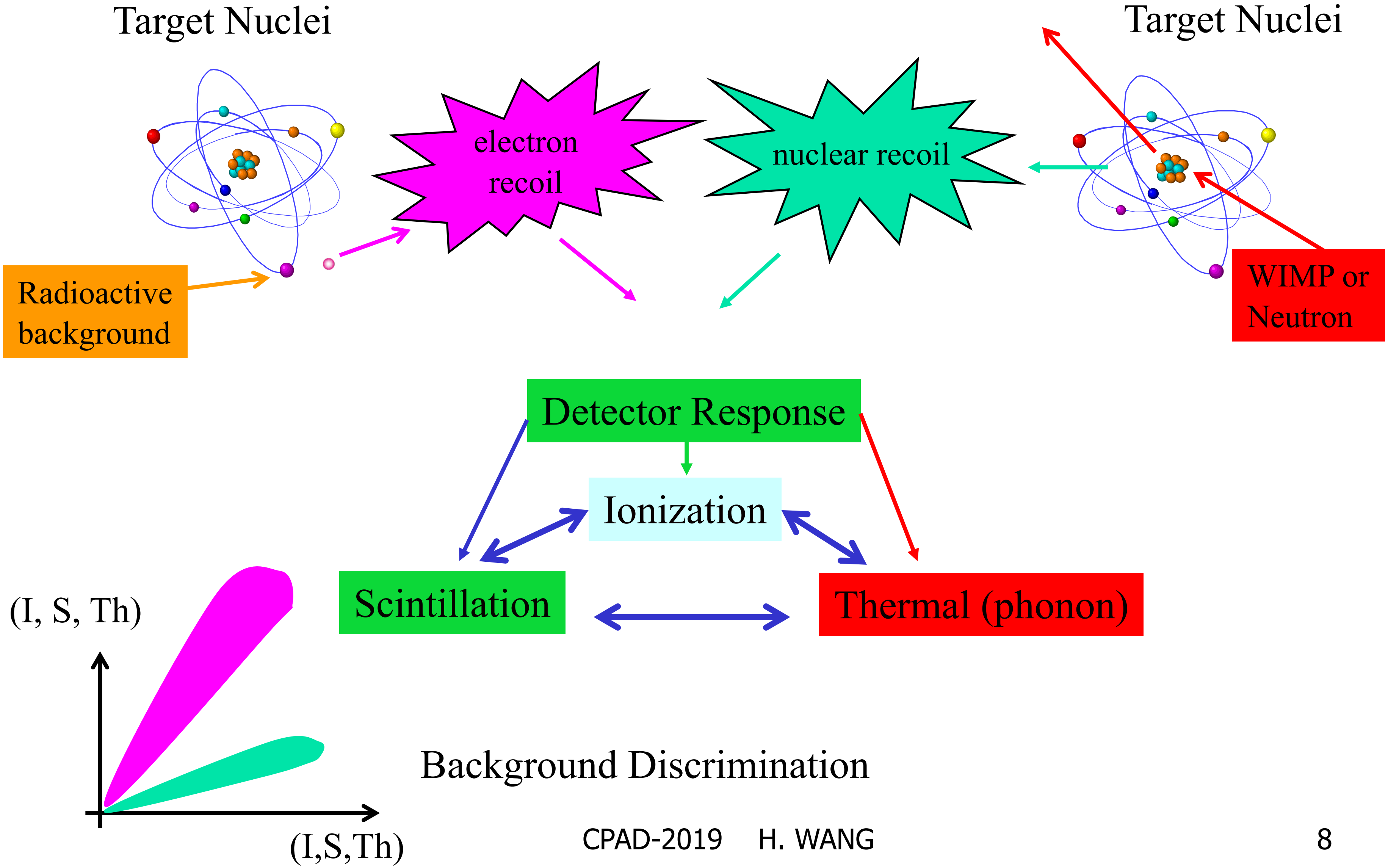
Why Xenon

- Available in Large Quantities
- Large abundance for both $s_{½}$ (^{129}Xe~26%) and s_0 (^{132}Xe~27%)
- High Atomic Number ($Z_{Xe}=54$, $\sigma_{WIMP\text{-}Nucleon} \propto A^2$)
- High Density (~ 3g/cm^3 liquid) (compact detector design)
- High Scintillation Light (175nm) & Ionization Yield
- Scintillation decay profile difference (S, I) (PSD)
- Large quenching factor (observed energy/e.e.Energy)
- Can be Highly Purified
  - long light attenuation length (~m)
  - long free electron life time (~5ms)
- Gamma & Recoil signal Discrimination
- Capable of Scale up to Large Volume (ton)
- No Long Lived Radioactive Isotopes (low background)

Today we know argon from underground sources has low or none ^{39}Ar
Princeton discovery => **DarkSide**

Old Slide

Detector response to WIMPs and Background



Target Nuclei

Target Nuclei

electron recoil

nuclear recoil

Radioactive background

WIMP or Neutron

Detector Response

Ionization

Scintillation

Thermal (phonon)

(I, S, Th)

(I,S,Th)

Background Discrimination

Old Slide

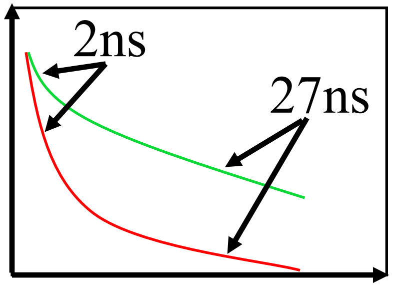
Liquid Xenon Scintillation Mechanism

(A) Pulse Shape discrimination: due to decay profile difference between nuclear recoil & electron recoil

(B) When E_{drift} applied, and measure E_i & E_s, Very good background rejection due to $(E_i/E_s)_{M.I.P.} >> (E_i/E_s)_{H.I.P.}$

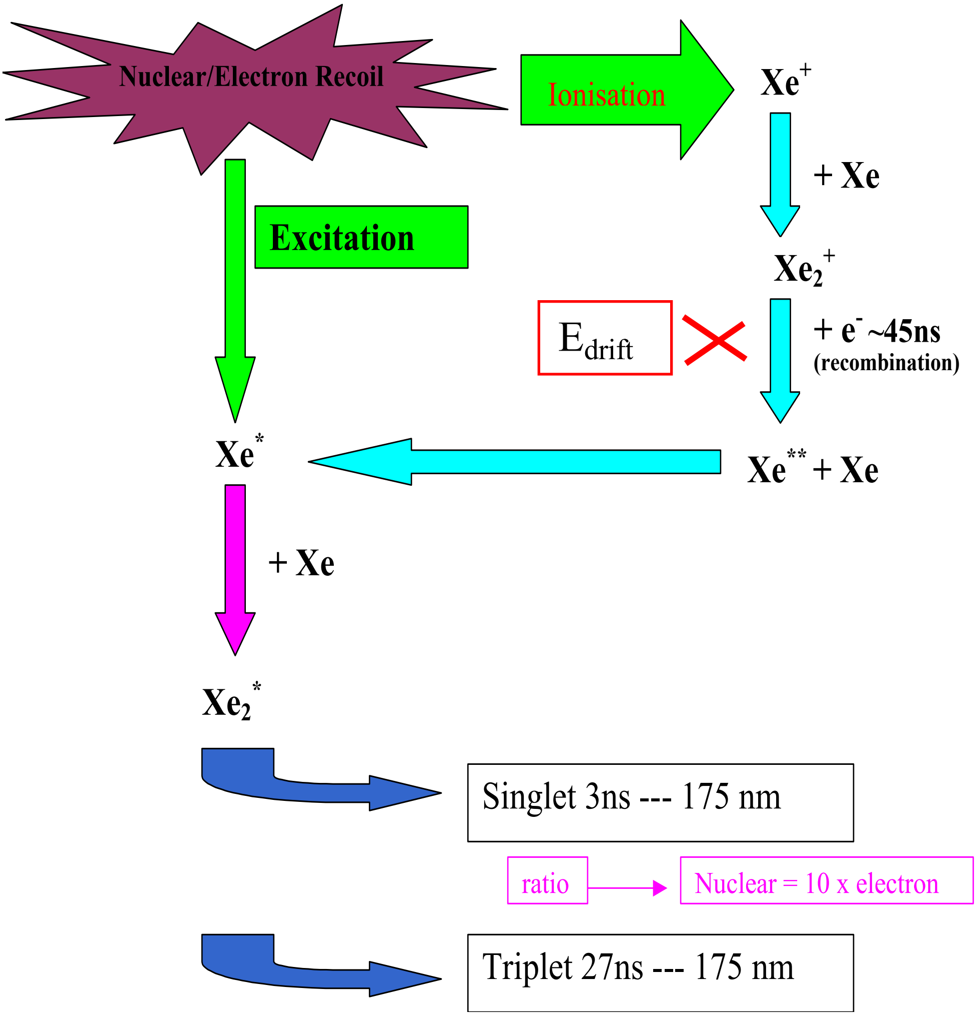
ZEPLIN I (A)

ZEPLIN II (A&B)



Nuclear recoil

Electron recoil



Nuclear/Electron Recoil

Ionisation

Xe^+

+ Xe

Xe_2^+

E_{drift}

+ e^- ~45ns
(recombination)

Excitation

Xe^*

Xe^{**} + Xe

+ Xe

Xe_2^*

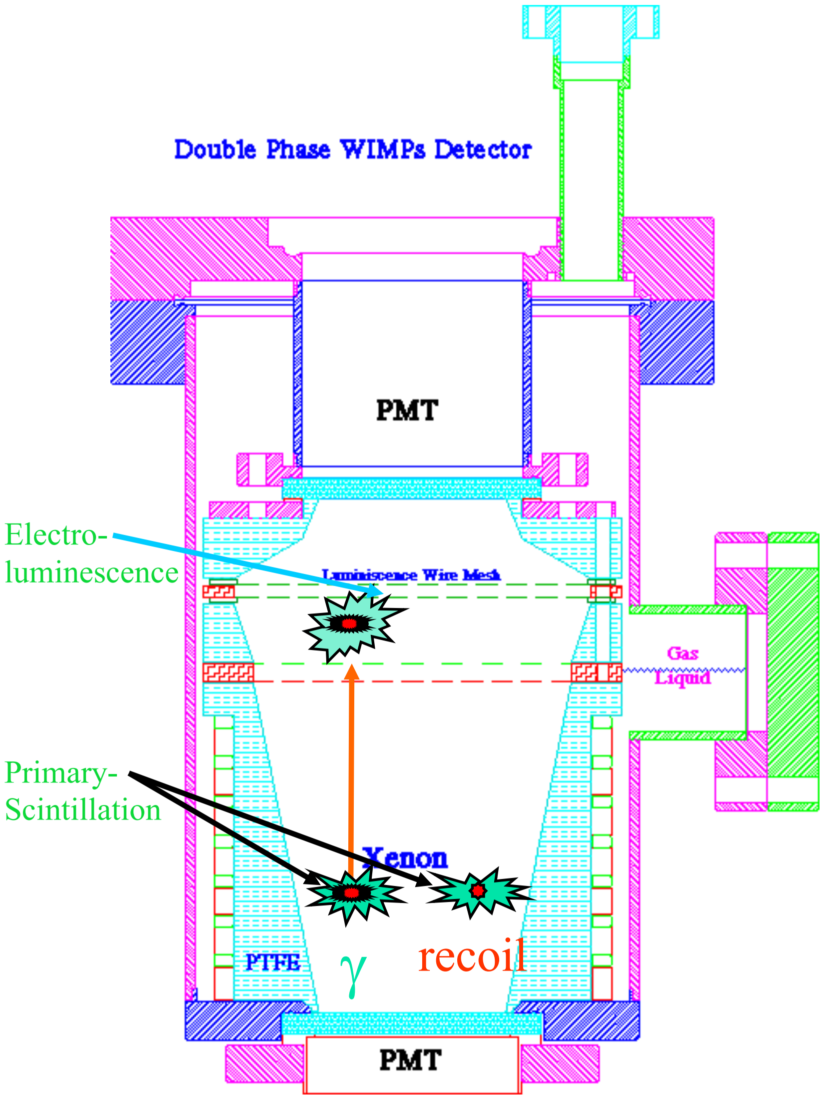
Singlet 3ns --- 175 nm

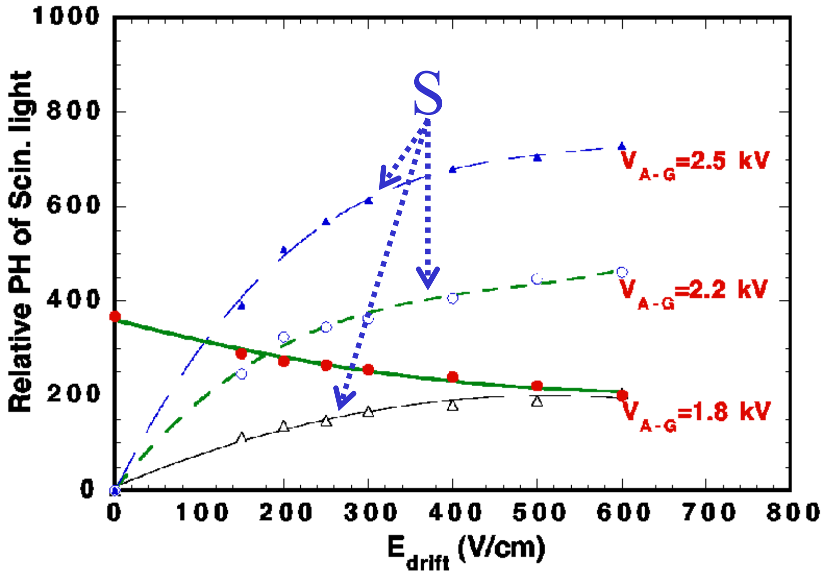
ratio → Nuclear = 10 x electron

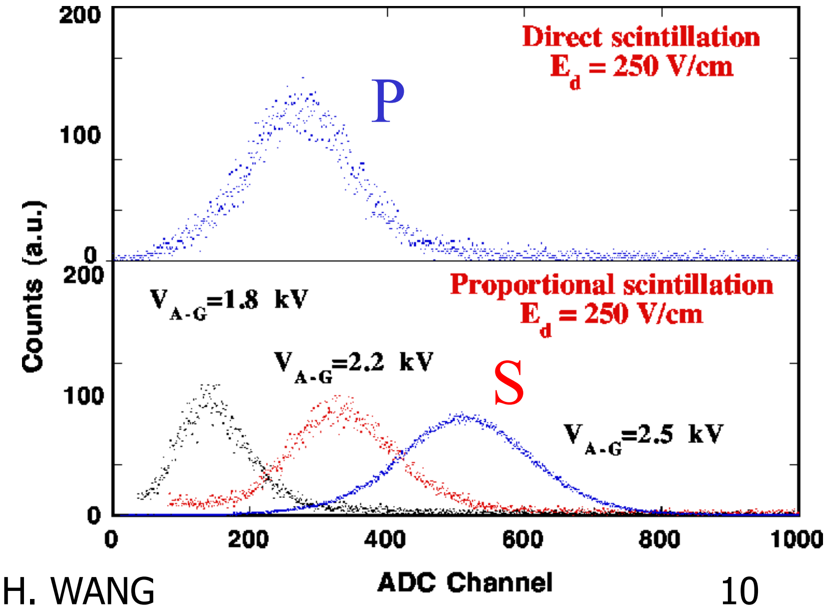
Triplet 27ns --- 175 nm

Xenon Two-Phase Prototype Detector

2-phase first proposed by: B. A. Dolgoshein, et al., Sov. Phys. JETP Lett. 11 351 (1970)







The ZEPLIN II Collaboration

Zoned Electro-luminescence and Primary Light In Noble-gases

PF Smith

DB Cline, M Atac, Y Seo, F Sergiampietri(a), H Wang
Physics and Astronomy, UCLA , (a) Pisa

JT White, J Gao
Department of Physics, Texas A&M University

Collaboration members as of 2002

P Picchi, L Periale, G Mannocchi, F Pietropaolo
ICGF-CNR-Torino/INFN-Padova

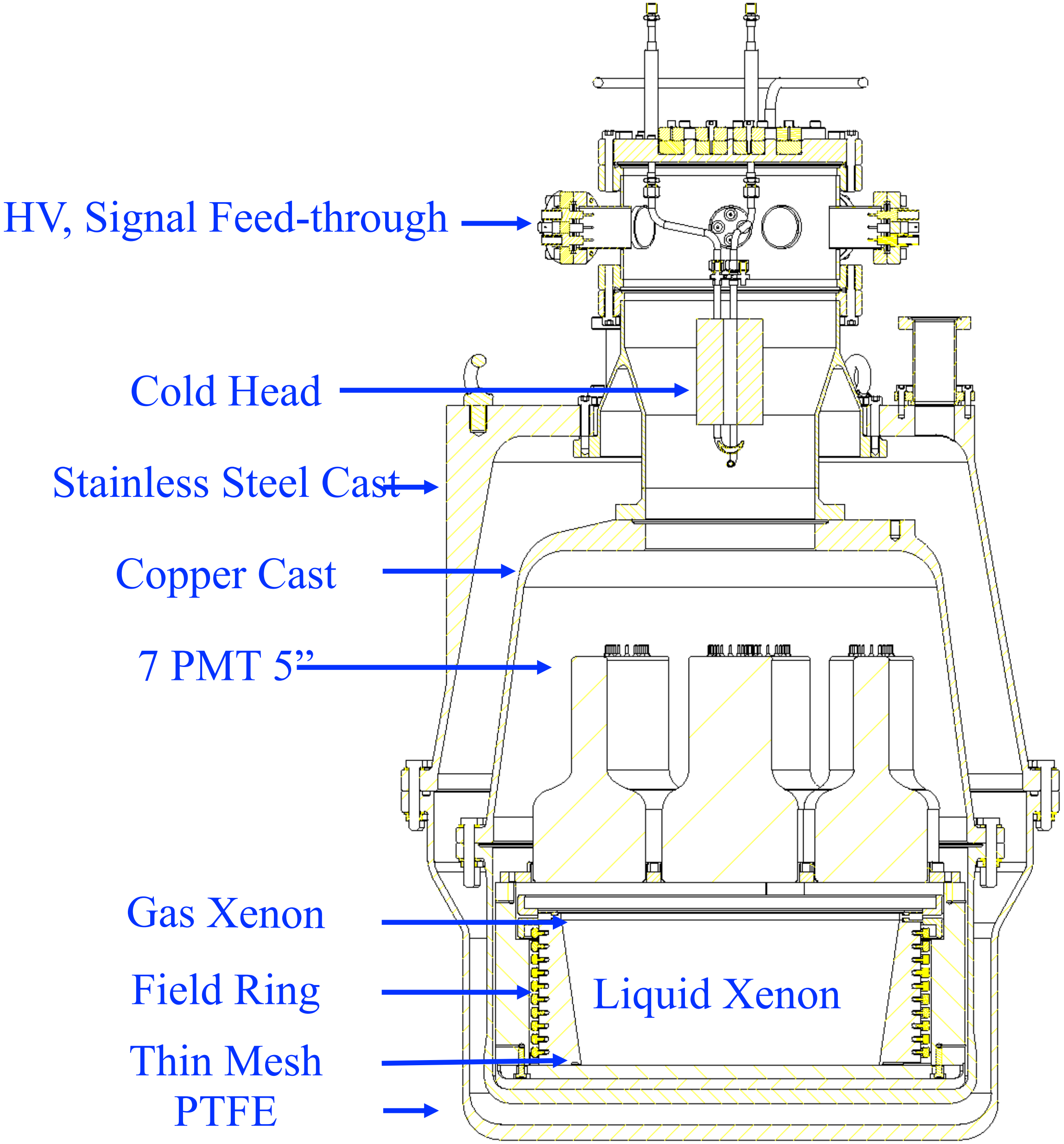
GJ Alner, SP Hart, JD Lewin, RM Preece, JW Roberts, NJT Smith, PF Smith
Particle Physics Department, Rutherford Appleton Laboratory, Chilton, Oxon

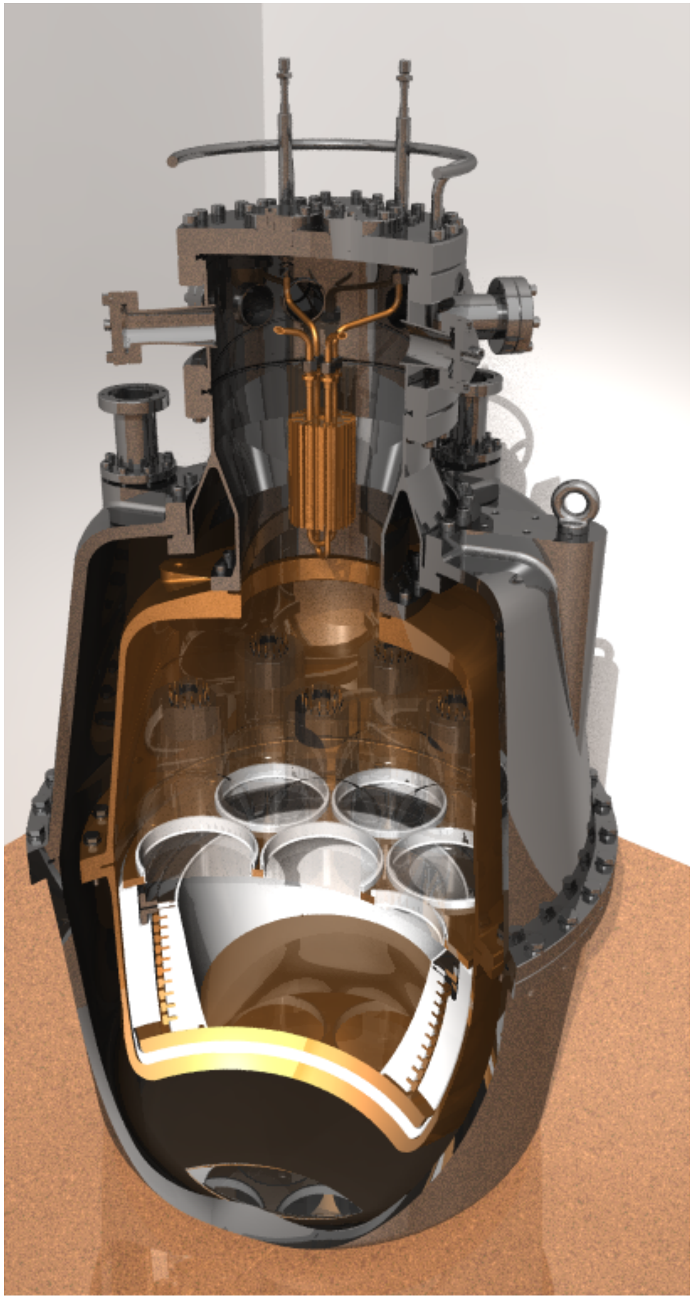
B Ahmed, A Bewick, D Davidge, JV Dawson, AS Howard, I Ivaniouchenkov, WG Jones, MK Joshi, V Lebedenko, I Liubarsky, R Lüscher, T J Sumner, J J Quenby
Blackett Laboratory, Imperial College of Science, Technology and Medicine, London

MJ Carson, T Gamble, VA Kudryavtsev, TB Lawson, MJ Lehner, PK Lightfoot, JE McMillan, B Morgan, SM Pealing, M Robinson, NJC Spooner, DR Tovey
Department of Physics and Astronomy, University of Sheffield

ZEPLIN II

Astropart. Phys. 28 287 (2007)

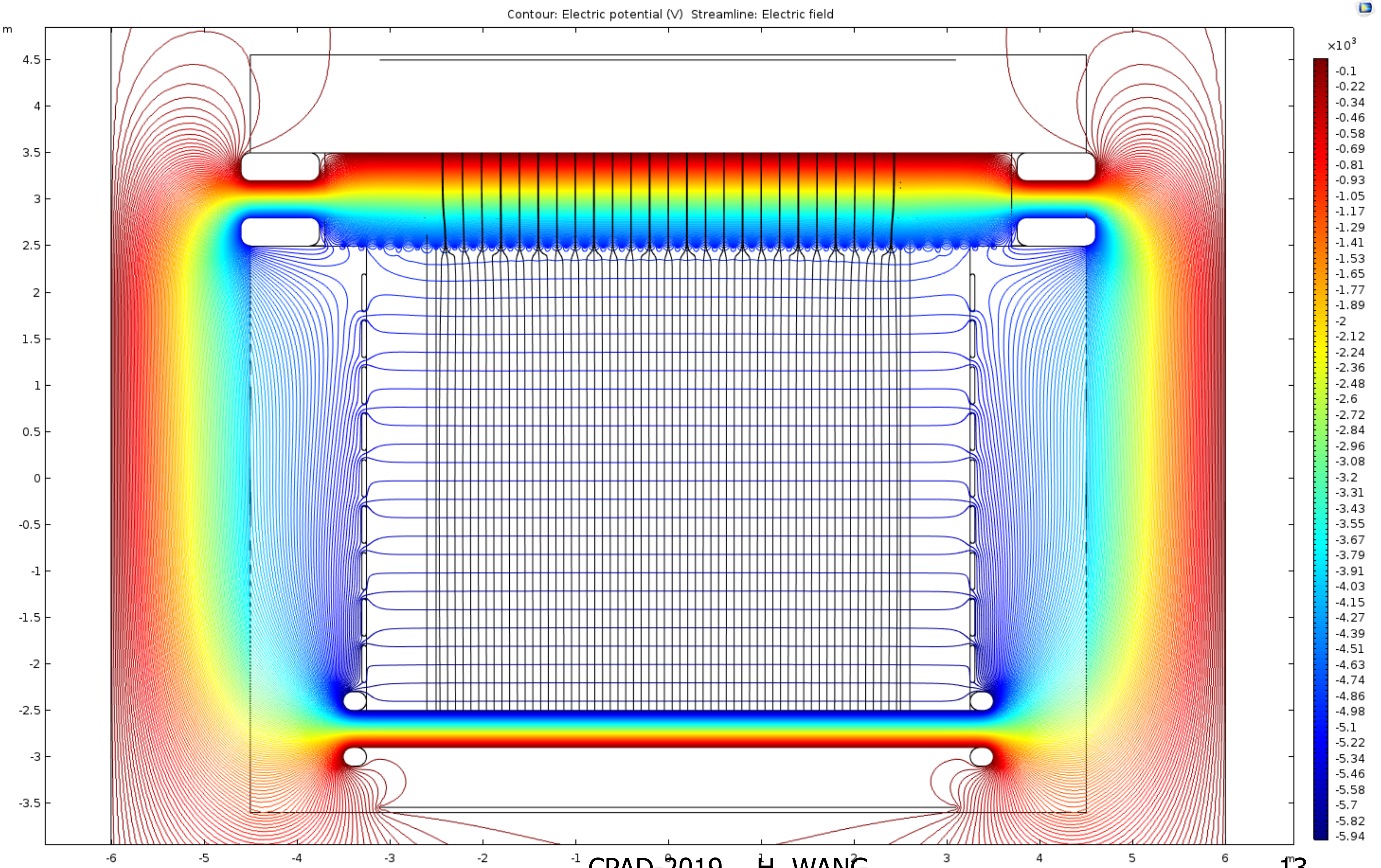




Rendered by Roy Preece (RAL)

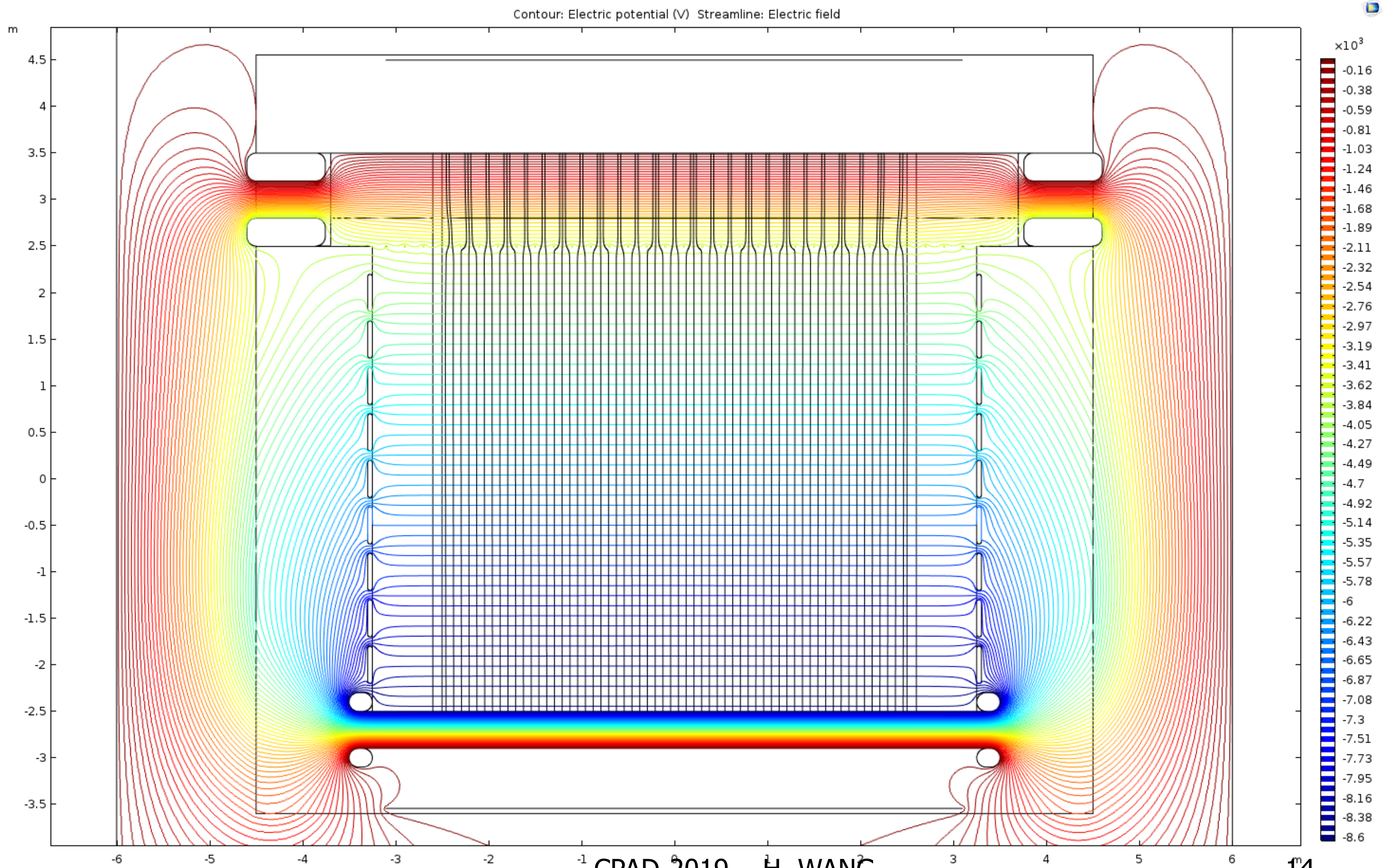
E_{drift}=200 V/cm E_{el}=5.79 kV/cm

V_{anode}=5211 V $V_{first\ ring}$=156 V $V_{cathode}$=-744 V



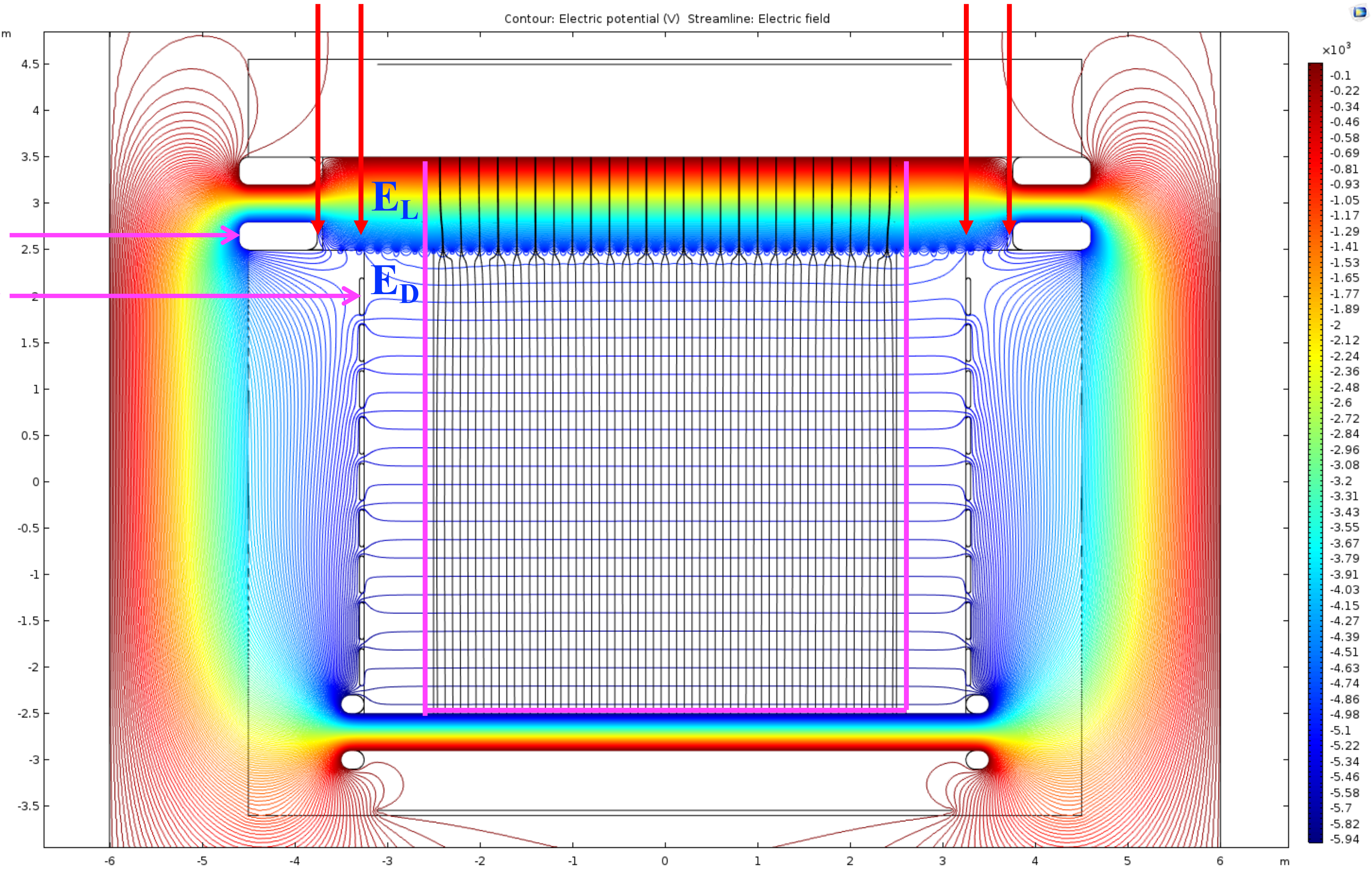
E_{drift}=1000 V/cm E_{el}=4.2 kV/cm

V_{anode}=3780 V $V_{first\ ring}$=-370 V $V_{cathode}$=-4870 V



TPC Field Uniformity: Electron Transparency through grid requires increased E-field after grid. This leads to effective potential on grid different than the set potential value

1. Boundary shape should be optimized (both anode/Cathode),
2. Applied potential compensated



grid

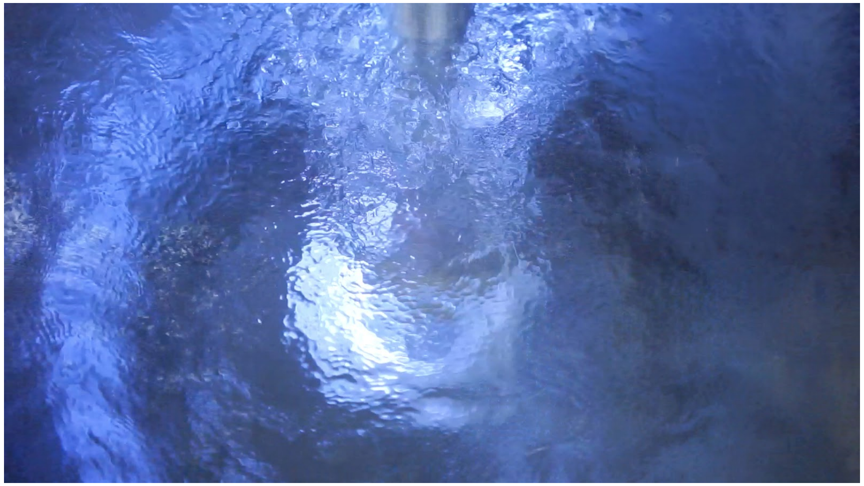
1st ring

E_L

E_D

DUNE prototype HV FT

Sparking in argon

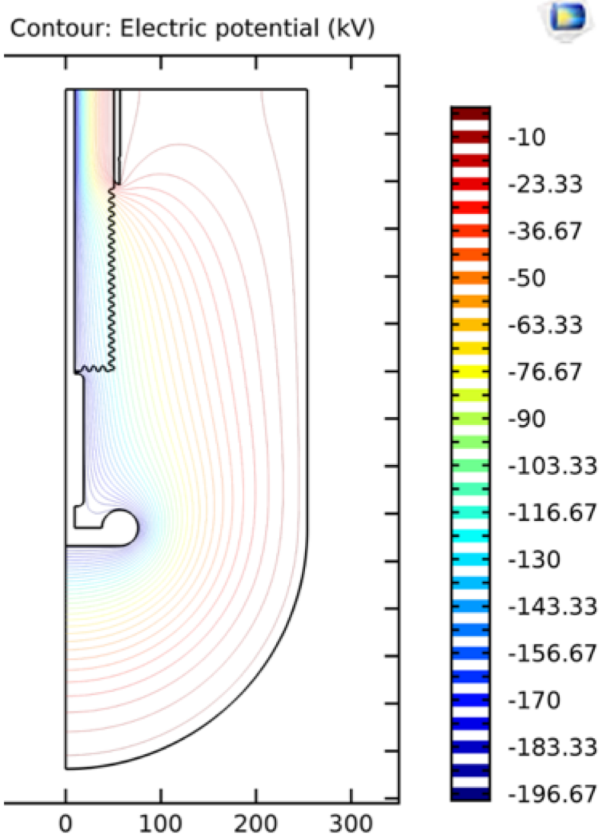


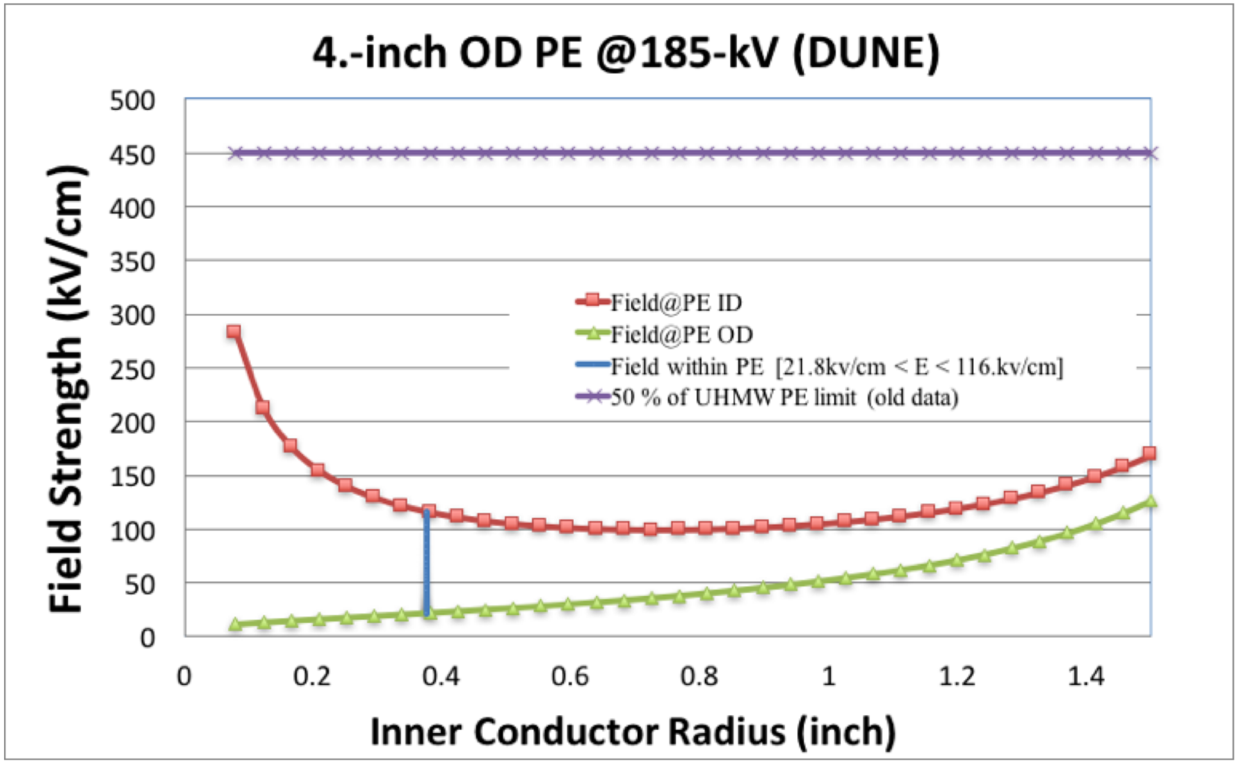
All FTs have one thing in common that the location of the strongest field strength it introduces in any detector is near the end of the ground ring. If this field strength is higher than that of the breakdown voltage of gas argon/xenon at liquid argon/xenon temperature, then eventually breakdown happens when a bubble is created locally associated with charge.

To overcome this, the simplest way is to build the HV FT such that the strongest field outside the FT exposed to liquid argon/xenon is less than the breakdown field of the cold argon/xenon gas. To do so with the conventional design, one has to increase the outer diameter of the feedthrough to take advantage of the $E \propto 1/r$ relationship, then the breakdown **WILL NOT** happen.

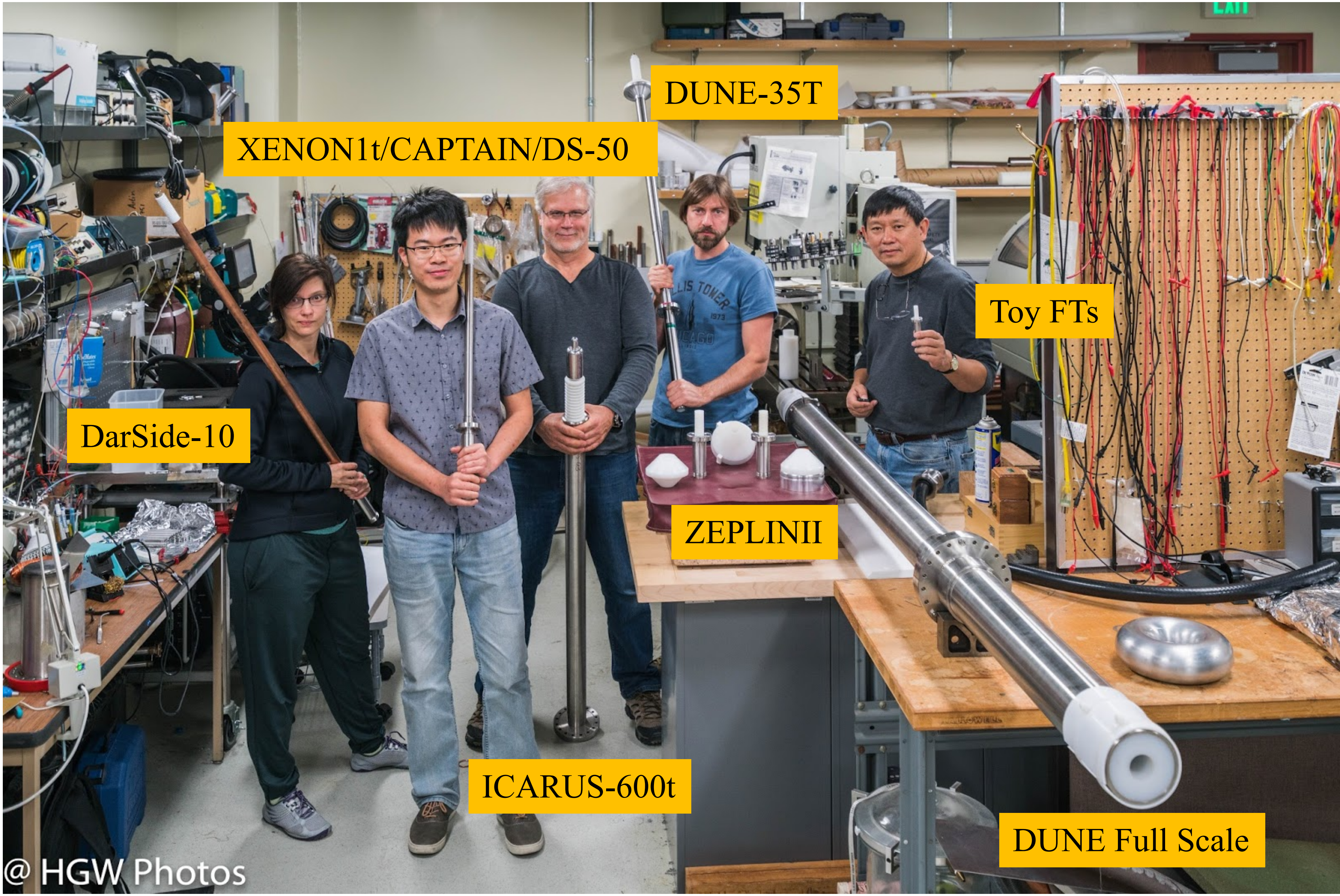
Basic Optimization of High Voltage Feedthrough

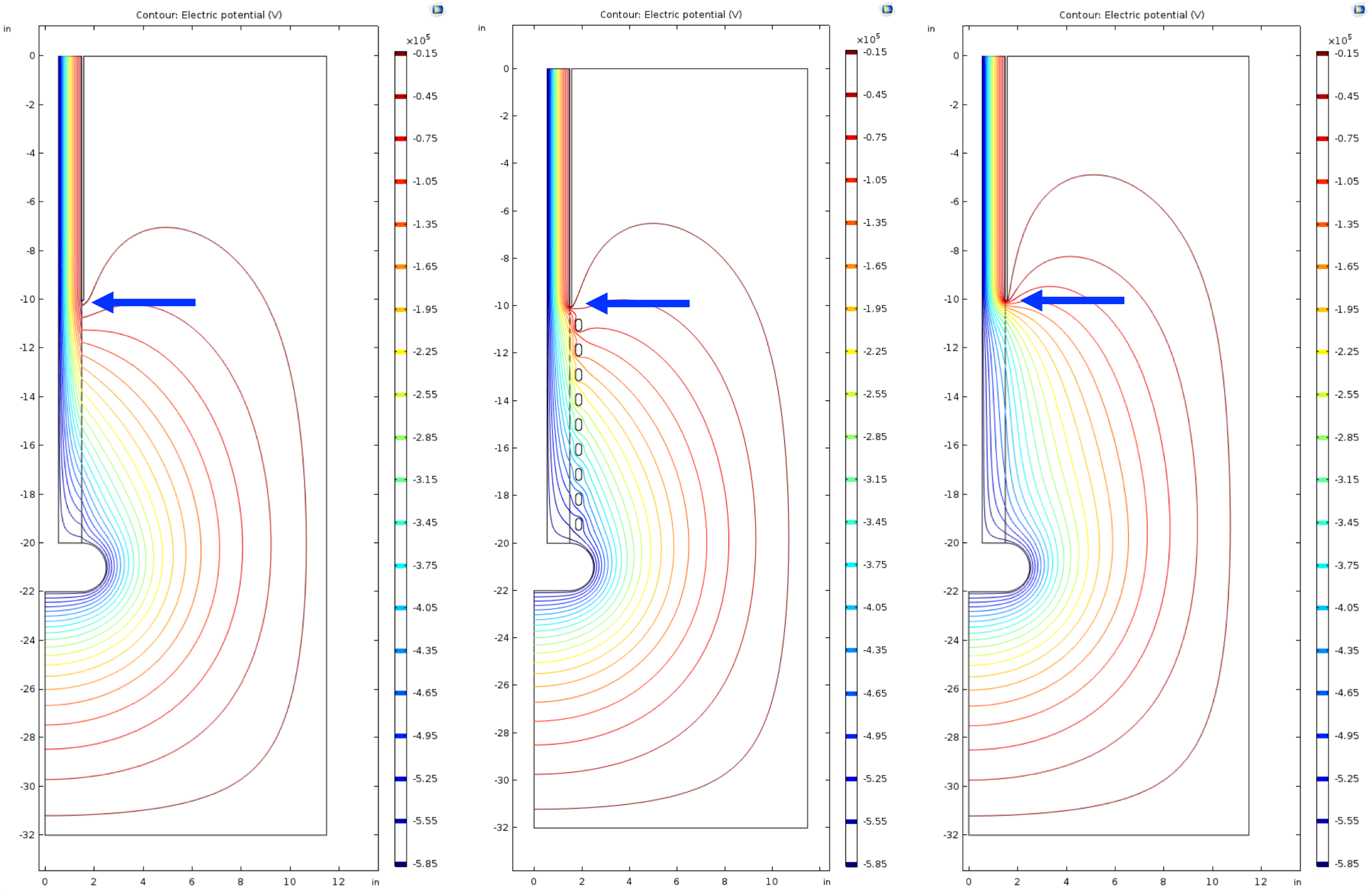
Minimize E-field strength at outer insulator surface to below breakdown field strength in **cold gas** (not liquid)



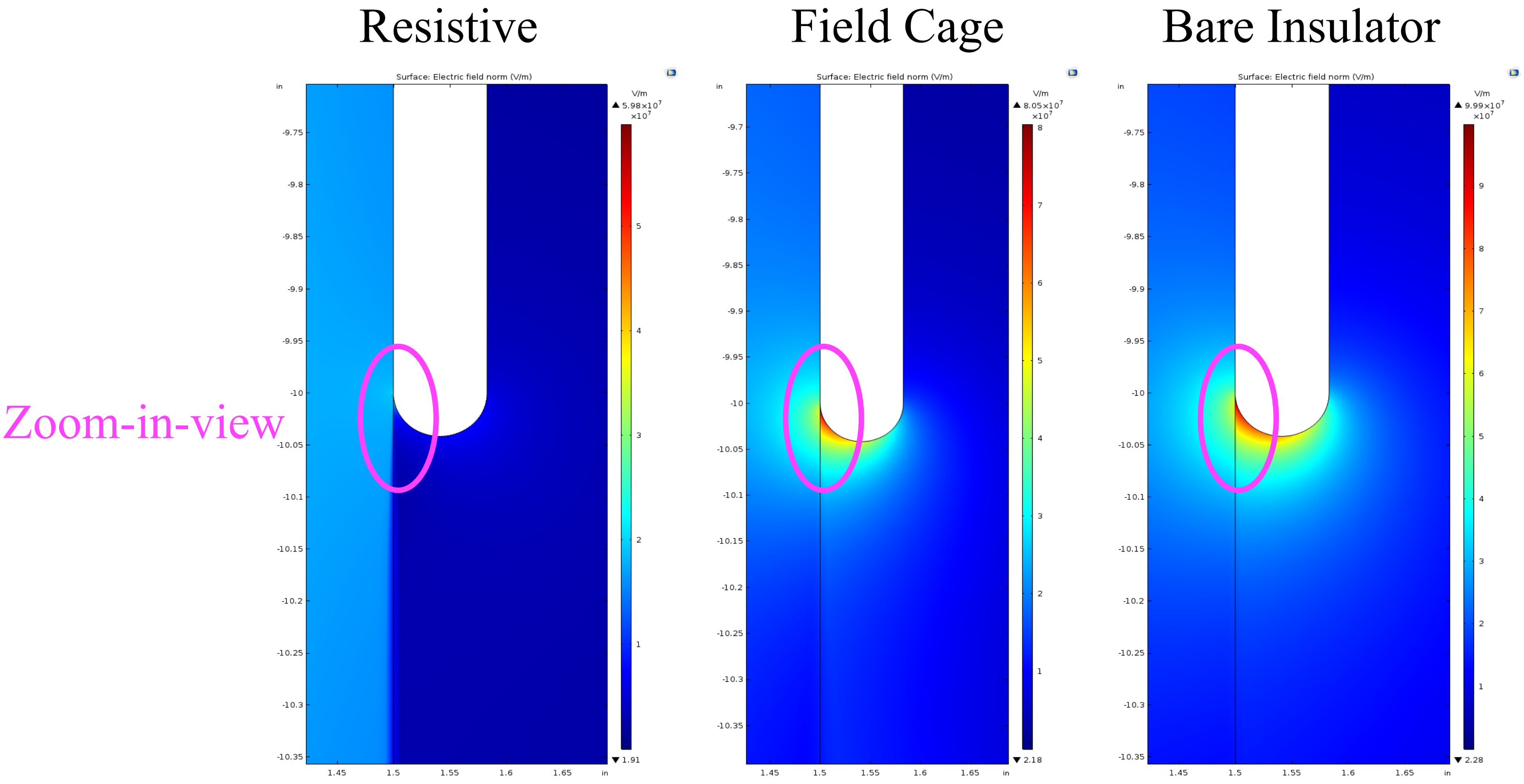


High Voltage Feed-Throughts Used in Varies Experiments & Lab Tests

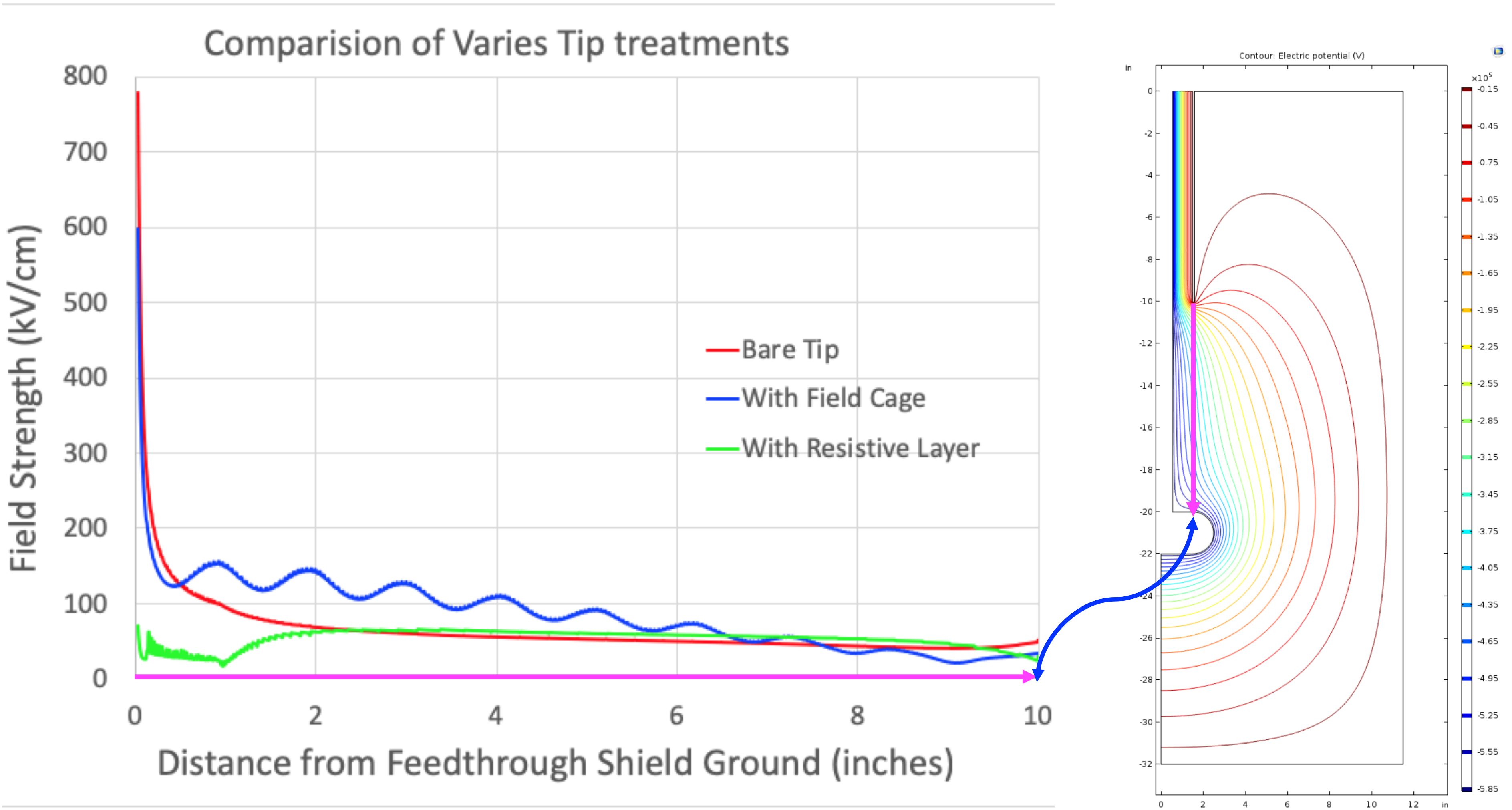




Expected electrostatic field distribution (the geometry was set for DUNE dual-phase with **600kV** setting): left: with resistive coating, middle: with field cage, right: without resistive coating. It is clear that equipotential lines, on the resistive coated case, are all evenly spread while the uncoated case (including the field caged), equipotential lines are pushed up and curling near the grounded edge hence form every strong field.



Expected electrostatic field strength map zoom-in-view at the shield grand (the geometry was set for DUNE dual-phase with 600kV setting): left: with resistive coating, middle: with field cage, right: without resistive coating. It is clear that field strength hot spot, on the resistive coated case, is eliminated.

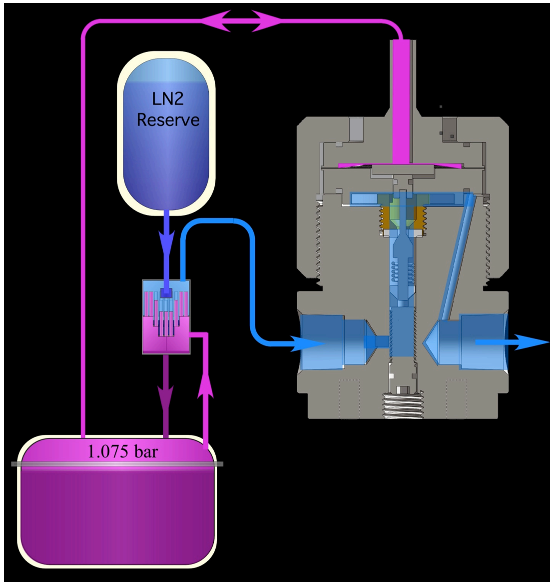


Field strength along the surface of the HV FT below the ground termination. It is clearly shown that the field cage shaping rings (blue curve) doesn't help the case. The resistive layer case (green) completely eliminate the high field near the ground termination.

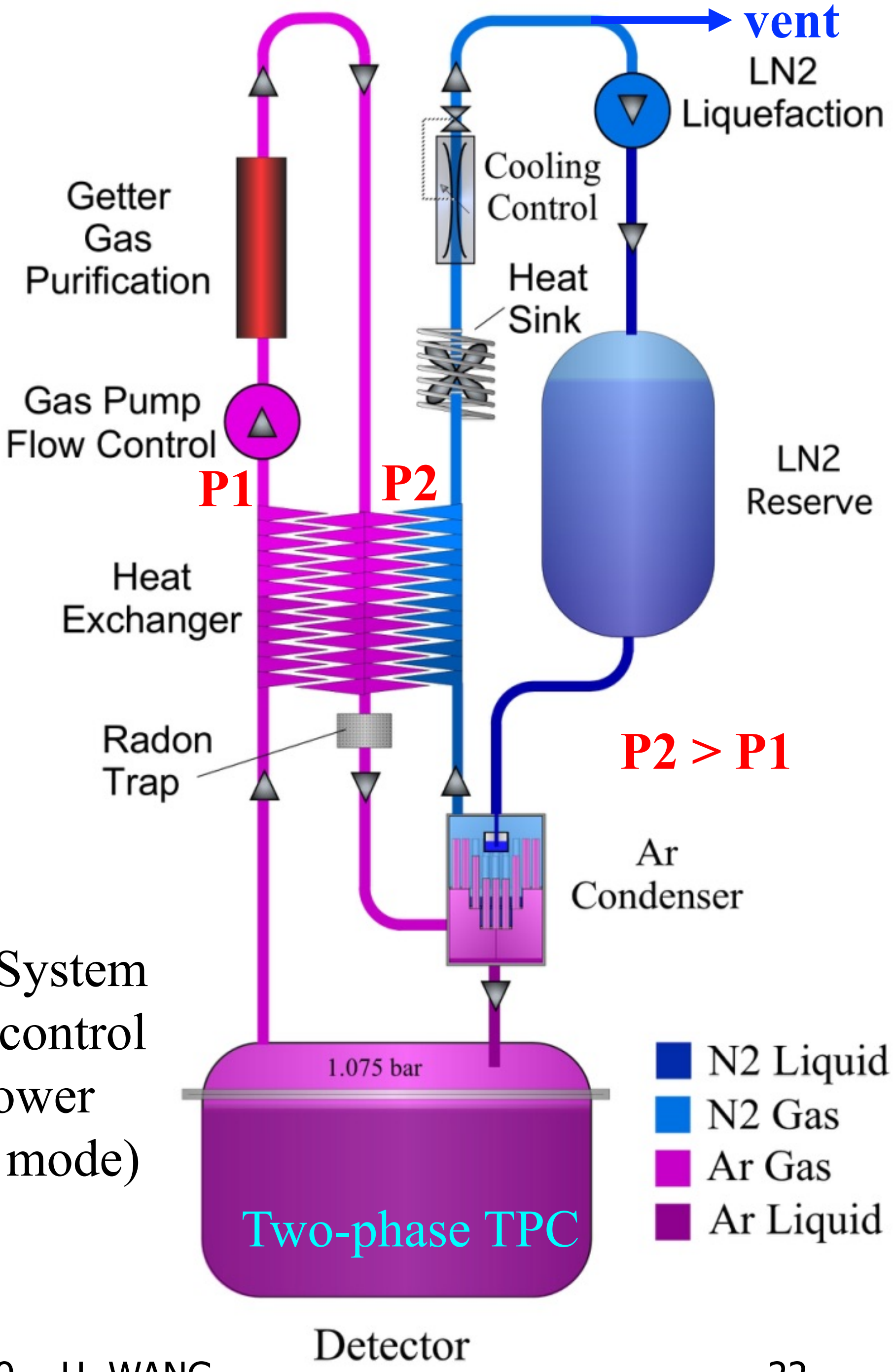
Cryogenics System

No commercial sources for UAr

- **LN2 as cooling source (closed loop)**
- **Ar Purification (closed loop)**
- **Condenser (LN2 heat-exchange)**
- **Delivery**
- **Radon Filter (self cooling trap)**
- **Full heat recovery**
- **Remote (material background)**
- **Strategic gas routing for purity**



Black Out Safe System
passive cooling control
(no electric power
required in safe mode)



Argon Condenser Concept and Test

100% Stainless Steel

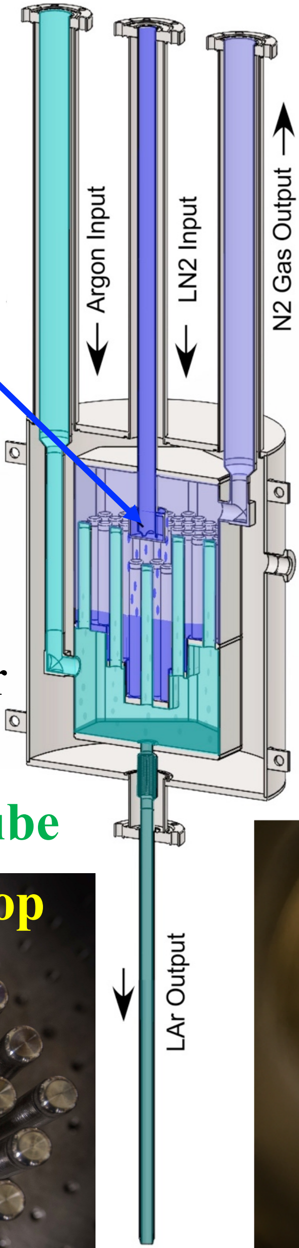
By design there are:

1. No heater controls,
2. No “temperature” sensors

Chicken Feeder
Auto LN2 Delivery

2.2 kW latent heat only

Argon “inside tube” **4.7 kW** w/heat exchanger



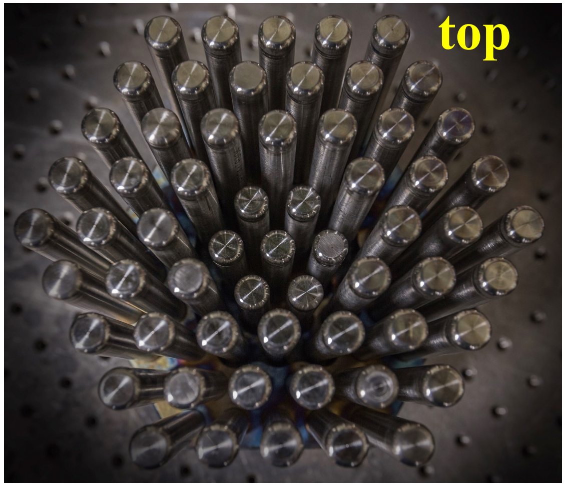
GN2 vent flow control determines cooling power

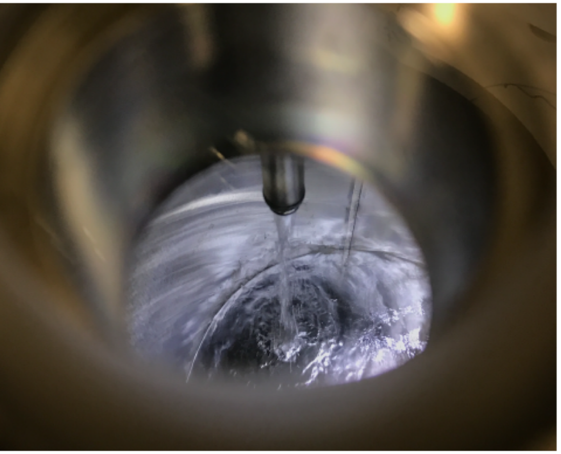
Liquid argon fast drop no freezing above triple point pressure

LN2 level auto balance

Integrated N2 and Ar pressure sensor ports

LN2 “out side” tube

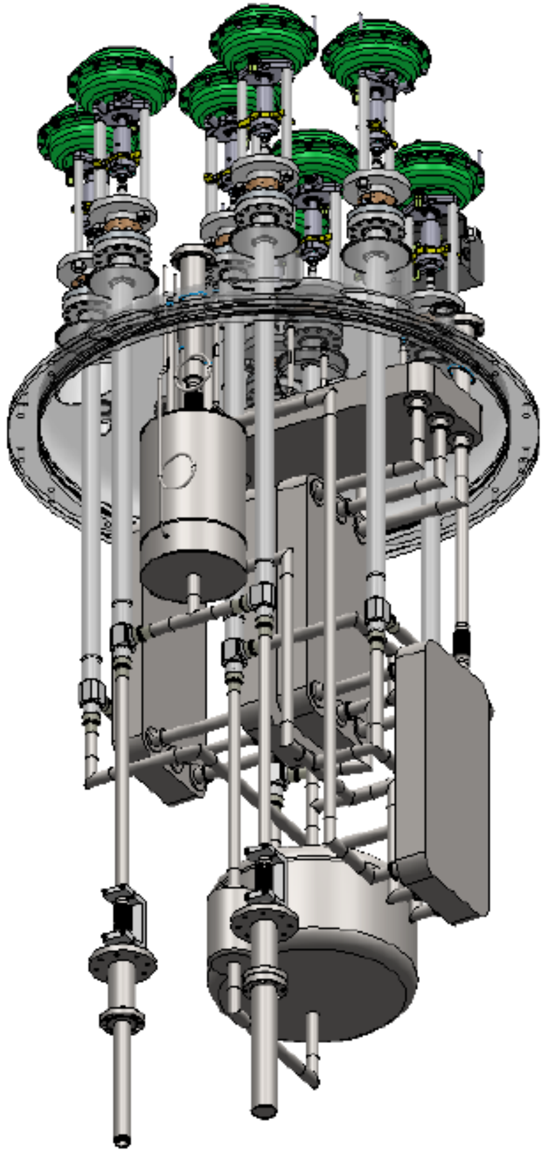


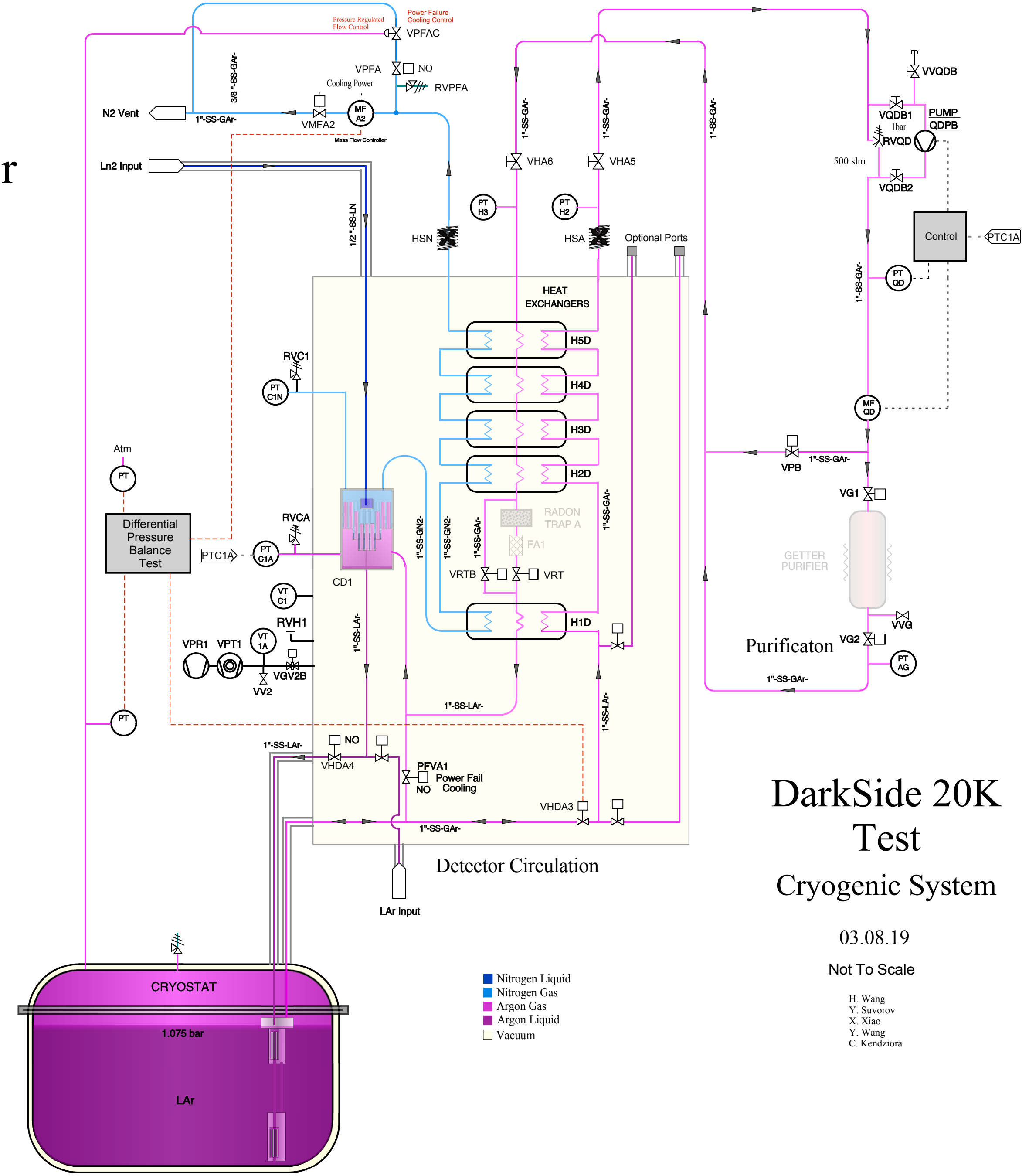


https://youtu.be/Be9Uy3UDfsI

DarkSide-20k UAr
Gas Handling system

0-15 kW variable cooling power





Detector Circulation

Purificaton

- 🟦 Nitrogen Liquid
- 🟦 Nitrogen Gas
- 🟪 Argon Gas
- 🟪 Argon Liquid
- ☐ Vacuum

DarkSide 20K
Test
Cryogenic System

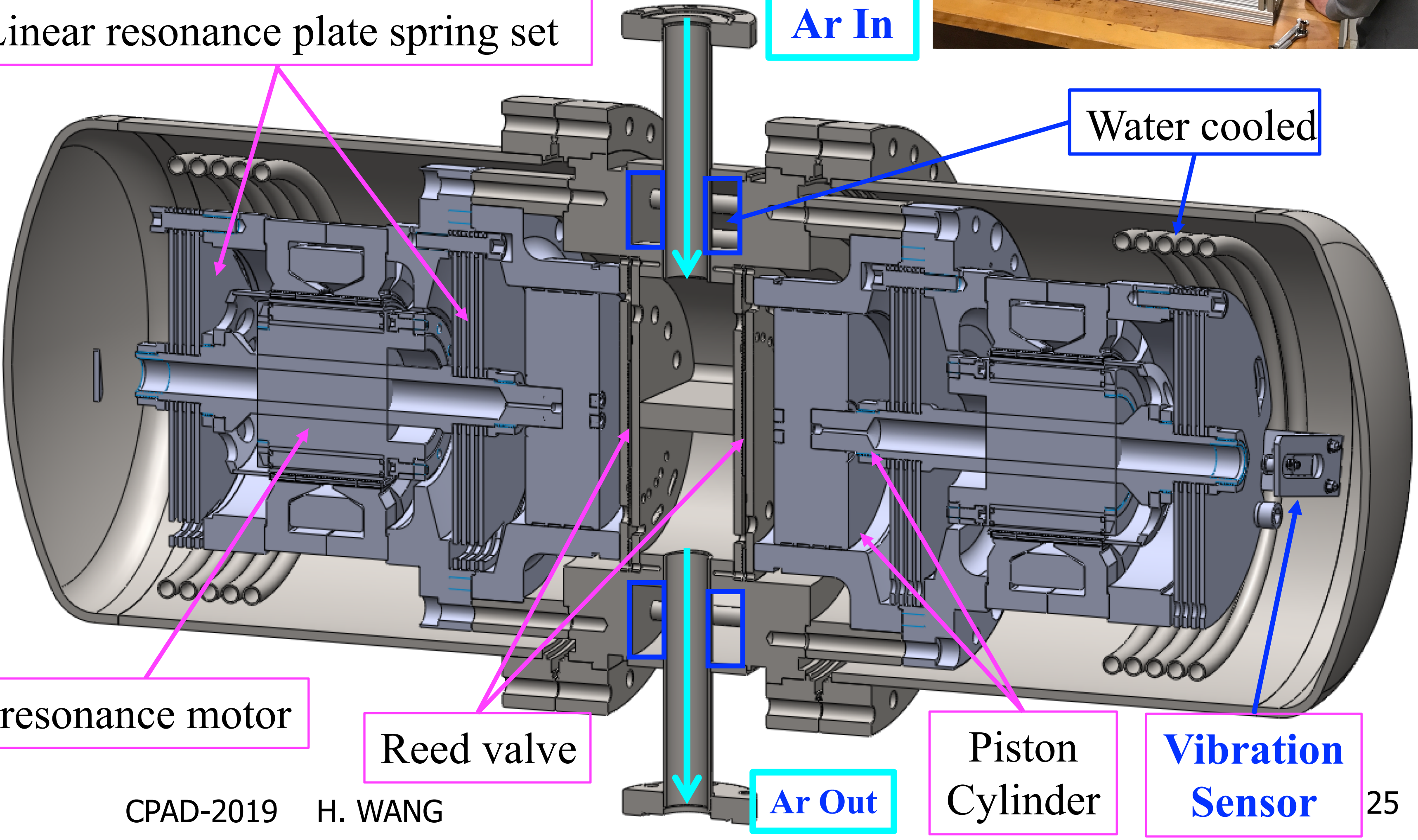
03.08.19

Not To Scale

H. Wang
Y. Suvorov
X. Xiao
Y. Wang
C. Kendziora

DarkSide Gas Circulation Pumps

Balanced weight opposing motors to double the pumping speed and cancel “completely” the mechanics vibrations. Resonance frequency matched to power line source frequency: **500slm**



Linear resonance plate spring set

Ar In

Water cooled

resonance motor

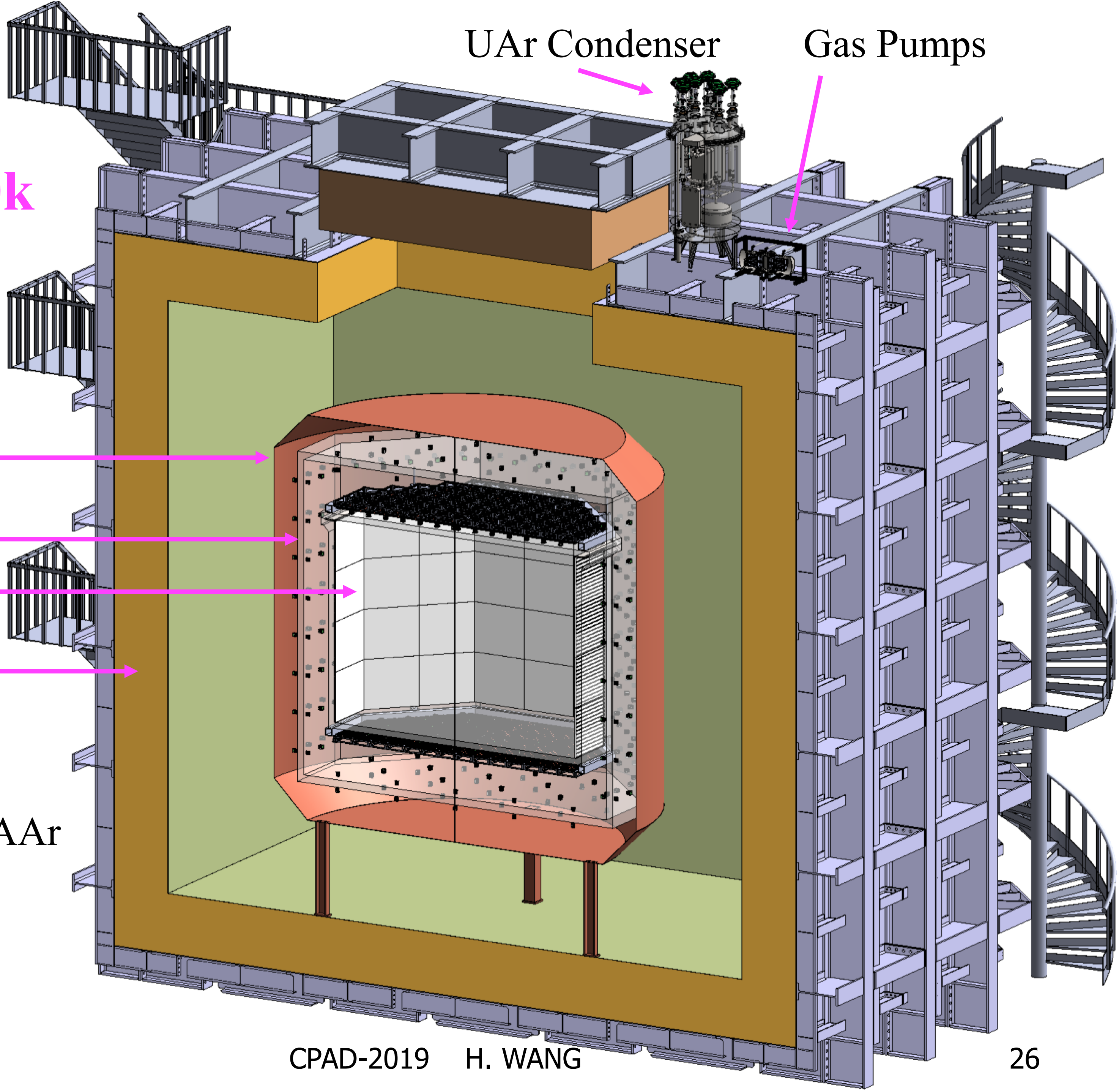
Reed valve

Ar Out

Piston Cylinder

Vibration Sensor

DarkSide-20k



UAr Condenser

Gas Pumps

Optical & EM barrier

nVeto

TPC

Cryostat

TPC 50T UAr
Veto Shield 700T AAr

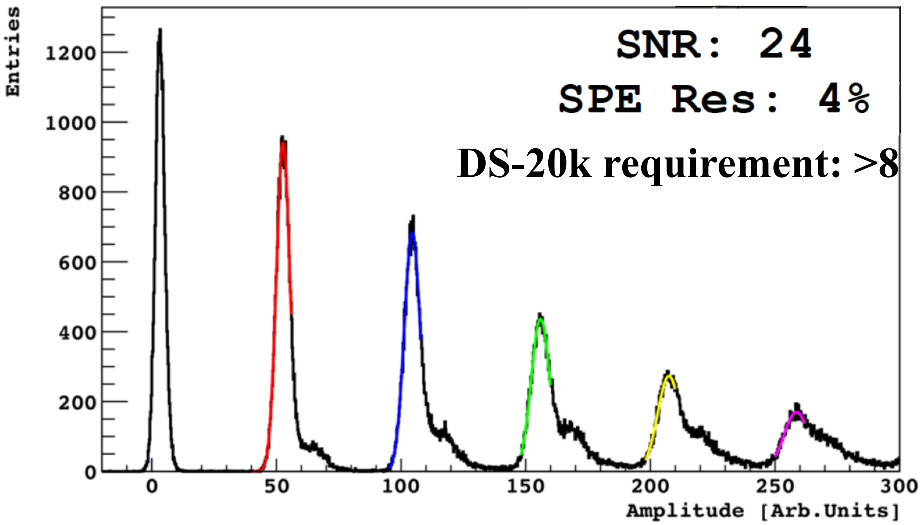
New Technologies Enabling **DarkSide-20k**

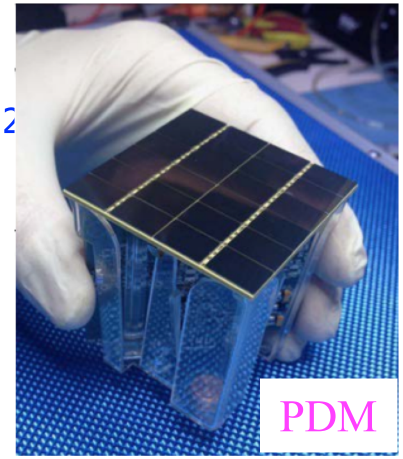
Four new key technologies enabling DarkSide-20k

- SiPM-based PhotoDetector Modules: for enhanced light-detection and reduced radioactivity [LNGS, Italy]
- Urania: for high through-put extraction of low radioactivity underground argon (UAr) [Colorado, USA]
- Aria: for high through-put purification of the UAr [Sardinia, Italy]
- Membrane Cryostat: as developed in the ProtoDUNE projects [CERN, France/Switzerland]

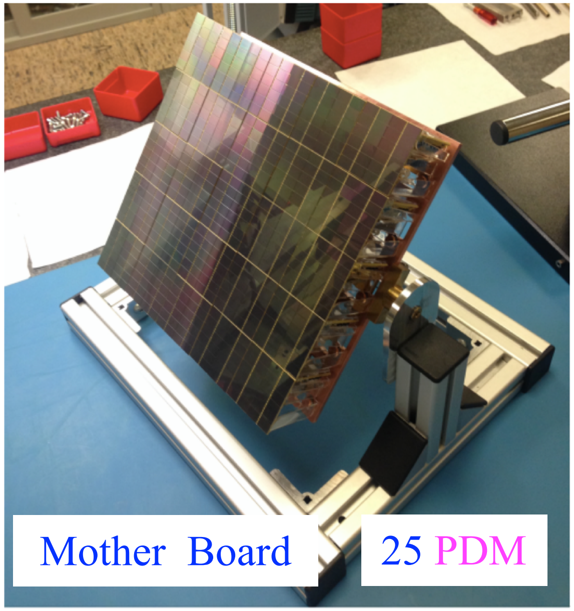
New photosensors – Silicon PhotoMultipliers (SiPMs)

- 5×5 cm^2 single-channel modules (array of 24 SiPMs) – Photon Detection Modules (PDMs)
- < 10 ns timing resolution
- PDE 50%
- Gain > 10^6
- 0.1 Hz/mm^2 dark count rate (cryogenic electronics)
- Single PE resolution
- Signal/Noise ~ 24
- Power consumption < 100 µW/mm^2
- Compact and radio-clean
- 8280 PDMs in TPC
- ~3000 PDMs in Veto





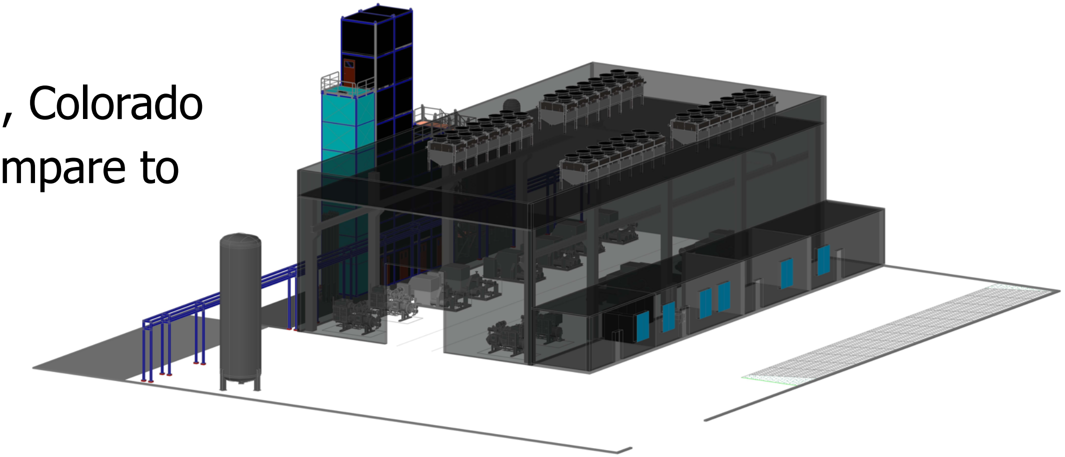
5cm x 5cm



25 cm x 25 cm

Low radioactivity Argon – procurement with Urania and purification with Aria

- **Urania plant** (extraction of UAr)
  - – extraction plant at Cortez mine, Colorado
  - – 330 kg/day UAr production (compare to 153 kg/6 years for DS-50)
- 99.99% purity
- 55 tonnes for DS-20k
- Will provide UAr for ARGO



Urania plan

Urania at Cortez, CO

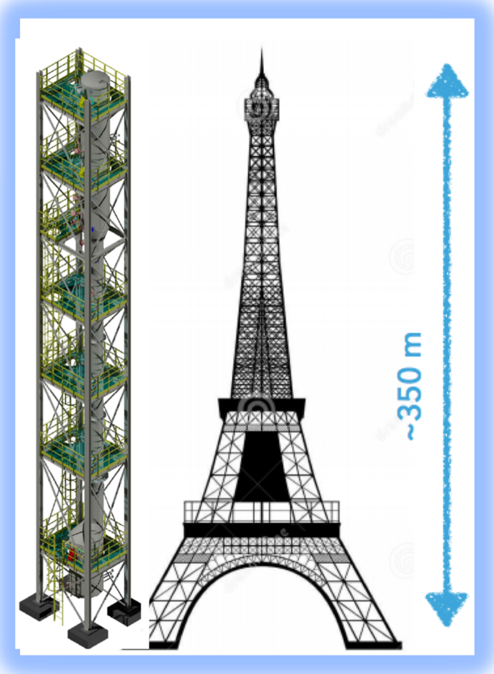
Aria at Sardinia

Low radioactivity Argon – purification at ARIA PLANT

Aria plant

- Distillation plant in Seruci, Sardinia
- production of depleted argon DAr with 0.01 content of ^{39}Ar compared to UAr → required for tonne-like light DM experiment
- removal of impurities such as Kr
- isotopic cryogenic distillation of ^{39}Ar and ^{40}Ar
- 350 m tall distillation column under construction in Sardinia: Seruci I (30 cm diameter column) with depletion factor of 10
- Chemical purification rate: 1 tonne/day

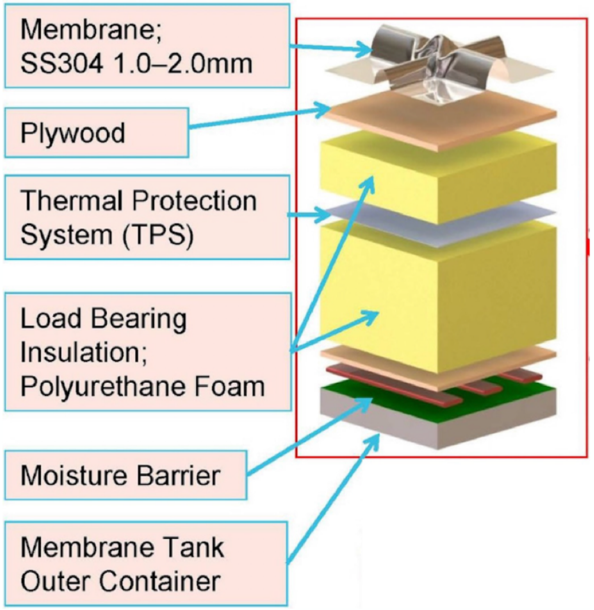
Seruci 0 – prototype
Column tested



Seruci 1

ProtoDUNE cryostat

- ProtoDUNE style membrane cryostat
- filled with 750t atmospheric argon.



Membrane;
SS304 1.0–2.0mm

Plywood

Thermal Protection
System (TPS)

Load Bearing
Insulation;
Polyurethane Foam

Moisture Barrier

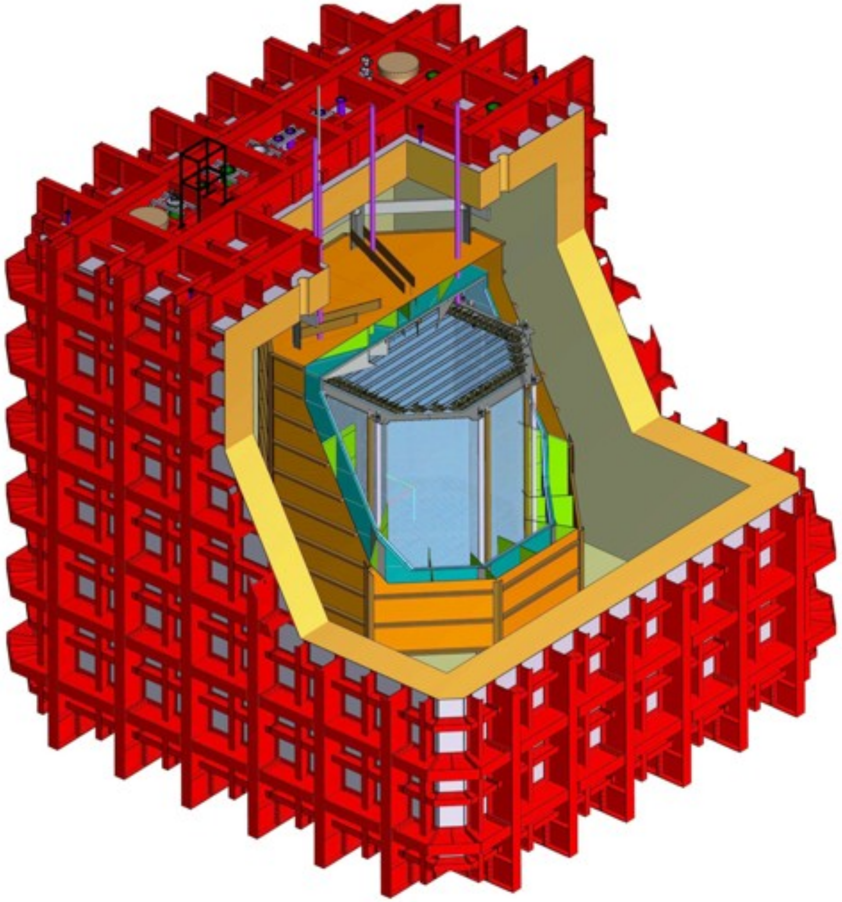
Membrane Tank
Outer Container

Background-free:

< 0.1 instrumental background event in 200 tonne-year exposure

DarkSide-20k at Gran Sasso:

- 50 ton Depleted Ar sealed in sealed acrylic dual phase Ar TPC detector
- Builds upon experience from DEAP3600 acrylic TPC vessel production
- 30-t LAr fiducial volume
- Neutron veto: Gd loaded acrylic panels and Atmospheric Ar
- Separate cryogenic systems for DAr and AAr (controlled coupled together)
- Light detection by Silicon Photomultipliers in TPC and Veto
- nVeto enclosed in optical and EM barrier
- Placed inside ProtoDUNE-like cryostat.



DARKSIDE

GADMC

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IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY
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JOINT INSTITUTE FOR NUCLEAR RESEARCH JINR
Laurentian University Université Laurentienne
INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati
LPNHE PARIS

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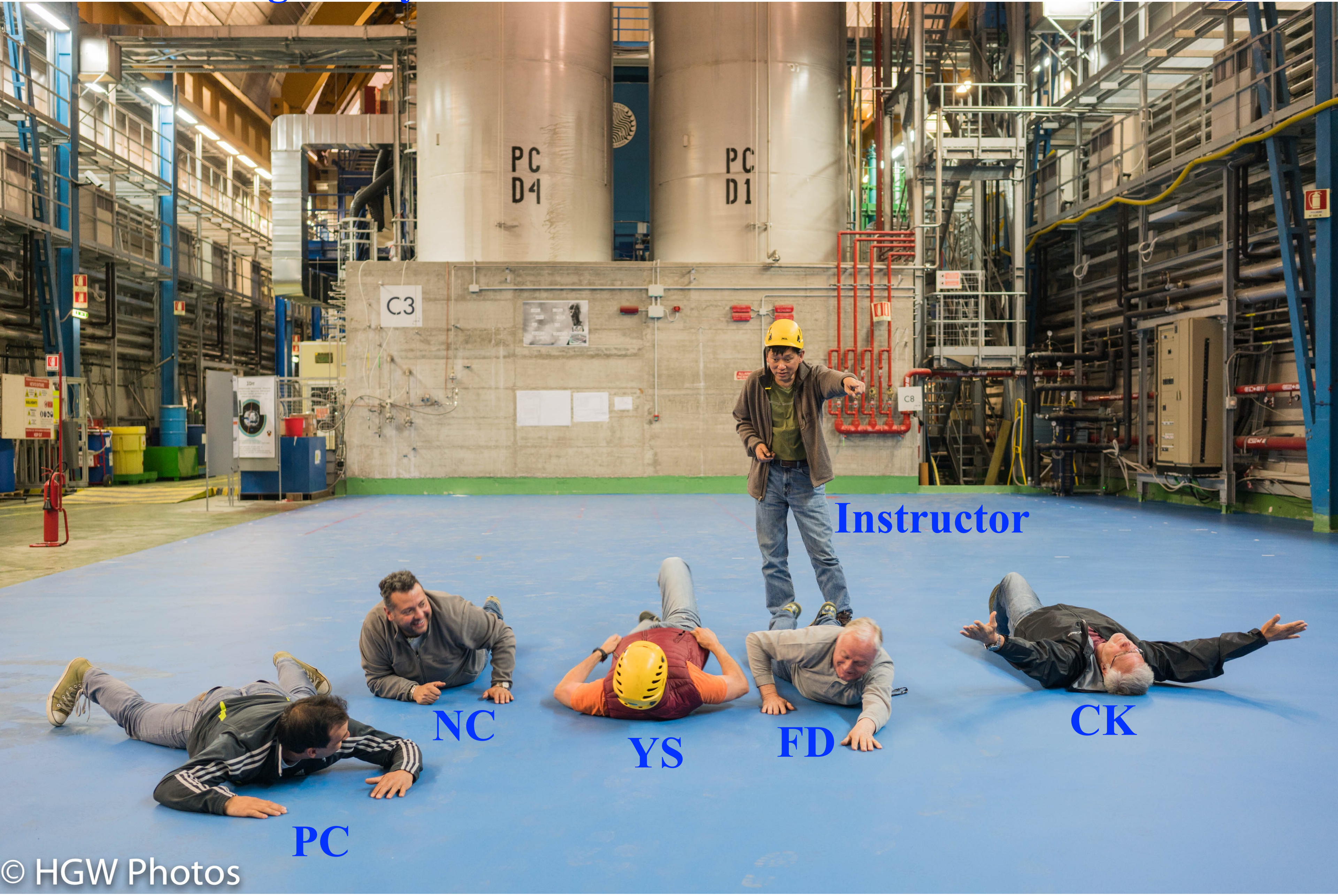
Getting Ready for DarkSdie-20k

LNGS@Hall_C



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