Some design considerations for XLZD and beyond

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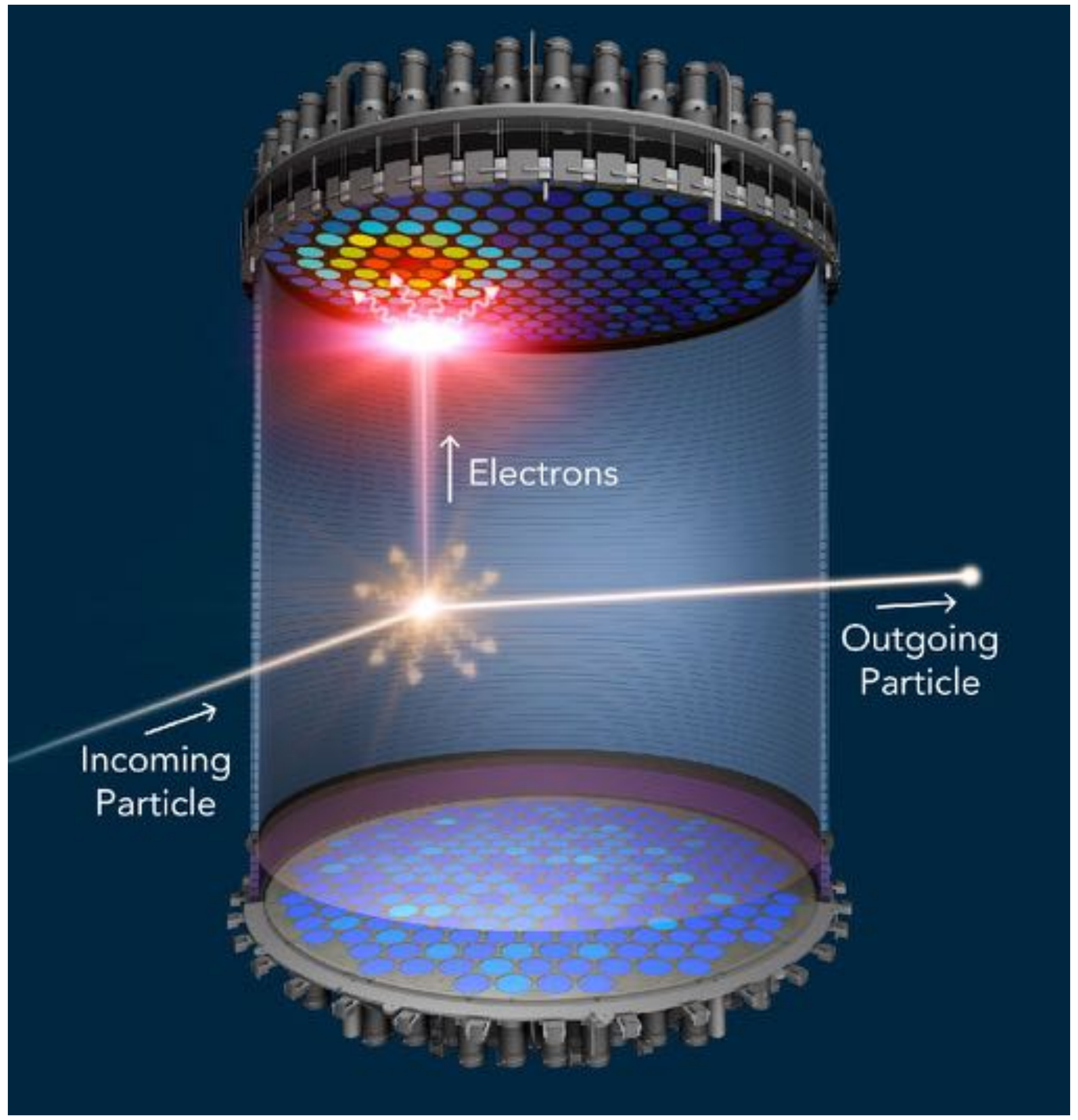
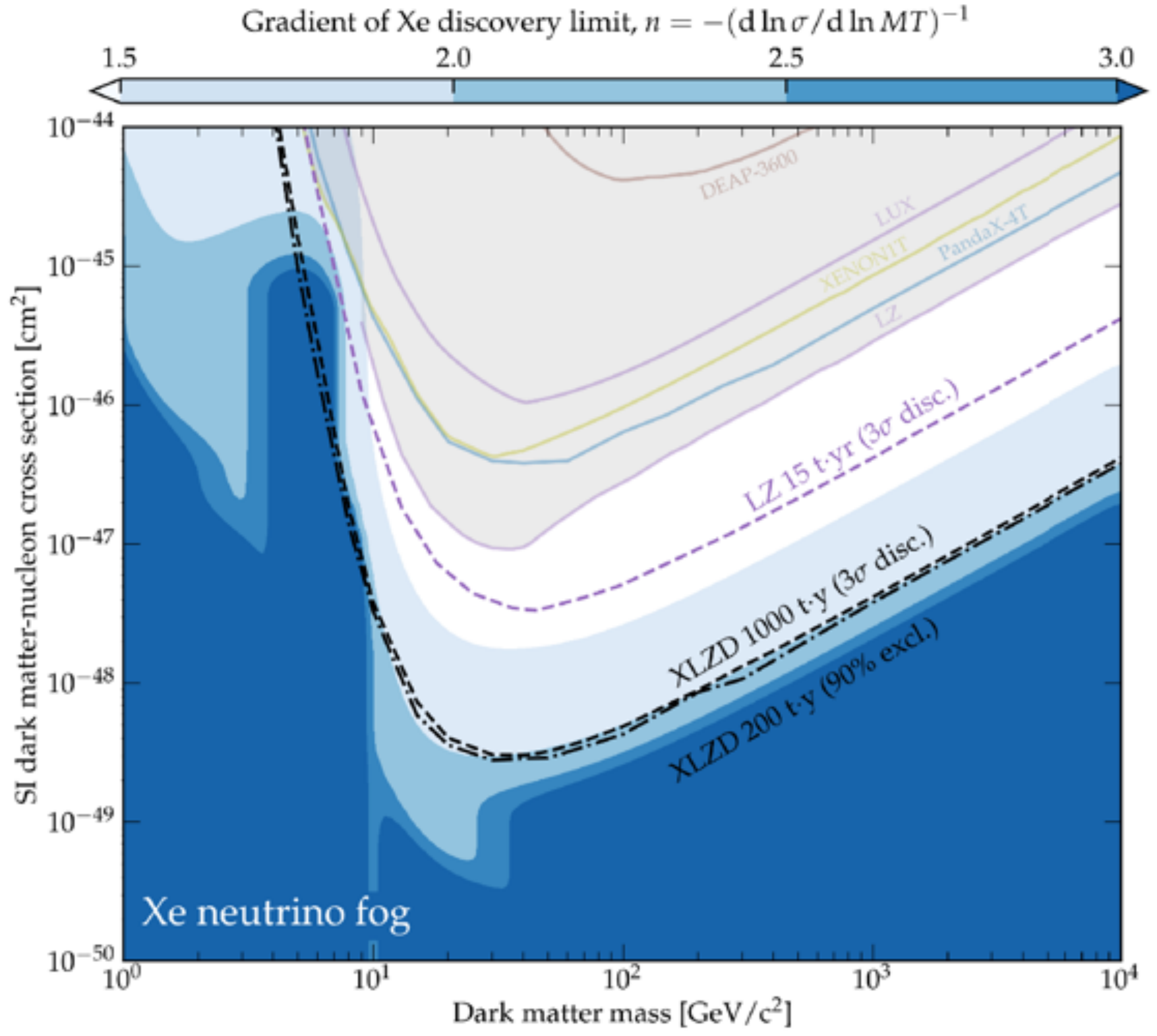
XLZD, and beyond

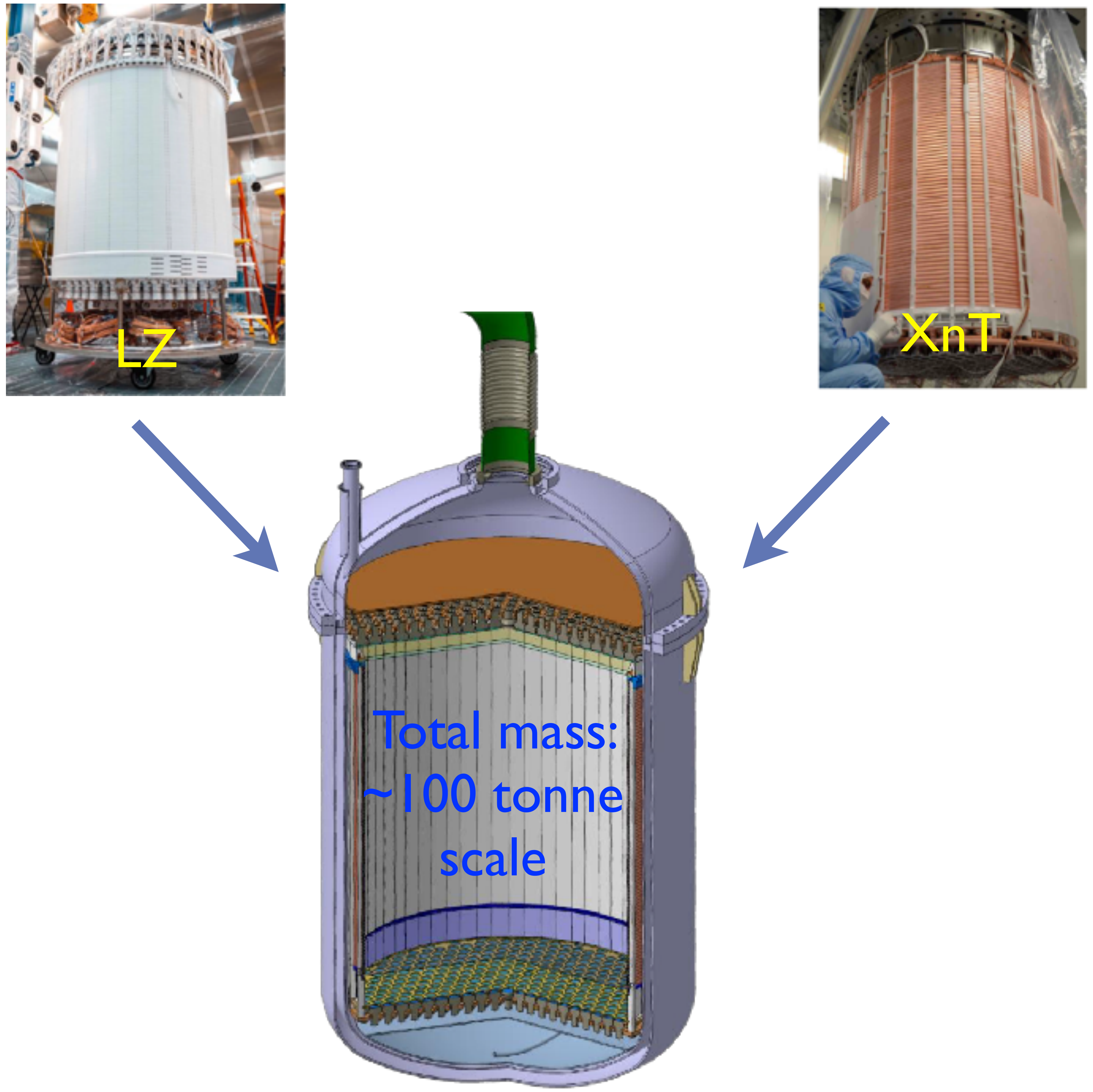
- XLZD: XENONnT + LZ + Darwin
  - Goal: definite search for > 10 GeV dark matter (DM): 1000 ton-year exposure with ~100 ton instrument.
  - Significant ßß reach.
- This talk:
  - Compare requirements for dark matter and ßß decay
  - Technology for XLZD 100 ton instrument
  - Some thoughts on a 1000 ton instrument





XLZD design status

- XLZD consortium recently formed.
- Two successful design heritages, based on several iterations each
  - XENON10, 100, 1T, nT
  - ZEPLIN II/III, LUX, LZ
- Most decision choices have not been made, and in this talk I *strictly offer my own thoughts. I do not speak for the consortium.*
- Scales:
  - LZ / XnT: 1.5 m
  - XLZD ~ 3 m,
  - 1 kton ~ 7 m

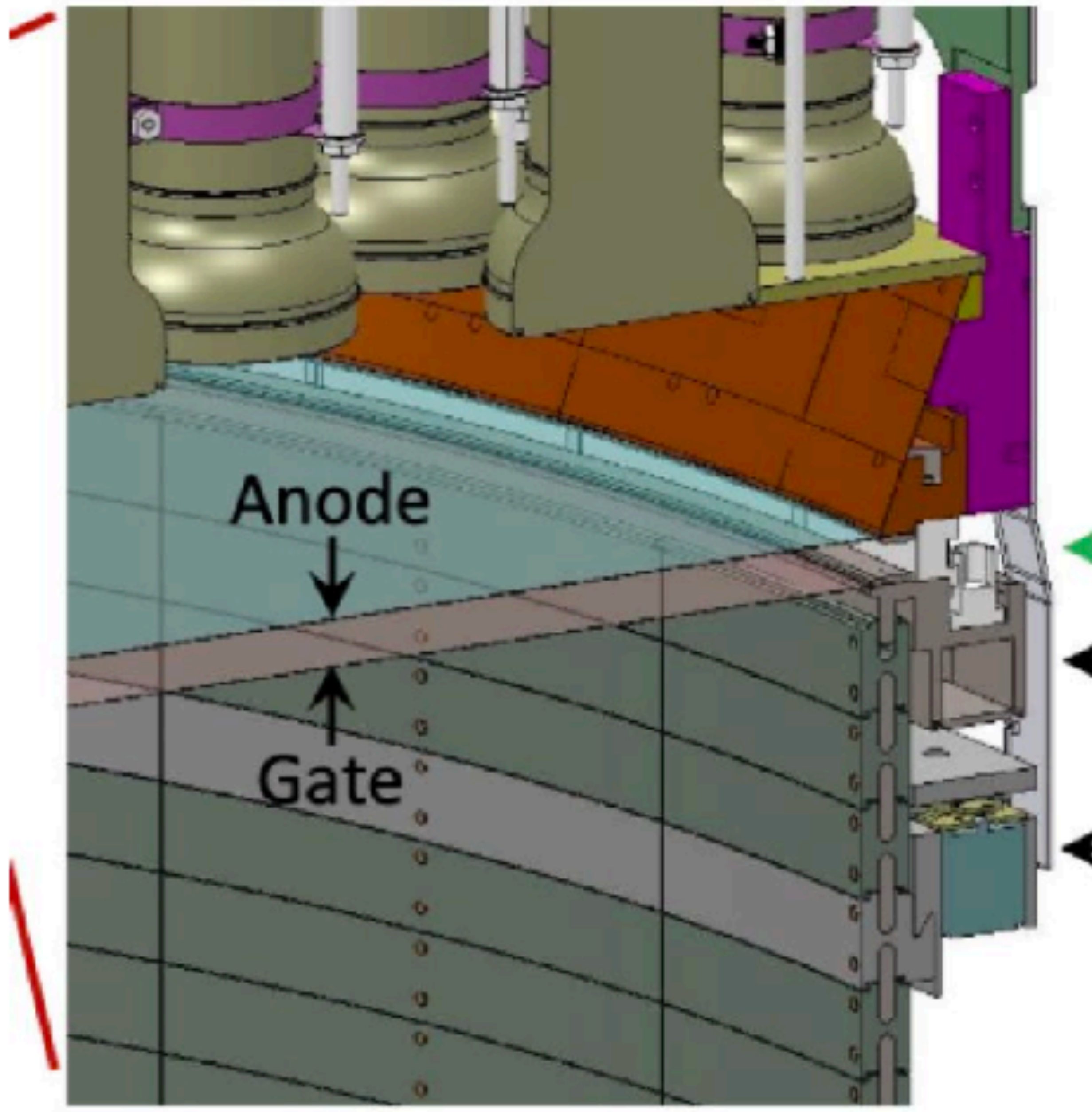


1st XLZD Meeting: KIT in Karlsruhe, Germany, June 2022.

Are requirements for DM and ßß compatible?

- Readout in general more demanding for DM, due to low energy
- Charge measurement: DM requires sensitivity to near a single electron
  - Not possible in macroscopic detector with out "gain" mechanism.
  - Charge amplifier readout noise cannot approach 1 e- for C of pF or more, without "skipper" mechanism, which is slow. Long wire C ~ 50 pF.
    - Massive array of micro sensors???
- DM approach: extract electrons to gas, produce electroluminescence - "proportional scintillation", or S2.
    - Other schemes possible - GEMs in gas, bubble assisted Liquid Hole Multiples
  - Amplification to light or charge in liquid possible, but requires very high fields.
    - Demonstrated only in small prototypes with limited gain.
    - Spoils energy resolution for ßß decay
- Any readout will require high fields, with additional electrodes. S2 requires grid below liquid surface, to produce large (2-5 keV/cm in LXe) extraction and electroluminescence field.

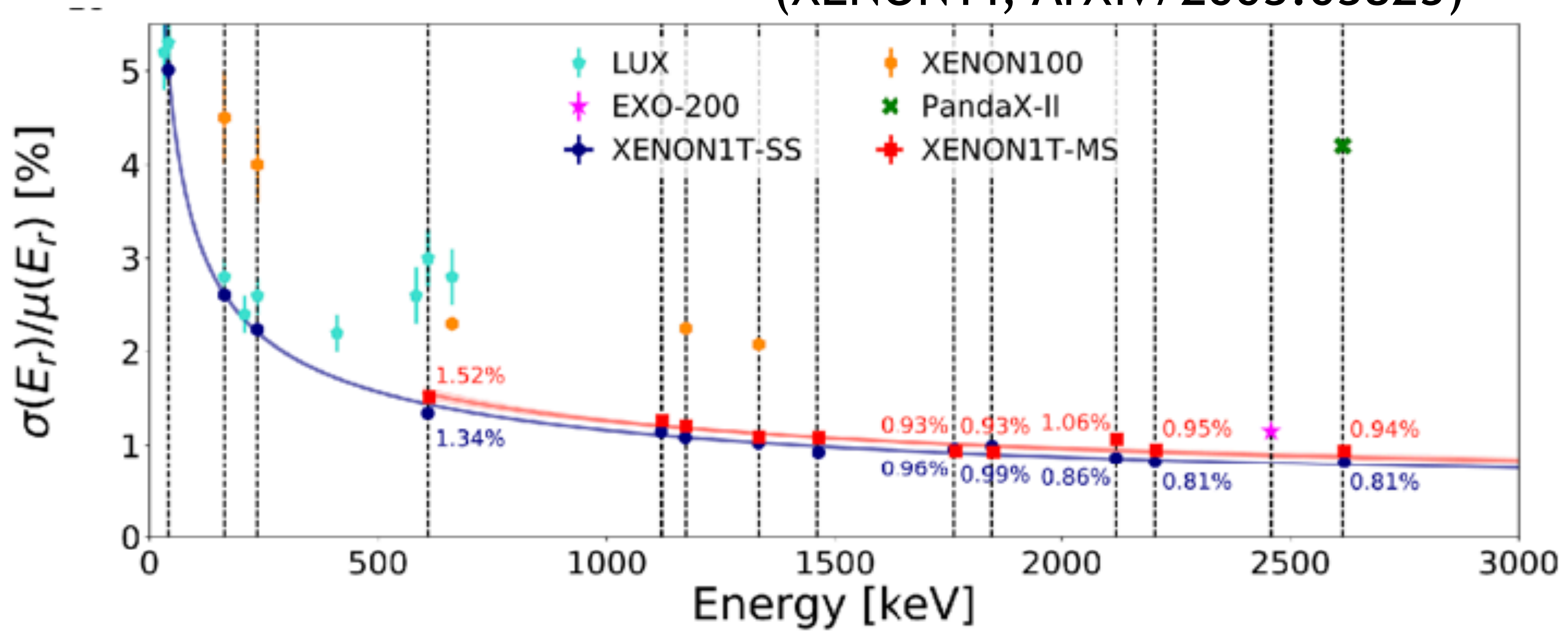
GAS PHASE AND ELECTROLUMINESCENCE REGION



DM and ßß requirements

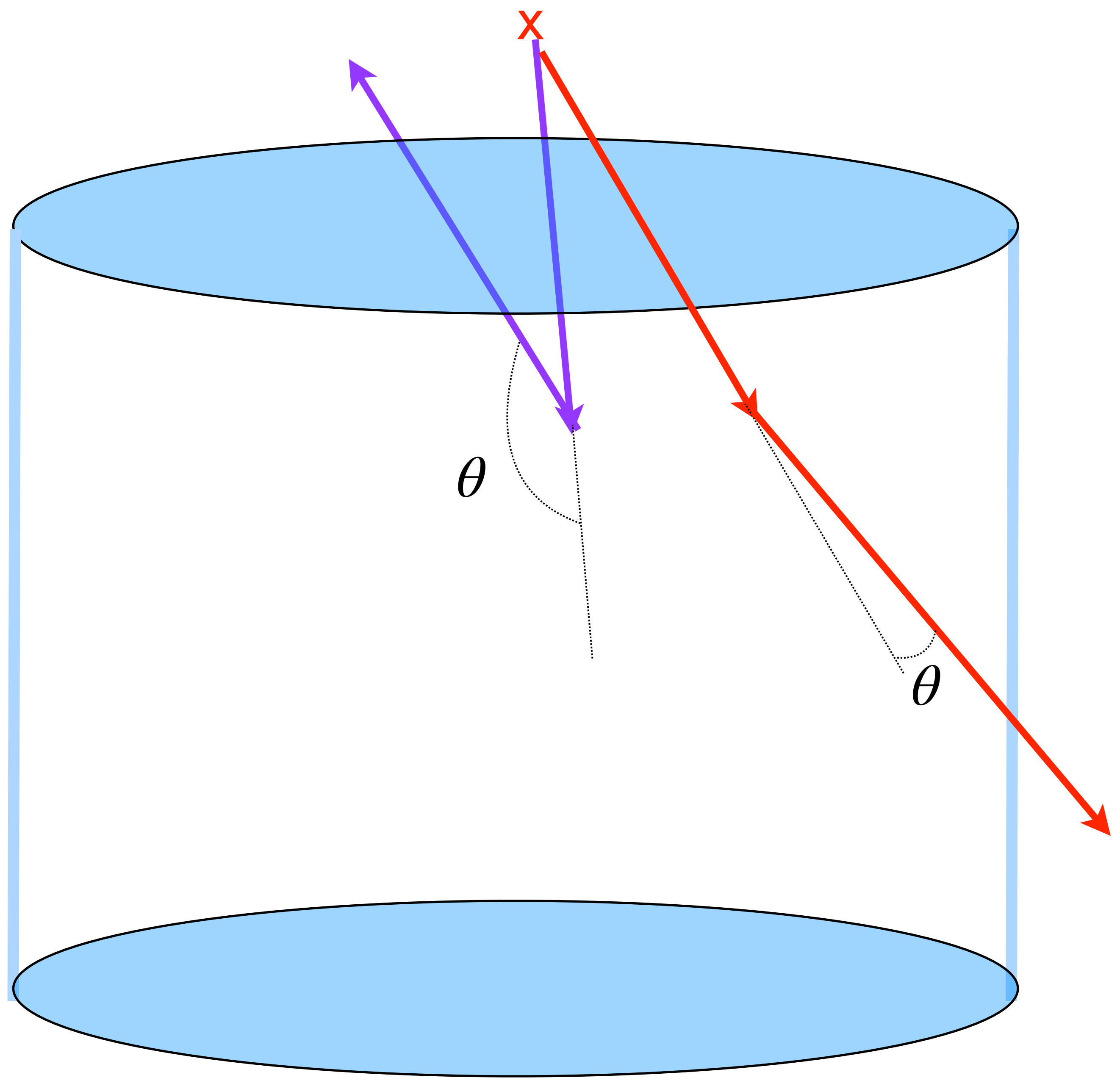
- DM needs high light collection
  - Because light collection less efficient than charge, energy threshold set by light signal
  - To date, LCE (measured photo-electrons per initial photon) ~ 12%
- DM has used PMTs
  - High QE for 175 nm light - 30% or more
  - Low dark current, which is key for achieving
- Could DM switch to SiPMs?
  - Main issue is dark current, which sets light threshold. Historically, SiPM dark current much to high at 175 K (acceptable at LAr 87 K), but recent progress makes SiPMs plausible.
- Good energy resolution in dual phase detectors
  - High light yield
  - S2 uniformity must be controlled

(XENON1T, ArXiv/2003.03825)



DM and ßß requirements

- Backgrounds in general more demanding for *ßß* decay
  - No ER/NR discrimination
  - Poorer self shielding for high energy, large angle scatters
- ^{222}Rn a problem for both, for different reasons
  - DM: rare, "naked" decay of daughter ^{214}Pb in active region
  - *ßß* decay: 2448 keV gamma from ^{214}Bi decaying in inactive region
- PMTs. Now quite good, remaining hot elements being worked on. Not obvious PMTs worse the SiPMs going forward.



low angle scatters have greater path to exit detector,

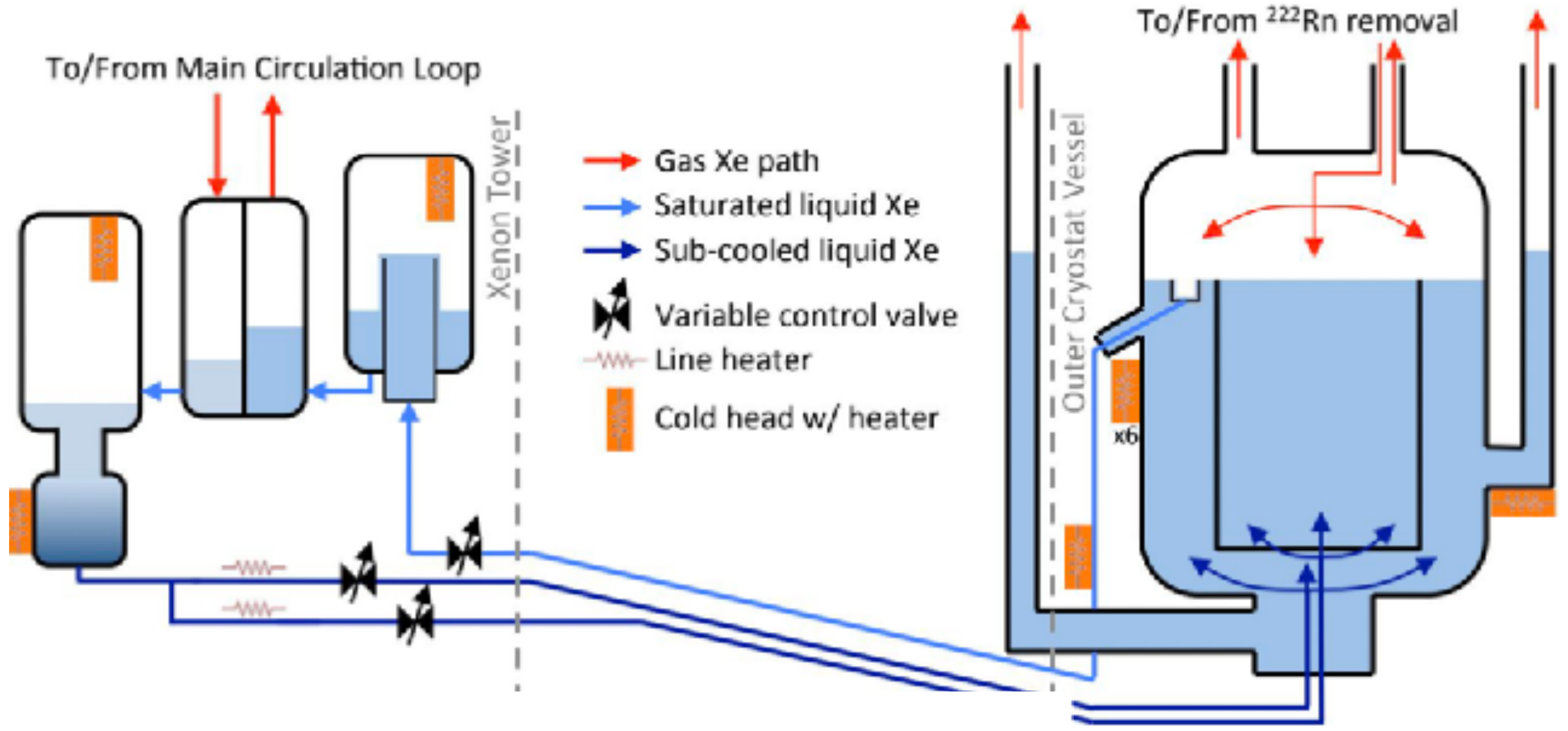
$$P(L) = \frac{1}{\lambda} e^{\frac{-L}{\lambda}}$$

- Conclusion: No fundamental tension between DM and *ßß* requirements.

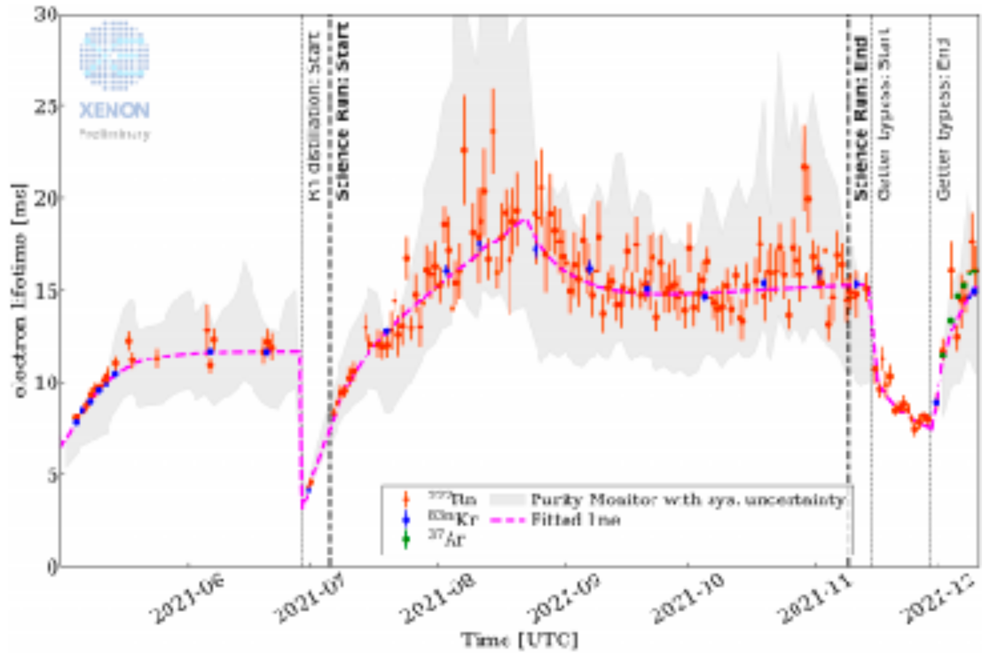
Purification

- DM (and ßß decay) and LAr neutrino world have had markedly different approaches to purification. LAr "easier".
  - Issue is mostly O_2 and H_2O capturing electrons. These predominantly outgas from plastics (G10 in LAr, PTFE in LXe, cables)
  - Diffusion follows Arrhenius $D = Ae^{\frac{-E_a}{kT}}$. $T_{RT} : T_{LXe} : T_{LAr} \sim 1 : 1/2 : 1/4$. If reduced by 10^4 for LXe, then reduced by 10^8 for LAr
- Historically, DM experiments used high efficiency heated getters to purify GXe.
  - To achieve fast LXe processing, developed dual-phase heat exchange systems, and large pumps and gas handling systems.
  - Very successful at minimizing charge loss, which is most difficult issue: > 10 meter drift lengths (> 10 ms lifetime) achieved reliably.
- The DUNE world has long purified fully in the liquid phase, using simpler zeolites or other "filters", and powerful commercial liquid pumps. Often, the gas blanket above the liquid is separately condensed and passed through a liquid phase filter.
- XENONnT recently adapted this liquid phase method, to very good effect.

LZ heat exchange and buffer system



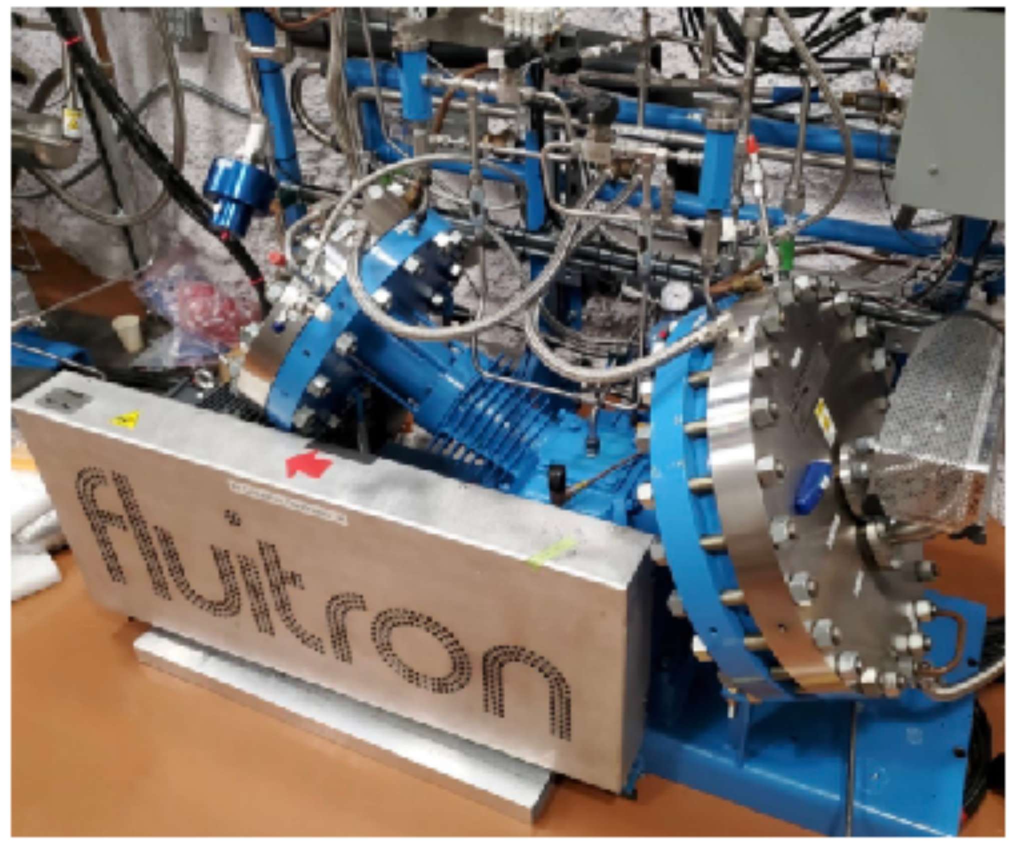
XENONnT charge drift purity

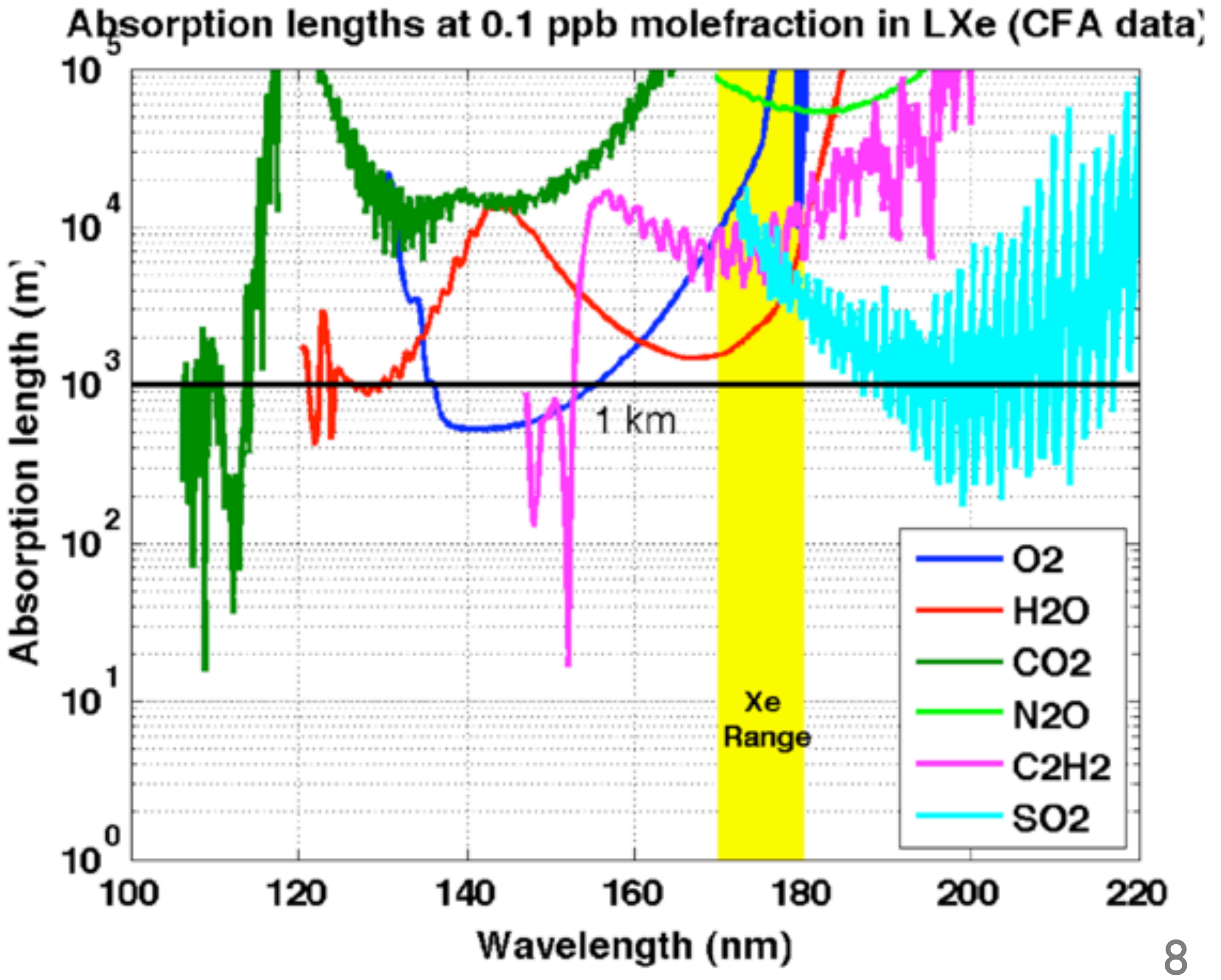


XLZD Design: Purification

- In my opinion, this liquid phase approach should have long been the preferred method. The efficiency of the getter was not needed, as the issue has been flow rate to process the TPC fluid.
- Scaling to 1000 tons should be straightforward.
  - The requirements will scale modestly with increased detector size, but the flow rate should scale with M or $M^{2/3}$.
  - However, Rn emanation from the filter (and pump) remains an issue.
  - The commercial pumps are not ideal - expensive and are said to have reliability issues.
- Light collection more subtle - now in range of Rayleigh scatters, which amounts to a diffusion process - total travel much greater than detector size. However this is unlikely to become dominant, given the absorption cross sections.

LZ circulation compressor

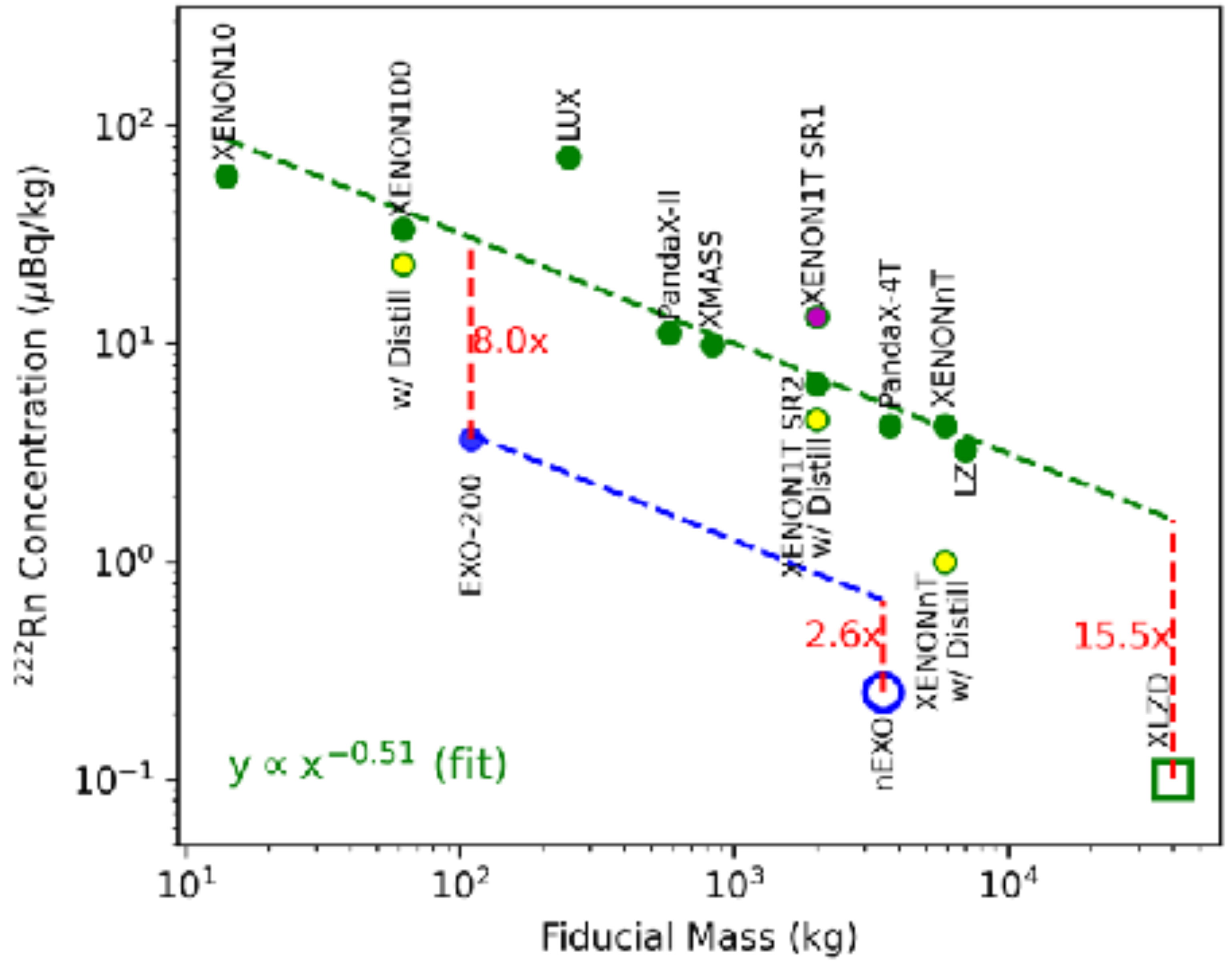




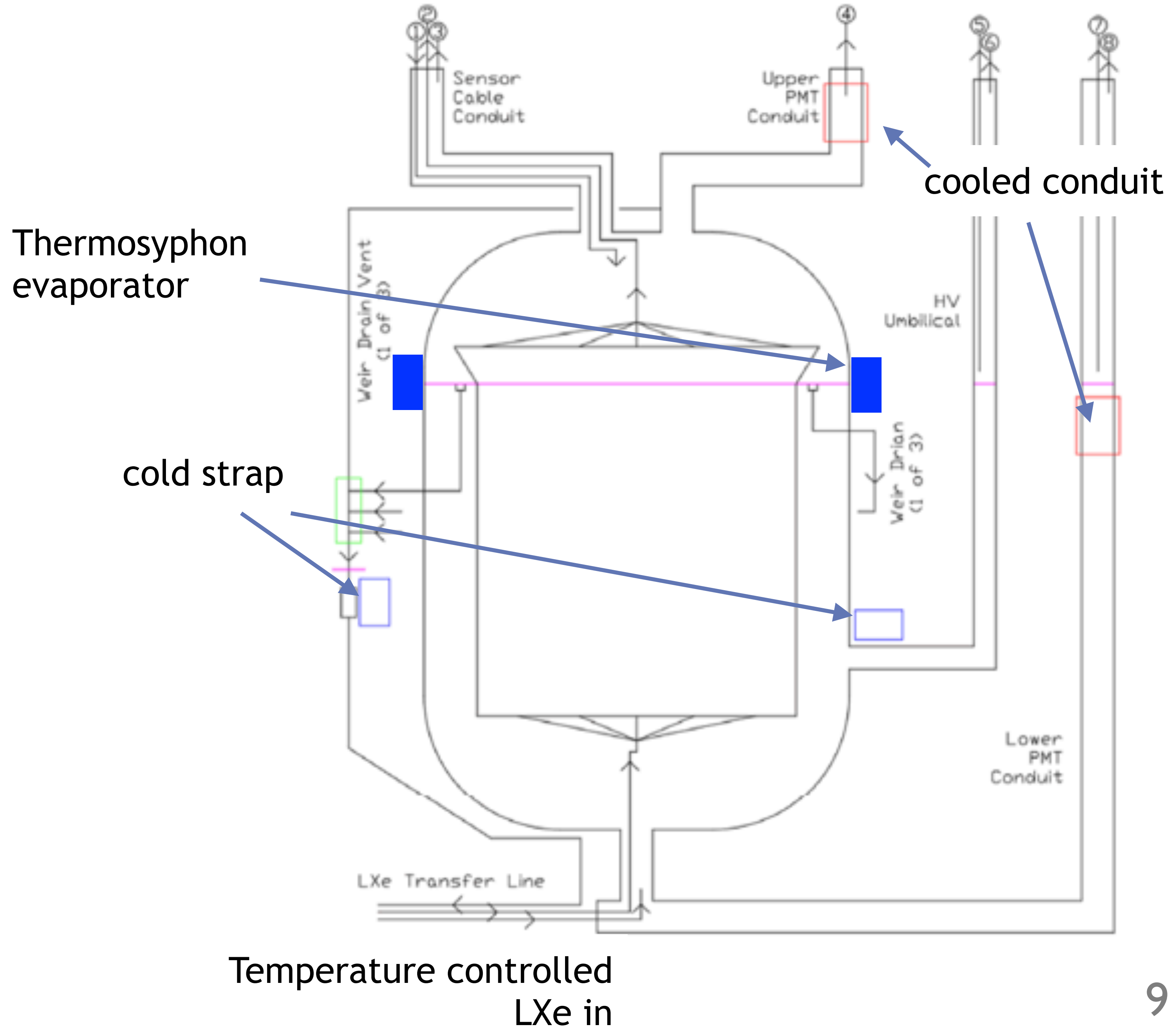
Radon

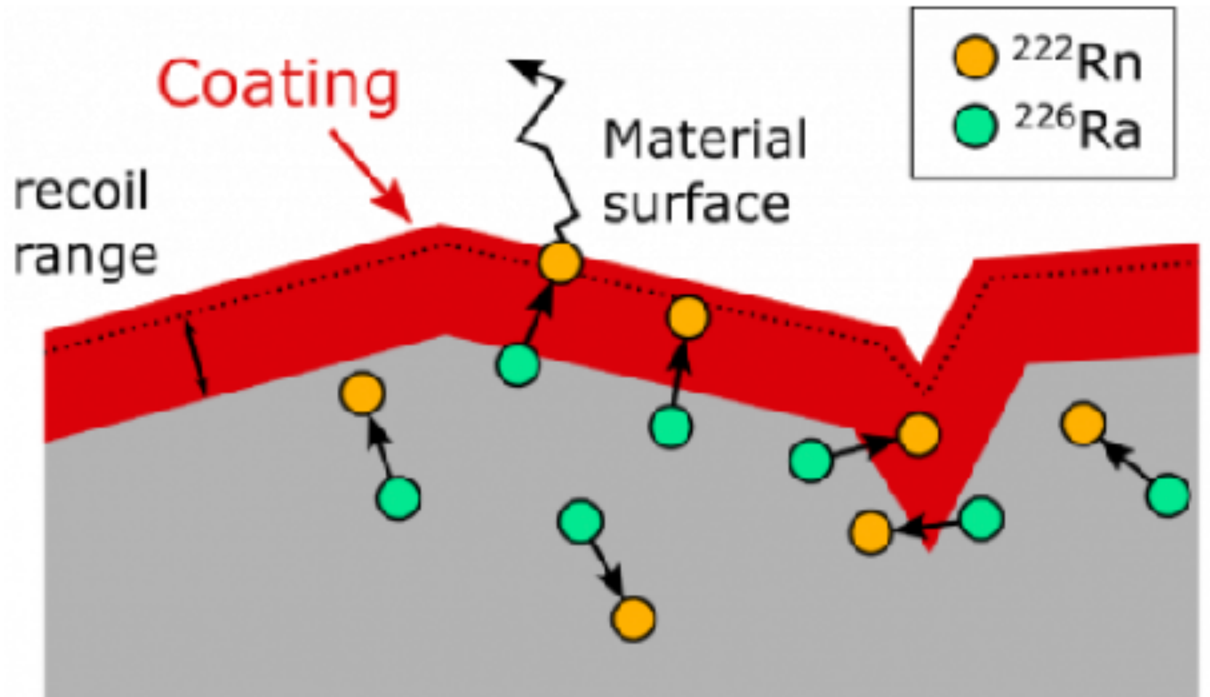
- ^{222}Rn has been most difficult in all recent LXe large DM experiments
  - Emanation from all wetted components, including purification systems.
  - Goal is to reduce to 10% of solar pp neutrinos, allowing several physics measurements in electron recoil channel
- Multiple approaches to reducing
  - Screening: highly successful, but challenging at XLZD level
  - Stable fluid - tagging + decay - LZ design / contrast with EXO/nEXO/ Kamland, SNO, etc.
    - Stable fluid complicates calibration
  - Sealed TPC
  - Coatings, e.g. on Ti.

Rn concentration



LZ Internal Circulation and Thermal control





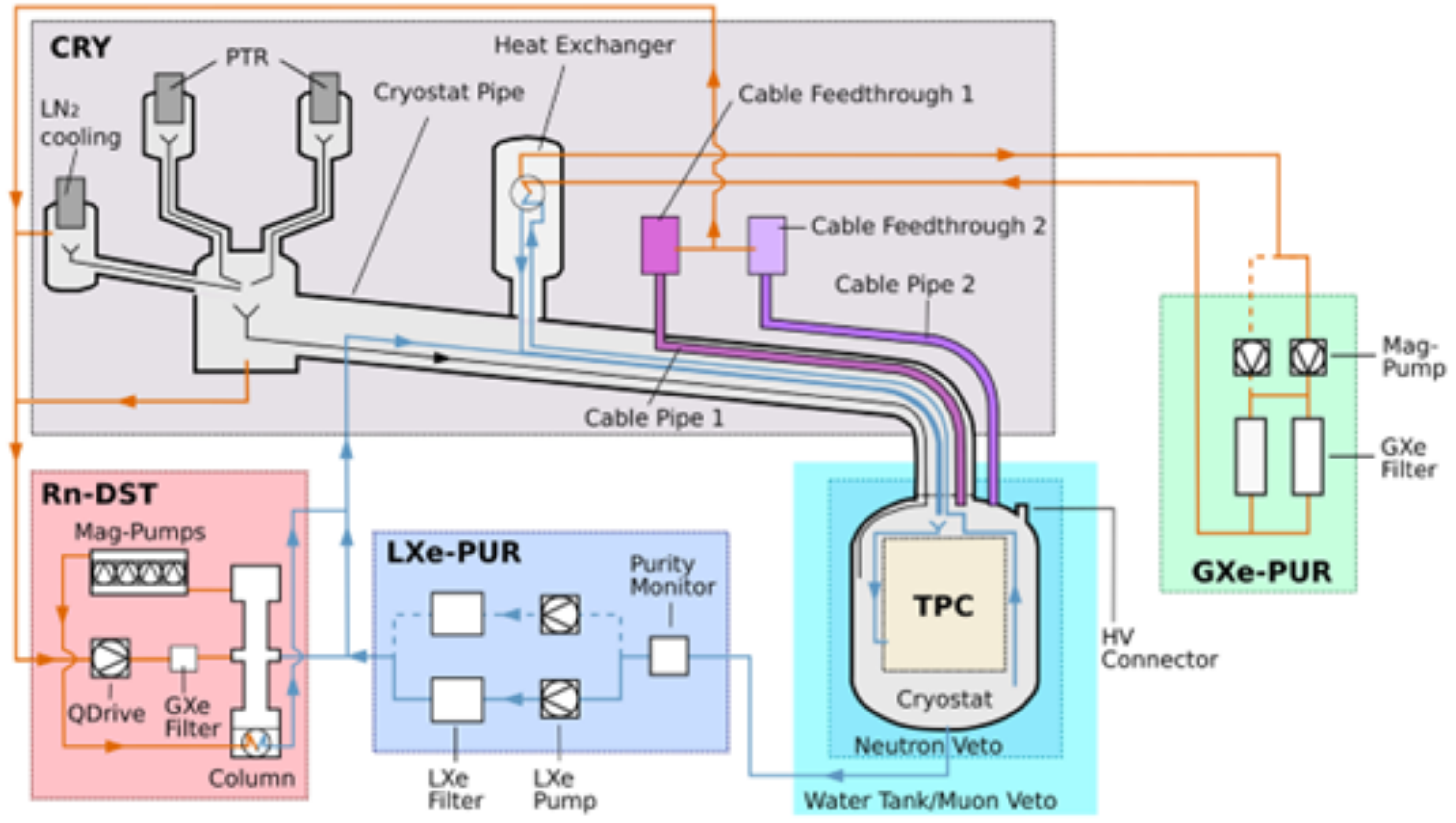
(from Baudis, lowrad23)

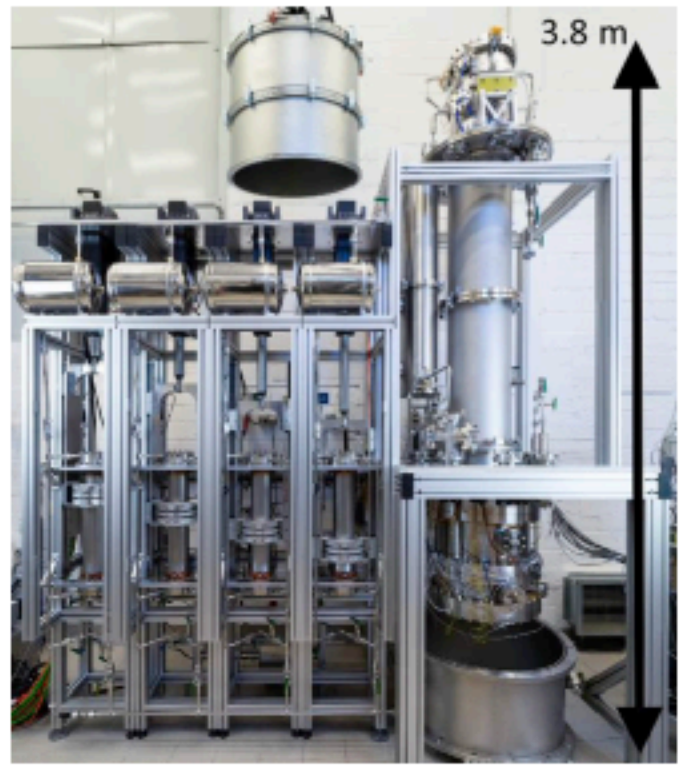
Radon, Krypton

- Direct removal in liquid phase, possible, but challenging.
  - Reduction: $r = \dfrac{\tau_{Rn}}{\tau_{Rn} + T_{circ}}$
  - Factor of 10 at 100 tons requires ~200 tons/day processing.
- Online distillation for XnT reduced Rn by ~4. (previous talk by C.Weinheimer)
  - Challenge of scaling pumps
- Phase swing absorption is possible alternative - SLAC R&D

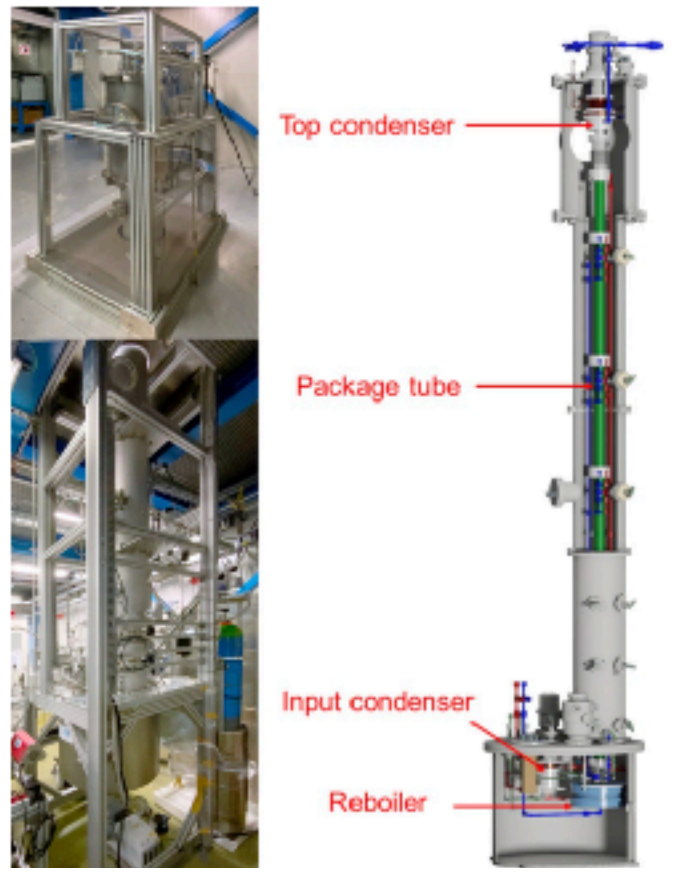
- Kr must be removed for ^{85}Kr - not an issue for *ßß* decay.
  - Also effectively removed by distillation, either offline or online.
  - LZ used offline chromatographic system

XENONnT purification system





Rn distillation column for XENONnT (reduce ^{222}Rn - hence also ^{214}Bi - from pipes, cables, cryogenic system)



Kr distillation column for XENONnT, EPJ-C 77, 2017

(from Baudis, lowrad23)

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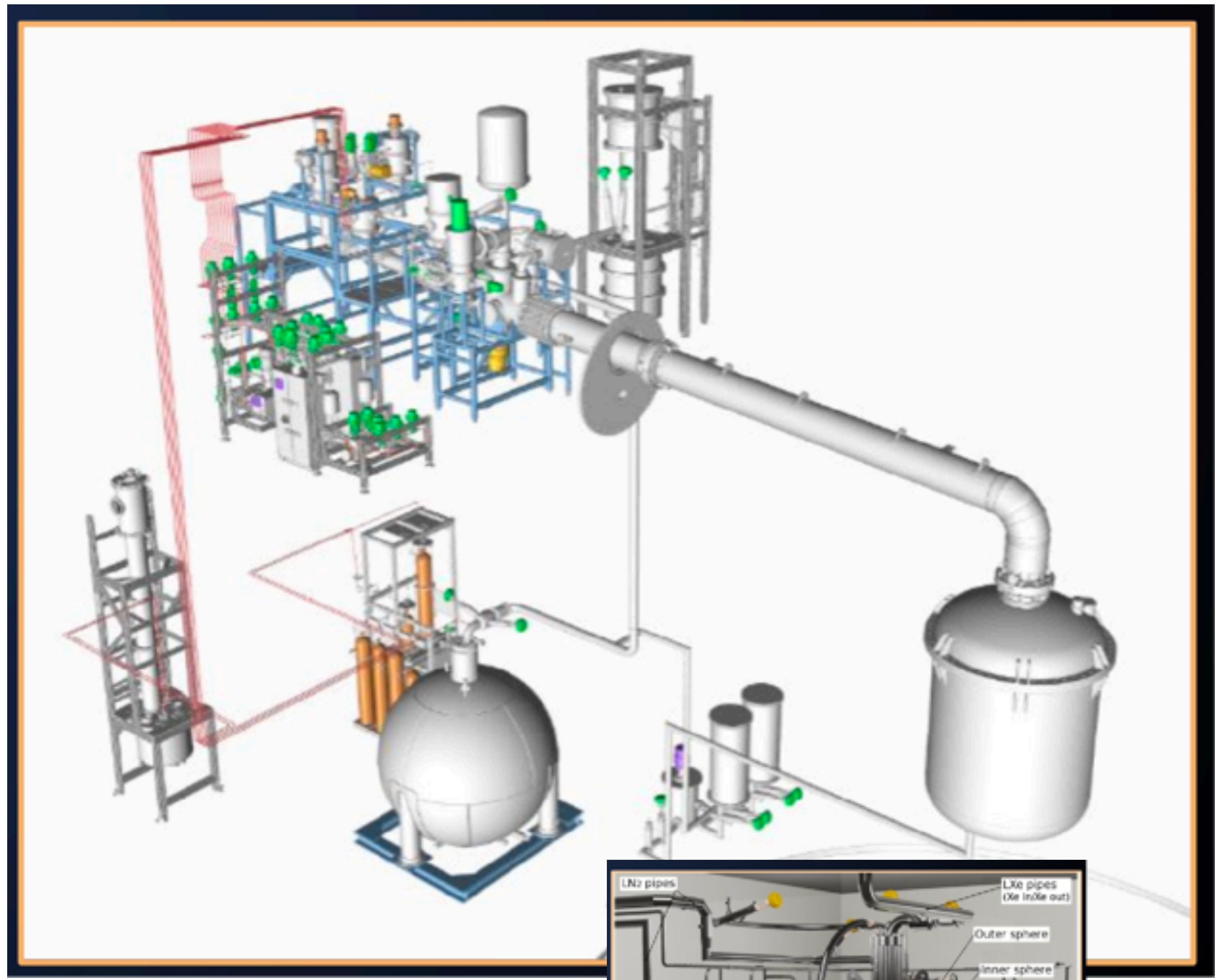
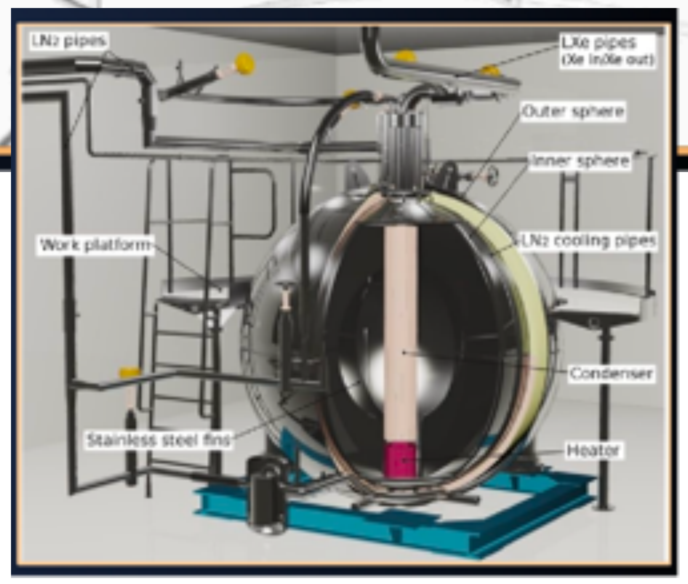
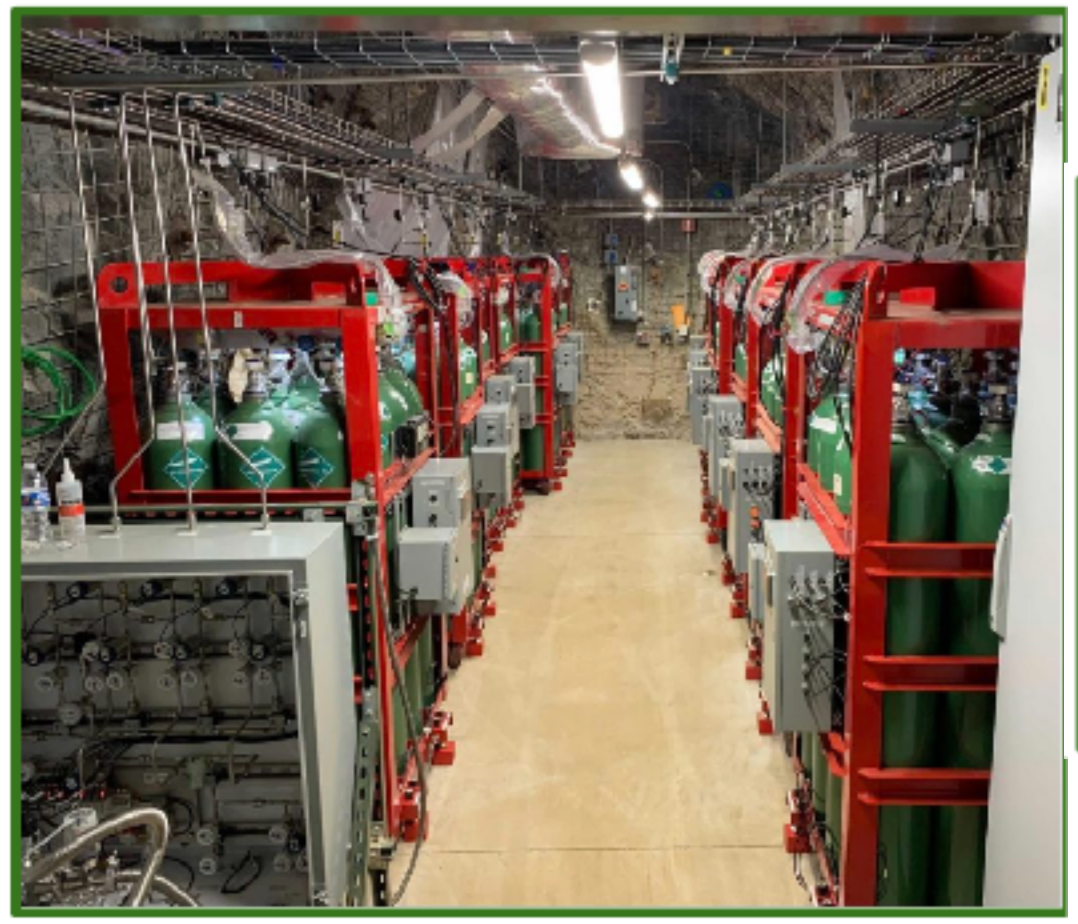
Cryogenics and Xe handling

- Major issue is "fail-safe" recovery of Xe in event of power outage or other problems
- Hard to make general observations, as many details depend on underground infrastructure
- XENONnT (and X1T) featured liquid (or gas) recovery to a combination cryogenic and pressure vessels, based on available LN.
- LZ recovery based on commercial compressors to standard cylinders, based on available diesel generators.

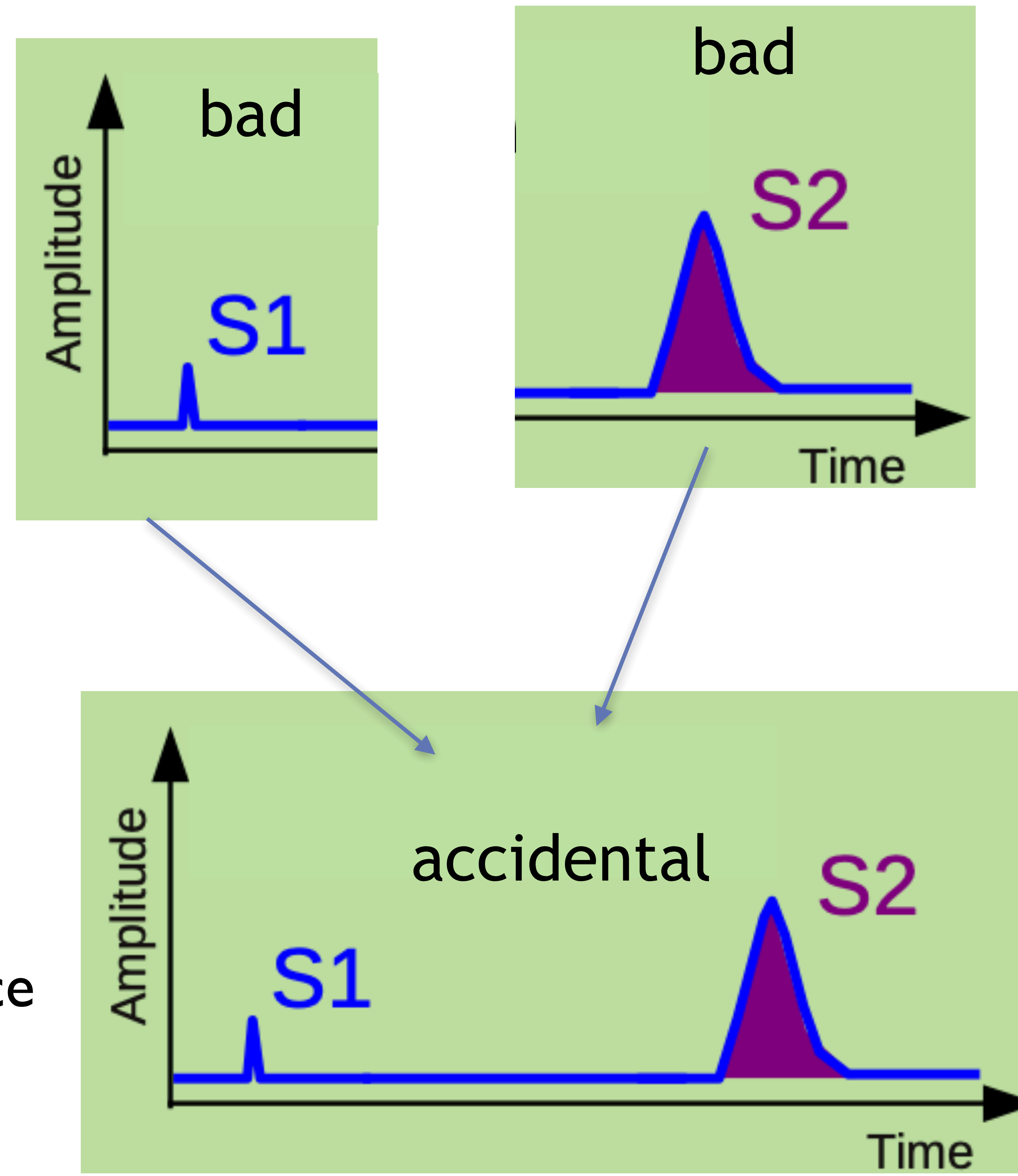




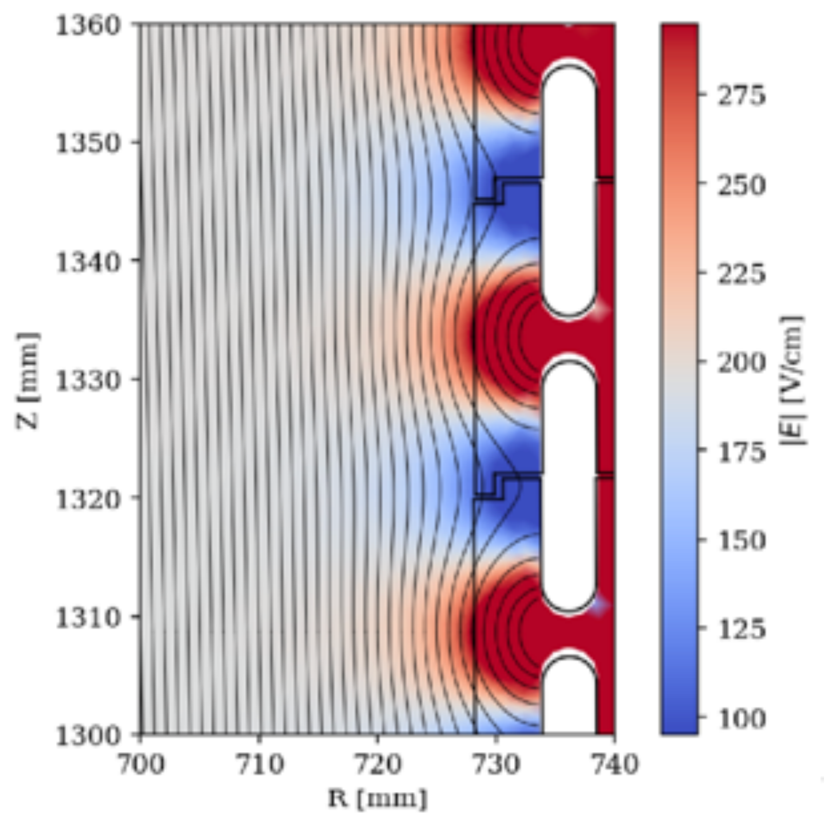


Accidental coincident events

- Accidental coincidence of isolated S1s (with no S2), and isolated S1s (with no S2) have emerged are significant, but not yet dominant background in recent DM detectors.
  - example - 1.2 events in first LZ result, at S1 threshold.
- There are many potential sources, with the the rates from each not fully understood. Study in XnT and LZ data ongoing.
- Isolated S1s:
  - Single photo-electron (SPE) pileup: important up to 4 or 5 PE. Dominate SPE rate (in LZ) is fluorescence following S2. Scale with S2 size and rate; likely scales as $M^{2/3}$. Also PMT (or SiPM) dark rate, also $M^{2/3}$, possibly other discharge sources. $M^{2/3}$ is 4.6 x 10->100 tons.
  - Multiple PE. There is some rate of these extending to large size. May come from regions with no change, such as below the cathode, or at irregular fields as the walls. Possibly from PMT “flashers”, known since at least SNO. Also possibly leakage from other inert Xe in skin or around grids. Most of these scale a $M^{2/3}$.
- Isolated S2s:
  - Single electrons follow large events, at same S2 location. From both trapped charges at liquid, and release from negative impurity ions along S2 drift path. Grid discharge may also contribute
  - Multiple electrons: pile-up of single electrons. Events near liquid surface. Directly created by multiplication during emission from sharp points (A. Bailey thesis). Other discharge? Likely scale as $M^{2/3}$.



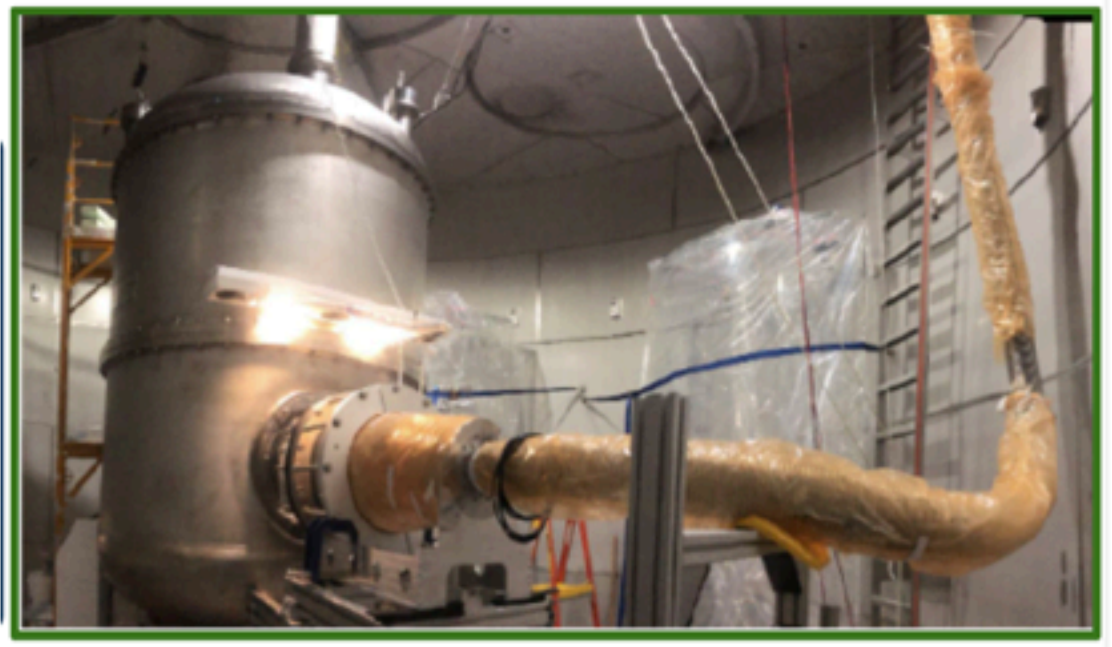
example: loss at walls

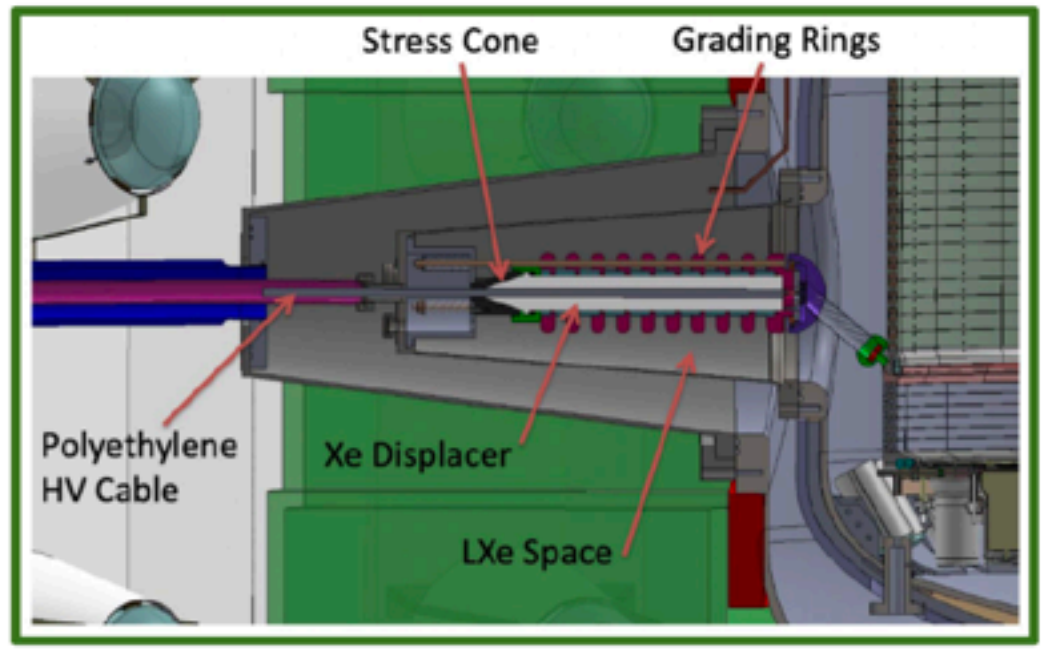


High voltage

	Cathode - Design (kV)	Cathode - Achieved (kV)
LUX	100	9
EXO-200	50	12
X1T	100	12
XnT	24	2.75
LZ	50	32

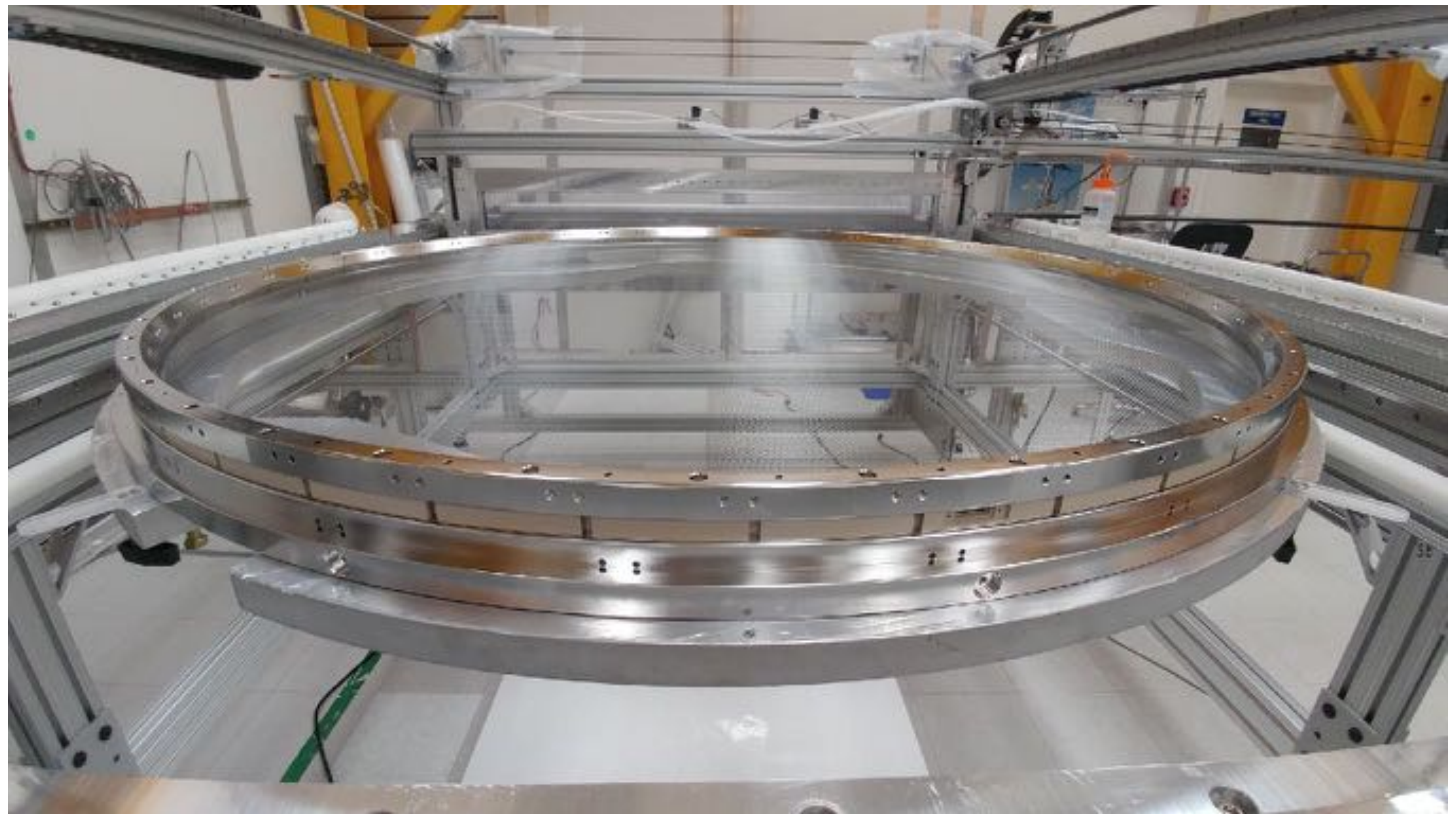
- High voltages arguably biggest challenge for LXe TPCs.
  - Drift field optimally ~200-300 V/cm
  - Extraction field: 2 kV cm - ~5 kV/cm
  - Optimal configuration has not yet been achieved.
- HV feedthrough mostly a solved problem
  - Example: ProtoDUNE LAr - 3.6 m drift, 180 kV, 500 V/cm
  - However:
    - More expensive LXe buffer around cable
    - DUNE detectors not sensitive to low levels of light from discharge as seen with DM/ßß decay light collection.





Grids

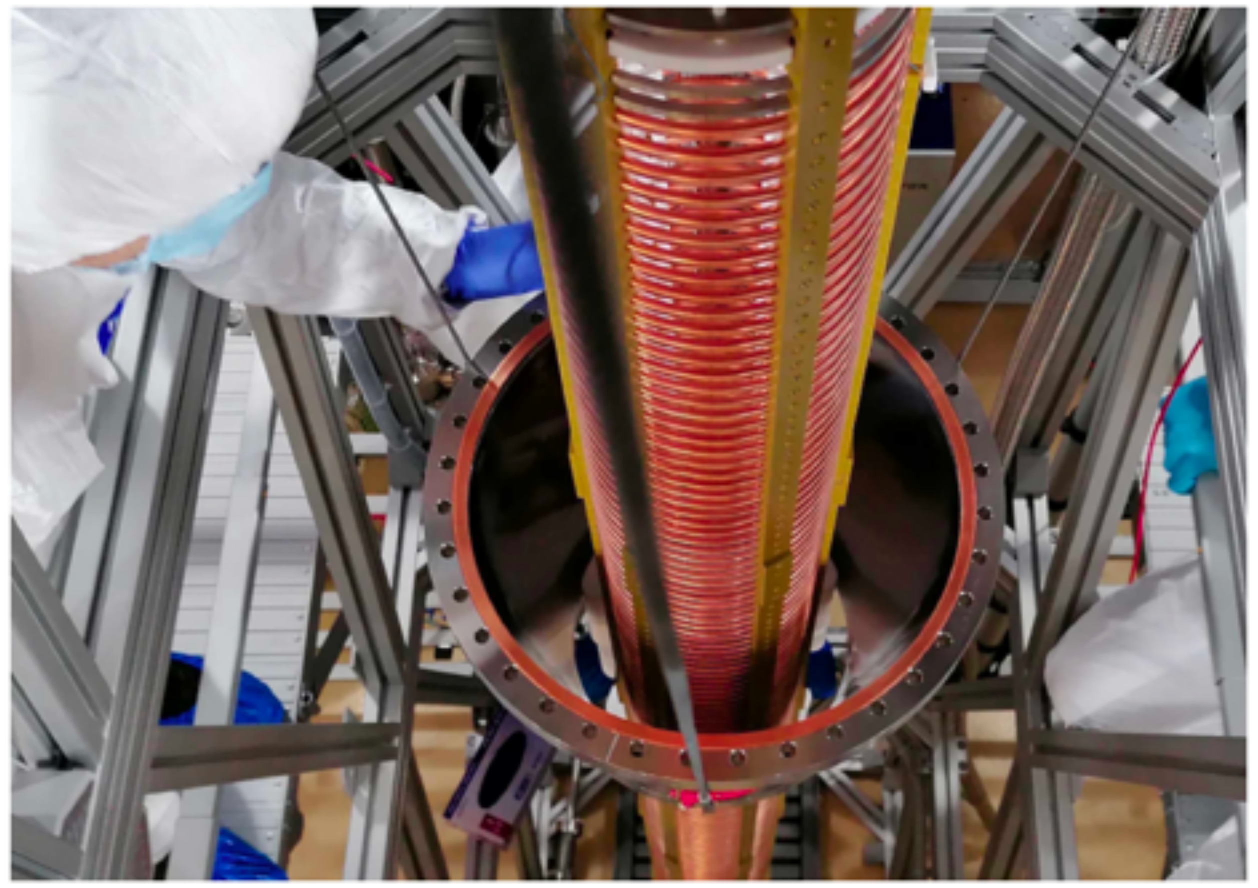
- Electrode grids one of the biggest scaling challenges.
- Mechanics
  - Deflection under electrostatic load: $\delta z \propto \frac{Tension}{L^2}$
  - LZ/XnT ~1.5 m grids near practical limit for SS.   Probable use of spacer to reduce span
- Electron emission from cathode and gate
  - Fundamentally, tradeoff between light collection and surface fields on grids.
  - Passivation used by LZ, XnT.   Had impact, but not fully developed
  - Other metals - e.g. BeCu ~50 kV/cm SS surface field limit.
  - Coatings?
- Several production methods
  - Not practical at XLZD scale (?): commercial fine mesh, electro-etched meshes
  - Stretched wires - XnT, LUX, others
  - Loom woven meshes - LZ
  - New: spot welded mesh - KIT.
- Uniformity of grids important for high fidelity signal shape - important at low energy



Testing

- High voltage testing is key
- Only recently pursued at large scale
- Not trivial
  - Very high background rate in unshielded environment.
    - SLAC 1.5 m Ø gas test: 40 kg Xe
  - Need (?) single electron sensitive readout to test for low level emission
- Shieled, underground testing for XLZD being serious considered - Kamioke?

Zurich

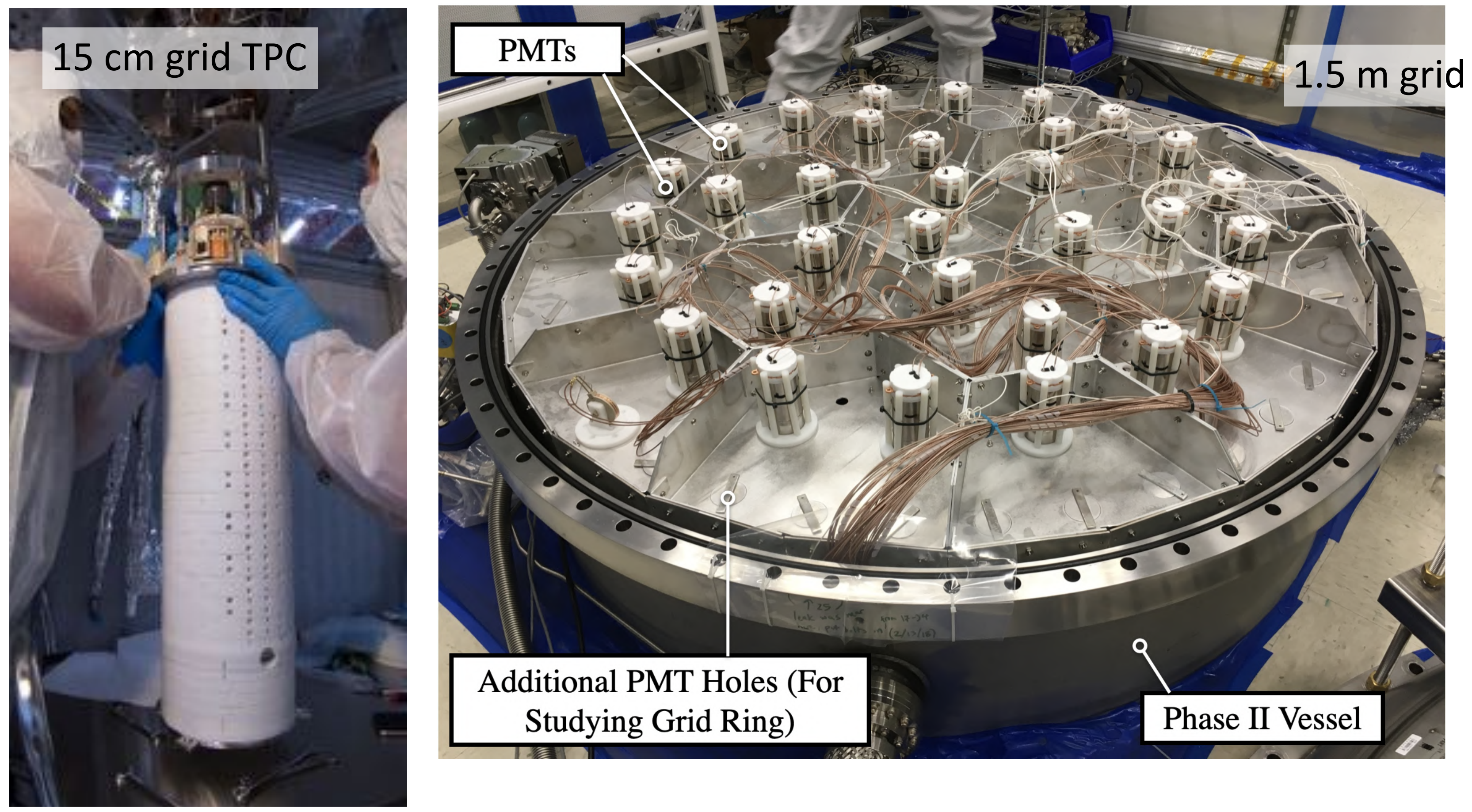


Xenoscope, JINST 16, P08052, 2021

Freiburg

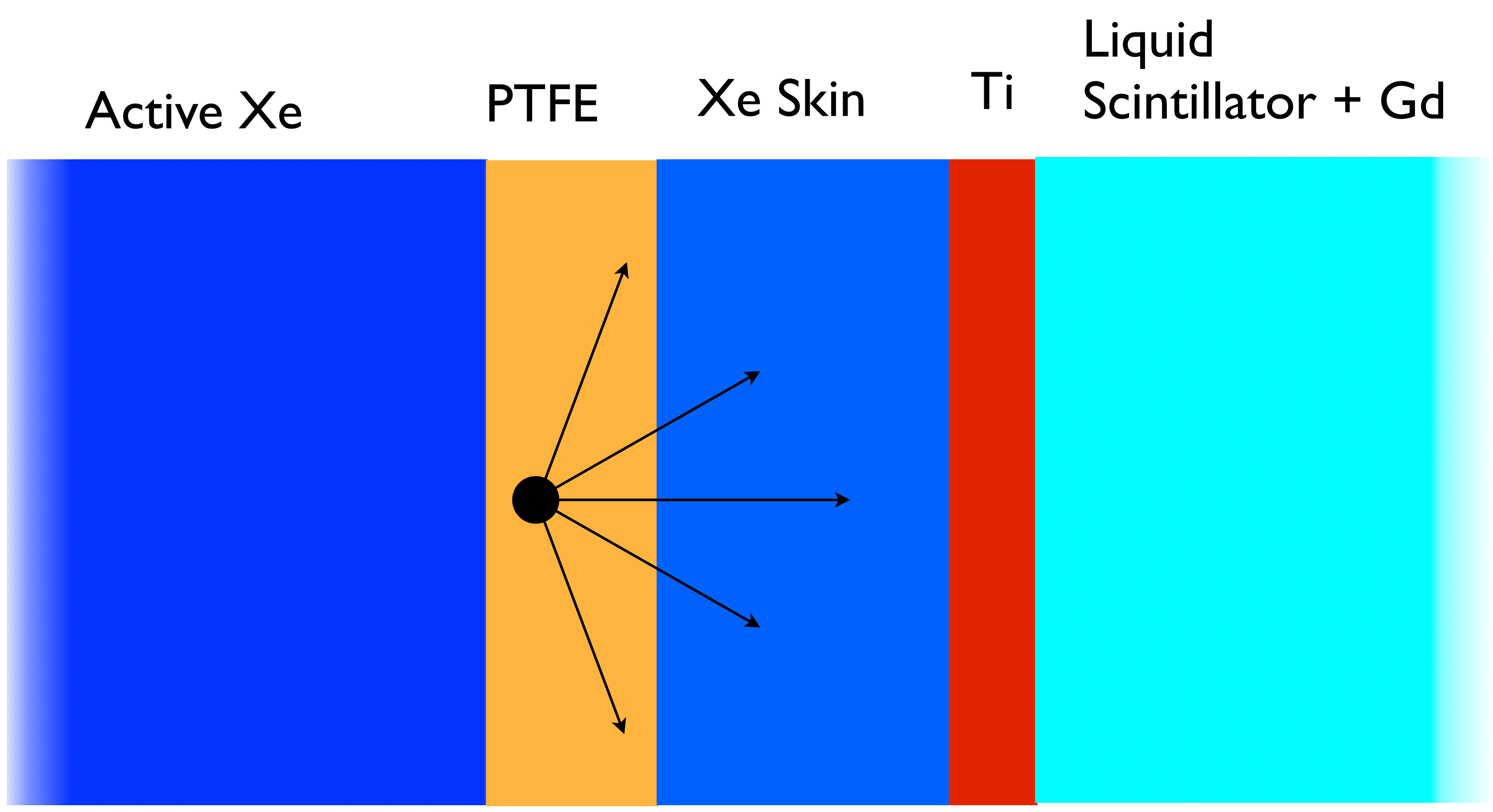
Pancake, Test electrodes with 2.6 m Ø

SLAC



Veto / Outer detector

- For large DM experiment, main use is neutron tag, with signal boosted by capture on Gd.
  - XnT: Gd-loaded water (though Gd not yet deployed); LZ: Gd-loaded scintillator
  - Gd: σ_n=240 kb, largest for stable elements, greatly reducing capture time: 200 μs -> ~30 μs at 0.1% doping
  - Big gamma signature (3-5 gammas, ~8 MeV) following capture
  - Recently water based scintillator liquid scintillator attractive (see Theia talk by Kaptanoglu), if Gd doped
- For ßß decay, LZ outer detector + LXe skin highly effective for gamma rays.
  - Skin is ~5 cm thick layer used as HV standoff, lined with reflective PTFE and readout with PMTs.
  - Only efficient gamma veto requires both skin and outer detector:
    - Skin (≥ 2 cm LXe) absorbs > ~30% of MeV gamma rays.
    - TPC + outer scintillator, or TPC + skin, only 70% efficient vetos of internally generated gamma rays
    - TPC + skin + outer scintillator can exceed 95% efficiency



Innovation at 100 ton scale

- Several quite different designs are being proposed
  - Example - single phase with S2 production in liquid
- Especially for dark matter, there are a number of cautionary tales of problems due to small details.
  - Examples: regions of poor light collection in XMASS, DEAP
  - Unexpected backgrounds in CDMS I + EDLEWEISS, CRESST, PICO.
- Need testing at scale - full size, full voltage, low rate

- Probably less of a concern at high energy of *ßß* decay, but worth keeping in mind.

Towards 1000 tons

- This is not large compared to DUNE - scale of ProtoDUNE
- 7 m LXe detector
- Self shielding will be very powerful
- Several things not really harder than 10, or 100 tons:
  - Purification, HV feedthrough,
- Harder:
  - Grid mechanics
  - Liquid surface alignment with grids
- Ti cryostat required?

Ti, SS radioactivity - LZ