Design of a cryogenic capacitive liquid level sensor

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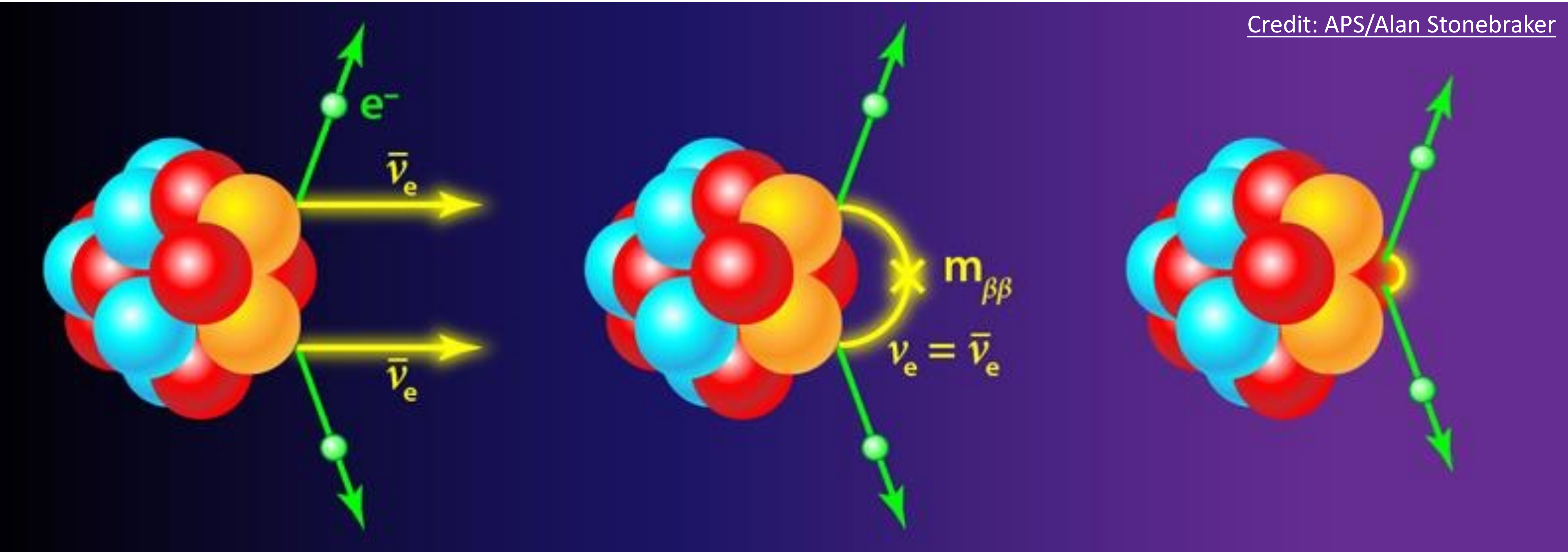
The end goal: nEXO

LoLX

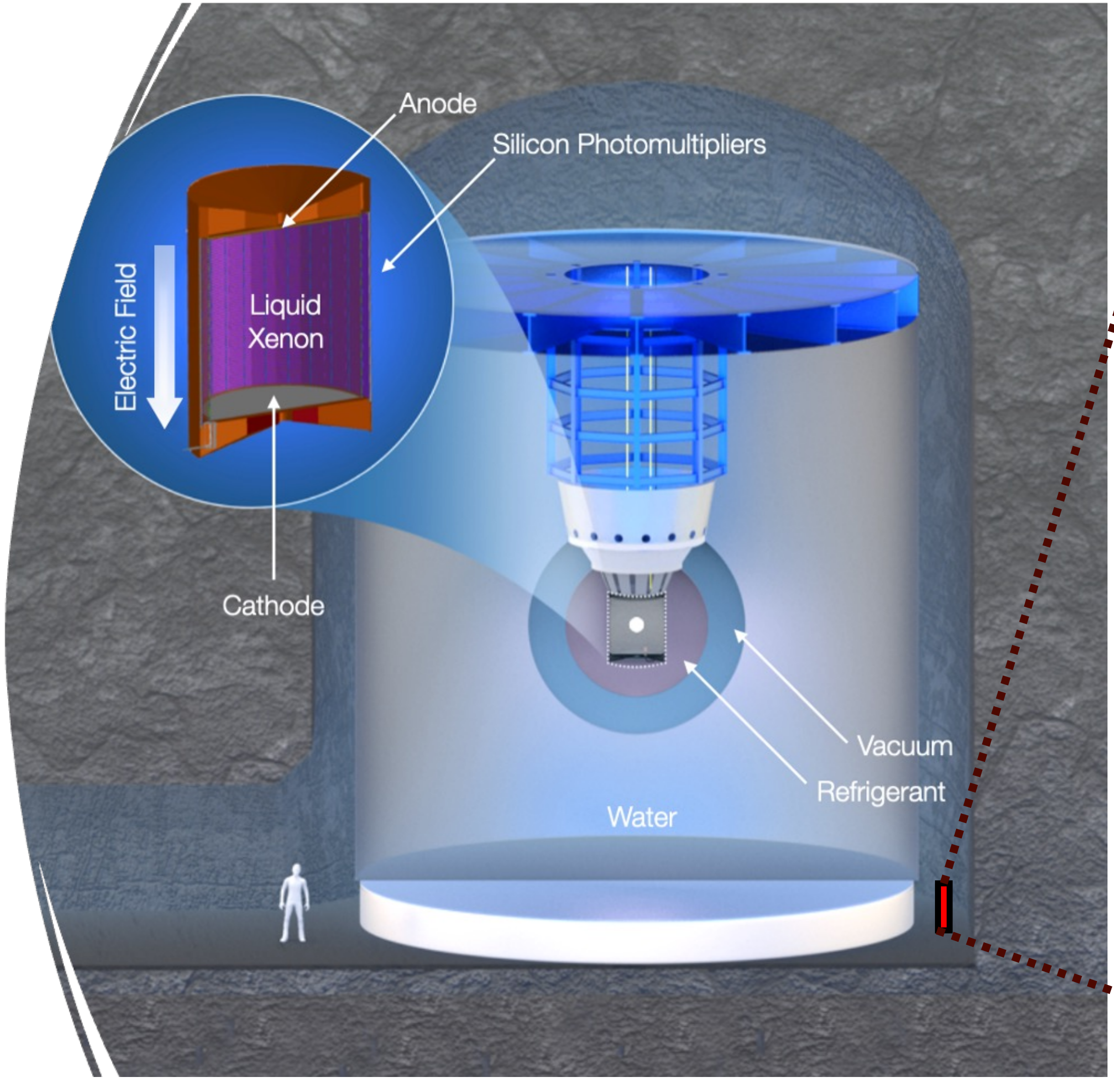


nEXO will search for $0\nu\beta\beta$ using a liquid xenon (LXe) time-projection chamber and silicon photomultipliers (SiPMs).

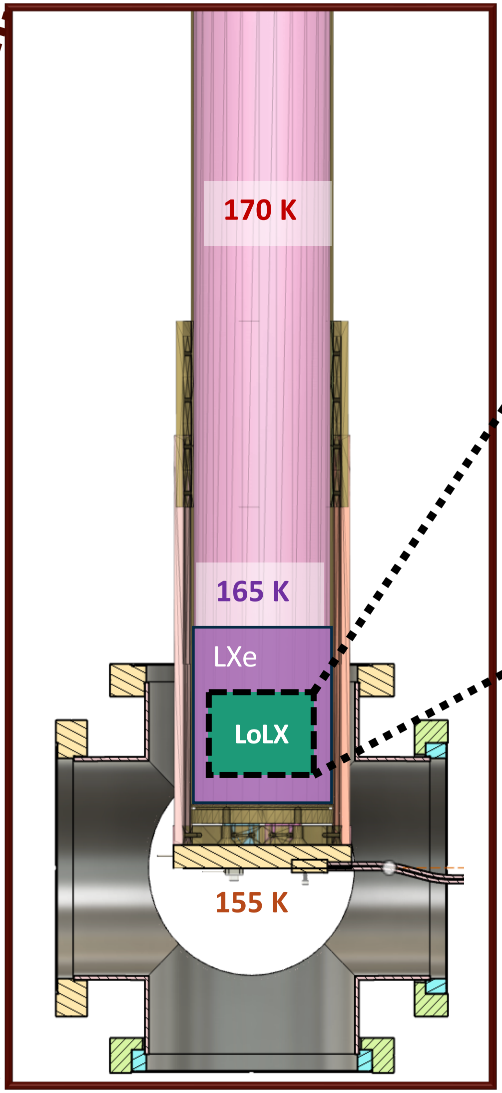
If found, $0\nu\beta\beta$ would demonstrate physics beyond the Standard Model.

Scaling back a little…

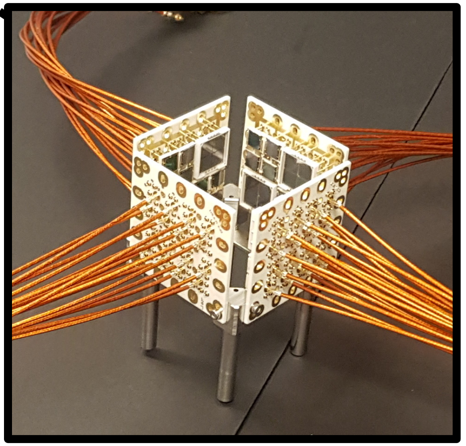
nEXO: 40-50k SiPMs



The LoLX cryostat. Credit: David Gallacher



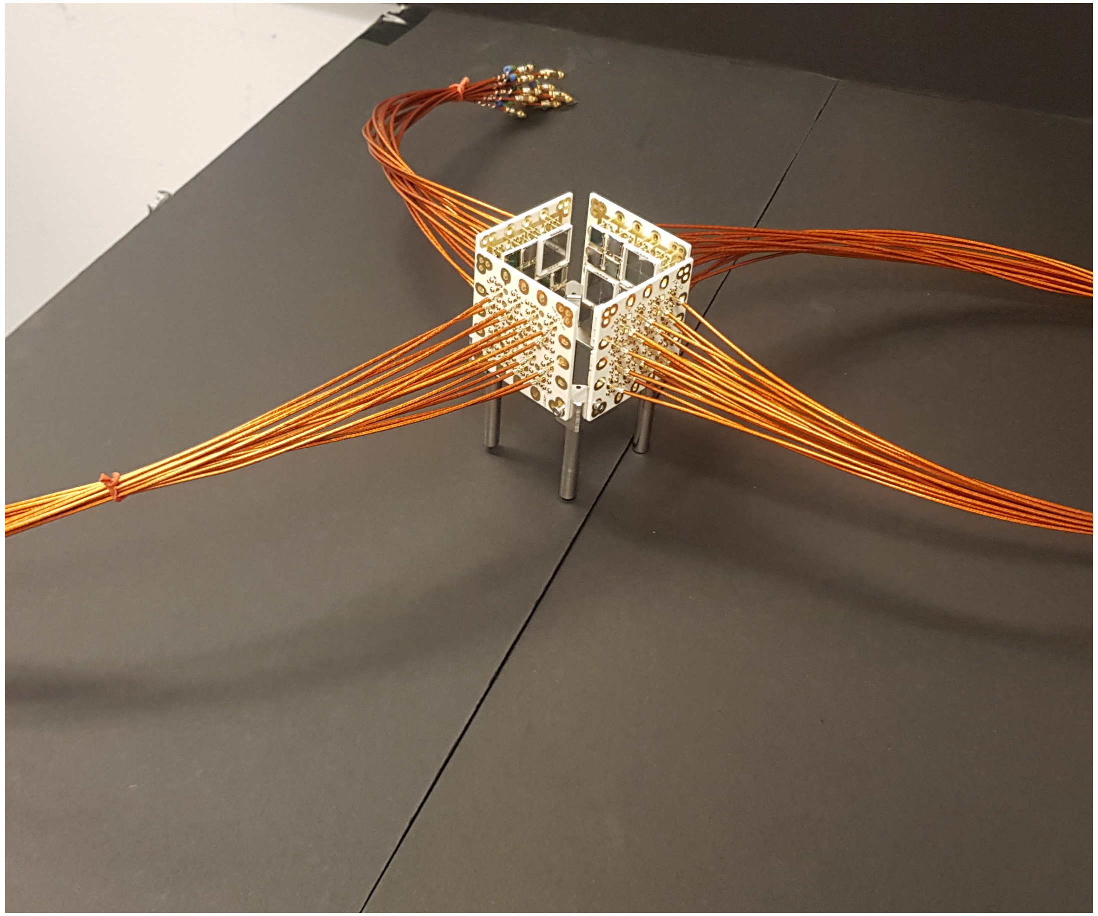
LoLX: 80 SiPMs



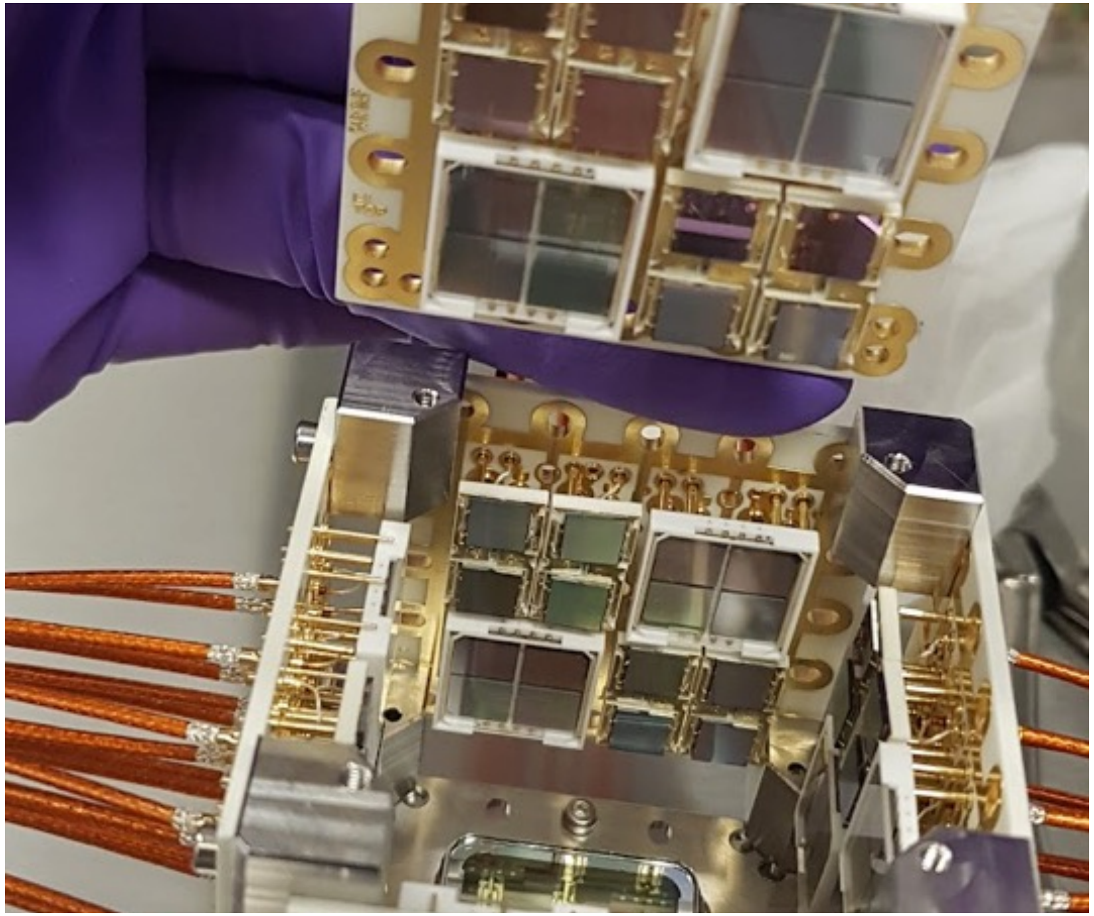
What is LoLX for?

The LoLX experiment is

Studying scintillation light in LXe



Characterizing SiPMs in LXe

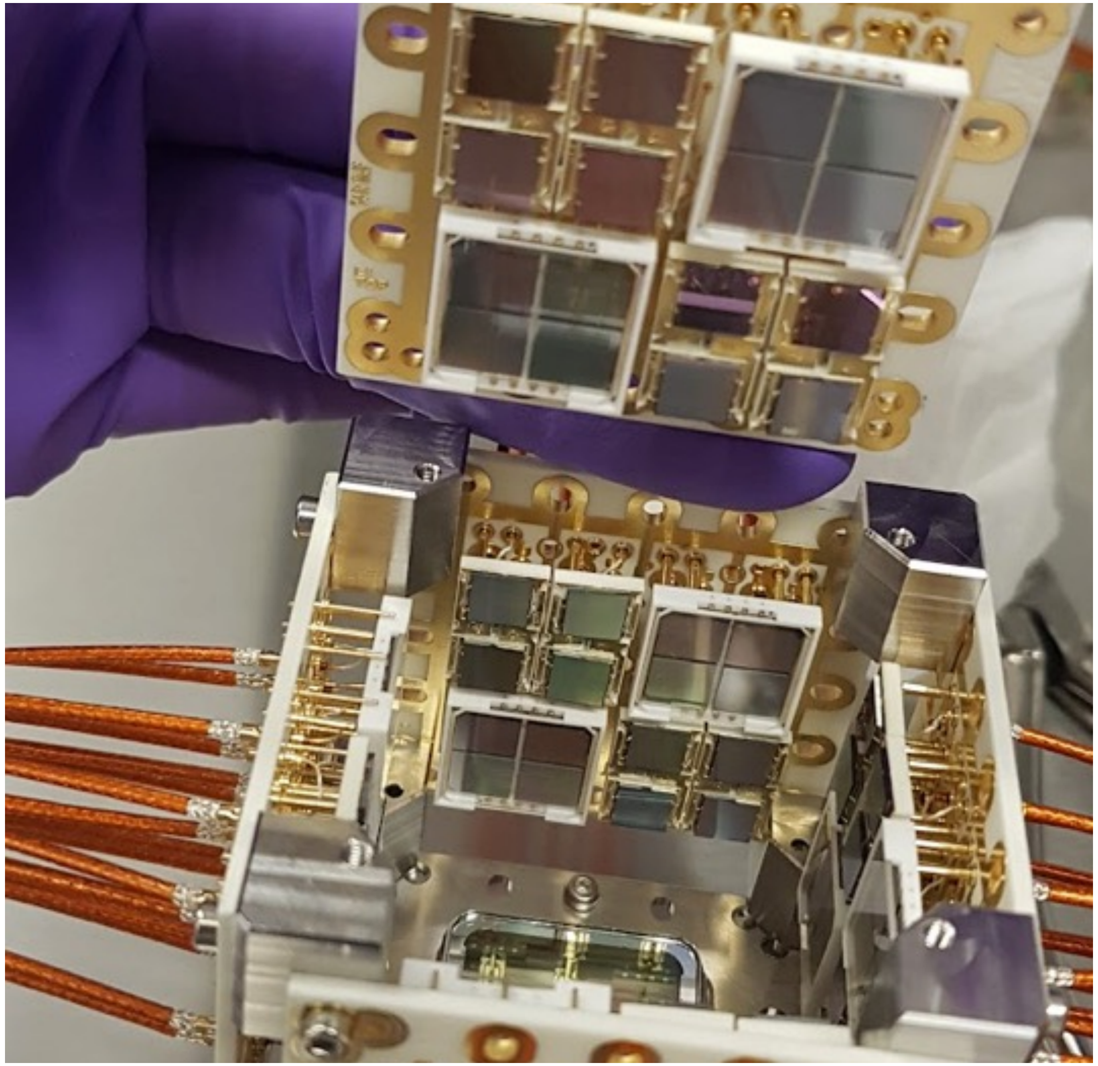


Photos: Stéphanie Bron

Why do we need a liquid level sensor?

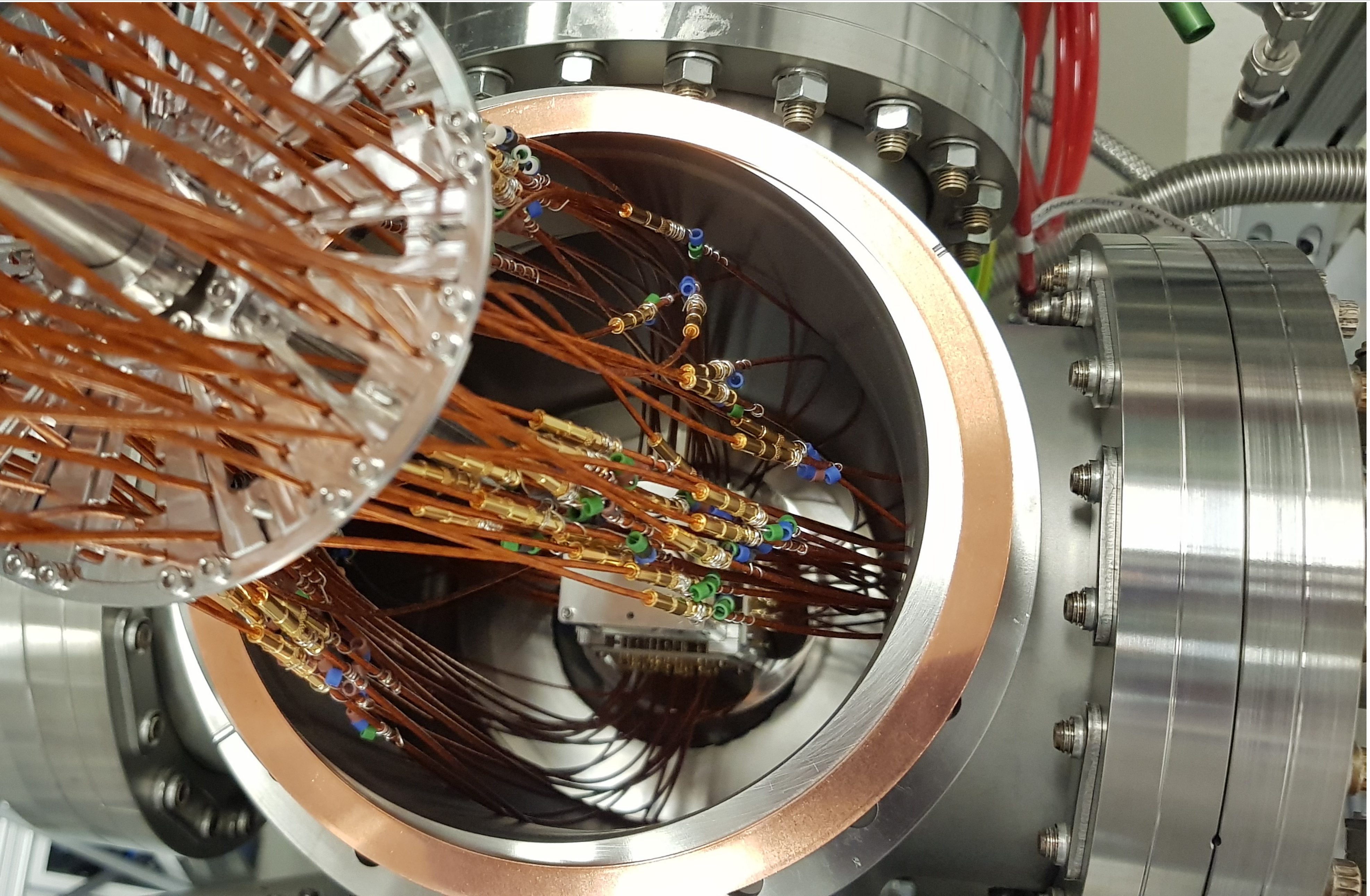
LoLX

- To know if the SiPMs are working properly, we need to know which of them are submerged
- A liquid level sensor would tell us what to expect from the SiPM responses and confirm temperature uniformity



Constraints on the liquid level sensor

LoLX



Space

See picture

Liquid xenon

Cryogenic environment

Low dielectric constant

Purity

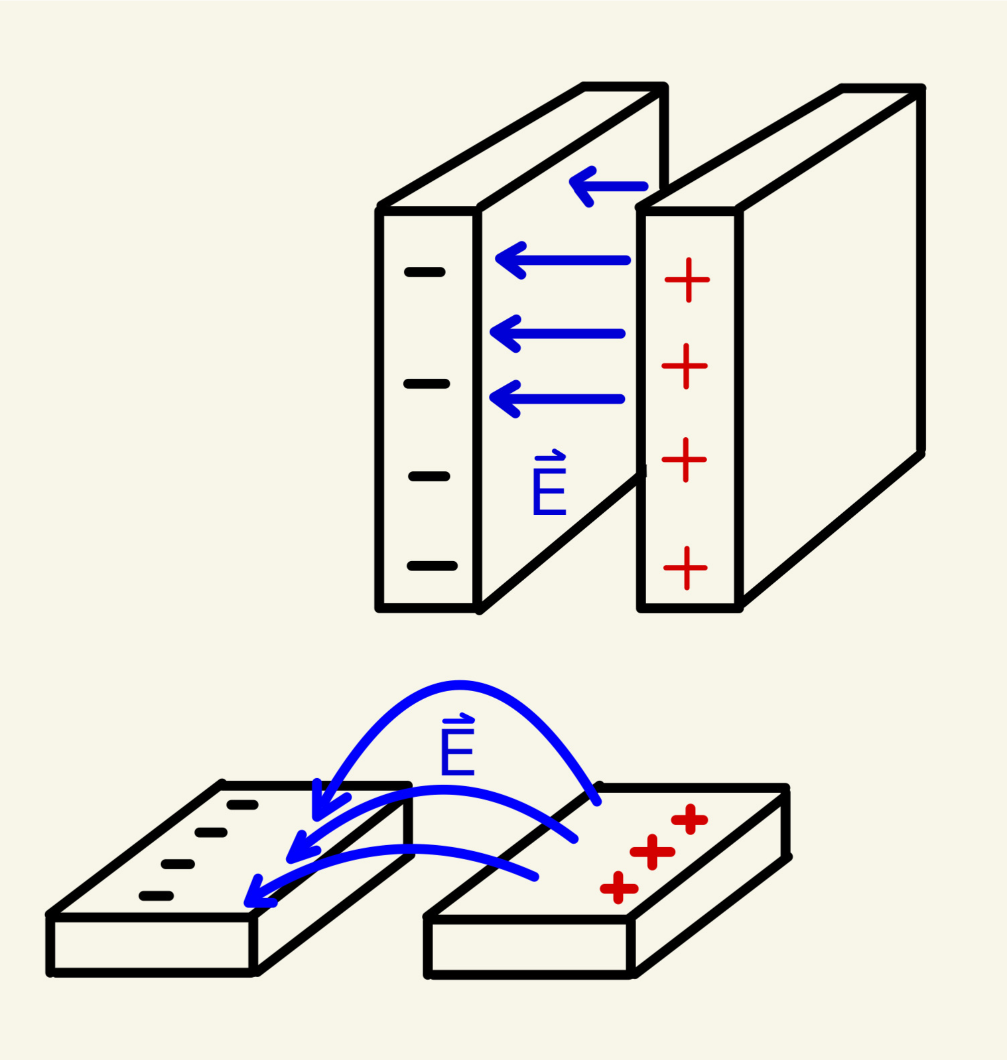
Low outgassing required

LoLX

Prototyping

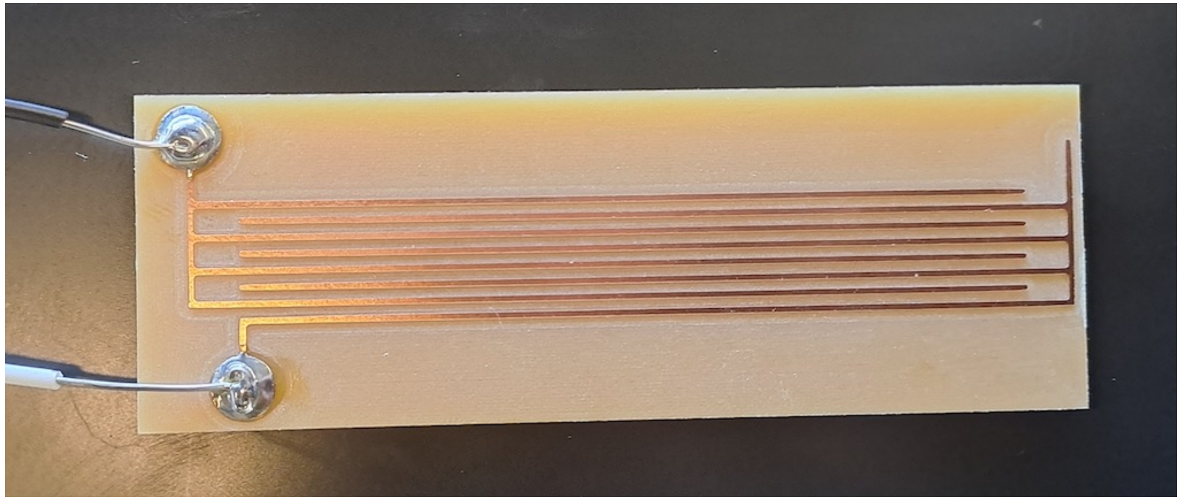
How do we meet all these constraints?
How do we test the sensor outside the LoLX cryostat?

Idea: 2D capacitor



- A capacitor which would adhere to the wall
- Un-modelable if electrodes are too wide

Interdigitated coplanar capacitor

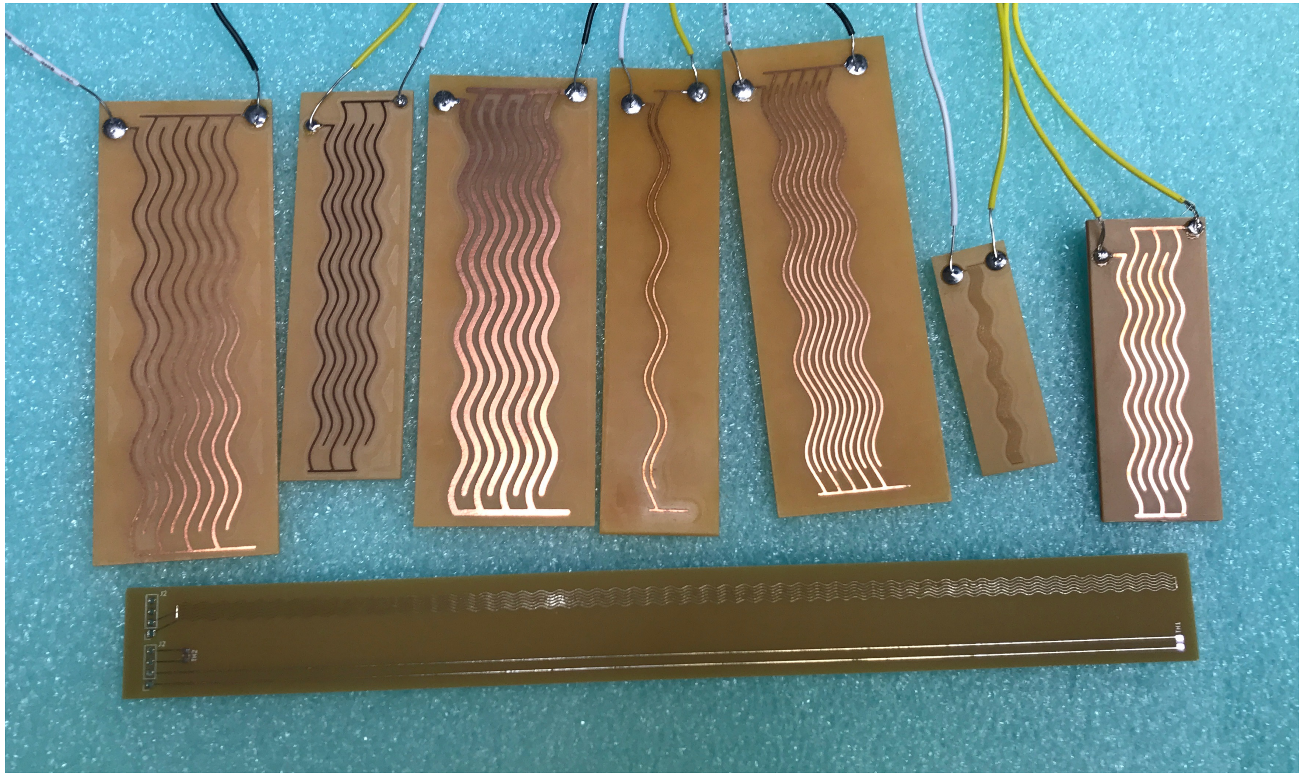


Sinusoidal interdigitated capacitor

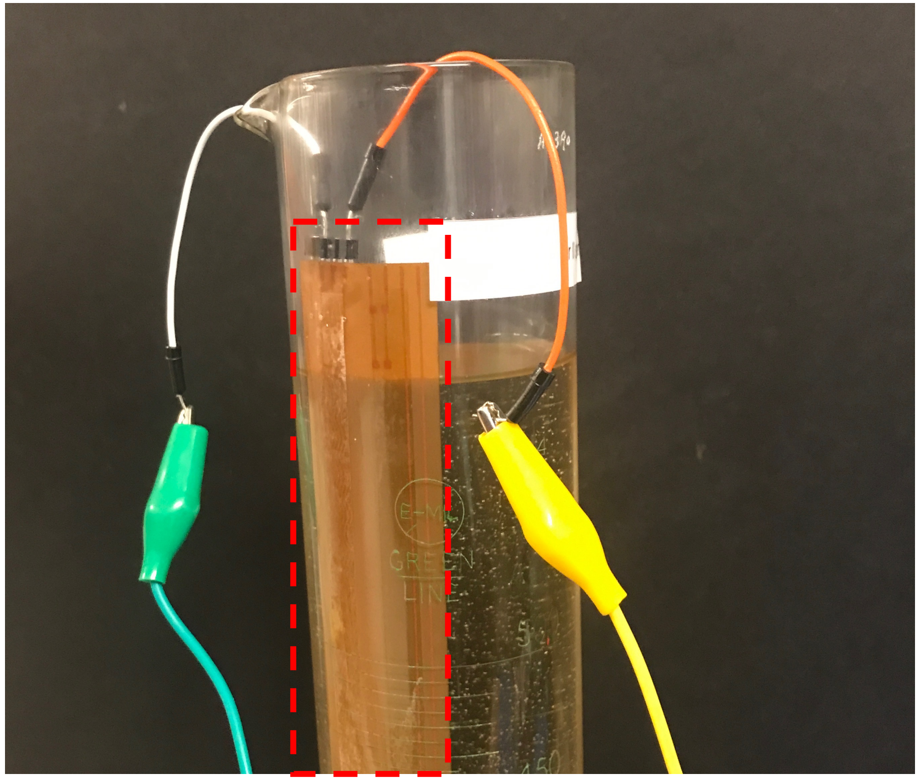
- With a sinusoid, we can have thinner, fewer electrodes for same capacitance – better modeling
- Edges are less sharp – softer discontinuities at top and bottom
- Two questions:
  - Will the capacitance-liquid height relationship be linear?
  - Can we model this well?

Let's do some tests!

"Homemade" prototypes on FR1

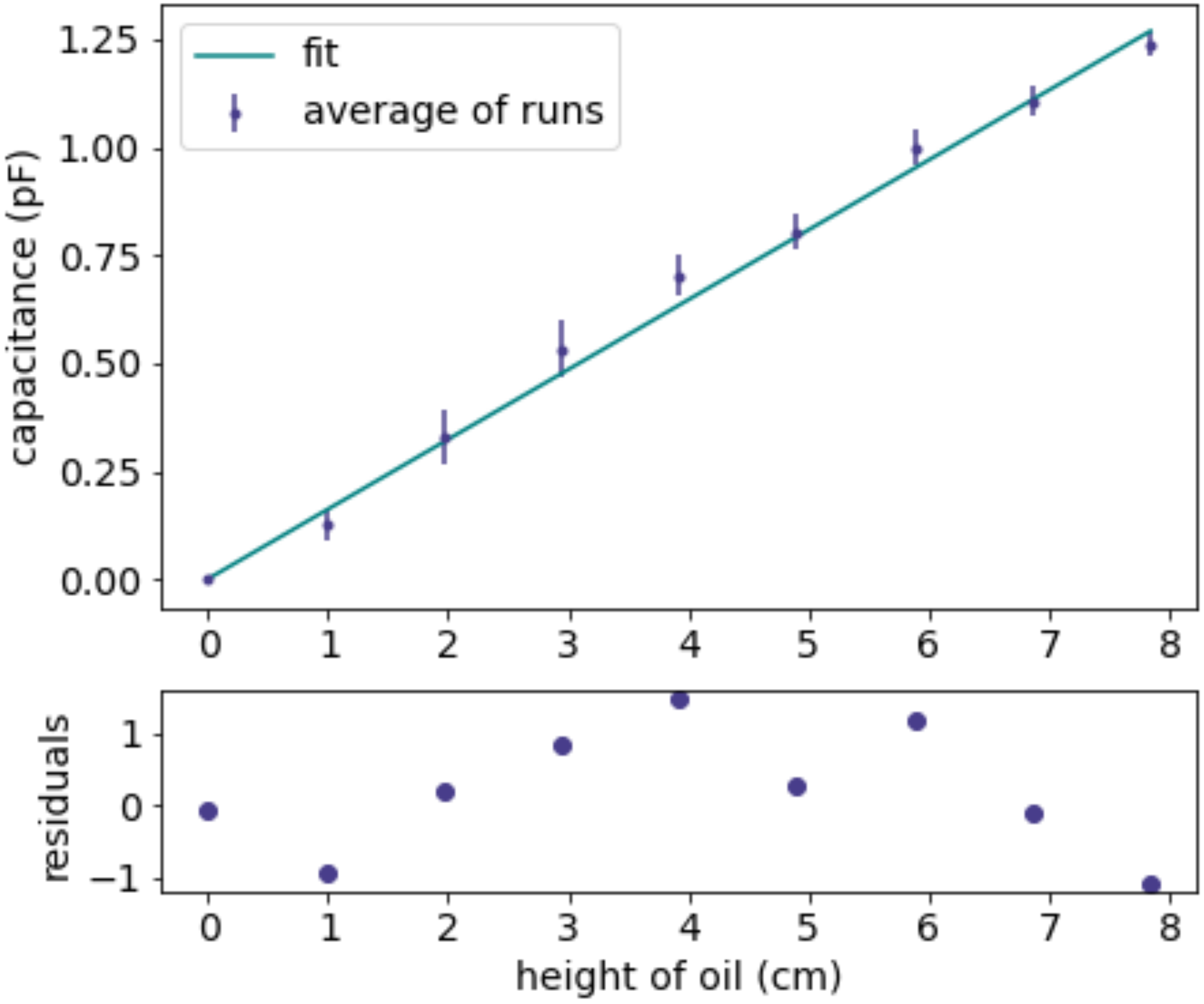


Tests in non-cryogenic dielectric

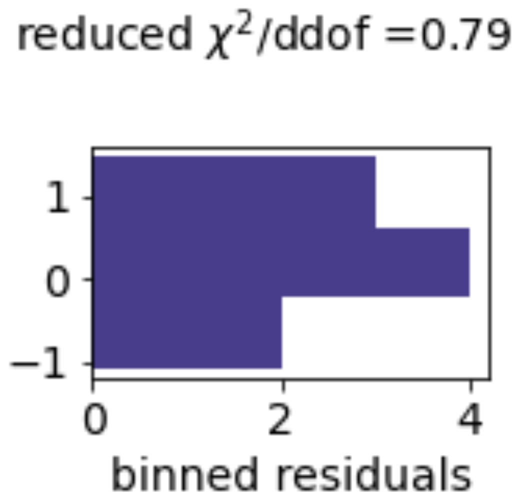


sensor

Linearity

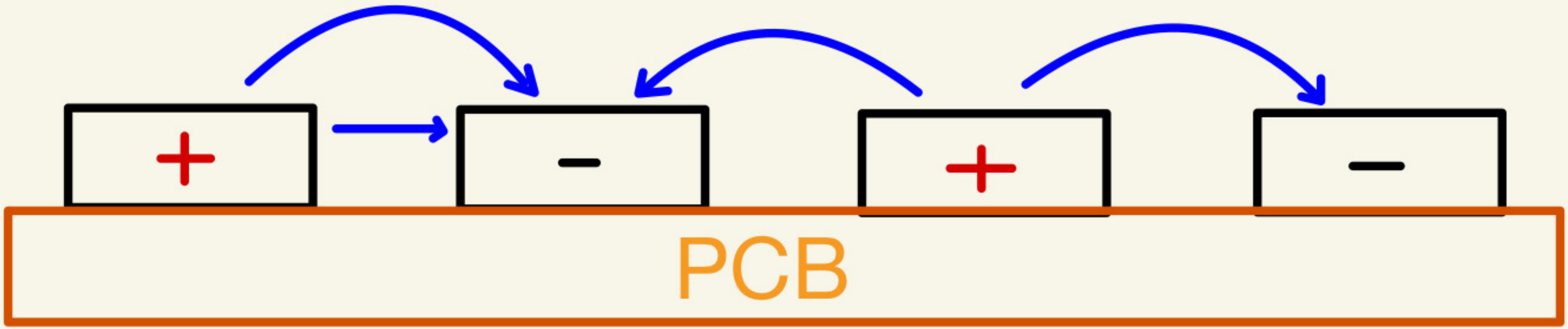


- Capacitance vs dielectric height in sunflower oil (ε_r = 3.29)
  - ε_{LXe}= 1.85
- Residuals seem random



Modeling this capacitor

- Calculate parallel plate capacitance for infinitesimal section
- Integrate over length of sinusoid
- Iterate over only adjacent pairs
  - If you don't believe me, draw a Gaussian surface

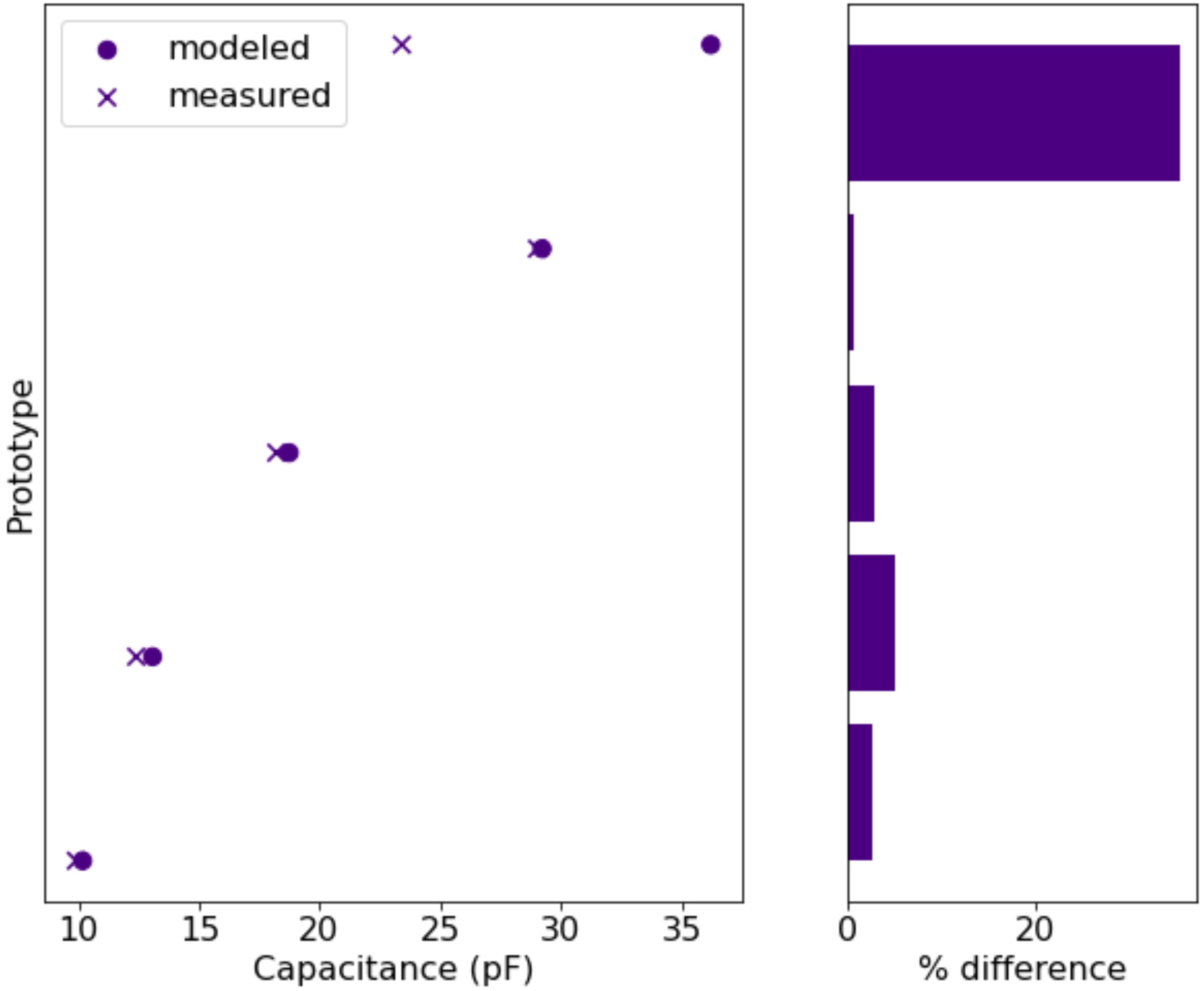


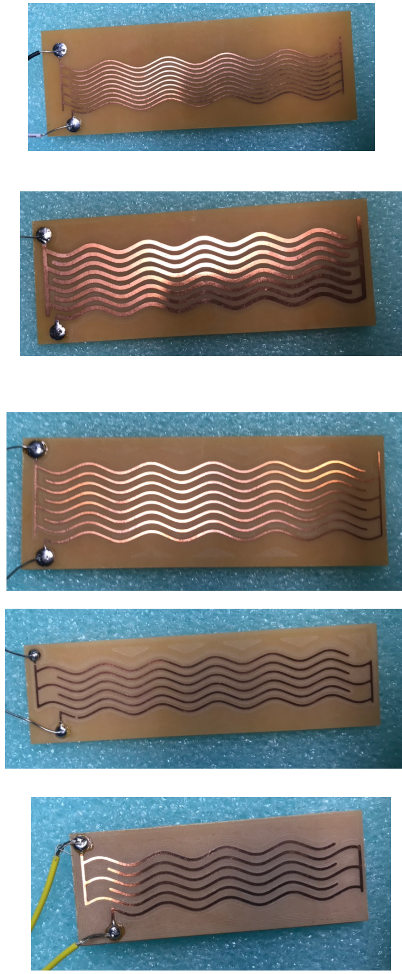
- Find a way to model PCB thickness

Prediction capability

- Multiple prototypes, varying:
  - Number of electrodes
  - Width
  - Length
  - Separation

- Still working on the model, this is its present accuracy





LoLX

From capacitor to sensor

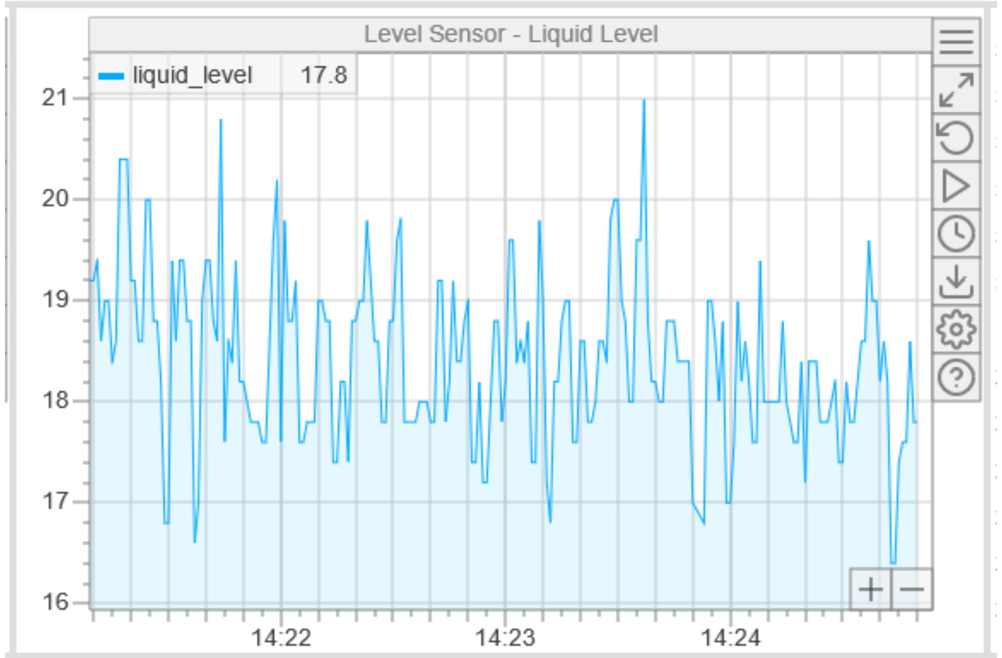
Final version manufactured by PCBway

Electronics readout by FDC1004, Arduino Uno and MIDAS

Electronics readout

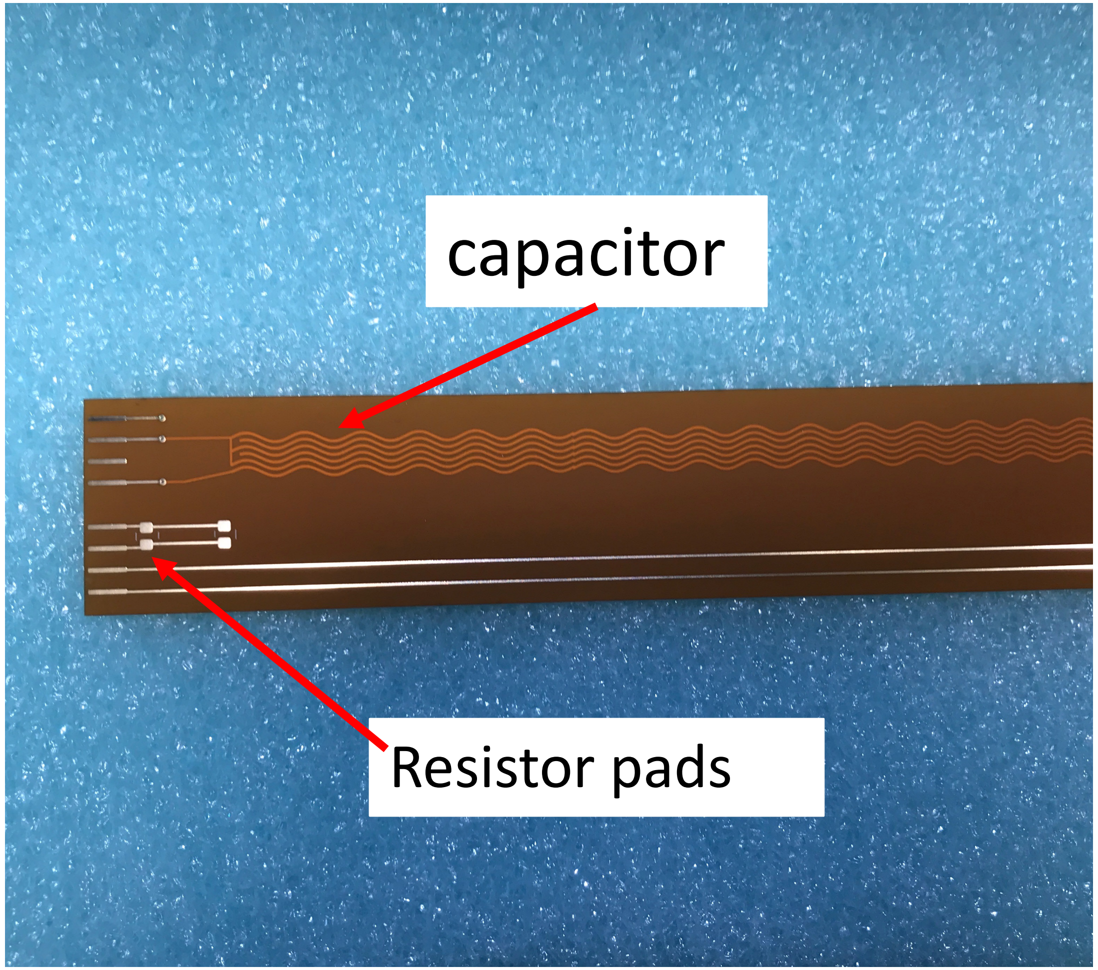
LoLX

- FDC1004 capacitance-to-digital evaluation board
  - Can offset 96 pF
  - Reads a range of 15 pF



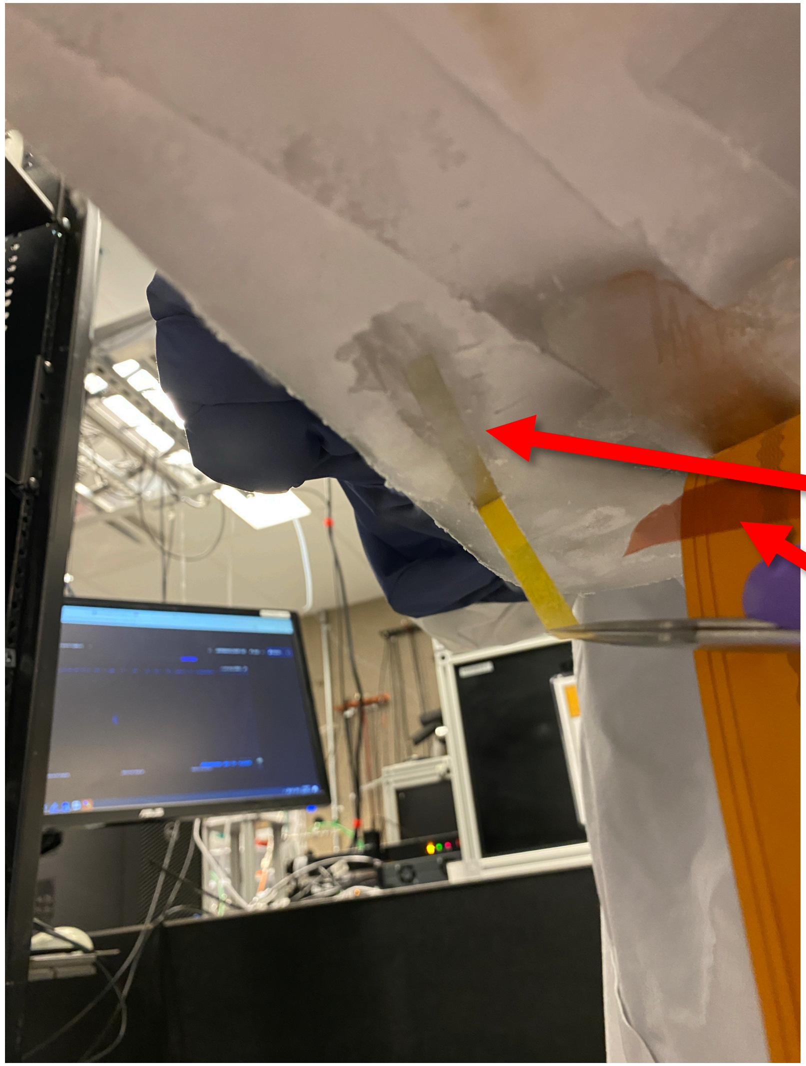
Liquid level readout from a pilot sensor in LN2

The final design



- Multilayer Kapton PCB
- 30 cm long, above the level of liquid xenon
- Projected capacitive sensitivity of 0.1889 ± 0.0001 pF/cm in LXe
  - This corresponds to a liquid level resolution of < 1 mm
- Calibration
  - Temperature-sensitive resistors
- Cabling and feedthrough
  - Kapton-insulated twisted pair
  - Pin feedthrough flange

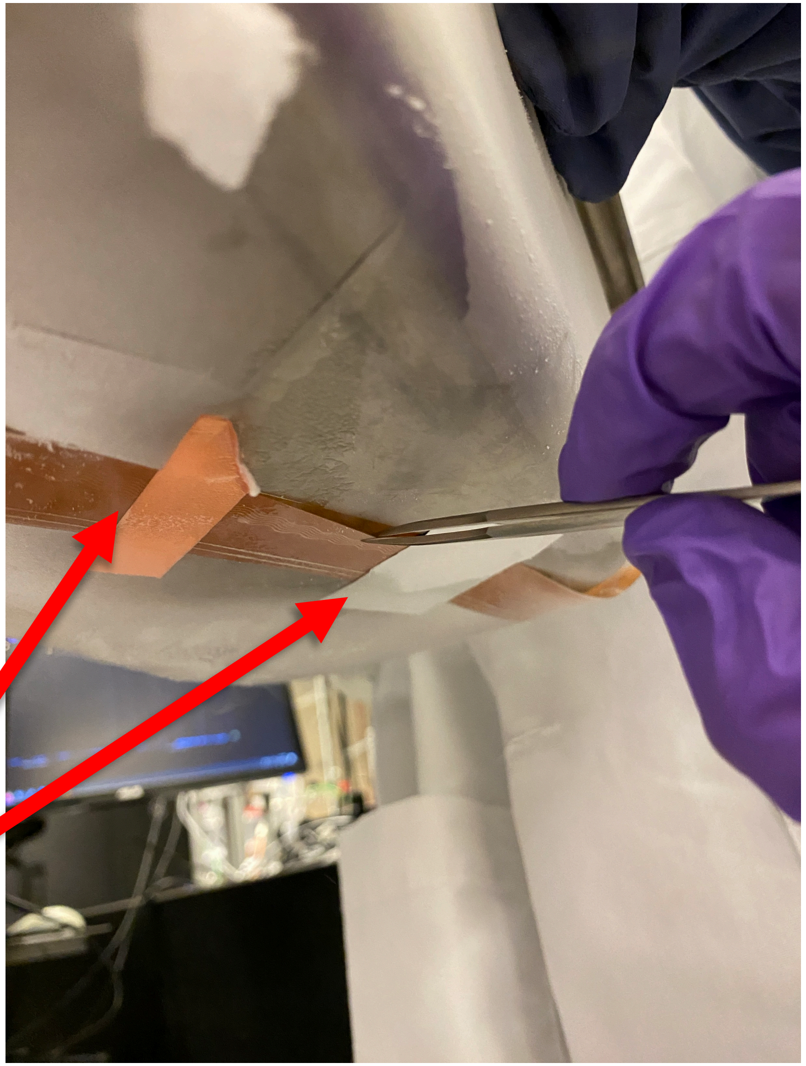
Choosing an adhesive



We cooled various tapes down to 165K in a mixture of LN2 and dry ice

Kapton tapes delaminated…

But Al and Cu tapes stick!



Conclusions

Summary

- We developed a custom capacitive liquid xenon level sensor due to our constraints
- Thin, flat capacitor with sinusoidal electrodes that adheres to the cryostat wall
- Electronics readout using available-to-purchase materials

What's next?

- Installation at the next run of LoLX, in March
- Improving the model of the capacitance
- Make code and design publicly available on BvL GitHub page

Thank you!

Acknowledgements:

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McGill Faculty of Science, McGill Physics Department

Backup: capacitance calculation

Capacitor of thickness *t*, width *w*, plate separation *d*, length *L*, submerged in dielectric *k* to height *h*

$$C = ((k-1)h + L)\frac{\epsilon_0(w+t)}{d}$$

$$L = \int_0^l \sqrt{1+(bcos(bx))^2}\,dx = \frac{2\sqrt{b^2+1}(E(bx|\frac{b^2}{b^2+1}))}{b}$$