An Atmospheric Xenon TPC for Neutrinoless Double Beta Decay

Nicholas Byrnes

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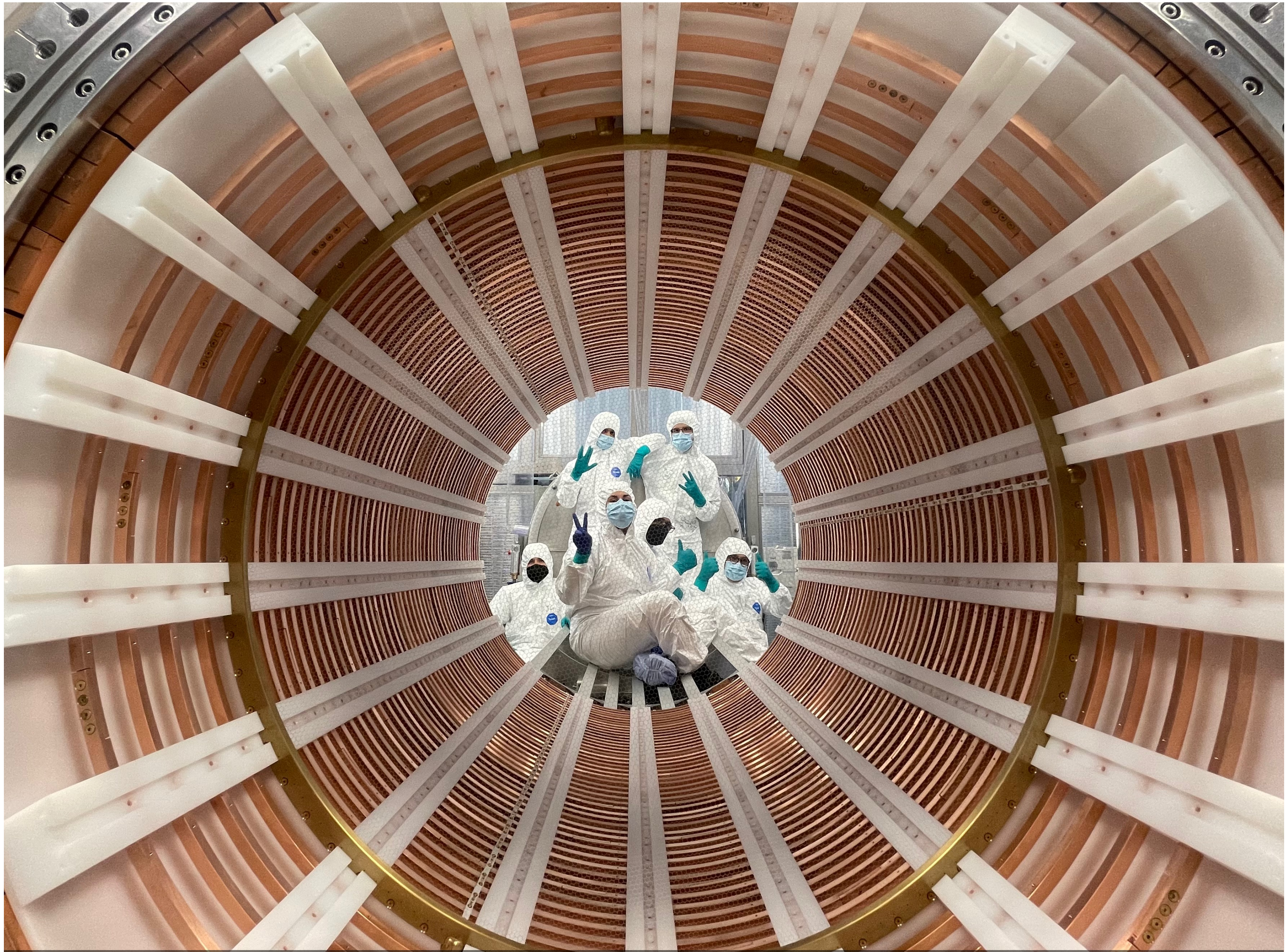
Wait, Atmospheric Pressure?

- To date, the most prominent TPC designs in $0\nu\beta\beta$ searches have used either liquid or high-pressure gaseous ^{136}Xe.
- This is for a simple, and persuasive, reason: As you increase the density of the detector medium, you increase the mass of the target isotope relative to your detector volume.
- If we set that logic aside for a moment, we can ask what overlooked advantages might an atmospheric-pressure TPC offer in the search for $0\nu\beta\beta$?

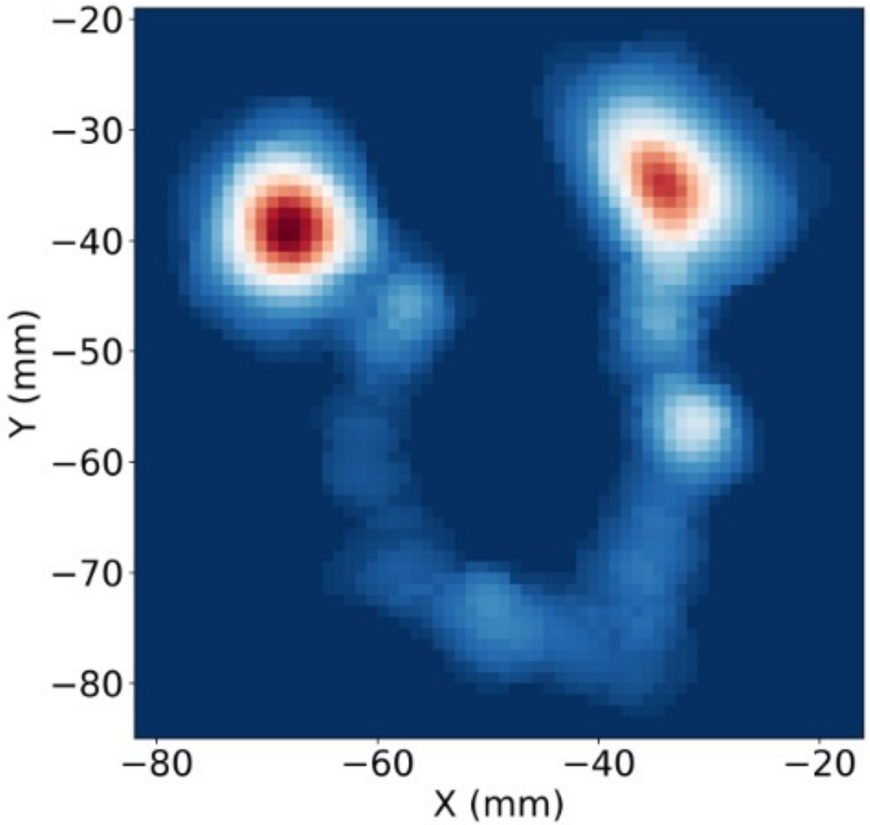


The NEXT-100 Fieldcage and EL region, with assembly crew for scale.

Carmen Romo-Luque (2022). Status of the NEXT experiment for neutrinoless double beta decay searches. In *Proceedings of The 22nd International Workshop on Neutrinos from Accelerators — PoS (NuFact2021)*. Sissa Medialab.

Why Atmospheric Pressure?

- At atmospheric pressures, the gas handling and circulation system is simplified compared to that of high pressure TPCs and doesn't need to contend with cryocooling to the same extent as a liquid TPC.
- As the volume of a high-pressure system increases, so too does the force generated by the gas inside. An atmospheric-pressure detector doesn't have to contend with the strain induced by this force.
- The risk of catastrophic loss of ^{136}Xe is substantially lower at STP.
- The quality of the track topology increases as you lower the pressure of your TPC despite the increased effect of diffusion. This is due to the track length dependence on pressure being $\sim 1/\rho$, while the diffusion dependence is $\sim 1/\sqrt[6]{\rho}$.
  - See Ben Monreal's talk from yesterday for a more in-depth explanation!



$$L = E \times \int \left(\rho \frac{dE}{dx}\right)^{-1} \propto \frac{1}{\rho}$$

$$\sigma^2 = 2DT \propto \frac{1}{\sqrt[3]{\rho}},$$

where $D = \frac{v\lambda}{3}, \quad \rho \propto \frac{1}{\lambda^3}$

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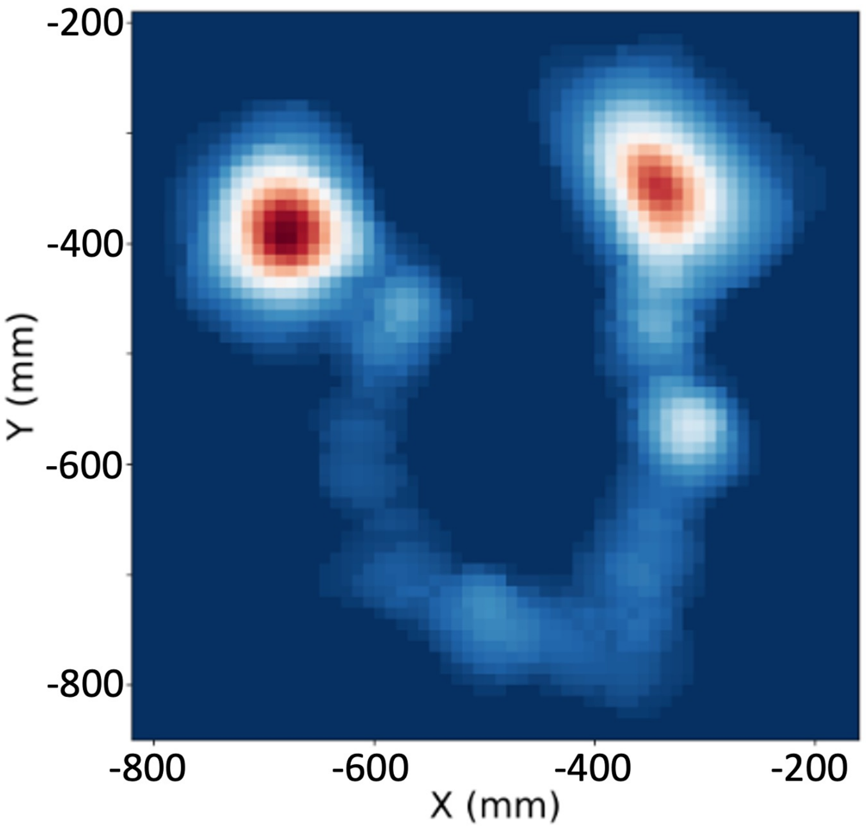

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Why Atmospheric Pressure (Cont.)?

- As the density of your medium decreases, so does the electron density within the track. With the right drift velocity, just the right amount of diffusion, and a sufficiently fast, pixilated readout, it might be possible to identify the ionization electrons individually.
    - By tracking the exact time and position of each ionization electron arrival, your topological resolution is only limited by your diffusion.
    - By discretely counting each ionization electron, the detector energy resolution will only be affected by the intrinsic electron-ion recombination, electron survival probability, and any uncertainty in electron-pileup.

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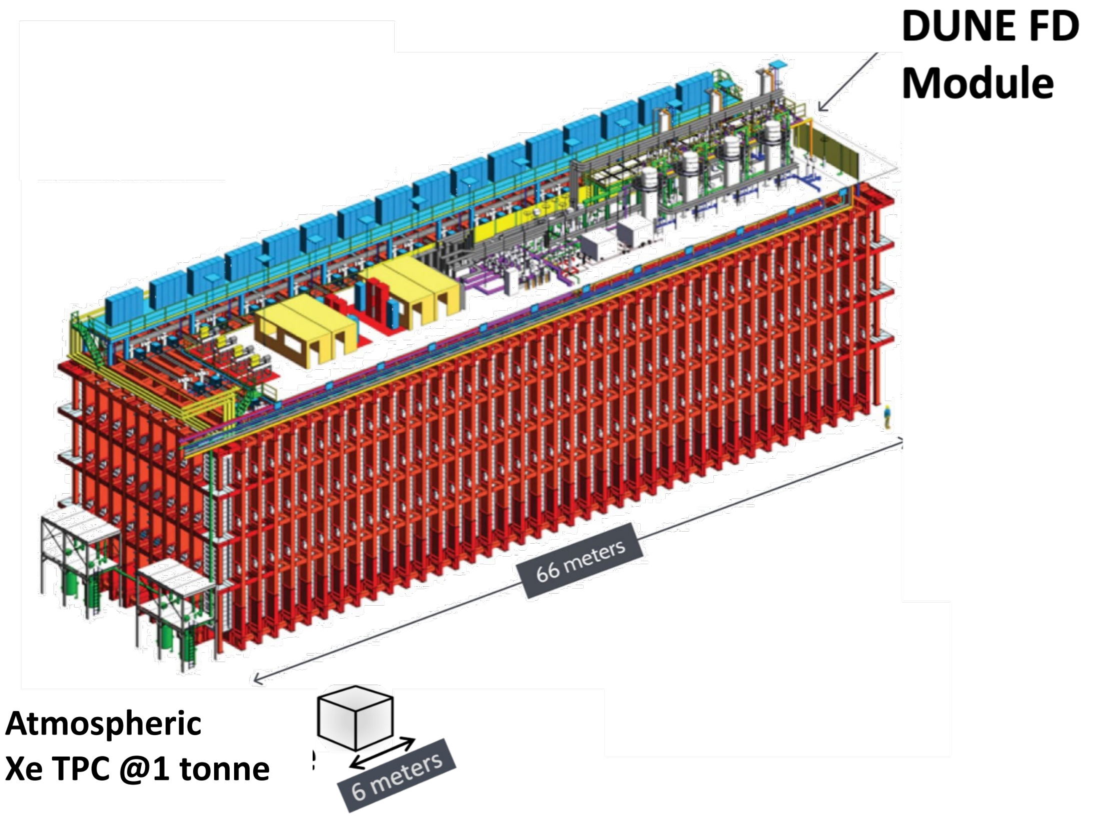
Readout Speed **Number of Pixels** **Diffusion**

The Atmospheric Xenon TPC Design

- To contain 1 tonne of xenon, the AXe TPC requires a volume of $182m^3$. While large, this is still within the realm of possibility.
- The pixilated readout will be divided into a grid of hexagonal or square cells ($\lesssim 1\ cm^2$), comprised of multiple panels.
- Each cell will have to contain a method of gain amplification and a readout with a fast enough timing resolution to avoid pileup.
- Finally, we are considering various electron cooling gasses, primarily CH_4 or CO_2, as a means of controlling the electron diffusion.



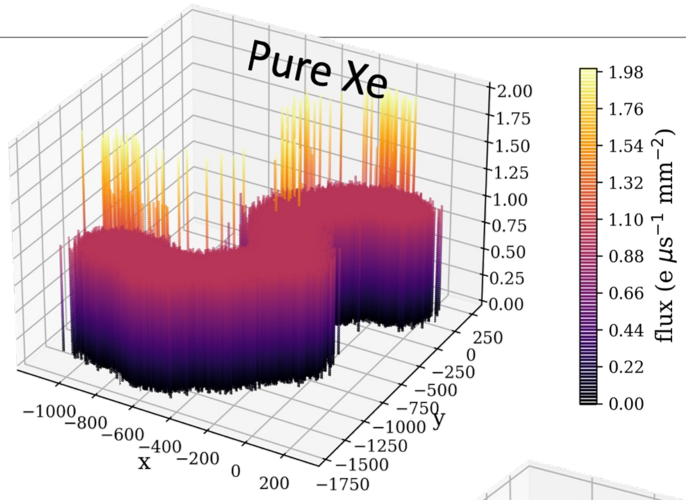
Preliminary Simulations

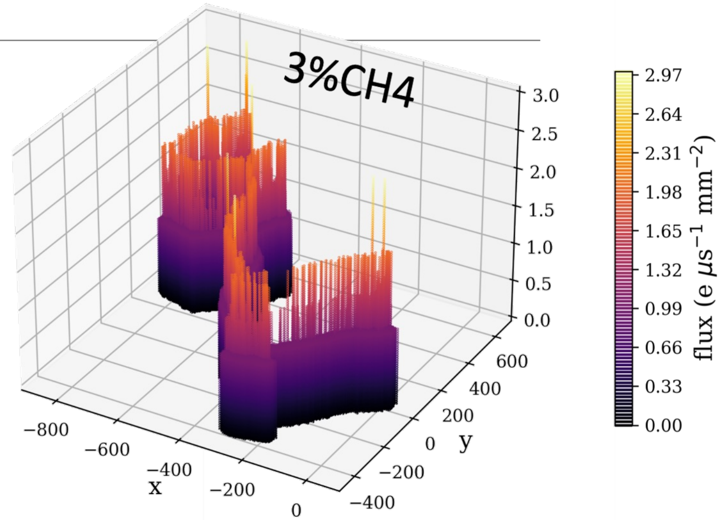
- To quantify how the timing, detection cell size, and diffusion impact the energy resolution in this concept, I created a prototype cylindrical detector (L = 12.5 m, r = 5 m) in Geant4

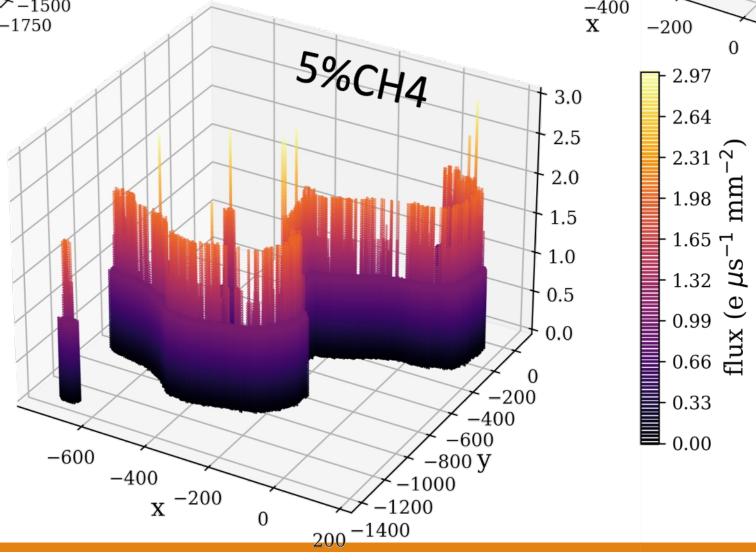
- 0νββ events are simulated in the center of the x-y plane, 5 meters from the readout.

- The tracks are then drifted and diffused towards the readout plane, where their x-y position and arrival time are recorded.

- This data is then sorted into bins and used to calculate the flux per cell.



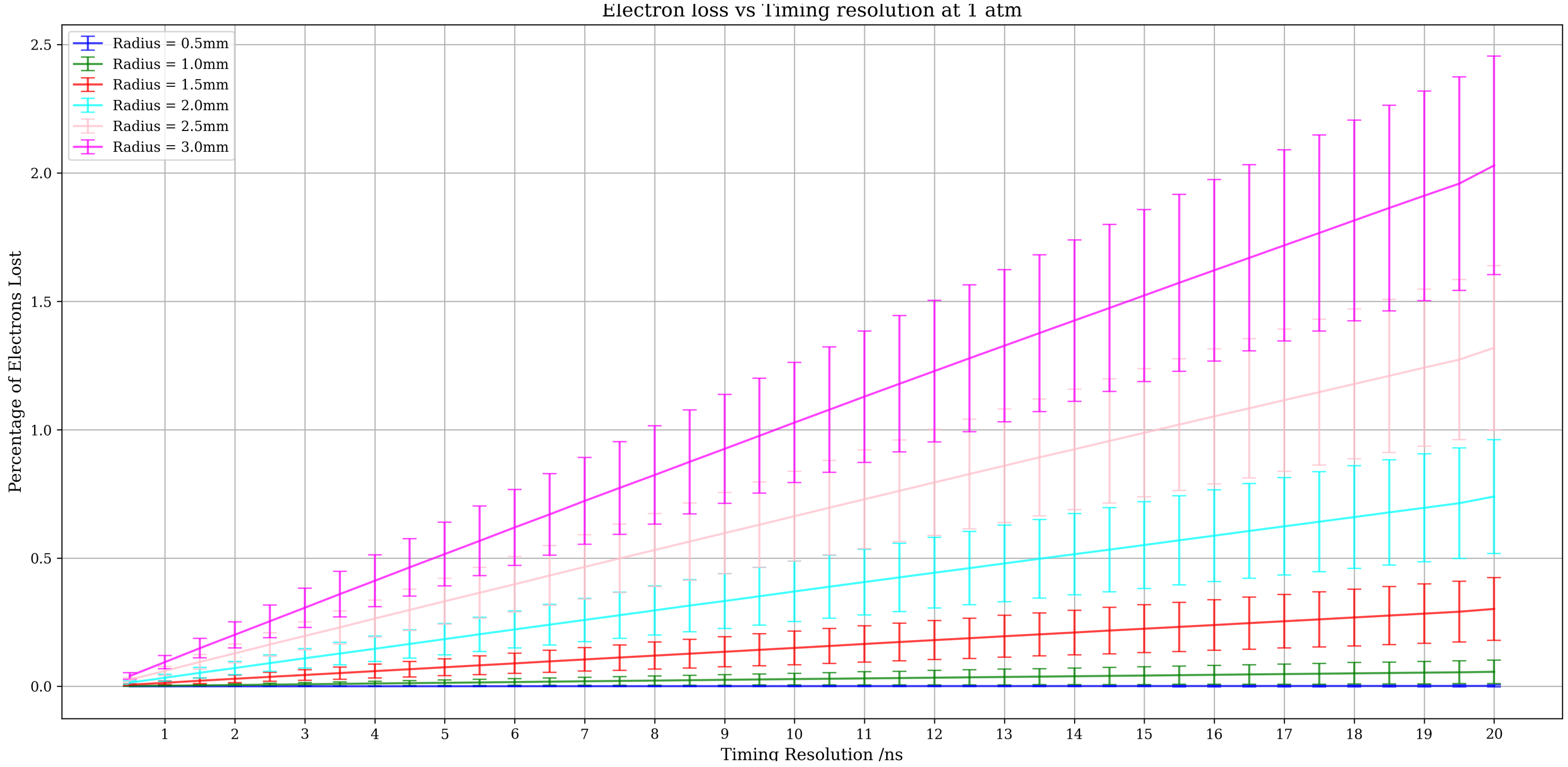




Preliminary Simulations

- Using the binned flux information, we can analyze potential performance characteristics.
- By varying the bin size and shape, we can replicate different cell geometries and sizes.
- We can then count the Δt between electrons arriving in each bin and compare that against varied values of t_{res} to find the electrons lost due to pileup.
- The uncertainty of this loss serves as a proxy for the energy resolution of this detector.

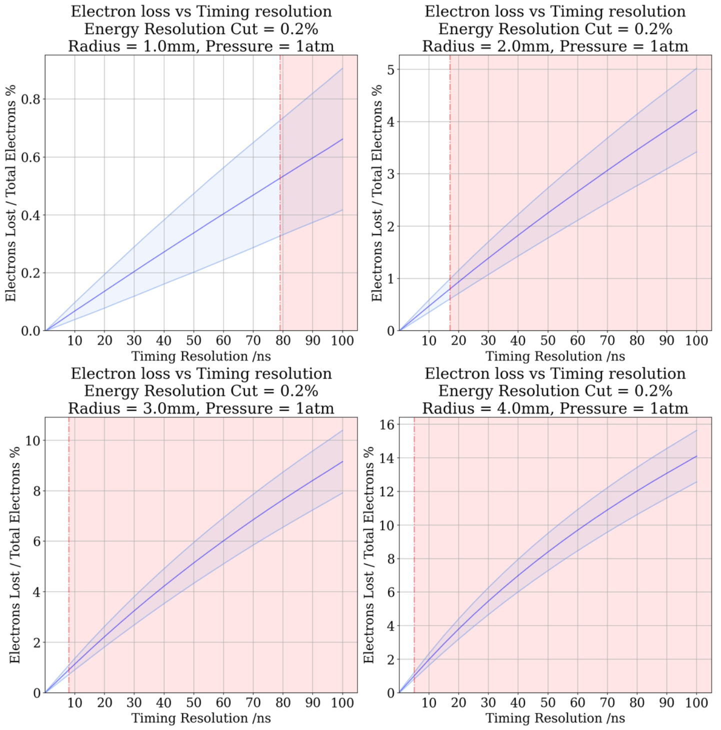
Electron Loss, 1 bar Xenon+3%CH4

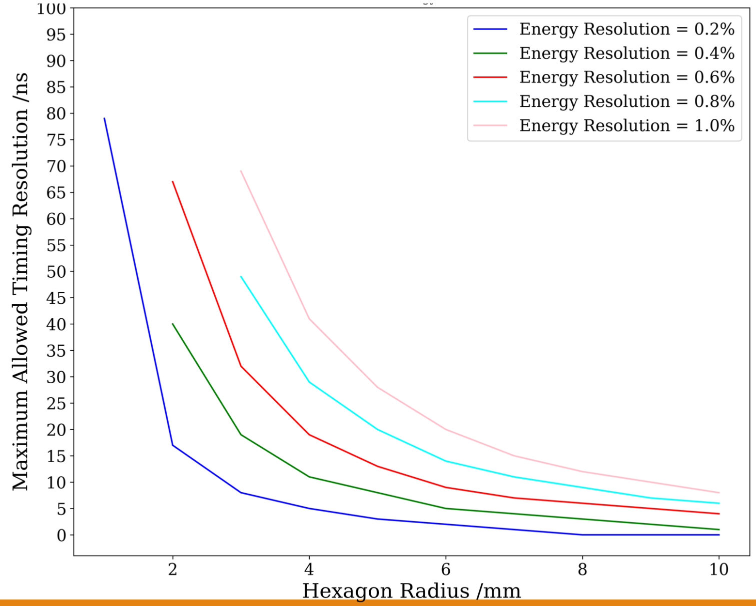


Preliminary Simulations

- By placing performance limits based on the desired energy resolution, we can then exclude values of t_{res} that fail to meet certain benchmarks.
- We repeat this for varied detector parameters, including cell geometry/sizing, gas mixtures, and pressure to establish the baseline for detector performance.
- Work is still ongoing to characterize across all these parameters in determining the realistic energy resolution of this detector concept.
- Concurrent work is also ongoing to understand the topological performance of the detector given its highly pixilated readout, including the use of GNNs.

1 bar Xenon+3%CH4





Conclusions

There are both design and physics implications for an atmospheric-pressure TPC in $0\nu\beta\beta$ searches that makes it an attractive option.

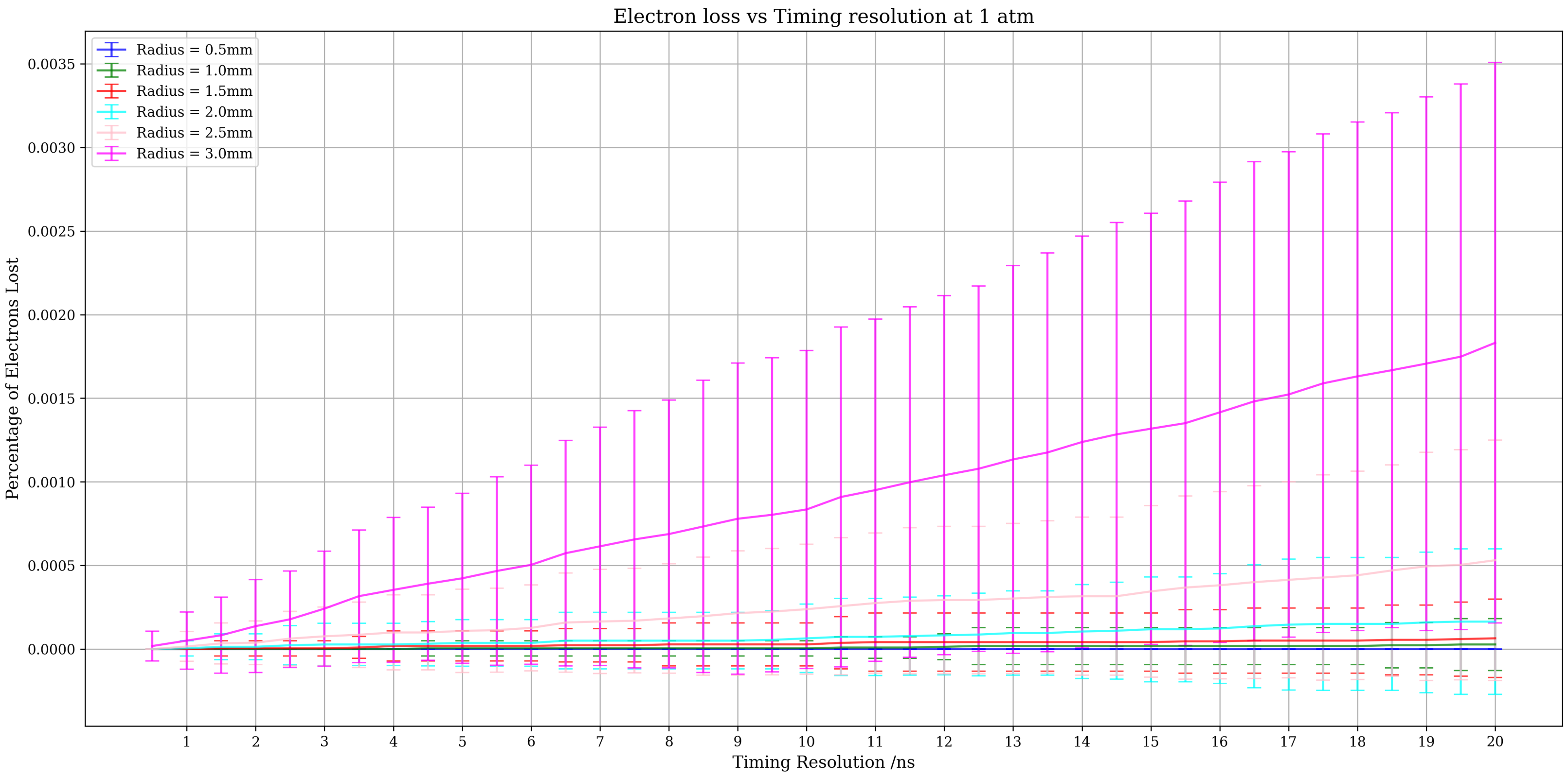
An Atmospheric Xe TPC will be small compared to that of next generation large-scale TPCs already in development such as the DUNE FDs.

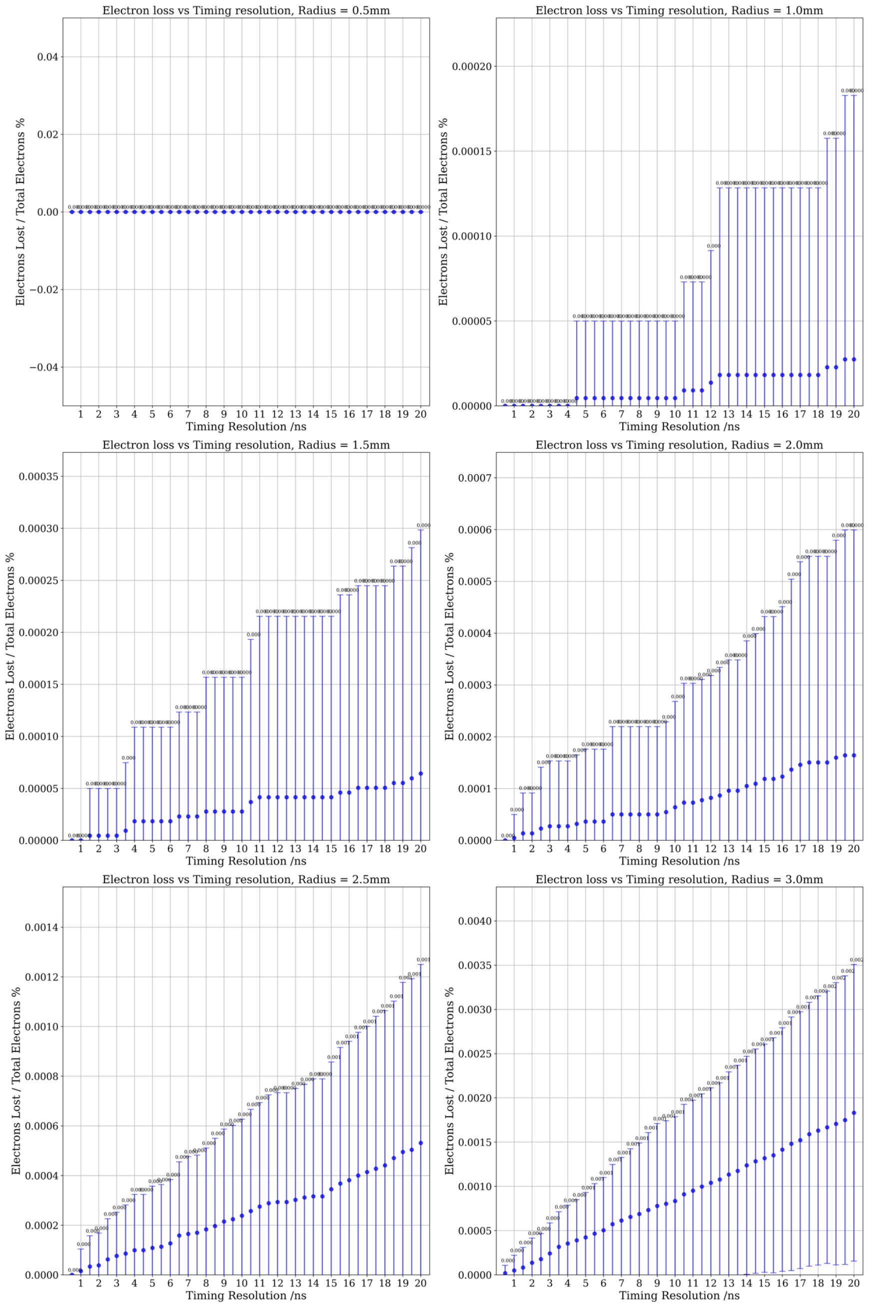
Work has already been started in simulating an Atmospheric Xe TPC and characterizing its performance, with early energy sensitivity predictions completed for a variety of detector parameters.

Work is also ongoing to understand the topological identification power of an Atmospheric Xe TPC using the precise location information and GNNs.

Backup Slides

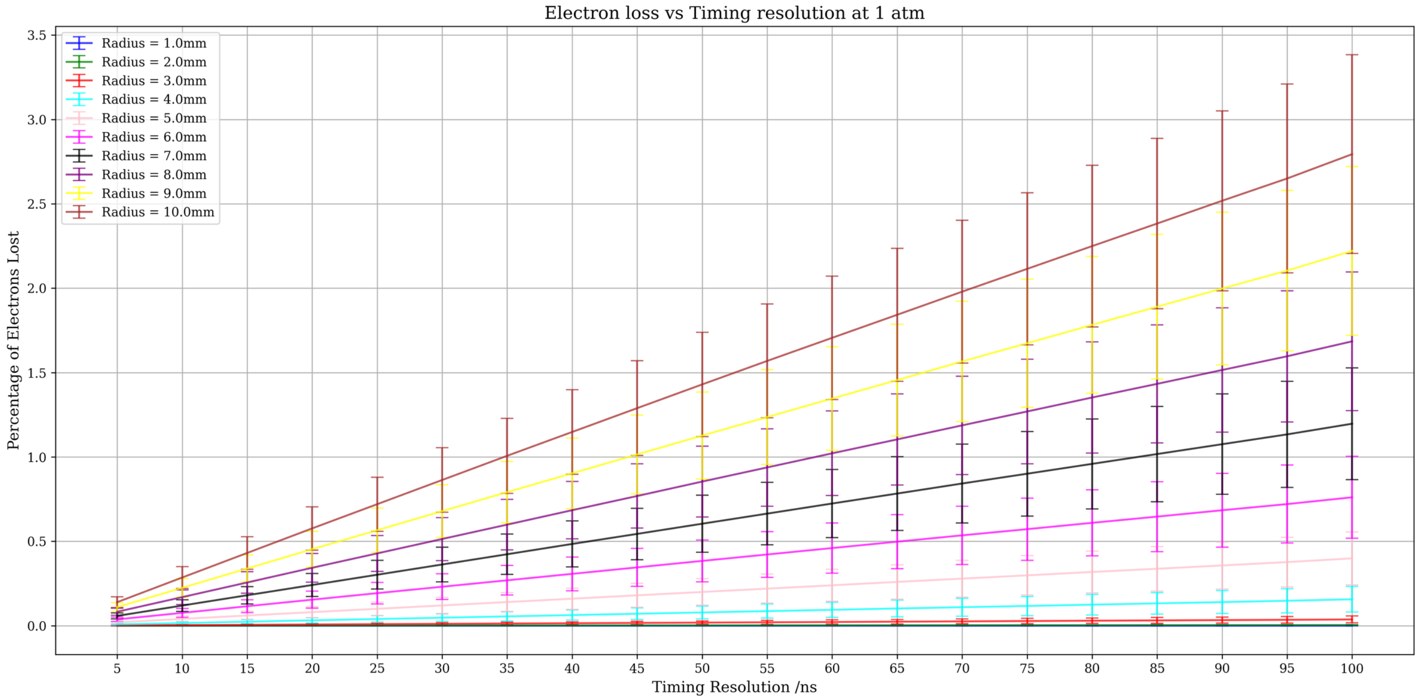
Pure Xe
r = 1-10mm
t = 0-3.5ns

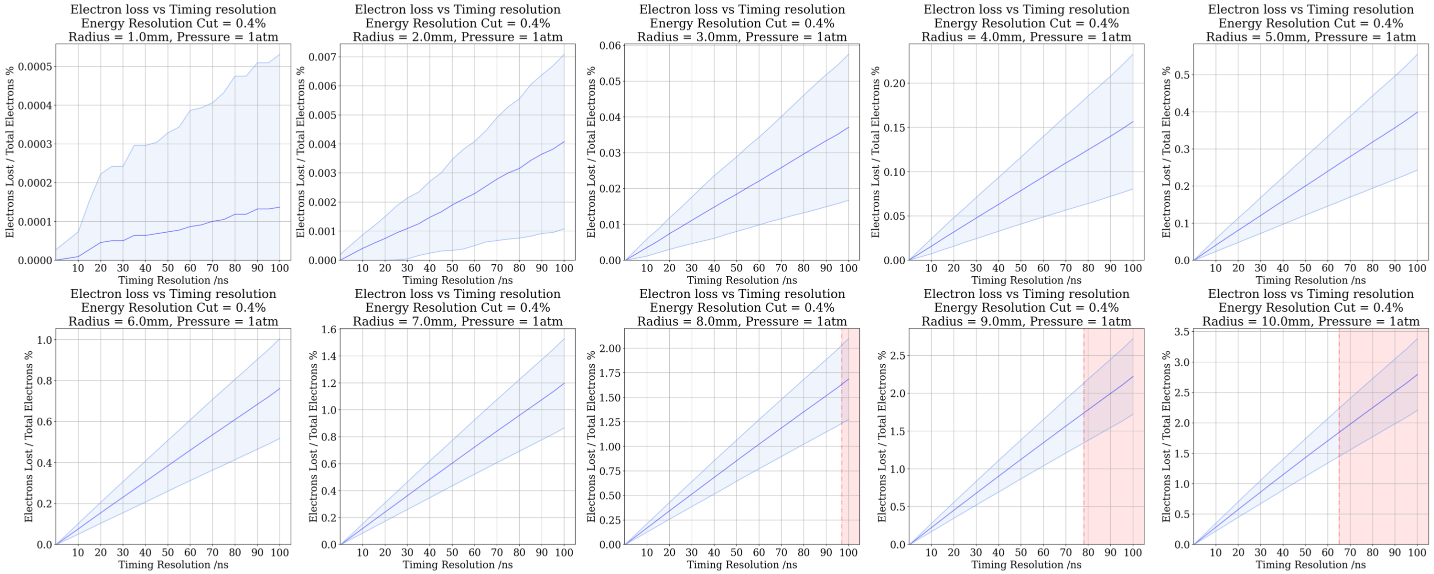


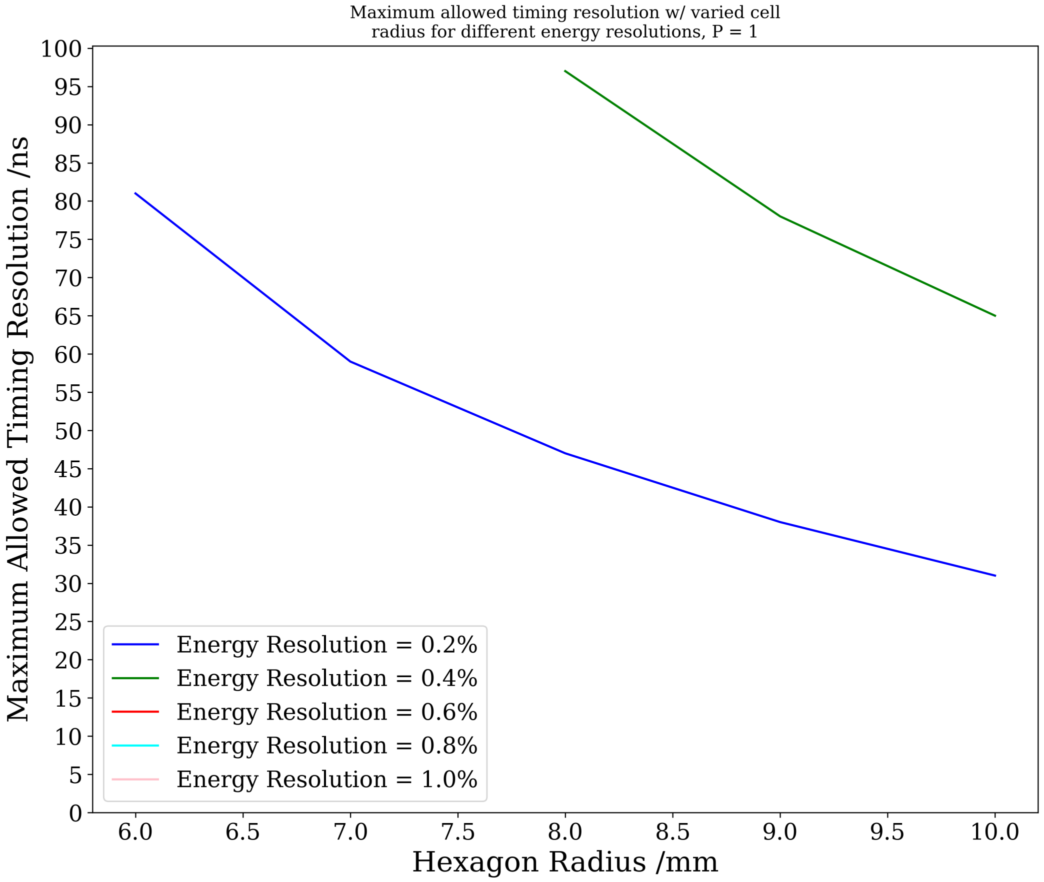


Pure Xe, r = 1-10mm, t = 0-100ns

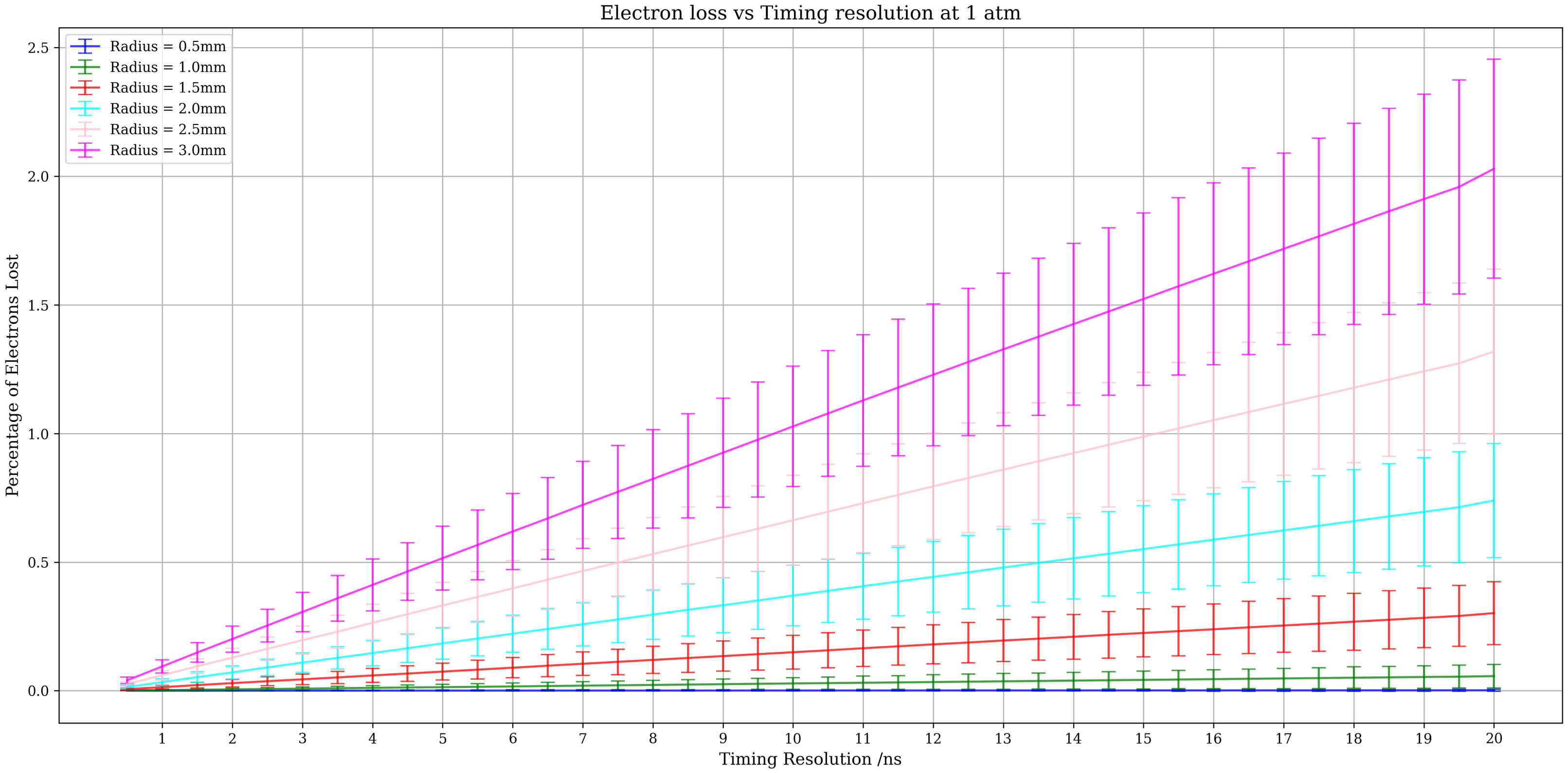
Note for anybody looking over my back ups and is confused by this legend: This plot only shows points where the detector is incapable of exceeding the E_{res} cuts applied. Pure Xe only faces E_{res} limitations below 0.4% at the shown radii and timing resolutions. I am lazy and didn't remove the legend entries above that. I am extending the analysis to a larger selection of t_{res} to find the breaking point.

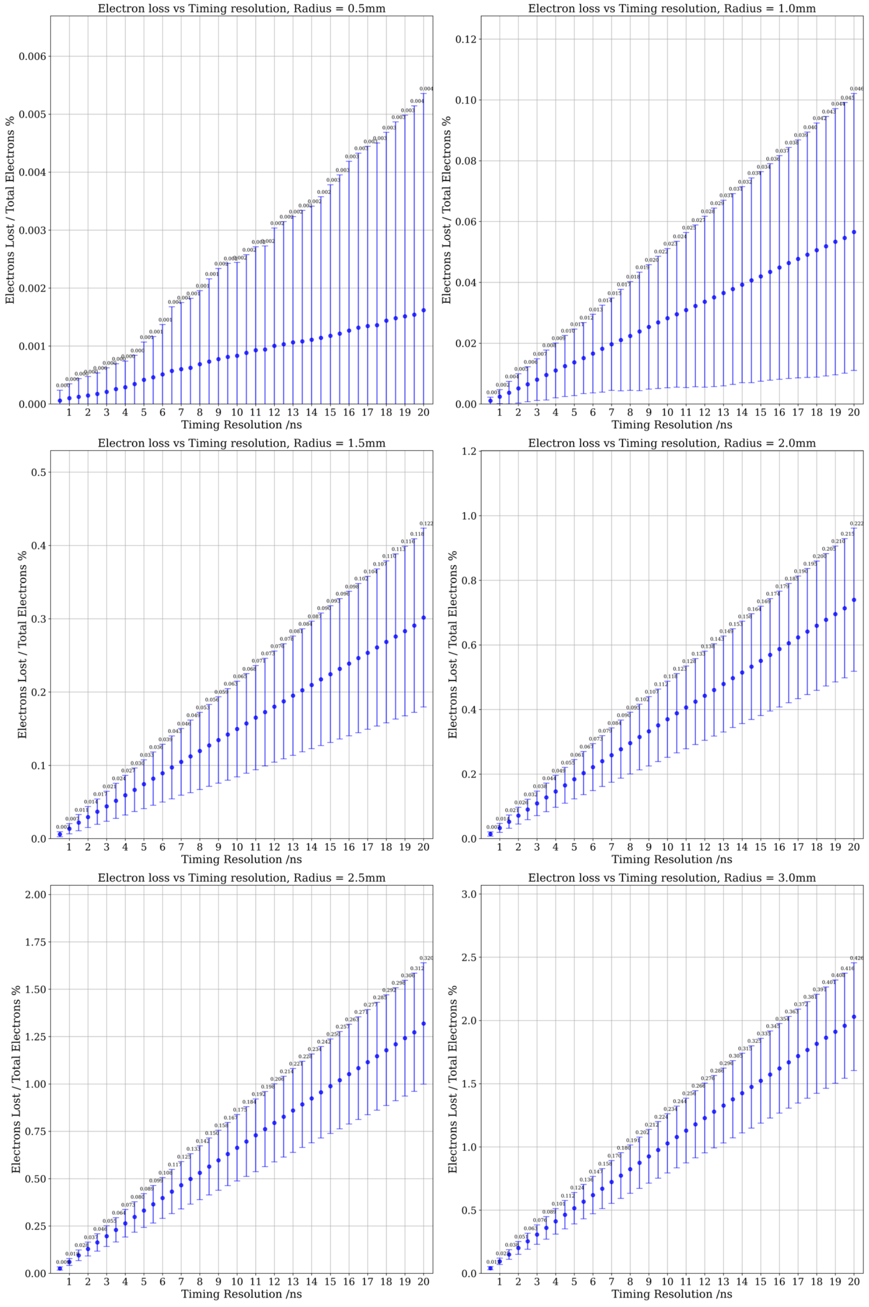




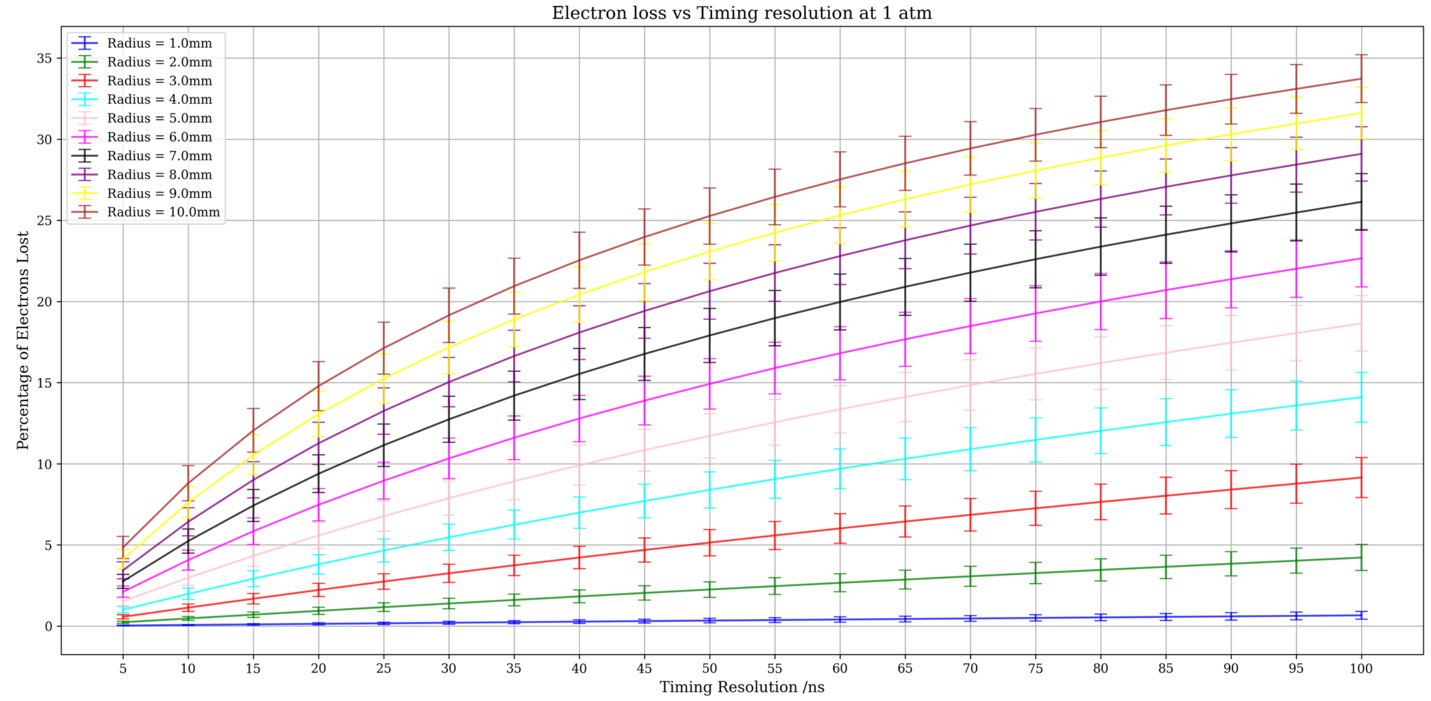


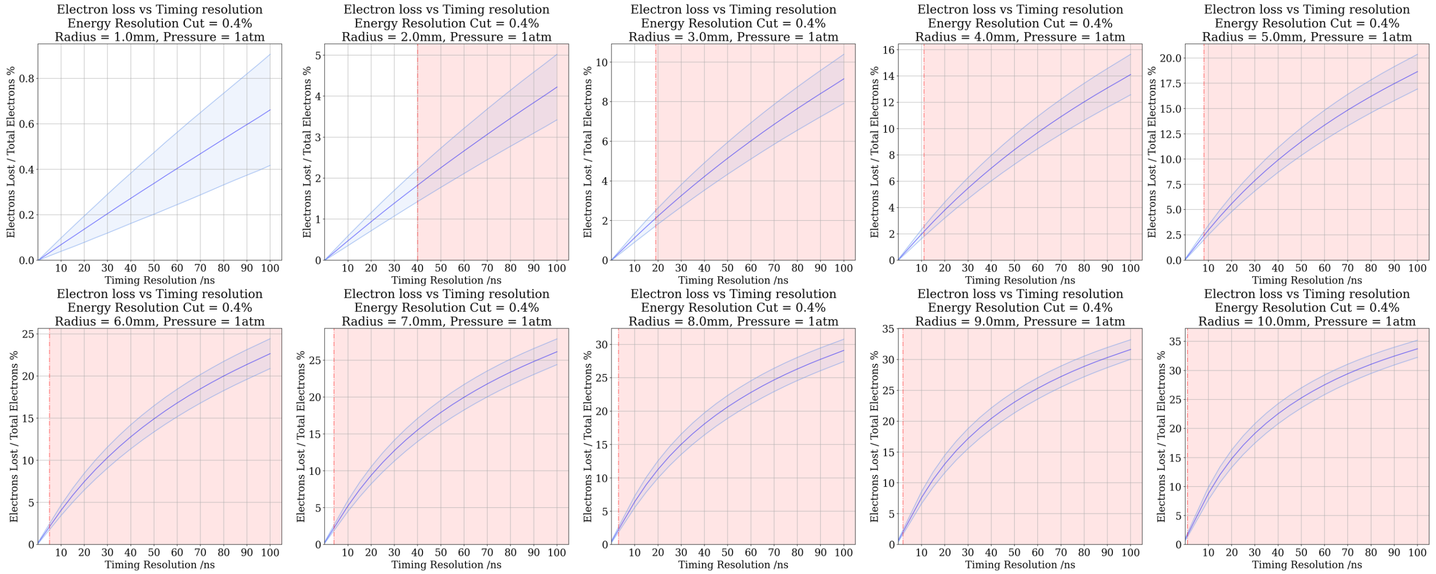
Xe+3%CH4
r = 0.5-3mm
t = 0-20ns

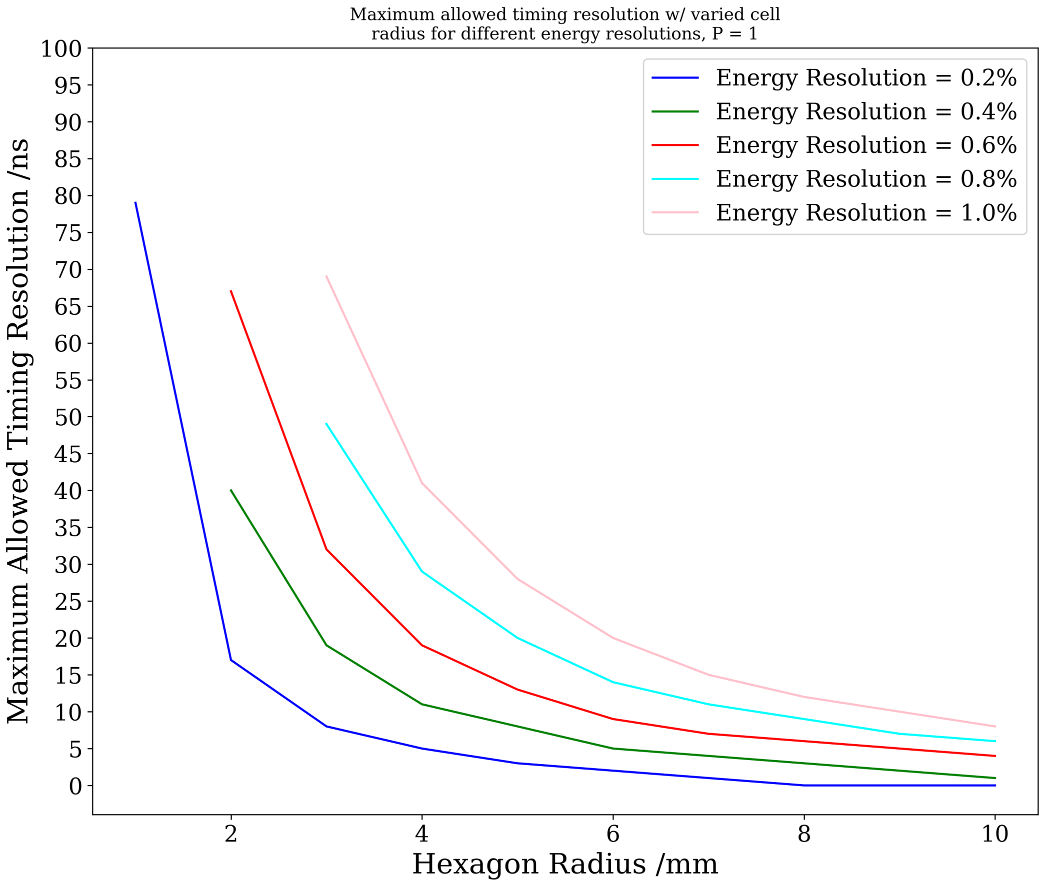




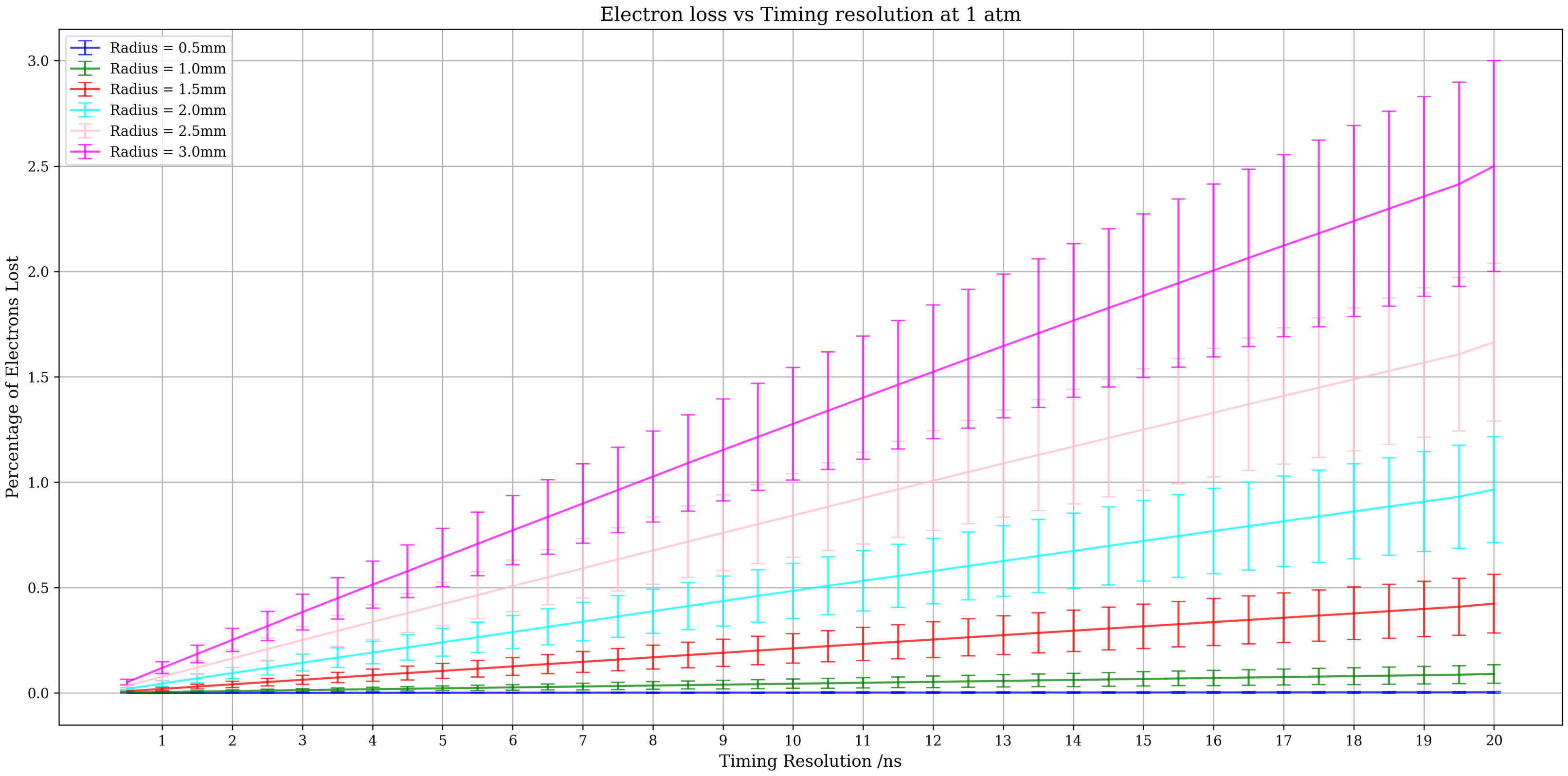
Xe+3%CH4, r = 1-10mm, t = 0-100ns

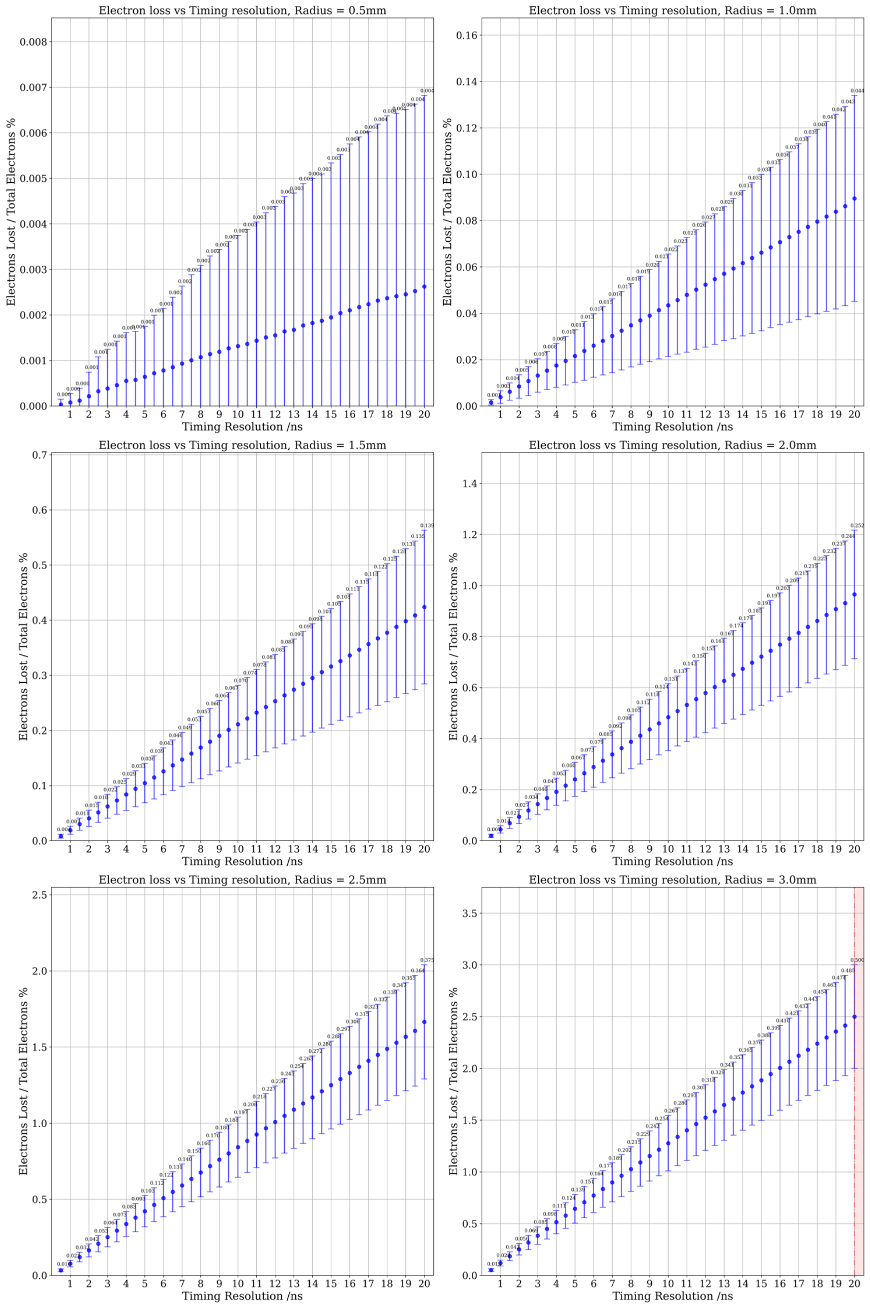






Xe+5%CH4
r = 0.5-3mm
t = 0-20ns





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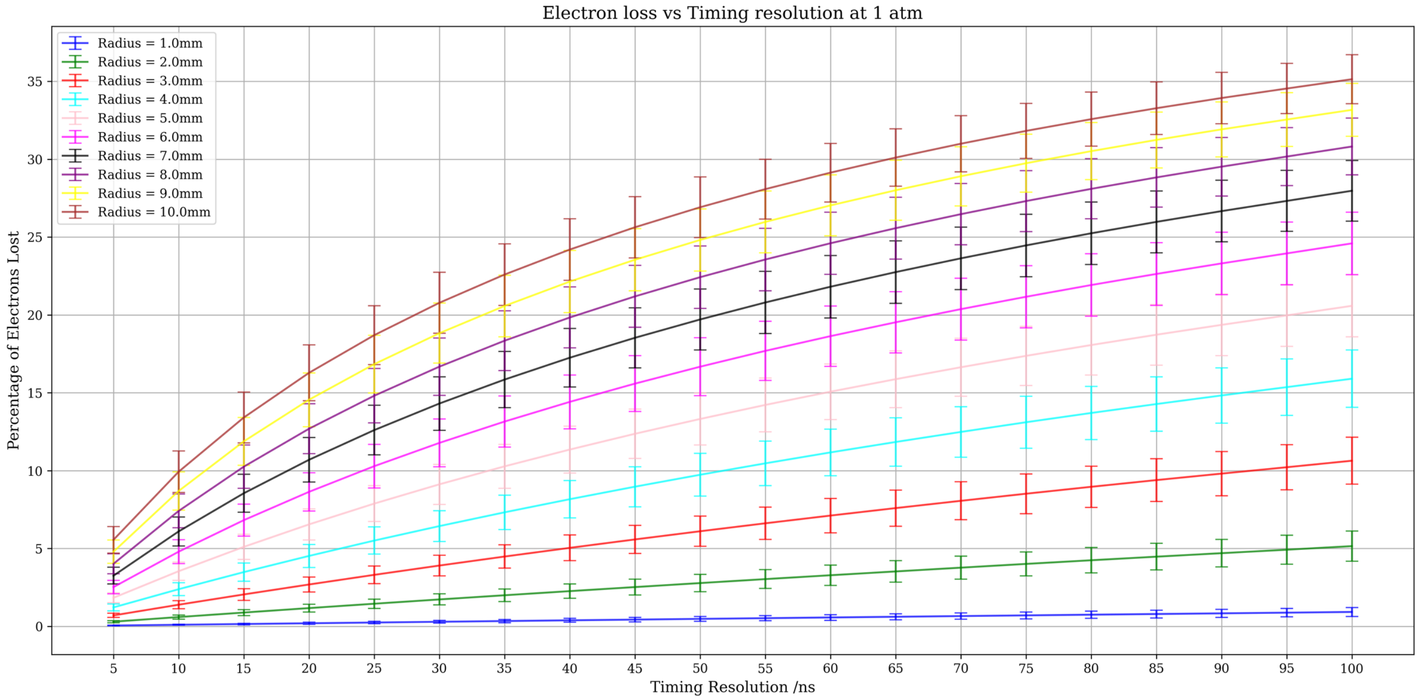
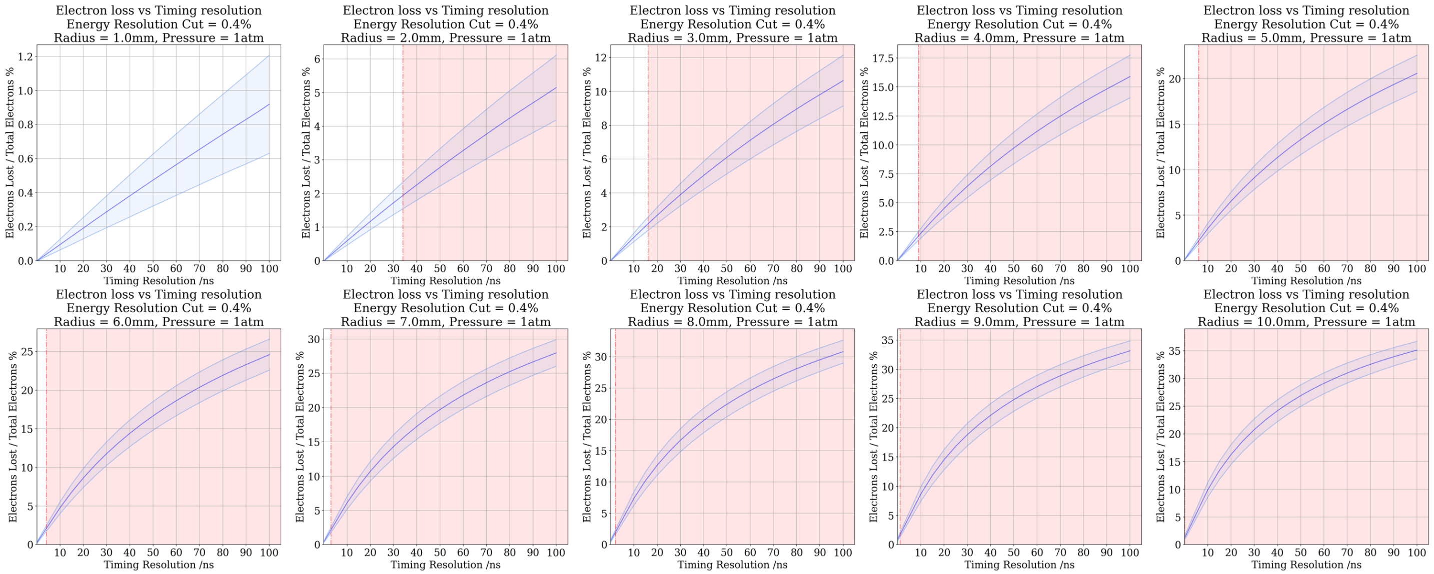
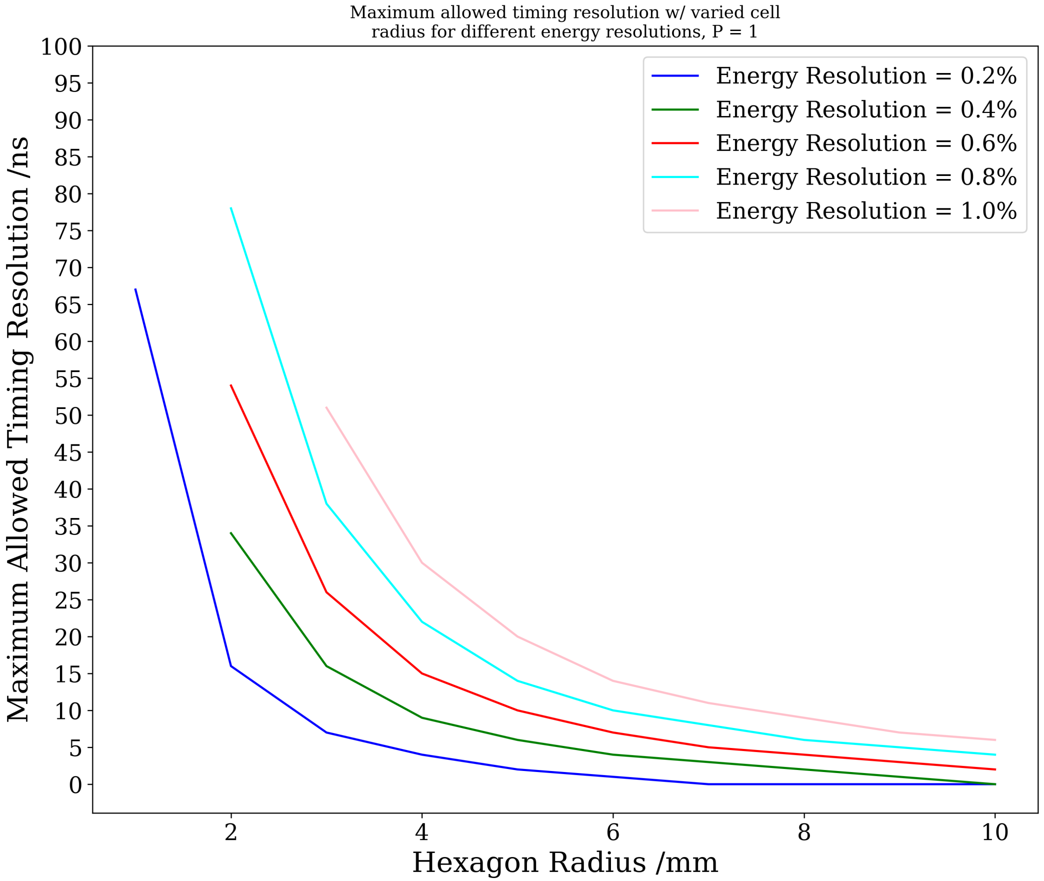
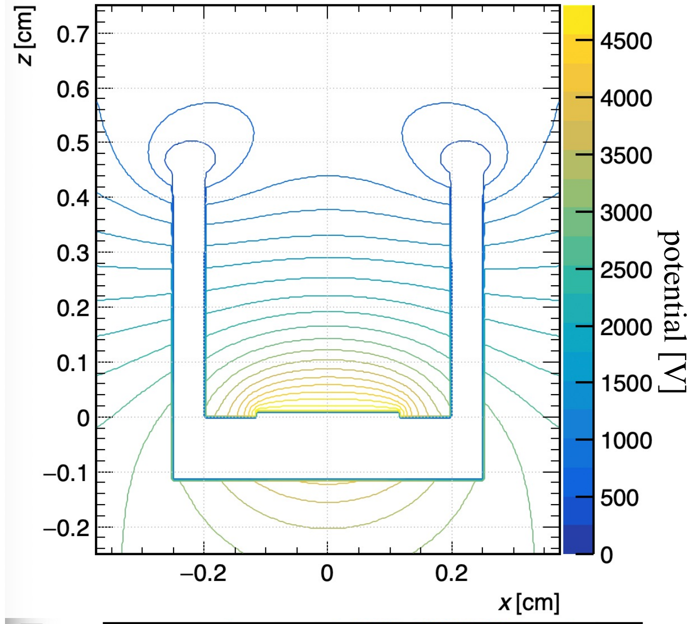


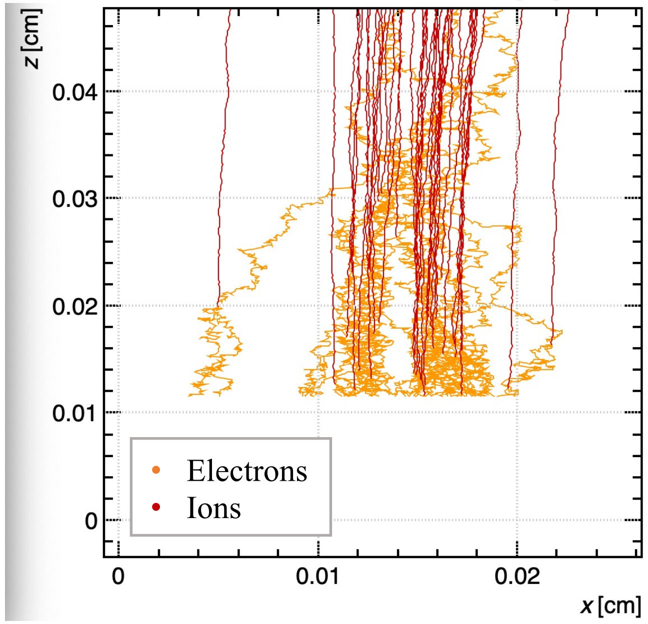


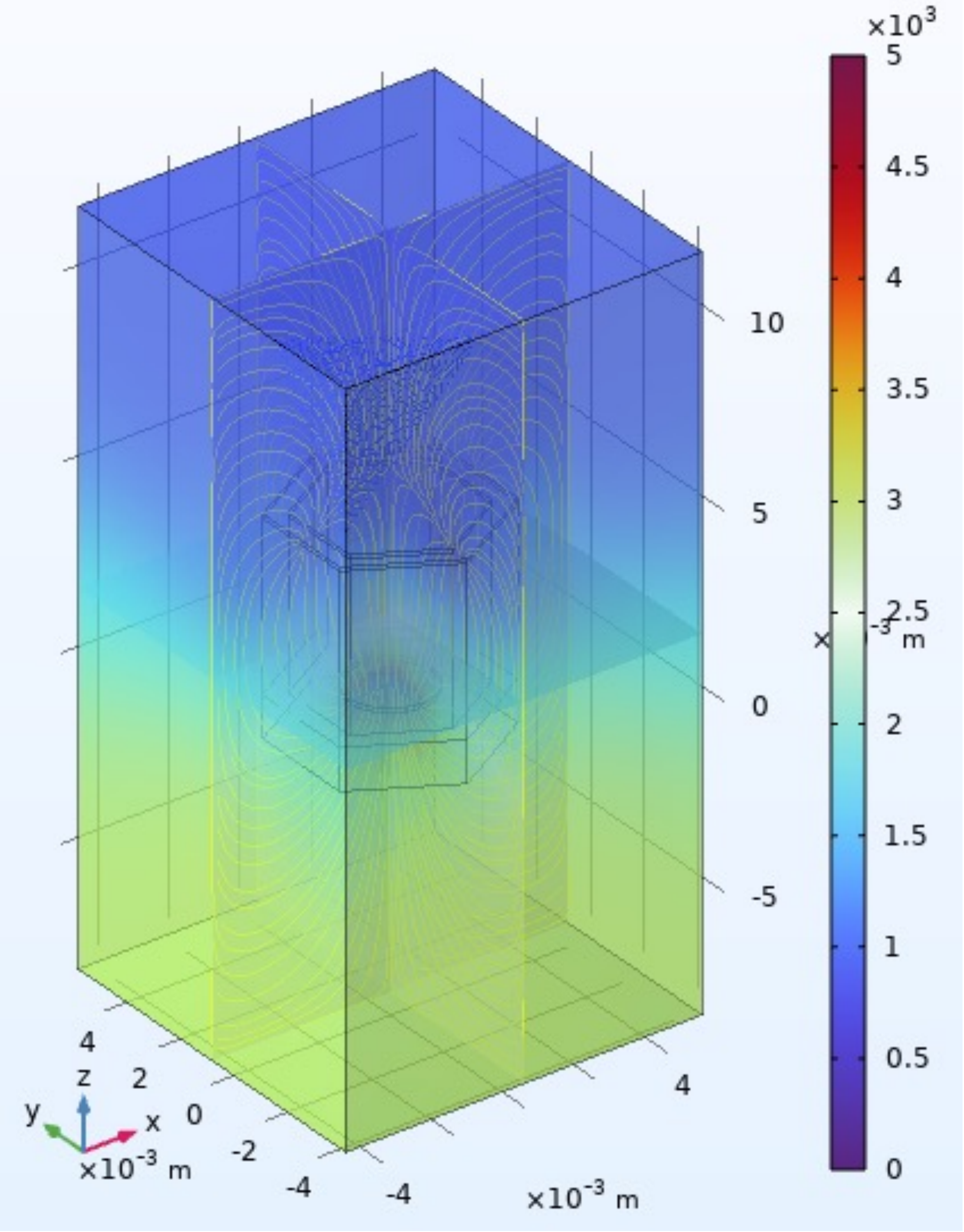


Cell Geometry Simulation

- Geometry and field maps modeled in COMSOL.
- Read to Garfield++ where the gas is modeled via PyBoltz.
- Electron avalanche details read out to measure the number and time range of arrivals.







Limitations Imposed by Cell Geometry

- The number of required cells gets big. This is where managing the diffusion vs topology really comes in.
- The avalanche process needs to generate enough electrons to measure, and must be quick enough to avoid wide pulses that might interfere.
- Early looks show that the pulse width impact on energy resolution is small, luckily.