DC Voltage Breakdown Studies

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Published Results

Dielectric Strength of Noble and Quenched Gases for High Pressure Time Projection Chambers

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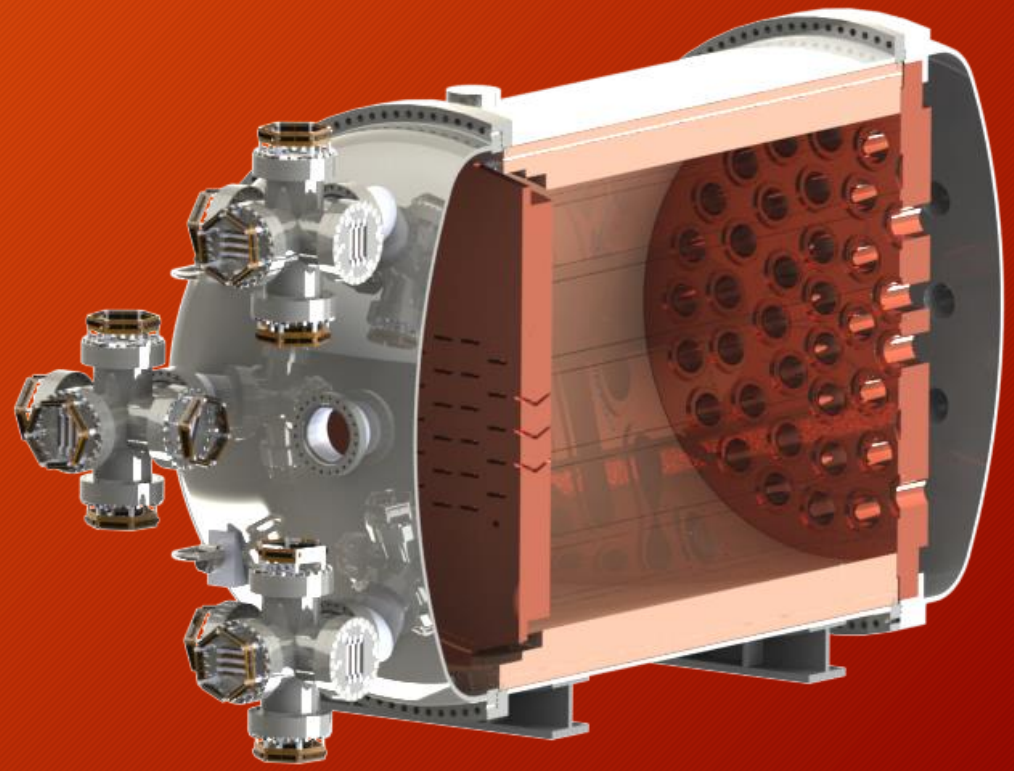
https://arxiv.org/abs/2107.07521

NEXT Experiment

To the right is an iteration of the NEXT experiment

Every iteration of the NEXT experiment uses High Pressure Xenon Gas alongside High Voltage Components

The Breakdown strength of Xenon at high pressure is instrumental in the detector design and construction



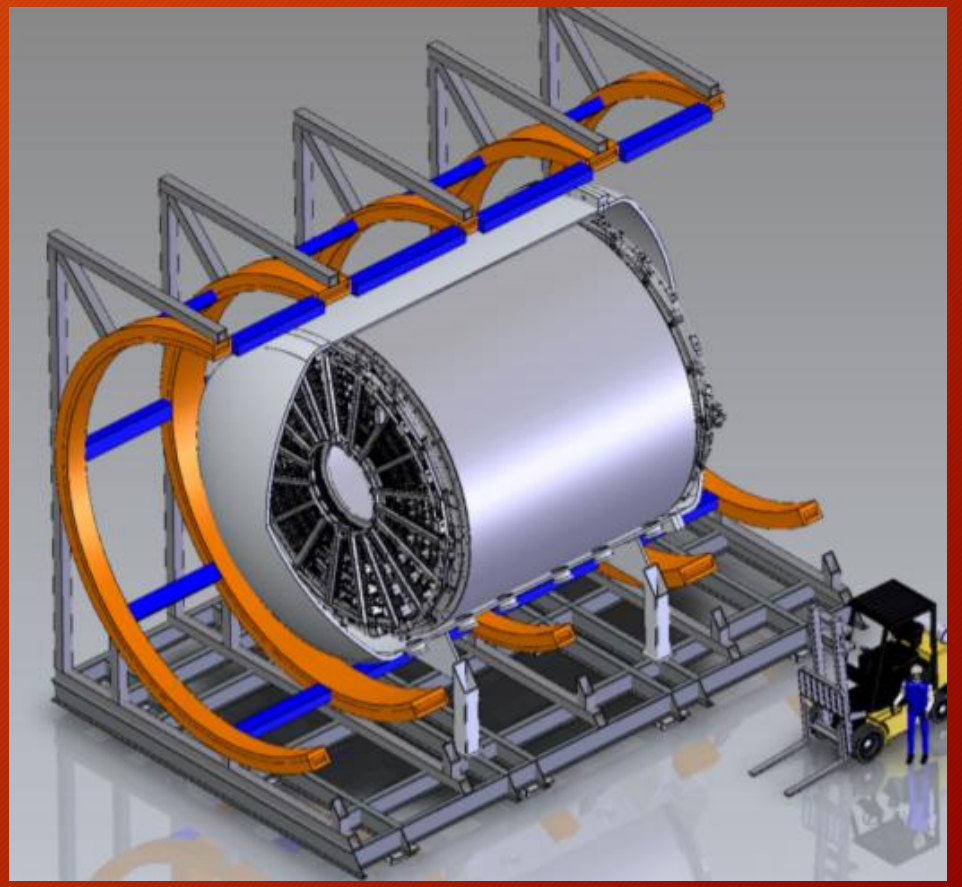
DUNE Near Detector MPD

The High-Pressure Gas Time Projection Chamber to be used in the DUNE near detector is pictured on the right

They are considering using a mixture of 90% Argon and 10% of another gas

The 10% mixtures that are being considered are CO_2, CH_4, and CF_4

The breakdown strengths of these mixtures at high pressures would make detector design an easier and streamlined process



Townsend Criterion/First Ionization Coefficient

Townsend's First Ionization Coefficient

$$\alpha = Ape^{-\frac{Bp}{E}}$$

A,B = Empirical Constants based on gas properties

α represents the amount of ionization that is possible over a certain length, a common unit is cm^{-1}.

Townsend's Breakdown Criterion

$$e^{\alpha d} = 1 + \frac{1}{\gamma_{se}}$$

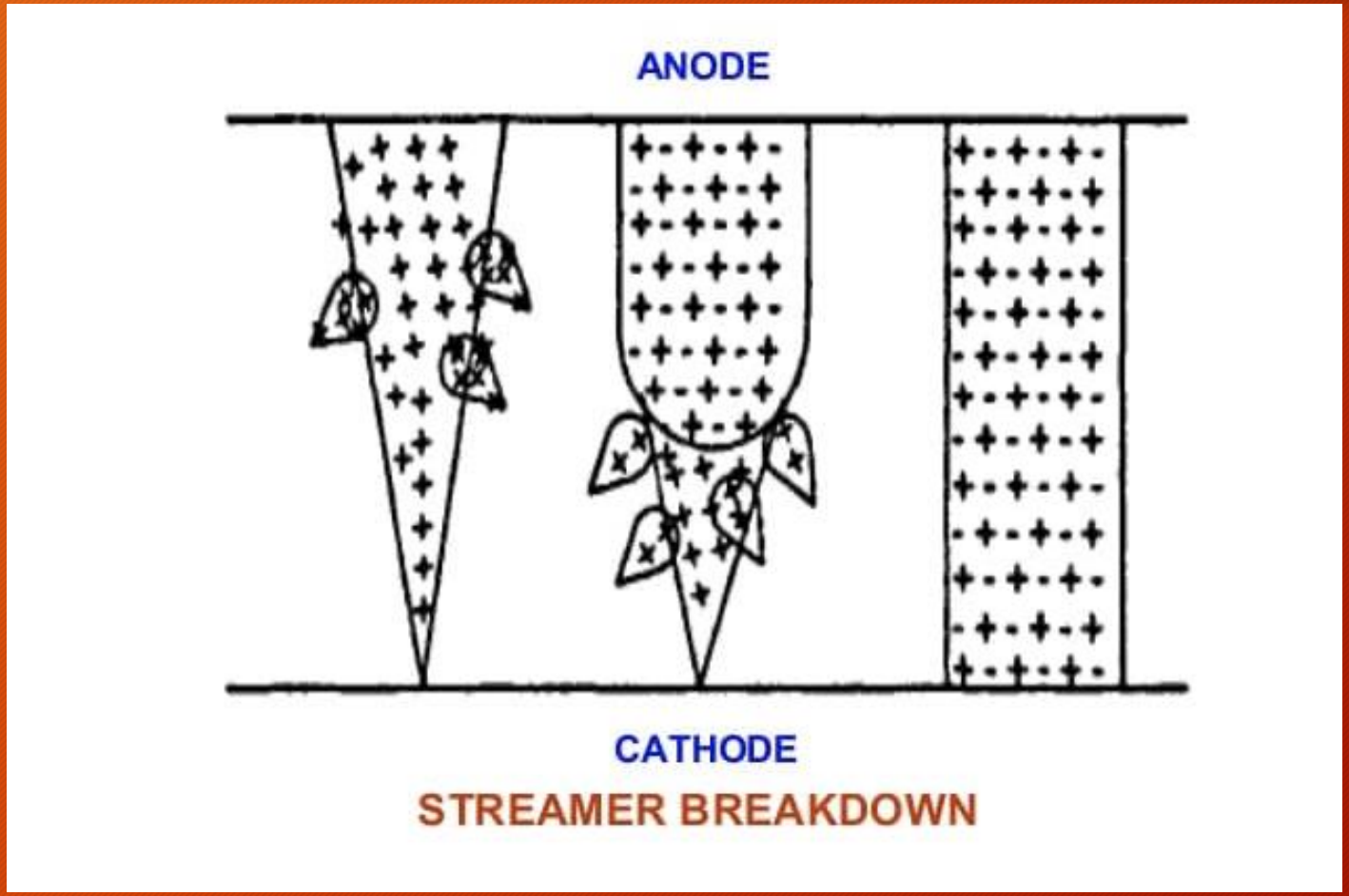
γ_{se} is the secondary emission coefficient and represents the number of electrons that are excited off the electrode surface and is directly related to the work function of the metal and the surrounding gas

A. M. Howatson,An introduction to gas discharges,eng, [1st ed.]., The Commonwealth and internationallibrary. Applied electricity and electronics division ; v.8 (Pergamon Press, Oxford).

Paschen's Law

$$V_B = \frac{Bp\,\mathrm{d}}{\ln(Apd) - ln\left(ln\left(1 + \frac{1}{\gamma_{se}}\right)\right)}$$

Streamer Breakdown



Meek-Raether Criterion

The meek-rather criterion states that a streamer is most likely to form when the “avalanche gain” reaches around 10^8

$$e^{\alpha d} = 10^8$$

Meek-Raether
Breakdown Criterion

$$e^{\alpha d} = 1 + \frac{1}{\gamma_{se}}$$

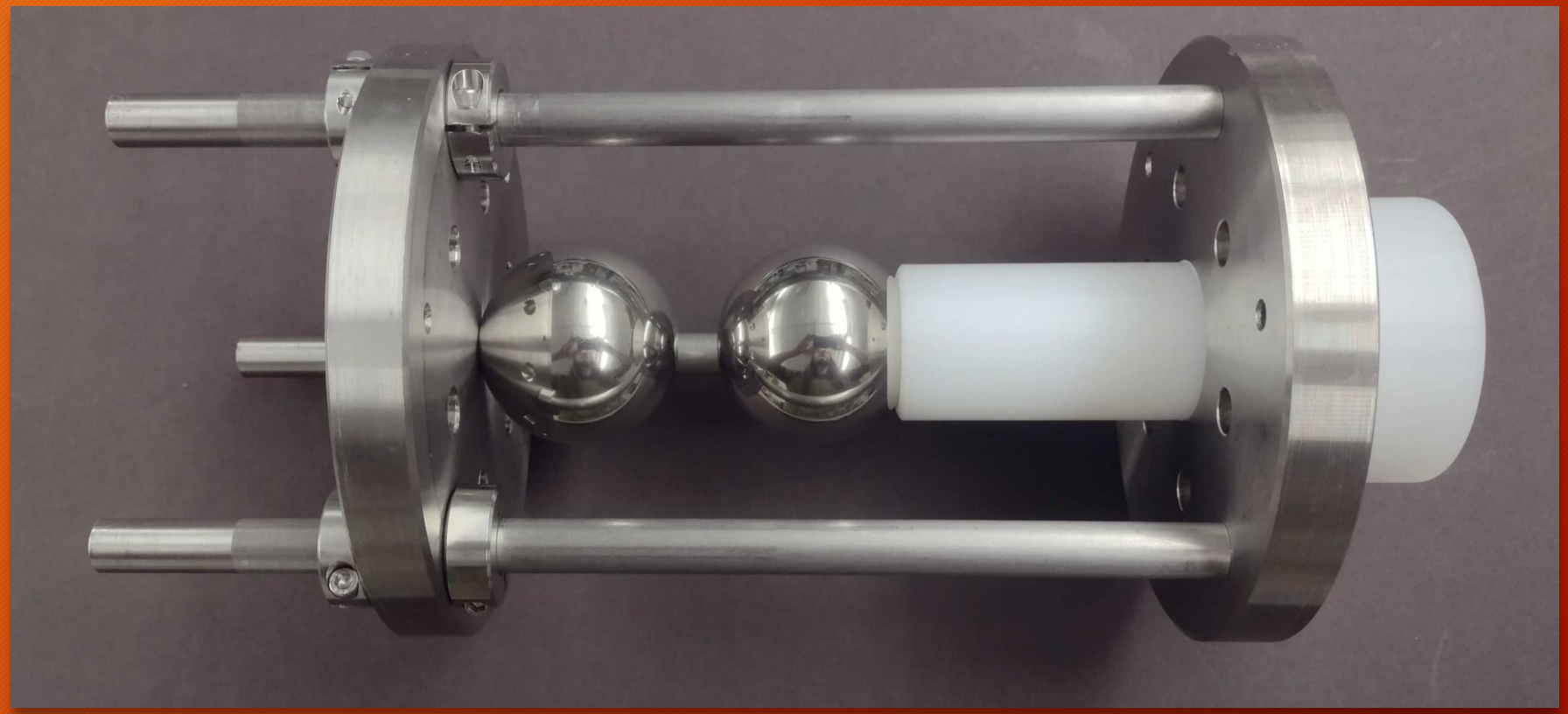
Townsend
Breakdown Criterion

J. M. Meek and J. D. Craggs,Electrical breakdown ofgases(1978).

Higher Pressure Experimentation

- Papers and the theory do show that the breakdown generally follows the Paschen law at lower pd values
- At intermediate pd values experimental curves generally follow the meek criterion
- There is not many papers that cite the validity of the laws up and into the high-pressure region, but there is evidence that the Townsend coefficient is valid in air up to 5 bar
- We have characterized the high-pressure region and shown that Paschen's Law is indeed inaccurate in this region

The Electrodes



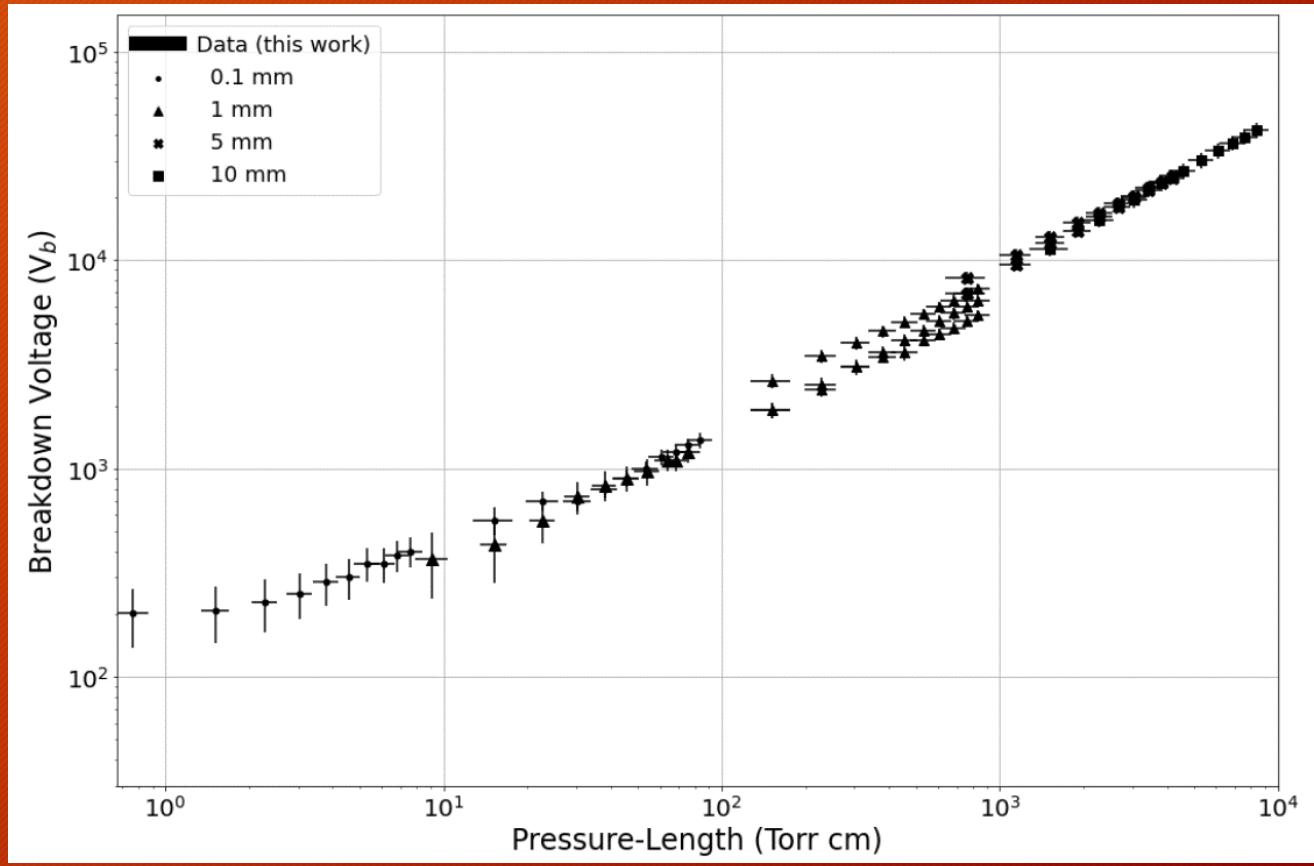
Current Results in Argon

To the right is breakdown data that was all performed with Argon gas

The data ranges from mbar pressures to 10 bar

The electrode separation distances are .1 mm, 1 mm, 5 mm, 1 cm

The values obtained cover a large range of pd values utilizing the same setup, as intended

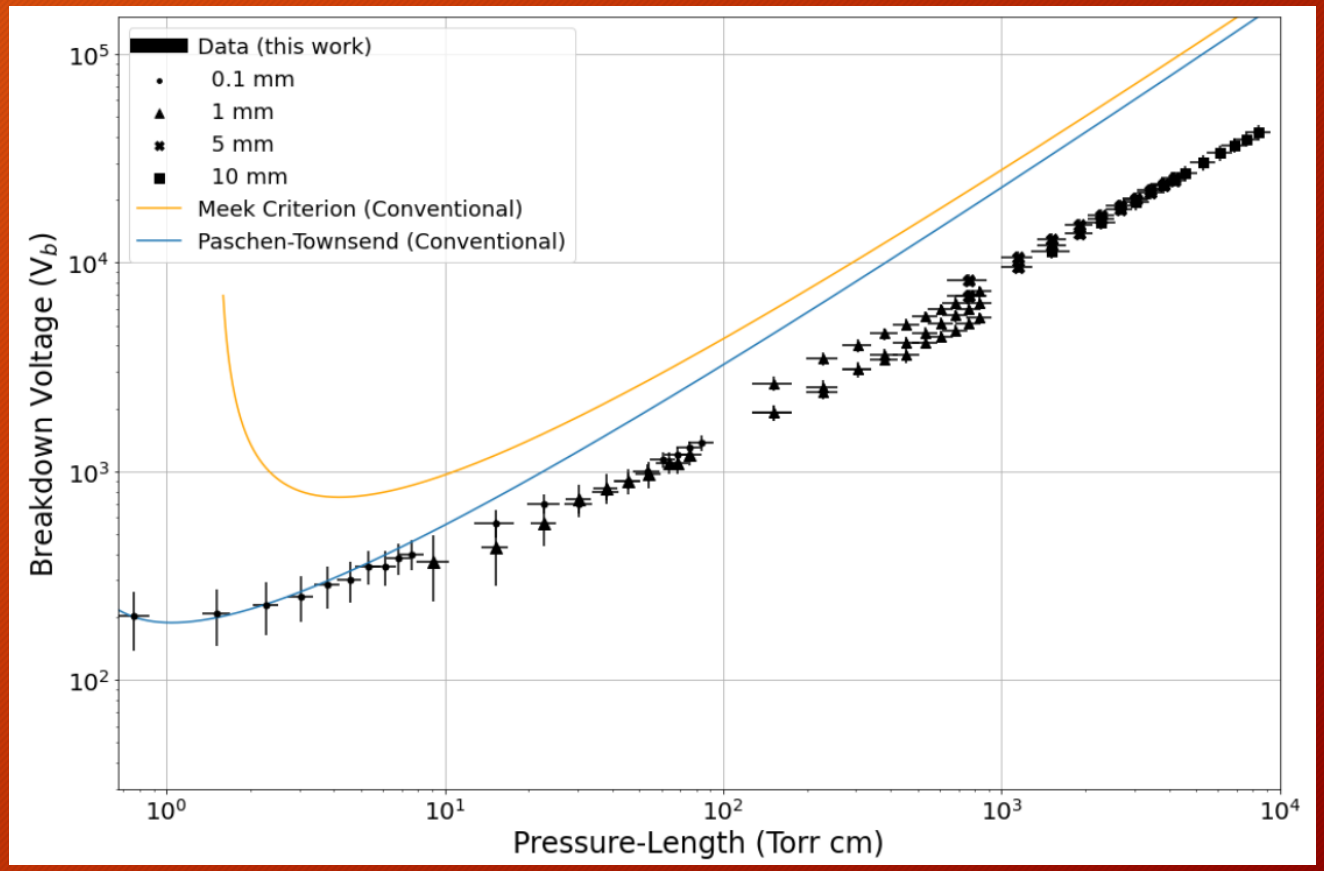


Theoretical Comparisons

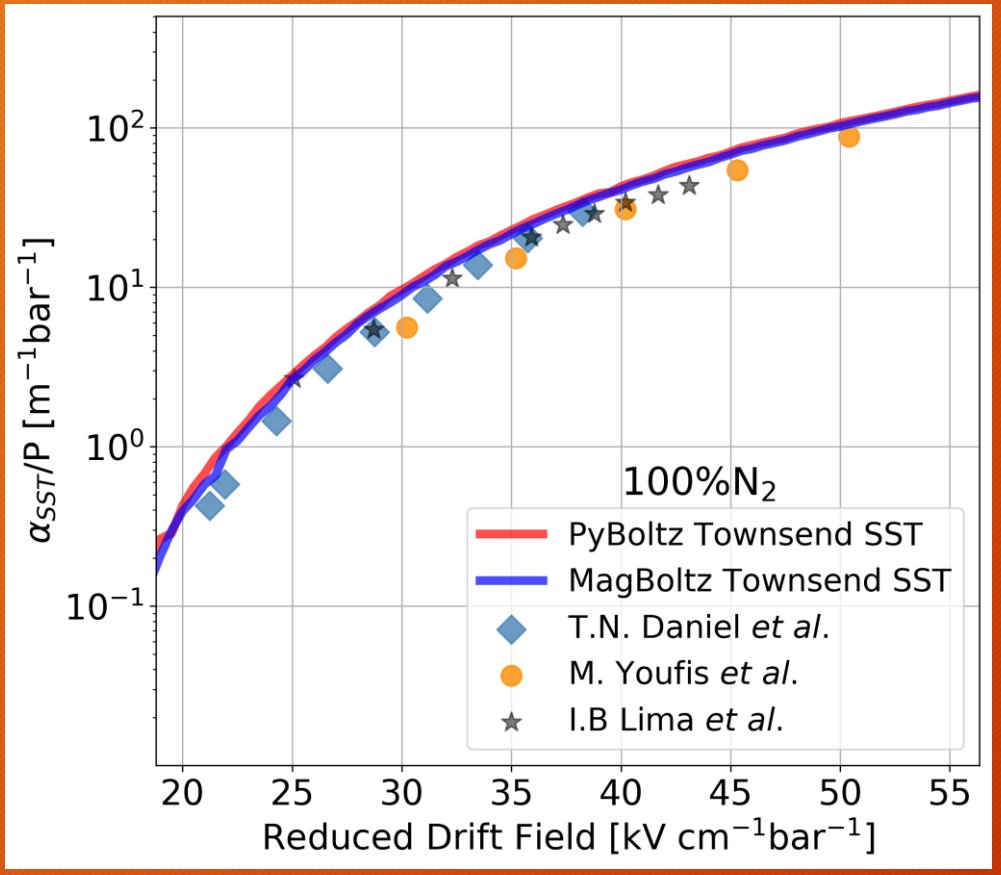
The Paschen law is shown in blue on the graph to the right using accepted values for the A,B, and γ_{se}

The meek criterion is also shown in orange as well, with the separation between the two being constant at higher pressures

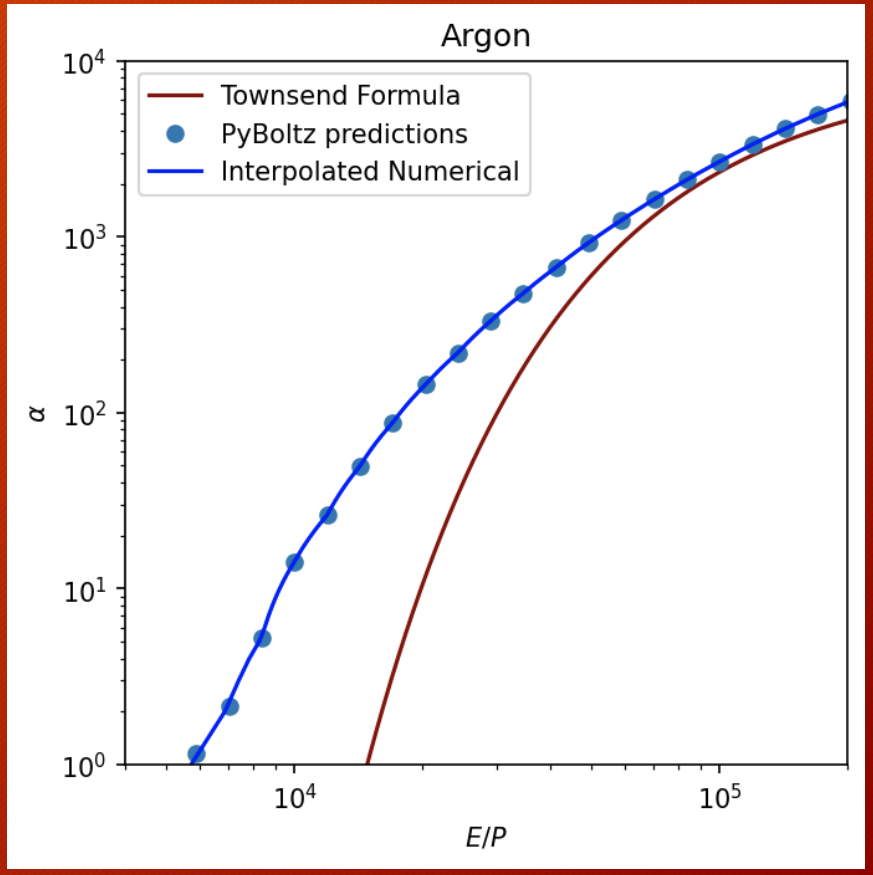
The data clearly follows a separate slope at higher pressures indicating an extension to the existing criterions/laws is necessary



Microphysical Modeling



- Pyboltz is a python version of the MagBoltz code that calculates gas transport properties
- This produces many values including Townsend's First ionization coefficient
- We used this data instead of the approximation to model breakdown

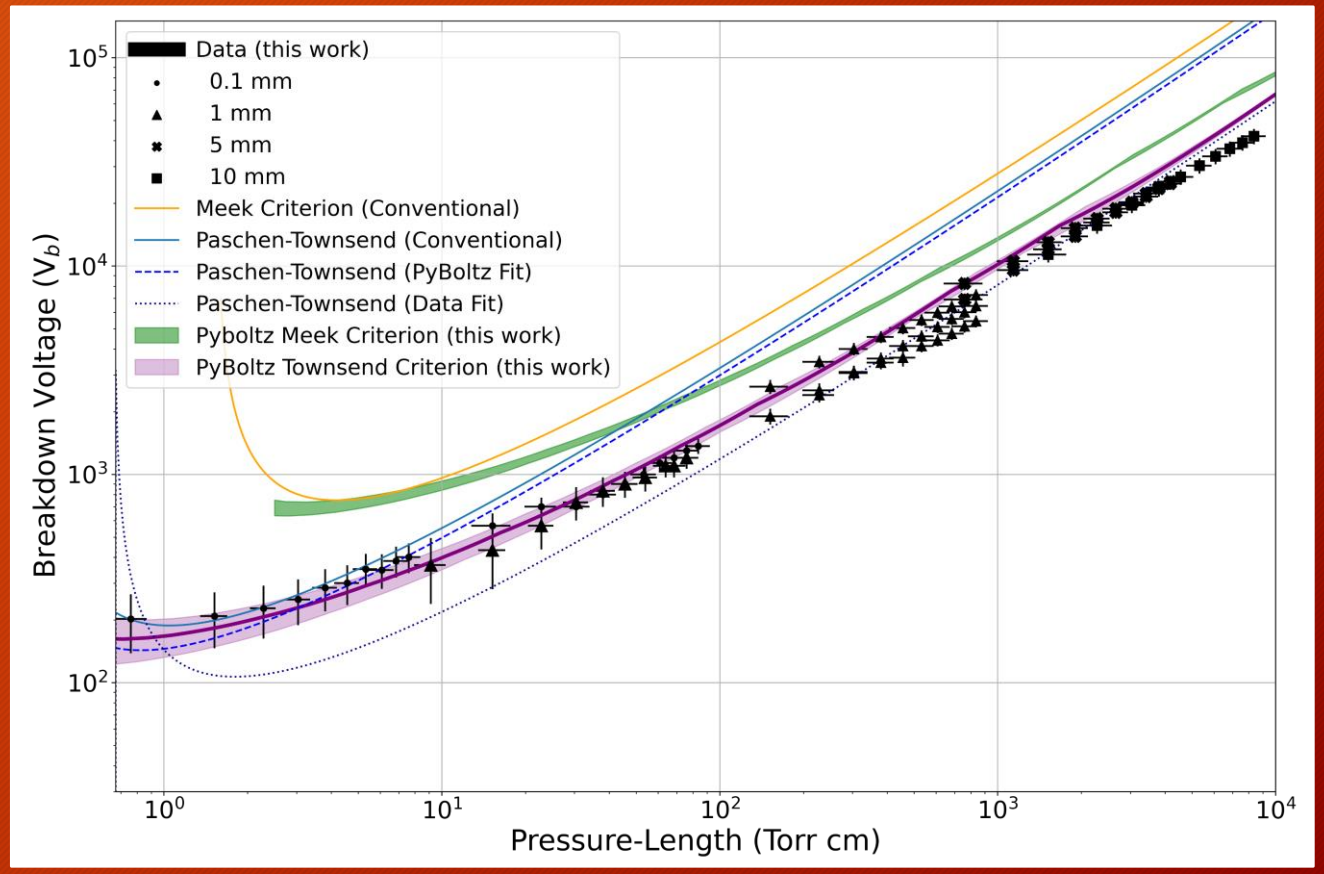


Argon Theoretical Comparisons

Since there is a good amount of uncertainty with gamma_se we plotted a range of values for each theoretical line, which is a large range that should cover all the gamma values with little effect on the breakdown voltage

The purple line is the PyBoltz prediction using the Townsend criterion and the argon data seems to follow this trend

The Green line is the PyBoltz prediction using the meek criterion

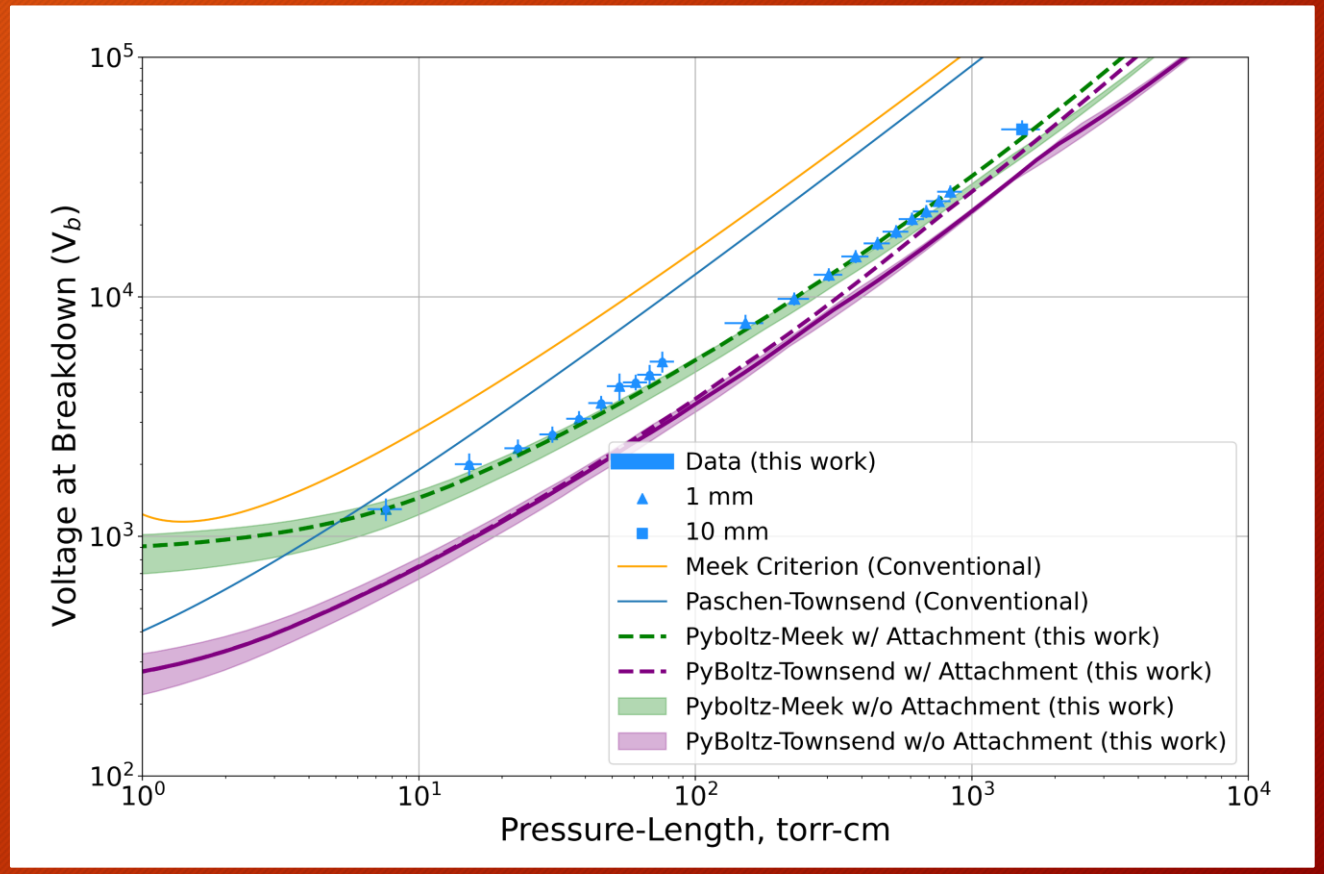


CO2 Theoretical Comparisons

In the case of CO2 which is a molecular “quenched” gas, not a noble gas, it seems to follow the green line which is the PyBoltz prediction using the meek criterion

The noble gases follow the Townsend criterion, and the molecular “quenched” gases seem to follow the meek criterion

On this plot the effect of attachment is shown as the dotted line, the top end of the data seems to follow but it is unclear, and only becomes apparent at high pd

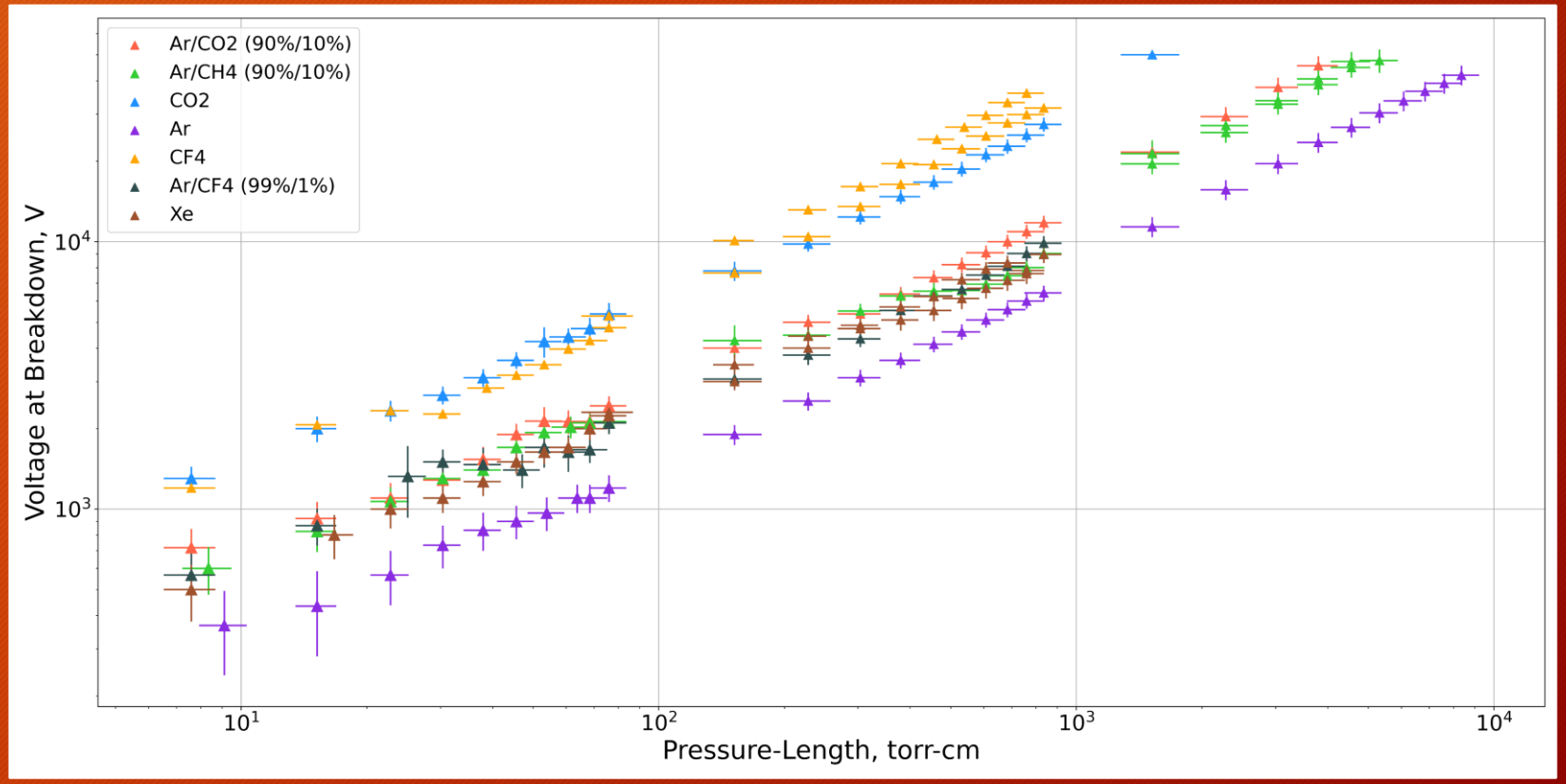


Various Gases

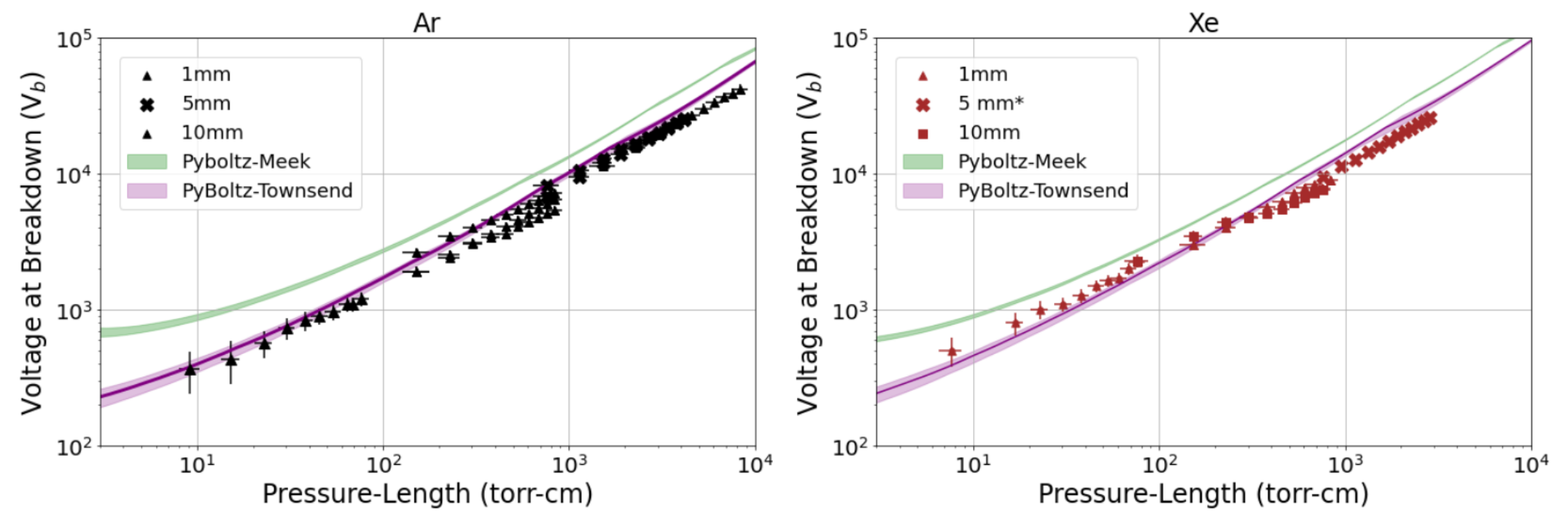
We performed tests with Argon, CO2, Ar-CO2, CF4, Ar-CF4, Ar-CH4, Xe

The CO2 and CF4 have the highest breakdown, on the same order of magnitude

The mixtures and xenon were also on the same order of magnitude, all higher than Argon



Results in Various Gases



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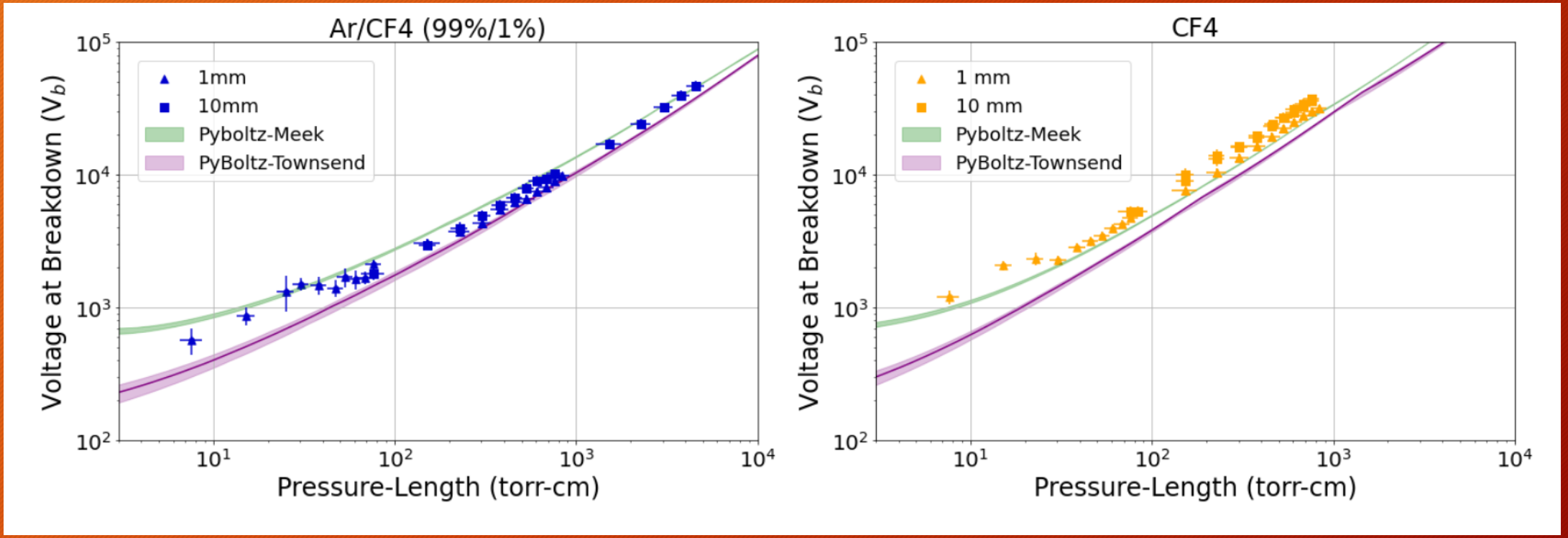
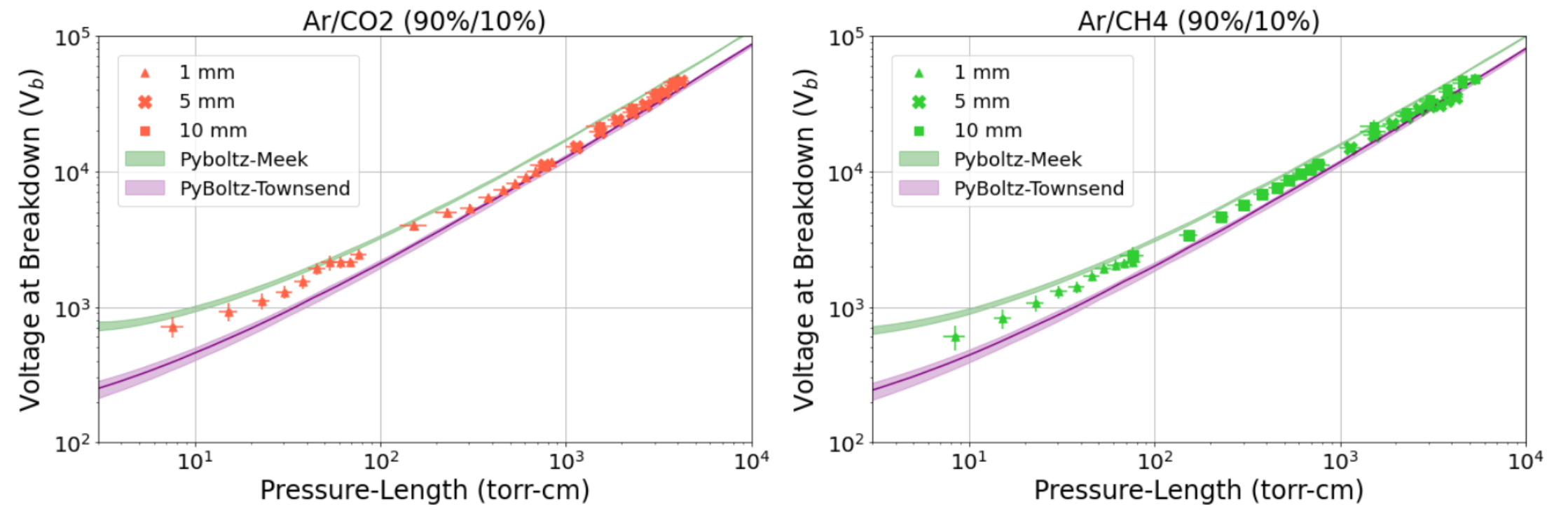


Results in Various Gases



Extrapolated Values

We were able to take Argon data all the way up to 1 cm at 10 bar, so we used this data to extrapolate the values of the other gases

We used the models to extrapolate out the Breakdown voltages of the different gases at 1 cm gap distance and 10 bar since our feedthrough restricted our range

This puts the breakdown of pure CO2 at 1 cm gap distance and 10 bar around 171,200 Volts

Projected Breakdown Voltage at 10 bar, 1 cm (kV)							
	Ar	Xe	Ar-CF_4	Ar-CH_4	Ar-CO_2	CO_2	CF_4
Townsend	**52.6**	**75.4**	61.7	63.9	68.6	129.5	179.7
Meek	69.9	98.9	72.1	80.3	87.3	**171.2**	**212.2**

Summary

- Many have studied gas breakdown by theory and experiment, but no predictive theory in the high-pressure region(1-10 bar) was available.
- We have taken data in a range of gases of interest to particle physics experiments over gap sizes 0.1-10mm and pressures 0.1-10bar.
- Both traditional Townsend and Meek breakdown formalisms are shown to be inaccurate at high pressures.
- We have developed a new model that makes first principles theoretical predictions in this regime.
- Our theoretical predictions reproduce data very well using a Pyboltz-Townsend criterion in nobles and Pyboltz-Meek criterion in quenched gases.
- Example code for simulating breakdown strengths in your favorite gas mixtures now available in the PyBoltz repository.

The End

Thank you for listening,

Any Questions?

Enhancement factor

Calculated the field enhancement factor due to the spherical electrode geometry

This enhancement of the field is due to the spherical geometries we have used

Since we only used 1 cm maximum separation distance it only accounts for a maximum of 6% uncertainty in the electric field