Drift Properties of Noble Gases in Negative Ion Drift TPCs

ELIZABETH TILLY – WELLESLEY COLLEGE

WORK CARRIED OUT DURING PHD AT THE UNIVERSITY OF NEW MEXICO

CPAD – OCTOBER 2026

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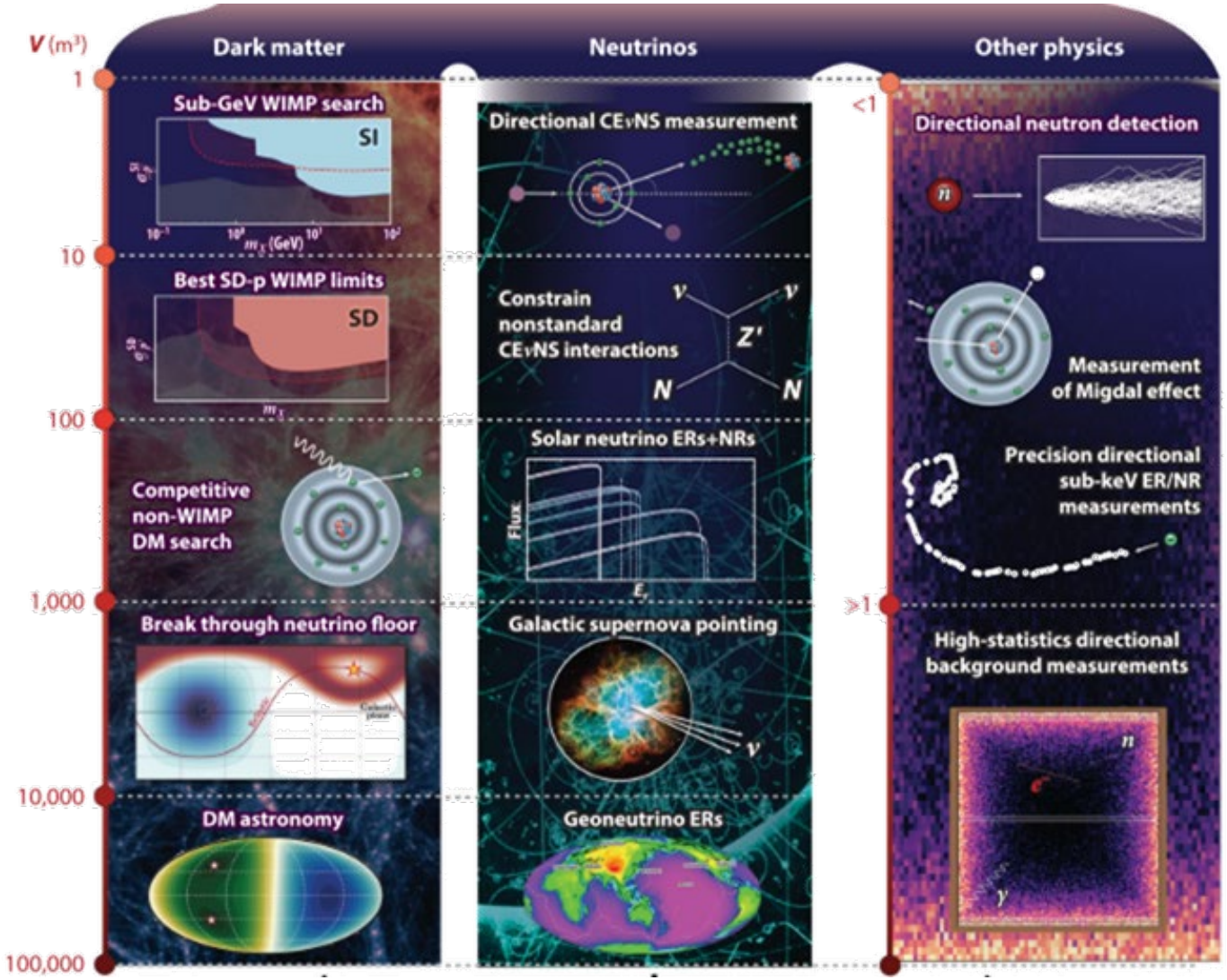
Directionality for Rare-Event Searches



S. Vahsen et al Annu. Rev. Nucl. Part. Sci. 2021. 71 189-224 [2102.04596 (arxiv.org)]

Noble Gases as Targets

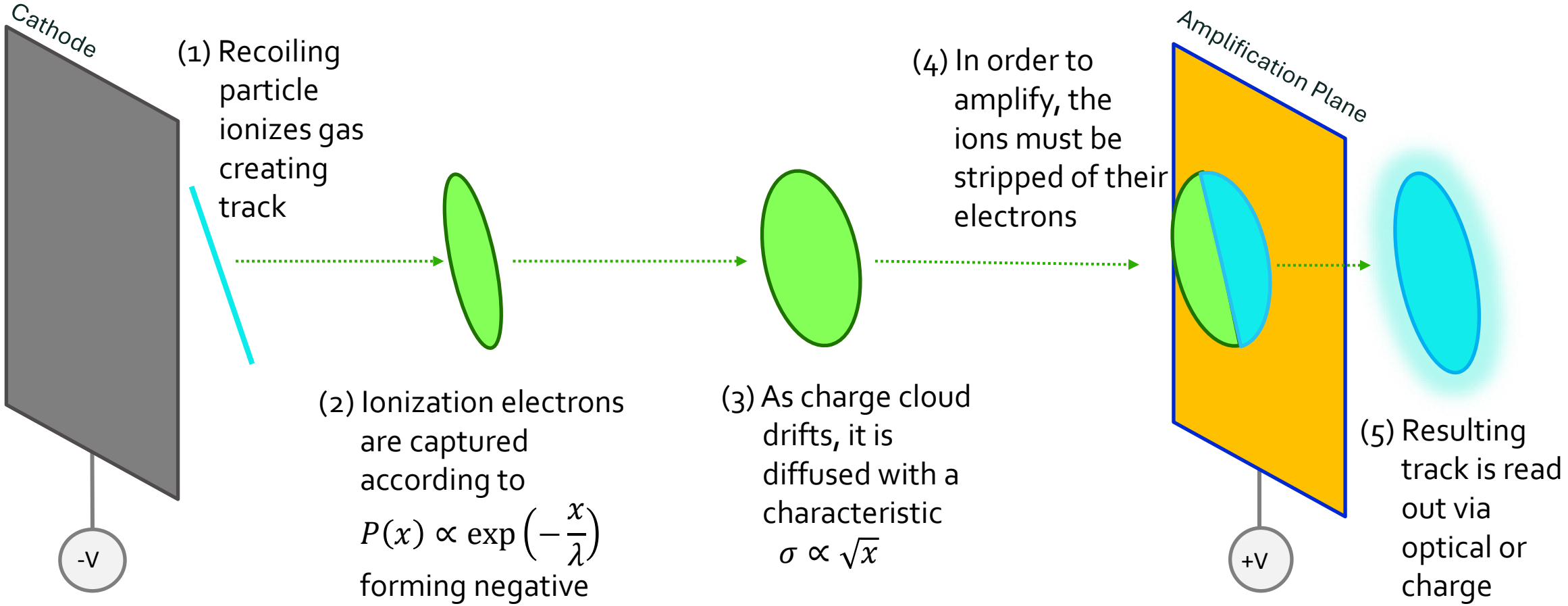
Far from a comprehensive list…

- Gaseous He, Ar, Xe and CF_4 for WIMP DM searches
  - J.F. Castel *et al.* JINST **19** C05029 (2024)
  - F.D. Amaro *et al.* Particles ***4*** 343-353 (2021)
  - S.E. Vahsen *et al.* (2020) arxiv:2008.12587
  - C. Deaconu *et al.* Phys. Rev. D **95** 122002 (2017)
  - K. Nakamura *et al.* JINST **7** C02023 (2012)
- Gaseous Xe for neutrinoless double beta decay
  - K. Mistry, D. R. Nygren, (2025) arxiv:2512.19290
  - I.G. Irastorza *et al.* JCAP **01** 033 (2016)
- Gaseous He, Ar, Xe, CF_4 in Migdal Effect searches
  - D. Yi *et al. Nature* **649**, 580–583 (2026)
  - H.M. Araújo *et al.* (MIGDAL collaboration), Astropart. Phys. **151** 102853 (2023)
  - K.D. Nakamura *et al.* PTEP **1** 013C01 (2021)
- Gaseous Ar in collider-based neutrino experiments
  - R.M. Amarinei, *et al.* JINST **18** P12001 (2023)
  - A. Abed Abud, *et al.* (2022) arXiv:2203.06281

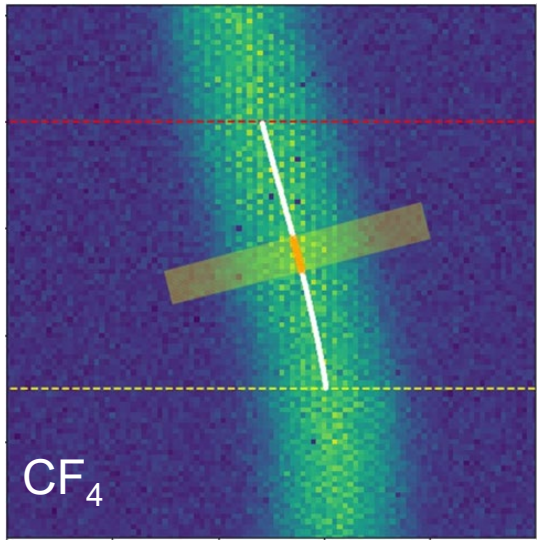
And the list goes on…

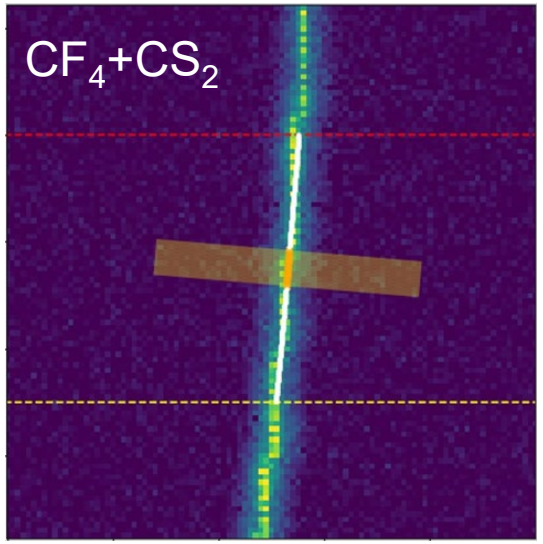
Negative Ion Drift Low-Pressure Gas TPCs

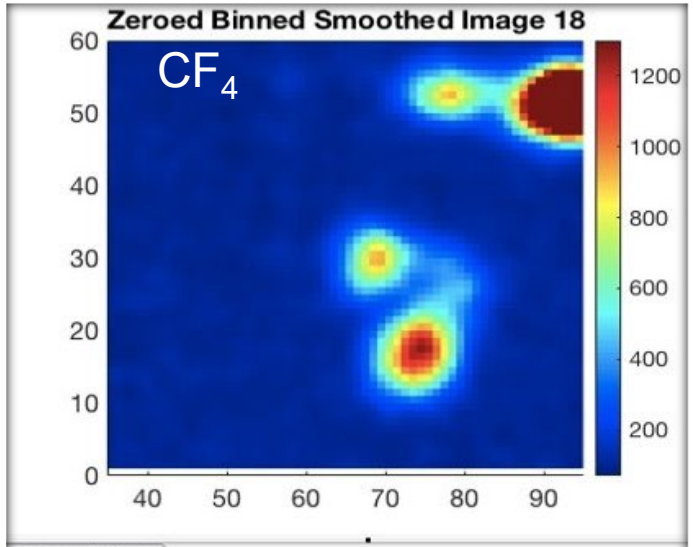
Lower diffusion + Longer Tracks = Better Directional Resolution

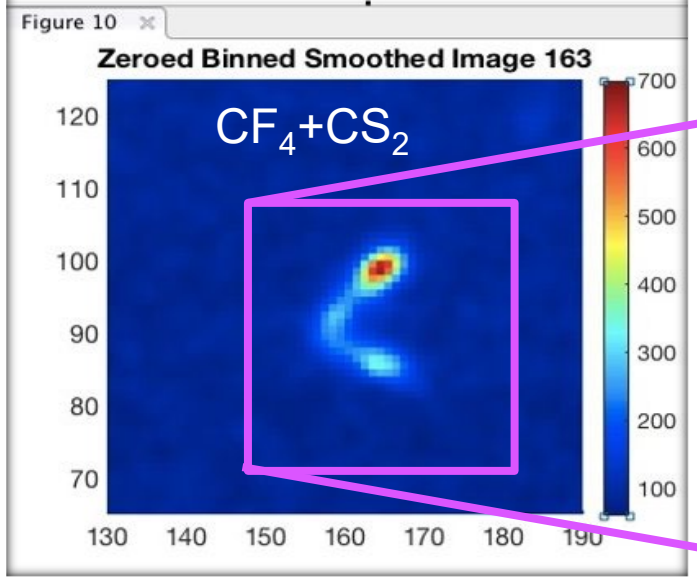


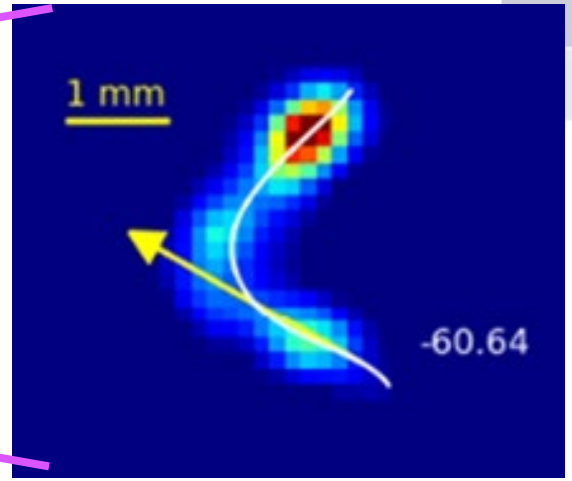
Advantages of Negative Ion Drift (NID)











150 Torr CF_4 + X torr CS_2	
CS_2 (Torr)	σ(μm)
0	~400
2.9	133.53
4.2	126.10
5.4	125.09
45 Torr CF_4 + X torr CS_2	
0	~550
4	~150-200

Gains for these tracks are on the order of 10^5!

Thermal Drift

- At low electric fields, ions are nearly in thermal equilibrium with the gas. As a consequence:
  - Diffusion width evolves according to the following

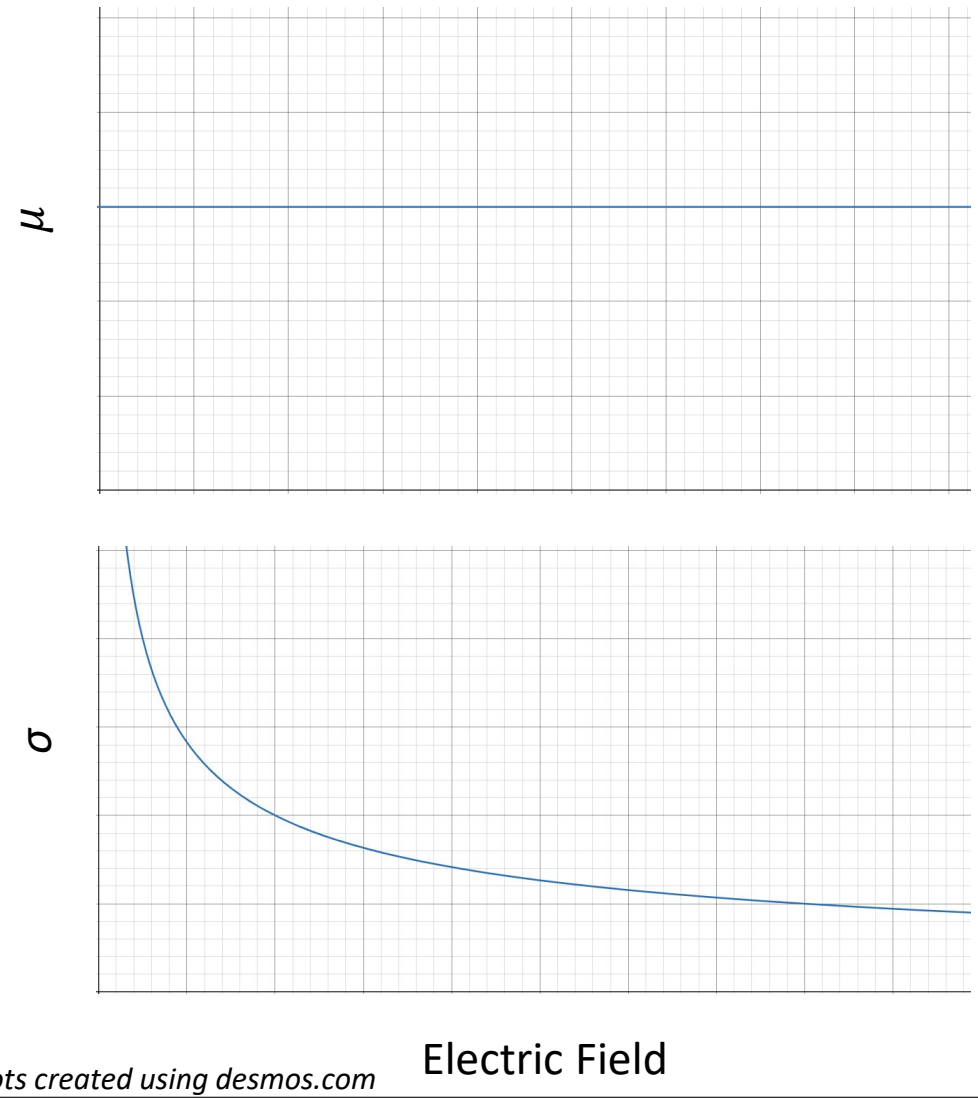
$$\sigma^2 = \frac{2kT}{e}\frac{L}{E}$$

  - Mobility is constant with E/P

$$\mu = \frac{v_d}{E}$$

- At higher fields (i.e. more energetic systems):
  - Mobility and diffusion are larger at higher fields
  - Diffusion becomes axially dependent

v_d = drift velocity, μ= mobility, E = Electric Field, e = ion charge, kT = thermal energy, L = drift length, σ = diffusion width



Plots created using desmos.com

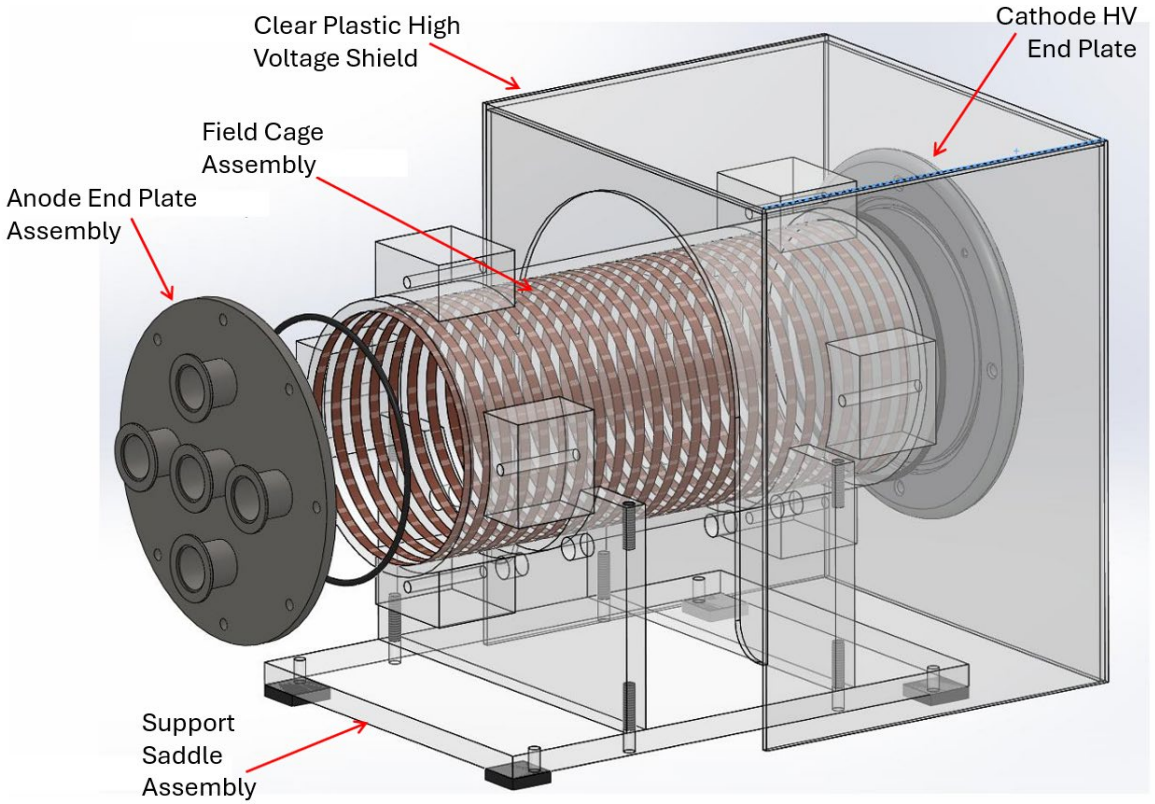
Optimizing/Testing Different Gas Mixtures

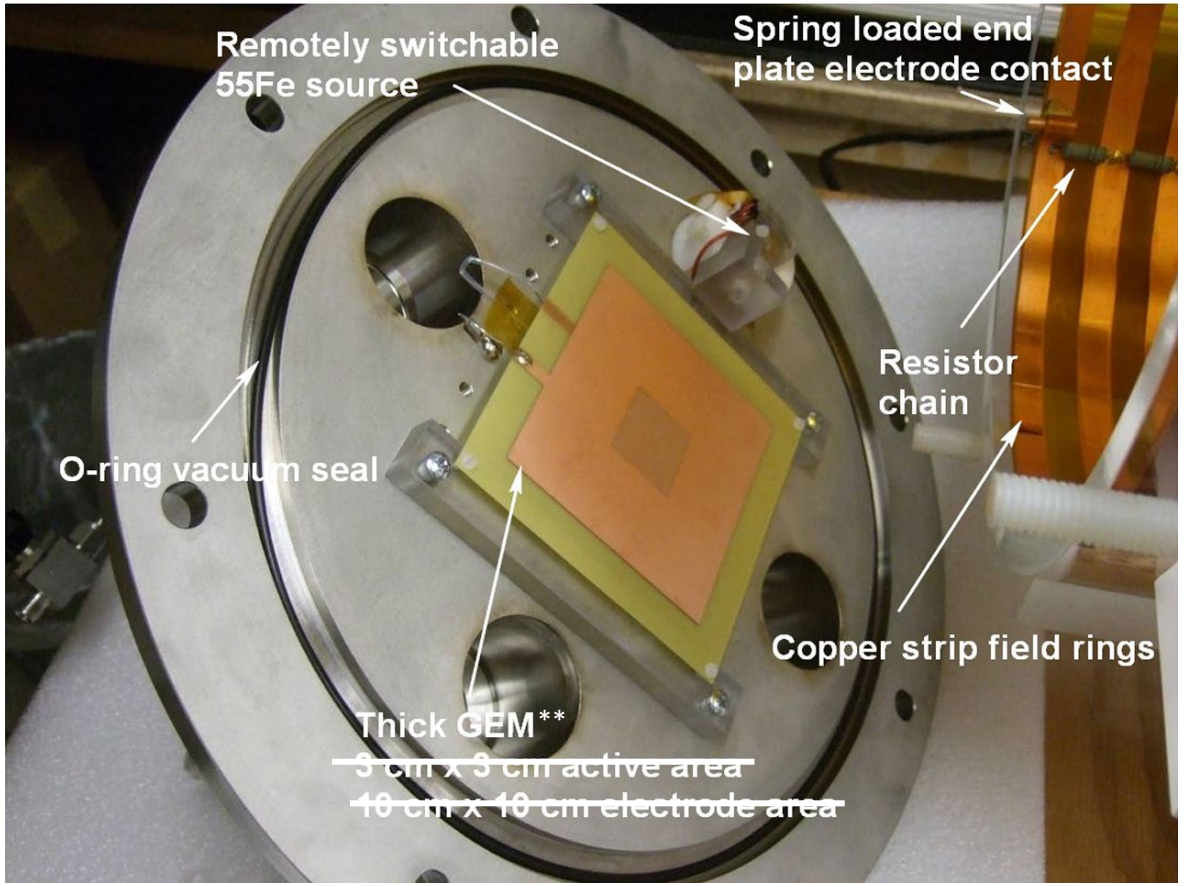
GOAL: Explore gas mixtures with high quantities of the **target gas** maintaining **negative ion benefits**

- Target Gases: **Xe, Ar, He, CF_4** NID gases: **SF_6 and CS_2**
  - Of interest to Migdal searches, Directional Dark Matter searches, Neutrino Studies, etc

- Properties of interest for Noble Gas NID TPCs:
  - Diffusion = Track broadening from stochastic motion within the gas → NID is narrower
  - Mobility = Proportionality constant between drift velocity and field → NID is slower
  - Gain = Stable operation and amplification capability → electron stripping is required for avalanche amplification in NID but NID gases increase stability
  - Attachment Length = Mean distance before electrons are captured in the gas → Must have short attachment length

The Detector

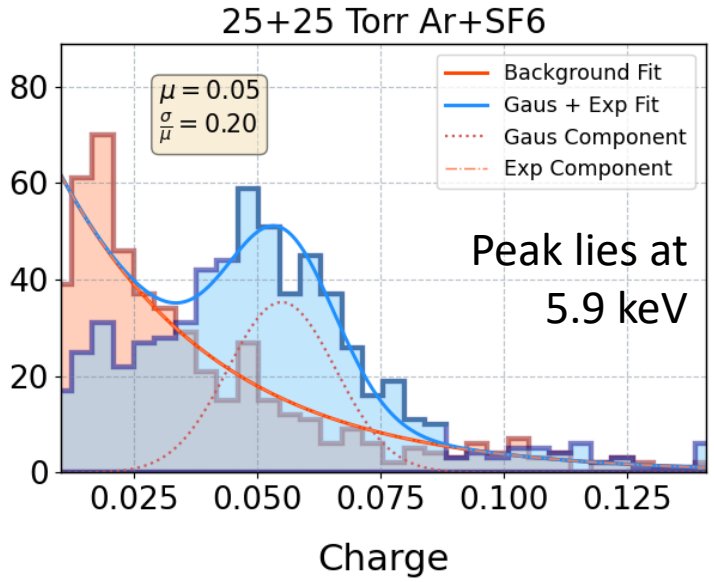




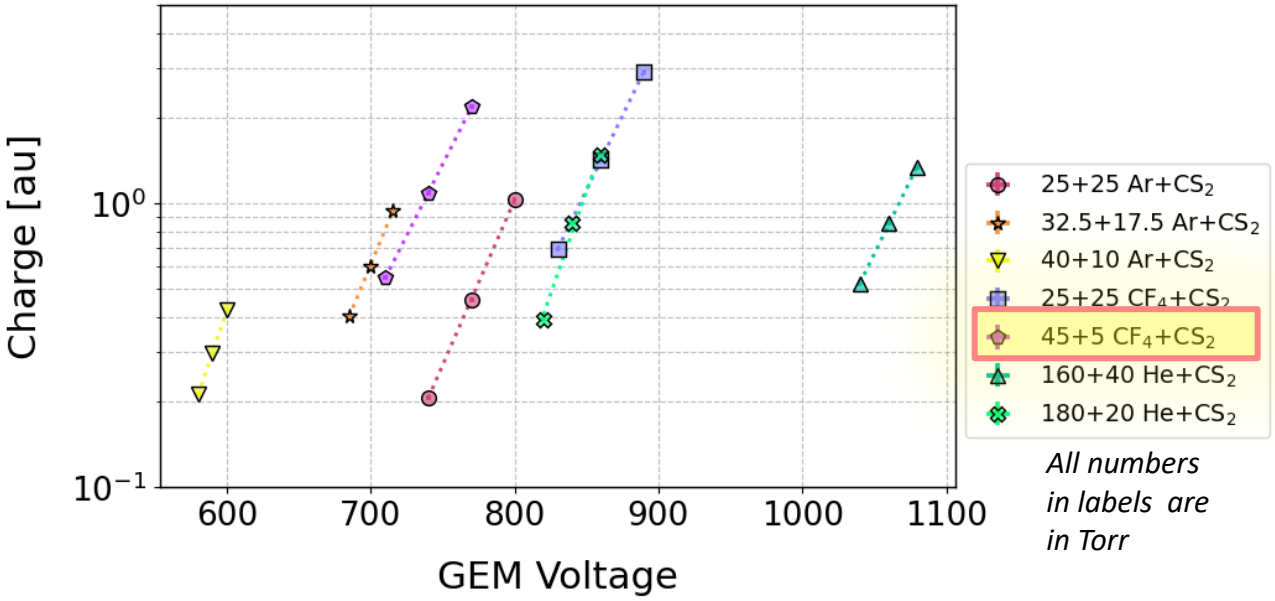
N.S. Phan *et al* 2017 *JINST* **12** P02012

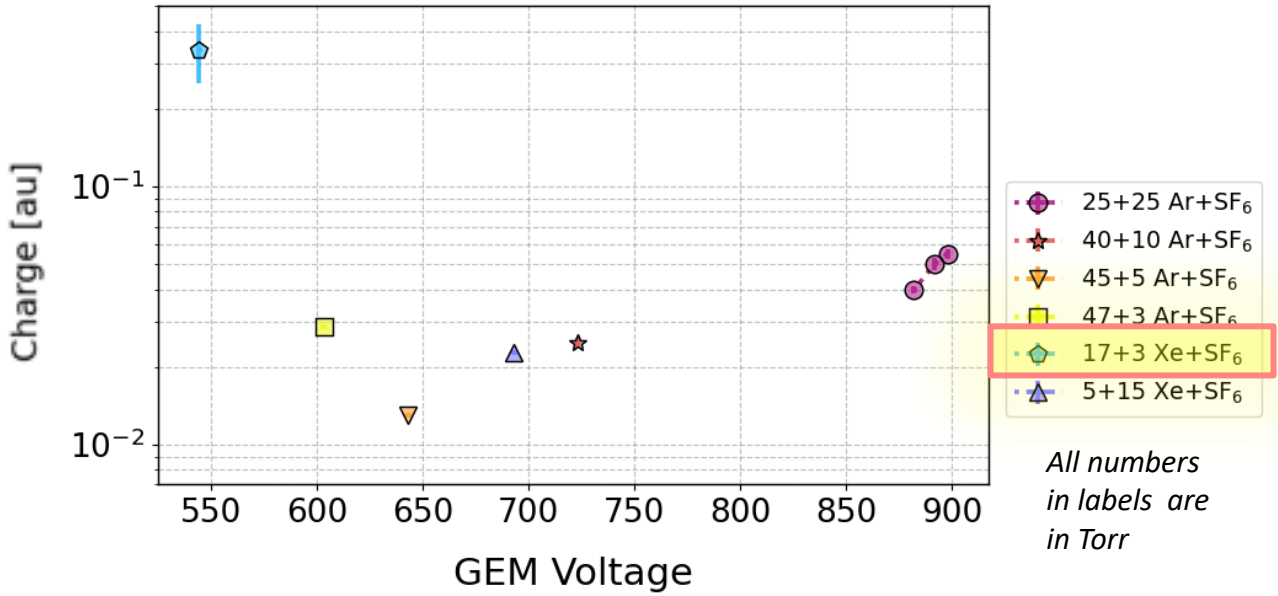
** THGEM we used is 400 um thick and has 10x10 cm active area, a pitch of 0.5mm, and a hole diameter of 0.3mm

Relative Gains

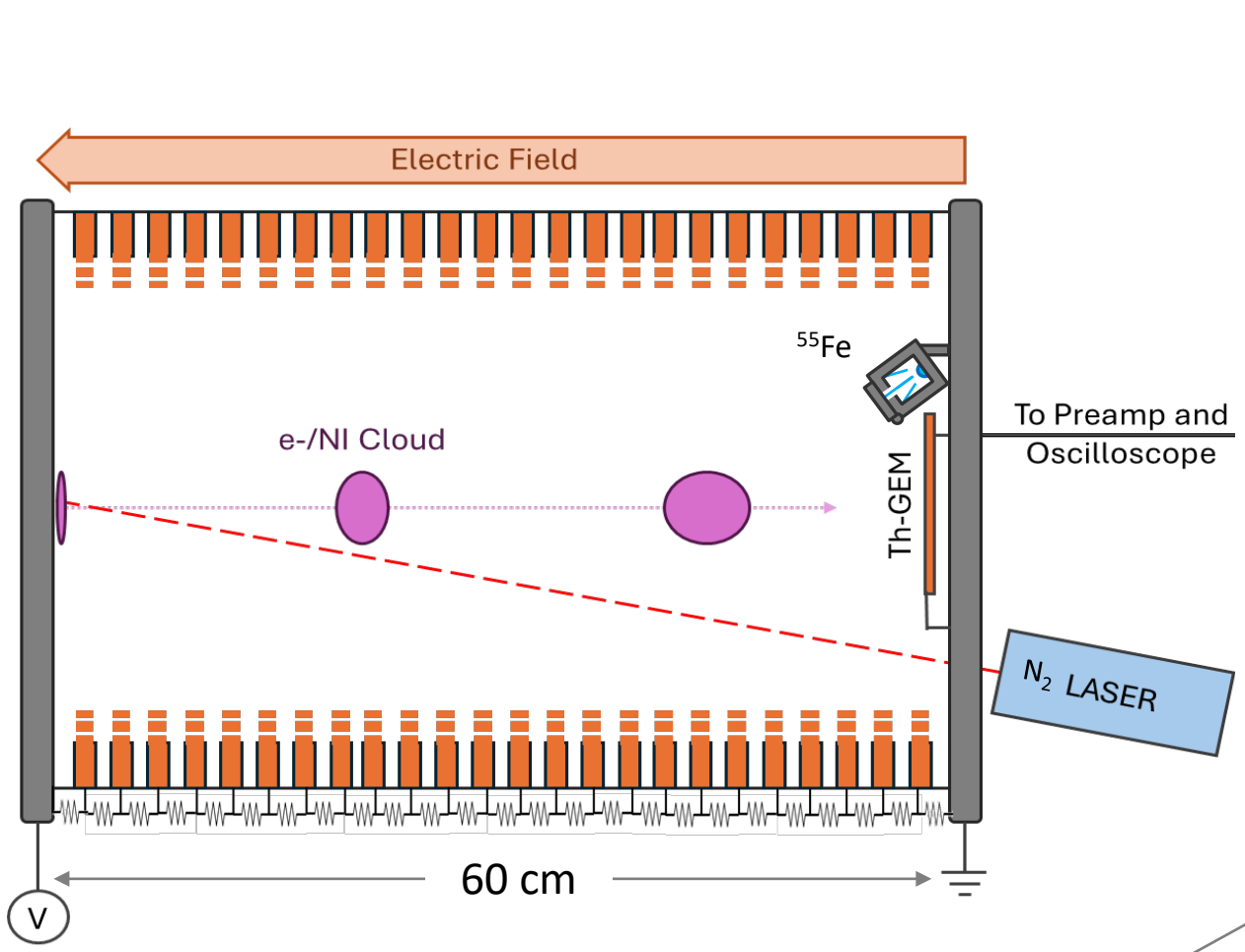


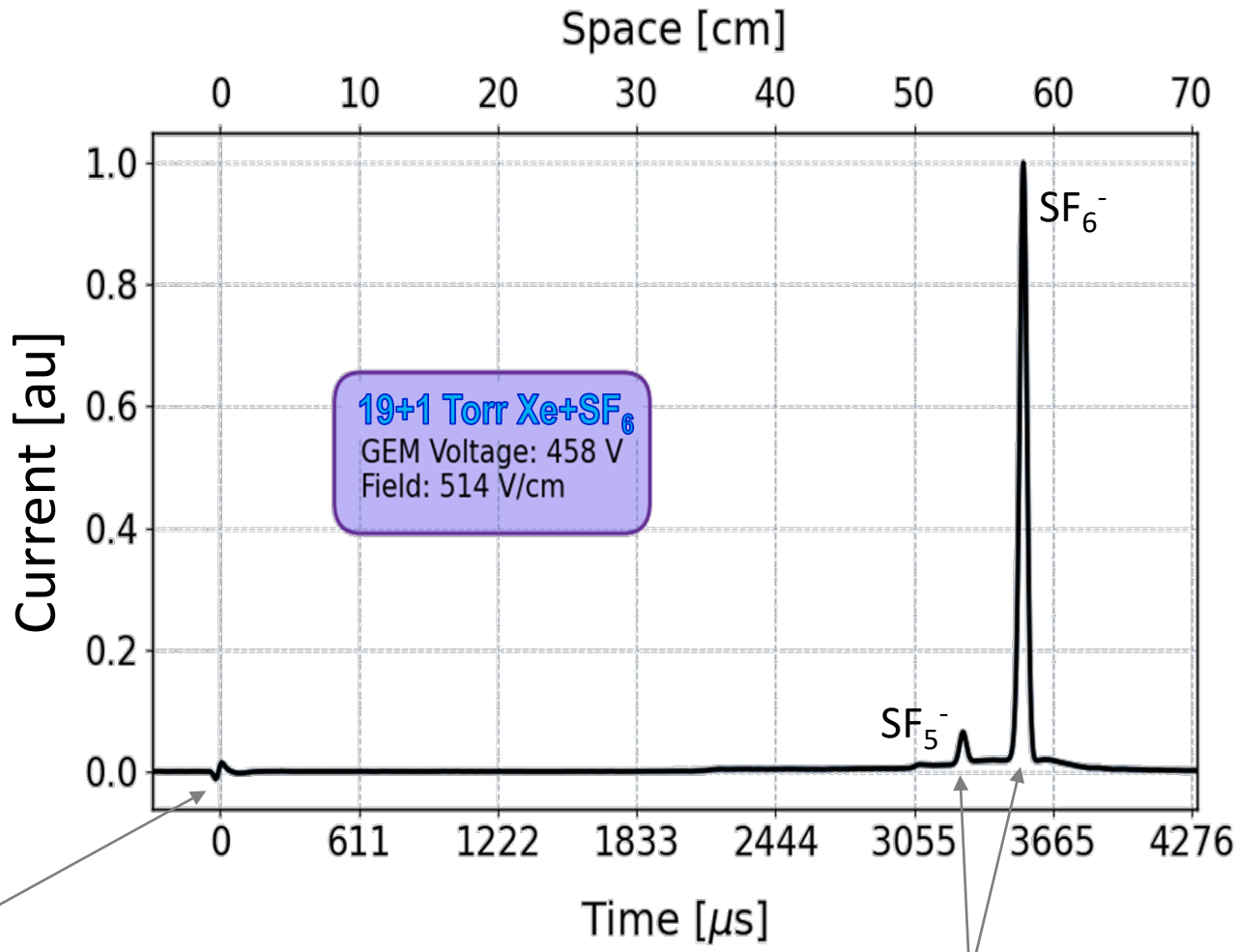
- Strongly electronegative SF_6 and CS_2 ions must be stripped before amplification
- CS_2-based mixtures had higher gains, in general, than SF_6-based mixtures
- $\frac{\sigma}{\mu} \approx 20\%$ for CS_2 and 25% for SF_6
- Stable operation resolving 5.9 keV peak from ^{55}Fe with as little as **3 Torr SF_6 and 5 Torr CS_2**!





Laser-based Measurements





RFI Signal induced by Laser firing → t_0

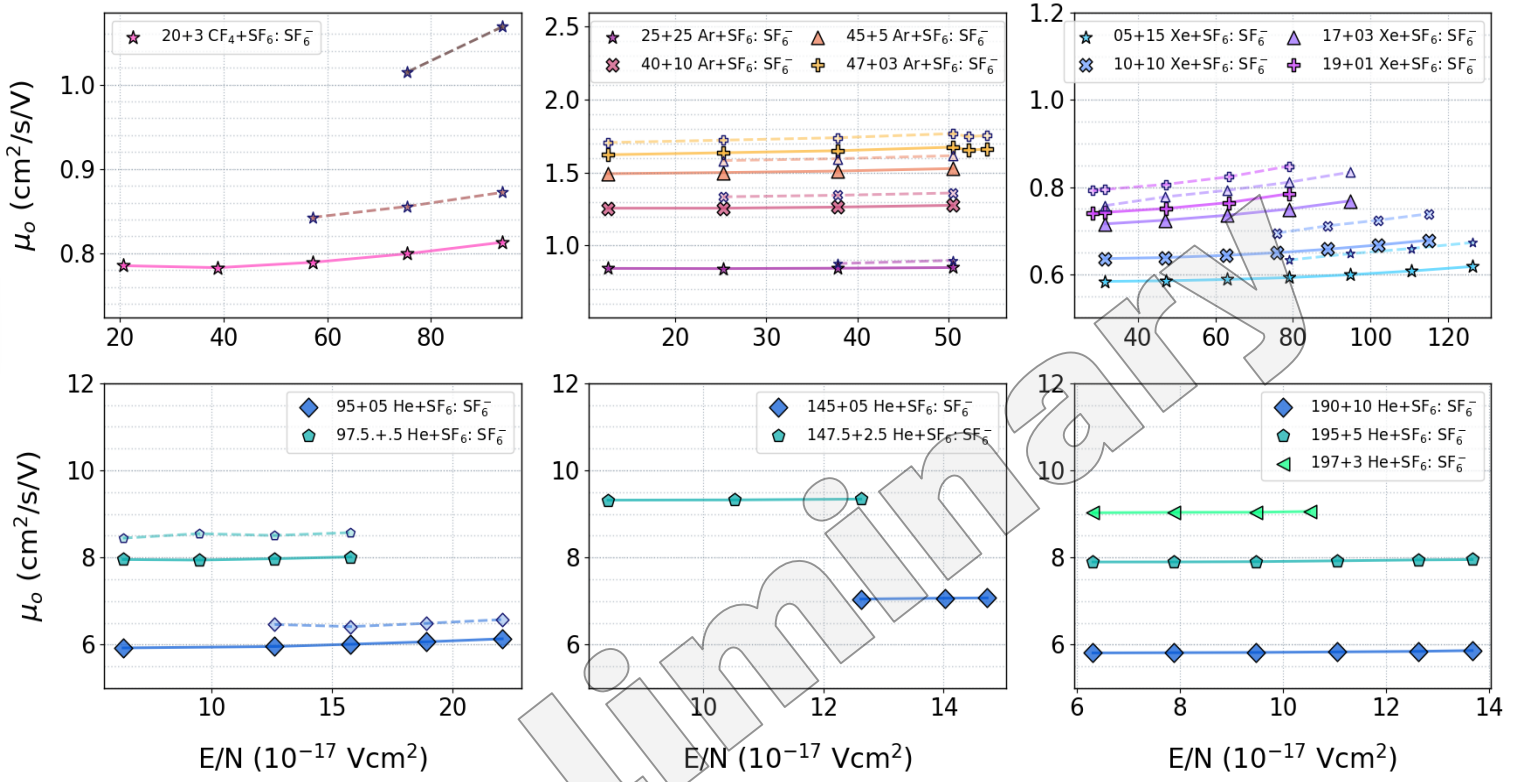
Signal from charge cloud → t_a

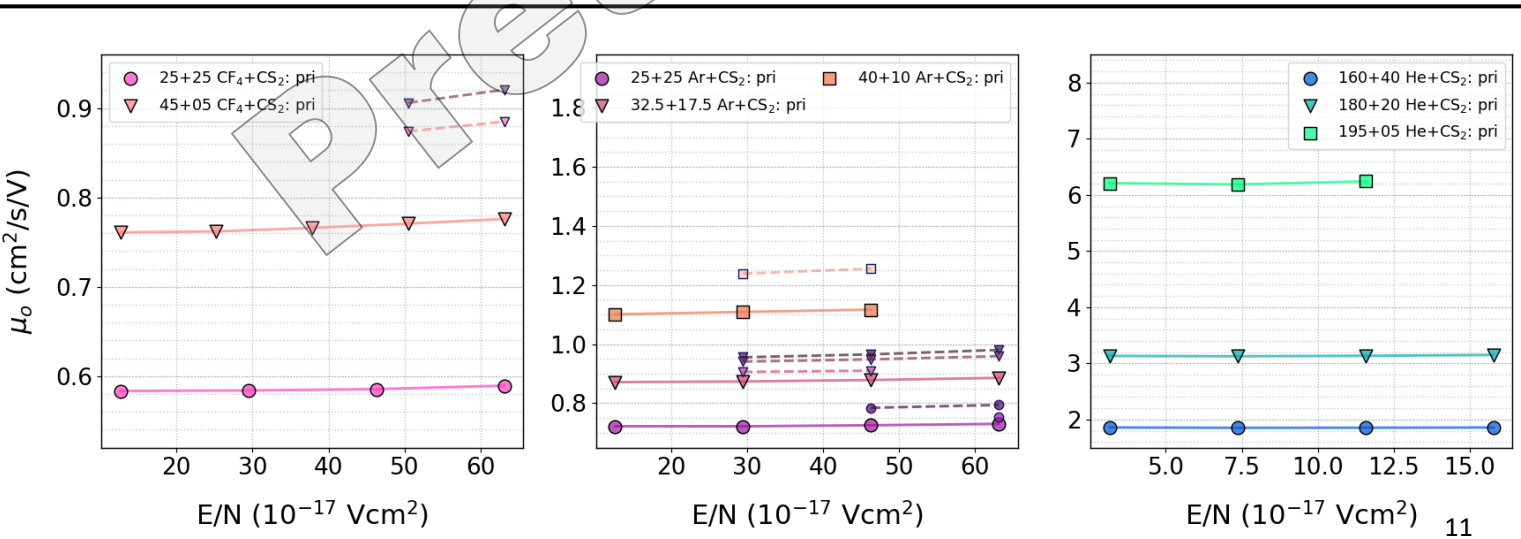
Mobility

- $\mu_o = \frac{v_d}{E}\frac{N}{N_o}$
  - N and N_o are gas density in detector and at STP, v_d is drift velocity, E is Electric Field
- Mobilities are roughly 2 orders of magnitude lower than in the pure noble gases
- Many minority species were noted with mobilities around ~10-20% of the primary species

Mobility at 600 V/cm and 3 Torr SF_6			
Gas	P_{total} (Torr)	ED* μ_o $(cm^2s^{-1}V^{-1})$	NID μ_o $(cm^2s^{-1}V^{-1})$
Xe	20	188	**0.77**
Ar	50	325	**1.64**
He	200	796	**9.03**

* S. Biagi (1995). https://magboltz.web.cern.ch/magboltz/





Preliminary

Mobility

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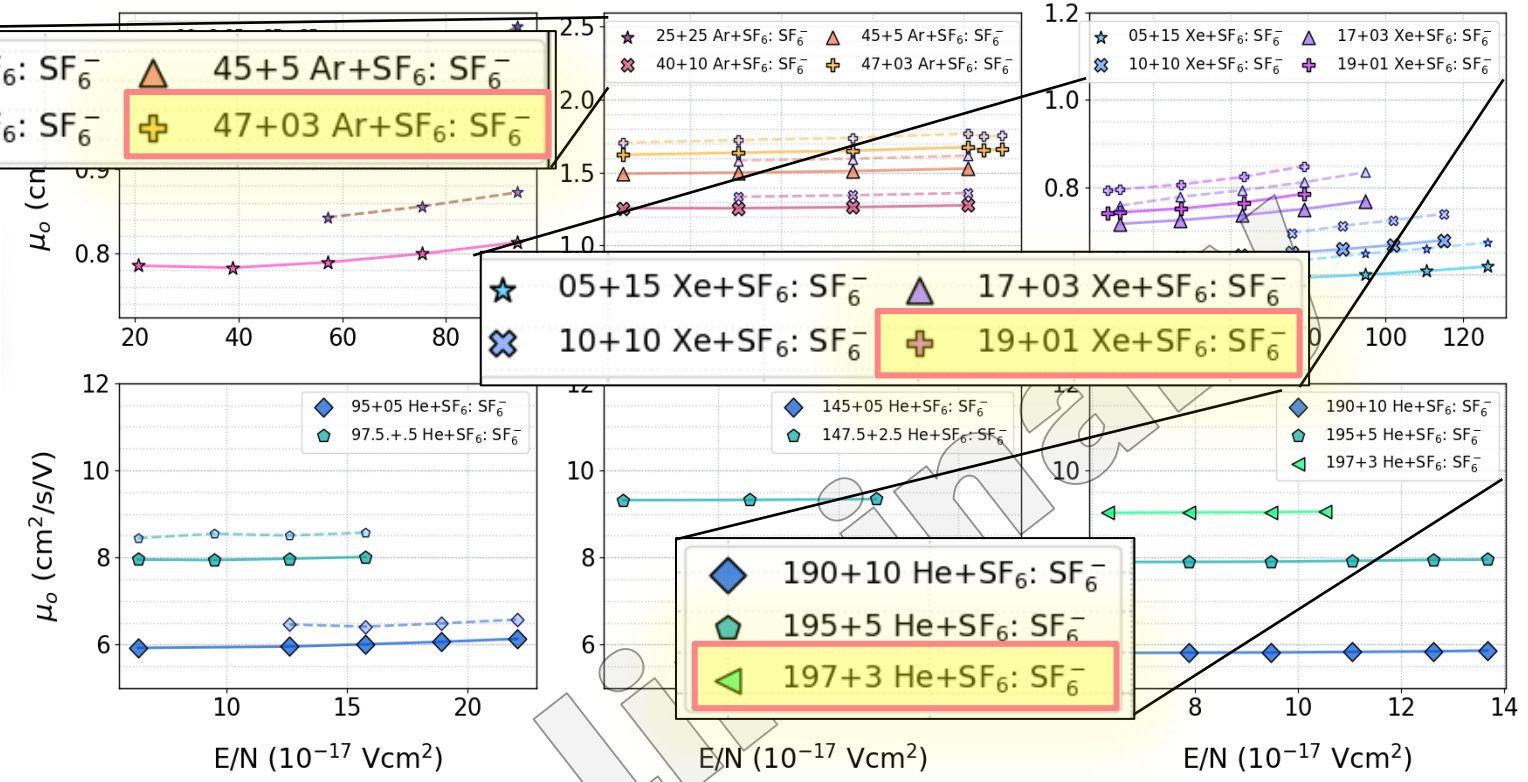
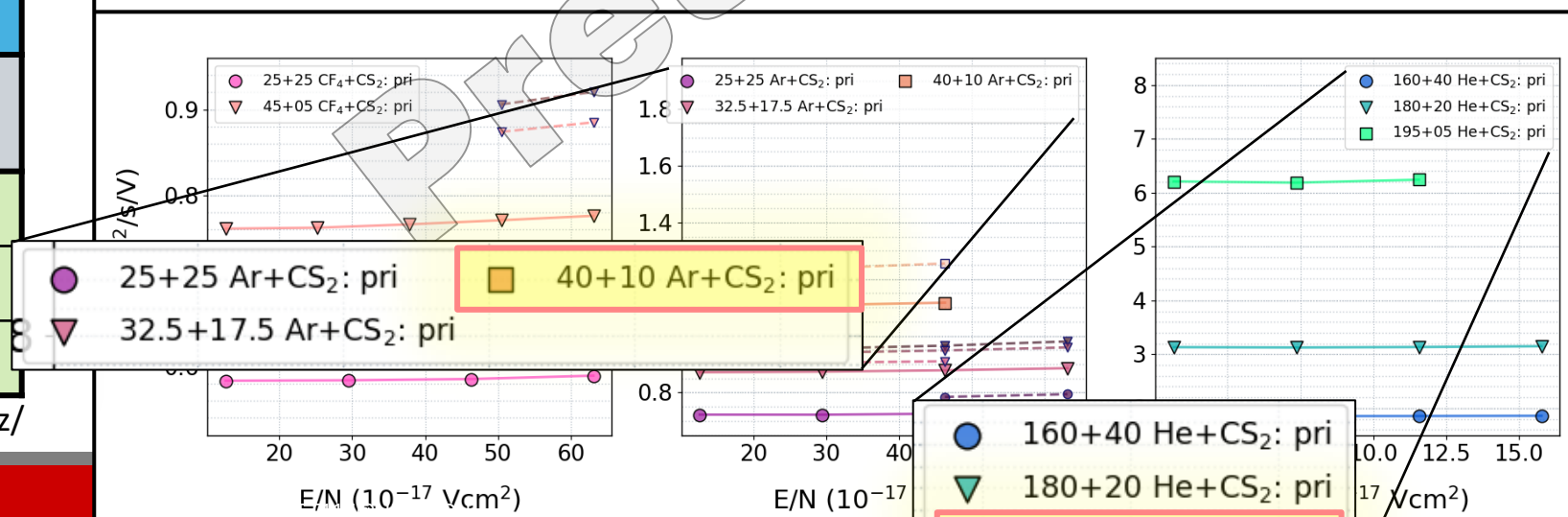


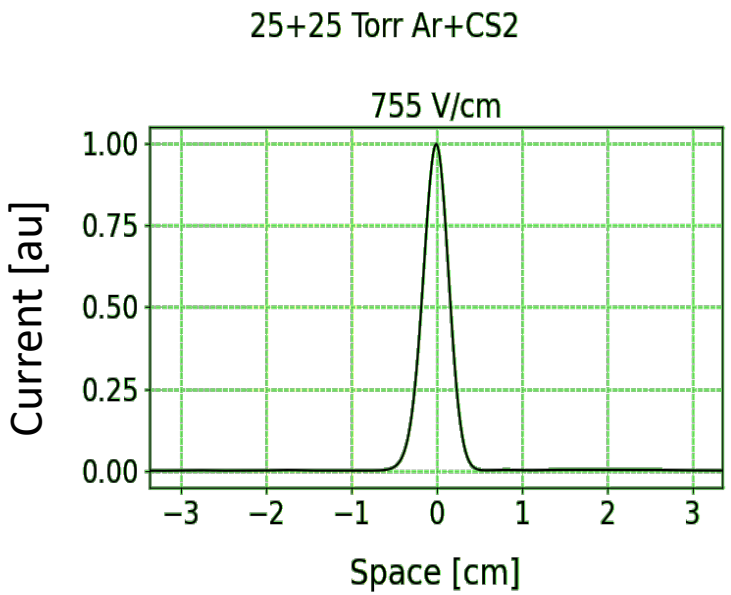


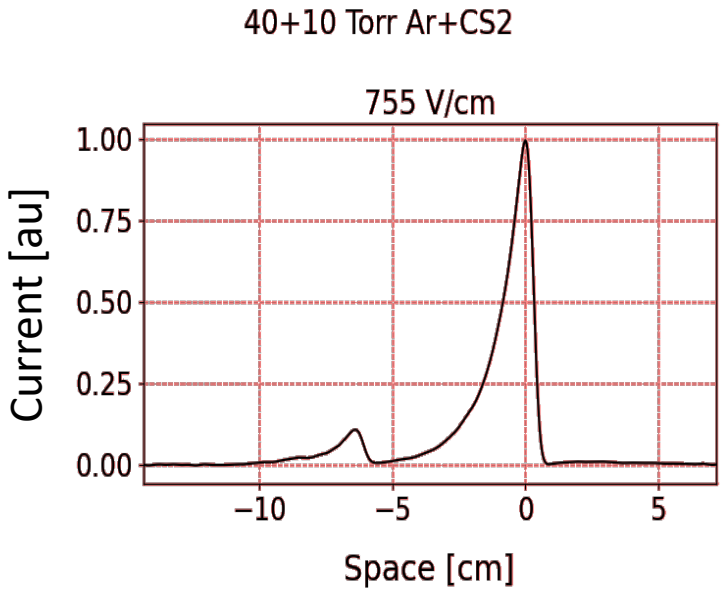
Preliminary

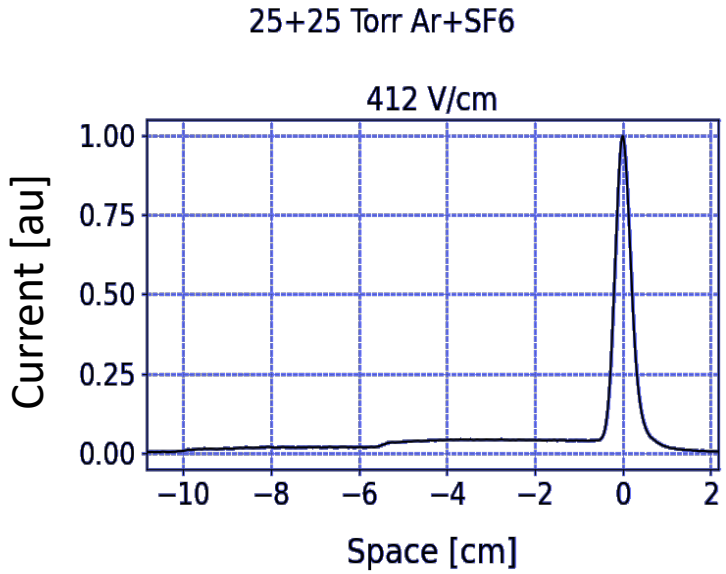
Waveform Shape

Fitting Functions Used to model Diffusion width, σ (and attachment length, λ = 1/L)

- Gaussian: $G(t) = \exp\left[-\frac{(t-m)^2}{\sqrt{2\sigma^2}}\right]$
- Exponentially Modified Gaussian: $EMG(t) = \frac{L}{2}\exp\left[\frac{L}{2}(2m + L\sigma^2 - 2t)\right]\operatorname{erfc}\left[\frac{m+L\sigma^2-t}{\sqrt{2\sigma^2}}\right]$
- Step + Gaussian: $SG(t) = \frac{h}{2}\left(1 - \operatorname{erfc}\left[\frac{x-m}{\sqrt{2\sigma^2}}\right]\right) + G(t, m, \sigma)$







Longitudinal Diffusion

- $\sigma_z = D'_L\sqrt{58.3\ cm}$
  - D'_L is longitudinal diffusion coefficient used by Garfield and Magboltz. It relates to the normal Diffusion coefficient, D, by $D' = \sqrt{2D/v_d}$
- Diffusion can be suppressed by ~ an order of magnitude with as little as 1 Torr SF_6 or 5 Torr CS_2
- In many cases it's nearly thermal!

Diffusion Coefficient at 600 V/cm and 3 Torr SF_6			
Gas	P_{total} (Torr)	ED D'_{long}* ($\mu m/\sqrt{cm}$)	NI D'_{long} ($\mu m/\sqrt{cm}$)
Xe	20	941	**165**
Ar	50	1143	**154**
He	200	1063	**~77**

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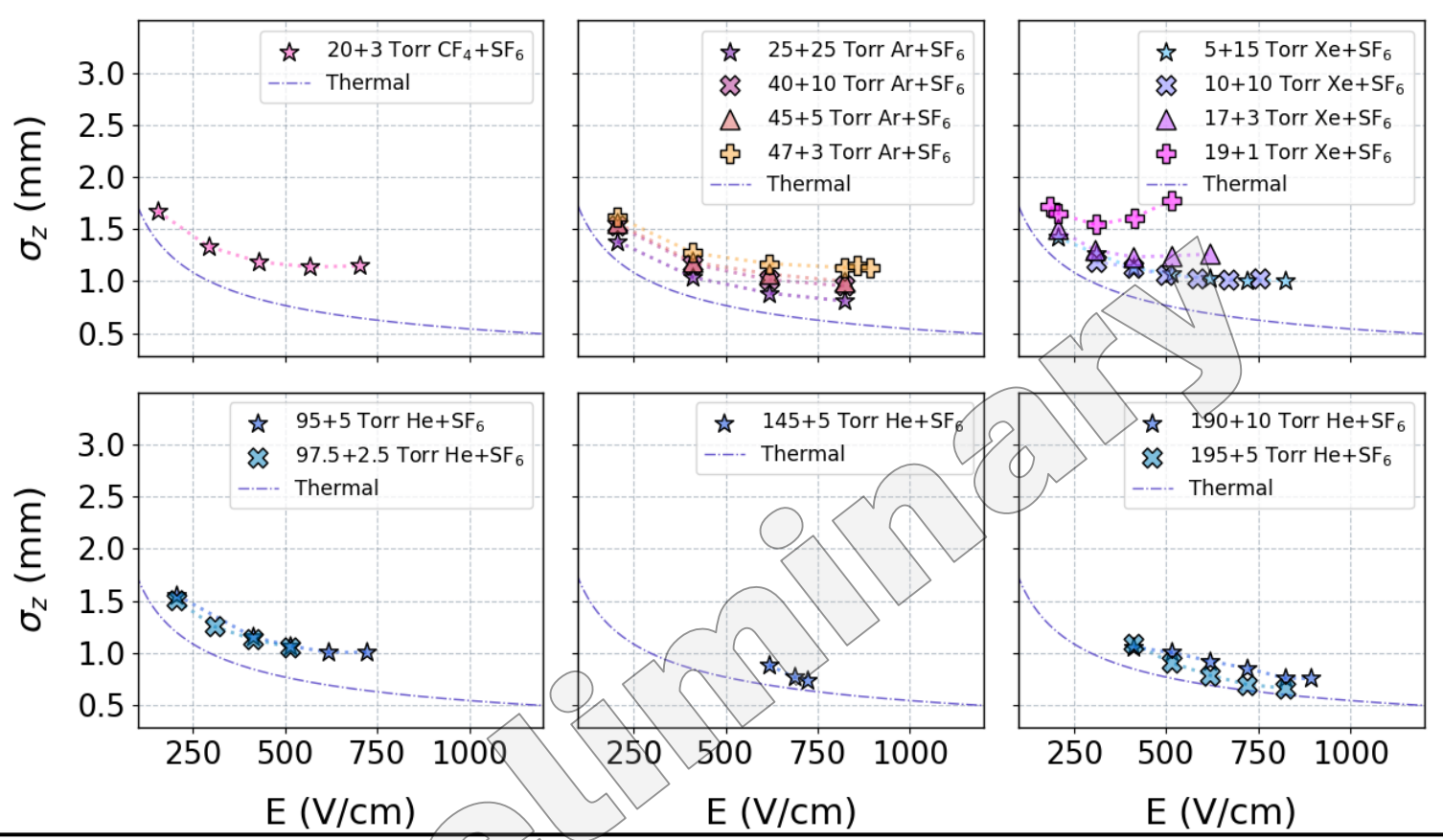
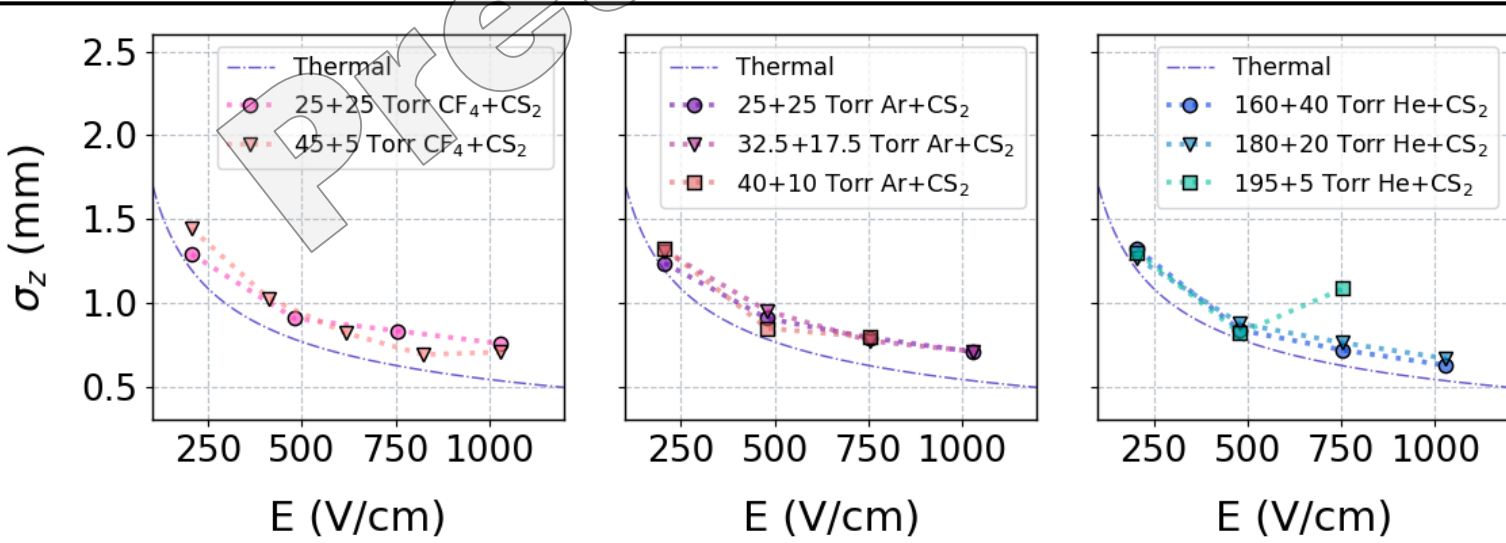




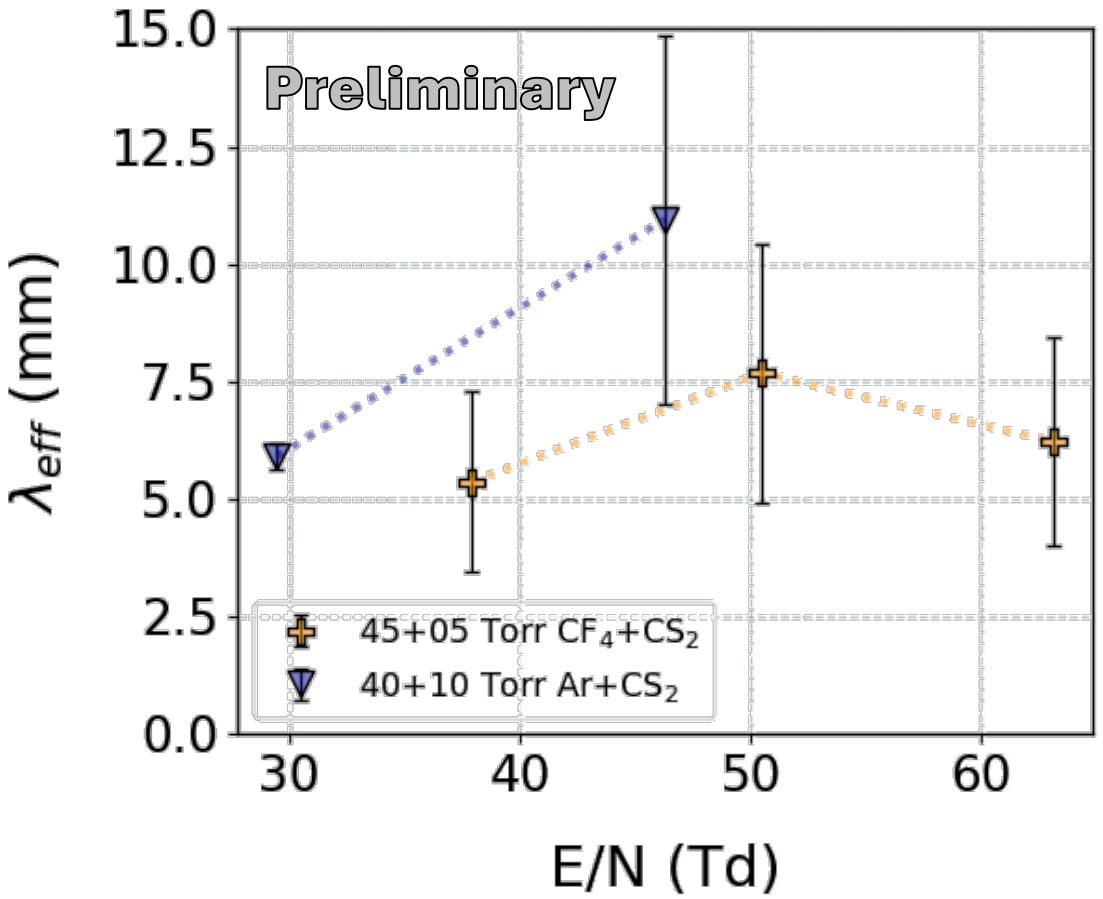
Preliminary

Attachment Length in CS_2 Mixtures

- Attachment could only be measured in a subset of the data
- CS_2 + Ar and CF_4 mixtures had large attachment lengths!

Consequences of high attachment for tracking detectors:

1. Exponentially modified waveforms along drift axis
2. "Mixed Drift" waveforms if drift length too short
   - Leads to waveform distortion
   - Leads to mixed gain for ED and NID components of the waveform



Conclusions

- Negative ion drift properties in mixtures of Xe, Ar, He, and CF_4 with either SF_6 or CS_2 have been measured with very low partial pressures of the NID component
- Stable gain for Fe-55 peak noted in many of the mixtures
- Diffusion was suppressed by ~1 order of magnitude
- Mobility was slowed by 2 orders of magnitude
- In some cases, attachment length could also be measured!

Special thanks to my collaborators on this project:

Dinesh Loomba and Drew Gibson and the UNM group

Diffusion Coefficient at 600 V/cm and 3 Torr SF_6

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Fermilab/DOE GIRA Award
Awarded to E.Tilly

Backups

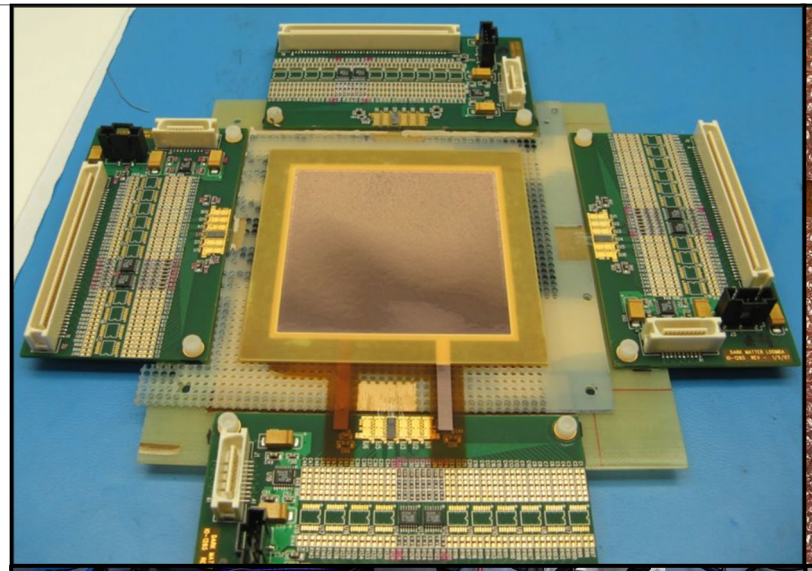
Notable Papers Regarding NID

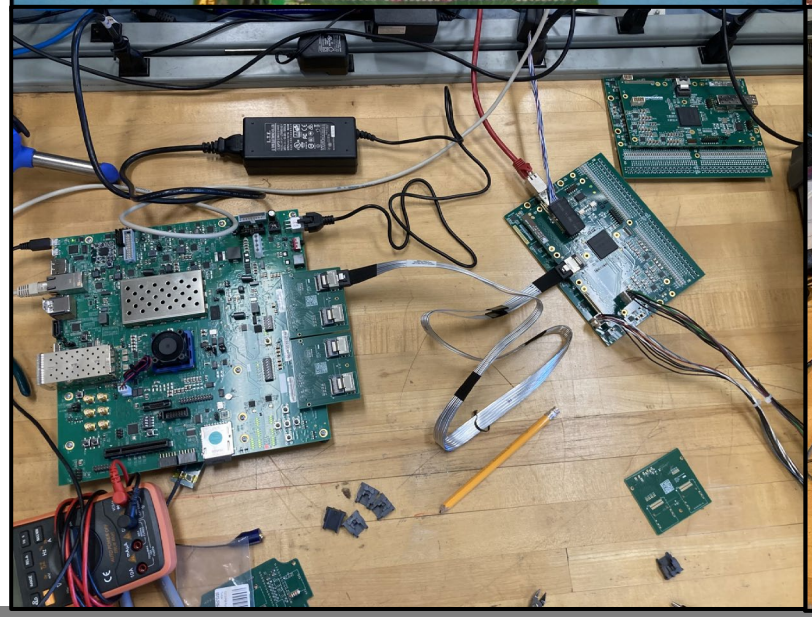
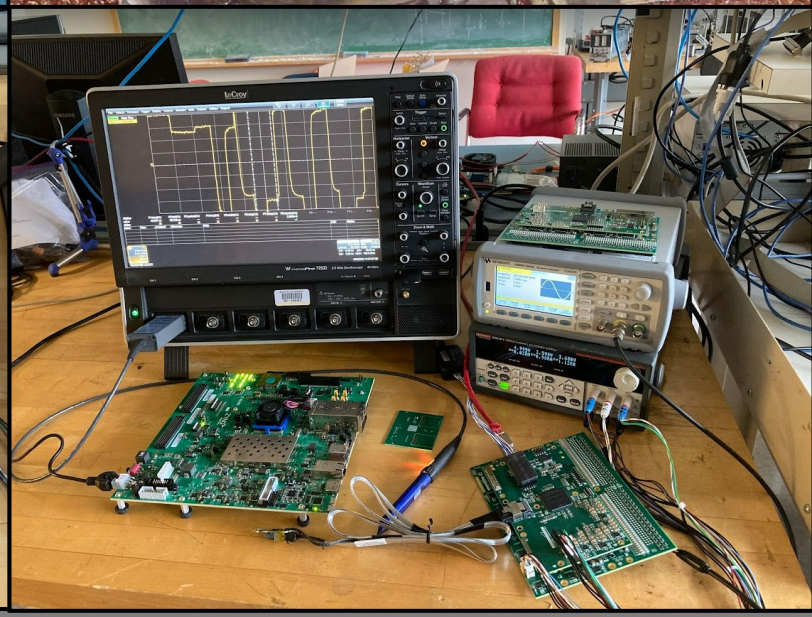
- C.J. Martoff *et al* 2000 *NIMA* **440** 335 (https://doi.org/10.1016/S0168-9002(99)00955-9)
  - The original NID Paper
- N.S. Phan *et al* 2017 *JINST* **12** P02012 (https://doi.org/10.1088/1748-0221/12/02/P02012)
  - Established SF_6 as an ideal NID gas
- J.B.R. Battat *et al* 2017 *AstroPart Phys* **91** 65 (https://doi.org/10.1016/j.astropartphys.2017.03.007)
  - DRIFT Experiment results using minority NI species to fiducialize leading to 54 day zero-background run

The Future of these studies

1. Paper coming soon!
2. Development of a novel low-pressure NI TPC
   - 10cm x 10cm 2D strips at 200 µm pitch
     - Gas Electron Multiplier (GEM) at 140 µm pitch to amplify the signal from the tracks
   - Front-end electronics assembled, adapted, tested and characterized with collaborators at Boston University

Ed Kearns Alex Madorsky Lila Smith

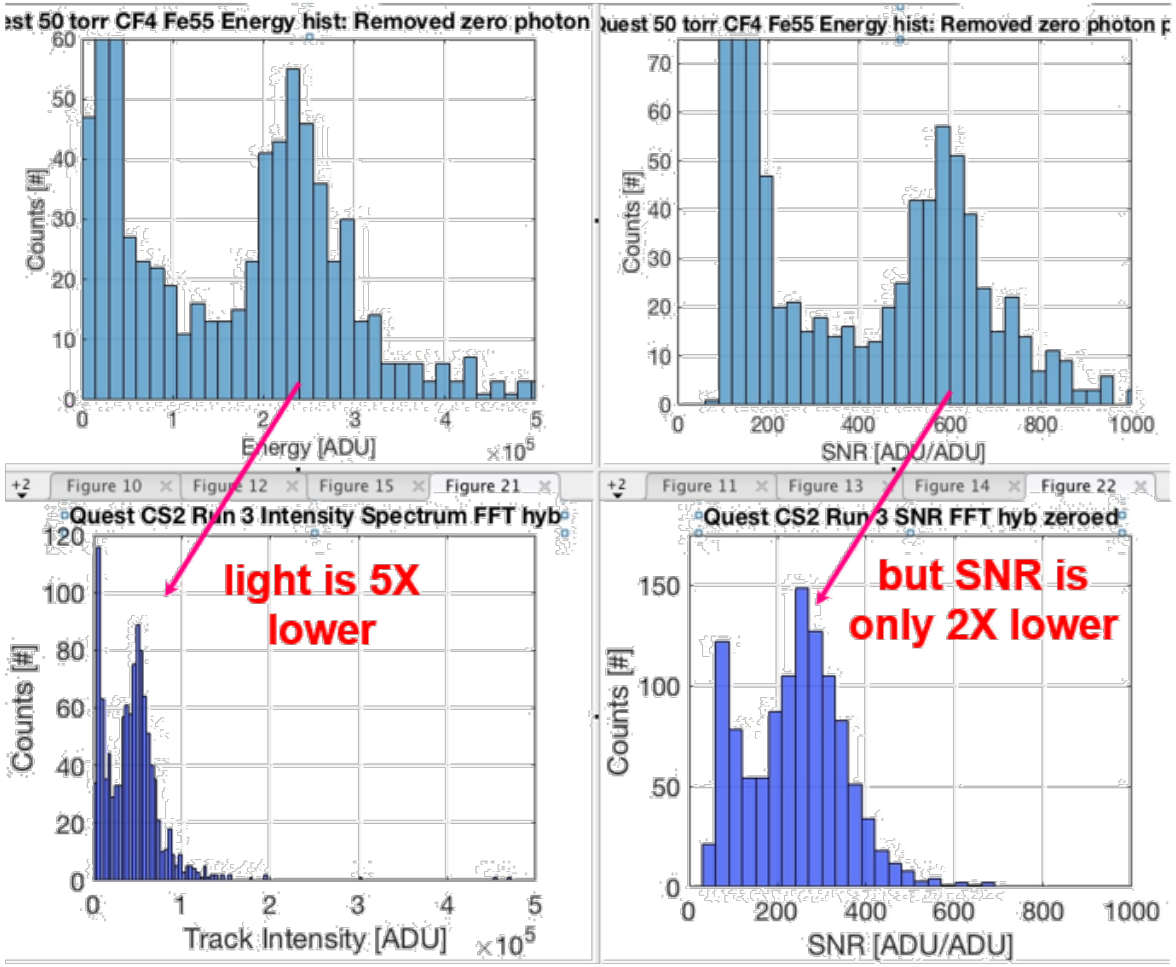


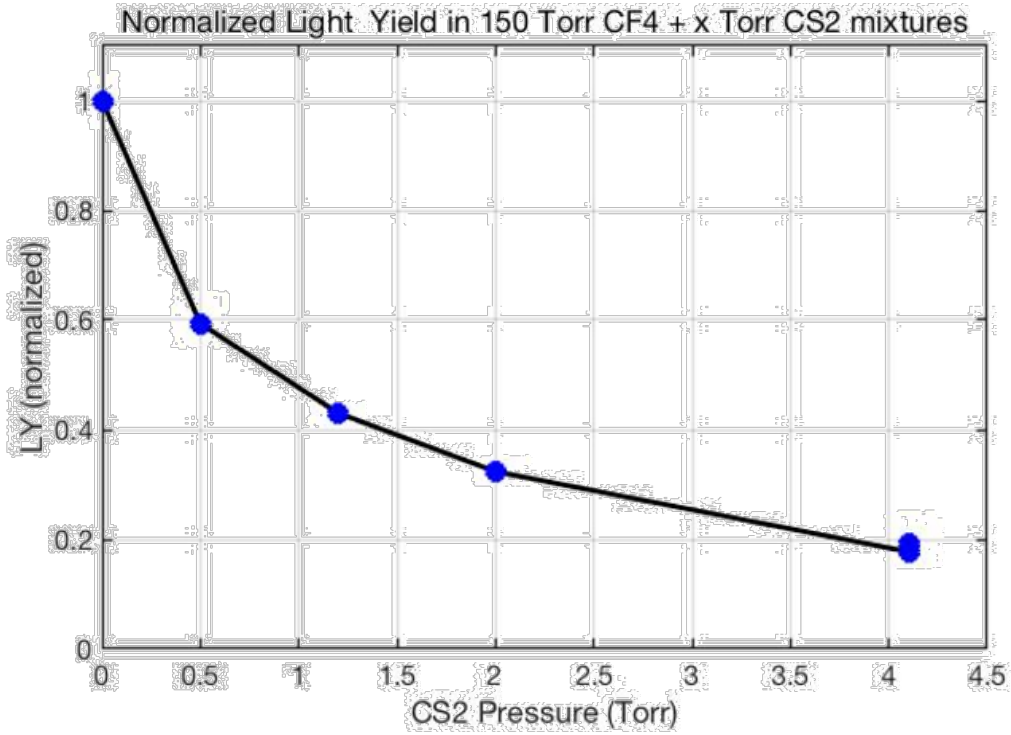



Light Yield in NID

50 Torr CF4:

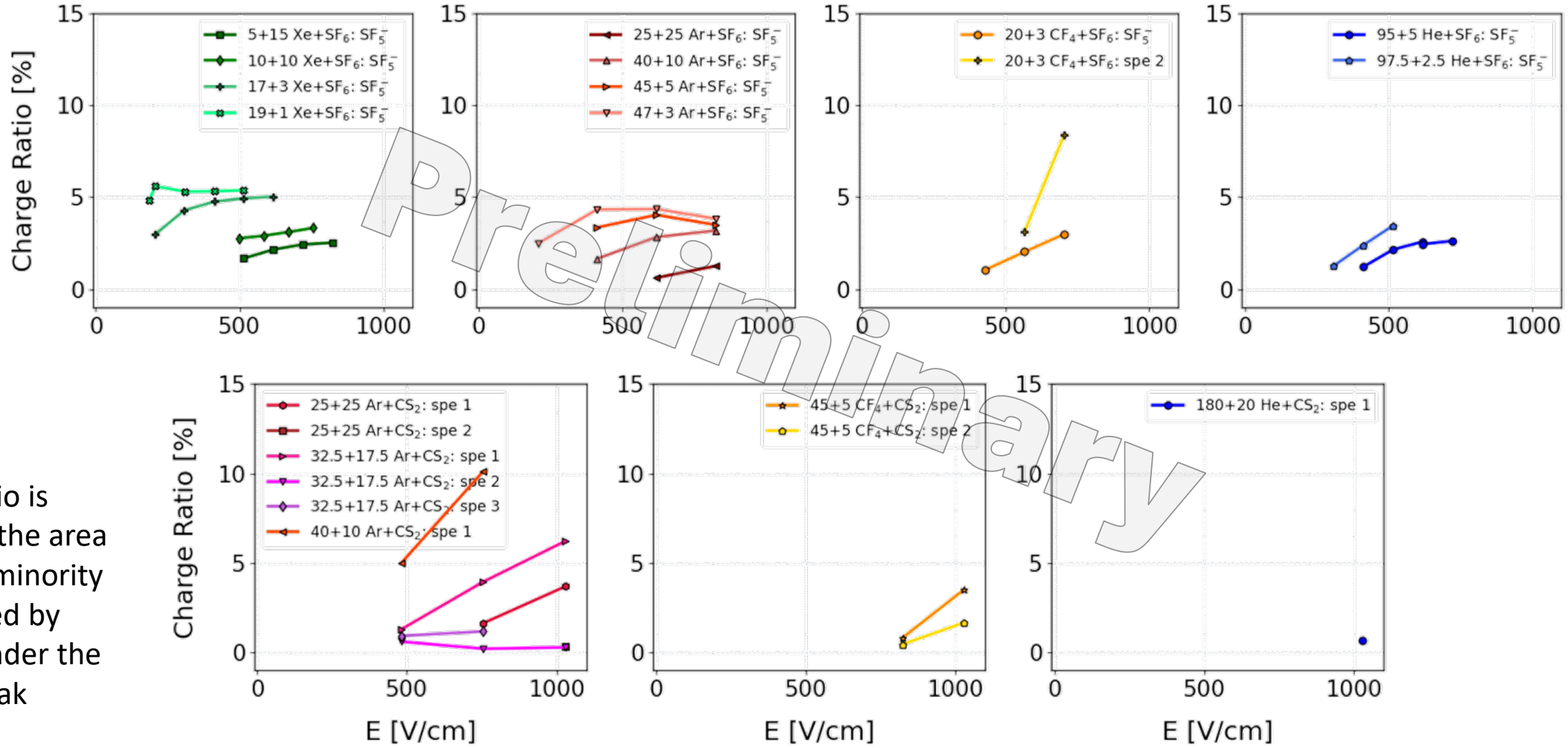
45 Torr CF4 + 4.3 Torr CS2





Courtesy of D. Loomba RD51 Collab. Meeting 6/14/22

Minority Species Area



Preliminary

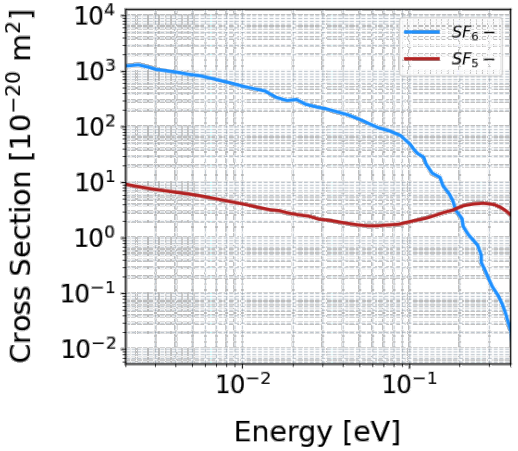
Charge Ratio is defined as the area under the minority peak divided by the area under the primary peak

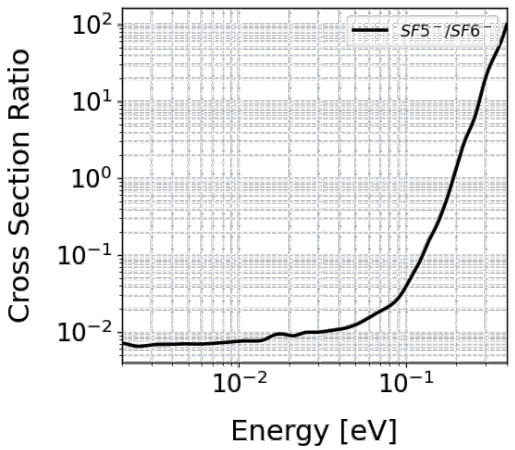
Measuring Electron Energy

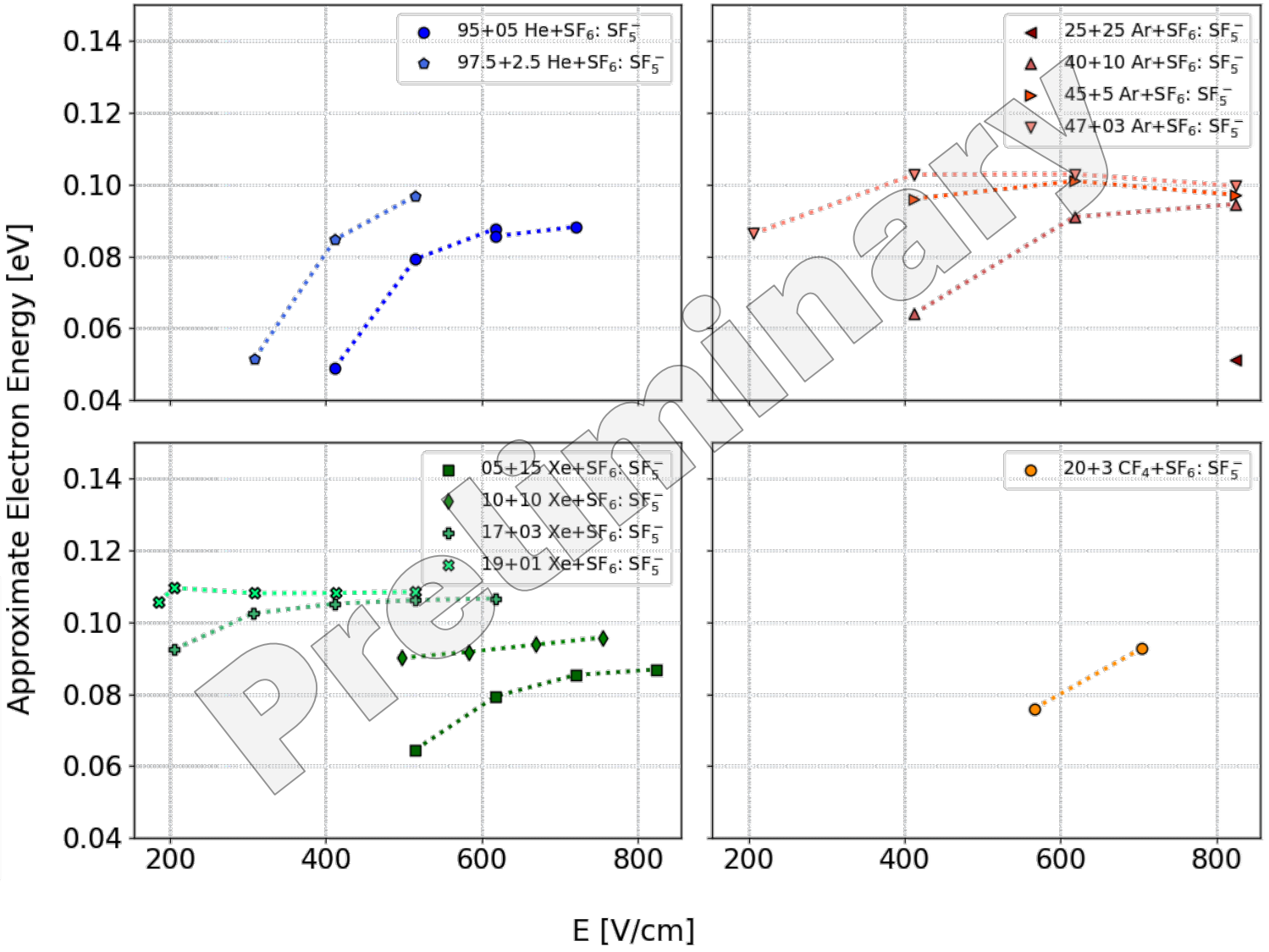
- Under a very simple assumption:

$$\frac{A_{SF_5^-}}{A_{SF_6^-}} = \frac{\sigma_{SF_5^-}}{\sigma_{SF_6^-}}$$

- We can use the area ratios to get approximate electron energies (pre-capture)
  - Note: different electronegativities mean these two species probably have different gains
    - Thus, this is more likely an upper limit on the energy







Preliminary

Dealing with Water

- Small amounts of water in detector lead to ‘water-shelves’ on left side of waveform
- Compromises measurement of minority area and diffusion sigma of main peak
- Include 1 or 2 step functions in fit:

$$S_{\pm}(x) = A\frac{h_{\pm}}{2}\left(1 - \mathrm{erf}\left(\pm\frac{x-\mu}{\sqrt{2\sigma^2}}\right)\right)$$

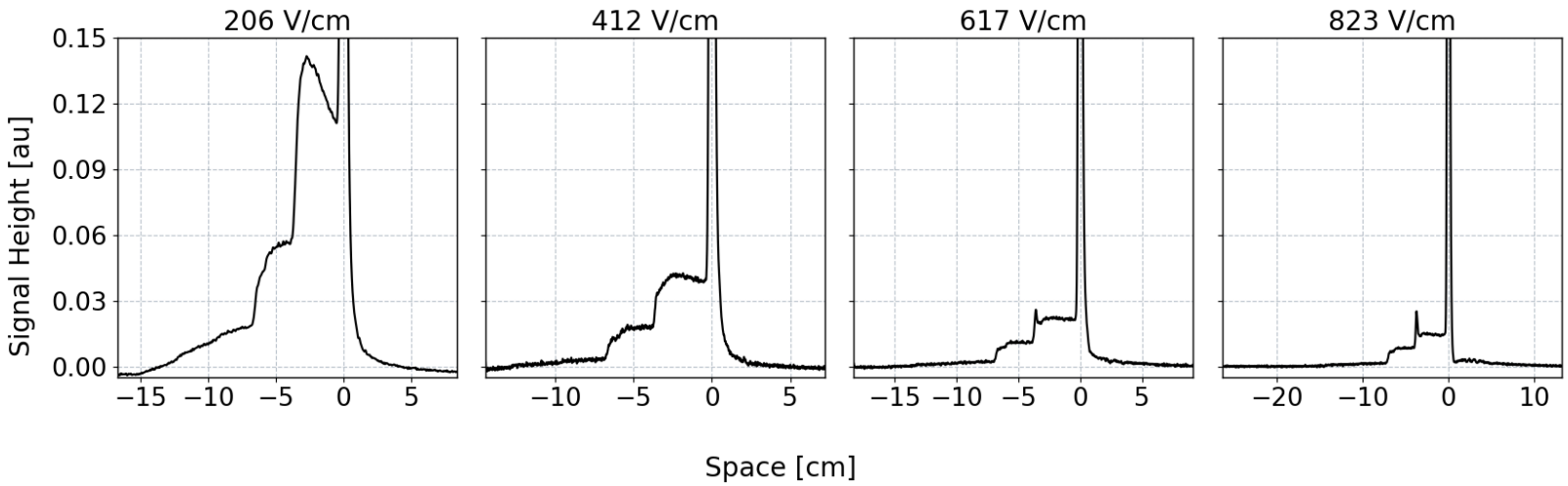
$$G(x) = A\exp\left(-\frac{(x-\mu)^2}{\sqrt{2\sigma^2}}\right)$$

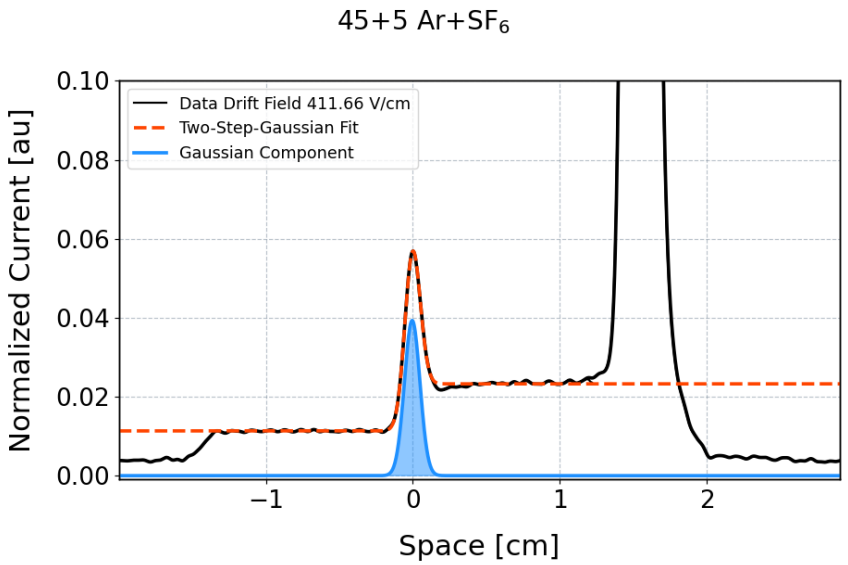
  - For minority area:

$$F(x) = S_{+}(x) + S_{-}(x) + G(x)$$

  - For main peak diffusion:

$$F(x) = S_{+}(x) + G(x)$$



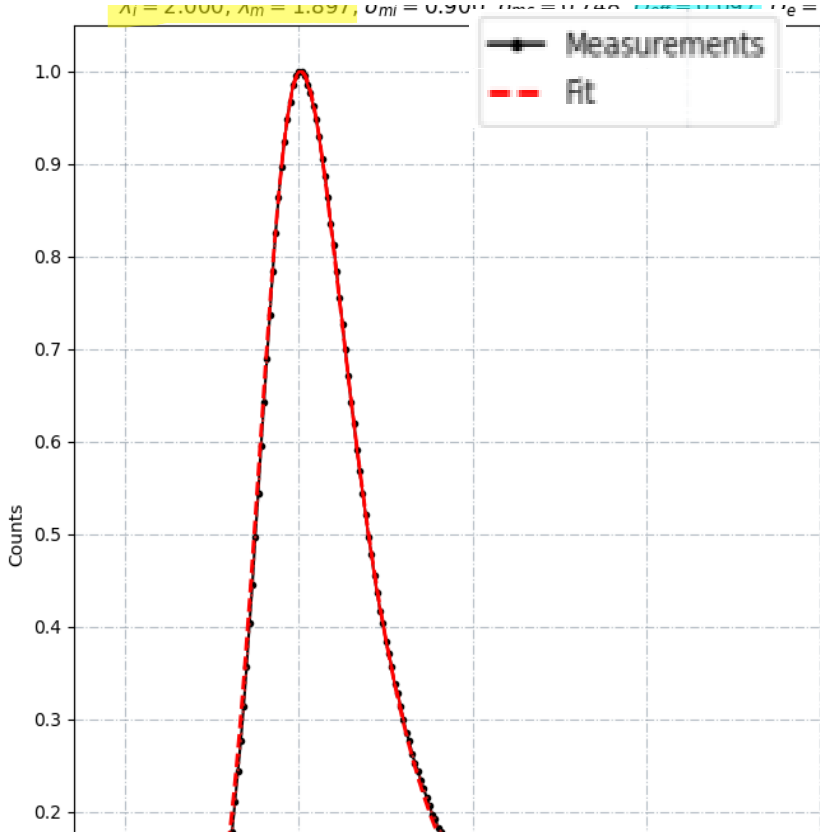


Exponentially Modified Gaussian

$$F(x) = \frac{A\lambda}{2}\exp\left(\frac{\lambda}{2}(2\mu + \lambda\sigma^2 - 2x)\right)\operatorname{erfc}\left(\frac{m + \lambda\sigma^2 - x}{\sqrt{2\sigma^2}}\right)$$

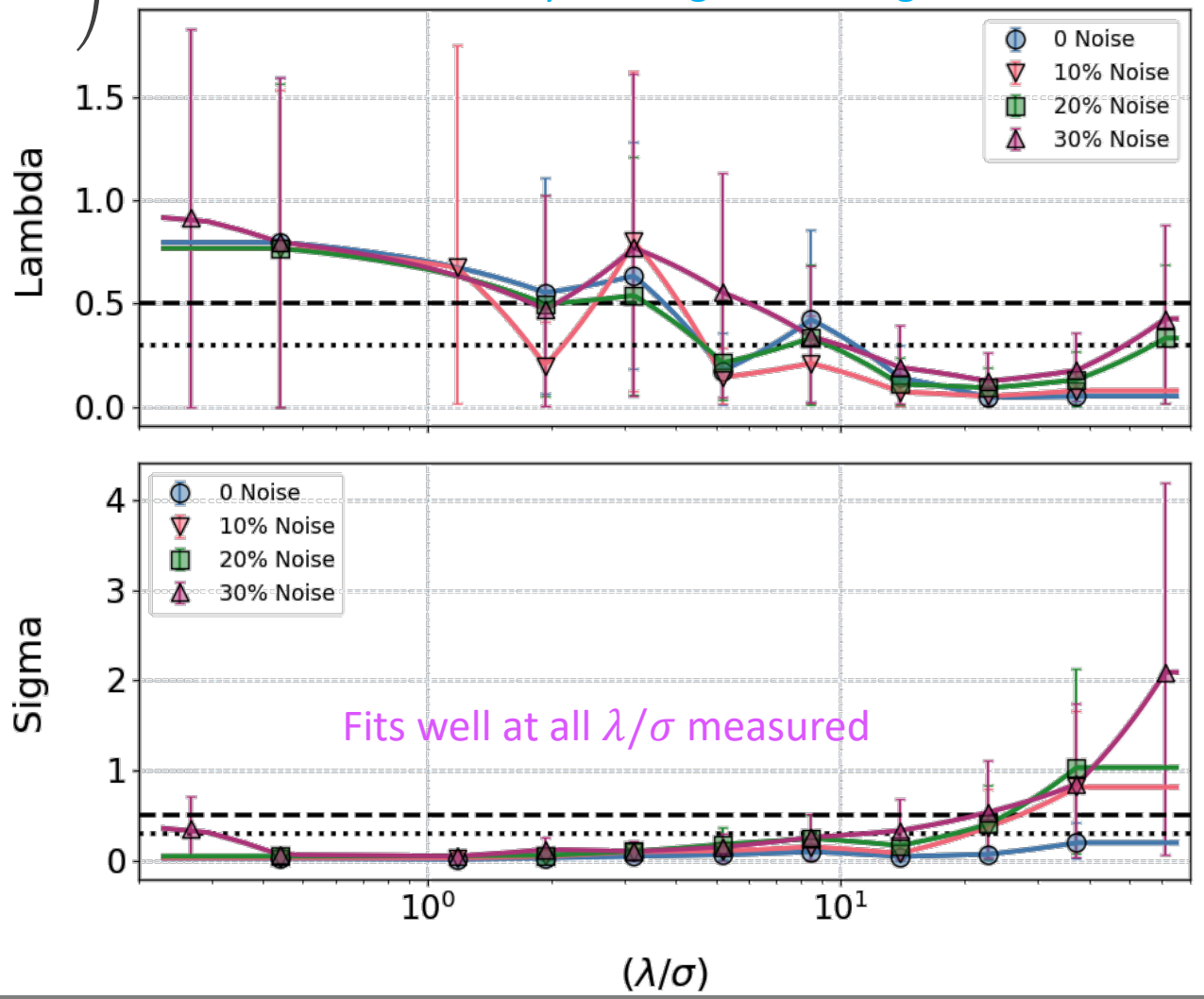
λ = mean free path of attachment (i.e. attachment length)

σ = diffusion



Fit Residuals

Has a fairly small 'good-fit' region



Negative Ion Species Cross Sections

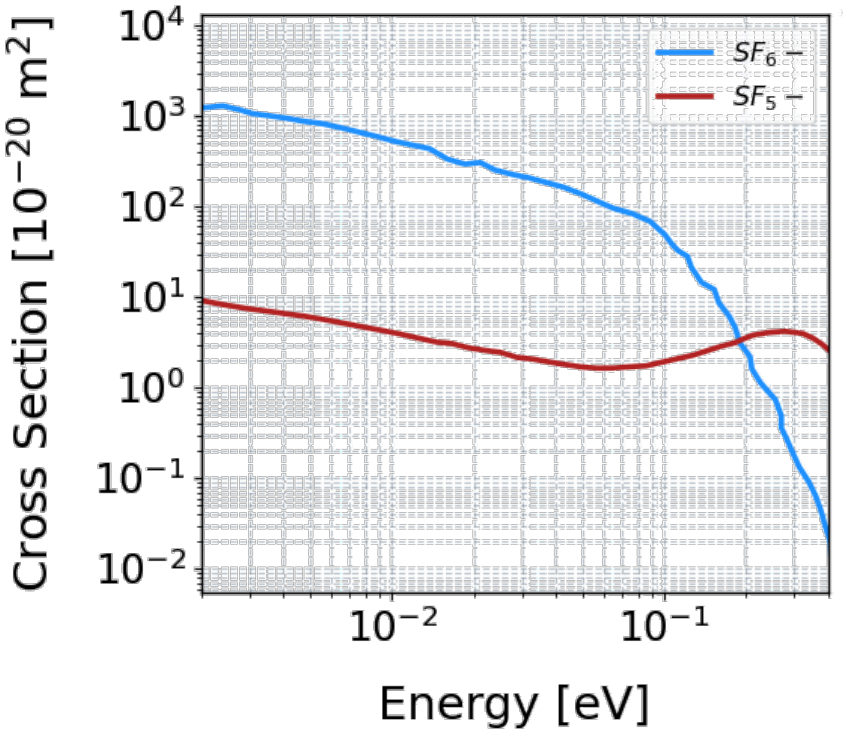
Standard capture and dissociation process for SF_6:

$$e^- + SF_6^- \rightarrow SF_6^{-*}$$
$$SF_6^{-*} + SF_6 \rightarrow SF_6^- + SF_6$$
$$SF_6^{-*} \rightarrow SF_5^- + F$$

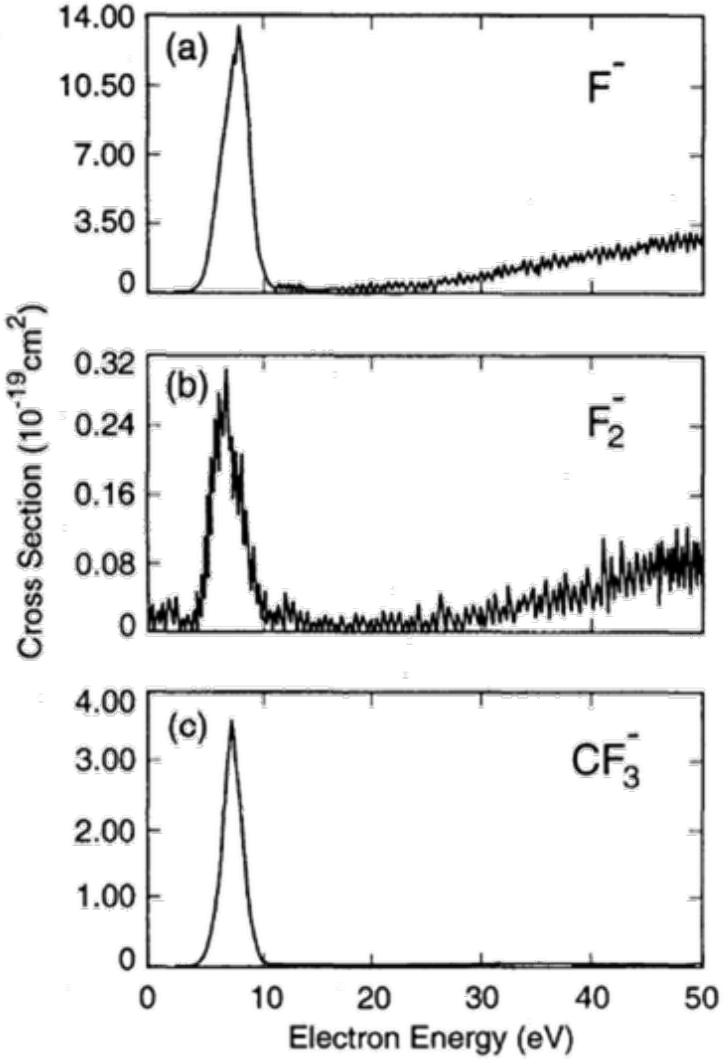
Standard dissociation processes for CF_4:

$$CF_4^- \rightarrow F^- + CF_3$$
$$CF_4^- \rightarrow CF_3^- + F$$

CS_2 likely forms NI in a similar process as SF_6.

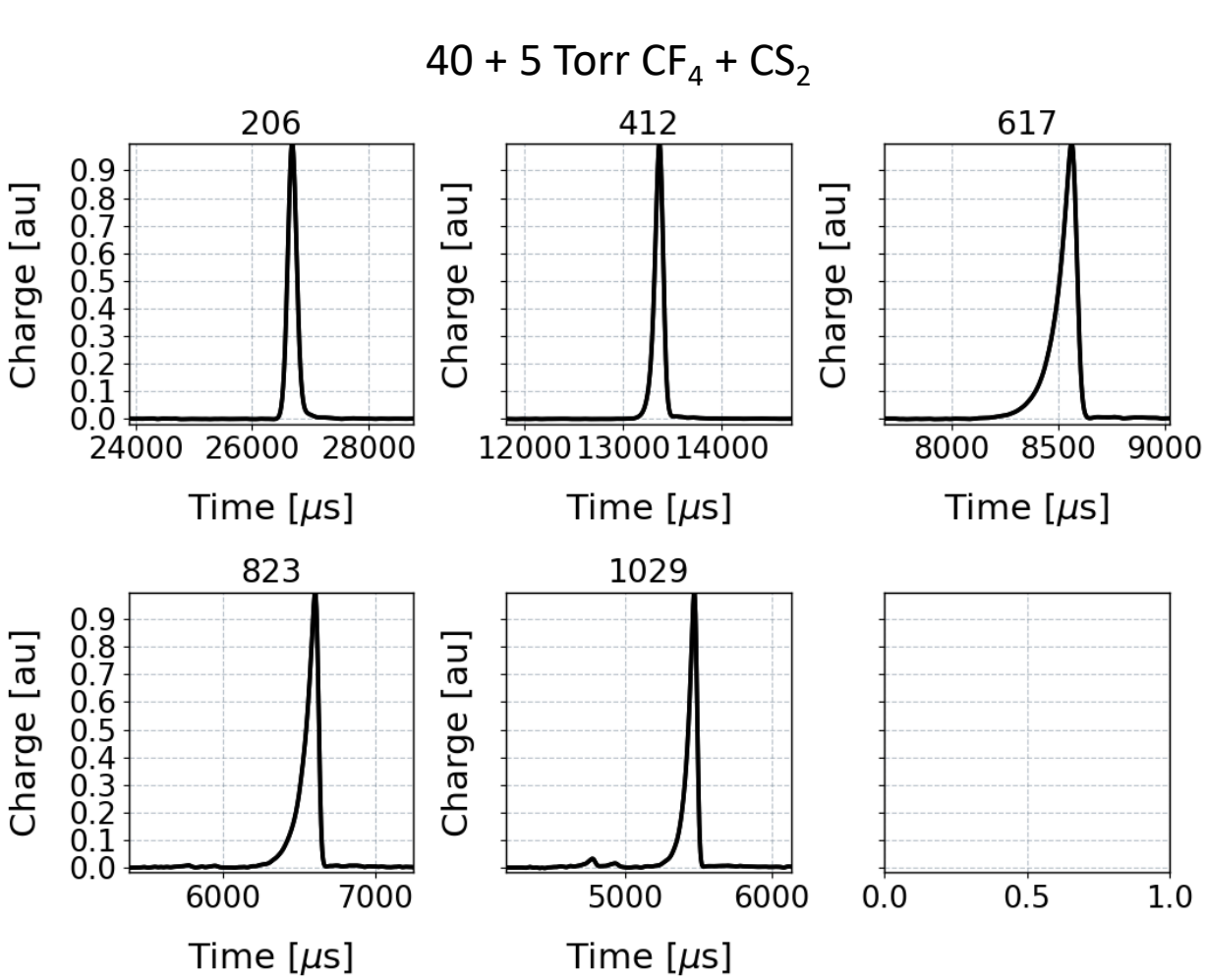


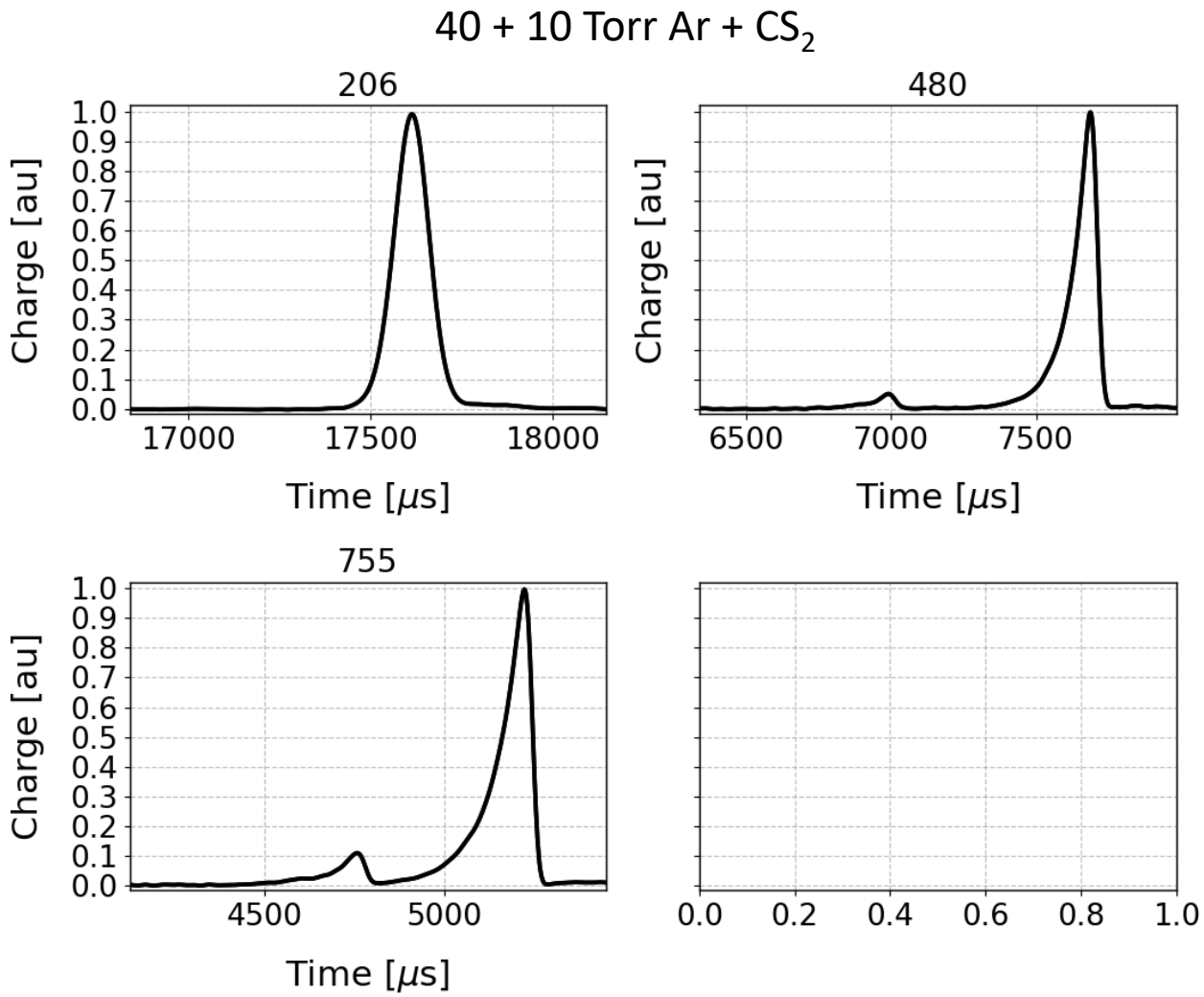
L. G. Christophorou, J. K. Olthoff, Int. J. of Mass Spectrom. 205 (1) 27–41 (2001)



I. Iga, M. V. V. S. Rao, S. K. Srivastava, and J. E. Nogueira, Z. Phys. D 24, 111 (1992).

Select Averaged Waveforms with Attachment





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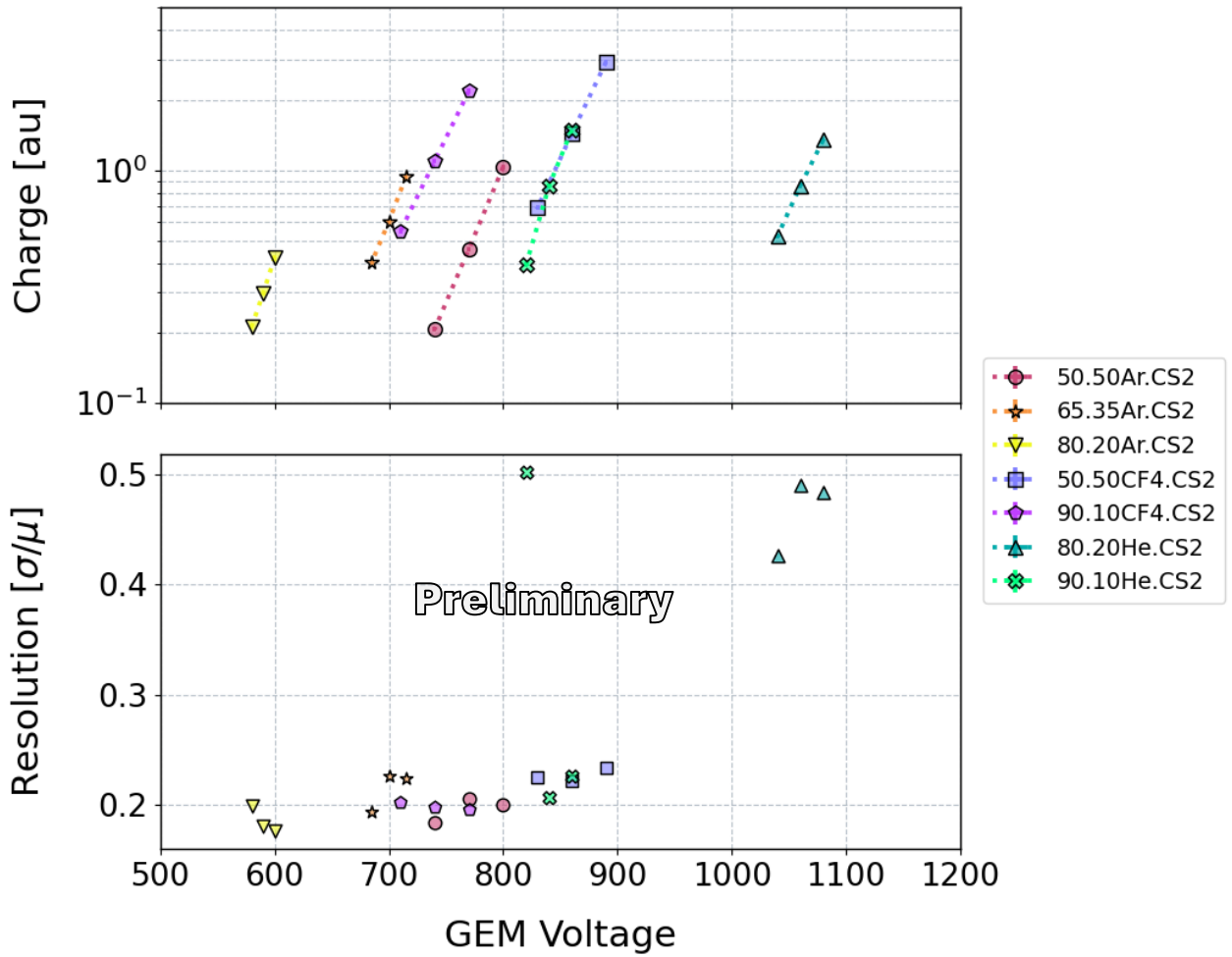
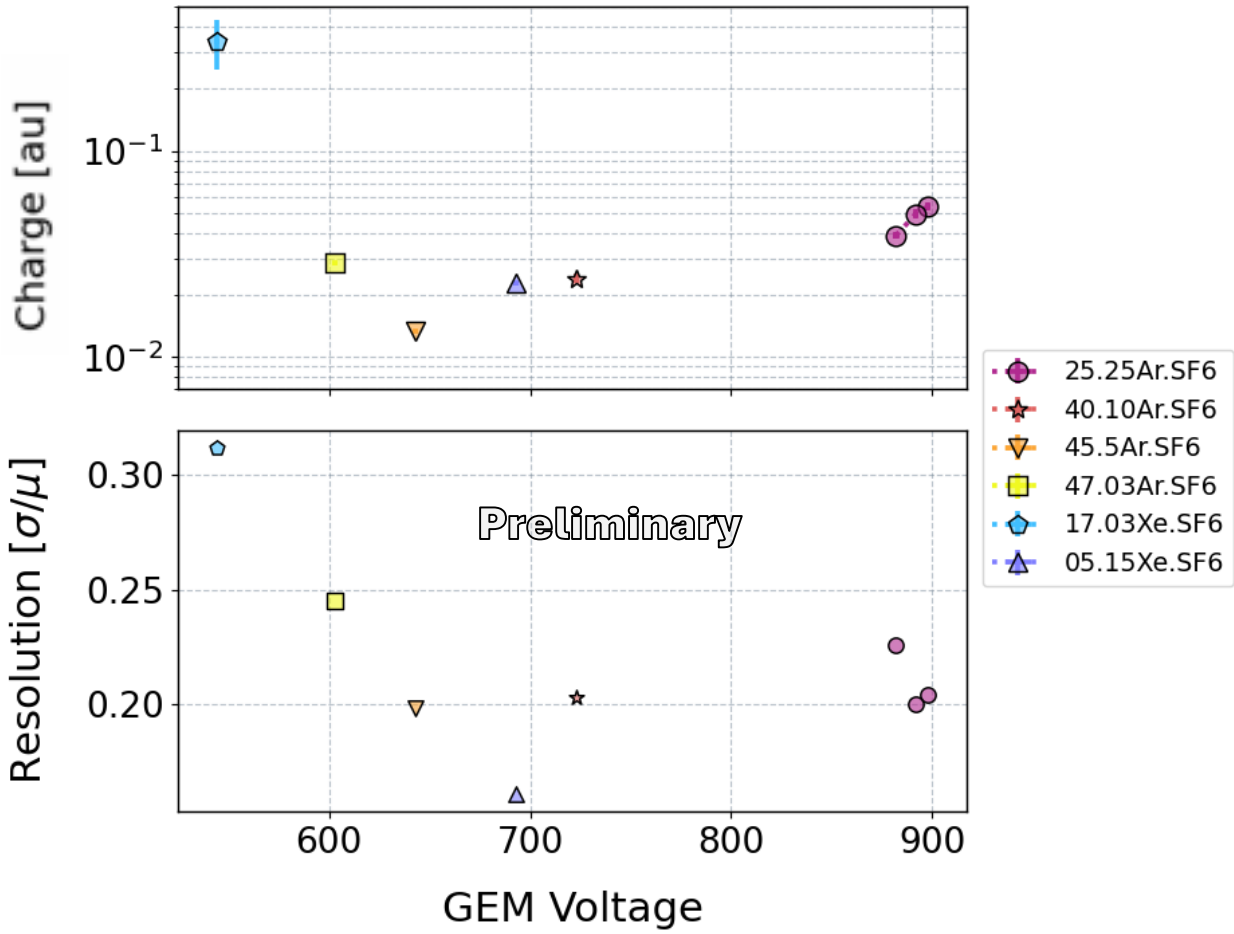
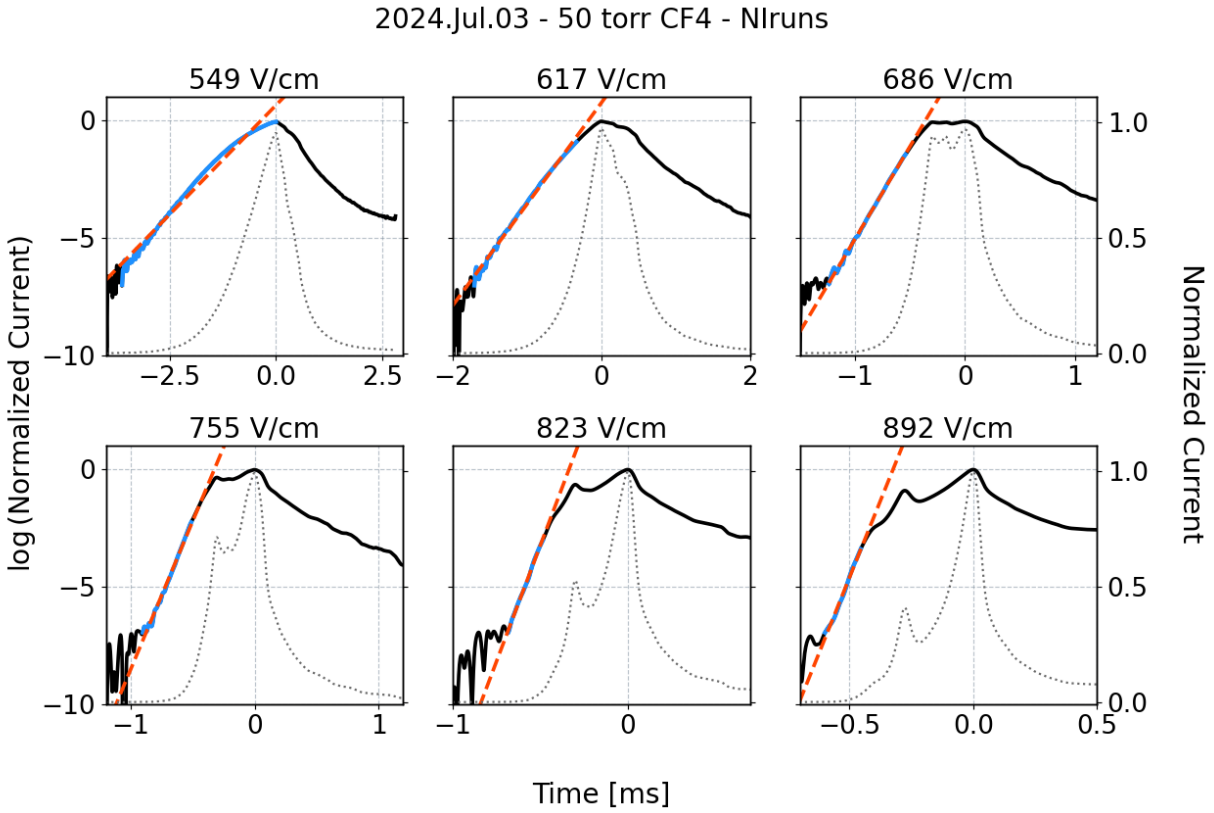
Energy Resolution

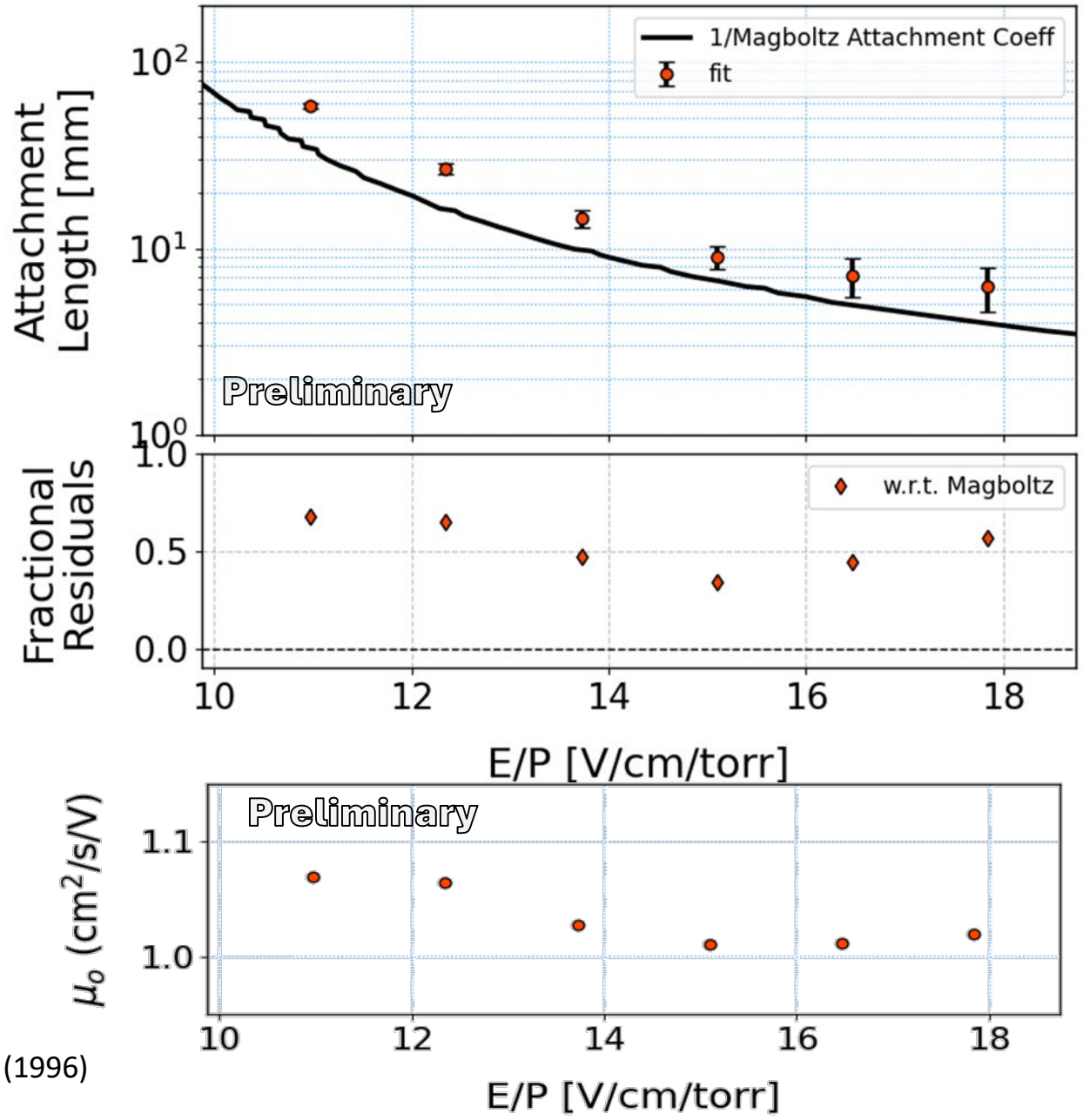




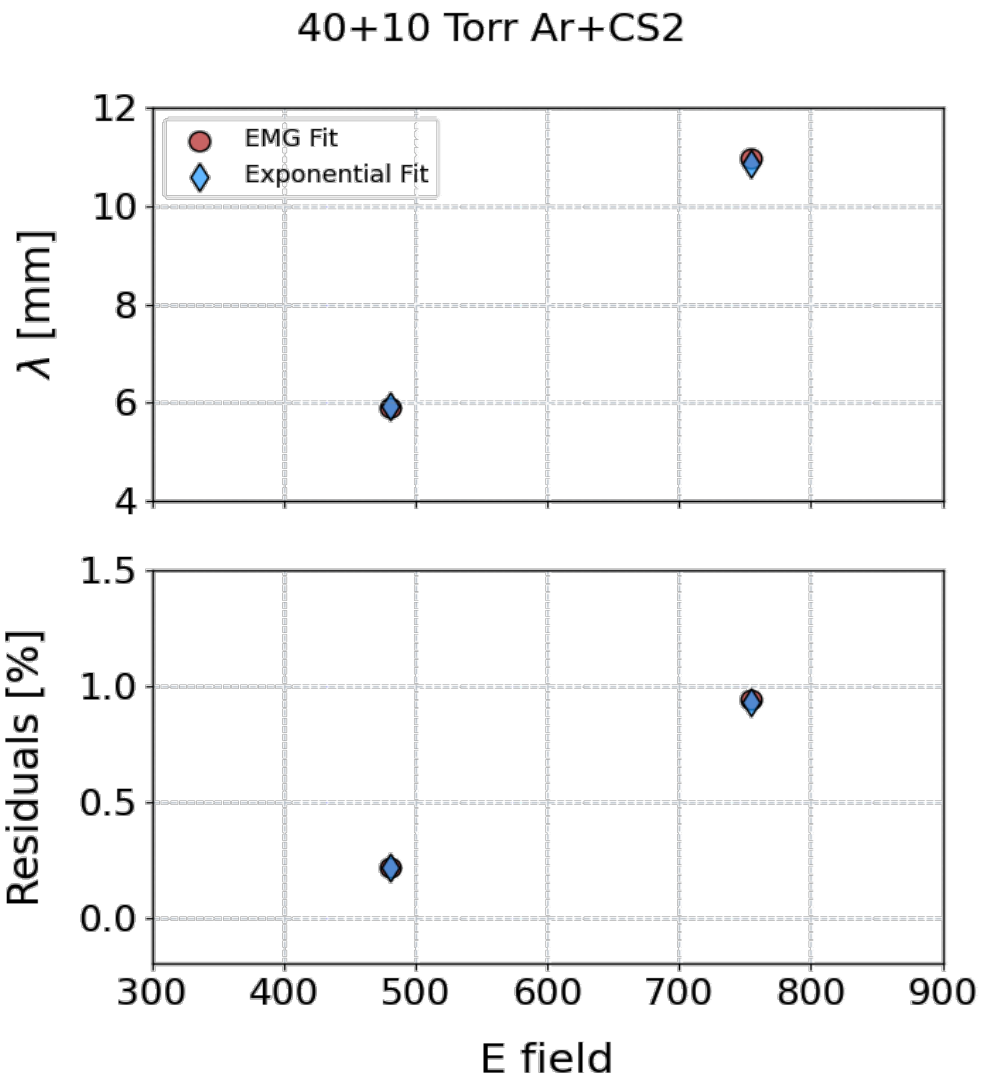
Aside: Attachment in CF_4

- By measuring the exponential portion of the waveform, we reconstruct measured attachment to within 80%





L. G. Christophorou, J. K. Olthoff, M. V. Rao, *J. Phys. Chem. Ref. Data* 25, 1341–1388 (1996)
S. Biagi (1995). https://magboltz.web.cern.ch/magboltz/

Bridging the Gap Between Exponential Fit and EMG

- Exponential fits on CF_4 waveforms reproduced Christophorou's recommended attachment length to within 8%
- Measurements made in Ar+CS_2 found very good agreement between exponential and EMG fits →
- EMG fits were chosen instead of exponential fits in order to measure both attachment and diffusion width
  - Exponential fits could not be verified on waveforms with $\lambda < 5mm$
    - This region falls roughly in our EMG 'good-fit' region, thus it was straightforward to use EMG results