Electron interactions with Ar/CF4 in GEMs

Simulations of simultaneous light and charge production in Argon/CF4 mixtures

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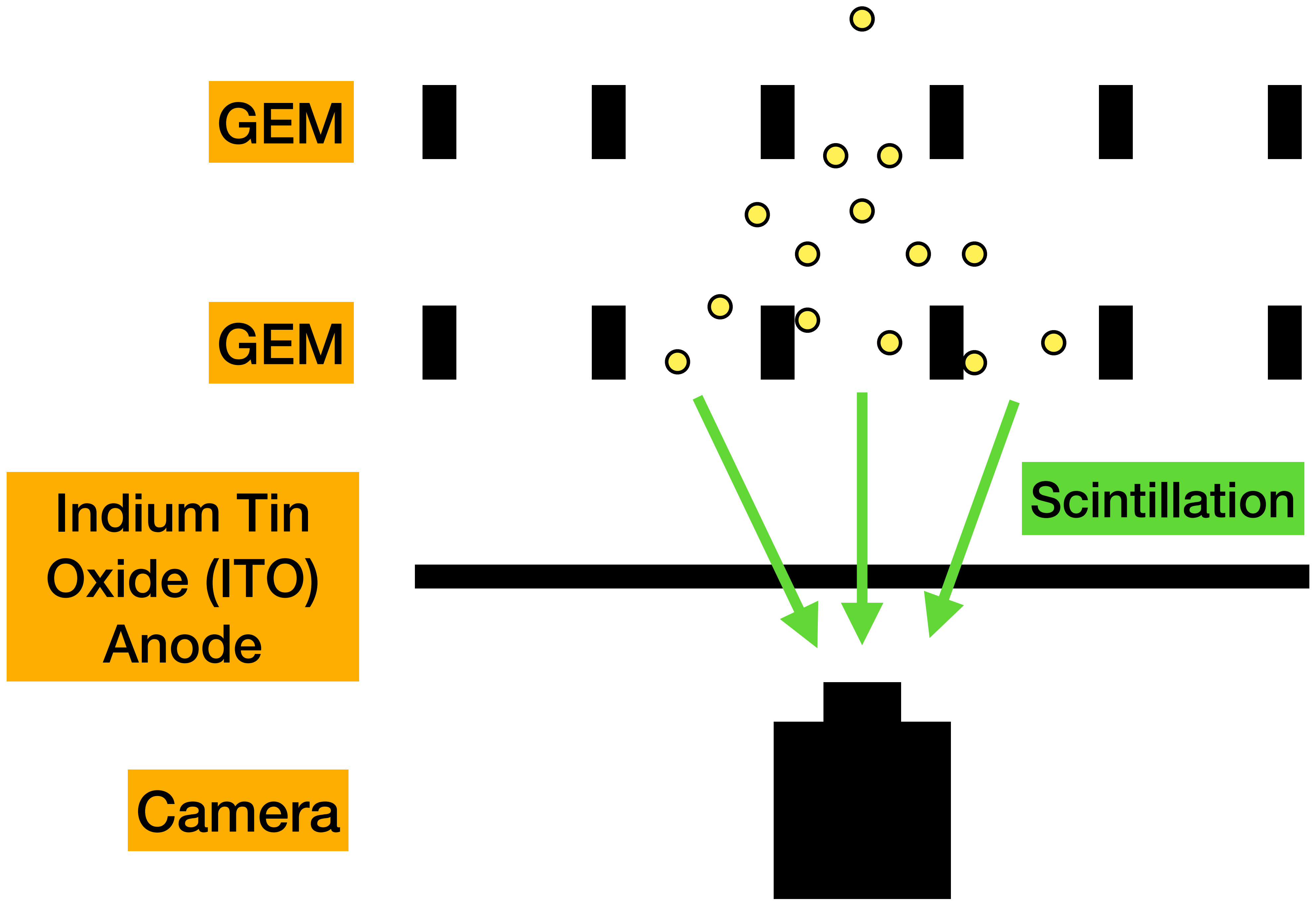
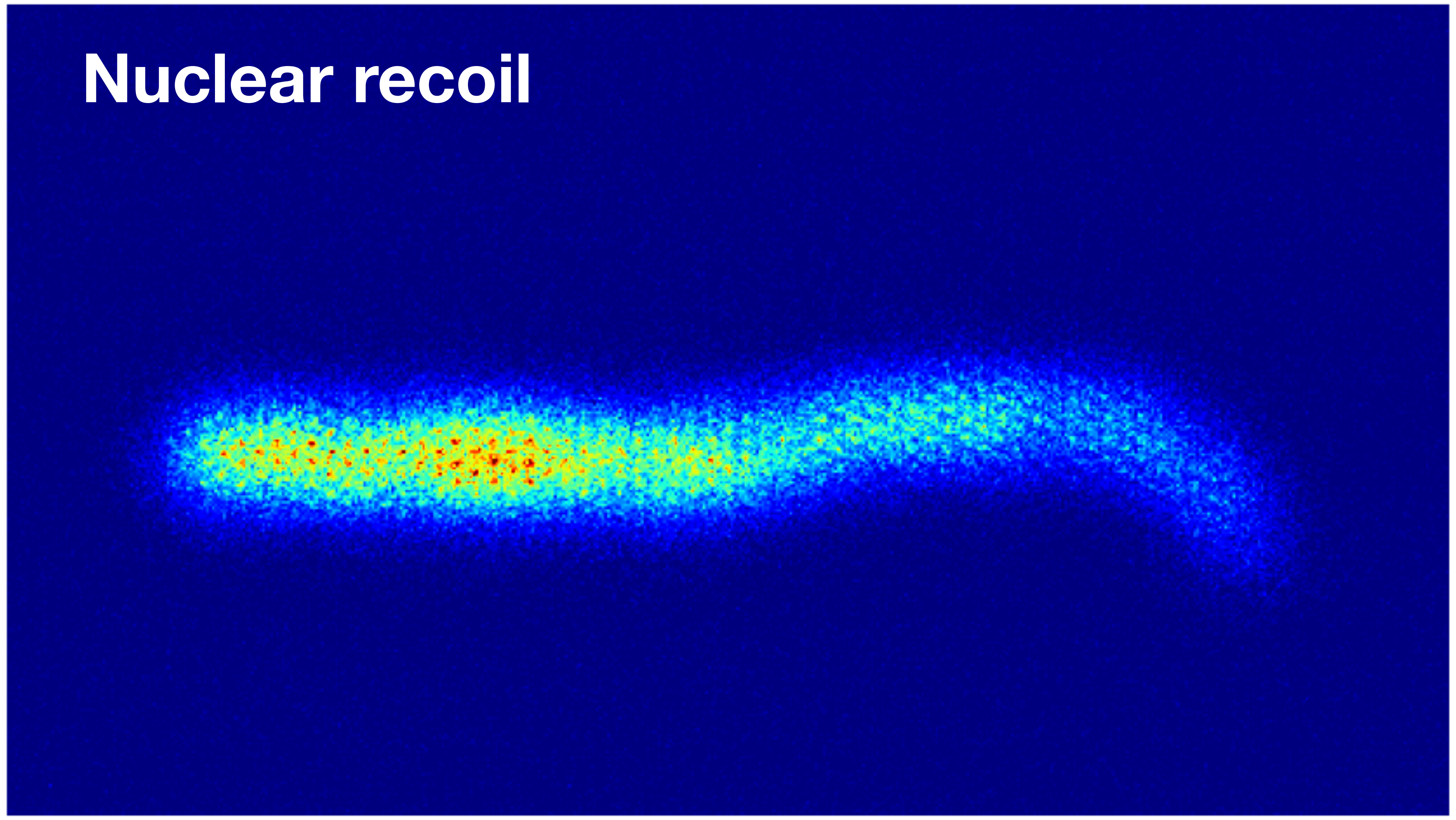
PPD Summer Studentship

Measurements in MIGDAL

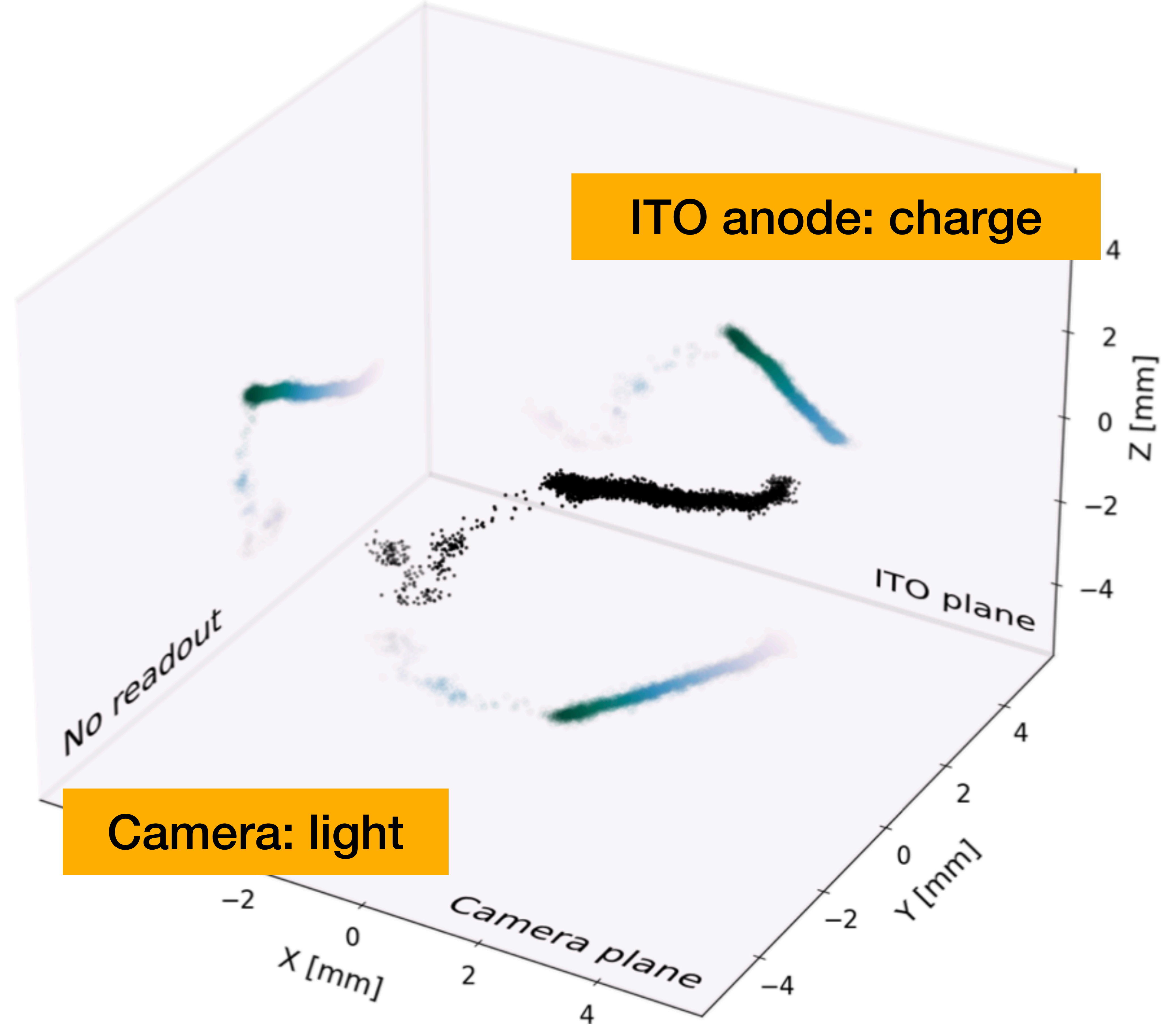
- Looking for an electron recoil (ER) and nuclear recoil (NR) originating from a common vertex





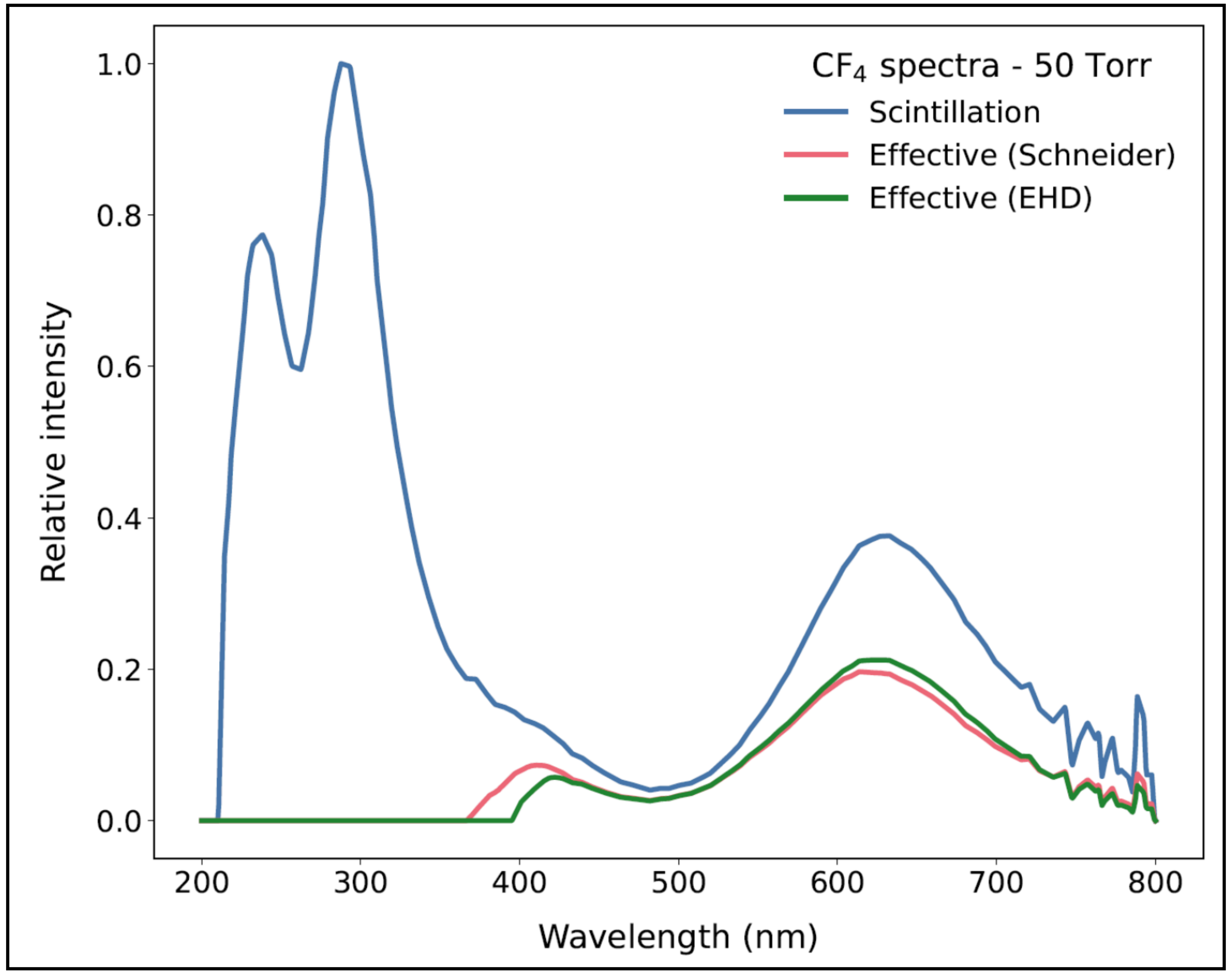
Why use a gaseous detector?

- Cost per unit volume is low
- Allows for 3D track reconstruction and resolution of distinct ER and NR tracks
- This is achieved through <u>simultaneous measurement of visible scintillation light produced and charge collected at ITO anode</u>
- We would like to simulate light and charge collection in order to understand the processes occurring
- We can then optimise the performance of the detector



Which gas is suitable?

- CF_4 is a good choice
- Scintillates visibly with a spectrum compatible with MIGDAL's CMOS camera readout
- Low atomic number of C and F means Auger electron/characteristic x-ray production will be well below 5keV threshold



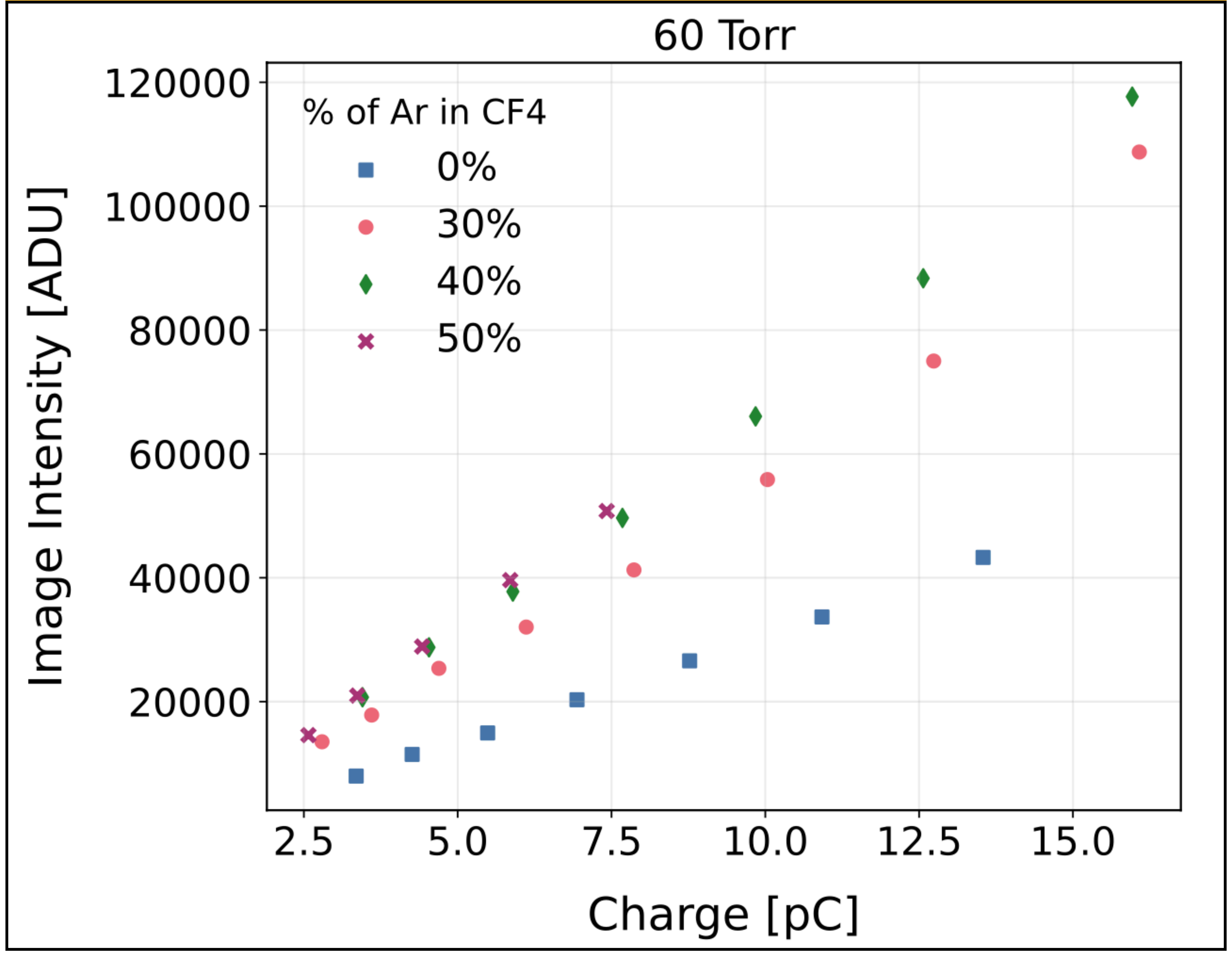
And at what pressure?

- Low pressure preferable for increased track length, so we can clearly distinguish Migdal event topologies
- Low pressure also reduces photon interaction probabilities, reducing their contribution to background
- However, an intense neutron source would be required for a significant number of interactions with gas
- We have such a source at NILE!

Adding noble gases to CF4

- Ar and Xe are already used in leading dark matter detectors
- The Migdal effect could increase the sensitivity of these experiments to lower-mass particles
- Also: Ar and CF4 interact, causing more visible light to be produced for a given amount of charge collected at the anode
- So we can lower the energy threshold without increasing GEM dV, and improve signal to noise ratio on tracks above the threshold
- Measurements suggest the effect is not present in Ne, with Xe yet to be investigated

MIGDAL data: simultaneous light and charge measurement



Preliminary work

To simulate a GEM, we need:

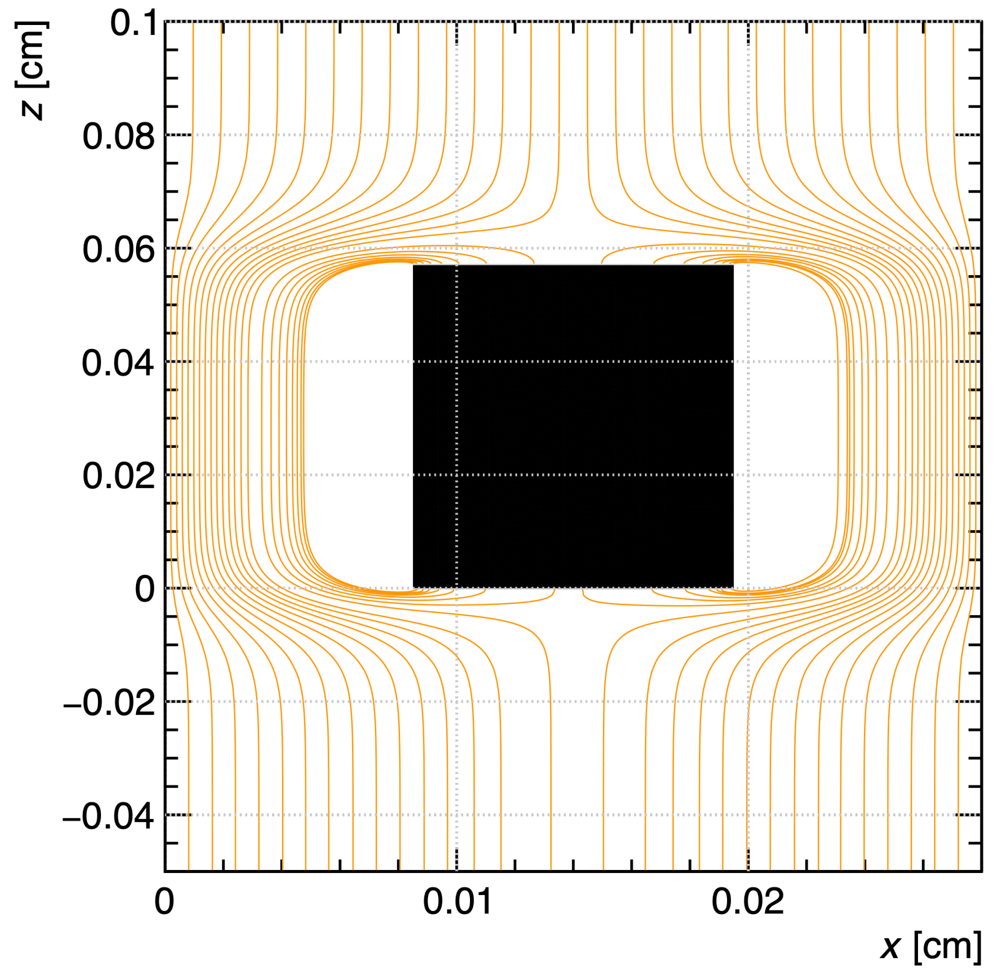
Component	Program Used
A 3D model of the GEM	Gmsh
An electric field map in and around the GEM	Elmer
Electron-gas interaction cross sections, gas properties	Magboltz
A way to drift electrons in the presence of gas & E-field	Garfield++

Preliminary work

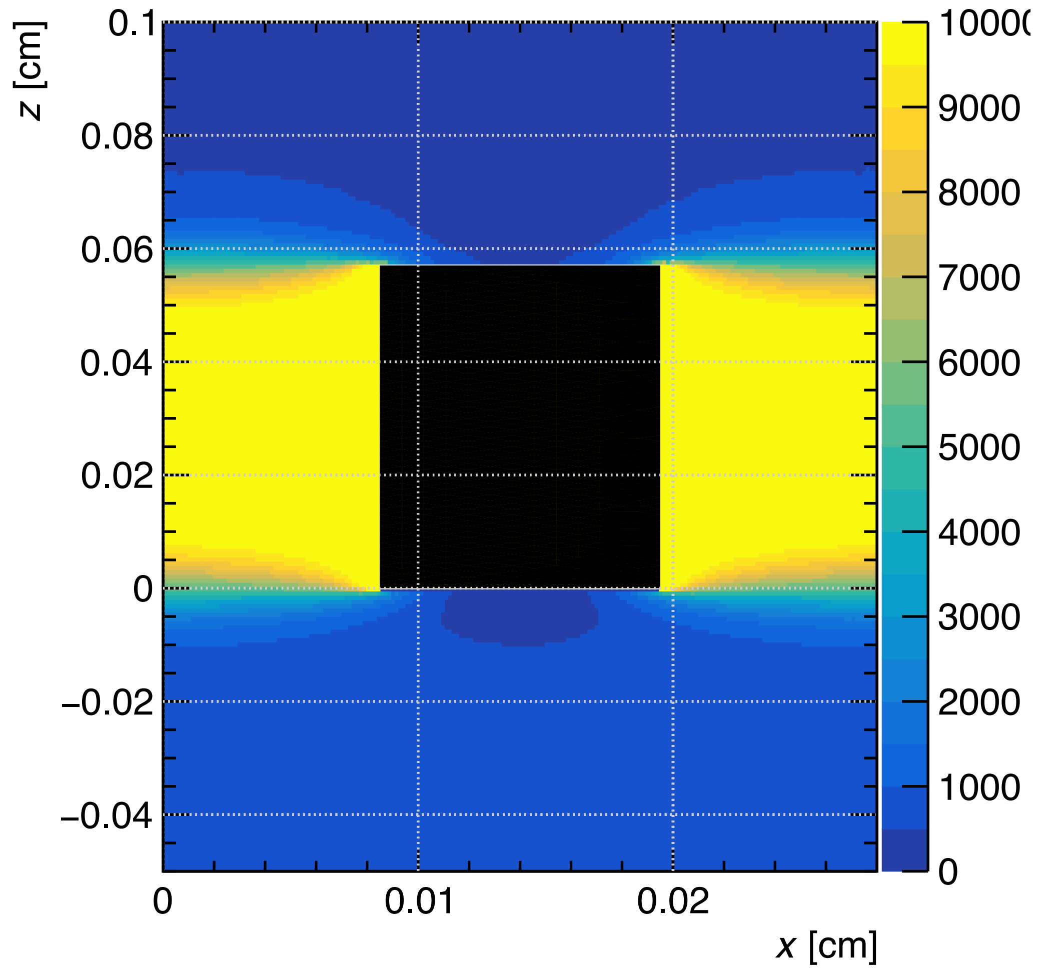
Testing the single GEM model

dV across GEM: 600V

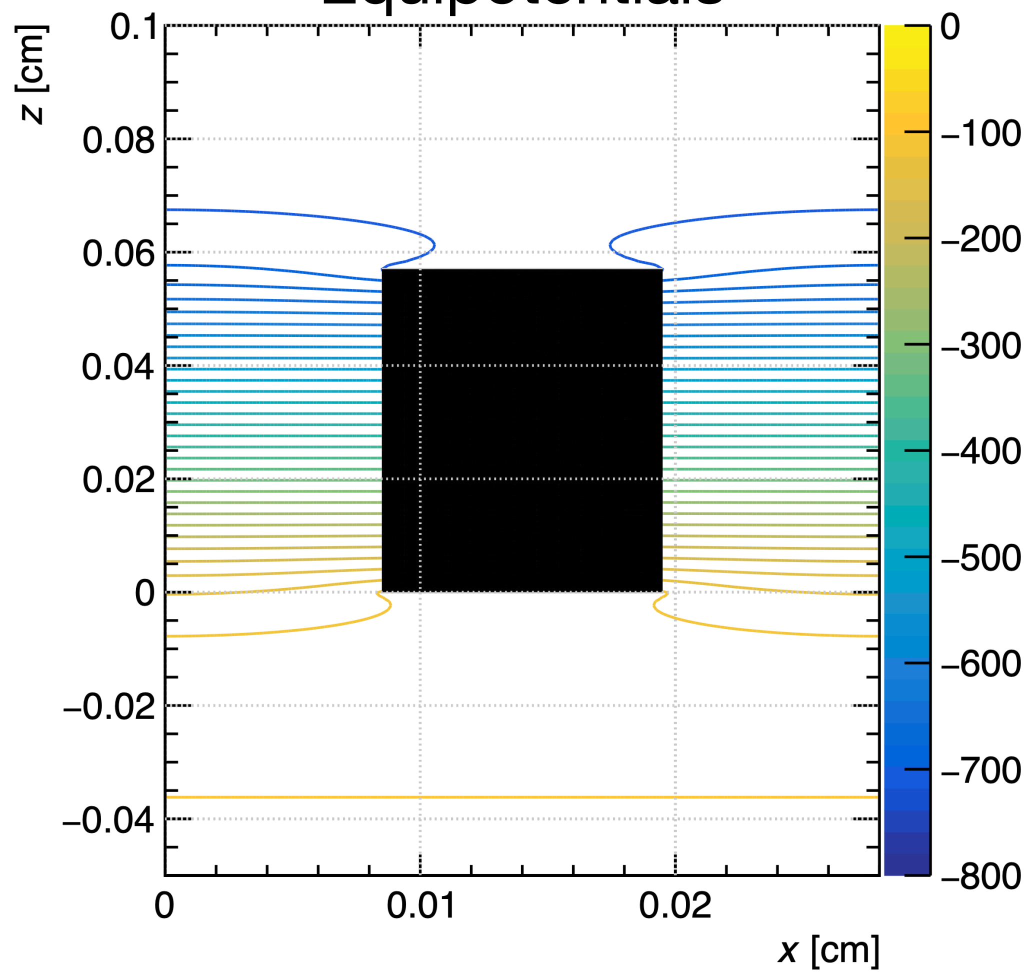
E-field lines



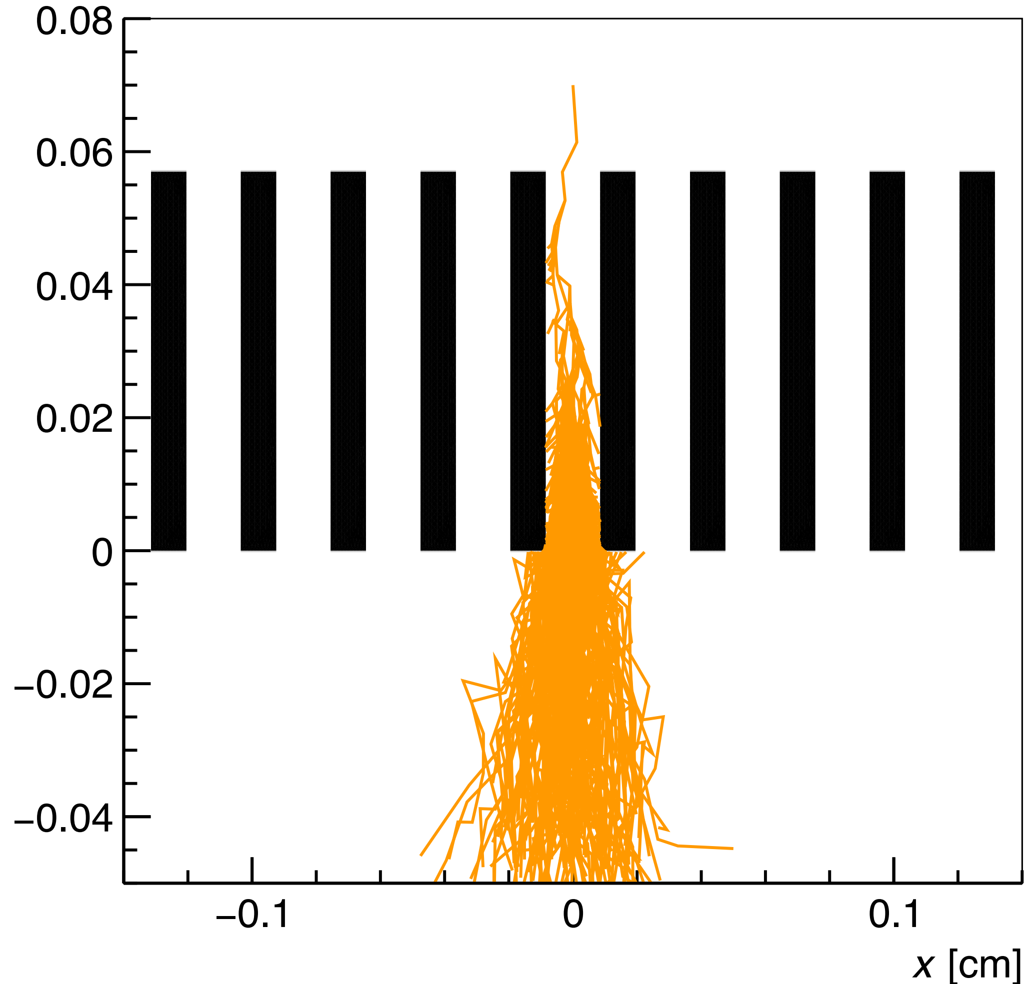
E-field magnitude

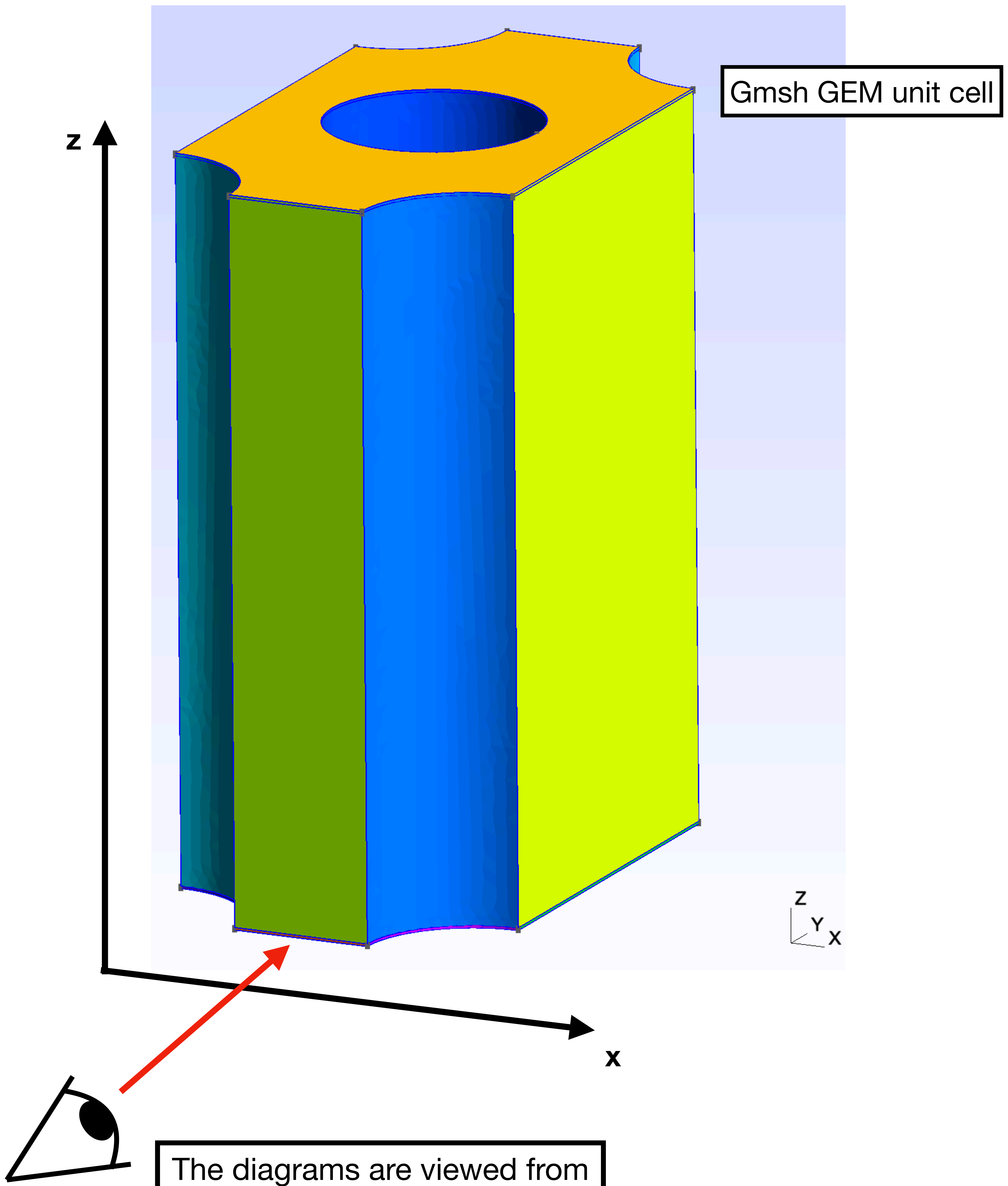


Equipotentials



Avalanche (single primary electron)





The diagrams are viewed from this perspective, with the GEM wall in the middle

Current work

Gas gain simulations
(charge measurement)

→

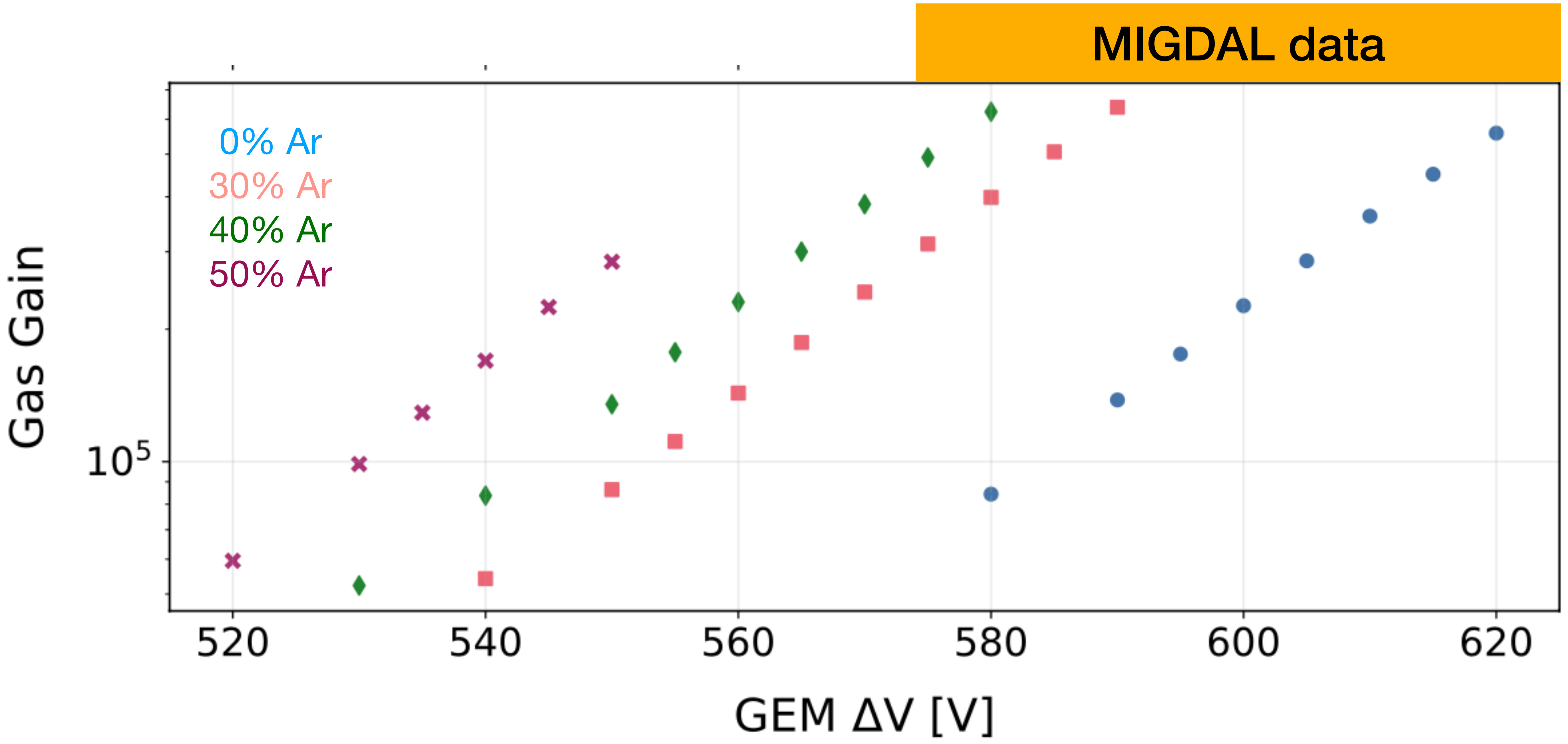
Simultaneous light & charge simulations

- Once we are confident that we are simulating charge correctly, move on to simultaneous light & charge

Gas gain simulation

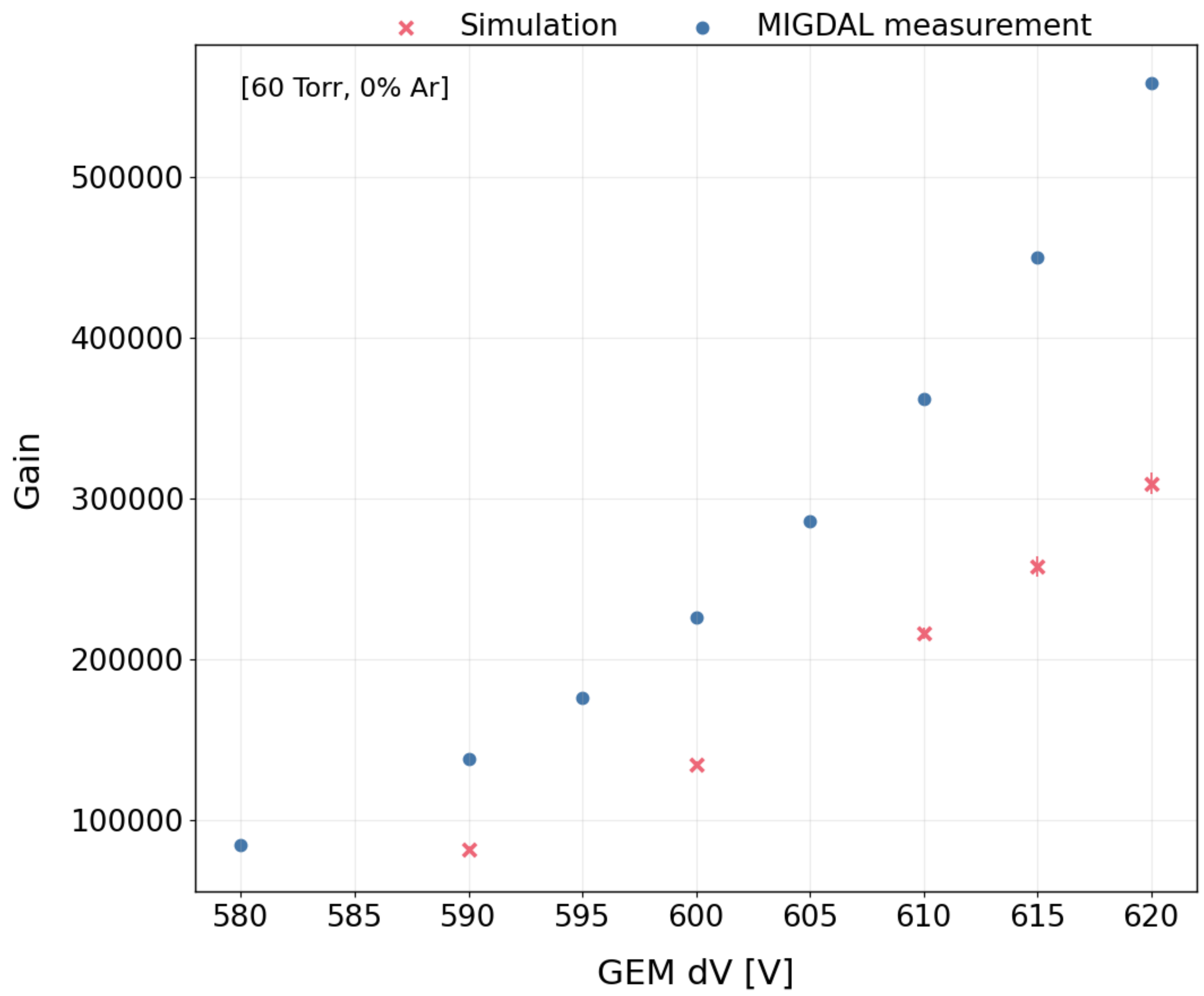
Procedure

- Simulate an avalanche in a double GEM starting from a single electron
- Track number of electrons that make it to the anode
- Plot the distribution and find the mean
- Compare to MIGDAL data



Gas gain simulation

- The distribution of avalanche sizes was well-described by a skew-Gaussian distribution
- This was fitted to histograms of gain and a mean was found
- Simulation results agree with MIGDAL data to within a factor of two
- At low pressures, there is a documented discrepancy (~2x) between GEM gain simulated in Garfield++ and experimental measurements



Current work

Gas gain simulations
(charge measurement)

→

Simultaneous light & charge simulations

- The discrepancy is small
- Would be good to know if the rough shape of the light and charge simulation data is consistent with measurement even if the values don't exactly match
- So we move on from charge measurement

Amedo et al, *Observation of strong wavelength-shifting in the argon-tetrafluoromethane system.* Front. Detect. Sci. Technol 1:1282854. doi: 10.3389/fdest.2023.1282854

Light & charge simulation

Understanding visible scintillation mechanisms

CF_4

$$e^- + CF_4 \rightarrow e^- + CF_4^* \rightarrow e^- + F + CF_3^*(2A_2'',1E')$$

$$CF_3^*(2A_2'',1E') \rightarrow CF_3^*(1A_1') + h\nu(630nm)$$

Ar

$$e^- + Ar \rightarrow e^- + Ar^{**}$$

$$Ar^{**} + CF_4 \rightarrow Ar + CF_4^* \rightarrow Ar + F + CF_3^*(2A_2'',1E')$$

$$CF_3^*(2A_2'',1E') \rightarrow CF_3^*(1A_1') + h\nu(630nm)$$

- Orange: Electron collision (tracked by Garfield++)
- Cyan: Intermediate process
- Green: Visible scintillation process

The bracketed symbols (e.g. $2A_2''$) specify the symmetry and multiplicity of the excited state

Light & charge simulation

Collision tracking in Garfield++

- Detailed collision output produced from Garfield++/Magboltz
- We can count how many collisions resulted in a given process
- We can also track the location of these collisions, and restrict tracking to areas of interest

description	energy
ELASTIC ANISOTROPIC CF4	0
ION CF3 +	15.7
ION CF2 +	21.47
ION CF +	29.14
ION F +	34.5
ION C +	34.77
DOUBLE ION CF3 + , F +	36
DOUBLE ION CF2 + , F +	40
IONS CF3 ++ OR CF2 ++	41
DOUBLE ION CF + , F +	43
DOUBLE ION C + , F +	63
ATTACHMENT	0
VIB V2 ANISOTROPIC	-0.0539
VIB V2 ANISOTROPIC	0.0539

Light & charge simulation

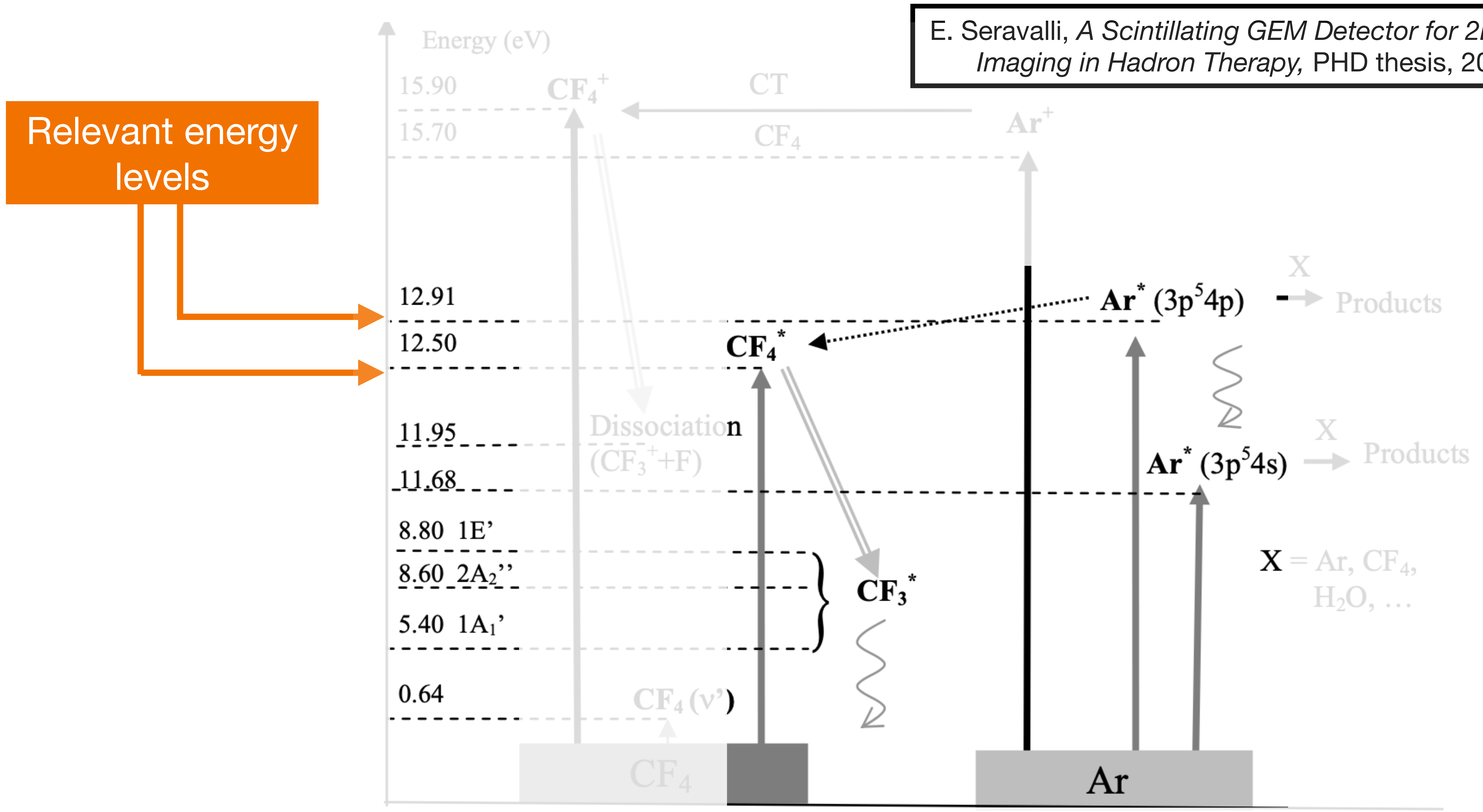
Tracking visible scintillation

- Energy levels identified in Magboltz (see below)
- This allows for the tracking of scintillation by tracking the number of collisions in these levels

$e^- + CF_4 \rightarrow e^- + CF_4^* \rightarrow e^- + F + CF_3^*(2A_2'', 1E')$	
NEUTRAL DISS NON-DIPOLE	12.5

$e^- + Ar \rightarrow e^- + Ar^{**}$	
EXC 2P10 J=1	12.907

Paschen notation



E. Seravalli, *A Scintillating GEM Detector for 2D Dose Imaging in Hadron Therapy*, PHD thesis, 2008

Light & charge simulation

- Assume one visible photon will inevitably be released when a collision results in CF4* or Ar** production
- Therefore, by tracking visible scintillation related collisions, we can estimate how much visible light is produced
- Plot this against number of electrons collected at the anode for different CF4/Ar ratios
- In reality, some Ar** will de-excite before interacting with CF4, so make the de-excitation probability a parameter
- Compare to MIGDAL data

CF_4

$$e^- + CF_4 \rightarrow e^- + CF_4^* \rightarrow e^- + F + CF_3^*(2A_2'',1E')$$

$$CF_3^*(2A_2'',1E') \rightarrow CF_3^*(1A_1') + h\nu(630nm)$$

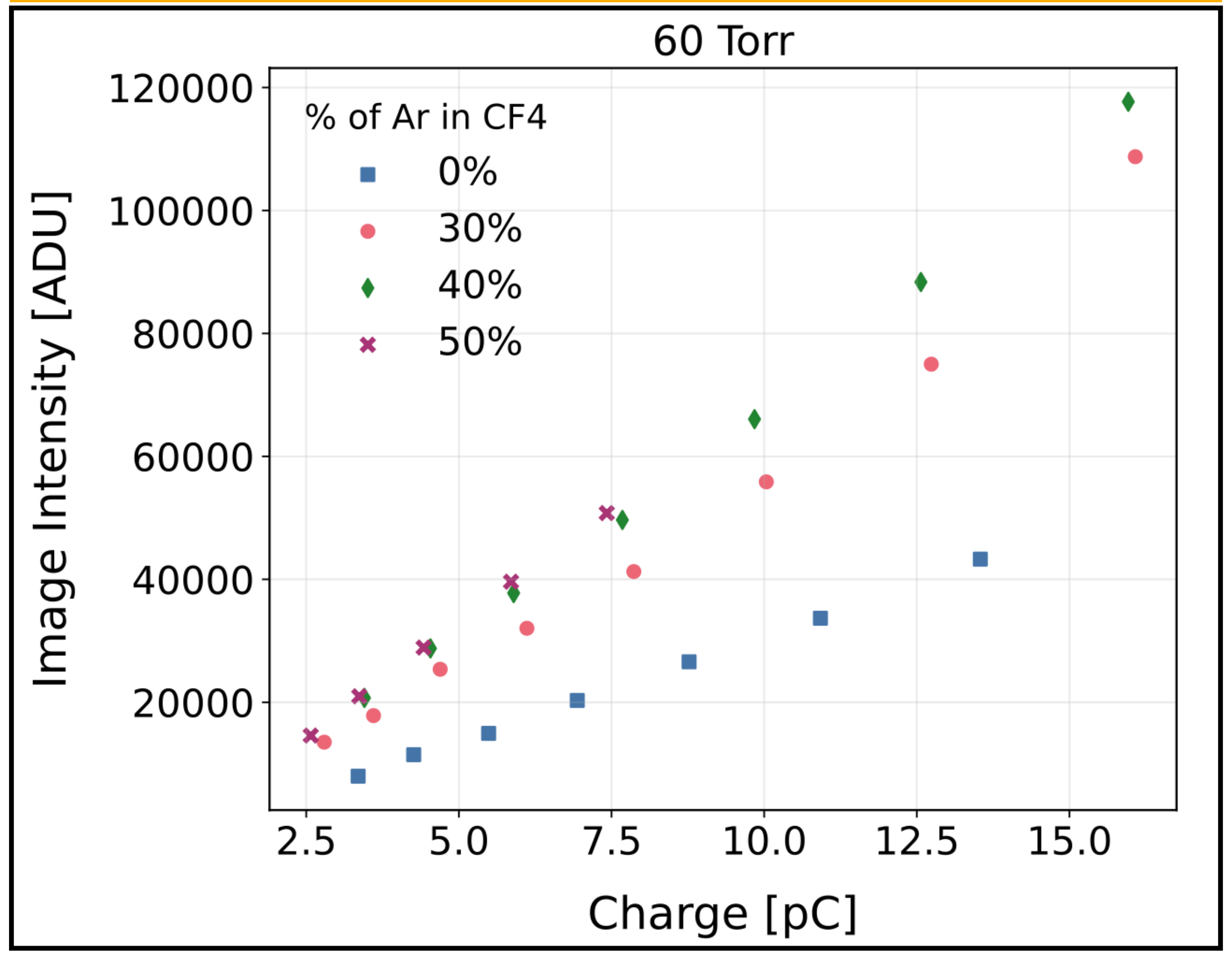
Ar

$$e^- + Ar \rightarrow e^- + Ar^{**}$$

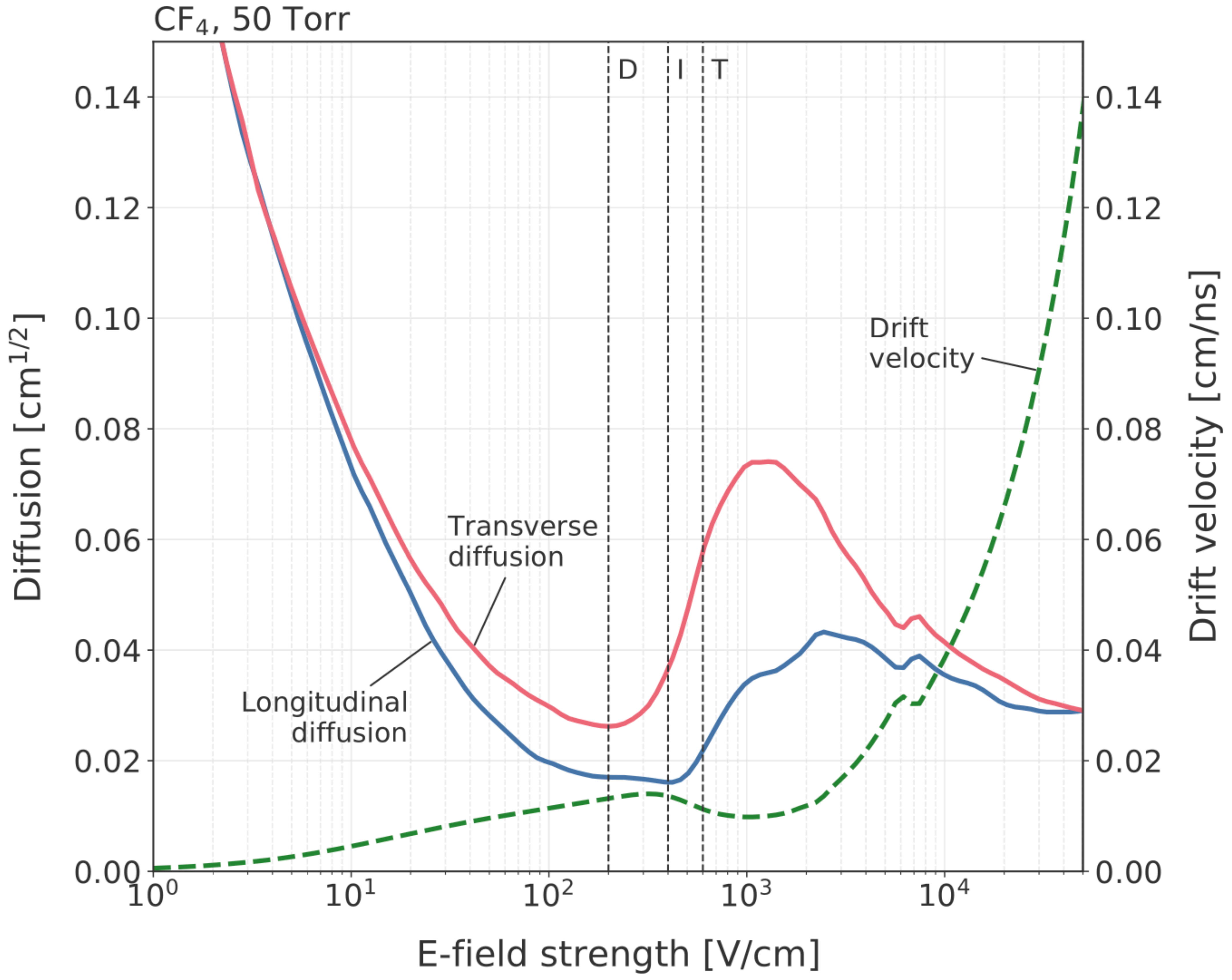
$$Ar^{**} + CF_4 \rightarrow Ar + CF_4^* \rightarrow Ar + F + CF_3^*(2A_2'',1E')$$

$$CF_3^*(2A_2'',1E') \rightarrow CF_3^*(1A_1') + h\nu(630nm)$$

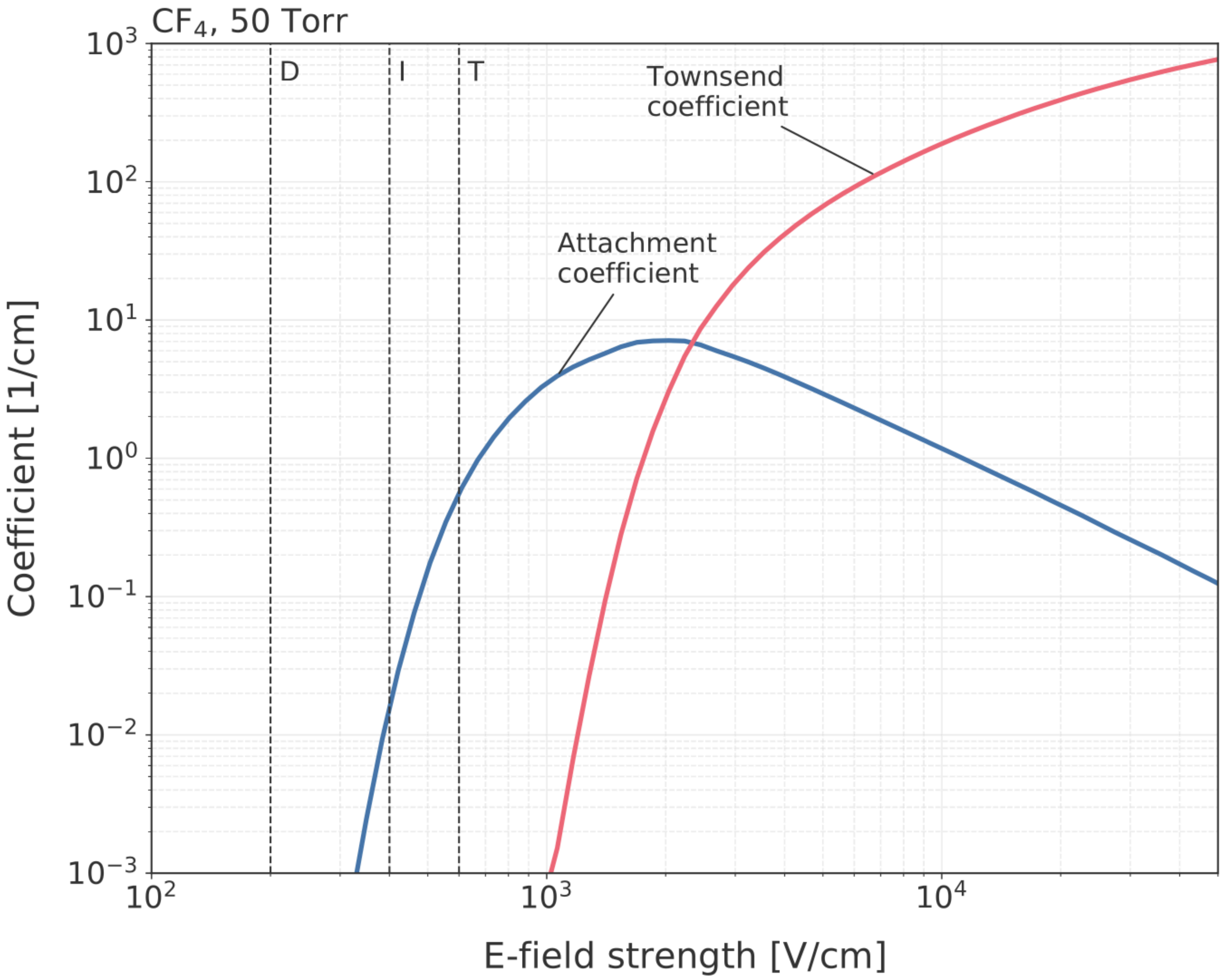
MIGDAL data



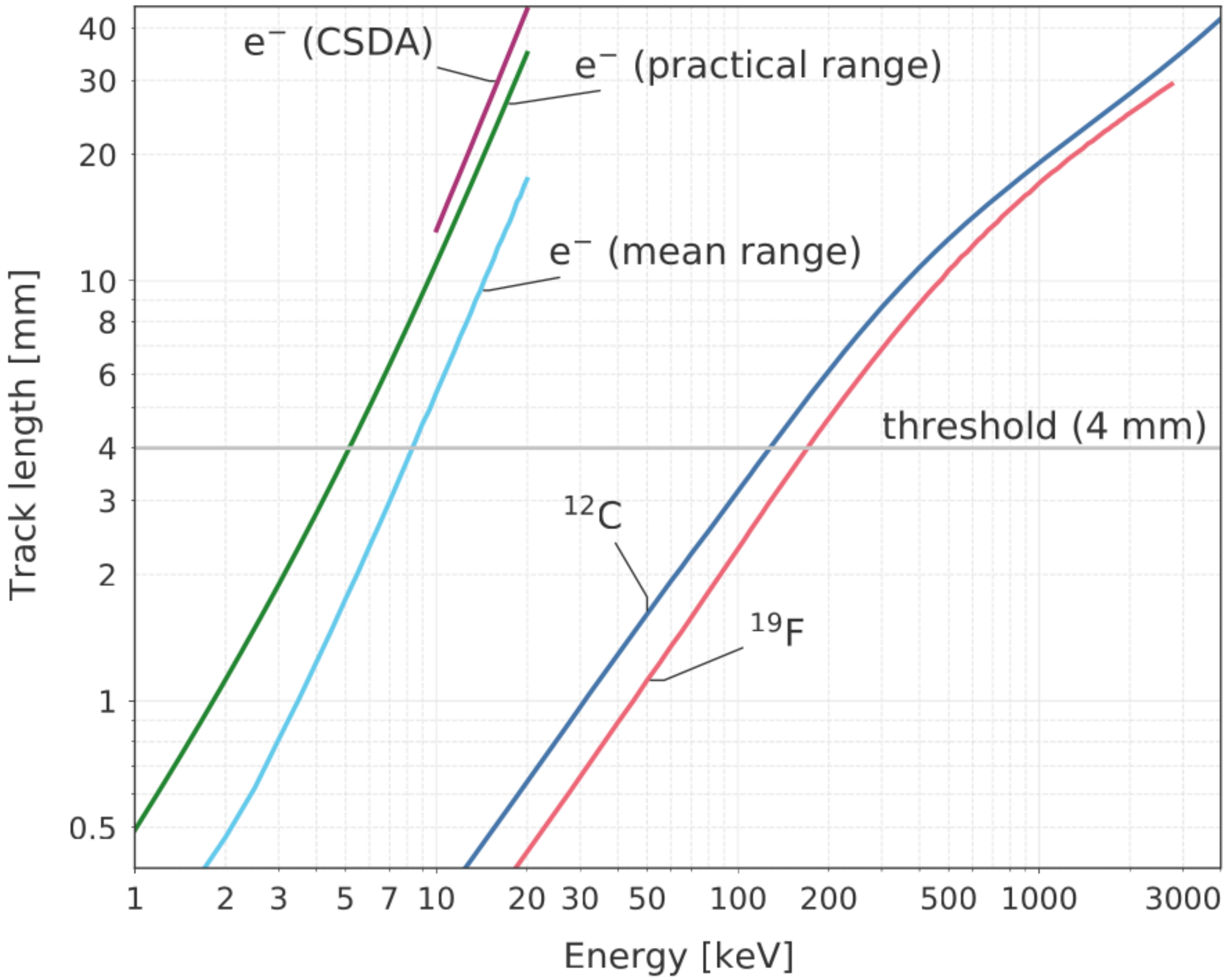
Backup Slides



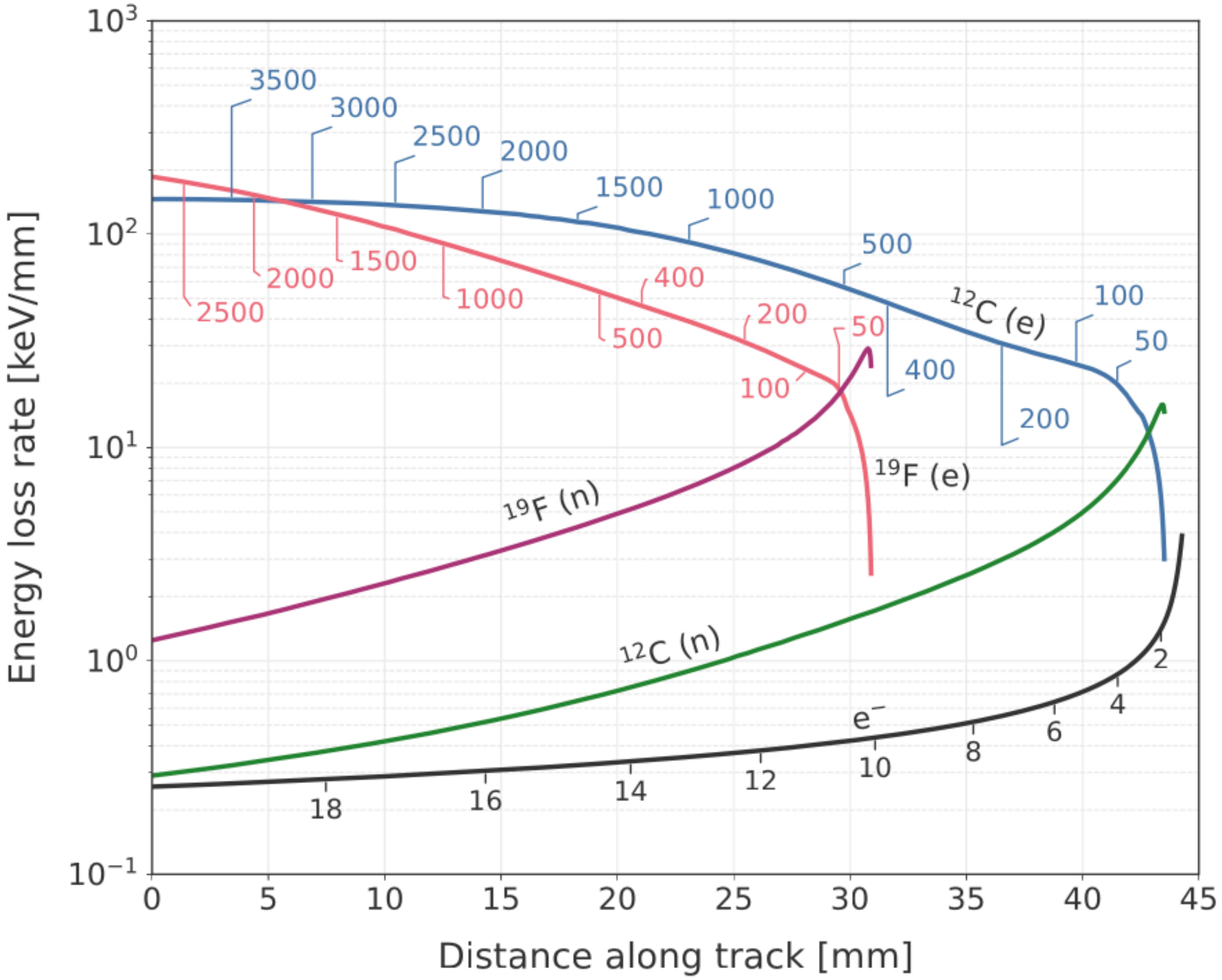
CF$_4$, 50 Torr
D
I
T
Transverse diffusion
Longitudinal diffusion
Drift velocity
Diffusion [cm$^{1/2}$]
Drift velocity [cm/ns]
E-field strength [V/cm]



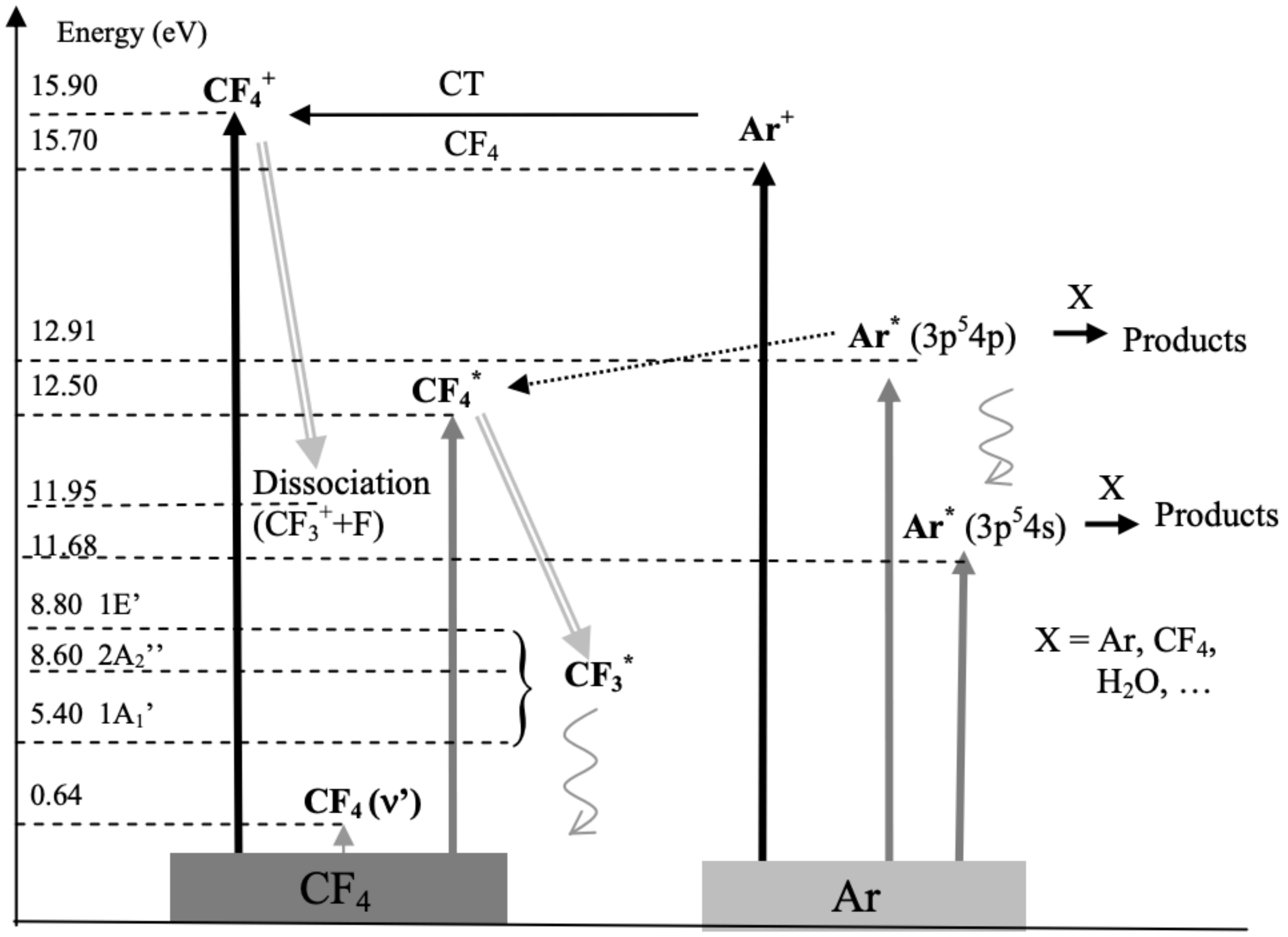
CF$_4$, 50 Torr
D
I
T
Townsend coefficient
Attachment coefficient
Coefficient [1/cm]
E-field strength [V/cm]



e⁻ (CSDA)
e⁻ (practical range)
e⁻ (mean range)
threshold (4 mm)
^{12}C
^{19}F
Track length [mm]
Energy [keV]



^{12}C (e)
^{19}F (e)
^{19}F (n)
^{12}C (n)
e⁻
Energy loss rate [keV/mm]
Distance along track [mm]


Energy (eV)
15.90
15.70
12.91
12.50
11.95
11.68
8.80 1E'
8.60 2A2''
5.40 1A1'
0.64
CF4+
CT
CF4
Ar+
Ar* (3p54p)
X
Products
CF4*
Dissociation
(CF3++F)
Ar* (3p54s)
X
Products
CF3*
X = Ar, CF4,
H2O, …
CF4 (ν')
CF4
Ar