NEWS-G

New Experiments With Spheres-Gas

# Detector Response Modelling Of NEWS-G Dark Matter Search Experiment

Yuqi Deng

Supervisor: Marie-Cécile Piro

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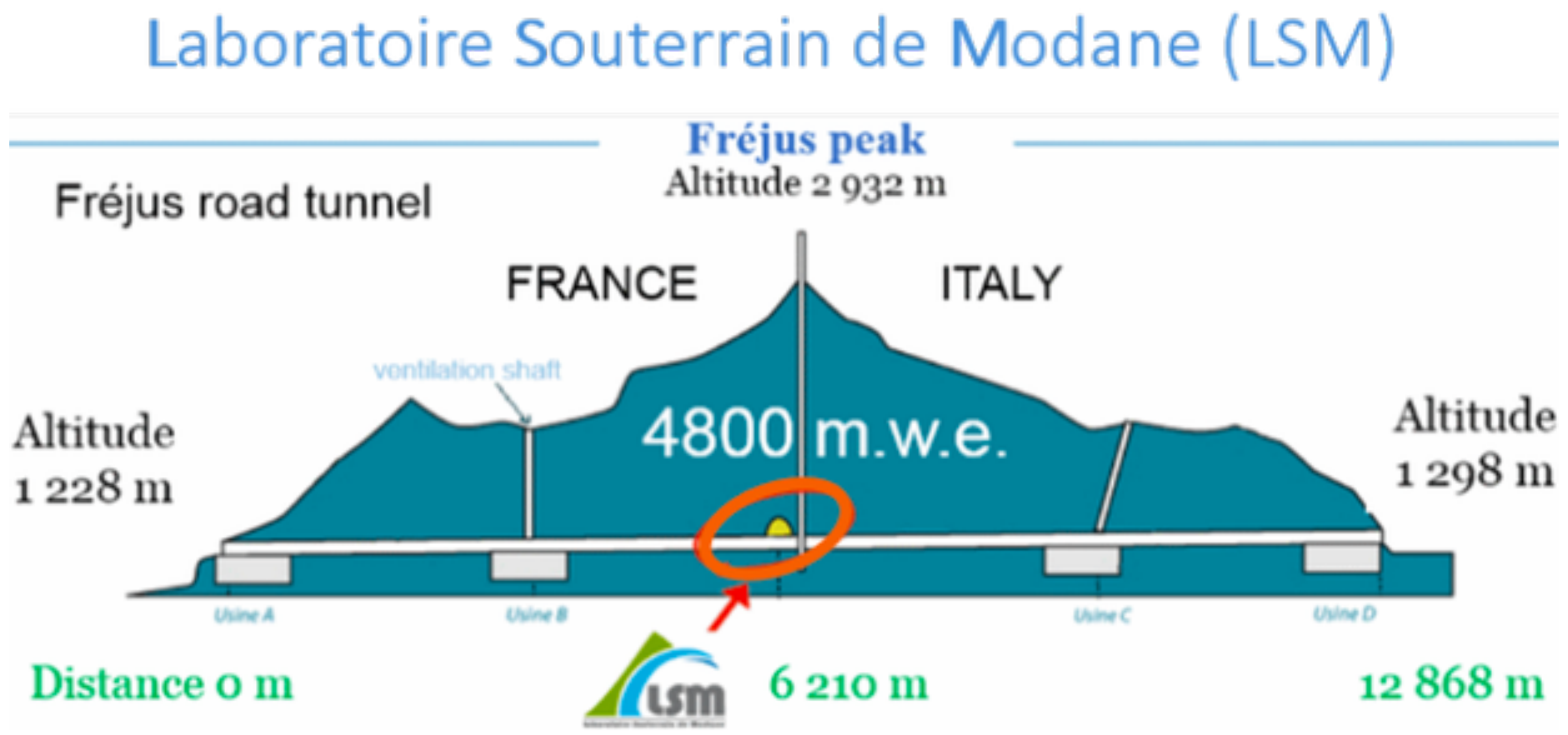
UNIVERSITY OF ALBERTA

Arthur B. McDonald Canadian Astroparticle Physics Research Institute

- New Experiments With Spheres-Gas (NEWS-G): search for low-mass WIMPs
- Spherical proportional counters (SPC):
  - SEDINE at LSM: 60 cm diameter sphere with a 6.3mm diameter spherical sensor
  - SNOGLOBE at LSM: 1.35 m diameter sphere and multi-anode sensor
  - SNOGLOBE at SNOLAB
  - 30 cm diameter sphere at U of A

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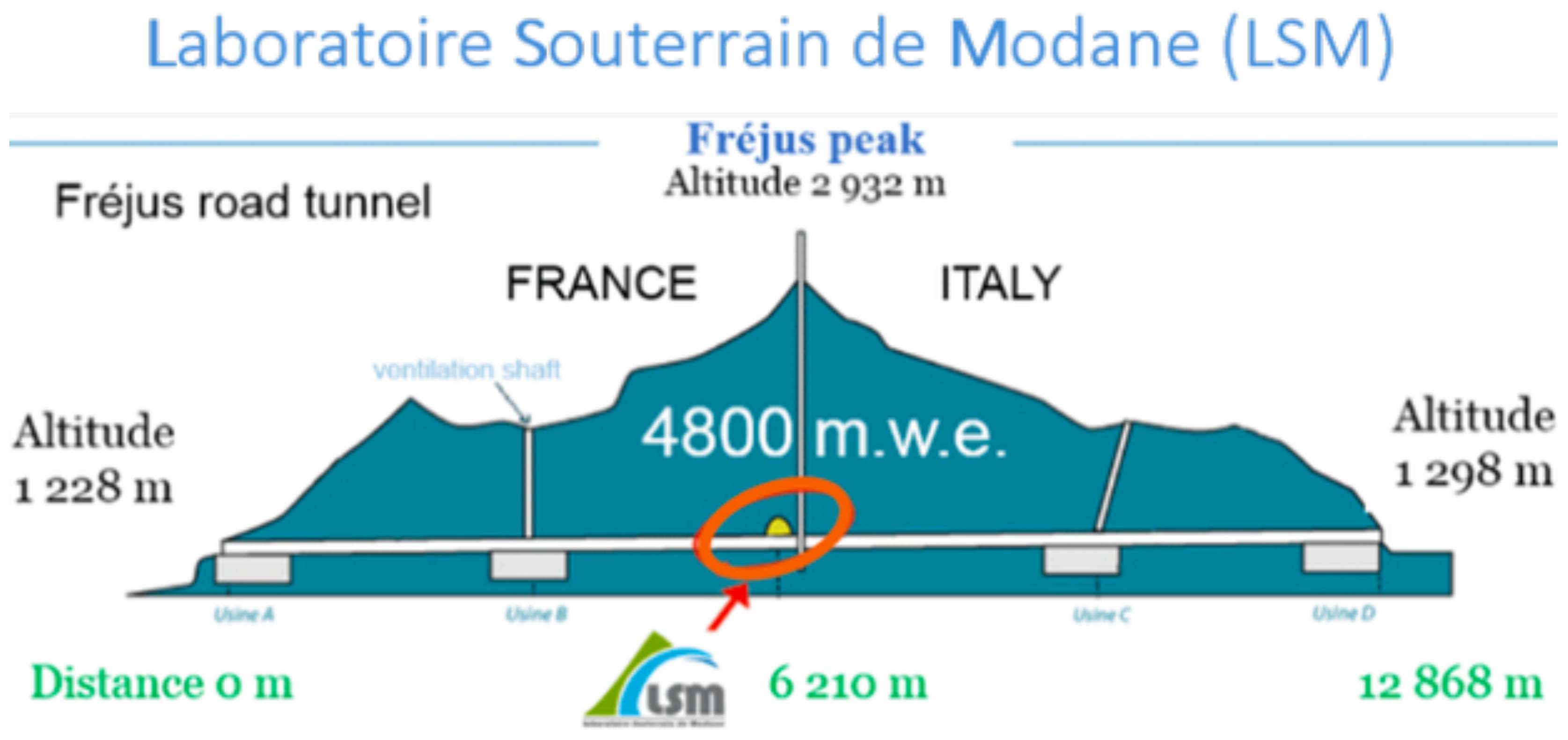


Physics and non-physics data were taken with a 1.35m diameter SPC under 135 mbar using pure CH4 at LSM in 2019

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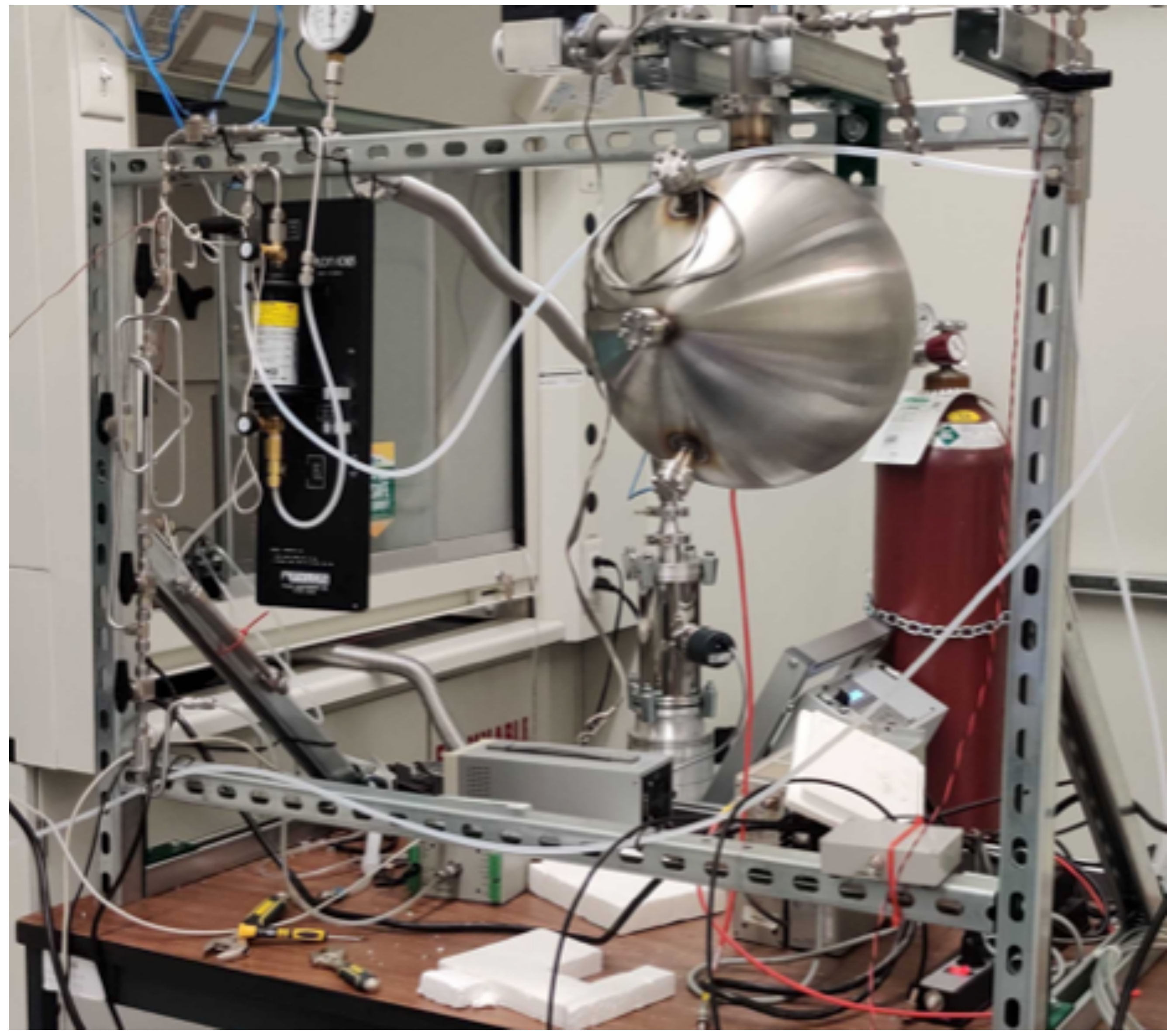
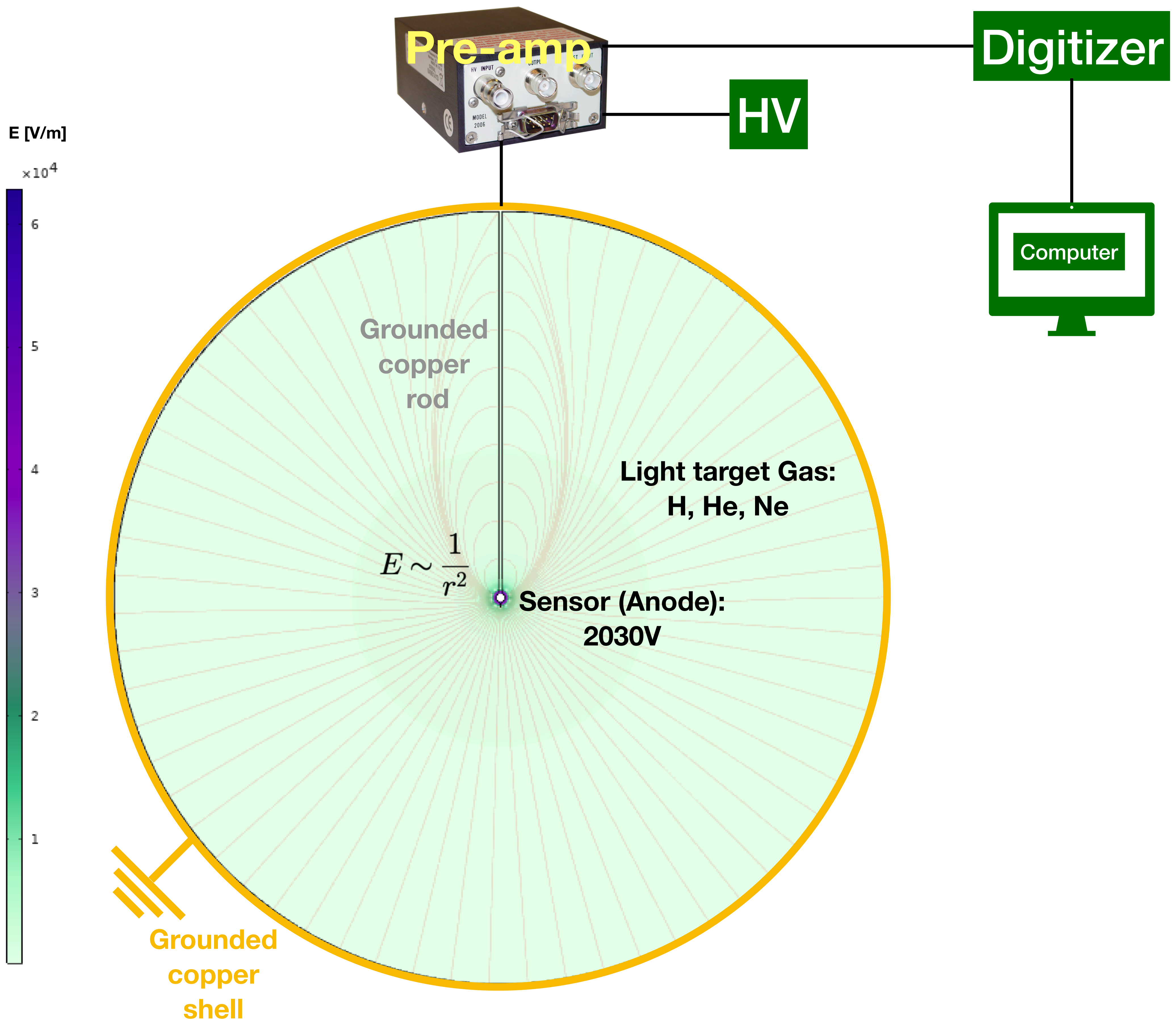
The new SPC is currently installed in SNOLAB






Primary Ionization

Electrons drift towards centre due to electrostatic force applied by the sensor

Secondary ionization:

Primary electrons gaining enough kinetic energy under high Efield near anode can ionize secondary ion/electron pairs

Electron Reach sensor

Secondary positive ions drift away from sensor

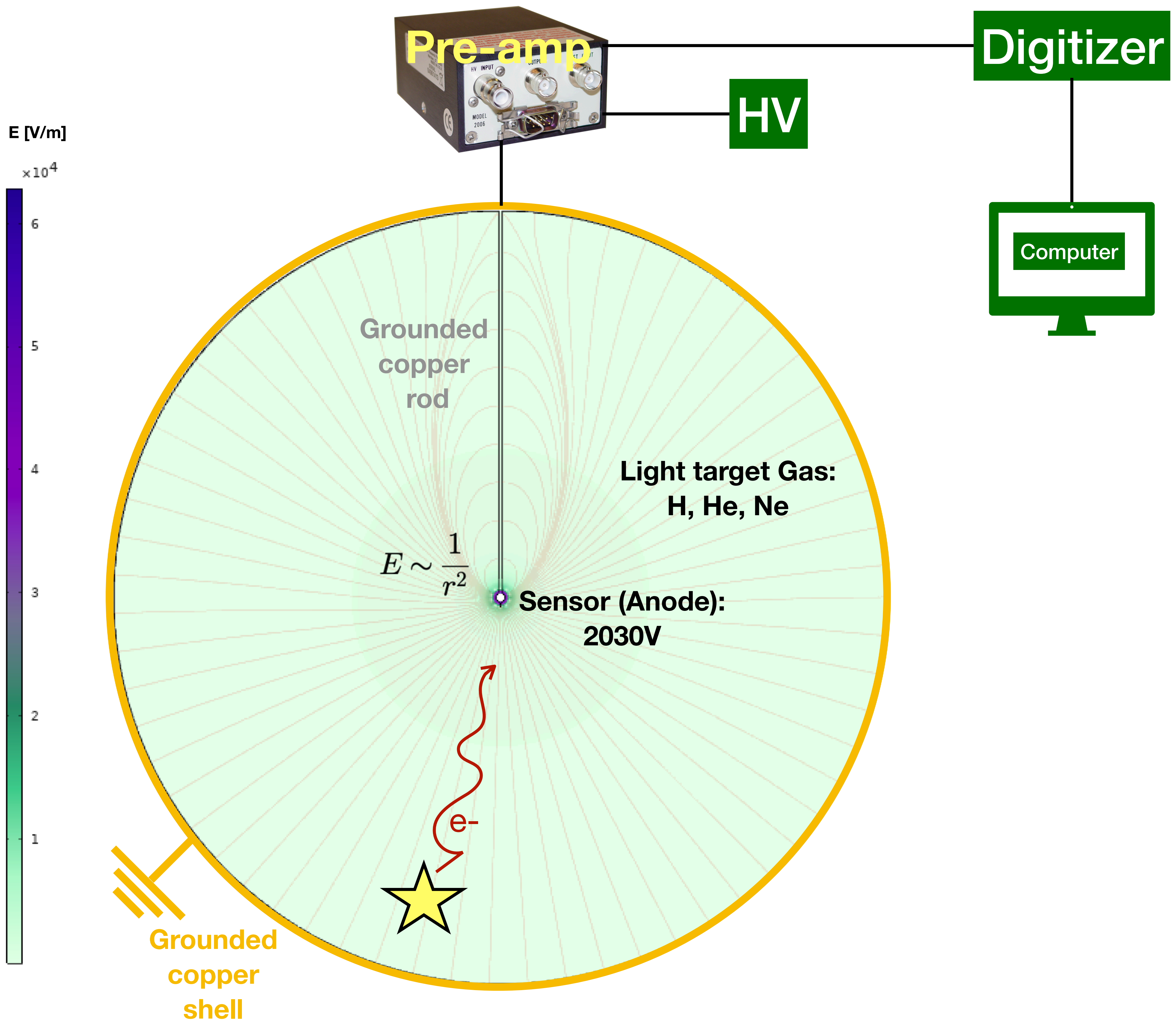
Induce current

Current signal

Pre-amplifier response

Voltage signal

Digitizer

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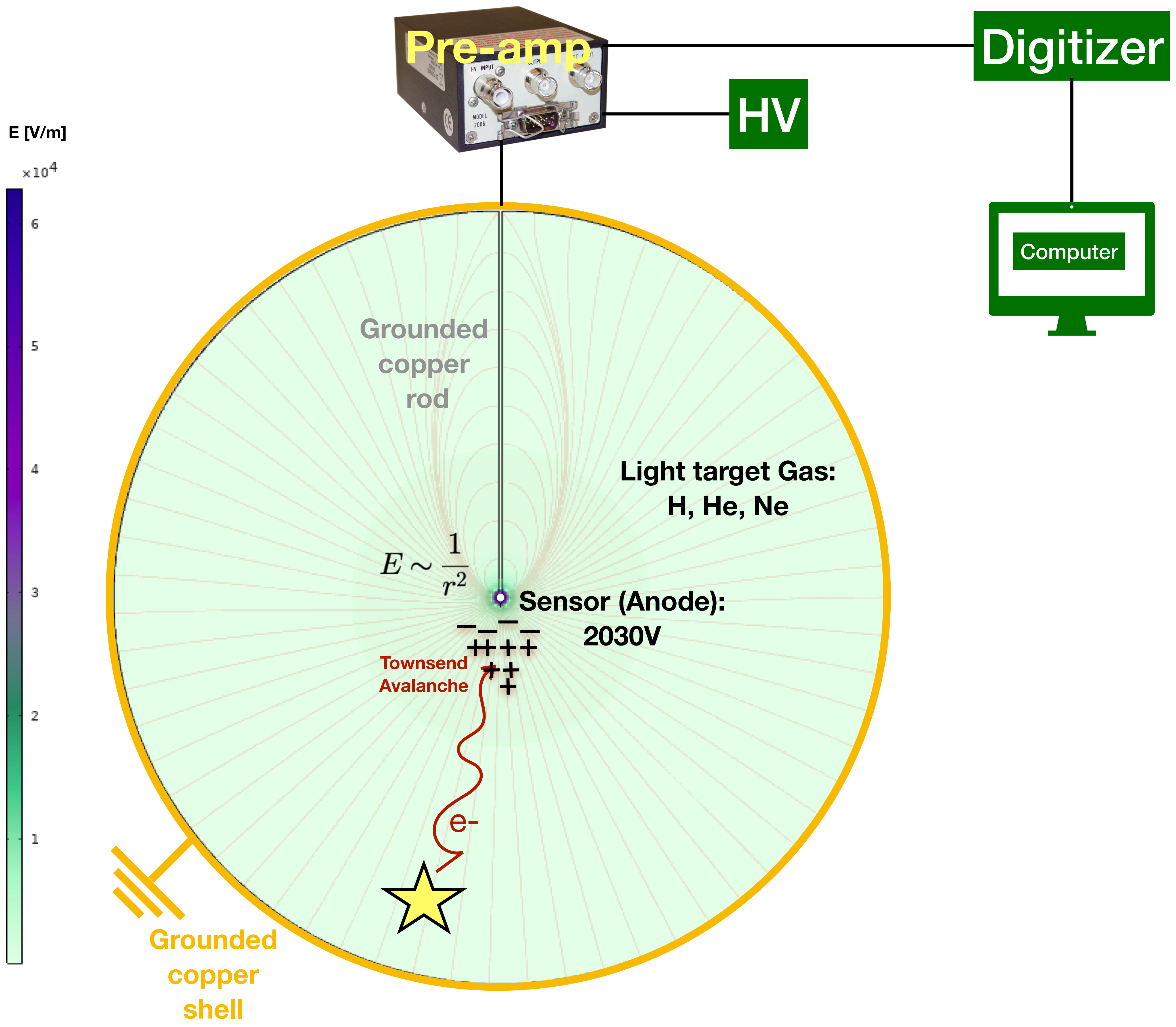
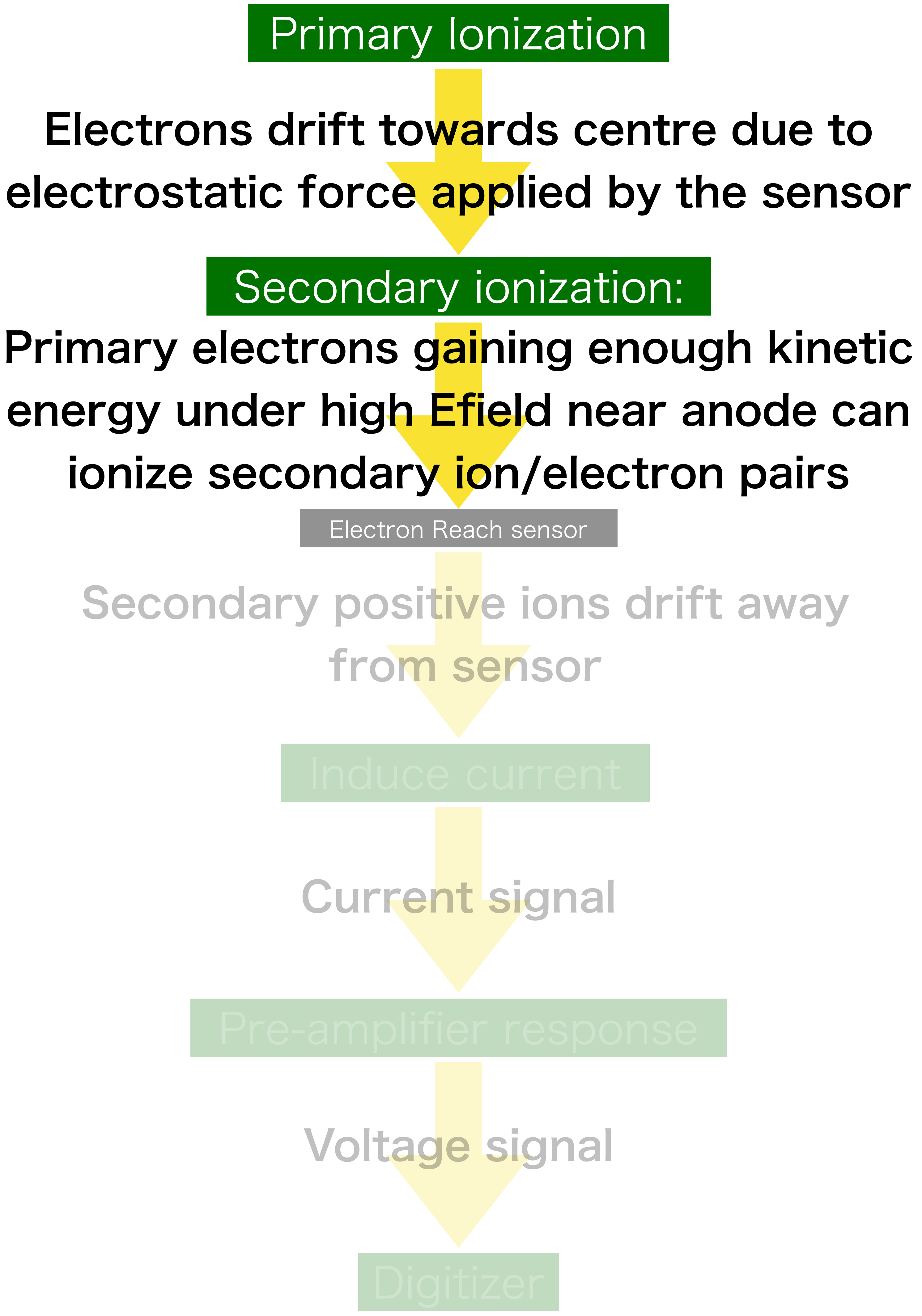


Pre-amp
Digitizer
HV
Computer
E [V/m]
×10^4
Grounded copper rod
Light target Gas: H, He, Ne
$E \sim \frac{1}{r^2}$
Sensor (Anode): 2030V
Townsend Avalanche
e-
Grounded copper shell

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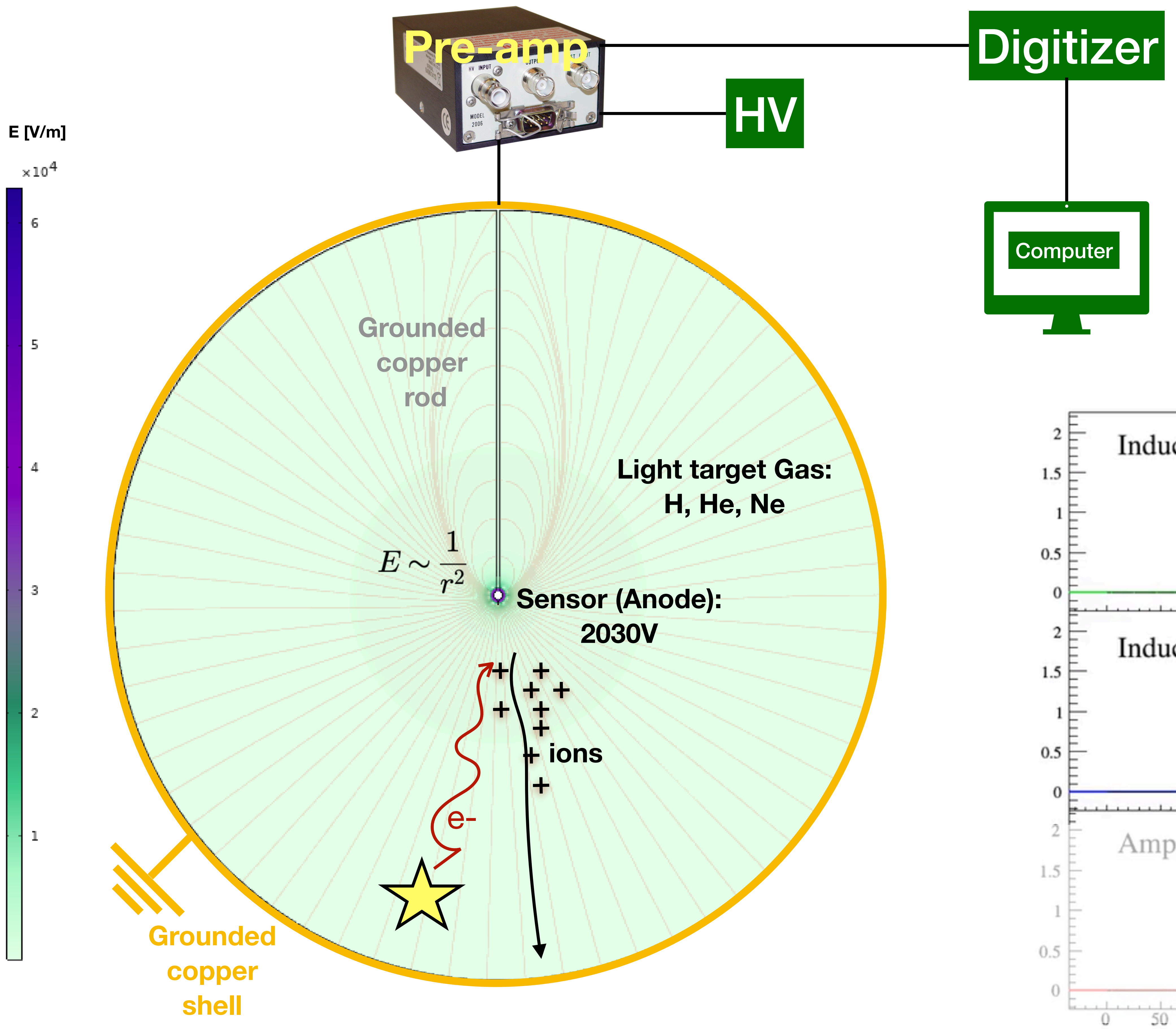


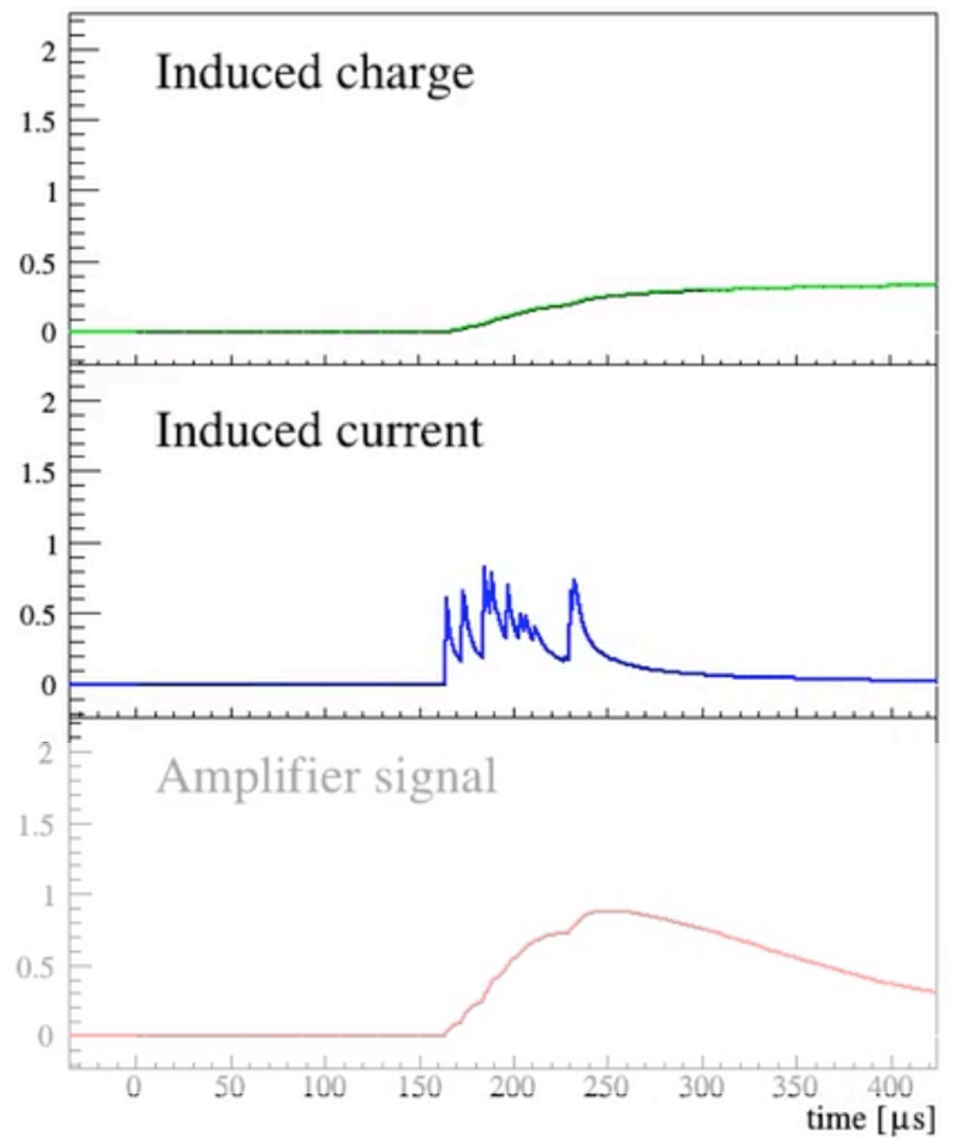


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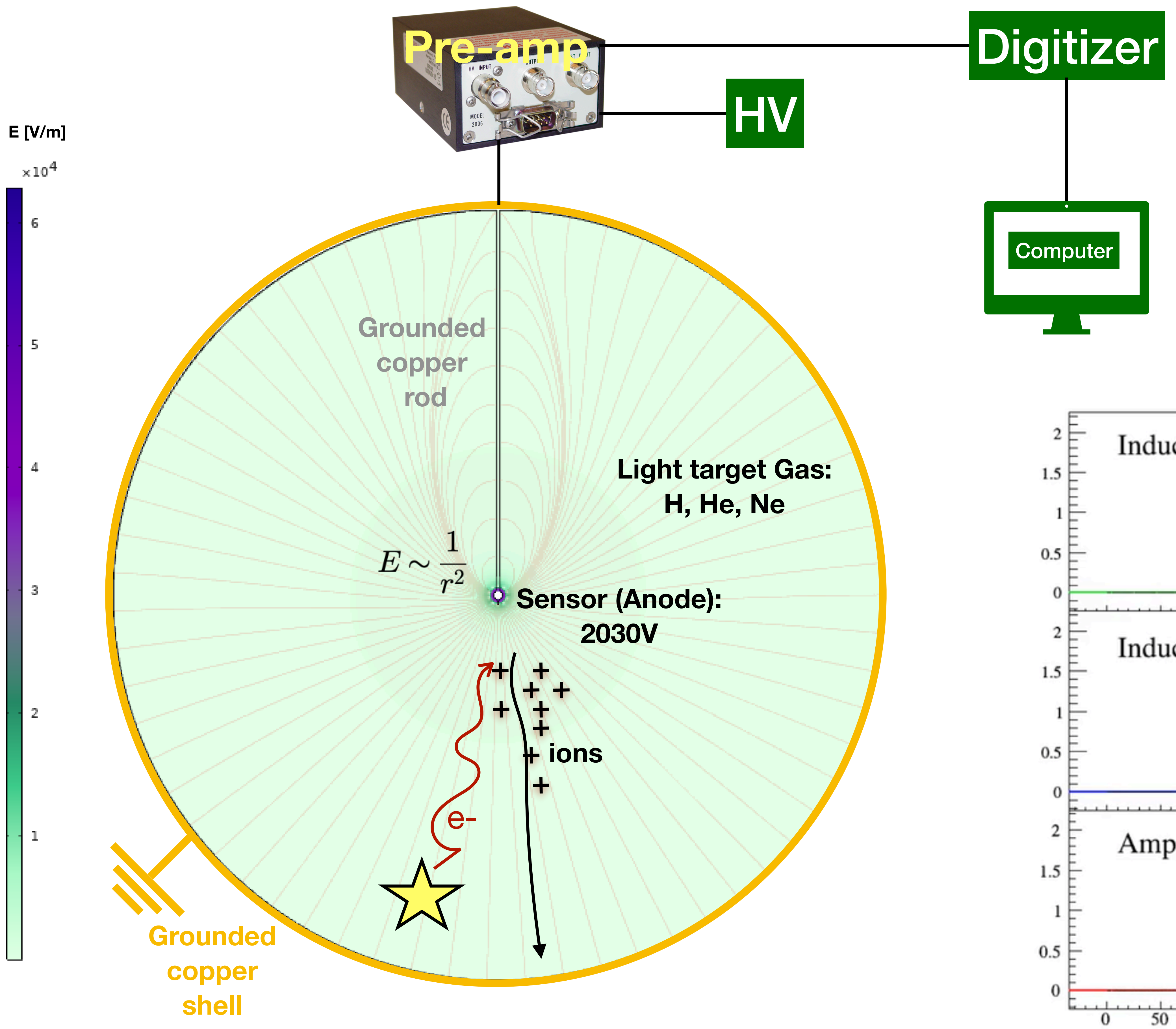


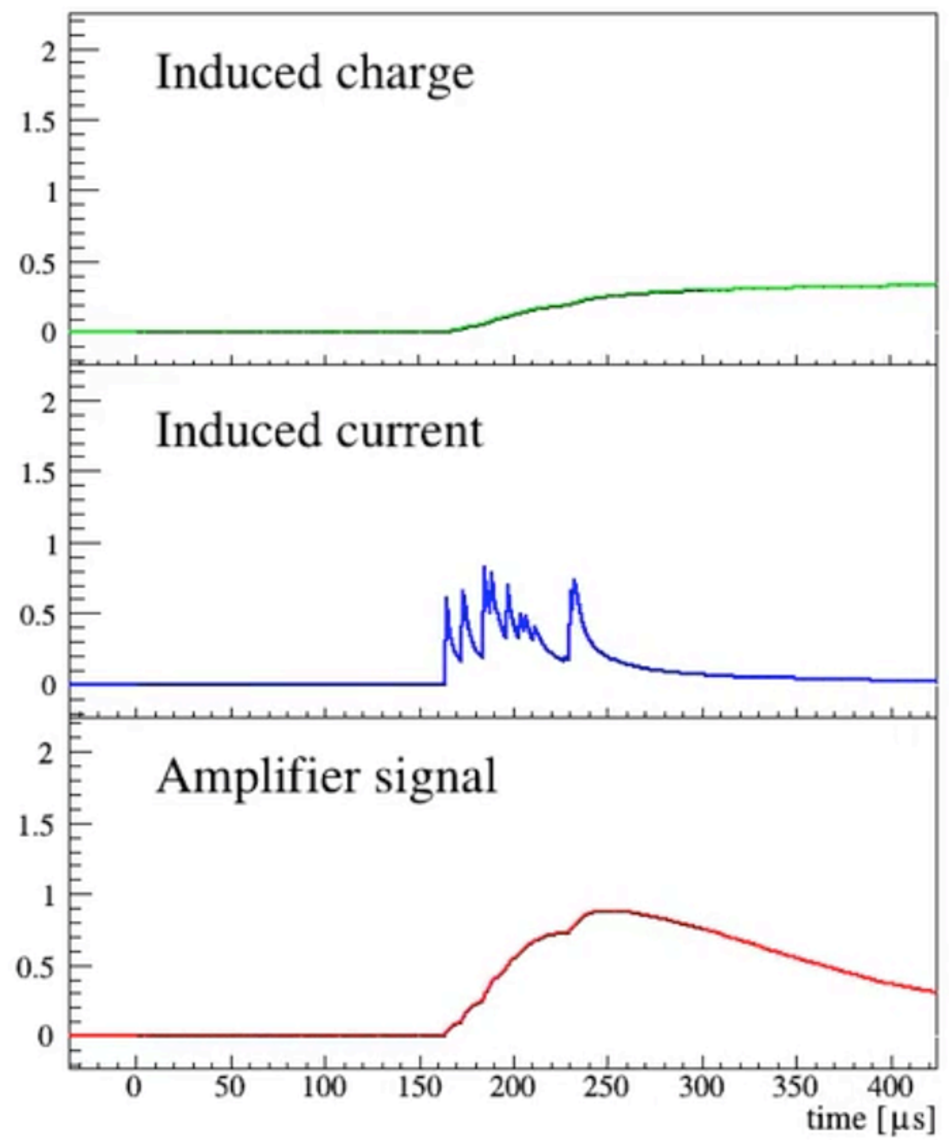


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Digitizer

- Radioactive source Ar37 along with pure CH4 was filled in SPC
- Ar37 emit X-rays at 270 eV and 2.8 keV induced by electron capture in L and K shell
- X-rays are uniformly distributed throughout the detector


**Calibration runs**

Ar37 | UV laser

Electrons drift towards centre due to electrostatic force applied by the sensor

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Secondary positive ions drift away from sensor

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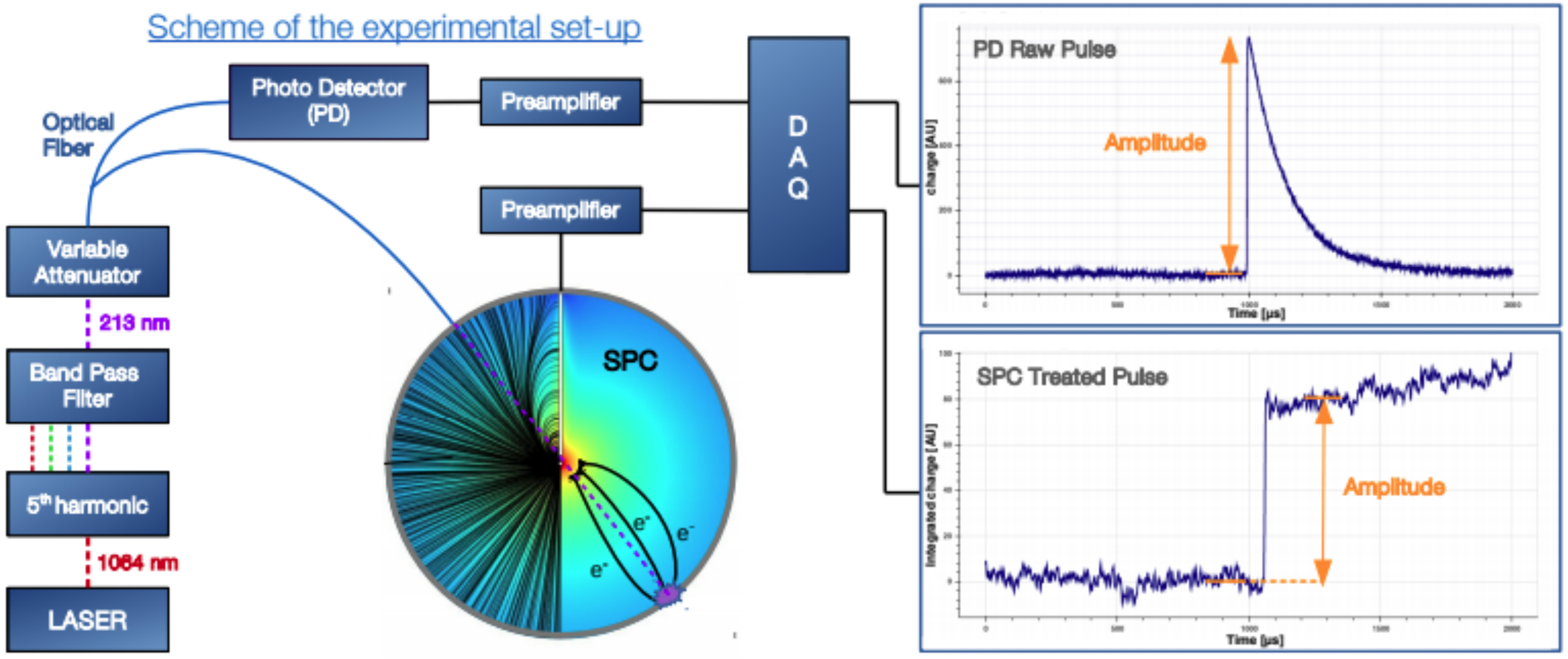



Q. Arnaud et al., Precision laser-based measurements of the single electron response of SPCs for the NEWS-G light dark matter search experiment, arXiv:1902.08960

- Drift time: electron travel time from cathode to anode
- Compare with data and verify our understanding on the physics happened in our detector, identify different interactions
- Determine cut efficiency/WIMP signal acceptance, further extracting the WIMPs limits on cross section etc

**Step1: Electric field simulation: Finite element software COMSOL**

Step2: Primary ionization

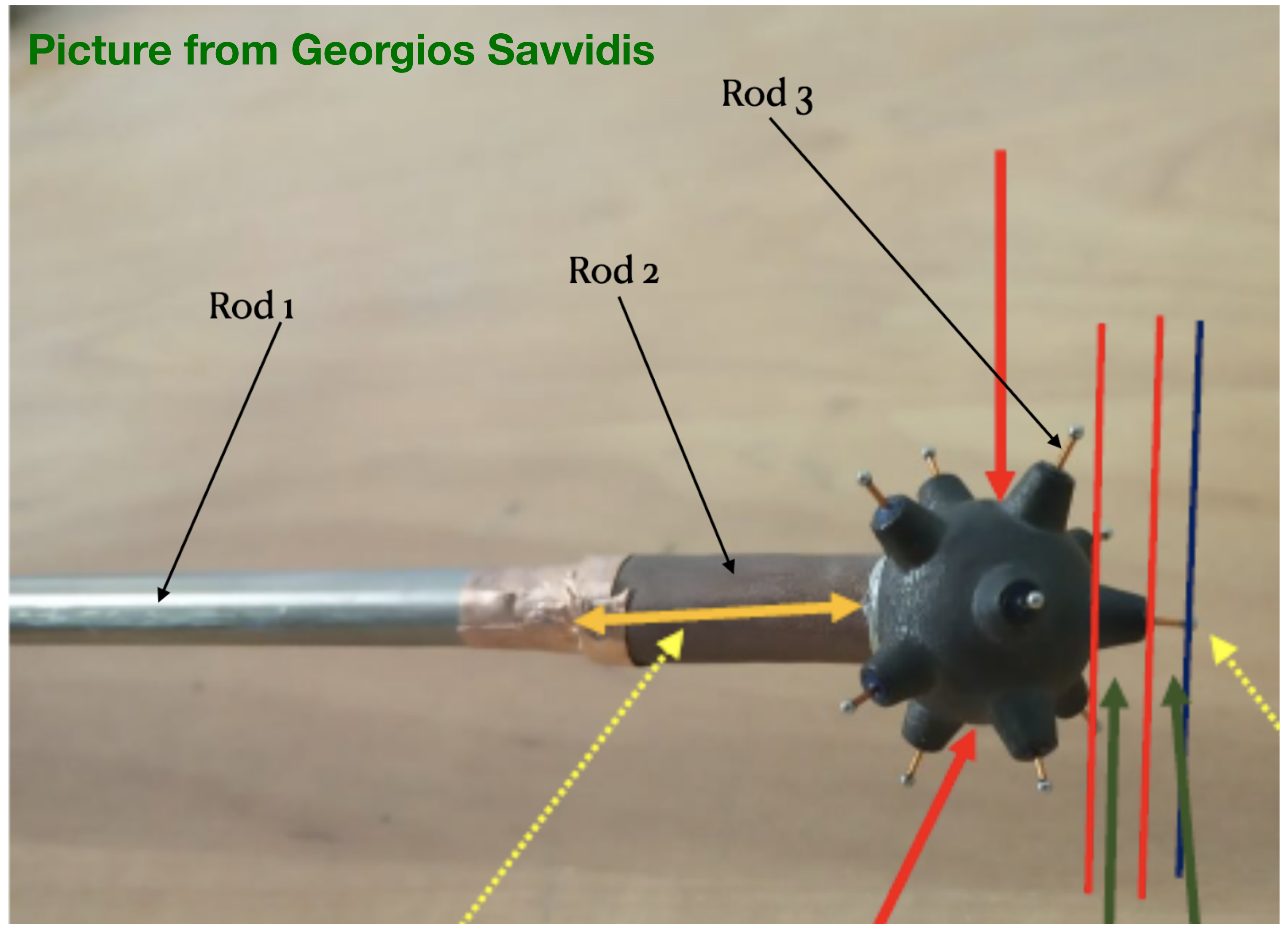
Step3: electron transportation

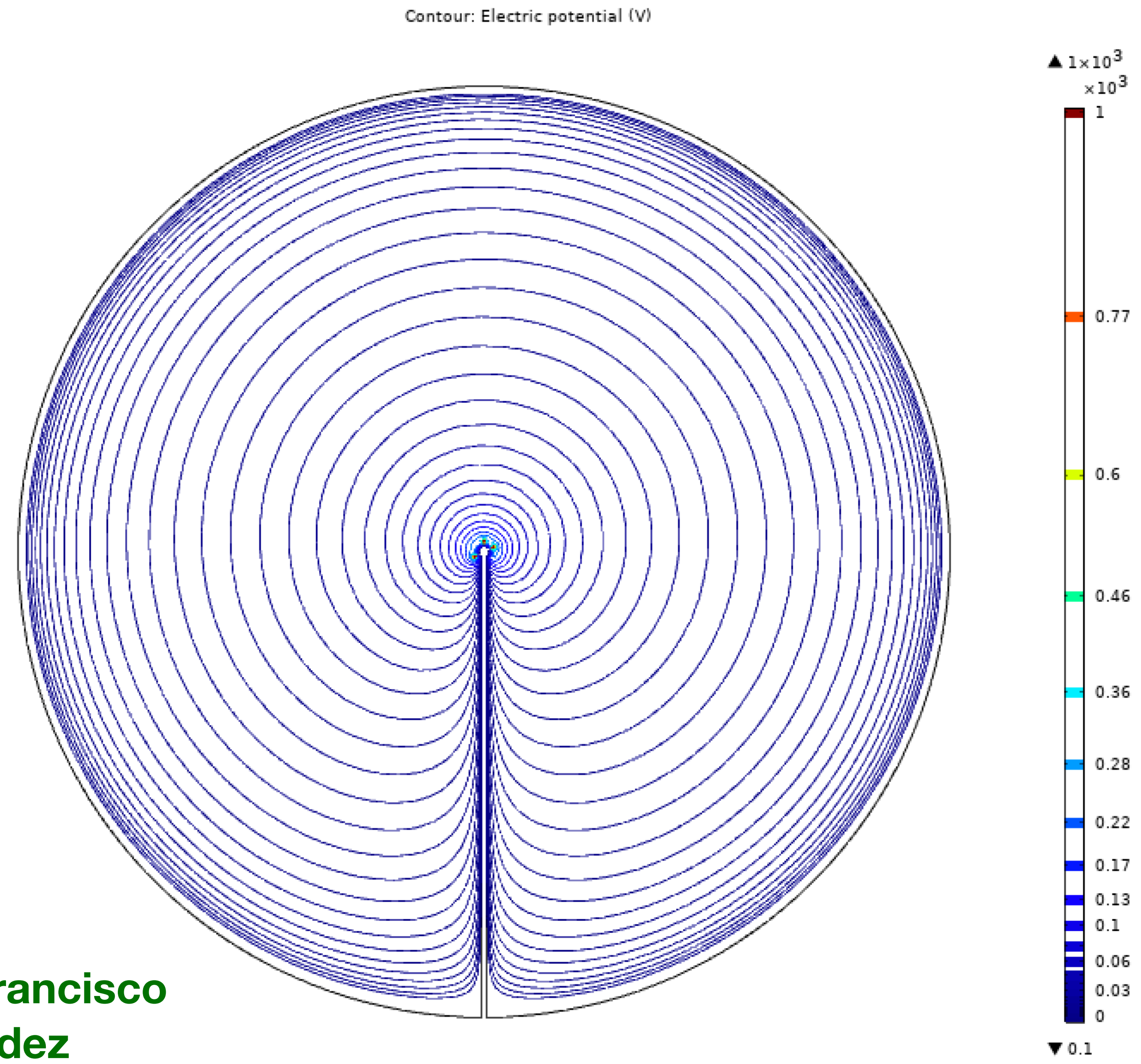
Electron drift time determined

Step4: signal formation

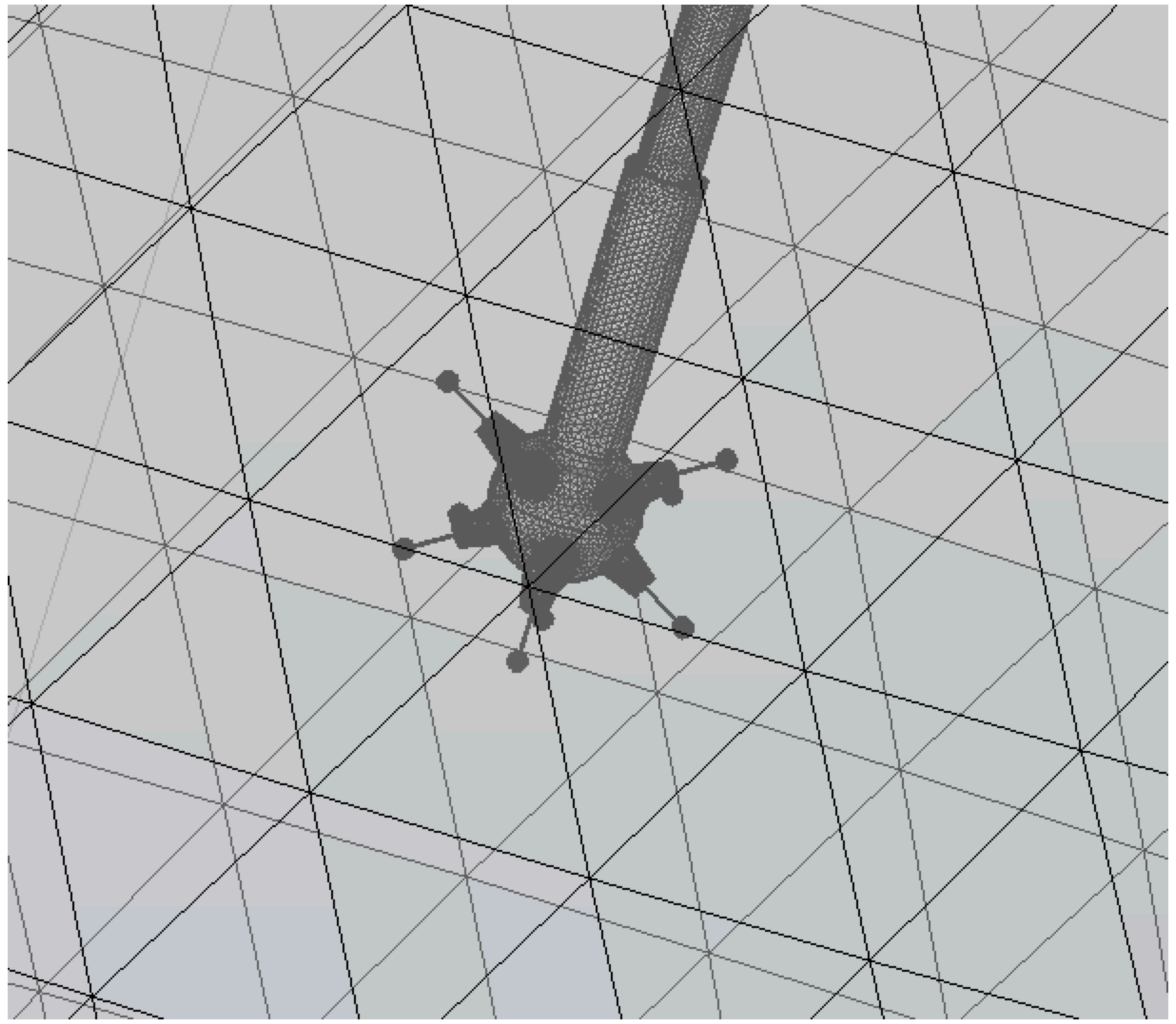
Rise time determined

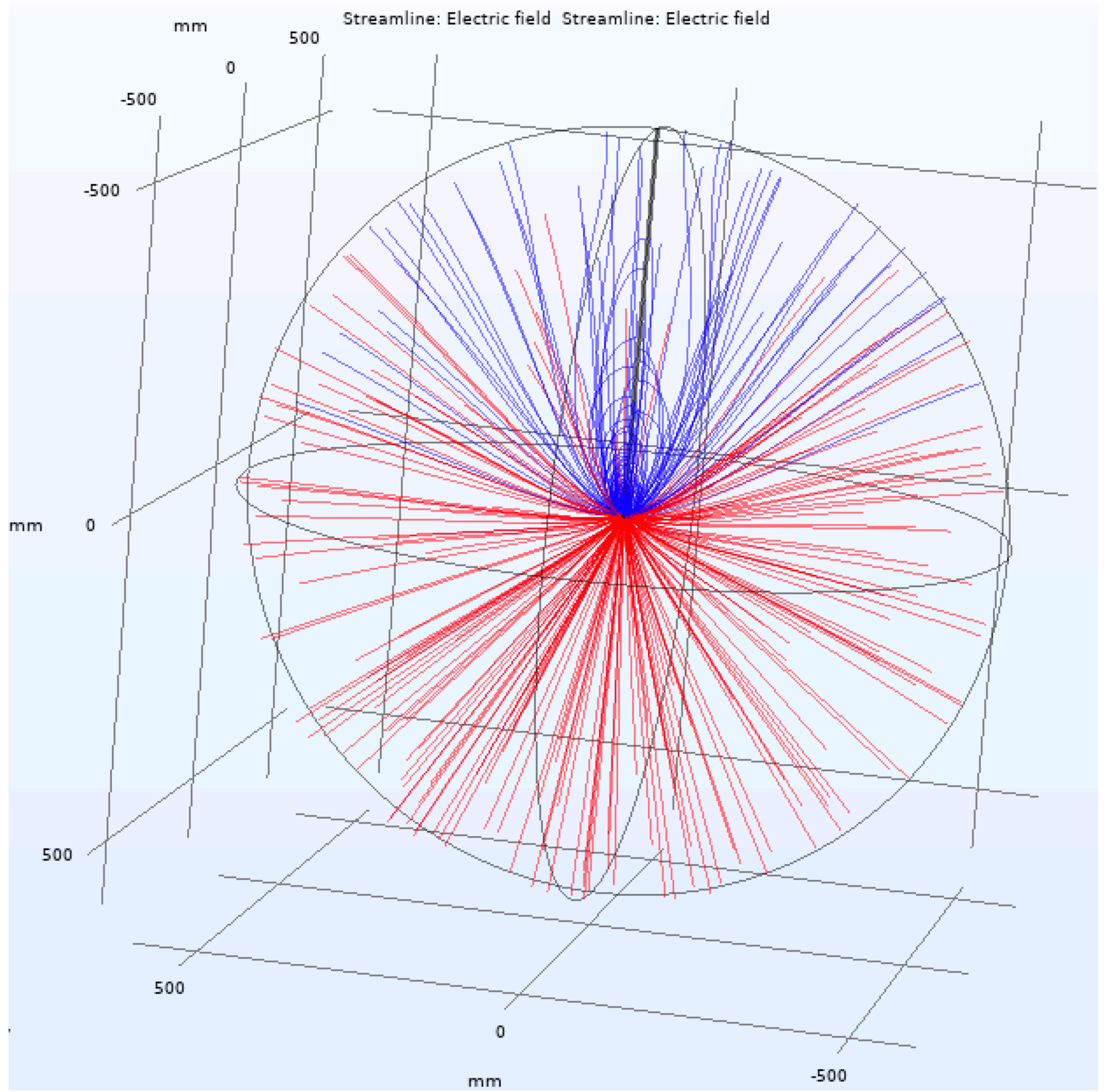
Picture from Georgios Savvidis




A simulation work done by Francisco Vazquez de Sola Fernandez





Step1: Electric field simulation: Finite element software COMSOL

Step2: Primary ionization (Ar37 Events)

Step3: electron transportation

Electron drift time determined

Step4: signal formation

Rise time determined

- **The Conway Maxwell - Poisson (COM-Poisson) distribution:**

$$P(x|\lambda,\nu) = \frac{\lambda^x}{(x!)^\nu Z(\lambda,\nu)}$$

$$Z(\lambda,\nu) = \sum_{j=0}^{\infty} \frac{\lambda^j}{(j!)^\nu} \quad \lambda \in \{\mathbb{R} > 0\}, \quad \nu \in \{\mathbb{R} \geq 0\}$$

- **The assumption that the number of primary electrons produced follows poisson distribution doesn't significantly affect simulation result:**

A. Expectation value is a function of deposited energy:

$$\mu = \frac{E}{W(E)}$$

B. W is the mean energy needed to create electron/ion pair in gaseous detectors.

C. W values being measured in pure CH4 under 135 mbar is 31.2 eV for 2.8keV X-rays

Step1: Electric field simulation: Finite element software COMSOL

Step2: Primary ionization

Step3: electron transportation

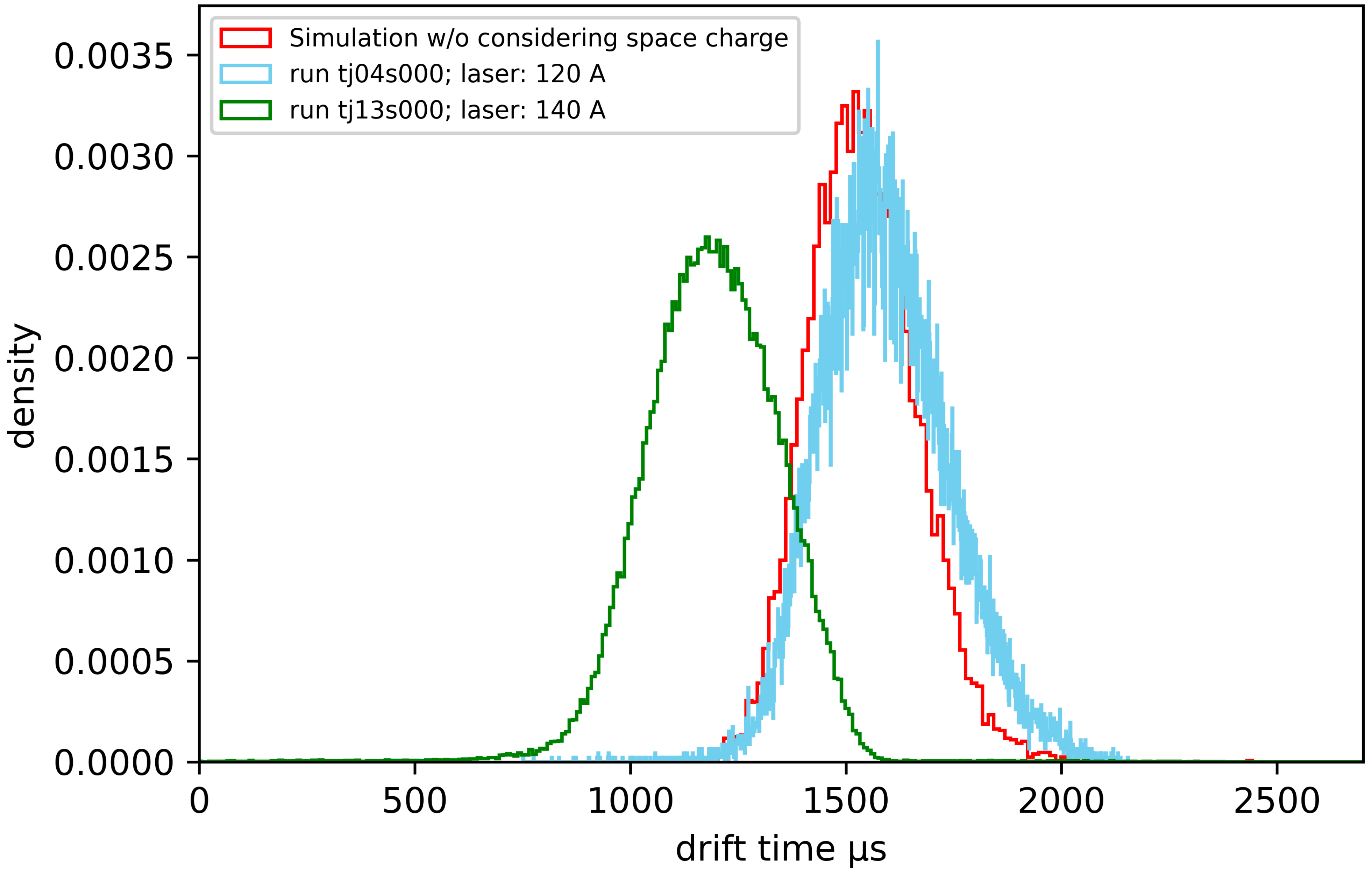
Electron drift time determined

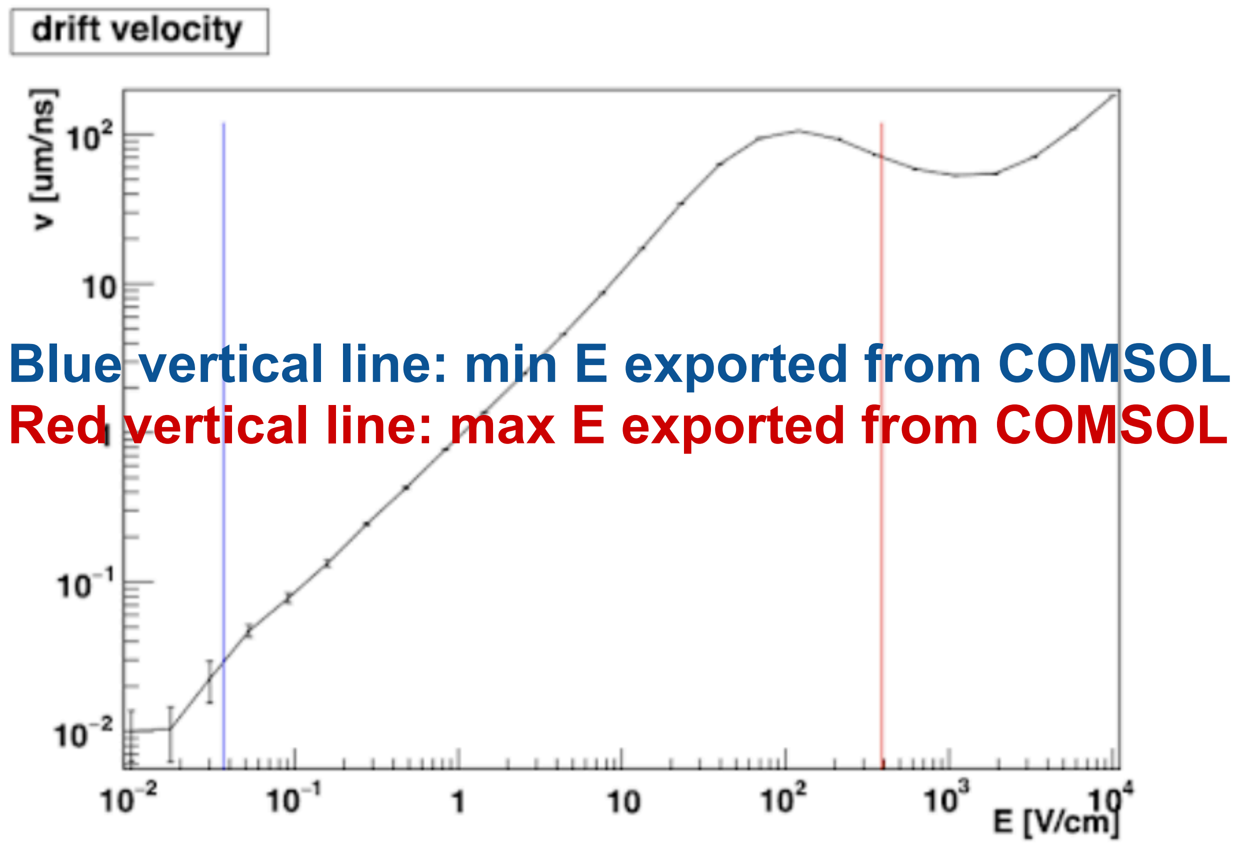
Step4: signal formation

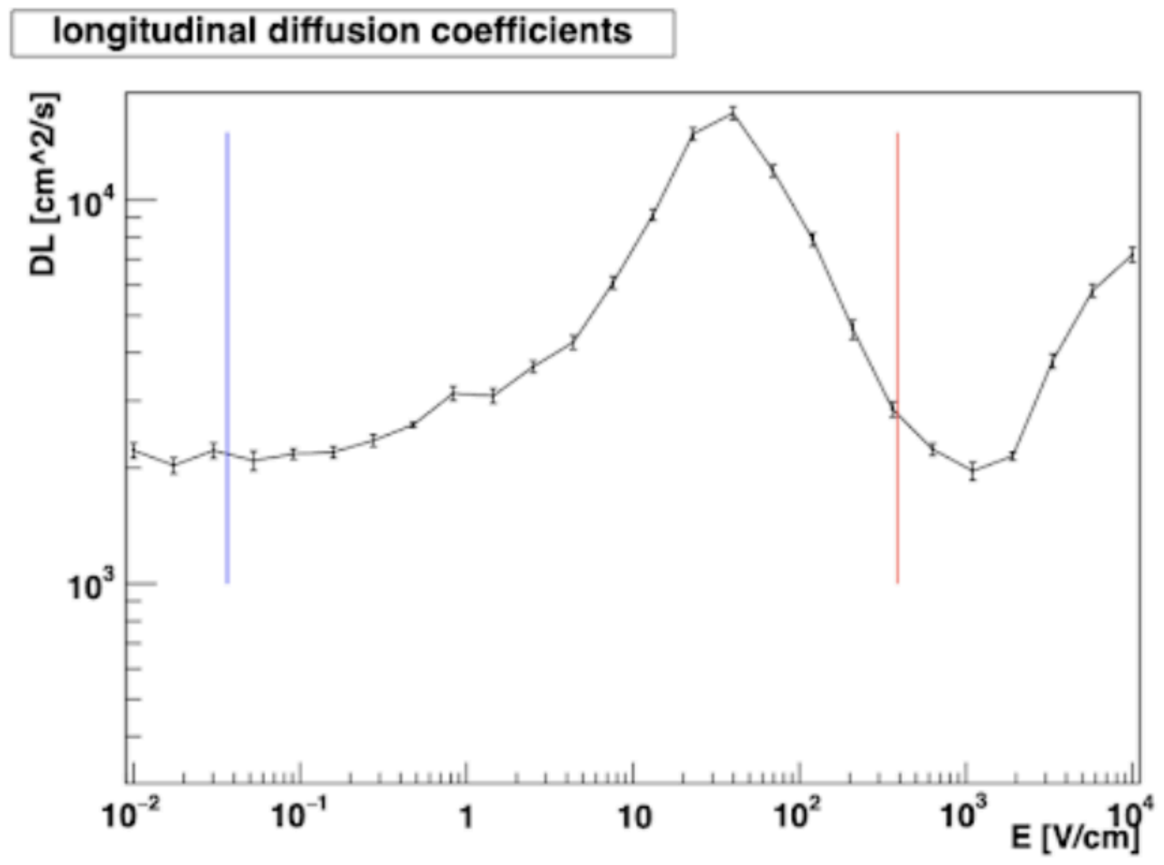
Rise time determined

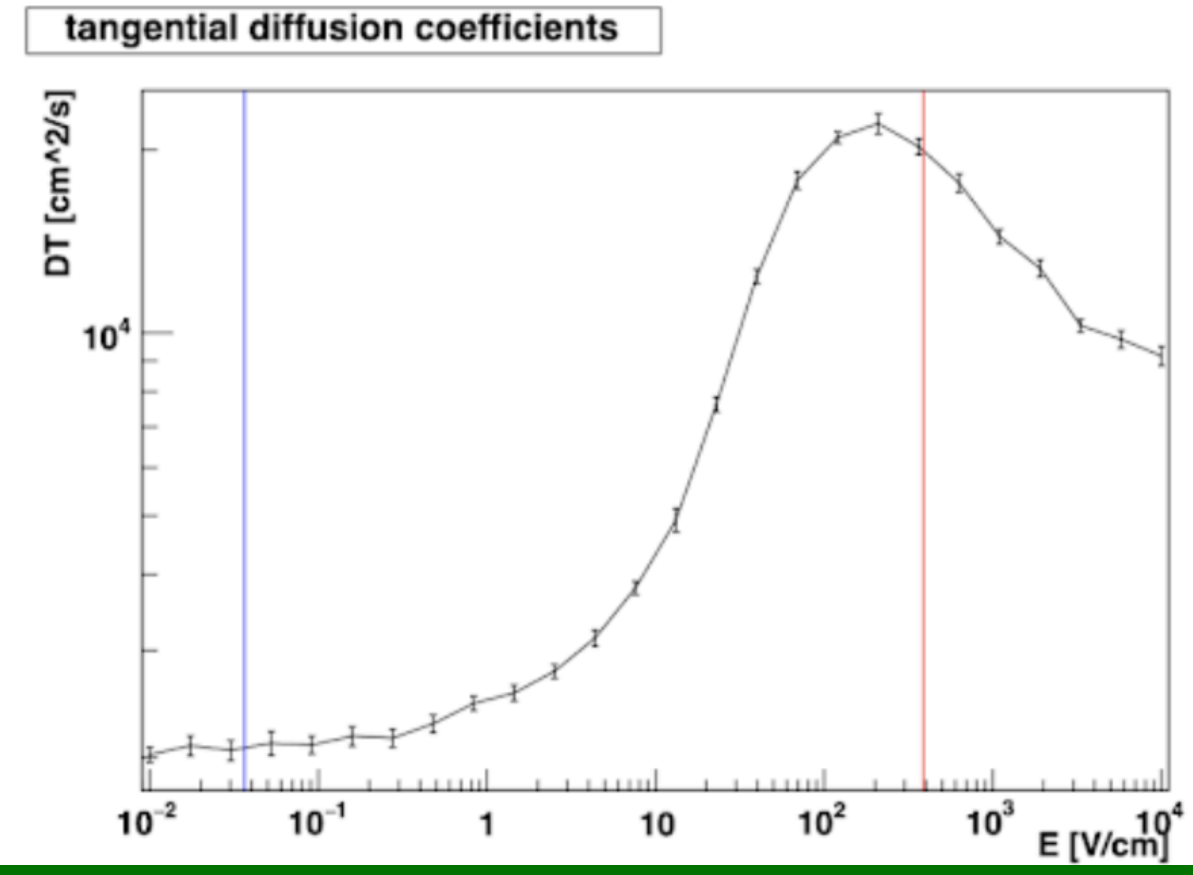
- **CERN simulation package: Magboltz:**
  - Output: drift parameters: drift velocities, longitudinal/ transverse diffusion coefficients
- **Monte Carlo Integration method to determine the drift time**

120A and 140 A laser drift time data compare with laser events drift time simulation without considering space charge



# SPC detector response modelling

Step1: Electric field simulation:
Finite element software COMSOL

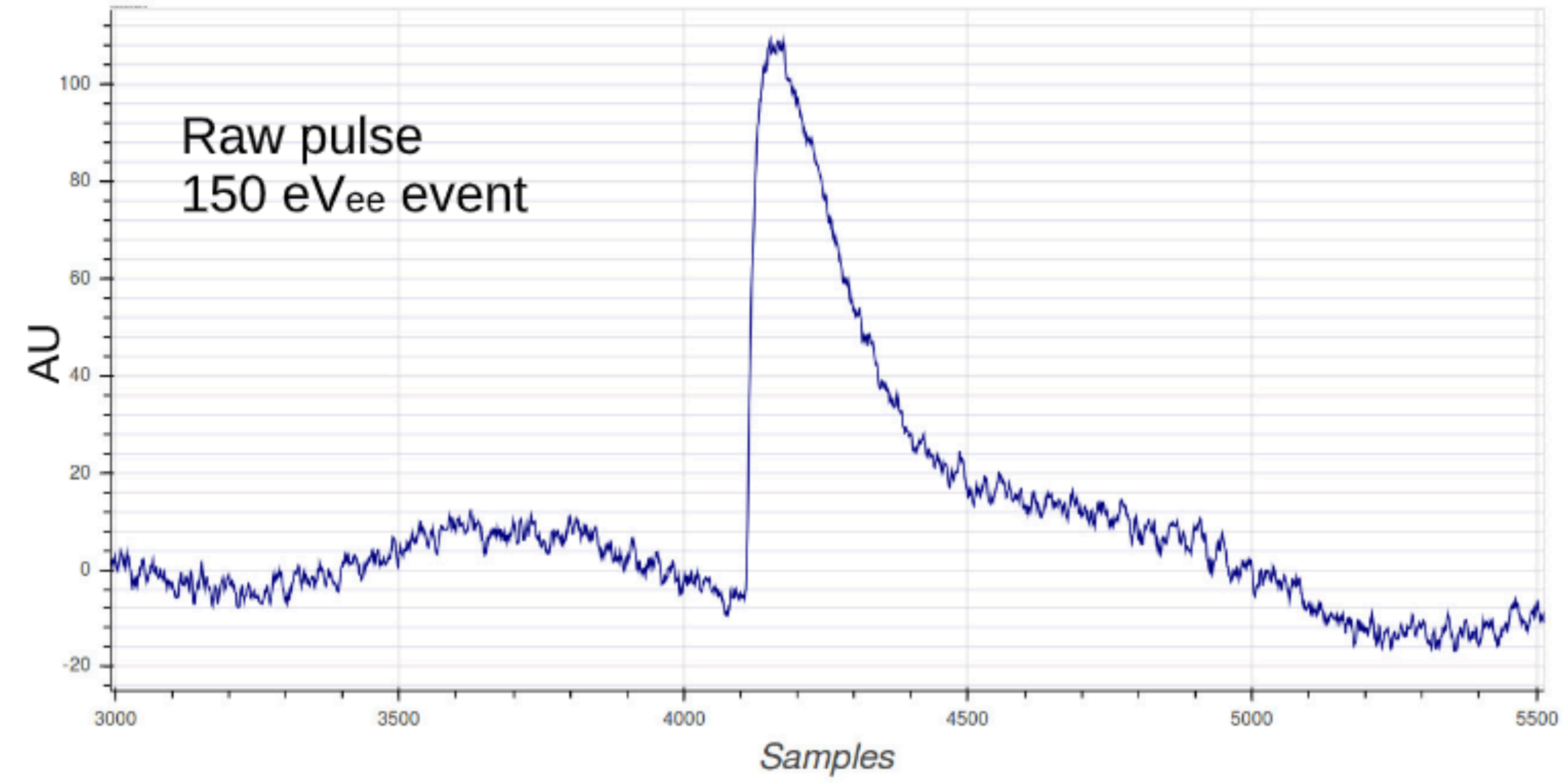
Step2: Primary ionization

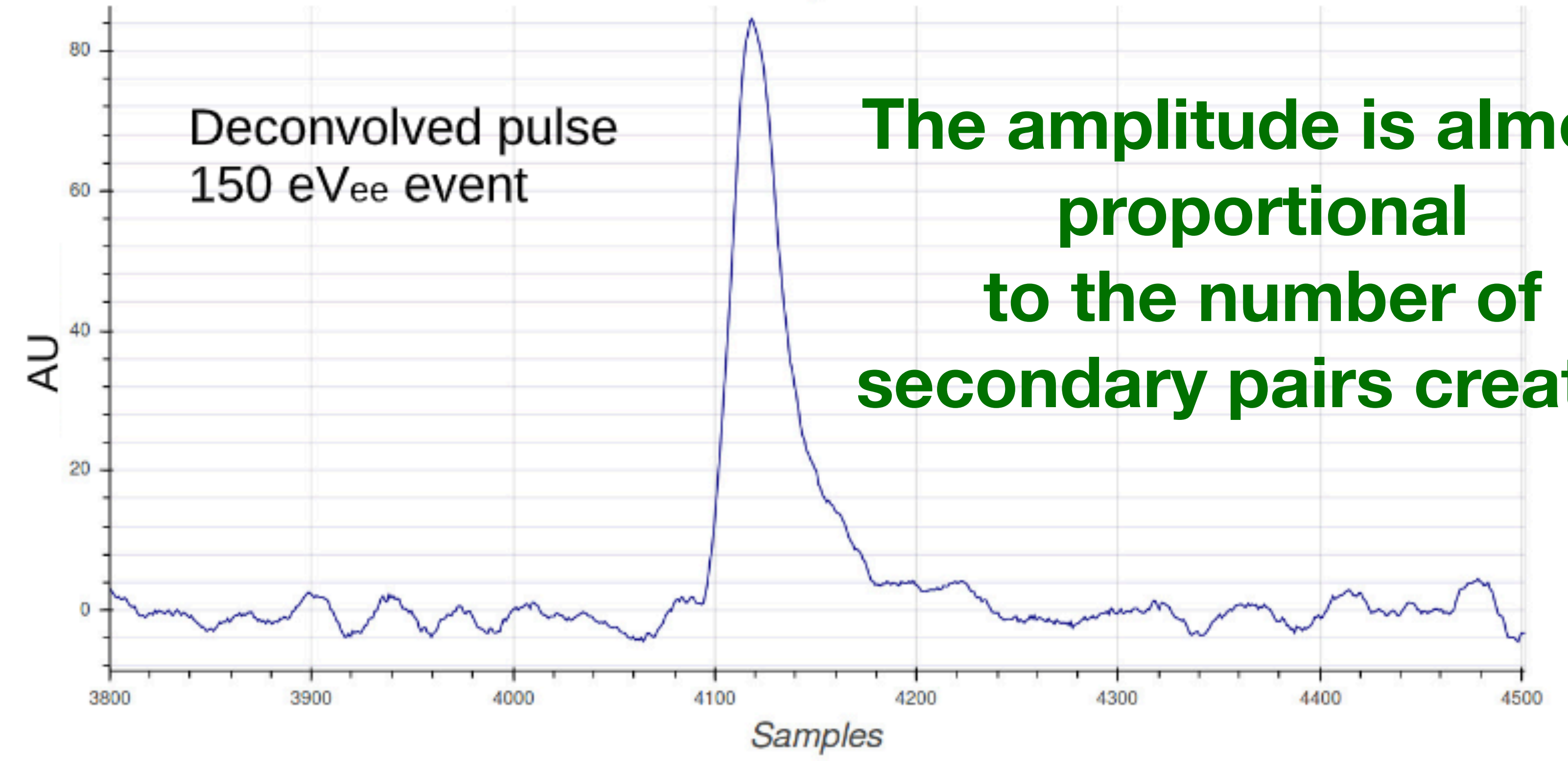
Step3: electron transportation

Electron drift time determined

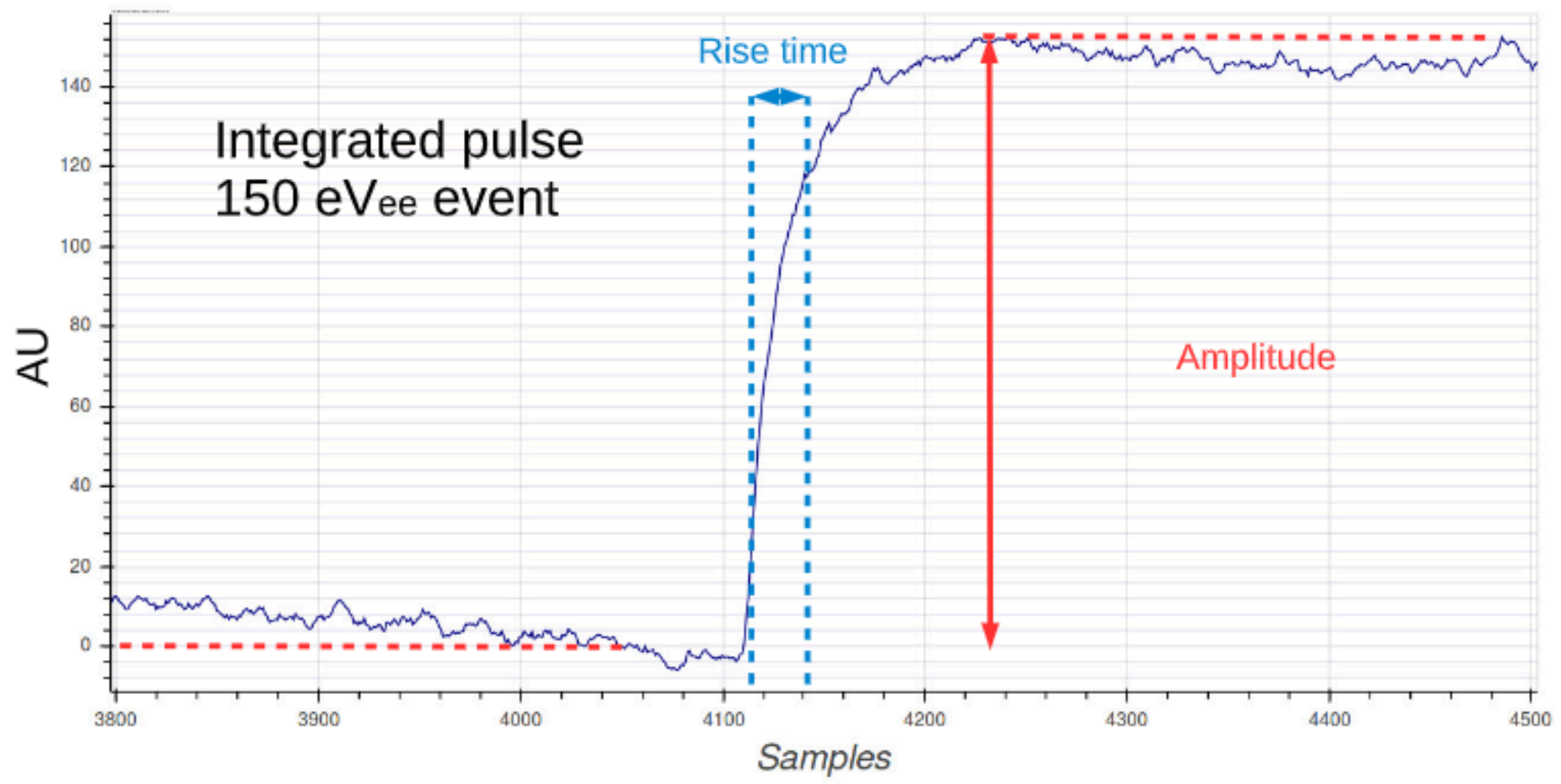
Step4: signal formation

Rise time determined




**The amplitude is almost proportional to the number of secondary pairs created**




- **Secondary ionization:**
  - PEs reaching high E field region will gain enough kinetic energy from collisions with gas molecules to ionize the gas and create secondary electron/ion pairs
  - Number of secondary ionizations can be parametrized by Polya distribution:

$$P\left(\frac{n}{\langle n\rangle}\right) = \frac{(1+\theta)^{(1+\theta)}}{\Gamma(1+\theta)}\left(\frac{n}{\langle n\rangle}\right)^{\theta}\exp\left[-(1+\theta)\frac{n}{\langle n\rangle}\right]$$

- **Rise time: time difference between 75% and 10% of the amplitude**

Step1: Electric field simulation: Finite element software COMSOL

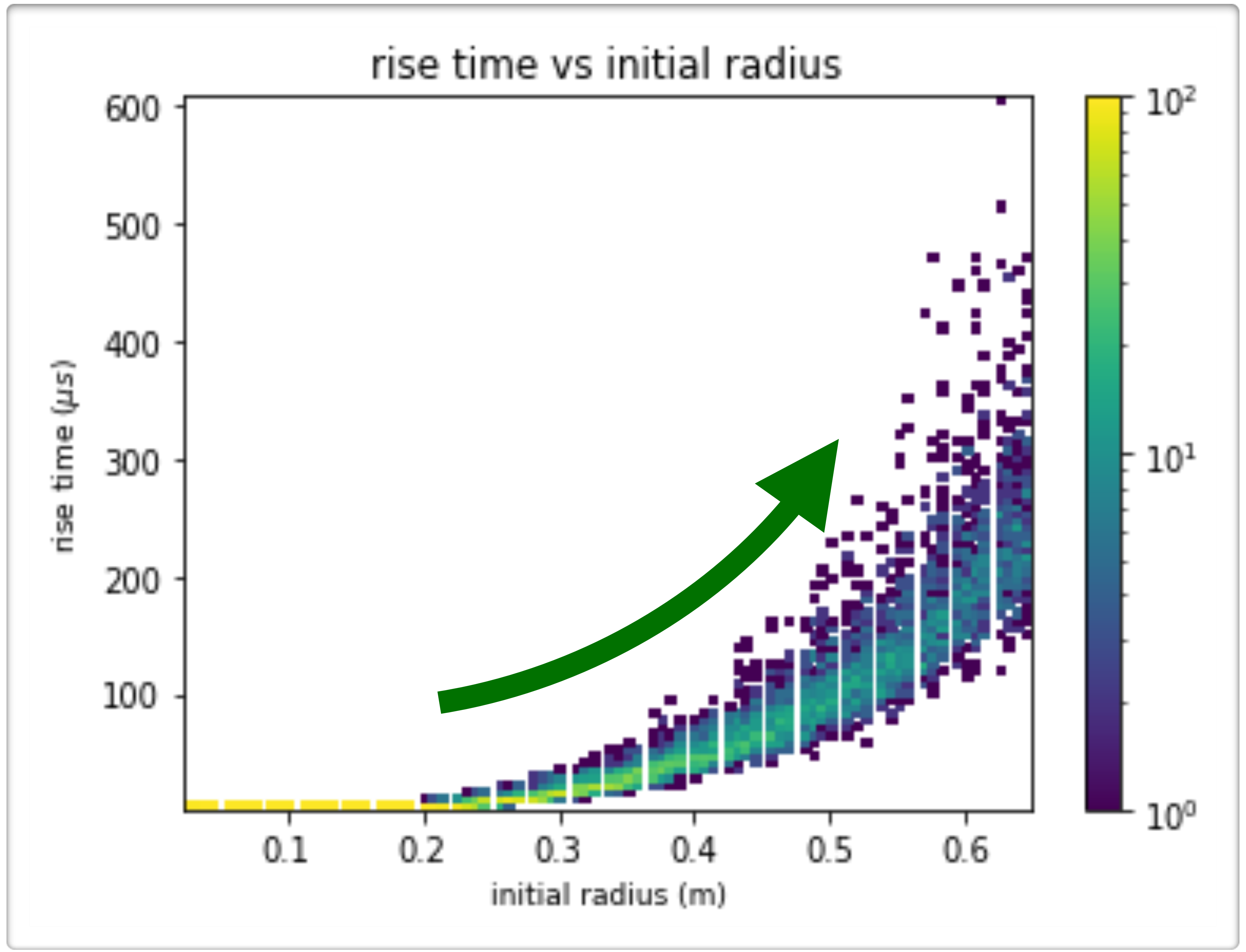
Step2: Primary ionization

Step3: electron transportation

Electron drift time determined

Step4: signal formation

Rise time determined

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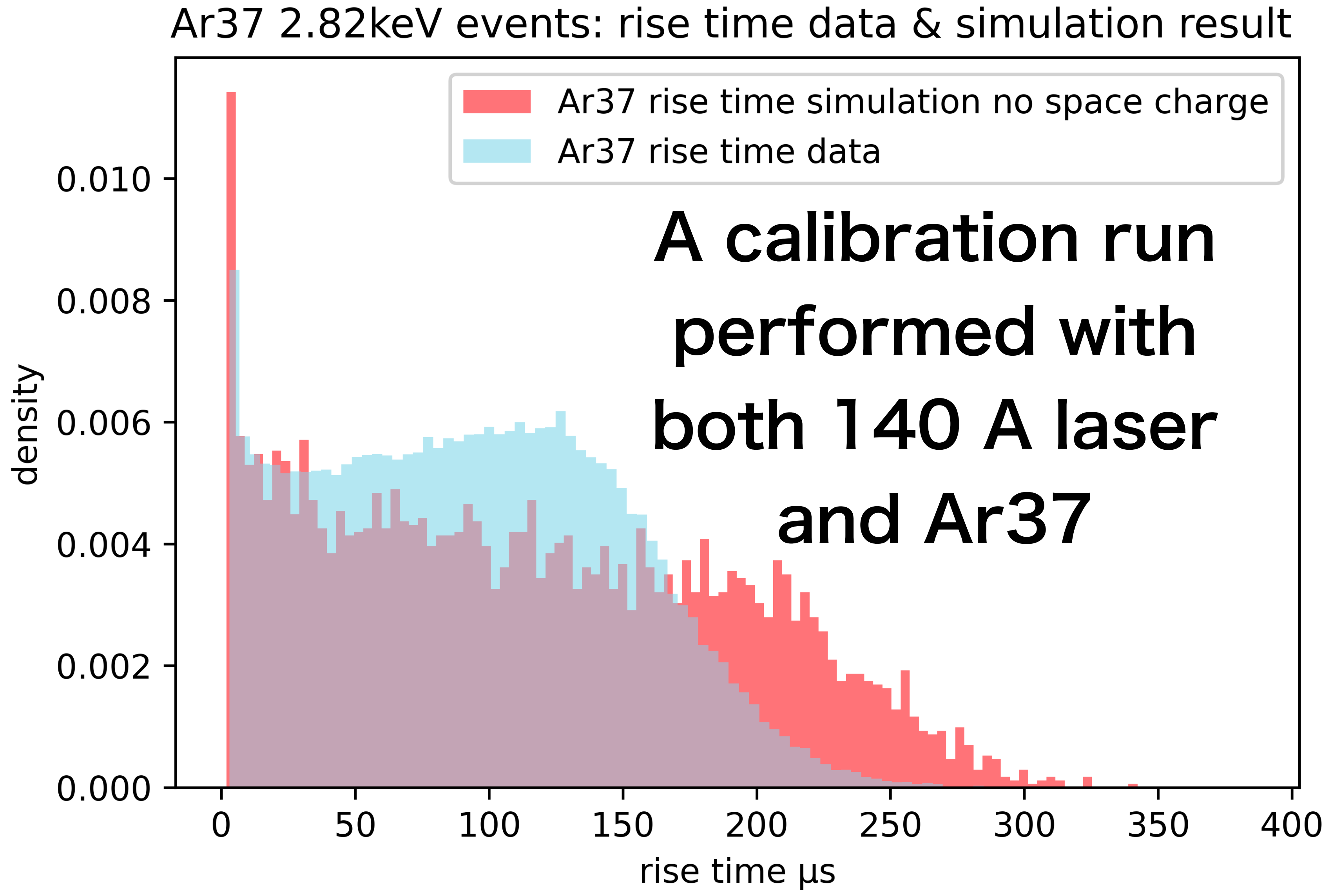
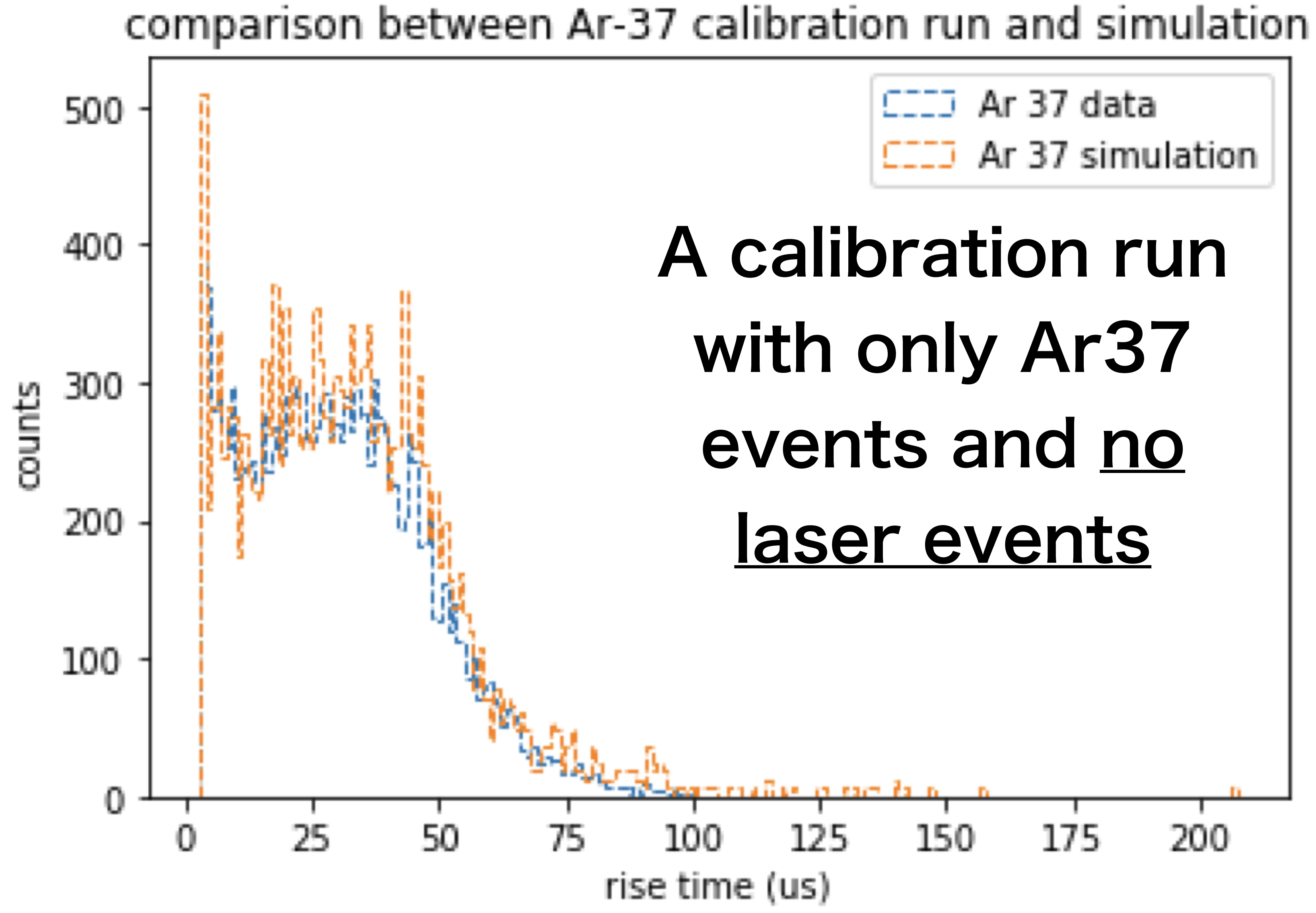
- **Rise time: time difference between 75% and 10% of the amplitude**
  - represents how much diffusion the charges undergo; Higher starting point results in more dispersion of charges
  - Discriminate bulk events and surface events

Ar37 events rise time simulation:
events uniformly distributed in sphere

Same method



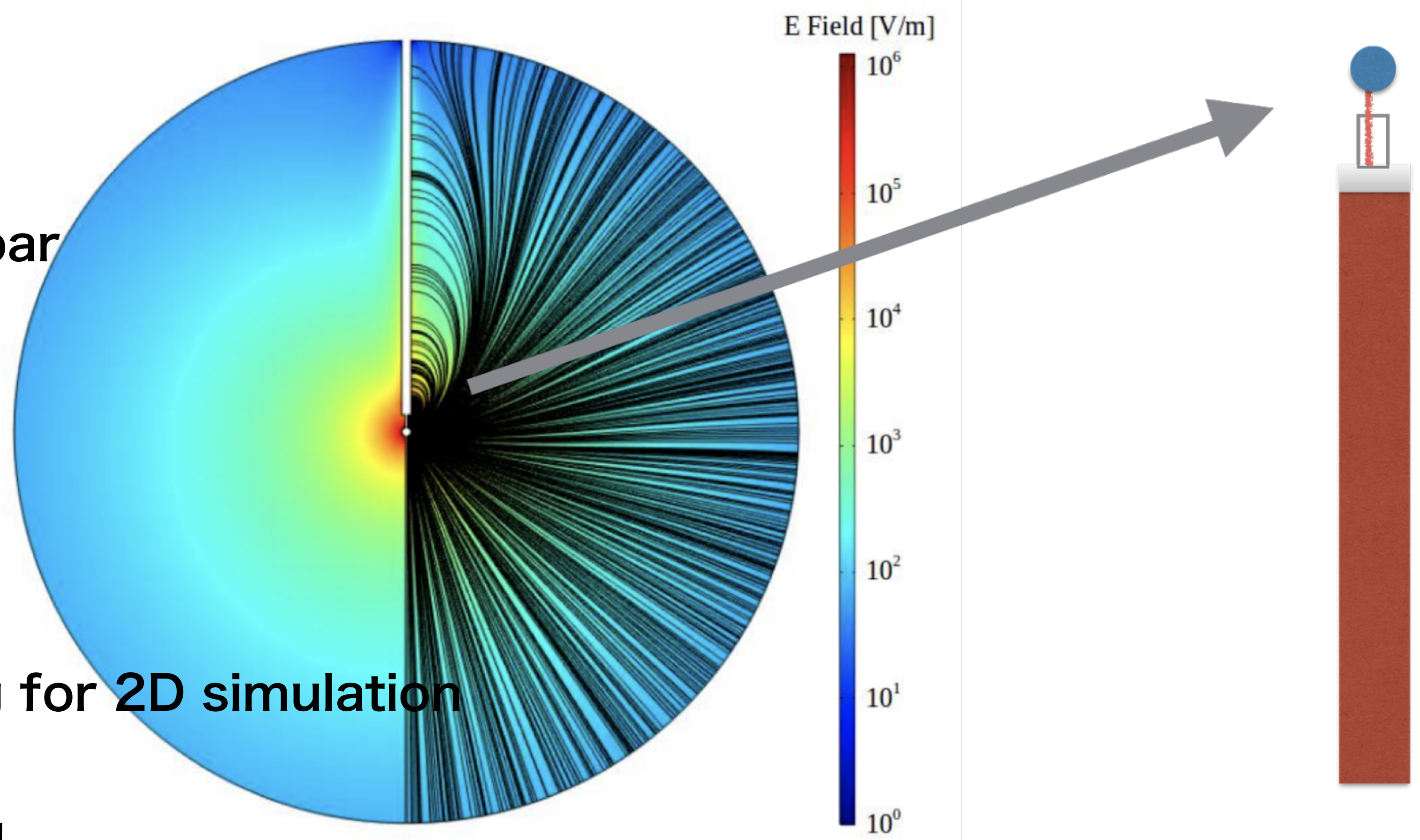




## Simulation for SNOGLOBE

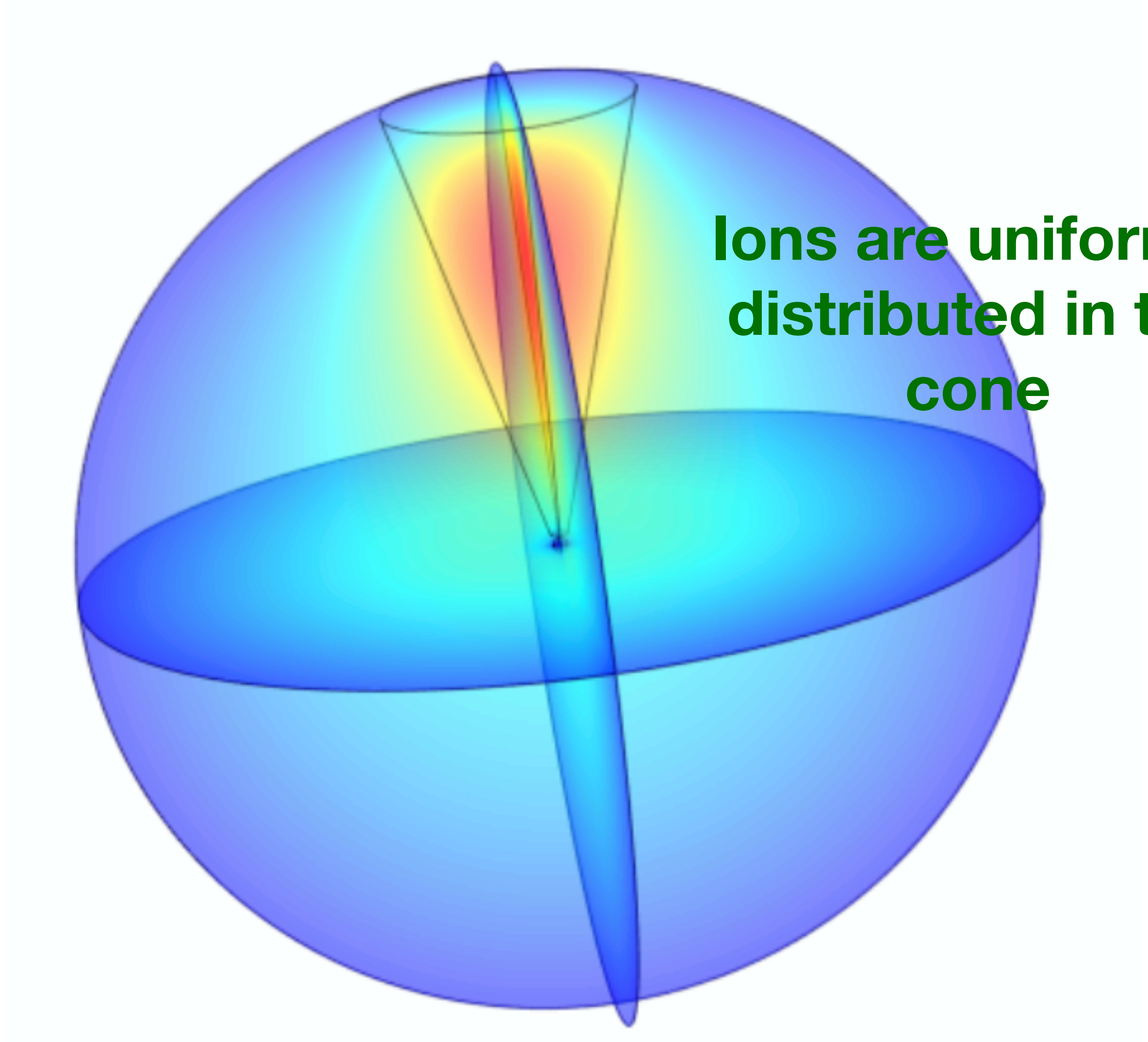
- Tuning the model used to model primary ionization or pulse shape doesn't improve the result;
- The amount of oxygen introduced to the detector is unknown, which can trap electrons and reduce the number of electrons that reach the sensor.
- The significant disagreement is most likely due to the secondary ions created during avalanche (especially from laser events), called space charge effect

## Simulation for SEDINE:

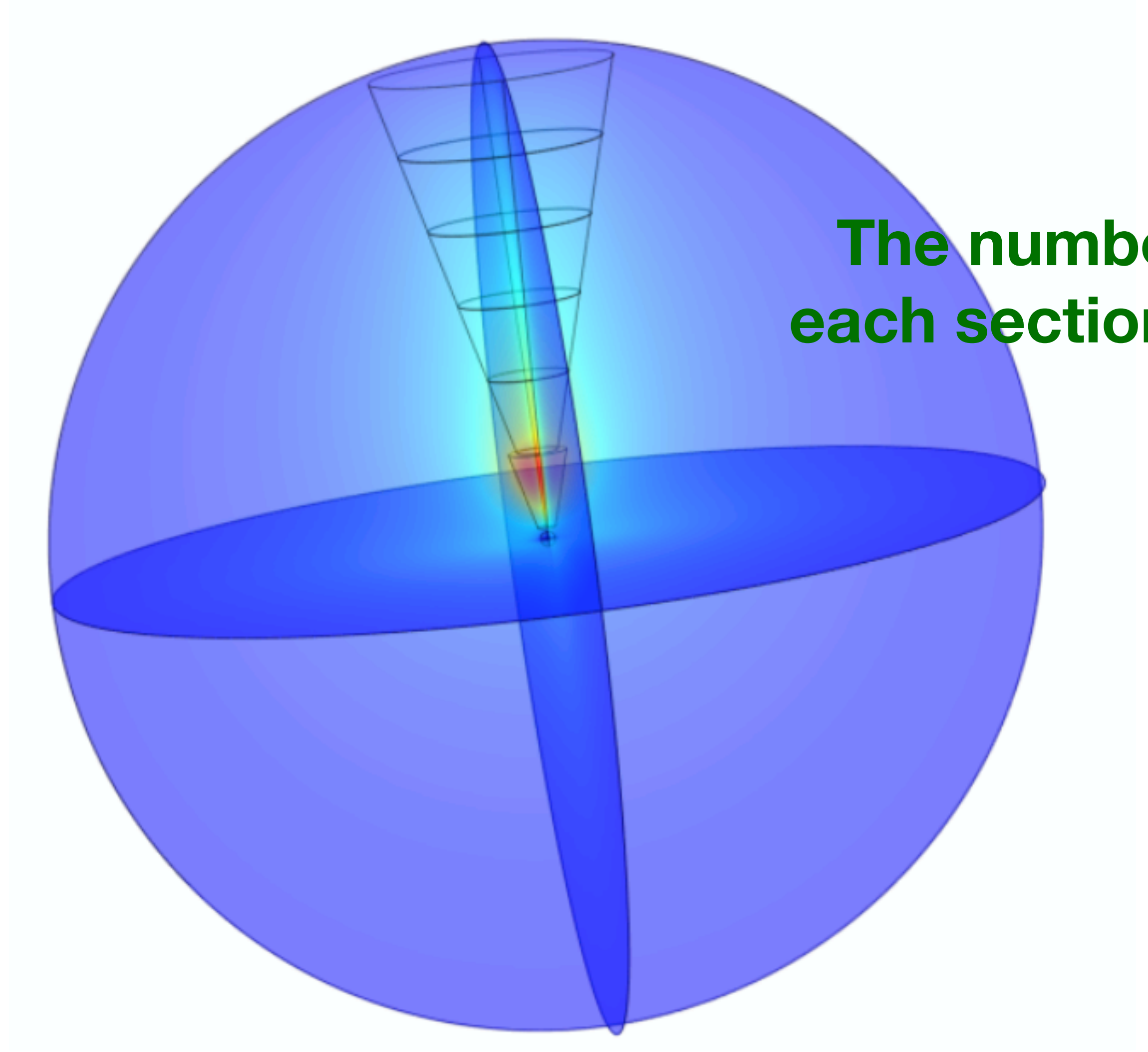
1. An SPC of 60cm diameter
2. 99.3% Ne + 0.7% $CH_4$ under 3.1 bar
3. Ar 37 at 2.8 keV
4. W value 28 eV
5. Simpler sensor geometry allowing for 2D simulation
6. Magboltz and COMSOL were used



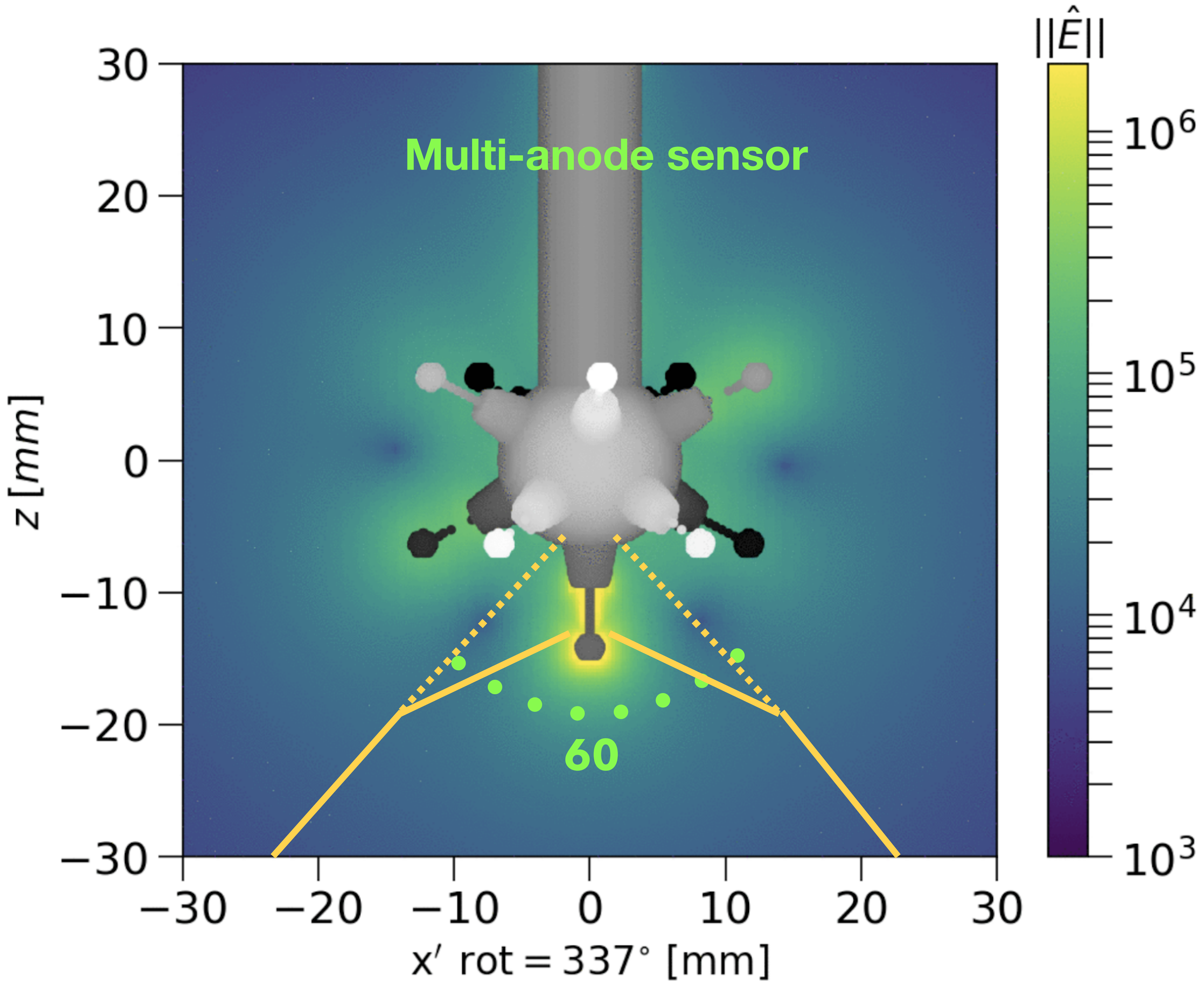
- COMSOL Efield simulation:
  - Specify the volume charge density for certain geometry
  - Geometry: Cone
  - Two different ways of distributing space charges (plots below)
  - Different simulations has been done for various open angle of the cone (10, 30, 60 degree), and various number of ions in the detector according to data

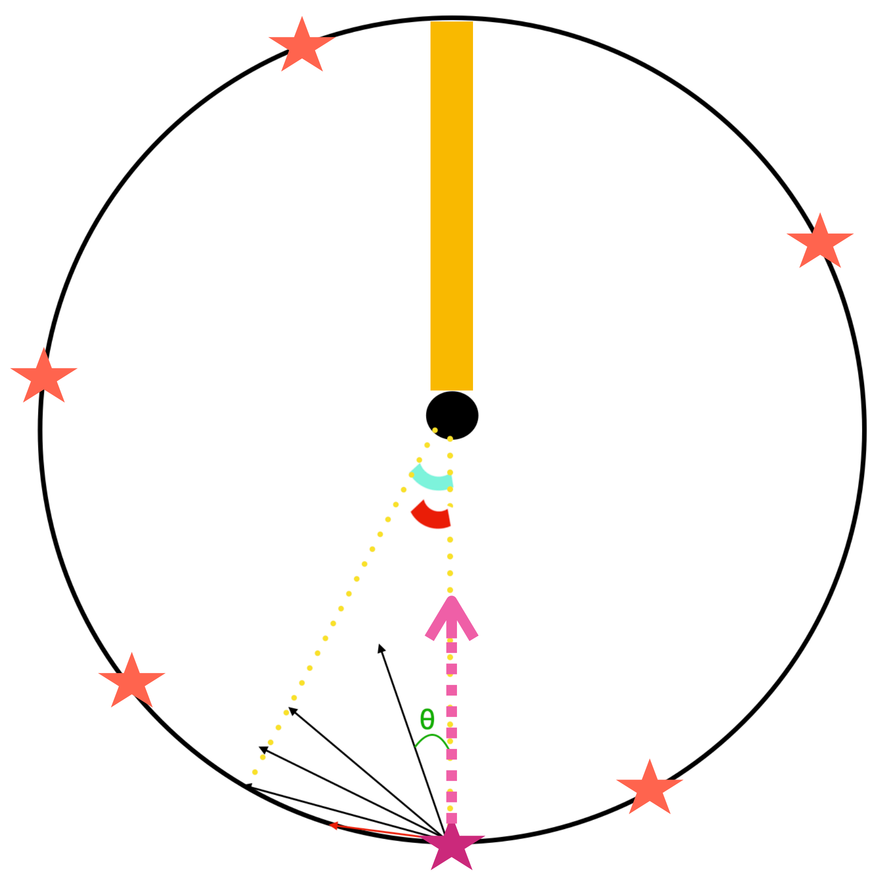


Ions are uniformly distributed in the cone



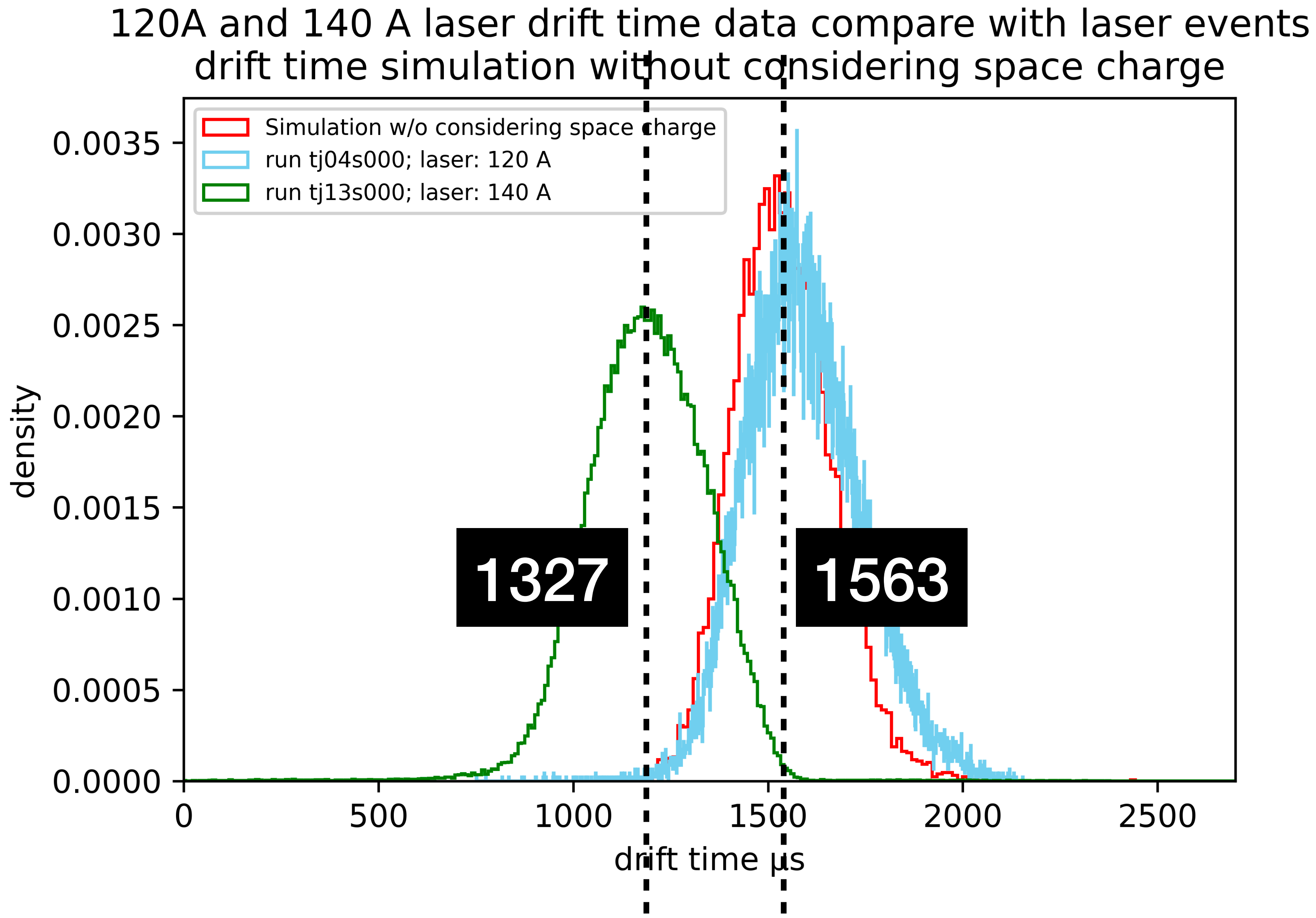
The number of ions in each section is the same



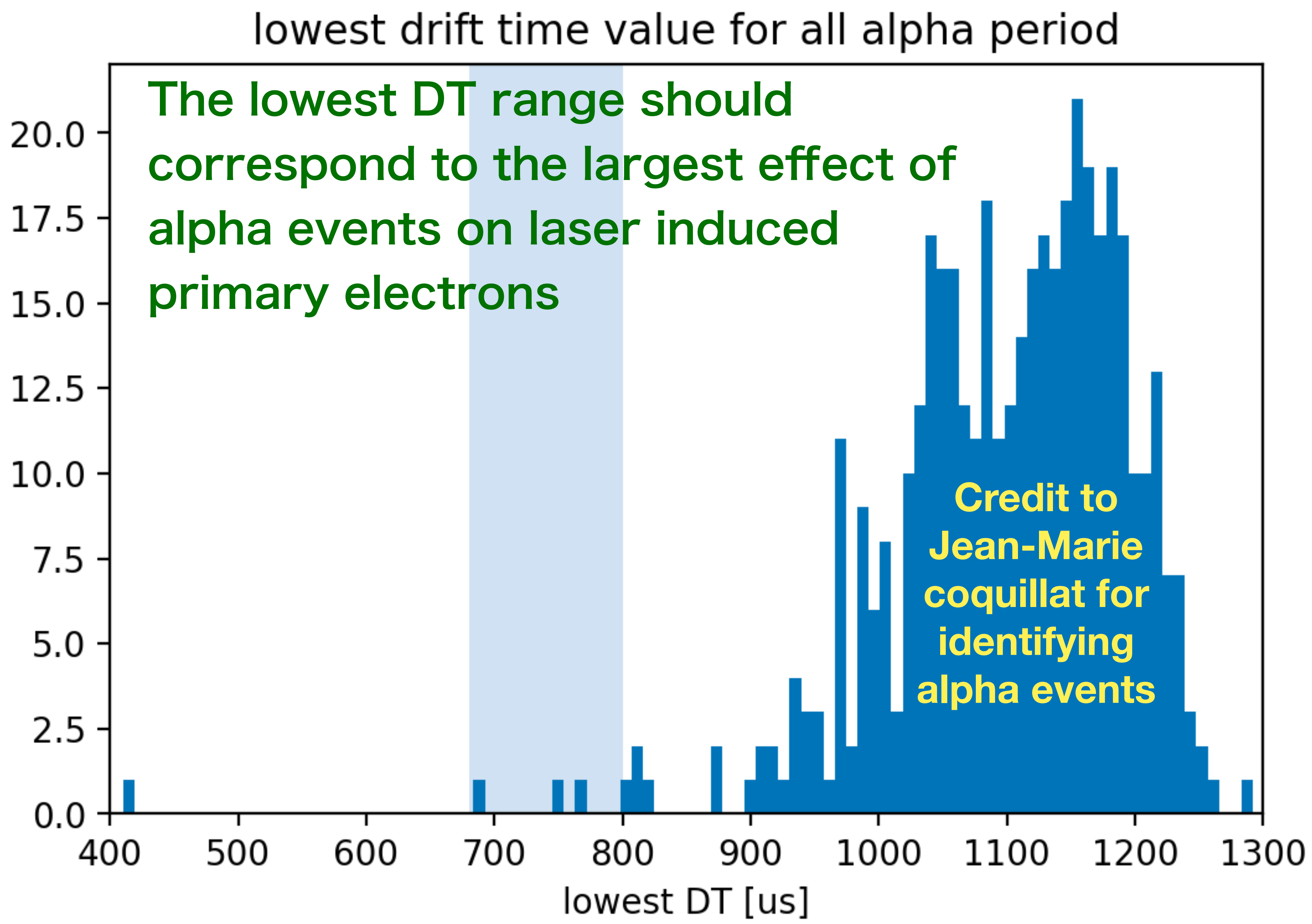




Alpha events and laser events originating from very south point and pointing towards the centre will have the largest space charge effect

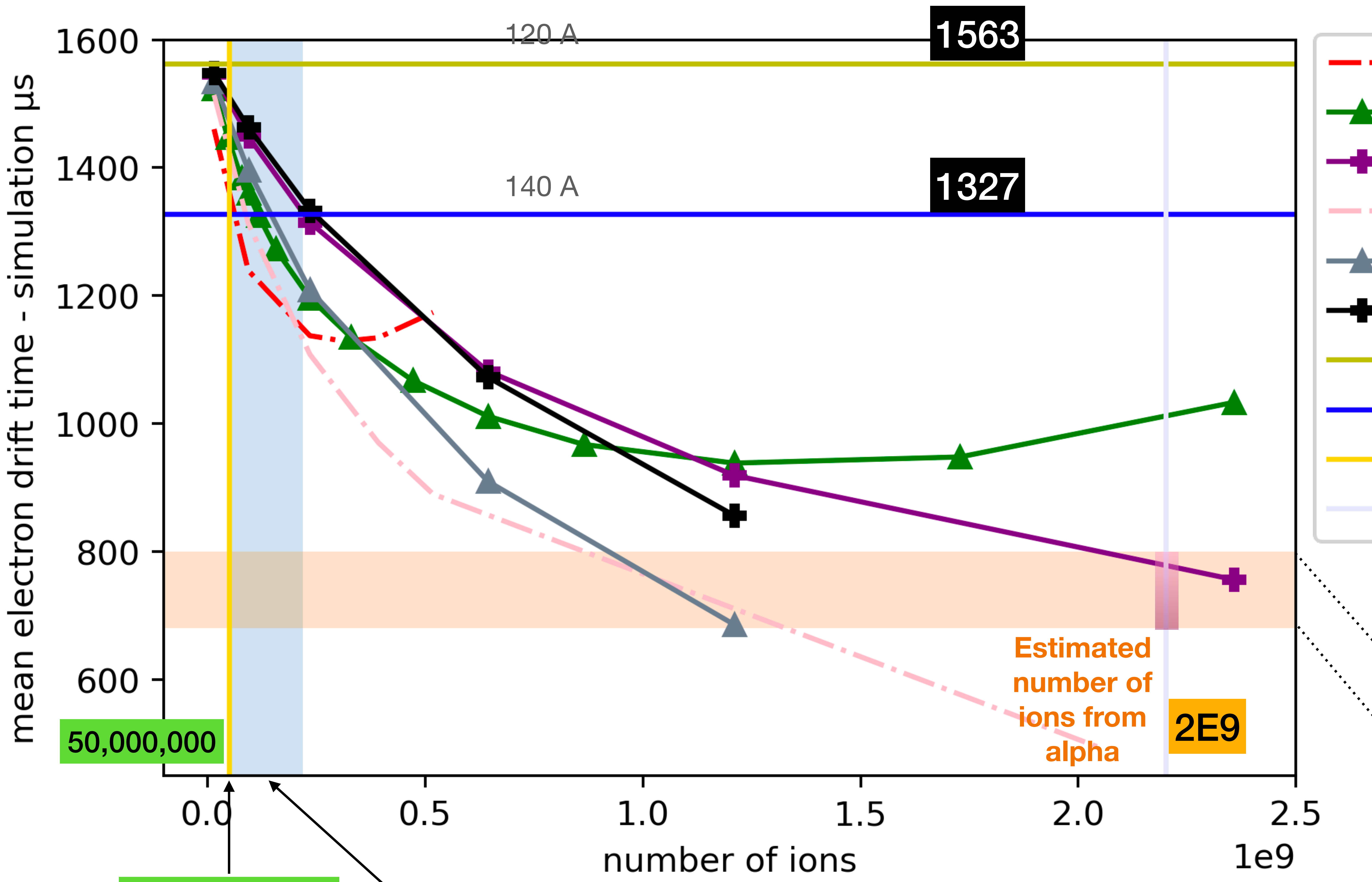
- **Ion drifting simulation:**
  - Ion drift time: 5-7 s
- **Laser events:**
  - laser event rate is known and number of ions created during avalanche can be determined by pulse's amplitude
  - 140 A laser events: **24,000,000 - 50,000,000** ions accumulated in detector




- **Alpha events**
  - Maximally 5.3 MeV deposited in the detector
  - W value: 28 eV
  - Maximally ~ **2E9** number of ions created per alpha event
  - Low event rate, no charge accumulation

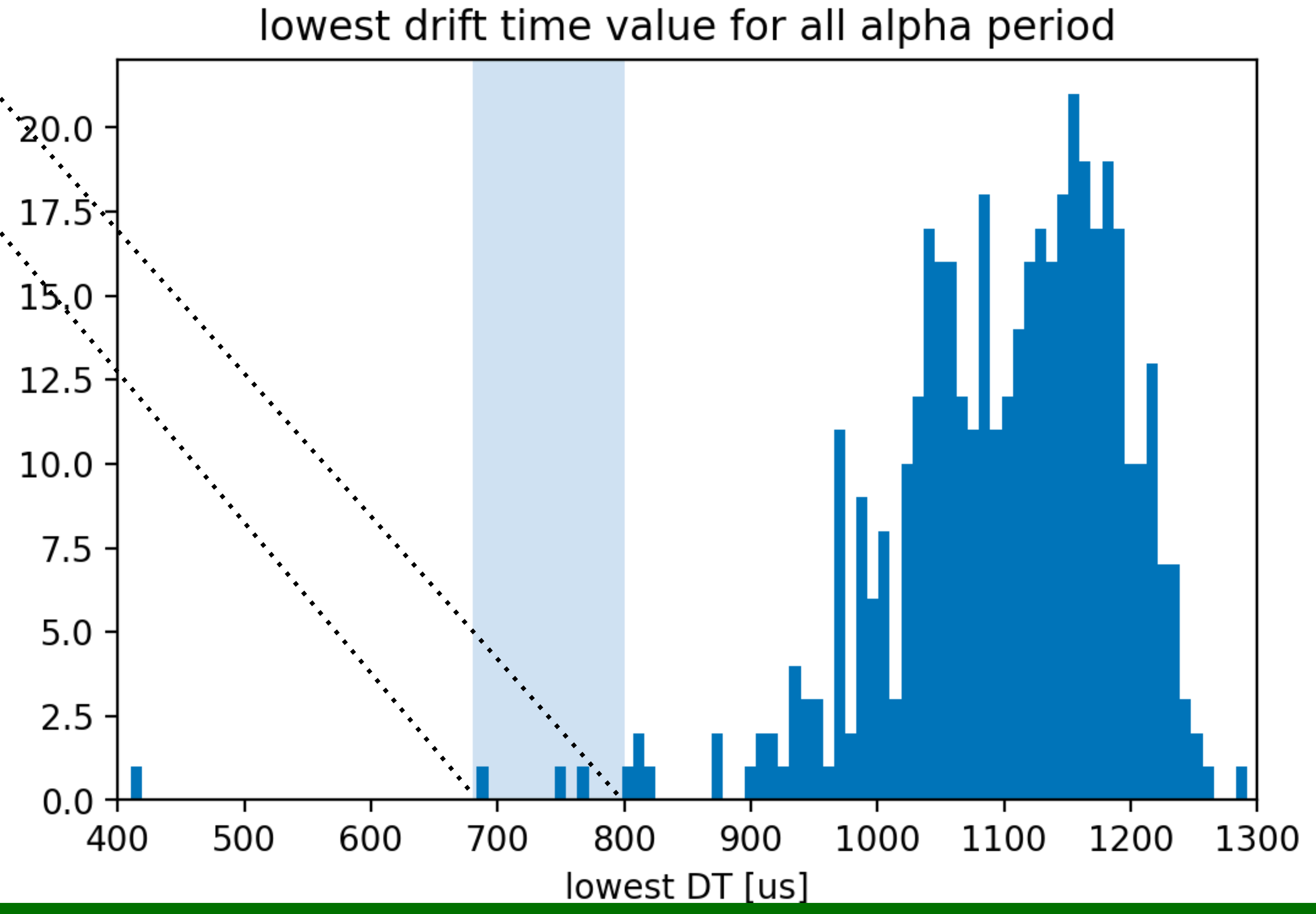


# Model agreement with observed space charge number



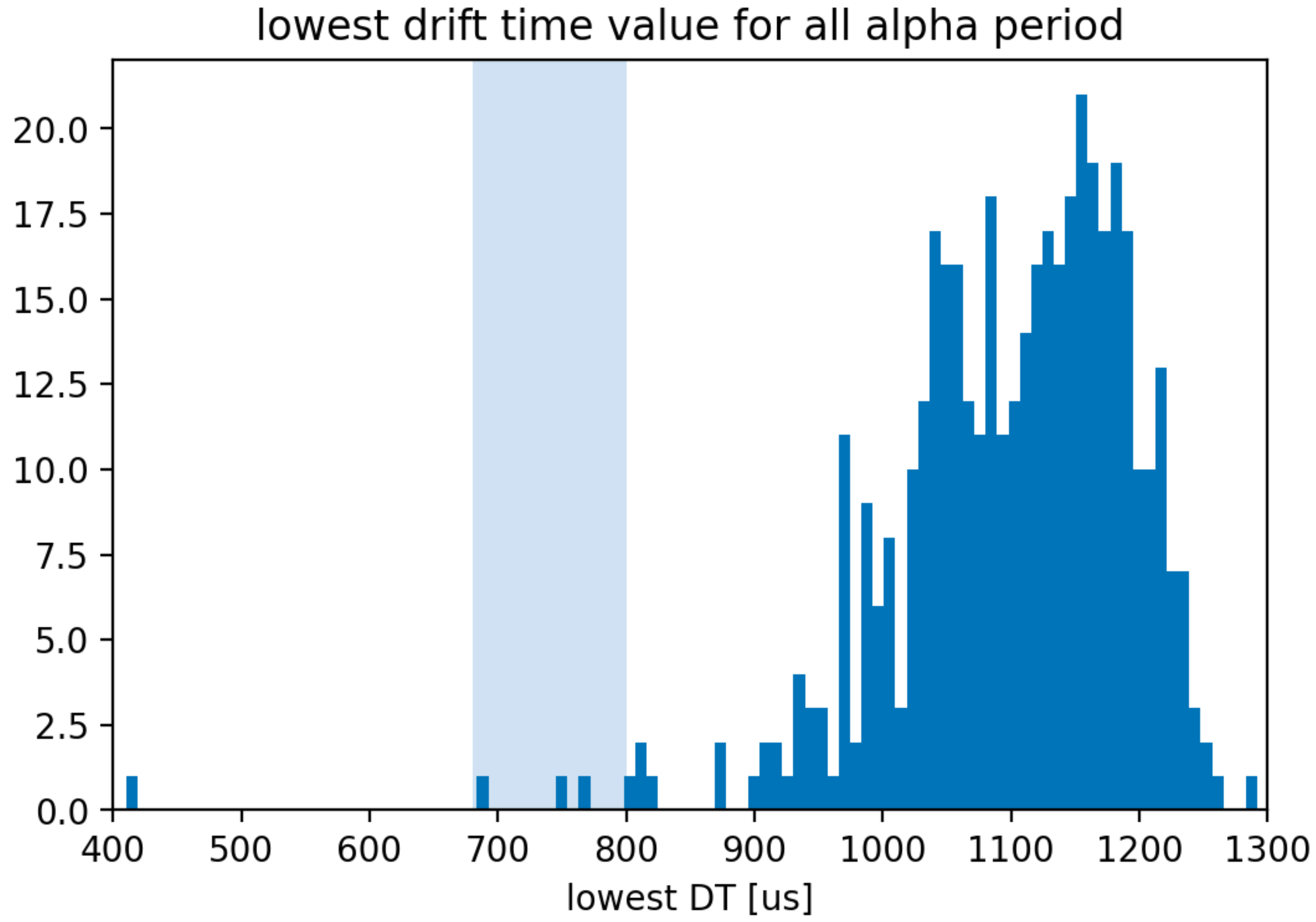

Upper limit of ions observed from 140 A laser data

Num of ions expected from all considered configurations' simulation



## Simulation efforts

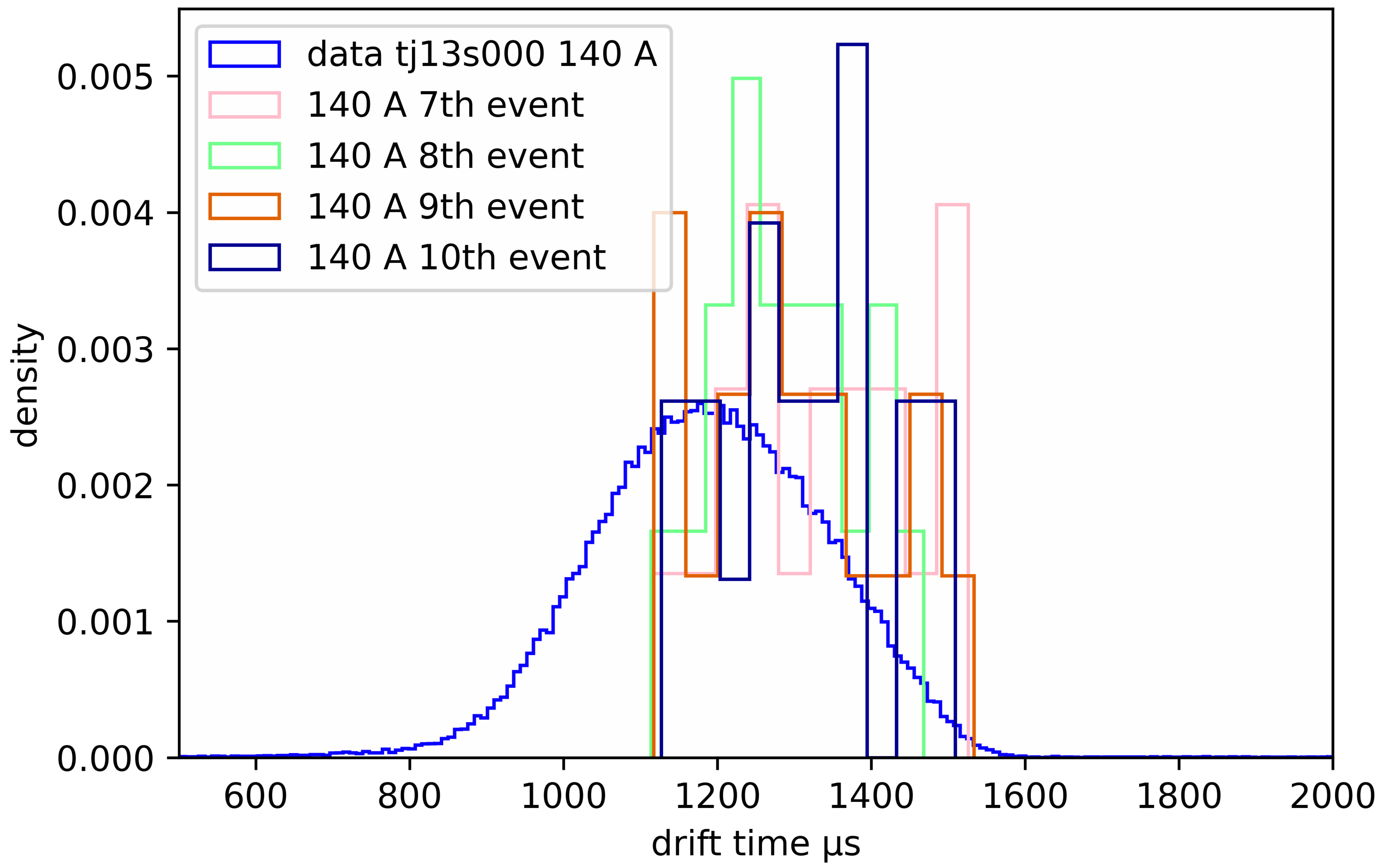
- Avalanche simulation for single primary electron using Garfield++
  - Study the exact spatial and temporal distribution of ions
  - Study how space charge effect vary from event to event
  - Explore how space charges spread with single ball sensor and multi-anode sensor

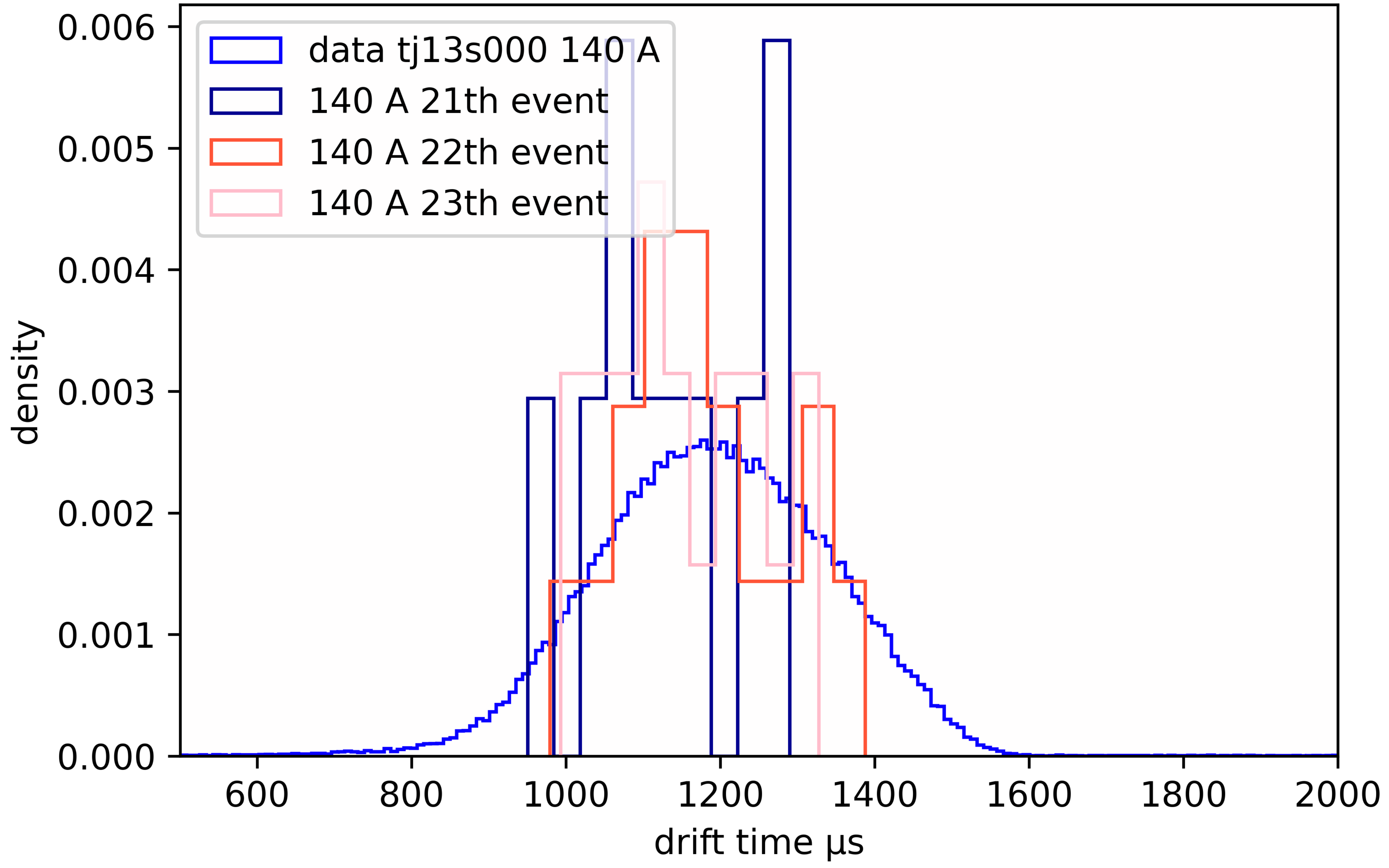



## Experimental efforts

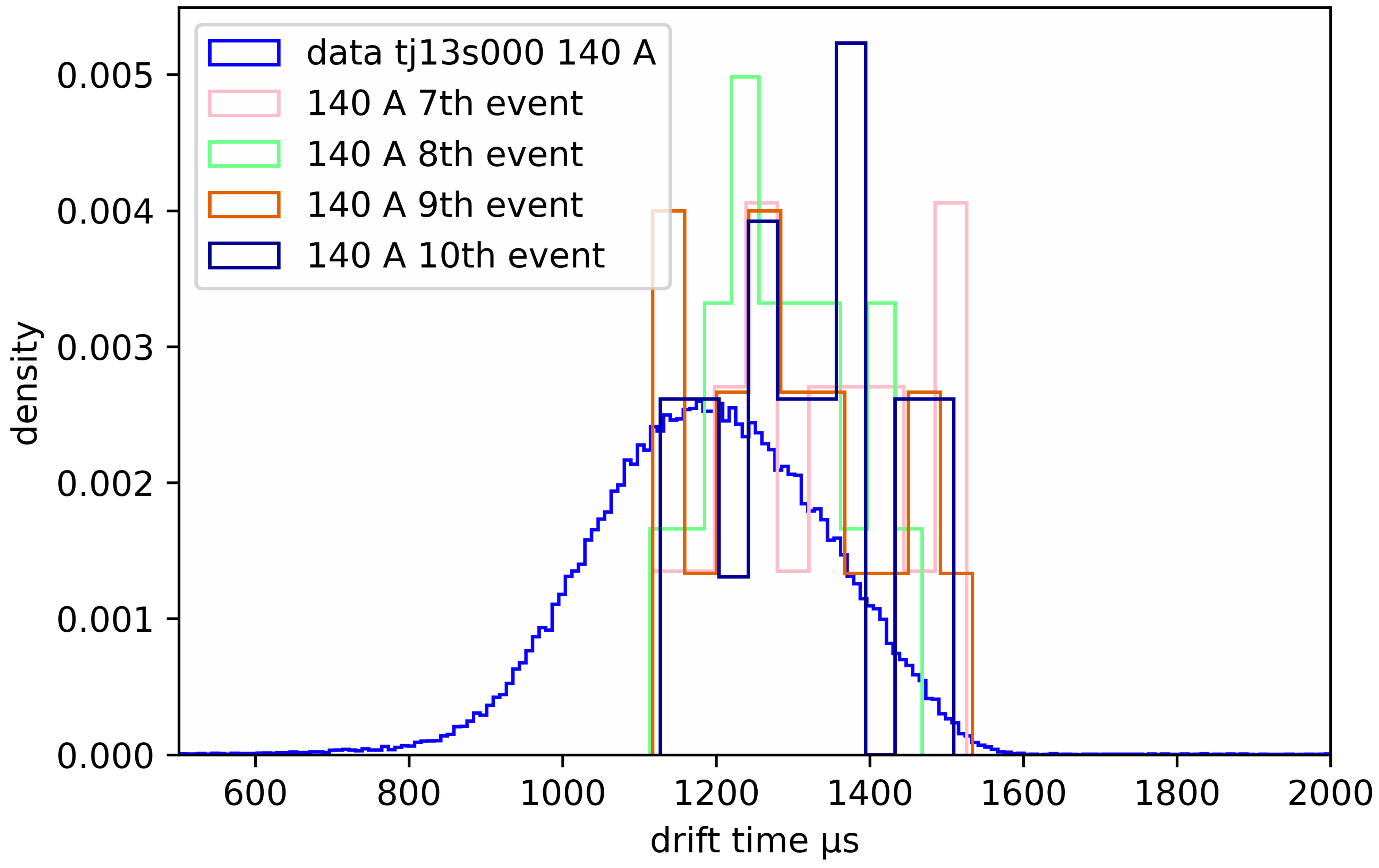
- More dedicated physics runs will be taken (U of A)
  - Use Ar37 source only without triggering laser (rise time simulation)
  - Take more runs with various laser intensities
  - Vary the sensor voltage
  - Collect drift time data immediately after triggering the laser for studying space charge accumulation process
  - Choose appropriate electronics so alpha events will not be saturated
  - Longer physics run for collecting more alpha events, compare with simulated drift time drop during alpha events

# Extra slides


data tj13s000 140 A
140 A 7th event
140 A 8th event
140 A 9th event
140 A 10th event
density
0.000
0.001
0.002
0.003
0.004
0.005
600
800
1000
1200
1400
1600
1800
2000
drift time μs


data tj13s000 140 A
140 A 21th event
140 A 22th event
140 A 23th event
density
0.000
0.001
0.002
0.003
0.004
0.005
0.006
600
800
1000
1200
1400
1600
1800
2000
drift time µs

- Space charge effect vary event by event
- Avalanche simulation: space charge spatial distribution vary from event to event

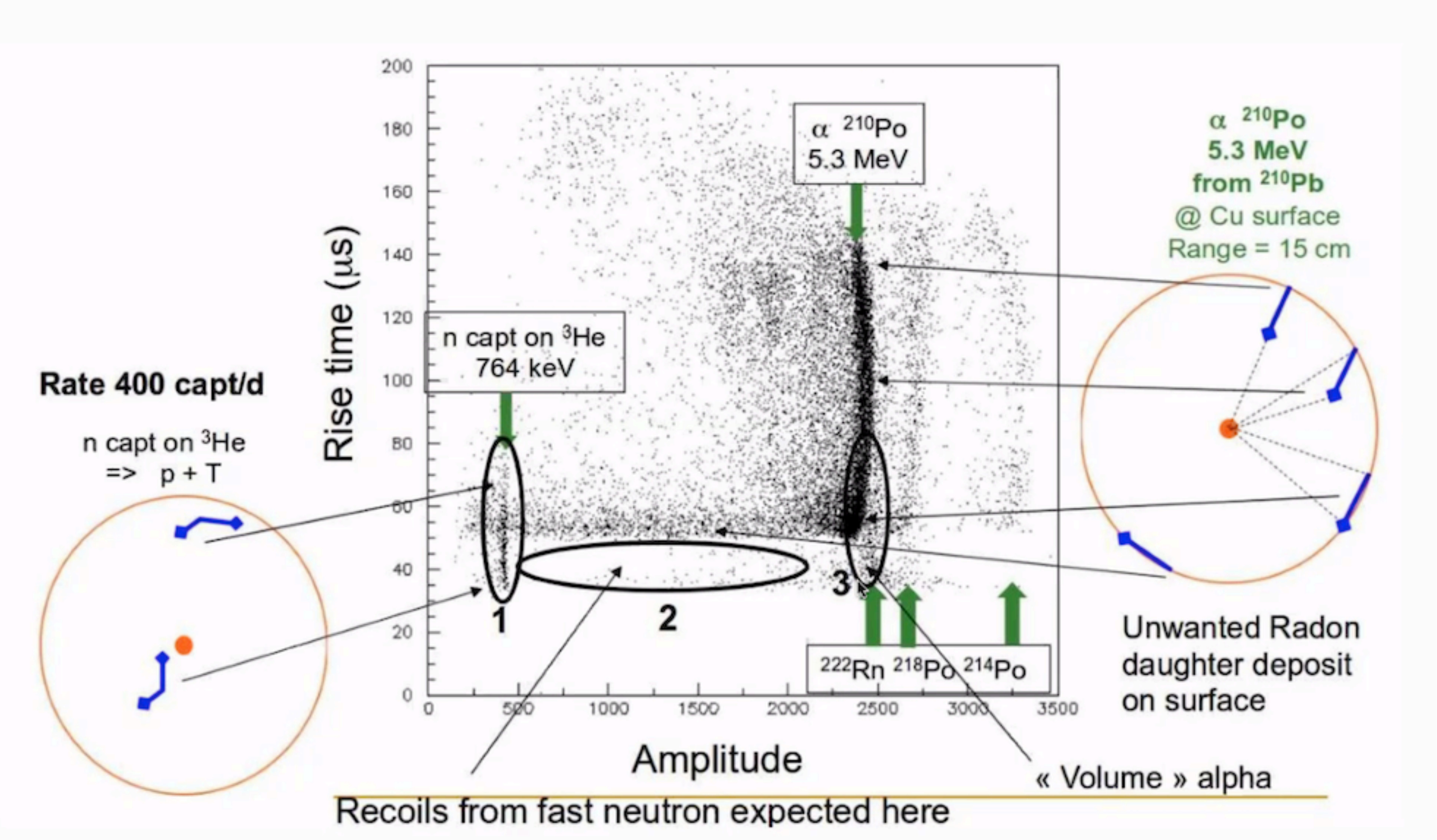


Space charges due to laser events
&
Introduce why we study alpha events other than laser events

# Space charges approximation

- Updated mean gain: ~70 ADU, 170 pairs/ADU
  - ~63.1 ADU for tj13s000
  - Approximate the number of space charges induced by alphas
  - Estimate the number of space charges induced by laser events observed by sensor

- 5.3 MeV alpha events:
  - W value 28 eV
  - ~2E9 number of ions created per alpha event
- the number of ions existed in the detector induced by laser events (140 A tj13s000) is approximately 24,000,000 - 50,000,000 if we agree that the ion drift time is ~5-7s



Rate 400 capt/d
n capt on ³He
=> p + T
n capt on ³He
764 keV
α ²¹⁰Po
5.3 MeV
α ²¹⁰Po
5.3 MeV
from ²¹⁰Pb
@ Cu surface
Range = 15 cm
Rise time (μs)
Amplitude
1
2
3
²²²Rn ²¹⁸Po ²¹⁴Po
Unwanted Radon daughter deposit on surface
« Volume » alpha
Recoils from fast neutron expected here

Step1: Electric field simulation:
Finite element software COMSOL

Step2: Primary ionization
(Ar37 Events)

Step3: electron transportation

Electron drift time determined

Step4: signal formation

Rise time determined

- **The Conway Maxwell - Poisson (COM-Poisson) distribution:**

$$P(x|\lambda,\nu) = \frac{\lambda^x}{(x!)^\nu Z(\lambda,\nu)}$$

$$Z(\lambda,\nu) = \sum_{j=0}^{\infty} \frac{\lambda^j}{(j!)^\nu} \quad \lambda \in \{\mathbb{R} > 0\}, \quad \nu \in \{\mathbb{R} \geq 0\}$$

- **The assumption that the number of primary electrons produced follows poisson distribution doesn't significantly affect simulation result:**

A. Expectation value is a function of deposited energy:

$$\mu = \frac{E}{W(E)}$$

B. W is the mean energy needed to create electron/ion pair in gaseous detectors.

C. W values being measured in pure CH4 under 135 mbar is 31.2 eV for 2.8keV X-rays

D. At 2.8 keV, the mean number of primary electrons being ionized is ~ **90**

- **Initial kinetic energy is not high enough to further ionize gas molecules before entering high E field region**

Step1: Electric field simulation: Finite element software COMSOL

Step2: Primary ionization

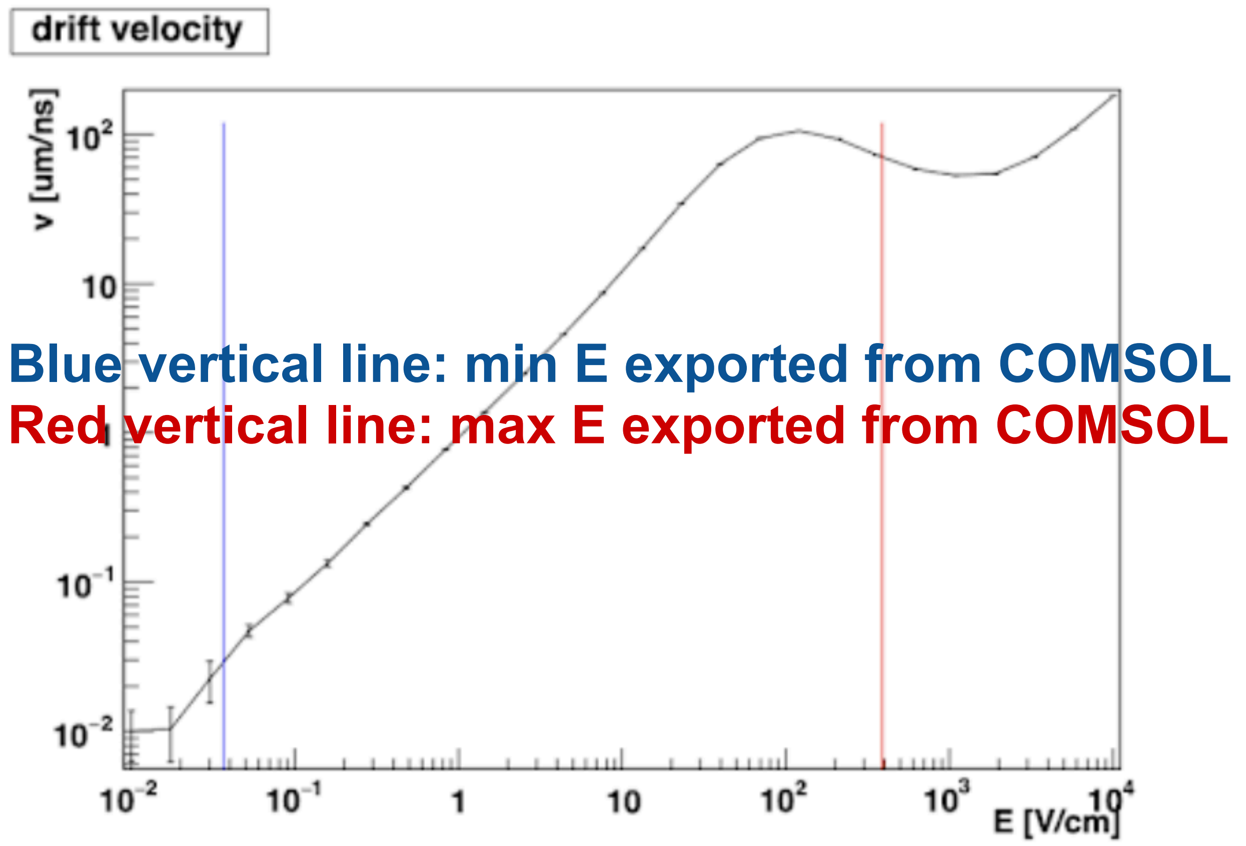
Step3: electron transportation

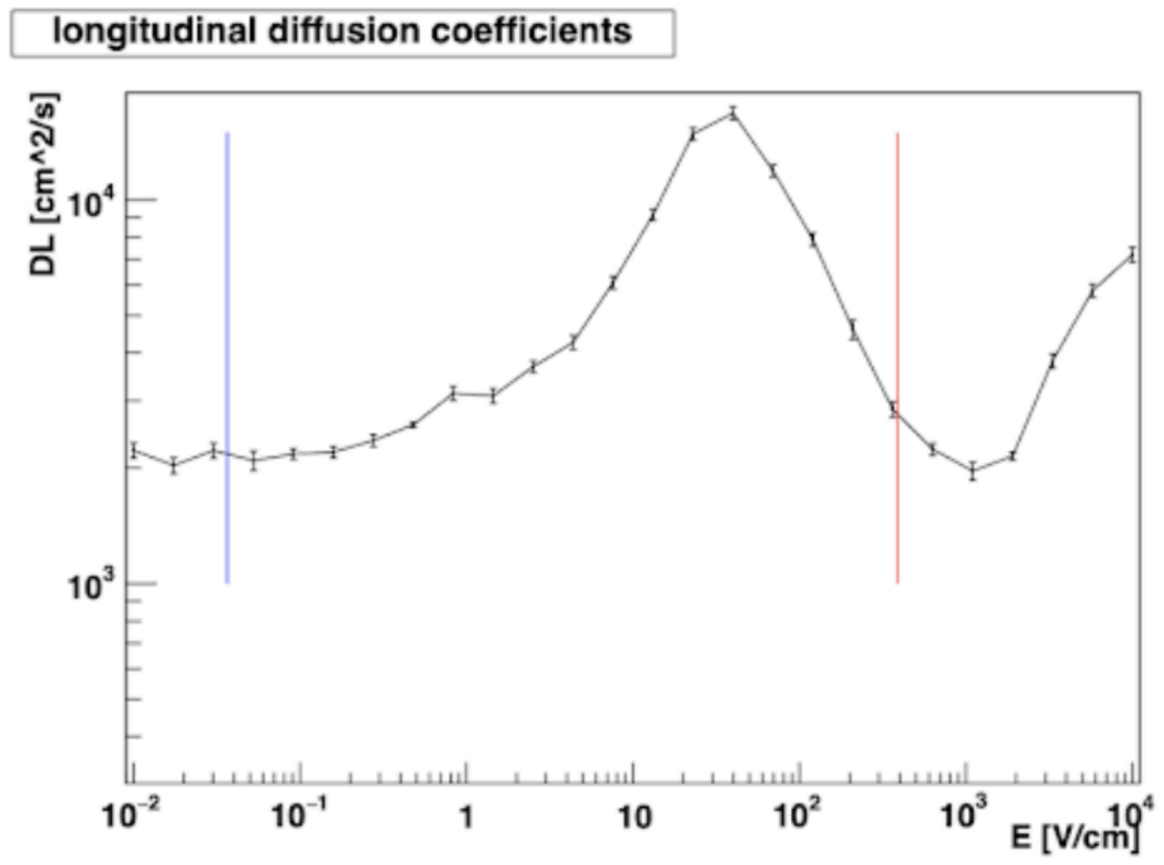
Electron drift time determined

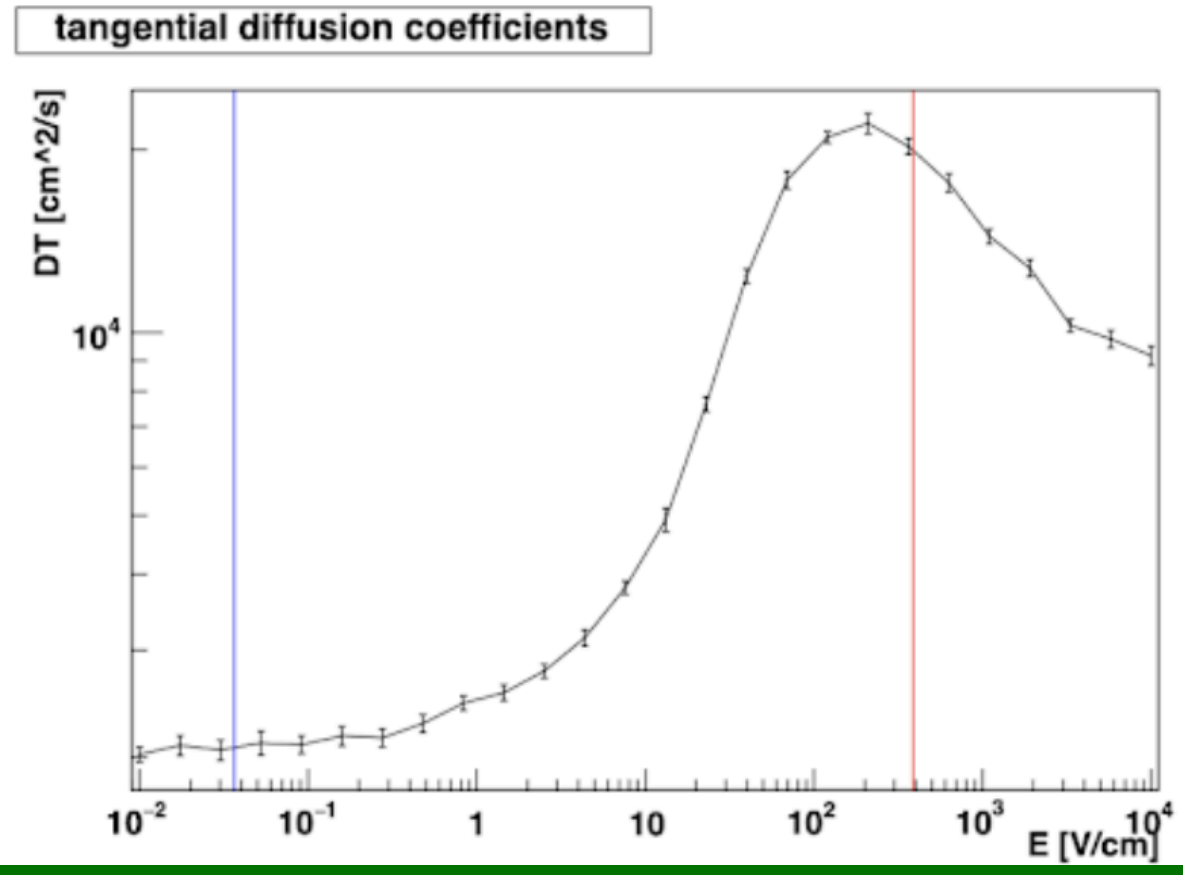
Step4: signal formation

Rise time determined

- **Drift velocity of electrons: constant in material under uniform electric field**
- **Fick's 2nd law:**
  - Charges diffuse in the gas due to scattering on the atoms of the gas
  - Describes how concentration change with respect to time
  - Expression in 1D: $\frac{\partial \varphi}{\partial t} = D \frac{\partial^2 \varphi}{\partial x^2}$
  - Fundamental solution: $\varphi(x,t) = \frac{1}{\sqrt{4\pi D t}} \exp\left(-\frac{x^2}{4Dt}\right)$
  - Standard deviation: $\sqrt{2Dt}$
- **CERN simulation package: Magboltz:**
  - Output: drift parameters: drift velocities, longitudinal/ transverse diffusion coefficients
- **Monte Carlo Integration method to determine the drift time**



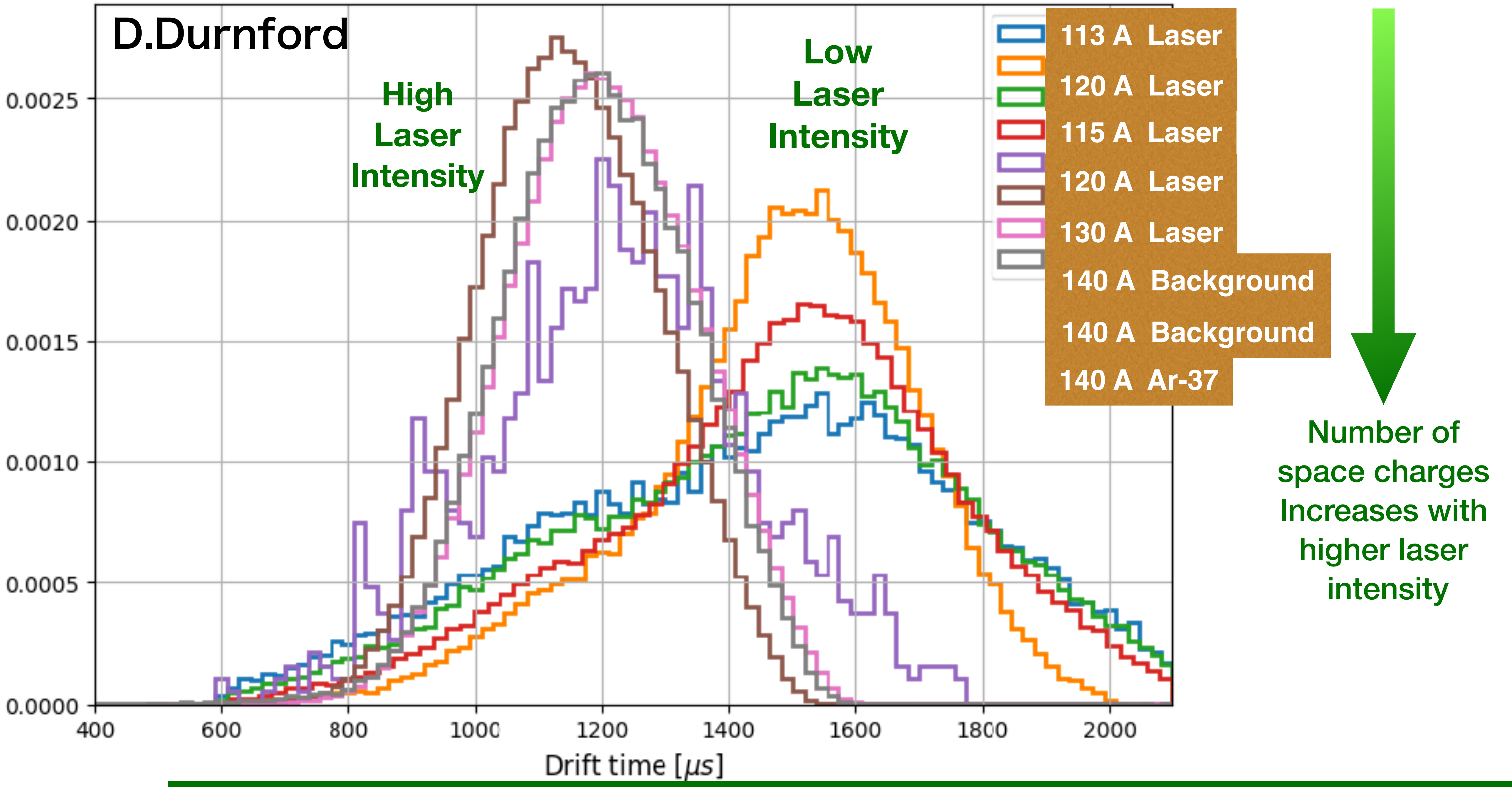



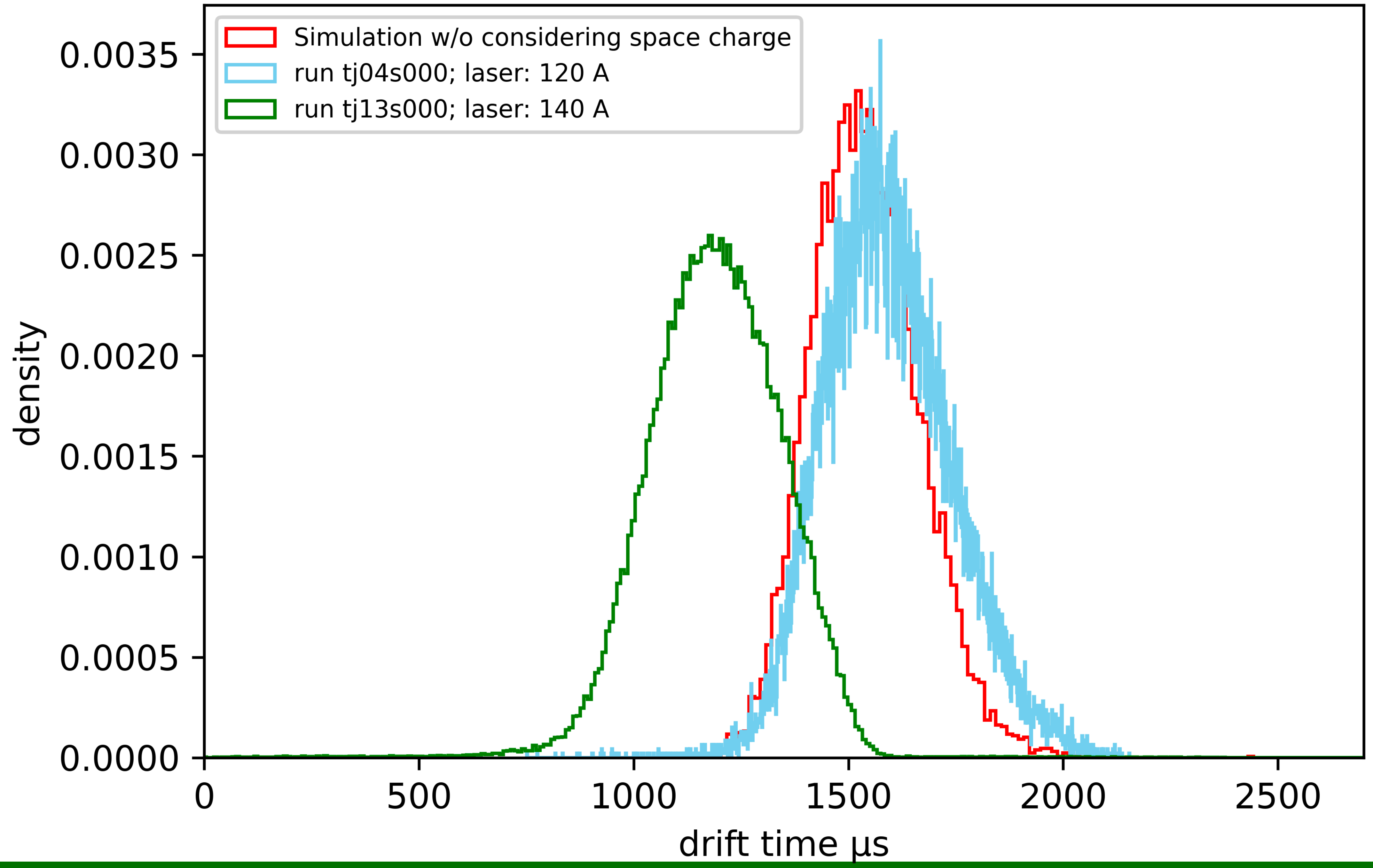
Laser events drift time simulation:
Events all originates from very south point of SPC

- **Left:** Laser LSM data show a different mean drift time between high and low laser intensity
- **Right:** Simulation shows agreement with real data at low laser intensity
- The decrease of drift time for higher laser intensity run can possibly be explained by space charge

* Some data sets have lower tails due to alpha correlated events which cannot be effeciently removed in low-intensity laser data




120A and 140 A laser drift time data compare with laser events drift time simulation without considering space charge



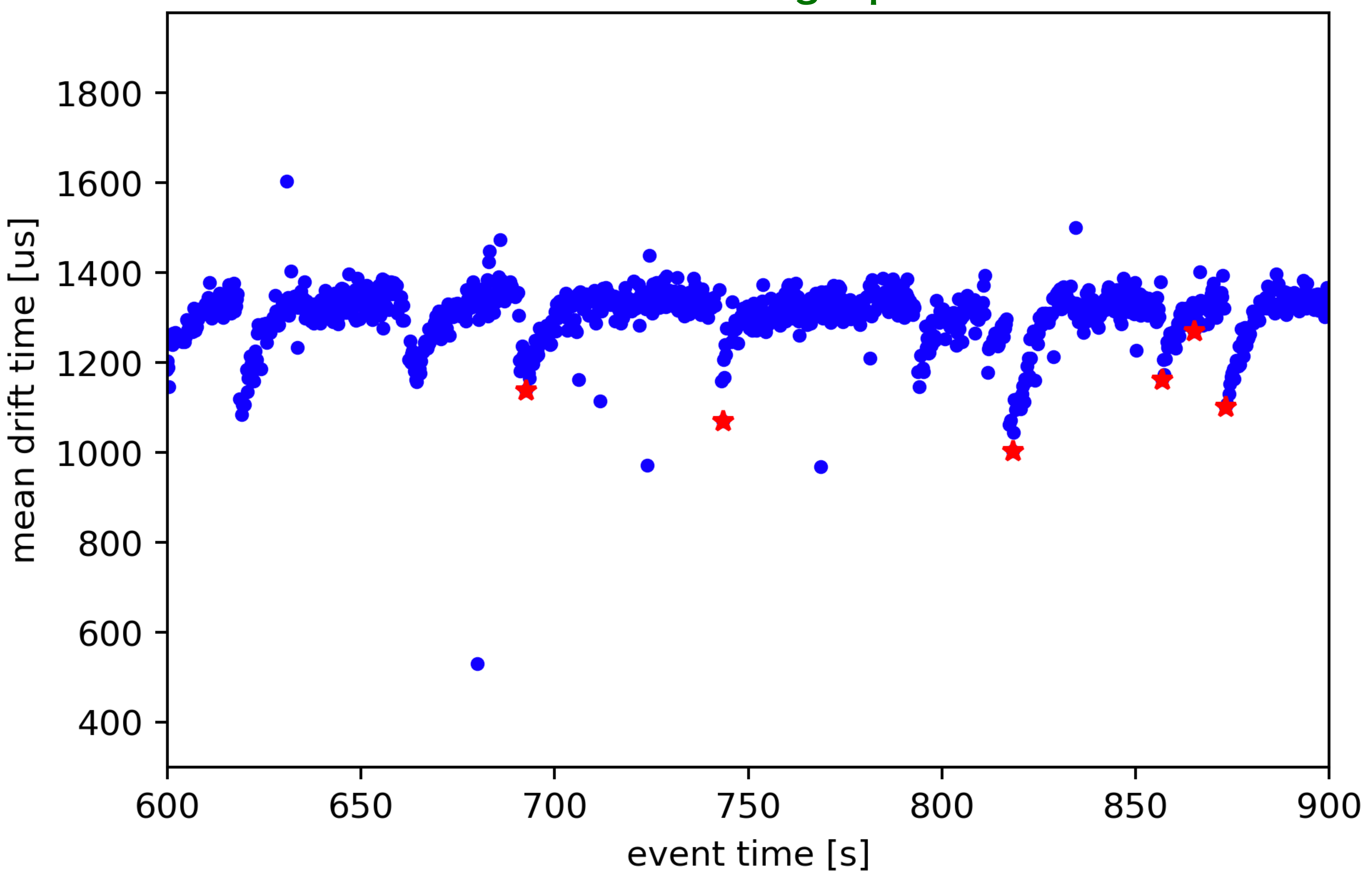
- **Ion drifting simulation:**
  - The number of secondary ions due to 140 A laser events **seen** by the detector is known
  - Drifting is affected by the ions Efield interaction
  - Assuming the diffusion of ions can be neglected
  - Assuming reduced ion mobility $K_0$ of all kinds of ion species is 2.2 [cm2/V/s]
  - Drift velocity depends on the Efield:

$$K_0 = K\frac{n}{n_0} = K\frac{T_0}{T}\frac{p}{p_0}$$

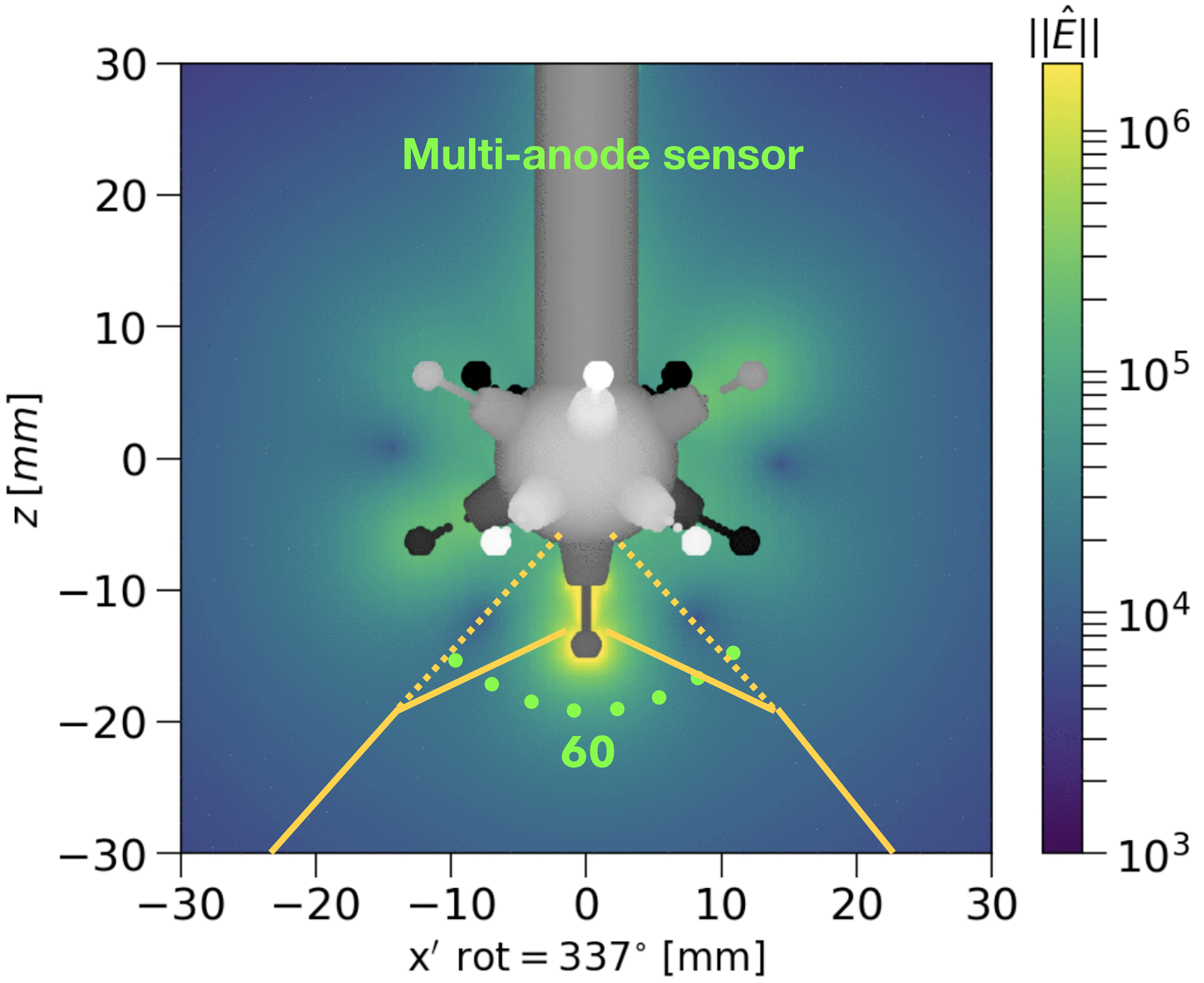
$$v_d = KE$$

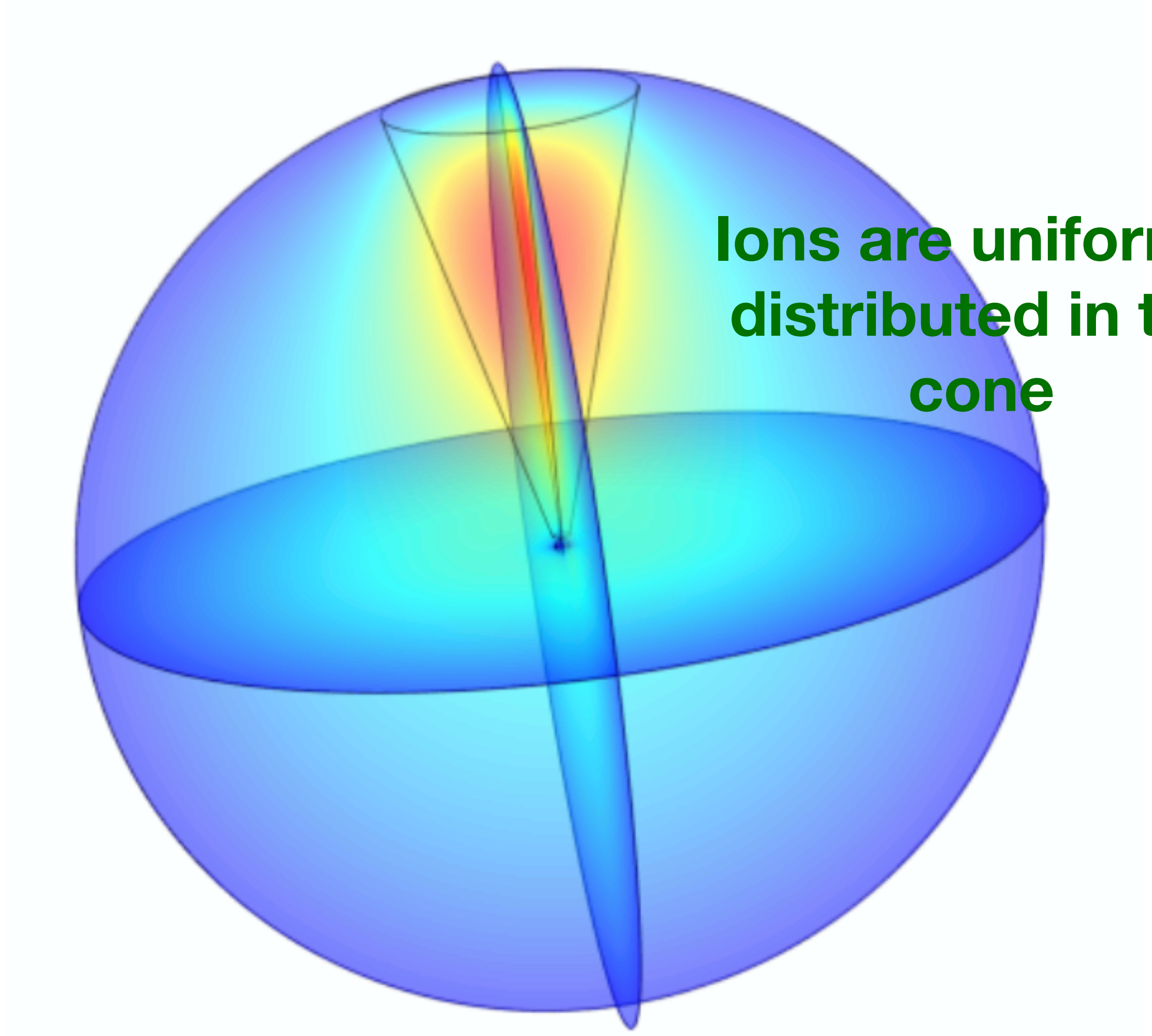
- **Ion drift time: 5 ~ 7s**
  - The number of ions exist in the detector can be deduced knowing the laser event rate.

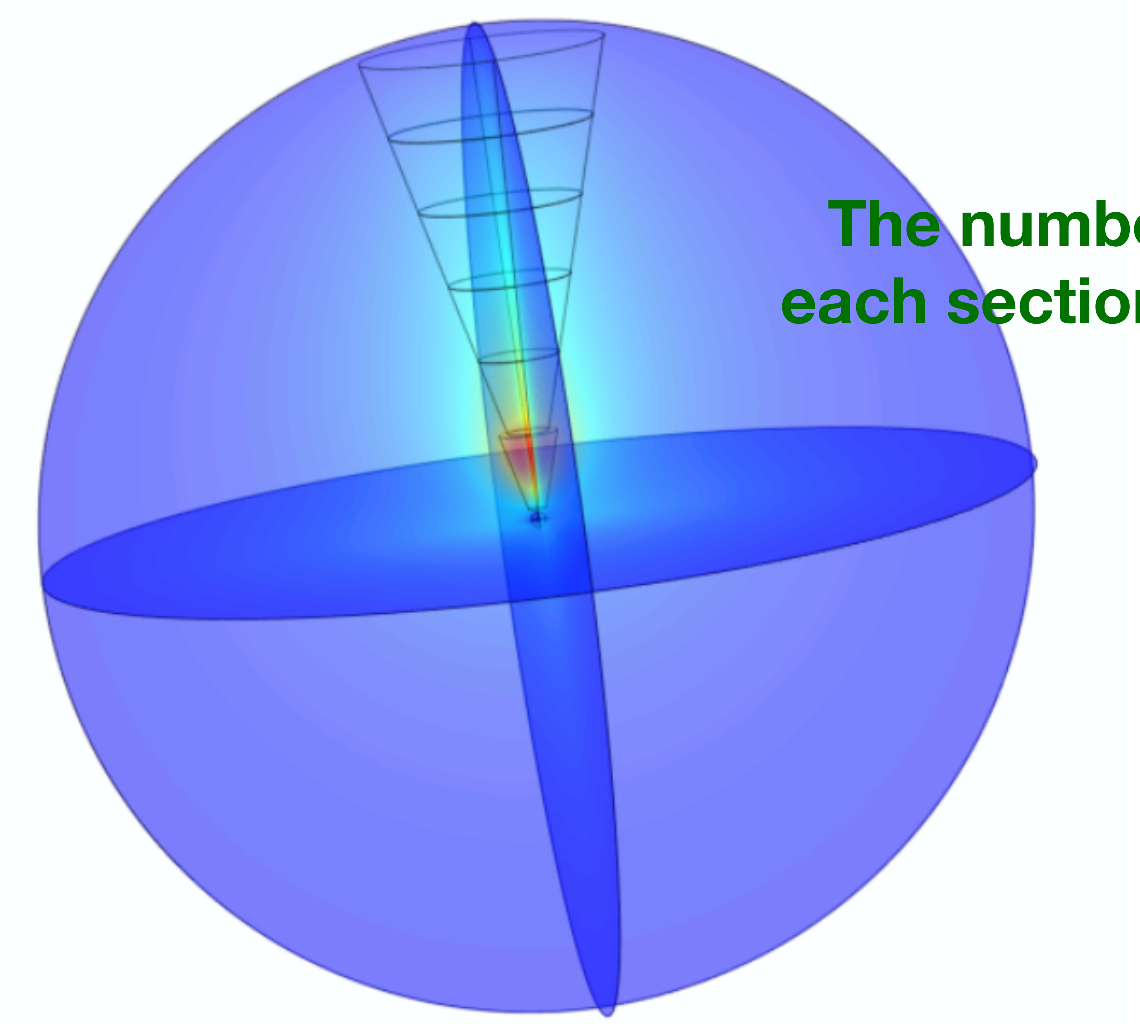
drift time data during alpha events



- COMSOL Efield simulation:
  - Specify the volume charge density for certain geometry
  - Geometry: Cone
  - Two different ways of distributing space charges (plots below)
  - Different simulations has been done for various open angle of the cone (10, 30, 60 degree), and various number of ions in the detector according to data



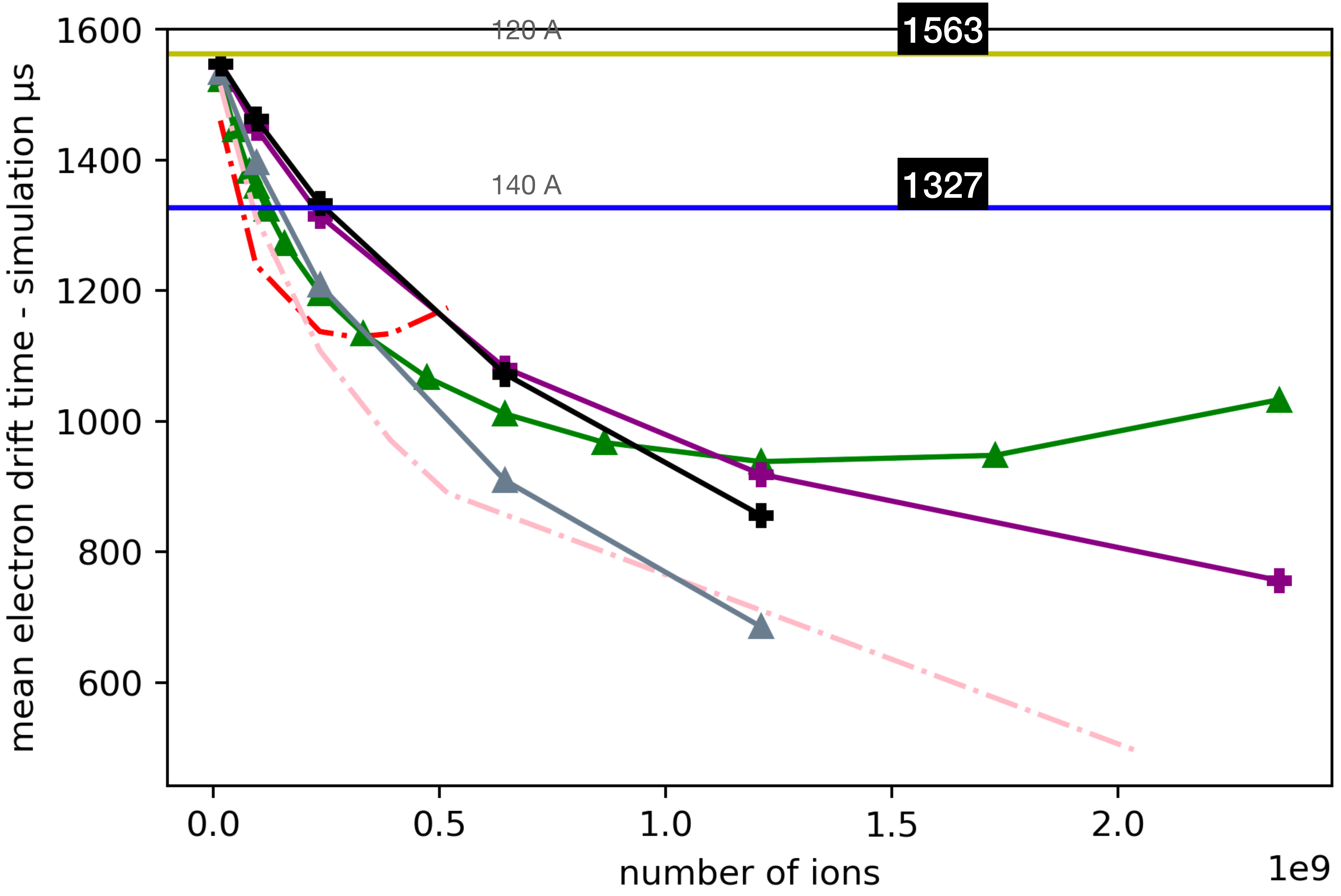



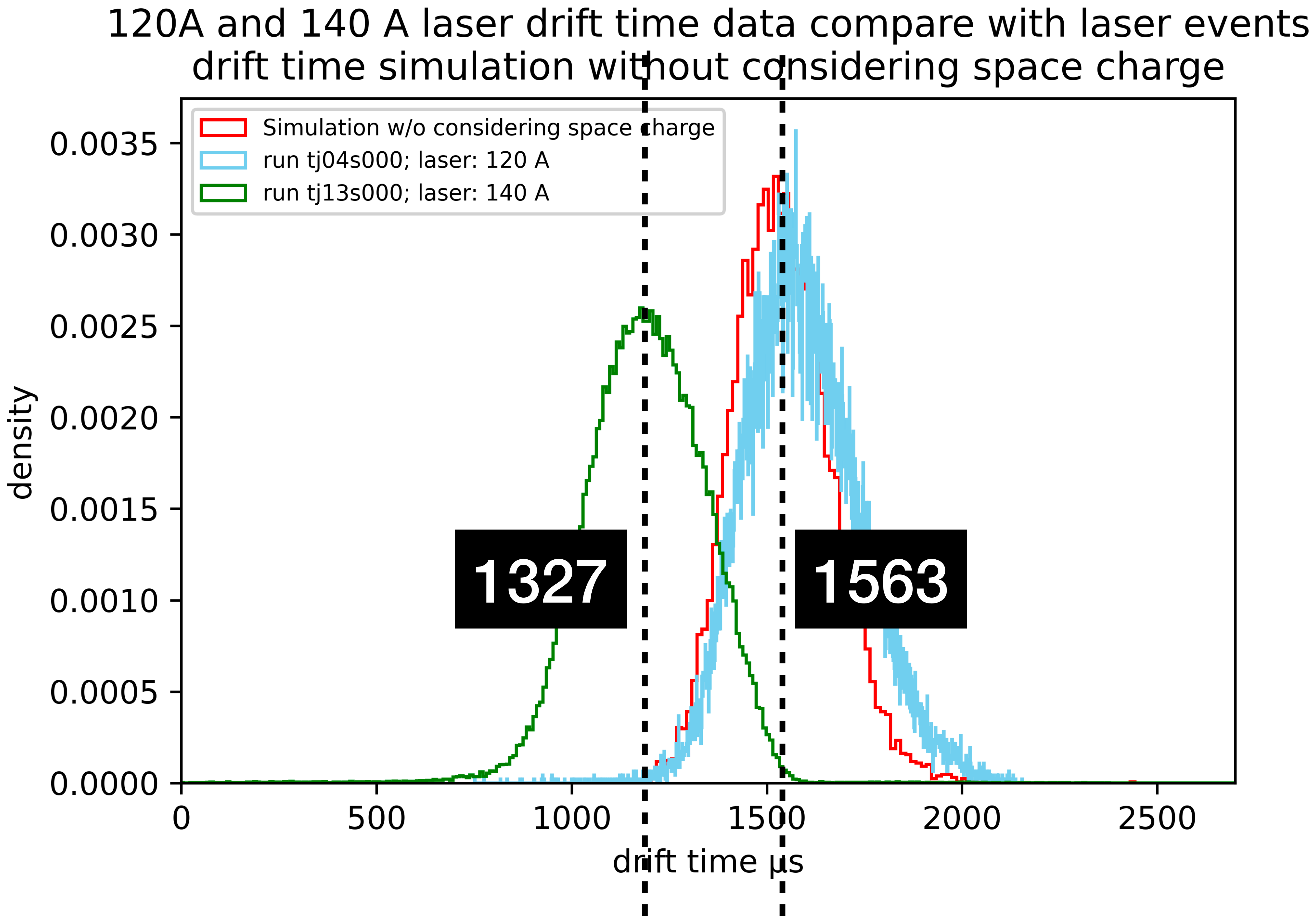



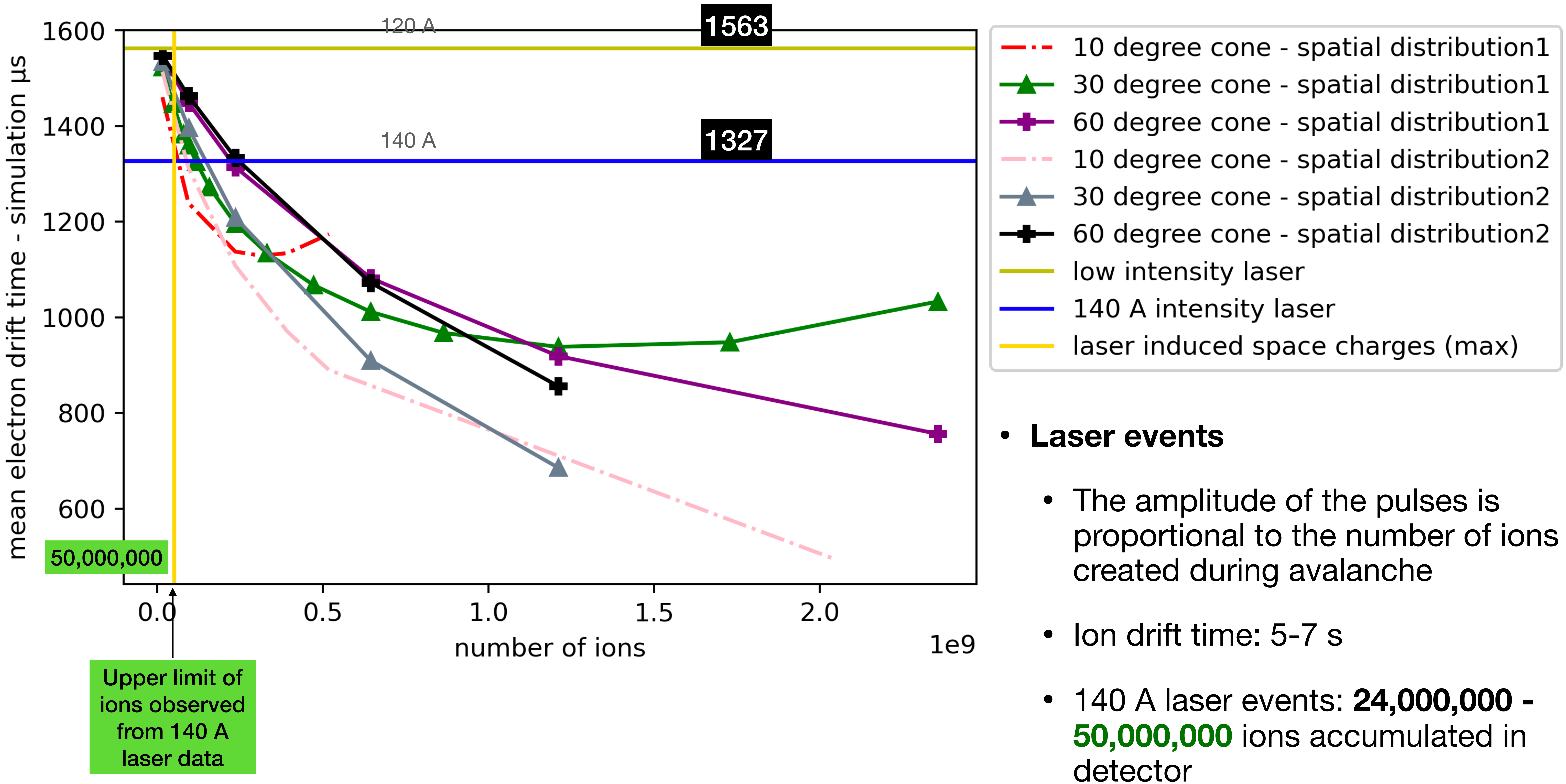


- **This space charge simulation result will be compared with real laser drift time data for both 120 A & 140 A and alpha events**

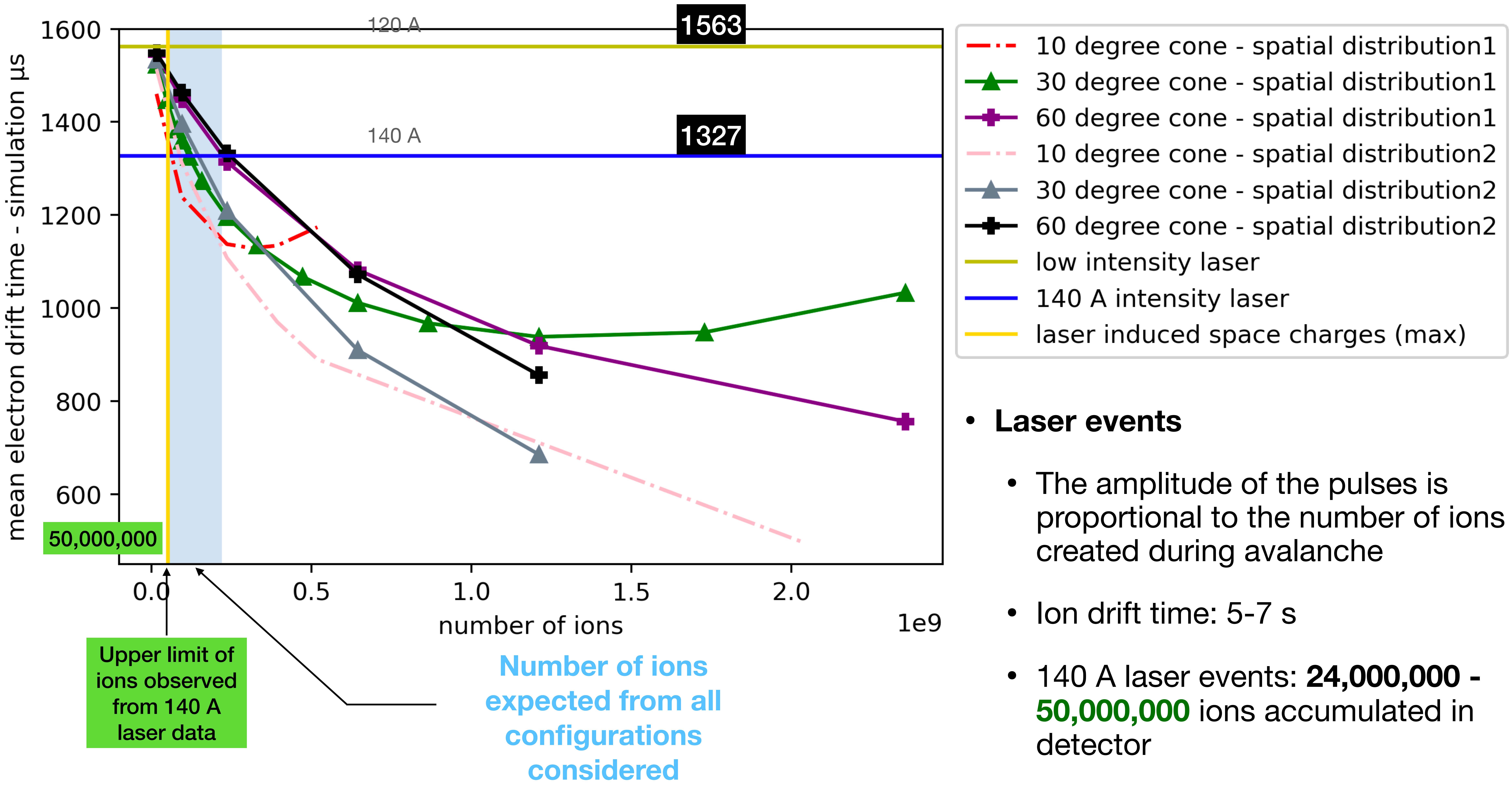
## Comparison of simulation results with laser mean drift time data



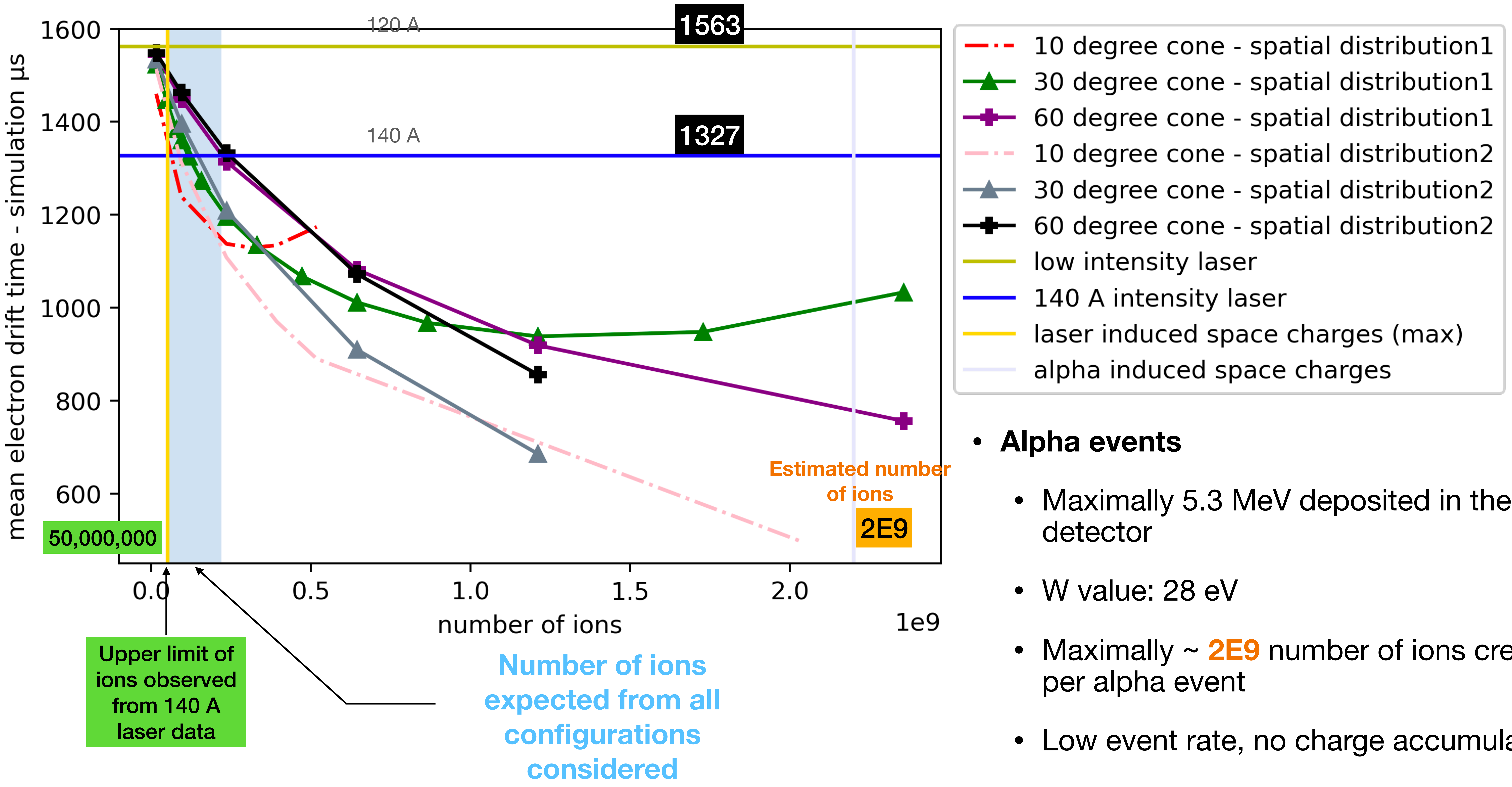





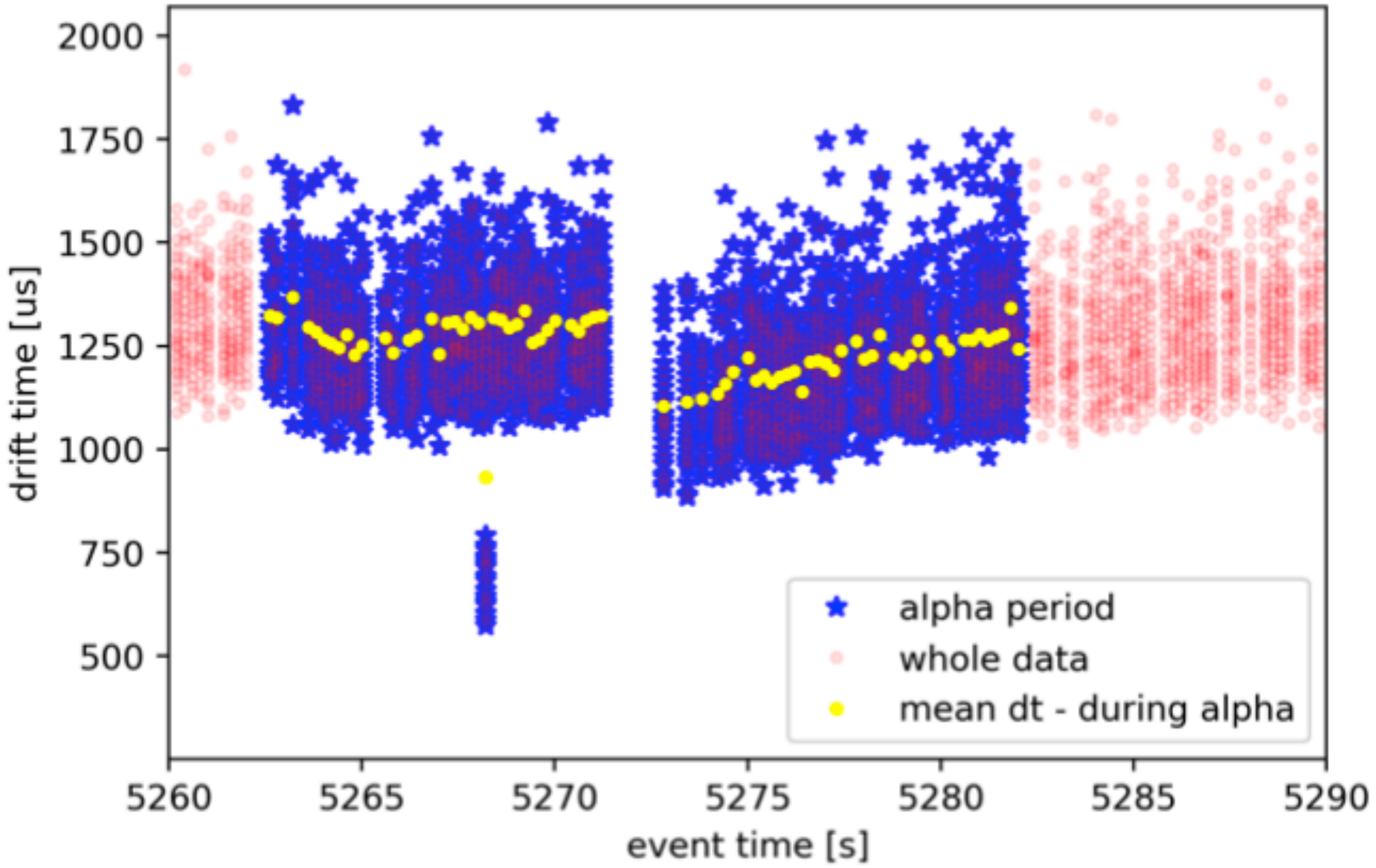

- **Laser events**
  - The amplitude of the pulses is proportional to the number of ions created during avalanche
  - Ion drift time: 5-7 s
  - 140 A laser events: **24,000,000 - 50,000,000** ions accumulated in detector

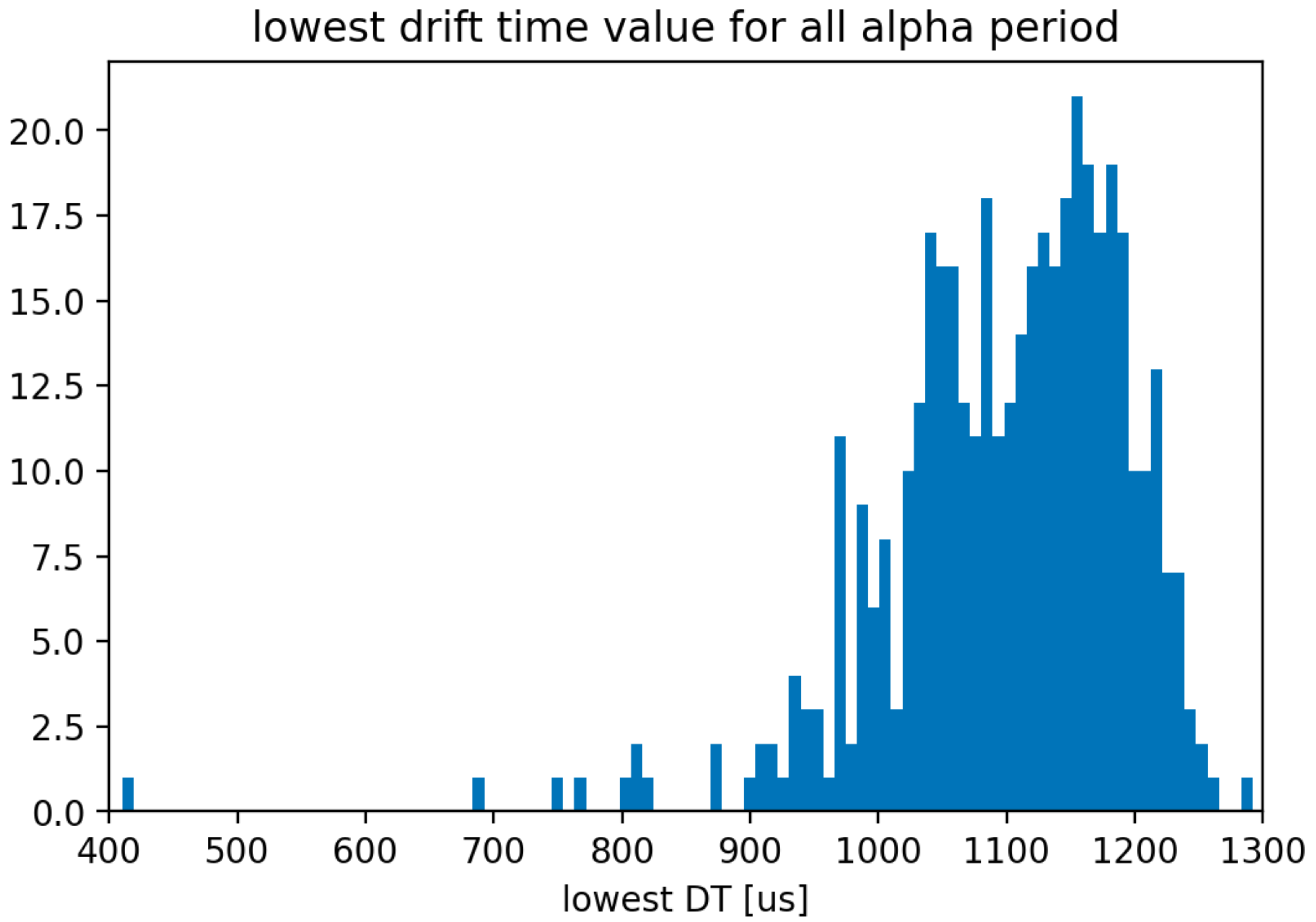



- **Laser events**
  - The amplitude of the pulses is proportional to the number of ions created during avalanche
  - Ion drift time: 5-7 s
  - 140 A laser events: **24,000,000 - 50,000,000** ions accumulated in detector



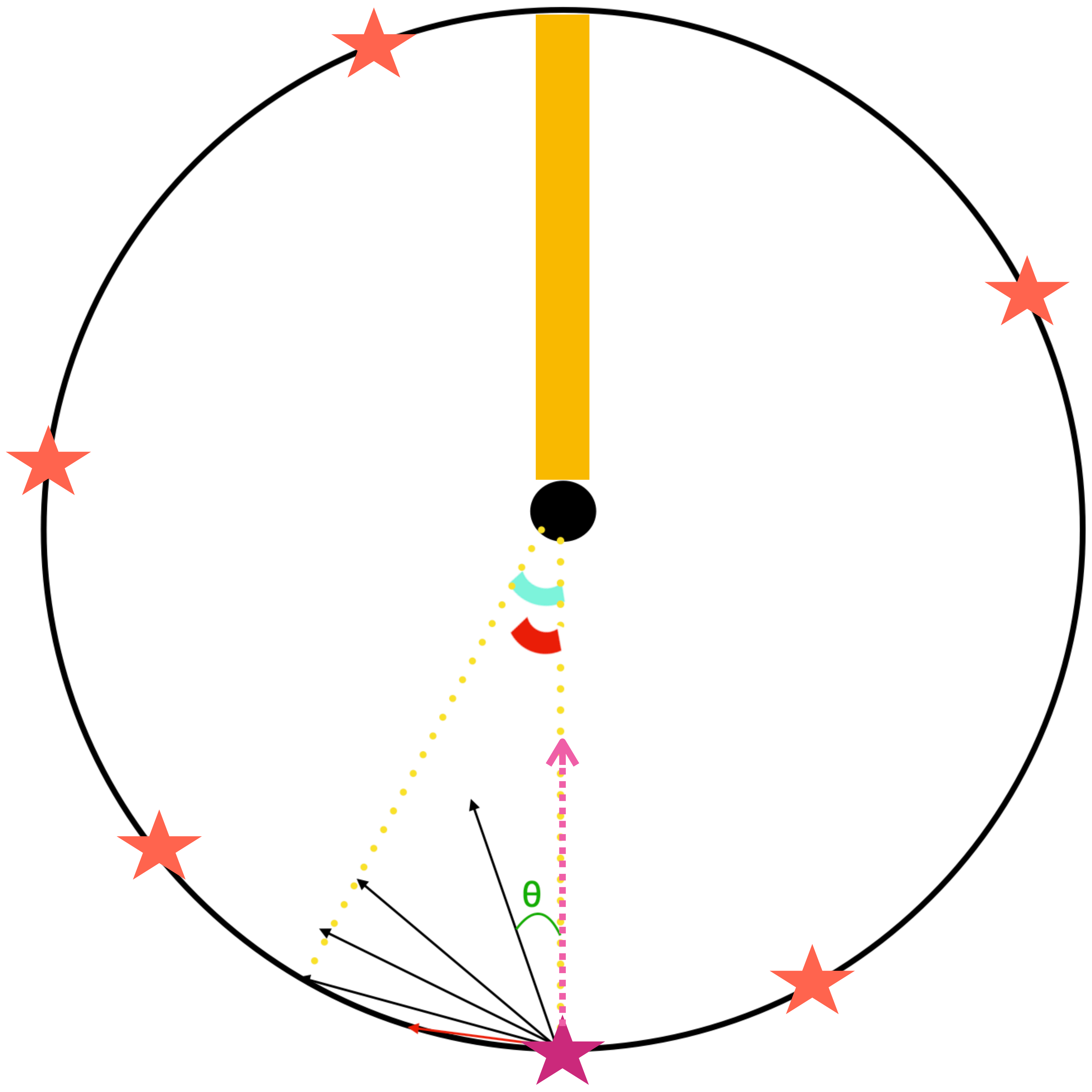

- **Alpha events**
  - Maximally 5.3 MeV deposited in the detector
  - W value: 28 eV
  - Maximally ~ 2E9 number of ions created per alpha event
  - Low event rate, no charge accumulation



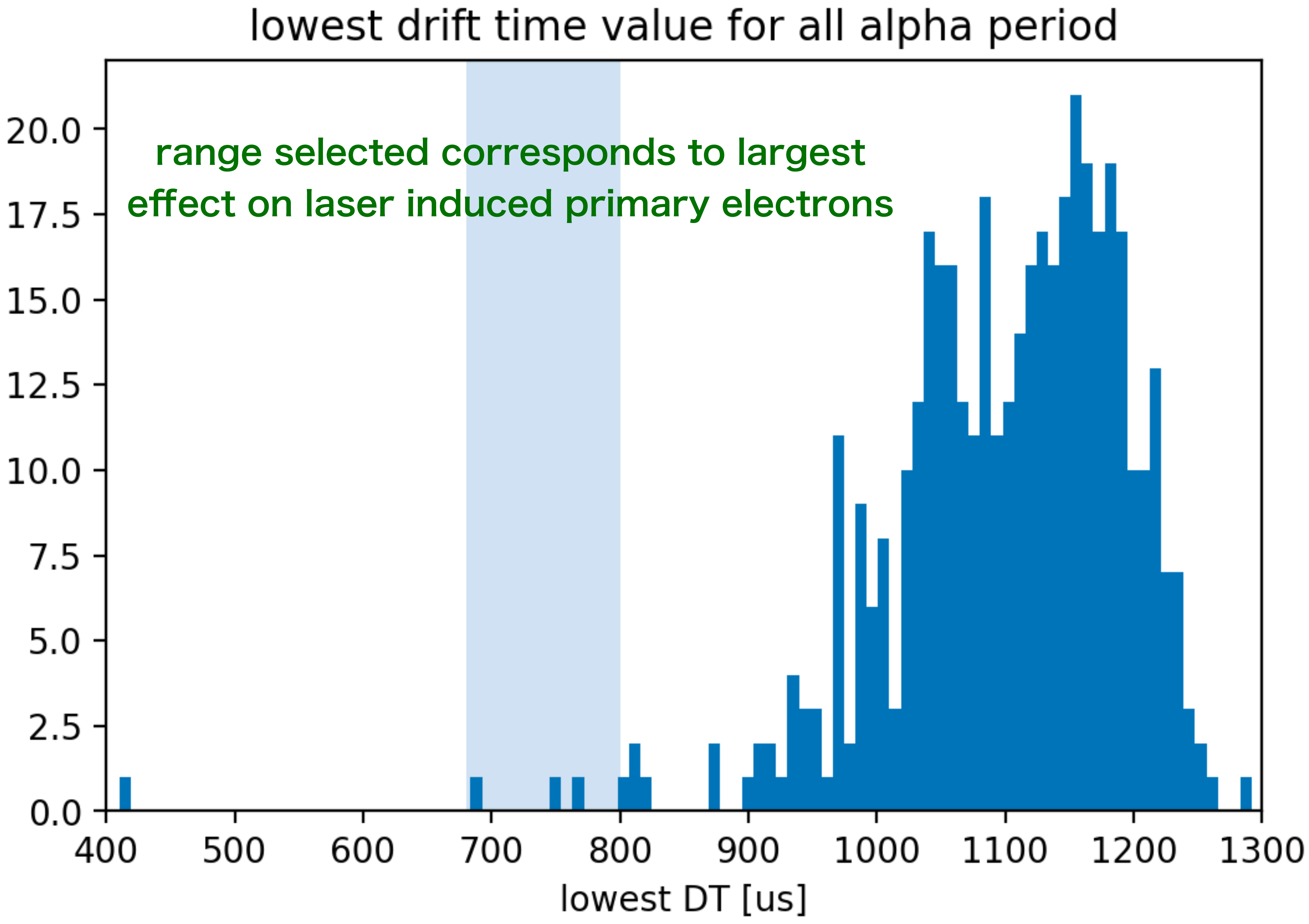




- 140 A laser mean drift time values per event VS time
- Periods affected by alpha events are identified (Credit to Jean-Marie coquillat)
- The lowest electron mean drift times for each alpha period are selected

- Each alpha event will contribute one lowest drift time value to this plot
- Collect all the lowest drift time value for all the alpha events




Alpha events originating from very south point and pointing towards the centre will have the largest space charge effect



Step1: Electric field simulation:
Finite element software COMSOL

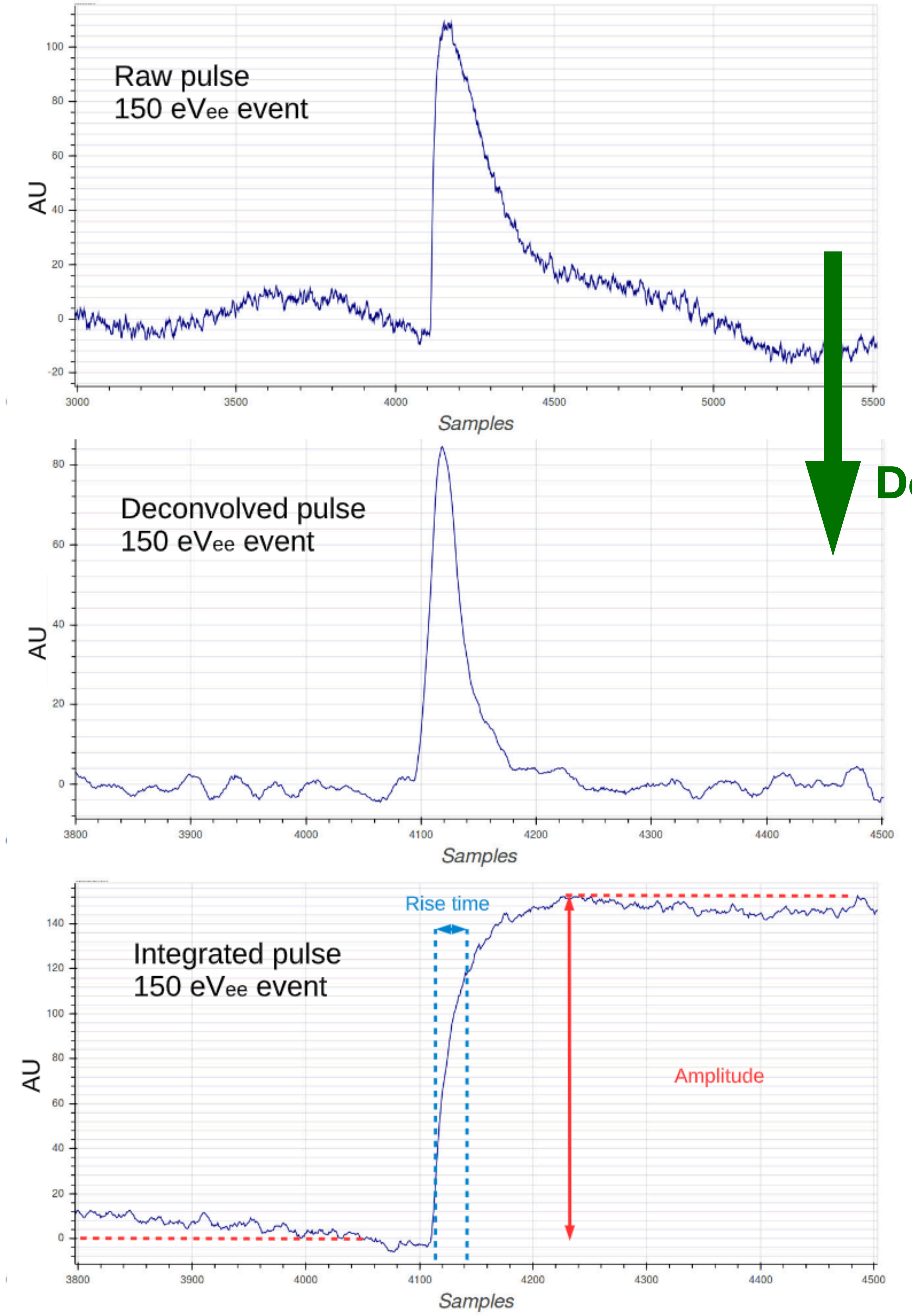
Step2: Primary ionization

Step3: electron transportation

Electron drift time determined

Step4: signal formation

Rise time determined




Deconvolve