NEWS-G

New Experiments With Spheres-Gas

Detector Response Modelling and Space Charge Study Of NEWS-G

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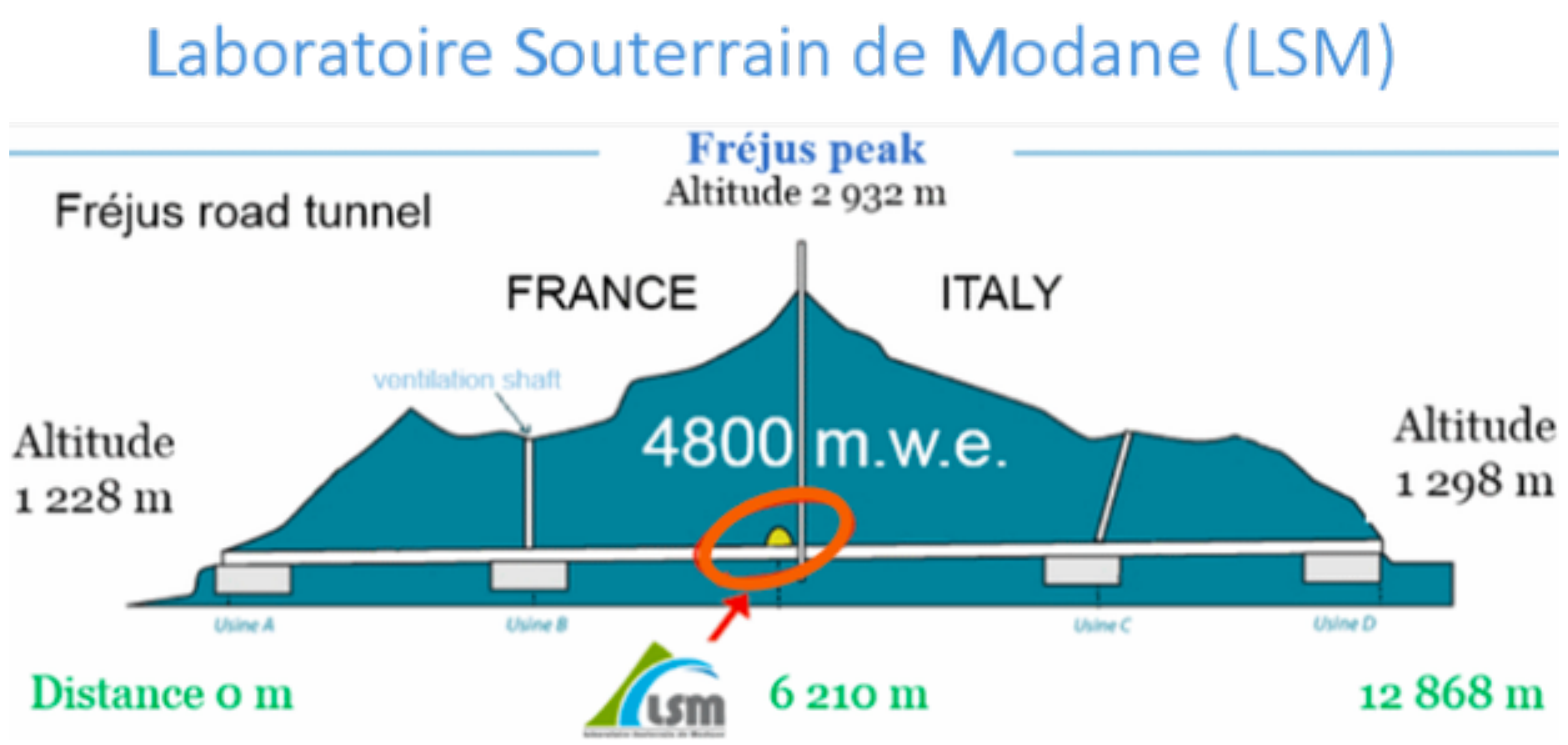
UNIVERSITY OF ALBERTA

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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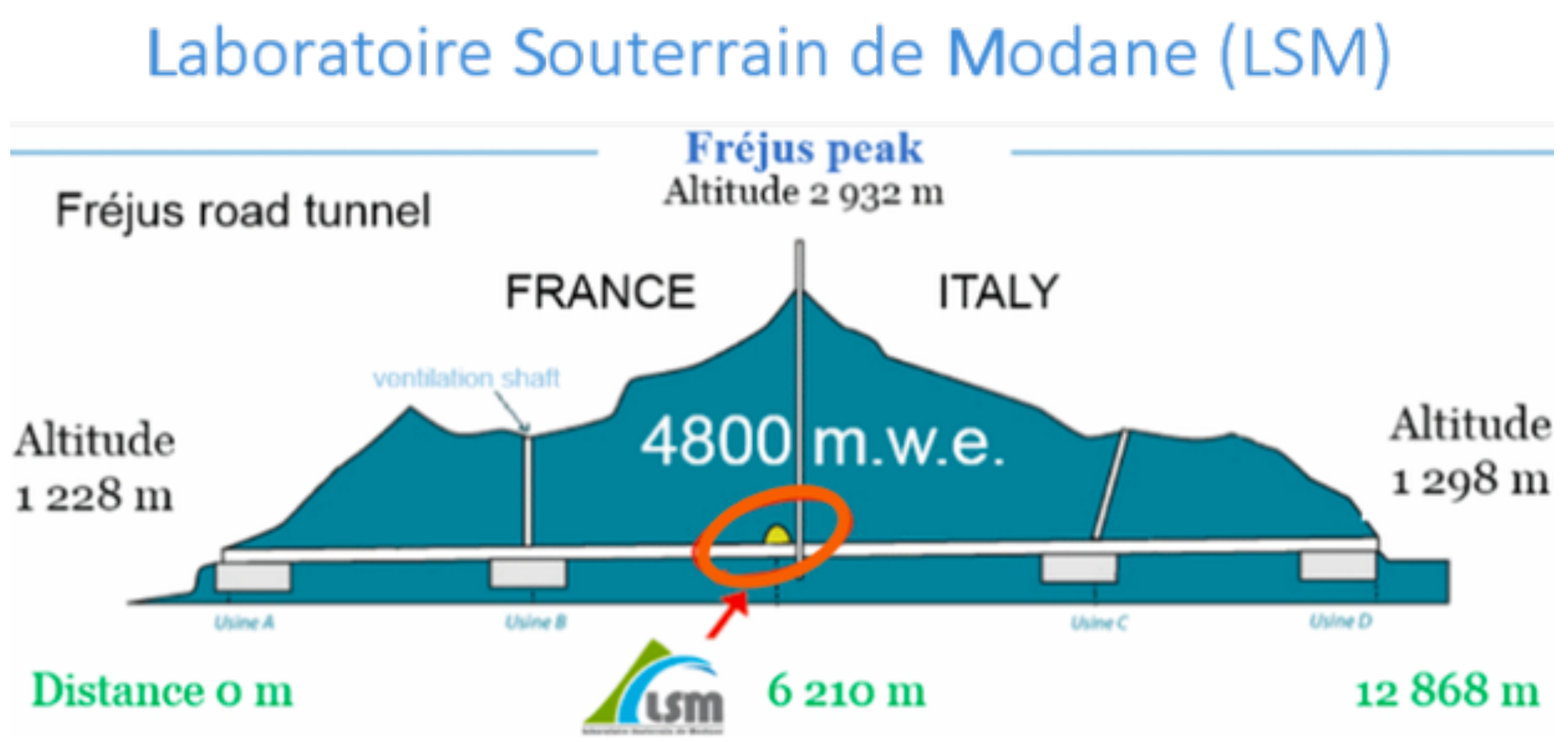

Physics and non-physics data were taken with a SNOGLOBE under 135 mbar using pure CH_4 at LSM in 2019

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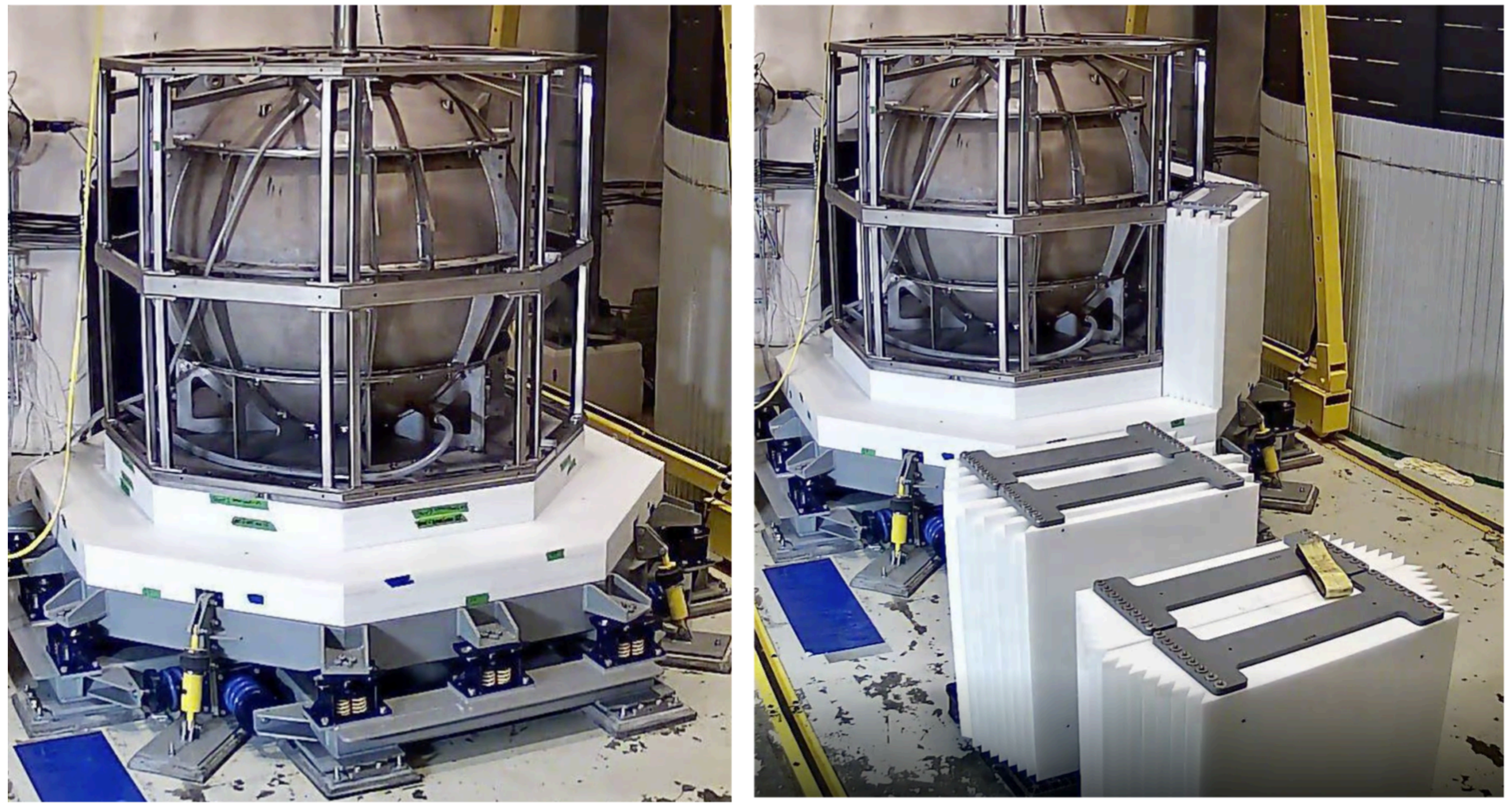
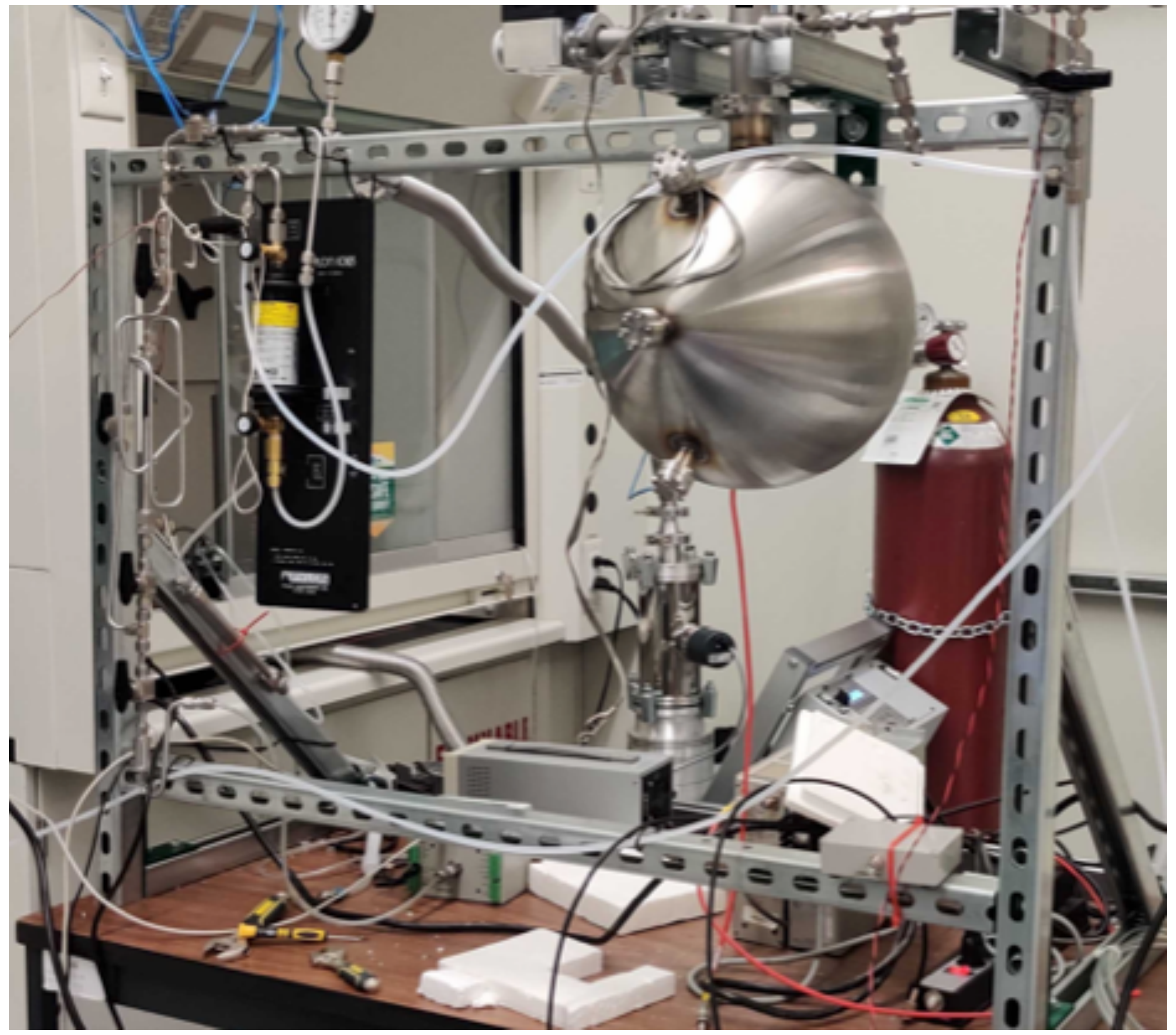
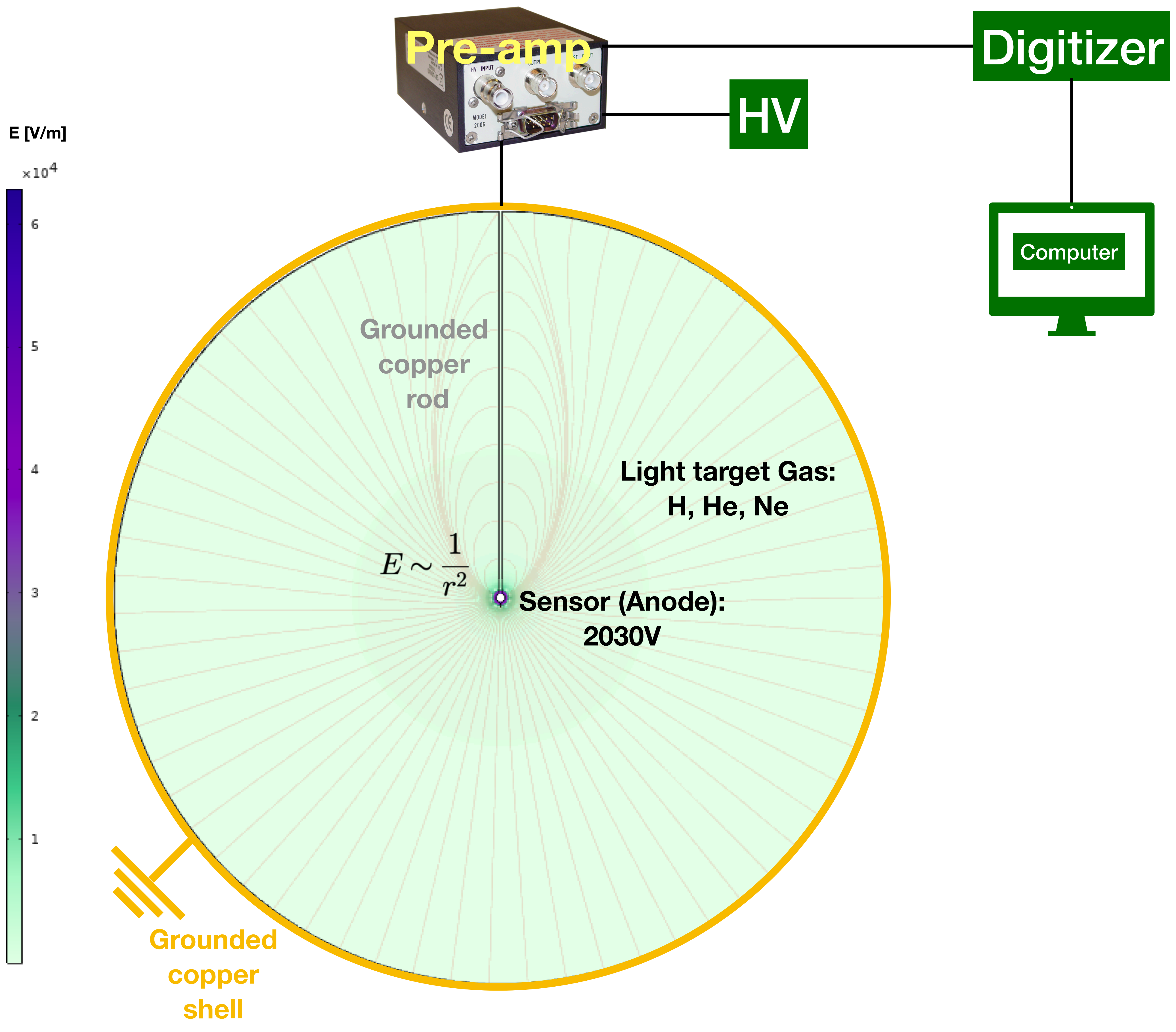
The new SPC is currently installed in SNOLAB







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

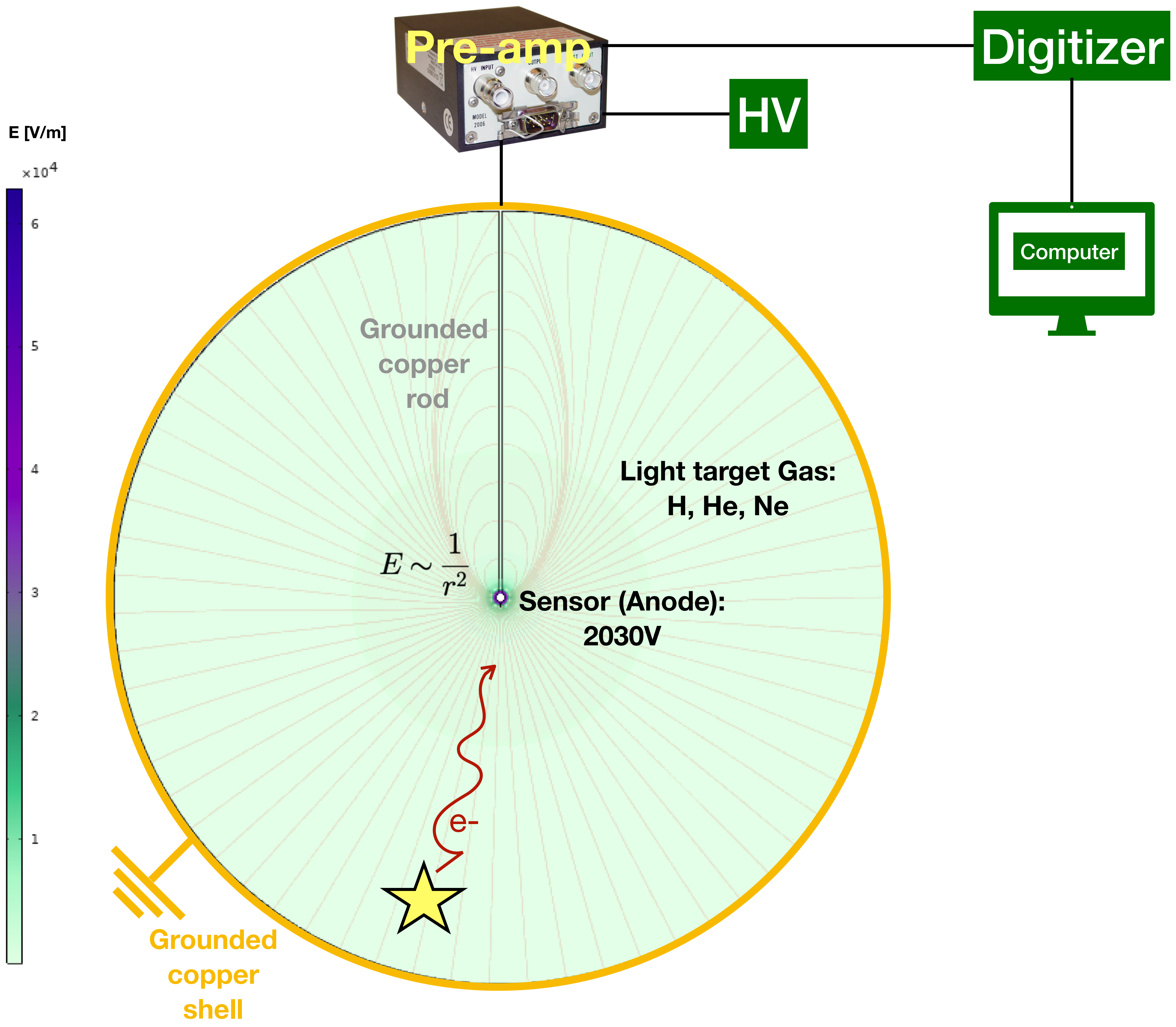
Induce current

Current signal

Pre-amplifier response

Voltage signal

Digitizer



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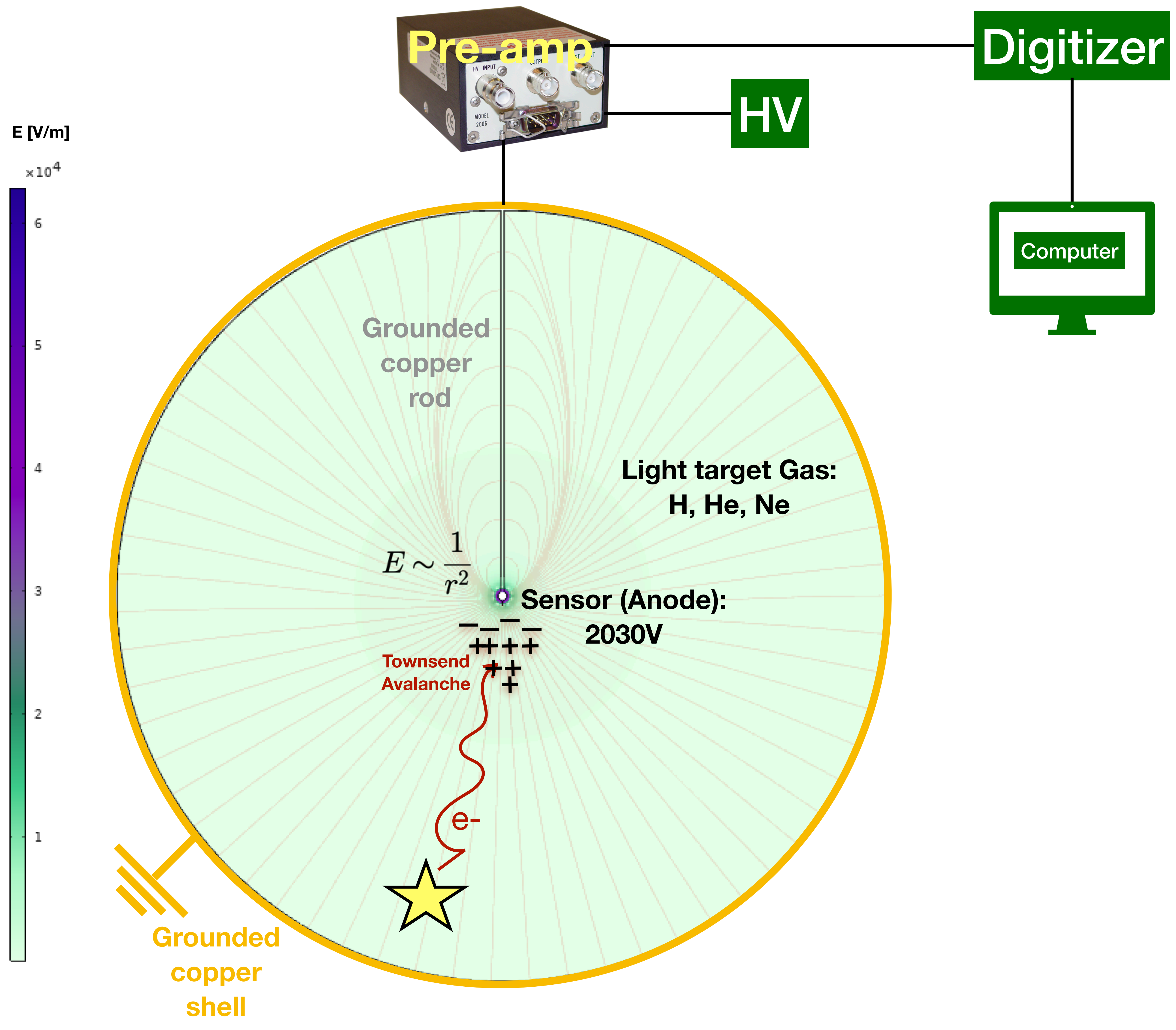

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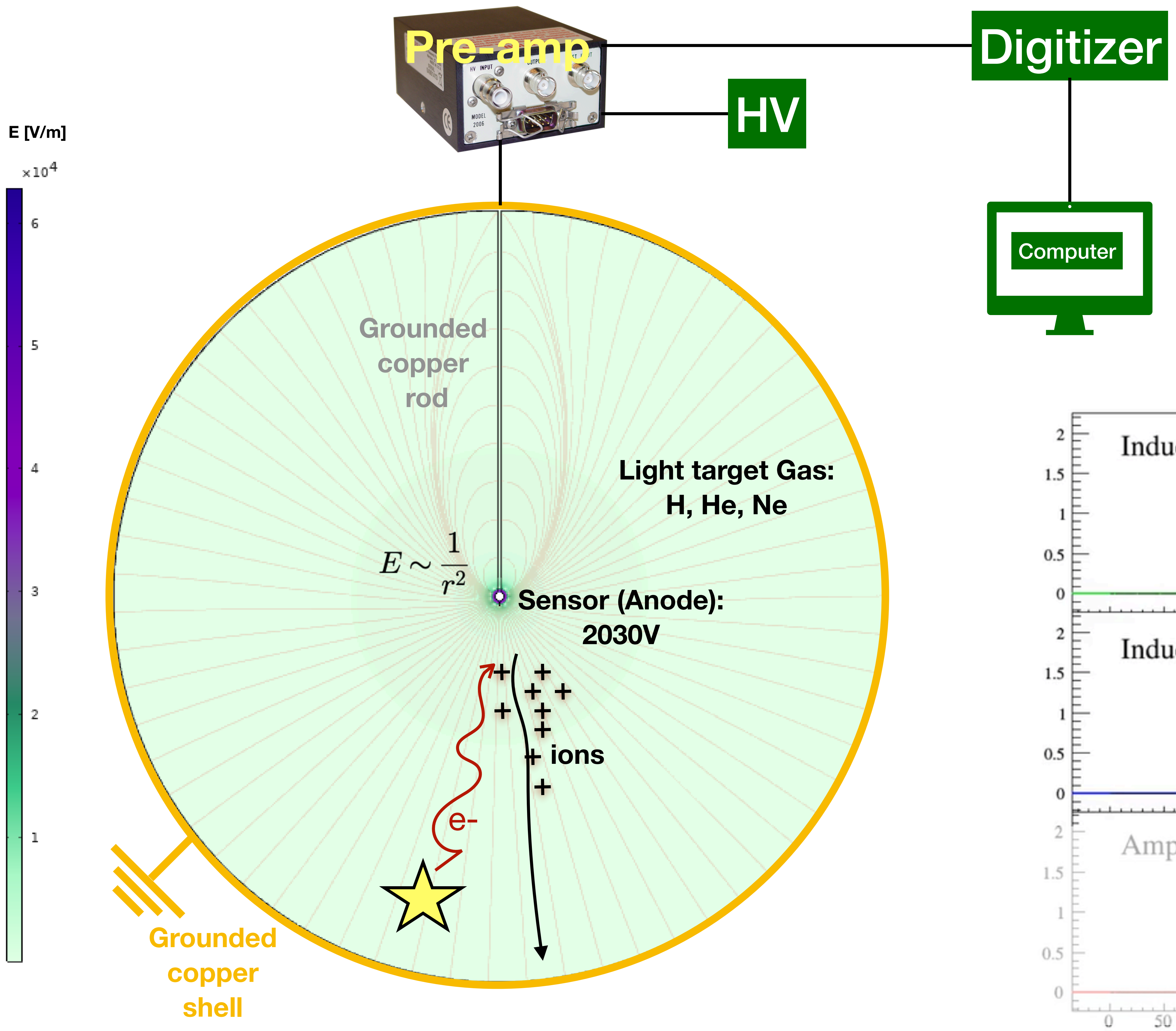

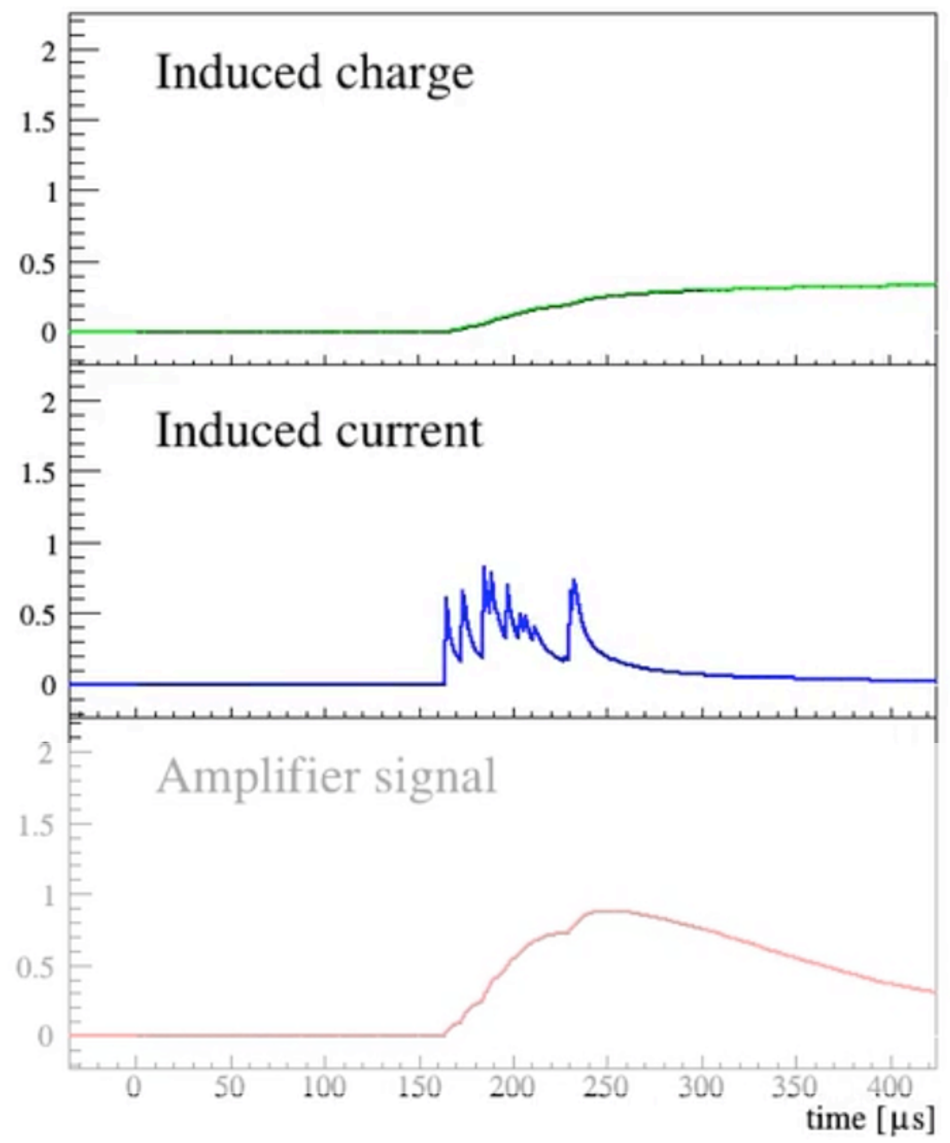

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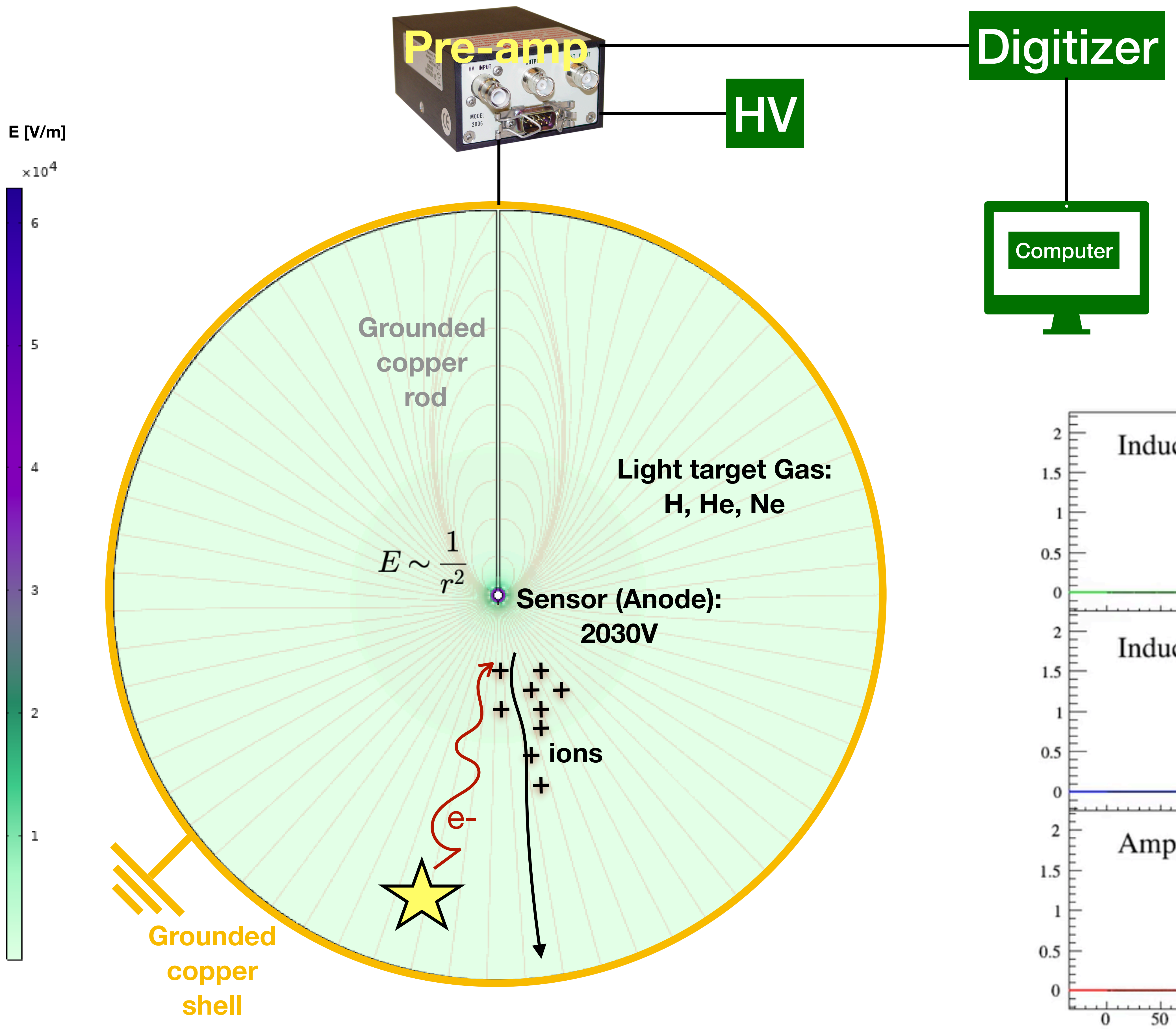

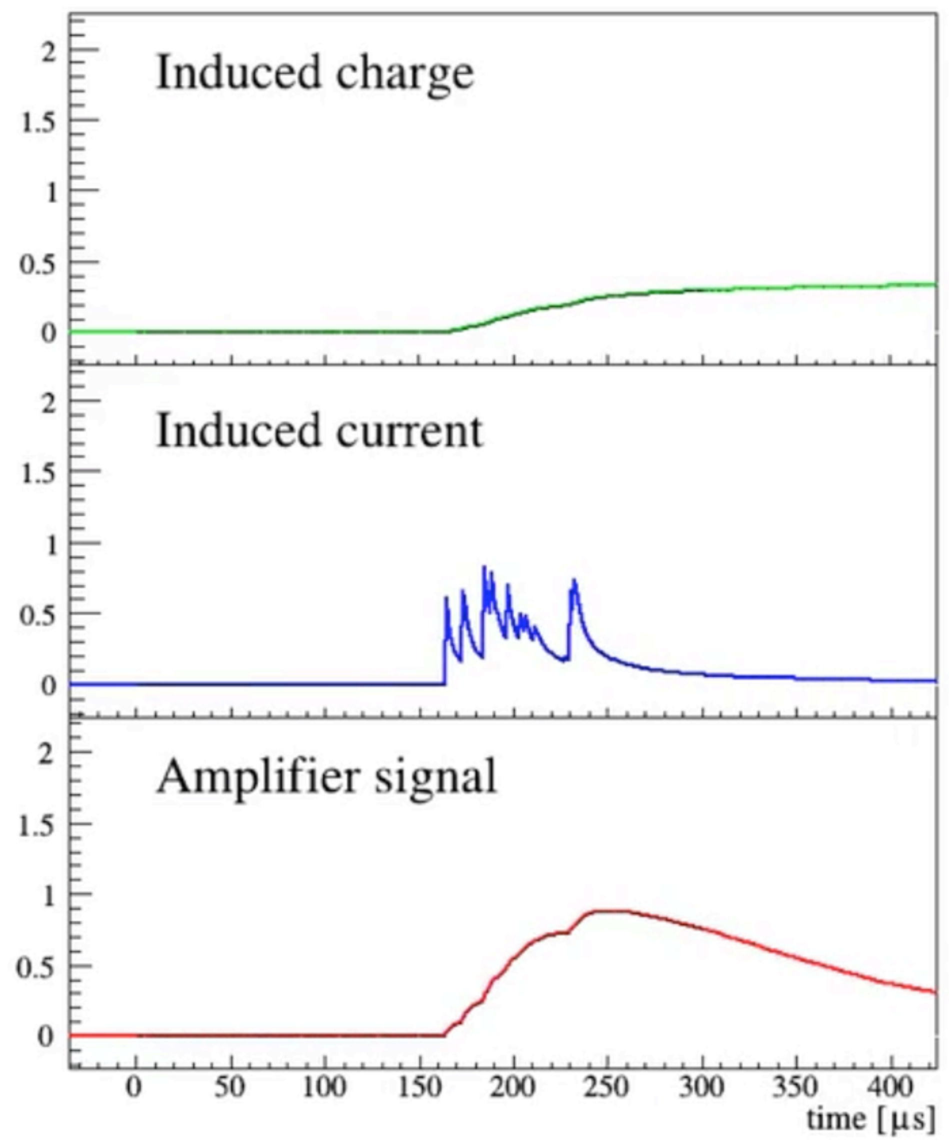

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- Radioactive source Ar37 along with pure CH4 was filled in SPC
- Ar37 emit X-rays at 270 eV and 2.8 keV induced by electron capture in L and K shell
- X-rays are uniformly distributed throughout the detector

Calibration runs

Ar37 | UV laser

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

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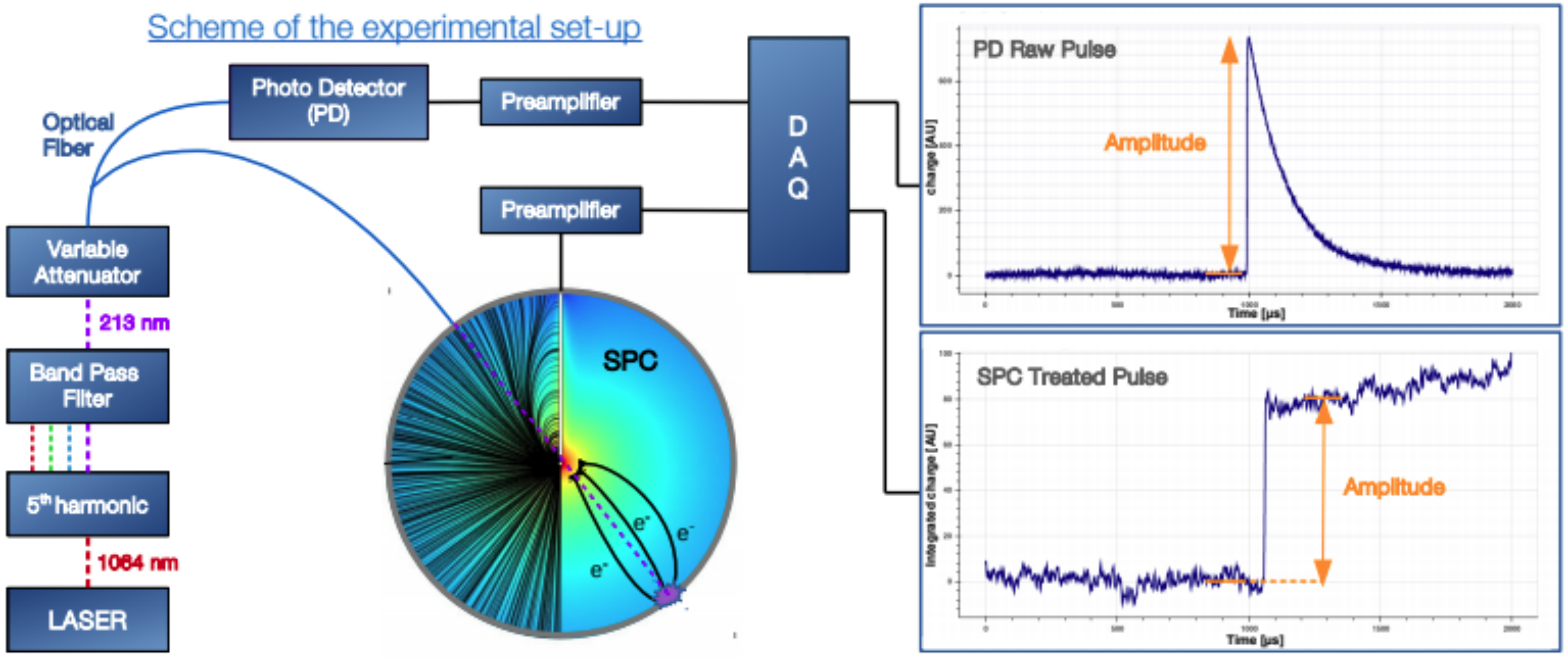


Q. Arnaud et al., Precision laser-based measurements of the single electron response of SPCs for the NEWS-G light dark matter search experiment, arXiv:1902.08960

- 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

SPC detector response modelling

Step1: Electric field simulation:
Finite element software COMSOL

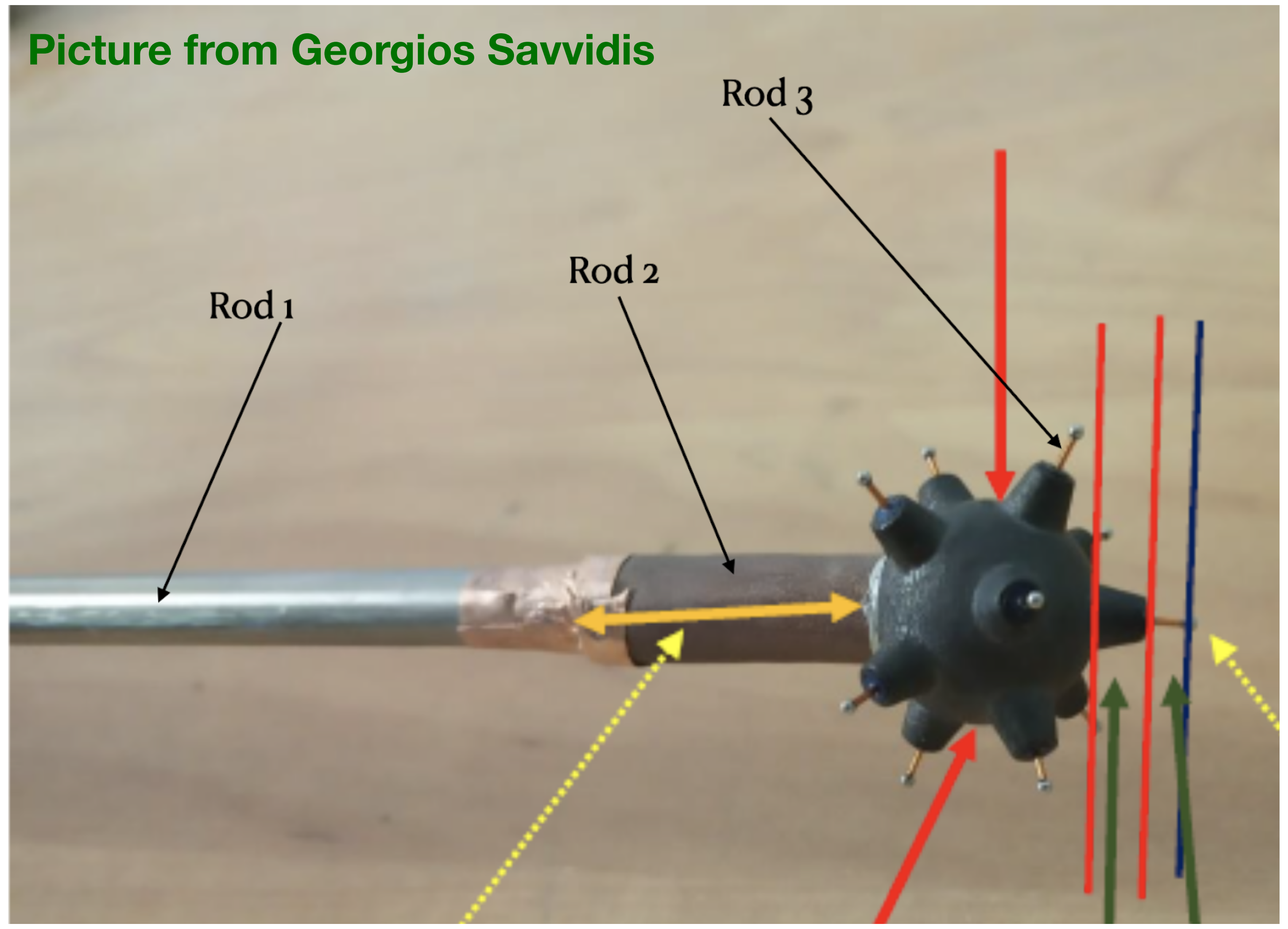
Step2: Primary ionization

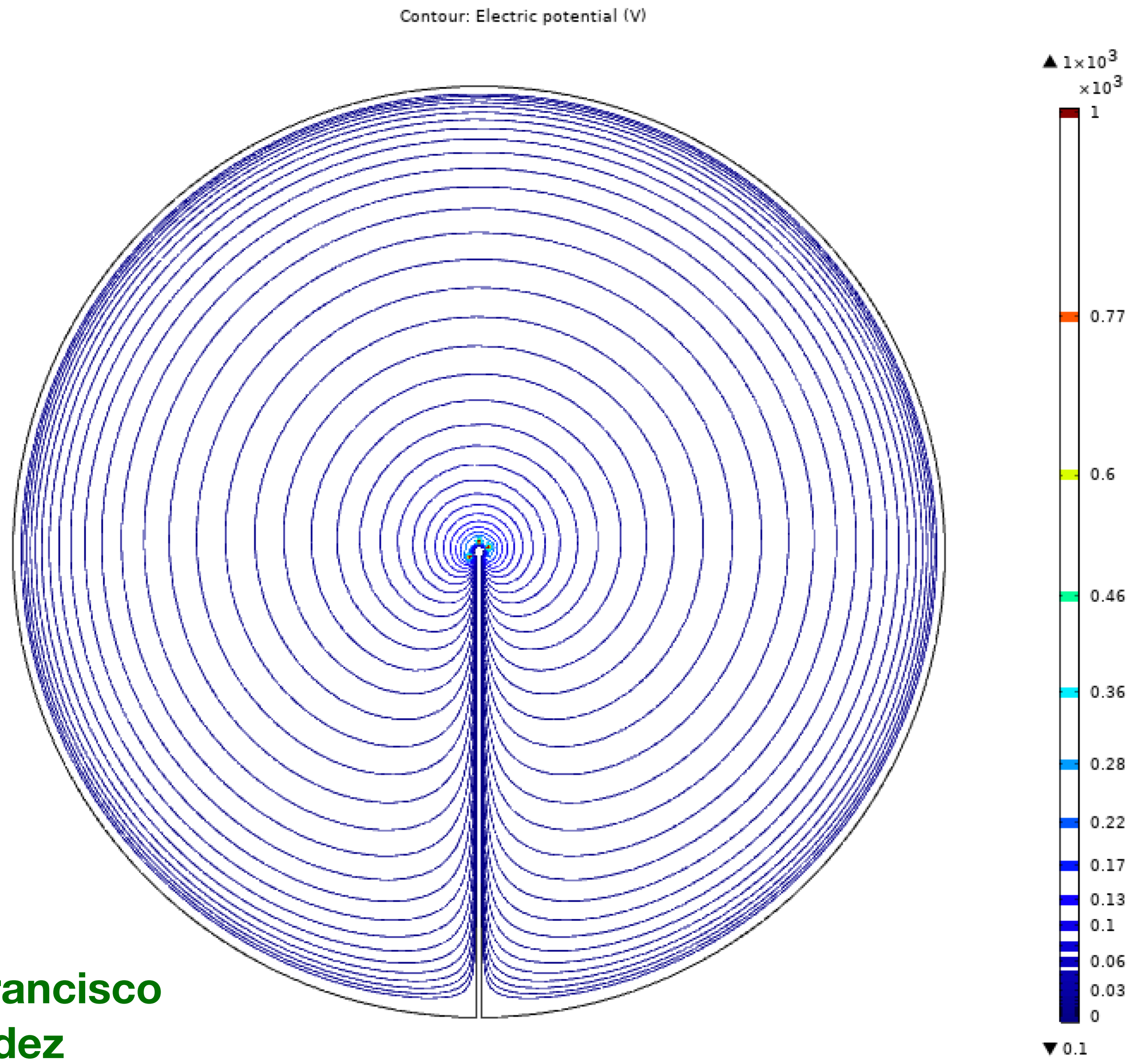
Step3: electron transportation

Electron drift time determined

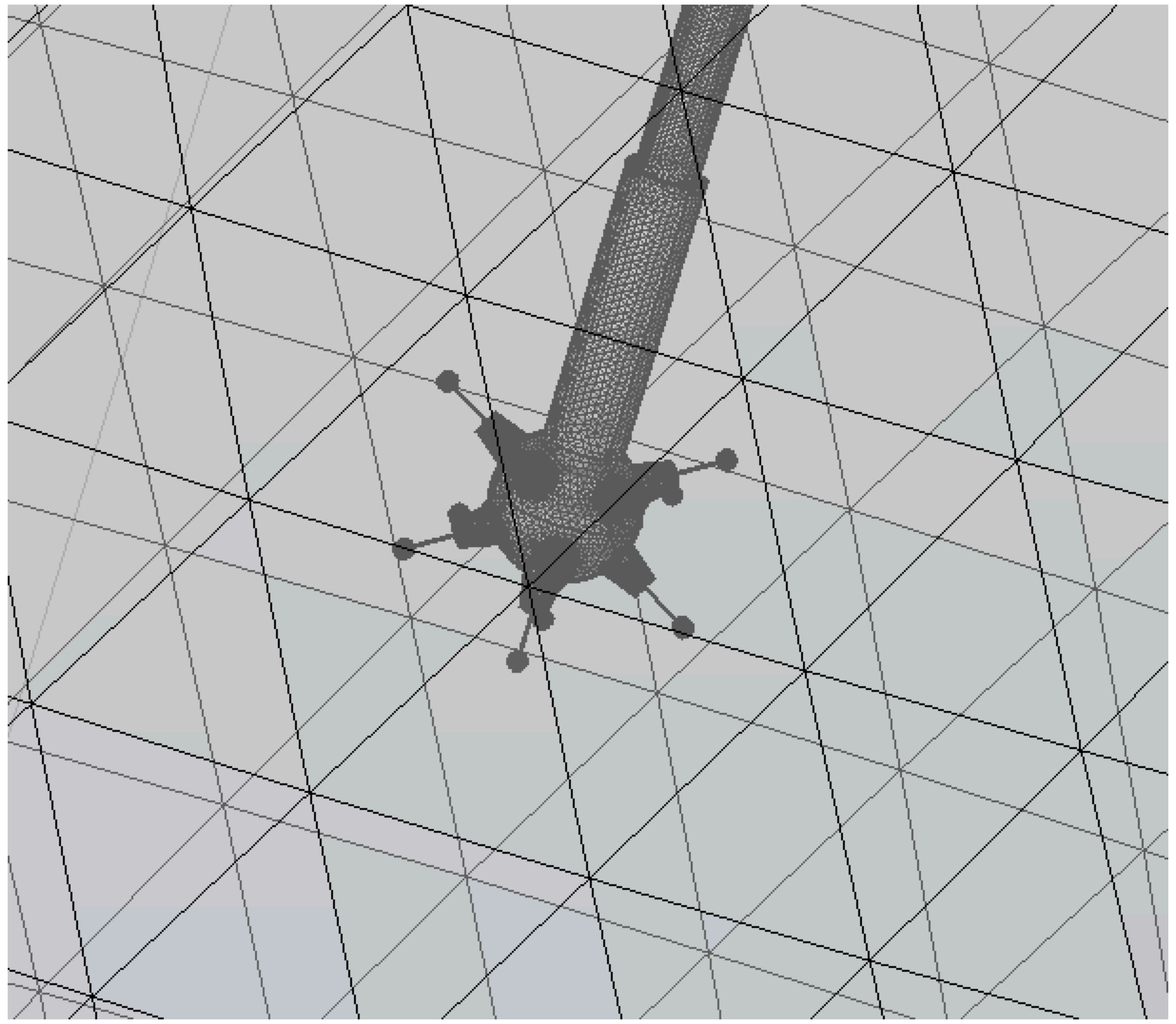
Step4: signal formation

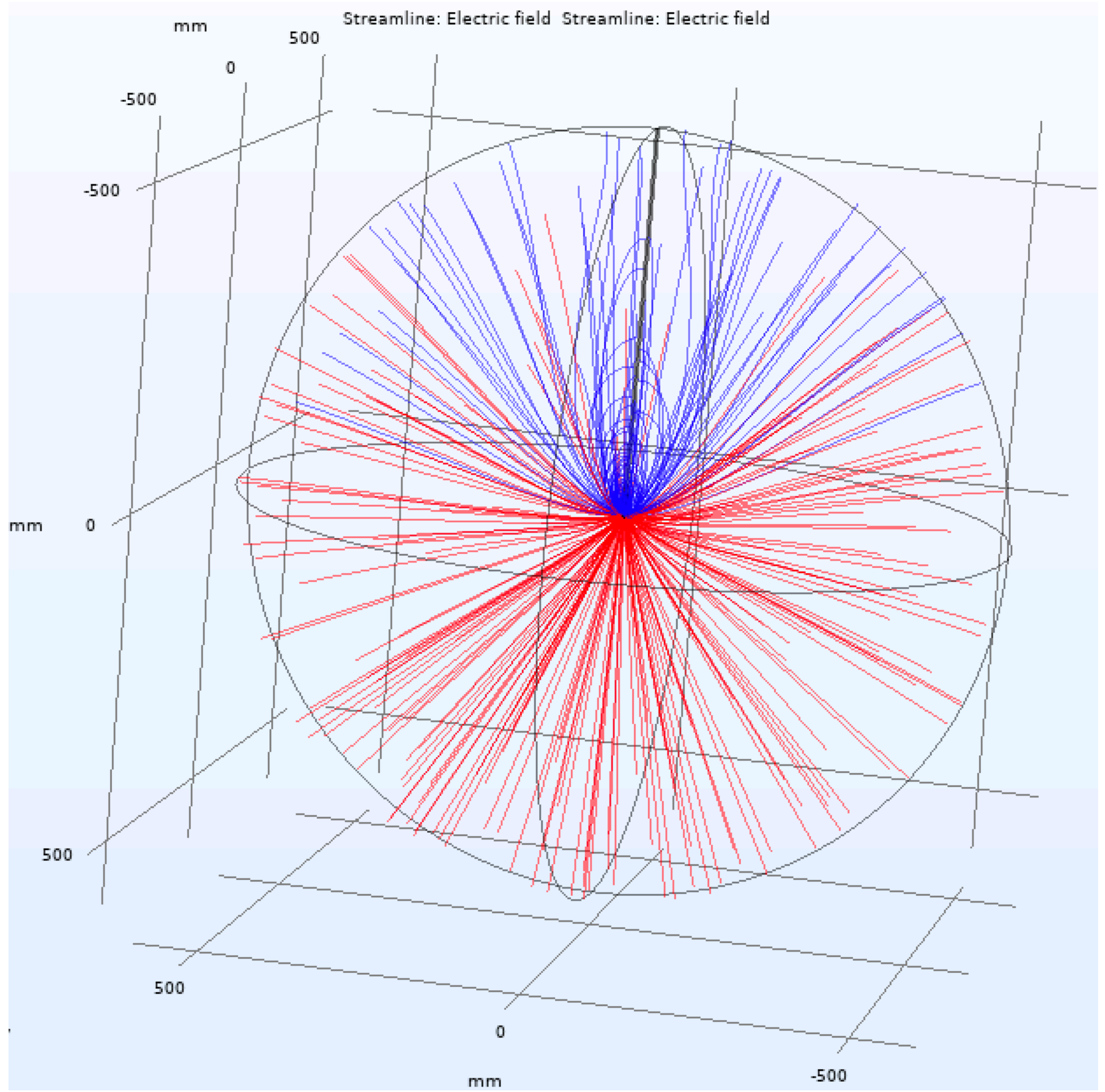
Rise time determined





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 measured by Daniel Durnford with pure CH4 under 135 mbar is 30 eV (for 2.8keV X-rays)

Step1: Electric field simulation: Finite element software COMSOL

Step2: Primary ionization

Step3: electron transportation

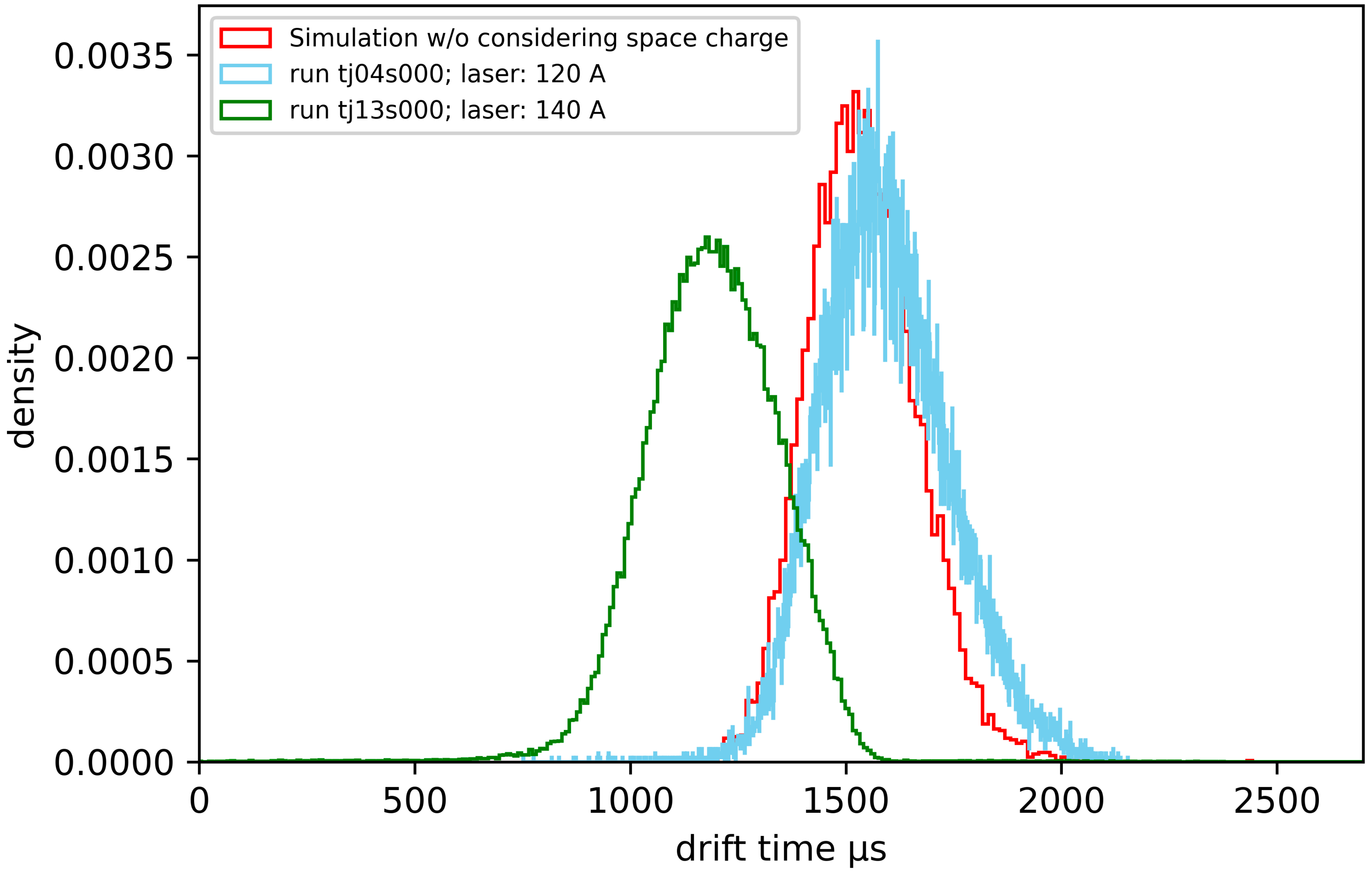
Electron drift time determined

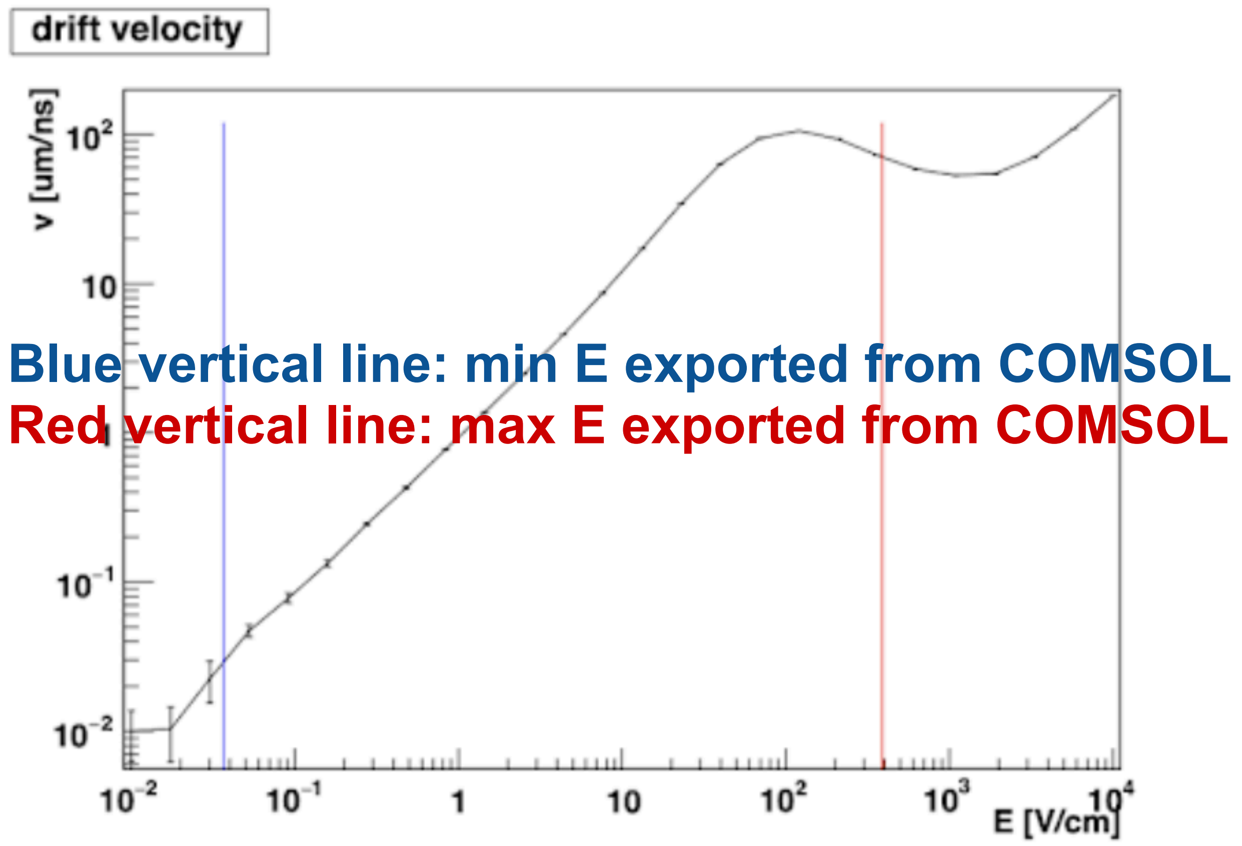
Step4: signal formation

Rise time determined

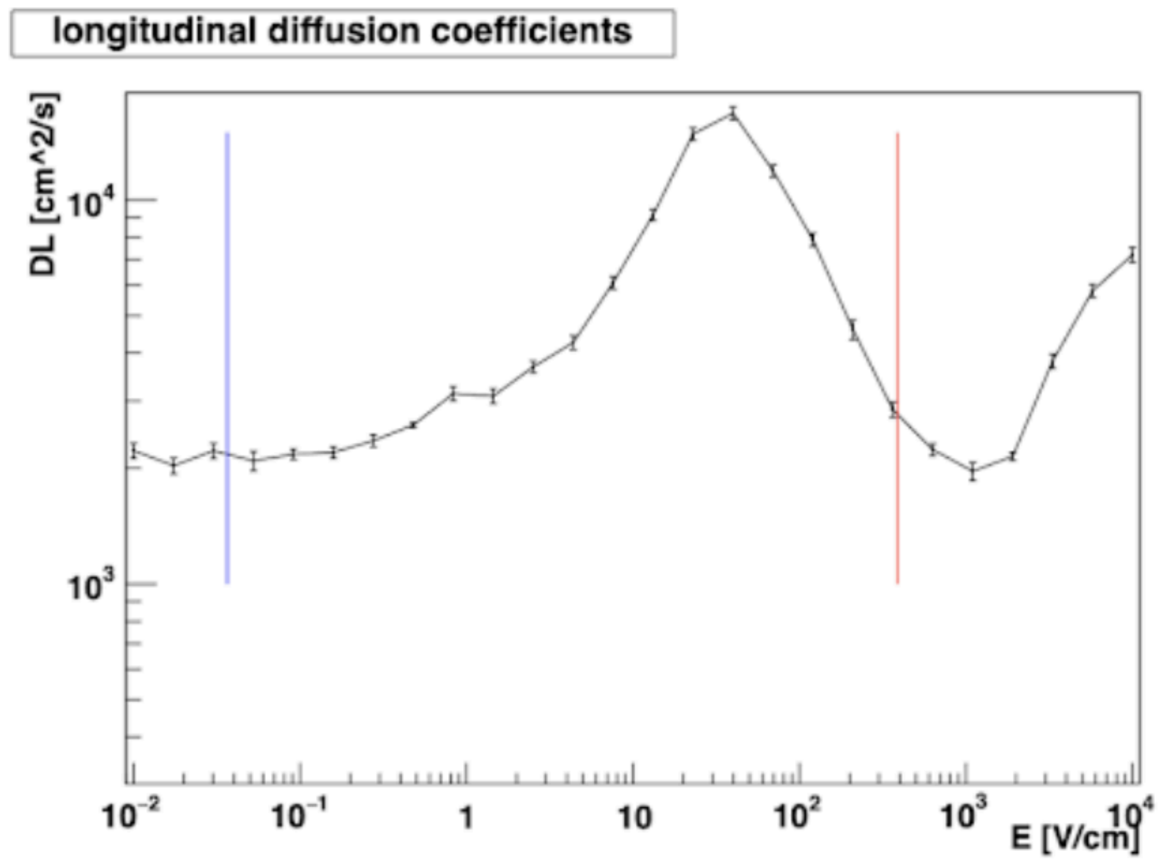
- **CERN simulation package: Magboltz:**
  - Output: drift parameters: drift velocities, longitudinal/ transverse diffusion coefficients
- **Monte Carlo Integration method to determine the drift time**

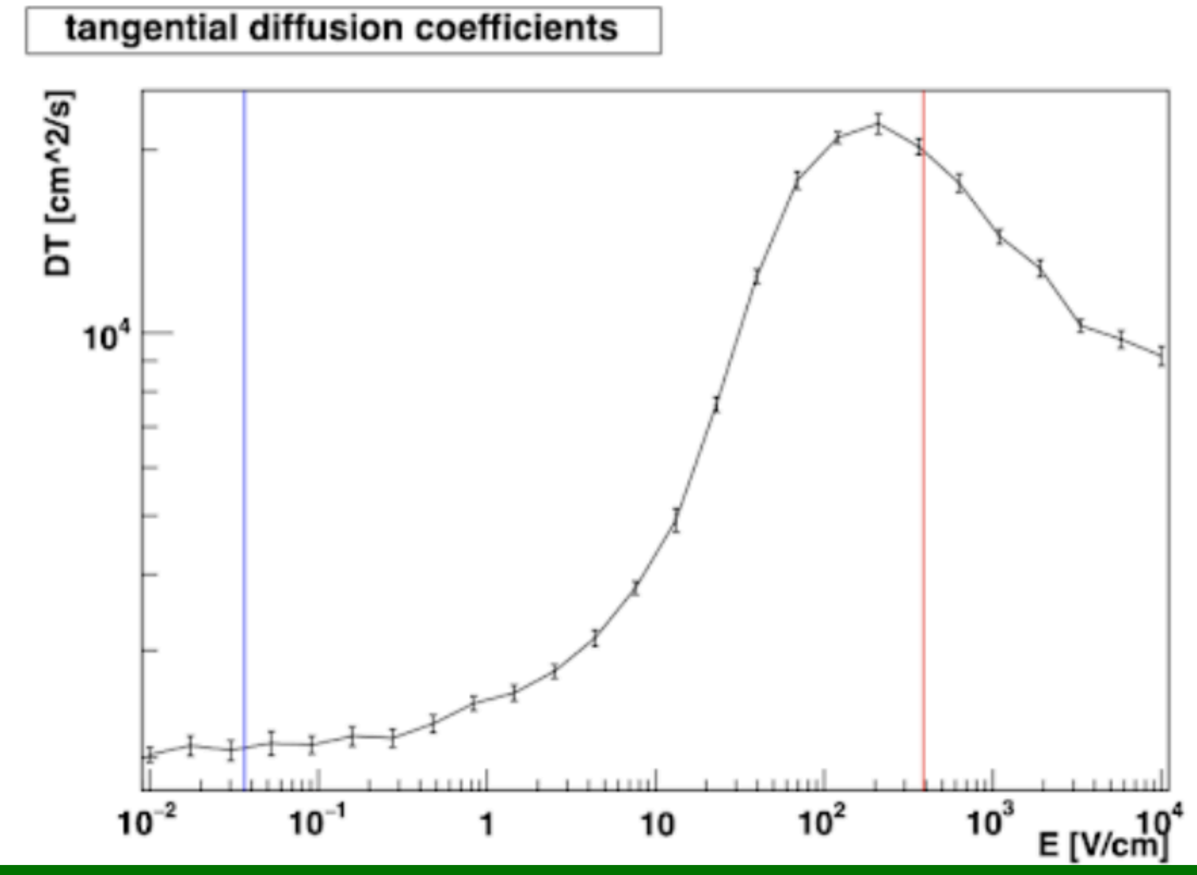
120A and 140 A laser drift time data compare with laser events drift time simulation without considering space charge





Blue vertical line: min E exported from COMSOL
Red vertical line: max E exported from COMSOL





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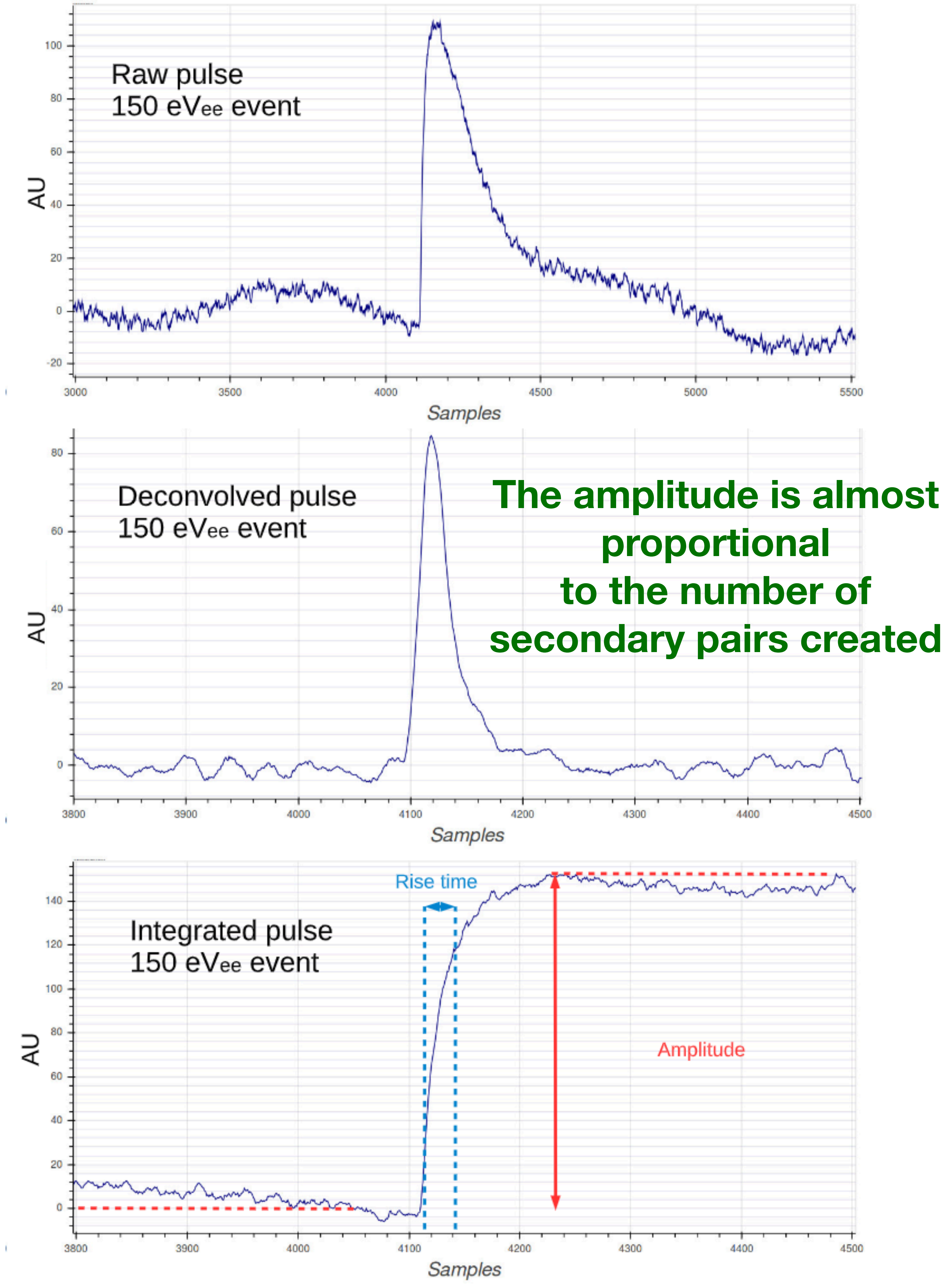

- **Secondary ionization:**
  - PEs reaching high E field region will gain enough kinetic energy from collisions with gas molecules to ionize the gas and create secondary electron/ion pairs
  - Number of secondary ionizations can be parametrized by Polya distribution:

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

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

Step1: Electric field simulation: Finite element software COMSOL

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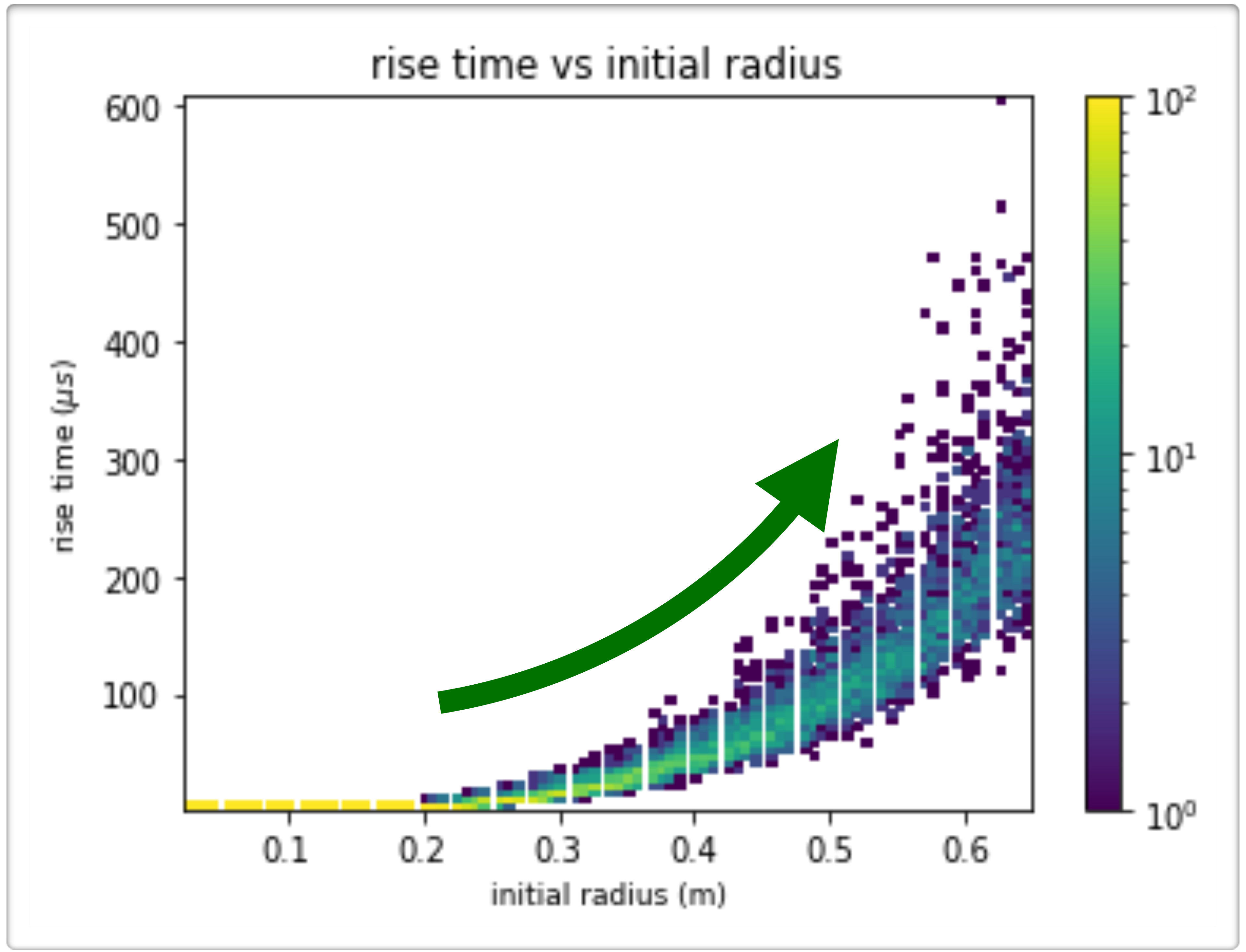

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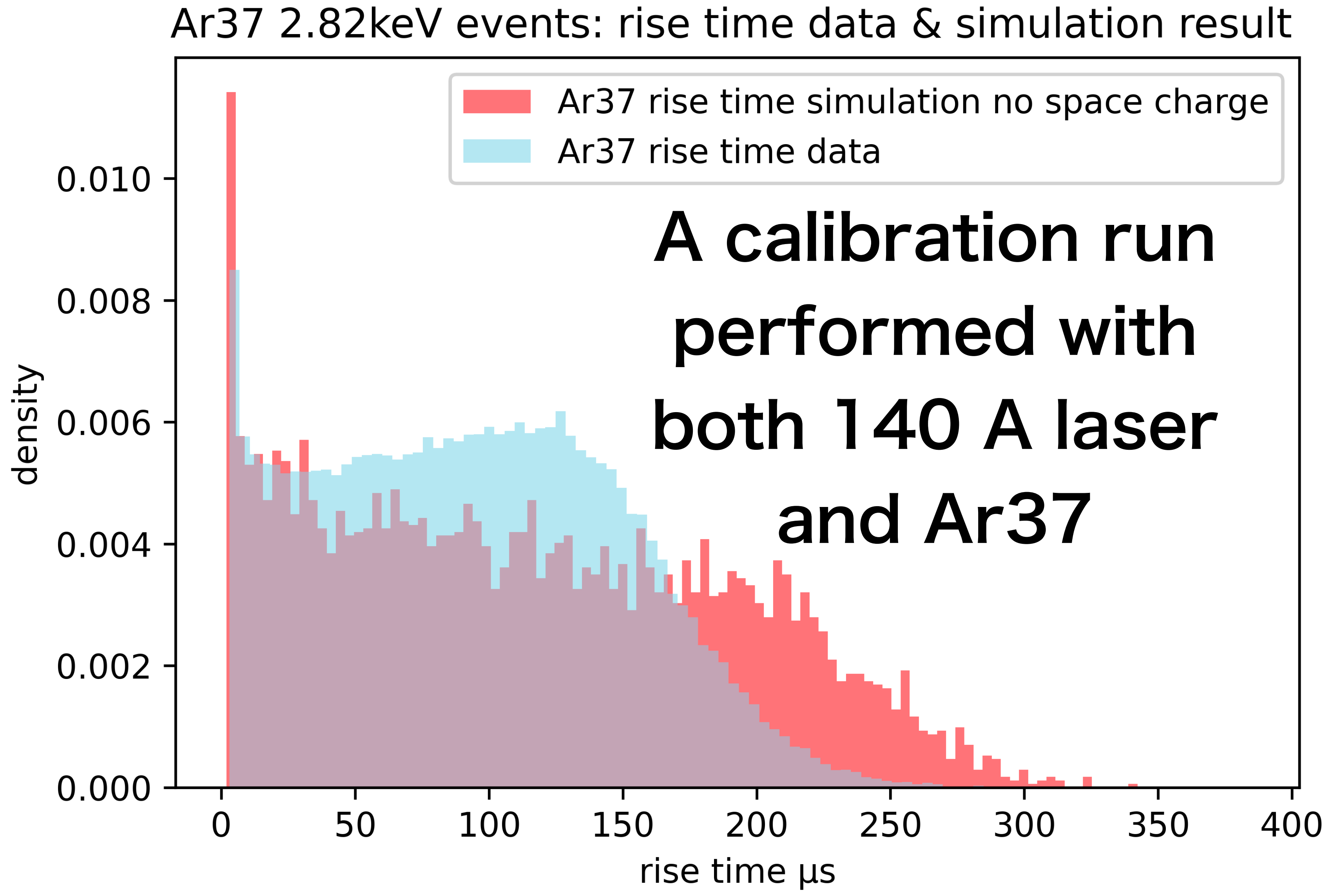
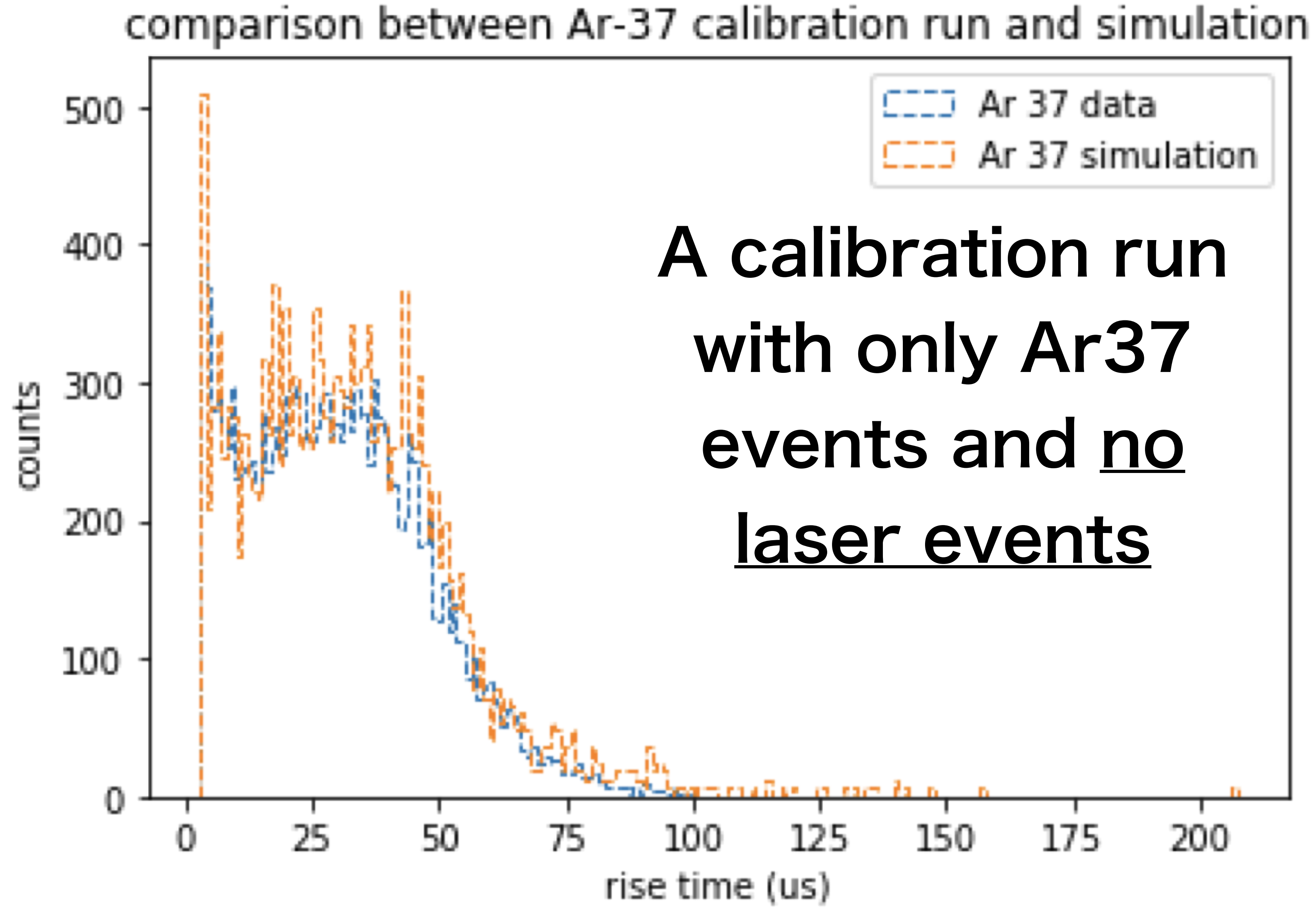
- **Rise time: time difference between 75% and 10% of the amplitude**
  - represents how much diffusion the charges undergo; Higher starting point results in more dispersion of charges
  - Discriminate bulk events and surface events

Ar37 events rise time simulation: events uniformly distributed in sphere

Same method



Larger volume : higher Ar37 event rate

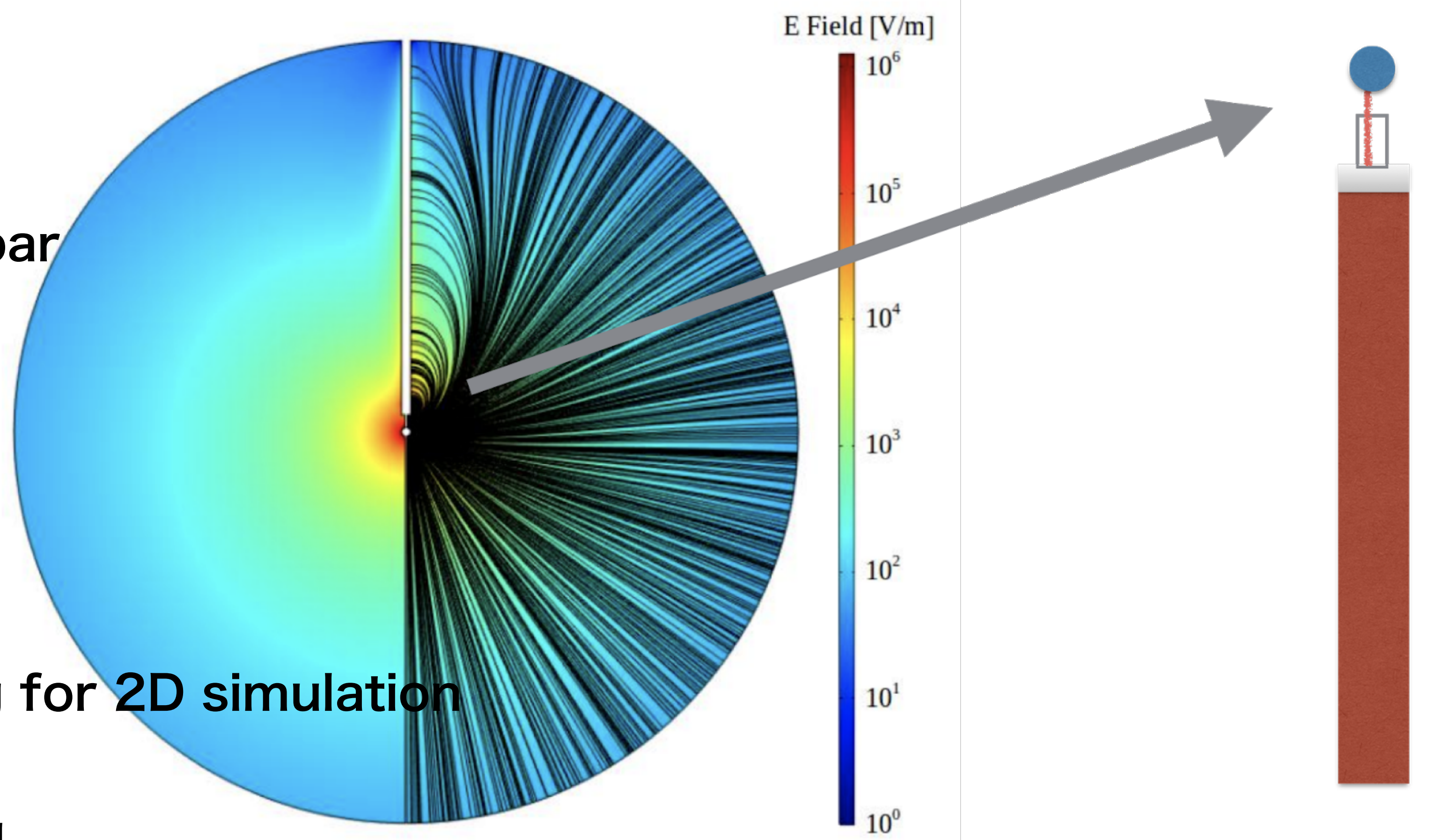


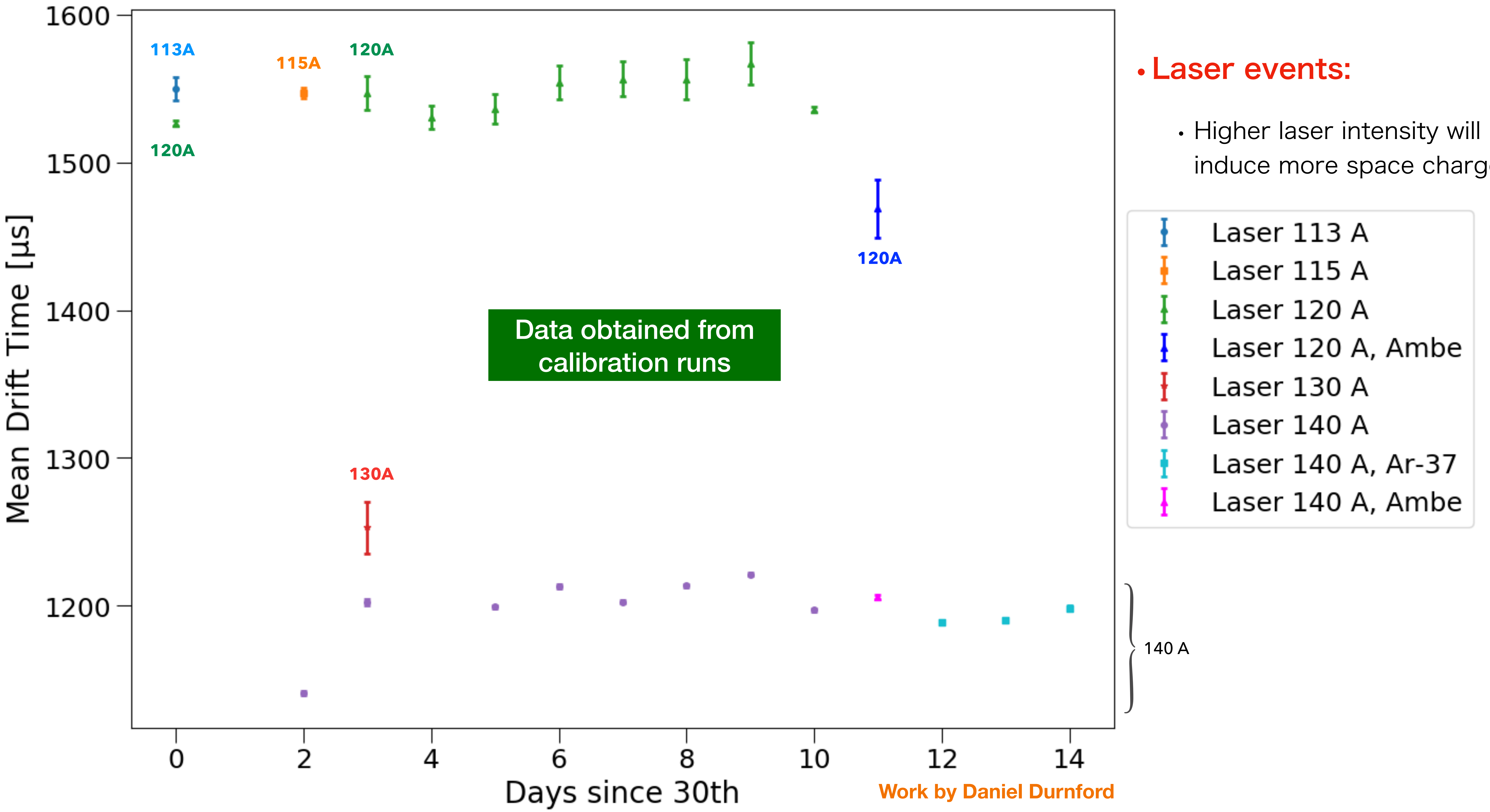
Simulation for SNOGLOBE

- Tuning the model used for primary ionization or creating 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% CH4 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

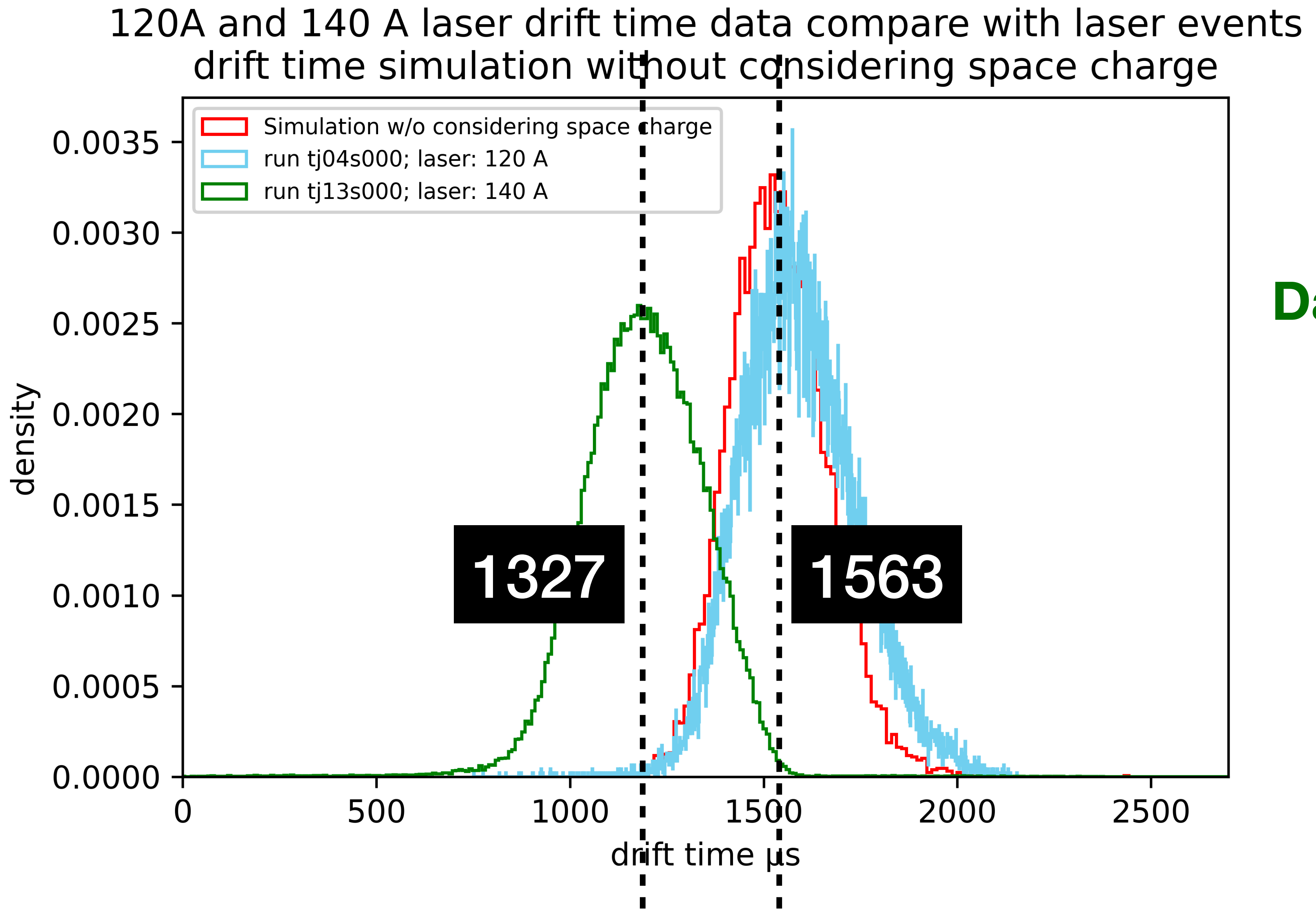




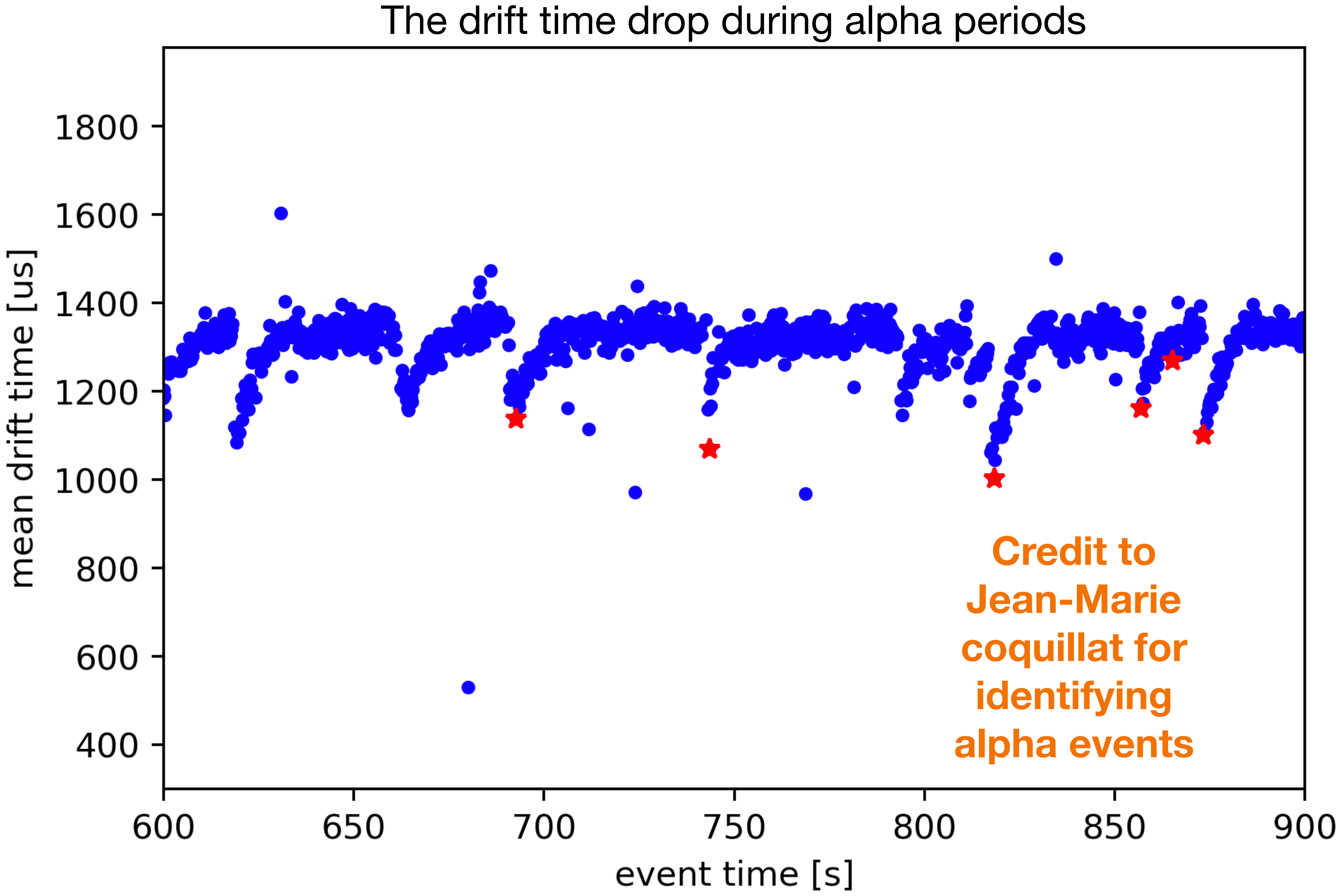
- **Laser events:**
  - Higher laser intensity will induce more space charge

- **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



Data obtained from calibration runs



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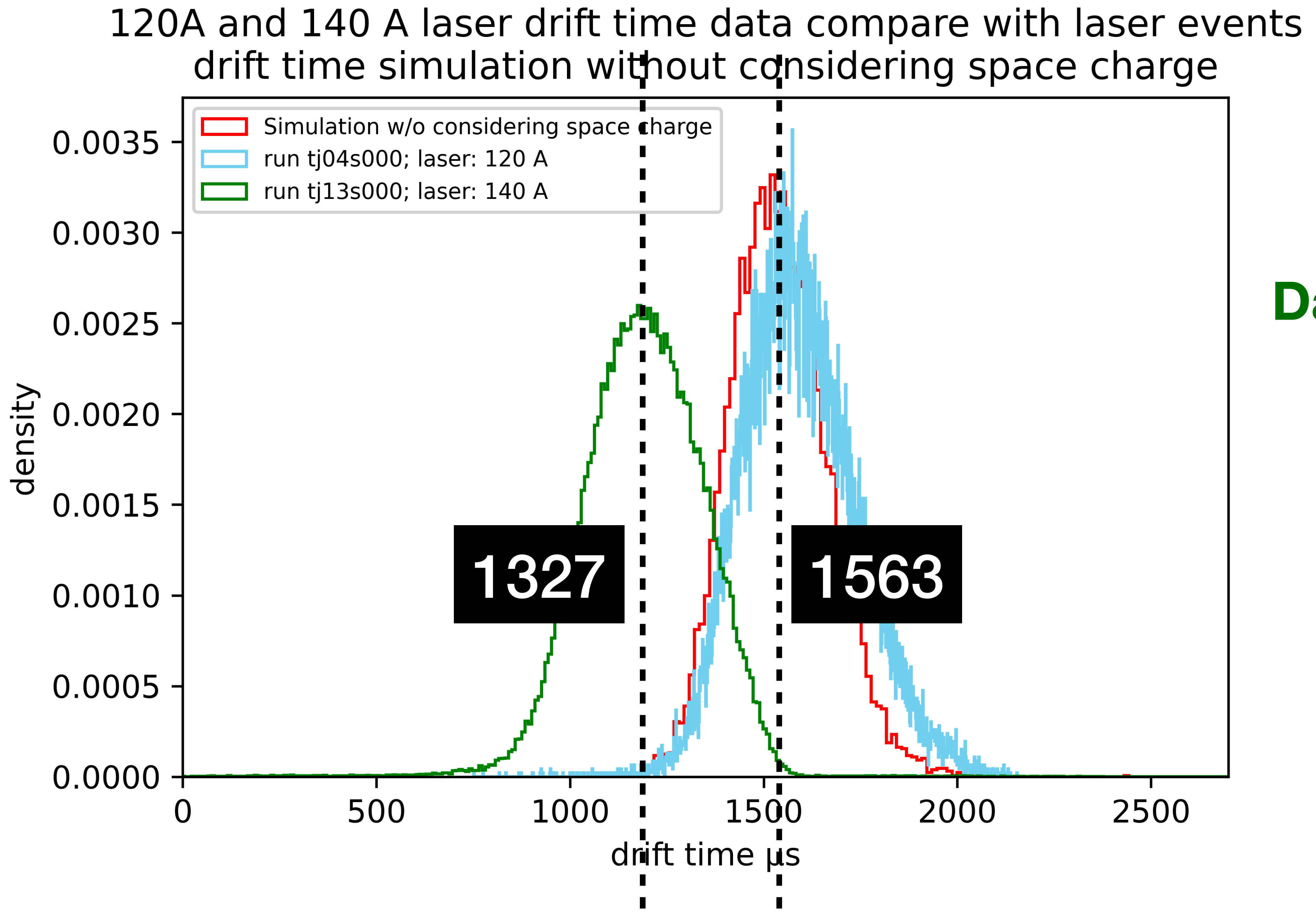

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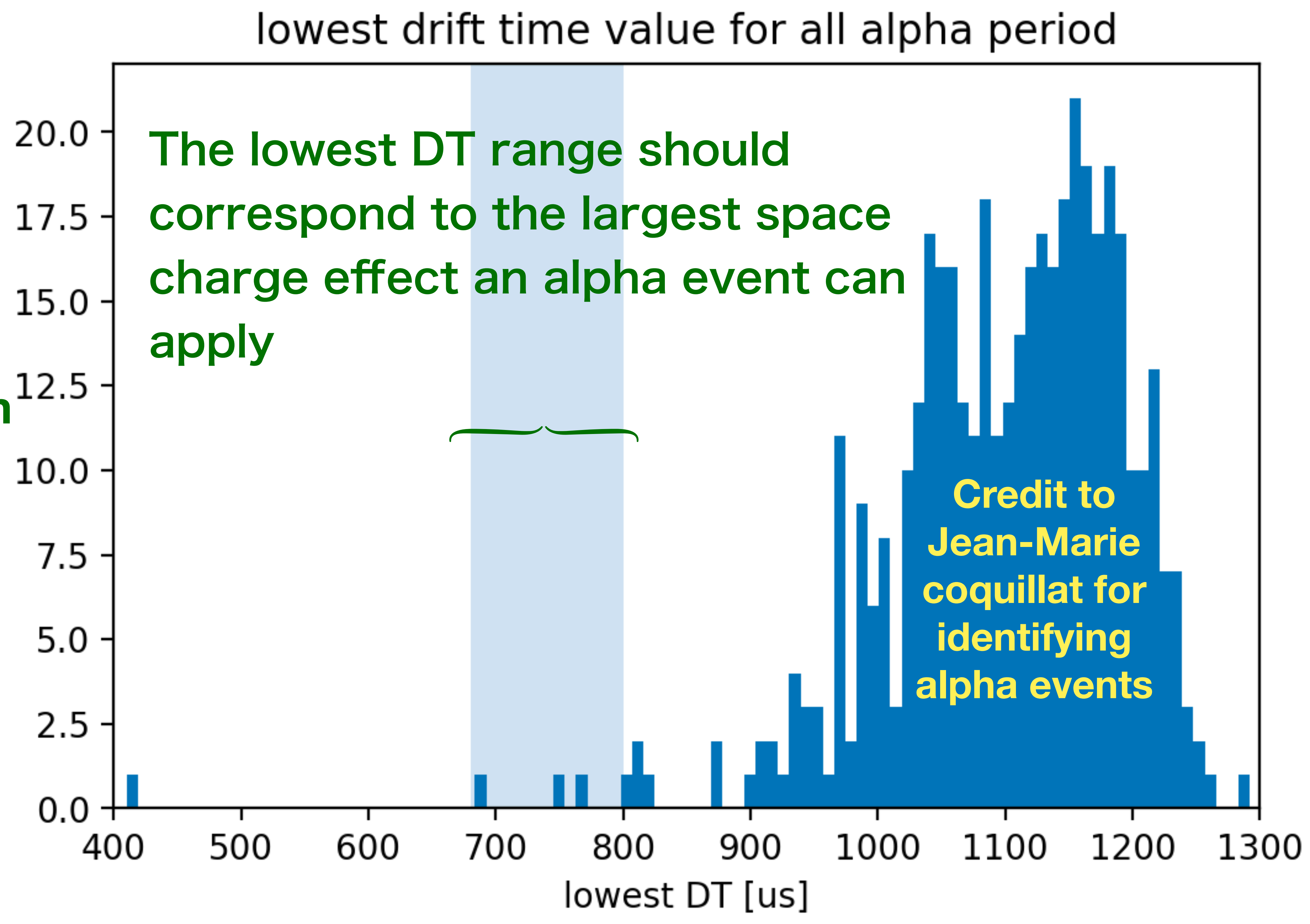
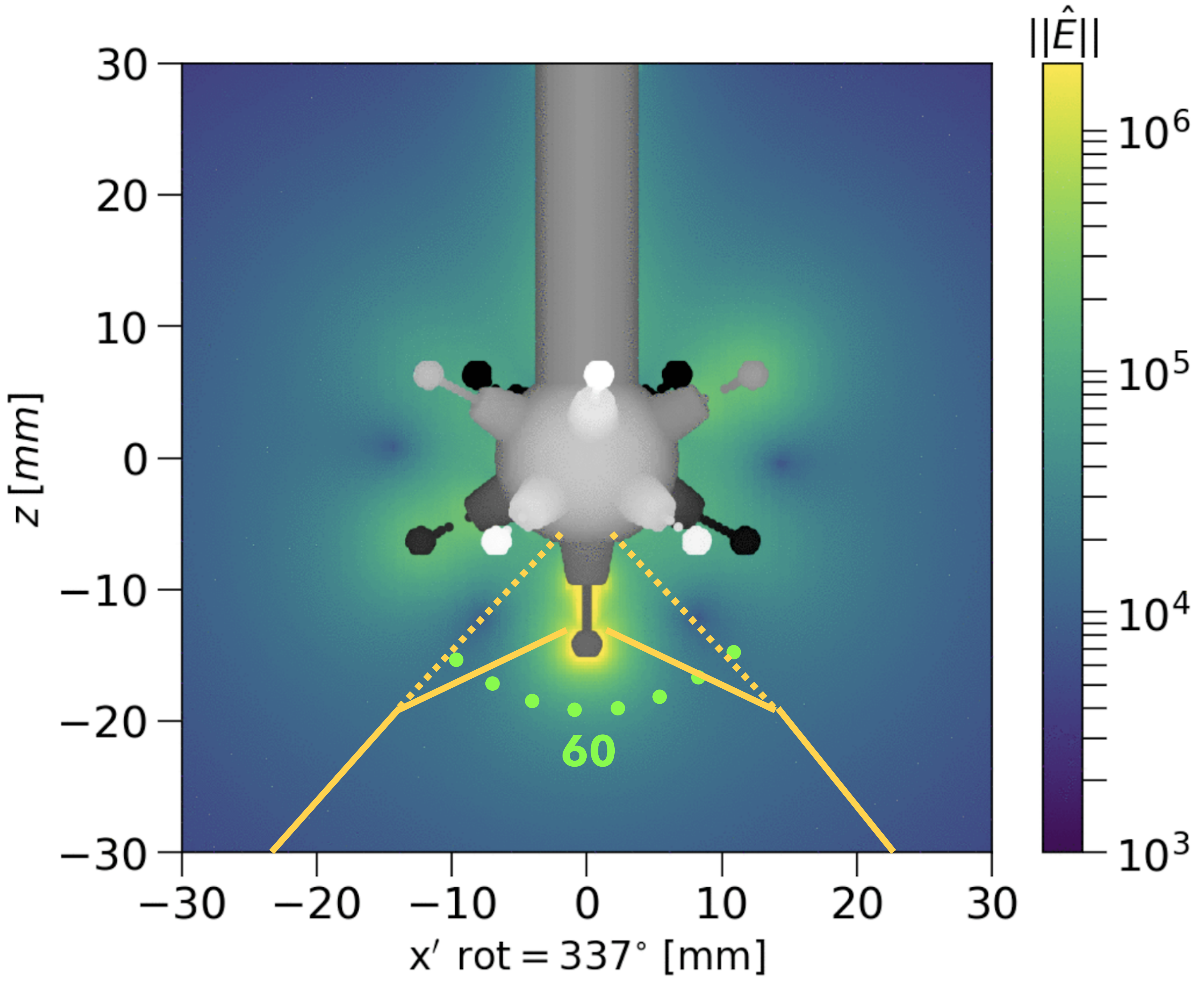
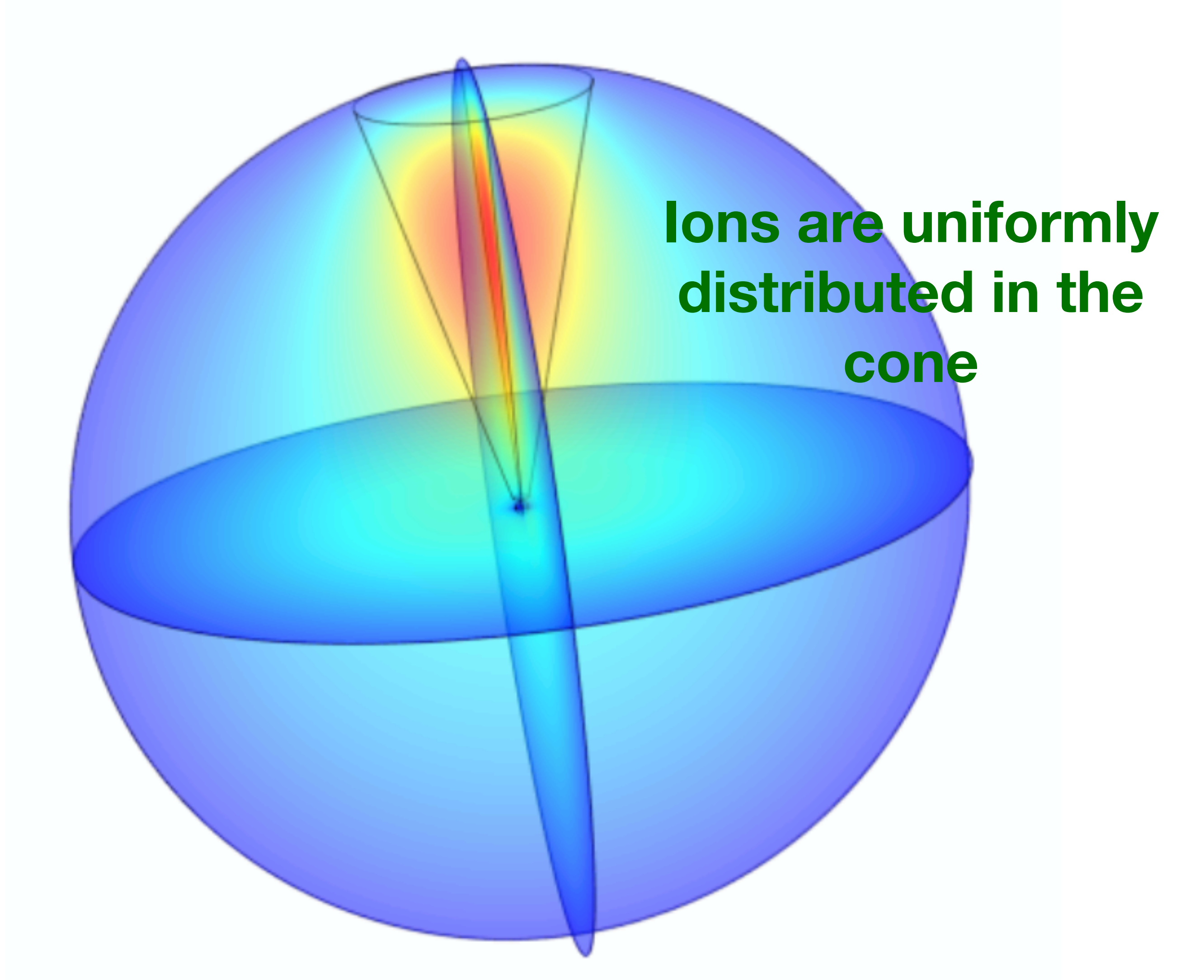
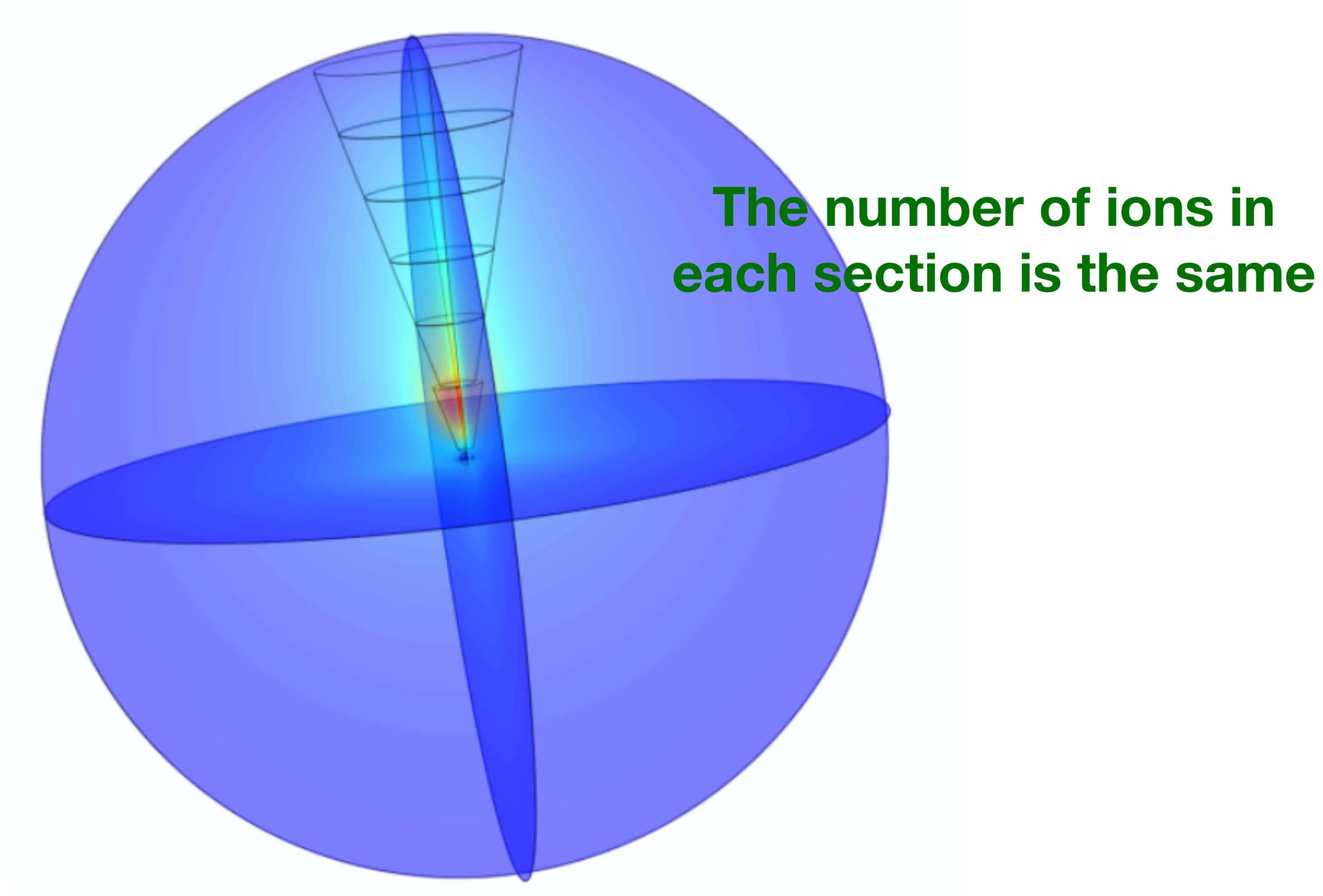
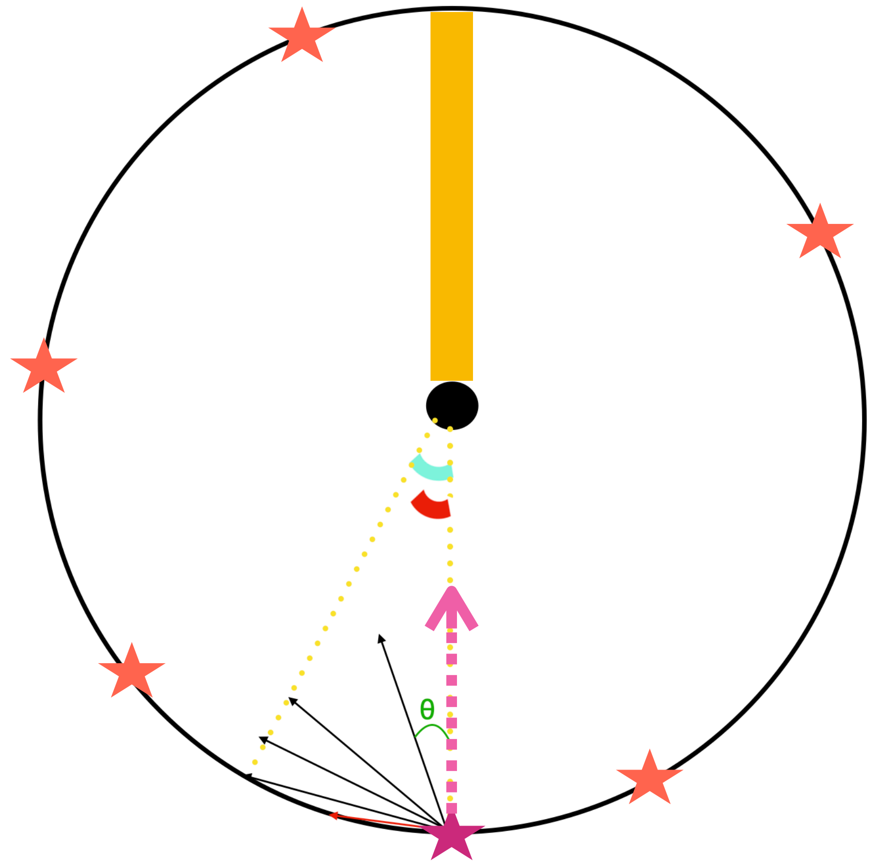


- COMSOL Efield simulation:
    - Specify the volume charge density for certain geometry
    - Geometry: Cone
    - Two different ways of distributing space charges (plots below)
    - Different simulations has been done for various open angle of the cone (10, 30, 60 degree), and various number of ions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

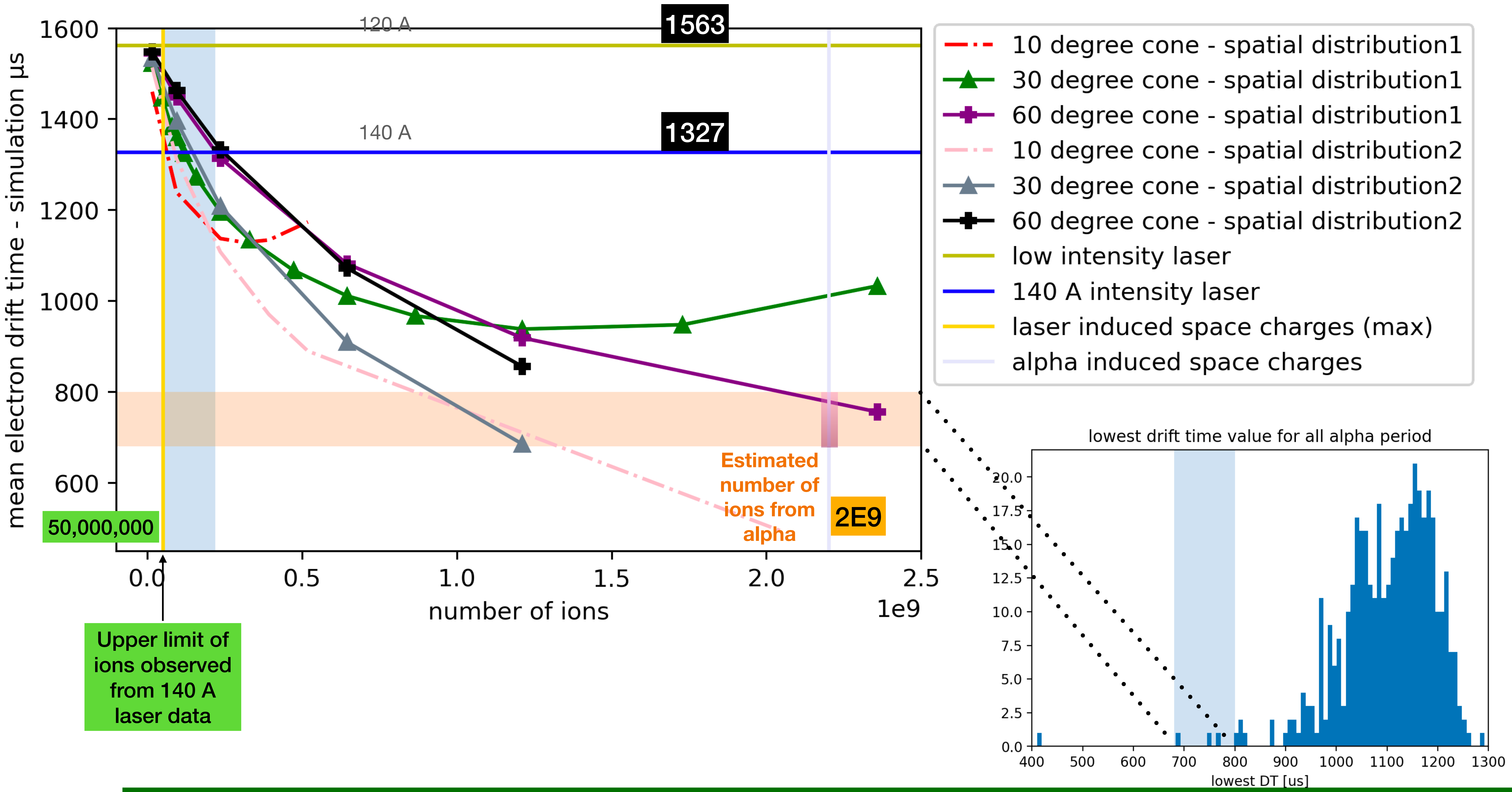


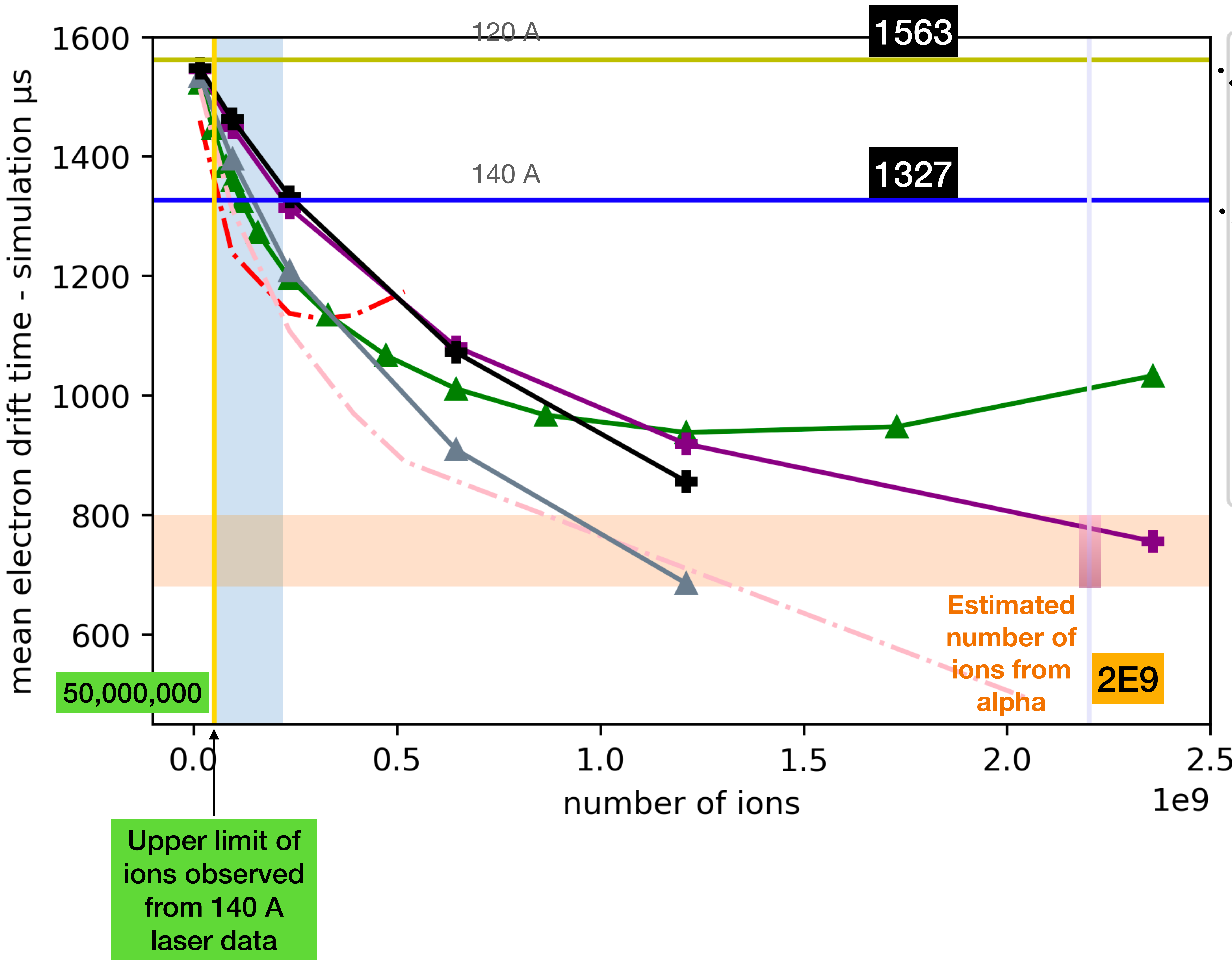






Alpha events and laser events originating from very south point and pointing towards the centre will have the largest space charge effect


1600
1400
1200
1000
800
600
mean electron drift time - simulation µs
120 A
140 A
1563
1327
50,000,000
Estimated number of ions from alpha
2E9
0.0
0.5
1.0
1.5
2.0
2.5
1e9
number of ions
10 degree cone - spatial distribution1
30 degree cone - spatial distribution1
60 degree cone - spatial distribution1
10 degree cone - spatial distribution2
30 degree cone - spatial distribution2
60 degree cone - spatial distribution2
low intensity laser
140 A intensity laser
laser induced space charges (max)
alpha induced space charges
Upper limit of ions observed from 140 A laser data
lowest drift time value for all alpha period
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
400
500
600
700
800
900
1000
1100
1200
1300
lowest DT [us]



1563
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mean electron drift time - simulation μs
1600
1400
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0.0
0.5
1.0
1.5
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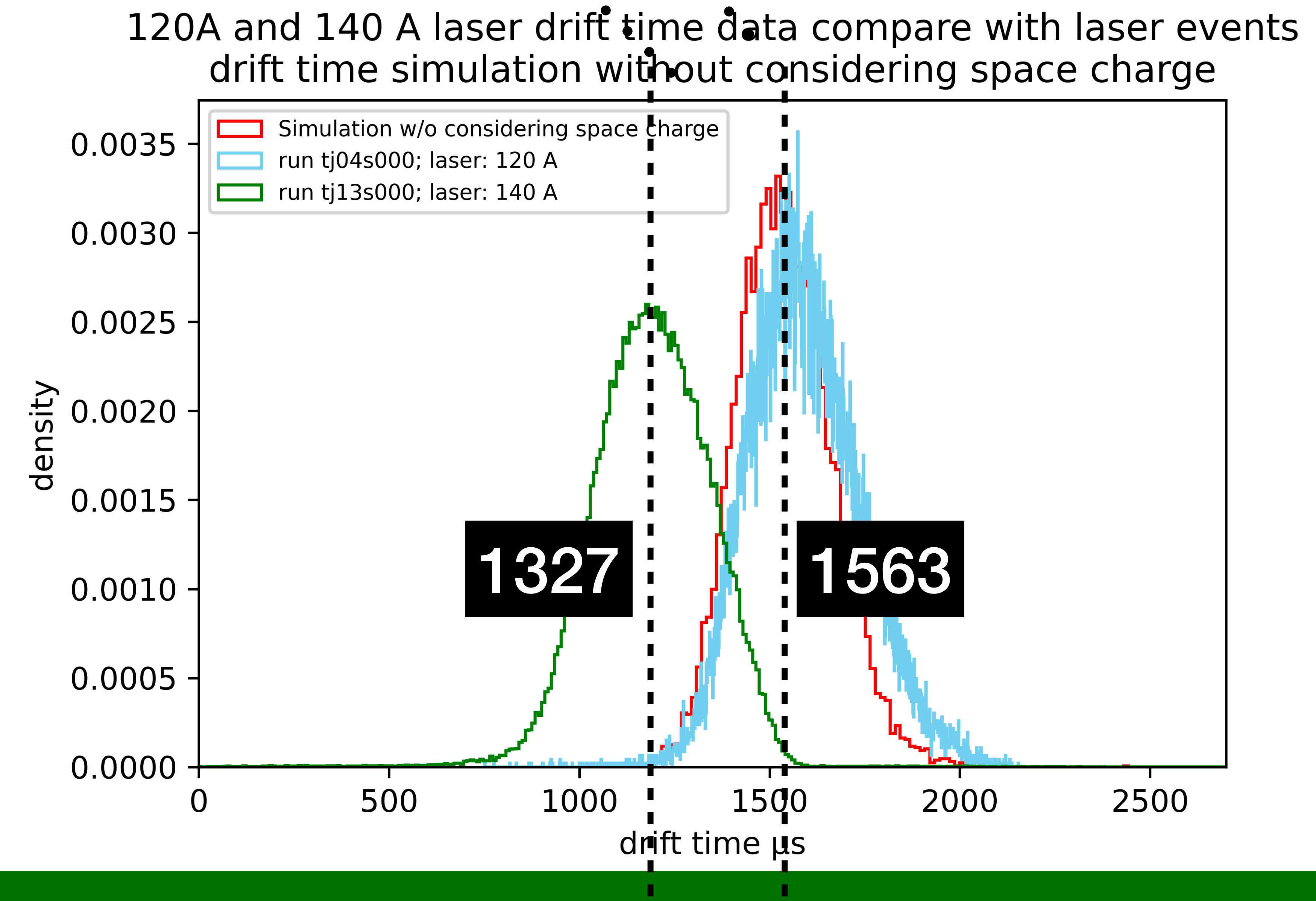
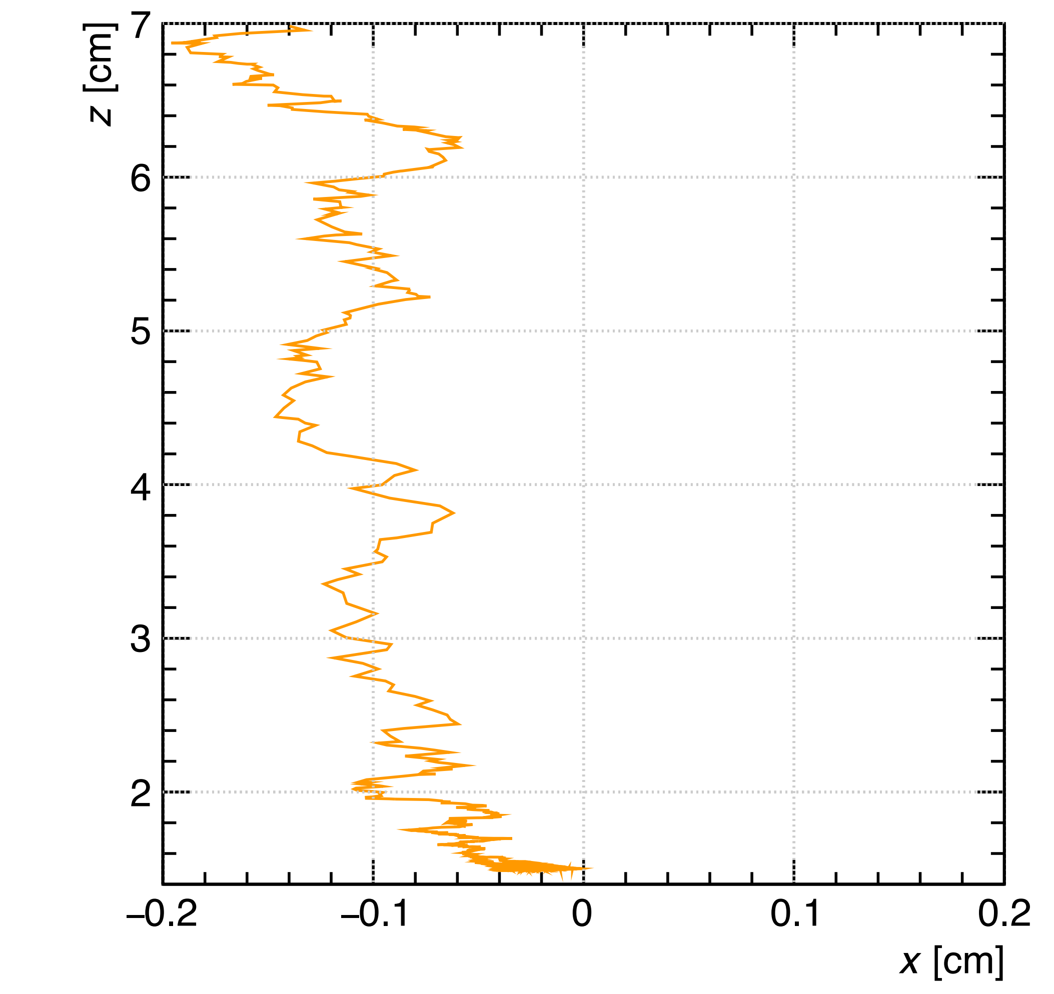
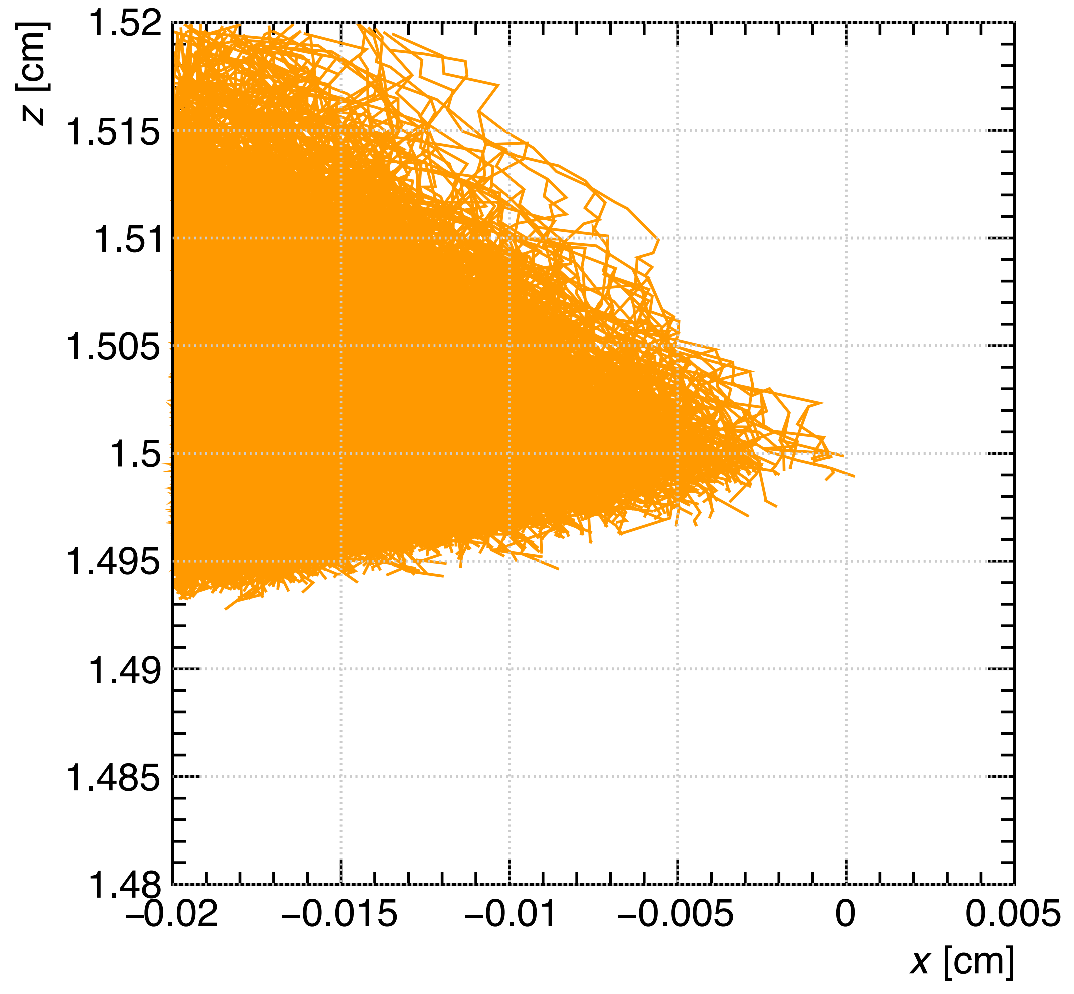
2.5
1e9
number of ions
50,000,000
Estimated number of ions from alpha
2E9
Upper limit of ions observed from 140 A laser data
10 degree cone - spatial distribution1
30 degree cone - spatial distribution1
60 degree cone - spatial distribution1
10 degree cone - spatial distribution2
30 degree cone - spatial distribution2
60 degree cone - spatial distribution2
low intensity laser
140 A intensity laser
laser induced space charges (max)
alpha induced space charges



120A and 140 A laser drift time data compare with laser events drift time simulation without considering space charge
Simulation w/o considering space charge
run tj04s000; laser: 120 A
run tj13s000; laser: 140 A
density
drift time μs
1327
1563



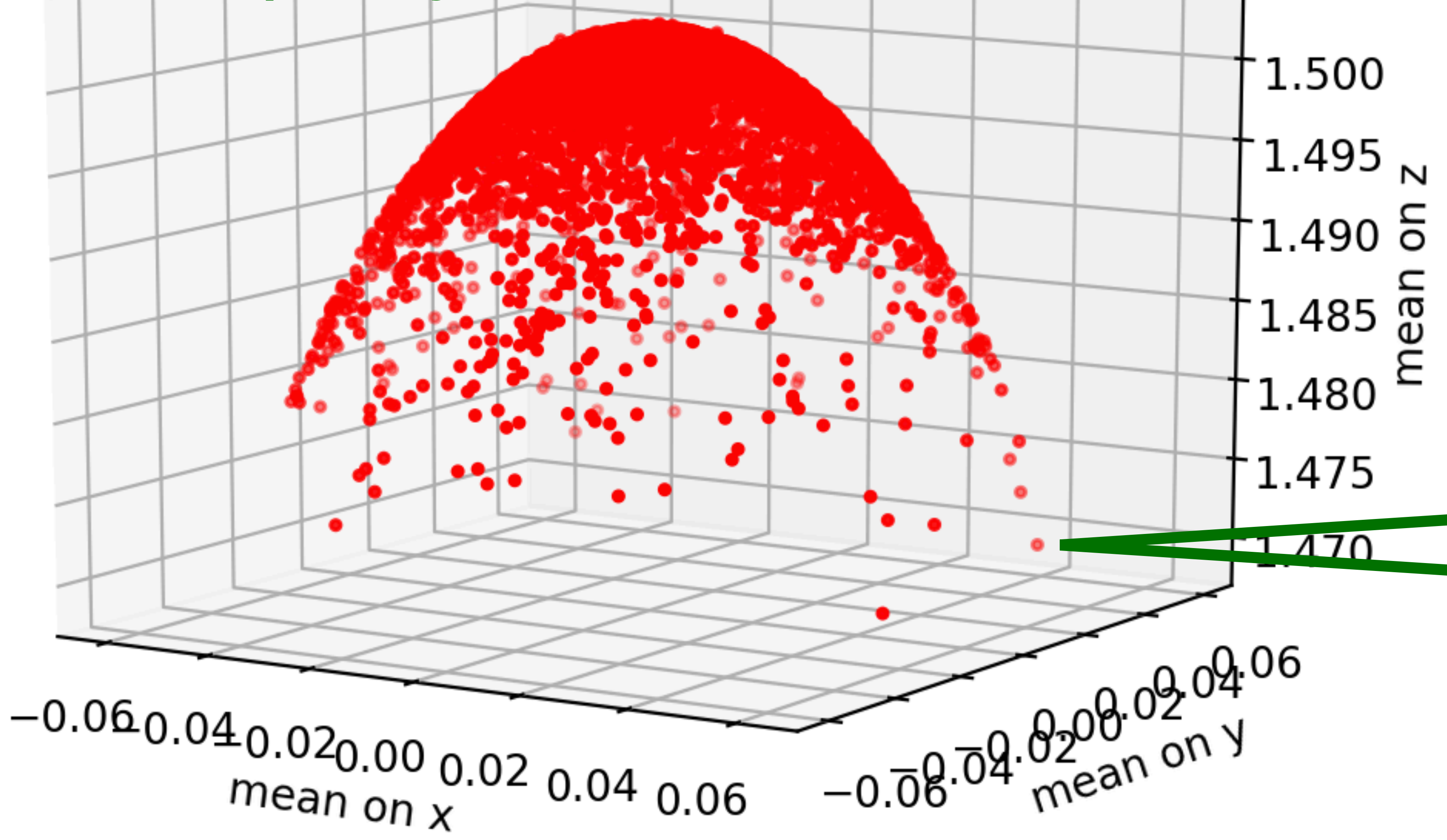


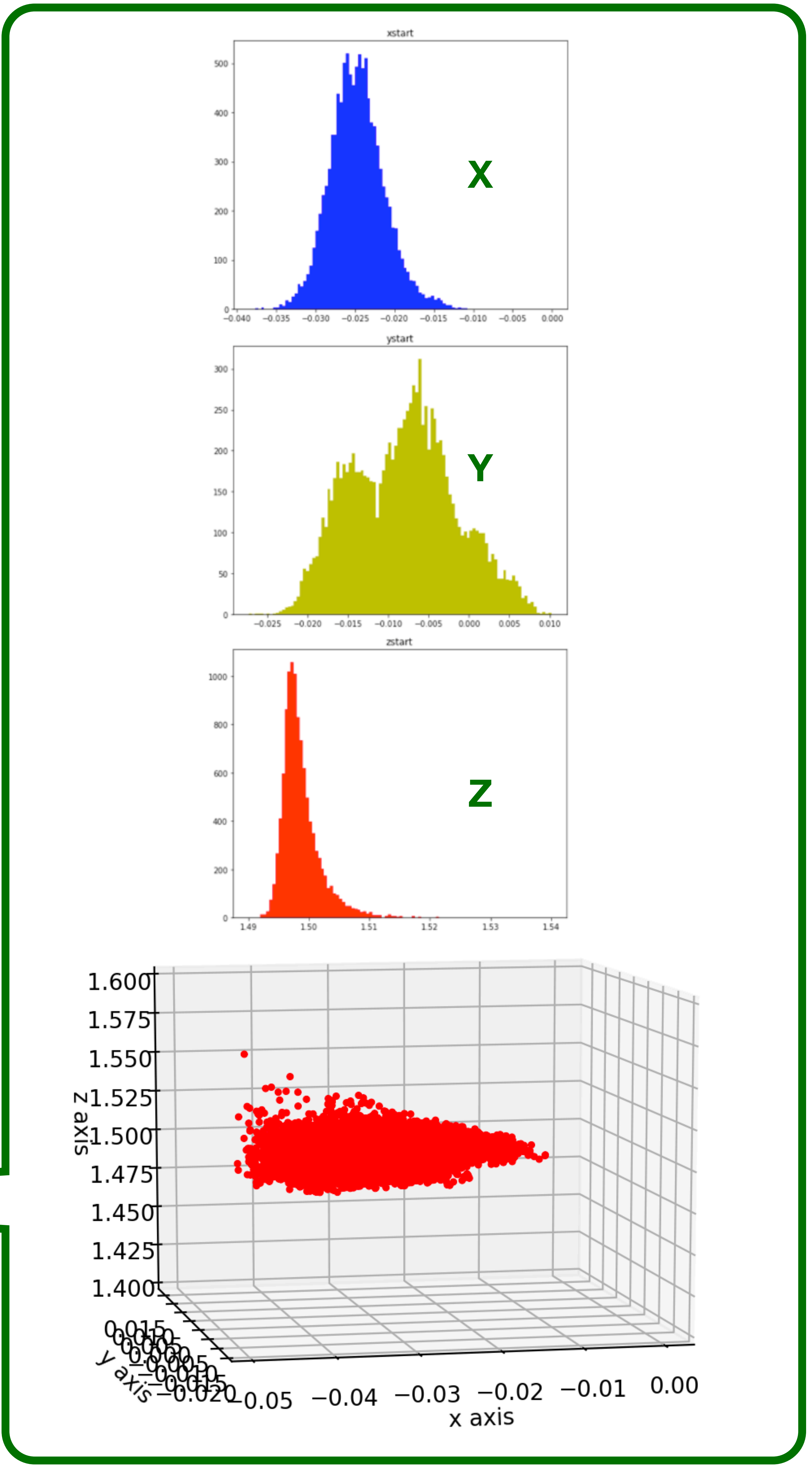
Drift lines of one primary electron's avalanche process

Garfield++ simulation

- Monte Carlo Integration method is applied before drifting to high amplification region;
- Microscopic tracking method is used for simulating avalanche
    - Spatial distribution of ions
    - Number of space charges created for every step

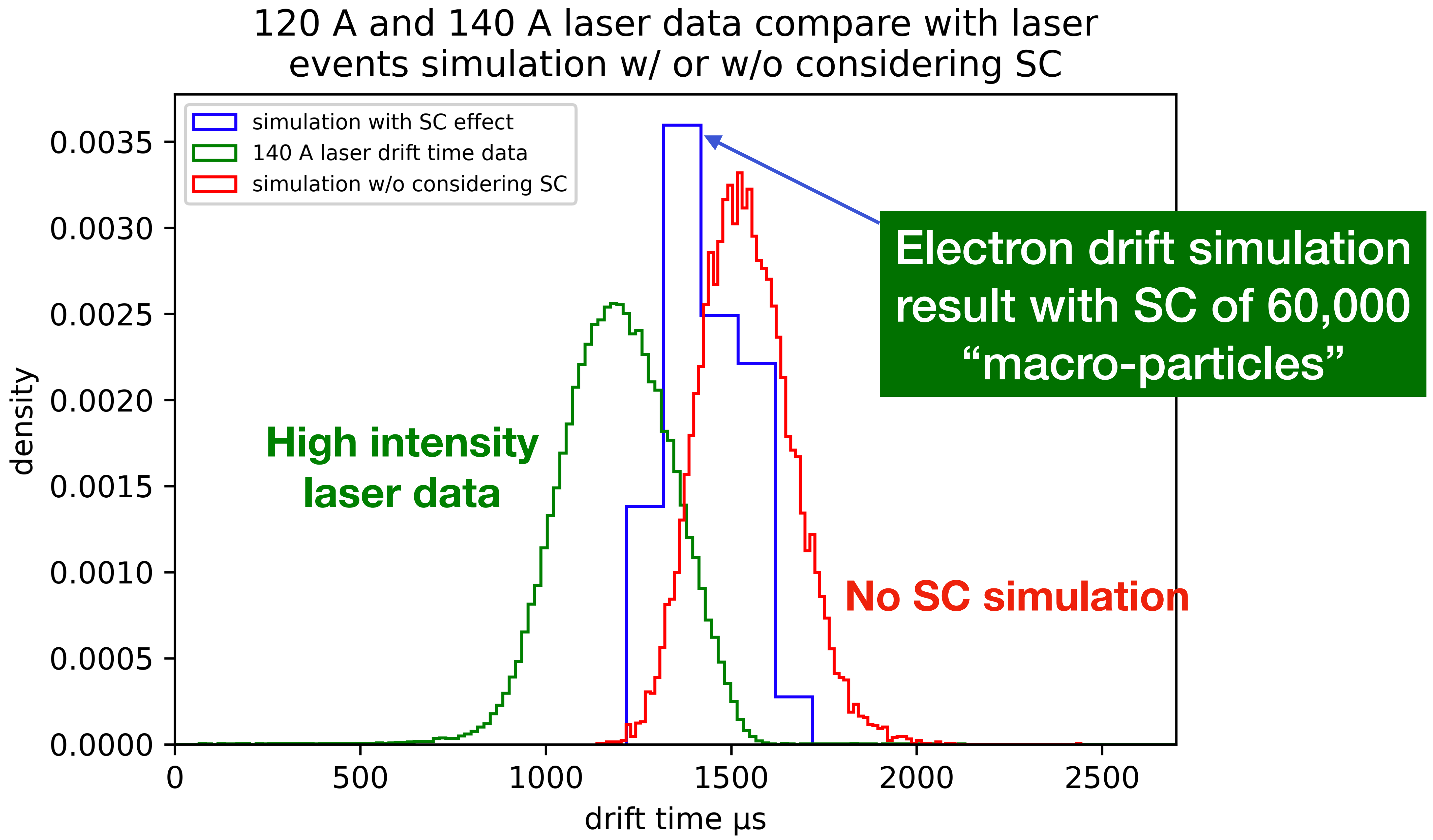
~ 50,000 primary electron's avalanche distribution





Self consistent ion drift motion simulation:

- Inter-particle coulomb force should be included;
  - Parallel programs that can exchange information on multi-core machines are needed to calculate space charge effect
- Consider drifting ions as in the form of “macro-particle”
  - Take into account the various ion mobilities of all possible ion species in methane
  - High resolution needed

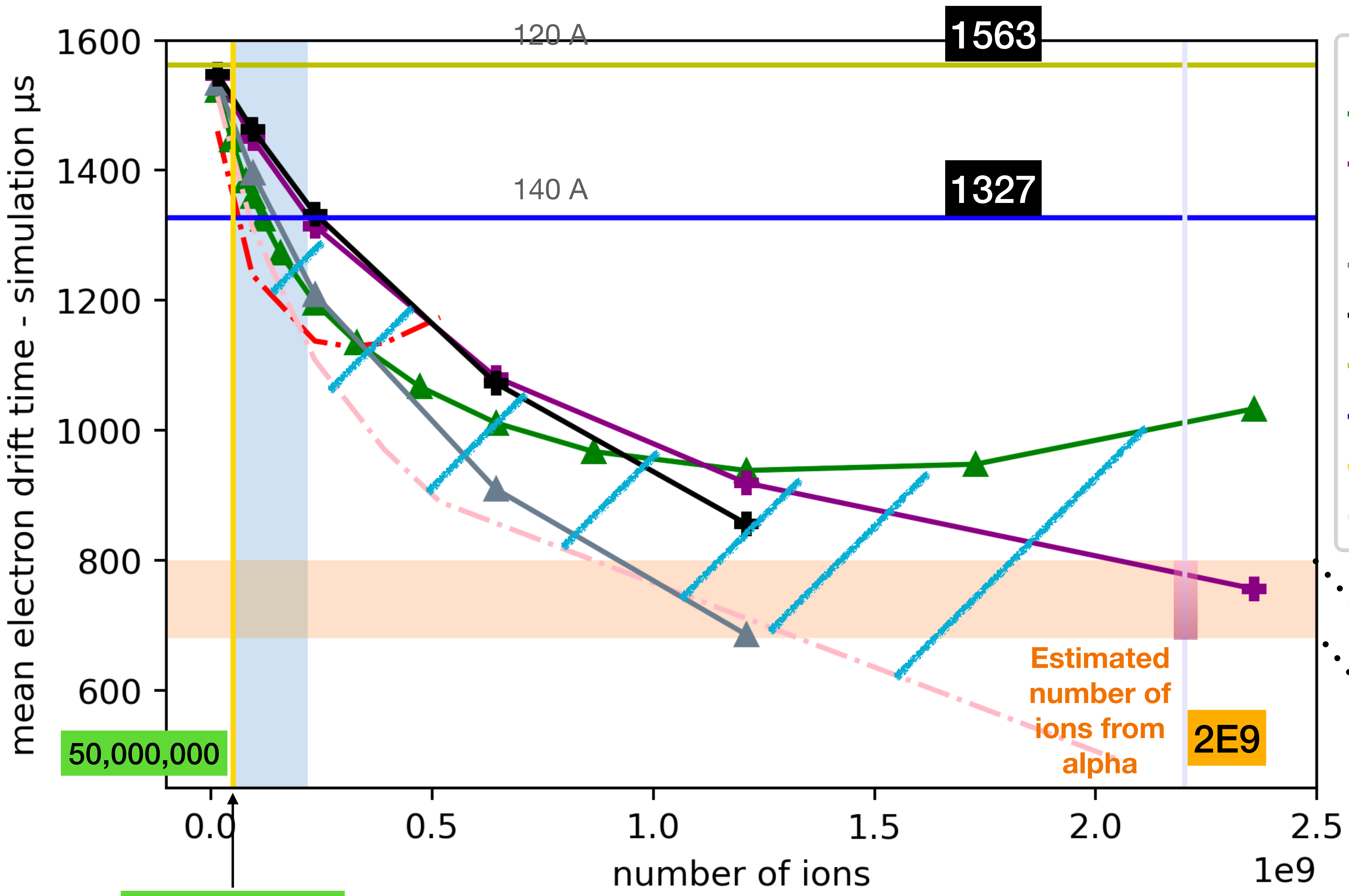


Experimental efforts

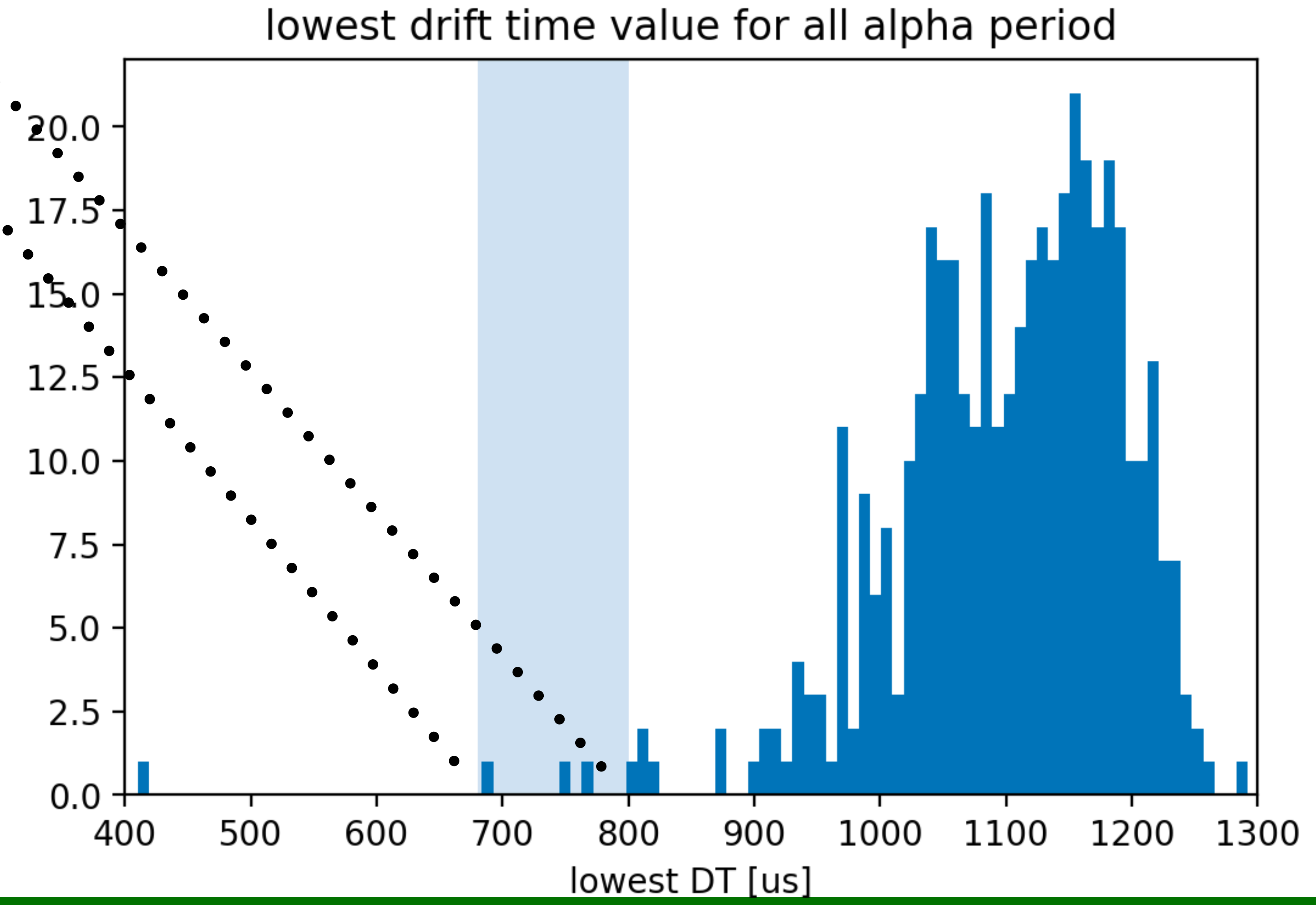
- More dedicated physics runs will be taken (U of A)
  - Use Ar37 source only without triggering laser (rise time simulation)
  - Take more runs with various laser intensities
  - Collect drift time data immediately after triggering the laser for studying space charge accumulation process
  - Choose 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

Thank you!

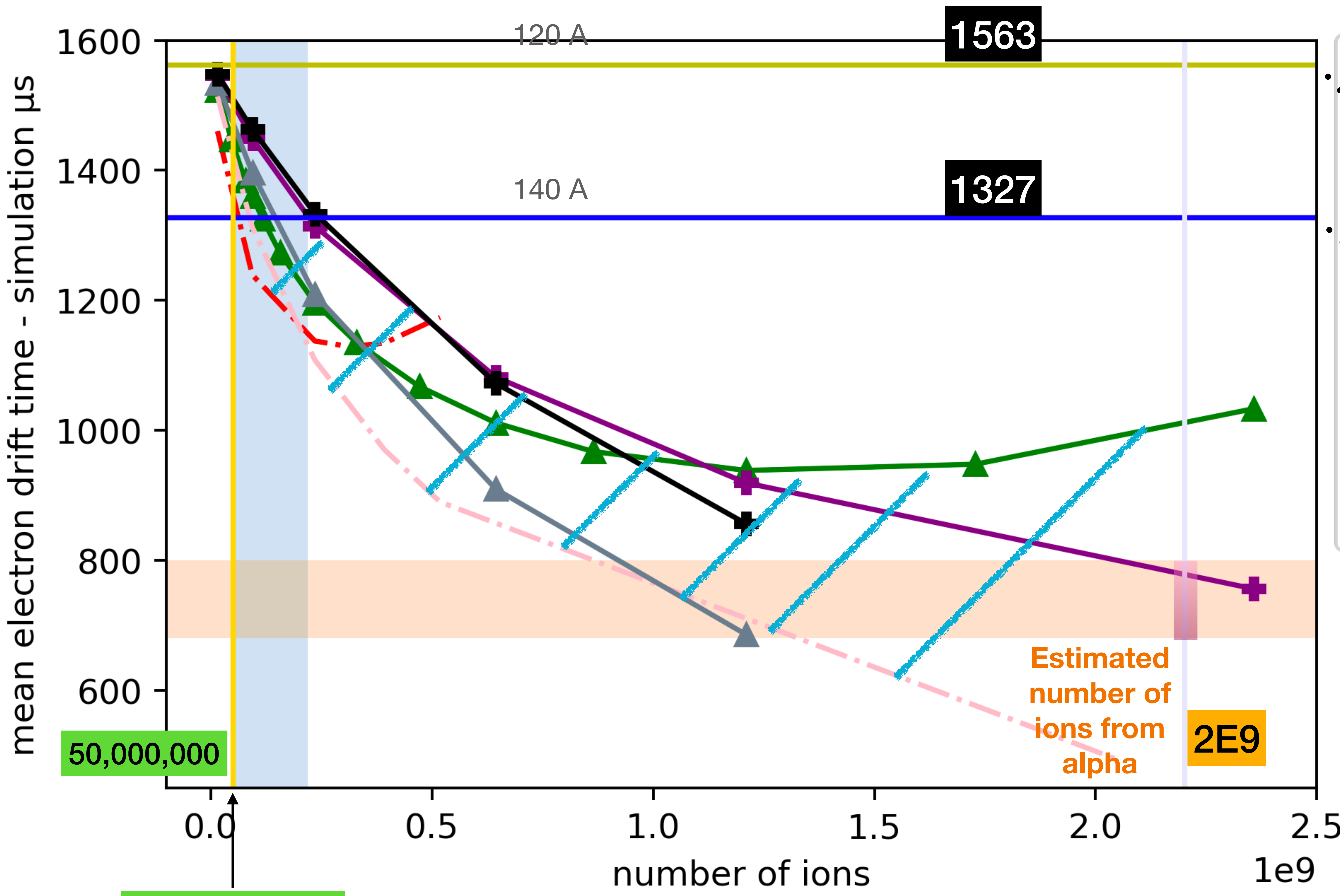
Extra slides



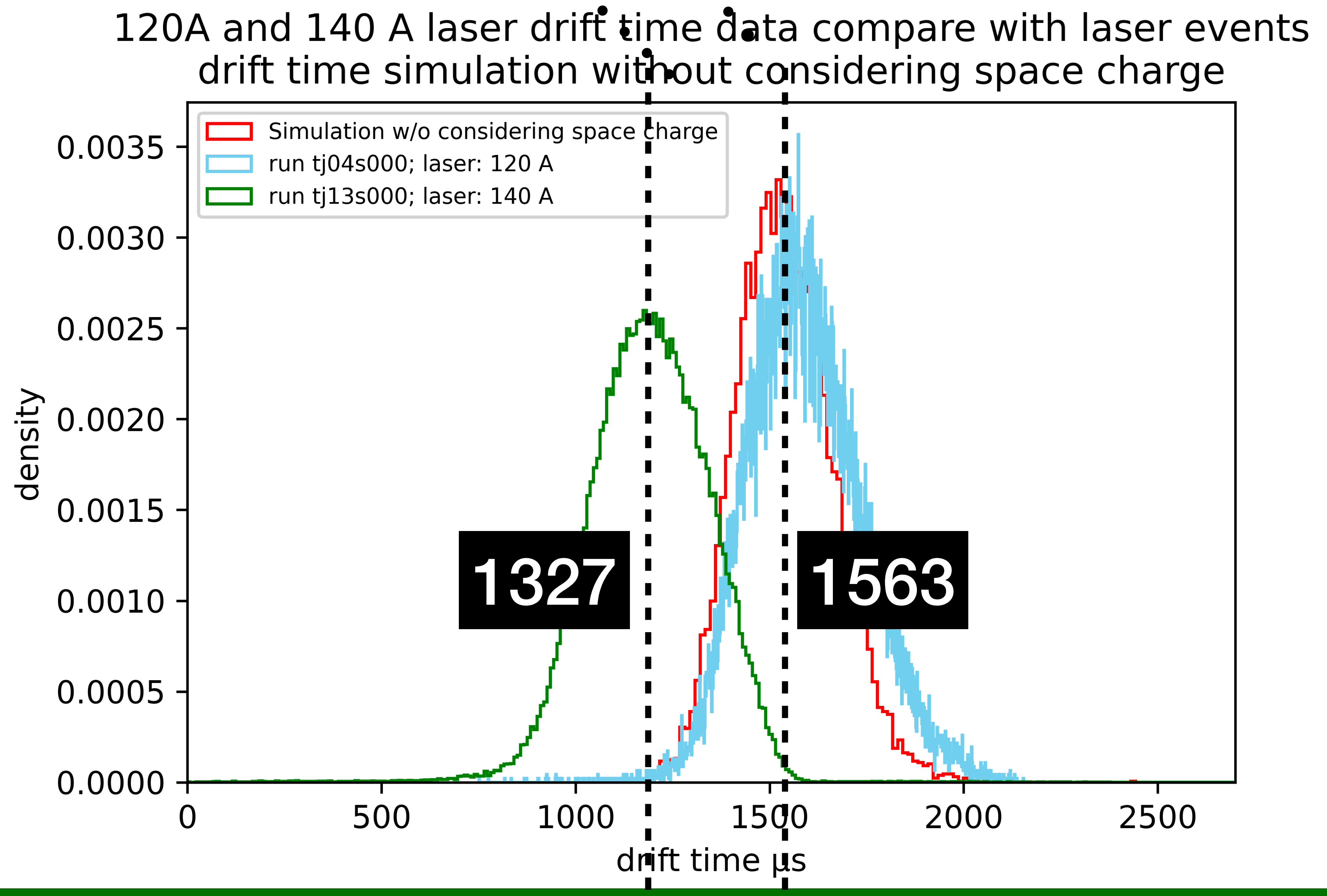
Upper limit of ions observed from 140 A laser data

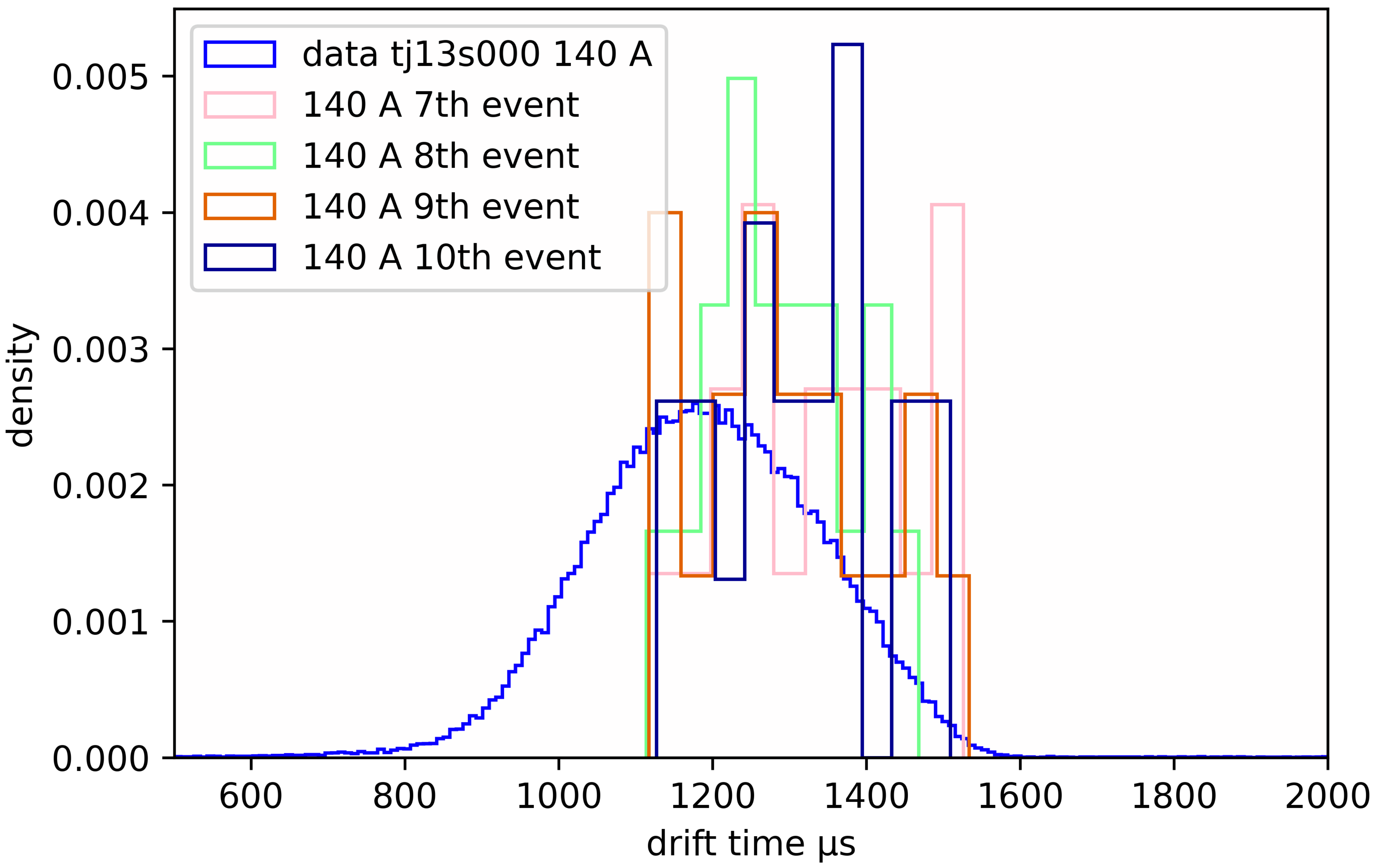


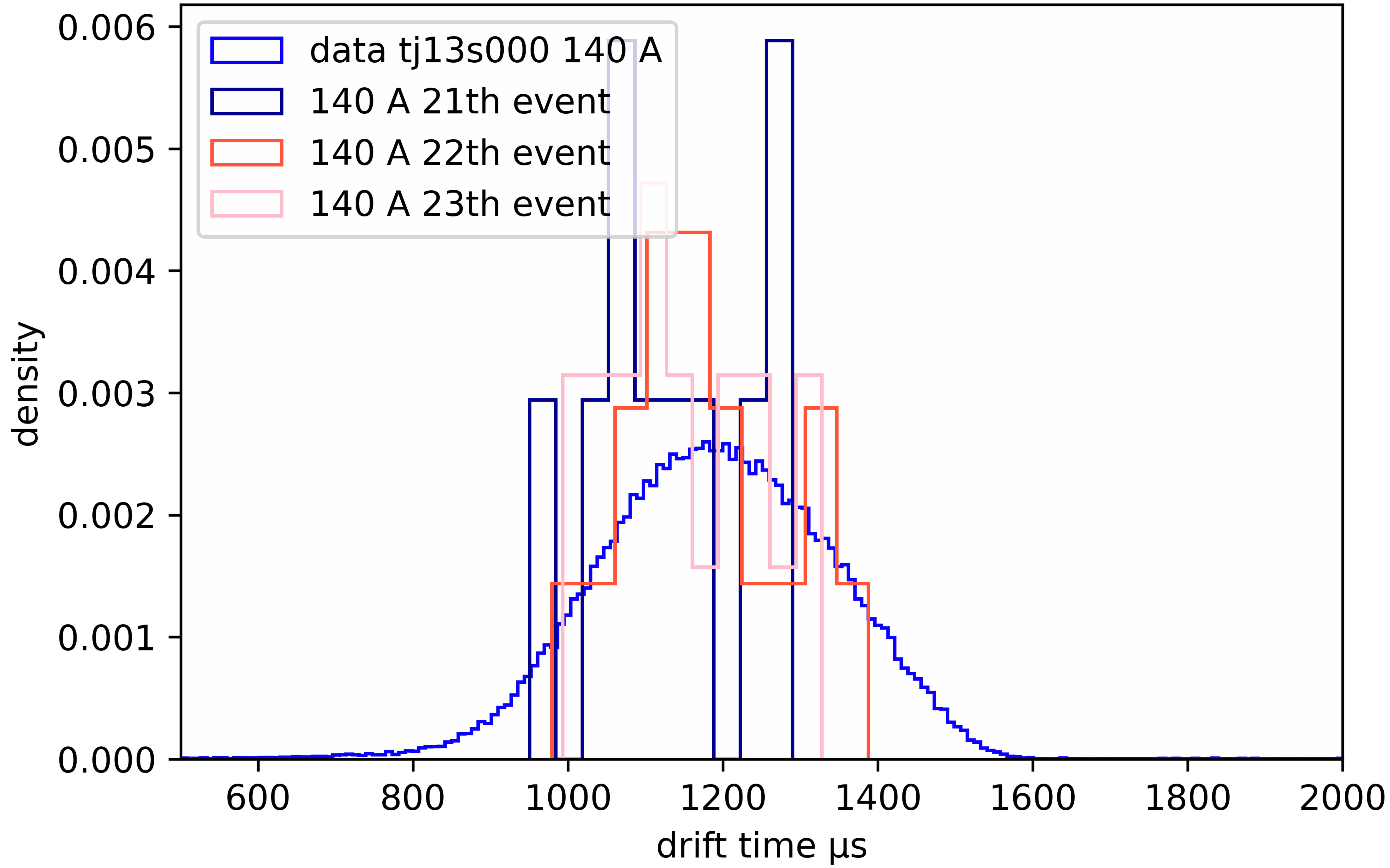
Model agreement with observed space charge number



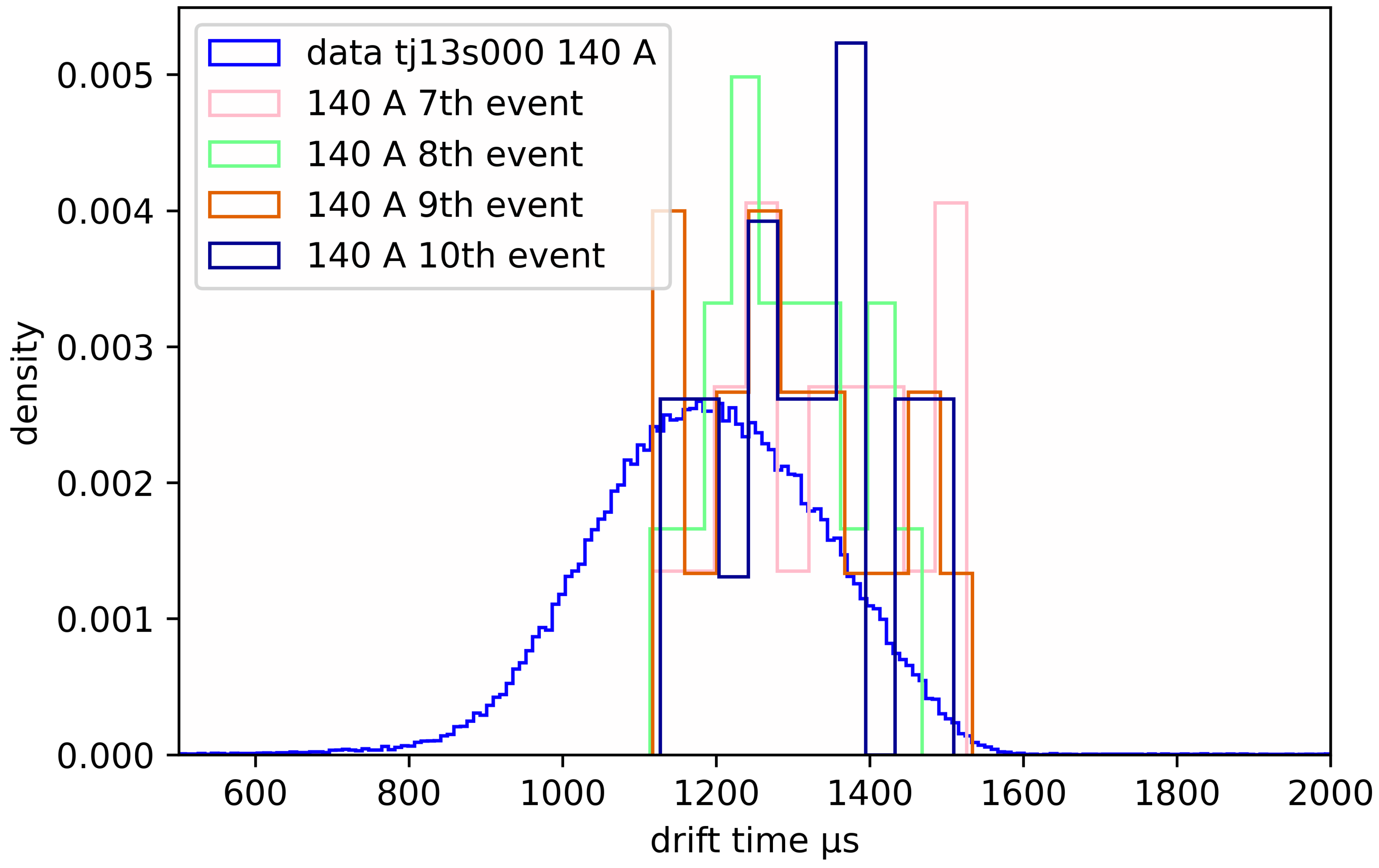
Upper limit of ions observed from 140 A laser data

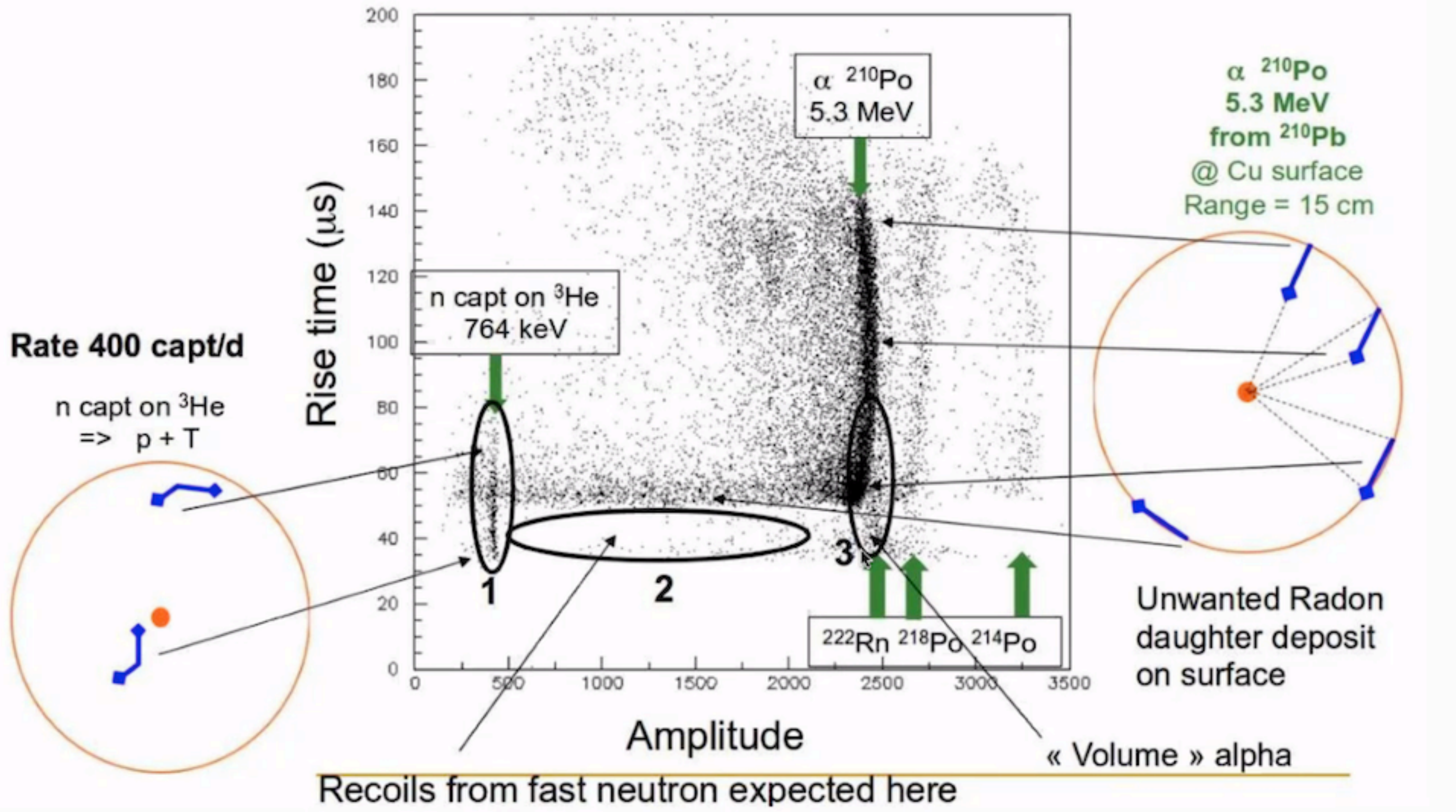



data tj13s000 140 A
140 A 7th event
140 A 8th event
140 A 9th event
140 A 10th event
density
0.000
0.001
0.002
0.003
0.004
0.005
600
800
1000
1200
1400
1600
1800
2000
drift time μs


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




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

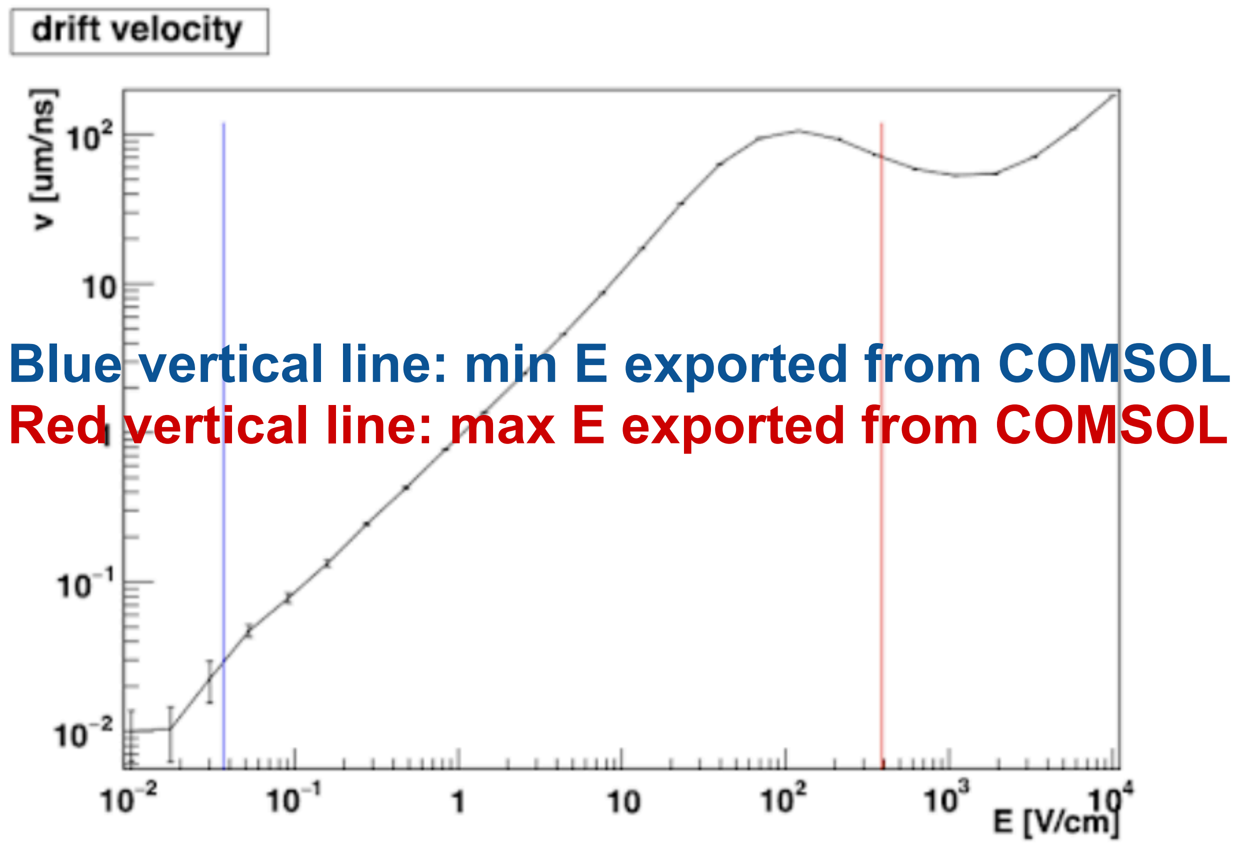
Step3: electron transportation

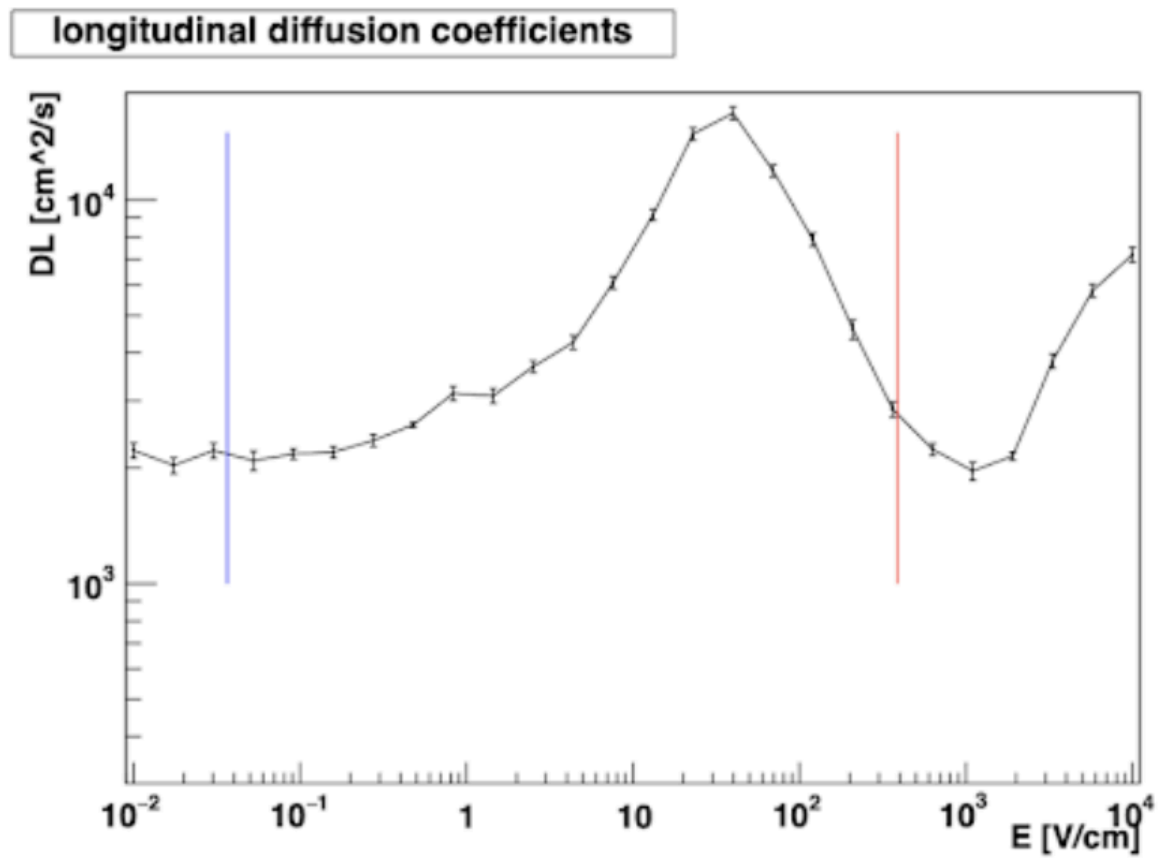
Electron drift time determined

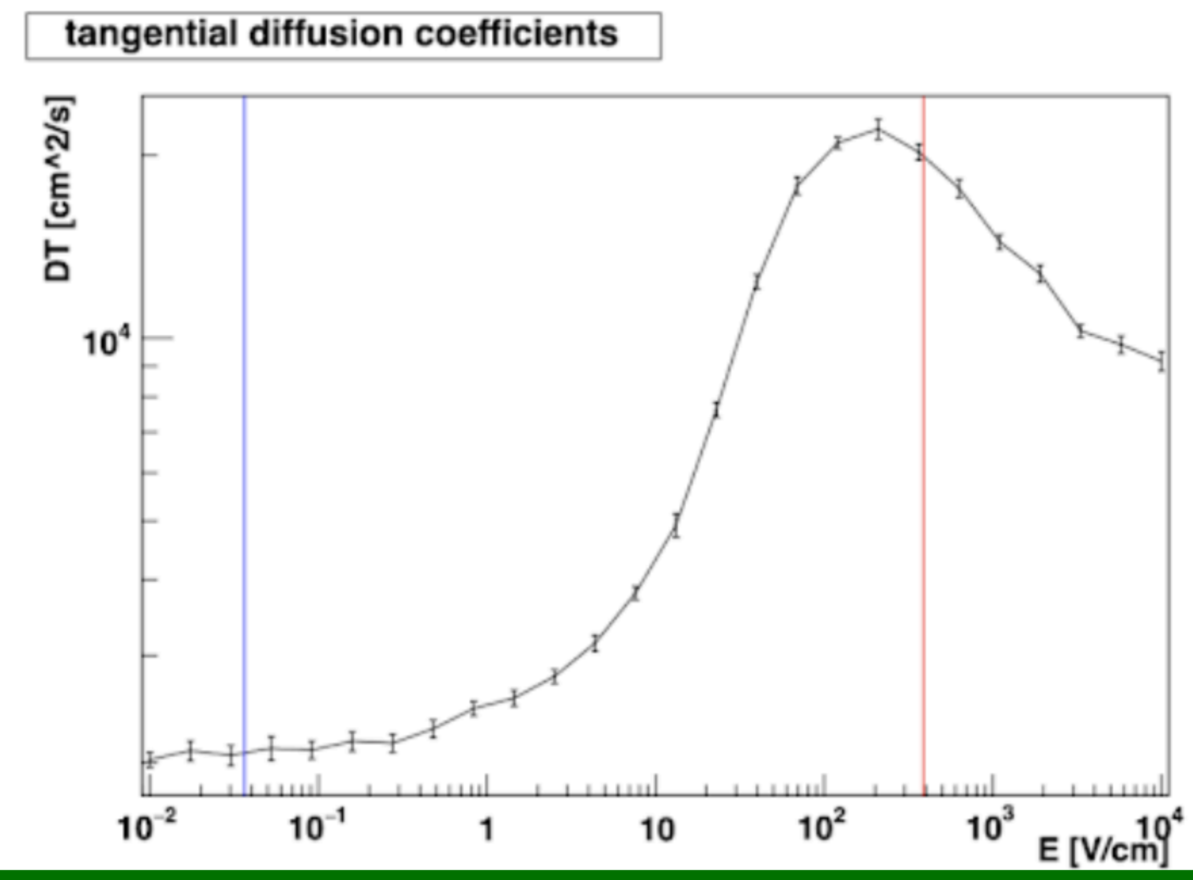
Step4: signal formation

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**



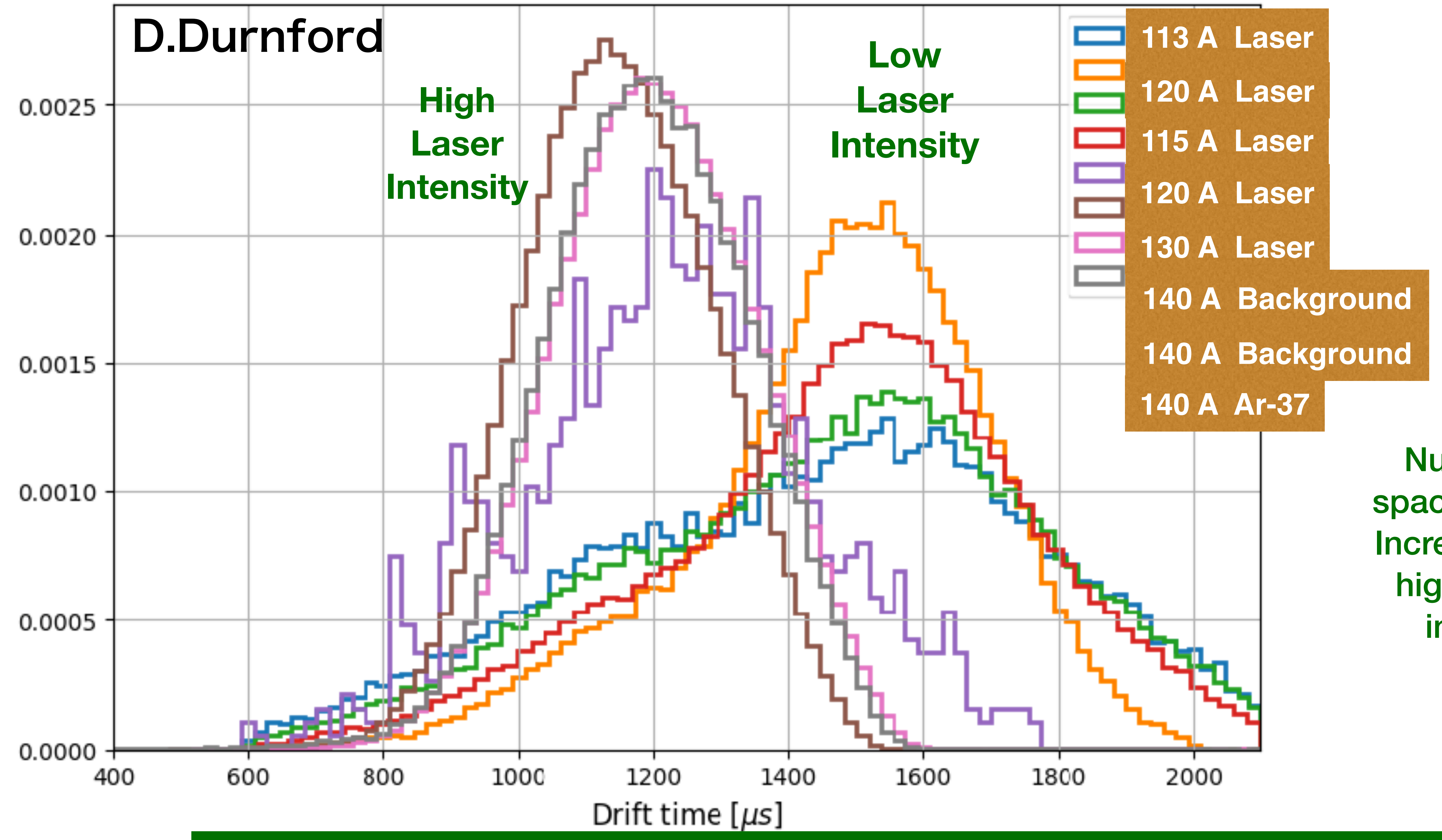




Laser events drift time simulation:
Events all originates from very south point of SPC

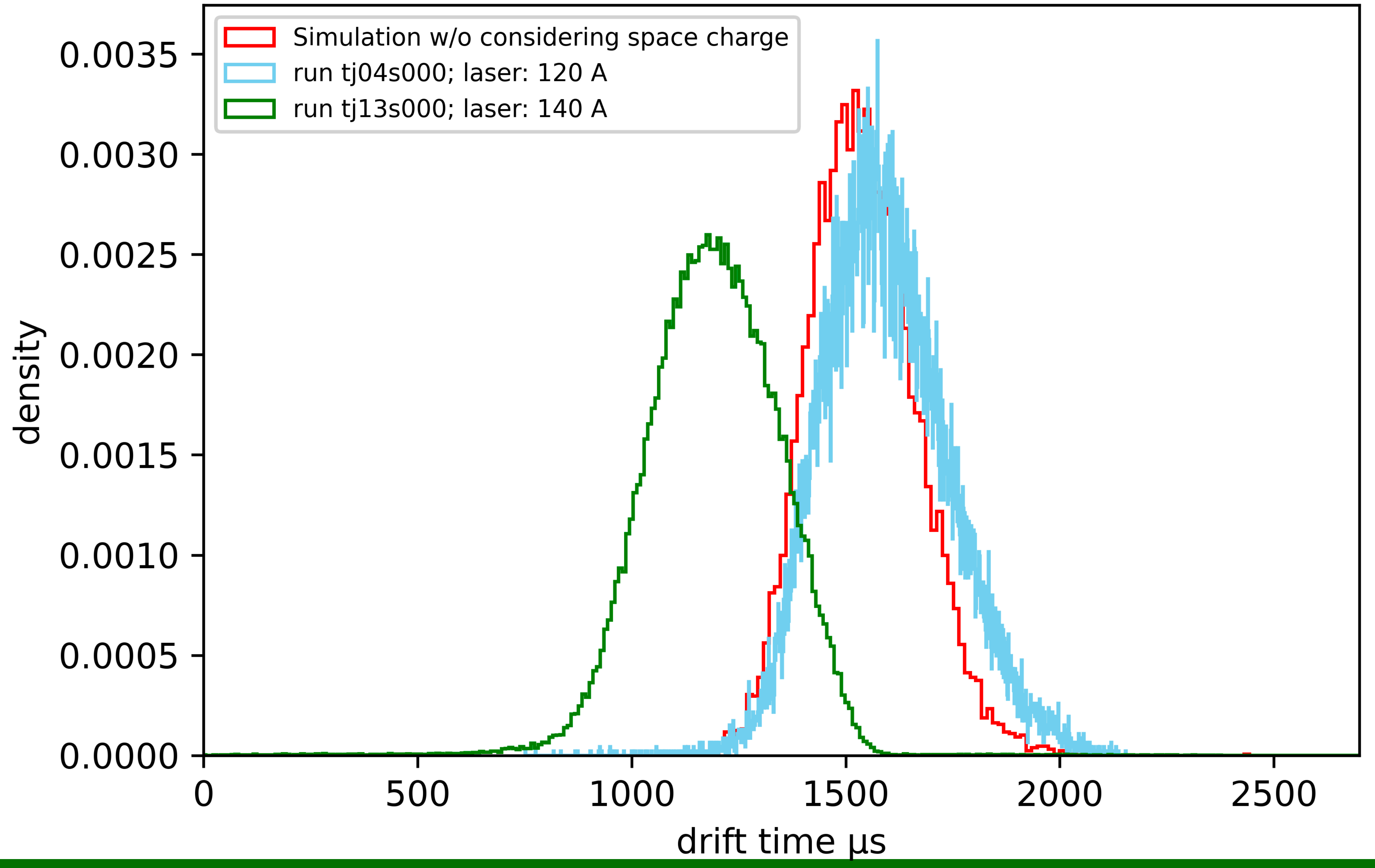
- **Left:** Laser LSM data show a different mean drift time between high and low laser intensity
- **Right:** Simulation shows agreement with real data at low laser intensity
- The decrease of drift time for higher laser intensity run can possibly be explained by space charge

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



Number of space charges Increases with higher laser intensity

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



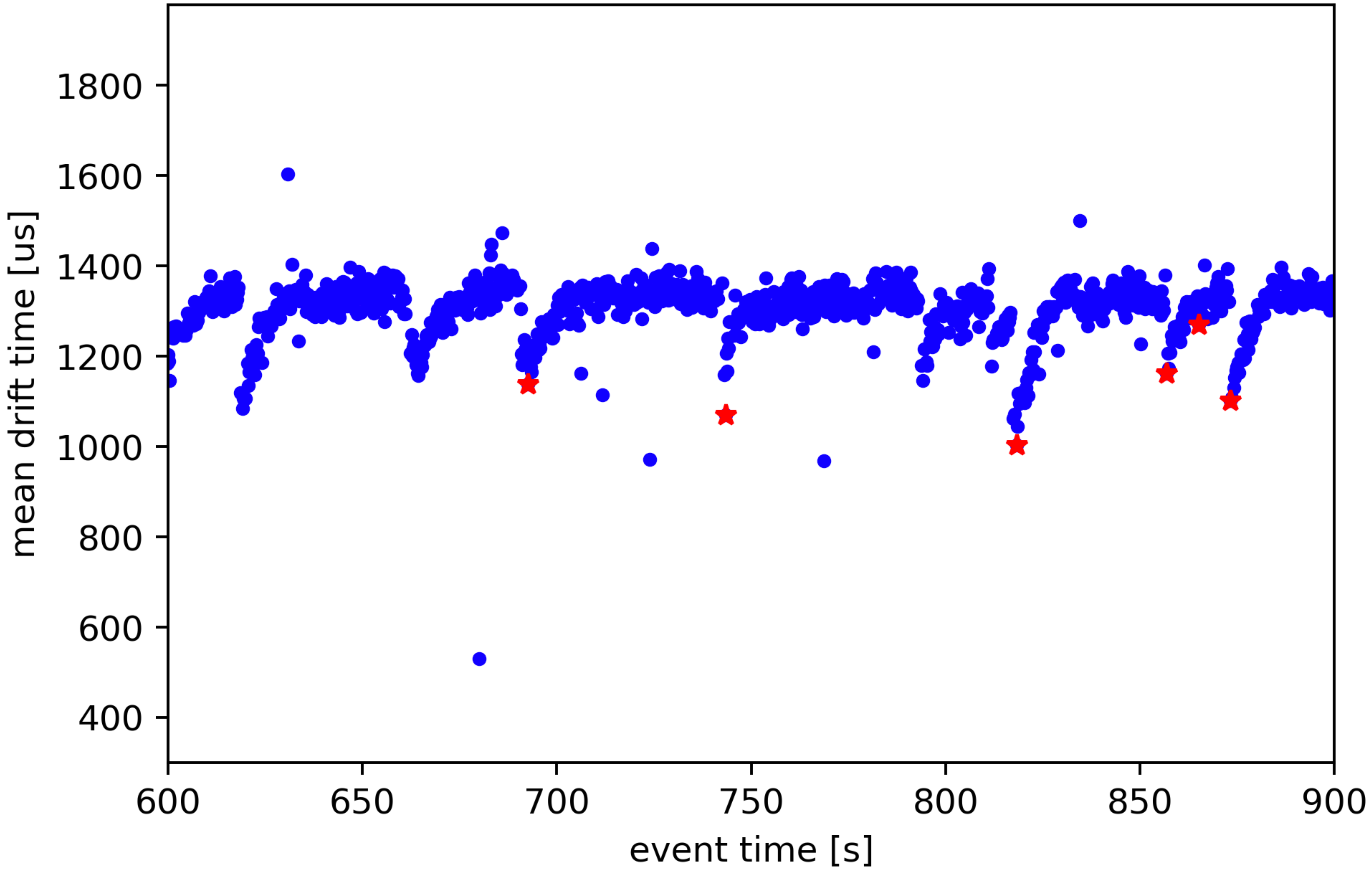
- **Ion drifting simulation:**
  - The number of secondary ions due to 140 A laser events **seen** by the detector is known
  - Drifting is affected by the ions Efield interaction
  - Assuming the diffusion of ions can be neglected
  - Assuming reduced ion mobility K_0 of all kinds of ion species is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

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

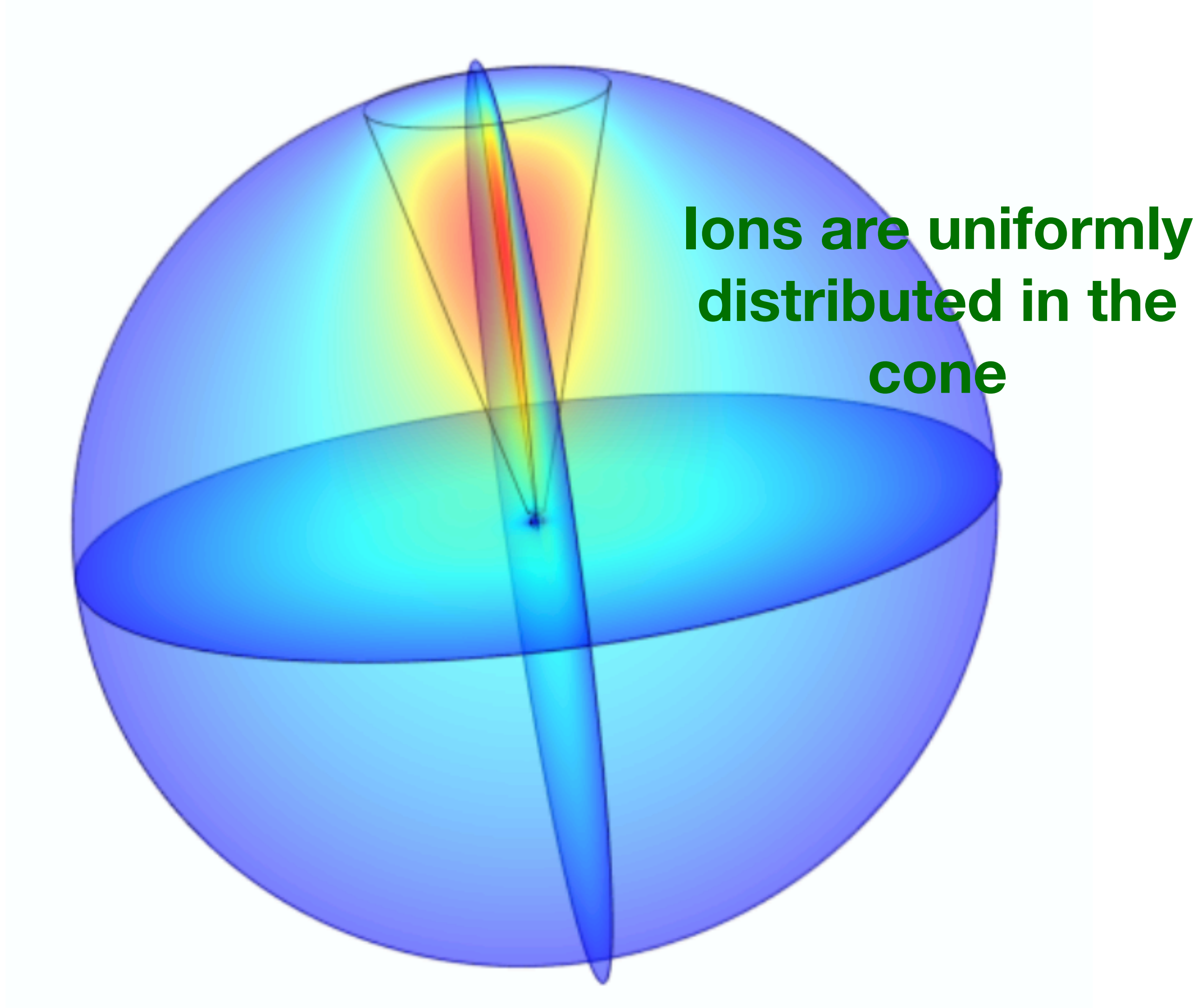
$$v_d = KE$$

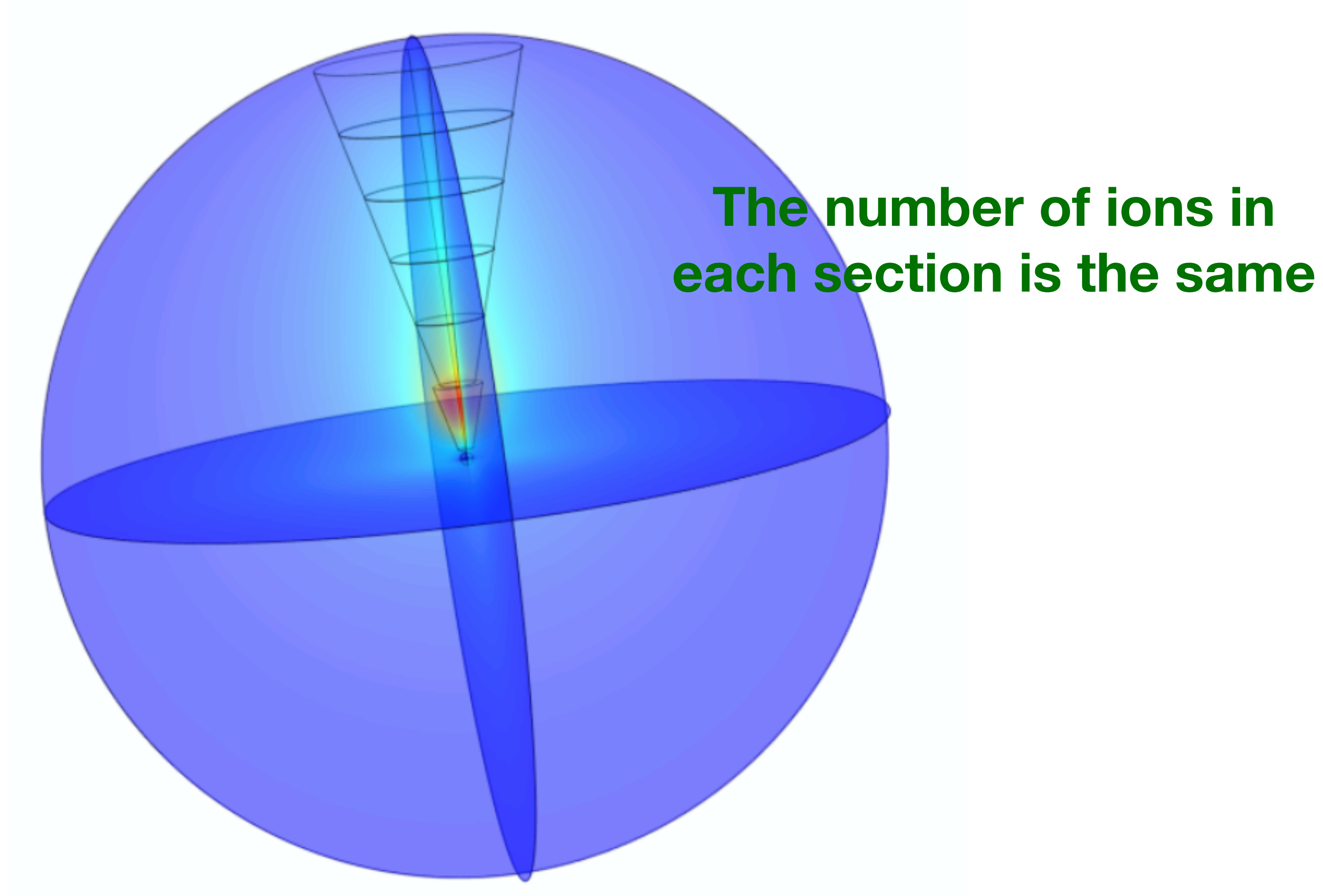
- **Ion drift time: 5 ~ 7s**
  - The number of ions exist in the detector can be deduced knowing the laser event rate.

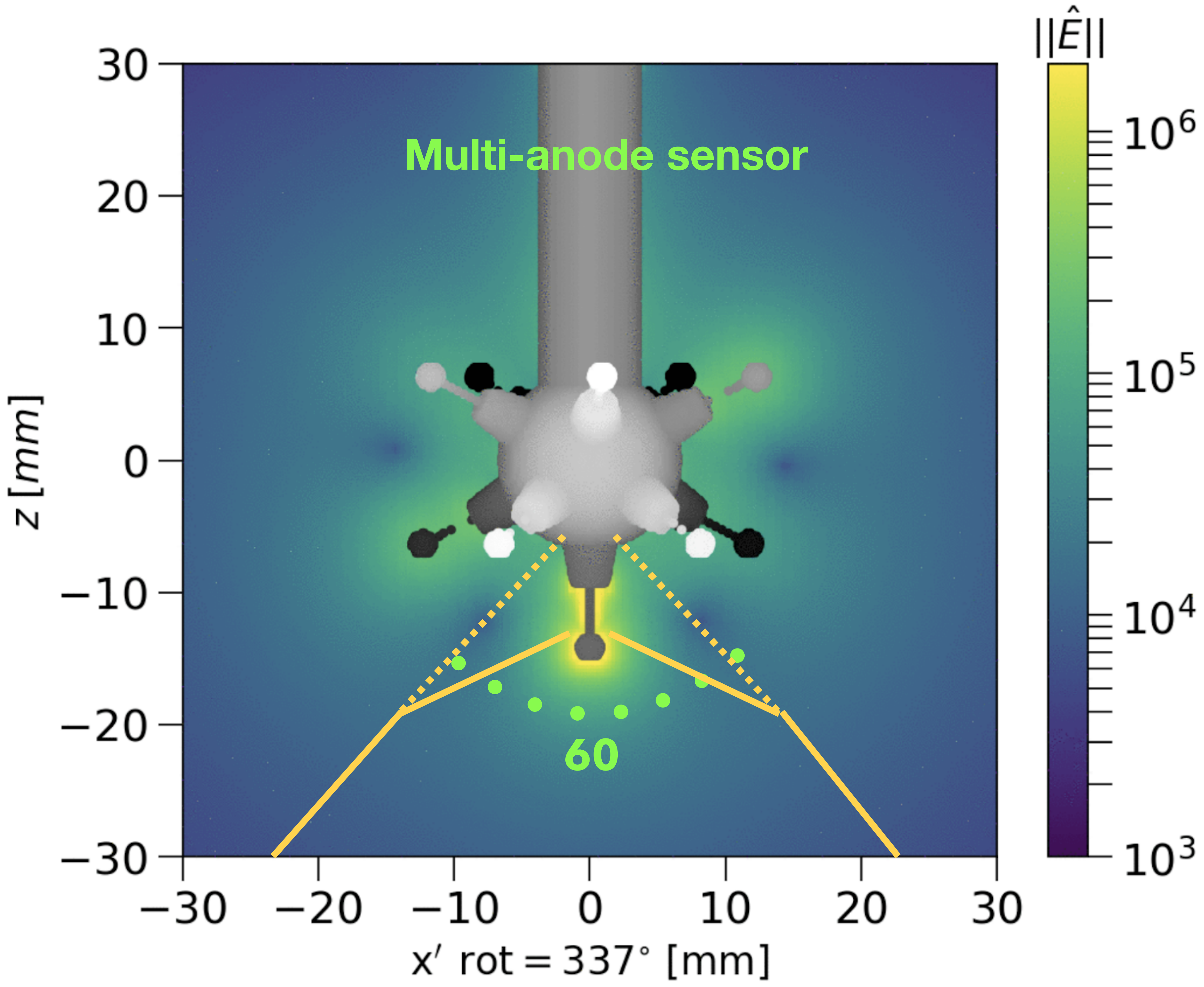
drift time data during alpha events

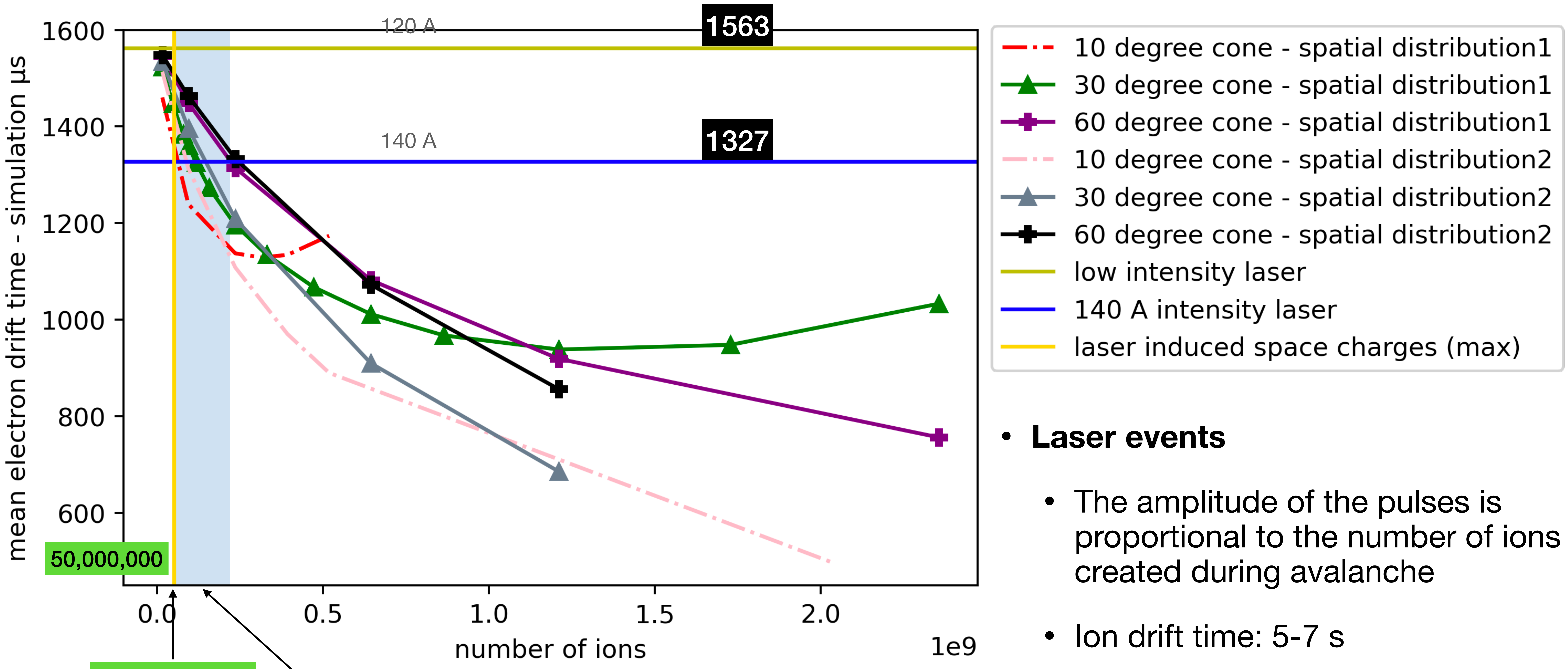


- COMSOL Efield simulation:
  - Specify the volume charge density for certain geometry
  - Geometry: Cone
  - Two different ways of distributing space charges (plots below)
  - Different simulations has been done for various open angle of the cone (10, 30, 60 degree), and various number of ions in the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





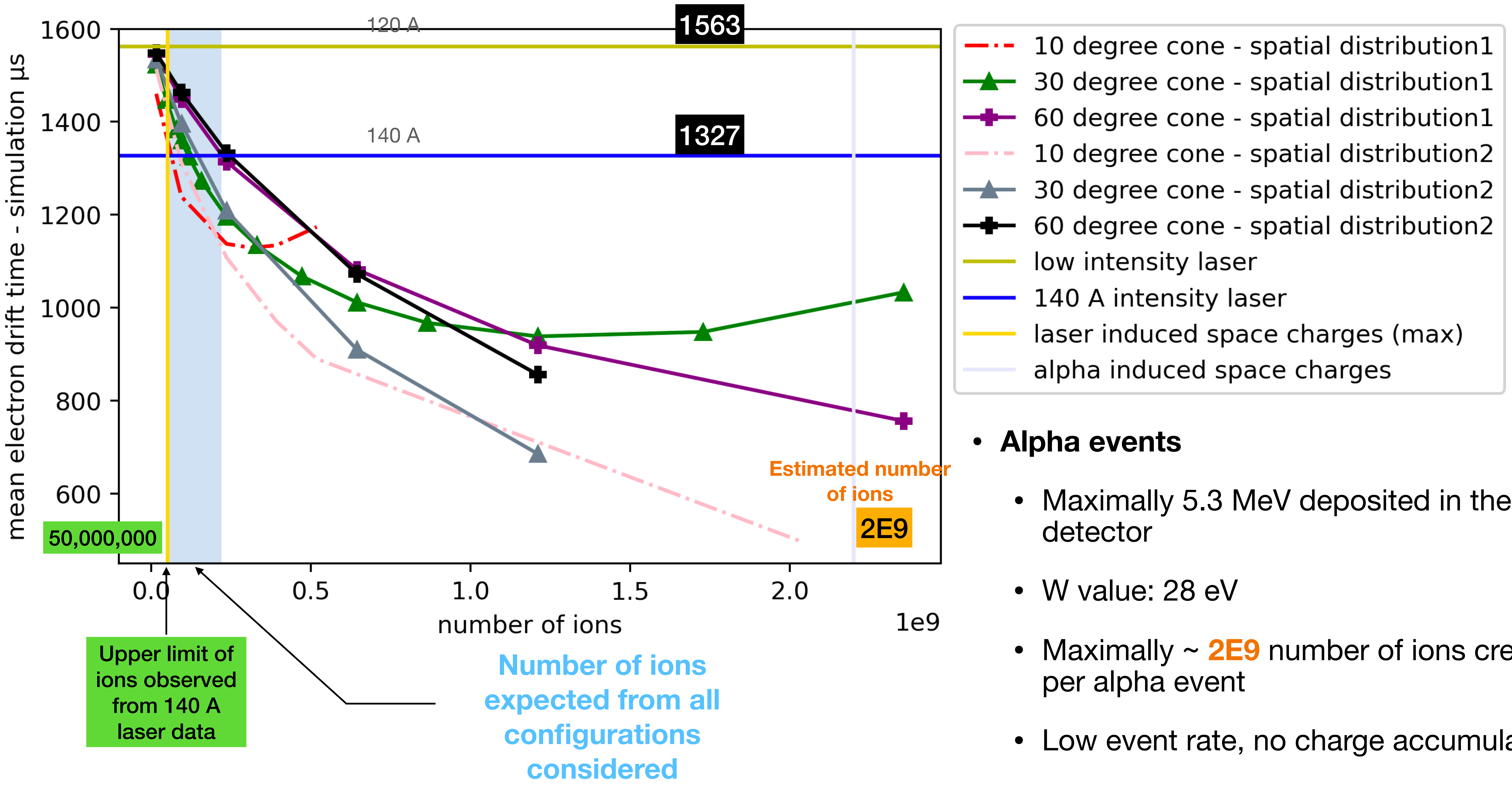




Upper limit of ions observed from 140 A laser data

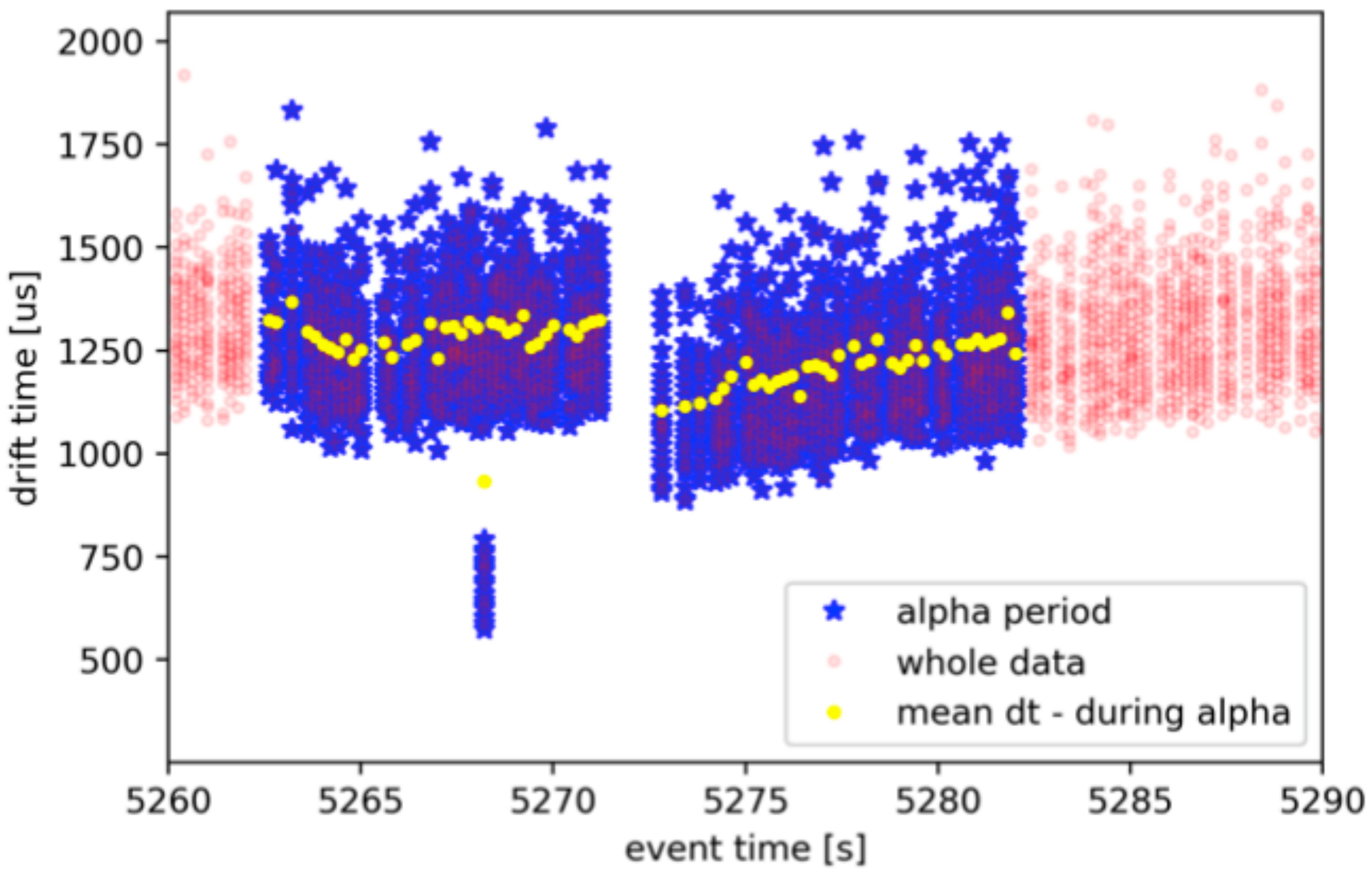
Number of ions expected from all configurations considered

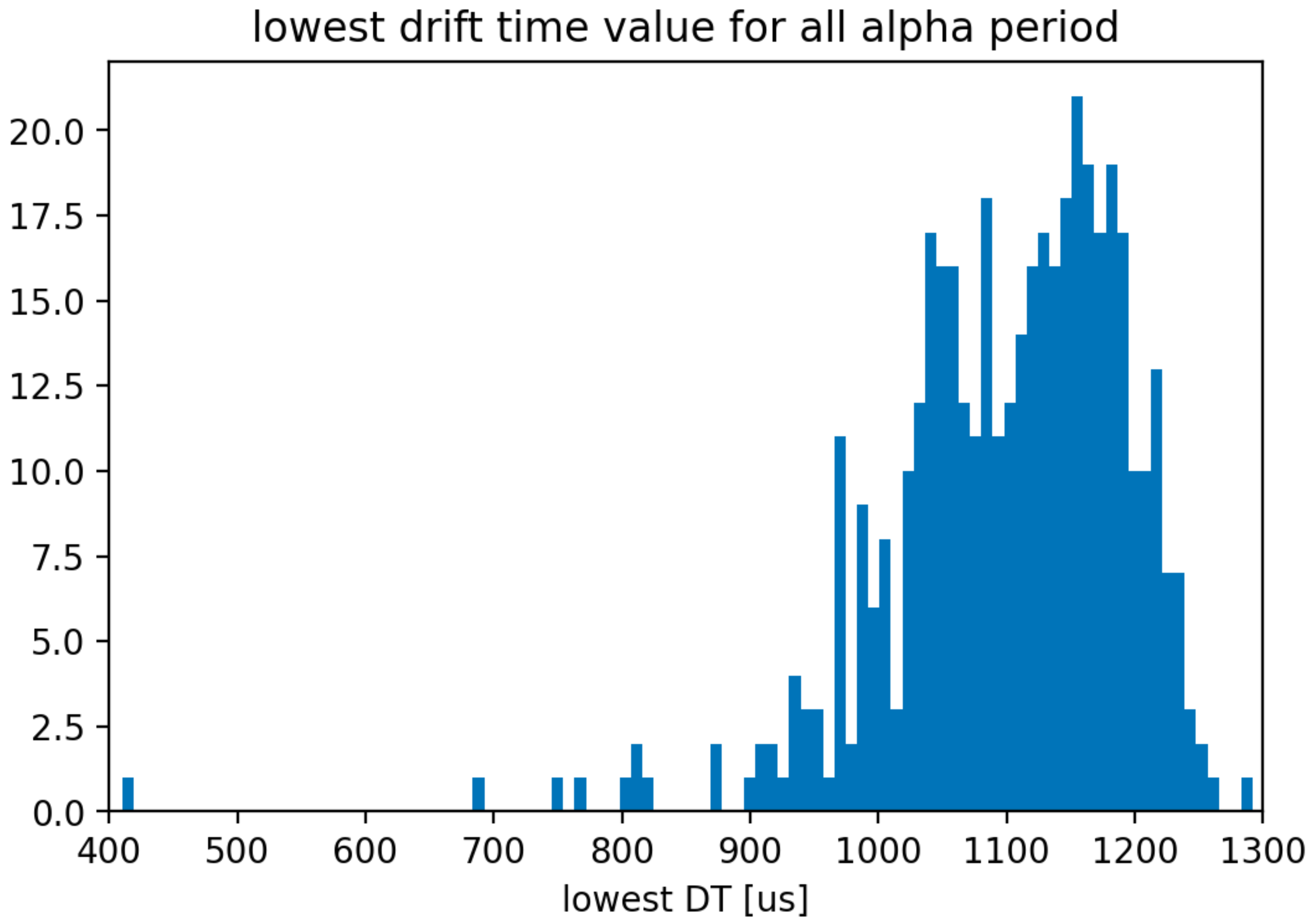
- **Laser events**
  - The amplitude of the pulses is proportional to the number of ions created during avalanche
  - Ion drift time: 5-7 s
  - 140 A laser events: **24,000,000 - 50,000,000** ions accumulated in detector



- **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

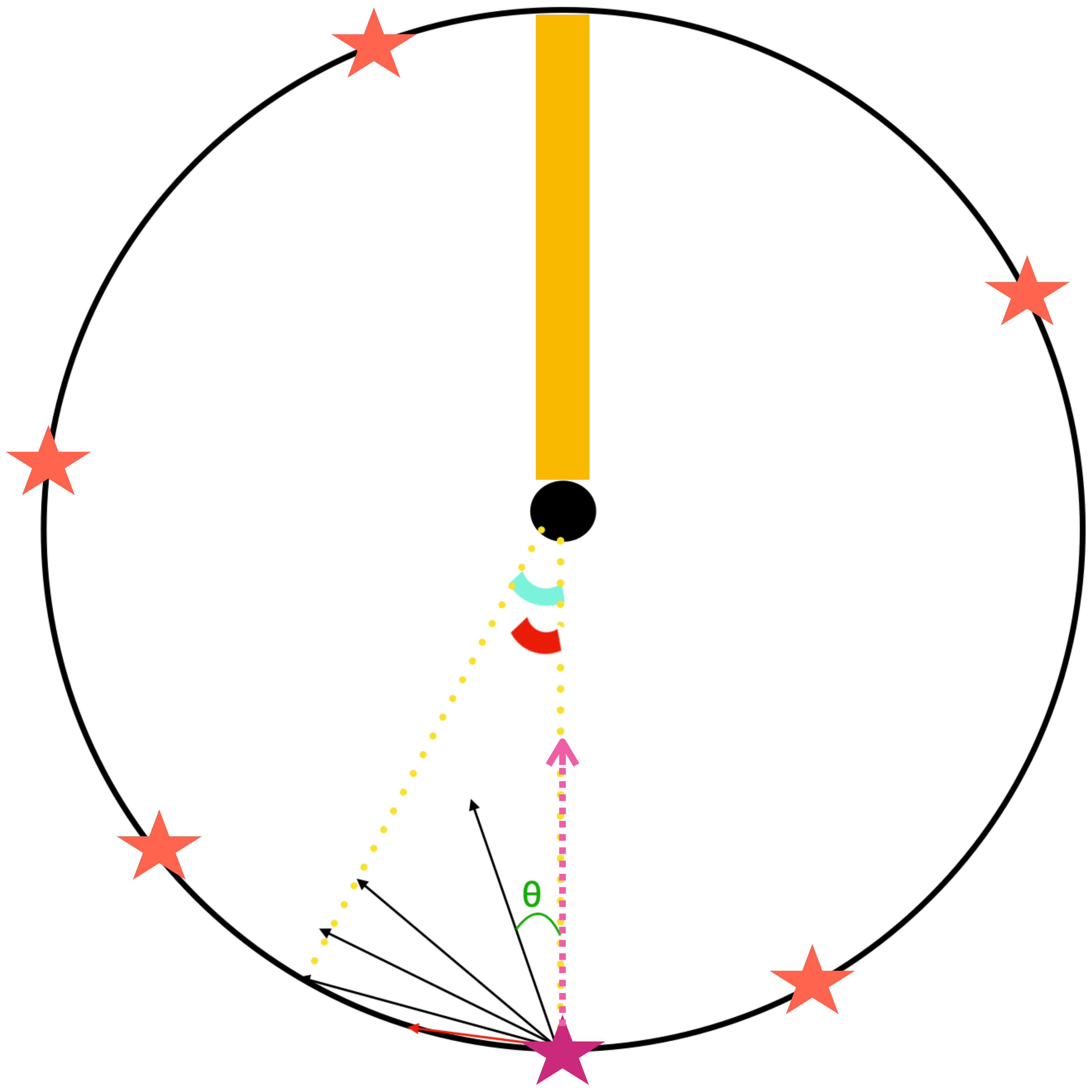
Alpha Space charge number approximation



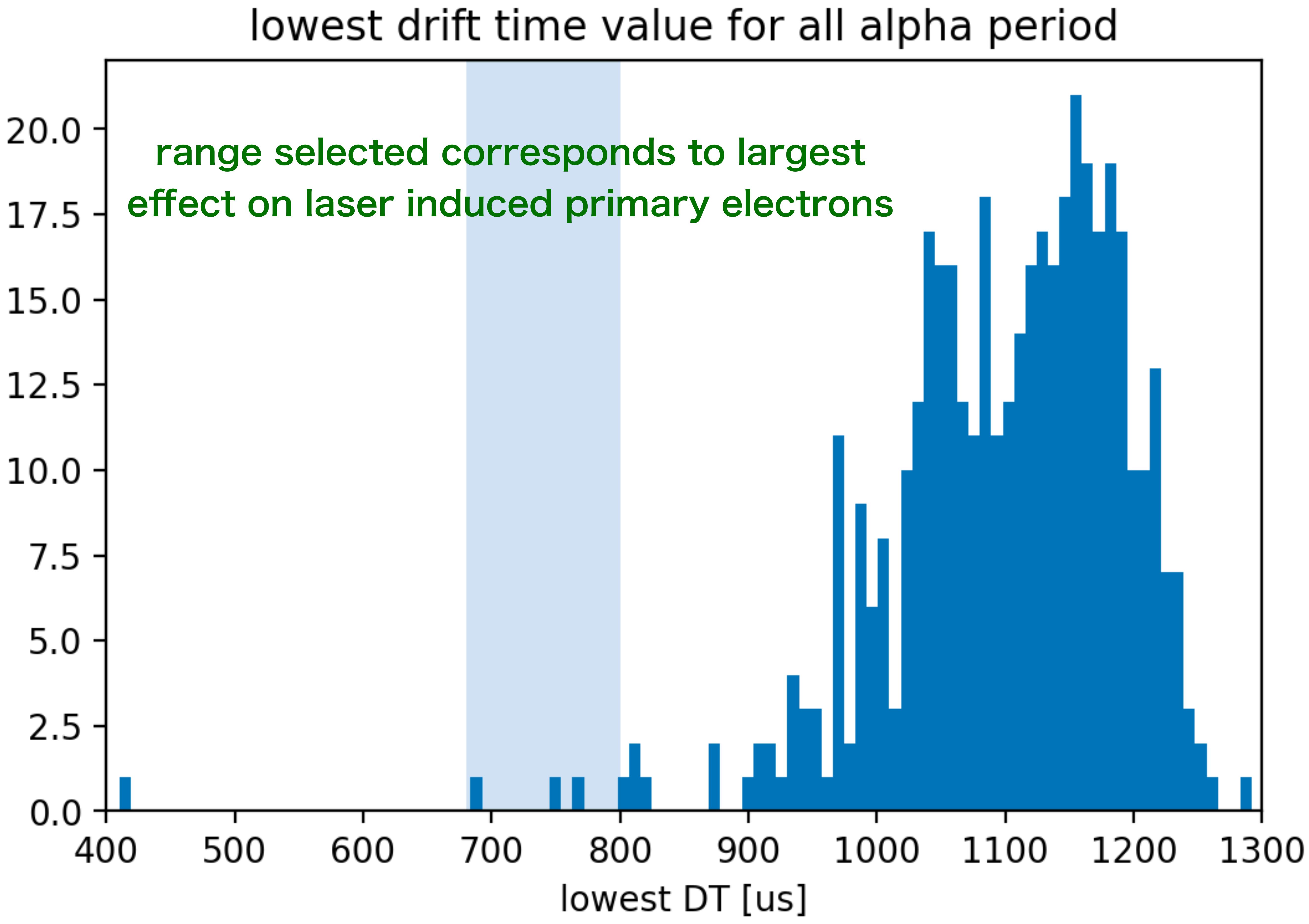


- 140 A laser mean drift time values per event VS time
- Periods affected by alpha events are identified (Credit to Jean-Marie coquillat)
- The lowest electron mean drift times for each alpha period are selected

- 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