EP-DT
Detector Technologies

DRD1
Gaseous Detector Technologies

GDD
Gas Detectors Development Group

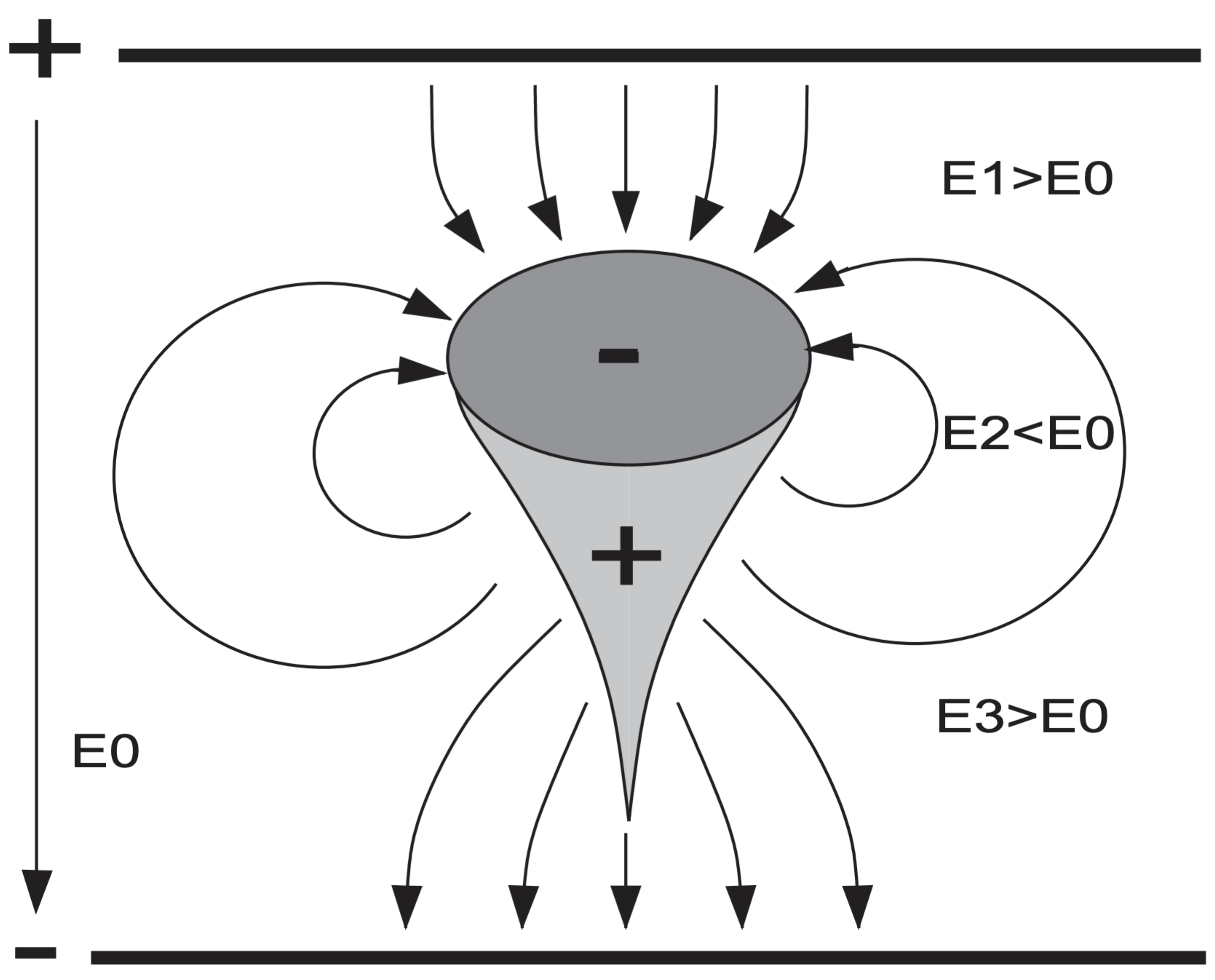
Space-charge effects in simulations of large avalanche dynamics

Tom Szwarcer | University of Oxford

Supervisors: Djunes Janssens, Heinrich Schindler

The space charge effect

- During avalanches, non-negligible fields may arise from the space charge distribution
- These charges modify the background applied field
- A significant background field modification may lead to a gain modification



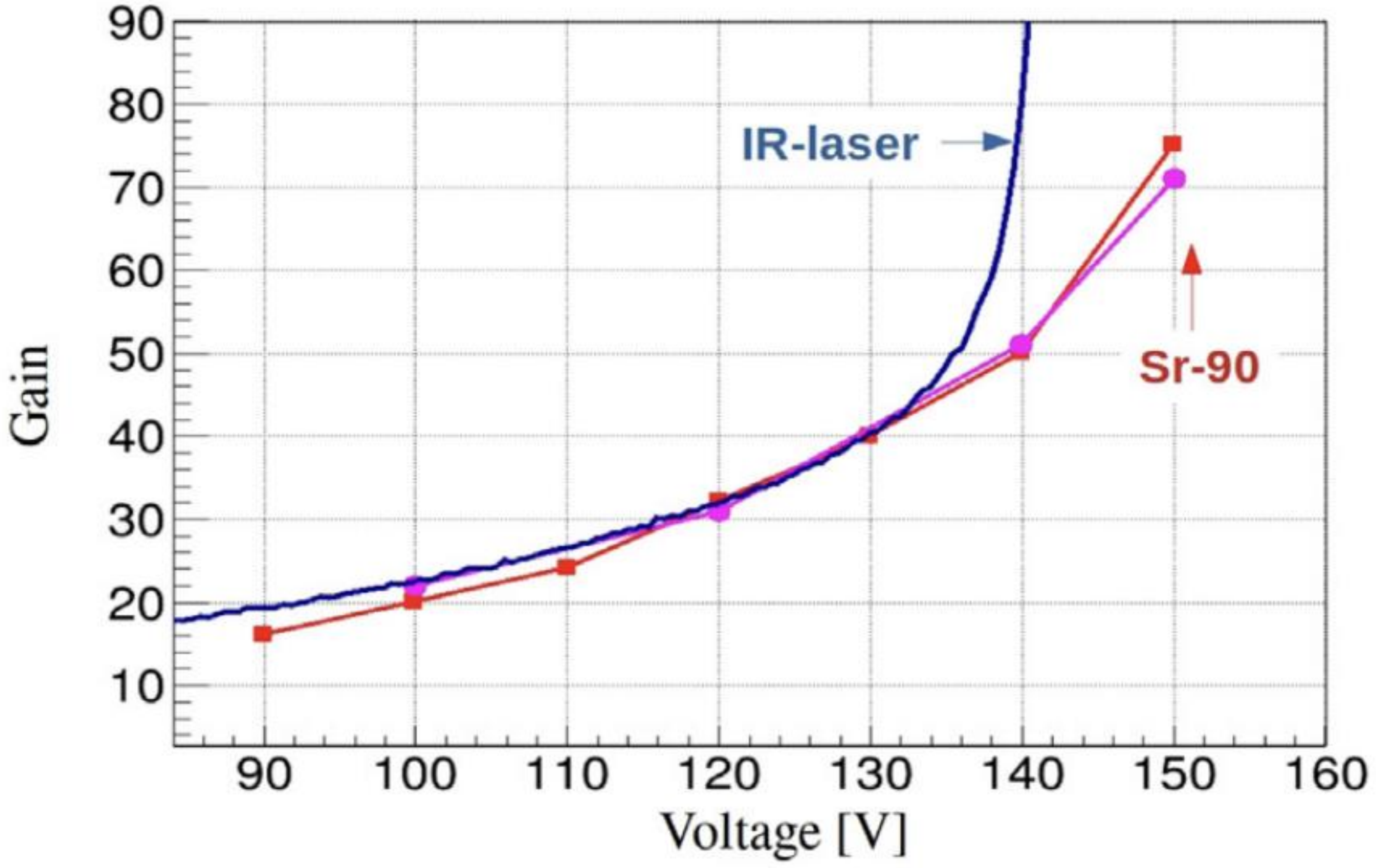
C. Lippmann, W. Riegler, Nuclear Instruments and Methods in Physics Research A 517 (2004) 54–76

The space charge effect

LGADs: we see a gain reduction for a larger number of starting charges

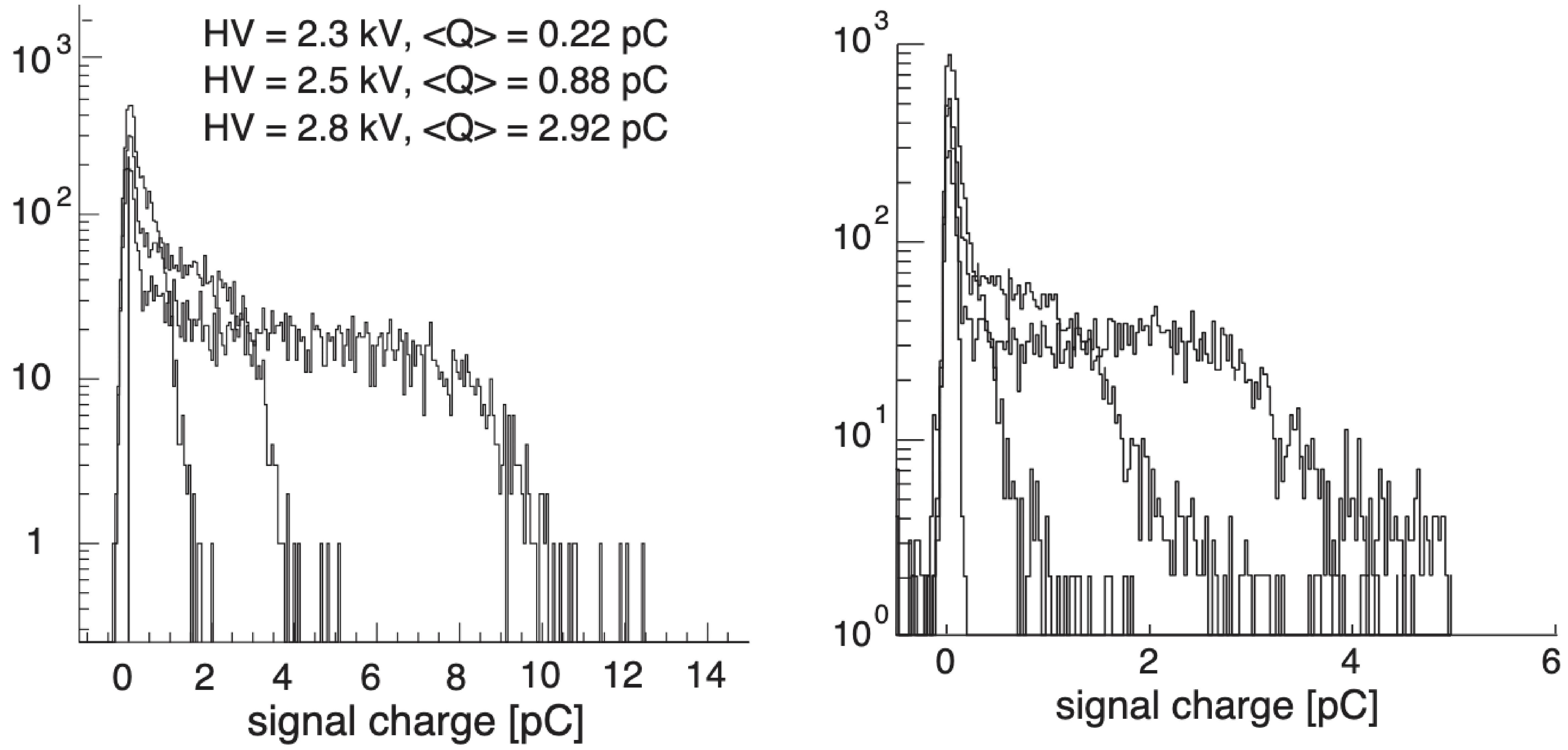
RPCs: we see a gain-limiting effect

E. Currás, M. Fernández and M. Moll, Nuclear Inst. and Methods in Physics Research, A 1031 (2022) 166530



LGAD gain reduction with the higher charge deposition of the Sr-90 source compared to IR laser.

C. Lippmann, W. Riegler / Nuclear Instruments and Methods in Physics Research A 517 (2004) 54–76



Charge spectra for an RPC

Left: simulation without the space charge effect

Right: measurement

Space charge in Garfield++

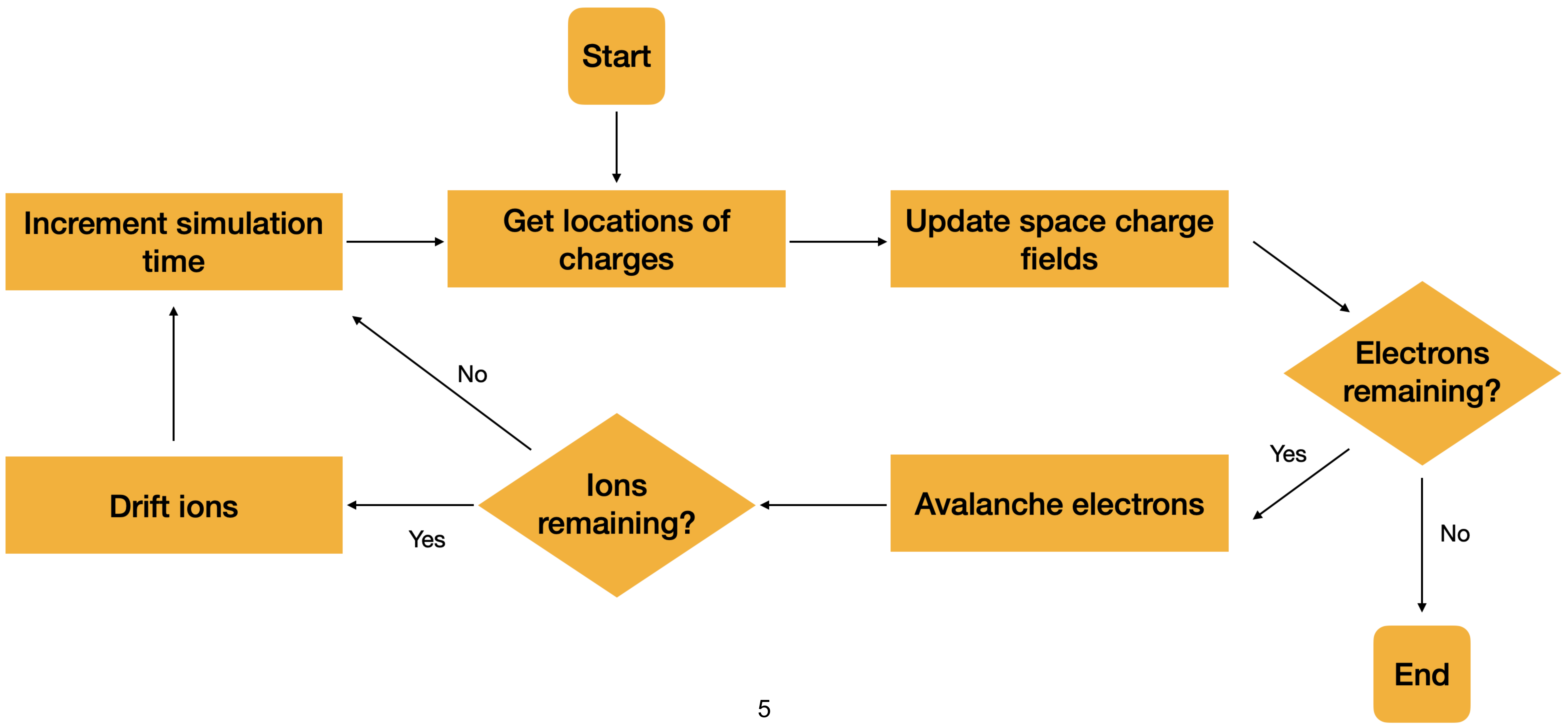
Based on the work of C. Lippmann, W. Riegler, Nuclear Instruments and Methods in Physics Research A 517 (2004) 54–76

Existing space charge implementation (AvalancheGridSpaceCharge)	Goals of this project
Electrons are transported between nodes of a grid	Allow electrons to be transported arbitrarily by AvalancheMicroscopic
Ions are not transported	Allow ions to be transported arbitrarily by AvalancheMC
Limited to an RPC	Use a general geometry
Uses axisymmetric rings of charge, with the possibility of using a parallel plate boundary condition (i.e. mirror charges)	Compare the use of charged rings to a point charge approach* and investigate whether the free space boundary condition is 'good enough'

*In this presentation we will focus on the charged ring approach only.

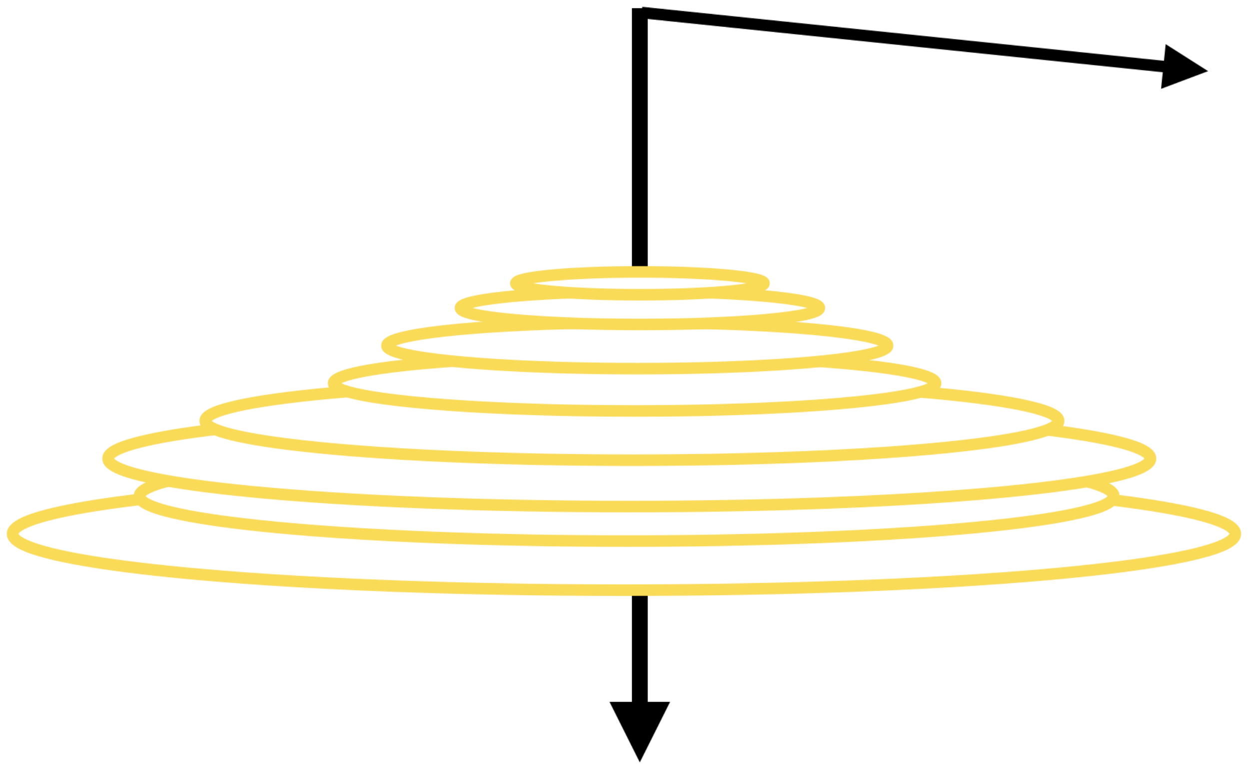
Structure of the simulations

- Divide simulations into time windows
- Add the fields of any new charges (e.g. those created from ionisation) after the time window
- We should keep time windows short: if there's large amplification over a time window there may be many charges unaccounted for
- An adaptive time window approach was implemented to manage this issue



Axisymmetric approximation

- Approximate the avalanche as having cylindrical symmetry
- The radius is centred on the mean position of the particles
- Free space boundary condition used



ComponentChargedRing

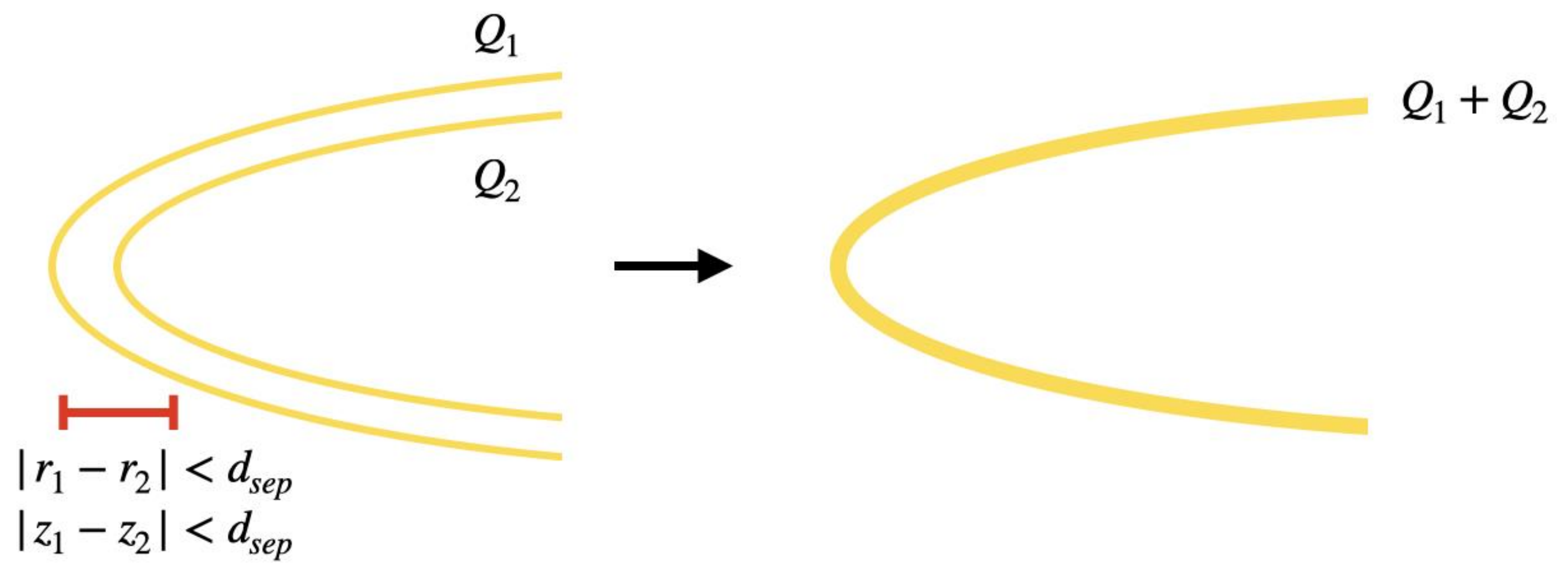
A new class was created: **ComponentChargedRing**

- Charges can be added at arbitrary positions in 3D space and are converted to charged rings
- Symmetry axis can be dynamically updated to track the mean position of the avalanche
- Functions to handle divergences were written
- Functions to add, remove, and merge rings were added
- Functions borrowed from AvalancheGridSpaceCharge as well as new functions were profiled line-by-line with Valgrind/Callgrind; significant optimisations were made

ComponentChargedRing: tolerances

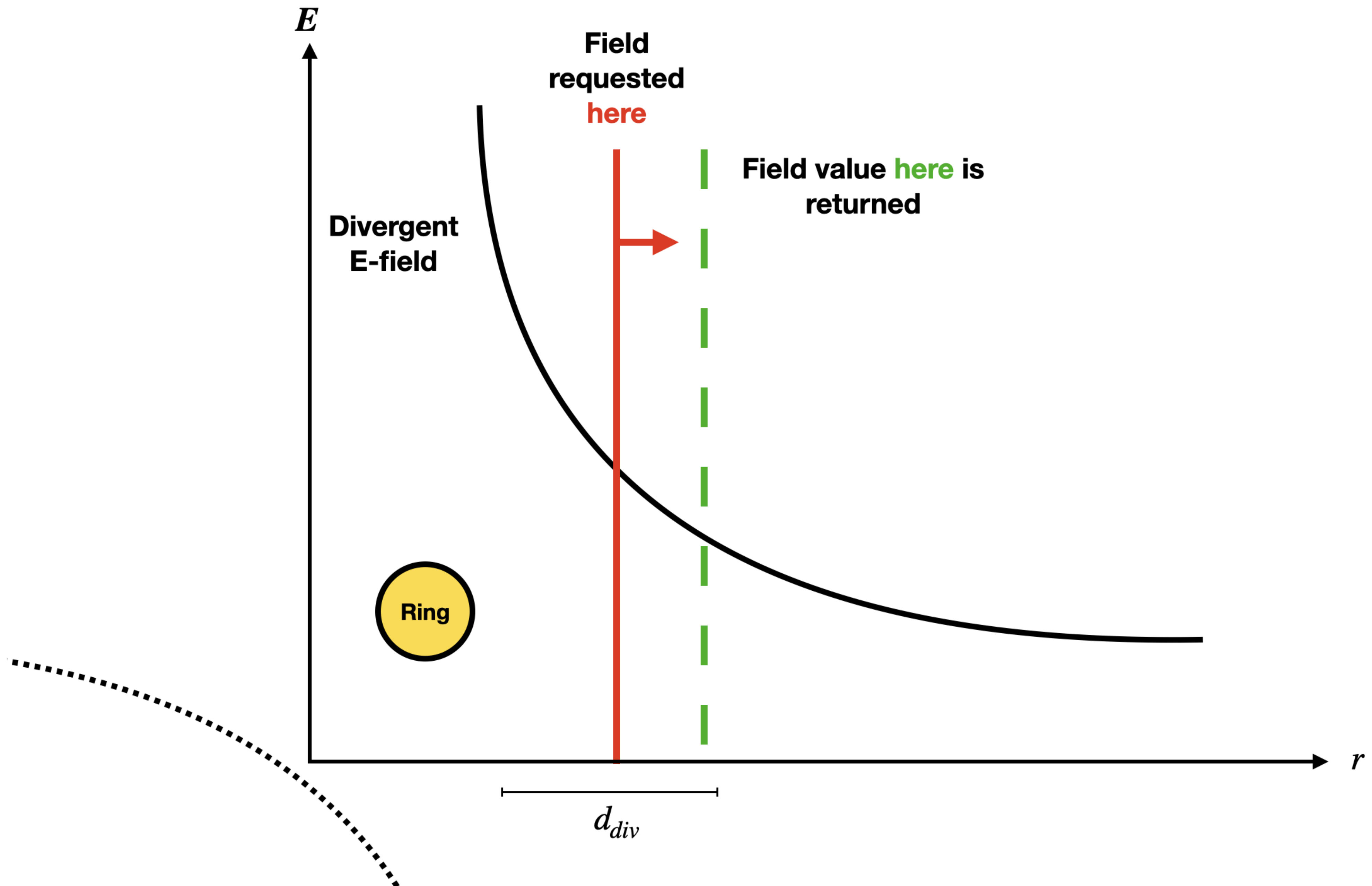
Ring separation tolerance

- If two rings are closer together than this tolerance, they will be merged
- Rings added with a radius less than this tolerance are added as point charges on the axis of symmetry
- This can be used to limit the number of rings, and reduce computation time



Divergence-handling tolerance

- If the electric field is requested within one tolerance of a ring or point charge, the field value one tolerance away is returned instead
- An efficient check of whether there are divergences was implemented
- Logic was written to preserve the sign of the field, using the relative position of the ring and field point



Simulating with ComponentChargedRing

How many charges are needed to significantly modify the field?

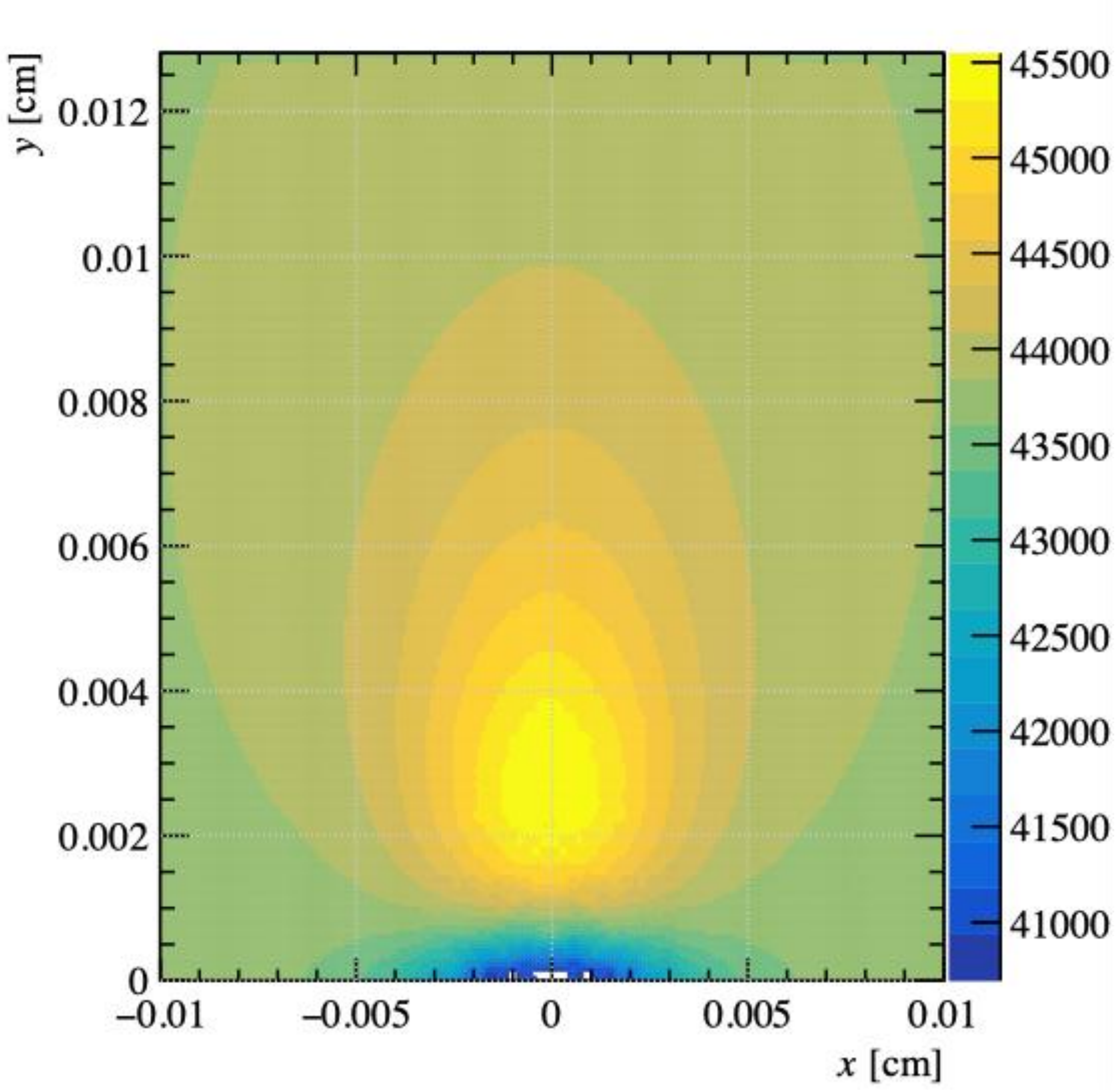
Using an applied field of 44kV/cm, in a parallel plate setup

These plots show the end of the avalanche, when all electrons have been evacuated

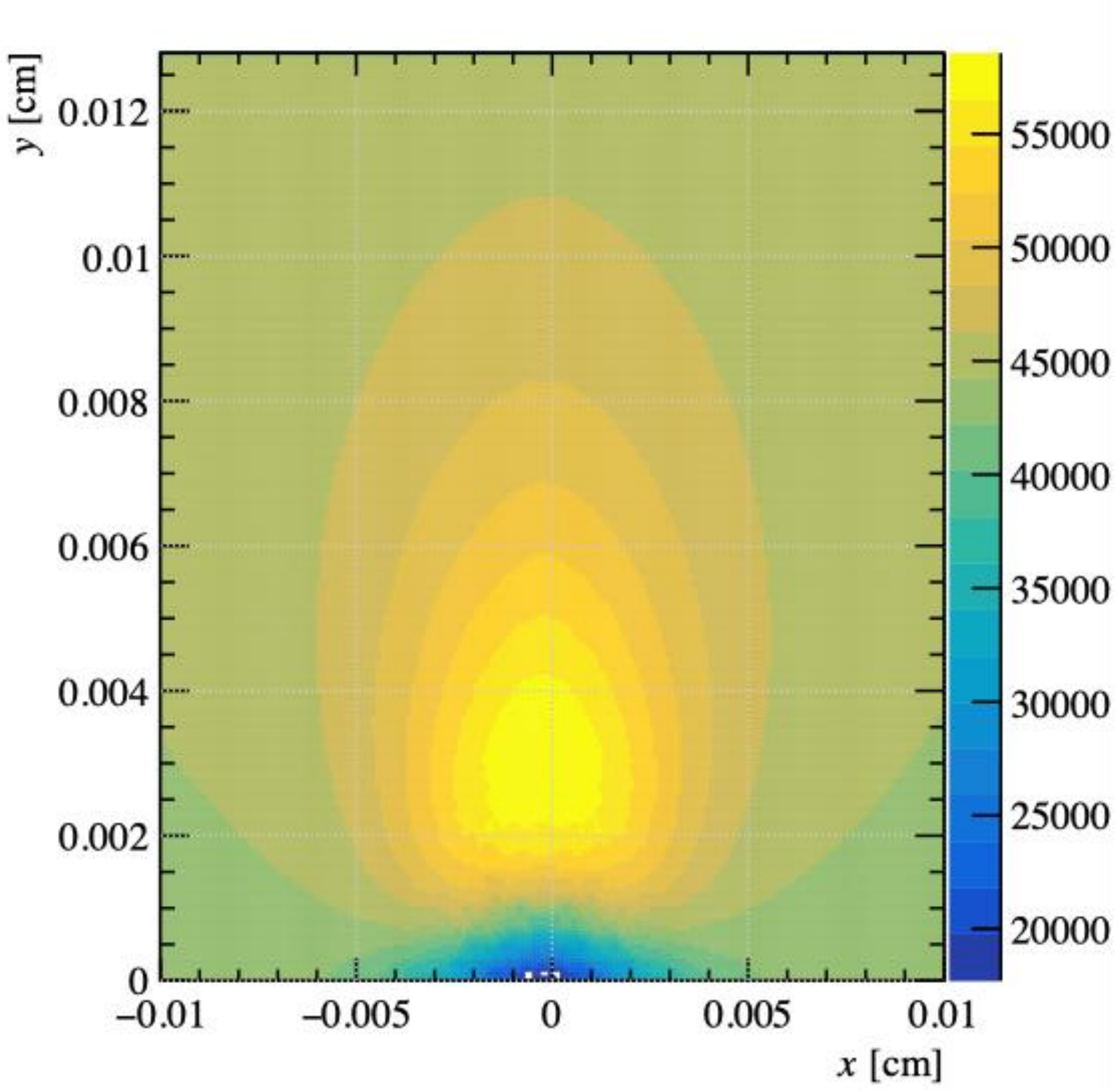
We start to see significant field modifications at 10^6 ionisations

We add initial electrons at the same place and time to ensure a single large avalanche

Units of the field in the plots are V/cm



1.7×10^5 ionisations
(20 initial electrons)



1.5×10^6 ionisations
(200 initial electrons)

Simulating with ComponentChargedRing

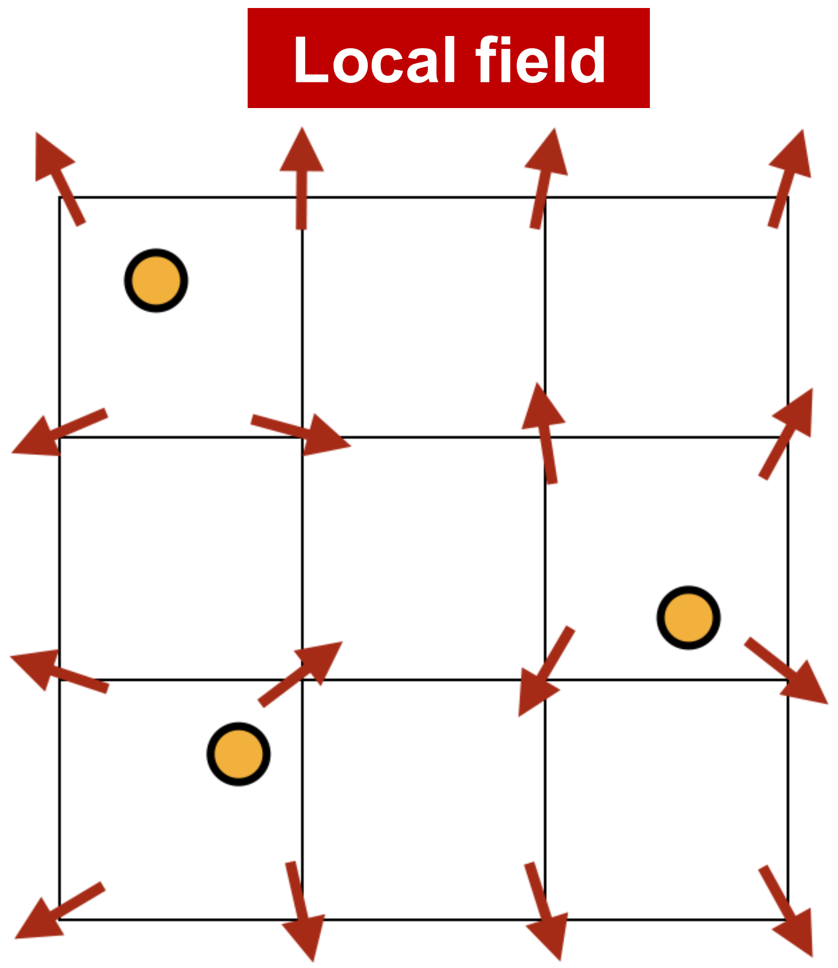
Getting to 10^6 ionisations takes a very long time, even when we limit the number of rings.

For each **time window**
    For each **electron**
        For each **time the field is requested**
            For each **ring in the simulation**

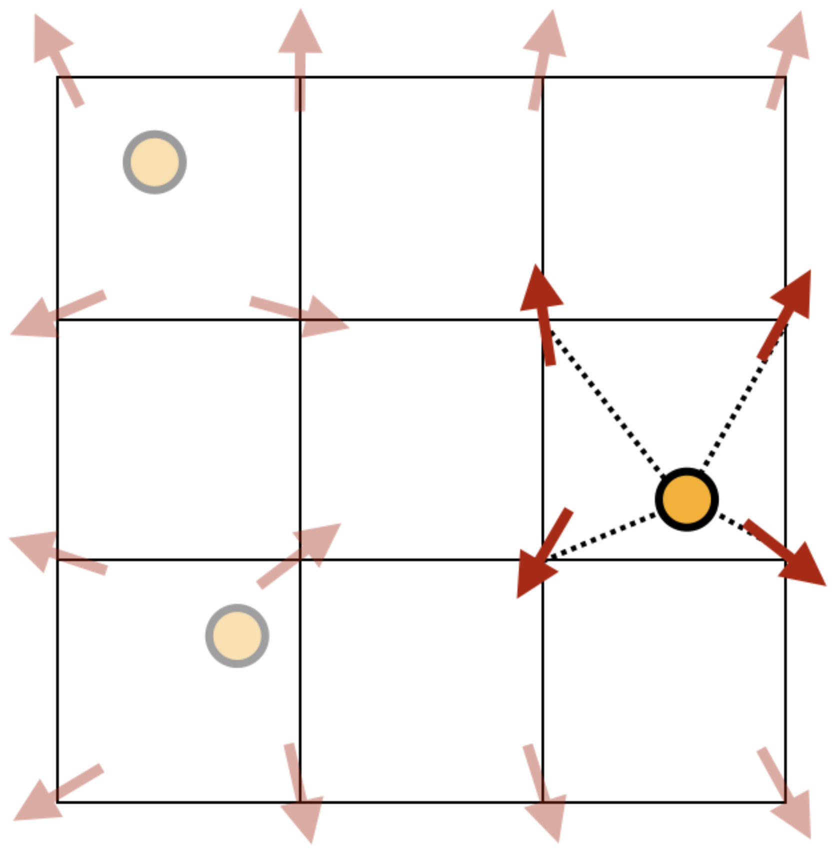
- Retrieve elliptic integral value from a huge array
- Perform multiple operations on it to get the correct field
- Handle any divergences
- Check if the ring should be treated as an on-axis point charge

Even with optimised code all of this adds up, and **large simulations are not feasible unless we use a grid** to pre-compute fields before each time window.

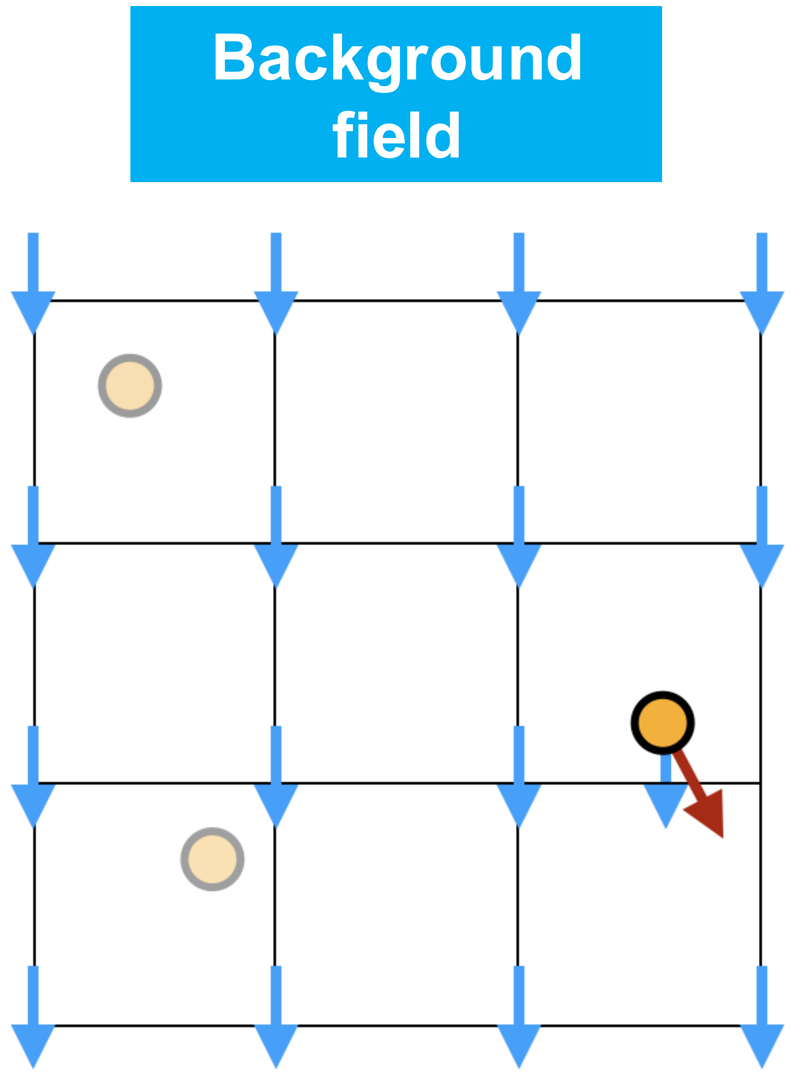
The grid-based approach in microscopic simulations



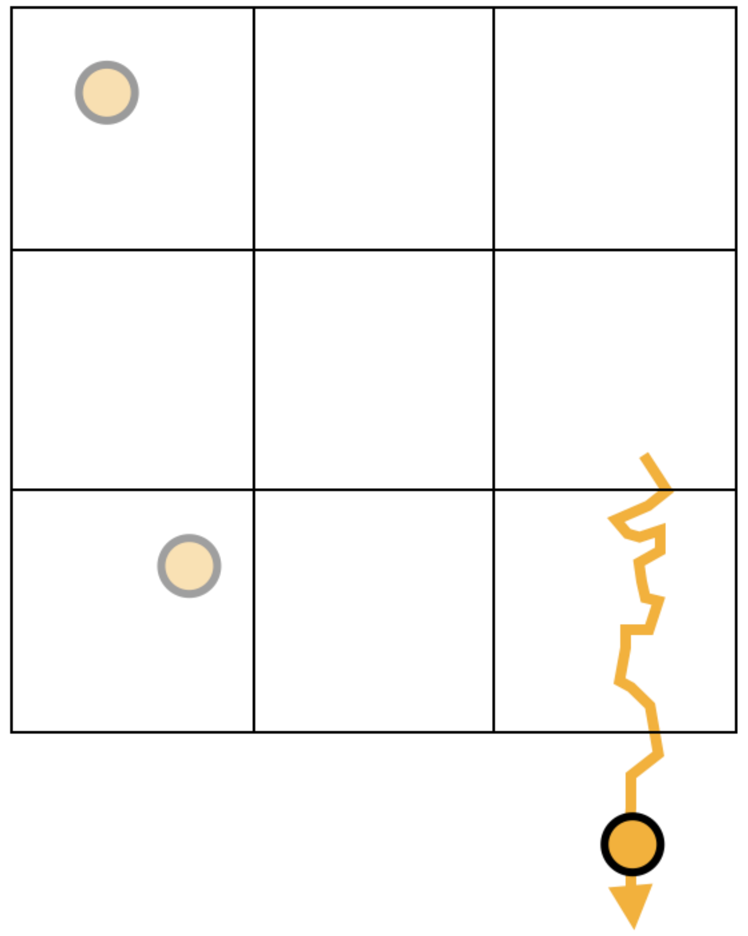
1. Calculate field on the grid nodes from the distribution of charges



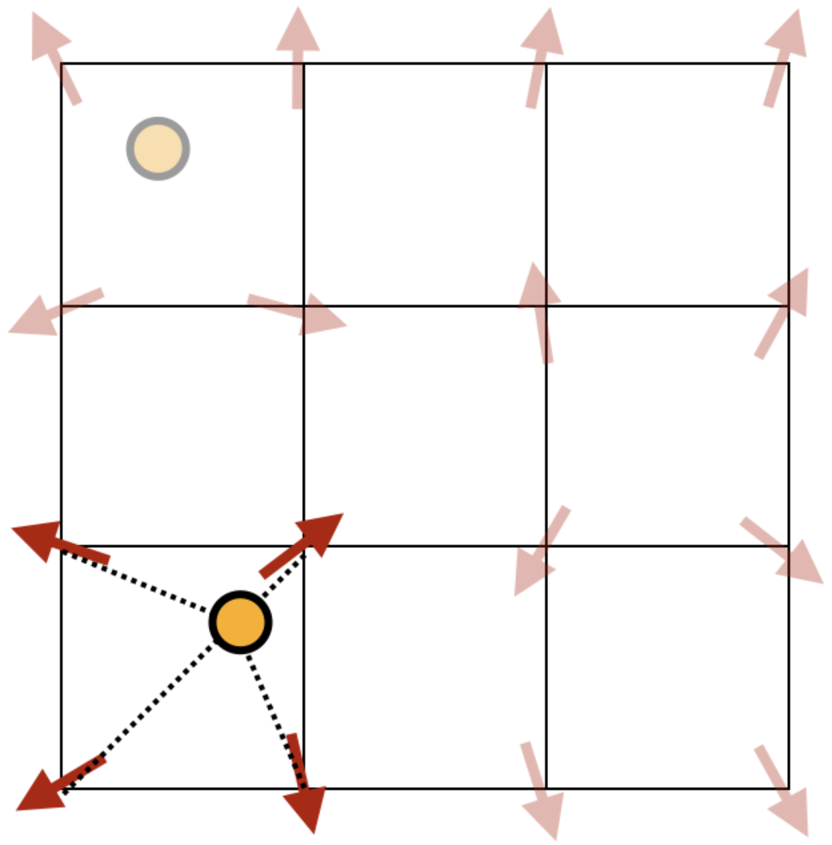
2. Find the local field at a charge's position by interpolating the field from the nearest nodes



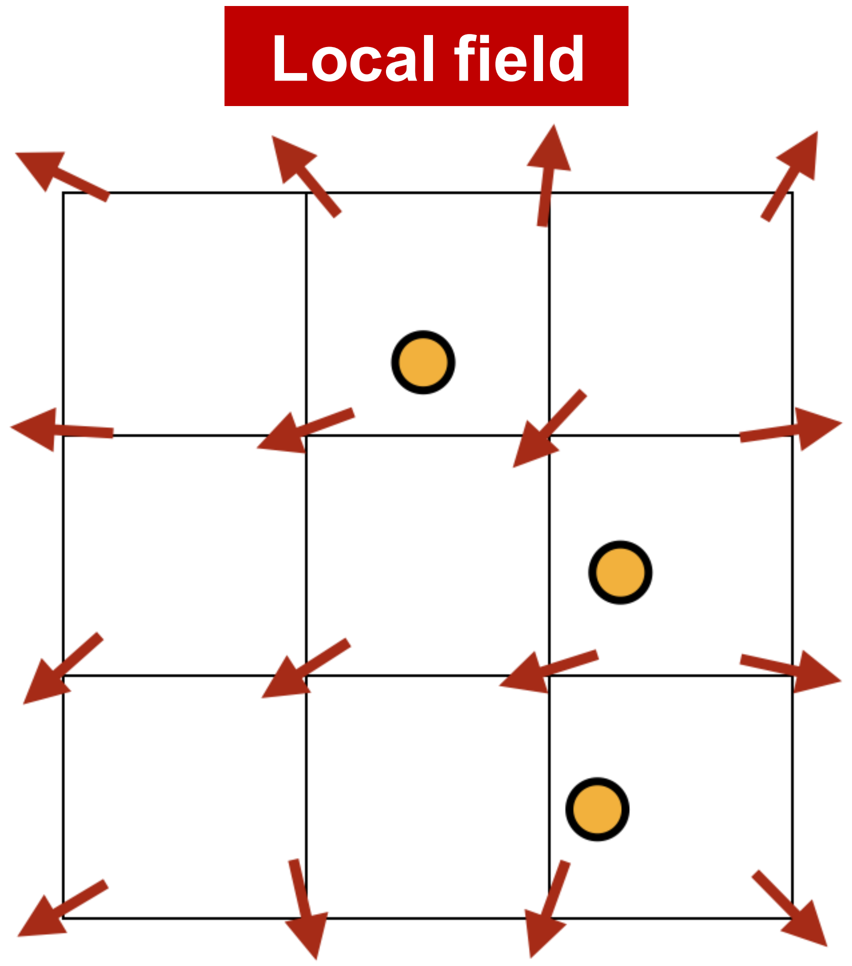
3. Add this to the background field at the charge's position



4. Drift the charge in the presence of these fields



5. Repeat from step 2 for the other charges



6. When all charges have been drifted, recalculate the field for the resulting charge distribution

Grid-based approach

2D (r,z) grids are strongly preferred:

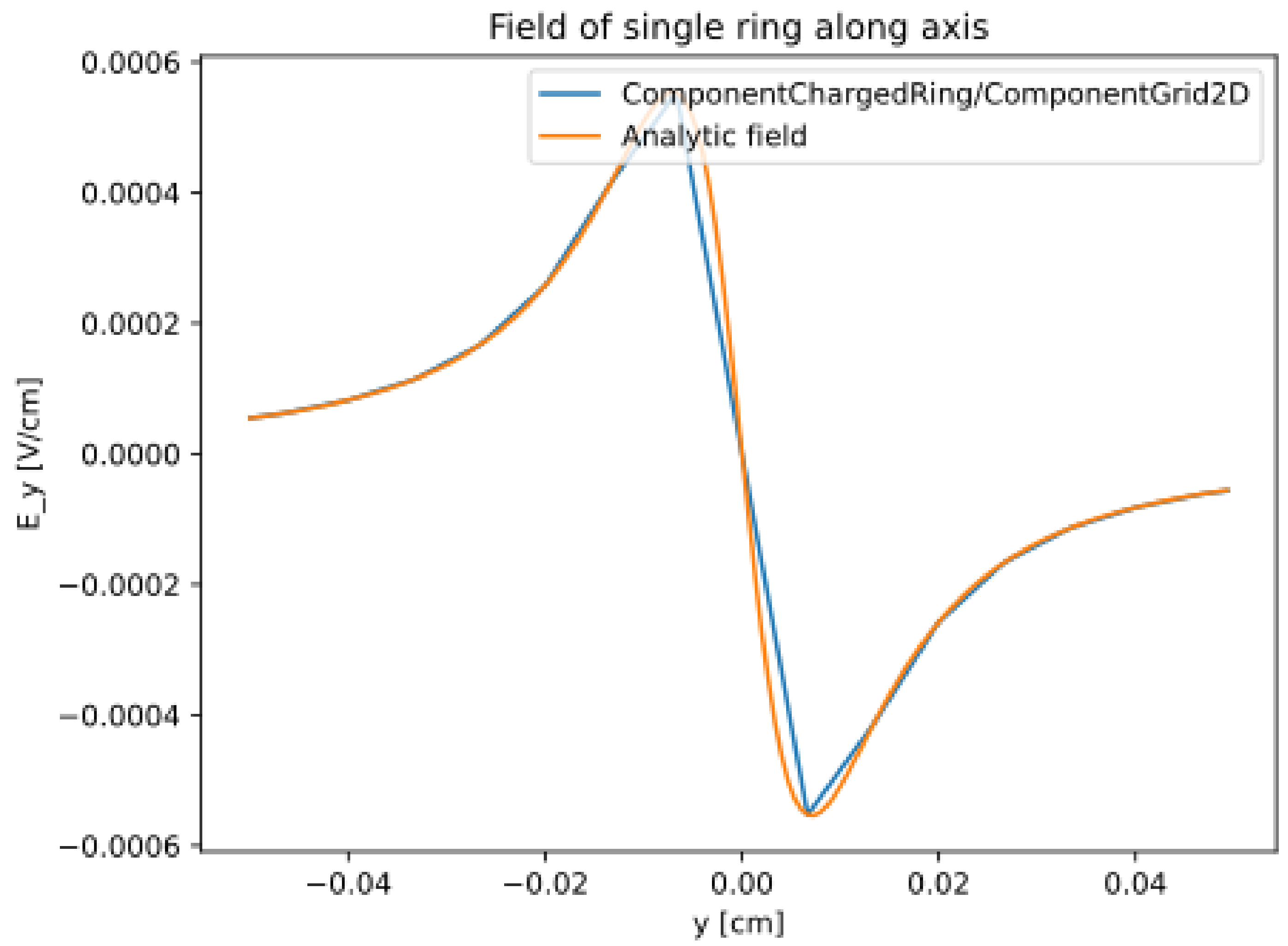
- The field at each node must be calculated; 3D grids have more nodes to iterate over
- A 3D grid implementation won't give a significant speedup below 10^6 electrons

ComponentChargedRing can be readily interfaced with grid classes, e.g. ComponentGrid

A basic 2D grid class (ComponentGrid2D) was written, allowing 2.2×10^6 ionisations to be reached in ~45 mins

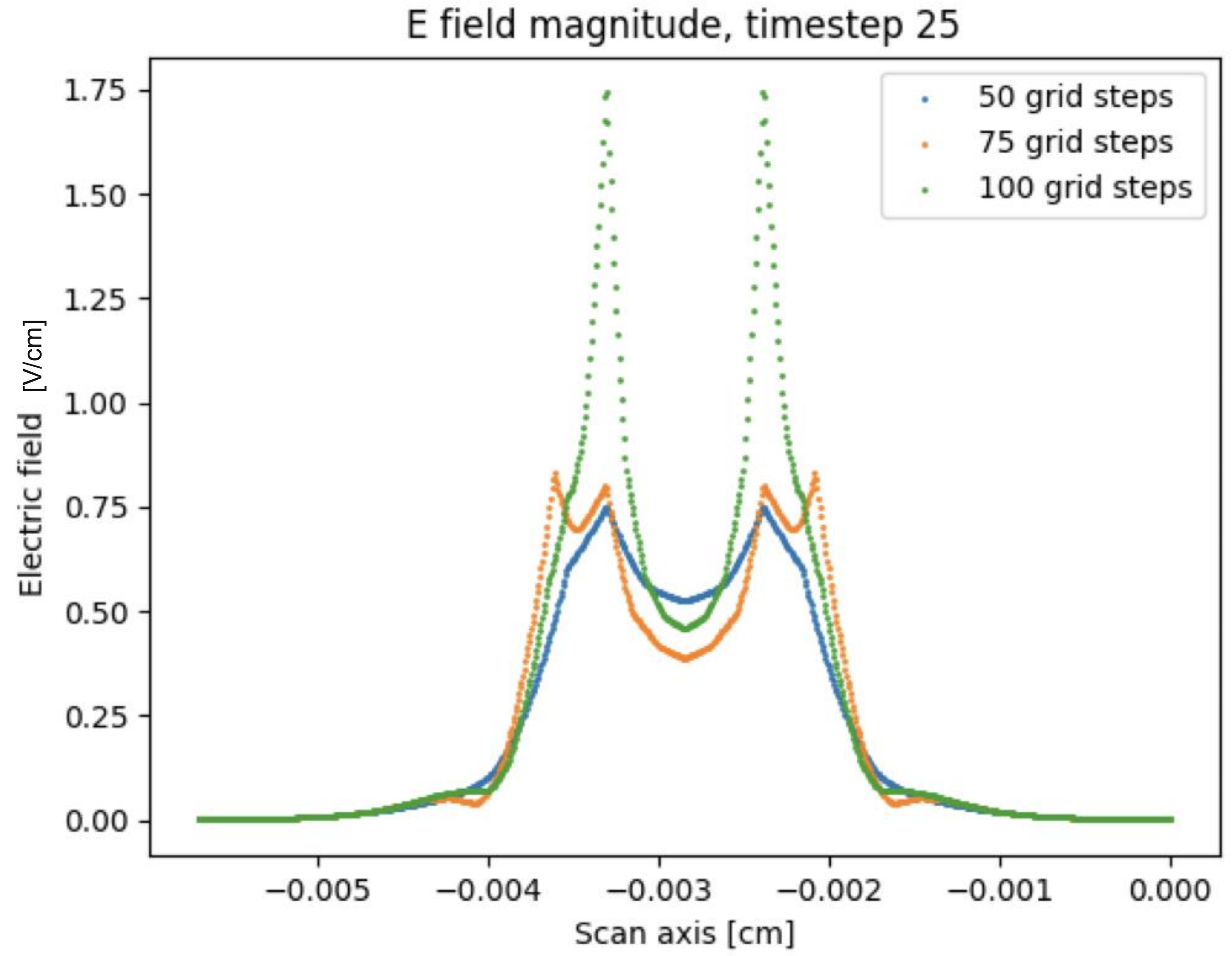
The field was found to strongly depend on the grid spacing for coarse grids. It was found to have converged at around ~2×10^4 nodes/cm in each direction

However, for large numbers of active particles, the field will get smoothed out anyway, so coarser grids could probably be used

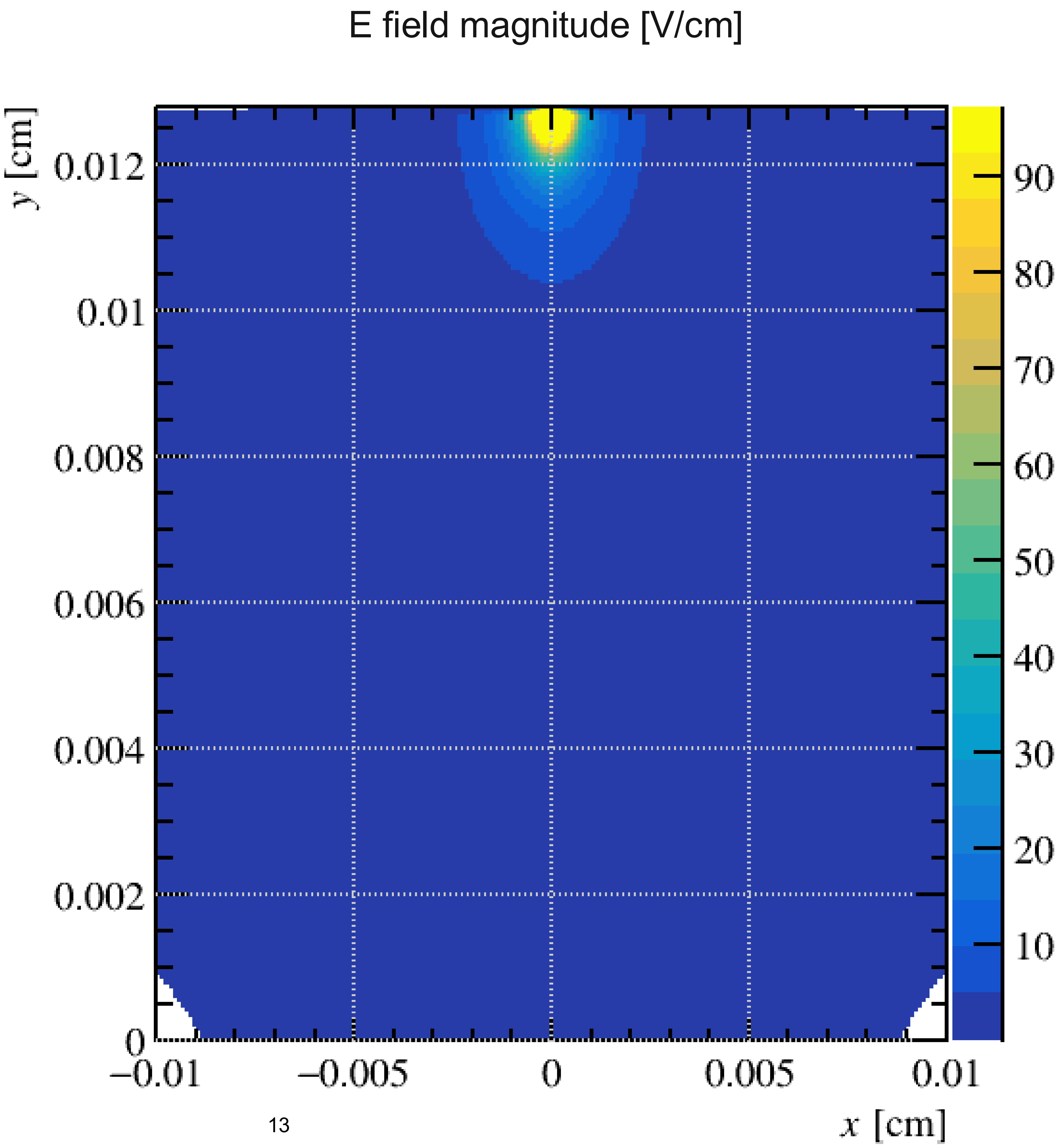


Top: field of a single ring, note the interpolation

Bottom: strong dependence of field on grid spacing for coarse grids (no field convergence)



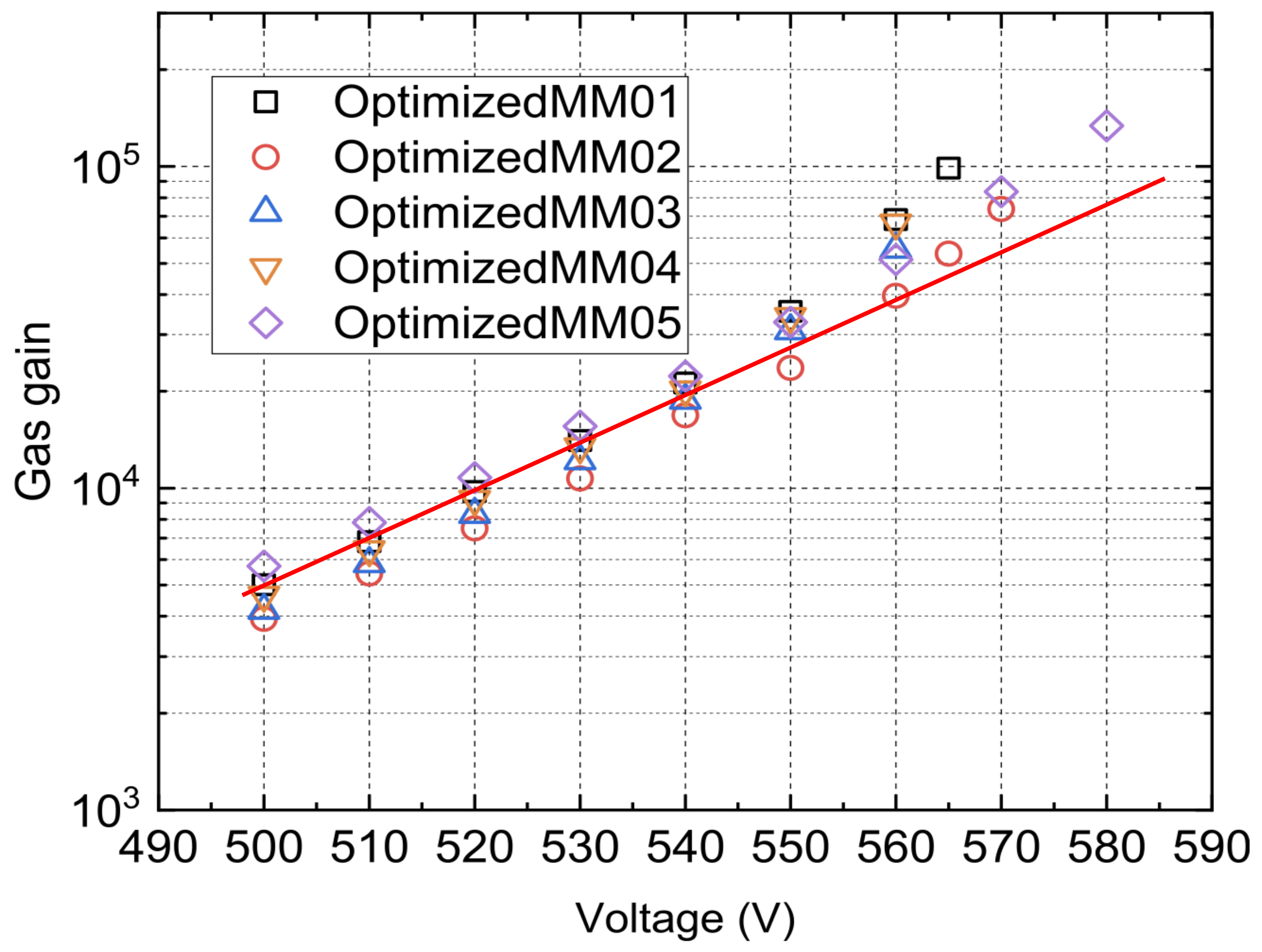
- Background field not included
- 1.6×10^6 ionisations
- Note the symmetry-induced dip in magnitude along the axis

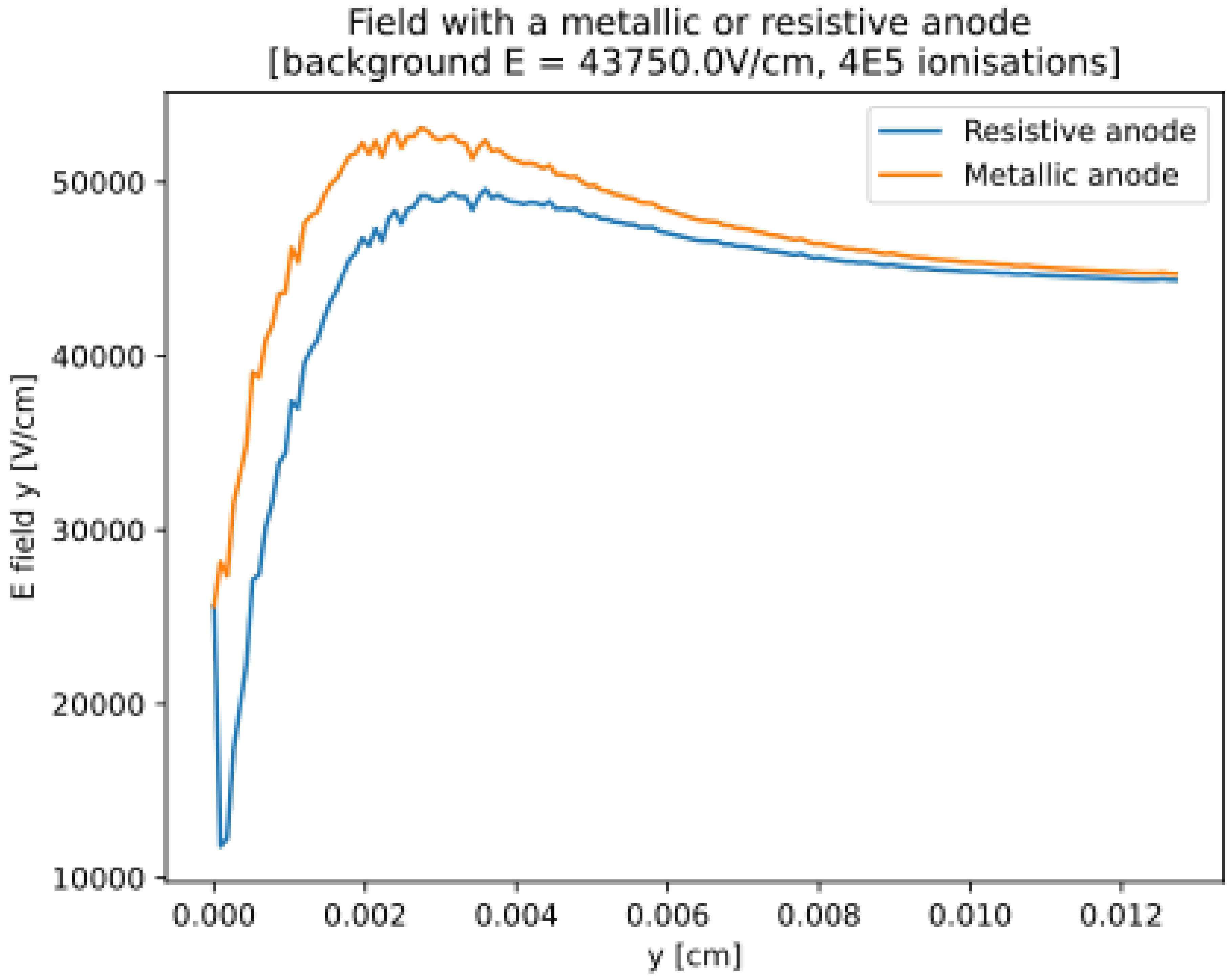


Effect of a resistive anode

To see if space charge could cause superexponential behaviour in resistive Micromegas, the field modification due to a resistive anode was investigated.

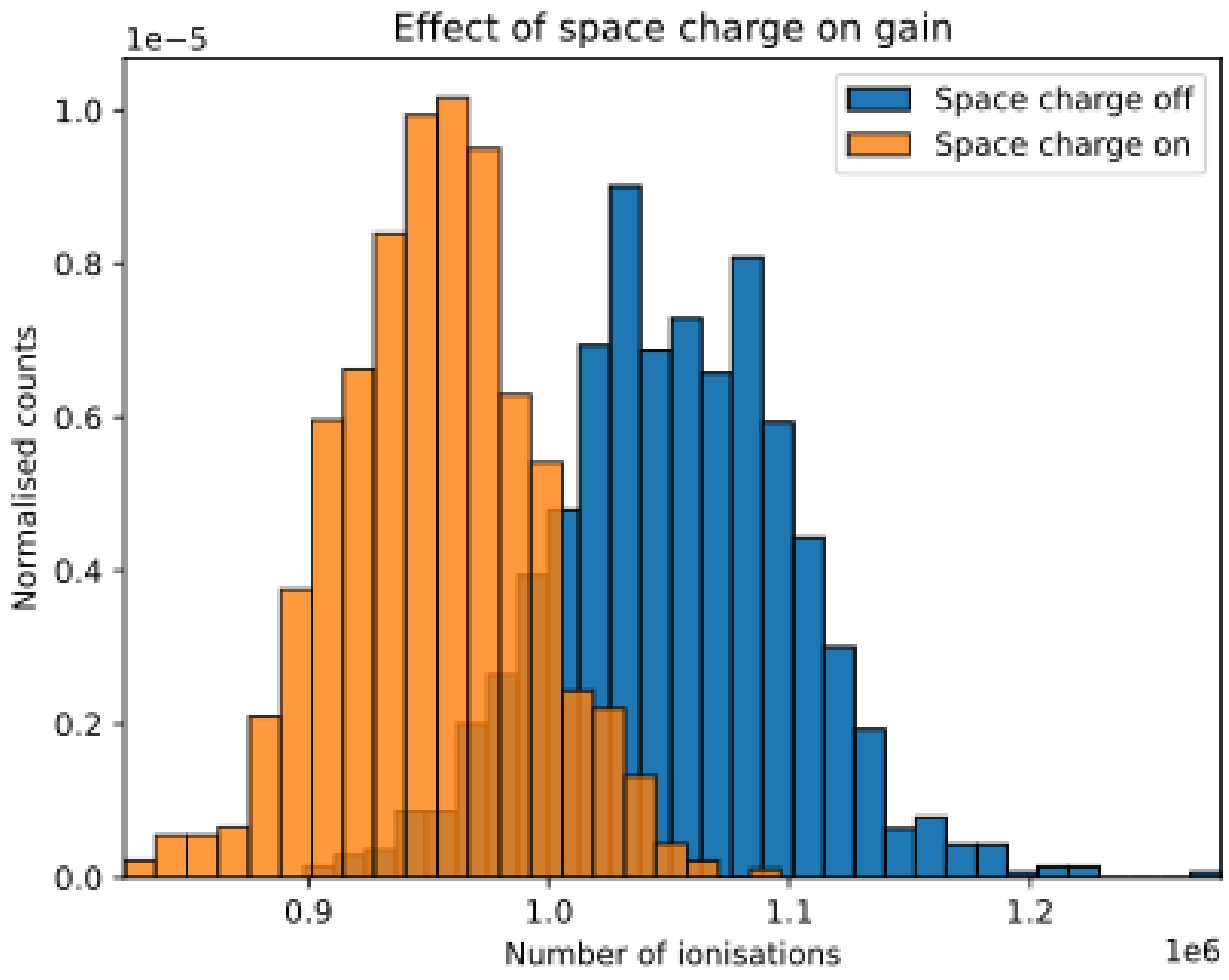
- Electrons were added as charged rings 'stuck' on the anode
- There was a field reduction, which would imply a stronger gain limiting effect
- So, space charge effects probably aren't the cause





Effect of the space charge field on gain

- Parallel plate geometry
  - d = 128μm, dv = 540V
- 200 electrons added at the same location and time in each run
- We see a gain limiting effect, which we expect due to the field reduction



Space charge enabled: $\mu = 9.52\times10^{5}$, SD = 1539, N = 696

Space charge disabled: $\mu = 1.05\times10^{6}$, SD = 1506, N = 1100

Multiple ring systems

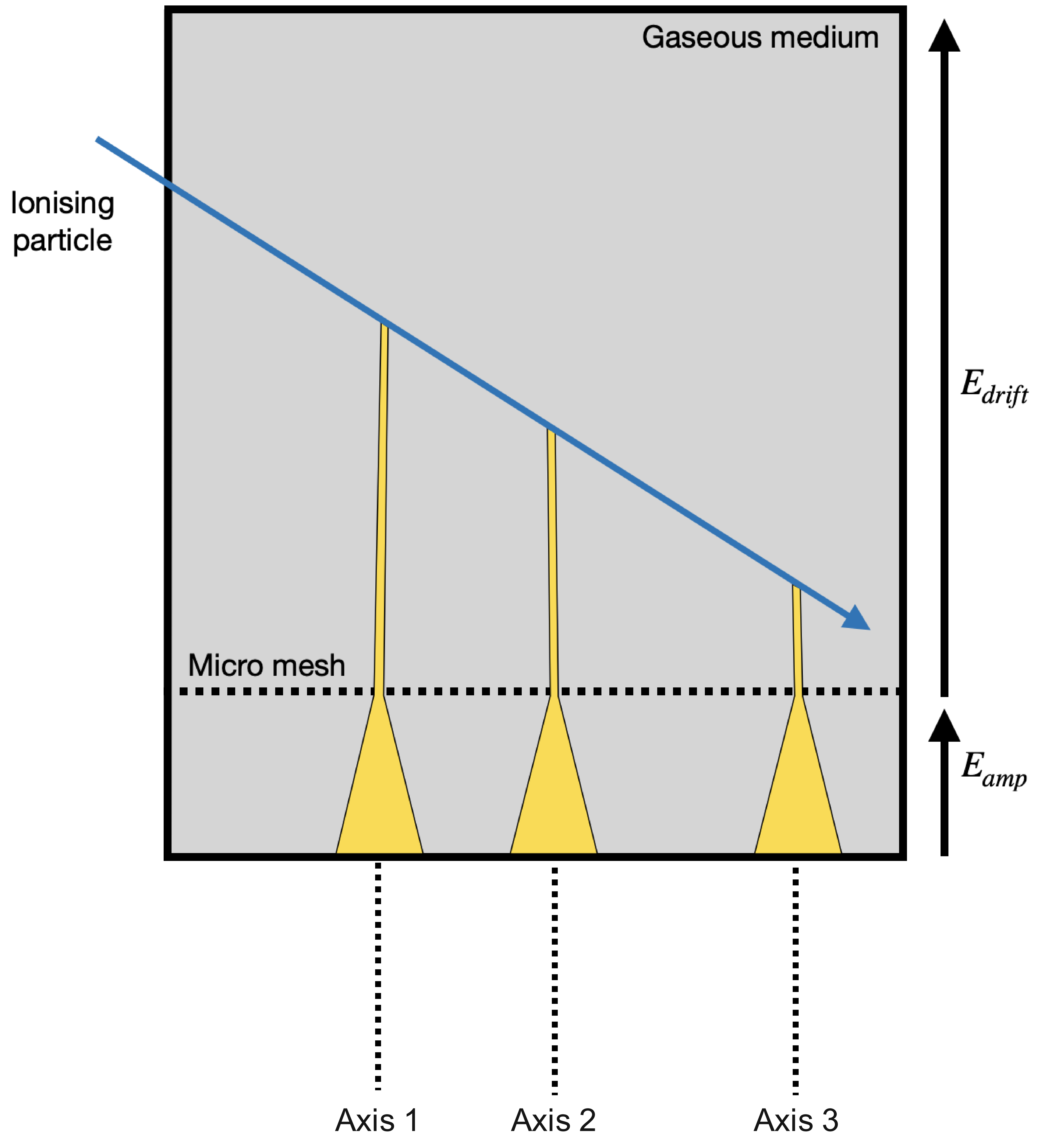
Up to now we have been dealing with a single system of charged rings

With real detectors in mind, we are more interested in having multiple systems active at once

We get multiple ring systems when:

- We have multiple clusters formed from a track

- Charges from a deposition in a 'blob' diffuse away from each other

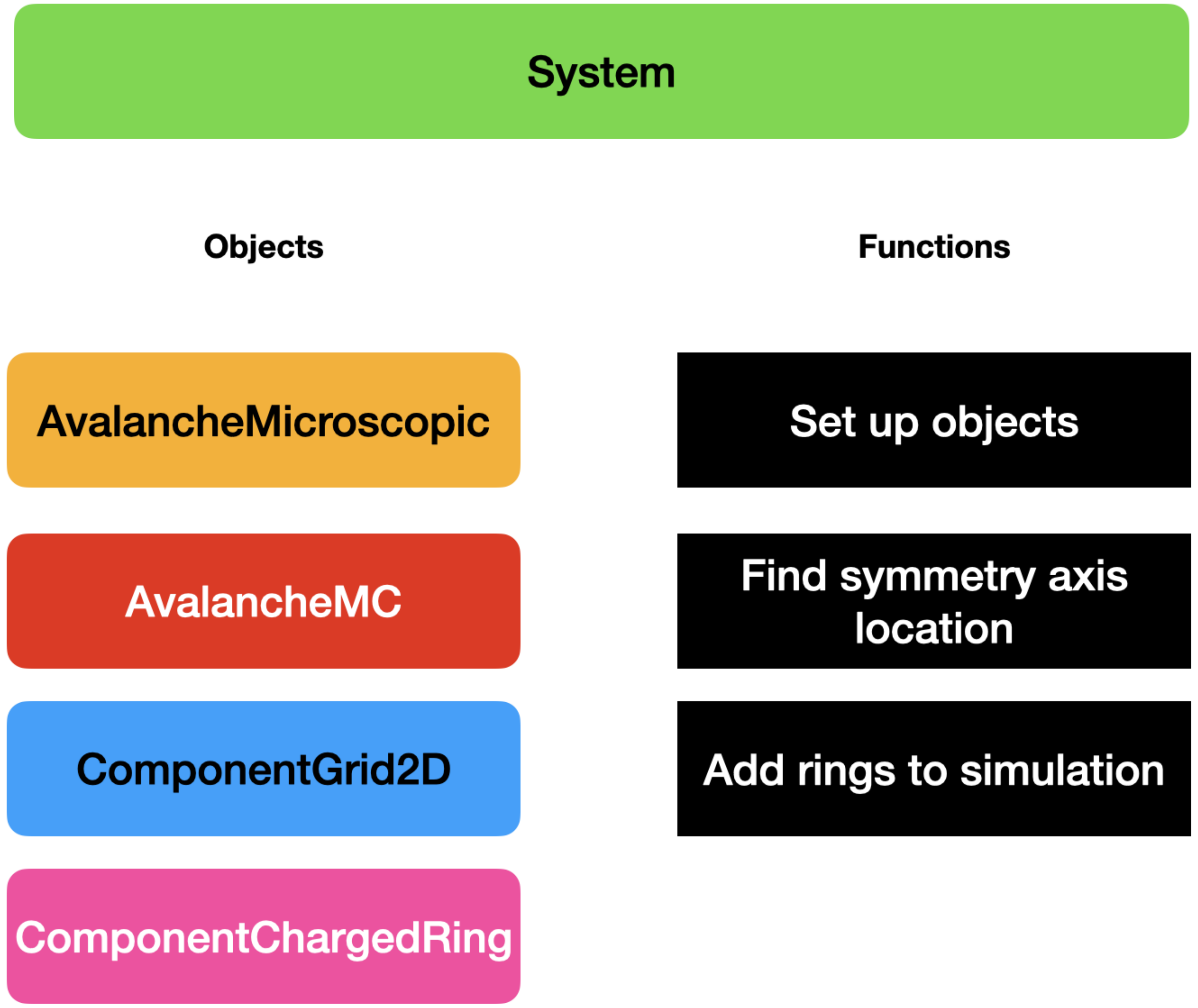


We need a separate symmetry axis for each ring system

Multiple ring systems

Use a vector of System objects

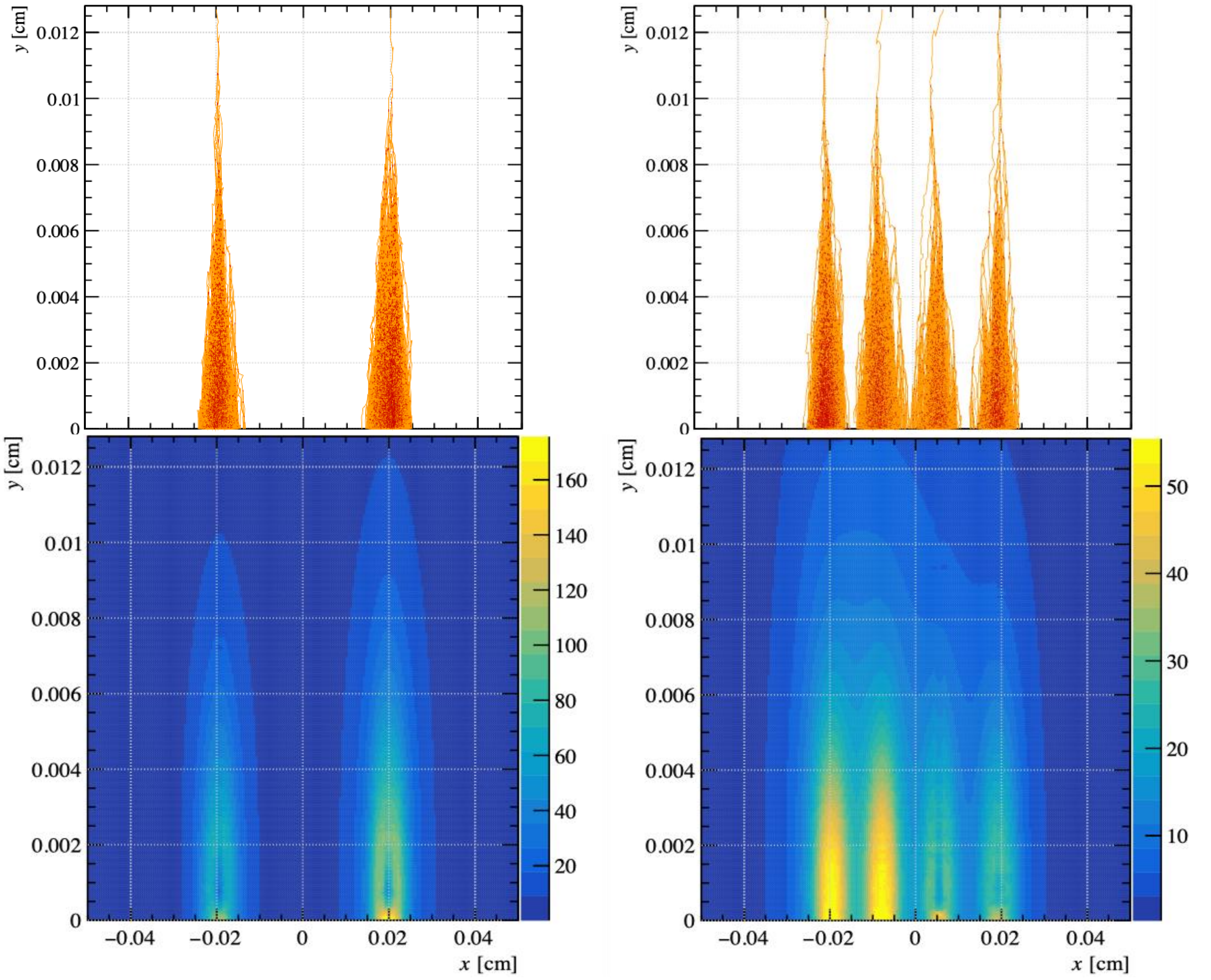
- We need one Avalanche object per system so that we can keep track of which particles are in which system.
- We need one ComponentGrid2D and ComponentChargedRing object per system as both use symmetry axes, and there is a unique axis per system
- We use a single Sensor object. This ensures all particles feel the field from all systems.



Multiple ring systems

Background field not included as the space charge field was weak (~10^3 charges per ring system). Units are V/cm.

Top: drift lines (electrons, ions)
Bottom: space charge E-field magnitude



Project report viewable here

Conclusion

A semi-analytic, axisymmetric approach for including the space charge effect in microscopic simulations was investigated

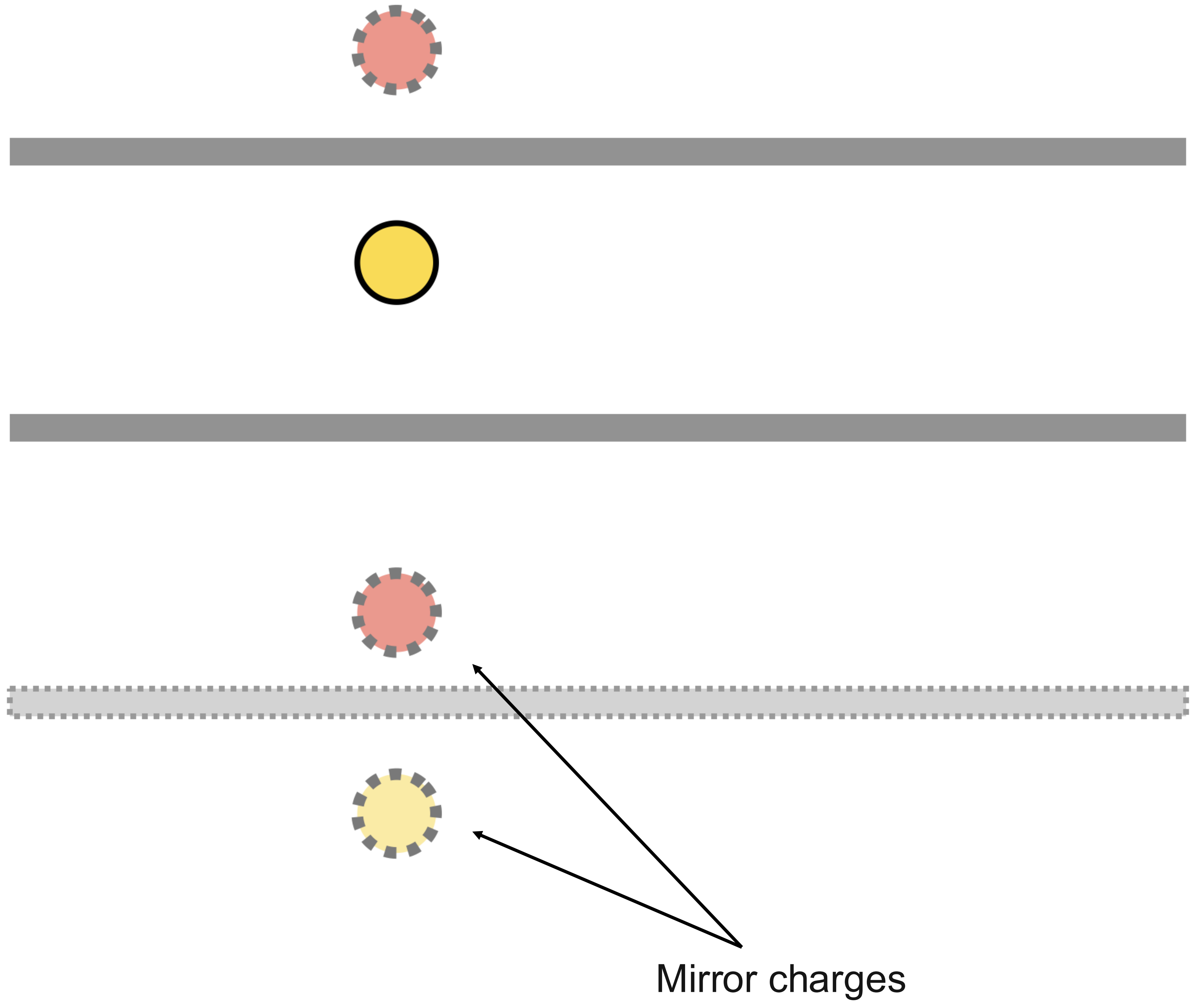
- The new class ComponentChargedRing was added to Garfield++
- Grid-based and grid-free approached were investigated
- Charge densities required for significant field modification were investigated
- Effect of using a resistive anode was investigated
- A gain limiting effect was observed
- Proof of concept technique of simulating multiple ring systems was developed and applied to a Micromegas

Future work: compare to FEM/neBEM approaches, apply this method to LGADs

Questions

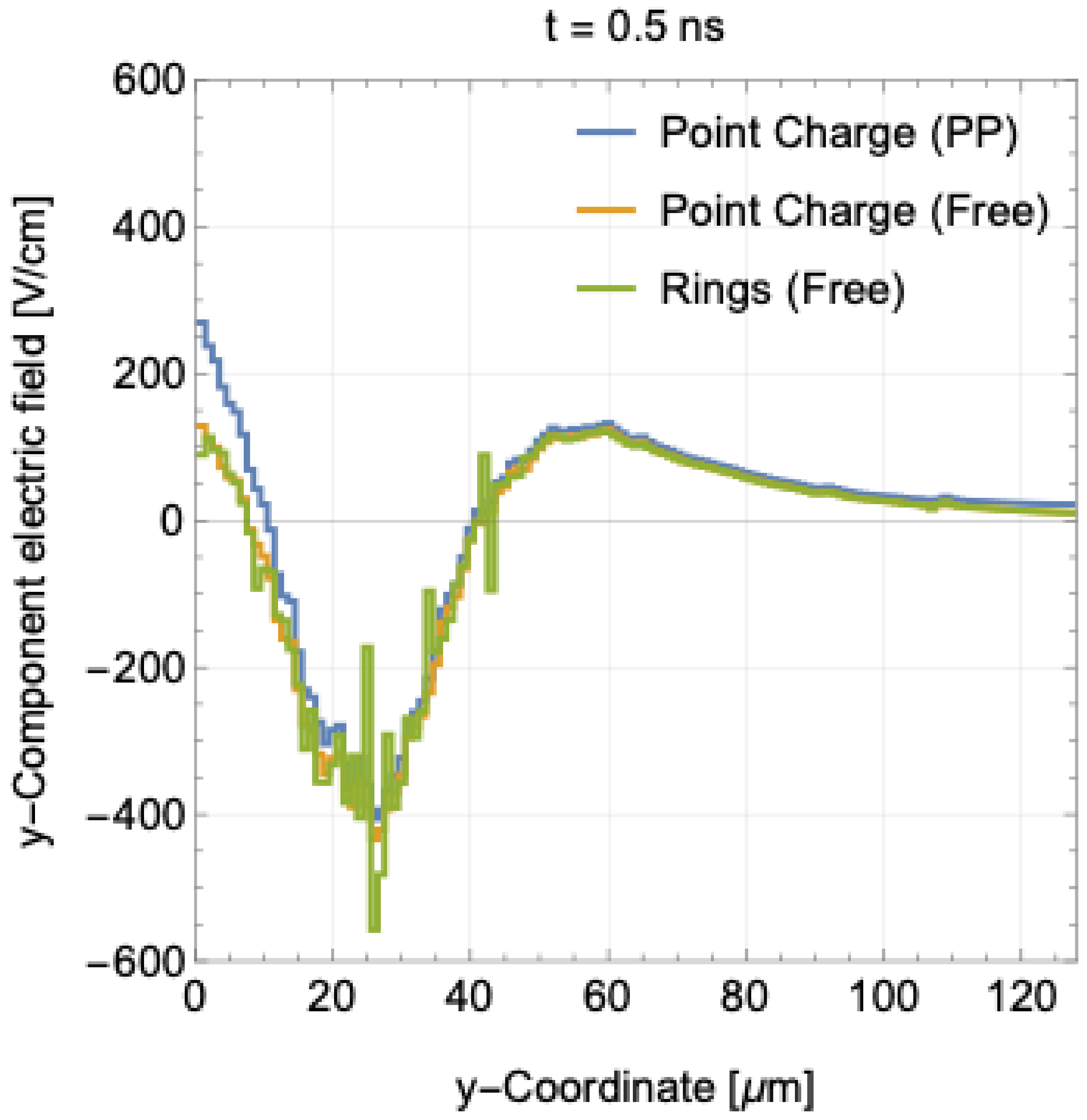
Point charge approach

- For a point charge in a parallel plate, the analytic field expression involves infinitely many mirror charges
- These can be expressed as an integral over a Bessel function
- This is expensive to compute, so a grid is used for efficiency
- We pre-compute the field maps on the grid and use symmetry to reduce memory usage



Point charges

- There is good agreement between free charged rings and point charges except at the anode
- Here, mirror charges from the parallel plate boundary condition cause the field to be modified
- Computation time and memory space are limiting factors



Comparison of the electric field for different approaches to space charge effect simulations