

Time projection chambers

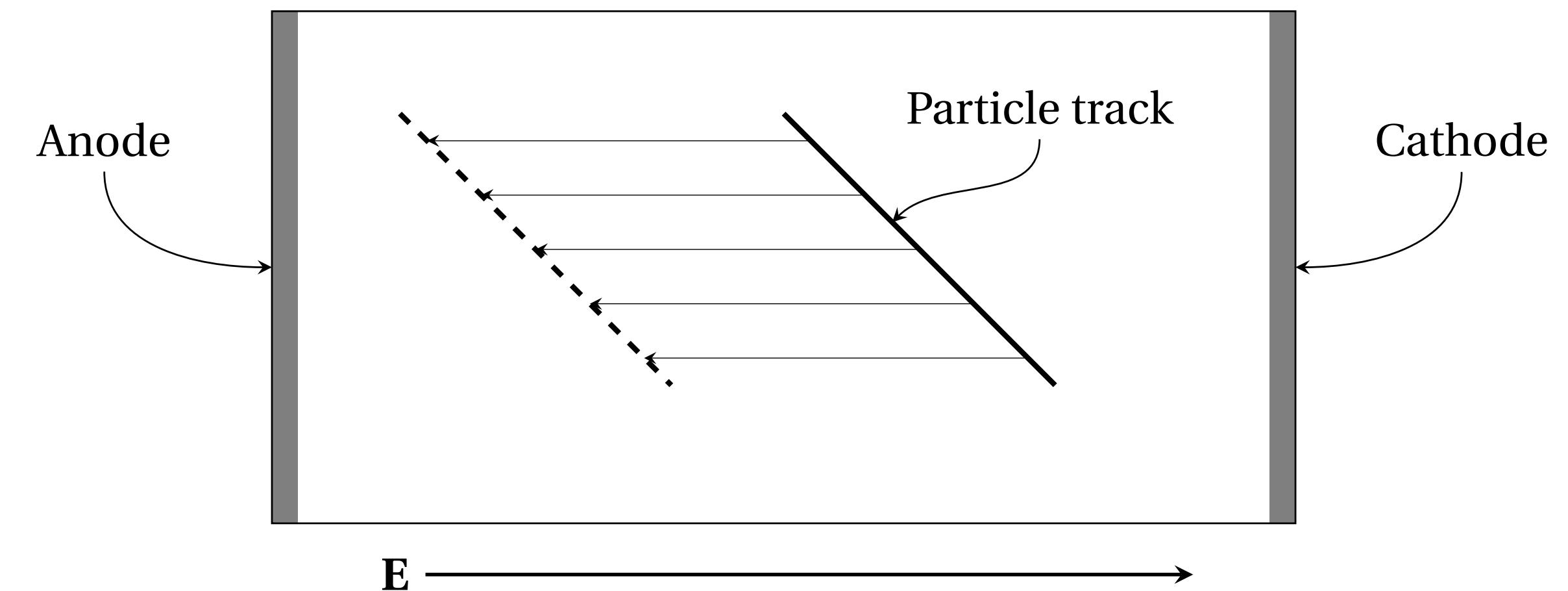
No, it's not a place to time travel...

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Principle of operation

- Charged particles traveling through matter ionize atoms or molecules
- Primary electrons released from ionization are guided to a sensor via an electric field
- Electrons arriving at the sensor anode are multiplied locally to produce a signal
- The signals are recorded in both amplitude and time by digital electronics



Drift time along the electric field
 E directly proportional to
distance to Anode

TPCs are imaging detectors that produce 3D images of charged particle tracks

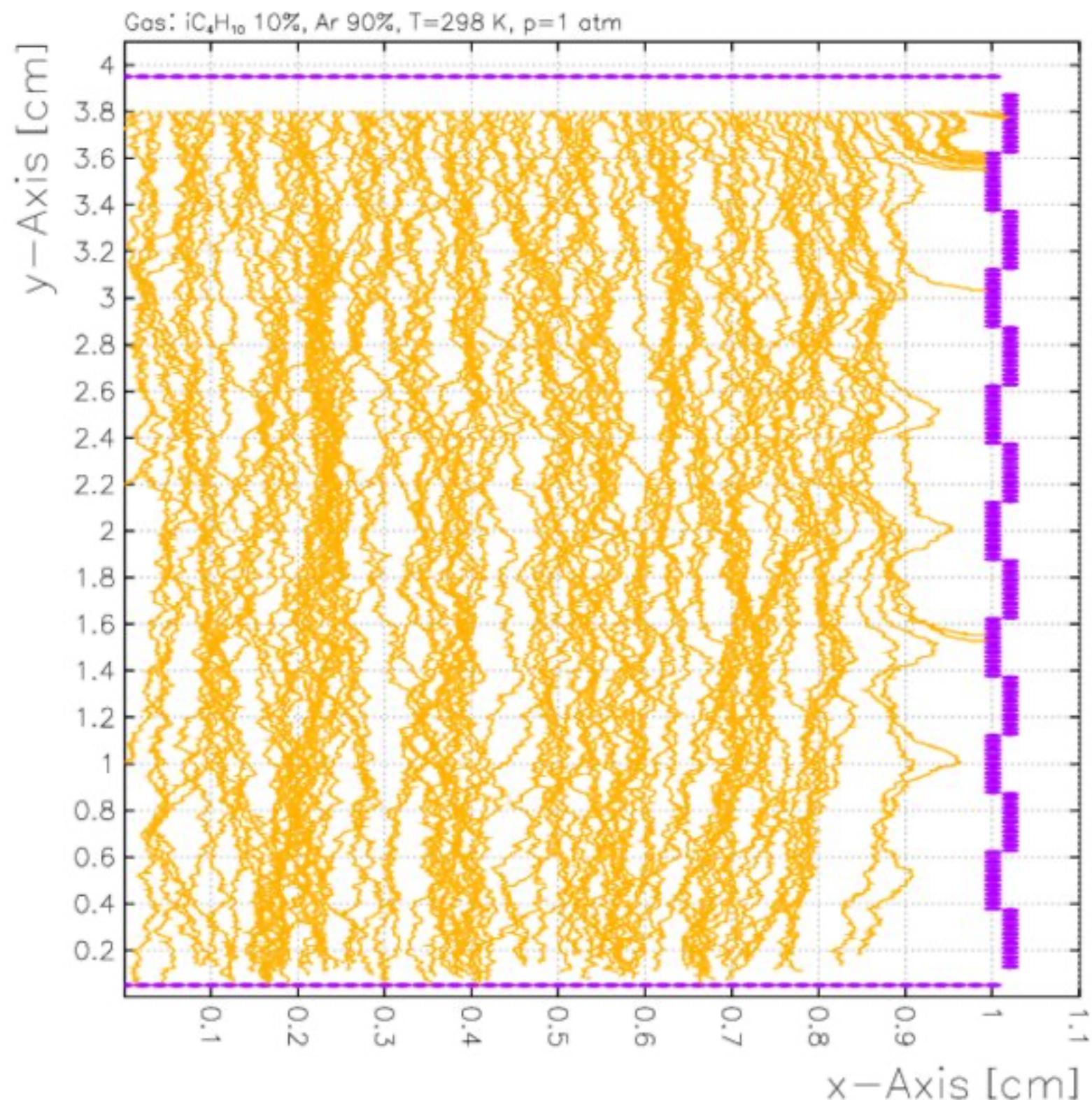
Drift velocity

- Propagation of electrons
 - Follow Langevin's equation
 - $\tau = mv_D/eE$ is the mean time between collisions
 - $\omega = eB/m$ is the cyclotron frequency
 - $\mu = e\tau/m$ is the electron mobility
- Electrons have a constant velocity
 - Essential to TPC concept

$$m \frac{d\mathbf{v}}{dt} = e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) - \frac{m}{\tau} \mathbf{v},$$

$$\mathbf{v}_D = \frac{\mu E}{1 + \omega^2 \tau^2} [\hat{\mathbf{E}} + \omega \tau (\hat{\mathbf{E}} \times \hat{\mathbf{B}}) + \omega^2 \tau^2 (\hat{\mathbf{E}} \cdot \hat{\mathbf{B}}) \hat{\mathbf{B}}].$$

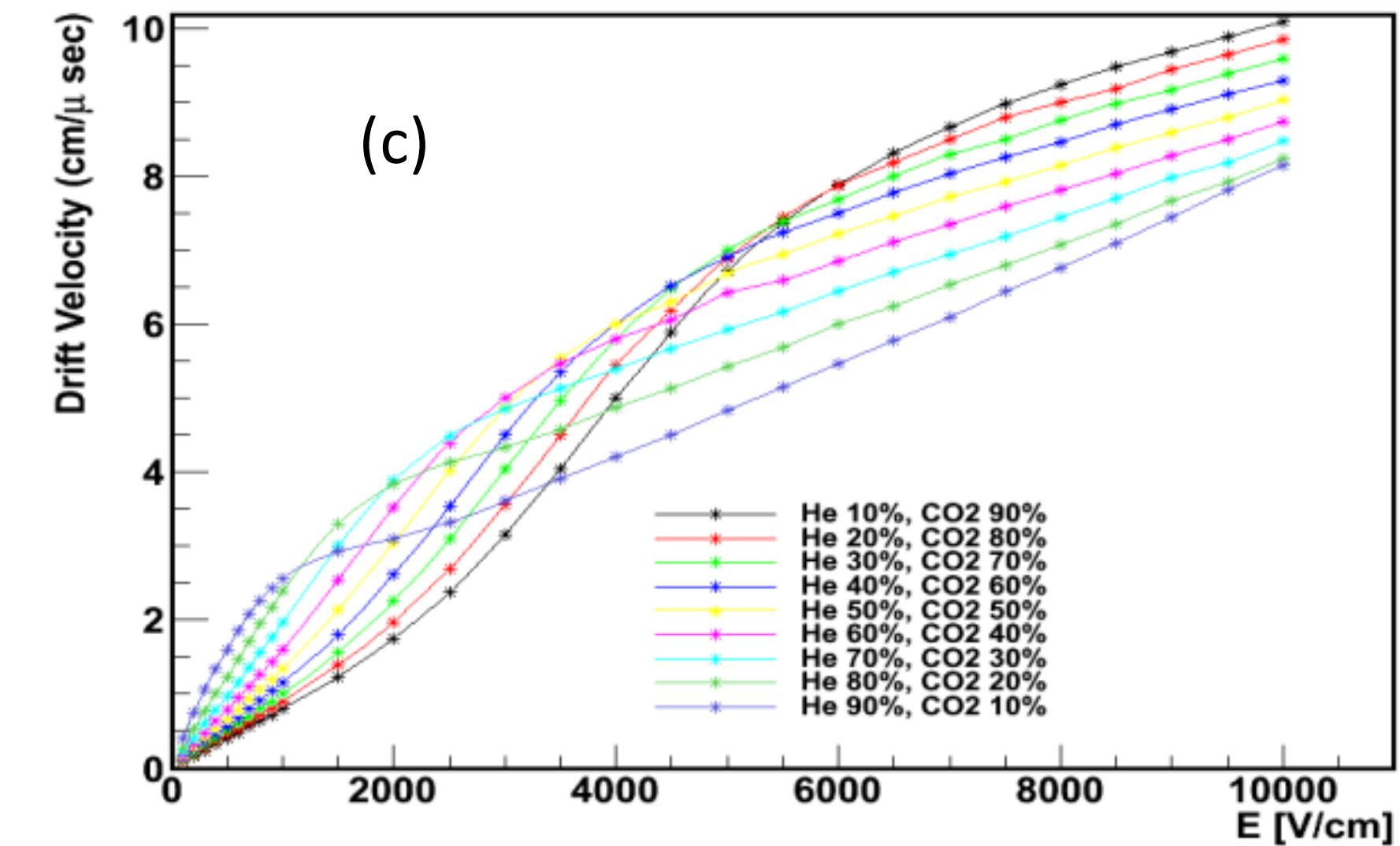
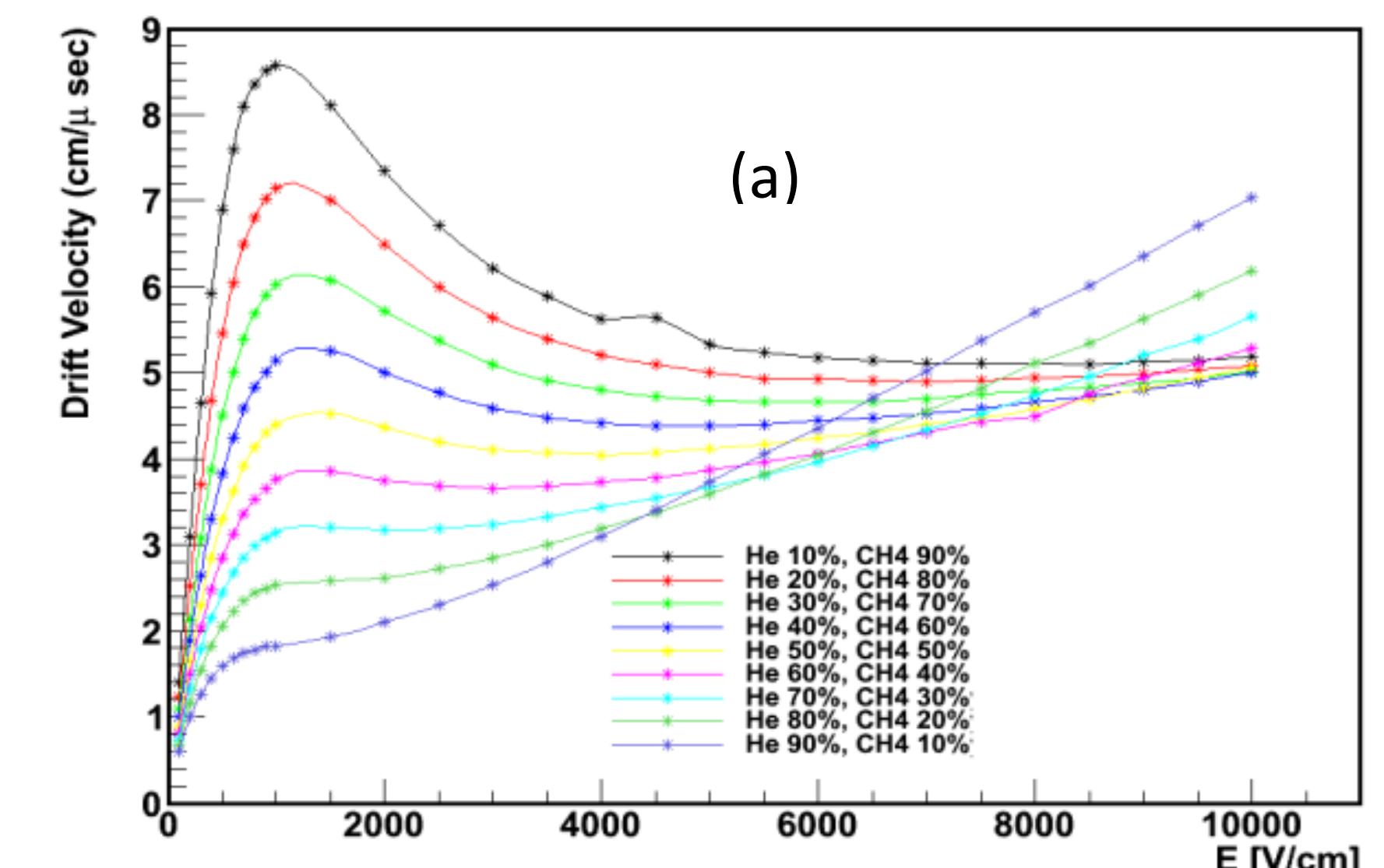
Layout of the cell



Plotted at 10.18.11 on 06/09/12 with Garfield version 7.44.

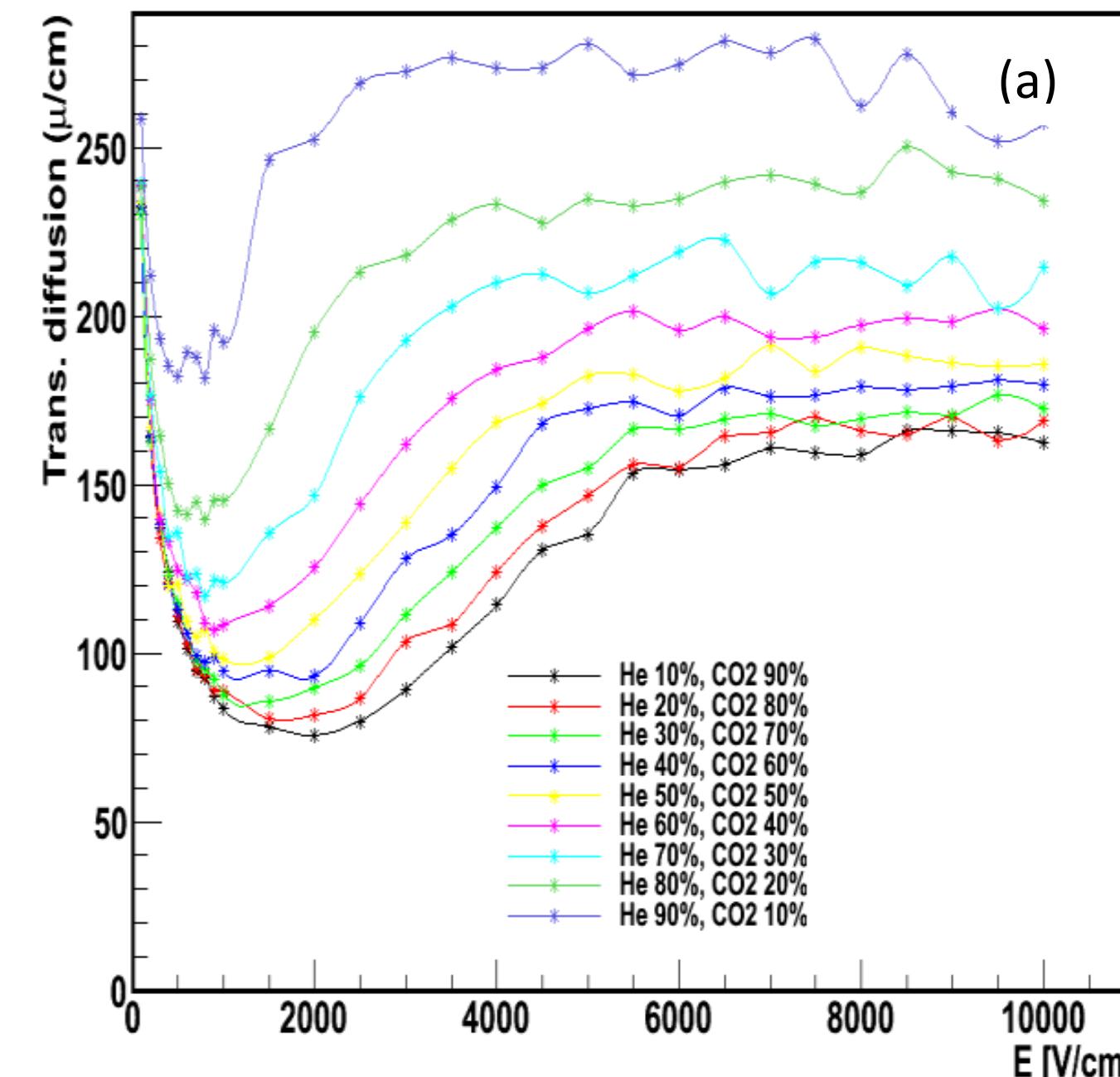
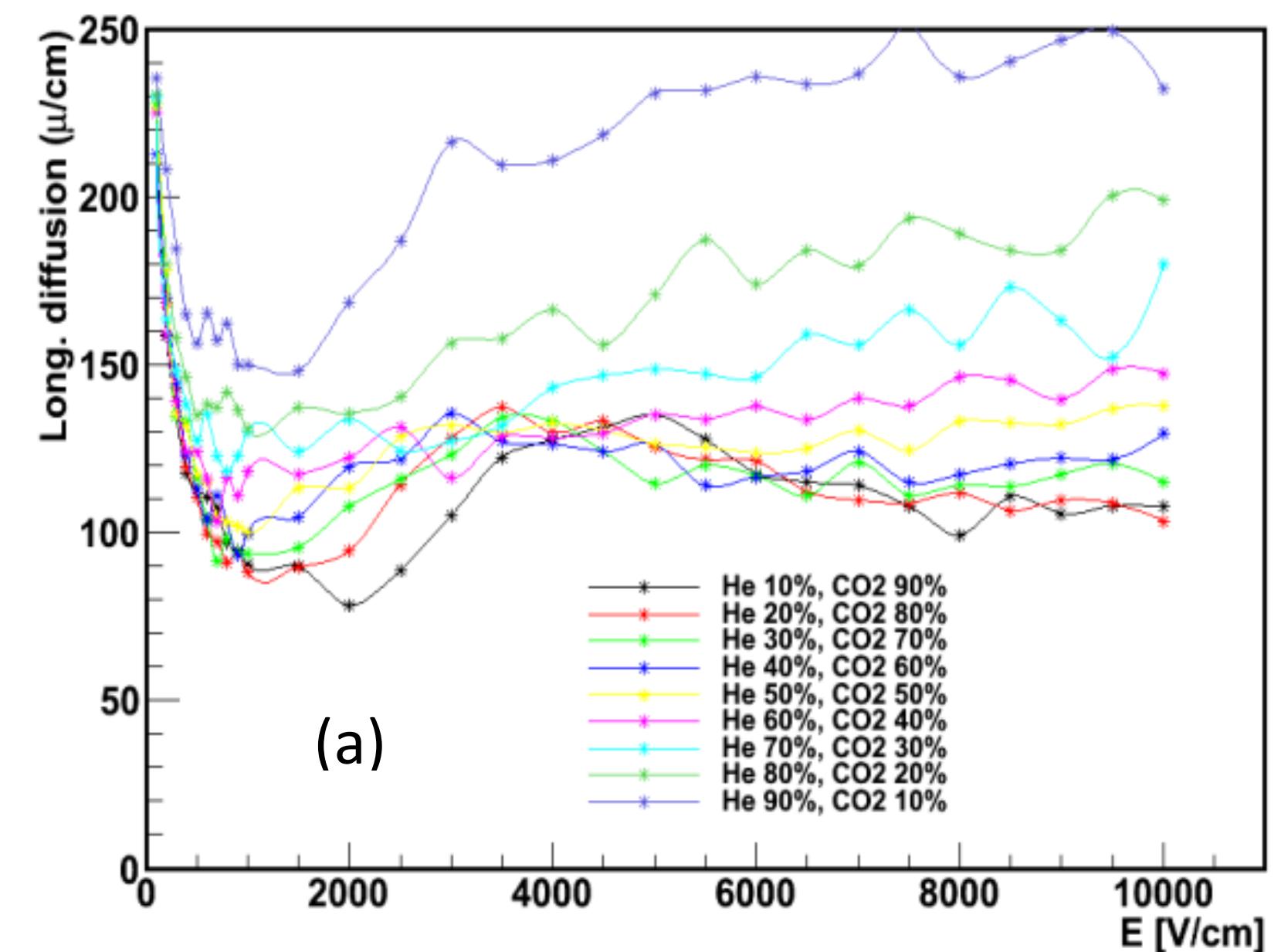
Drift velocities

- Measured in 1 atm gas mixtures
- Order of magnitude $\sim 1\text{-}10 \text{ cm} / \mu\text{s}$
- Electronegative pollutant such as O_2 , Cl_2 , Br_2 remove primary electrons
- The slower the drift velocity, the longer the dead time of the TPC (time needed to drift all primary electrons to the anode)
- Positive ions resulting from ionization are much (1000x) slower!



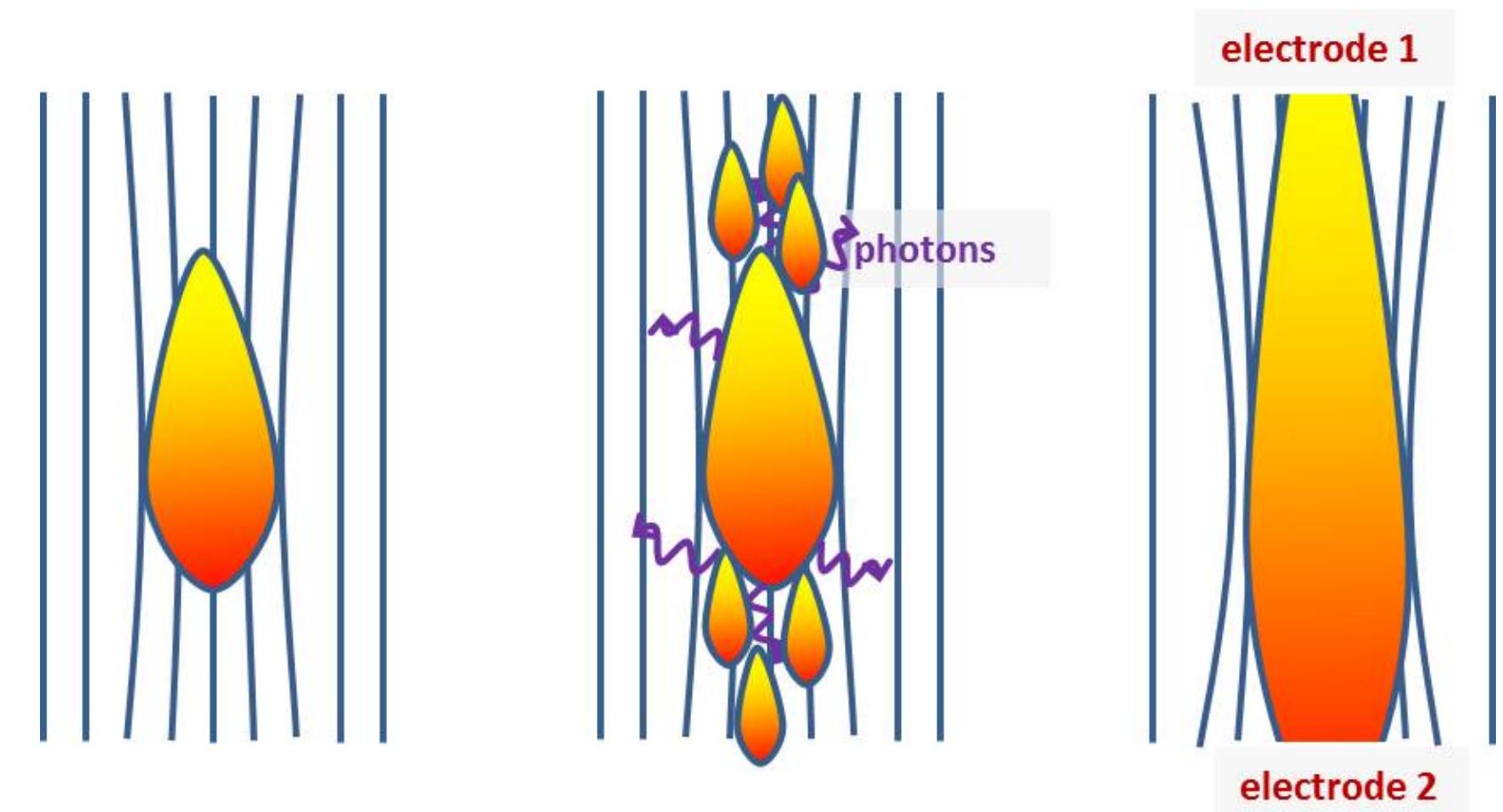
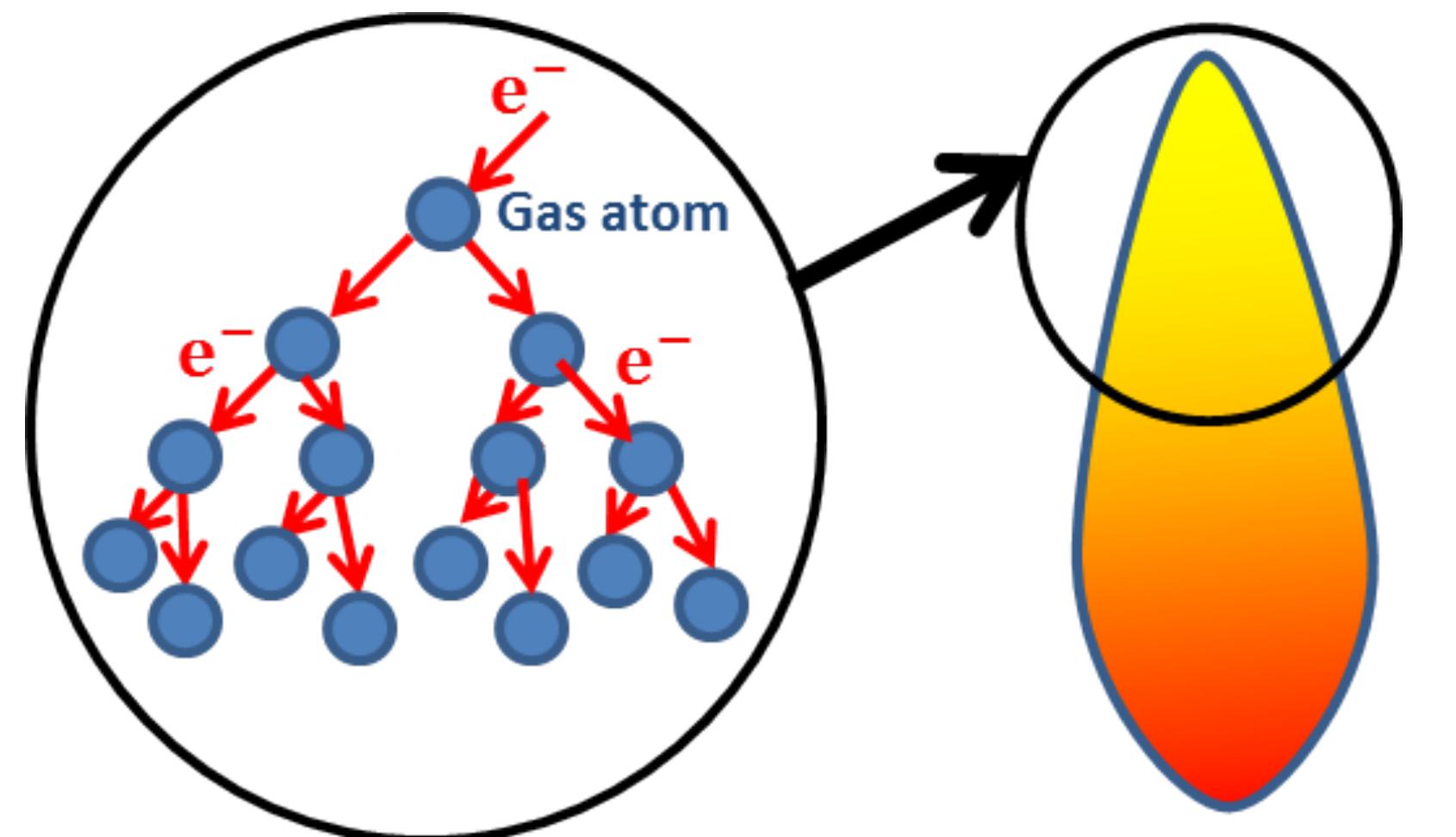
Electron diffusion

- Effects of gas molecules/atoms on electron motion
 - Longitudinal diffusion: fluctuations in drift velocity due to collisions
 - Transverse diffusion: scattering of electrons on molecules/atoms
- Transverse diffusion can be reduced by magnetic field aligned with electric field
 - Electron follow helicoidal trajectories that confines them transversally



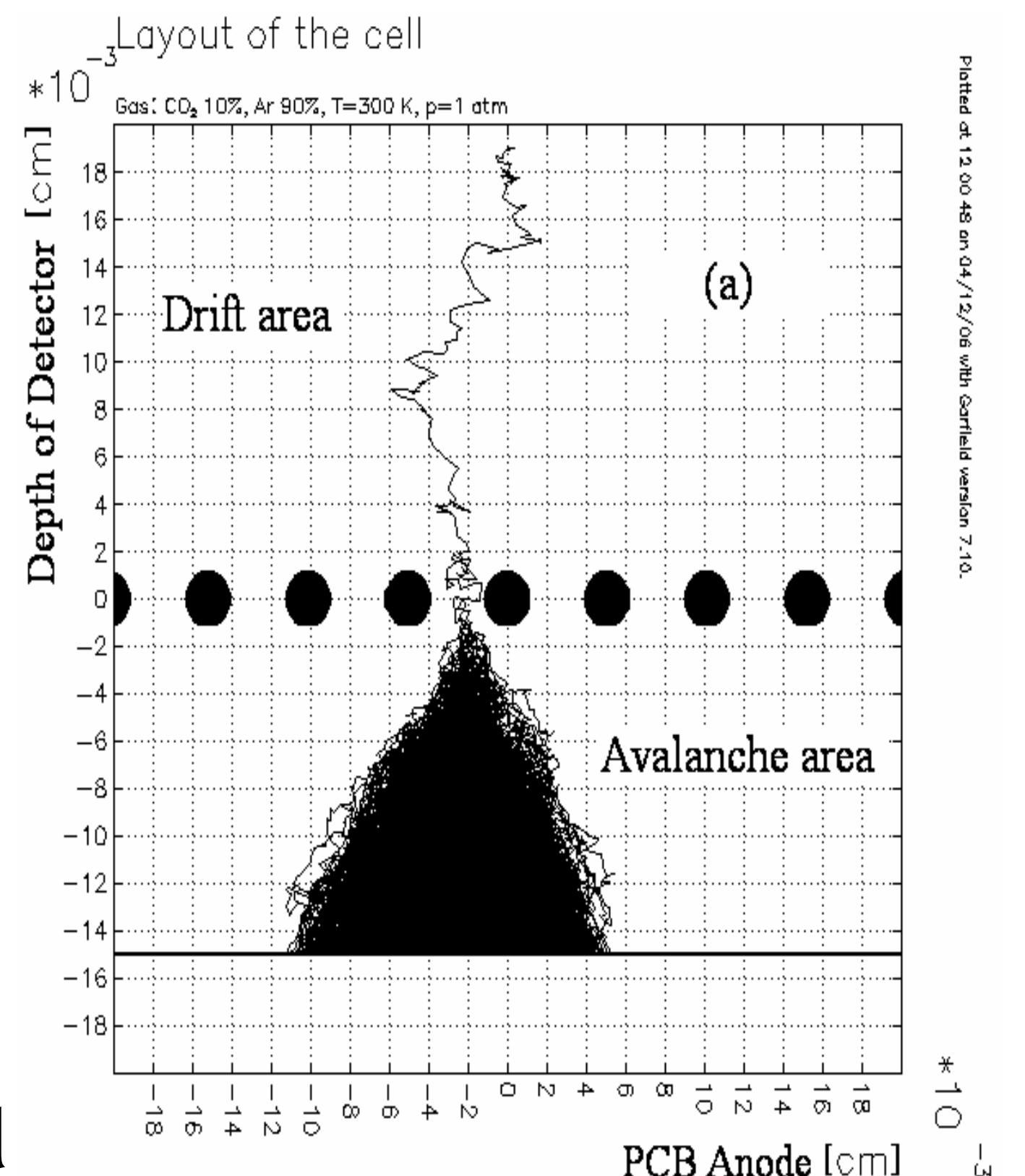
Electron multiplication

- Avalanche process
 - At high electric field, electron velocity large enough to ionize other atoms/molecules
 - Gain depends on multiplication distance and mean free path of electrons
- Sparking limit
 - Photons produced in avalanche can trigger secondary ionization
 - This runaway process can lead to formation of streamers that become conductive



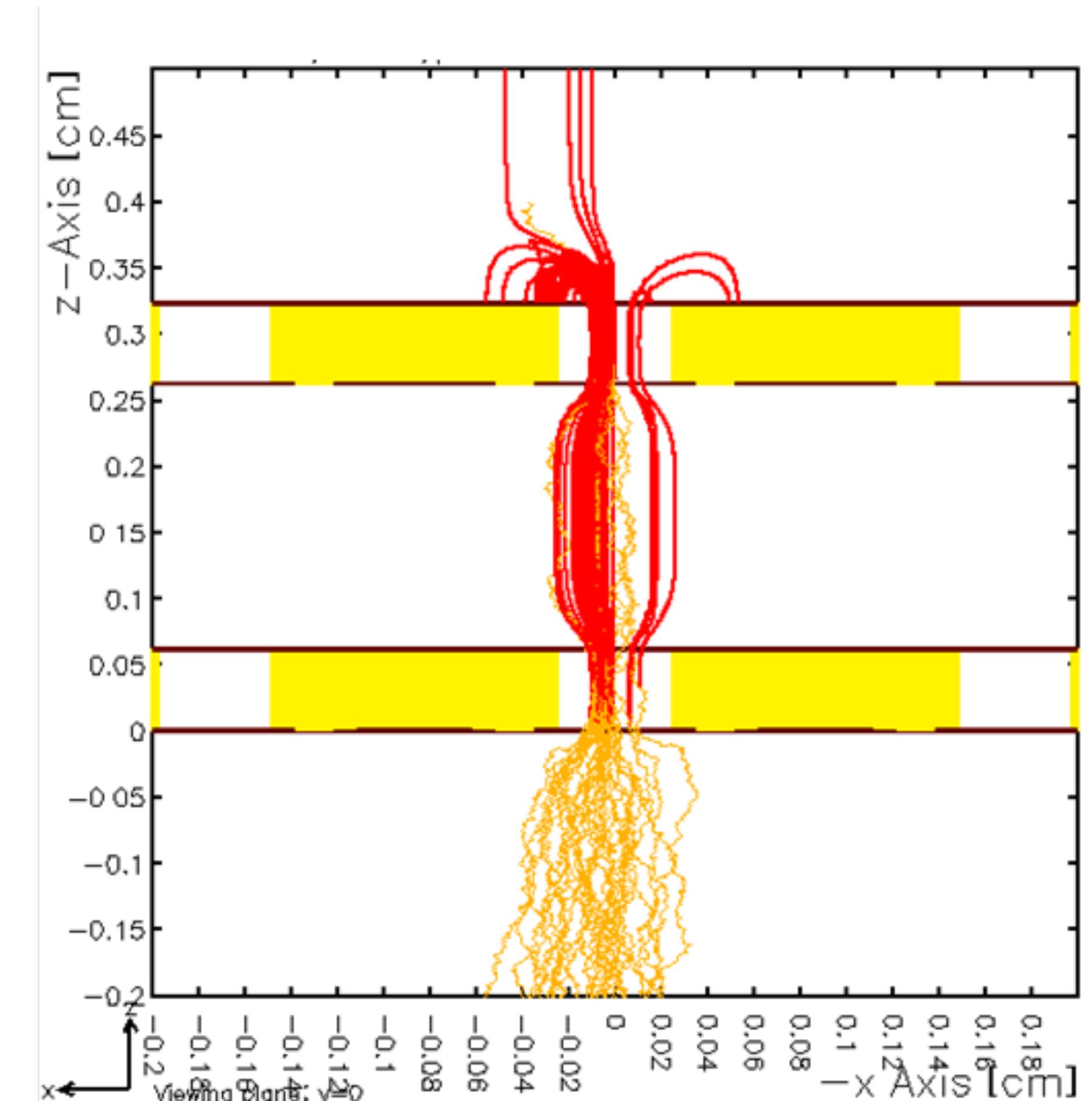
Some gas magic...

- Penning effect
 - Admixture of a gas with lower ionization potential
 - Photons from main gas initiate other avalanches
 - Multiplication gain is increased
- Quencher effect
 - Admixture of gas with vibration or rotation modes
 - Photons from main gas excite quencher gas modes
 - Runaway process is suppressed and higher gains can be reached



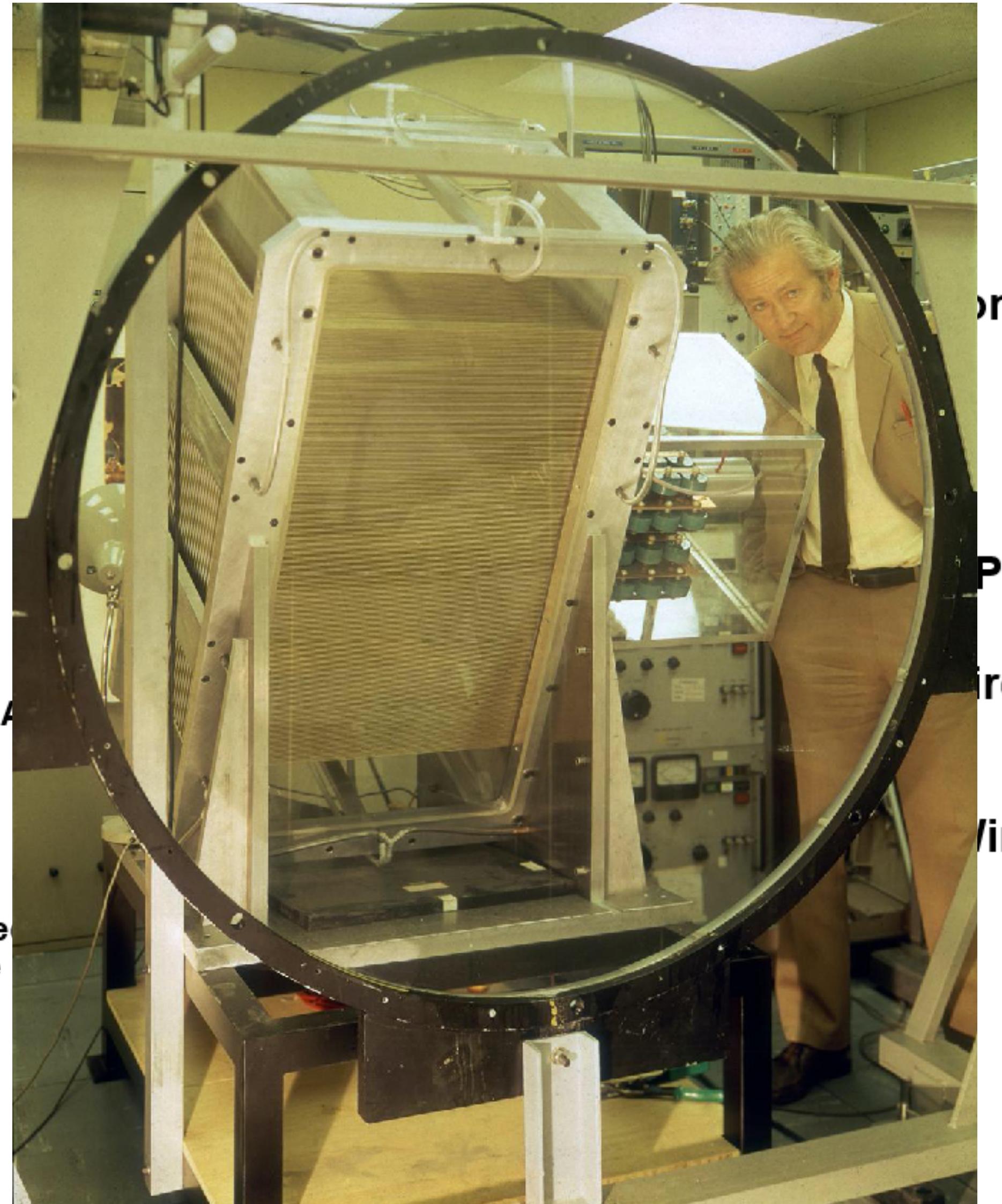
Positive ion back flow issue

- Positive ions produced from ionization
 - Drift in opposite direction of electrons
 - Have much lower mobility than electrons
 - Produced in large numbers in avalanche site
 - Can distort electric field in drift region
 - Can remove primary electrons in drift region by recombination
- Modern electronics multipliers
 - Designed to minimize the effects of ion back flow



Electron multiplication: MWPC

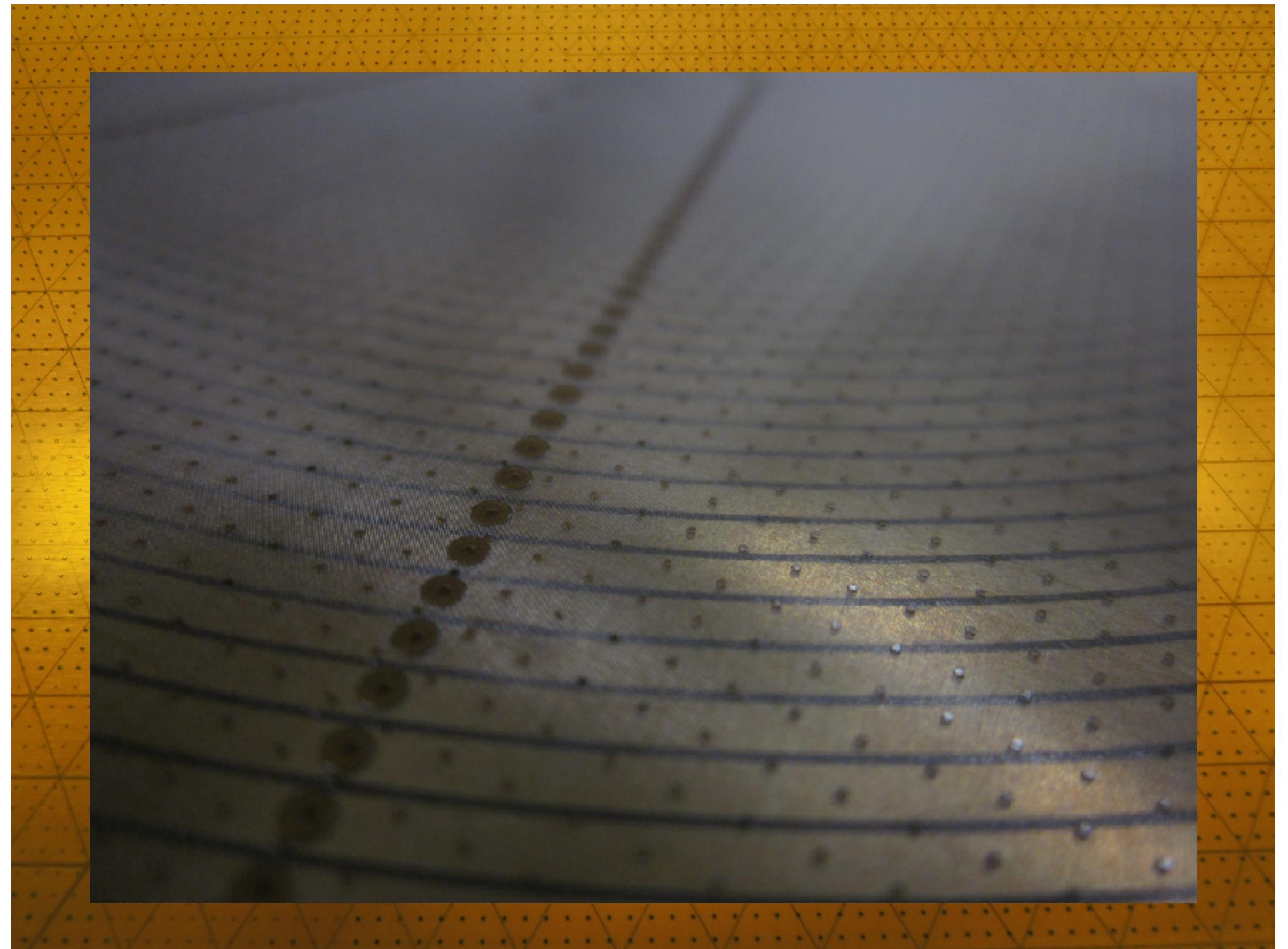
- Multi Wire Proportional Counter
 - Early days of TPCs
 - High electric field gradient close to wire
 - Signal read on pads and wires
 - Nobel prize 2005 (R. Sharpak)
- Drawbacks
 - Not very robust mechanically
 - Aging issues from discharges on wire
 - Large ion back flow



Induced
on the

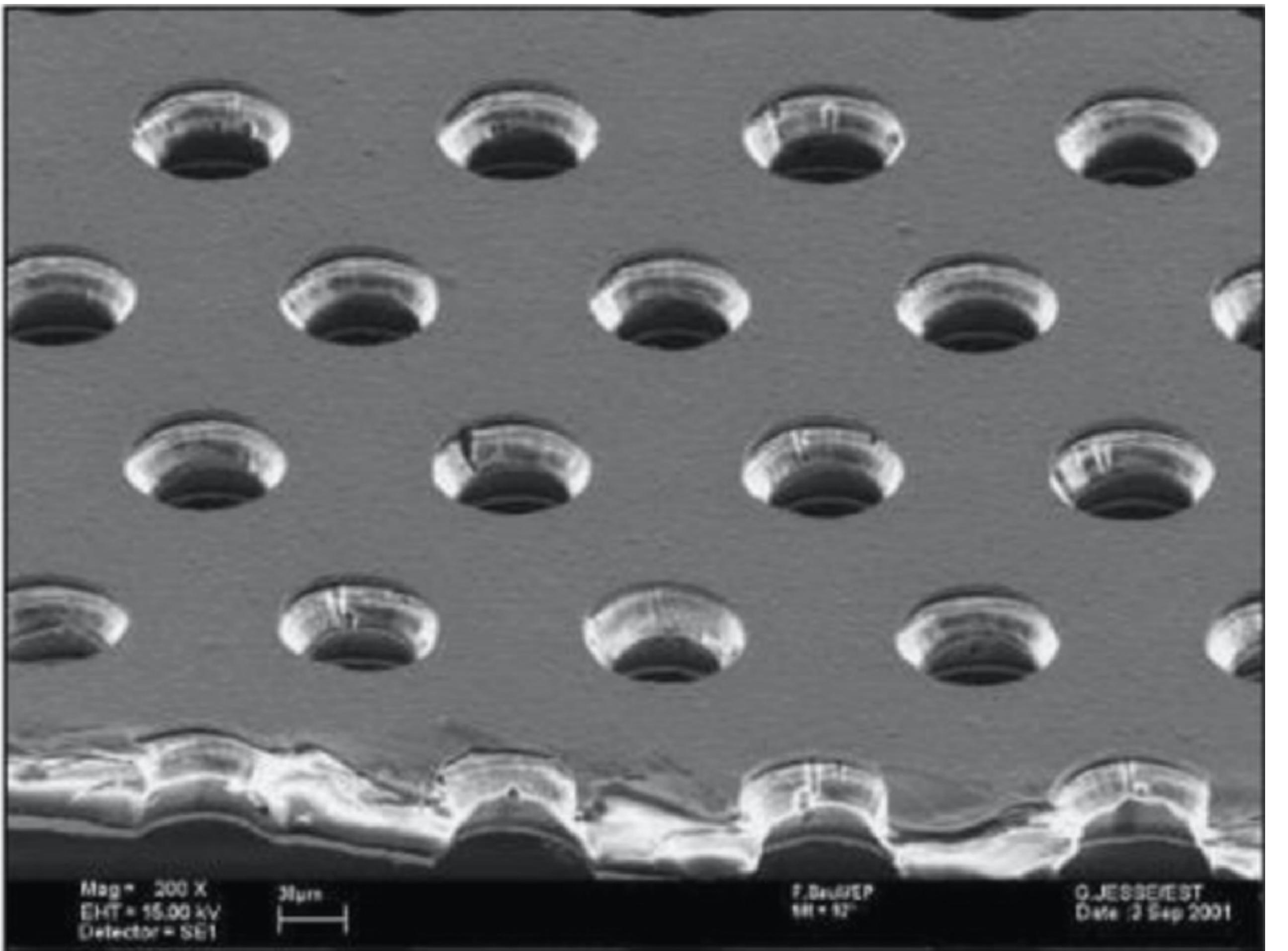
Electron multiplication: Micromegas

- Thin mesh suspended above pads
 - Typical distance: $\sim 100 \mu\text{m}$
 - Mesh held via insulating pillars
 - Primary electrons go through mesh and create avalanche in the gap
- Advantages
 - Anode pads are on a PCB (Printed Circuit Board) and can have any geometry
 - Large surfaces can be equipped
 - Very robust against sparking



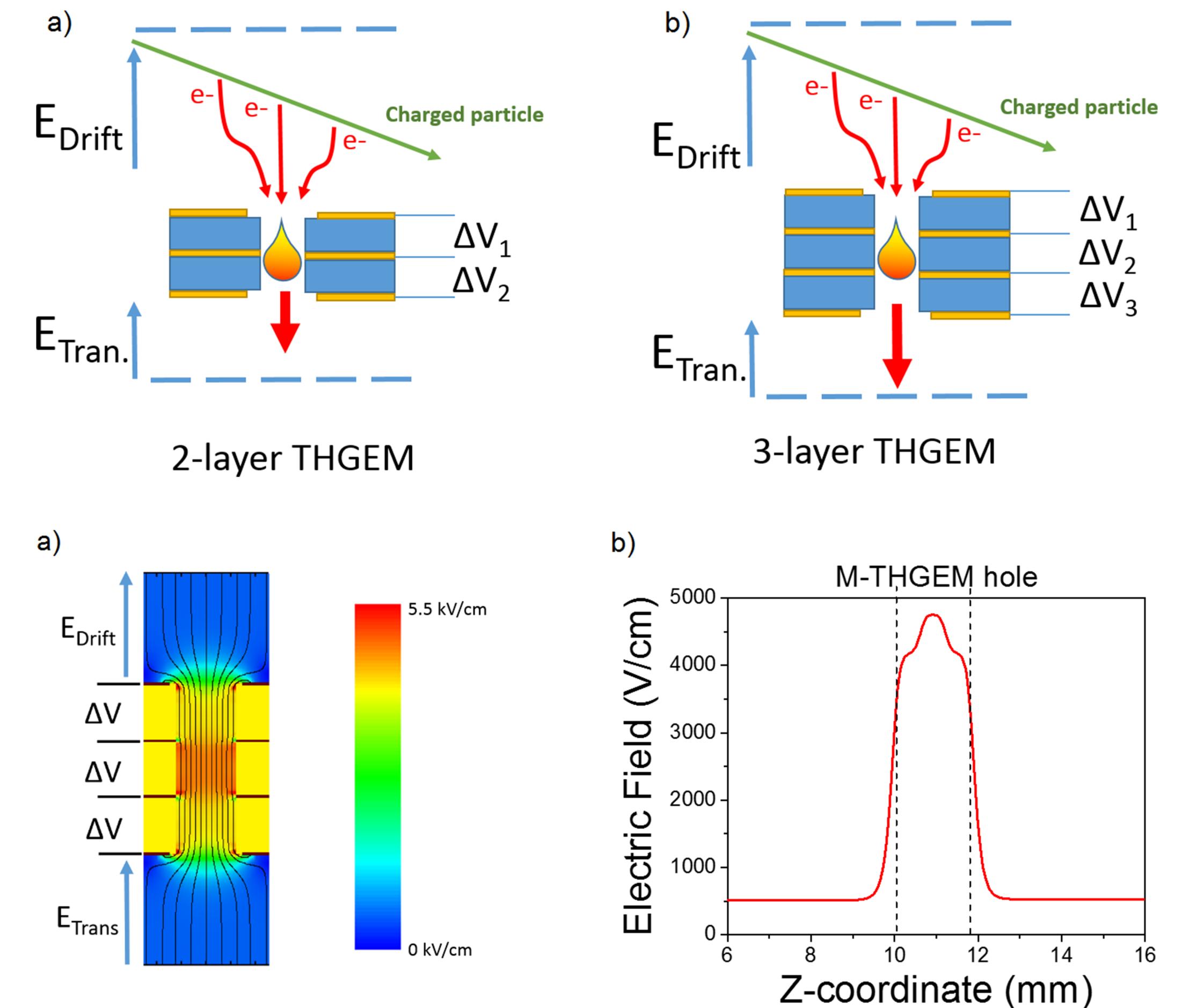
Electron multiplication: GEMs

- Gas Electron Multipliers
- Thin foils covered with Cu layers on both sides and drilled with many holes
- Typical hole size: $\sim 100 \mu\text{m}$
- Field gradient in holes large enough to trigger avalanches
- Transmission device: multiplied electron emerge on opposite side from primaries
- Can be stacked in multiple layers



Next generation: multi-THGEMs

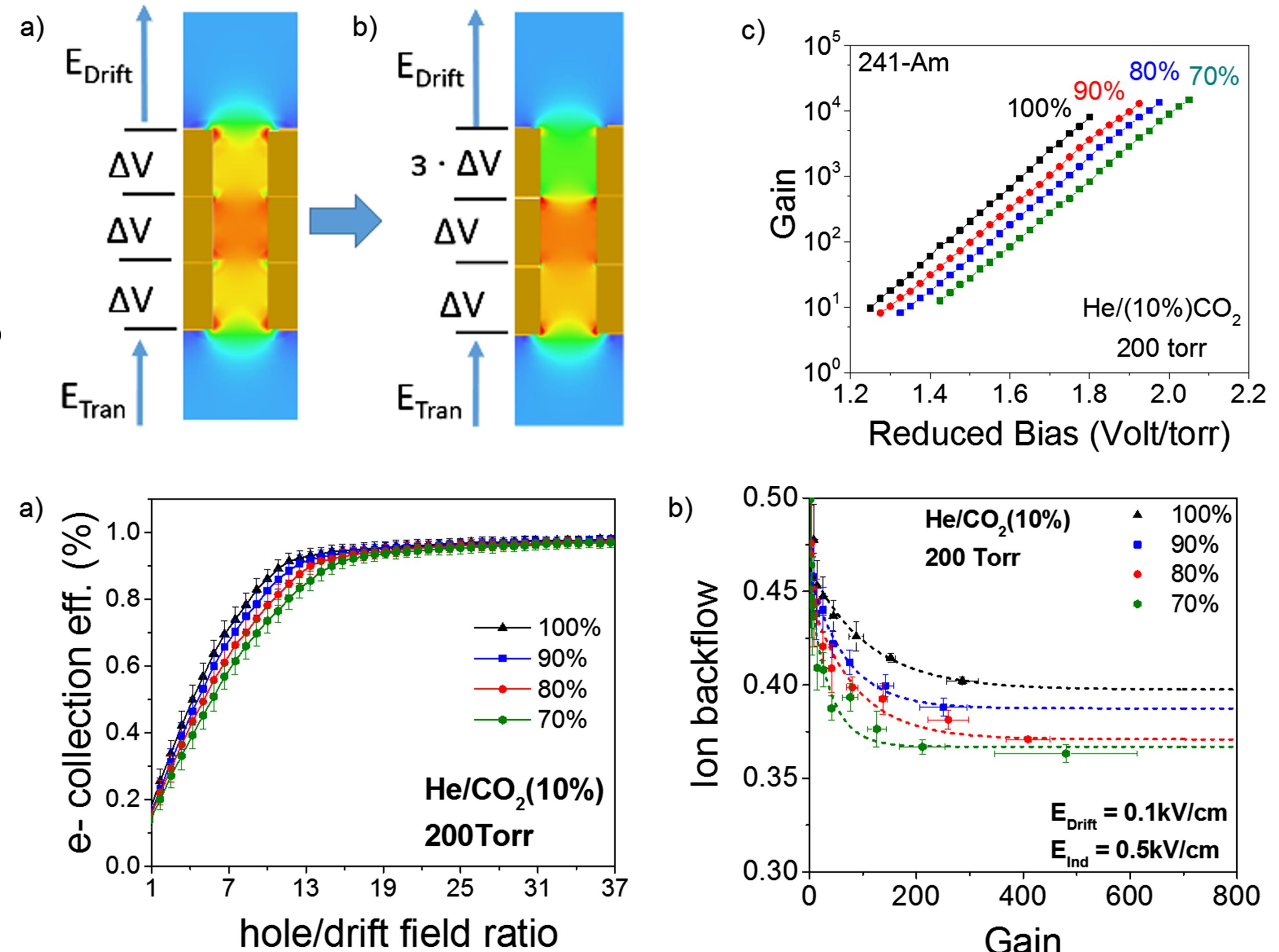
- Combine several THGEMs
- More robust mechanically
- Use as chain of electron “preamplifiers” before final stage (usually Micromegas)
- Electric field gradient profile can be adjusted inside hole
- Triple THGEM first used in the prototype AT-TPC



M. Cortesi et al., Rev. Sci. Instrum. 88, 013303 (2017)

Positive ion back flow suppression

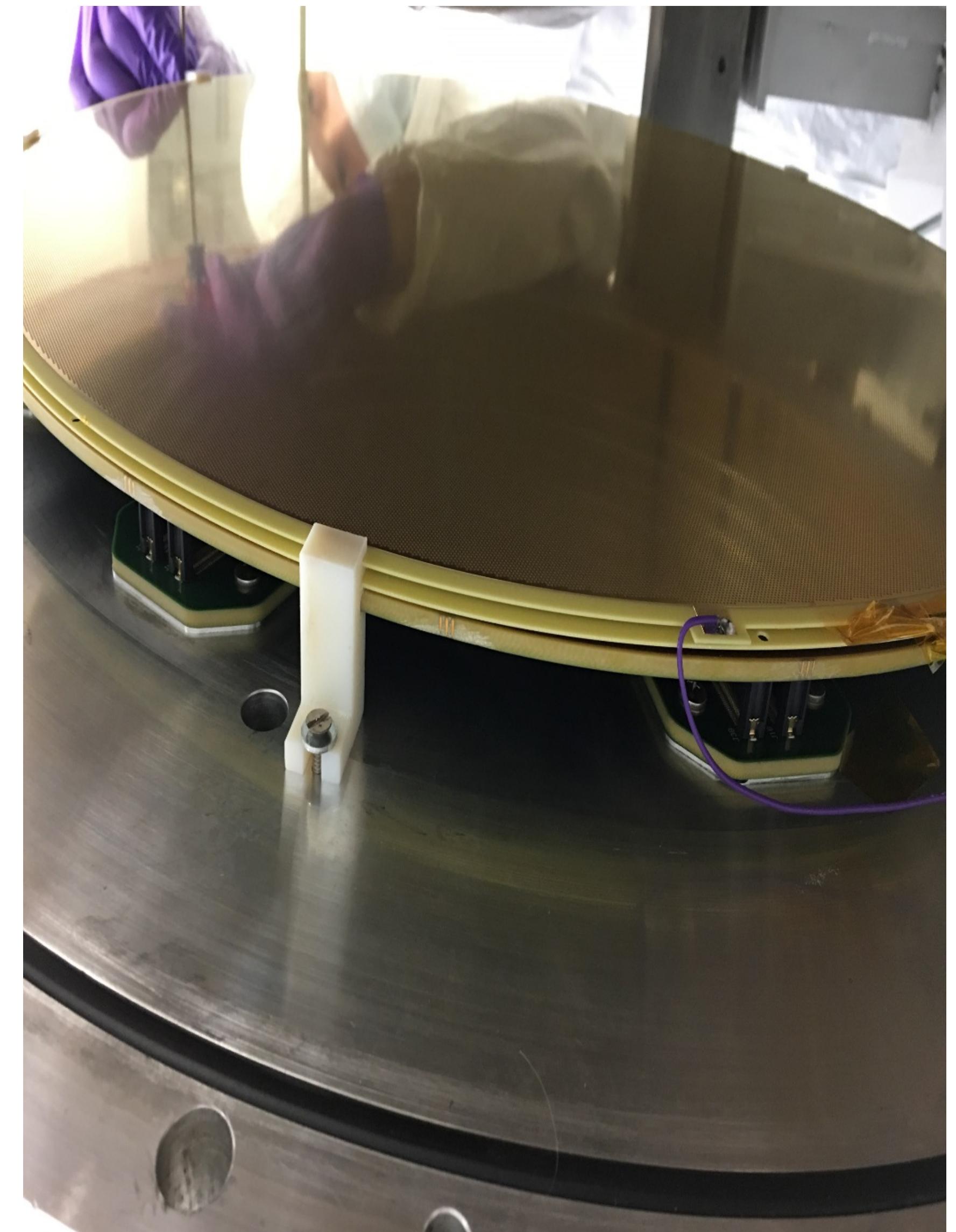
- Preventing positive ions from escaping to the sensing volume
- Fraction “3” varied from 100% to 70%
- Lower field at top forces more positive ions to recombine inside hole
- Maximum achievable gain unchanged
- Electron collection efficiency not much affected



M. Cortesi et al., Rev. Sci. Instrum. 88, 013303 (2017)

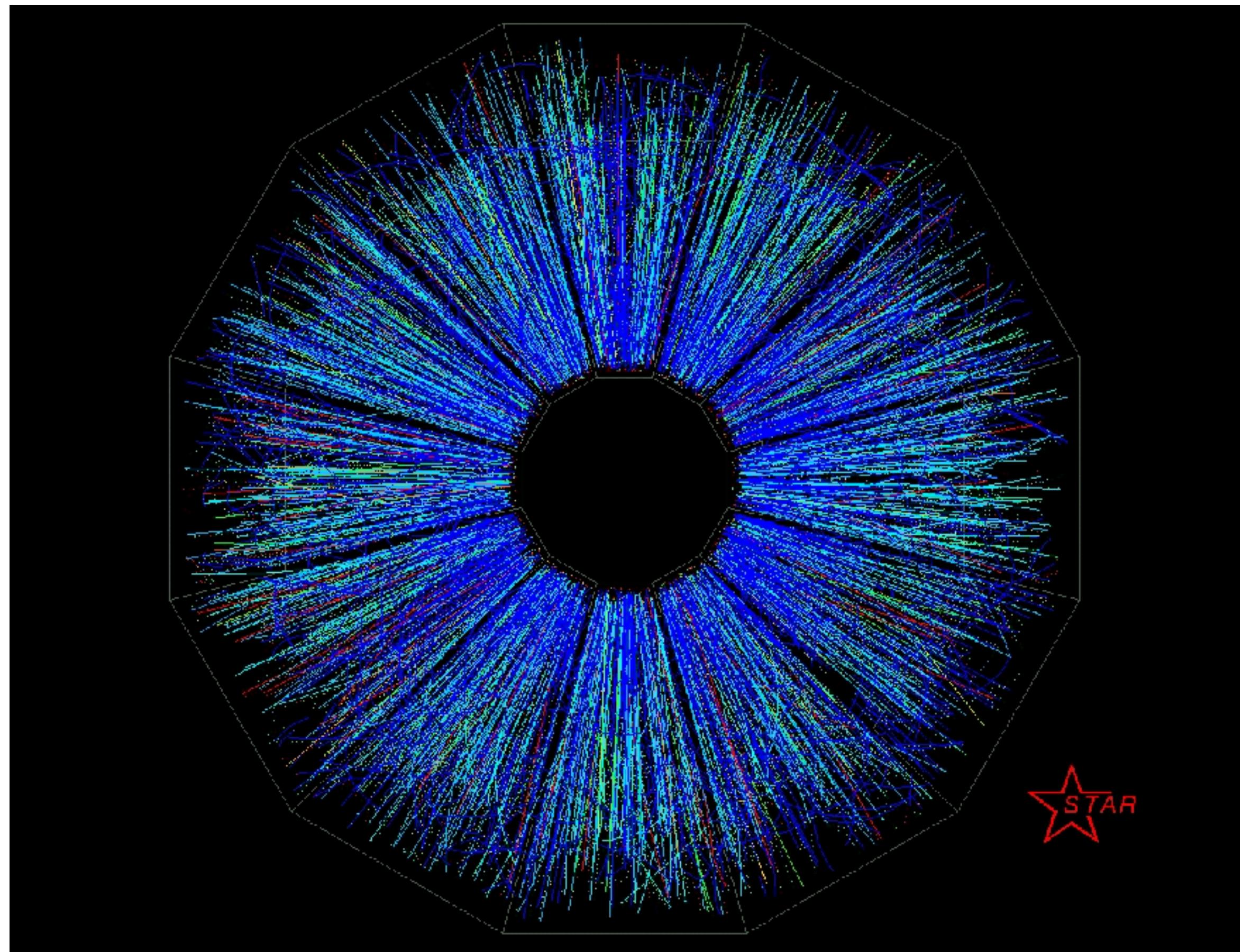
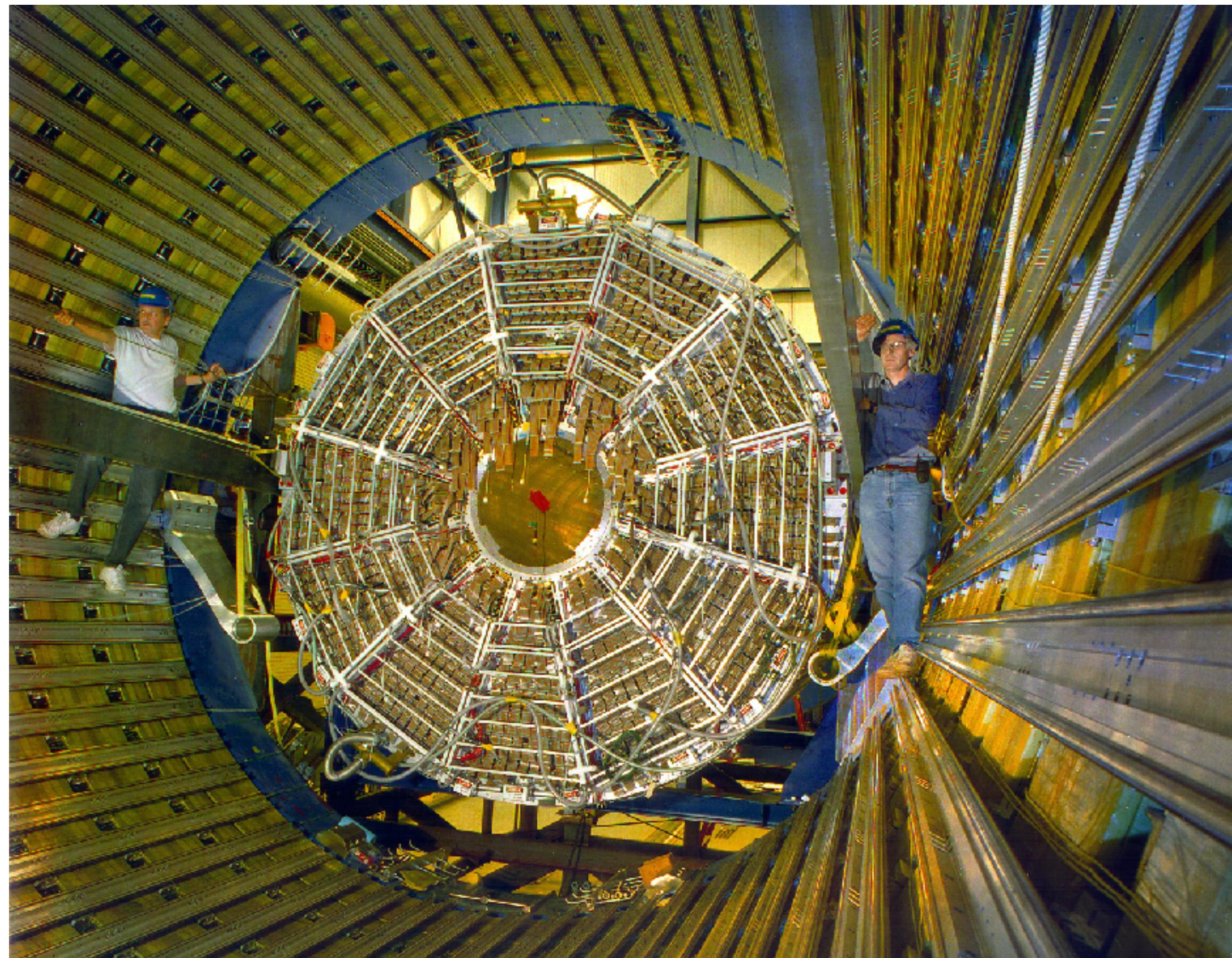
Combining multiplication devices

- THGEMs or M-THGEMs used as electron preamplifiers
- Example: 2 THGEMs on top of Micromegas
- Cascade allows to relax gain on each stage of electron amplification
- Limit ion back flow from the last stages
- Top THGEM can be used as a gating grid



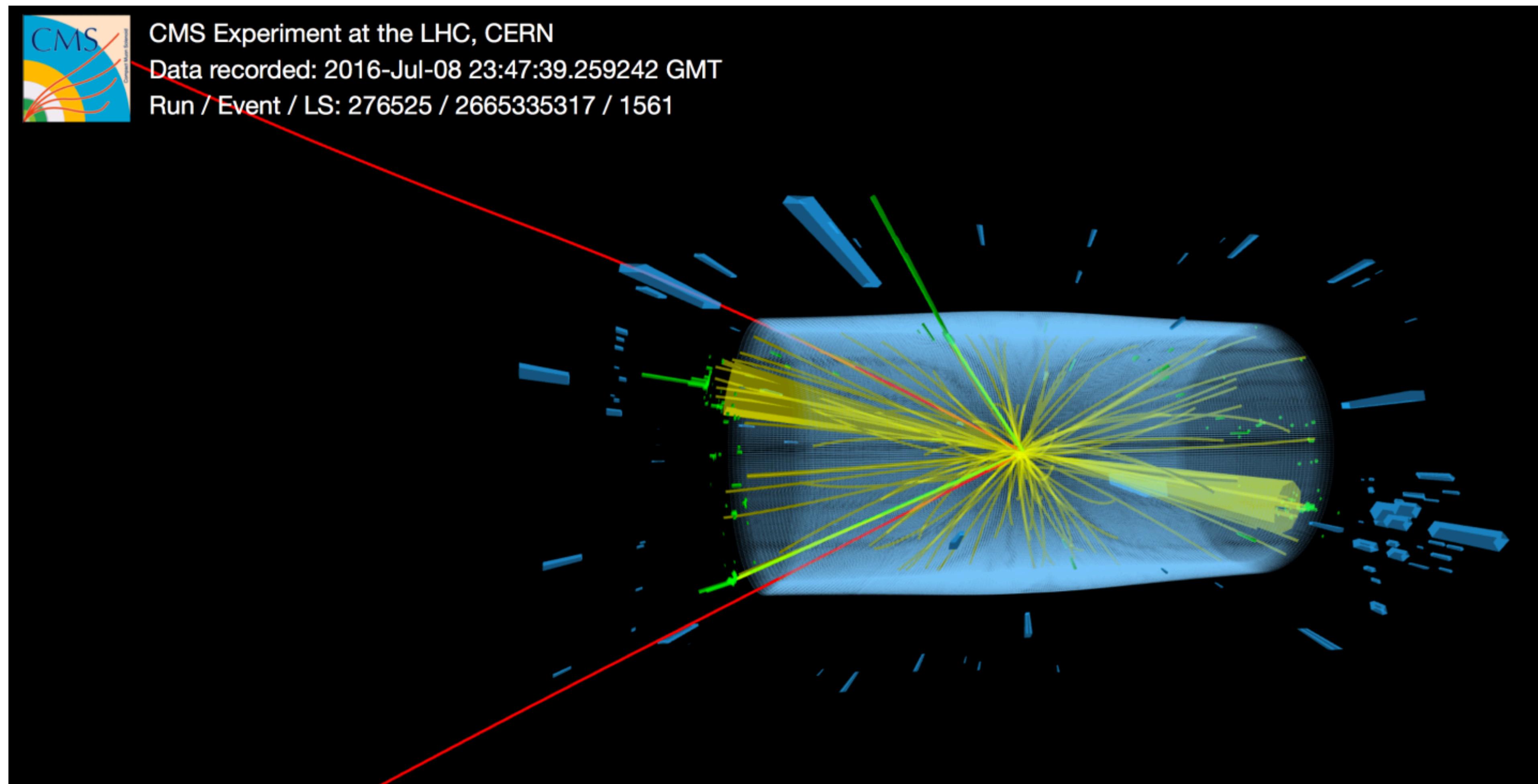
TPC examples: STAR (RHIC)

Discovery of the quark-gluon plasma



TPC example: CMS (CERN)

Candidate Higgs boson event



Concluding remarks

- TPCs as active targets cannot be the same like TPCs as particle trackers
- Accommodate wide variety of detector gases
- Electron amplification techniques much more developed
- Accommodate wide range of energy losses and charge distributions
- Trigger generation in self-contained geometries is tricky
- Data analysis is complex due to wide variety of events
- All these challenges can be met!