Time projection chambers

No, it’s not a place to time travel…

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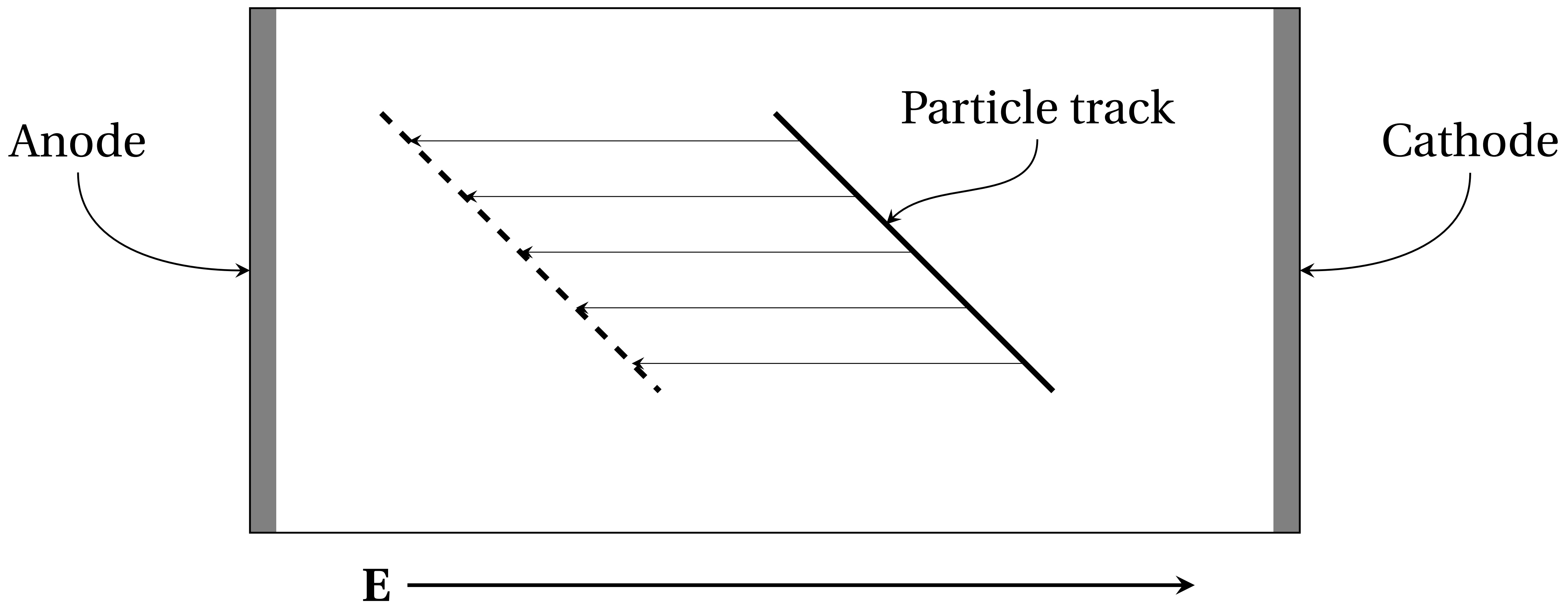
Principle of operation

- 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

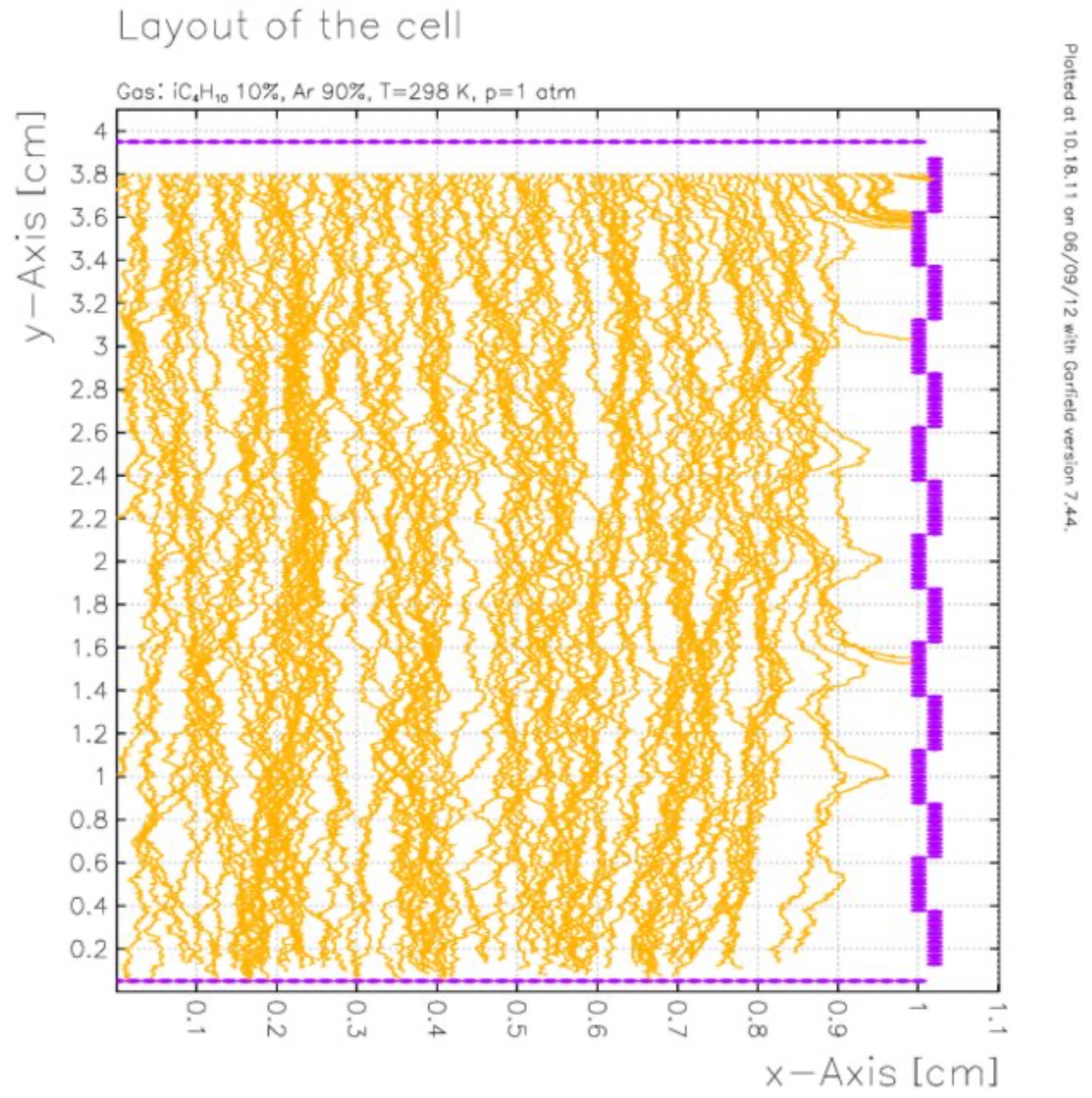
TPCs are imaging detectors that produce 3D images of charged particle tracks

Drift velocity

- Propagation of electrons
  - Follow Langevin's equation
  - $\tau = m v_D / eE$ 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

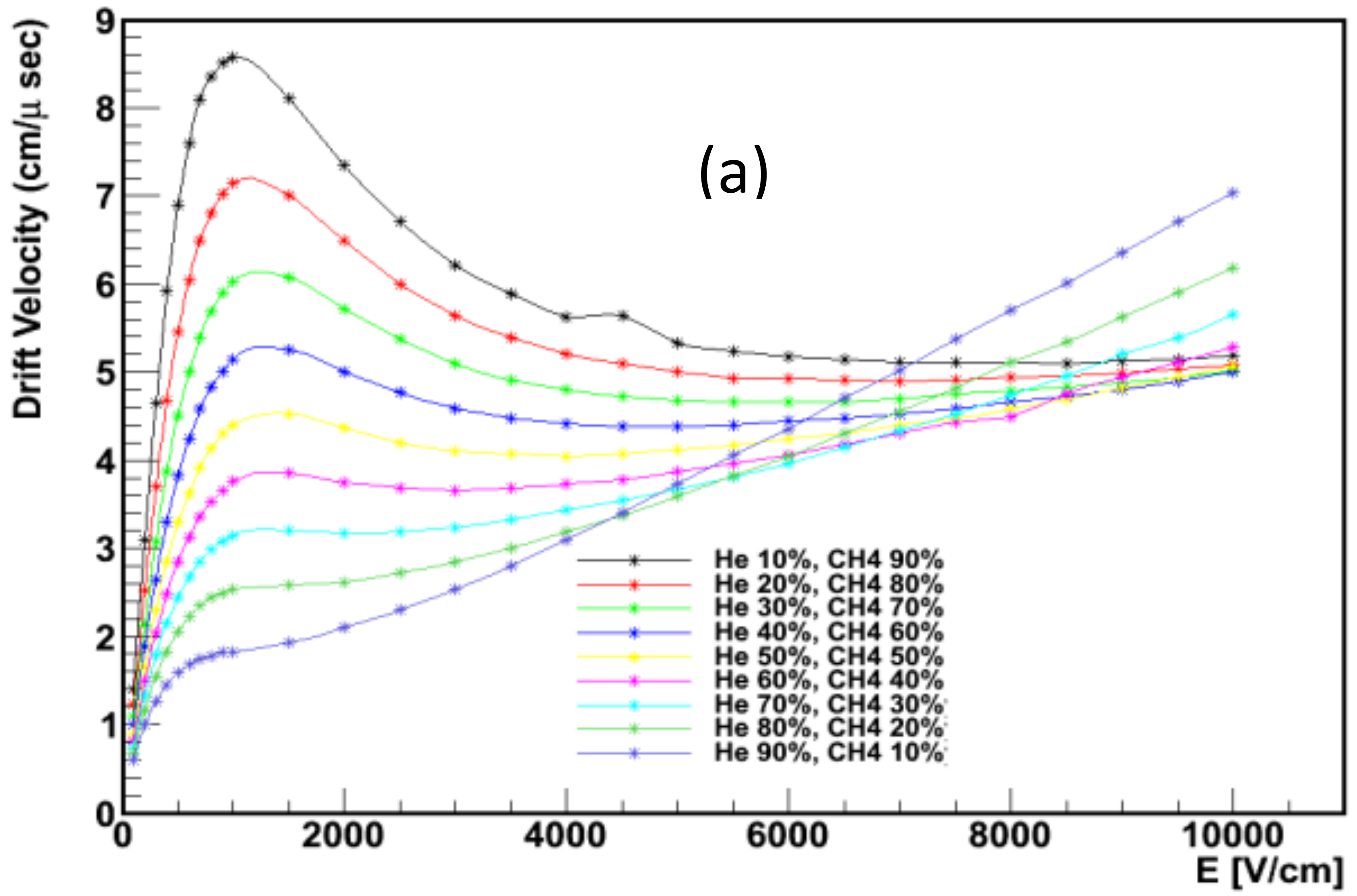
$$m\frac{d\mathbf{v}}{dt} = e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) - \frac{m}{\tau}\mathbf{v},$$

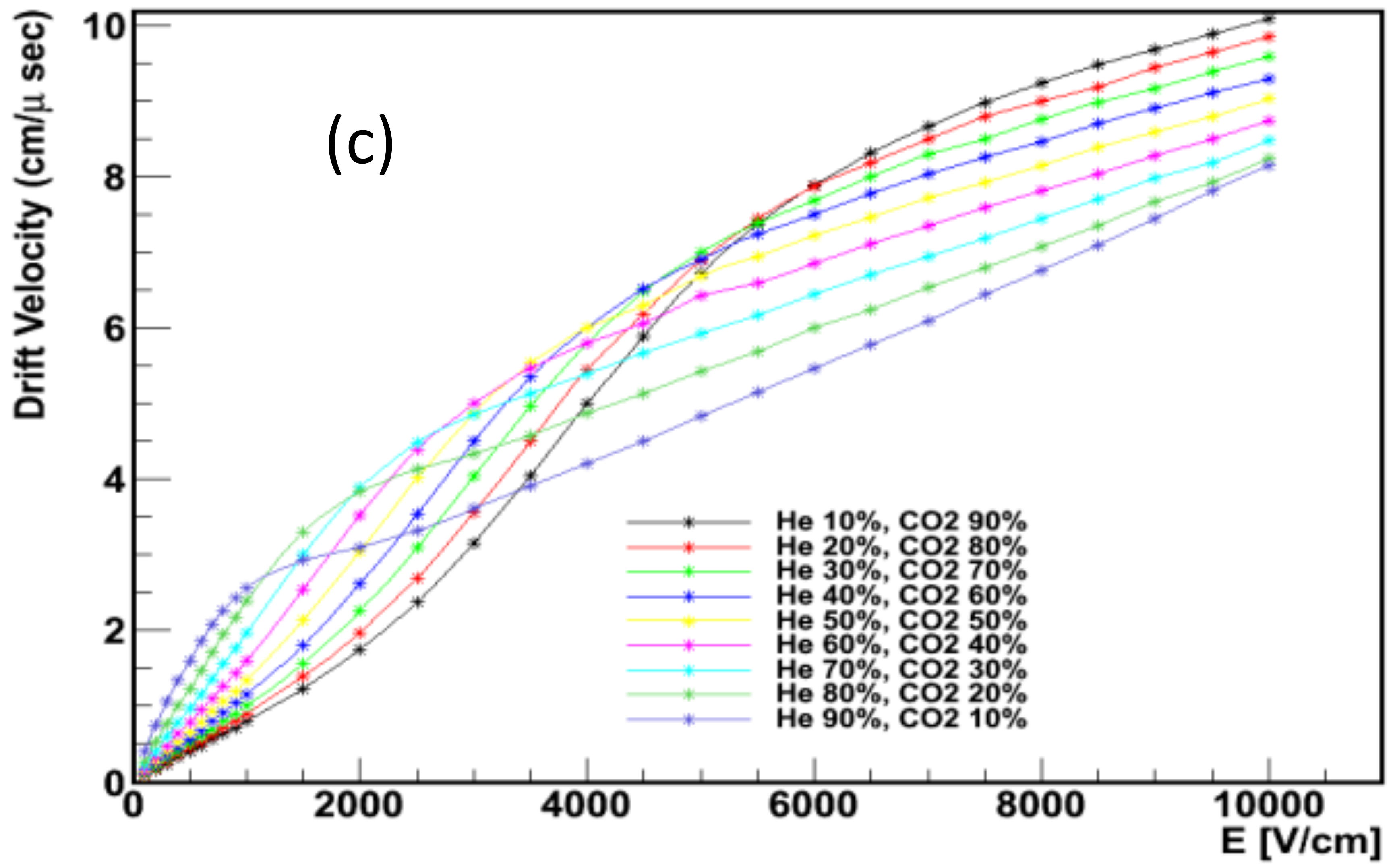
$$\mathbf{v}_D = \frac{\mu E}{1+\omega^2\tau^2}\left[\hat{\mathbf{E}} + \omega\tau\left(\hat{\mathbf{E}} \times \hat{\mathbf{B}}\right) + \omega^2\tau^2\left(\hat{\mathbf{E}} \cdot \hat{\mathbf{B}}\right)\hat{\mathbf{B}}\right].$$



Drift velocities

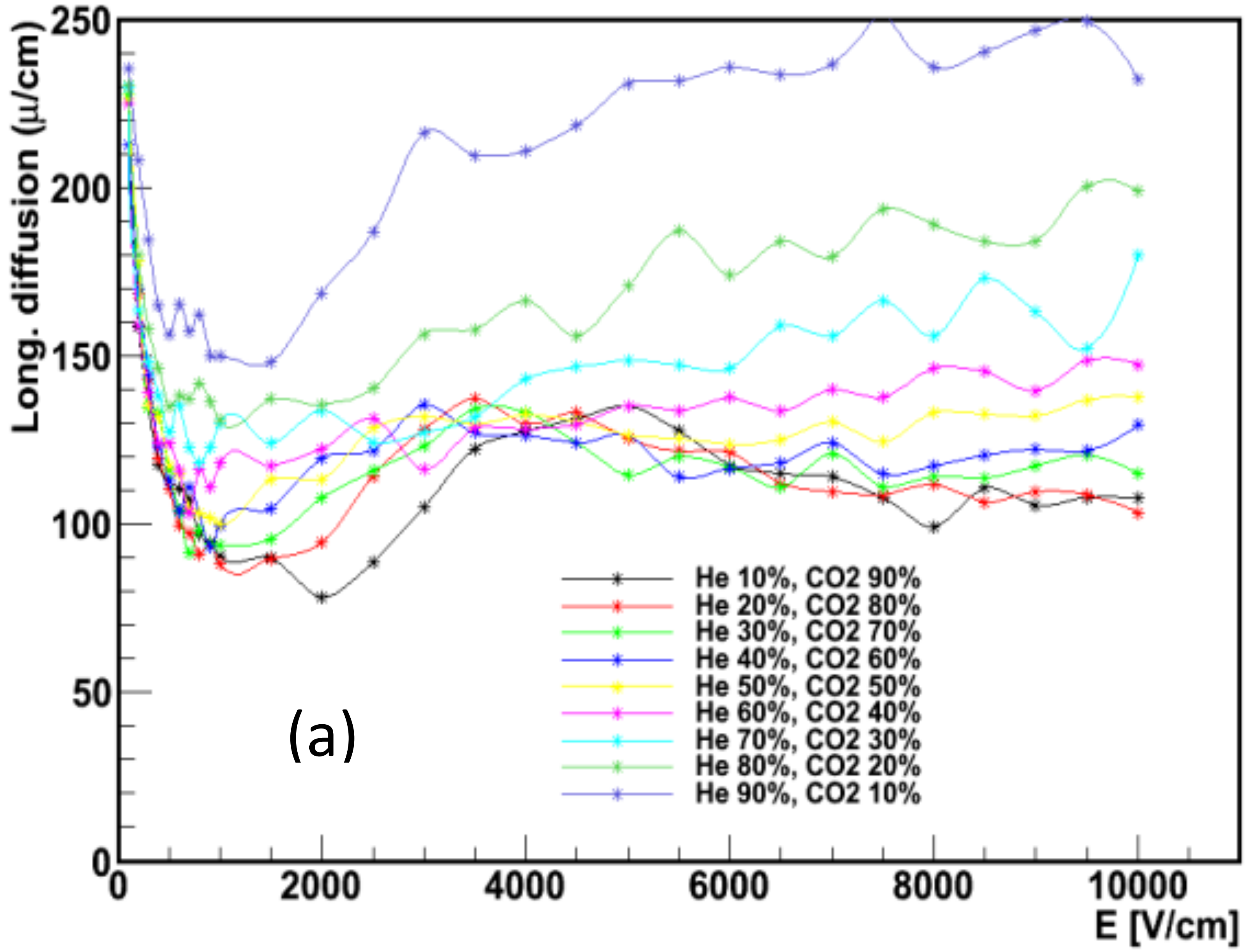
- Measured in 1 atm gas mixtures
- Order of magnitude ~ 1-10 cm / μs
- Electronegative pollutant such as O_2, Cl_2, Br_2 remove primary electrons
- The slower the drift velocity, the longer the dead time of the TPC (time needed to drift all primary electrons to the anode)
- Positive ions resulting from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

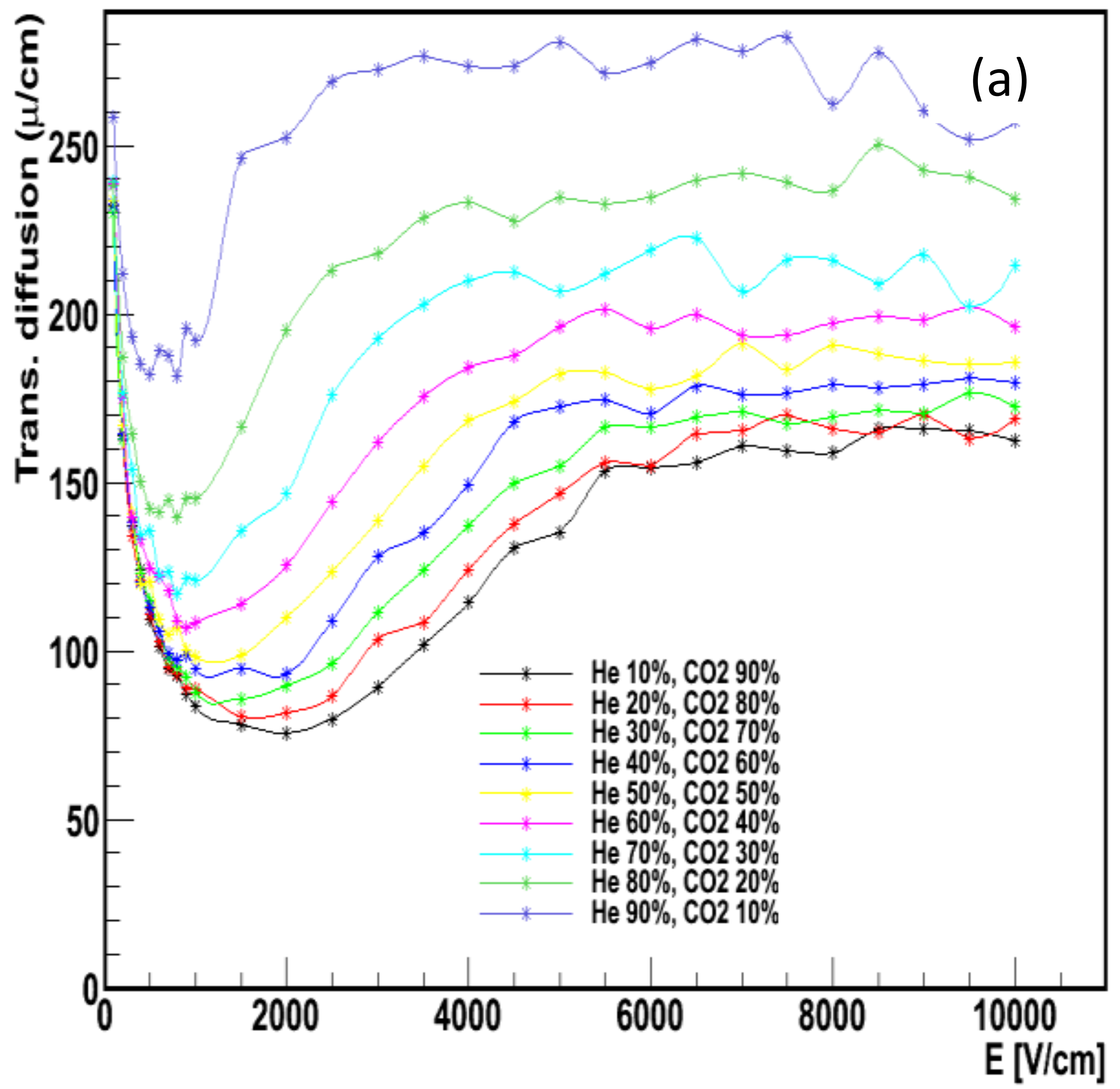




Electron diffusion

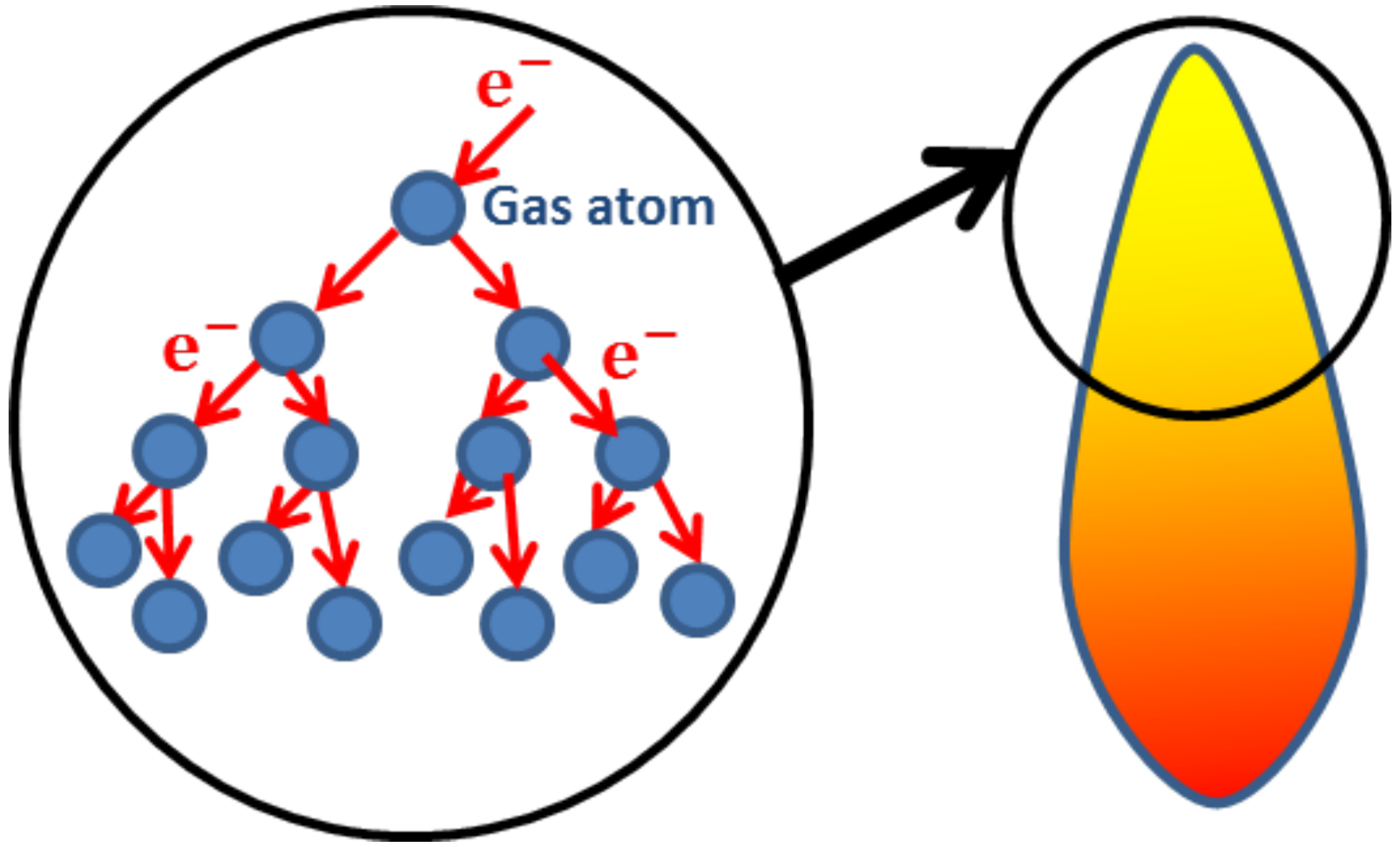
- Effects of gas molecules/atoms on electron motion
  - Longitudinal diffusion: fluctuations in drift velocity due to collisions
  - Transverse diffusion: scattering of electrons on molecules/atoms
- Transverse diffusion can be reduced by magnetic field aligned with electric field
  - Electron follow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

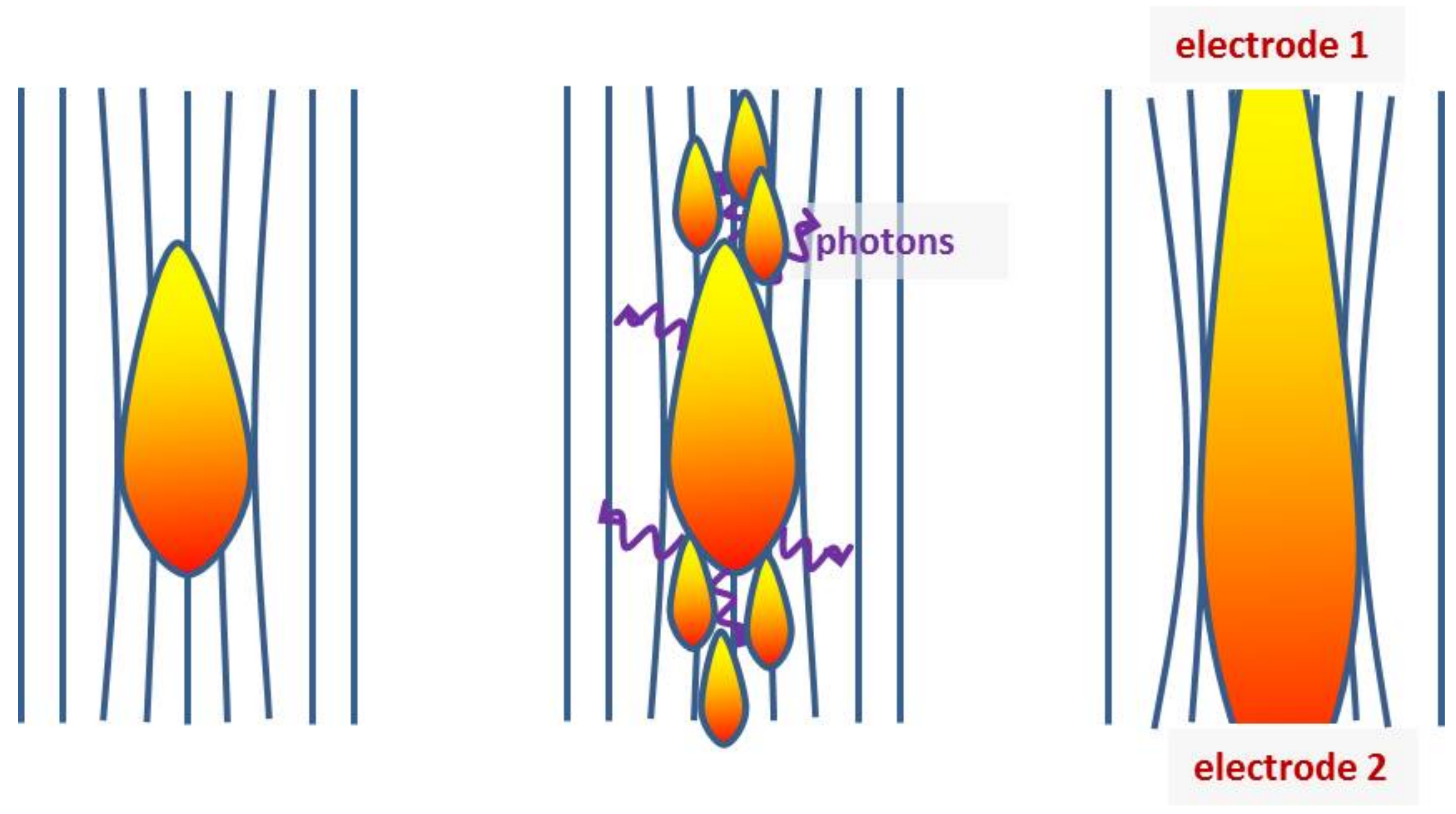




Electron multiplication

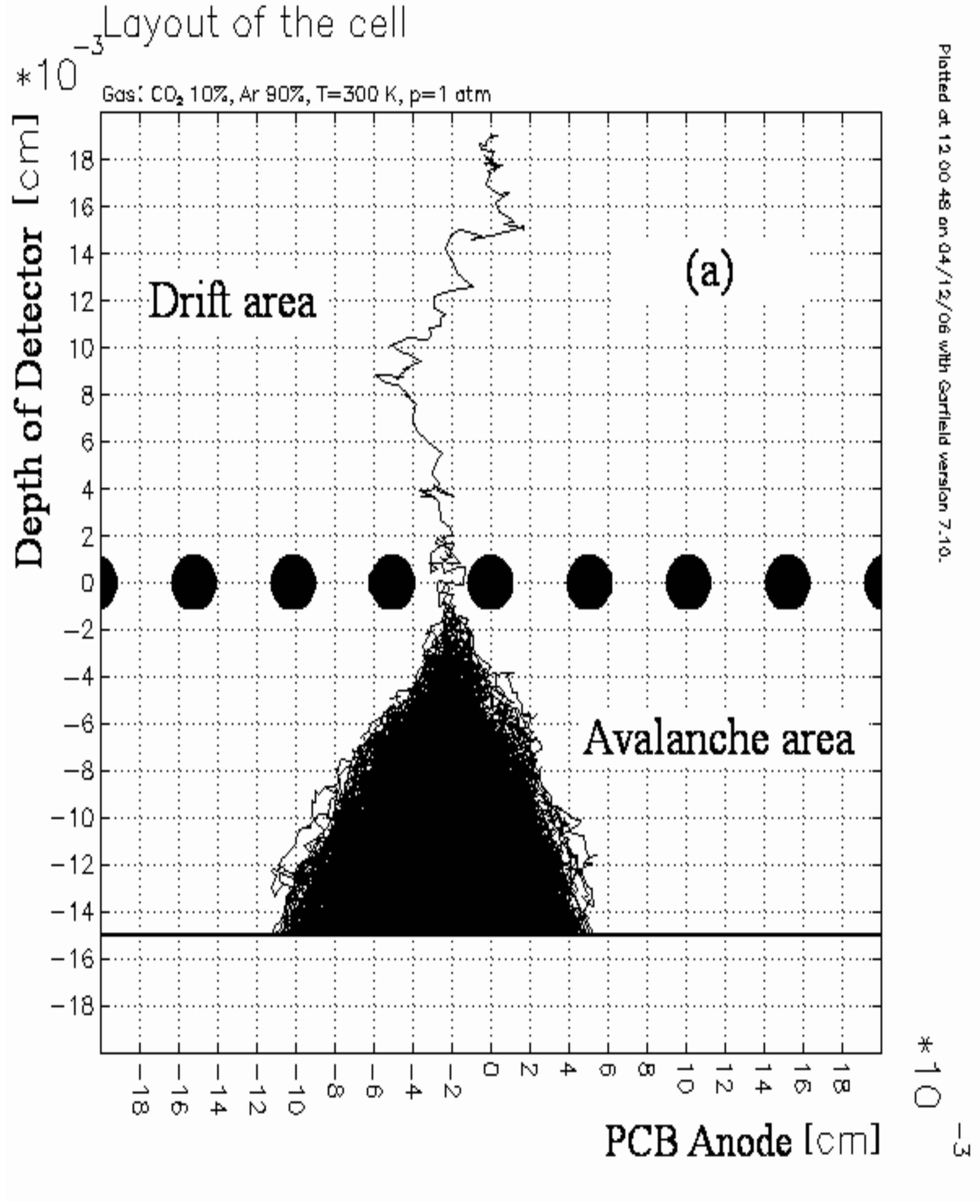
- Avalanche process
  - At high electric field, electron velocity large enough to ionize other atoms/molecules
  - Gain depends on multiplication distance and mean free path of electrons
- Sparking limit
  - Photons produced in avalanche can trigger secondary ionization
  - This runaway process can lead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





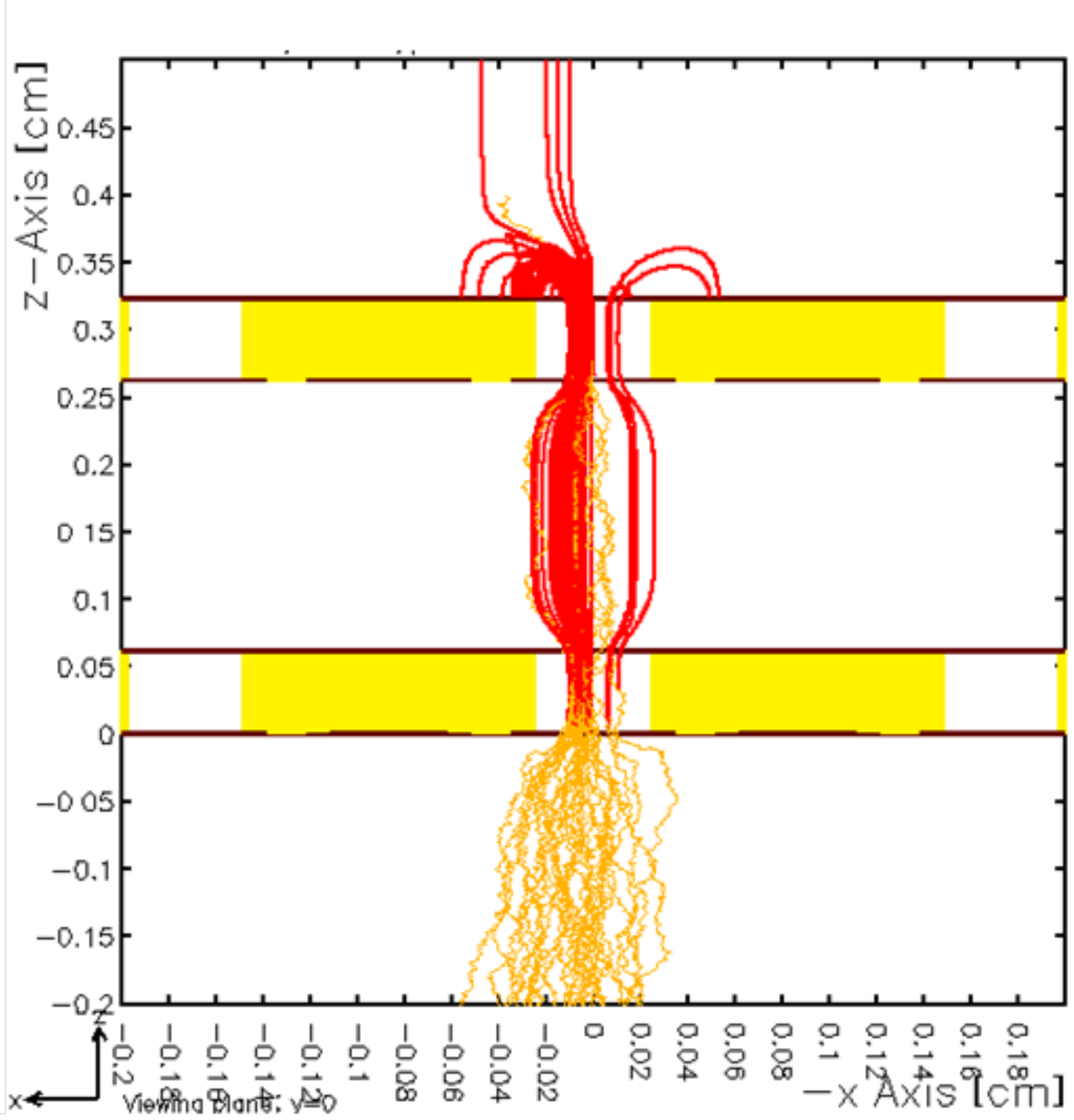
Some gas magic...

- 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



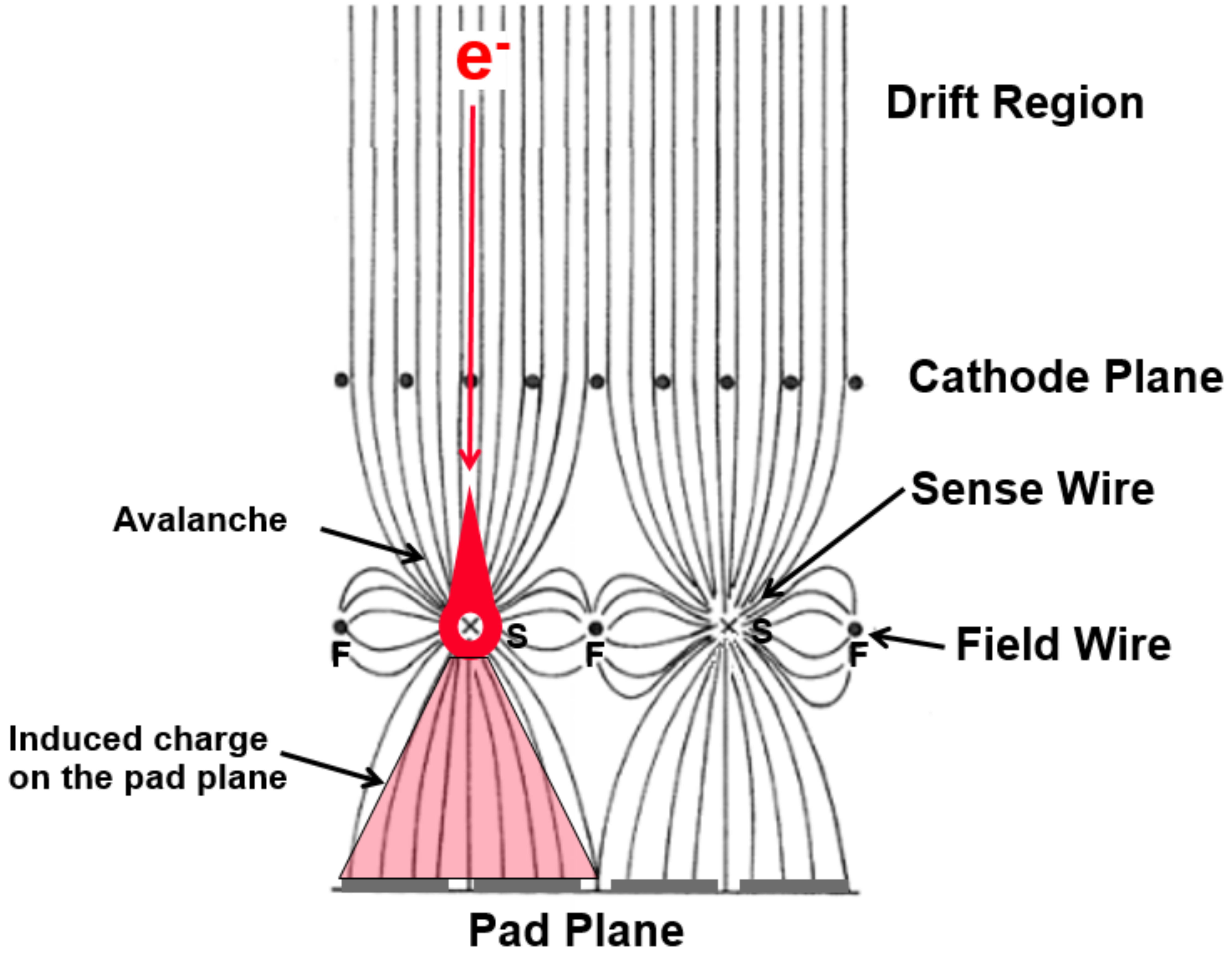
Positive ion back flow issue

- 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 electrons 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



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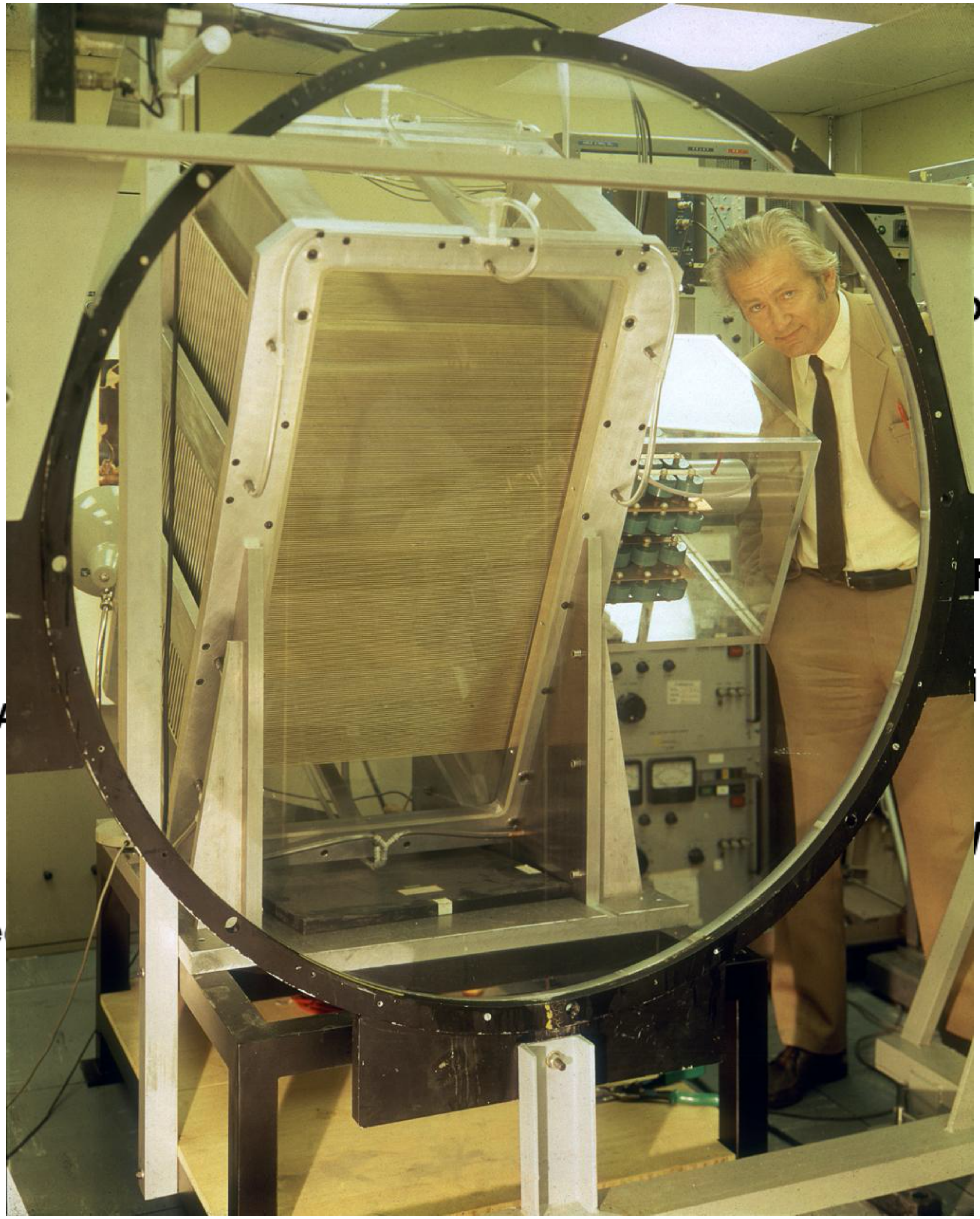
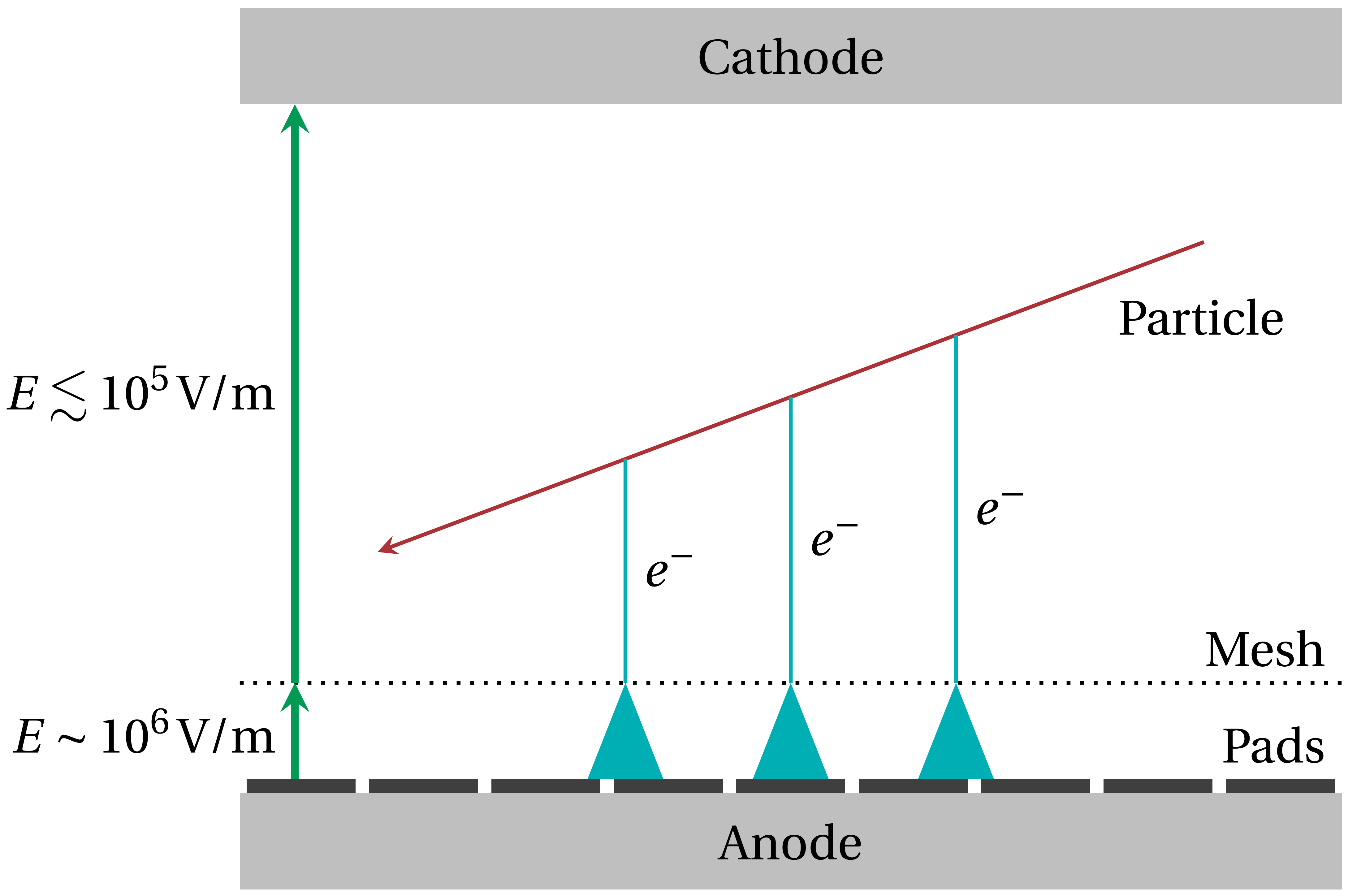


Electron multiplication: Micromegas

- Thin mesh suspended above pads
  - Typical distance: ~100 μm
  - 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



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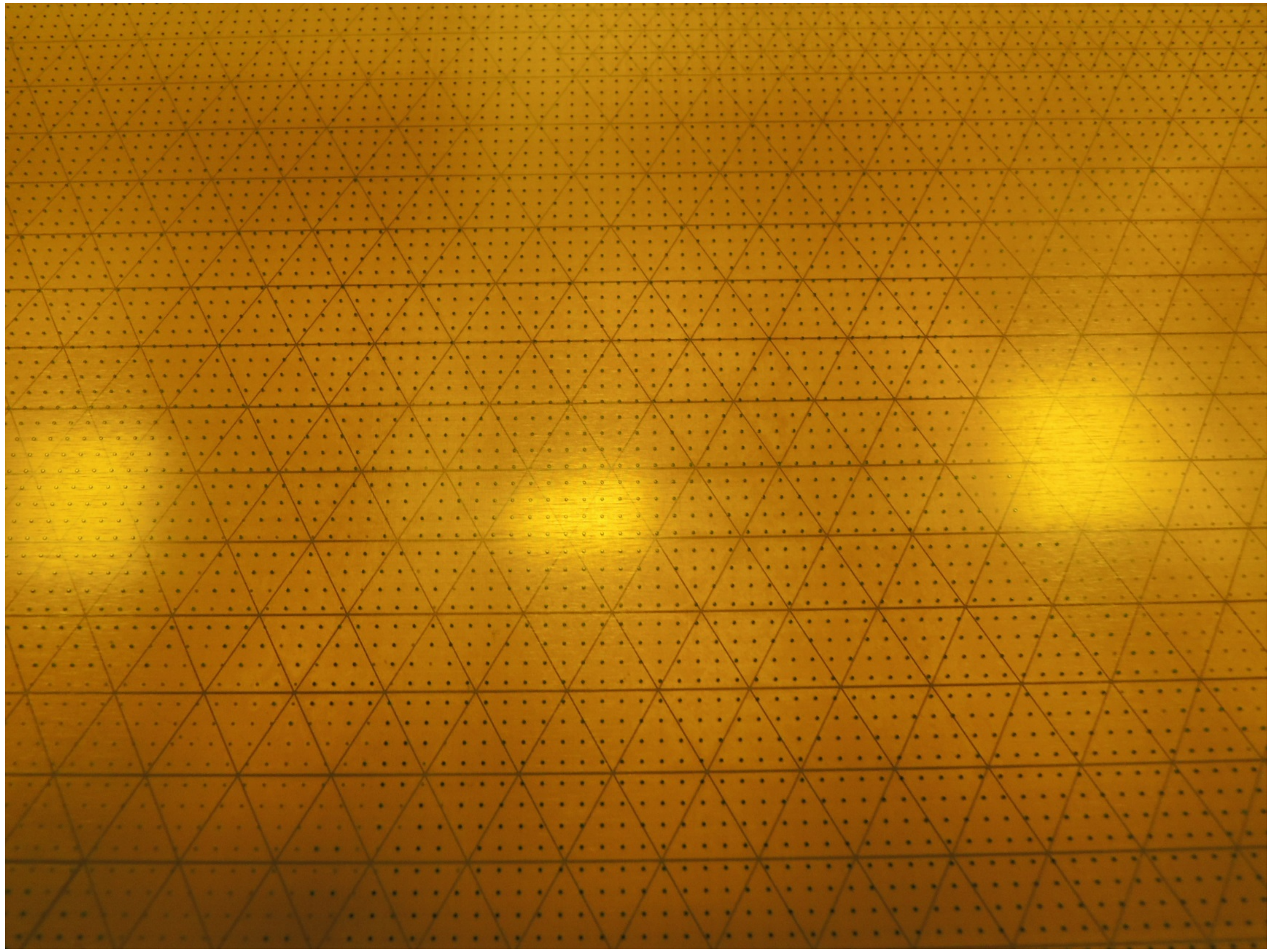

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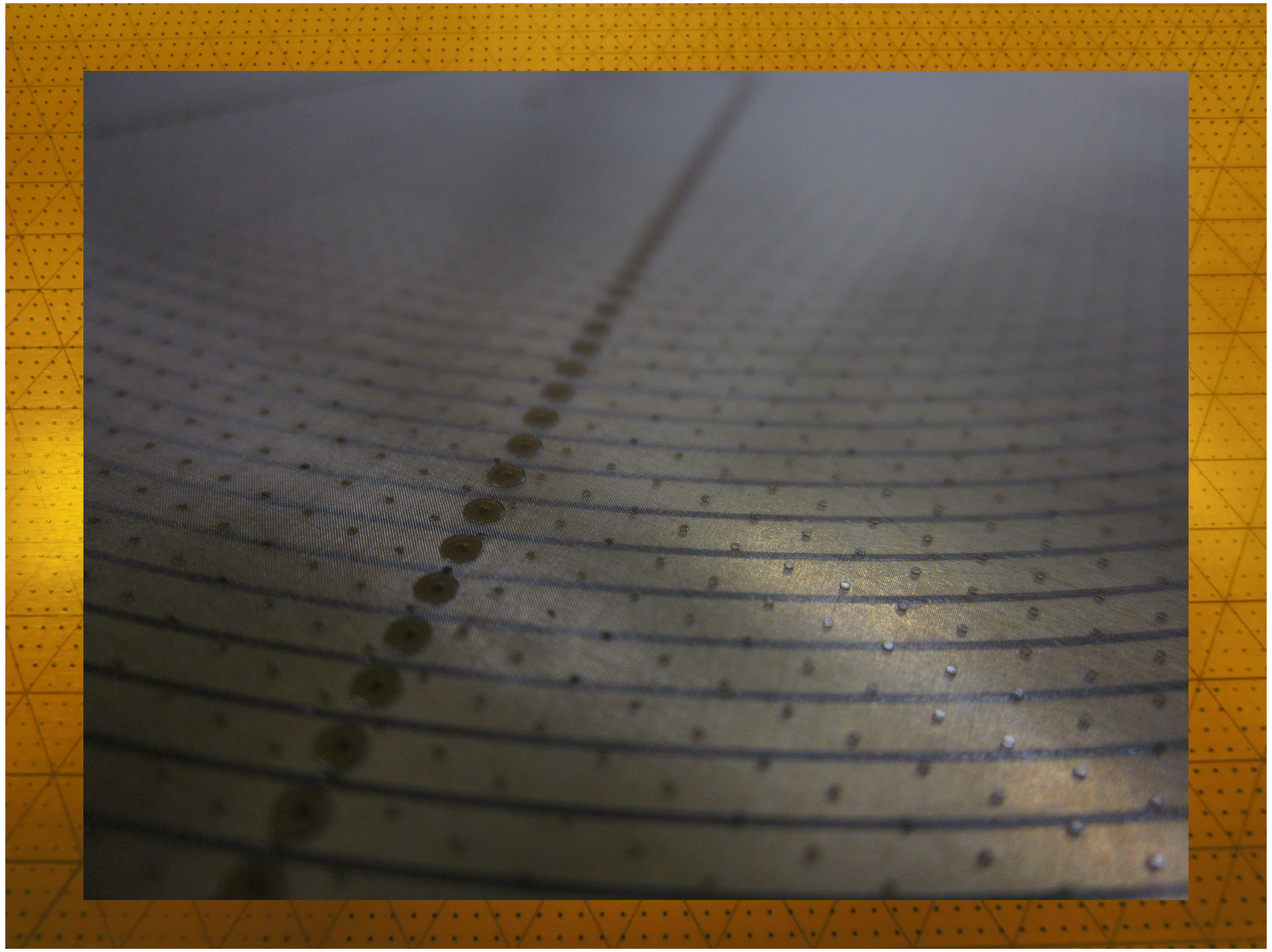
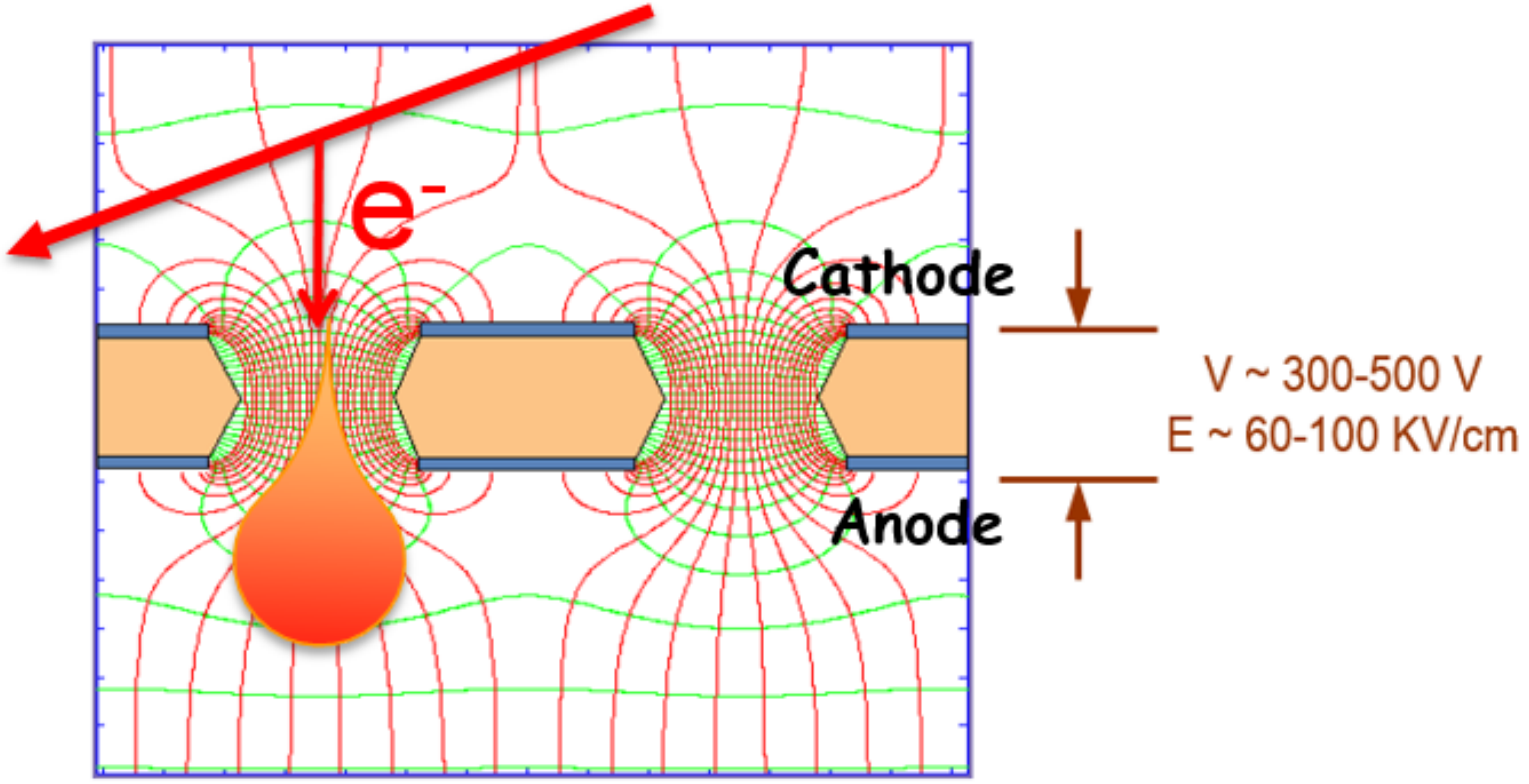


Electron multiplication: GEMs

- Gas Electron Multipliers
- Thin foils covered with Cu layers on both sides and drilled with many holes
- Typical hole size: ~100 μm
- 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



F. Sauli, NIMA 805, 2 (2016)

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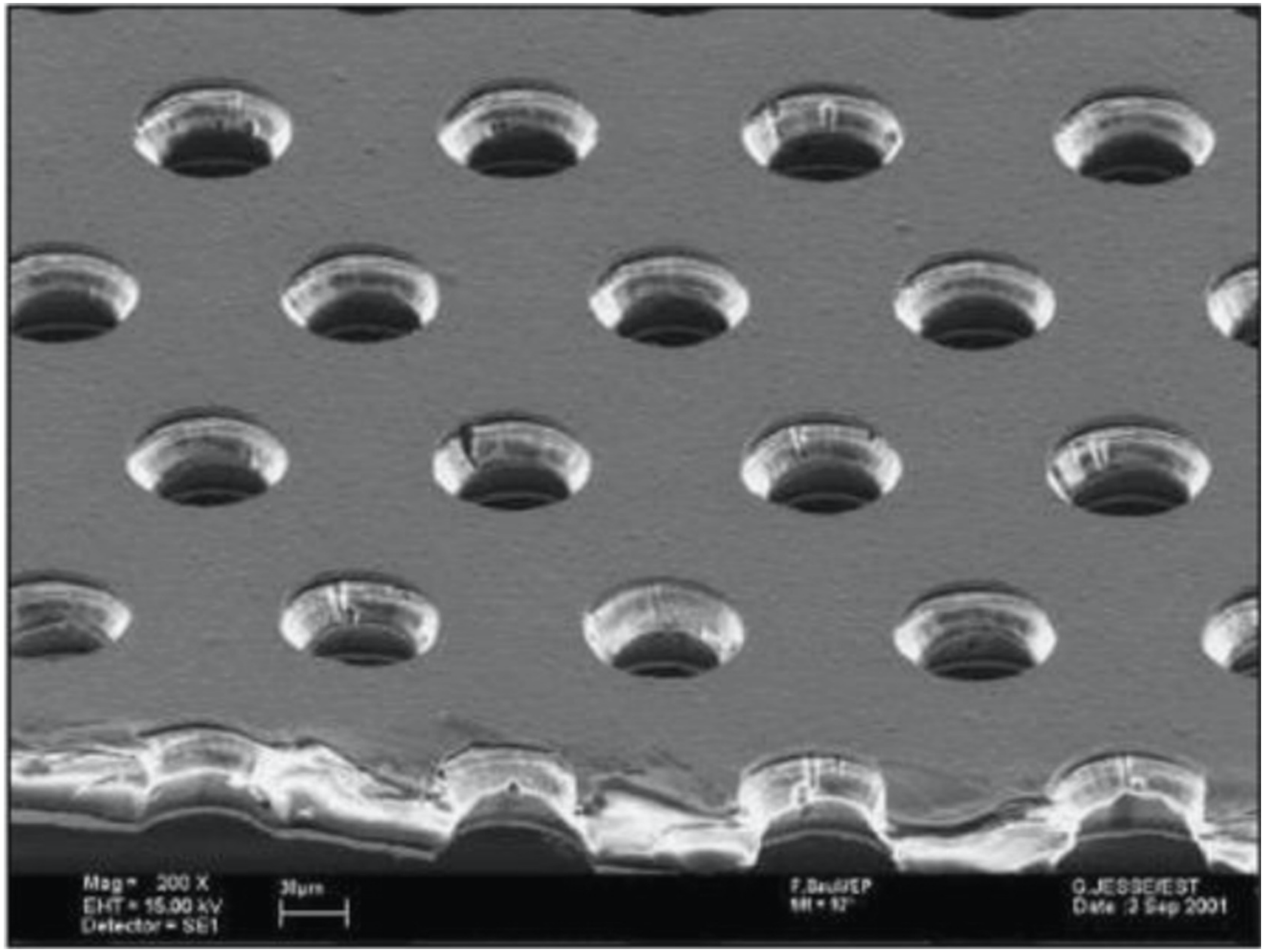

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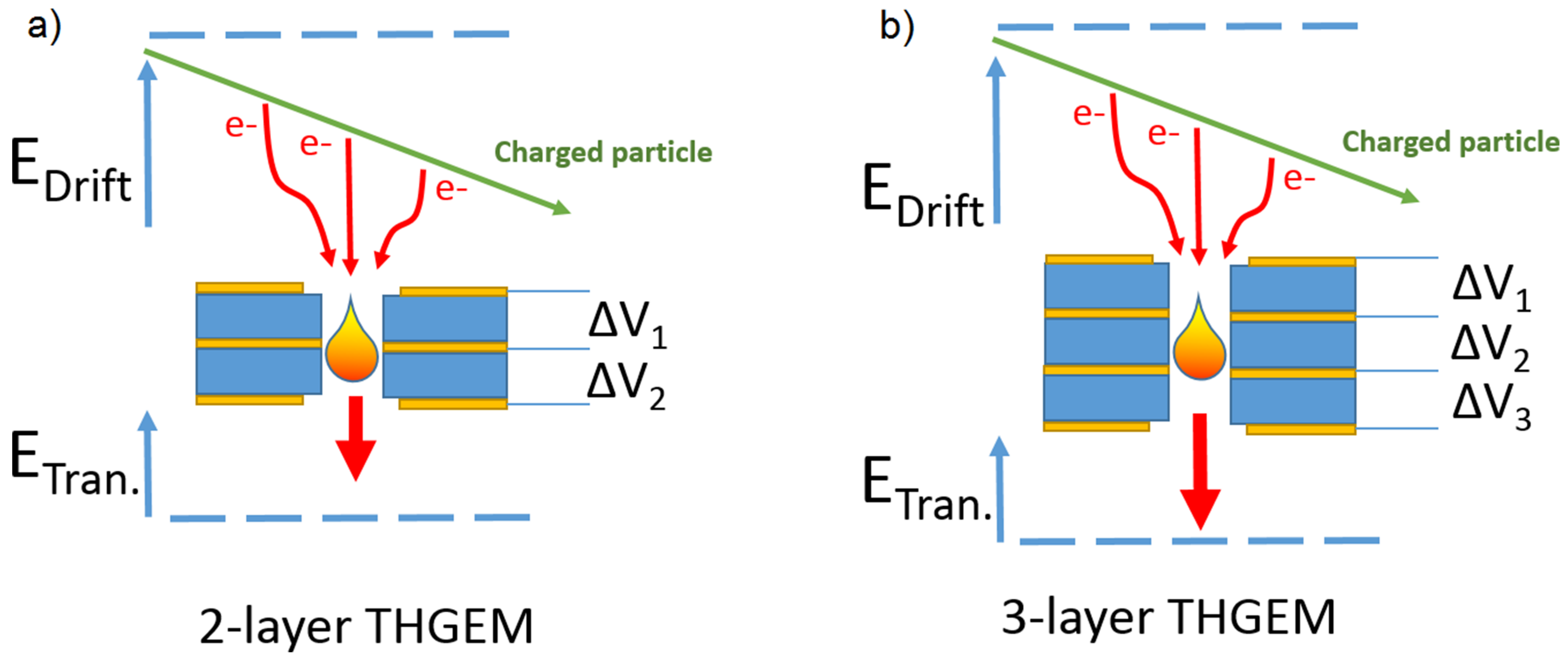
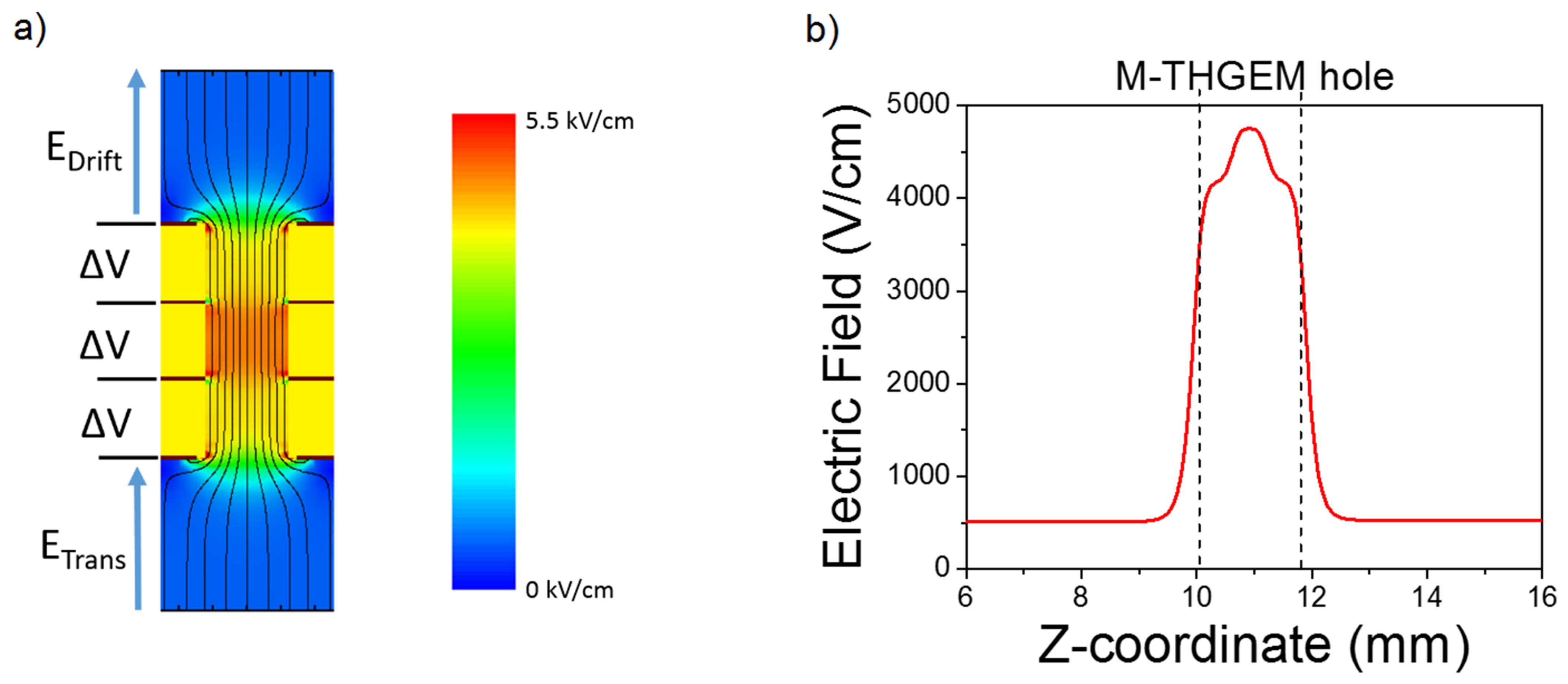
Next generation: multi-THGEMs

- 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

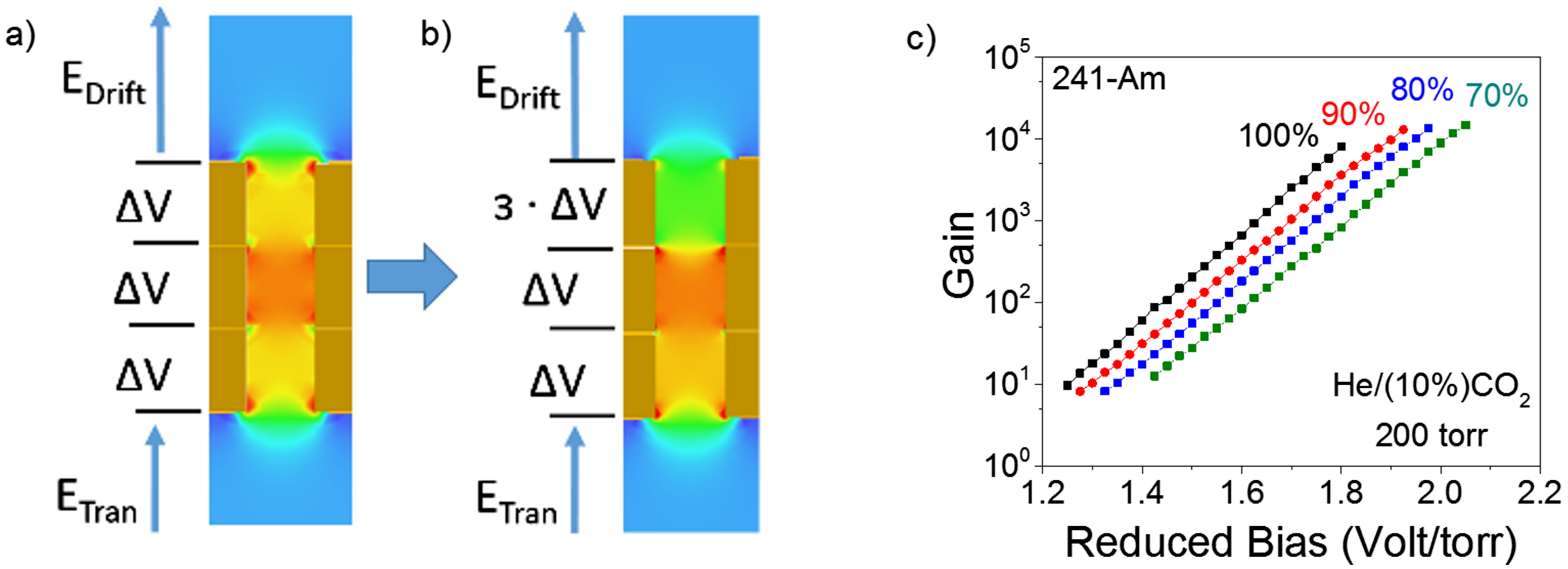


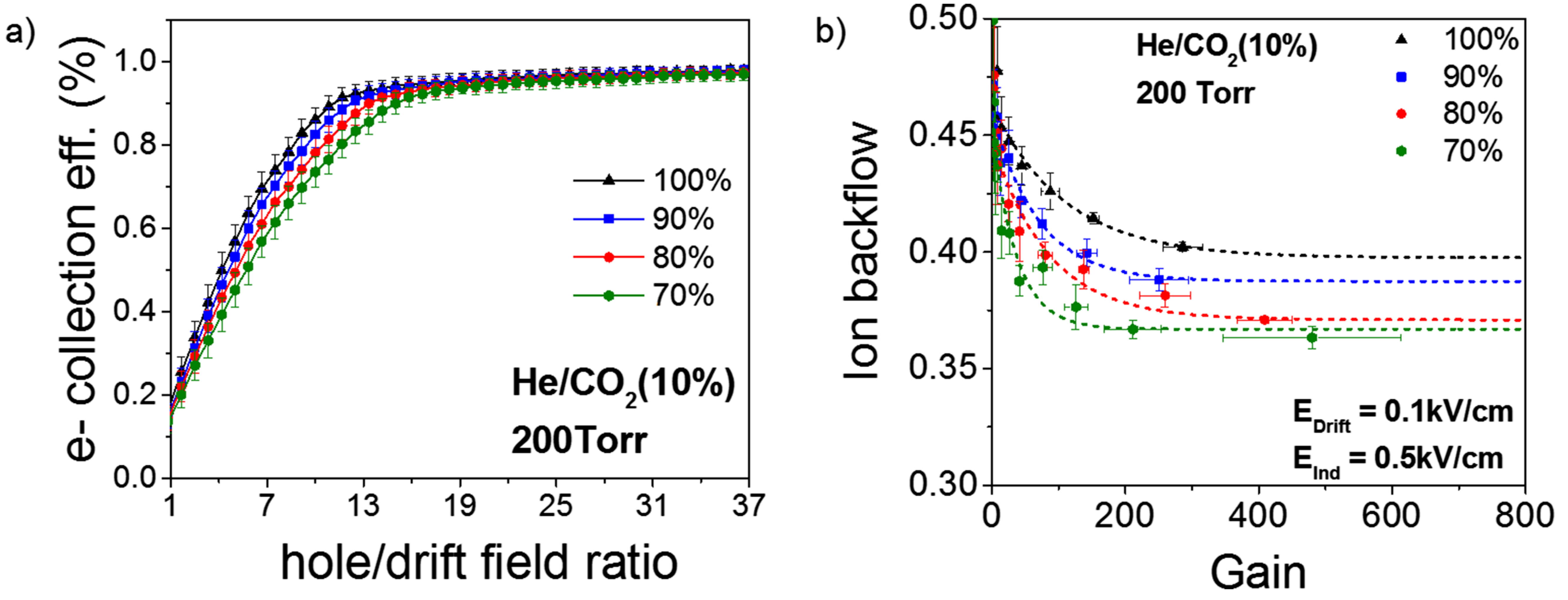


M. Cortesi et al., Rev. Sci. Instrum. 88, 013303 (2017)

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





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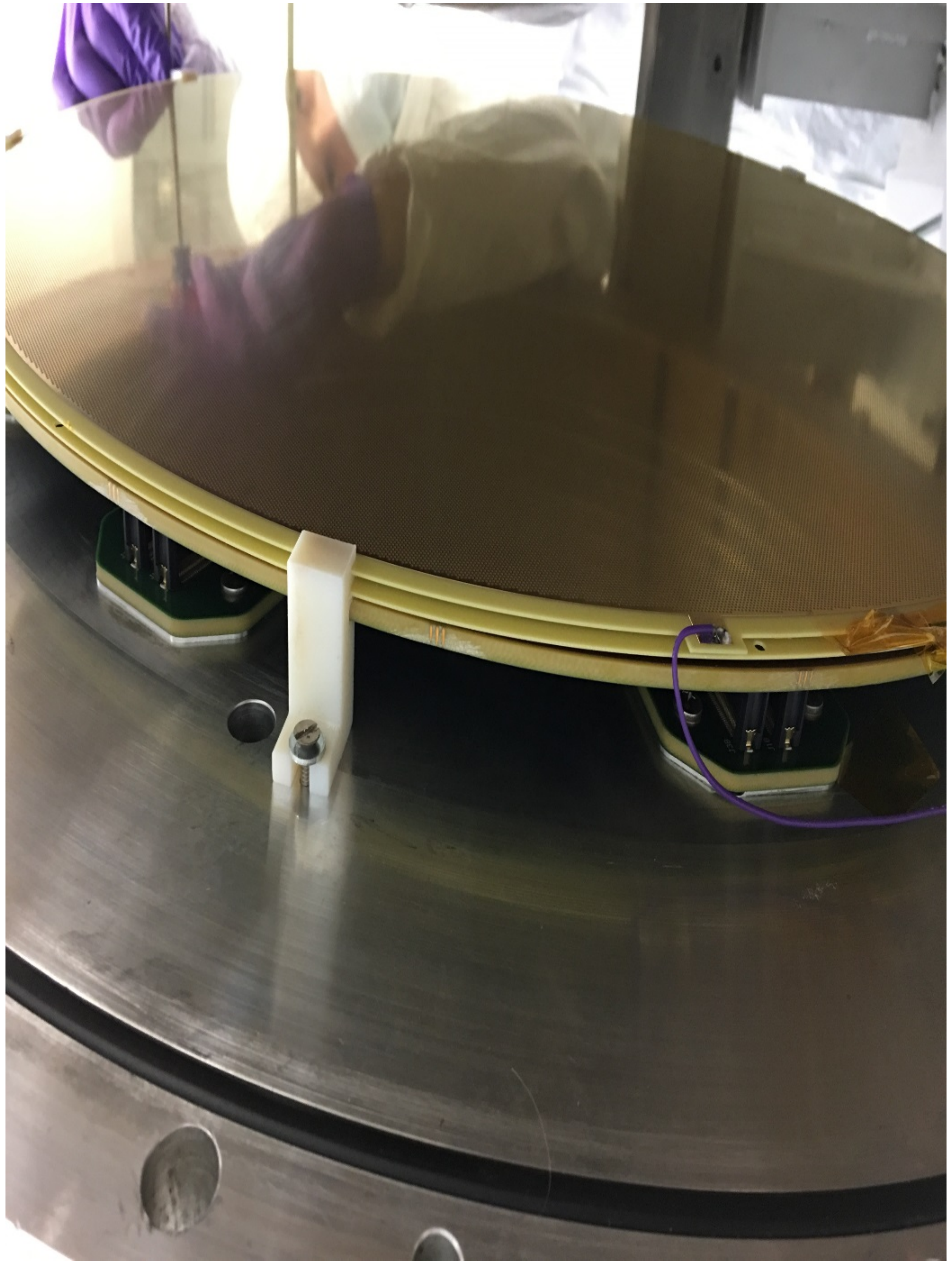
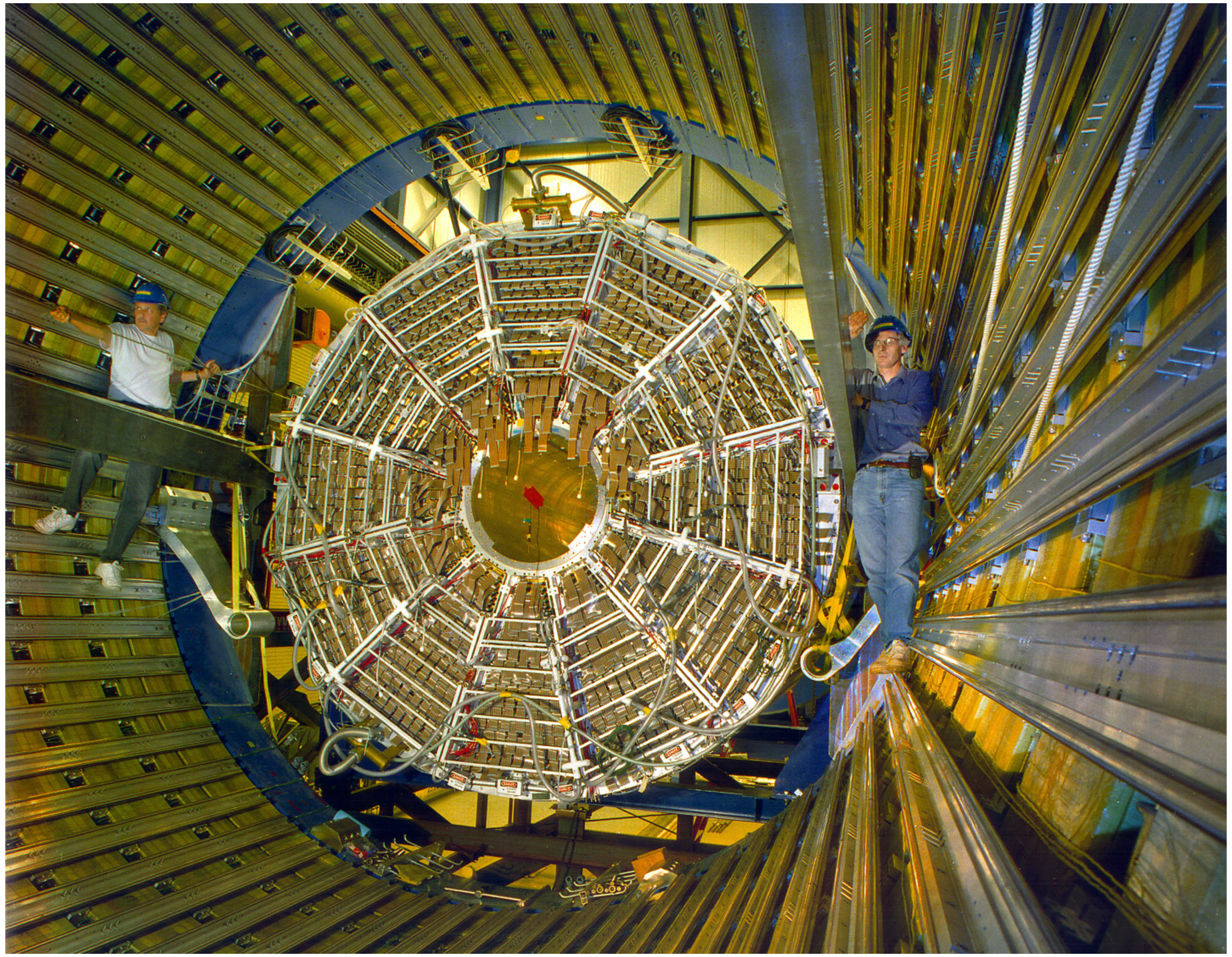
Combining multiplication devices

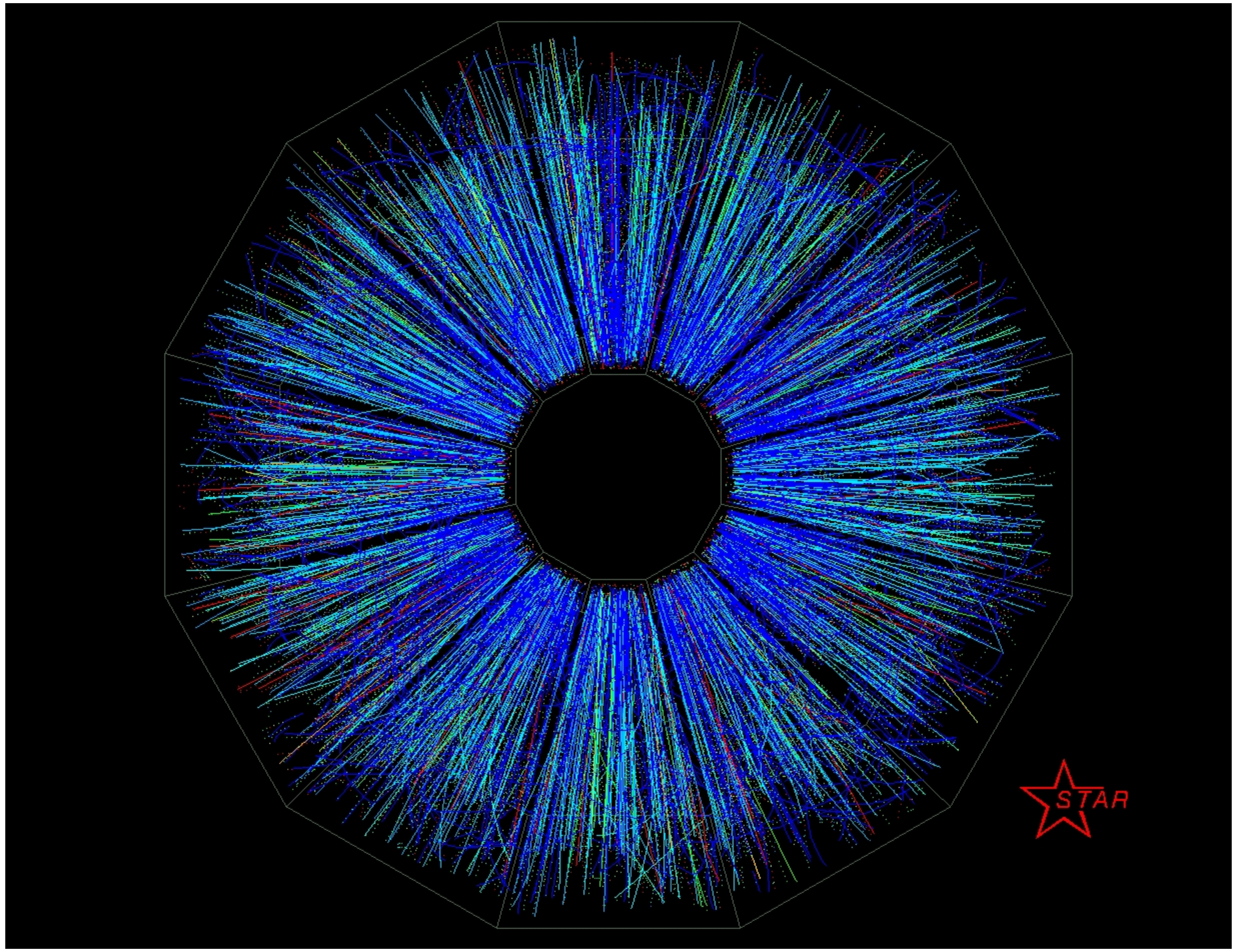
- THGEMs or M-THGEMs used as electron preamplifiers
- Example: 2 THGEMs on top of Micromegas
- Cascade allows to relax gain on each stage of electron amplification
- Limit ion back flow from the last stages
- Top THGEM can be used as a gating grid



TPC examples: STAR (RHIC)

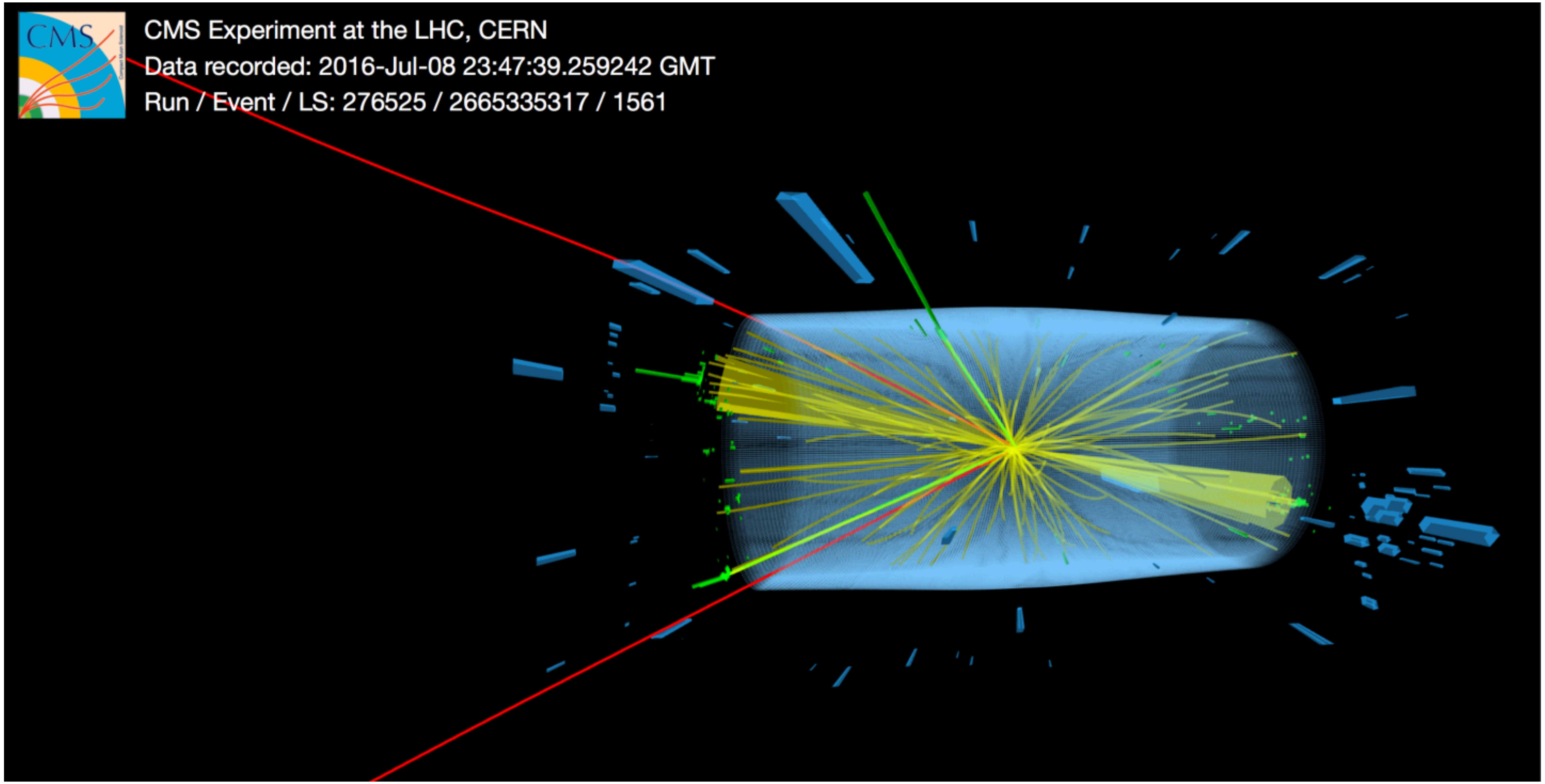
Discovery of the quark-gluon plasma





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!