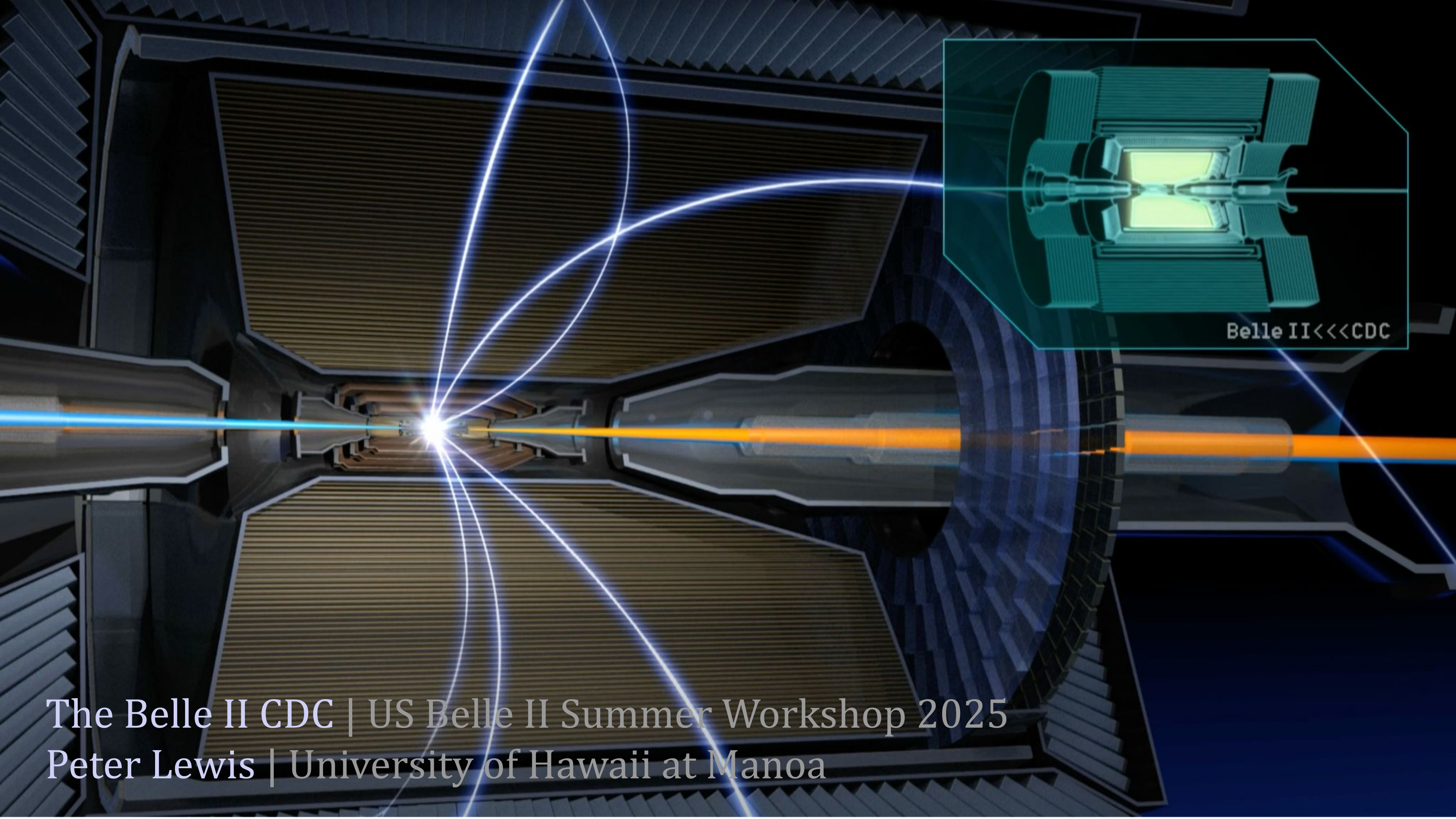


The Belle II CDC | US Belle II Summer Workshop 2025

Peter Lewis | University of Hawaii at Manoa

This talk

What this talk is supposed to be about: **the CDC**

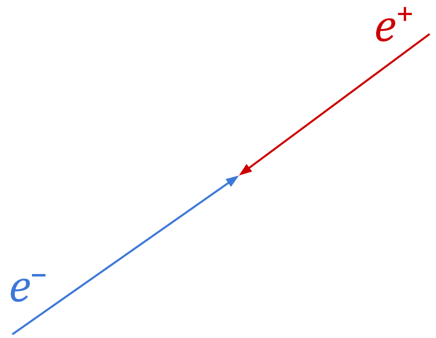
What this talk is really about: *everything you will ever need to know about gaseous detectors*… so that you can understand what's going on with the CDC

(adapted from an 18-hour lecture series…)

Highly interactive: please just shout out answers!

Let’s play pretend:

Imagine SuperKEKB is the **world’s first particle collider** and you are designing the Belle II detector *from first principles*. What would you come up with?

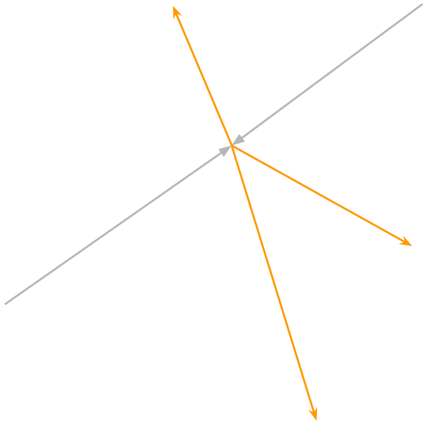


Let’s follow the logic…

What does the detector need to do?

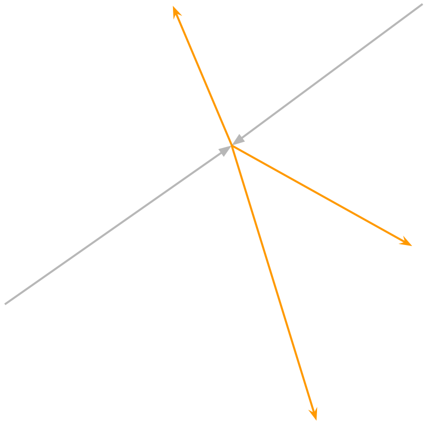
Detect “everything” (four-momenta) for all final-state particles in the decays:

- Neutrals (photons, K_L^0, . . .) $\longrightarrow$ not our business today
- **Charged** ($e, \mu, \pi^{\pm}, K^{\pm}, p$)



So this is our task: design, from scratch, something that *detects charged particles and measures their four-momenta.* To factorize this:

- Measure three-momenta
- Uniquely identify *species* (uniquely identified via *mass*)



Q: how does one "detect" a charged particle?

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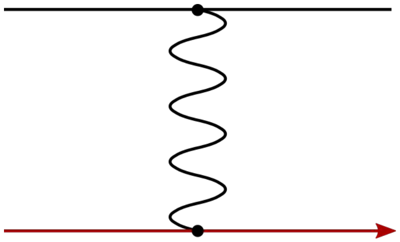
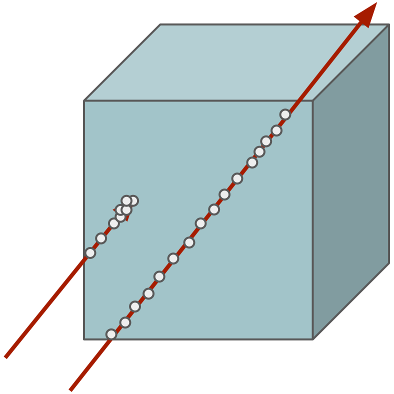
A: via *energy deposited* in a detector material:

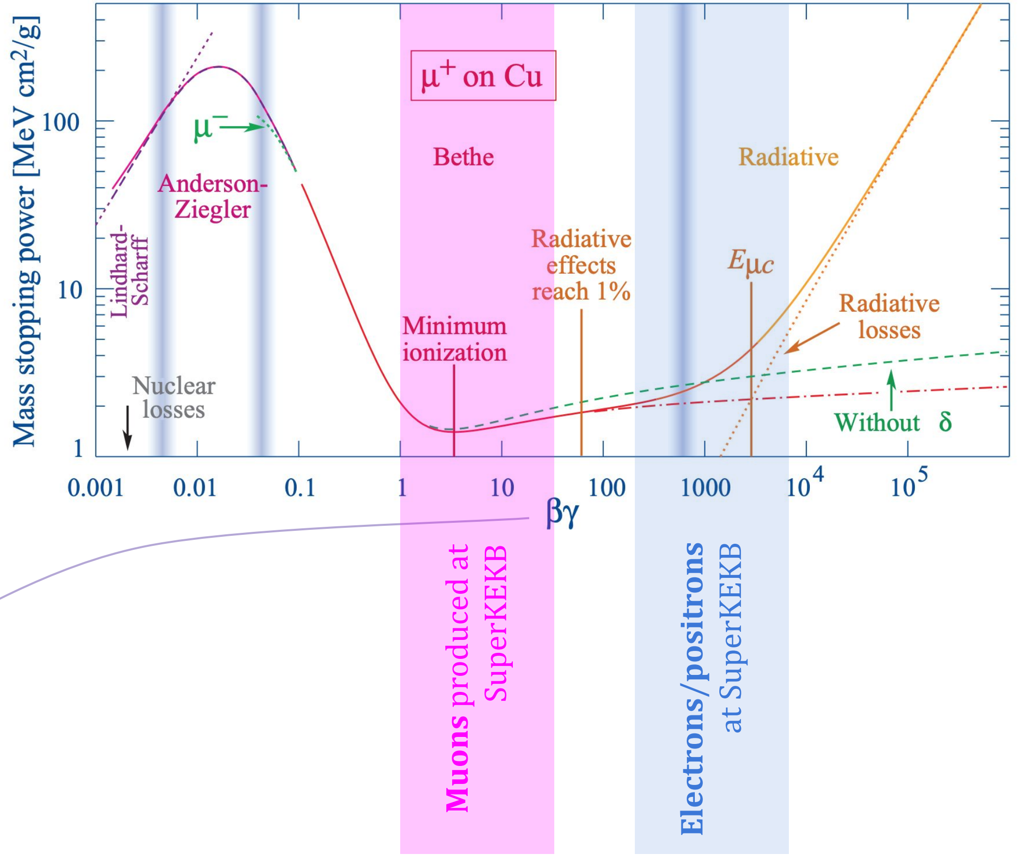




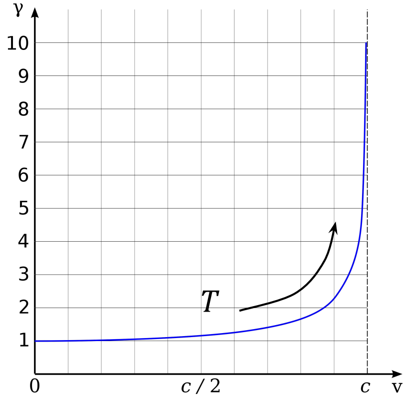
There are a **large number** of *primary* electromagnetic interactions. Each interaction causes **small energy loss** or **small deflection**. Particle can **transit** or **stop** in material.

Energy *deposited in a material* per unit length (per unit *density*):

"dE/dx"

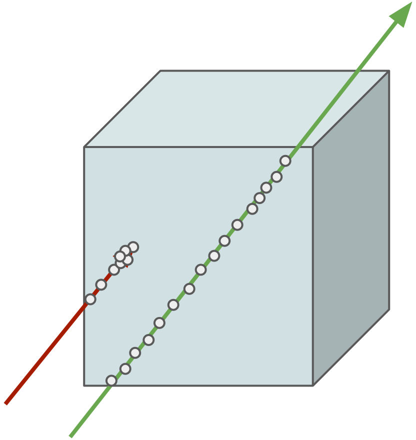


$$\gamma = \sqrt{1 + \left(\frac{p}{m_0}\right)^2}$$



$$\beta = \frac{v}{c}$$

Q: Which of these types of measurements do we want?



Non-destructive: only small KE captured, but *trajectory* can be seen

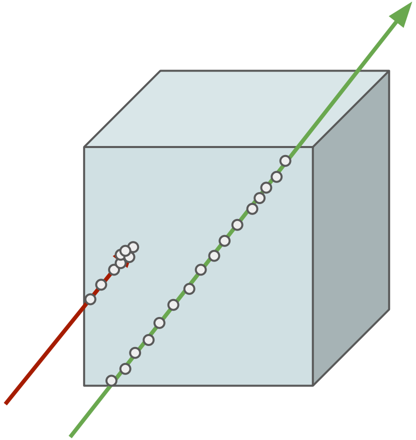
Destructive: ~all KE of particle captured in ionization

Q: Which of these types of measurements do we want?

A: Non-destructive

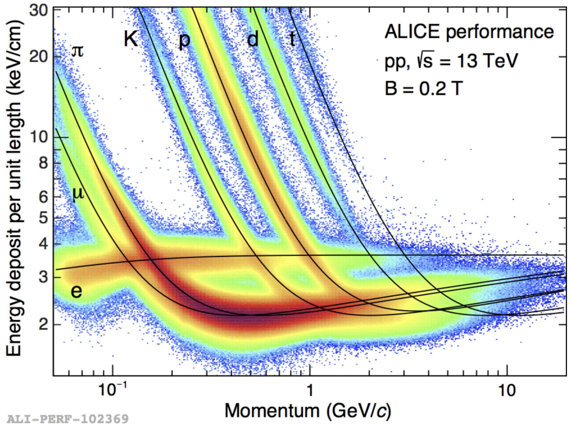
Non-destructive: only small KE captured, but *trajectory* can be seen

Excellent reconstruction of three-momentum*, plus *some* species information via dE/dx



Destructive: ~all KE of particle captured in ionization

Good *E* measurement, but **poor** three-momentum measurement and **poor** ability to separate species.

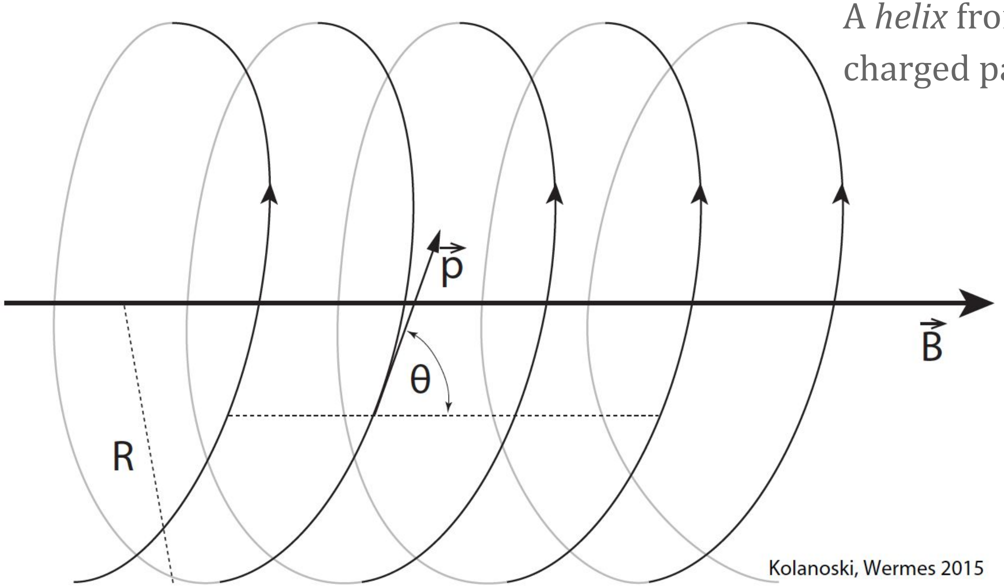


*Q: Wait… how can you get |*p*| from a *trajectory*? What's missing?

Q: Wait… how can you get |*p*| from a *trajectory*? What's missing?

A: Add a magnetic field

A *helix* from flight of a charged particle



$$R = \frac{v_T}{\omega_B} = \frac{\gamma\, m\, v_T}{|q|\, B} = \frac{p_T}{|q|\, B}$$

Transverse momentum from *radius of curvature*

$$\sin\theta = \frac{p_T}{p}$$

Total momentum from polar angle

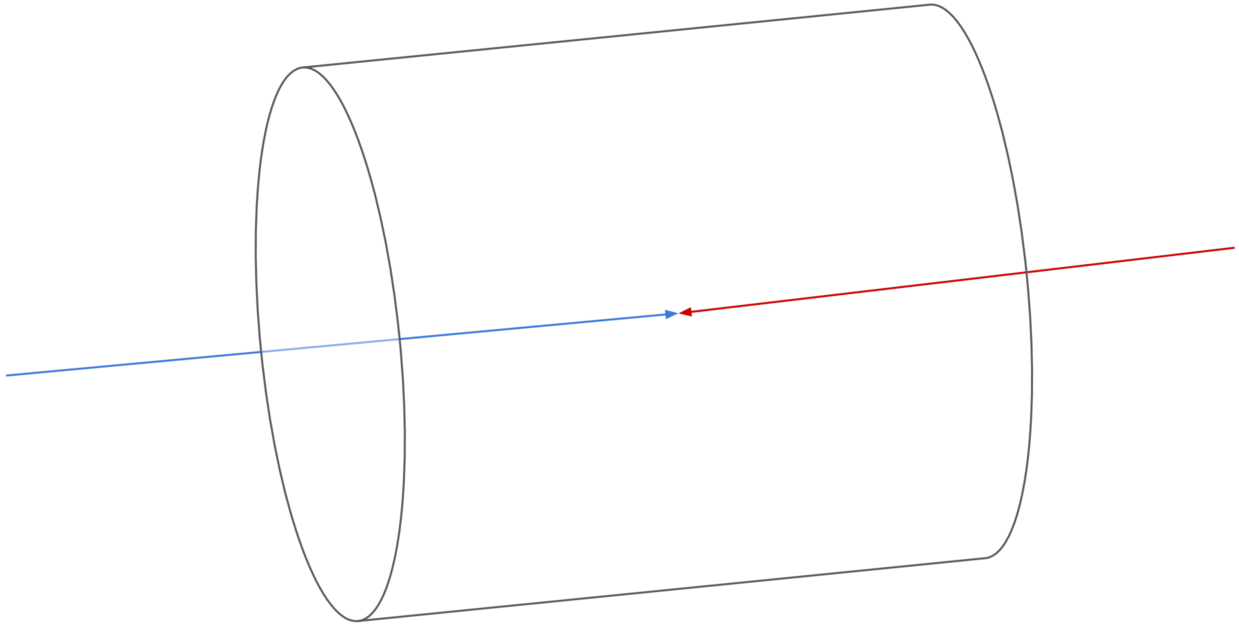
OK, so we need a *non-destructive measurement* in the presence of a *magnetic field*.

Q: What type of detector should we use for *non-destructive* measurement?

OK, so we need a *non-destructive measurement* in the presence of a *magnetic field*.

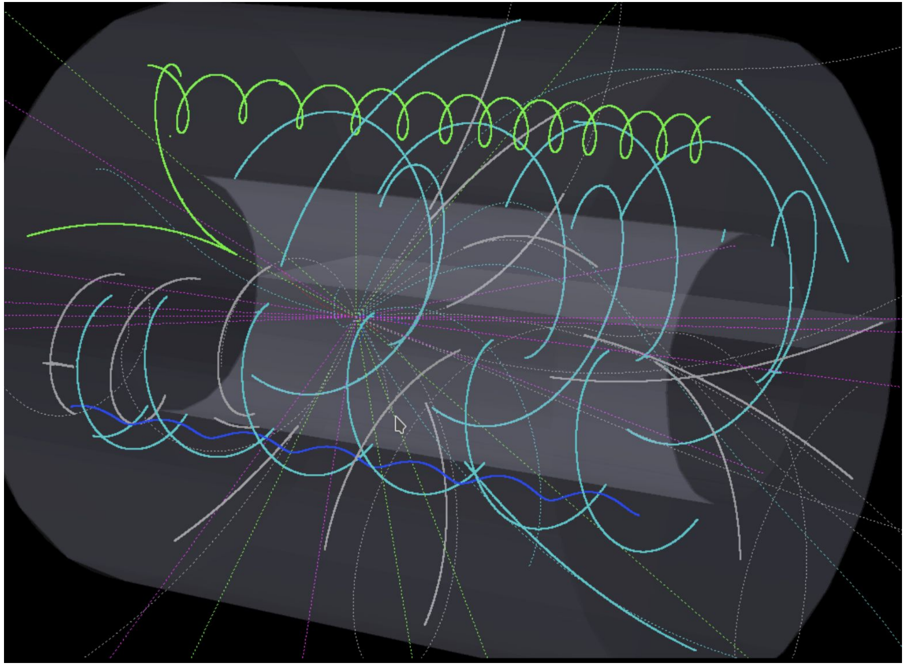
Q: What type of detector should we use for *non-destructive* measurement?

A: Use *gas* as our detection medium, and make it *big*:

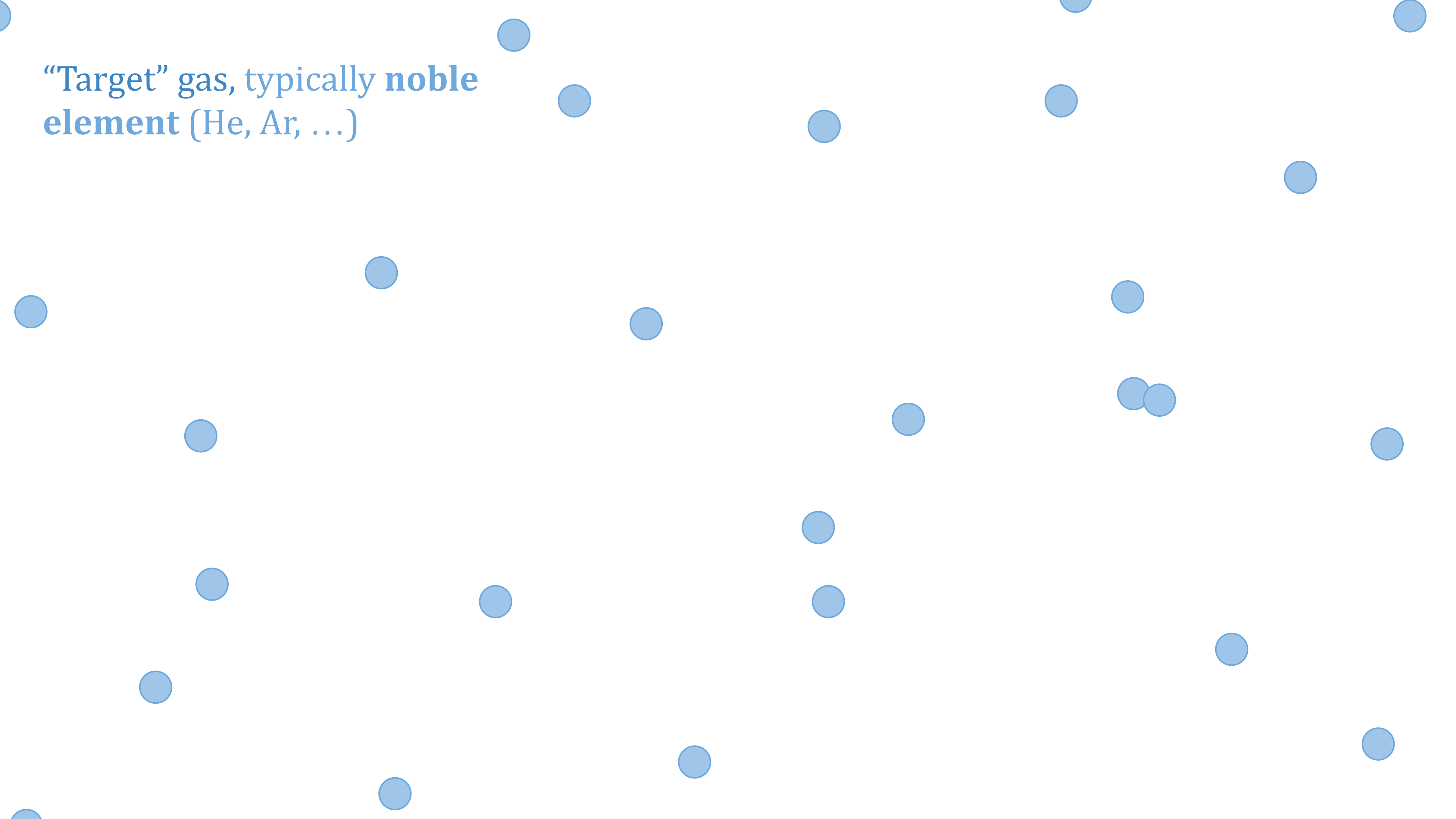


(but it needs to be *annular* to leave room for beam pipes and vertexing…)

OK, we have energy deposited in a gas in a big volume… but how do we actually *detect* that charge?

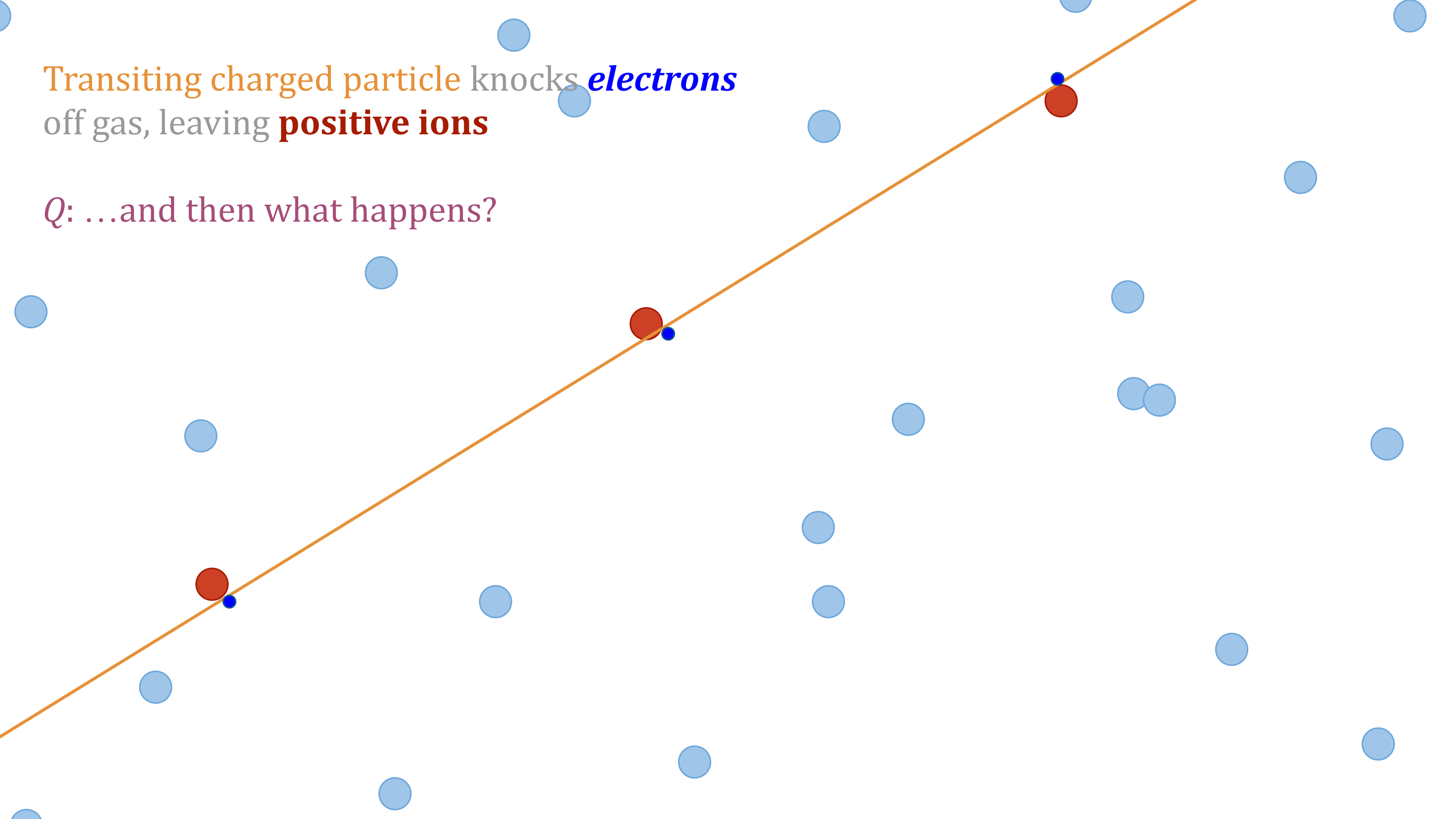


Let’s take a closer look at what we actually mean by “energy deposited” …

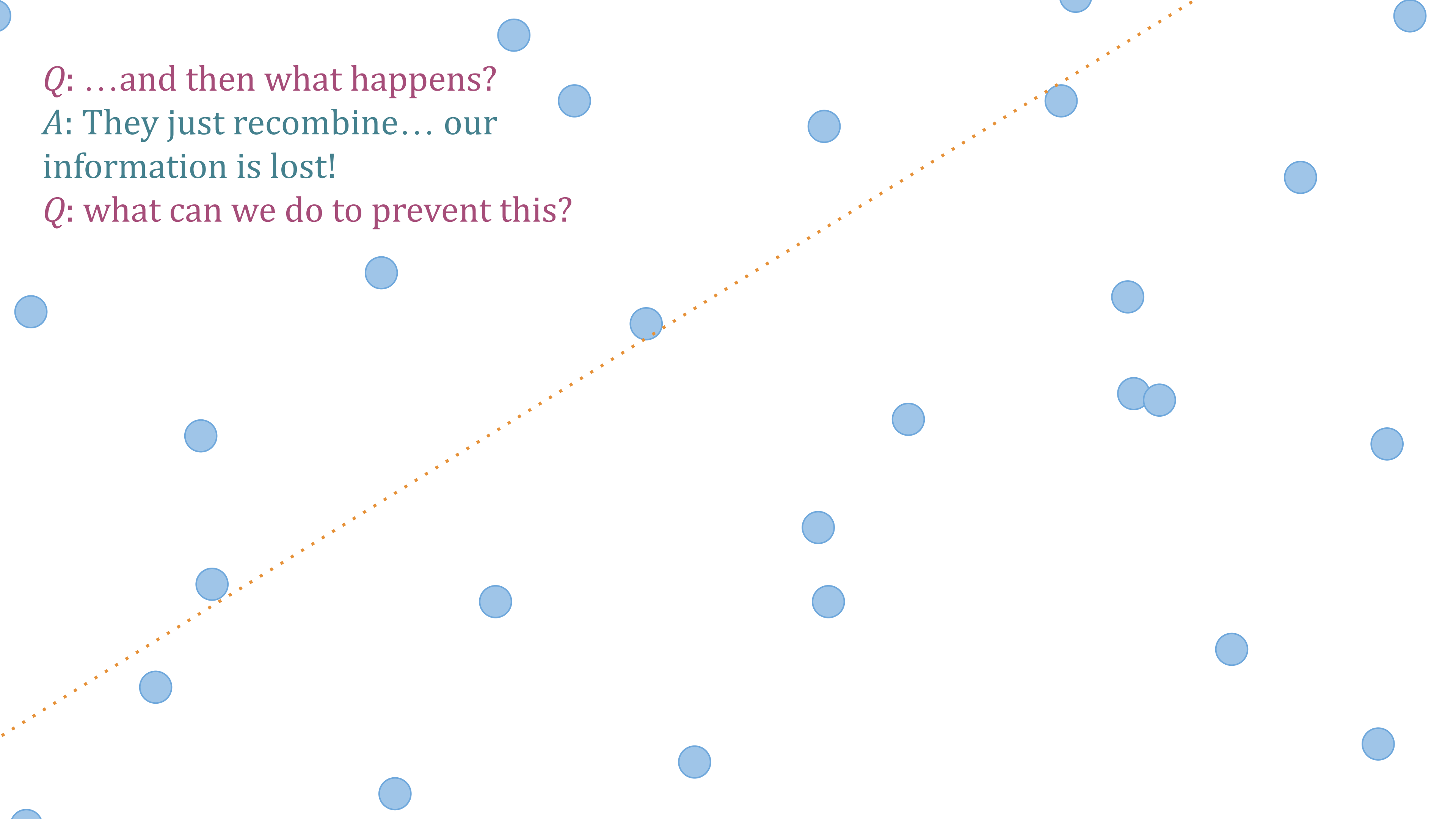

"Target" gas, typically **noble element** (He, Ar, . . .)

Transiting charged particle knocks ***electrons*** off gas, leaving **positive ions**

Q: …and then what happens?

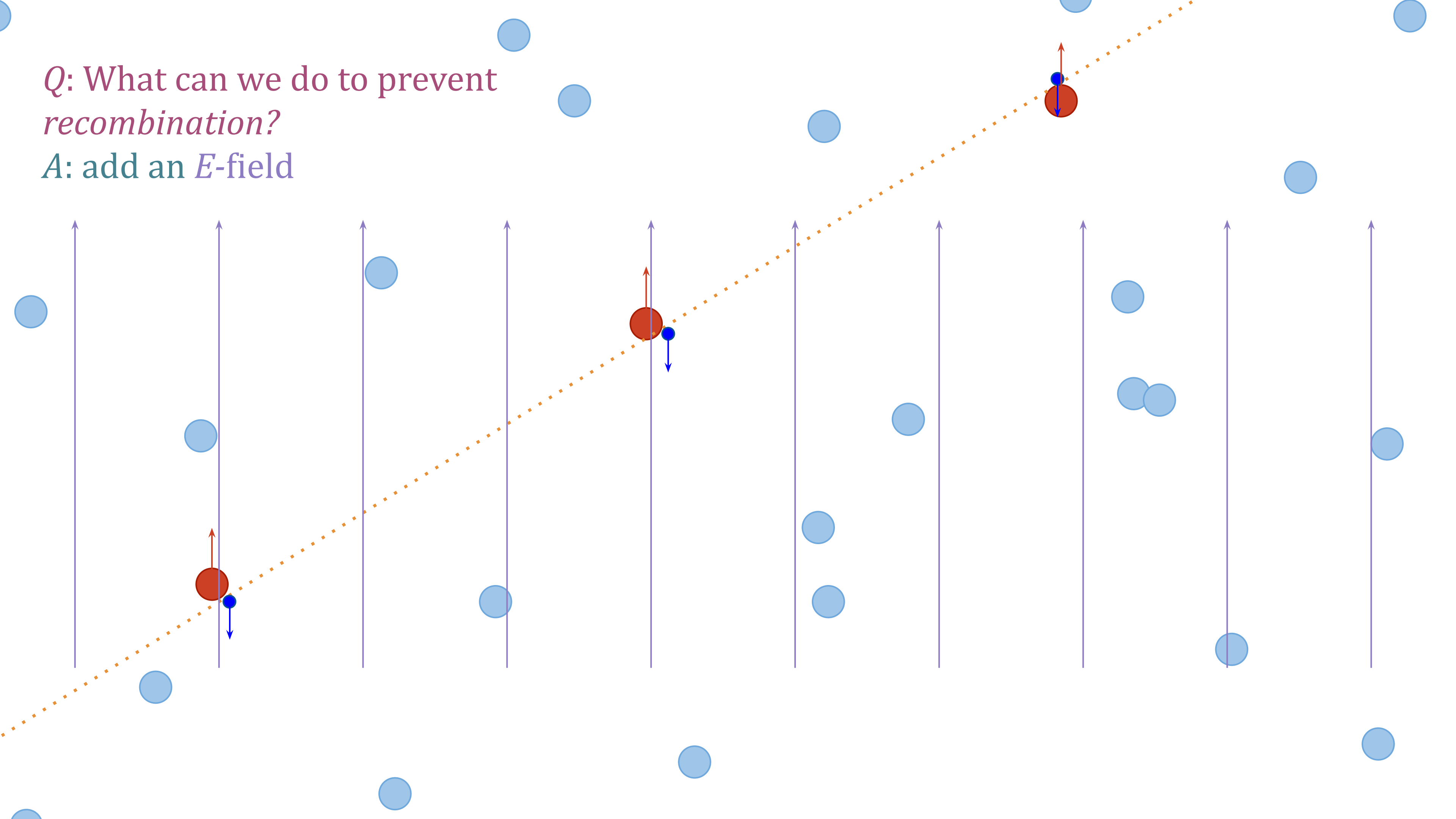


Q: …and then what happens?
A: They just recombine… our information is lost!
Q: what can we do to prevent this?



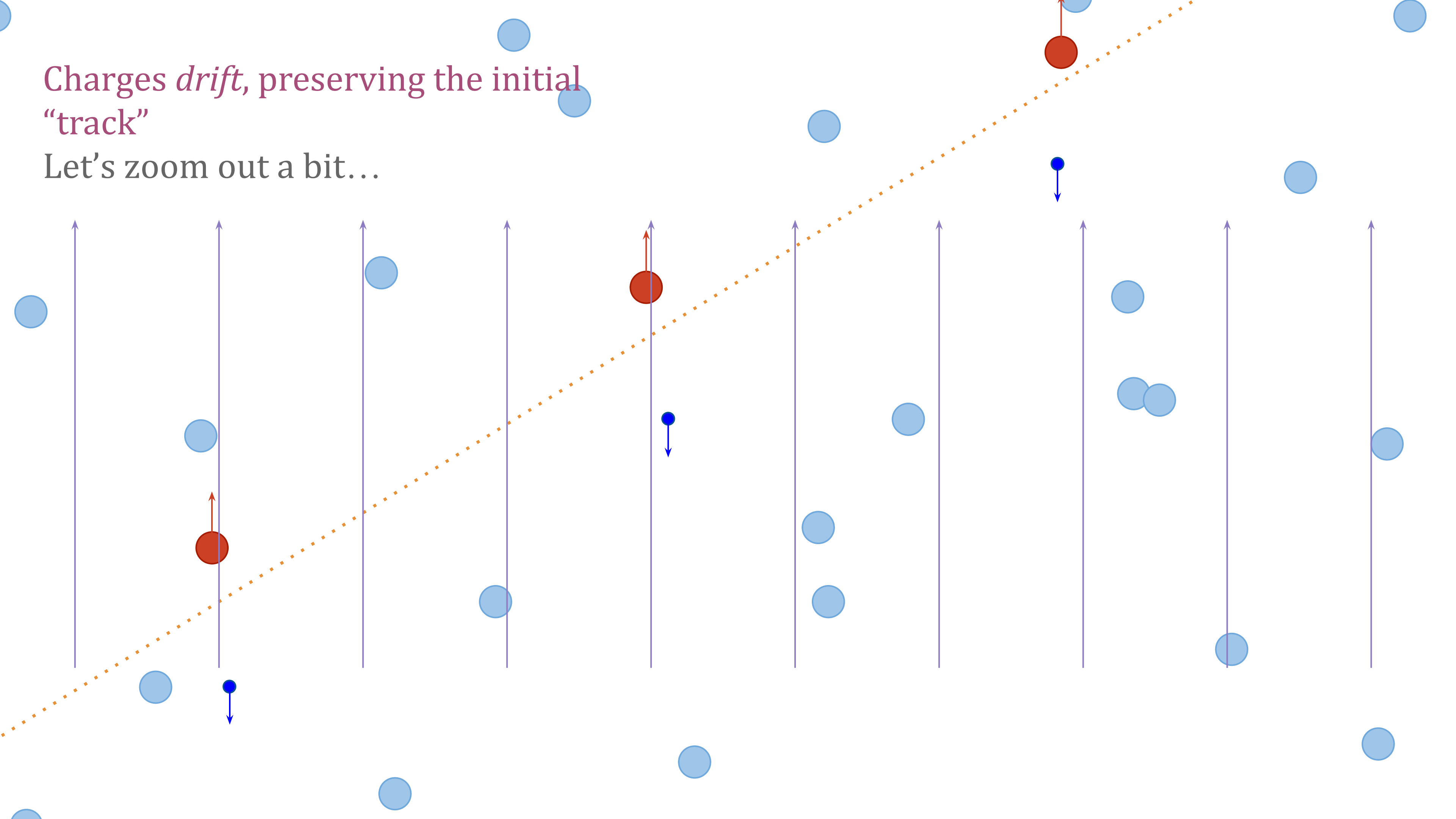
Q: What can we do to prevent *recombination?*

A: add an *E*-field

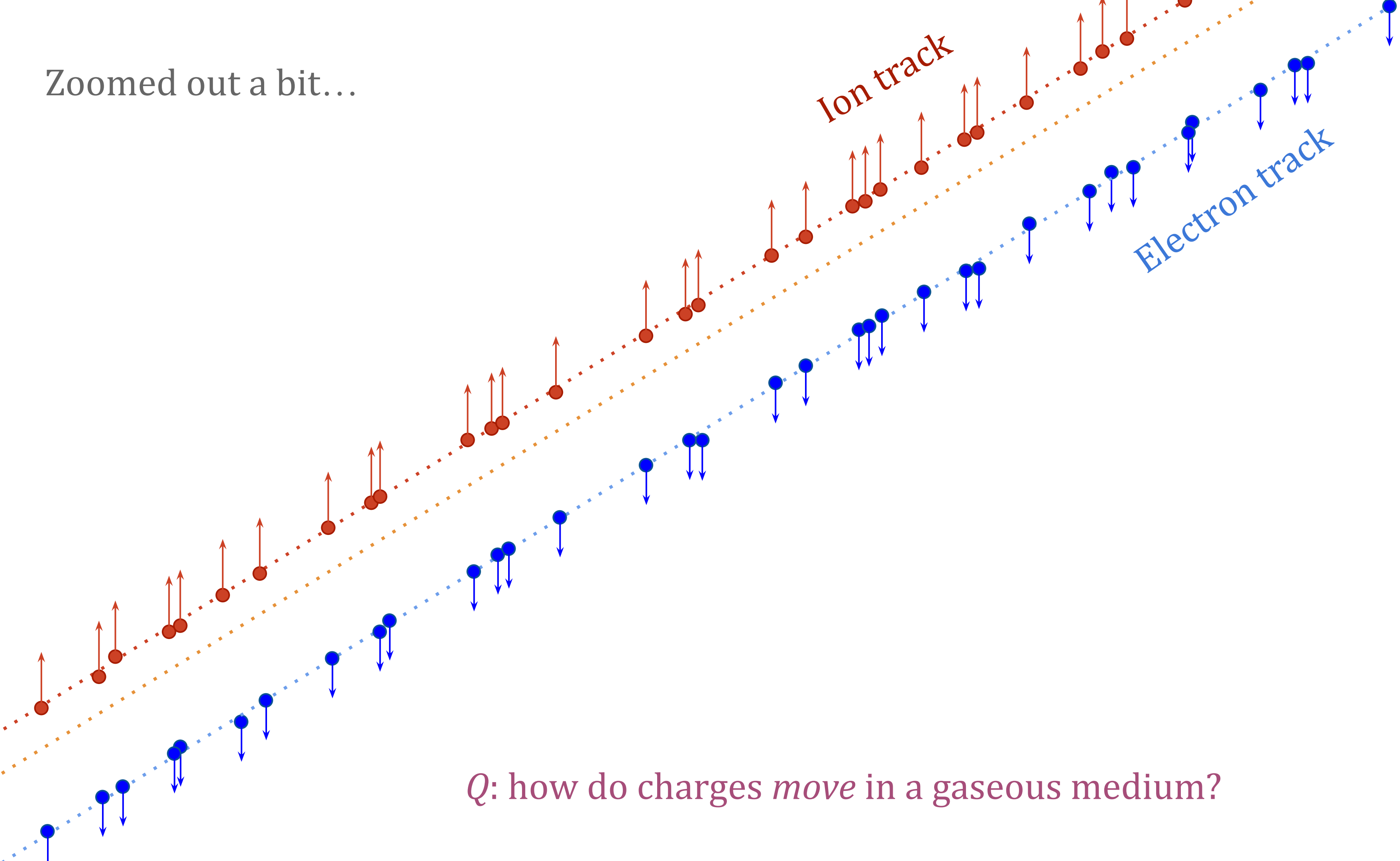


Charges *drift*, preserving the initial “track”

Let’s zoom out a bit…



Zoomed out a bit…



Q: how do charges *move* in a gaseous medium?

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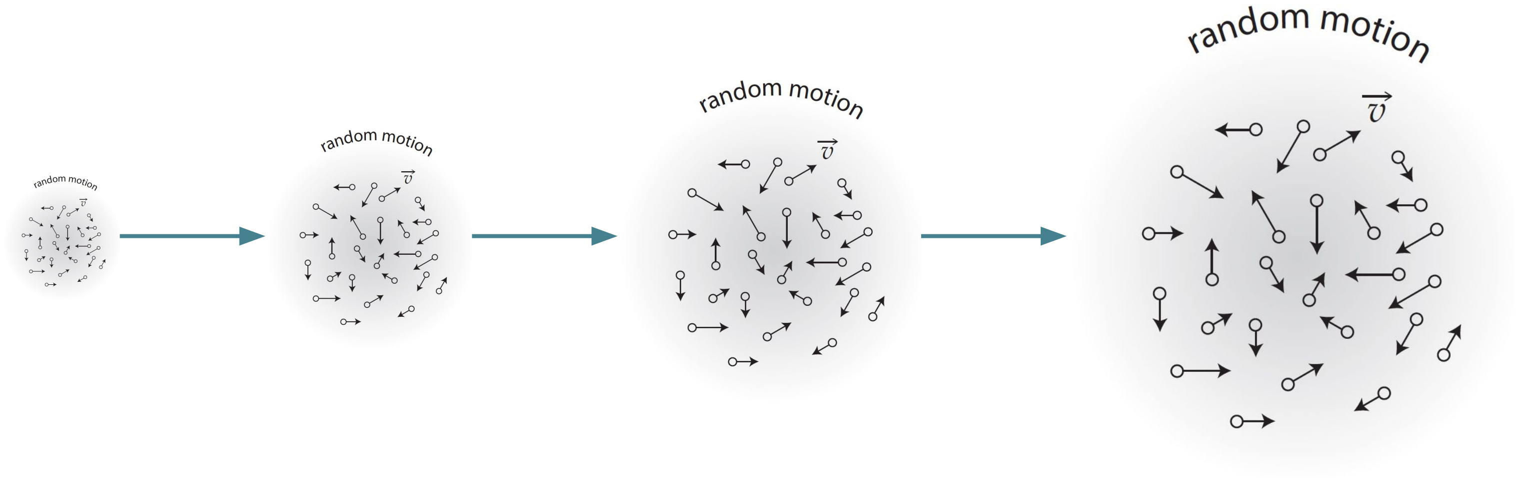
A: **bulk** motion is *constant v*, with a *random-walk thermal diffusion* along the way:



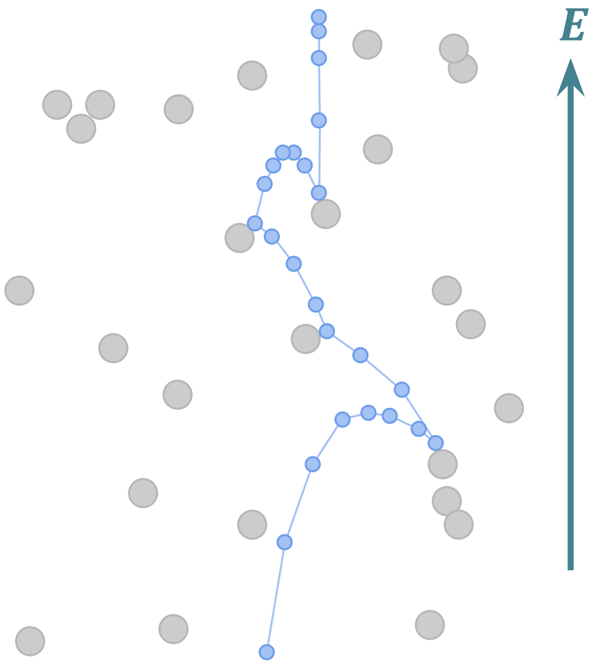
Diffusion width goes like sqrt(*drift distance*)... we want *short drift distances*

Q: Wait, but why is *v* constant… shouldn't it be **accelerating** (constant F)?

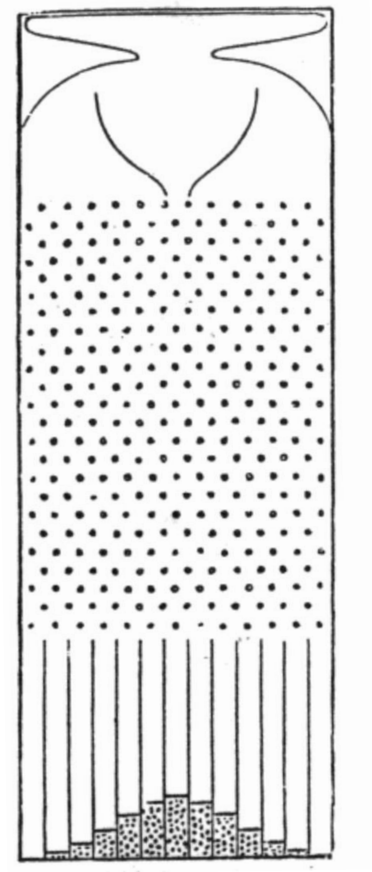
Q: Wait, but why is *v* constant… shouldn't it be accelerating?

A: Mean motion is mean of *free paths* between (frequent) collisions.

Each collision both causes *rebound* and *lateral scattering* (diffusion)



This is a surprisingly good model for charge transport!



Q (challenge question): What can you do to *speed up* the drift velocity *without increasing diffusion*?

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A: Make *E-field* higher?

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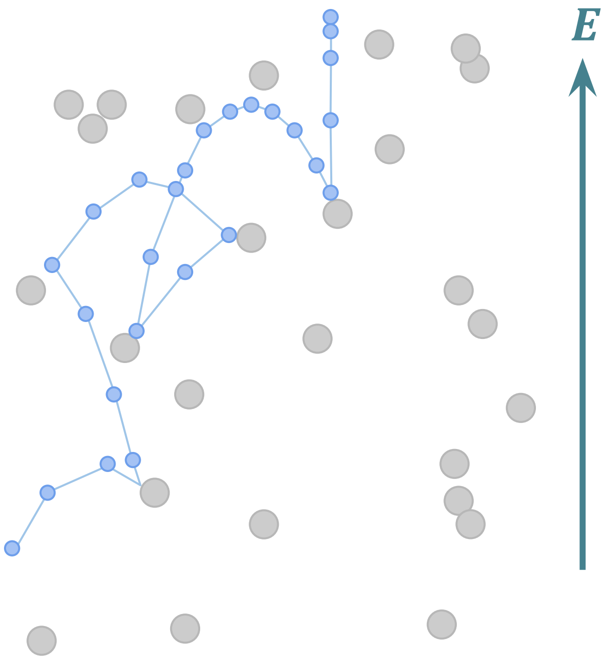
A: Make *E-field* higher?

Higher E-field means *more-energetic scatters…*

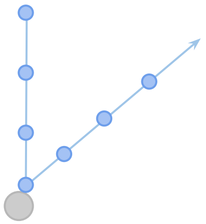
- More diffusion
- *Diminishing returns* for drift velocity



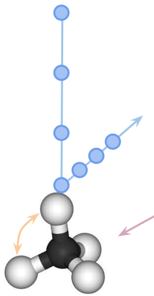
Let's add a *different gas…*

Add a *quenching gas*… typically **hydrocarbon**

Collision with **noble element** is *elastic*… like a billiards ball:



Hydrocarbons have *many internal degrees of freedom*… collisions can be *inelastic*



CH_4 (methane)

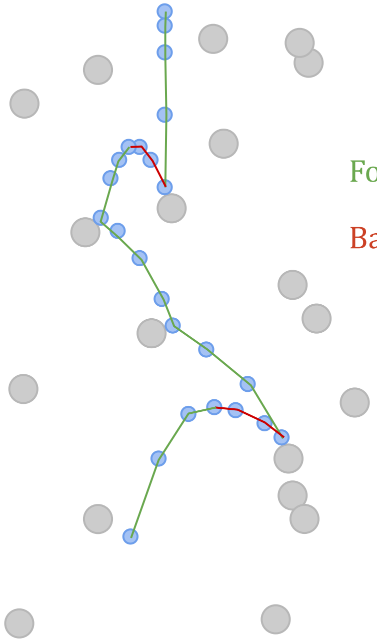
Exciting the vibrational modes of the molecule *steals* energy from the electron, “cooling” it:

- Decreased diffusion
- *Increased drift speed*…

Wait, how does *stealing* kinetic energy from the electron make it go *faster*? (Any ideas?)

Wait, how does *stealing* kinetic energy from the electron make it go *faster*?

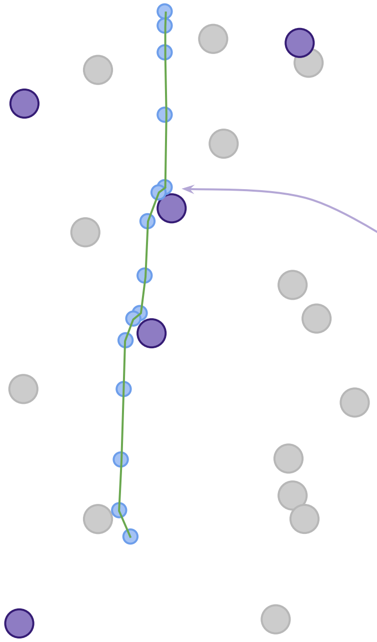
No quencher



Forward motion

Backward motion

With quencher



Typically we will use something like 90:10 mixture (noble target element : quencher)

Charges *slow or stop* here and accelerate from a stop. Better than getting bounced back up!

(excitation of inelastic modes depends on energy, so cranking *E* up beyond a certain point will make your charge *slow down*!)

OK, so we use a gas with a quencher. But *how do we actually measure the charge?*

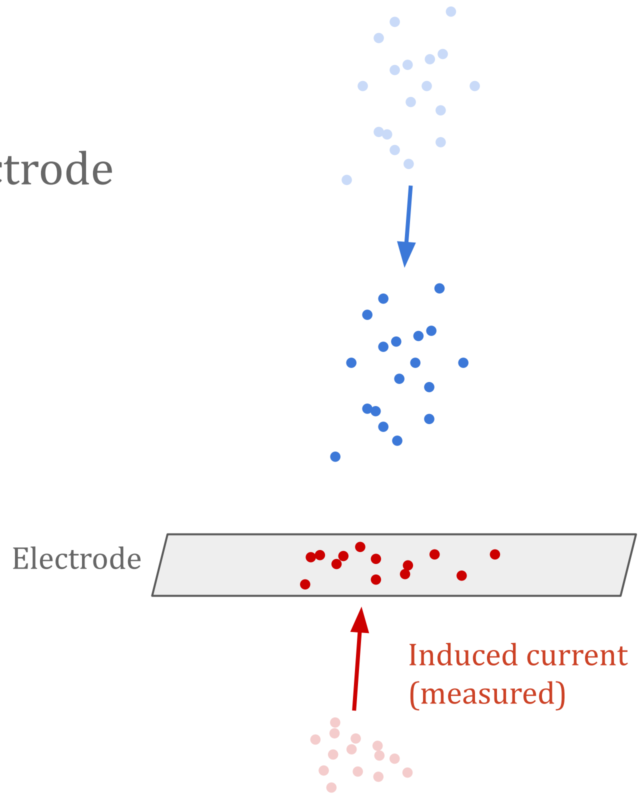
Q: *How do we actually measure the charge?*

A: Induced currents.

Shockley-Ramo theorem: current is induced on electrode due to *motion* of charges near it:

$$I = q\vec{v} \cdot \vec{E}_w$$

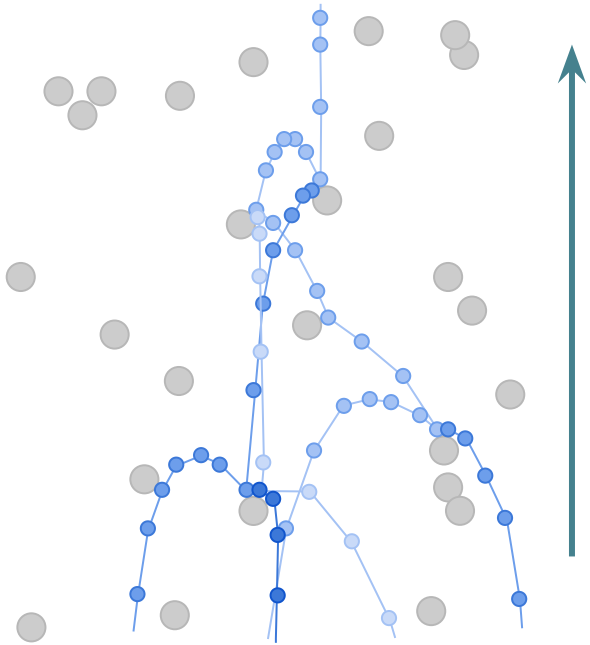
Weighting field (field on charge if electrode had unit potential and all other electrodes are grounded). Purely a function of **geometry**.



Q: evidently we need *a lot of charge* (q) traveling *fast* (v). *How*?

Q: How do we get *a lot of charge* (q) traveling *fast* (v)?

A: Charge amplification (*avalanche gain*)



This requires *far higher E-fields* than you need for drift

Enough energy at collisions to **ionize gas further**, creating an avalanche: *exponential growth* of charge

Q: But *how* do you create fields strong enough for this?

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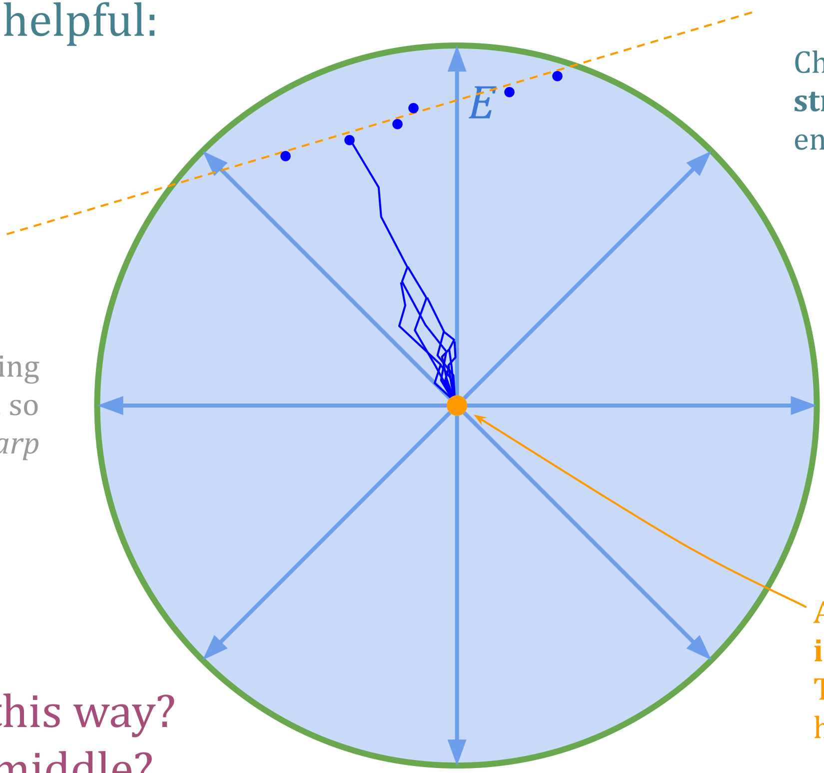
A: Cylindrical geometries are helpful:



Charge drifts to *anode*. Field is **strongly enhanced there**, encouraging avalanching

Cathode (ground potential)

Nice feature! Avalanching starts very close to middle, so the induced pulse is *sharp*

Anode wire (HV)**. Signal is induced on here.**
Typically want a *very thin wire* here for max gain!

Q: Why do we want the field this way?
Why not drift the ions to the middle?

Q: Why not drift the ions to the middle?

A: Ions have low *mobility*: it is hard for the E-field to make them move (high m/q ratio). They are then *slower* (factor of ~100) than electrons. Remember Shockley-Ramo:

$$I = q\vec{v} \cdot \vec{E}_w$$

We would get ~100 times less signal from ions–and they are *very* difficult to make avalanche (so far less q also).

Hmmm. Then the ions *clear* slowly…

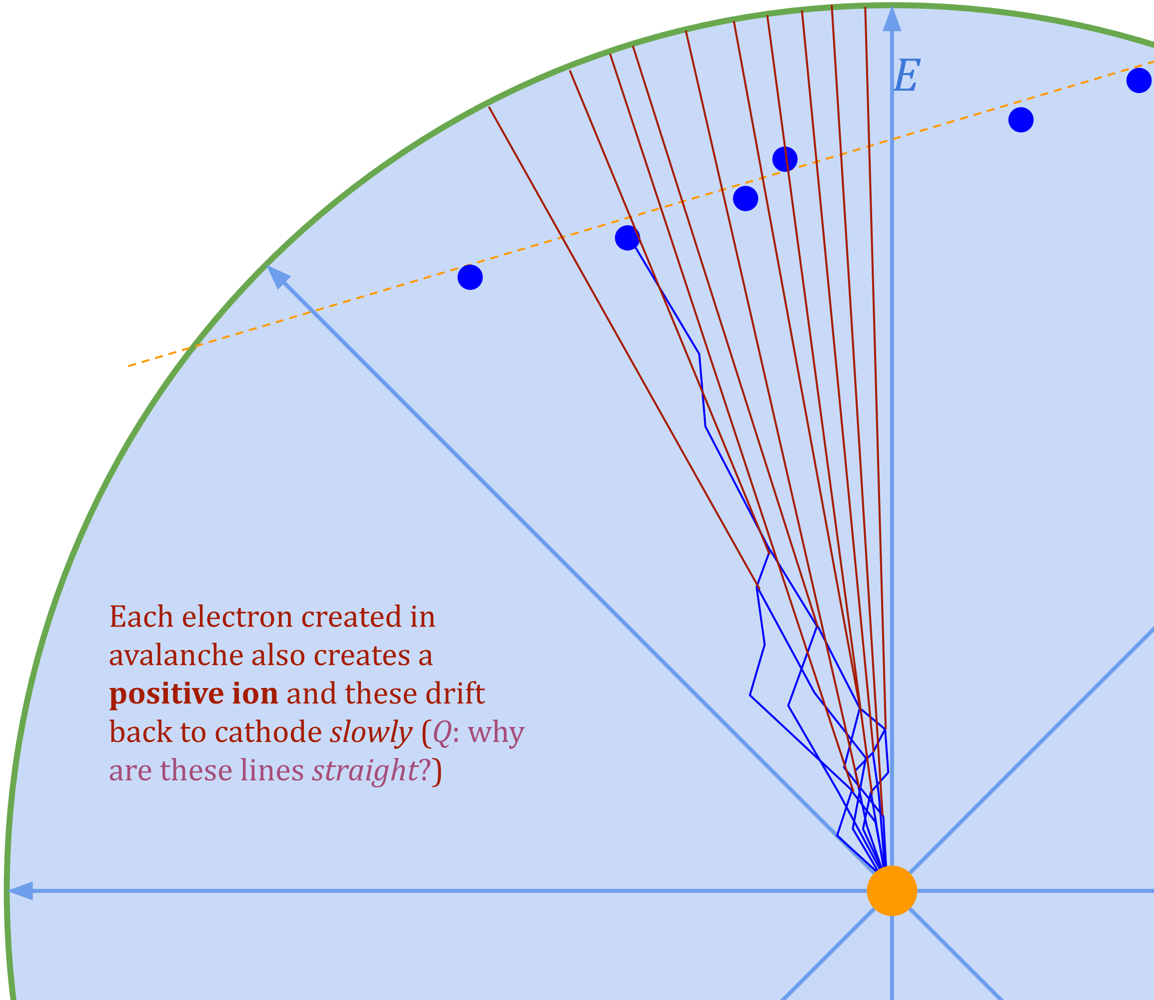
The ions *clear* slowly…

Leads to *space-charge effects:*

- Build up of positive charge in volume
- Modifies *E-field*
- Recombines with electrons
- **Lumpy** in space and time

So we want to strictly *limit* the growth of the avalanche (more is not necessarily better!)

So let's try to keep the avalanche process under control. How?



Q: How can we keep the avalanching process under control?

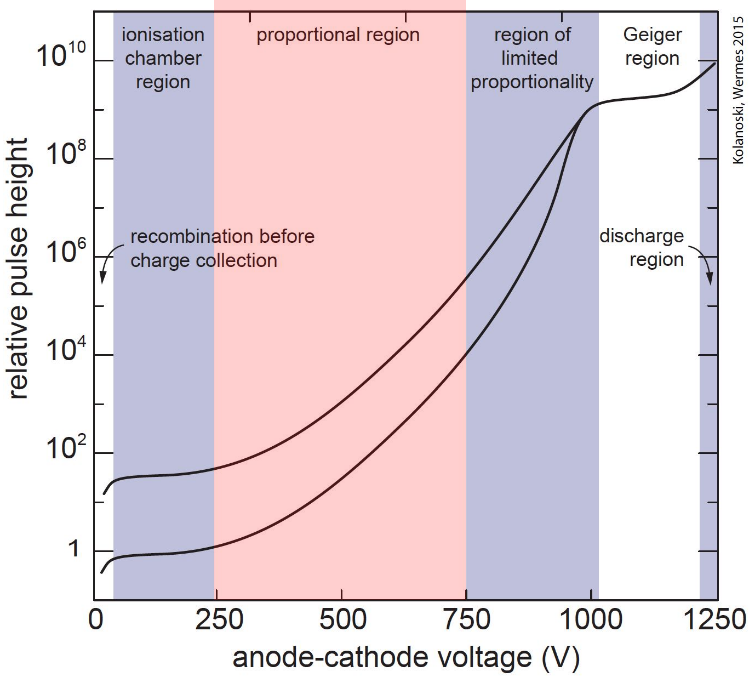
A: Quenching gasses work here too!

- "Cools" electrons (steals KE)
- Absorb UV photons that cause secondary showers
    - These can cause *runaway* avalanches

It's kind of magic! The same kinds of additives that gave us *high drift velocity and low diffusion* also keep the avalanches under control!

- Keeps signals in proportional region
- Limits space-charge effects
- Prevents runaway avalanches

We want to be here!



Q: There's a **big downside** to using hydrocarbons in this environment. Any clue what it is?

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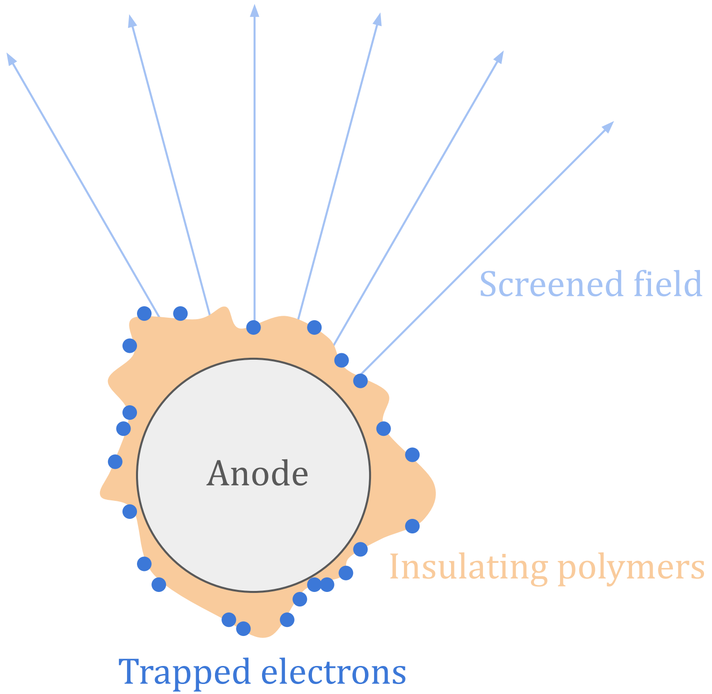
A: hydrocarbons are like Legos. They love to *chain up* into complex **polymers:**

Detector **aging** (boo plasma chemistry!):

- Hydrocarbons in gas break apart in avalanche
- E-field gathers negative-charged fragments at anode
- These combine to form **long-chain polymers**
- These are *insulating*, so electrons get trapped on surface
- This *screens* the electric field
- Leads to a **decrease in gain** (both long- and short-terms!)
- Damage is *permanent*

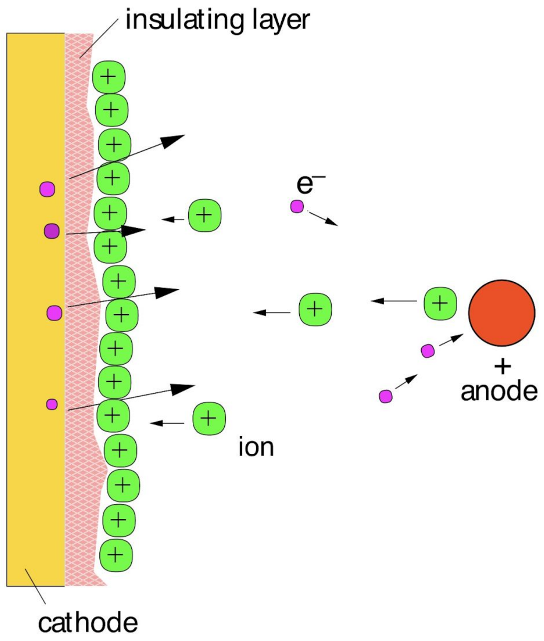


Something different happens to the *cathode*…

Something different happens to the *cathode*…

The **Malter effect** (*boo* plasma chemistry!!):

- The positive-charged polymer fragments gather at the **cathode**
- Long-chain **polymer deposits** now lead to accumulation of **positive ions** over time
- These **pull** **electrons** out of cathode (unique to Malter)
- Some of these escape and drift to the anode, creating a *self-sustaining and ultimately fatal current*
    - (“Current blowup” or “leak(age) current”)
- Also “permanent”



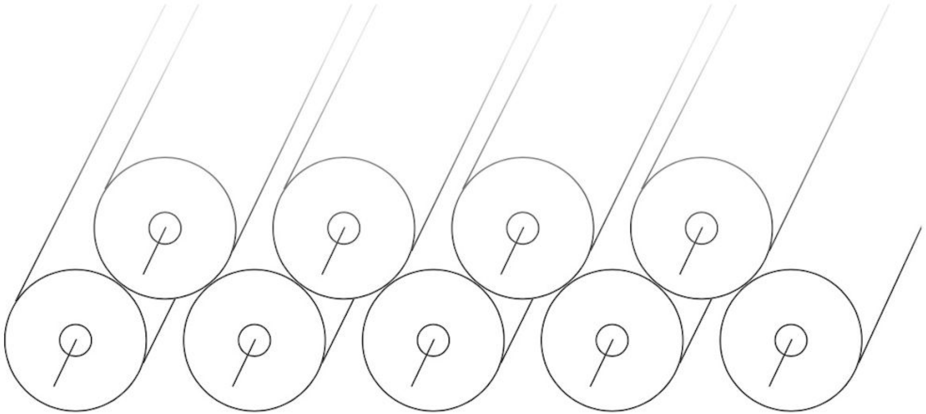
Bummer. But let’s get back to designing our detector…

Let's get back to designing our detector…

What we've decided:

- We want a cylindrical (really *annular*) gas-filled detector
- We want to detect charge in cylindrical cells consisting of thin *anode wires* surrounded by cathodes

So, something like this:

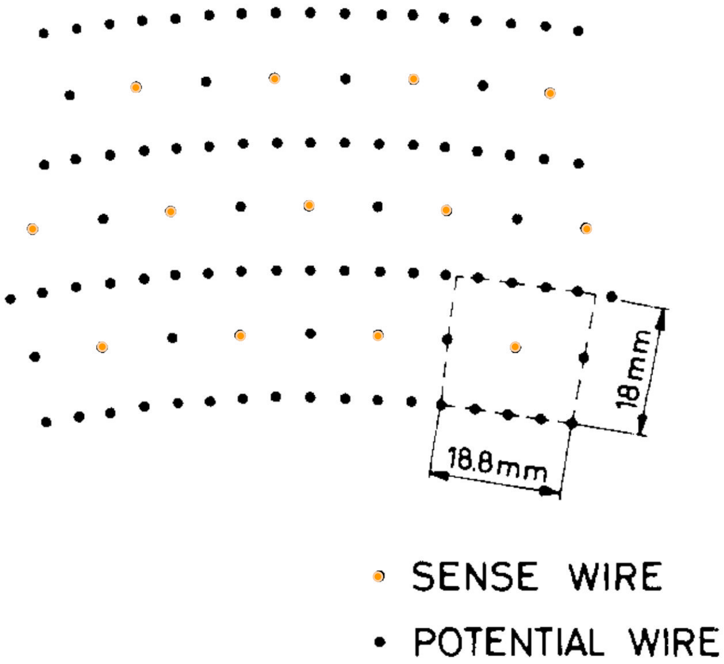


Metal tubes

Q: can you do better than this?

Q: can you do better than this?

A: let's get rid of all this extra material…



If we understand the field inside these cells very well, we can use the *time* of arrival of charges…

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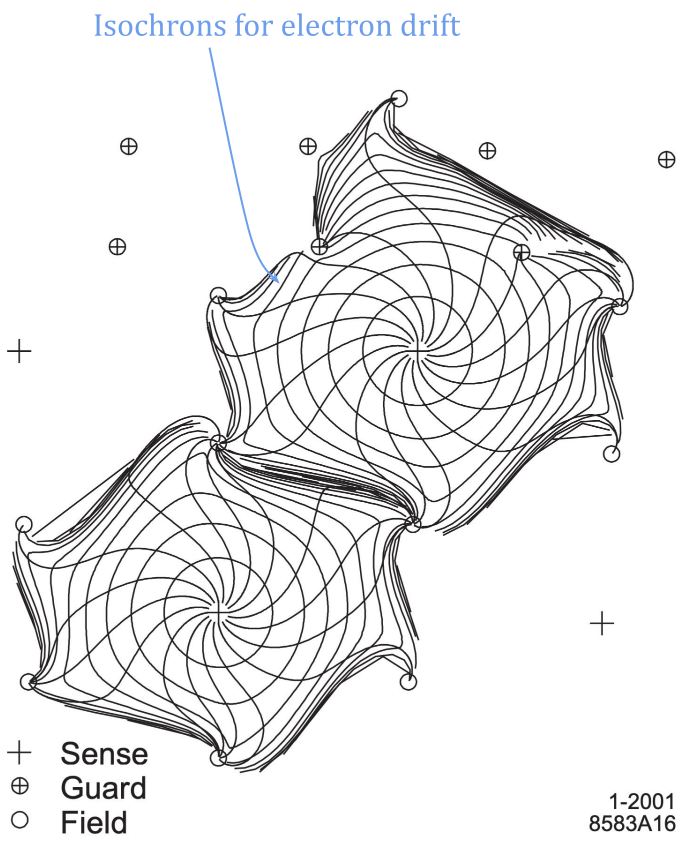

This is (finally!) a *drift chamber*

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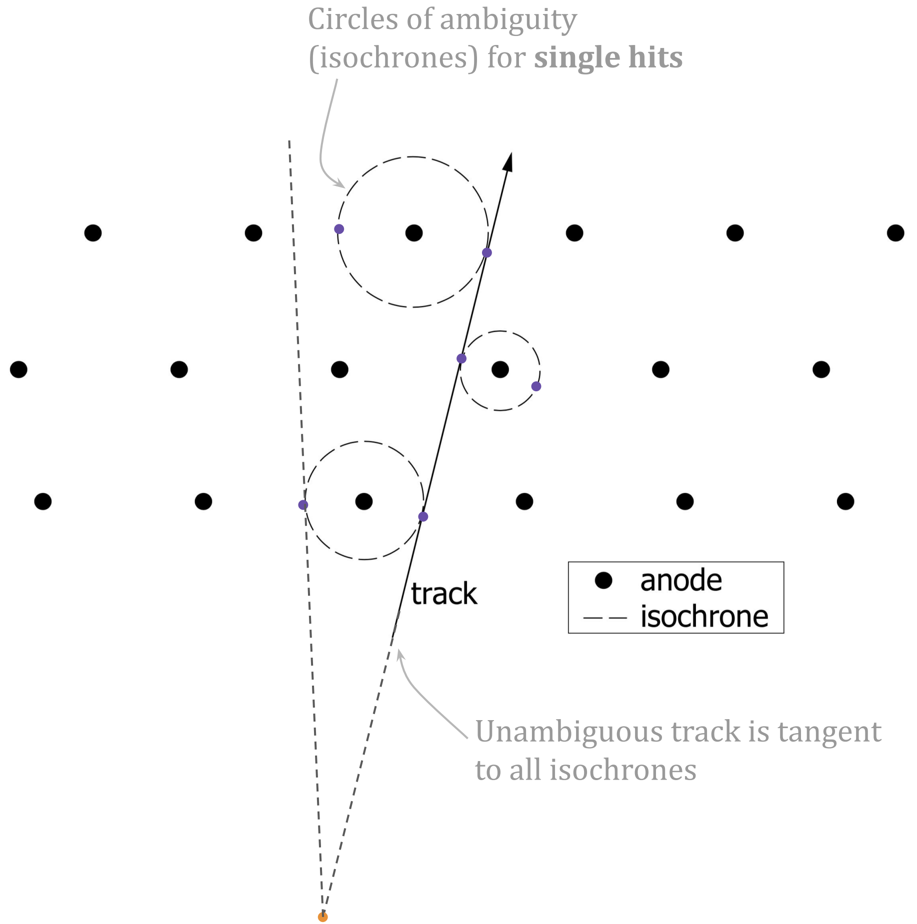
With timing info, our position measurements are *far* more precise than just the size of the cell



With a large number of cells, we can measure track trajectory extremely well…

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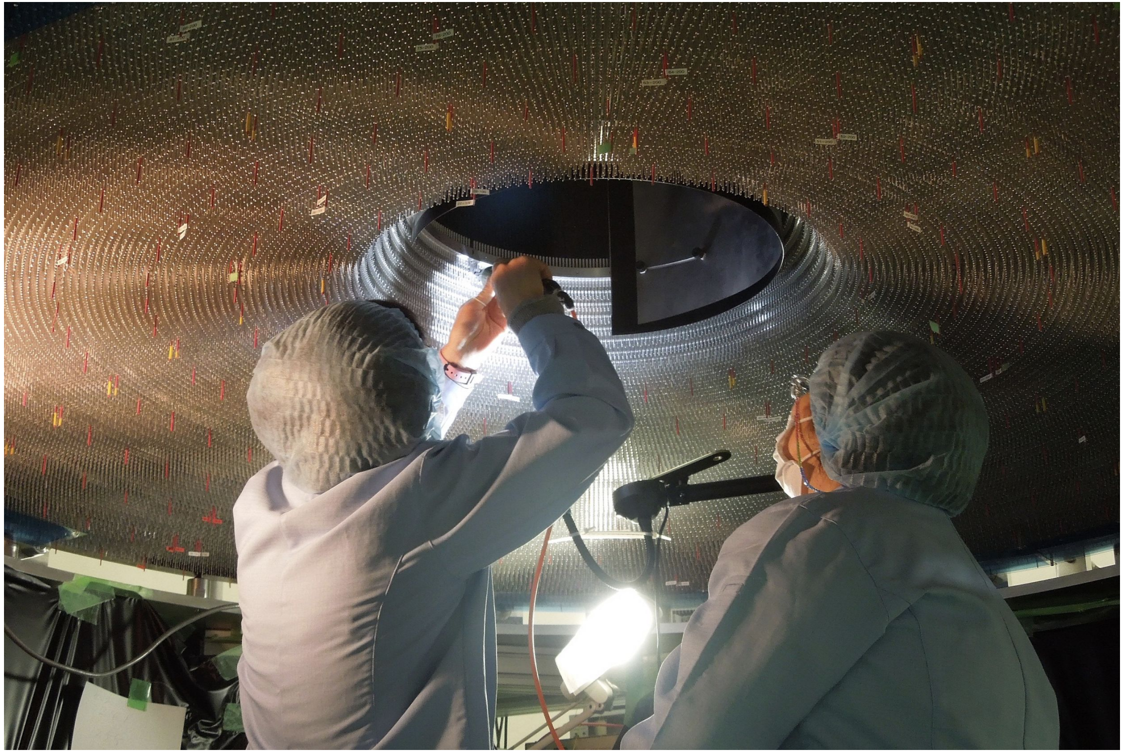
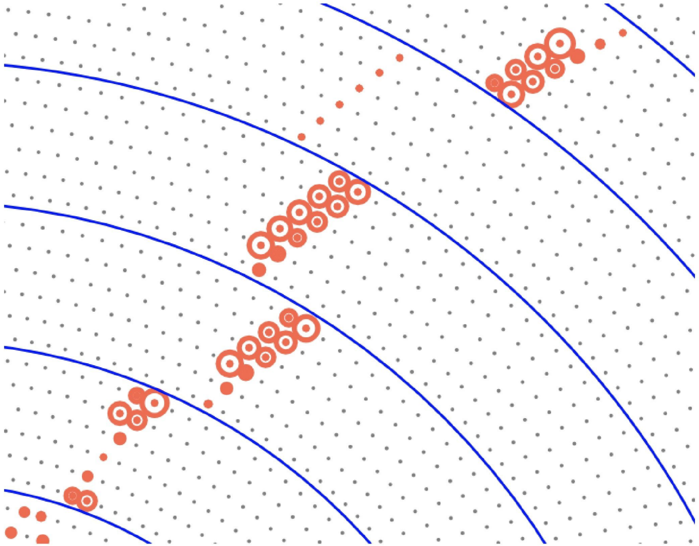
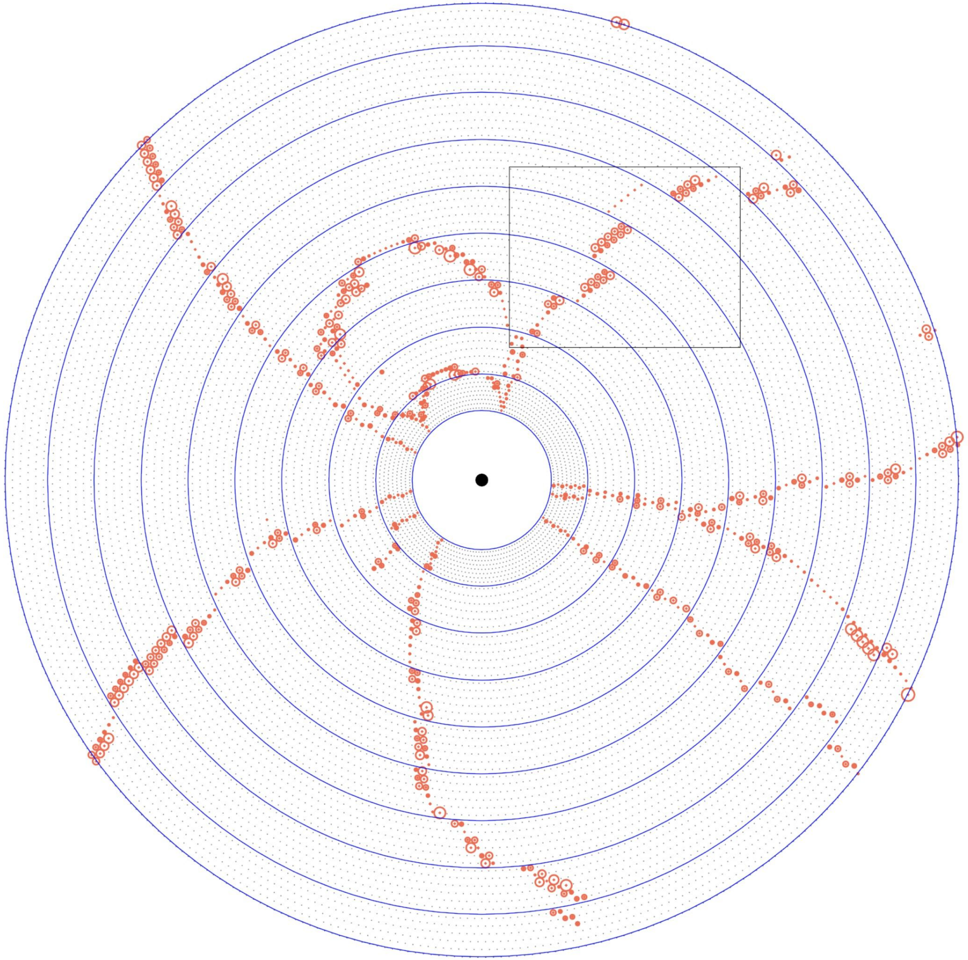


We meet the Belle II drift chamber (CDC) at last!

Let's look at what the data looks like…





Q: What's with these *offsets* between layers?

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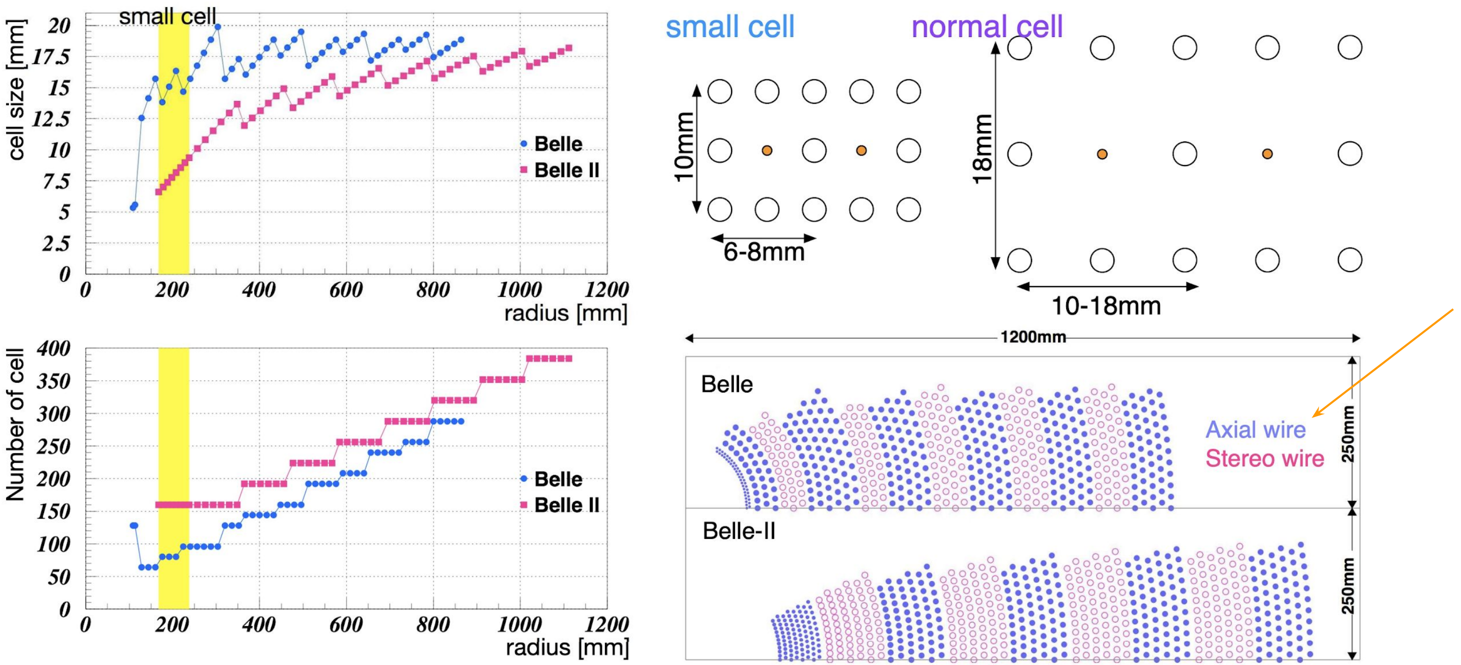
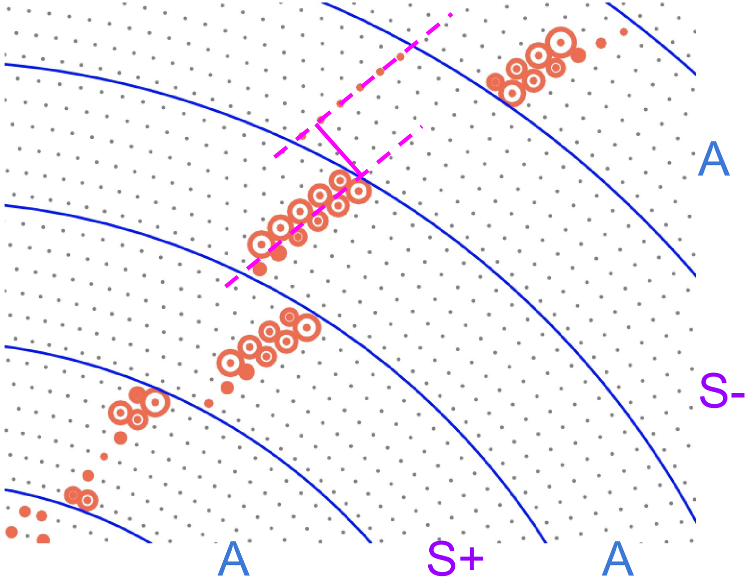
A: We can't detect position of one hit along the wire. But we can *infer* it if the wires are not totally parallel:

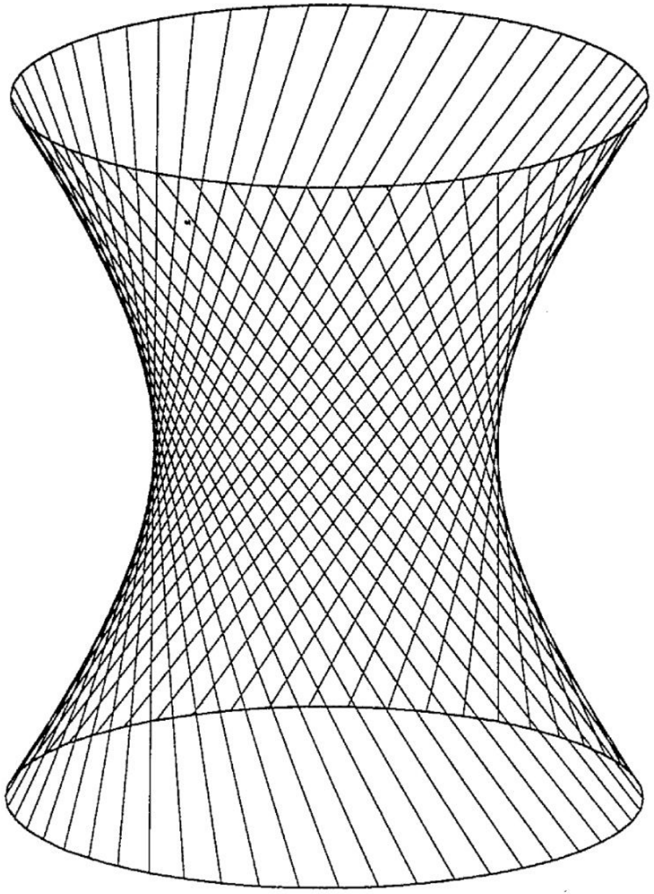


Stereo wires

- Every other *superlayer* is rotated ~±50 mrad relative to the axial (parallel) layers
- The ***mismatch*** in the position of a hit between axial and stereo superlayers gives you the position in *z*:



Twisting creates *hyperboloids*



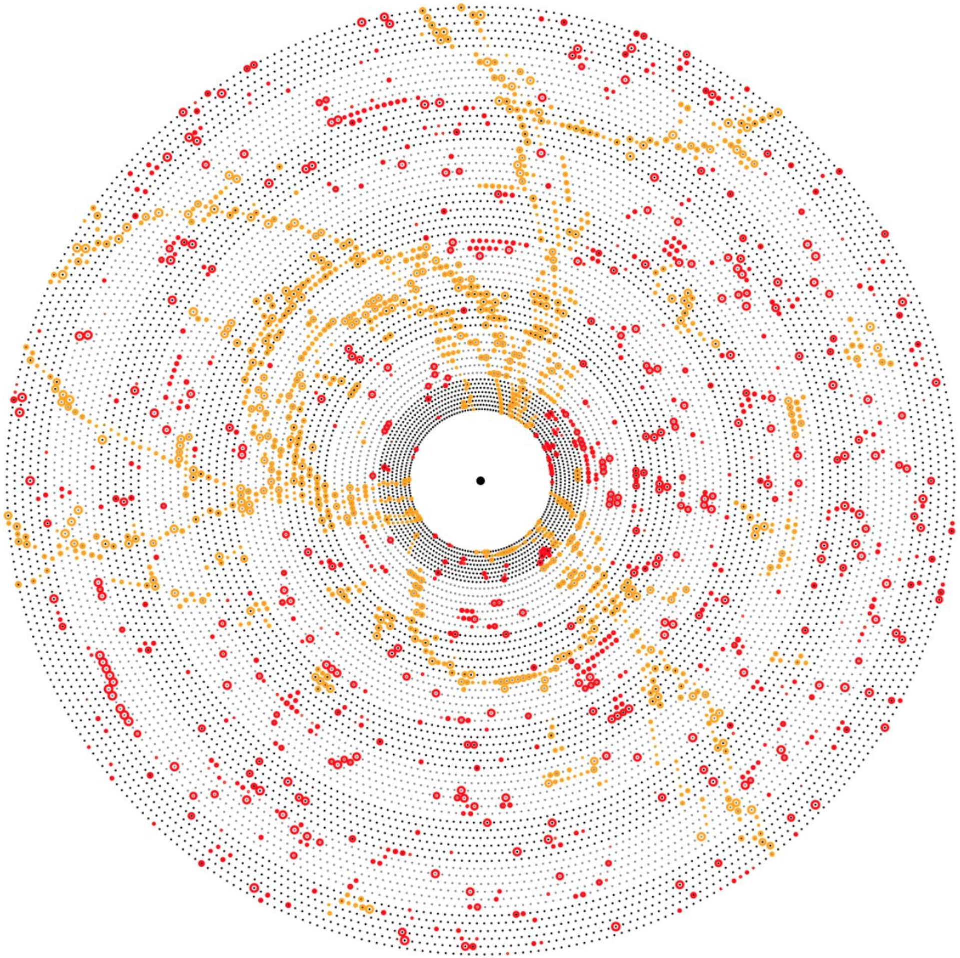
Operational challenges of CDC:

- Very high **background hit** rates (especially in *inner* layers)
  - High **occupancy** (makes tracking difficult)
  - Space-charge effects ⟶ decrease and instability in gain (long- and short-term)
  - Aging (probably)
  - Malter (now confirmed)

This gets *very technical very fast*:

- There's a ton of chemistry involved (gas properties and additives, contaminants, etc)
  - We have been injecting *water* (!!) to control aging, and as quencher
- Controlling and monitoring gas system, including additives, has proven difficult

Still, the path forward appears fairly clear…



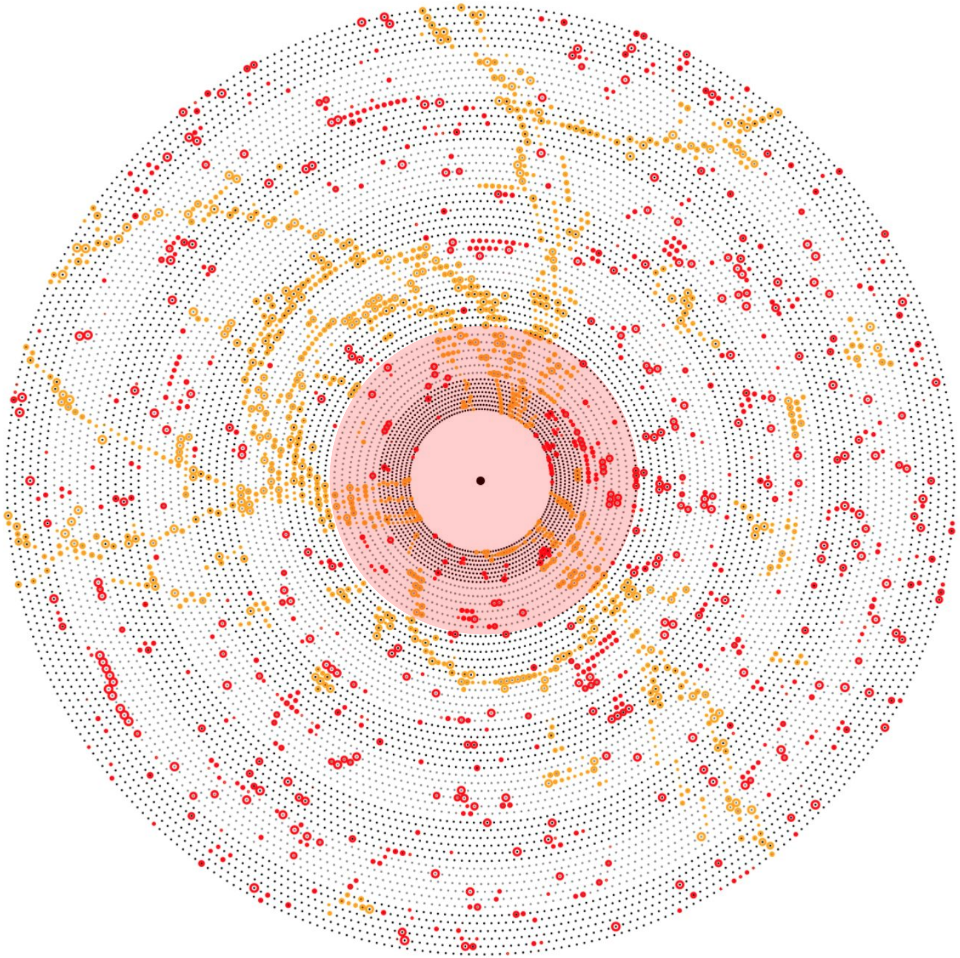
CDC: the way forward

Operations:

- New: constructing **test chambers** for:
  - Aging tests
  - “Malter healing” tests
  - Etc.

Upgrades:

- (other options, but this is plan A)
- Remove current CDC
- Build new CDC without inner layers
- Apply knowledge learned from test chambers (gas/additives/run conditions) to prevent similar problems in future
- (Possibly add new silicon layers in abandoned volume)



Thank you… questions?