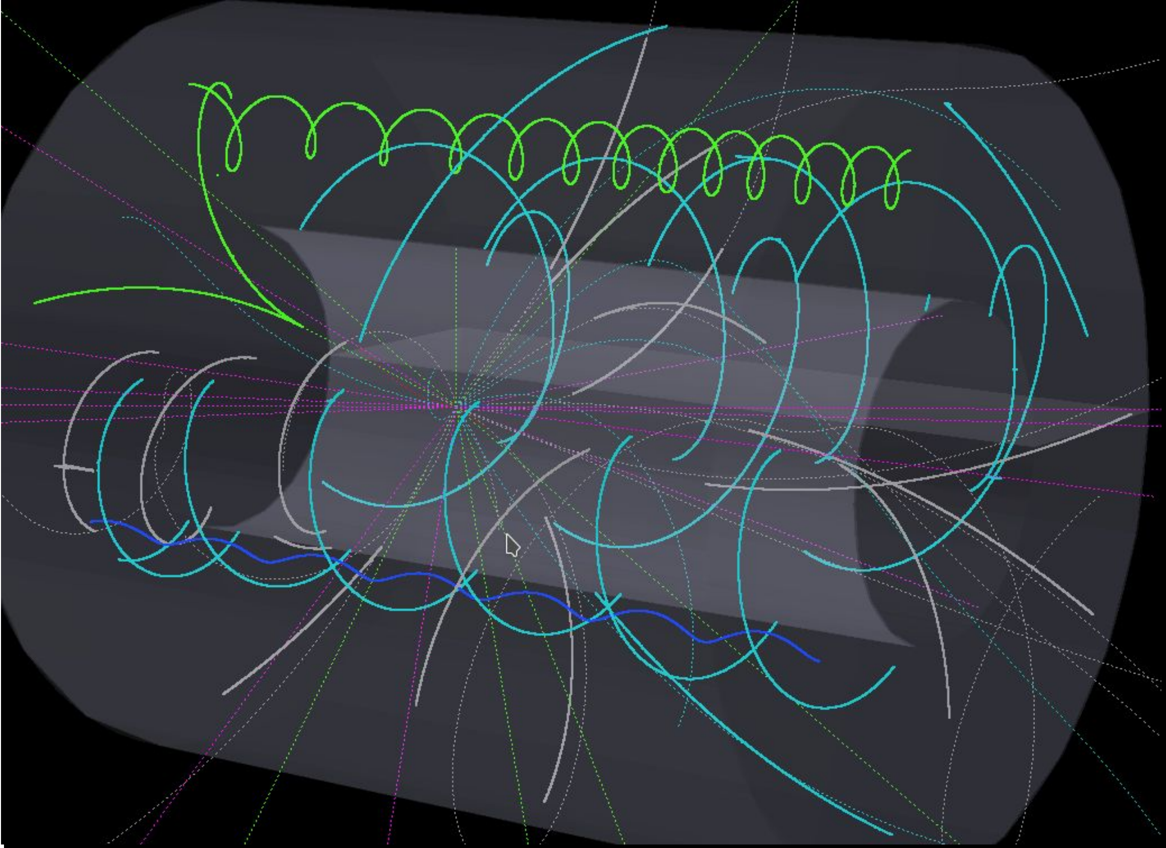


# A Belle II tracking TPC concept, and related technology R&D

Peter Mandeville Lewis | University of Hawaii

# Belle II

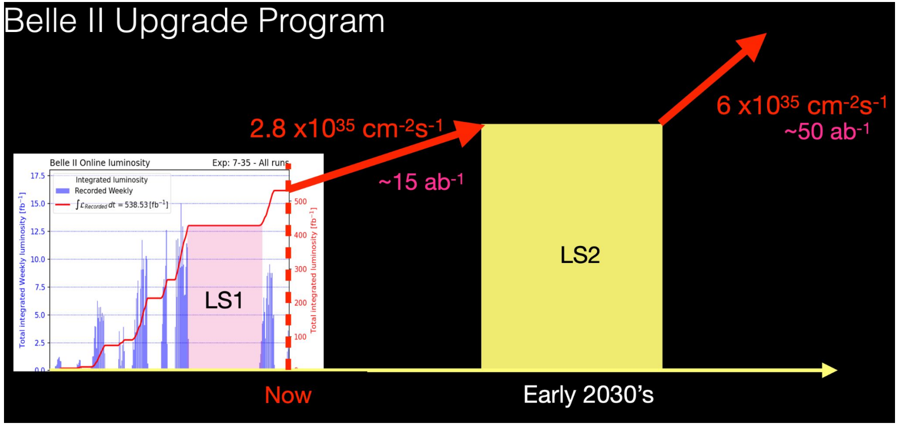
***Intensity Frontier*** e+ e– collider @ 10.58 GeV

Status:

- Just completed a first long shutdown (“LS1”)
- Main tracker is gas drift chamber–showing signs it will not survive
- Current max lumi is **~1/50 of target**

Upgrades:

- LS2 planned for ~2032
- Major tracking upgrades are mandatory; but what will this entail?



# These slides

Two stapled-together talks

1. Summary of Masters thesis on speculative Belle II TPC concept. This is not a mature effort, and *officially speaking, there is no Belle II TPC!*
2. Brief introduction to newly funded R&D project with implications for tracking TPCs

# Belle II tracker

Central beam pipe: diameter 3cm → 2cm (Beryllium)

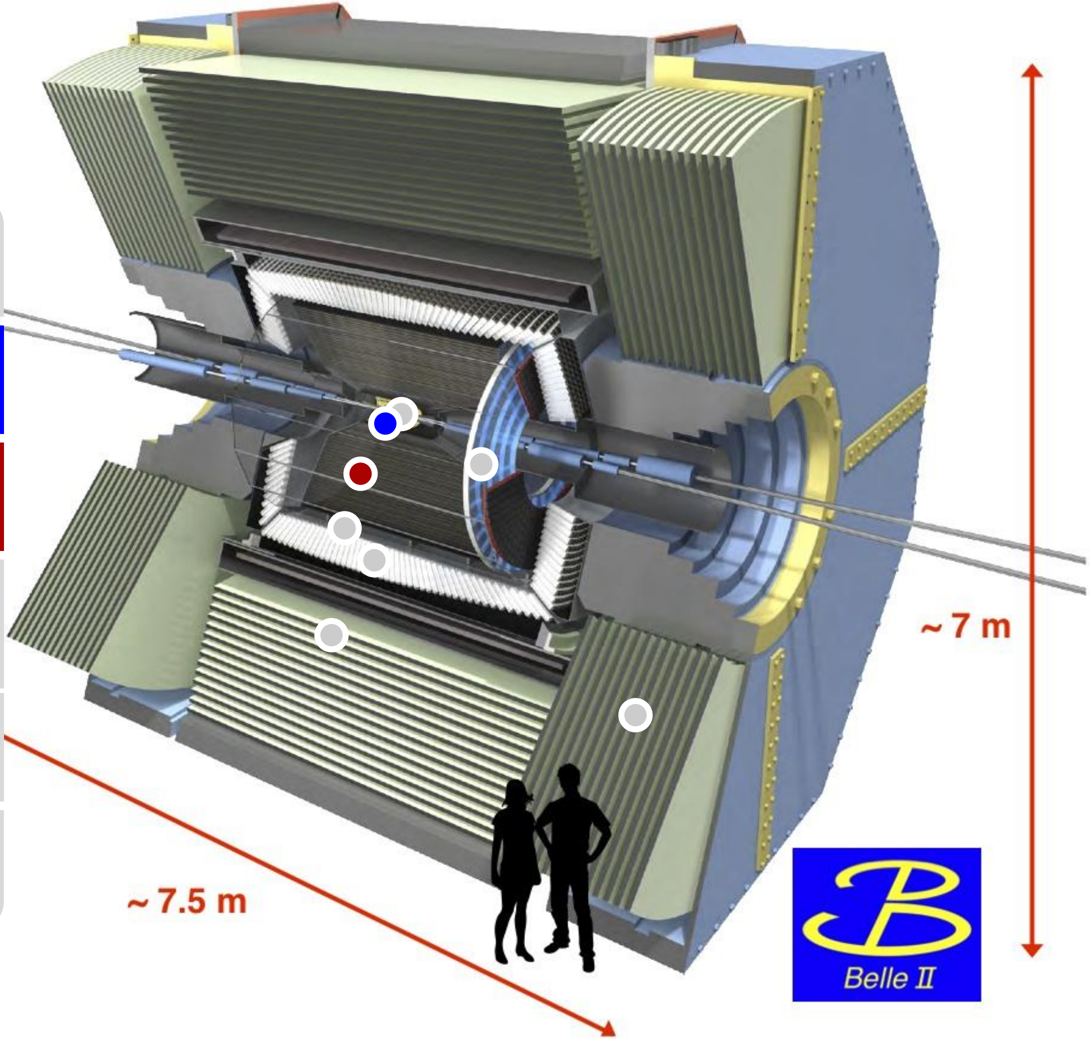
**Vertexing:** 2 layers of pixels + 4 double-sided strips

**Tracking:** 14K-wire drift chamber

**PID:** time-of-flight (barrel), threshold Cherenkov aerogel → time-of-propagation (barrel), proximity focusing aerogel (endcap)

EM calorimetry: CsI → same crystals upgrade of electronics and processing with legacy CsI(Tl) crystals

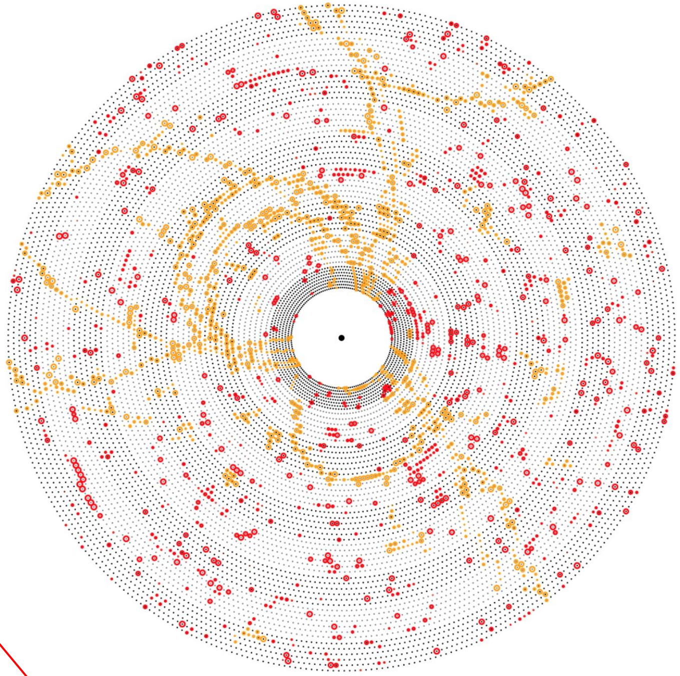
KL and $\mu$: scintillators replace RPCs (endcap and inner two layers of barrel)



# Options for future trackers

For *high event rate* (>100kHz) and *modest track momentum* (<1GeV)

- *Drift chamber*
  - effectively 2D → **high occupancies** from beam-induced backgrounds
- *Silicon tracker*:
  - **Expensive**
  - High $X_0$ → **degraded performance**
- *TPC*:
  - High-resolution 3D → **low occupancies**
  - **Far cheaper**
  - Minimal $X_0$ → **ideal performance**



Belle II drift chamber:
**14,000 cells;** 1% of hits are signal

Same volume with 200μm$^3$ voxels:
**$10^{12}$ voxels**

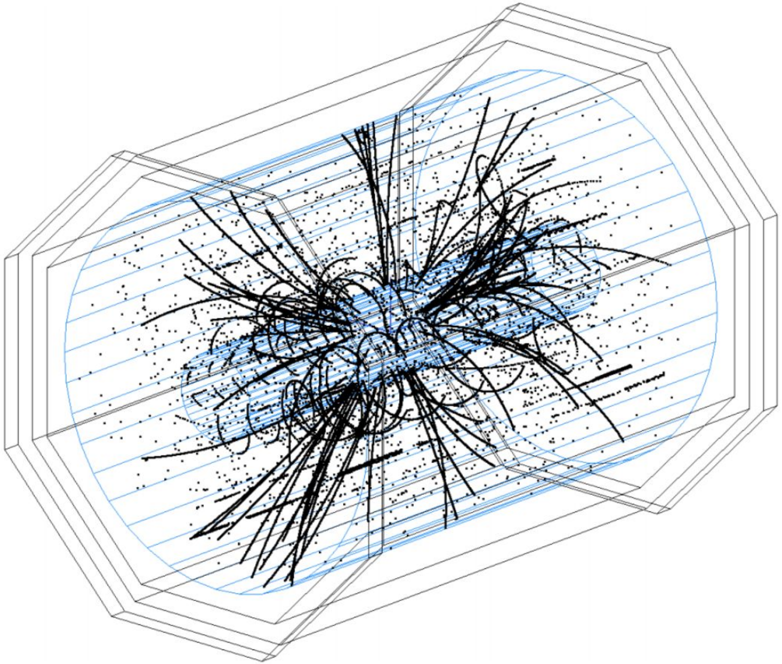
***But the case isn't so clear-cut…***

# Primary technical concerns

"This won't work because…"

1. TPC can't provide a **trigger**
2. Slow $v_{drift}$ → large event/background **pileup**
3. High event rates → no gating → bad **ion backflow** → decreased resolution
4. Long drift length → high **diffusion** → decreased resolution
5. No **dE/dx** for low-$p_T$ tracks

*Today*: address these one-by-one with simulation, with a proof-of-concept detector based on a **Belle II upgrade**

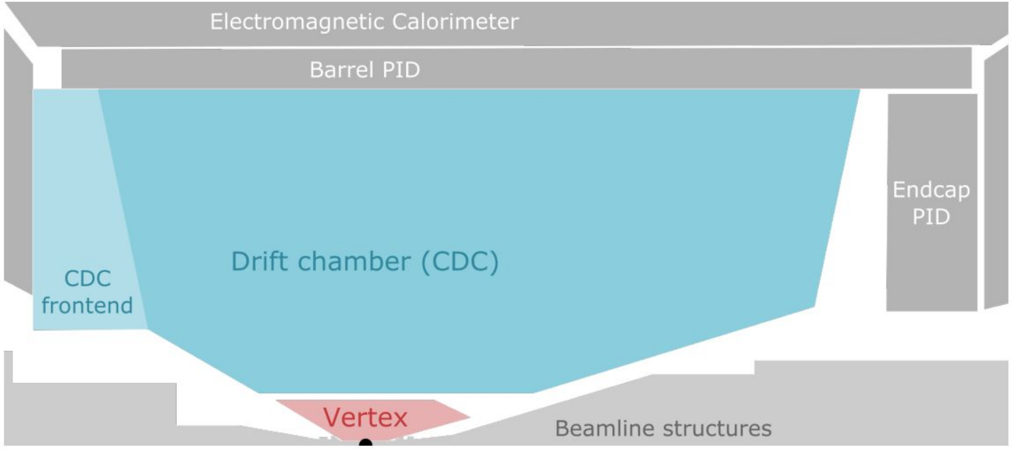


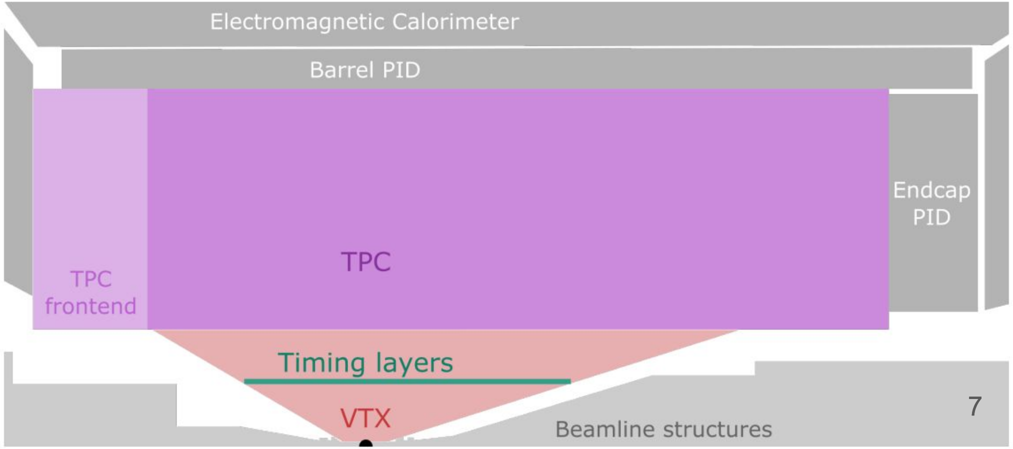
A **single** simulated LCTPC event with beam backgrounds

# Basic concept

Geometry constrained by Belle II layout (*top*)

- Abandon the inner volume to **silicon pixels (VTX)**
- Fill remaining volume with **single drift volume** and read out on BWD end
- Use T2K gas mixture Ar:$CF_4$ :i$C_4H_{10}$ (95:3:2) at atmospheric pressure
- Readout via **GridPix**:
  - Silicon pixels (Timepix3) with integrated MICROMEGAS
  - 55x55 µm pixels

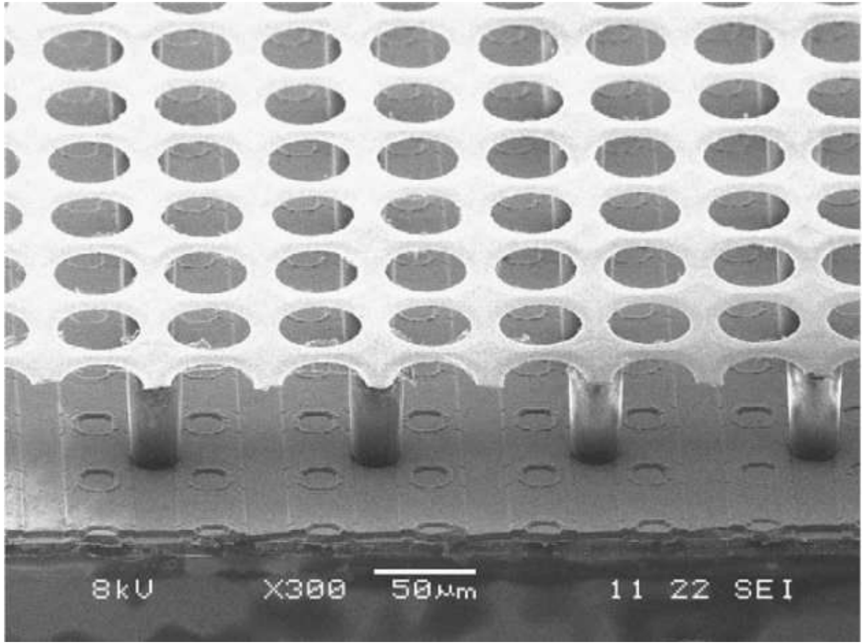


# Why GridPix?

A number of attractive features for us

- 1:1 mapping of electrons:pixels → **optimal resolution**
- Intrinsically **low ion backflow** (IBF)
- Could be used in **binary readout** → reduction of data throughput
- It is *real*, so we can confidently (and easily) simulate it

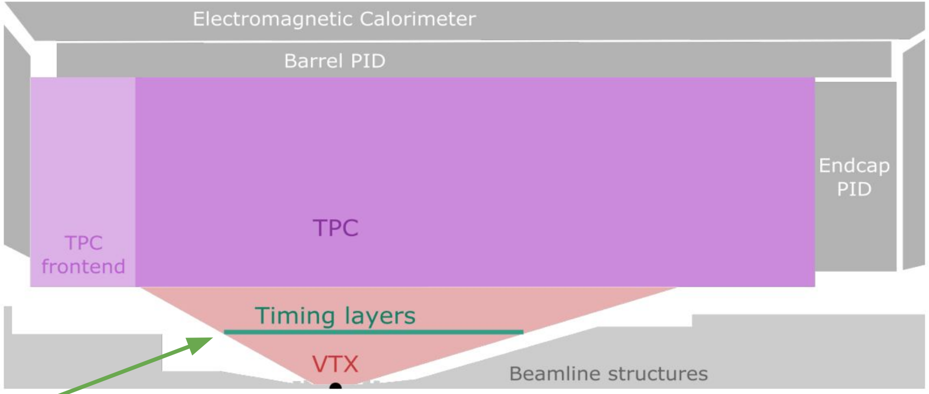


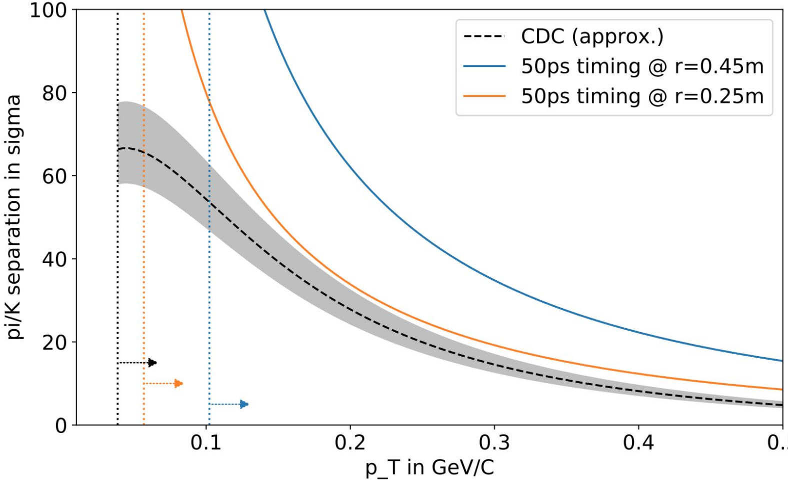

Ultimately, we would require a purpose-designed sensor, but we use GridPix for the proof-of-principle

# Concern 1: trigger

*Solution*: fast timing layers

- Fast silicon (assume **50 ps** resolution); LGADs or something else
- At low radius (25 or 45 cm)
- Multilayer coincidence triggering (assuming 10 $cm^2$ coincidence regions)
- Results from toy simulation:
    - **Viable trigger option** with very low fake rate
    - *Bonus*: **far better PID** for low-p tracks (concern 5)



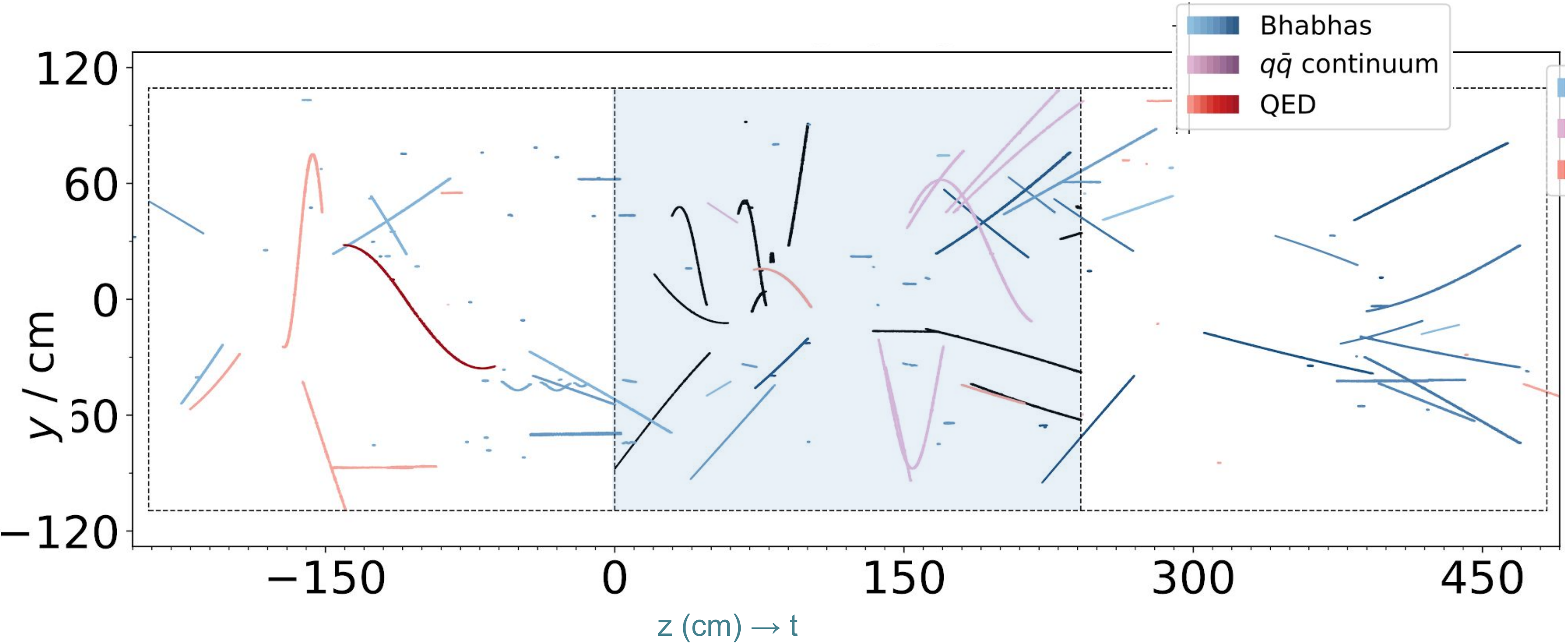

*So*: trigger isn't a problem but an **opportunity**

# Concern 2: pileup

*First*: event pileup

- High event rates + slow drift time → overlapping events
- **Untriggered** events like Bhabhas will still overlap physics and be read out
- With *continuous readout* and an *external trigger*, one “event” is like a **snapshot** of a continuous reel of tracks…

# Could a TPC work?



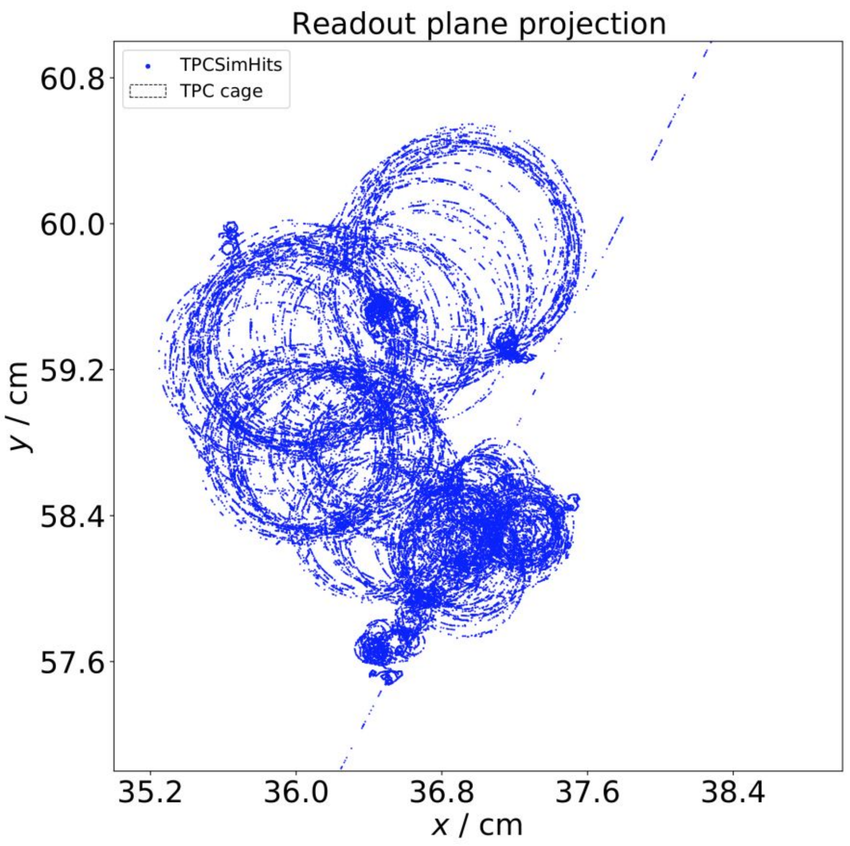

This is at 5x maximum Belle II lumi… “extra” tracks are easy to identify; **not a major issue**

# Concern 2: pileup

*Second*: background pileup

- Beam-induced backgrounds produce mostly **low-energy photons**
- These Compton-scatter to produce copious low-energy electrons in the drift volume…
- …***microcurlers***…
- …that ionize far more than MIPs over their path
- TPC would **integrate** these backgrounds over 30 μs drift time (over 7400 beam crossings)

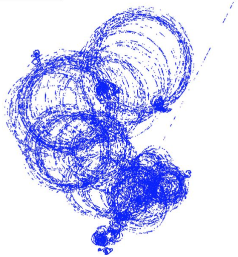
Ultra-high luminosity *necessarily* means high beam-induced backgrounds… **is it tolerable?**

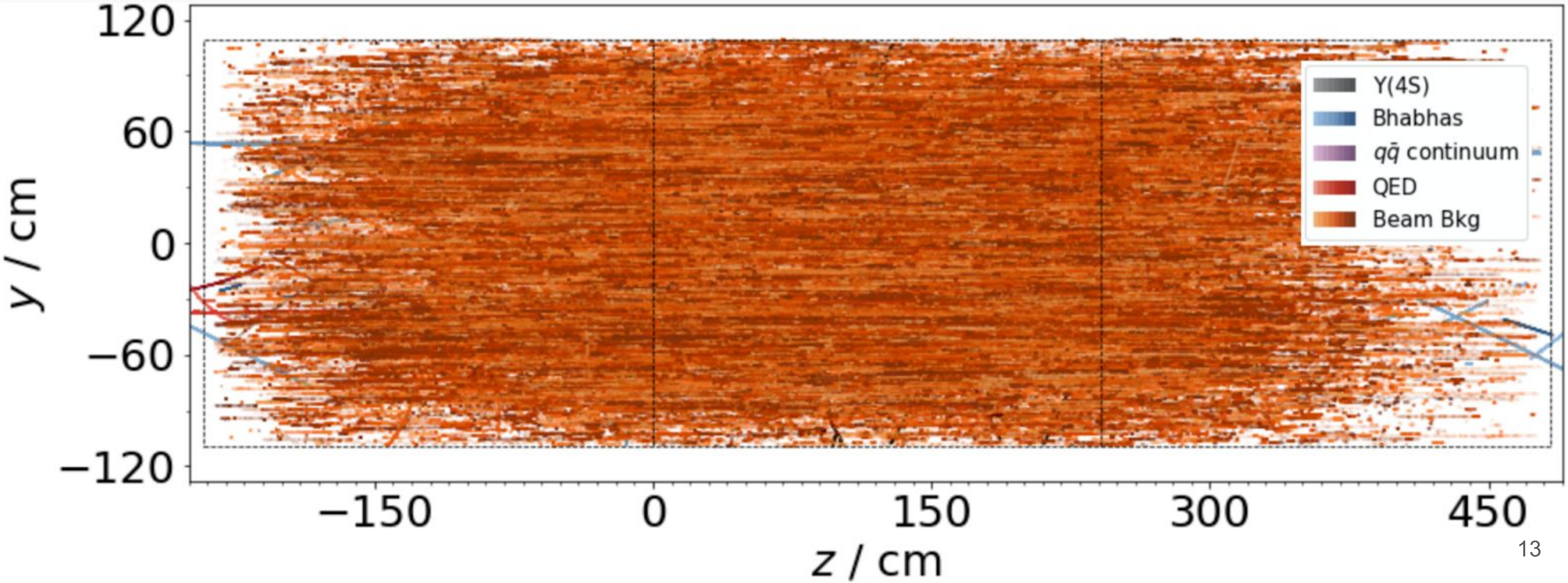


# Could a TPC work?

Typical *background* pileup

These are almost entirely *microcurlers*





# Concern 2: Pileup

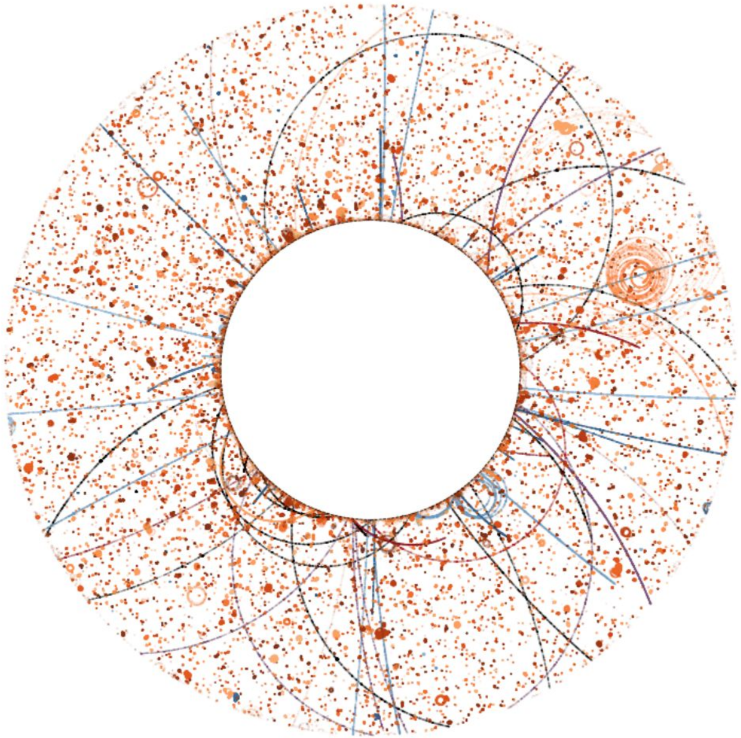
*Remember*

- CDC is 2D, TPC is 3D
- CDC is triggered, TPC integrates all backgrounds

So *which one wins?* **The TPC does**, because **1T is a *lot* more than 10K**

However, **injection backgrounds** are not simulated and *very large* (though probably not larger than existing backgrounds by $10^{12}/10^{5}$…)

*So*: pileup is a technical challenge but not a showstopper



# Concern 3: IBF

## Ungated, continuous operation

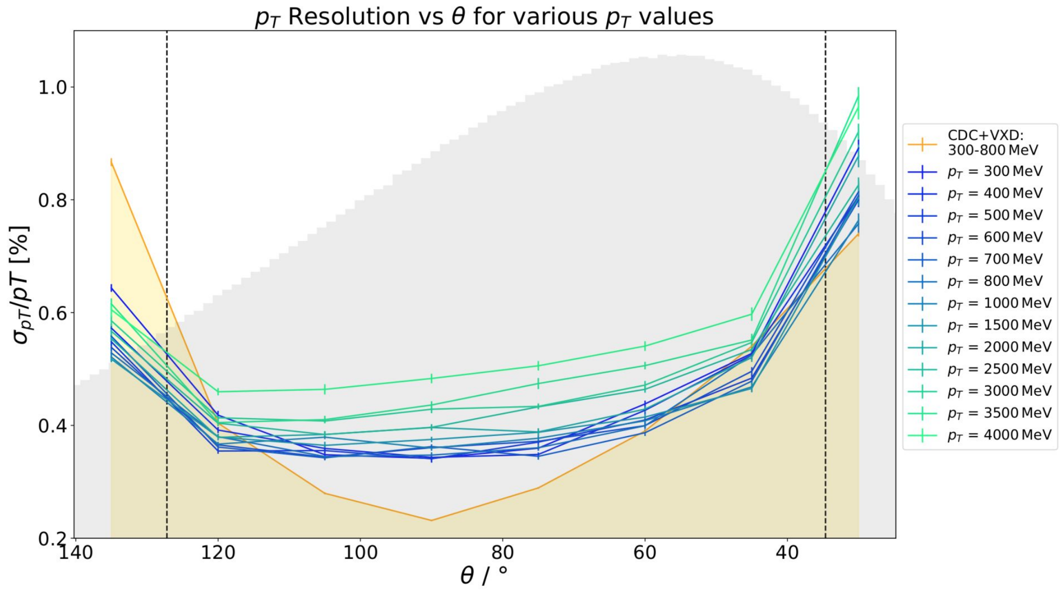
- Event time occupancy is ~15% → gating is not possible
- GridPix are intrinsically low-IBF (~1% at a gain of 2000)
- Projected ion densities with 5x luminosity will be **comparable** to other tracking TPCs, but:
  - our tracking requirements are more stringent
  - our beam background simulation does not include **injection backgrounds**
- These are integrated over and may be ***very*** large due to continuous injection schemes

Ion backflow due to integrated backgrounds is **the** major unresolved technical challenge; solvable with clever design? (see next section)

# Concern 4: diffusion

Suitable tracking performance?

- Forward/backward tracks have more hits (unlike CDC), improving resolution
- Overall, resolution is comparable to CDC
- The material budget of the inner detectors is more relevant than diffusion in the TPC




*So*: diffusion does not significantly degrade resolution due to **large number of hits**

# So, *could* a TPC work?

**Yes!**

But the case becomes far more convincing with some *technology development*…

# Toward an "ideal" gaseous TPC detector

"Maximally performant"

*At The University of Hawaii at Manoa*
**Peter Mandeville Lewis**, Tanner Polischuk, Yubo Han, James Harrison, Sven Vahsen

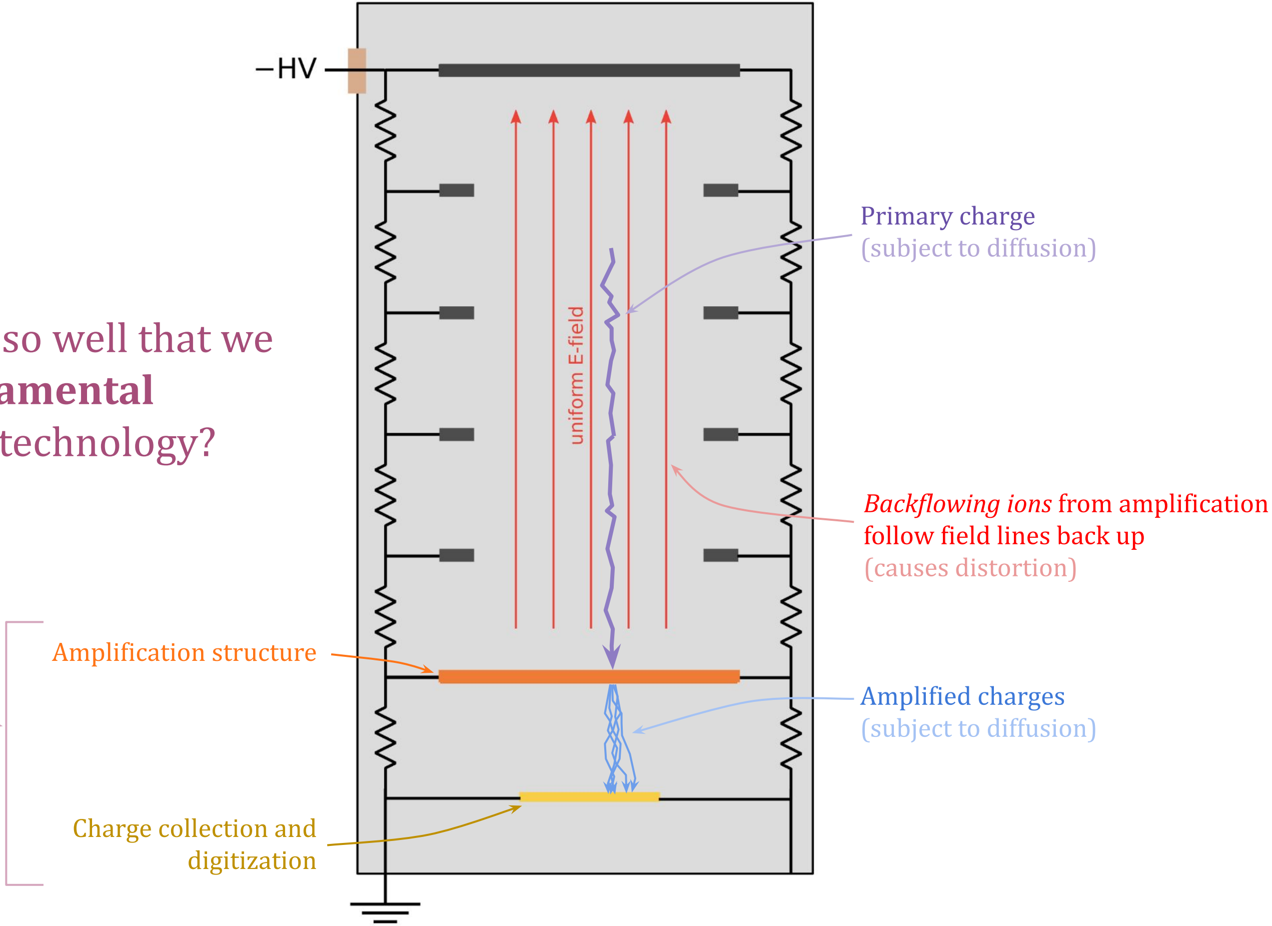
*At Lawrence Berkeley National Laboratory*
Peter Sorensen, Carl Grace

*At The University of Texas at Arlington*
Yuan Mei

# The question

Can we do *this stuff* so well that we are limited by **fundamental physics** and not by technology?

(for *any* application)



# What are the key metrics?

GridPix (adapted from [link])

Current state-of-the-art

3D spatial resolution

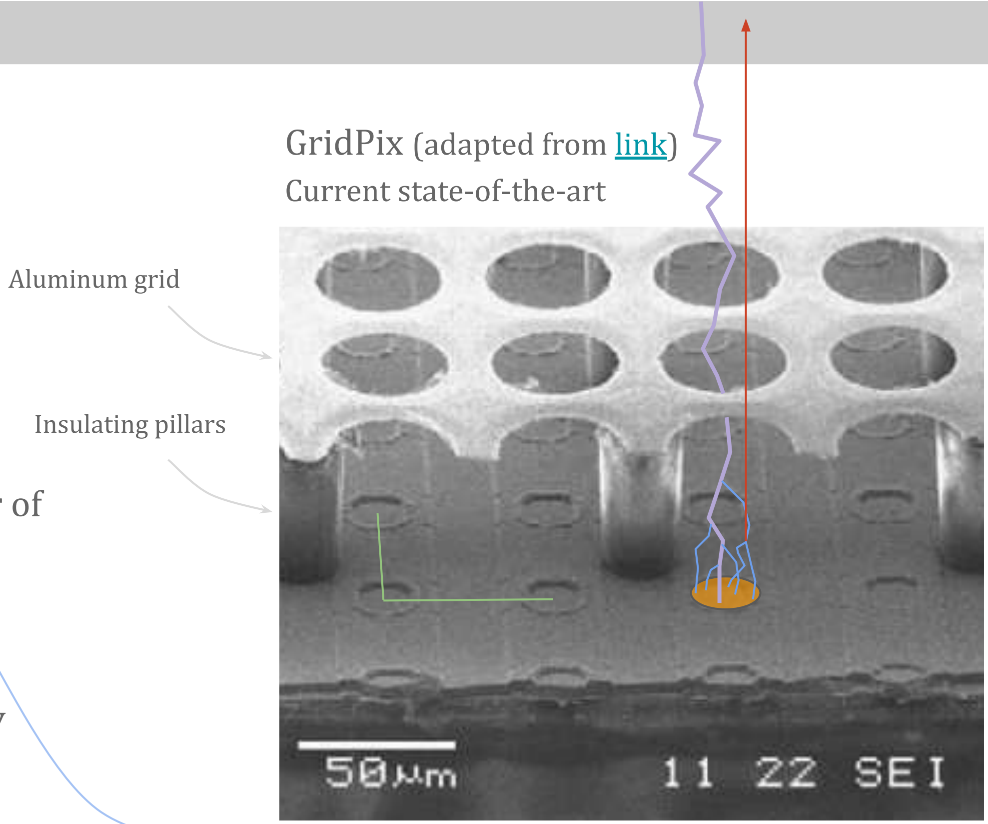
- *x* and *y*: sensor pitch
- *z*: drift velocity × time resolution

Single charge detection efficiency

- ε = number pixel *hits* divided by number of *primary charges*
- (Assuming it *can* detect single charges)

Ion backflow

- IBF: number *backflowing ions* divided by number of *primary charges*
- (relevant for *high-rate* detectors)




One **primary charge** produces one **hit**

# What would *ideal* mean?

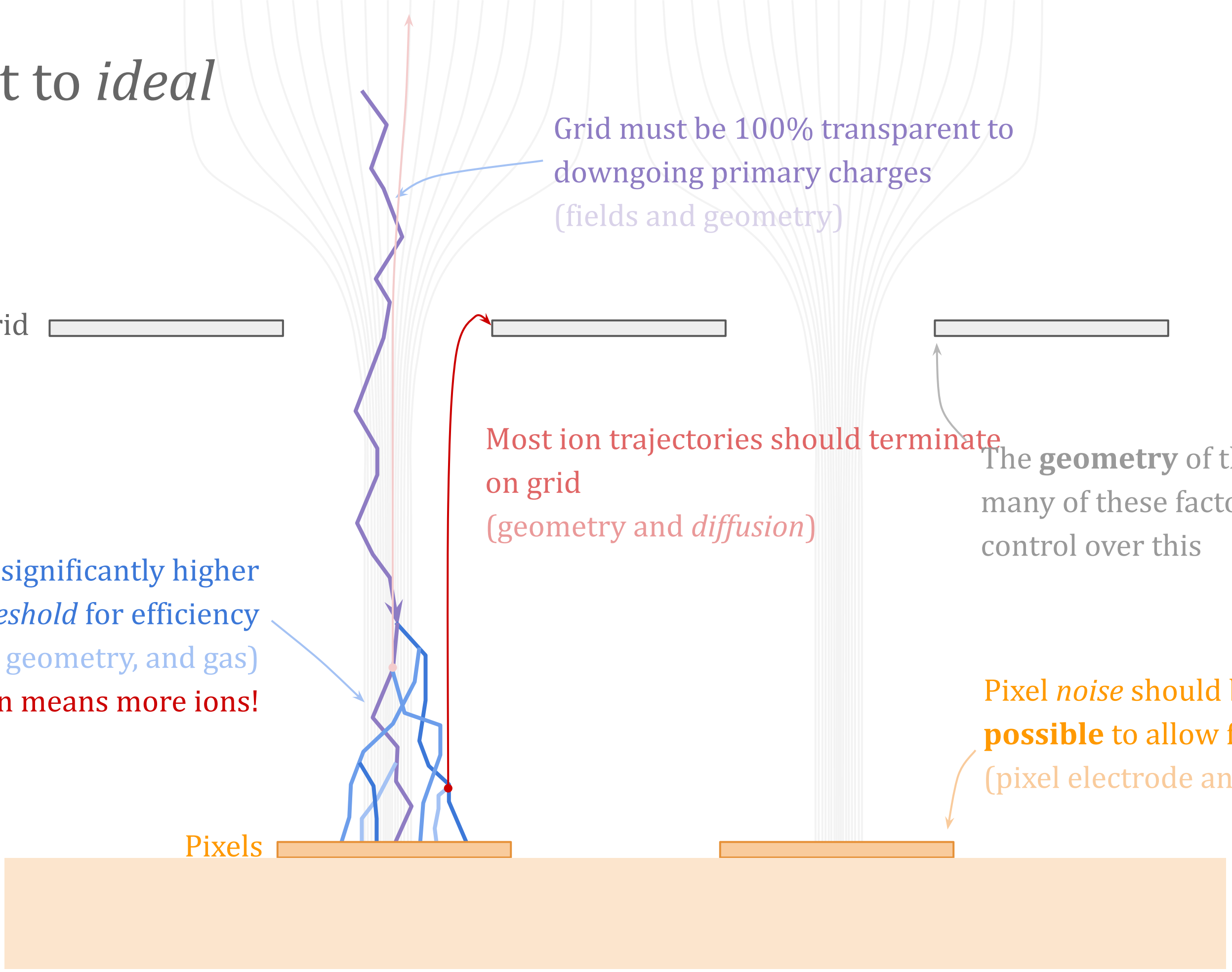
| Metric | "Ideal" value | Current (GridPix) |
|---|---|---|
| 3D spatial resolution | Much better than *diffusion*<br>Electron drift: mm–cm<br>Negative ion drift: 100μm–mm | *x*/*y*: 55μm/√12 = **16μm**<br>*z* (*t*): comparable (depends on gas, fields) |
| Single charge efficiency | >0.95 | Electron drift: >0.95<br>Negative-ion drift: ~0.60 [source] |
| Ion backflow fraction × gain | <1 (less than irreducible *primary* ions) | ~0.01×2000 = 20 |

This is *very good*… but not "ideal"

GridPix comes pretty close to ideal performance…

…how could we get *ideal*?

# How to get to *ideal*




Grid must be 100% transparent to downgoing primary charges
(fields and geometry)

Most ion trajectories should terminate on grid
(geometry and *diffusion*)

The **geometry** of the grid determines many of these factors: we need control over this

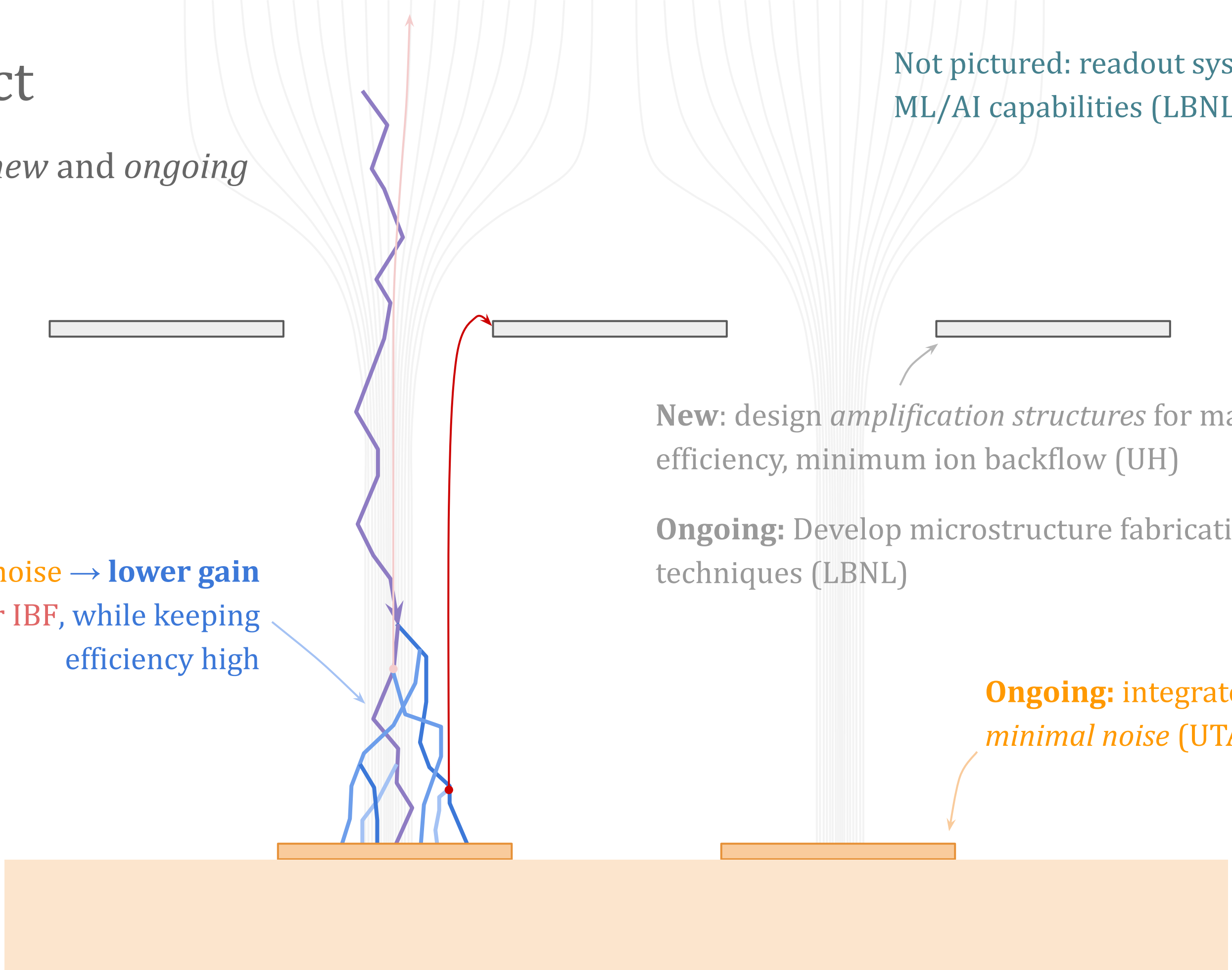
*Gas gain* needs to be significantly higher than *pixel threshold* for efficiency
(fields, geometry, and gas)
*But*: more gain means more ions!

Pixel *noise* should be **as low as possible** to allow for low thresholds
(pixel electrode and gate design)

# Our project

A synthesis of *new* and *ongoing* efforts

Not pictured: readout system, including ML/AI capabilities (LBNL and UH)



**New**: design *amplification structures* for maximum efficiency, minimum ion backflow (UH)

**Ongoing:** Develop microstructure fabrication techniques (LBNL)

Lower pixel noise → **lower gain** → lower IBF, while keeping efficiency high

**Ongoing:** integrate CMOS pixels with *minimal noise* (UTA)

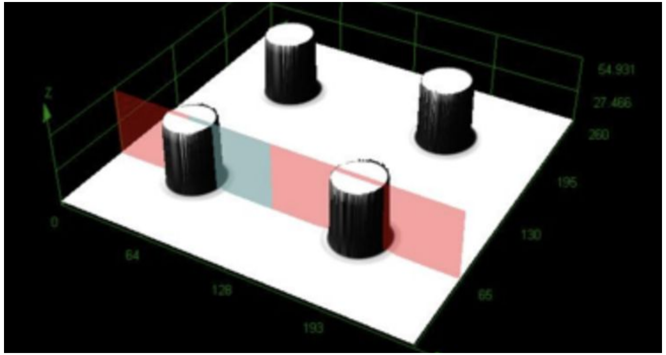
# Amplification structures

Ongoing work at LBNL (Sorensen + UH)

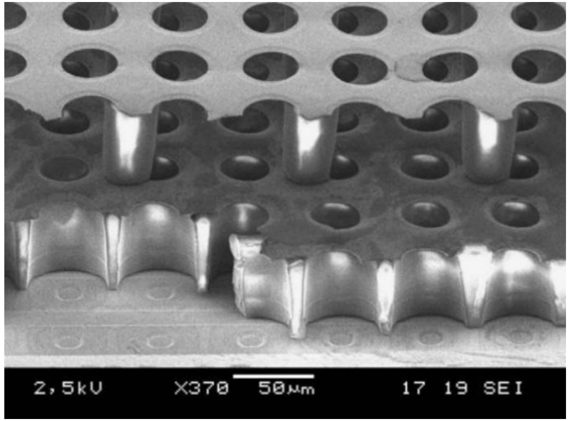
- First trying to replicate GridPix process:
    - Thin patterned Al atop SU-8 photoresist
    - ~50µm pillars remain after development of SU-8
- Proximate goal is for *focusing* structures; eventually amplification
- Current status: learning how to build SU-8 under Al without warping the Al… it is tricky!

Ultimately, we hope this develops into a *US-based microstructure fabrication facility* that limits reliance on European facilities

Scan of produced SU-8 pillars



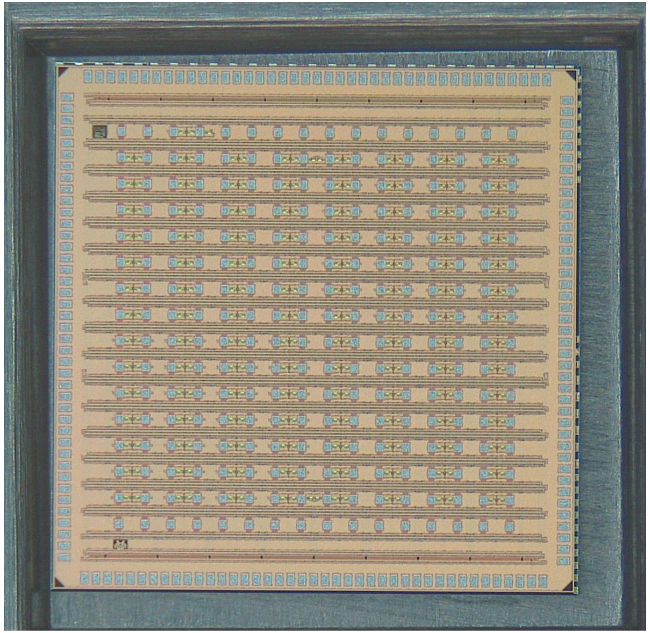
TwinGrid: an *extremely ambitious* possibility



# Pixel chip

**G3pix**: Lab-Directed R&D project at LBNL (Mei and Sorensen)

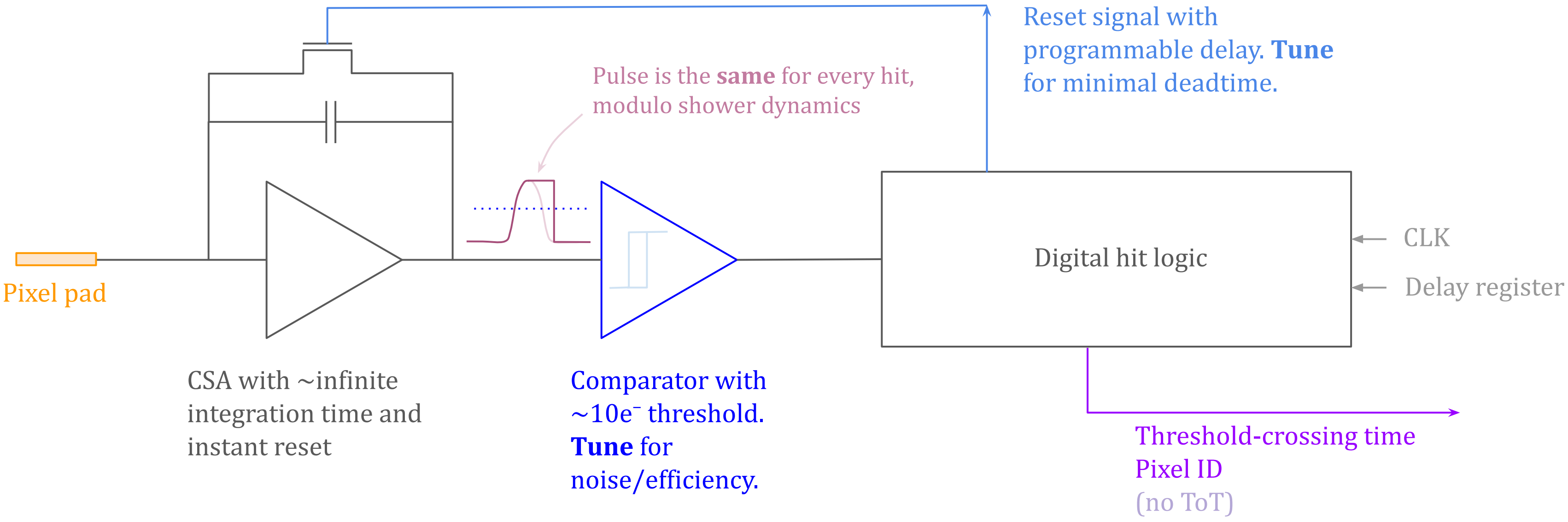
- Targeting a ***3e*** noise pixel chip (!!!)
  - $\mathcal{O}(100)$ reduction in noise → needs $\mathcal{O}(100)$ less gain for same efficiency → $\mathcal{O}(100)$ reduction in *ion backflow*
  - Or: efficiency → 1 in *low-gain* applications like negative ion drift
- *Status*: testing of first chips commencing now, both at Berkeley at at Arlington



| | |
|---|---|
| Efficiency | *e* drift: >0.95<br>NID: ~0.60 |
| IBF × gain | ~20 |

# ASIC concept

Lean completely into the "**single-charge counting** regime":




This is a far simpler device than most modern pixel chips. Barely at initial concept stage.

# Readout system

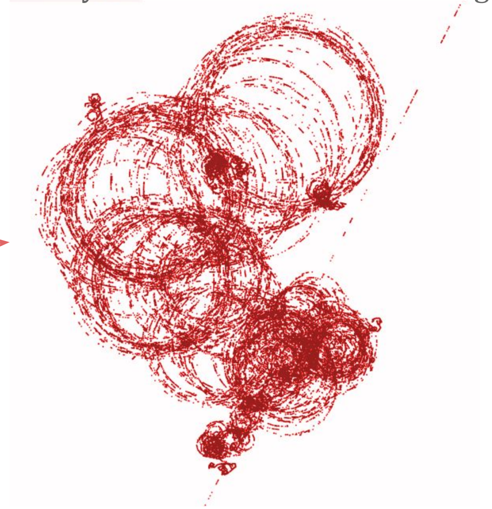
## ML/AI capable frontend (Grace + UH)

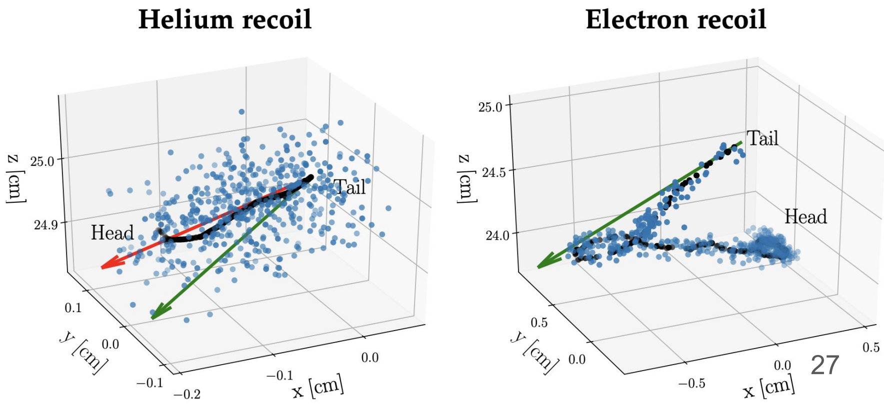
An ideal *readout system* will need realtime hit logic capabilities:

- High-rate tracking detectors: *microcurlers* can be overwhelming (>99% of hits) but are distinctive
- Low-*E* nuclear recoil detectors: realtime **recoil discrimination** to reject overwhelming rates of *electron recoils*

This is *essential*: even an "ideal" detector could be inoperable at high rates

Simulation of a *microcurler*, seen end-on, from preliminary studies on a Belle II tracking TPC.



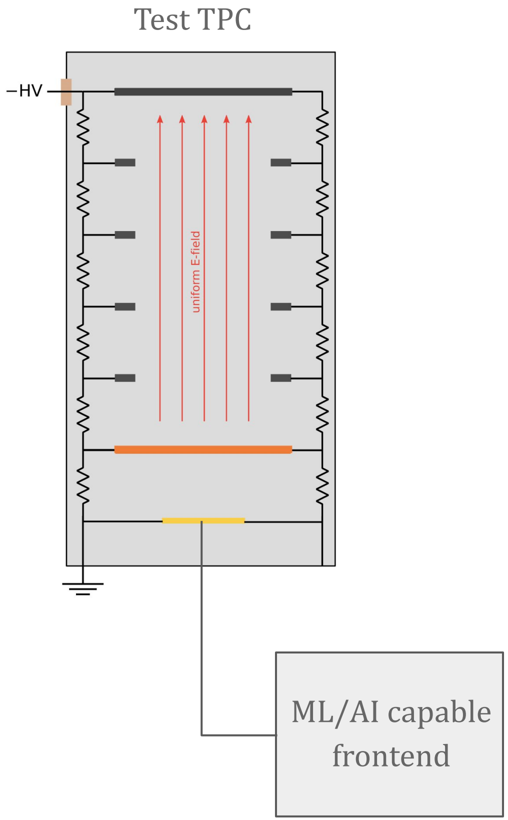


# Integration

*Flexible, Ideal MPGD system* (FIMS): Putting this all together (Lewis)

- Four-year EPSCoR funding starting ~now
- UH team includes:
  - Yubo Han, postdoc: working with Grace to design and deploy ML/AI hit logic at frontend
  - Tanner Polischuk, postdoc: working with Sorensen to develop ideal amplification structures
  - James Harrison, PhD student: simulation, integration, and source tests

Development with an eye towards Belle II tracking upgrade (~2032) and CEνNS @ SNS applications



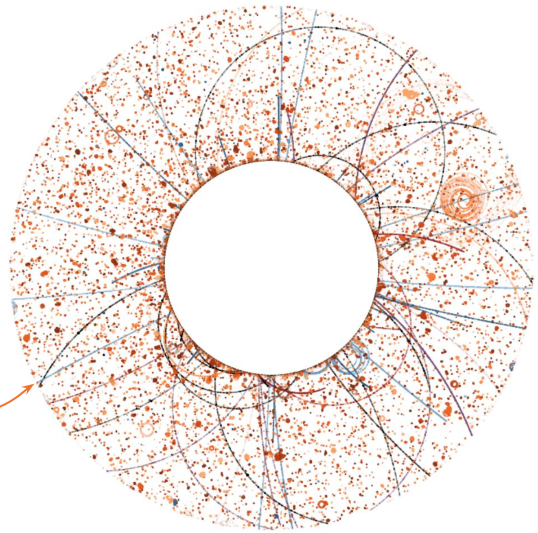
# Applications

Can one technology be *ideal* for extreme **opposite** use cases?

Tracking TPCs at high-luminosity colliders [Lewis]

- Minimum ionizing tracks in very high-background environment
- Electron drift (high gain, high diffusion)
- **Ion backflow** is *critical*
- Frontend hit processing to reject ubiquitous *microcurlers*

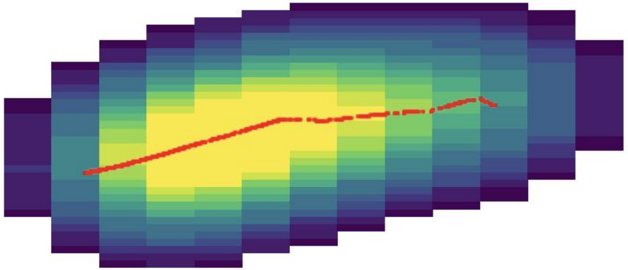
Belle II tracking TPC concept [link]



Directional Dark Matter detection [Vahsen]

- Tiny nuclear recoils in low-background environment
- Negative ion drift (low gain, low diffusion)
- Ion backflow is irrelevant
- **Resolution** and **efficiency** (via *gain*) is *critical*
- Frontend hit processing for recoil discrimination

Low-E nuclear recoil [link]



Test campaigns for both applications planned

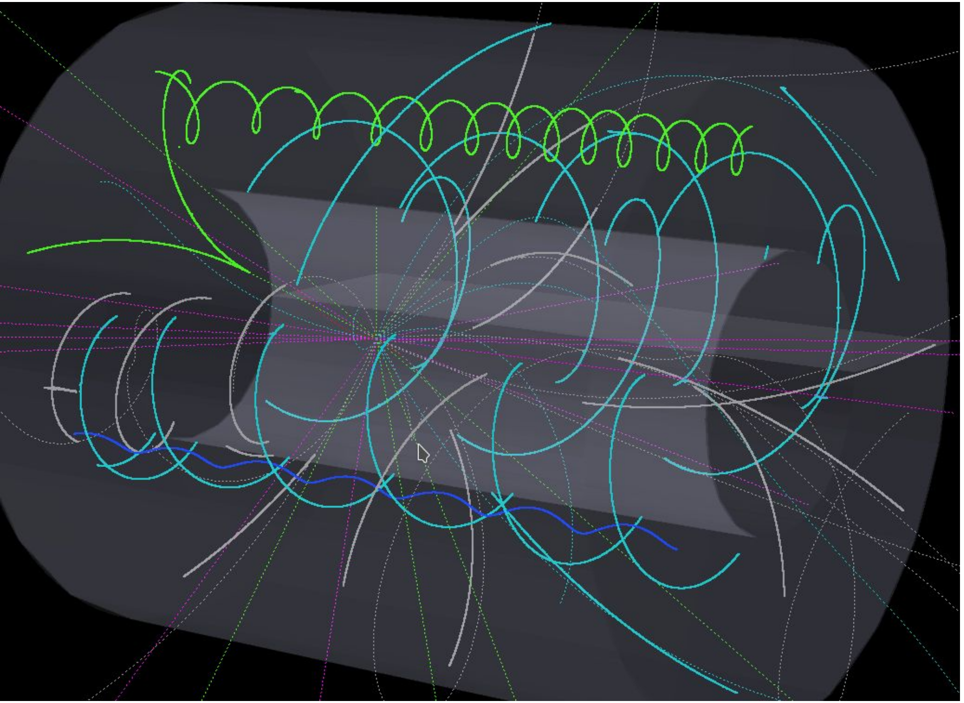
# Summary

There's a Belle II TPC concept targeting 2032 LS, but it is stalled.

The concept requires InGrid pixels

We've launched a new R&D program (FIMS) to develop an "ideal" InGrid system in the next 4-5 years

This program is *not* a Belle II effort; eyes on MIGDAL, CYGNUS, EIC Detector 2, CEvNS, etc.!



# Thank you!

# Resources

Bonn Master's thesis from Andreas Loeschcke Centeno
[https://docs.belle2.org/record/2631/files/BELLE2-MTHESIS-2021-073.pdf]

This whitepaper
[arXiv:2203.07287]

Belle II upgrade whitepaper
[https://arxiv.org/abs/2203.11349]

Timing layer whitepaper
[https://arxiv.org/abs/2203.04847]

A TPC-based tracking system for a future Belle II upgrade

Andreas Löschcke Centeno[1], Christian Wessel[1], Peter M. Lewis *[1], Oskar Hartbrich[2], Jochen Kaminski[1], Carlos Mariñas[3], and Sven Vahsen[2]

[1] *University of Bonn, Institute of Physics, Nußallee 12, 53115 Bonn, Germany*
[2] *University of Hawaii, Department of Physics and Astronomy, 2505 Correa Rd., Honolulu, HI 96822, USA*
[3] *University of Valencia - CSIC, Instituto de Fisica Corpuscular (IFIC), Spain*

March 15, 2022