Ultra-Low-Background Material Screening with the BetaCage Time Projection Chamber

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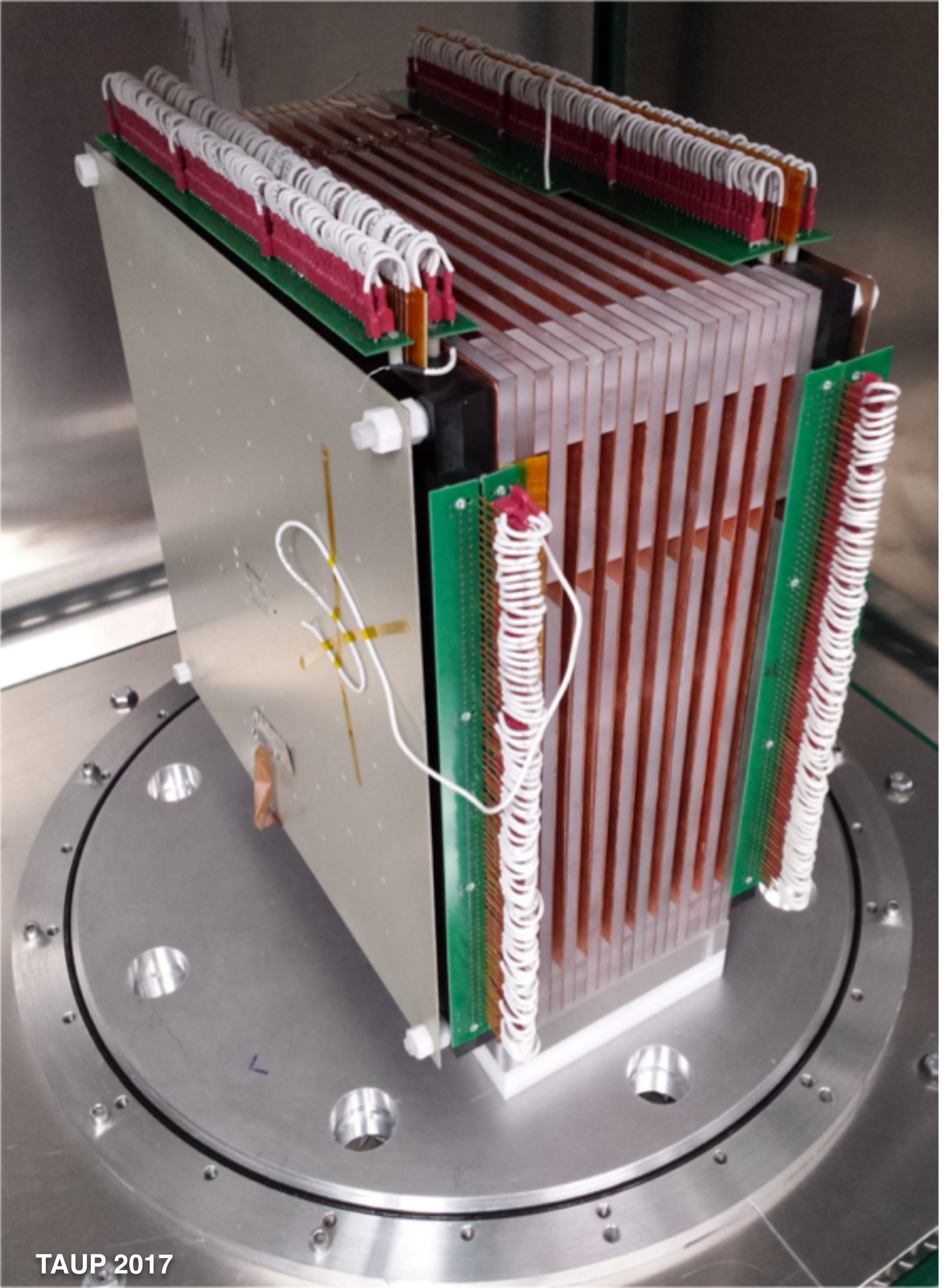
TAUP 2017

Wednesday, July 26, 2017

TAUP

This work was supported in part by the National Science Foundation (Grant No. PHY-1506033) and by the South Dakota Board of Regents



BetaCage Collaborators

South Dakota School of Mines & Technology
- R. W. Schnee
- E. H. Miller
- M. A. Bowles
- M. D. Thompson

California Institute of Technology
- S. Golwala
- R. H. Nelson
- Z. Ahmed

Pacific Northwest National Laboratory
- R. A. Bunker

University of Alberta
- D. Grant
- P. Davis

Rare-Event Searches & Material Radiopurity

from radon + progeny plate-out

- Neutrons from (α,n) reactions: LZ, Darkside: where "plate-out" of radon daughter leads to reactions on the interior surfaces
- Surface α's: CLEAN, DEAP: high *surface* α*-rate* → event (mis-)reconstruction into the detector fiducial volume

- Pb-210 ERs: SuperCDMS *Soudan*, DAMIC, .. (many!)
- Pb-206 NRs: Dominant for SuperCDMS *Soudan & SNOLAB (expected)*, XENON1T, LZ, CUORE, & DarkSide

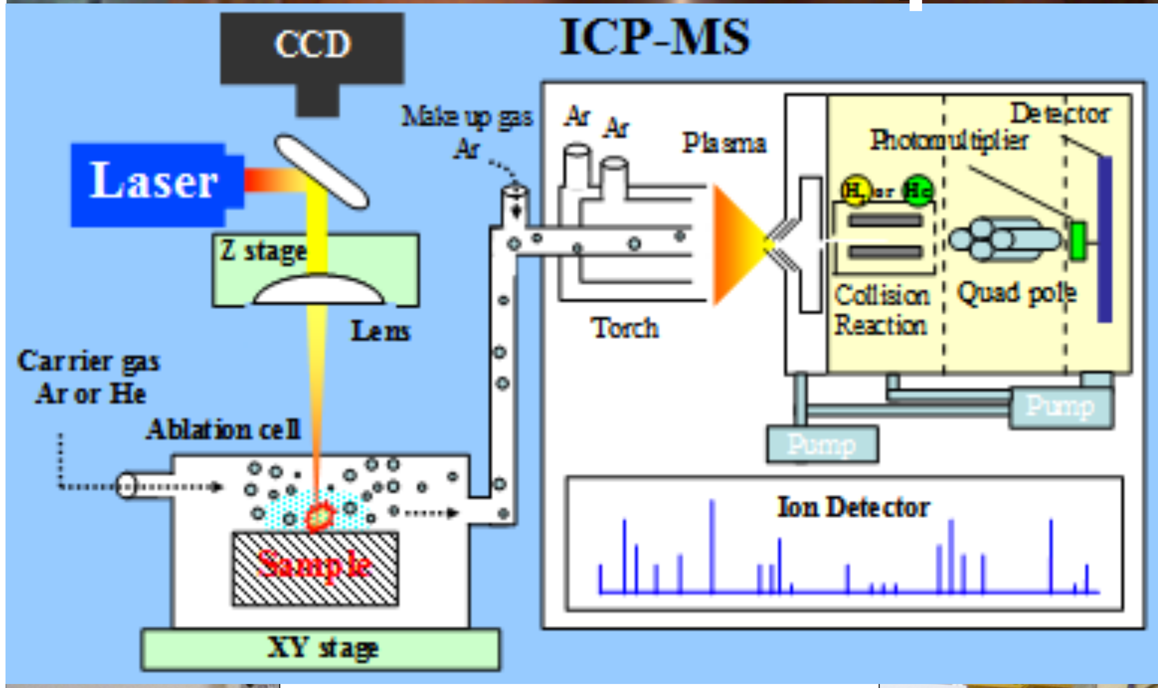
Low-energy β-emitters: ^{32}Si, ^{3}H, ^{39}Ar, ^{14}C

- ^{32}Si dominant background for DAMIC & SuperCDMS *SNOLAB* …^{3}H contamination
- ^{39}Ar DEAP, & Darkside (TPC+cryostat materials)

Assay Methods & Disadvantages

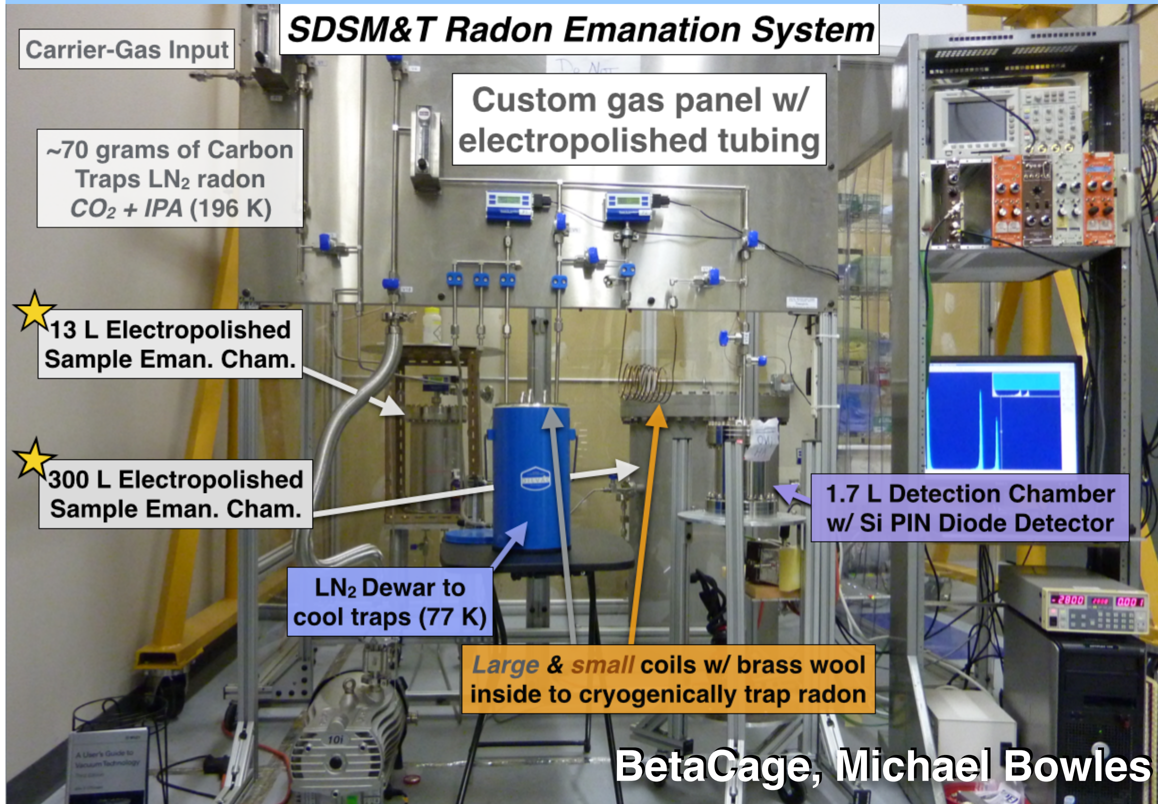
High Purity Germanium γ Screening

- High-resolution (keV) spectra (up to MeV)
- Size-limited & threshold ~10’s keV
- Typically insensitive to low-energy betas



Mass Spectroscopy (E/B field separation)

- Isotopic sensitivity: ≥ ppq [ppm-ppb]
- Low number of isotopes in sample
- Destructive & potential contamination

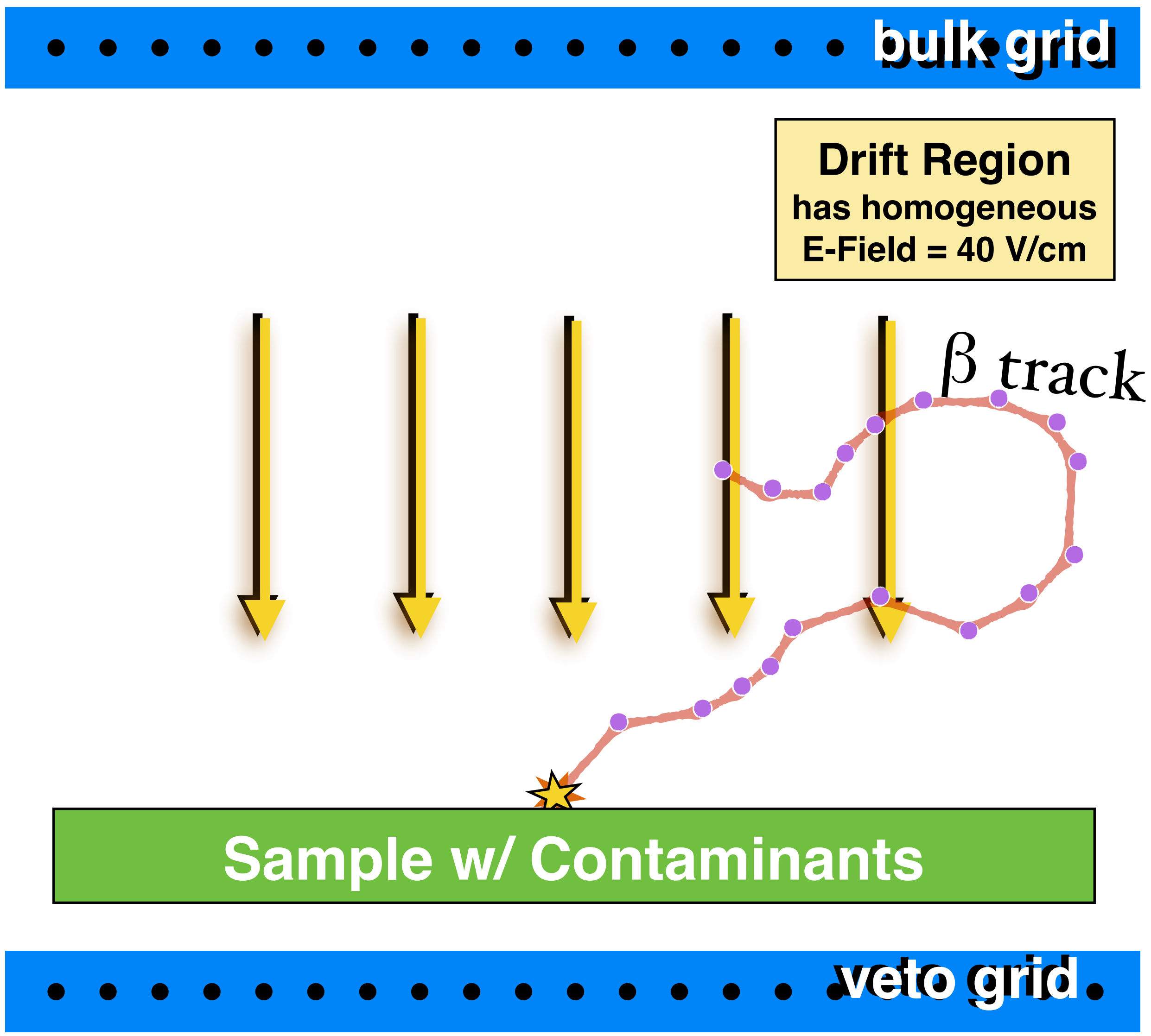


Alpha Counting (e.g. using electrostatics)

- Can measure lots of material!
- Carry hard-to-reject backgrounds

BetaCage Detector Design

- **Goal:** perform fast, high-sensitivity isotopic material assay
- Time projection chamber (TPC) made from very radio-pure materials carrying a large sample area
    - Gas stops all α's + low-energy β's
- Shield external radiation (gammas)
    - Deploy deep underground (muons)
- *XY* grids with ≈ cm spatial resolution
- Trigger grid provides signal start time



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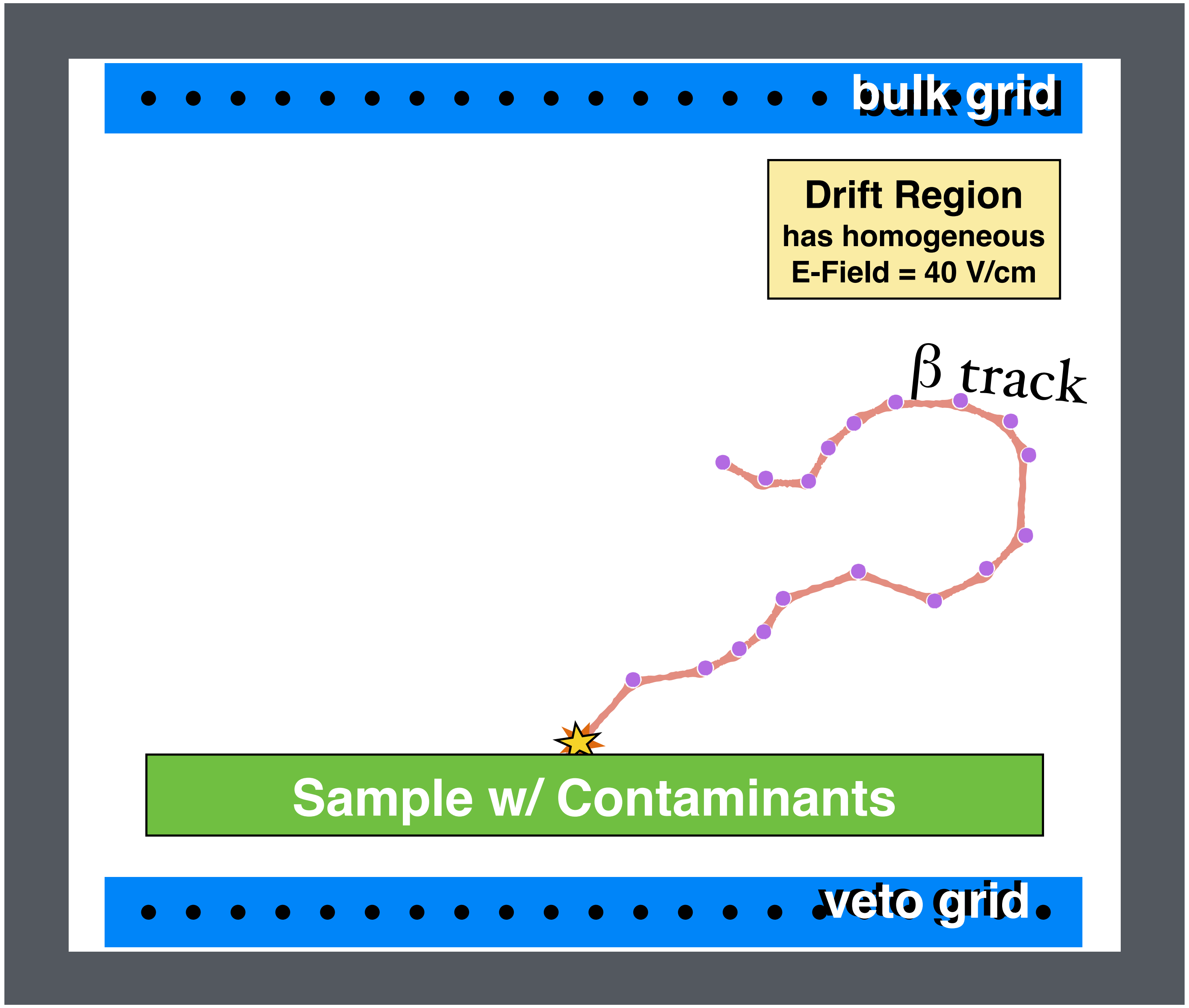

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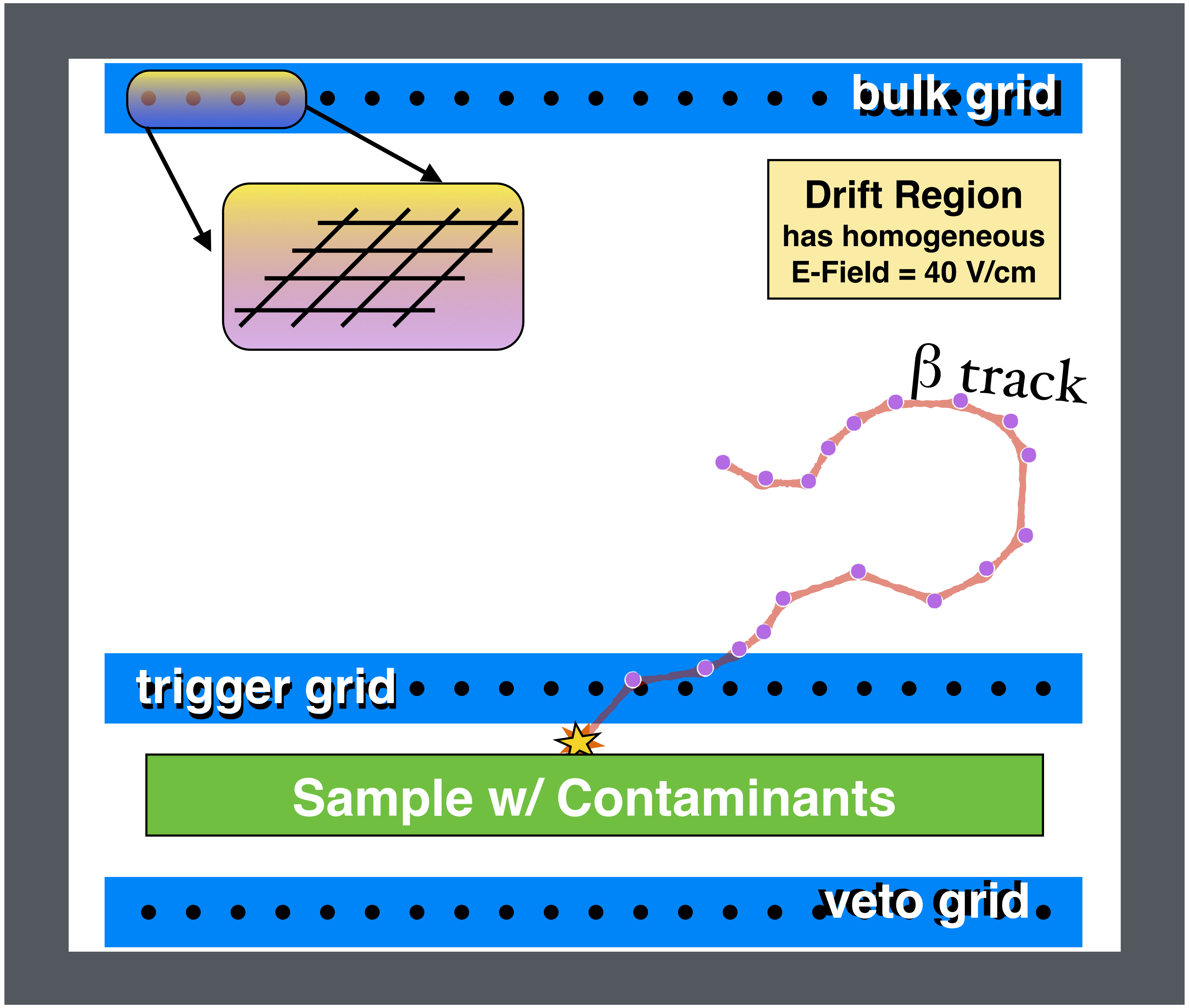


Superb Background Rejection

Background Veto:

A. Doesn't *cross* trigger grid

B. Track not 100% in target gas

C. *Crosses* veto grid

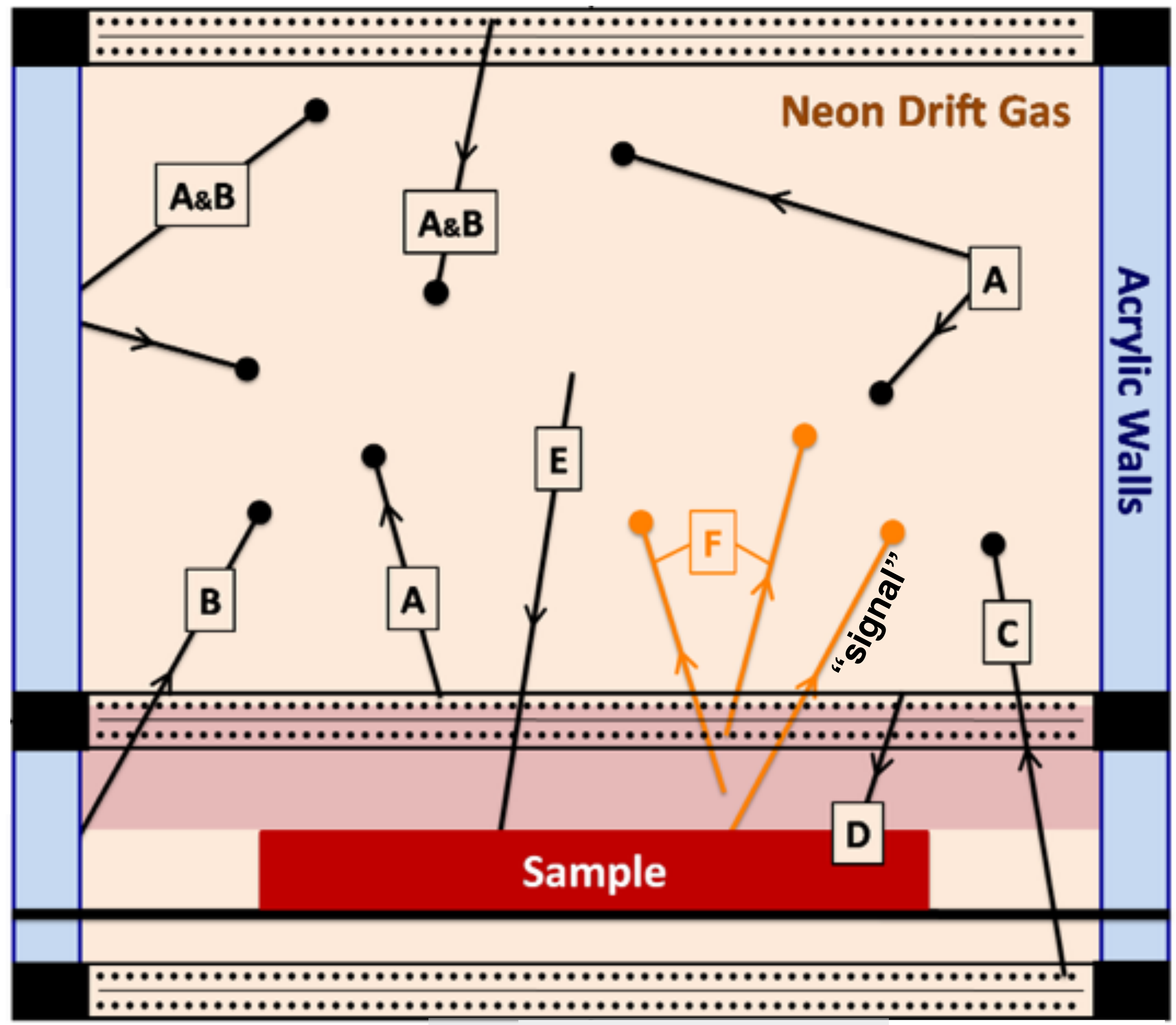
D. No Energy in bulk grid

E. Wrong track direction: dE/dx

Straightforward for α particles

F. Track doesn't start low enough

Straightforward for α particles



from arXiv:1404.5803

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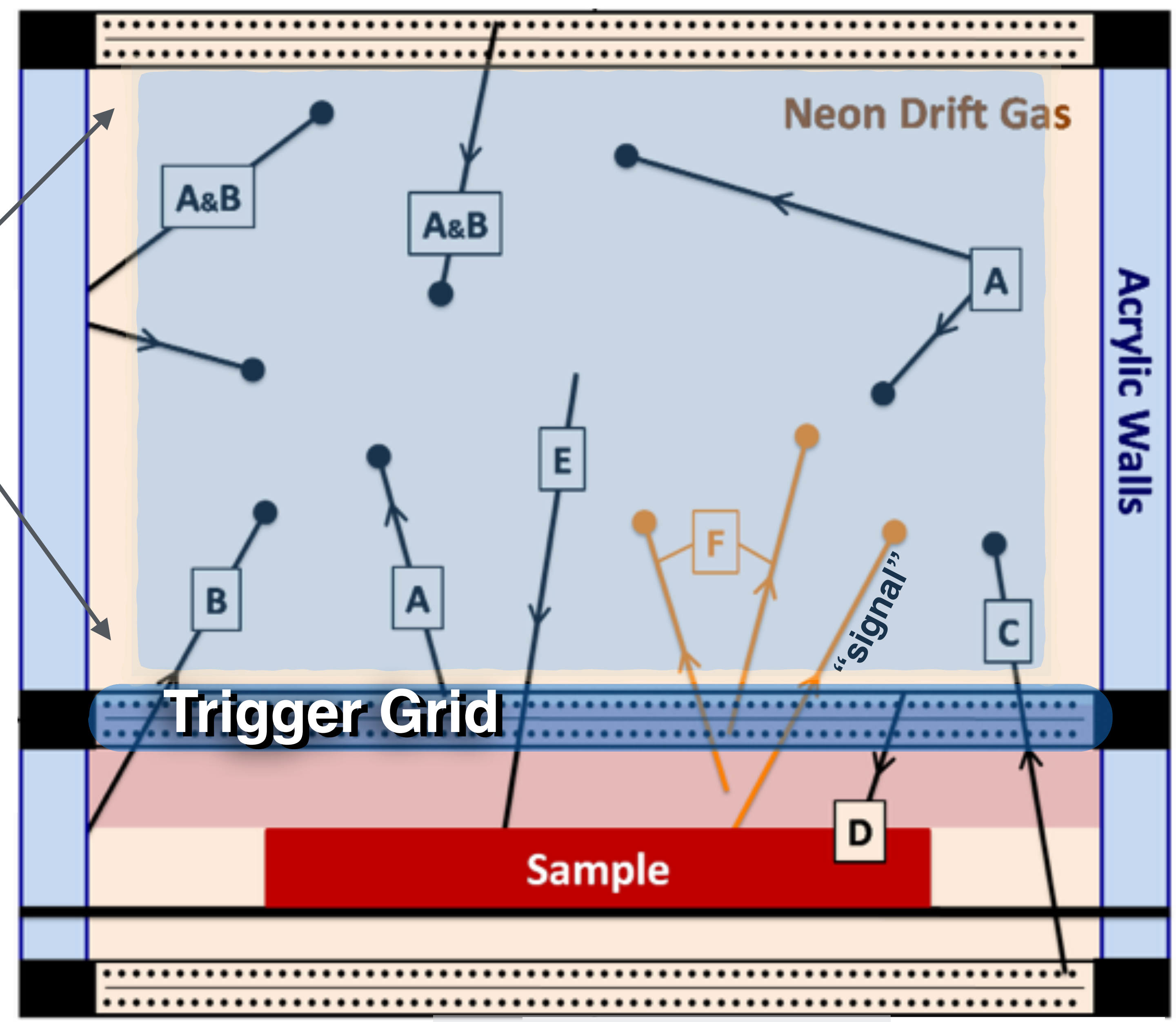

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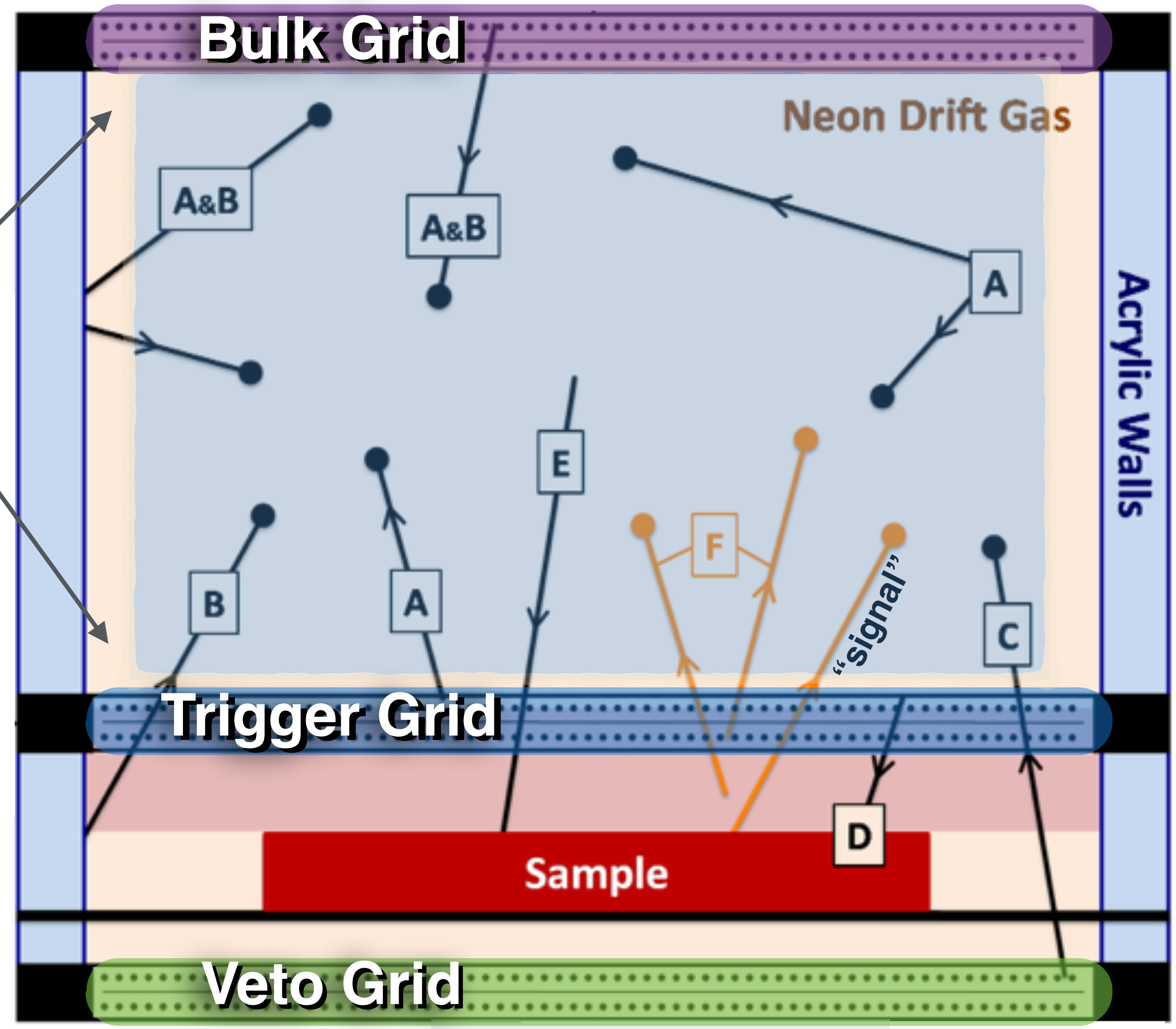

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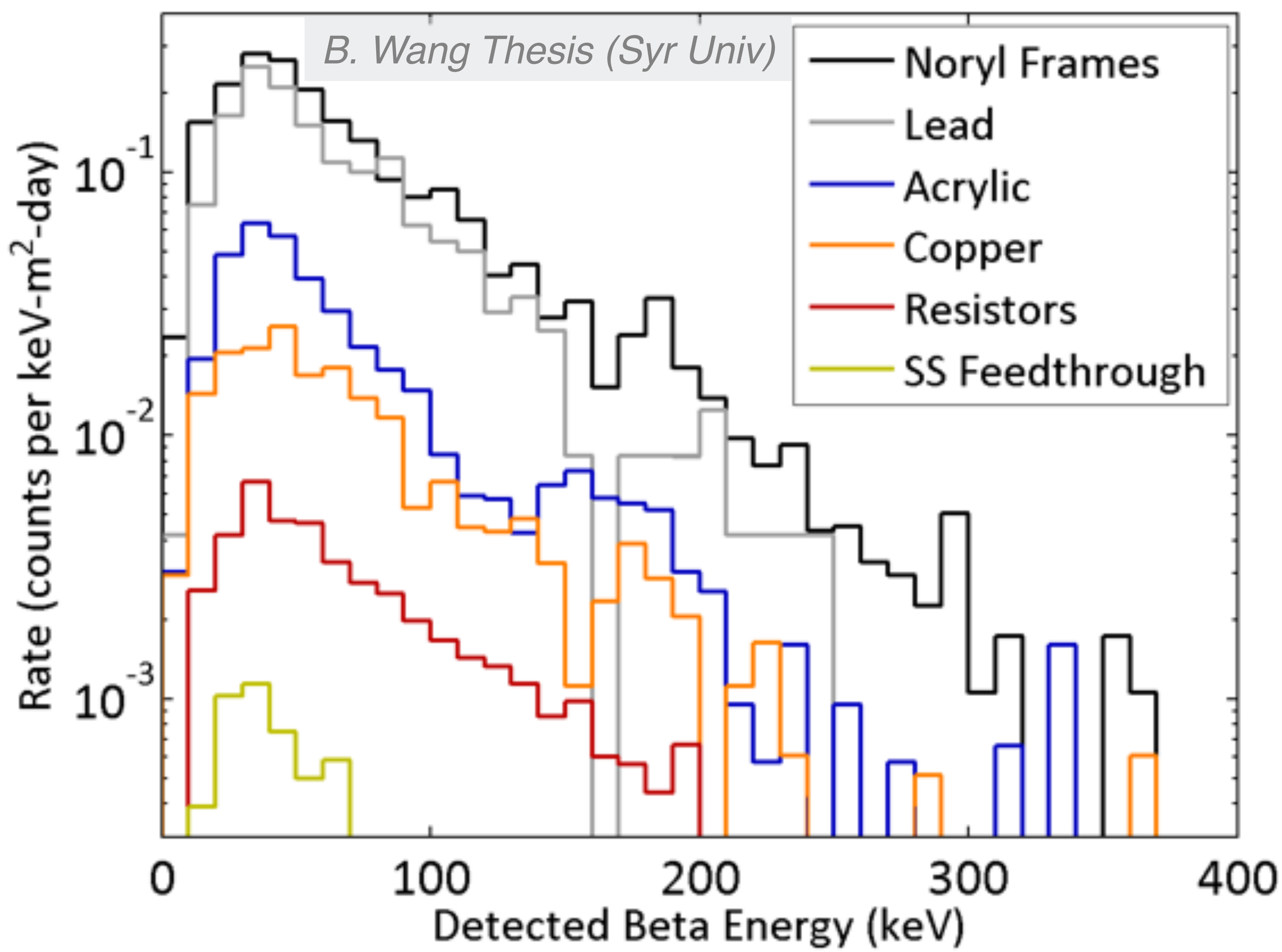
BetaCage Backgrounds

- Simulations indicate external γ's from surface of lead shield dominate β-screening backgrounds
- β background expectation: 0.3 keV^{-1} m^{-2} day^{-1}



<u>*BetaCage Sensitivity*</u>

β: 0.1 keV^{-1} m^{-2} day^{-1}

employing bkgd subtraction

limited by compton scatters in the sample from external gammas

BetaCage Backgrounds

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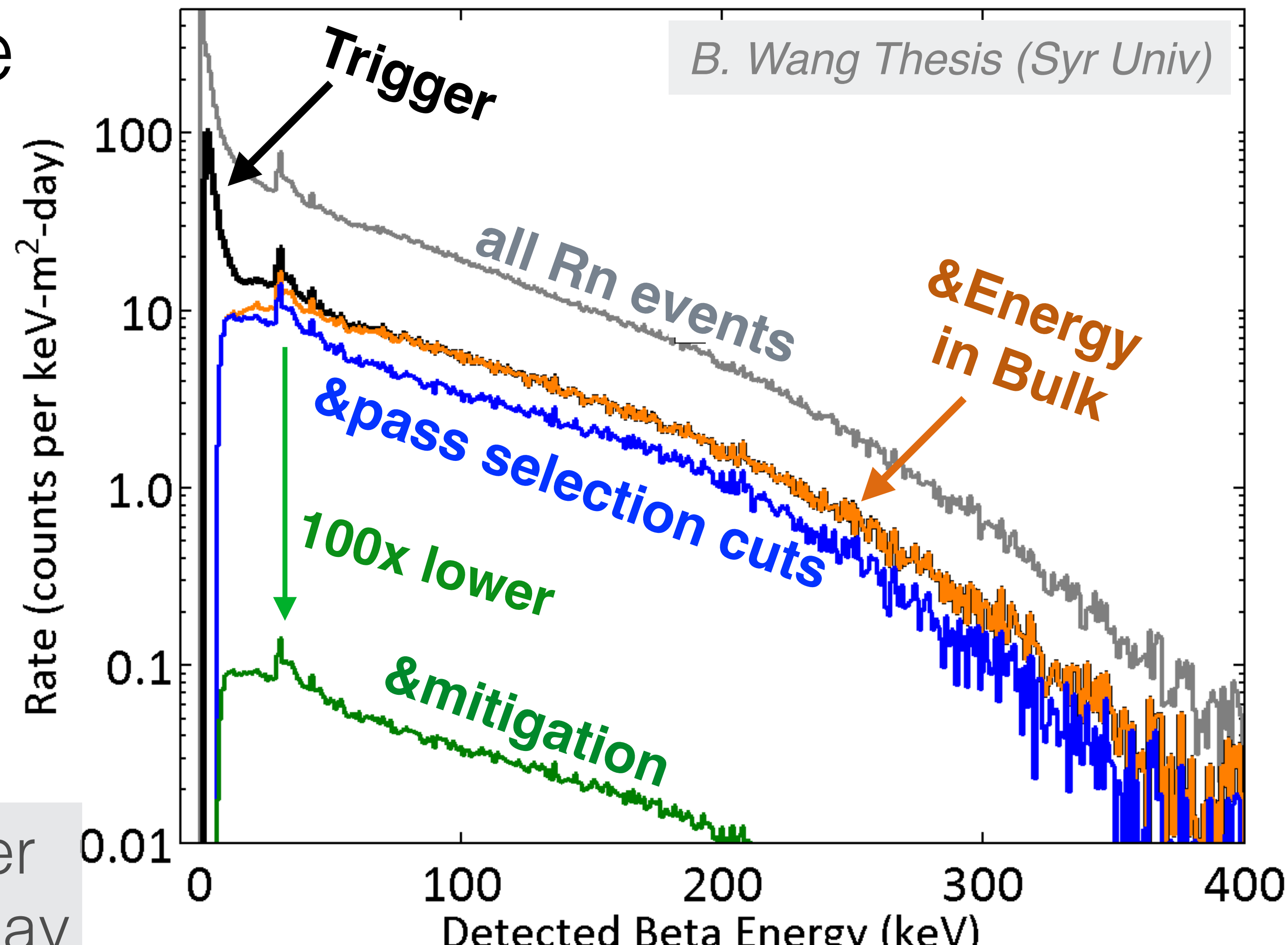
- ^{222}Rn reduction x100 can be acheived w/ 80 K carbon trap (LRT 2017, E. H. Miller)



<u>BetaCage Sensitivity</u>

β: 0.1 keV^{-1} m^{-2} day^{-1}

employing bkgd subtraction

α: 0.1 m^{-2} day^{-1}

signal limited

limited by Rn daughter implanation during assay

Si-32 Contamination & Sensitivity

- Silicon target experiments *e.g.* SuperCDMS, DAMIC face a major background from ^{32}Si & ^{32}P β decays

✦ ^{32}Si / ^{32}P *β pairs event multiplicity*

★ DAMIC measured ^{32}Si rate:

★ $R_{DAMIC} = 80^{+110}_{-65}$ / kg / day (95% C.L.)

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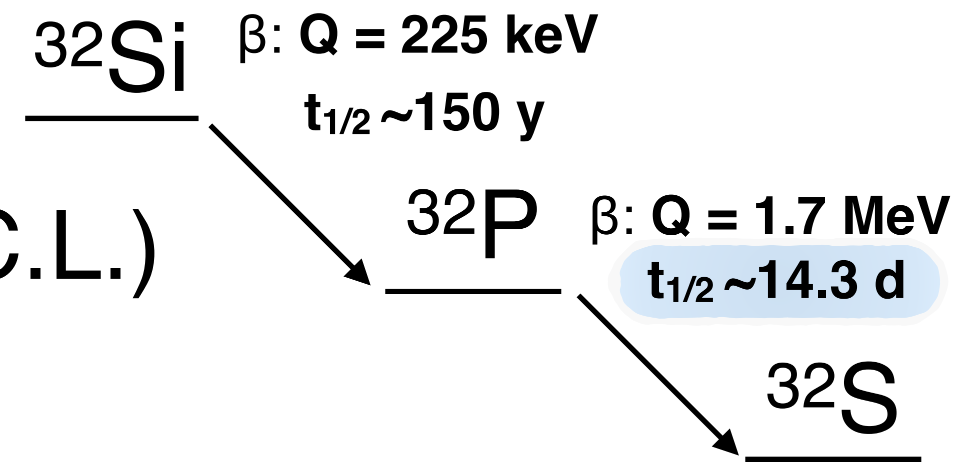

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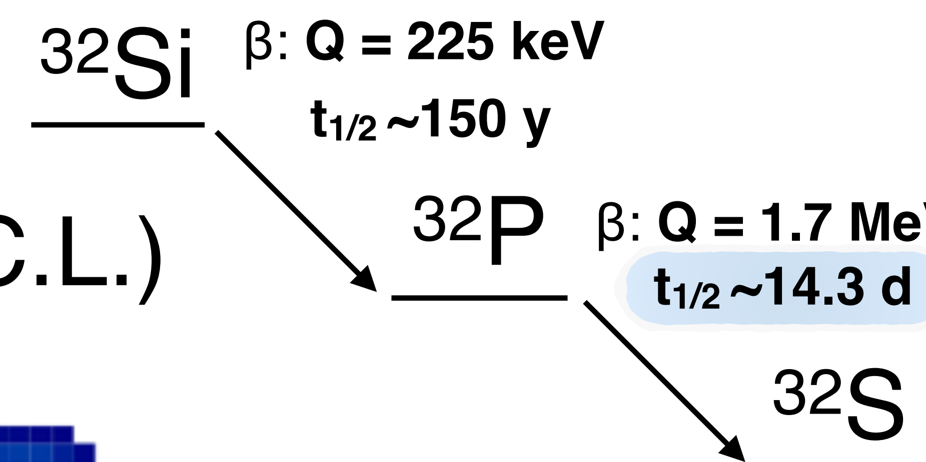

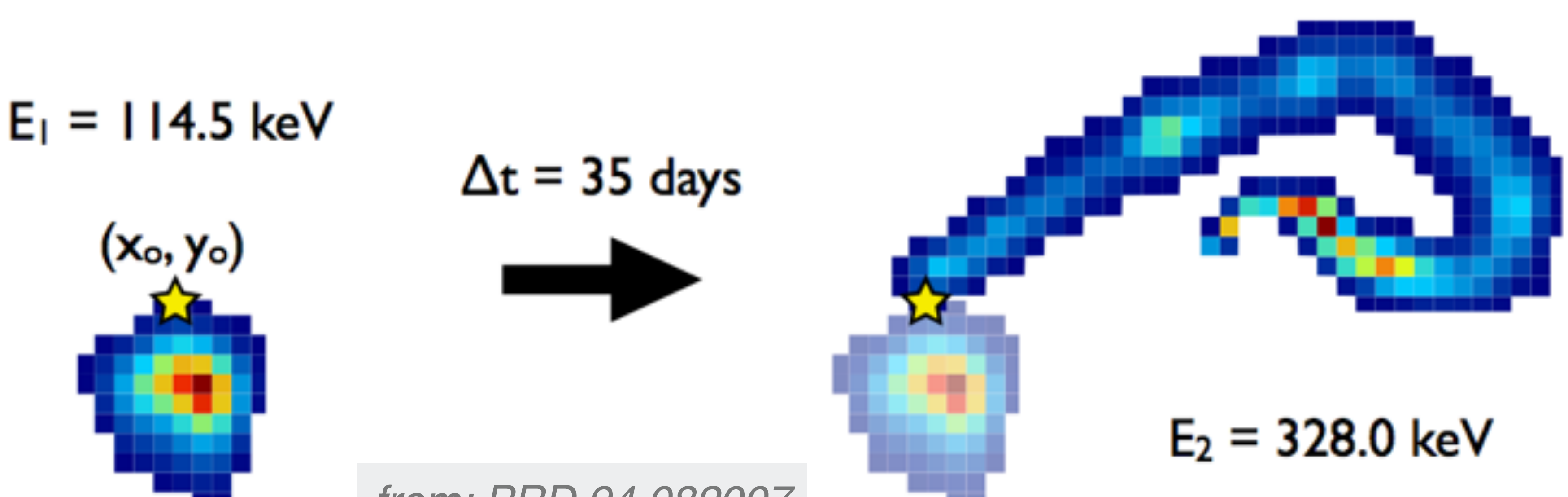

from: PRD 94.082007

event multiplicity in DAMIC CCDs

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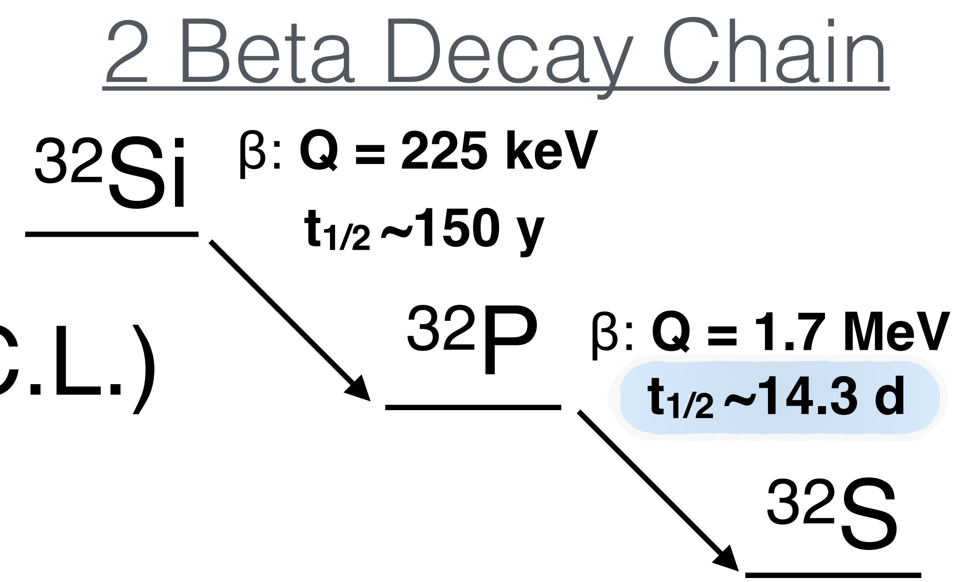
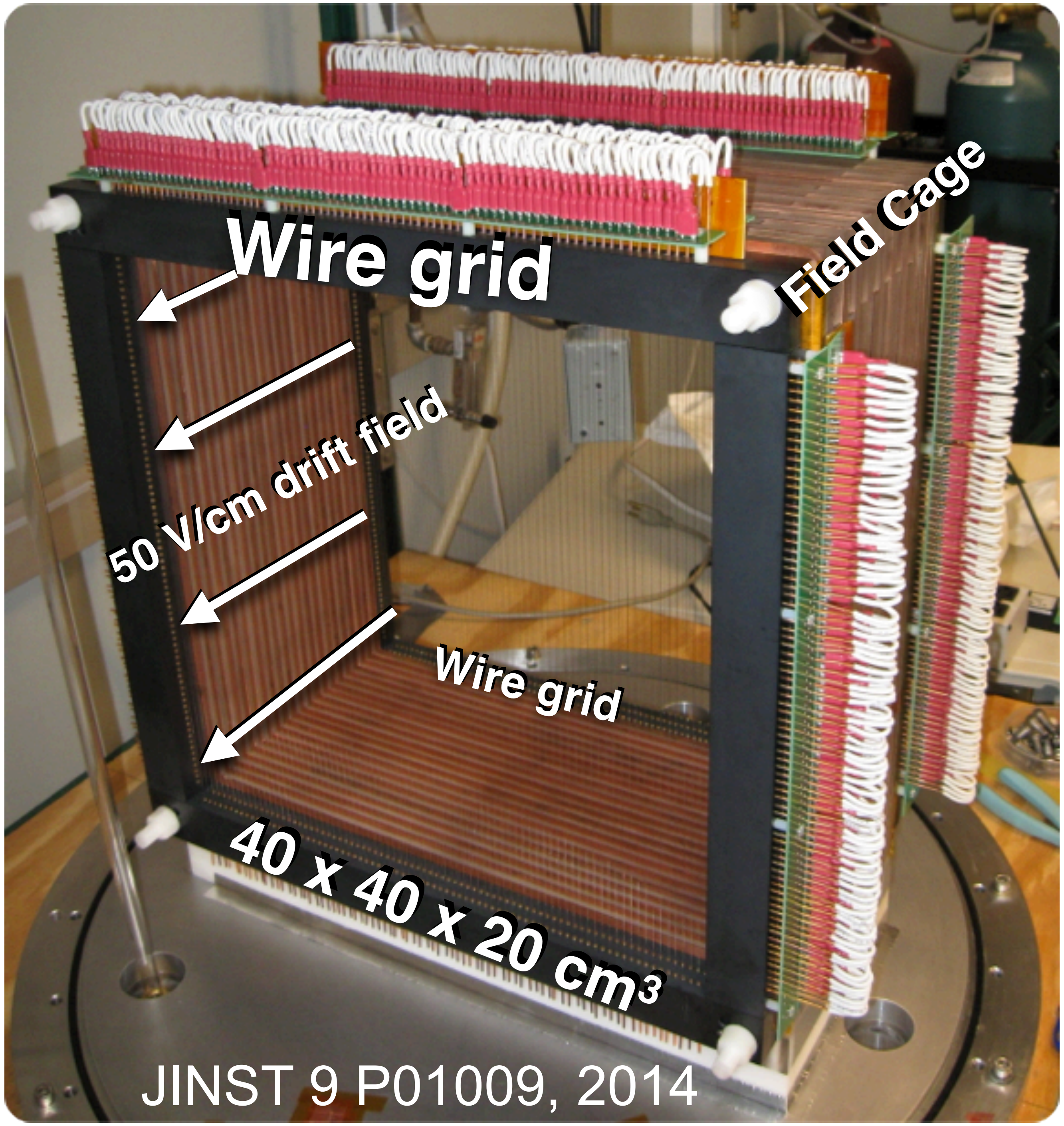


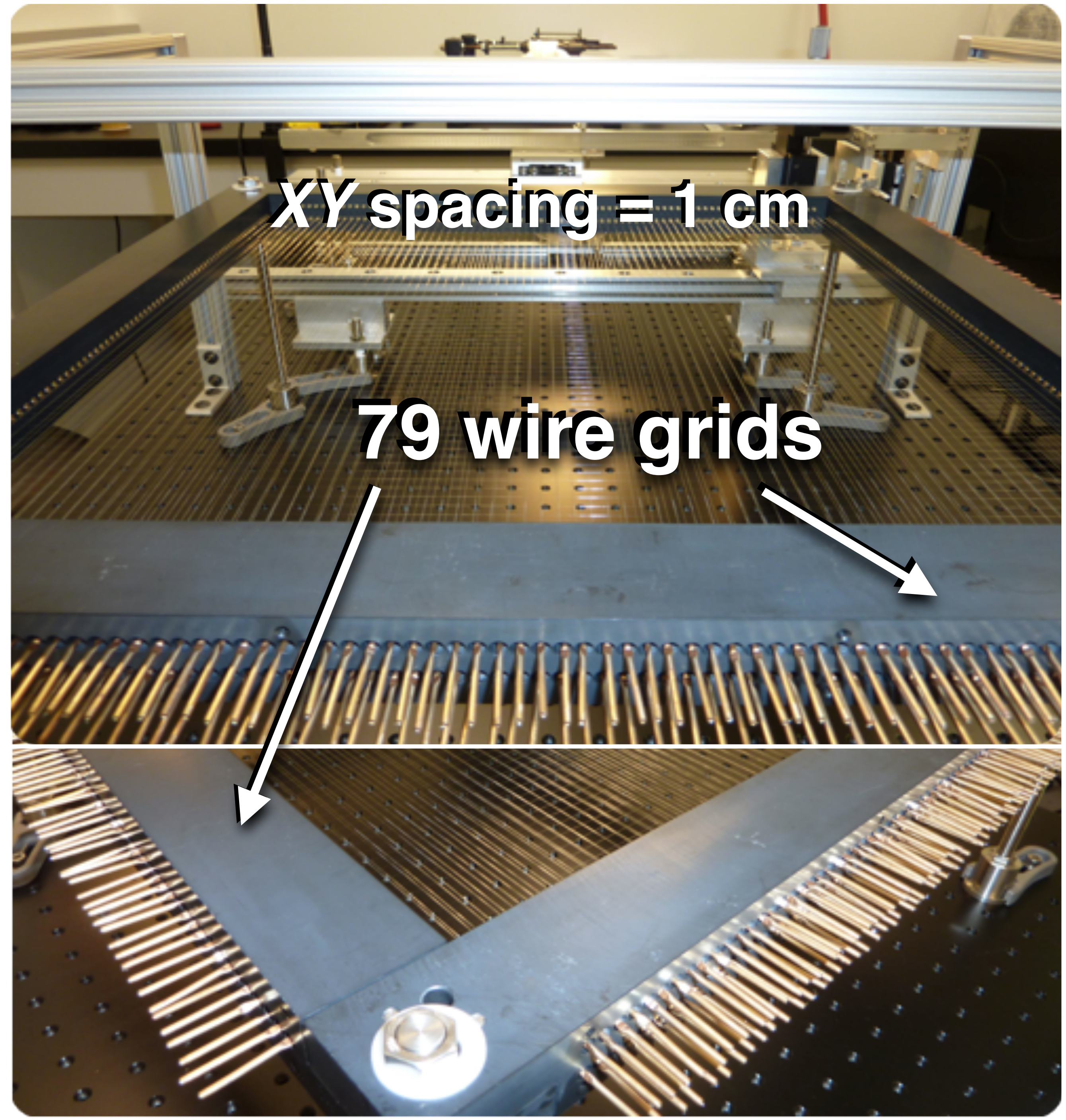
BetaCage Sensitivity

★ Surface β's: can ID 1% R_{DAMIC} in 35 days

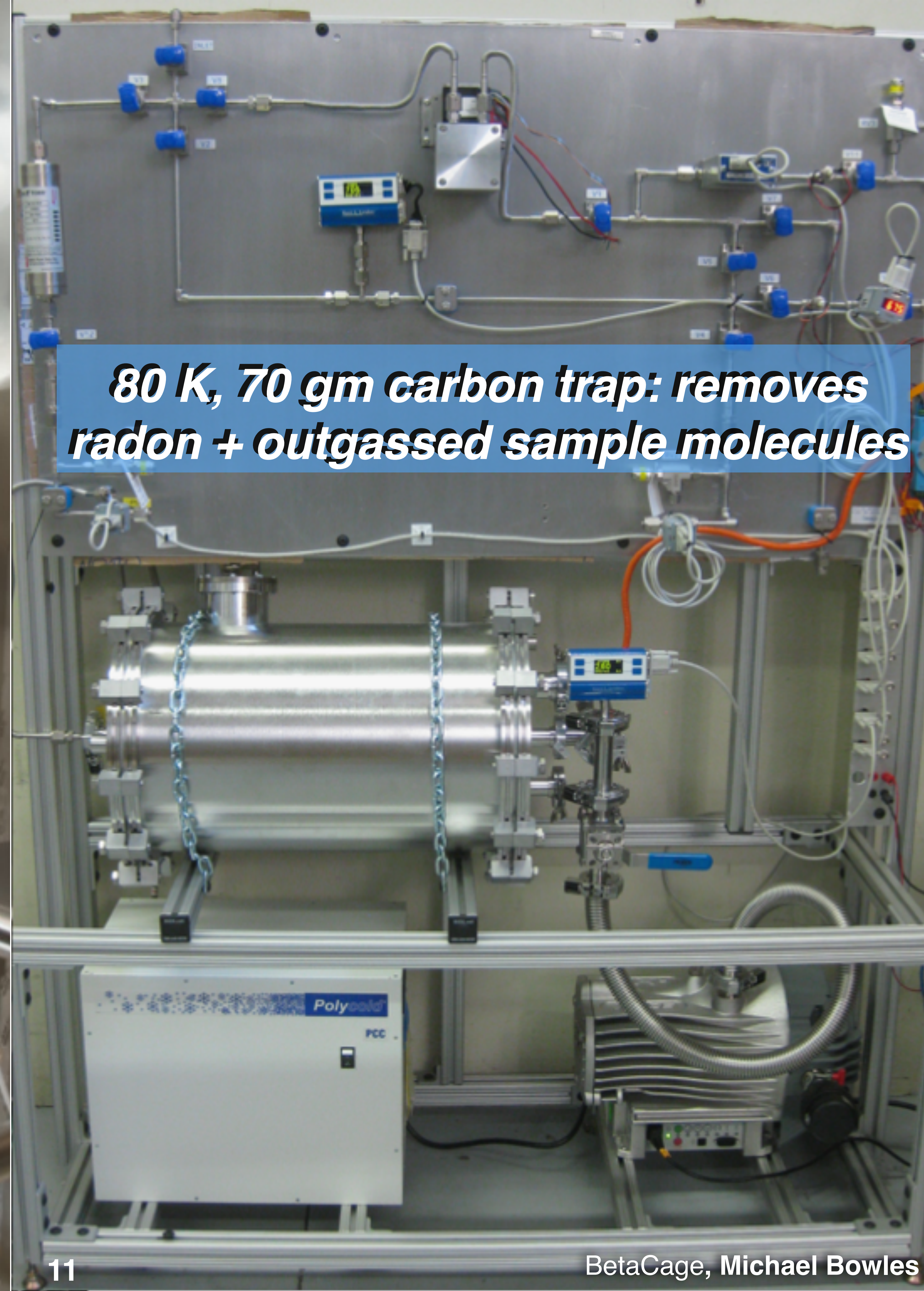
★ Bulk β's: can ID 1/4 R_{DAMIC} 3σ using *event multiplicity* on ^{32}Si & ^{32}P decays in 60 days (for 500 μm thick samples)

BetaCage Prototype



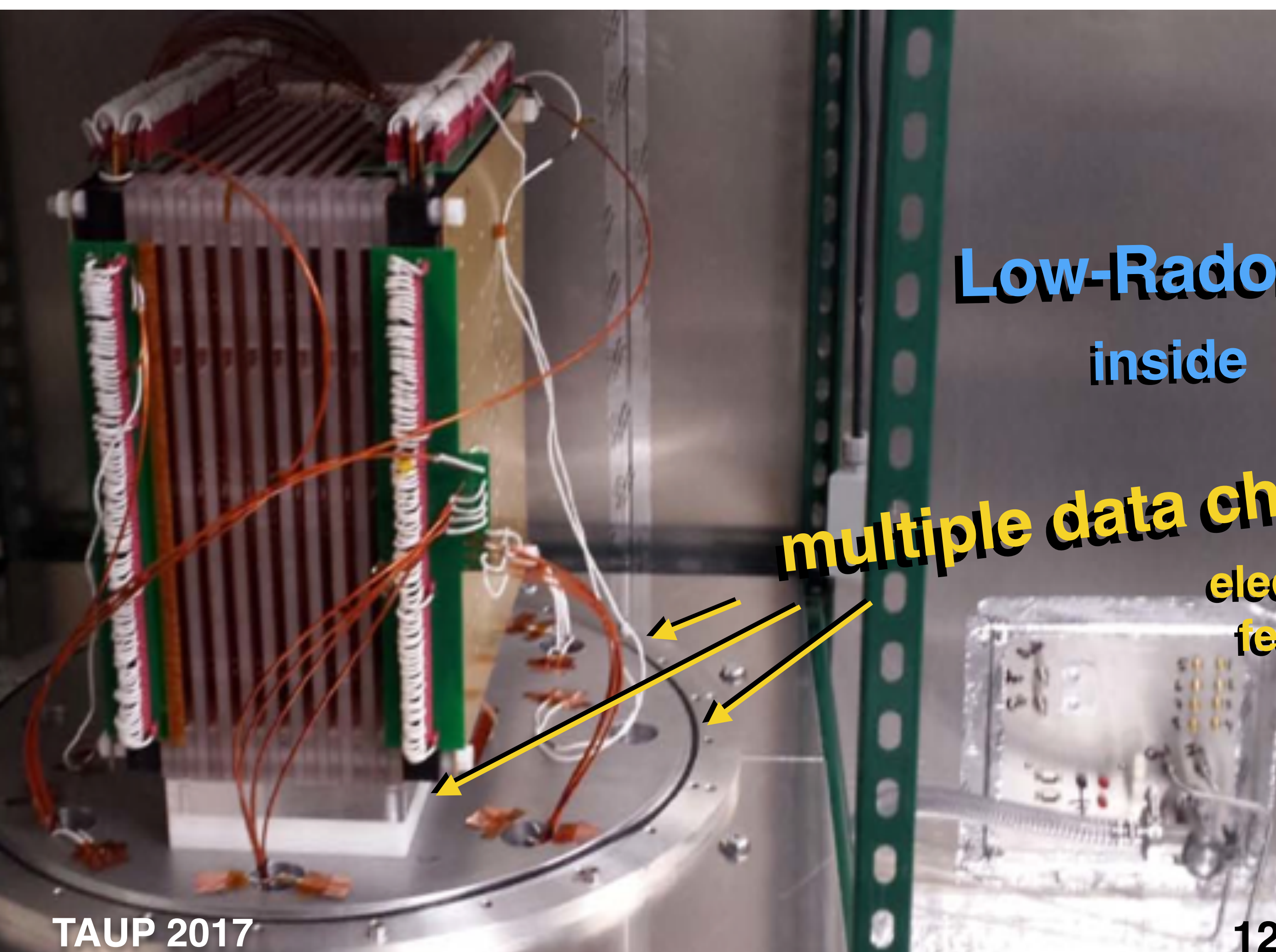


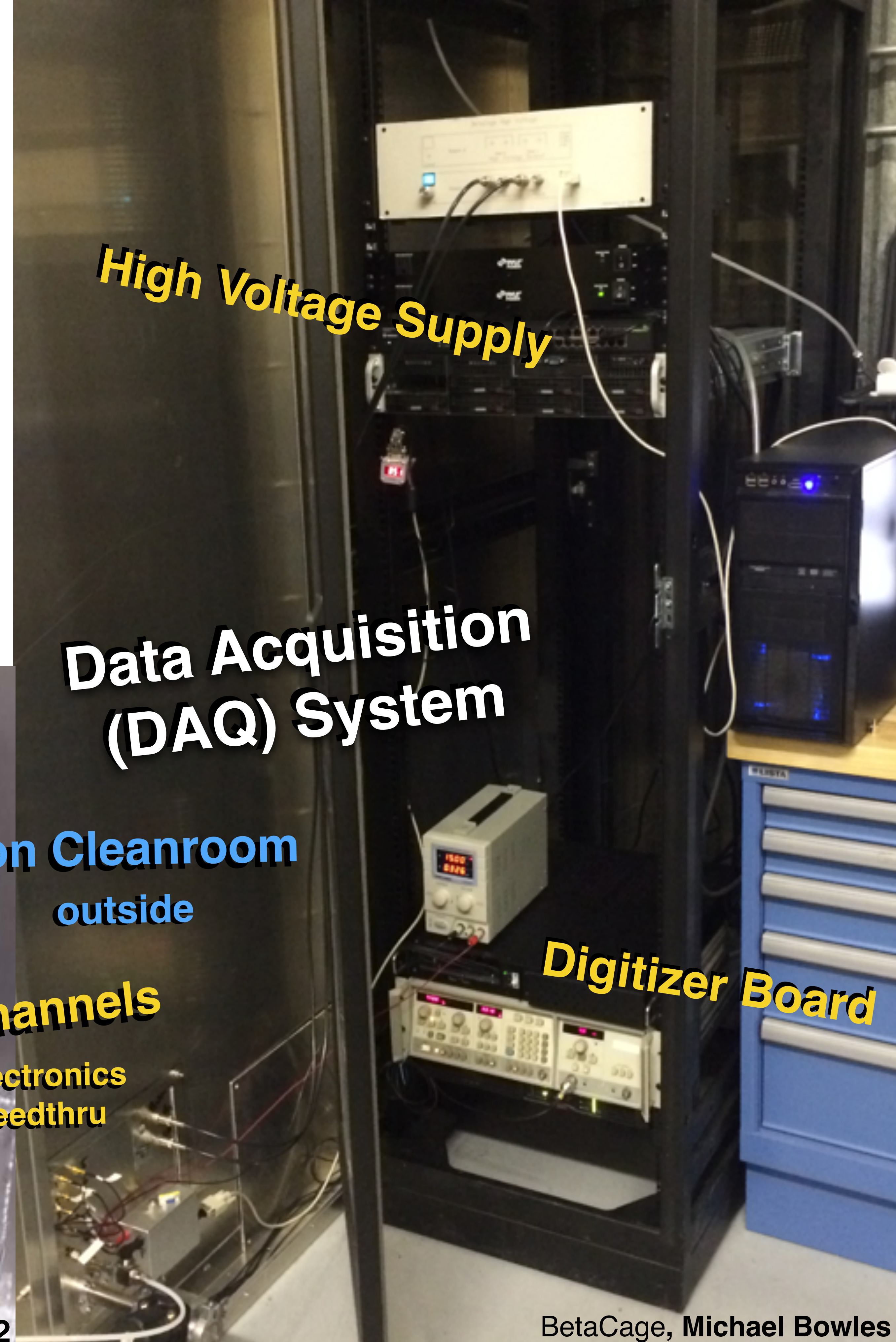

Very Low-Radon Cleanroom
50 V/cm drift field
40 x 40 x 20 cm3


80 K, 70 gm carbon trap: removes radon + outgassed sample molecules
Polycold
PCC

- Live-monitoring software with low-level trigger/pulse data & operating conditions of vessel
  - Have turned on High Voltage to see sparks during ramp up
- Calibration w/ alpha sources

★ Implement track reconstruction



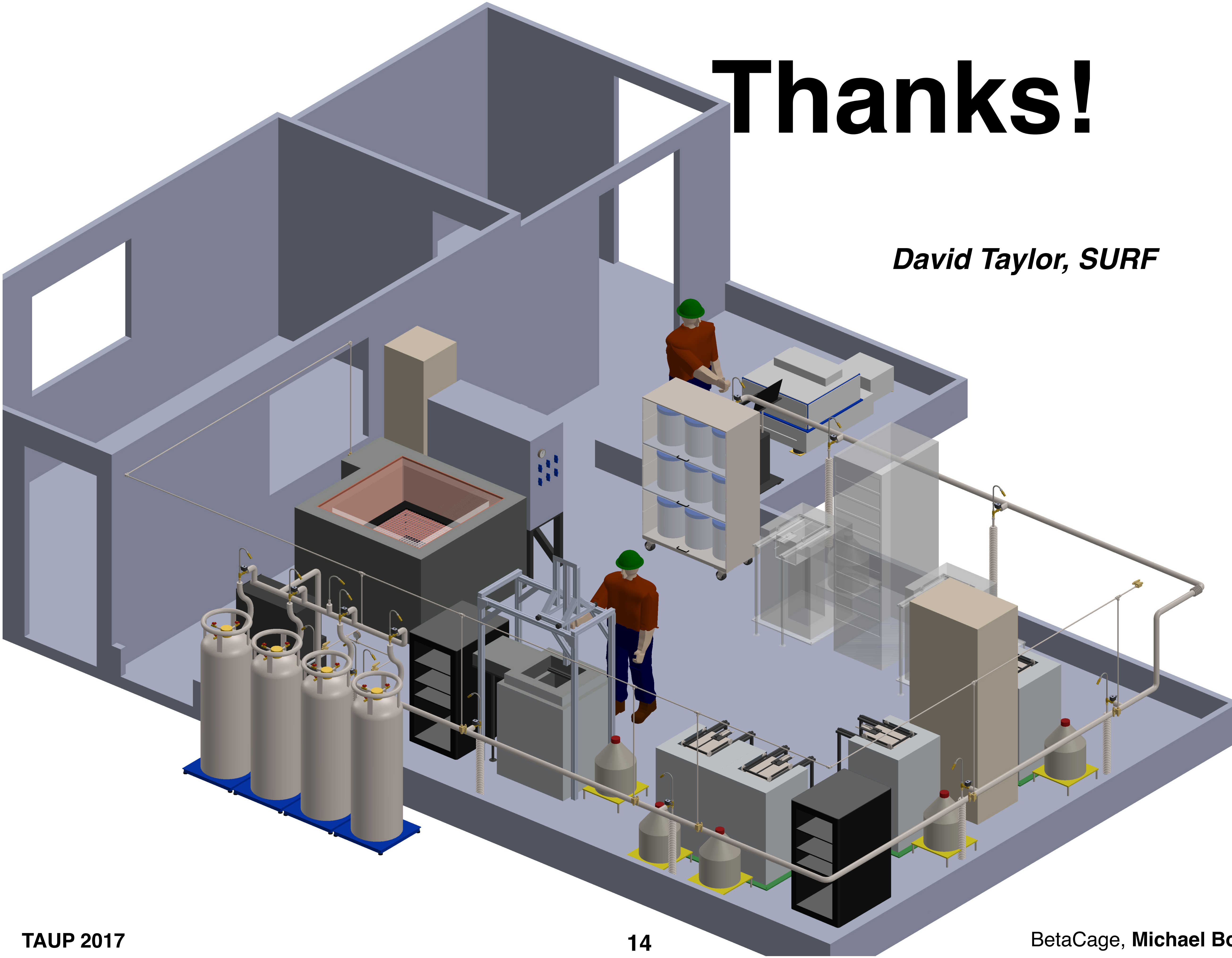


BetaCage Outlook

- BetaCage will provide incredible sensitivity to α's and low-energy β's on material surfaces & within the bulk of
  - ✦ Expected sensitivity: 0.1 β keV^{-1} m^{-2} day^{-1}, 0.1 α m^{-2} day^{-1}
- Design has matured w/ Prototype commissioning in progress
  - Continue estimating assay sensitivity: simulating internal U/Th material contamination levels & external backgrounds

★ Short term: Demonstrate Prototype sensitivity ~ 0.1 α m^{-2} day^{-1}

Thanks!



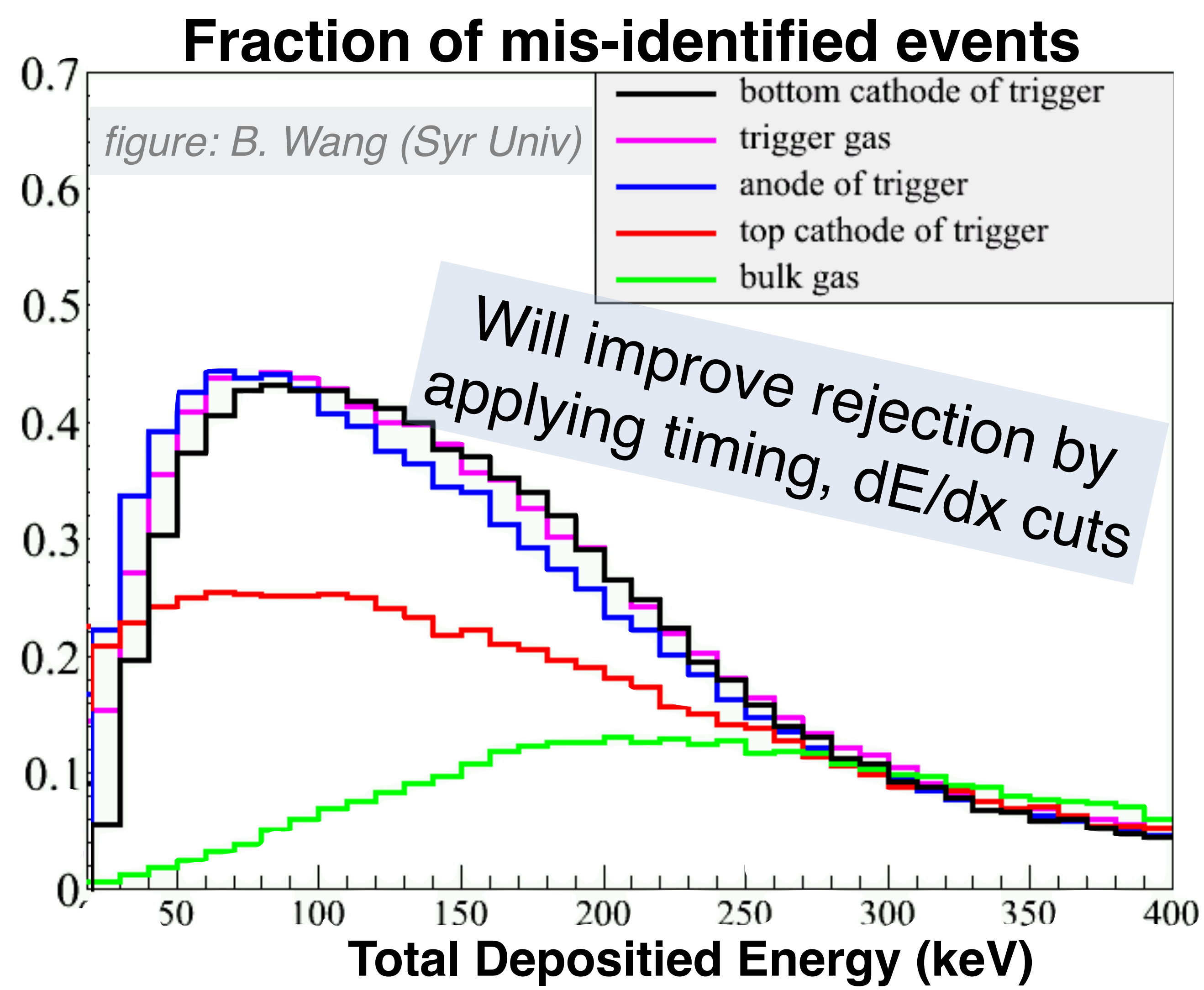
David Taylor, SURF

Radon Daughters Backgrounds

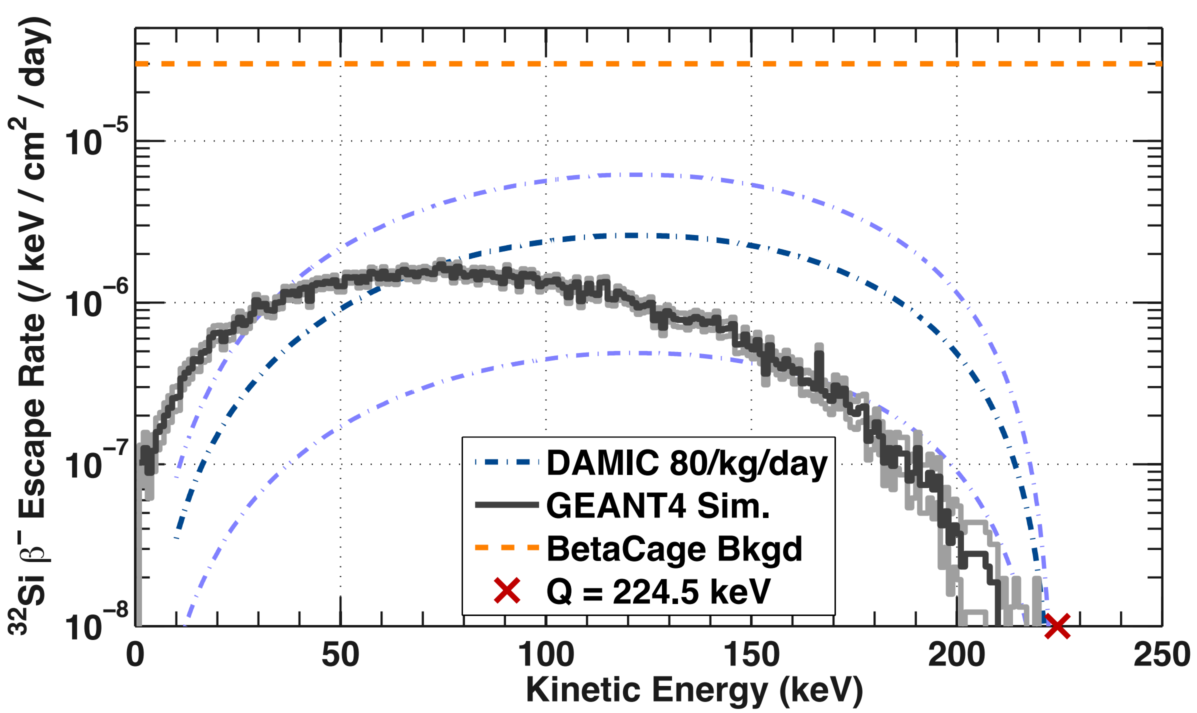
- Radon daughters (Po, Pb) on trigger grid wires + in gas are a dangerous alpha & beta background for the BetaCage
  - Still can veto most events from wires: using trigger signal
  - Beta-emitters elsewhere can be vetoed almost perfectly!

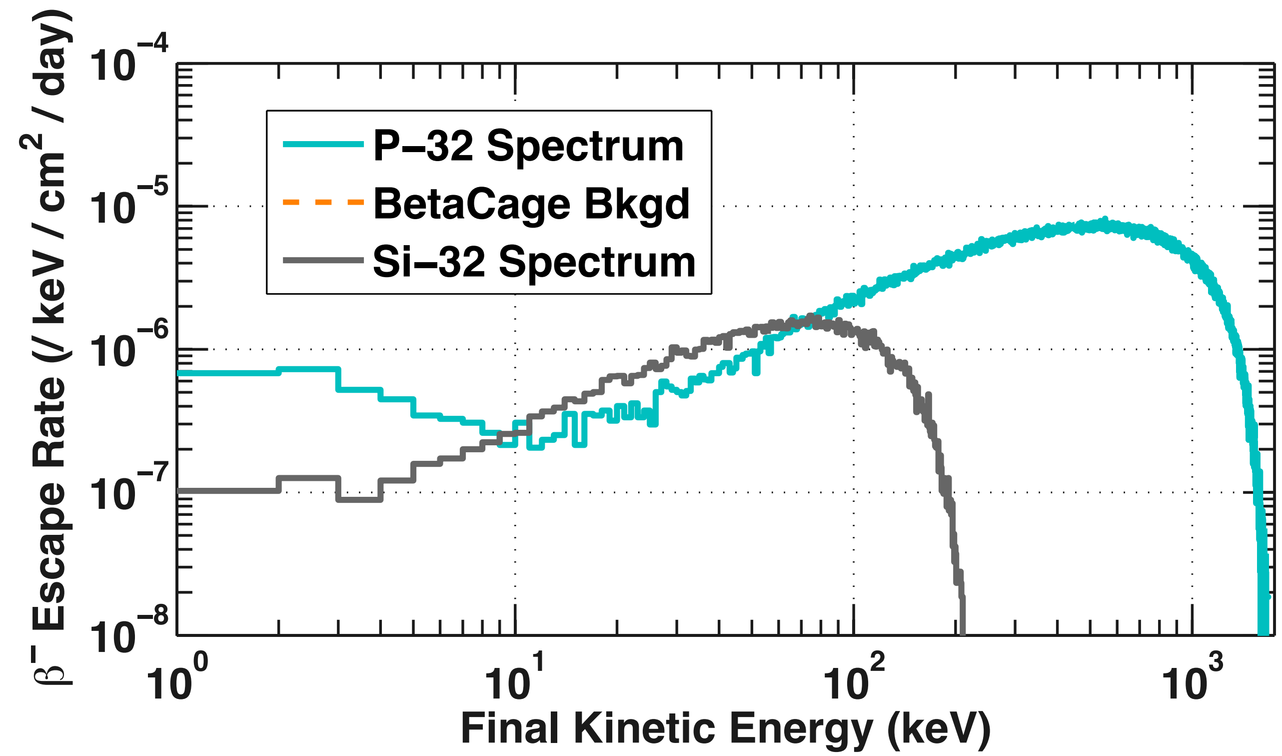
Main Sources of Background

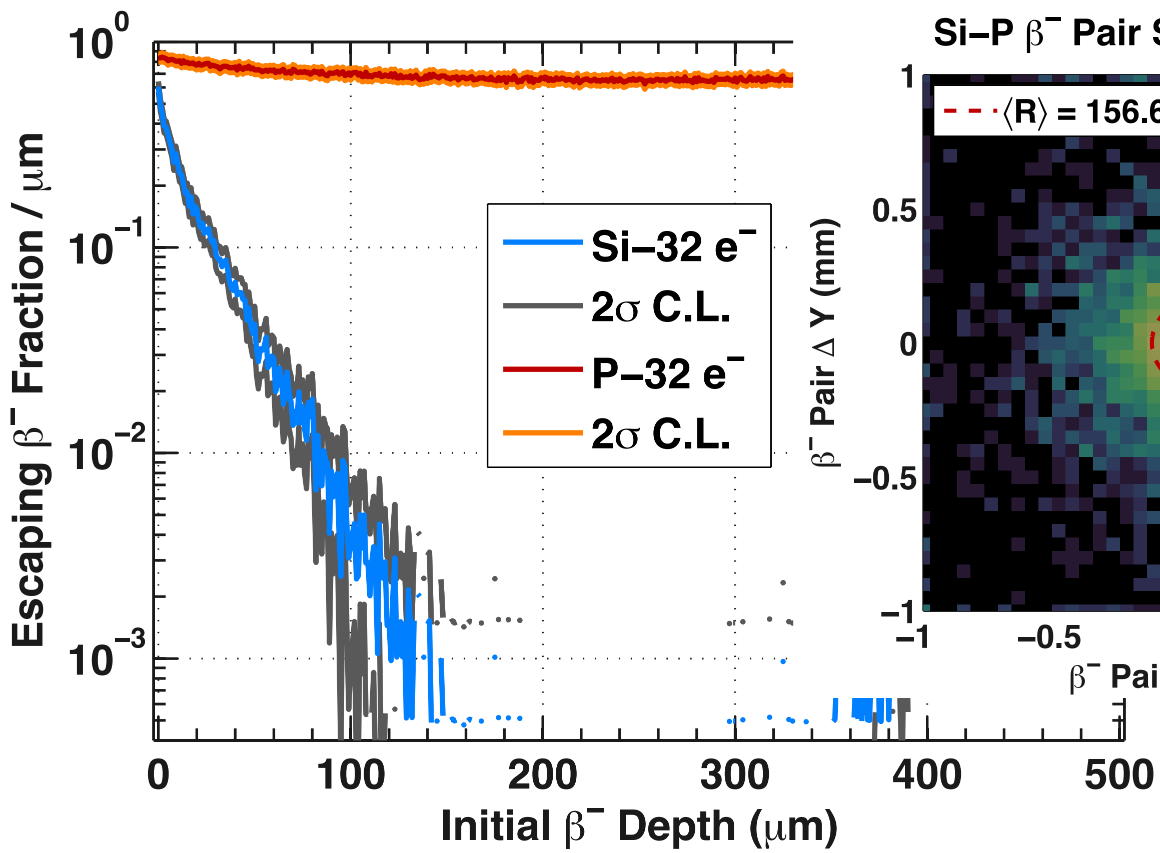
1. (Un)clean cathode/anode wire
2. During the assembly of the detector in the cleanroom
3. Plate-out from radon-222 during detector lifetime

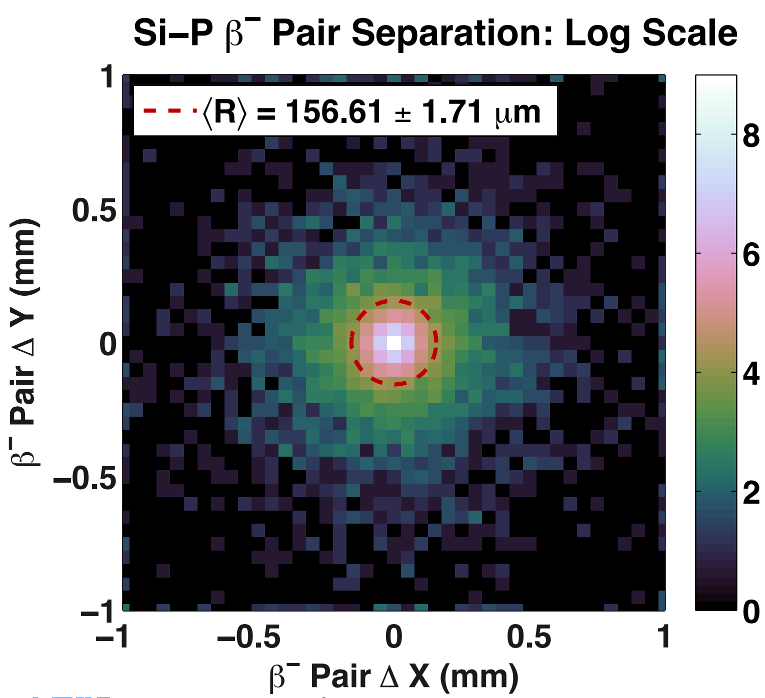


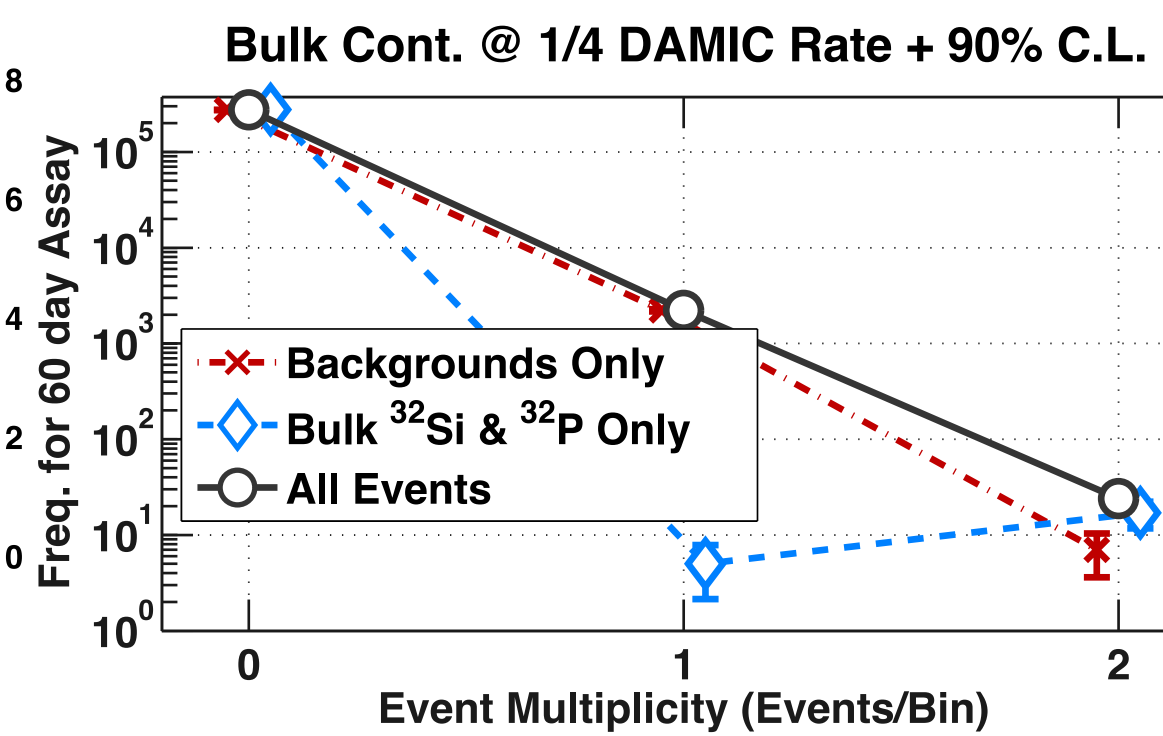
backupSi-32 Contamination











Radon Mitigation w Cooled Carbon Trap

Relatively small tube: L = 25-cm (length) & φ = 2.5-cm (diameter)

70 grams of high-quality synthetic carbon [1]:

$\rho = 0.6\ \mathrm{g/cm^3}$ (density) & $S = 1342\ \mathrm{m^2/g}$ (surface area)

For Q = 8 lpm (circulation flow rate) & T = 170 K (trap temperature):

$\mu_s = 4Q/\pi\,\varphi^2 \approx 26\ \mathrm{cm/s}$ (superficial velocity through trap)

$k_a(S,T) \approx 1.4\mathrm{x}10^7\ \mathrm{cm^3/g}$ (dynamic adsorption coefficient) [2]

$\tau_{trap} = Tk_a\rho L/(273\ \mathrm{K})\mu_s \approx 56$ days ('punch-through' time) [2]

Survival fraction for radon atoms entering the trap:

$\exp(-\tau_{trap}/5.52\ \mathrm{d}) \approx 3.8\mathrm{x}10^{-5}$

Considering flush time of 0.6-m^3 detector volume yields:

x100 reduction!

[1] Blucher GmbH 102688, see *www.bluecher.com/en/technology*

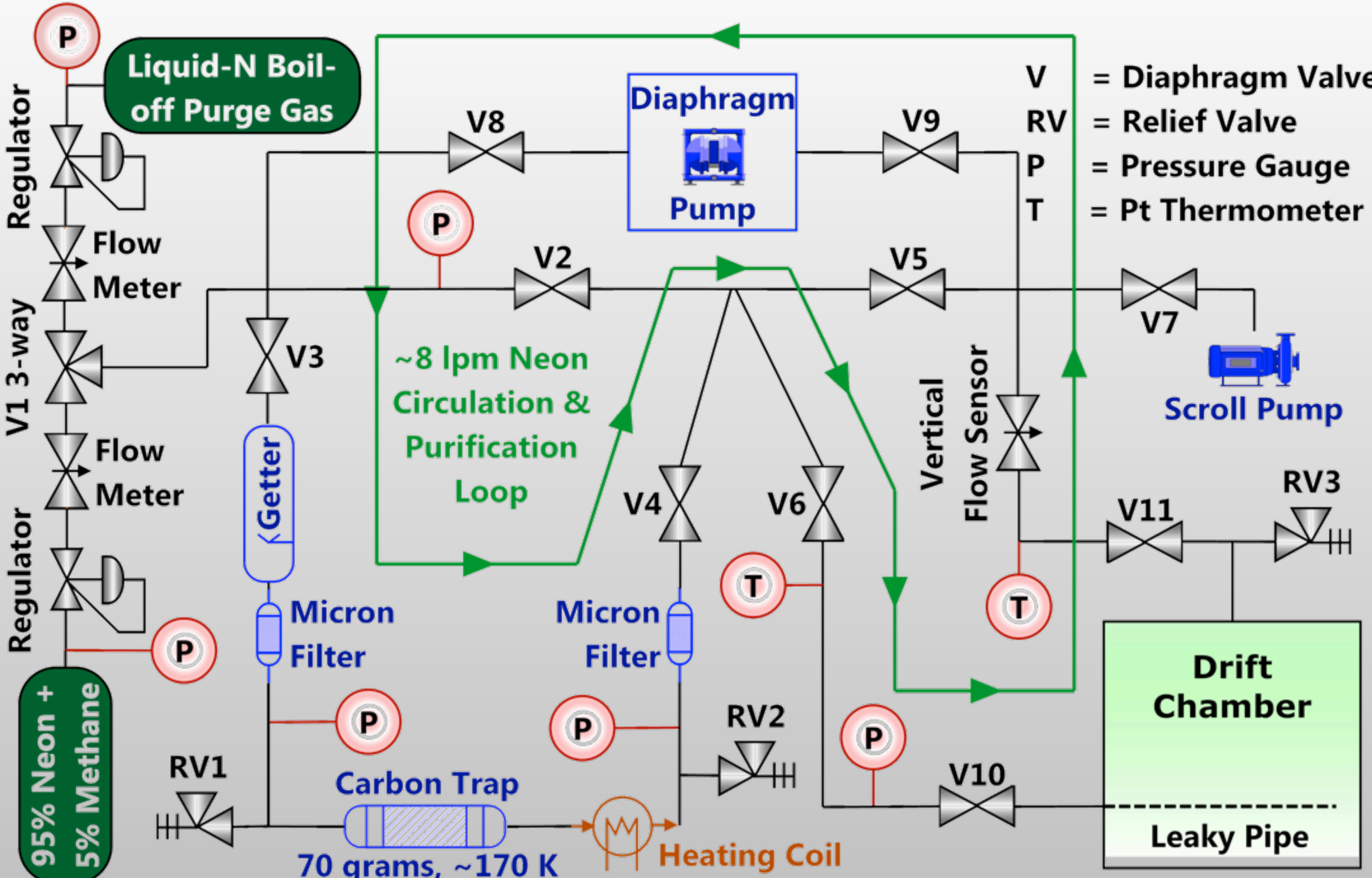
[2] K.P. Strong & D.M. Levins, *DOE Nuclear Air Cleaning Conference* (1978)

[3] J.B.R. Battat *et al.*, JINST, 9 (2014) P11004

[4] H. Sigmen & G. Zuzel, Applied Radiation and Isotopes, 67 (2009) p. 922

[5] Mitigation allows use of relatively leaky mini-diaphragm circulation pump

Radon Mitigation w Cooled Carbon Trap



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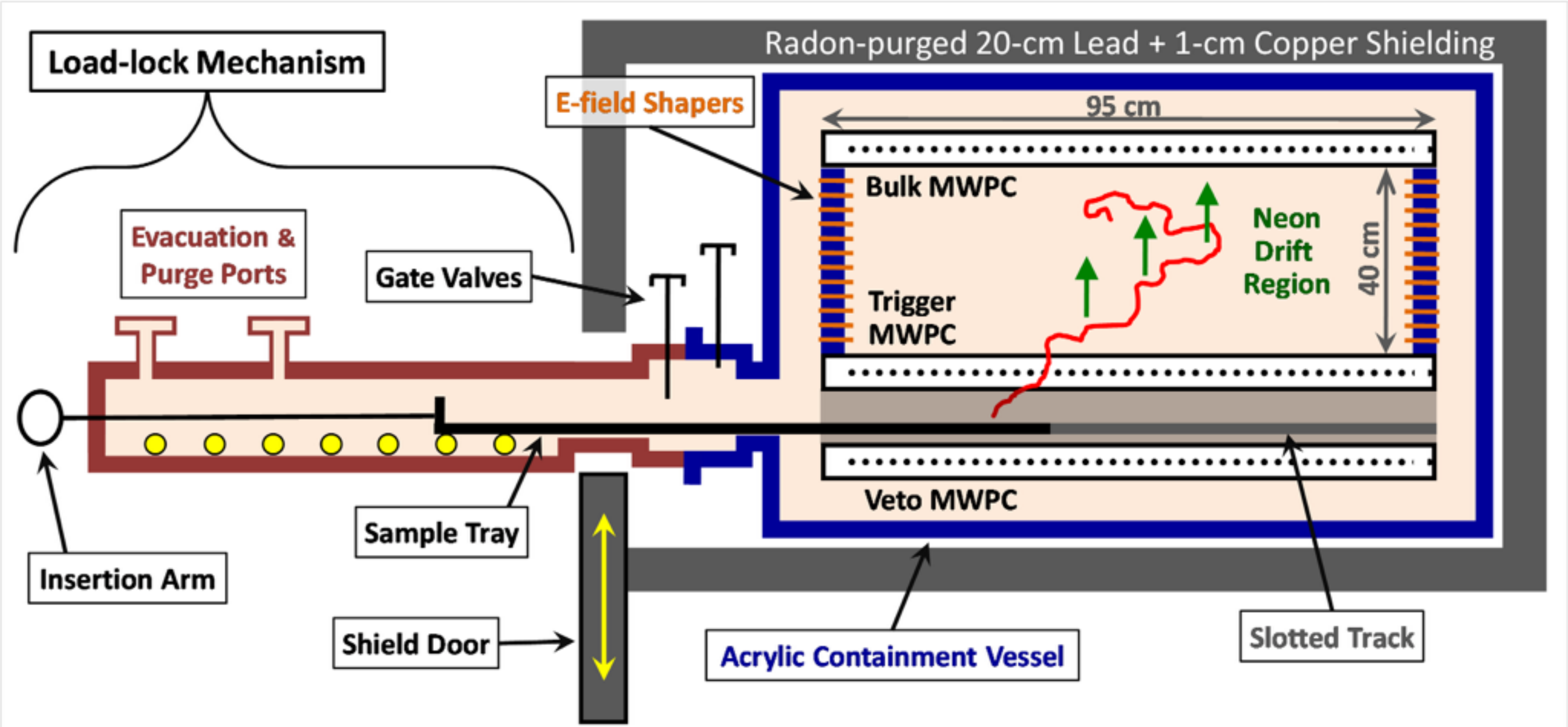
Load-lock Mechanism
Radon-purged 20-cm Lead + 1-cm Copper Shielding
E-field Shapers
95 cm
Bulk MWPC
Evacuation &
Purge Ports
Gate Valves
Neon
Drift
Region
40 cm
Trigger
MWPC
Veto MWPC
Sample Tray
Insertion Arm
Shield Door
Acrylic Containment Vessel
Slotted Track