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ACTIVE TARGET DETECTORS

OUTLINE

I. Why Active Targets?

II. Technological challenges and solutions

III. Data analysis challenges and solutions

IV. A few results

- What is all the fuss with active targets?
  - Since the last decade, a large number of active target projects have emerged in the field of low energy nuclear physics
  - This emergence is mainly driven by two factors
    - The availability of low energy radioactive beams with good emittance
    - Significant advances in detector and data acquisition technologies

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  - This emergence is mainly driven by two factors
    - The availability of low energy radioactive beams with good emittance
    - Significant advances in detector and data acquisition technologies
- Scientific progress and technological advances go hand in hand
  - Scientific ideas drive technology advances, but new ones spring from their realization

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  - **Low recoil energies**: in inverse kinematics the recoil particles have very low energies in peripheral reactions such as (d,p) and (α,α')
  - **Thick targets and large solid angle**: to compensate the limited intensity of secondary beam, thick targets and high detection efficiency without loss of resolution are needed

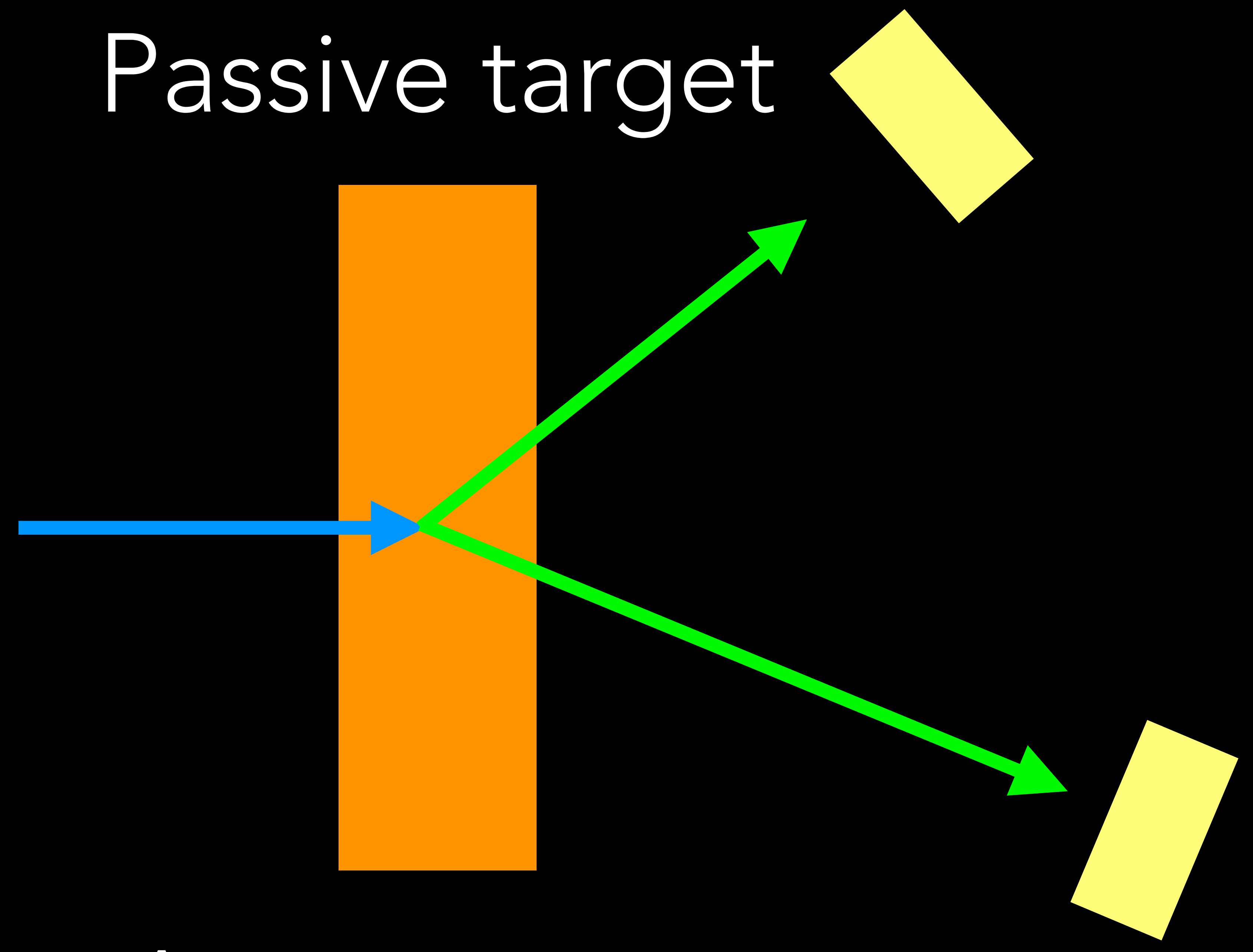
ACTIVE TARGET: THE BIG IDEA

- Device that is at the same time a target and a detector

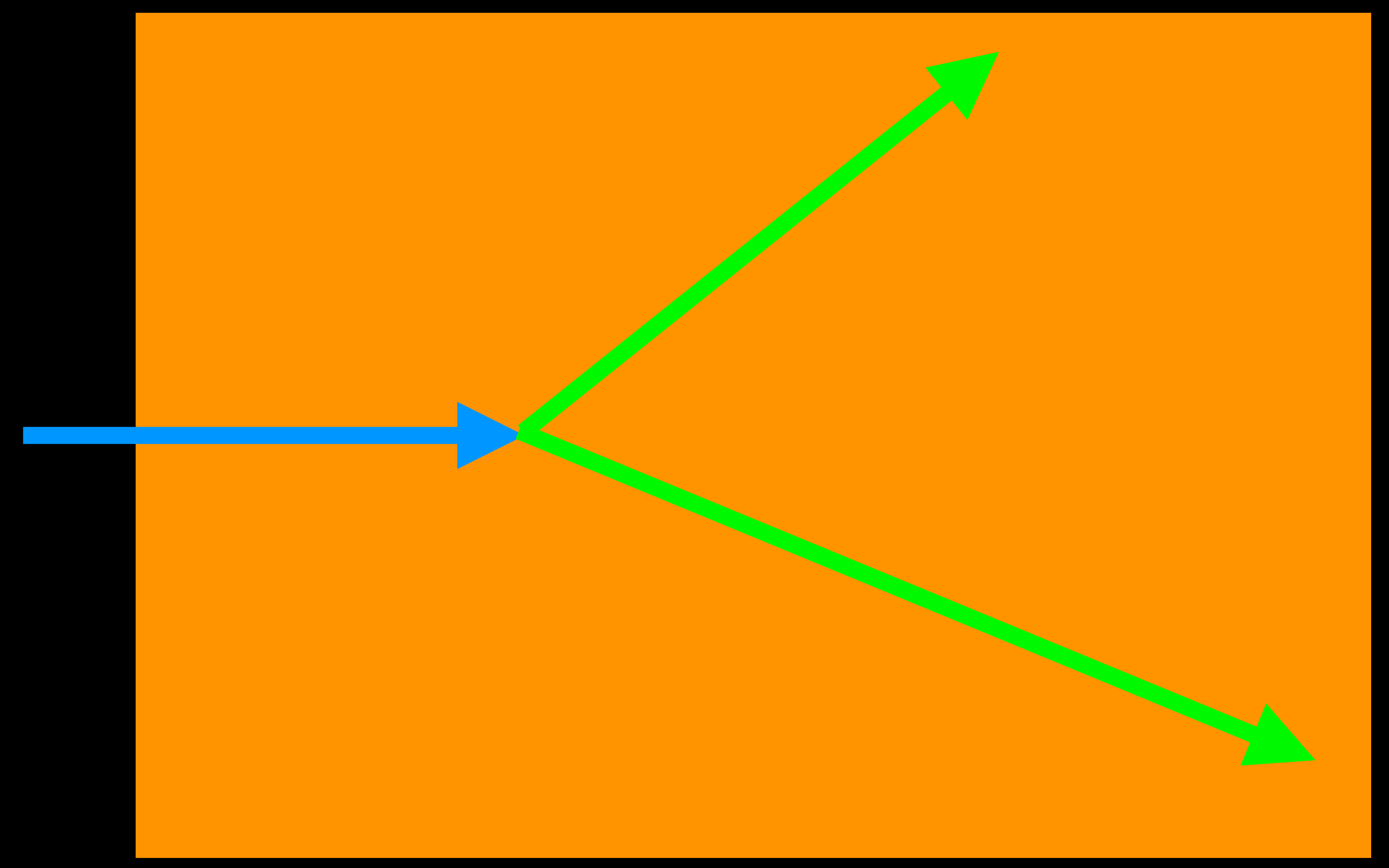
- Passive target
  - No knowledge of where the reaction took place
  - Particles can only be detected if they escape the target material

- Active target
  - Reaction vertex location can be determined
  - Particles are detected within the target material

Passive target



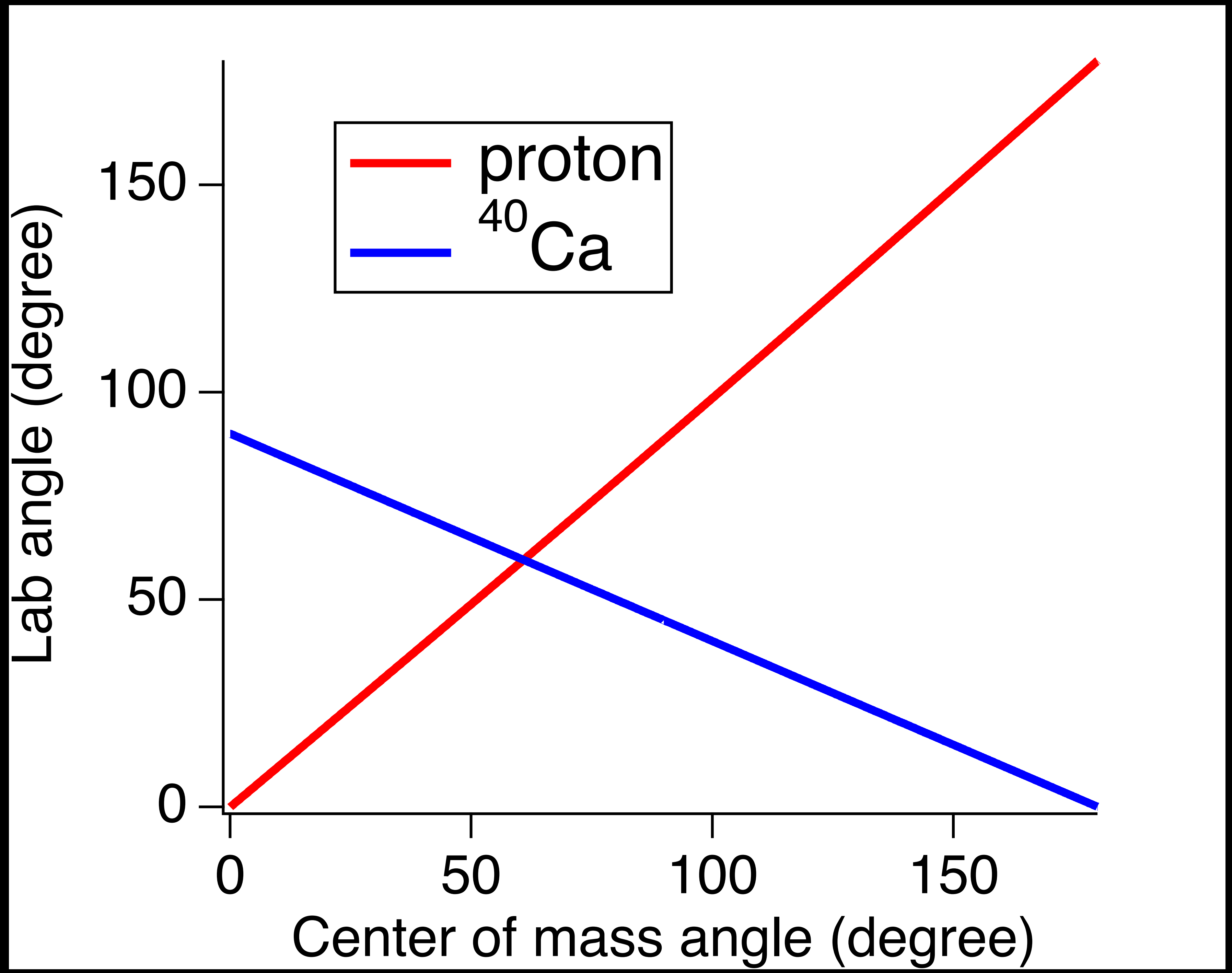
Active target



DIRECT KINEMATICS: ENERGETICS

- Study nuclei of target material
  - Beam of light nuclei (p, d, t, ^3He, ^4He)
  - Target of heavier nuclei under study

- Example: proton elastic scattering at 10 MeV on ^{40}Ca
  - Energy of outgoing proton almost constant
  - Easily escapes the target at almost all angles
  - ^{40}Ca has very low recoil energy and is stuck inside target



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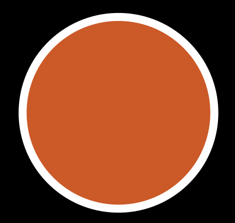

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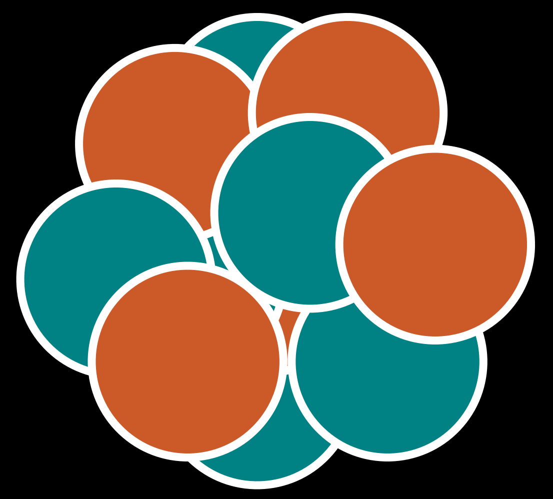
^{40}Ca



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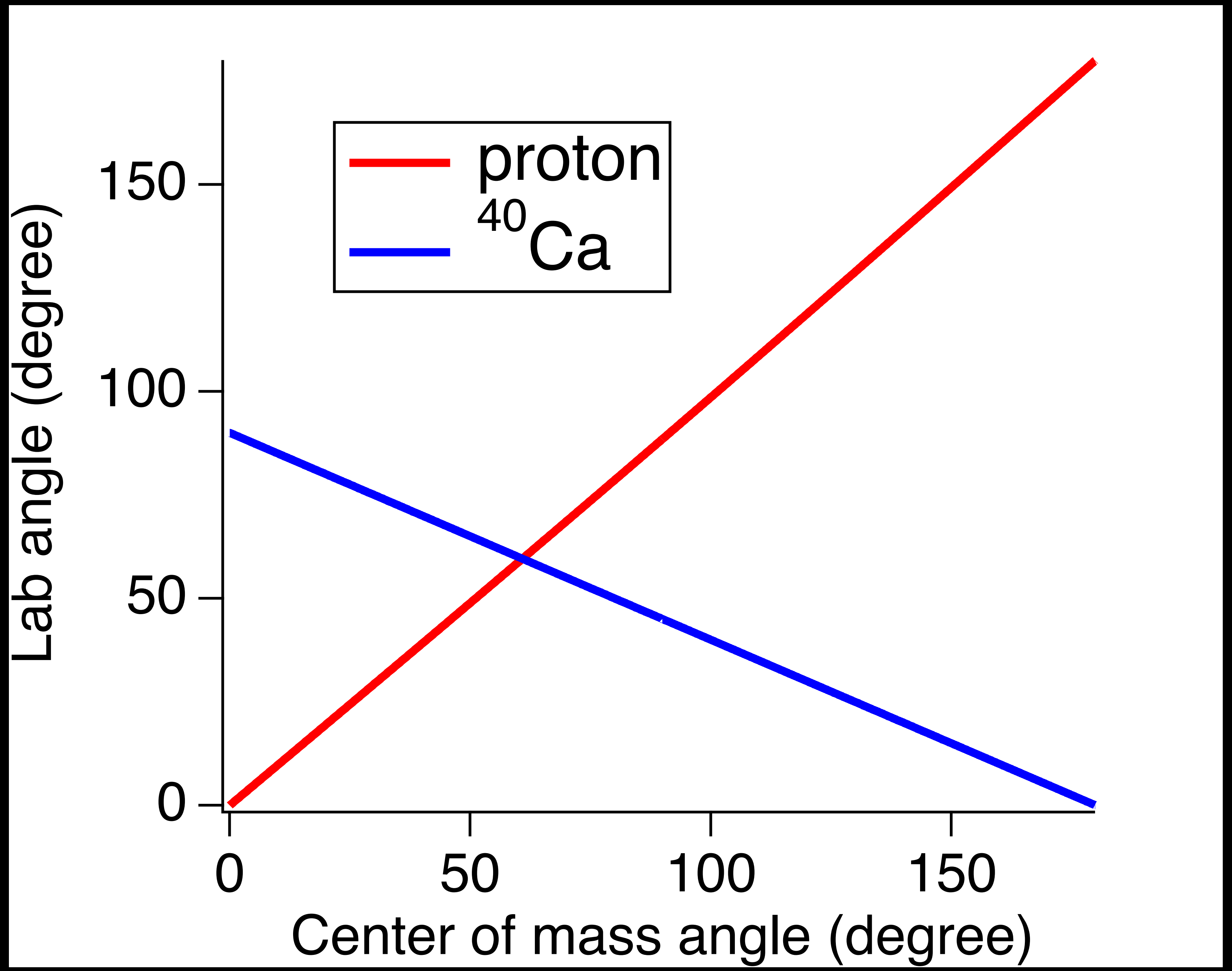

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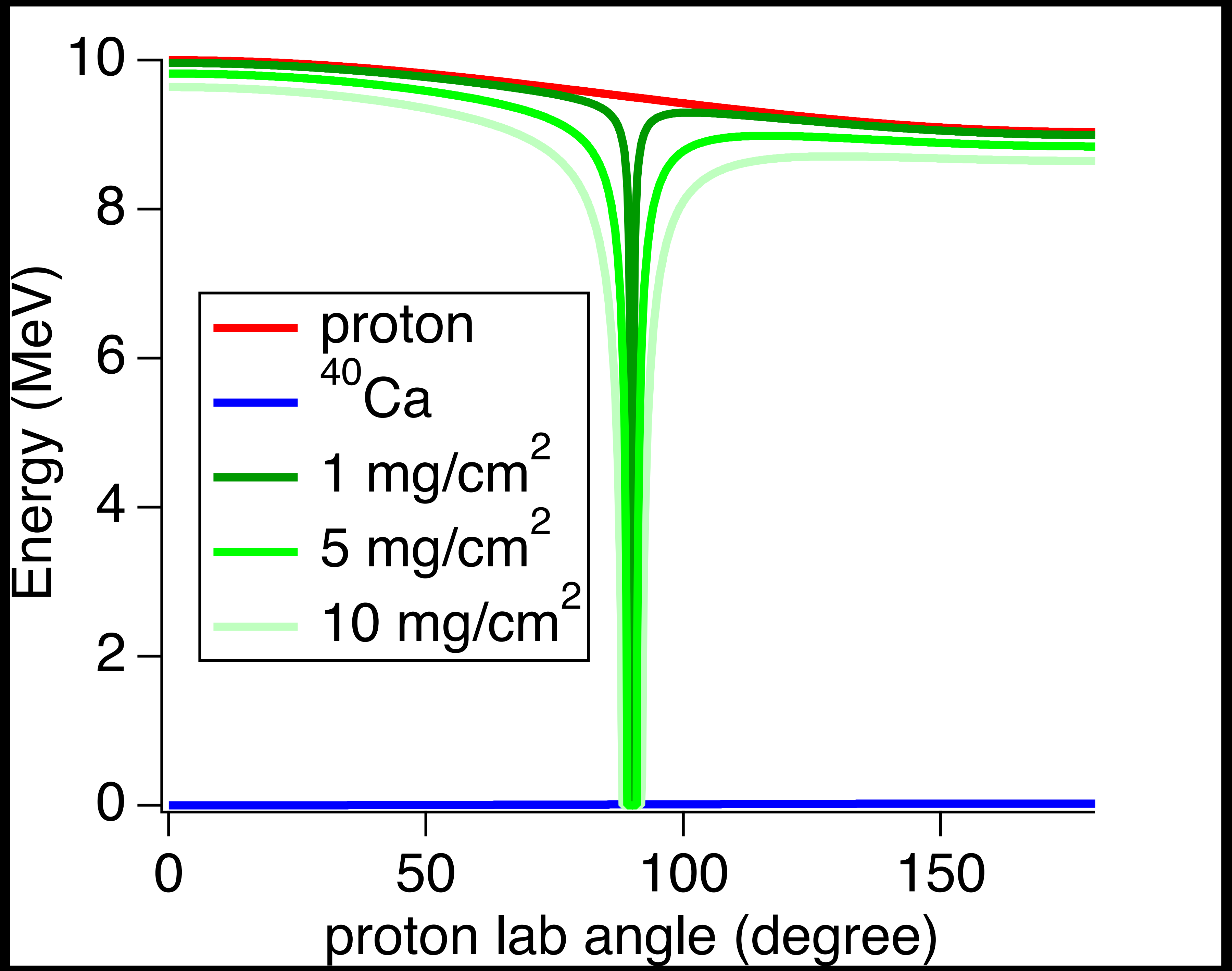
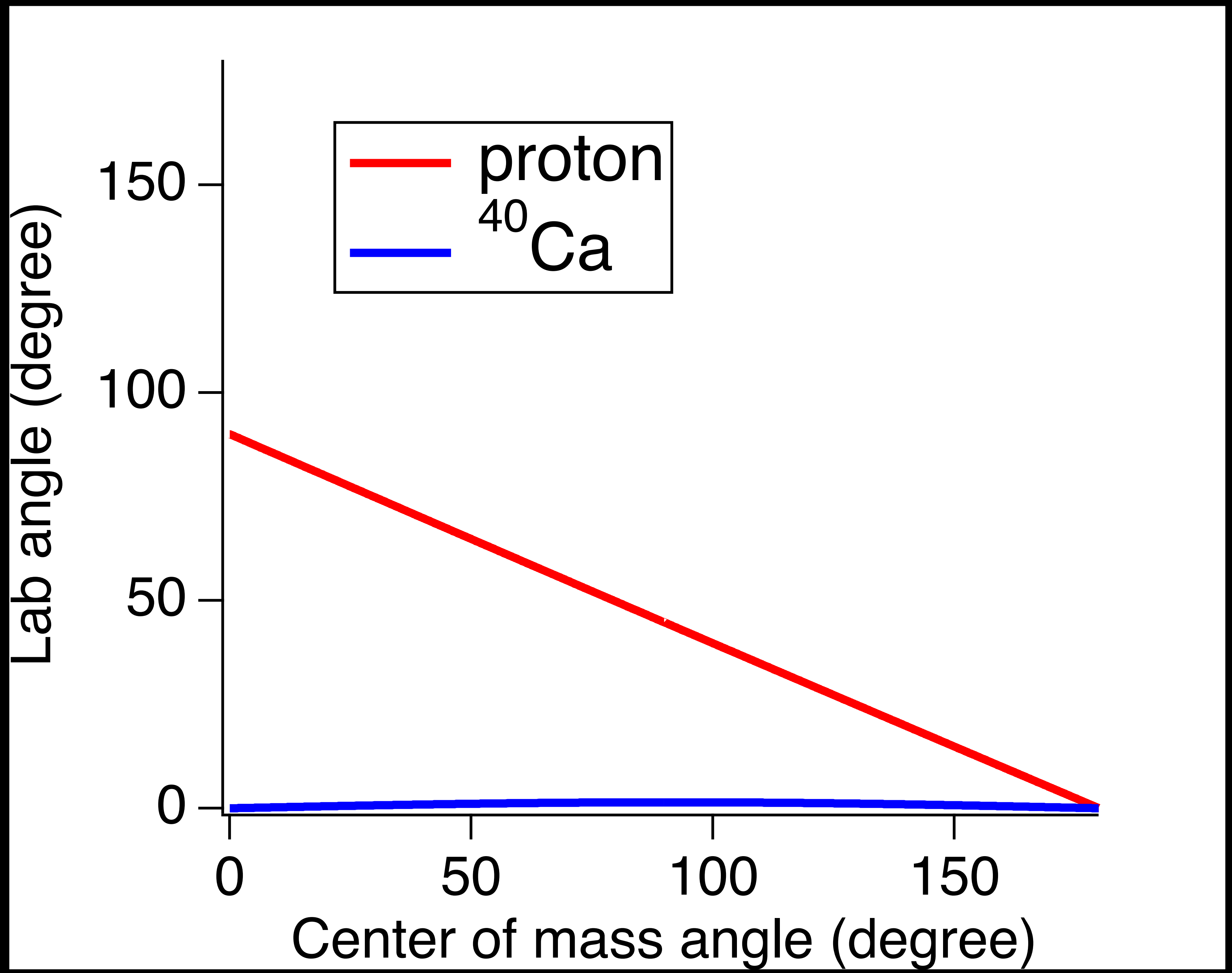


INVERSE KINEMATICS: ENERGETICS

- Beam and target roles are reversed
  - Beam now carries most of the center of mass motion
  - ^{40}Ca deflection angle very small
  - Kinematics properties of reaction can only be extracted from proton
- Energies drastically different
  - Proton energy varies from 0 to 40 MeV
  - Maximum cross section region is cut off (close to 90° in lab)



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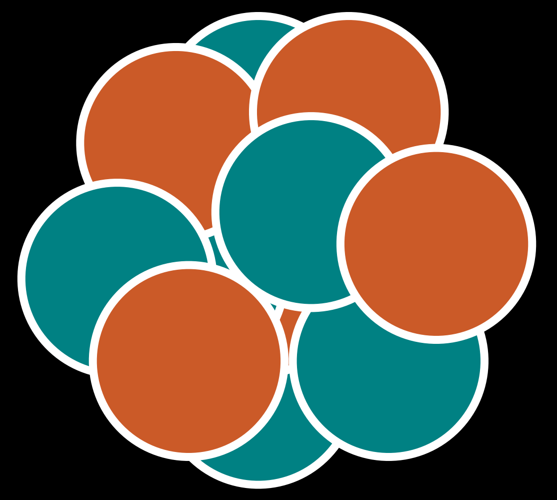

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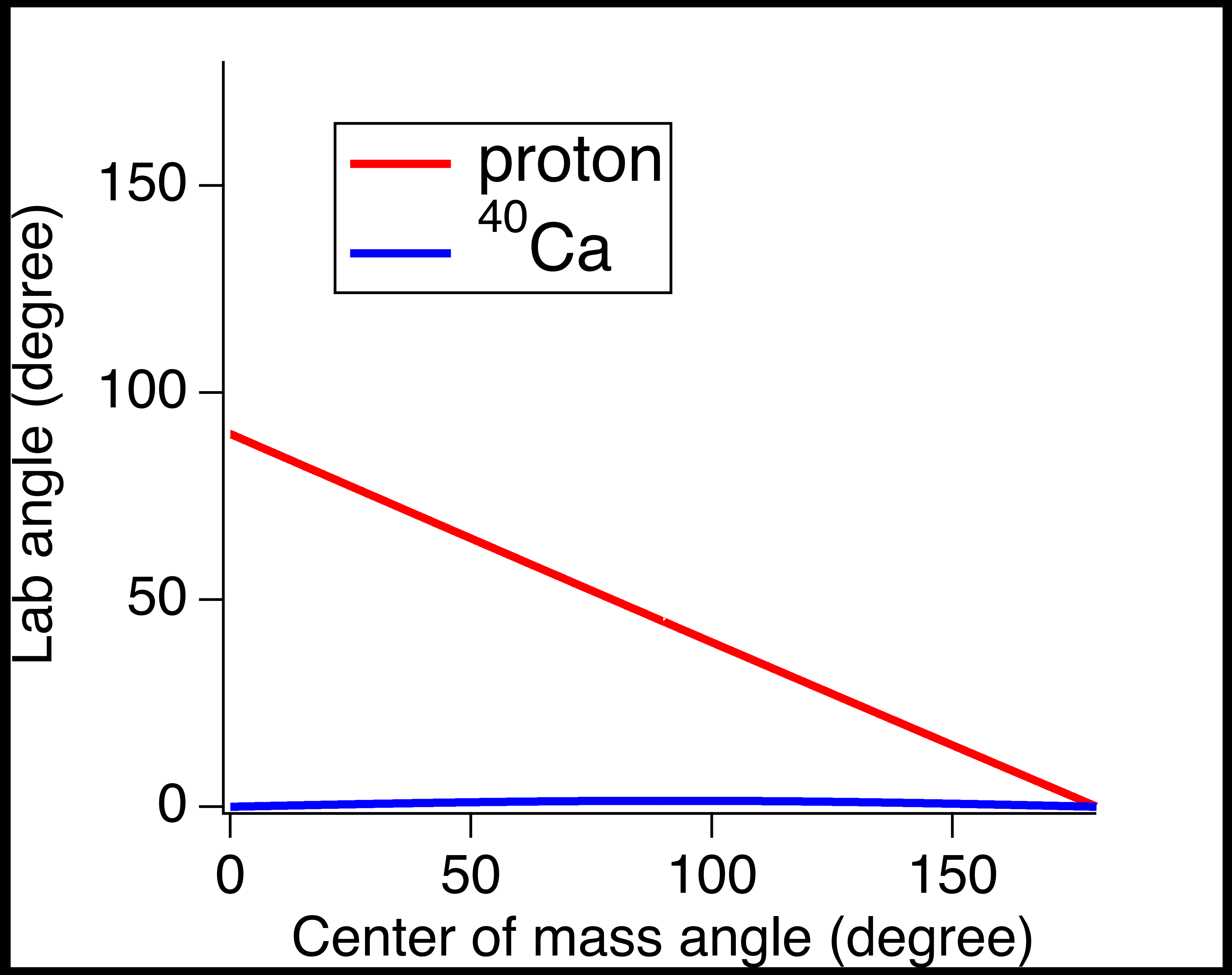

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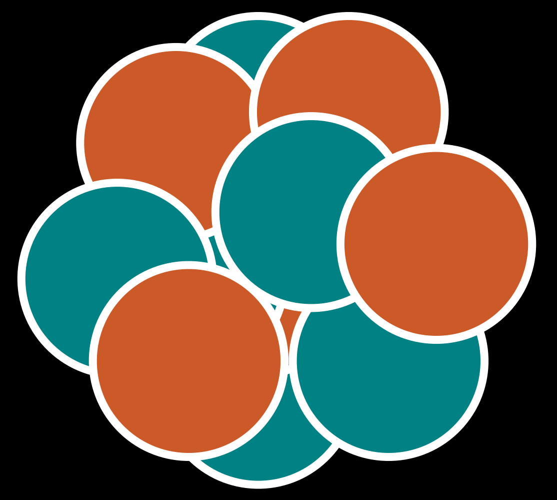

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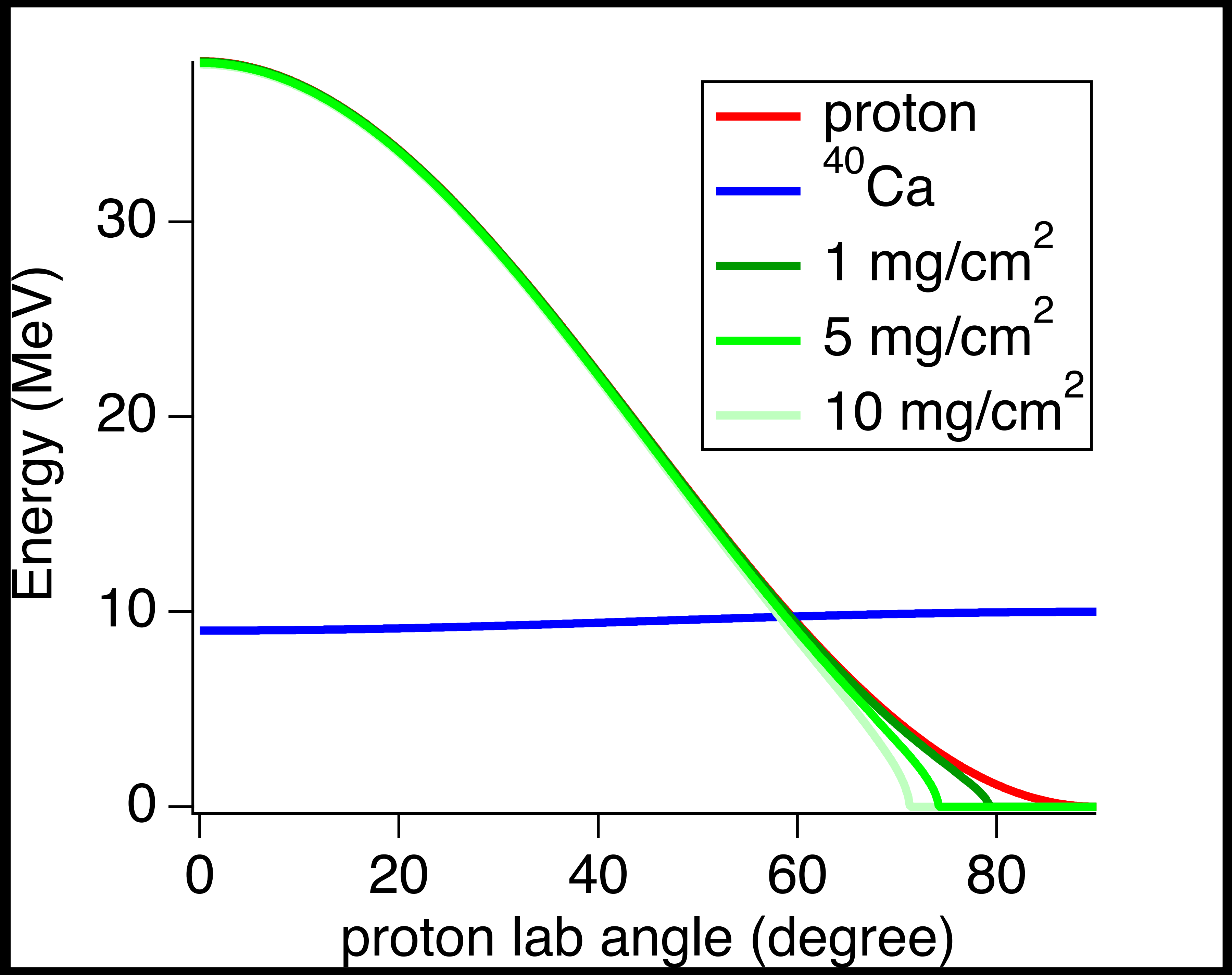

ACTIVE TARGETS TO THE RESCUE!

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- Use volume of gas as target material AND detector medium
  - Gas-based tracking detectors already exist: Time Projection Chambers
  - No need for particles to escape target in order to be detected
  - Reaction vertex measurement: no resolution loss due to unknown reaction site

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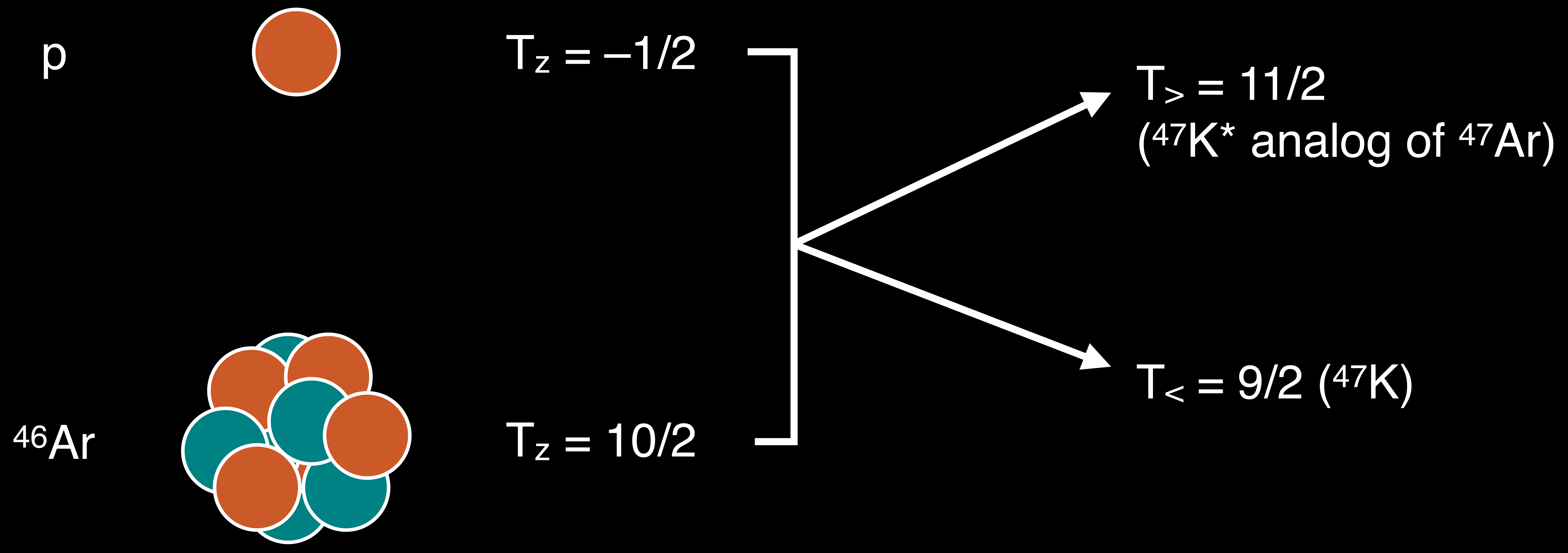
  - Reaction vertex measurement: no resolution loss due to unknown reaction site
- Increase target thickness while retaining resolutions of a thin target
  - Necessary to reduce luminosity loss due to small radioactive beam intensities
  - Allow measurement of excitation functions using vertex energy
  - Large solid angle coverage close to 4π

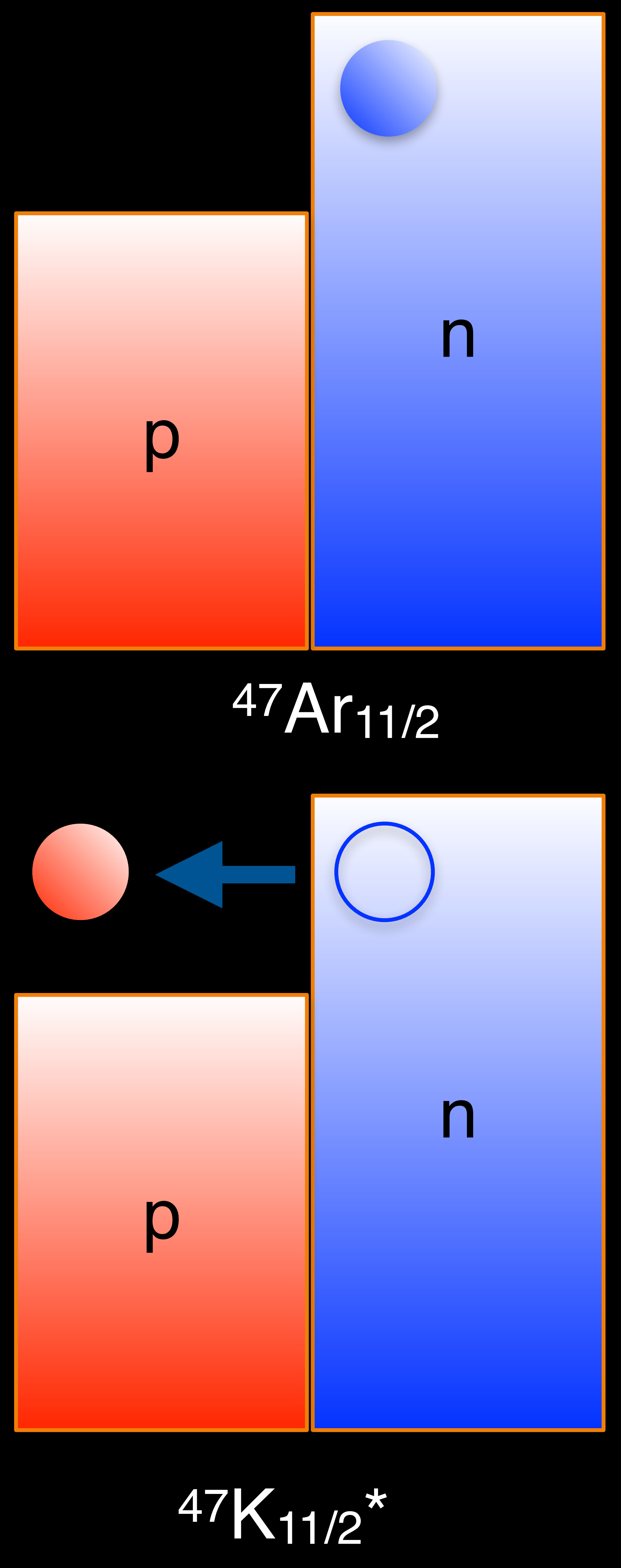
PHYSICS THEMES LIST (NON EXHAUSTIVE)

- Resonant scattering: cluster structure and analog resonances
- Excitation functions of reactions of astrophysical importance
- Fusion cross sections and fission barrier studies
- Transfer reactions: single particle structure of nuclei far from stability
- Giant resonance excitations via inelastic scattering
- Gamov-Teller strength in exotic nuclei via charge-exchange reactions
- Exotic and rare decays

PROTON RESONANT SCATTERING

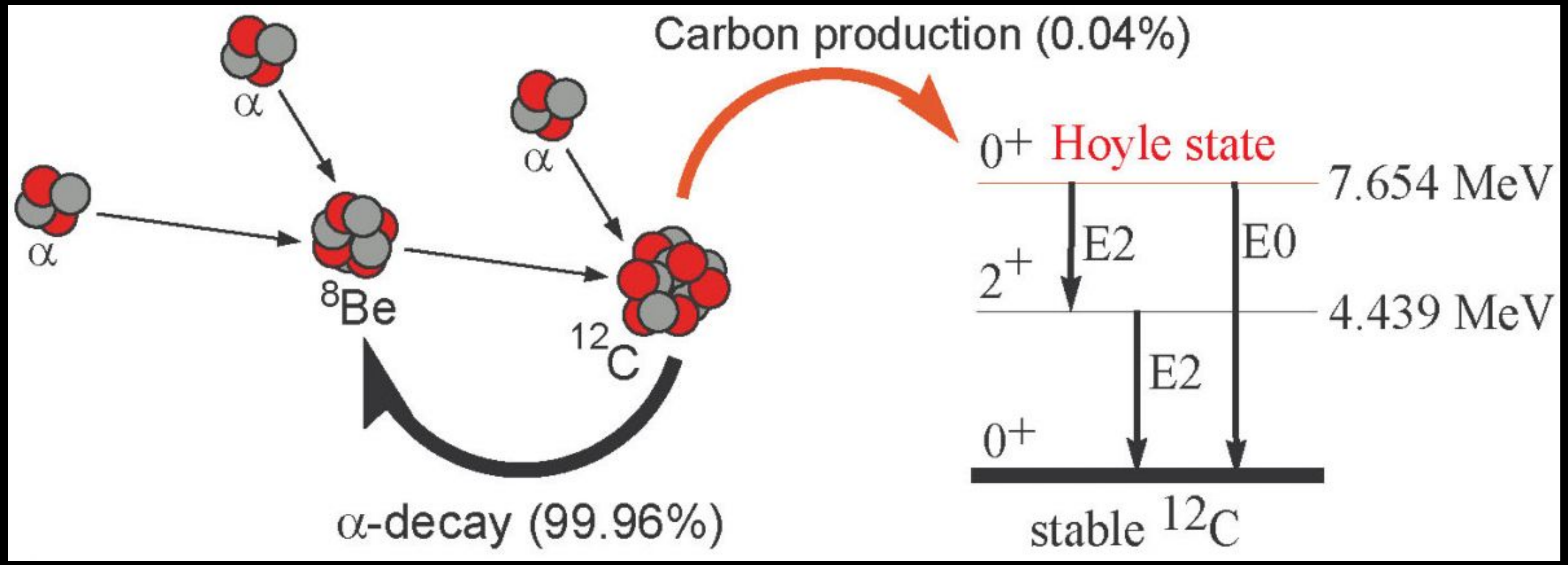
- Proton scattering around the Coulomb barrier populate $T_<$ and $T_>$ states (resonances) of compound nucleus
- ^{47}Ar bound states have similar WF as analog $T_>$ states in ^{47}K

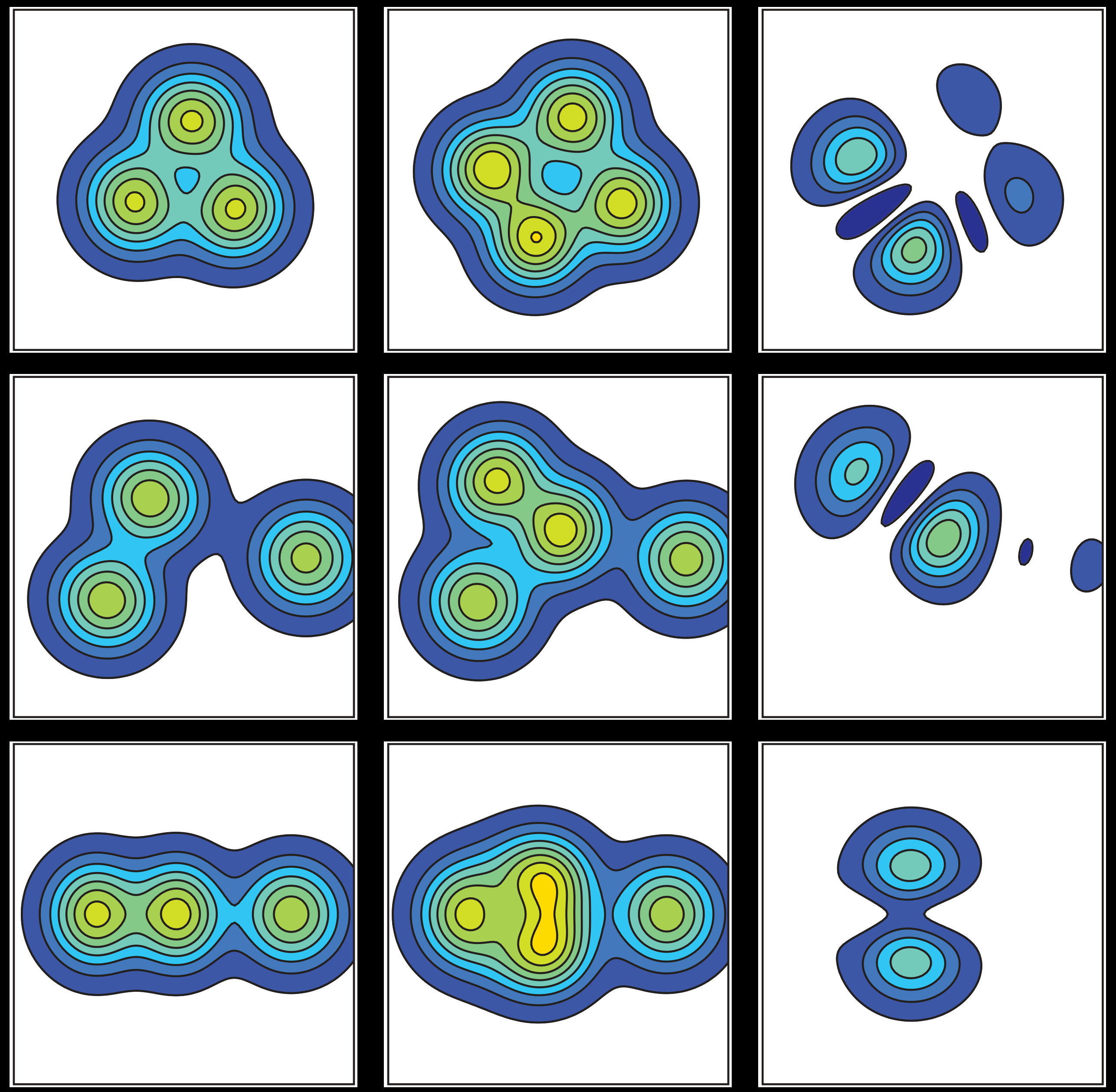




RESONANT ALPHA SCATTERING

- Populate α-cluster states in compound nucleus
  - Several calculations predict α condensation in high level states
  - Famous example is the 3-α 0^+ state in ^{12}C (Hoyle state)
  - Neutron-rich nuclei may exhibit similar molecular structure
  - States can be populated in resonant α scattering ($^6He+^4He$: ^{10}Be, $^{10}Be+^4He$: ^{14}C for instance)

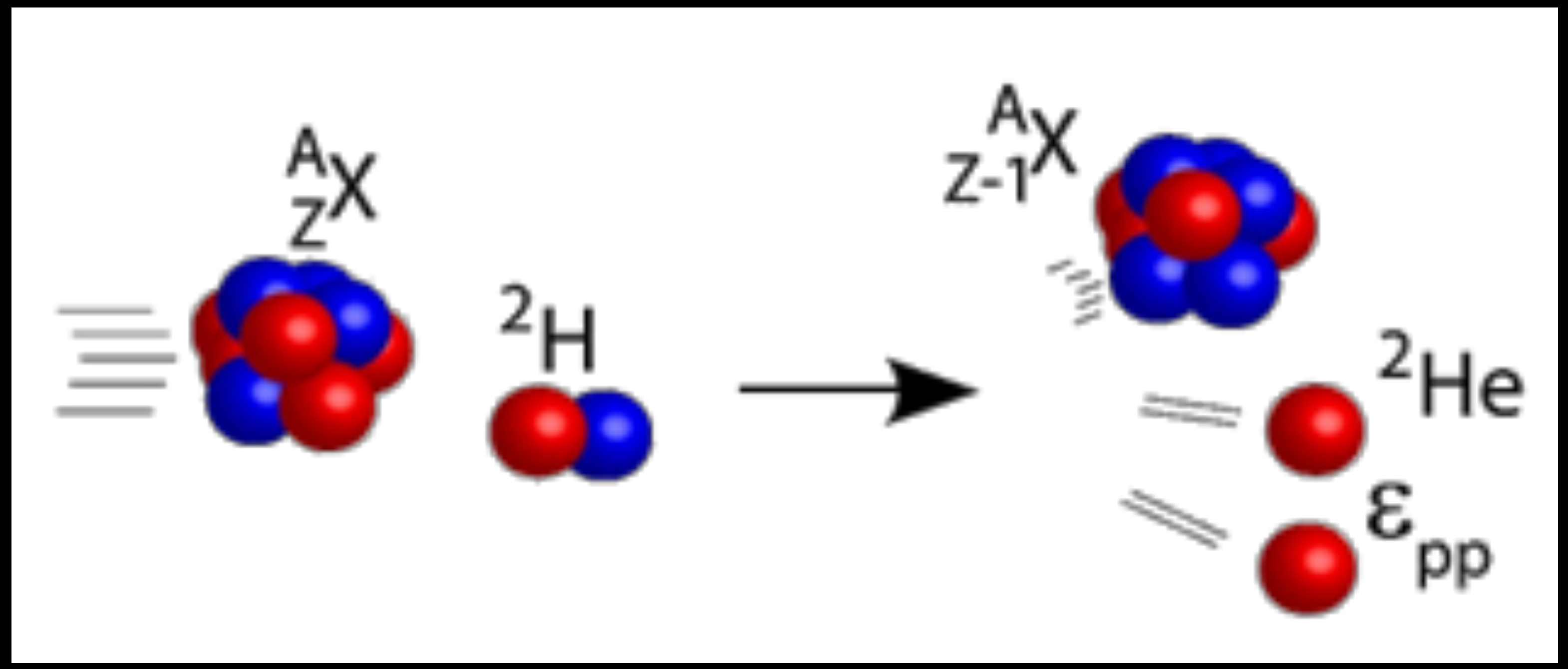


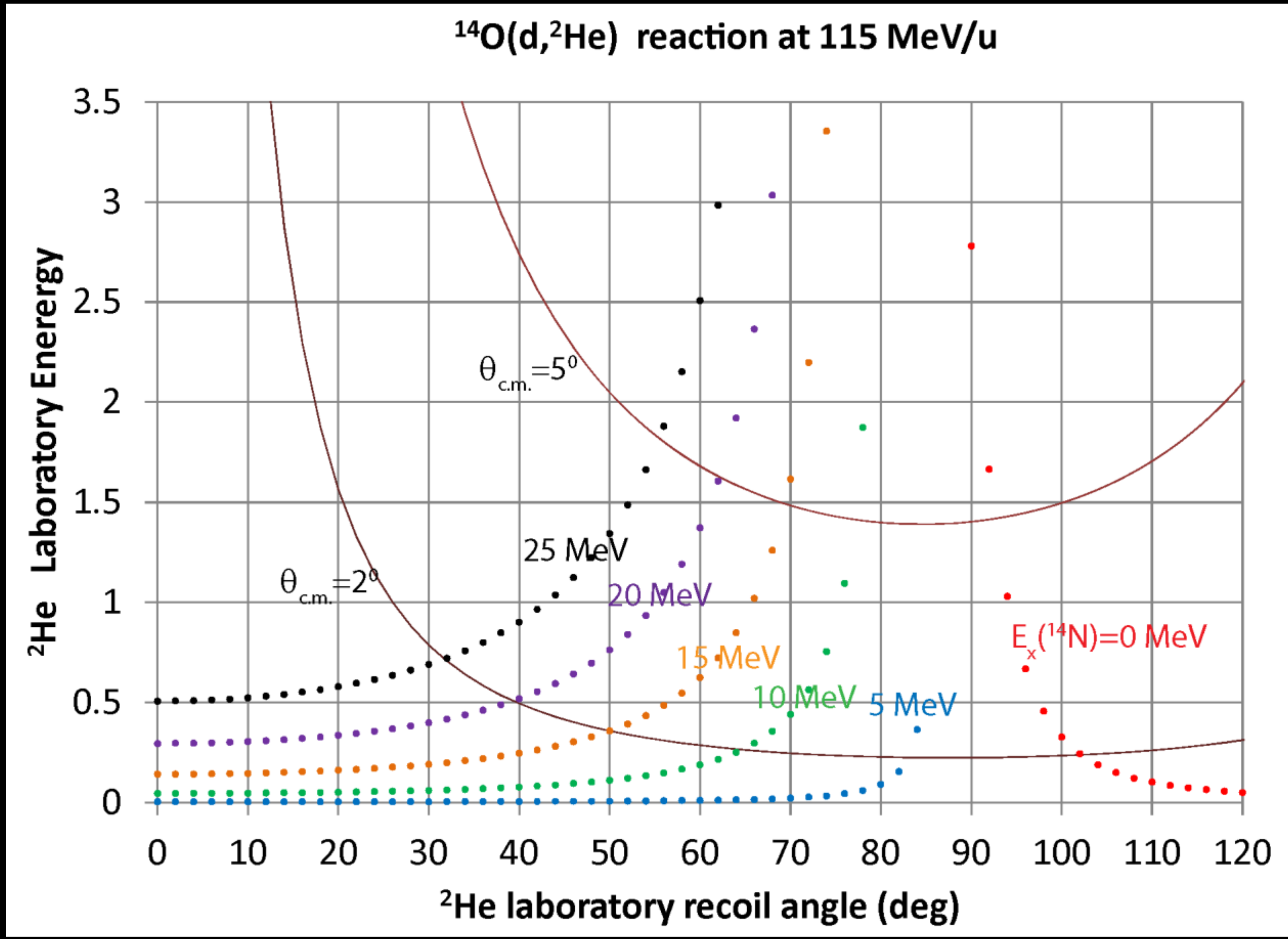


T. Suhara and Y. Kanada-En'yo. Cluster structures of excited states in ^{14}C. Phys. Rev. C, 82:044301, 2010

REACTIONS AT HIGH ENERGY

- Charge-exchange reactions
  - Probe the spin-isospin response of nuclei (measure Gamow-Teller strength)
  - Can reach strength at higher energy than β^+ and β^- decay
  - Extensively used in direct kinematics (ex: (p,n), (d,^{2}He), (^{3}He,t), (t,^{3}He),…)
  - Much more challenging on radioactive nuclei in inverse kinematics
  - Example: ^{14}O(d,^{2}He) at 115 MeV/u, energy of protons is very low





CHALLENGES OF ACTIVE TARGETS

- Beam-related issues
  - Large amount of primary electrons from beam tracks
    - Space charge effects can create “dead region” in beam track region
    - Large amount of charge deposited on electron multipliers can create saturation effects
  - Time structure of radioactive beam
    - Low duty factor beam structure are commonplace when using charge breeder systems
    - TPCs are inherently slow detectors and easily subject to pile-up

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- Trigger generation: how to select "interesting" events only
  - Because of its nature, an active target "sees" all types of events
  - Most likely event: beam slowing down in gas without making nuclear reaction
  - Next to most likely: elastic scattering of beam on gas nuclei

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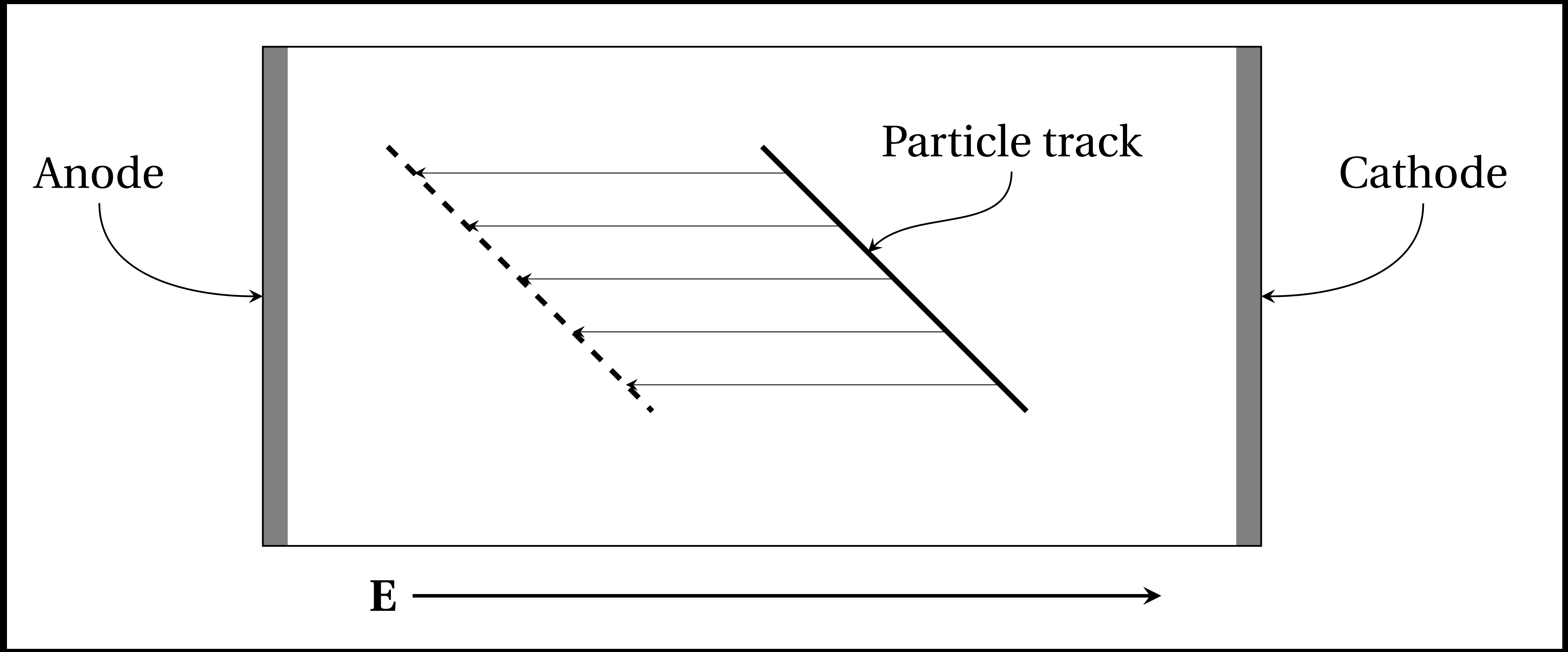
- Possible solutions
  - Use of ancillary (external) detectors to generate trigger
    - Requires particles to escape gas volume
  - Generate "internal" trigger from geometry of tracks themselves
    - Requires special electronics with constant monitoring of signals

TIME PROJECTION CHAMBERS

- 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

DRIFT VELOCITY

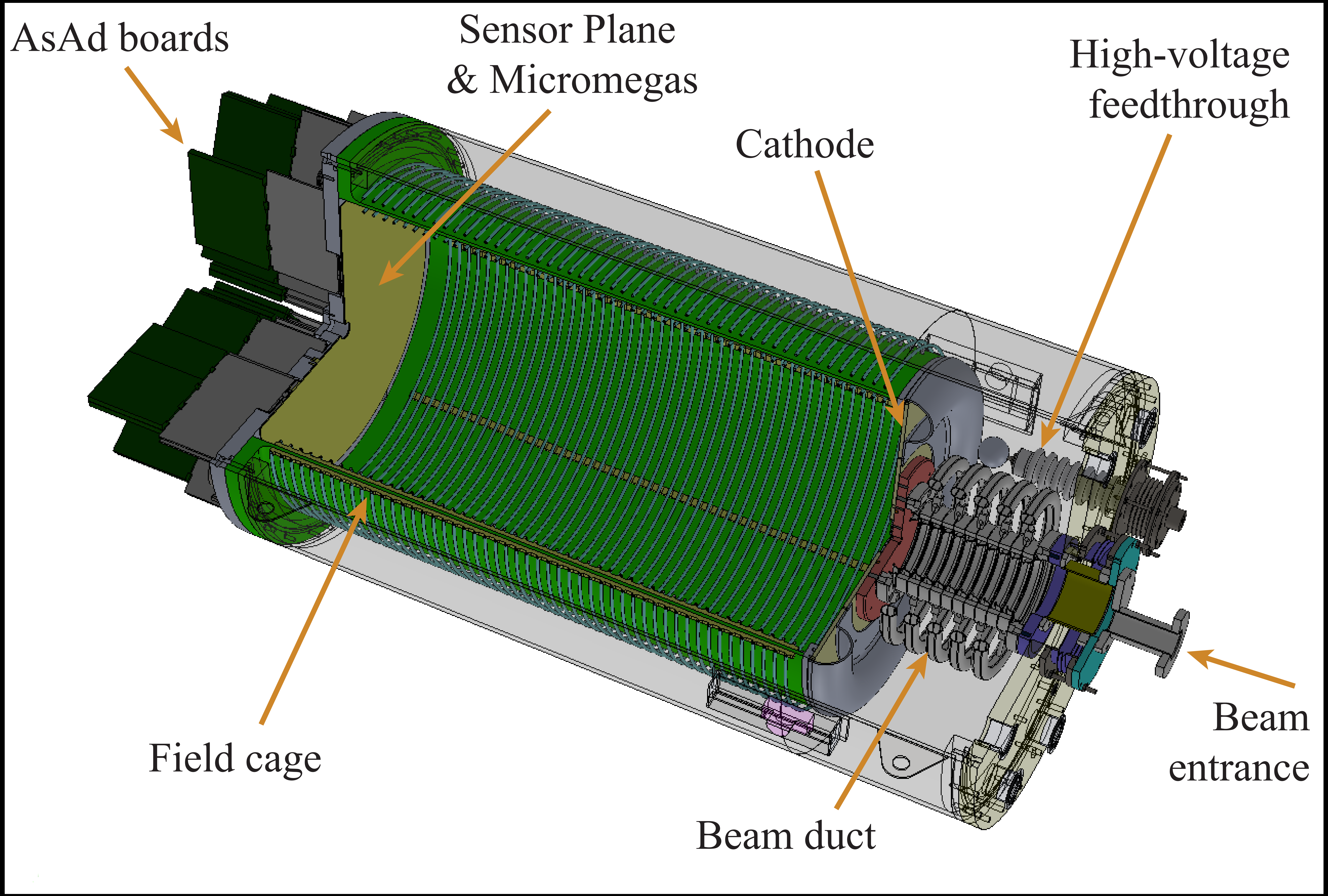
- Propagation of electrons
  - Follow Langevin's equation
  - $\tau = mv_D/eE$ is the mean time between collisions
  - $\omega = eB/m$ is the cyclotron frequency
  - $\mu = e\tau/m$ is the electron mobility
- Electrons have a constant velocity
  - Essential to TPC concept

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

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

THE AT-TPC AT NSCL

- Cylindrical volume
  - 250 liters (1 m long by 55 cm wide)
  - Oriented on beam axis
  - Electrons produced in gas drift towards sensor plane parallel to beam direction
  - Surrounding volume filled with insulator gas such as N_2



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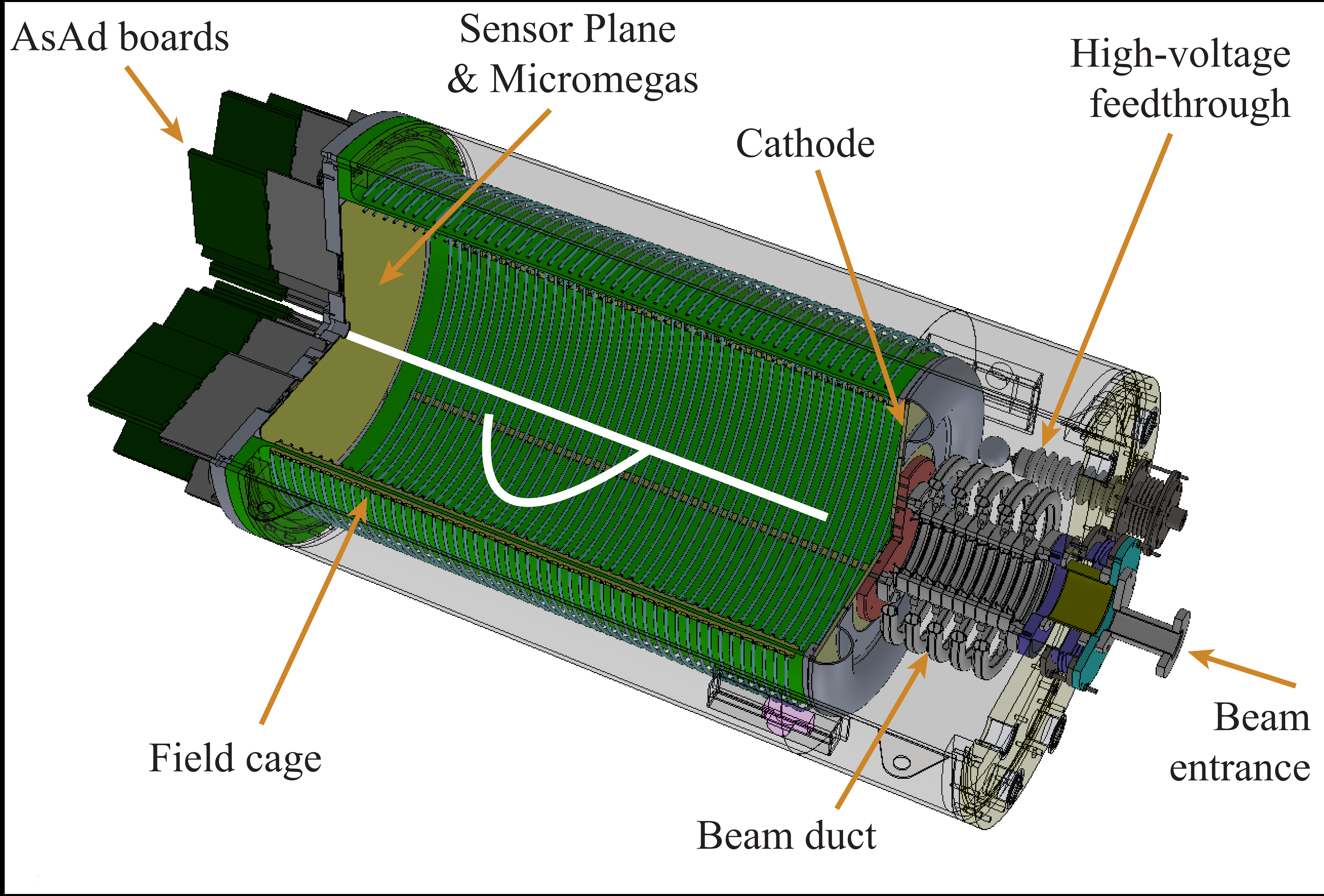

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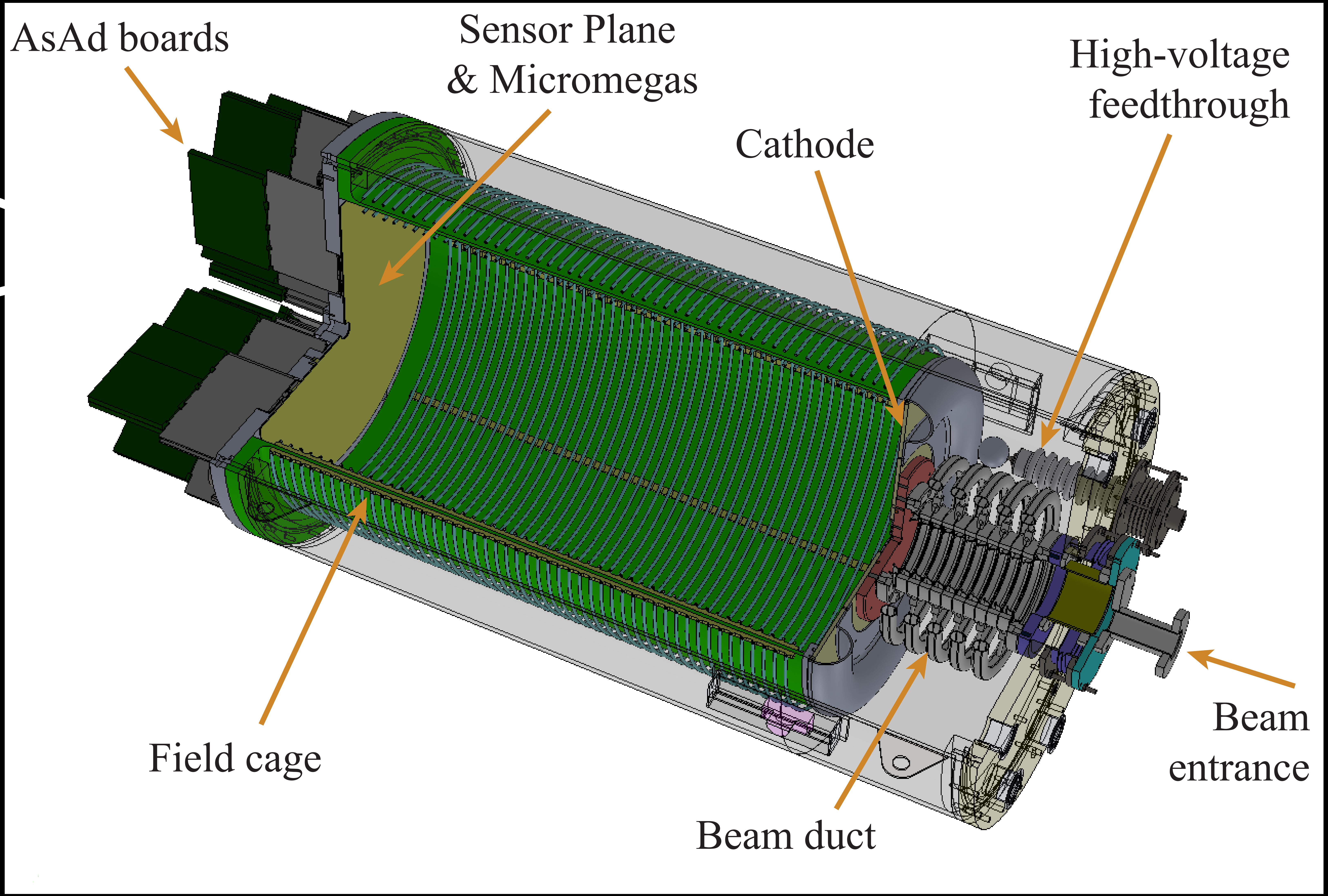
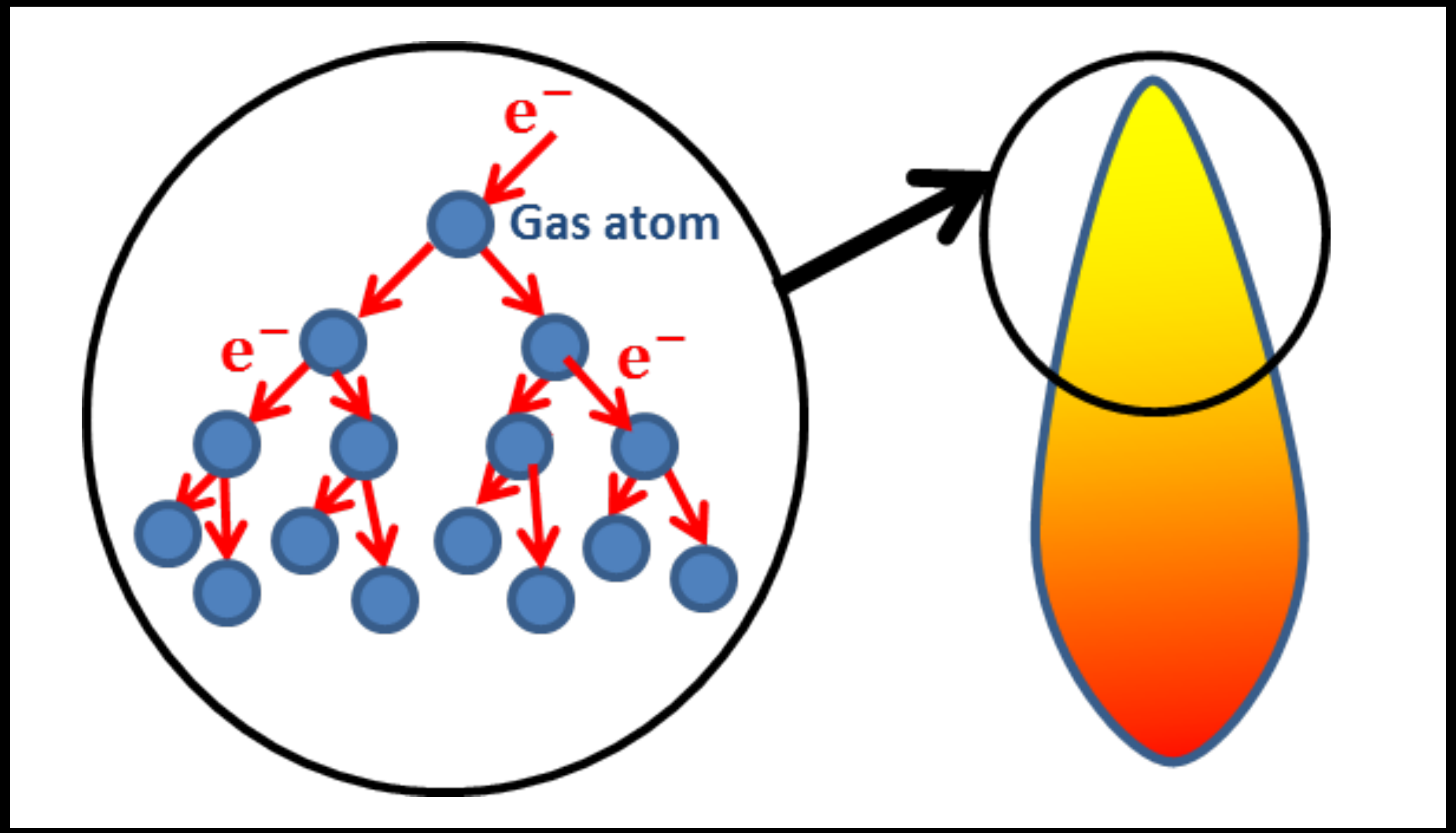


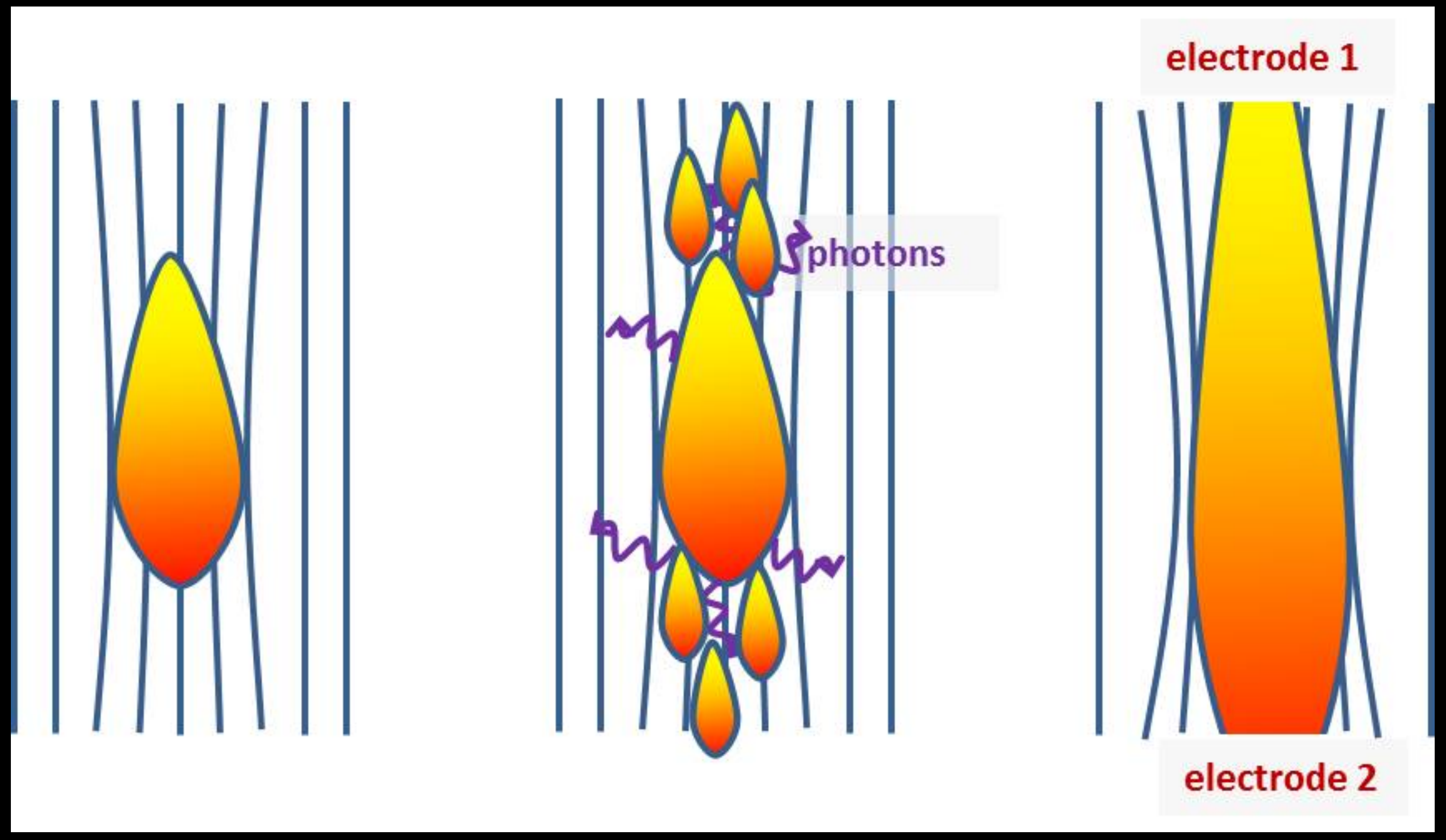
ELECTRON MULTIPLICATION

- 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



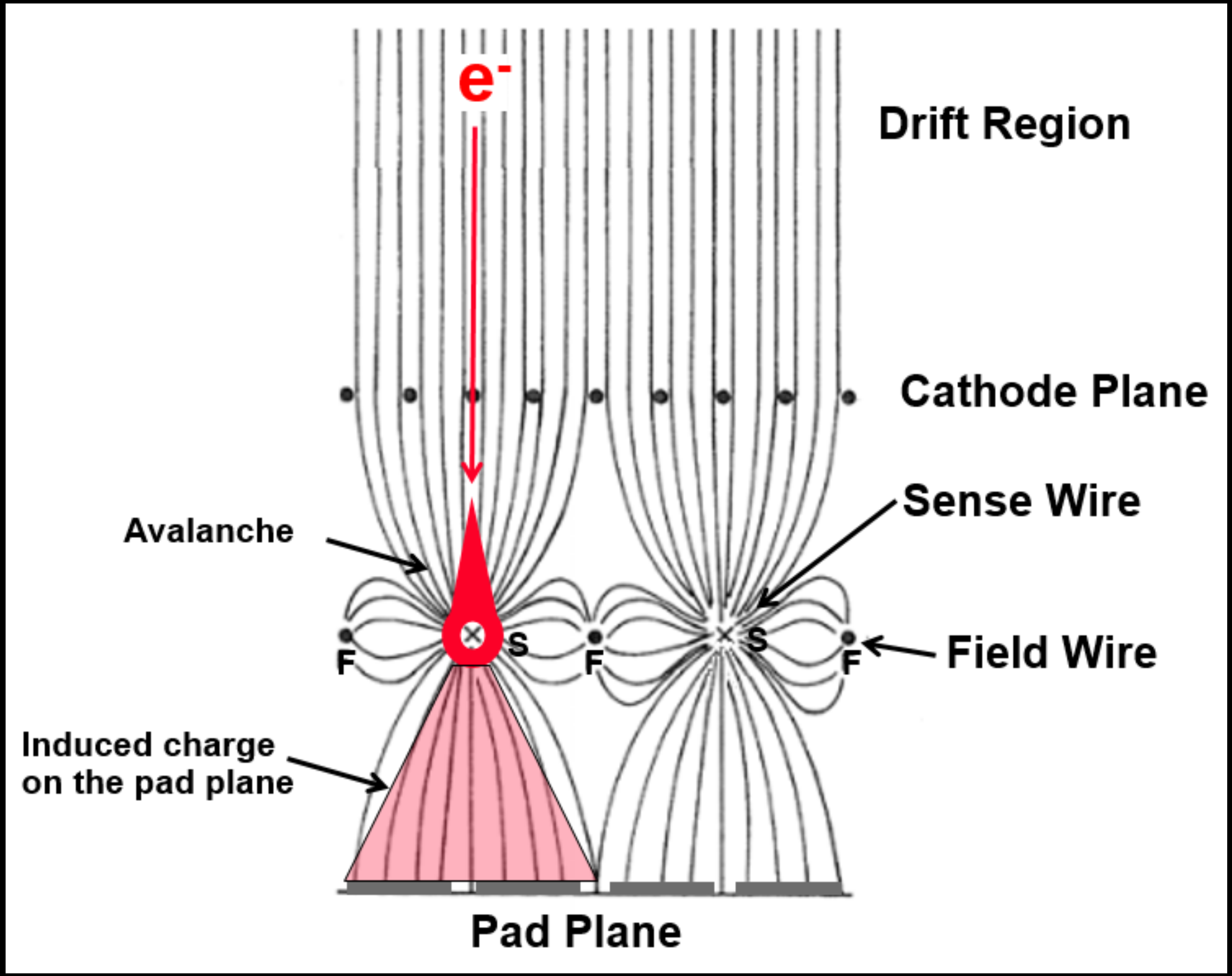
$$G = e^{\alpha d}$$

- Sparking limit
  - Photons produced in avalanche can trigger secondary ionization
  - This runaway process can lead to formation of streamers that become conductive



MULTIPLICATION DEVICES: MWPC

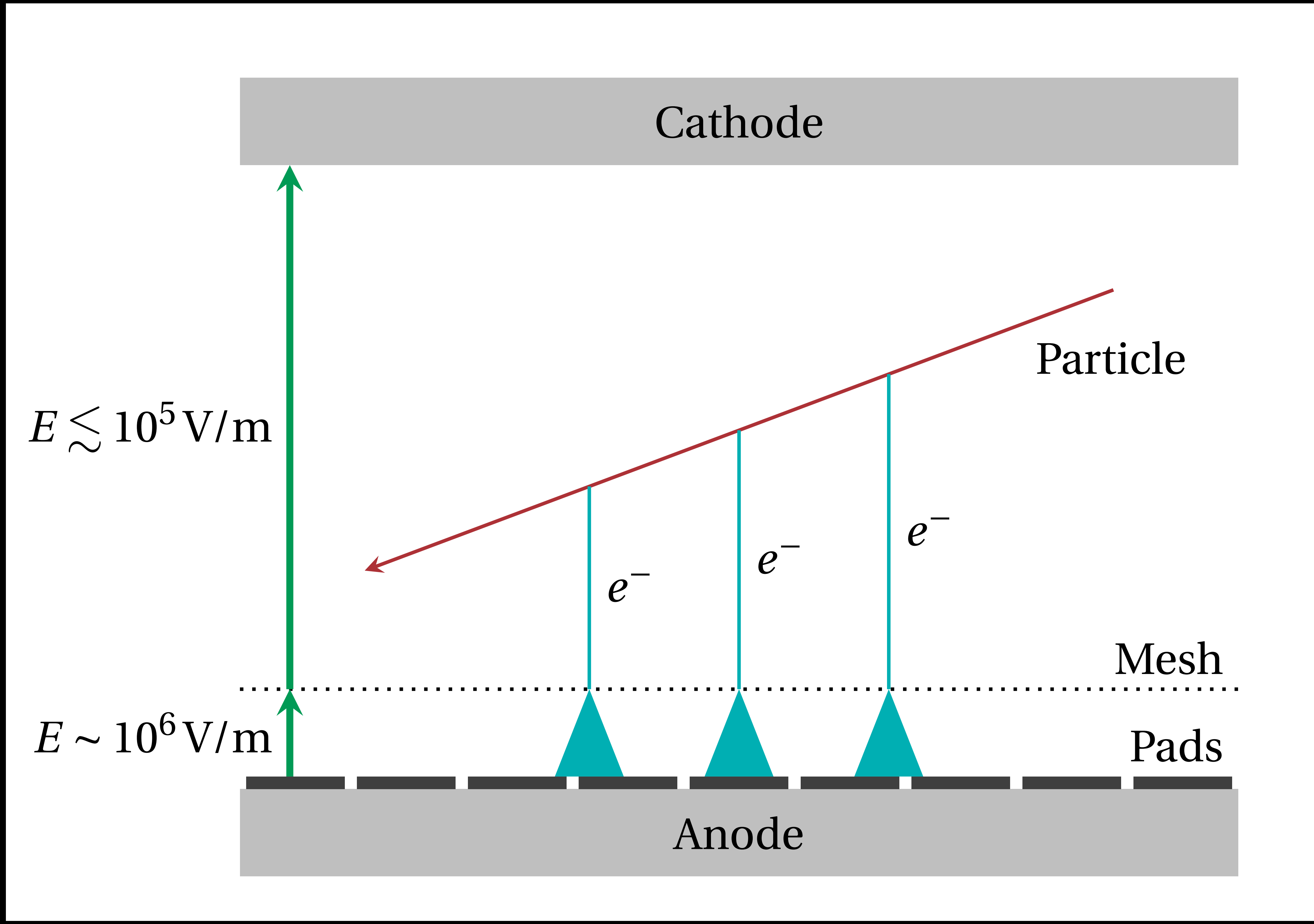
- Multi Wire Proportional Counter
  - Early days of TPCs
  - Nobel prize 2005 (R. Sharpak)
  - High electric field gradient close to wire
  - Signal read on pads and wires



- Drawbacks
  - Not very robust mechanically
  - Aging issues from discharges on wire
  - Large ion back flow

MULTIPLICATION DEVICES: 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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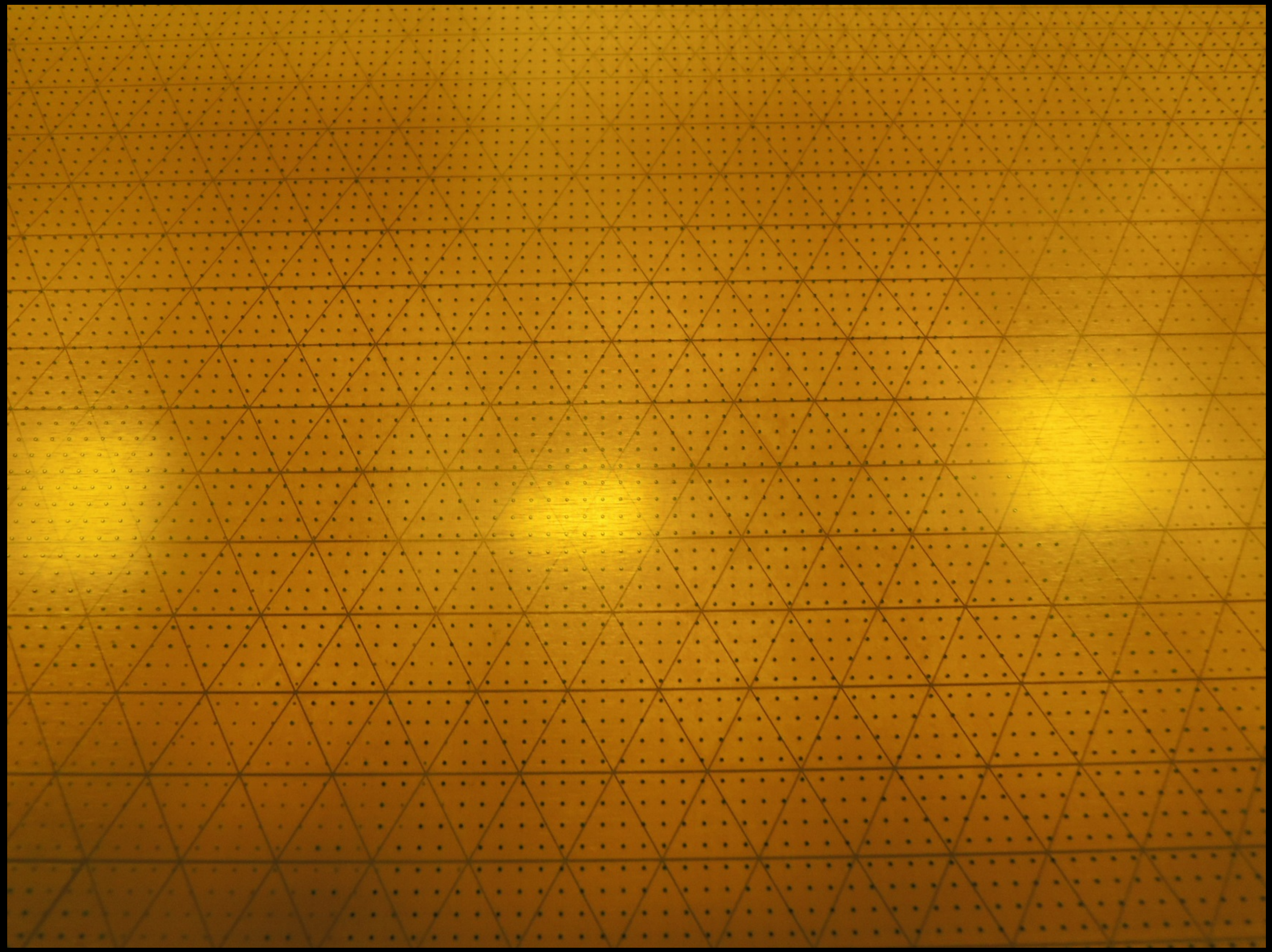

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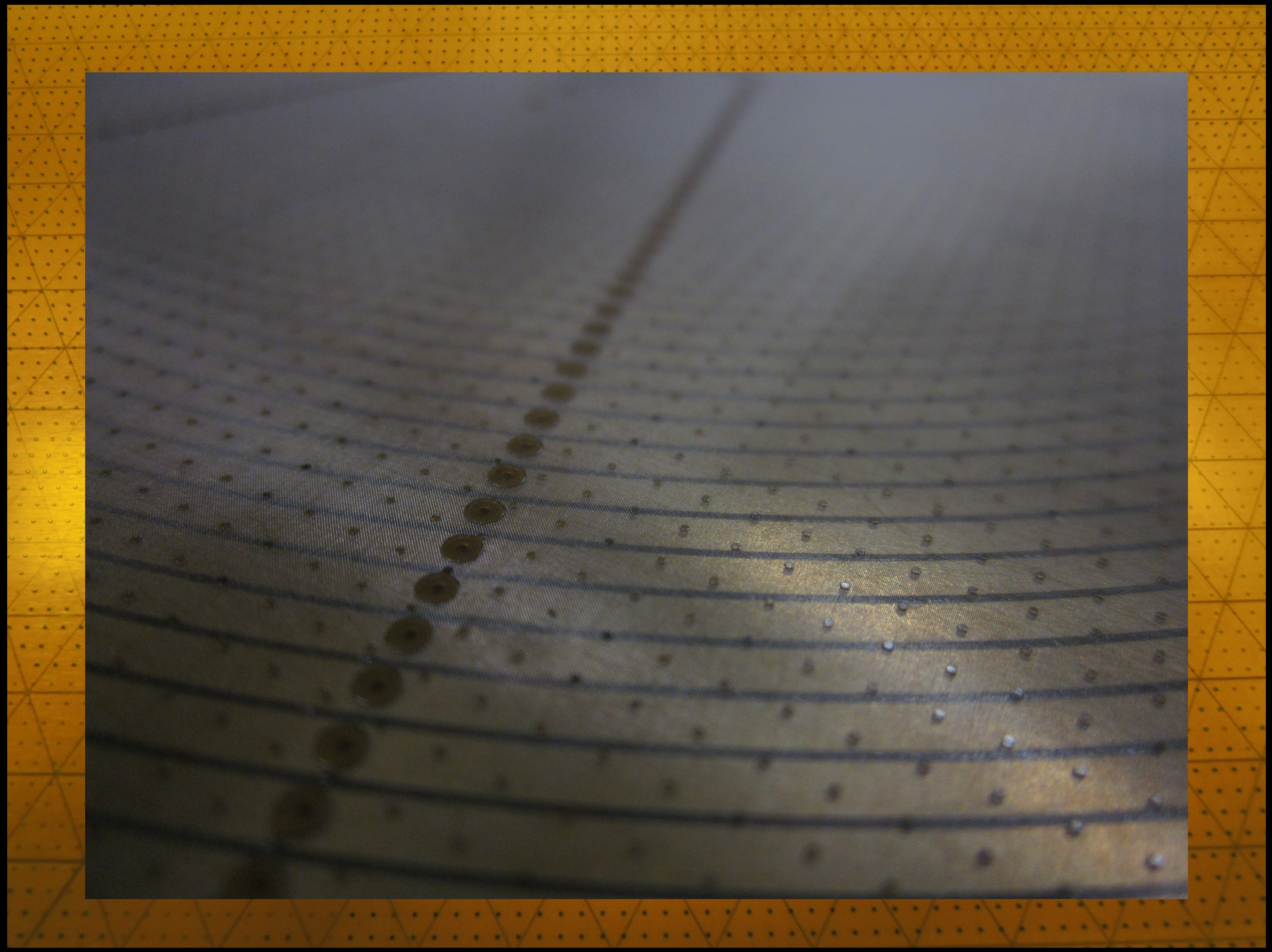
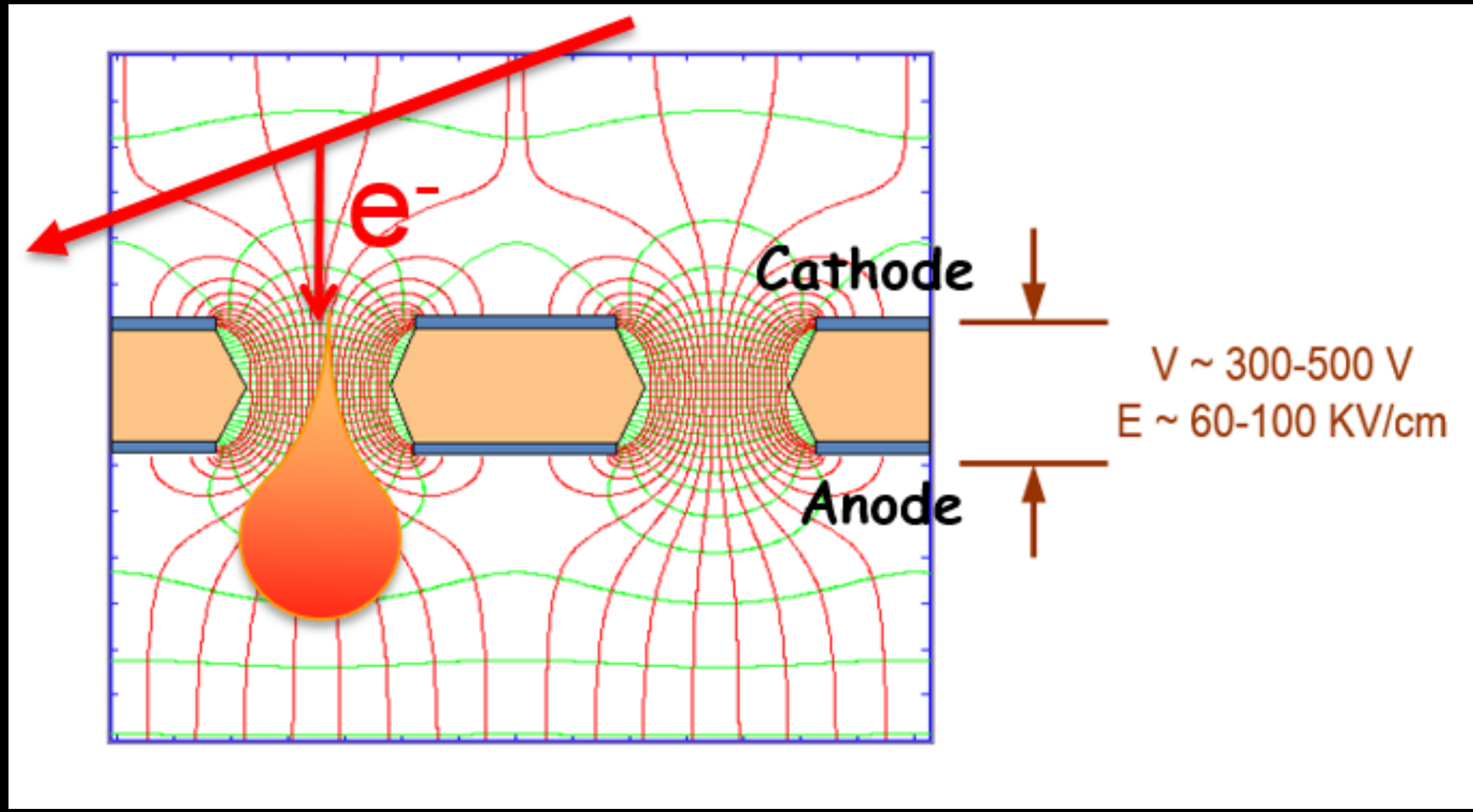
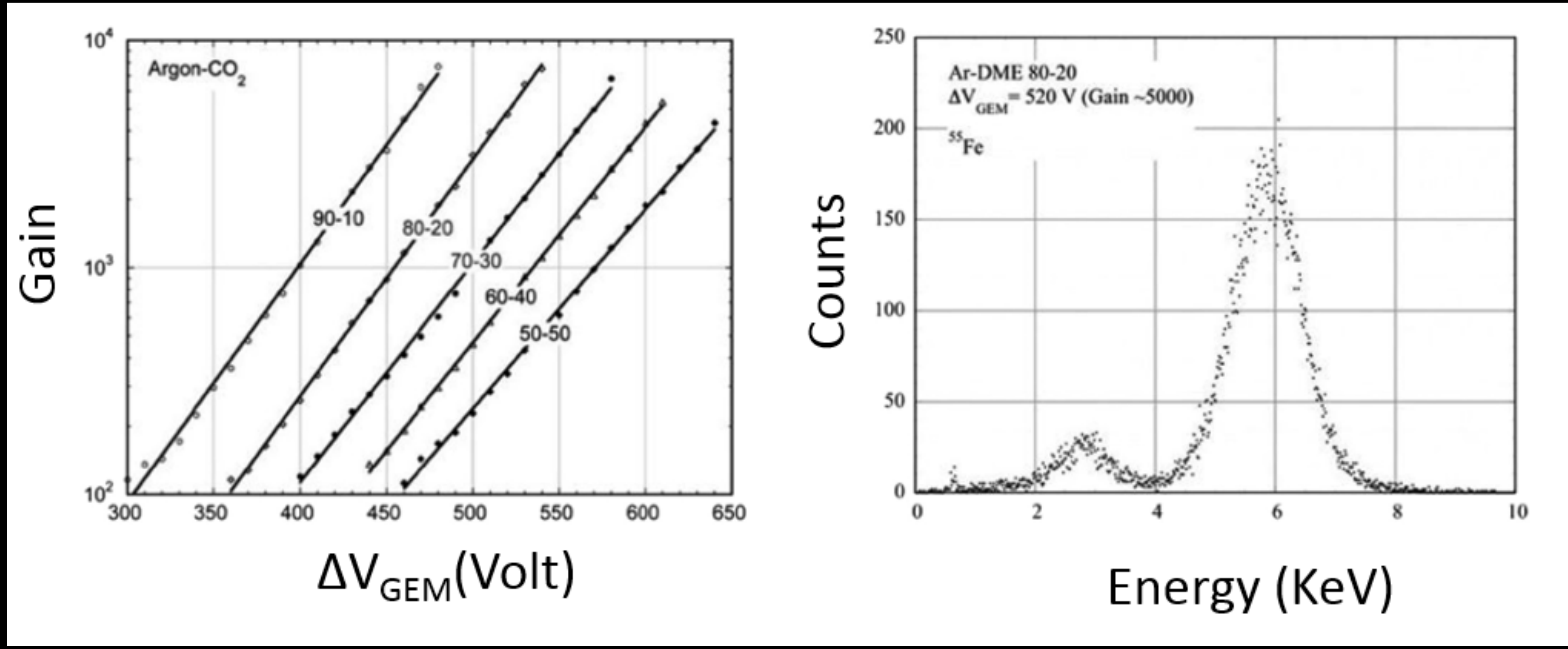


MULTIPLICATION DEVICES: GEMS AND THGEMS

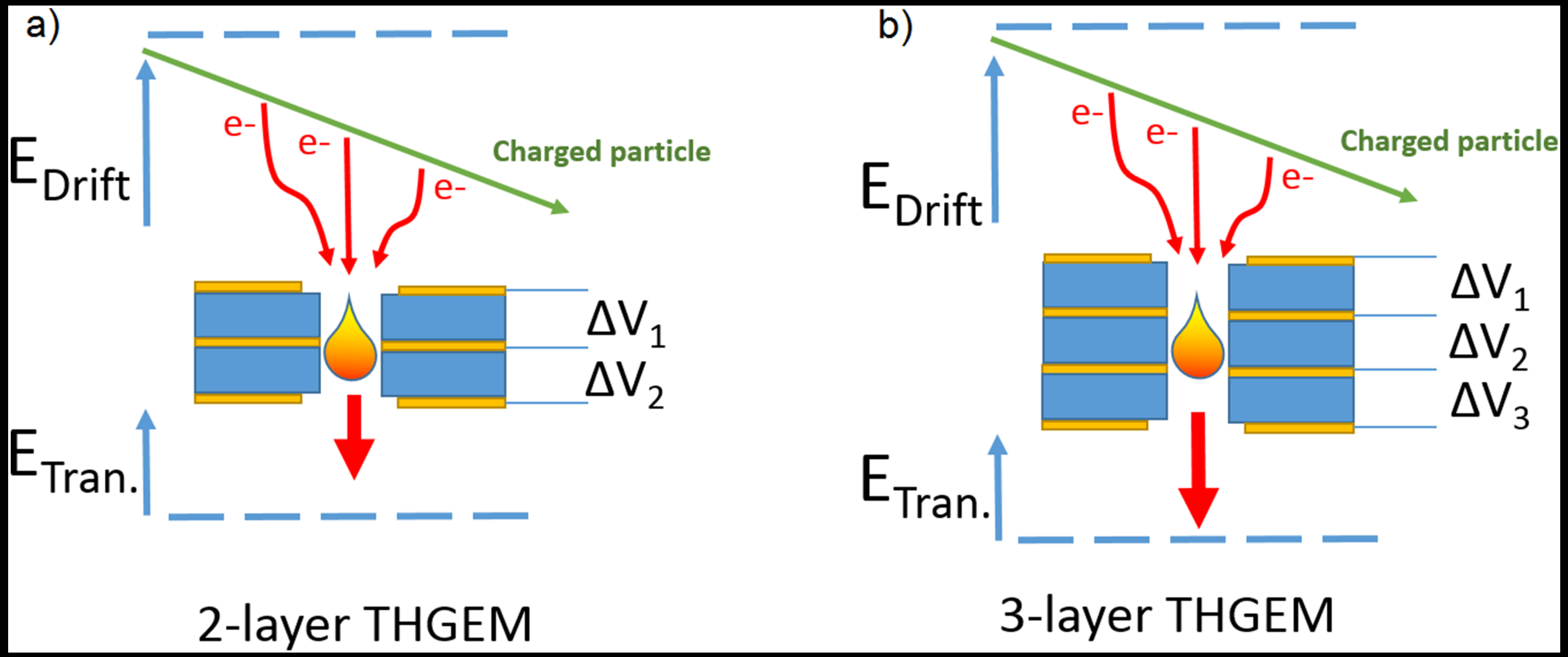
- Gas Electron Multipliers
  - Thin foils covered with Cu layers on both sides and drilled with many holes
  - Field gradient in holes large enough to trigger avalanches
  - Transmission device: multiplied electron emerge on opposite side from primaries
- Thick GEM
  - Same idea but with PCB rather than foil
  - Much more robust electrically and mechanically

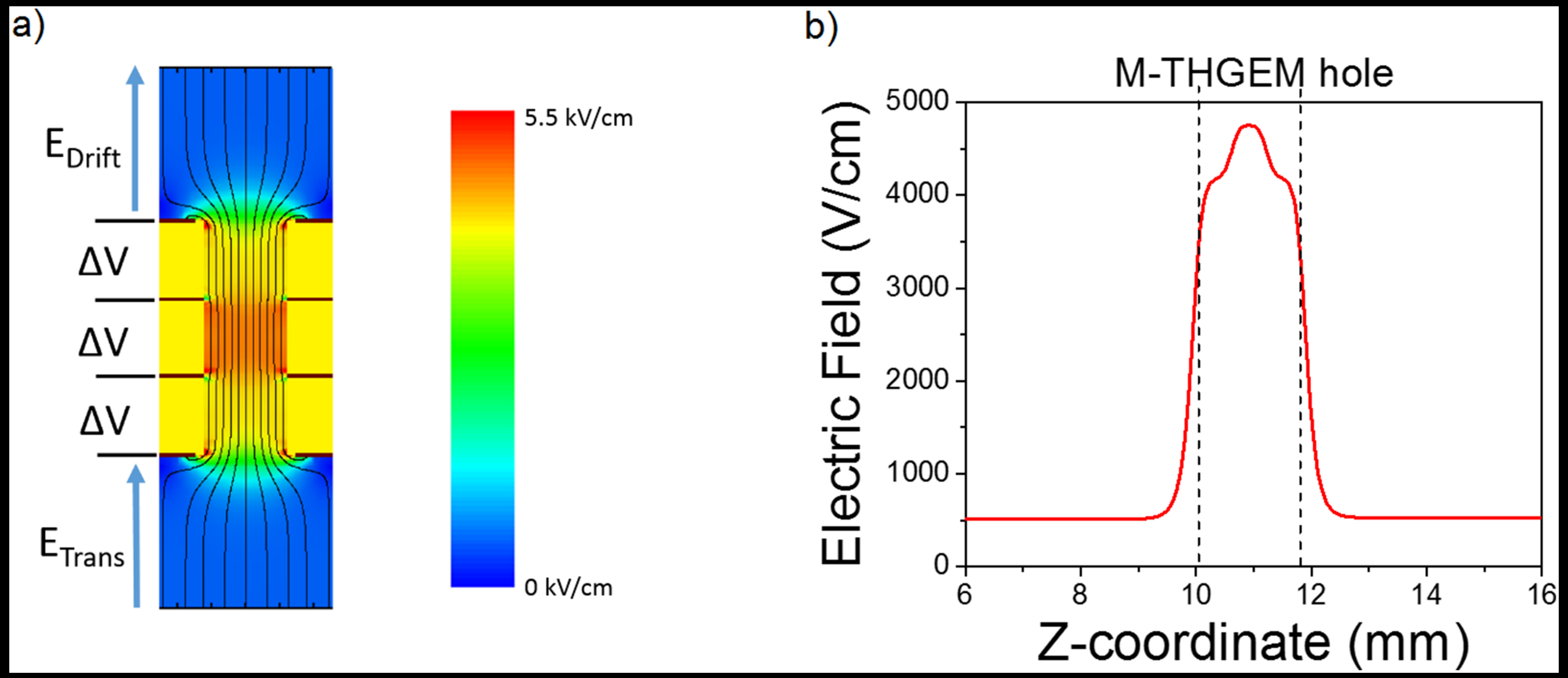




THE NEXT GENERATION: MULTI-THGEMS

- 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

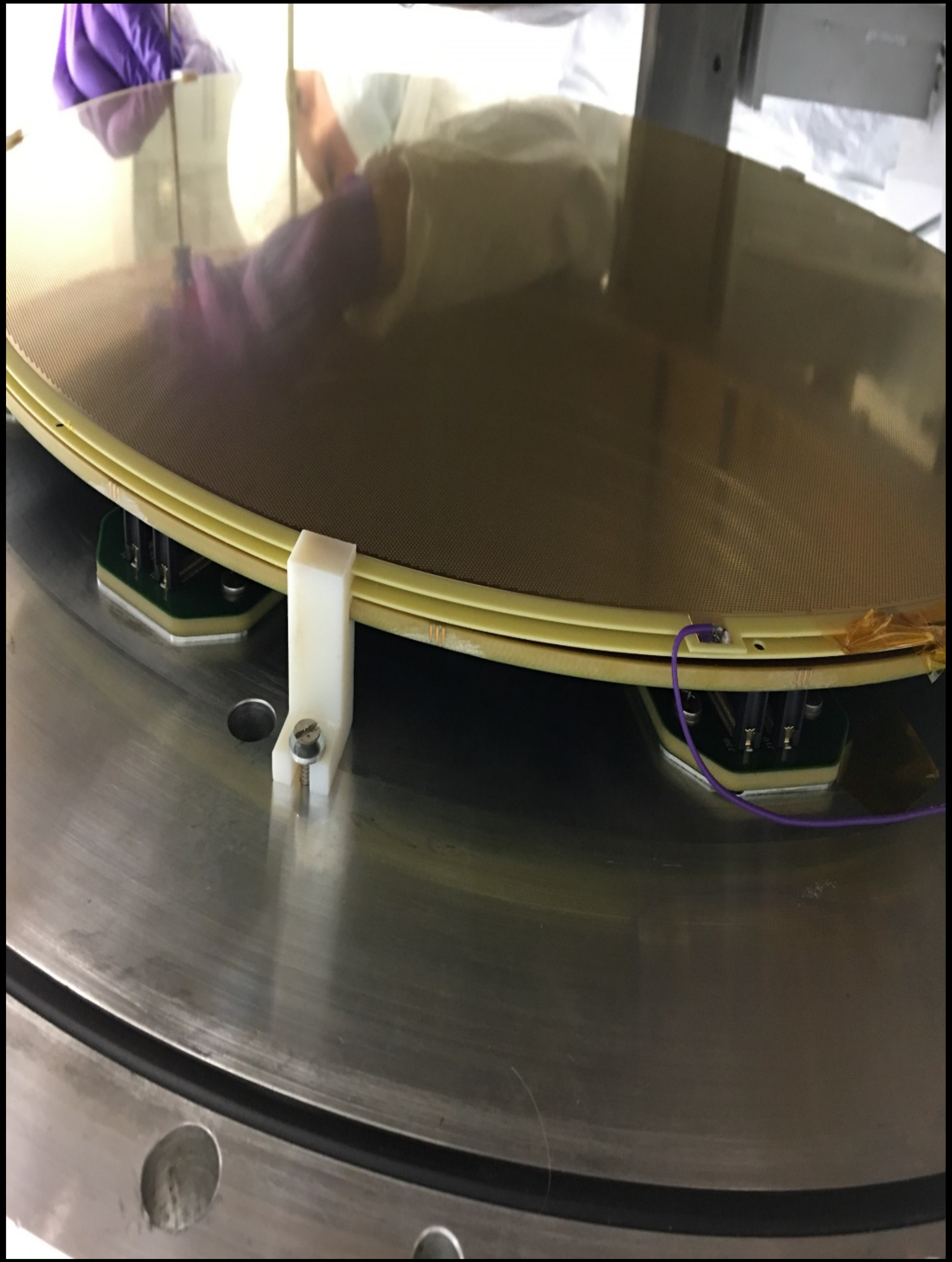




M. Cortesi et al., Rev. Sci. Instrum. 88, 013303 (2017)

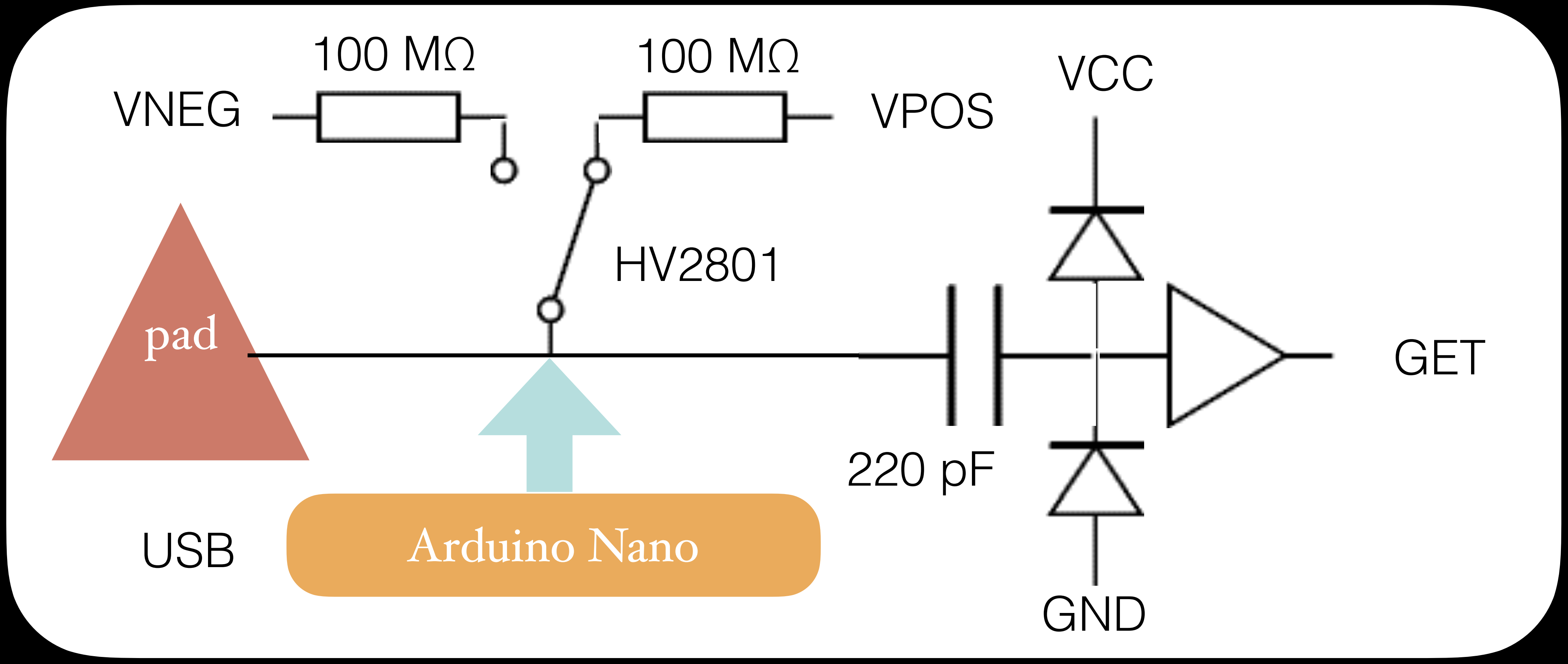
COMBINING MULTIPLICATION DEVICES

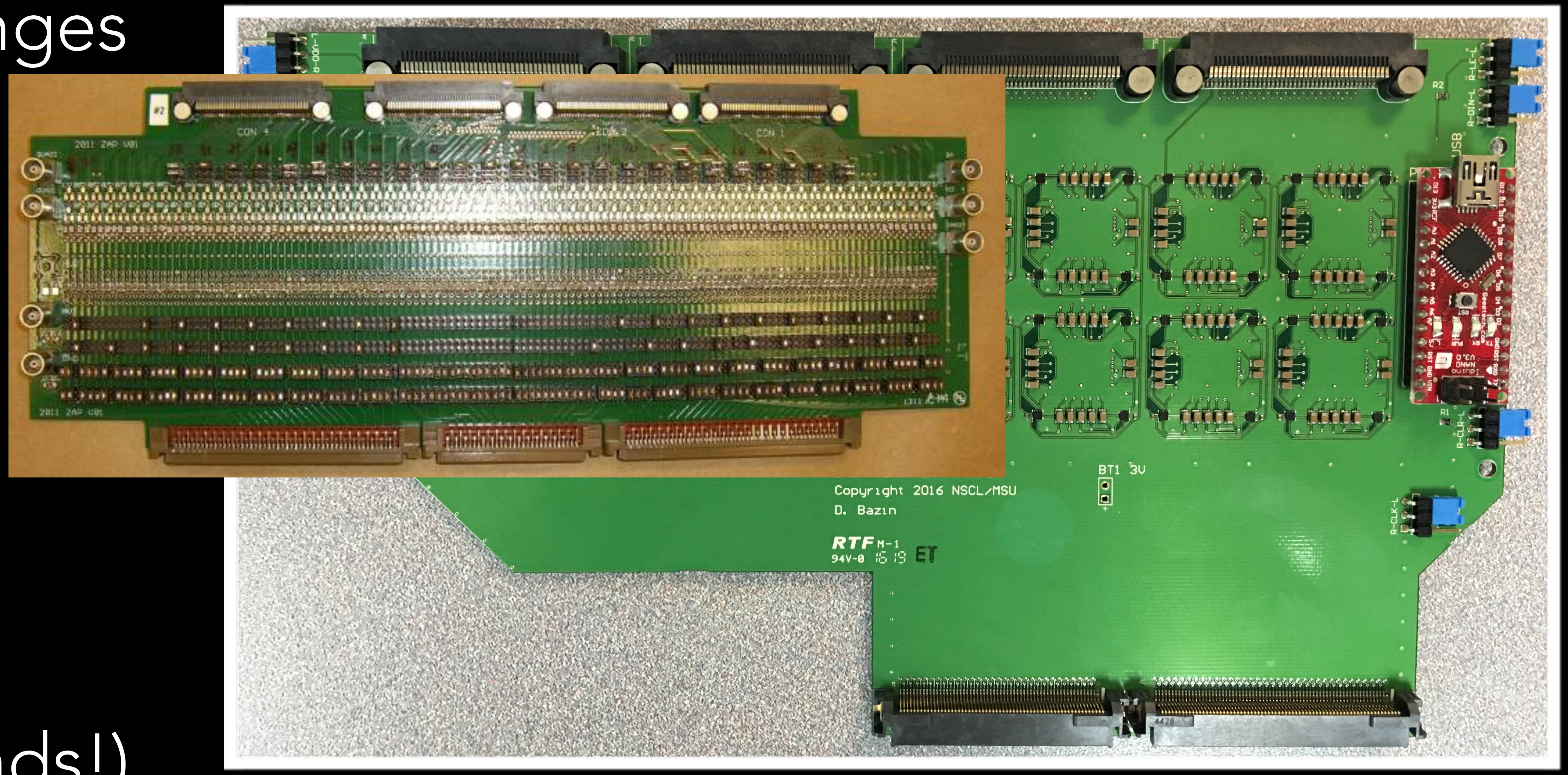
- THGEMs or M-THGEMs used as electron preamplifiers
  - Example: two THGEMs on top of Micromegas
  - Cascade allows to relax gain on each stage of electron amplification
  - Limit ion back flow from the last stages
  - Top THGEM can be used as a gating grid



INDIVIDUAL PAD POLARIZATION

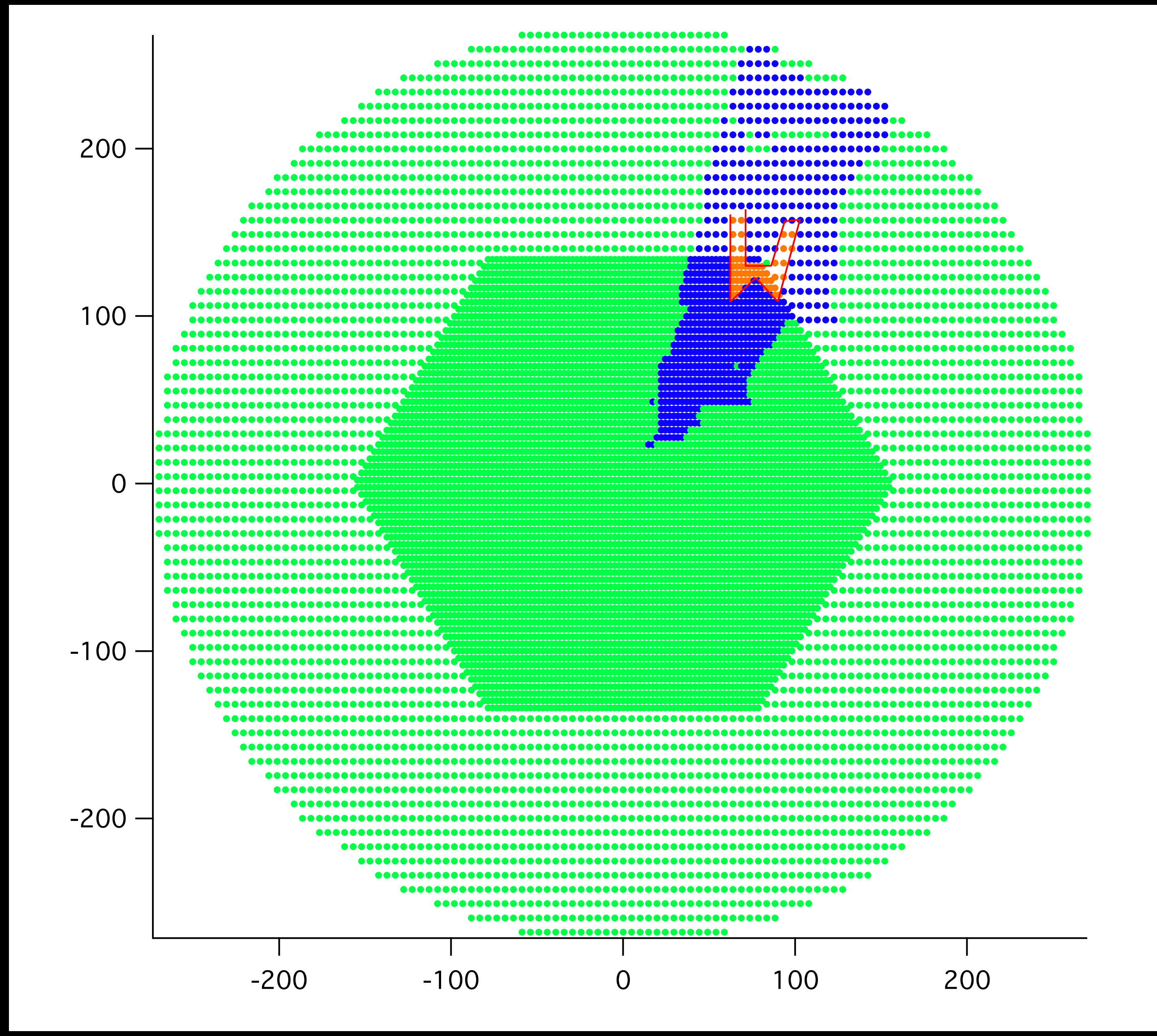
- Micromegas avalanches are localized
  - Very small gap (100 μm)
  - Gain depends on field gradient between each pad and the mesh
  - Varying the potential on a given pad changes the gain for that pad only
- Implementation
  - Protection circuit of electronics equipped with jumpers (256 pads) …
  - … or programmable HV switch (10,000 pads!)

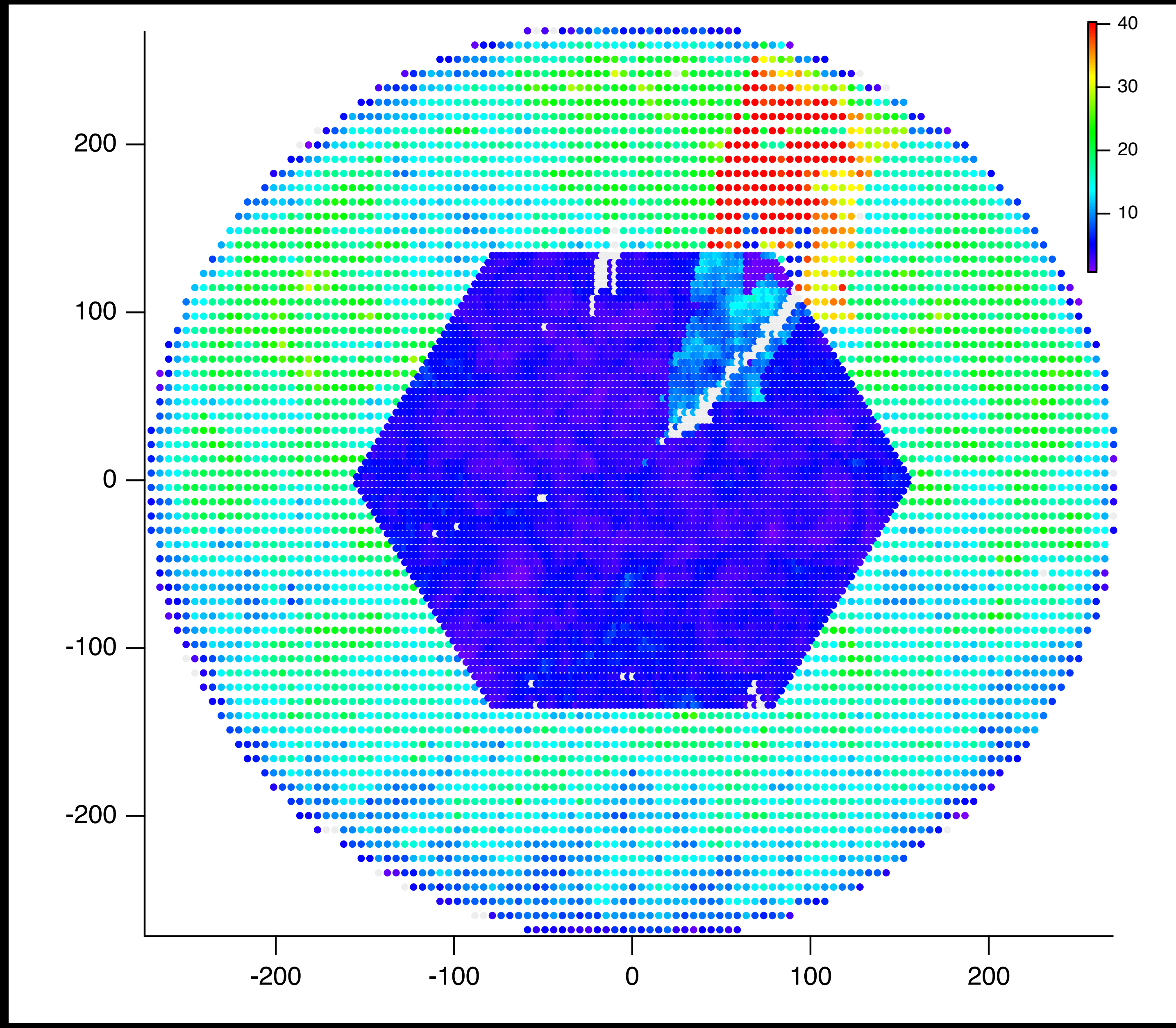




TEST ON AT-TPC

- Programmatic method necessary
  - 10,240 pads to consider!
  - Map of pads assigned via software
    - Green: ground (0V)
    - Blue: -40V (more gain)
    - Red: +40V (less gain)
  - Data taken using α particles from source covering whole volume
  - All pads have same electronic gain



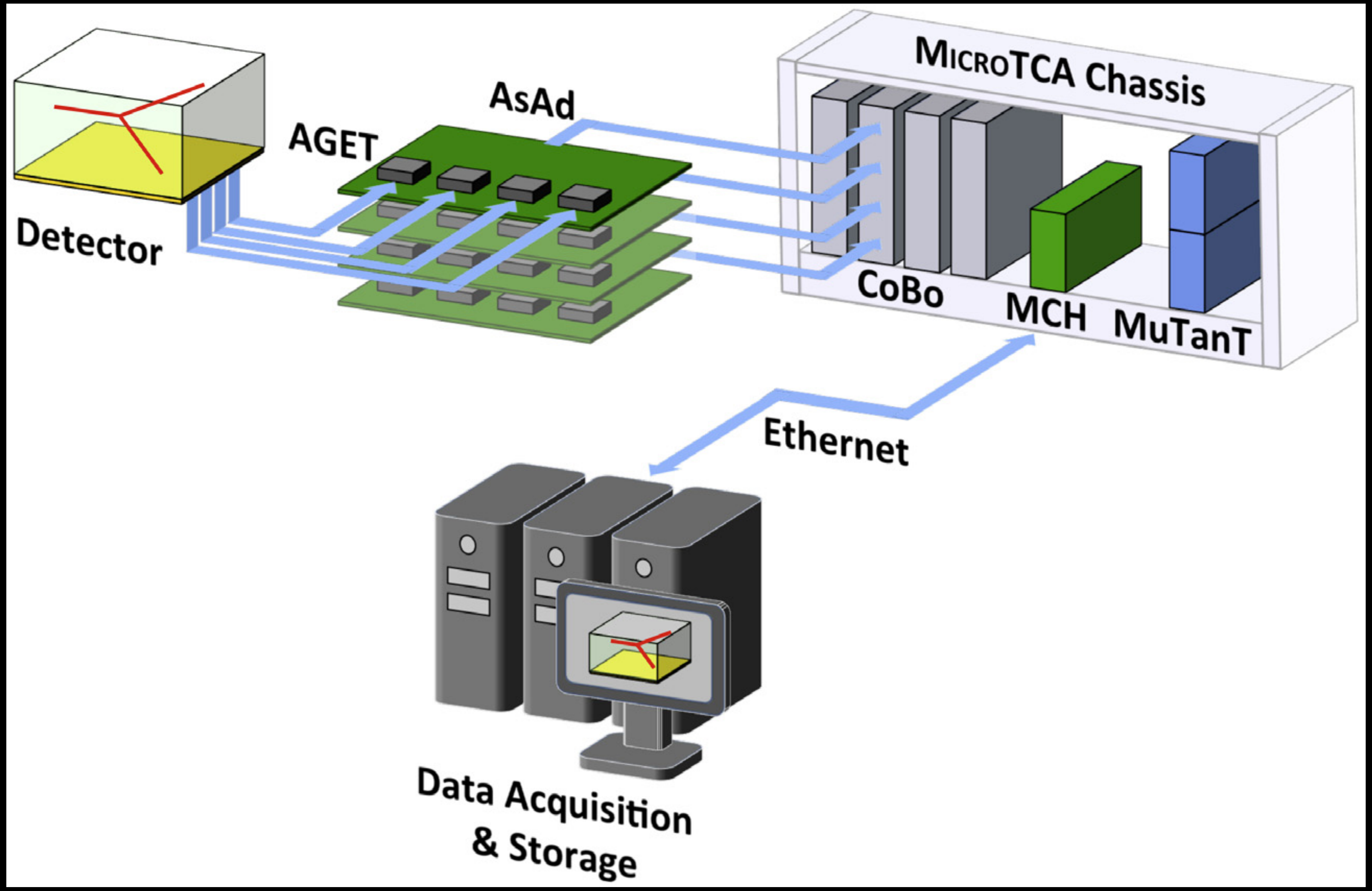


ACTIVE TARGET ELECTRONICS

- Requirements
  - Time evolution of signals contains essential information: record traces
  - Large number of pads: cost per channel should be minimized
  - Huge amounts of data: parallel architecture and data reduction are paramount
  - Active Targets without trigger detectors: good trigger generation
- Technology choices
  - Analog memory arrays (Switch Capacitor Array or SCA) are the cheapest
  - Data reduction schemes implemented in fast FPGA (Field Programmable Gate Arrays)
  - Trigger generation scheme using discriminators to generate live multiplicity

GENERAL ELECTRONICS FOR TPC (GET)

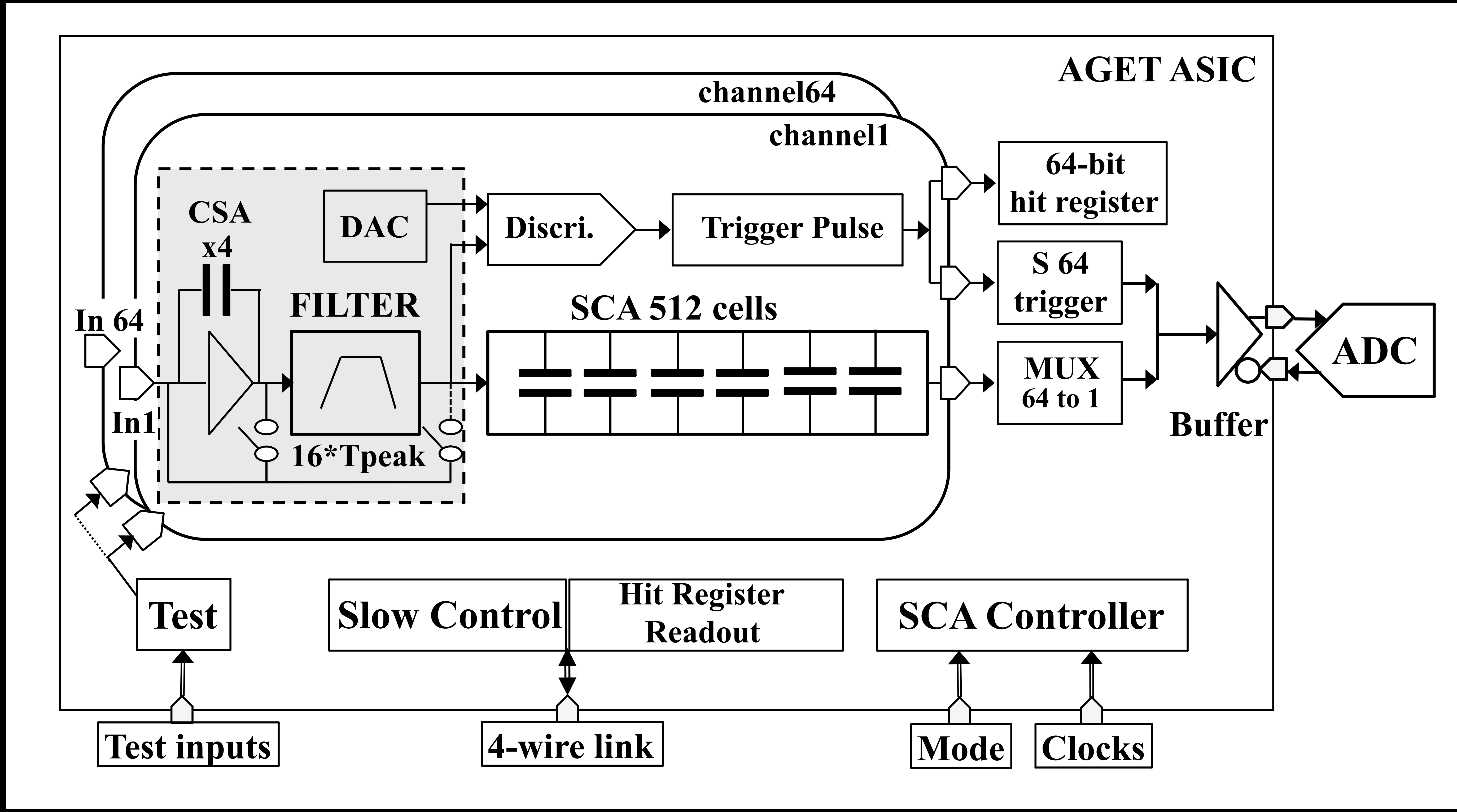
- Specifically designed for Active Targets
  - Adjustable gain on each individual pad (from 120 fC to 10 pC)
  - Up to 512 time samples recorded
  - Sampling frequency range 1-100 MHz
  - Each channel equipped with discriminator and threshold
  - Shaping time from 70 ns to 1 μs
  - Charge resolution < 850 e^-



E. Pollacco et al., NIM 887, 81 (2018)

FRONT END FEATURES

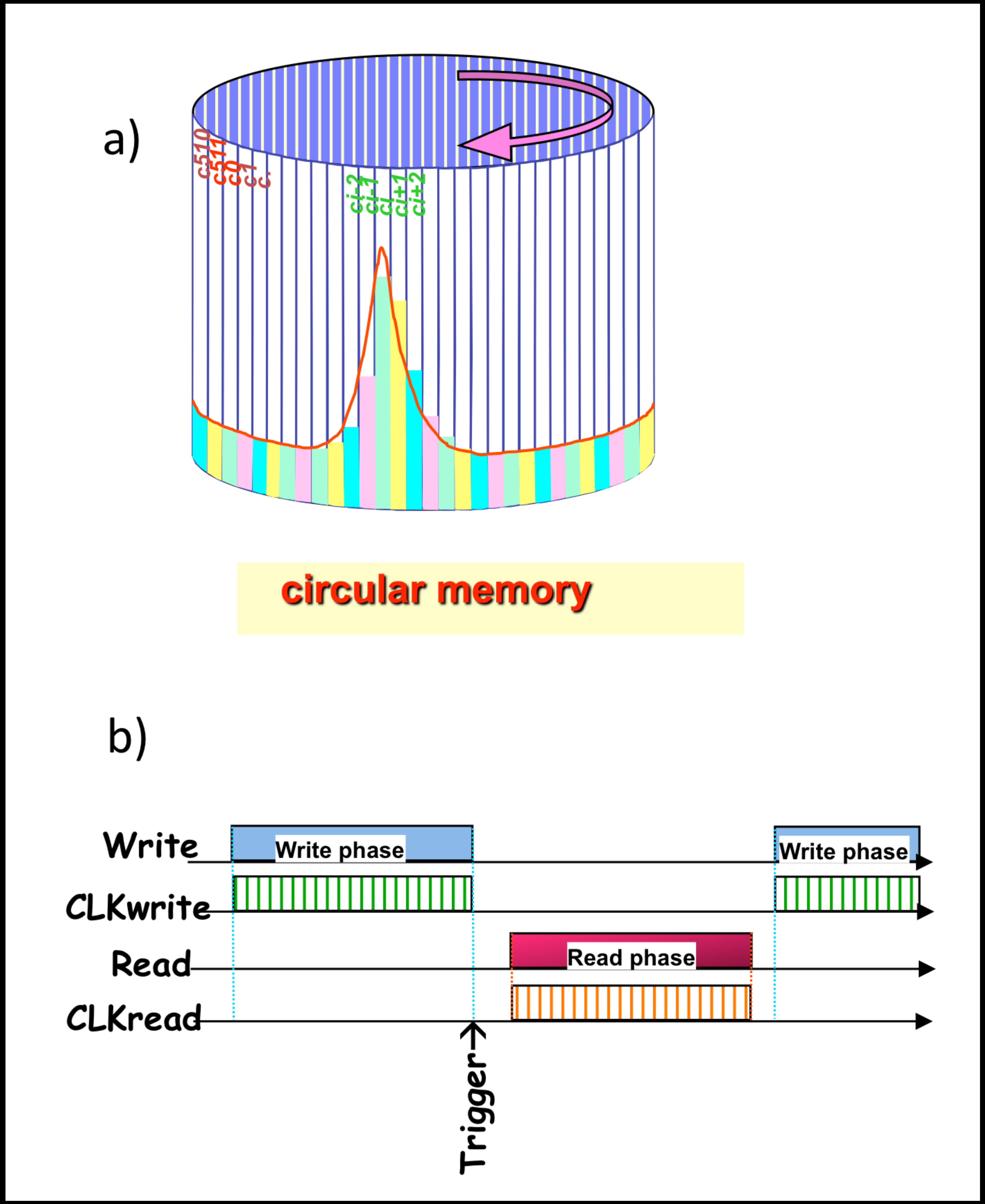
- Writing phase
  - Live analog signals are stored in SCA used as a circular buffer
  - Live discriminator bits are combined in hit register and summed as multiplicity signal
  - Multiplicity signal is converted by flash ADC and sent out to back end electronics
  - Some stages of the CSA can be bypassed



E. Pollacco et al., NIM 887, 81 (2018)

FRONT END FEATURES

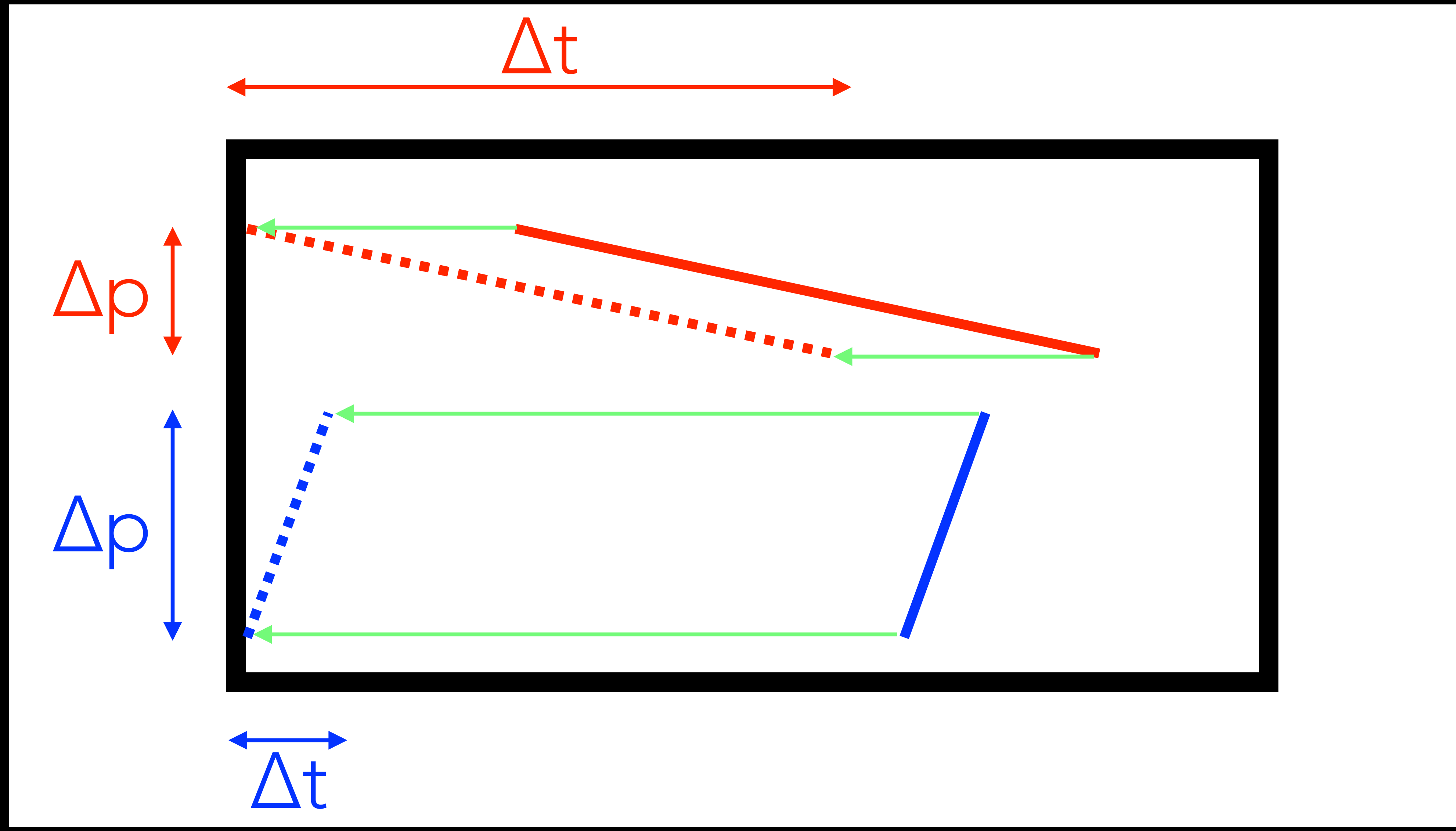
- Reading phase
  - SCA array set in read mode
  - Pointer of first time sample set to desired value (going back in time)
  - Depending on reading mode, selected SCA cells are converted by flash ADC and sent to back end
  - Data reading is multiplexed and sent through a single flash ADC
  - Data from front-end (AsAd) is serial



P. Baron, IRFU

BACK END PROCESSING

- Concentration Boards (CoBo)
  - Data reduction and multiplicity integration
  - Readout modes
    - Full (no reduction)
    - Partial (pads above threshold)
    - Zero-suppressed (baseline removal)
  - Multiplicity sliding window
    - Integrate multiplicities within time window
    - Value updated every 40 ns

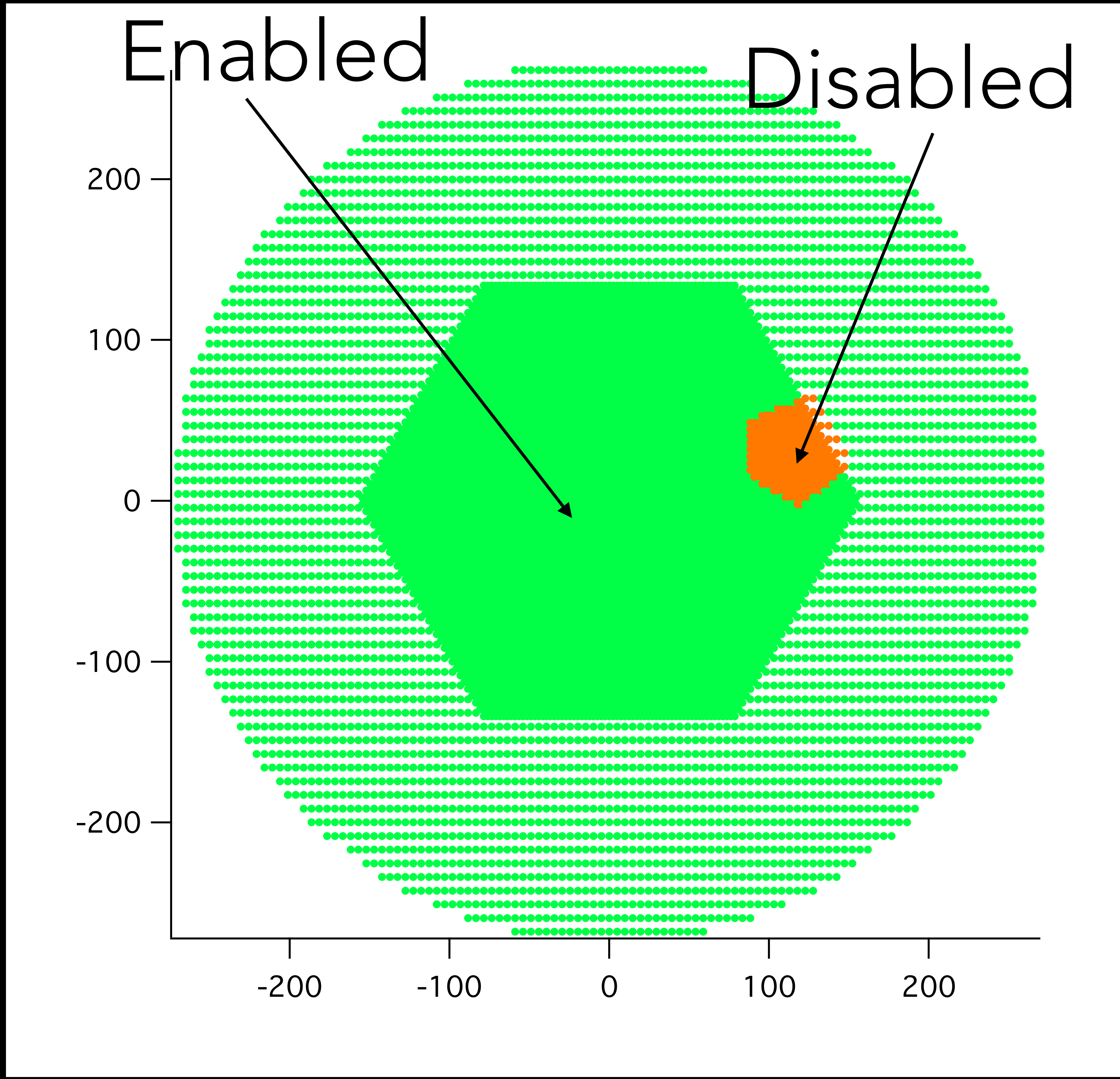


CLOCK AND TRIGGER

- Mutant module
  - Clock distribution throughout the whole system
  - Trigger generation
    - Gather sliding window multiplicities from all CoBos and sum them
    - Also gather hit patterns (level 2)
    - Level 1: trigger if global multiplicity above (or below) a given threshold
    - Level 2: trigger if hit pattern matches predefined configuration

INTERNAL TRIGGER GENERATION

- Trigger exclusion regions
  - Discriminators on each individual pads can be enabled or disabled
  - Region where electrons from beam tracks are collected (“beam pads”) can be excluded from multiplicity
  - Scattered particles that exit the beam exclusion region generate a trigger



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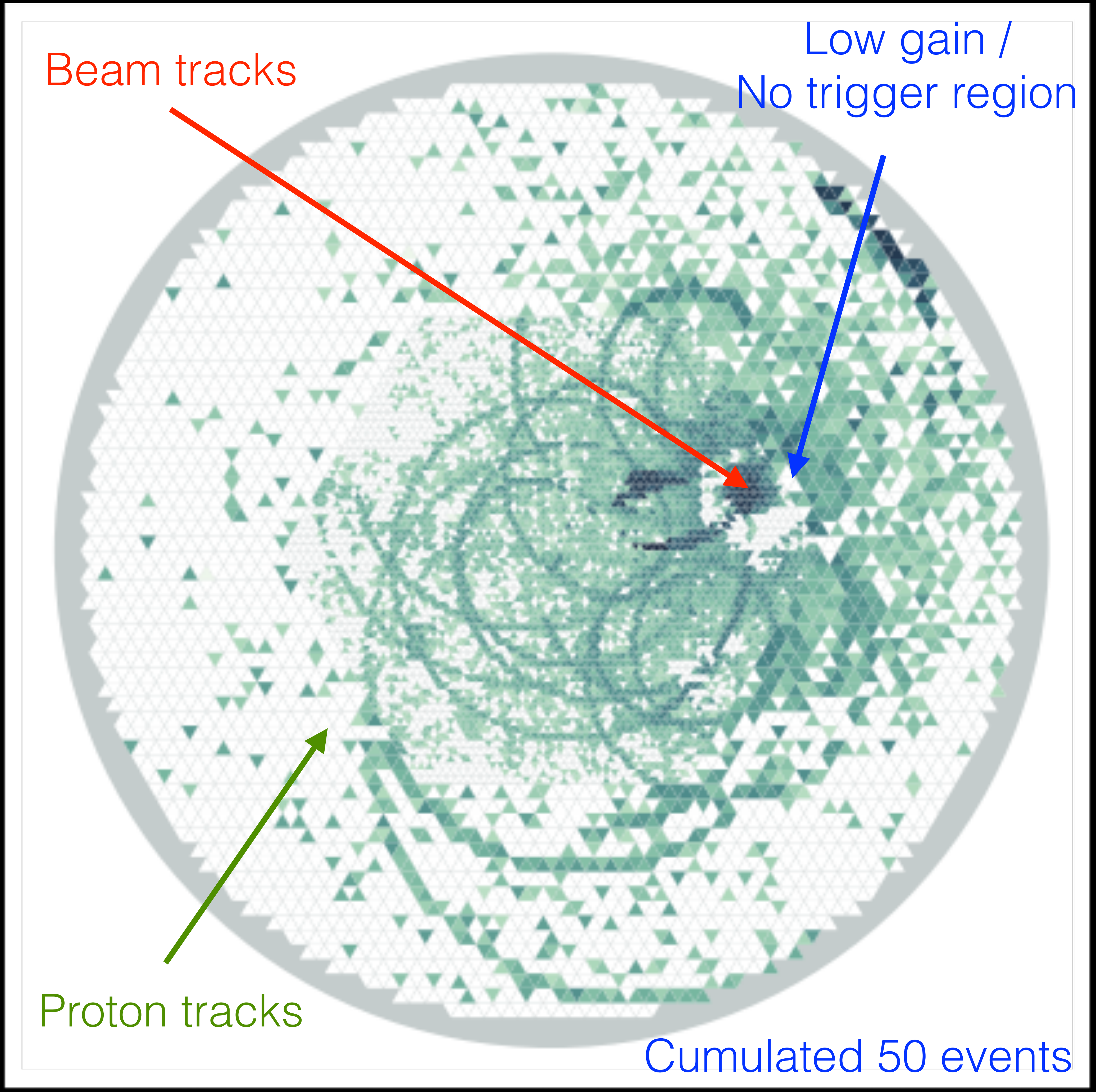
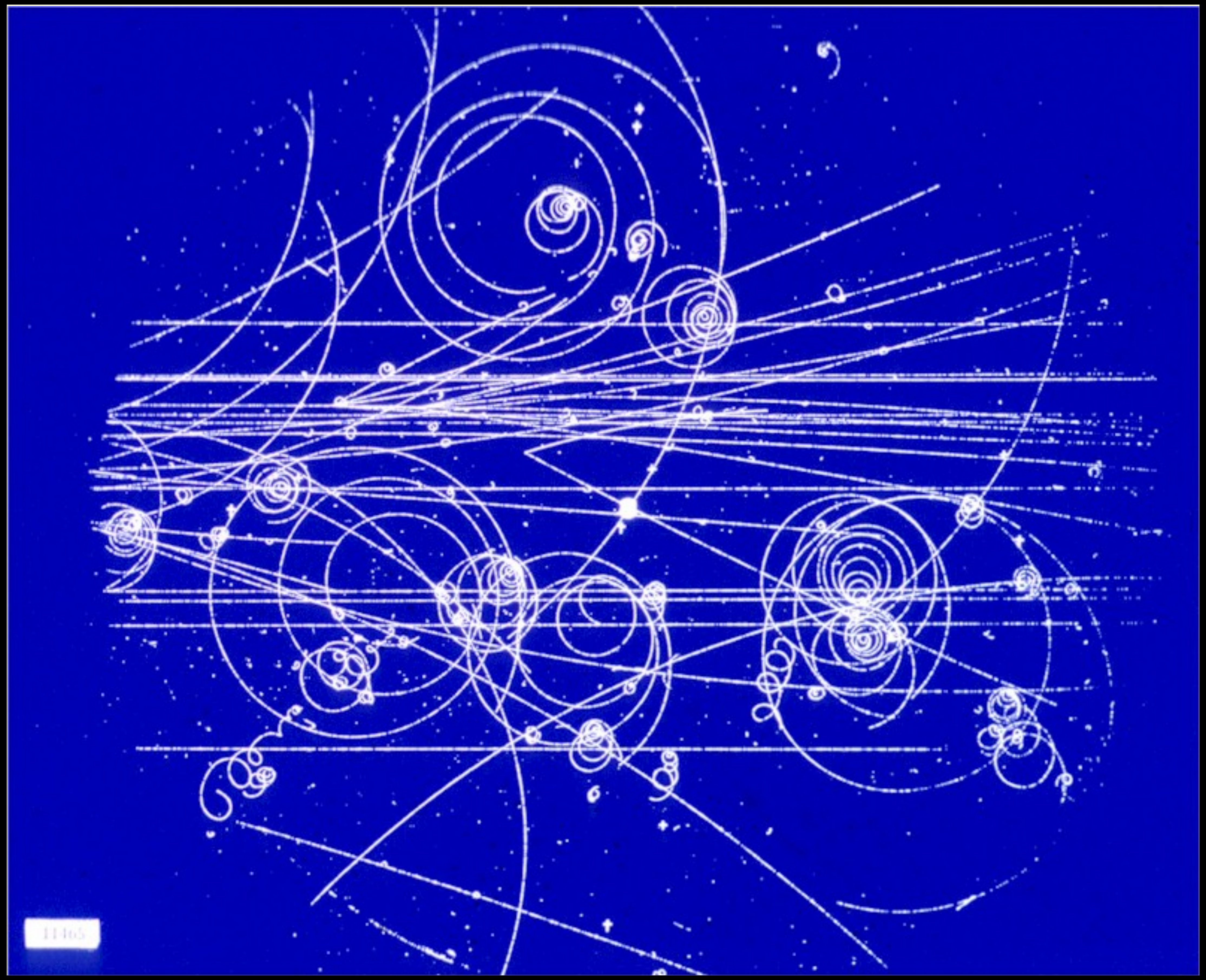


BUBBLE CHAMBERS

- The first active target detector
  - Chamber filled with superheated liquid
  - Charged particles create local phase transitions that result in the formation of bubbles
  - Pictures of the tracks are taken with a camera
- Tedious analysis!
  - People look at each picture and identify interesting events
  - Later on automated methods were used to help, but still very slow (30 s per photo)



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PUT YOUR BRAIN IN A COMPUTER

- Humans have evolved to be excellent at pattern recognition
  - Survival skill: spot the tiger hiding in the forest, the fruits hanging in the trees
  - Human brains can easily extract signal from noise and identify patterns
- Computers have never encountered this type of problem!
  - Algorithms are needed to emulate these cognitive functions in computers
  - Recent years have seen an explosion of pattern recognition methods
  - Face recognition (your cell phone), self-driving cars, etc…
  - Many of these methods can be applied to active target data analysis

ANALYSIS PHASES

- Three main tasks
  - Cleaning (removing noise or spurious signals)
  - Classifying (identifying the type of event)
  - Fitting (extracting physics parameters from data)
- Each phase present its own set of challenges
  - Cleaning: finding criteria that cleans effectively without removing good data
  - Classifying: anticipating classes of events (using simulations)
  - Fitting: find robust methods and avoid local minima

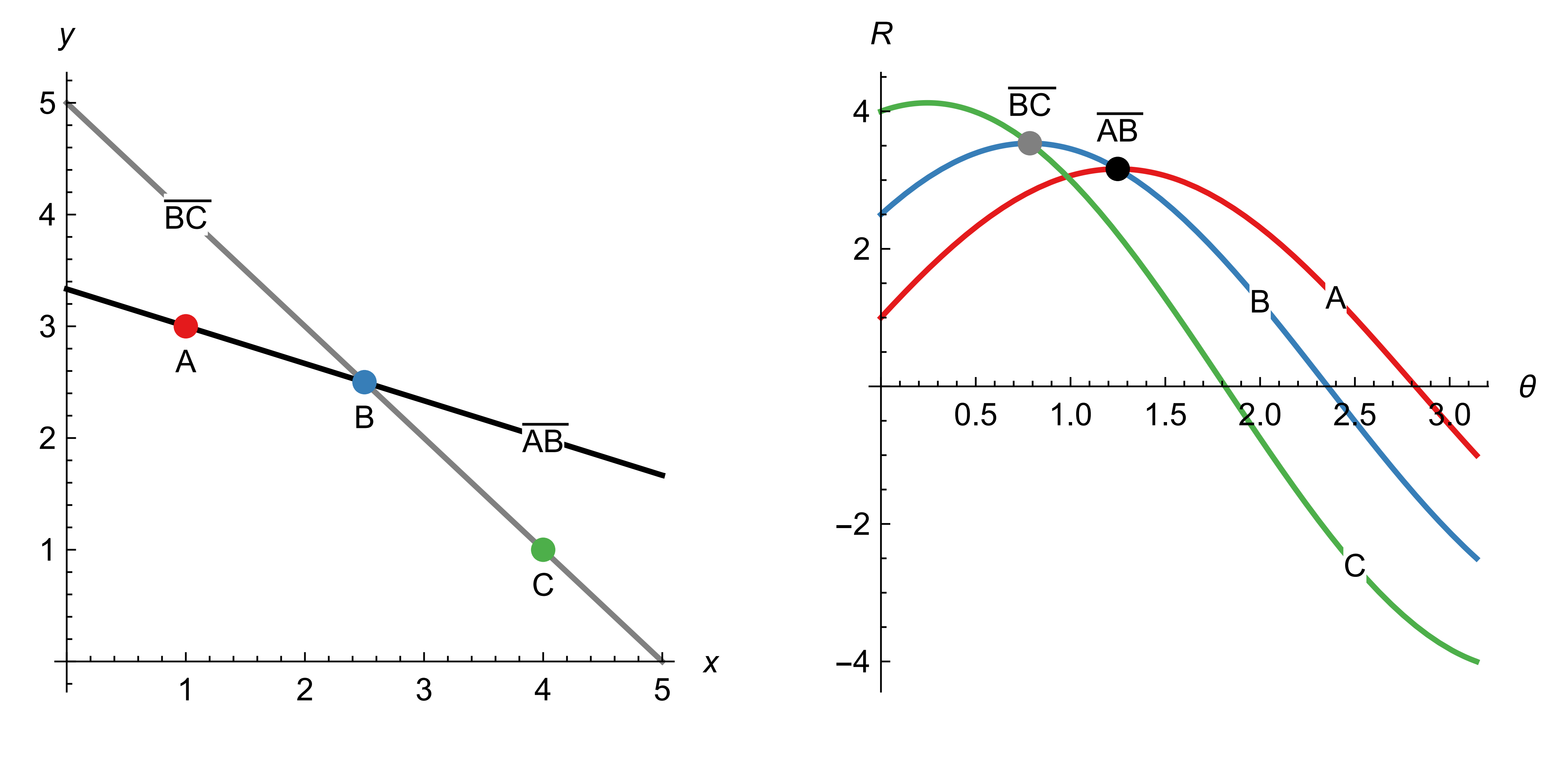
HOUGH TRANSFORM: EYES FOR A COMPUTER

- Pattern recognition algorithms
  - Linear Hough transformation to find points along straight lines

$$R = x\cos(\theta) + y\sin(\theta)$$

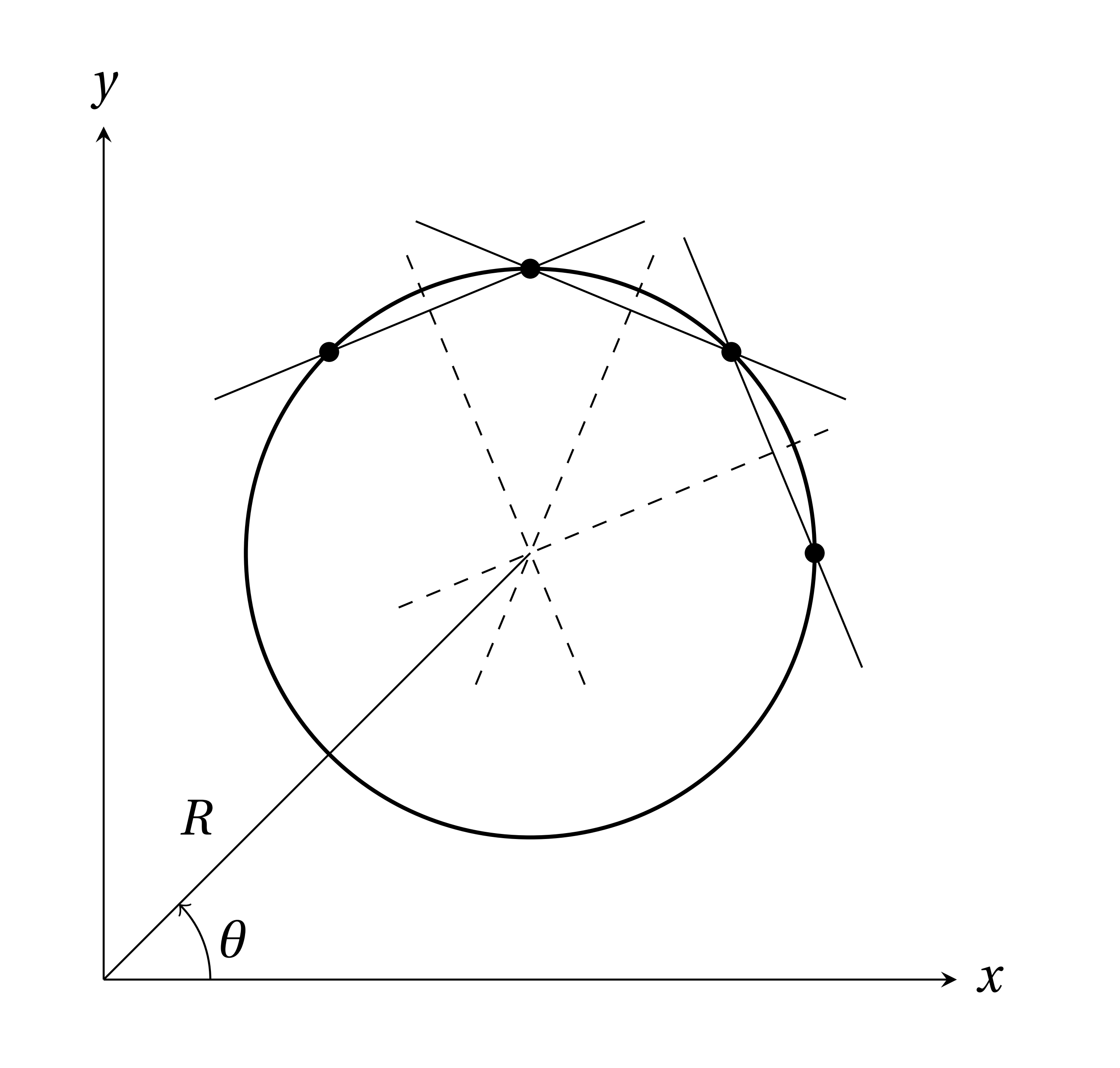
  - Circular Hough transformation to find points on a circle

$$R = \frac{(x_1^2 - x_0^2) + (y_1^2 - y_0^2)}{2[(x_1 - x_0)\cos(\theta) + (y_1 - y_0)\sin(\theta)]}$$

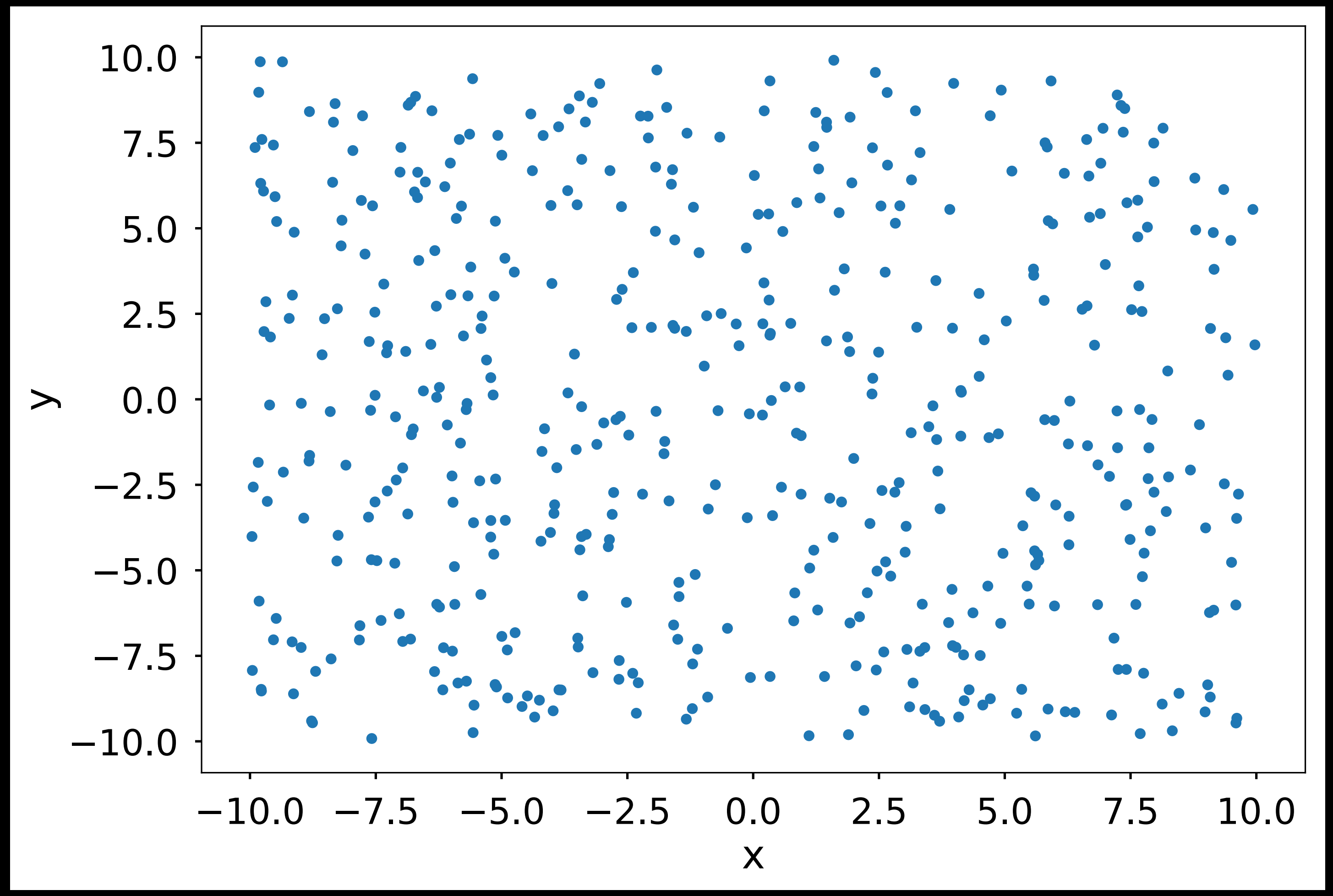


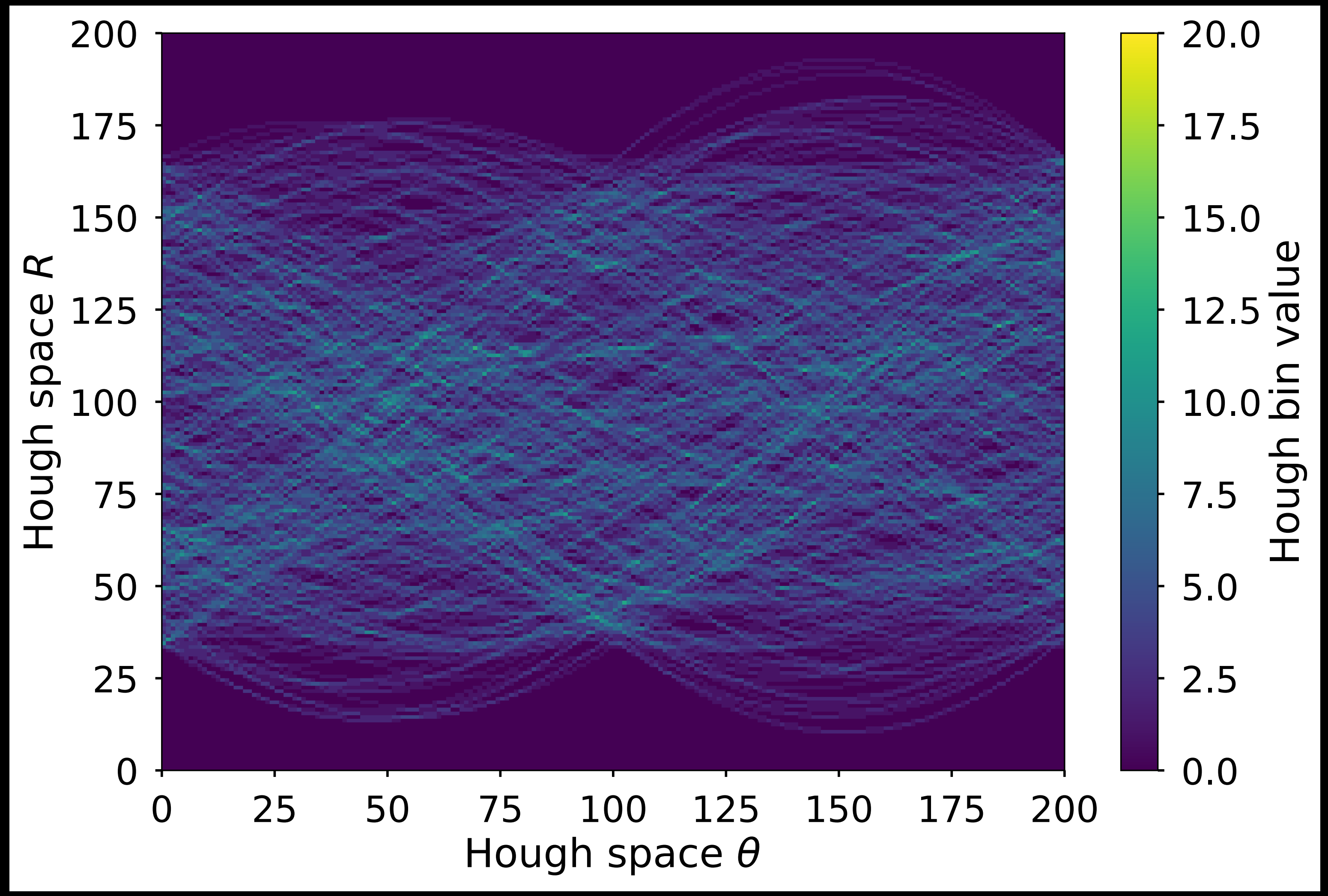
(a) Coordinate space

(b) Hough space

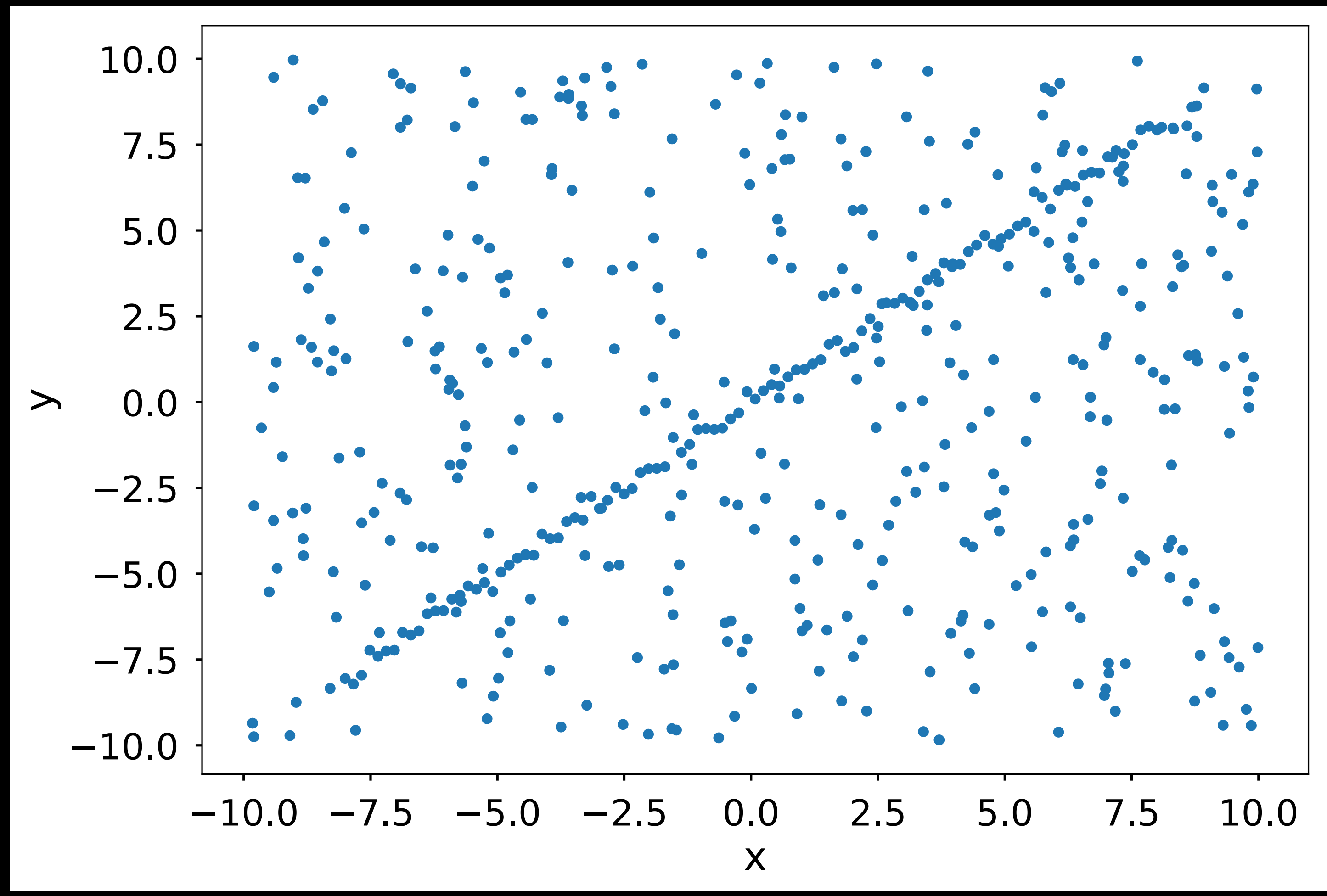


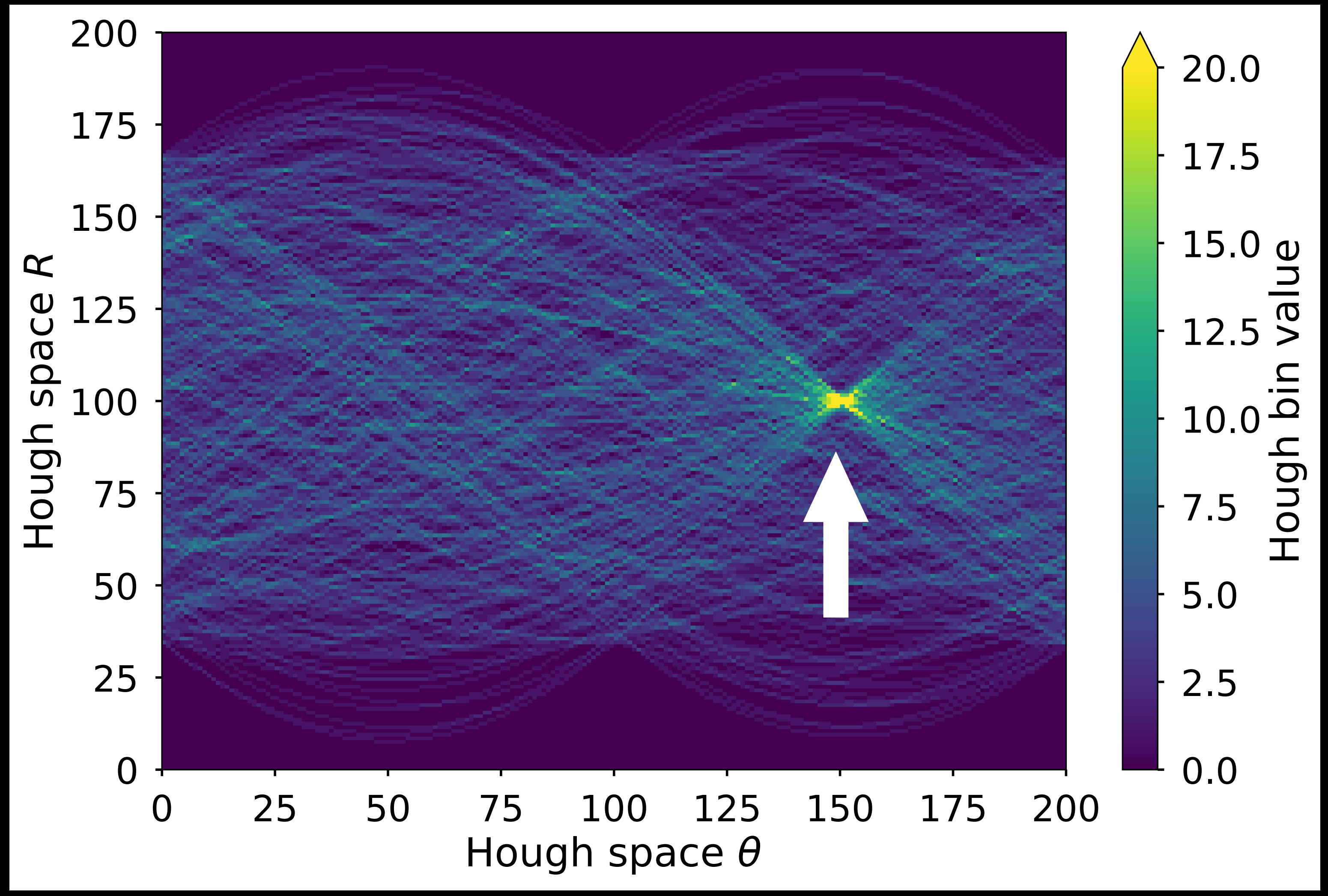
LINEAR HOUGH TRANSFORM





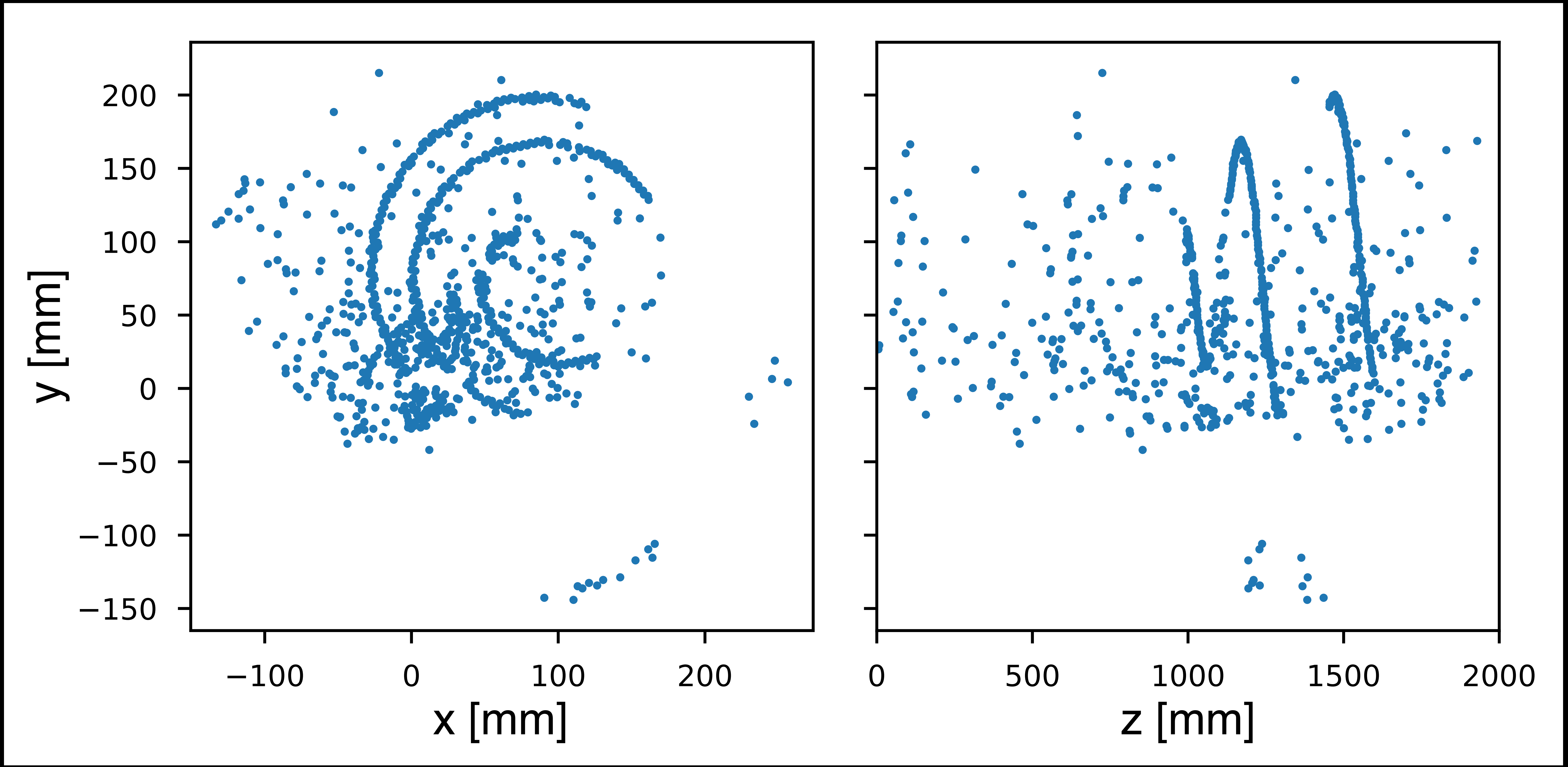
$$R = x\cos(\theta) + y\sin(\theta)$$



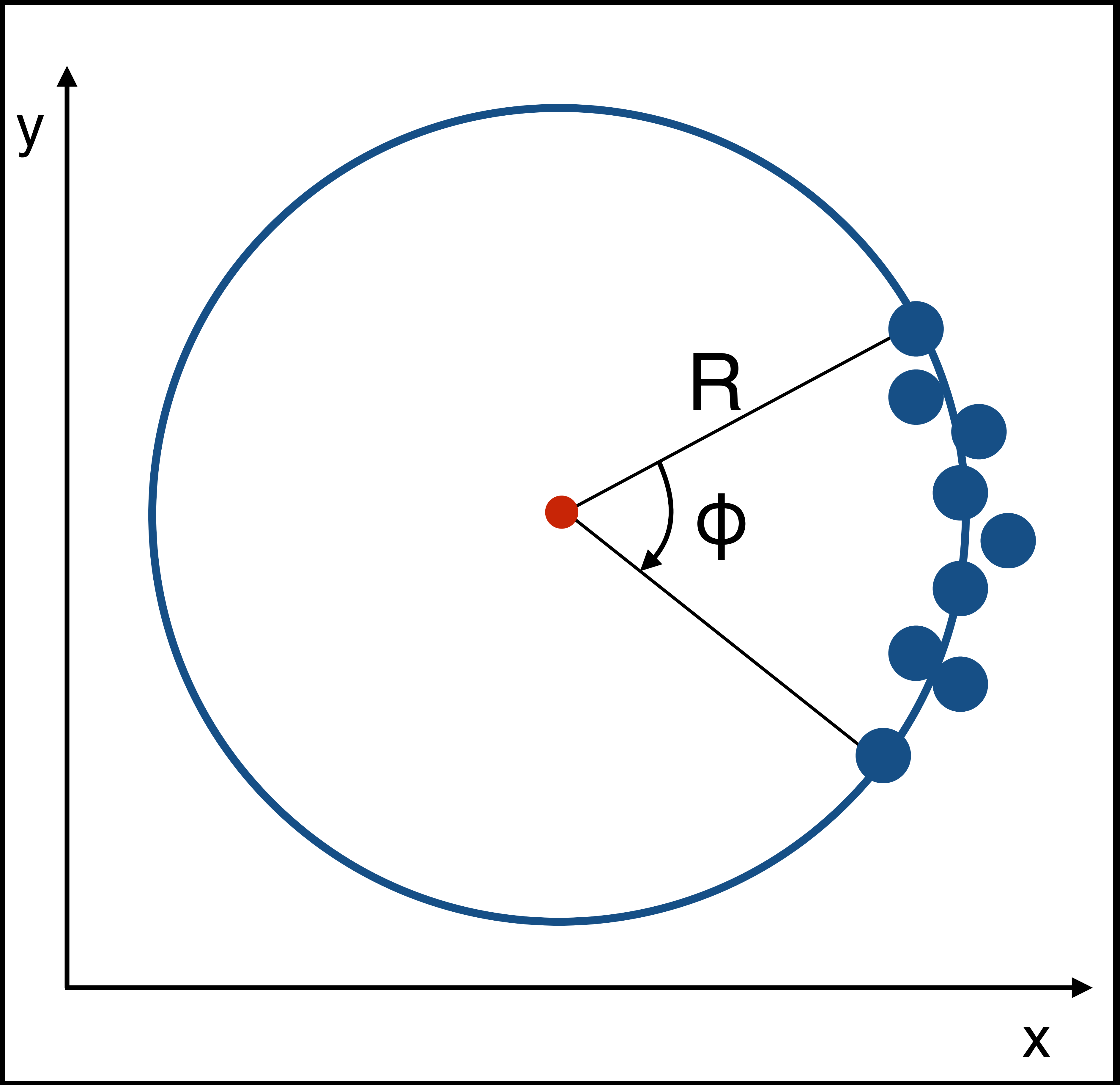


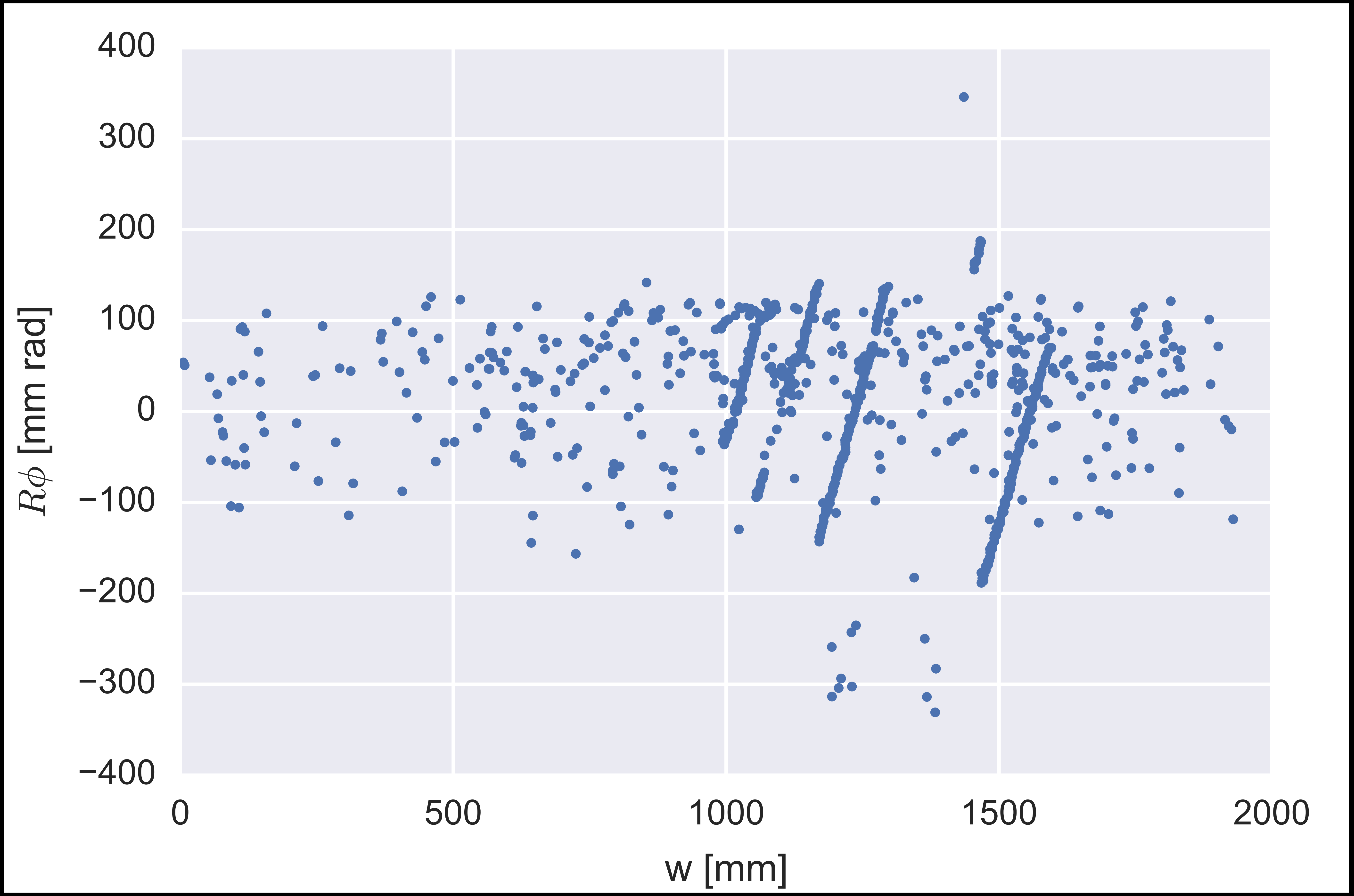
EXAMPLE ON AT-TPC DATA

- Very noisy and incomplete data!
- Use circular Hough to identify rough center of spiral
- Transform data into RΦ coordinates
- Use linear Hough to identify lines



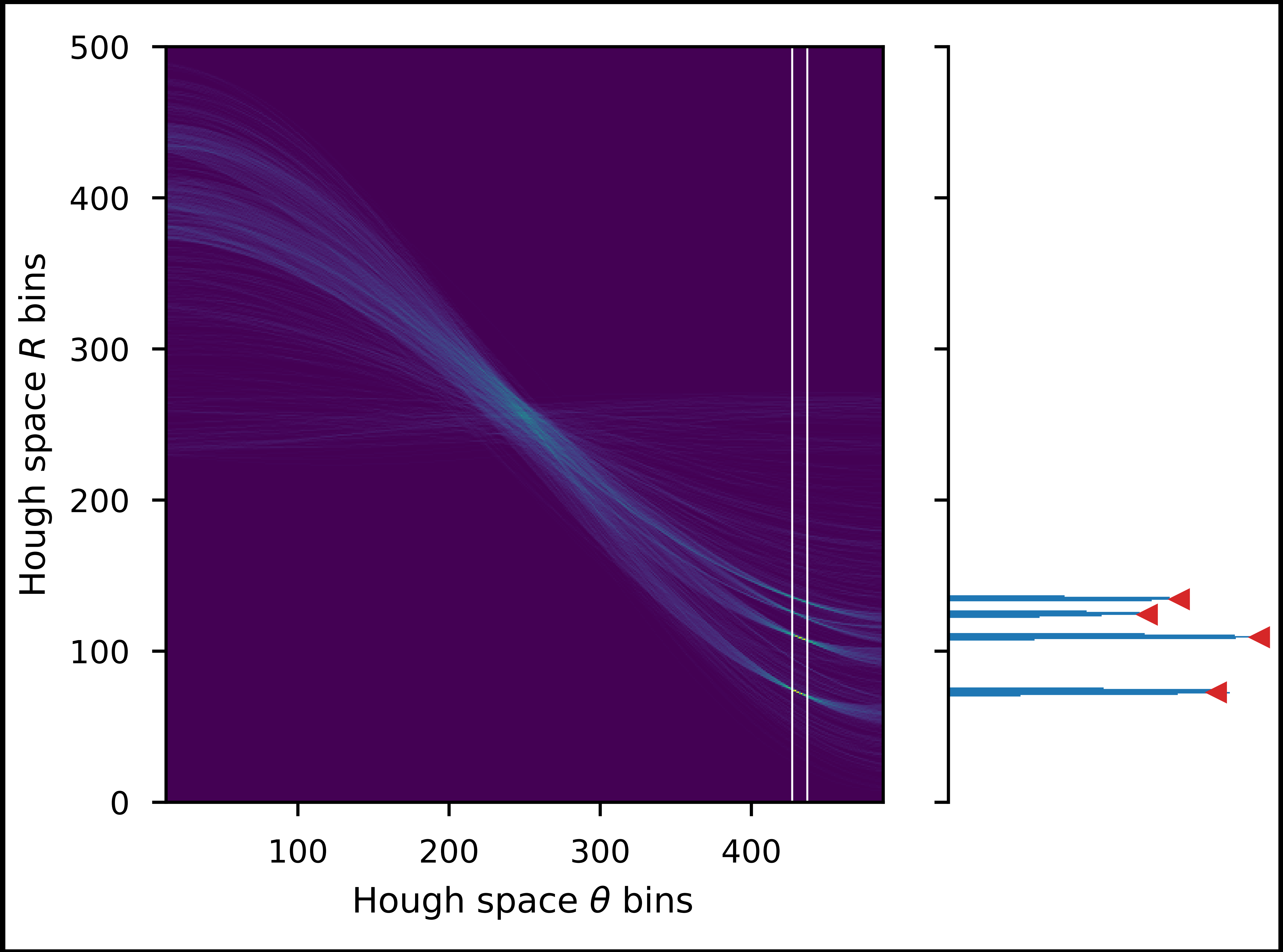
CLEANING AT-TPC DATA

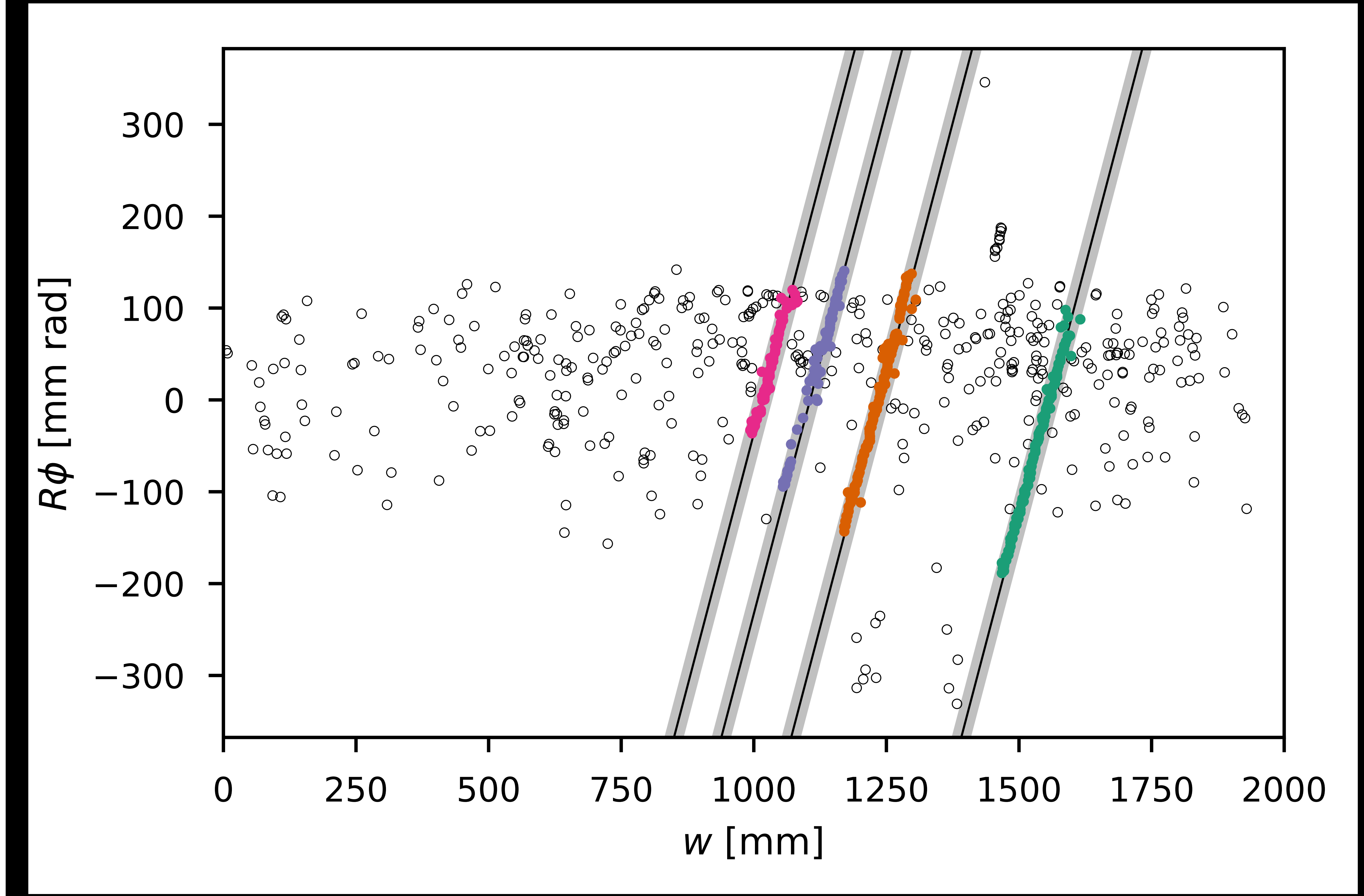




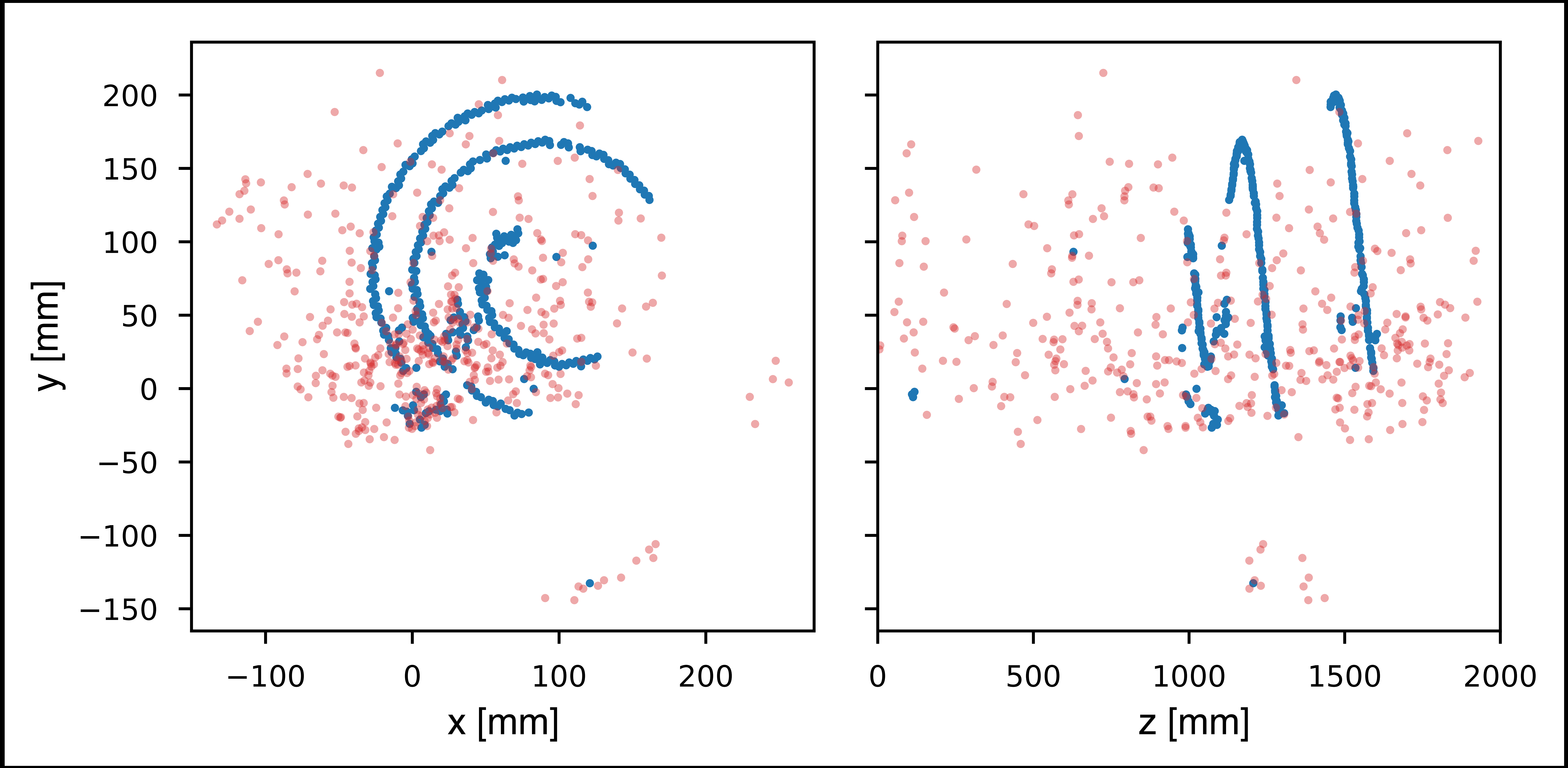
$$w = R\phi$$

CLEANING AT-TPC DATA





CLEANING AT-TPC DATA

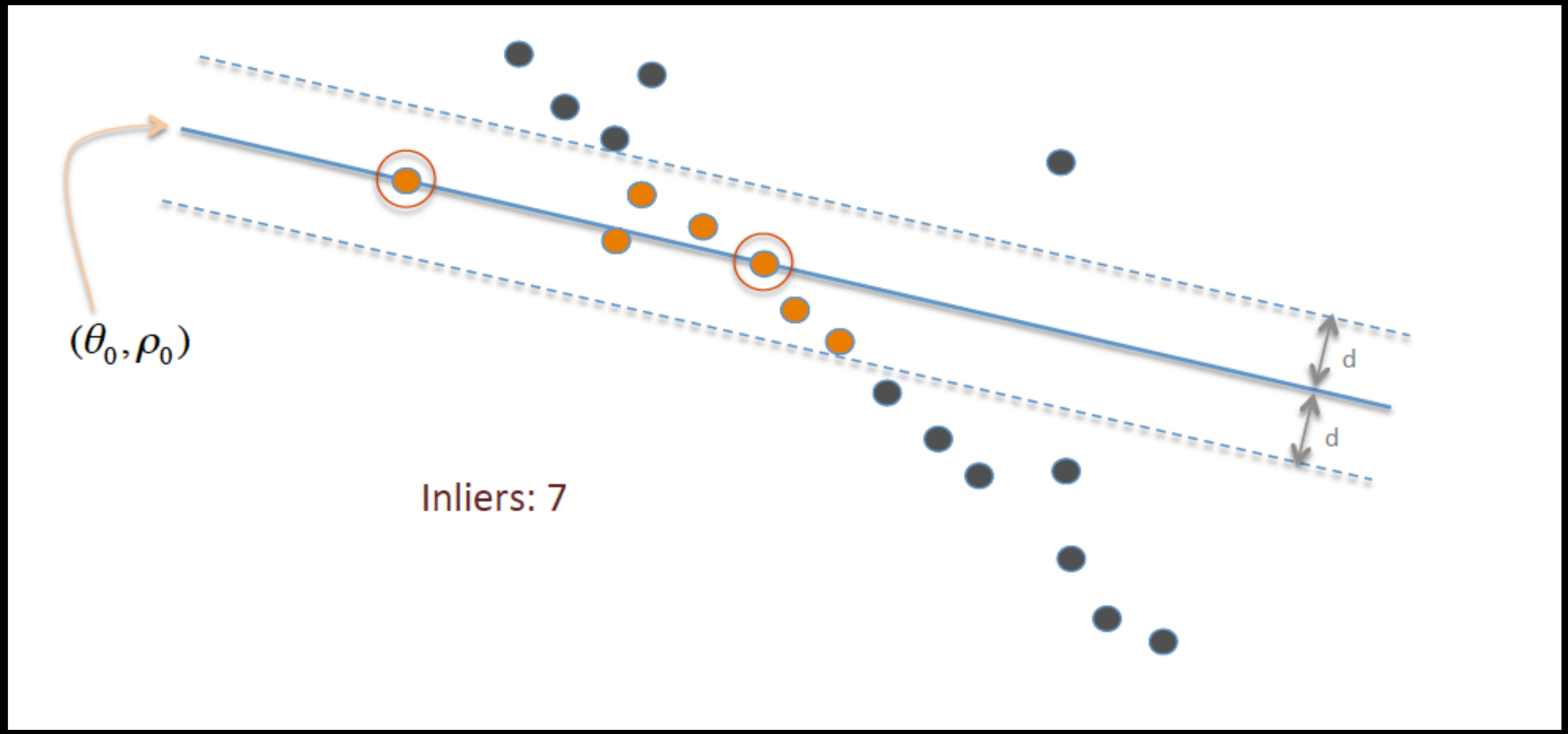


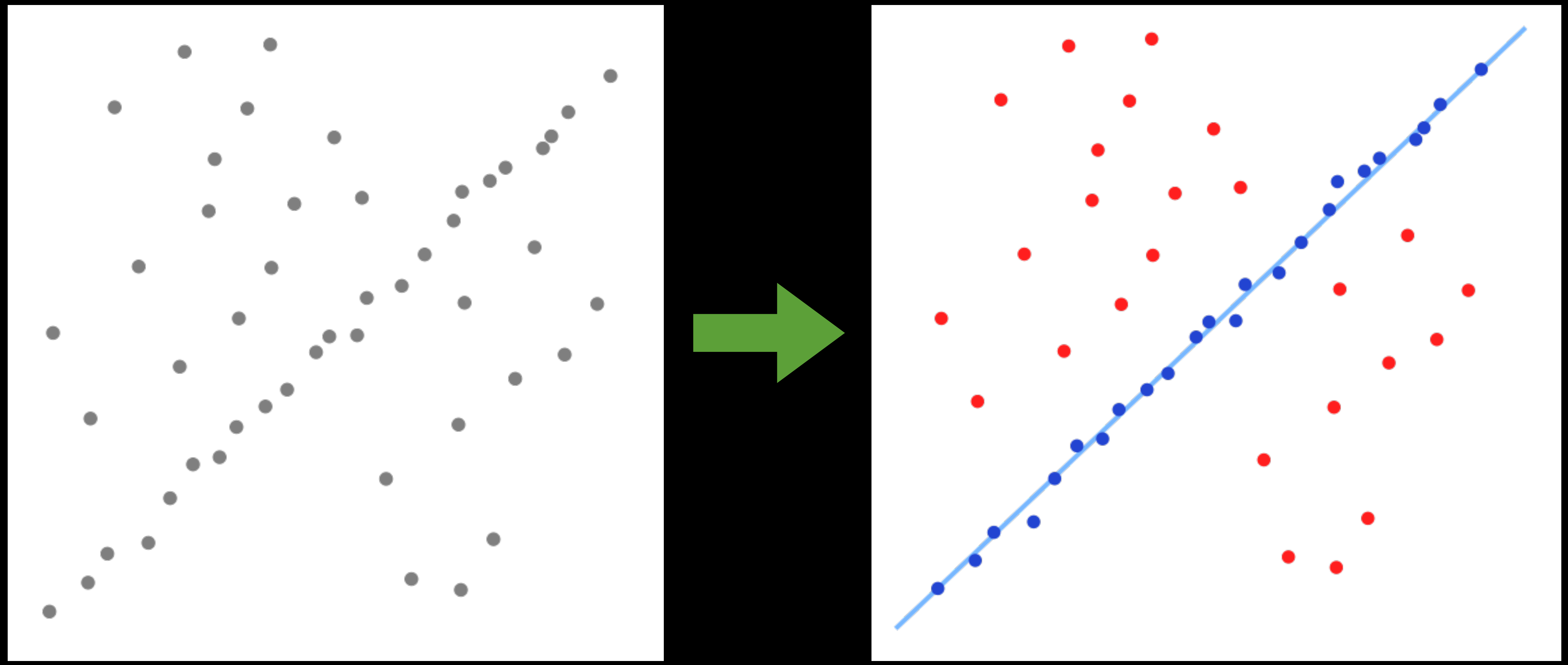
J. Bradt, Ph. D. Dissertation, 2017

https://publications.nscl.msu.edu/thesis/%20Brandt_2017_5279.pdf

RANSAC METHOD

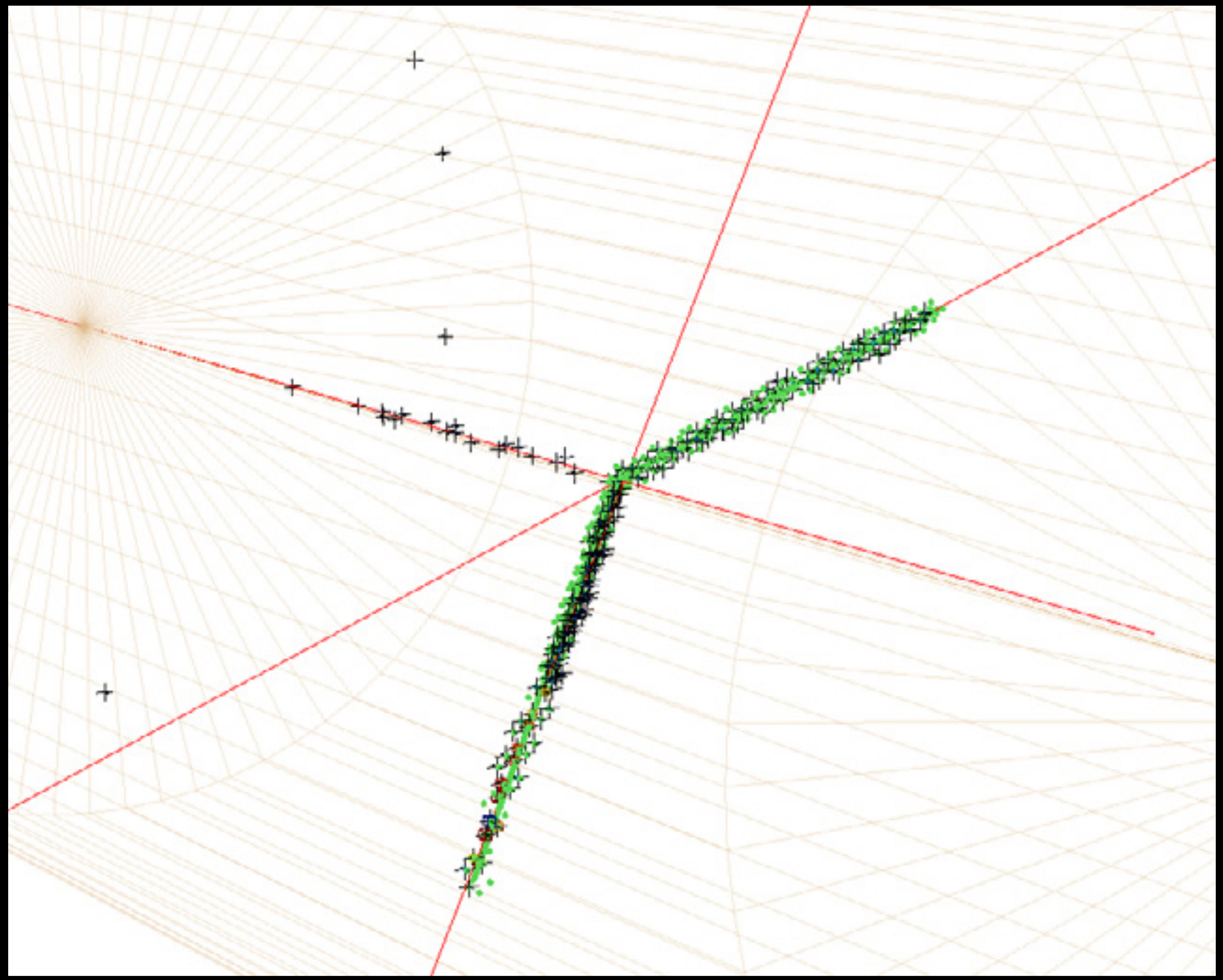
- Random Sample Consensus
  - Select random sample from data
  - Fit model to this subset
  - Test fit on other data than subset
  - Data that fits well is part of consensus
  - Repeat and keep best fit
- Parameters
  - Maximum distance from fit for inliers
  - Minimum number of points for good fit





RANSAC METHOD

- Advantages
  - Can find tracks in 3D
  - Once best fit is found, eliminate inliers from data set and run again
  - Can find multiple tracks
  - Fast algorithm (at least for straight tracks)
- Drawbacks
  - Requires parameter adjustment
  - No convergence criteria

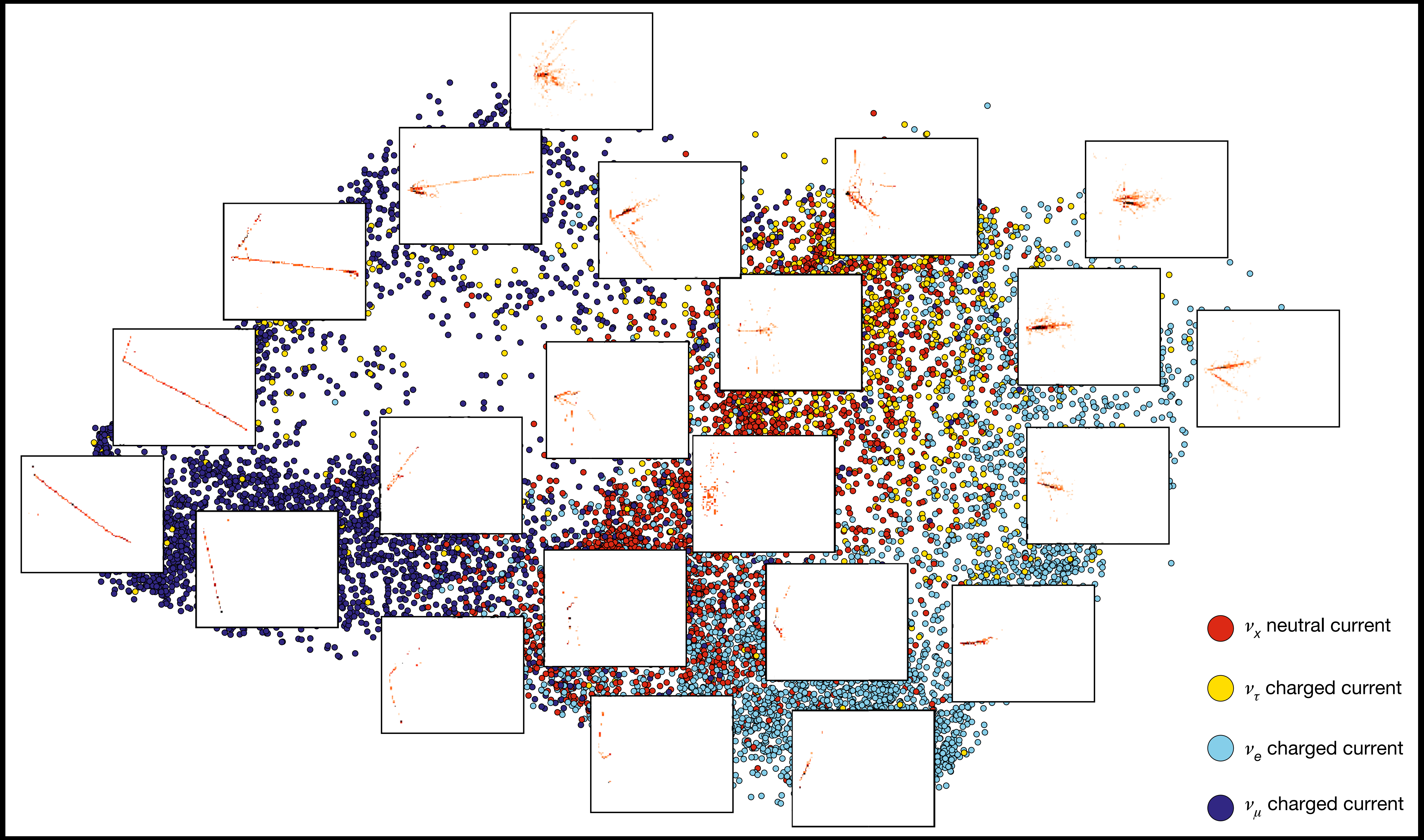


$^{4}He + ^{4}He$ elastic scattering in AT-TPC

Y. Ayyad et al., NIM A880, 166 (2018)

CLASSIFICATION

- Determine classes of events
- Not all events are interesting
- Categorize events based on their data
- Ultimately: make trigger decision during data taking
- This is already being done in high energy physics!

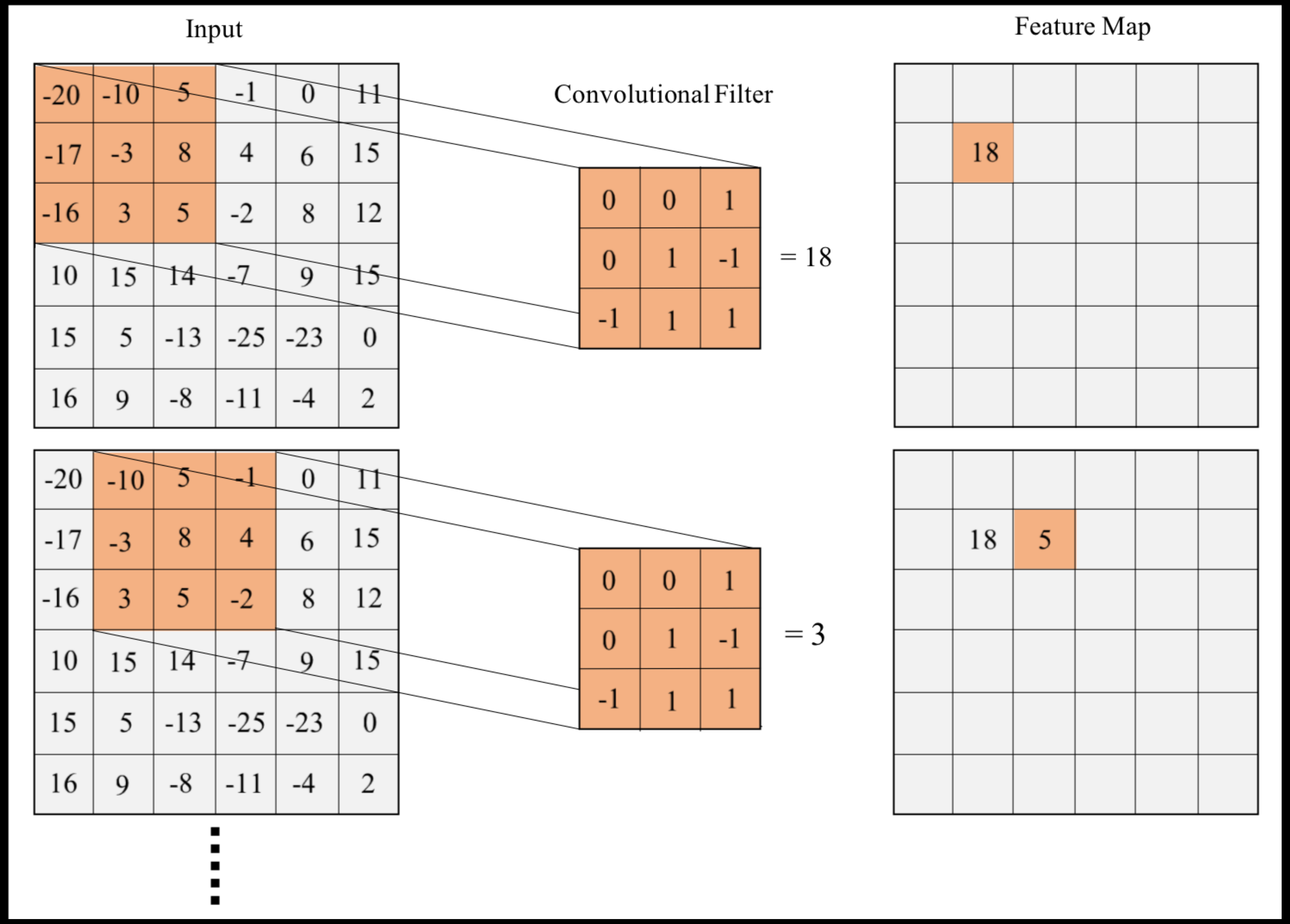


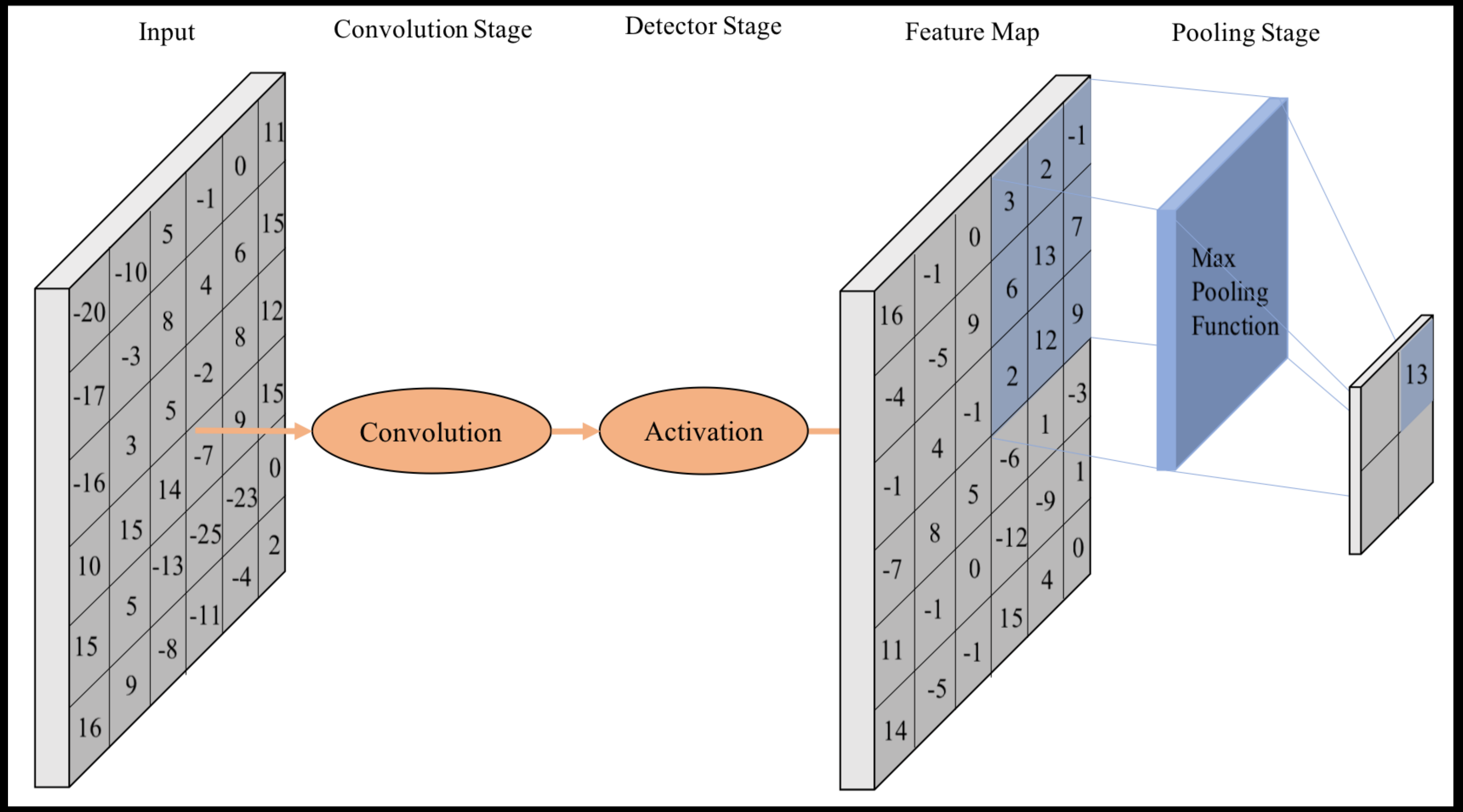
Training data for CNN analysis of NOvA

A. Radovic et al., Nature 560, 41–48 (2018)

CONVOLUTED NEURAL NETWORKS

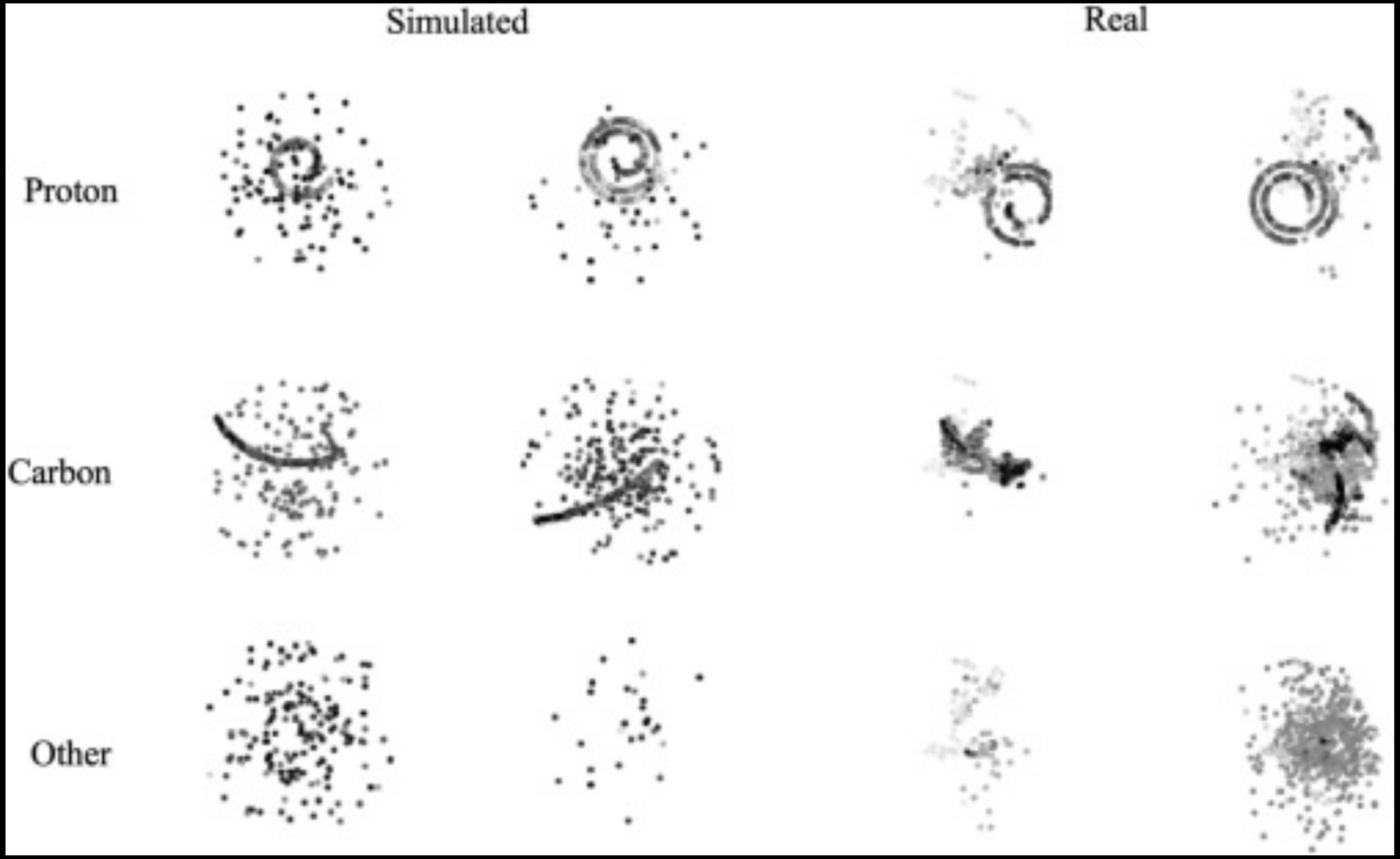
- Image recognition expert
  - Convolution filters designed to extract different features of data
  - Feature maps are then processed and reduced using pooling stage
  - Several convolution layers can be assembled to form a deep learning NN
  - In the end, the most important is to train the CNN on a wide variety of samples





TEST ON AT-TPC DATA

- Classify events
  - ^{46}Ar scattering on C_4H_{10}
  - Recoil can either be p of ^{12}C
  - Both types of events are observed in the AT-TPC
  - Neural networks are trained on simulated data only
  - Downsampling necessary to reduce number of inputs



M. P. Kuchera et al., NIM A 940, 156 (2019)

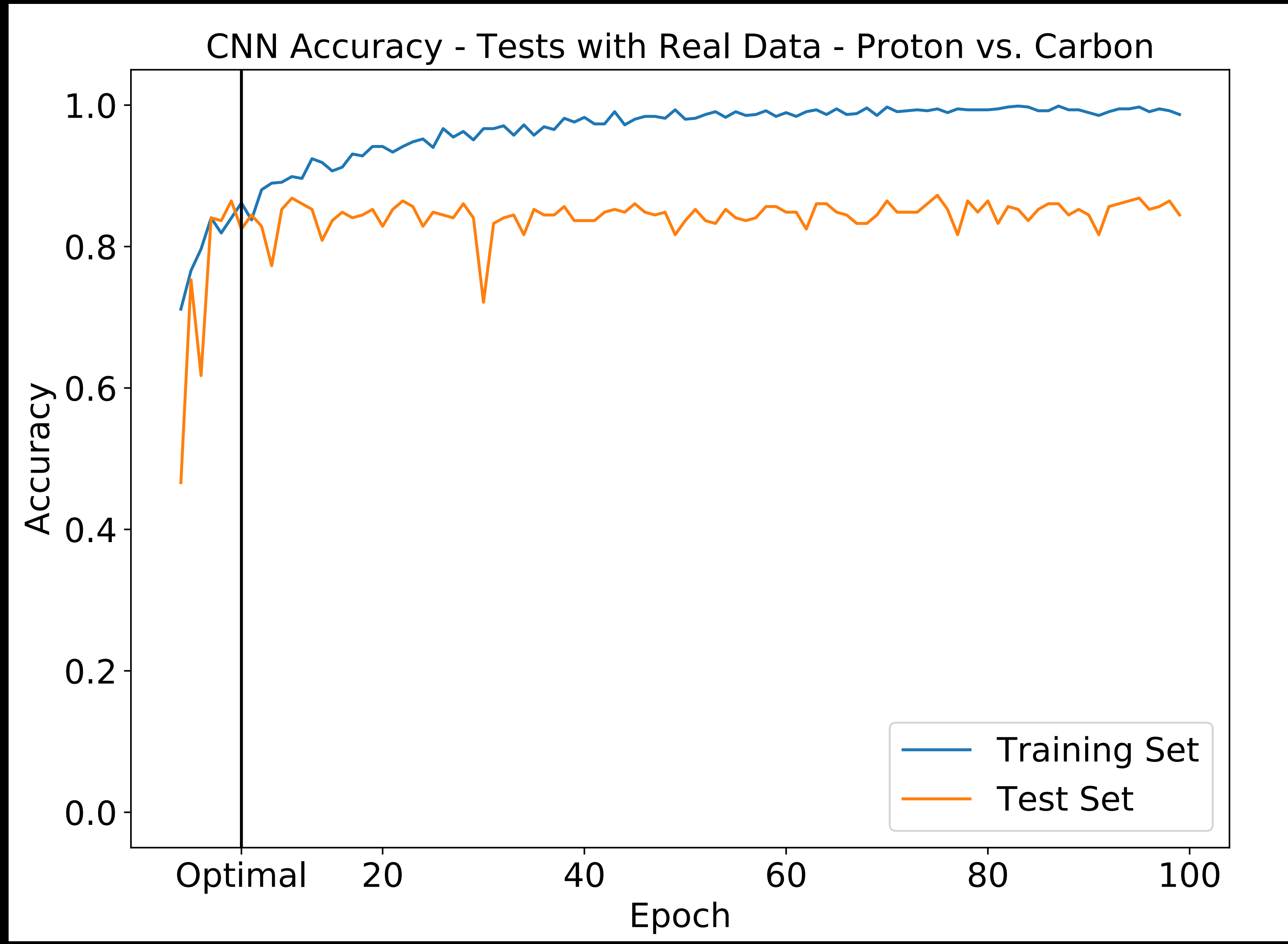
NEURAL NETWORKS RESULTS

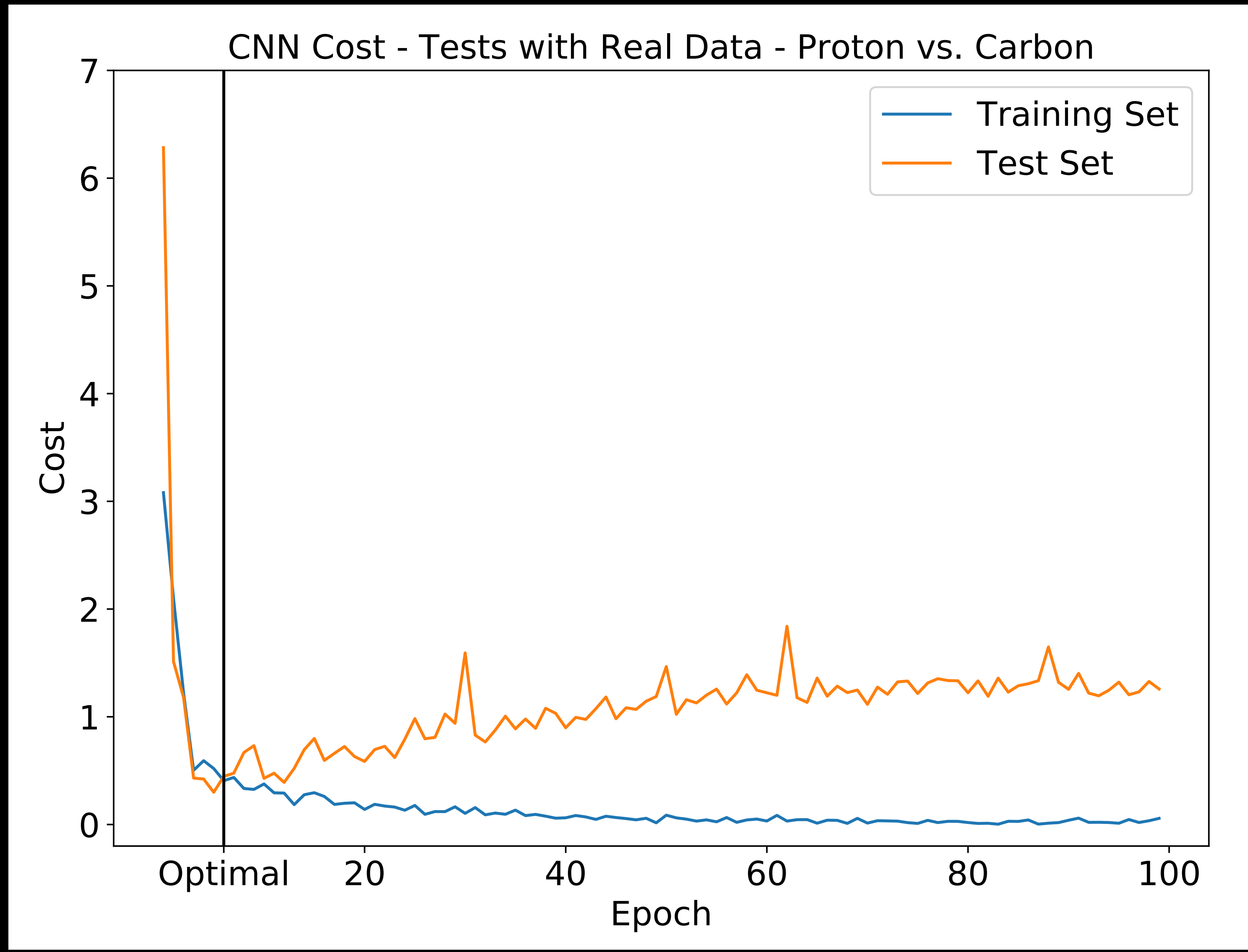
- Amount of training necessary
  - Overfitting: no improvement after the optimal number of passes through training
  - Cost function shows the same trend
- Performance
  - Simulated vs real data

Class	F1 Score		
	LR	NN	CNN
Proton	0.55	0.69	0.77
Carbon	0.87	0.97	0.78
Other	0.71	0.75	0.93

Class	F1 Score		
	LR	NN	CNN
Proton	0.61	0.65	0.64
Carbon	0.41	0.46	0.38
Other	0.83	0.78	0.86

M. P. Kuchera et al., NIM A 940, 156 (2019)



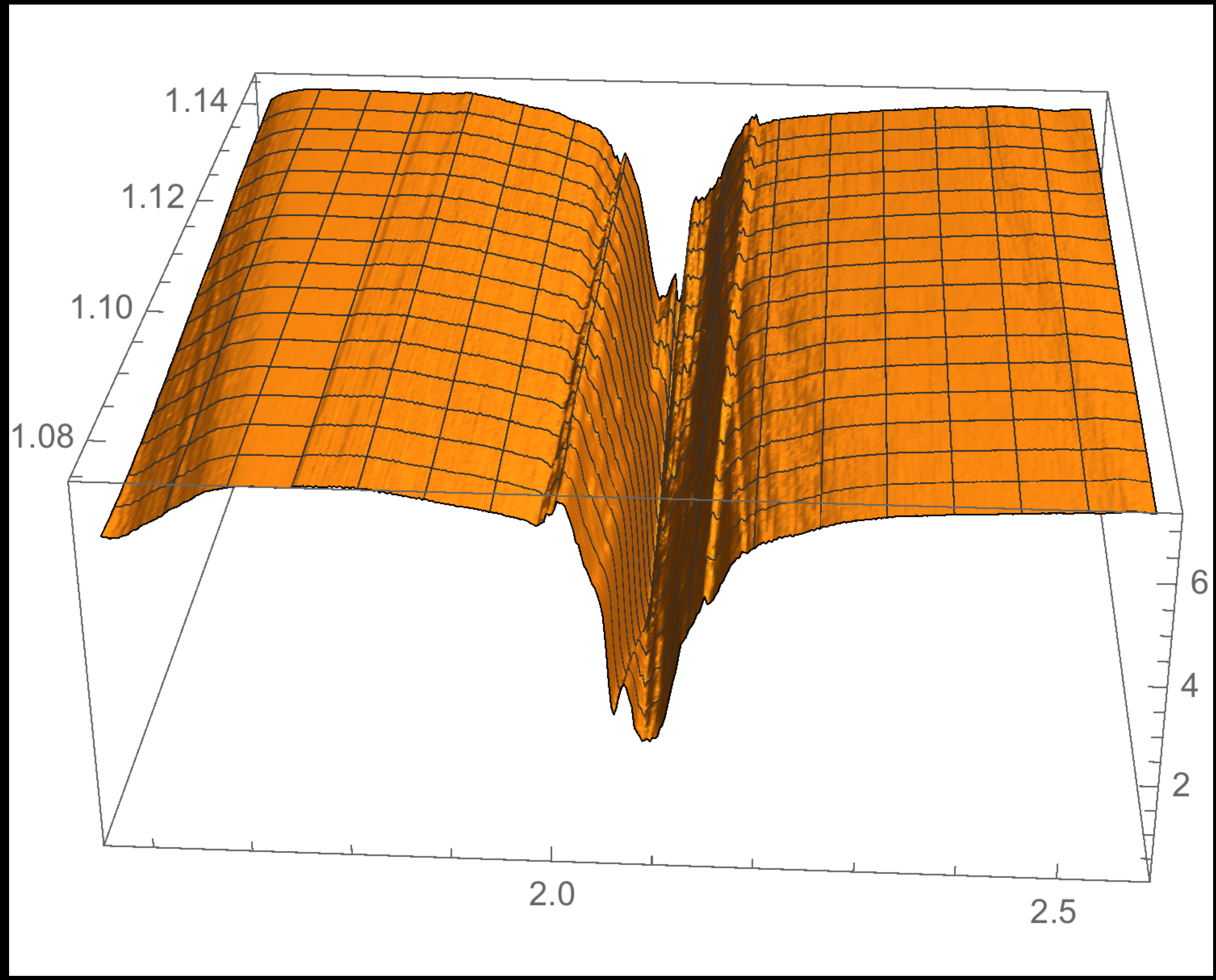


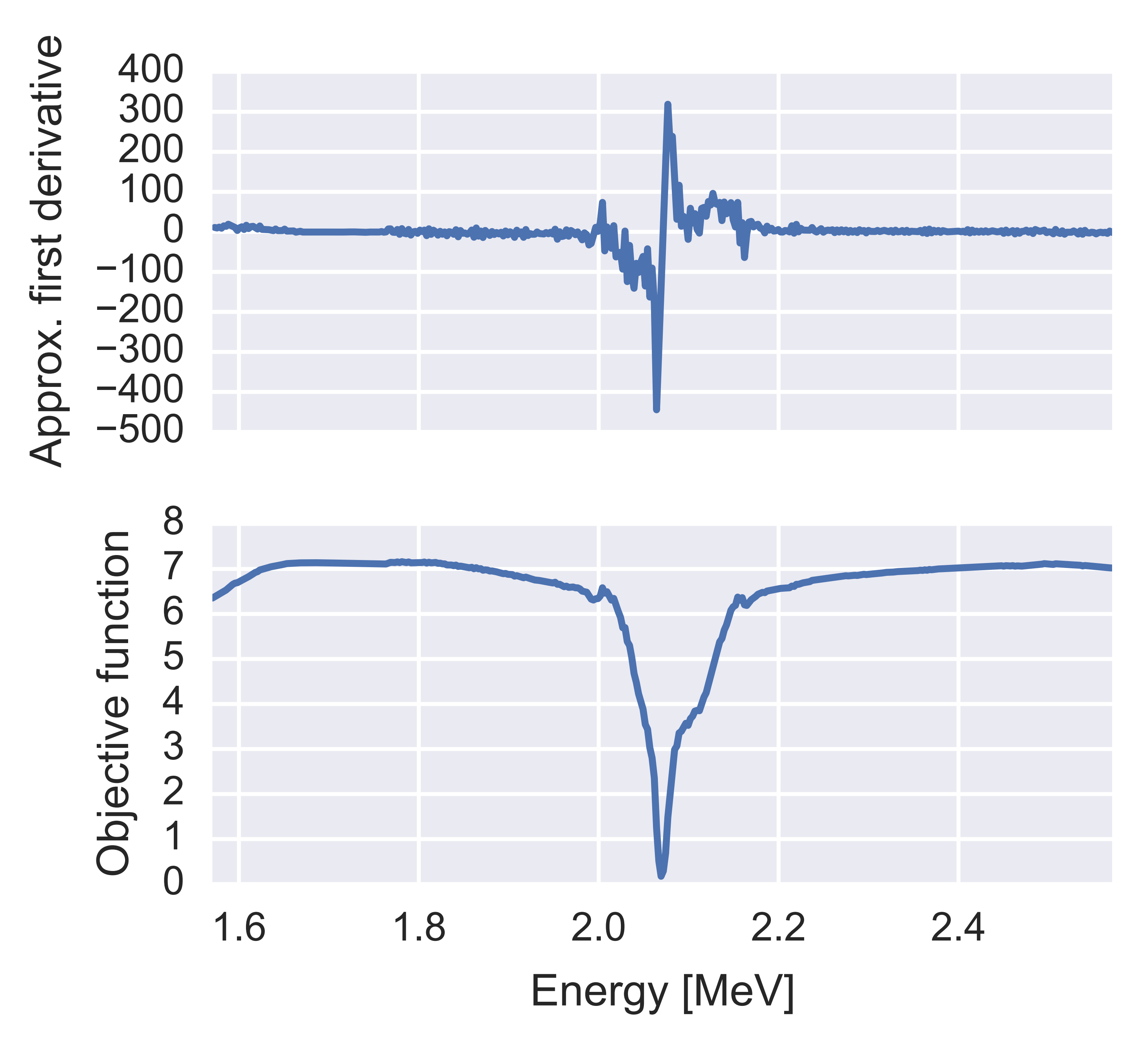
FITTING

- Extract physical parameters
  - Need good initial guess
  - Define objective function
  - Use robust algorithm
- Methods
  - Results from cleaning algorithms
  - Least-square on positions, energies
  - Gradient, Monte-Carlo, etc…

GRADIENT METHODS

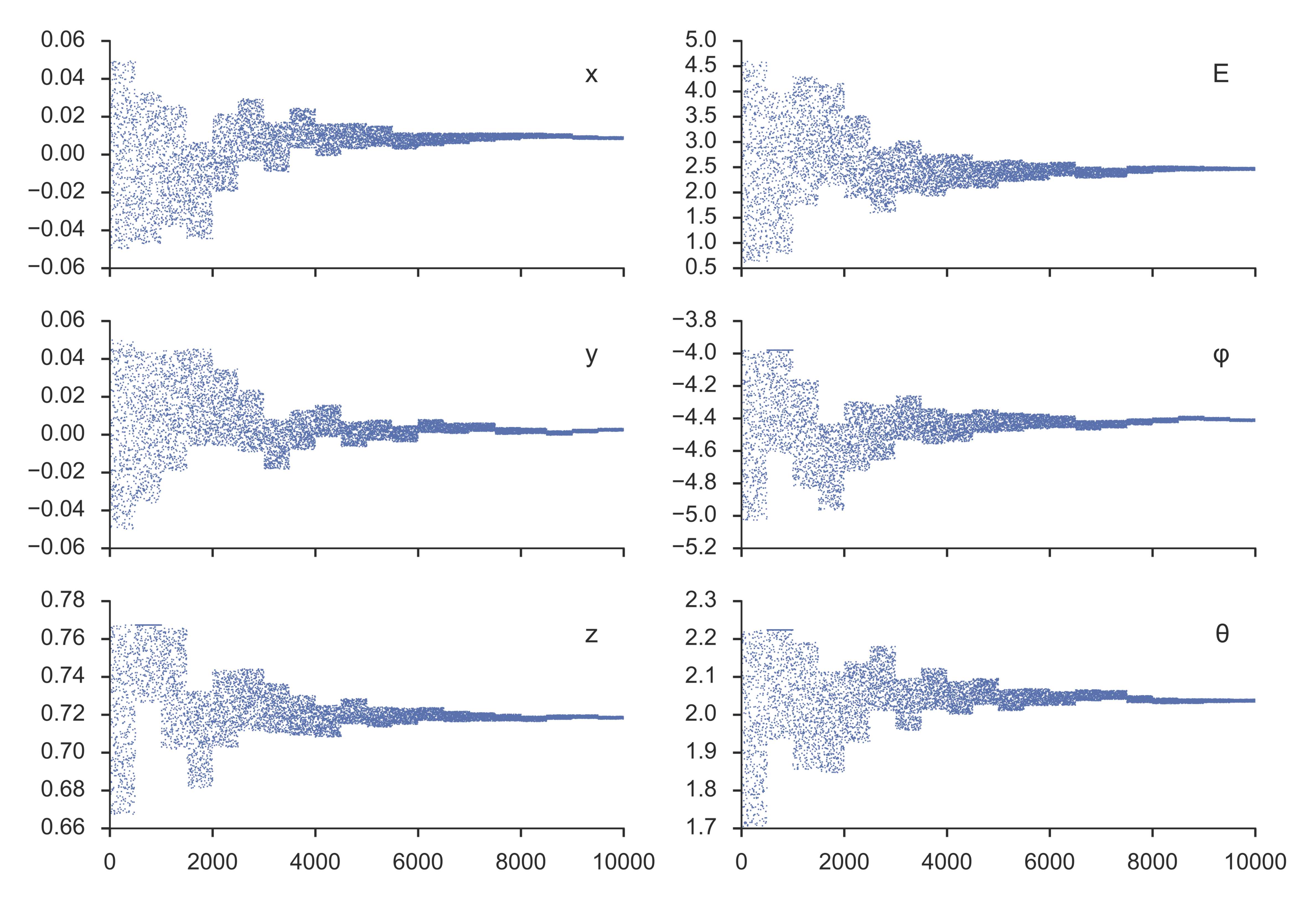
- Most used fitting methods
  - Rely on good derivatives of the objective function
  - Signal variation on pads highly non-linear
  - Example shows energy χ^2 as a function of energy and scattering angle
  - Algorithm most likely to get trapped in local minima





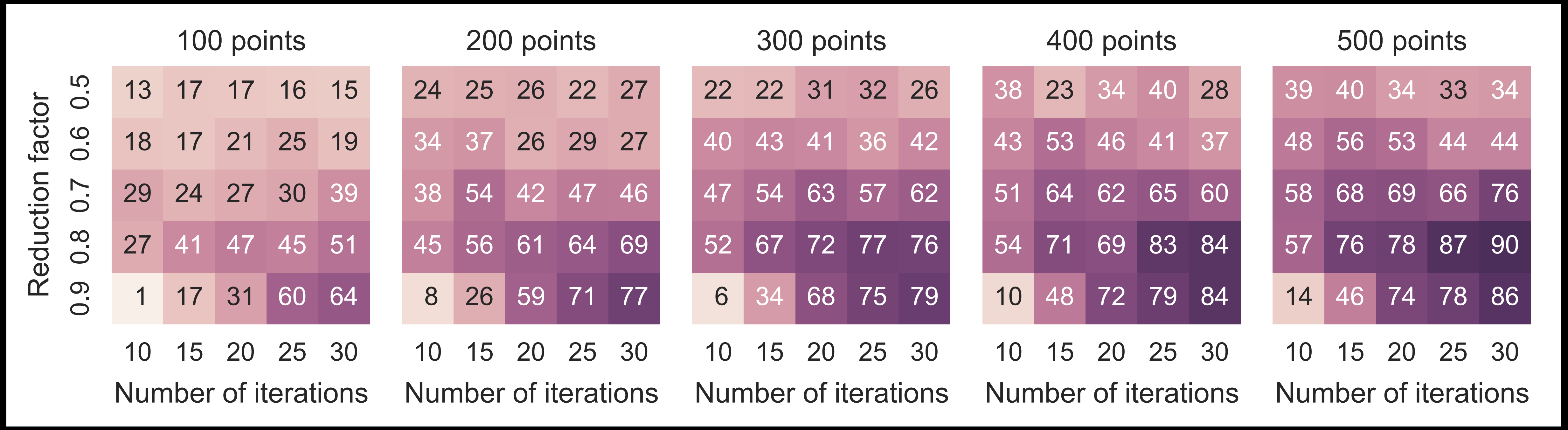
MONTE-CARLO FITTING

- Iterative method based on simulation
  - Generate set of randomly simulated events within parameter space
  - Select track with the lowest value of the objective function
  - Recenter the parameter space around best value and shrink by scale factor
  - Repeat process for a fixed number of iteration or until achieved precision is satisfactory

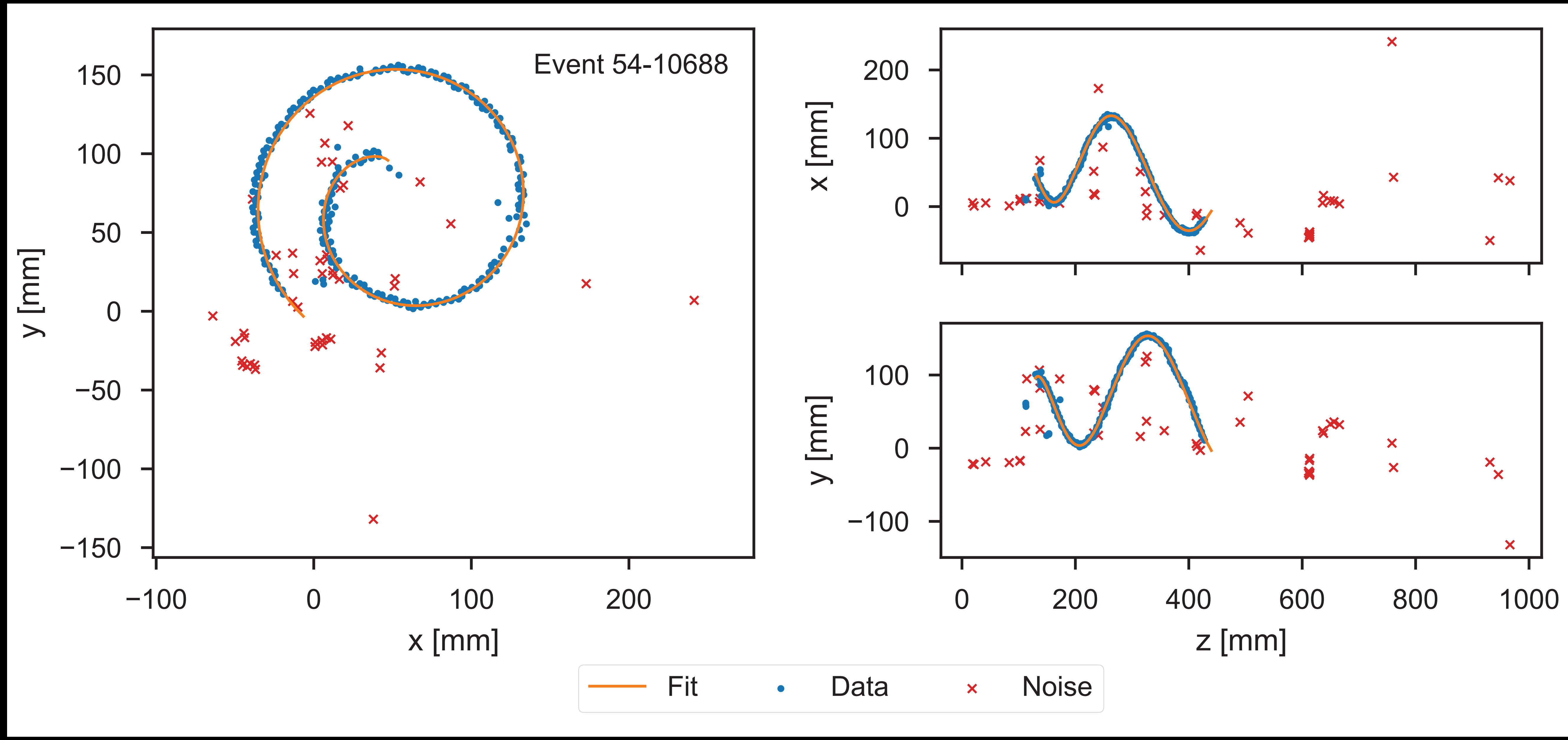


MONTE-CARLO FITTING

- Advantages
  - Very robust against non-linearities
  - Unlikely to fall into local minima
  - So far has given the best results
- Drawbacks
  - Relies on simulations
  - Requires numerous trials (1000's per event)
  - Needs parallel programming and processing



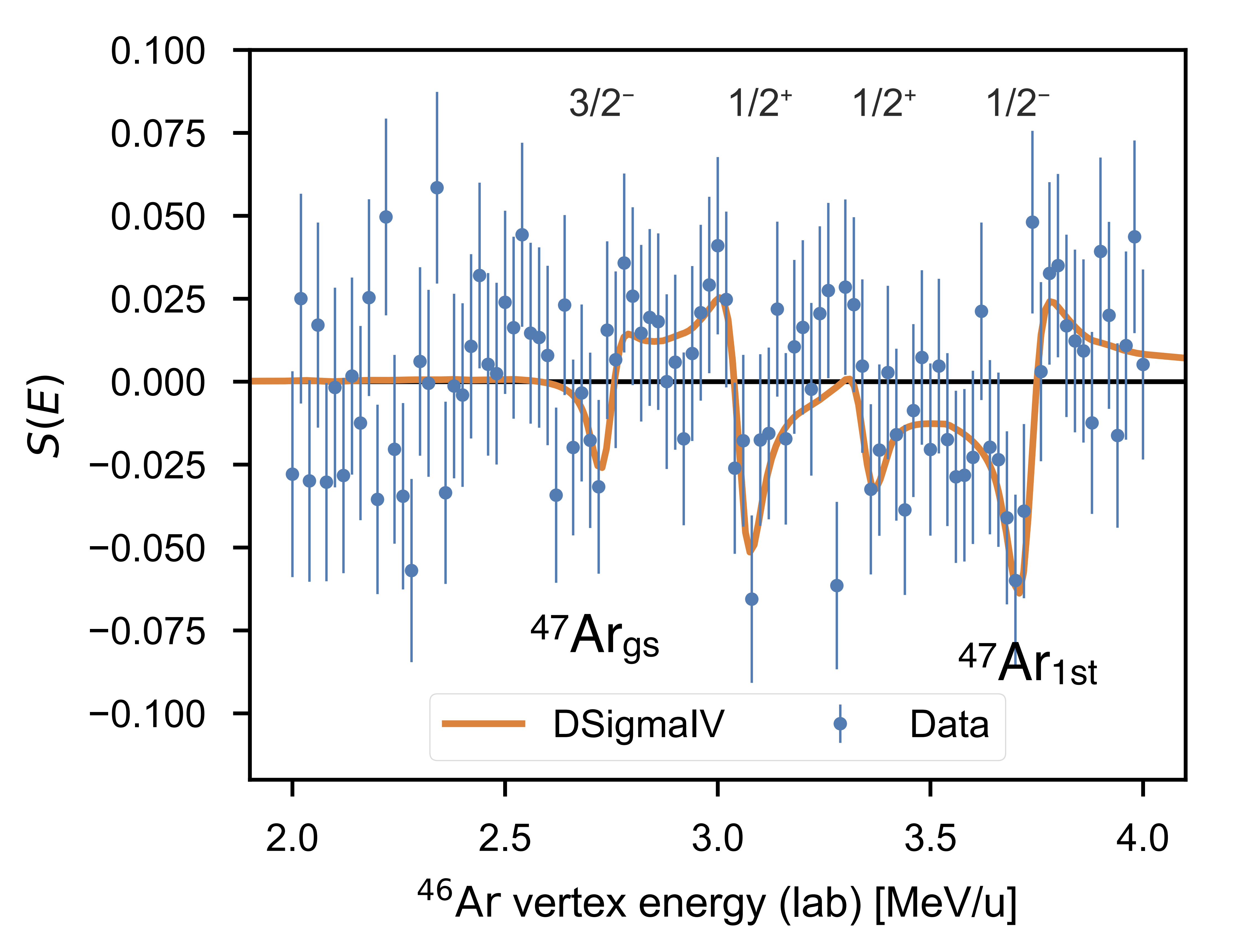
Performance study



Example from AT-TPC data

RESULTS: AT-TPC

- Fit using four resonances by adjusting energies, spectroscopic factors, widths in R-matrix calculation
- $T_>$ resonances in $^{47}K^*$ analog to $^{47}Ar_{gs}$ and $^{47}Ar_{1st}$, as well as possibly $T_<$ resonances
- Statistics is borderline

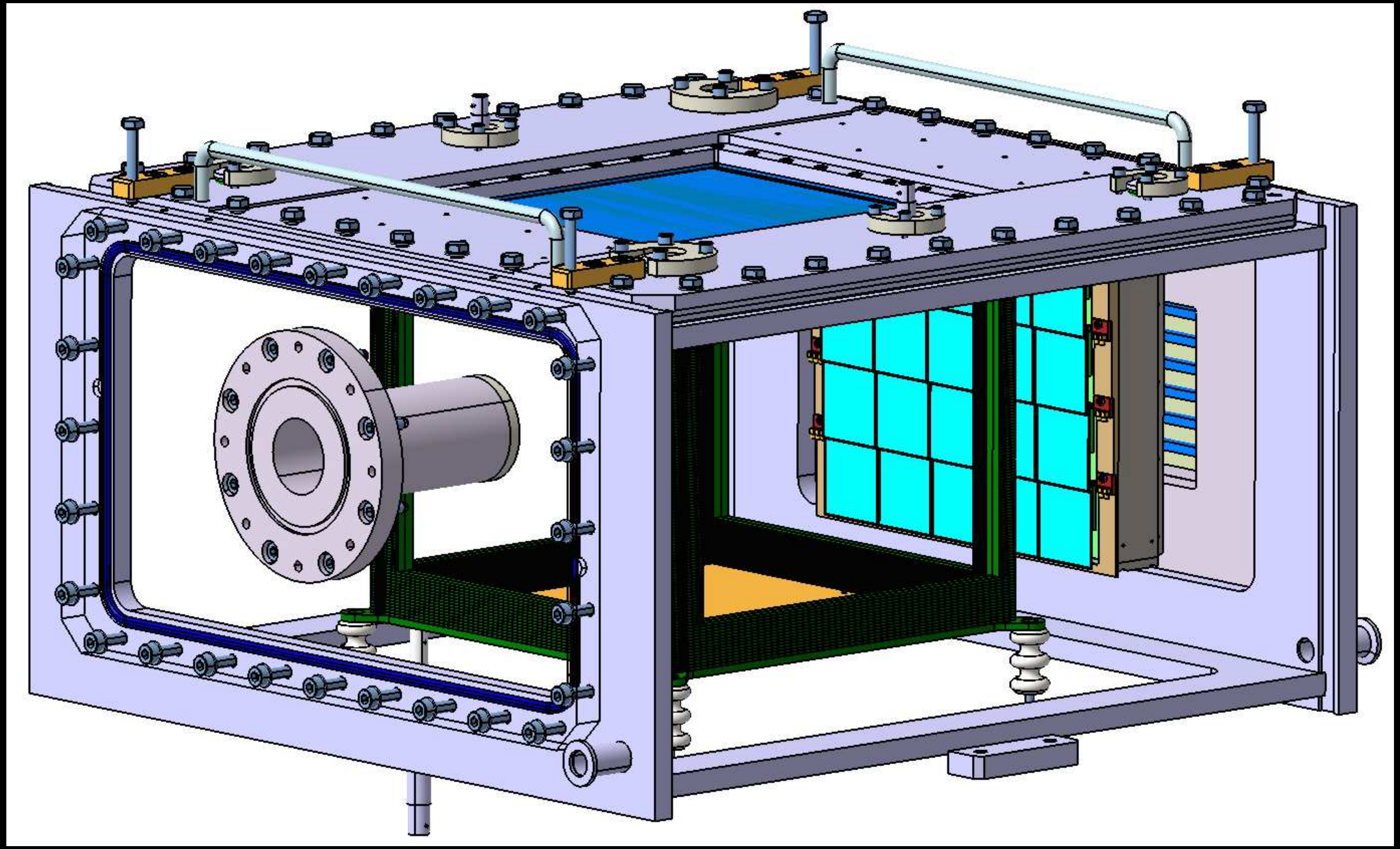


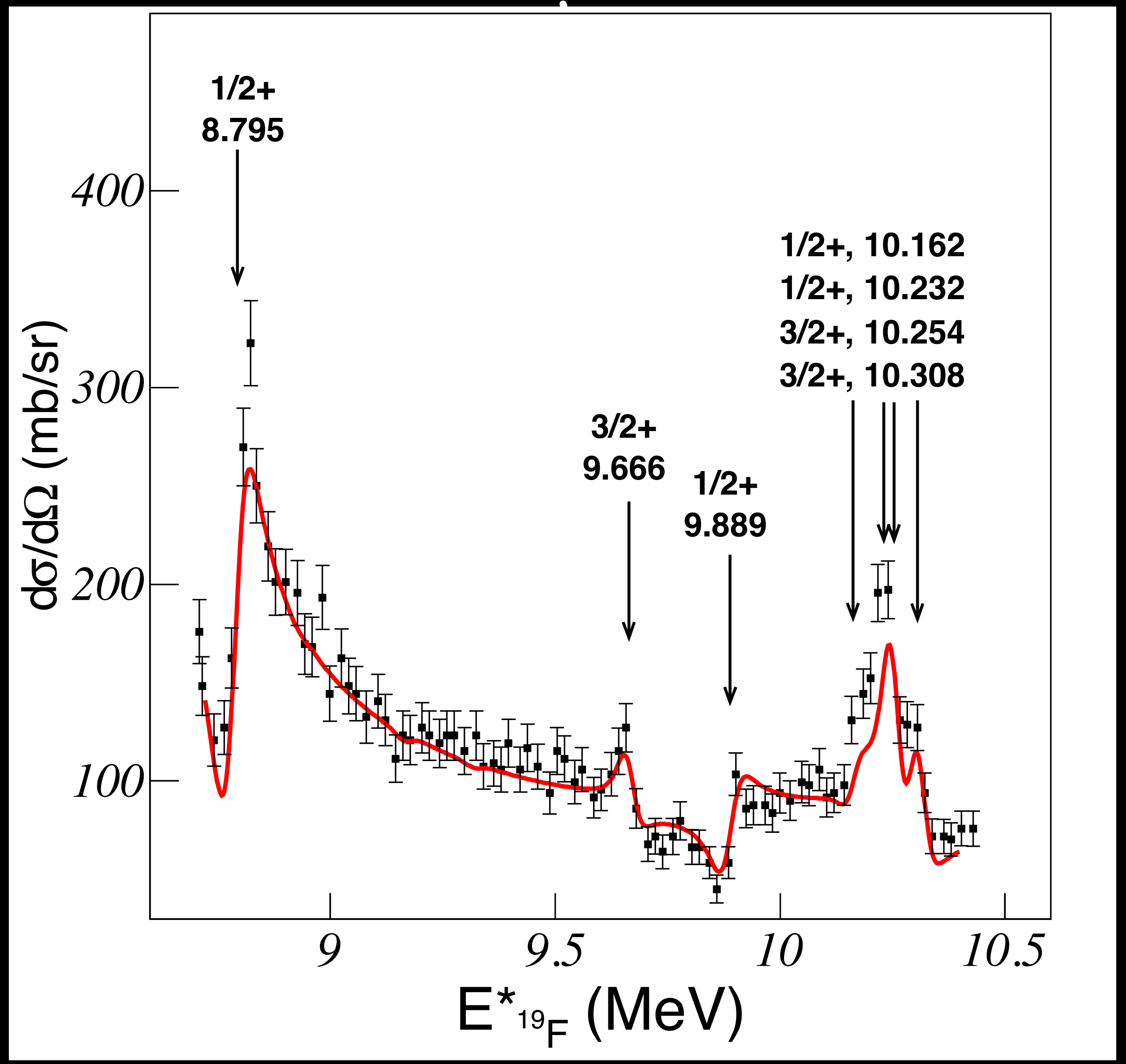
J. Bradt et al., Phys. Lett. B 778, 155 (2018).

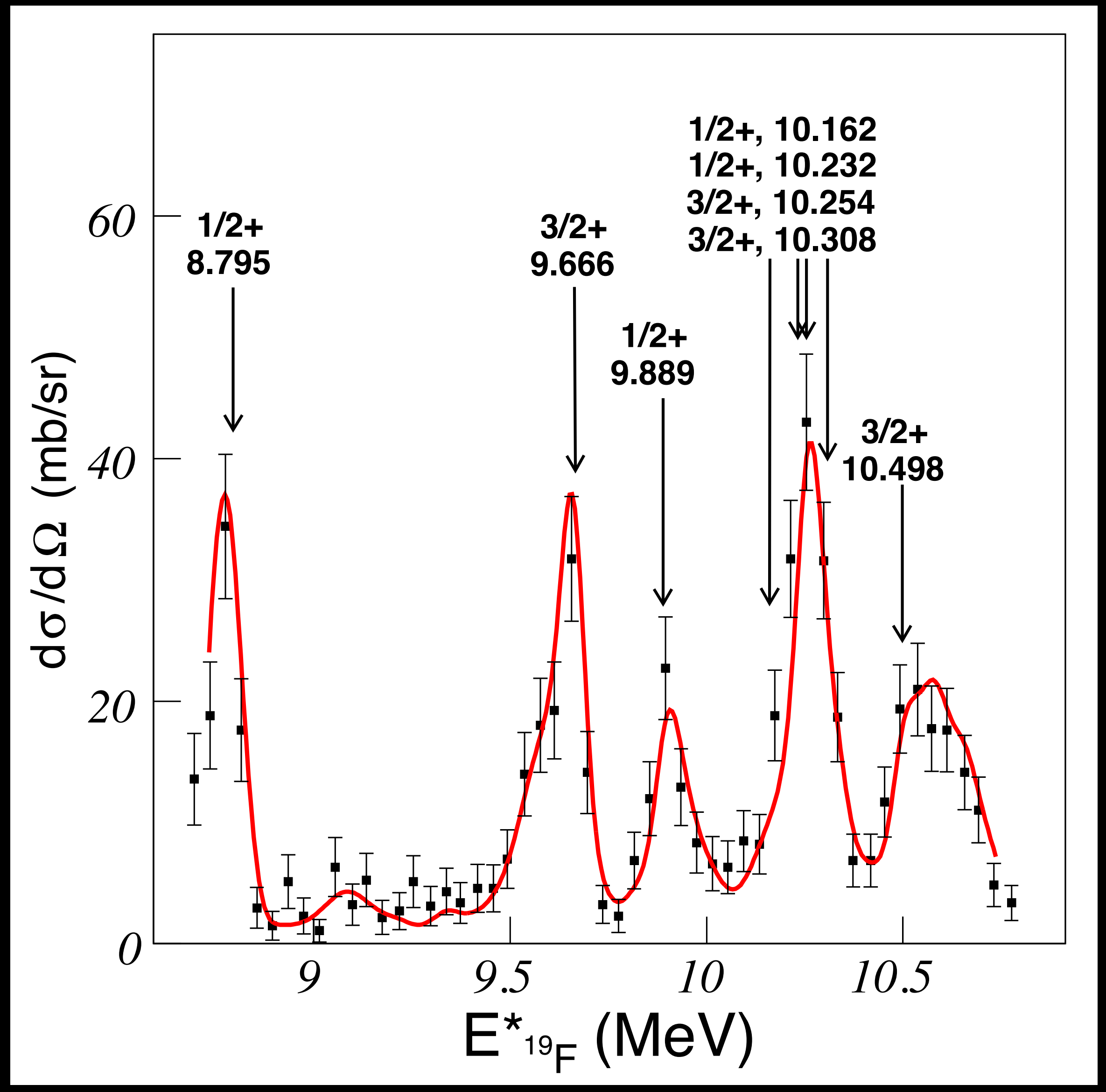
E_{res}^{CM} (keV)	E_x (keV)	J^π	T_z	S	Γ (keV)	Γ_p (keV)	F	p
$2680 \pm 108 \pm 20$	$0 \pm 91 \pm 28$	$3/2^-$	$11/2$ (^{47}Ar)	$0.27 \pm 0.03\ ^{+0.21}_{-0.13}$	15(10)	4.3(4)	2.14	0.15
$2990\ ^{+117}_{-124} \pm 20$	$310\ ^{+91}_{-92} \pm 28$	$1/2^+$	$9/2$ (^{47}K)	$0.027 \pm 0.006\ ^{+0.013}_{-0.007}$	30(10)	20(2)	3.59	0.04
$3280\ ^{+125}_{-127} \pm 20$	$600\ ^{+92}_{-93} \pm 28$	$1/2^+$	$9/2$ (^{47}K)	$0.008 \pm 0.002\ ^{+0.005}_{-0.006}$	18(10)	8.0(8)	0.68	0.58
$3650\ ^{+137}_{-147} \pm 20$	$970\ ^{+95}_{-99} \pm 28$	$1/2^-$	$11/2$ (^{47}Ar)	$0.42 \pm 0.05 \pm 0.09$	34(10)	24(2)	5.50	0.01

RESULTS: ACTAR

- Perpendicular geometry: electrons drift perpendicular to beam direction
- Ancillary detectors: Silicon and CsI detectors detect particles that escape gas volume
- Commissioning experiment using ^{18}O on proton (isobutane target)
- Resonances in (p,p) and (p,α) channels







B. Mauss et al., NIM A 940, 498 (2019)

THE FUTURE OF ACTIVE TARGETS

- Active target TPCs are 3D cameras for nuclear reactions
- First results from existing devices encouraging
- Gain in luminosity paramount for rare isotope beams
- Other methods (passive target) still preferred for higher intensities
- Limitations can be overcome using clever design and electronic tricks
- Applications to new types of reactions and physics themes are likely
- Active target detectors are fun!

ACTIVE TARGETS AROUND THE WORLD

Table 1: Active Targets in operation or being constructed.

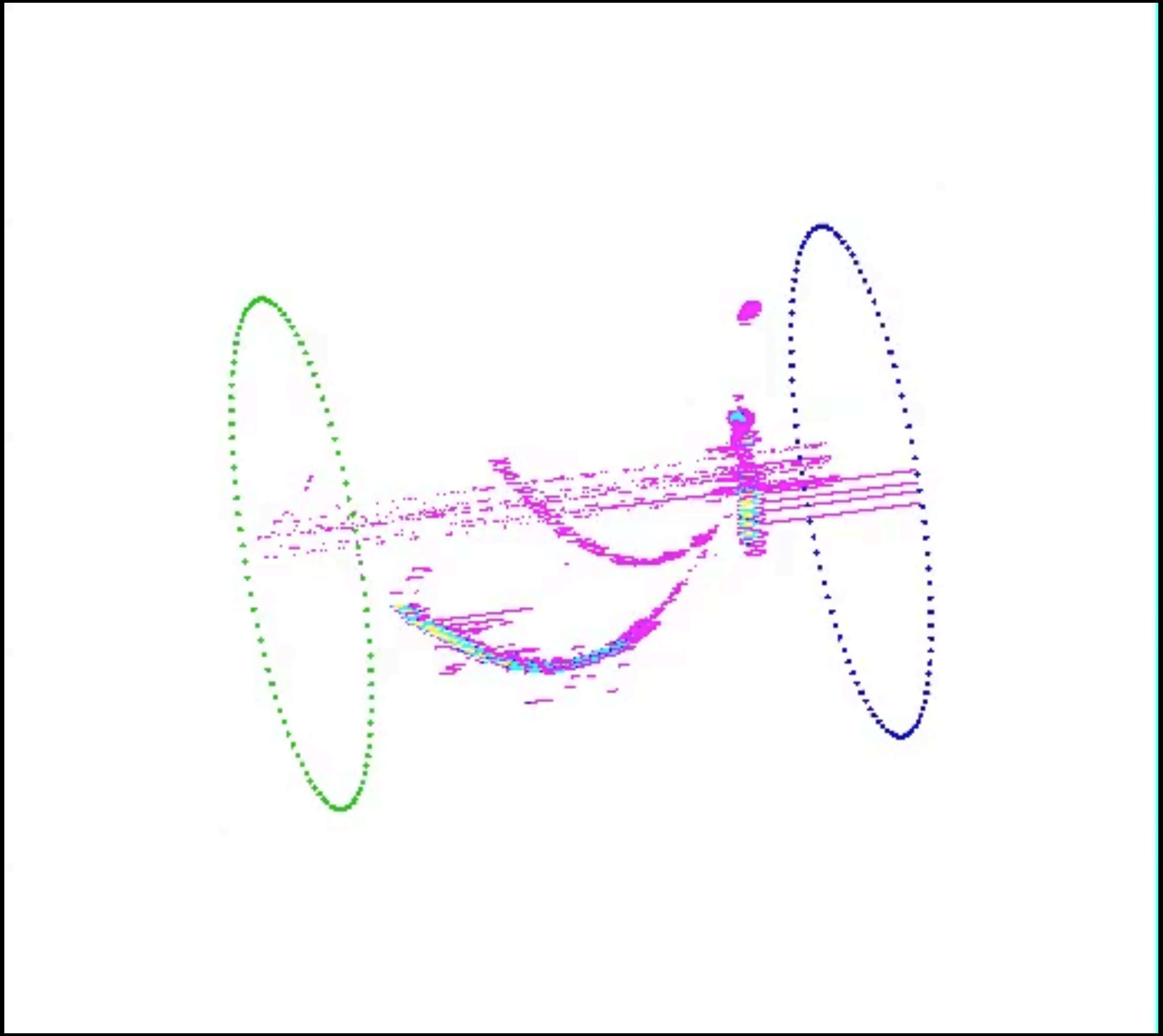
Name	Lab	gas ampl.	Volume [liter]	Volume [cm^3]	pressure [atm]	Energy [MeV/n]	elec tronics	N^0 of chan.	sta tus[a]	ref
Ikar	GSI	NA	75	$60 \cdot 20^2\pi$	10	$\gtrsim 700$	FADC	6*3	O	[43]
Maya	GANIL	wire	7.5	$30 \cdot 28.3^2$	0.02-2	2-60	gassiplex	1024	O	[44]
ACTAR TPC	GANIL	μmegas	8	20^3	0.01-3	2-60	GET	16000	C,P	[17]
MSTPC[b]	CNS	wires	21 [c]	$70 \cdot 15 \cdot 20$	<0.3	0.5-5	FADC	128	O	[23] [45]
CAT	CNS	GEM	2.5	$10 \cdot 10 \cdot 25$	0.2-1	100-200	FADC	400	T	[21]
MAIKo	RNCP	μ-PIC	2.7	14^3	0.4-1	10-100	FADC	2×256	T	[18]
pAT-TPC	MSU	μmegas	47	$50 \cdot 12.5^2\pi$	0.01-1	1-10	GET	256	T,O	[22]
AT-TPC	FRIB	μmegas	200	$100 \cdot 25^2\pi$	0.01-1	1-100	GET	10240	O	[46]
TACTIC	TRIUMF	GEM	7.5	$24 \cdot 10^2\pi$	0.25-1	1-10	FADC	48	T	[19]
ANASEN	FSU/ LSU	wires	13	$43 \cdot 10^2\pi$	0.1-1	1-10	ASIC	512	O	[9]
MINOS	IRFU	μmegas	6	6000	1	>120	feminos	5000	O	[47]
O-TPC	TUNL	grid	19	$21 \cdot 30^2$	0.1	~10 CCD	optical	2048× 2048	O	[48]
SpecMAT	Leuvan	μmegas					GET		T	[28]
TexAT	Texas AM	μmegas	5	$(22.4)^2 \cdot 10.15$			GET	1024	T	[19]
ACTAF	FAIR	wires	200	$100 \cdot 25^2\pi$	20	1000	FADC	288	T	[49]
IRIS ATTPC	TRIUMF	μmegas + TGEM			1-10		GET		P	[50]

[a] O: operational, C: under construction, P: Project, T: test device

[b] Two GEM versions: GEM-MSTPC (CNS) [51, 52] GEM-MSTPC (KEK) [53, 54] [c] GEM-MSTPC (CNS): $23.5 \cdot 29.5 \cdot 10.0$, GEM-MSTPC (KEK): $10cm \cdot 10.0 \cdot 10.0$

Y. Ayyad et al., Eur. Phys. J. A 54, 181 (2018)

Run 252
Event 30626



Run 252
Event 30626