Exotic decay modes
of medium-mass proton drip-line nuclei

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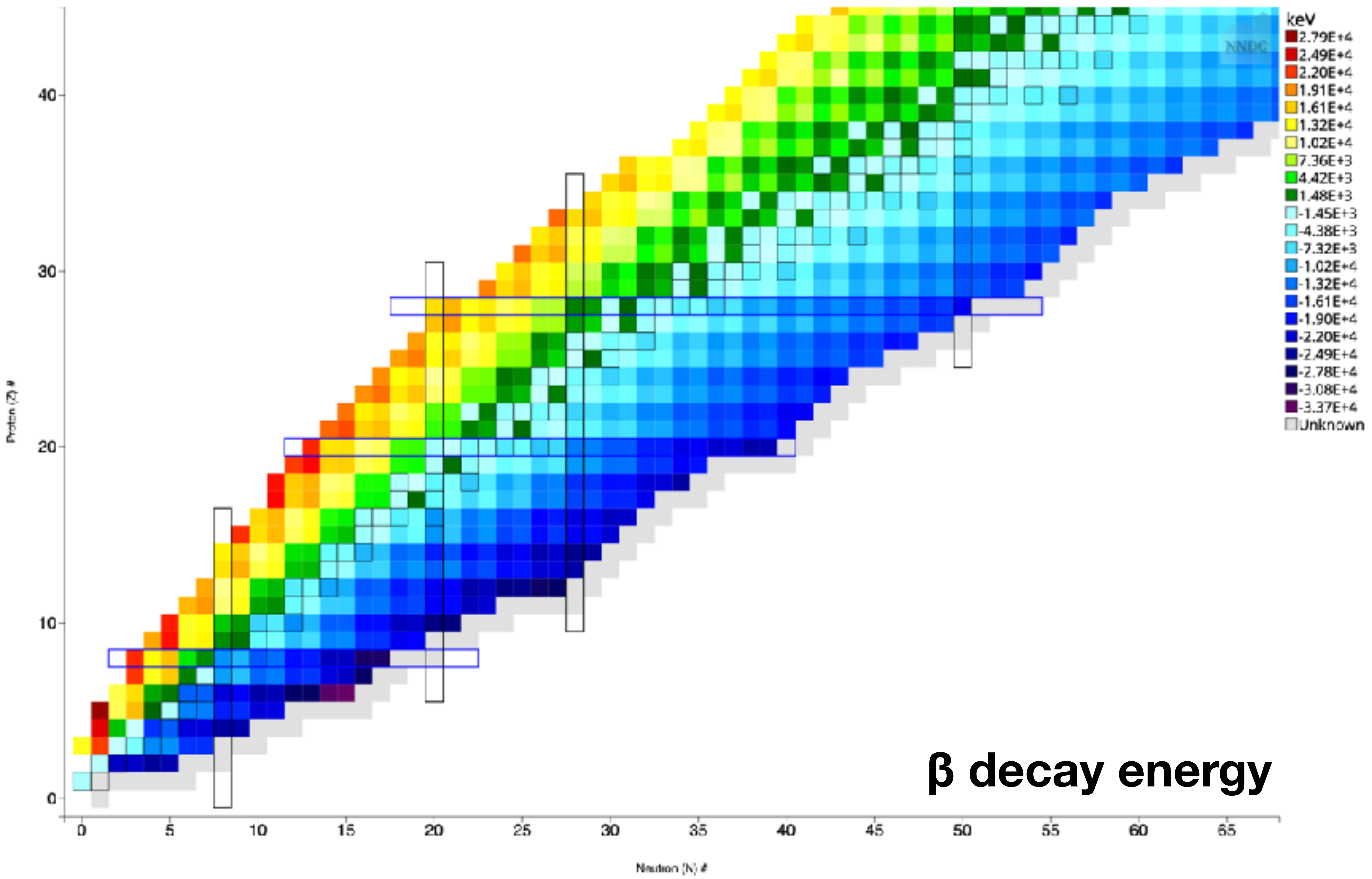
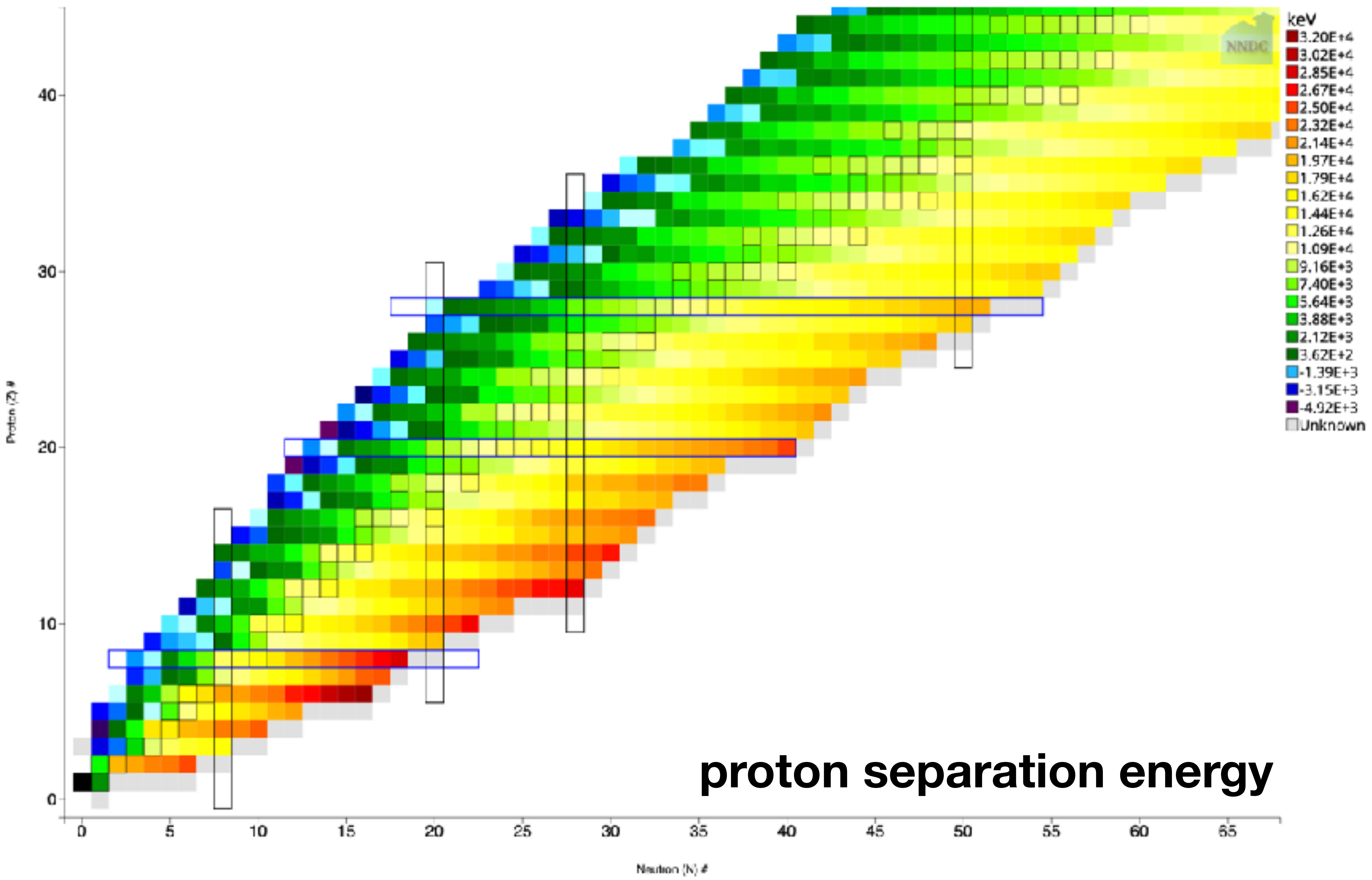
Outline

- Introduction
- Experimental technique
  - General experiment's principle
  - Detector: Optical Time Projection Chamber
- **Study of neutron-deficient Ge and Zn isotopes at MSU**
- **Study of ^{22,23}Si at TAMU**
- Summary

Introduction

Introduction - nuclei close to the proton drip-line





https://www.nndc.bnl.gov/nudat3/

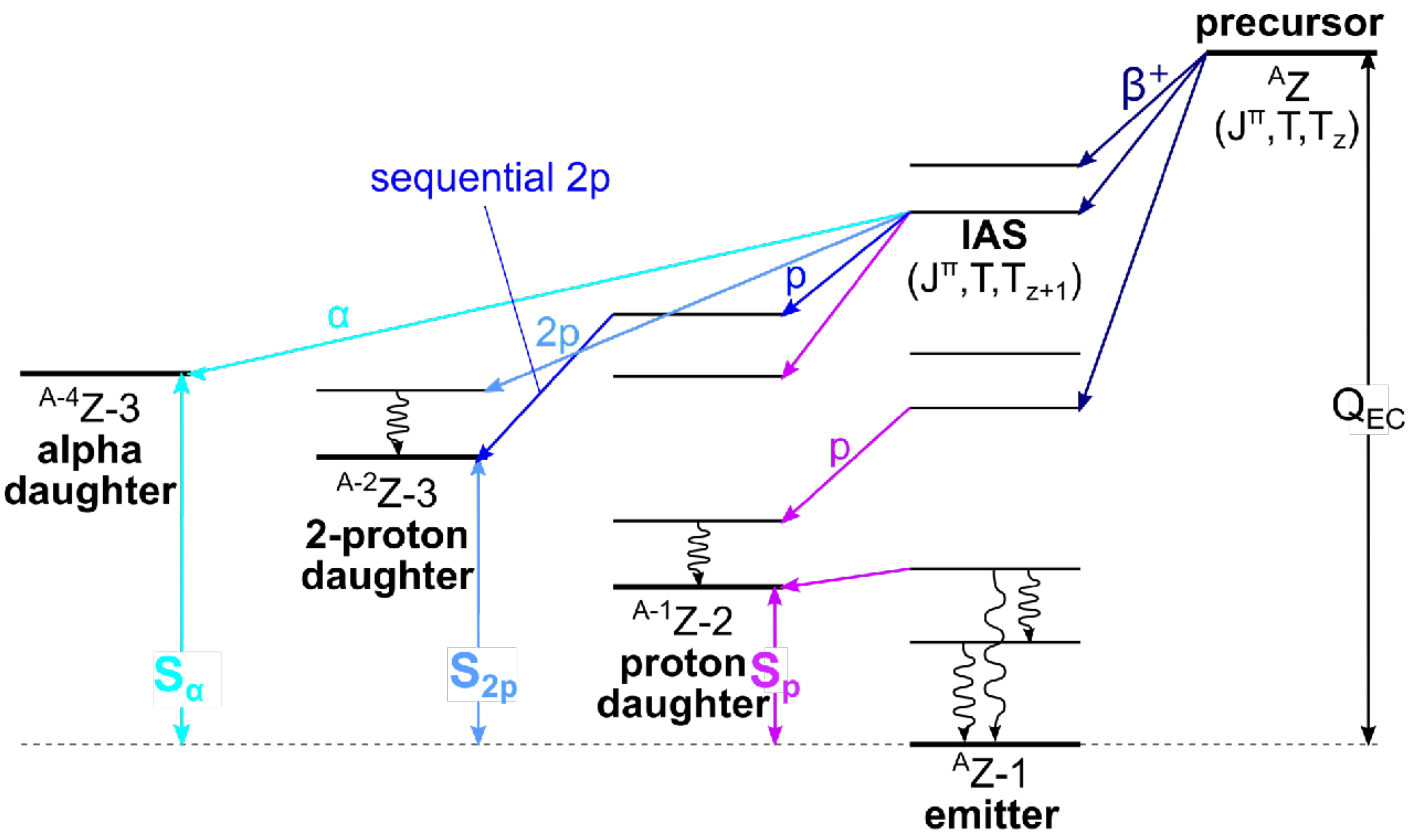
- Increasing β decay energy
- Decreasing separation energies Sp, S2p etc.

→

- Population of highly excited (particle unbound) states in daughter nuclei
- **β-delayed (multi-) particle emission (βp, β2p etc.)**

Introduction: β-delayed charged (multi-) particle emission

- Highly competitive to de-excitation via γ-emission
- Has to be taken into account while studying β-decay strength (B) distribution of high-energy, unbound states for **a complete picture of the nuclear structure**



Why study?

Comparison of experimental studies
(B distribution, $T_{1/2}$)
with theory

Check of nuclear structure and interaction models far from stability

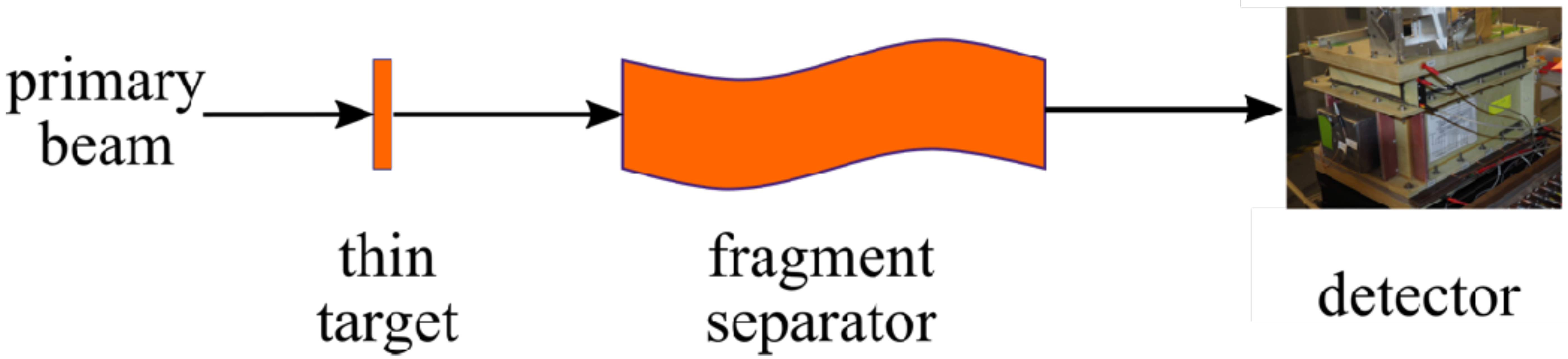
Competition between β-decay and particle capture shapes the rp-process path

Input for the astrophysical rp-process modeling

Abundance of the elements in the Universe

Experimental technique

General principle of our experiments

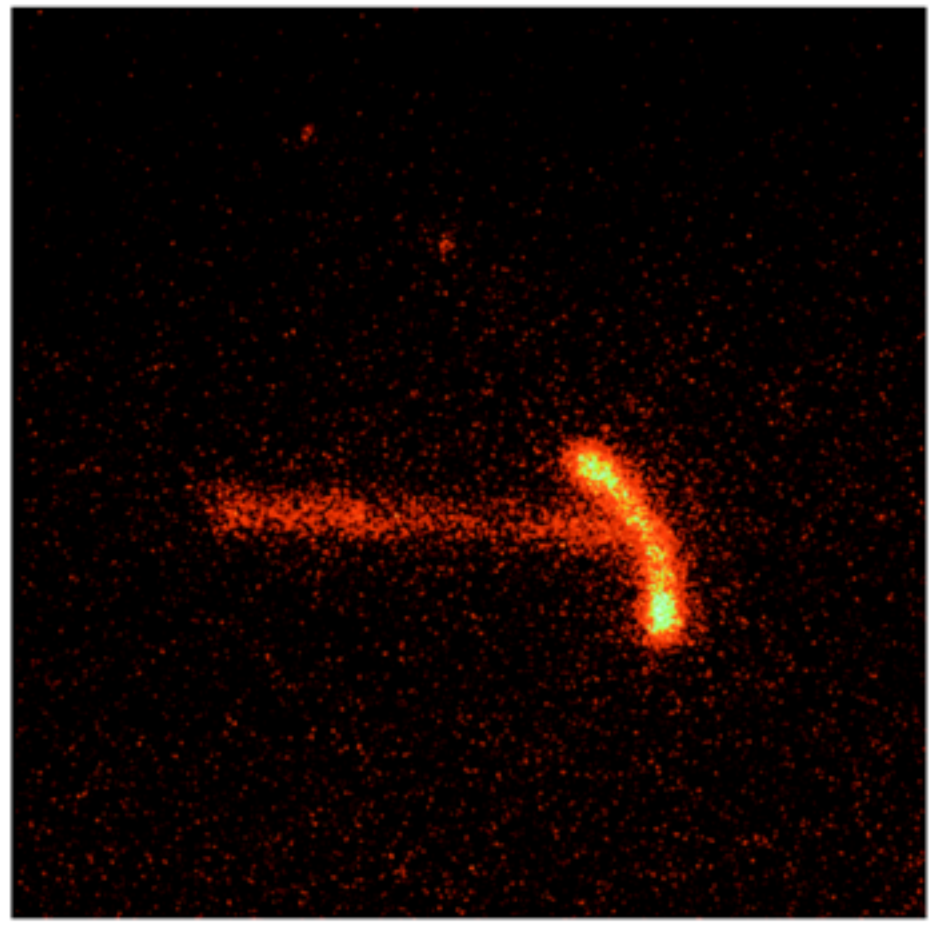


- Production in projectile fragmentation reaction with thin target
- In-flight separation in fragment separator
- Ion-by-ion identification ⟶ trigger
- Implantation into **Optical Time Projection Chamber**
- Detection of decays within active volume of the detector

Detection: Optical Time Projection Chamber

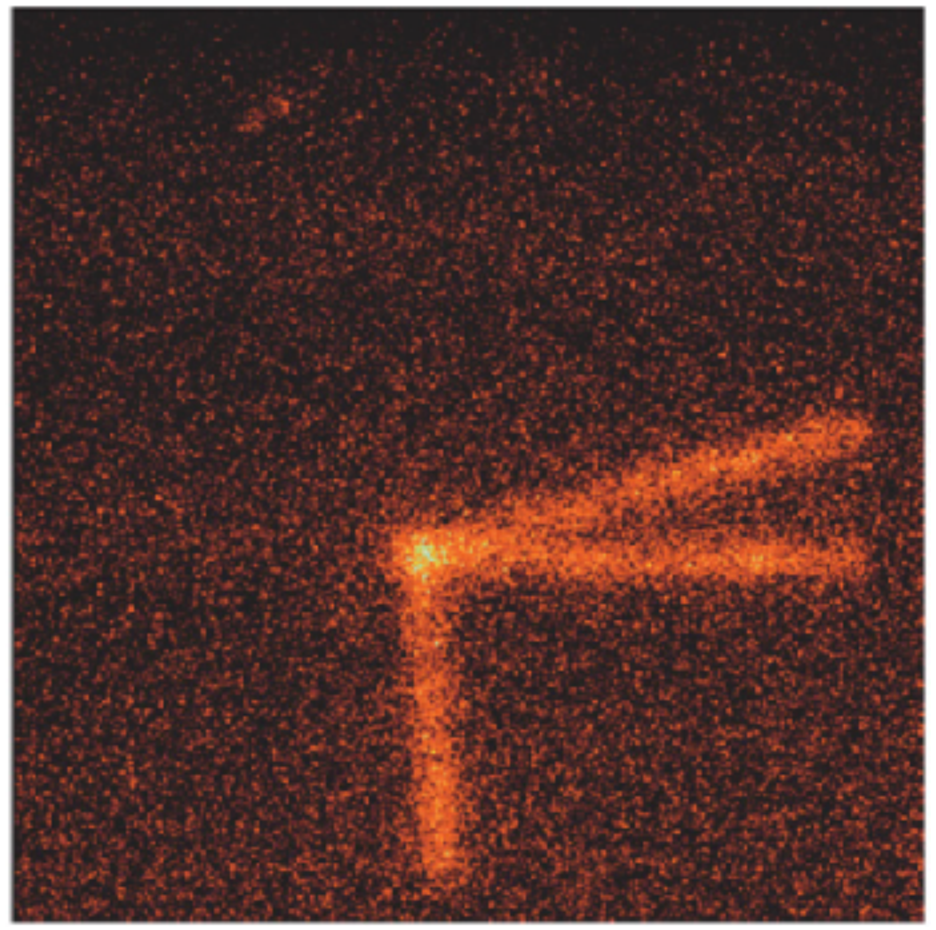
- Developed in mid 2000s at the Faculty of Physics, UW
- Study of 2p radioactivity in ^{45}Fe
- Successfully used for investigation of rare decay modes since then

^{45}Fe 2p



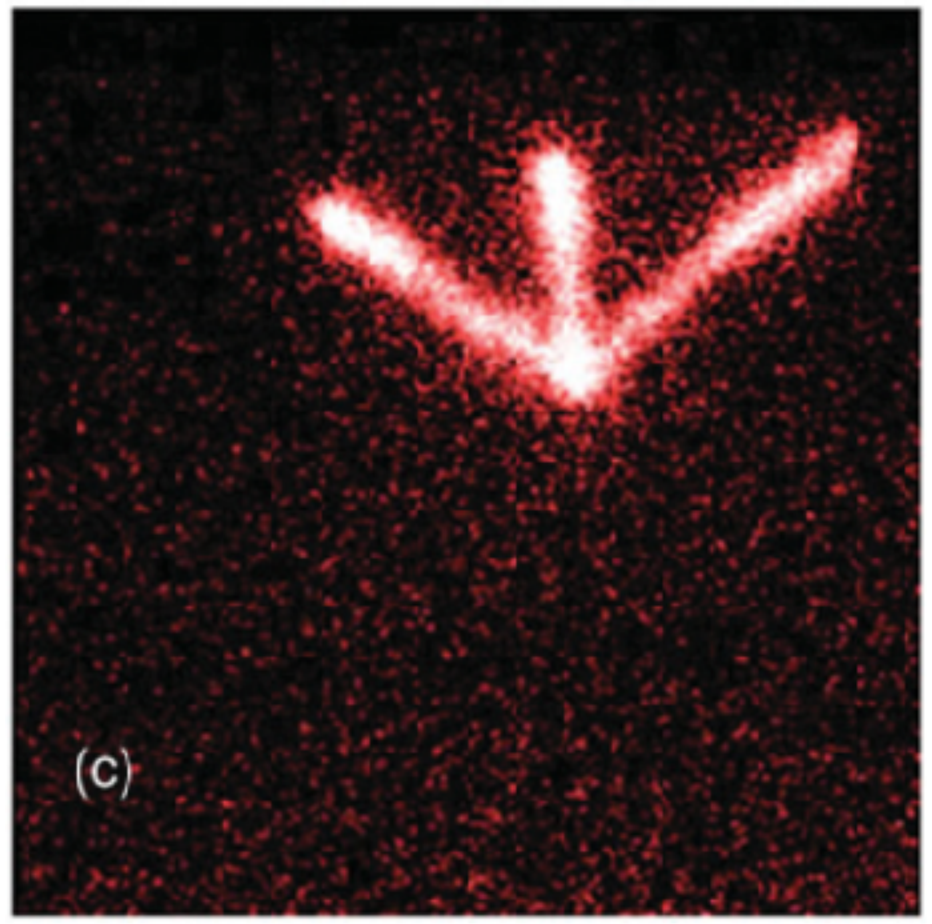
K. Miernik et al., PRL 99, 192501 (2007)

^{45}Fe β3p



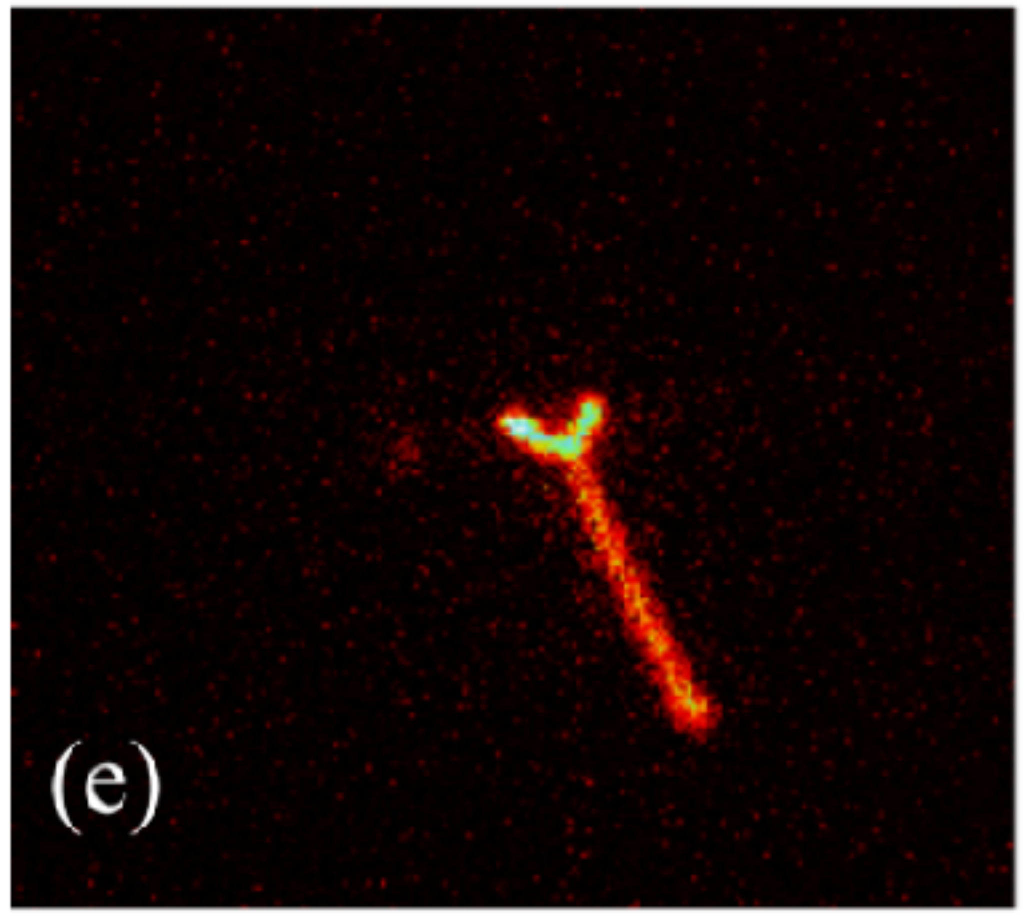
K. Miernik et al., Phys. Rev. C 76, 041304(R) (2007)

^{43}Cr β3p



M. Pomorski et al., Phys. Rev. C 83, 014306 (2011)

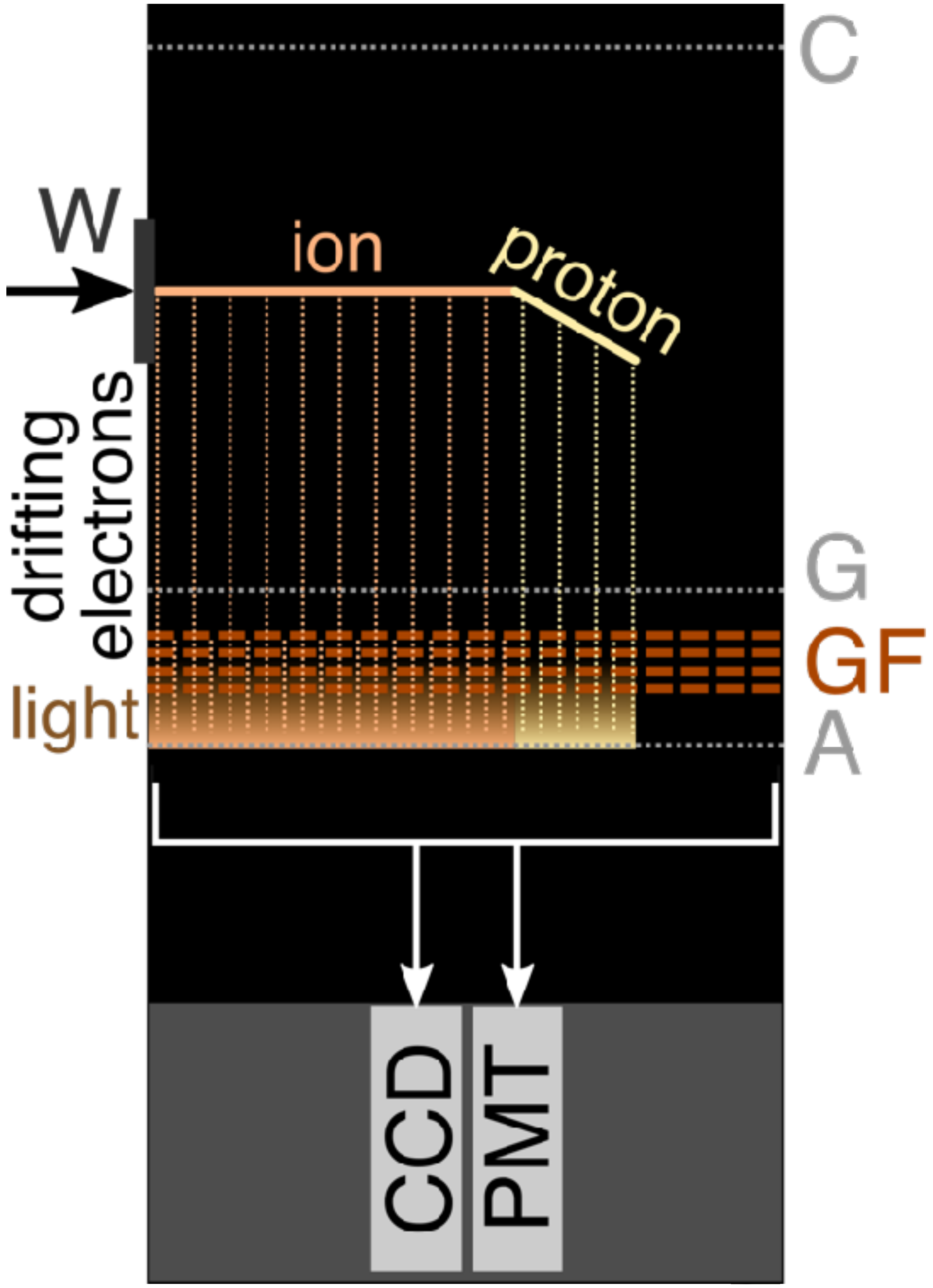
^{31}Ar β3p

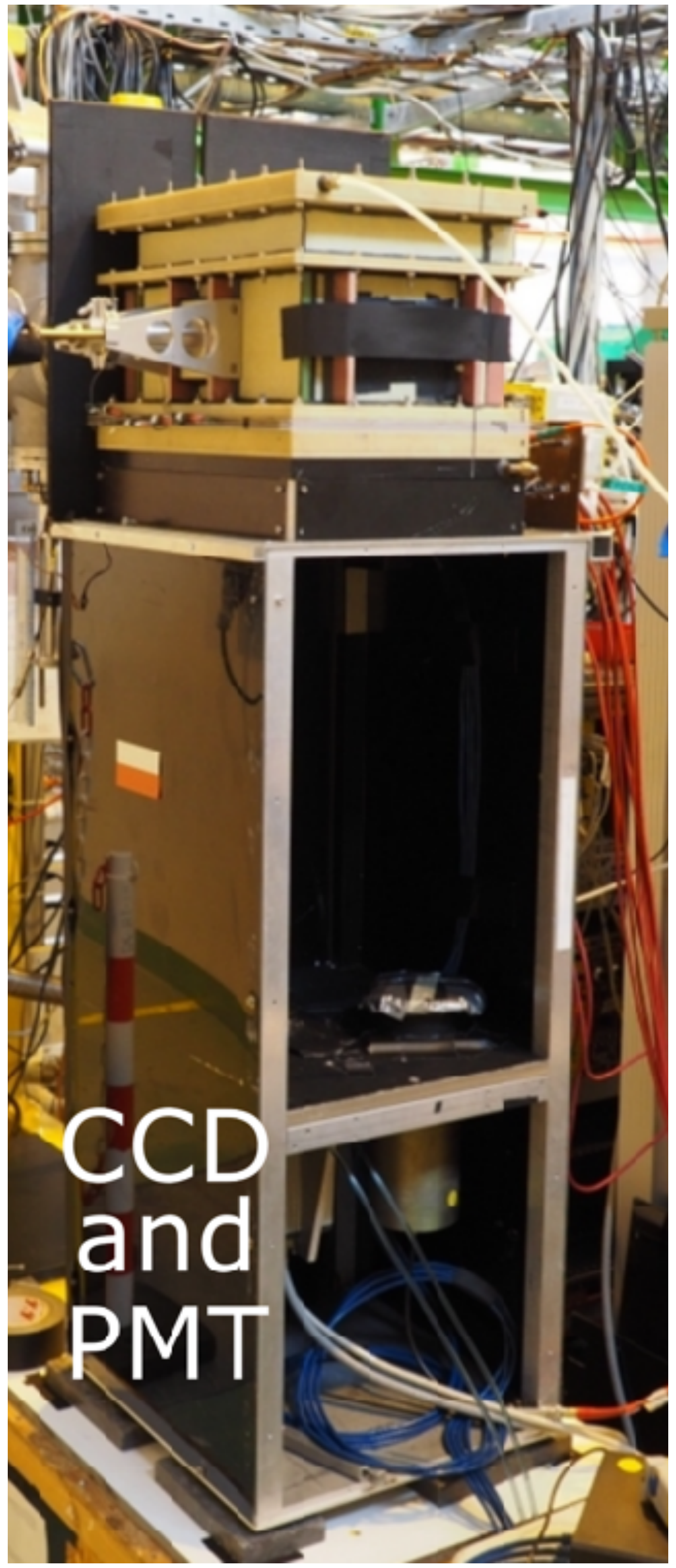


A. A. Lis et al., Phys. Rev. C 91, 064309 (2015)

Detection: Optical Time Projection Chamber

- Active volume 33 cm x 20 cm x 21 cm
- Filled with gas mixture at atmospheric pressure immersed in vertical E
- Ion implantation and decay
- Electrons along the trajectories drift in E with v_{drift} “downwards”
- Gating electrode (G) - allows for “dual sensitivity mode” = detecting of both ion and proton
- Stack of GEM foils - electrons multiplication (~10x on each foil)
- HV between GEM foils and anode (A) - secondary ionisation, light emission
- CCD camera and photomultiplier tube (PMT) mounted below the polycarbonate window





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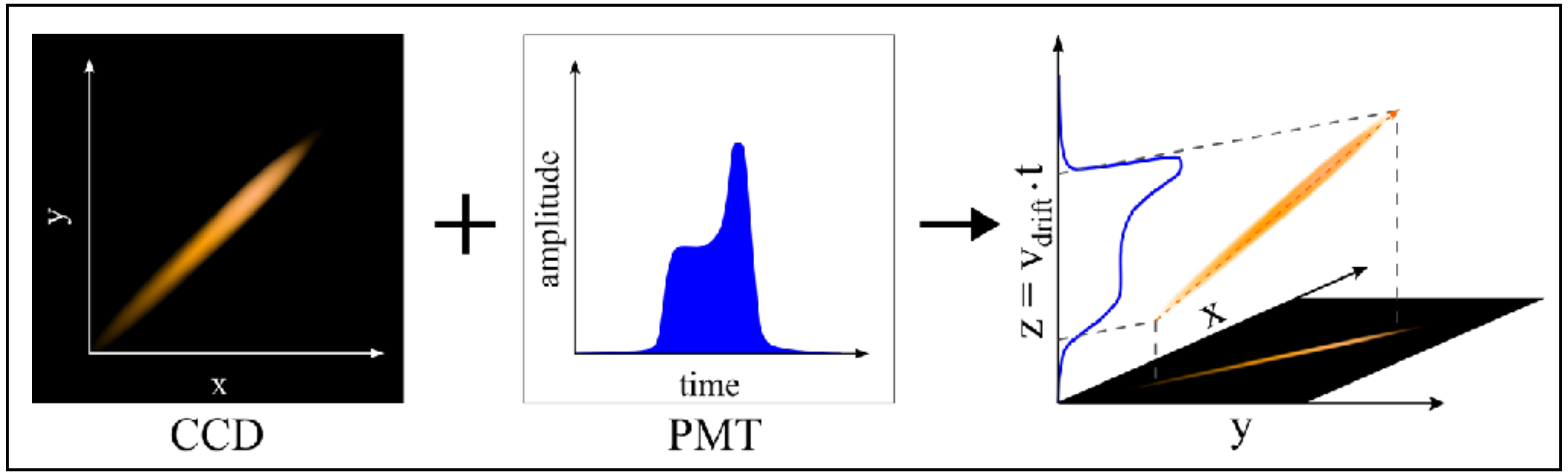
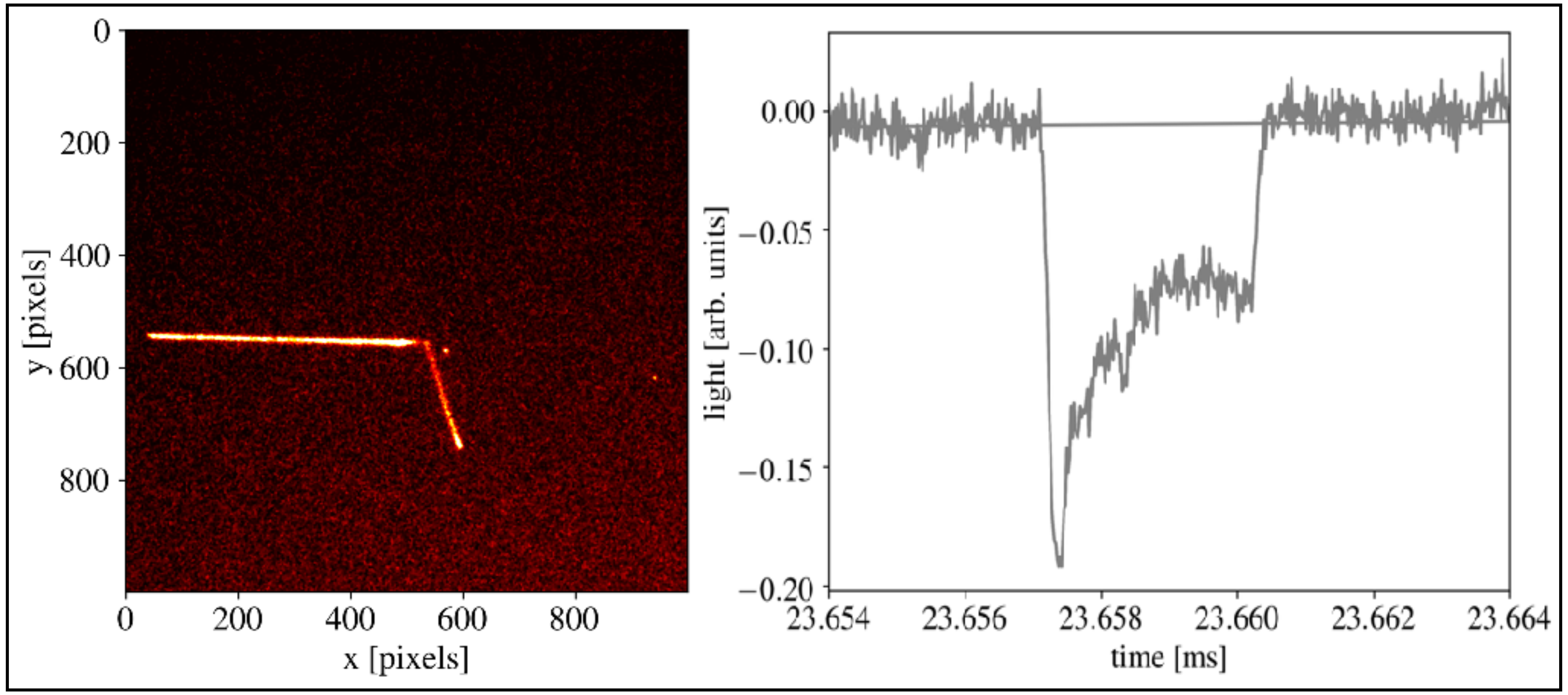


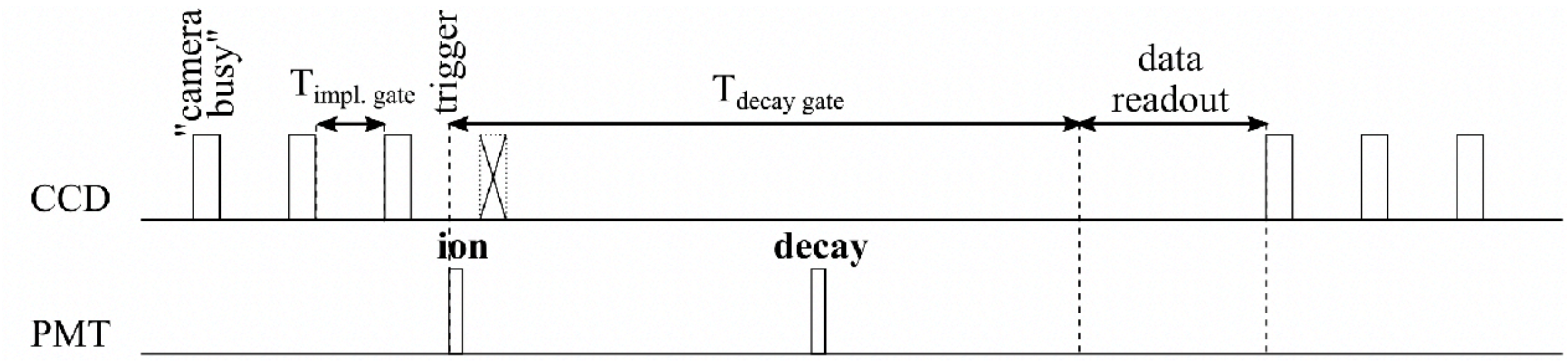


Real event of βp emission from [23]Si

- Reconstruction of 3D trajectory:
  - CCD camera = x-y plane
  - PMT signal = light in time
  - With known v_{drift} (typically 1-1.2 cm/μs) - z-coordinate
  - Range in gas depends on energy
  - Fitting of the Bragg curve shape

OTPC’s extended exposure mode

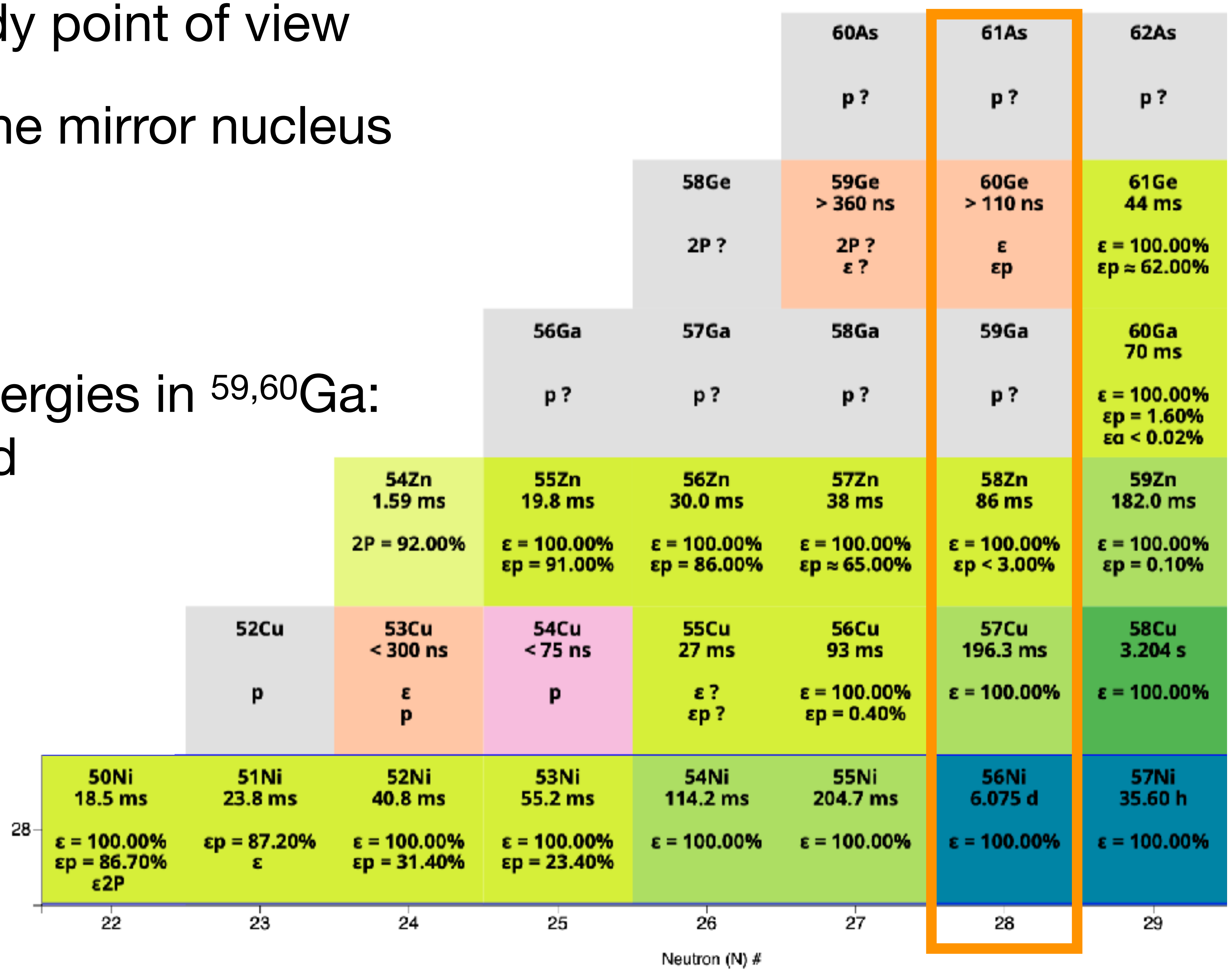
- **No trigger:** CCD camera running continuously frames (“implantation gate”, few tens of ms)
- **Trigger:** current frame extended by an observation-window time (“decay gate”, a few $T_{1/2}$ long)



Study of neutron-deficient Ge and Zn isotopes at MSU

Region around ^{60}Ge

- Region interesting from the 2p decay study point of view
- ^{60}Ge: heaviest semi-magic nucleus with the mirror nucleus (^{60}Ni) that can be studied.
- Is N=28 still a magic number there?
- High Q_{EC} of ^{59,60}Ge and low separation energies in ^{59,60}Ga: energetically possible decay via β-delayed (multi-) proton emission
- ^{57,58}Zn - lying on rp-process path



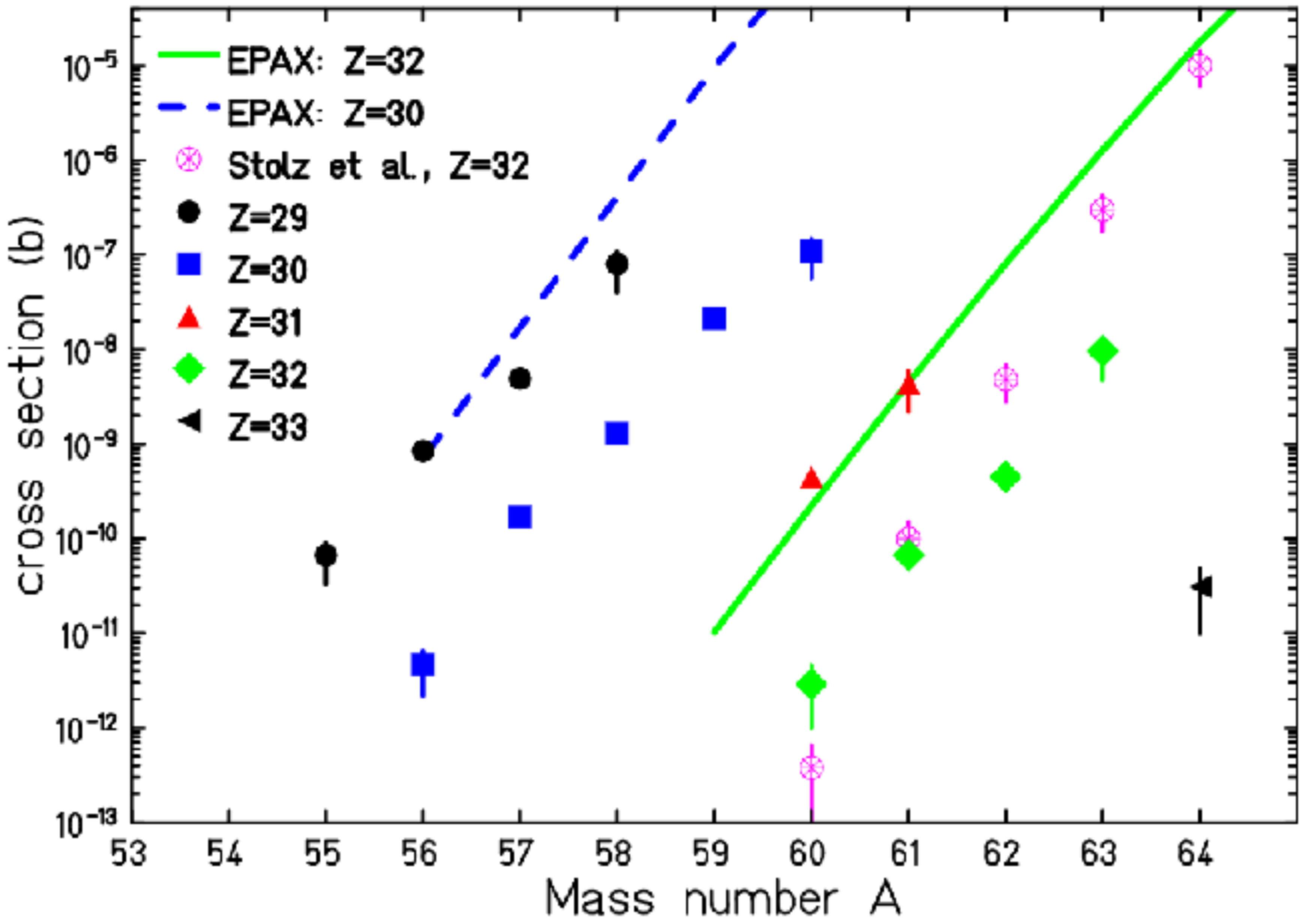
https://www.nndc.bnl.gov/nudat3/

Previous studies: ^{60}Ge

- Discovered in 2005 at NSCL by Stolz et al. (^{78}Kr beam on Be target)
  - 3 ions identified directly on basis of ToF and ΔE
  - No decay observed - only lower limit on half-life estimated $T_{1/2} > 110$ ns.
  - Measured cross-section found smaller than predictions (abrasion-ablation model and EPAX2 parametrization)
    - possible reason: very short $T_{1/2}$
    - σ for less exotic Ge isotopes also lower than predictions (smaller discrepancy)

    A. Stolz et al., Phys. Lett. B 627 (2005) 32–37

- Investigated shortly after at GANIL by Blank et al. (^{70}Ge beam on Ni target)
  - 4 ions identified, no decay data
  - Measured cross-sections higher than previously, but still lower than predictions



B. Blank et al., Eur. Phys. J. A 31, 267-272 (2007)

What about ^{59}Ge?

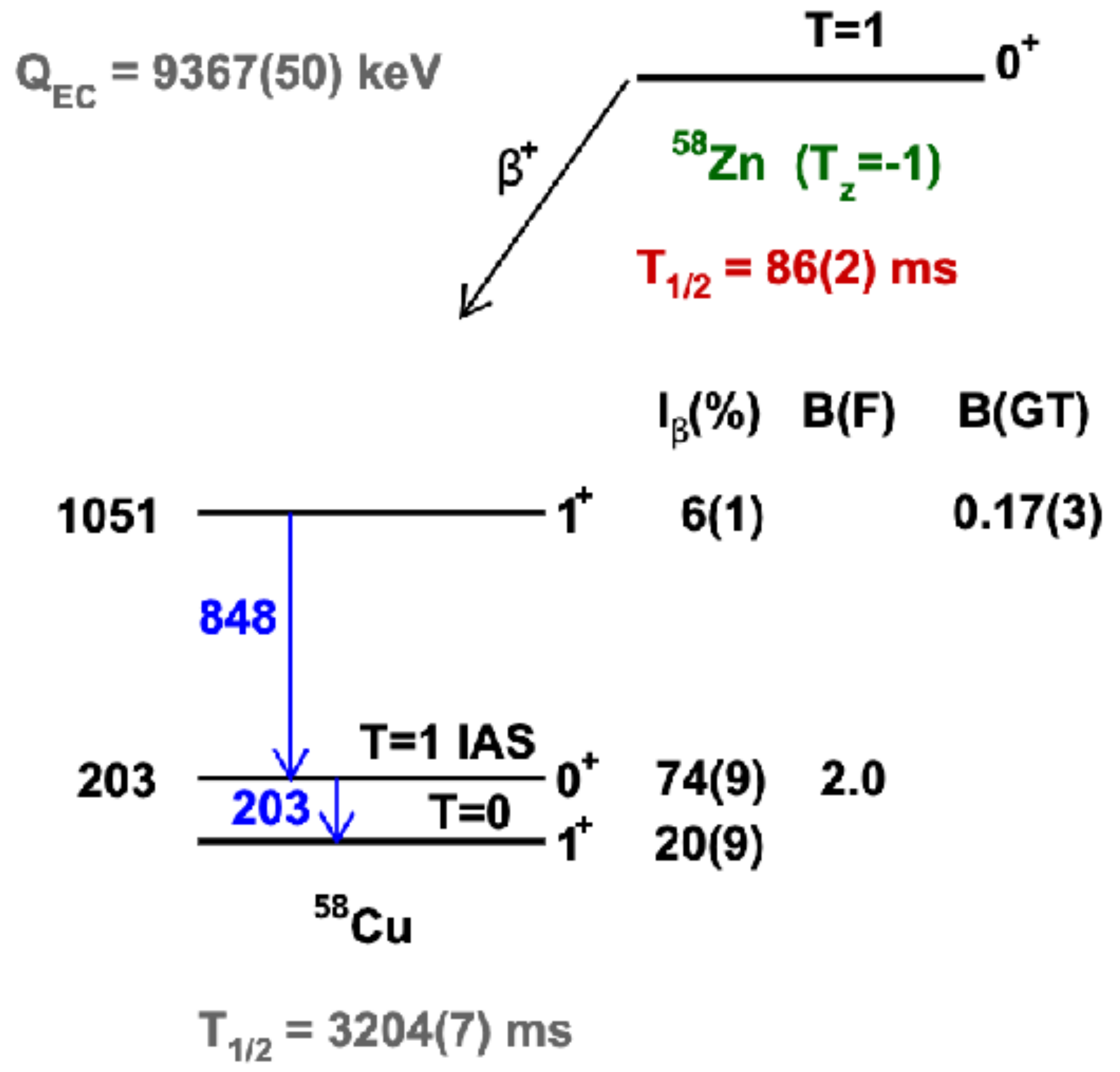
- **Not identified before**
- Properties predicted theoretically:
  - S_p = 0.19(14) MeV, S_{2p} = -1.16(14) MeV
    ^{59}Ge listed as one of "the most promising candidates for the illusive diproton emission"

    B. Brown et al., Phys. Rev. C 65, 045802
  - Three-body core+p+p model calculations of half-lifes as a function of the decay energies:
    ^{58}Ge predicted to be the heaviest 2p-decay candidate

    L. V. Grigorenko and M. V. Zhukov, Phys. Rev. C 68, 054005 (2003)

Previous studies: ^{58}Zn

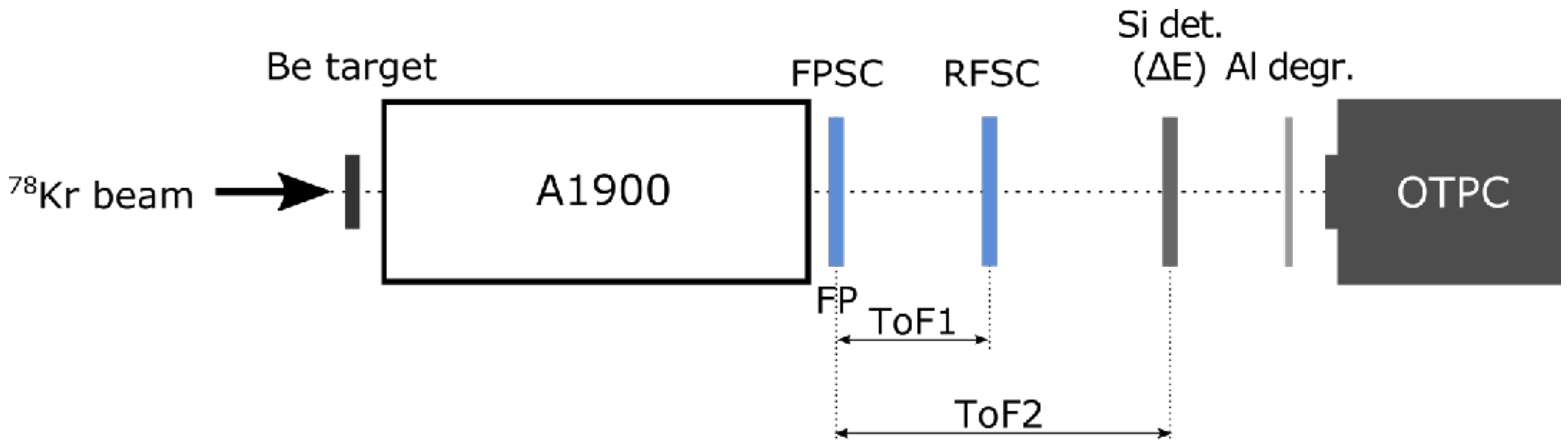
- Produced and identified for the first at the Los Alamos Meson Physics Faculty in late '80s
  - The heaviest $T_z = -1$ nucleus studied until that time
  - Mass measurement performed
    K. K. Seth et al., Phys. Lett. B 173, 397-399 (1986)
- β decay study: ISOLDE, late ‘90s
  - Detection setup: HPGe detector for γ ray measurement, β telescope and a charged particle detector
  - $T_{1/2}$ = 86(16) ms measured
  - B(GT) to an excited state at 1051 keV
  - Upper limit on βp branching ratio: $b_{\beta p} < 3\%$
    A. Jokinen et al., Eur. Phys. J. A 3, 271-276 (1998)
- Further research performed recently at GANIL
  - Neither new γ transitions nor βp observed
  - Half-life: $T_{1/2}$ = 86(2)
  - Absolute B(F) and B(GT) calculated
    L. Kucuk et al., Eur. Phys. J. A (2017) 53: 134



L. Kucuk et al., Eur. Phys. J. A (2017) 53: 134

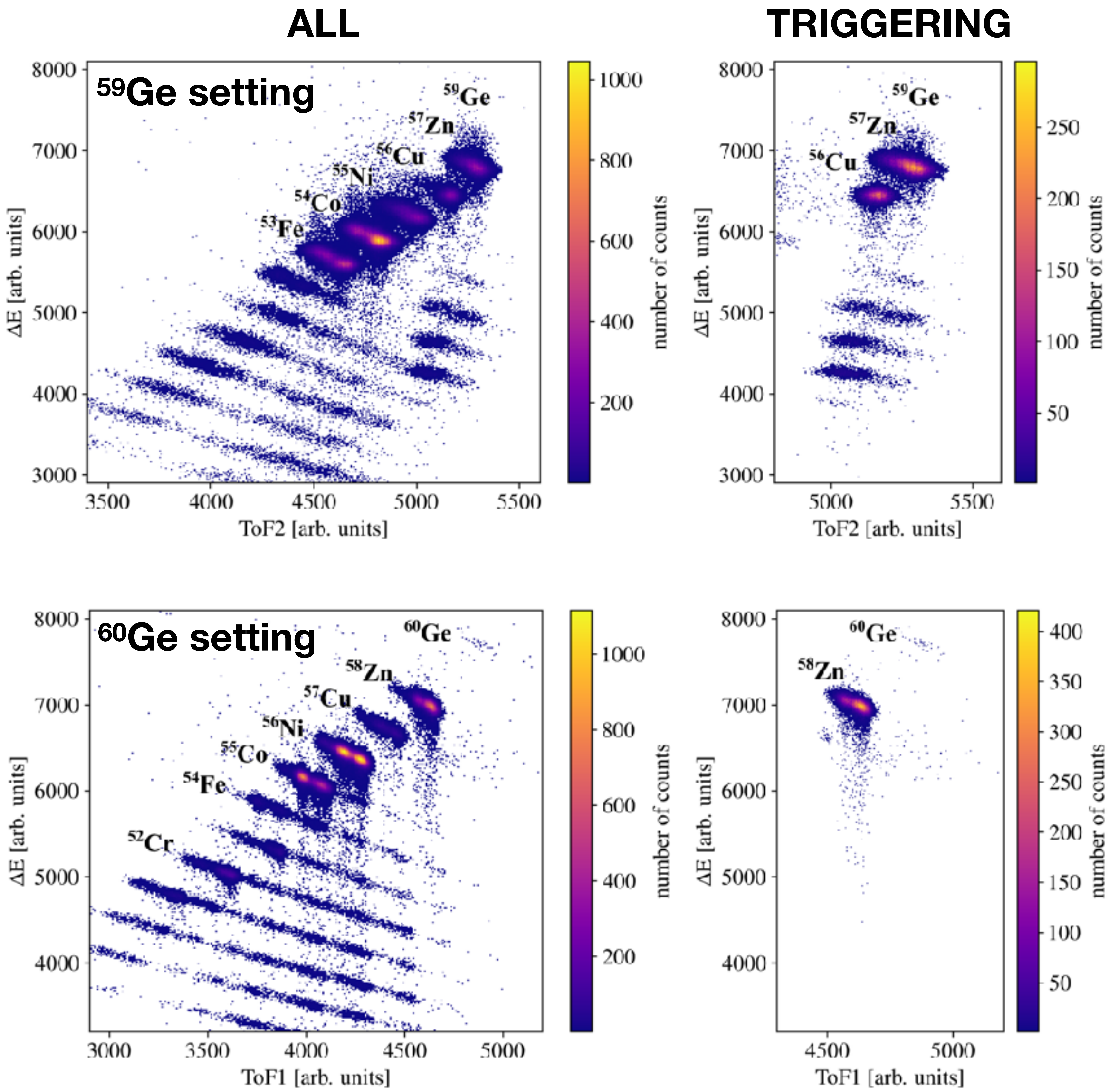
Experimental details: MSU experiment

- National Superconducting Cyclotron Laboratory, MSU
- Fragmentation reaction of a ^{78}Kr beam (150 AMeV) on a 200 mg/cm^2 Be target
- A1900 separator (ion optics set individually for each of $^{59-62}$Ge)
- Ion-by-ion identification (ToF1,2 vs ΔE)
- Ions implanted into OTPC detector filled with 49.5% He + 49.5% Ar + 1% CO_2



Experimental details: MSU experiment

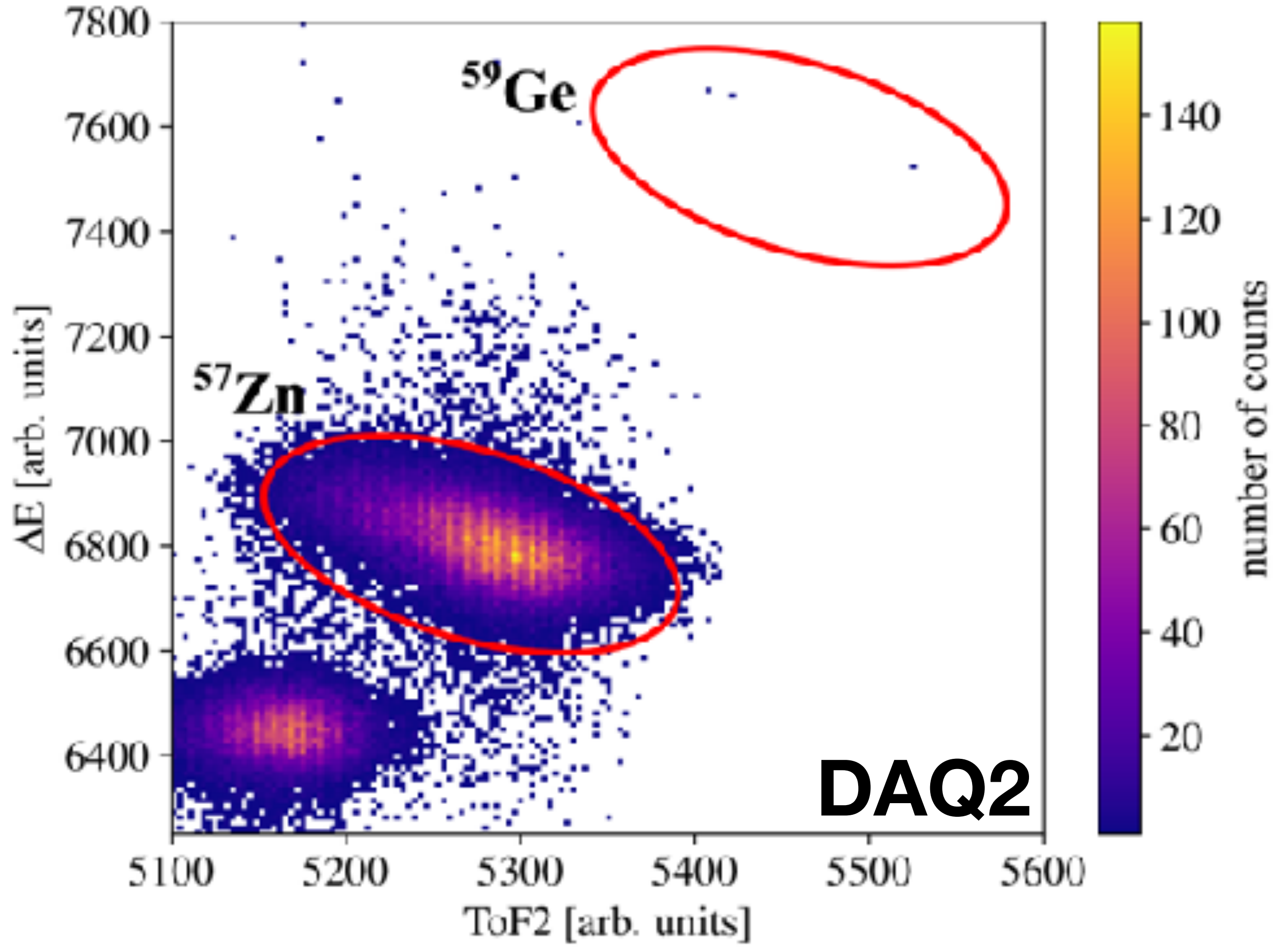
- Two independent data acquisition systems (both time-stamped):
  - **DAQ1**:
    - Running continuously, all ions
    - ΔE, ToF1 and ToF2 (time-to-amplitude converter)
  - Hardware gates on ΔE and ToF1 ⟶ **trigger** (beam off)
  - **DAQ2**:
    - Triggering ions only
    - PMT waveform
    - CCD image
    - Waveforms of ΔE signal from Si detector, and of both ToF1 and ToF2

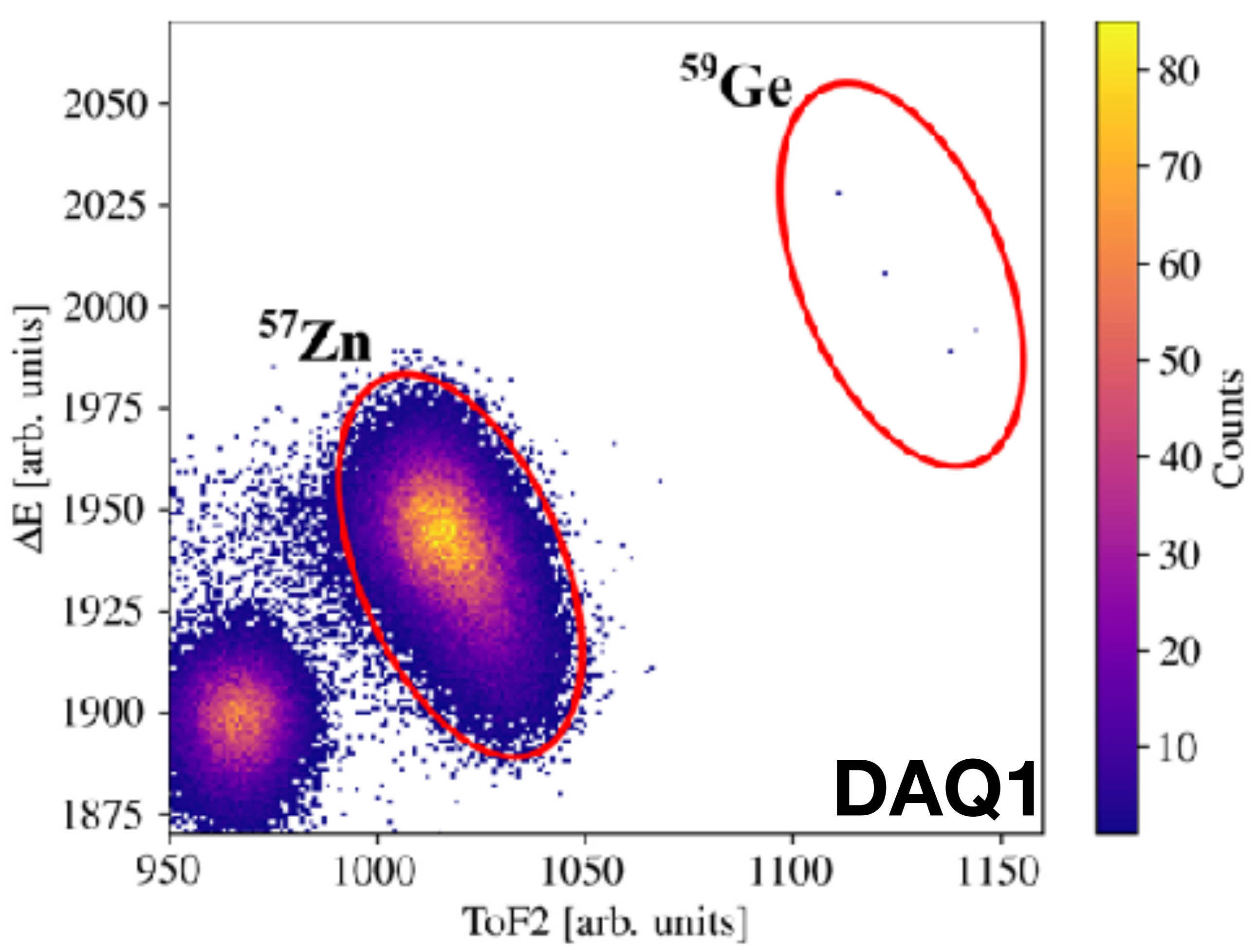


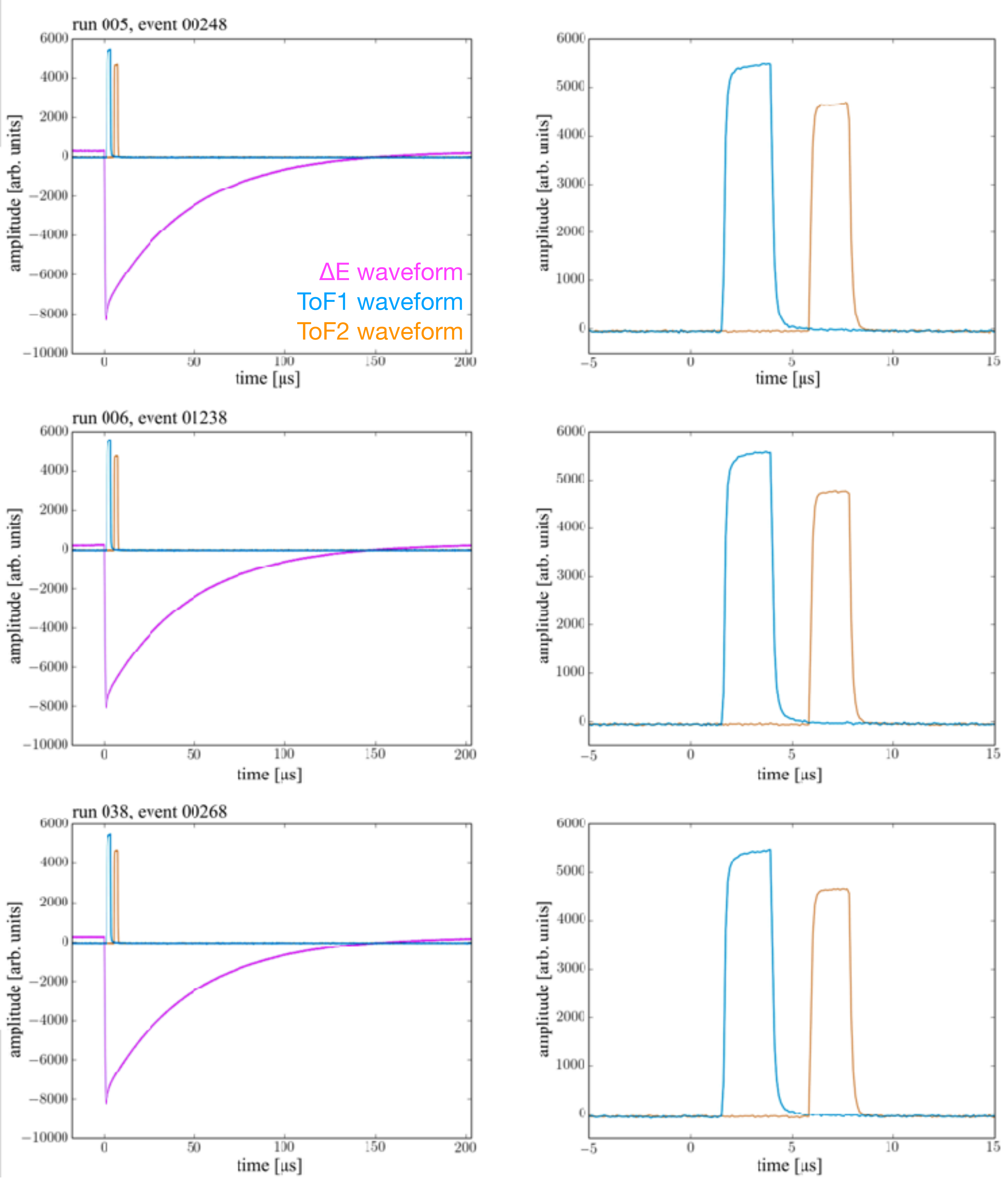
Results: ^{59}Ge

- **First identification of the new isotope**
  - 4 events in DAQ1
  - 3 events in DAQ2 (one during dead time)
- No implantation into OTPC detector

A. A. Ciemny et al., Phys. Rev. C 92, 014622 (2015)

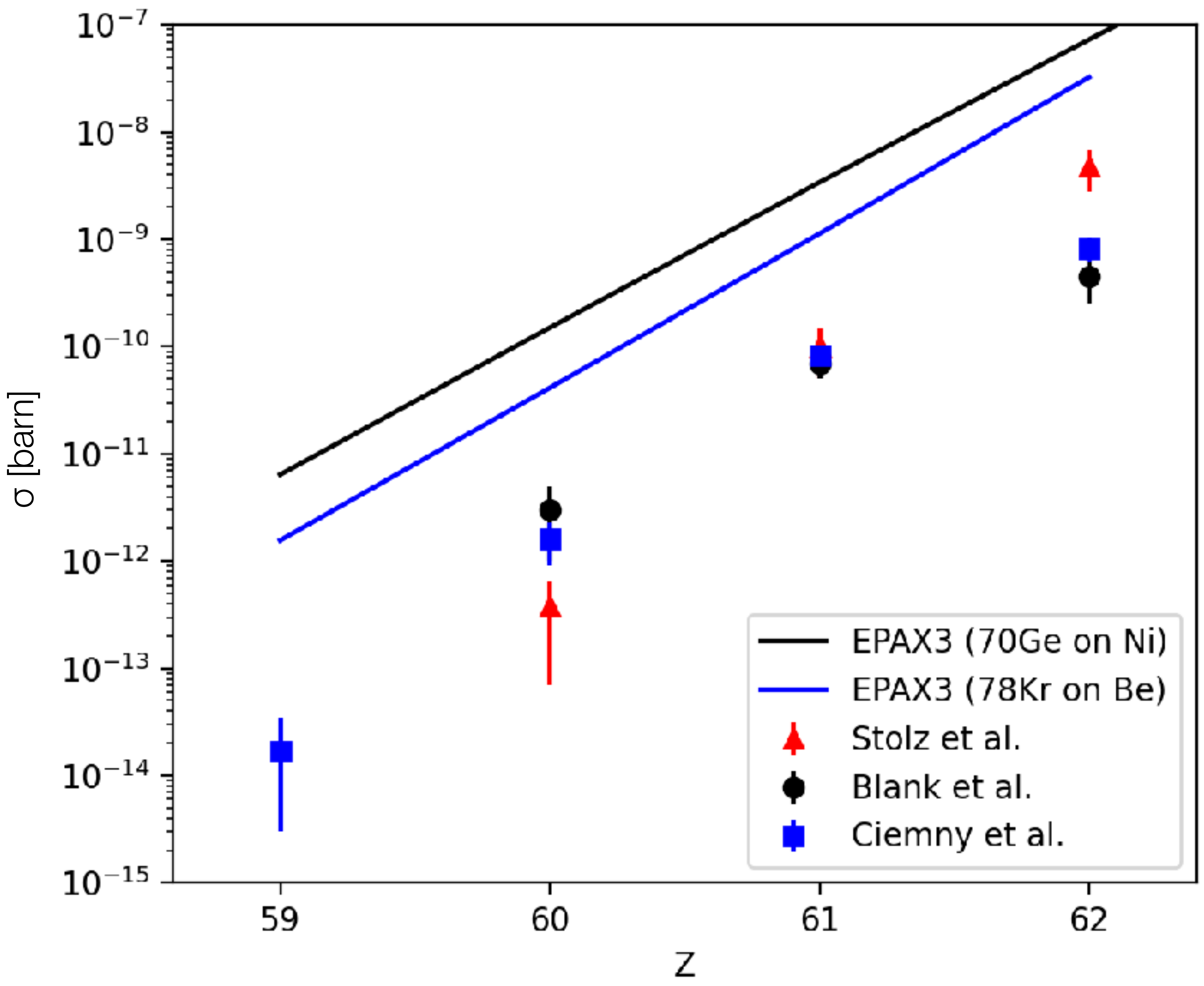






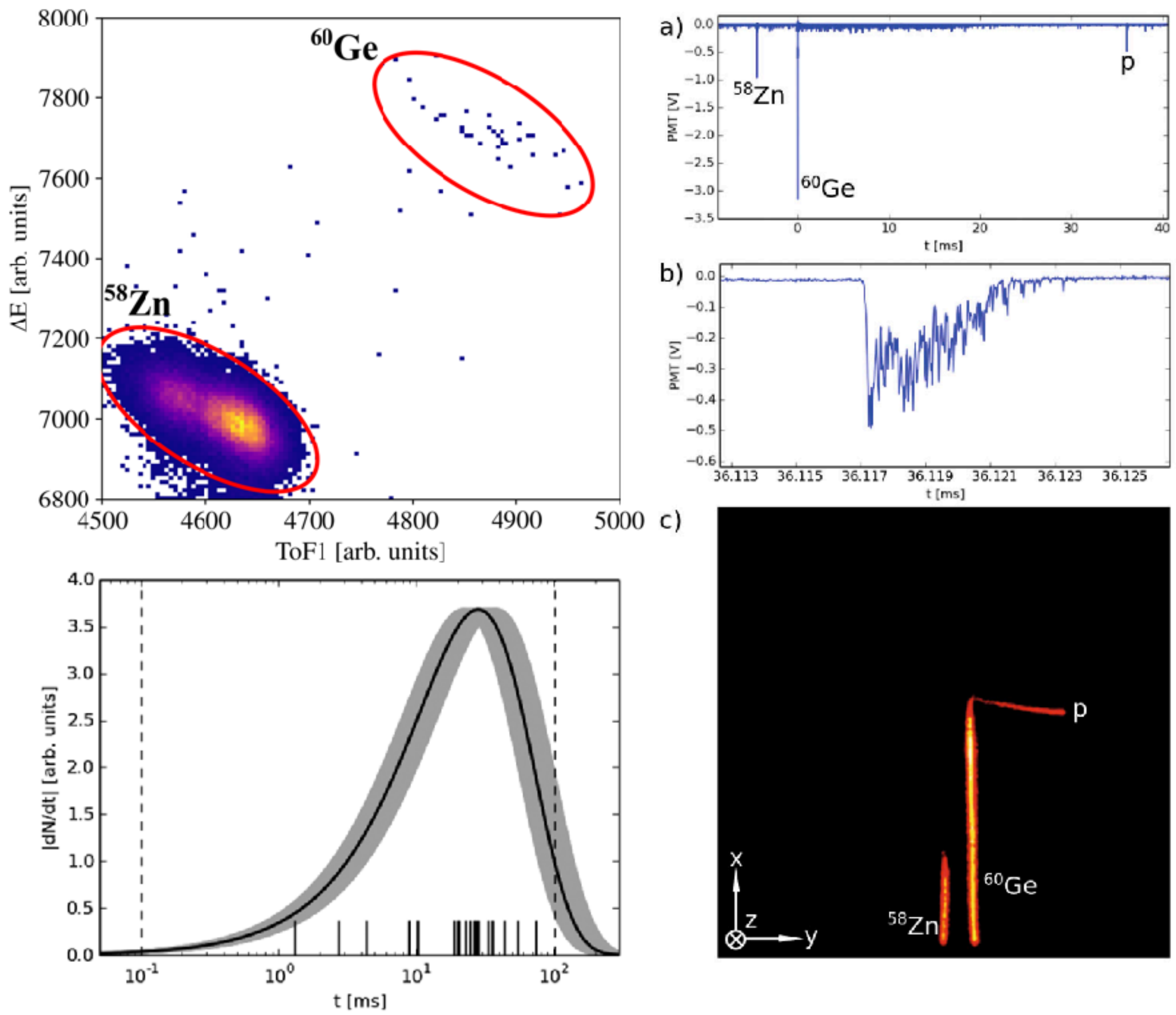
Results: Ge isotopes production cross-sections

- Smooth trend as a function of mass
- Z=60:
  - No kink (no in-flight loss of ^{60}Ge)
  - 4x larger σ than previous A1900 experiment (Stolz et al.)
  - Still 2x lower than Blank et al.
  - ^{70}Ge on Ni - better choice?
- EPAX3 parametrization:
  - overestimating the σ for production of Ge isotopes (for both beam + target combinations)
  - the more exotic nucleus, the bigger discrepancy



Results: ^{60}Ge

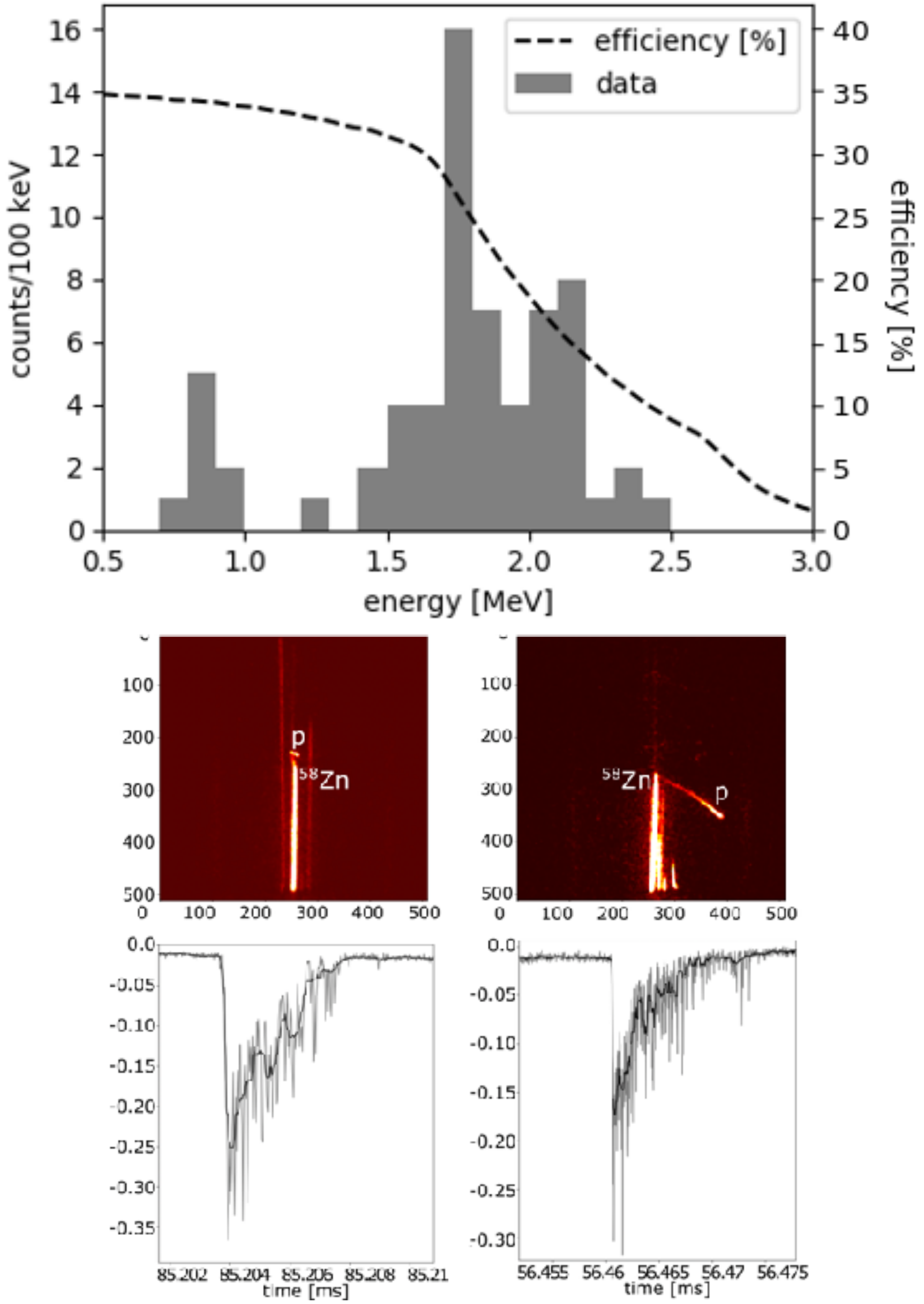
- 41 events identified by the OTPC DAQ, 28 implanted into the OTPC active volume
- 19 decays observed, 11 protons stopped inside the chamber
- All of protons emitted “downwards” or nearly horizontal (due to the drift of the ions towards cathode)
- $b_{\beta p} \approx 100\%$
- $T_{1/2} = 20^{+7}_{-5}$ ms



A. A. Ciemny et al., Eur. Phys. J. A (2016) 52: 89

Results: ^{58}Zn

- First observation of βp from ^{58}Zn
  - Over 36k implanted ions
  - 88 protons detected
  - 33 stopped within active volume of the detector
  - Branching ratio $b_{\beta p}$ = 0.7(1)% (compatible with upper limit of 3% given by Jokinen et al.)



A. A. Ciemny et al., Phys. Rev. C 101, 034305 (2020)

Results: ^{58}Zn

- B(GT) strengths calculated for decay to three low-lying proton-unbound levels in ^{58}Cu
- B(GT) comparable to the value of 0.17(3) obtained by Kucuk et al.
- **βp emission should not be neglected when looking at B(GT), even when its probability is very small**

- Results compared to B(GT) distribution calculated within QRPA aproach:
    - Spherical solution for ^{58}Zn (2p above doubly magic ^{56}Ni): Peaks below 2.5 MeV and above 7 MeV
    - Solution for slightly deformed (β = -0.1) ^{58}Zn: Enhancement of the B(GT) at $E_x \approx 5$ MeV

P. Sarriguren, Phys. Rev. C 83, 025801 (2011)

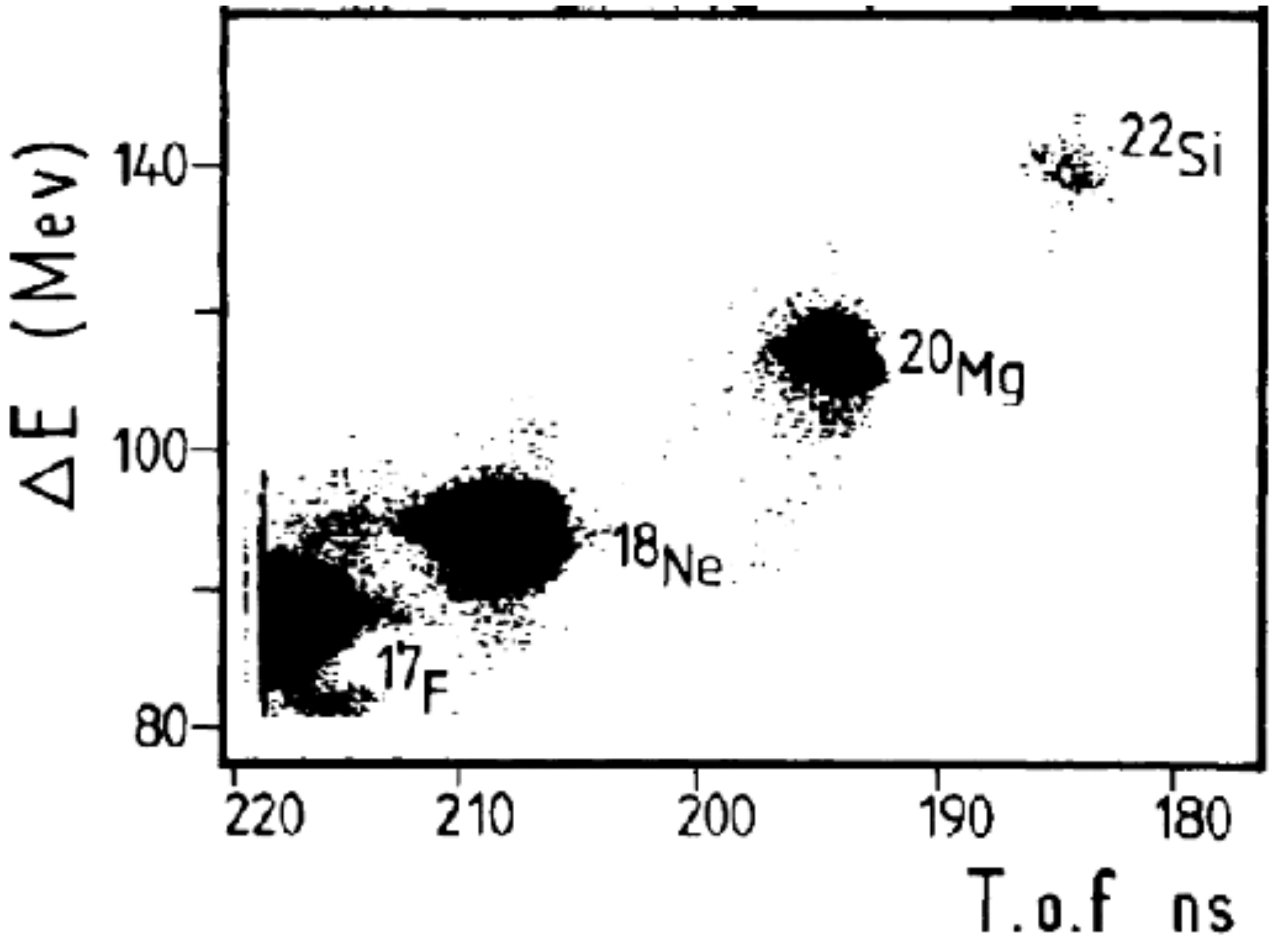
E_x MeV	$b_{\beta p}$ %	B(GT)	Ref.
0	0	0.30(13)	Kucuk et al.
1.051	0	0.17(3)	Kucuk et al.
≈3.75	⩾0.06(2)	⩾0.015(8)	this work
≈4.65	0.20(6)	0.13(6)	this work
≈5.0	0.05(3)	0.05(4)	this work

A. A. Ciemny et al., Phys. Rev. C 101, 034305 (2020)

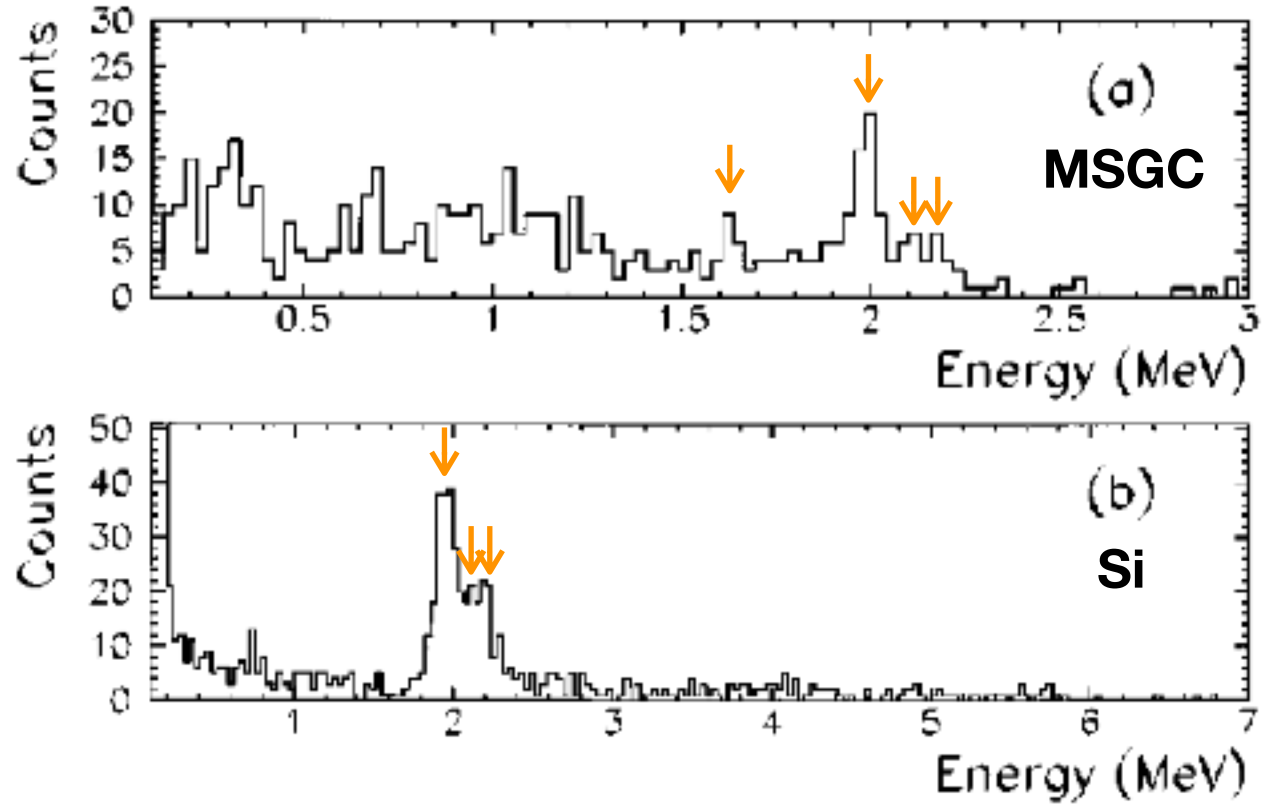
Study of $^{22,23}Si$ at TAMU

Previous studies: ^{22}Si

- Lightest Si isotope and lightest T_z = -3 nucleus to date
- First identified at GANIL (161 ions) in 1987
- A decade later, ^{22}Si decay re-investigated at GANIL
  - β-delayed proton emission discovered
    - 4 proton transitions between 1.6 and 2.2 MeV
    - one broad proton distribution around 1 MeV
    - $b_{\beta p} \approx 100\%$
    - $T_{1/2}$ = 29(2) ms.



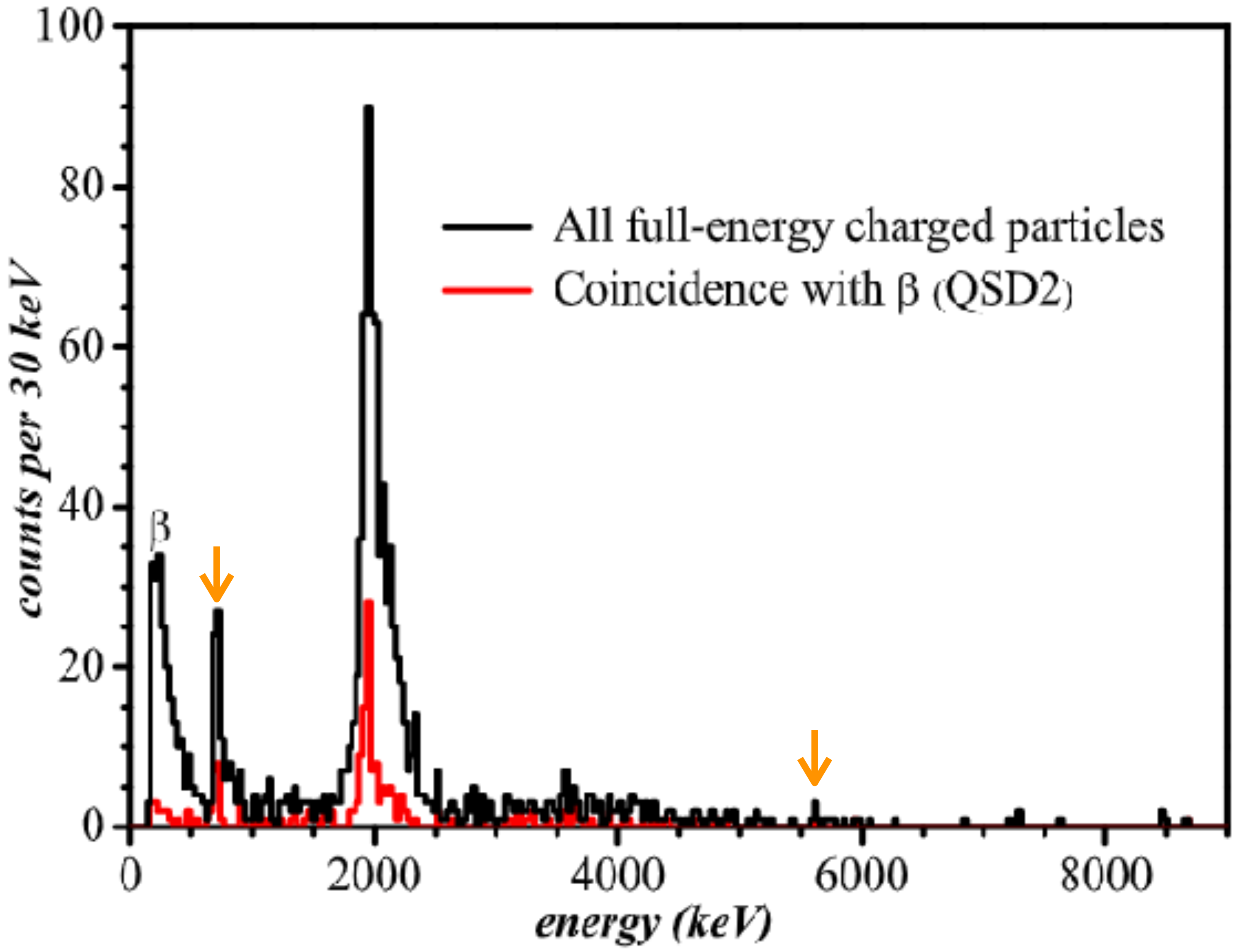
M. G. Saint-Laurent et al., Phys. Rev. Lett. 59, 33-35 (1987)



B. Blank et al., Phys. Rev. C 54, 572-575 (1996)

Previous studies: ^{22}Si

- Recent studies performed at RIBLL1 (Lanzhou, China)
  - Silicon array + HPGe clover detectors (p-γ coincidences)
  - β2p emission from IAS in ^{22}Al
    - E_{sum} = 5600 (70) keV ($b_{\beta 2p}$ = 0.7(3)%)
    - 5 events
  - new 680 keV peak identified in βp spectrum
  - $T_{1/2}$ = 27.8 (35) ms



X. X. Xu et al., Phys. Lett. B 766 (2017) 312-316

- Large mirror asymmetry (compared to the mirror ^{22}O β decay) in ^{22}Si decay to low-lying states: δ = 209(96)

J. Lee et al., Phys. Rev. Lett. 125, 192503 (2020)

Previous studies: ^{23}Si

- Lightest T_z = -5/2 isotope discovered so far
- First observed at GANIL in 1985 (74 ions)

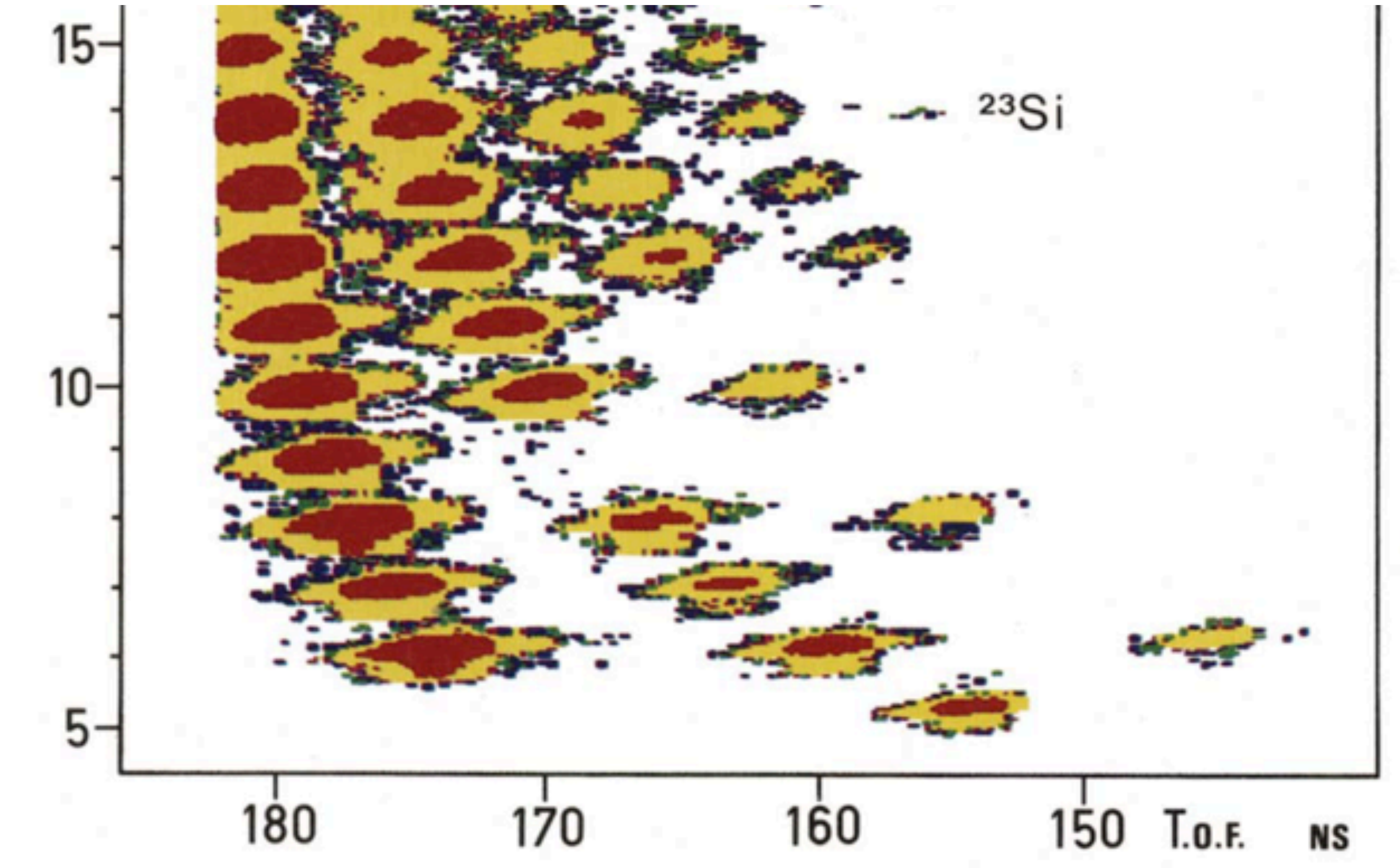
  M. Langevin et al., Nucl. Phys. A 455 (1986) 149-157

- First spectroscopy studies also at GANIL 10 years later
  - βp (14 transitions) and β2p (2) emission identified ($b_{\beta 2p} = 3.6(4)\%$, $b_{\beta(p+2p)} \approx 92\%$)
  - $T_{1/2} = 42.3(4)$ ms

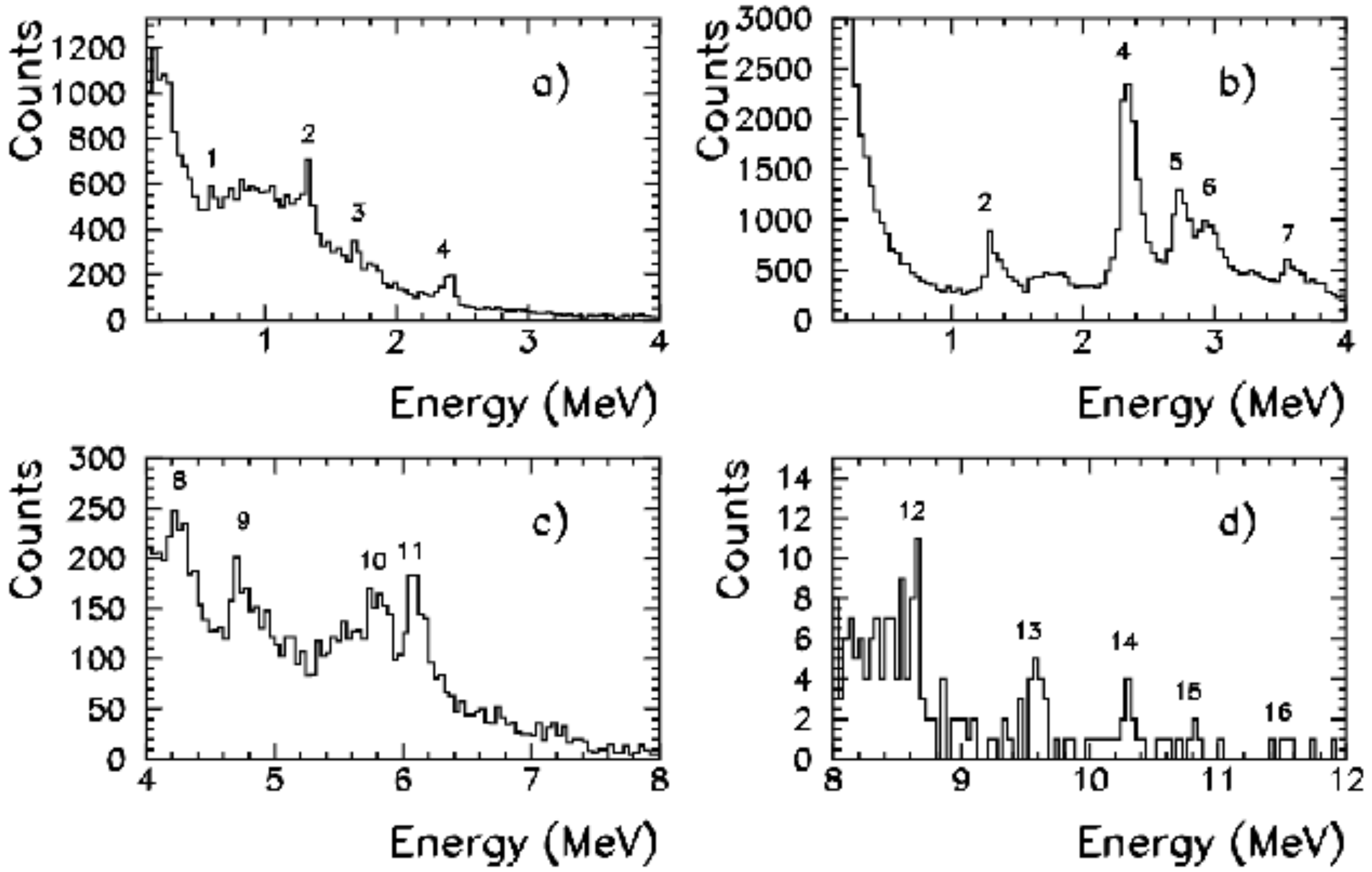
  B. Blank et al., Z. Phys. A 357, 247–254 (1997)

- New study in RIBBL1 - both protons and γs
  - New transition added
  - $T_{1/2} = 40.2(19)$ ms

  Wang et al., Int. J. of Mod. Phys. E 27, No. 2 (2018) 1850014



M. Langevin et al., Nucl. Phys. A 455 (1986) 149-157



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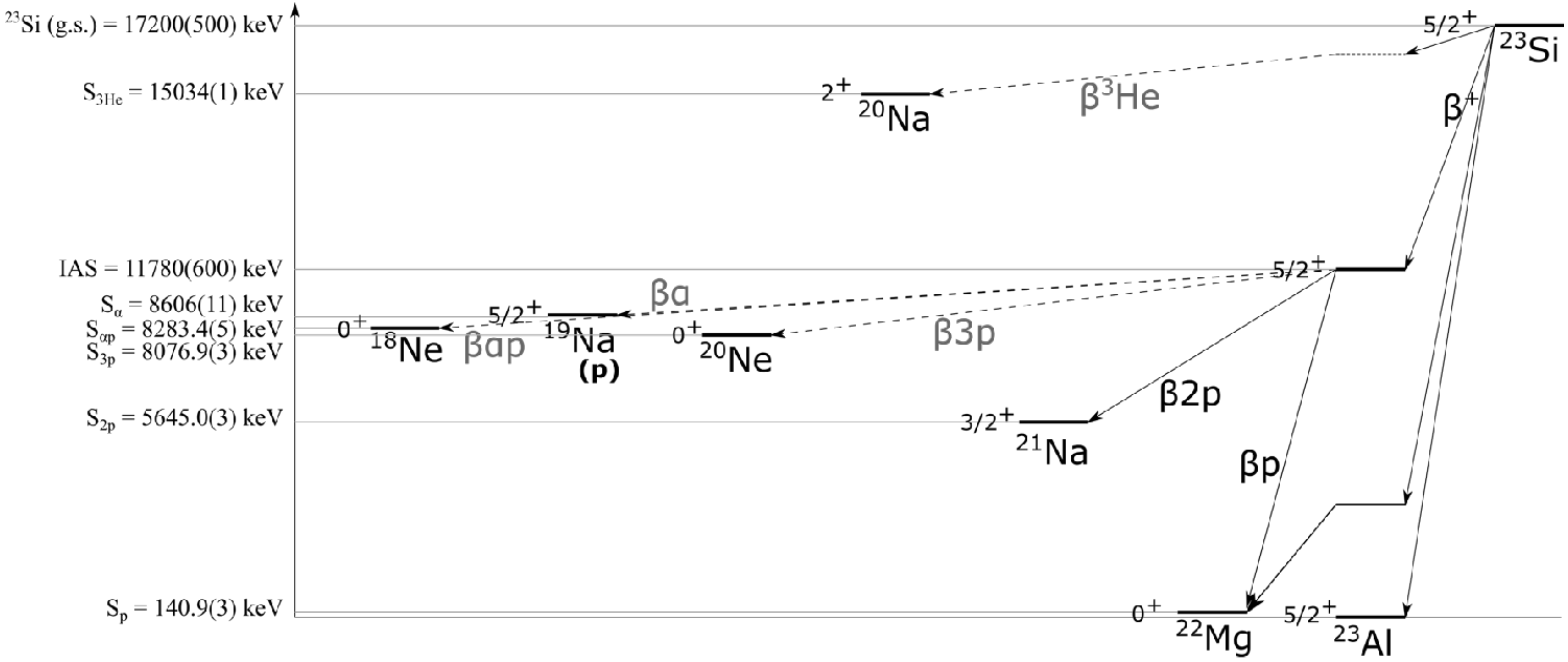
  - βp (14 transitions) and β2p (2) emission identified ($b_{\beta 2p}$ = 3.6(4)%, $b_{\beta(p+2p)}$ ≈ 92%)
  - $T_{1/2}$ = 42.3(4) ms
    B. Blank et al., Z. Phys. A 357, 247–254 (1997)
- New study in RIBBL1 - both protons and γs
  - New transition added
  - $T_{1/2}$ = 40.2(19) ms
    Wang et al., Int. J. of Mod. Phys. E 27, No. 2 (2018) 1850014

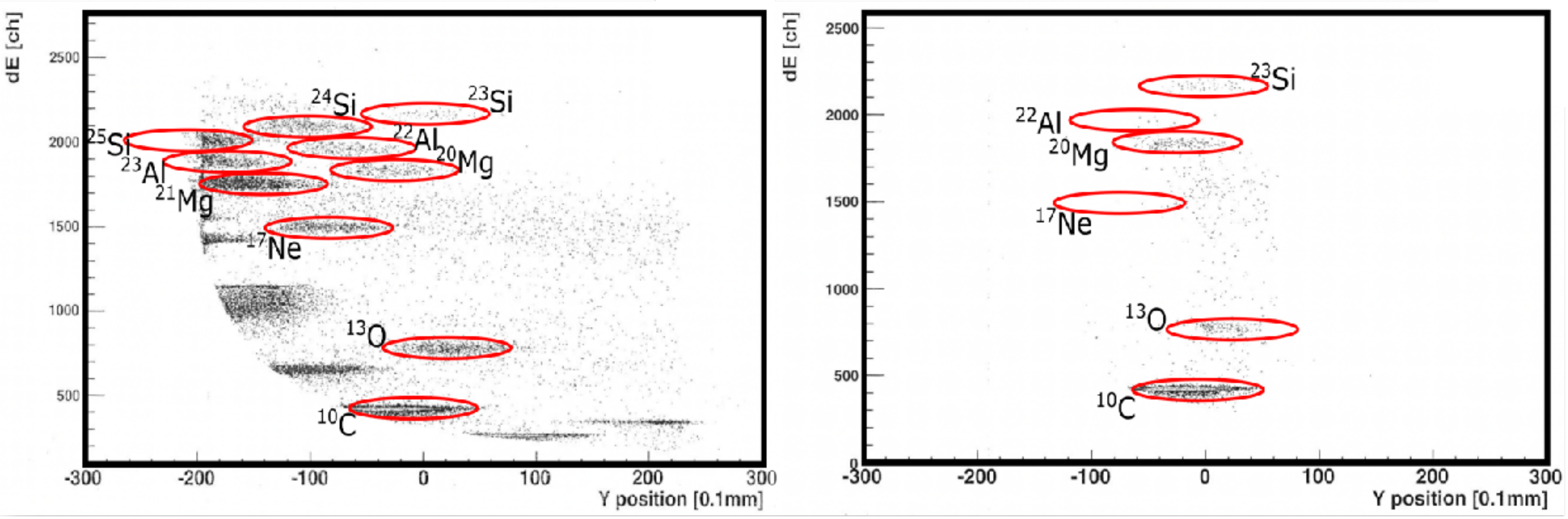
Blank *et al.*		Wang *et al.*		
E_p [keV]	br [%]	E_p [keV]	br [%]	decay channel
600(60)	< 3	673(36)	2.4(1)	βp
1320(40)	10(1)	1346(39)	5.1(4)	βp
1700(60)	< 5	1631(46	4.6(6)	βp
2400(40)	32(2)	2309(41)	21(2)	βp
2830(60)	14(1)	2730(43)	9.6(1)	βp
3040(60)	7.8(6)	3015(45)	8.9(5)	βp
3650(60)	7.2(6)	3524(65)	8.0(5)	βp
		3811(51)	6.2(1)	βp
4370(60)	2.0(2)	4134(52)	5.0(1)	βp
4760(60)	2.7(2)	4799(56)	2(1)	βp
5860(100)	1.9(2)	5857(66)	0.9(9)	β2p
6180(100)	1.7(2)	6000(64)	0.6(6)	β2p
8680(70)	0.4(1)			βp
9670(70)	0.11(4)			βp
10410(70)	0.07(3)			βp
10930(80)	0.09(3)			βp
11620(100	0.03(2)	.		βp

Previous studies: ^{23}Si



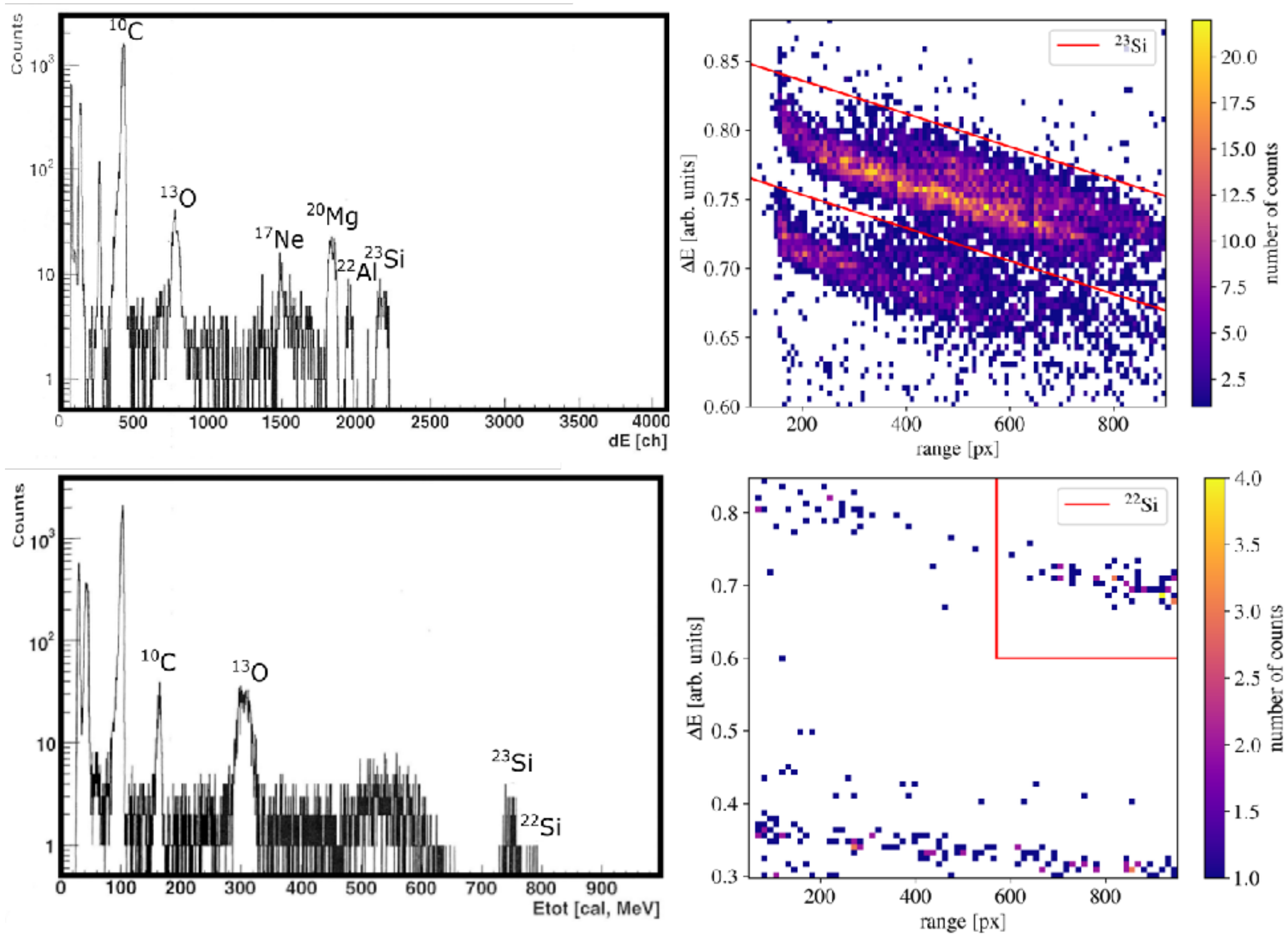
Experimental details: TAMU experiment

- $^{22,23}Si$ ions produced in fragmentation reaction of ^{28}Si beam (45 AMeV) on 150 μm Ni
- Separation of reaction products by means of MARS separator
- During tuning phase:
  - 300 μm thick Si detector (segmented along y-axis) at the focal plane
  - Ion-by-ion ΔE-y identification (MARS vertically dispersive)
  - Slits used to cut off most of the contaminants



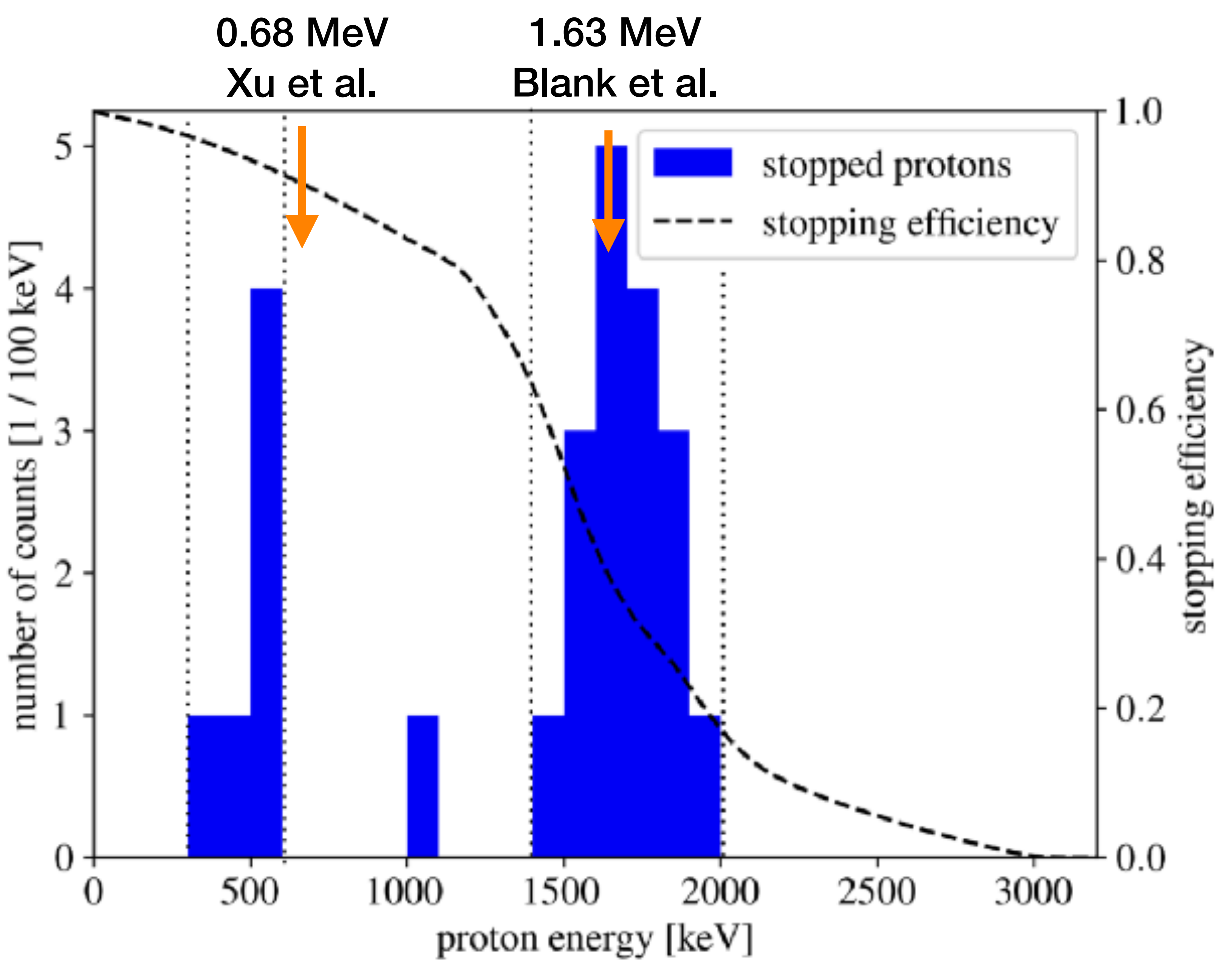
Experimental details: TAMU experiment

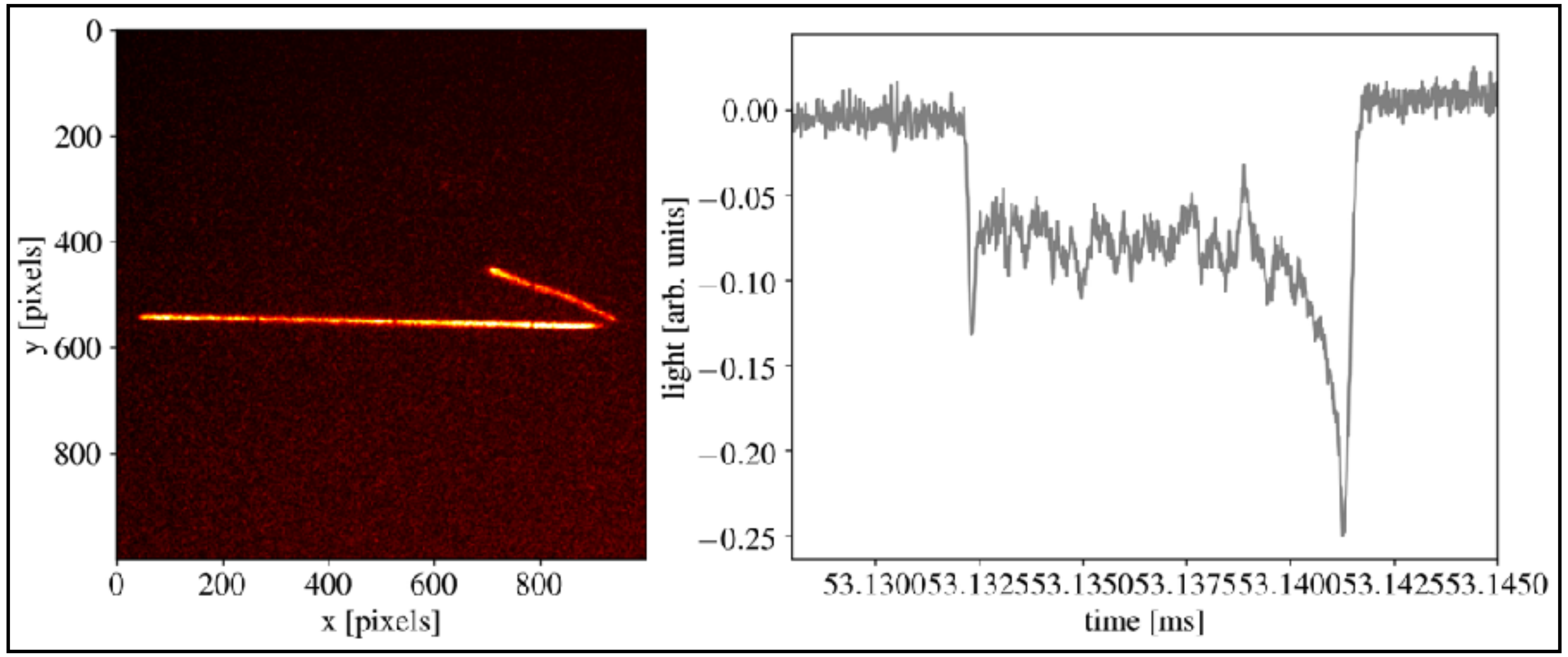
- During data-taking diagnostic Si detector removed
- Ions implanted into active volume of the OTPC detector (69% He + 29% Ar + 2% CF_4)
- Gate on ΔE signal from another Si detector ⟶ trigger (beam off)
- Identification:
  - ΔE from Si detector
  - Ions range in OTPC gas

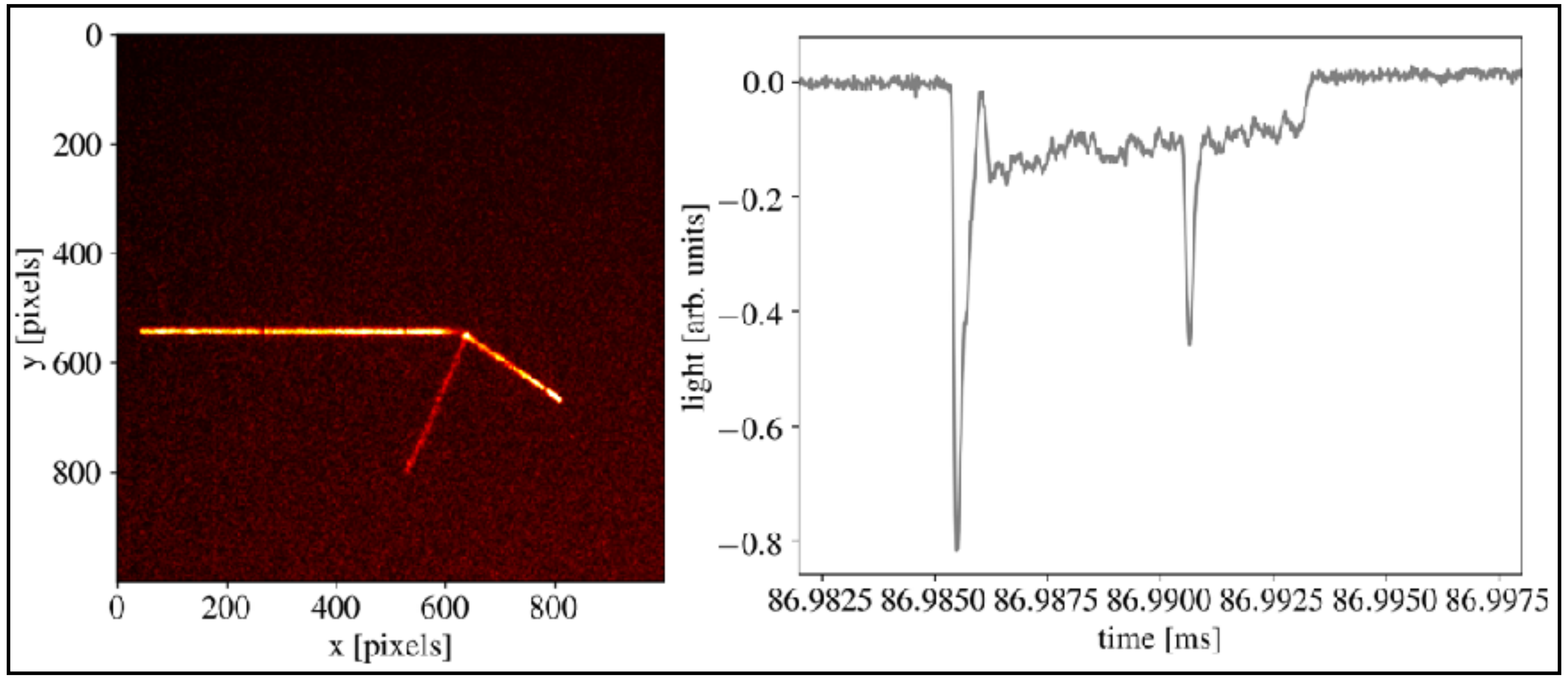


Results: ^{22}Si

- 120 identified ^{22}Si ions, 60 implanted correctly
- βp and β2p emission from ^{22}Si confirmed
  - $b_{\beta p} = 95^{+14}_{-12}$ %
  - 2 events with β2p: $b_{\beta 2p} = 3^{+4}_{-2}$ %
    (partial branching ratio $b_{\beta 2p}$ = 0.7(3)% by Xu et al.)
- Around 50% of βp stopped inside OTPC
- $T_{1/2} = 24^{+4}_{-3}$ ms (in agreement with lit.)



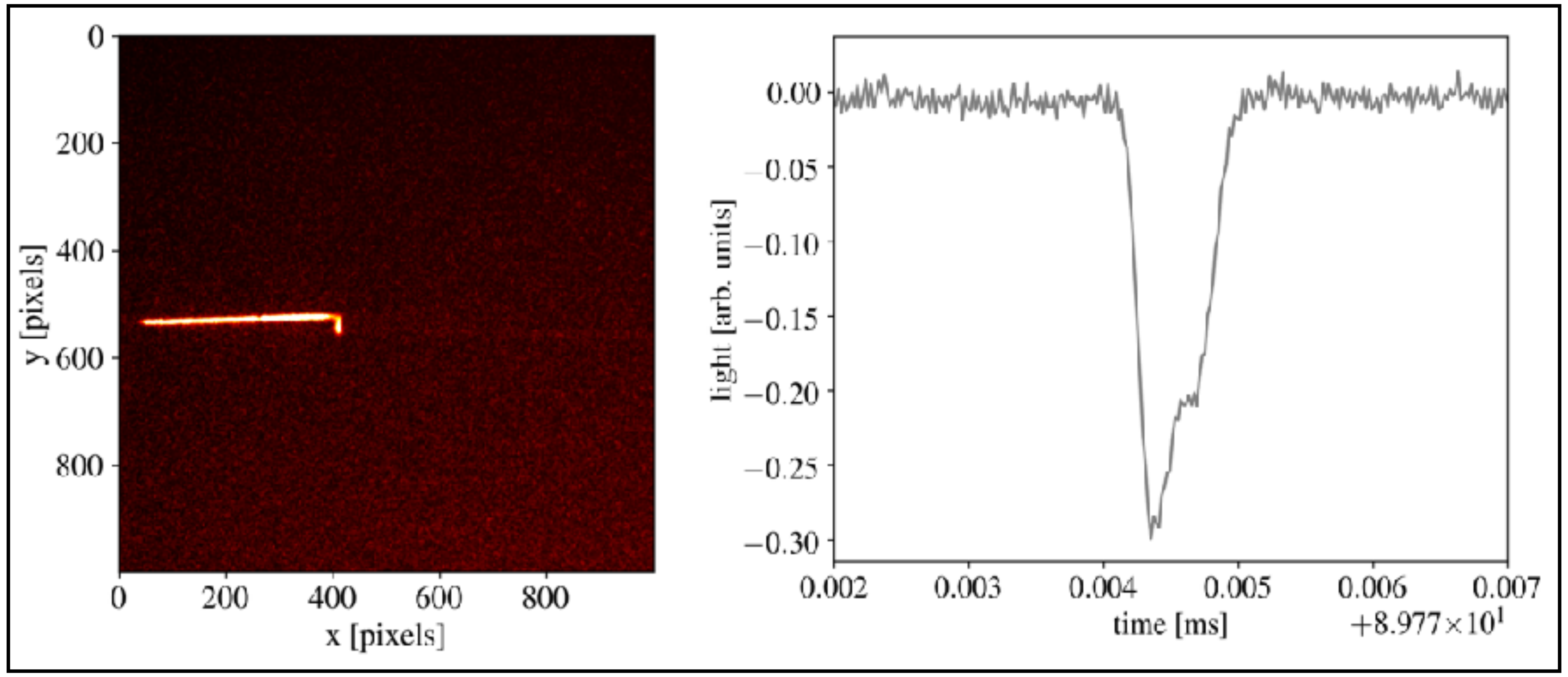




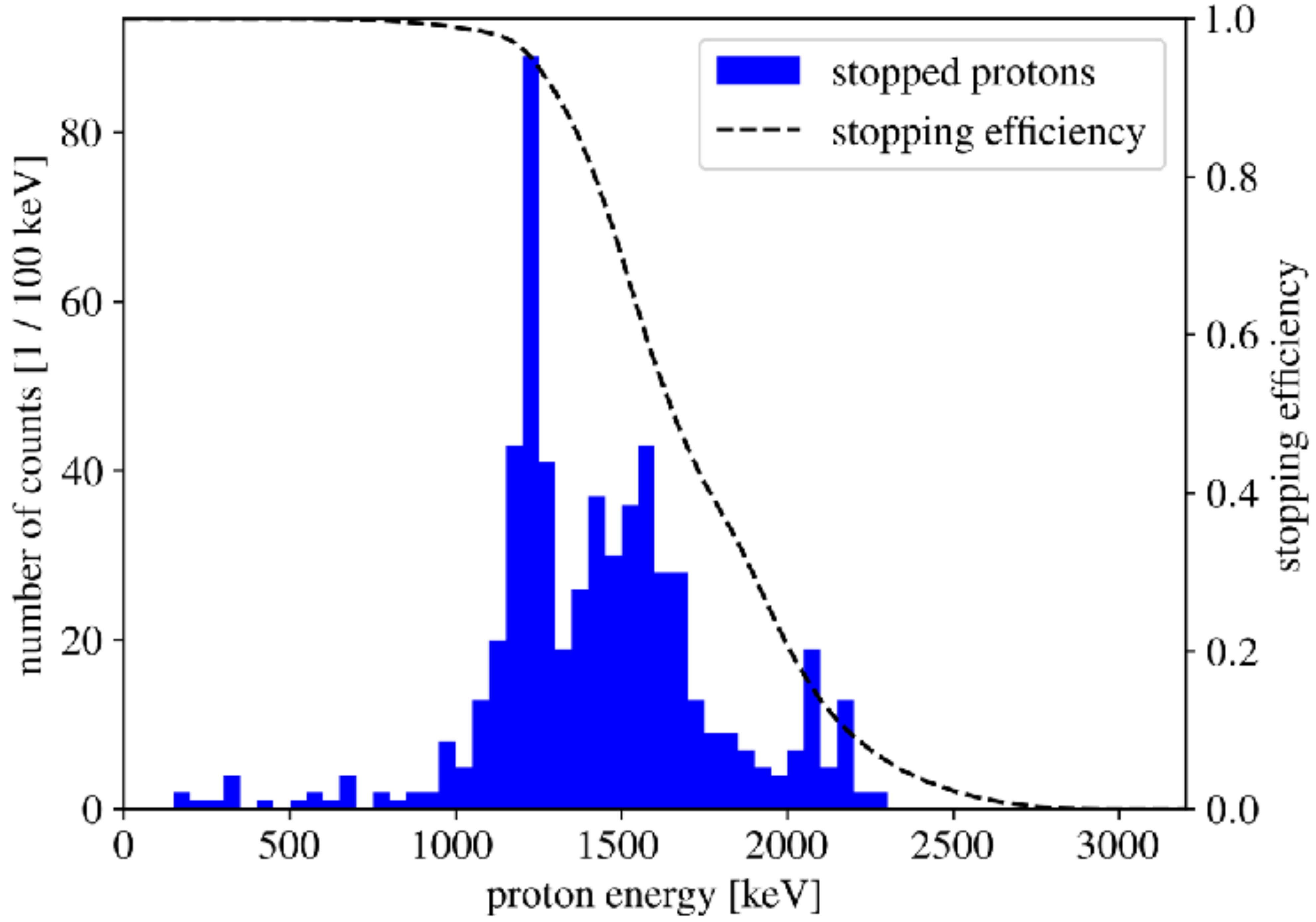
Results: ^{23}Si

- Almost 7.5 k ^{23}Si ions implanted into the active volume of the OTPC
- Confirmation of previously known channels:
  - $b_{\beta p}$ = 81.8(11)% (in agreement with 92% by Blank et al.)
  - $b_{\beta 2p}$ = 7.7(4)%
- $T_{1/2}$ = 46(1) ms

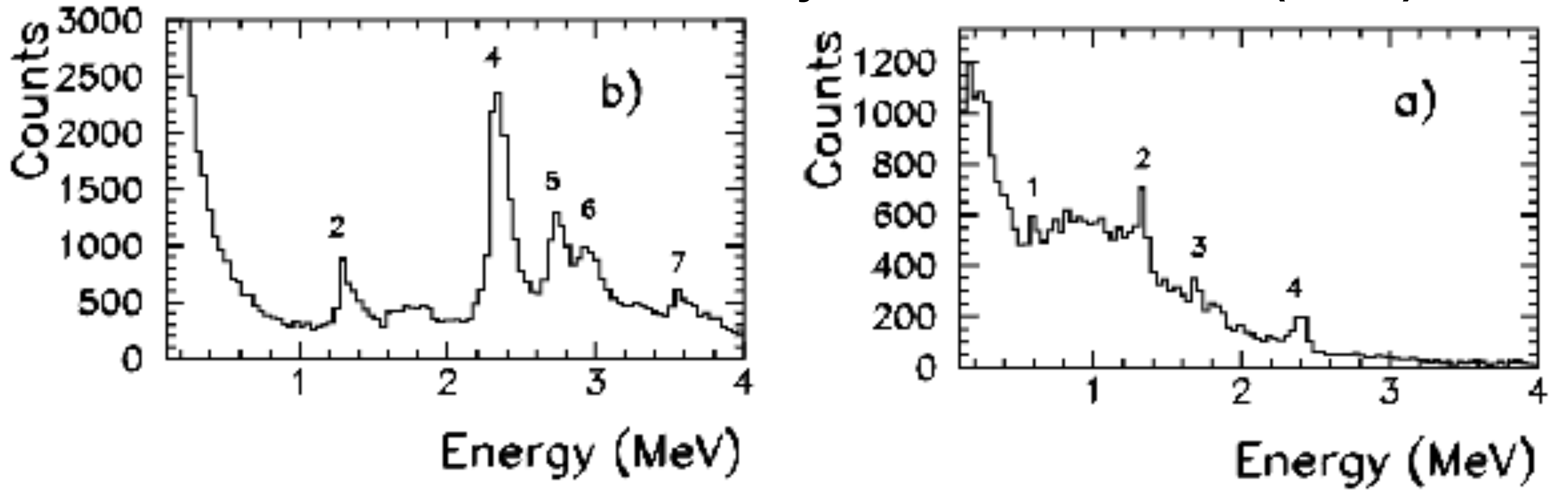
→ missing 10% might be due to decay to the ground state in ^{23}Al

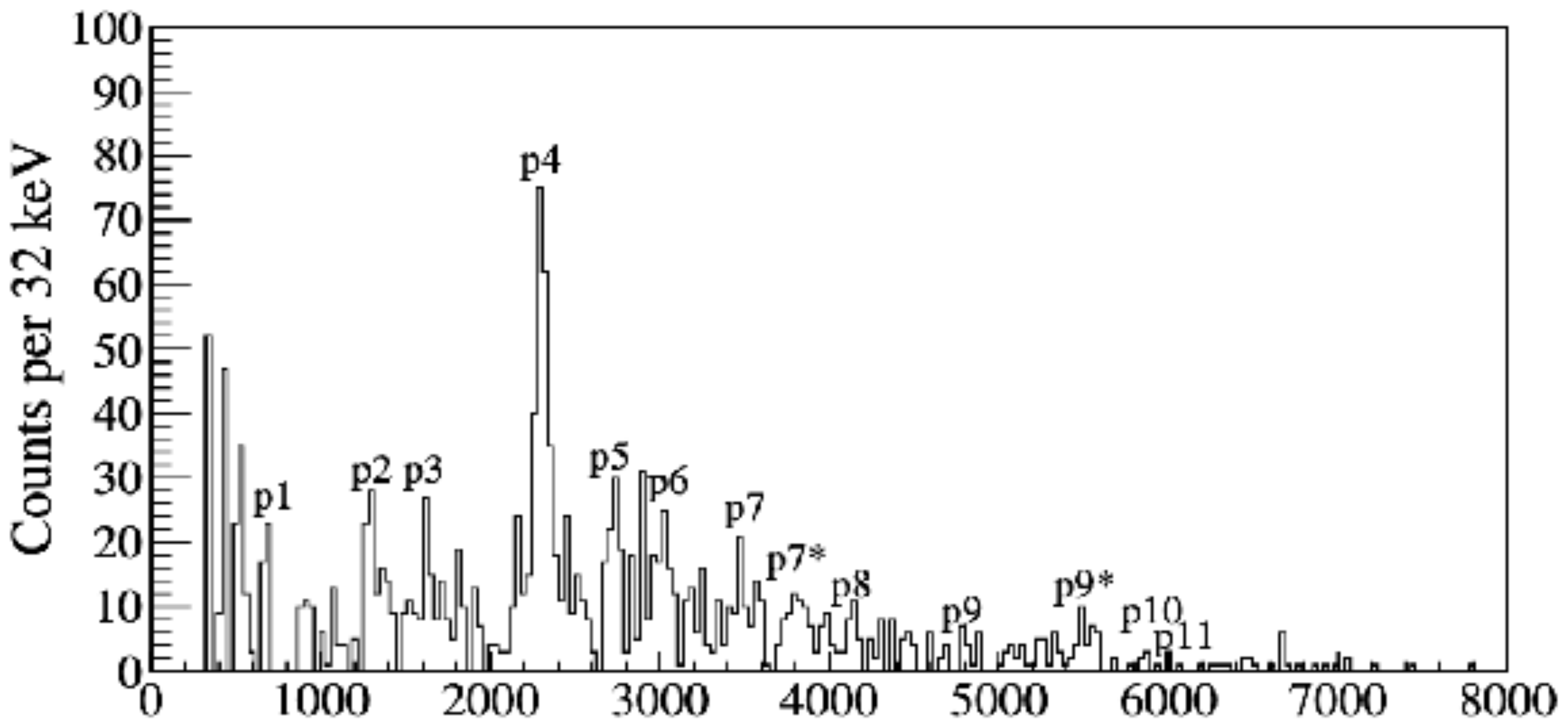


Results: βp emission from ^{23}Si



B. Blank et al., Z. Phys. A 357, 247–254 (1997)





Wang et al., Int. J. of Mod. Phys. E 27, No. 2 (2018) 1850014

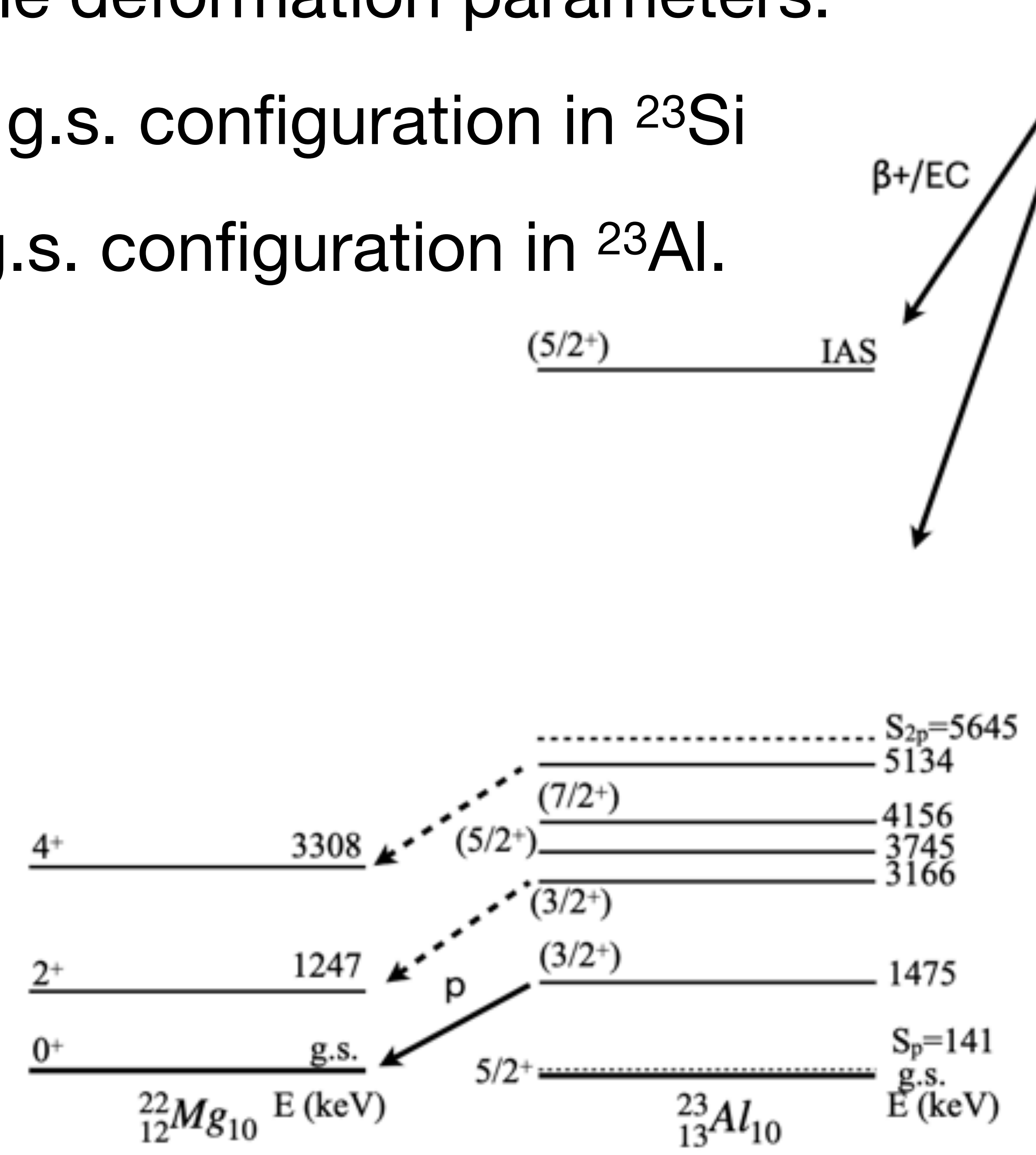
Proton-group energy (keV)	This work Events	Branching	Literature Proton energy Blank et al. (keV)	Wang et al. (keV)	Branching Blank et al.	Wang et al.
300	8^{+4}_{-3}	$(0.12^{+0.06}_{-0.04})$ %	–	–		
650	8^{+4}_{-3}	$(0.12^{+0.06}_{-0.04})$ %	600(60)	673(36)	<3 %	2.4(1) %
1250	230±16	(3.6±0.2) %	1320(40)	1346(39)	10(1) %	5.1(4) %
1550	200±15	(4.6±0.3) %	1700(60)	1631(46)	<5 %	4.6(6) %
2050	52±8	(4.4±0.7) %	2400(40)	2309(41)	32(2) %	21(2) %

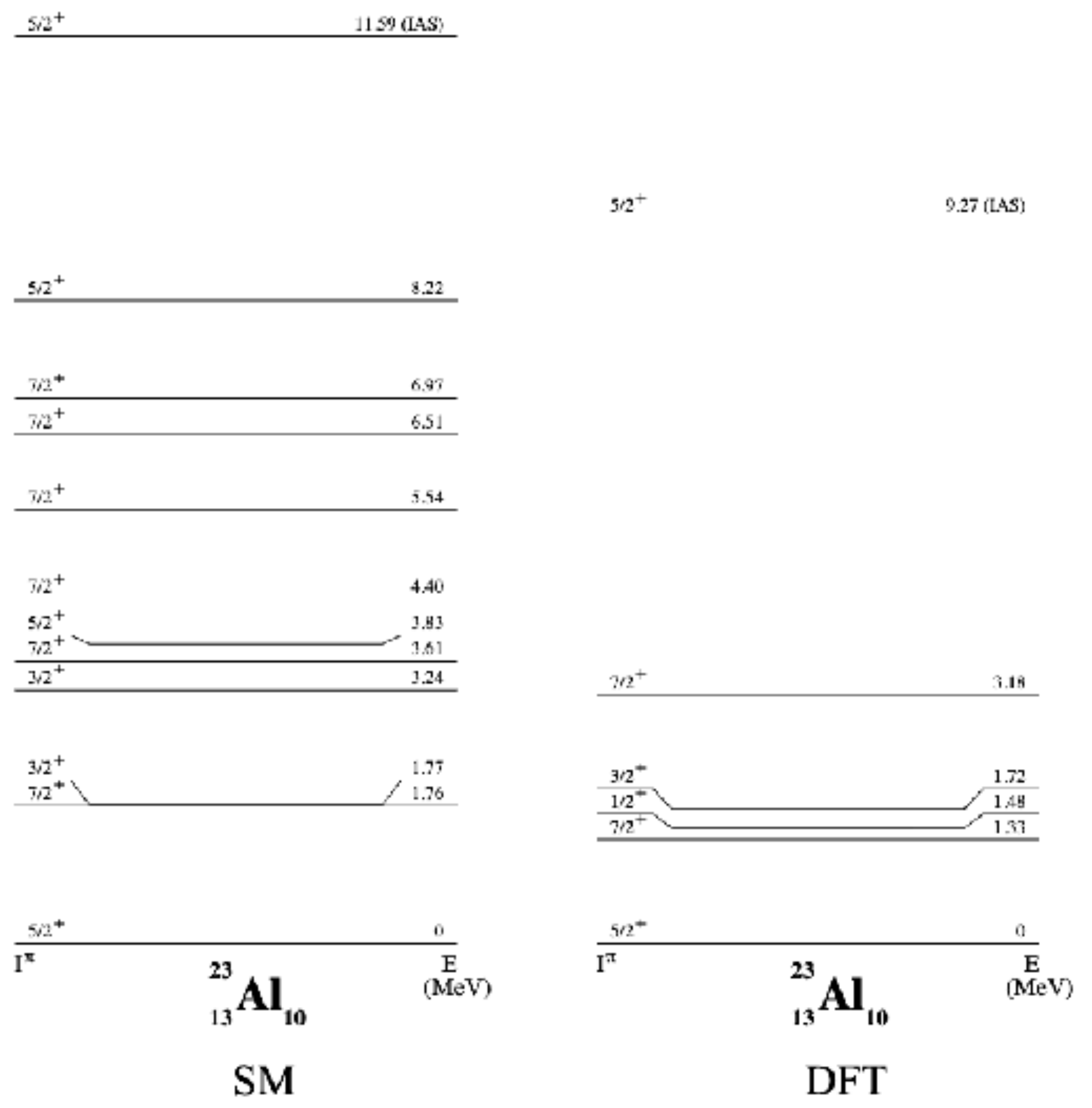
^{23}Si β decay - DFT-NCCI calculations

- β decay of ^{23}Si investigated using shell-model approach, sufficiently accurate description of the low-lying spectrum of ^{23}Al
  B. Blank et al., Zeitschrift für Physik A Hadrons and Nuclei 357, 247 (1997)
- DFT-rooted No-Core Configuration Interaction model:
  W. Satuła, P. Bączyk, J. Dobaczewski, and M. Konieczka, Phys. Rev. C 94, 024306 (2016)
  - Extension of conventional density functional theory
  - Treating properly isospin and rotational symmetries
  - Global model - applicable to a broad range of nuclei (cannot compete with fine-tuned SM)
  - **AIM: validating of the new approach in a nucleus where benchmark SM results exist (no local adjustment of underlying functional's parameters)**
- Configuration space:
  - g.s. and two lowest particle-hole configurations in ^{23}Si
  - g.s. and 13 excited configurations in the daughter nucleus ^{23}Al

^{23}Si β decay - DFT-NCCI calculations

- Relatively well converged solutions for ground states, excited states in ^{23}Al below 3.5 MeV and IAS in ^{23}Al (Above 3.5 spectrum incomplete due to limitations in the size of the adopted configuration space)
- At low energies well compatible with SM results
- Decay to IAS dominates ($|M_F| \approx \sqrt{4.9}$ and $|M_{GT}| \approx 1.5$)
- GT decay to the lowest-lying states: $|M_{GT}|$ well below unity
- Due to shape difference predicted for ^{23}Si (weakly deformed oblate) and ^{23}Al (well deformed prolate) Calculated mean quadrupole deformation parameters:
    - β_2=0.090, γ=60° for the g.s. configuration in ^{23}Si
    - β_2=0.345, γ=0° for the g.s. configuration in ^{23}Al.

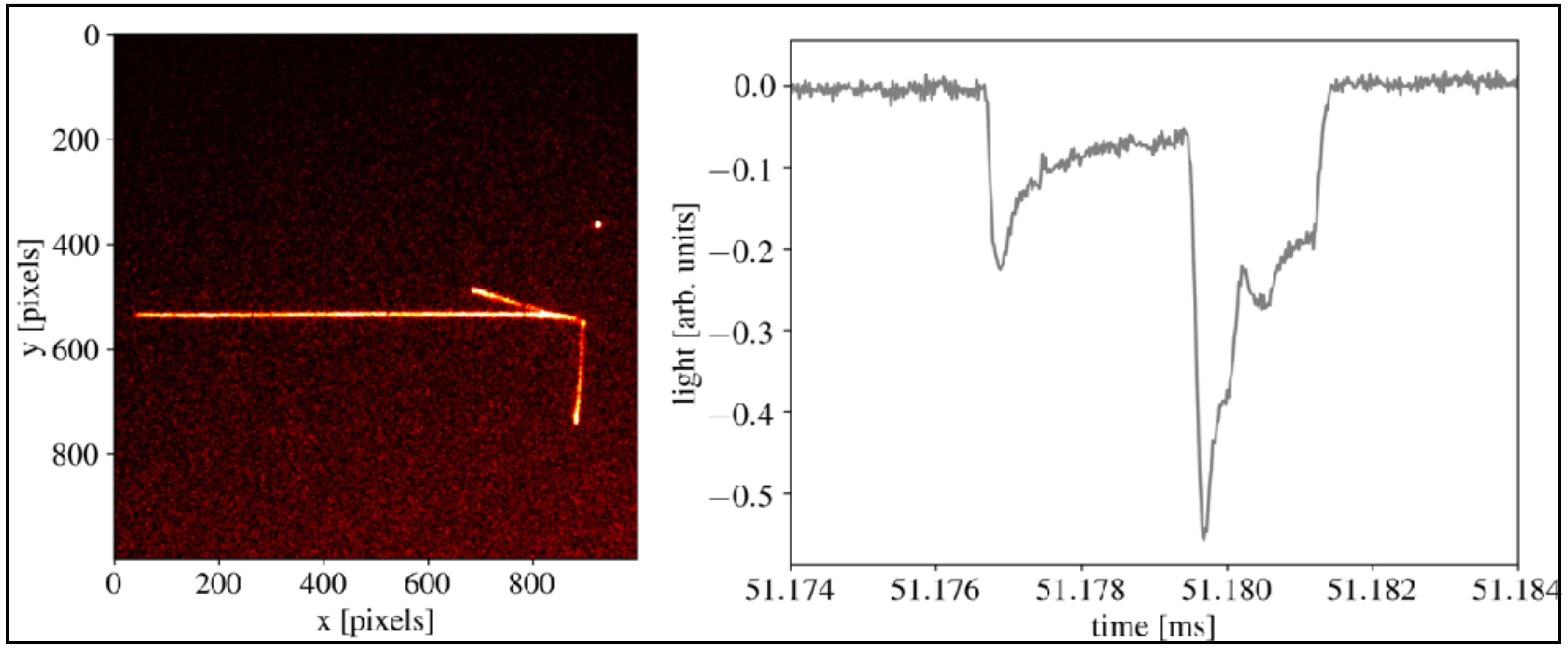


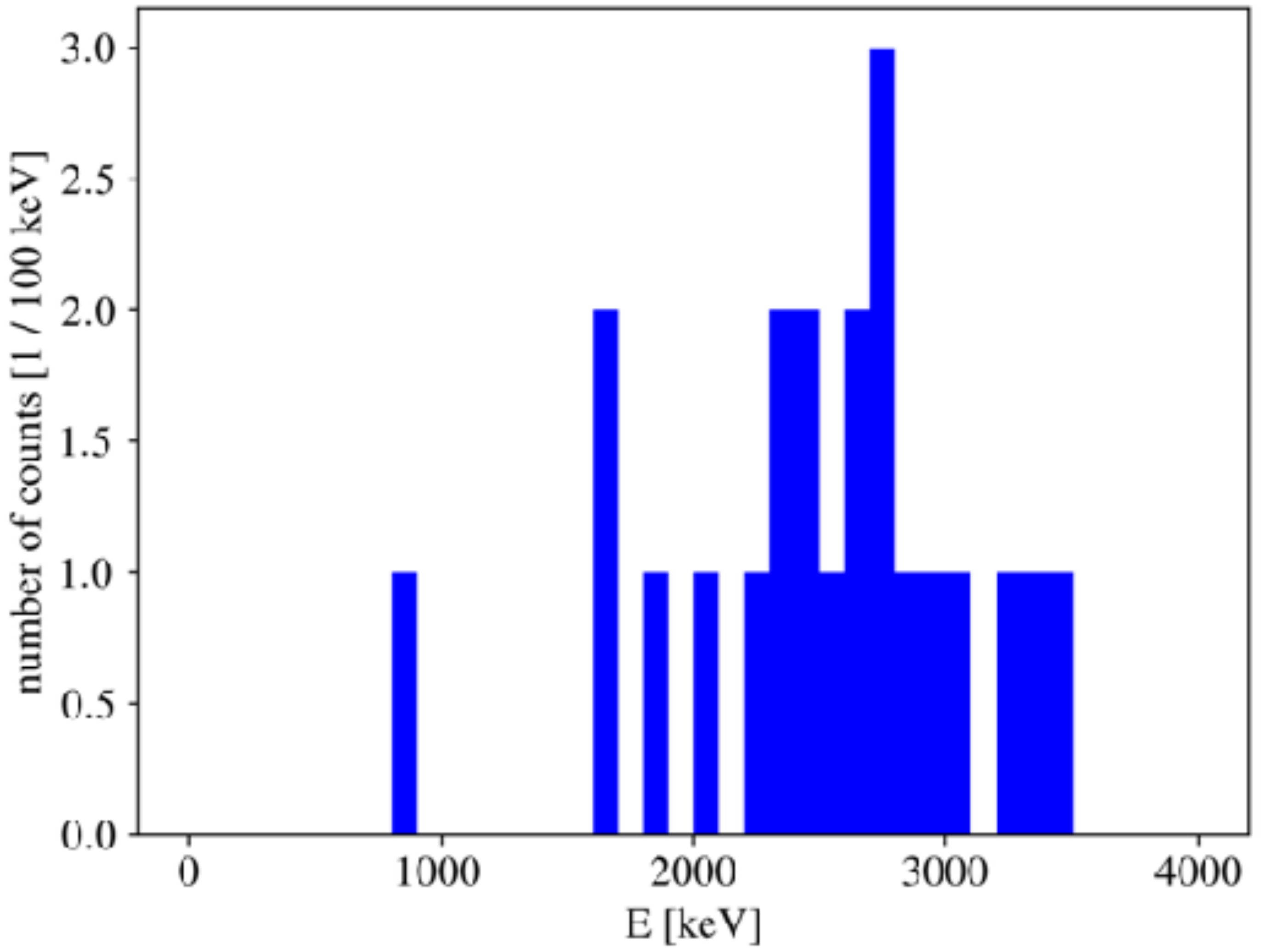


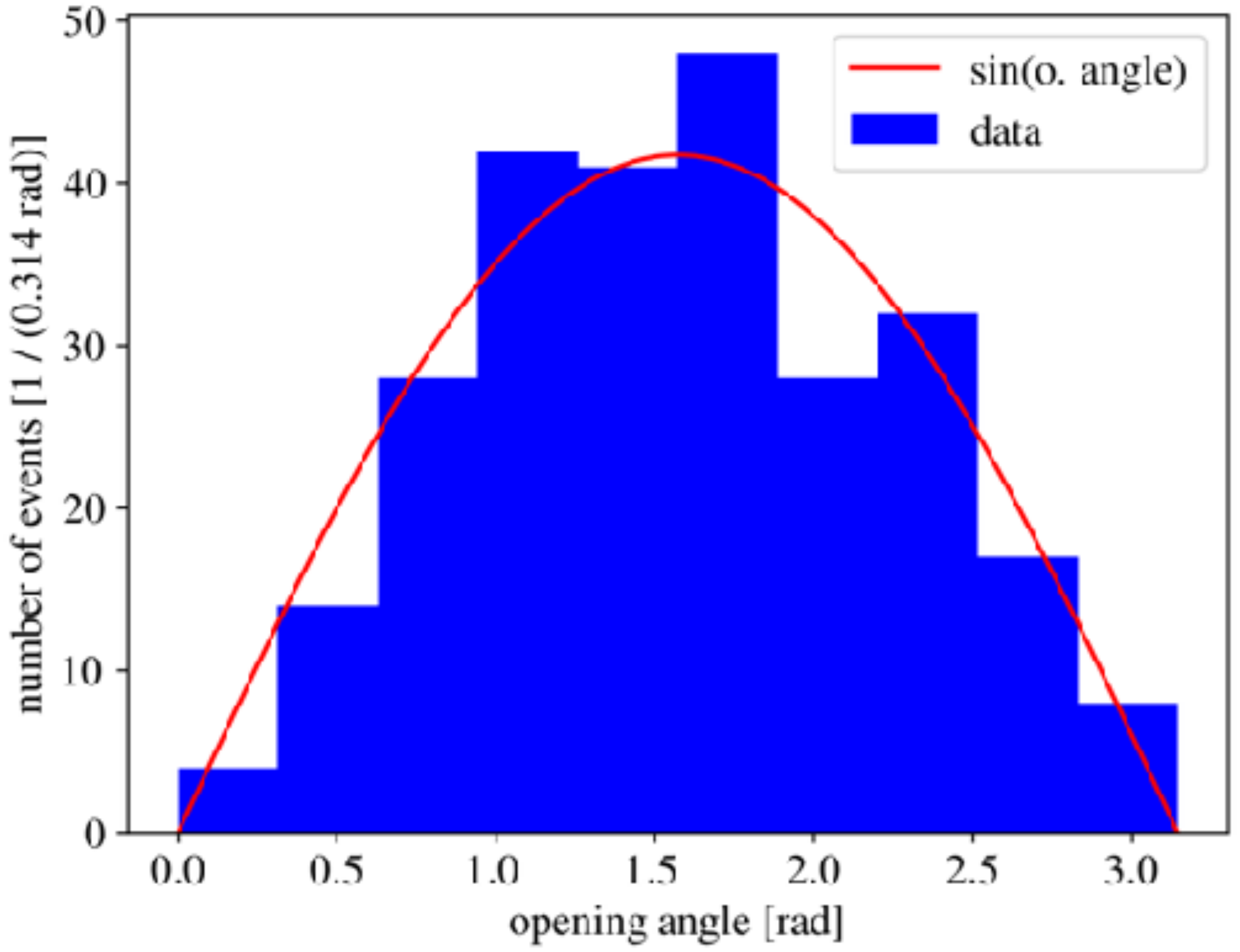
Results: β2p emission from ^{23}Si

- 553 identified events
- Total branching ratio: $b_{\beta 2p}$ = 7.73(35)%
- Both protons stopped in the OTPC: 22 events
- “peak” around 2.7 MeV?
- Opening angle distribution: sequential emission

Blank *et al.*		Wang *et al.*		
E_p [keV]	br [%]	E_p [keV]	br [%]	decay channel
5860(100)	1.9(2)	5857(66)	0.9(9)	$\beta 2p$
6180(100)	1.7(2)	6000(64)	0.6(6)	$\beta 2p$

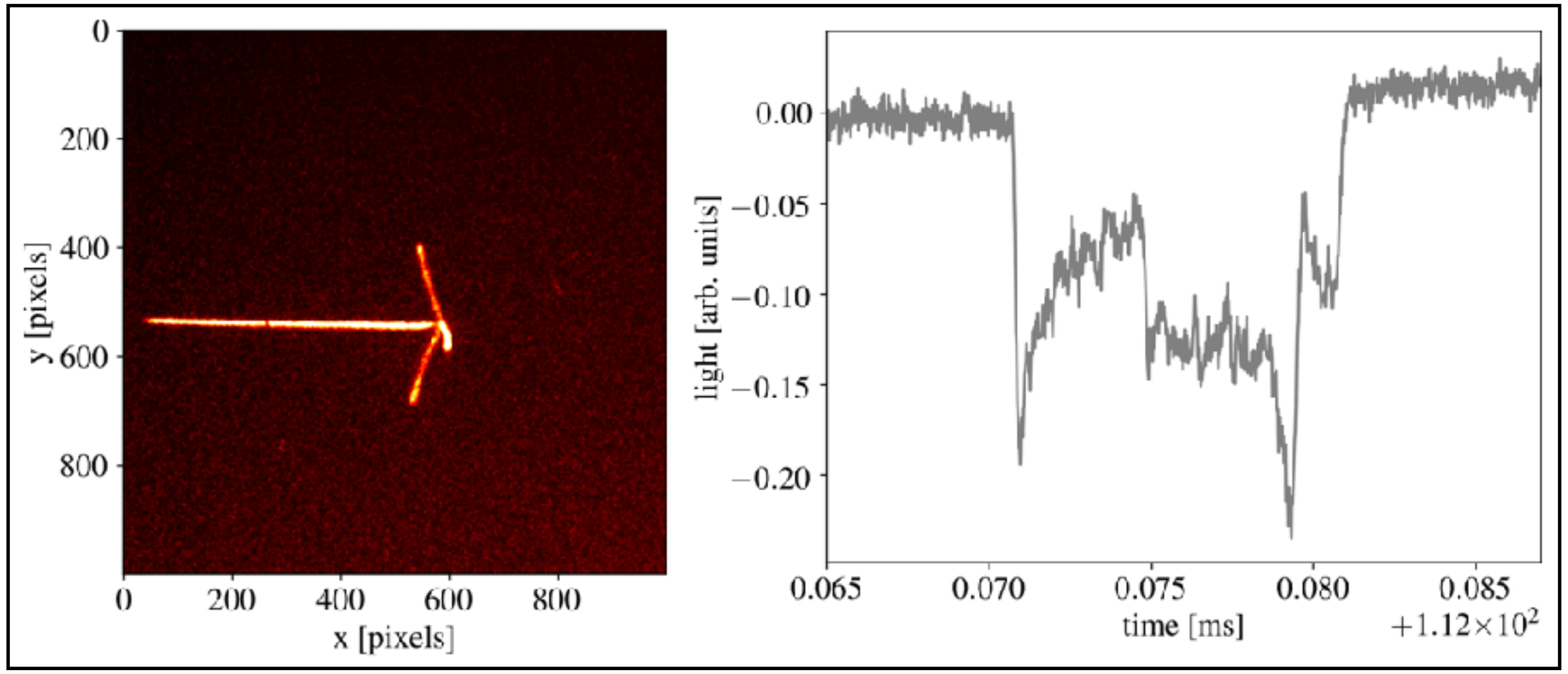




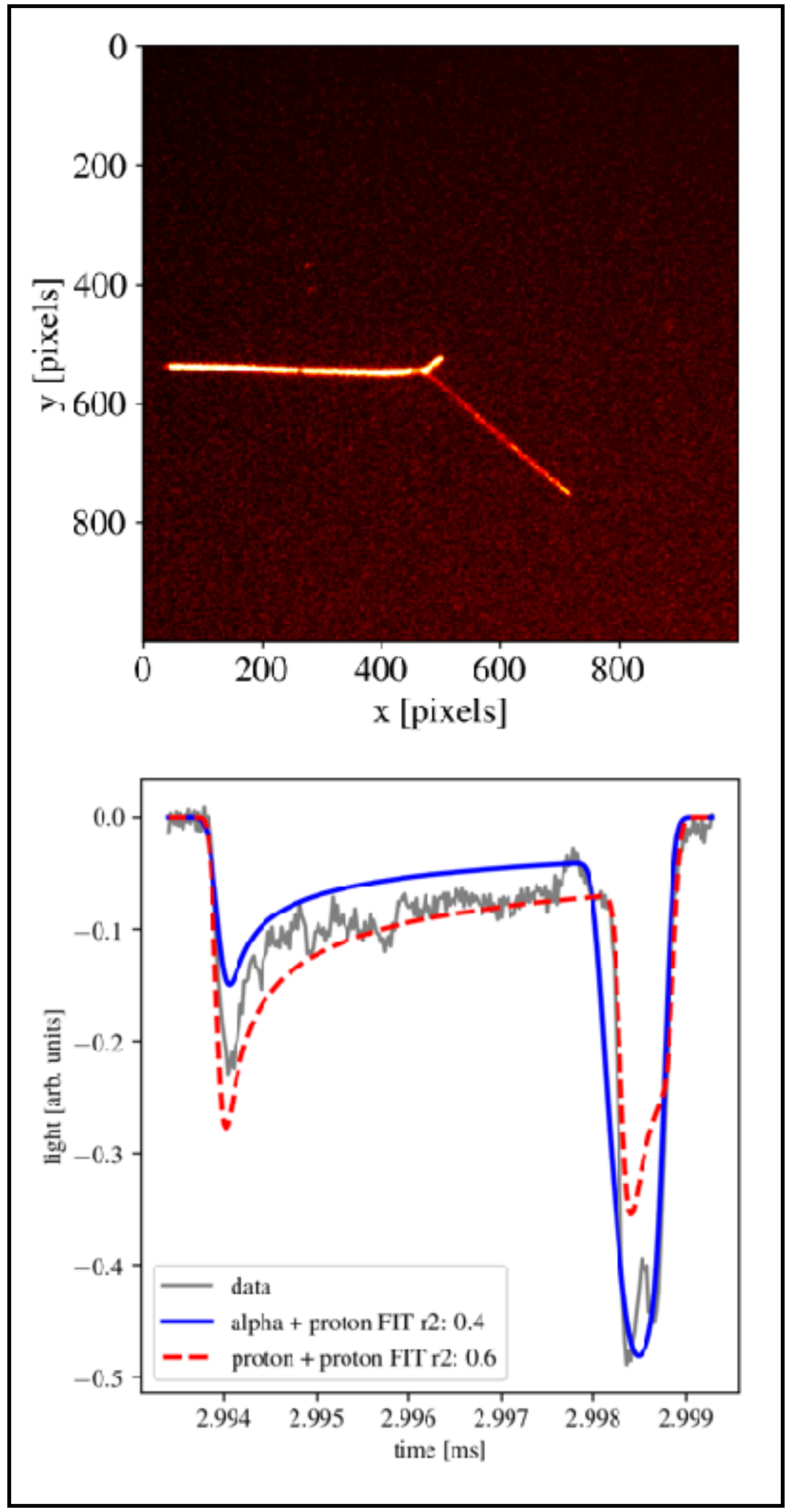


Results: ^{23}Si - new decay channels

- Energy window for decay via IAS:
  $E_{IAS} - S_{3p} = 3.7(6)$ MeV
- **β3p emission identified**
- 2 events, $b_{\beta 3p} = 0.029^{+38}_{-19}$ %
  - $E_1 = 3.6(4)$ MeV
  - $E_2 > 2.7(7)$ MeV



Results: ^{23}Si - new decay channels

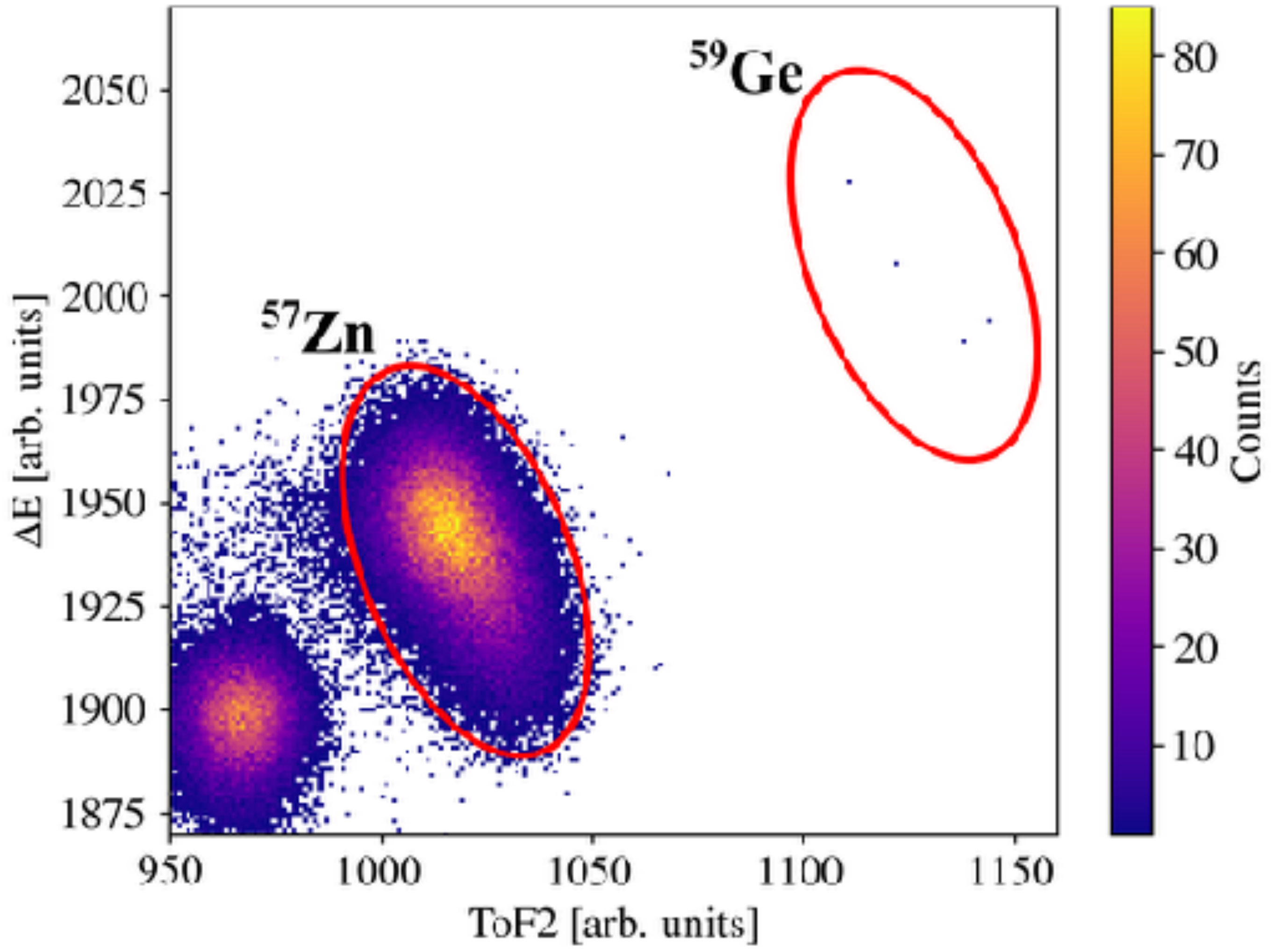


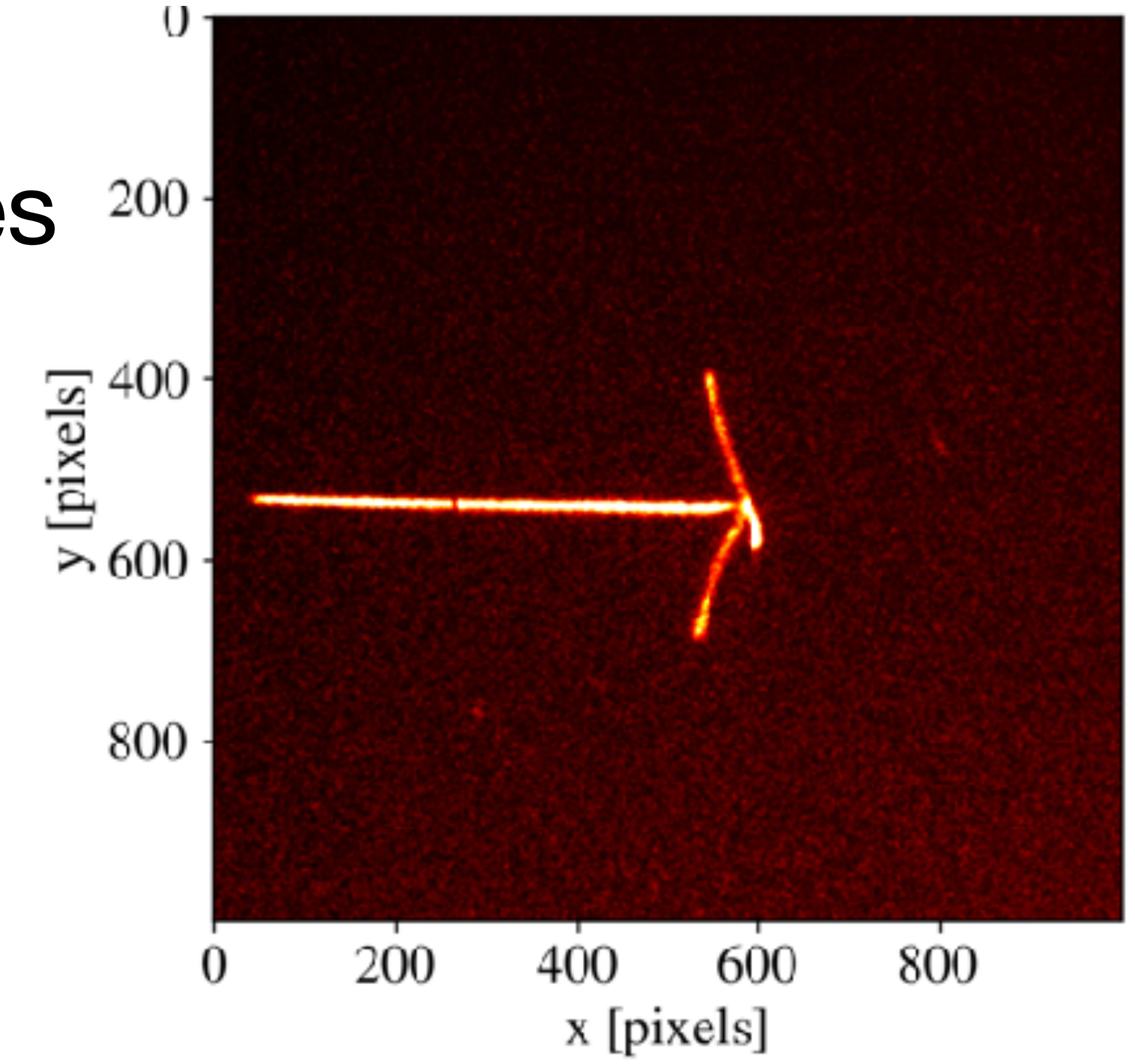
- Energy window for decay via IAS:
  $E_{IAS} - S_{\alpha p} = 3.2(6)$ MeV
- **βpα: tentative identification (one event)**
  - Energetically possible
  - Light ratio CCD/PMT + shape
  - $b_{\beta p\alpha} = 0.014^{+33}_{-12}$ %
  - $E_p = 1.6(1)$ MeV, $E_\alpha = 1.2(4)$ MeV
  - β2p scenario: 1.6(1) and 0.4(2) MeV

Summary

Two experiments performed with OTPC:

- Ge and Zn isotopes (NSCL, MSU)
  - New isotope ^{59}Ge identified
  - β decay of ^{60}Ge studied for the first time ($b_{\beta p} \approx 100\%$)
  - βp from ^{58}Zn observed for the first time, non-negligible B(GT) despite small b
  - Cross-sections for production of neutron-deficient Ge isotopes
- ^{22,23}Si (TAMU):
  - Known channels βp and β2p in ^{22,23}Si confirmed
  - New decay modes in ^{23}Si: β3p and βpα





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C. Mazzocchi [1], D. Bazin [2], T. Baumann [2], A. Bezbakh [3], B.P. Crider [2], M. Ćwiok [1], W. Dominik [1], A. Fijałkowska [1,4], T. Ginter [2], S. Go [5], R. Grzywacz [5,6], J. Hooker [7,8], C. Hunt [7,8], Z. Janas [1], Ł. Janiak [9], H. Jayatissa [7,8], G. Kamiński [3,10], K. Kolos [5], A. Korgul [1], E. Koshchiy [7], M. Kuich [1], E. Kwan [2], S.N. Liddick [2,11], K. Miernik [1], S.V. Paulauskas [2,3], J. Pereira [2], M. Pfützner [1], M. Pomorski [1], B. Roeder [7], G.V. Rogachev [7,8], K.P. Rykaczewski [6], A. Saastamoinen [7], W. Satuła [1], S. Sharma [1], J. Singh [1], N. Sokołowska [1], C. Sumithrarachchi [2], Y. Xiao [5]

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…and thank you for your attention!