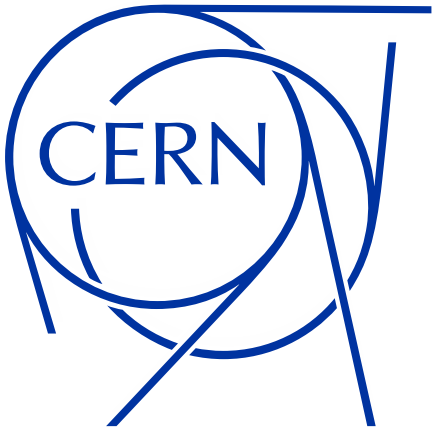


From Shell Gaps to Shape Coexistence: Probing the Island of Inversion N=40 through the b-decay of ^{67}Mn

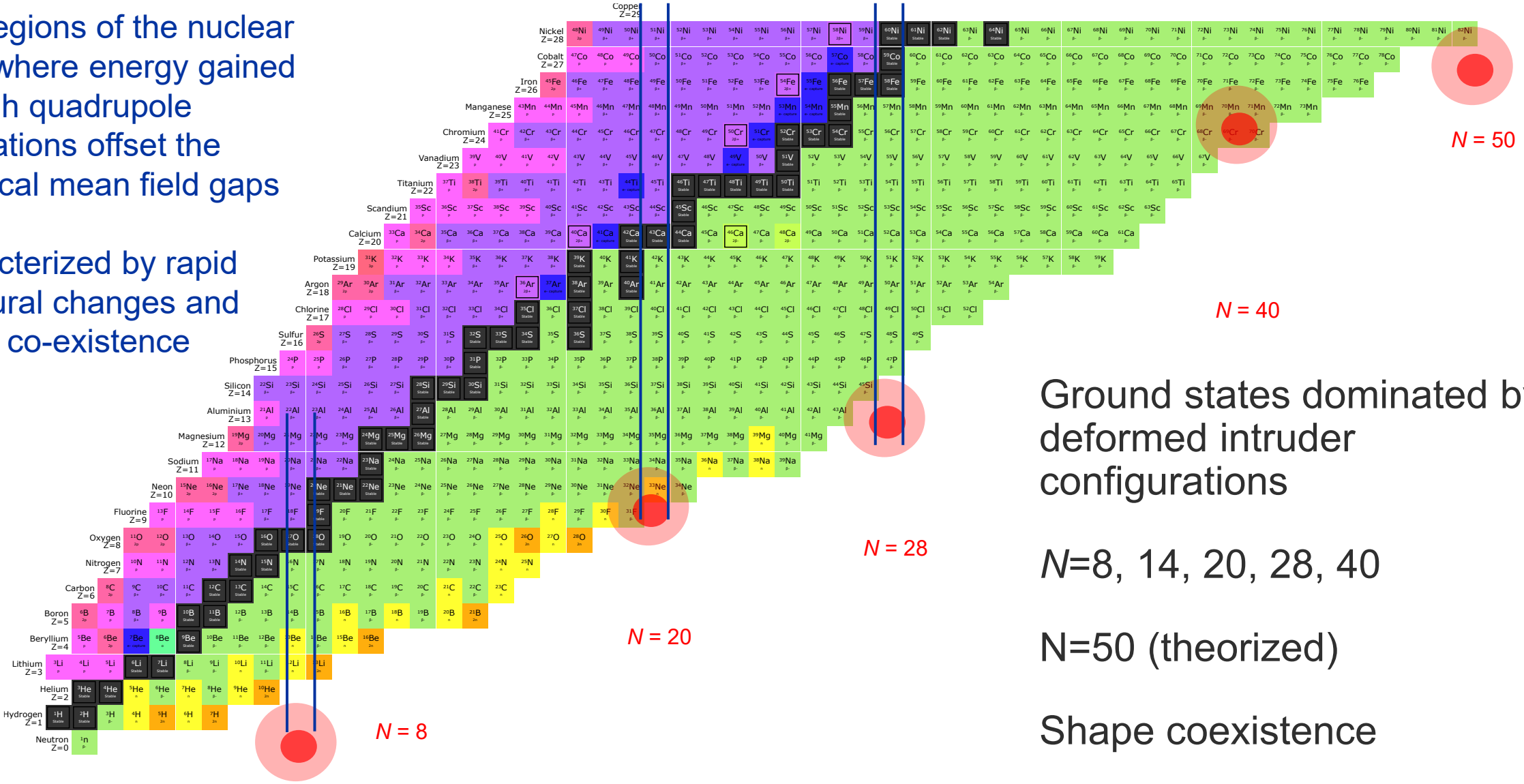
Victoria Vedia **victoria.vedia@cern.ch**

22nd of Sep 2025

Islands of Inversion (I.o.I.)

IoI: Regions of the nuclear chart where energy gained through quadrupole correlations offset the spherical mean field gaps

Characterized by rapid structural changes and shape co-existence



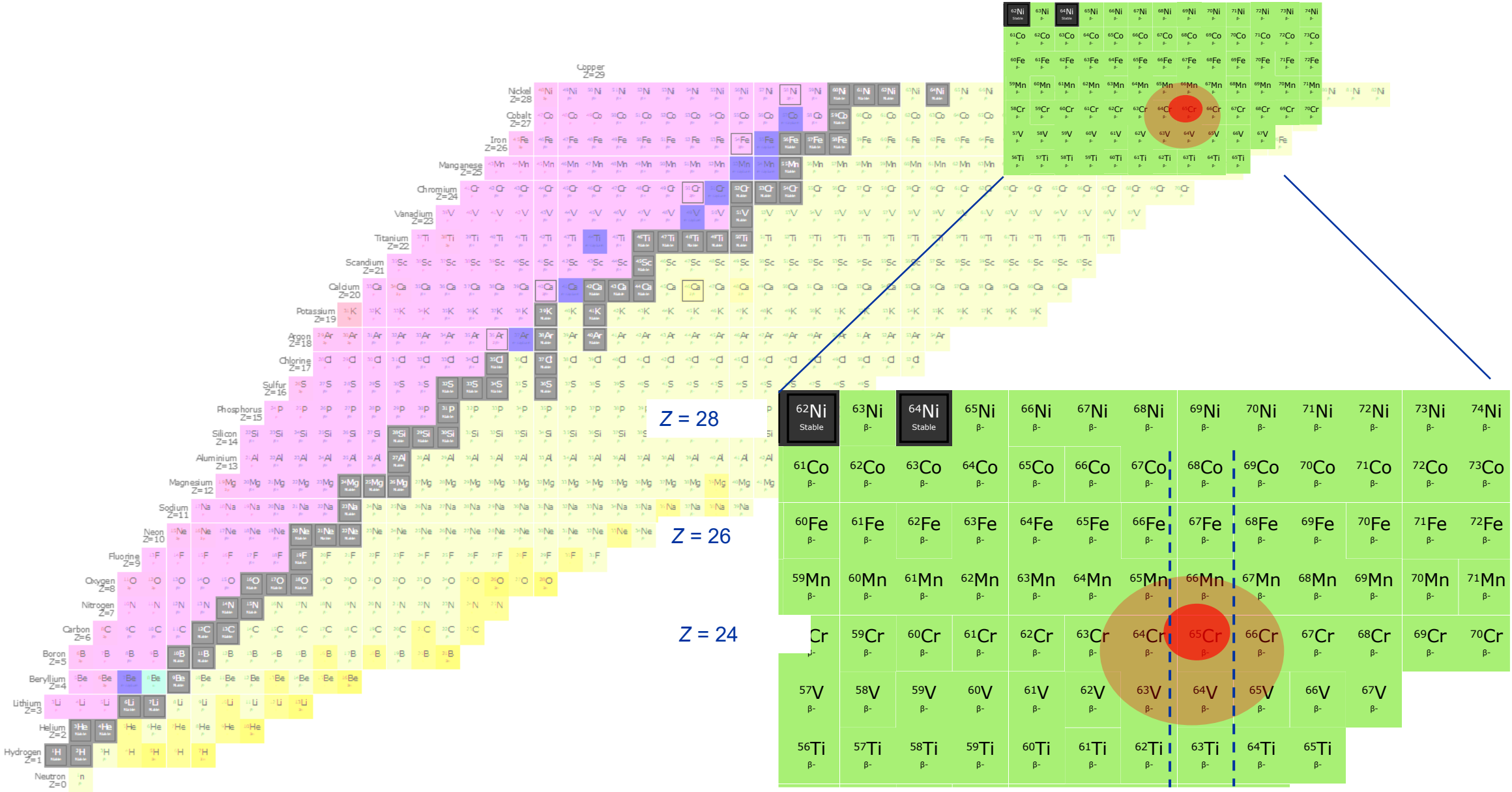
Ground states dominated by deformed intruder configurations

N=8, 14, 20, 28, 40

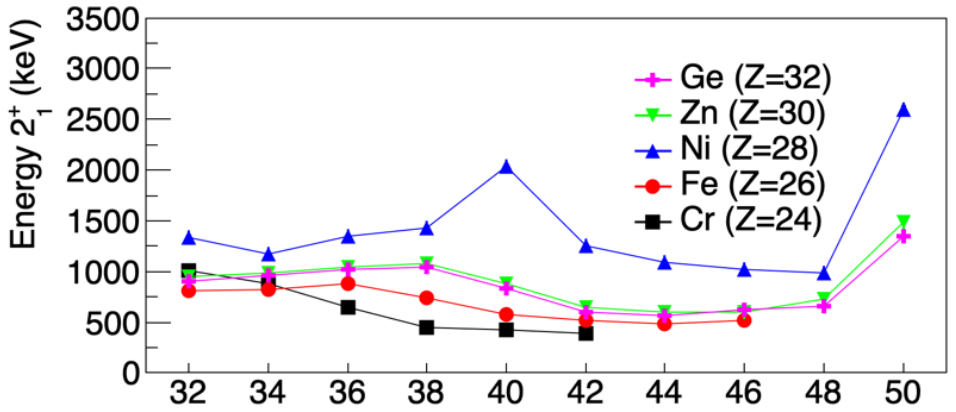
N=50 (theorized)

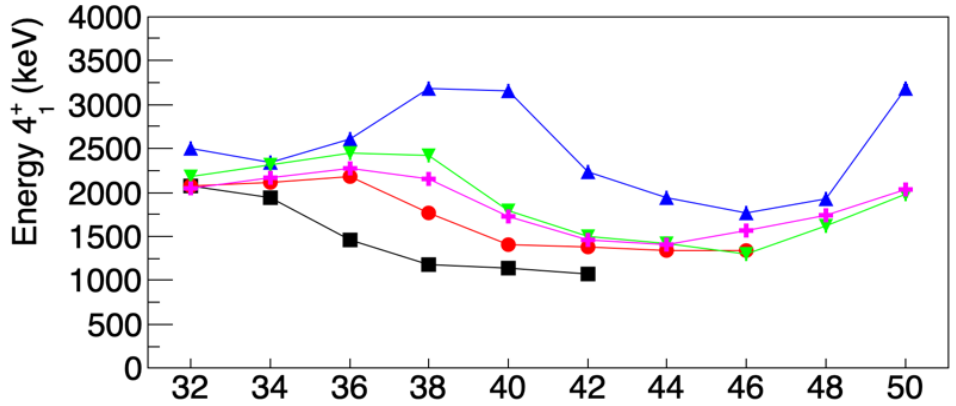
Shape coexistence

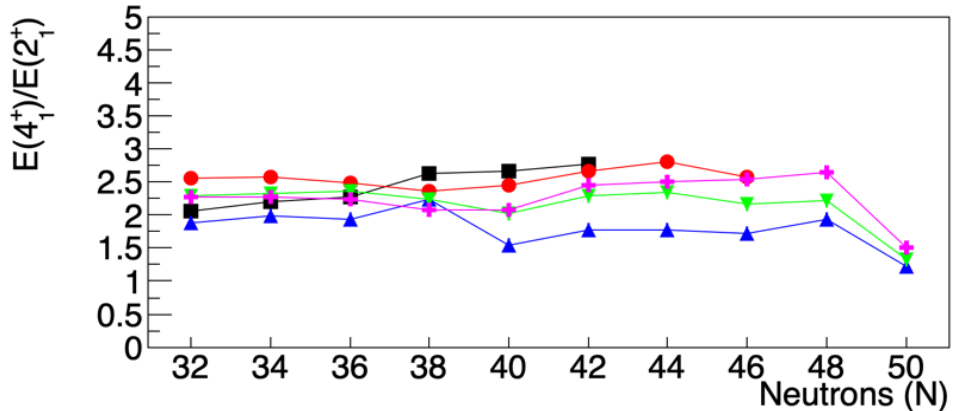
N=40n Island of Inversion

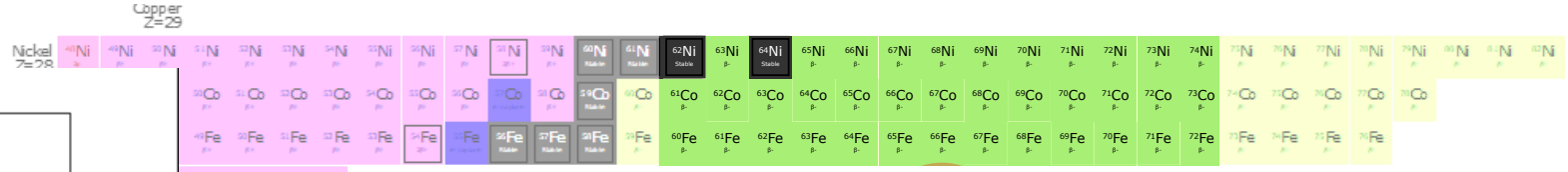


At N = 40

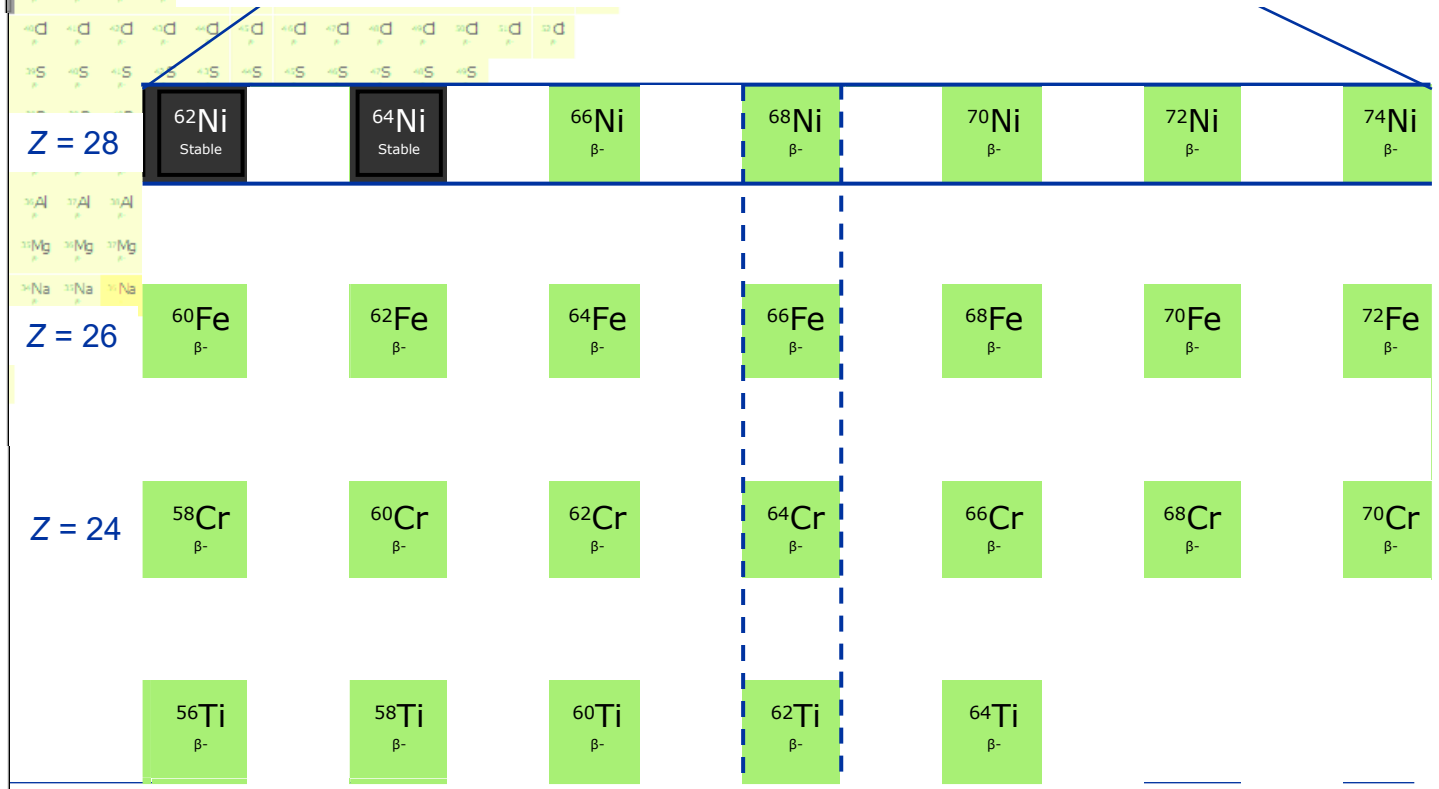




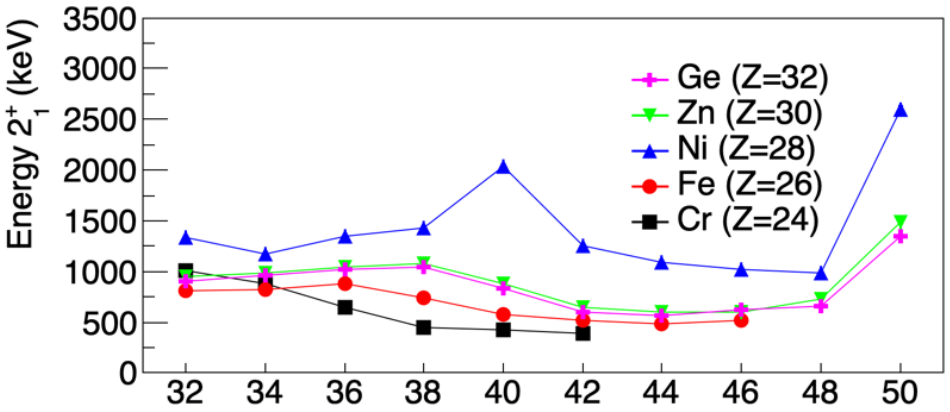


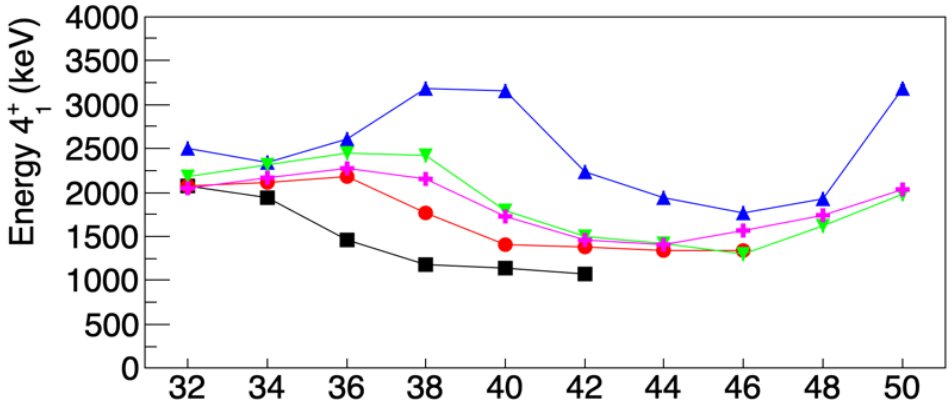


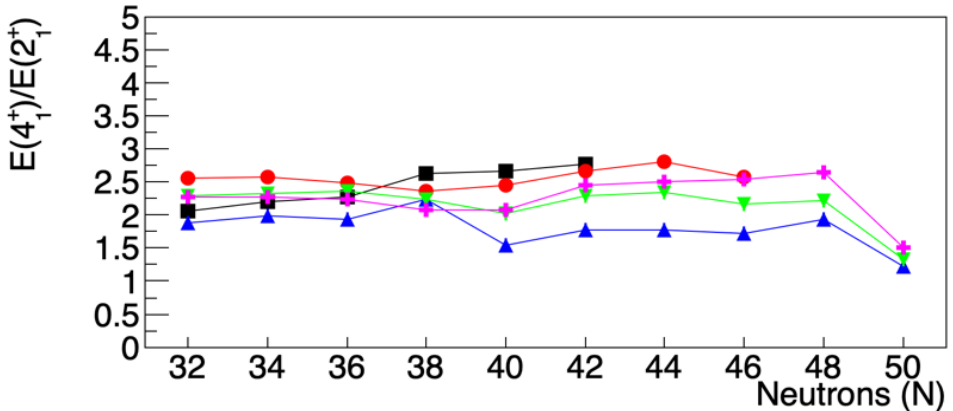
- Fe (Z = 26) and Cr (Z = 24) isotopes in this region exhibit increasingly collective behavior as evidenced by rapid drop in the energies of the 2^+ state
- Open proton shell and promotion of neutron pairs across the subshell gap favours development of quadrupole correlations

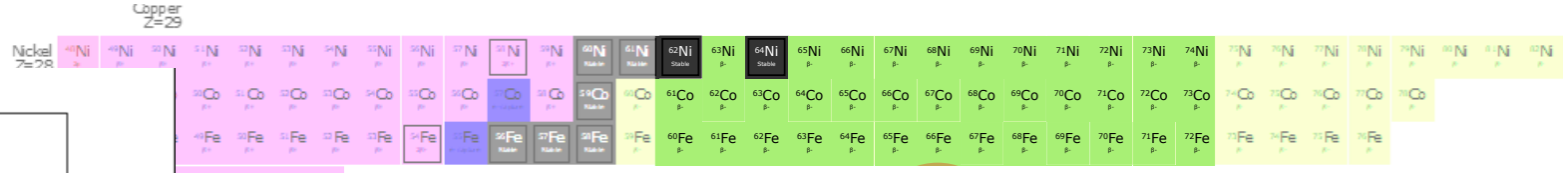


At N = 40









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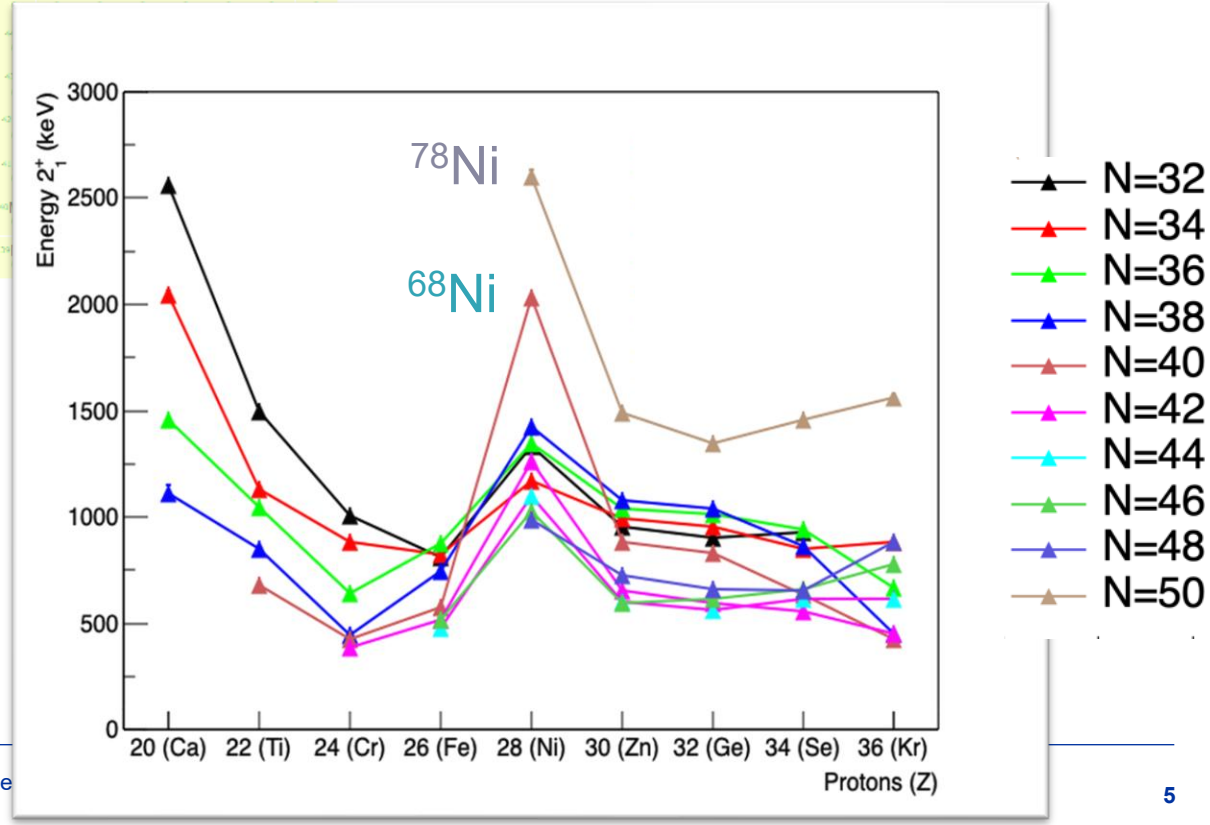
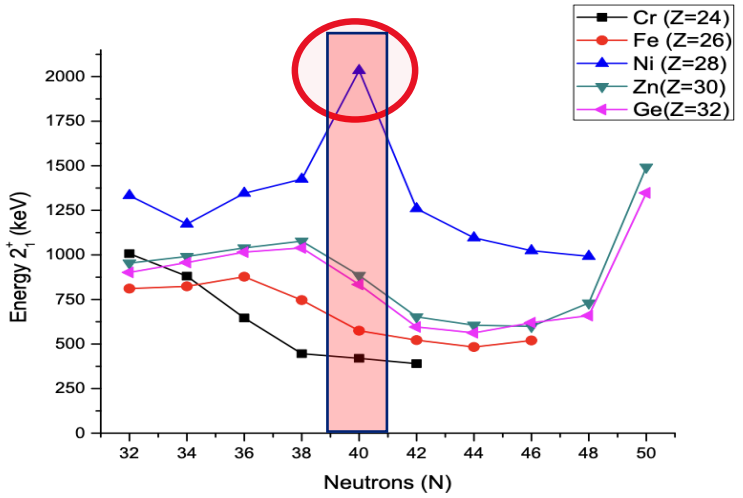
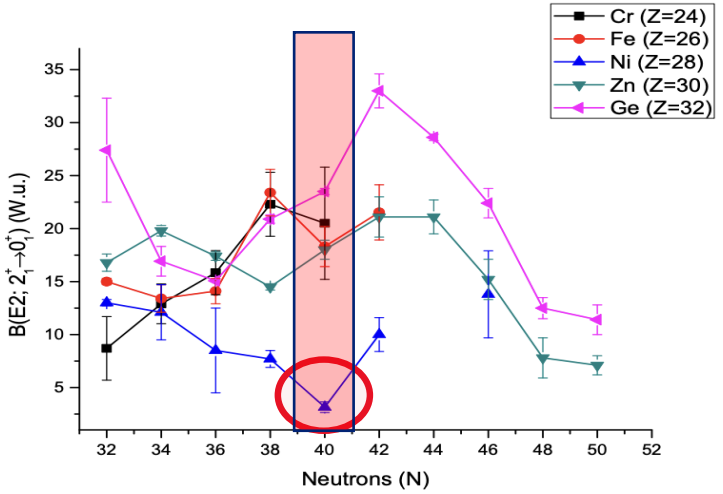


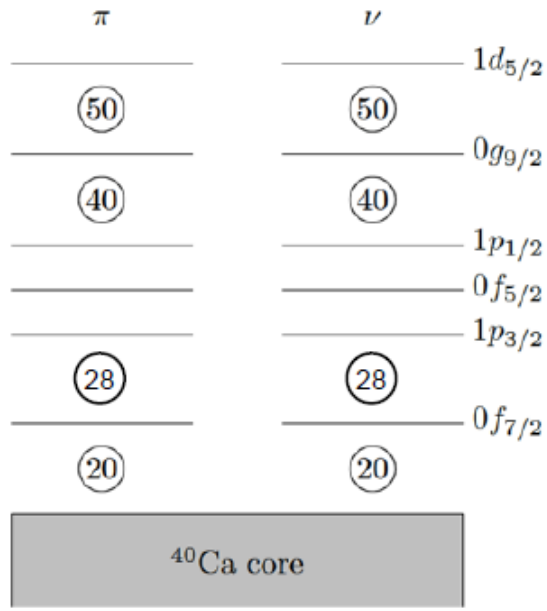
N=40 Island of Inversion

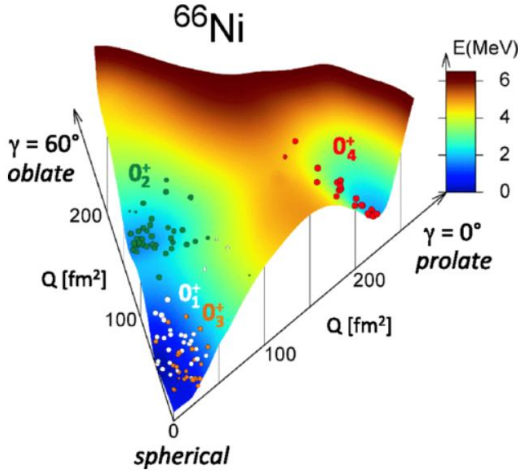
- Large energy gap between the *pf* shell and $0g_{9/2}$ neutron shell
- Sub-shell closure at *N*=40?
- Proton-neutron tensor force reduces N=40 gap as *Z* decreases
- Systematics indicate a sudden increase in collectivity around *N*=40 and *Z*<28
- Shape coexistance in I.o.I. N=40

S. Leoni et al. PRL 118, 162502







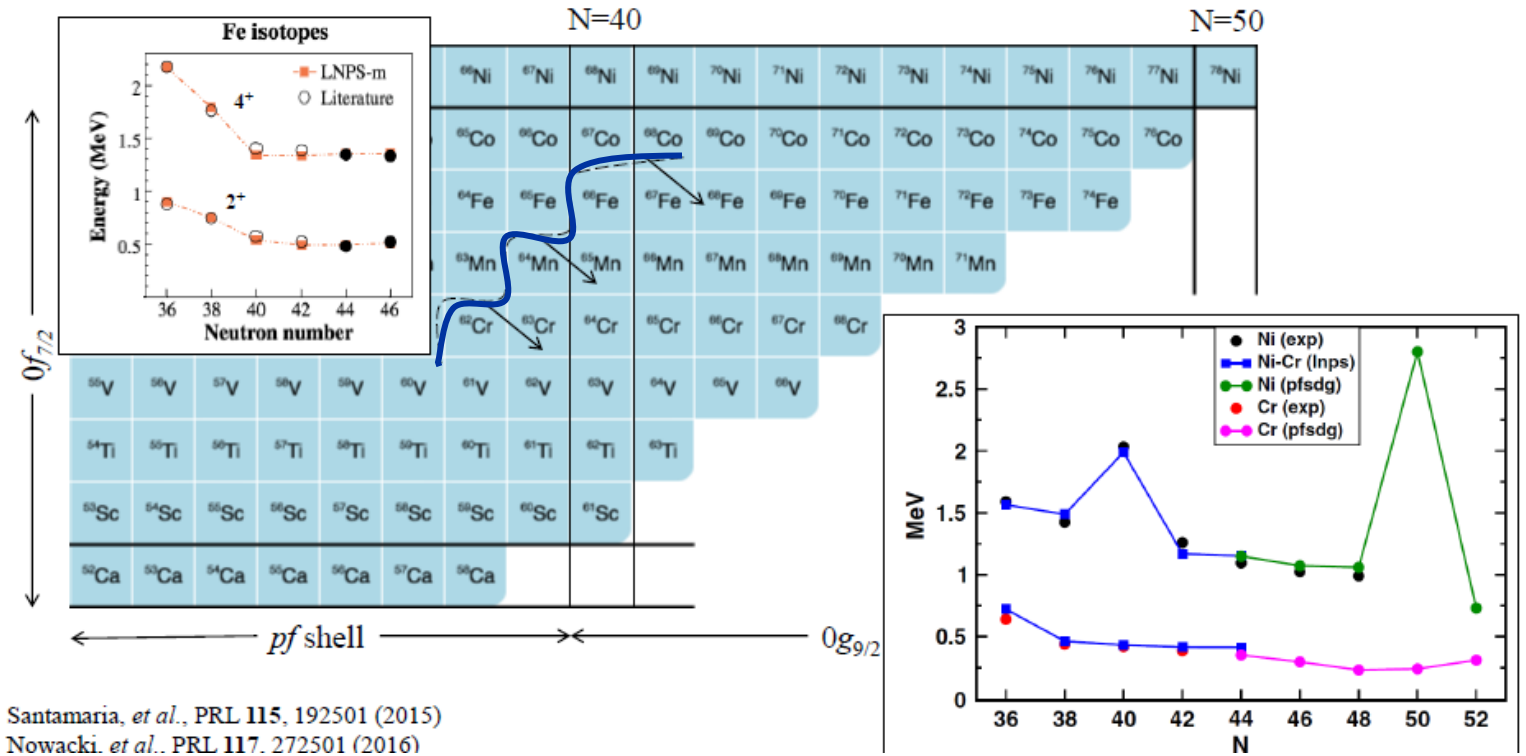


O. Sorlin *et al.*, PRL 88, 092501 (2002).

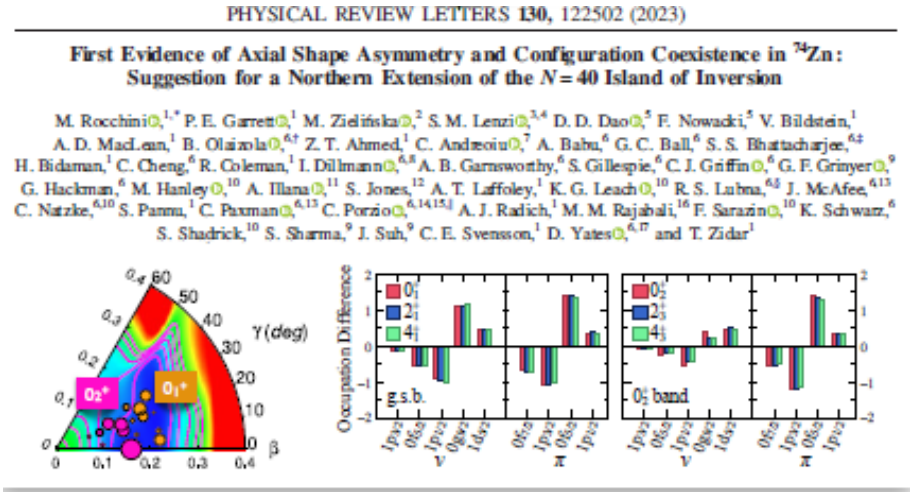
S. Leoni *et al.* PRL 118, 162502

Merging Islands of Inversion

---- Limits of IoI (Previously thought)



Santamaria, *et al.*, PRL **115**, 192501 (2015)
Nowacki, *et al.*, PRL **117**, 272501 (2016)

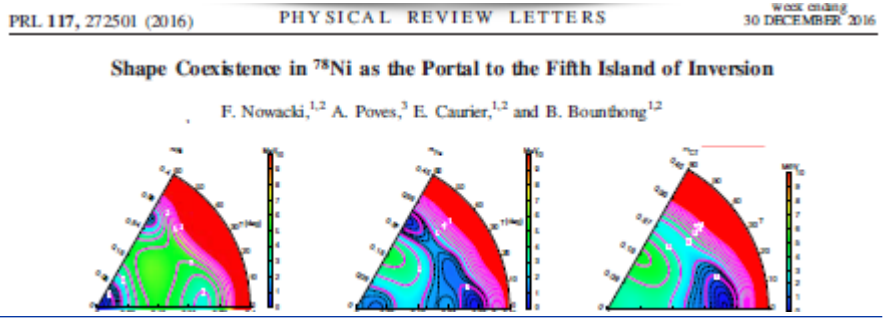

PHYSICAL REVIEW LETTERS **130**, 122502 (2023)

First Evidence of Axial Shape Asymmetry and Configuration Coexistence in ^{74}Zn: Suggestion for a Northern Extension of the $N = 40$ Island of Inversion

M. Rocchini, P. E. Garrett, M. Zielińska, S. M. Lenzi, D. D. Dao, F. Nowacki, V. Bildstein, A. D. MacLean, B. Olaizola, Z. T. Ahmed, C. Andreoiu, A. Babu, G. C. Ball, S. S. Bhattacharjee, H. Bidaman, C. Cheng, R. Coleman, I. Dillmann, A. B. Garnsworthy, S. Gillespie, C. J. Griffin, G. F. Grinyer, G. Hackman, M. Hanley, A. Illana, S. Jones, A. T. Laffoley, K. G. Leach, R. S. Lubna, J. McAfee, C. Natzke, S. Pannu, C. Paxman, C. Porzio, A. J. Radich, M. M. Rajabali, F. Sarazin, K. Schwarz, S. Shadrick, S. Sharma, J. Suh, C. E. Svensson, D. Yates, and T. Zidar

A shore of the N = 40 “island of inversion” appears to manifest above Z = 26, previously thought as its northern limit in the chart of the nuclides

- Merge of N=40 and N=50 I.o.I suggested (LSSM)
- Norther shore of I.o.I N=40 above Z=26

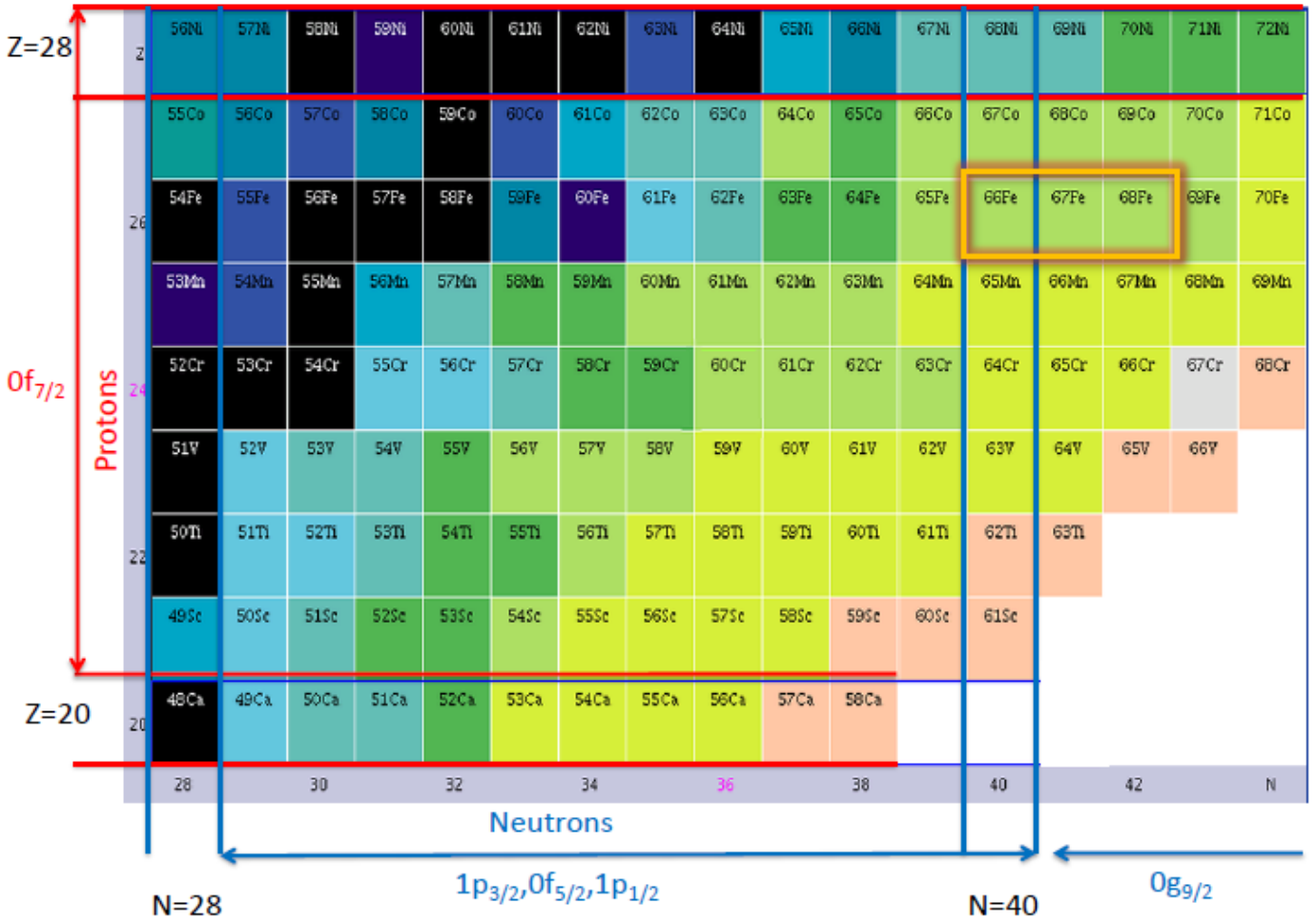

PRL **117**, 272501 (2016) PHYSICAL REVIEW LETTERS week ending 30 DECEMBER 2016

Shape Coexistence in ^{78}Ni as the Portal to the Fifth Island of Inversion

F. Nowacki, A. Poves, E. Caurier, and B. Bounthong

Region of Interest: I.o.I. N=40

β decay of Mn isotopes with GRIFFIN spectrometer at TRIUMF



Data Collected during

S1723 Experiment

Co-spokespersons

B. Olaizola and J. Smith.

Data analyzed at TRIUMF by

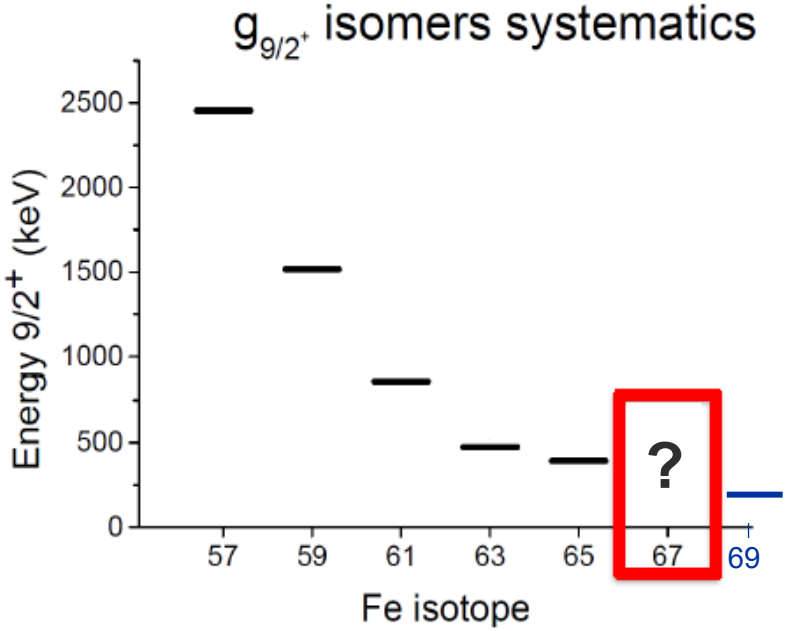
Victoria Vedia: **A=67**

Rashmi Umashankar A=68

See talk of R. Umashankar later this session!

β decay of ^{67}Mn: ^{67}Fe Measurement Goals

- Expand Level Scheme
  - Only two transitions and two levels
- $g_{9/2}$ isomer (systematics)
- Transition strength (level lifetimes):
  - Gain insights from state-of-the-art theoretical calculations
- Shape co-existence:
  - Deformed band built on g.s.
  - Spherical band built on isomer $g_{9/2}^{+}$



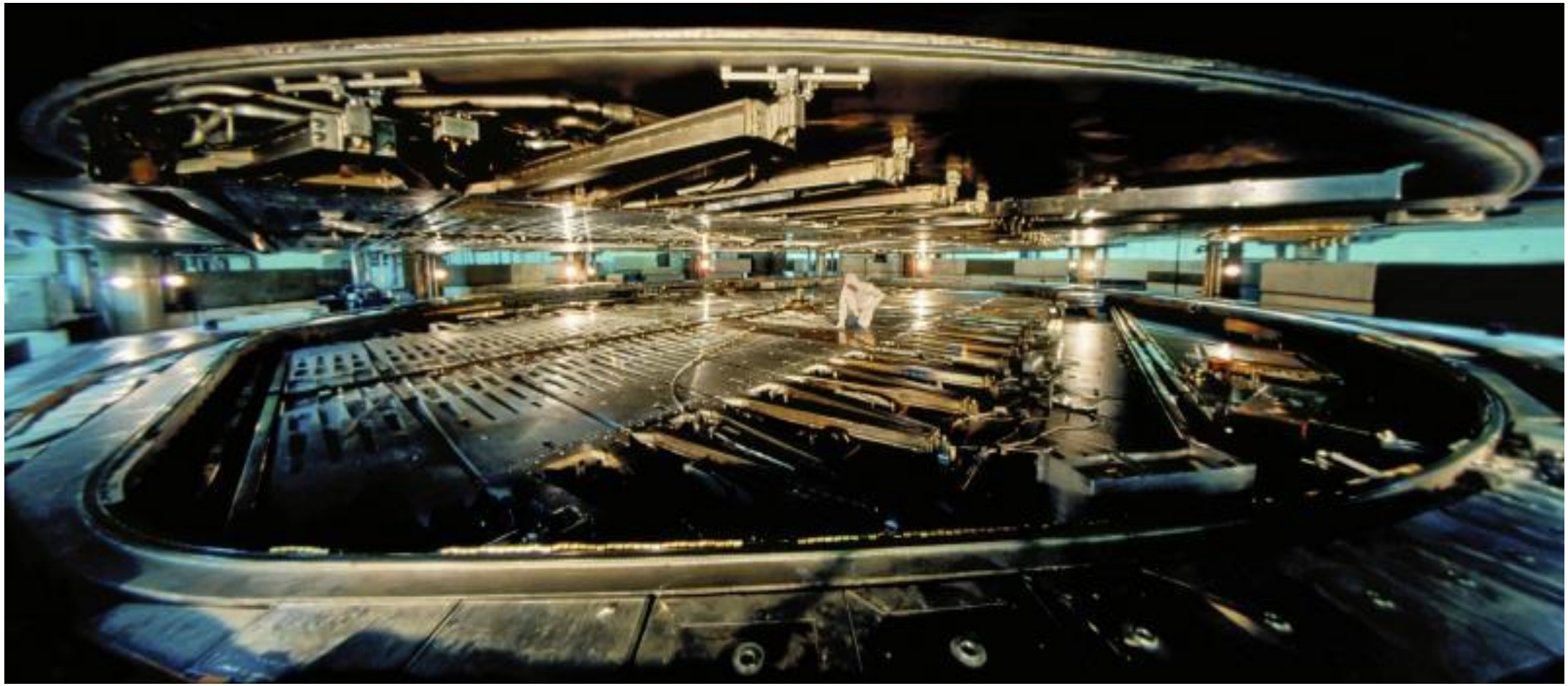
- Systematic of the $9/2^+$ isomer in odd Fe isotopes.
- They are interpreted as neutron excitations across N=40
- It was expected a $9/2^+$ g.s. for ^{67}Fe,

B. Olaizola PhD Thesis, 2013

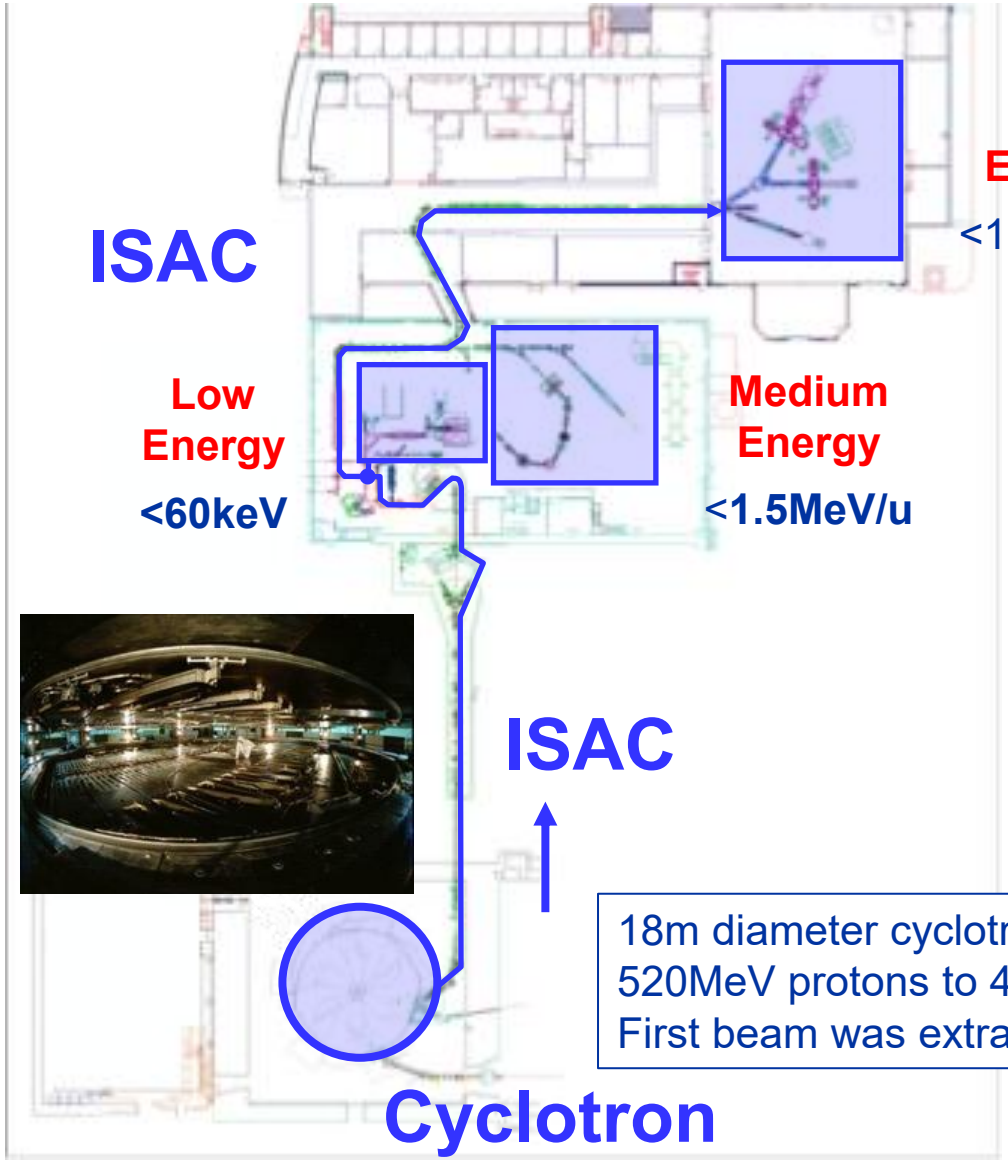
W. S. Porter et al., PRC 105, L041301 (2022)

TRIUMF: Canada's National Laboratory for Accelerator-based Science

Cyclotron with **18m** of diameter, **520 MeV** proton beam

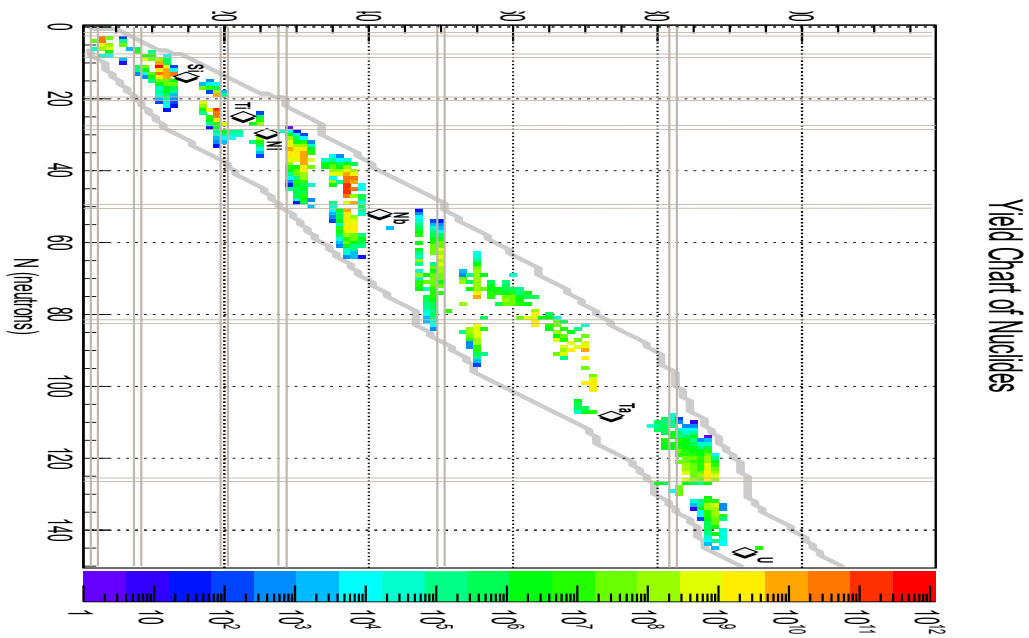


TRIUMF-ISAC:Isotope Separator and ACcelerator



520MeV p^+ at 100μA on ISOL target

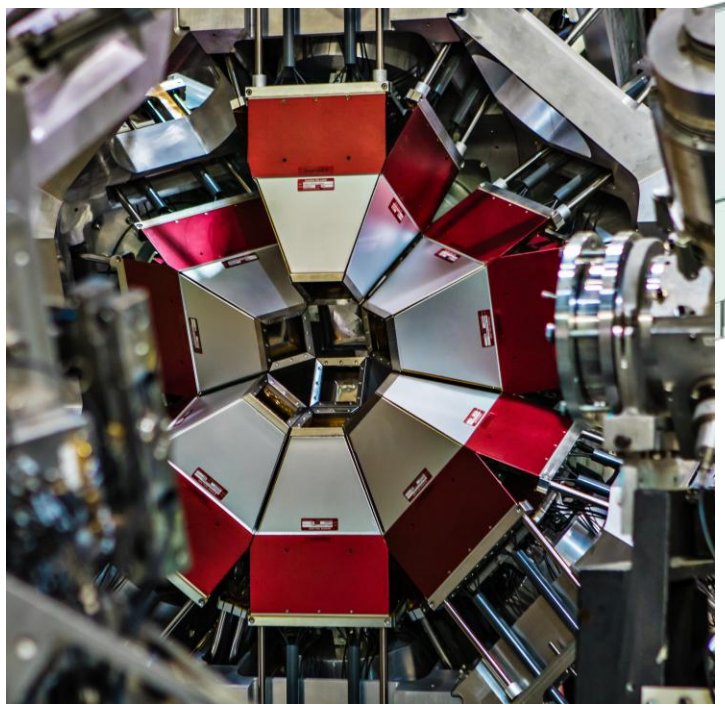
Targets: SiC, TiC, NiO, Nb, ZrC, Ta, TaC, ThO, UO, UCx
Ion sources: Surface, TRILIS, FEBIAD, IG-LIS

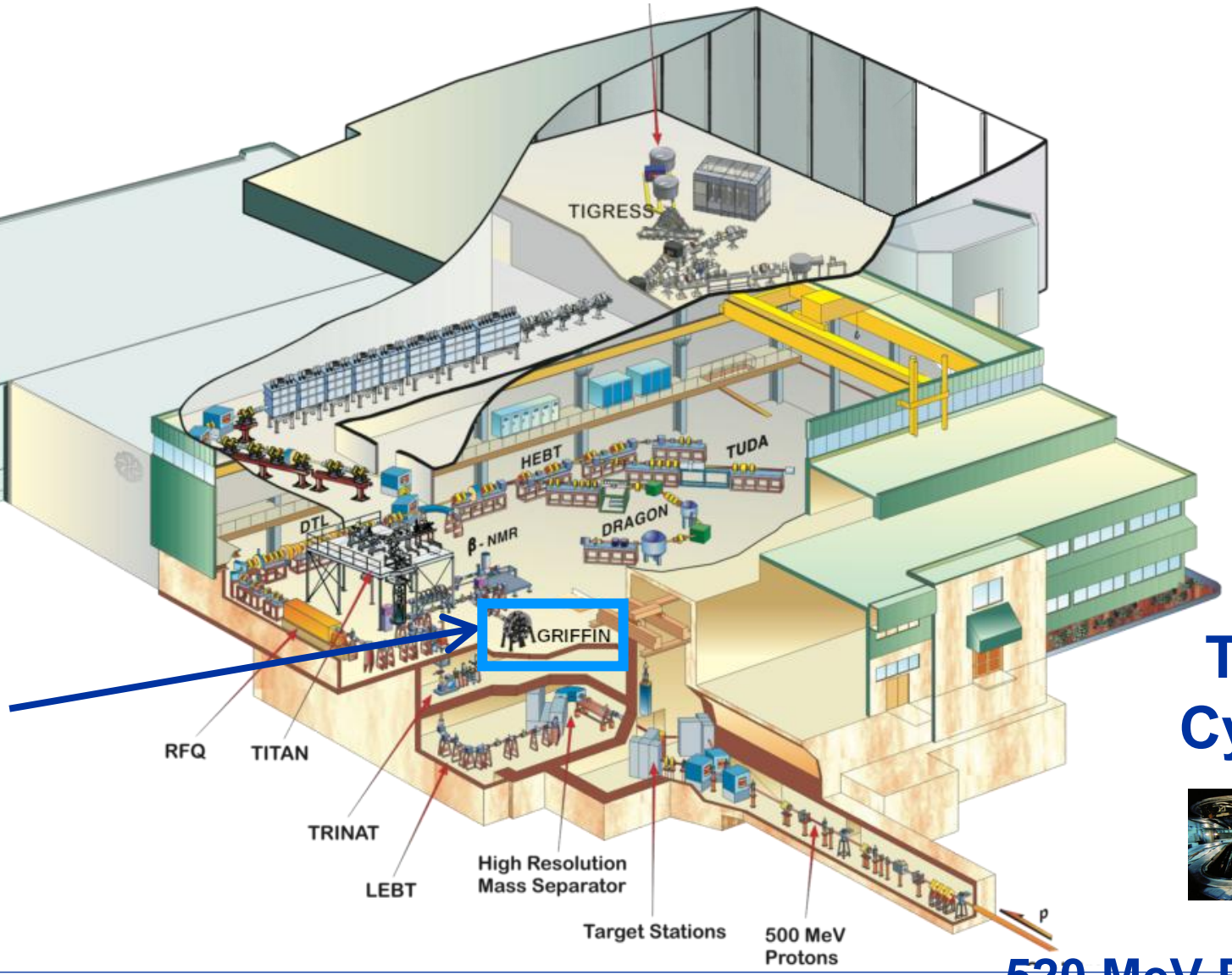


18m diameter cyclotron producing 520MeV protons to 4 beamlines.
First beam was extracted in 1974.

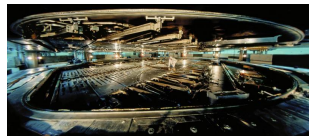
β Decay Studies and γ-Ray Spectroscopy at ISAC

GRIFFIN



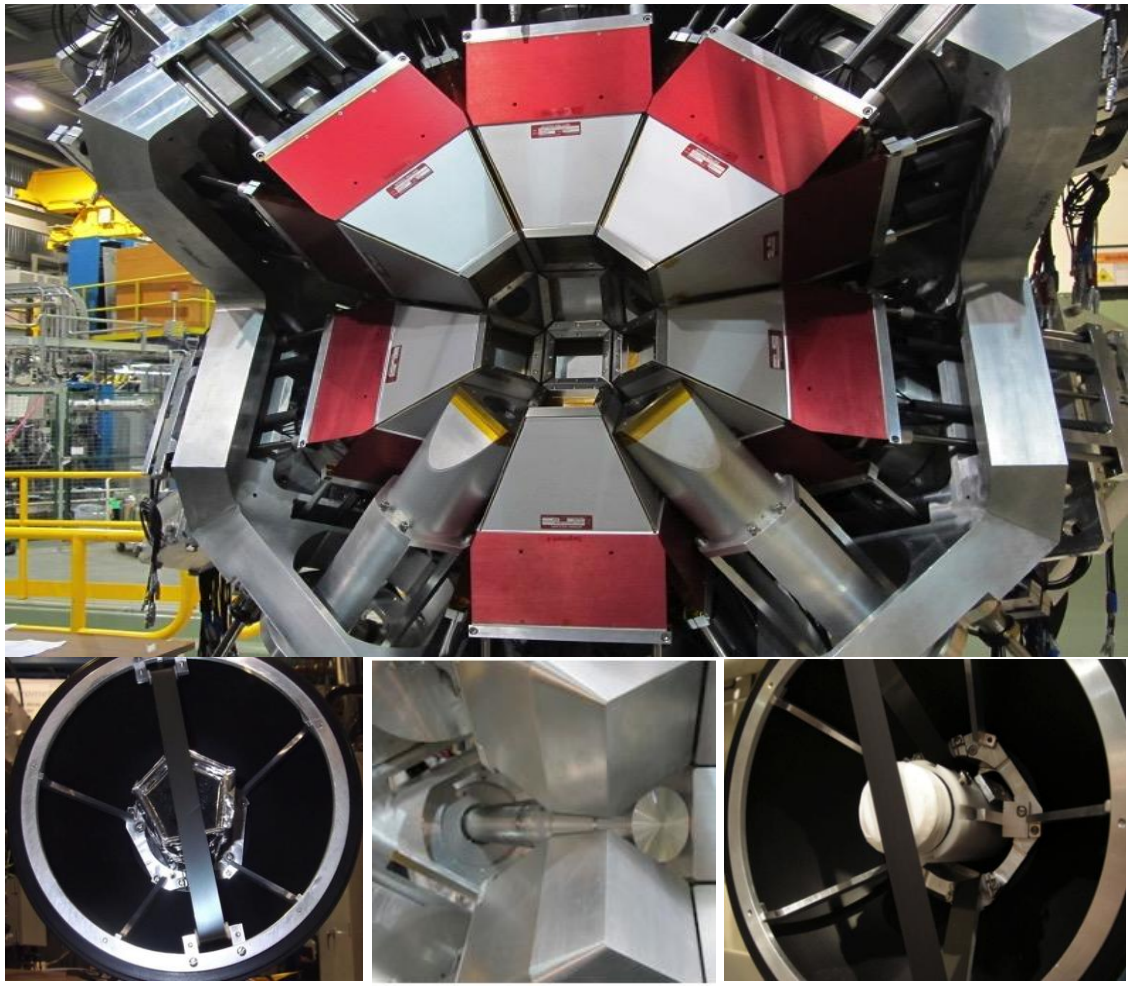


TRIUMF Cyclotron



520 MeV Protons

GRIFFIN Experimental Setup



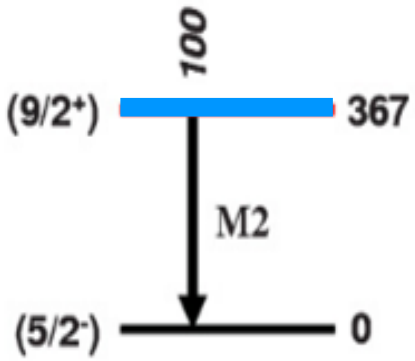
SCEPTAR LaBr$_3$(Ce) ZDS

- **16 BGO Suppressed HPGe clovers**
  - 15% efficiency at 1332 keV
  - **4032** crystals pairs at **51 unique angles** for γ-γ angular correlation studies
- **β tagging scintillators**
  - SCEPTAR and ZDS
- **8 BGO Suppressed LaBr$_3$(Ce)**
  - Lifetime measurements via Ultra Fast Timing techniques $\gamma\gamma$(t)

Previous Work

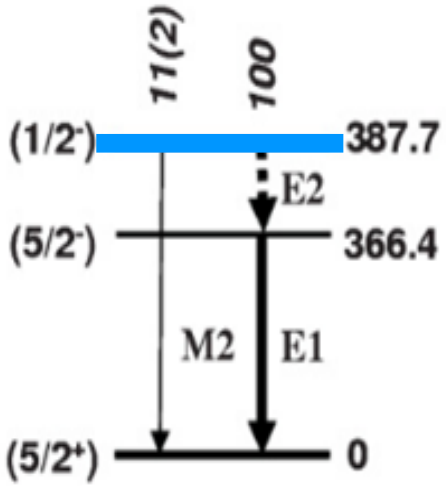
Fragmentation Isomeric Studies

367:$T_{1/2}$=43(30)μs



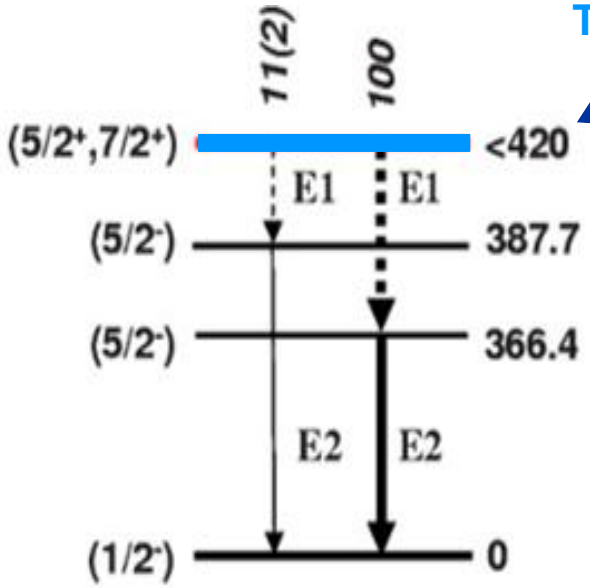
R.Grzywacz, et al.,
PRL 81,766 (1998)

388:$T_{1/2}$=75(21)μs



M. Sawicka, *et al.*,
EPJA 16 (2003)

β Decay Studies



$T_{1/2}$=64(14)μs

Isomer

J. M. Daugas, *et al.*,
PRC 83, 054312 (2011)

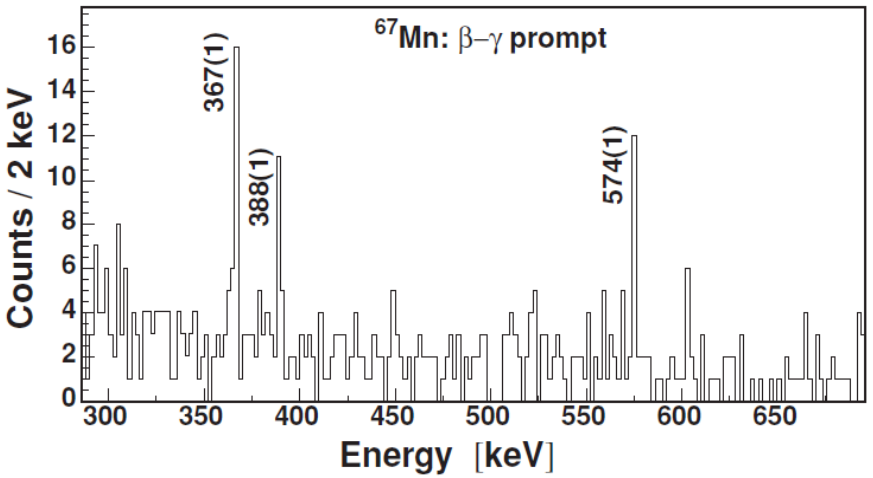
D. Kameda, *et al.*,
PRC 86, 054319 (2012)

- No delayed γ-rays
- Suggested Isomer Energy <420 keV
- Mean $T_{1/2}$=64(14)μs from previous studies

β Decay of ^{67}Mn

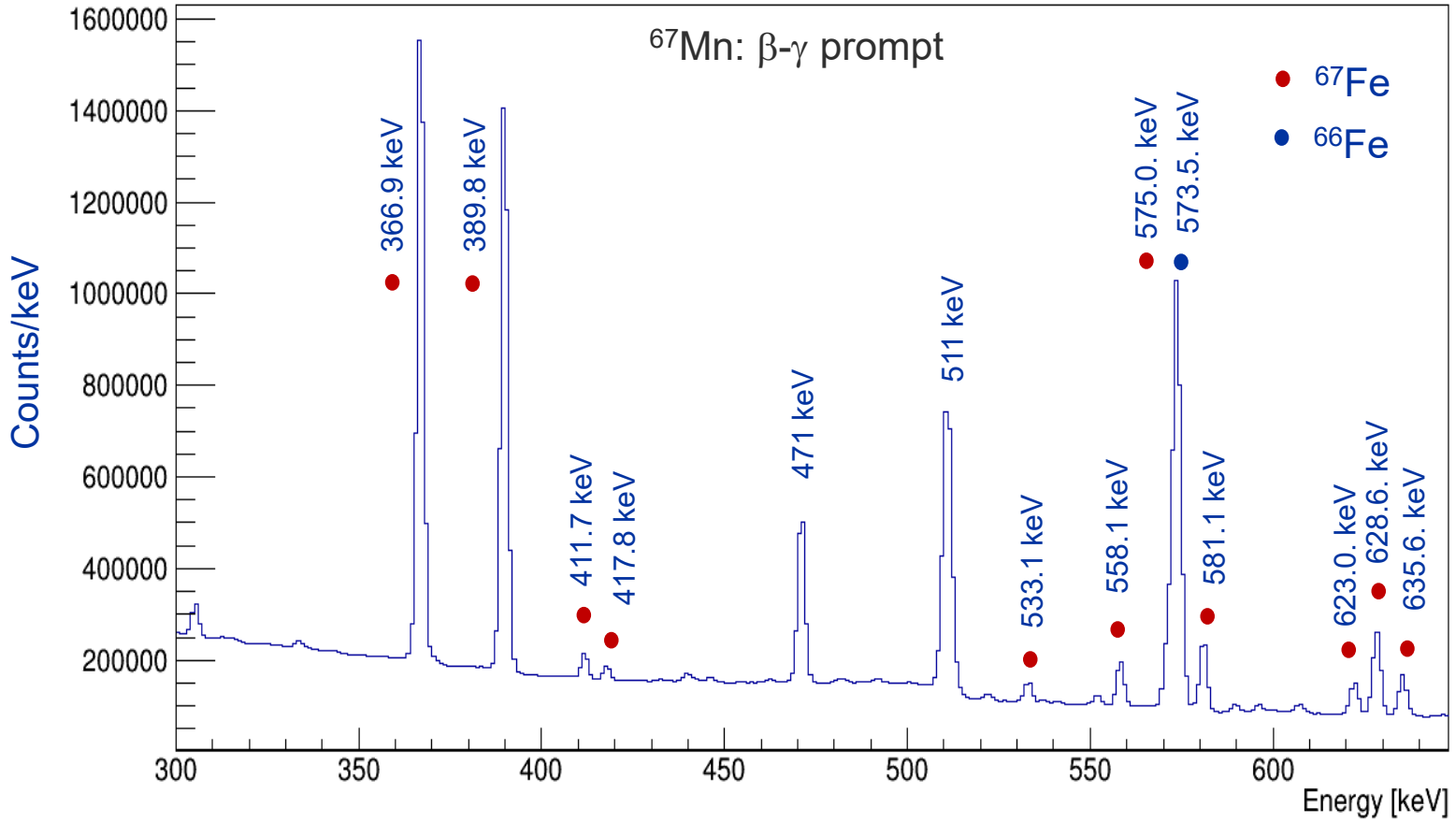
A factor x10^5 more statistics

Previous β decay study



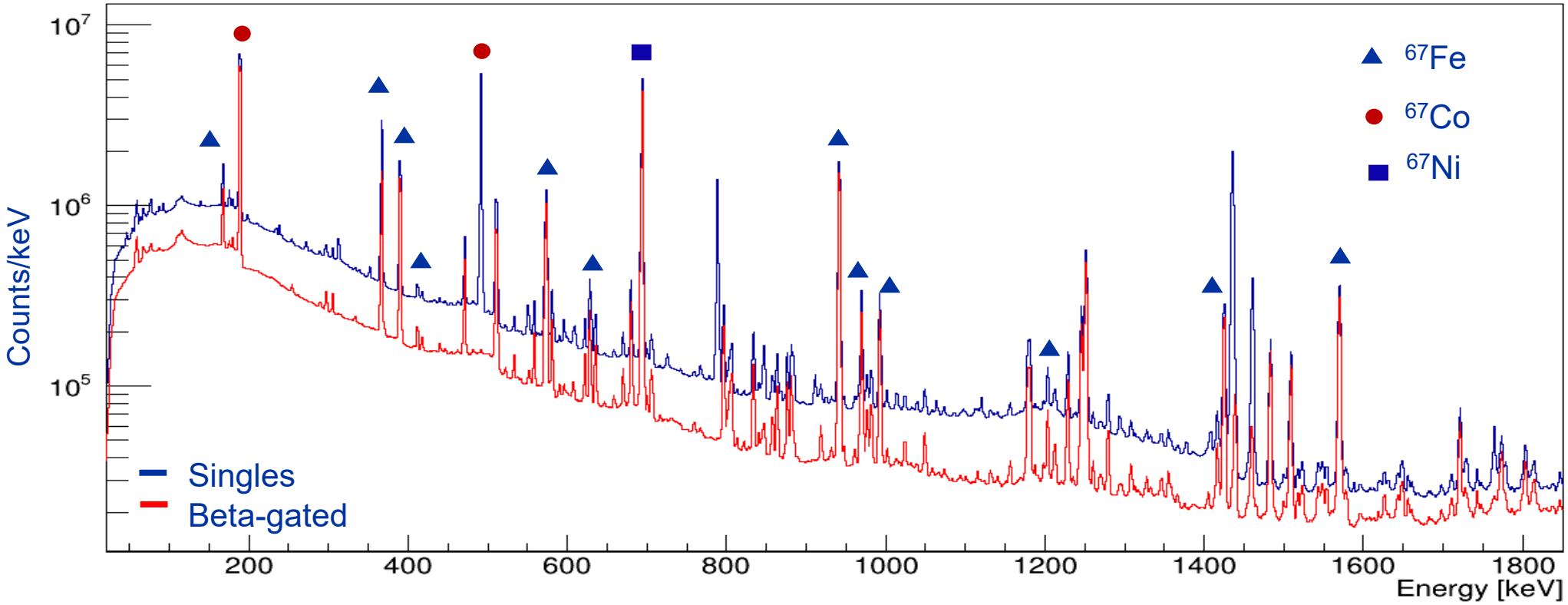
J. M. Daugas, *et al.*, PRC 83, 054312 (2011)

Present β decay study

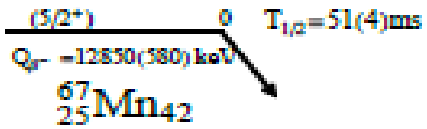


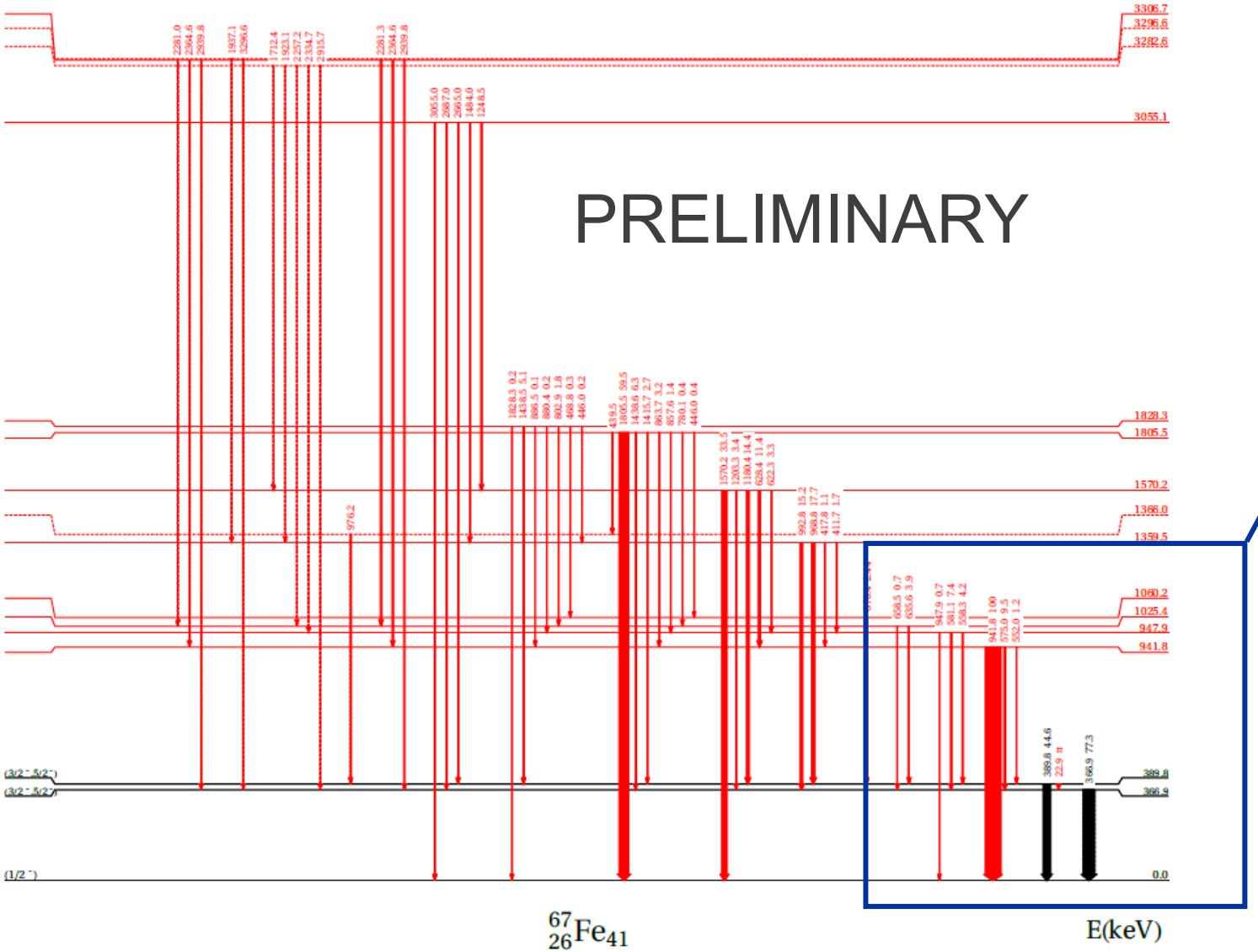
β Decay of ^{67}Mn: High-Statistics Dataset

- **^{67}Fe**: **>30 new** transitions and **>10 new** levels
- **^{66}Fe**: **>16 new** observed transitions and **12 levels -> β-n branch**
- **^{67}Co** and **^{67}Ni** : > **6 new** transitions each and **>3 new** levels
- Many more transitions to be placed

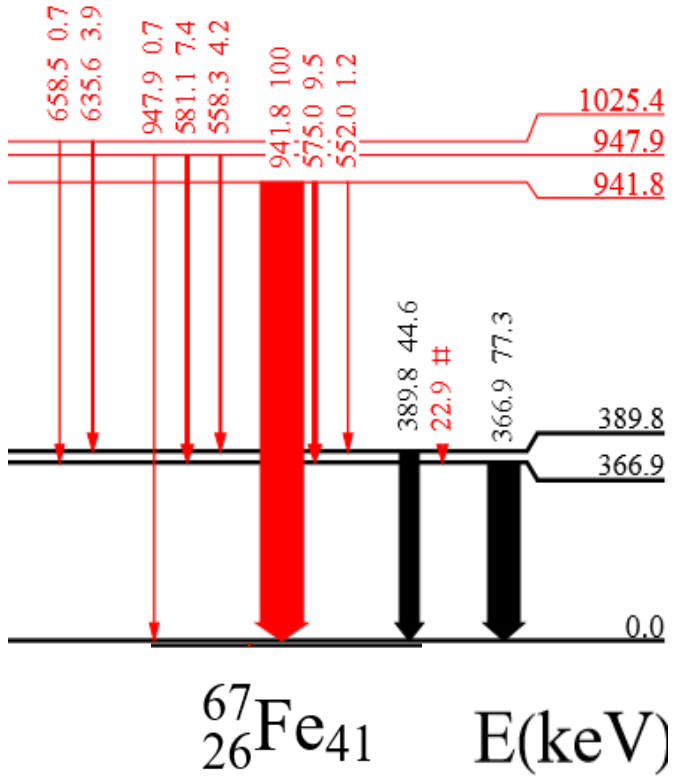


Level Scheme ^{67}Fe





Low-lying structure in ^{67}Fe

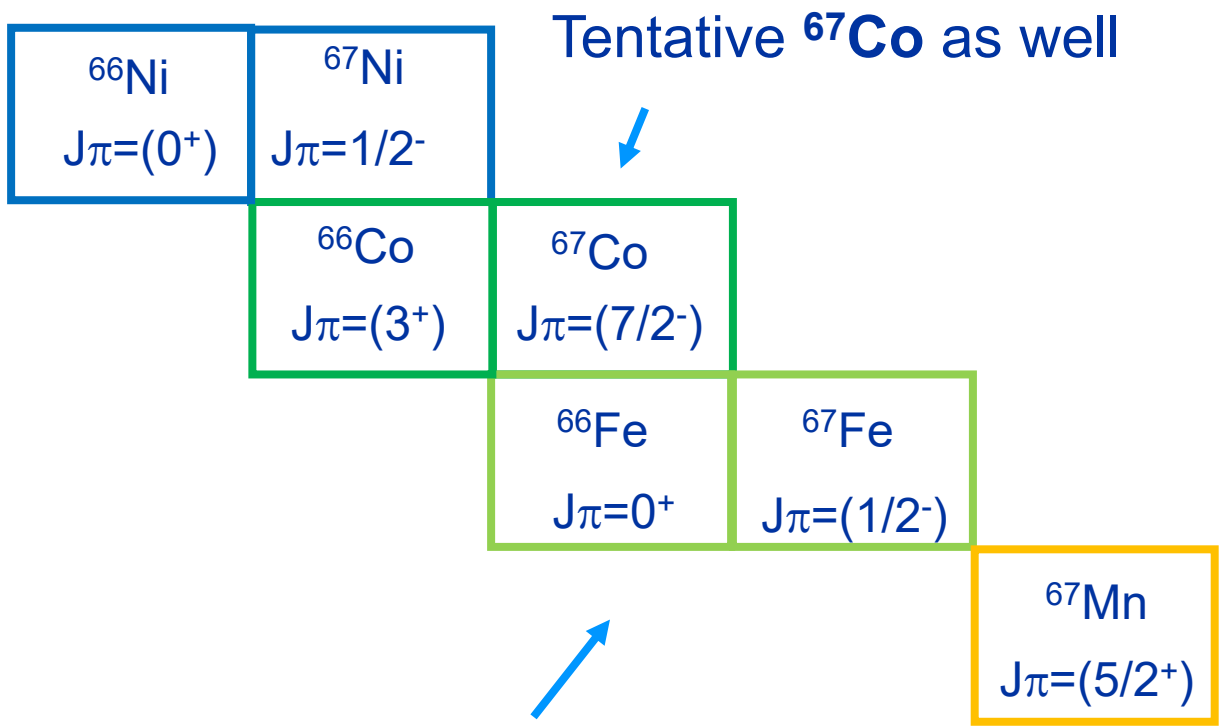


941.8 keV: Most intense γ-ray, connects 941.8-keV level and g.s

22.9-keV: γ-ray connecting 366-keV and 389-keV inferred.

Spin and Parity in A=67 and A=66 Chain

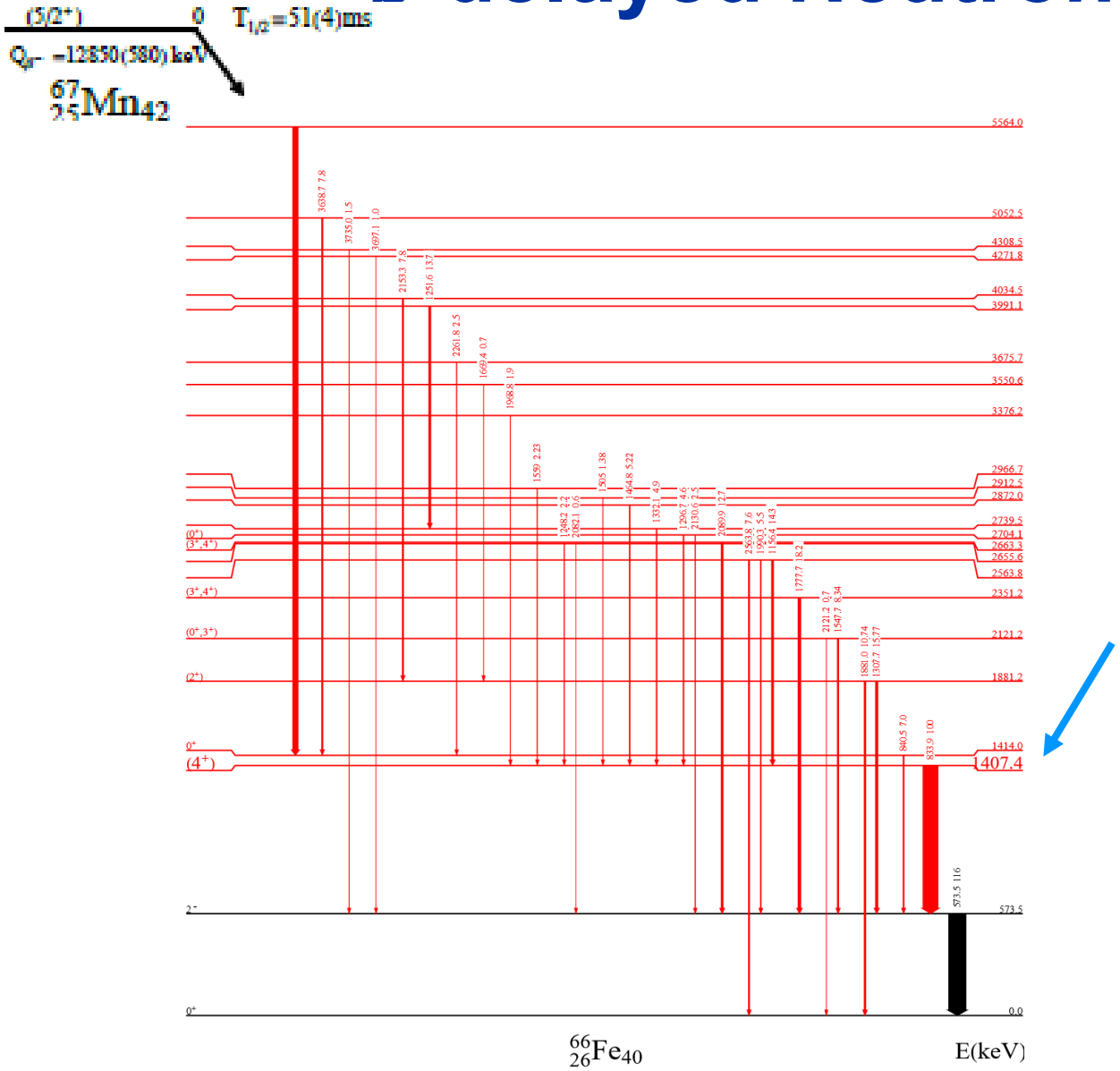
The Spin and Parity of both **^{67}Mn** and **^{67}Fe** are tentative



^{66}Fe structure vi the β–n of **^{67}Mn**

β-delayed Neutron Emission of ^{67}Mn

PRELIMINARY



Very rich structure: more than**16 new** observed transitions and >**12 levels** not observed in the isobaric β decay.

Large number of excited states with **spins 4⁺ suggesting** a **higher spin of the ^{67}Mn** than previously assigned (5/2⁺)

Intense feeding to the **first 4⁺** state **at 1407-keV**

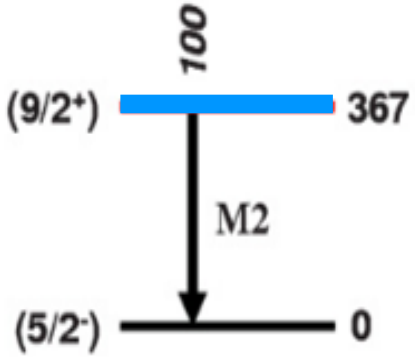
Future work

- Beta feeding and Log Ft values
- Pn value
- γ–γ angular correlations
  - Spin and parity assignments

Searching for the Isomer in ^{67}Fe

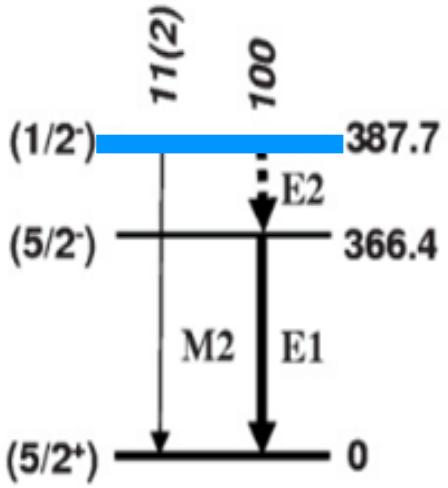
Previous Studies

367:$T_{1/2}$=43(30)μs



R.Grzywacz, et al.
in PRL.81,766 (1998)

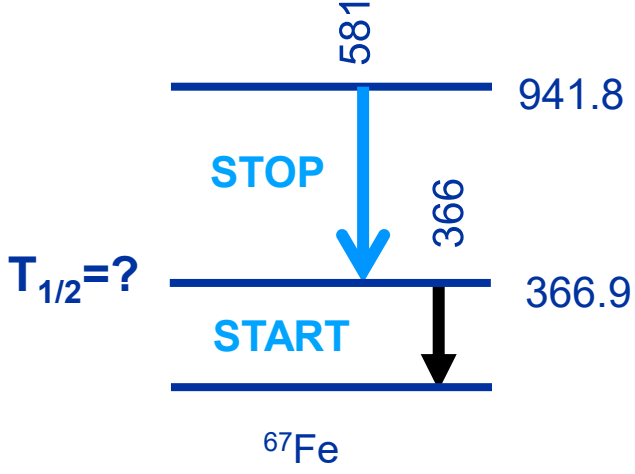
388:$T_{1/2}$=75(21)μs

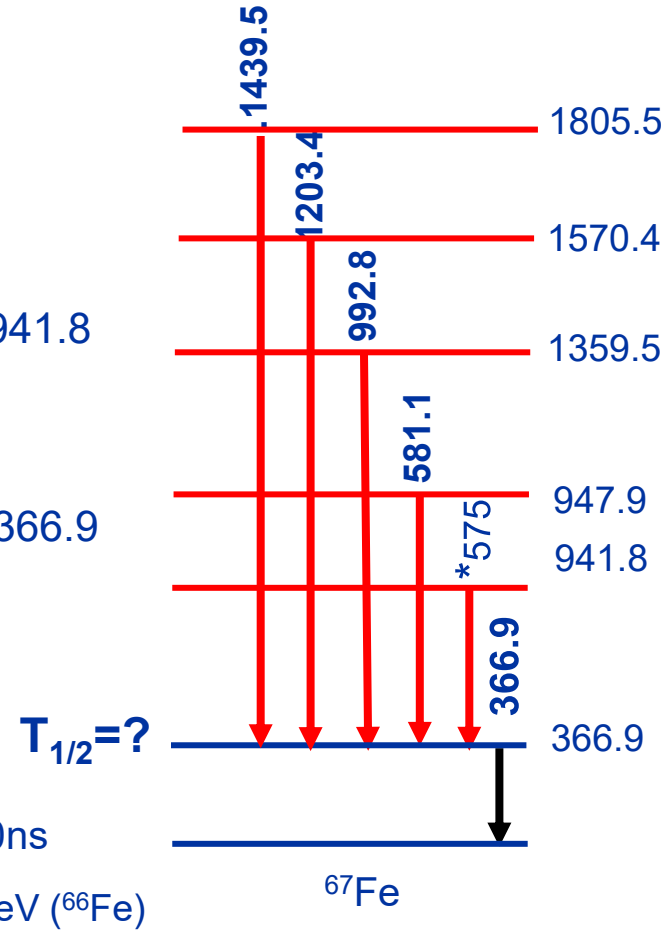


M. Sawicka, *et al.* in T*he European Physical Journal A* 16 (2003)

Time differences γ–γ (t) -> HPGe–HPGe

Exp Technique:
Example 366.9 keV



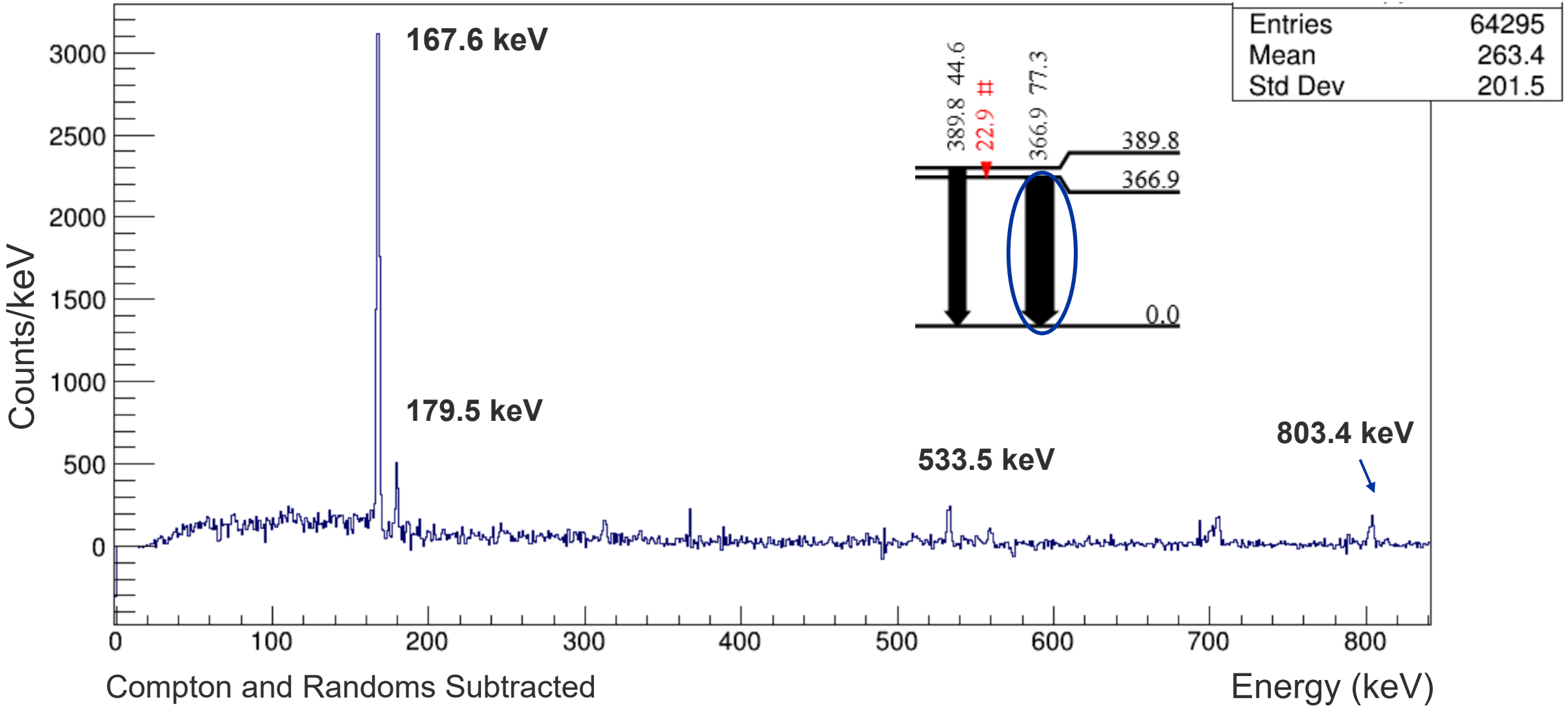


Time resolution of GRIFFIN 20ns

* Doublet of 575 (^{67}Fe) and 574 keV (^{66}Fe)

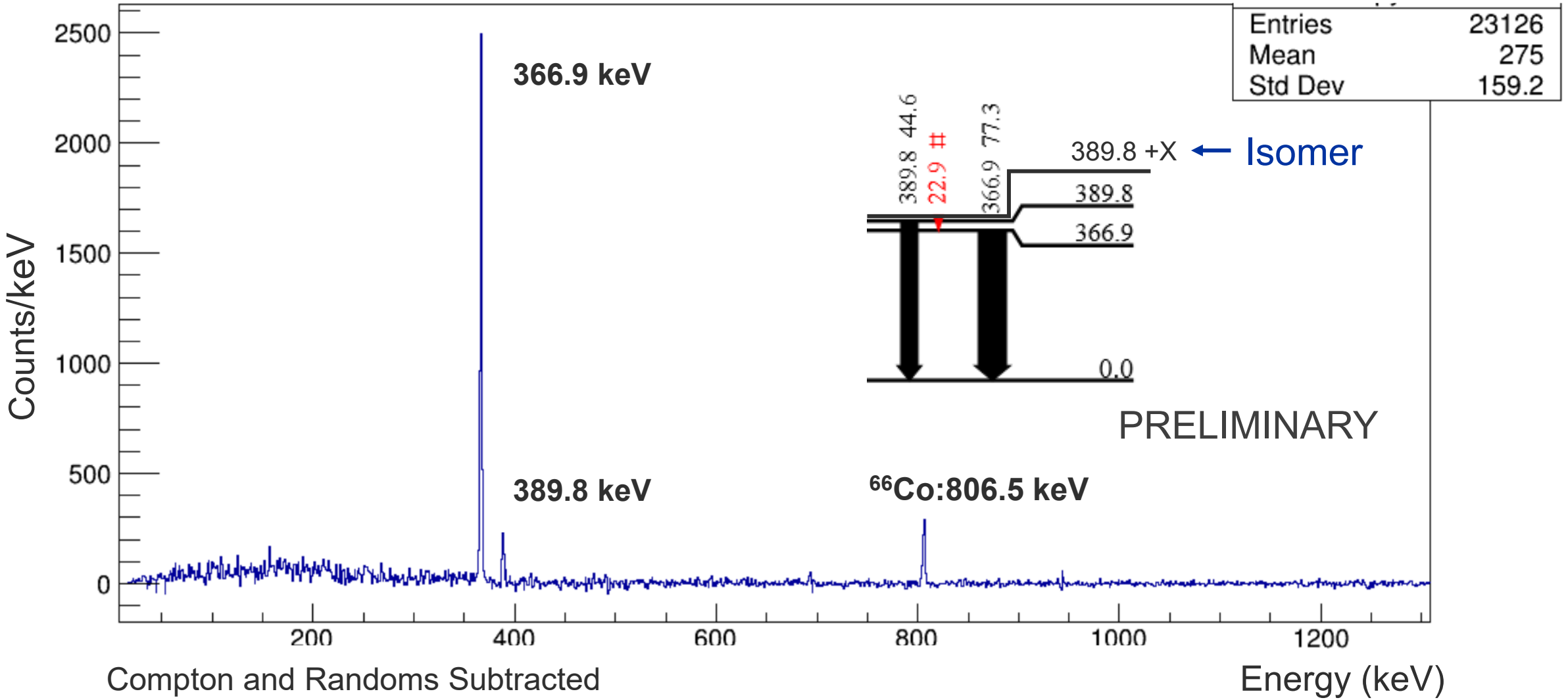
Searching for the Isomer in ^{67}Fe

Delayed γ–γ Coincidences gated on 366.9-keV γ-ray, window>5μs



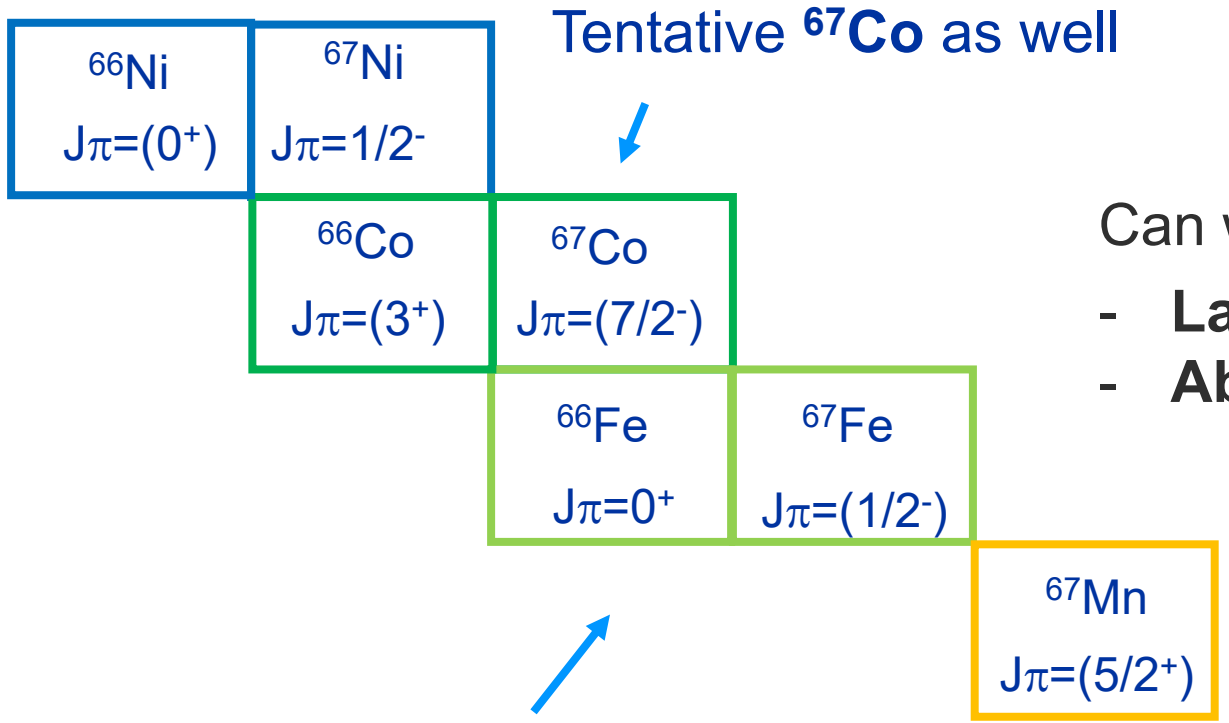
Searching for the Isomer in ^{67}Fe

Delayed γ–γ Coincidences gated on 167.6-keV γ-ray, window>5μs



Spin and Parity in A=67 and A=66 Chain

The Spin and Parity of both **^{67}Mn** and **^{67}Fe** are tentative



^{66}Fe structure vi the β–n of **^{67}Mn**

Can we learn more from state-of-the-art theory

- **Large-scale shell model (LSSM)**
- **Ab initio VS-IMSRG**

Theory: Large-Scale Shell Model

LNPS interaction: Successfully reproduces nuclear structure around N=40 I.o.I

- ^{48}Ca core, $\pi(pf)$, $\nu(f_{5/2}\ p_{3/2}\ p_{1/2}\ g_{9/2}\ d_{5/2})$

S.M. Lenzi, F. Nowacki, A. Poves
J. Benito, Private Communication

Negative Parity Band

Collective $1/2^-$ g.s. wavefunction; head of a deformed band

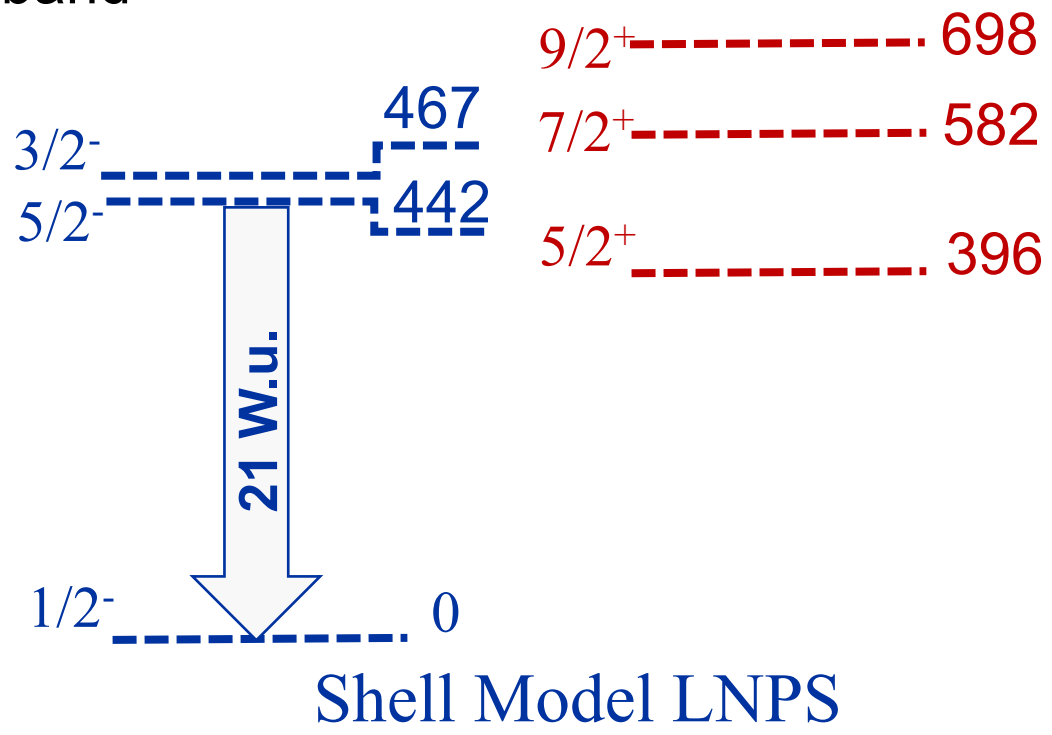
Highly collective E2 from first excited state to g.s.

Ground-state intruder configuration signature of I.o.I.

Positive Parity Band

Isomer interpreted as the $5/2^+$ bandhead

Deformation drives inversion of $9/2^+$ and $5/2^+$

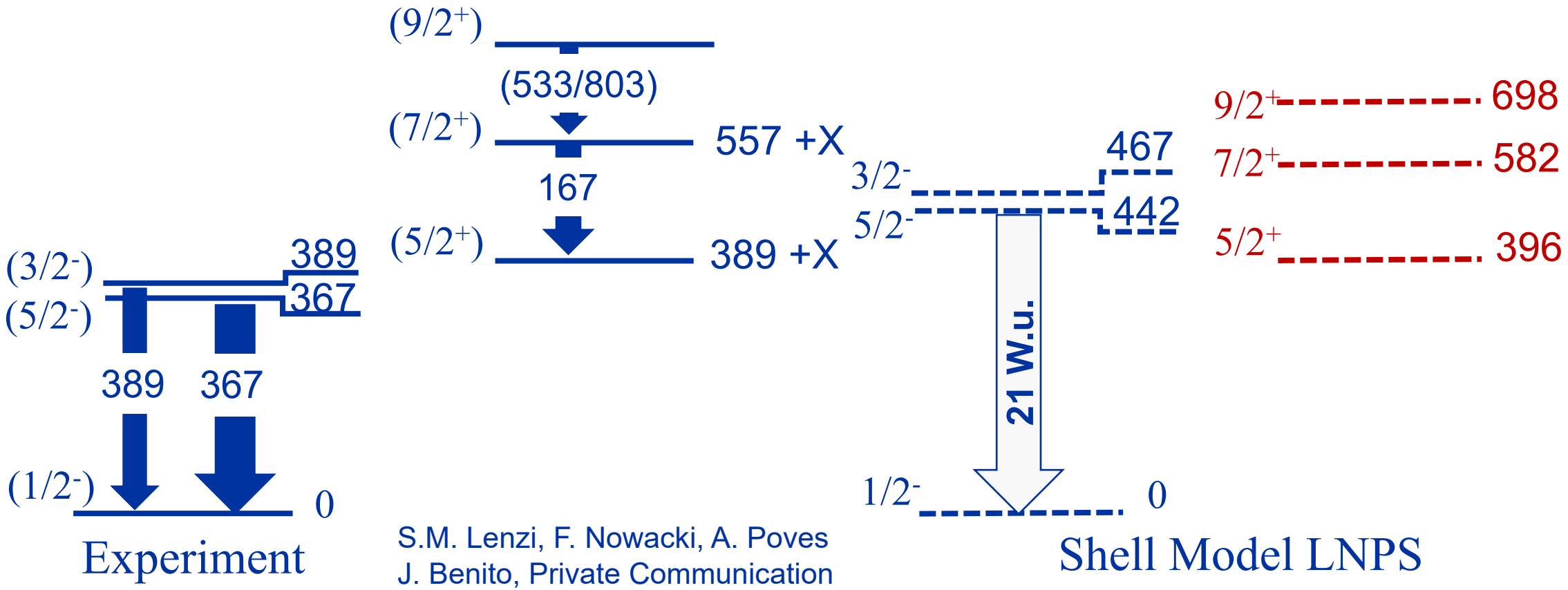


Theory: Large-Scale Shell Model

LNPS interaction: Successfully reproduces nuclear structure around N=40 I.o.I

Agrees well with experimental results (low-lying structure)

Firm spin/parity assignments + transition strengths to confirm theoretical picture



Theory: Ab Initio VS-IMSRG

Valence space in-medium similarity renormalization group (VS-IMSRG)

Global description of open shell nuclei from light to ^{208}Pb NN+3N forces

Recent campaign explored **N=40** I.o.I. from **Ca to Ni**

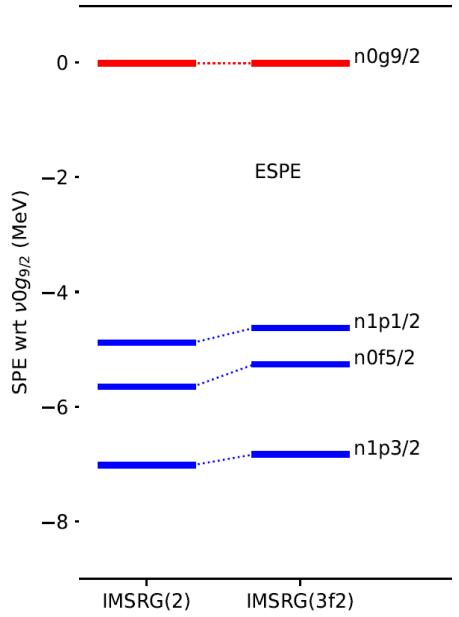
Predicts intruder configurations: **Summit at Cr**

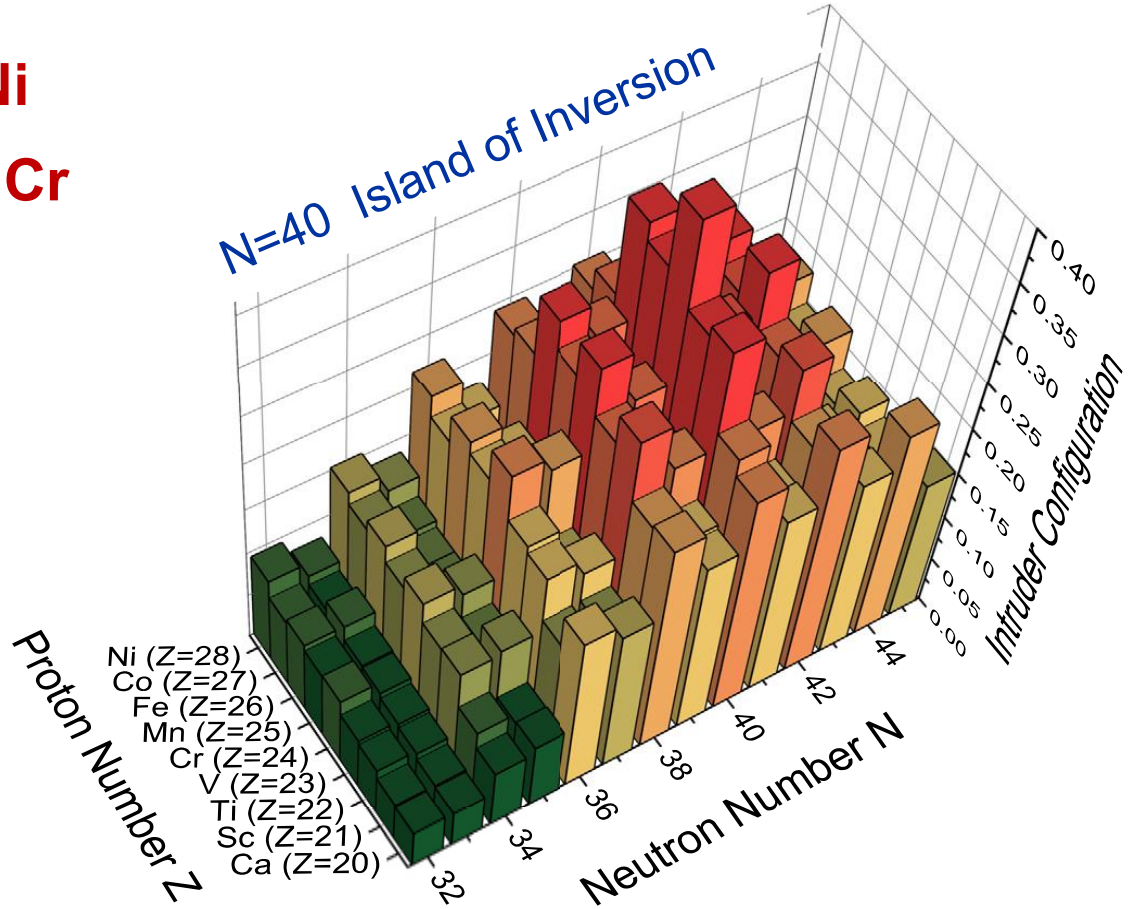
Less deformation from large N=40 shell gap

Compare with **^{67}Fe** exp results

Shell evolution/missing physics

- Valence-space orbits
- Many-body truncation
- Assess deformation





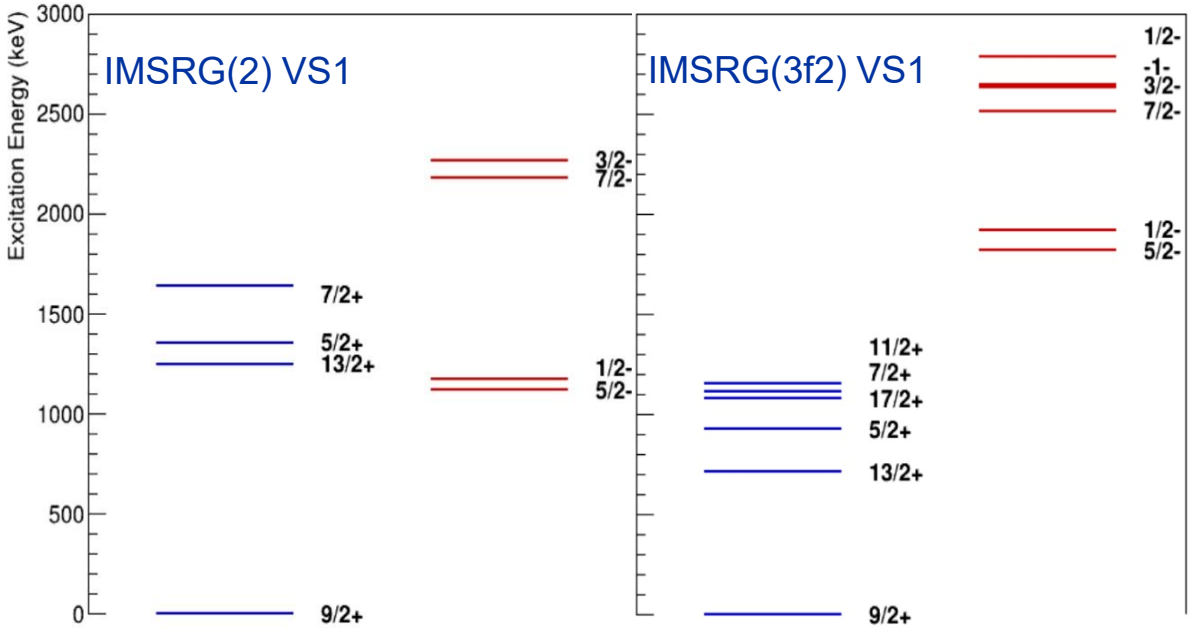
Silwal et al., PLB (2022)

Theory: Ab Initio VS-IMSRG ^{67}Fe Spectrum

Valence space in-medium similarity renormalization group (VS-IMSRG)

Spherical $9/2^+$ ground state predicted, large gap w/ negative parity band

Improved many body (2->3f2): Compresses +/- bands, **increases N=40 gap (?)**



B.C. He, T. Miyagi, J.D. Holt Private Communication

Theory: Ab Initio VS-IMSRG ^{67}Fe Spectrum

Valence space in-medium similarity renormalization group (VS-IMSRG)

Spherical $9/2^+$ ground state predicted, large gap w/ negative parity band

Improved many body (2->3f2): Compresses +/- bands, **increases N=40 gap (?)**

Increased valence space (+$d_{5/2}$ $s_{1/2}$): No significant change, **N=40 gap too large (?)**

Ab initio description of N=40

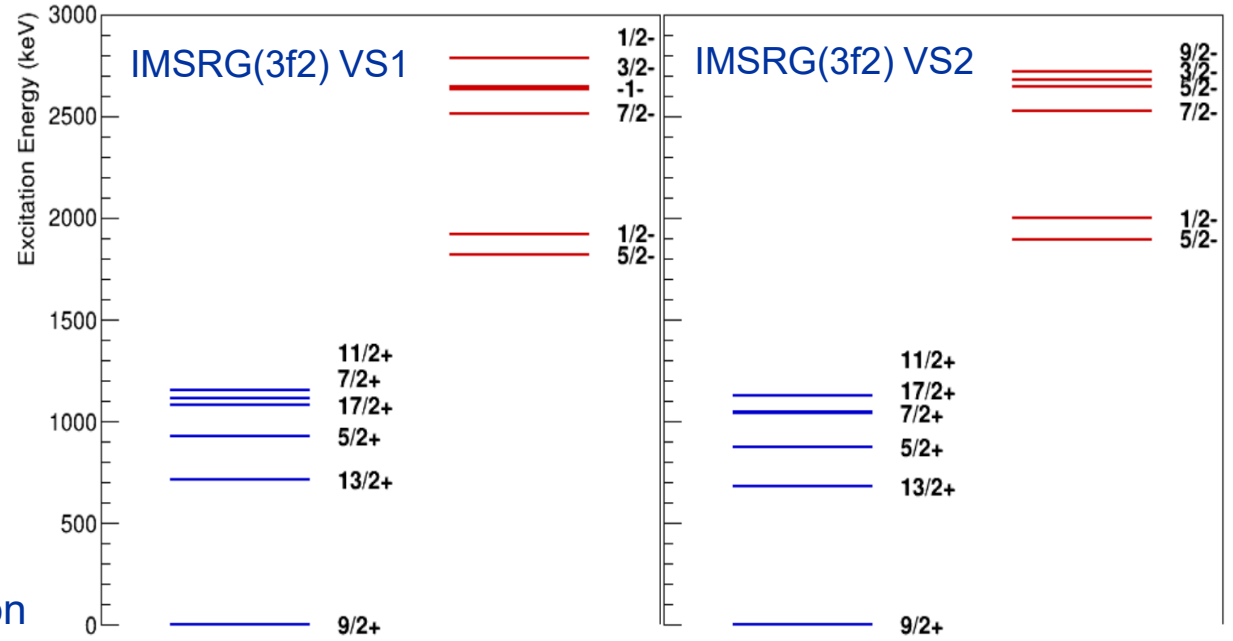
Perturbatively improve SPEs (T. Miyagi)

Full IMSRG(3)

Compare monopole MEs/SPE with LNPS

Firm spin/parities needed in ^{67}Fe and region!

B.C. He, T. Miyagi, J.D. Holt Private Communication



Summary

- **Level scheme of ^{67}Fe** expanded: >30 new transitions and >10 new levels
- First detailed spectroscopy for I.o.I. past N=40
- **Isomer** measured as a doublet at **389+X keV;** completes n-rich Fe systematics
- LSSM calc. (LNPS): Collective g.s **1/2$^-$**, isomer interpreted as **5/2$^+$** band head
  - ➢ Indicates I.o.I extends past **N=40**
- Ab initio VS-IMSRG: **9/2$^+$ g.s.,** small change enlarging VS + many-body trunc.
  - ➢ Indicates too large N=40 gap: further comparison with LSSN + exp. needed

Outlook and Next Steps

^{67}Fe analysis

- Firm spin/parity assignments
  - ➢ ^{67}Fe g.s via β-n population in ^{66}Fe and associated γ–γ angular correlations
  - ➢ ^{67}Fe excited states via γ–γ angular correlations
  - ➢ Confirm theoretical interpretations
- Lifetime measurements of 366-keV & 389-keV levels ->Transitions Strengths

Full decay chain analysis

- ^{67}Ni further info on N=40 shell gap
- β-n branch to ^{66}Fe, Pn value

Thank you!

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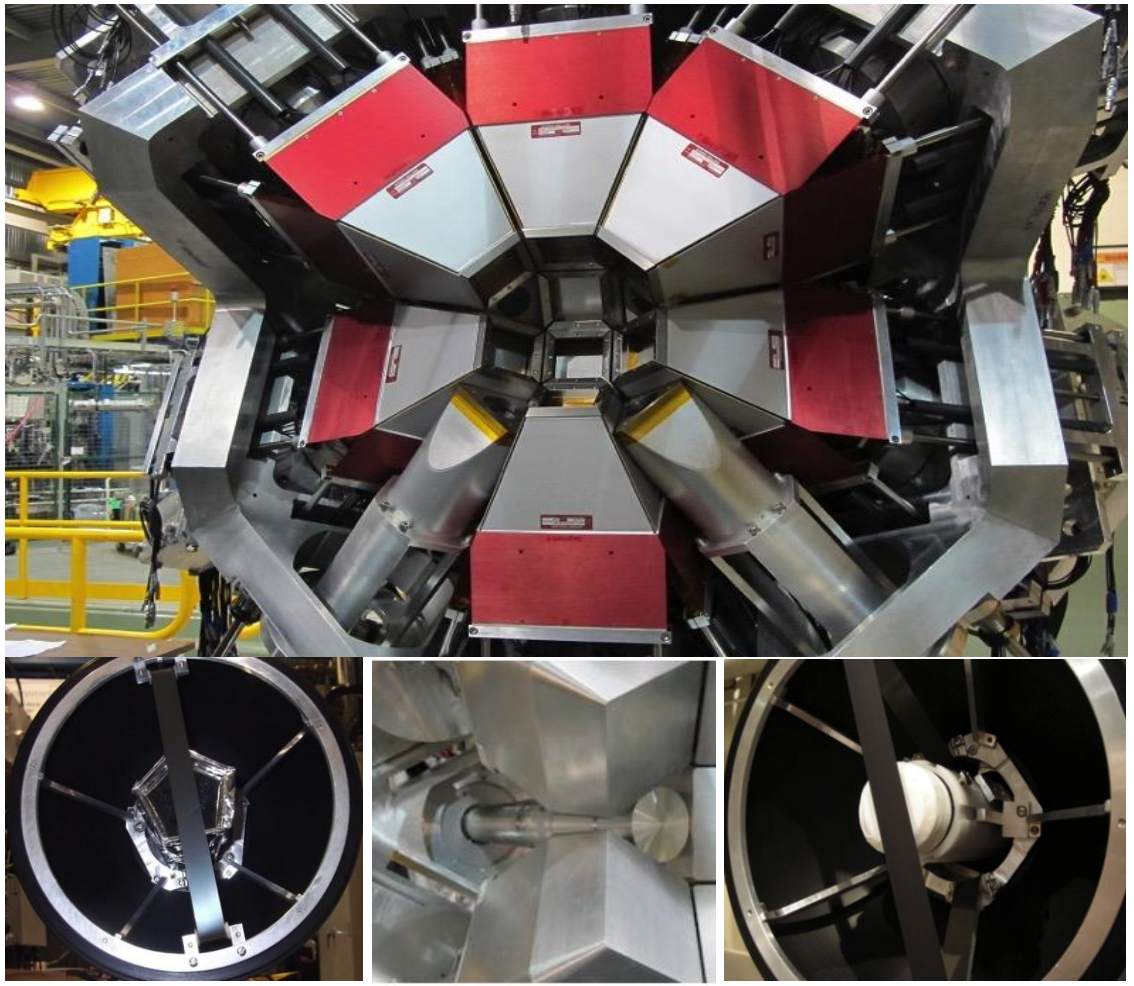
GRIFFIN Experimental Setup



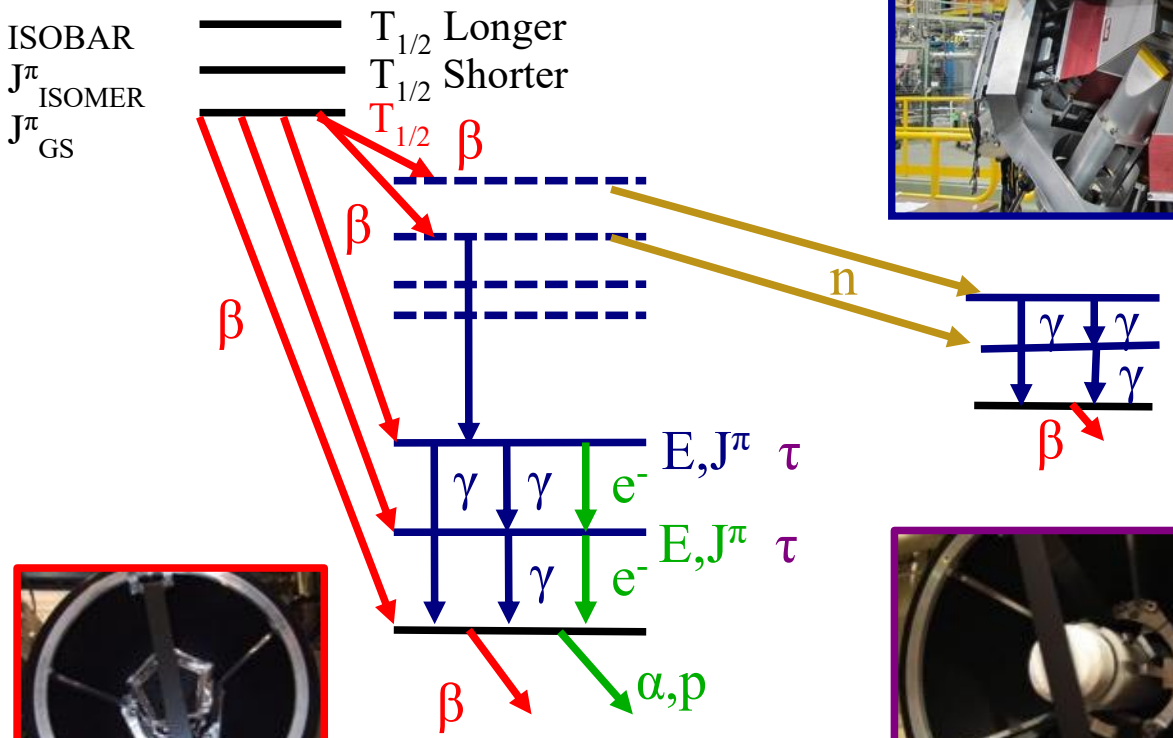
SCEPTAR LaBr$_3$(Ce) ZDS

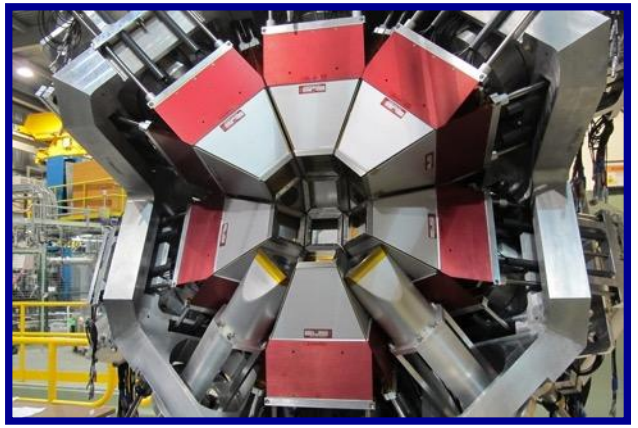
- **16 BGO Suppressed HPGe clovers**
  - 15% efficiency at 1332 keV
  - **4032** crystals pairs at **51 unique angles** for γ-γ angular correlation studies
- **β tagging scintillators**
  - SCEPTAR and ZDS
- **8 BGO Suppressed LaBr$_3$(Ce)**
  - Lifetime measurements via Ultra Fast Timing techniques $\gamma\gamma$(t)

Complete Set of Ancillary Detectors at GRIFFIN

Fast, in-vacuum tape system

Enhances decay of interest





HPGe: 16 Compton-suppressed Clovers

Detect gamma rays and determines branching ratios, multipolarities and mixing ratios

PACES: 5 Cooled Si(Li)s

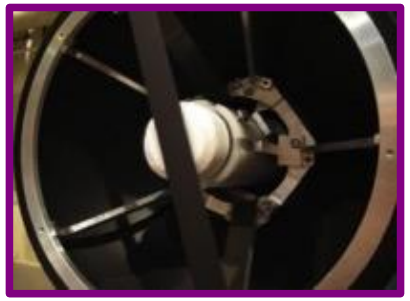
Detects Internal Conversion Electrons and alphas/protons

$LaBr_3$: 8 Compton-suppressed $LaBr_3$

Fast-timing of photons to measure level lifetimes

DESCANT Neutron array

Detects neutrons to measure beta-delayed neutron branching ratios



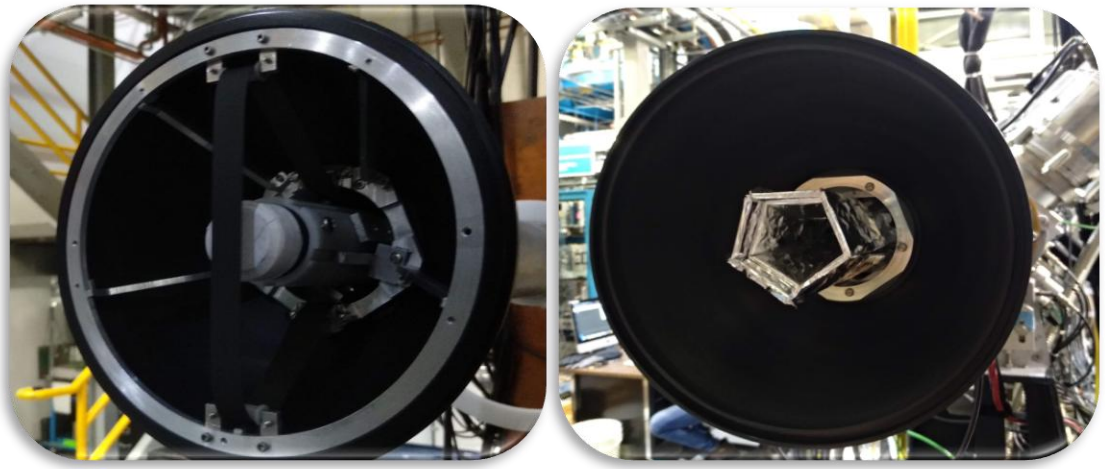
Zero-Degree Fast scintillator

Fast-timing signal for betas

The ARIES Detector

Motivation

- **Main ancillary** detector at GRIFFIN -> Design for GRIFFIN geometry
- **ARIES** : Good features of ZDS and SCEPTAR + New capabilities - Drawbacks
- **Leverage Technologies** (Flex circuit, Al coating by Magneton Sputtering, Mux Circuit)



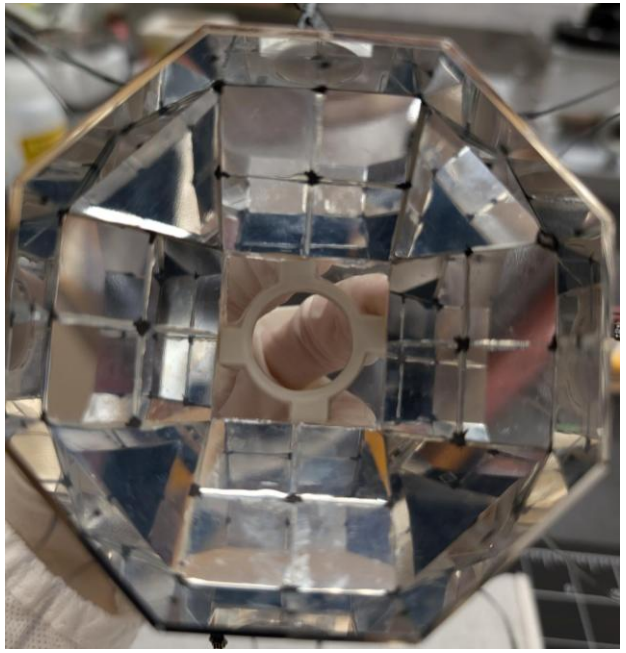
ZDS and SCEPTAR features

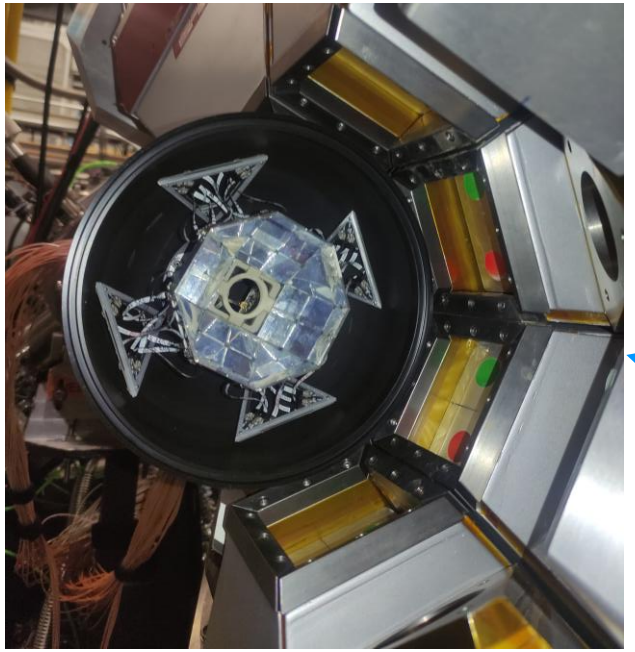
Combine β-**detection** efficiency **80%**
Fast-Tming capabilities ->ZDS

Improved ARIES features

β-**detection** efficiency : **91.5%**

ARIES Matches GRIFFIN Geometry 1:1





76 channels in two self-supporting halves of a rhombicuboctahedron

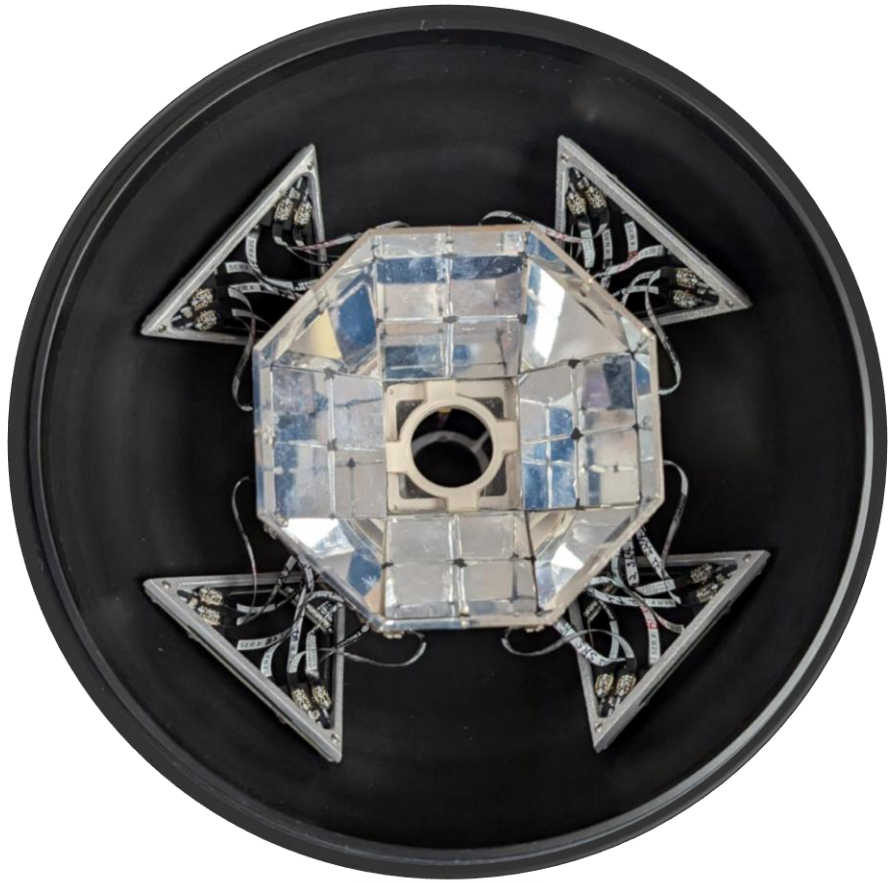
- 1 paddle for each **HPGe** crystal
- 8 triangles for each **$LaBr_3$**(Ce)
- 4 paddles downstream (**ZDS)**

36 (US)+**40** (DS)= **76**

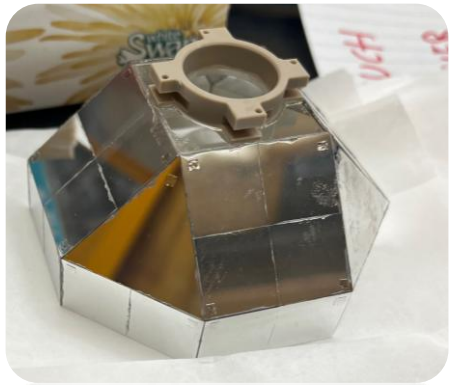
The ARIES Detector

New Capabilities

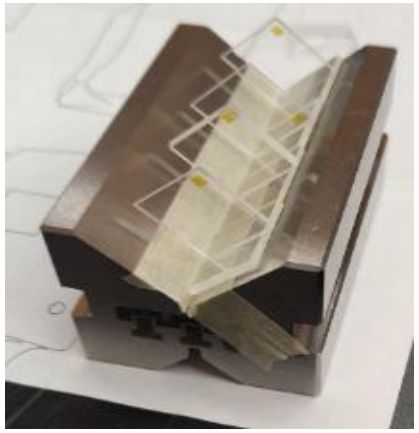
- β–γ angular correlations >114 unique angles
- High granularity and low γ-ray attenuation
- Superior count-rate capability ~20MBq
- Ultra Fast Timing $\beta\gamma\gamma(t)$ statistic x2
- Easy and economical to be replaced
- Background reduction (vetoing HPGe signals from punch-through e^-)

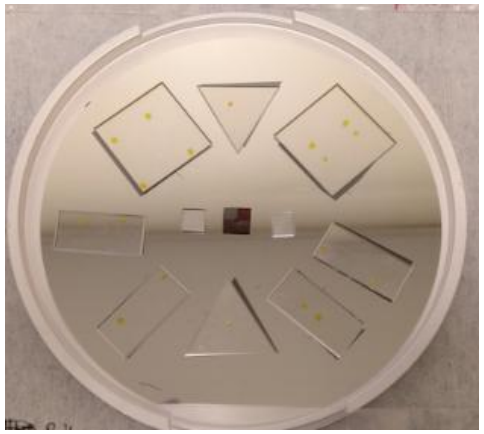


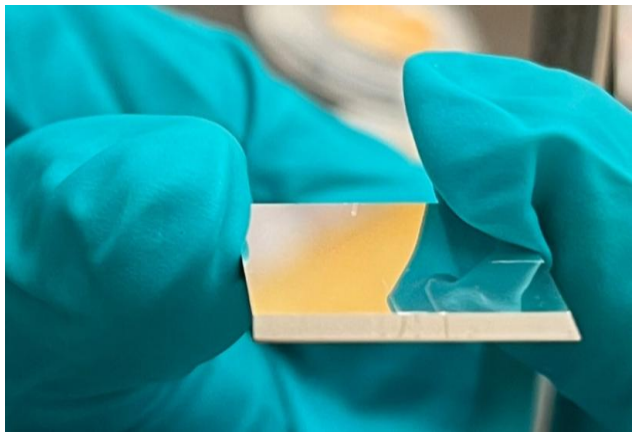
ARIES Scintillators

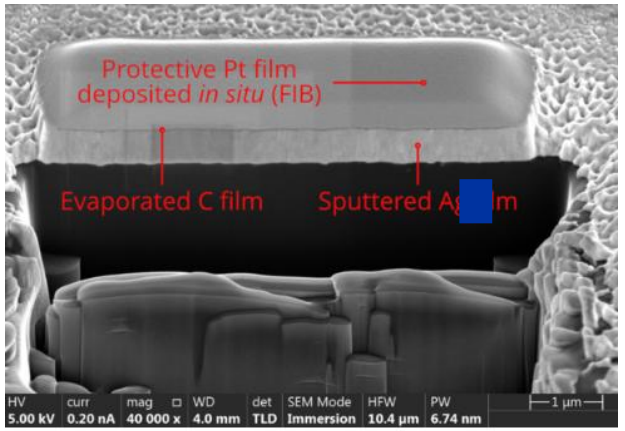


- **76 Paddles:**
  - Ultra Fast **BC-418** plastic scintillator of **1.5 mm** thickness
  - Rise time of **500 ps** and Decay time of **1.4 ns**
- **Ultra thin Reflective Coating: < 300 nm of Aluminum**
- **Self supported structure :** To minimize γ-ray attenuation, and maximize solid-angle coverage



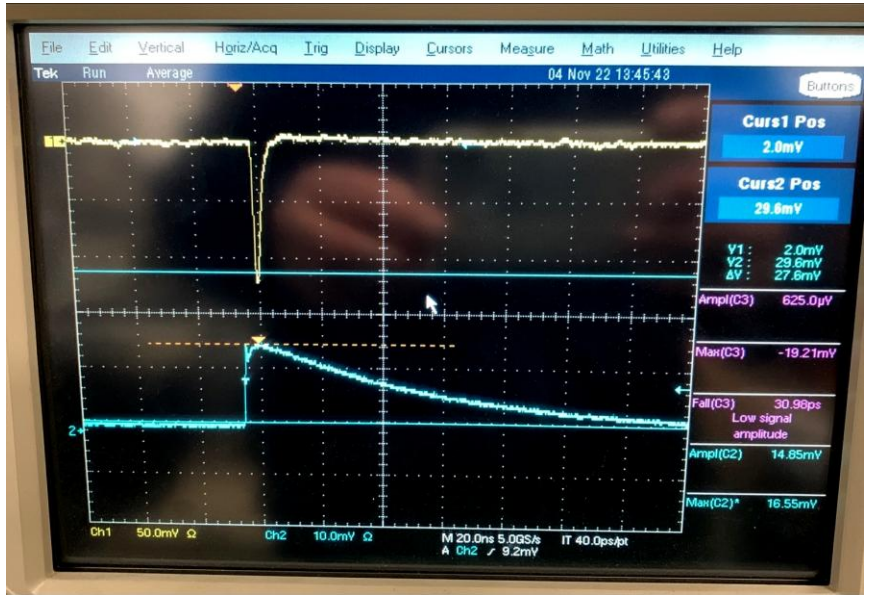


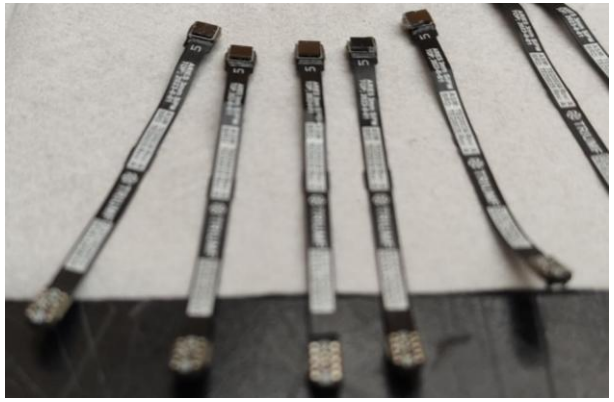


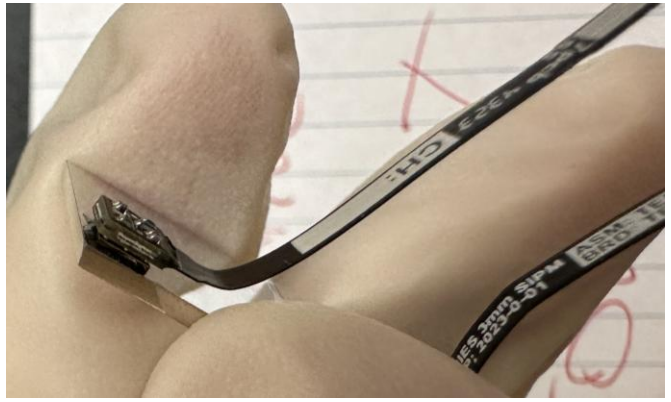


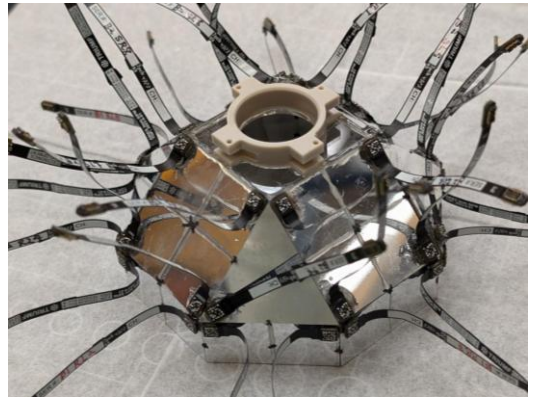
ARIES Electronics

- **Light readout: Ultra-Fast, High-gain SiPM (J-Series) of**
  - 3x3 mm^2, Fill Factor of 75% and 5,676 microcells
  - 110 ps of rise time
  - 2 outputs SO (Energy) and FO (Timing)
- **Detachable Tentacles:**
  - Flexible printed circuit boards of ~50µm thickness
  - Cemented to the plastic Scintillators (Optical Cement)
- **Minimal γ-ray attenuation:** All electronic boards and supporting structures occupy the shadow zones





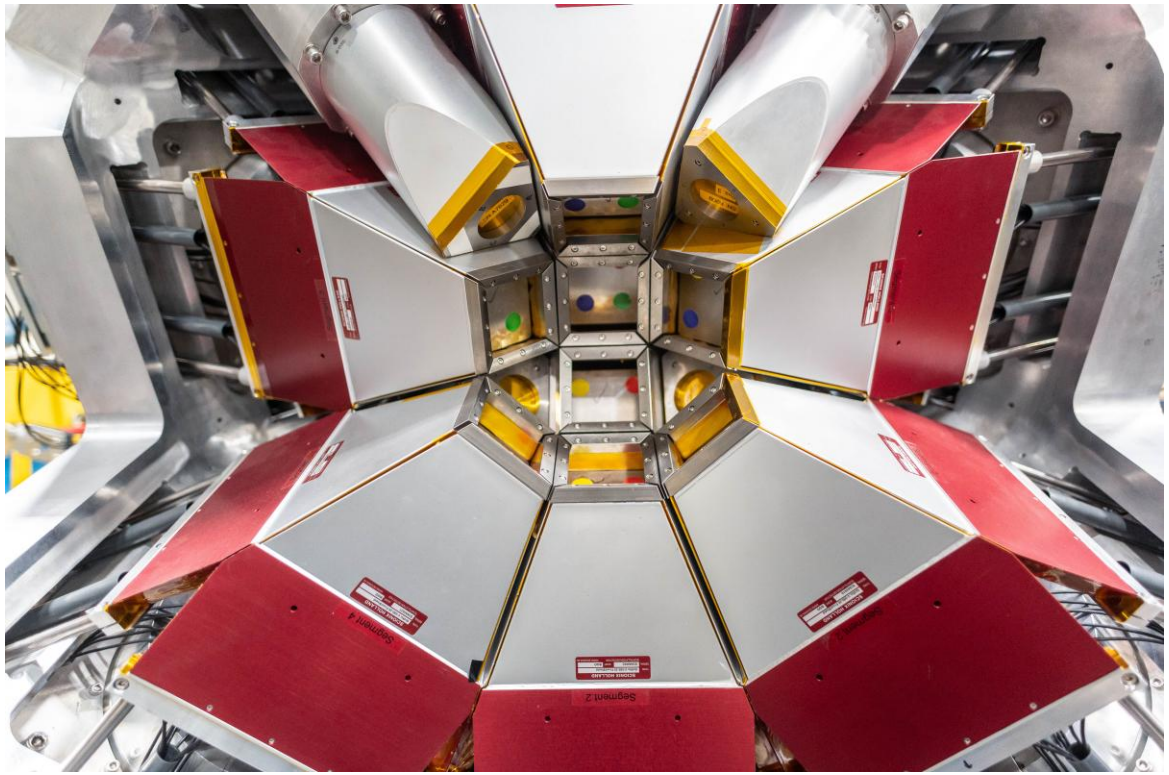




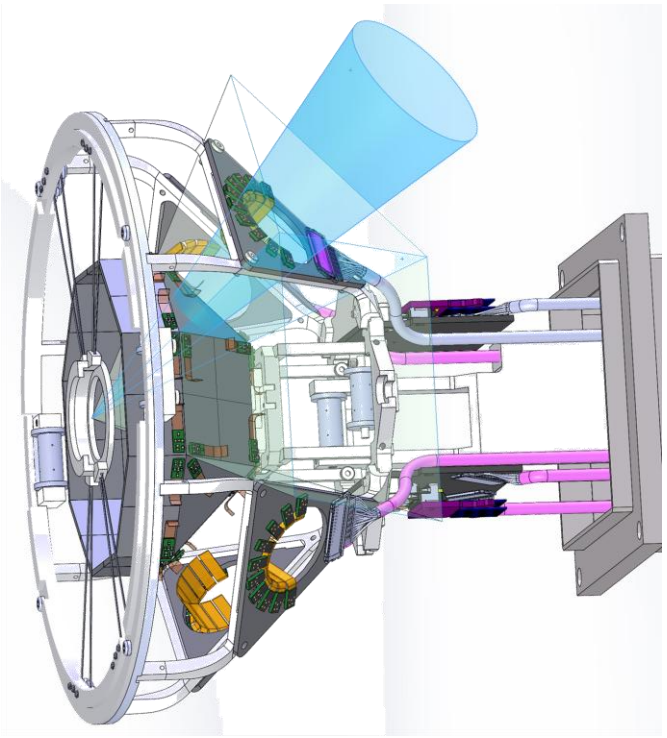
The ARIES Detector

- **Minimal γ-ray attenuation:**

All electronic boards and supporting structures occupy the shadow zones of the hevimet of the the BGO suppression shields. No components are blocking the either the HPGe nor the $LaBr_3$(Ce).

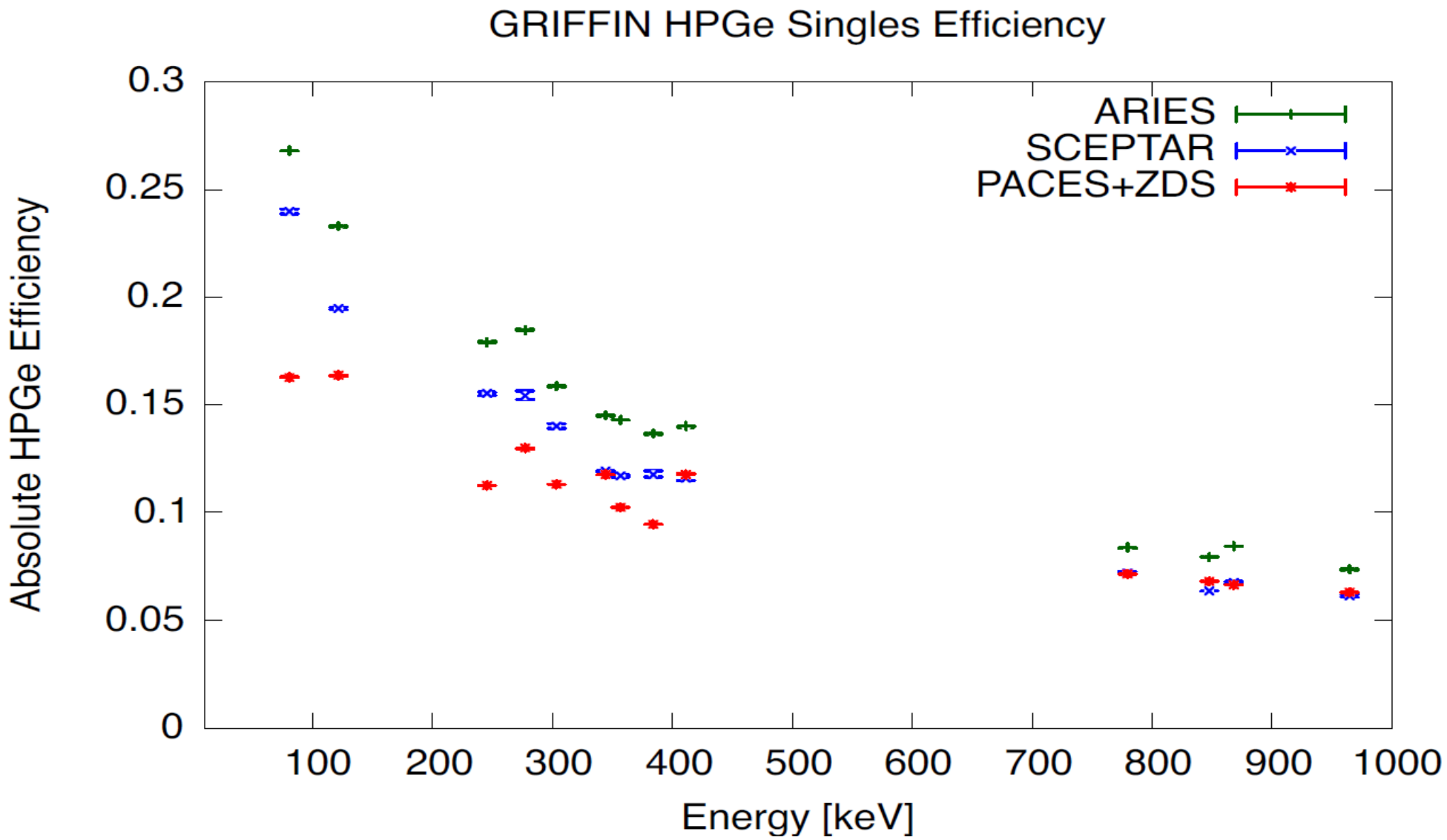


Shadow zone of hevimet: γ-rays are not measured

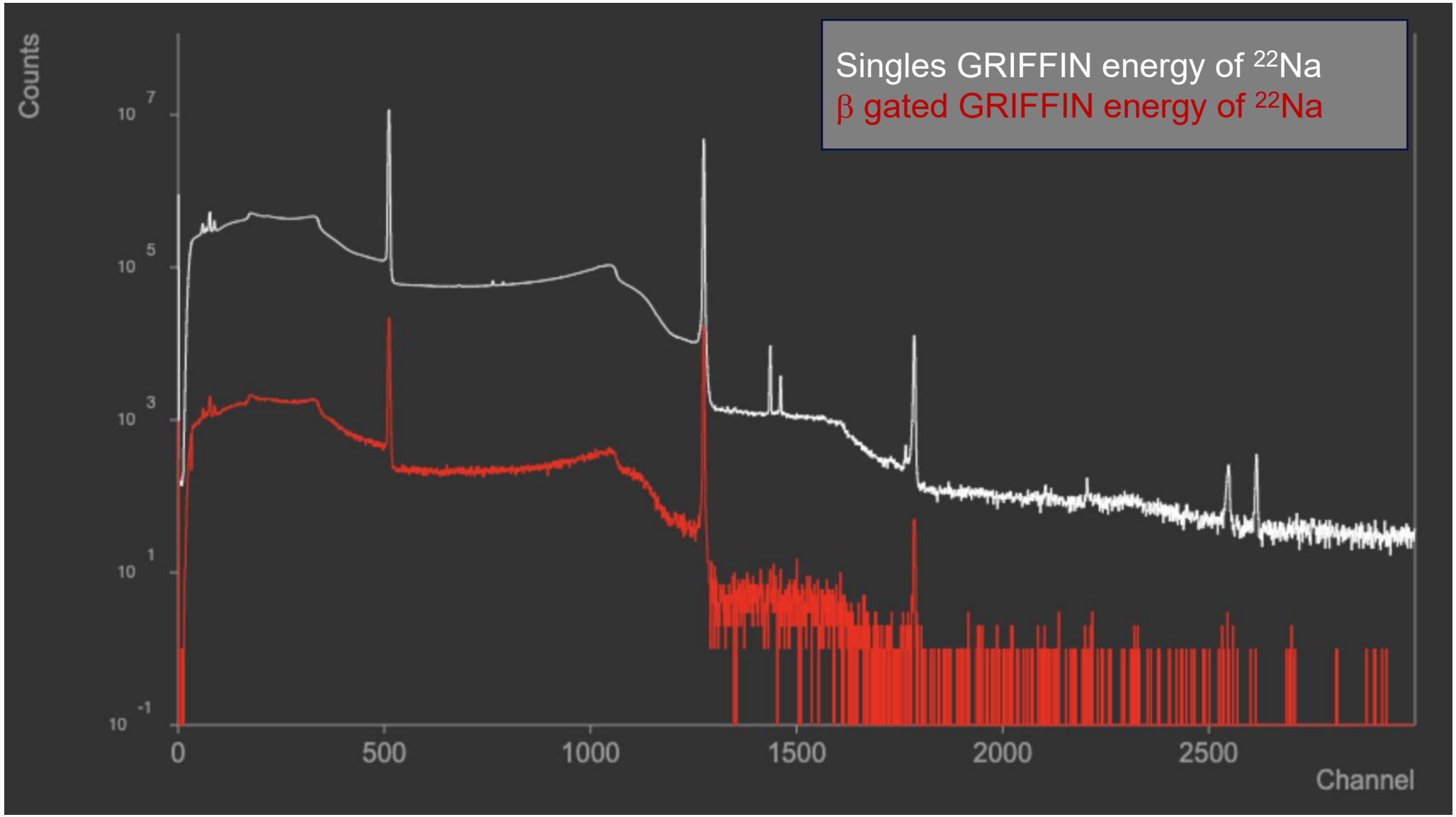


Blue cone indicates the solid angle coverage of $LaBr_3$(Ce)

The ARIES Detector



ARIES β tagging, Reduction of Background



The ARIES Detector

Summary

- **β-tagging array** and **main ancillary detector of GRIFFIN** facility
- High-efficiency and Ultra-fast β-particles detector
- β–γ angular correlations >**114 unique angles**
- Ultra-Fast β coincidence timing signal from >91% solid angle coverage.
- Lifetime Measurements down to the few ps range

Thank you!

Special Thanks to: Adam Garnsworthy, Rashmi Umashankar, Miles Constable, Shaun Georges and the ARIES team

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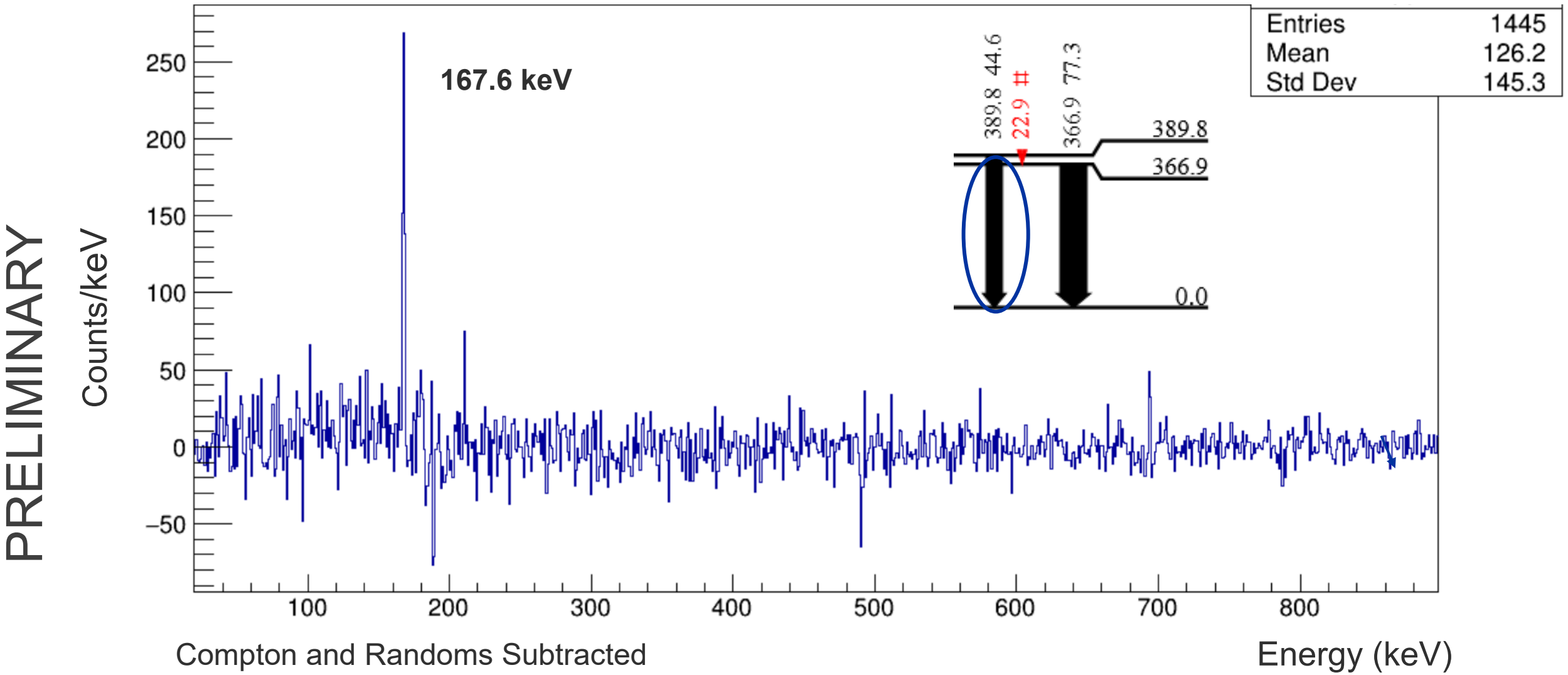
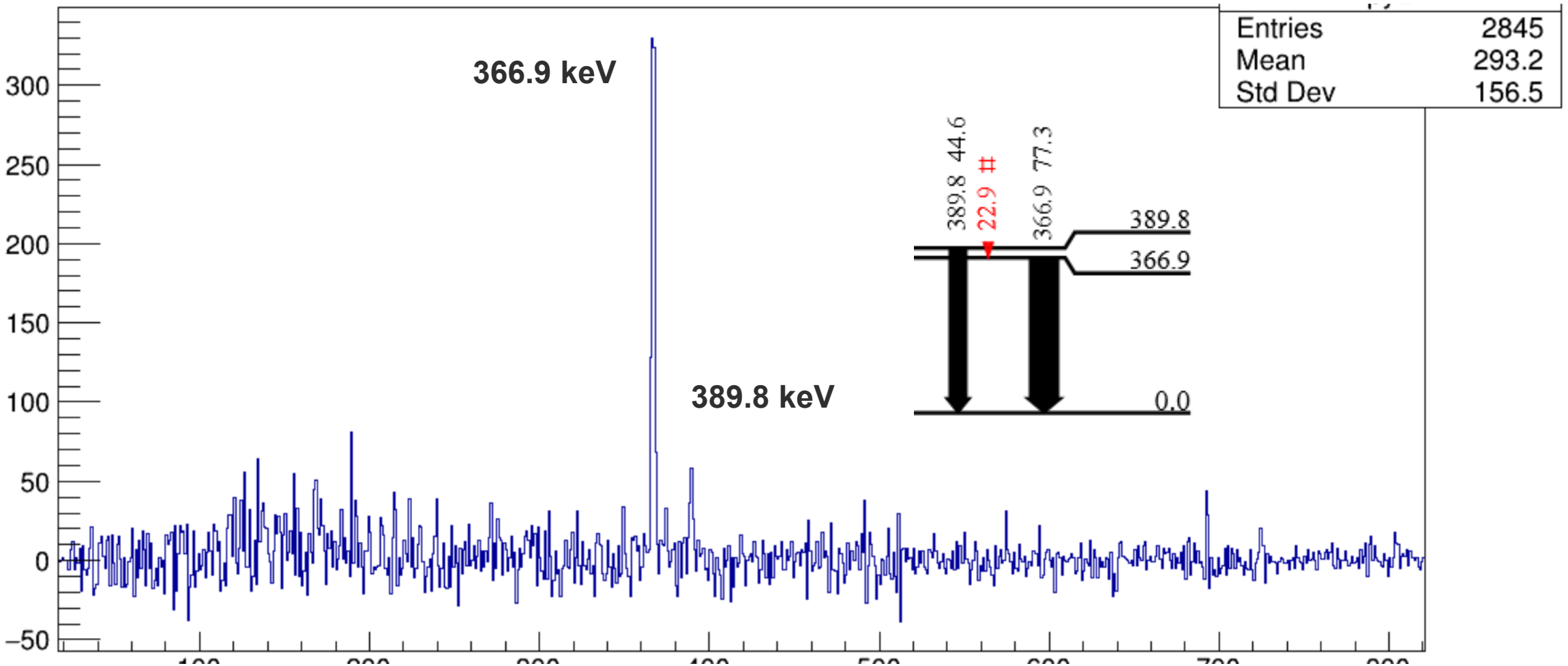
Searching for the Isomer in ^{67}Fe

Delayed γ–γ Coincidences gated on 389.8-keV γ-ray, window>5μs



Searching for the Isomer in ^{67}Fe

Delayed γ–γ Coincidences gated on 179.6-keV γ-ray, window>5μs



Searching for the Isomer in ^{67}Fe