Towards a nuclear explanation for the large amount of ^{44}Ti produced in Core Collapse Supernovae

Spokesperson: Alex Murphy
Data Analysis: Vincent Margerin

Preliminary RESULTS

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

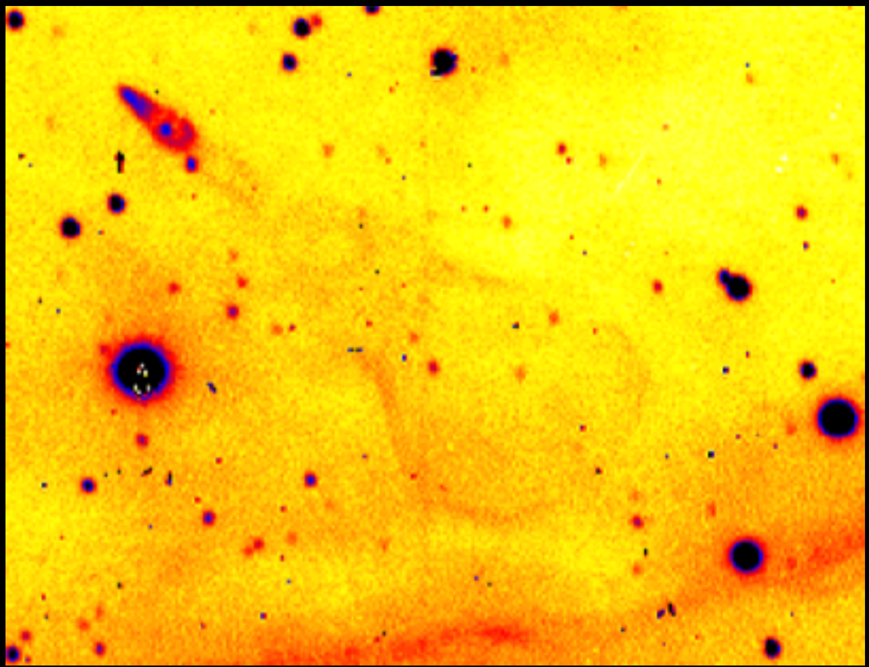
Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Measurement of the ^{44}Ti(α,p)^{47}V reaction cross section, of relevance to gamma-ray observation of core collapse supernovae, using reclaimed ^{44}Ti.

IS543

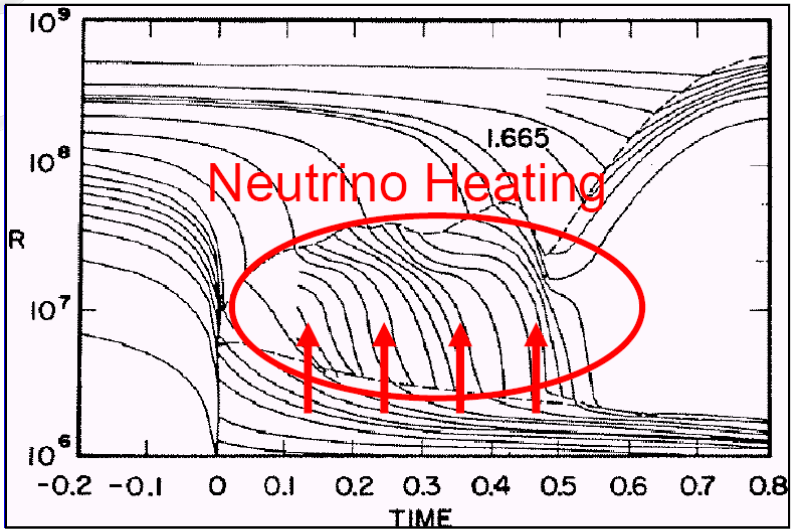
January 6, 2012

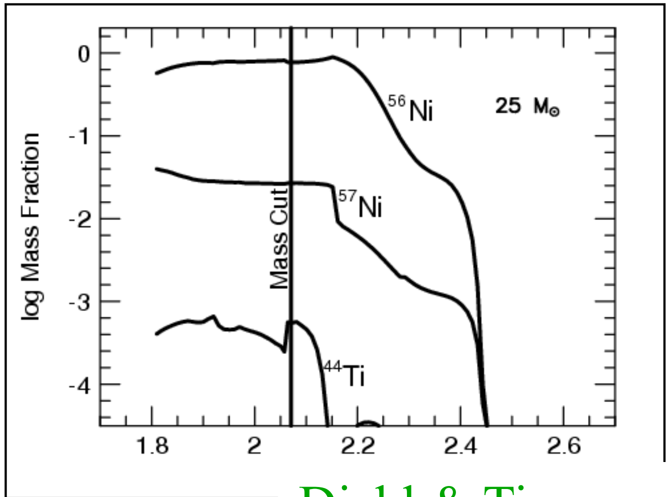

Optical



The Importance of ^{44}Ti

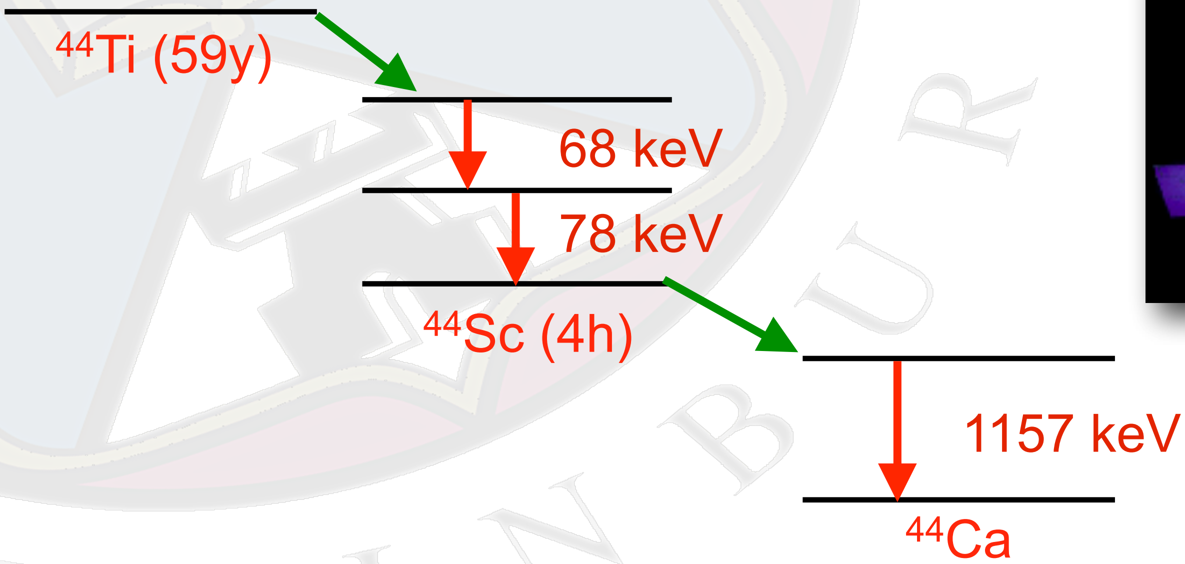
- Produced in Si layer above collapsed core
- QSE, α-rich freeze-out
- Amount ejected sensitively depends on location of the 'mass cut'
- ^{44}Ti that is ejected will become a γ-ray emitter
- Material that 'falls back' is not available for detection
- ^{44}Ti yield is sensitive to the explosion mechanism
- Thus, very useful for models to make compare against

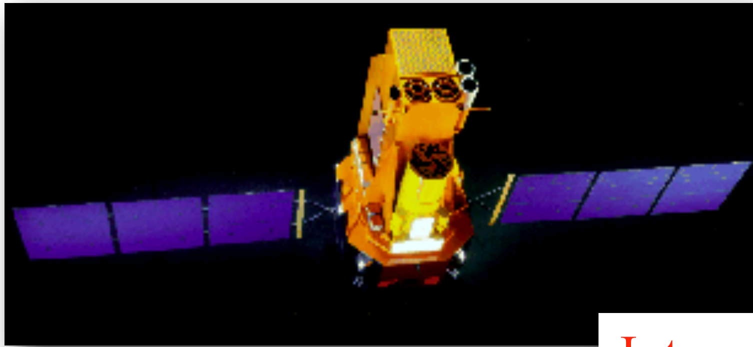




Diehl & Timmes *et al.* (1998)

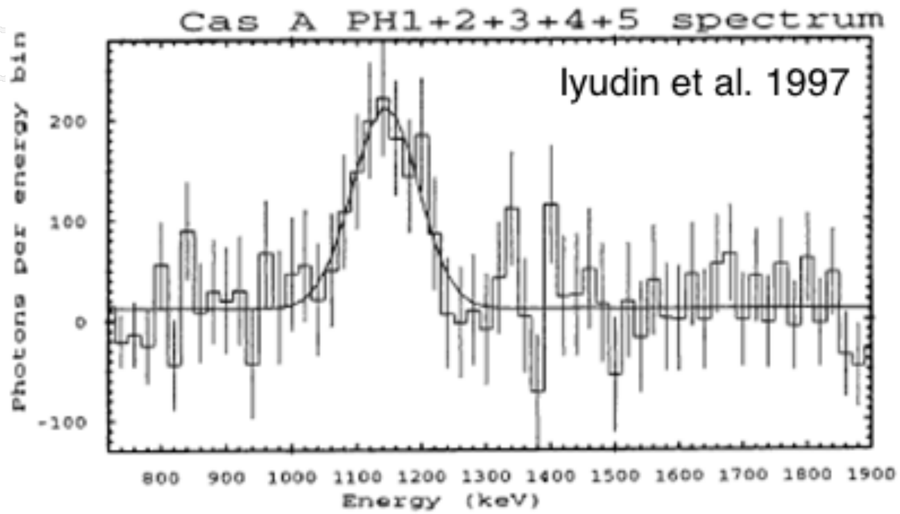
Gamma-ray emission from ^{44}Ti

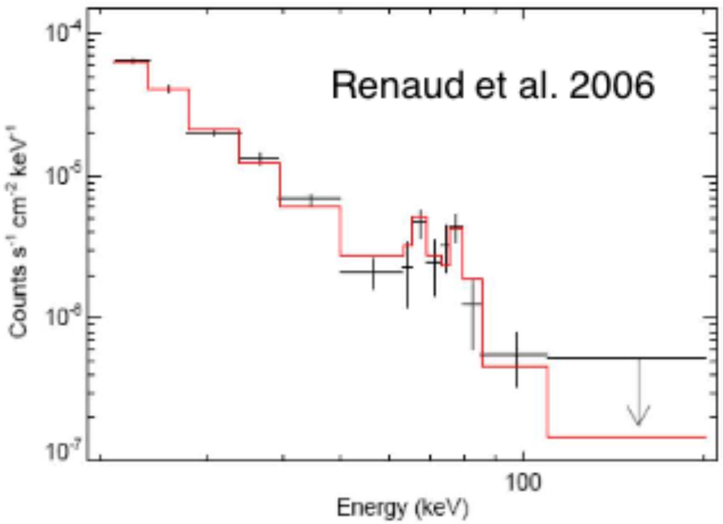




Integral

IBIS Cas-A





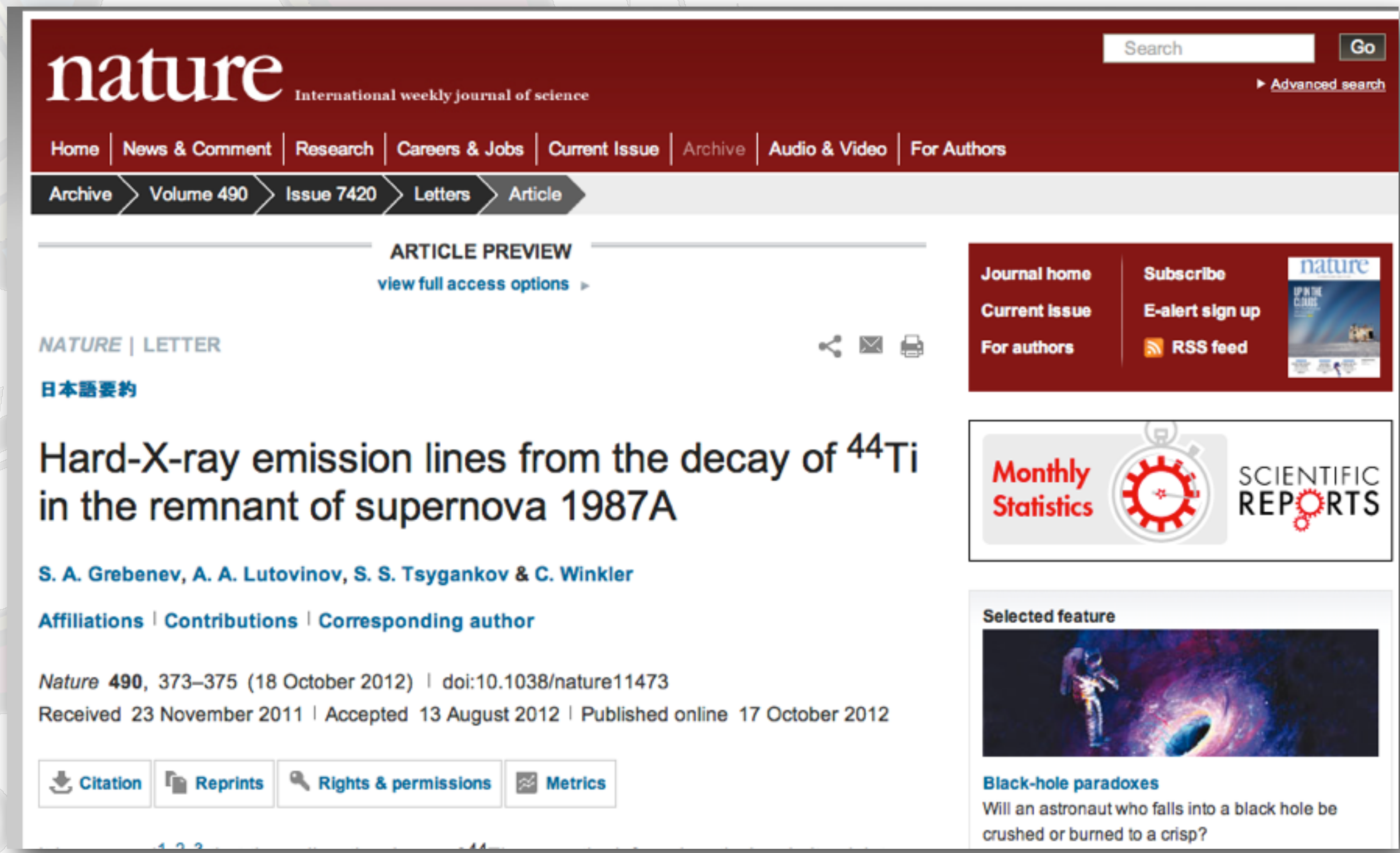
Observational data

Observational data

Cassiopeia-A, first Detection (1994):

- ^{44}Ti 1.157MeV lines by CGRO on COMPTEL
- ^{44}Sc lines now also seen by PDS on BEPPO-SAX and by INTEGRAL IBIS/ISGRI (lines resolved!)
- Combined analysis: **$1.6^{+0.6}_{-0.3} \times 10^{-4}\ M_{\odot}$**

  (Astrophys. J. 647 L41 (2006)



^{44}Sc lines of SN1987A seen by INTEGRAL IBIS/ISGRI

$3.1 \pm 0.8 \times 10^{-4}\ M_{\odot}$

How does this yield compare with prediction?

- Wide variety of progenitor models and masses 'standard' simulations produce ***at most***

$1.0 \times 10^{-4}\ M_{\odot}$

(Ap.J. Suppl. 191, Ap.J. 718 357-367 (2010); Ap.J. 464 (1996) 332-341)

- Where ^{44}Ti has been seen, there is more than can be explained
- Thus there is some tension between observed and predicted yields.

Key Reactions

Reaction rate sensitivity studies:

- *The et al*: ApJ 504 (1998) 500
- *Magkotsios et al*: APJS 191 (2010) 66

- Papers agree, $^{44}Ti(\alpha,p)$ most important reaction
- Importance stems from it being the bottle neck in reaction flow as material drops out of QSE

ORDER OF IMPORTANCE OF REACTIONS PRODUCING ^{44}Ti AT $\eta = 0$[a]

	Reaction	Slope
#1	$^{44}Ti(\alpha, p)^{47}V$	−0.394
	$\alpha(2\alpha, \gamma)^{12}C$	+0.386
	$^{45}V(p, \gamma)^{46}Cr$	−0.361
	$^{40}Ca(\alpha, \gamma)^{44}Ti$	+0.137
	$^{57}Co(p, n)^{57}Ni$	+0.102
	$^{36}Ar(\alpha, p)^{39}K$	+0.037
	$^{44}Ti(\alpha, \gamma)^{48}Cr$	−0.024
	$^{12}C(\alpha, \gamma)^{16}O$	−0.017
	$^{57}Ni(p, \gamma)^{58}Cu$	+0.013
	$^{58}Cu(p, \gamma)^{59}Zn$......	+0.011
	$^{36}Ar(\alpha, \gamma)^{40}Ca$	+0.008
	$^{44}Ti(p, \gamma)^{45}V$	−0.005
	$^{57}Co(p, \gamma)^{58}Ni$	+0.002
	$^{57}Ni(n, \gamma)^{58}Cu$	+0.002
	$^{54}Fe(\alpha, n)^{57}Ni$	+0.002
	$^{40}Ca(\alpha, p)^{43}Sc$	−0.002

[a] Order of importance of reactions producing ^{44}Ti at $\eta = 0$ according to the slope of $X(^{44}Ti)$ near the standard reaction rates.

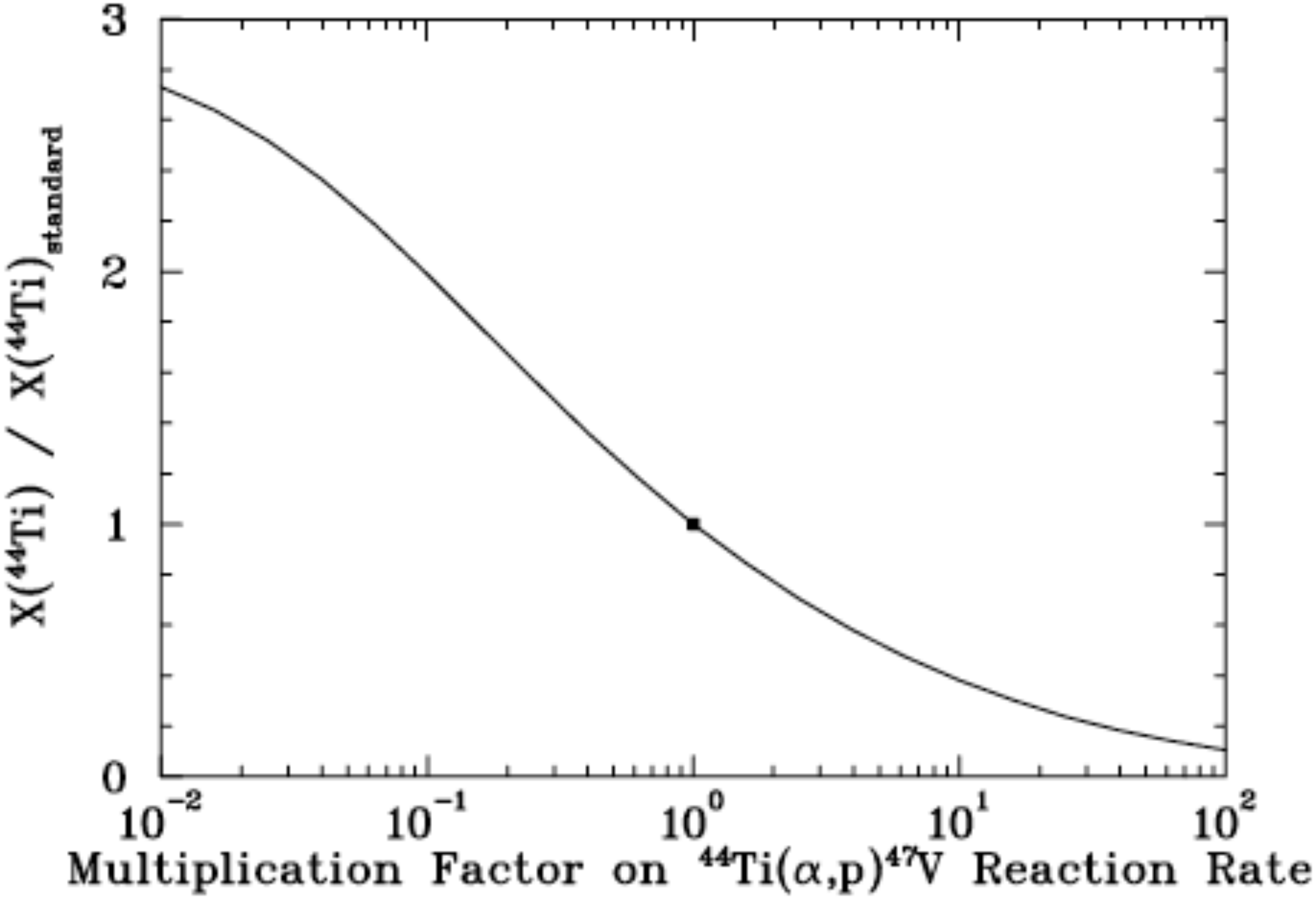
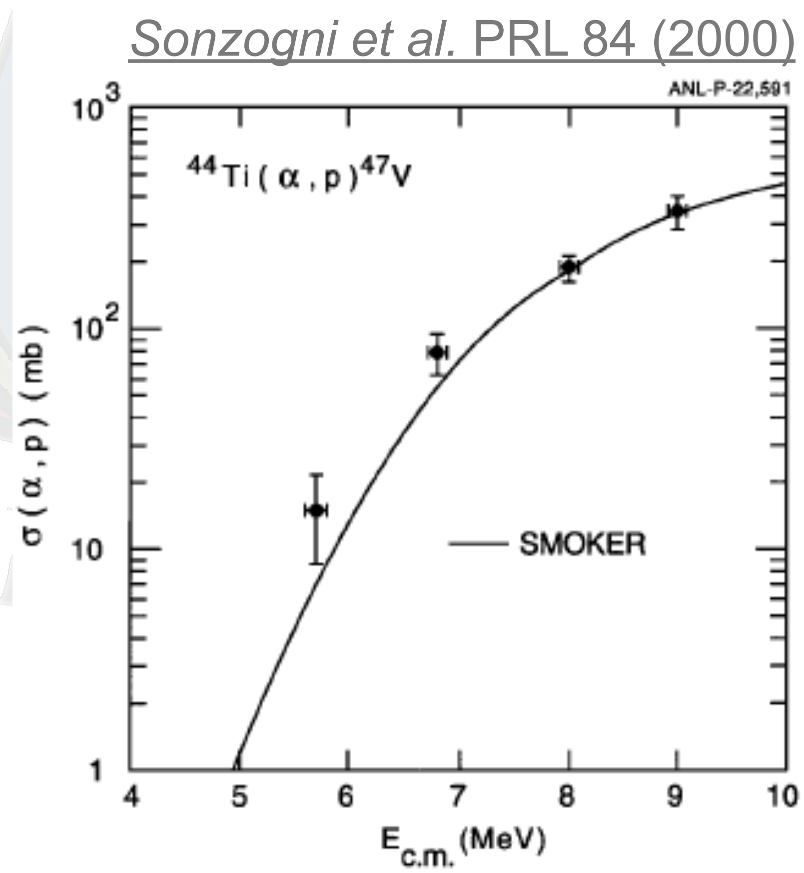


FIG. 9.—Final $X(^{44}Ti)$ dependence on the reaction rate of $^{44}Ti(\alpha, p)^{47}V$

The *et al*. Astrophys. J.504, (1998) 500.

44Ti(α,p) Previous data



- Astrophysical region is 2-6 MeV
- Hoffman *et al*. APJ 715 (2010) 1383
  - New evaluation of ^{44}Ti(α,p) reaction rate
  - Conclude that ^{44}Ti(α,p) uncertainty has been underestimated (x3)

Data achieved with ~10^5 pps on target

A New Proposal

- Direct ^{44}Ti(α,p)^{47}V, in inverse kinematics
- ^{44}Ti beam
- Helium gas cell
- Silicon strip detectors

^{44}Ti Beam

- Part of the ERAWAST project

Exotic Radionuclides from Accelerator WAste for Science and Technology

- Chemically separate ^{44}Ti from highly irradiated accelerator components of PSI
- SINQ neutron spallation facility:
  - >10 yrs of ~2 mA 590 MeV
  - >10 yrs of cooling

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R Dressler *et al* 2012 *J. Phys. G: Nucl. Part. Phys.* **39** 105201 doi:10.1088/0954-3899/39/10/105201

^{44}Ti, ^{26}Al and ^{53}Mn samples for nuclear astrophysics: the needs, the possibilities and the sources

FREE ARTICLE

R Dressler[1], M Ayranov[1], D Bemmerer[2], M Bunka[1], Y Dai[1], C Lederer[3], J Fallis[4], A StJ Murphy[5], M Pignatari[6], D Schumann[1], T Stora[7], T Stowasser[1], F-K Thielemann[6] and P J Woods[5]

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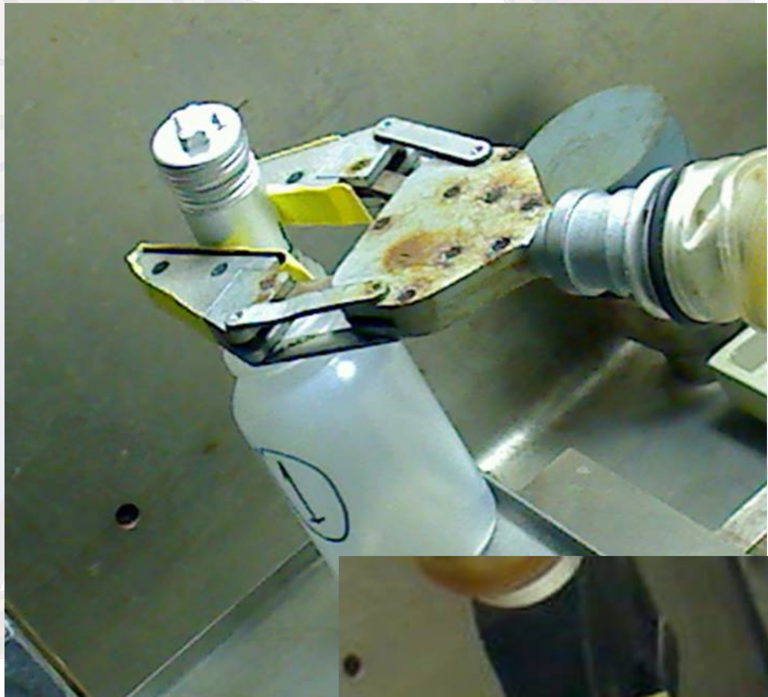
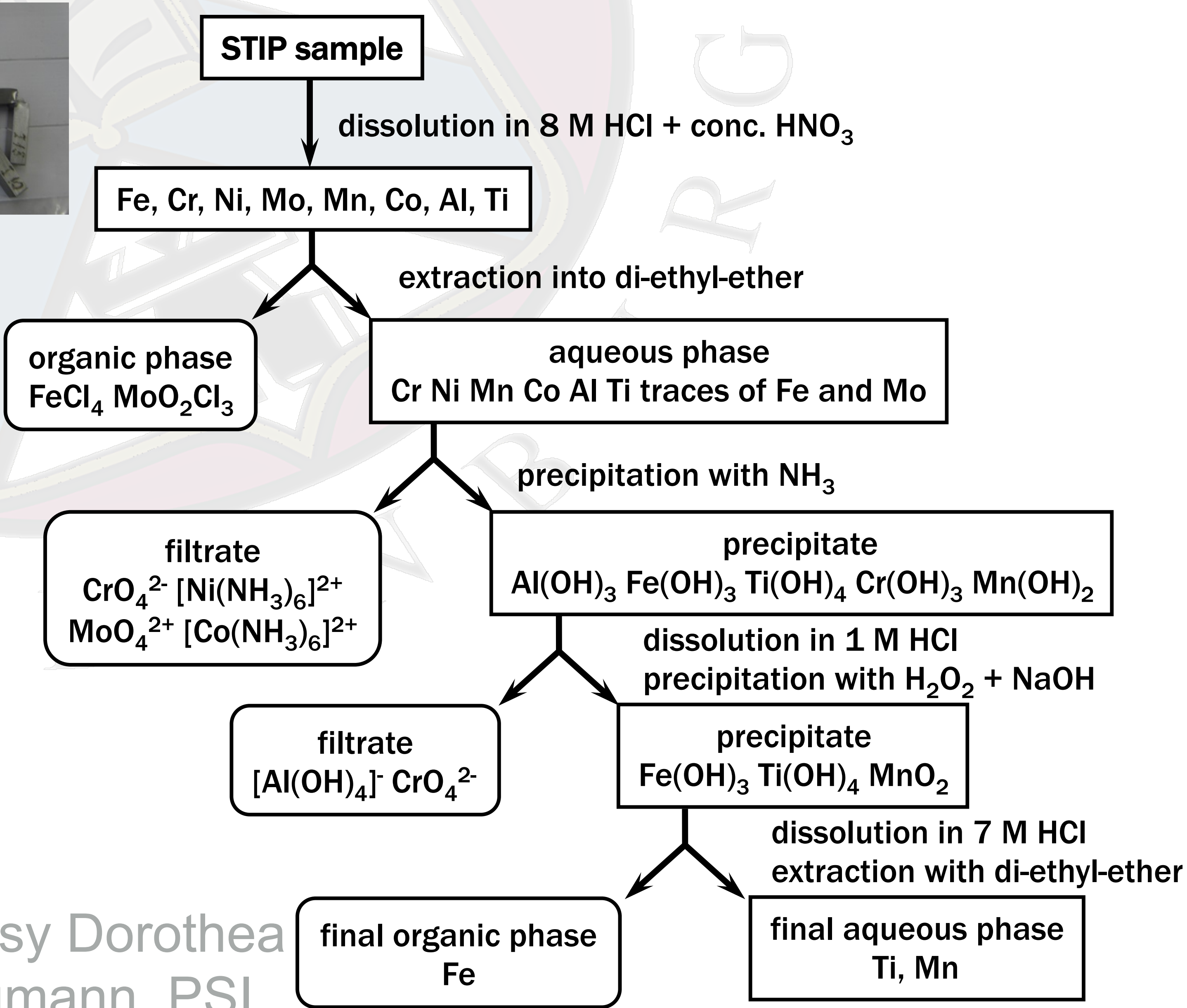
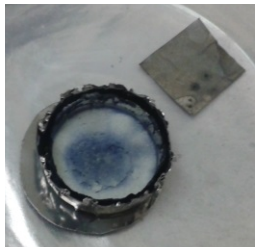


courtesy Dorothea Schumann, PSI

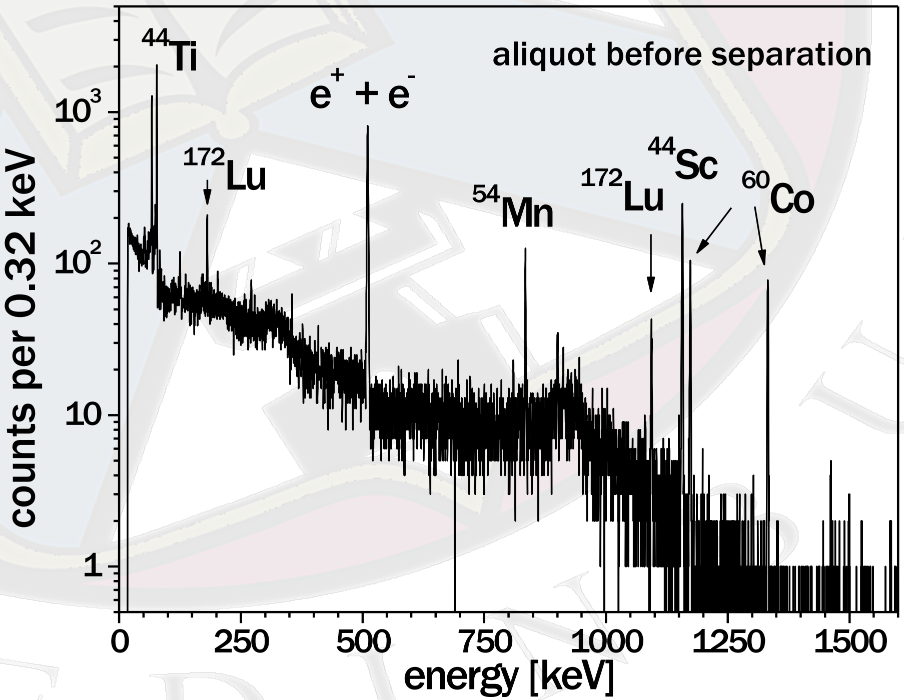
Separation scheme of STIP samples

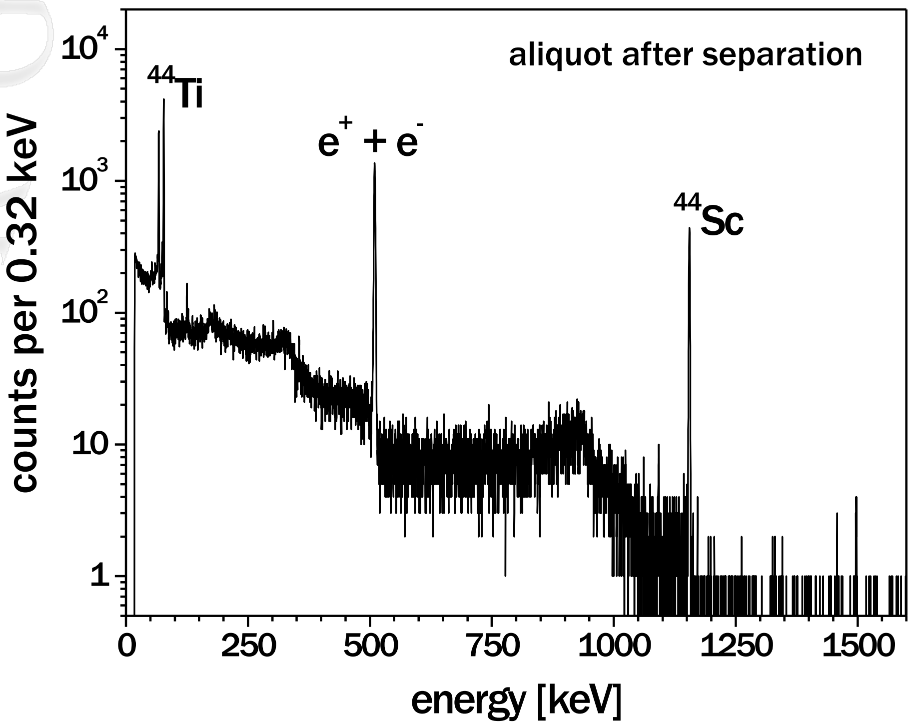




courtesy Dorothea Schumann, PSI

Quality of chemical separation





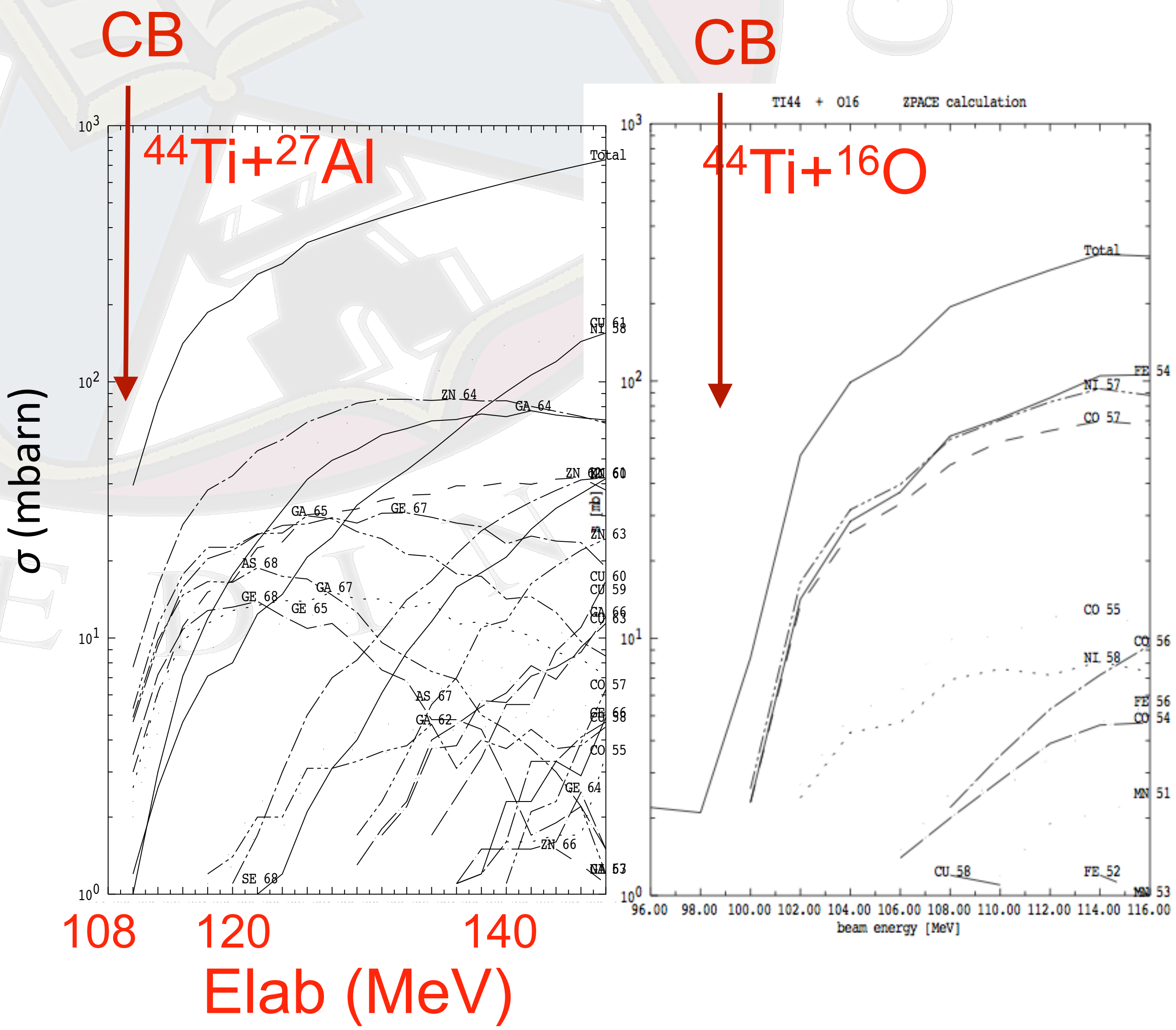
- total used material ~ 60 g 9.5% Cr, 1% W, 0.5% Mn, 0.25% V
- ^{44}Ti: Available: few x 100 MBq; separated 135 MBq; **used 50 MBq**
- ^{26}Al: 300 Bq ≈ 9.8 x 10^{15} atoms
- ^{54}Mn:70 MBq
- ^{53}Mn: ~ 3 x 10^{19} atoms

courtesy Dorothea Schumann, PSI

^{44}Ti Delivery from PSI

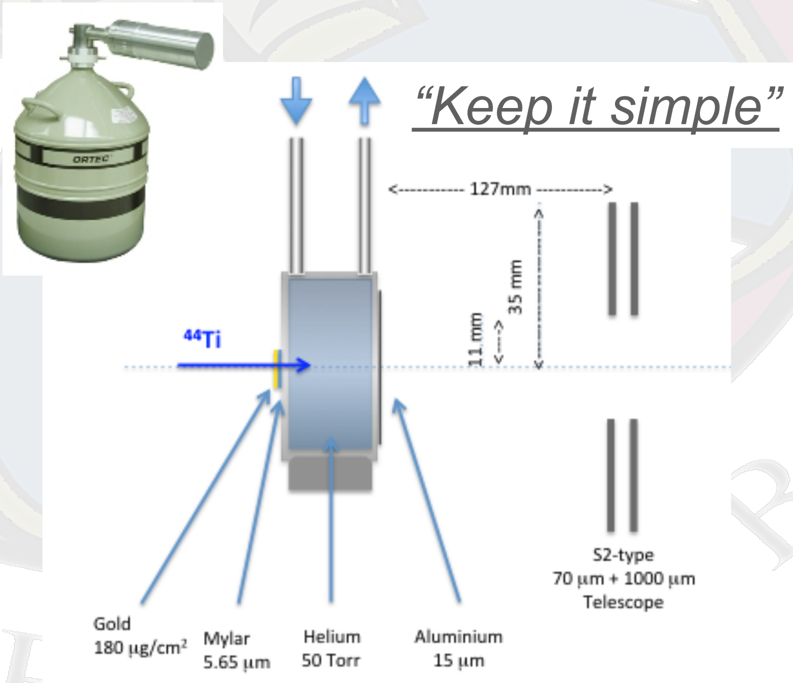
- Foil inserted in a standard target container in the ISOLDE Class A target laboratory,
- Connected to VADIS FEBIAD ion source (VD5 config')
- A large CF_4 gas leak ➔ TiFx molecular ions.
- Installed on GPS Front End
- TiF^{3+} molecular beam extracted.
- Dissociation during charge breeding in REX-ISOLDE
- Accelerated
- ~5x10^{6} decreasing to ~5x10^{5} pps over ~100 hours.
- No significant apparent isobaric contamination

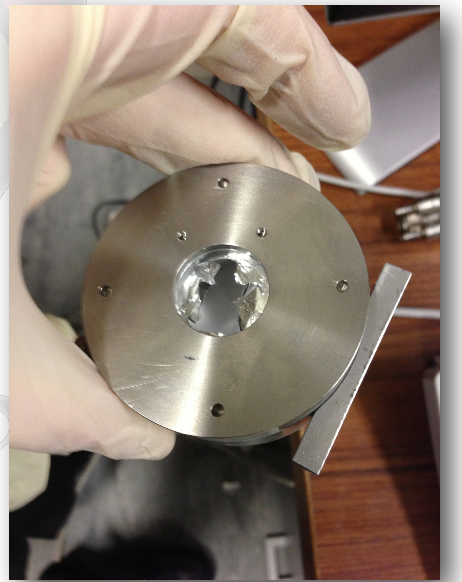
Beware fusion-evaporation

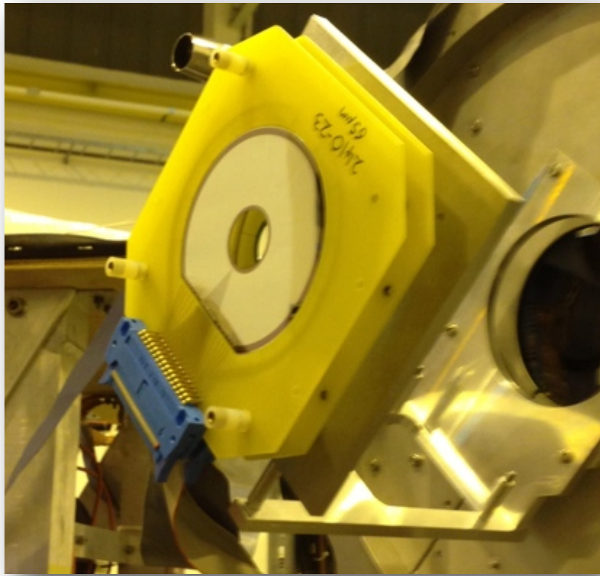


- Entrance window kept thin to keep beam energy low
- Required <9μm entrance window
- ~6μm used (20% uncertainty).

^{44}Ti Experiment configuration



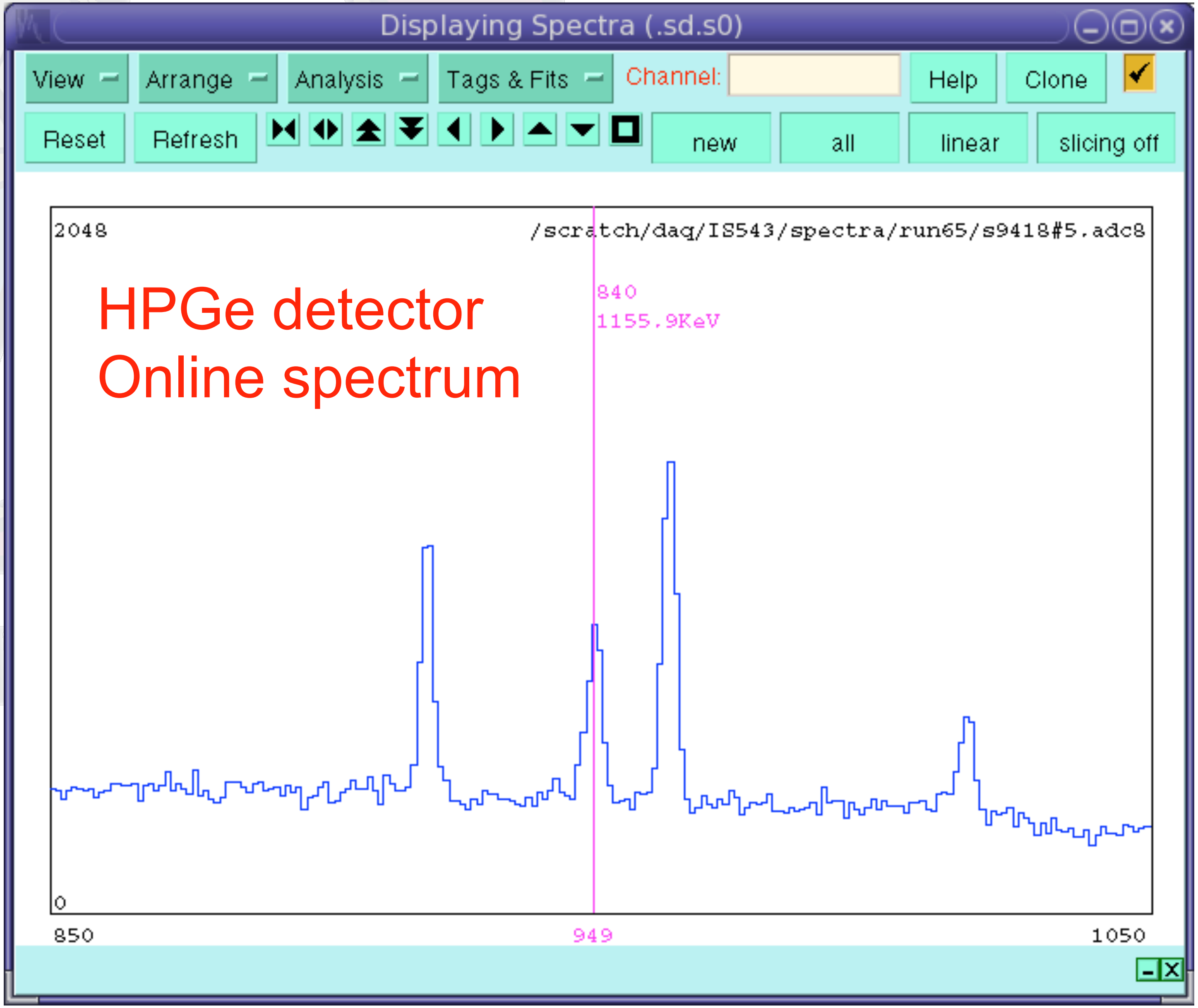


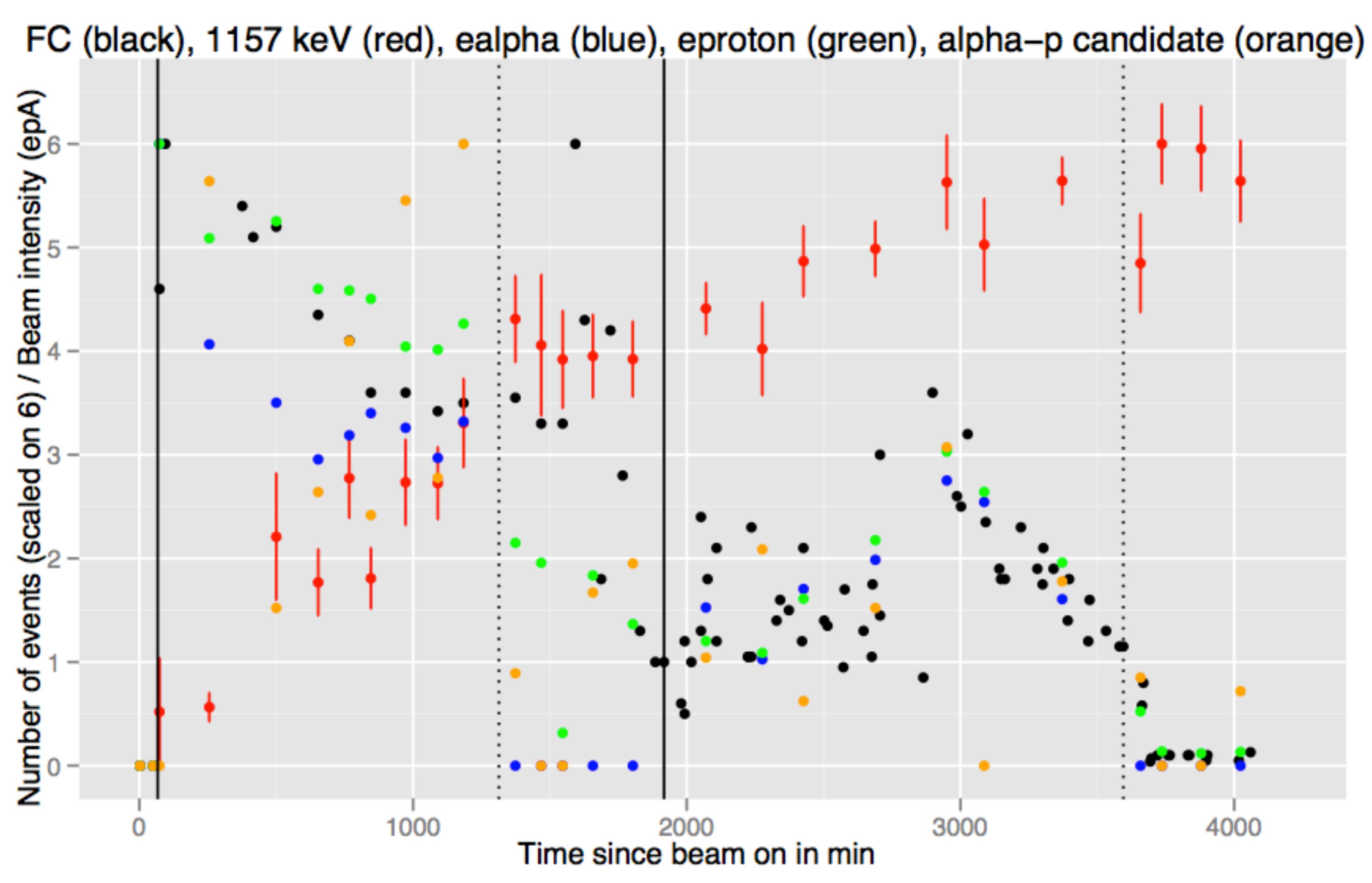


- 2cm 60 Torr ^{4}He gas cell
- ~6μm Al entrance window; 15 μm exit window
- MSL S2-type DSSD, inner diameter 18 mm, outer diameter 100 mm
- 48 circular strips, 16 azimuthal sectors
- 127 & 137 mm downstream: ΔE 65 μm; E 10000 μm

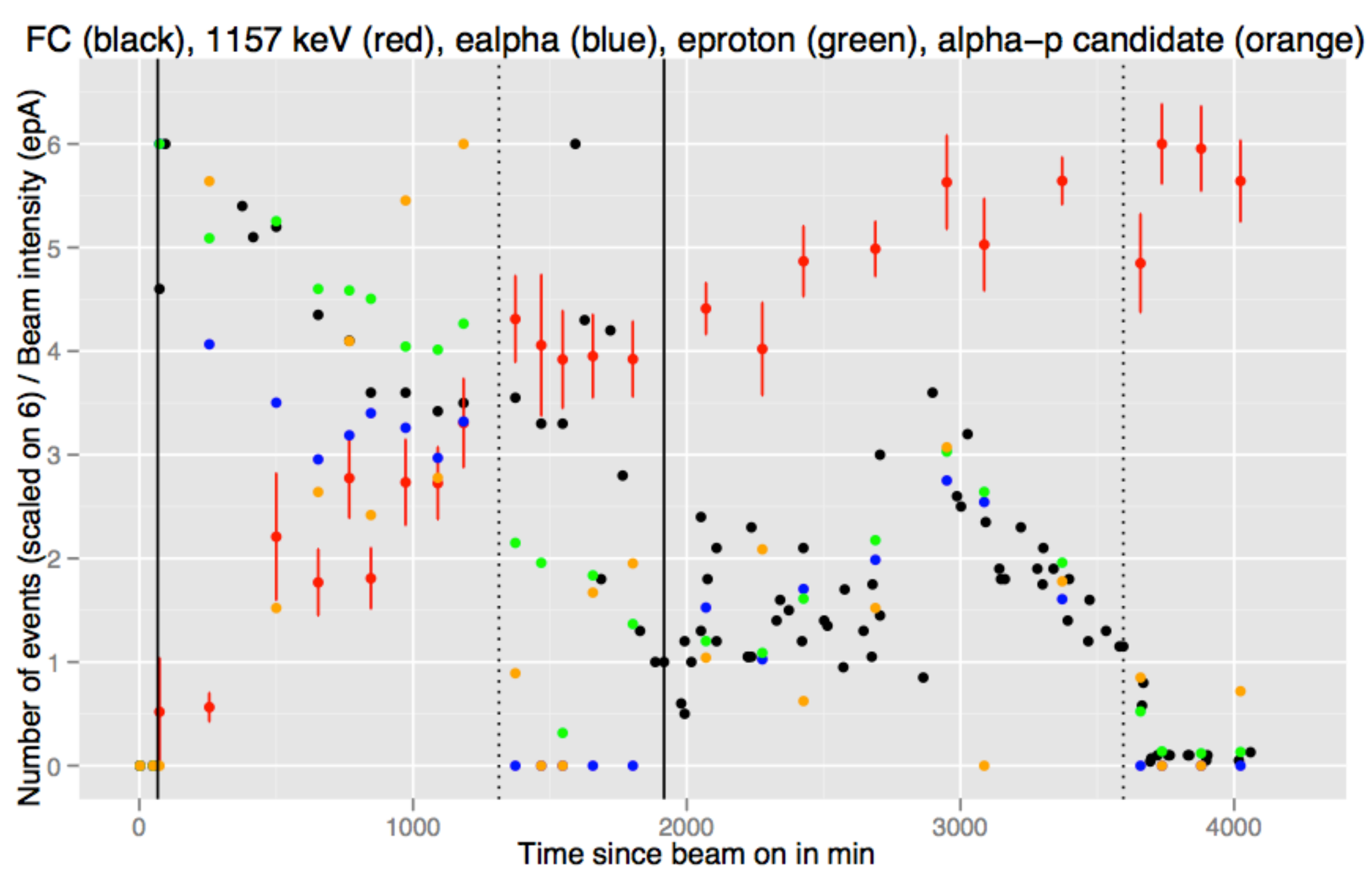
1 year ago

Beam Delivery


Displaying Spectra (.sd.s0)
View
Arrange
Analysis
Tags & Fits
Channel:
Help
Clone
Reset
Refresh
new
all
linear
slicing off
2048
/scratch/daq/IS543/spectra/run65/s9418#5.adc8
840
1155.9KeV
HPGe detector
Online spectrum
0
850
949
1050

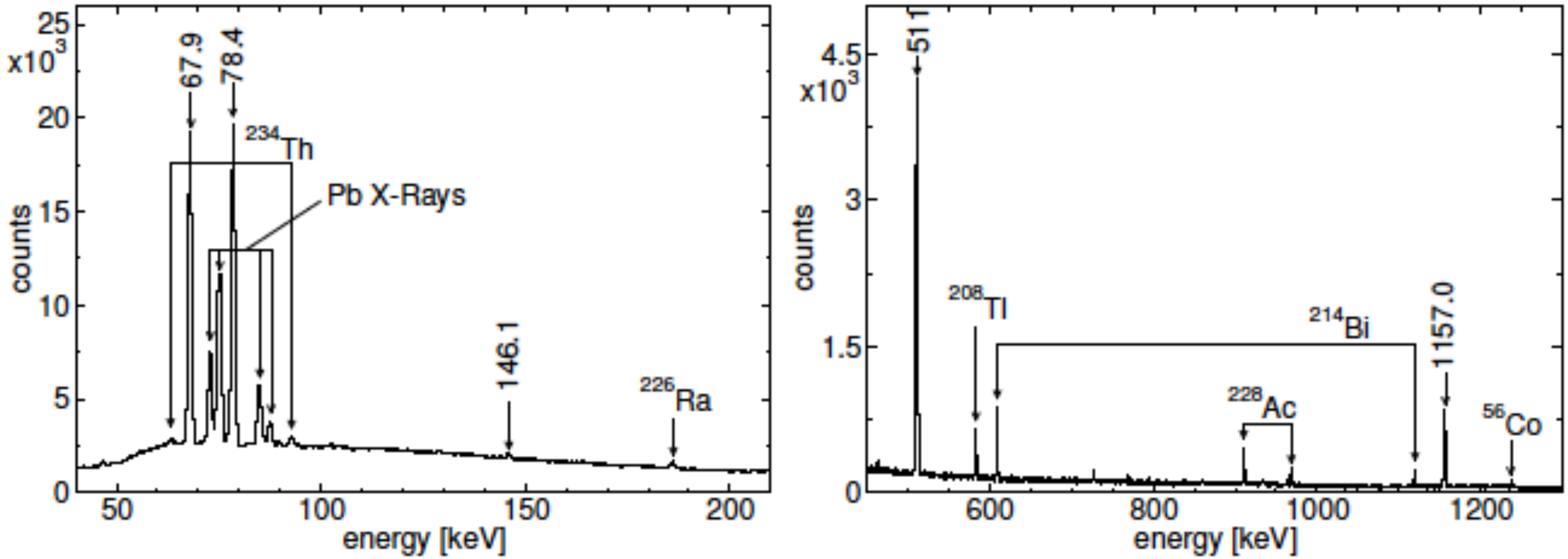


- Faraday cup readings
- Started at about 7epA, ended at about 0.5 epA
- Use of photo diodes showed beam to be (almost) pure ^{44}Ti

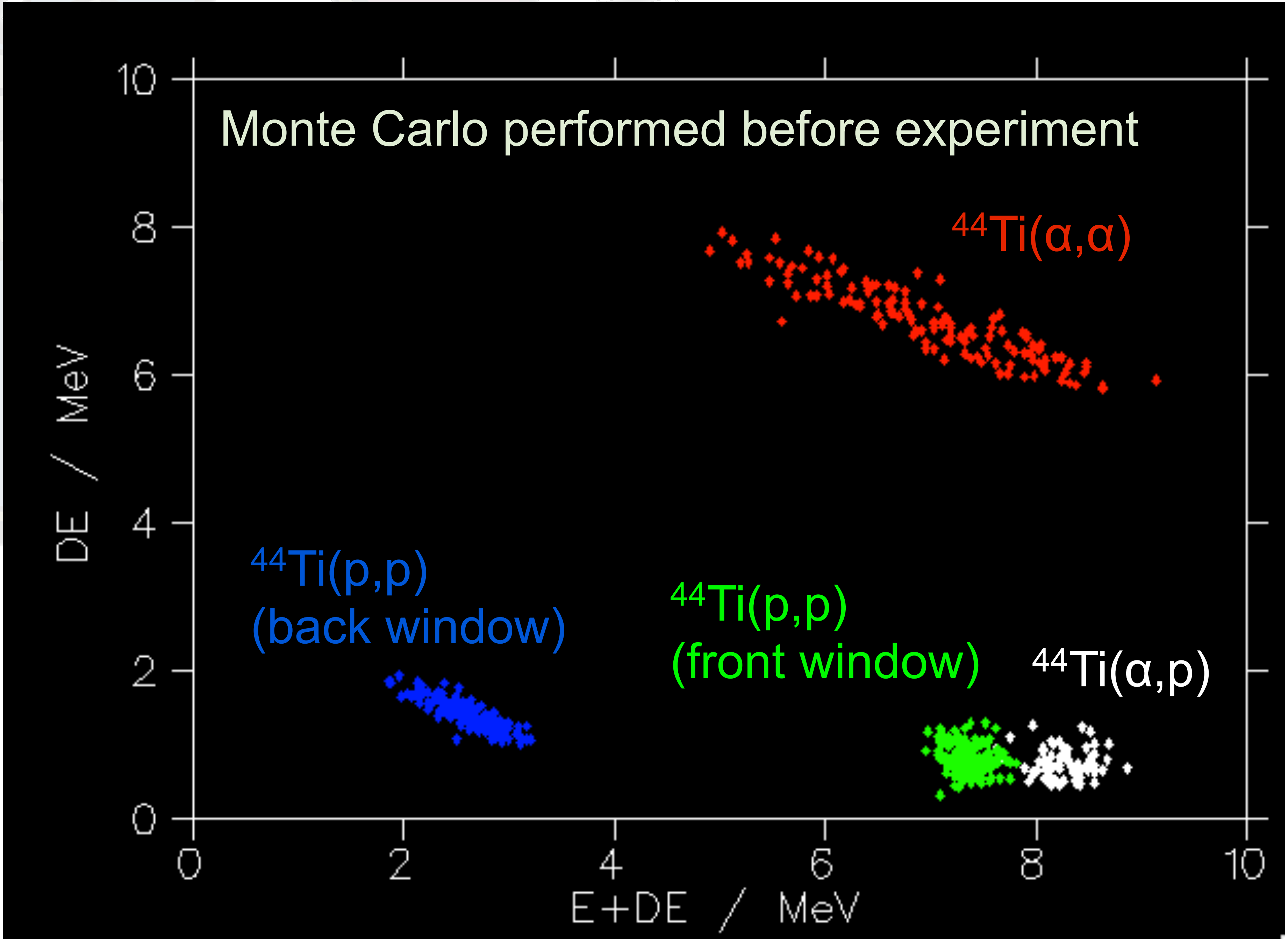


- Increasing yield of ^{44}Ti decay gamma rays (HPGe)
- Elastic scattering yields
- 2.16 MeV/u ^{44}Ti $^{13+}$

[Later: Post experiment HPGe counting]

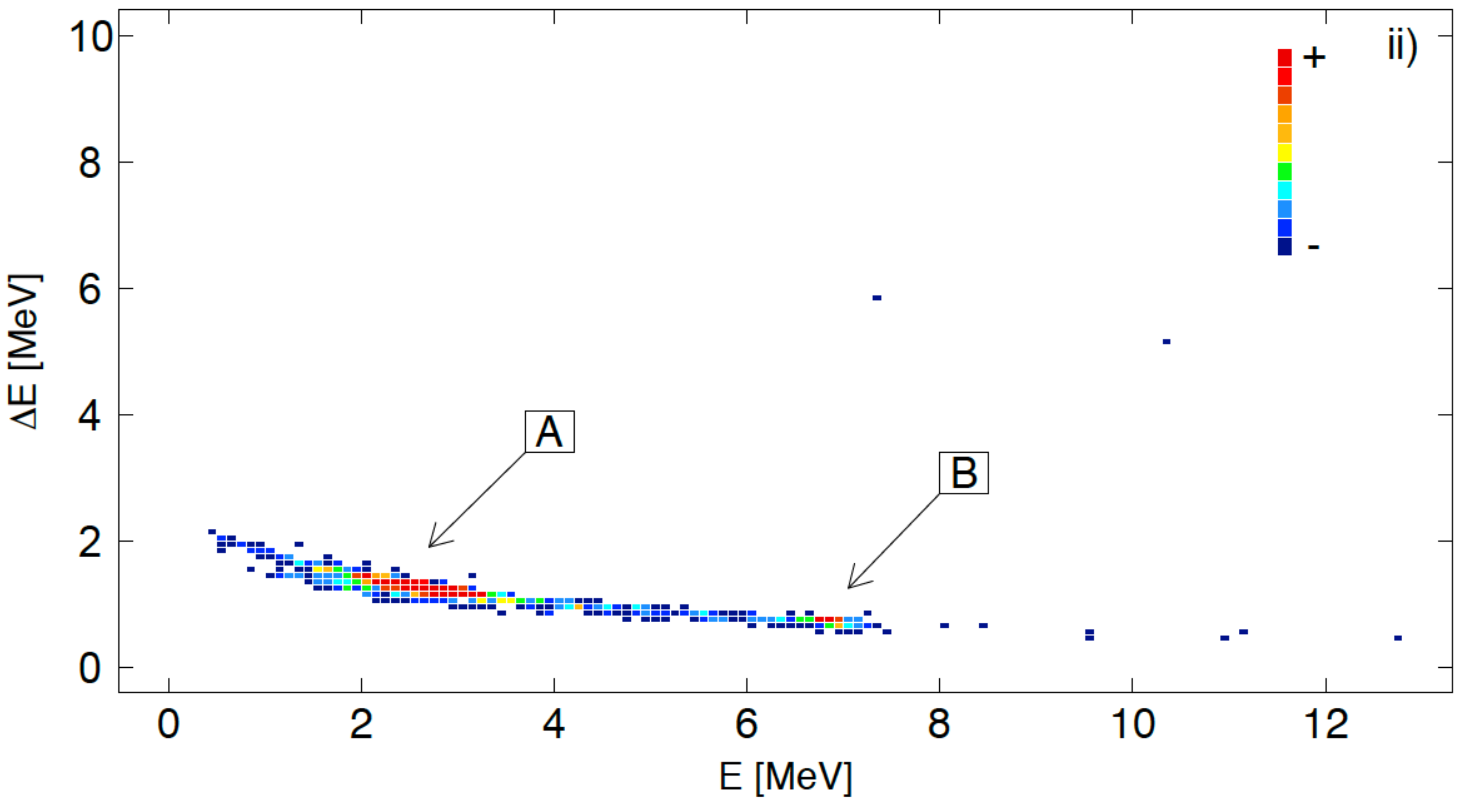


- HPGe counting on exit window after experiment
- Consistent estimate of total beam exposure
- ~30% of beam 'missed' entrance window, deposited on cell

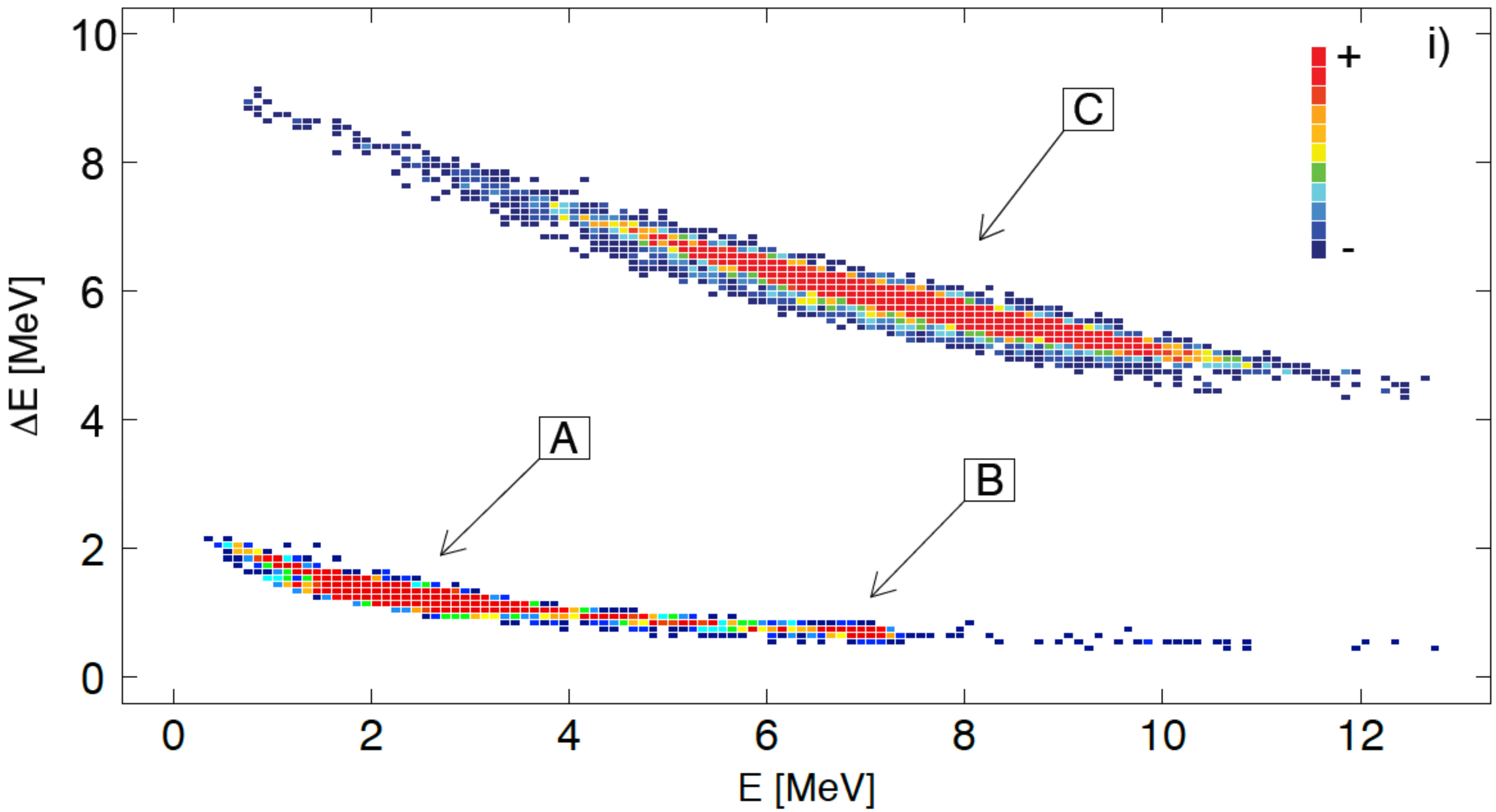


Monte Carlo performed before experiment
44Ti(α,α)
44Ti(p,p)
(back window)
44Ti(p,p)
(front window)
44Ti(α,p)
DE / MeV
E+DE / MeV
0
2
4
6
8
10

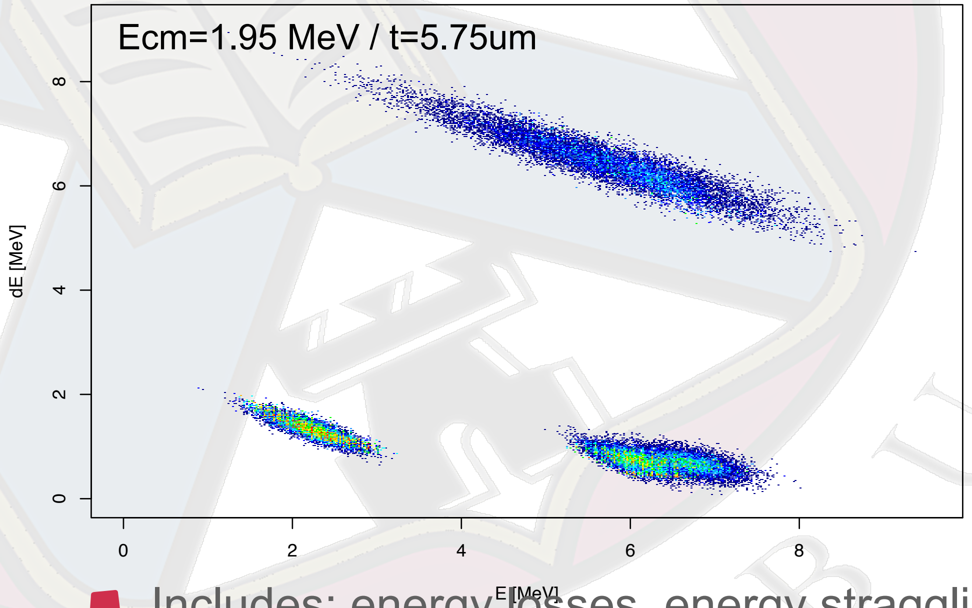
Data! Gas out

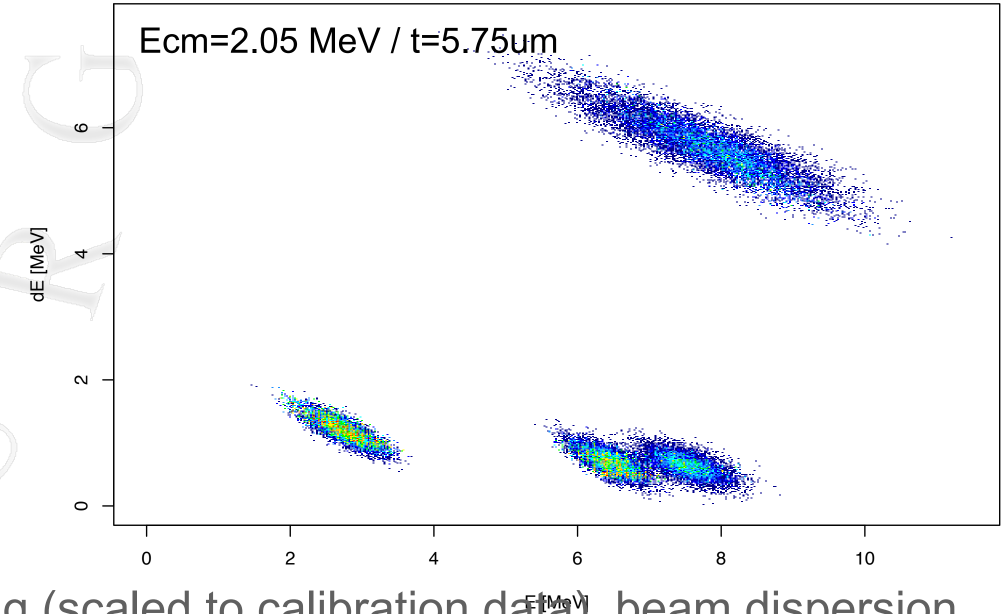


Data! Gas In



Monte Carlo

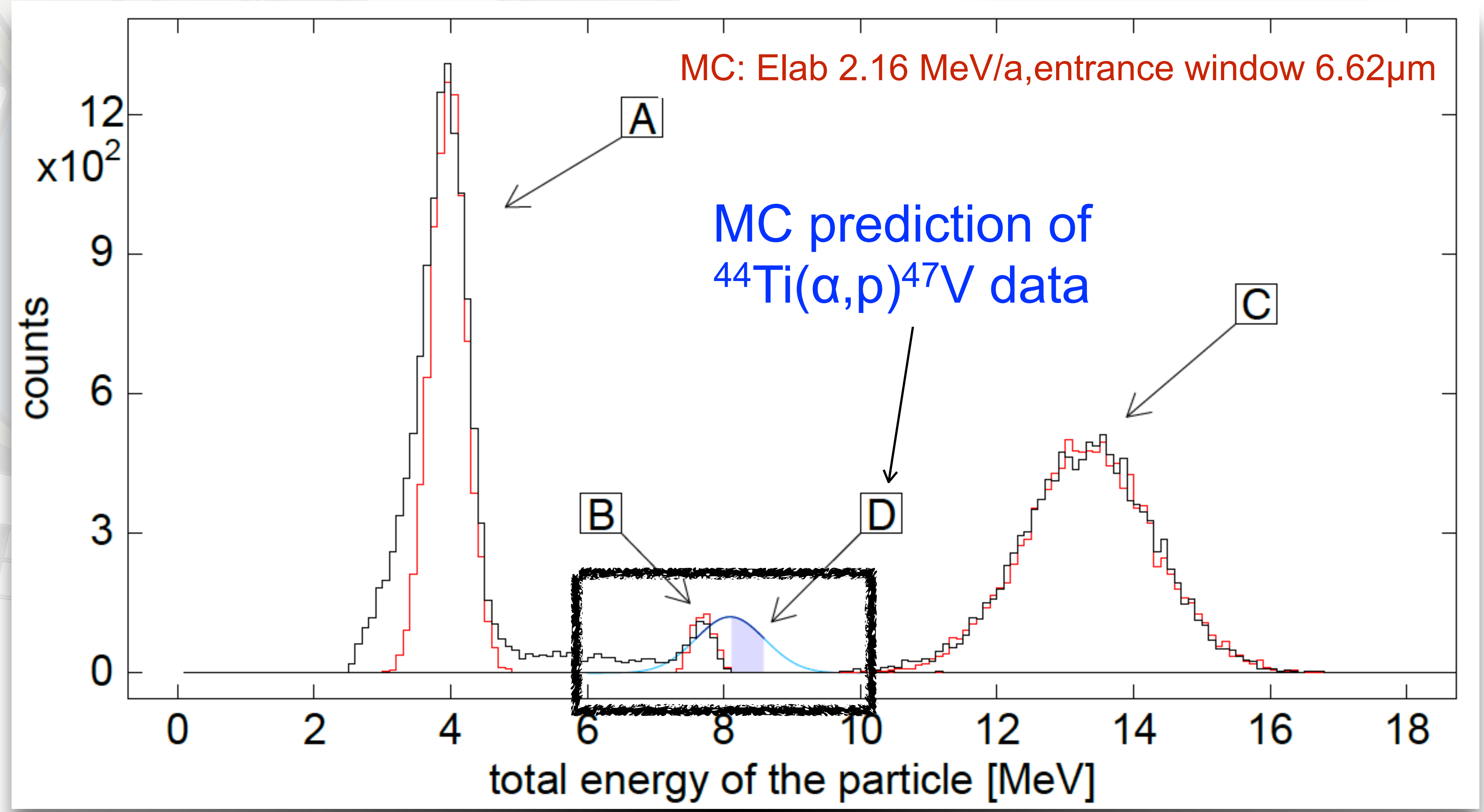




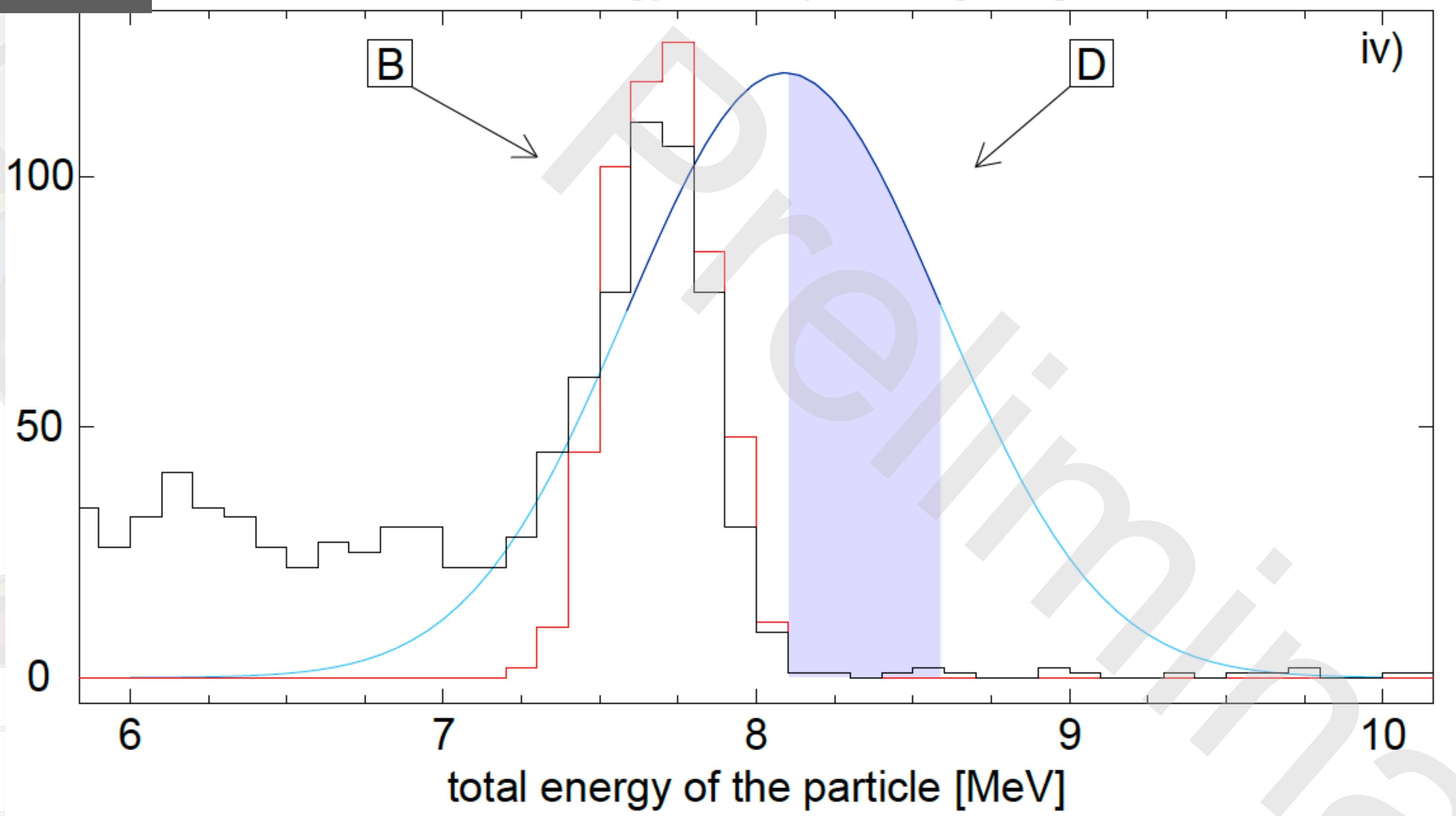
- Includes: energy losses, energy straggling (scaled to calibration data), beam dispersion,
- Gaussian smearing, detector dead-layers, p/a quenching, isotropic scattering in cm,
- experimental coincidence requirements
- Consistent description of (α,α) and (α,p) from window obtained

Beam energy (before entrance window)	2.16 MeV/u
Mean $^{44}Ti(\alpha,p)$ E_{cm}	4.15+/-0.23 MeV
Thickness of entrance window:	6.62+/-0.05 μm

Project data as total energy



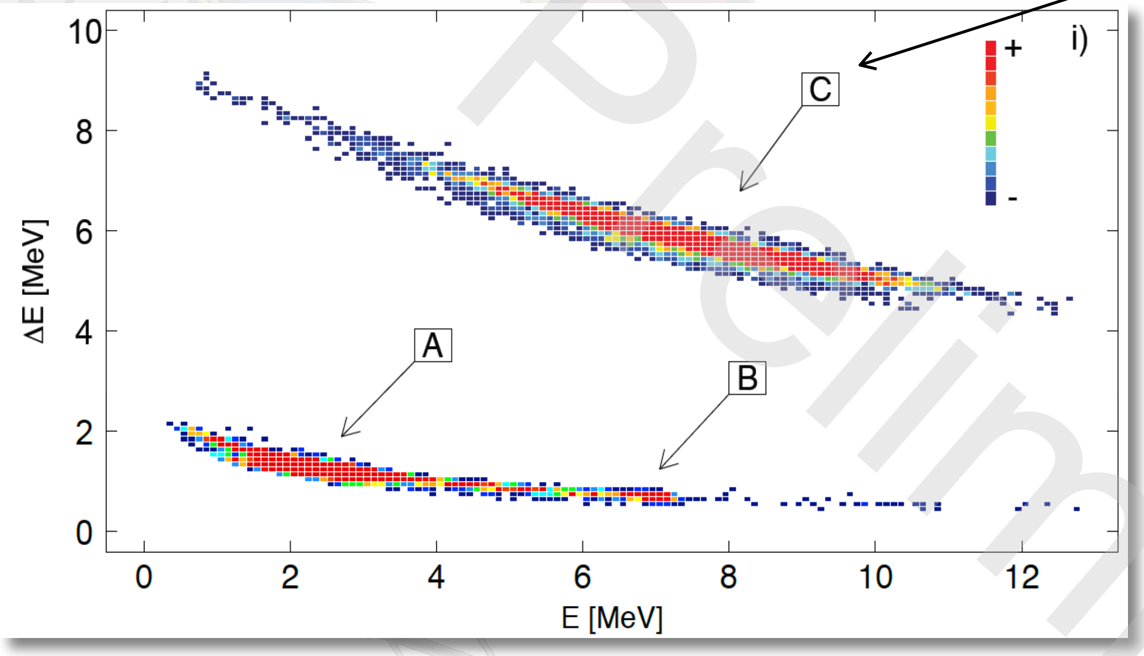
Statistics



- Estimated <1 (α,p) event above centroid of (α,α) events
- 5 events between centroid and +1σ
- Consistent with background rate (gas out run and side bands)
- Consider them ALL to be signal (most conservative)
- More sophisticated analysis to come…

Convert to cross section

$^{44}Ti(\alpha,\alpha)^{44}Ti$
Rutherford scattering

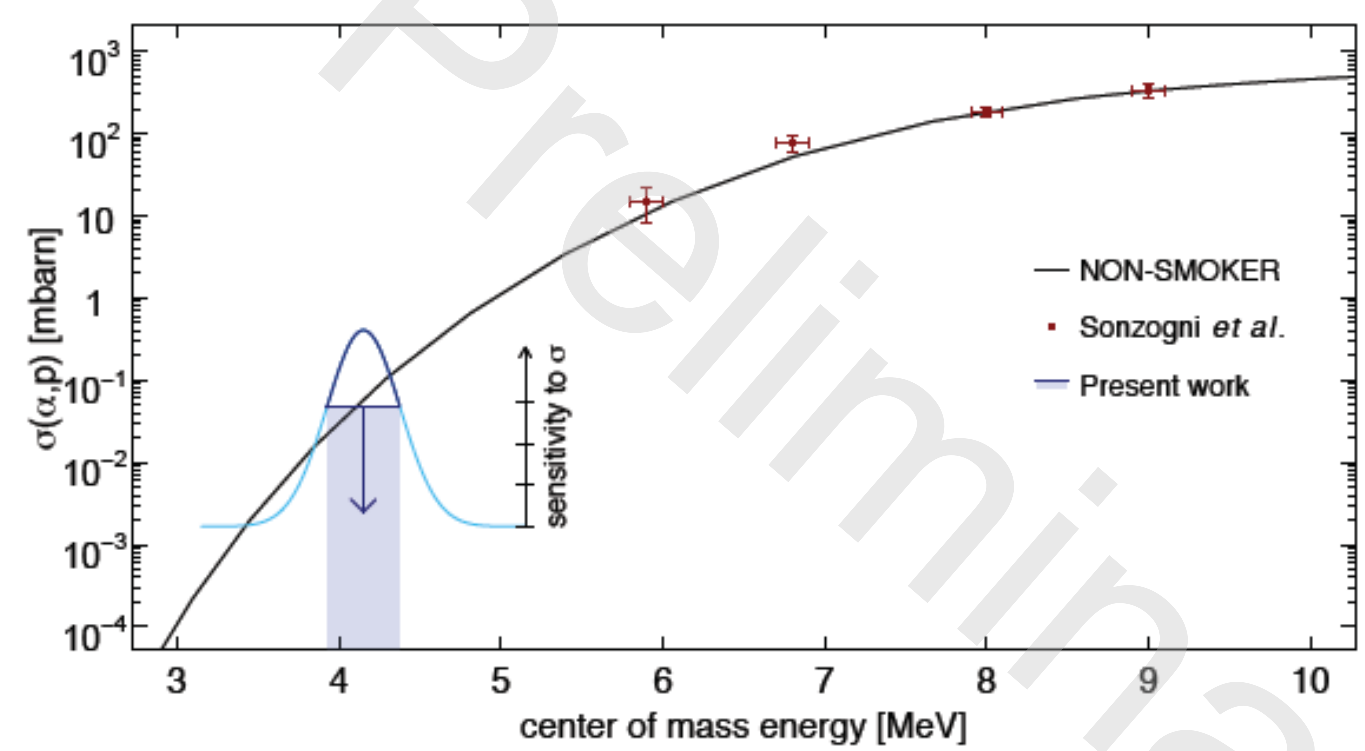


- Use absolute cross section from $^{44}Ti(\alpha,\alpha)^{44}Ti$ Rutherford scattering
- Include additional factor for difference in c.m. angular coverage of $^{44}Ti(\alpha,\alpha)^{44}Ti$ reactions as compared to $^{44}Ti(\alpha,p)^{47}V$

Upper limit of 40 μbarns

Preliminary

Interpretation



- Suppose the NON-SMOKER cross-section were correct…
- Then given our beam intensity and energy distribution, what yield would we have observed? 88 μbarn

Tentative implication:

- If result ‘typical’ at all energies, then reaction rate reduced by factor of >2.2
- ^{44}Ti production increases by >35%

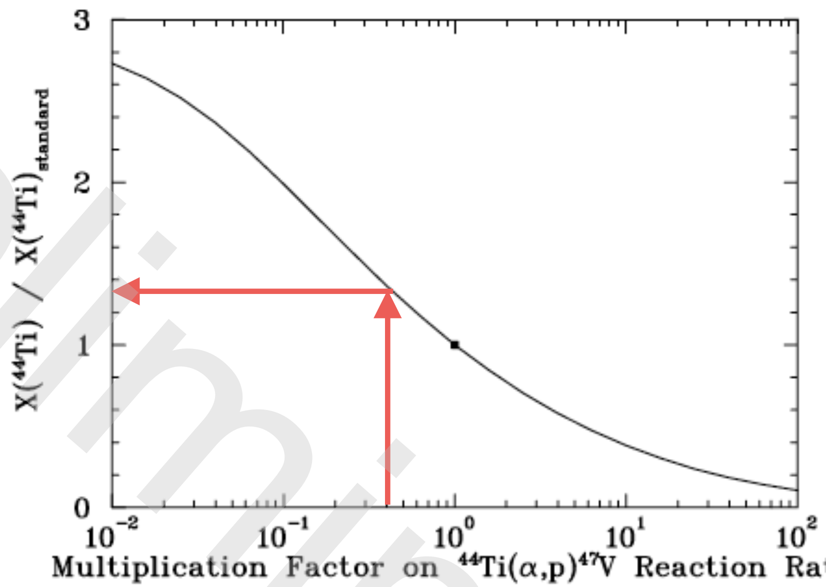


FIG. 9.—Final $X(^{44}Ti)$ dependence on the reaction rate of $^{44}Ti(\alpha, p)^{47}V$

Preliminary

SN1987A Observed: **$3.1 \pm 0.8 \times 10^{-4}$ M$_\odot$**

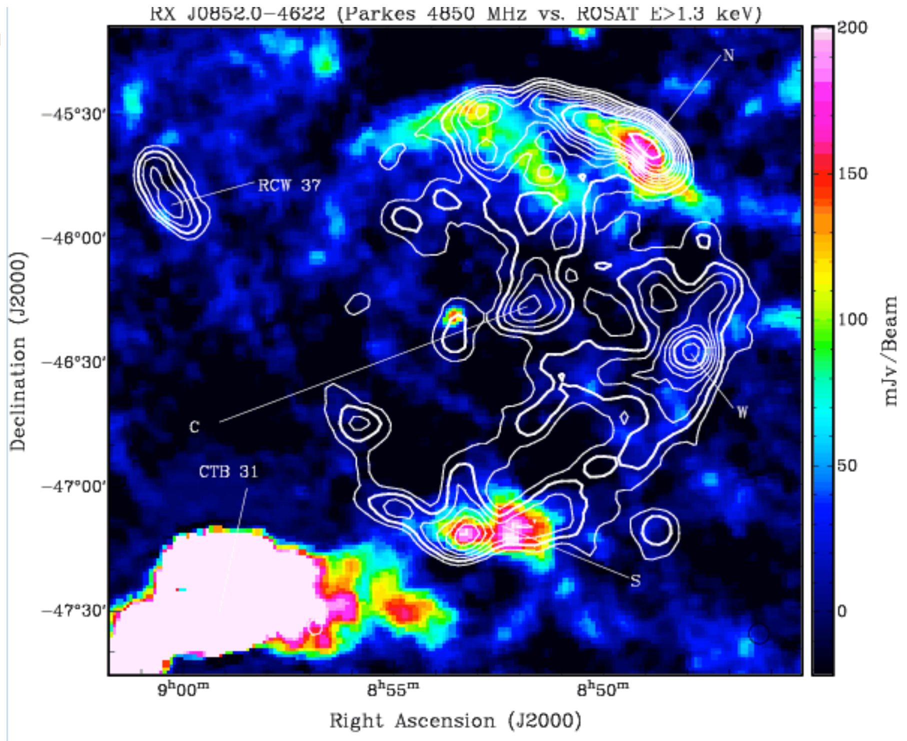
Cas-A Observed: **$1.6^{+0.6}_{-0.3} \times 10^{-4}$ M$_\odot$**

Closer

(‘new’) ^{44}Ti production: >**1.35 M$_\odot$**

And finally… RXJ852.0-4622 in Vela…

- ROSAT discovered a nearby (200pc) supernova remnant
- 1.157 MeV γ-line emission seen by COMPTEL (Nature 396, 142 (1998))
- XMM Newton observations (A&A 429 (2005) 225-234)
- Assuming a standard Ti yield of 5×10^{-5} $M_{\odot}$ gives age of 700 years
- However, there is no historical counterpart known for this period



- But if yield is higher, age must be greater…
- …which might explain the lack of a historical record?

Publication submission soon…

Towards a Nuclear Explanation for the Observation of ^{44}Ti Isotopic Excesses in Core Collapse Supernovae

V. Margerin,[1] A. St. J. Murphy,[1,*] T. Davinson,[1] R. Dressler,[2] J. Fallis,[3] A. Kankainen,[4,5,†] M. Kowalska,[6] A. M. Laird,[7] G. Lotay,[1,‡] D. J. Mountford,[1] C. D. Murphy,[1] C. Seiffert,[6] D. M. Schumann,[2] T. Stowasser,[2] T. Stora,[6] C. H.-T. Wang,[8] and P. J. Woods[1]

[1]*School of Physics and Astronomy, The University of Edinburgh, Edinburgh, EH9 3JZ, Scotland*
[2]*Laboratory of Radiochemistry and Environmental Chemistry, Paul Scherrer Institut, CH-5232, Switzerland*
[3]*TRIUMF, Vancouver, British Columbia V6T 2A3, Canada*
[4]*Department of Physics, University of Jyväskylä, P.O. Box 35, FI-40014 University of Jyväskylä, Finland*
[5]*Helsinki Institute of Physics, P.O. Box 64, FI-00014 University of Helsinki, Finland*
[6]*CERN (Organisation Européenne pour la Recherche Nucléaire), CH-1211 Genève 23, Switzerland*
[7]*Department of Physics, University of York, York, YO10 5DD, England*
[8]*Department of Physics, Aberdeen University, Aberdeen, AB24 3UE, Scotland*
(Dated: November 22, 2013)

The underlying physics triggering core collapse supernovae is not fully understood. A satellite based γ-ray observation of the isotope ^{44}Ti may solve this problem. The amount of this isotope in stellar ejecta, available for satellite observatory detection, is thought to depend on the explosion mechanism. The most influential reaction to the amount of ^{44}Ti produced in supernovae is $^{44}Ti(\alpha, p)^{47}V$. Here we report on a direct study of this reaction conducted a the REX-ISOLDE facility, CERN. The experiment was performed, for the first time, at a centre of mass energy that is within the Gamow window for core collapse supernovae, 4.15±0.23 MeV energy range. The experiment employed a beam of ^{44}Ti derived from highly irradiated components of the SINQ spallation neutron source of the Paul Scherrer Institute. No yield above background was observed, enabling an upper limit for the rate of this reaction to be determined. This result is below expectation, suggesting that the $^{44}Ti(\alpha, p)^{47}V$ reaction proceeds more slowly than previously thought. Implications for astrophysical event, such as remnant age, are discussed.

PACS numbers: 25.60.Pj, 26.30.-k, 26.50.+x

The team: T. Davinson, R. Dressler, J. Fallis, H. Ishiyama, A. Kankainen, M Kowalska, A. Laird, G. Lotay, D. Mountford, V. Margerin, ASM, C. Murphy, C. Seiffert, D. Schumann, T. Stowasser, T. Stora, C.H.-T. Wang and P. J. Woods

Thank you!