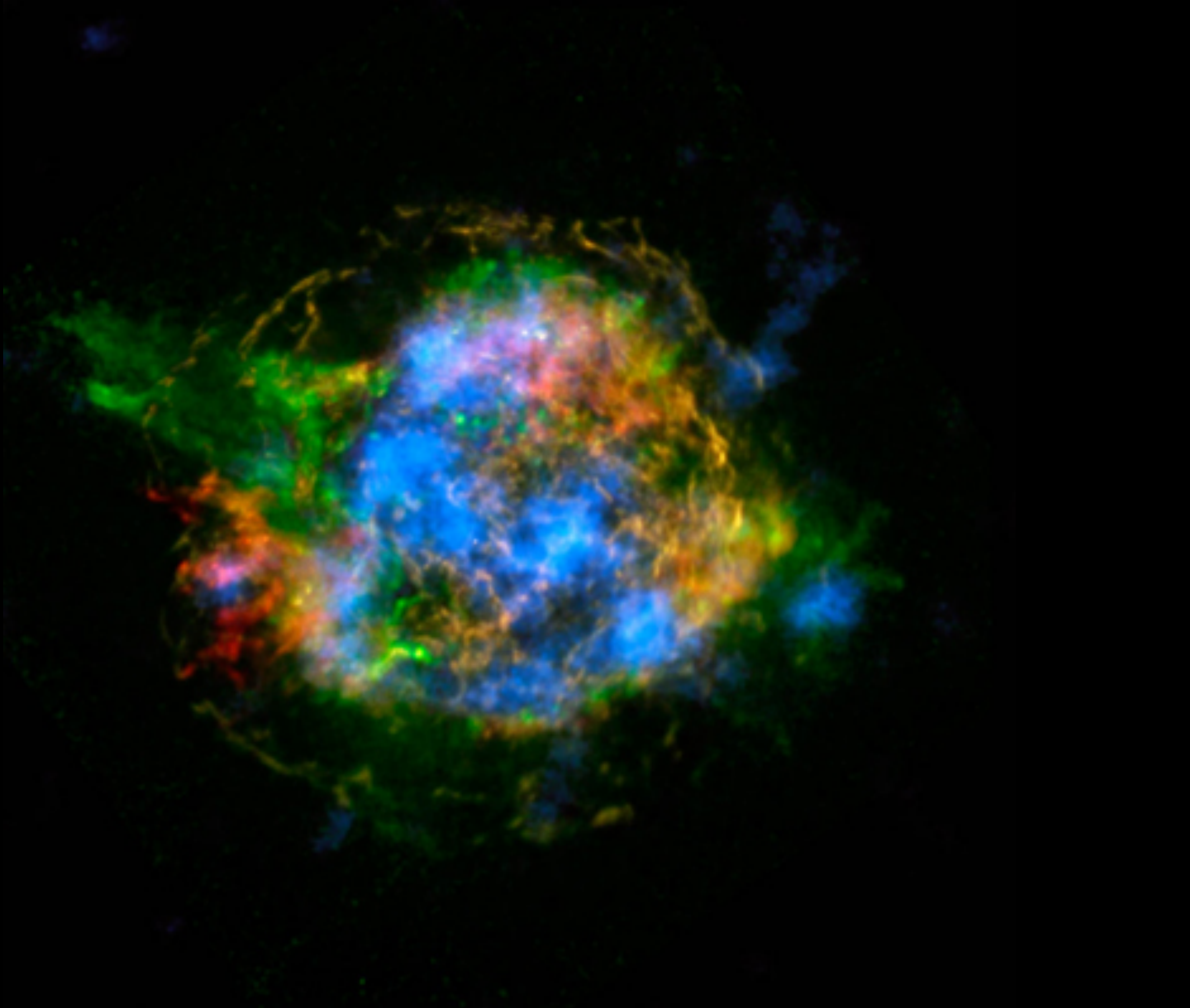
ISAC's continuing mission to explore the stars

Alison Laird

THE UNIVERSITY of York

Outline

- Exploring the stars
- ISAC's unique fleet
- The first mission …
- Pushing the limits
- The continuing mission
- Summary



NuSTAR observations of Cassiopeia A

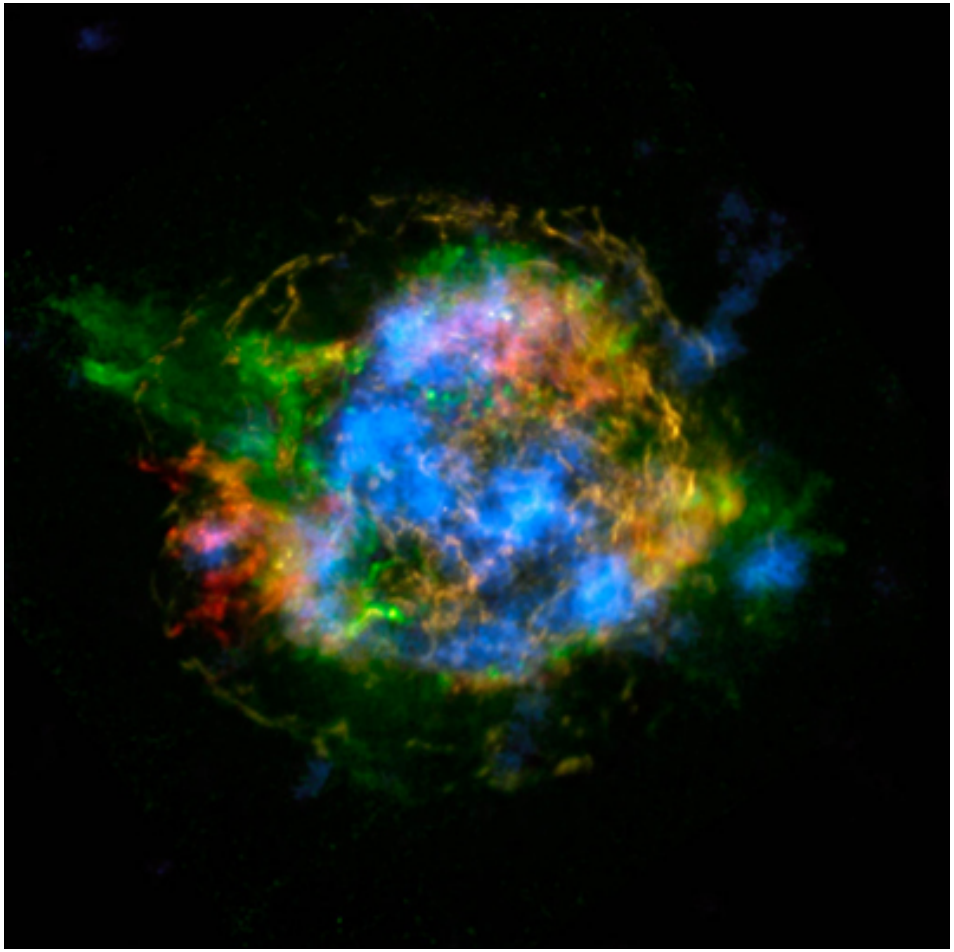
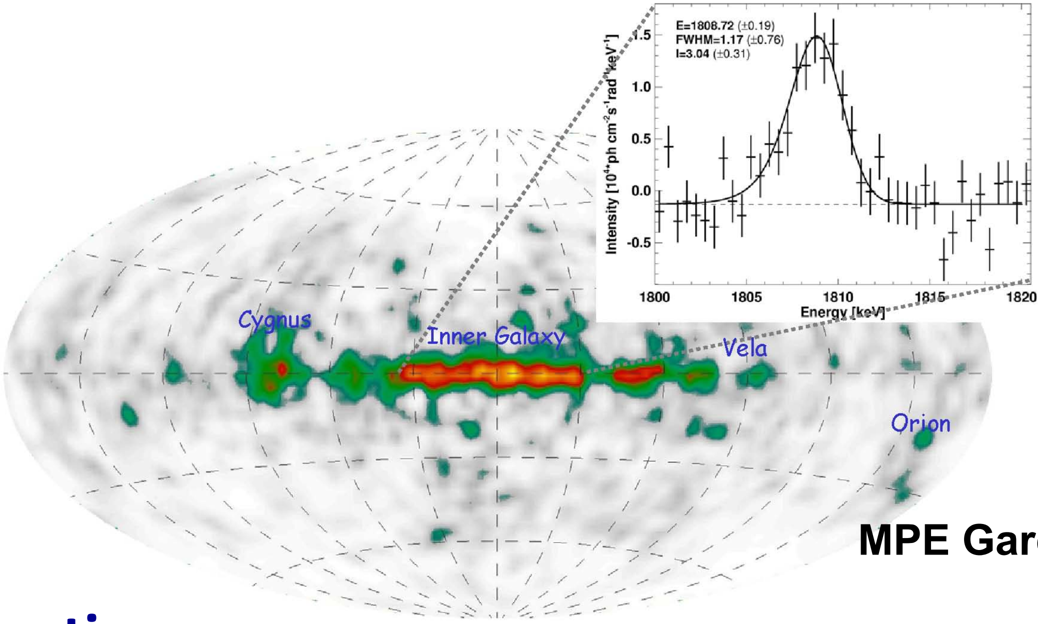


Image of Cas A from NuSTAR – red shows Fe, blue is Ti, green is Si
⇒ can study relative Ti/Ni yields in specific regions
⇒ explosion is highly asymmetric (also abundance highly asymmetric)
⇒ can use relative yields (not just total) to probe explosion characteristics
⇒ need robust (and consistent) nuclear physics input

^{26}Al in the Galaxy

$^{26}\mathrm{Al}$ ($T_{1/2}$ = 7.4 10^5 yr): $^{26}\mathrm{Al} \xrightarrow{\beta+} {}^{26}\mathrm{Mg}^* \xrightarrow[1.809\ \mathrm{MeV}]{\gamma} {}^{26}\mathrm{Mg}$



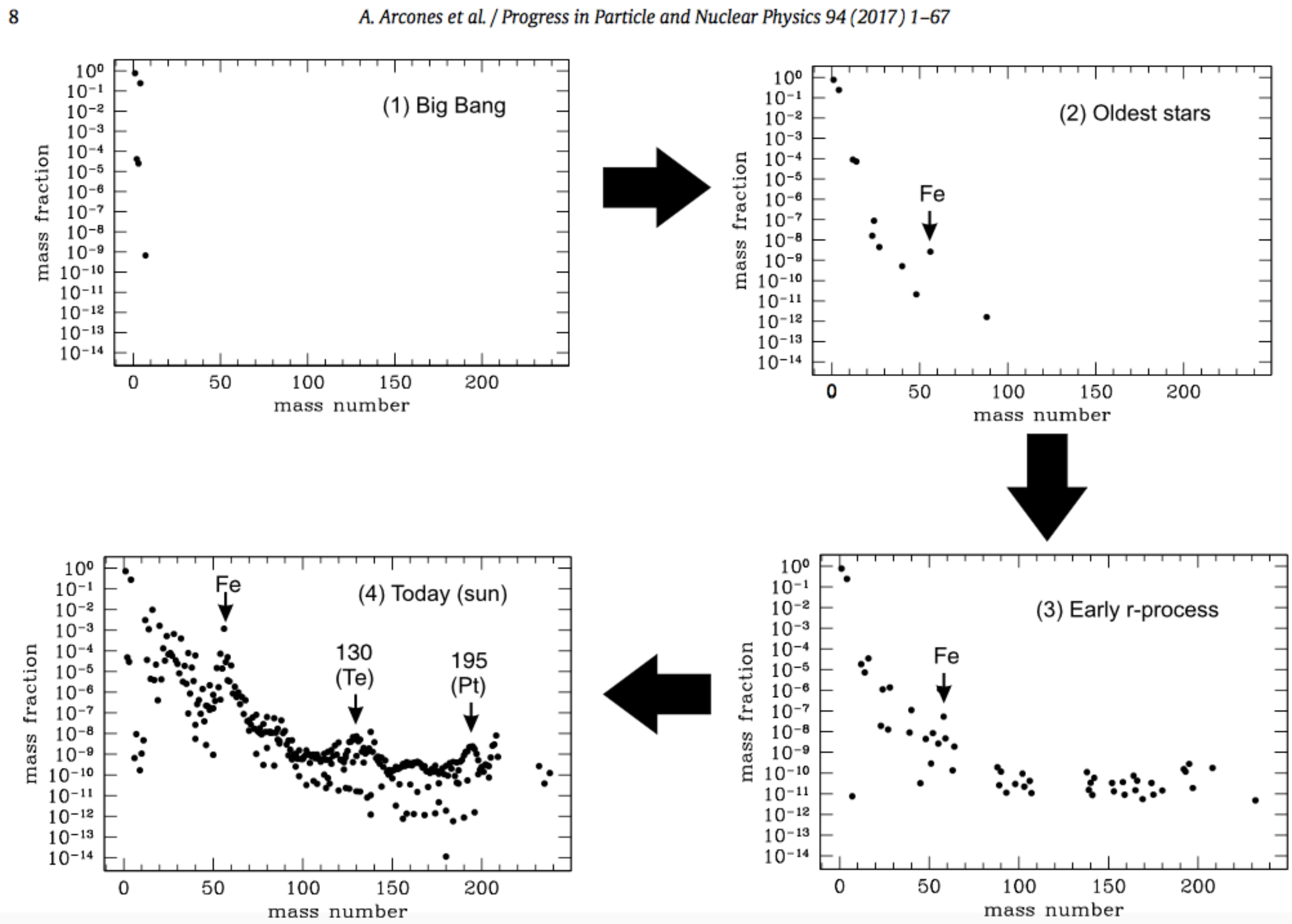
MPE Garching/R. Diehl

γ-ray observations

- COMPTEL@CGRO, SPI@INTEGRAL
- synthesised throughout Galaxy
- 2-3 solar masses equilibrium mass
- Doppler shift of line indicates co-rotation with Galaxy

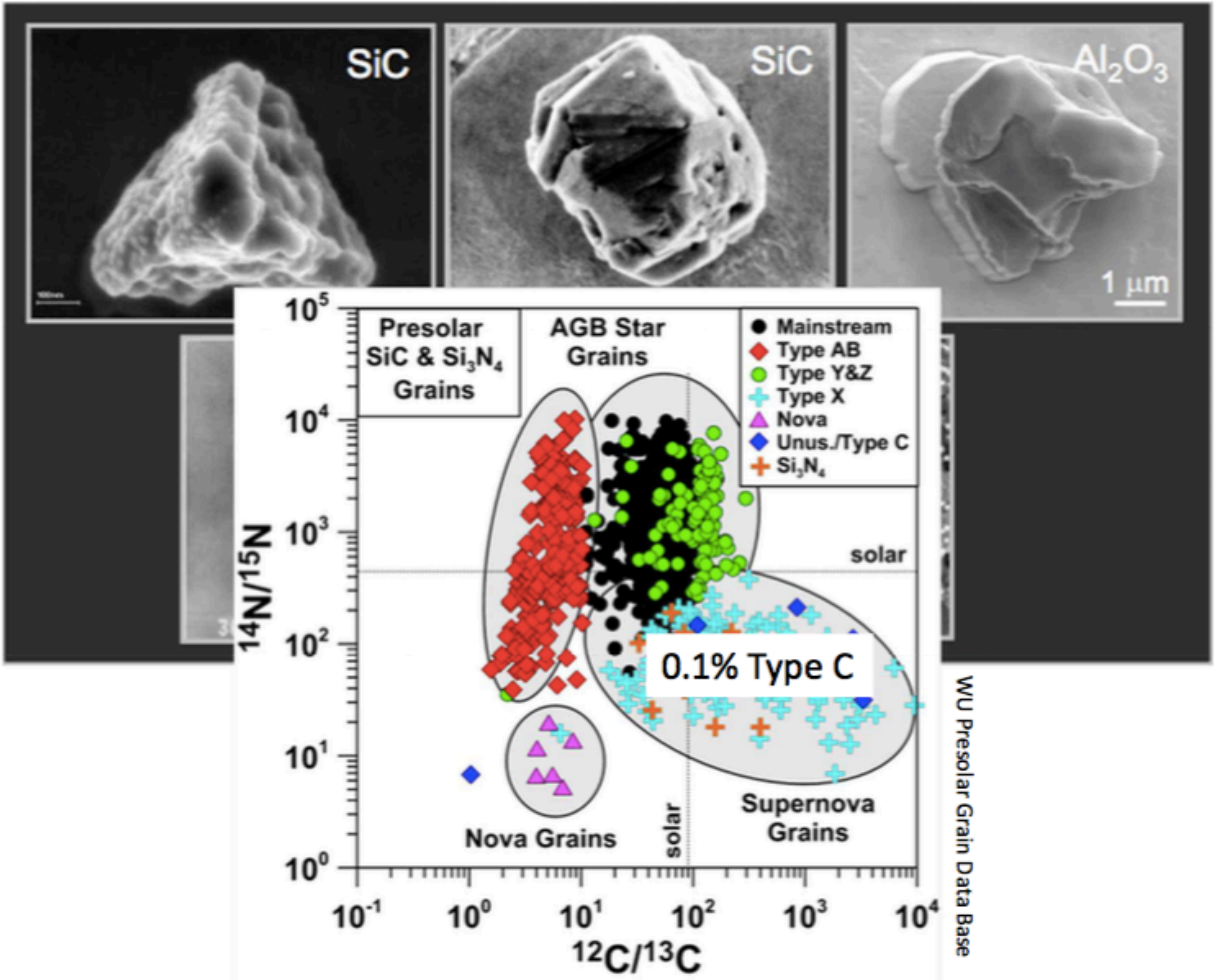
=> *Unambiguous direct evidence for nucleosynthesis in stars*

Evolution of chemical elements



8 A. Arcones et al. / Progress in Particle and Nuclear Physics 94 (2017) 1–67

To understand origin and evolution of elements we need to understand the contribution from different stars and explosions, at different times.



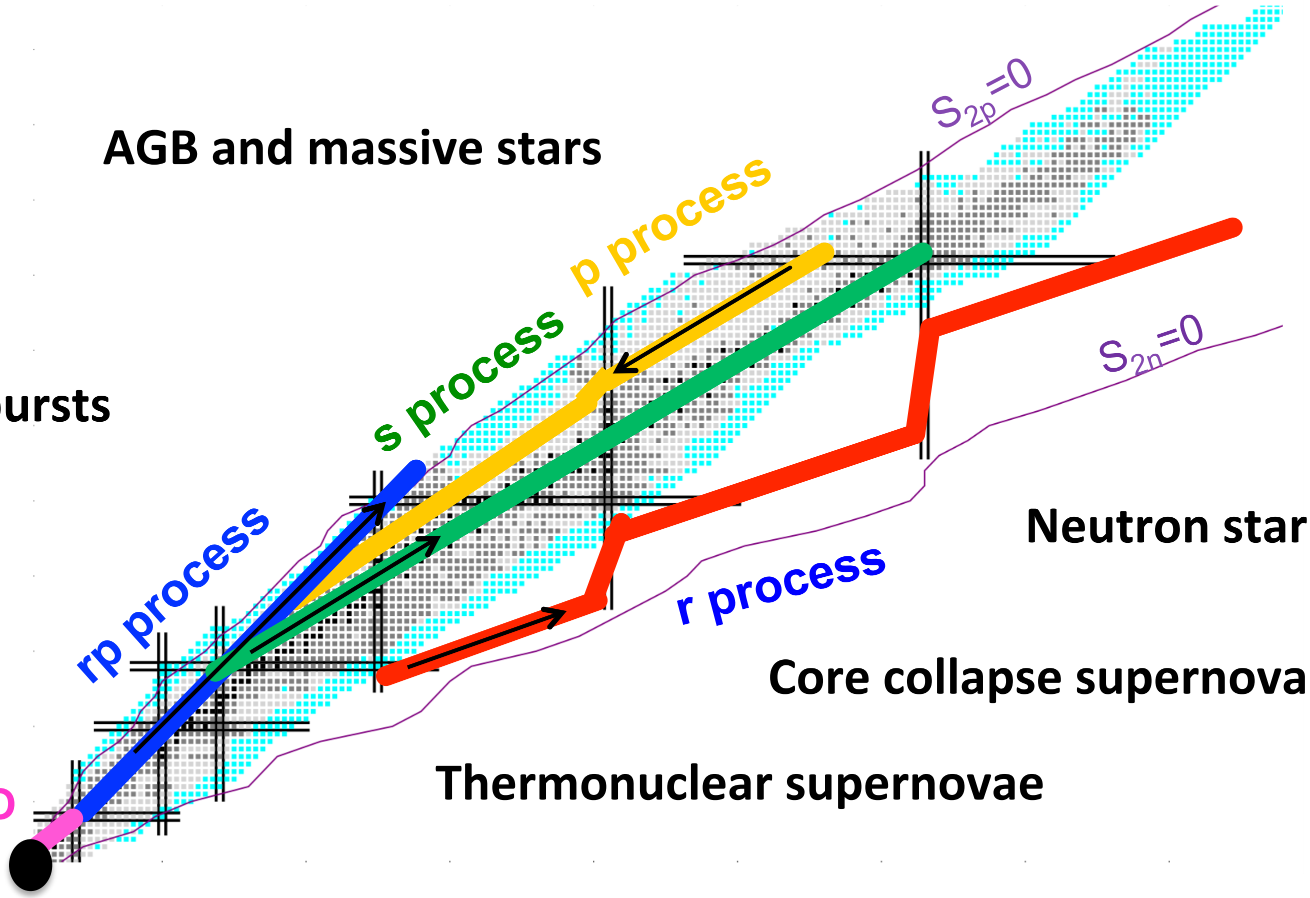
0.1% Type C

WU Presolar Grain Data Base

AGB and massive stars

X-ray bursts

Novae



BBN

Neutron star mergers

Core collapse supernovae

Thermonuclear supernovae

AGB and massive stars

To model these stars and stellar explosions, the models need the **thermonuclear reaction rate.**

In the case of individual, narrow resonances dominating the rate, then

$$N_A\langle\sigma v\rangle = 1.54 \times 10^{11}(\mu T_9)^{-3/2}\omega\gamma \exp\left(-11.605\frac{E_R}{T_9}\right)$$

Otherwise we measure the **cross section** over the appropriate energy range (Gamow window) for the temperature of the environment.

ISAC’s unique fleet

In the last two decades, ISAC has achieved around **ten direct measurements** for nuclear astrophysics with radioactive beams, as well as a number of indirect studies (see Dr Davids' talk later today).

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This has only been made possible by:

- ✓ High intensity radioactive beams
- ✓ Beam energies needed for astrophysics
- ✓ High quality beam (energy spread, time spread, purity, etc)
- ✓ Dedicated facilities

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This unique combination has proven extremely powerful for nuclear astrophysics, with many high profile publications…

VOLUME 90, NUMBER 16 PHYSICAL REVIEW LETTERS week ending 25 APRIL 2003

^{21}Na(p, γ)^{22}Mg Reaction and Oxygen-Neon Novae

S. Bishop,[1] R. E. Azuma,[2] L. Buchmann,[3] A. A. Chen,[1,*] M. L. Chatterjee,[4] J. M. D'Auria,[1,†] S. Engel,[5] D. Gigliotti,[6] U. Greife,[7] M. Hernanz,[8] D. Hunter,[1] A. Hussein,[6] D. Hutcheon,[3] C. Jewett,[7] J. José,[8,9] J. King,[2] S. Kubono,[10] A. M. Laird,[3] M. Lamey,[1] R. Lewis,[11] W. Liu,[1] S. Michimasa,[10] A. Olin,[3,12] D. Ottewell,[3] P. D. Parker,[11] J. G. Rogers,[3] F. Strieder,[5] and C. Wrede[1]

THE

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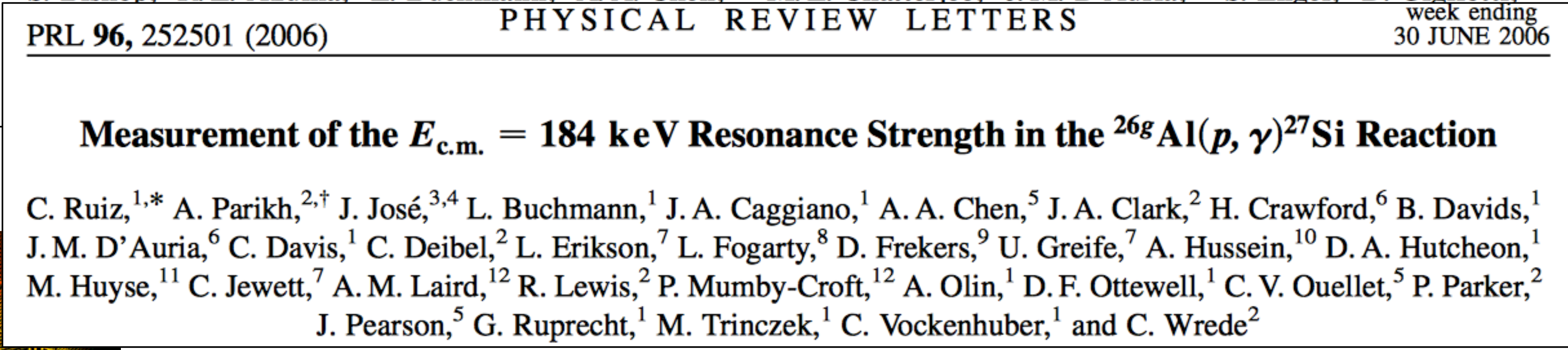

PRL 96, 252501 (2006) PHYSICAL REVIEW LETTERS week ending 30 JUNE 2006

Measurement of the $E_{\text{c.m.}} = 184$ keV Resonance Strength in the ^{26g}Al$(p, \gamma)^{27}$Si Reaction

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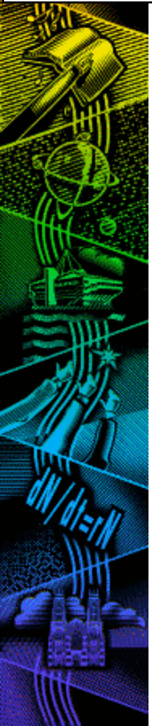

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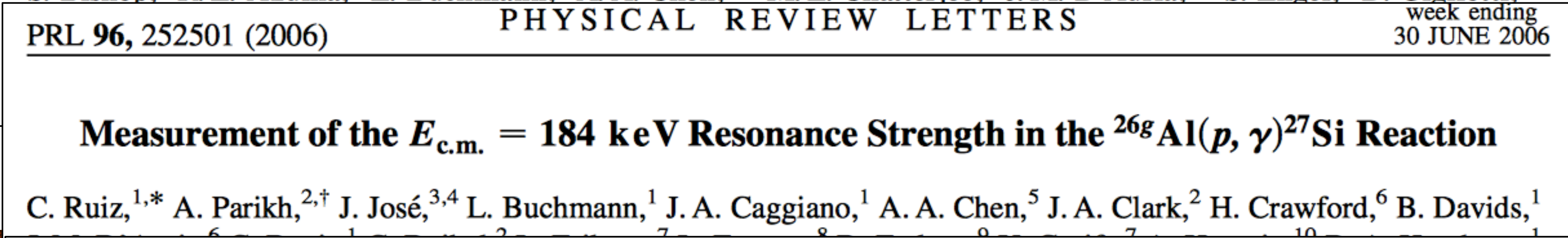

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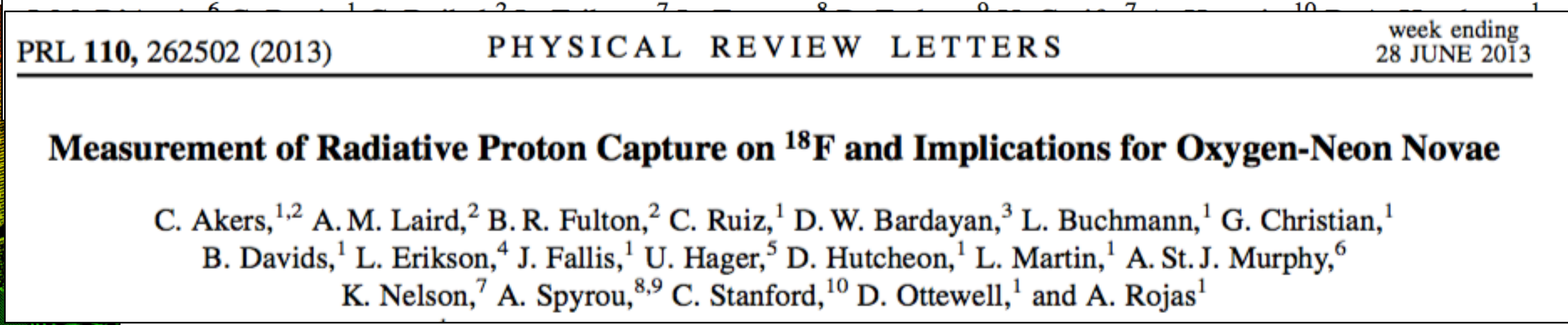

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Measurement of Radiative Proton Capture on ^{18}F and Implications for Oxygen-Neon Novae

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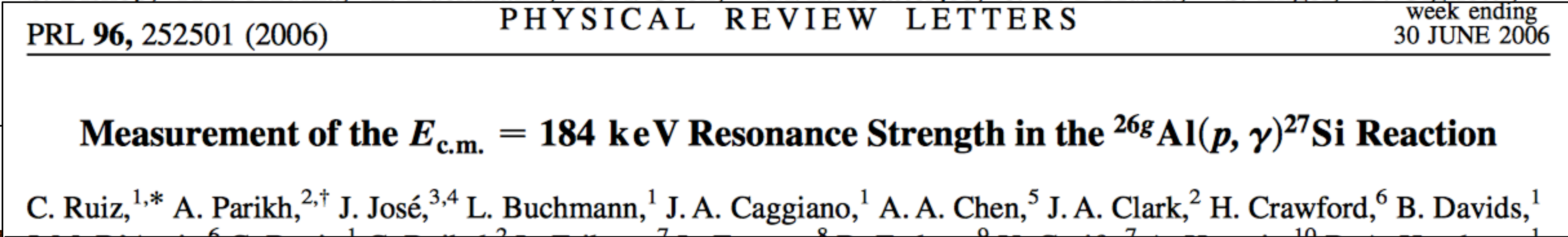
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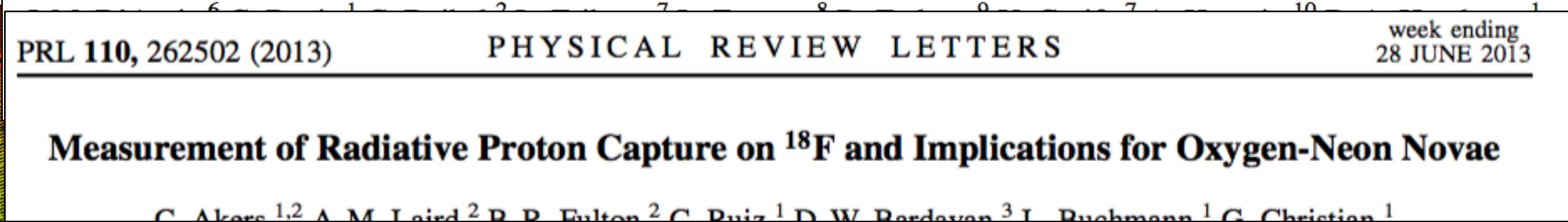
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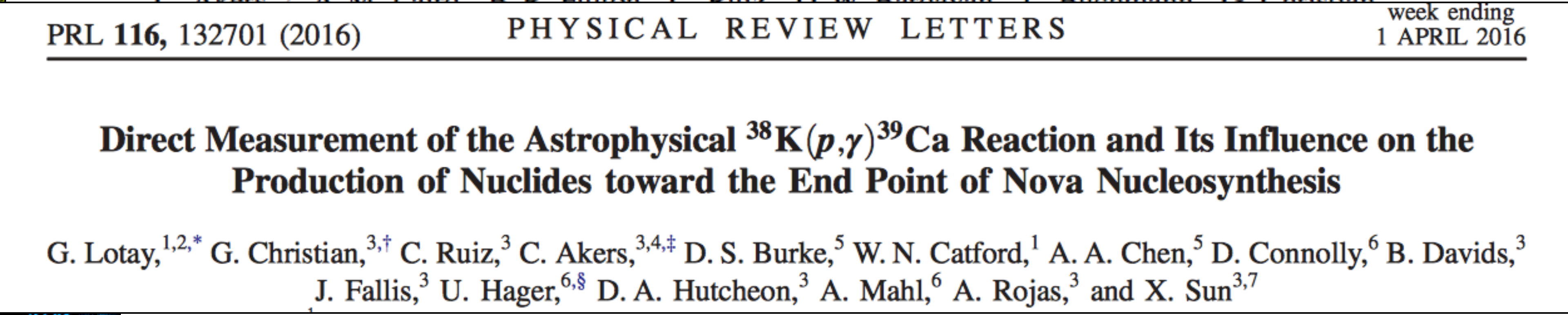
PRL 116, 132701 (2016) PHYSICAL REVIEW LETTERS week ending 1 APRIL 2016

Direct Measurement of the Astrophysical ^{38}K(p,γ)^{39}Ca Reaction and Its Influence on the Production of Nuclides toward the End Point of Nova Nucleosynthesis

G. Lotay,[1,2,*] G. Christian,[3,†] C. Ruiz,[3] C. Akers,[3,4,‡] D. S. Burke,[5] W. N. Catford,[1] A. A. Chen,[5] D. Connolly,[6] B. Davids,[3]
J. Fallis,[3] U. Hager,[6,§] D. A. Hutcheon,[3] A. Mahl,[6] A. Rojas,[3] and X. Sun[3,7]

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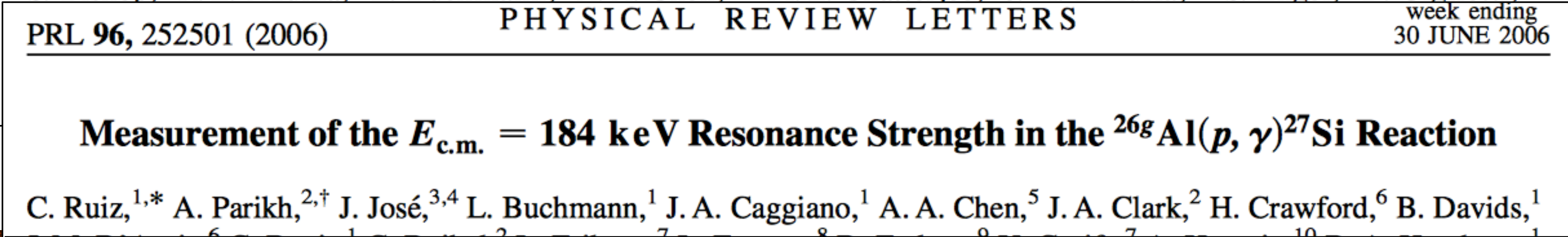

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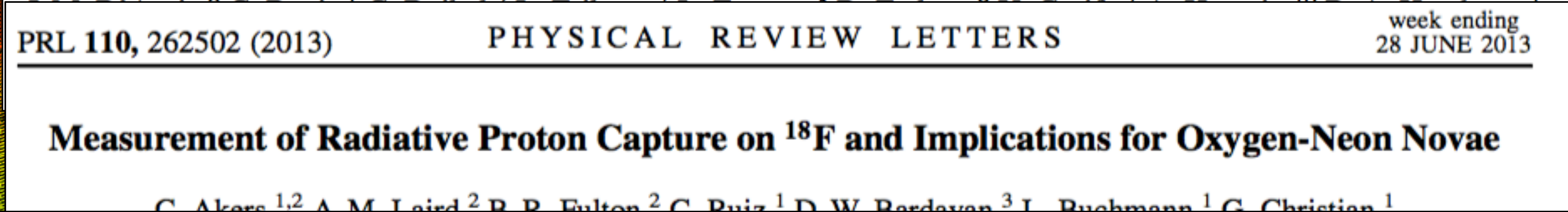

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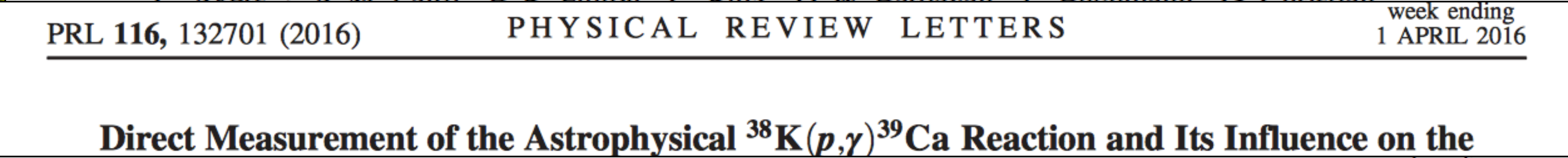

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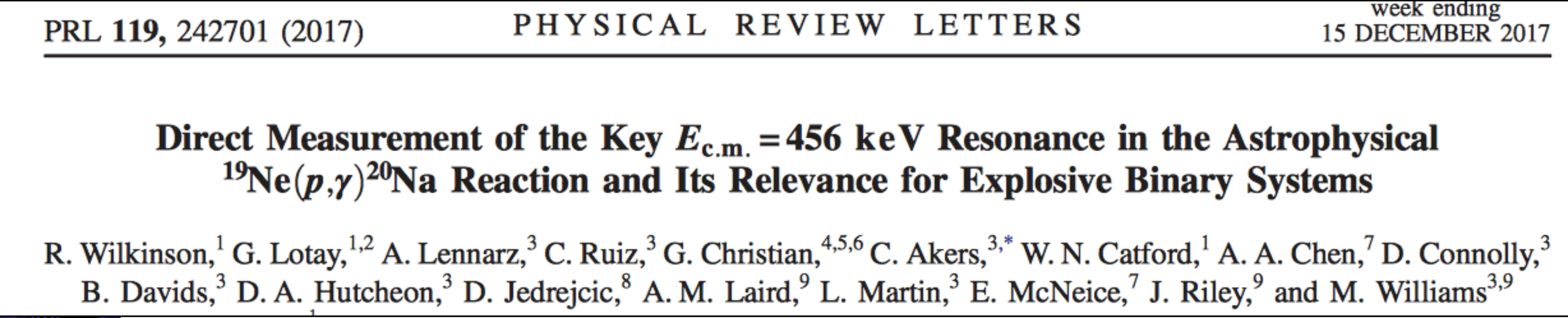

PRL 119, 242701 (2017) PHYSICAL REVIEW LETTERS week ending 15 DECEMBER 2017

Direct Measurement of the Key $E_{\text{c.m.}} = 456$ keV Resonance in the Astrophysical ^{19}Ne(p,γ)^{20}Na Reaction and Its Relevance for Explosive Binary Systems

R. Wilkinson,[1] G. Lotay,[1,2] A. Lennarz,[3] C. Ruiz,[3] G. Christian,[4,5,6] C. Akers,[3,*] W. N. Catford,[1] A. A. Chen,[7] D. Connolly,[3] B. Davids,[3] D. A. Hutcheon,[3] D. Jedrejcic,[8] A. M. Laird,[9] L. Martin,[3] E. McNeice,[7] J. Riley,[9] and M. Williams[3,9]

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✓ Dedicated facilities

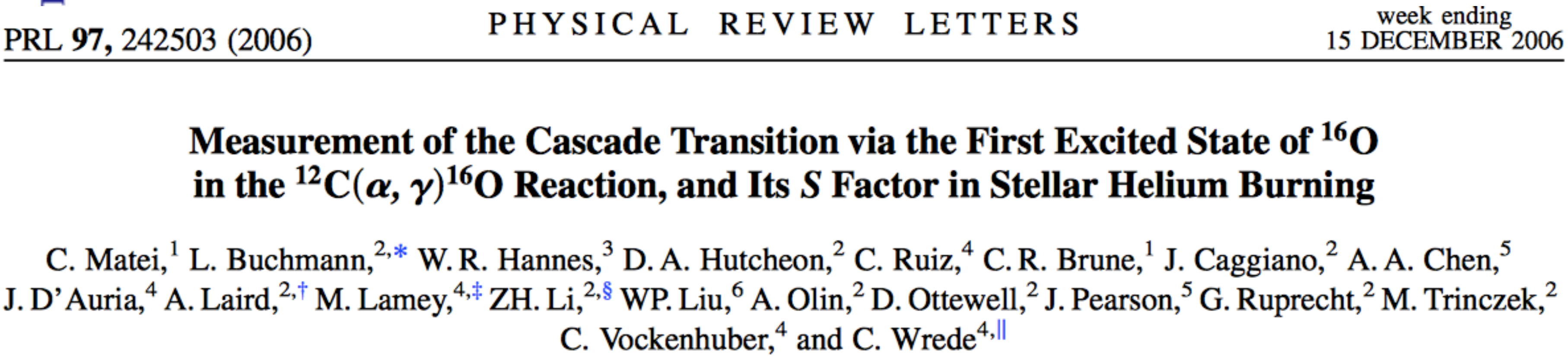
This unique combination has proven extremely powerful for nuclear astrophysics, with many high profile publications.

Indeed, several stable beam measurements have also resulted in high profile papers.

PRL **97,** 242503 (2006) PHYSICAL REVIEW LETTERS week ending 15 DECEMBER 2006

Measurement of the Cascade Transition via the First Excited State of ^{16}O in the ^{12}C(α, γ)^{16}O Reaction, and Its S Factor in Stellar Helium Burning

C. Matei,[1] L. Buchmann,[2,*] W. R. Hannes,[3] D. A. Hutcheon,[2] C. Ruiz,[4] C. R. Brune,[1] J. Caggiano,[2] A. A. Chen,[5] J. D'Auria,[4] A. Laird,[2,†] M. Lamey,[4,‡] ZH. Li,[2,§] WP. Liu,[6] A. Olin,[2] D. Ottewell,[2] J. Pearson,[5] G. Ruprecht,[2] M. Trinczek,[2] C. Vockenhuber,[4] and C. Wrede[4,||]



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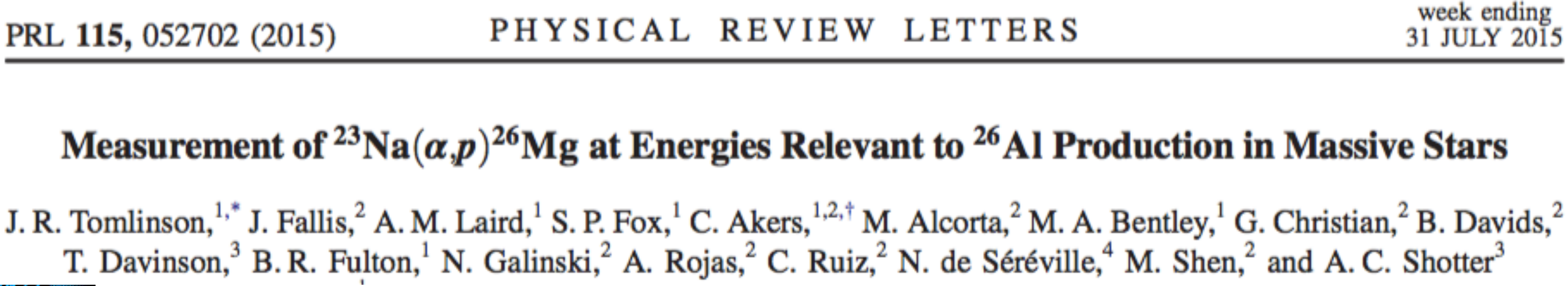

PRL **115,** 052702 (2015) PHYSICAL REVIEW LETTERS week ending 31 JULY 2015

Measurement of ^{23}Na(α,p)^{26}Mg at Energies Relevant to ^{26}Al Production in Massive Stars

J. R. Tomlinson,[1,*] J. Fallis,[2] A. M. Laird,[1] S. P. Fox,[1] C. Akers,[1,2,†] M. Alcorta,[2] M. A. Bentley,[1] G. Christian,[2] B. Davids,[2] T. Davinson,[3] B. R. Fulton,[1] N. Galinski,[2] A. Rojas,[2] C. Ruiz,[2] N. de Séréville,[4] M. Shen,[2] and A. C. Shotter[3]

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PRL **97,** 242503 (2006)

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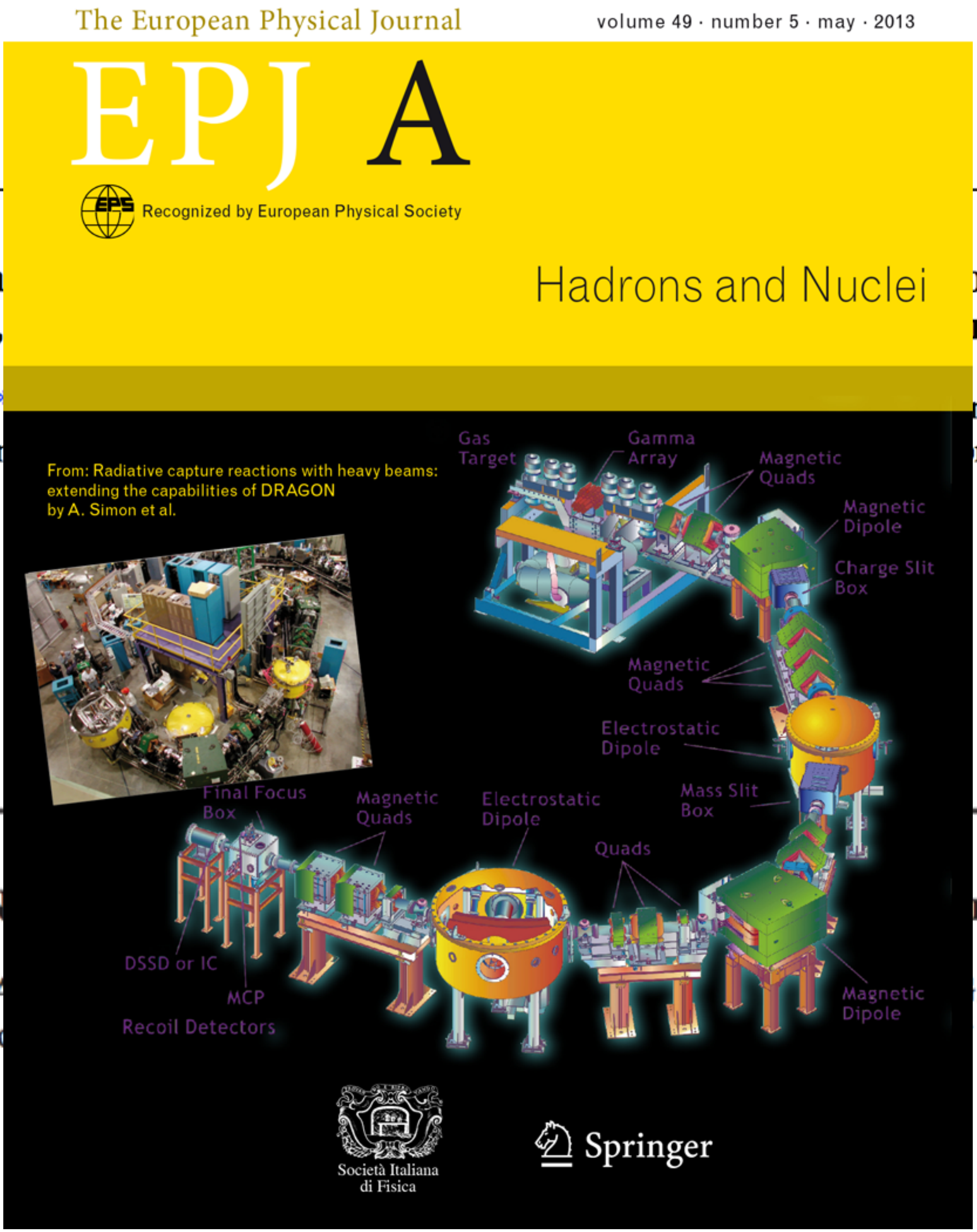

The European Physical Journal

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EPJ A

Recognized by European Physical Society

Hadrons and Nuclei

From: Radiative capture reactions with heavy beams: extending the capabilities of DRAGON by A. Simon et al.

Società Italiana di Fisica

Springer

PRL **115,** 052702 (2015)

week ending
31 JULY 2015

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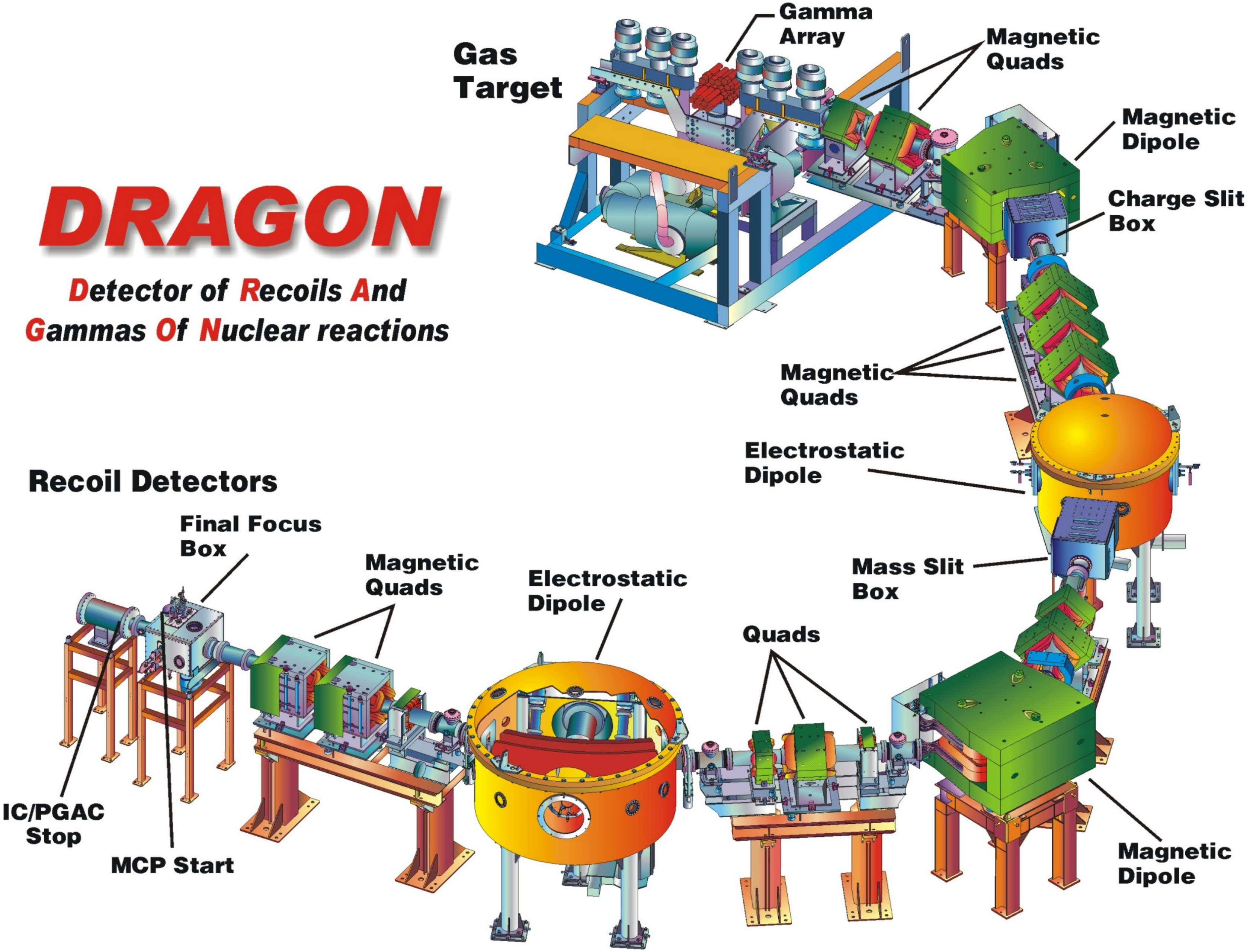
T. Davinson,[3] B. R. Fult and A. C. Shotter[3]

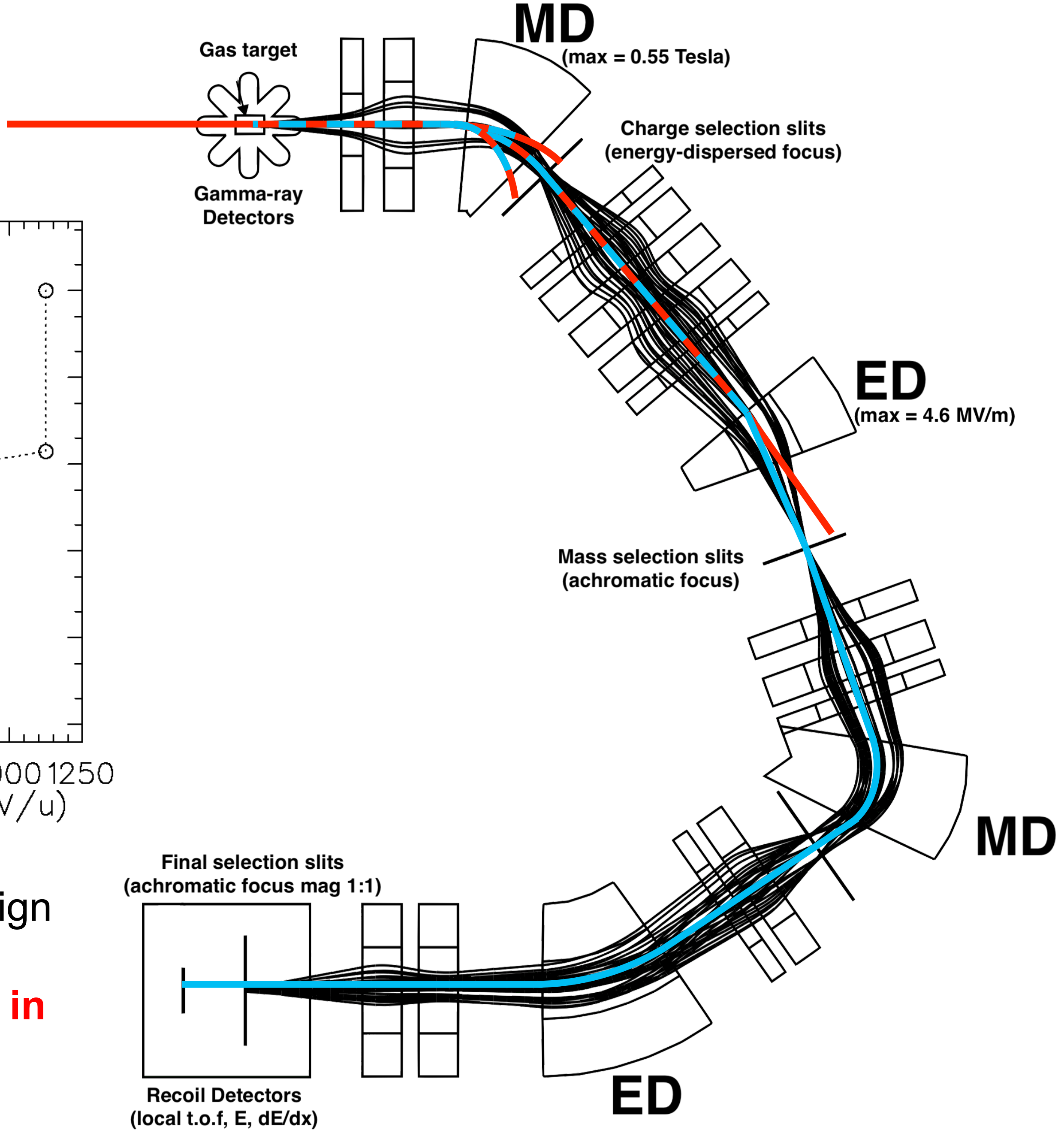
Detector of **R**ecoils **A**nd **G**ammas **O**f **N**uclear reactions

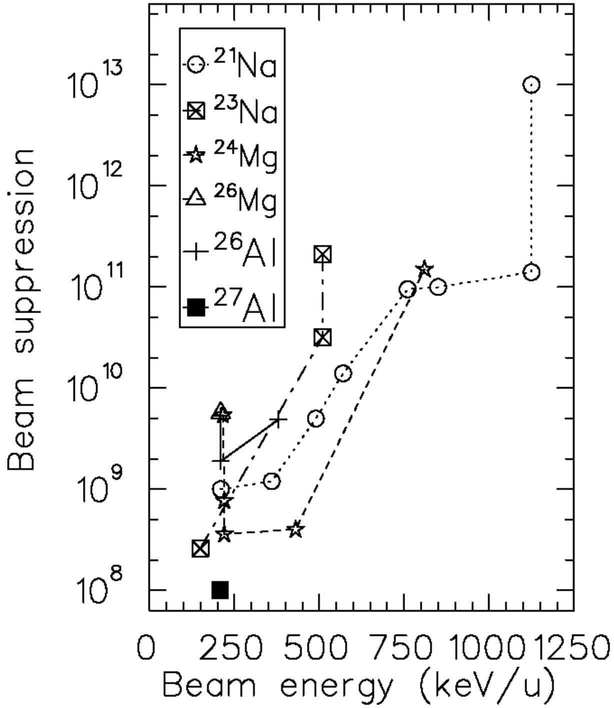
The DRAGON recoil separator

DRAGON

Detector of **R**ecoils **A**nd **G**ammas **O**f **N**uclear reactions

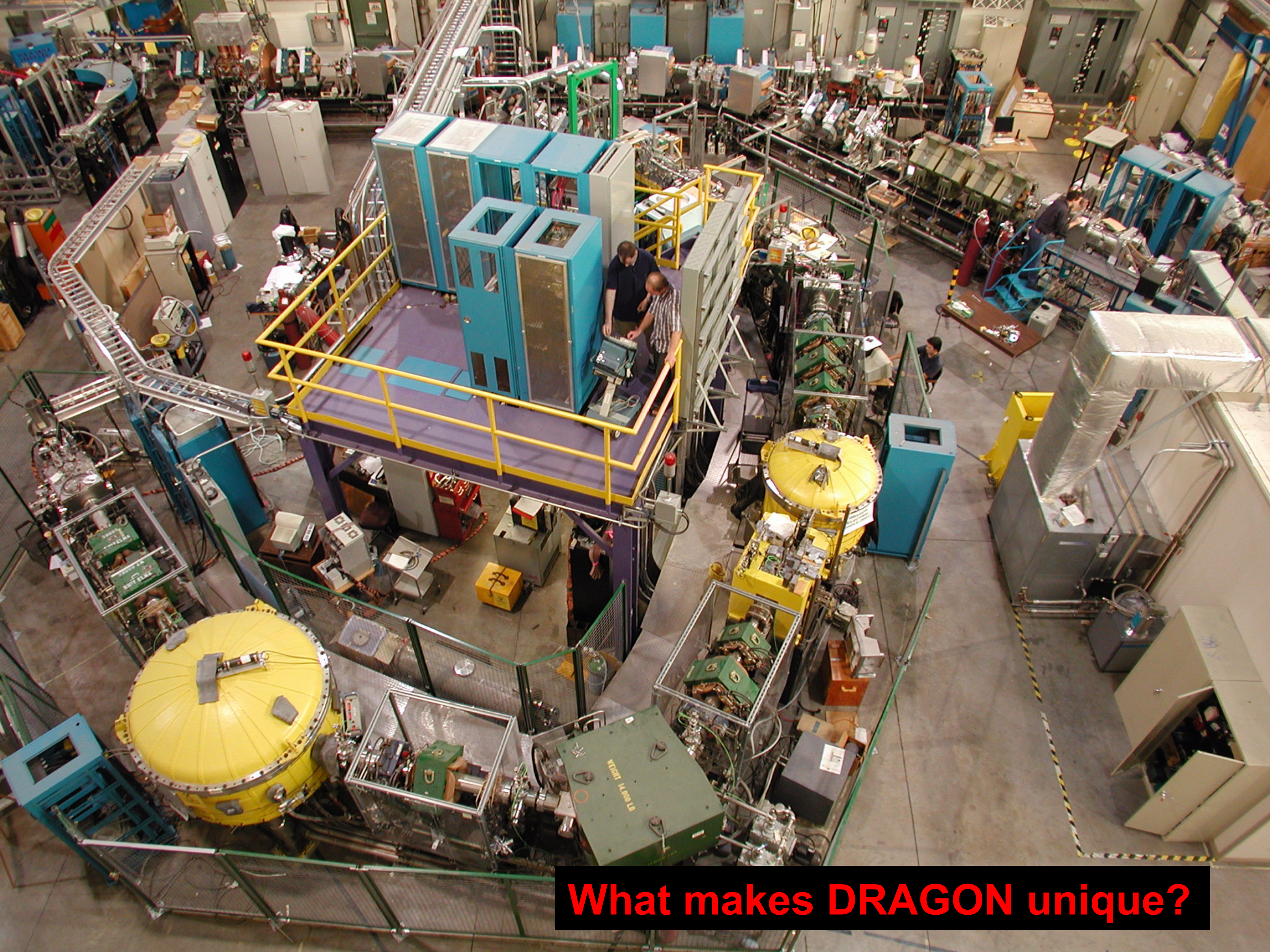




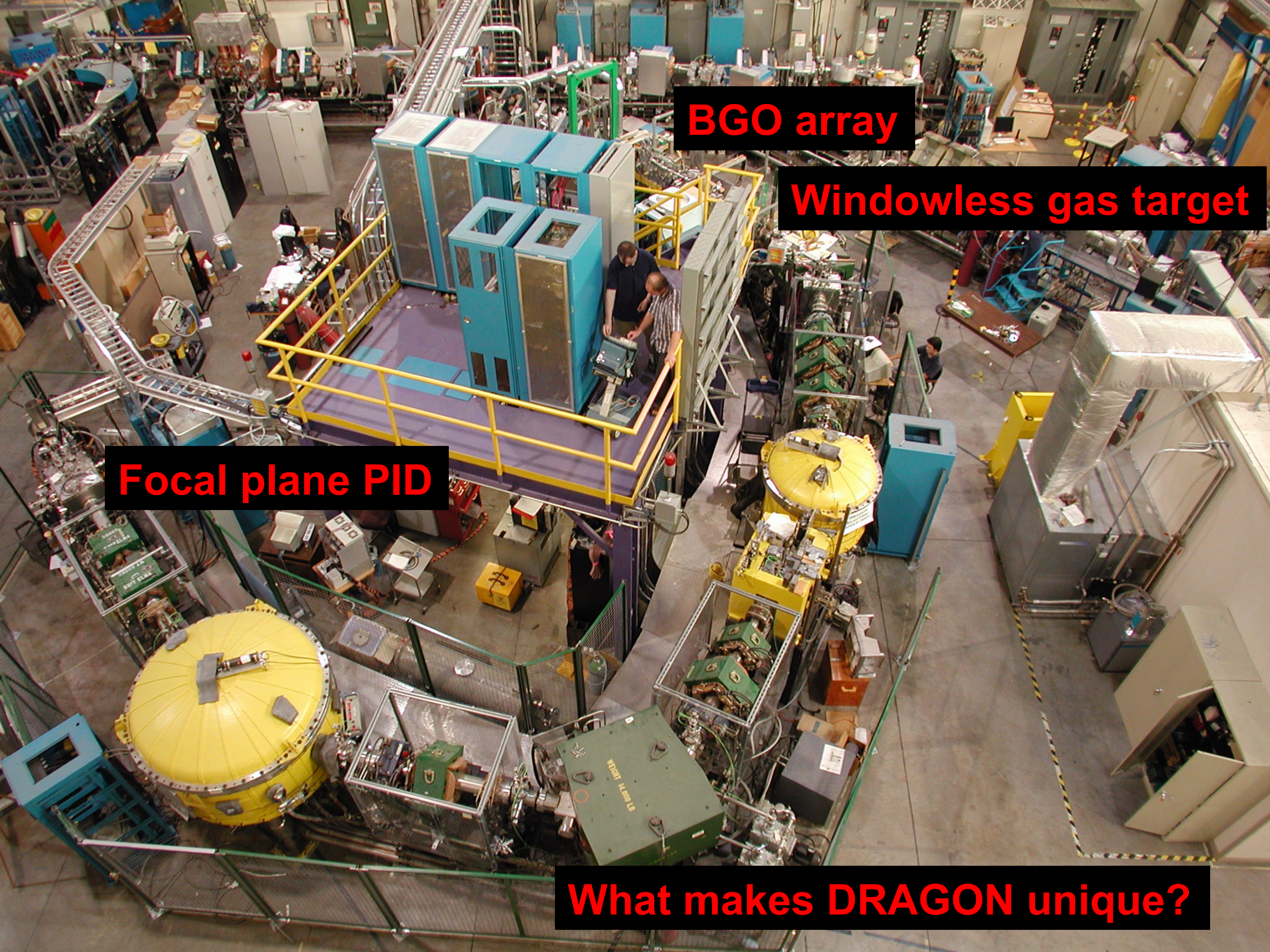


Dave Hutcheon’s design

Best beam rejection in the world.



What makes DRAGON unique?



What makes DRAGON unique?

BGO array

Windowless gas target

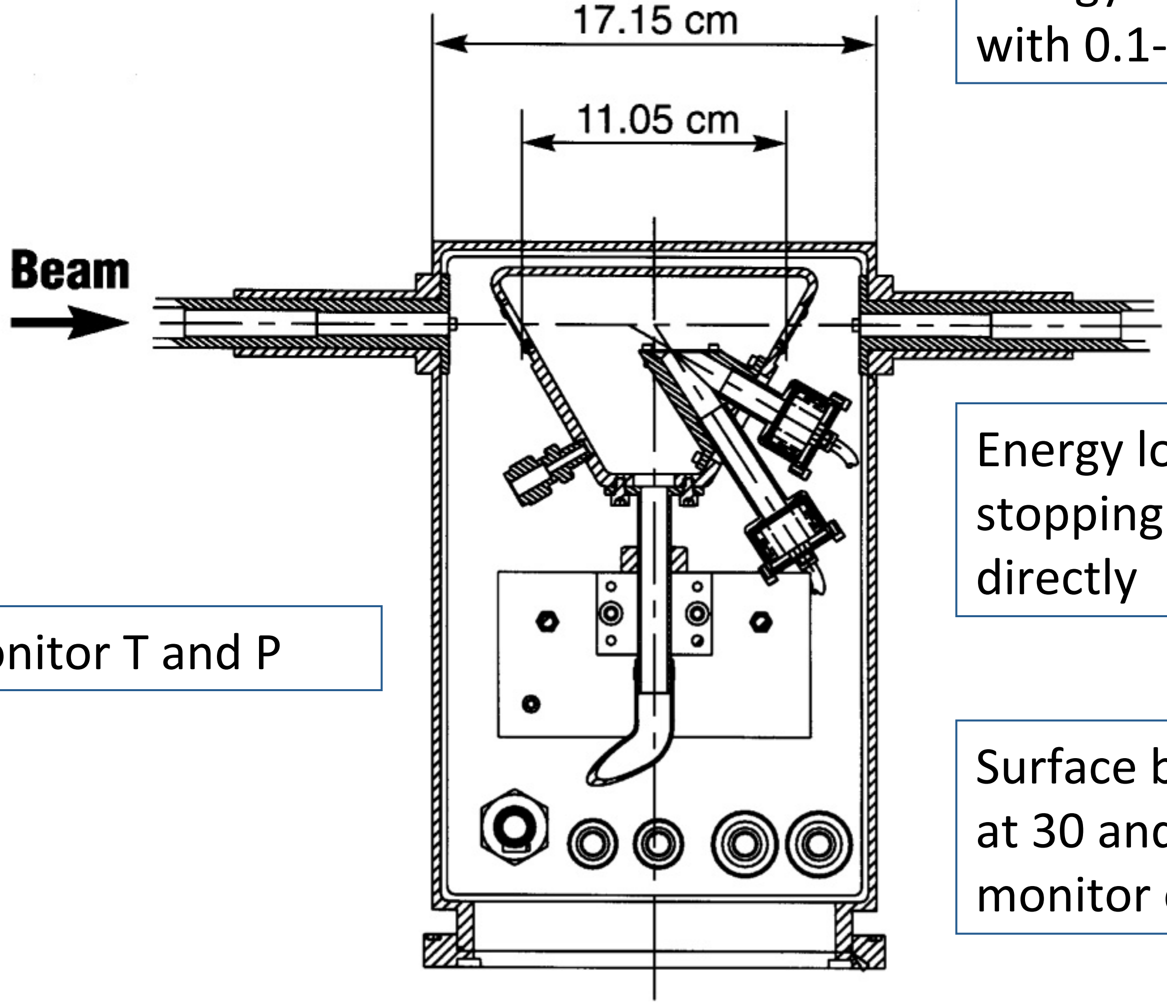
Focal plane PID

DRAGON gas target

Windowless, differentially pumped, recirculating **gas target** (H_2 or He)

1-10 mbar (pumping constraints) → ≲6 x 10^{18} at/cm² H_2

LN_2 cooled zeolite cleaning trap



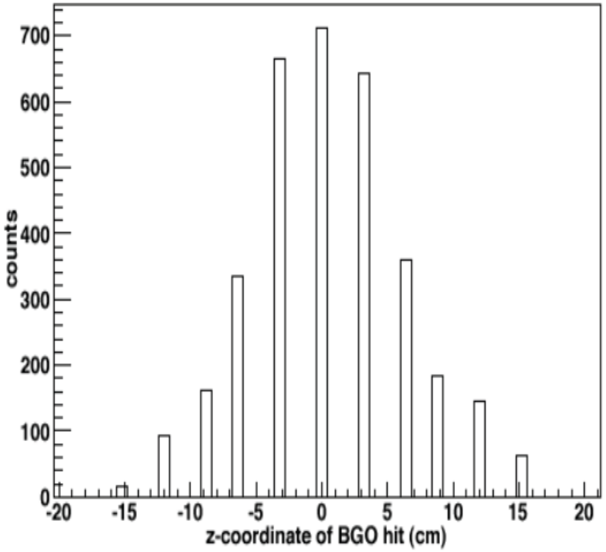
Energy can be measured with 0.1-0.2 % accuracy

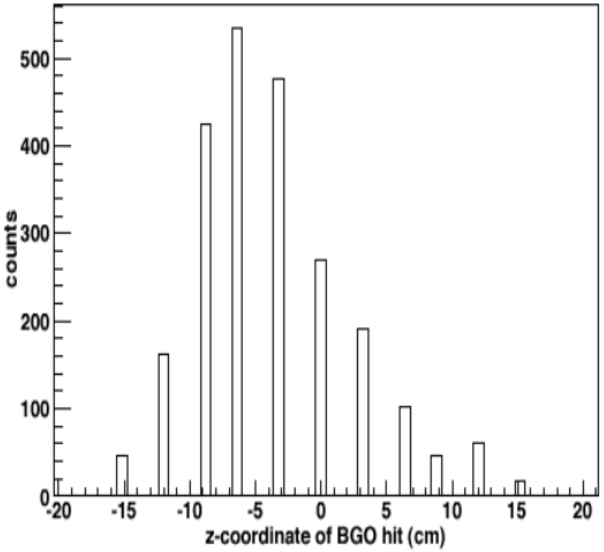
Energy loss & therefore stopping power measured directly

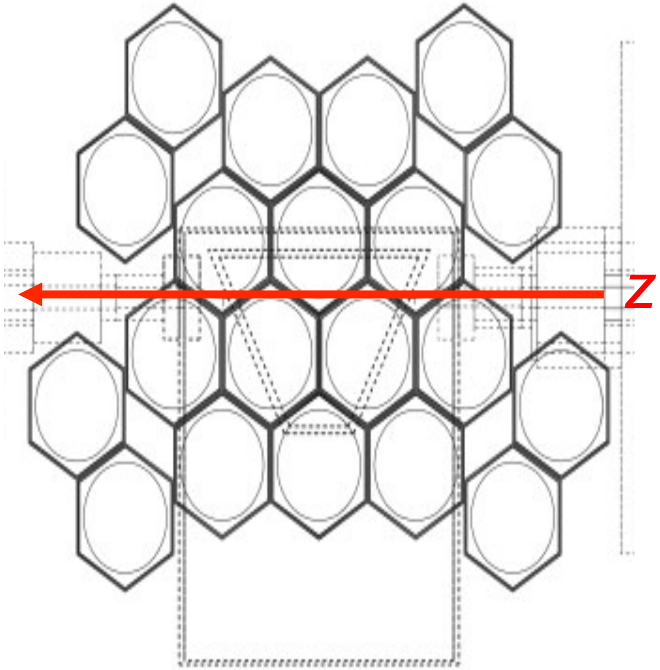
Monitor T and P

Surface barrier detectors at 30 and 57 deg. to monitor elastic scattering.

BGO Array



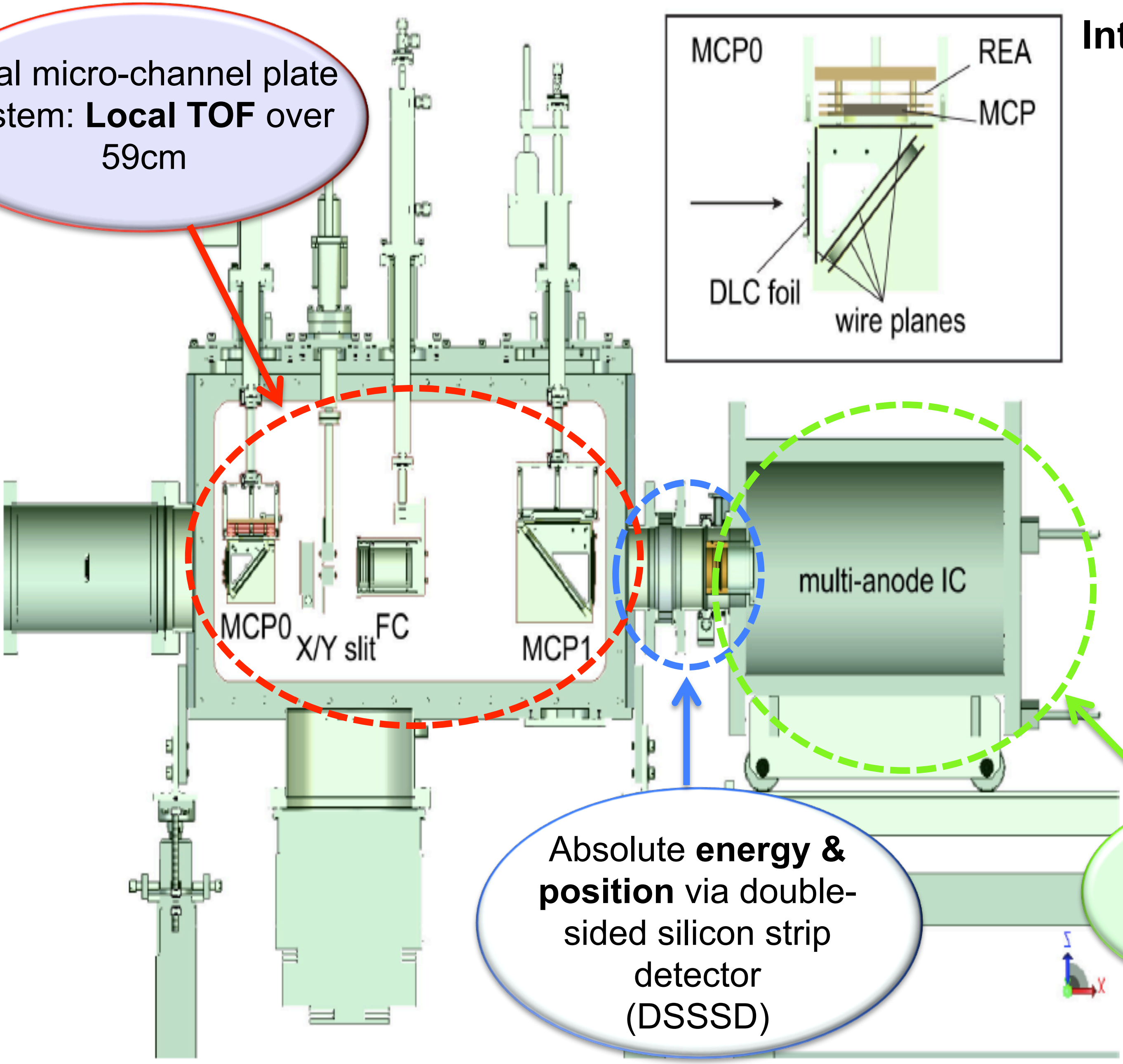




BGO array ‘tags’ recoil at focal plane.
Very high efficiency (40-90%!).

Use BGO crystal z-coordinate to extract resonance position within extended gas target.

Focal plane detectors - PID



Dual micro-channel plate system: **Local TOF** over 59cm

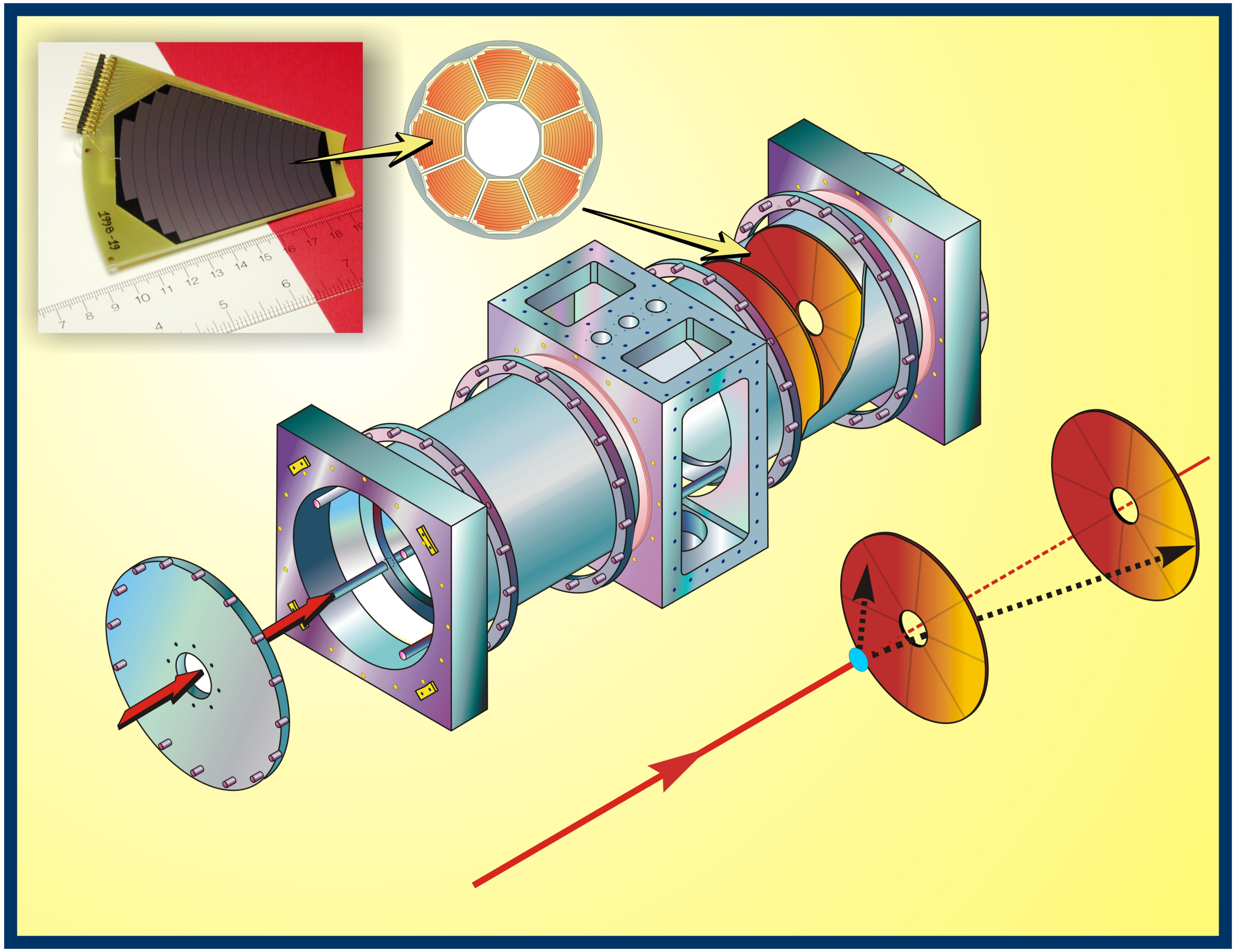
Absolute **energy & position** via double-sided silicon strip detector (DSSSD)

ΔE-E in ionization chamber for **Z-identification**

Interchangeable end detectors
IC or DSSSD
(Depending on reaction)

- Particle ID
- Local TOF
- ΔE/E, Total E

TRIUMF UK Detector Array



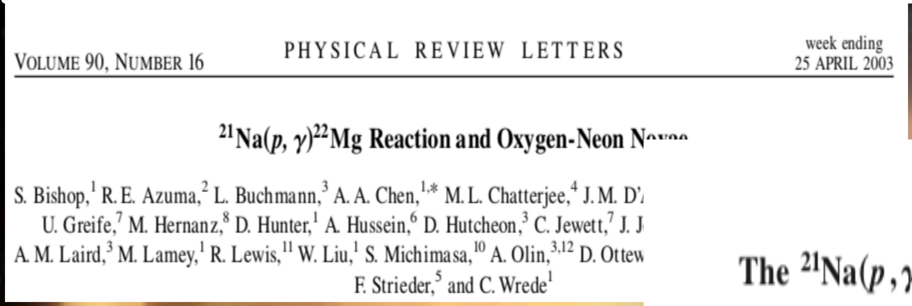
Versatile charged particle detection, based on silicon strip detector and high-linearity, low noise electronics.

Highly configurable setup, can be optimised for reaction under study.
High efficiency, high resolution.
512 separate detector channels, giving energy, timing and angle/position.
And, of course, the copper shack!

In the beginning….

In the beginning….
there was ^{21}Na…and lots of it!

^{21}Na(p,γ)^{22}Mg for ^{22}Na production in Classical Novae



VOLUME 90, NUMBER 16 PHYSICAL REVIEW LETTERS week ending 25 APRIL 2003

^{21}Na(p, γ)^{22}Mg Reaction and Oxygen-Neon N

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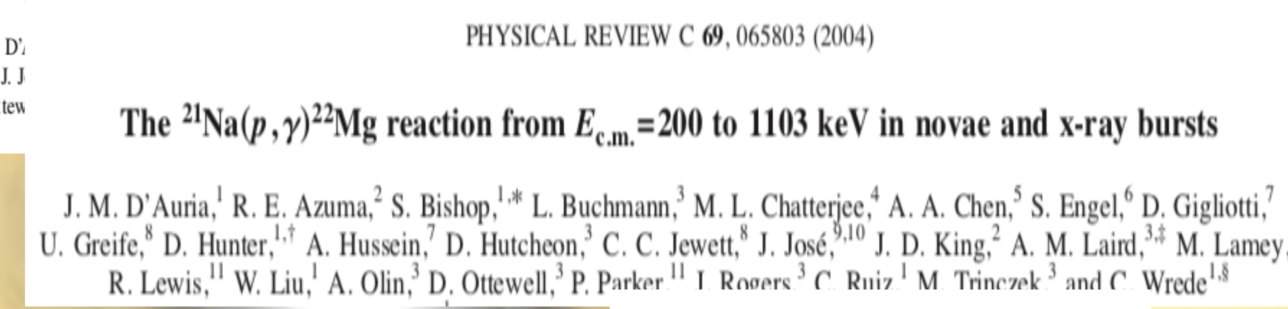

PHYSICAL REVIEW C **69**, 065803 (2004)

The ^{21}Na(p,γ)^{22}Mg reaction from $E_{c.m.}$=200 to 1103 keV in novae and x-ray bursts

J. M. D'Auria,[1] R. E. Azuma,[2] S. Bishop,[1,*] L. Buchmann,[3] M. L. Chatterjee,[4] A. A. Chen,[5] S. Engel,[6] D. Gigliotti,[7]
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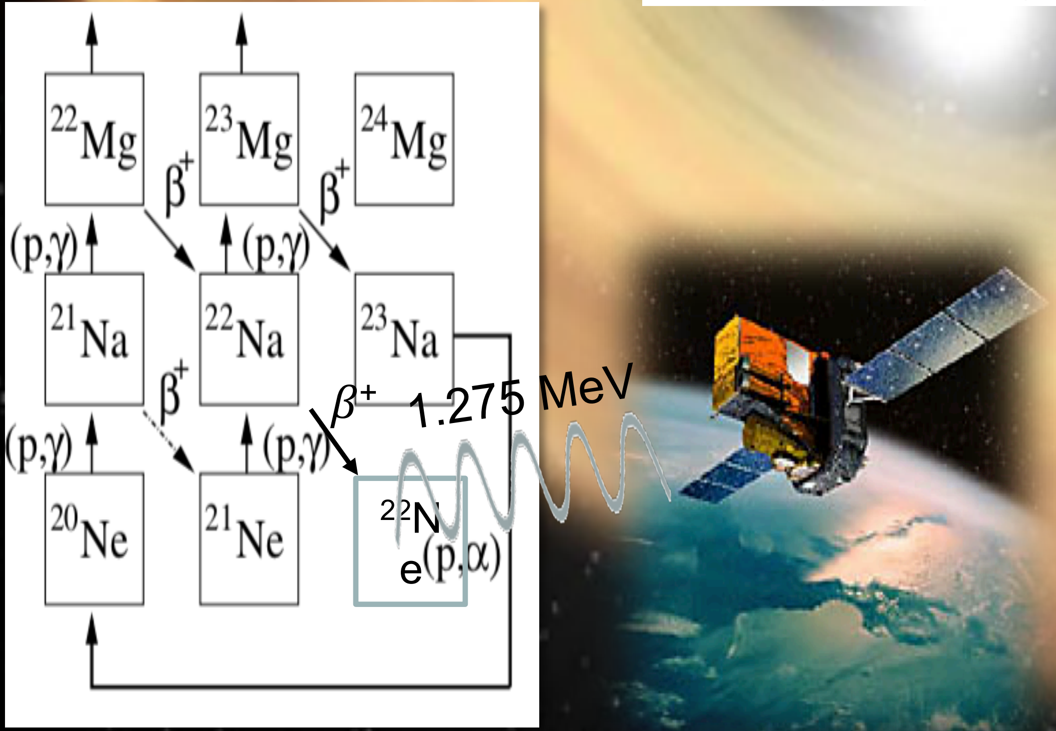
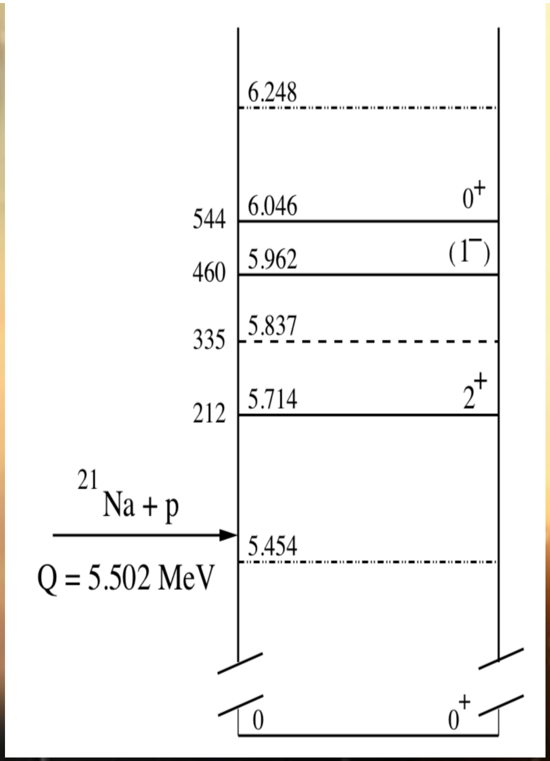
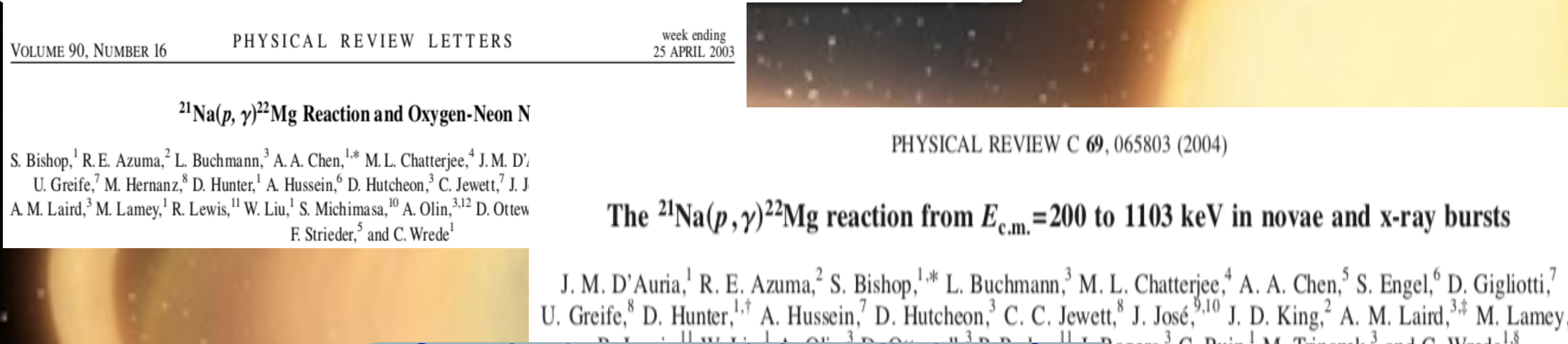




^{21}Na(p,γ)^{22}Mg for ^{22}Na production in Classical Novae



VOLUME 90, NUMBER 16 PHYSICAL REVIEW LETTERS week ending 25 APRIL 2003

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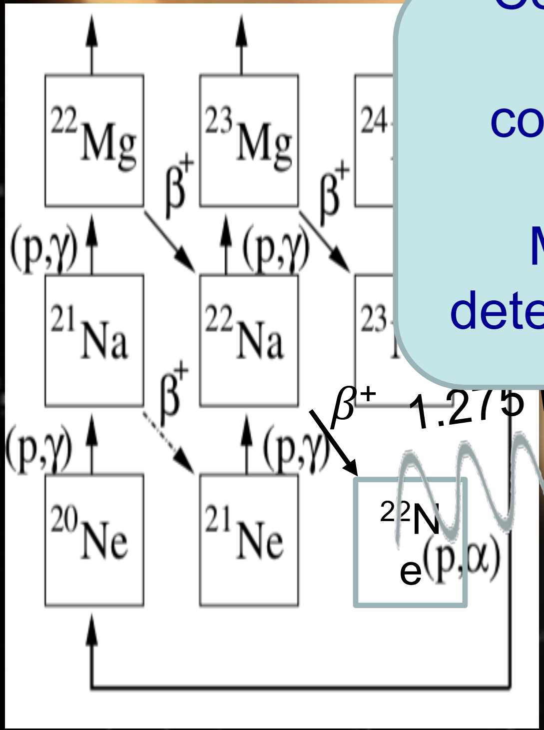
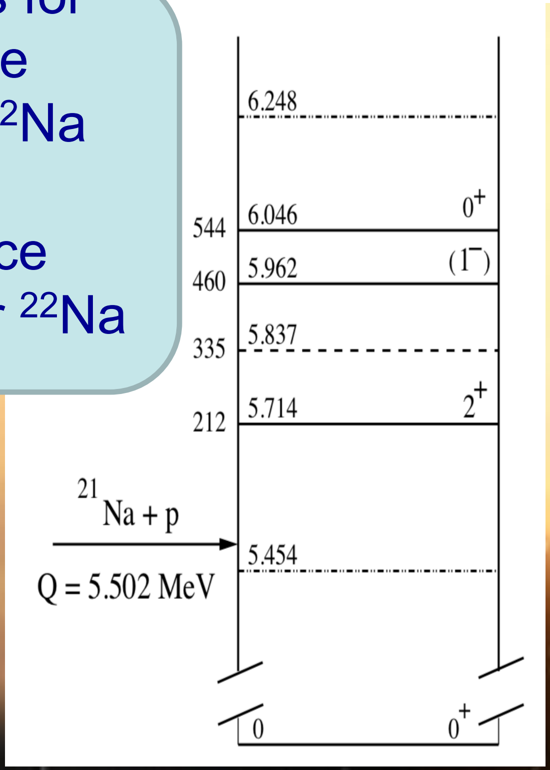
gers,[3] C. Ruiz,[1] M. Trinczek,[3] and C. Wrede[1,§]

Conclusions: model predictions for Oxygen-Neon Novae became consistent with upper limits of ^{22}Na observations…

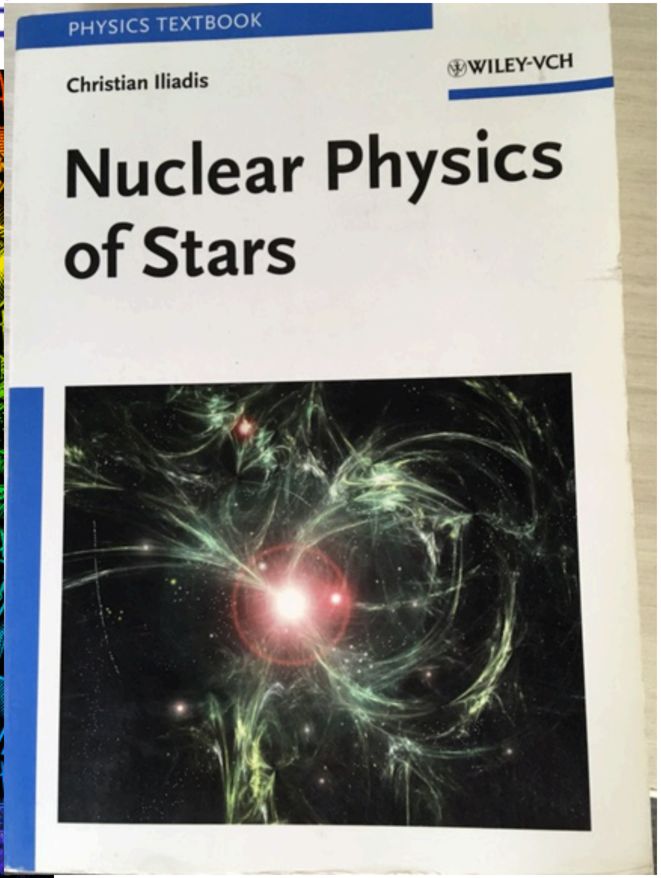
Maximum detectability distance determined to be 1 kiloparsec for ^{22}Na from these novae.





The Textbook case

Nuclear Physics of Star,
C. Iliadis
J. Wiley & Sons, 2007



PHYSICS TEXTBOOK

Christian Iliadis

WILEY-VCH

Nuclear Physics of Stars

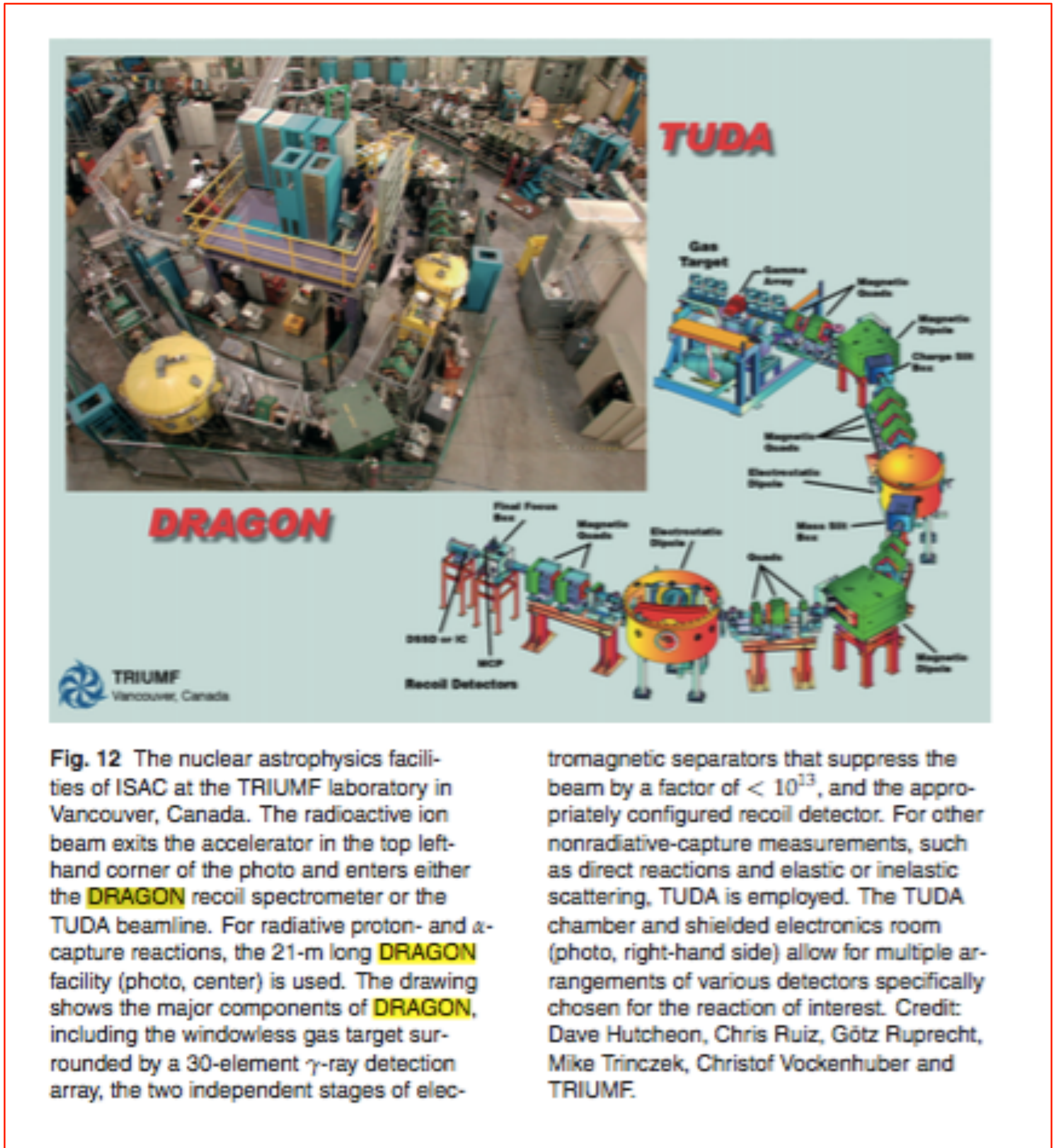


Fig. 12 The nuclear astrophysics facilities of ISAC at the TRIUMF laboratory in Vancouver, Canada. The radioactive ion beam exits the accelerator in the top left-hand corner of the photo and enters either the DRAGON recoil spectrometer or the TUDA beamline. For radiative proton- and α-capture reactions, the 21-m long DRAGON facility (photo, center) is used. The drawing shows the major components of DRAGON, including the windowless gas target surrounded by a 30-element γ-ray detection array, the two independent stages of electromagnetic separators that suppress the beam by a factor of $< 10^{13}$, and the appropriately configured recoil detector. For other nonradiative-capture measurements, such as direct reactions and elastic or inelastic scattering, TUDA is employed. The TUDA chamber and shielded electronics room (photo, right-hand side) allow for multiple arrangements of various detectors specifically chosen for the reaction of interest. Credit: Dave Hutcheon, Chris Ruiz, Götz Ruprecht, Mike Trinczek, Christof Vockenhuber and TRIUMF.

The Textbook case

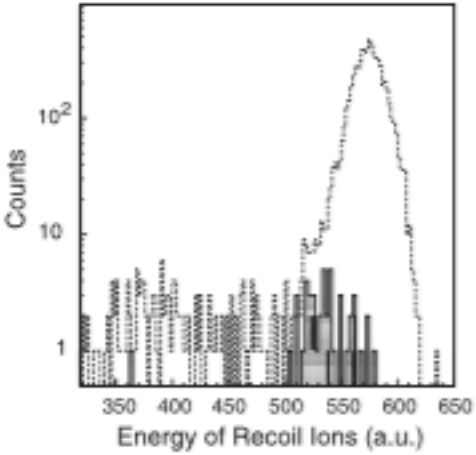
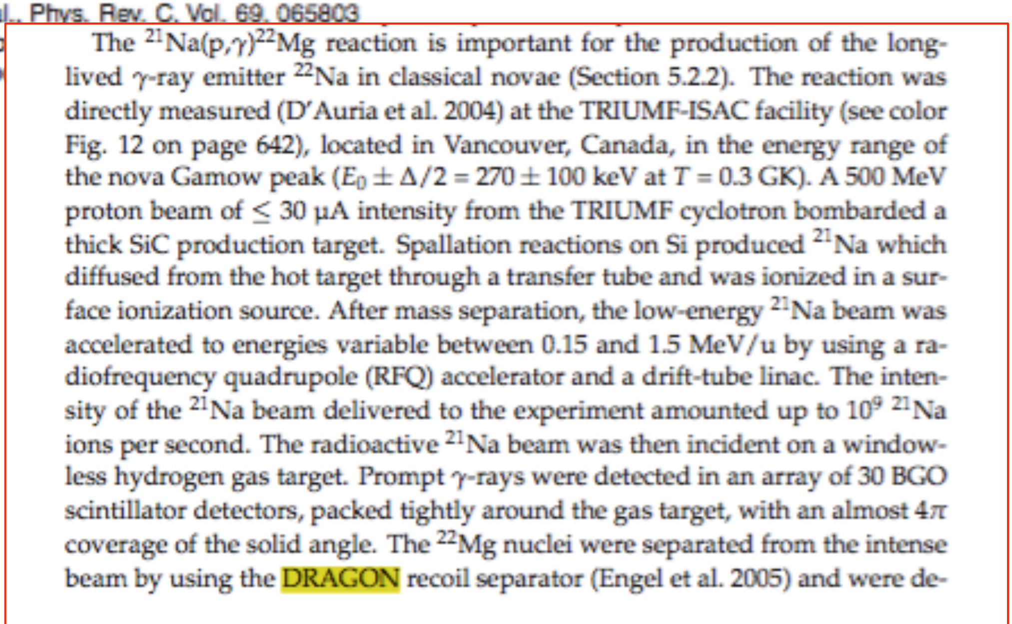


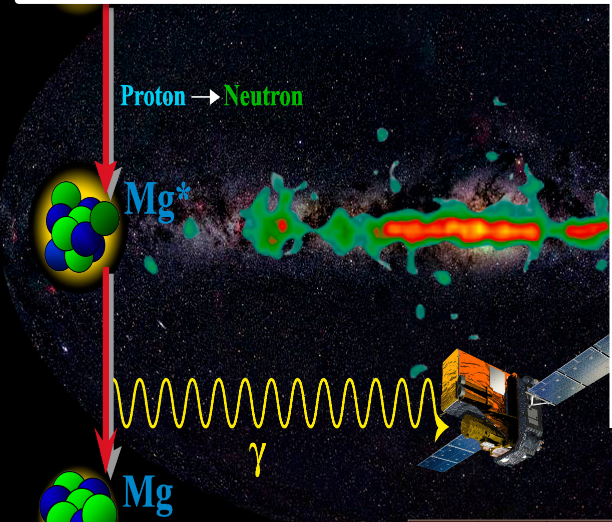
Fig. 4.41 Pulse height spectrum of heavy ions detected at the focal plane of a recoil separator in the study of the E_r^{cm} = 207 keV resonance in ^{21}Na(p,γ)^{22}Mg. The dashed histogram shows the singles spectrum and is dominated by ^{21}Na beam particles leaking through the separator. The shaded spectrum displays those heavy ions which are in coincidence with prompt γ-rays detected in a BGO array surrounding the hydrogen gas target. These correspond to the reaction products ^{22}Mg since ^{21}Na beam particles are not in coincidence with prompt γ-rays. Reprinted with permission from J. M. D'Auria et al., Phys. Rev. C, Vol. 69, 065803 (2004). Cop Physical So

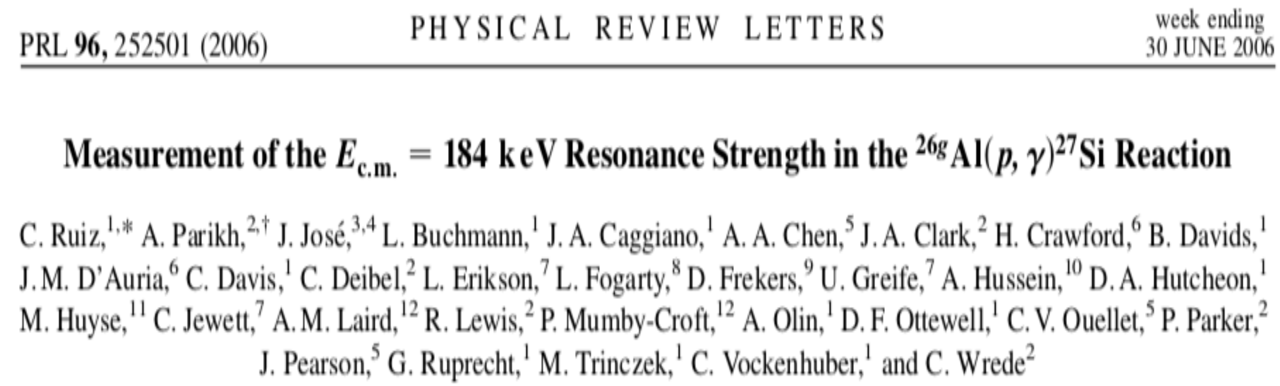


The ^{21}Na(p,γ)^{22}Mg reaction is important for the production of the long-lived γ-ray emitter ^{22}Na in classical novae (Section 5.2.2). The reaction was directly measured (D'Auria et al. 2004) at the TRIUMF-ISAC facility (see color Fig. 12 on page 642), located in Vancouver, Canada, in the energy range of the nova Gamow peak ($E_0 \pm \Delta/2 = 270 \pm 100$ keV at $T = 0.3$ GK). A 500 MeV proton beam of ≤ 30 μA intensity from the TRIUMF cyclotron bombarded a thick SiC production target. Spallation reactions on Si produced ^{21}Na which diffused from the hot target through a transfer tube and was ionized in a surface ionization source. After mass separation, the low-energy ^{21}Na beam was accelerated to energies variable between 0.15 and 1.5 MeV/u by using a radiofrequency quadrupole (RFQ) accelerator and a drift-tube linac. The intensity of the ^{21}Na beam delivered to the experiment amounted up to 10^9 ^{21}Na ions per second. The radioactive ^{21}Na beam was then incident on a windowless hydrogen gas target. Prompt γ-rays were detected in an array of 30 BGO scintillator detectors, packed tightly around the gas target, with an almost 4π coverage of the solid angle. The ^{22}Mg nuclei were separated from the intense beam by using the DRAGON recoil separator (Engel et al. 2005) and were de-

DRAGON highlights

^{26}Al(p,γ)^{27}Si: ^{26}Al galactic map

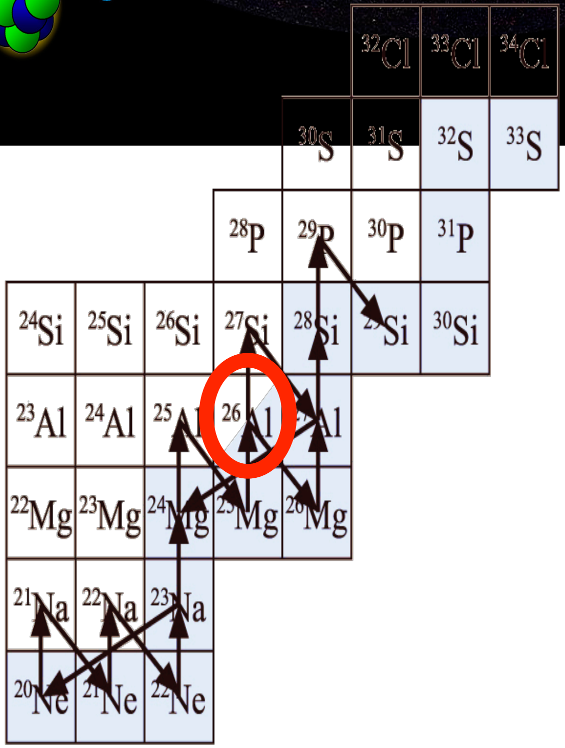


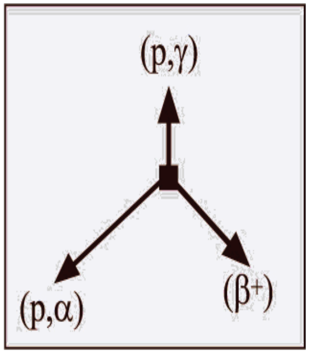


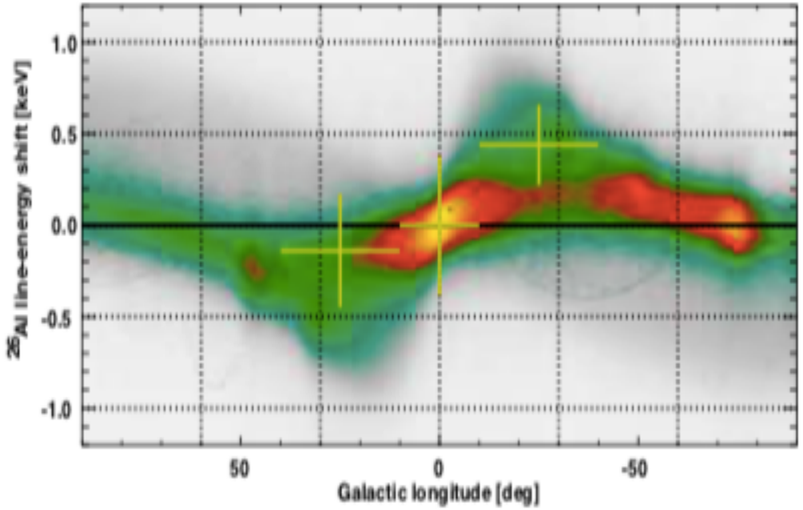
PRL **96,** 252501 (2006) PHYSICAL REVIEW LETTERS week ending 30 JUNE 2006

Measurement of the $E_{\mathrm{c.m.}} = 184$ keV Resonance Strength in the ^{26g}Al$(p,\gamma)^{27}$Si Reaction

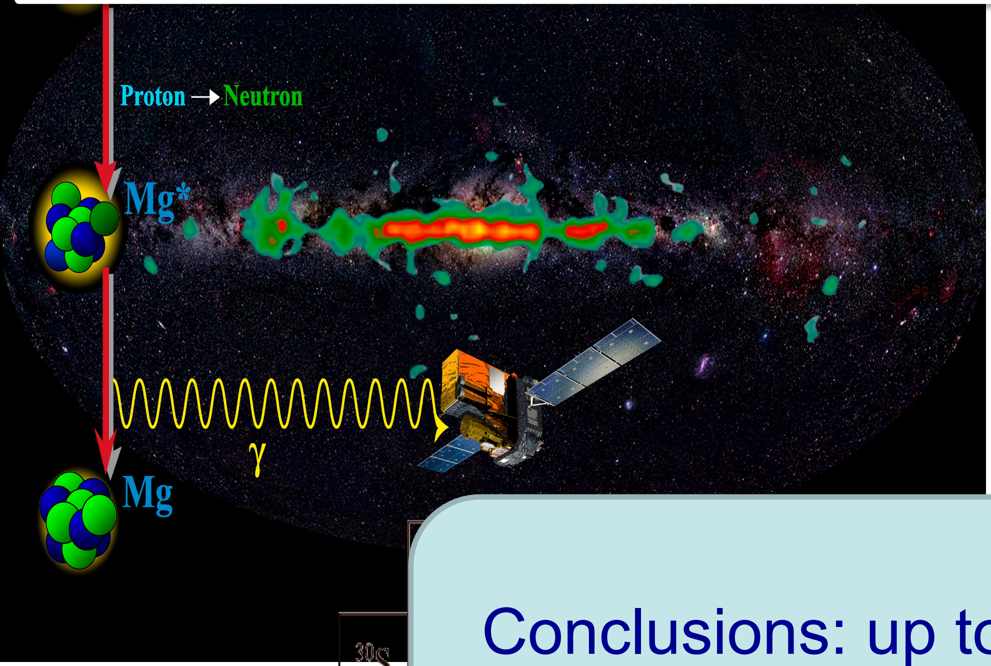
C. Ruiz,[1,*] A. Parikh,[2,†] J. José,[3,4] L. Buchmann,[1] J. A. Caggiano,[1] A. A. Chen,[5] J. A. Clark,[2] H. Crawford,[6] B. Davids,[1] J. M. D'Auria,[6] C. Davis,[1] C. Deibel,[2] L. Erikson,[7] L. Fogarty,[8] D. Frekers,[9] U. Greife,[7] A. Hussein,[10] D. A. Hutcheon,[1] M. Huyse,[11] C. Jewett,[7] A. M. Laird,[12] R. Lewis,[2] P. Mumby-Croft,[12] A. Olin,[1] D. F. Ottewell,[1] C. V. Ouellet,[5] P. Parker,[2] J. Pearson,[5] G. Ruprecht,[1] M. Trinczek,[1] C. Vockenhuber,[1] and C. Wrede[2]

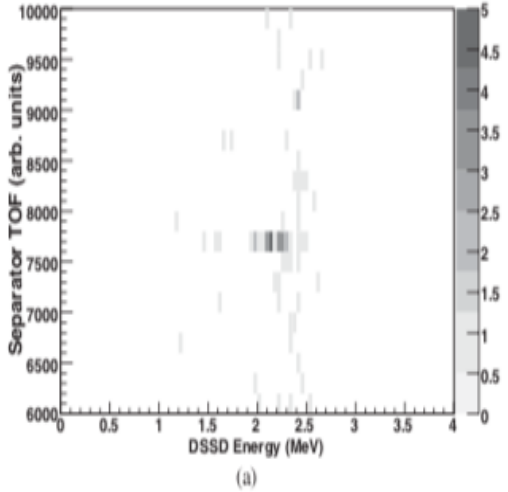




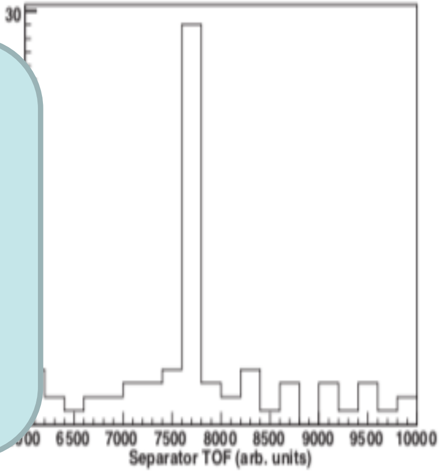


^{26}Al(p,γ)^{27}Si: ^{26}Al galactic map

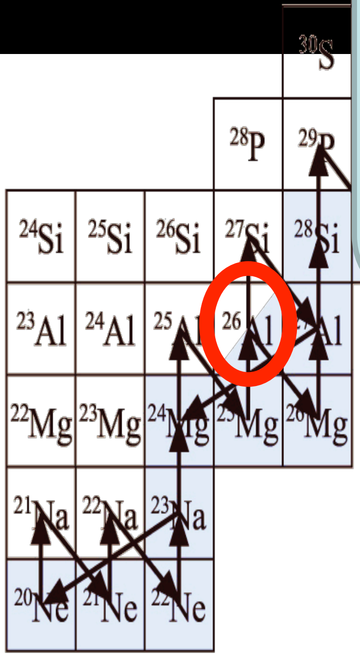




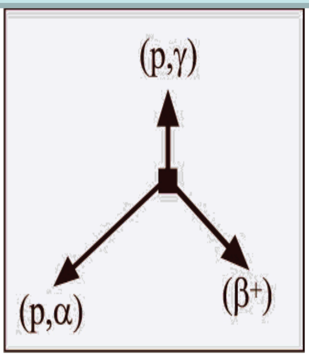
(a)



(b)



Conclusions: up to 20% of ^{26}Al observed in Galaxy could be from novae…. (but no more)



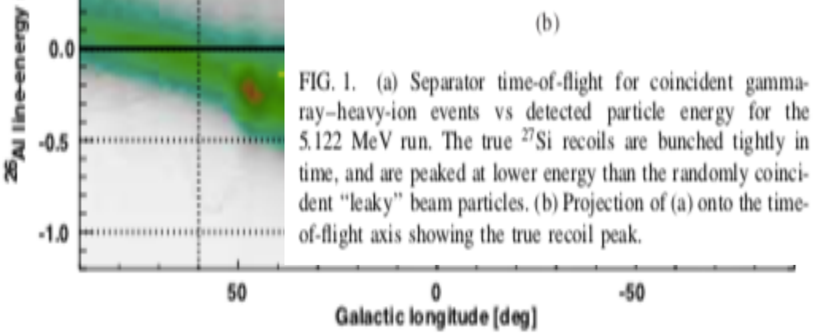
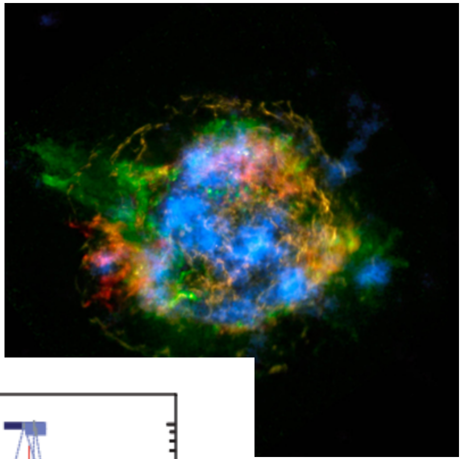


FIG. 1. (a) Separator time-of-flight for coincident gamma-ray–heavy-ion events vs detected particle energy for the 5.122 MeV run. The true ^{27}Si recoils are bunched tightly in time, and are peaked at lower energy than the randomly coincident "leaky" beam particles. (b) Projection of (a) onto the time-of-flight axis showing the true recoil peak.

$^{40}Ca(\alpha,\gamma)^{44}Ti$: ^{44}Ti SN remnant map



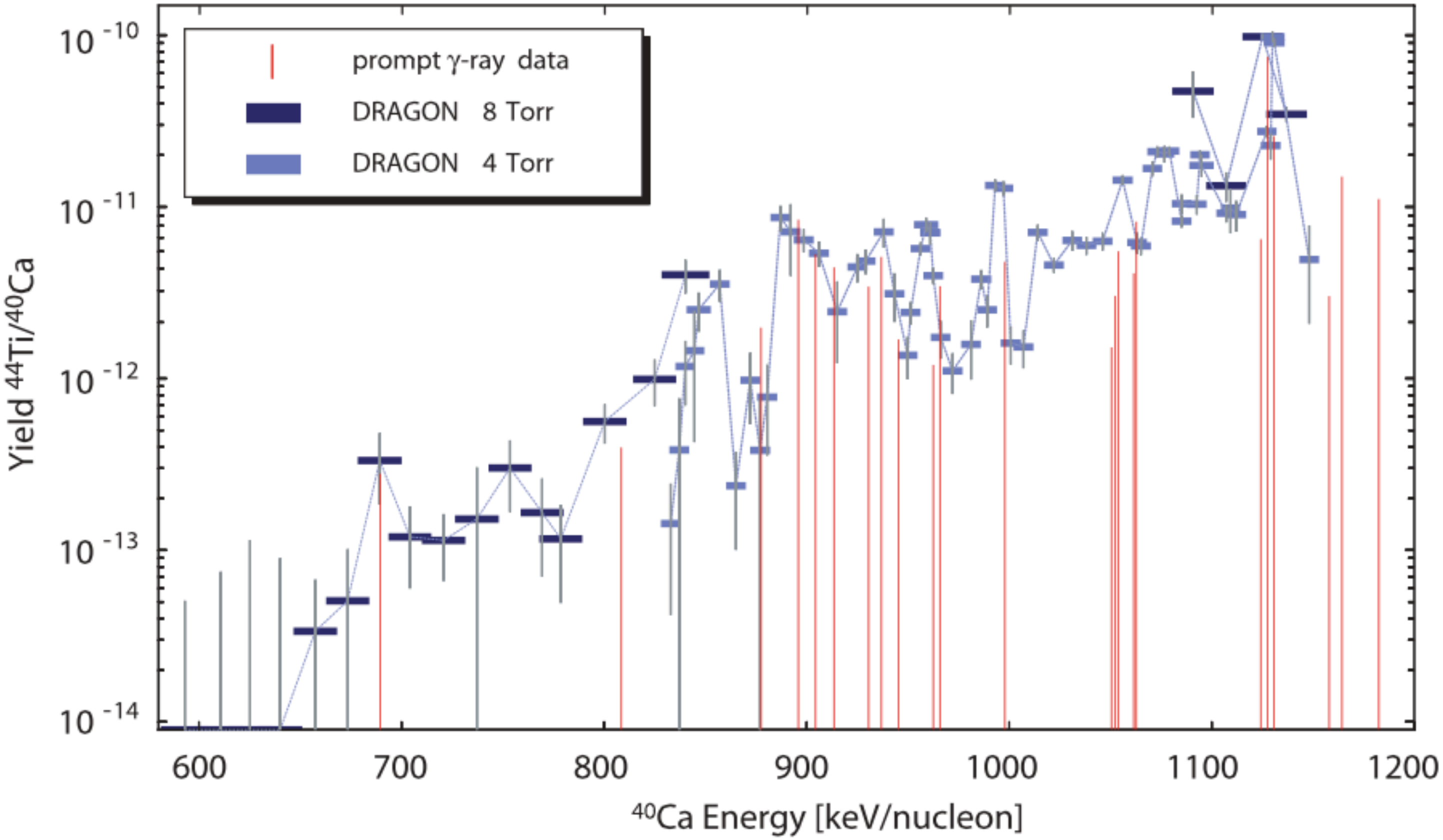
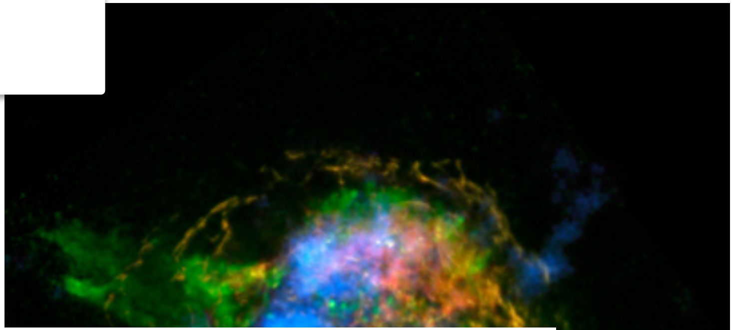
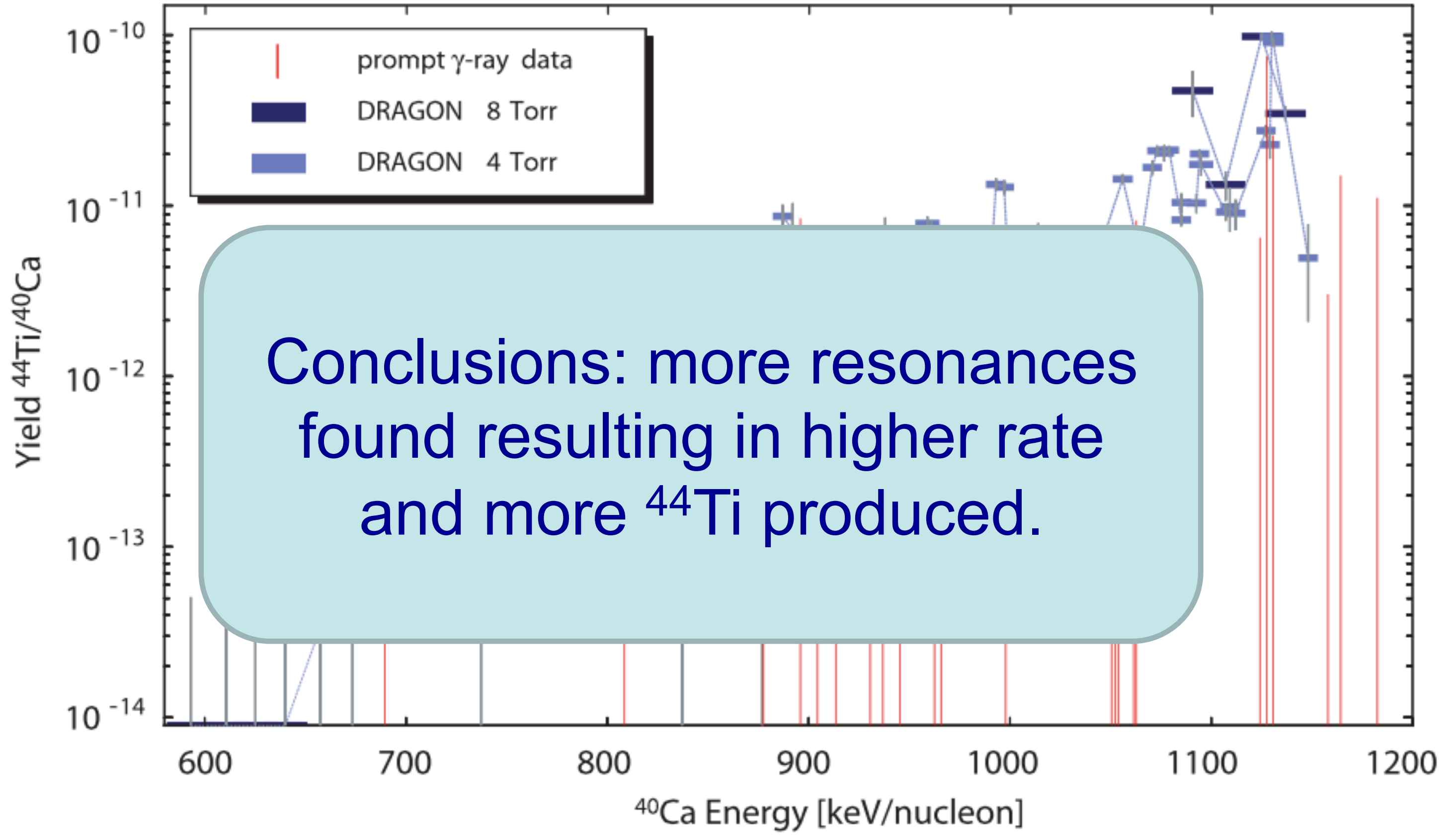


FIG. 8. (Color online) Excitation function of the $^{40}Ca(\alpha, \gamma)^{44}Ti$ reaction measured at DRAGON. Data sets at 4 and 8 Torr are indicated in different shades, and the connecting lines are only to guide the eye. The yield at each measurement point depends on how many narrow resonances are hit, and thus overlapping bars at different pressures agree with each other only if the same resonances are hit in both cases. At the four lowest energies we observed only upper limits. For comparison, vertical lines indicate known resonance strengths from prompt γ-ray studies.

^{40}Ca(α,γ)^{44}Ti: ^{44}Ti SN remnant map





Conclusions: more resonances found resulting in higher rate and more ^{44}Ti produced.

FIG. 8. (Color online) Excitation function of the ^{40}Ca(α,γ)^{44}Ti reaction measured at DRAGON. Data sets at 4 and 8 Torr are indicated in different shades, and the connecting lines are only to guide the eye. The yield at each measurement point depends on how many narrow resonances are hit, and thus overlapping bars at different pressures agree with each other only if the same resonances are hit in both cases. At the four lowest energies we observed only upper limits. For comparison, vertical lines indicate known resonance strengths from prompt γ-ray studies.

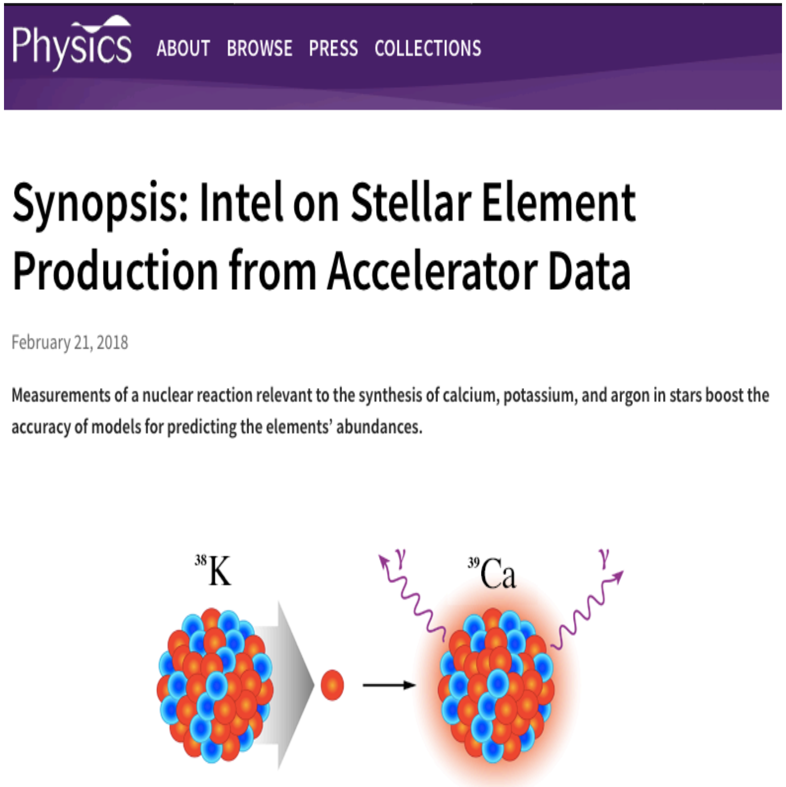
^{38}K(p,γ)^{39}Ca for Ca/Ar production in Classical Novae

Editors' Suggestion

Featured in Physics

Direct measurement of astrophysically important resonances in ^{38}K(p,γ)^{39}Ca

G. Christian,[1,2,*] G. Lotay,[3,†] C. Ruiz,[2] C. Akers,[2,4,‡] D. S. Burke,[5] W. N. Catford,[3] A. A. Chen,[5] D. Connolly,[6,§] B. Davids,[2] J. Fallis,[2,¶] U. Hager,[6] D. Hutcheon,[2] A. Mahl,[6] A. Rojas,[2] and X. Sun[2,7,**]

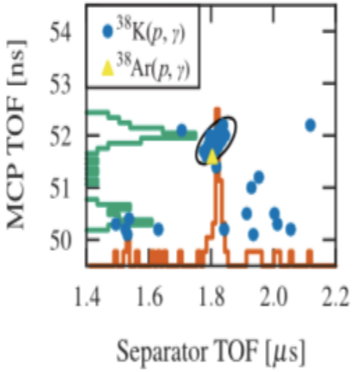


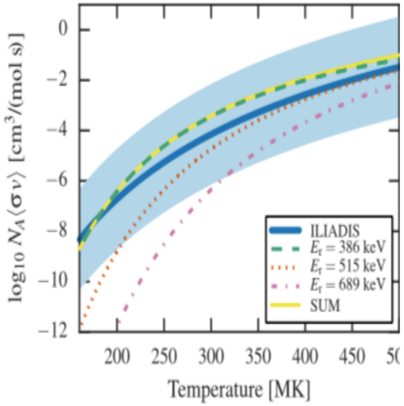
Physics ABOUT BROWSE PRESS COLLECTIONS

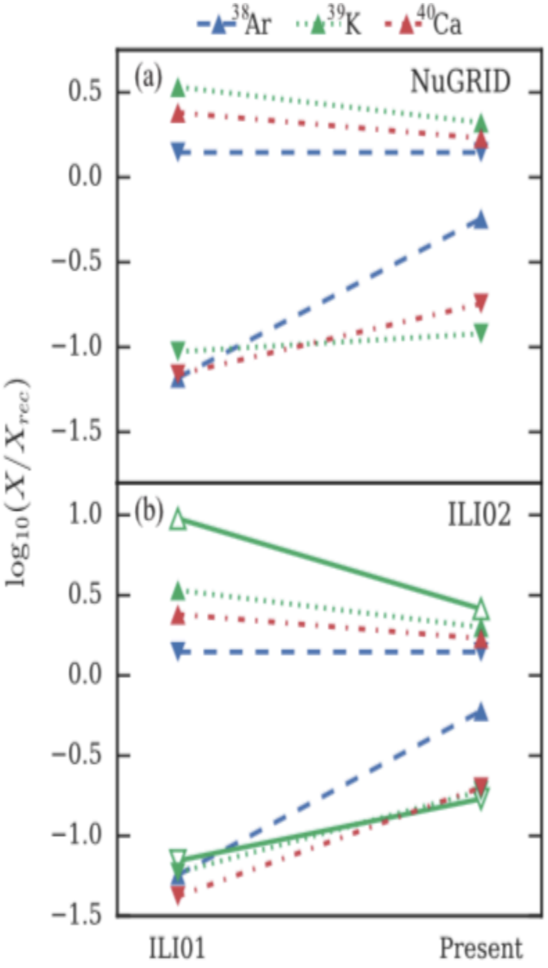
Synopsis: Intel on Stellar Element Production from Accelerator Data

February 21, 2018

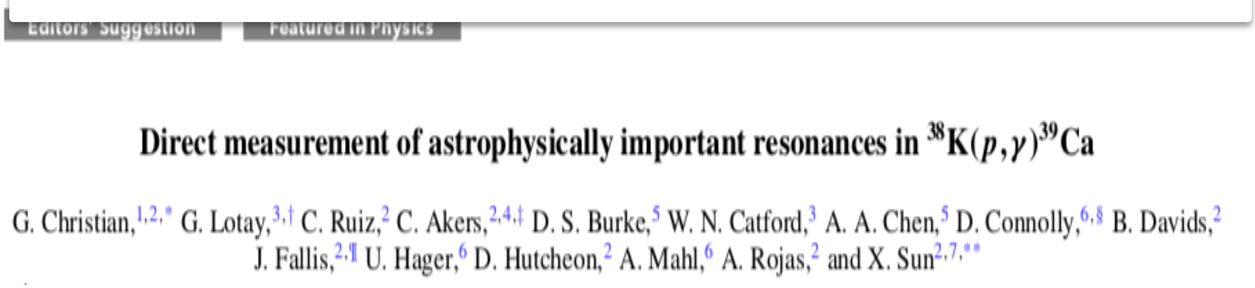
Measurements of a nuclear reaction relevant to the synthesis of calcium, potassium, and argon in stars boost the accuracy of models for predicting the elements' abundances.







^{38}K(p,γ)^{39}Ca for Ca/Ar production in Classical Novae



Direct measurement of astrophysically important resonances in ^{38}K(p,γ)^{39}Ca

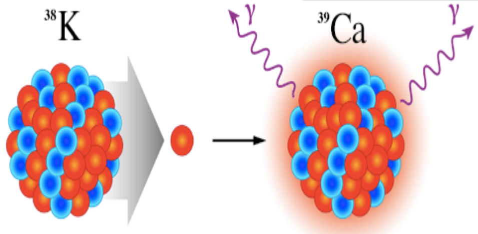
G. Christian,[1,2,*] G. Lotay,[3,†] C. Ruiz,[2] C. Akers,[2,4,‡] D. S. Burke,[5] W. N. Catford,[3] A. A. Chen,[5] D. Connolly,[6,§] B. Davids,[2] J. Fallis,[2,¶] U. Hager,[6] D. Hutcheon,[2] A. Mahl,[6] A. Rojas,[2] and X. Sun[2,7,**]

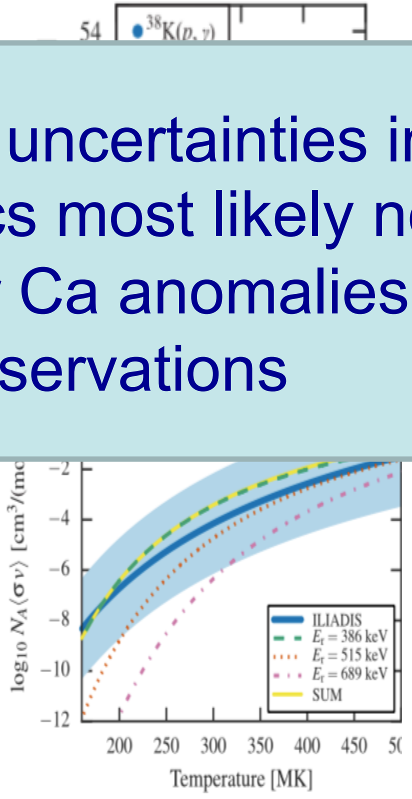
Synopsis: Intel on St
Production from Acc

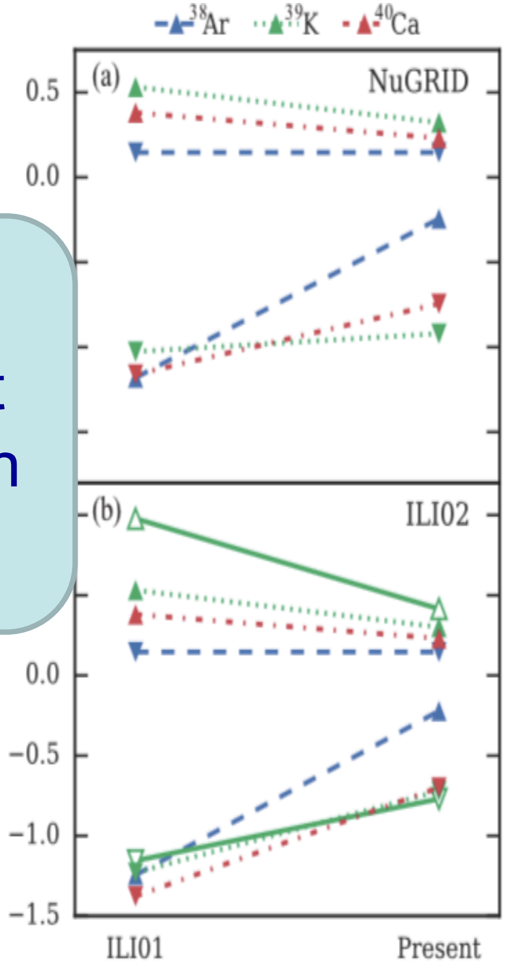
February 21, 2018

Measurements of a nuclear reaction relevant to the synt
accuracy of models for predicting the elements' abunda

Conclusions: uncertainties in nuclear physics most likely not explanation for Ca anomalies in nova observations

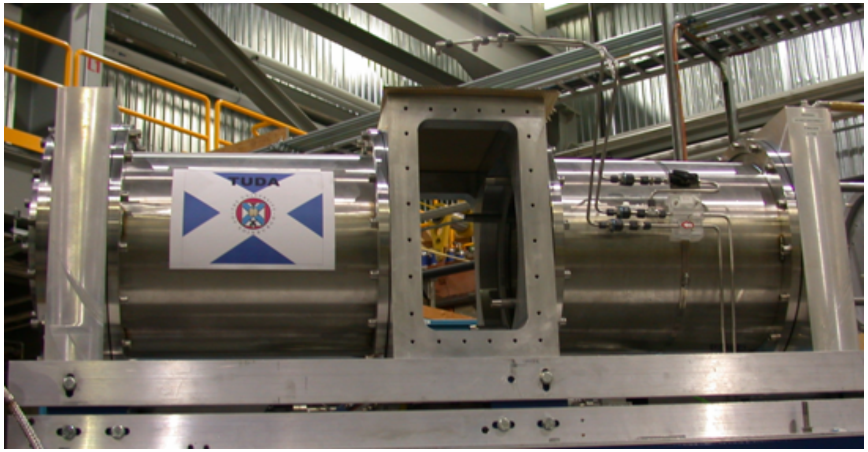


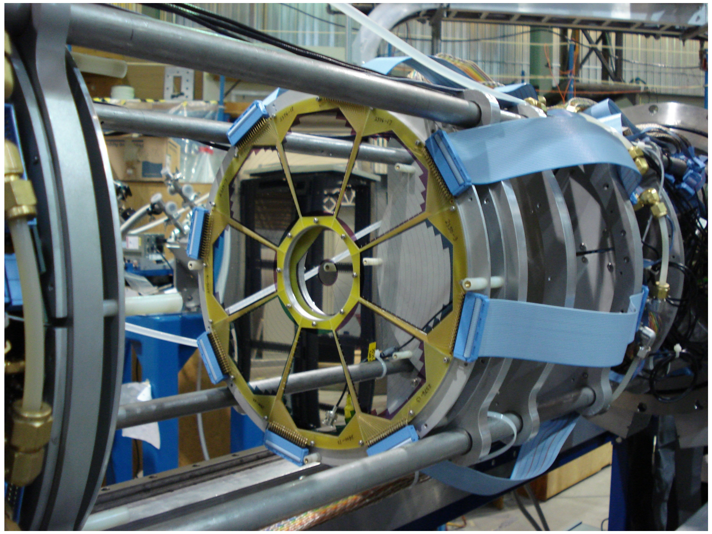


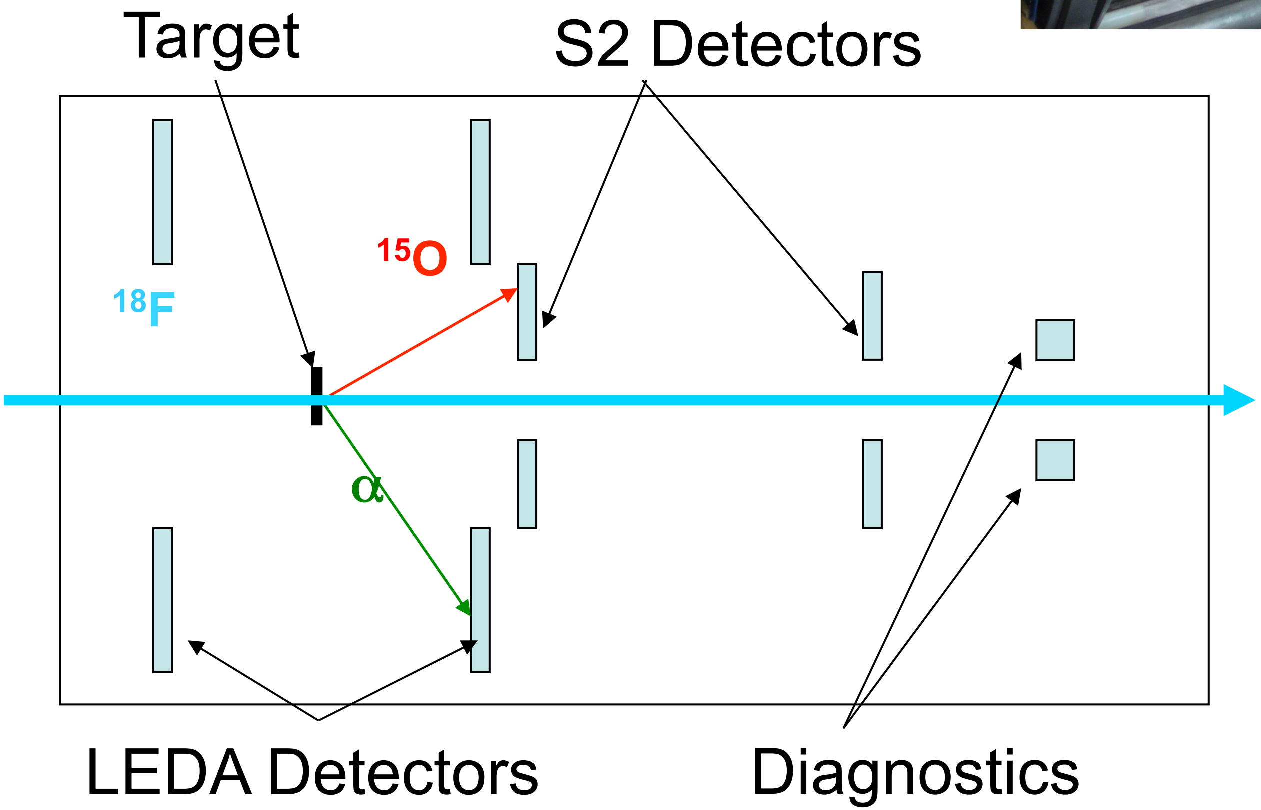


TUDA highlights

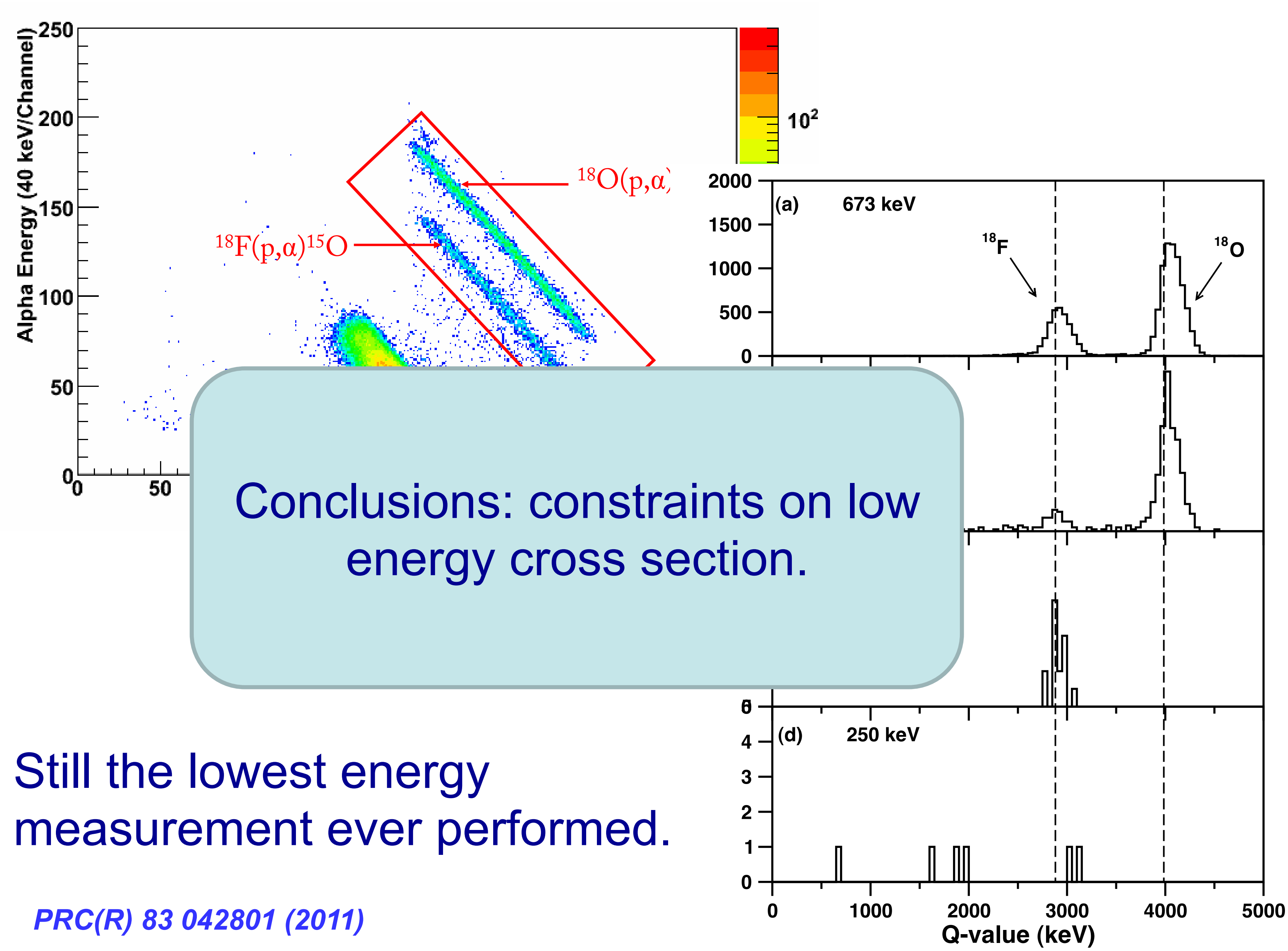
$^{18}F(p,\alpha)^{15}O$ for ^{18}F destruction in classical novae







The $^{18}\text{F}(p,\alpha)^{15}\text{O}$ data

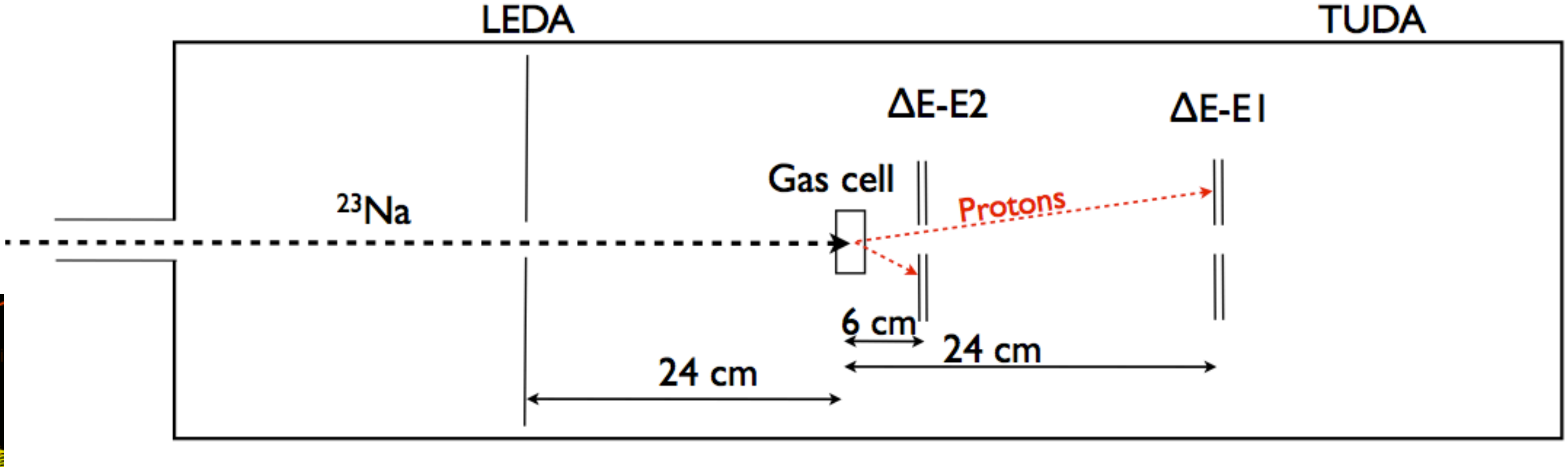


Conclusions: constraints on low energy cross section.

Still the lowest energy measurement ever performed.

PRC(R) 83 042801 (2011)

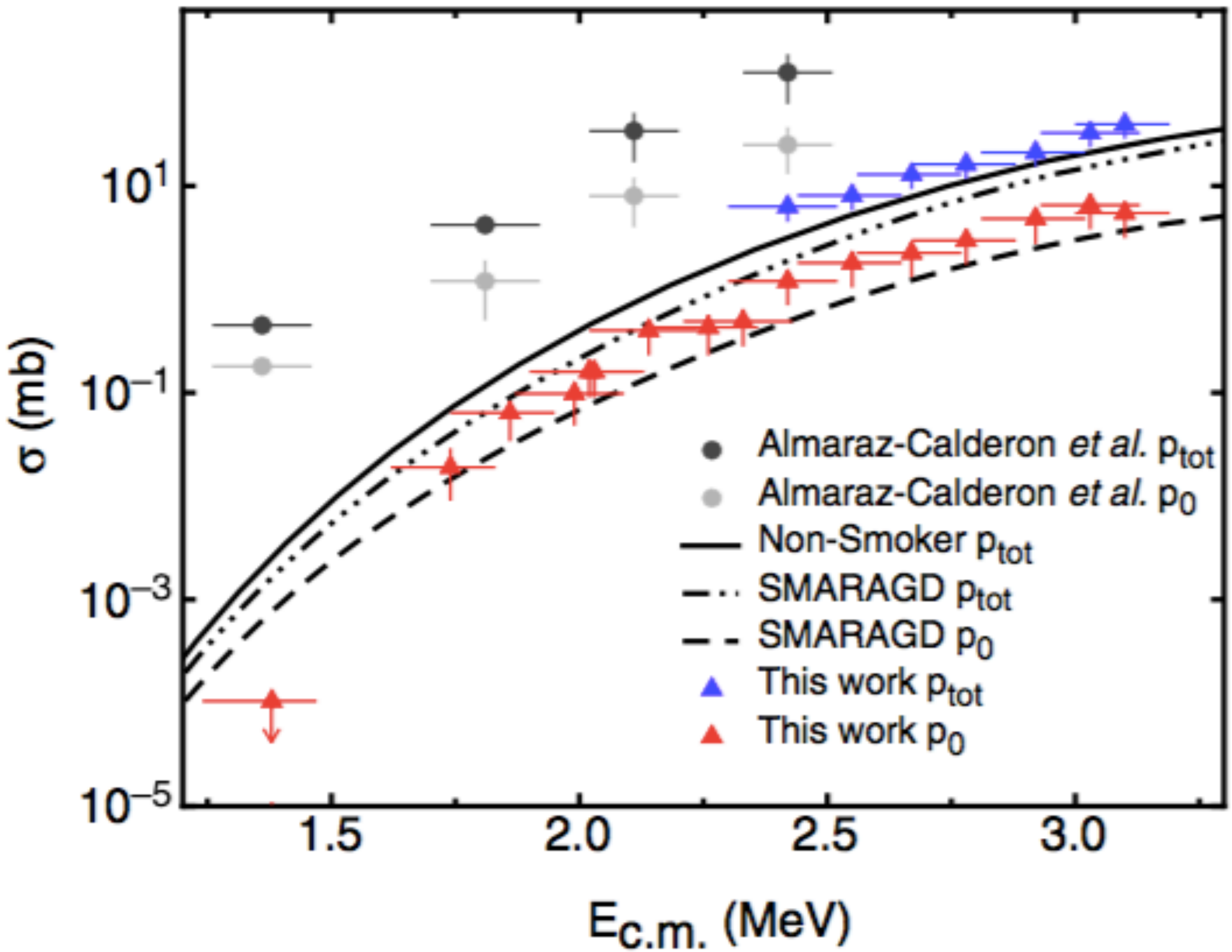
^{23}Na(α,p)^{26}Mg – ^{26}Al in massive stars



Gas cell target:
110 Torr of ^{4}He.
Entrance window 2.5 um Nickel.
Exit window 6 um Nickel.
Cell length window to window = 2cm.

Silicon Detector Arrays:
DE-E2 covers ~ 9° - 39°
DE-E1 covers ~ 3° - 8.9°

PD on target ladder to measure energy loss through window material at each incident beam energy.



Similar setup used for ^{21}Na(α,p)^{24}Mg *(publication in preparation)* and for planned **^{18}Ne(α,p)^{21}Na** measurement -> key reaction in X-ray bursts.

Pushing the limits

$^{18}F(p,\gamma)^{19}Ne$ – low intensity limit

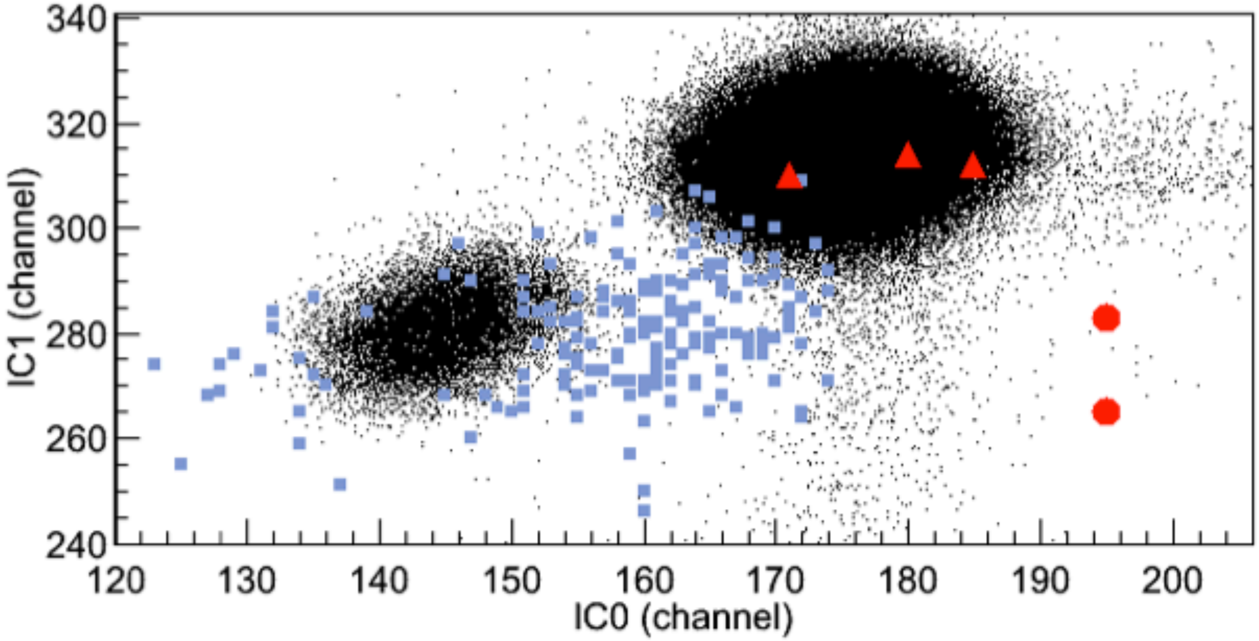


FIG. 1. Energy loss vs. energy loss plot obtained from the first two anodes in the IC. The attenuated beam run is shown in black and two well-separated loci are clearly visible signifying the presence of both ^{18}F and ^{18}O. Circles (triangles), both red online, correspond to observed ^{19}Ne (^{18}F) events when the separator was tuned to recoils. Squares (blue online) correspond to ^{19}F recoils during the separate ^{18}O beam run.

Beam intensity ~ 10^6 pps – too low for reliable FC reading.

Normalisation using elastic scattering and simulations.

^{58}Ni(p,γ)^{59}Cu measurement – high mass limits

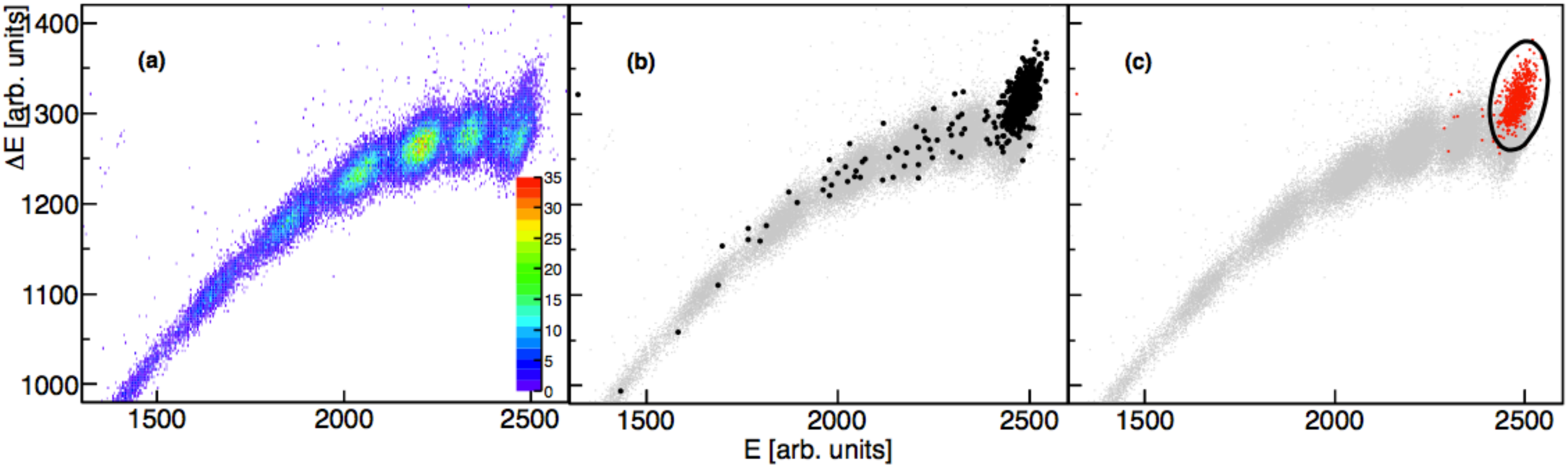


Fig. 2. Energy loss vs. total energy for (a) singles, (b) recoils coincident with γ-rays (black circles) and (c) recoils coincident with γ-rays with additional condition on separator and MCP time-of-flight (red squares). In panels (b) and (c) the shaded area denotes the singles histogram plotted for reference. Black contour denotes the range of true events

Eur. Phys. J. A (2013) **49**: X

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PHYSICAL JOURNAL A

^{76}Se(α,γ)^{80}Kr publication in preparation

Radiative capture reactions with heavy beams: extending the capabilities of DRAGON

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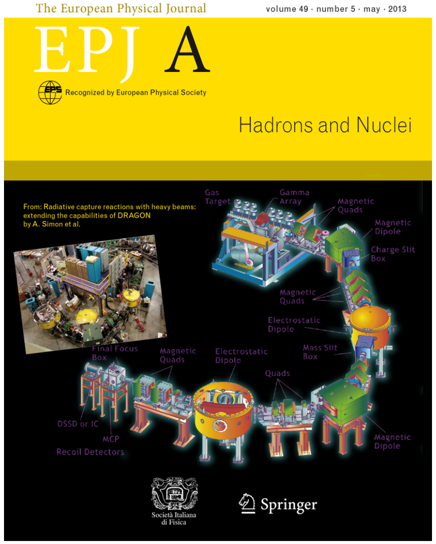

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The impact of ISAC

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THE EFFECTS OF THERMONUCLEAR REACTION-RATE VARIATIONS ON NOVA NUCLEOSYNTHESIS: A SENSITIVITY STUDY

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TABLE 12

INFLUENCE OF REACTION-RATE VARIATIONS ON ISOTOPIC ABUNDANCES IN NOVA NUCLEOSYNTHESIS[a]

Reaction-Rate Variation[b]	Isotopic Abundance Change[c]
CO Nova Models	
$^{17}\mathrm{O}(p,\gamma)^{18}\mathrm{F}$	$^{18}\mathrm{F}$
$^{17}\mathrm{O}(p,\alpha)^{14}\mathrm{N}$	$^{17}\mathrm{O}$, $^{18}\mathrm{F}$
$^{18}\mathrm{F}(p,\alpha)^{15}\mathrm{O}$	$^{18}\mathrm{F}$
$^{22}\mathrm{Ne}(p,\gamma)^{23}\mathrm{Na}$	$^{22}\mathrm{Ne}$, $^{23}\mathrm{Na}$, $^{24}\mathrm{Mg}$, $^{25}\mathrm{Mg}$, $^{26}\mathrm{Al}$
$^{23}\mathrm{Na}(p,\gamma)^{24}\mathrm{Mg}$	$^{24}\mathrm{Mg}$
$^{26}\mathrm{Mg}(p,\gamma)^{27}\mathrm{Al}$	$^{26}\mathrm{Mg}$
$^{26}\mathrm{Al}^{g}(p,\gamma)^{27}\mathrm{Si}$	$^{26}\mathrm{Al}$
ONe Nova Models	
$^{17}\mathrm{O}(p,\gamma)^{18}\mathrm{F}$	$^{17}\mathrm{O}$, $^{18}\mathrm{F}$
$^{17}\mathrm{O}(p,\alpha)^{14}\mathrm{N}$	$^{17}\mathrm{O}$, $^{18}\mathrm{F}$
$^{17}\mathrm{F}(p,\gamma)^{18}\mathrm{Ne}$	$^{17}\mathrm{O}$, $^{18}\mathrm{F}$
$^{18}\mathrm{F}(p,\alpha)^{15}\mathrm{O}$	$^{16}\mathrm{O}$, $^{17}\mathrm{O}$, $^{18}\mathrm{F}$
$^{21}\mathrm{Na}(p,\gamma)^{22}\mathrm{Mg}$	$^{21}\mathrm{Ne}$, $^{22}\mathrm{Na}$, $^{22}\mathrm{Ne}$
$^{22}\mathrm{Ne}(p,\gamma)^{23}\mathrm{Na}$	$^{22}\mathrm{Ne}$
$^{23}\mathrm{Na}(p,\gamma)^{24}\mathrm{Mg}$	$^{20}\mathrm{Ne}$, $^{21}\mathrm{Ne}$, $^{22}\mathrm{Na}$, $^{23}\mathrm{Na}$, $^{24}\mathrm{Mg}$, $^{25}\mathrm{Mg}$, $^{26}\mathrm{Mg}$, $^{26}\mathrm{Al}$, $^{27}\mathrm{Al}$
$^{23}\mathrm{Mg}(p,\gamma)^{24}\mathrm{Al}$	$^{20}\mathrm{Ne}$, $^{21}\mathrm{Ne}$, $^{22}\mathrm{Na}$, $^{23}\mathrm{Na}$, $^{24}\mathrm{Mg}$
$^{26}\mathrm{Mg}(p,\gamma)^{27}\mathrm{Al}$	$^{26}\mathrm{Mg}$
$^{26}\mathrm{Al}^{g}(p,\gamma)^{27}\mathrm{Si}$	$^{26}\mathrm{Al}$
$^{26}\mathrm{Al}^{m}(p,\gamma)^{27}\mathrm{Si}$	$^{26}\mathrm{Mg}$
$^{29}\mathrm{Si}(p,\gamma)^{30}\mathrm{P}$	$^{29}\mathrm{Si}$
$^{30}\mathrm{P}(p,\gamma)^{31}\mathrm{S}$	$^{30}\mathrm{Si}$, $^{32}\mathrm{S}$, $^{33}\mathrm{S}$, $^{34}\mathrm{S}$, $^{35}\mathrm{Cl}$, $^{37}\mathrm{Cl}$, $^{36}\mathrm{Ar}$, $^{37}\mathrm{Ar}$, $^{38}\mathrm{Ar}$
$^{33}\mathrm{S}(p,\gamma)^{34}\mathrm{Cl}$	$^{33}\mathrm{S}$, $^{34}\mathrm{S}$, $^{35}\mathrm{Cl}$, $^{36}\mathrm{Ar}$
$^{33}\mathrm{Cl}(p,\gamma)^{34}\mathrm{Ar}$	$^{33}\mathrm{S}$
$^{34}\mathrm{S}(p,\gamma)^{35}\mathrm{Cl}$	$^{34}\mathrm{S}$, $^{35}\mathrm{Cl}$, $^{36}\mathrm{Ar}$
$^{34}\mathrm{Cl}(p,\gamma)^{35}\mathrm{Ar}$	$^{34}\mathrm{S}$
$^{37}\mathrm{Ar}(p,\gamma)^{38}\mathrm{K}$	$^{37}\mathrm{Cl}$, $^{37}\mathrm{Ar}$, $^{38}\mathrm{Ar}$
$^{38}\mathrm{K}(p,\gamma)^{39}\mathrm{Ca}$	$^{38}\mathrm{Ar}$

THE EFFEC TIONS ON NOVA

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$^{17}\mathrm{F}(p,\gamma)^{18}\mathrm{Ne}$	$^{17}\mathrm{O}$, $^{18}\mathrm{F}$
$^{18}\mathrm{F}(p,\alpha)^{15}\mathrm{O}$	$^{16}\mathrm{O}$, $^{17}\mathrm{O}$, $^{18}\mathrm{F}$
$^{21}\mathrm{Na}(p,\gamma)^{22}\mathrm{Mg}$	$^{21}\mathrm{Ne}$, $^{22}\mathrm{Na}$, $^{22}\mathrm{Ne}$
$^{22}\mathrm{Ne}(p,\gamma)^{23}\mathrm{Na}$	$^{22}\mathrm{Ne}$
$^{23}\mathrm{Na}(p,\gamma)^{24}\mathrm{Mg}$	$^{20}\mathrm{Ne}$, $^{21}\mathrm{Ne}$, $^{22}\mathrm{Na}$, $^{23}\mathrm{Na}$, $^{24}\mathrm{Mg}$, $^{25}\mathrm{Mg}$, $^{26}\mathrm{Mg}$, $^{26}\mathrm{Al}$, $^{27}\mathrm{Al}$
$^{23}\mathrm{Mg}(p,\gamma)^{24}\mathrm{Al}$	$^{20}\mathrm{Ne}$, $^{21}\mathrm{Ne}$, $^{22}\mathrm{Na}$, $^{23}\mathrm{Na}$, $^{24}\mathrm{Mg}$
$^{26}\mathrm{Mg}(p,\gamma)^{27}\mathrm{Al}$	$^{26}\mathrm{Mg}$
$^{26}\mathrm{Al}^{g}(p,\gamma)^{27}\mathrm{Si}$	$^{26}\mathrm{Al}$
$^{26}\mathrm{Al}^{m}(p,\gamma)^{27}\mathrm{Si}$	$^{26}\mathrm{Mg}$
$^{29}\mathrm{Si}(p,\gamma)^{30}\mathrm{P}$	$^{29}\mathrm{Si}$
$^{30}\mathrm{P}(p,\gamma)^{31}\mathrm{S}$	$^{30}\mathrm{Si}$, $^{32}\mathrm{S}$, $^{33}\mathrm{S}$, $^{34}\mathrm{S}$, $^{35}\mathrm{Cl}$, $^{37}\mathrm{Cl}$, $^{36}\mathrm{Ar}$, $^{37}\mathrm{Ar}$, $^{38}\mathrm{Ar}$
$^{33}\mathrm{S}(p,\gamma)^{34}\mathrm{Cl}$	$^{33}\mathrm{S}$, $^{34}\mathrm{S}$, $^{35}\mathrm{Cl}$, $^{36}\mathrm{Ar}$
$^{33}\mathrm{Cl}(p,\gamma)^{34}\mathrm{Ar}$	$^{33}\mathrm{S}$
$^{34}\mathrm{S}(p,\gamma)^{35}\mathrm{Cl}$	$^{34}\mathrm{S}$, $^{35}\mathrm{Cl}$, $^{36}\mathrm{Ar}$
$^{34}\mathrm{Cl}(p,\gamma)^{35}\mathrm{Ar}$	$^{34}\mathrm{S}$
$^{37}\mathrm{Ar}(p,\gamma)^{38}\mathrm{K}$	$^{37}\mathrm{Cl}$, $^{37}\mathrm{Ar}$, $^{38}\mathrm{Ar}$
$^{38}\mathrm{K}(p,\gamma)^{39}\mathrm{Ca}$	$^{38}\mathrm{Ar}$

The continuing mission

^{7}Be(α,γ)^{11}C – starts tomorrow!

^{11}C(p,γ)^{12}N – link between pp-chains and CNO

^{15}O(α,γ)^{19}Ne – alternative approach to ^{18}F(p,γ)

^{18}F(p,α)^{15}O – reduce uncertainties in ^{18}F destruction

^{18}Ne(α,p)^{21}Na – key reaction in X-ray bursts

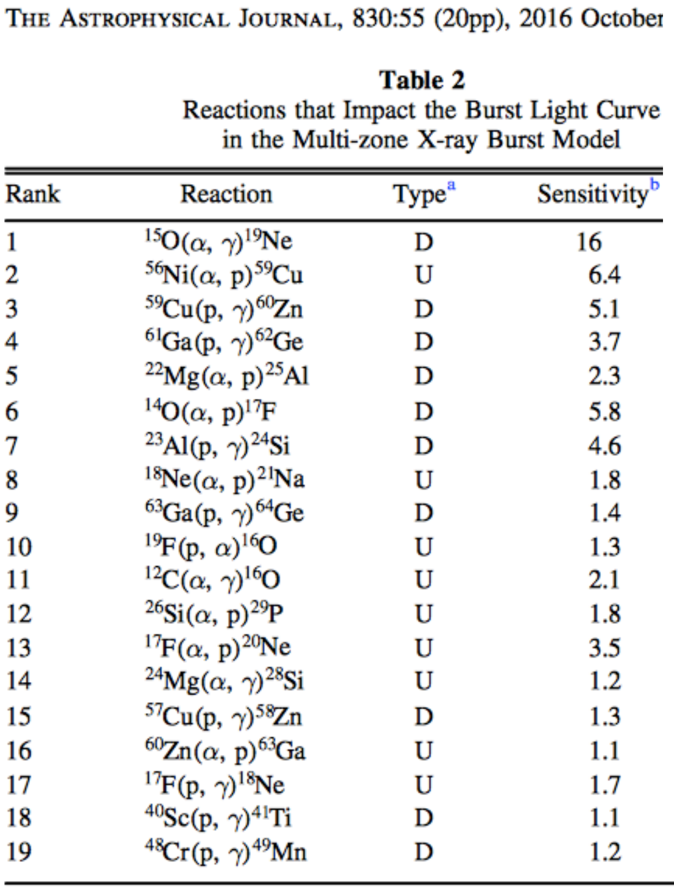
^{37}Ar(p,γ)^{38}K – nova nucleosynthesis

…

Need to keep developing high intensity ISOL beams.
DRAGON and TUDA continue to be competitive.

To be continued …. X-ray bursts

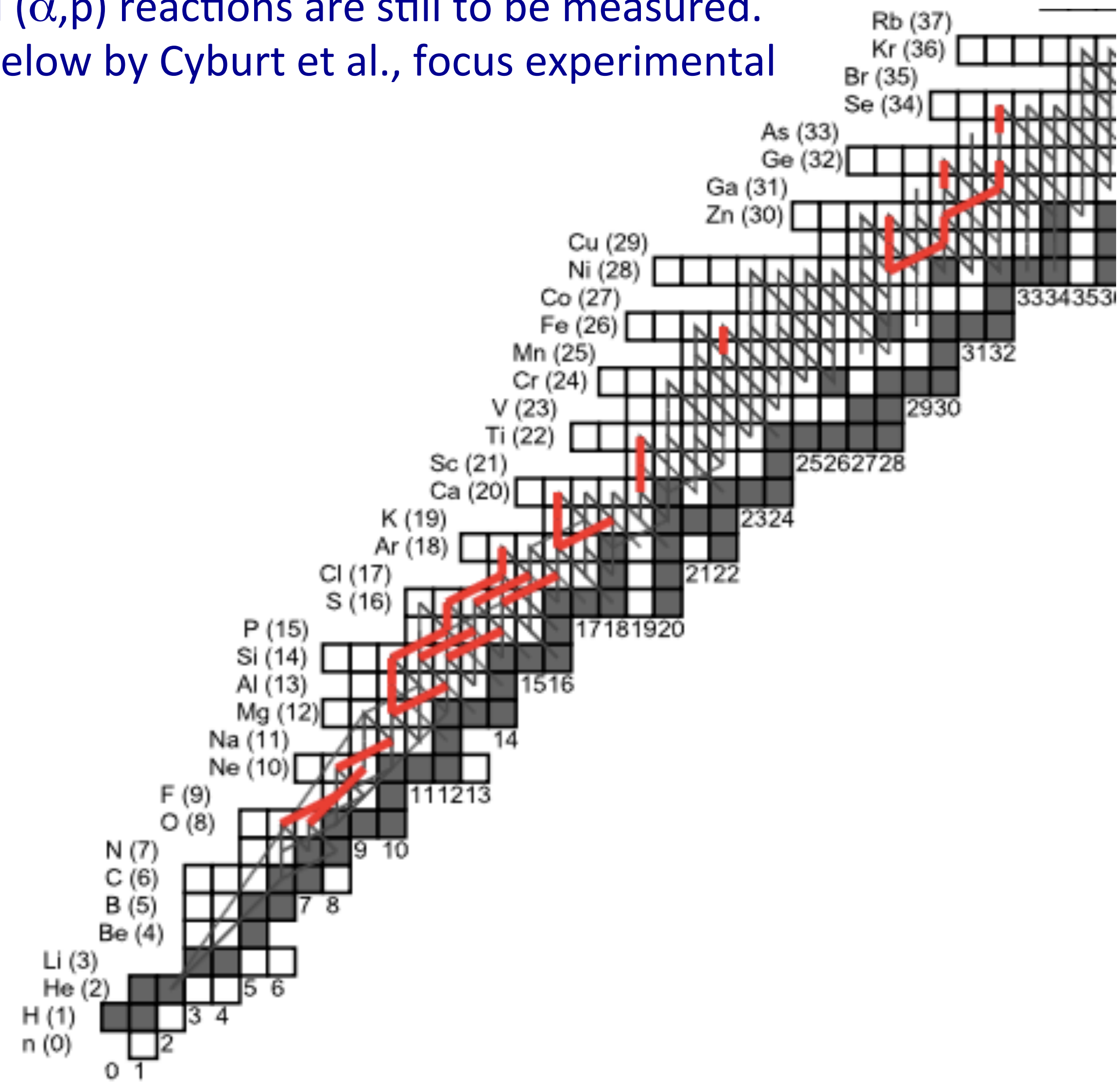
In X-ray bursts, key (p,γ) and (α,p) reactions are still to be measured. Sensitivity studies, such as below by Cyburt et al., focus experimental effort.



The Astrophysical Journal, 830:55 (20pp), 2016 October

Table 2
Reactions that Impact the Burst Light Curve in the Multi-zone X-ray Burst Model

Rank	Reaction	Type[a]	Sensitivity[b]	
1	^{15}O(α, γ)^{19}Ne	D	16	
2	^{56}Ni(α, p)^{59}Cu	U	6.4	
3	^{59}Cu(p, γ)^{60}Zn	D	5.1	
4	^{61}Ga(p, γ)^{62}Ge	D	3.7	
5	^{22}Mg(α, p)^{25}Al	D	2.3	
6	^{14}O(α, p)^{17}F	D	5.8	
7	^{23}Al(p, γ)^{24}Si	D	4.6	
8	^{18}Ne(α, p)^{21}Na	U	1.8	
9	^{63}Ga(p, γ)^{64}Ge	D	1.4	
10	^{19}F(p, α)^{16}O	U	1.3	
11	^{12}C(α, γ)^{16}O	U	2.1	
12	^{26}Si(α, p)^{29}P	U	1.8	
13	^{17}F(α, p)^{20}Ne	U	3.5	
14	^{24}Mg(α, γ)^{28}Si	U	1.2	
15	^{57}Cu(p, γ)^{58}Zn	D	1.3	
16	^{60}Zn(α, p)^{63}Ga	U	1.1	
17	^{17}F(p, γ)^{18}Ne	U	1.7	2
18	^{40}Sc(p, γ)^{41}Ti	D	1.1	2
19	^{48}Cr(p, γ)^{49}Mn	D	1.2	2



ISAC's fleet of facilities ideally suited to tackling these reactions.

Nuclear astrophysics is a rapidly evolving field:

✧ Now in multi-messenger era

✧ New observations, new techniques and vast amount of data (e.g. Gaia) have significantly reduced astrophysical uncertainties

✧ Stellar and explosion models now in 3D, identifying new processes

=> Reducing nuclear physics uncertainties is critical for interpreting the wealth of new data.

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ISAC's capabilities remain world-leading and ideally suited to tackle the new demands and challenges in nuclear astrophysics.

Thank you for your attention.
Merci.

Pat Walden
1944-2018
Proton Hall → ISAC
TUDA

John D'Auria
1939-2017
TISOL → ISAC
DRAGON

Successful ISAC programme

Reaction	Motivation	Intensity (s^{-1})	Purity (beam:cont.)
$^{21}\mathrm{Na}(p,\gamma)^{22}\mathrm{Mg}$	1.275 MeV line emission in ONe novae	5×10^{9}	100%
$^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$	Helium burning in red giants	3×10^{11} to 1×10^{12}	
$^{26g}\mathrm{Al}(p,\gamma)^{27}\mathrm{Si}$	Nova contribution to galactic ^{26}Al	3×10^{9}	30,000:1
$^{12}\mathrm{C}(^{12}\mathrm{C},\gamma)^{24}\mathrm{Mg}$	Nuclear cluster models	3×10^{11}	
$^{40}\mathrm{Ca}(\alpha,\gamma)^{44}\mathrm{Ti}$	Production of ^{44}Ti in SNII	3×10^{11}	10,000:1 – 200:1
$^{23}\mathrm{Mg}(p,\gamma)^{24}\mathrm{Al}$	1.275 MeV line emission in ONe novae	5×10^{7}	1:20 – 1:1,000
$^{17}\mathrm{O}(\alpha,\gamma)^{21}\mathrm{Ne}$	Neutron poison in massive stars	1×10^{12}	
$^{18}\mathrm{F}(p,\gamma)^{19}\mathrm{Ne}$	511 keV line emission in ONe novae	2×10^{6}	100:1
$^{33}\mathrm{S}(p,\gamma)^{34}\mathrm{Cl}$	S isotopic ratios in nova grains	1×10^{10}	
$^{16}\mathrm{O}(\alpha,\gamma)^{20}\mathrm{Ne}$	Stellar helium burning	1×10^{12}	
$^{17}\mathrm{O}(p,\gamma)^{18}\mathrm{F}$	Explosive hydrogen burning in novae	1×10^{12}	
$^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$	Solar neutrino spectrum	5×10^{11}	
$^{58}\mathrm{Ni}(p,\gamma)^{59}\mathrm{Cu}$	High mass tests (p-process, XRB)	6×10^{9}	
$^{26m}\mathrm{Al}(p,\gamma)^{27}\mathrm{Si}$	SNII contribution to galactic ^{26}Al	2×10^{5}	1:10,000
$^{38}\mathrm{K}(p,\gamma)^{39}\mathrm{Ca}$	Ca/K/Ar production in novae	2×10^{7}	1:1
$^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}$	^{19}F abundance in nova ejecta	2×10^{7}	1:1 to 4:1
$^{22}\mathrm{Ne}(p,\gamma)^{23}\mathrm{Na}$	NeNa cycle; explosive H burning in classical novae	2×10^{12}	
$^{7}\mathrm{Be}(\alpha,\gamma)^{11}\mathrm{C}$	ν-p process		1:200 to 1:1000