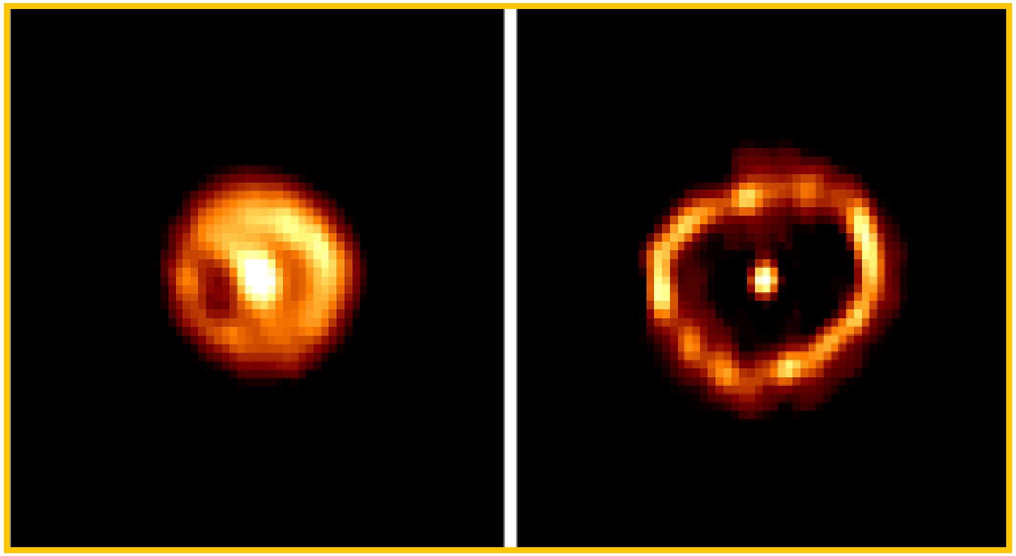
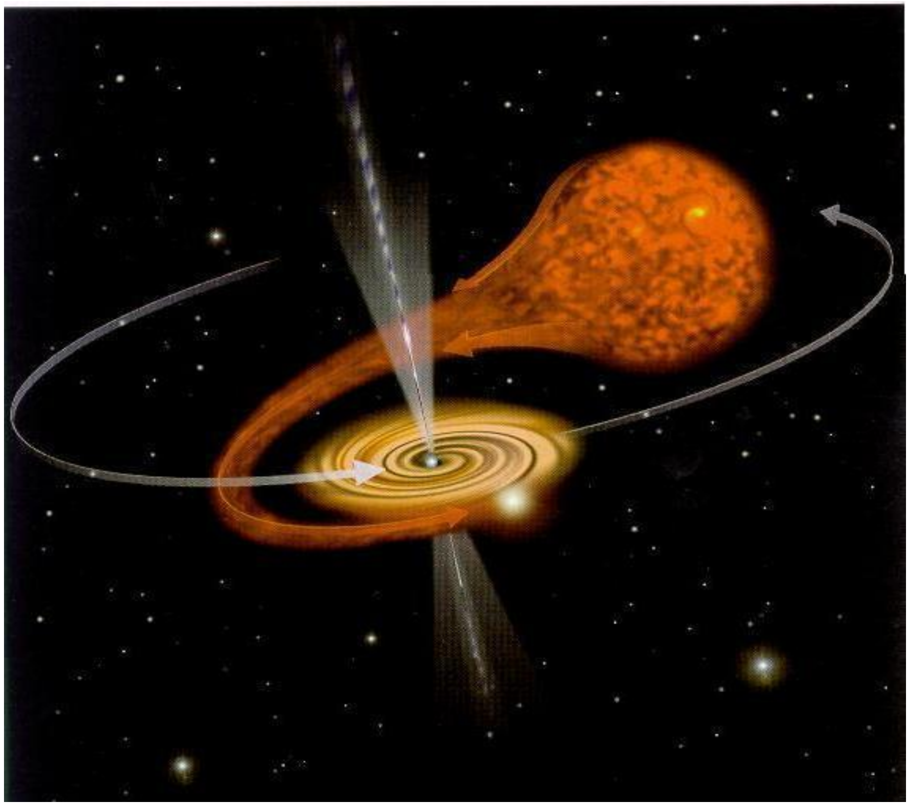
Nuclear Reaction Measurements for Explosive Nuclear Astrophysics

PJ Woods

University of Edinburgh



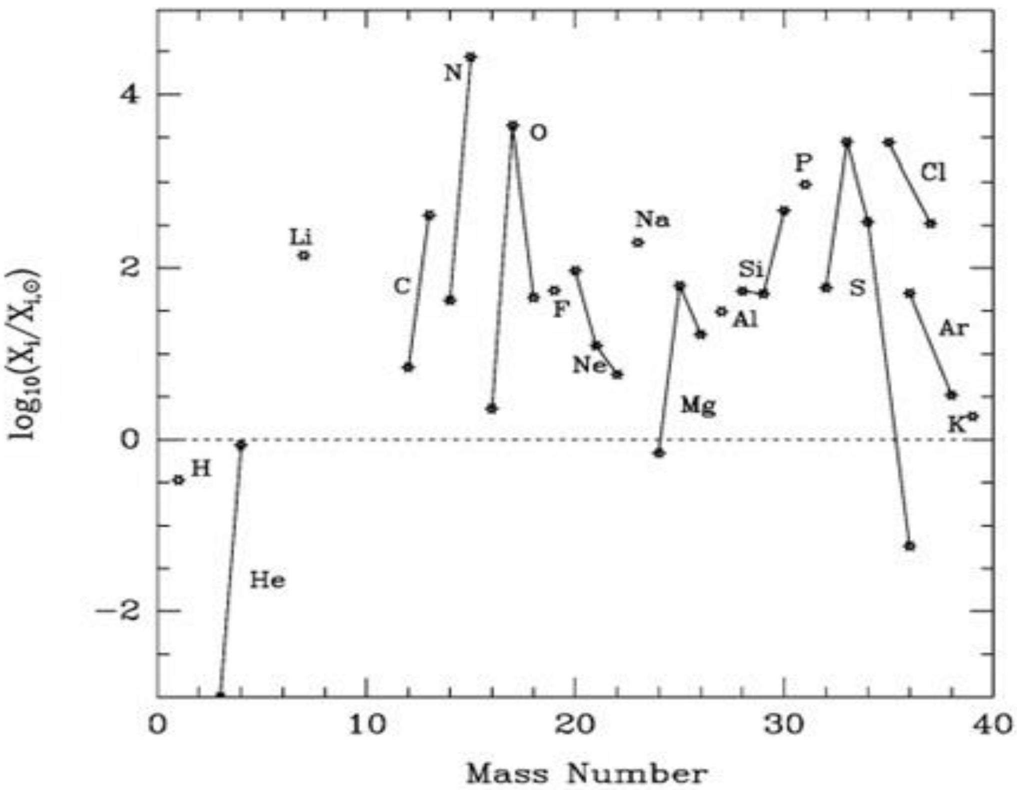
Explosive H burning in Novae



Isaac Newton, Principia Mathematica (1666): ‘from this fresh supply of new fuel those old stars, acquiring new splendour, may pass for new stars’

Elemental abundances in novae ejecta

1.35 M_{Sun} ONe nova

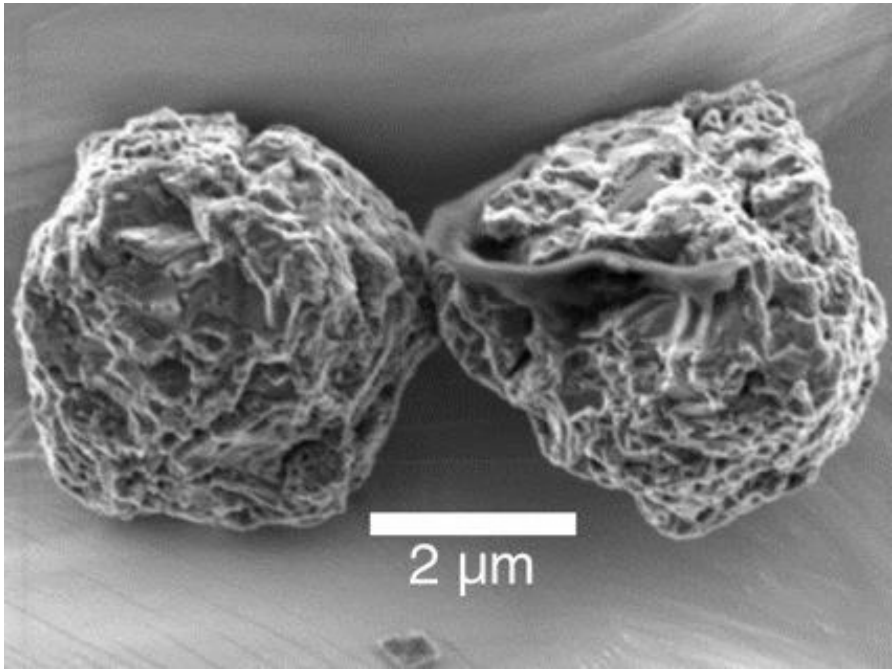


J. José, M. Hernanz, C. Iliadis. Nucl Phys A**, 777**, (2006), 550-578

Presolar grains

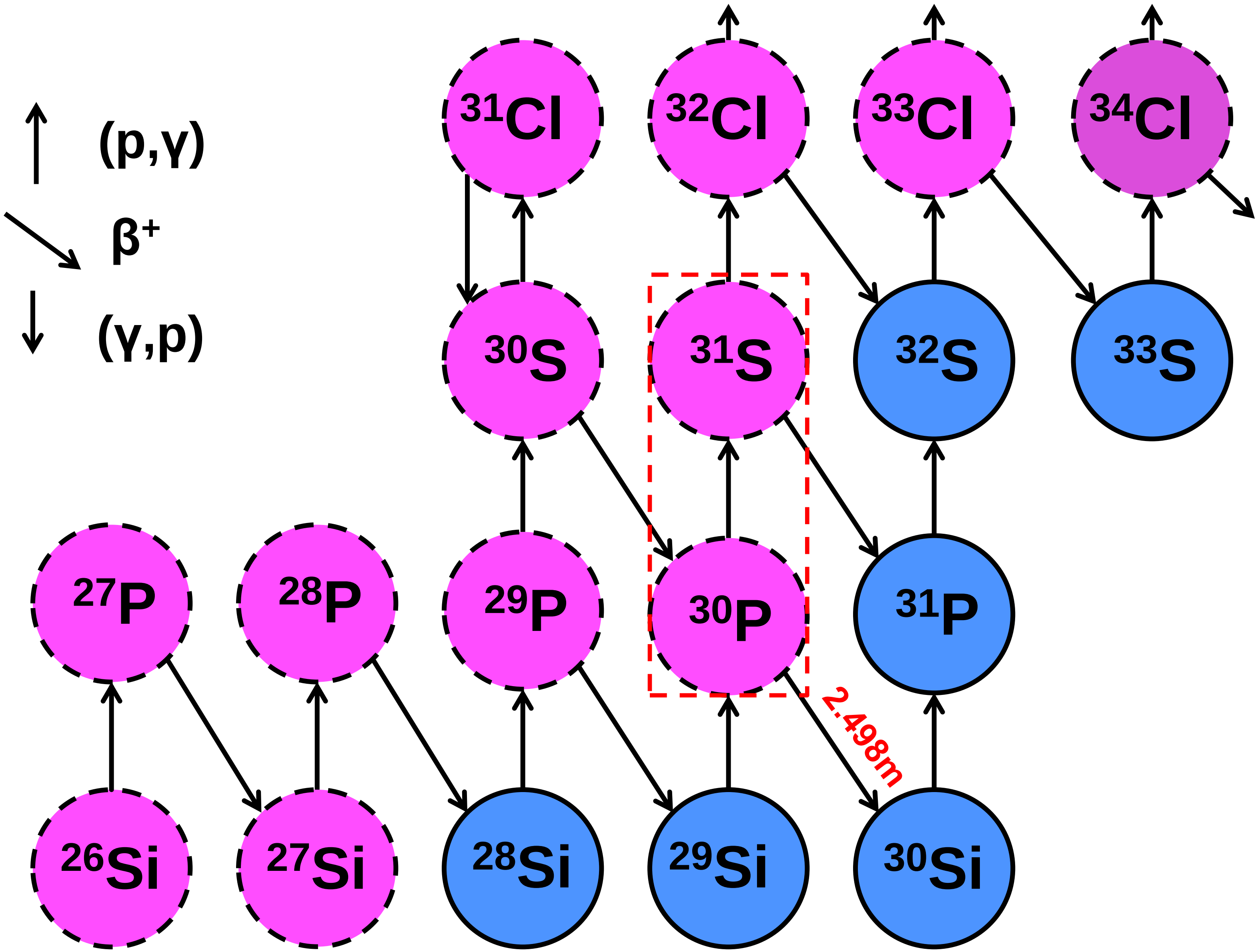
- **Grains of nova origin are thought to have a large $^{30}Si/^{28}Si$ ratio.**

- **Abundance of ^{30}Si is determined by the competition between the ^{30}P β^+ decay and the $^{30}P(p,\gamma)^{31}S$ reaction rate.**

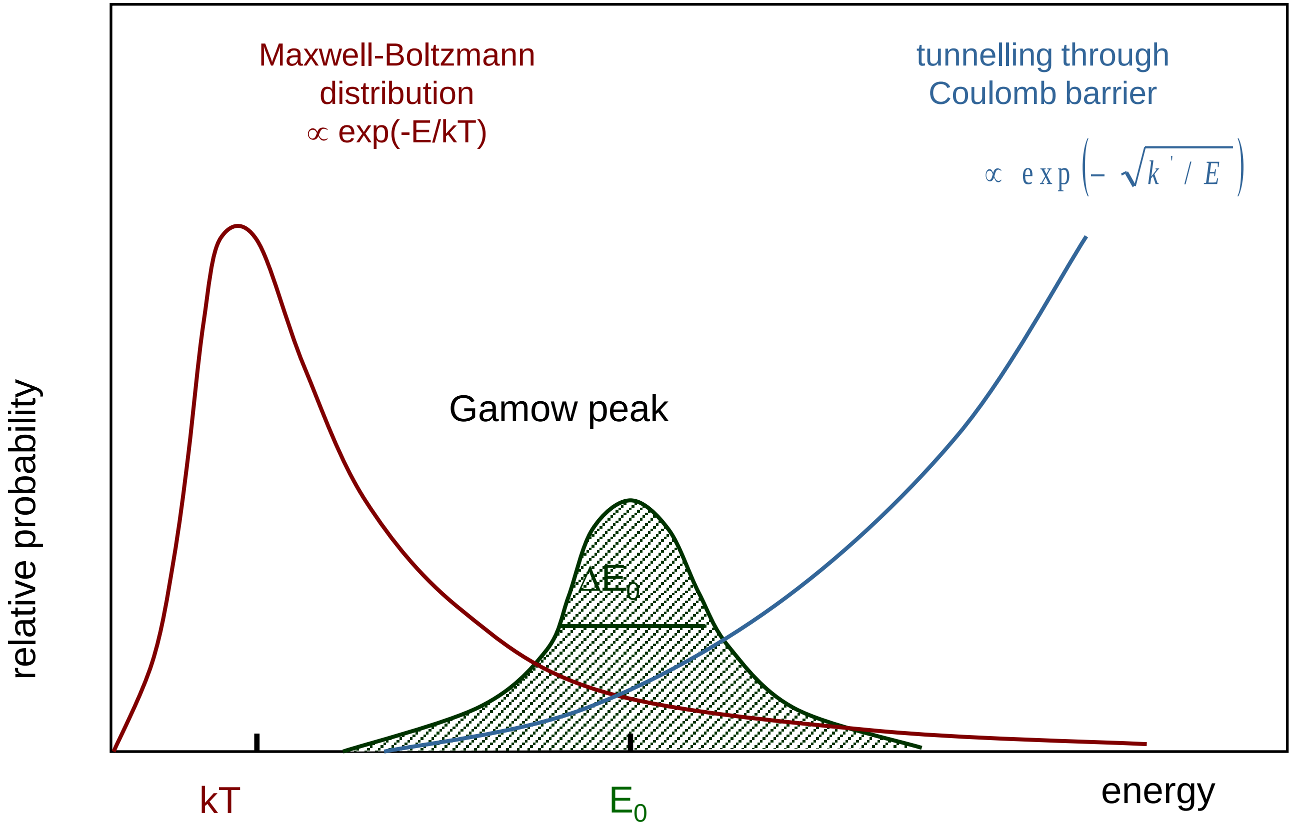


Andrew M Davis. University of Chicago

Novae Nucleosynthesis



H burning reactions at stellar energies

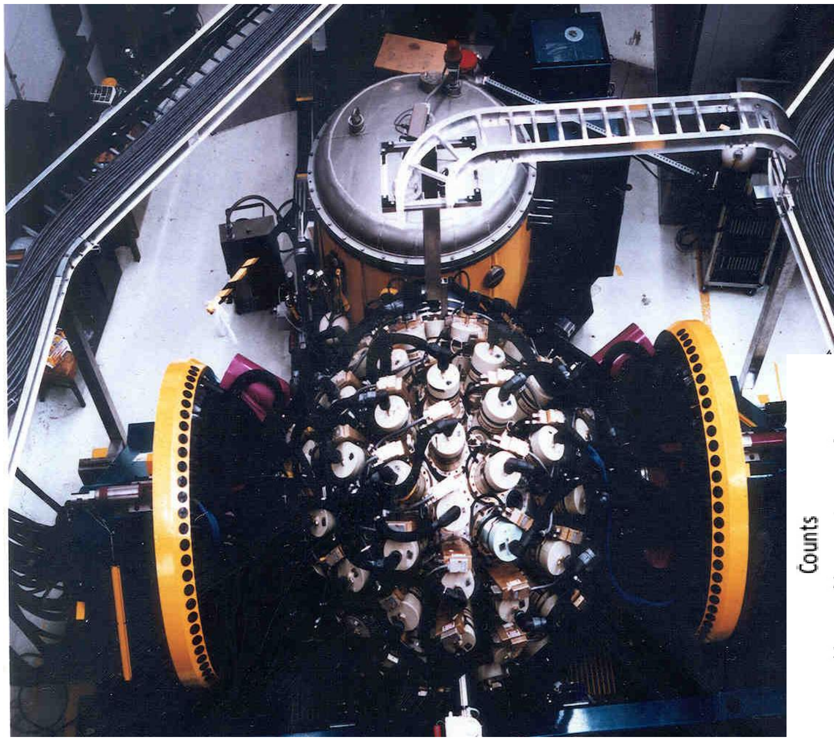


Reaction rate can be dominated by a few resonances in Gamow burning window

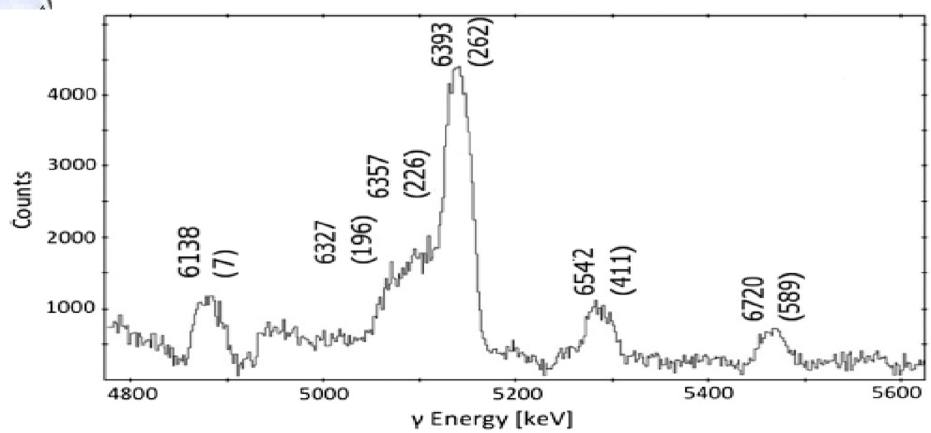
PRL **108,** 262502 (2012) PHYSICAL REVIEW LETTERS week ending 29 JUNE 2012

Key Resonances in the ^{30}P(p, γ)^{31}S Gateway Reaction for the Production of Heavy Elements in ONe Novae

D. T. Doherty,[1] G. Lotay,[1] P. J. Woods,[1] D. Seweryniak,[2] M. P. Carpenter,[2] C. J. Chiara,[2,3] H. M. David,[1] R. V. F. Janssens,[2] L. Trache,[4] and S. Zhu[2]



Identified using
^{4}He + ^{28}Si → ^{31}S + n reaction
with Gammasphere Ge-array



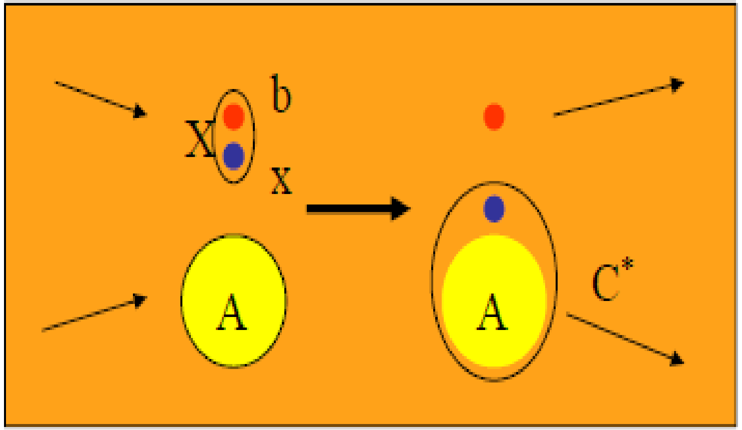
However, key resonance strengths, ω_γ, unknown

$$\omega\gamma = \frac{2J_R + 1}{(2J_1 + 1)(2J_2 + 1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma_{tot}}$$

use transfer reactions to estimate Γ_p for (p,γ) reactions

where resonance has $\Gamma_p << \Gamma_\gamma$, ω_γ is proportional to Γ_p.

Γ_p α P_l (barrier penetration factor) X S(spectroscopic factor)

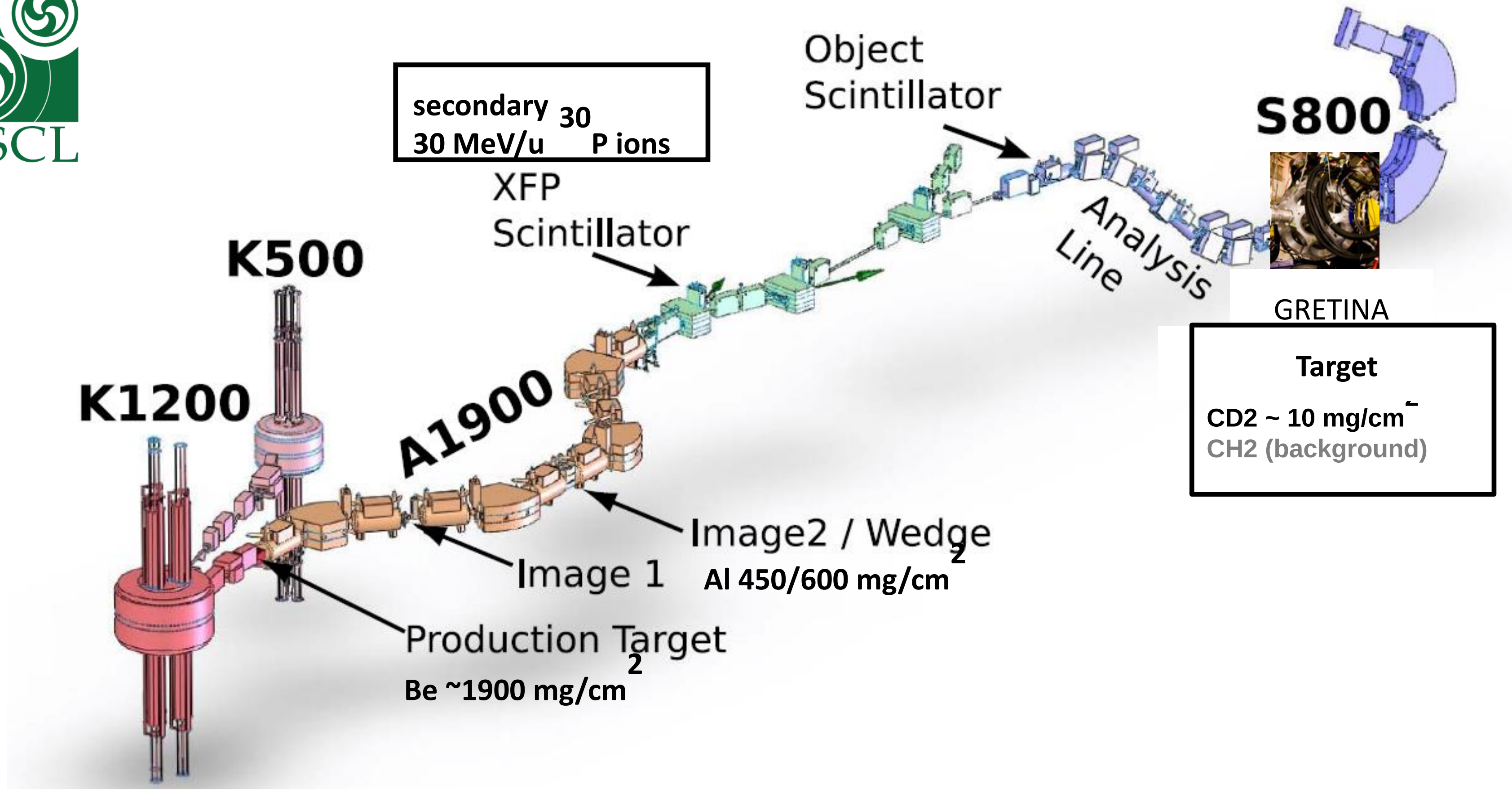


$\sigma_{transfer} = \sigma_{DWBA}$ X S

P.J. Woods, A Kankainen, H. Schatz, et al.

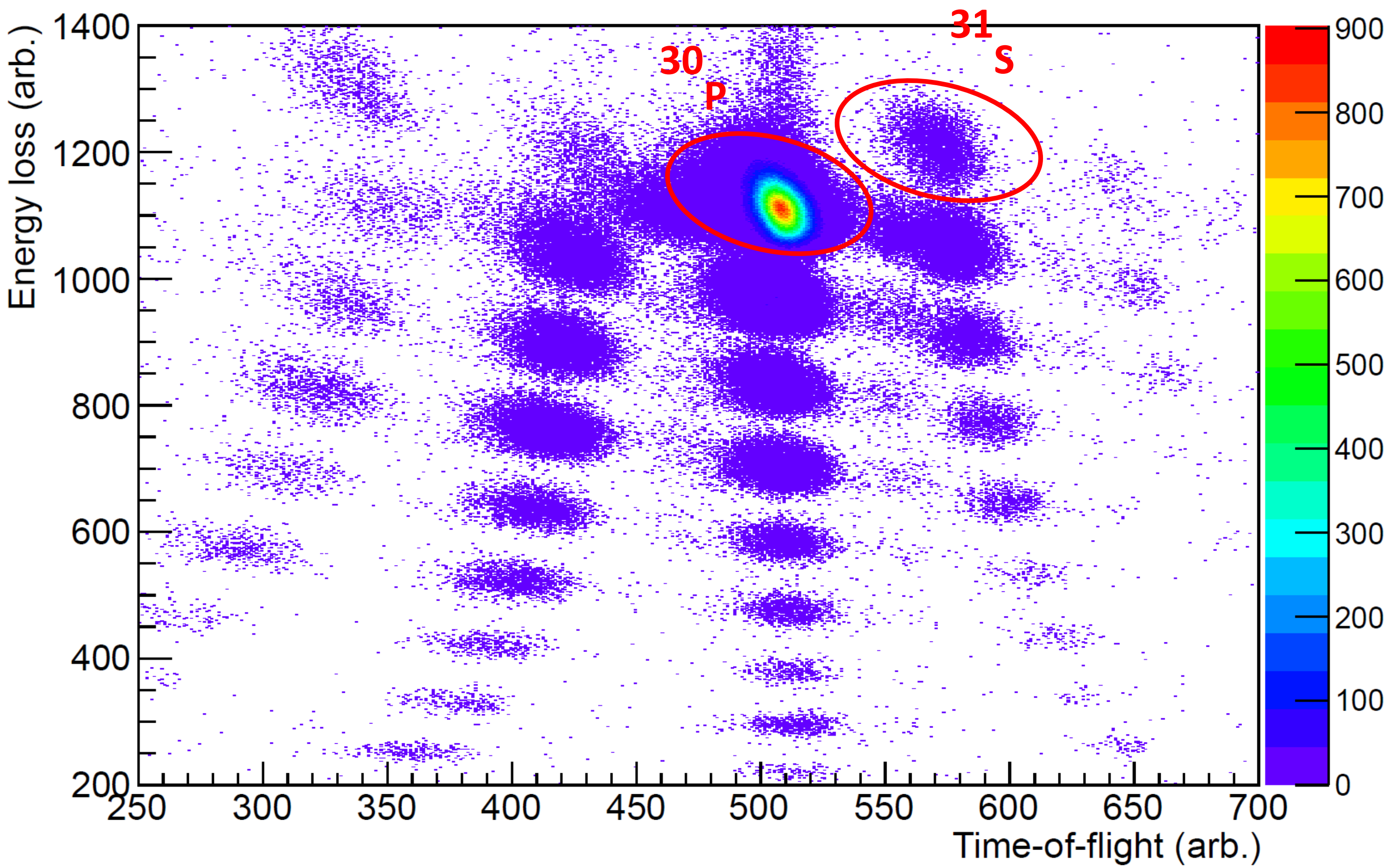
(d,n) transfer reaction cross-section measurements as a surrogate for (p,γ)

NSCL

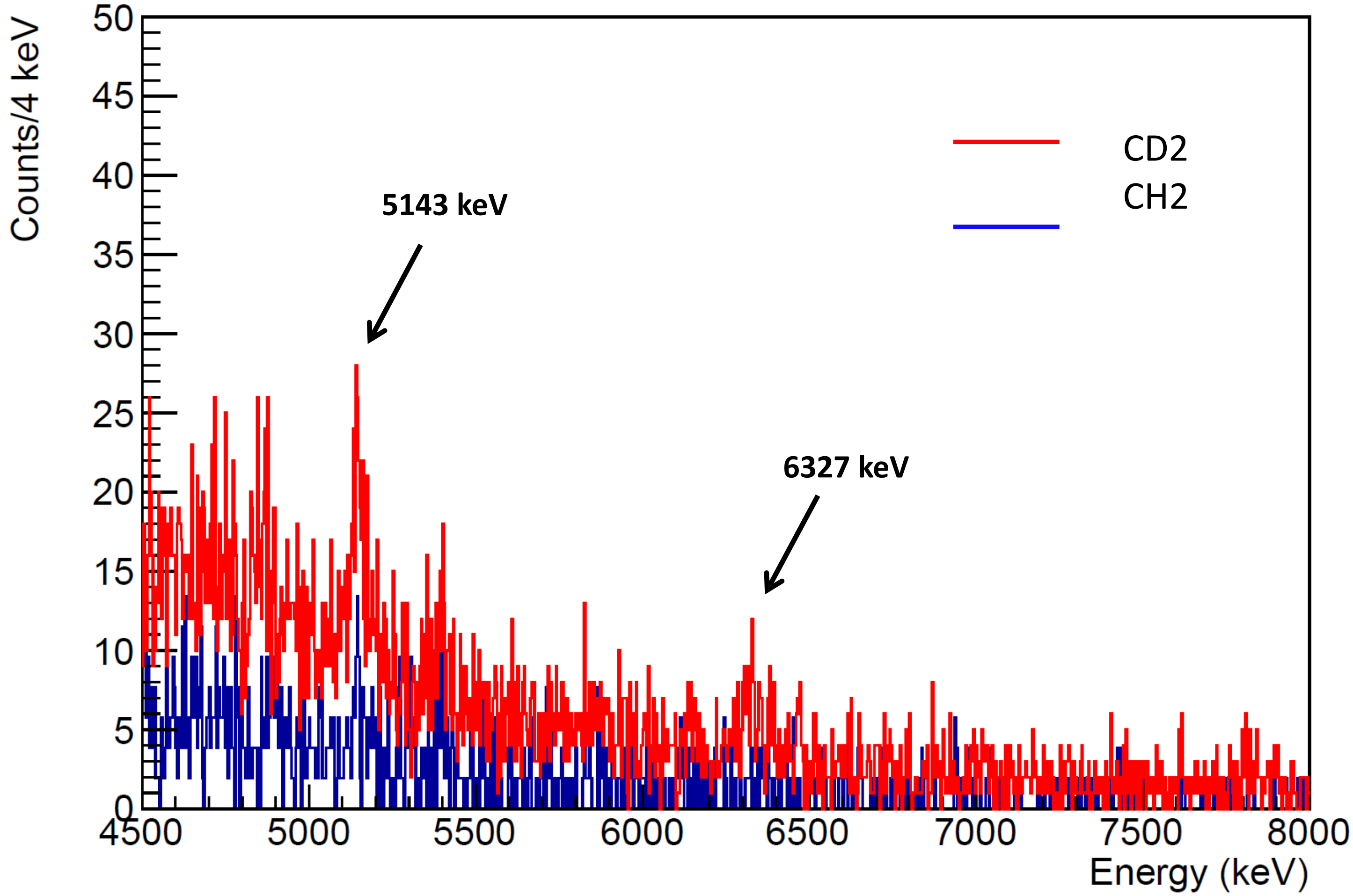


Primary beam: 150 MeV/u ^{36}Ar^{18+}

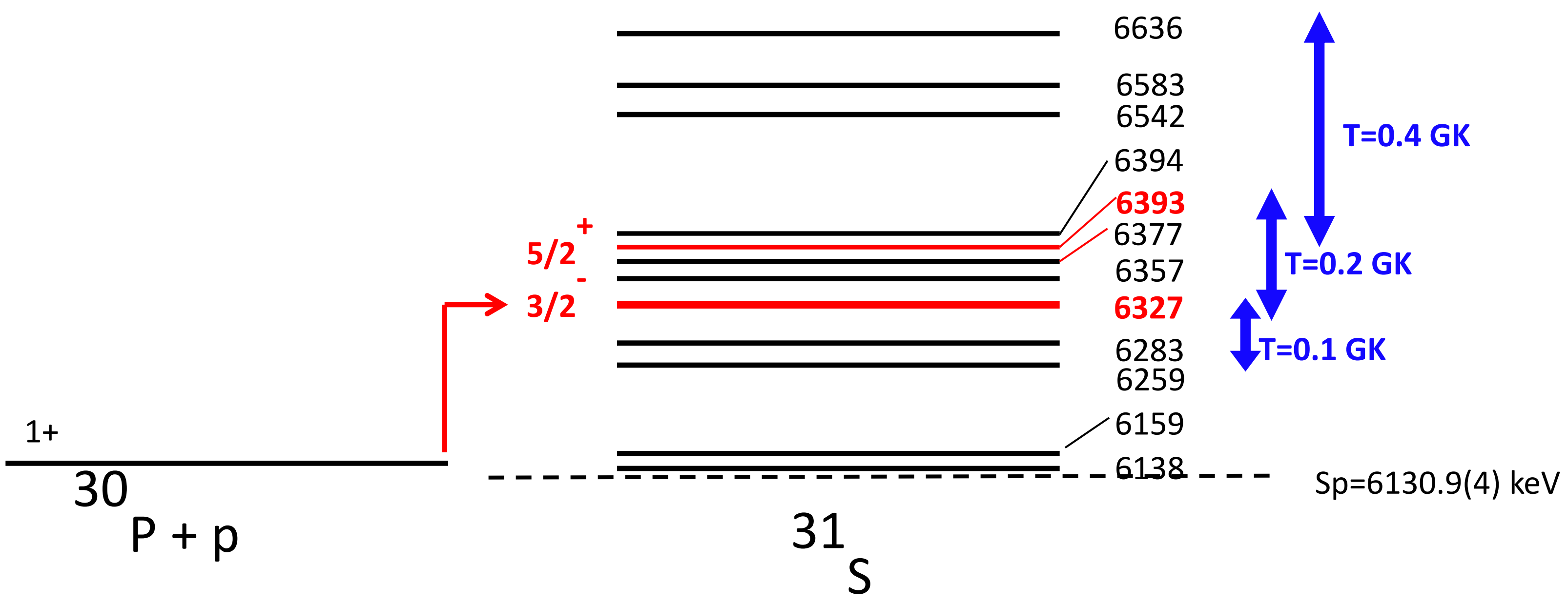
Particle identification: ^{31}S



^{31}S γ-ray energy spectrum



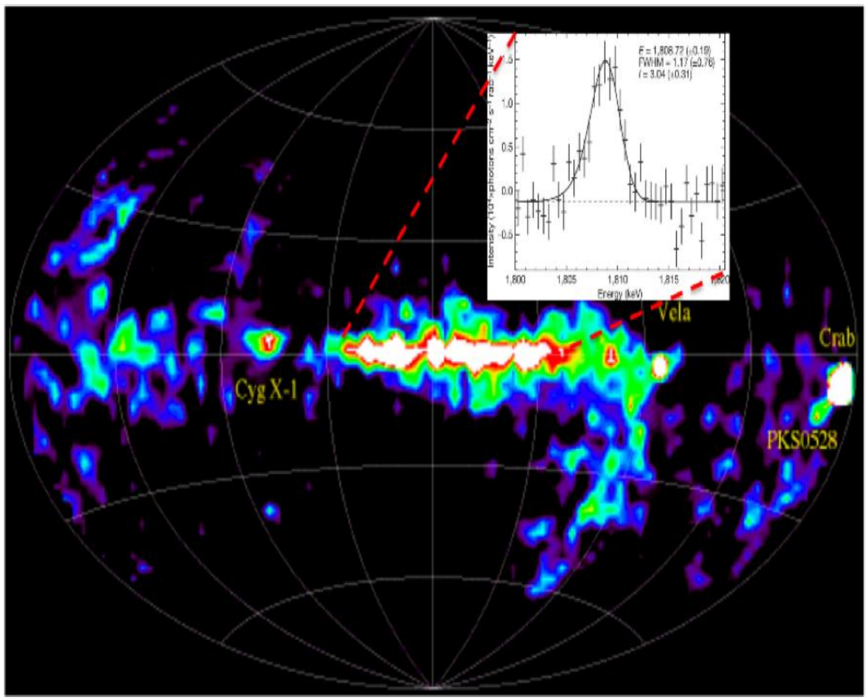
Levels above the proton threshold energy in ^{31}S

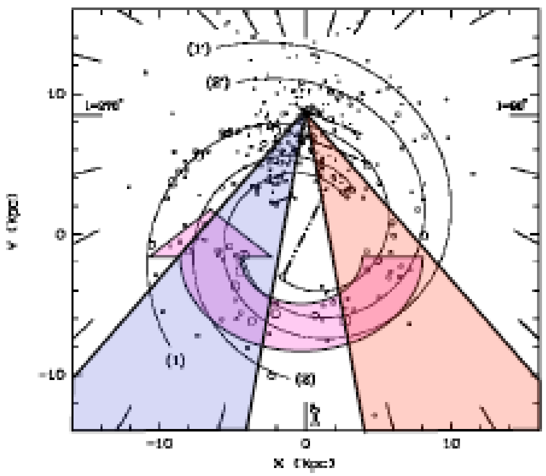


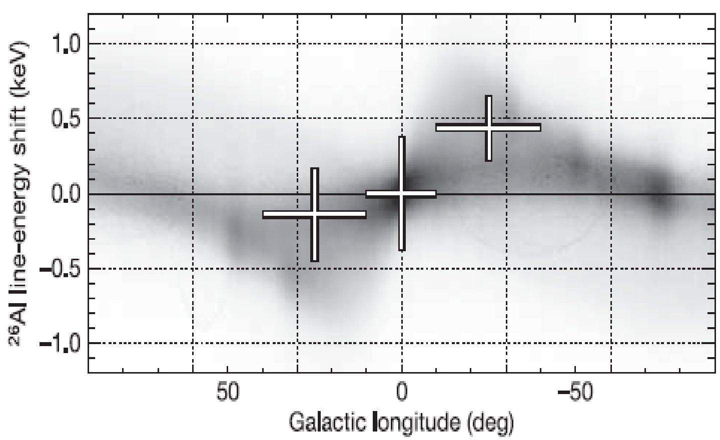
Extracted Γ_p values from cross-section indicate reaction rate is entirely dominated by a single strong –ve parity resonance at 196 keV

Galactic abundance distribution of the cosmic γ-ray emitter ^{26}Al

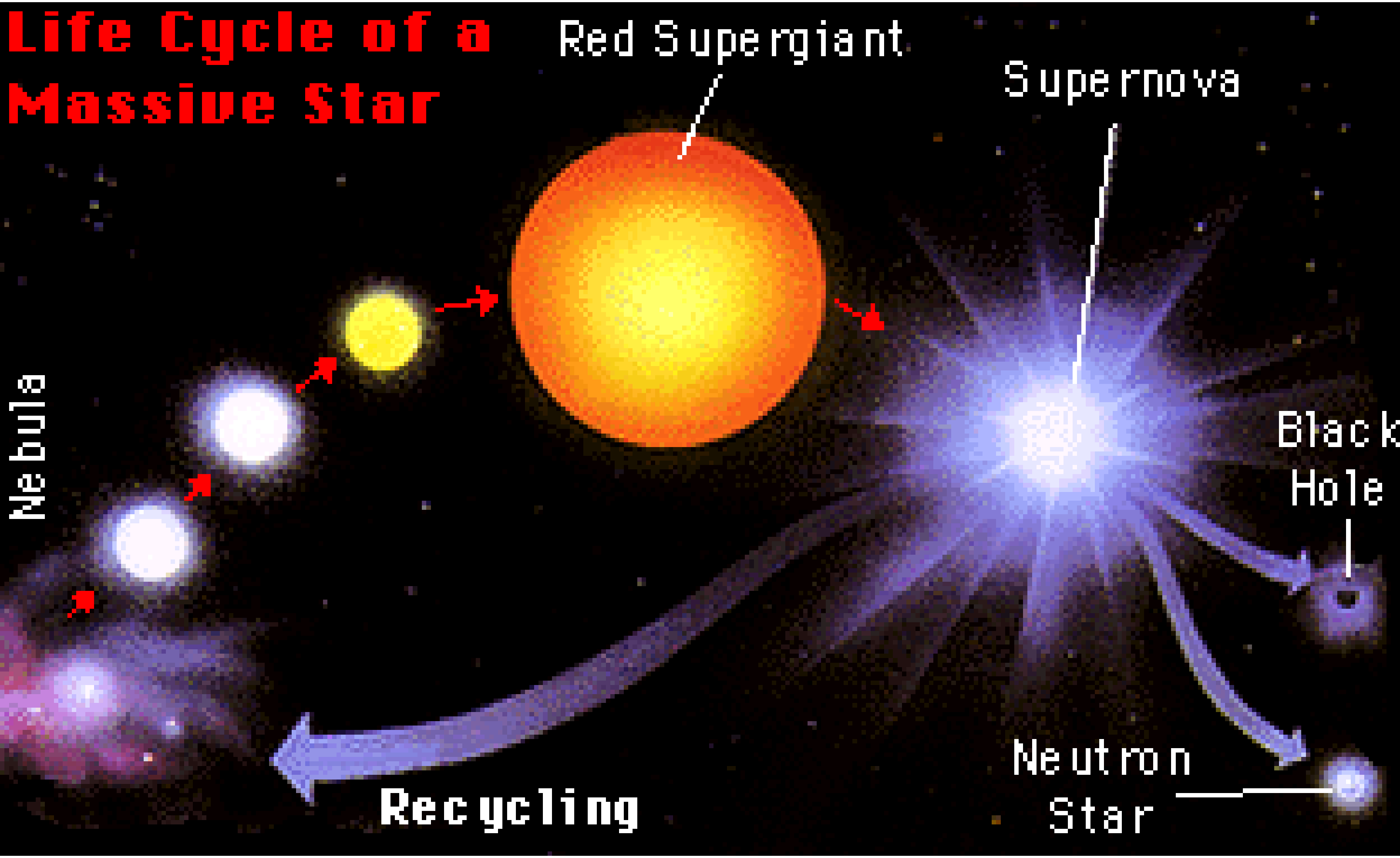
INTEGRAL satellite telescope - 2.8(8) M_{sun} of ^{26}Al in our galaxy
[R. Diehl, *Nature* ***439*** *45(2006)*]



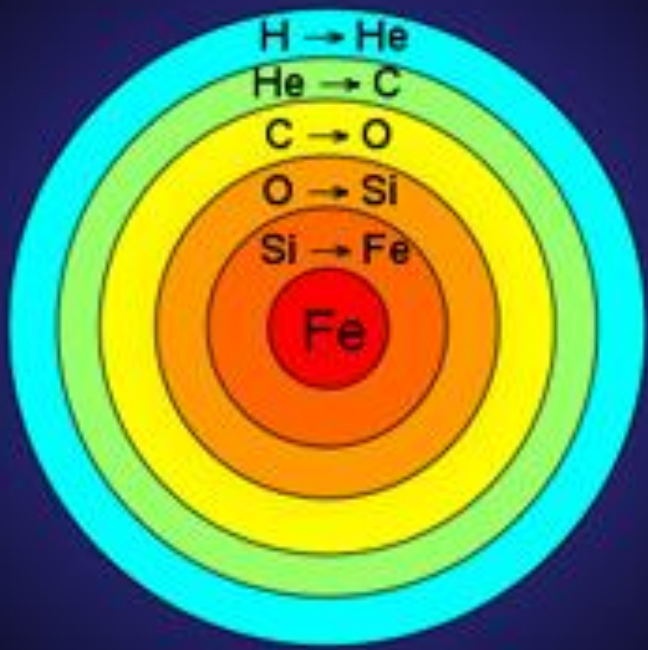




Supernova Cycle



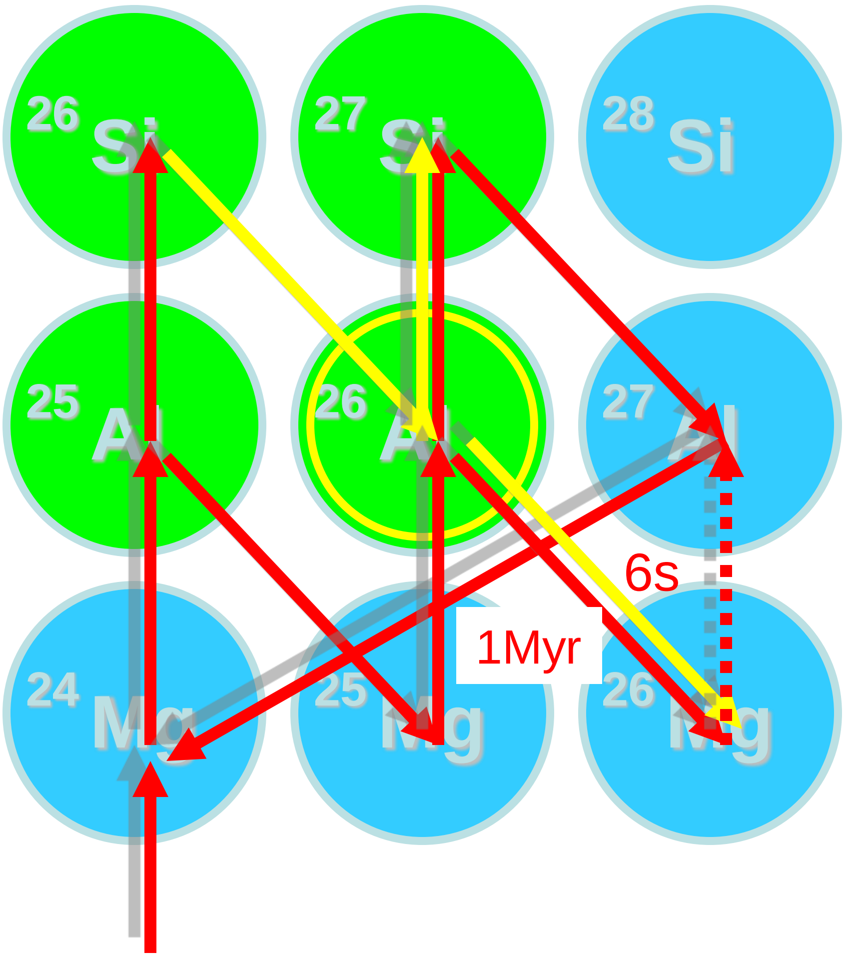
Stellar Life

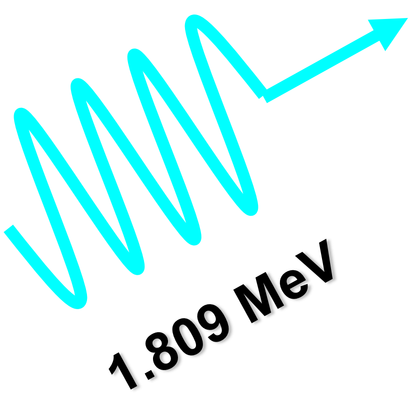


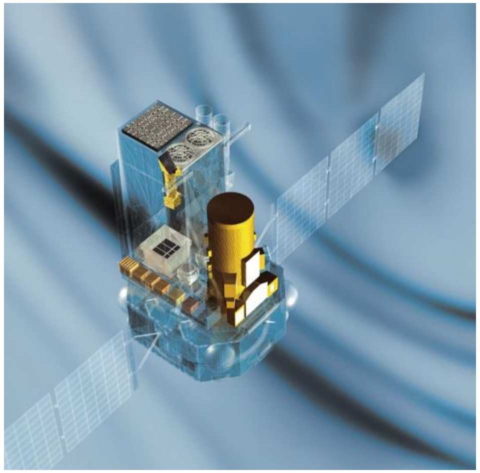
For a 25 solar mass star:

Stage	Duration
H → He	7×10^6 years
He → C	7×10^5 years
C → O	600 years
O → Si	6 months
Si → Fe	1 day
Core Collapse	1/4 second

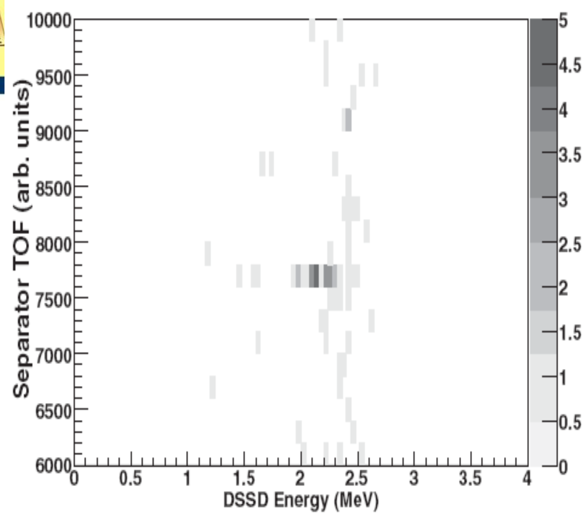
Hydrogen burning in Mg – Al Cycle







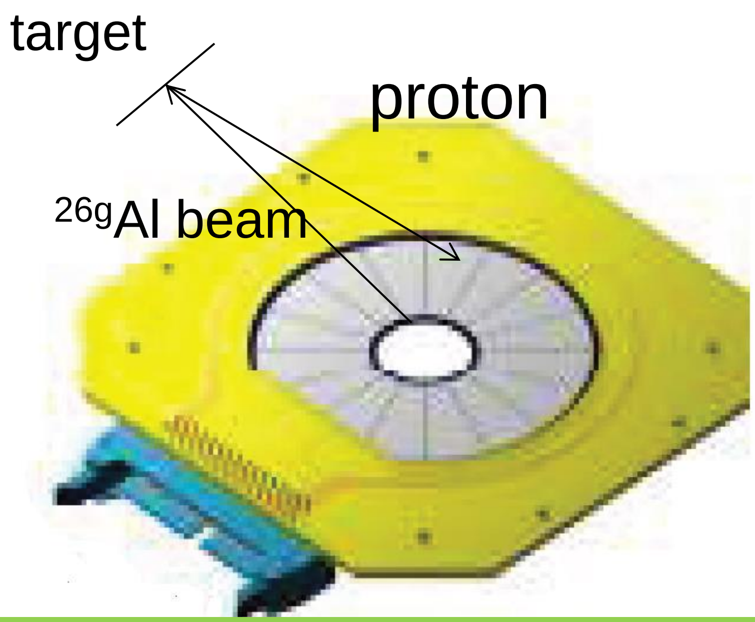
Direct measurement of $^{26g}Al(p,\gamma)^{27}Si$ reaction on 189 keV resonance, PRL 96 252501(2006)



→ lower energy resonances may dominate destruction of ^{26}Al burning in massive stars?

High resolution d(^{26g}Al,p)^{27}Al study of analog states of ^{27}Si resonances using Edinburgh TUDA Si array @ ISAC II Triumf

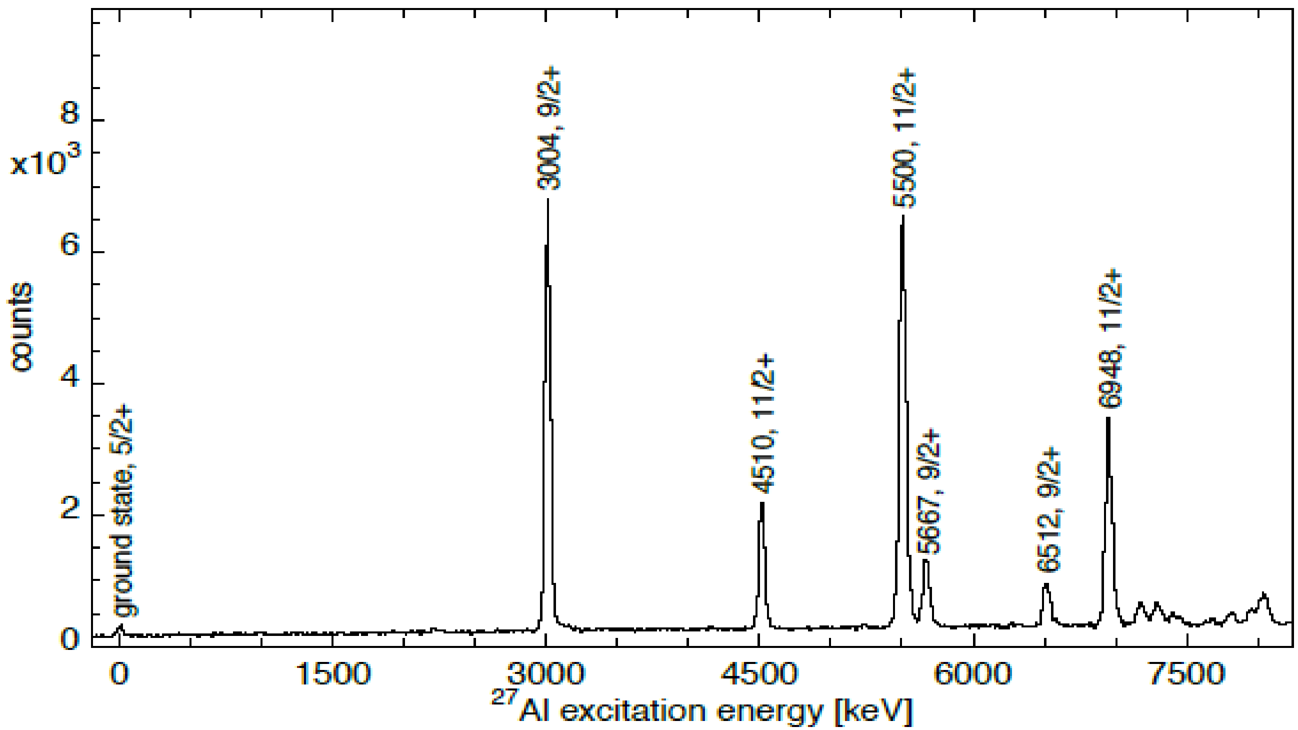
150 MeV ^{26g}Al beam bombarding 50 μg.cm^{-2} $(CD_2)_n$ target
I_{beam}~ 5*10^8 pps



Silicon detectors placed at backward angles, corresponding to forward angle transfer in CoM

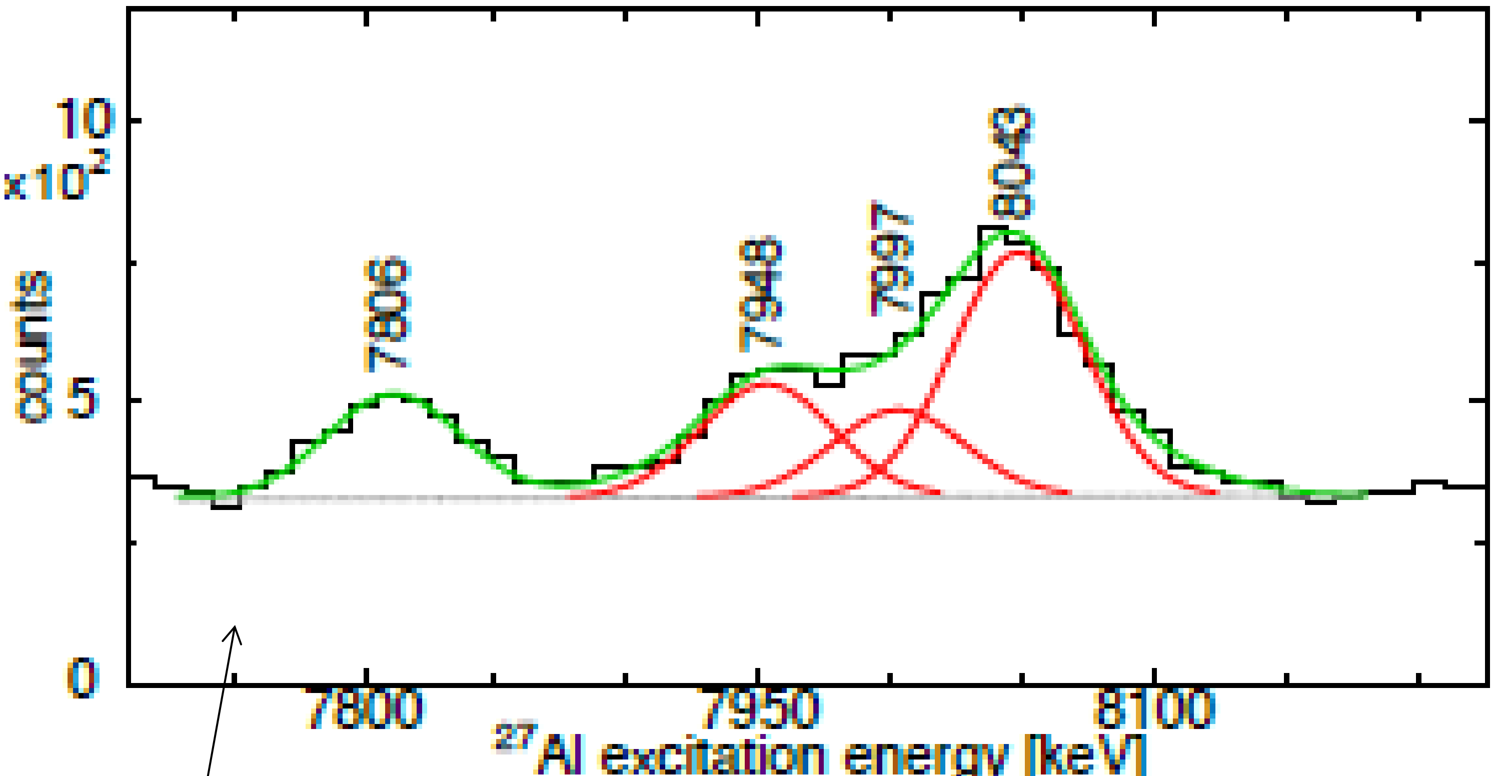
Inverse Kinematic Study of the $^{26g}Al(d,p)^{27}Al$ Reaction and Implications for Destruction of ^{26}Al in Wolf-Rayet and Asymptotic Giant Branch Stars

V. Margerin,[1] G. Lotay,[1,2,3,*] P. J. Woods,[1] M. Aliotta,[1] G. Christian,[4] B. Davids,[4] T. Davinson,[1] D. T. Doherty,[1,†] J. Fallis,[4] D. Howell,[4] O. S. Kirsebom,[4,‡] D. J. Mountford,[1] A. Rojas,[4] C. Ruiz,[4] and J. A. Tostevin[2]

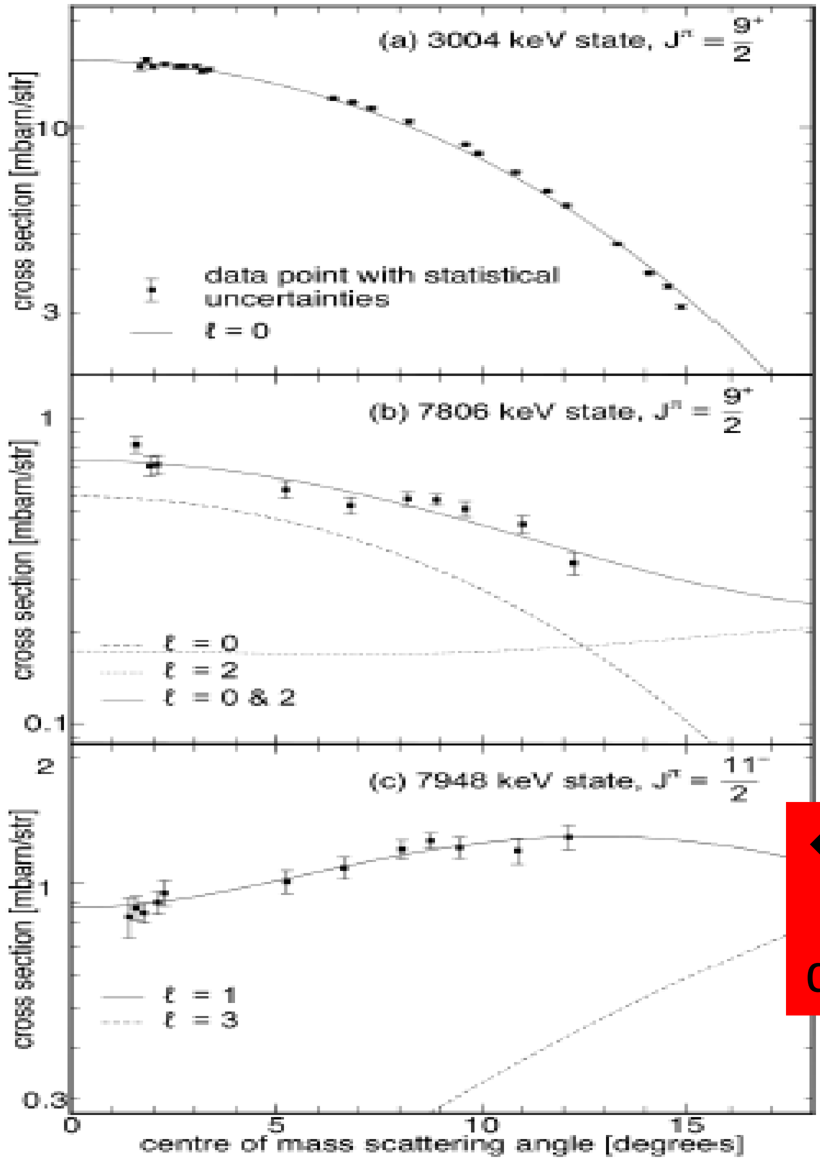


Energy Resolution in lab frame ~ 40 keV (FWHM)

Analogue states to key astrophysical resonances

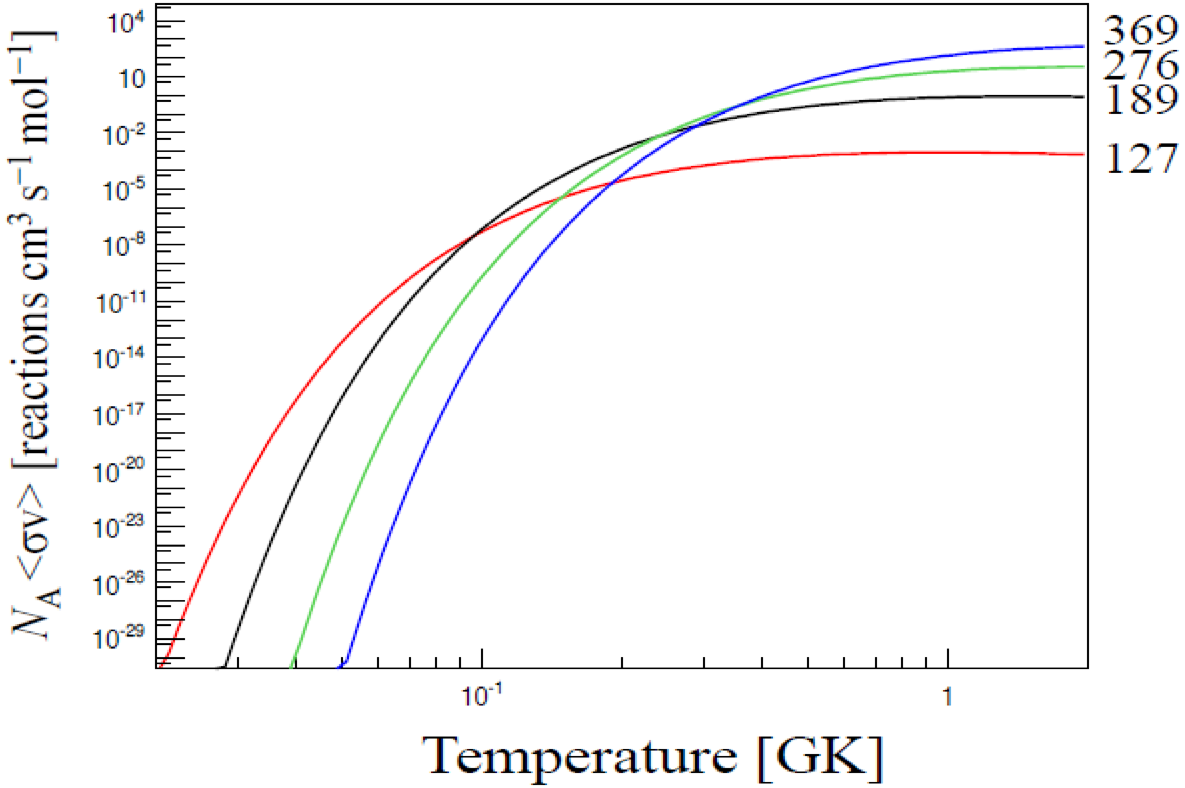


Continuous background due to protons from fusion
reactions with Carbon atoms in target



← Strong single particle –ve parity state dominates destruction in novae

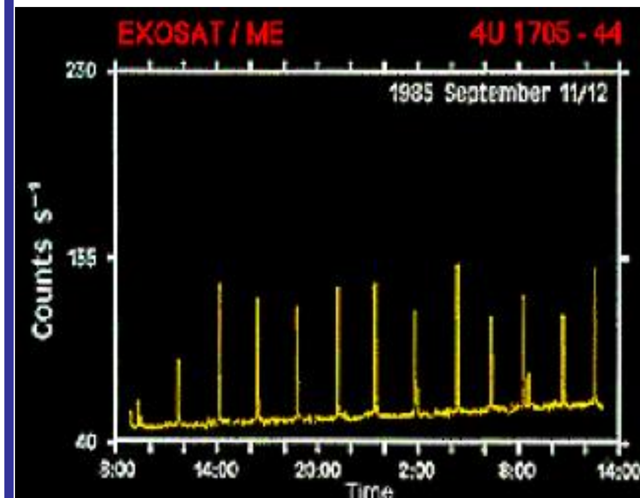
$^{26}Al(p,\gamma)^{27}Si$ reaction rate

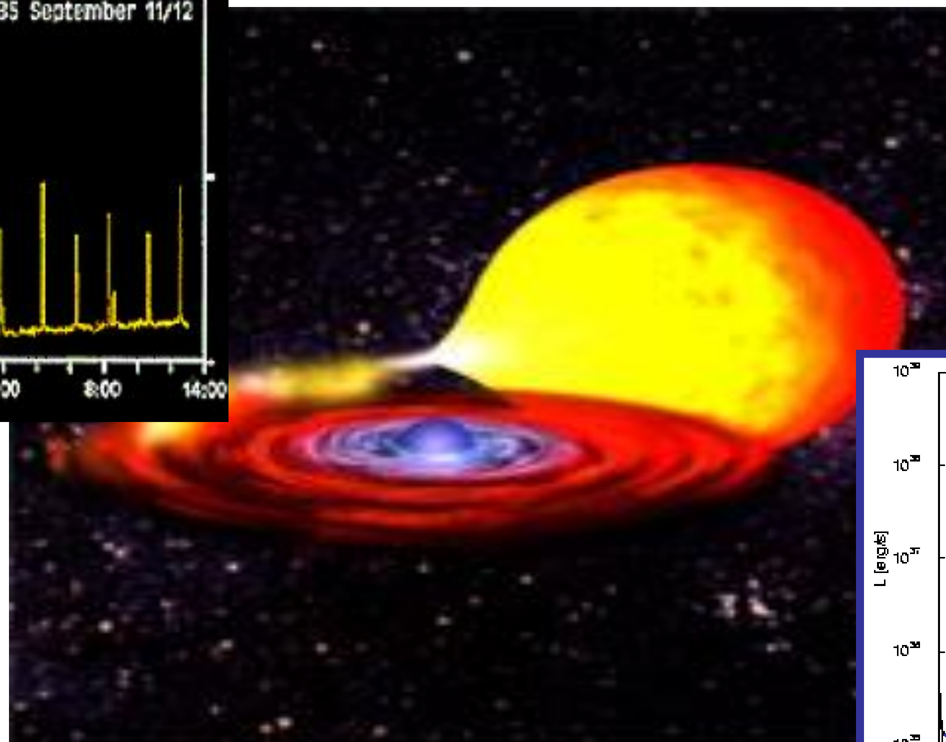


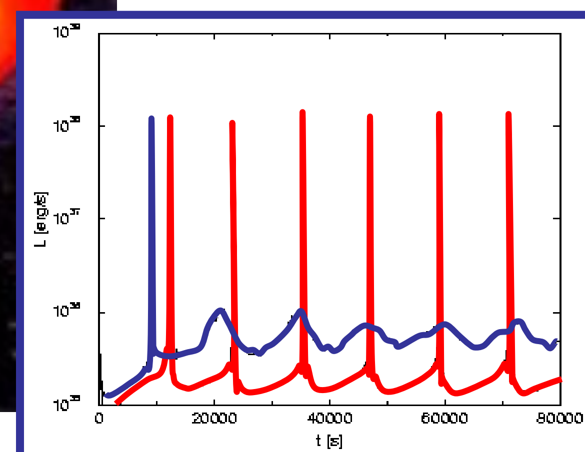
→ Conclude 9/2$^+$ 127 keV resonance in ^{27}Si dominates burning of ^{26}Al in Wolf Rayet and AGB stellar environments ~ 0.3- 0.8 .10^8 K

See also independent study by Pain et al. PRL 114,212501 (2015)

The $^{15}O(\alpha,\gamma)^{19}Ne$ reaction: the nuclear trigger of X-ray bursts







Reaction regulates flow between the hot CNO cycles and rp process
→ critical for explanation of amplitude and periodicity of bursts

THE ASTROPHYSICAL JOURNAL, 301:629–633, 1986 February 15

A NEW ESTIMATE OF THE $^{19}Ne(p, \gamma)^{20}Na$ AND $^{15}O(\alpha, \gamma)^{19}Ne$ REACTION RATES AT STELLAR ENERGIES

K. LANGANKE,[1] M. WIESCHER,[2] AND W. A. FOWLER
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena

AND

J. GÖRRES
Department of Physics, University of Pennsylvania, Philadelphia
Received 1985 May 24; accepted 1985 August 19

$^{15}O(\alpha,\gamma)^{19}Ne$ reaction rate predicted to be dominated by a single resonance at a CoM energy of 504 keV

Key unknown - α-decay probability from excited state at 4.03 MeV in ^{19}Ne compared to γ-decay, predicted to be ~ 10^{-4}

PHYSICAL REVIEW C **67**, 065808 (2003)

Astrophysical rate of $^{15}O(\alpha,\gamma)^{19}Ne$ via the (p,t) reaction in inverse kinematics

B. Davids,* A. M. van den Berg, P. Dendooven, F. Fleurot,† M. Hunyadi, M. A. de Huu, R. H. Siemssen, H. W. Wilschut, and H. J. Wörtche

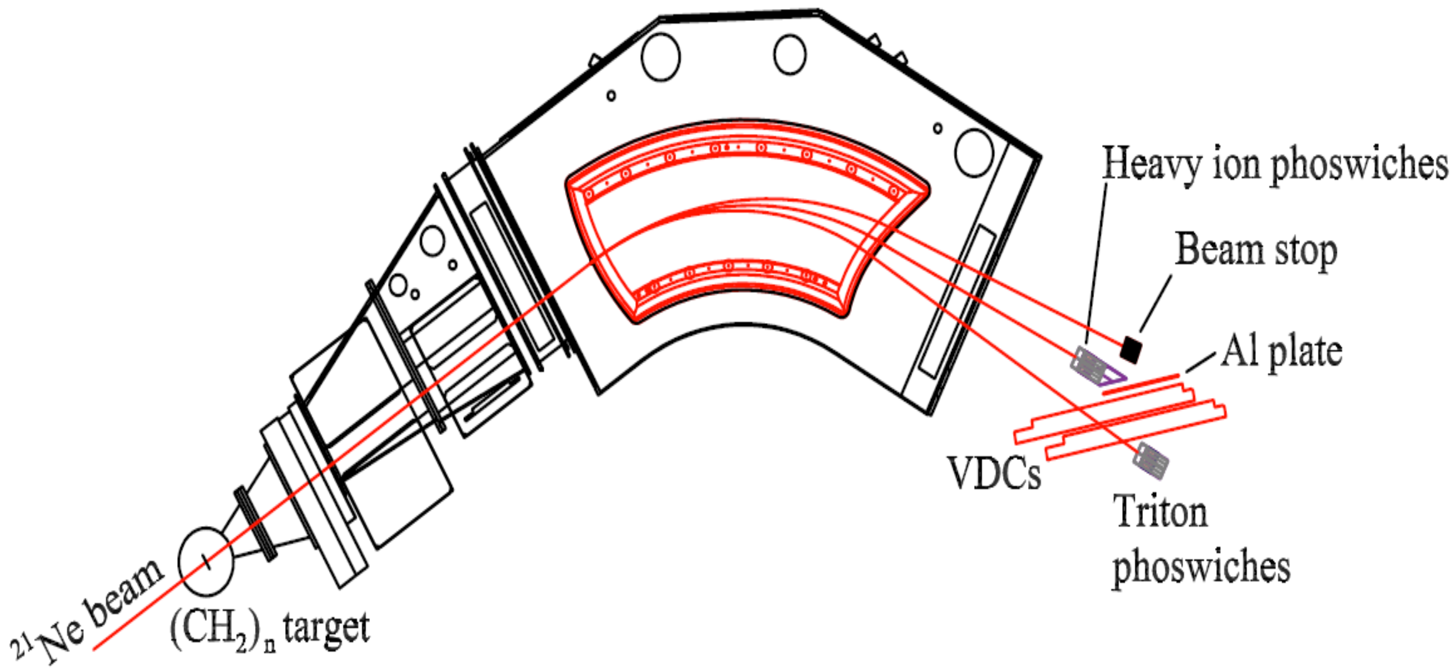
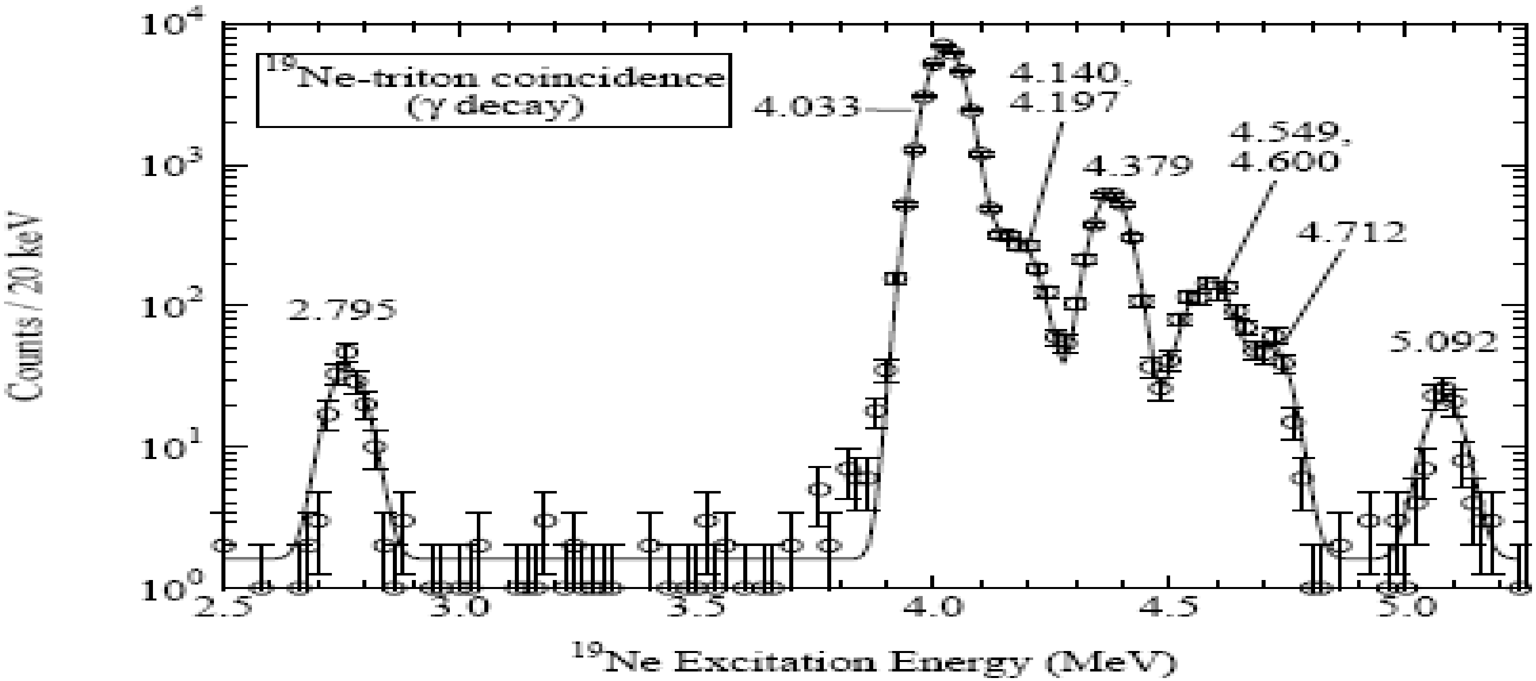
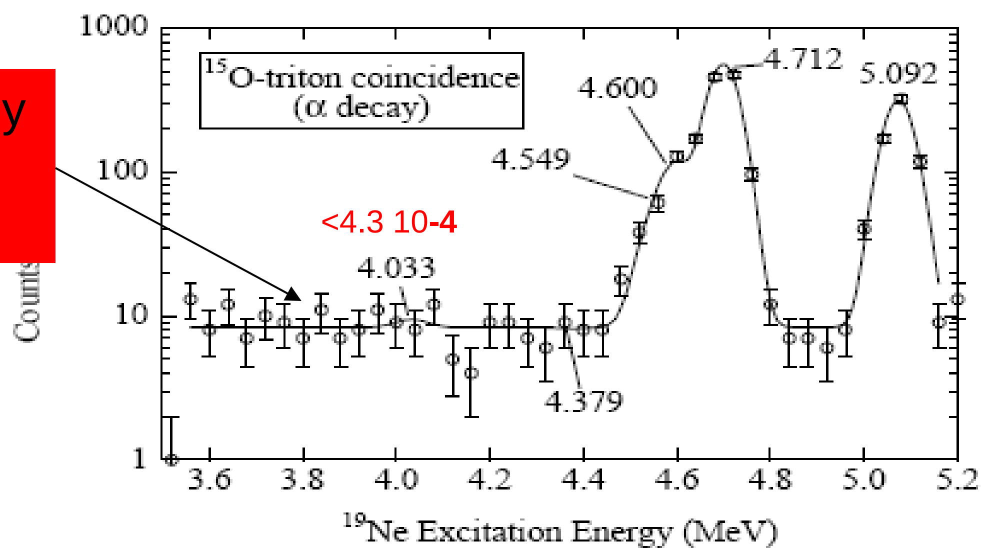


FIG. 1. (Color online) Experimental setup for the measurement of α-decay branching ratios of states in ^{19}Ne using a recoil coincidence technique at the Big-Bite Spectrometer of the KVI.

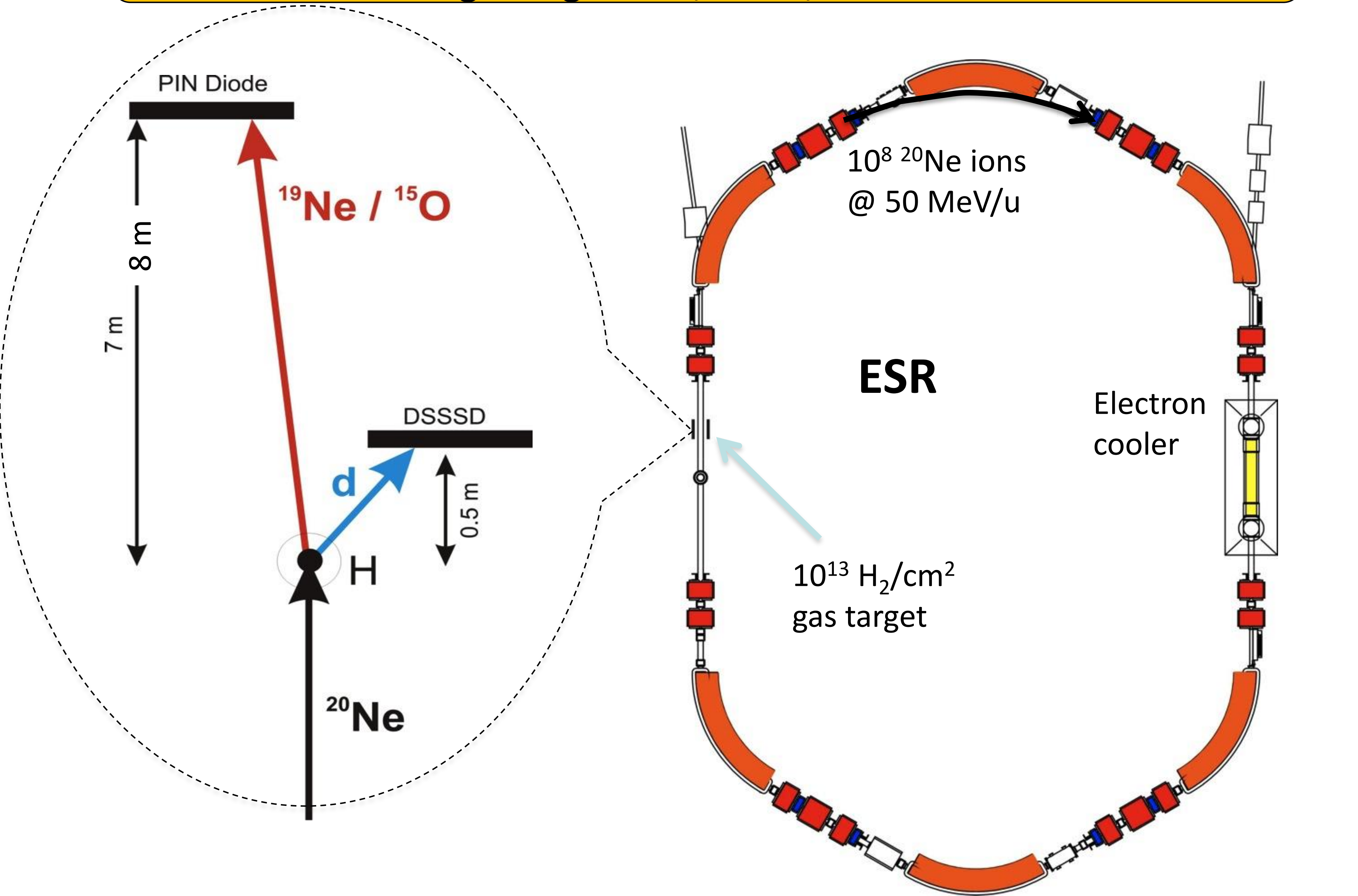
$p(^{21}Ne,^{3}H)^{19}Ne^{*}$



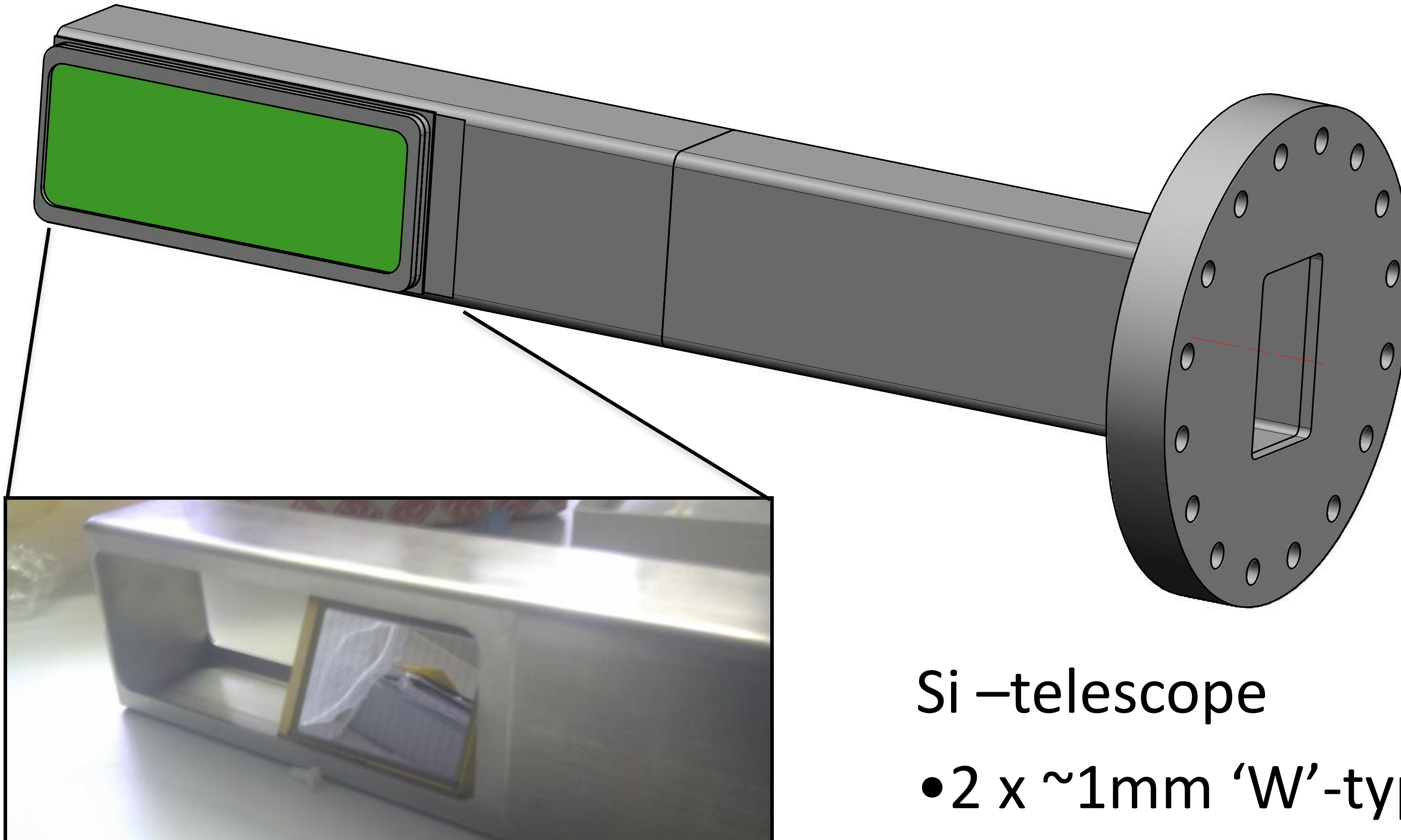
Background produced by reactions of ^{21}Ne beam with ^{12}C in target



Study of the p(^{20}Ne,^{2}H)^{19}Ne transfer reaction on the ESR heavy ion storage ring @GSI, PJW, Y Litvinov et al.

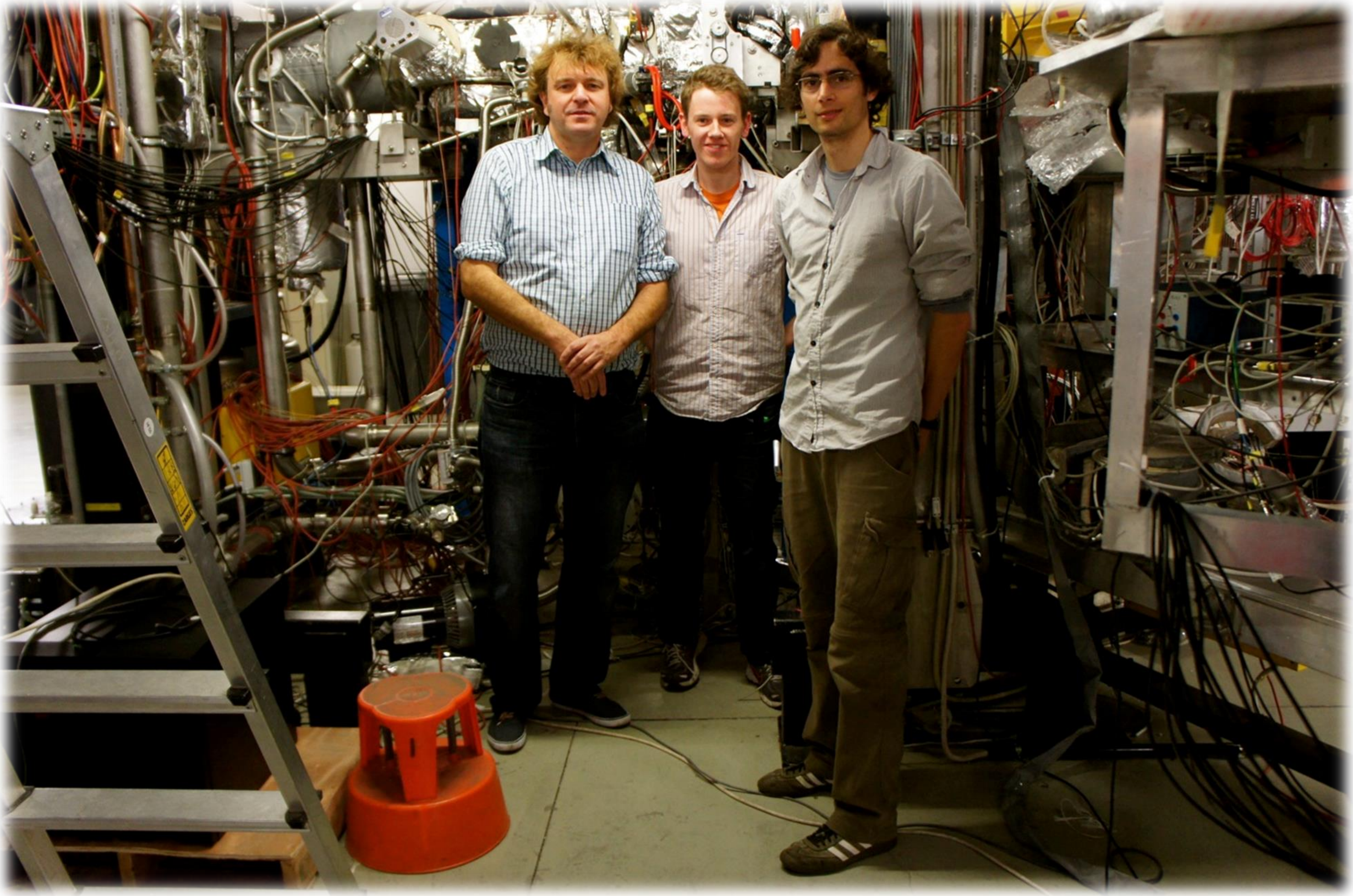


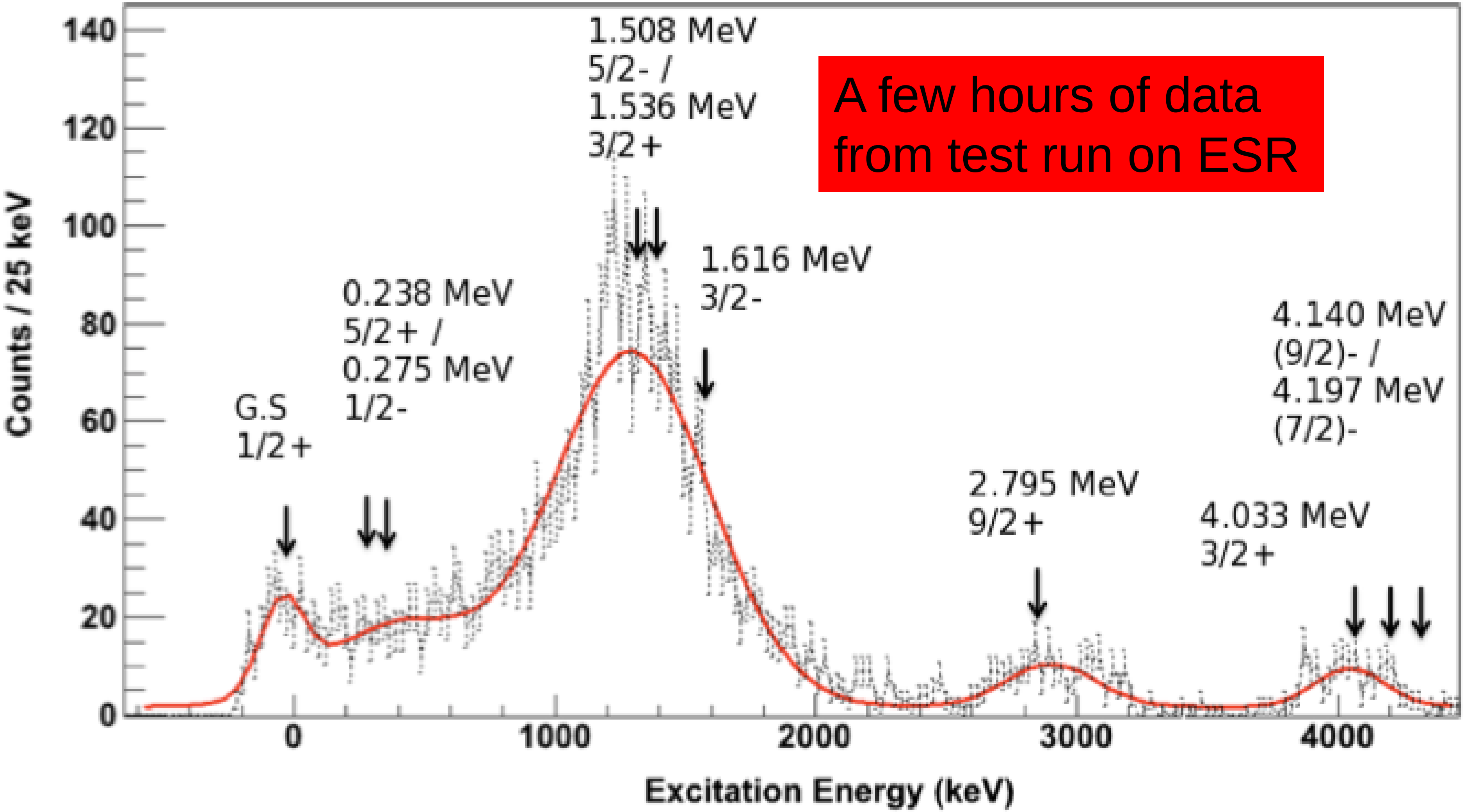
Detector Pocket



Si –telescope

- 2 x ~1mm ‘W’-type detectors
- 16x16 strips





DT Doherty, PhD Thesis (2014)

→ p(^{20}Ne,^{2}H)^{19}Ne reaction looks promising

Can we find a new approach that can utilises this reaction, and combines necessary features?

→ Discussions with Lolly, Valerie, Dan and Alan yesterday

(i) Require a 0° spectrometer, to identify α particles <1°

(VAMOS a good option)

(ii) A target containing enough protons, and robust under beam current of at least ~1pnA (Kapton?!)

(iii) High granularity/efficiency Silicon strip detector system (MUST2/MUGAST) latter combines measuring γ-branch

Summary and Outlook

Exciting new challenges being addressed at the interface between nuclear structure and reactions, and explosive nuclear astrophysics.

New techniques and approaches required to address these challenges. We made some good progress this week!

TSR@ISOLDE – Injection of RIBs into ring at MeV/u energies

Spokesperson: K Blaum (Heidelberg)

Deputies: R Raabe (Leuven), PJW (Edinburgh)

entire issue of EPJ 207 1-117 (2012)

In-ring DSSD System for ultra-high resolution (d,p), (p,d) and (^{3}He,d) transfer studies of astrophysical resonances → Newly funded UK ISOL-SRS project (Spokesperson PJW)

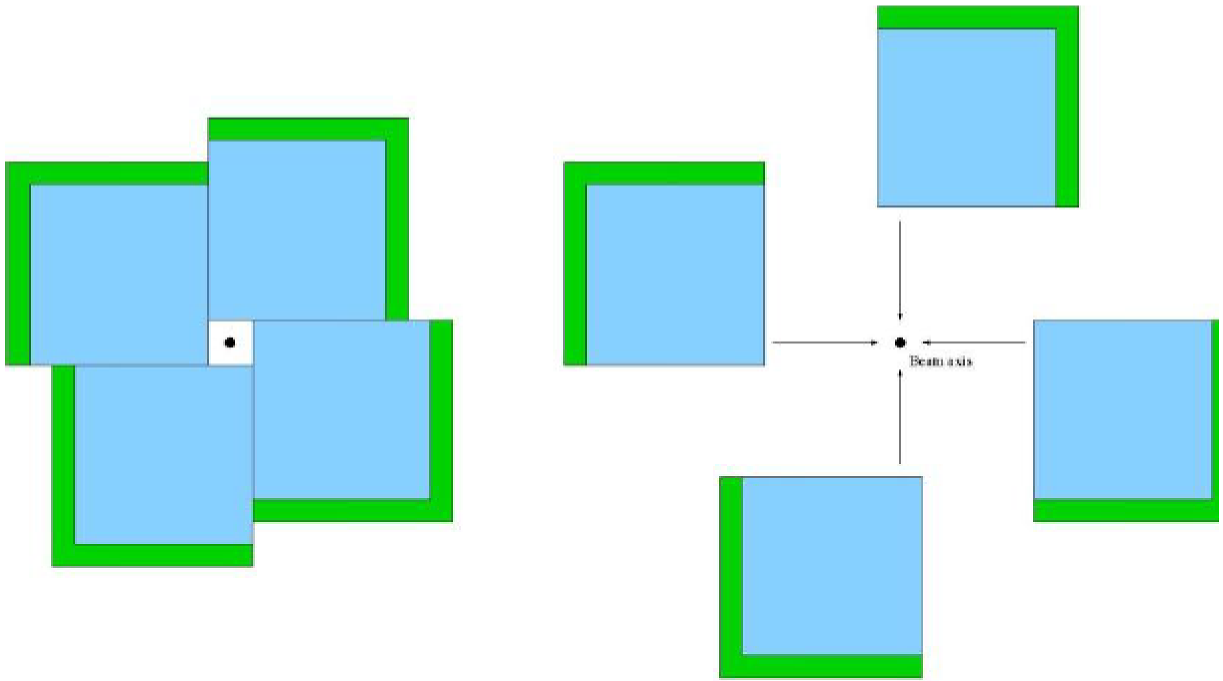


Figure 1: Illustration of upstream or downstream assembly of 4 DSSDs about beam axis

For ultra high resolution mode resolution should be entirely limited by transverse beam emittance

→ resolutions approaching 10 keV FWHM attainable