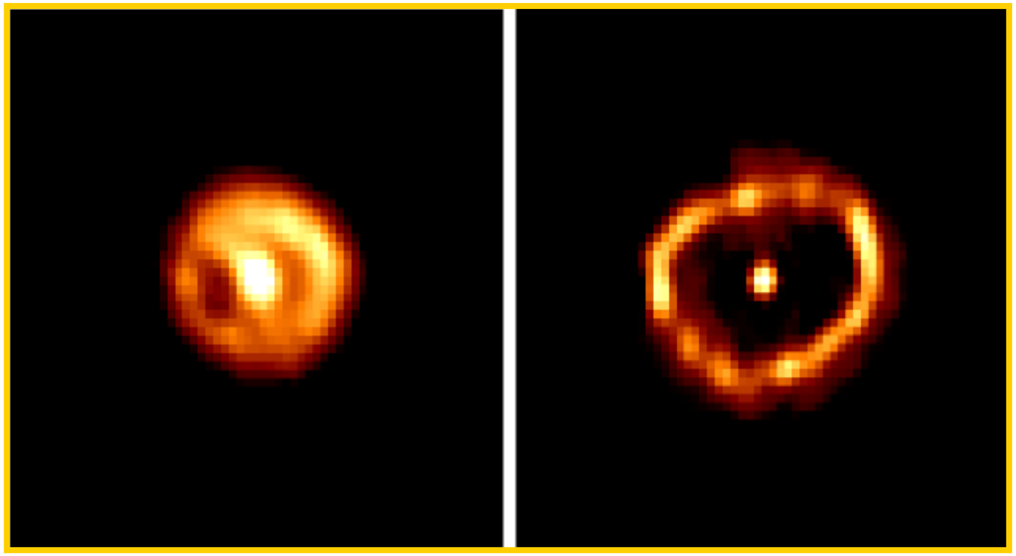
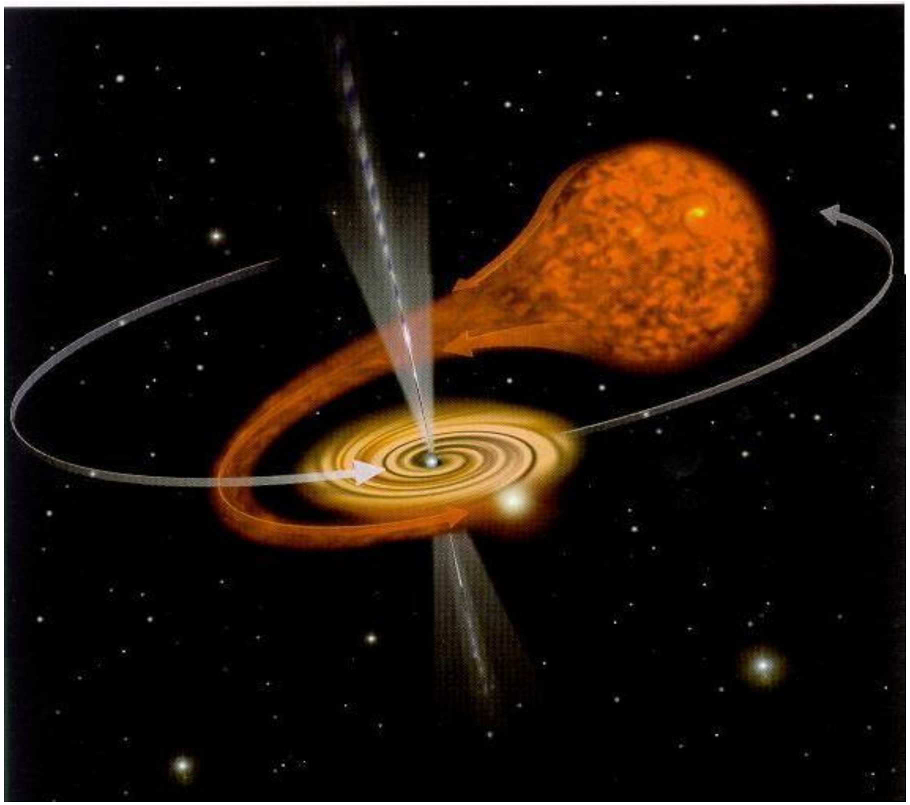
H/He burning reactions on unstable nuclei for Nuclear Astrophysics

PJ Woods

University of Edinburgh



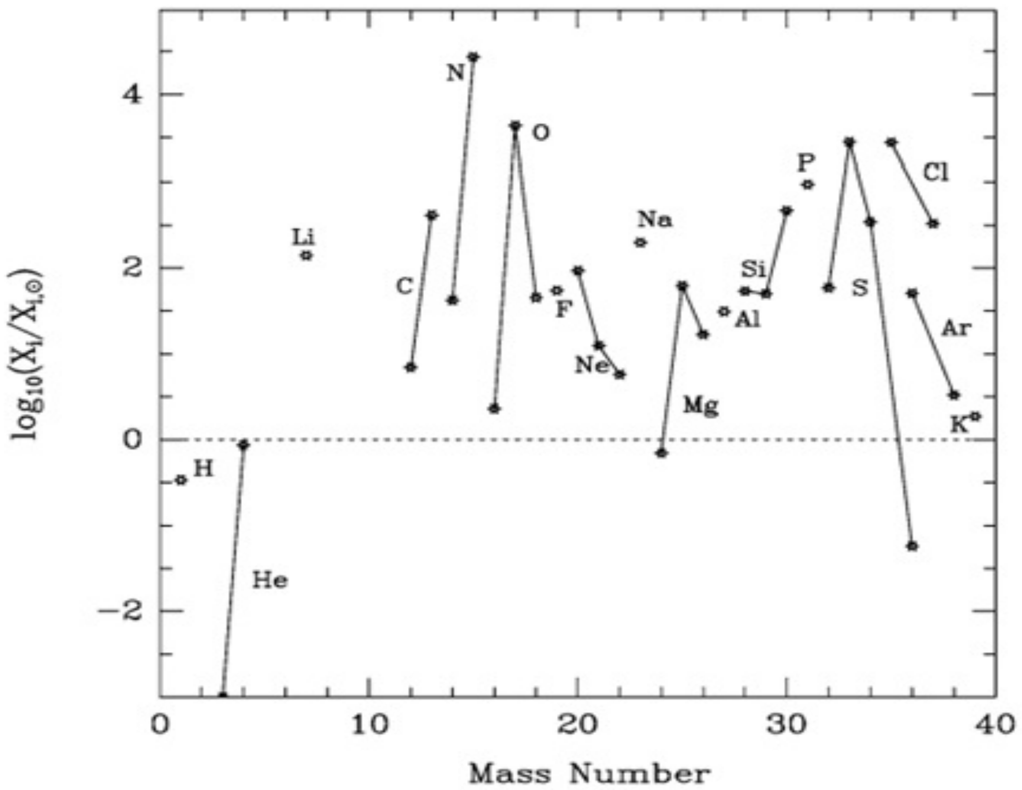
Explosive H/He burning in Binary Stars



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

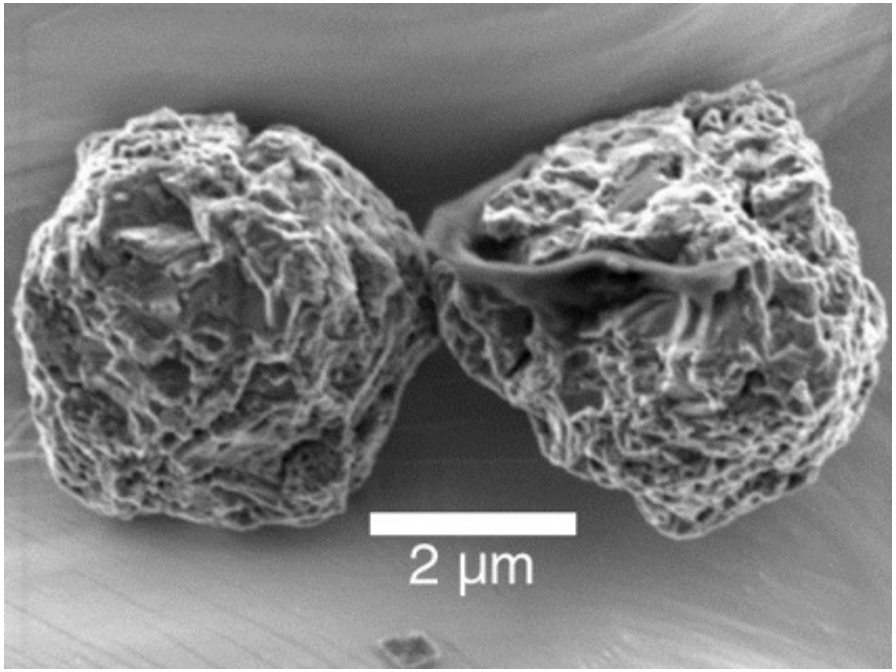


J. José, M. Hernanz, C. Iliadis. Nucl Phys A**, 777**, (2006), 550-578

Presolar grains

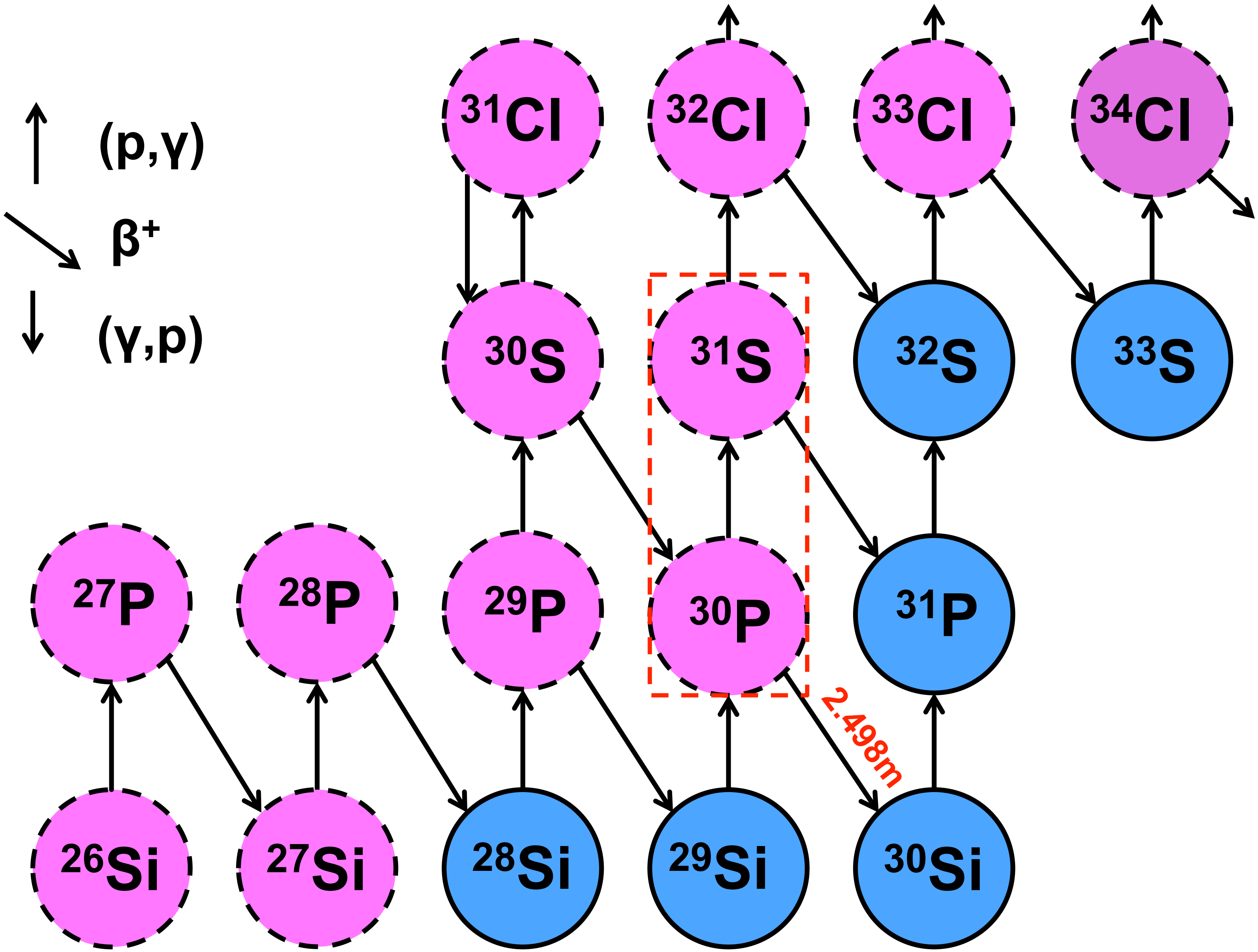
- **Grains of nova origin are thought to have a large $^{30}Si/^{28}Si$ ratio.**

- **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.**

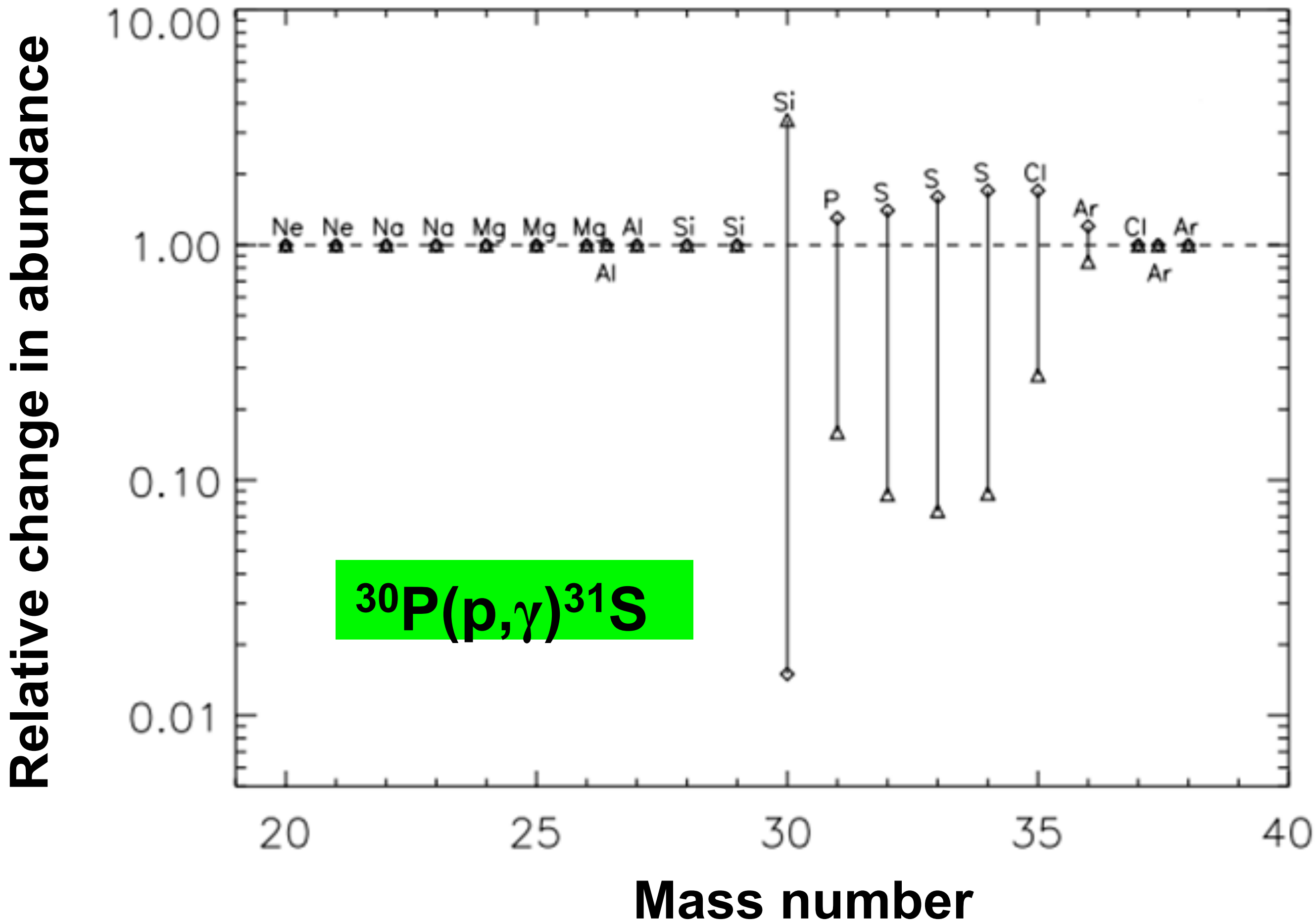


Andrew M Davis. University of Chicago

Novae Nucleosynthesis

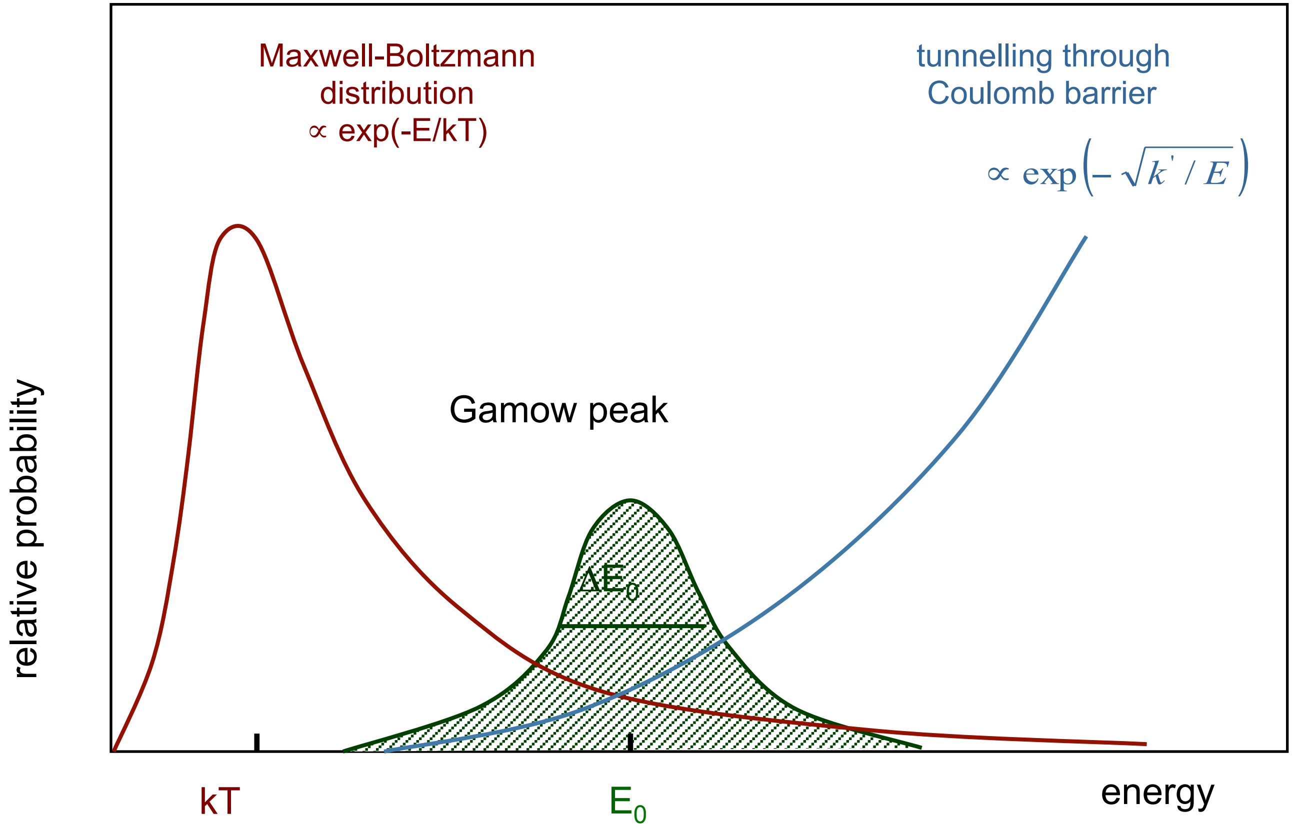


Sensitivity to uncertainty in $^{30}P(p,\gamma)^{31}S$ reaction rate



C. Iliadis, A. Champagne, J José *et al.,* Astrophys. J. Suppl. Ser. **142,** 105 (2002)

H/He burning reactions at stellar energies

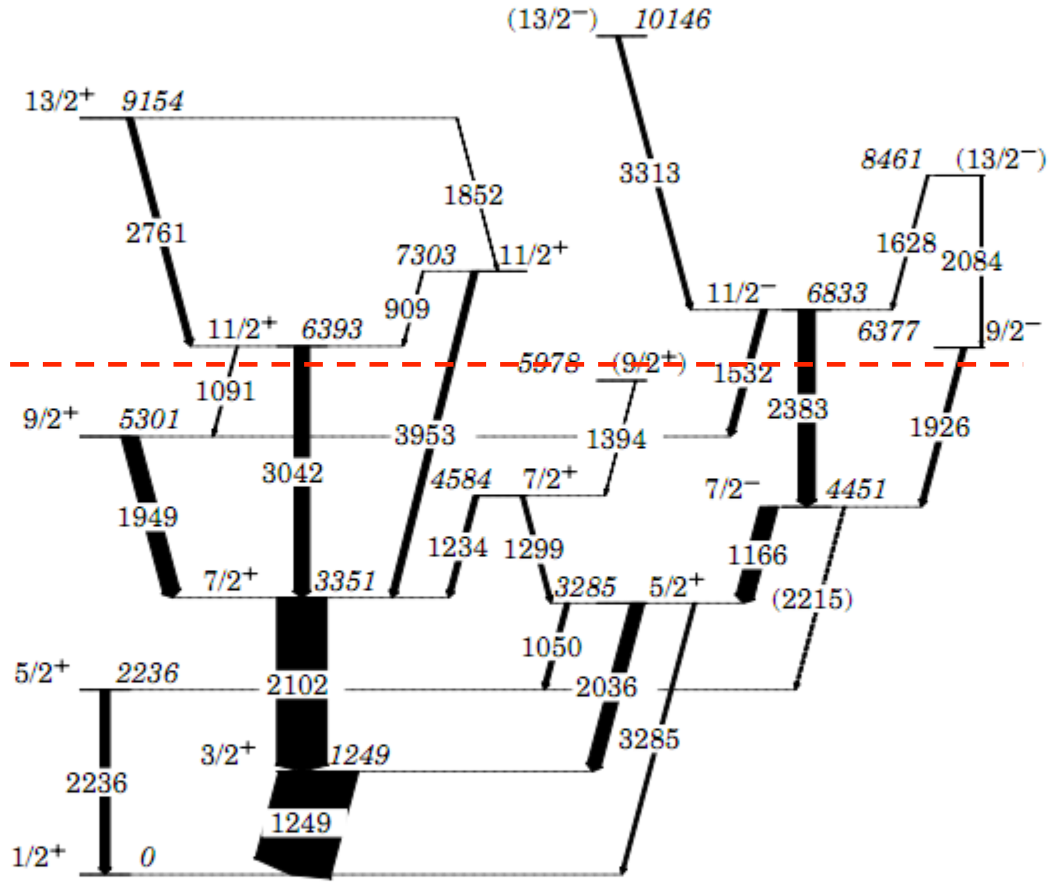


Reaction rate often dominated by a few resonances in Gamow burning window

Known ^{31}S level scheme

- States populated by $^{20}Ne(^{12}C,n)^{31}S$

^{31}S proton threshold

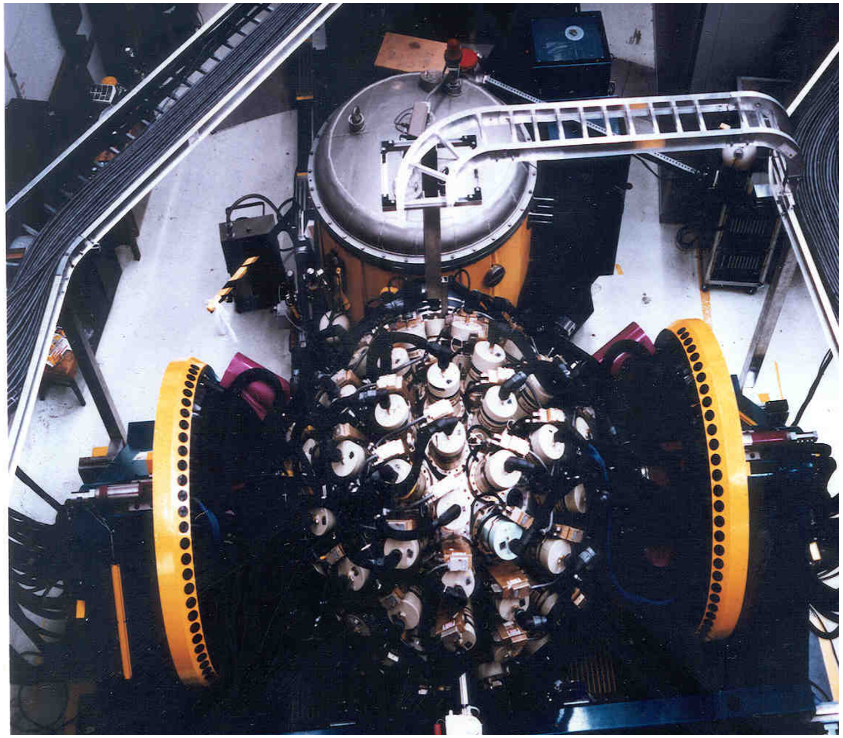


D.G. Jenkins et al, Phys. Rev. C. **72.** (2005)

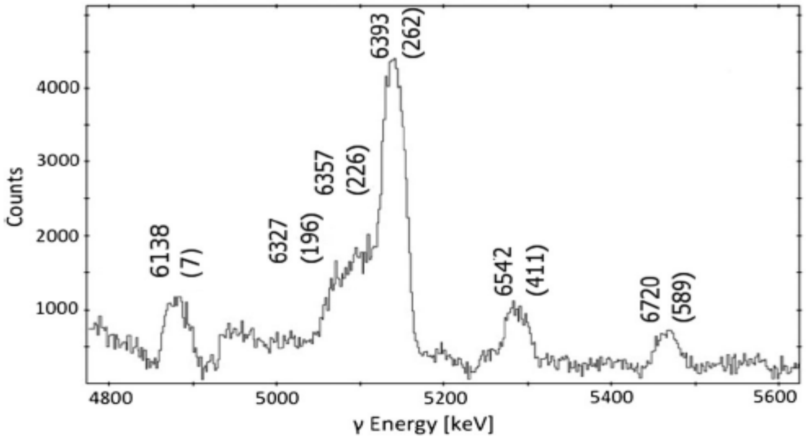
PRL **108,** 262502 (2012) PHYSICAL REVIEW LETTERS week ending 29 JUNE 2012

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

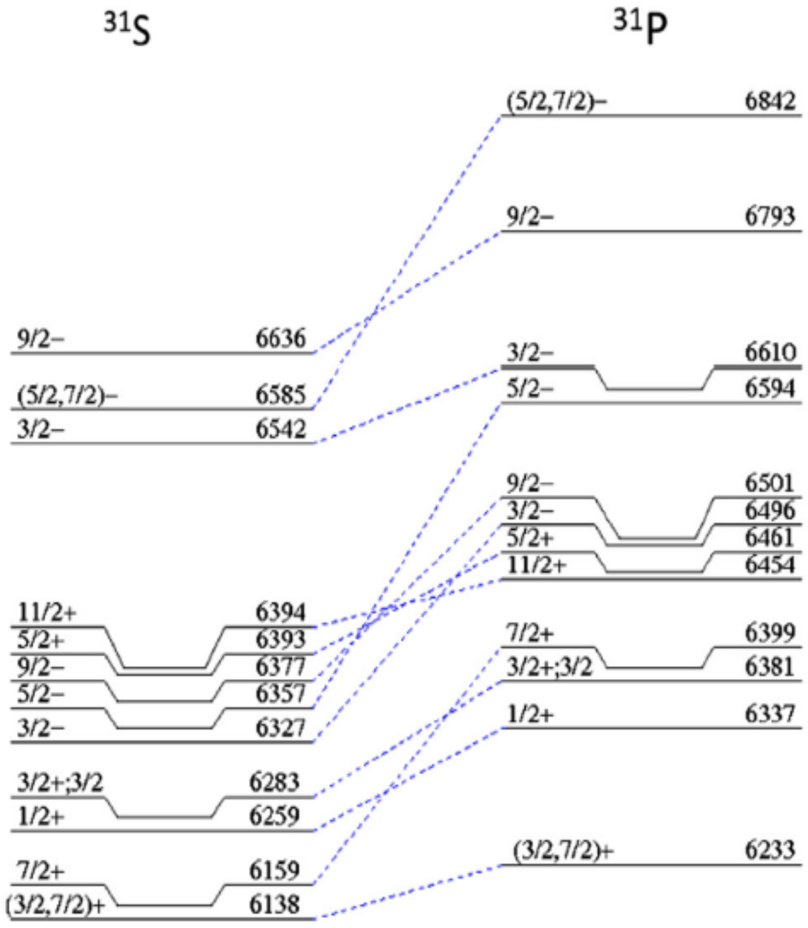
D. T. Doherty,[1] G. Lotay,[1] P. J. Woods,[1] D. Seweryniak,[2] M. P. Carpenter,[2] C. J. Chiara,[2,3] H. M. David,[1] R. V. F. Janssens,[2] L. Trache,[4] and S. Zhu[2]



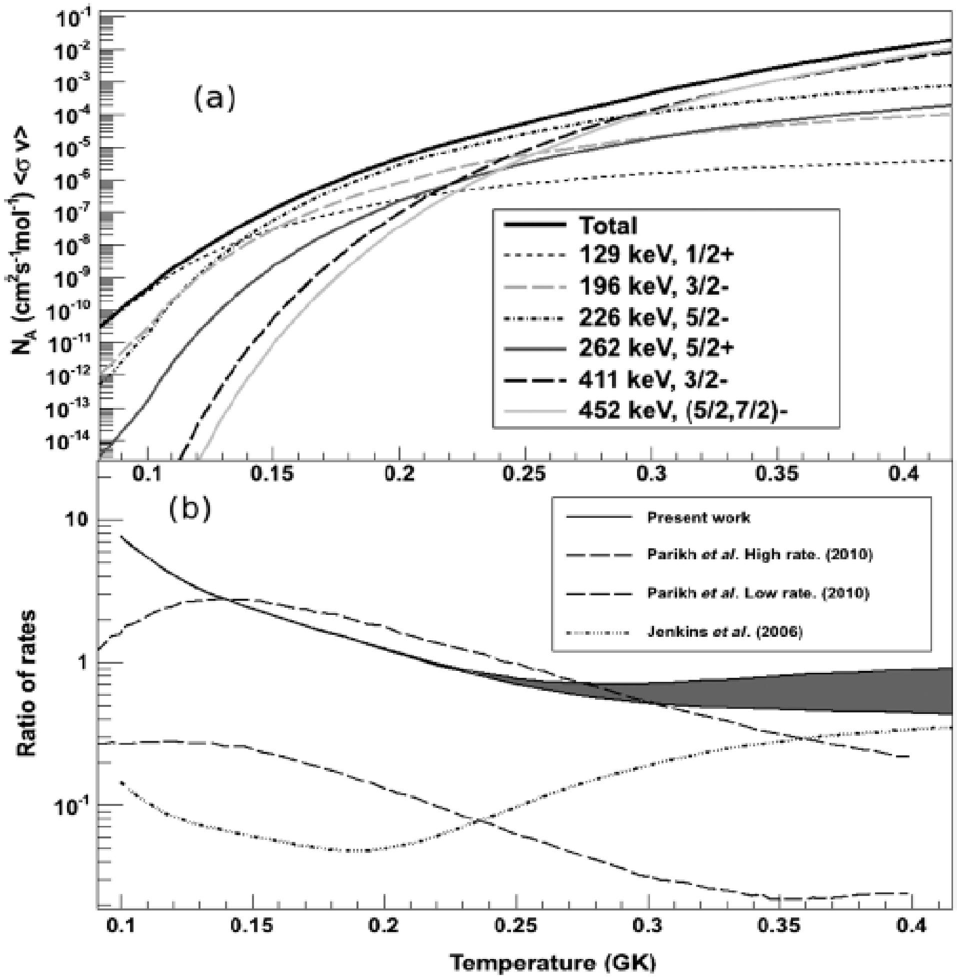
$^{4}He + ^{28}Si \rightarrow ^{31}S + n$ fusion reaction



Pairing of new levels with analog states in mirror nucleus



$^{30}P(p,\gamma)^{31}S$ reaction rate using new resonance data

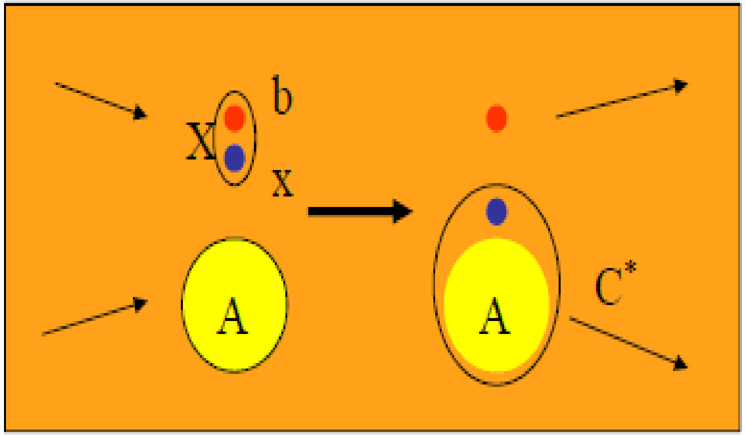


However, key resonance strengths, ω_γ , based on systematic values for proton spectroscopic factors

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

use transfer reactions to estimate Γ_p for (p,γ) reactions where resonance has $\Gamma_p << \Gamma_\gamma$, ω_γ is proportional to $\Gamma_{p.}$

$\Gamma_p \, \alpha \; P_l$ (barrier penetration factor) X S(spectroscopic factor)

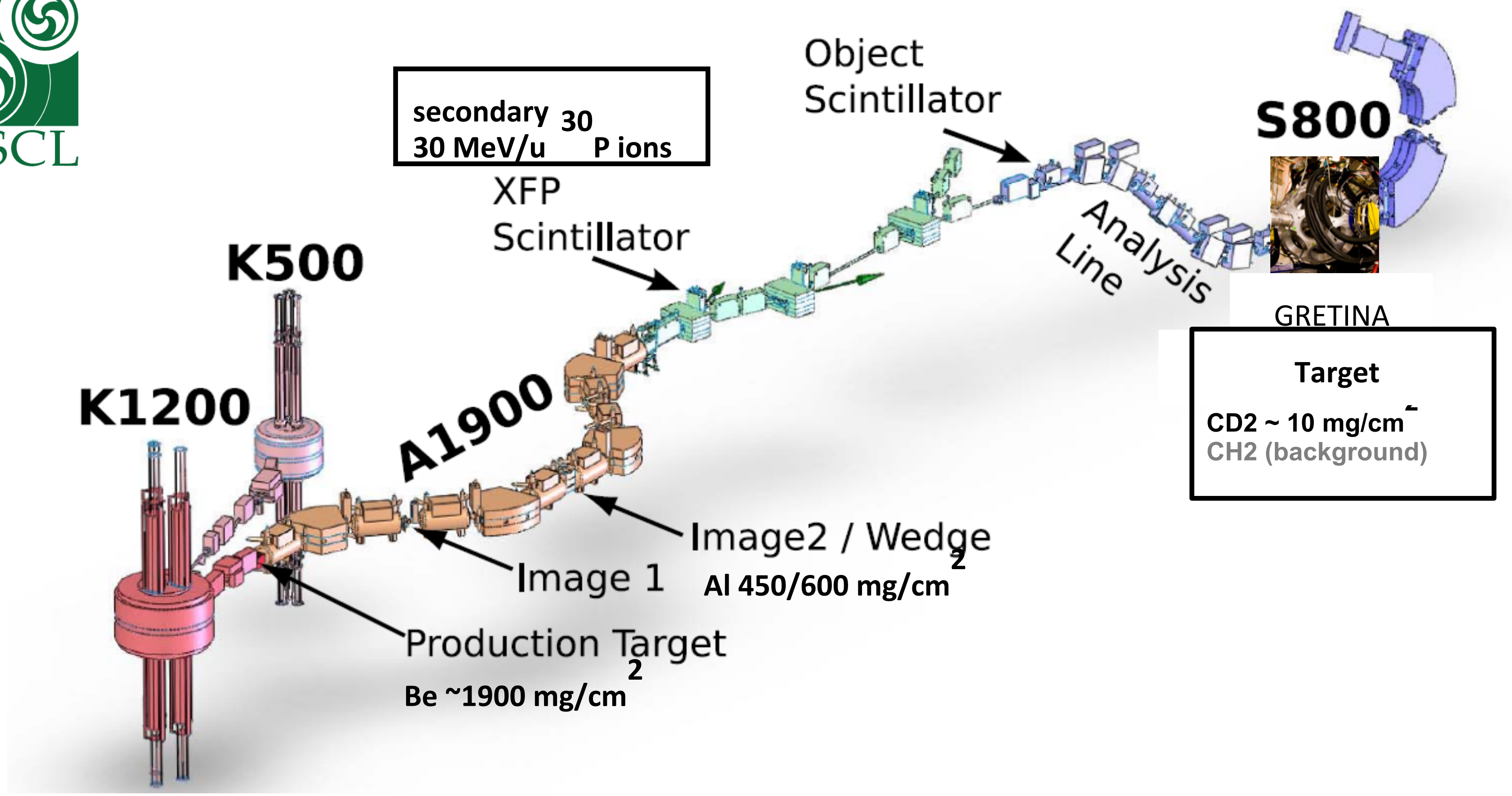


$$\sigma_{transfer} = \sigma_{DWBA} \text{ X S}$$

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

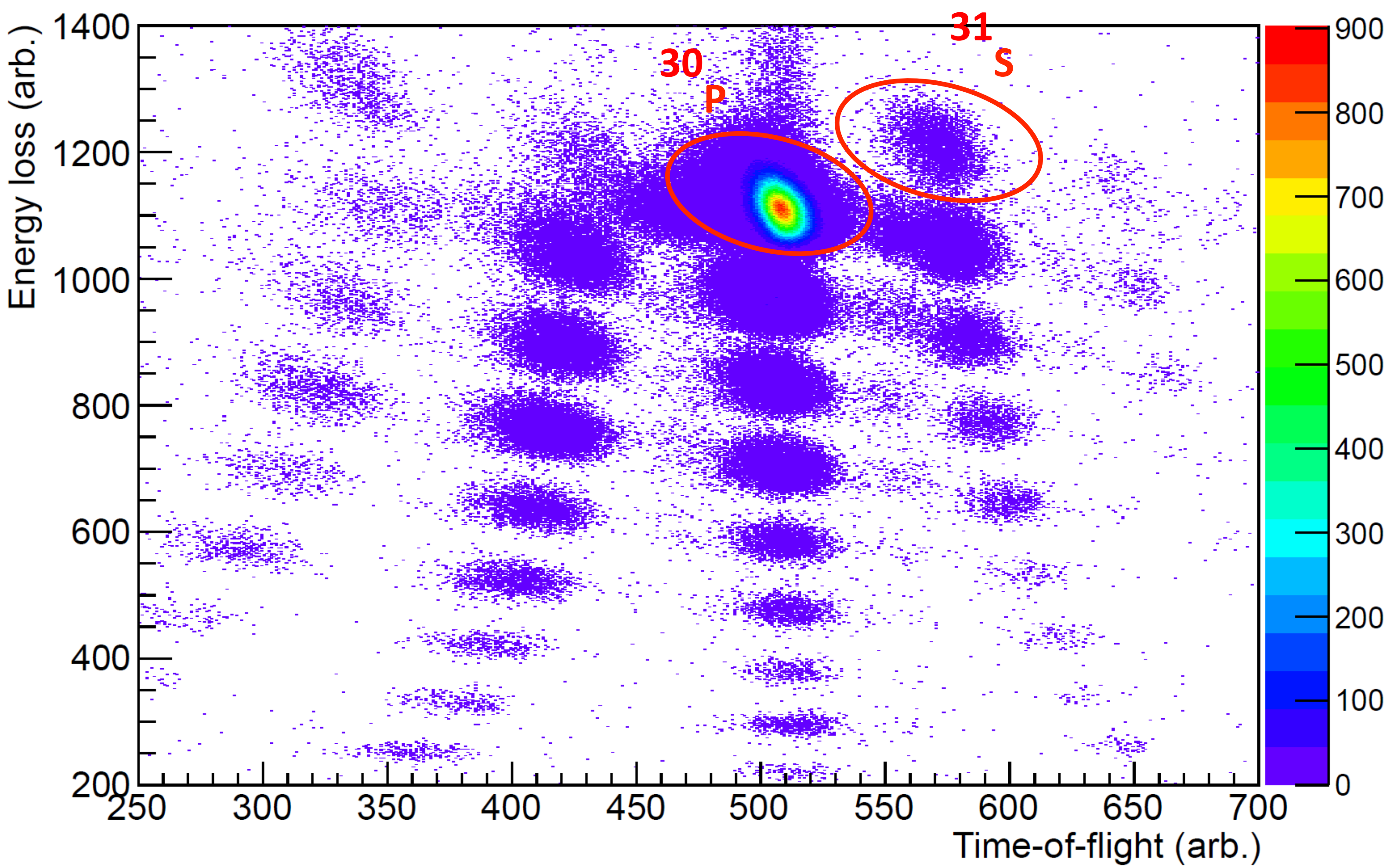
(d,n) transfer reaction cross-section measurements as a surrogate for (p,γ)

NSCL

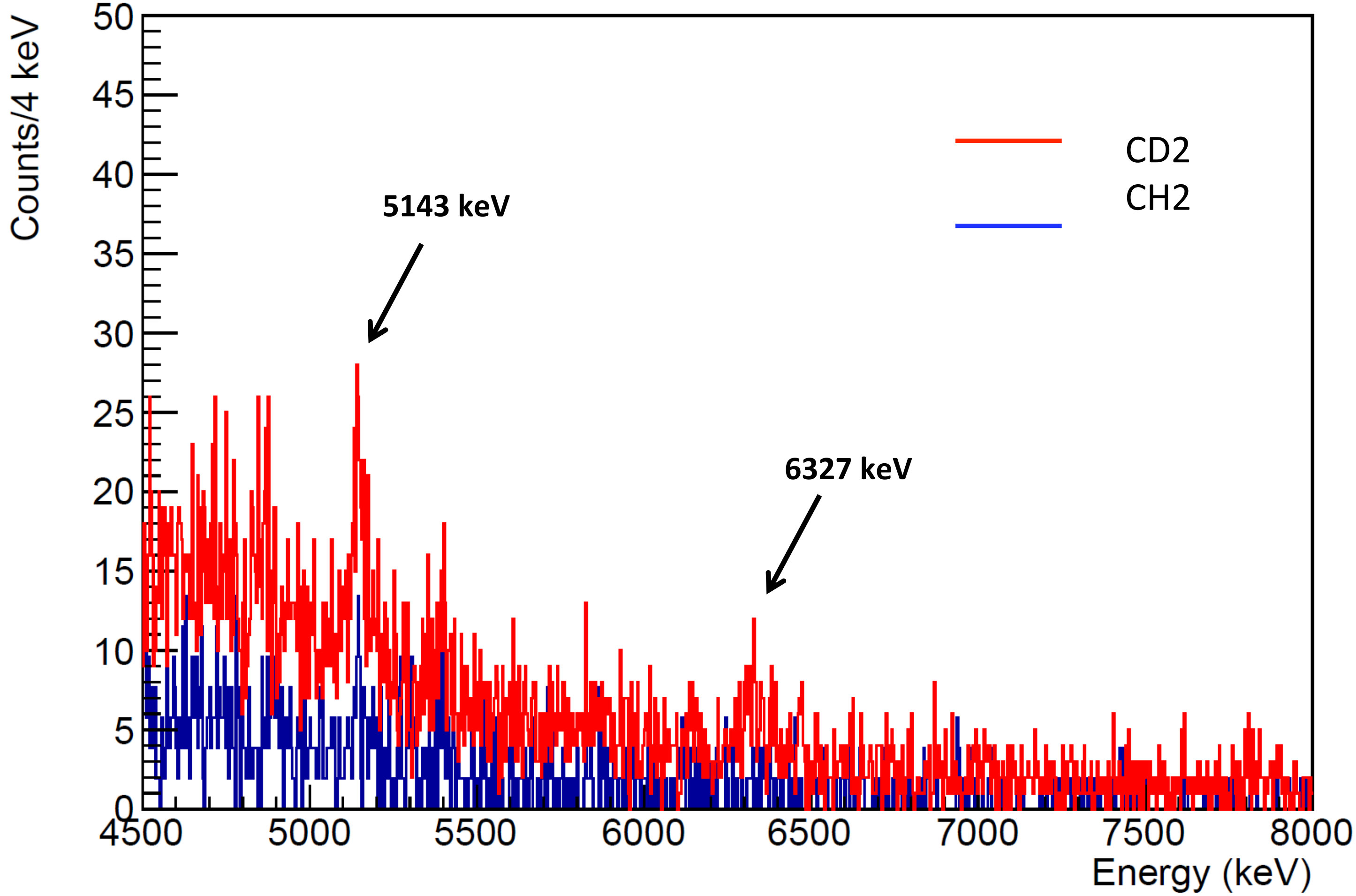


Primary beam:
150 MeV/u $^{36}Ar^{18+}$

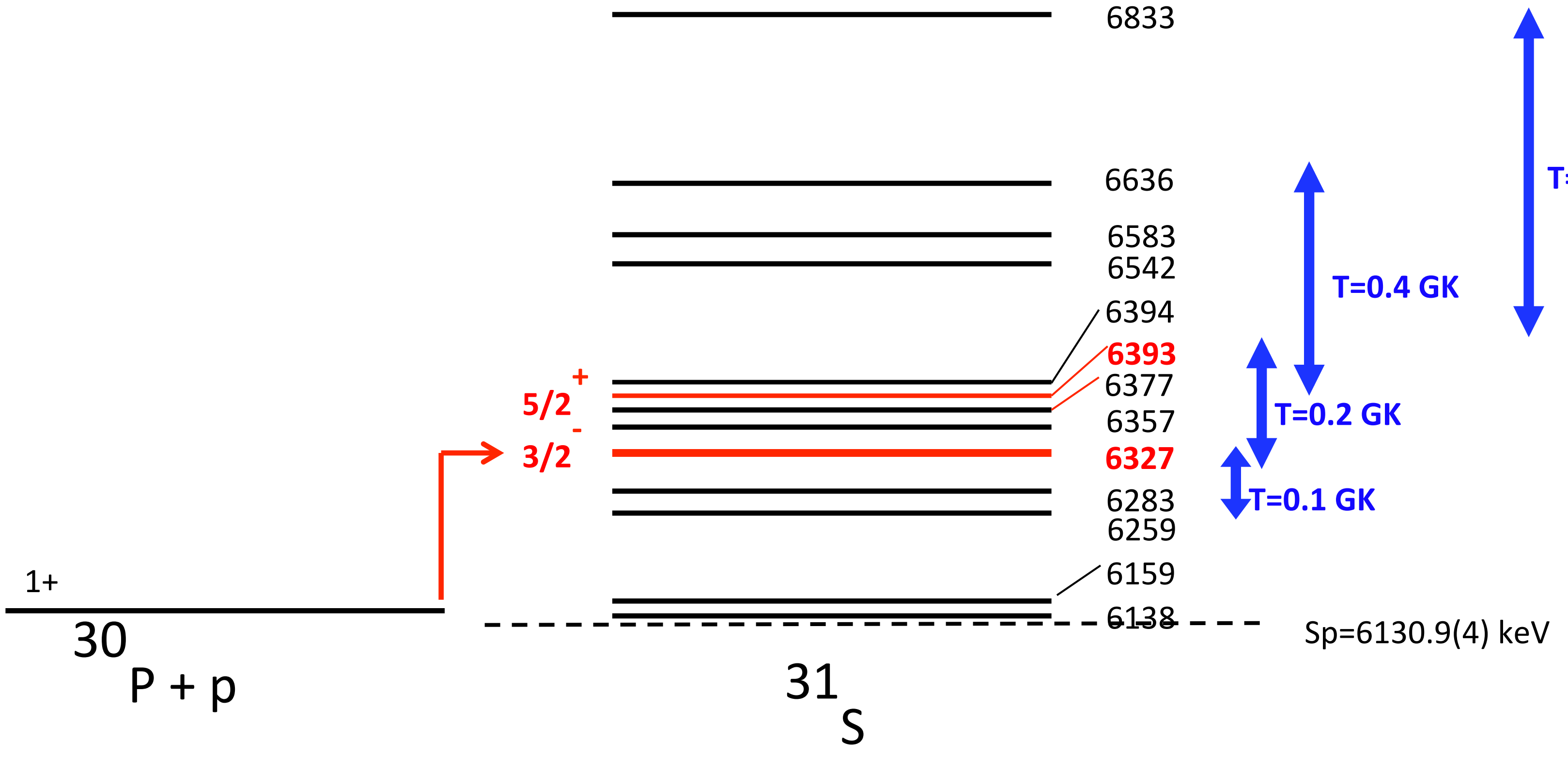
Particle identification: ^{31}S



^{31}S γ-ray energy spectrum



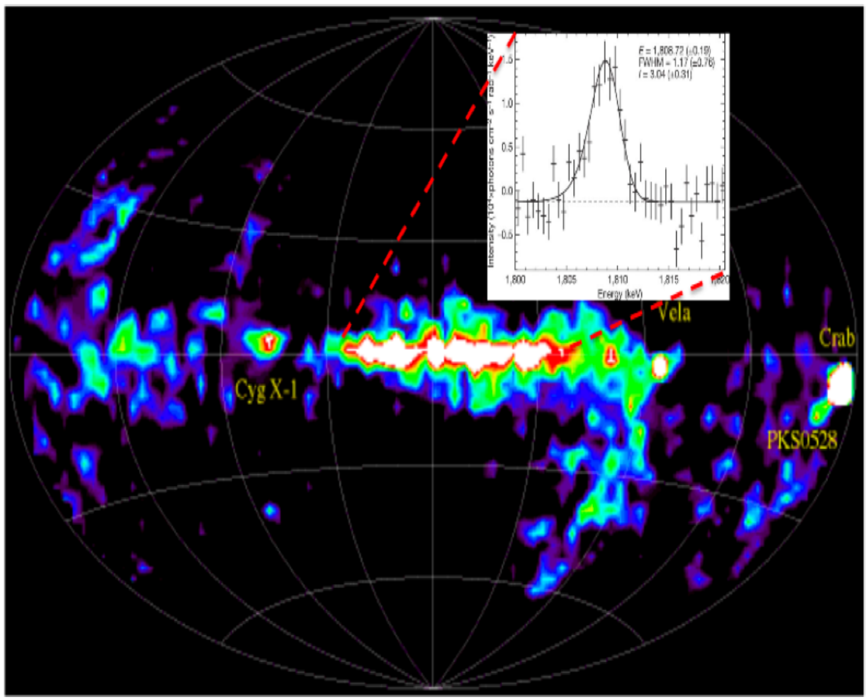
Levels above the proton threshold energy in ^{31}S

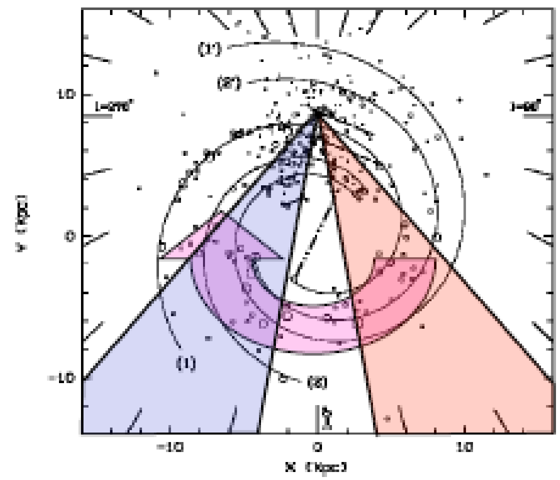


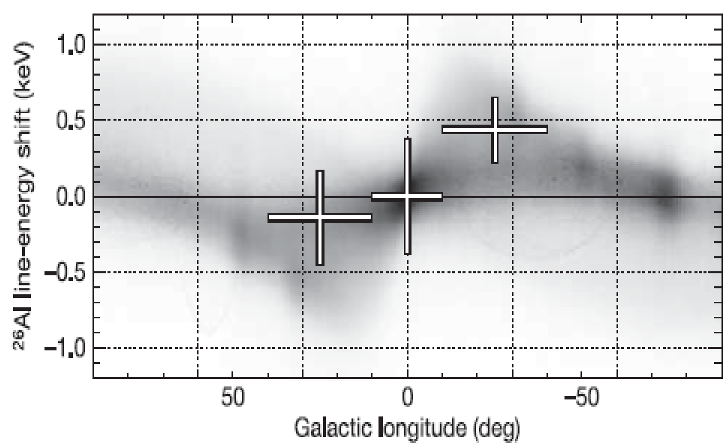
Calculations of extracted Γ_p values from cross-section data being performed by F Nunes (MSU)

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

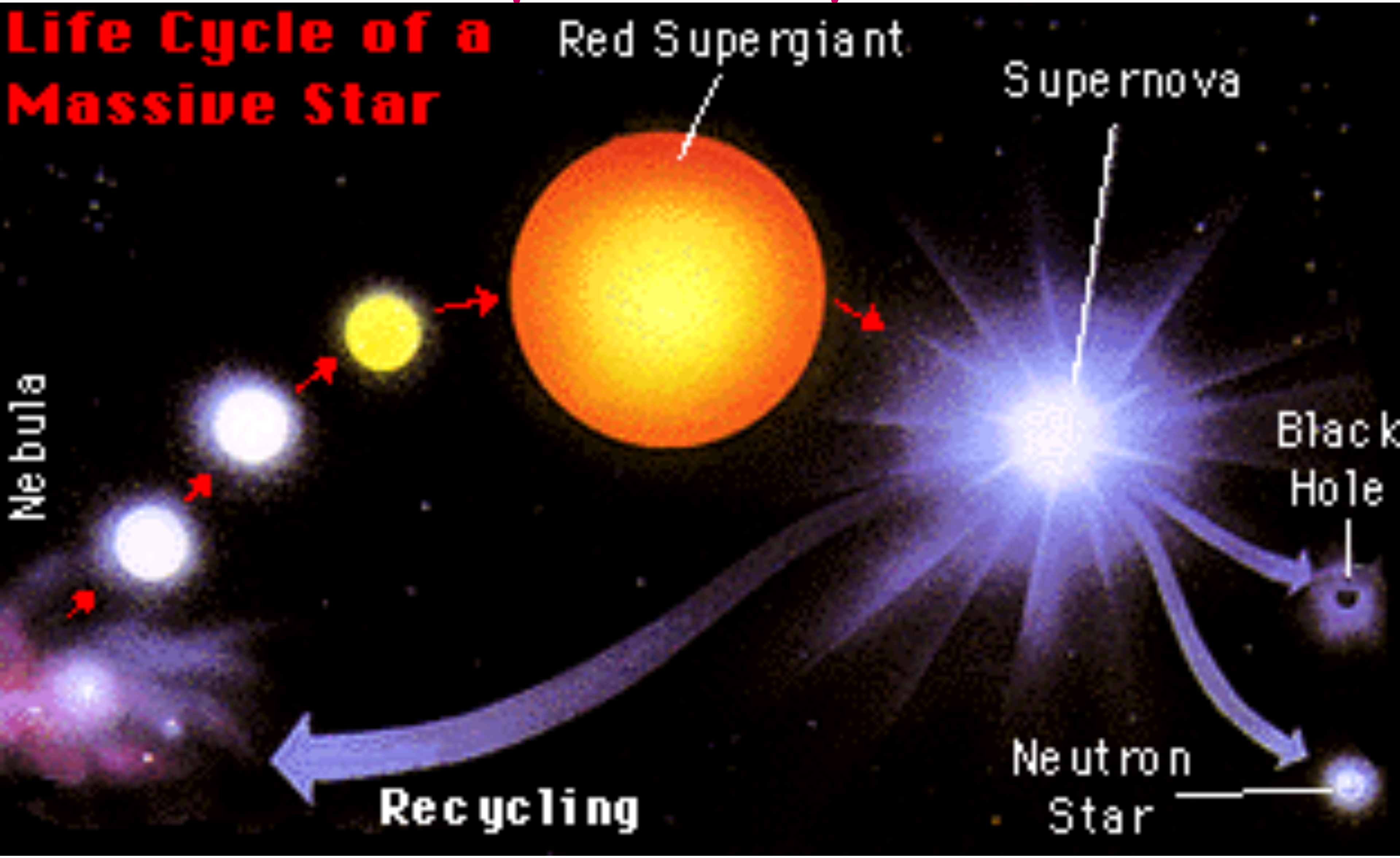
INTEGRAL satellite telescope - 2.8(8) M_{sun} of ^{26}Al in our galaxy
[R. Diehl, *Nature* ***439*** *45(2006)*]



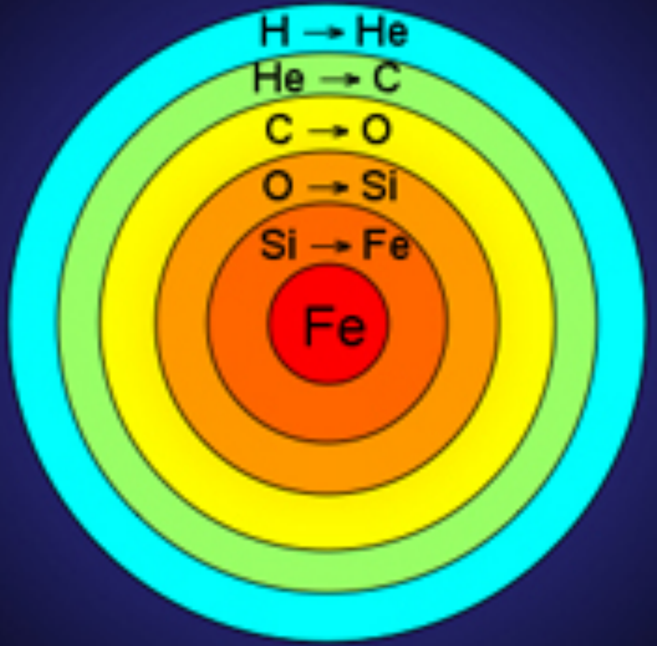




Supernova Cycle



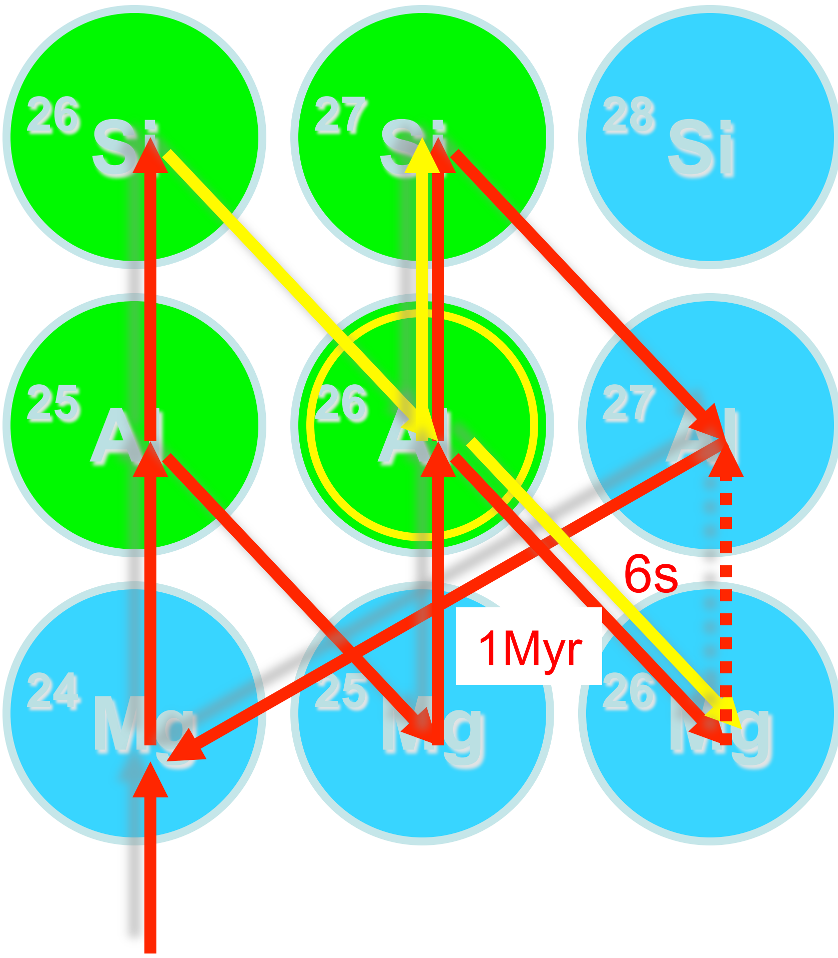
Stellar Life

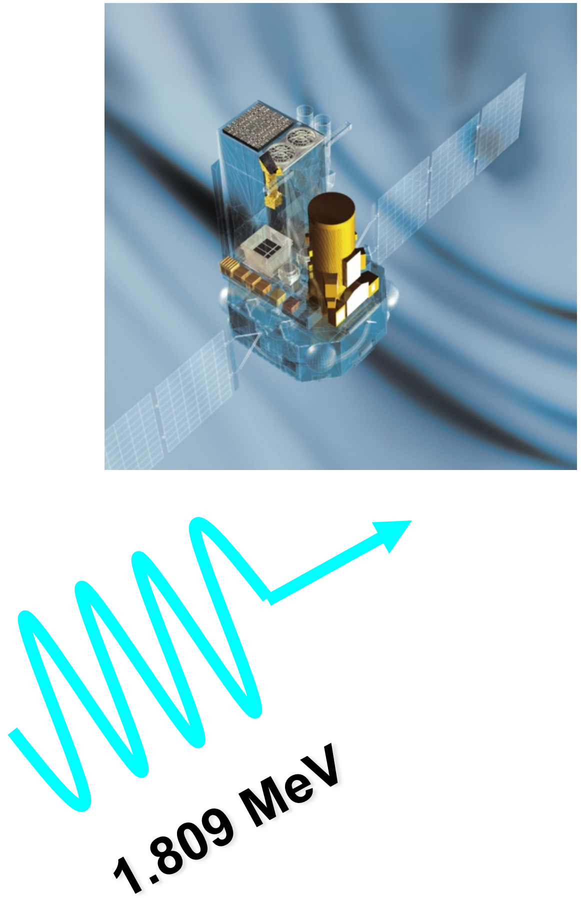


For a 25 solar mass star:

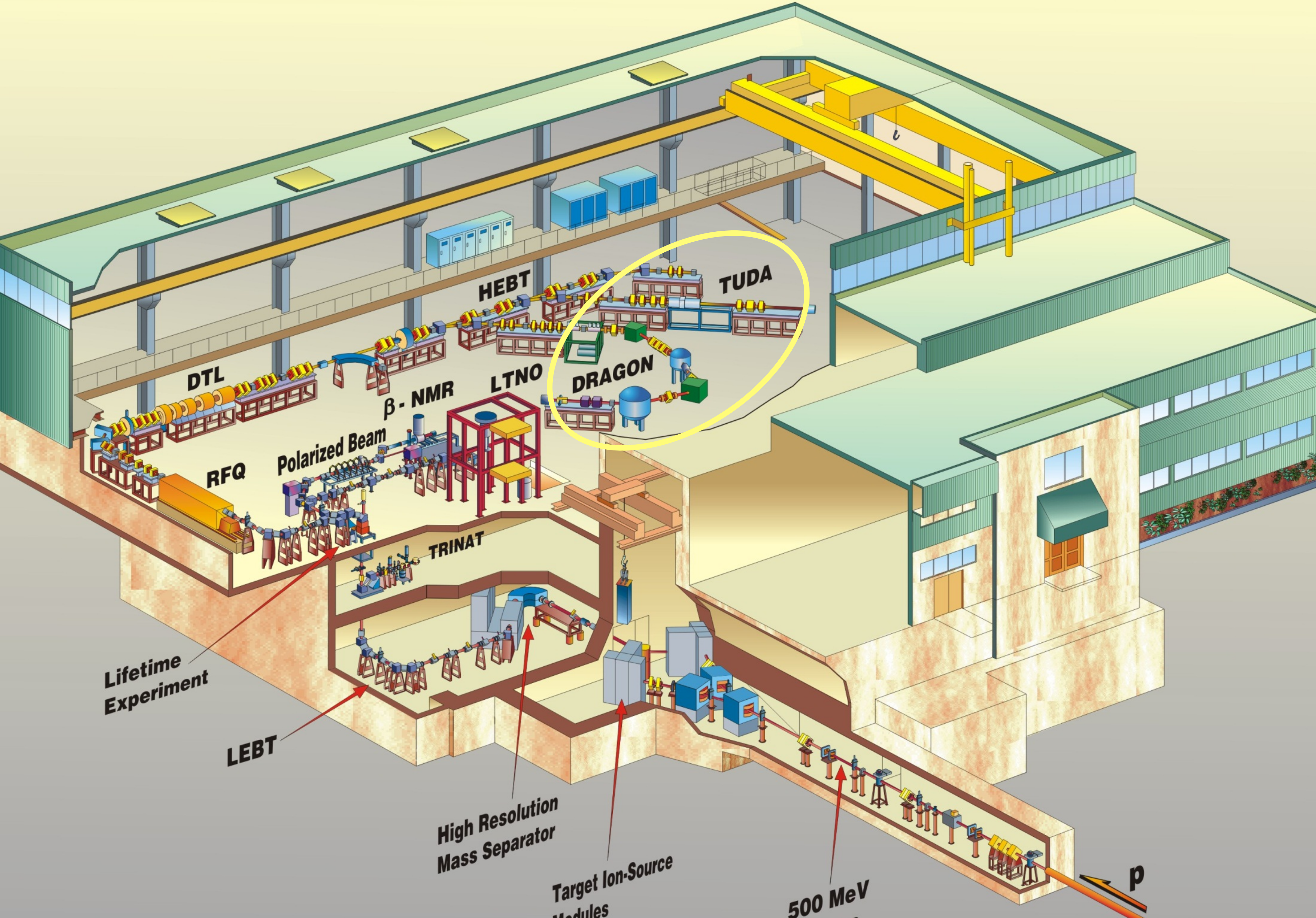
Stage	Duration
H → He	7×10^6 years
He → C	7×10^5 years
C → O	600 years
O → Si	6 months
Si → Fe	1 day
Core Collapse	1/4 second

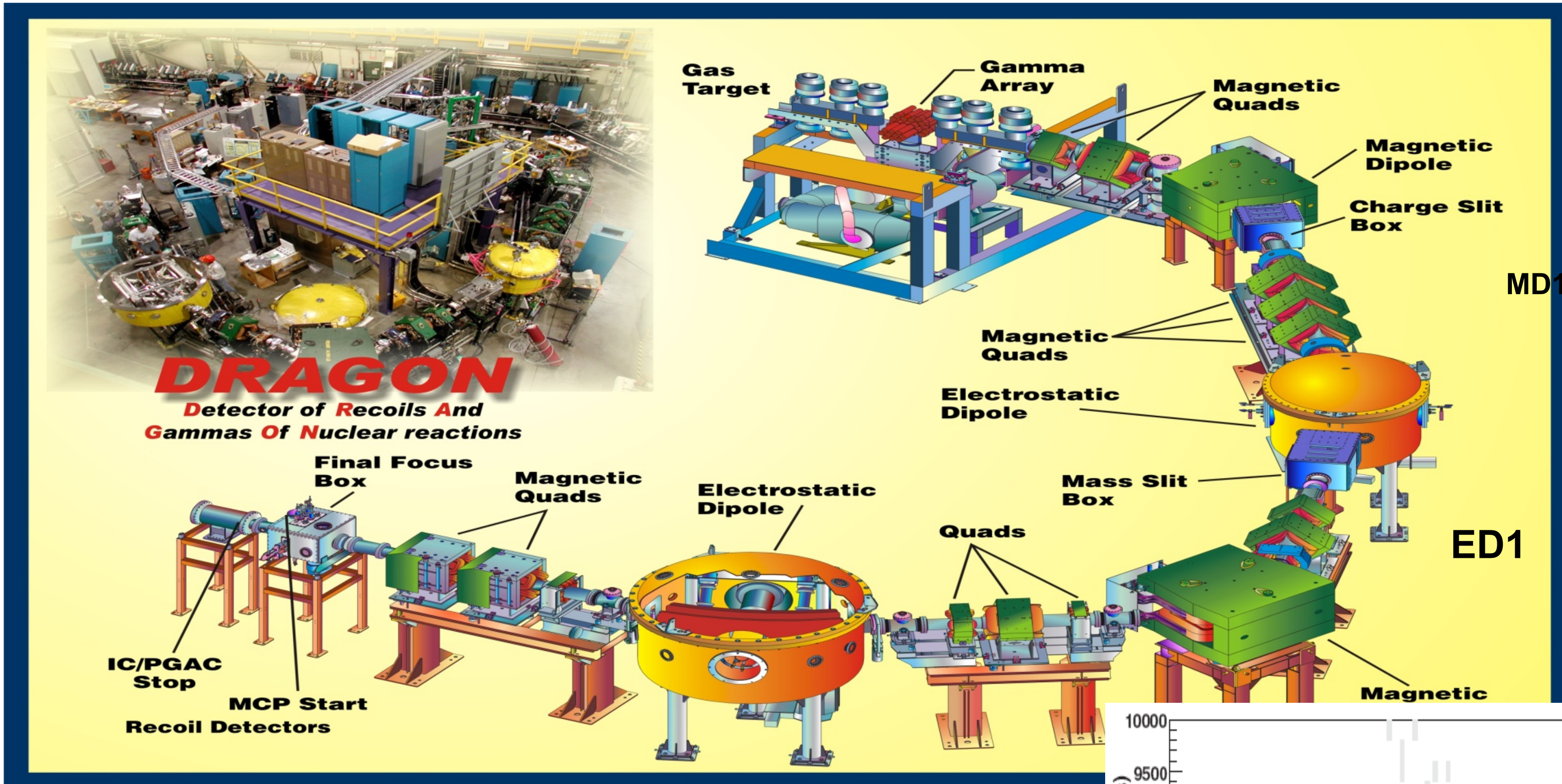
Hydrogen burning in Mg – Al Cycle



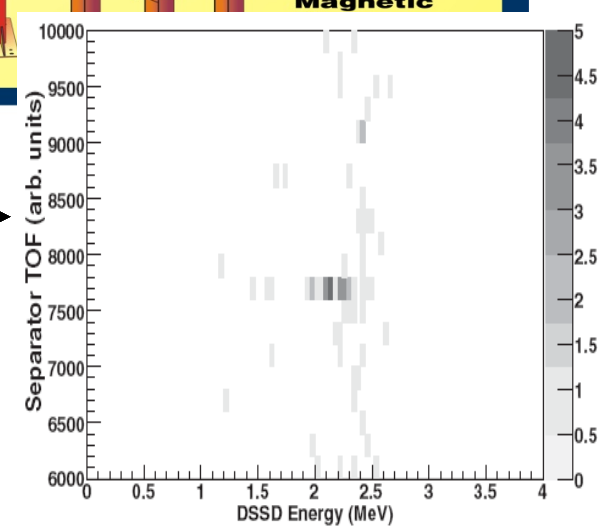


ISAC at TRIUMF





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

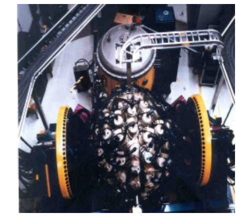


→ lower energy resonances may dominate destruction of ^{26}Al burning in massive stars?

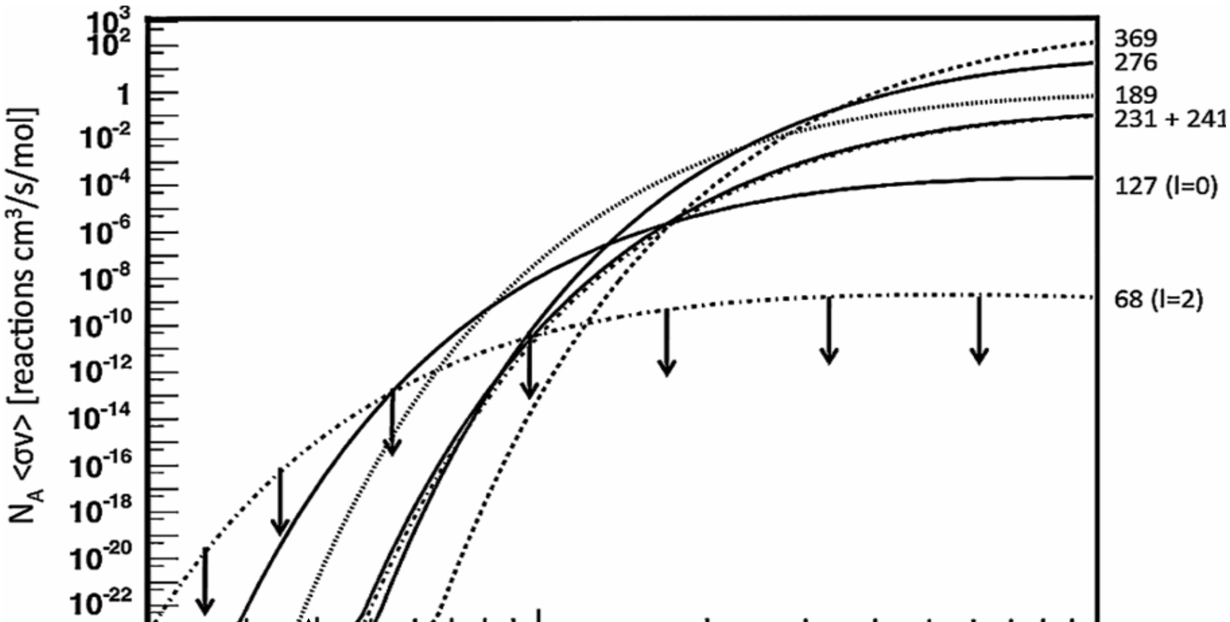
PRL **102,** 162502 (2009) PHYSICAL REVIEW LETTERS week ending 24 APRIL 2009

Identification of Key Astrophysical Resonances Relevant for the $^{26g}Al(p,\gamma)^{27}Si$ Reaction in Wolf-Rayet Stars, AGB stars, and Classical Novae

G. Lotay,[1] P. J. Woods,[1] D. Seweryniak,[2] M. P. Carpenter,[2] R. V. F. Janssens,[2] and S. Zhu[2]



Factor ~ 10^4 reduction in uncertainties in estimated $^{26g}Al(p,\gamma)^{27}Si$ reaction rate

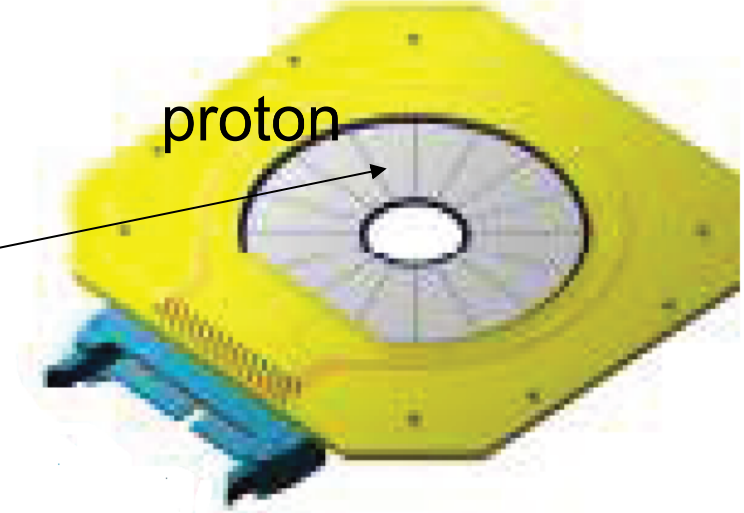


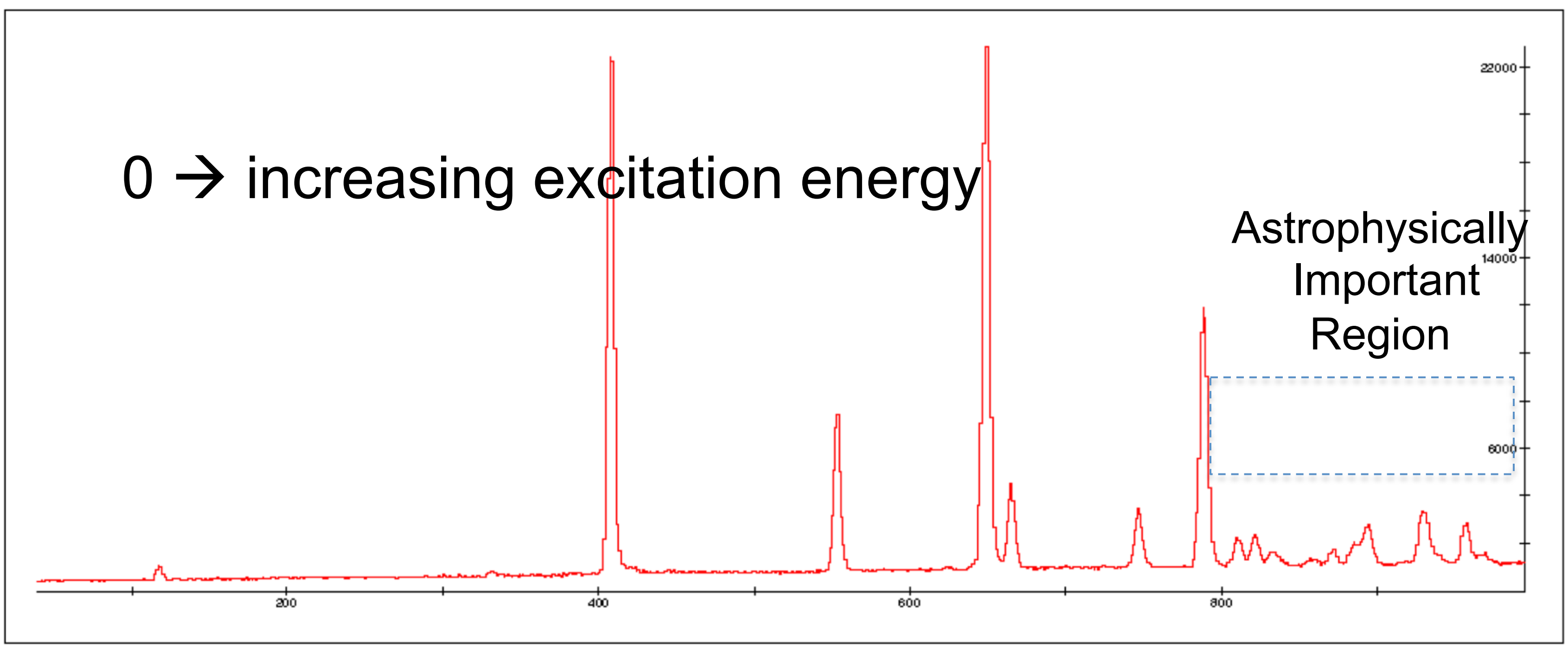
10^8 K

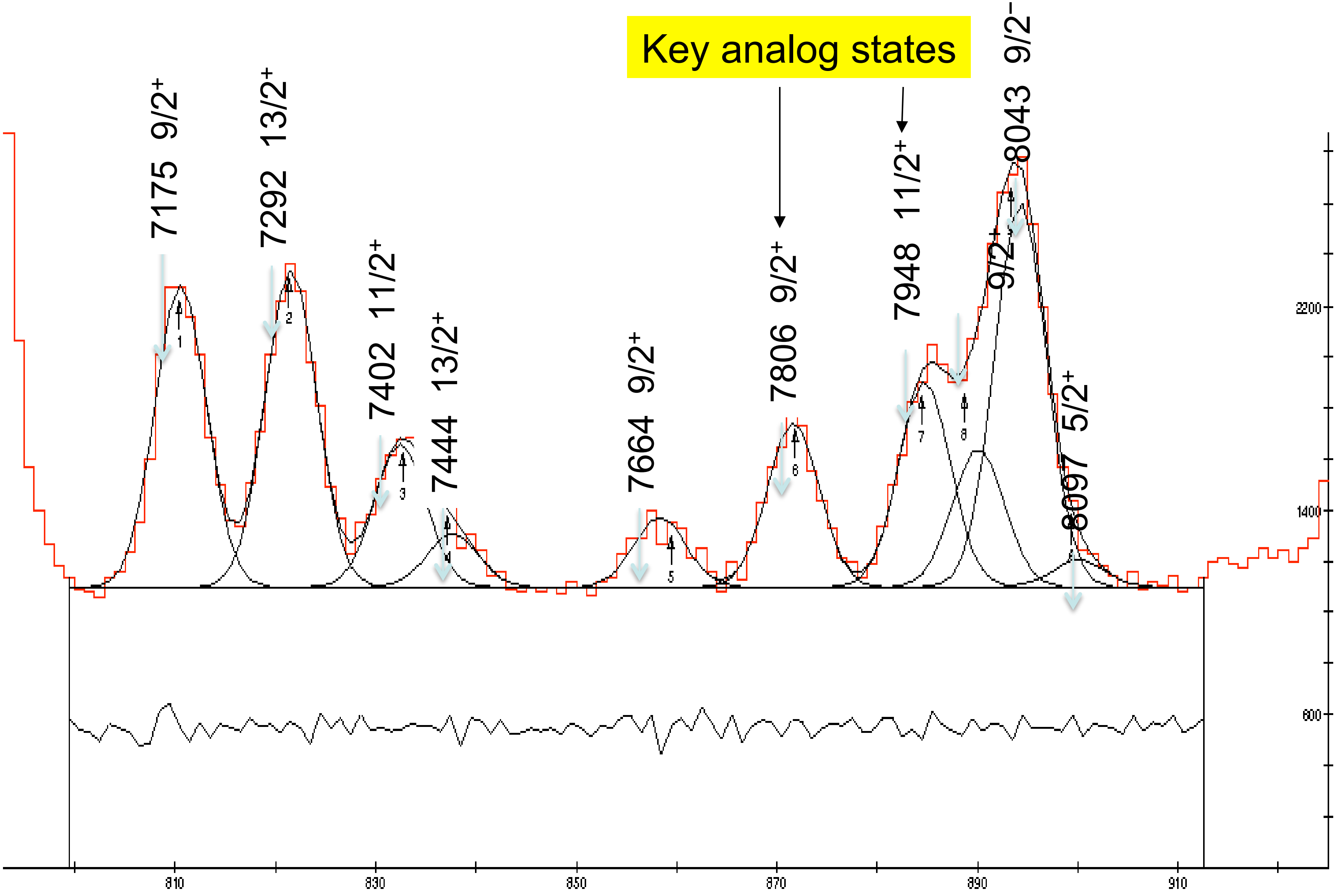
However, resonance strengths for critical low T ^{26}Al burning regime in Wolf-Rayet stars still need to be determined

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

150 MeV ^{26g}Al → $(CD_2)_n$ target
I_{beam} ~ $5*10^8$ pps

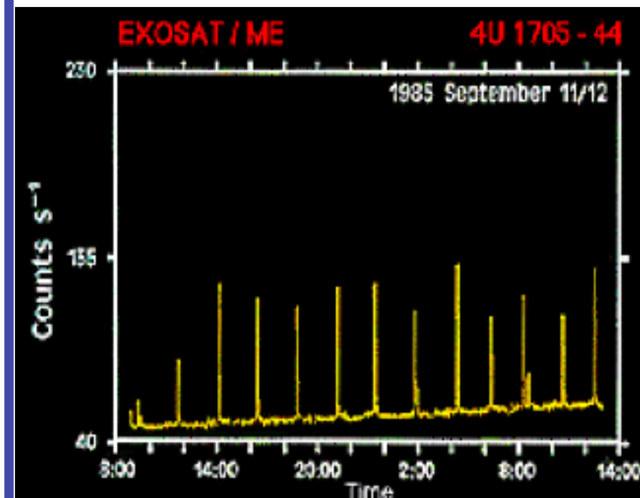


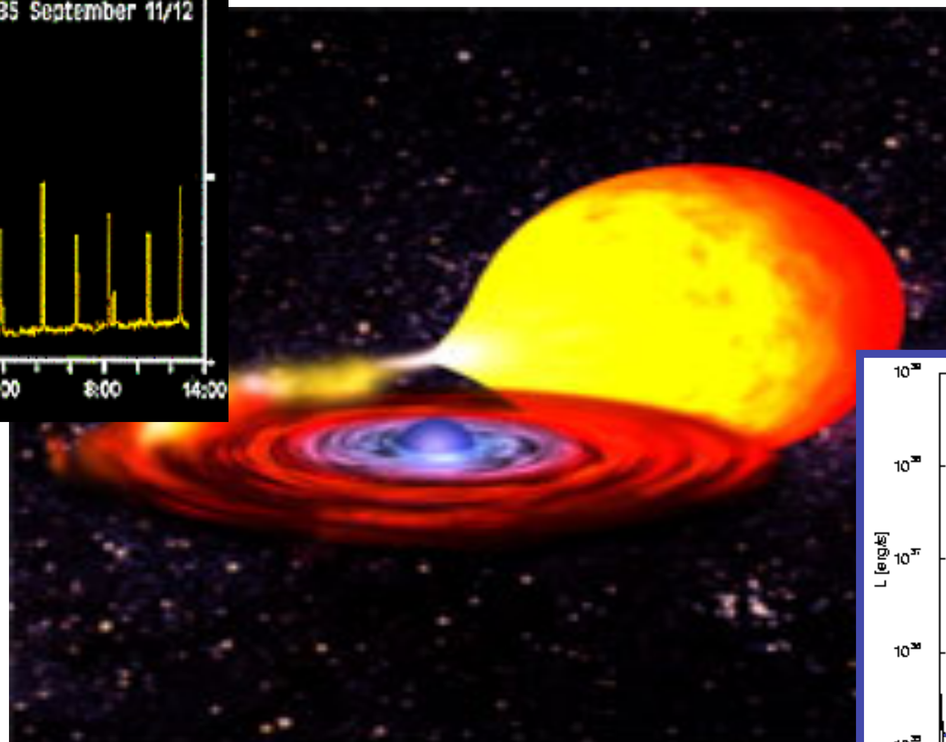


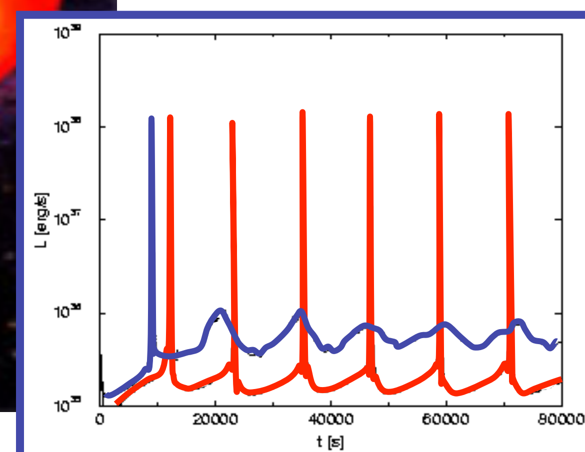


→ Lower energy resonance strength much higher than expected?

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

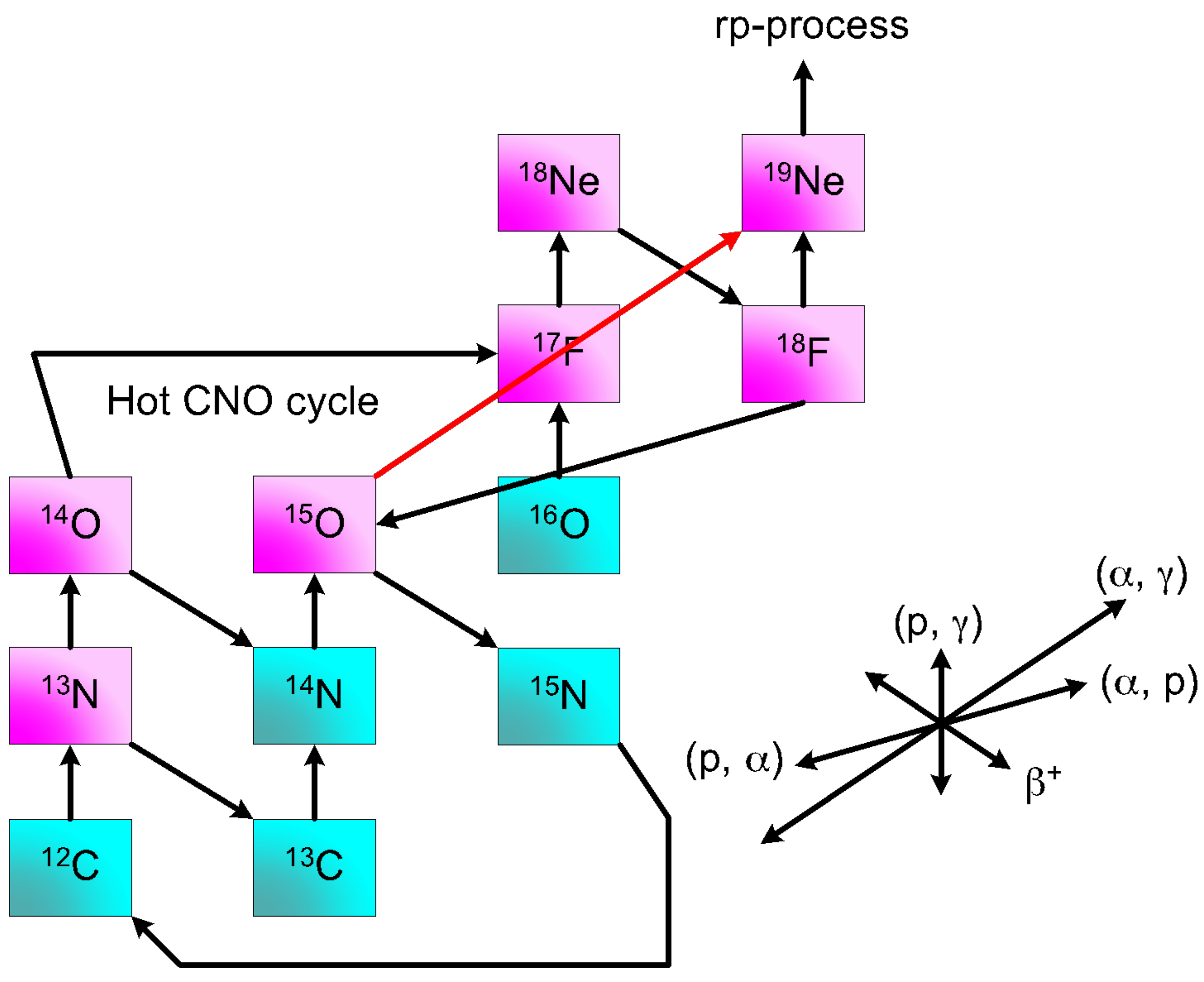






Reaction regulates flow between the hot CNO cycles and rp process
→ critical for explanation of amplitude and periodicity of bursts

The Hot CNO Cycles



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

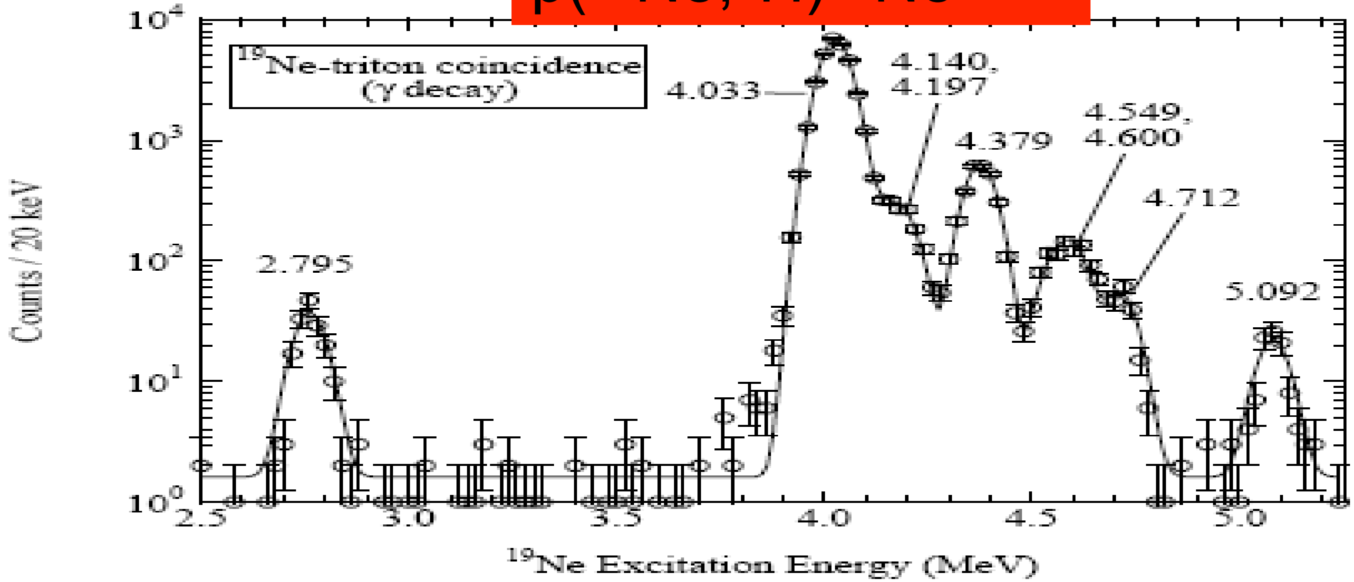
Key unknown - α-decay probability from excited state at 4.03 MeV in ^{19}Ne compared to γ-decay, predicted to be ~ 10^{-4}

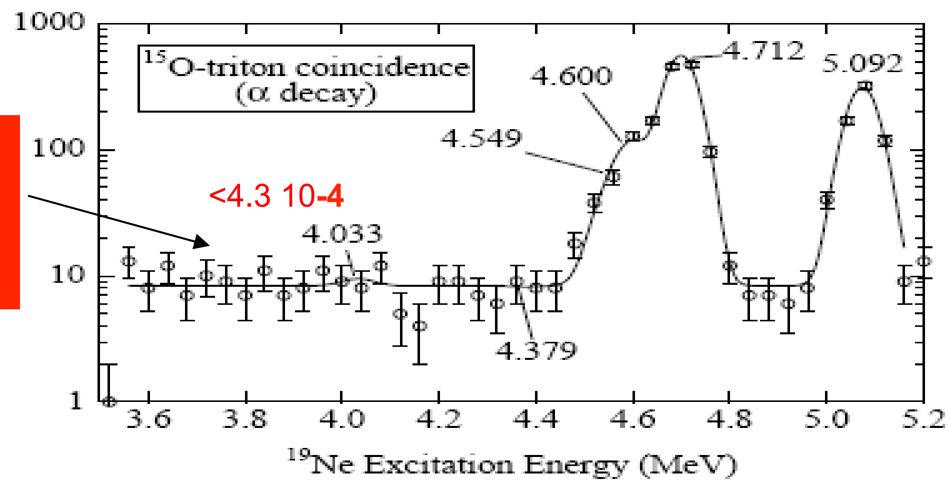
PHYSICAL REVIEW C 67, 065808 (2003)

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
Kernfysisch Versneller Instituut, Zernikelaan 25, 9747 AA Groningen, The Netherlands

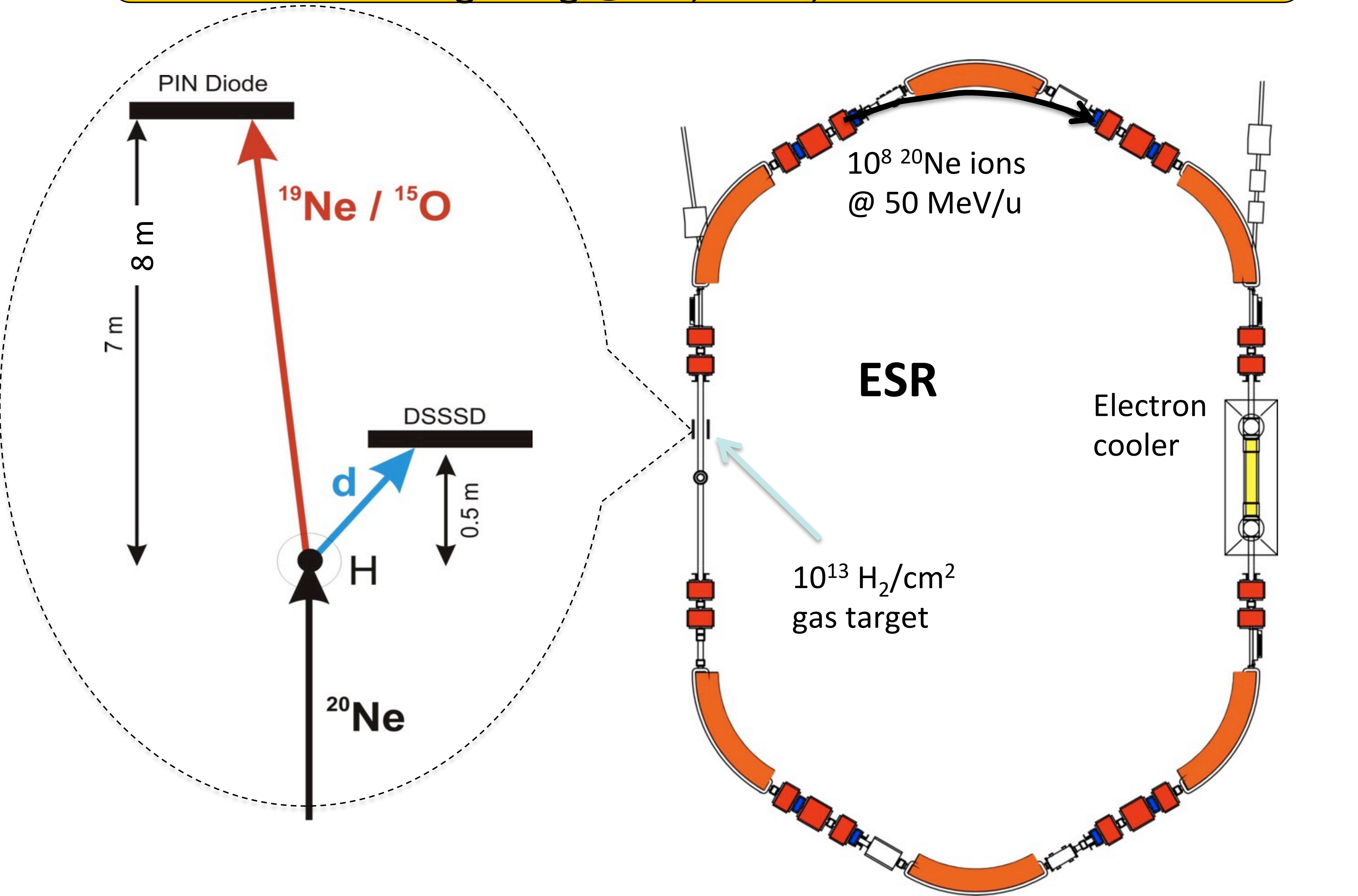
$p(^{21}Ne,^{3}H)^{19}Ne^{*}$



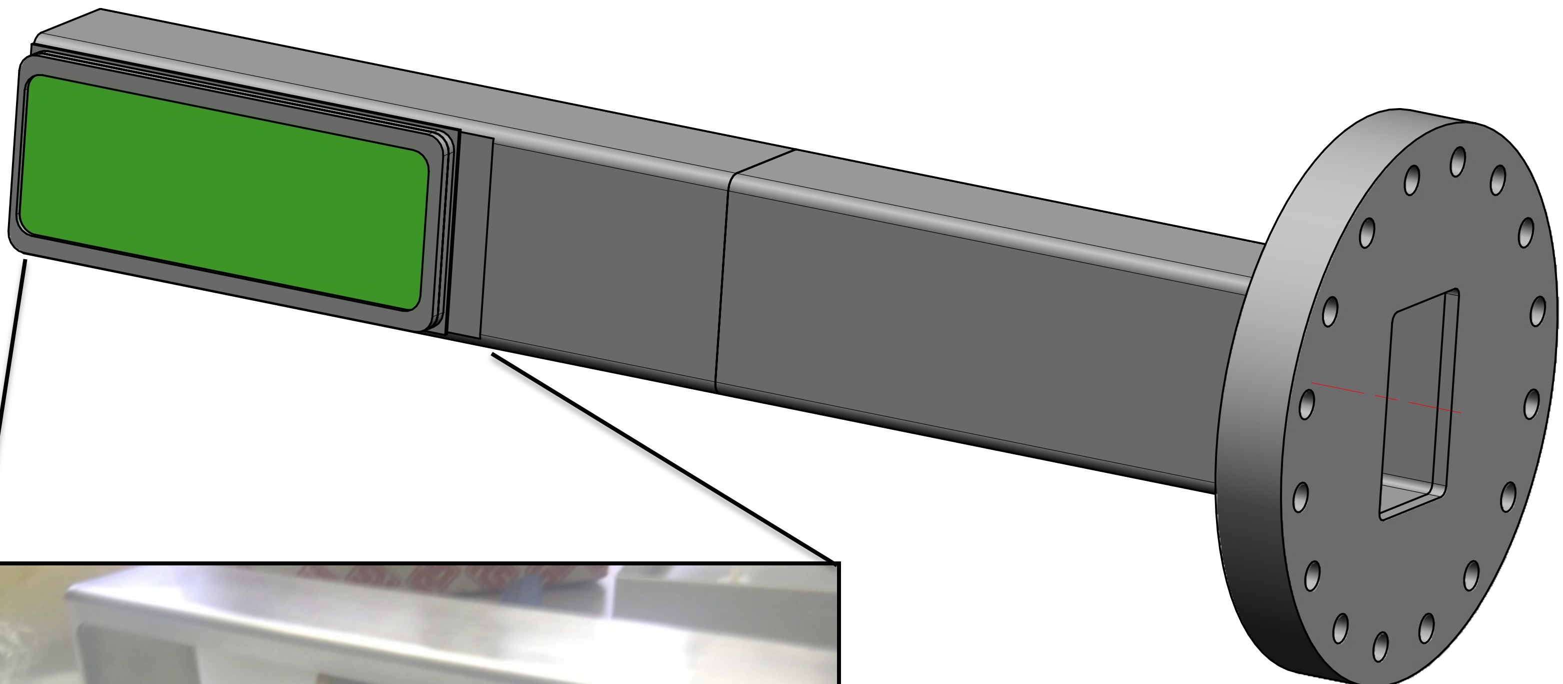


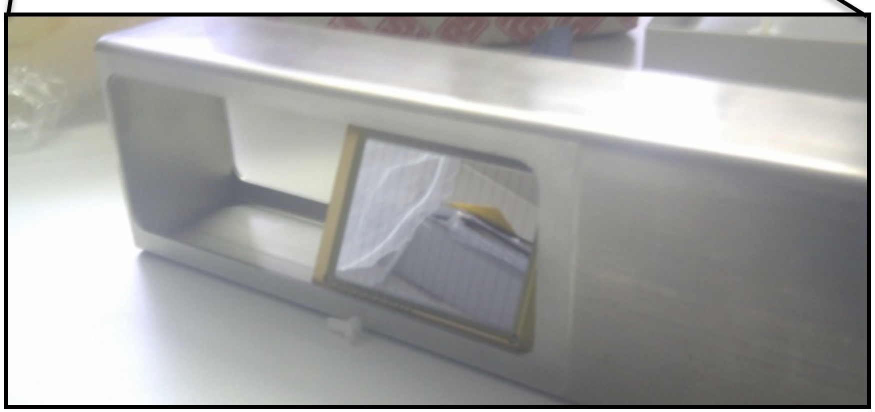
Background produced by reactions of ^{21}Ne beam with ^{12}C in target

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

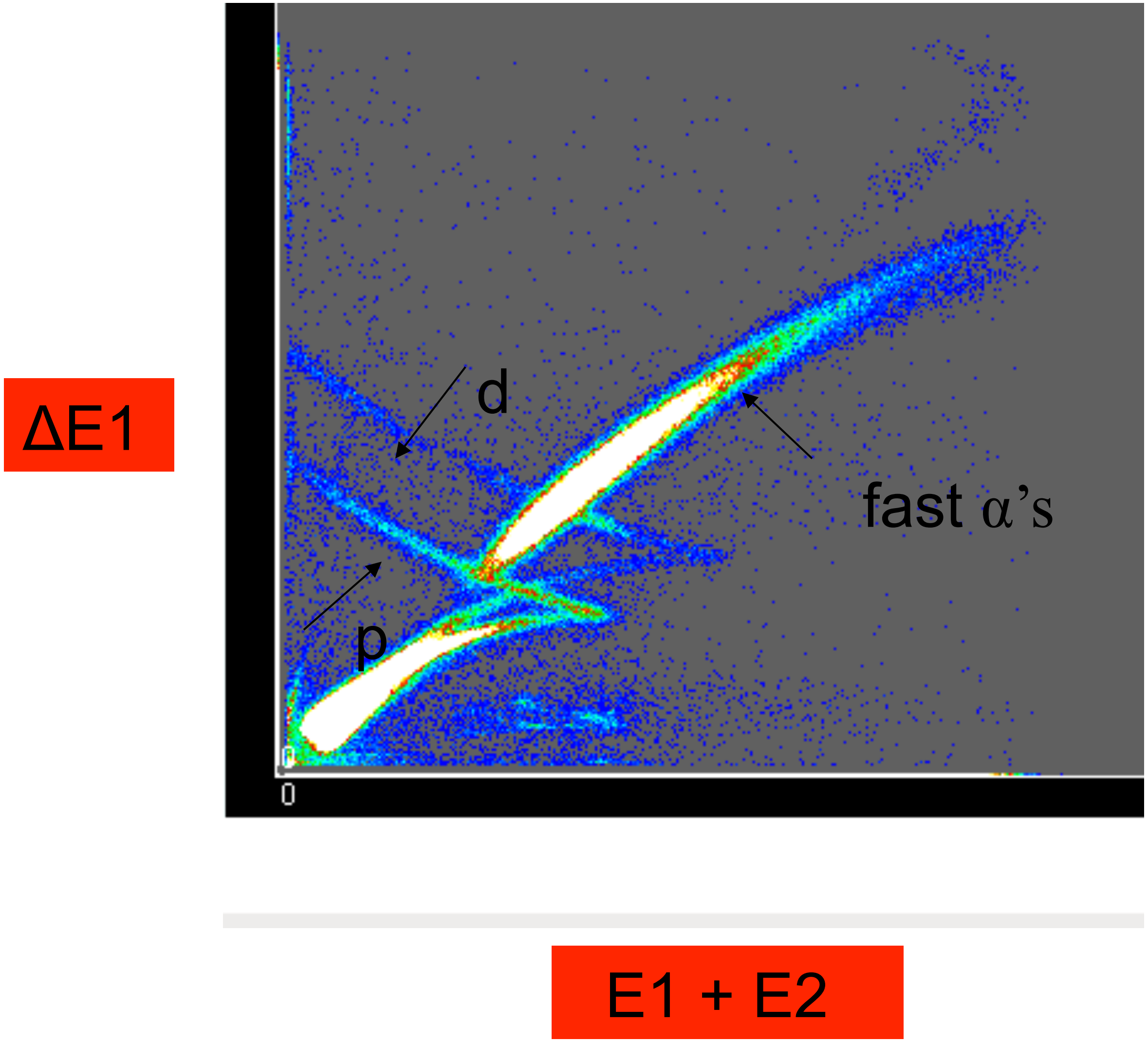


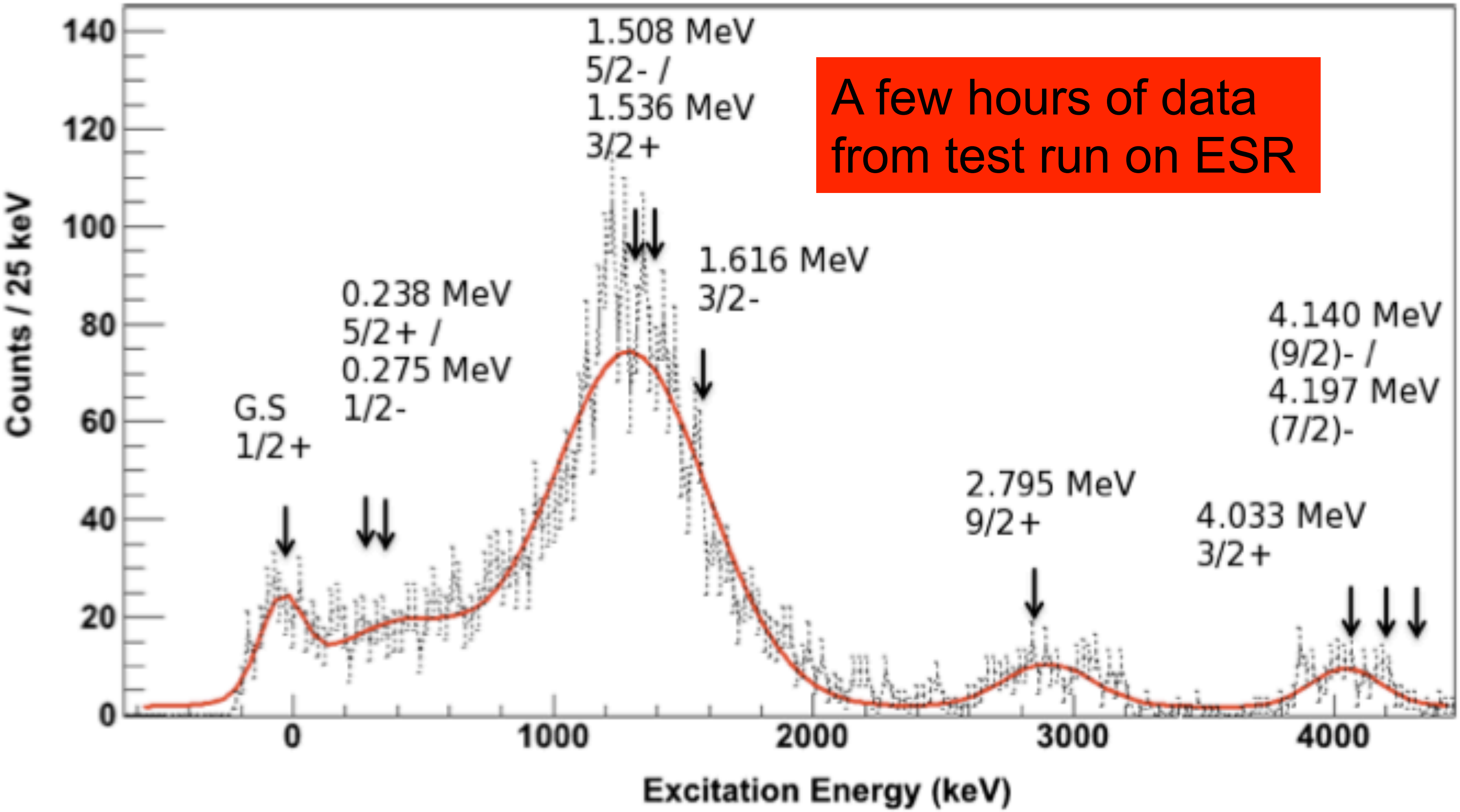


Si –telescope

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

Particle ID plot for DSSD





A few hours of data from test run on ESR

DT Doherty, PhD Thesis (2014)

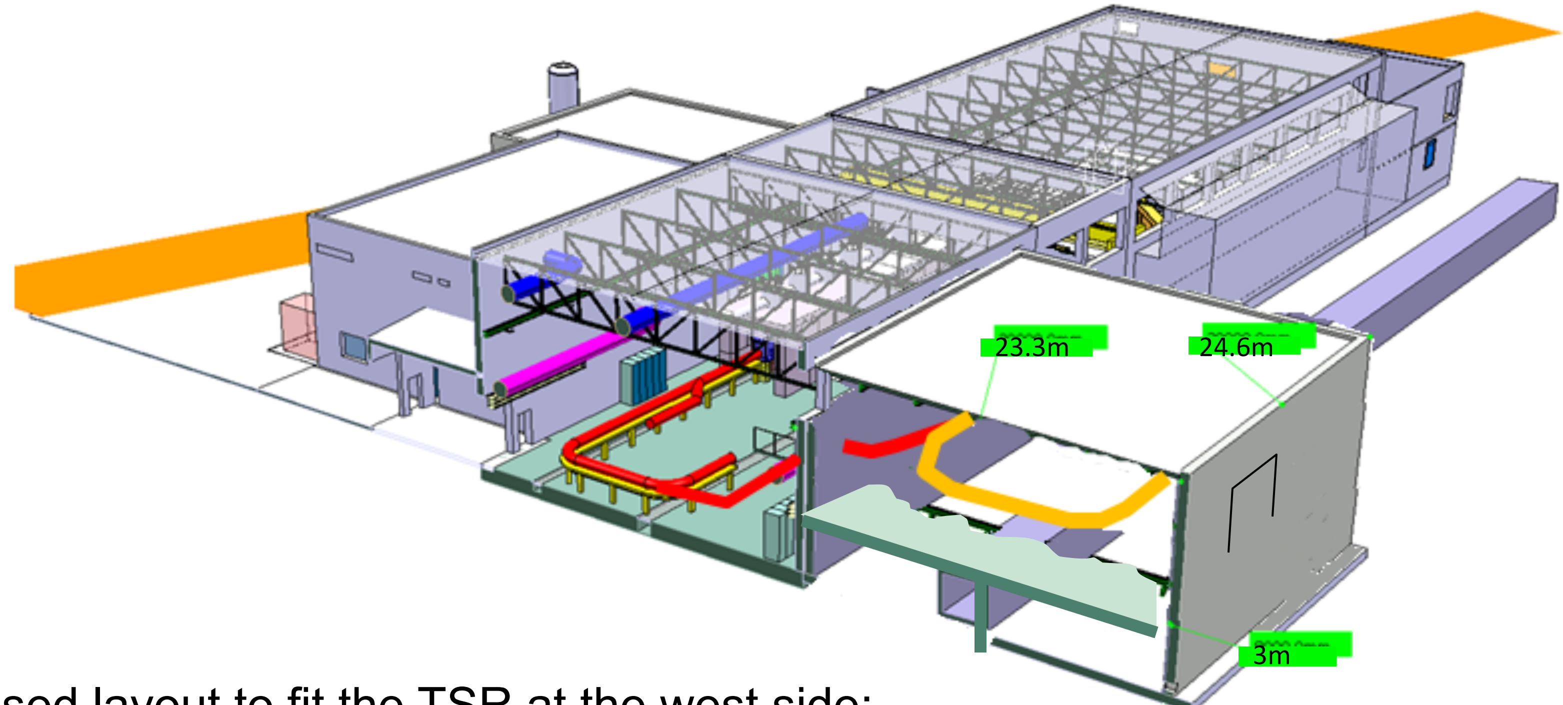
TSR@ISOLDE – Injection of RIBs into ring at MeV/u energies

Spokesperson: K Blaum (Heidelberg)

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

entire issue of EPJ 207 1-117 (2012)

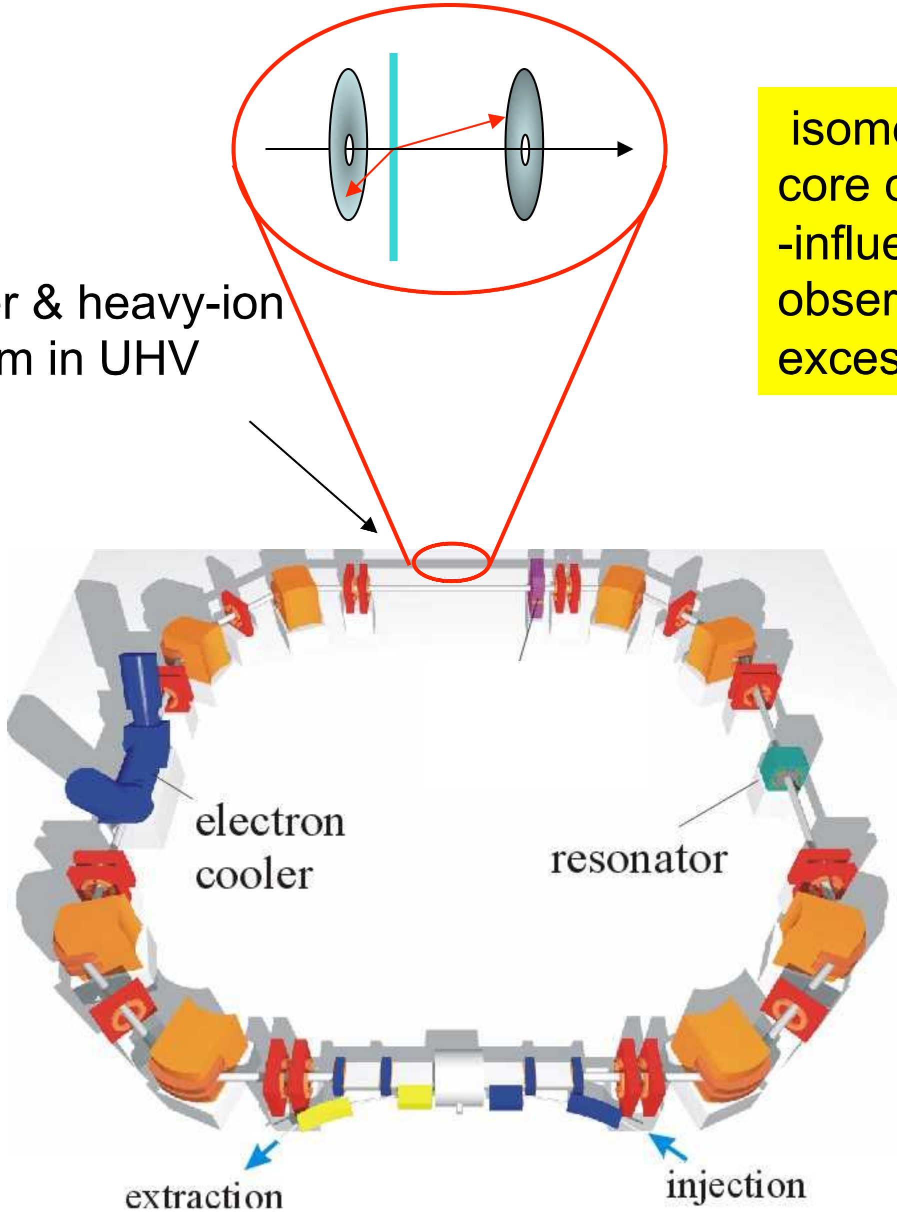
ISOLDE site (west) side



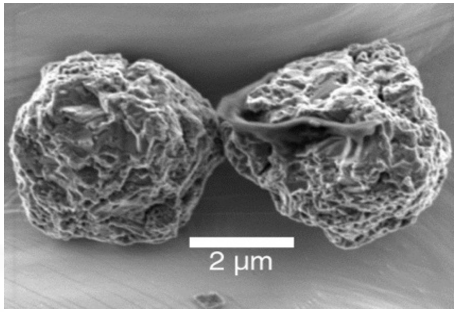
Proposed layout to fit the TSR at the west side:
- Installation above the CERN infrastructure-tunnel

Future $^{26m}Al(d,p)^{27}Al$ study on TSR storage ring@ISOLDE

In-ring target chamber & heavy-ion recoil detection system in UHV



isomer can be excited in core collapse supernovae -influences ‘extinct’ ^{26}Al observed in meteorites as excess ^{26}Mg



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)

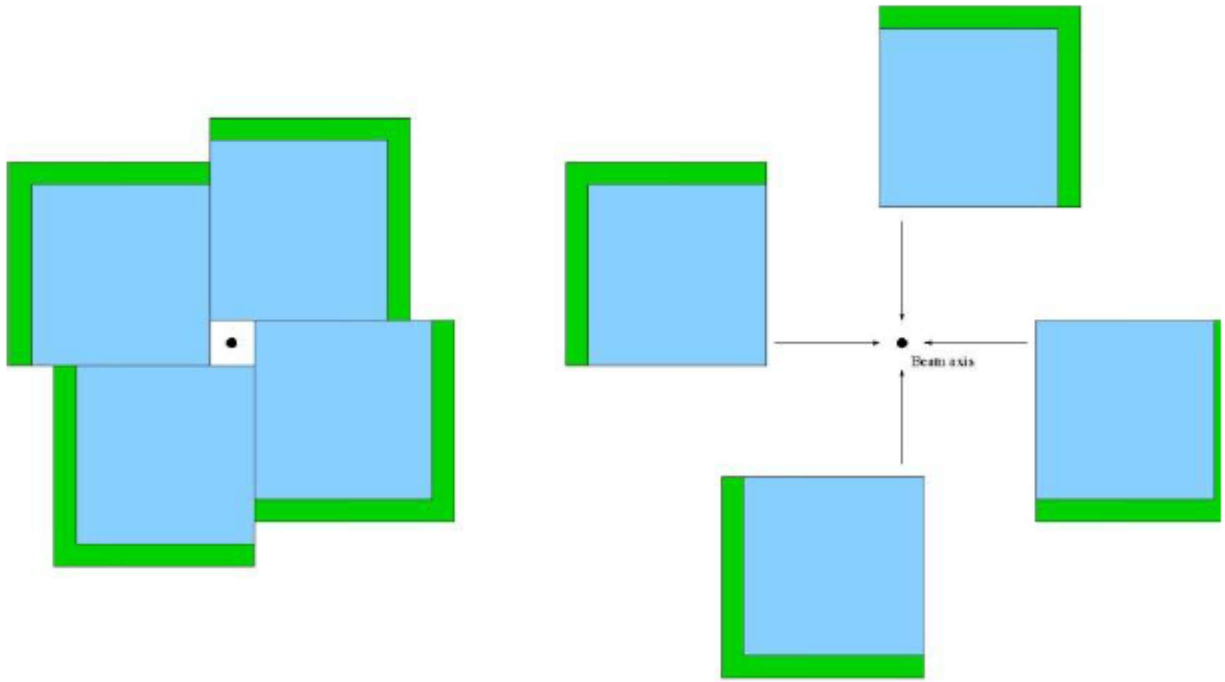
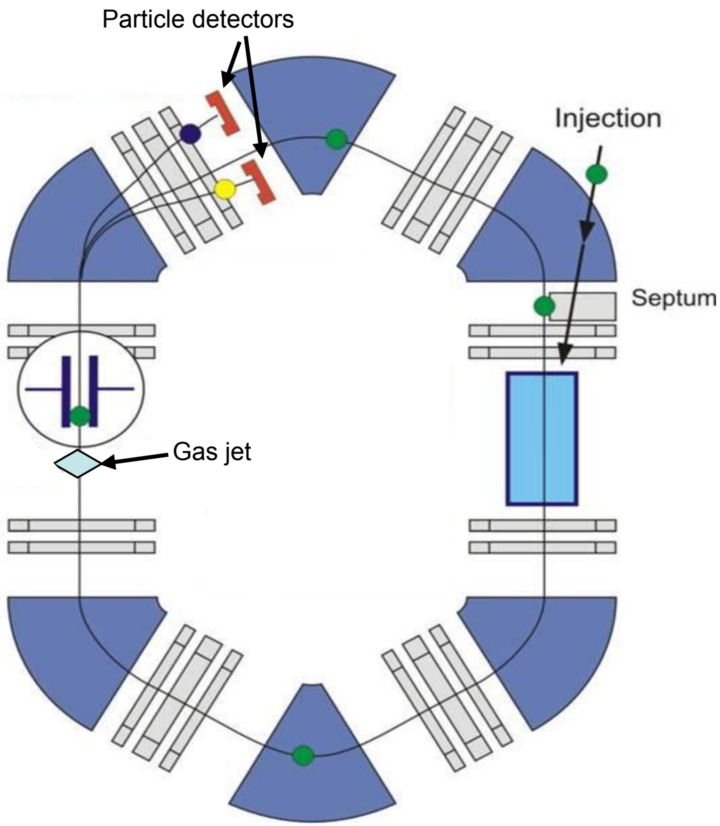


Figure 1: Illustration of upstream or downstream assembly of 4 DSSDs about beam axis

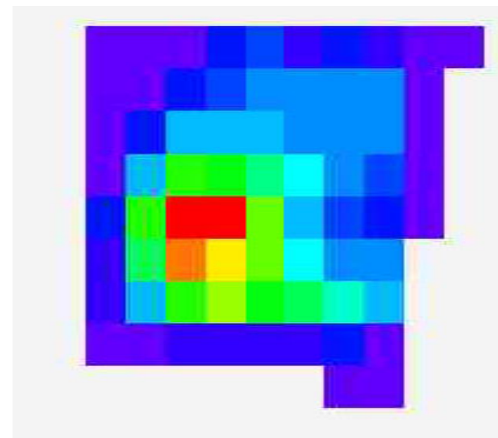
For ultra high resolution mode resolution should be entirely limited by transverse beam emittance

→ resolutions approaching 10 keV FWHM attainable

Pioneering new technique on ESR (Heil, Reifarth) – heavy recoils detected with double-sided silicon strip detector (Edinburgh)



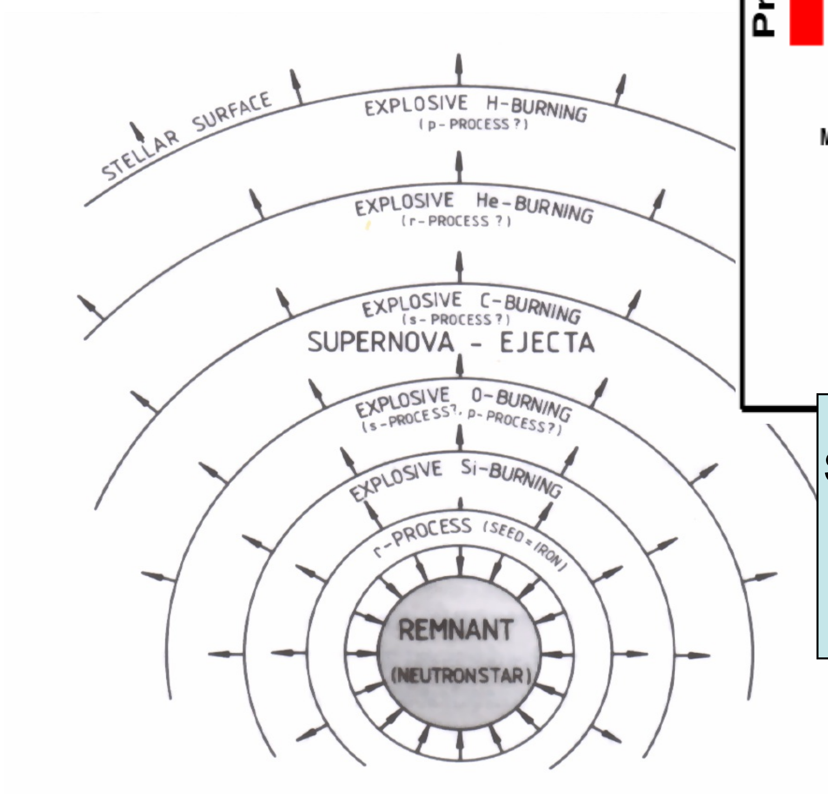
Position distribution of recoiling ions measured by DSSD

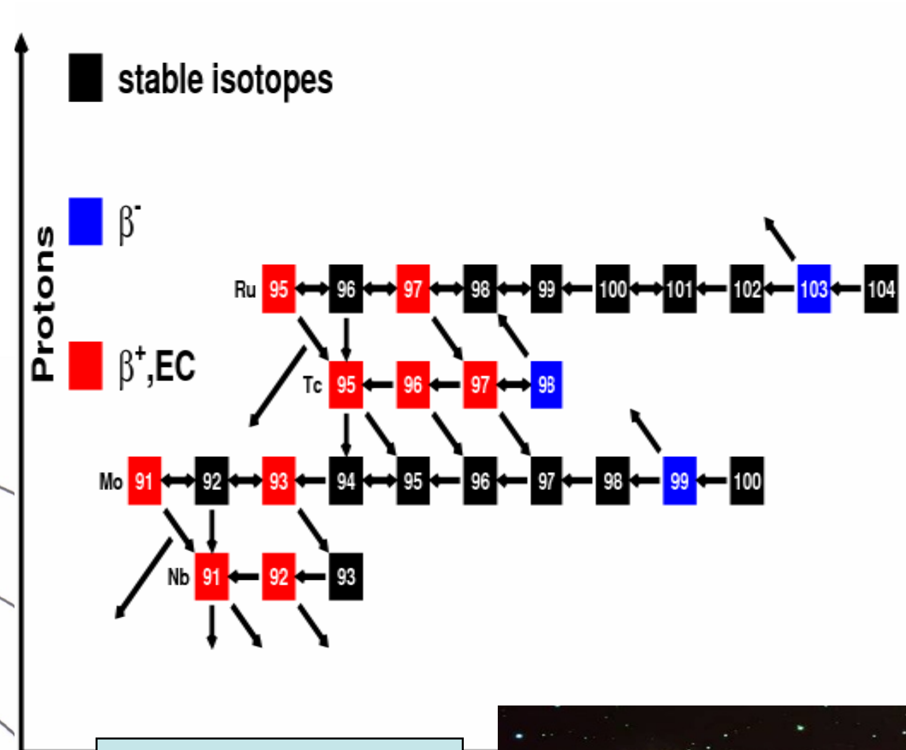


σ 96Ru(p,γ)= 3.6(5) mb @ ~10 MeV/u

New DSSD system developed (Edinburgh/GSI/Frankfurt) for p-process capture reactions in Gamow burning window
→ CRYRING@GSI

Puzzle of the origin of heavy ‘p-nuclei’ – abundant proton-rich isotopes eg ^{92}Mo and ^{96}Ru





Supernova shock passing through O-Ne layers of progenitor star

Summary

We are entering an exciting phase of development combining a variety of different experimental approaches to determine key H/He burning reaction rates for explosive astrophysical scenarios such as Novae, Supernovae and X-ray bursts.