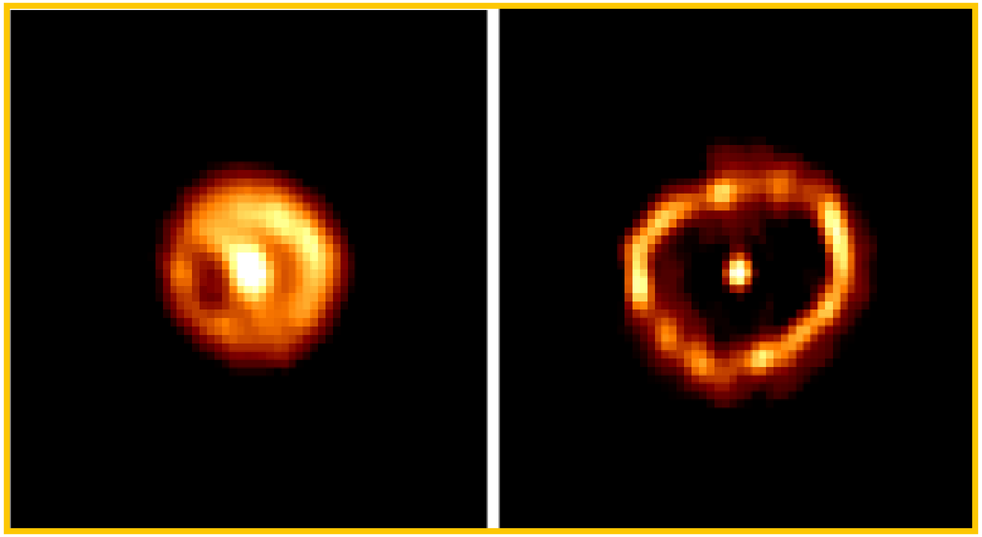
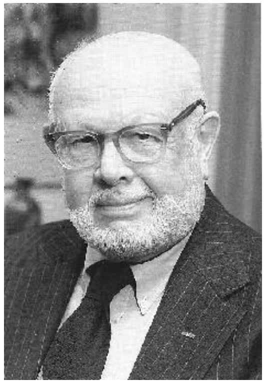
Experiments for Explosive Nuclear Astrophysics

PJ Woods, University of Edinburgh,
Goethe University of Frankfurt

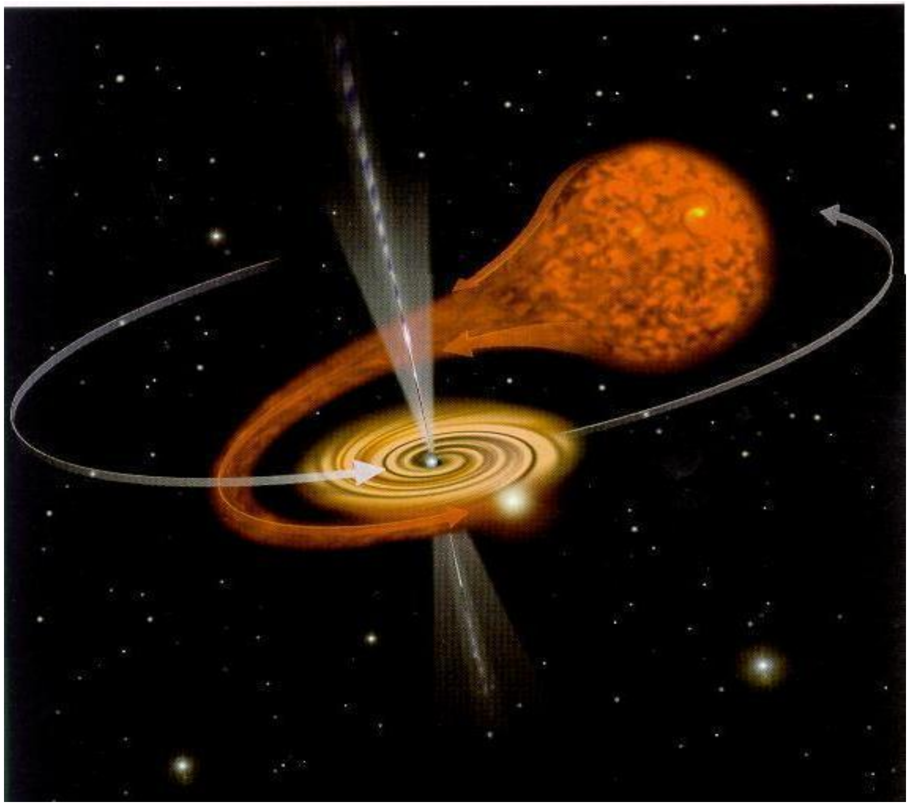


"We stand on the verge of one of those exciting periods which occur in science from time to time. In the past few years, it has become abundantly clear that there is an urgent need for data on the properties and interactions of radioactive nuclei for use in **nuclear astrophysics"**

Willie Fowler, Nobel Laureate



Explosive H/He burning in Binary Stars

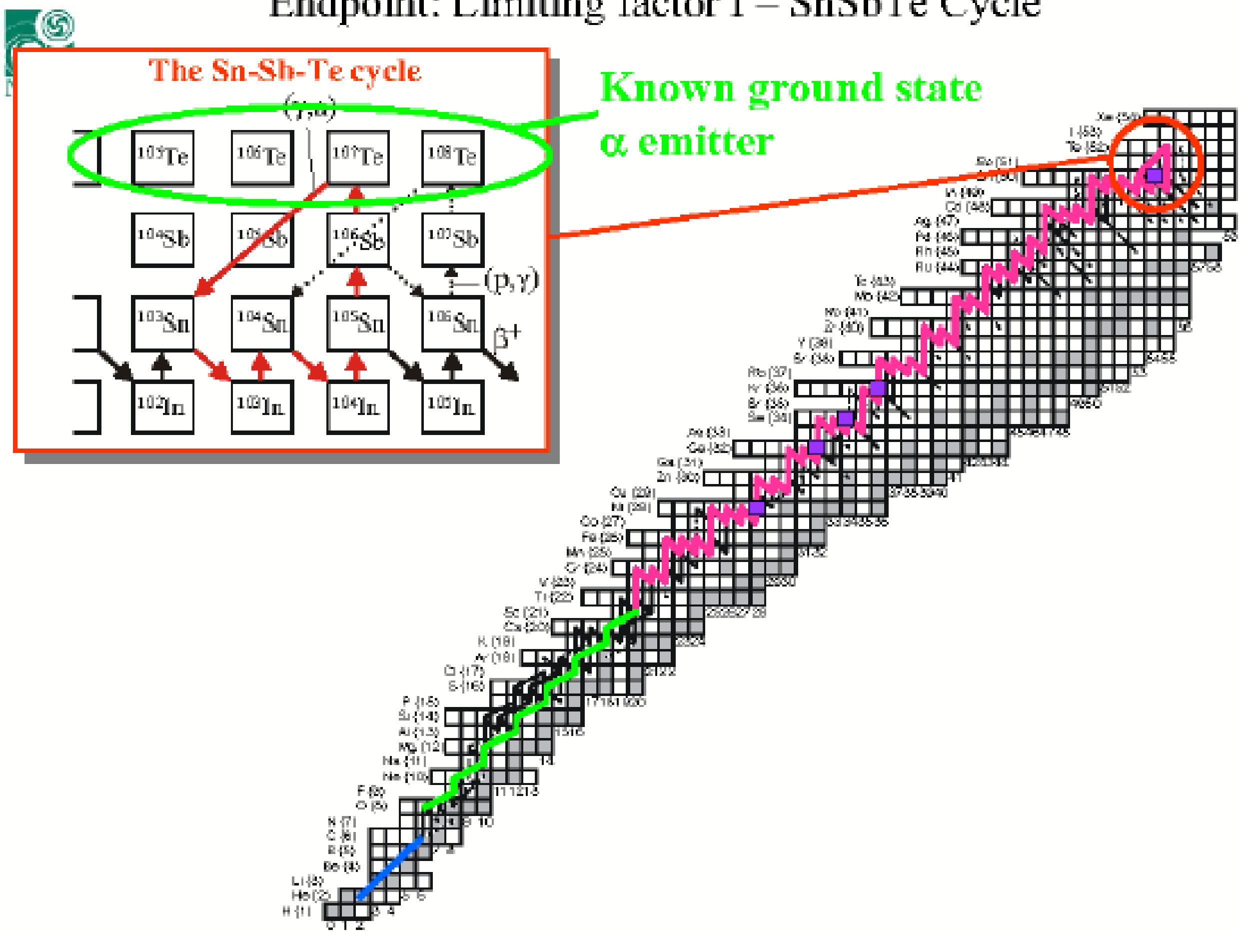


Isaac Newton, Principia Mathematica (1666): ‘from this fresh supply of new fuel those old stars, acquiring new splendour, may pass for new stars’

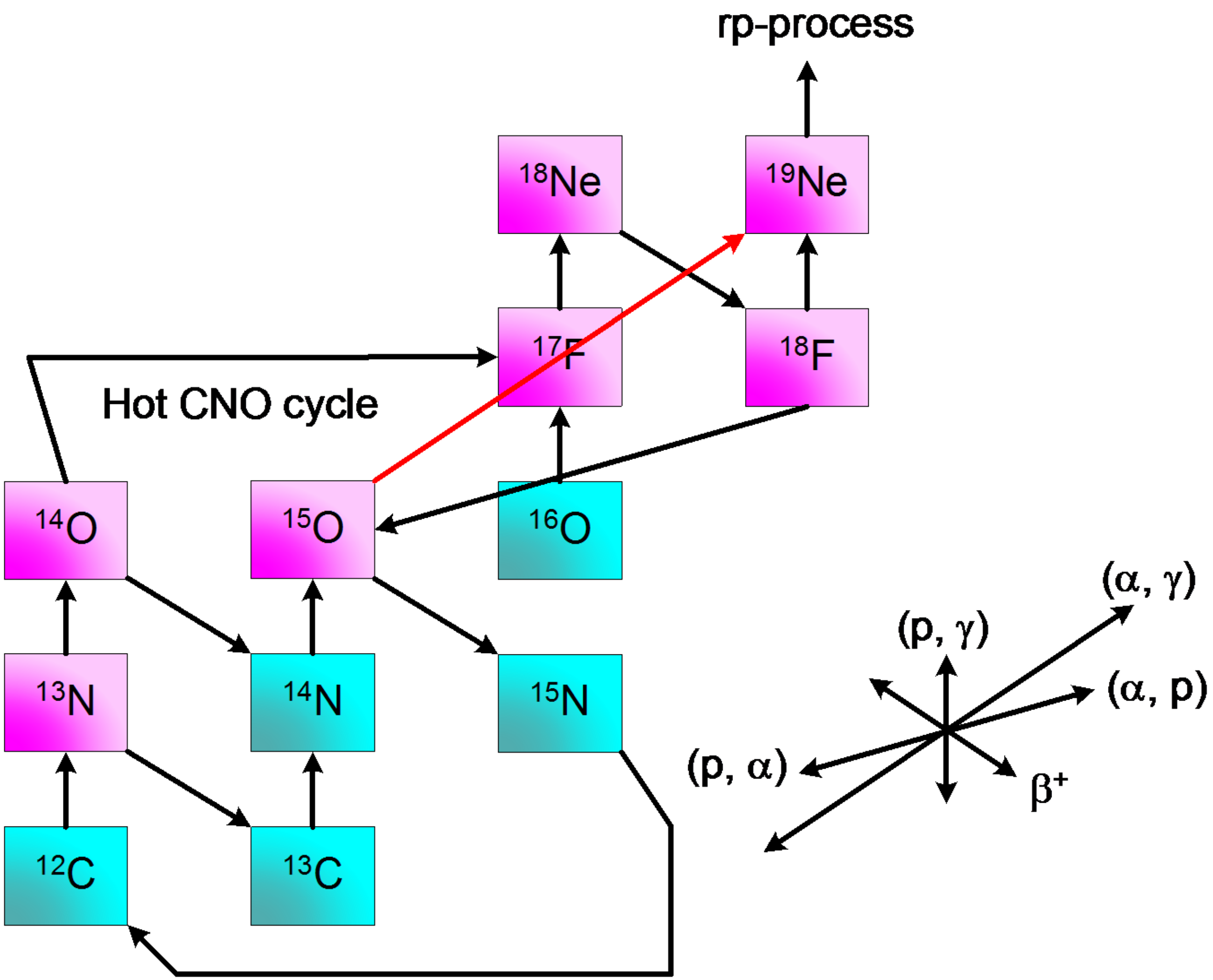
The endpoint of the rp-process

?

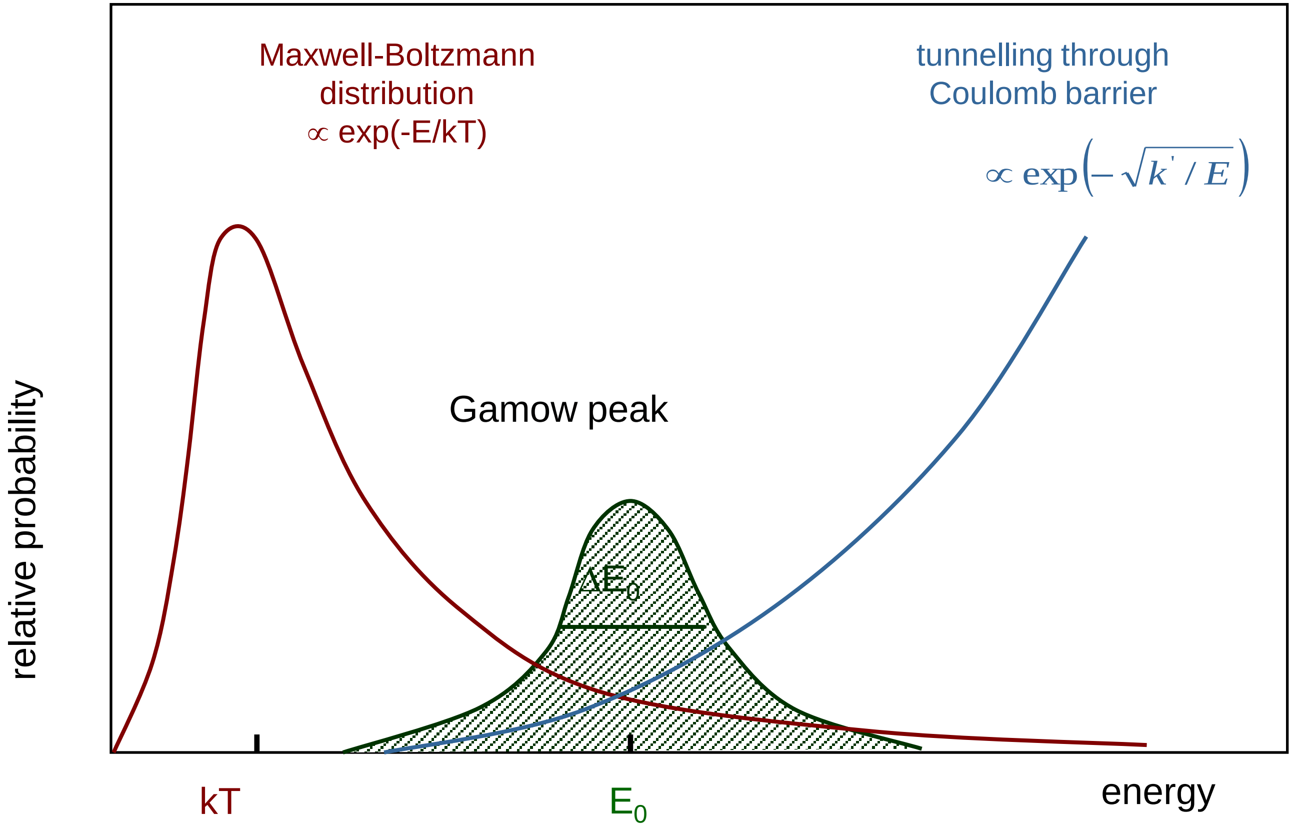
Endpoint: Limiting factor I – SnSbTe Cycle



The Hot CNO Cycles



H/He fusion reactions at stellar energies



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

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

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AND
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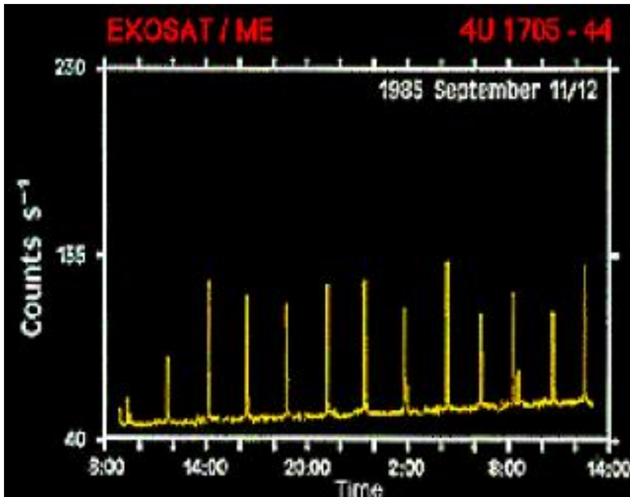
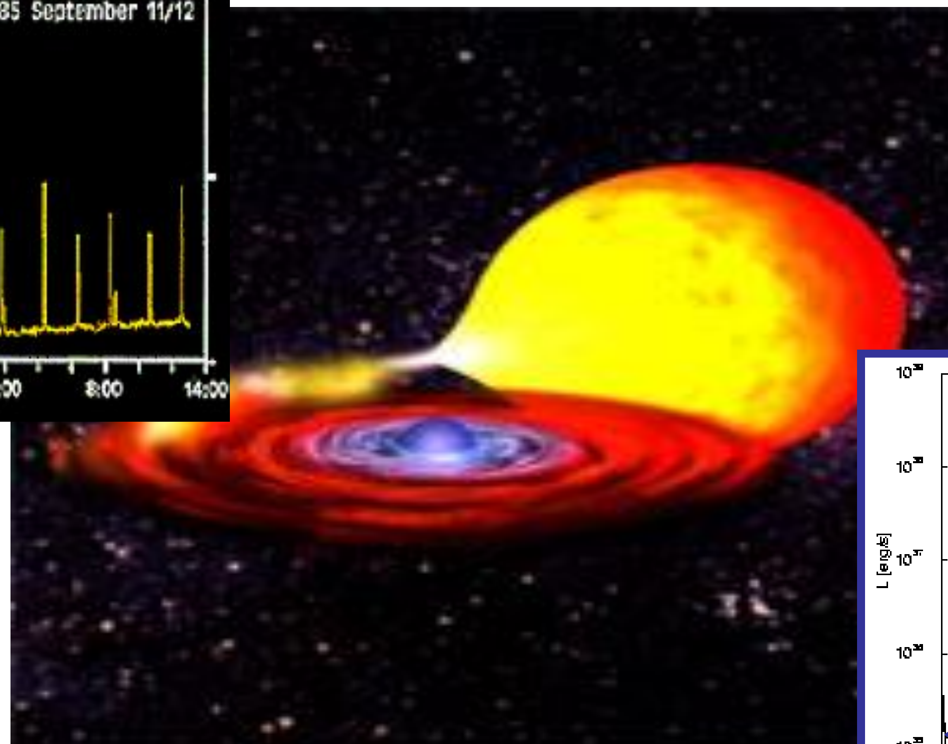
Department of Physics, University of Pennsylvania, Philadelphia
Received 1985 May 24; accepted 1985 August 19

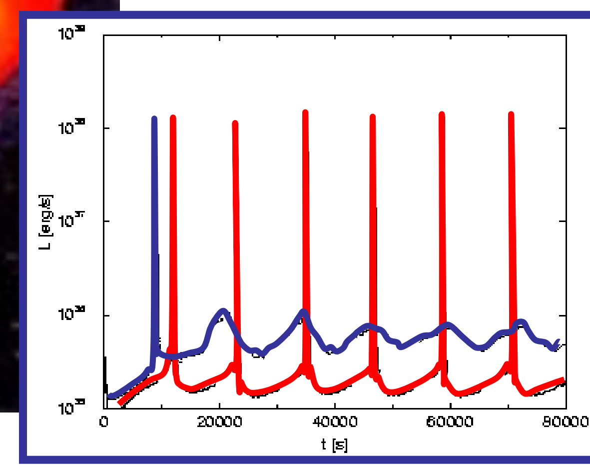
$^{15}O(\alpha,\gamma)^{19}Ne$ reaction rate predicted to be dominated by a single resonance at a CoM energy of 504 keV

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

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

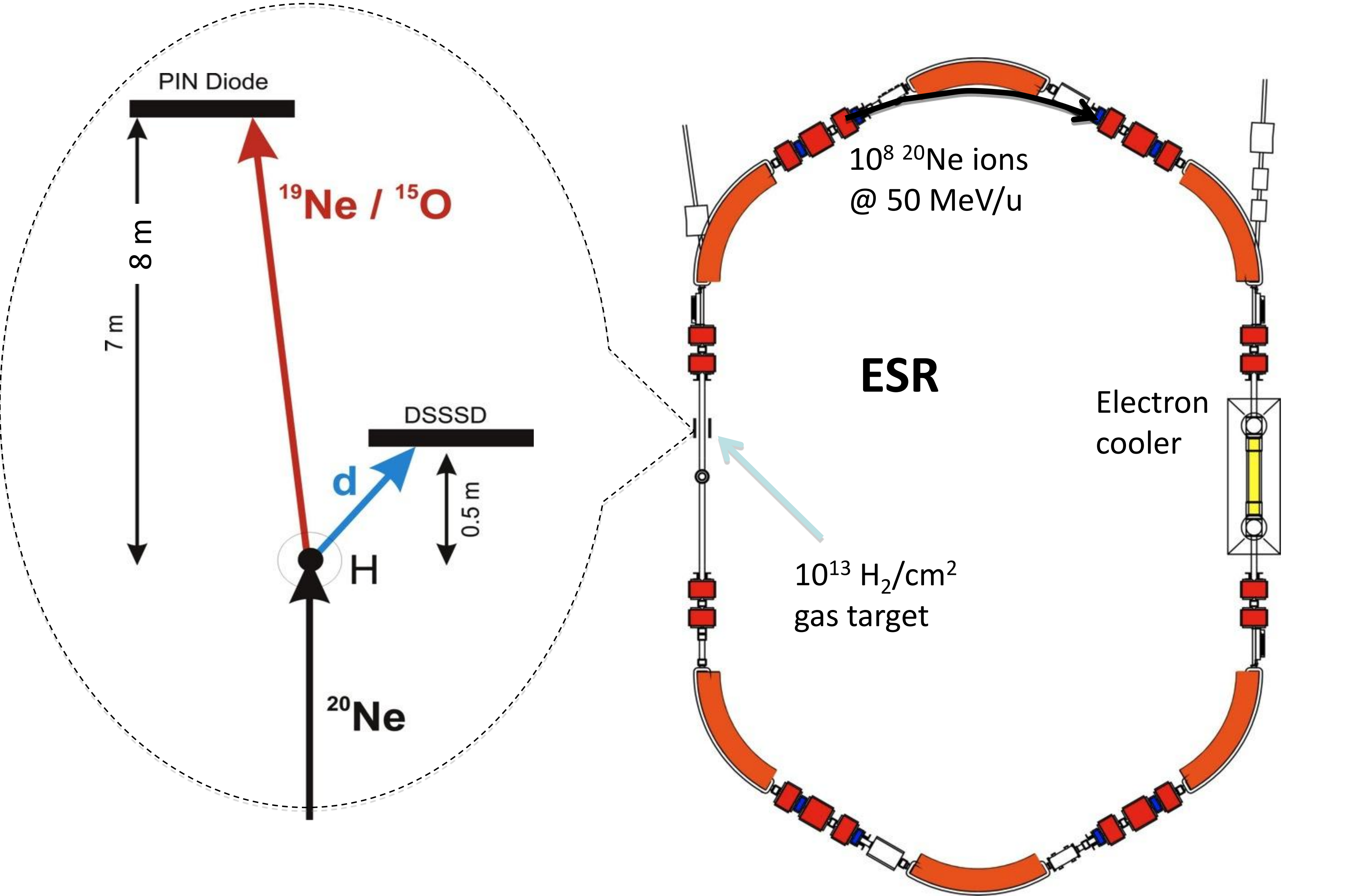


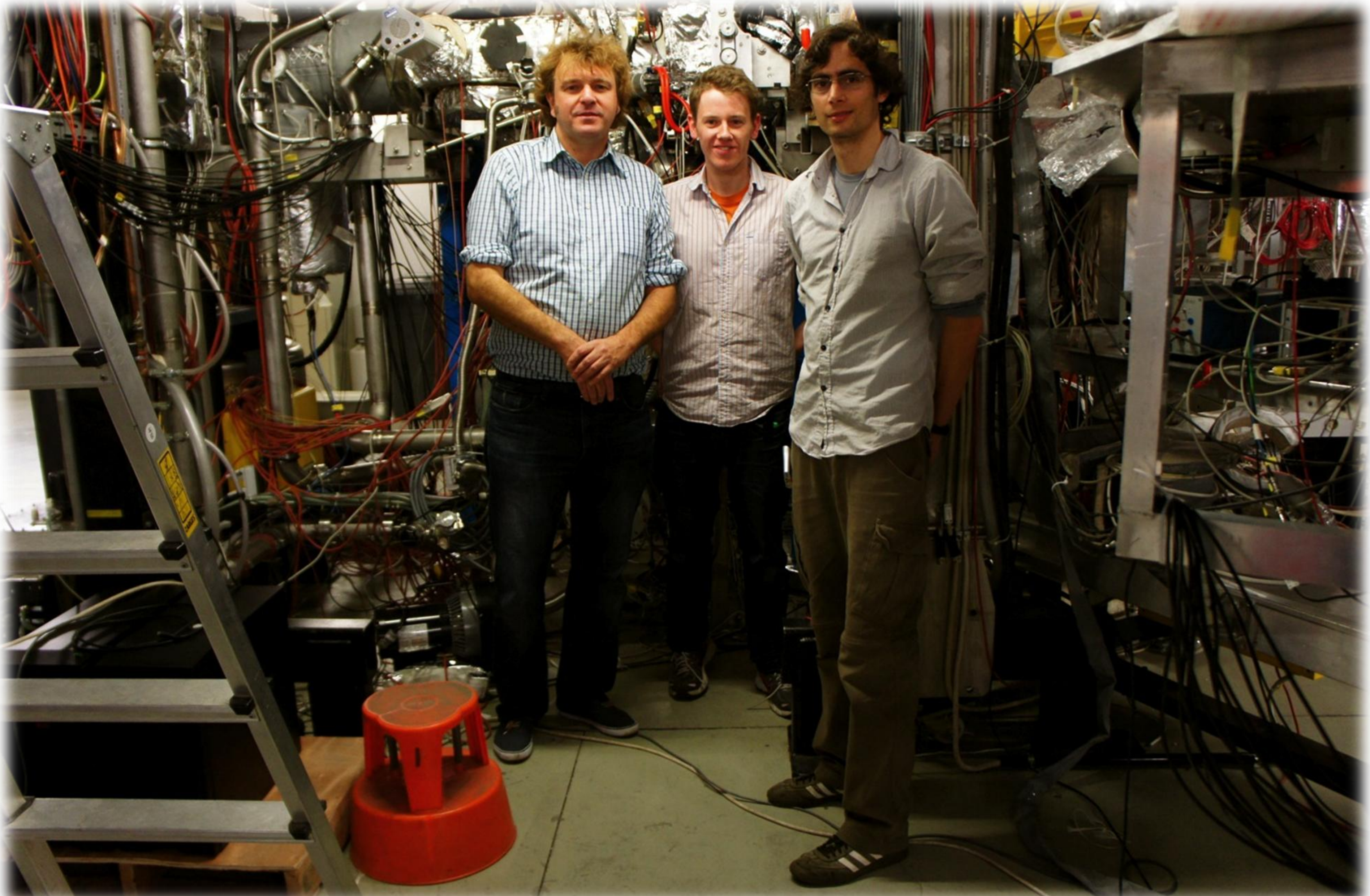




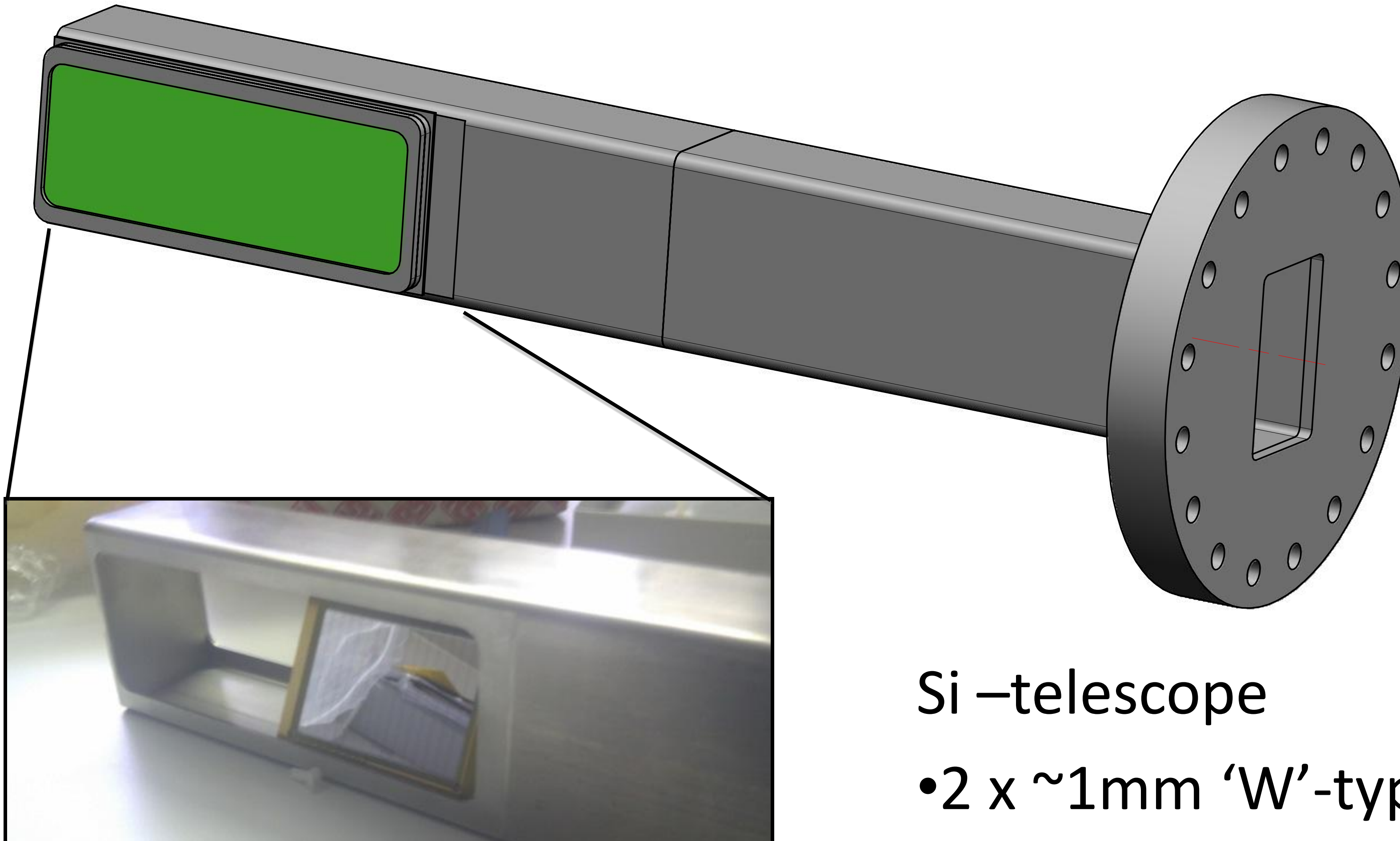
Reaction regulates flow between the hot CNO cycles and rp process
→ critical for explanation of amplitude and periodicity of bursts

Study of the $^{20}Ne(p,^{2}H)^{19}Ne$ transfer reaction on the ESR





Detector Pocket

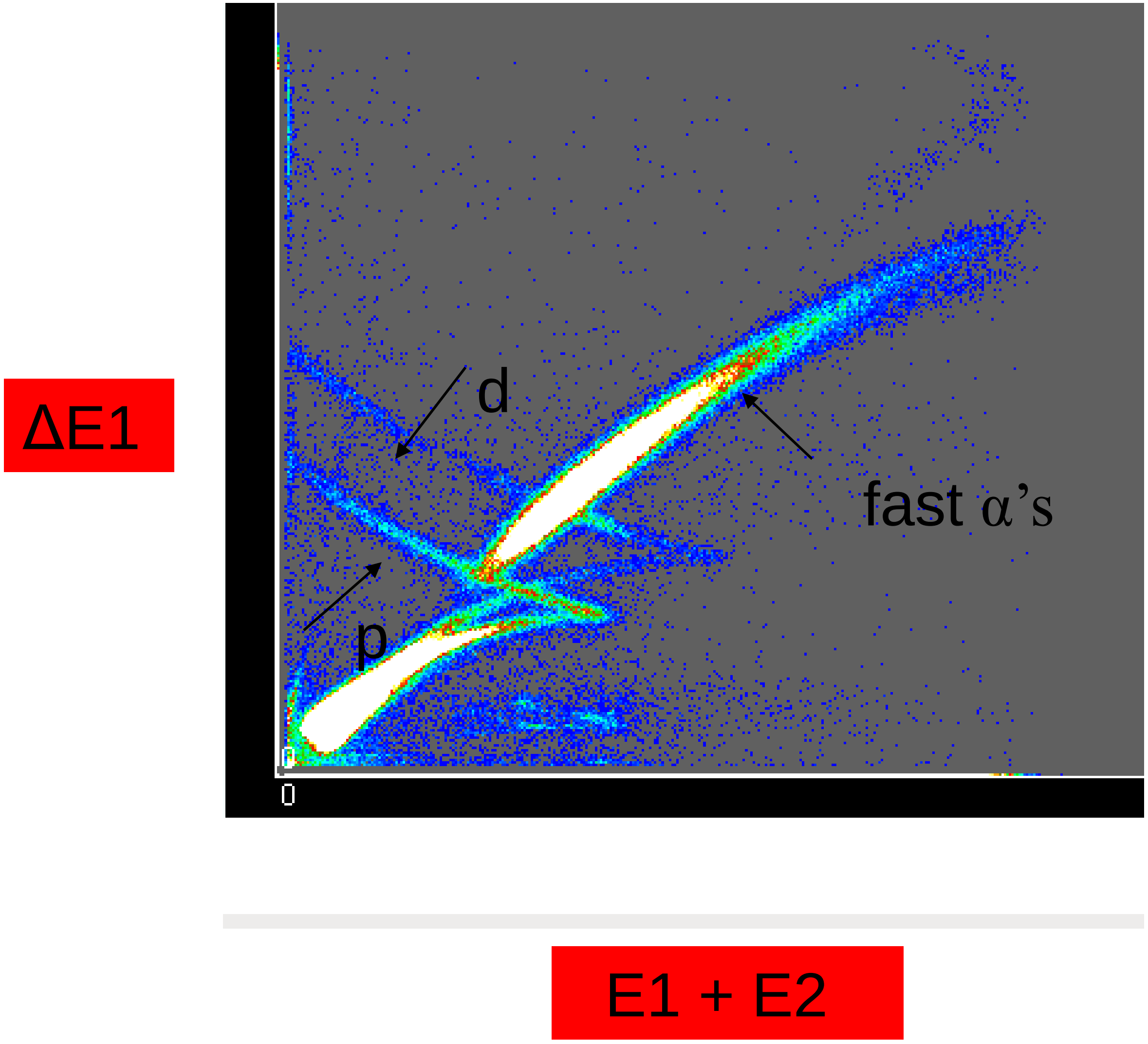


Si –telescope

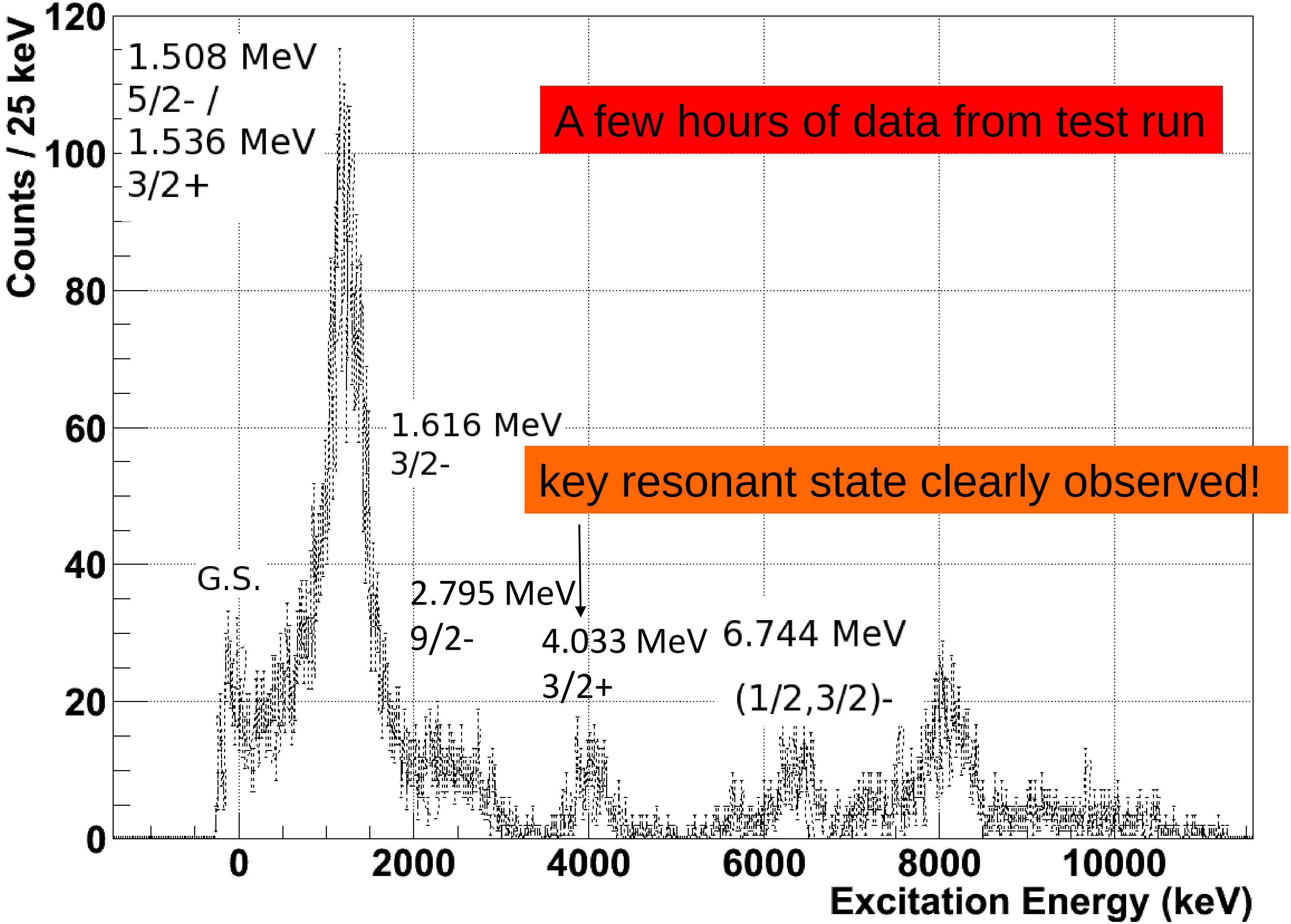
•2 x ~1mm ‘W’-type detectors

•16x16 strips

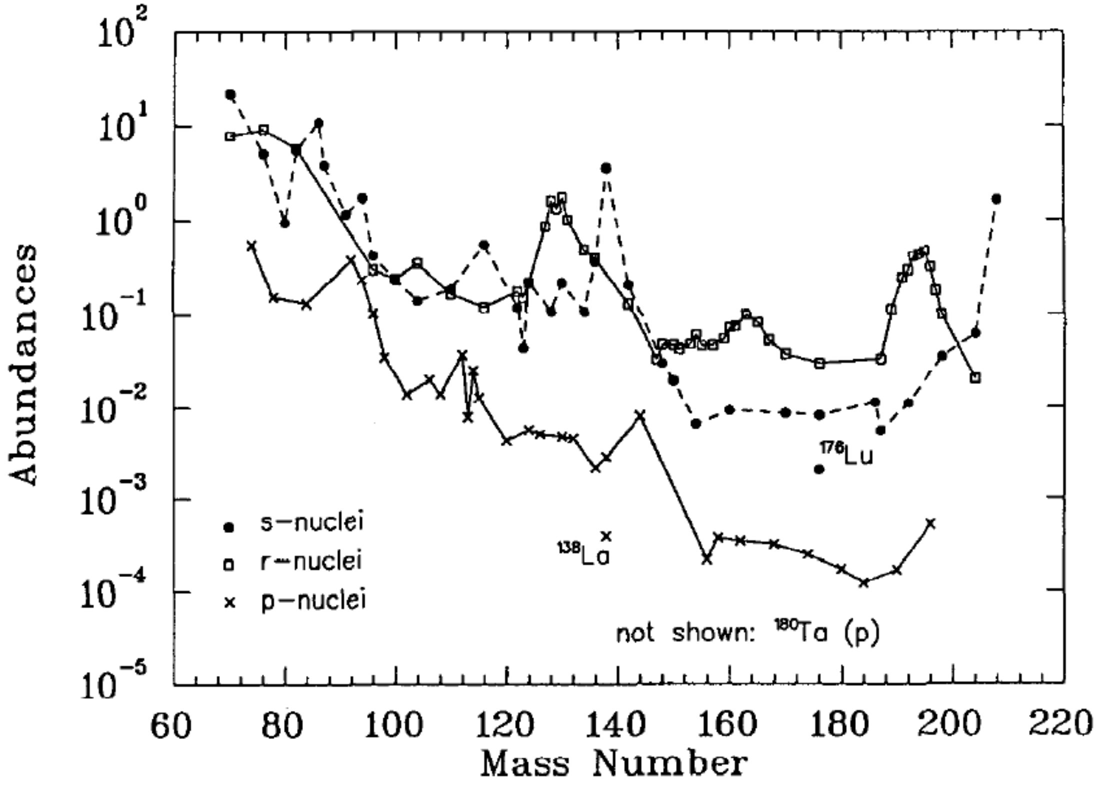
Particle ID plot for DSSD



Excitation Energy Spectrum @ 72mm

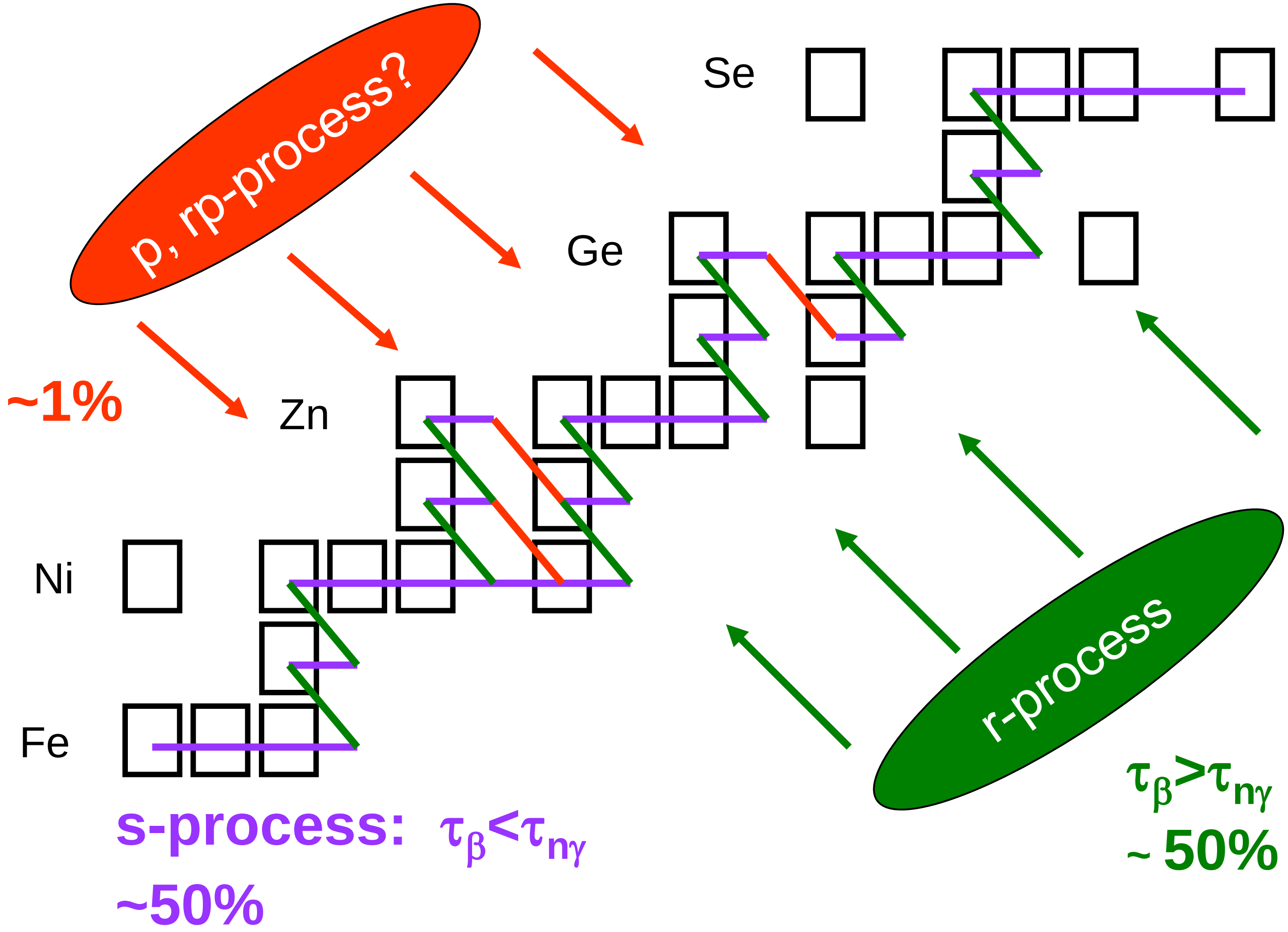


Heavy Element Abundance: Solar System

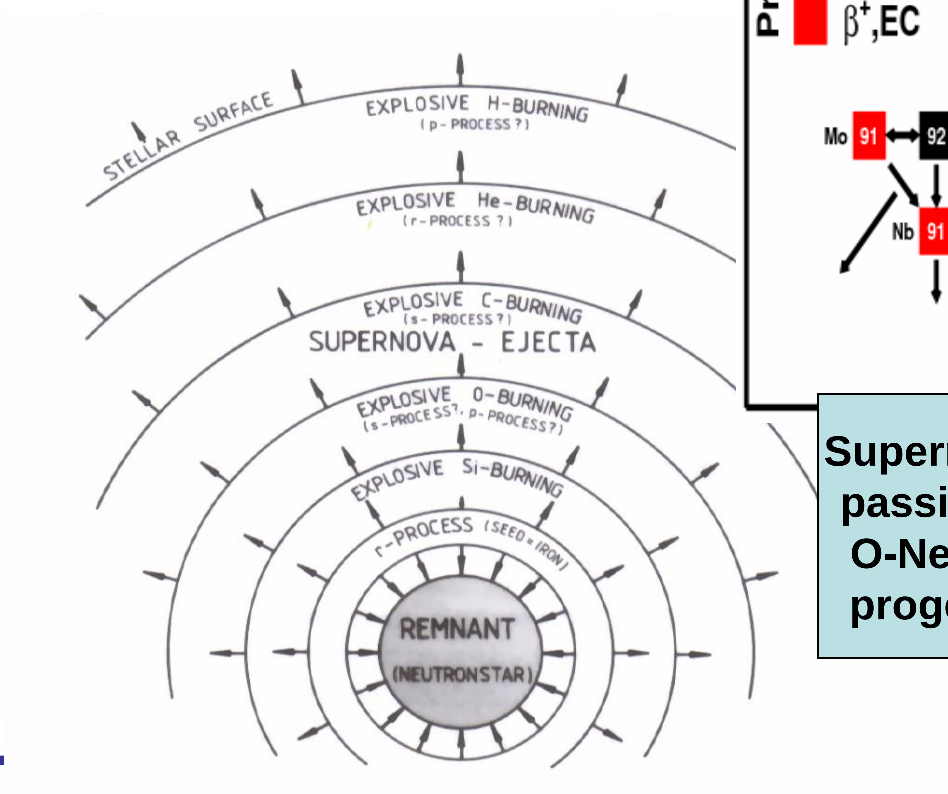


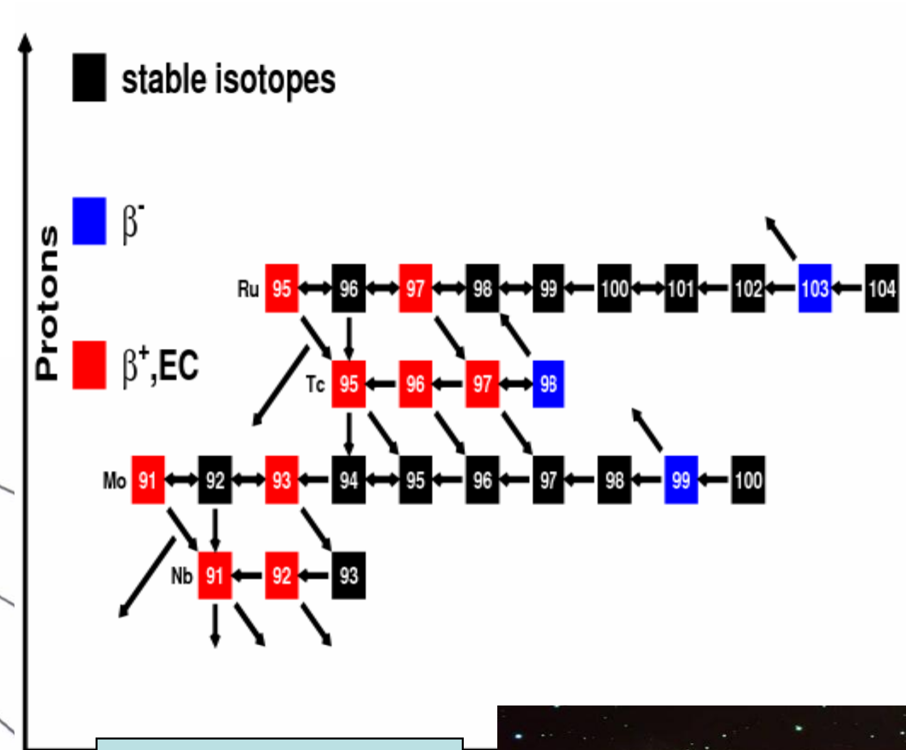
from *B.S.Meyer*, Ann. Rev. Astron. Astrophys. 32 (1994) 153

Nucleosynthesis above Fe



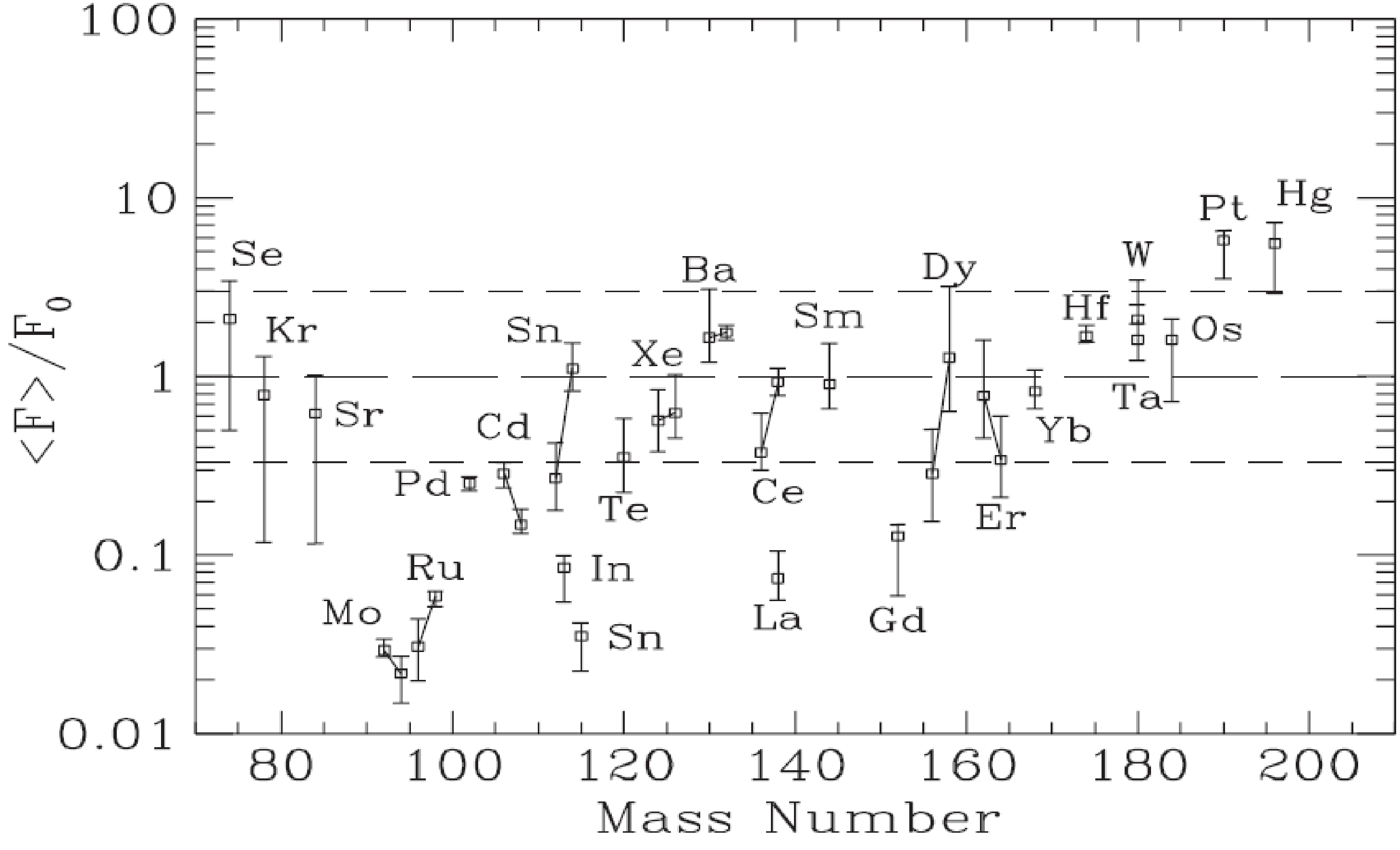
Puzzle of the origin of heavy 'p-nuclei' – abundant proton-rich isotopes eg ^{92}Mo and ^{96}Ru





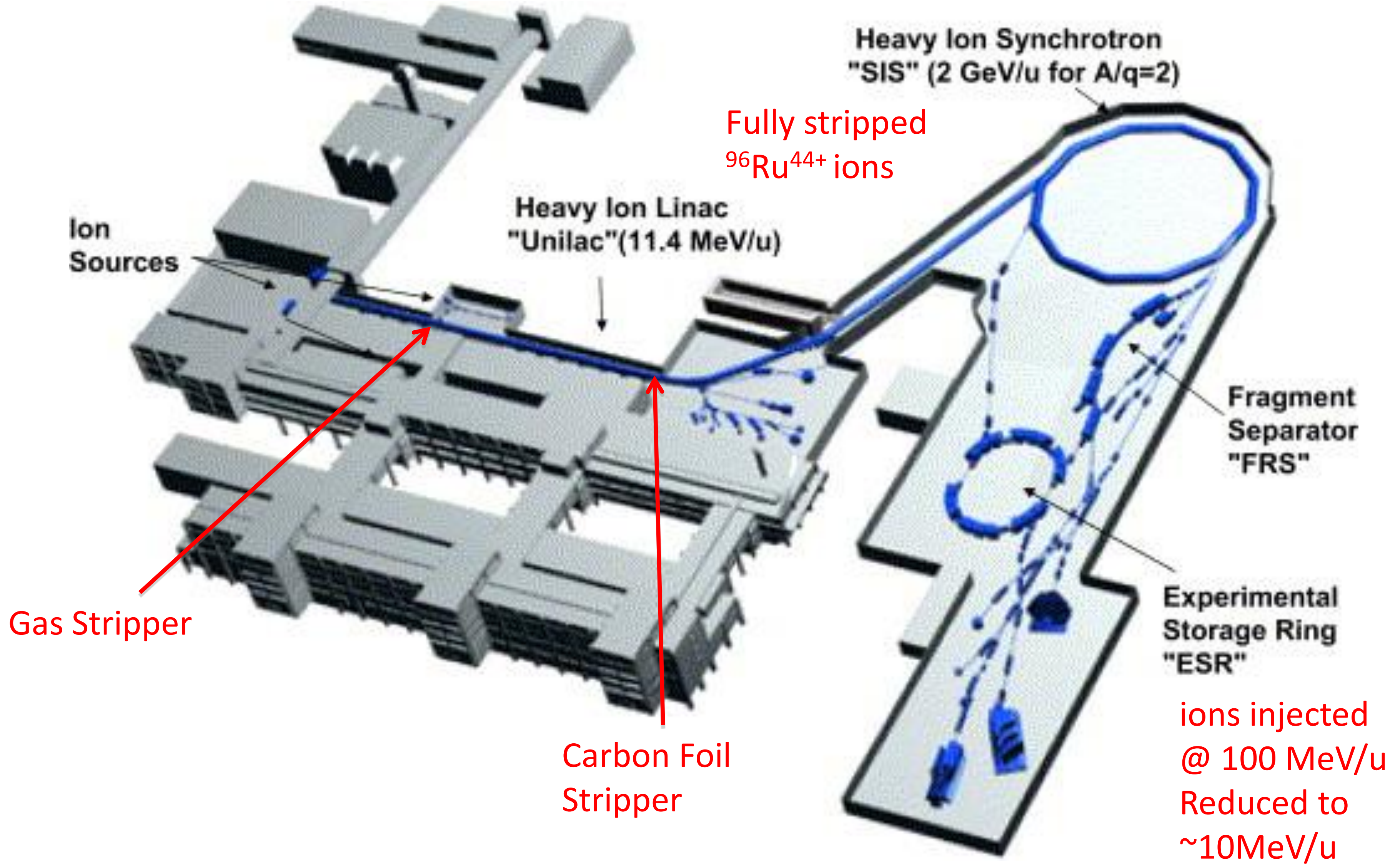
Supernova shock passing through O-Ne layers of progenitor star

Predicted p-nuclei abundances compared to observed abundances

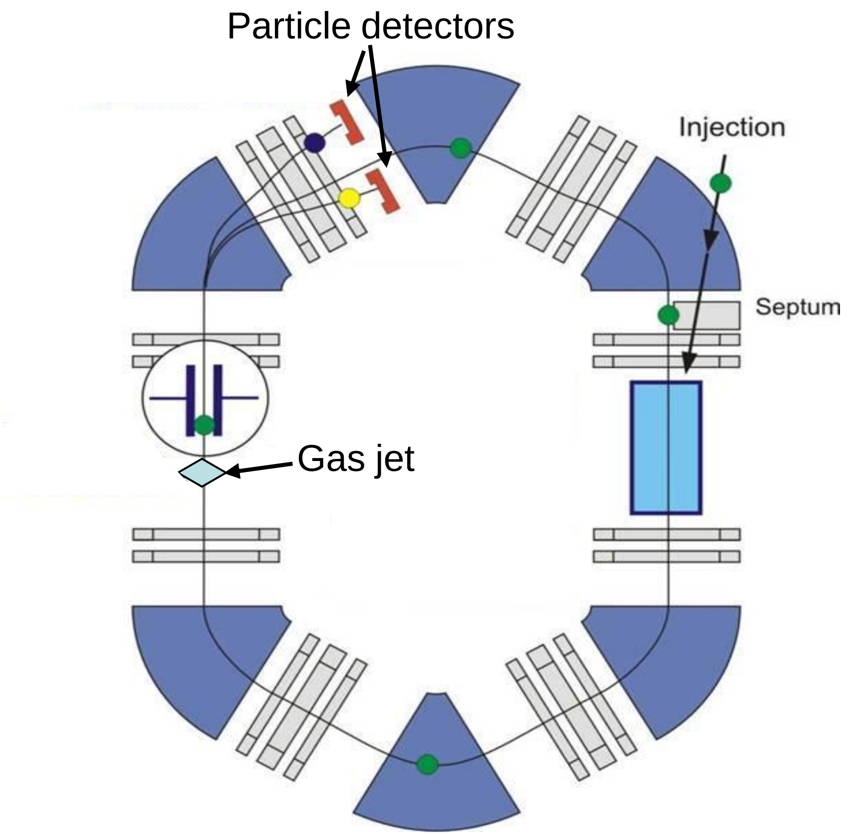


Arnould & Goriely Phys. Rep. **384**,1 (2003)

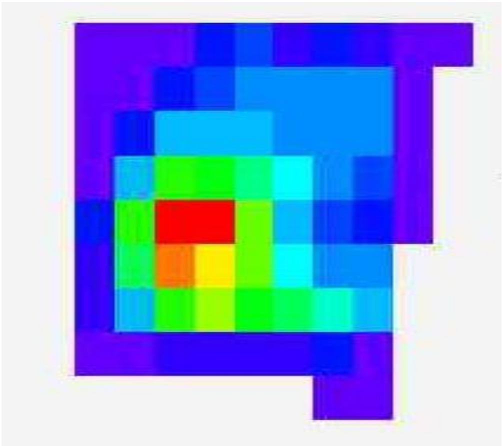
Study of $^{96}Ru(p,\gamma)^{97}Nb$ reaction with decelerated beams using the ESR storage ring at GSI



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



$\sigma(p,\gamma)$= 3.6(5) mb

New DSSD system being developed (Edinburgh/GSI/Frankfurt) for use in UHV allowing p-process reaction measurements in Gamow energy region on ESR (2014) and then CRYRING

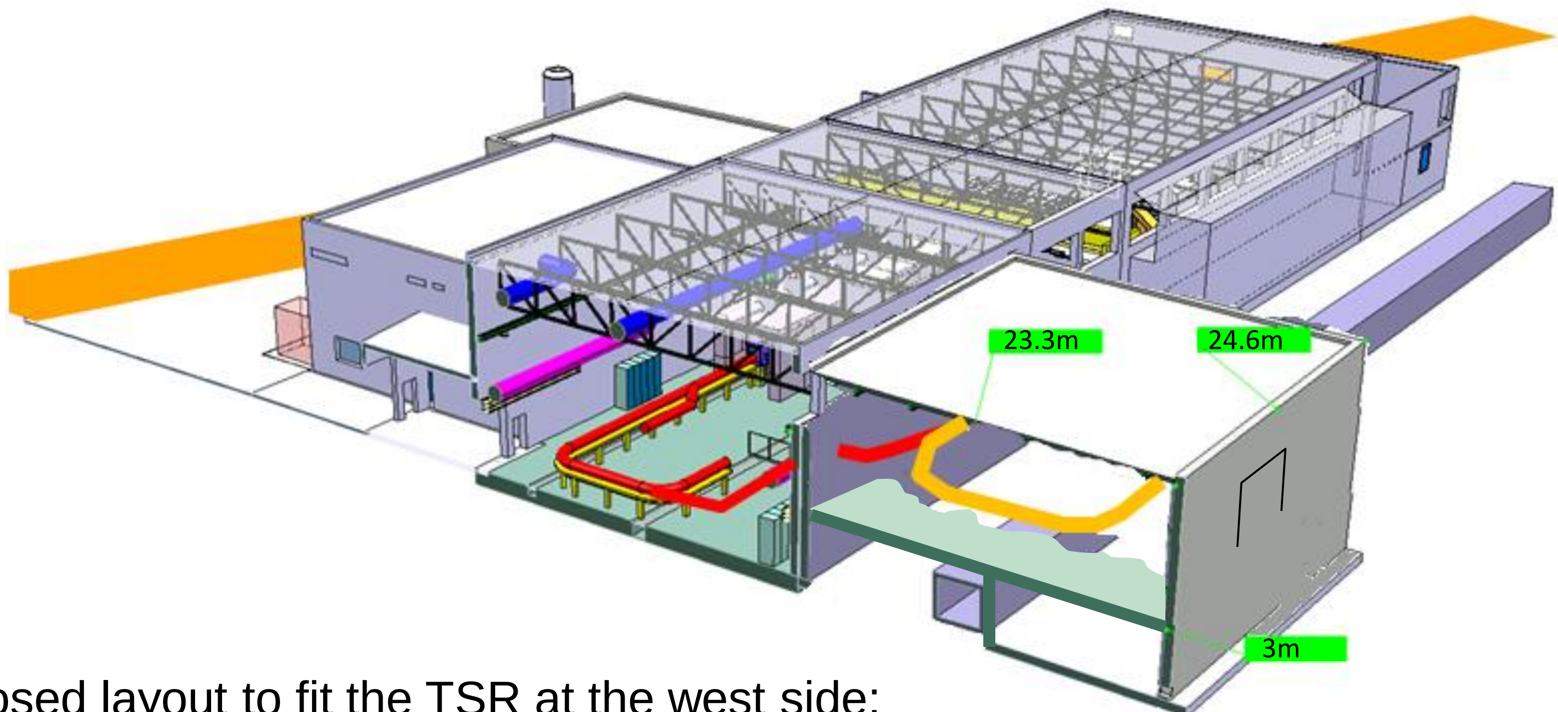
TSR@ISOLDE – RIBs injected directly at low energy

Spokesperson: K Blaum (Heidelberg)

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

entire issue of EPJ 207 1-117 (2012)

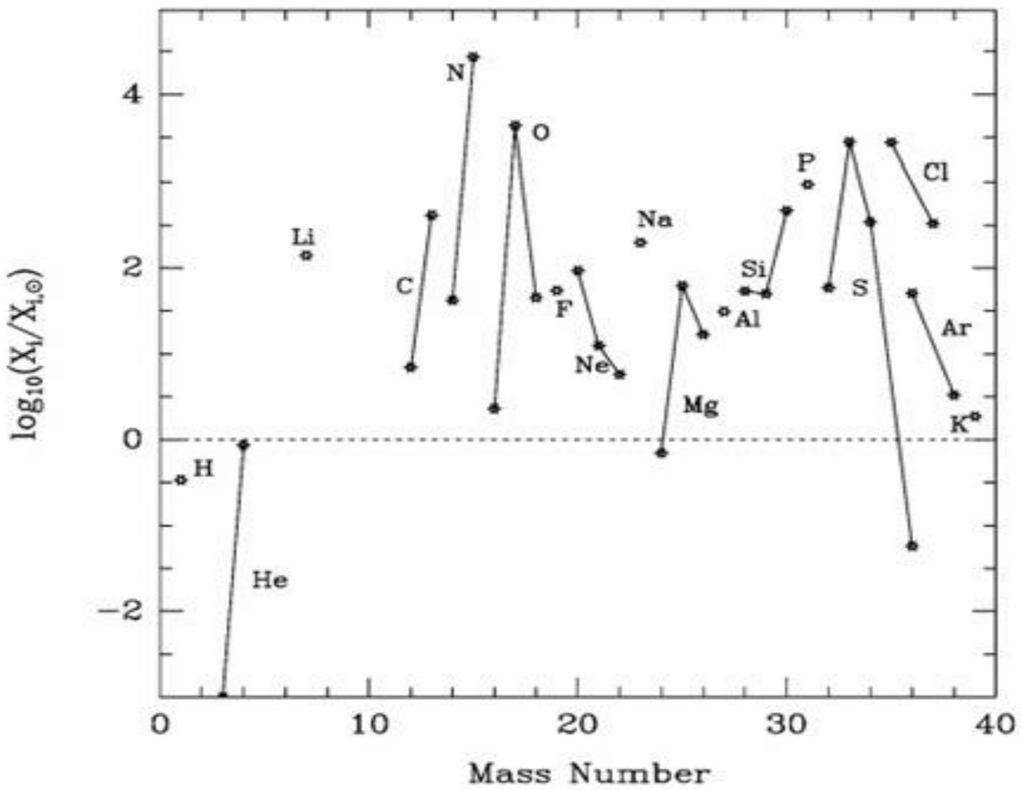
ISOLDE site (west) side



Proposed layout to fit the TSR at the west side:
- Installation above the CERN infrastructure-tunnel
→ Proposal supported by CERN management

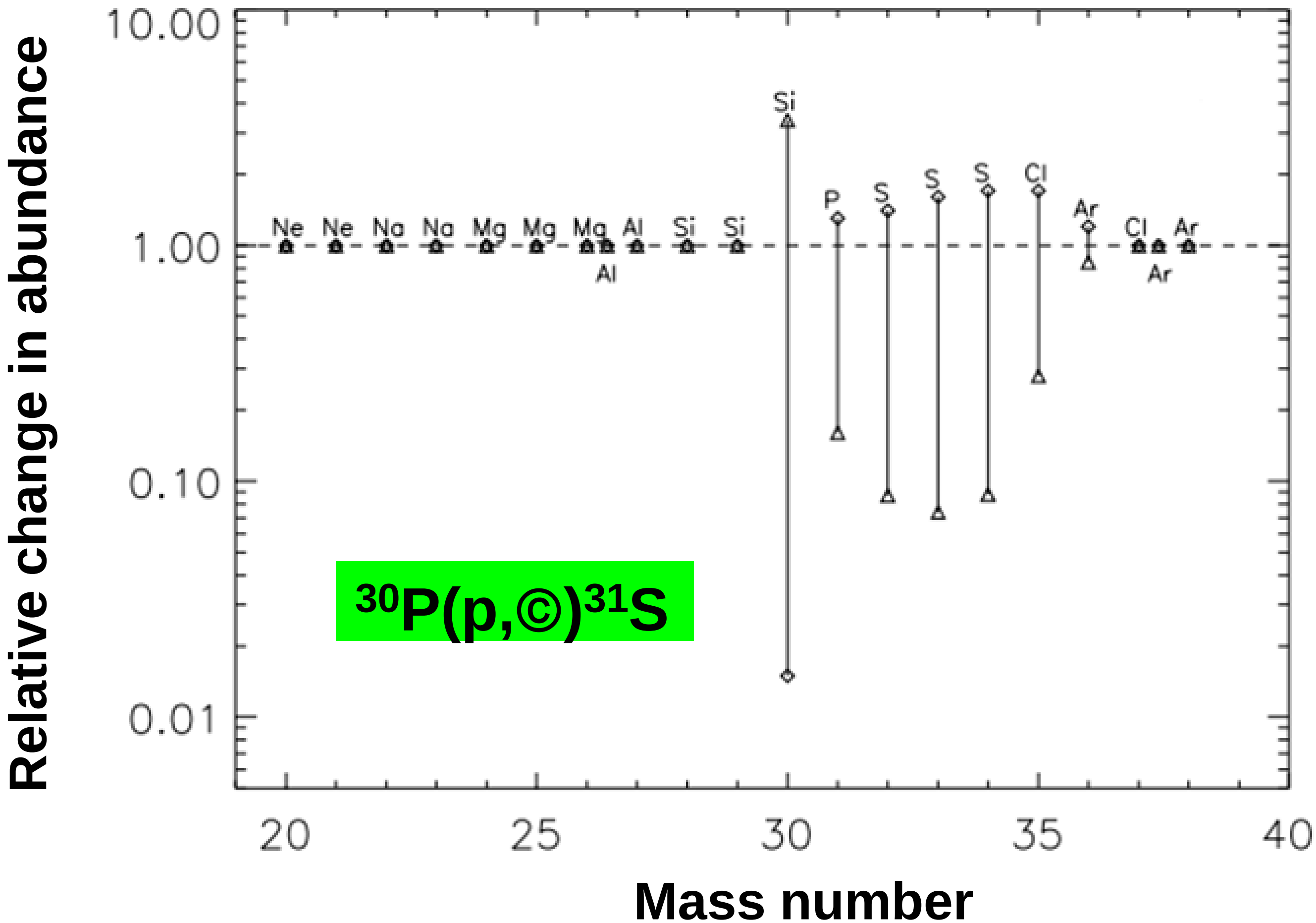
Abundances in novae ejecta

1.35 M_{Sun} ONe nova



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

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

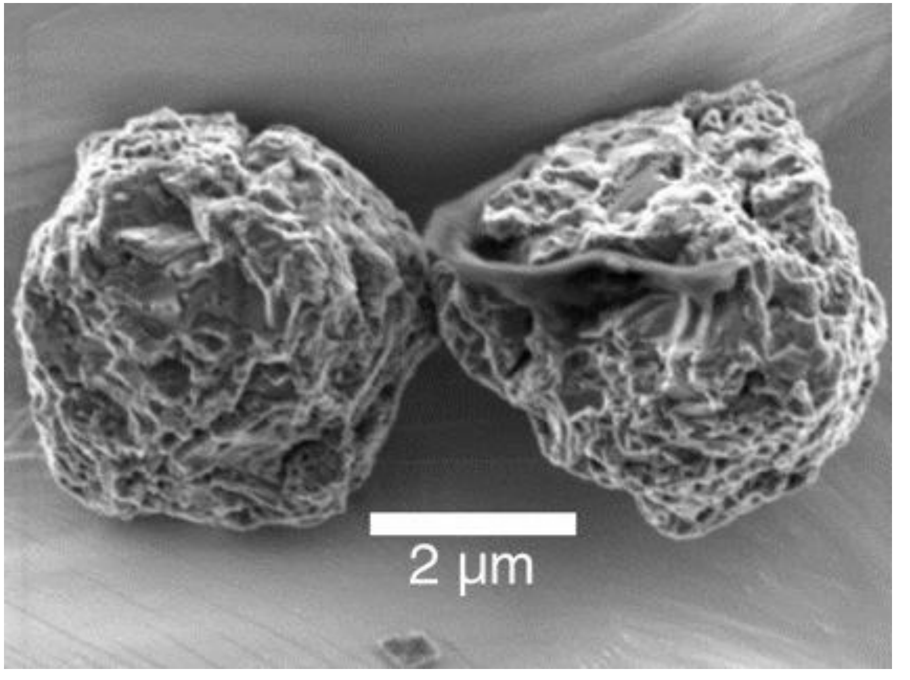


C. Iliadis, A. Champagne, J José *et al.,* Astrophys. J. Suppl. Ser. **142,** 105 (2002)

Presolar grains

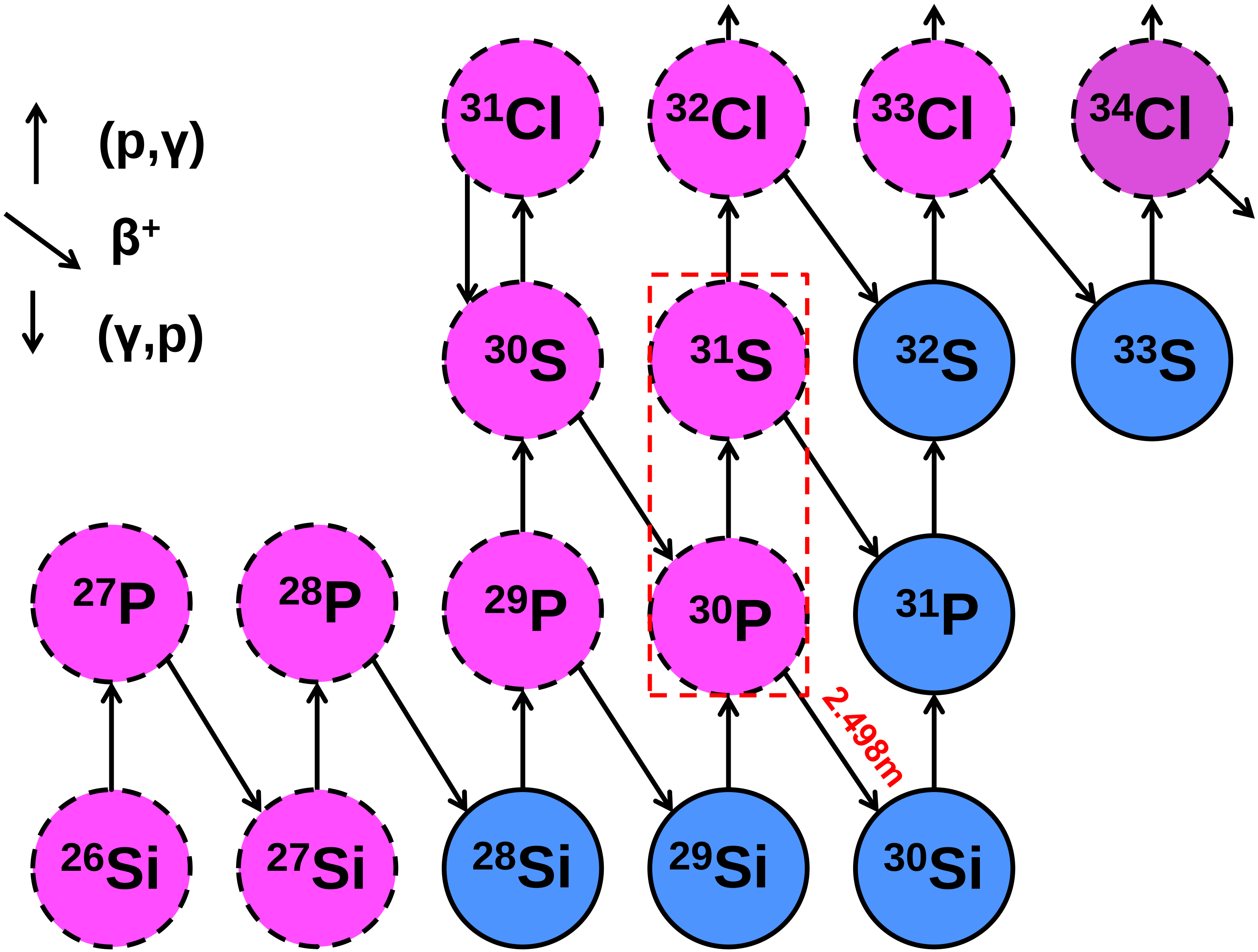
- **Grains of nova origin are thought to have a large $^{30}Si/^{28}Si$ ratio.**

- **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

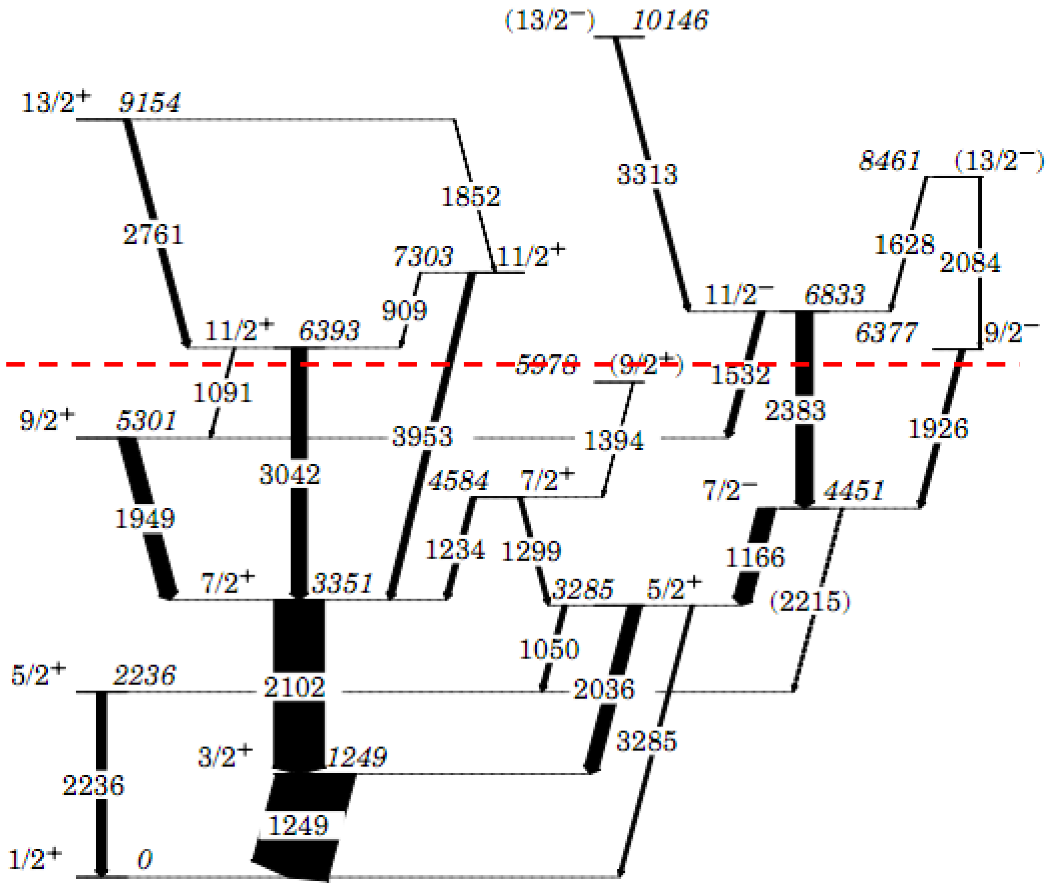
Novae Nucleosynthesis



Known ^{31}S level scheme

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

^{31}S proton threshold

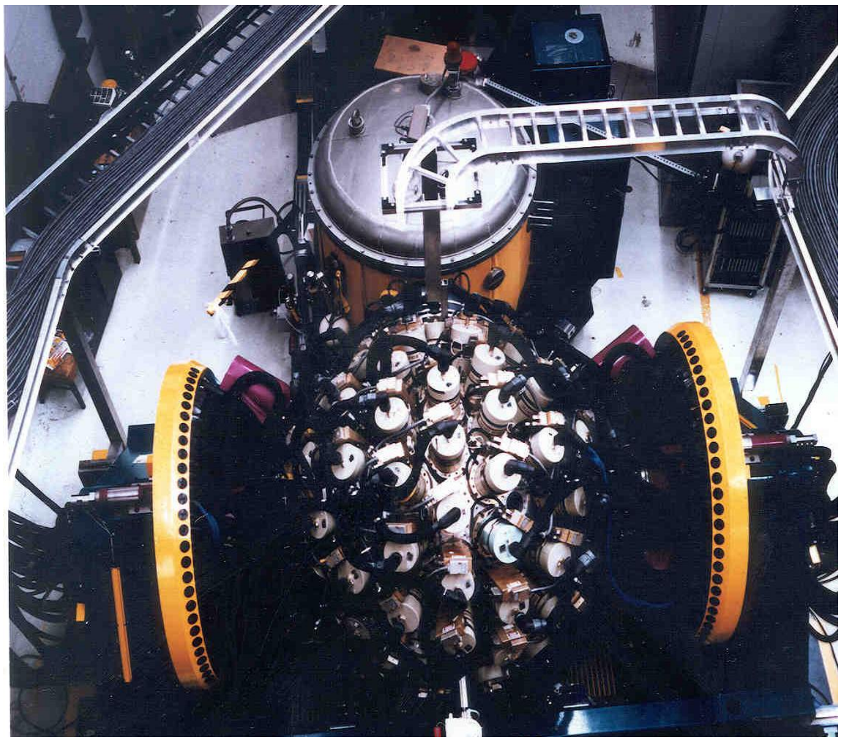


D.G. Jenkins et al, Phys. Rev. C. **72.** (2005)

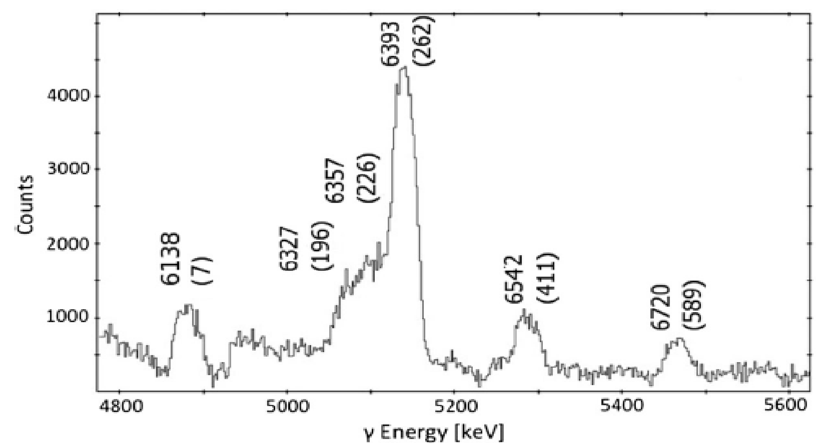
PRL **108,** 262502 (2012) PHYSICAL REVIEW LETTERS week ending 29 JUNE 2012

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

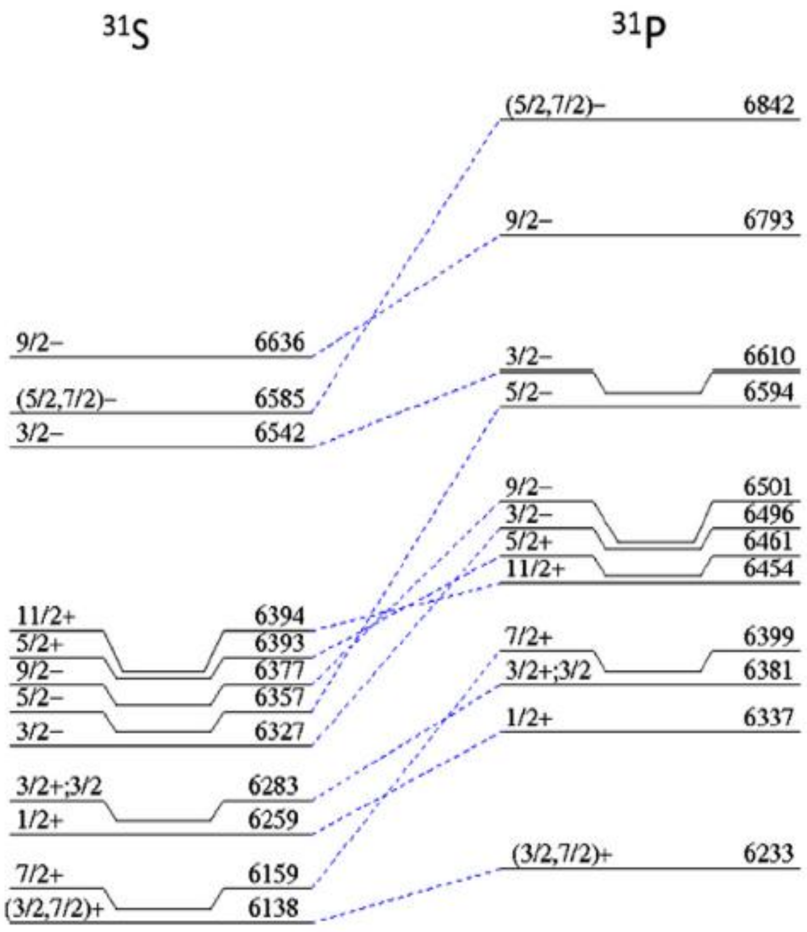
D. T. Doherty,[1] G. Lotay,[1] P. J. Woods,[1] D. Seweryniak,[2] M. P. Carpenter,[2] C. J. Chiara,[2,3] H. M. David,[1] R. V. F. Janssens,[2] L. Trache,[4] and S. Zhu[2]



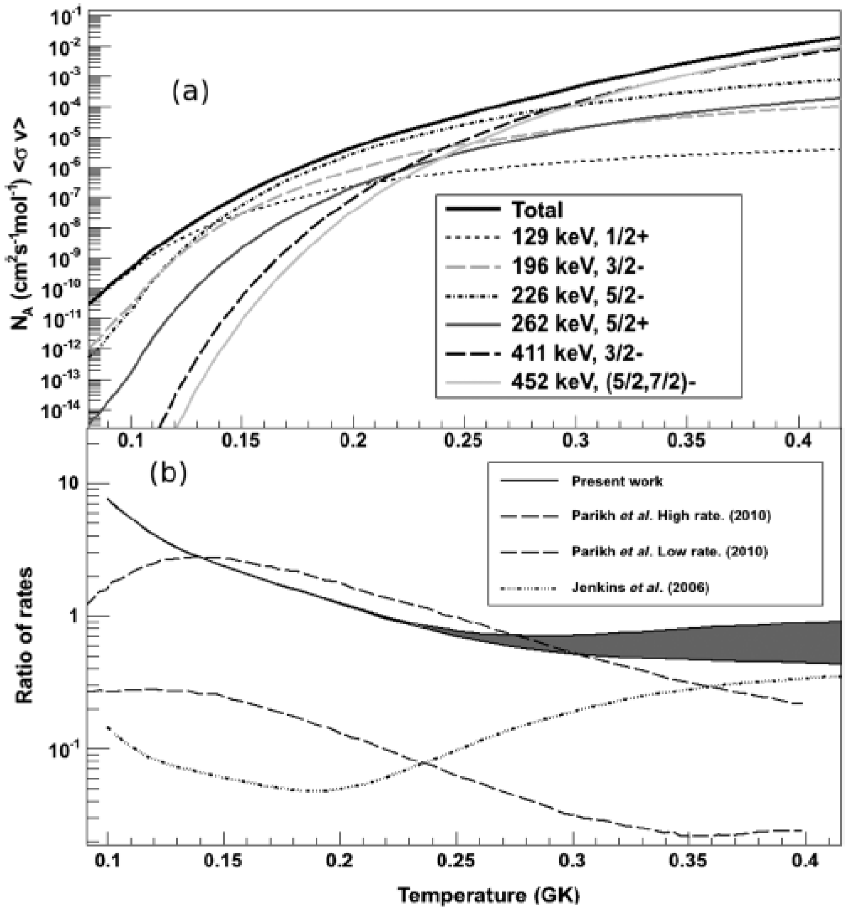
$^{4}He + ^{28}Si \rightarrow ^{31}S + n$ fusion reaction



Identification of levels in Mirror Nuclei

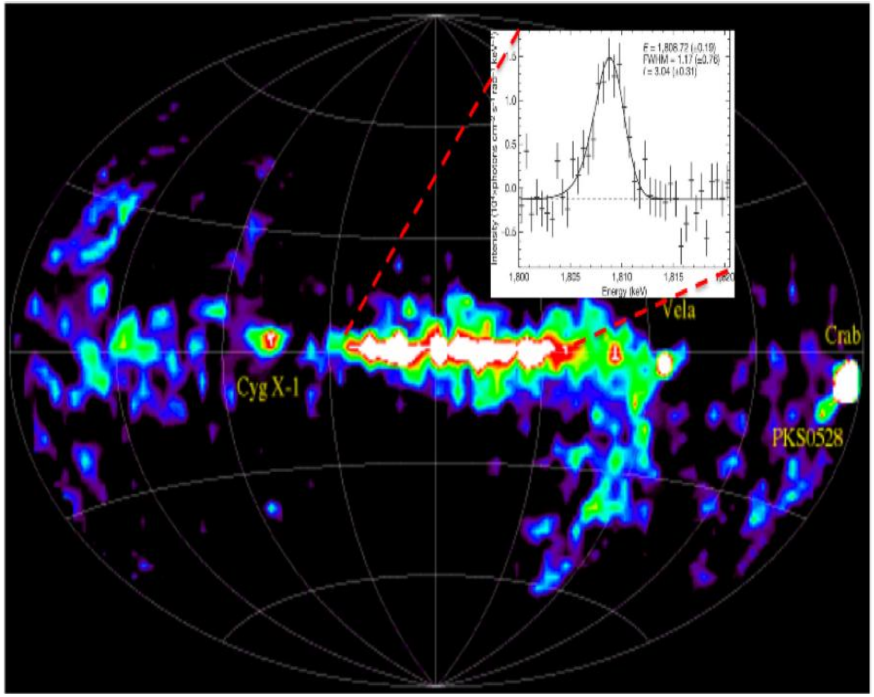


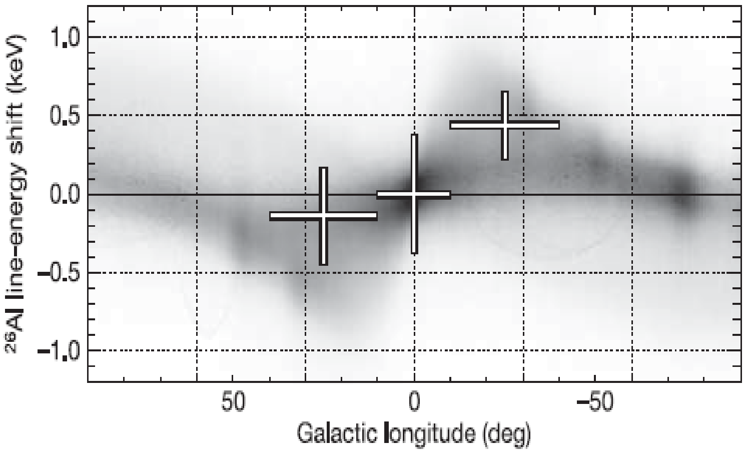
$^{30}P(p,\gamma)^{31}S$ reaction rate using new resonance data



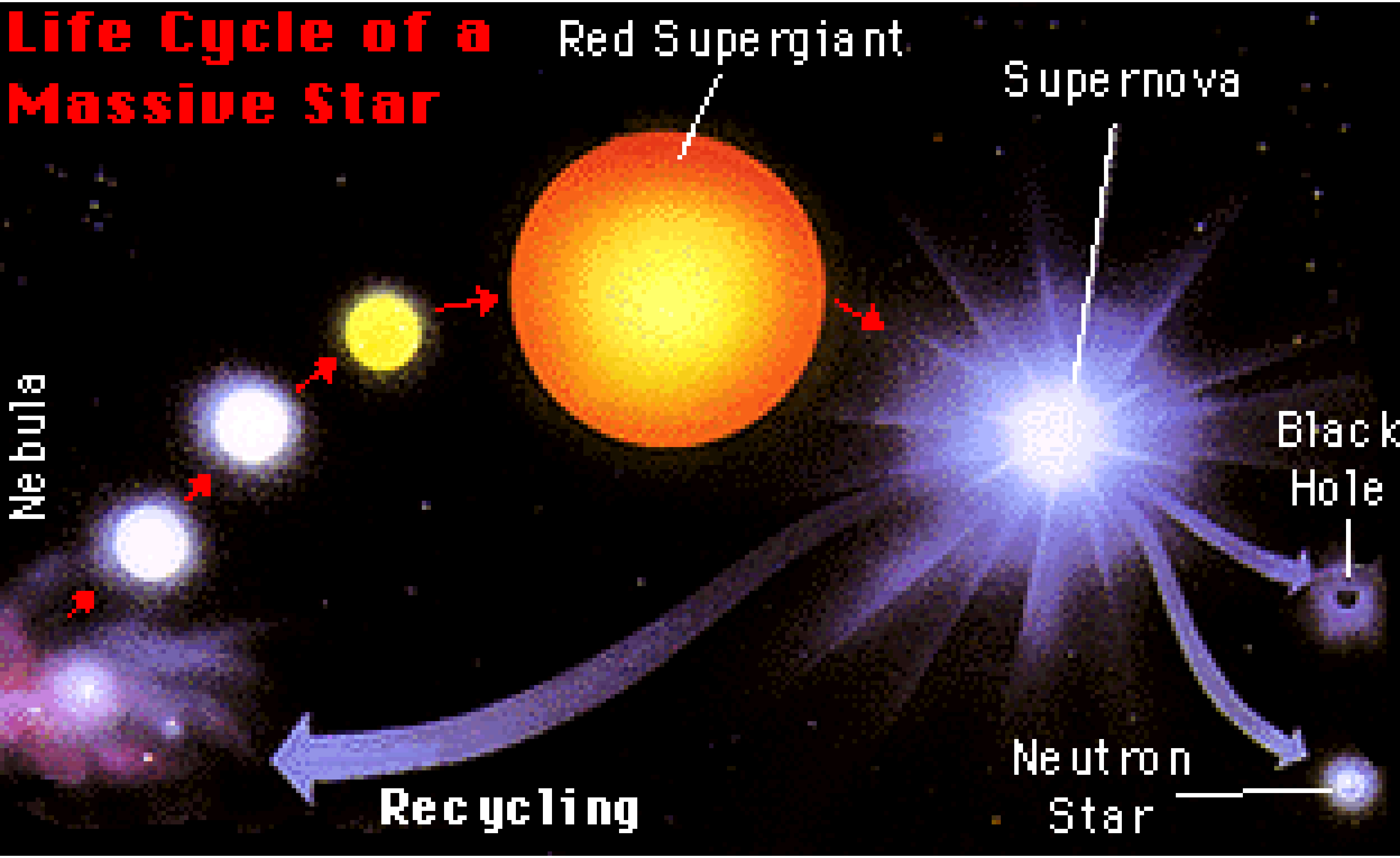
Galactic abundance distribution of the cosmic γ-ray emitter ^{26}Al

INTEGRAL Measured abundance 2.8(8) Solar Masses
[R. Diehl, *Nature* ***439***, *45(2006)*]

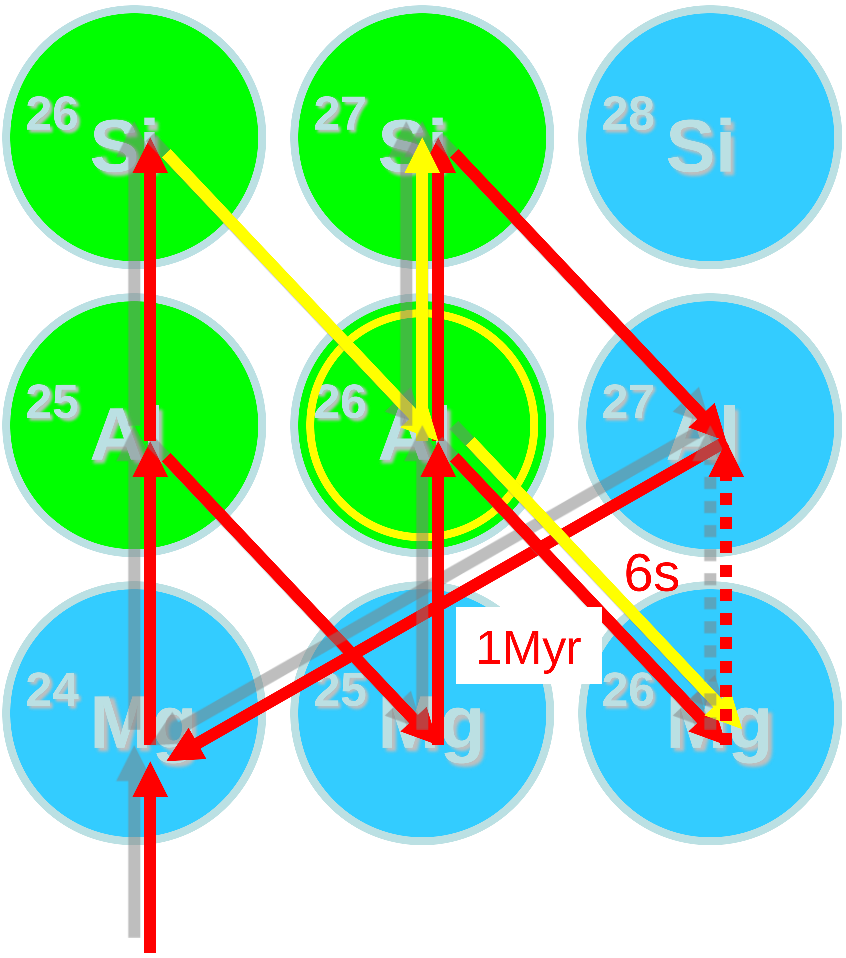


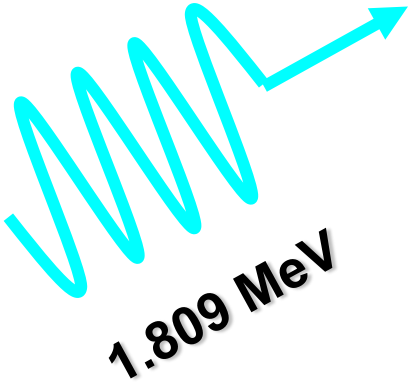


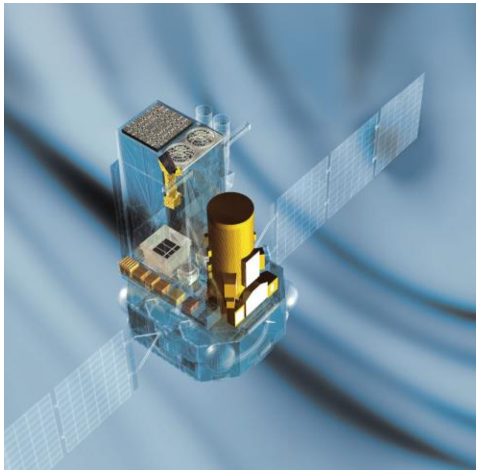
Supernova Cycle



Hydrogen burning in Mg – Al Cycle



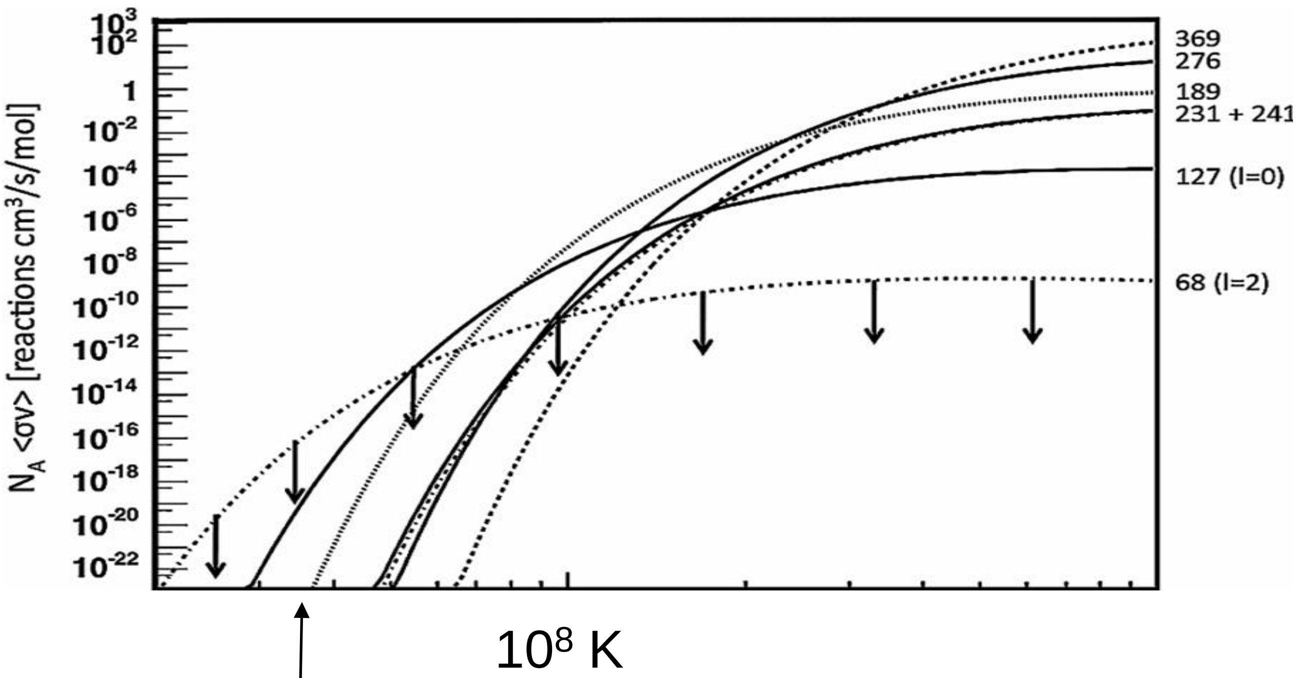




Identification of Key Astrophysical Resonances Relevant for the ^{26g}Al(p, γ)^{27}Si Reaction in Wolf-Rayet Stars, AGB stars, and Classical Novae

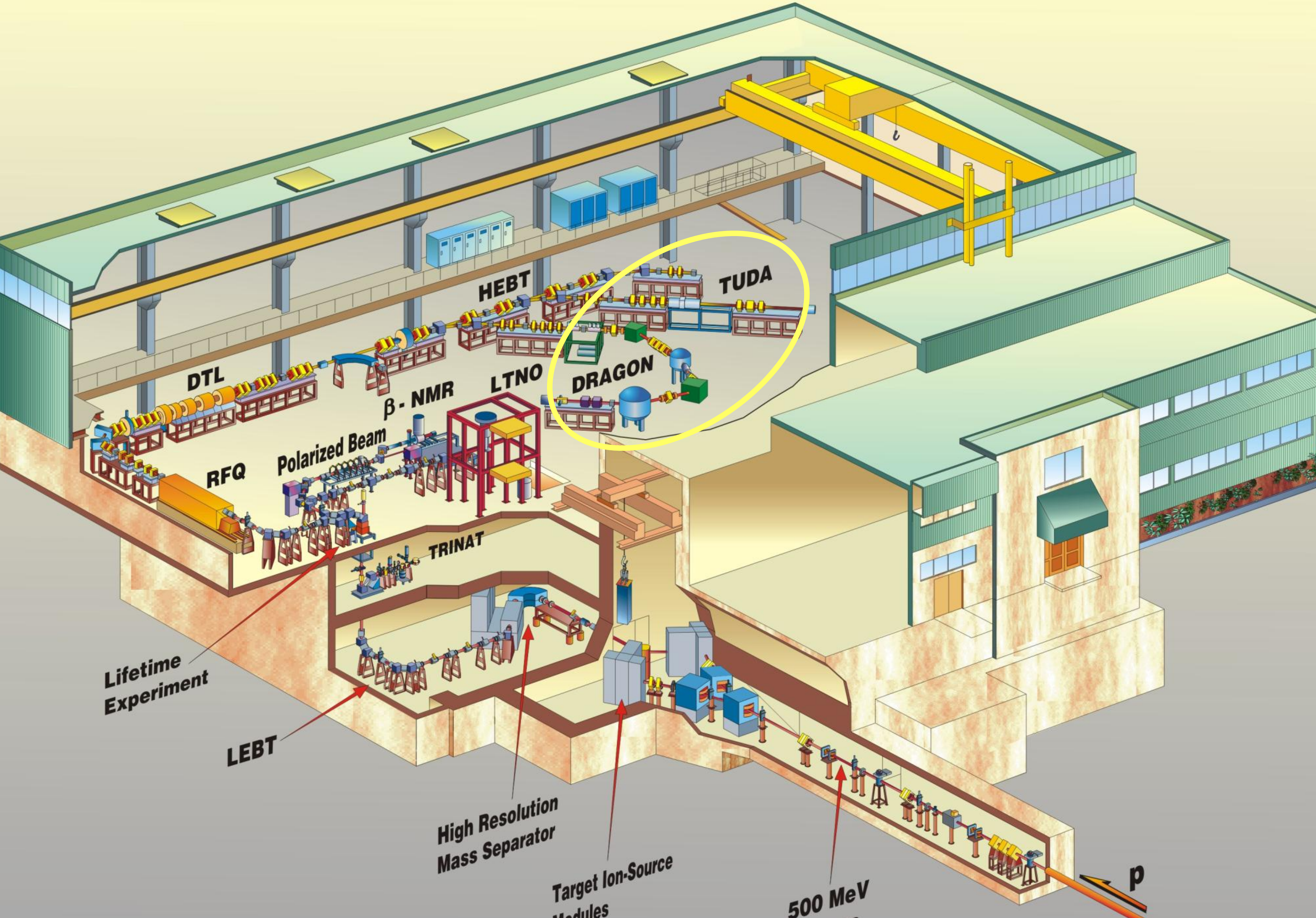
G. Lotay,[1] P. J. Woods,[1] D. Seweryniak,[2] M. P. Carpenter,[2] R. V. F. Janssens,[2] and S. Zhu[2]

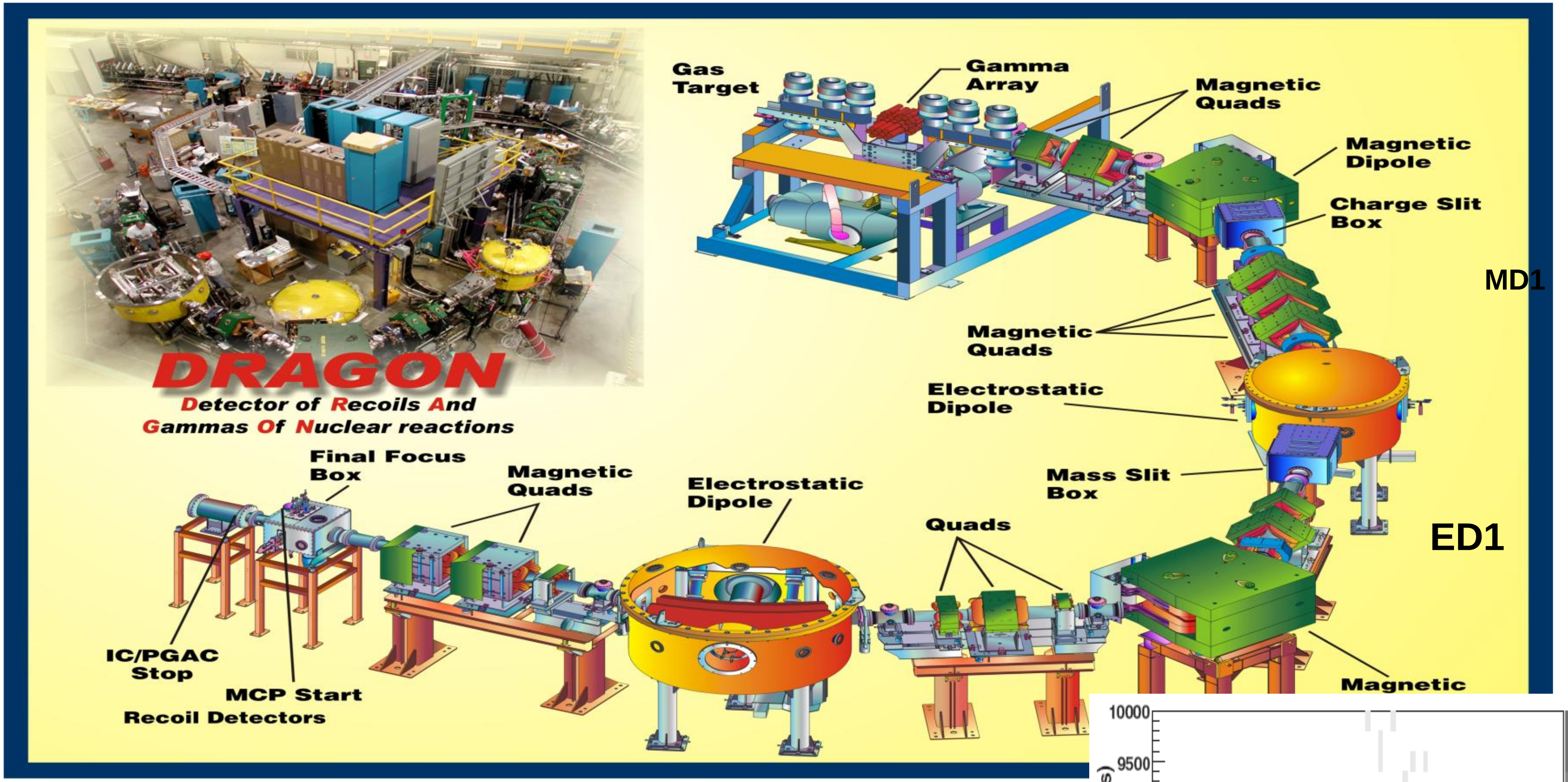
Estimated ^{26g}Al(p,γ)^{27}Si Reaction Rate



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

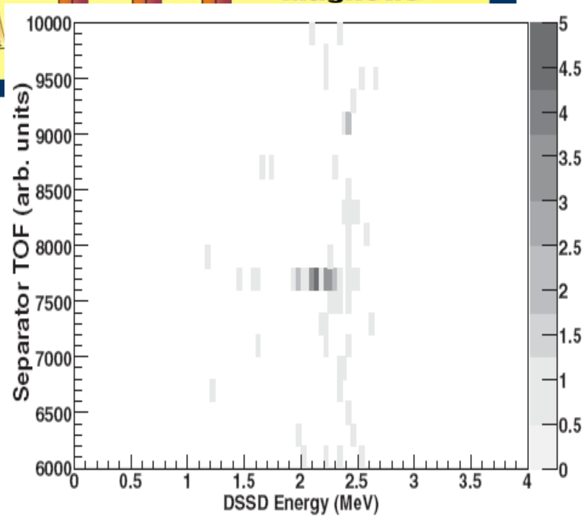
ISAC at TRIUMF





Direct measurement of ^{26g}Al(p,γ)^{27}Si reaction on 188 keV resonance, PRL 96 252501(2006)

→lower energy resonances may play dominant role for destruction of ^{26}Al burning in W-R stars



→ Problem is that most reactions on key low energy resonances cannot be measured directly

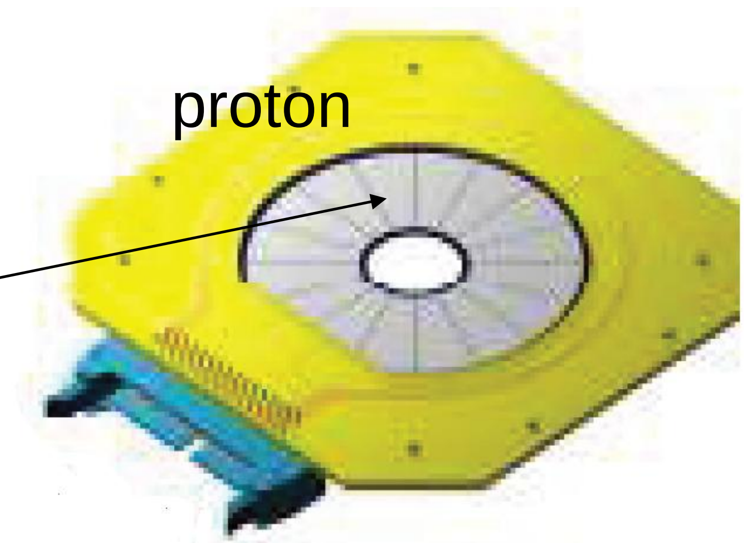
$$\omega\gamma = \frac{2J+1}{(2J_1+1)(2J_T+1)}\frac{\Gamma_1\Gamma_2}{\Gamma}$$

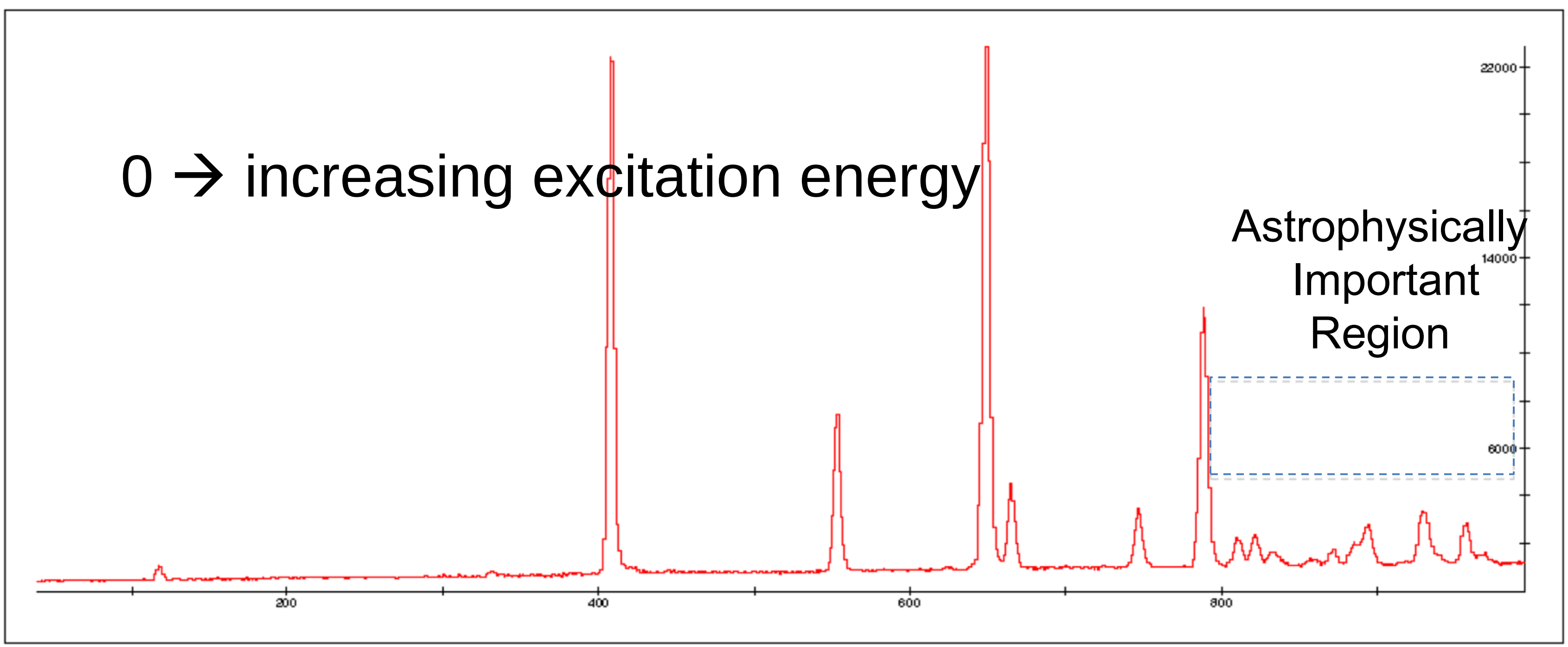
→ Use transfer reactions to determine Γ_p for (p,γ) reactions

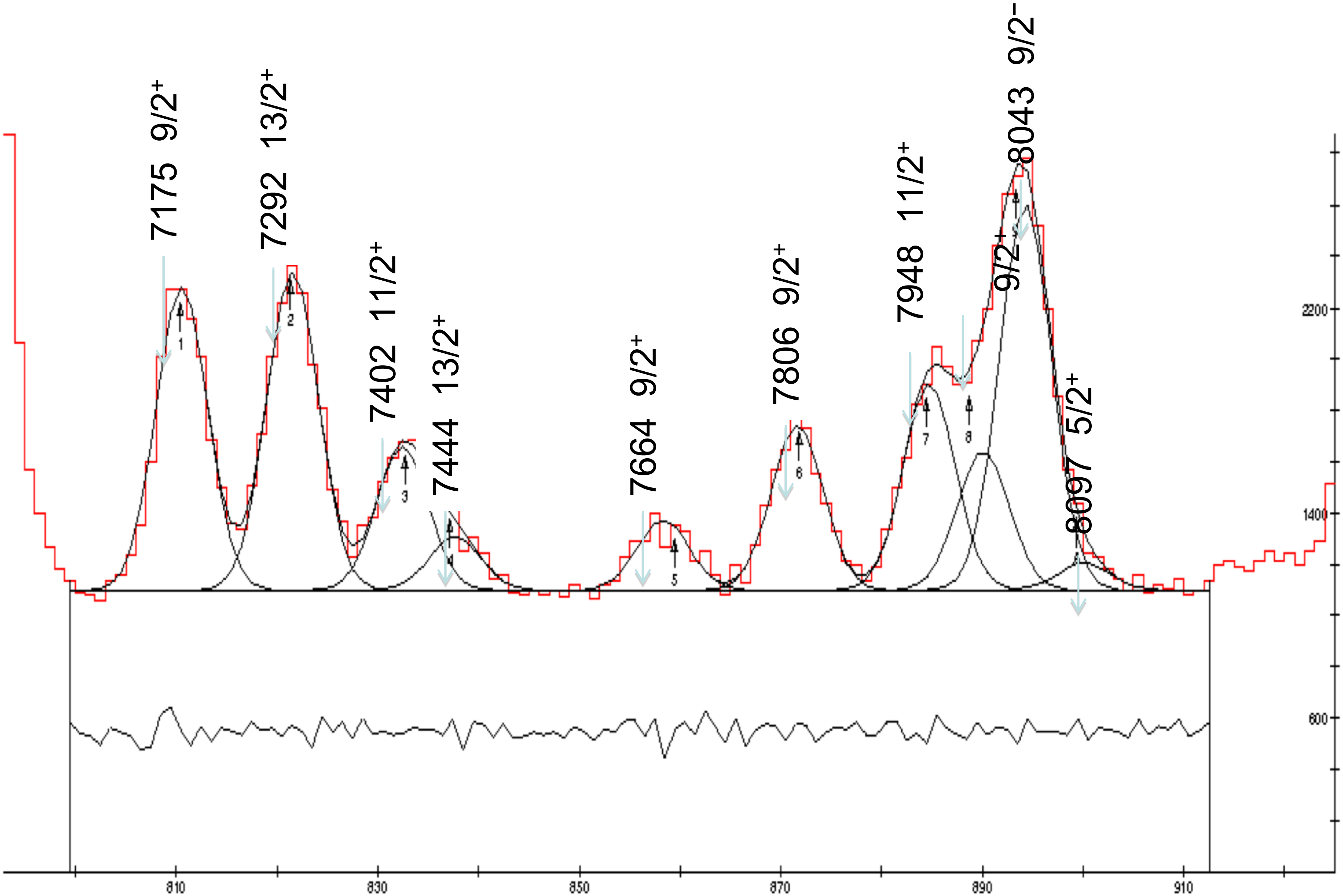
→ New high resolution study performed of the d(^{26g}Al,p)^{27}Al analogue reaction using the Edinburgh group's TUDA silicon strip detector array on the ISAC II facility at Triumf (June 2012)

NB exotic reaction since ^{26g}Al has $J^\pi = 5^+$!

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



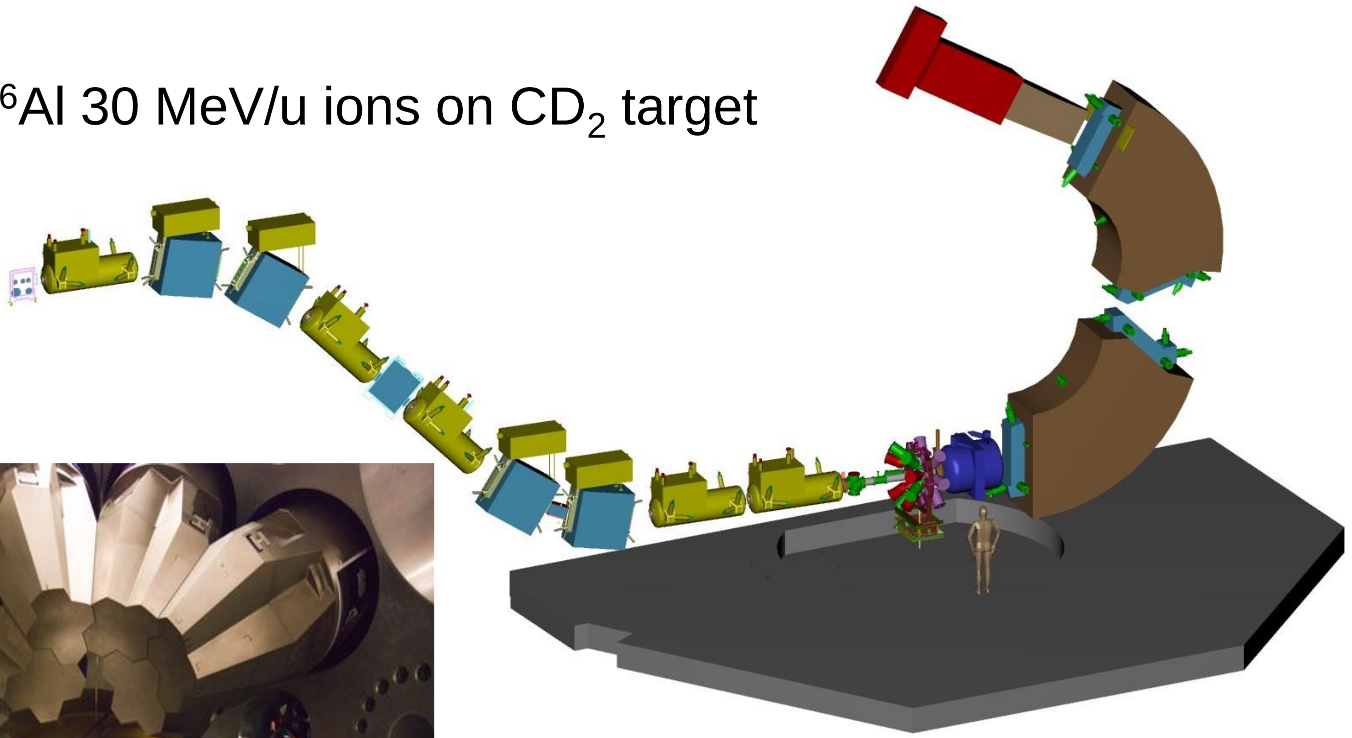


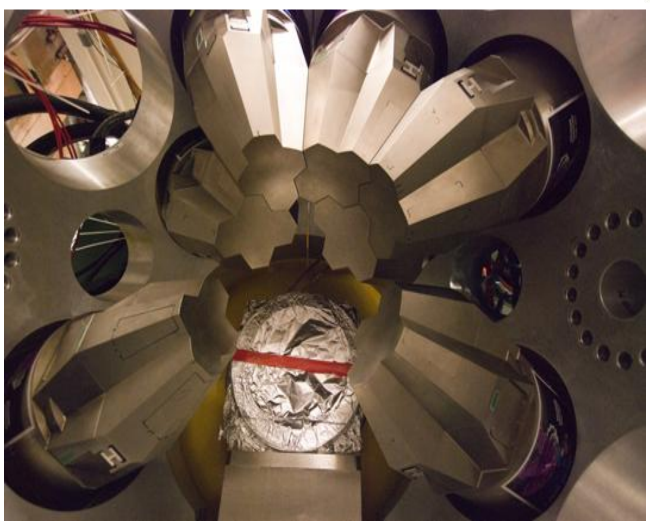


7175 9/2+
7292 13/2+
7402 11/2+
7444 13/2+
7664 9/2+
7806 9/2+
7948 11/2+
8043 9/2−
9/2+
8097 5/2+
2200
1400
600
810
830
850
870
890
910

New technique for (d,n) studies of (p,γ) resonance strengths with GRETINA gamma-array and S800 spectrometer
PJW, H Schatz et al, NSCL, April 2013

~10^{6} ^{26}Al 30 MeV/u ions on CD_2 target





Measure $\sigma(d,n)_{int} \rightarrow \Gamma_p$ for each key resonance

Conclusion

We are in a very exciting era coupling the properties and reactions of exotic nuclei with explosive nuclear astrophysics

Need a variety of facilities, and new techniques and equipment, to address the most interesting scientific issues