Experimental Nuclear Astrophysics: Lecture 3

Chris Wrede

National Nuclear Physics Summer School

June 20th, 2018

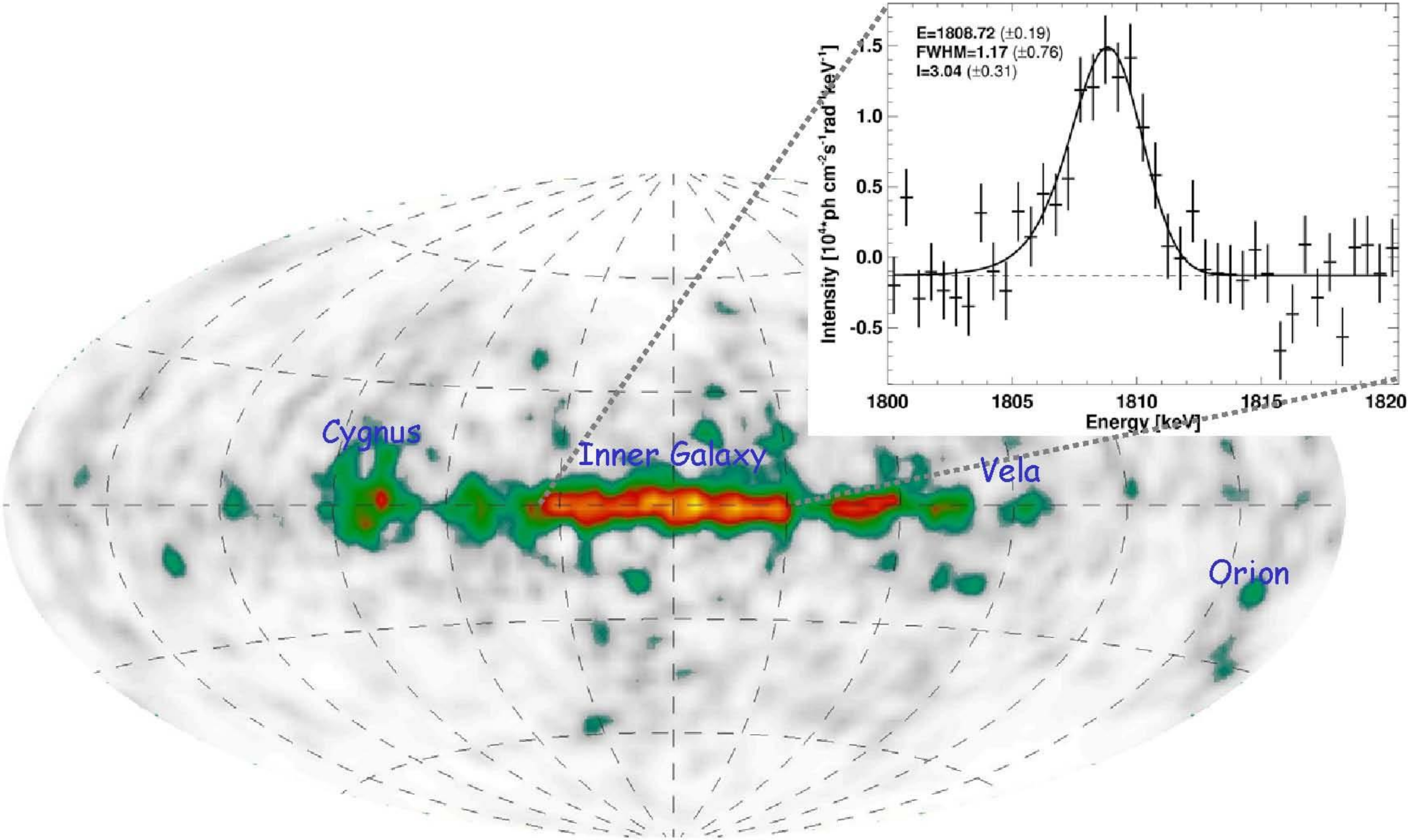
Outline

- Lecture 1: Introduction & charged-particle reactions
- Lecture 2: Neutron-induced reactions
- **Lecture 3: What I do (indirect methods)**

Today

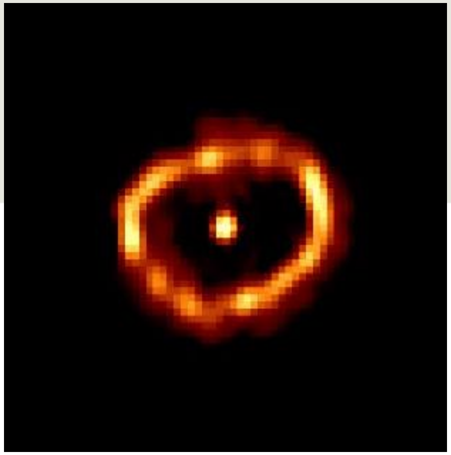
- Nova contribution to Galactic ^{26}Al?
- β decay of ^{26}P to probe ^{25}Al(p,γ)^{26}Si
- Are pre-solar “nova” grains from novae?
- β decay of ^{31}Cl to probe ^{30}P(p,γ)^{31}S
- Conditions for CNO-cycle breakout in X-ray bursts?
- β decay of ^{20}Mg to probe ^{15}O(α,γ)^{19}Ne

Radioactive ^{26}Al across Milky Way

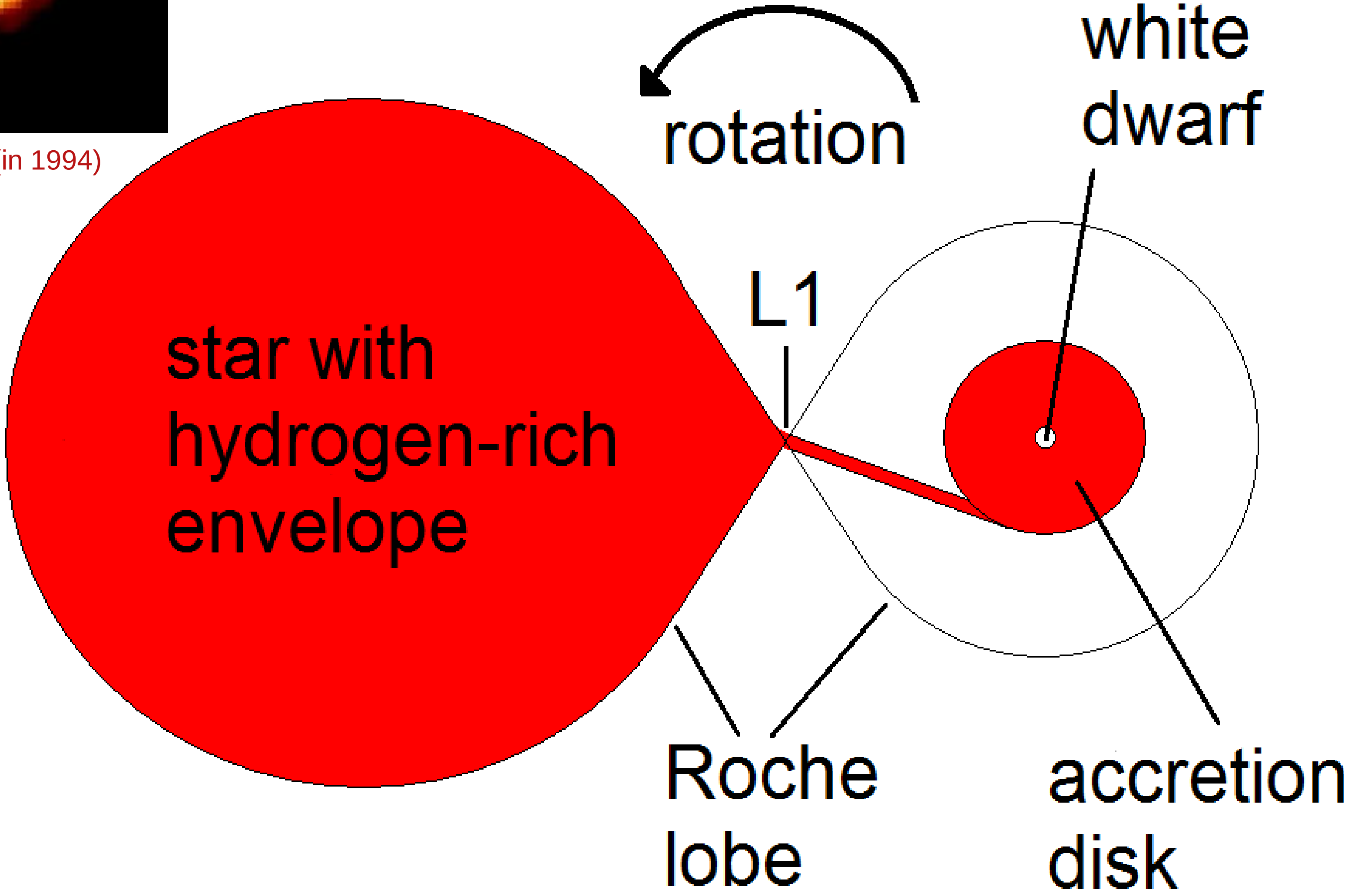


Data from COMPTEL & INTEGRAL-SPI
Figure courtesy of MPE Garching / Roland Diehl

Classical novae

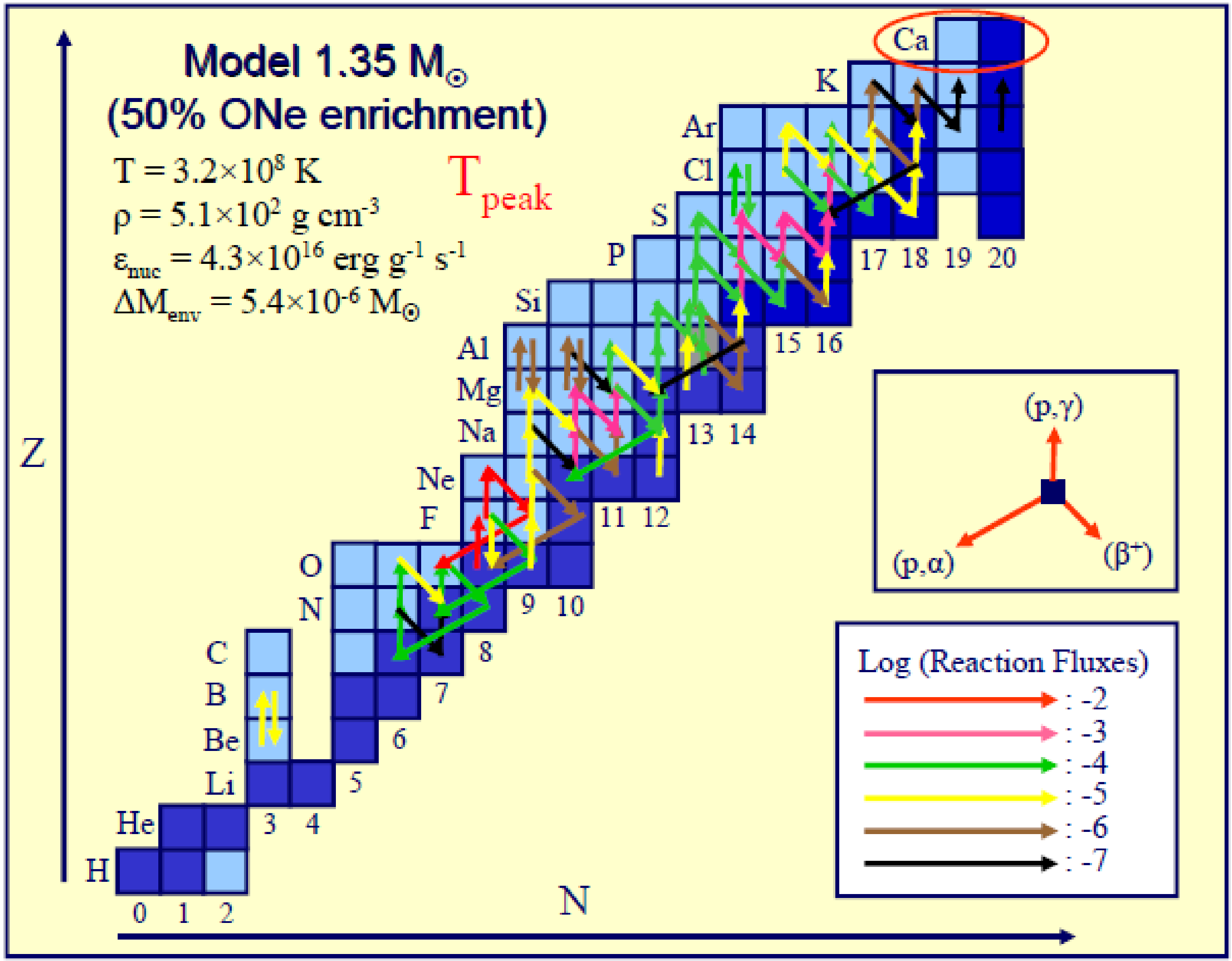


Nova Cygni 1992 (in 1994)
NASA, ESA, HST



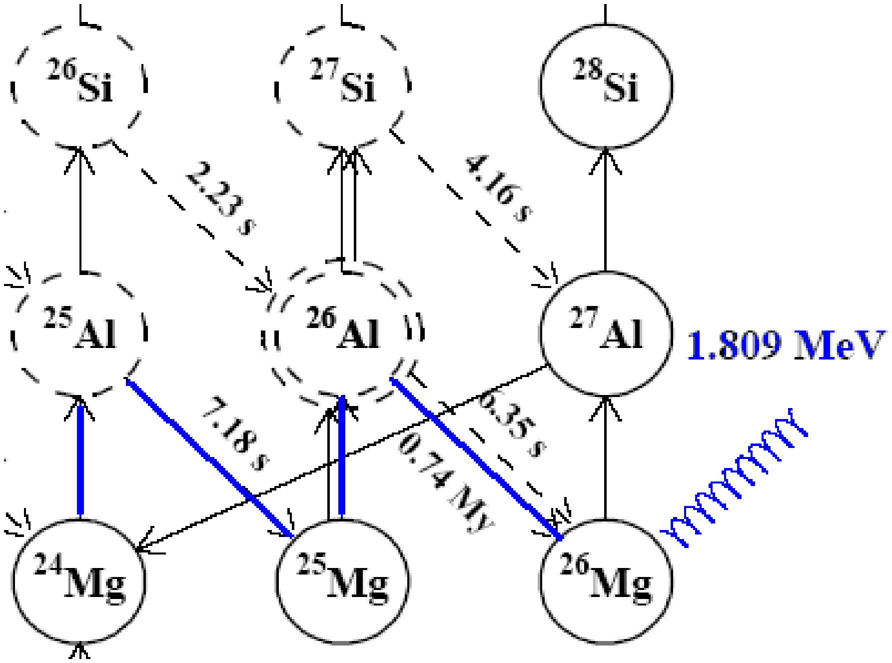
S. Starrfield *et al.*, (1971, 1972)
J. Jose *et al.*, Nucl. Phys **A777**, 550 (2006)

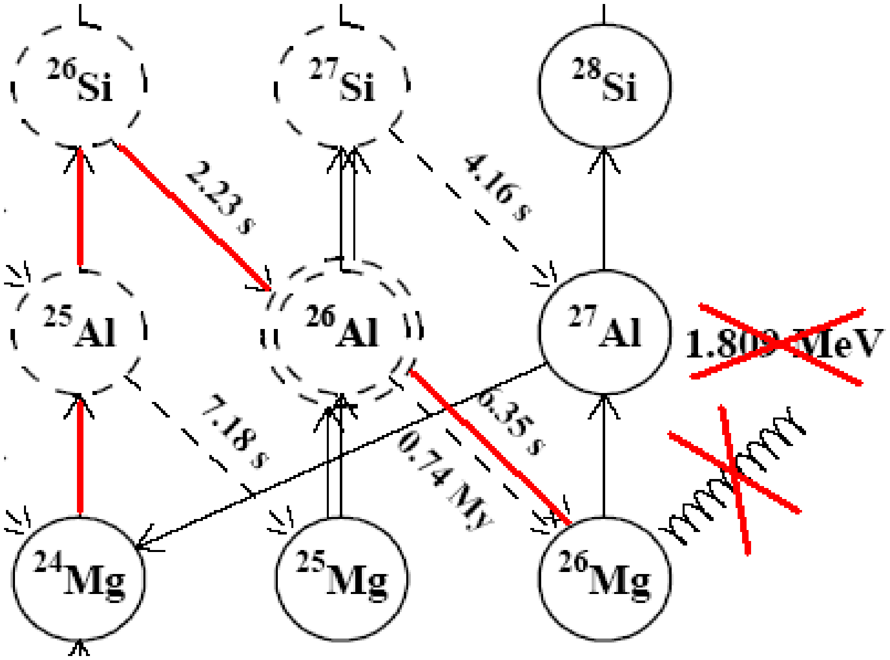
Nucleosynthesis in novae



J. Jose, Proceedings of Science, NIC XI 050 (2011)

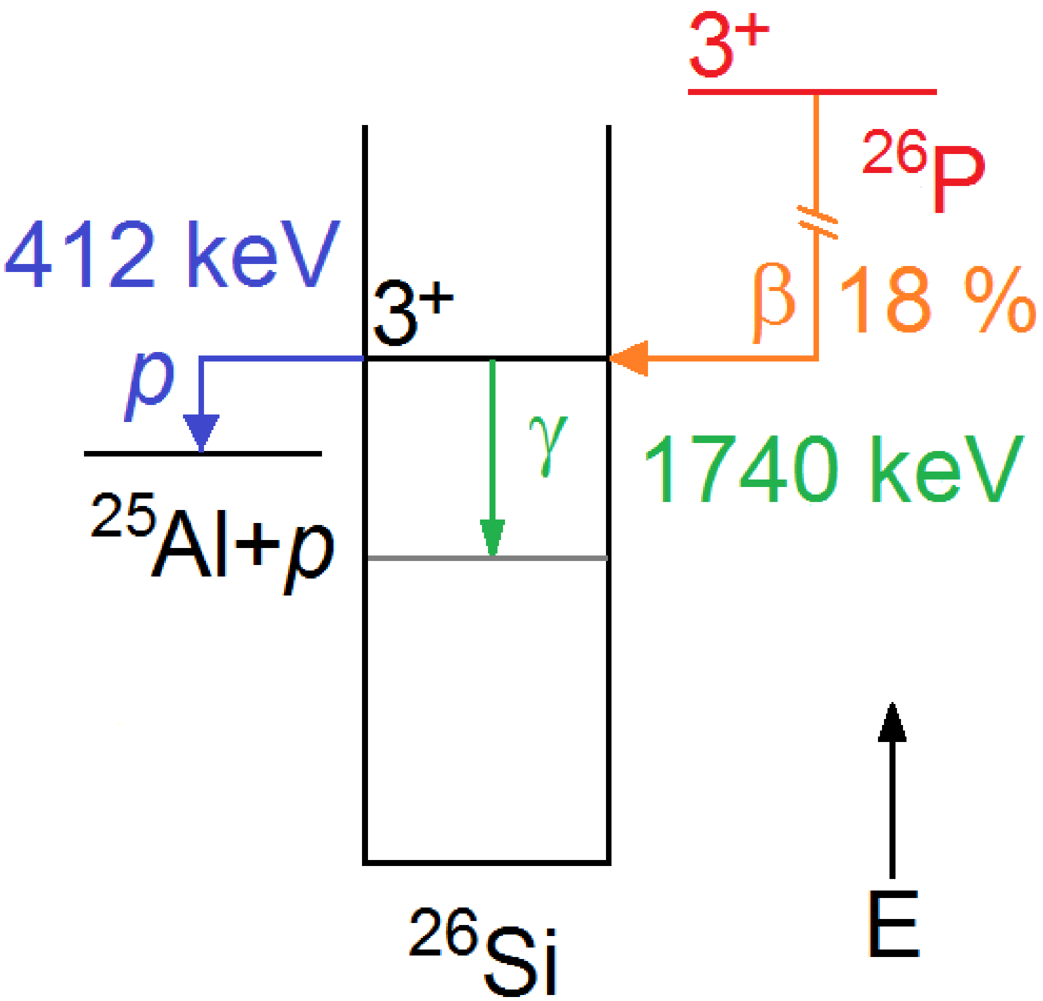
^{25}Al(p,γ)^{26}Si reaction in novae





Measuring key 3^+ ^{25}Al(p,γ)^{26}Si resonance strength with ^{26}P decay

$$\omega\gamma = \frac{7}{12}\frac{\Gamma_p\Gamma_\gamma}{\Gamma_p+\Gamma_\gamma}$$



NSCL experiment E10034
M. B. Bennett *et al.*, Phys. Rev. Lett. **111**, 232503 (2013)

NSCL

National user facility for rare isotope science and education:
Nuclear structure, nuclear astrophysics, fundamental symmetries, societal applications

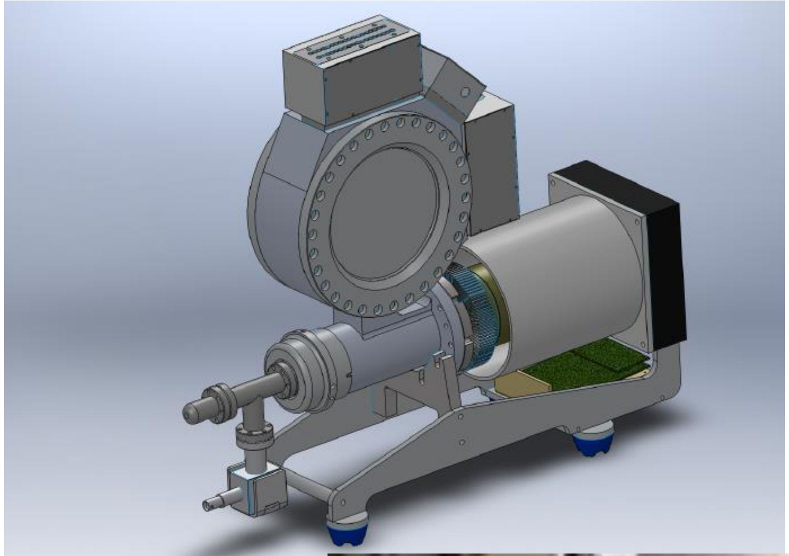
On Michigan State University campus

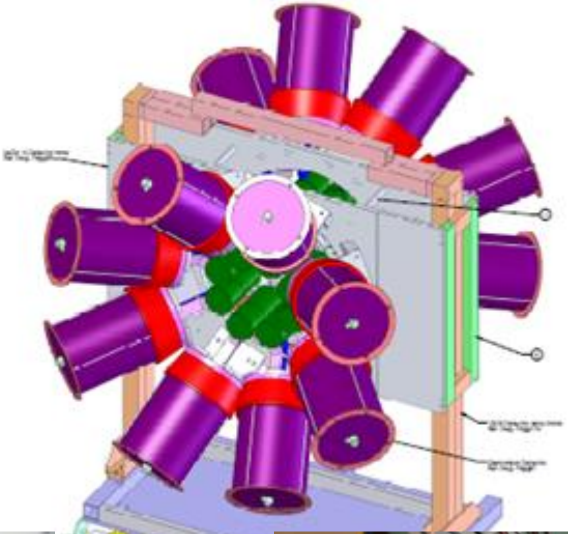
Production of ^{26}P at NSCL

- 150 MeV/u, 75 pnA ^{36}Ar beam, 1.55 mg/cm^2 Be target
- 75% pure beam of up to 100 ^{26}P ions per second at experiment

M. B. Bennett *et al.*, Phys. Rev. Lett. **111**, 232503 (2013)

Detectors



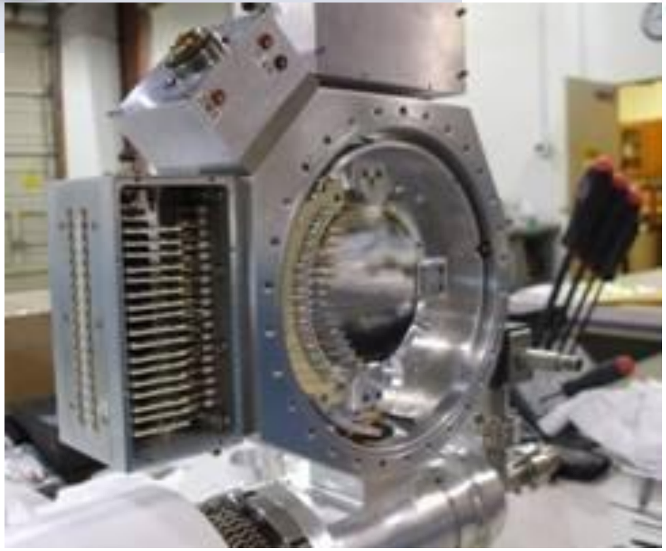


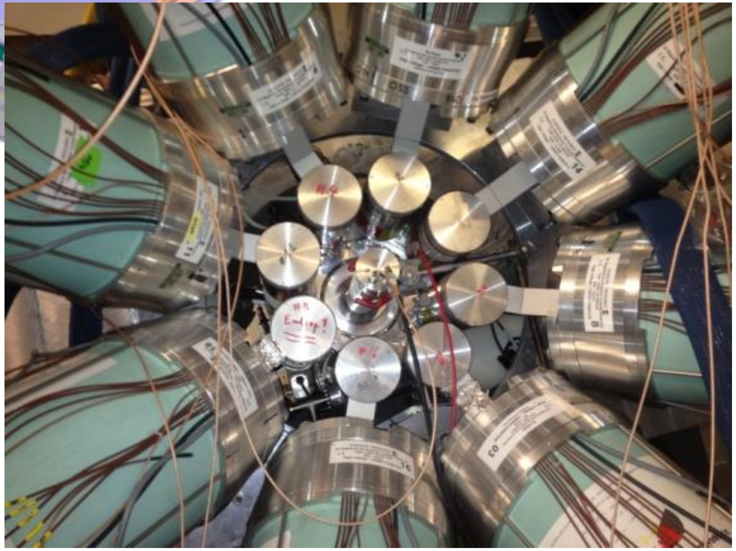
W. F. Mueller *et al.*, NIMA **466**, 492 (2001)

SeGA

GeDSSD

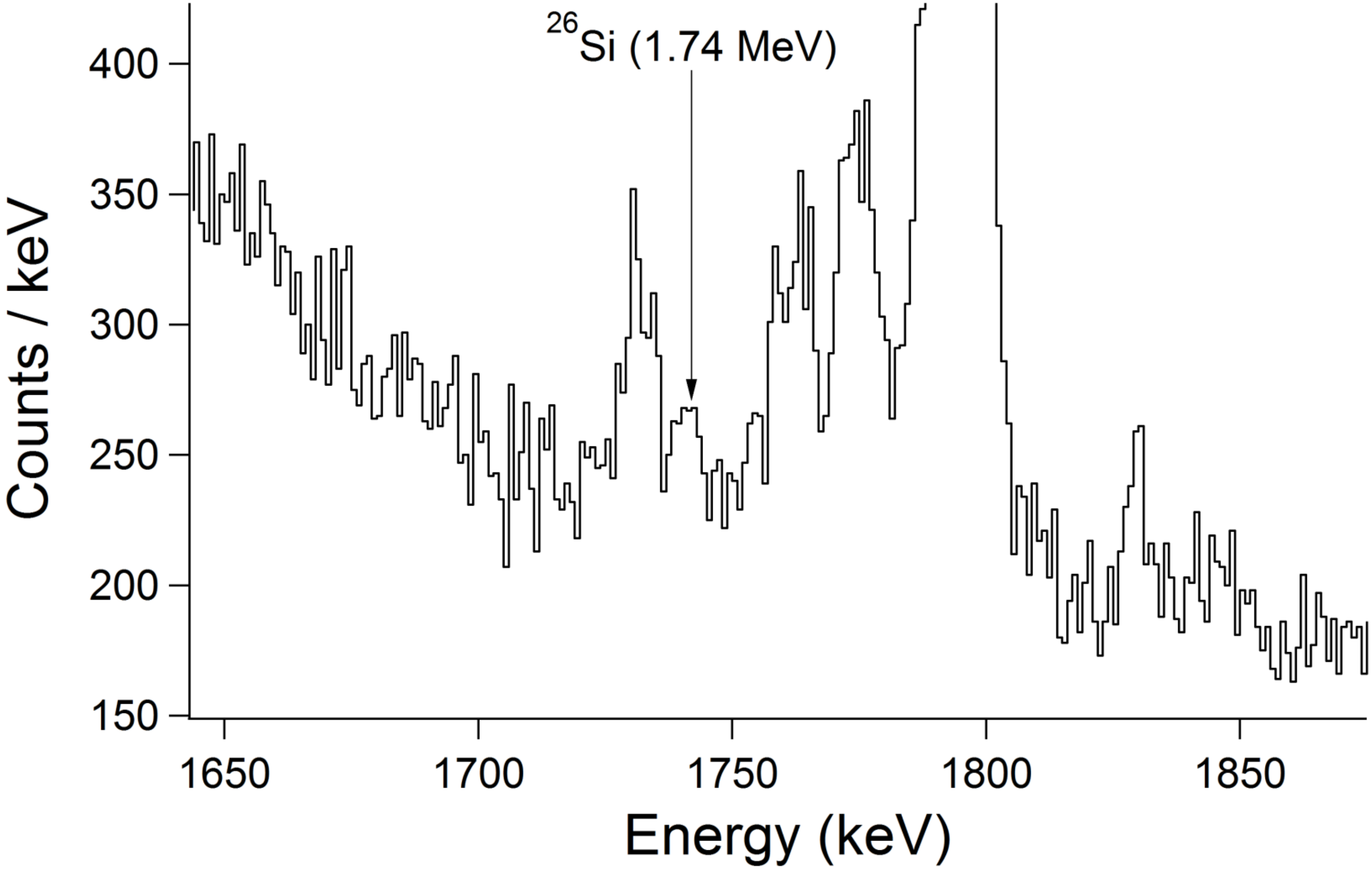
N. Larson, S. N. Liddick *et al.*, NIMA **727**, 59 (2013)





M. B. Bennett *et al.*, Phys. Rev. Lett. **111**, 232503 (2013)

$^{26}P(\beta^{+}\gamma)^{26}Si$ spectrum



M. B. Bennett *et al*., Phys. Rev. Lett. **111**, 232503 (2013)

Astrophysical Conclusions

Amount of ^{26}Al produced in novae on white dwarfs of different masses:

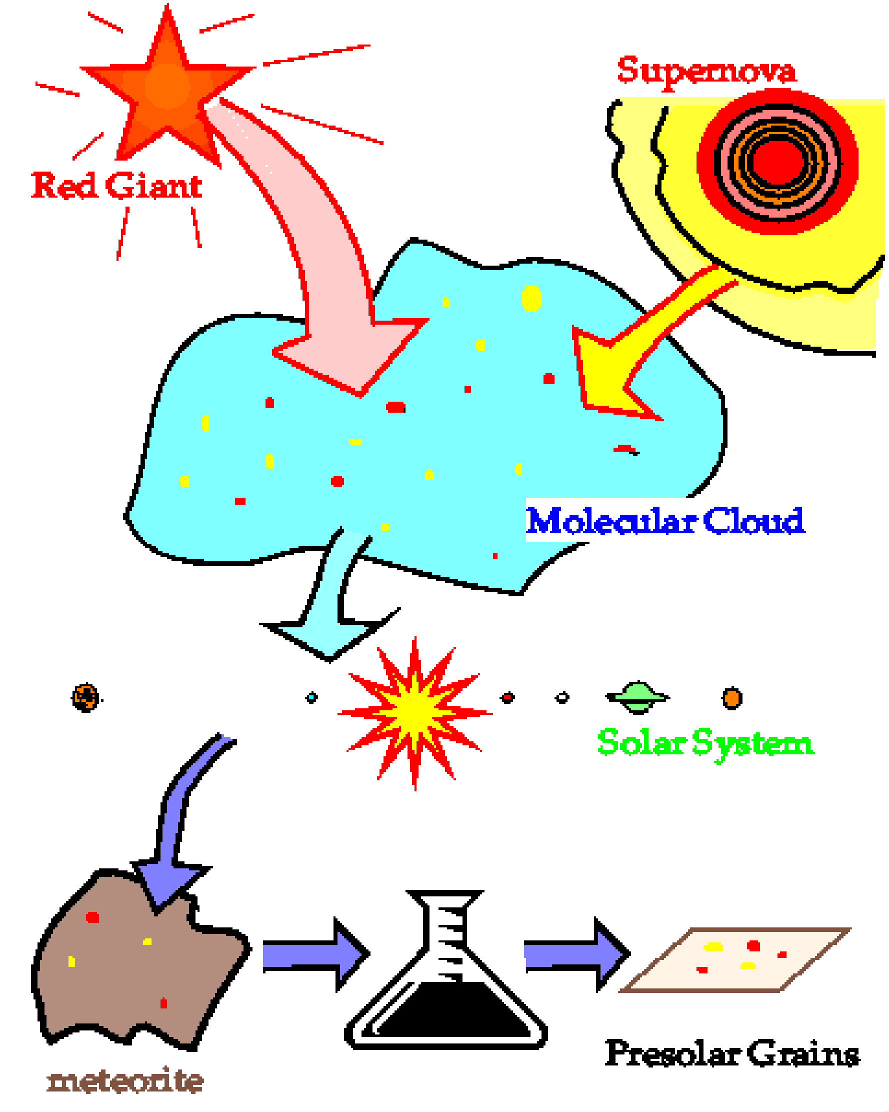
White-dwarf mass	$1.15M_\odot$	$1.25M_\odot$	$1.35M_\odot$
$M_{\rm tot}$ (10^{28} g)	4.9	3.8	0.90
$M(^{26}{\rm Al})/M_{\rm tot}$ (10^{-4})	$9.9^{+0.0(+0.0)}_{-0.1}$	$5.8^{+0.0(+0.0)}_{-0.1}$	$5.2^{+0.4(+4.8)}_{-0.3}$

Conclusion: novae produce *up to* 30% of the ^{26}Al in Milky Way

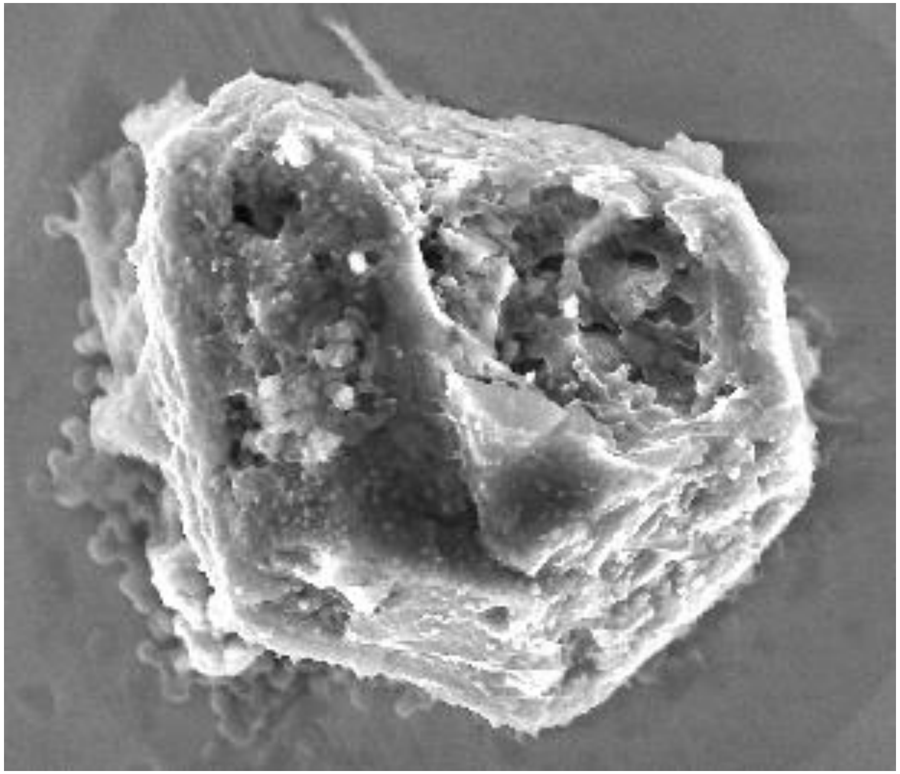
National Science Foundation
Michigan State University

M. B. Bennett *et al*., Phys. Rev. Lett. **111**, 232503 (2013)
Nucleosynthesis simulations by Jordi Jose (UPC Barcelona)

Pre-solar grains



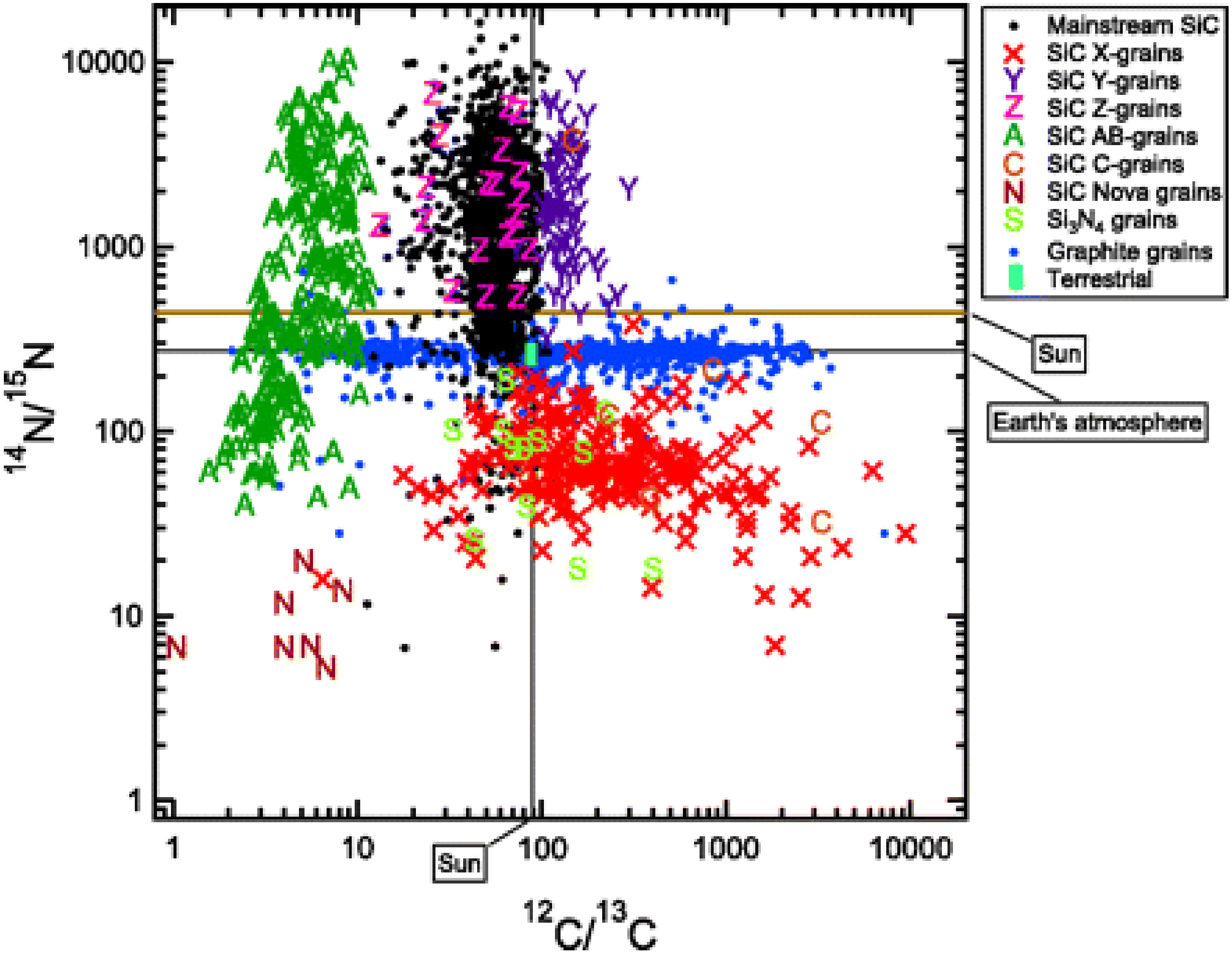
~1 micron



SiC Grain from Murchison meteorite

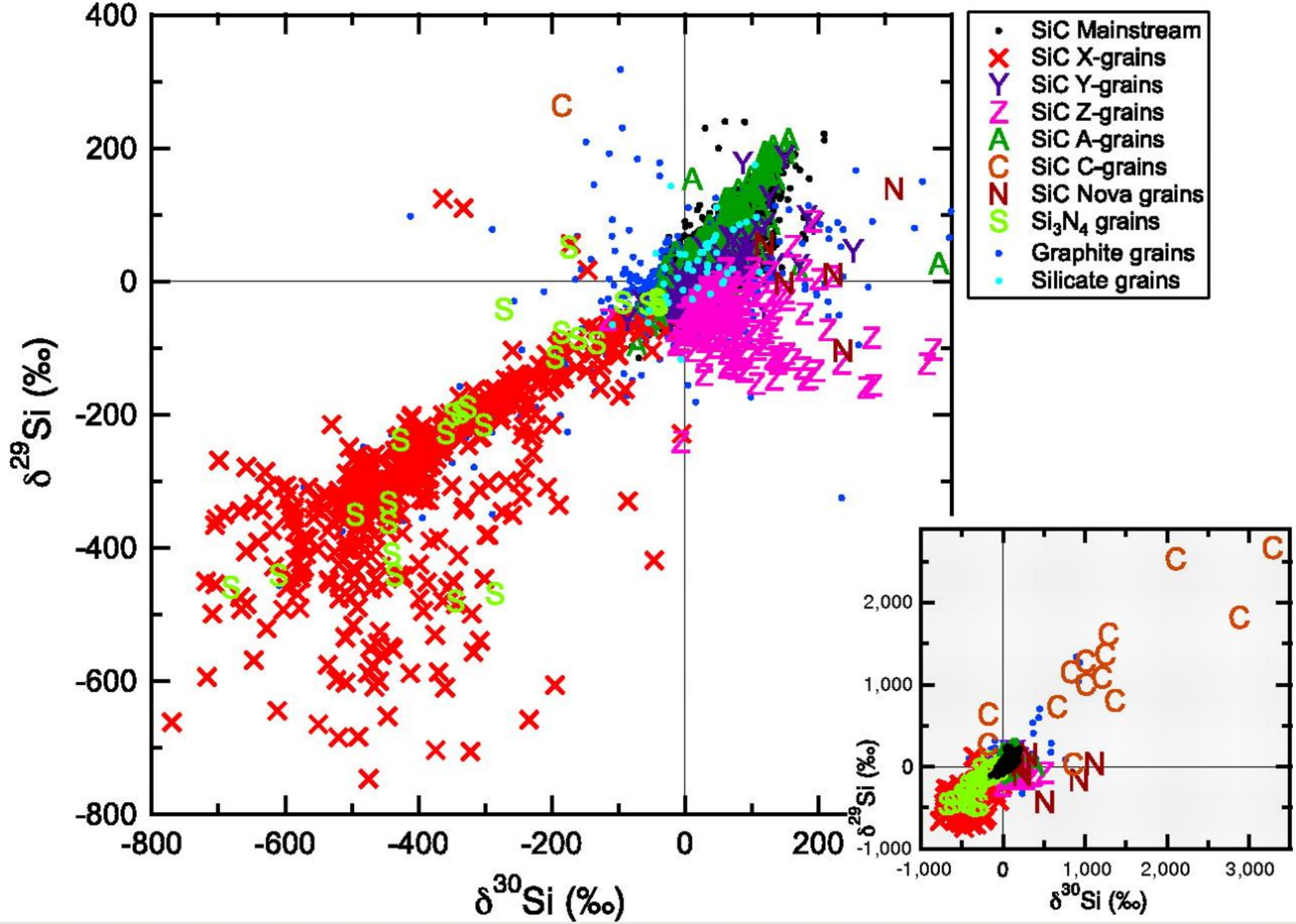
L. Nittler, www.presolargrains.net
www.dtm.ciw.edu/users/lrn/psg/types.html

Pre-solar nova grain candidates



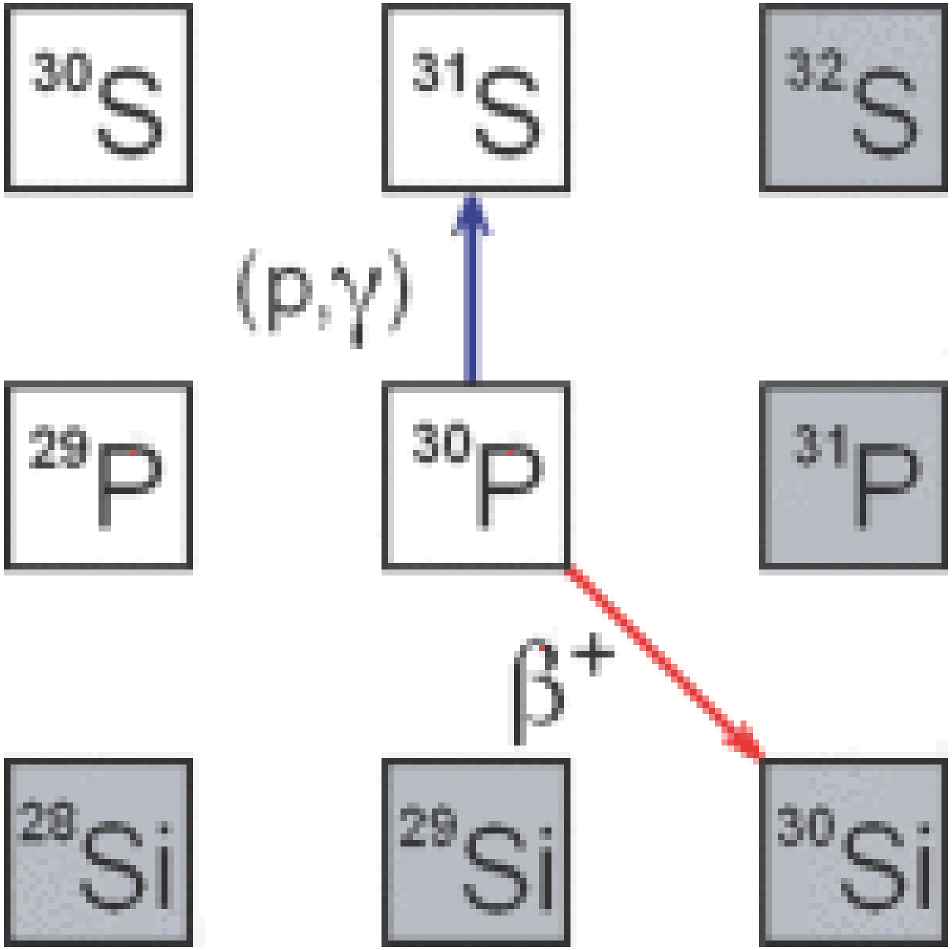
Andrew M. Davis, PNAS (2011)

Pre-solar nova grain candidates



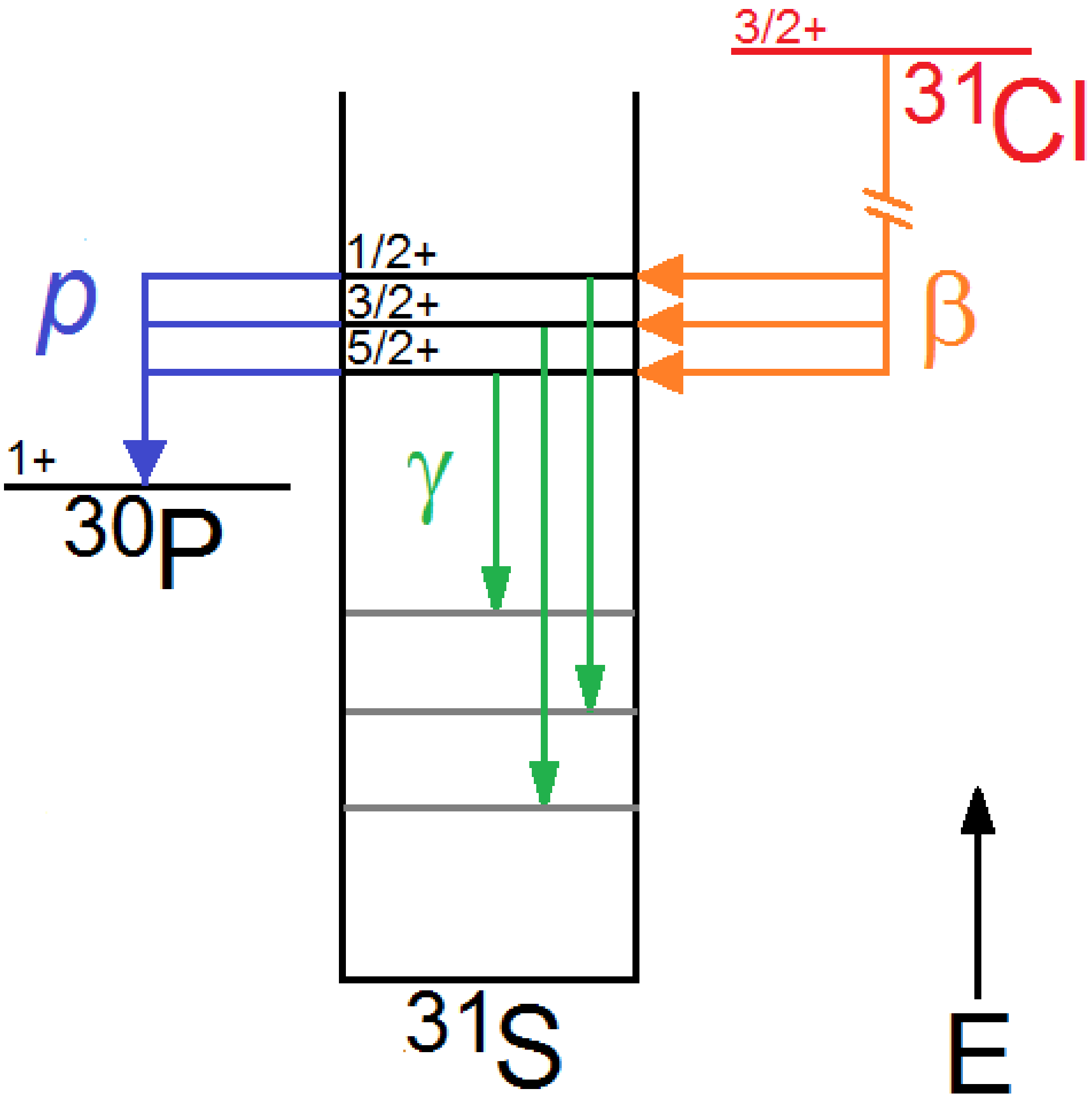
Andrew M. Davis, PNAS (2011)

What *should* a SiC nova grain look like?



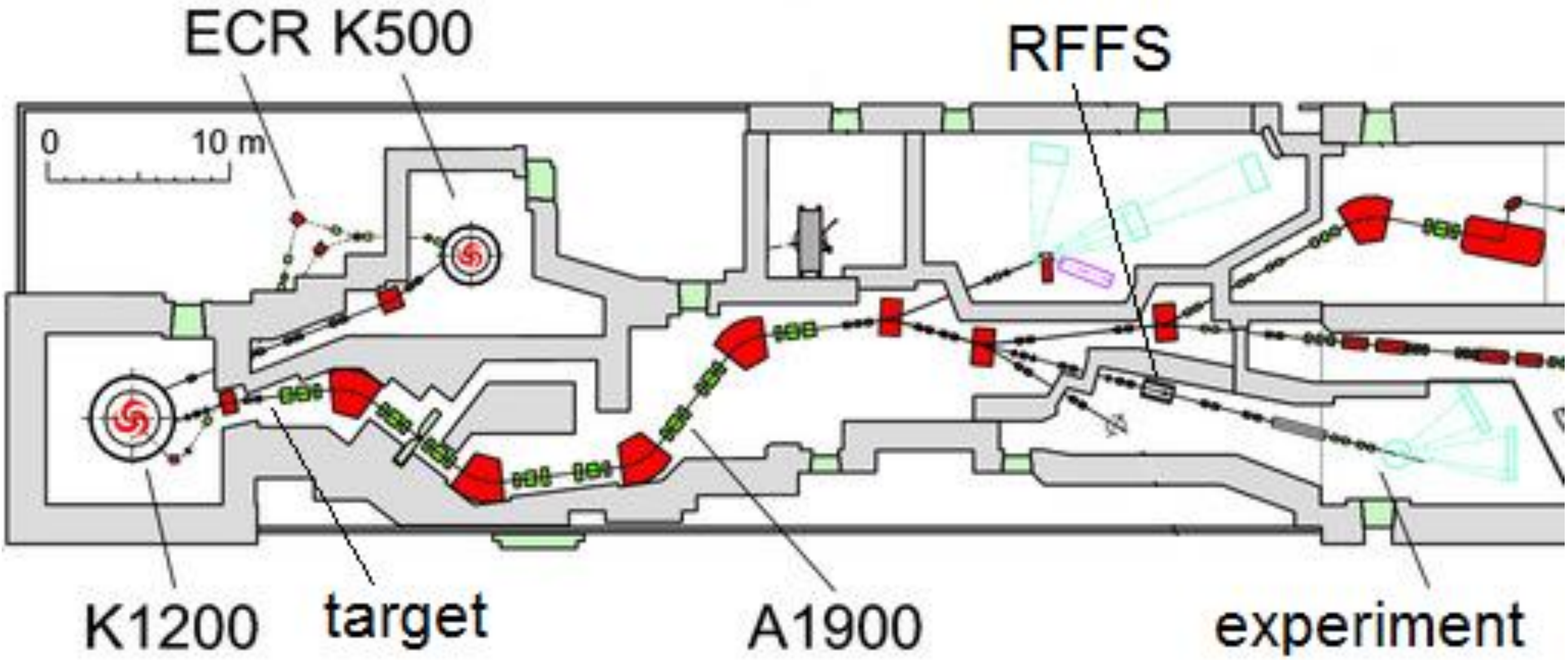
J. Jose *et al*. Astrophys. J. 612, 414 (2004)

Populating $^{30}P(p,\gamma)^{31}S$ resonances with ^{31}Cl decay



NSCL Experiment 12028
M. B. Bennett *et al.*, Phys. Rev. Lett. 116, 102502 (2016)
M. B. Bennett, Ph.D. thesis (MSU, 2016)

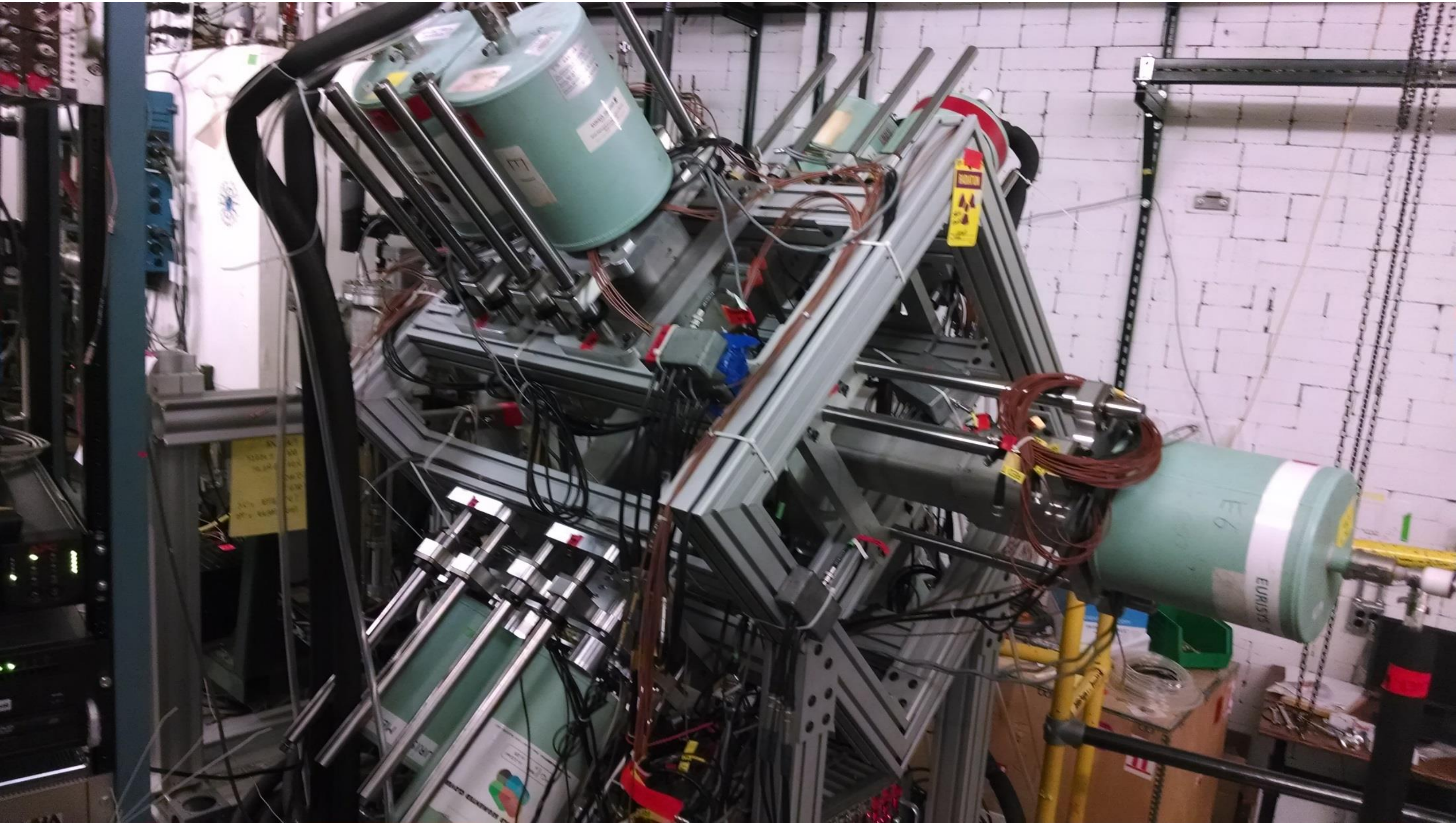
Production of ^{31}Cl at NSCL



- 150 MeV/u, 75 pnA ^{36}Ar beam, 1.63 mg/cm^2 Be target
- 95% pure beam of up to 9000 ^{31}Cl ions per second

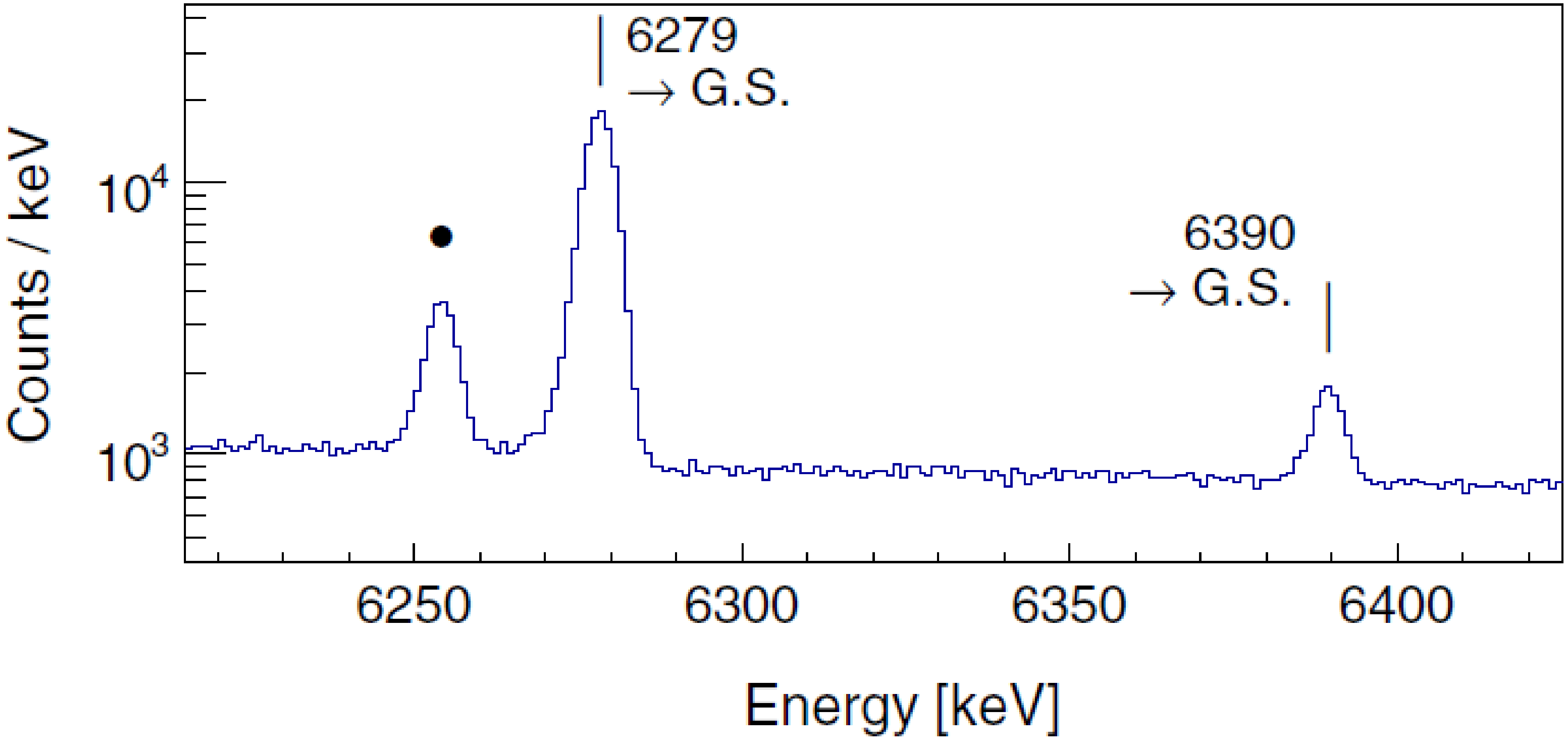
M. B. Bennett *et al*., Phys. Rev. Lett. 116, 102502 (2016)
M. B. Bennett, Ph.D. thesis (MSU, 2016)

CloverShare HPGe array



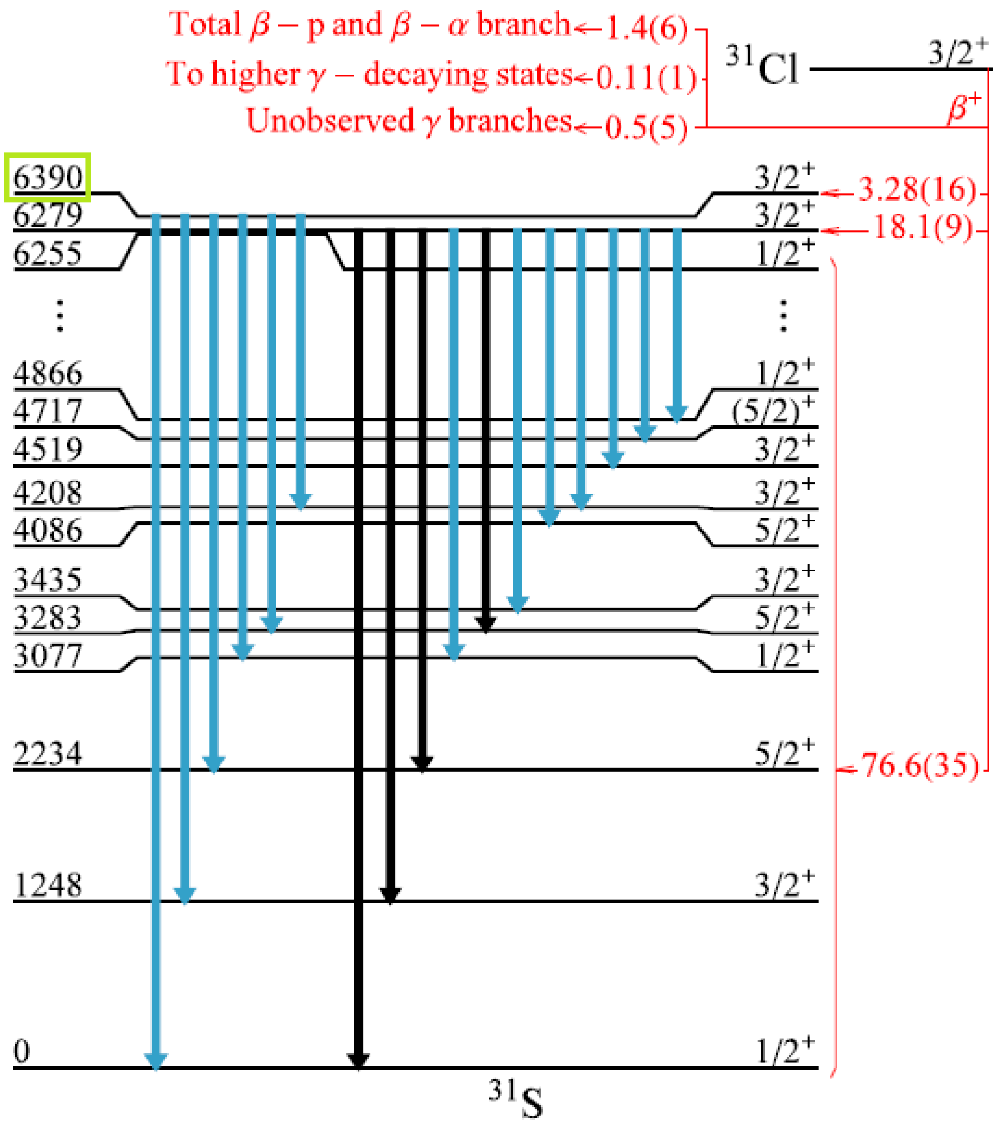
M. B. Bennett *et al.*, Phys. Rev. Lett. 116, 102502 (2016)
M. B. Bennett, Ph.D. thesis (MSU, 2016)

^{31}Cl(β γ) data



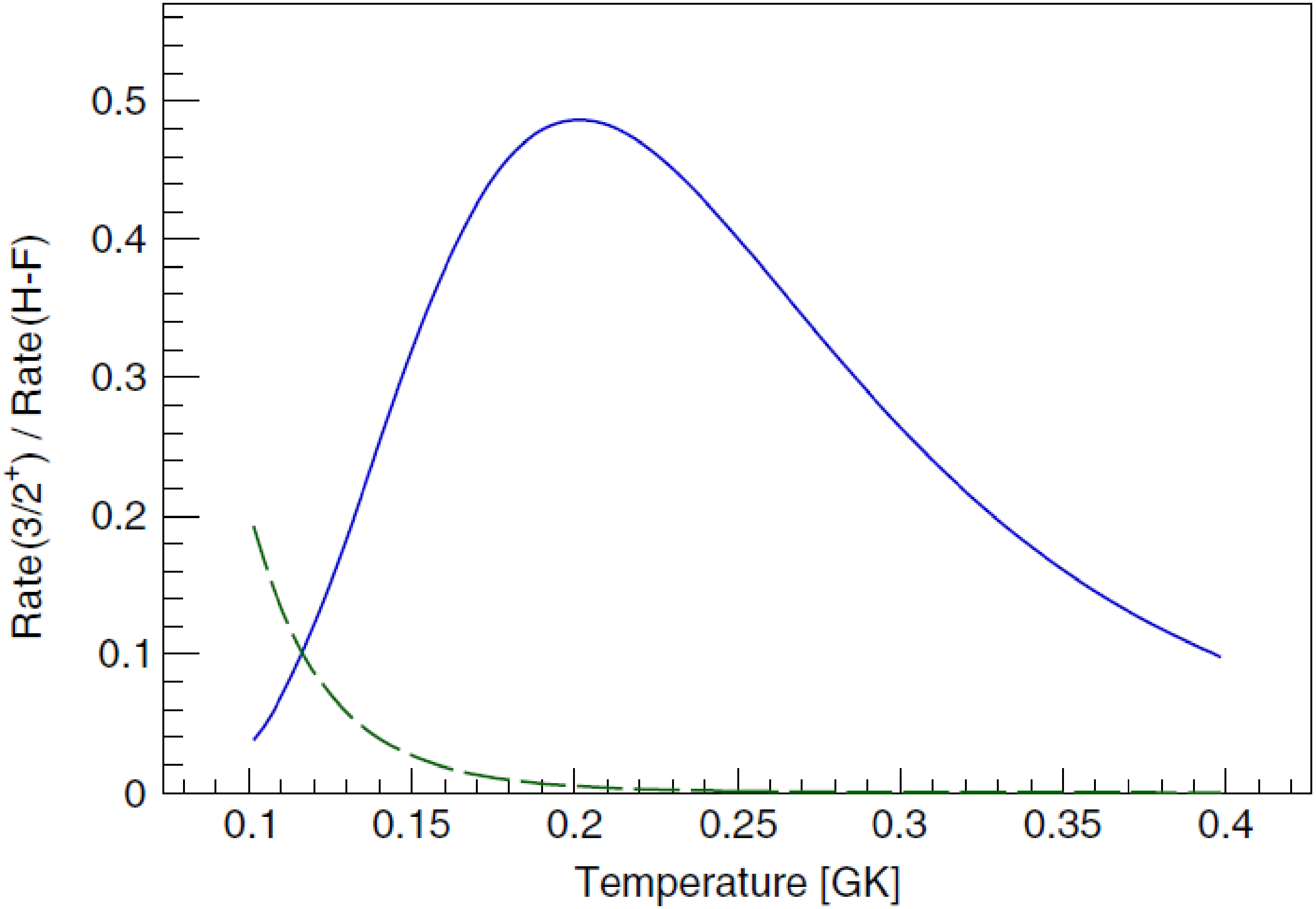
M. B. Bennett *et al.*, Phys. Rev. Lett. 116, 102502 (2016)
M. B. Bennett, Ph.D. thesis (MSU, 2016)

^{31}Cl β decay scheme: a new state!



M. B. Bennett *et al.*, Phys. Rev. Lett. 116, 102502 (2016)
M. B. Bennett, Ph.D. thesis (MSU, 2016)

Thermonuclear ^{30}P(p,γ)^{31}S reaction rate

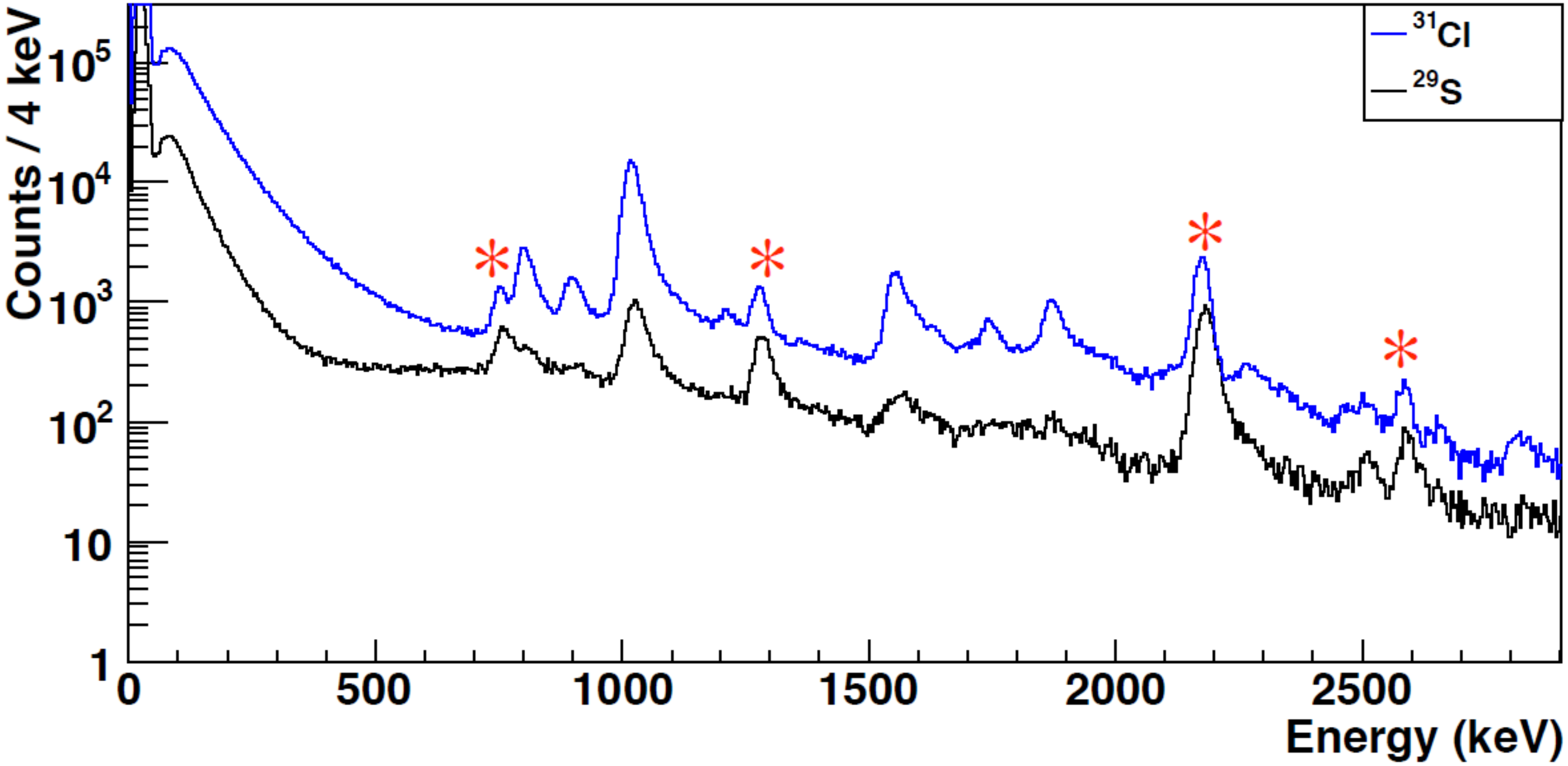


New state could be dominant ^{30}P(p,γ)^{31}S resonance in novae. Need to measure proton emission branch and lifetime to determine resonance strength…

M. B. Bennett *et al*., Phys. Rev. Lett. 116, 102502 (2016)
M. B. Bennett, Ph.D. thesis (MSU, 2016)

Low-energy β delayed charged particles

Measure ^{31}Cl(β p) ^{31}S through new ^{30}P(p,γ)^{31}S resonance to determine Γ_p/Γ

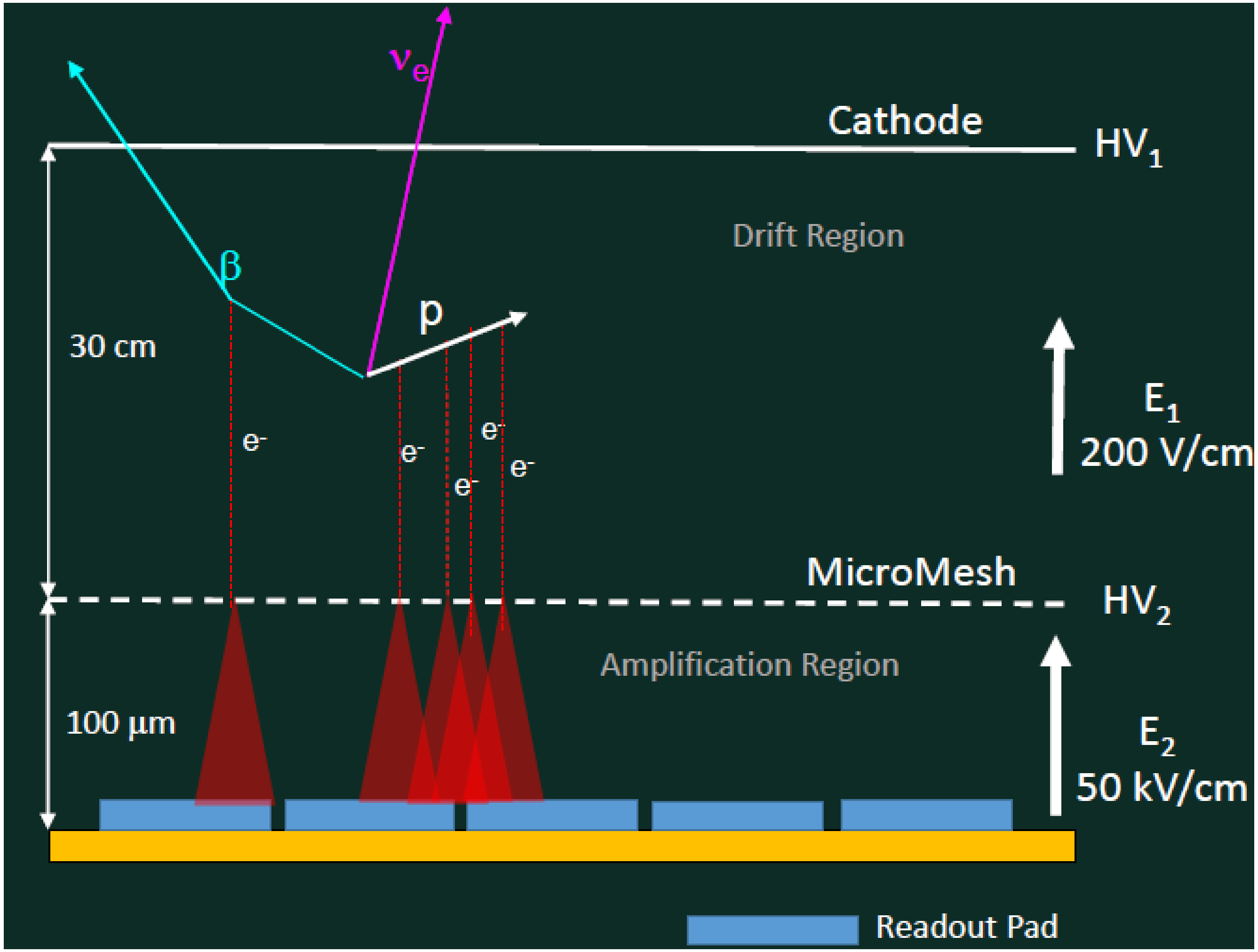


Challenge: usual method using Si detectors yields massive β-particle background

A. Saastamoinen, Ph.D. thesis (2011, Jyvaskyla)

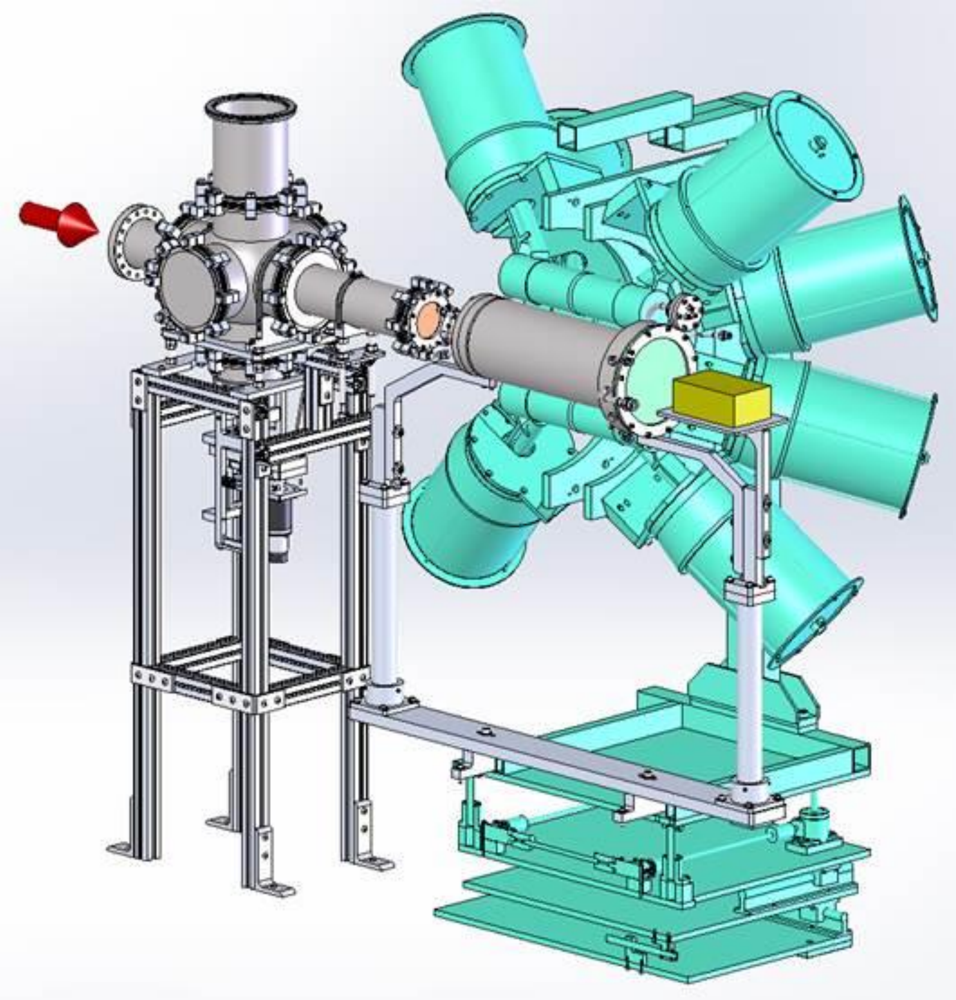
Solution: gas-filled detector

Micropattern gas amplifier: principle of operation



Y. Giomataris *et al.*, NIM A 376, 29 (1996)
E. Pollacco *et al.*, NIM A 723, 102 (2013)

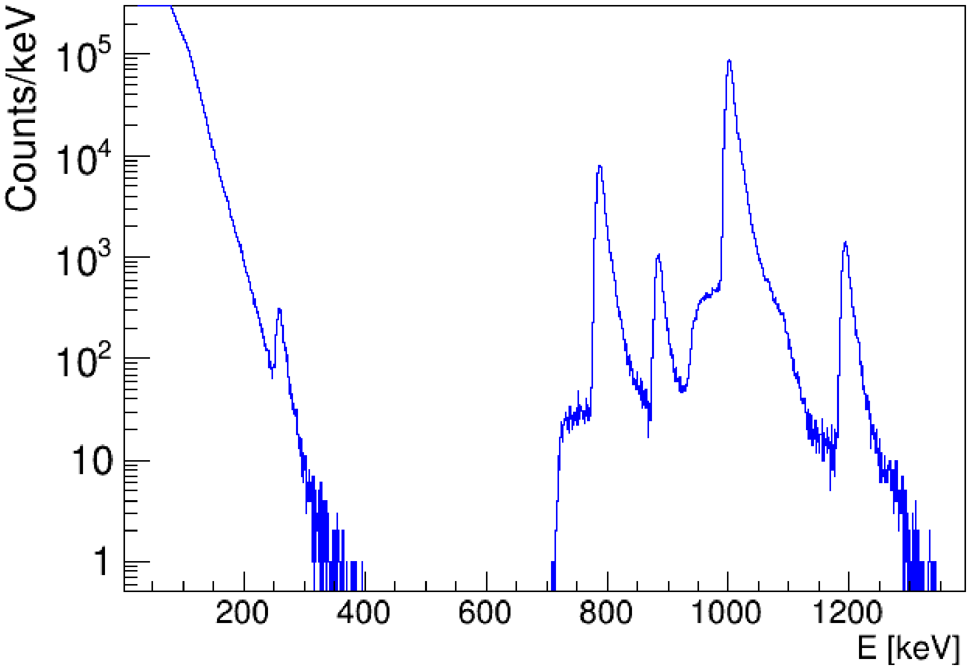
New “Proton Detector” at NSCL



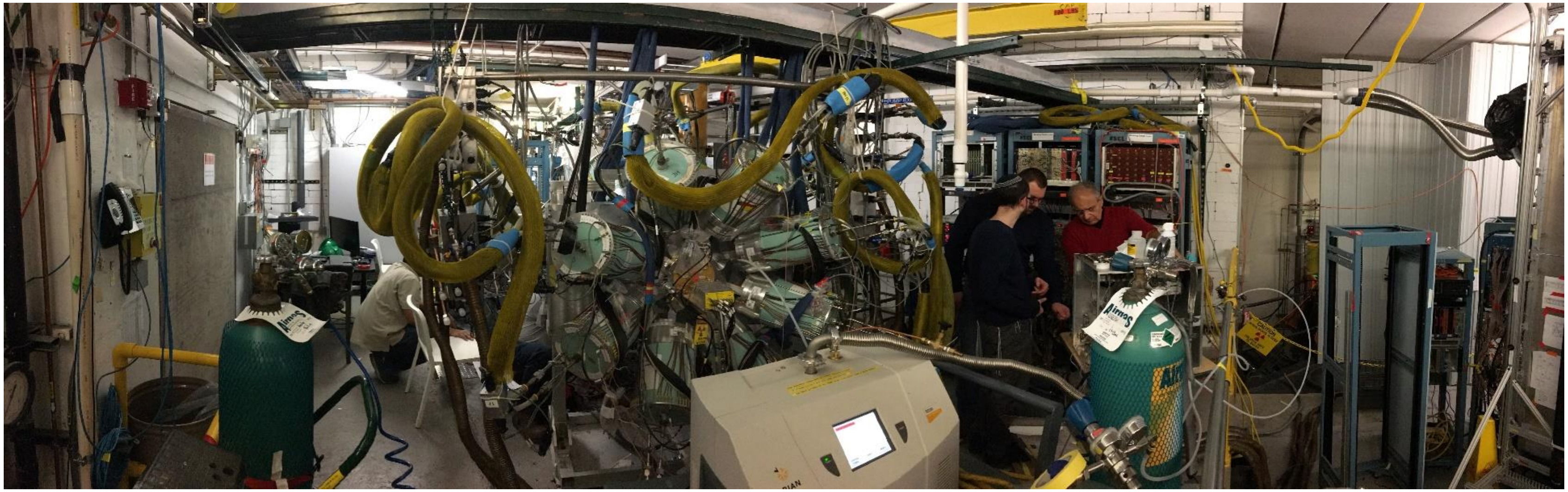
Measure ^{31}Cl(β p) ^{31}S through new ^{30}P(p,γ)^{31}S resonance and determine Γ_p/Γ

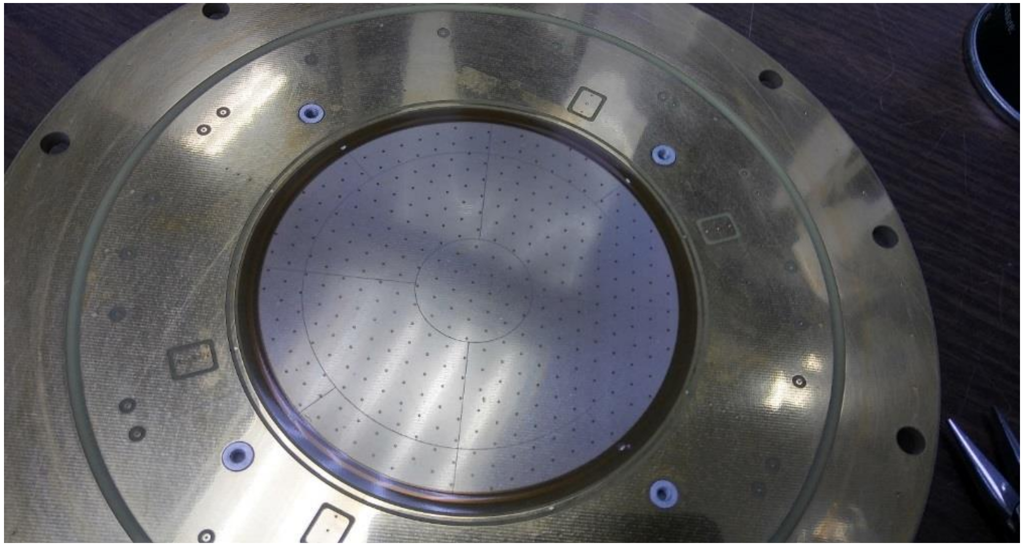
(NSCL E17024)

Geant4 simulation of ^{31}Cl decay by D. Perez-Loureiro

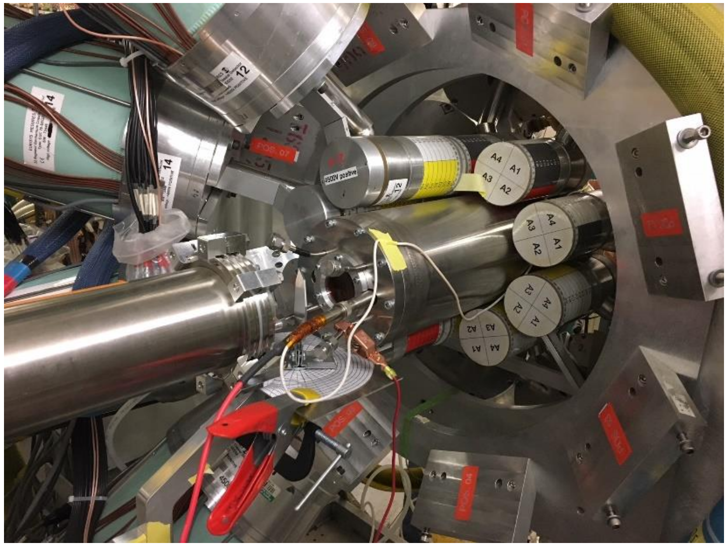


Proton Detector commissioning





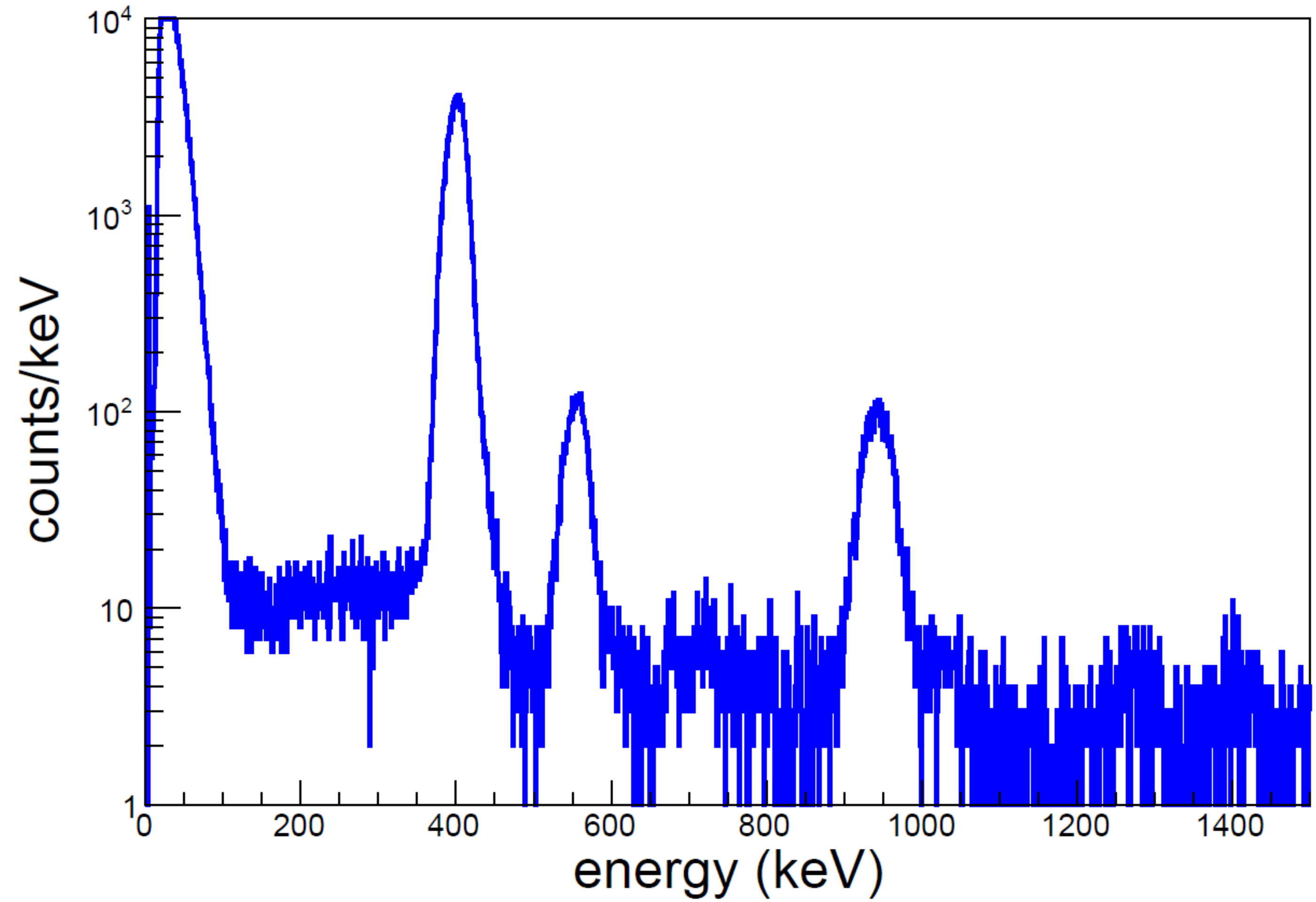
Micromegas



Proton Detector with part of SeGA around it

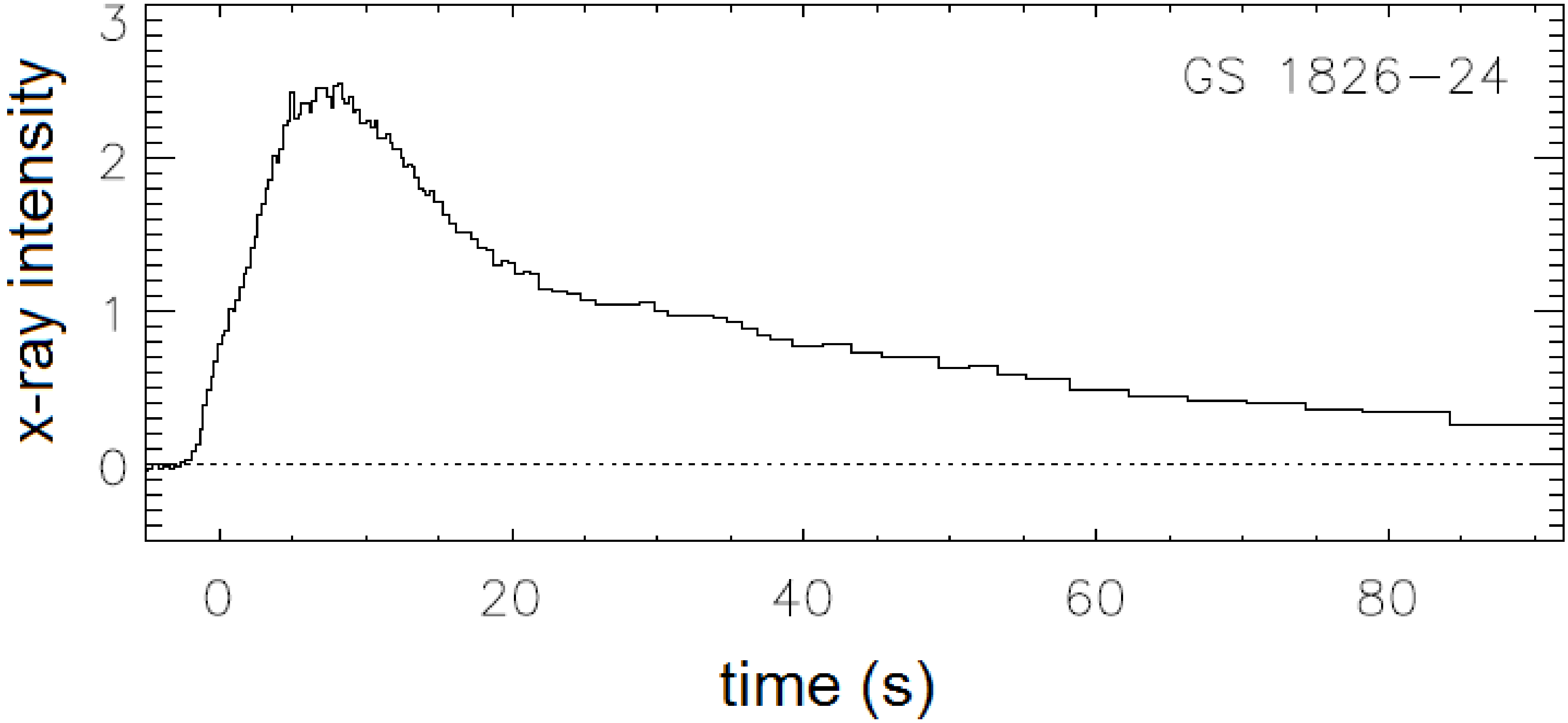
Commissioning experiment: $^{25}Si(\beta p)^{24}Mg$

(NSCL E17023)



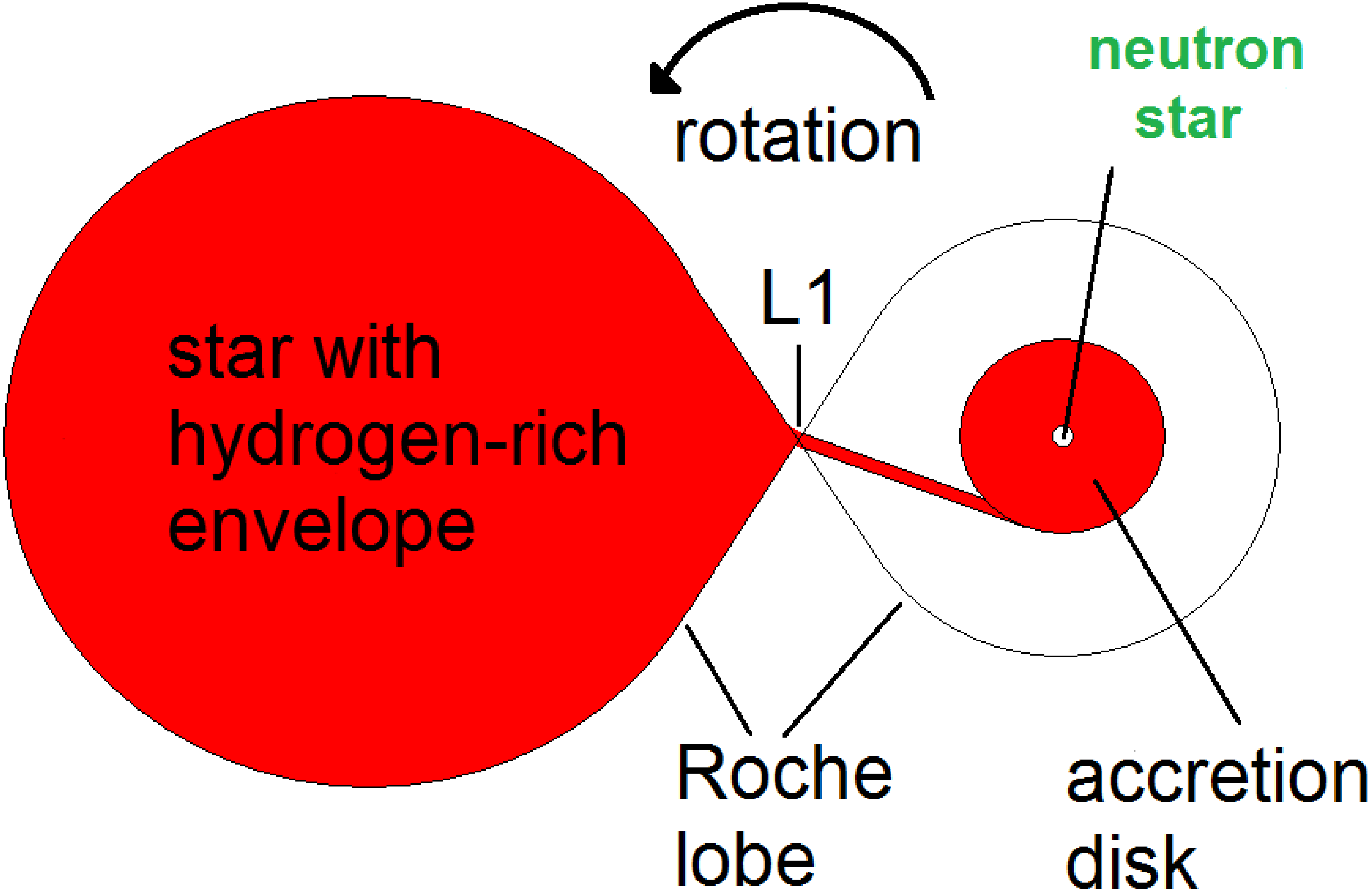
Ready to run $^{31}Cl(\beta\ p)^{31}S$ in Fall 2018 (will also measure ^{31}S lifetimes at TRIUMF in Fall 2018)

X-ray burst light curve

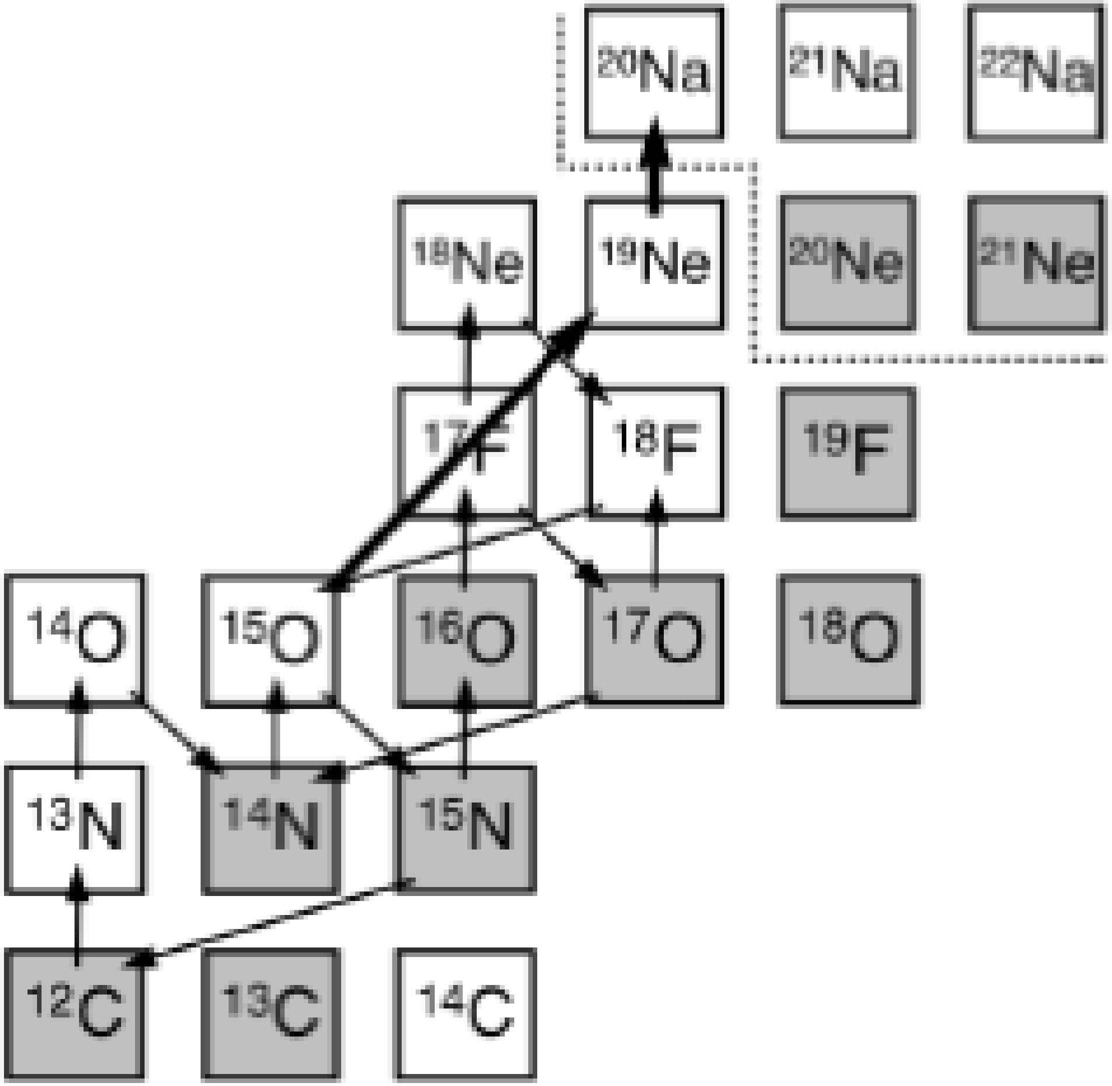


RXTE; Galloway *et al*., Astrophys. J. 179, 360 (2008)

X-ray burst


rotation
neutron star
star with hydrogen-rich envelope
L1
Roche lobe
accretion disk

Break out from hot CNO cycles



M. Wiescher *et al.*, J. Phys. G 25, R133 (1999)
C. Iliadis, AIP Conf. Proc. 1213, 3 (2010)

rp process

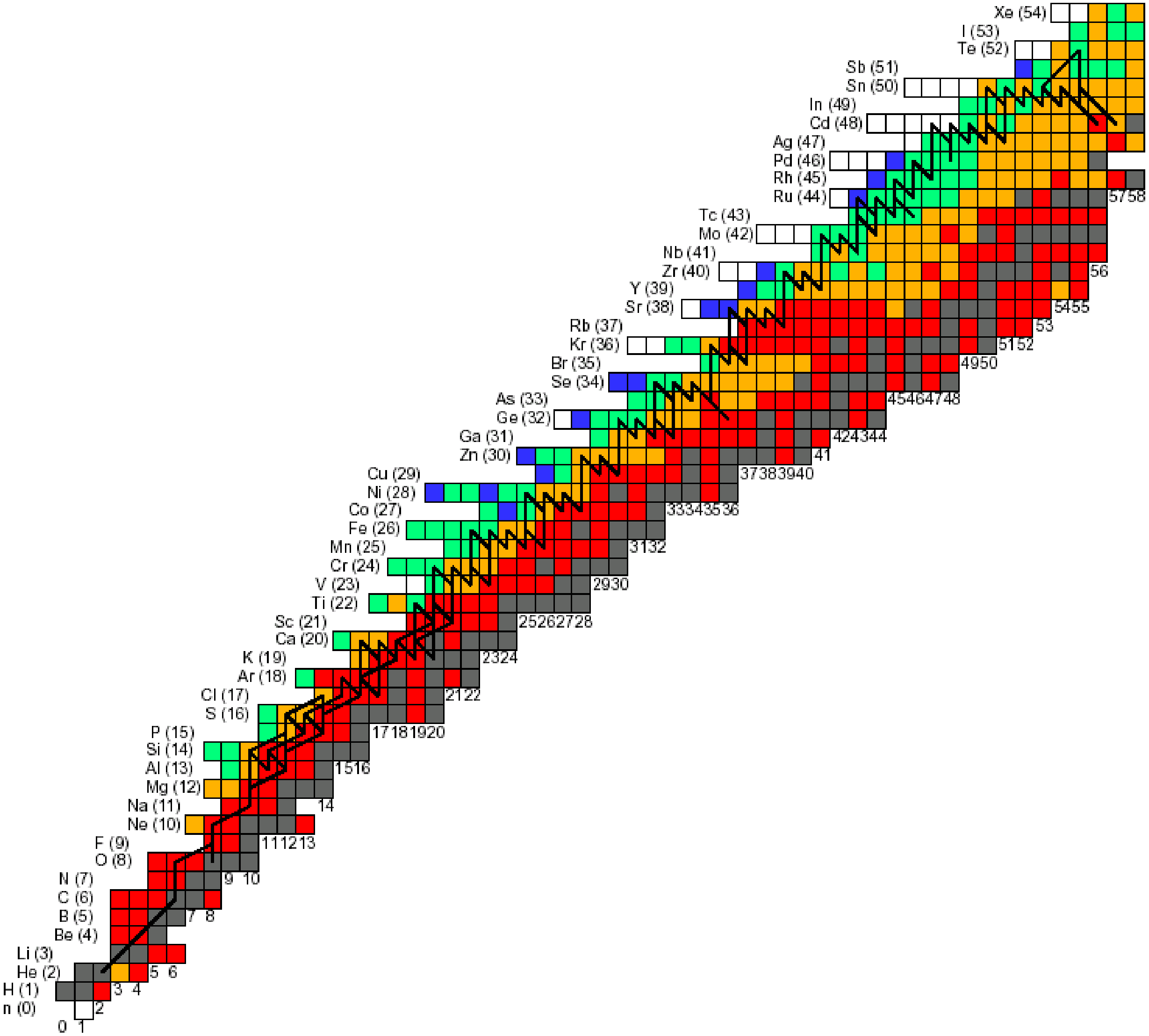
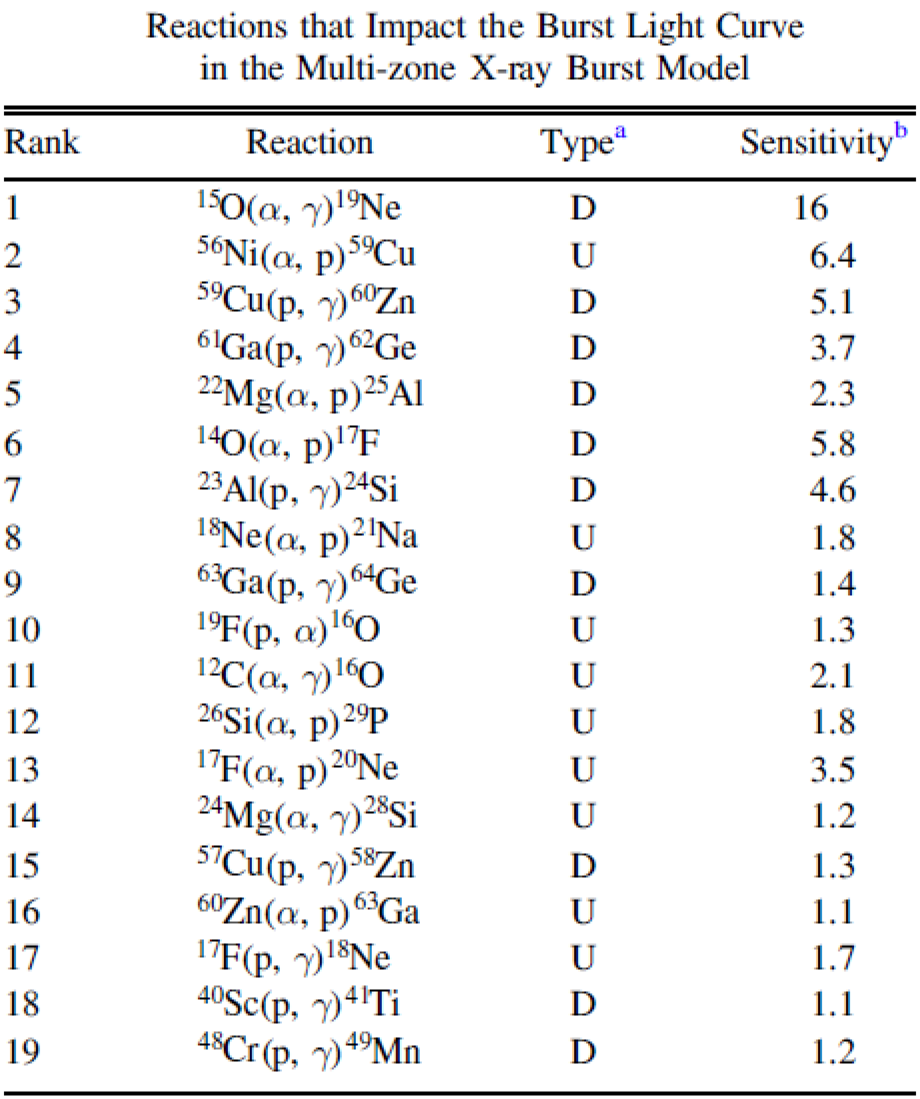


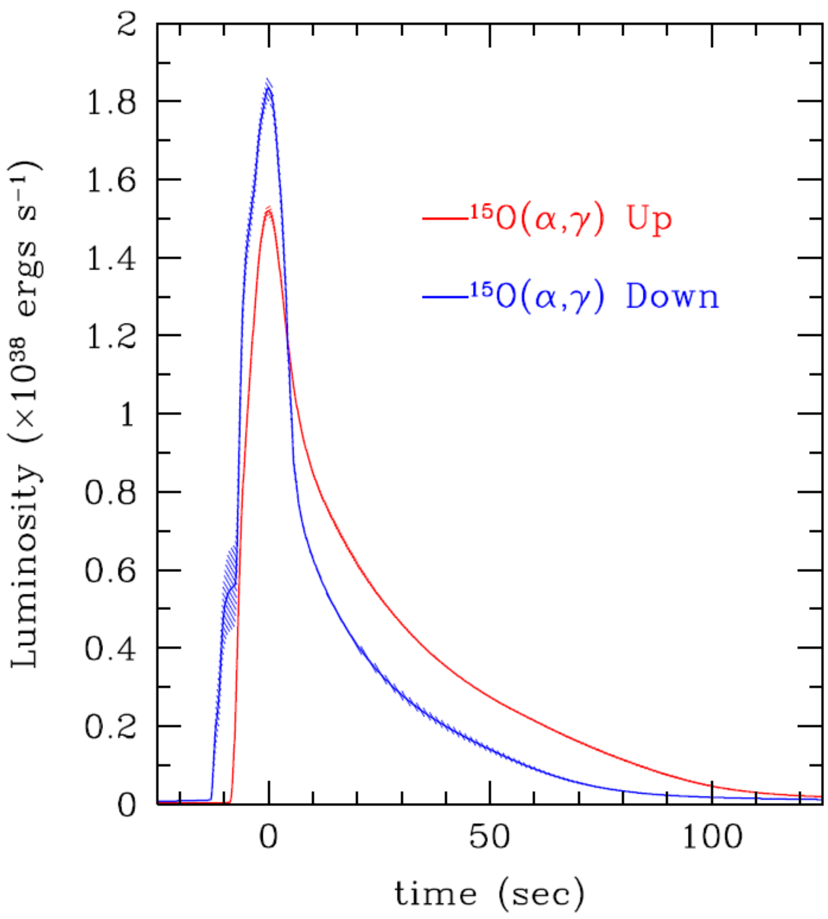
Figure: H. Schatz

Which reactions impact the X-ray burst light curve?



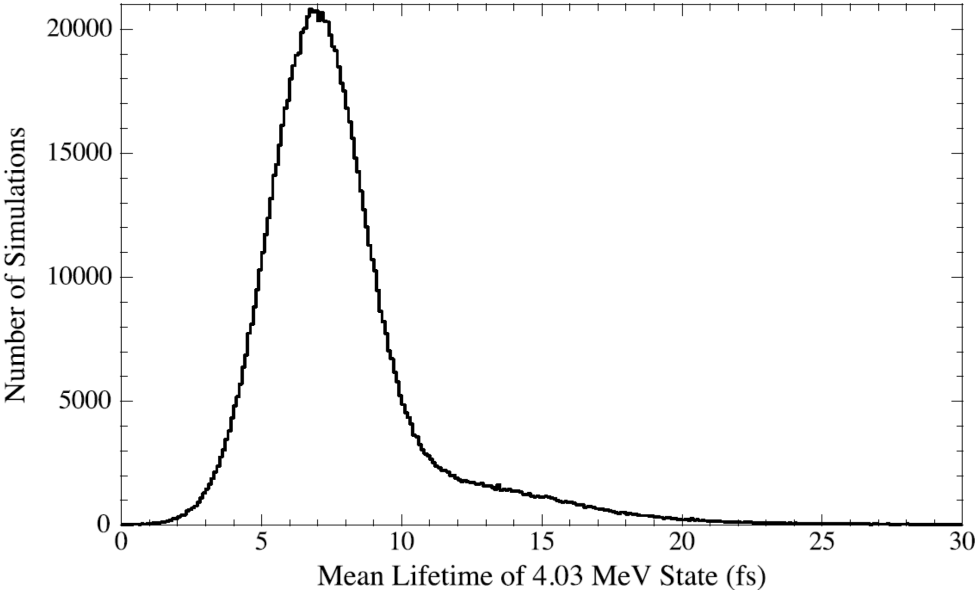
Reactions that Impact the Burst Light Curve
in the Multi-zone X-ray Burst Model

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



R. Cyburt *et al*., Astrophys. J. 830, 55 (2016)

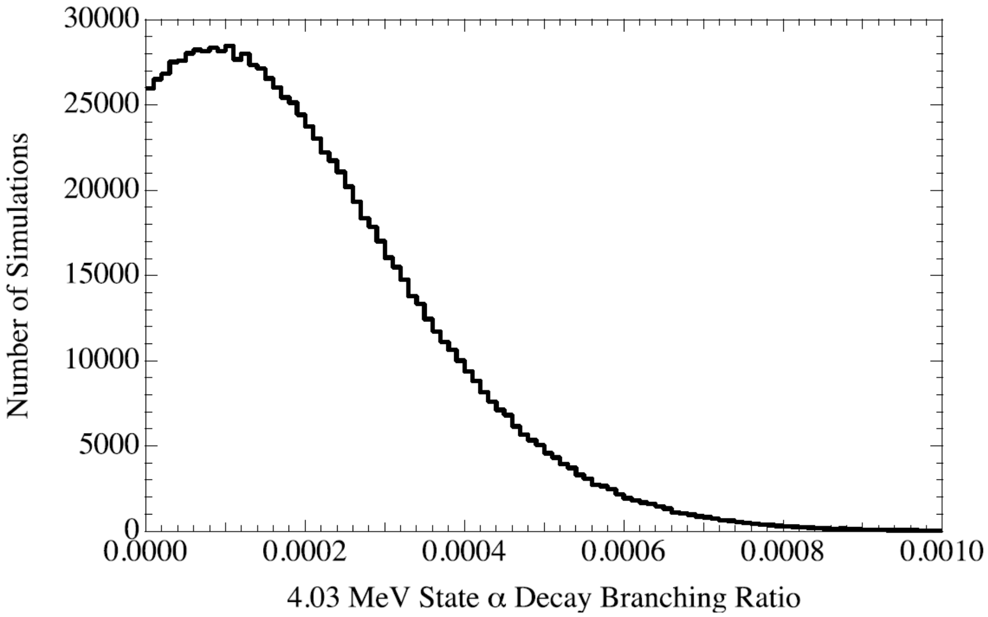
Key $^{15}O(\alpha,\gamma)^{19}Ne$ resonance



W. P. Tan *et al.*, Phys. Rev. C 72, 041302 (2005)
R. Kanungo *et al.*, Phys. Rev. C 74, 045803 (2006)

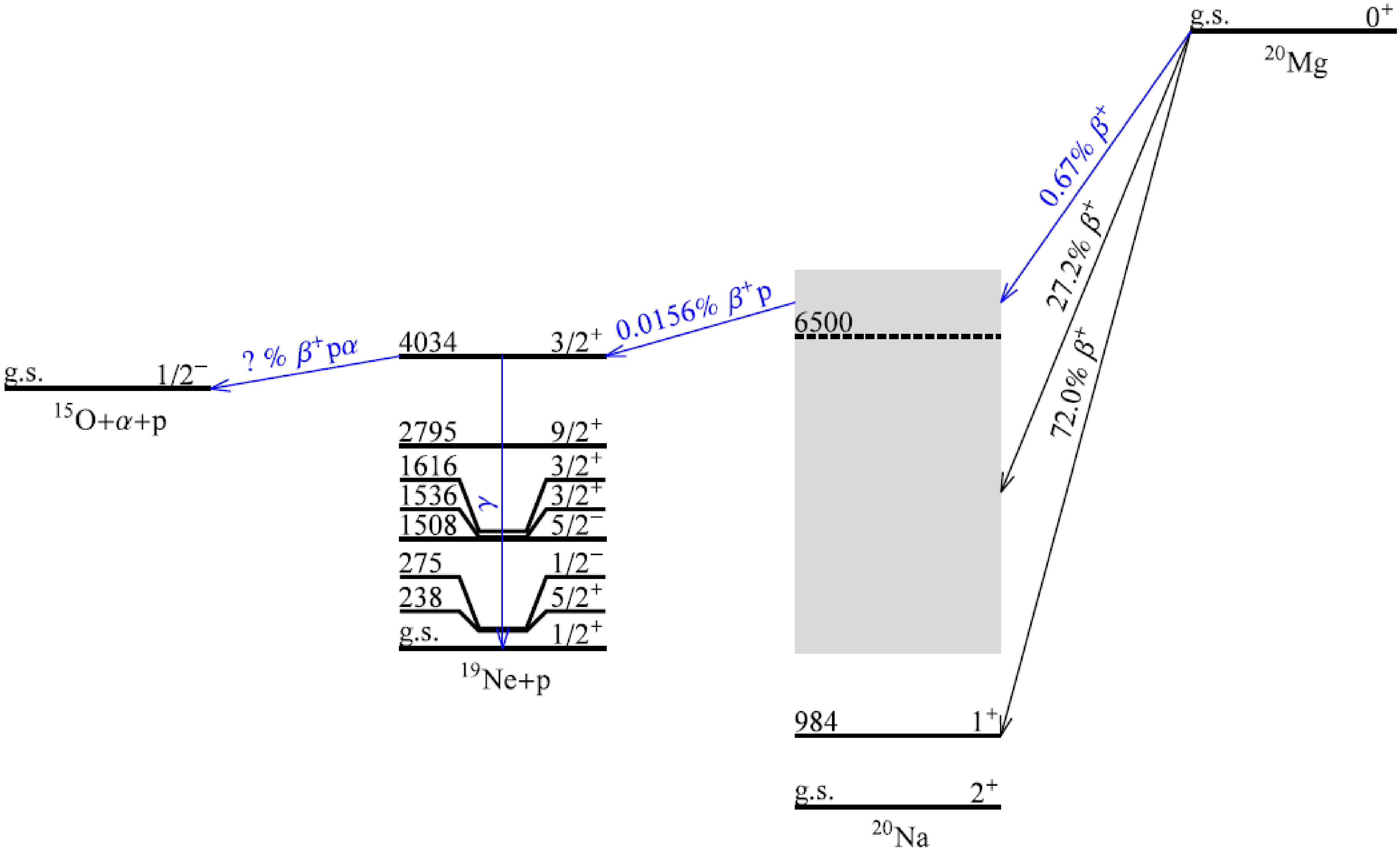
$$\omega\gamma \sim \frac{1}{\tau}\frac{\Gamma_\alpha}{\Gamma}$$

B. Davids *et al.*, Phys. Rev. C 67, 065808 (2003)
W. P. Tan *et al.*, Phys. Rev. Lett. 98, 242503 (2007)



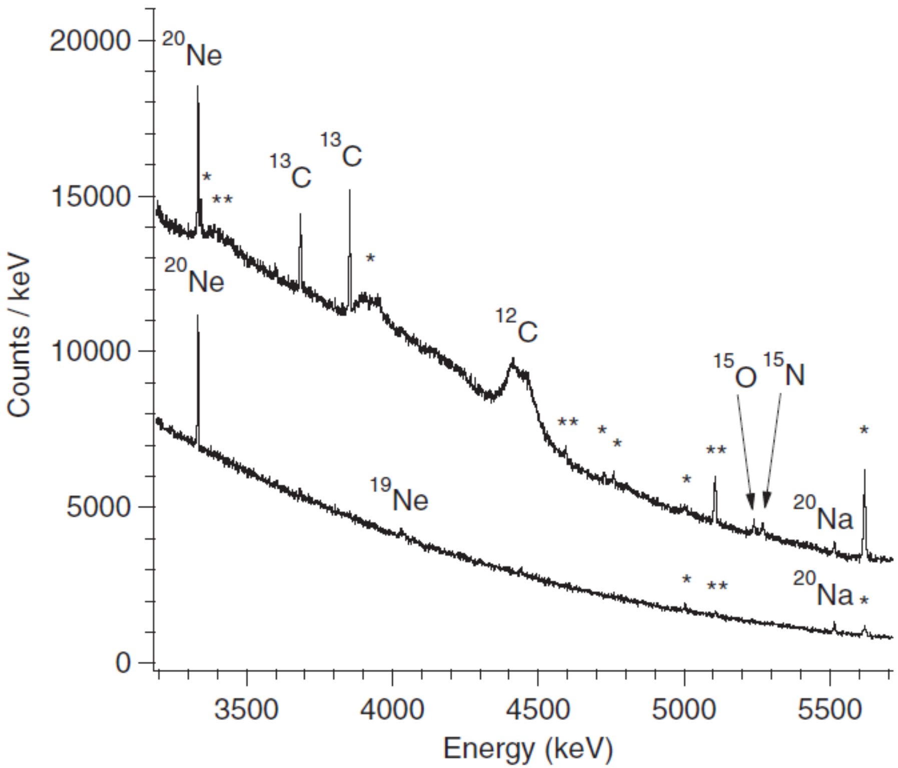
B. Davids *et al.*, Astrophys. J. 735, 40 (2011)

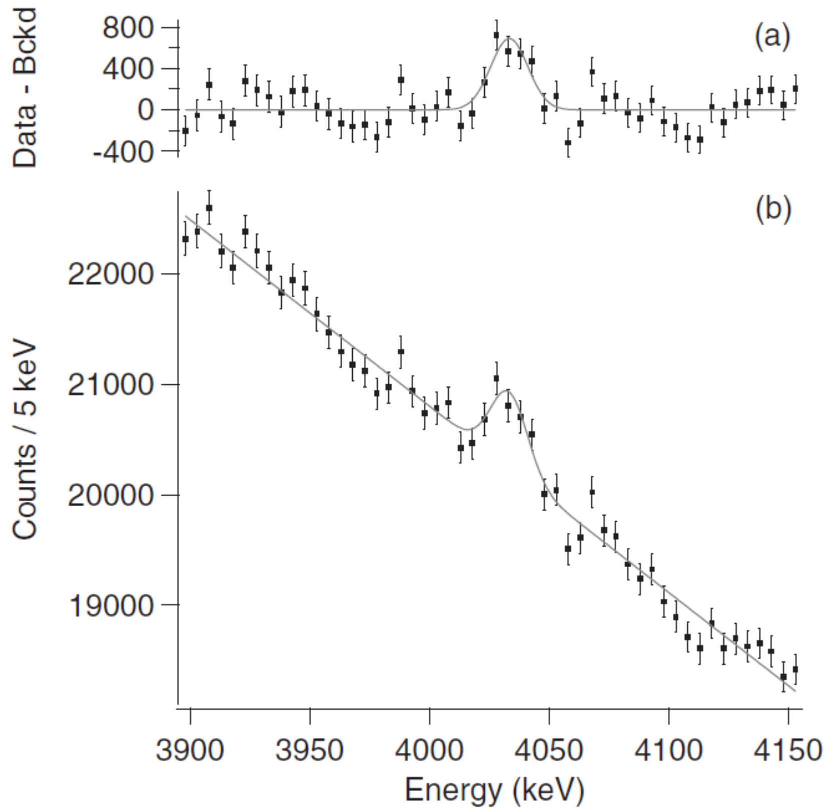
New idea: β decay of ^{20}Mg to probe key ^{15}O(α,γ)^{19}Ne resonance



C. Wrede *et al.*, Phys. Rev. C 96, 032801(R) (2017)

^{20}Mg(β *p* γ) spectra
(NSCL E14066)

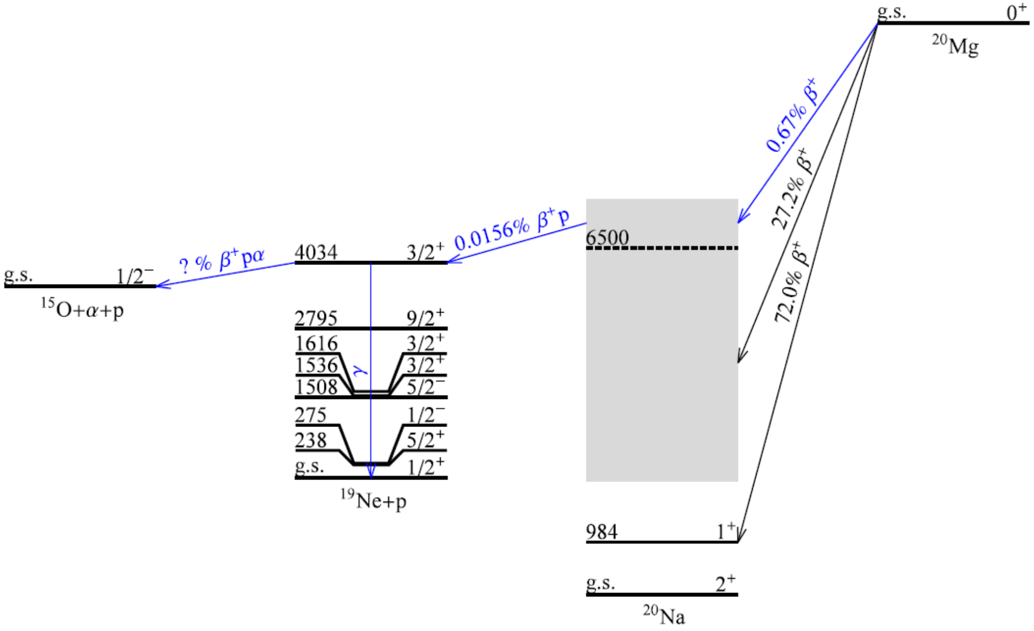




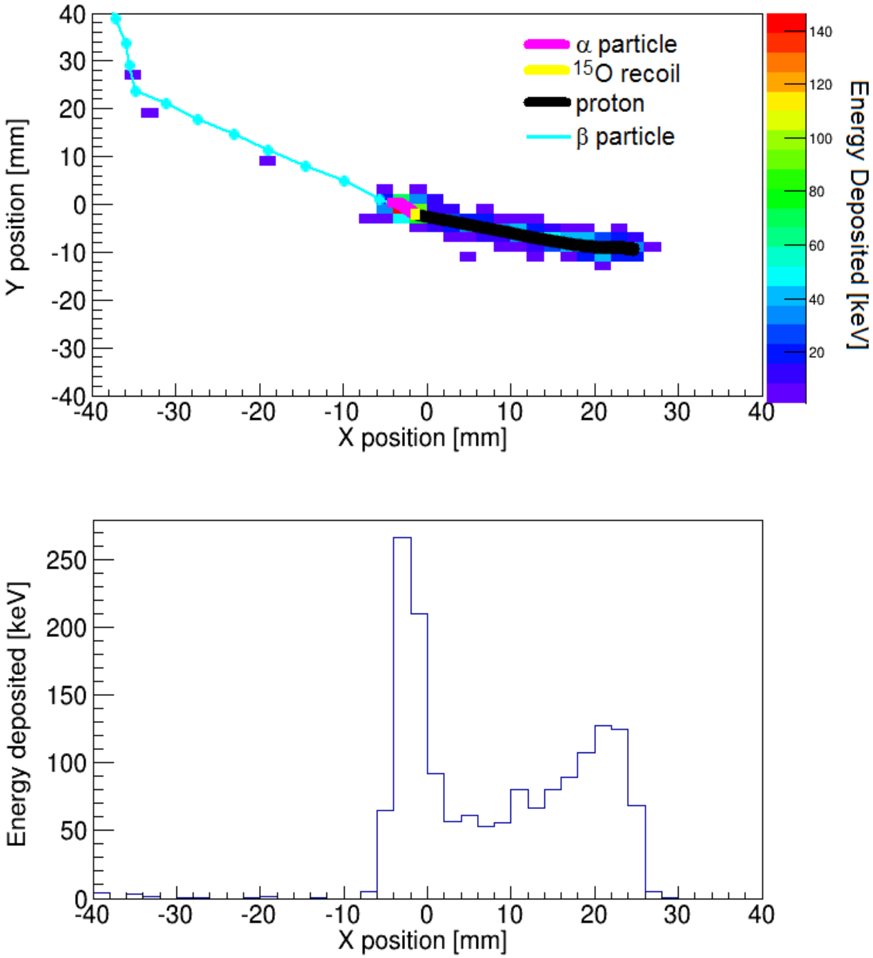
4033-keV ^{15}O(α,γ)^{19}Ne resonance is populated in ^{20}Mg β decay!

C. Wrede *et al.*, Phys. Rev. C 96, 032801(R) (2017)

Proton Detector upgrade to TPC



Geant4 simulation by D. Perez-Loureiro



Measure ^{20}Mg(β p α)^{15}O through 4033-keV ^{15}O(α,γ)^{19}Ne resonance to determine Γ_α/Γ (NSCL E18033)

C. Wrede *et al.*, Phys. Rev. C 96, 032801(R) (2017)

Summary

- ^{26}P β decay experiment to constrain ^{26}Al production in novae via ^{25}Al(p,γ)^{26}Si reaction rate
- ^{31}Cl β decay experiments to ID candidate pre-solar nova grains via ^{30}P(p,γ)^{31}S reaction rate
- ^{20}Mg β decay experiments to investigate CNO-cycle break out via ^{15}O(α,γ)^{19}Ne reaction in type I x-ray bursts

Collaborating institutions

For NSCL E10034, E12028, E14066 (beta-gamma work):

Colorado School of Mines
Joint Institute for Nuclear Astrophysics
McMaster University
Michigan State University
National Superconducting Cyclotron Laboratory
University of Notre Dame
Oak Ridge National Laboratory
Universitat Politècnica de Catalunya
University of Southern Indiana
University of Tennessee
Texas A&M University
University of Washington
Yale University

For NSCL E17023, E17024, E18033 (Proton Detector work):

CEA-Saclay
Michigan State University
National Superconducting Cyclotron Laboratory
Texas A&M University

Conclusions

- Nuclear physics affects the production of elements in stars
- Need nuclear astrophysics experiments to understand our origins!
- Direct measurements of nuclear cross sections at the relevant energies are challenging, but possible in many important cases
- Indirect cross-section measurements complement direct ones
- Other nuclear data also important: masses, weak interactions, …
- Nuclear theory complements nuclear experiment (unstable reactants, thermal excitations, dense matter equation of state, …)

Thank you for your attention!