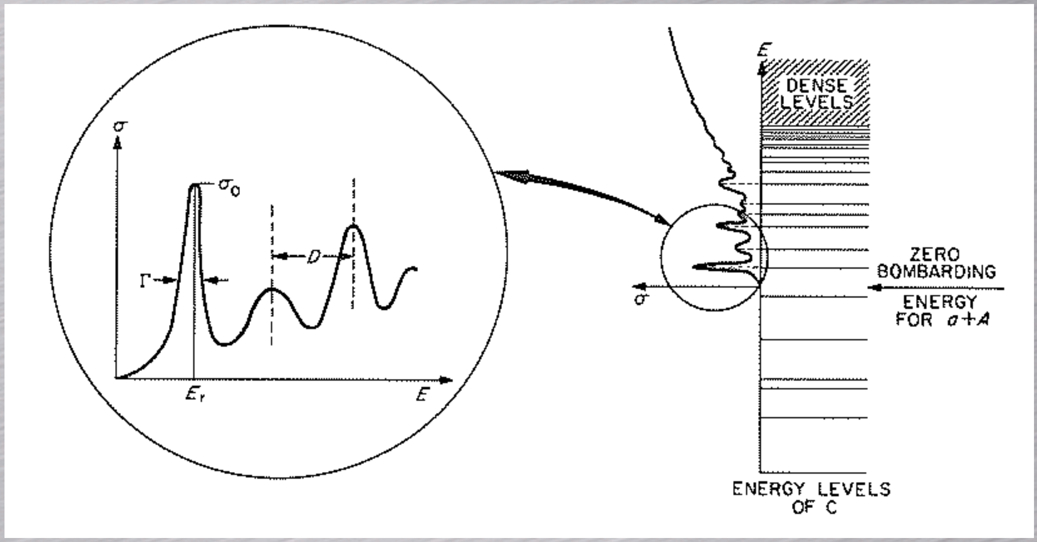
Resonances

- When energy corresponds to state in compound nucleus, cross section is enhanced
- These enhancements are resonances



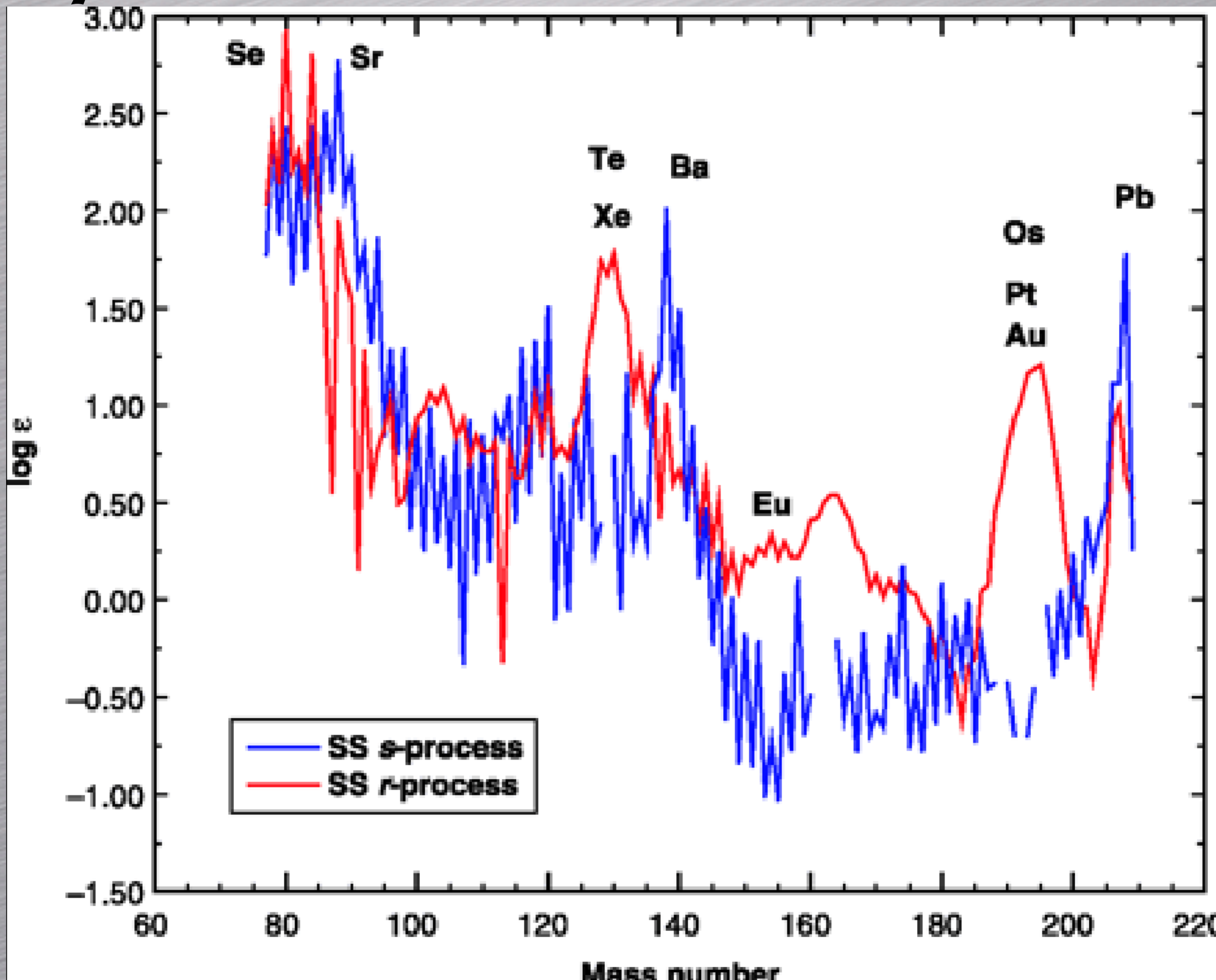
Direct and Indirect Measurements of Resonant Rates

- Direct measurement not generally feasible at all energies
- Must identify and measure energies of resonances with favourable spin and parity
- When resonances are narrow and don't interfere, decay properties can be measured to deduce strength

Major Stellar Fusion Processes

Fuel	Major Products	Threshold Temperature (K)
Hydrogen	Helium, Nitrogen	4 Million
Helium	Carbon, Oxygen	100 Million
Carbon	Oxygen, Neon, Sodium, Magnesium	600 Million
Oxygen	Magnesium, Sulfur, Phosphorous, Silicon	1 Billion
Silicon	Cobalt, Iron, Nickel	3 Billion

Heavy Element Abundances



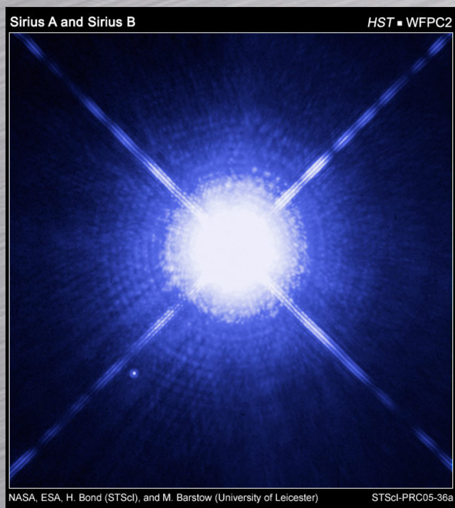
~1/2 of chemical elements w/ A > 70 produced in the rapid neutron capture *(r)* process: neutron captures on rapid timescale (~1 s) in a hot (1 billion K), dense environment (>10^{20} neutrons cm^{-3})

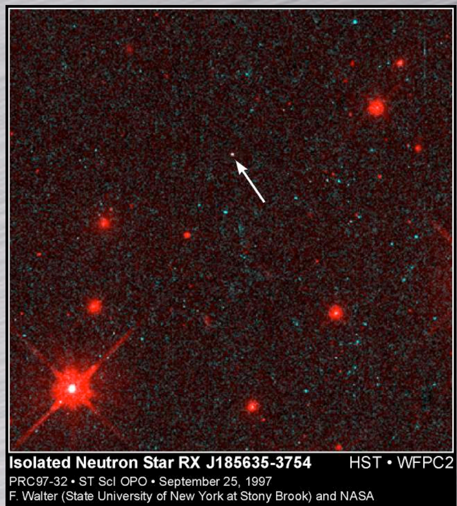
The other half are produced in the slow neutron capture process

The *r* Process Site?

Core-collapse supernovae favoured astrophysical site; explosion liberates synthesized elements, distributes throughout interstellar medium; Abundances of *r* process elements in old stars show consistent pattern for $Z > 47$, but variations in elements with $Z \leq 47$, implying at least 2 sites

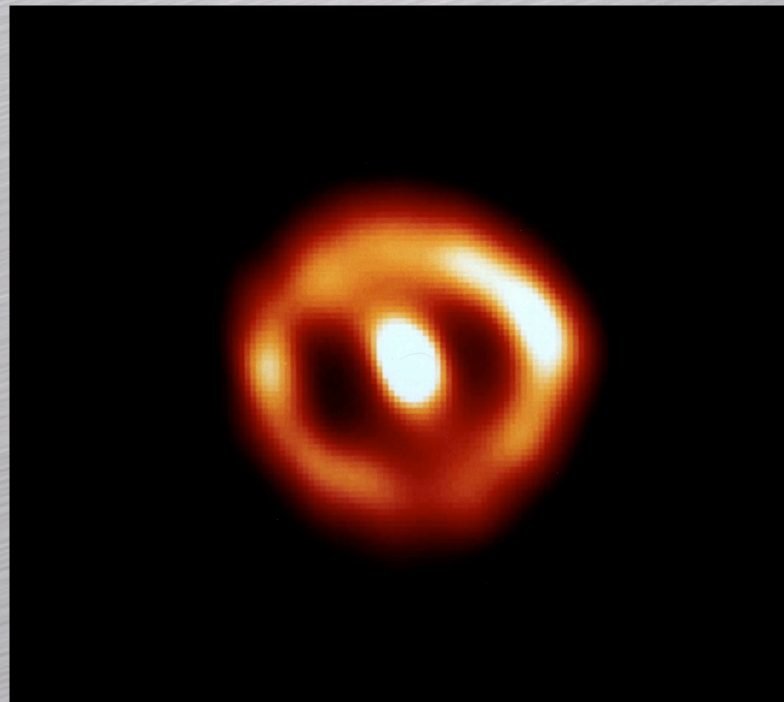
End States of Stellar Evolution: White Dwarves and Neutron Stars





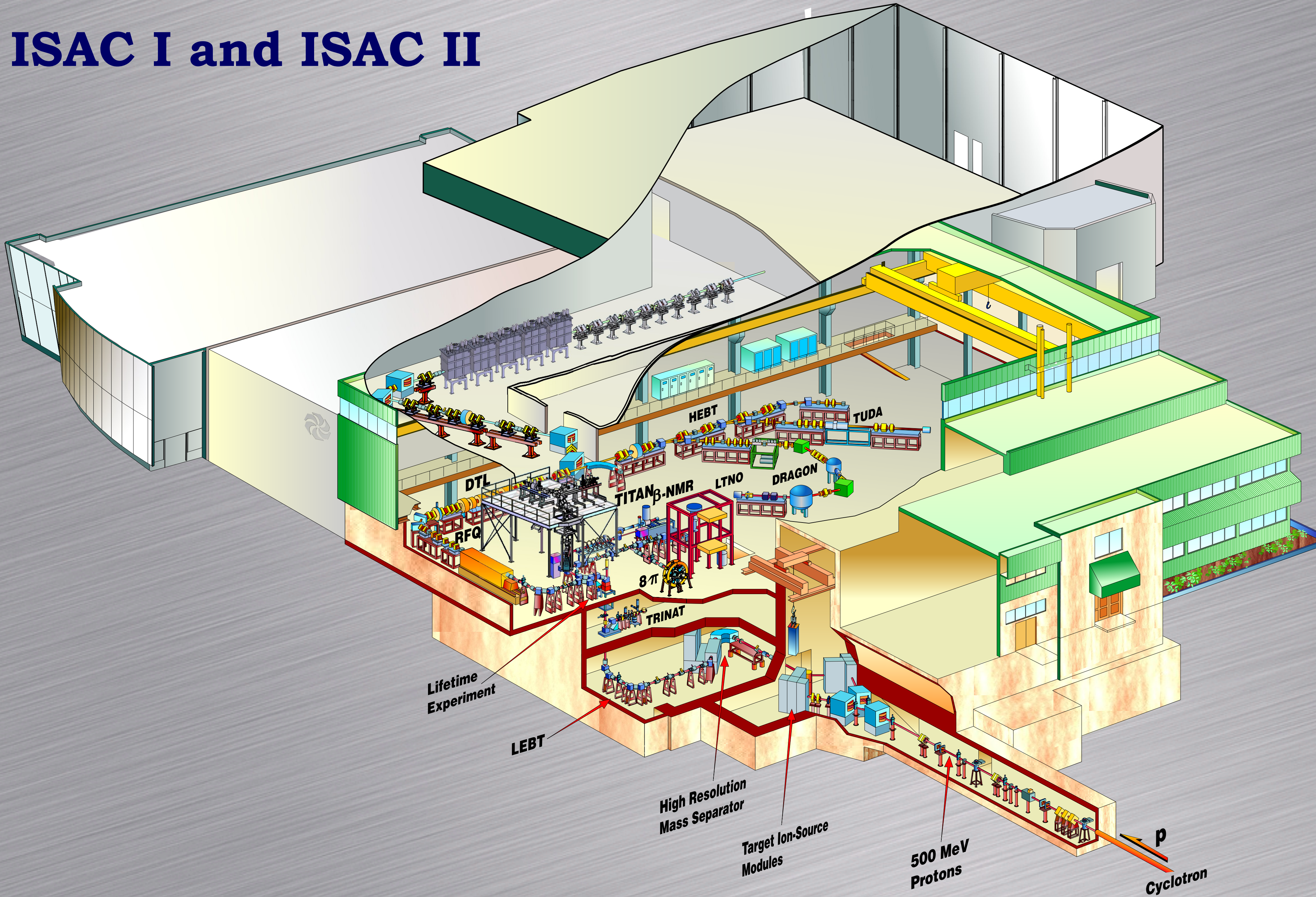
- White Dwarf: Stellar cinder left after typical and low-mass stars ($M < 8\ M_\odot$) exhaust core H and He fuel: composed mainly of C, O, Ne; $M \sim 0.6\ M_\odot$, $R \sim 6000$ km; supported by electron degeneracy pressure
- Neutron Star: End state of massive stars ($8\ M_\odot \leq M \leq 10\ M_\odot$) formed during supernova explosions: composed mainly of free neutrons, exotic nuclei; $M \sim 1.5\ M_\odot$, $R \sim 10$ km; supported by neutron degeneracy pressure

Novae

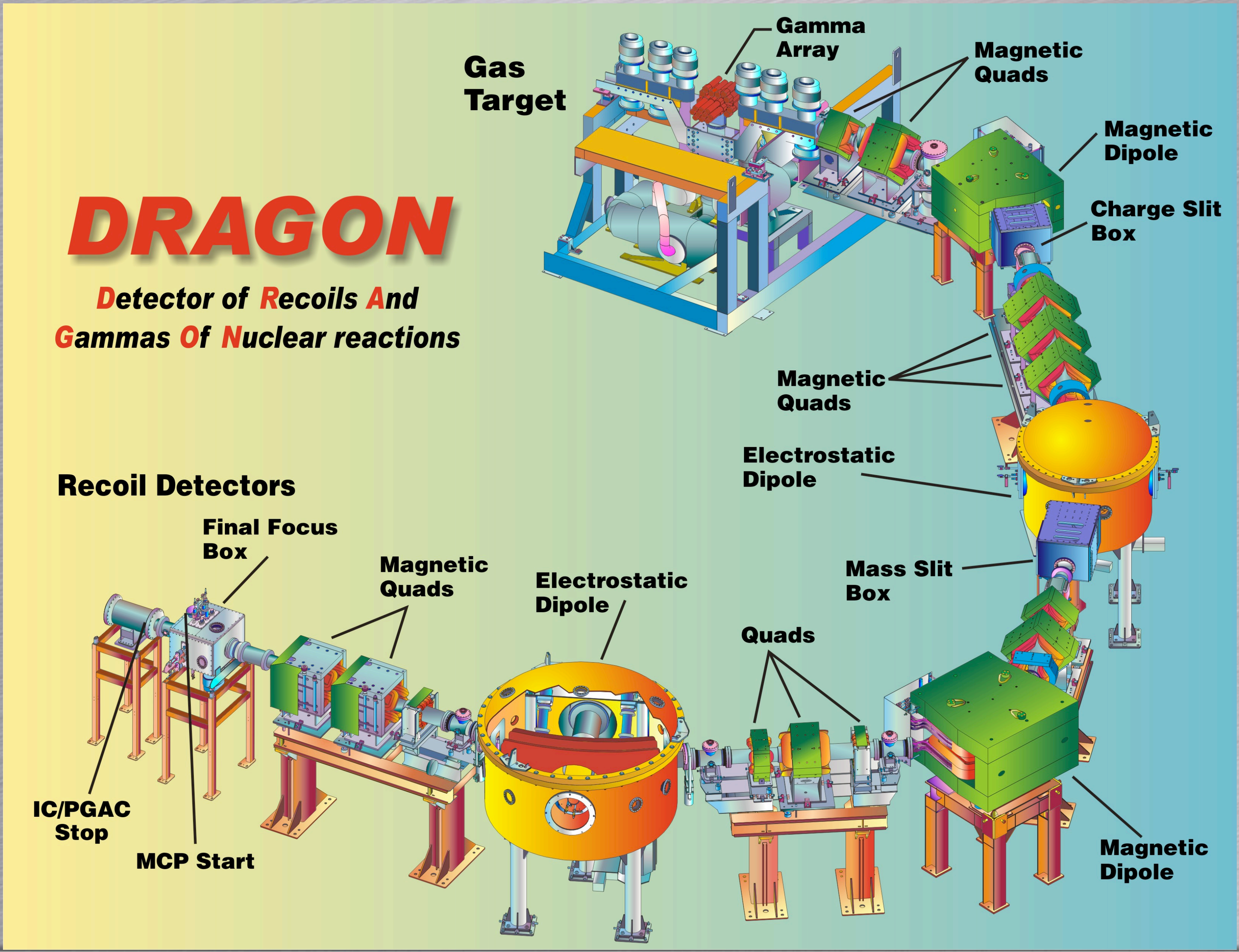


- Accretion of H- & He-rich matter from low-mass main sequence star onto surface of white dwarf via disk
- When accreted layer is thick enough, temperature and pressure at base sufficient to initiate thermonuclear runaway
- H in accreted layer is "burnt" via nuclear reactions
- Layer ejected, enriching ISM with nucleosynthetic products
- Repeats nearly ad infinitum w/ recurrence time ~ 10^{4-5} yr

ISAC I and ISAC II



Recoil Mass Separator

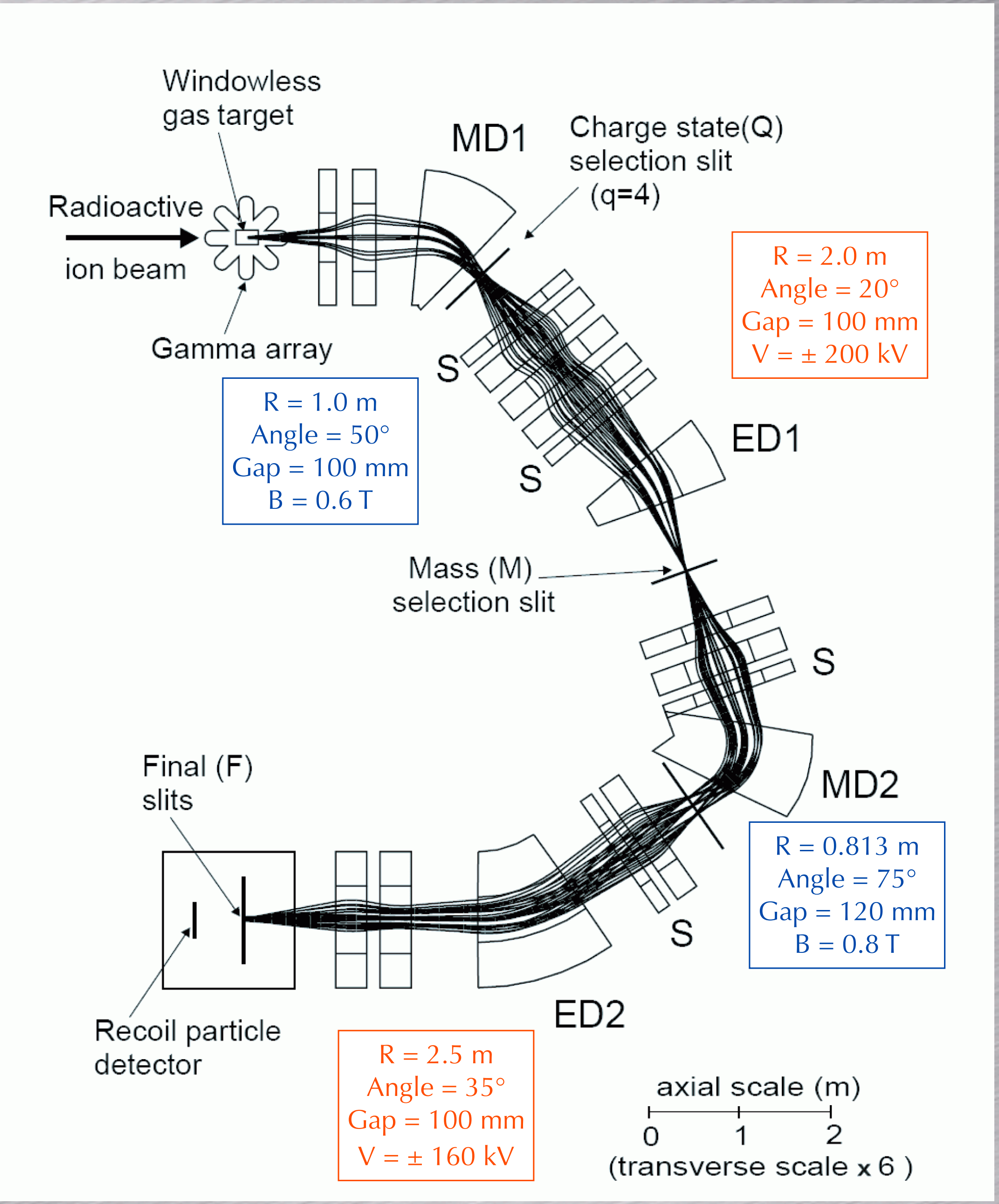


Radiative Capture Experiments at DRAGON

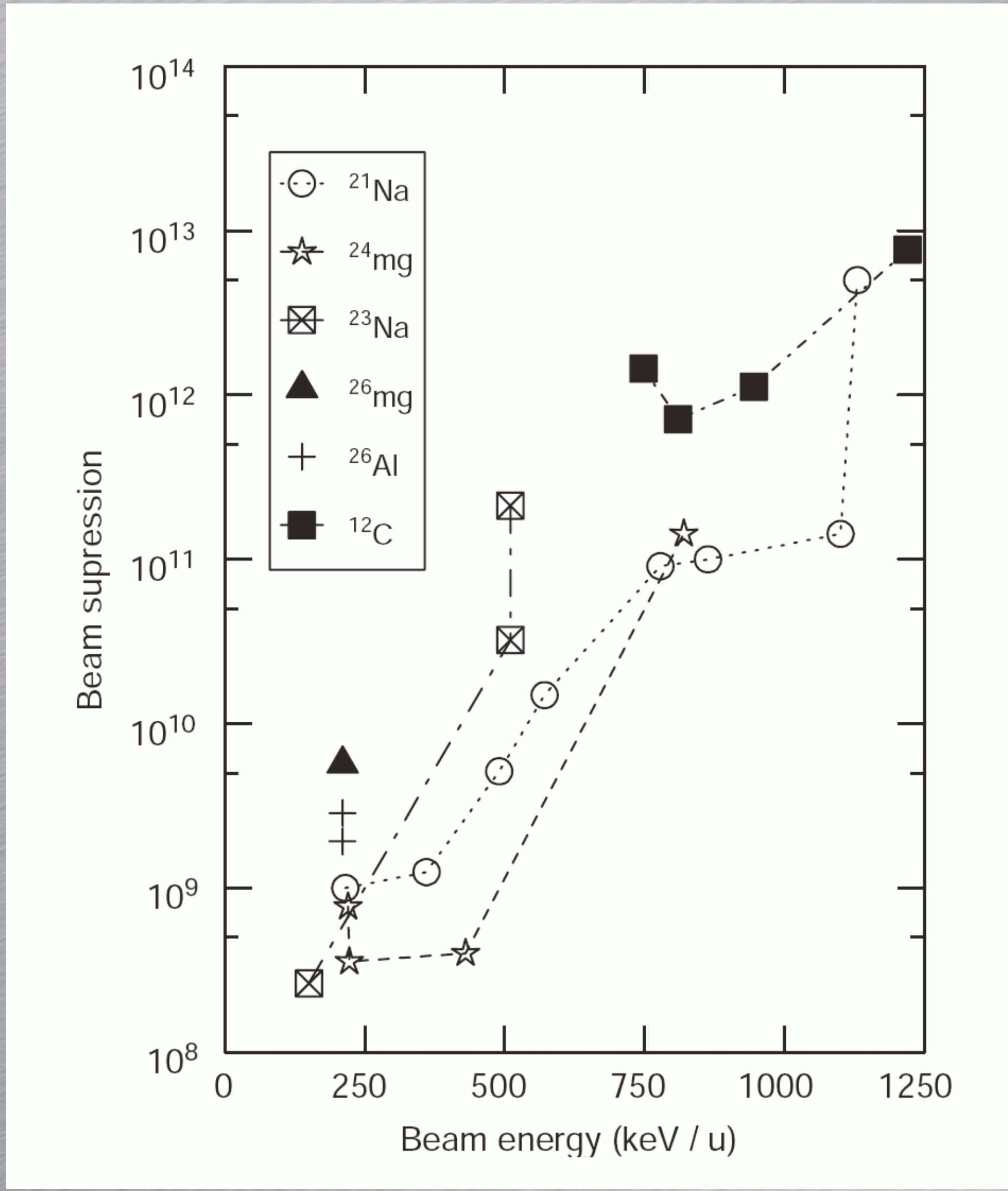
$$p_r = p_p$$

$$E_r = \frac{m_p}{m_r} E_p$$

$$Y = \frac{\lambda^2}{2} \frac{m_p + m_t}{m_t} \left(\frac{dE}{dx}\right)^{-1} \omega\gamma$$

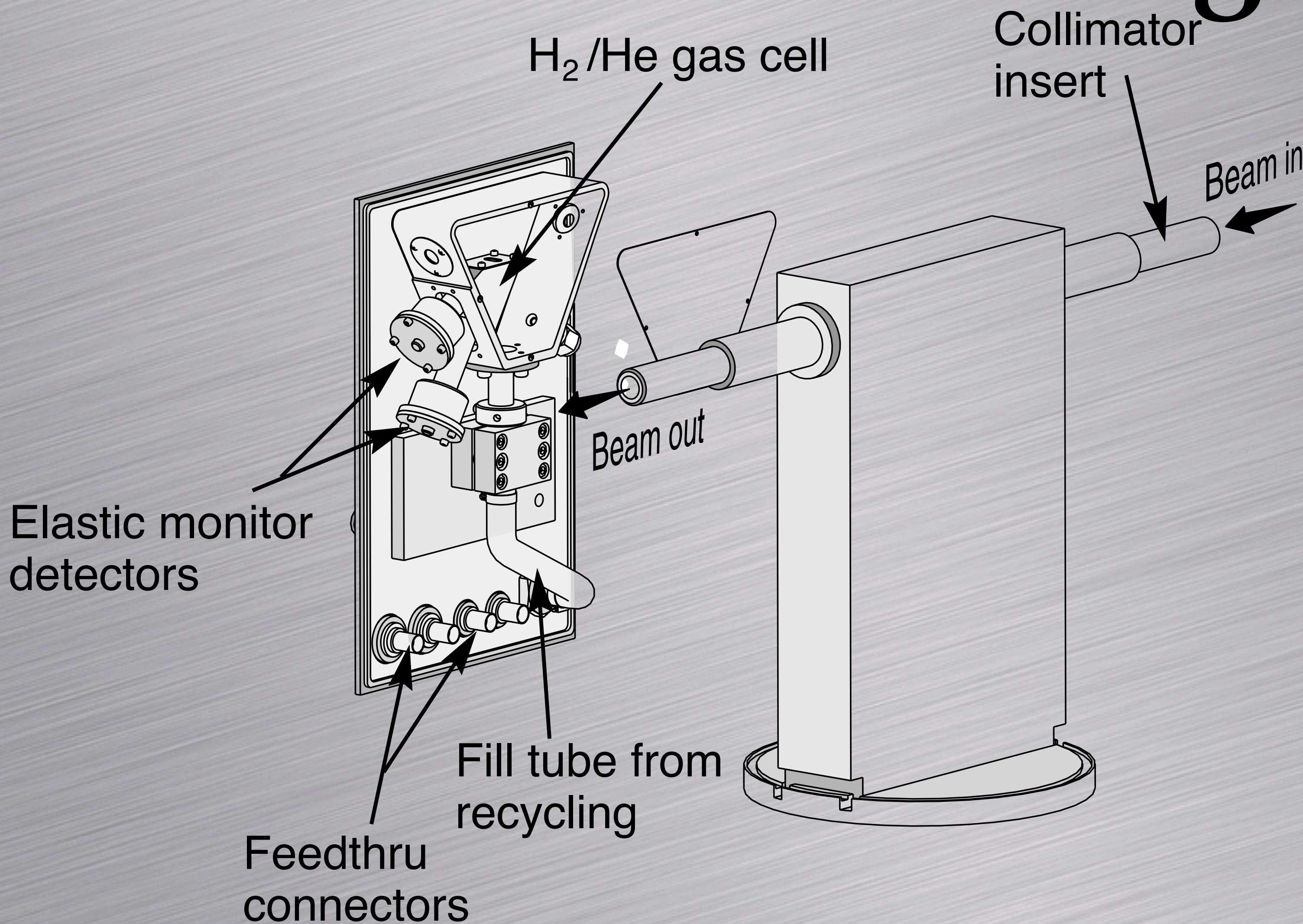


Beam Suppression



S. Engel *et al.*, NIM A 553 (2005) 491

Windowless Gas Target

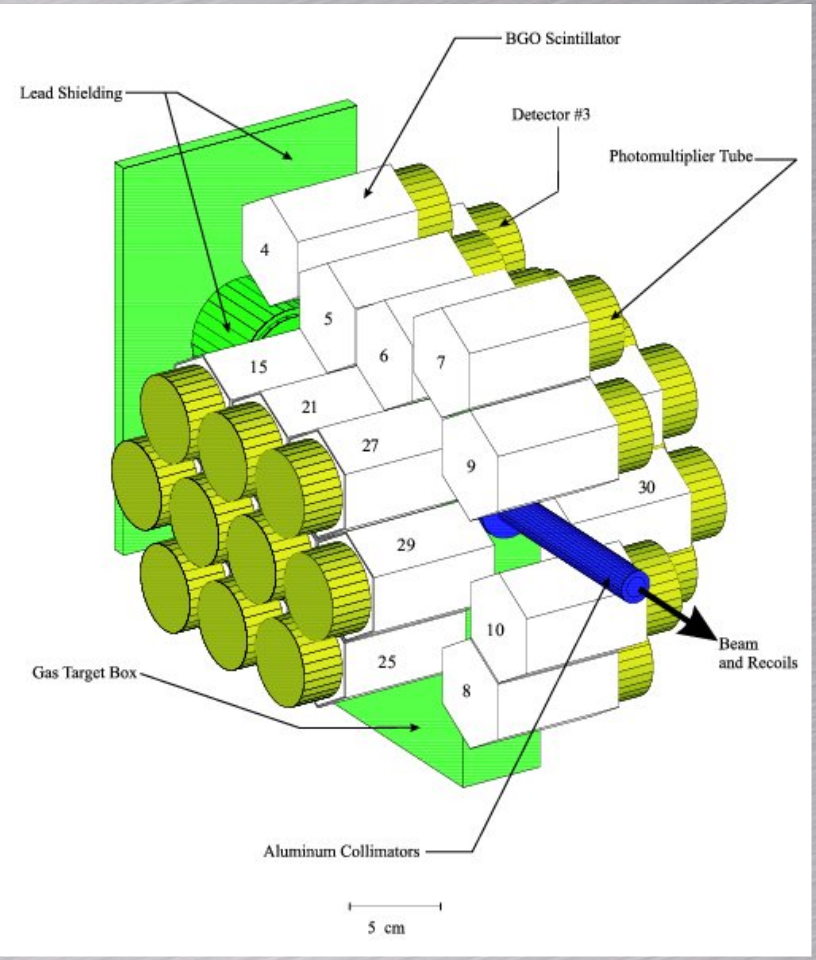


D.A. Hutcheon *et al.*, NIM A 498, 190 (2003)

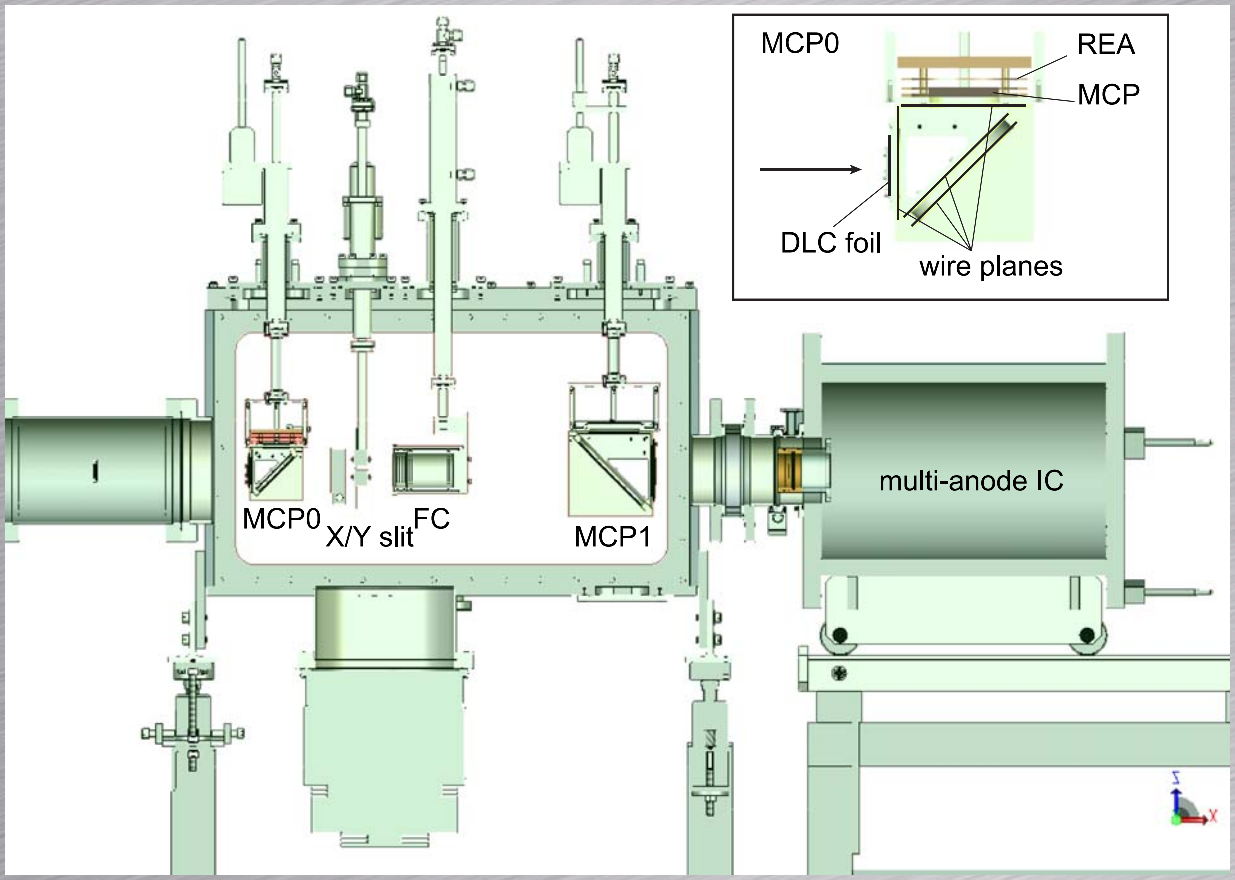
DRAGON Gamma Ray Detector Array

30 BGO γ ray detectors surrounding gas target

Geometric efficiency of 89-92%

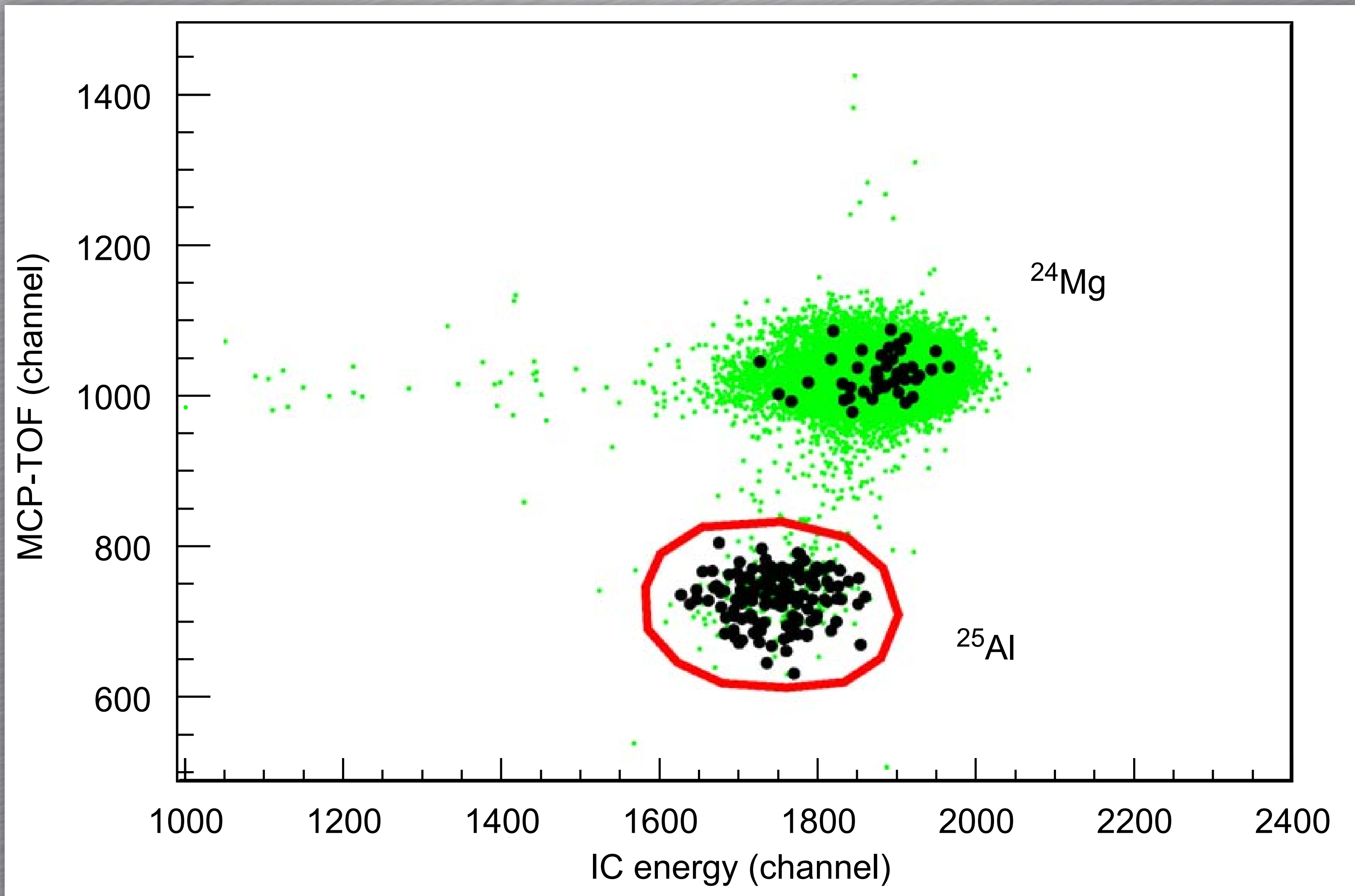


Focal Plane Detectors: Local Time-of-Flight System



- Two C foils separated by 59 cm generate secondary electrons detected by MCPs; 400 ps FWHM timing resolution
- Followed by Ionization Chamber or DSSD

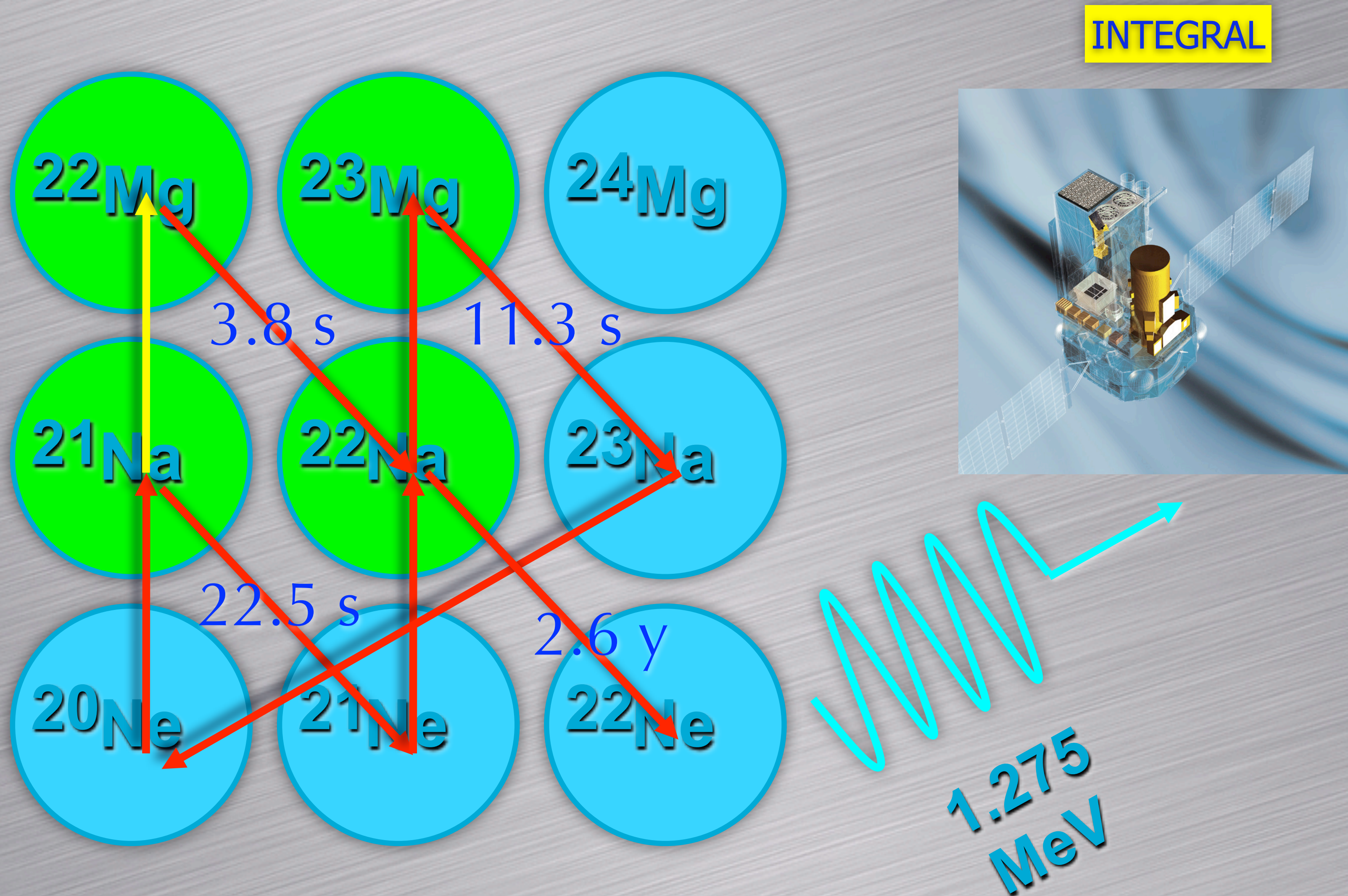
Particle Identification



$^{24}Mg(p,\gamma)^{25}Al$ at E_{rel} = 214 keV

C. Vockenhuber *et al.*, NIM A 603, 372-378 (2009)

^{22}Na formation: NeNaMg cycle



^{22}Na not observed by COMPTEL or INTEGRAL

Measurement of $^{21}Na(p,\gamma)^{22}Mg$

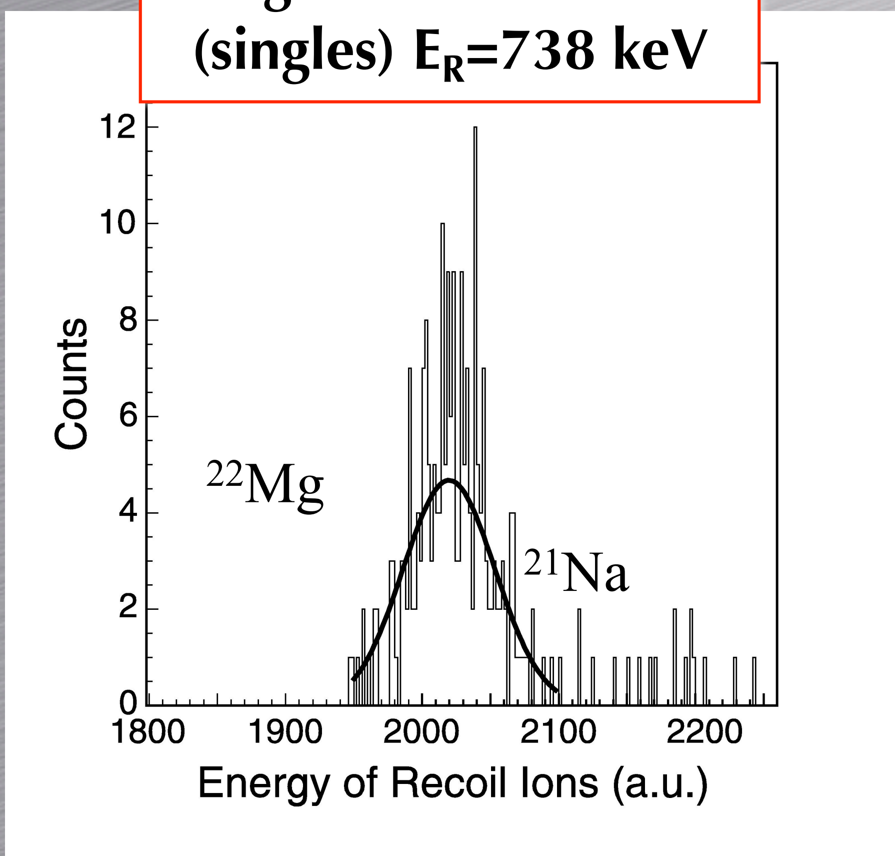
^{21}Na beam up to 2×10^9 per second

Determined resonance strengths for 7 states in ^{22}Mg between 200 and 1103 keV

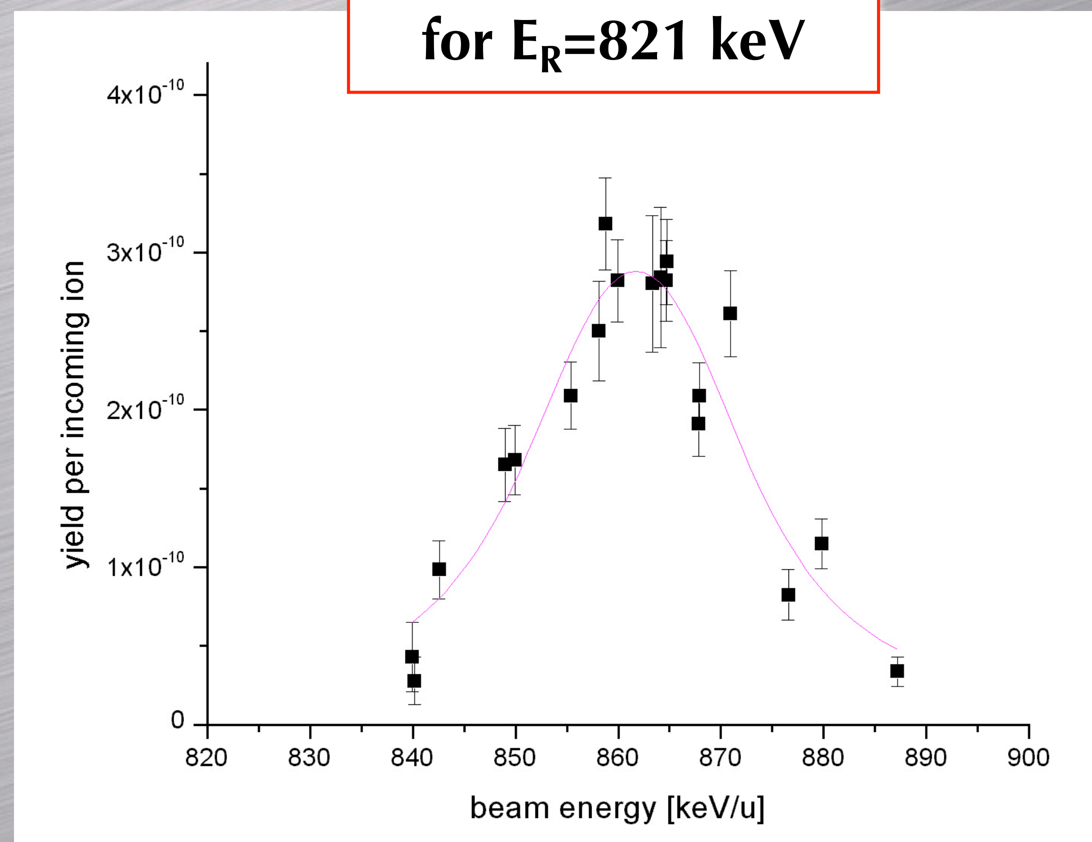
Detected recoils alone or in coincidence with prompt γ rays

D'Auria et al., PRC 69, 065803 (2004)

^{22}Mg recoils in DSSSD (singles) E_R=738 keV



Excitation function for E_R=821 keV

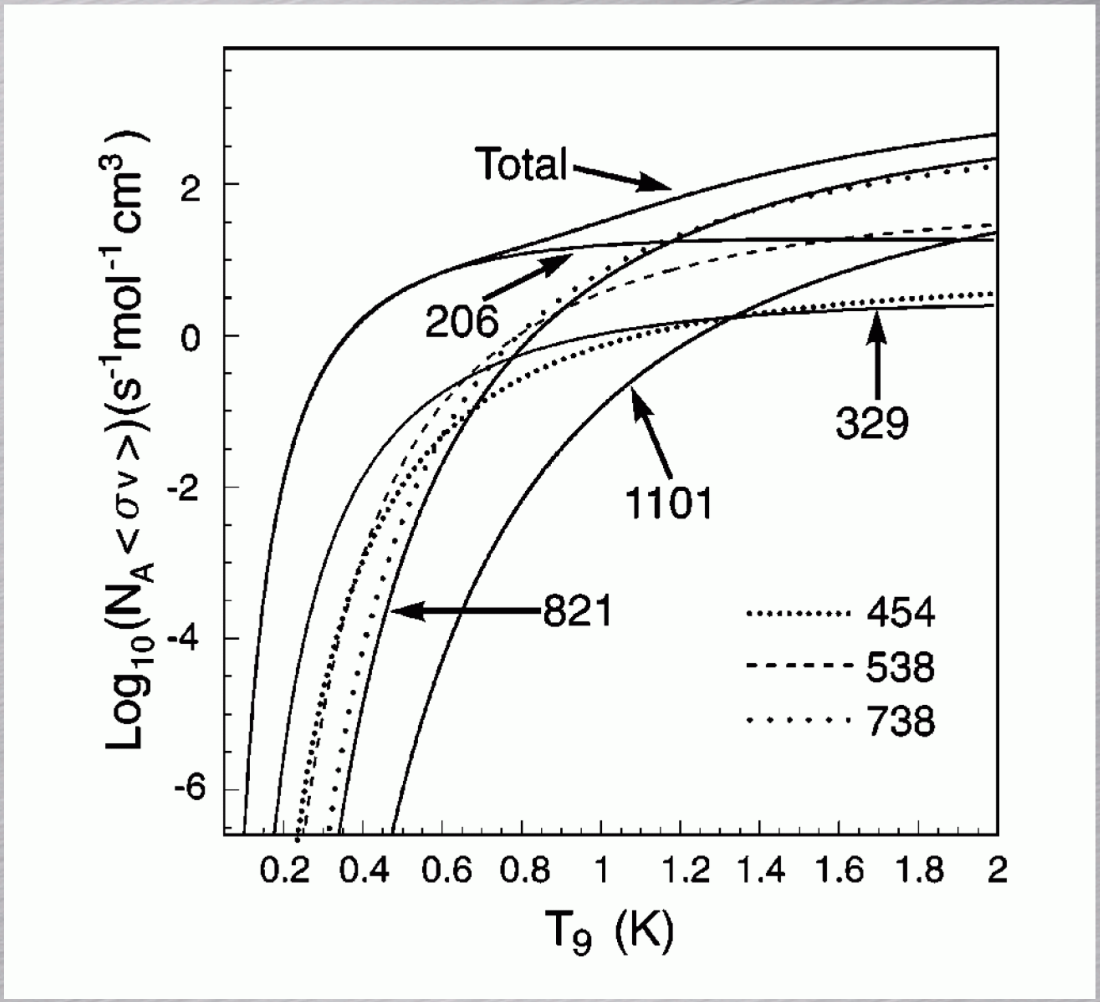


Estimated reaction rate for $^{21}Na(p,\gamma)^{22}Mg$ based on DRAGON data

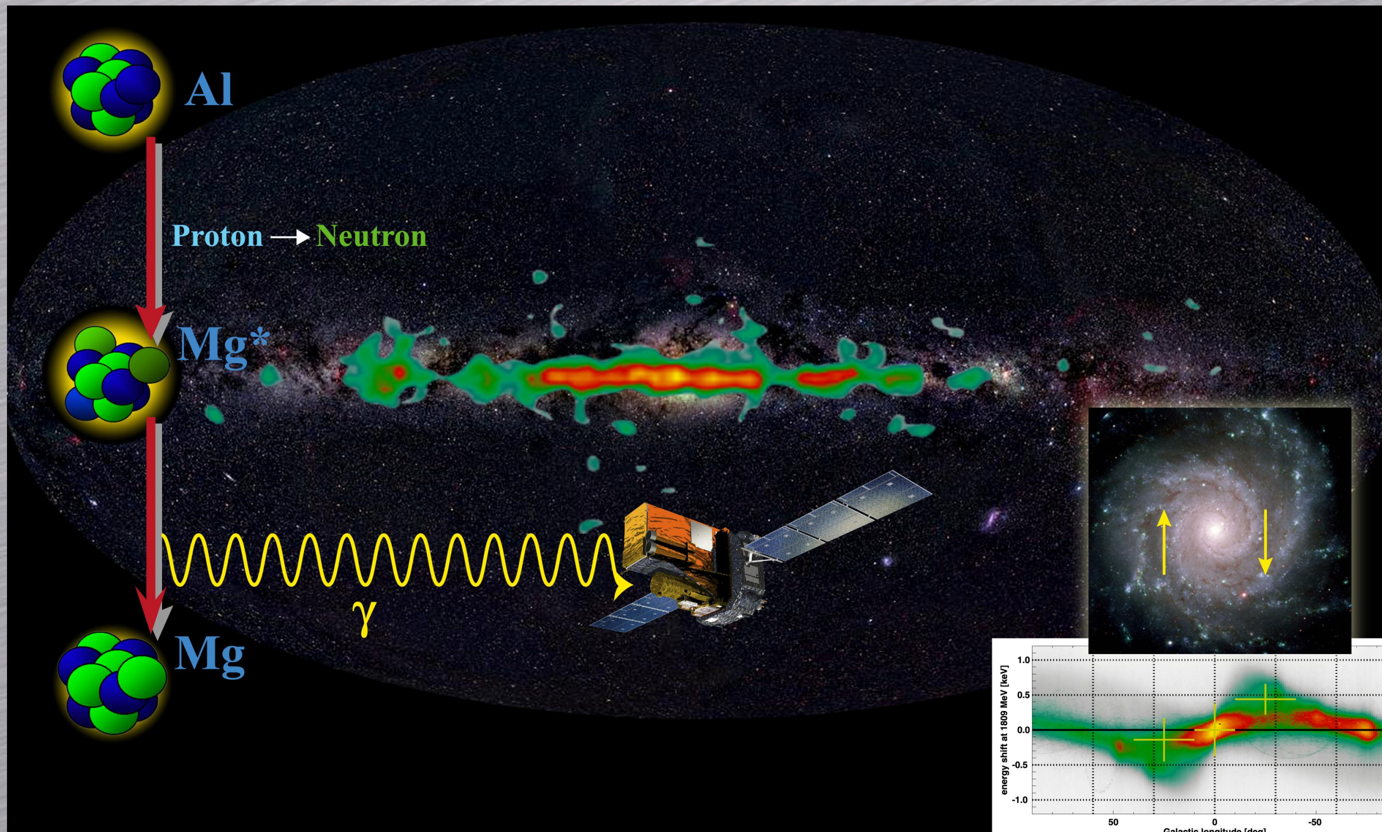
The lowest measured state at 5.714 MeV (E_{cm} = 206 keV) dominates for all nova temperatures and up to about 1.1 GK

Updated nova models showed that ^{22}Na production occurs earlier than previously thought while the envelope is still hot and dense enough for the ^{22}Na to be destroyed, resulting in lower final abundance of ^{22}Na

Reaction not significant for X-ray bursts



^{26}Al in the Milky Way



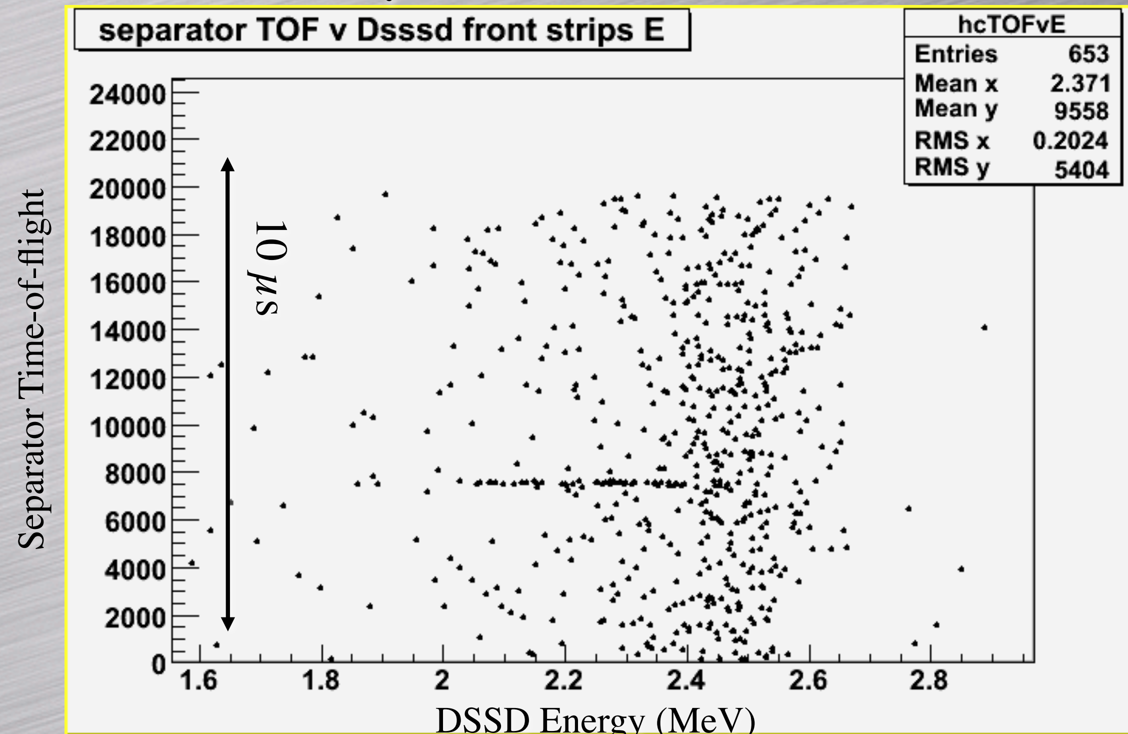
- Radioactive decay with mean lifetime 1 My: 1.8 MeV γ ray
- Galactic inventory ~ 3 solar masses
- Is ^{26}Al formed in novae as well as massive stars?
- Must measure rates of nuclear reactions that create and destroy ^{26}Al in novae to find out

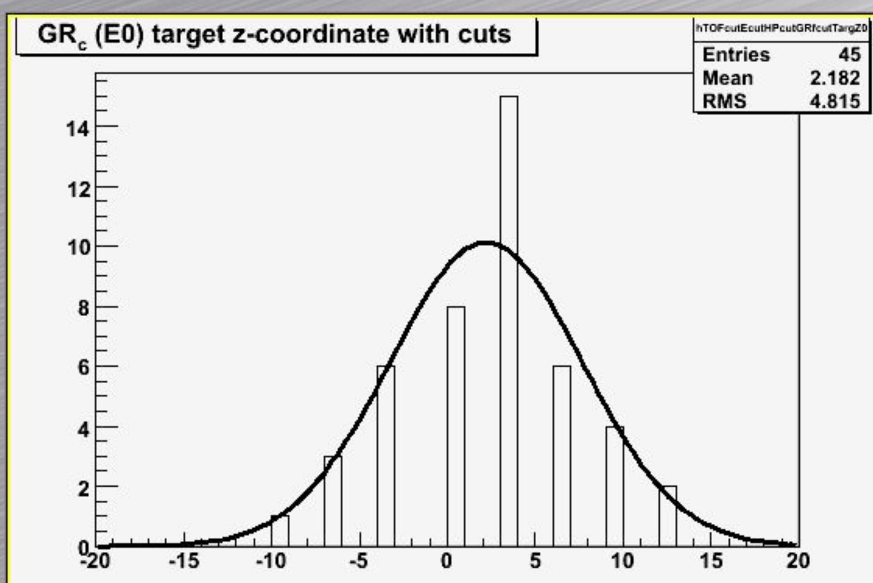
$^{26}Al + p \rightarrow ^{27}Si + \gamma$

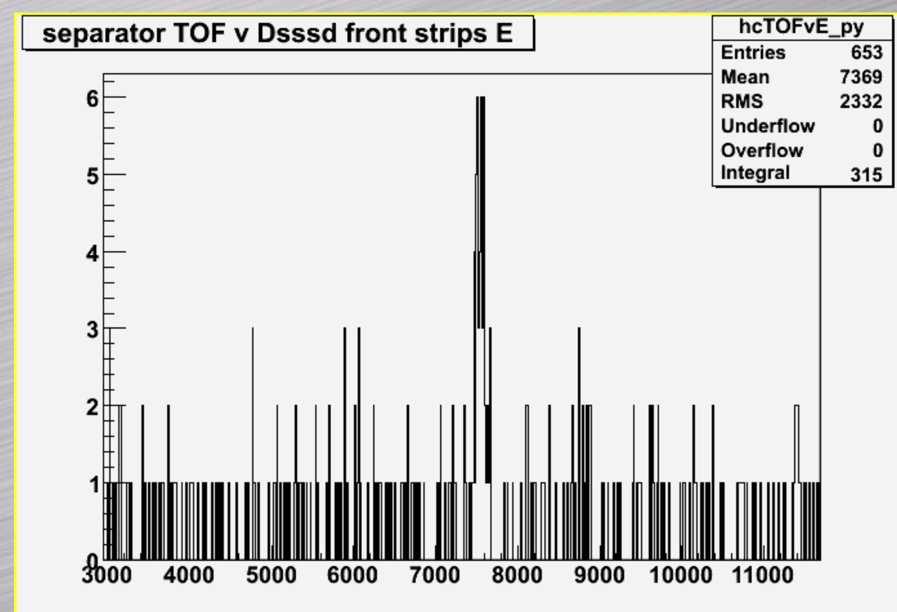
Average ^{26}Al beam intensity of 3.4 billion s^{-1}

Measured cross section of 184 keV resonance suggests novae are not dominant source of galactic ^{26}Al

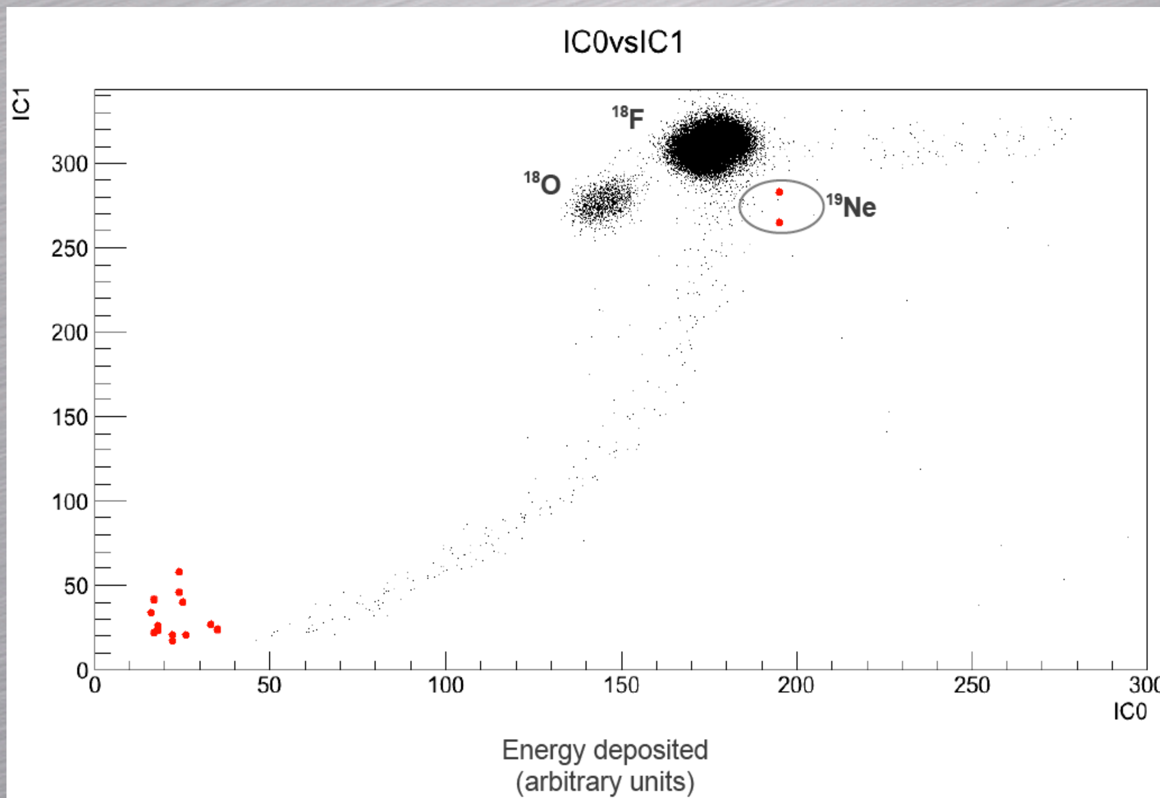
Ruiz *et al.*, PRL 96, 252501 (2006)







$^{18}F(p,\gamma)^{19}Ne$ Measurement



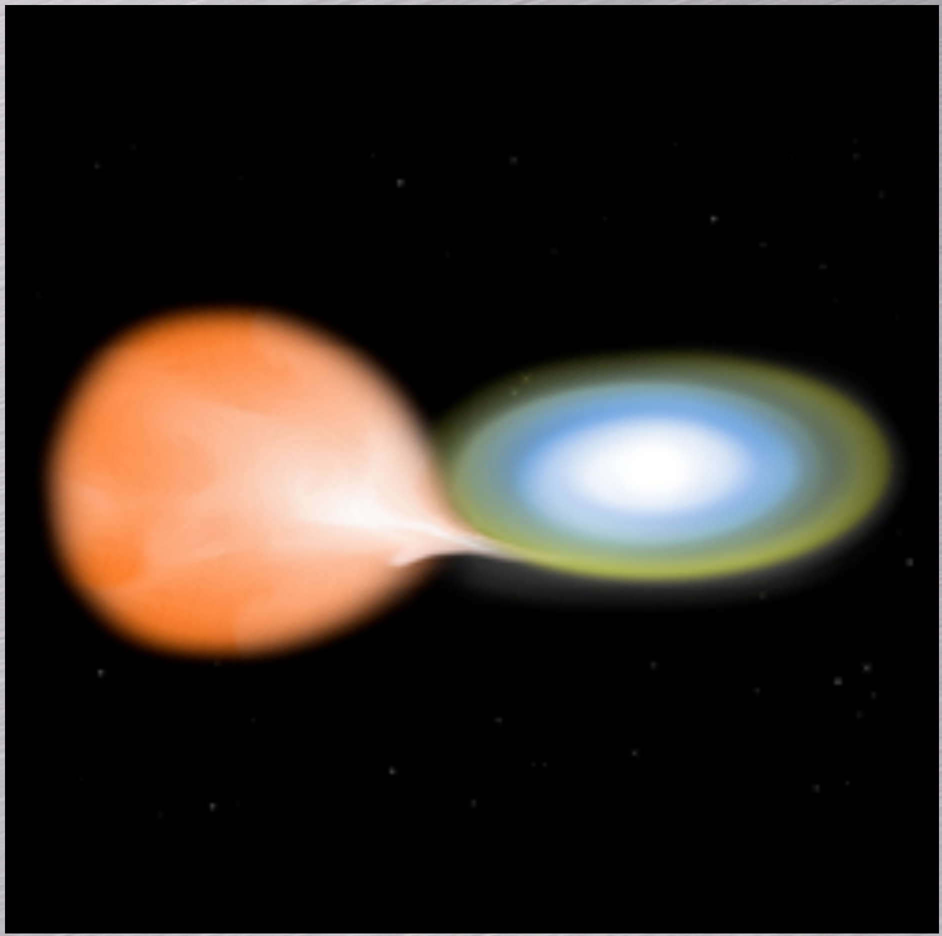
Measured at 665 keV resonance

Previously only upper limit from Rehm *et al.*, PRC 55, 566 (1997)

Resonance strength ~ 10 meV, not an important contributor

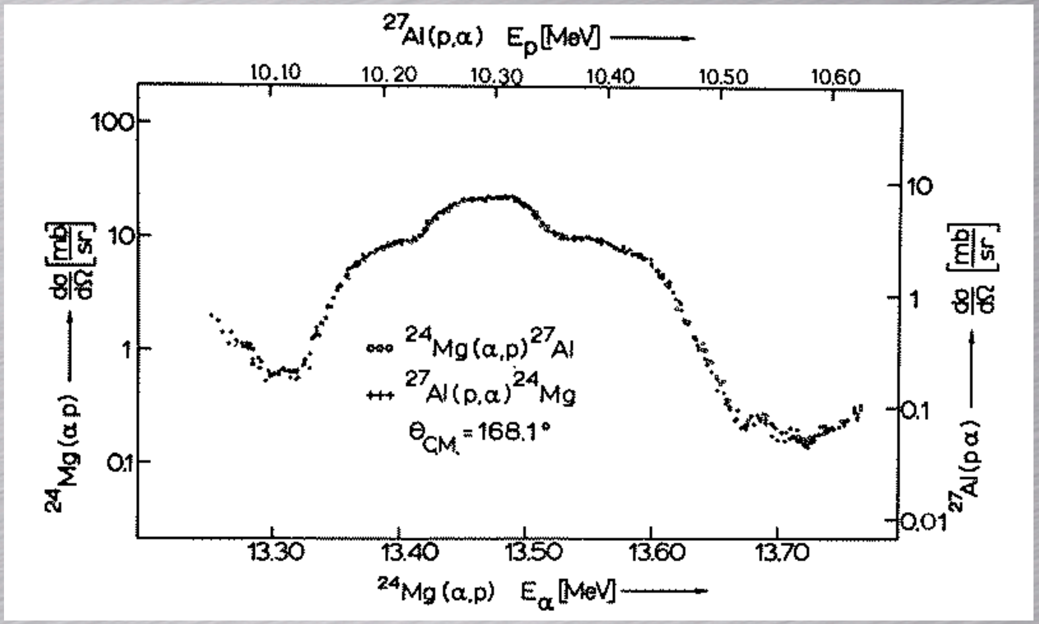
Type I X-Ray Bursts

- Accretion of hydrogen & helium from ordinary star onto neutron star via accretion disk in binary system triggers thermonuclear explosion
- Accreted layer of material heats up to ~ 1GK in < 1 s, cools over ~ 10-100 s
- Thermal emission from surface peaks in x-ray part of em spectrum, visible as Type I x-ray burst
- Explosion confined to thin shell on surface, repeats after further accretion



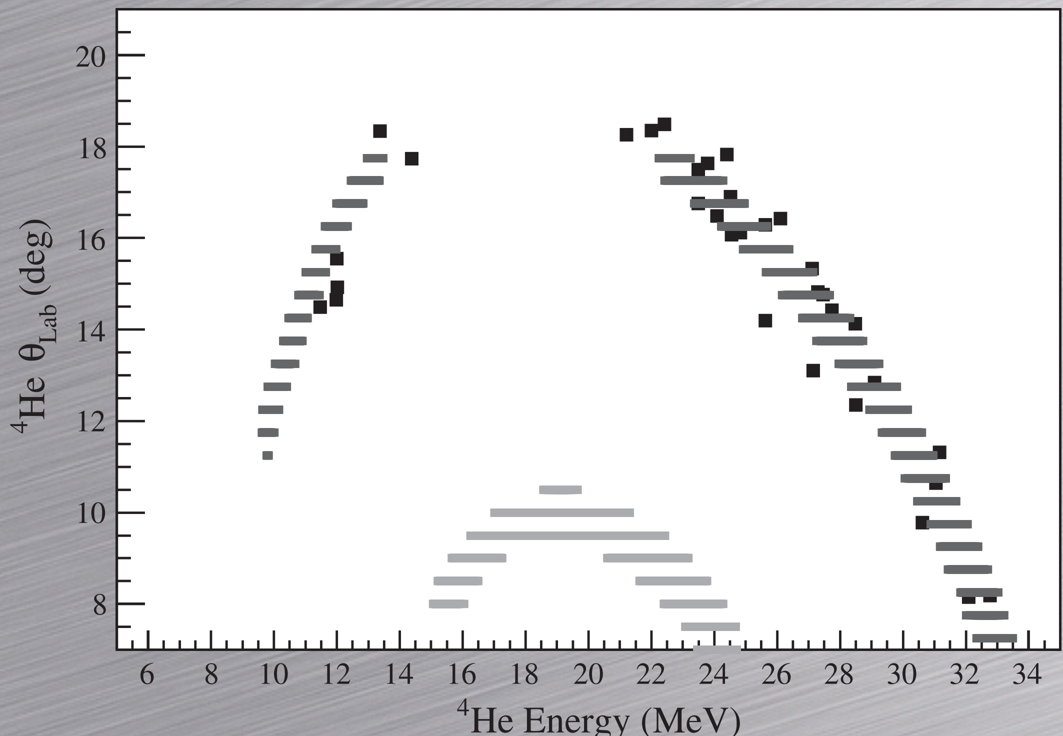
Inverse Reactions

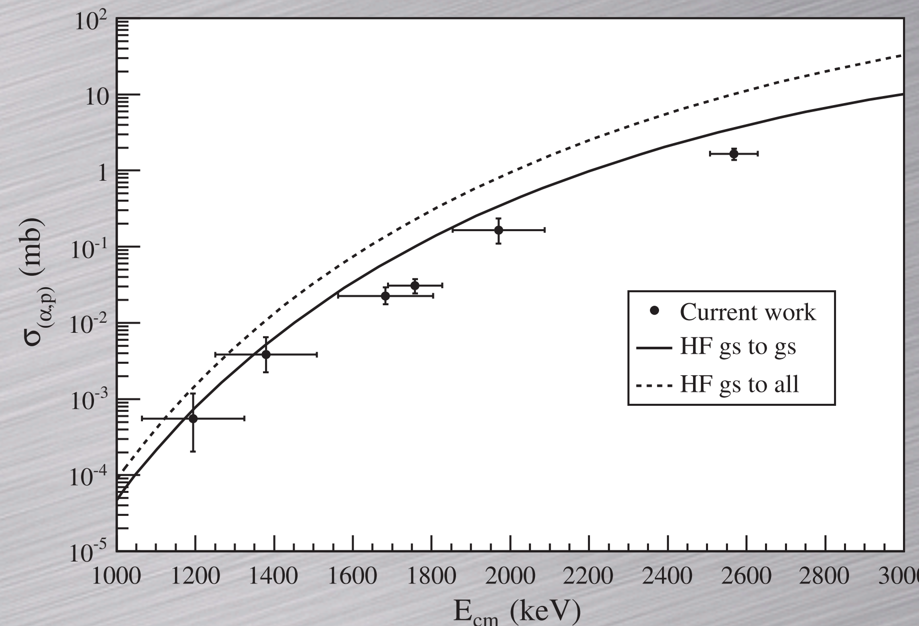
- Time-invariance of interactions implies that time-reversed reaction rates related by detailed balance theorem



$$\frac{\sigma(i \to f)}{(2J_b+1)(2J_T+1)p_i^2} = \frac{\sigma(f \to i)}{(2J_e+1)(2J_R+1)p_f^2}$$

$p(^{21}Na,\alpha)^{18}Ne$





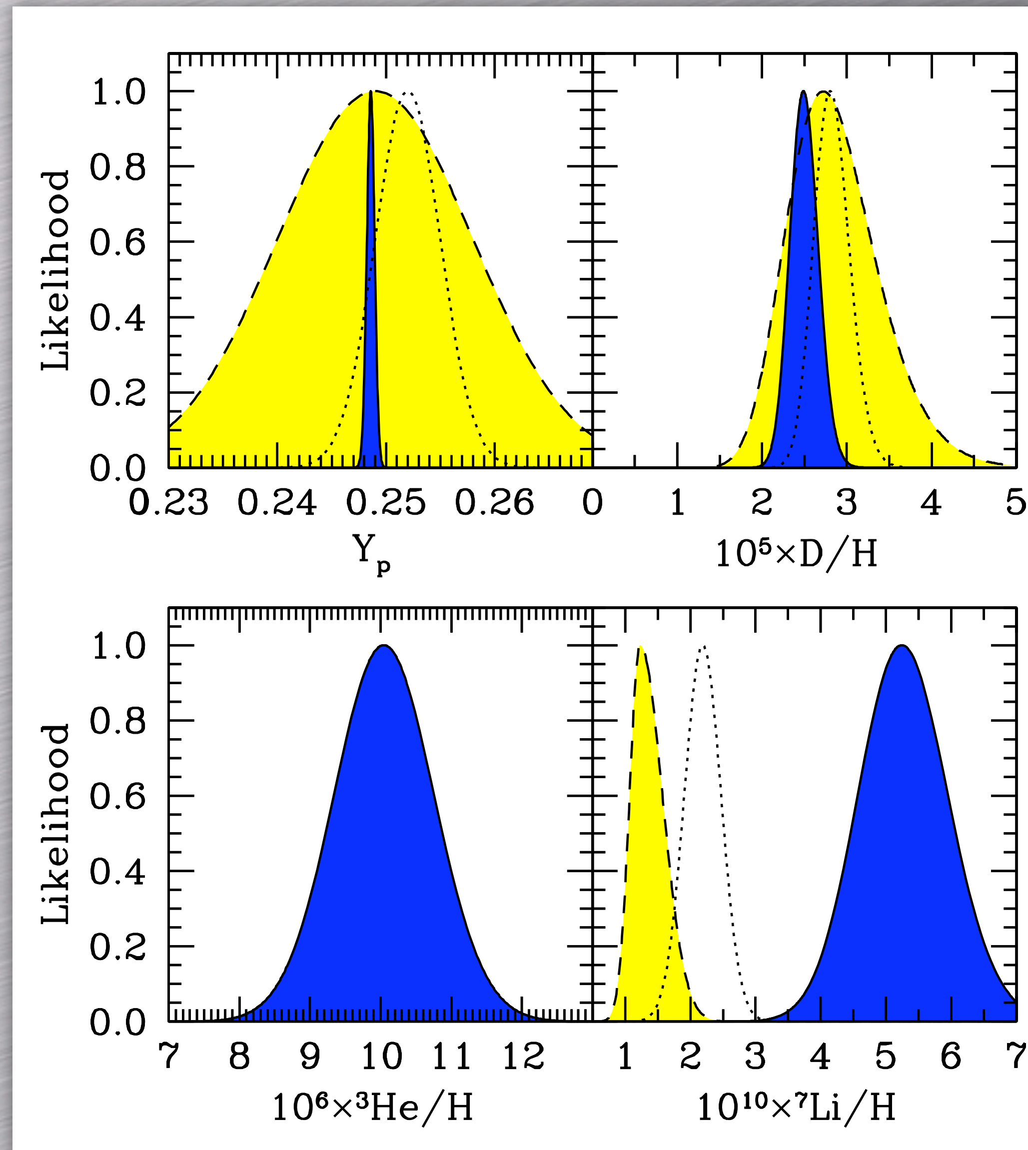
$^{18}Ne(\alpha,p)^{21}Na$ a breakout reaction from hot CNO cycles

Use detailed balance to relate (p,α) and (α,p) rates (g.s. only)

Salter *et al.*, Physical Review Letters 108, 242701 (2012)

^{7}Li in Big Bang Nucleosynthesis

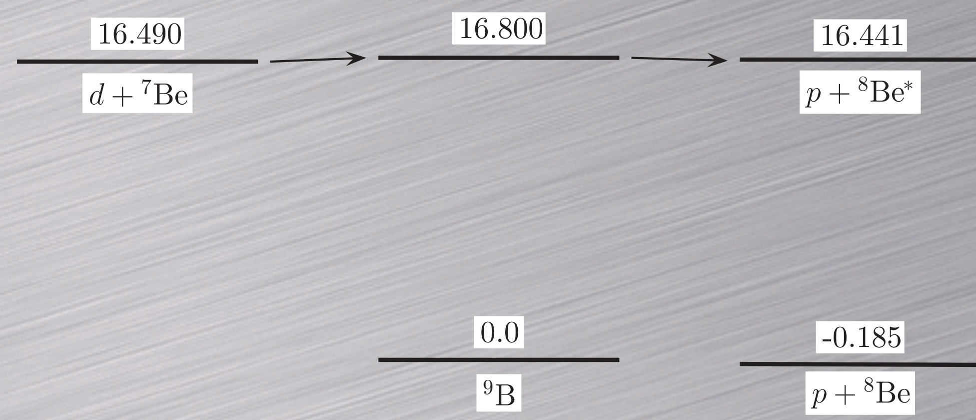
- BBN a robust prediction of hot big bang cosmology for > 40 yr
- Explains origin of large universal He abundance, trace quantities of D, ^{3}He, & ^{7}Li
- Given general relativity, cosmological principle, abundance predictions depend only on mean lifetime of neutron, number of active, light neutrino flavours, universal baryon density, and nuclear reaction rates
- ^{7}Li produced via ^{3}He$(\alpha,\gamma)^7$Be
- Primordial ^{7}Li abundance proportional to $S_{34}(300\ \text{keV})^{0.96}$

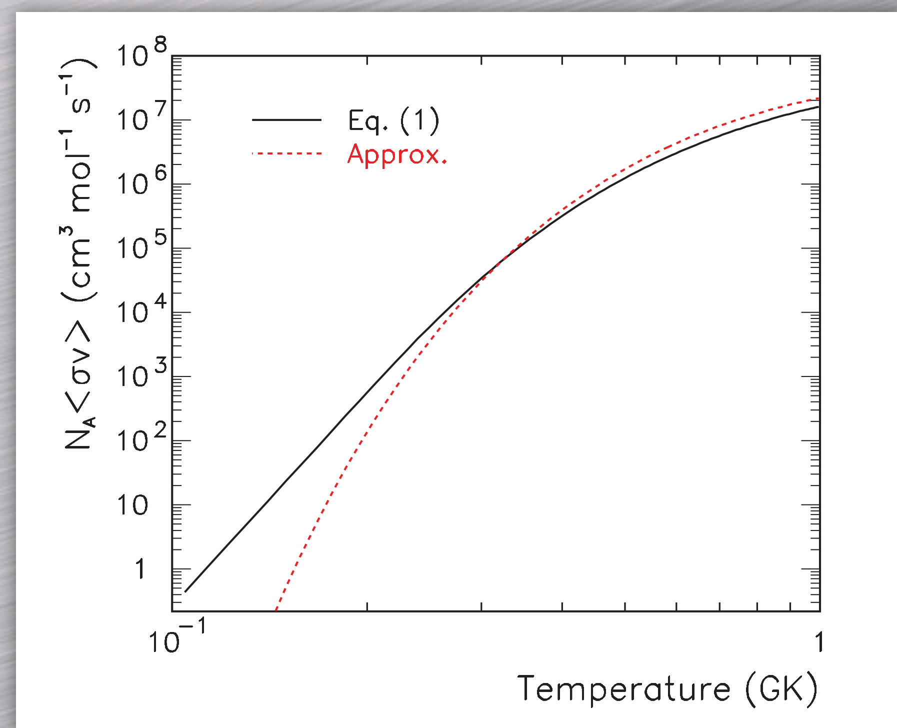


Cyburt *et al.*, JCAP 11, 012 (2008)

Proposed BBN ^{7}Be Destruction Mechanism

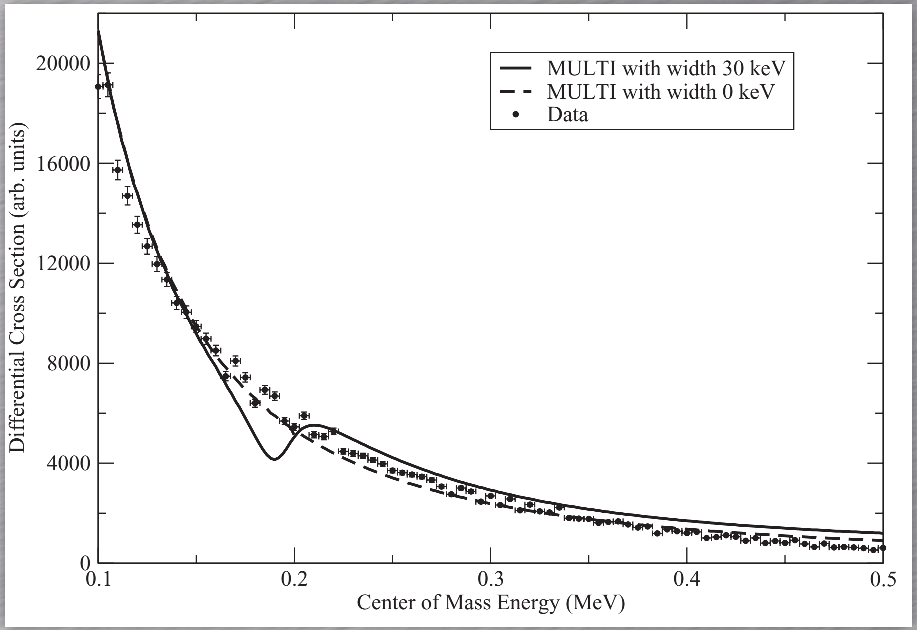
- Cyburt and Pospelov proposed resonant destruction of ^{7}Be via ^{7}Be(d,p)^{8}Be* reaction (IJMPE 21, 1250004, 2012) if 5/2+ resonance in ^{9}B had E_r = 170-220 keV, Γ = 10-40 keV
- Before we could look for it, Scholl *et al.* found it (but didn't know it) while studying GT transitions in the A = 9 system using ^{9}Be(^{3}He,t)^{9}B reaction (PRC 84, 014308, 2011)
- Resonance has E_r = 310(10) keV, Γ = 81(5) keV
- Checked effect on BBN using Kawano-Wagoner code, without narrow resonance approximation, reduction of ^{7}Be abundance strictly less than 3.5(8)%
- Kirsebom & Davids, PRC 84, 055801 (2011)





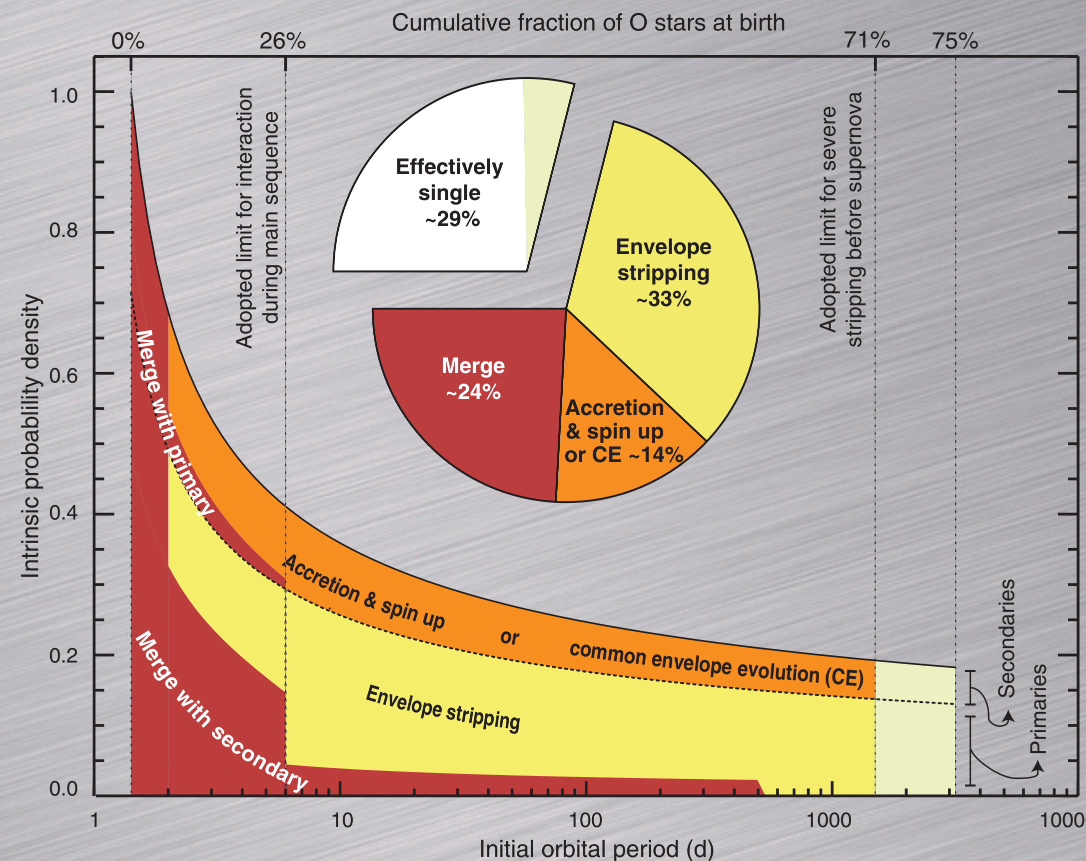
Direct search via ^{7}Be + d

- Direct search for resonances in ^{7}Be + *d* elastic scattering
- ORNL, beam intensity of 5×10^4 s^{-1}
- O'Malley *et al.*, PRC 84, 042801 (2011)



Massive Star Evolution

- New observational studies of O type stars quantified frequency and nature of binary interactions
- If correct, they dominate massive star evolution
- Sana *et al.*, Science 337, 444 (2012)



Solar System Abundances