Nuclear Astrophysics: A Few Basic Concepts and Some Outstanding Problems

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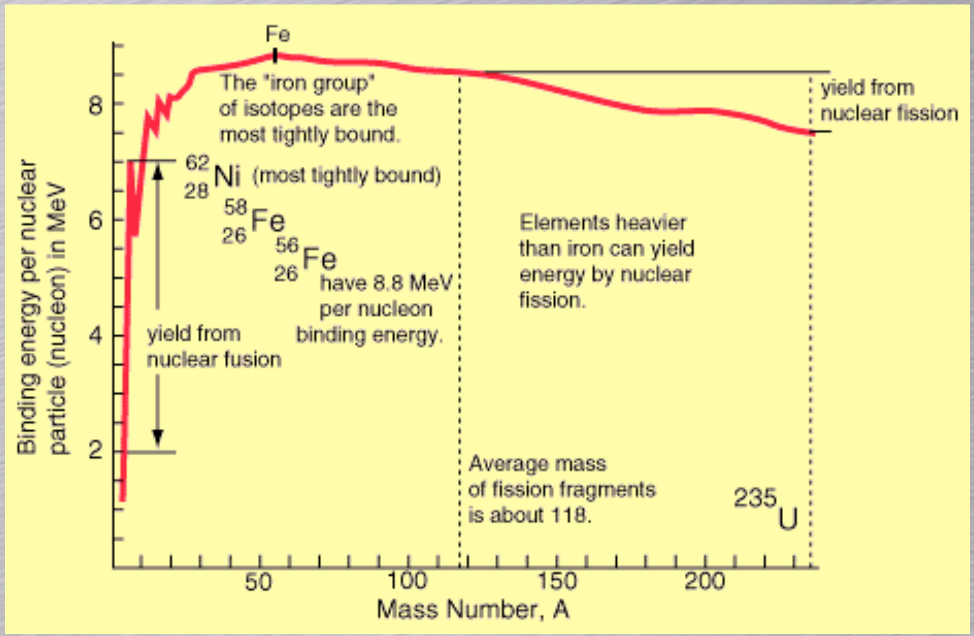
Exotic Beams Summer School 2012

Aims of Nuclear Astrophysics

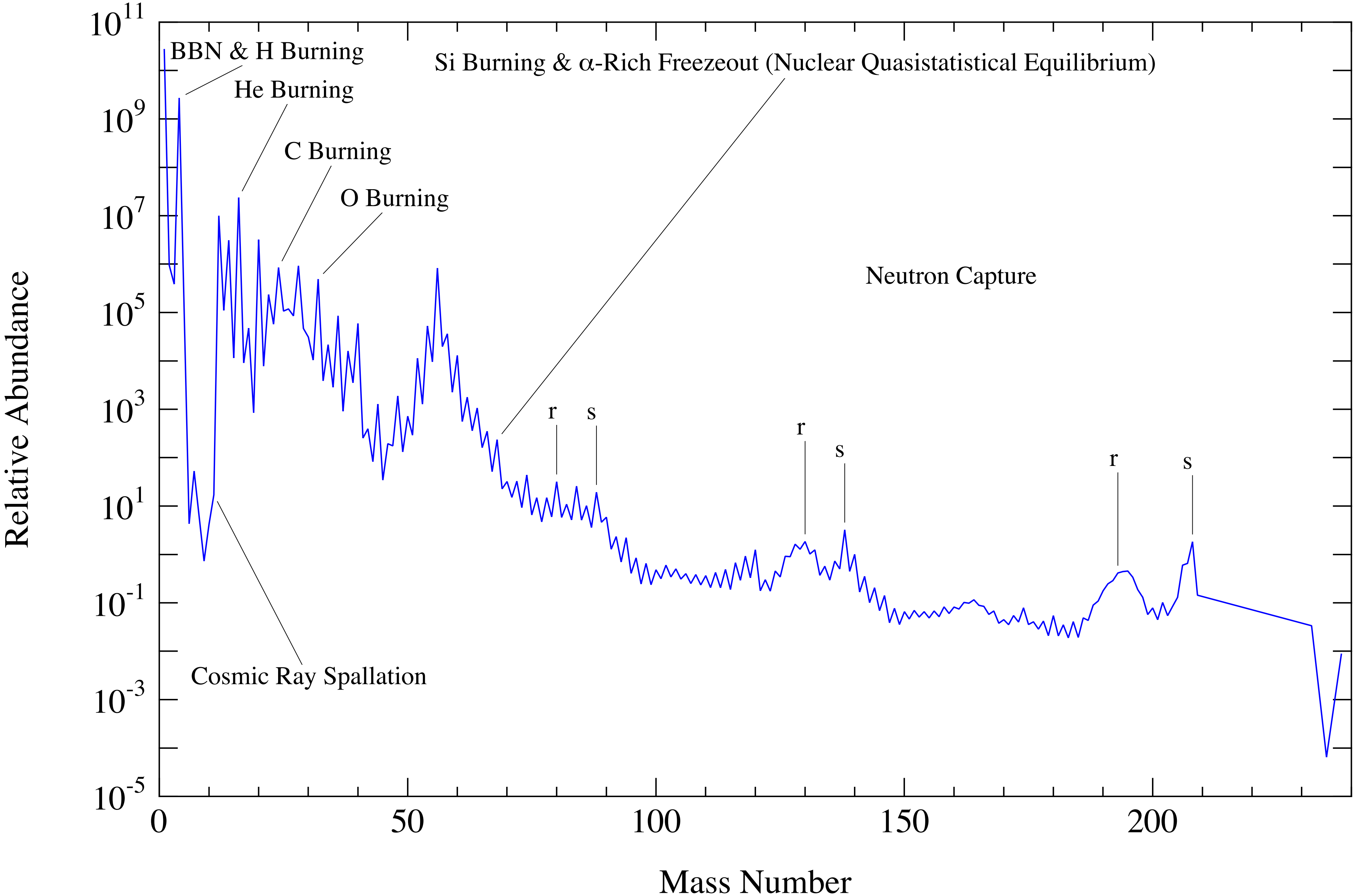
- How, when, and where were the chemical elements produced?
- What role do nuclei play in the liberation of energy in stars and stellar explosions?
- How are nuclear properties related to astronomical observables such as solar neutrino flux, γ rays emitted by astrophysical sources, light emitted by novae and x-ray bursts, et cetera?

Nuclear Astrophysics

- Nuclear reactions power the stars and synthesize the chemical elements
- We observe the elemental abundances through starlight and isotopic abundances in meteorites, and deduce the physical conditions required to produce them (Burbidge, Burbidge, Fowler and Hoyle, Reviews of Modern Physics 29, 547, 1957)
- Task of nuclear astrophysics is to understand abundances and energy release quantitatively

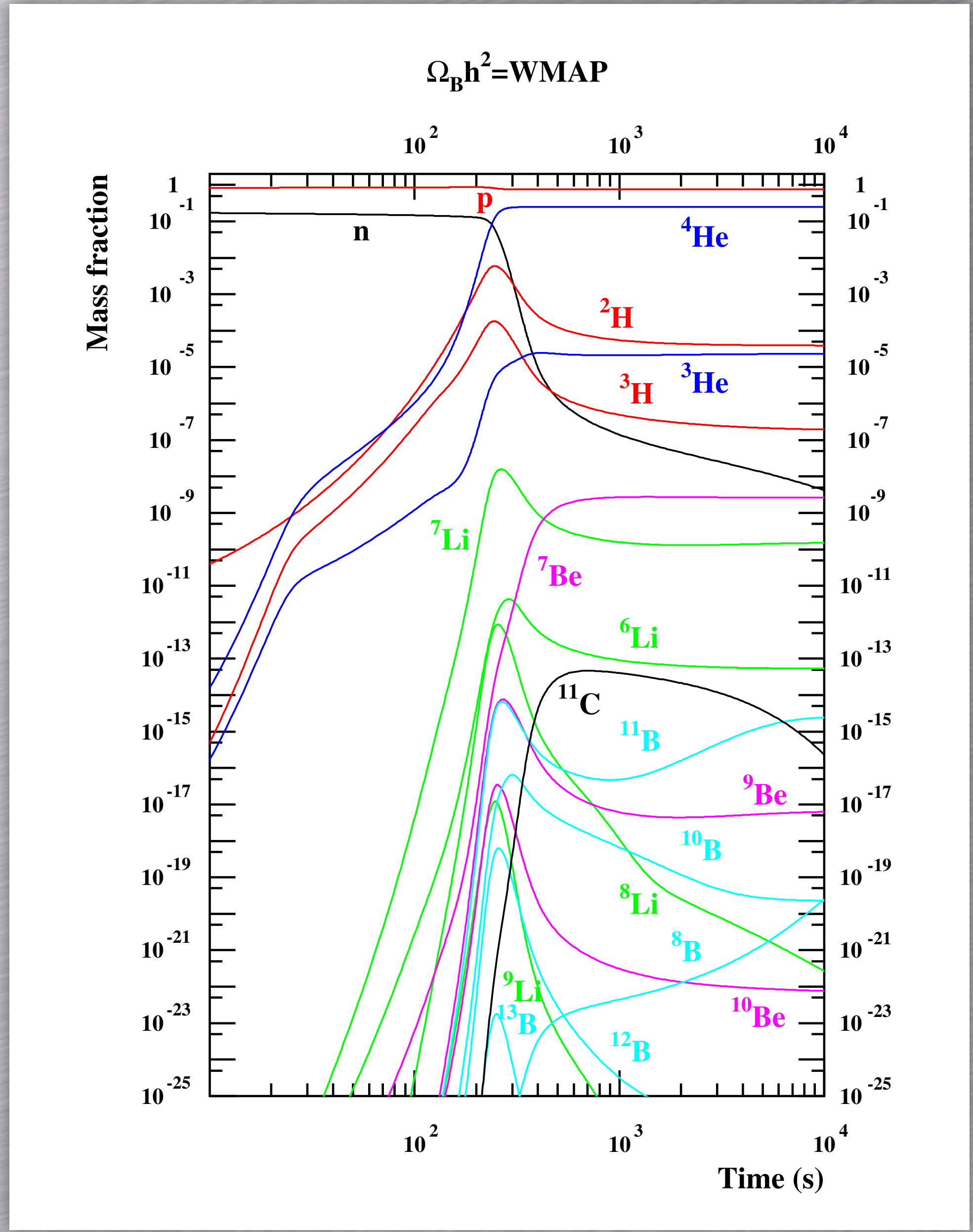


Solar System Abundances

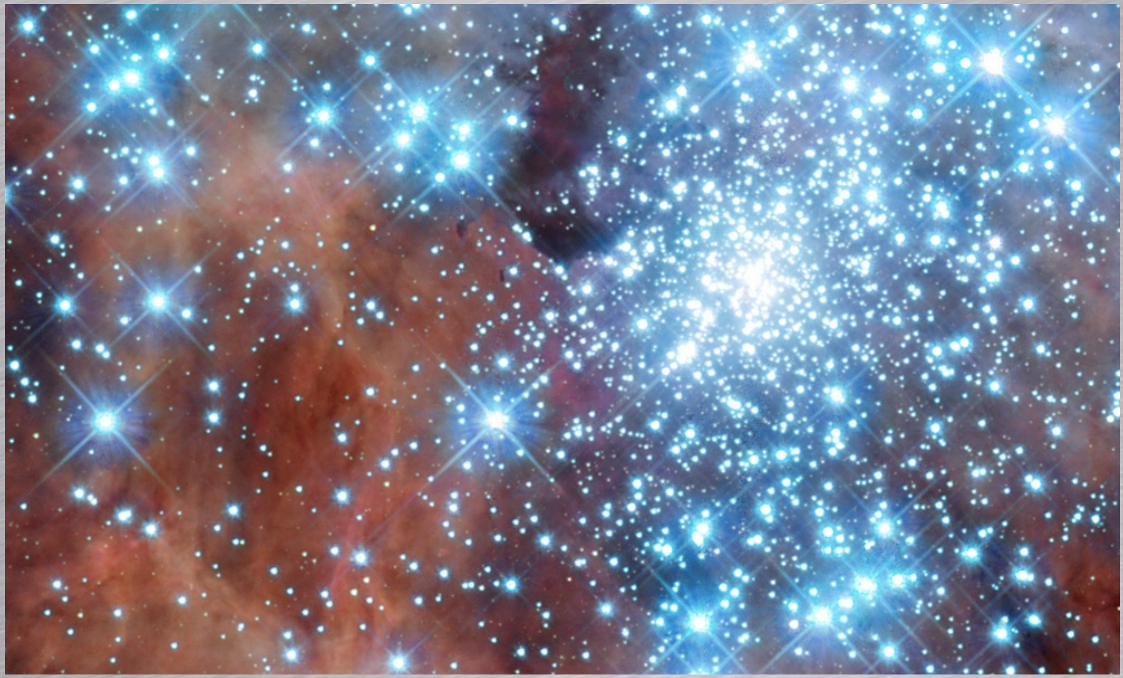


Primordial Nucleosynthesis

- Lightest nuclei produced during period of nuclear reactions in hot, dense, expanding universe
- Accounts for ^{2}H, ^{3}He, ^{4}He, and ^{7}Li
- Figure from Coc *et al.*, Astrophysical Journal 744, 158 (2012)



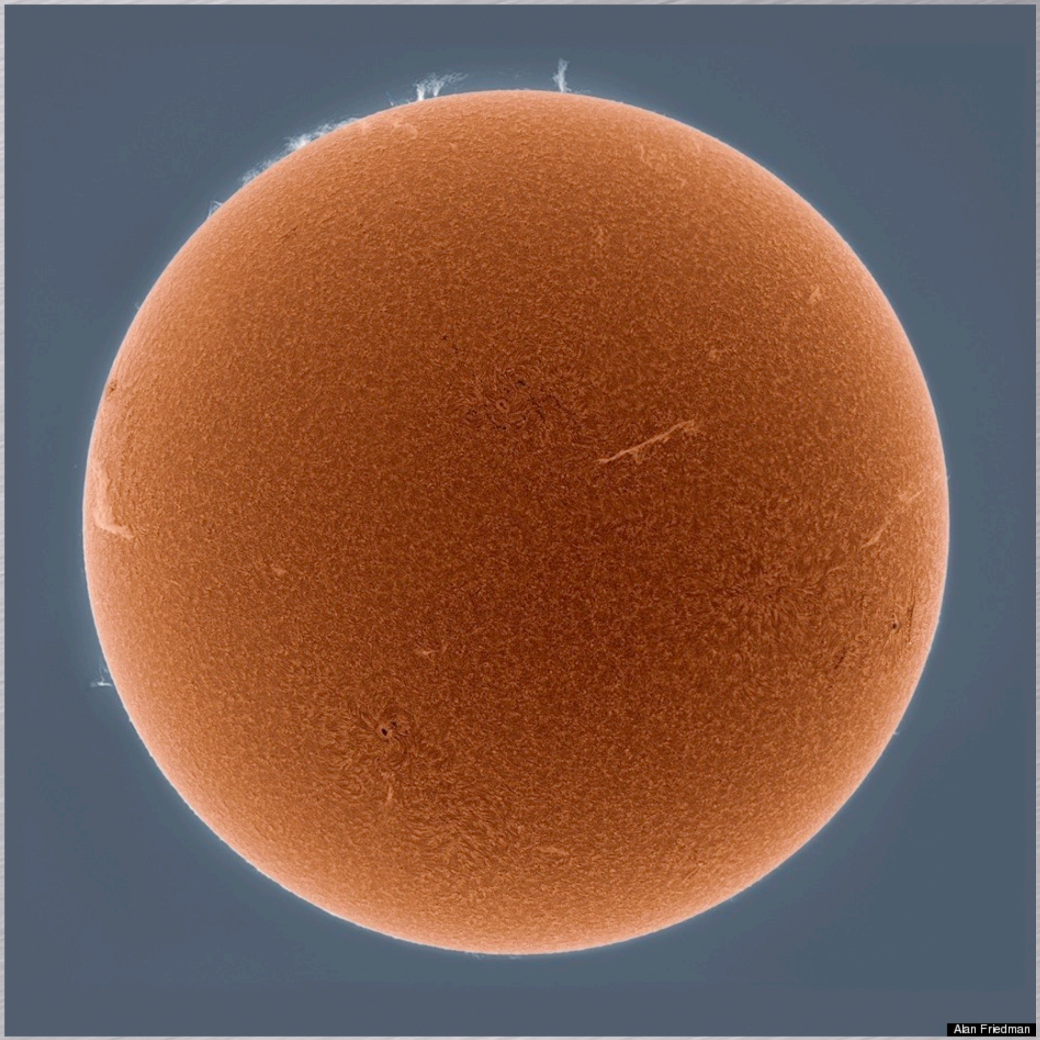
Stars



- Stars are hot balls of gas powered by internal nuclear energy sources
- The pressure at the centre must support the weight of the overlying layers: gravity tends to collapse a star under its own weight; as it shrinks, the pressure, temperature, and density all increase until the pressure balances gravity, and the star assumes a stable configuration
- For gas spheres at least 0.085 the mass of the Sun, the central temperature becomes hot enough to initiate thermonuclear fusion reactions
- Nuclear reactions in the hot, dense core are the power source of the Sun and all other stars

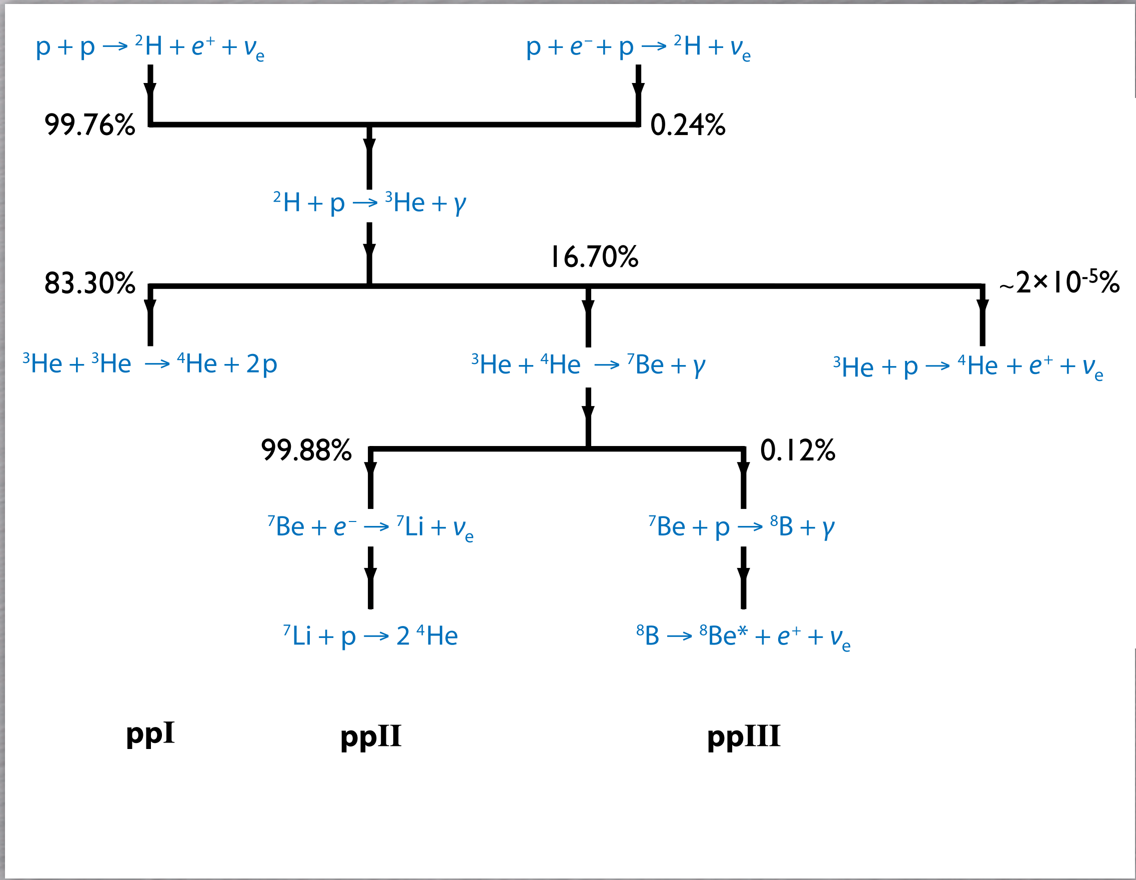
The Sun

- Solar centre is about 150 times the density of water (~8 times the density of uranium)
- Central pressure is > 200 billion atm
- Central temperature is 16 MK

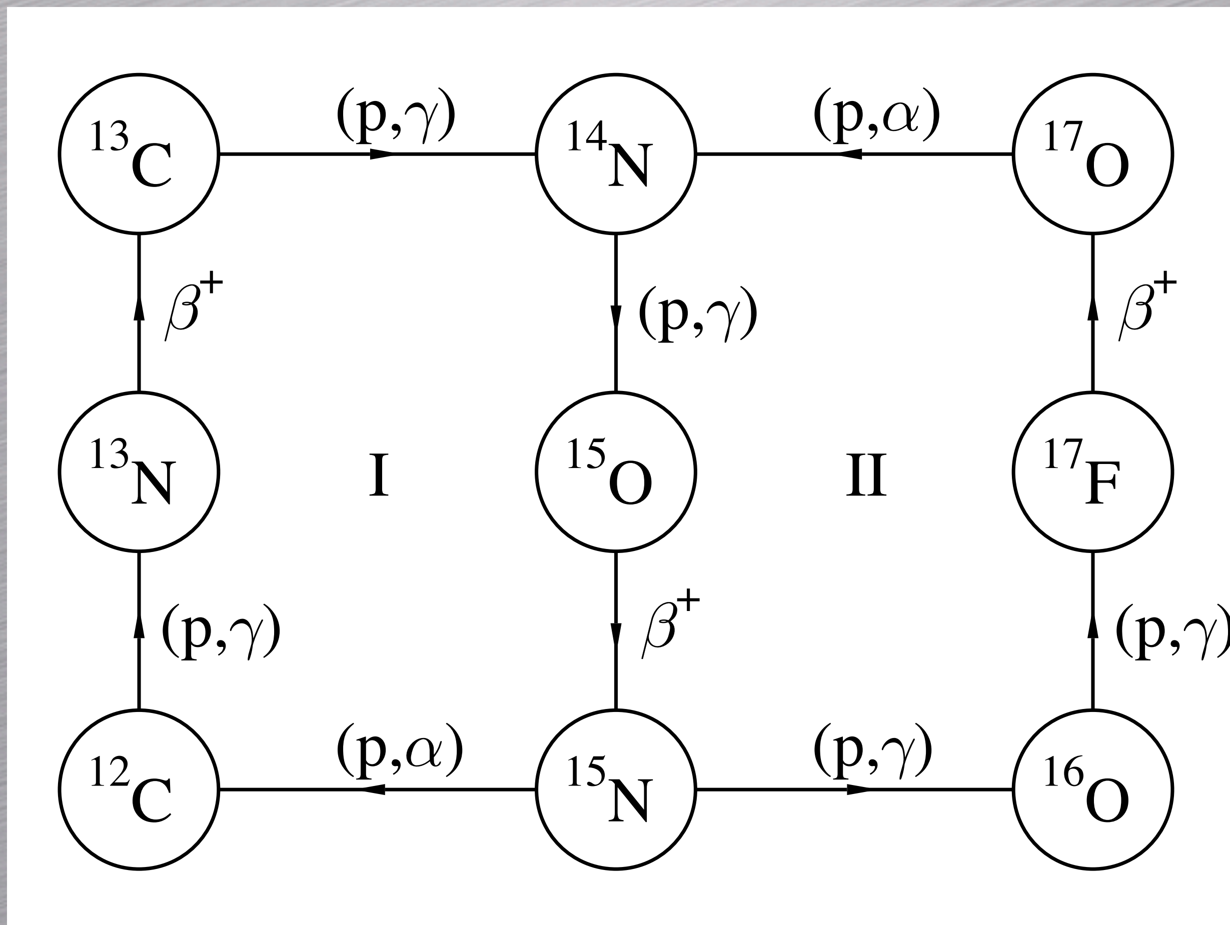


pp Chains

- Nuclear reaction rates determine energy release, neutrino production, and nucleosynthesis in Sun and other stars
- Adelberger *et al.*, Reviews of Modern Physics 83, 195 (2011)

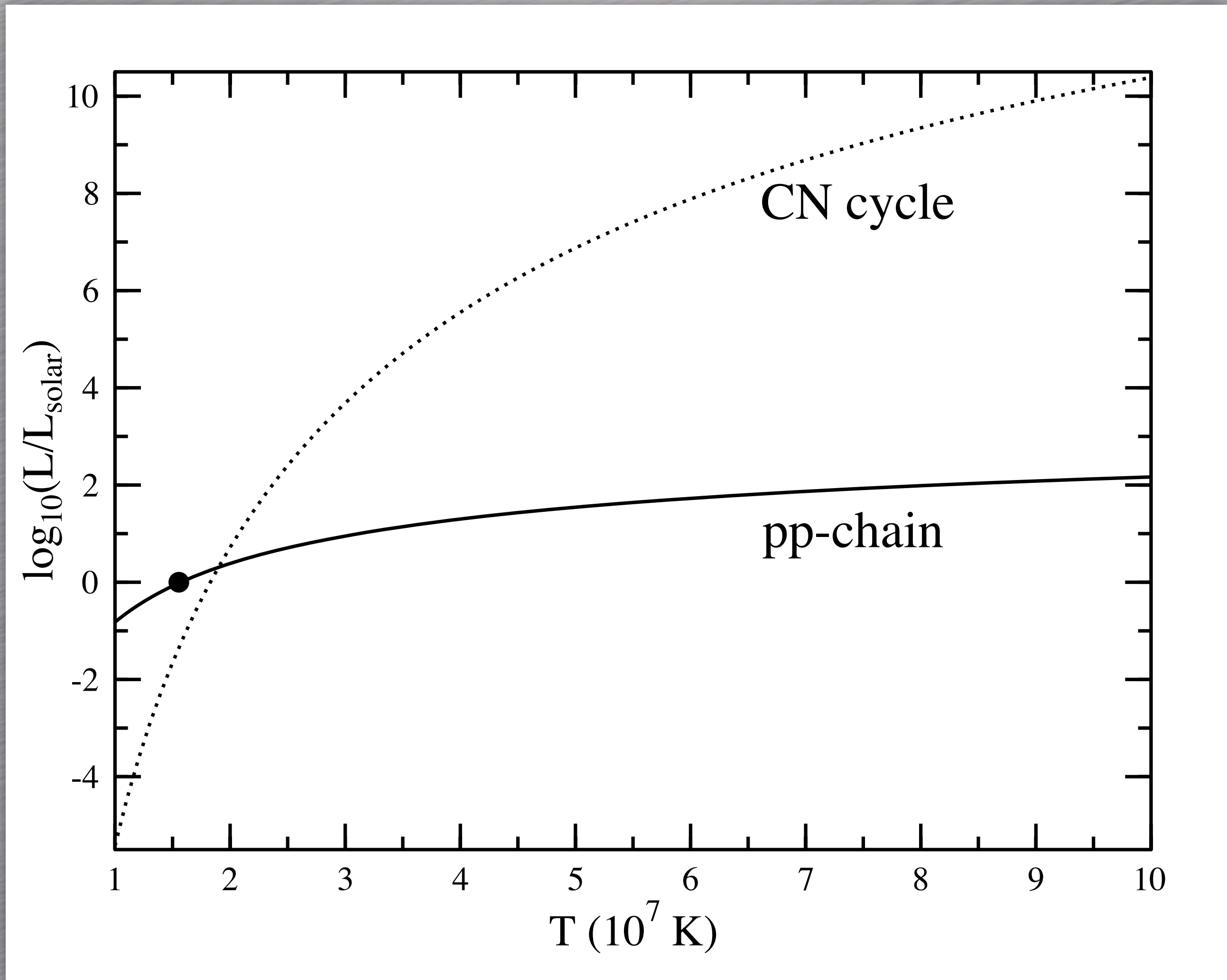


CNO Cycles

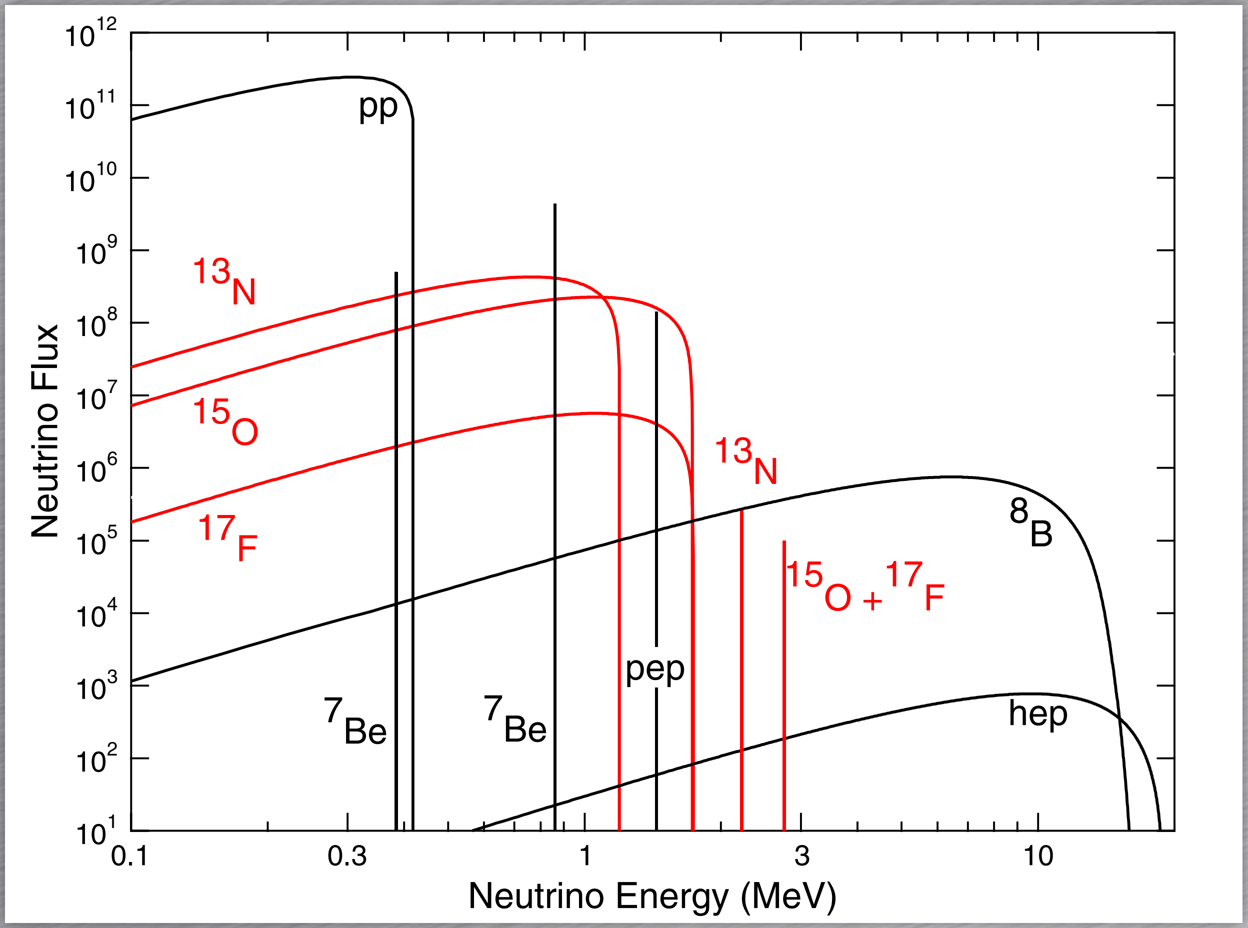


^{13}C
(p,γ)
^{14}N
(p,α)
^{17}O
β^+
(p,γ)
β^+
^{13}N
I
^{15}O
II
^{17}F
(p,γ)
β^+
(p,γ)
^{12}C
(p,α)
^{15}N
(p,γ)
^{16}O

Thermonuclear Power Sources



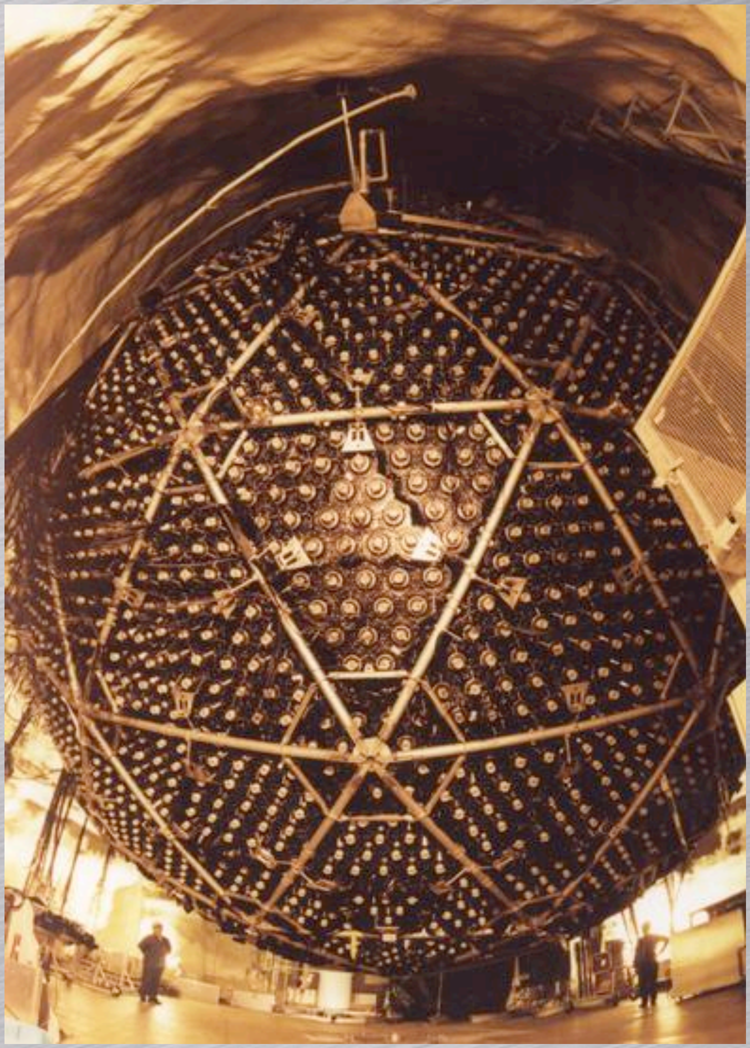
Solar Neutrino Fluxes



Stonehill, Formaggio, and Robertson, PRC 69, 015801 (2004)

Solar Neutrino Flux Measurements

- $^{3}He(\alpha,\gamma)^{7}Be$ and $^{7}Be(p,\gamma)^{8}B$ cross sections needed for predictions of solar neutrino fluxes
- ^{8}B solar ν flux now measured to ± 4.0% by SNO, ^{7}Be flux measured to ± 4.8% by Borexino
- $S_{34}(0)$ is the astrophysical S factor for the $^{3}He + \alpha \rightarrow {}^{7}Be + \gamma$ reaction at zero energy; most probable energy for reaction is 23 keV; $S_{17}(0)$ is the comparable quantity for the $^{7}Be(p,\gamma)^{8}B$ reaction
- ^{8}B flux $\propto S_{34}(0)^{0.81}, S_{17}(0)$
- ^{7}Be flux $\propto S_{34}(0)^{0.86}$



Reaction Rates

$$r = n_p\, n_t \int_0^\infty \sigma(v)\, \phi(v)\, v\, dv = n_p\, n_t < \sigma v >,$$

$$\tau_p(t) = \frac{1}{n_p < \sigma v >}, \text{ and analogously } \tau_t(p) = \frac{1}{n_t < \sigma v >}.$$

$$\frac{1}{\tau(t)} = \sum_{i=1}^{n} \frac{1}{\tau_i(t)}.$$

$$< \sigma v > = \sqrt{\frac{8}{\pi \mu}}\, (k\, T)^{-\frac{3}{2}} \int_0^\infty E\, \sigma(E)\, e^{-\frac{E}{k\, T}}\, dE.$$

Nonresonant Reaction Rates

$$\sigma(E) = \frac{S(E)}{E} e^{-\frac{2\pi Z_p Z_t e^2}{\hbar v}}, \text{ or } S(E) = E\,\sigma(E)\, e^{\frac{2\pi Z_p Z_t e^2}{\hbar v}}.$$

$$\sigma(E) = \frac{S(E)}{E} e^{-\frac{\pi Z_p Z_t e^2 \sqrt{2\mu}}{\hbar \sqrt{E}}} = \frac{S(E)}{E} e^{-\sqrt{\frac{E_G}{E}}}, \text{ where}$$

$$E_G = 2\mu \left(\frac{\pi Z_p Z_t e^2}{\hbar}\right)^2 = 2\,\mu c^2 \left(\pi Z_p Z_t \alpha\right)^2$$

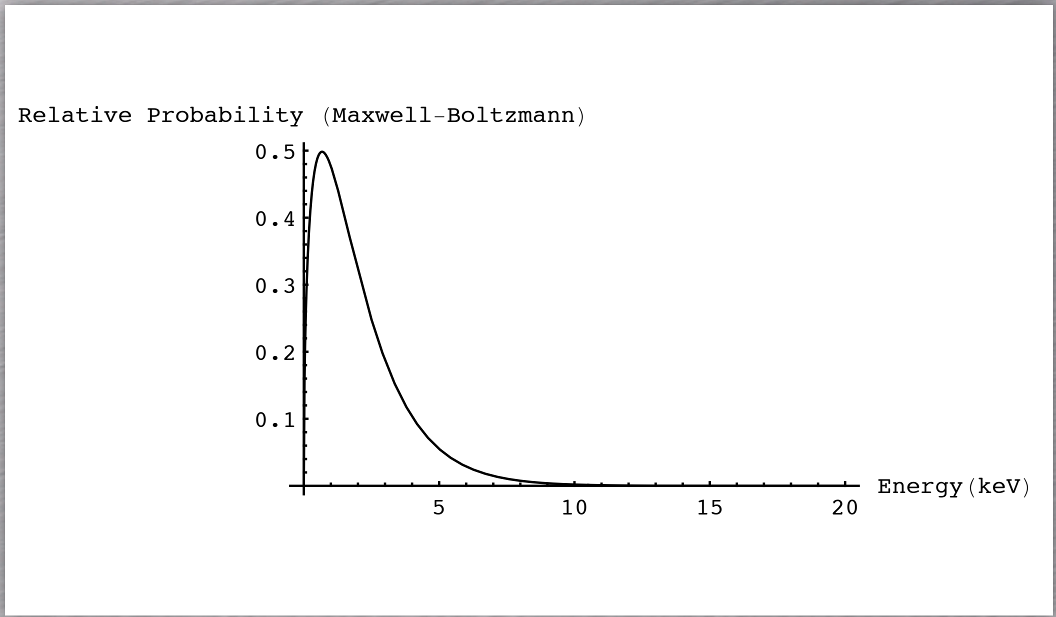
$$<\sigma v> = \sqrt{\frac{8}{\pi\mu}}\,(k\,T)^{-\frac{3}{2}} \int_0^\infty S(E)\, e^{-\left(\frac{E}{k\,T}+\sqrt{\frac{E_G}{E}}\right)} dE.$$

$$<\sigma v> = \sqrt{\frac{8}{\pi\mu}}\,(k\,T)^{-\frac{3}{2}}\, S(E_0) \int_0^\infty e^{-\left(\frac{E}{k\,T}+\sqrt{\frac{E_G}{E}}\right)} dE.$$

$$\frac{d}{dE}\left(\frac{E}{k\,T} + \sqrt{\frac{E_G}{E}}\right)_{E=E_0} = 0, \text{ or } E_0 = \left(\frac{kT\sqrt{E_G}}{2}\right)^{\frac{2}{3}}.$$

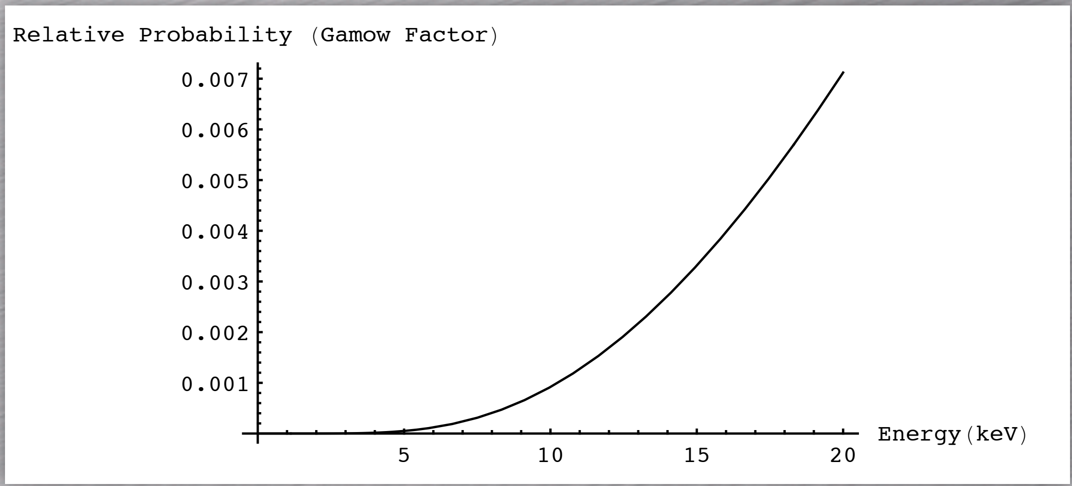
Solar Interior

- Solar plasma is to good approximation an ideal gas
- Described by Maxwell-Boltzmann distribution of thermal energies



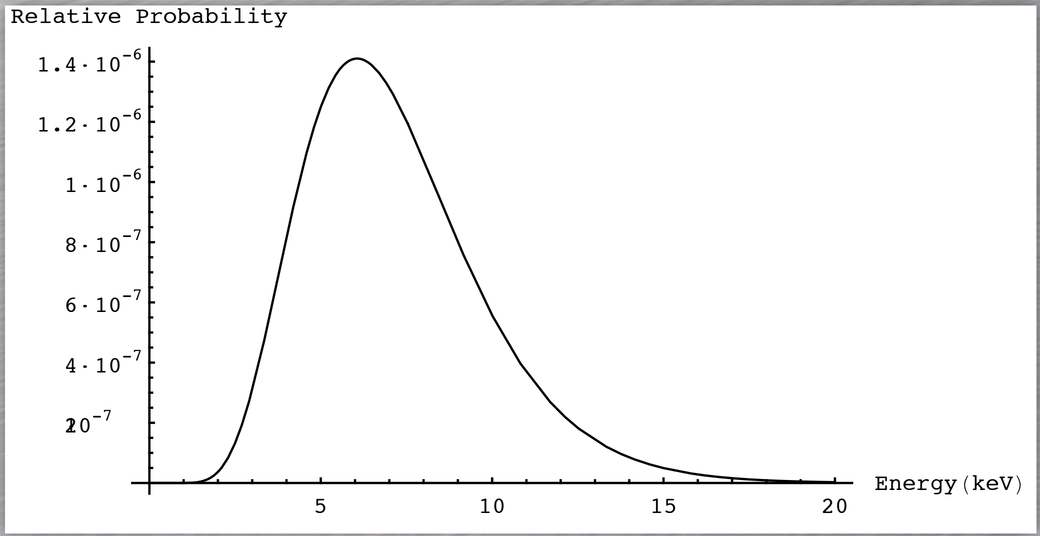
Coulomb Penetrability

- For non-resonant s-wave capture below the Coulomb barrier, charged particle induced reaction probability governed by the Gamow factor $e^{-2\pi\eta}$, where $\eta = 2\pi Z_p Z_t/(hv)$
- Coulomb barrier for p+p reaction is hundreds of keV



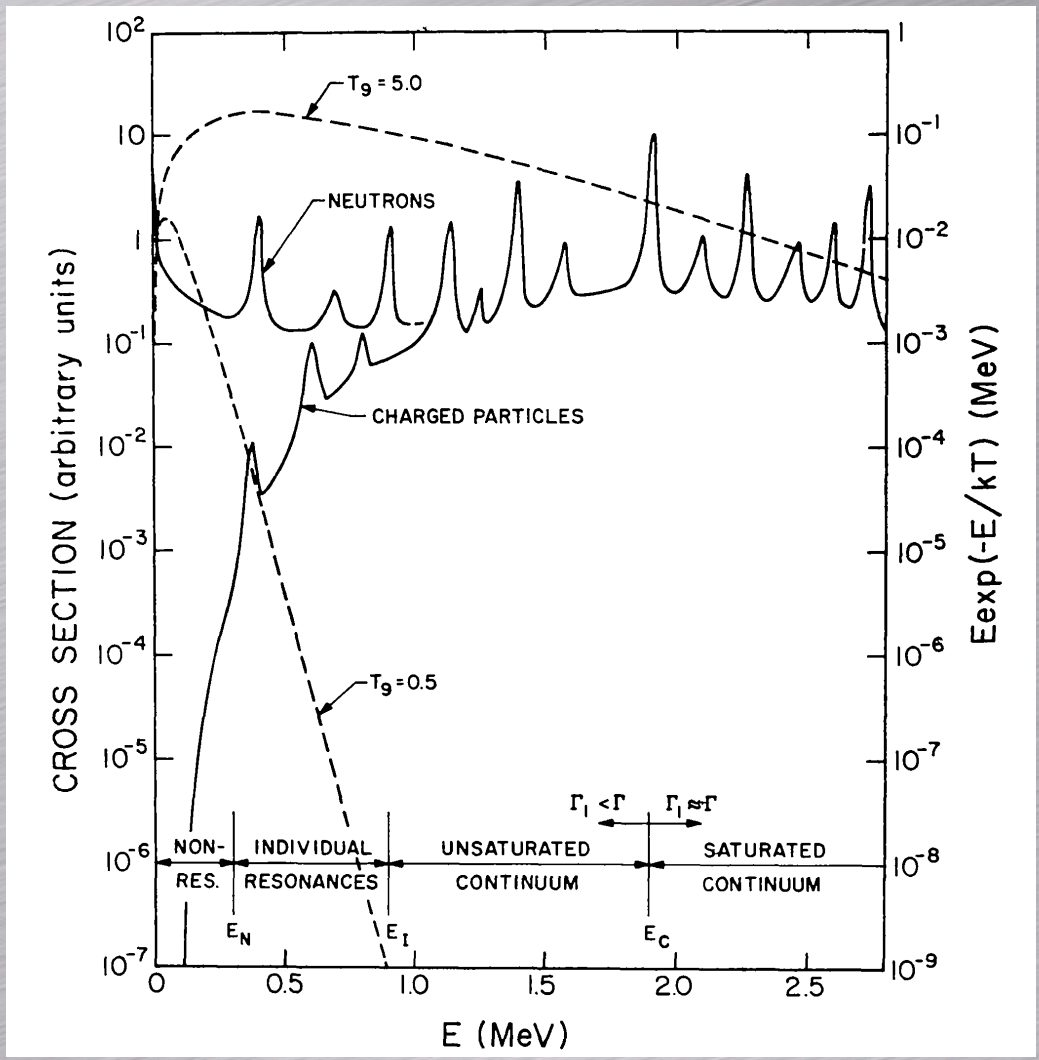
Gamow Peak

- Resulting asymmetric distribution known as the Gamow peak, centred about the most effective energy for thermonuclear reactions
- Is only 6 keV for pp reaction and 20 keV for $^{7}Be(p,\gamma)^{8}B$ reaction
- Implies important role for theory in extrapolation from energies accessible in laboratory



Reactions at Astrophysical Energies

- Coulomb repulsion strongly inhibits charged particle-induced reactions
- Neutron-induced reactions are hindered only by the centrifugal barrier



Resonances

$$\Gamma = \frac{\hbar}{\tau},$$

$$P(E) = \frac{1}{2\pi} \frac{\Gamma}{(E - E_i)^2 + (\Gamma/2)^2},$$

$\sigma_{resonance} \propto \Gamma_p \left(\Gamma - \Gamma_p\right) P(E_r)$, and its magnitude is therefore

$$\sigma_{resonance} = (2l + 1) \frac{\pi}{k^2} \frac{\Gamma_p \left(\Gamma - \Gamma_p\right)}{(E - E_r)^2 + (\Gamma/2)^2}.$$

$$\sigma_{p,e} = \frac{(2J + 1)}{\left(2J_p + 1\right)(2J_t + 1)} \frac{\pi}{k^2} \frac{\Gamma_p \Gamma_e}{(E - E_r)^2 + (\Gamma/2)^2} \equiv \omega \frac{\pi}{k^2} \frac{\Gamma_p \Gamma_e}{(E - E_r)^2 + (\Gamma/2)^2}.$$

Narrow Resonance Radiative Capture Reaction Rates

$$r_{pt} = n_p\, n_t < \sigma v >= n_p\, n_t \sqrt{\frac{8}{\pi\,\mu}}\ (k\,T)^{-\frac{3}{2}} \int_0^\infty E\,\sigma\,(E)\, e^{-\frac{E}{k\,T}}\, dE. \qquad (1)$$

$$r_{pt} = n_p\, n_t \sqrt{\frac{8}{\pi\,\mu}}\ \frac{E_r}{(k\,T)^{\frac{3}{2}}}\, e^{-\frac{E_r}{k\,T}} \int_0^\infty \omega\, \frac{\pi}{k^2}\, \frac{\Gamma_p\,(E_r)\,\Gamma_\gamma}{(E - E_r)^2 + (\Gamma/2)^2}\, dE$$

$$= n_p\, n_t \sqrt{\frac{8}{\pi\,\mu}}\ \frac{E_r}{(k\,T)^{\frac{3}{2}}}\, e^{-\frac{E_r}{k\,T}}\, \omega\, \frac{\pi}{k^2}\, \Gamma_p\,\Gamma_\gamma \int_0^\infty \frac{1}{(E - E_r)^2 + (\Gamma/2)^2}\, dE$$

$$= n_p\, n_t \sqrt{\frac{8}{\pi\,\mu}}\ \frac{E_r}{(k\,T)^{\frac{3}{2}}}\, e^{-\frac{E_r}{k\,T}}\, \omega\, \frac{\pi}{k^2}\, \Gamma_p\,\Gamma_\gamma\, \frac{\mathrm{Arctan}\left(\frac{E_r}{\Gamma/2}\right)}{\Gamma/2} \simeq n_p\, n_t \sqrt{\frac{8}{\pi\,\mu}}\ \frac{E_r}{(k\,T)^{\frac{3}{2}}}\, e^{-\frac{E_r}{k\,T}}\, \omega\, \frac{\pi}{k^2}\, \Gamma_p\,\Gamma_\gamma\, \frac{\pi/2}{\Gamma/2} \qquad (2)$$

$$= n_p\, n_t \sqrt{\frac{8}{\pi\,\mu}}\ \frac{E_r}{(k\,T)^{\frac{3}{2}}}\, e^{-\frac{E_r}{k\,T}}\, \omega\, \frac{\pi\,\hbar^2}{2\,\mu\,E}\, \Gamma_p\,\Gamma_\gamma\, \frac{\pi}{\Gamma} = n_p\, n_t\, \hbar^2 \left(\frac{2\,\pi}{\mu\,k\,T}\right)^{\frac{3}{2}} \omega\, \frac{\Gamma_p\,\Gamma_\gamma}{\Gamma}\, e^{-\frac{E_r}{k\,T}}$$

$$\equiv n_p\, n_t\, \hbar^2 \left(\frac{2\,\pi}{\mu\,k\,T}\right)^{\frac{3}{2}} \omega\gamma\, e^{-\frac{E_r}{k\,T}},$$

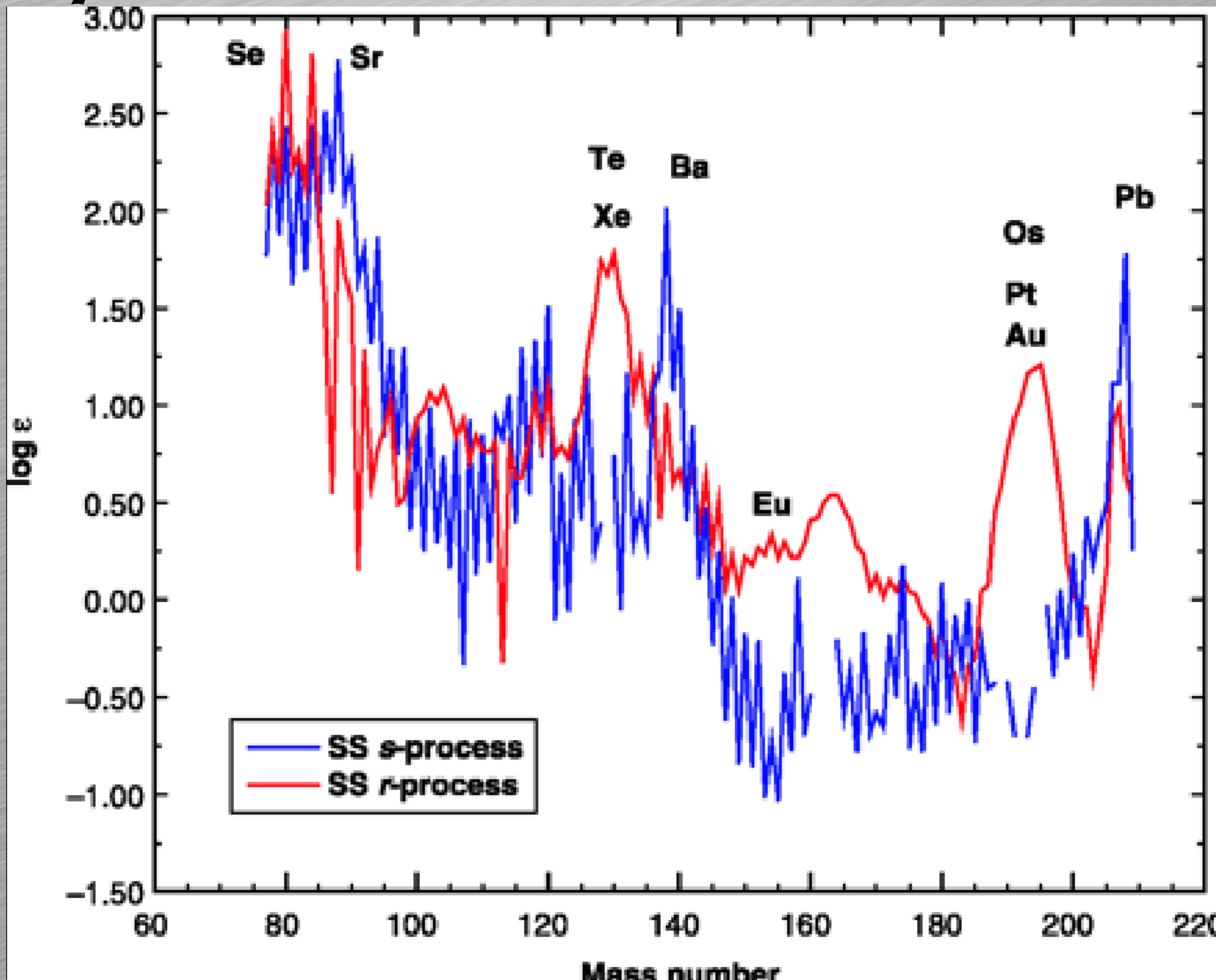
Direct and Indirect Measurements of Resonant Rates

- 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

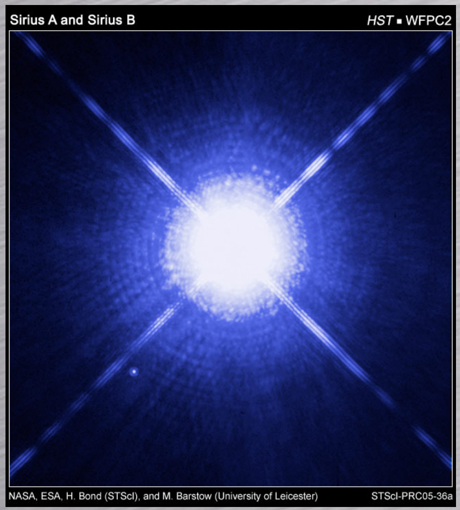


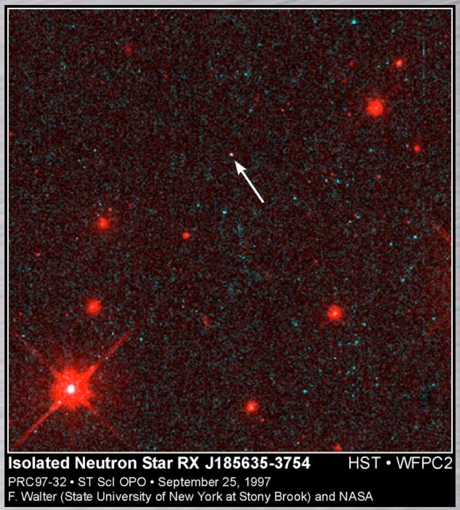
~1/2 of chemical elements w/ A > 70 produced in the rapid neutron capture *(r)* process: neutron captures on rapid timescale (~1 s) in a hot (1 billion K), dense environment ($>10^{20}$ neutrons cm^{-3})
The other half are produced in the slow neutron capture process

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

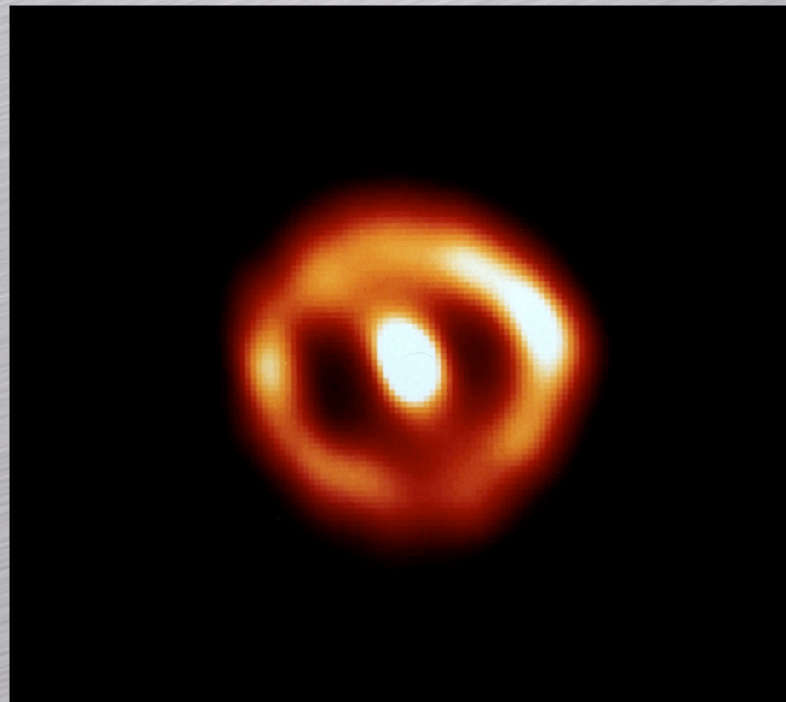
End States of Stellar Evolution: White Dwarves and Neutron Stars





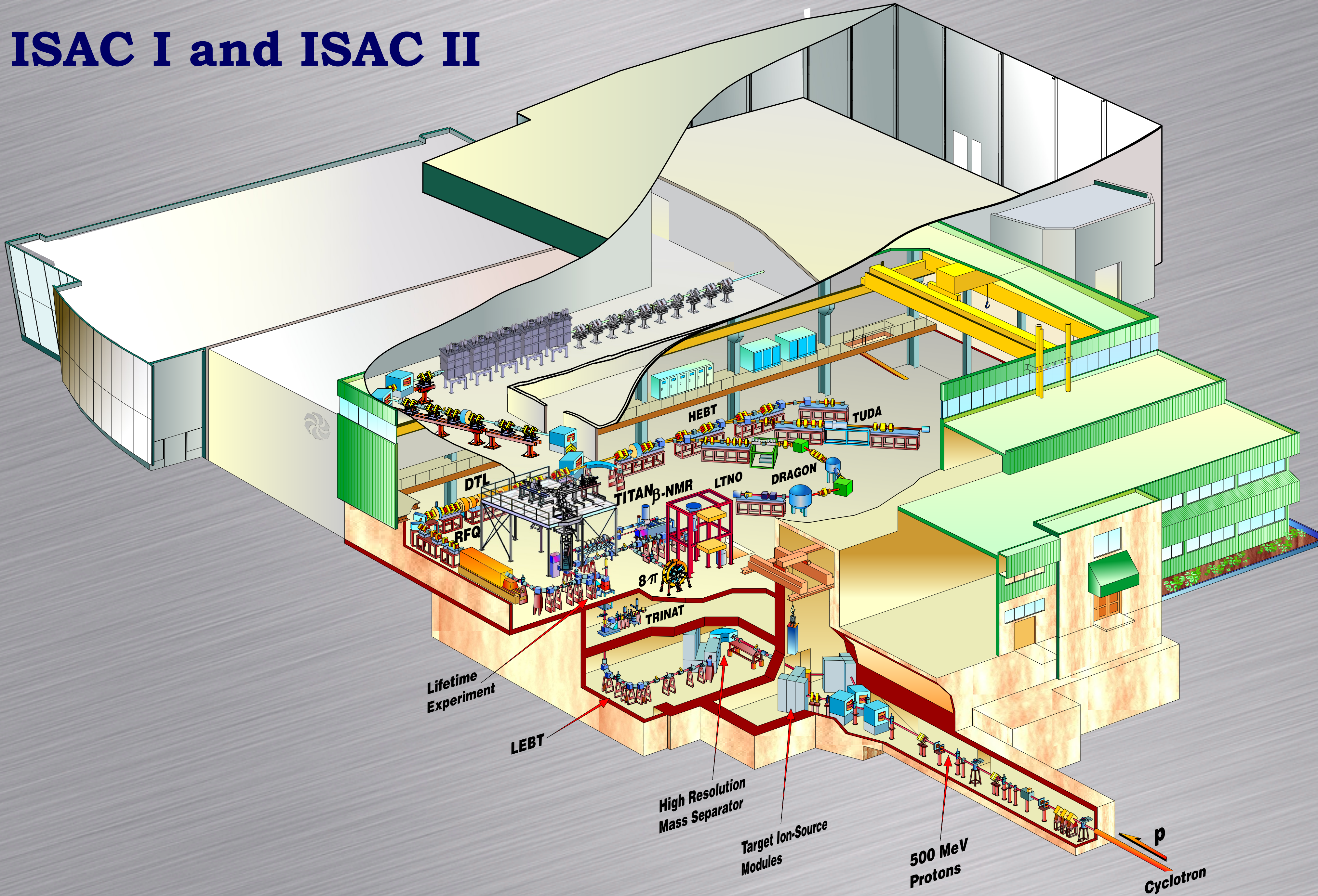
- White Dwarf: Stellar cinder left after typical and low-mass stars ($M < 8\ M_\odot$) exhaust core H and He fuel: composed mainly of C, O, Ne; $M \sim 0.6\ M_\odot$, $R \sim 6000$ km; supported by electron degeneracy pressure
- Neutron Star: End state of massive stars ($8\ M_\odot \leq M \leq 10\ M_\odot$)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

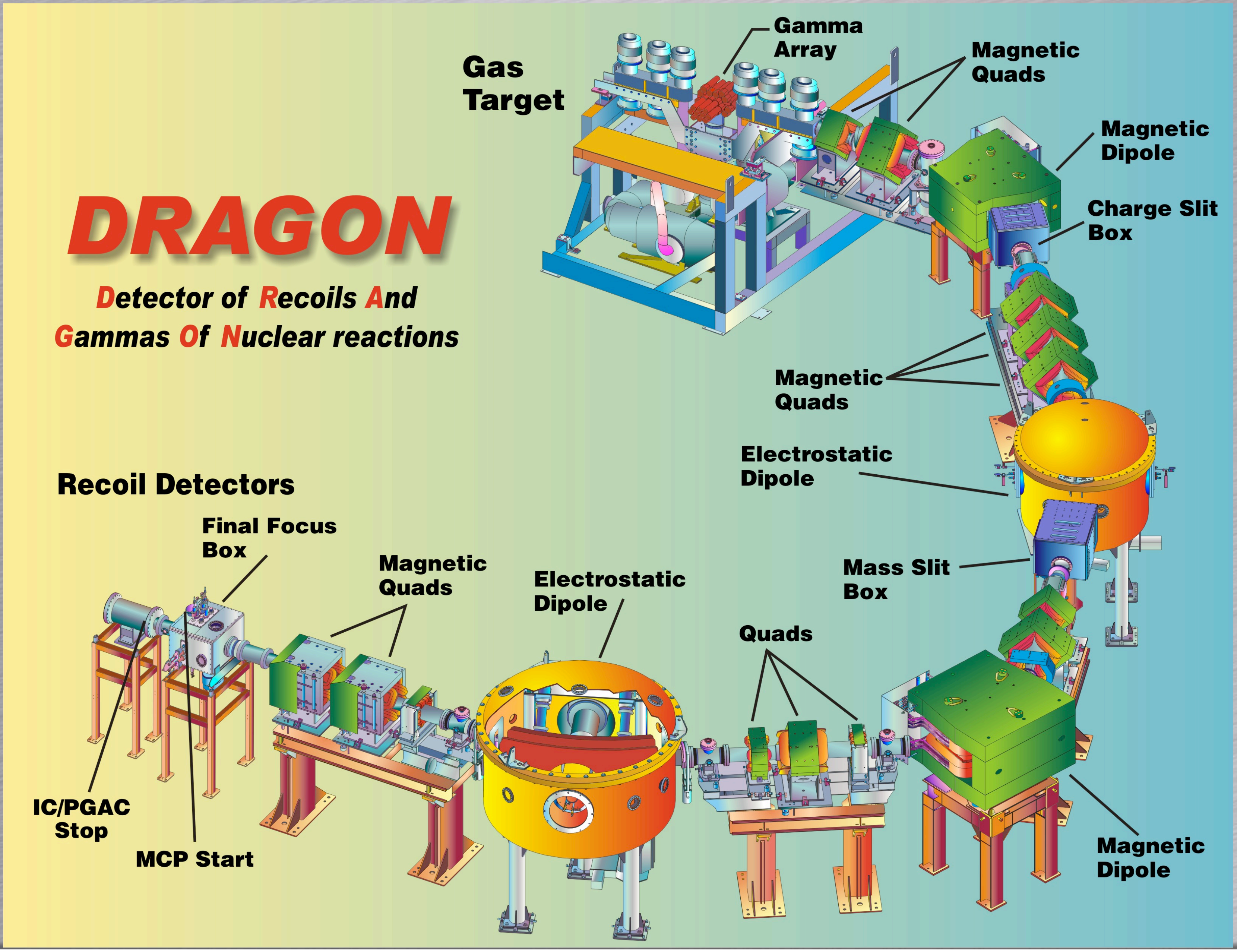


- Accretion of H- & He-rich matter from low-mass main sequence star onto surface of white dwarf via disk
- When accreted layer is thick enough, temperature and pressure at base sufficient to initiate thermonuclear runaway
- H in accreted layer is “burnt” via nuclear reactions
- Layer ejected, enriching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

ISAC I and ISAC II



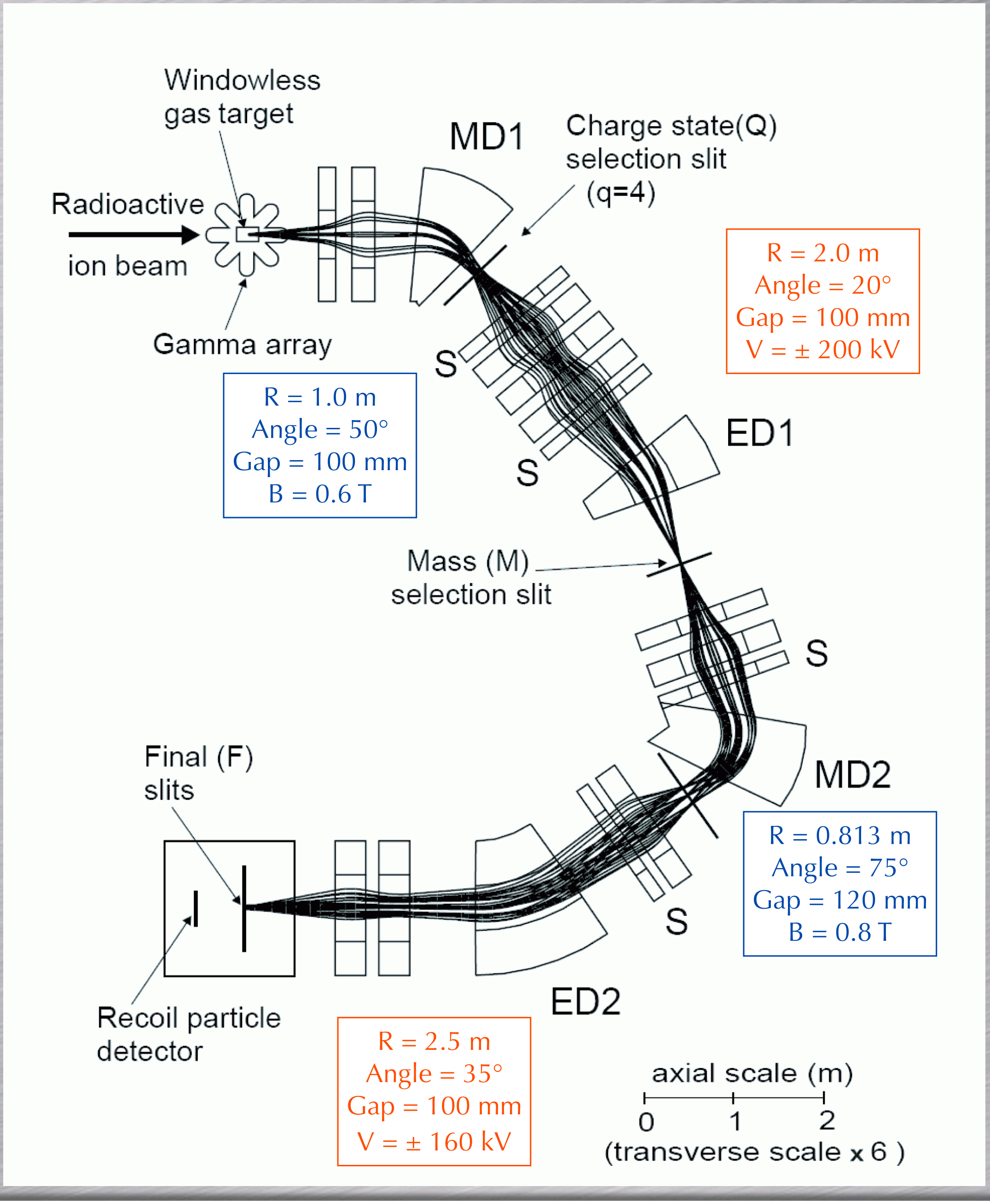
Recoil Mass Separator



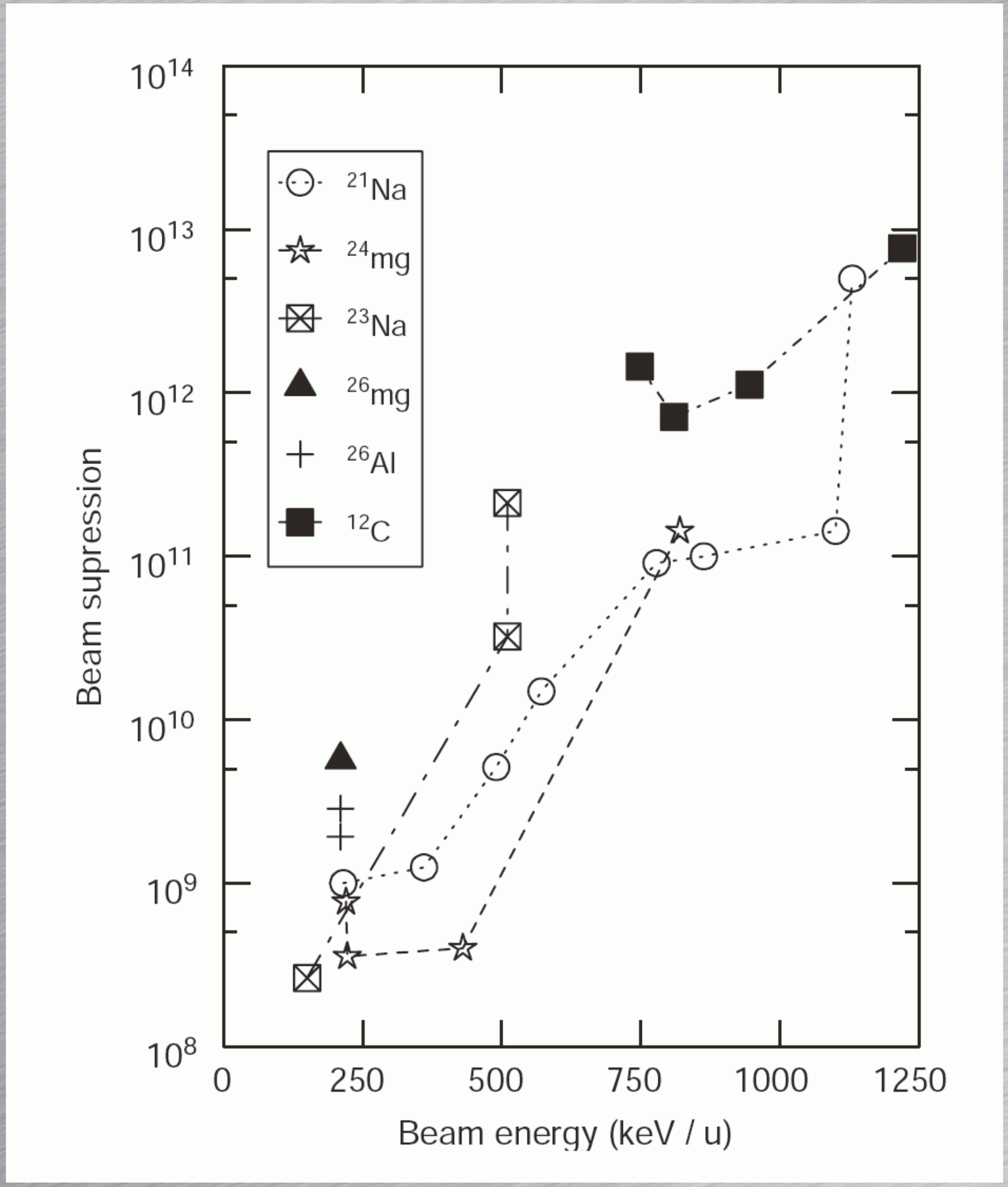
Radiative Capture Experiments at DRAGON

$$p_r = p_p$$

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

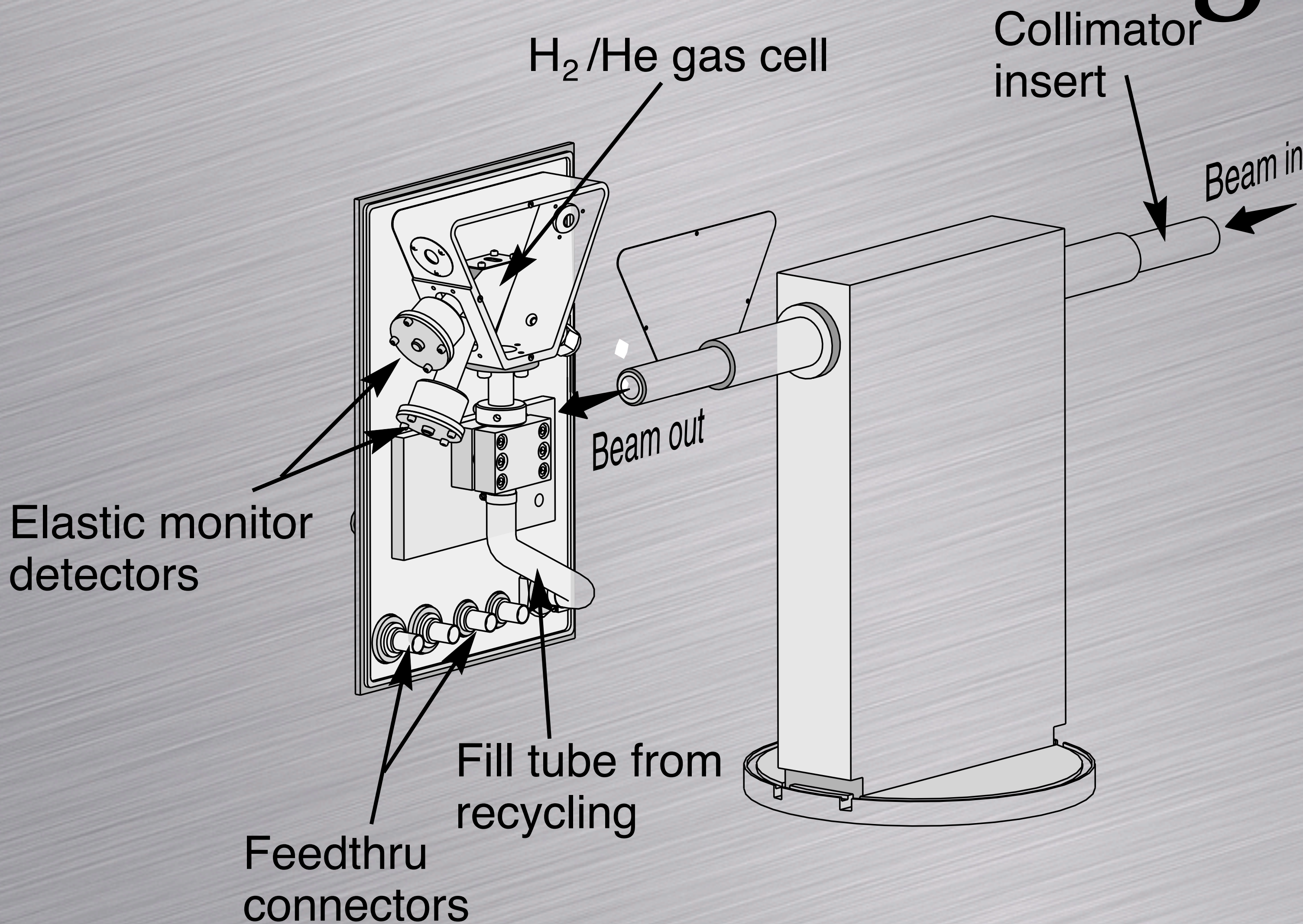


Beam Suppression



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

Windowless Gas Target

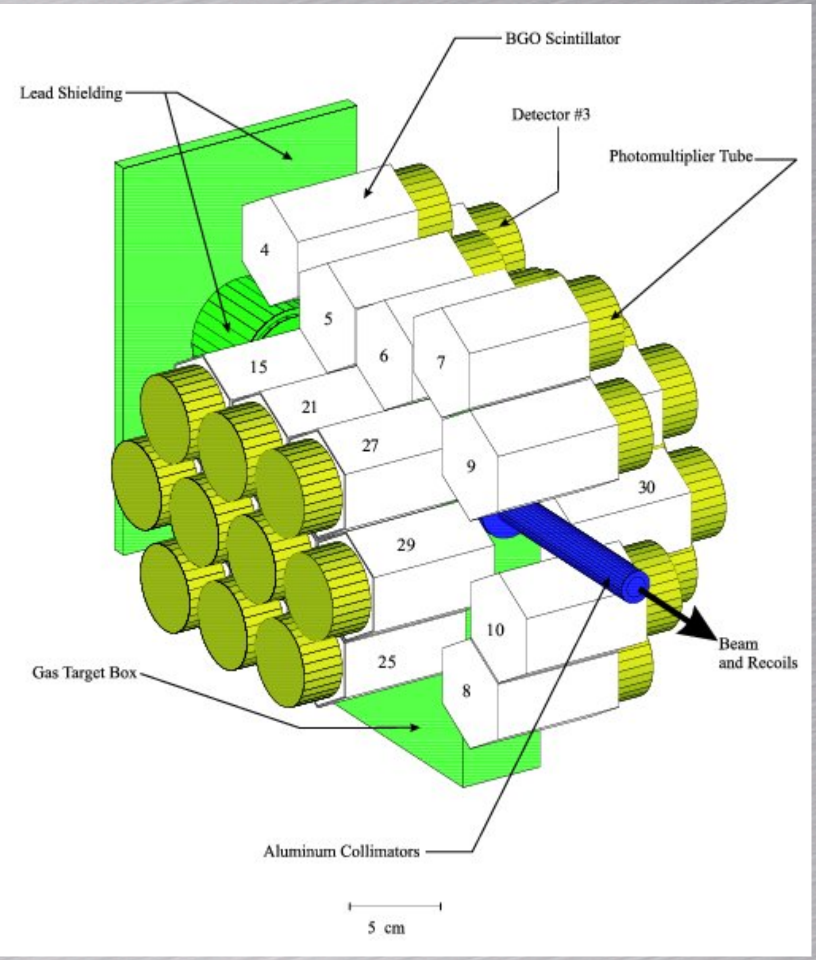


D.A. Hutcheon *et al.*, NIM A 498, 190 (2003)

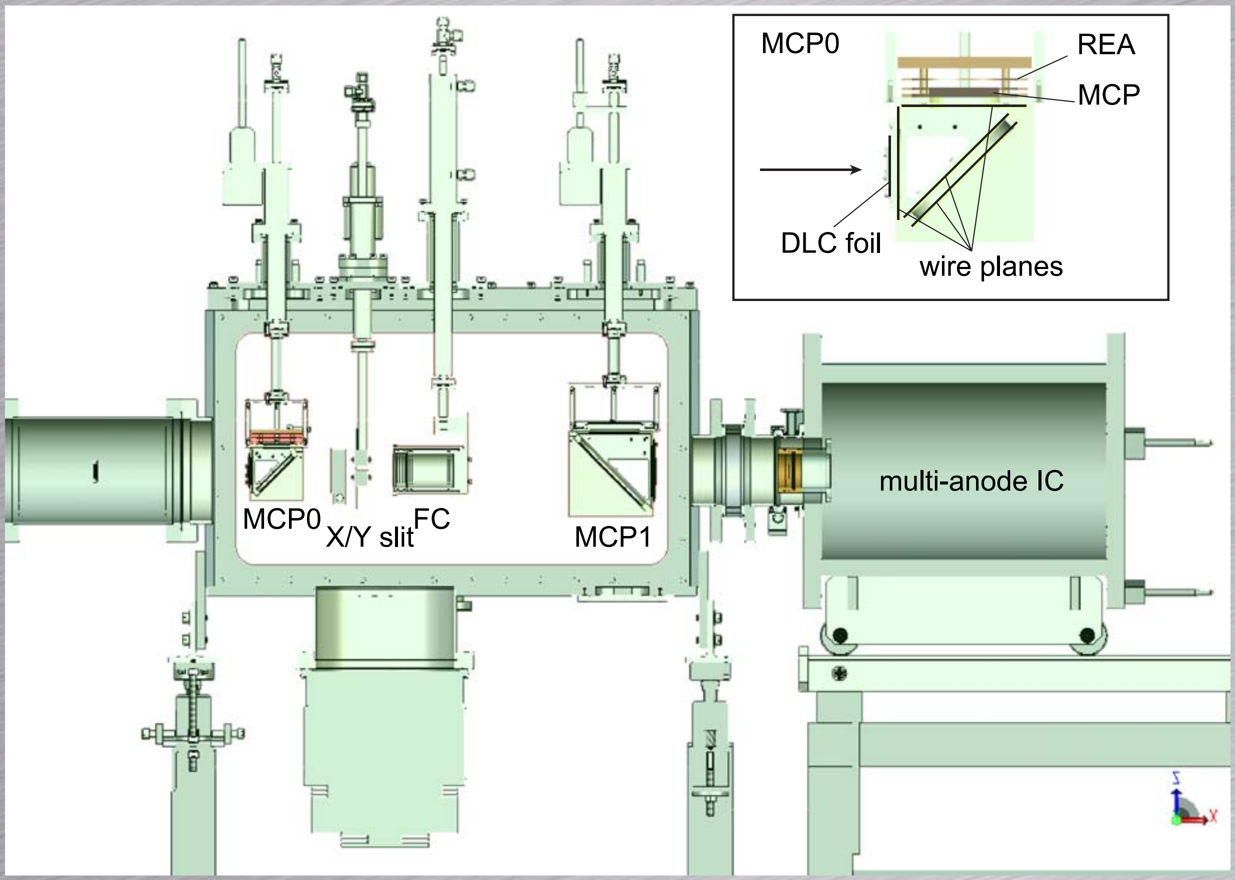
DRAGON Gamma Ray Detector Array

30 BGO γ ray detectors surrounding gas target

Geometric efficiency of 89-92%

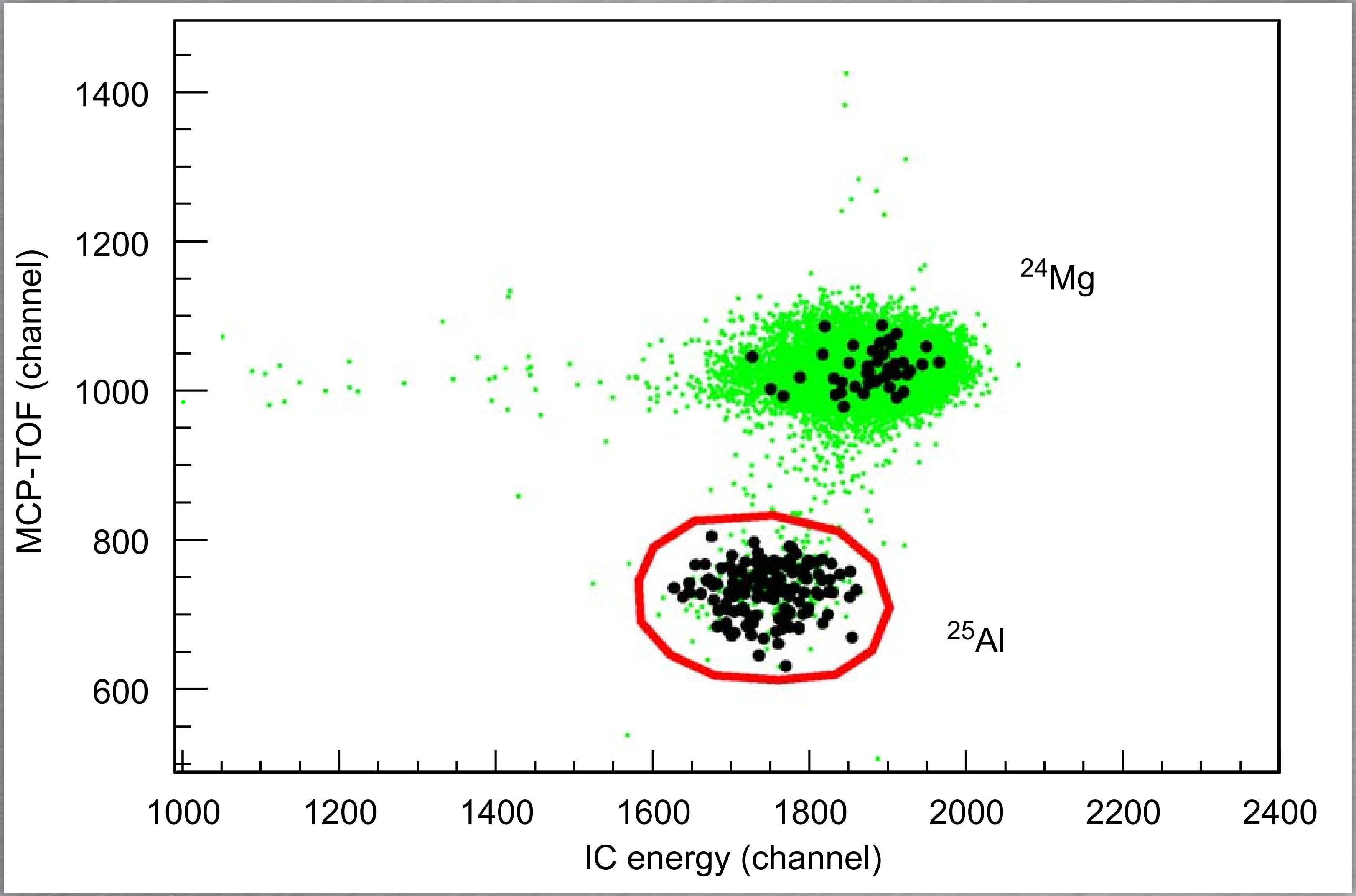


Focal Plane Detectors: Local Time-of-Flight System



- 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

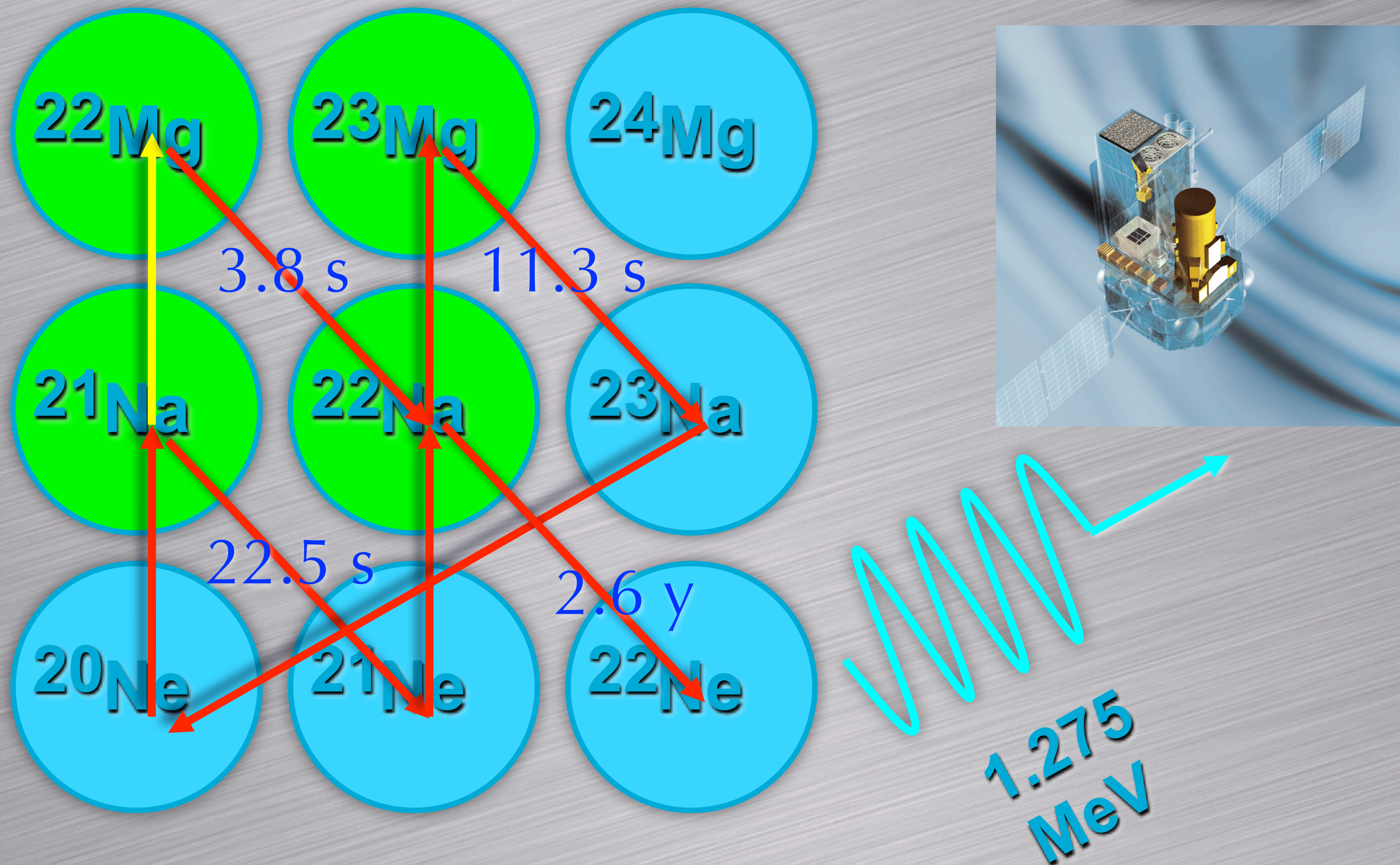


^{24}Mg(p,γ)^{25}Al at E_{rel} = 214 keV

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

^{22}Na formation: NeNaMg cycle

INTEGRAL

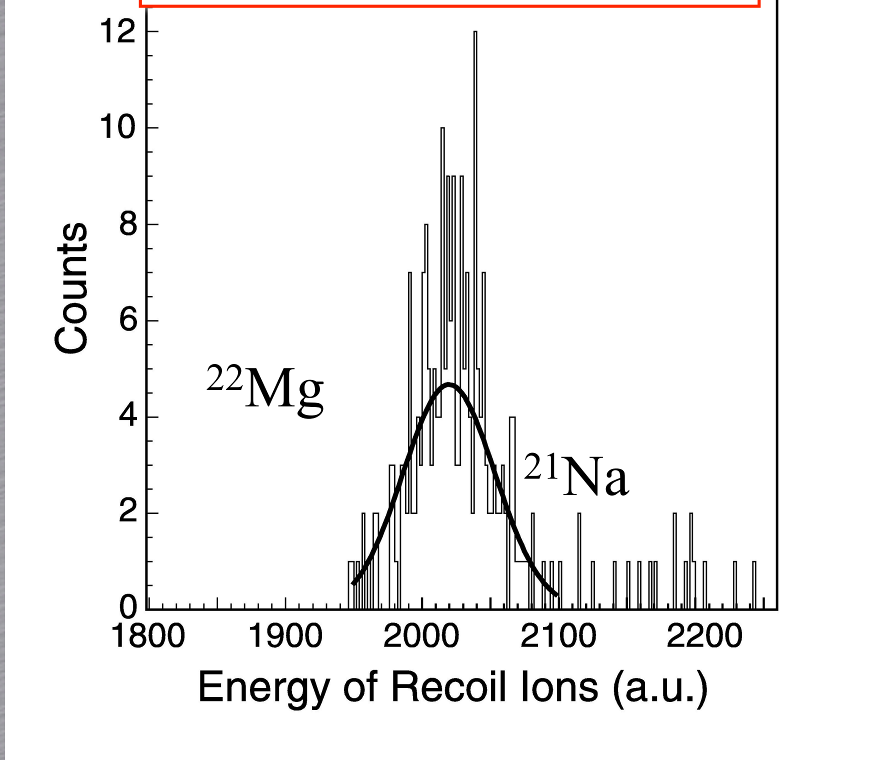


^{22}Na not observed by COMPTEL or INTEGRAL

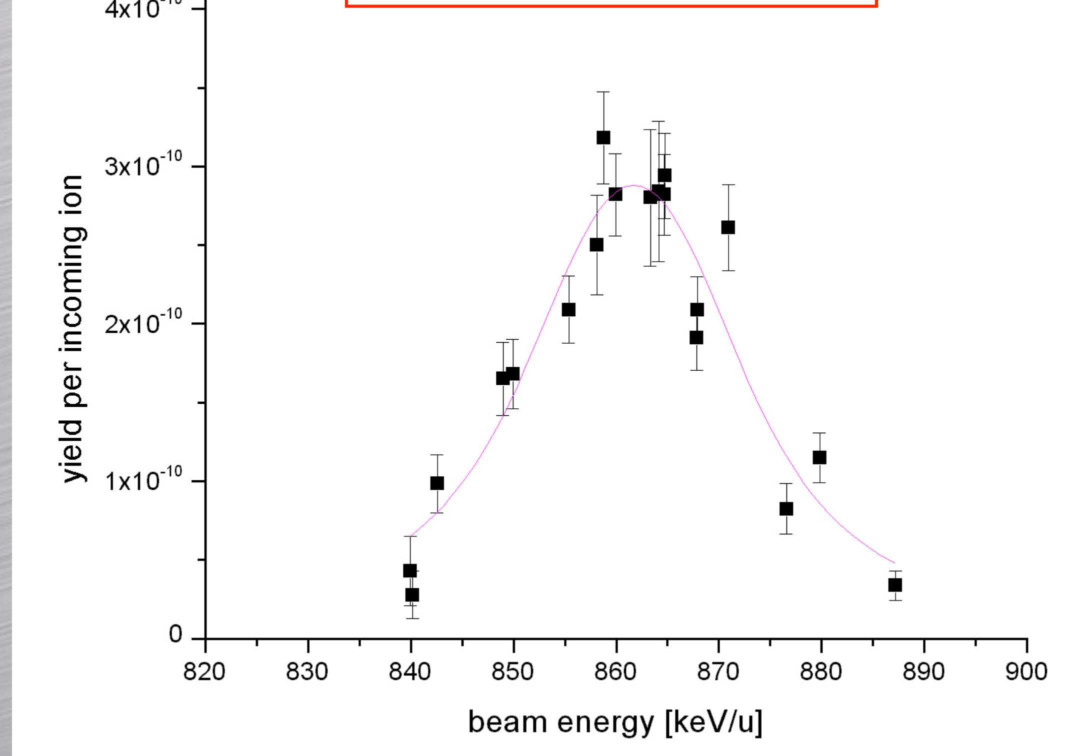
Measurement of $^{21}Na(p,\gamma)^{22}Mg$

- ^{21}Na beam on hydrogen target
- Scanned over each resonance in small energy steps
- Detected recoils alone or in coincidence with prompt γ rays

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



Excitation function for E_R=821 keV



$^{21}Na(p,\gamma)^{22}Mg$ resonance strengths

^{21}Na beam up to 2×10^9 per second

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

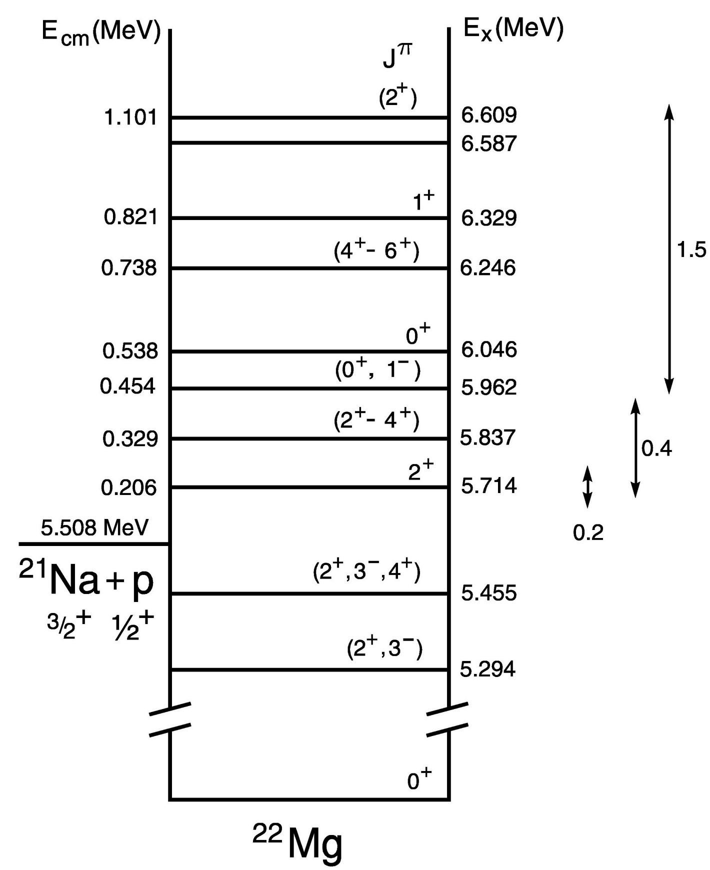
DRAGON operations:

- used DSSSD as focal plane detector
- used beta activity, FC and elastics for flux
- used BGO detection despite high γ background

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

TABLE I. $^{21}Na(p,\gamma)^{22}Mg$ resonance strengths and energies.

E_x (MeV)	$E_{c.m.}$ (keV)	Γ (keV)	$\omega\gamma$ (meV)
5.714	205.7±0.5		1.03±0.21
5.837	329		≤0.29
5.962	454±5		0.86±0.29
6.046	538±13		11.5±1.36
6.246	738.4±1.0		219±25
6.329	821.3±0.9	16.1±2.8	556±77
6.609	1101.1±2.5	30.1±6.5	368±62

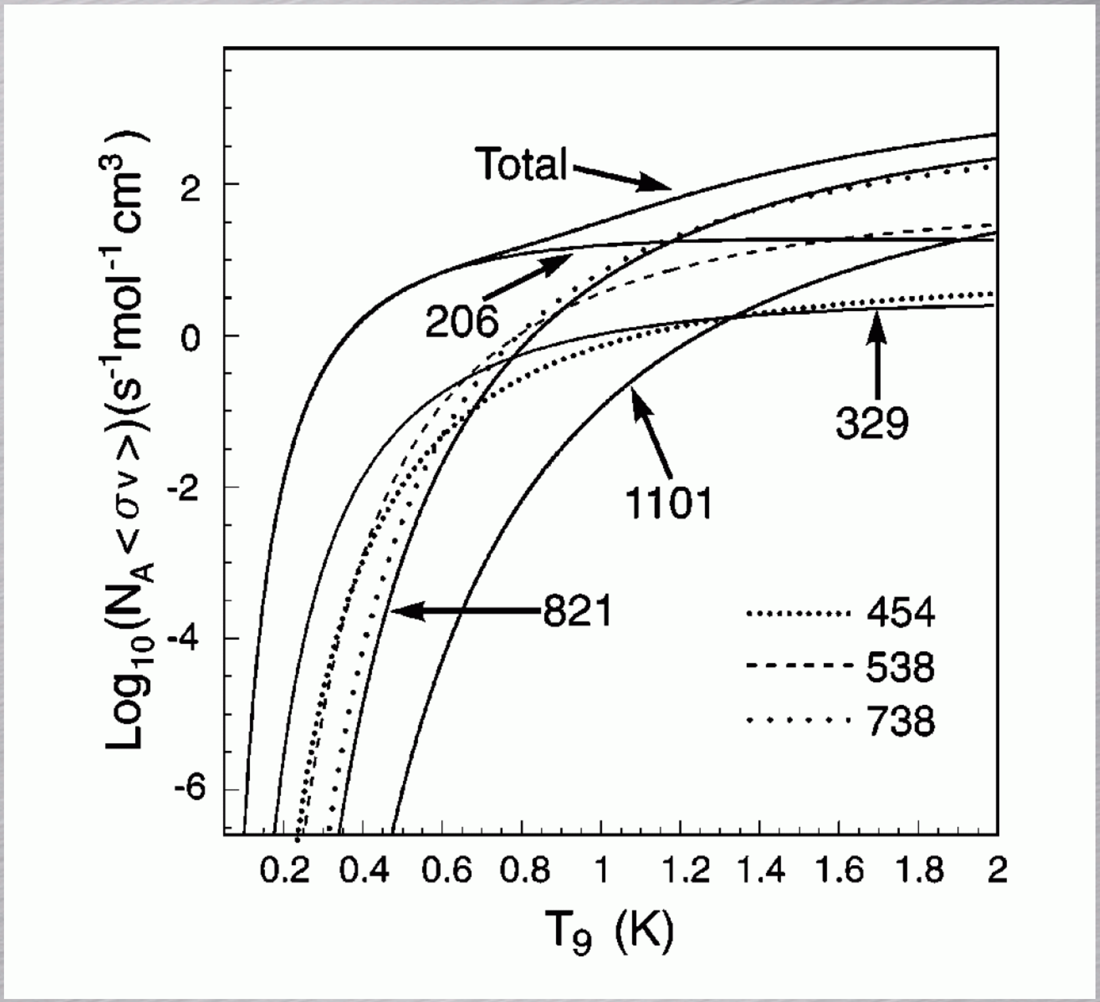


Estimated reaction rate for $^{21}Na(p,\gamma)^{22}Mg$ based on DRAGON data

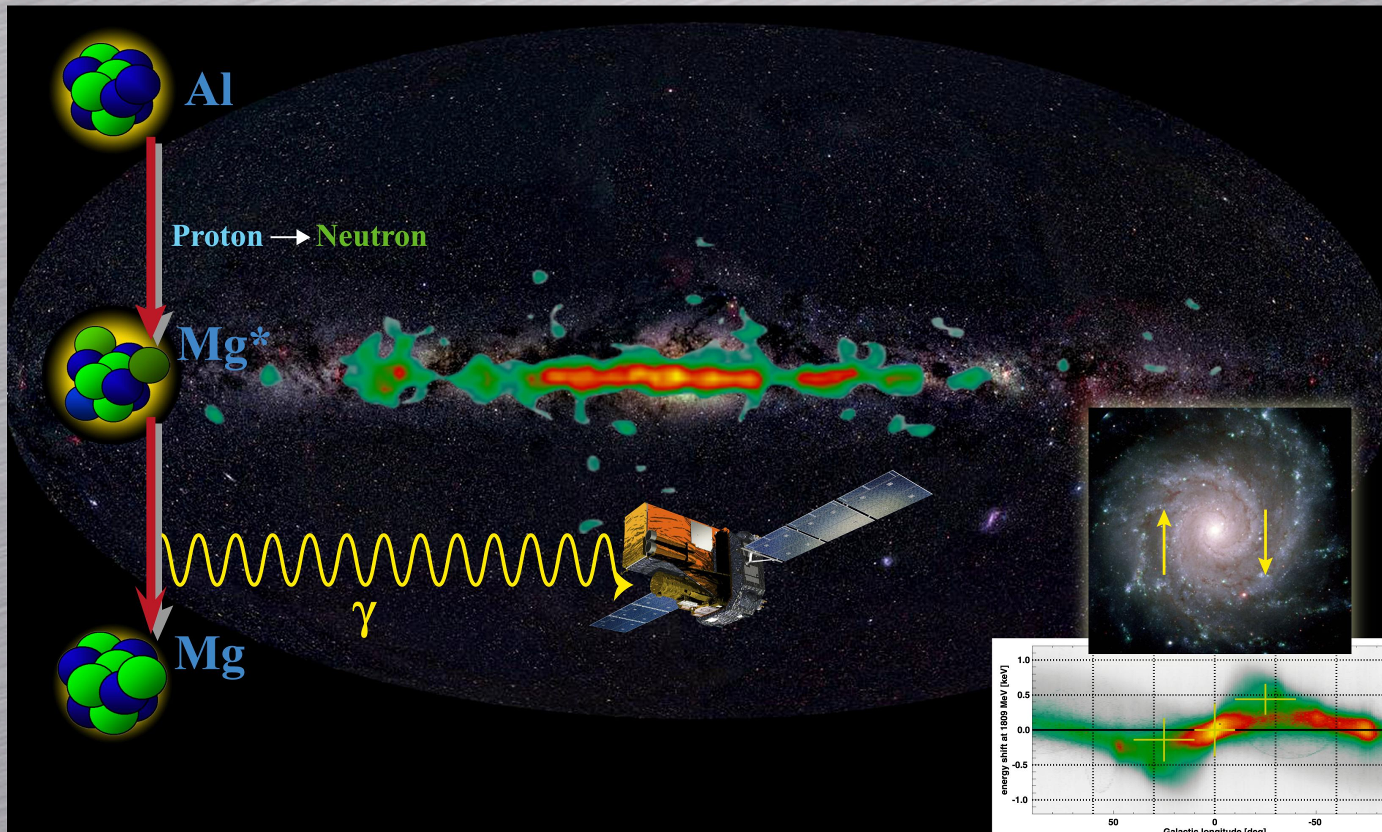
The lowest measured state at 5.714 MeV (E_{cm} = 206 keV) dominates for all nova temperatures and up to about 1.1 GK

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



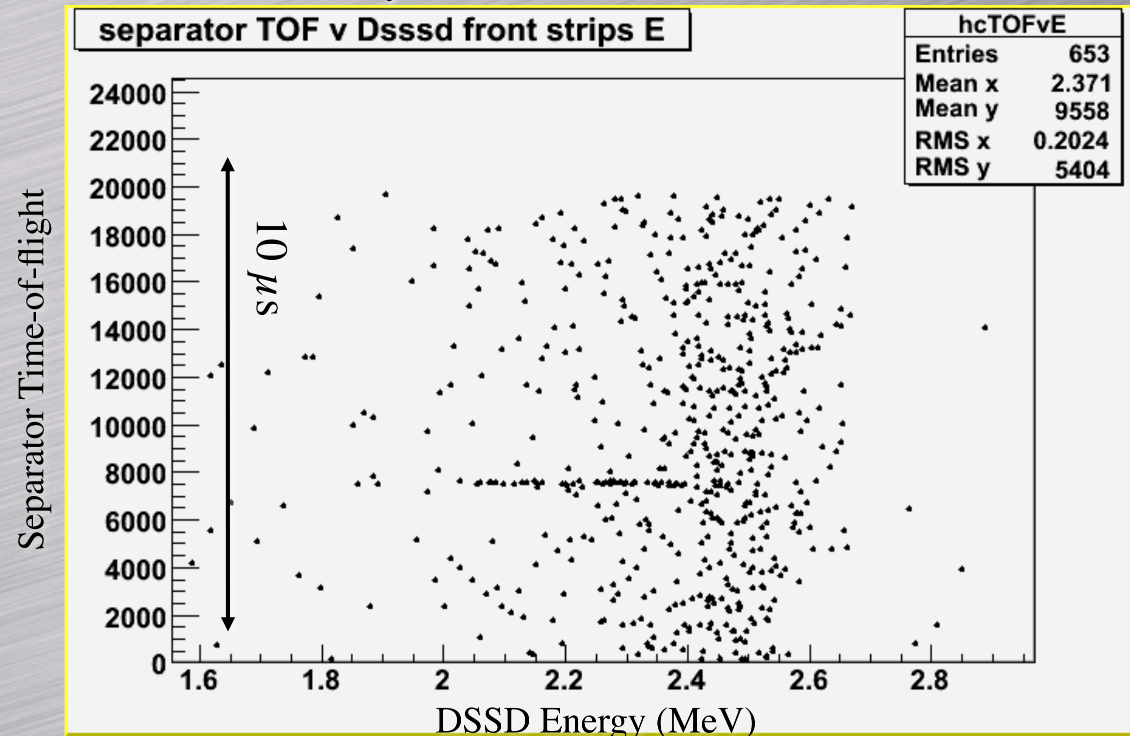
- Radioactive decay with mean lifetime 1 My: 1.8 MeV γ ray
- Galactic inventory ~ 3 solar masses
- Is ^{26}Al formed in novae as well as massive stars?
- Must measure rates of nuclear reactions that create and destroy ^{26}Al in novae to find out

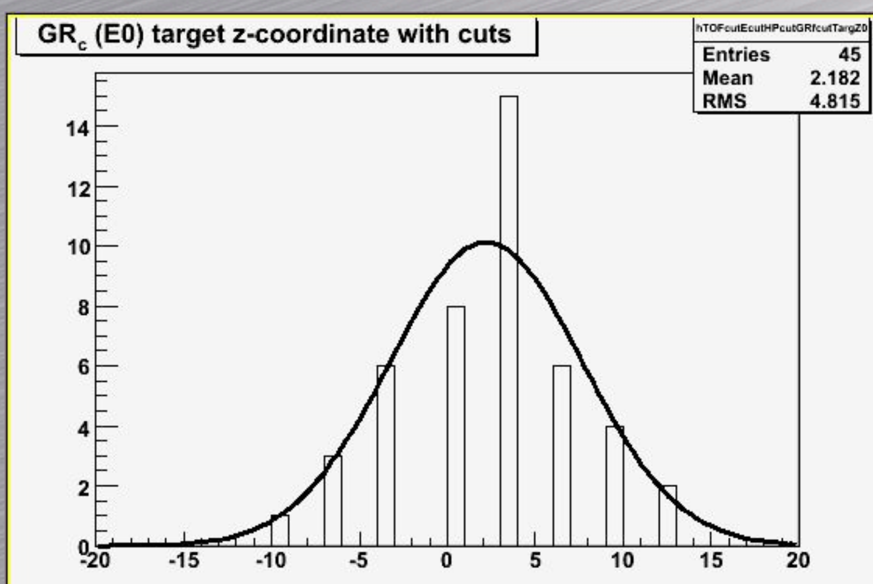
$^{26}Al + p \rightarrow {}^{27}Si + \gamma$

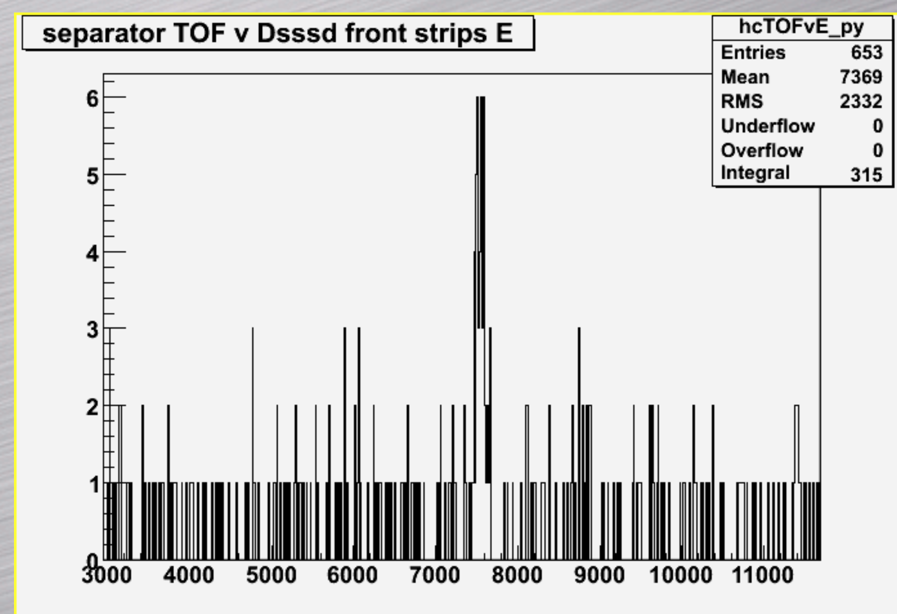
Average ^{26}Al beam intensity of 3.4 billion s^{-1}

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

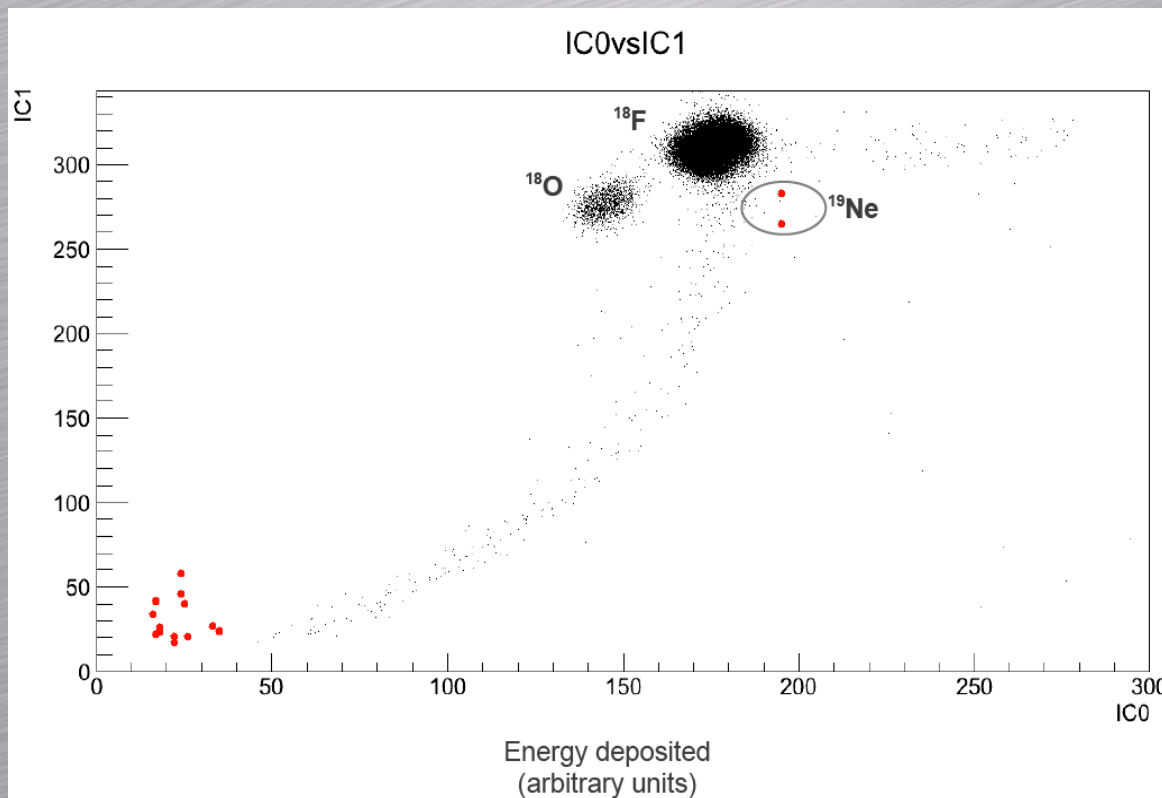
Ruiz *et al.*, PRL 96, 252501 (2006)







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