National Nuclear Physics Summer School 2011

Hosted by the Triangle Universities Nuclear Laboratory
at the University of North Carolina at Chapel Hill

June 20 - July 1, 2011

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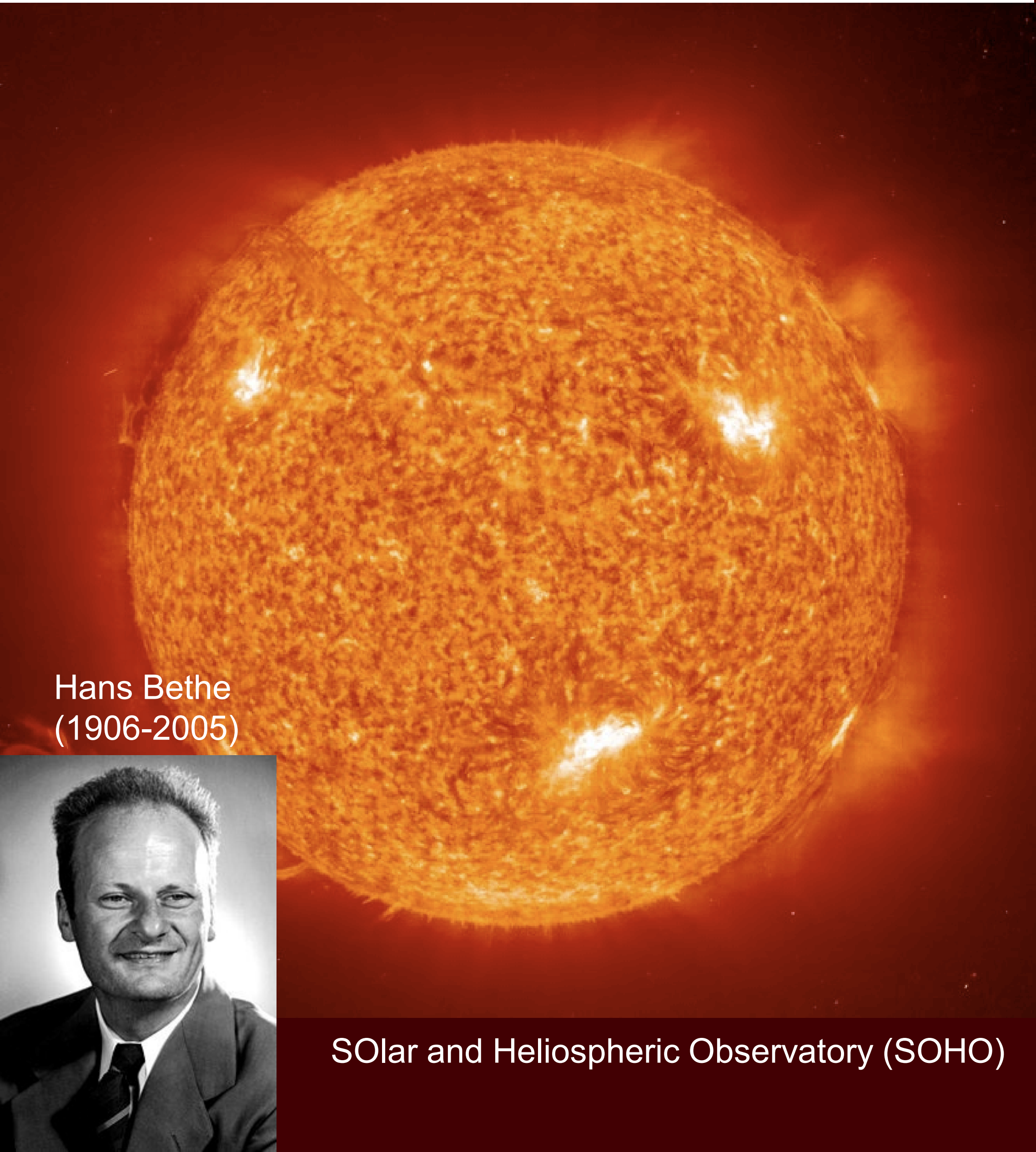
Introduction to Nuclear Astrophysics

Christian Iliadis

The 2011 National Nuclear Physics Summer School is being organized by Triangle Universities Nuclear Laboratory (TUNL). The school will be held on the campus of the University of North Carolina at Chapel Hill. The school is intended for advanced graduate students and beginning postdoctoral researchers in either experimental or theoretical nuclear physics. The primary aim is to provide future researchers with a broad perspective on current research in the field. Lecture courses will cover the major themes in nuclear physics research.

1. Introduction
2. Nuclear Reactions
3. Thermonuclear Reactions
4. Nuclear Burning Stages in Stars

1. Introduction



Hans Bethe
(1906-2005)

SOlar and Heliospheric Observatory (SOHO)

Life on Earth depends on nuclear processes deep inside the Sun

Fusion of H to He:

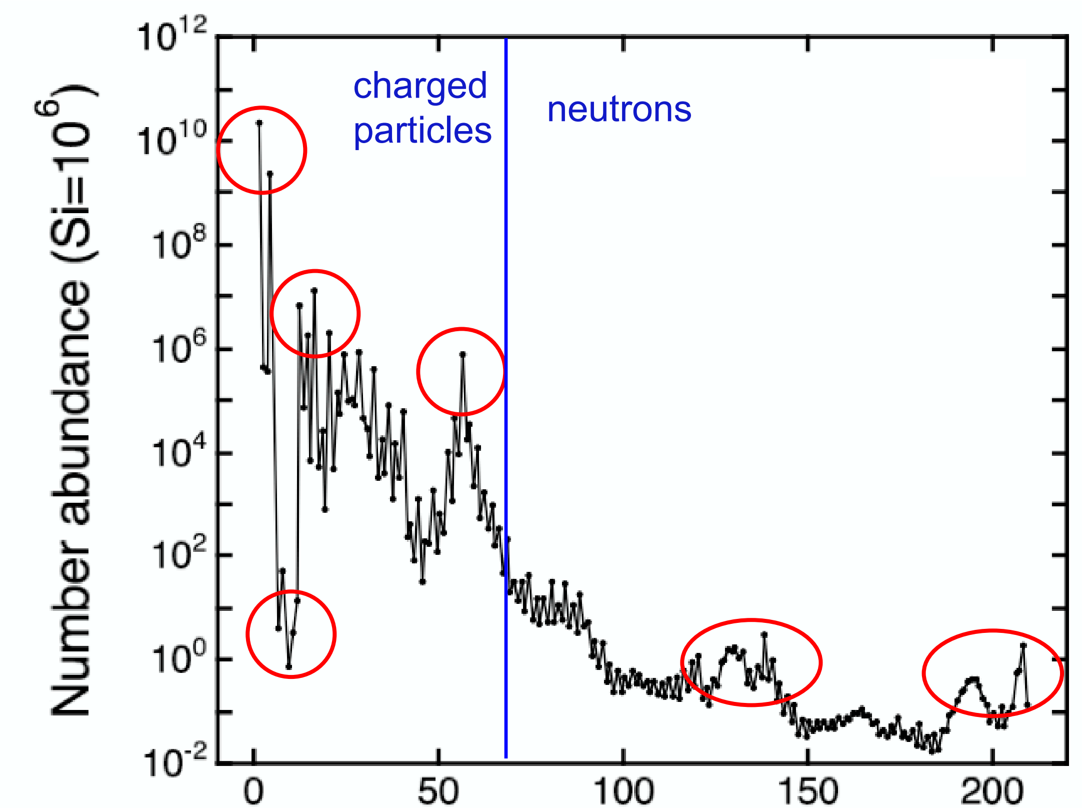
Bethe & Critchfield (1938)
[pp chains]
Bethe 1939; von Weizsäcker 1938
[CNO cycle]

Nobel prize to Hans Bethe (1967)

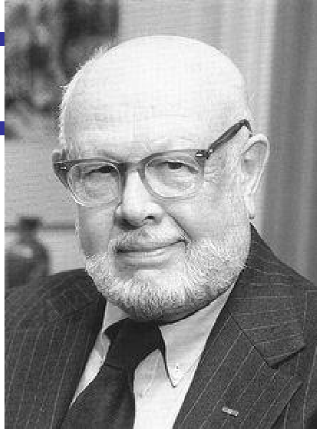
Accurate nuclear physics information is crucial for understanding of stars

How do other stars produce energy? How do they evolve?

Solar system abundances



Mass number A=N+Z



Willy Fowler
(1911-95)

- Suess & Urey, Rev. Mod. Phys. 28, 53 (1956)
- Lodders, Astrophys. J. 591, 1220 (2003)

Foundation of modern theory of nuclear astrophysics:

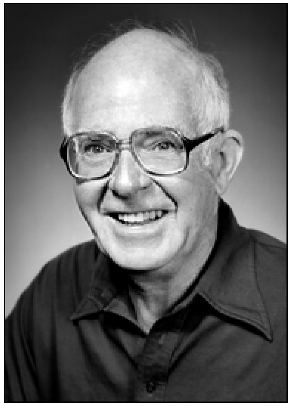
- Burbidge, Burbidge, Fowler and Hoyle (1957)
- Cameron (1957)

Nobel prize to Willy Fowler (1983)

Direct evidence for stellar nucleosynthesis

(i) Solar neutrinos

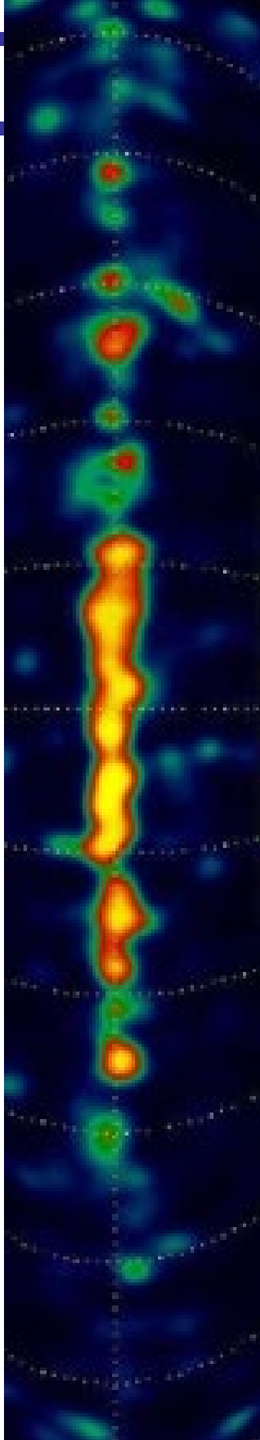
- first direct test of how Sun generates energy was performed by detecting solar neutrinos [from ^{8}B decay] at the Homestake gold mine, SD
- disagreement of predicted and measured neutrino flux: “solar neutrino problem” [giving later rise to discovery of neutrino oscillations]
- Nobel prize to Ray Davis (2002)



Ray Davis (1914-06)

(ii) γ-ray astronomy

- radioactive (‘live”) ^{26}Al has bee observed in the Galaxy [see image on right]
- $T_{1/2}(^{26}Al)$=720,000 years; time scale of Galactic chemical evolution: 10^9 years
- from photon intensity: 1-2 solar masses of ^{26}Al in Galaxy
- conclusion: nucleosynthesis is ongoing



COMPTEL map of 1.8 MeV photon intensity

Pablo Picasso
(1881-1973)

Guernica - 1937

“Computers are useless. They can only give you answers. What is needed are questions!”

Les Demoiselles d’Avignon - 1907

15 Key Questions in Nuclear Astrophysics

(i) Why do predictions of helioseismology disagree with those of the standard solar model?

(ii) What is the solution to the lithium problem in Big Bang nucleosynthesis?

(iii) What do the observed light-nuclide and s-process abundances tell us about convection and dredge-up in massive stars and AGB stars?

• (iv) What are the production sites of the γ-ray emitting radioisotopes ^{26}Al, ^{44}Ti and ^{60}Fe?

(v) What is the origin of about 30 rare and neutron deficient nuclides beyond the iron peak (p-nuclides)?

• (vi) What causes core-collapse supernovae to explode?

(vii) What is the extend of neutrino-induced nucleosynthesis (ν-process)?

(viii) What is the extend of the nucleosynthesis in proton-rich outflows in the early ejecta of core-collapse supernovae (νp-process)?

(ix) What are the sites of the r-process?

• (x) What causes the discrepancy between models and observations regarding the mass ejected during classical nova outbursts?

(xi) Which are the physical mechanisms driving convective mixing in novae?

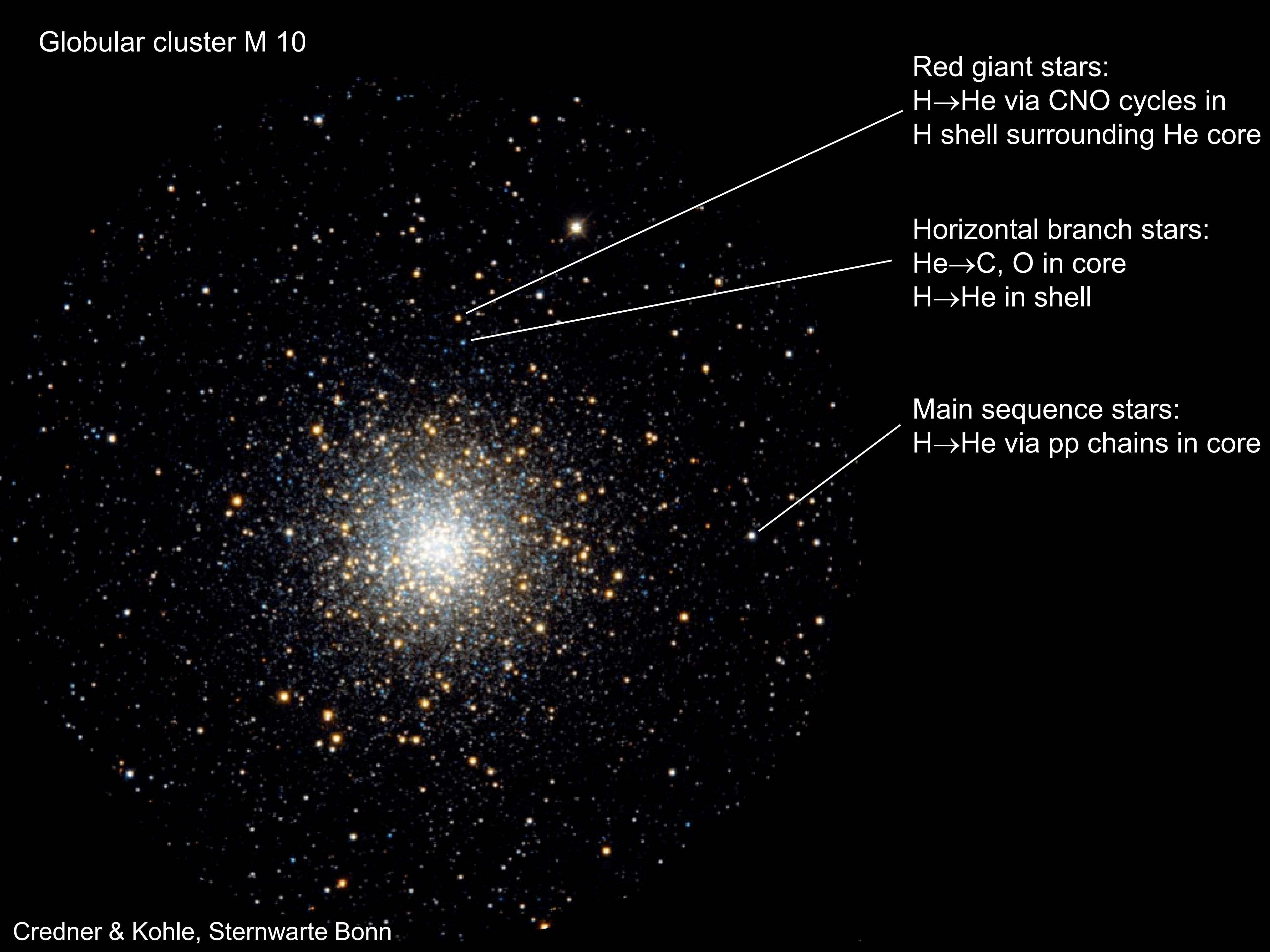
• (xii) What are the progenitors of type Ia supernovae?

• (xiii) What is the nucleosynthesis endpoint in type I X-ray bursts? Is there any matter ejected from those systems?

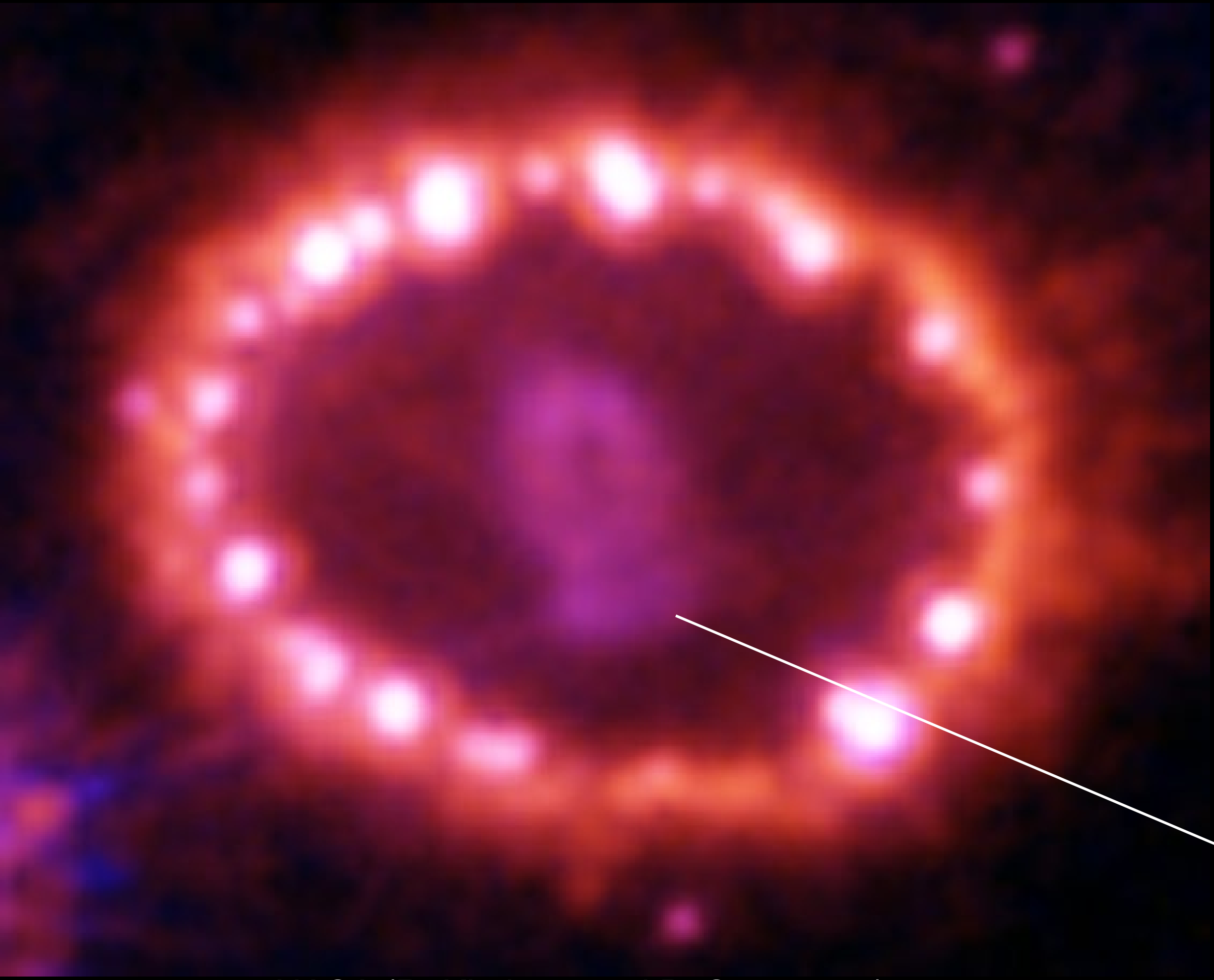
(xiv) What is the impact of stellar mergers on Galactic chemical abundances?

(xv) What are the production and acceleration sites of Galactic cosmic rays?

From: J. Jose & C. Iliadis, “The Unfinished Quest for the Origin of the Elements”, review article submitted to *Reports on Progress in Physics* (2011)


Globular cluster M 10
Red giant stars:
H→He via CNO cycles in
H shell surrounding He core
Horizontal branch stars:
He→C, O in core
H→He in shell
Main sequence stars:
H→He via pp chains in core
Credner & Kohle, Sternwarte Bonn

Supernova 1987A in LMC (a small galaxy nearby)



NASA (R. Kirshner and B. Sugerman)

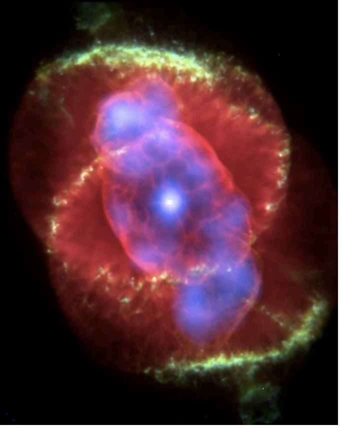
Brightest exploding star seen in 400 years

Explosion of massive (blue supergiant) star

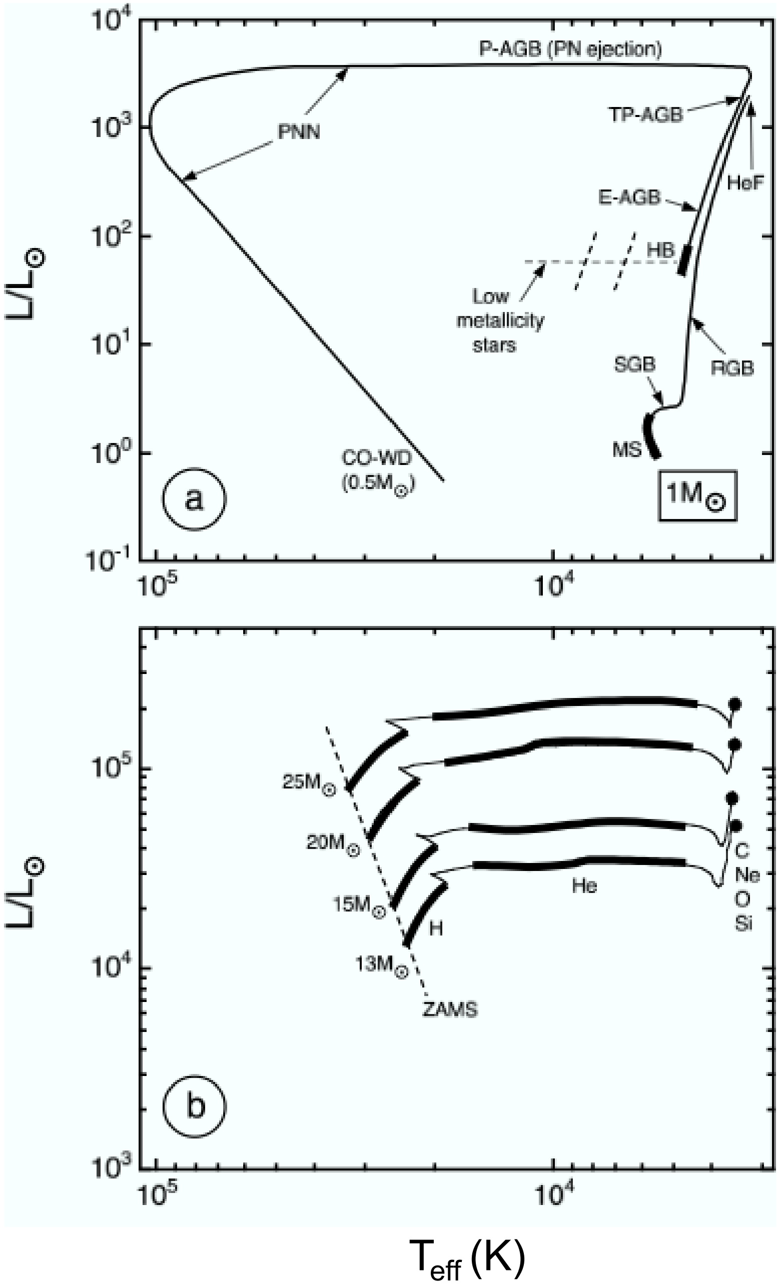
Supernova shock wave reaches gas previously ejected by central star

Debris from explosion

core collapse supernovae release an energy of $(1\text{-}2)\times10^{51}$ erg [1 erg=6.2×10^{5} MeV]



Cat's Eye nebula
(NGC 6543)



C. Iliadis, Nuclear Physics of Stars, Wiley-VCH (2007)

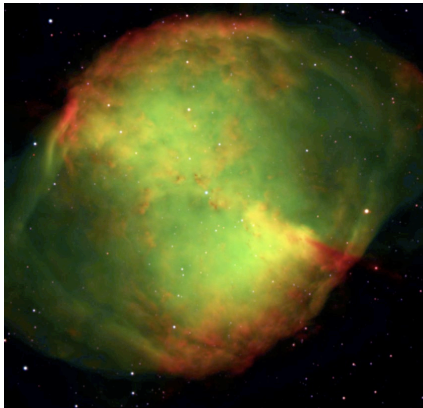
Hertzsprung-Russell diagram, a key to stellar evolution

Heavy lines: major nuclear burning stages in stellar core

Evolution of star mainly determined by its mass:

Larger mass:
→ larger T and P in core
→ faster nuclear energy generation
→ larger luminosity
→ faster fuel consumption
→ shorter lifetime

Dumbbell nebula (M27)



2. Nuclear Reactions

Definition of cross section:

$$\sigma \equiv \frac{(\text{number of interactions per time})}{(\text{number of incident particles per area per time})(\text{number of target nuclei within the beam})}$$

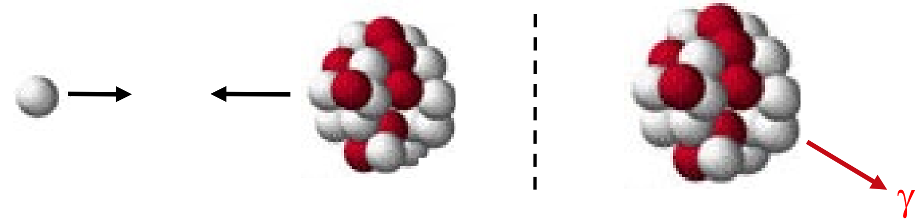
Unit: 1 barn=10^{-28} m^2

Task#1: consider $^1H + {}^1H \rightarrow {}^2H + e^+ + \nu$ (first step of pp chain) at E_{lab}=1 MeV

- σ_{theo}=8×10^{-48} cm^2 [E_{cm}=0.5 MeV]
- 1 ampere (A) proton beam; dense hydrogen gas target (10^{20} protons/cm^2)

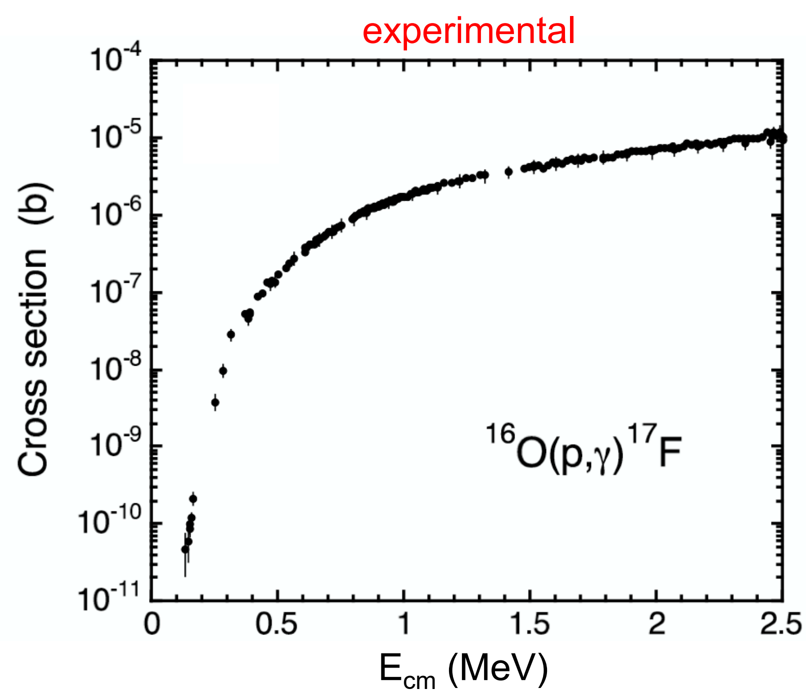
How long, on average, do you have to wait for 1 reaction to occur?

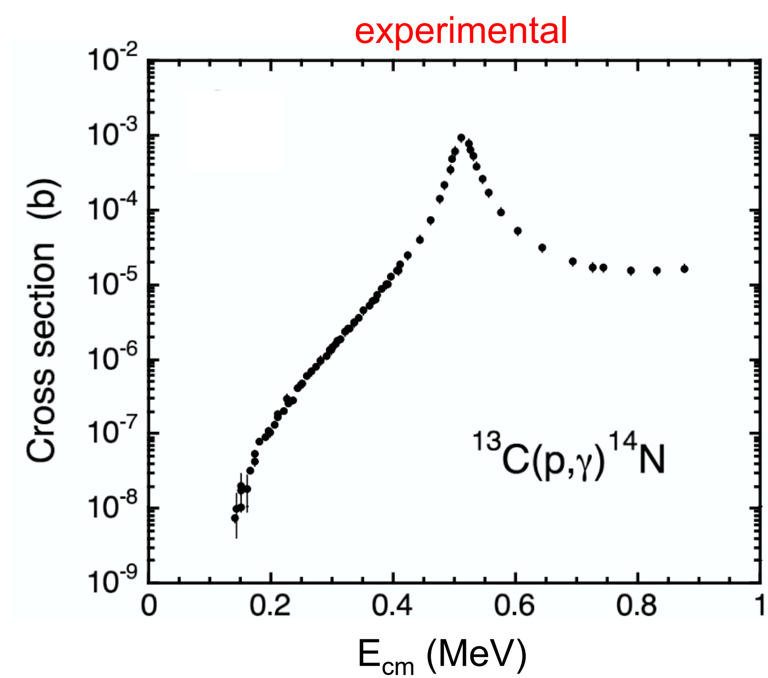
Cross sections



$$\sigma \equiv \frac{(\text{number of interactions per time})}{(\text{number of incident particles per area per time})(\text{number of target nuclei within the beam})}$$

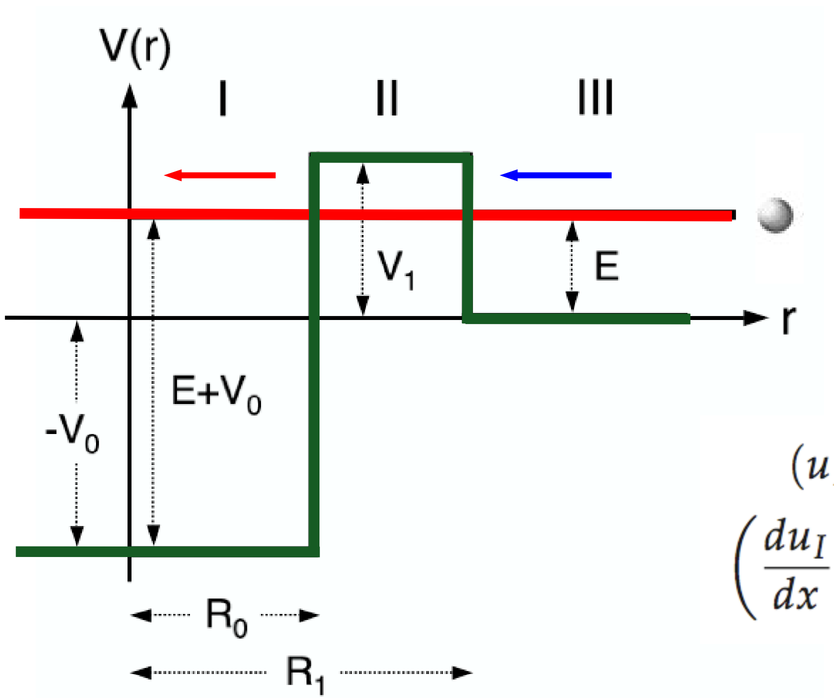
[unit: 1 barn=10^{-28} m^2]





- Why does the cross section fall drastically at low energies?
- Where is the peak in the cross section coming from?

A simple example in 1 dimension



Wave function solutions:

$$u_I = \boxed{A}e^{iKx} + \boxed{Be^{-iKx}}$$
$$u_{II} = Ce^{-\kappa x} + De^{\kappa x}$$
$$u_{III} = Fe^{ikx} + \boxed{Ge^{-ikx}}$$

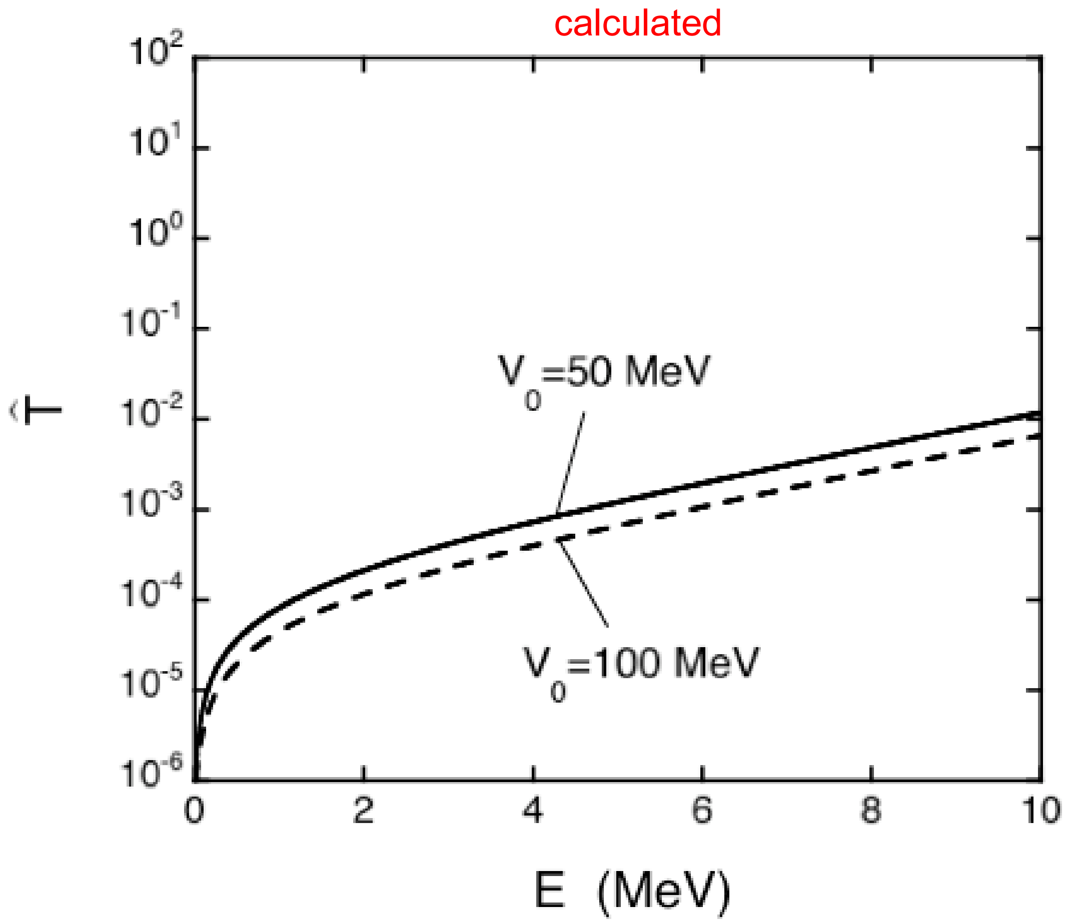
Continuity condition:

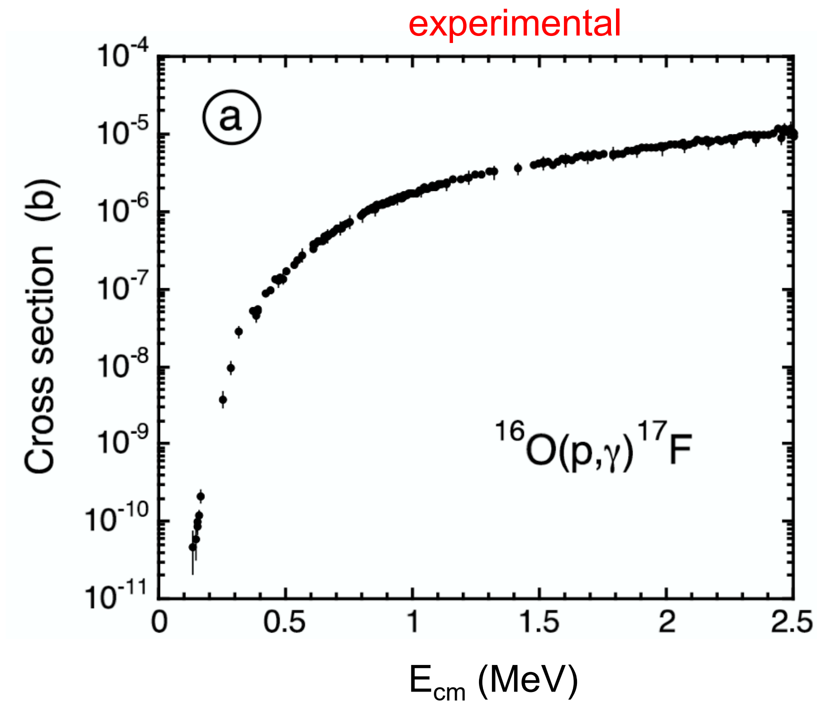
$$(u_I)_{R_0} = (u_{II})_{R_0} \qquad (u_{II})_{R_1} = (u_{III})_{R_1}$$
$$\left(\frac{du_I}{dx}\right)_{R_0} = \left(\frac{du_{II}}{dx}\right)_{R_0} \qquad \left(\frac{du_{II}}{dx}\right)_{R_1} = \left(\frac{du_{III}}{dx}\right)_{R_1}$$

Transmission coefficient: $\hat{T} = \frac{K}{k}\frac{|B|^2}{|G|^2} \approx e^{-(2/\hbar)\sqrt{2m(V_1-E)}(R_1-R_0)}$

(after lengthy algebra, and for the limit of low E)

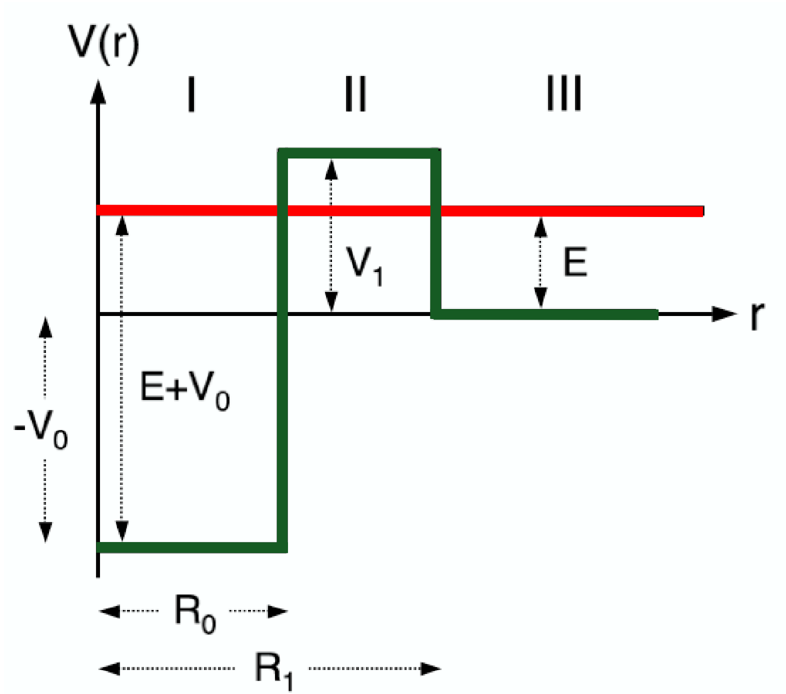
"Tunnel effect"





Tunnel effect is the reason for the strong drop in cross section at low energies!

Back to the simple potential, now in 3 dimensions



Wave function solutions:

$$u_I = \boxed{A'}\sin(Kr)$$
$$u_{II} = Ce^{-\kappa r} + De^{\kappa r}$$
$$u_{III} = \boxed{F'}\sin(kr + \delta_0)$$

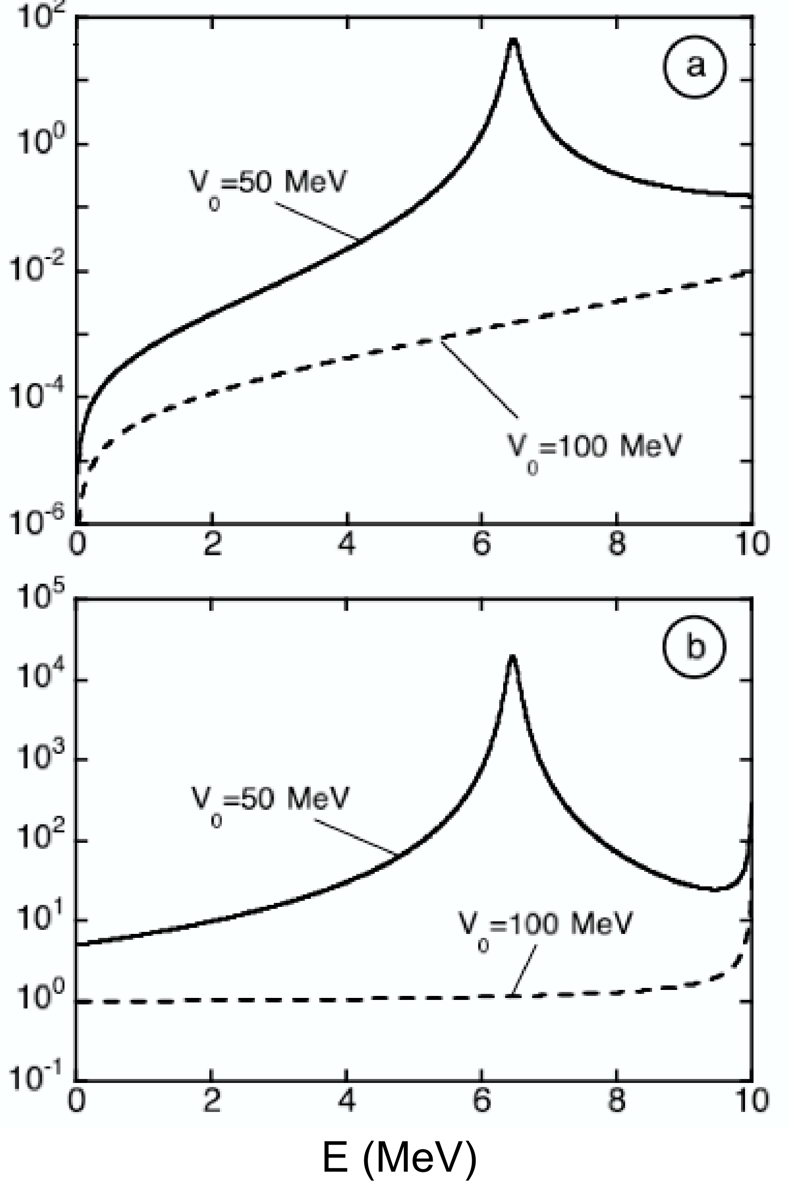
Continuity condition…

Wave intensity in interior region:
(after very tedious algebra)

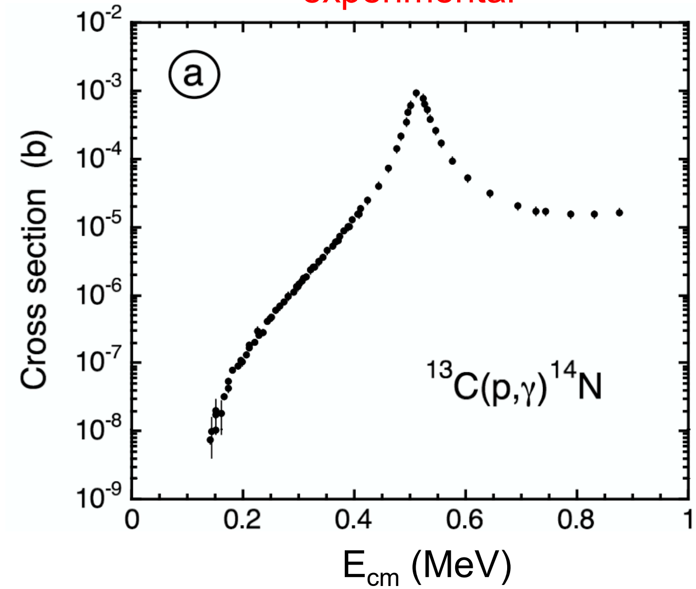
calculated

$$\frac{|A'|^2}{|F'|^2}$$

$$\frac{|A'|^2}{|F'|^2}\,\frac{1}{\hat{T}}$$



experimental

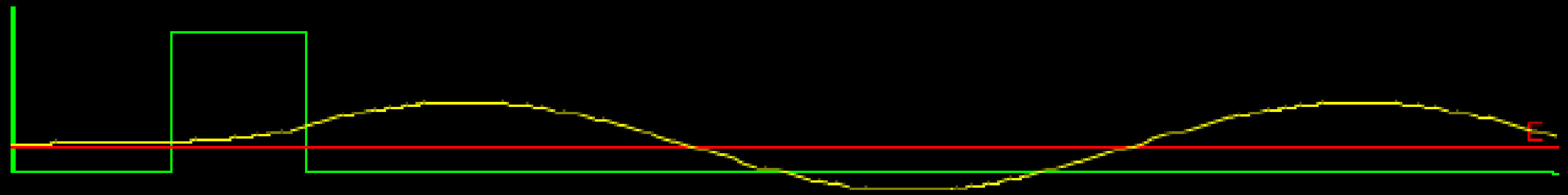


[change of potential depth V_0:
changes wavelength in interior region]

"Resonance phenomenon"

A resonance results from favorable wave function matching conditions at the boundaries!

Resonance phenomenon: radial wave function for varying potential depth V_0



Macroscopic analogy: Tacoma Narrows Bridge (1940)

Transmission through the Coulomb barrier

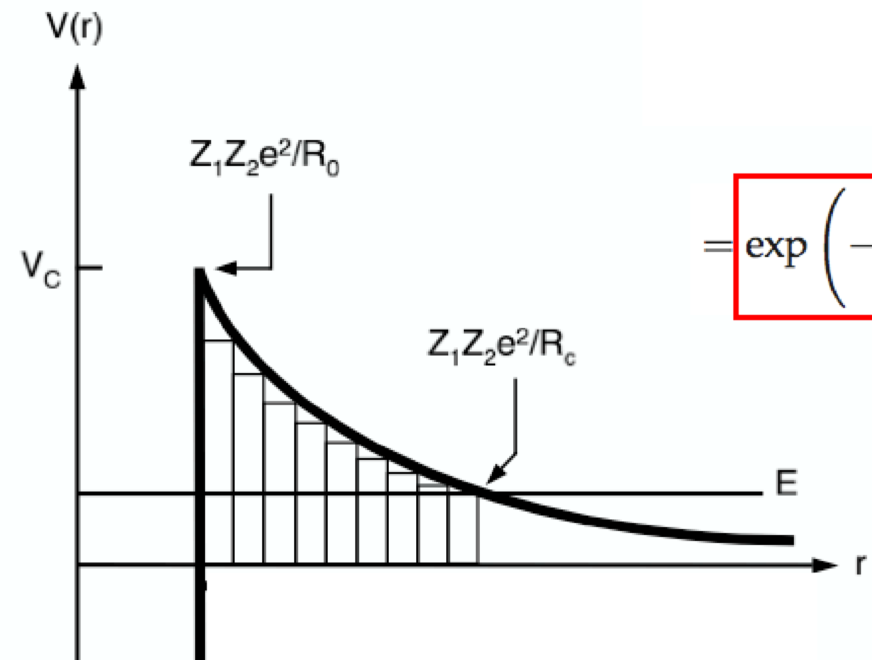
$$\hat{T} = \hat{T}_1 \cdot \hat{T}_2 \cdot \ldots \cdot \hat{T}_n \approx \exp\left[-\frac{2}{\hbar}\sum_i \sqrt{2m(V_i - E)}(R_{i+1} - R_i)\right]$$

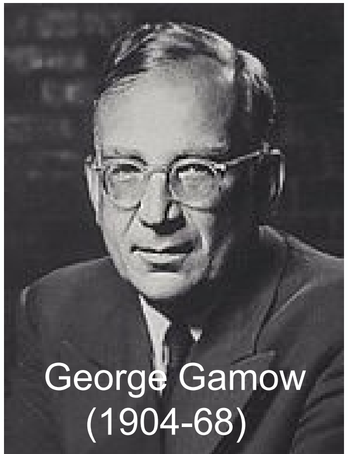
$$\xrightarrow[n \text{ large}]{} \exp\left[-\frac{2}{\hbar}\int_{R_0}^{R_c} \sqrt{2m[V(r) - E]}\, dr\right]$$

$$= \boxed{\exp\left(-\frac{2\pi}{\hbar}\sqrt{\frac{m}{2E}}Z_0 Z_1 e^2\right.}\left[1 + \frac{2}{3\pi}\left(\frac{E}{V_C}\right)^{3/2}\right] + \left.\frac{4}{\hbar}\sqrt{2mZ_0Z_1e^2R_0}\right)$$

[very low energies, zero angular momentum]

"Gamow factor" $e^{-2\pi\eta}$



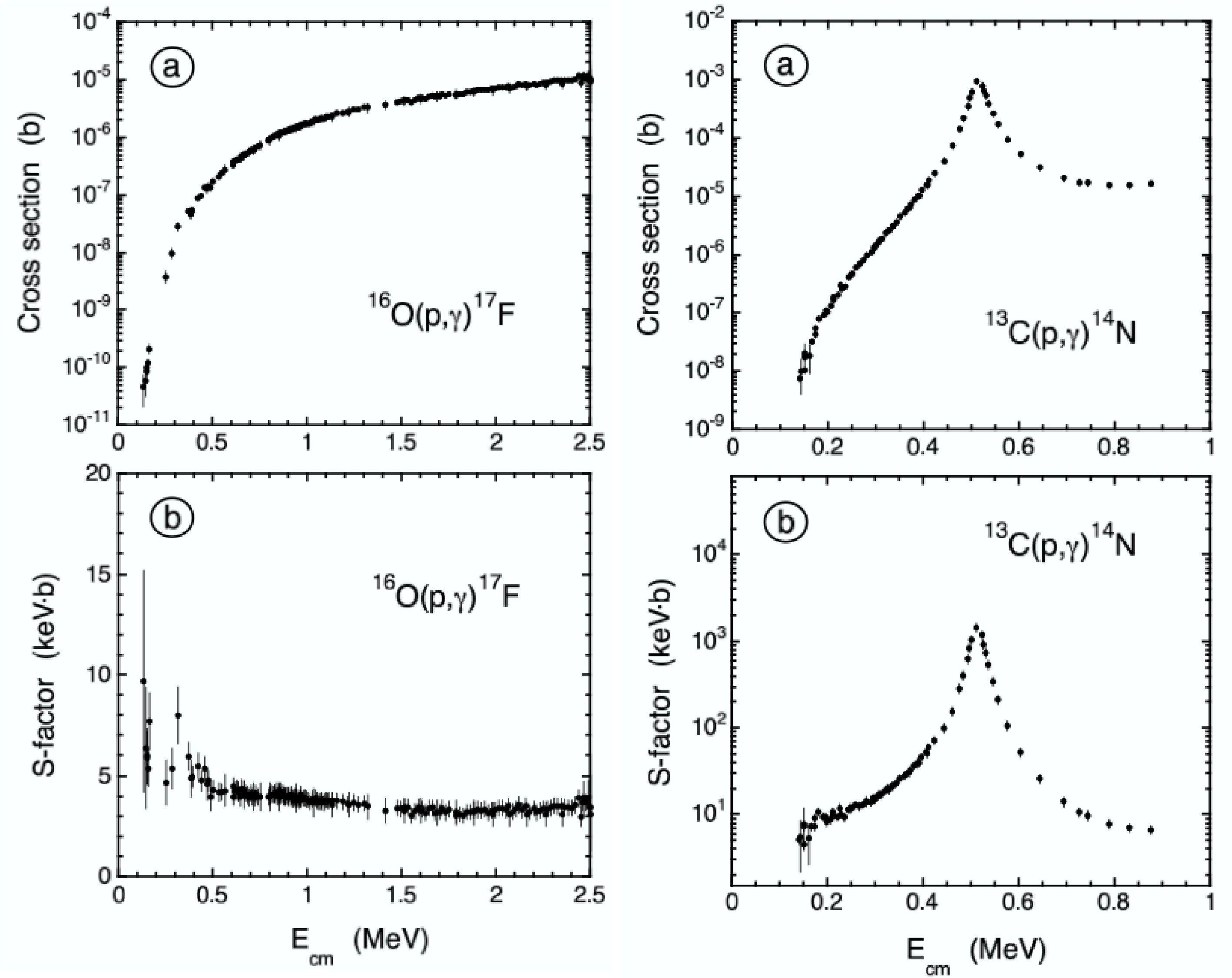

George Gamow (1904-68)

$$\sigma(E) \equiv \frac{1}{E}e^{-2\pi\eta}\boxed{S(E)}$$

"astrophysical S-factor"

cross sections

S-factors



Formal reaction theory: Breit-Wigner formula

Partial widths for incoming and outgoing channel

De Broglie wavelength

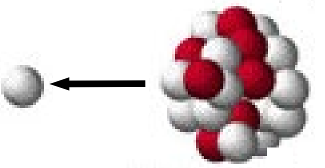
$$\sigma_{\mathrm{BW}}(E) = \frac{\lambda^2}{4\pi} \underbrace{\frac{(2J+1)(1+\delta_{01})}{(2j_0+1)(2j_1+1)}}_{\text{spin factor}} \frac{\Gamma_a \Gamma_b}{(E_r - E)^2 + \Gamma^2/4}$$

resonance energy

total width

Used for:
- for fitting data to deduce resonance properties
- for “narrow-resonance” thermonuclear reaction rates
- for extrapolating cross sections when no measurements exist
- for experimental yields when resonance cannot be resolved

What are “partial widths”?



probability per unit time for formation or decay of a resonance (in energy units)

For protons/neutrons:

$$\boxed{\Gamma_{\lambda c} = 2\frac{\hbar^2}{mR^2}\boxed{P_c}\boxed{C^2S}\boxed{\theta^2_{pc}}}$$

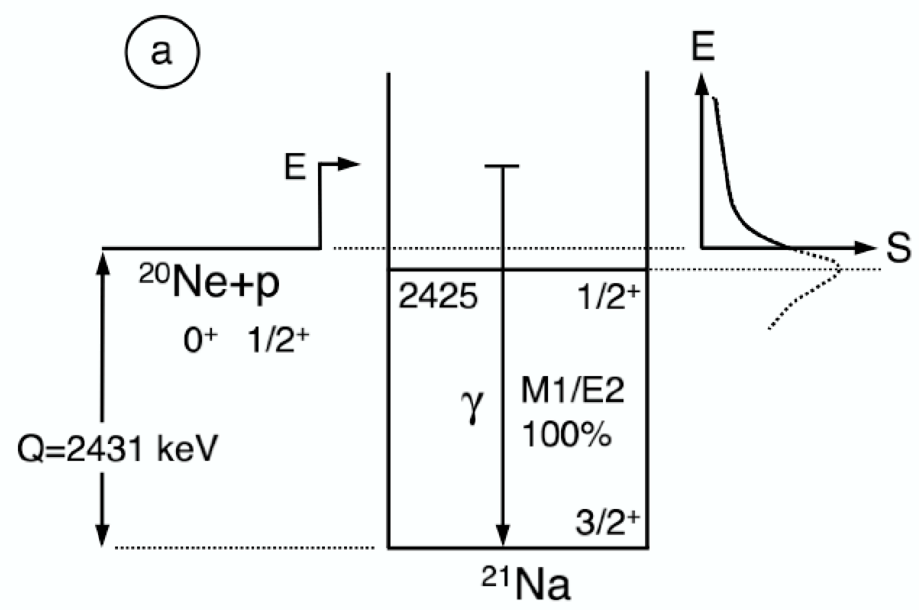
A partial width can be factored into 3 probabilities:

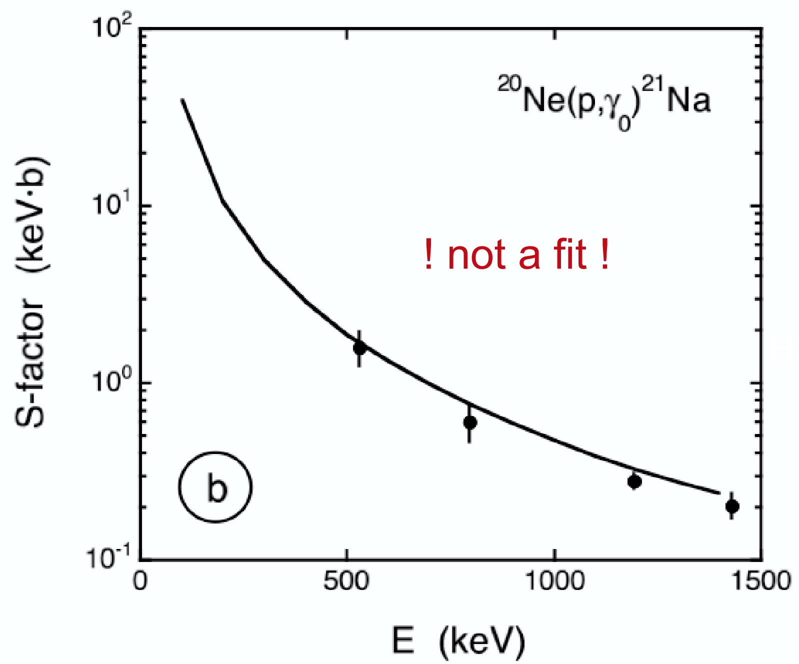
C^2S: probability that nucleons will arrange themselves in a “residual nucleus + single particle” configuration [“spectroscopic factor”]

θ^2: probability that single nucleon will appear on nuclear boundary [“dimensionless reduced single particle width”; Iliadis, NPA 618, 166 (1997)]

P_c: probability that single nucleon will penetrate Coulomb and centripetal barriers [“penetration factor”; strongly energy-dependent! see later]

Sensitive test of the Breit-Wigner formula





[Data points from Rolfs & Rodney, NPA 241, 460 (1975)]

- resonance energy obtained from known excitation energy
- proton partial width: estimated using C^2S from proton transfer
- γ-ray partial width estimated from measured lifetime (0.30 eV)

Breit-Wigner formula predicts accurately cross section extrapolated over 10^6 resonance widths!

Task #2:

The E_r^{cm} = 518 keV ($J^\pi = 1^-$) s-wave resonance (Fig. 3.11) in the ^{13}C(p,γ)^{14}N reaction (Q = 7550 keV) has an "observed" proton and γ-ray partial width of Γ_p^o = 37 keV and Γ_γ^o = 9.4 eV, respectively, at the resonance energy. Both values are given here in the center-of-mass system. They are derived from the results reported in King et al. 1994. The latter value corresponds to the γ-ray partial width of the $E1$ transition to the ^{14}N ground state ($J^\pi = 1^+$). By using the energy dependences of the partial widths, find for this particular resonance the center-of-mass energy at which $\Gamma_p^o \approx \Gamma_\gamma^o$. Approximate the s-wave penetration factor by the Gamow factor and disregard the small energy dependence of the dimensionless single-particle reduced width.

Hints/suggestions:

use the following expressions to scale the proton and g-ray partial widths:

$$\Gamma_p^0(E) = \Gamma_p^0(E_r)\frac{P_{\ell=0}(E)}{P_{\ell=0}(E_r)} \qquad \Gamma_{\gamma,E1}^0(E) = \Gamma_{\gamma,E1}^0(E_r)\left(\frac{E+Q}{E_r+Q}\right)^{2L+1}$$

3. Thermonuclear Reactions

For a reaction 0 + 1 $\rightarrow$ 2 + 3 we find from the definition of σ (see earlier) a "reaction rate":

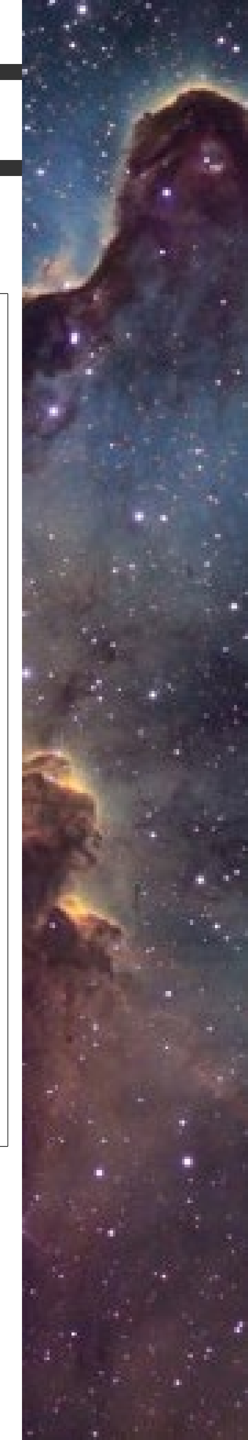
$$r_{01} = N_0 N_1 \int_0^{\infty} vP(v)\sigma(v)\,dv \equiv N_0 N_1 \langle \sigma v \rangle_{01}$$

For a stellar plasma: kinetic energy for reaction derives from thermal motion:

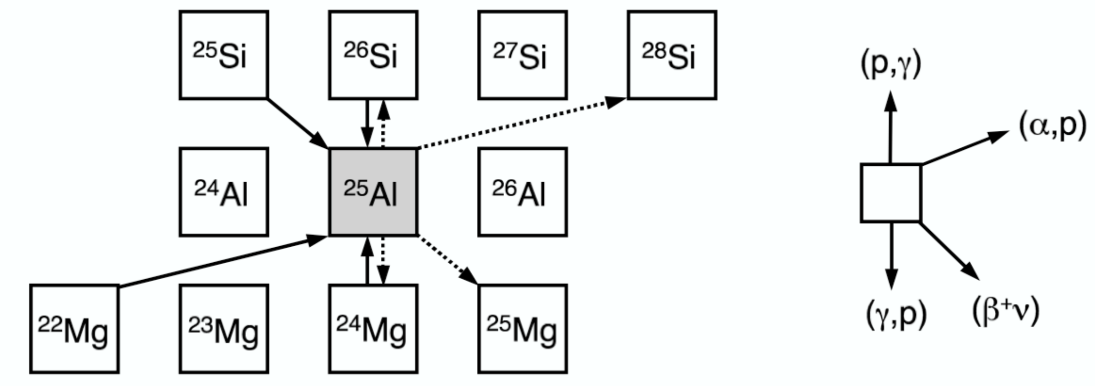
"Thermonuclear reaction"

For a Maxwell-Boltzmann distribution:

$$\langle \sigma v \rangle_{01} = \left(\frac{8}{\pi m_{01}} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^{\infty} E\,\underline{\sigma(E)}\,e^{-E/kT}\,dE$$



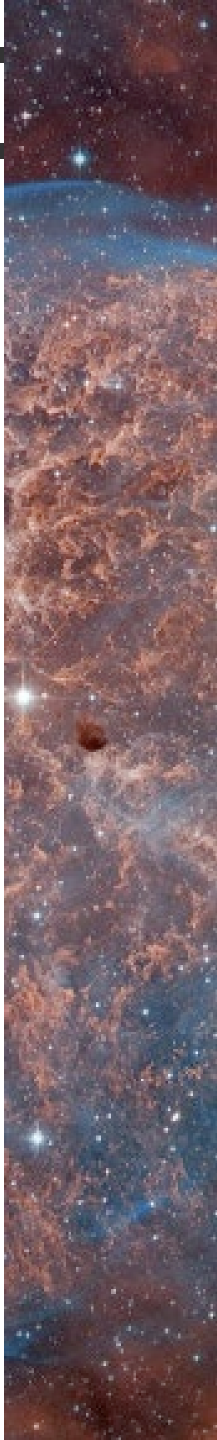
The interplay of many different nuclear reactions in a stellar plasma



$$
\begin{aligned}
\frac{d(N_{^{25}\mathrm{Al}})}{dt} = & \left.\begin{aligned} & N_{\mathrm{H}} N_{^{24}\mathrm{Mg}} \langle \sigma v \rangle_{^{24}\mathrm{Mg}(\mathrm{p},\gamma)} + N_{^{4}\mathrm{He}} N_{^{22}\mathrm{Mg}} \langle \sigma v \rangle_{^{22}\mathrm{Mg}(\alpha,\mathrm{p})} \\ & + N_{^{25}\mathrm{Si}} \lambda_{^{25}\mathrm{Si}(\beta^{+}\nu)} + N_{^{26}\mathrm{Si}} \lambda_{^{26}\mathrm{Si}(\gamma,\mathrm{p})} + \ldots \end{aligned}\right\} \text{production} \\
& \left.\begin{aligned} & - N_{\mathrm{H}} N_{^{25}\mathrm{Al}} \langle \sigma v \rangle_{^{25}\mathrm{Al}(\mathrm{p},\gamma)} - N_{^{4}\mathrm{He}} N_{^{25}\mathrm{Al}} \langle \sigma v \rangle_{^{25}\mathrm{Al}(\alpha,\mathrm{p})} \\ & - N_{^{25}\mathrm{Al}} \lambda_{^{25}\mathrm{Al}(\beta^{+}\nu)} - N_{^{25}\mathrm{Al}} \lambda_{^{25}\mathrm{Al}(\gamma,\mathrm{p})} - \ldots \end{aligned}\right\} \text{destruction}
\end{aligned}
$$

System of coupled differential equations: “nuclear reaction network”

Solved numerically
[Arnett, “Supernovae and Nucleosynthesis”, Princeton University Press, 1996]



Special case #1: reaction rates for smoothly varying S-factors ("non-resonant")

$$\sigma(E) \equiv \frac{1}{E} e^{-2\pi\eta} S(E)$$

$$N_A\langle\sigma v\rangle = \left(\frac{8}{\pi m_{01}}\right)^{1/2} \frac{N_A}{(kT)^{3/2}} \int_0^\infty E\,\sigma(E)\, e^{-E/kT}\, dE$$

$$= \left(\frac{8}{\pi m_{01}}\right)^{1/2} \frac{N_A}{(kT)^{3/2}} S_0 \int_0^\infty \boxed{e^{-2\pi\eta}\, e^{-E/kT}}\, dE$$

"Gamow peak"

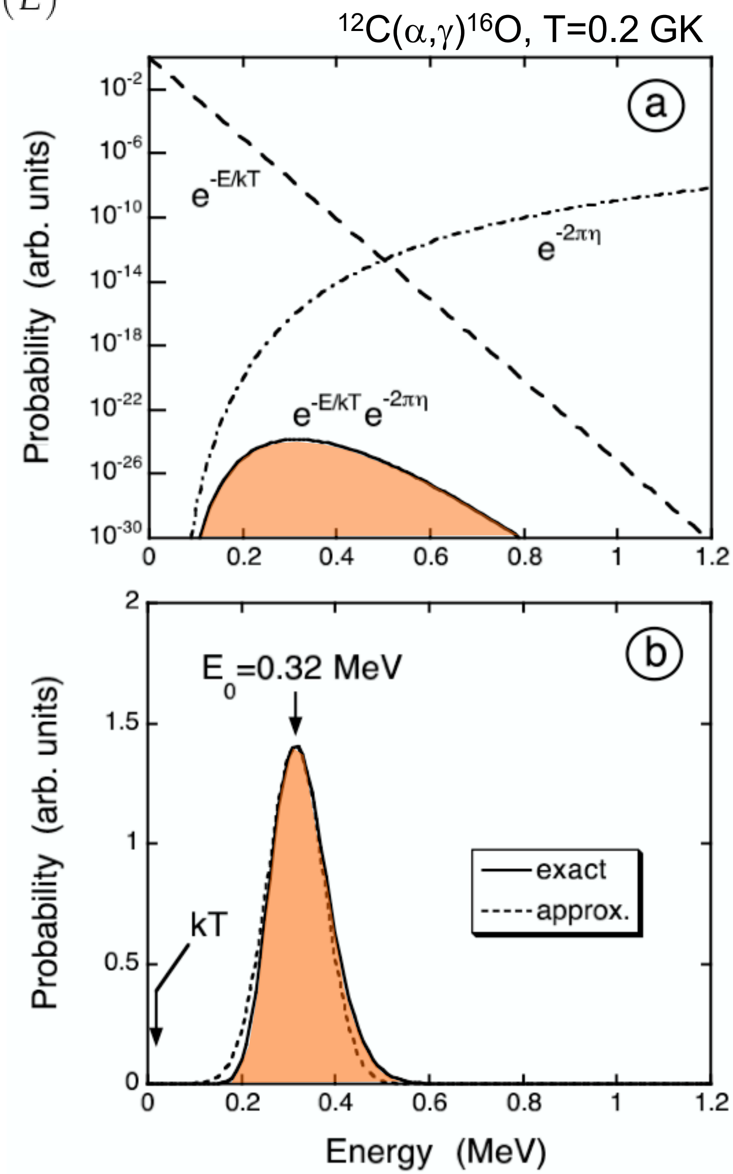
Represents the energy range over which most nuclear reactions occur in a plasma!

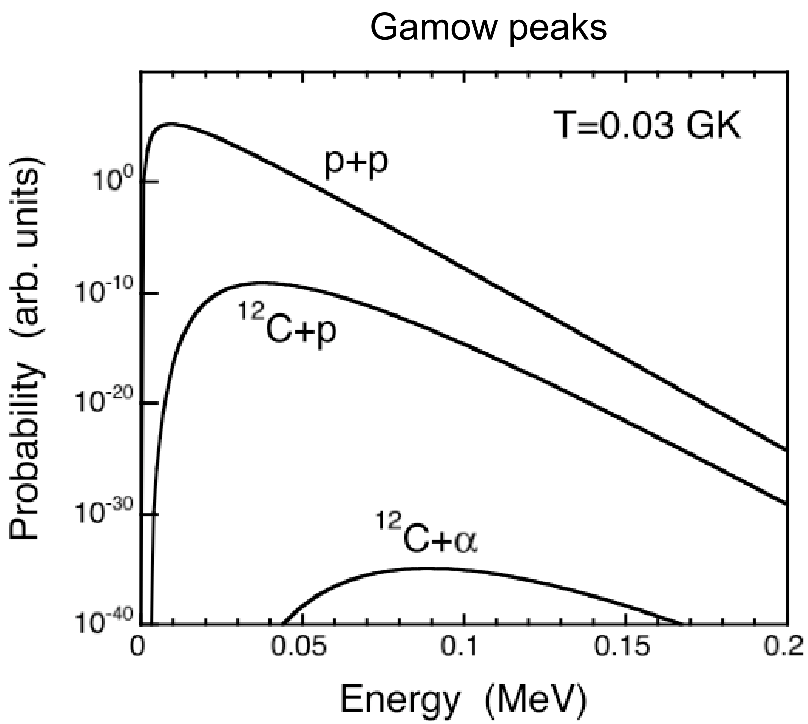
Location and 1/e width of Gamow peak:

$$E_0 = \left[\left(\frac{\pi}{\hbar}\right)^2 \left(Z_0 Z_1 e^2\right)^2 \left(\frac{m_{01}}{2}\right) (kT)^2\right]^{1/3}$$

$$= 0.1220 \left(Z_0^2 Z_1^2 \frac{M_0 M_1}{M_0 + M_1} T_9^2\right)^{1/3} \qquad \text{(MeV)}$$

$$\Delta = \frac{4}{\sqrt{3}}\sqrt{E_0 kT} = 0.2368 \left(Z_0^2 Z_1^2 \frac{M_0 M_1}{M_0 + M_1} T_9^5\right)^{1/6} \qquad \text{(MeV)}$$



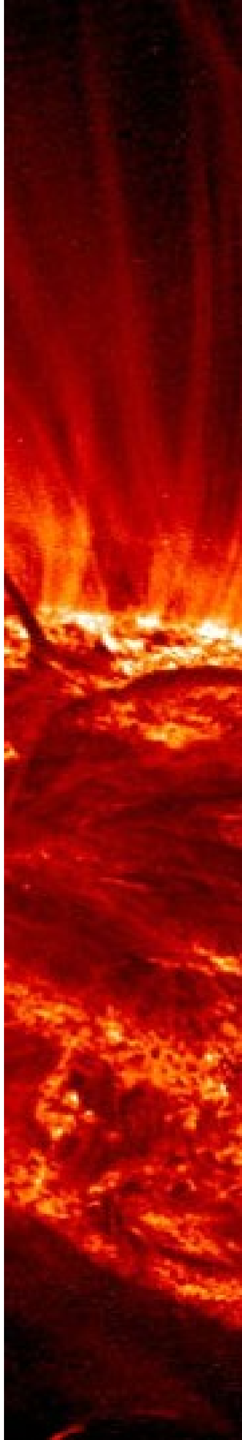


Important aspects:

(i) Gamow peak shifts to higher energy for increasing charges Z_p and Z_t

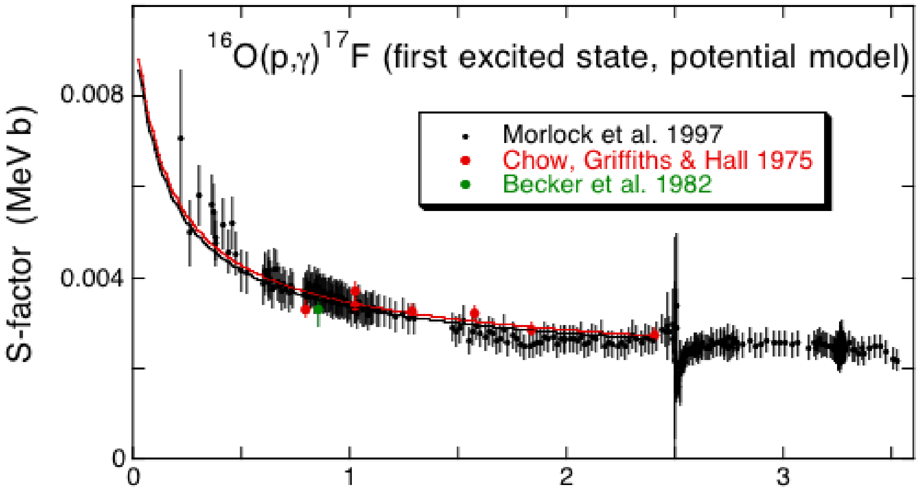
(ii) at same time, area under Gamow peak decreases drastically

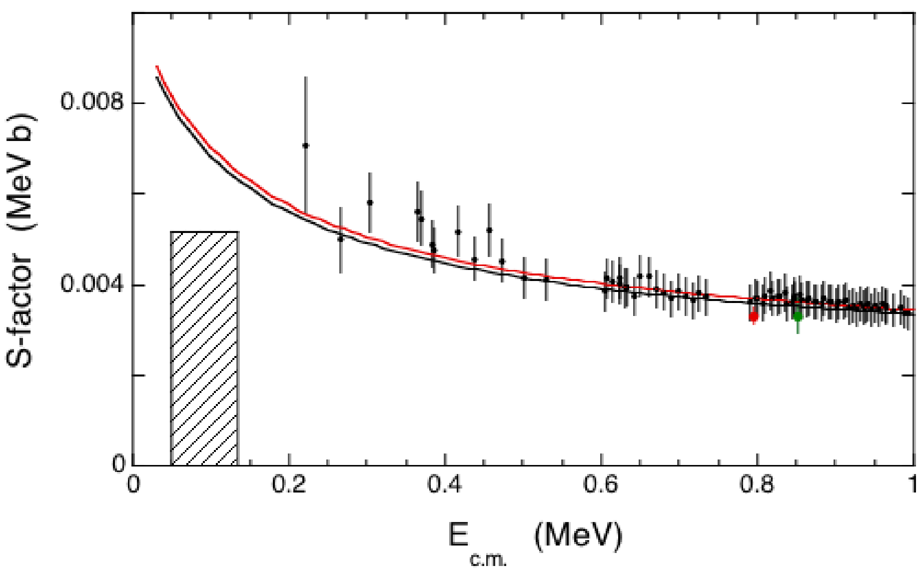
Conclusion: for a mixture of different nuclei in a plasma, those reactions with the smallest Coulomb barrier produce most of the energy and are consumed most rapidly ($\rightarrow$ stellar burning stages)

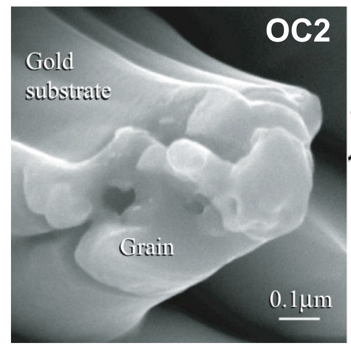


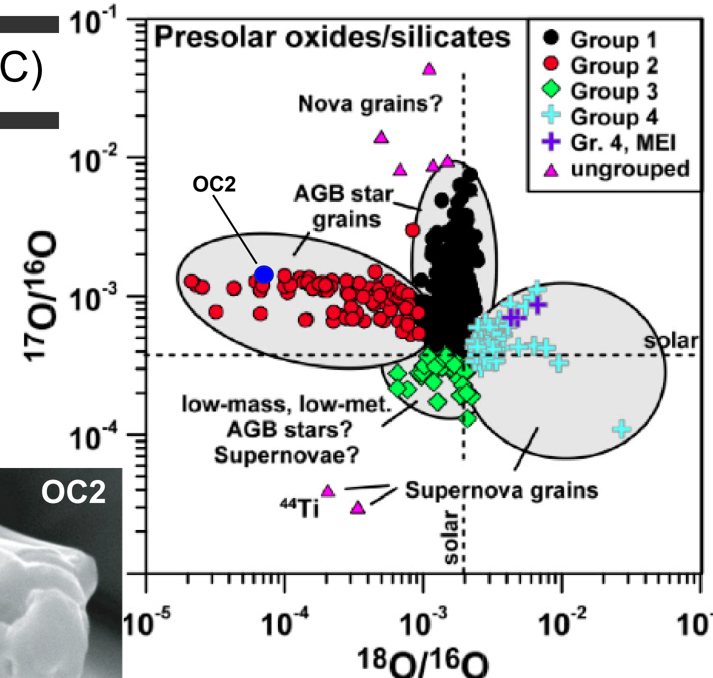
Example for smoothly varying σ: $^{16}O(p,\gamma)^{17}F$ direct capture (DC)

[Iliadis, Angulo, Descouvemont, Lugaro and Mohr, PR C 77, 045802 (2008)]









Reaction important for $^{17}O/^{16}O$ ratio predicted by models of massive AGB stars

New accurate cross section shows: there is presently no clear evidence of a **massive** AGB star origin for any observed stellar grain

Precise reaction rates are crucial!

Task #3: what causes the low-energy rise in the ^{16}O+p S-factor for the transition into the first excited state?

Steps/Hints:

(i) We can read the following S-factor values off the graph:
E_{cm}=0.03 MeV, S=0.008814 MeV b
E_{cm}=0.1 MeV, S=0.006843 MeV b
E_{cm}=0.4 MeV, S=0.004469 MeV b

(ii) Convert S-factors to cross section
(iii) Divide the cross section by the penetration factor; in order to do this, you need to determine the orbital angular momentum [before the interaction: p + ^{16}O; after interaction: ^{17}F in first excited state + E1 radiation]; use the numerical values for P from the file “Task3Help.pdf”

$$P_\ell = R\left(\frac{k}{F_\ell^2 + G_\ell^2}\right)_{r=R}$$

$$\rho = 0.218735 \cdot r\sqrt{\frac{M_p M_t}{M_p + M_t}E}$$

$$\eta = 0.157489 \cdot Z_p Z_t\sqrt{\frac{M_p M_t}{M_p + M_t}\frac{1}{E}}$$

where M_i, E and r are in units of u, MeV and fm, respectively.

(iv) What do you observe for the energy dependence of this “modified S-factor”?

Special case #2: reaction rates for (very) "narrow resonances" (Γ_i constant over total Γ)

Breit-Wigner formula (energy-**independent** partial widths)

$$N_A\langle\sigma v\rangle = \left(\frac{8}{\pi m_{01}}\right)^{1/2} \frac{N_A}{(kT)^{3/2}} \int_0^\infty E\,\sigma(E)\,e^{-E/kT}\,dE$$

$$= N_A \frac{\sqrt{2\pi}\hbar^2}{(m_{01}kT)^{3/2}} \underbrace{e^{-E_r/kT}} \underbrace{\omega\frac{\Gamma_a\Gamma_b}{\Gamma}} 2\pi$$

resonance energy needs to be known rather precisely [takes into account only rate contribution at E_r]

"resonance strength" $\omega\gamma$: proportional to area under narrow resonance curve

[For influence of uncertainties in E_r and $\omega\gamma$ on rate: see Thompson & Iliadis, NPA 647, 259 (1999)]

Task #4: although the Gamow peak concept is strictly defined only for non-resonant reactions, it is used all the time in nuclear astrophysics even in the case of resonances, where it is assumed that those resonances contribute the most to the total rate that are located inside the Gamow peak.

(i) Explain the reasoning behind this line of thought.
(ii) Also explain why these arguments do not always apply, especially not at higher temperatures.

Special case #3: reaction rates for "broad resonances"

Breit-Wigner formula (energy-**dependent** partial widths)

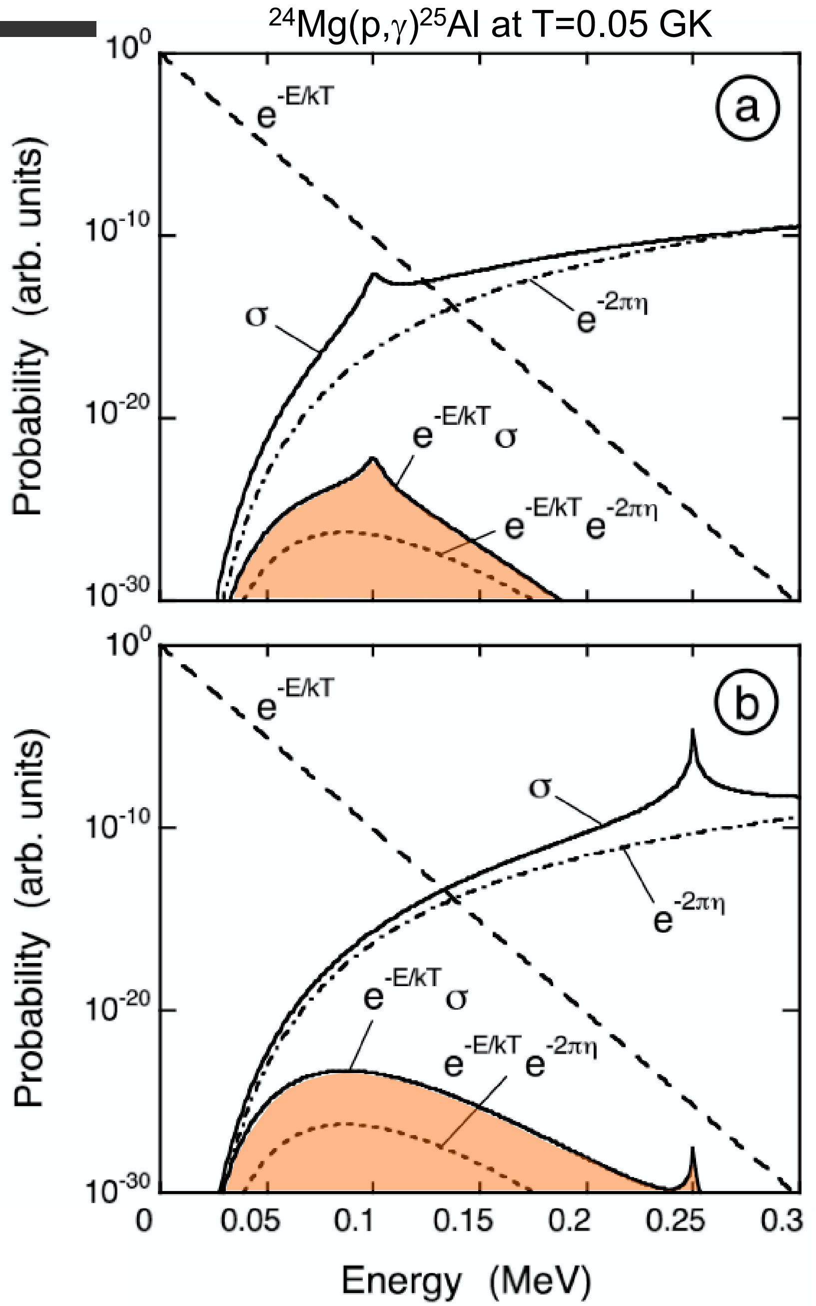
$$N_A\langle\sigma v\rangle = \left(\frac{8}{\pi m_{01}}\right)^{1/2} \frac{N_A}{(kT)^{3/2}} \int_0^\infty E\,\sigma(E)\,e^{-E/kT}\,dE$$

rate can be found from numerical integration

There are two contributions to the rate:

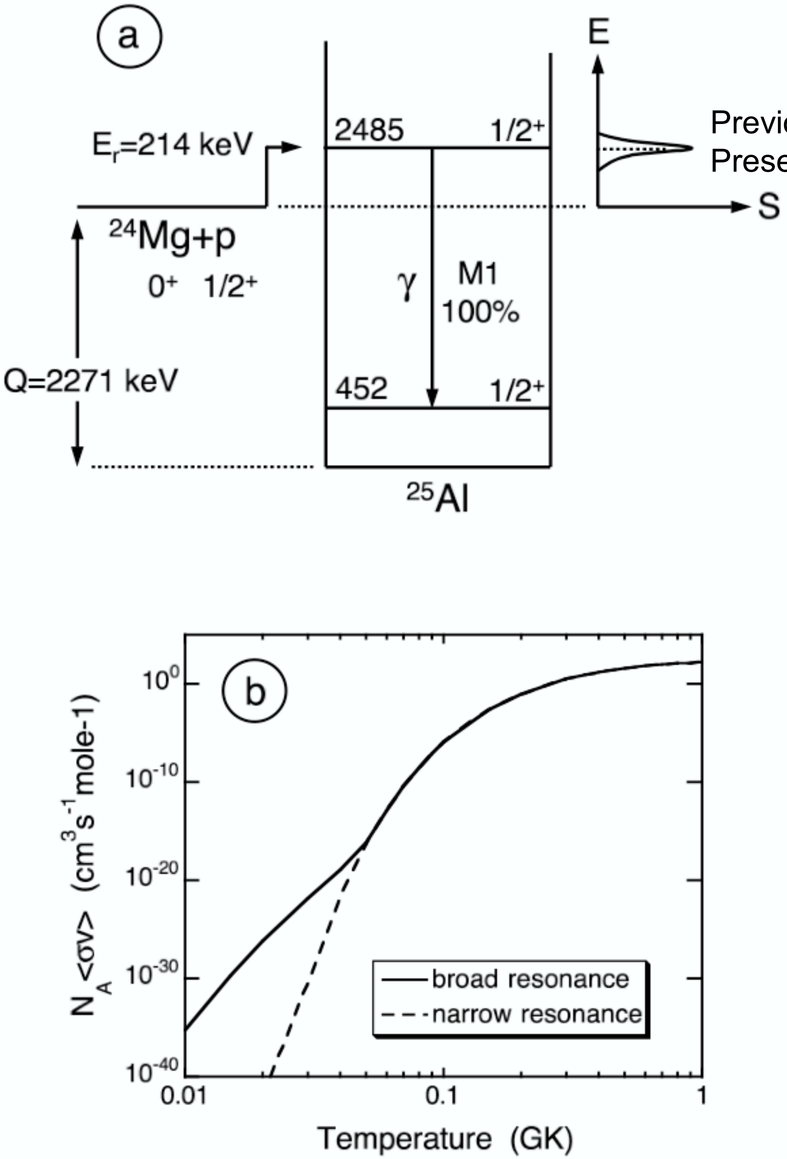
(i) from "narrow resonance" at E_r

(ii) from tail of broad resonance

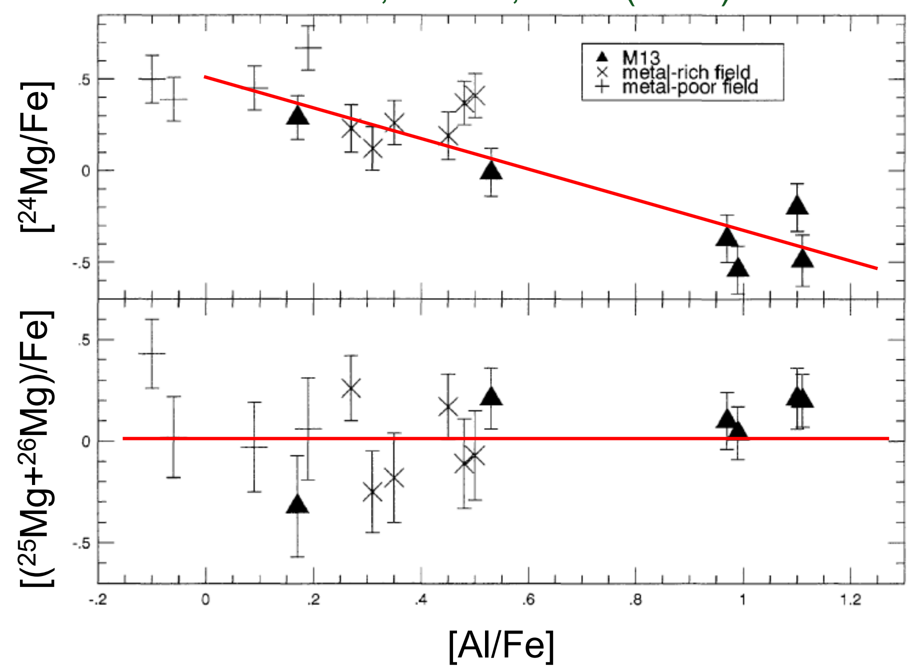


Example for resonance: E_r=214 keV in ^{24}Mg(p,γ)^{25}Al

[Powell, Iliadis et al., NPA 660, 349 (1999)]

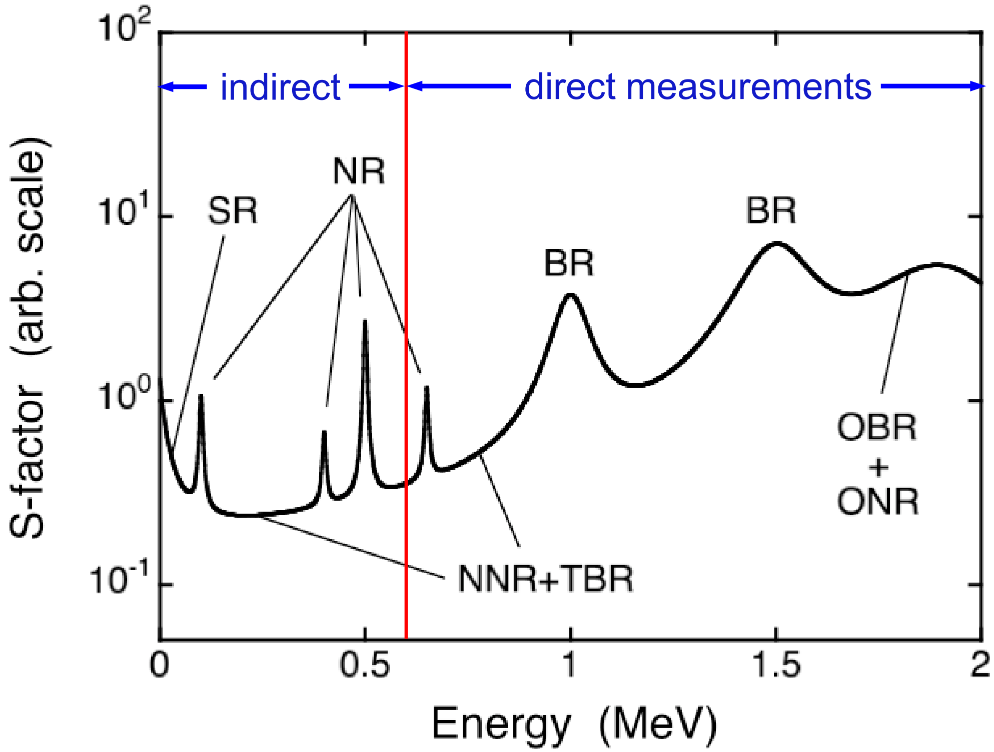


Shetrone, AJ 112, 2639 (1996)



Conclusion: ^{24}Mg-Al anticorrelation cannot be produced in globular cluster red giants at 50 MK

Total thermonuclear reaction rate

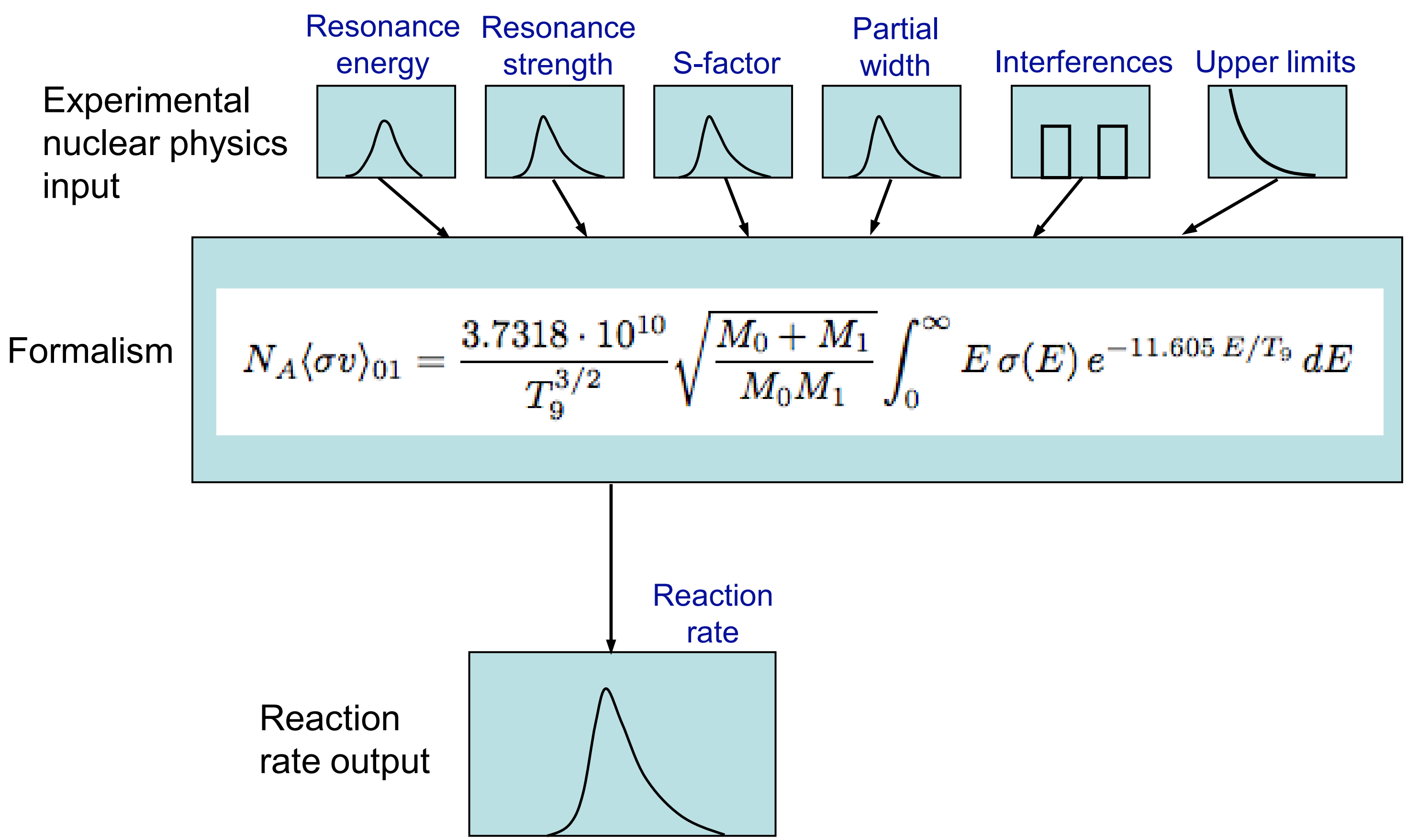


Need to consider:

- non-resonant processes
- narrow resonances
- broad resonances
- subthreshold resonances
- interferences
- continuum

every nuclear reaction represents a special case

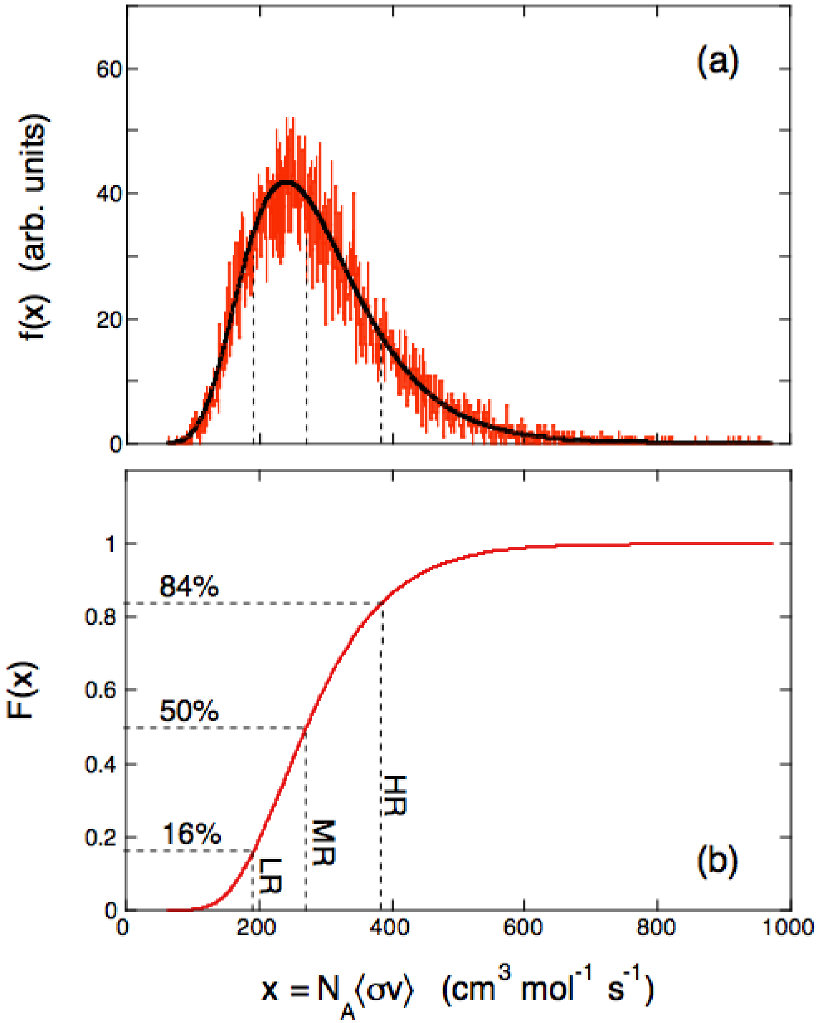
Monte Carlo method: a step forward



$$N_A\langle\sigma v\rangle_{01} = \frac{3.7318\cdot 10^{10}}{T_9^{3/2}}\sqrt{\frac{M_0+M_1}{M_0 M_1}}\int_0^\infty E\,\sigma(E)\,e^{-11.605\,E/T_9}\,dE$$

Lognormal probability density function:

Monte Carlo reaction rates for 62 reactions from ^{14}C to ^{40}Ca target nuclei



Schematic (not real) example:

$^{22}Ne(\alpha,\gamma)^{26}Mg$
at T=500 MK

E_r=300±15 keV
$\omega\gamma$=4.1±0.2 eV

10,000 samples

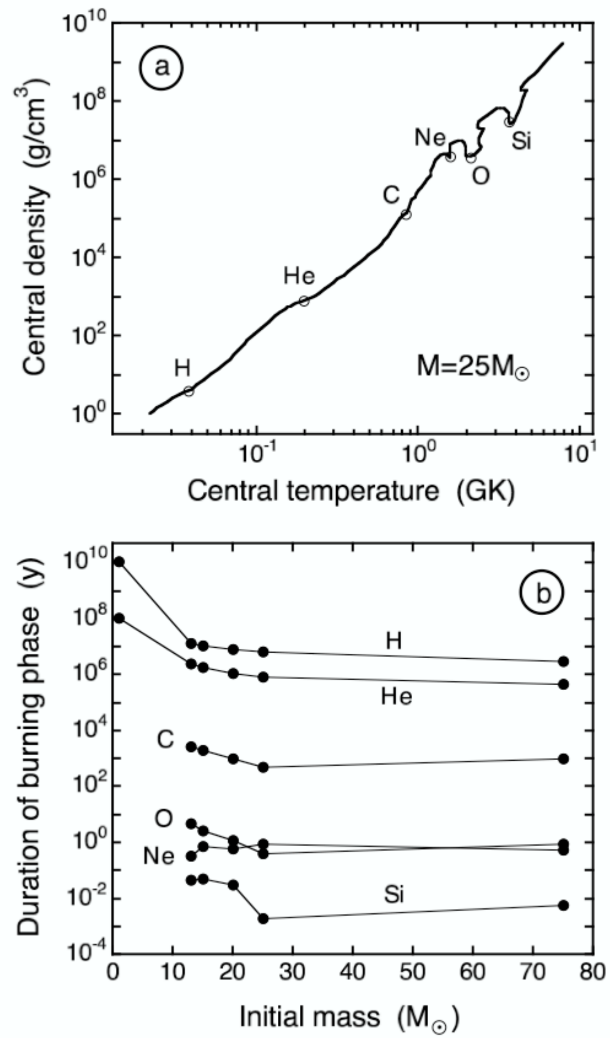
Foundation of our new library of thermonuclear reactions rates; will be used for simulations of massive stars, classical novae, AGB stars etc.

New evaluation of 62 nuclear reaction involving targets in the A=14-40 mass region:

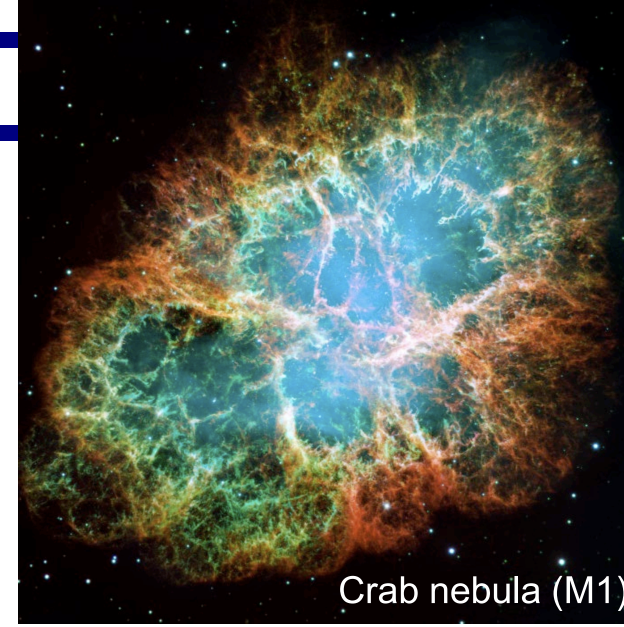
- Iliadis, Longland, Champagne, Coc & Fitzgerald, Nucl. Phys. A 841, 31 (2010)

4. Nuclear Burning Stages

- reactions with smallest Coulomb barrier proceed first, stabilizing star
- when nuclear fuel is consumed, star contracts gravitationally, T increases
- next available nuclear fuel (ashes of previous stage) burns, stabilizing star



Massive stars



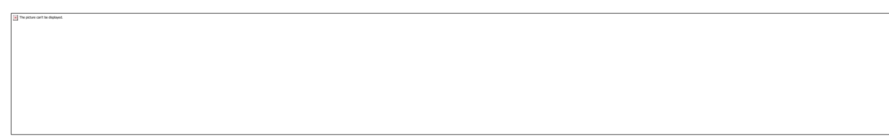
Crab nebula (M1)

Remnant of type II supernova

Nuclear energy release: H-burning ($6x10^{24}$ MeV/g)
He-burning ($6x10^{23}$ MeV/g)

hydrogen fuel is consumed slower

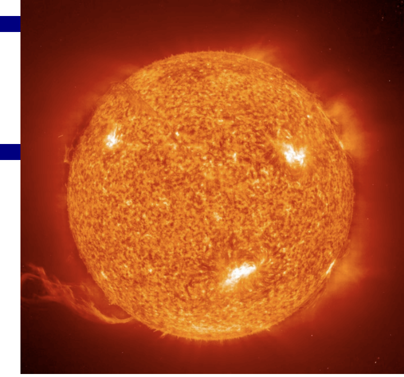
Stellar energy loss: H/He-burning (photons)
advanced stages (neutrinos)

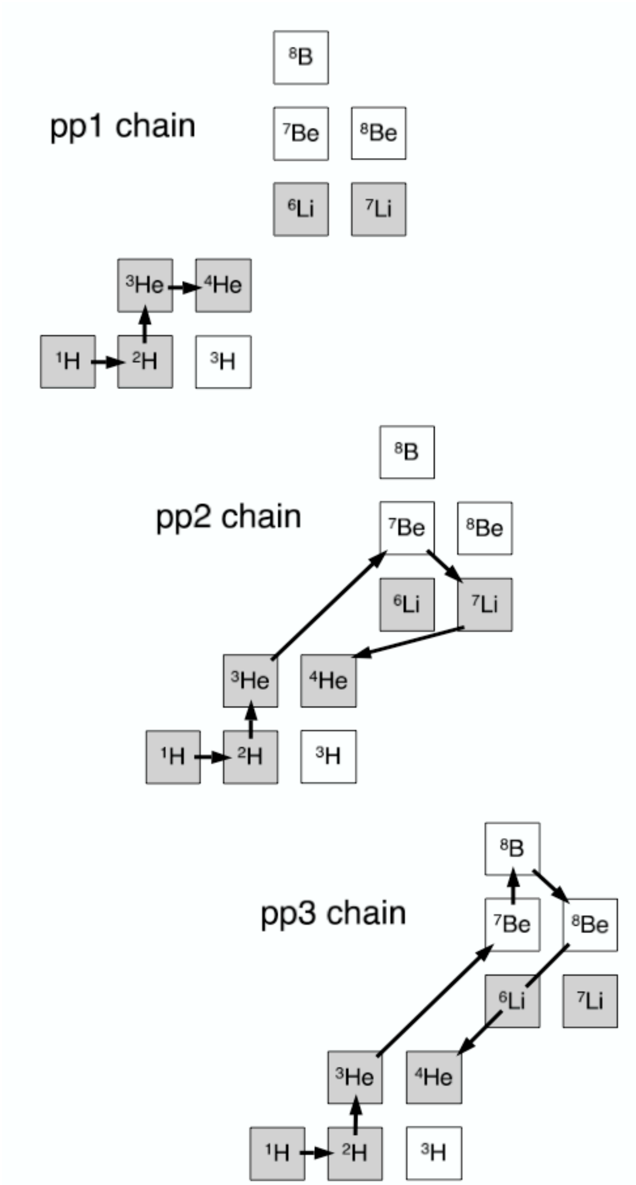


fuel consumption increases rapidly during later stages

[Woosley, Heger & Weaver, Rev. Mod. Phys. 74, 1015 (2002)]

Hydrostatic Hydrogen Burning: Sun (T=15.6 MK), stellar core (T=8-55 MK), shell of AGB stars (T=45-100 MK)

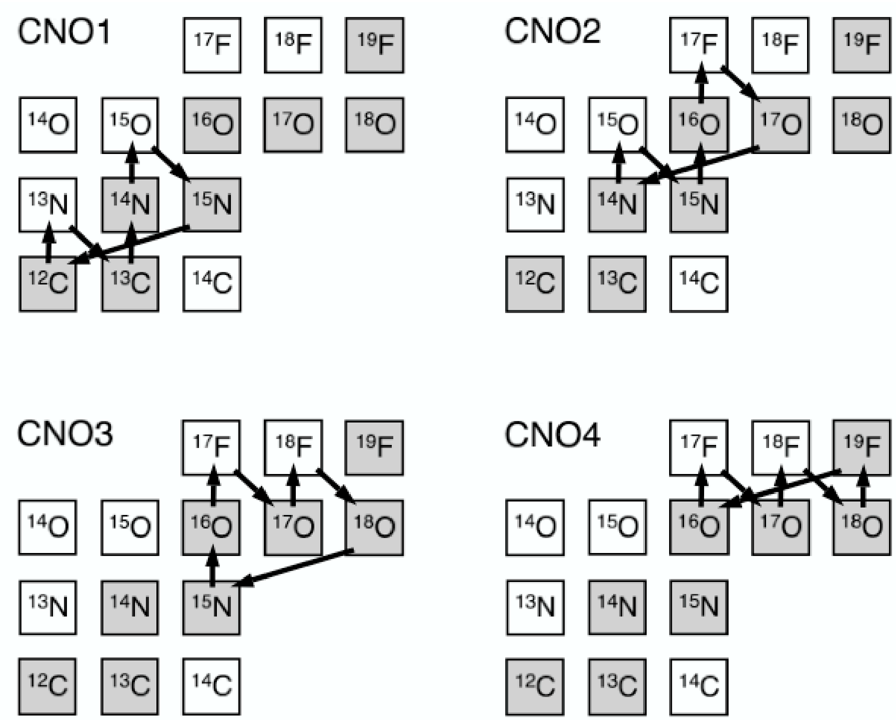




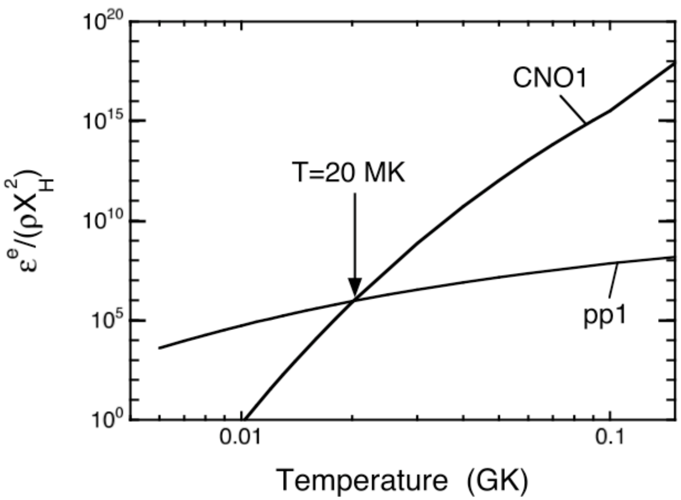
pp1 chain	pp2 chain	pp3 chain
$p(p,e^+\nu)d$	$p(p,e^+\nu)d$	$p(p,e^+\nu)d$
$\boxed{d(p,\gamma)^3He}$	$d(p,\gamma)^3He$	$d(p,\gamma)^3He$
$\boxed{^3He(^3He,2p)\alpha}$	$\boxed{^3He(\alpha,\gamma)^7Be}$	$^3He(\alpha,\gamma)^7Be$
	$^7Be(e^-,\nu)^7Li$	$^7Be(p,\gamma)^8B$
	$^7Li(p,\alpha)\alpha$	$\boxed{^8B(\beta^+\nu)^8Be}$
		$^8Be(\alpha)\alpha$

- $4H \rightarrow {}^4He$ releases 26.7 MeV
- reactions are non-resonant at low energies
- p+p has not been measured (see earlier)
- d+p, ^3He+^3He, $^3He+\alpha$ have been measured recently by LUNA collaboration
- 90% of Sun's energy produced by pp1 chain

Hydrostatic Hydrogen Burning: Sun (T=15.6 MK), stellar core (T=8-55 MK), shell of AGB stars (T=45-100 MK)

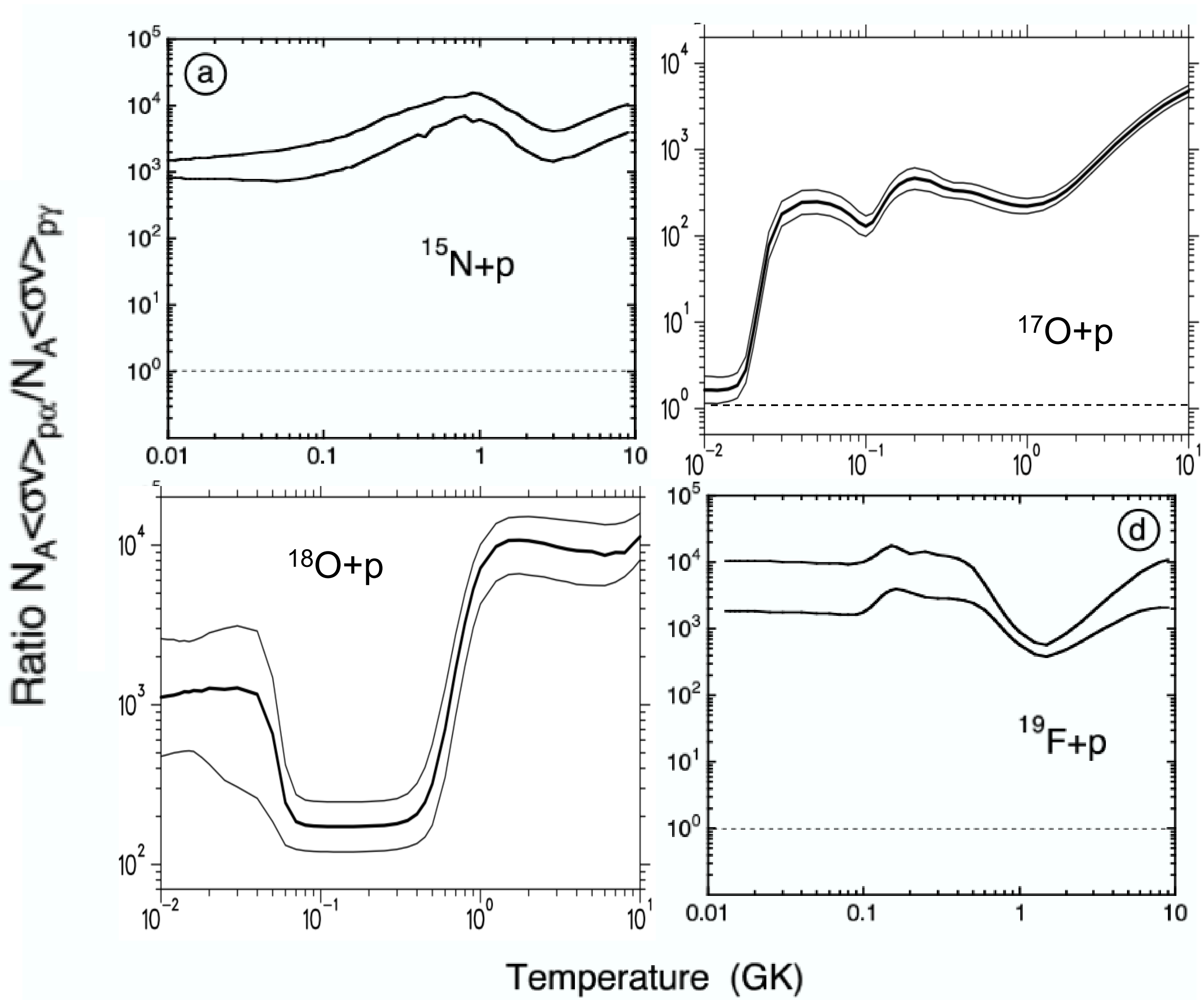


- ^{12}C and ^{16}O nuclei act as catalysts
- branchings: (p,α) stronger than (p,γ)
- $^{14}N(p,\gamma)^{15}O$ slowest reaction in CNO1 has been measured by LUNA/LENA
- solar: $^{13}C/^{12}C=0.01$; CNO1: $^{13}C/^{12}C=0.25$ ("steady state")
- T>20 MK: CNO1 faster than pp1
- CNO cycles in AGB stars: main source of ^{13}C and ^{14}N in Universe

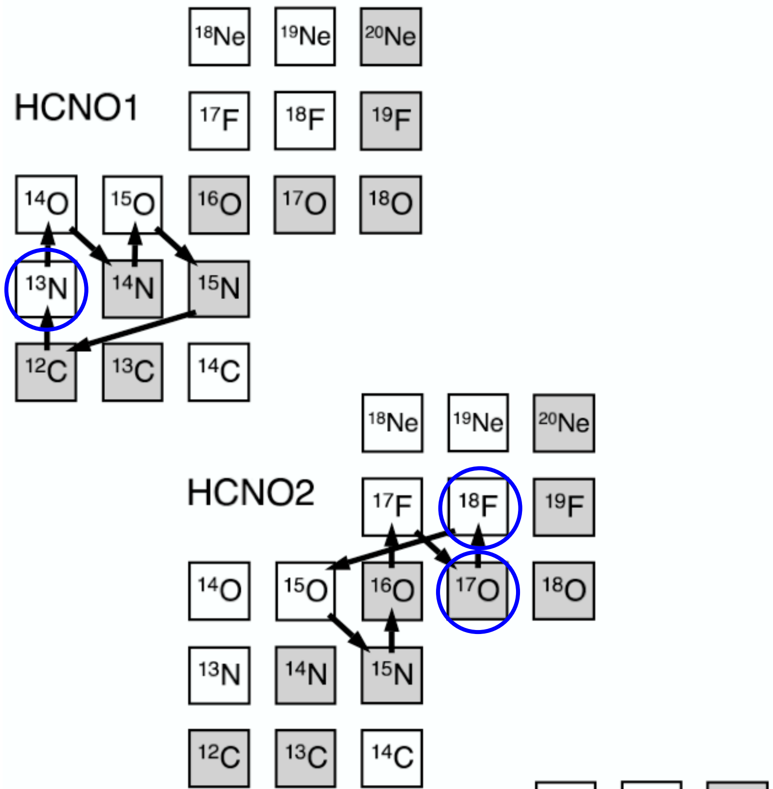


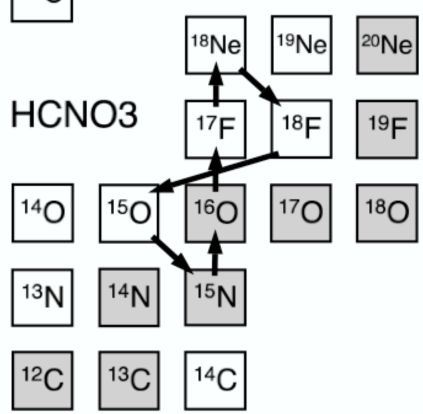
CNO1	CNO2	CNO3	CNO4
$^{12}C(p,\gamma)^{13}N$	$^{14}N(p,\gamma)^{15}O$	$^{15}N(p,\gamma)^{16}O$	$^{16}O(p,\gamma)^{17}F$
$^{13}N(\beta^+\nu)^{13}C$	$^{15}O(\beta^+\nu)^{15}N$	$^{16}O(p,\gamma)^{17}F$	$^{17}F(\beta^+\nu)^{17}O$
$^{13}C(p,\gamma)^{14}N$	$^{15}N(p,\gamma)^{16}O$	$^{17}F(\beta^+\nu)^{17}O$	$^{17}O(p,\gamma)^{18}F$
$\boxed{^{14}N(p,\gamma)^{15}O}$	$\boxed{^{16}O(p,\gamma)^{17}F}$	$^{17}O(p,\gamma)^{18}F$	$^{18}F(\beta^+\nu)^{18}O$
$^{15}O(\beta^+\nu)^{15}N$	$^{17}F(\beta^+\nu)^{17}O$	$^{18}F(\beta^+\nu)^{18}O$	$^{18}O(p,\gamma)^{19}F$
$^{15}N(p,\alpha)^{12}C$	$^{17}O(p,\alpha)^{14}N$	$^{18}O(p,\alpha)^{15}N$	$^{19}F(p,\alpha)^{16}O$

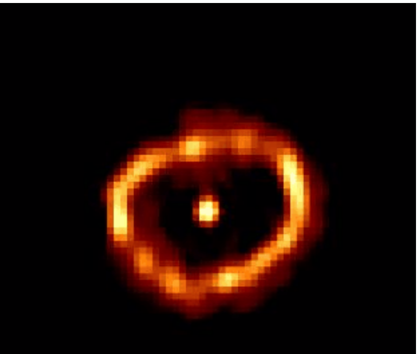
The 4 reaction branchings in the CNO cycles:



Explosive Hydrogen Burning: Classical novae (T=100-400 MK)

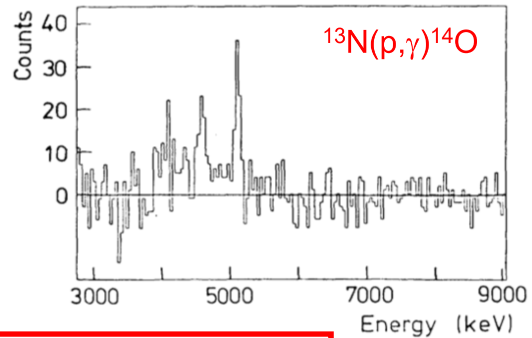






Nova Cygni 1992/HST

- all reactions [incl. $^{14}N(p,\gamma)^{15}O$] become faster than β-decays of ^{14}O, ^{15}O
- energy generation depends on β-decays ("β-limited CNO cycle")
- most abundant nuclides: ^{14}O, ^{15}O
- time for one HCNO1 cycle: 278 s (operates far from equilibrium)



Measurements:

$\boxed{^{13}N(p,\gamma)^{14}O: \rightarrow \text{Decrock et al. (1991)}}$

[1st direct RIB experiment for astrophysics]

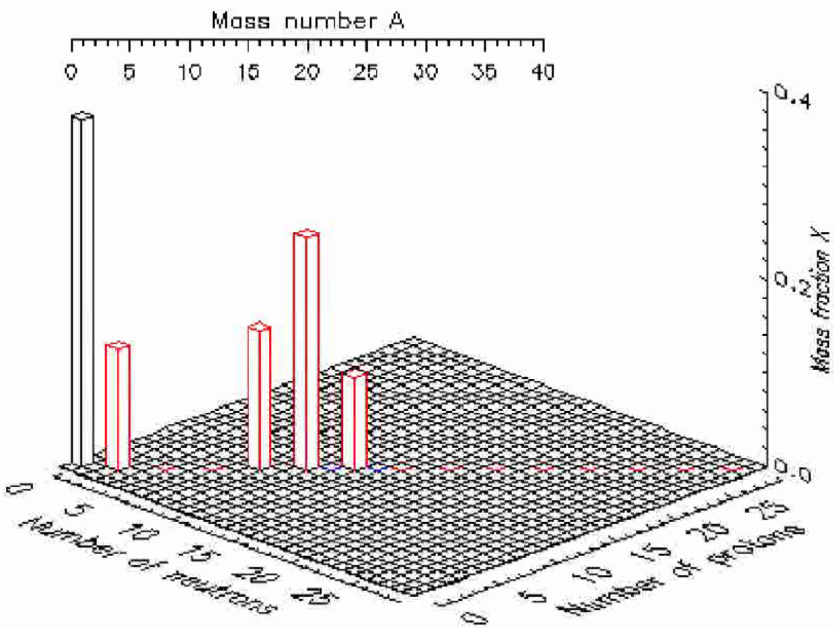
$^{17}O(p,\gamma)^{18}F$: → J. Newton et al. (LENA)

$^{18}F(p,\alpha)^{15}O$: → LLN, ORNL,…

Classical Novae are very special from the nuclear physics point of view:

• a restricted number of important nuclear reactions
• reaction can be measured directly in the Gamow peak
• the only stellar explosions mainly based on experiment

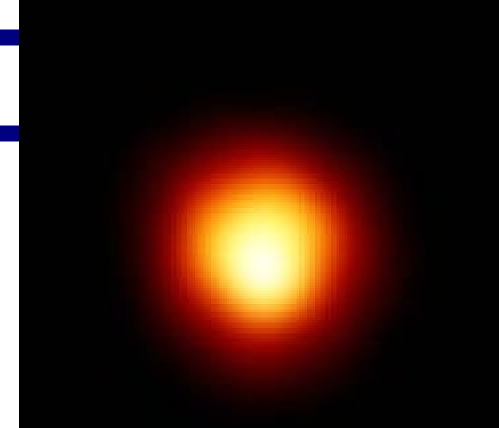
see reviews by:
• Jose, Hernanz & Iliadis, Nucl. Phys. A 777, 550 (2006)
• Starrfield, Iliadis, & Hix, Classical Novae, 2nd ed., Cambridge U. Press (2008)



Nucleosynthesis “sensitivity” study
[to quantify importance of nuclear reactions/motivate new experiments]:

• Iliadis, Champagne, Jose, Starrfield & Tupper, Astrophys. J. Suppl. 142, 105 (2002)
[classical novae; 7,000 network calculations]

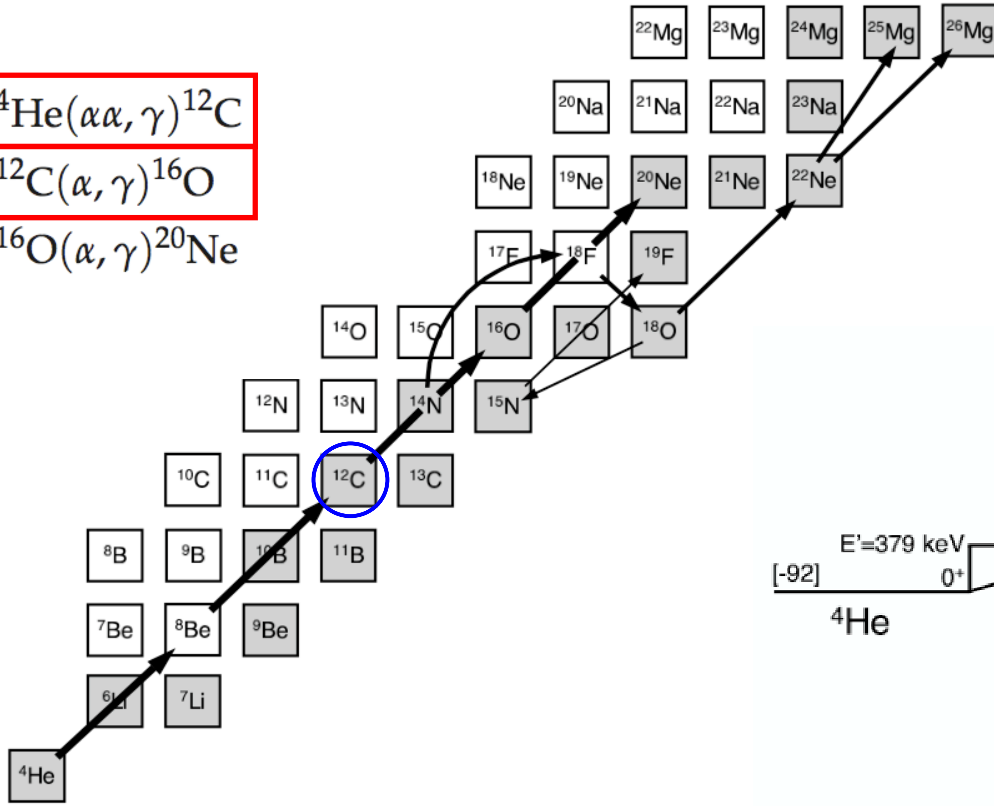
Helium Burning: Massive stars (T=100-400 MK)

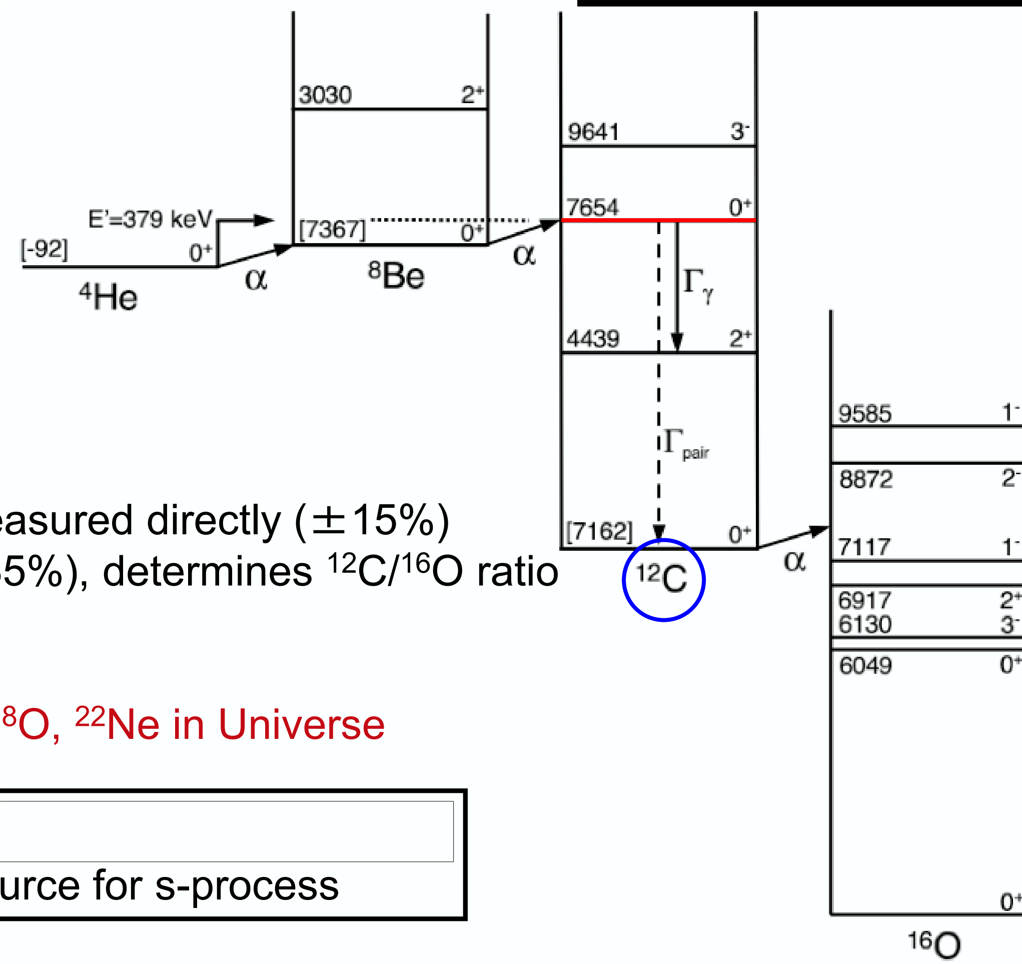

Betelgeuse (α Orionis)

$\boxed{{}^{4}\mathrm{He}(\alpha\alpha,\gamma){}^{12}\mathrm{C}}$

$\boxed{{}^{12}\mathrm{C}(\alpha,\gamma){}^{16}\mathrm{O}}$

${}^{16}\mathrm{O}(\alpha,\gamma){}^{20}\mathrm{Ne}$



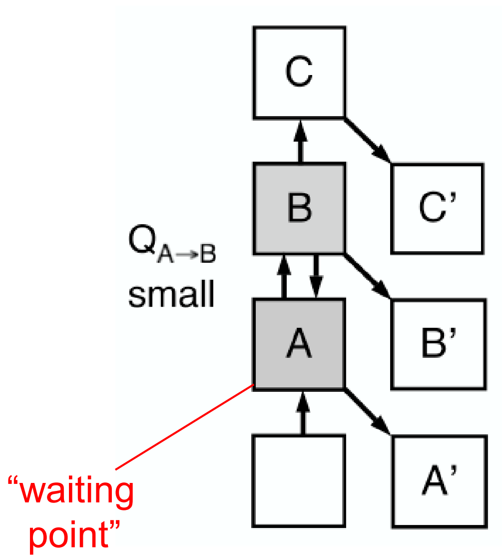


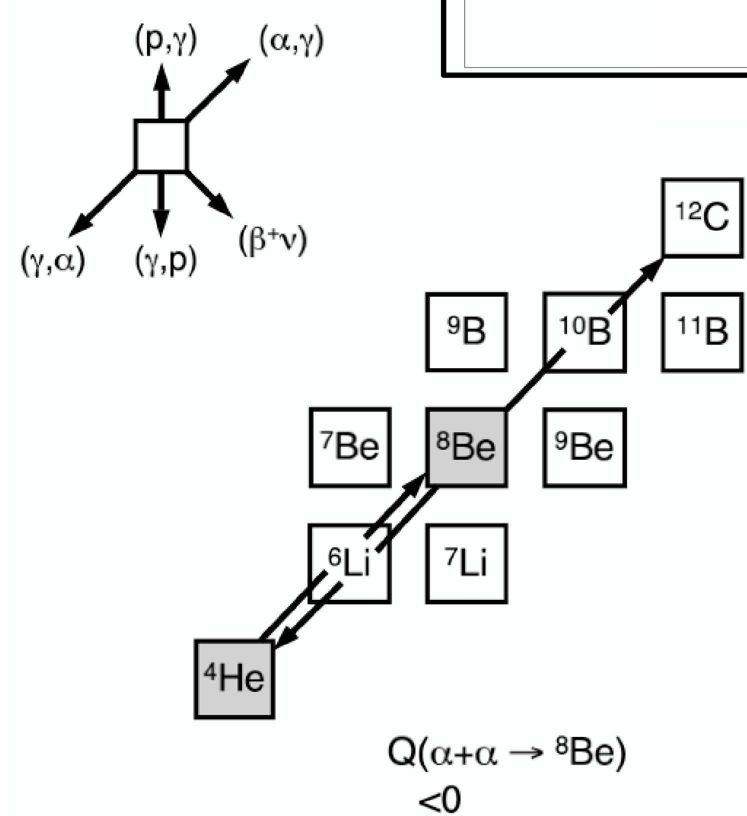
- 3α reaction cannot be measured directly ($\pm$15%)
- ${}^{12}\mathrm{C}(\alpha,\gamma){}^{16}\mathrm{O}$ slow (rate $\pm$35%), determines ${}^{12}\mathrm{C}/{}^{16}\mathrm{O}$ ratio
- ${}^{16}\mathrm{O}(\alpha,\gamma){}^{20}\mathrm{Ne}$ very slow
- ashes: ${}^{12}\mathrm{C}$, ${}^{16}\mathrm{O}$
- main source of ${}^{12}\mathrm{C}$, ${}^{16}\mathrm{O}$, ${}^{18}\mathrm{O}$, ${}^{22}\mathrm{Ne}$ in Universe


Fred Hoyle (1915-2001)

neutron source for s-process

Reaction Rate Equilibria: $r = r_{A\to B} - r_{B\to A} = 0$





From Saha statistical equation and reciprocity theorem we find:

$$\lambda_{A\to B\to(C\,\mathrm{or}\,B')} = \boxed{\frac{\lambda_{A\to B}}{\lambda_{B\to A}}}(\lambda_{B\to C}+\lambda_{B\to B'})$$

$$= N_a\left(\frac{h^2}{2\pi}\right)^{3/2}\frac{1}{(m_{Aa}kT)^{3/2}}\frac{(2j_B+1)}{(2j_A+1)(2j_a+1)}$$

$$\times\frac{G_B^{\mathrm{norm}}}{G_A^{\mathrm{norm}}G_a^{\mathrm{norm}}}\boxed{e^{Q_{A\to B}/kT}}(\lambda_{B\to C}+\lambda_{B\to B'})$$

independent of reaction rate for A→B!

Task #5: calculate the temperature dependence of the triple-α decay constant near 100 MK; how does your result explain qualitatively, for example, the helium flash at the onset of hydrostatic helium burning?

Hints: use the expression for the decay constant λ given below; the decay constant is related to the reaction rate via

$$\lambda_1(0) = \frac{1}{\tau_1(0)} = N_1 \langle \sigma v \rangle_{01} = \rho \frac{X_1}{M_1} N_A \langle \sigma v \rangle_{01}$$

where ρ is density, X is mass fraction, M is atomic mass

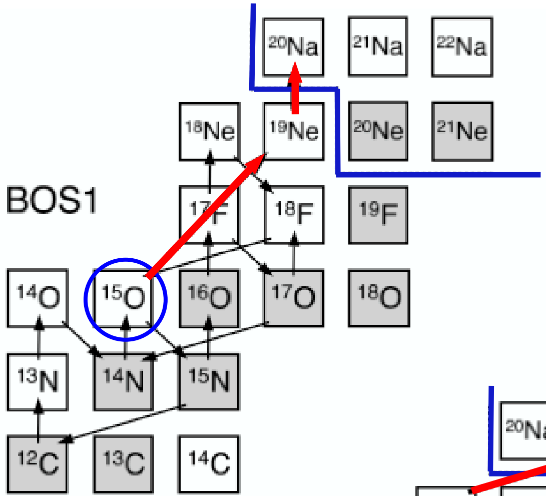
For the triple-α rate use the following expression:

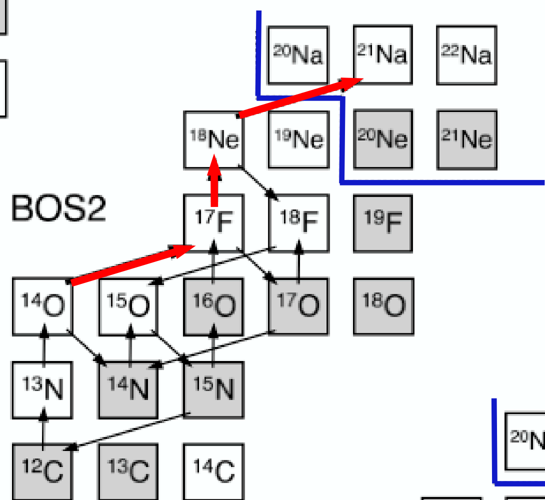
$$\begin{aligned} \lambda_{3\alpha} &= 0.23673 \frac{(\rho X_\alpha)^2}{T_9^3} e^{-11.6048 E'/T_9} \omega\gamma_{^8\mathrm{Be}(\alpha,\gamma)} \qquad (\mathrm{s}^{-1}) \\ &= 8.7590 \cdot 10^{-10} \frac{(\rho X_\alpha)^2}{T_9^3} e^{-4.4040/T_9} \qquad (\mathrm{s}^{-1}) \end{aligned} \tag{5.102}$$

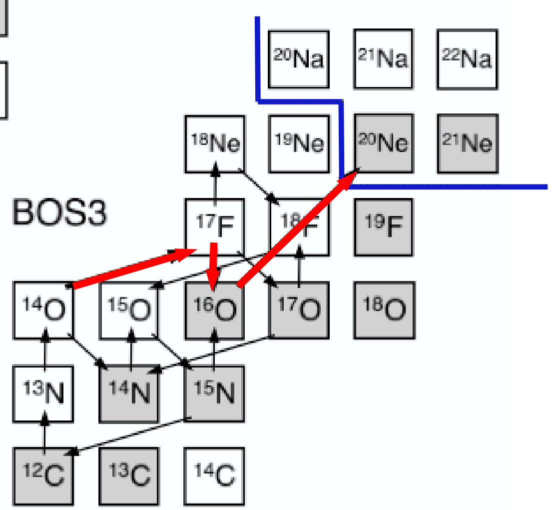
where we used $E' = 287.6\,\mathrm{keV} - (-91.84\,\mathrm{keV}) = 379.4\ \mathrm{keV}$ and $\omega\gamma_{^8\mathrm{Be}(\alpha,\gamma)} = \Gamma_{\mathrm{rad}} = 3.7 \cdot 10^{-3}$ eV. Note that this expression is valid only for temperatures of $0.1 \leq T_9 \leq 2$. For lower and higher temperatures, additional contributions to the reaction rates have to be taken into account (Angulo et al. 1999).

Explosive Hydrogen-Helium Burning: Type I X-ray bursts (T>500 MK)

Breakout sequences







I. $\boxed{^{15}O(\alpha,\gamma)^{19}Ne}$

$^{19}Ne(p,\gamma)^{20}Na$

II. $^{14}O(\alpha,p)^{17}F$

$^{17}F(p,\gamma)^{18}Ne$

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

III. $^{14}O(\alpha,p)^{17}F$

$^{17}F(\gamma,p)^{16}O$

$^{16}O(\alpha,\gamma)^{20}Ne$

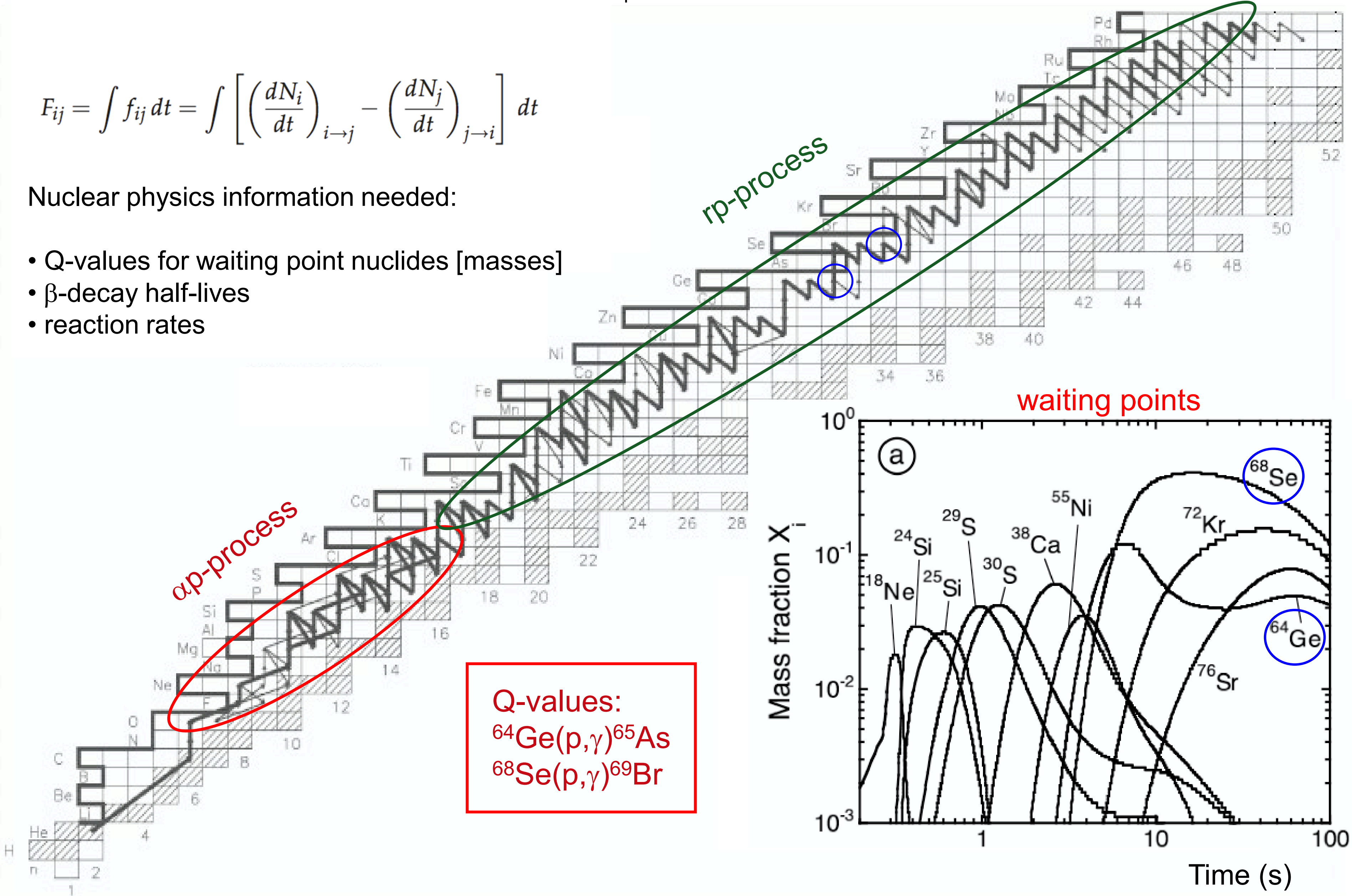
Experiments with radioactive ion beams

[neutron star: $1.3M_{sol}$, r=8 km, T_{peak}=1.4 GK, t=100 s]

$$F_{ij} = \int f_{ij}\,dt = \int \left[\left(\frac{dN_i}{dt} \right)_{i \to j} - \left(\frac{dN_j}{dt} \right)_{j \to i} \right] dt$$

Nuclear physics information needed:

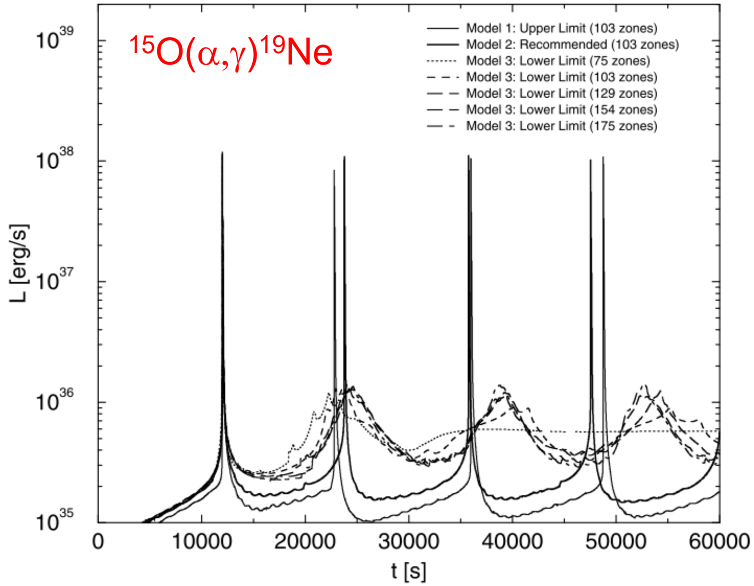
- Q-values for waiting point nuclides [masses]
- β-decay half-lives
- reaction rates

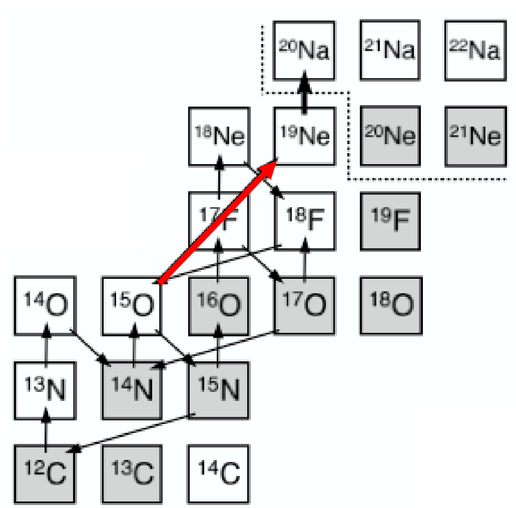


Network sensitivity study: Parikh et al., ApJS 178, 110 (2008); PRC 79, 045802 (2009)

What is the role of the $^{15}O(\alpha,\gamma)^{19}Ne$ breakout reaction?

Fisker, Goerres, Wiescher & Davids, Astrophys. J. 650, 332 (2006) [hydro code AGILE]





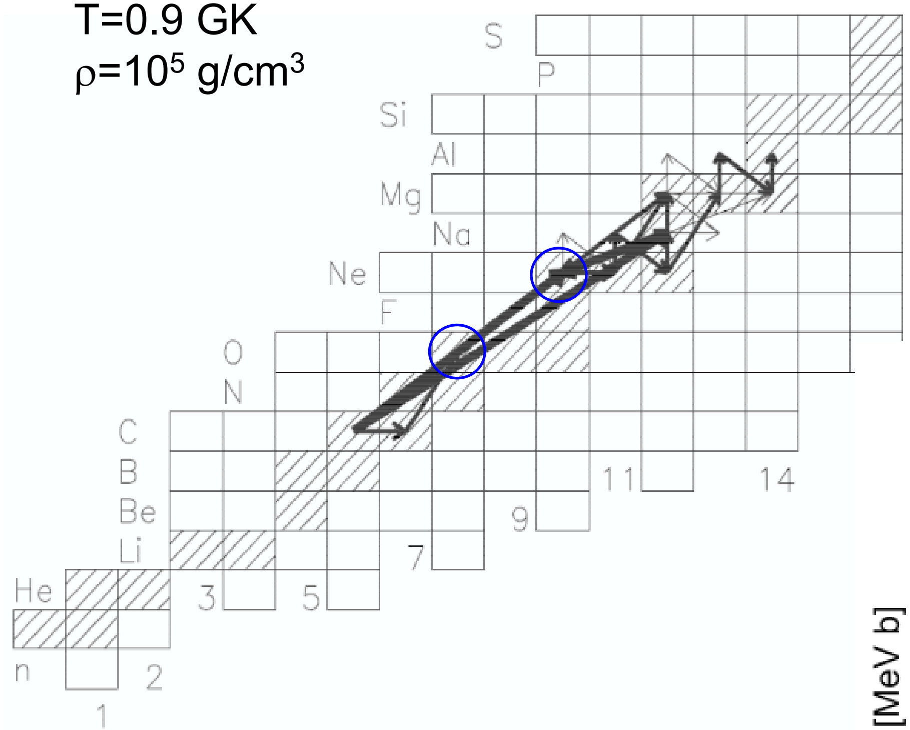
But: no significant effect on peak luminosity, recurrence time or nucleosynthesis in more recent hydro model studies!

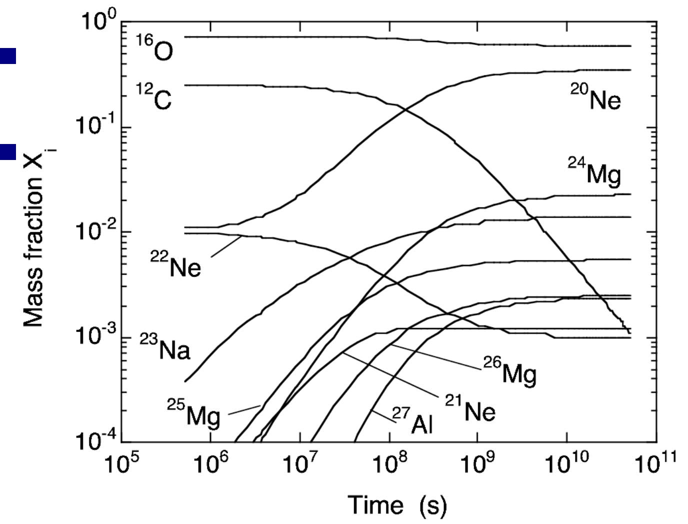
[Davids, Cyburt, Jose & Mythili, arxiv 1104.2877 (2011); hydro code SHIVA]

theoretical predictions are more reliable if reproduced by two independent stellar model codes

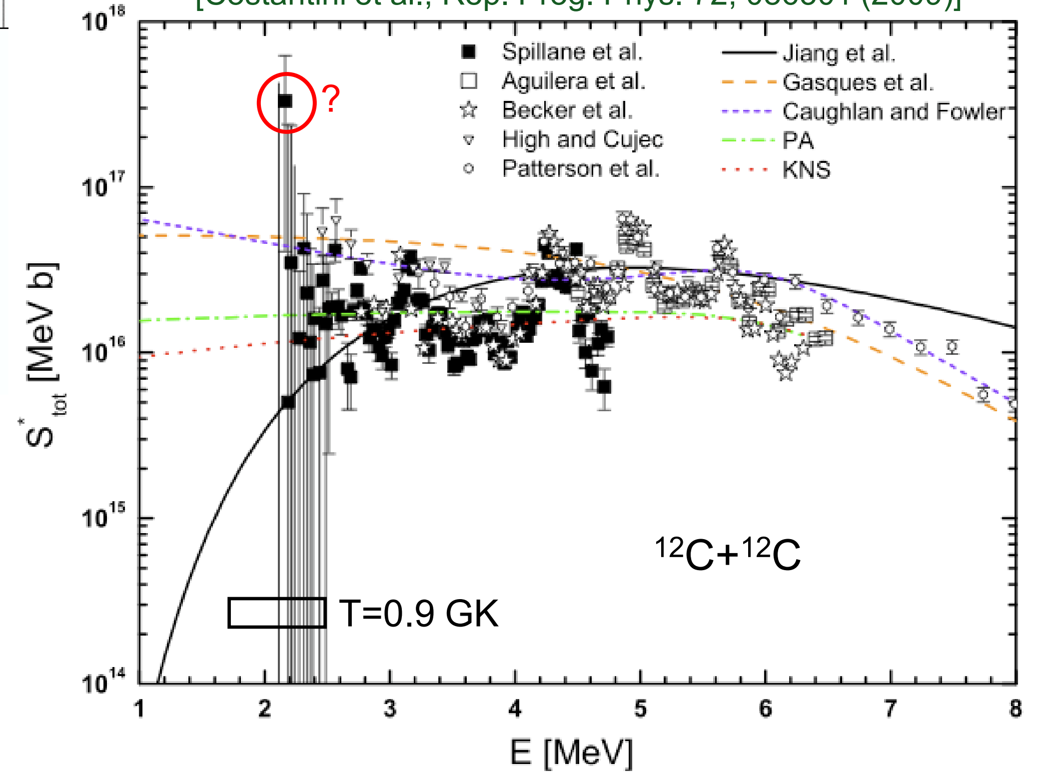
Carbon Burning: core (T=0.6-1.0 GK)

T=0.9 GK
$\rho = 10^5$ g/cm^3





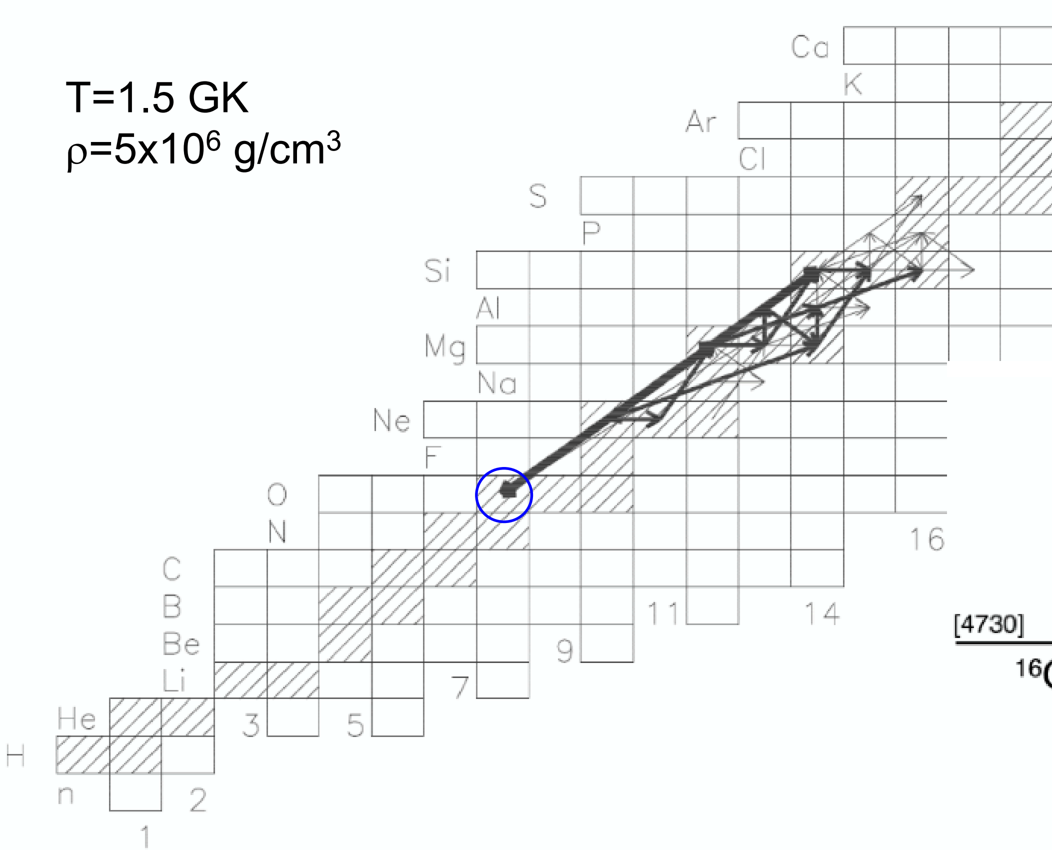
[Costantini et al., Rep. Prog. Phys. 72, 086301 (2009)]

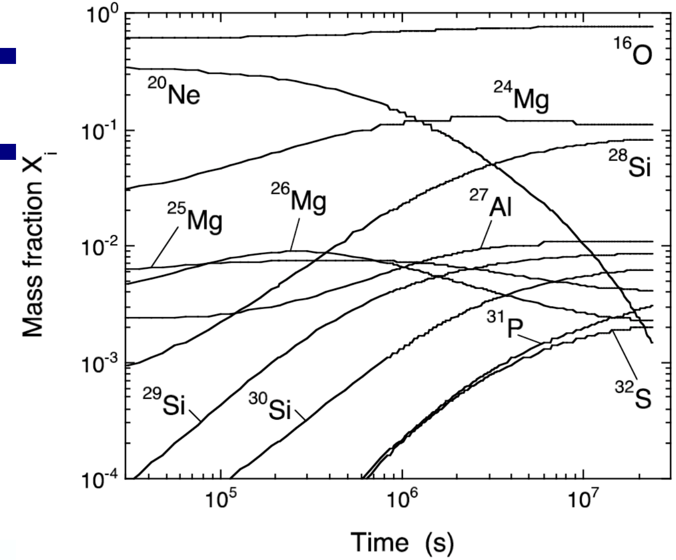


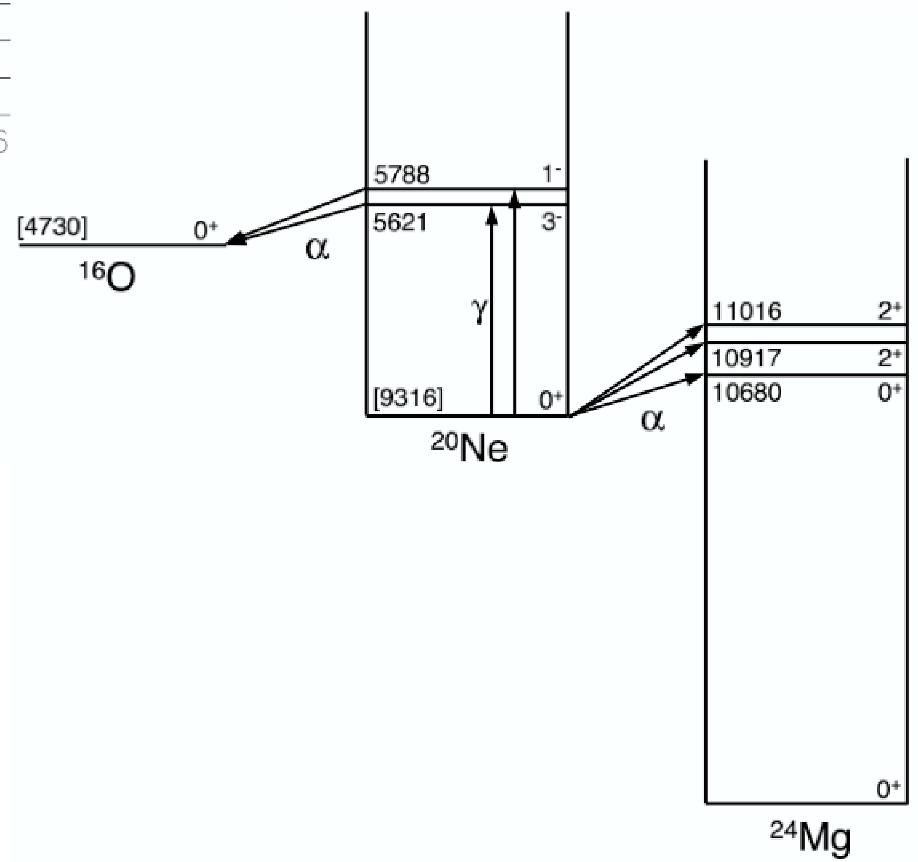
- Primary reactions:
  $^{12}C(^{12}C,p)^{23}Na$
  $^{12}C(^{12}C,\alpha)^{20}Ne$
  $^{12}C(^{12}C,n)^{23}Mg$
  + several secondary reactions

- ashes: ^{16}O, ^{20}Ne
- source of $^{20,21}Ne$, ^{23}Na, ^{24}Mg, ^{27}Al in Universe

Neon Burning: core (T=1.2-1.8 GK)

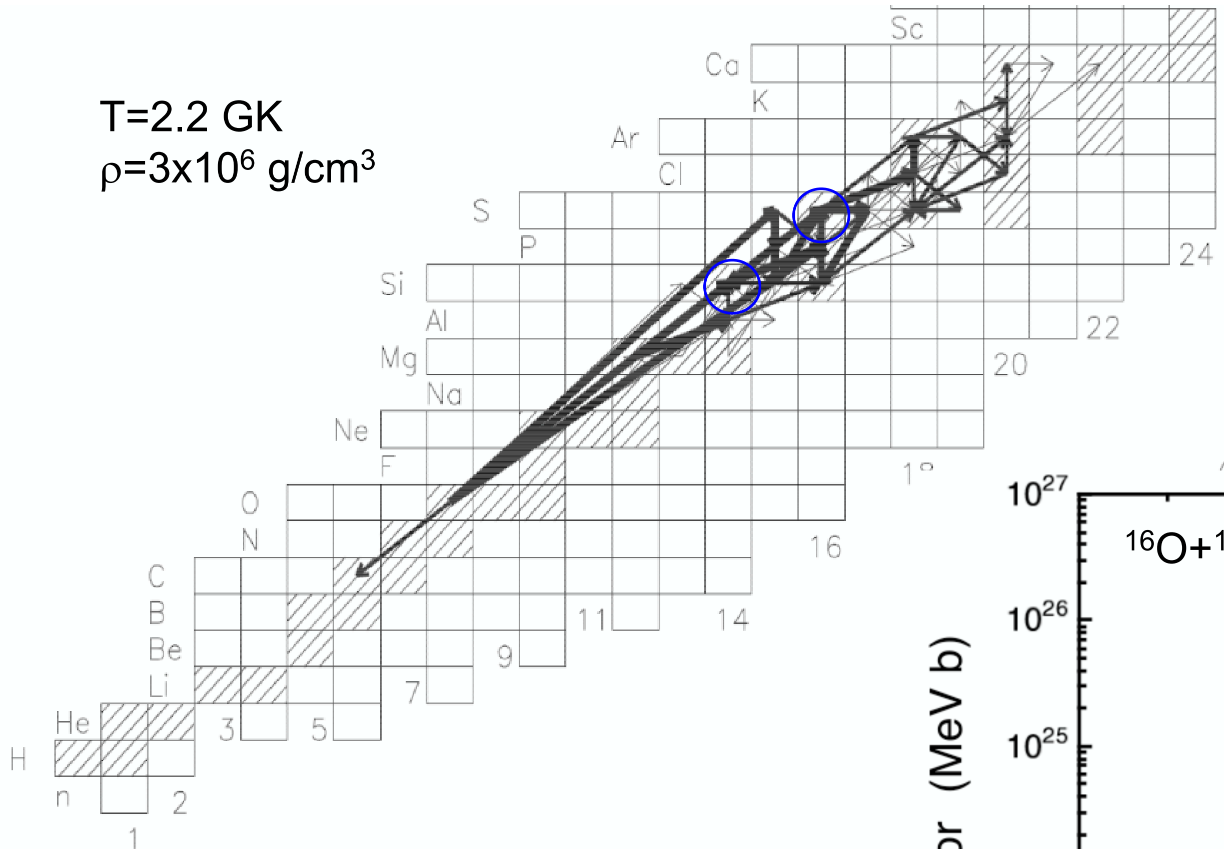


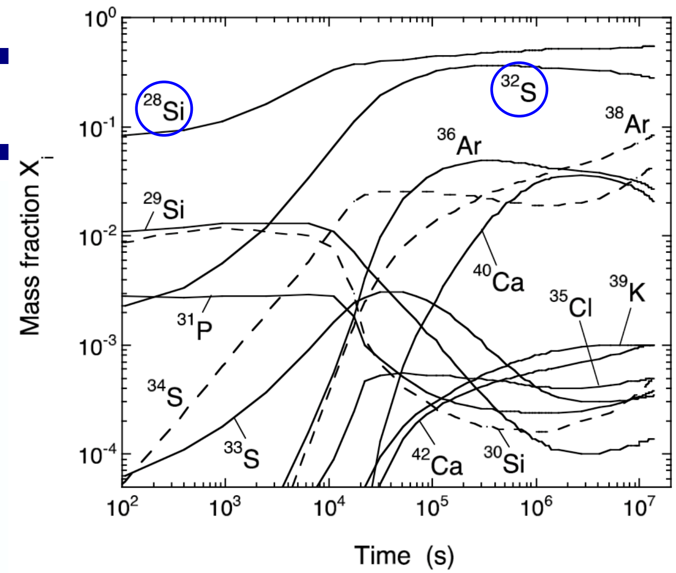


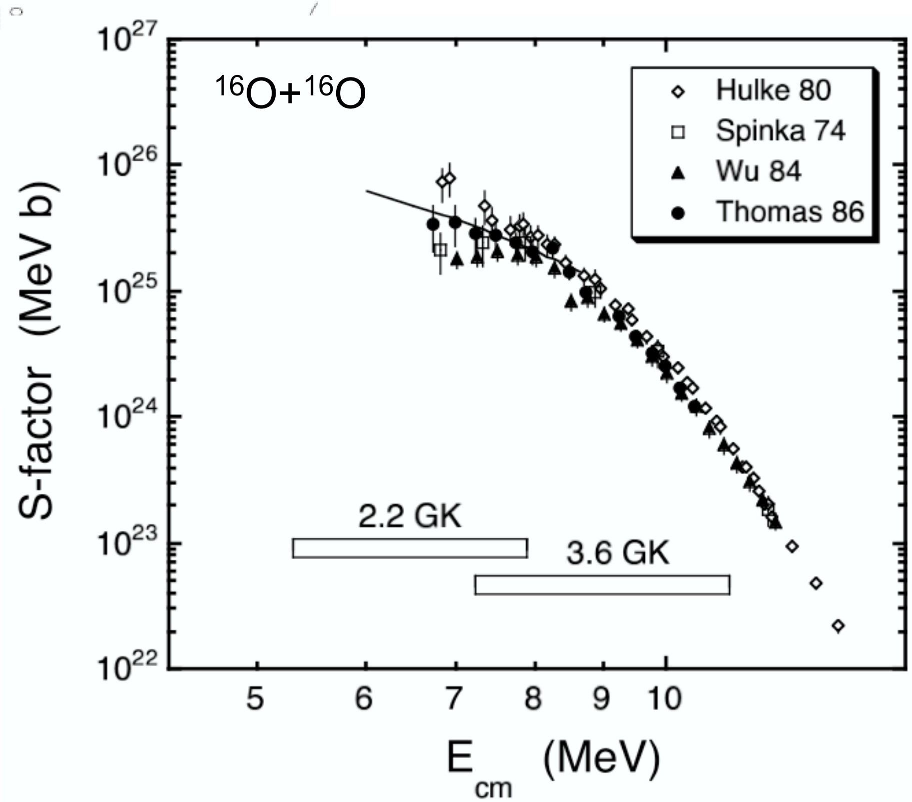


- Primary reaction:
  $\boxed{^{20}\mathrm{Ne}(\gamma,\alpha)^{16}\mathrm{O}}$ (Q=-4730 keV)
- Secondary reactions
  $^{20}\mathrm{Ne}(\alpha,\gamma)^{24}\mathrm{Mg}(\alpha,\gamma)^{28}\mathrm{Si}$
  + more
- ashes: $^{16}\mathrm{O}$

Oxygen Burning: core (T=1.5-2.7 GK)







- Primary reactions:
  $^{16}O(^{16}O,p)^{31}P$
  $^{16}O(^{16}O,\alpha)^{28}Si$
  ...

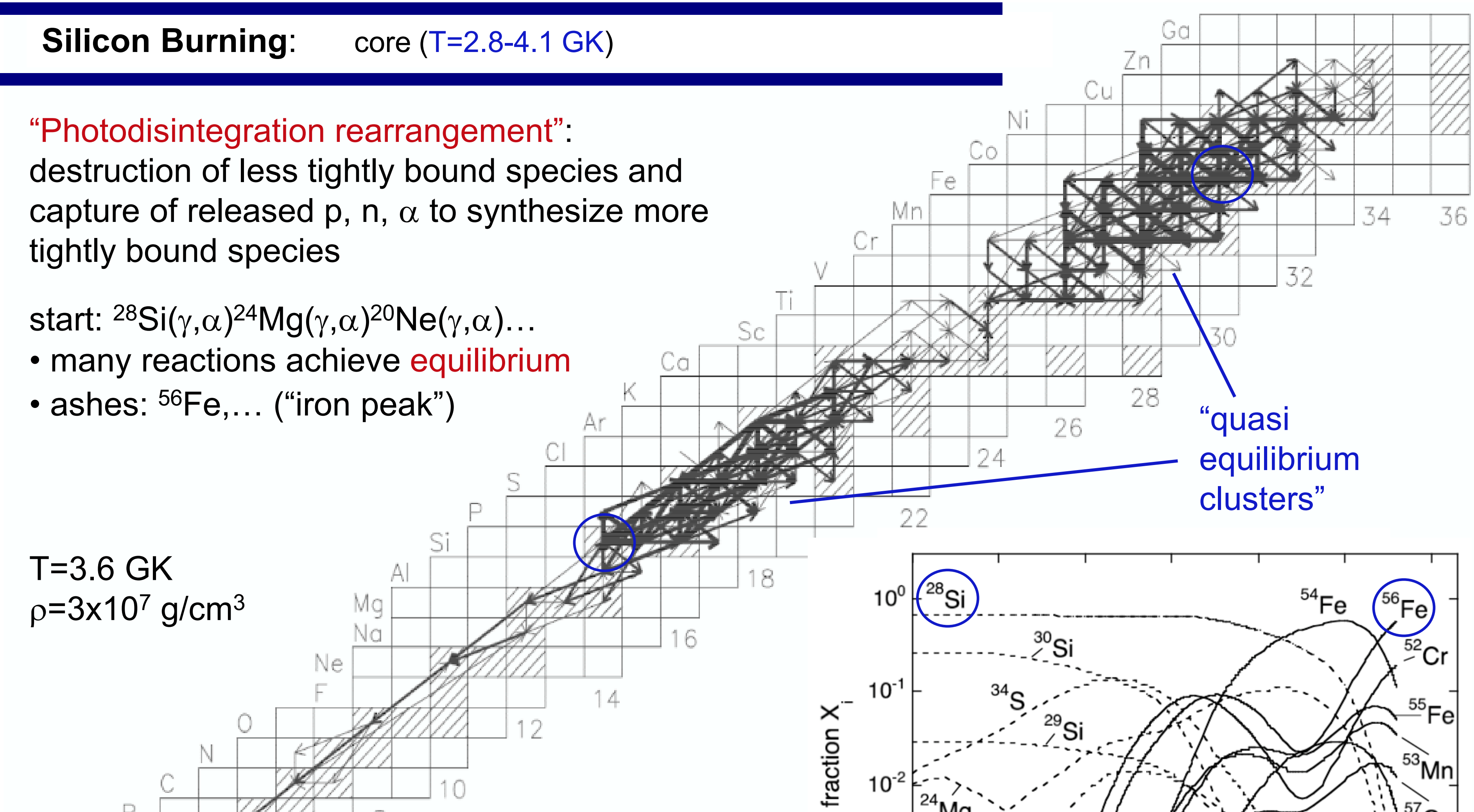
  \+ several secondary reactions
- ashes: ^{28}Si, ^{32}S

Silicon Burning: core (T=2.8-4.1 GK)

"Photodisintegration rearrangement":
destruction of less tightly bound species and capture of released p, n, α to synthesize more tightly bound species

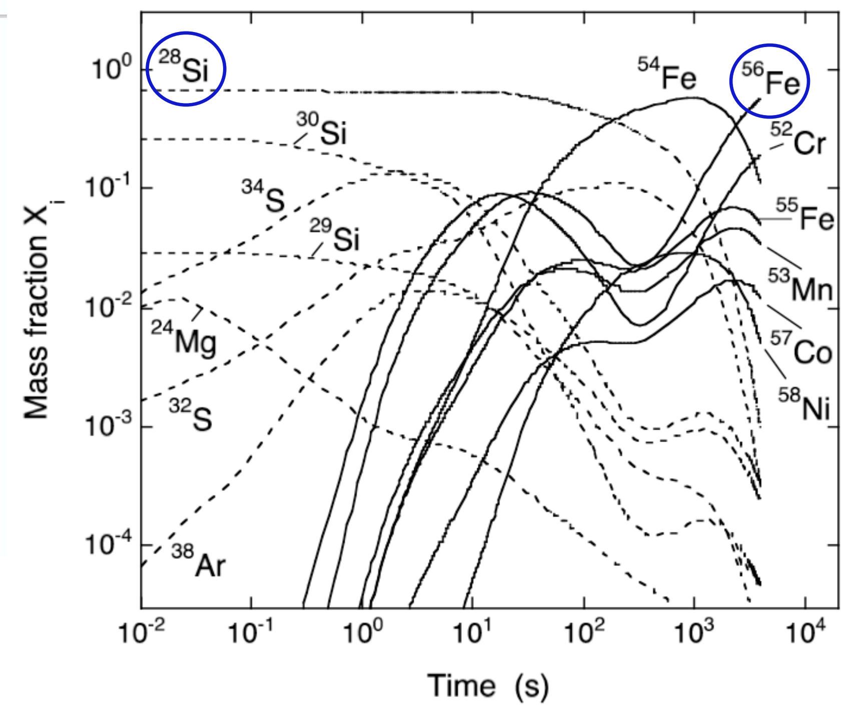
start: $^{28}Si(\gamma,\alpha)^{24}Mg(\gamma,\alpha)^{20}Ne(\gamma,\alpha)\ldots$
- many reactions achieve equilibrium
- ashes: ^{56}Fe,… ("iron peak")

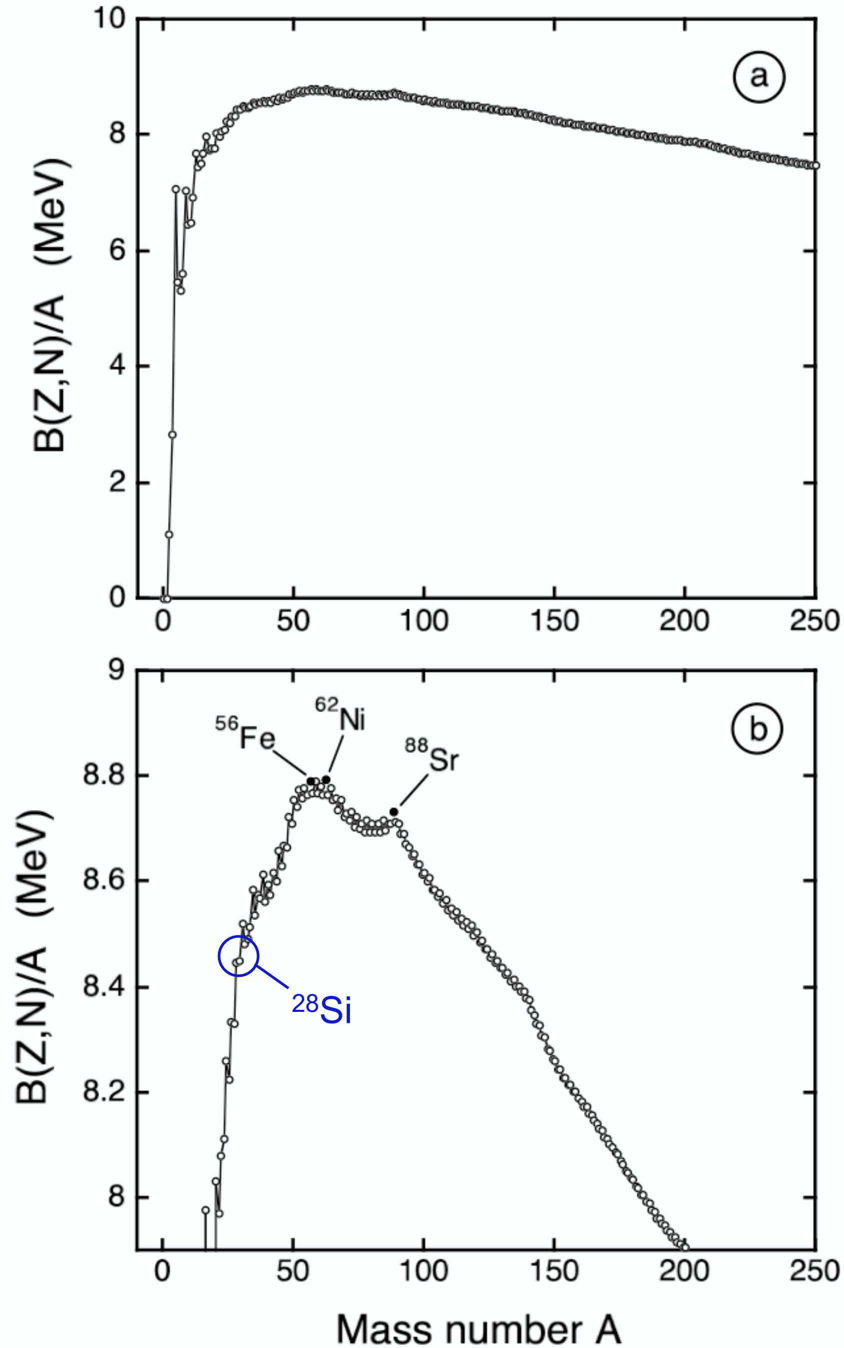
T=3.6 GK
$\rho = 3\times10^{7}$ g/cm^3



"quasi equilibrium clusters"

mediating reactions:
$^{42}Ca(\alpha,\gamma)^{46}Ti$
$^{41}K(\alpha,p)^{44}Ca$
$^{45}Sc(p,\gamma)^{46}Ti$





Experimental binding energies per nucleon

largest B/A for ^{62}Ni, ^{58}Fe, ^{56}Fe

Nuclear Statistical Equilibrium

As ^{28}Si disappears in the core at the end of Si burning, T increases, until all non-equilibrated reactions come into equilibrium [last reaction: 3α reaction]

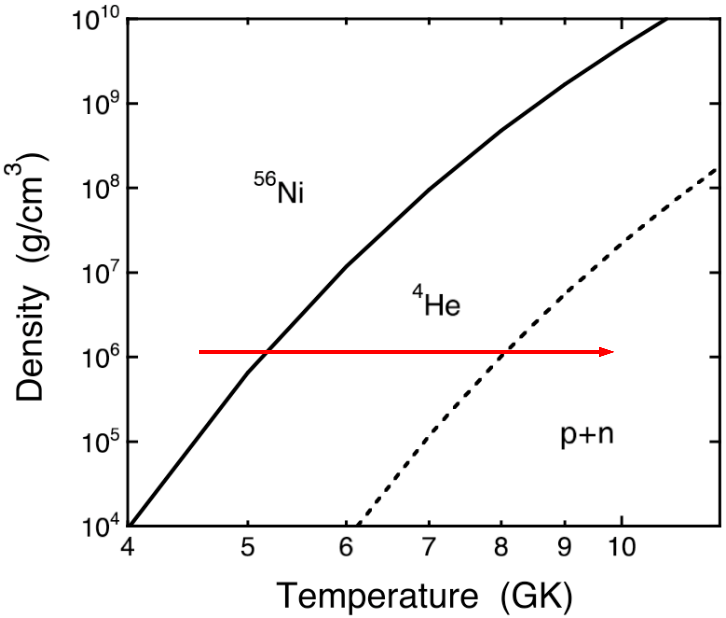
One large equilibrium cluster stretches from p, n, α to Fe peak:
"Nuclear Statistical Equilibrium" (NSE)

Abundance of each nuclide can be calculated from repeated application of Saha equation:

$$N_Y = N_{\rm p}^{\pi} N_{\rm n}^{\nu} \frac{1}{\theta^{A-1}} \left(\frac{M_Y}{M_{\rm p}^{\pi} M_{\rm n}^{\nu}} \right)^{3/2} \frac{g_Y}{2^A} G_Y^{\rm norm} e^{B(Y)/kT}$$

In NSE, abundance of any nuclide is determined by: temperature, density, neutron excess

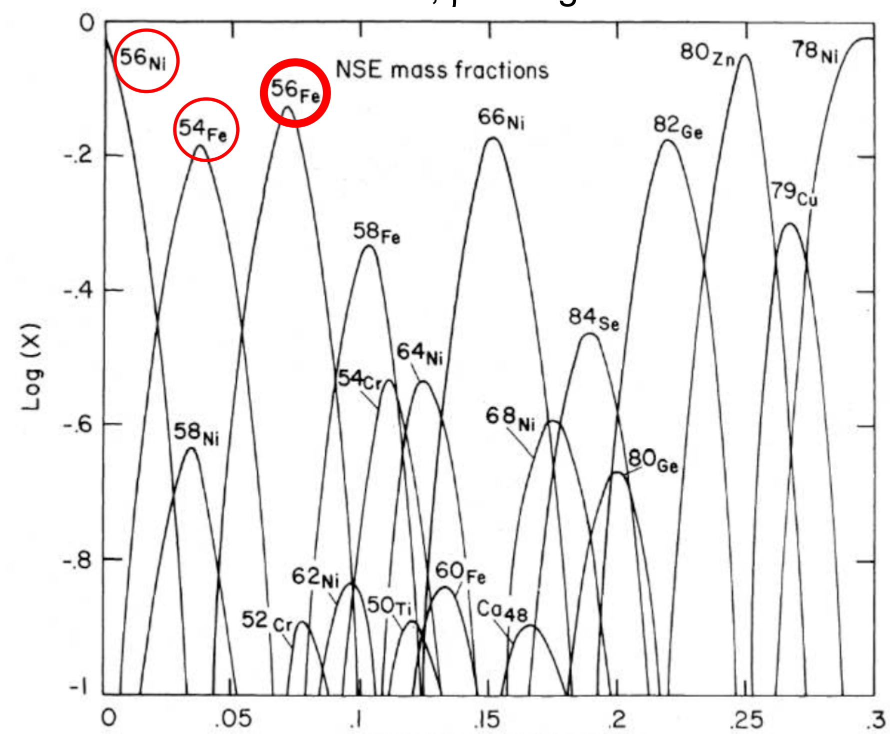
Represents number of excess neutrons per nucleon (can only change as result of weak interactions!)



Assume first that $\eta=0$ and Si burning has mainly produced ^{56}Ni (N=Z=28) in the Fe peak besides ^{4}He, p, n…

At ρ=const and T rising: increasing fraction of composition resides in light particles (p, n, α)

T=3.5 GK, $\rho=10^7$ g/cm^3



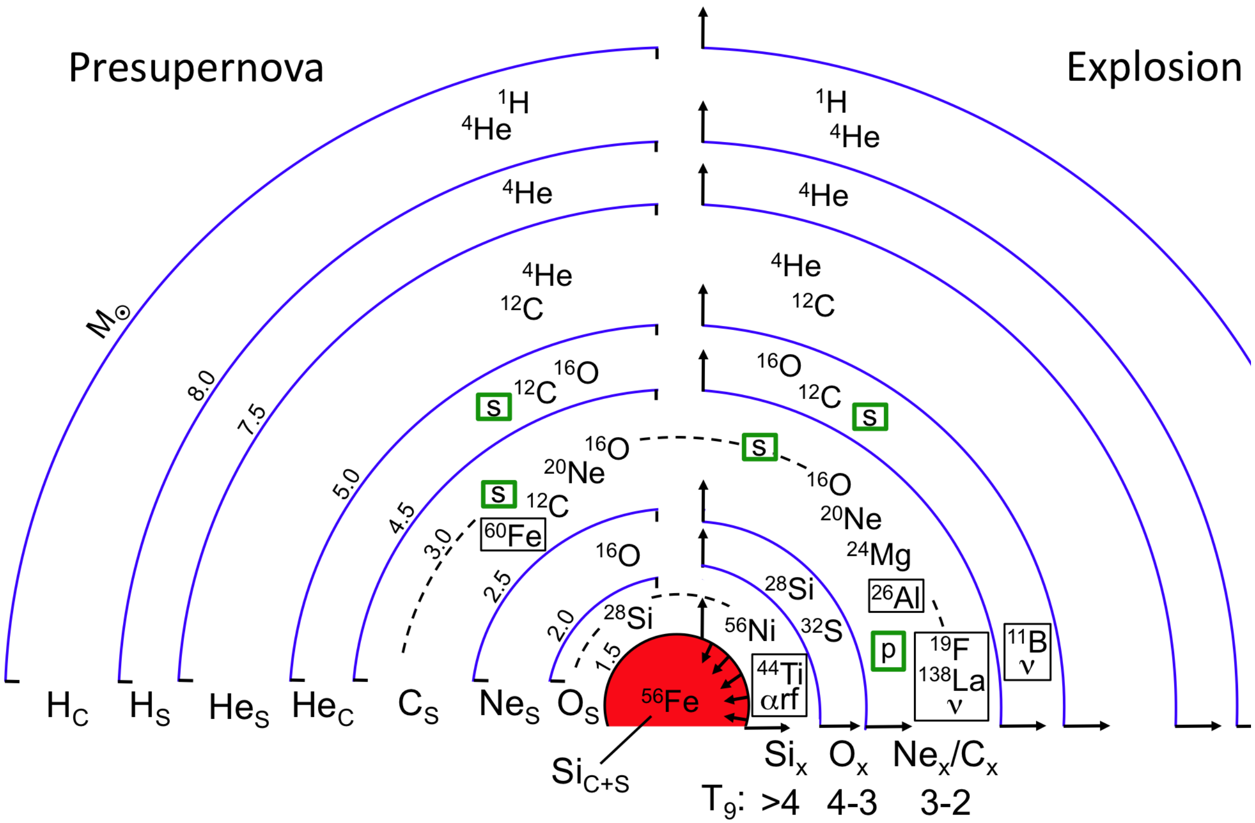
Dominant species:

^{56}Ni for $\eta=0$ (N-Z)/M=(28-28)/56=0
^{54}Fe for $\eta=0.04$ (N-Z)/M=(28-26)/54=0.04
^{56}Fe for $\eta=0.07$ (N-Z)/M=(30-26)/56=0.07
…

η needs to be monitored very carefully!
[stellar weak interaction rates need to be known]

[Hartmann, Woosley & El Eid, ApJ 297, 837 (1985)]

Onion shell structure of massive star [25 solar mass star of solar composition]



From: J. Jose & C. Iliadis, "The Unfinished Quest for the Origin of the Elements", review article submitted to *Reports on Progress in Physics* (2011)

No other nuclear energy source is available to core…

grows in mass; when it exceeds 1.4 times solar mass, electron degeneracy pressure is unable to counteract gravity…

two important effects:
(i) electron-capture on Fe peak nuclei removes electrons, thus decreasing pressure
(ii) NSE composition shifts to lighter nuclei (less stable!) removing energy, thus decreasing pressure

core collapses in free fall…

when $\rho=10^{14}$ g/cm^3 nuclei and nucleons feel short-range nuclear force (repulsive at very short r)

part of core rebounds, producing an outward moving shock wave…

The mystery of a core collapse supernova

within a fraction of a second, the core with a size of several thousand kilometers collapses to a proto-neutron star of several tens of kilometer radius.

shock moves outward into infalling matter and loses energy by: (i) photodisintegrating Fe peak nuclei into free nucleons, and (ii) emission of neutrinos

about 1 second after core collapse the shock reaches outer edge of core, has lost all its energy, and stalls!

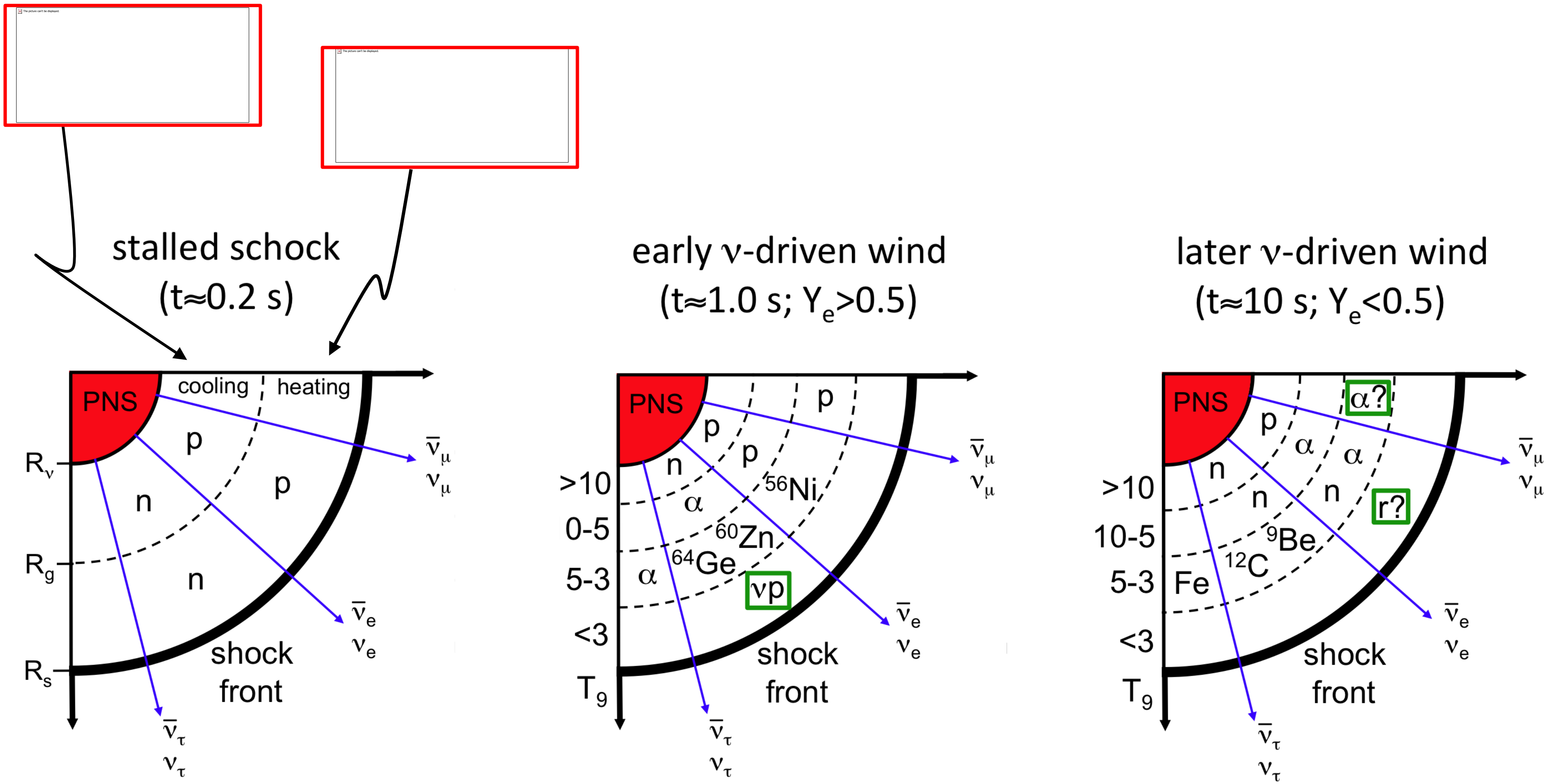
how exactly the shock is revived and disrupts star in a supernova is a mystery

during core collapse, a gravitational binding energy of several 10^{53} erg, representing a staggering 10% of the iron core's rest mass, is released in form of neutrino radiation; therefore, the stalled shock is thought to be revived by neutrinos and antineutrinos that emerge from the hot and dense proto-neutron star

only a fraction (1%) of the total gravitational binding energy, deposited by neutrinos as thermal energy of nucleons, leptons and photons in this region, would be required to initiate a powerful shock propagating through the stellar mantle and giving rise to an explosion

problem is highly complex, involving energy-dependent neutrino transport in three dimensions, a convectively unstable region near a compact hot and dense object, possible diffusive instabilities, magneto-rotational effects, and so on

Nucleosynthesis in the earliest ejecta: the α-, r-, and νp-processes

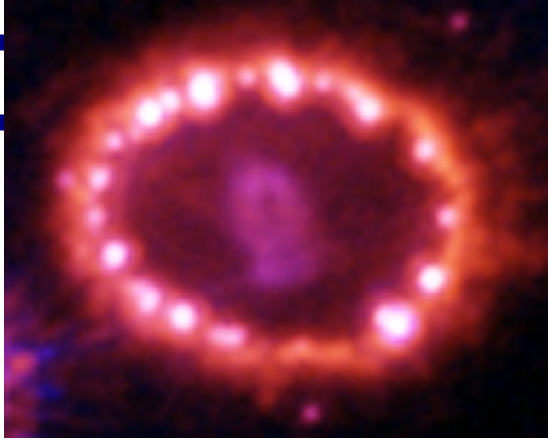


proton-rich wind

neutron-rich wind

R_ν: “neutrino sphere”
R_g: “gain radius”

“Complete” Explosive Si Burning (T>5 GK, $\rho>10^8$ g/cm^3)

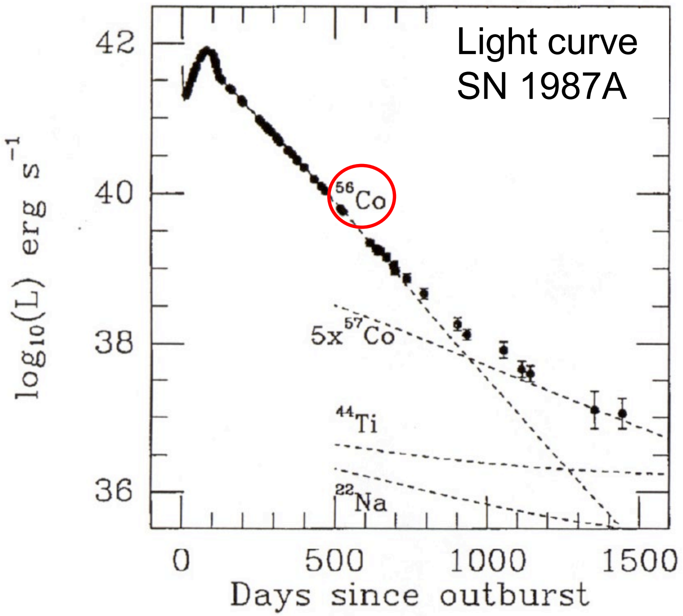


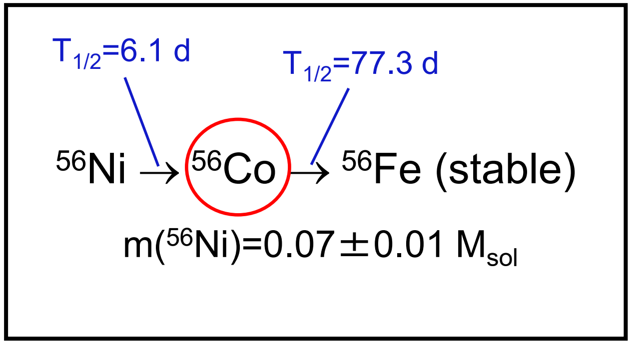
outgoing shock wave heats inner ^{28}Si layer of star to high T and ρ: matter approaches NSE, expands, cools (when shock moves outward), and reactions begin to fall out of equilibrium

nucleosynthesis depends critically on density (ρ), expansion time Scale (τ), and n, p, α abundances

if ρ large and/or τ large: NSE is terminated by lack of light particles (“particle-poor freeze-out”): ejected abundances are close to those derived from NSE [mainly ^{56}Ni since $\eta\approx0.003$]

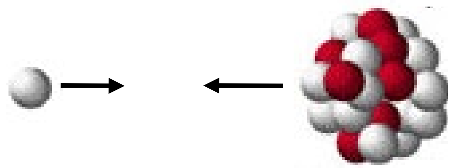
if ρ small and/or τ small: NSE is terminated by excess of α-particles (“α -rich freeze-out”): ejected abundances change somewhat from NSE [although still mainly ^{56}Ni for $\eta\approx0.003$; also ^{44}Ti]



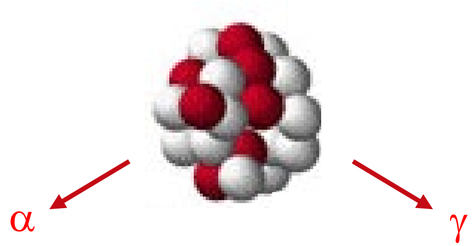


Nuclear astrophysics experiments: direct measurements

two nuclei with kinetic energies before reaction:

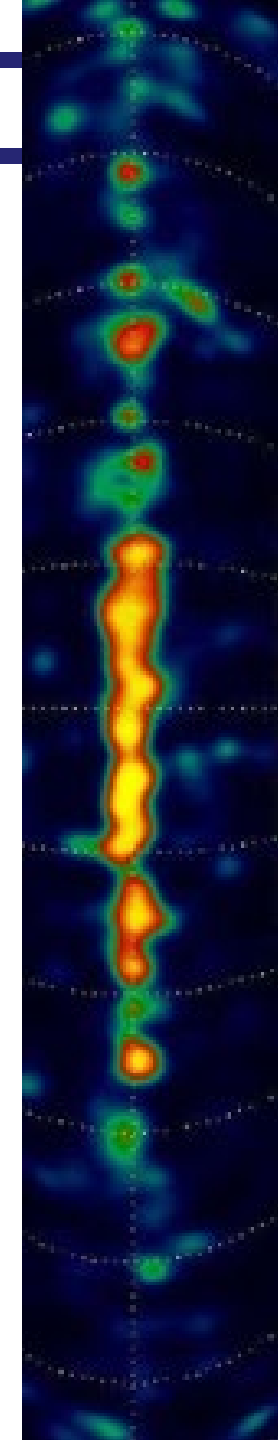


excited product nucleus after reaction:



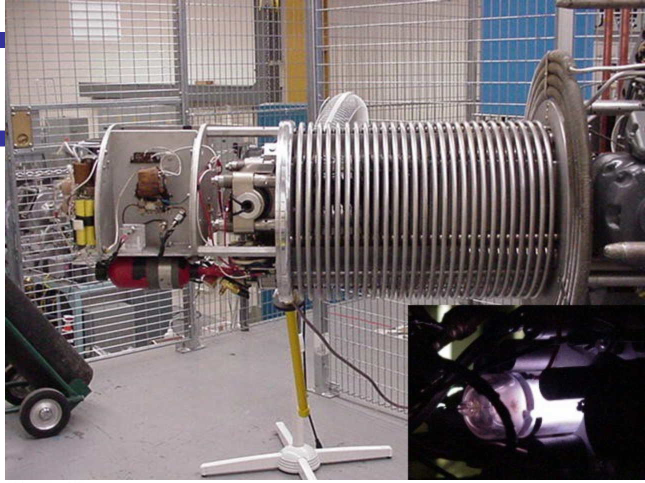
What we need:

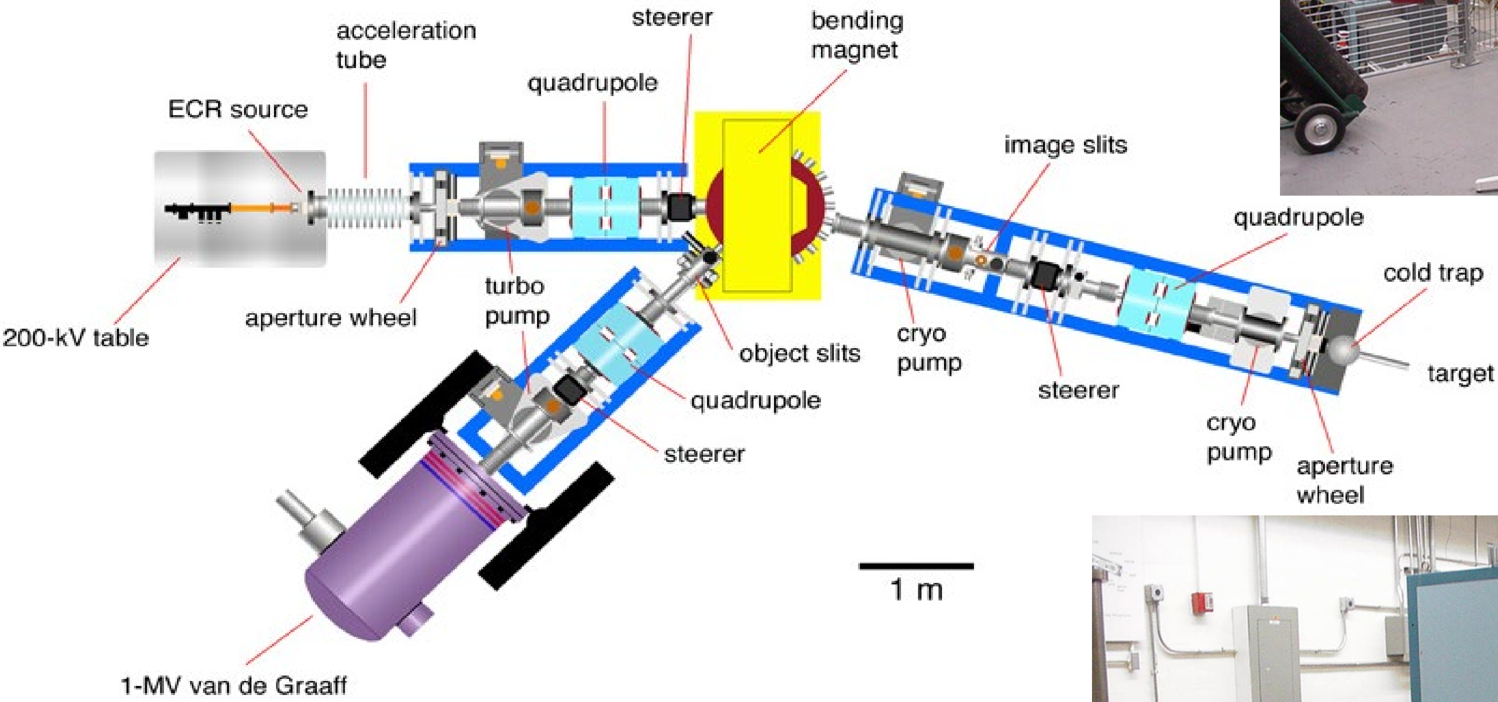
- accelerated ion beams
- targets
- detectors

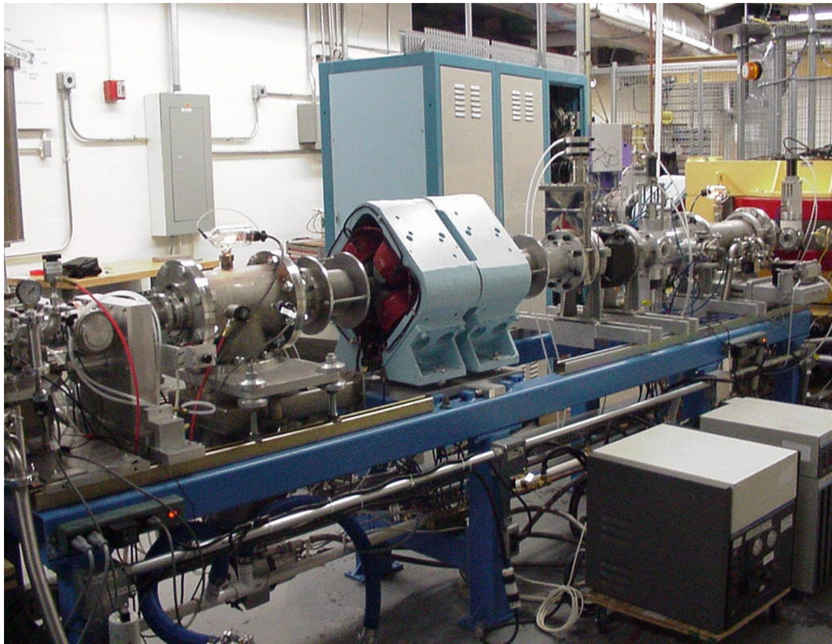


Laboratory for Experimental Nuclear Astrophysics

Cesaratto et al., Nucl. Instr. Meth. A623, 888 (2010)

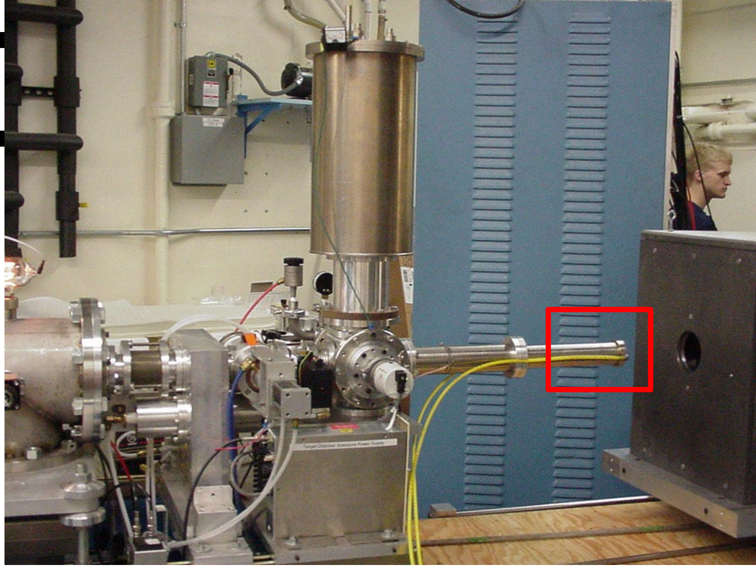


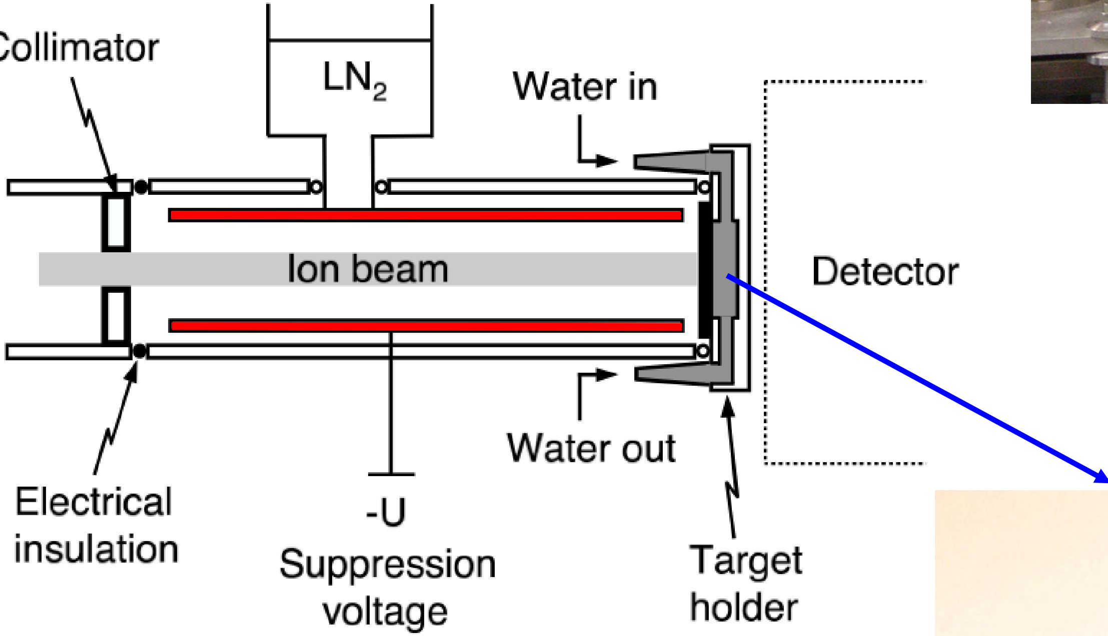


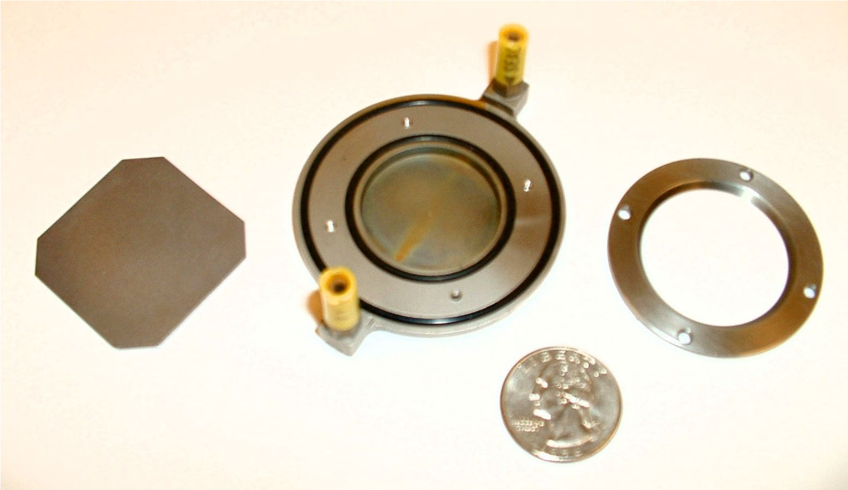


Target chamber design

Location where:
- reactions occur
- incident particle charge is measured







Beam power:
$P = U \cdot I = (0.1\ \mathrm{MV})(1000\ \mu\mathrm{A})$
$= 100\ \mathrm{W}$

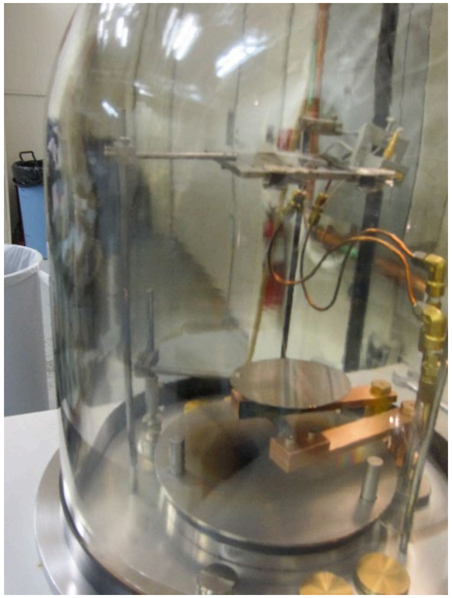
Target material deposited on a "backing"

targets should: (ideally)

- have a well-known stoichiometry
- not degrade under ion bombardment
- have no contaminants

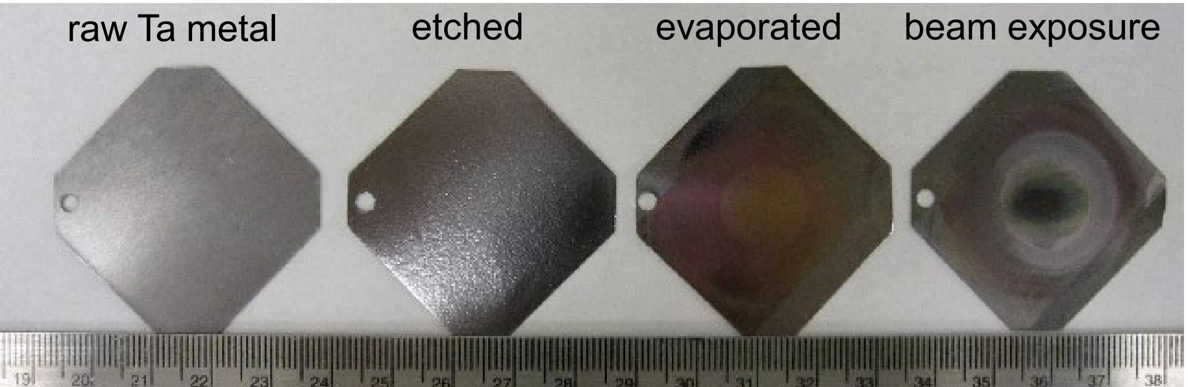
backings: Ta, Ni, Cu

contaminants: ^{11}B, ^{19}F, ^{13}C



evaporation onto backing

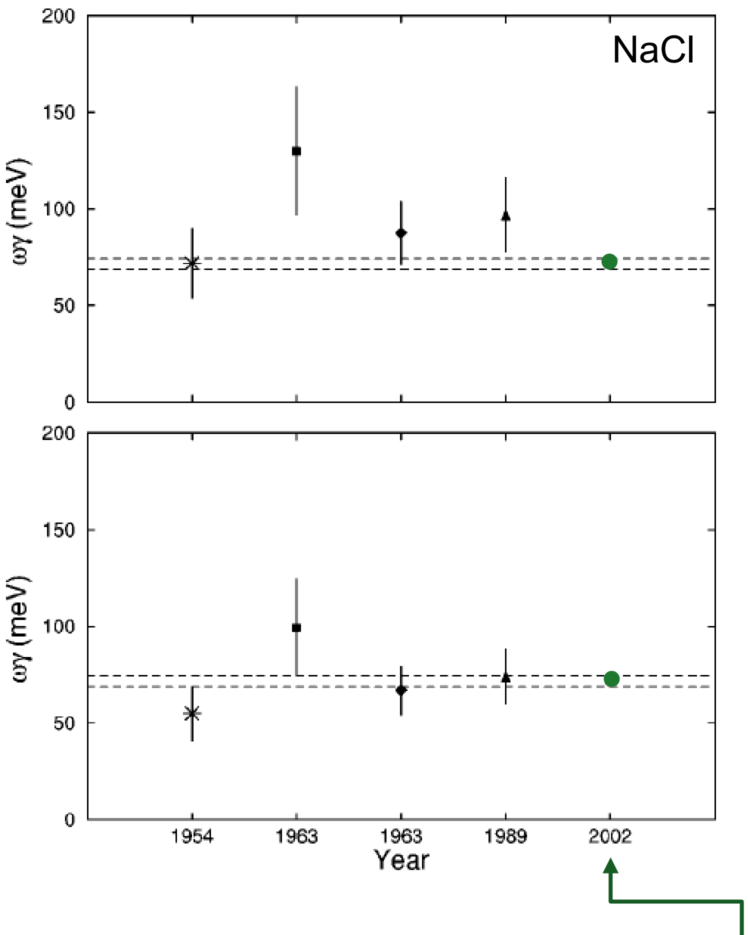
etching of backings using acids



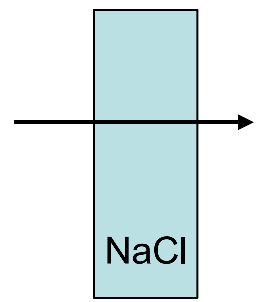
A common mistake…

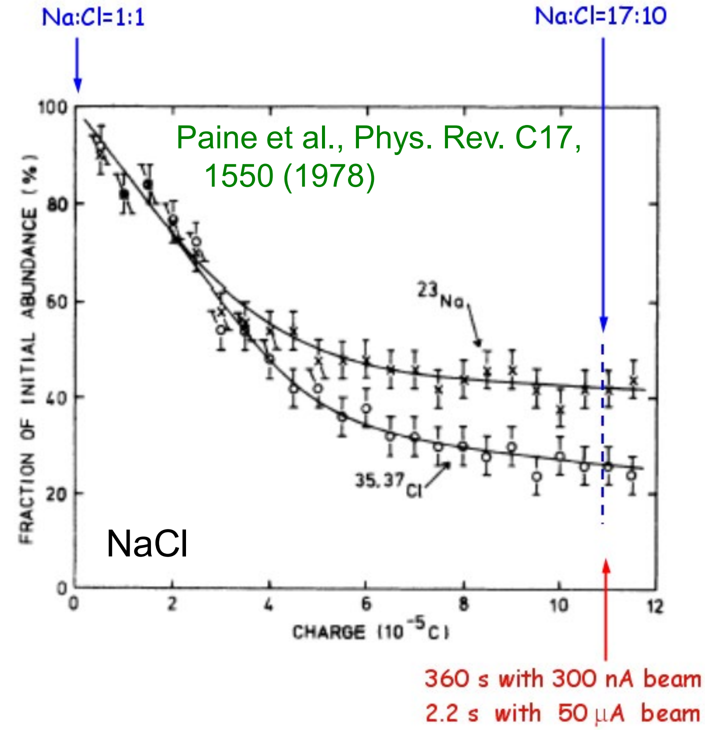
the ion beam can change the target stoichiometry!

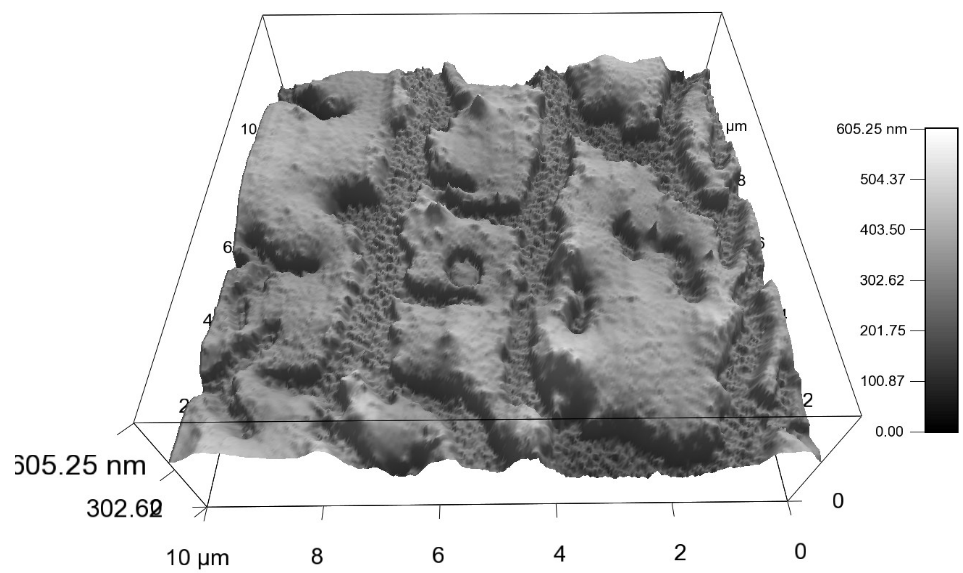
$^{23}Na(p,\alpha)^{20}Ne$: resonance at 338 keV



Rowland, Iliadis et al., Phys. Rev. C65, 064609 (2002)







Atomic Force Microscope image of Na_2WO_4 target

Detectors: semiconductors & scintillators

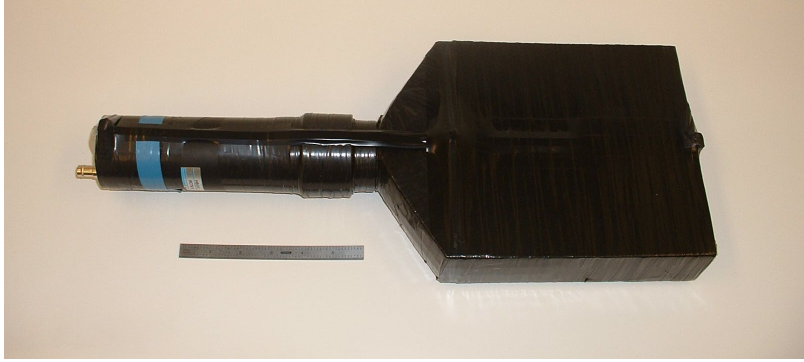
$$p + {}^{17}\mathrm{O} \rightarrow {}^{18}\mathrm{F} + \gamma$$
$$p + {}^{17}\mathrm{O} \rightarrow {}^{14}\mathrm{N} + \alpha$$

radiation [reaction products] deposits energy in matter

germanium [semiconductor for γ-rays]

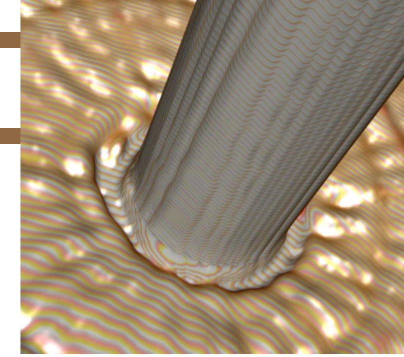
NaI(Tl) [scintillator for γ-rays]

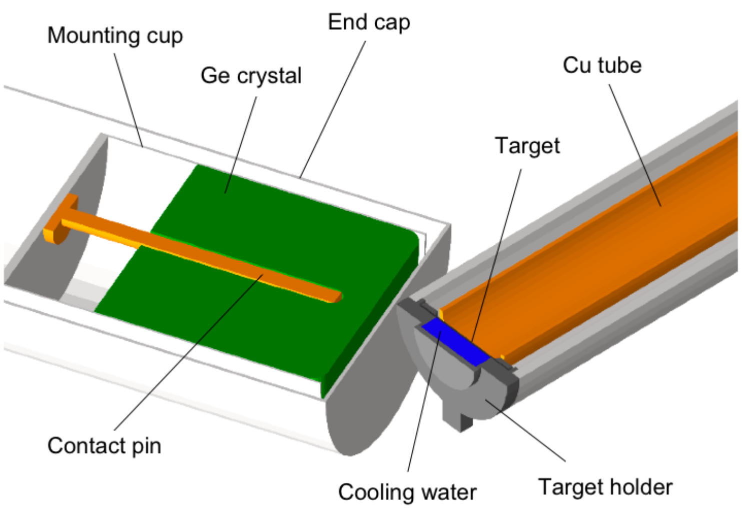
plastic [scintillator for muons]



silicon [semiconductor for charged particles]

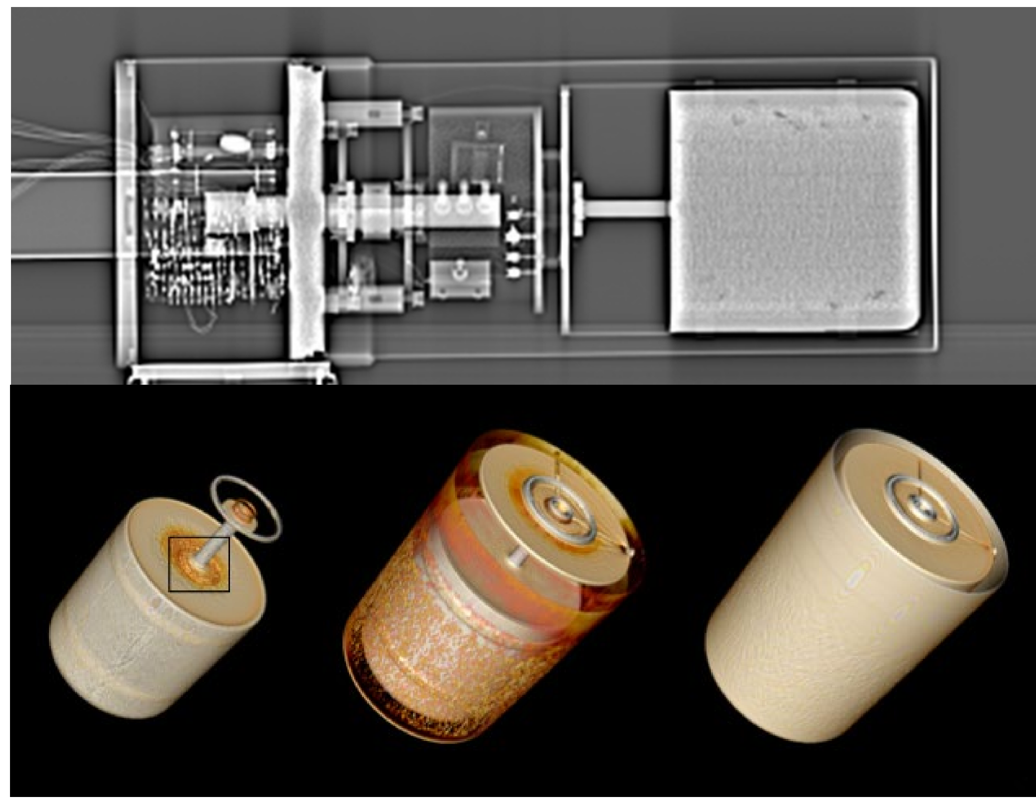
Detector Simulations and Calibrations using Geant4 and MCNP





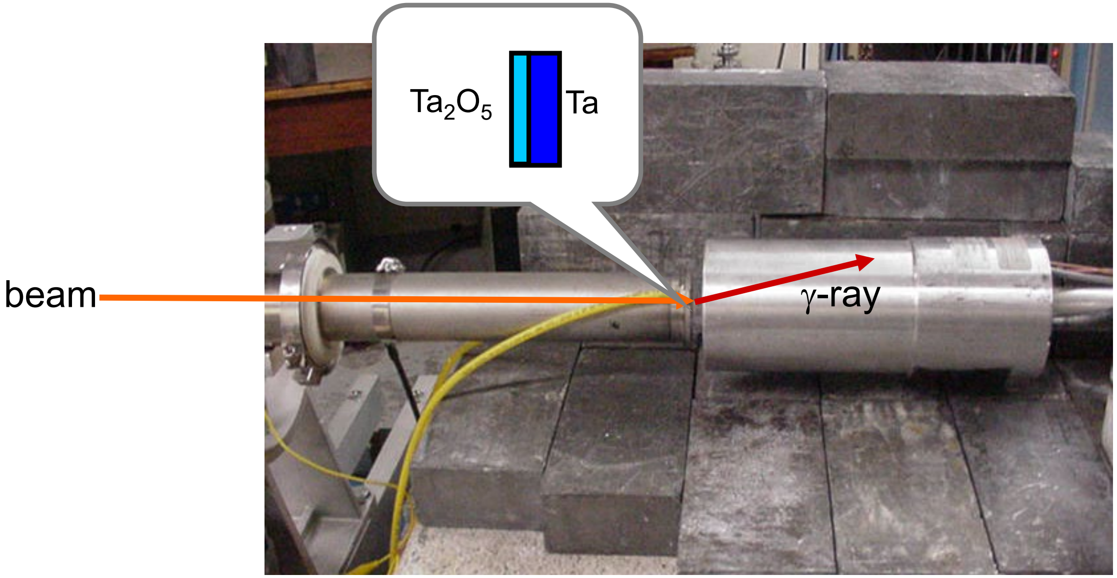
Computer Tomography (CT) at UNC Hospitals

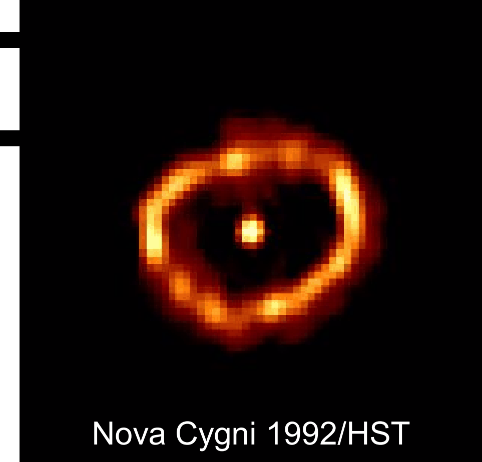
Computed Tomography (CT) Images



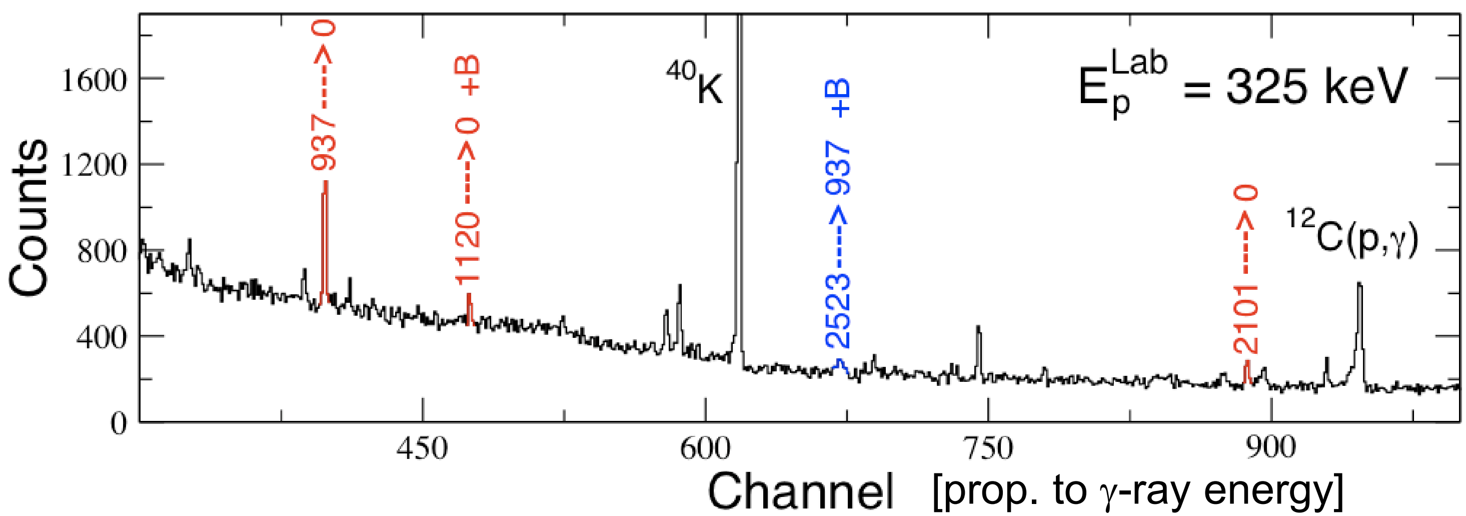
Carson, Iliadis et al., Nucl. Instr. Meth. A618, 190 (2010)

Measured germanium detector γ-ray pulse-height spectrum

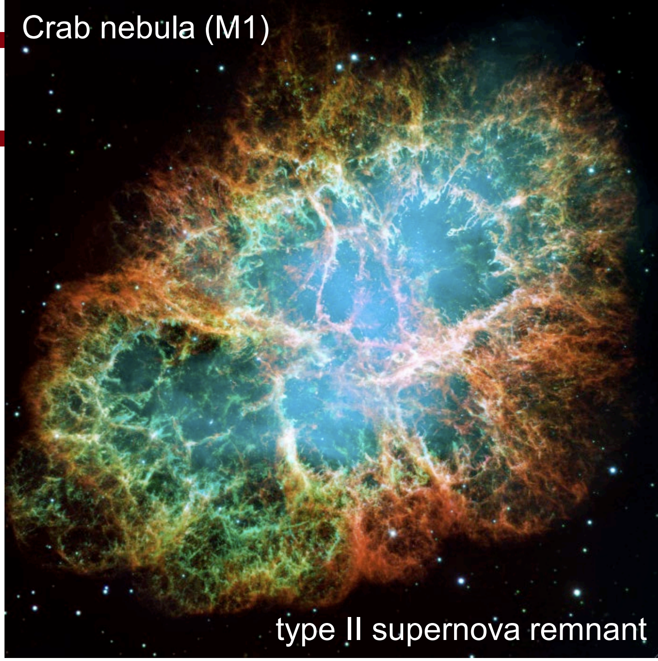




$$p + {}^{17}O \rightarrow {}^{18}F + \gamma$$



Background radiation: sources



90% p; 9% α; 1% HI
($1000\ m^{-2}s^{-1}$)

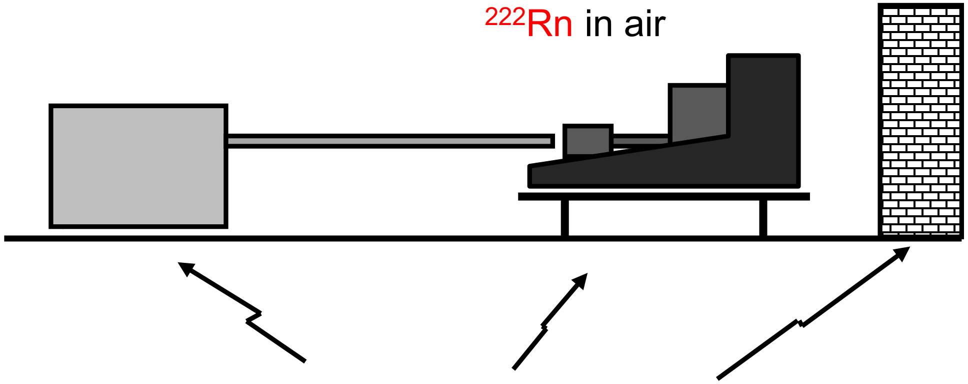
upper atmosphere: n, e, ν, p, μ, π

sea level: μ, n, e, p, π

absorbed by ceiling/floors

^{3}H, ^{14}C, ^{60}Co, ^{90}Sr , ^{137}Cs
- nuclear weapons testing
- nuclear power plants

^{222}Rn in air

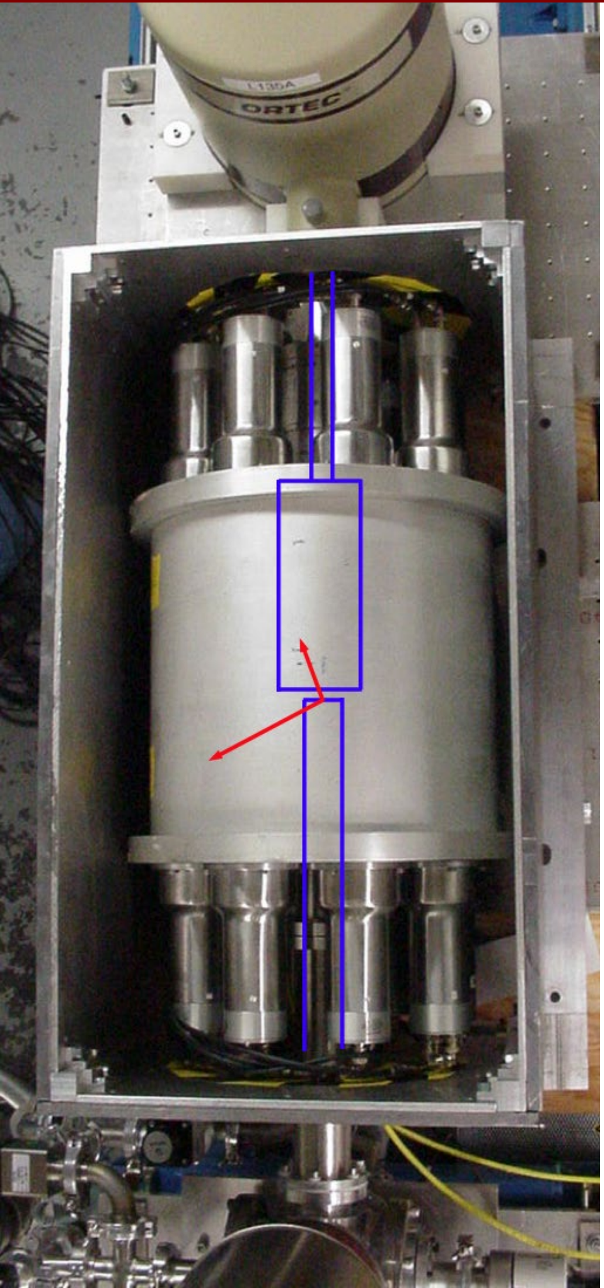


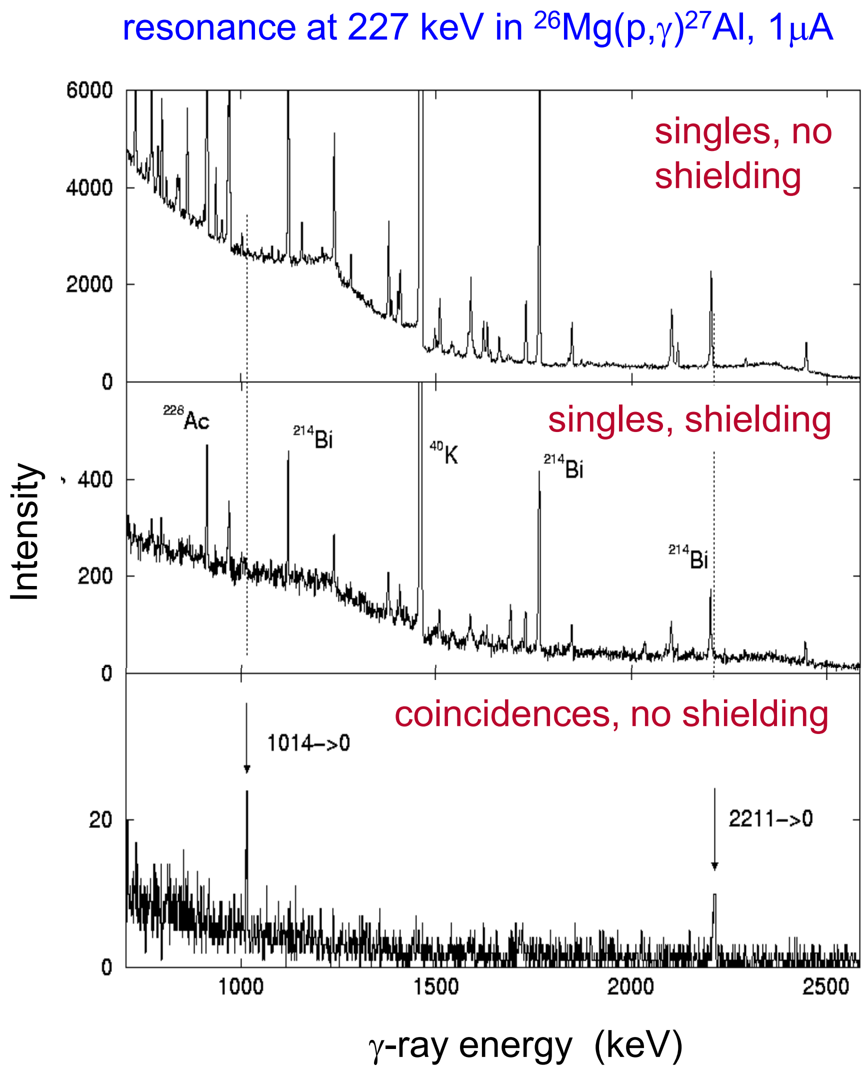
U, Th, ^{40}K in building/shielding/detector material

Half lives:

^{3}H:	12.3 y
^{14}C:	5730 y
^{40}K:	$1.3\cdot10^{9}$ y
^{60}Co:	5.2 y
^{90}Sr:	28.8 y
^{137}Cs:	30.2 y
^{222}Rn:	3.8 d
^{238}U:	$4.5\cdot10^{9}$ y
^{232}Th:	$1.4\cdot10^{10}$ y

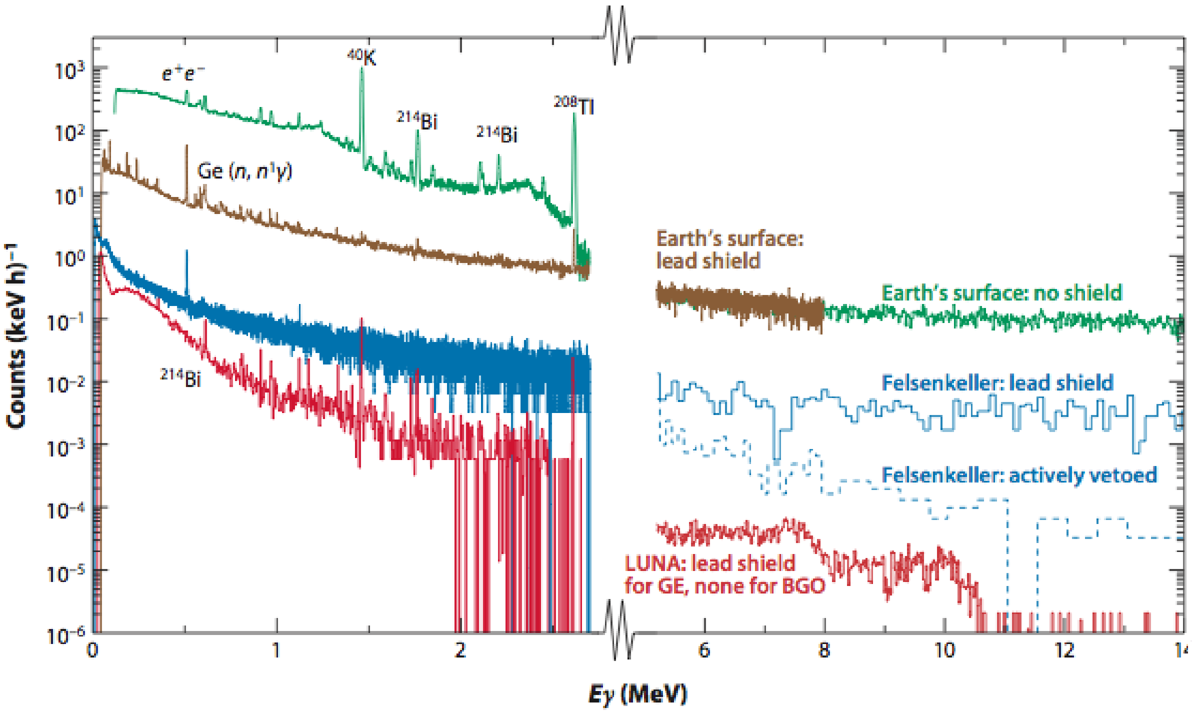
Coincidence-Anticoincidence Detection Apparatus





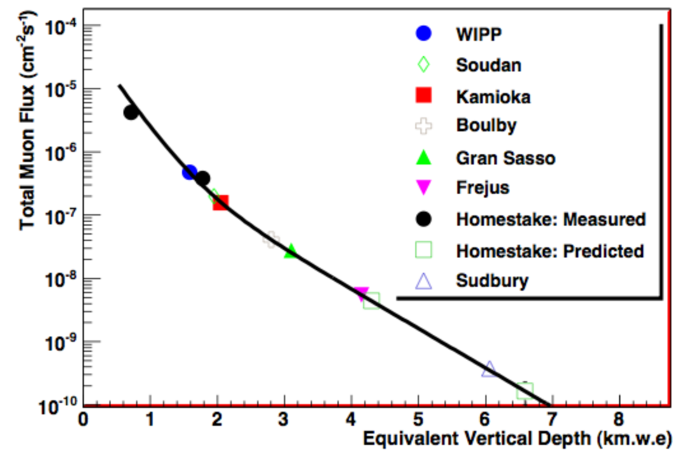
- Rowland, Iliadis et al., Nucl. Instr. Meth. A 480, 610 (2002)
- Longland, Iliadis et al., Nucl. Instr. Meth. A 566, 452 (2006)

Another background reduction technique: experiments underground

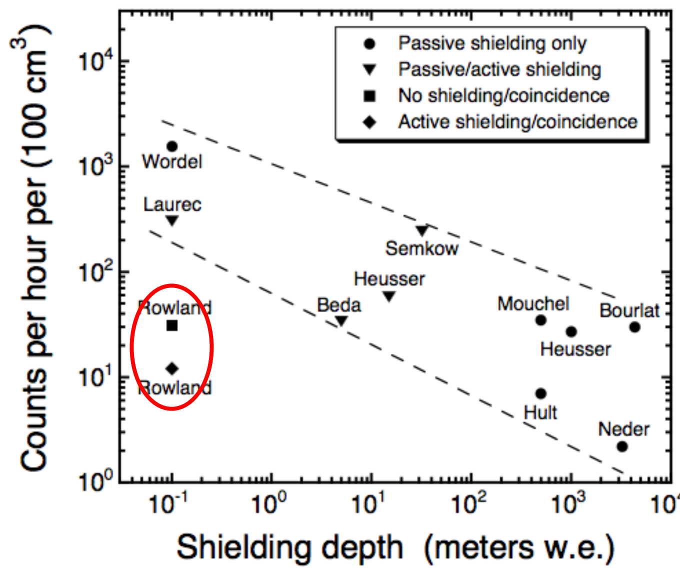


Broggini et al., Annu. Rev. Nucl. Part. Sci. 60, 53 (2010)

Gray et al., arxiv: 1007.1921



E_γ<3 MeV



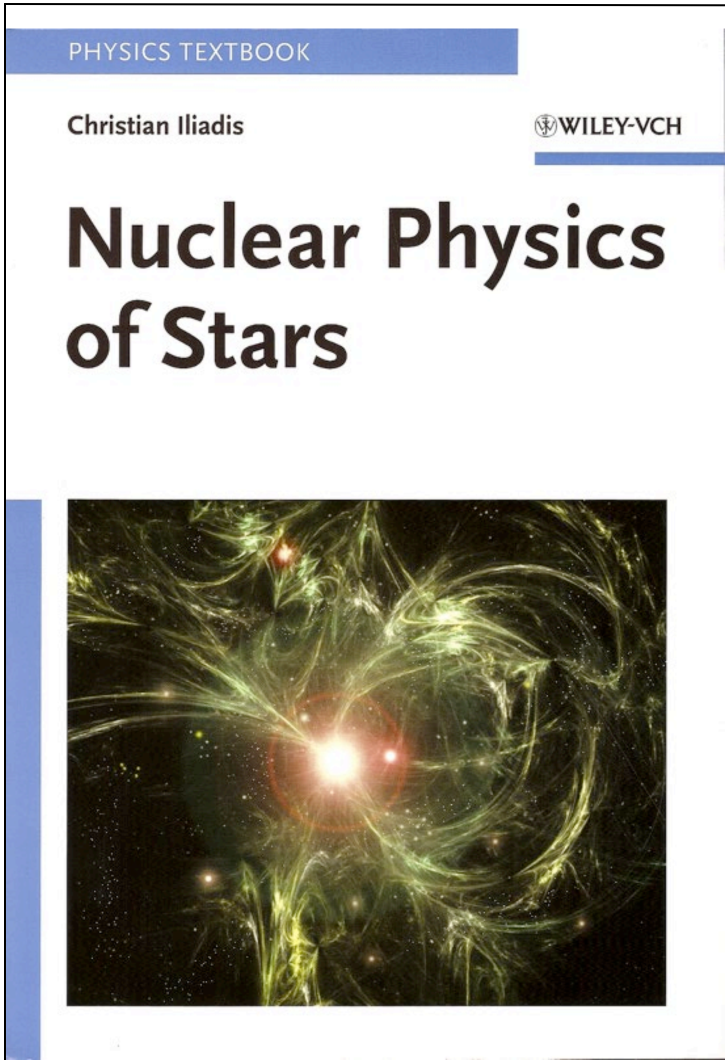
Iliadis, Nuclear Physics of Stars, Wiley (2007)

- at energies E_γ<3 MeV, specially selected materials must be used or background is not much reduced
- at energies E_γ>3 MeV, background is strongly reduced, even with conventional detectors
- beam-induced background is not reduced!

Nuclear astrophysics overviews/reviews:

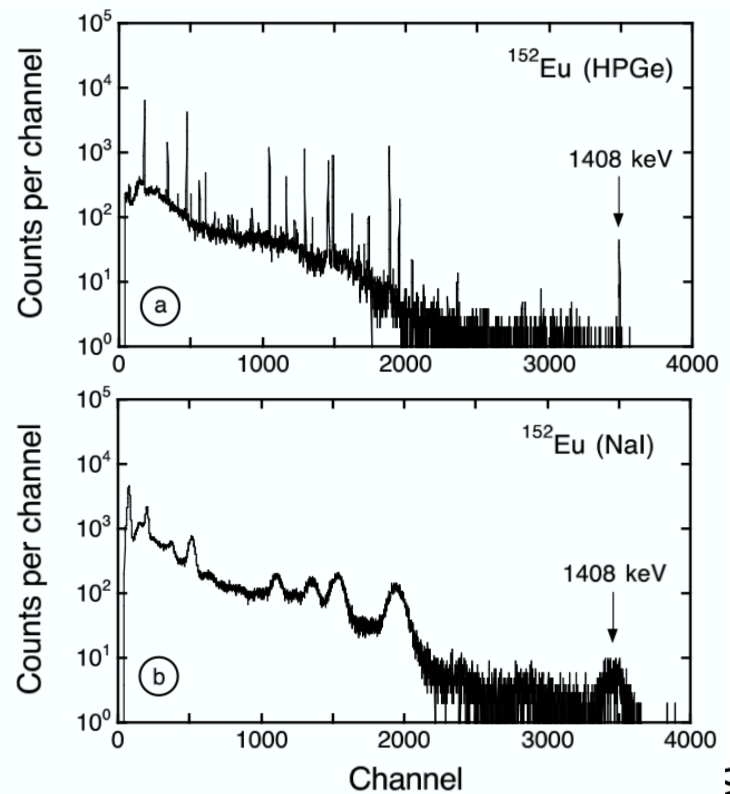
C. Iliadis, Introduction to Nuclear Astrophysics, CP1213, ed. Spitaleri, Rolfs & Pizzone (AIP, 2010) [22 pages]
very general introduction – advanced undergrad level

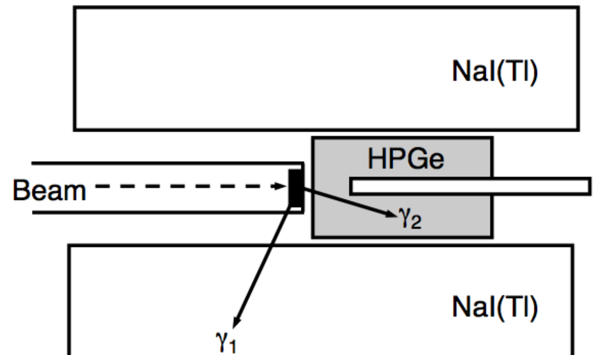
J. Jose & C. Iliadis, Nuclear astrophysics: the unfinished quest for the origin of the elements, Rep. Prog. Phys., in print
About 50 pages – advanced grad student level

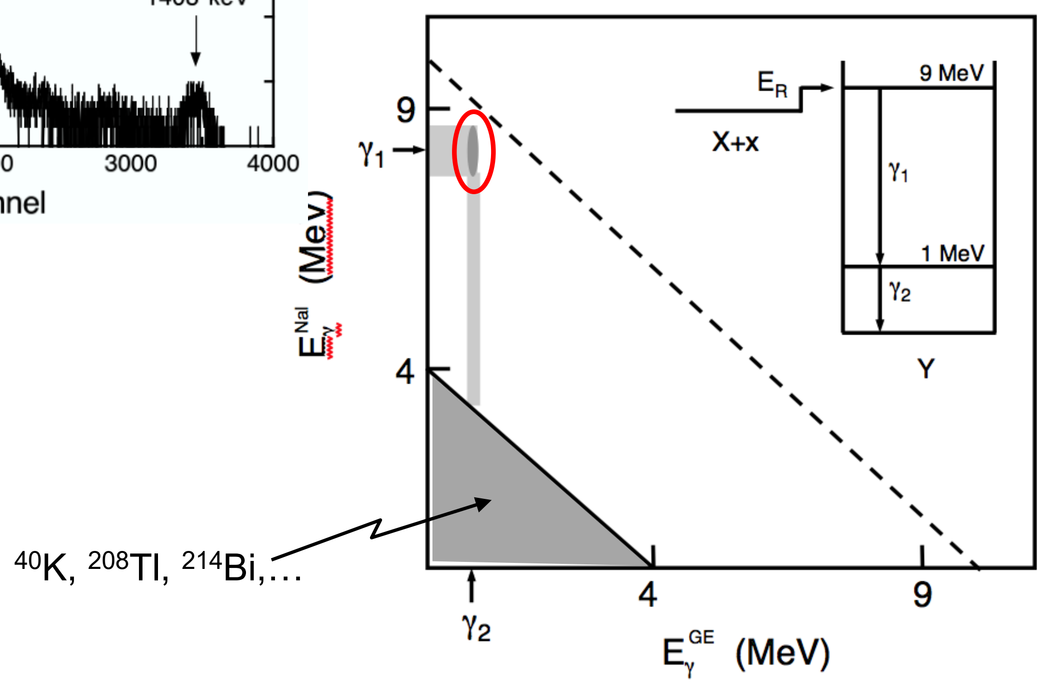


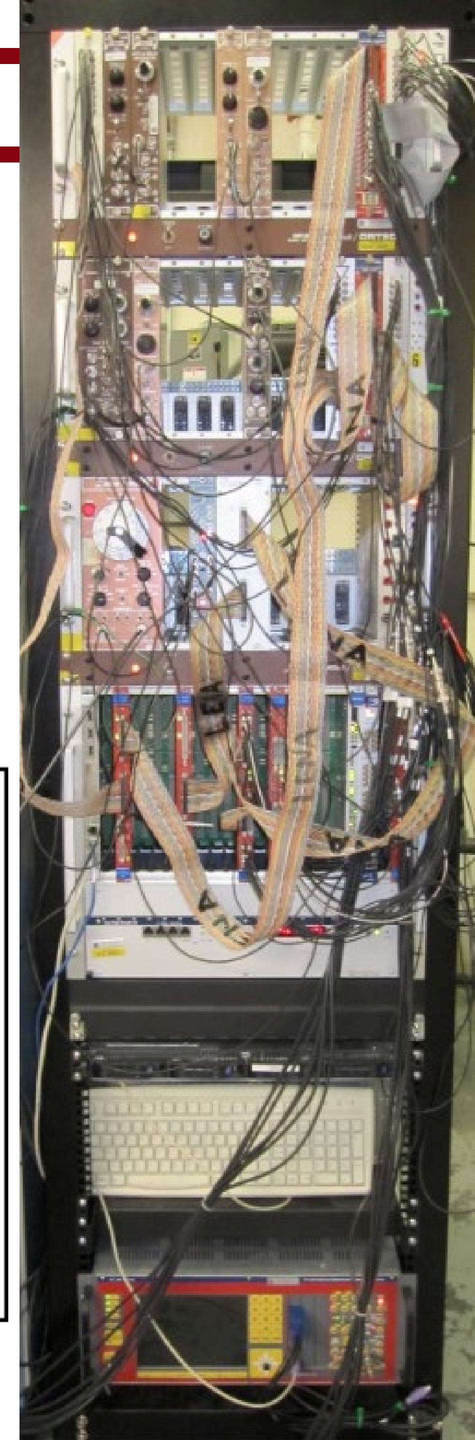
Extra slides

The power of electronics: coincidence gating



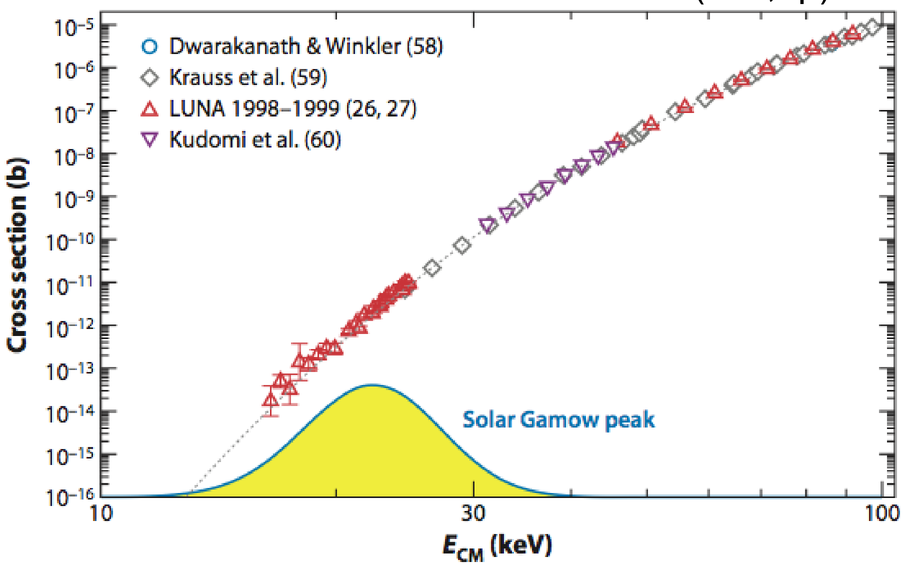


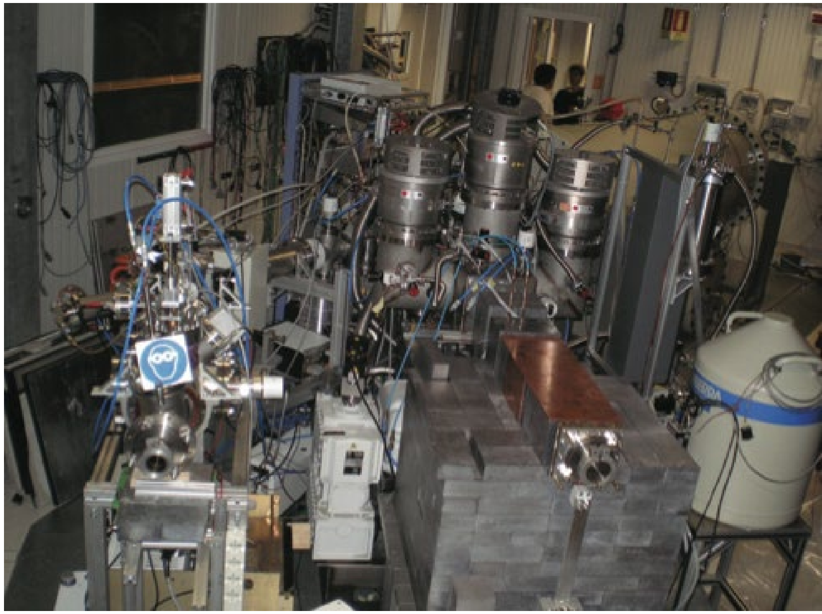




The pioneering Laboratory for Underground Nuclear Astrophysics (LUNA)

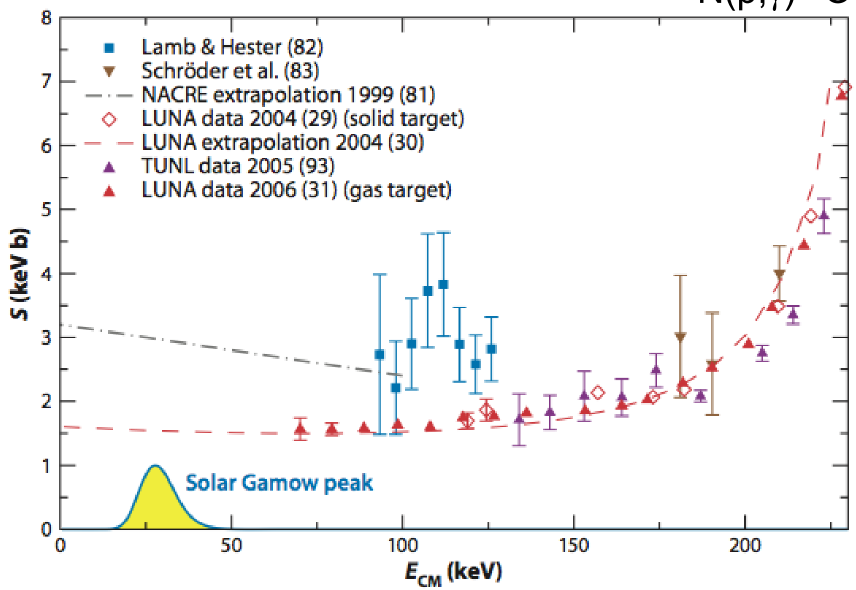
$^3He(^3He,2p)^4He$



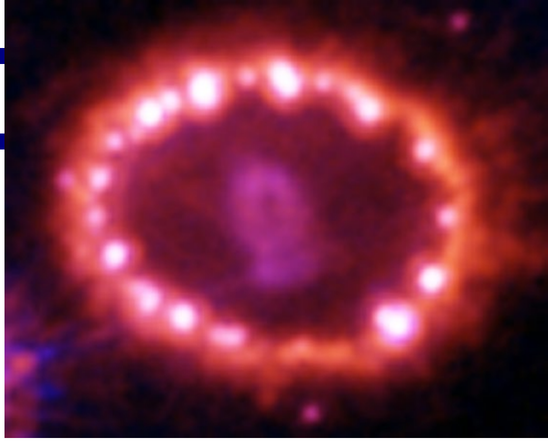


Broggini et al., Annu. Rev. Nucl. Part. Sci. 60, 53 (2010)

$^{14}N(p,\gamma)^{15}O$



“Incomplete” Explosive Si Burning (T>4-5 GK)



outgoing shock wave still moving in ^{28}Si layer, but T and ρ are smaller: ^{28}Si is dissociated, two quasi-equilibrium clusters form, and Fe peak nuclei are produced

process very similar to hydrostatic Si burning, except that:
(i) fast expansion causes freeze-out before NSE can be established
(ii) significant amount of ^{28}Si remains

main nucleosynthesis products: ^{28}Si, Fe peak species, intermediate-mass elements

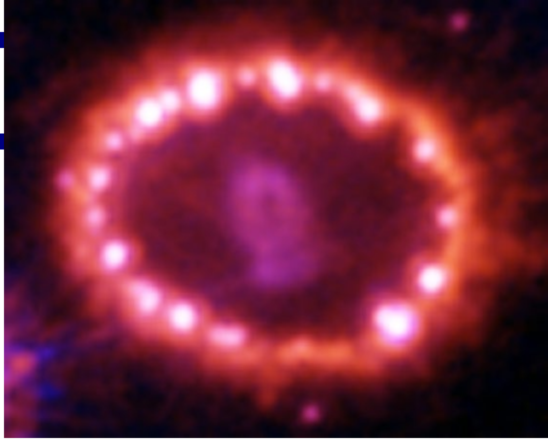
Explosive O Burning (T=3-4 GK)

next layer reached by shock is composed of ^{16}O

process similar to incomplete silicon burning [fuel (^{16}O) is dissociated, giving rise to two QSE clusters in the mass regions of silicon and the Fe peak]; however, temperature is lower and thus less matter is converted to the Fe peak and much more material remains locked in silicon

most abundant nuclides after freeze-out: ^{28}Si, ^{32}S, ^{36}Ar and ^{40}Ca (“α-elements”)

Explosive C and Ne Burning (T=2-3 GK)



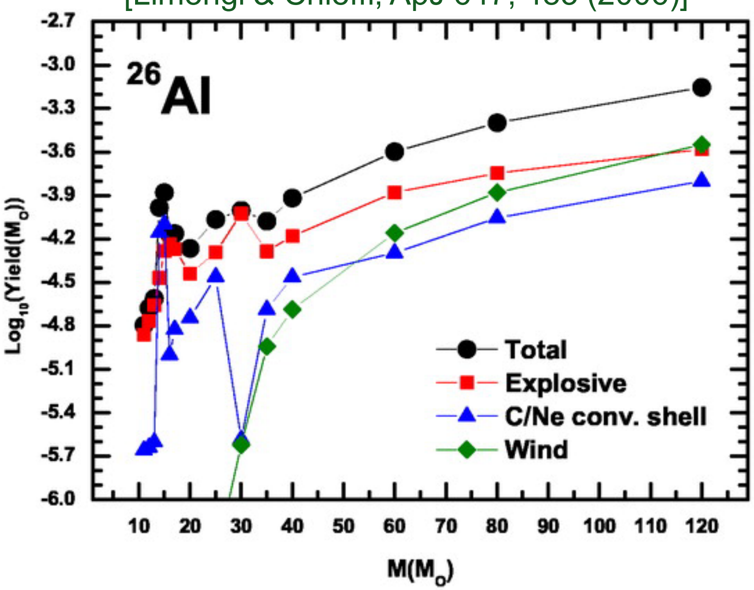
finally, shock encounters a zone mainly composed of ^{16}O, ^{20}Ne, ^{12}C

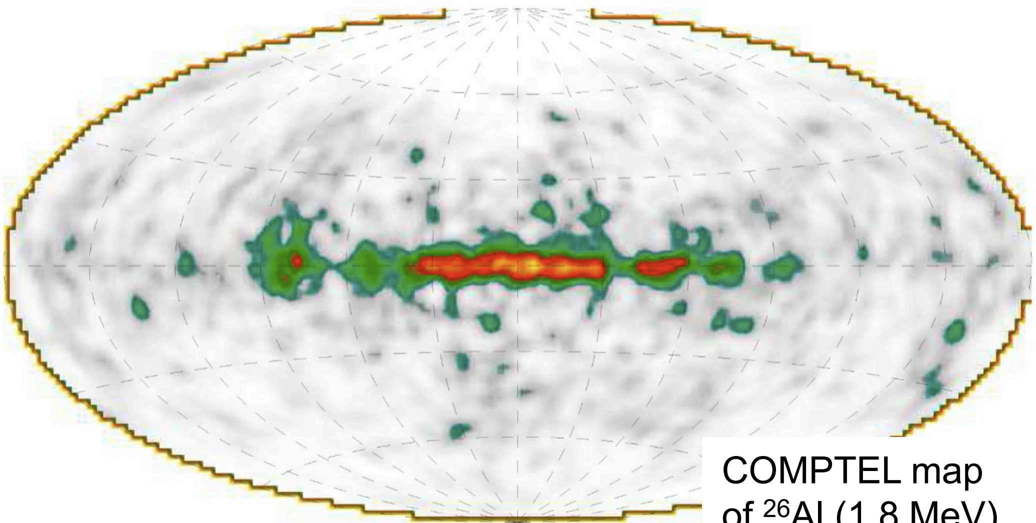
^{20}Ne [and to a lesser extend ^{12}C] burns explosively, but T and τ are too small for establishing QSE and the forward and reverse nuclear reactions operate far from equilibrium

abundance of a given species depends on initial composition and reaction rates.

after freeze-out most abundant species: ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si; also main site of ^{26}Al production

[Limongi & Chieffi, ApJ 647, 483 (2006)]



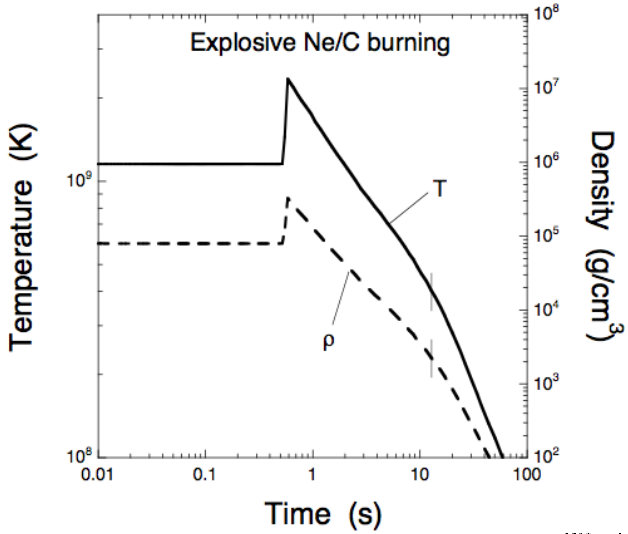


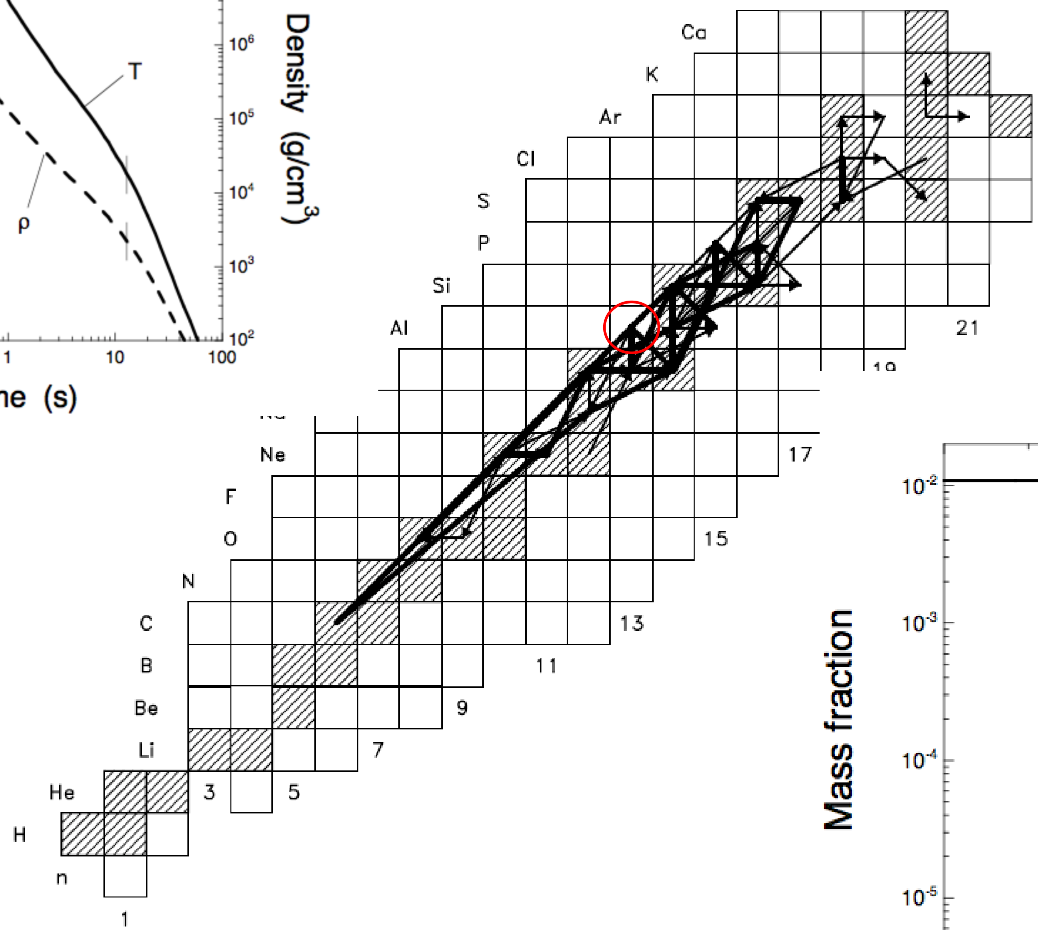
COMPTEL map of ^{26}Al (1.8 MeV)

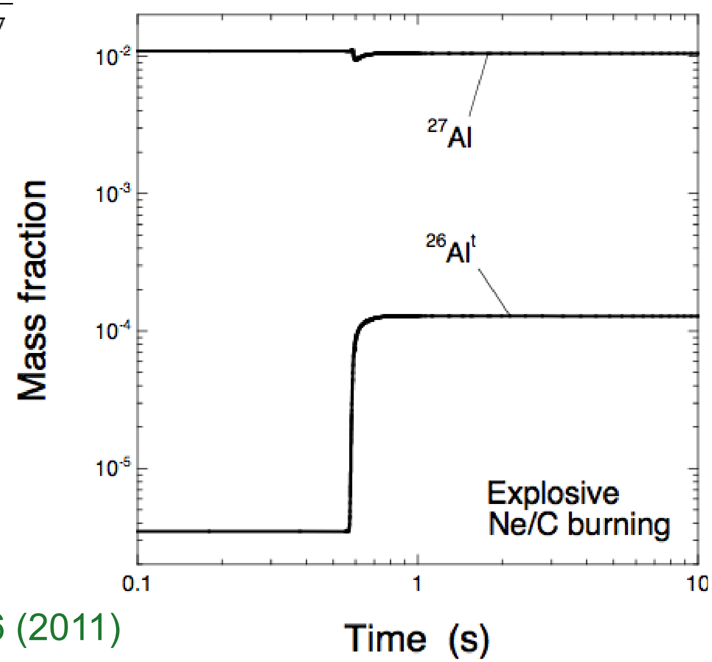
$T_{1/2}(^{26}\mathrm{Al})$=720,000 years

Most supernovae (approximately 85%) result from core collapse of massive stars (>11 M_{sol})

Main production Site of ^{26}Al: Explosive Ne/C burning







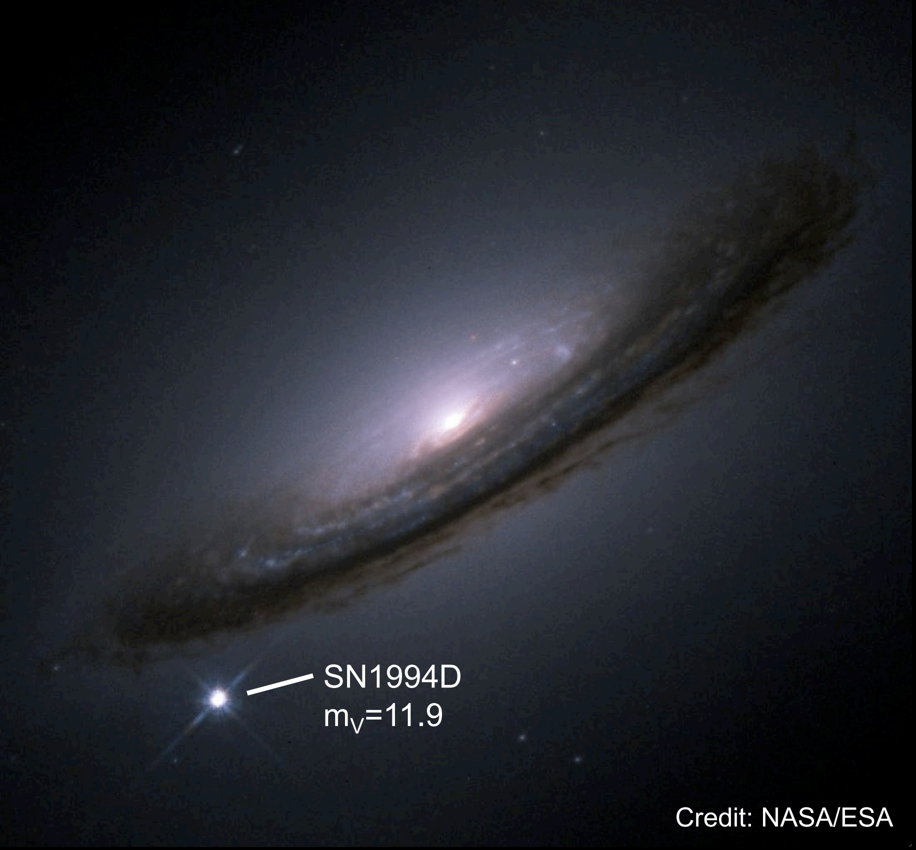
Sensitivity study: Iliadis, Champagne, Chieffi & Limongi, ApJS 193, 16 (2011)

Origin of the Nuclides: Current State of Knowledge

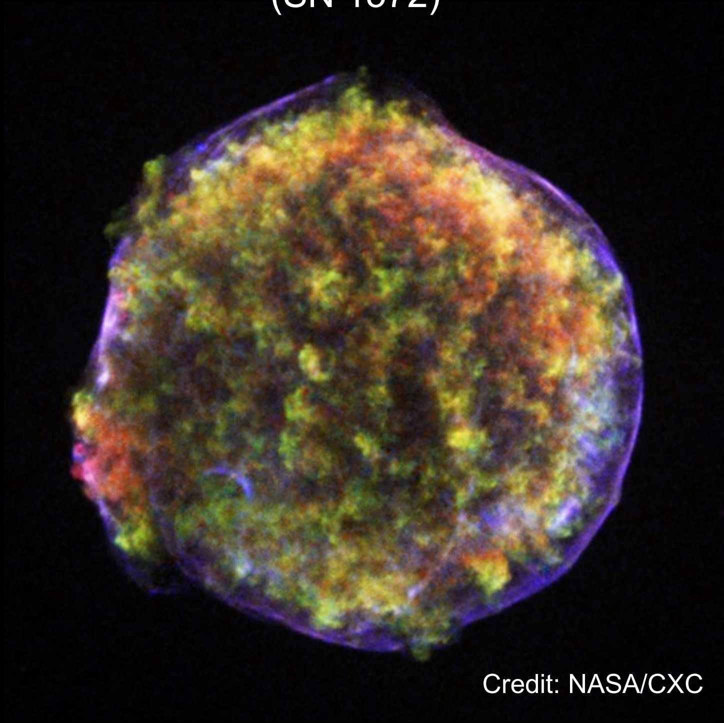
Nuclide	Origin	Nuclide	Origin	Nuclide	Origin
^{1}H	BB	^{17}O	CN	^{30}Si	C
^{2}H	BB	^{18}O	He	^{31}P	C
^{3}He	BB	^{19}F	[AGB, ν,...]	^{32}S	xO
^{4}He	BB	^{20}Ne	C	^{33}S	xO, xNe
^{6}Li	CR	^{21}Ne	C	^{34}S	xO
^{7}Li	[BB, AGB, CN]	^{22}Ne	He, AGB	^{36}S	[He(s), xC,...]
^{9}Be	CR	^{23}Na	C	^{35}Cl	xO
^{10}B	CR	^{24}Mg	C	^{37}Cl	[xO, He(s),...]
^{11}B	[CR, ν]	^{25}Mg	C, AGB	^{36}Ar	xO
^{12}C	AGB, He	^{26}Mg	C, AGB	^{38}Ar	xO
^{13}C	AGB, CN	^{26}Al	xC, xNe	^{40}Ar	[He(s), C,...]
^{14}N	AGB	^{27}Al	C	^{39}K	xO
^{15}N	CN	^{28}Si	xO	^{40}K	He(s)
^{16}O	He	^{29}Si	C	^{40}Ca	xO

Tab. 5.2 Origin of the light nuclides. The labels denote: Big Bang (BB); cosmic ray spallation (CR); asymptotic giant branch stars (AGB); ν-process (ν); classical novae (CN); helium, carbon, neon, oxygen burning in massive stars (He, C, Ne, O), where an "x" in front of the symbol of a burning stage indicates explosive rather than hydrostatic burning; the weak s-process component is denoted by He(s). Information from Woosley, Heger and Weaver 2002, Clayton 2003, José, Lattanzio and Limongi 2006 (priv. comm.). Uncertain or conflicting assignments are given in square parenthesis.

Supernova 1994D in galaxy NGC 4526



Remnant of Tycho's supernova (SN 1572)



- smaller fraction (approximately 15%) of supernovae are type Ia supernovae
- believed to occur in binary stars: CO white dwarf + other star
- high mass accretion onto white dwarf surface (to avoid classical nova!)
- white mass grows to near Chandrasekhar limit ($1.4M_{sol}$)
- carbon ignites under degenerate conditions (thermonuclear runaway)
- nuclear energy release disrupts white dwarf, no remnant left behind
- 10^{10} times solar luminosity
- nucleosynthesis in hottest zone: produces mainly ^{56}Ni via NSE at low neutron excess
- outer regions attain smaller temperatures: explosive Si and O burning
- standard candles