ASTROFISICA NUCLEARE

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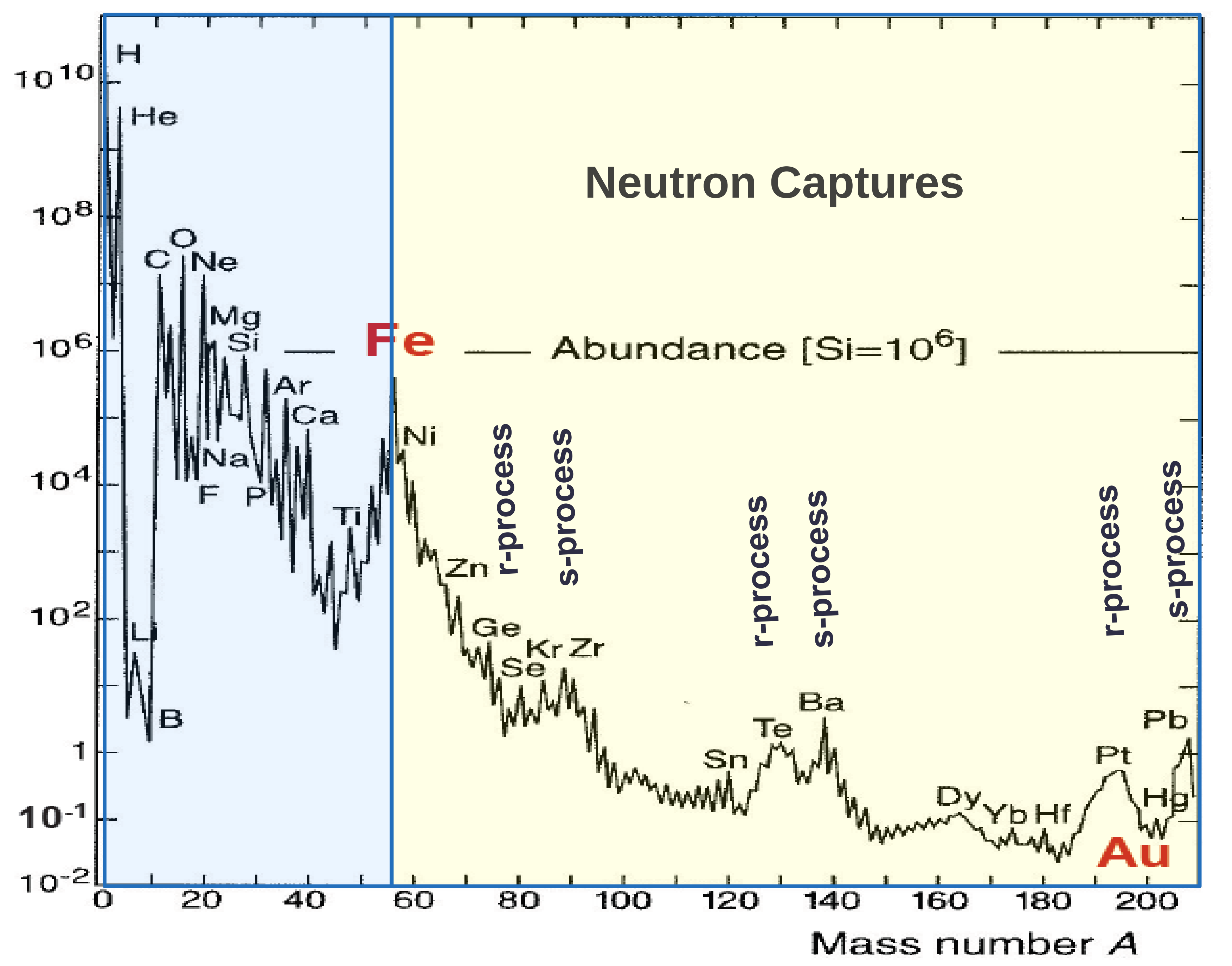
Summary

- State of the art & outlooks (in Italy).
- Some experimental results and astrophysical feedback

Astrophysical Context

- Energy generation in stellar interiors.
- Nucleosynthesis and chemical evolution.



Neutron Captures
Fe
Abundance [Si=10^6]
H
He
C
O
Ne
Mg
Si
Na
F
P
Ar
Ca
Ti
Li
B
Ni
Zn
Ge
Se
Kr
Zr
Sn
Te
Ba
Dy
Yb
Hf
Pt
Au
Hg
Pb
r-process
s-process
r-process
s-process
r-process
s-process
10^10
10^8
10^6
10^4
10^2
1
10^-1
10^-2
0
20
40
60
80
100
120
140
160
180
200
Mass number A

Stellar structure: basic equations (1d hydrostatic model)

$$\frac{dP}{dM_r} = -\frac{GM_r}{4\pi r^4}$$

***Hydrostatic* equilibrium**

$$\frac{dr}{dM_r} = \frac{1}{4\pi r^2 \rho}$$

Mass continuity

$$\frac{dT}{dM_r} = -\nabla \frac{GM_r T}{4\pi r^4 P}$$

Energy transport

$$\frac{dL_r}{dM_r} = \epsilon_{grav} + \epsilon_{nucl} + \epsilon_\nu$$

Energy conservation

Stellar structure: chemical evolution

Y_i=fraction by number

$$\frac{dY_i}{dt} = \left(\frac{dY_i}{dt}\right)_{nuc} + \left(\frac{dY_i}{dt}\right)_{mix} \qquad i = 1, \ldots\ldots\ldots, N$$

$$\left(\frac{dY_i}{dt}\right)_{nuc} = \sum_j c_i(j)\lambda_j Y_i + \sum_{j,k} c_i(j,k)\rho N_A < \sigma v >_{j,k} Y_j Y_k + \sum_{j,k,l} c_i(j,k,l)\rho^2 N_A^2 < \sigma v >_{j,k,l} Y_j Y_k Y_l$$

nuclear

$$\left(\frac{dY_i}{dt}\right)_{mix} = D\frac{\partial^2 Y_i}{\partial r^2} - \mathrm{v}\frac{\partial Y_i}{\partial r}$$

Mixing: dynamical or secular instabilities

Stellar structure: physical quantities

$$P = f(\rho, T, Y_i)$$

Equation of state

$$\kappa = g(\rho, T, Y_i)$$

***radiative* opacity**

$$\varepsilon_\nu = h(\rho, T, Y_i)$$

$$\varepsilon_g = -T\frac{dS}{dt} = -\frac{dE}{dt} + \frac{P}{\rho^2}\frac{d\rho}{dt}$$

$$\varepsilon_n = \sum_k Y_i Y_j \rho N_A \langle \sigma v \rangle_k Q_k$$

Energy sources or sinks:

Neutrinos, Gravitational, Nuclear

$$R_{jk} = n_j n_k \int_0^\infty \sigma(E)\left(\frac{2E}{\mu}\right)^{\frac{1}{2}} f(E)\,dE = n_j n_k < \sigma v >_{jk}$$

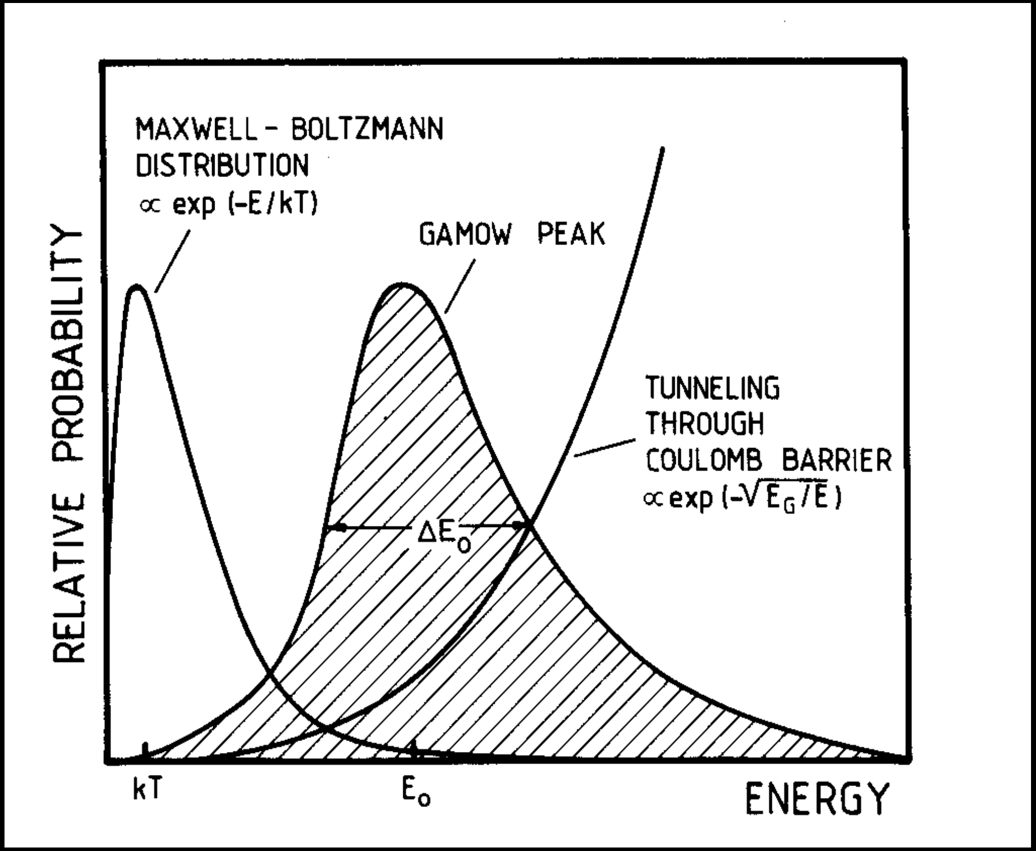
$$= \frac{Y_j Y_k}{\delta_{jk}} N_A \rho < \sigma v >_{jk}$$

$$f(E) = \frac{2}{\sqrt{\pi}} \frac{E^{\frac{1}{2}}}{(KT)^{\frac{3}{2}}} \exp\left(-\frac{E}{KT}\right)$$

$$\sigma(\mathrm{E}) = \frac{1}{\mathrm{E}} \mathrm{S}(\mathrm{E}) \exp\left(-31.29 \frac{\mathrm{Z}_j \mathrm{Z}_\mathrm{k} \mu^{1/2}}{E^{1/2}}\right)$$

$$v = \left| v_j - v_k \right|; \qquad \mu = \frac{A_j A_k}{A_j + A_k}; \qquad E = \frac{1}{2}\mu v^2$$

The Gamow Peak



$$E_{\max} = \left[\left(\frac{\mu}{2} \right)^{1/2} \frac{Z_j Z_k e^2 KT}{4 \varepsilon_0 \hbar} \right]^{2/3}$$

T = 16 MK (Sun)

p+p	5 KeV
3He+3He	20 KeV
3He+4He	21 KeV
14N+p	25 KeV

T = 70 MK (RGB)

14N+p	65 KeV

T = 200 MK (He-burning)

12C+α	300 KeV

T = 500 MK (C-burning)

12C+12C	1.5 MeV

Low-Energy Lab Measure: density & background

In the Sun:

$R_{Sun} \sim 10^{38}\ \mathrm{s}^{-1}$

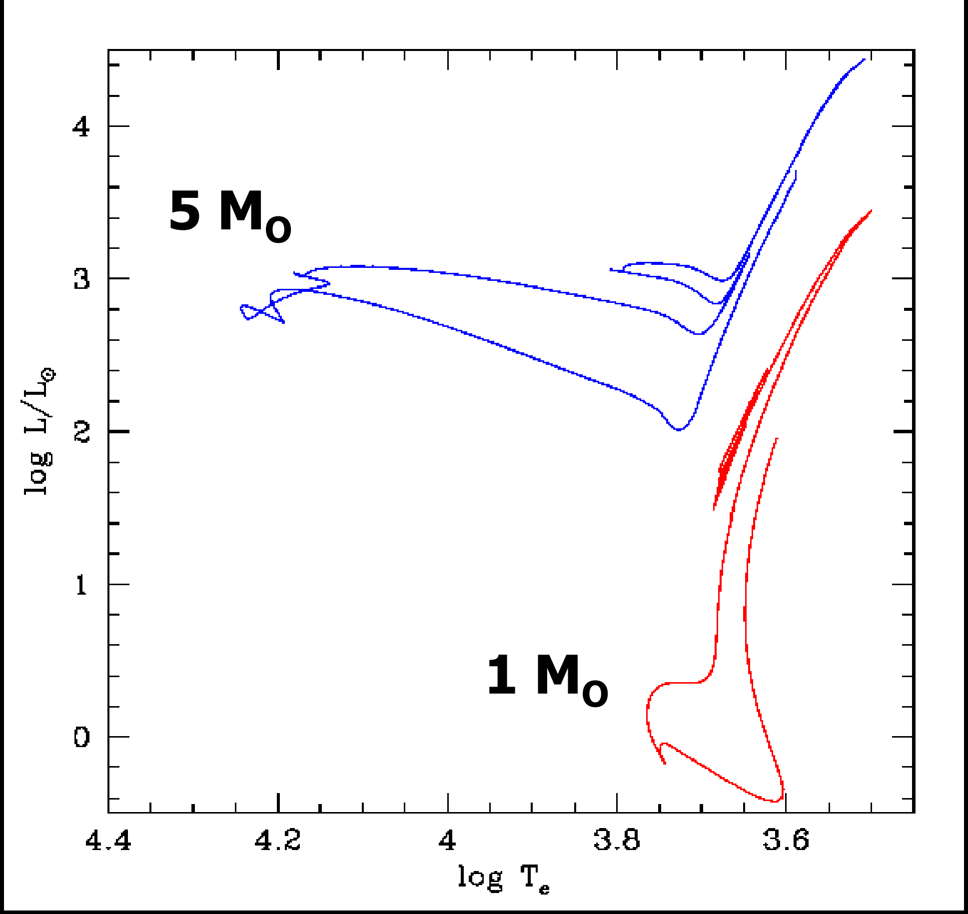
In the Lab:

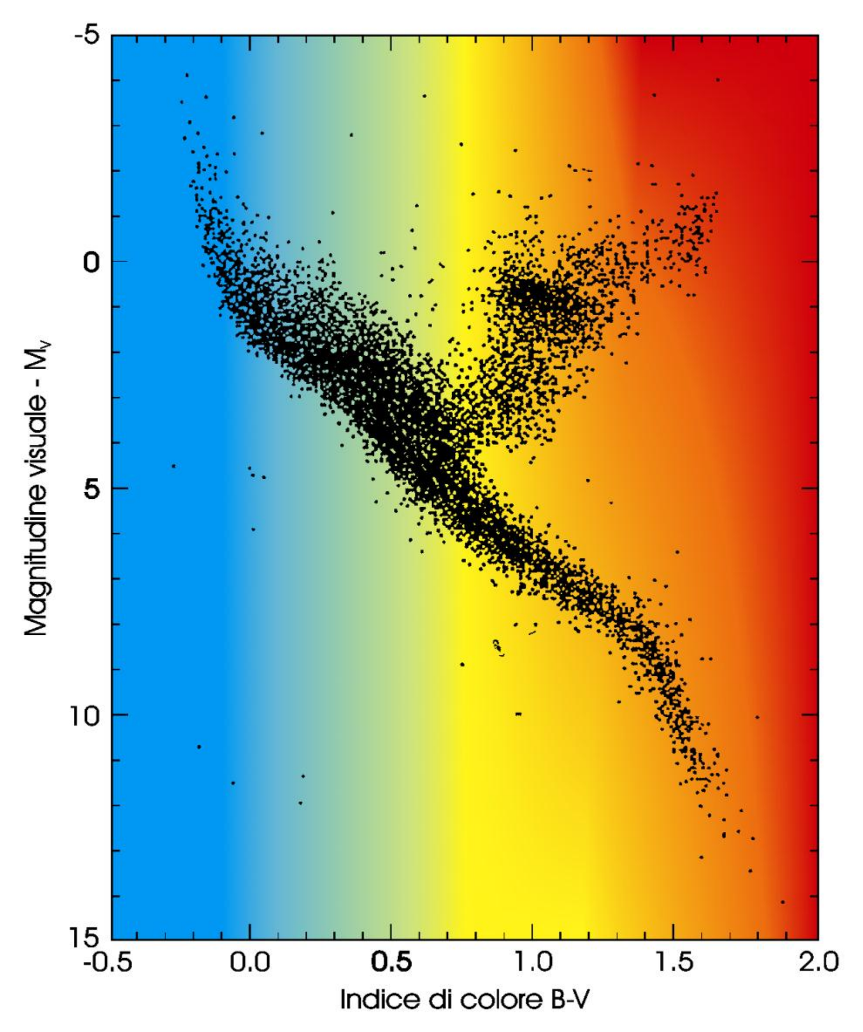
$1\ \mathrm{month}^{-1} < R_{Lab} < 1\ \mathrm{day}^{-1}$

In the Lab: background sources

Cosmic, Natural radioactivity, target/beam Impurities

Theory and its observational counterpart: the HR-Diagram





pp chain

$p + p \to D + e^+ + \nu$

$D + p \to {}^3He + \gamma$

$^3He + {}^3He \to {}^4He + 2p$

$^3He + {}^4He \to {}^7Be + \gamma$

$^7Be + e^- \to {}^7Li + \nu$

$^7Li + p \to {}^4He + {}^4He$

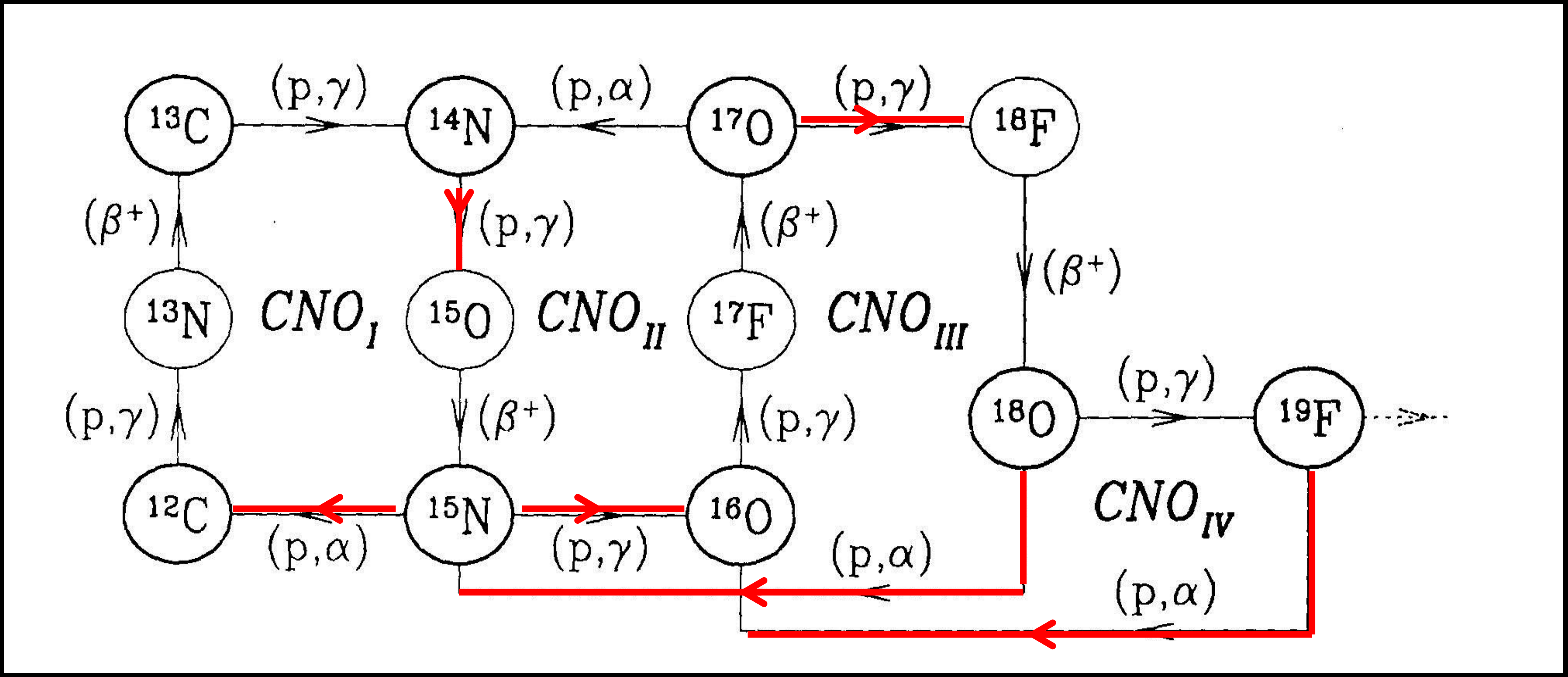
$^7Be + p \to {}^8B + \gamma$

$^8B \to {}^8Be + e^+ + \nu$

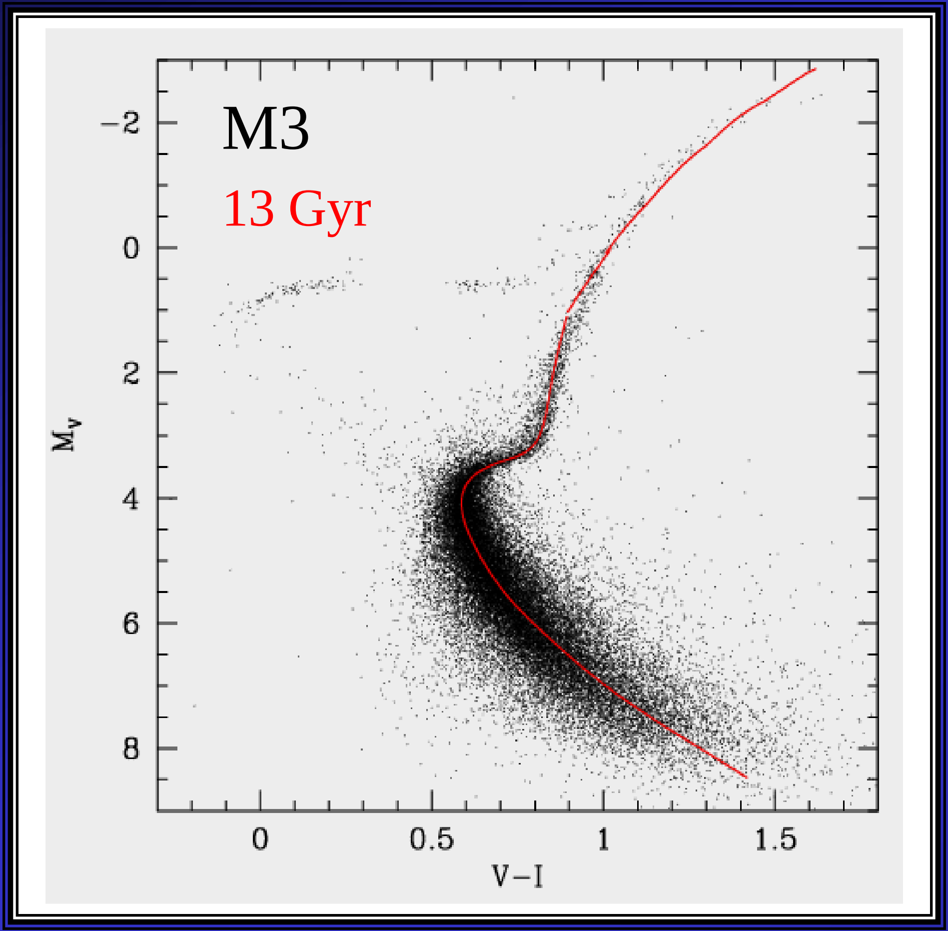
$^8Be \to {}^4He + {}^4He$

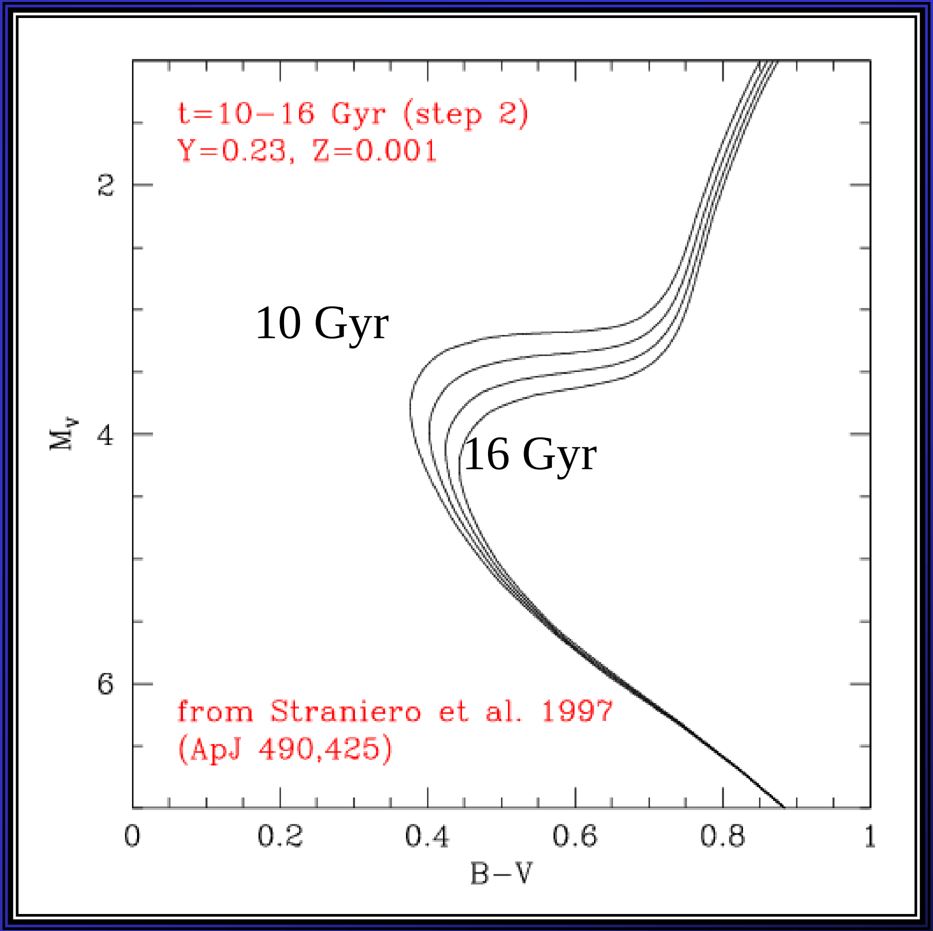
4 protons → ^4He + 25 MeV (γ) + 2 ν

CNO

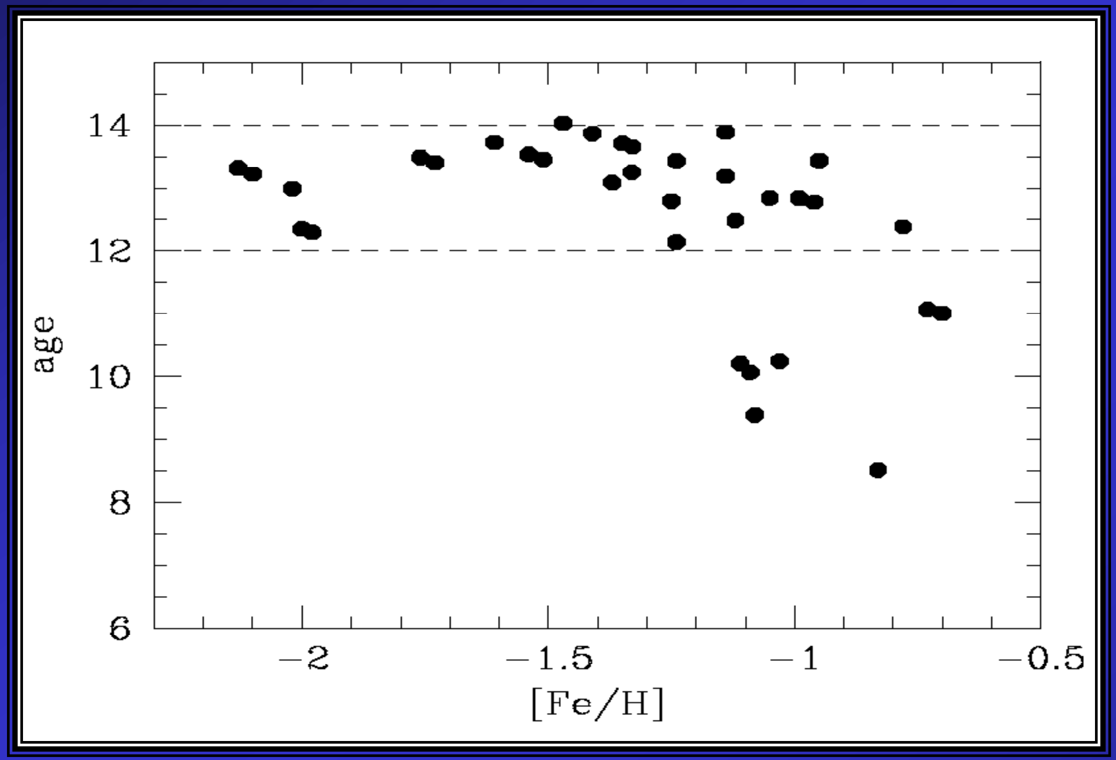

^{13}C
(p,γ)
^{14}N
(p,α)
^{17}O
(p,γ)
^{18}F
(β$^+$)
(p,γ)
(β$^+$)
(β$^+$)
^{13}N
CNO$_I$
^{15}O
CNO$_{II}$
^{17}F
CNO$_{III}$
(p,γ)
(β$^+$)
(p,γ)
^{18}O
(p,γ)
^{19}F
^{12}C
(p,α)
^{15}N
(p,γ)
^{16}O
CNO$_{IV}$
(p,α)
(p,α)

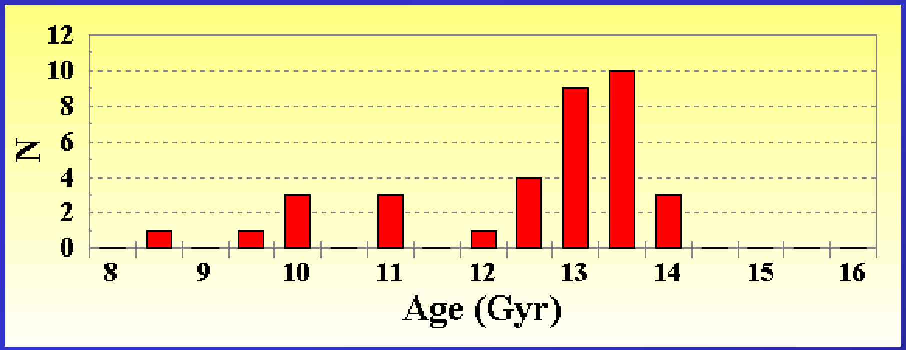
Turn off luminosity & Age





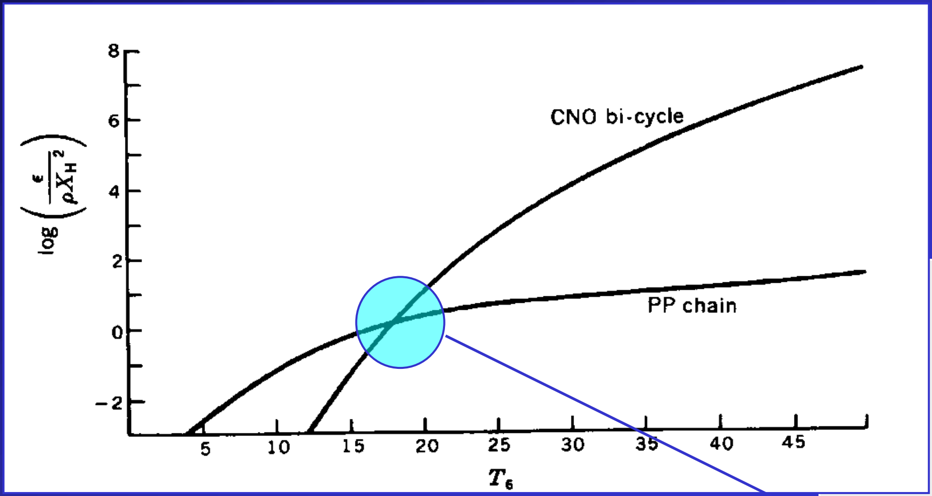
Fitting Cluster Turn-Off



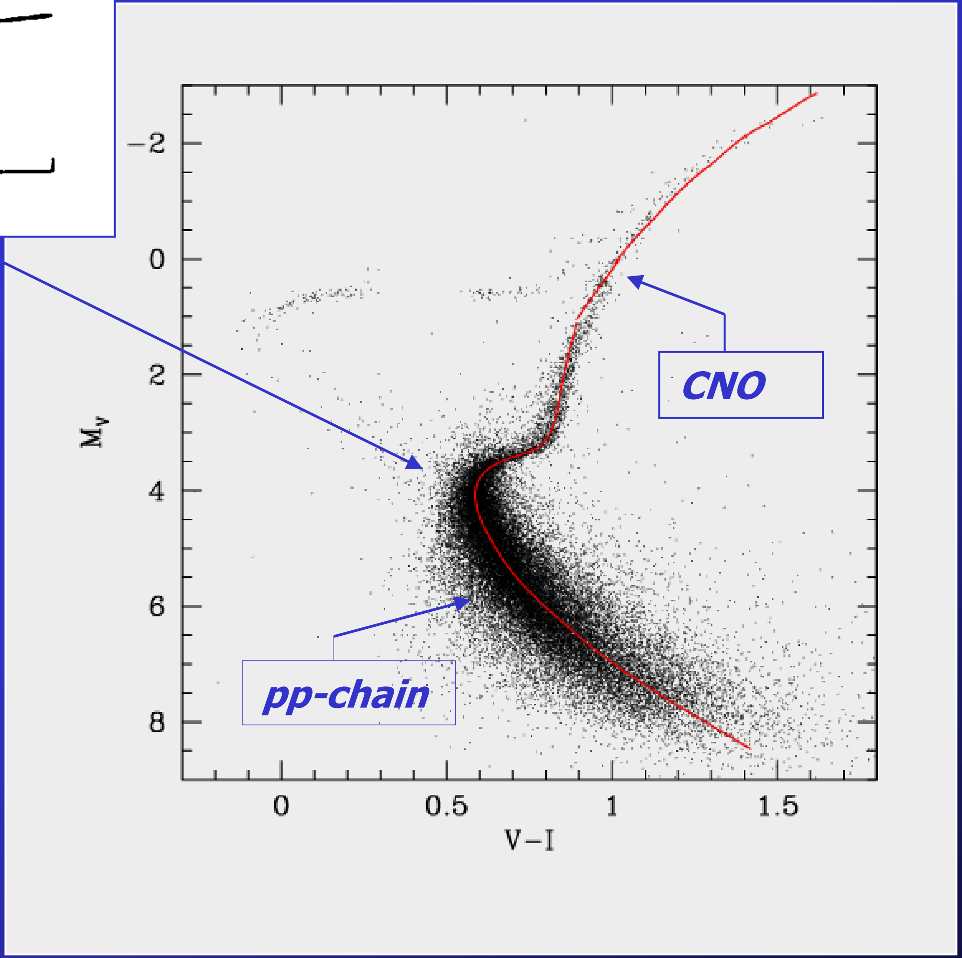


13.00 ± 0.5 Gyr

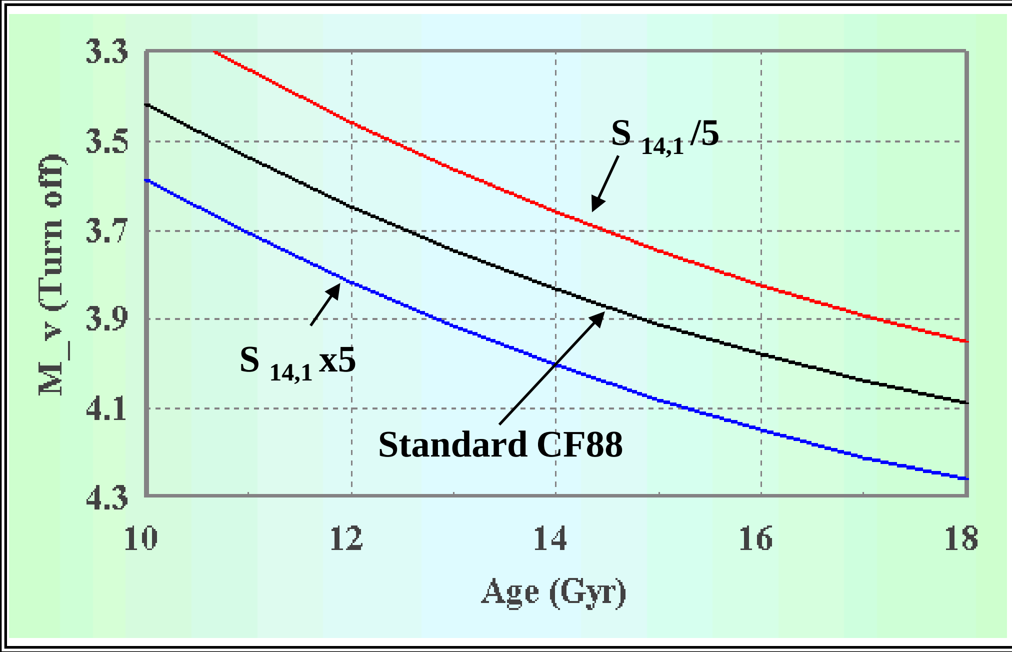
(Straniero et al. 2001)

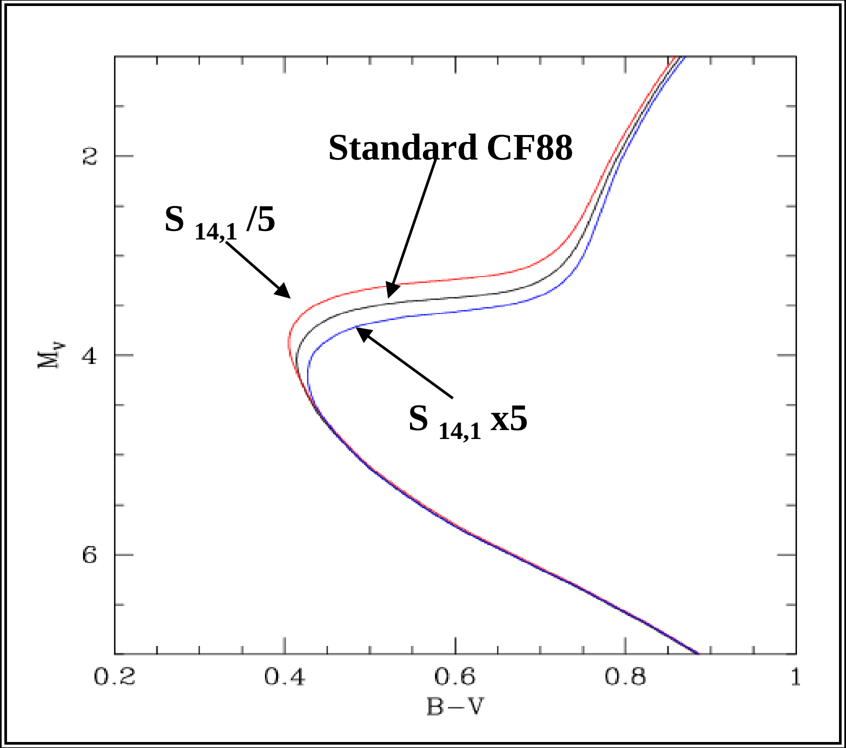


The onset of the CNO

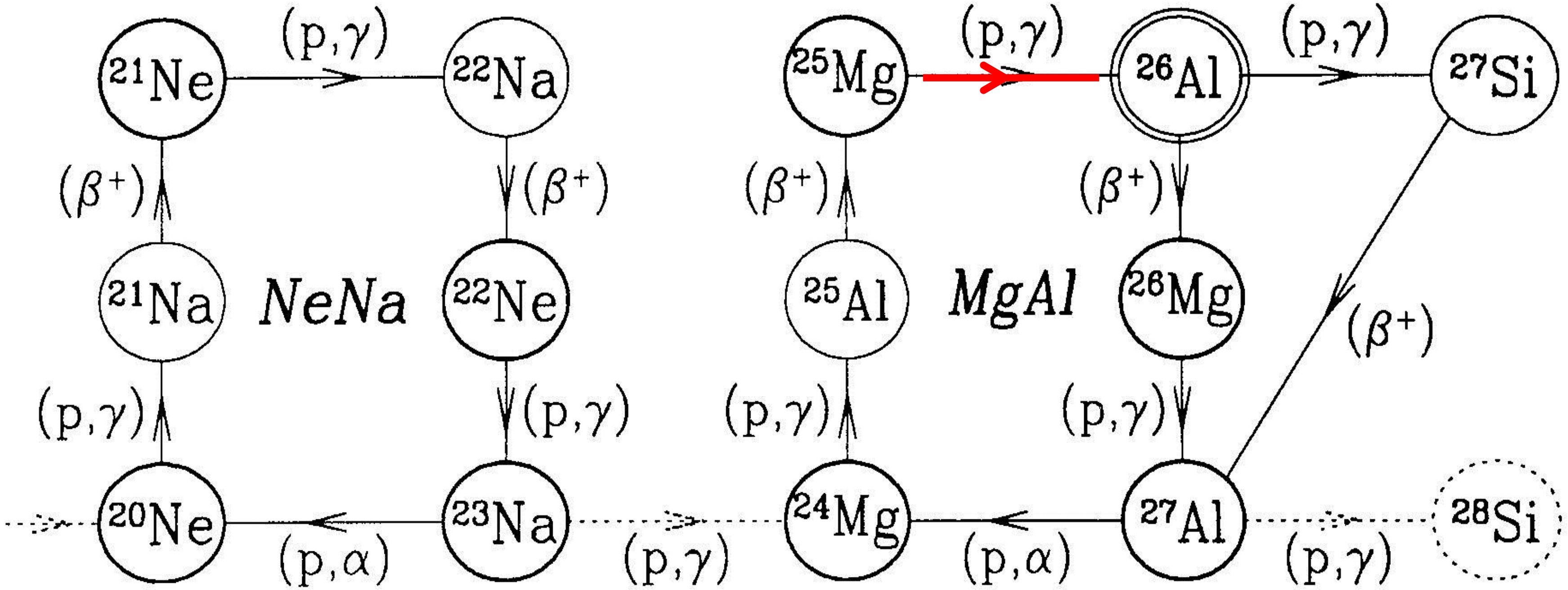


$^{14}N(p,\gamma)^{15}O$

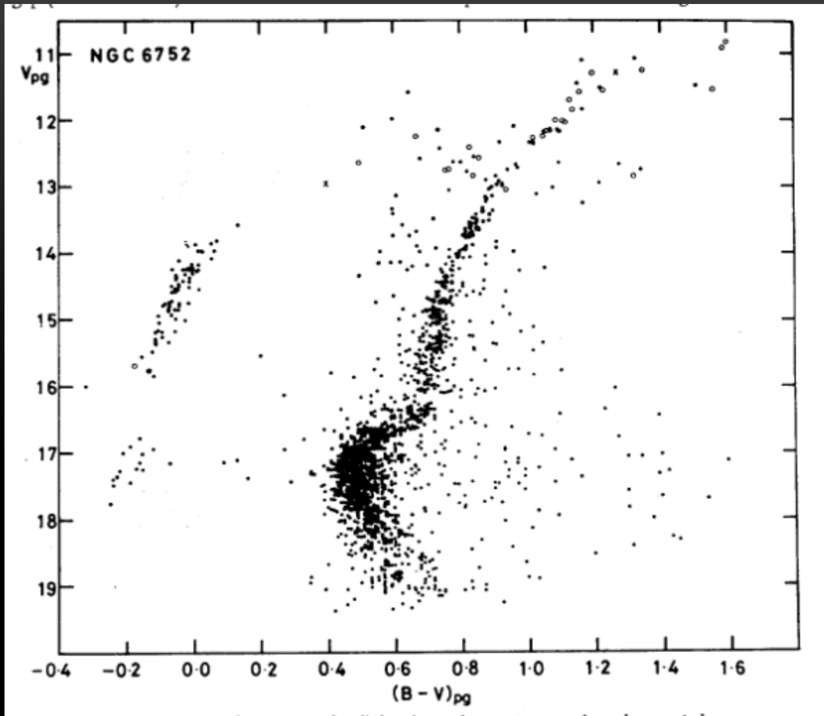




Ne-Na & Mg-Al

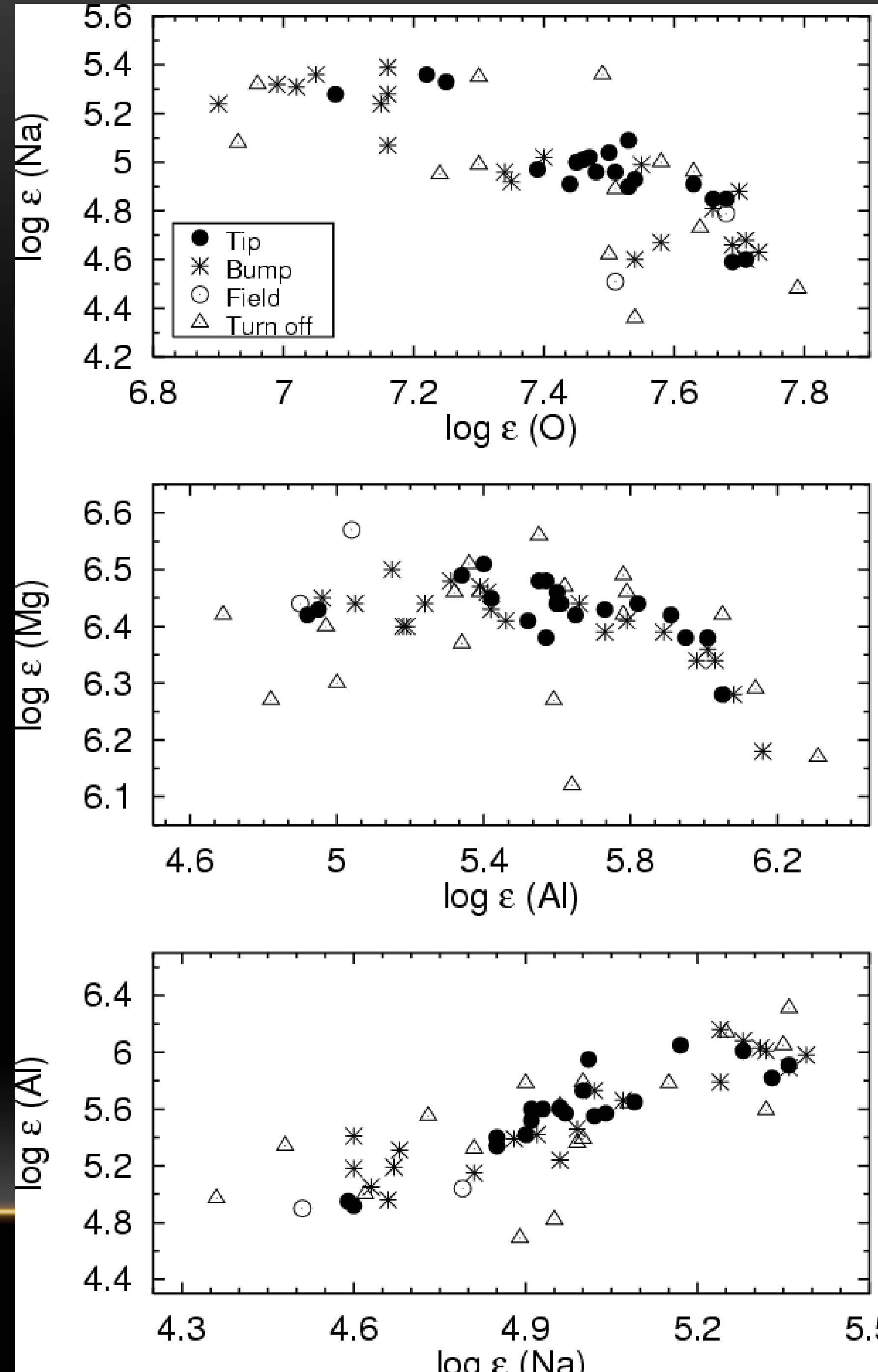


21Ne
22Na
21Na
22Ne
20Ne
23Na
NeNa
25Mg
26Al
27Si
25Al
26Mg
24Mg
27Al
28Si
MgAl
(p,γ)
(β+)
(p,α)

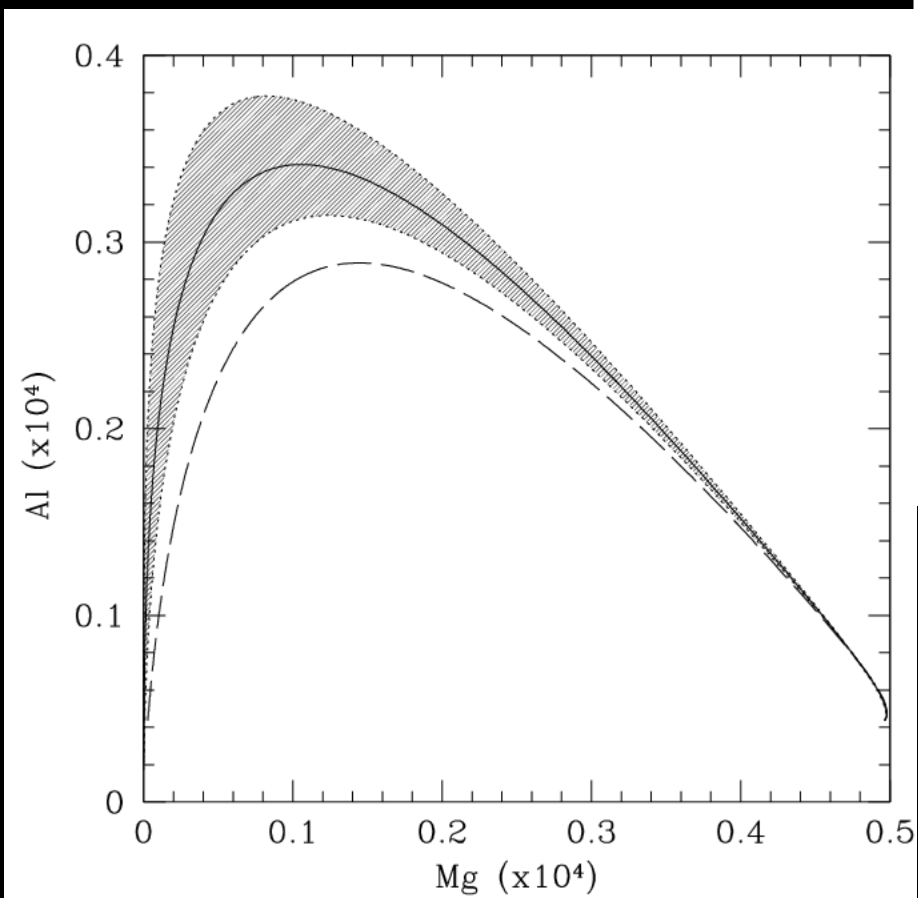


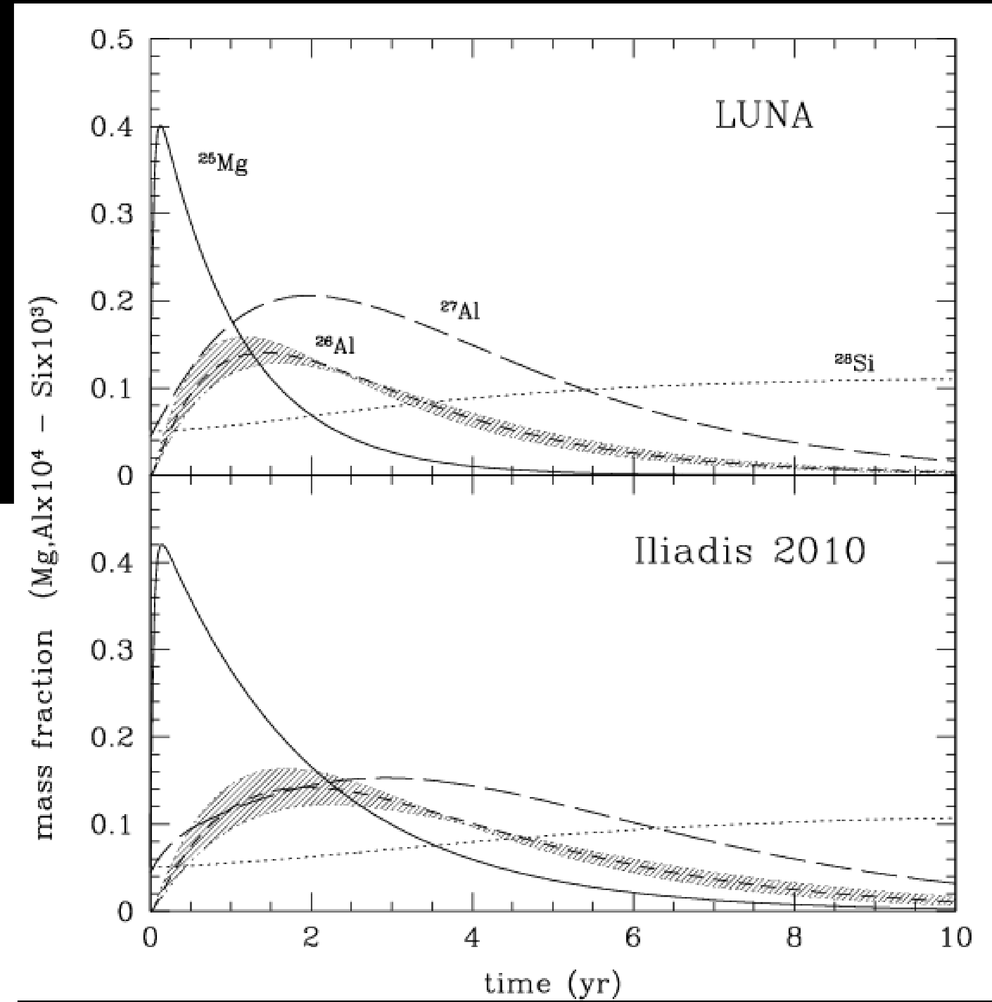
$$\left[\frac{X}{Fe}\right] = \log\left(\frac{X}{Fe}\right)_{*} - \log\left(\frac{X}{Fe}\right)_{\Theta}$$

$$A(X) = \log\varepsilon(X) = \log\left(\frac{N_X}{N_H}\right) + 12$$



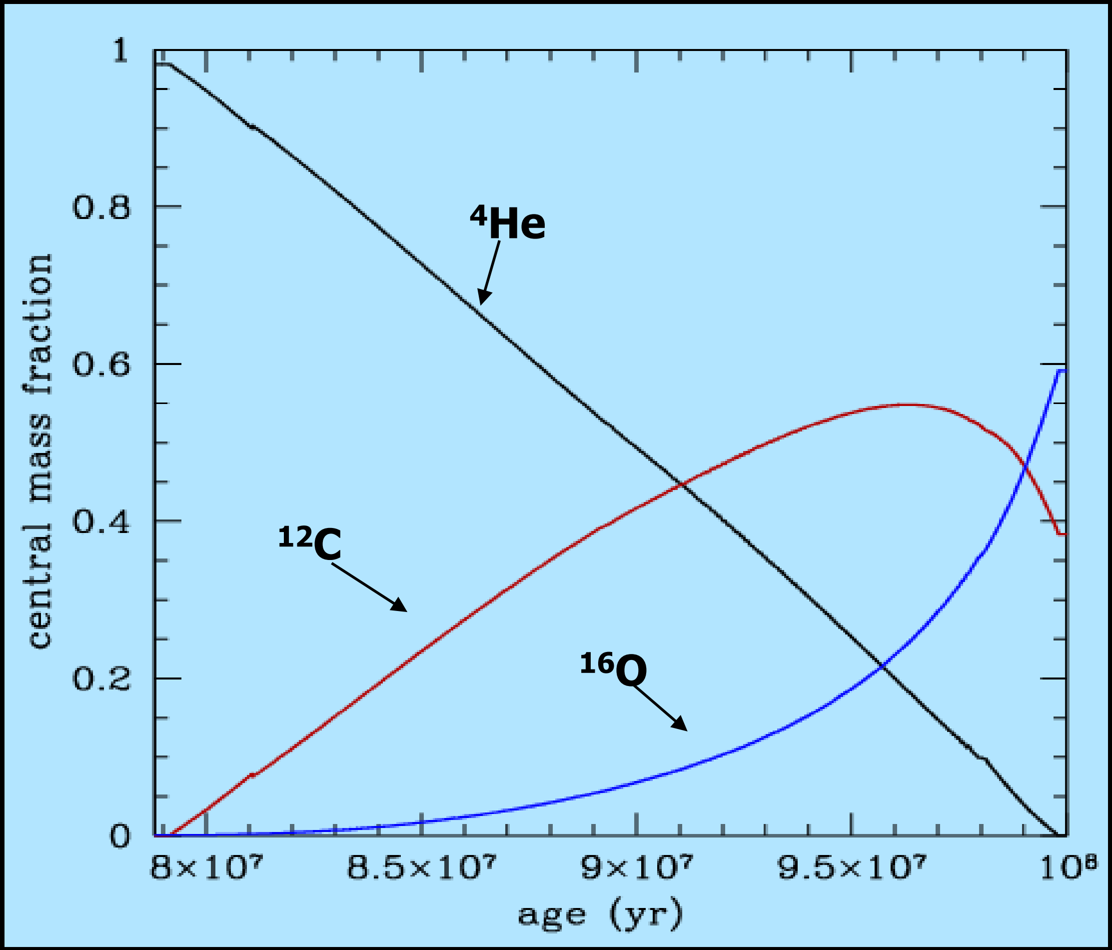
$^{25}Mg(p,\gamma)^{26}Al$





He-burning

$3\alpha \rightarrow {}^{12}C$ $\quad$ ${}^{12}C + \alpha \rightarrow {}^{16}O$



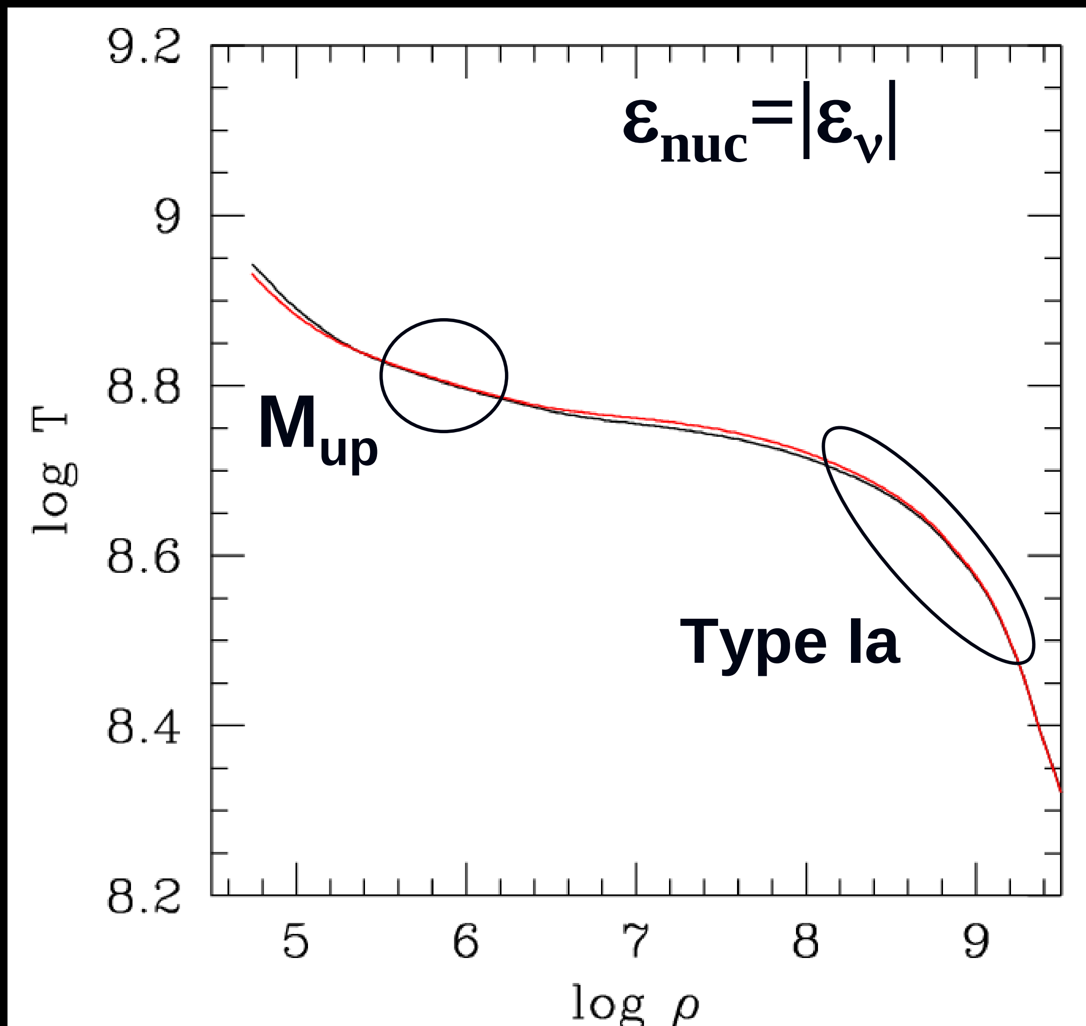
CORE HE-BURNING MODELS: $M = 3\ M_{\odot}$, $Z = 0.02$

Label (1)	f [a] (2)	τ_{He} [b] (3)	X_C [c] (4)	X_O [c] (5)	M_D [d] (6)
BSM	1	88	0.42	0.56	...
SM	1	145	0.19	0.79	0.31
PSM	1	134	0.40	0.58	0.27
HOM	1	153	0.42	0.56	0.32
LOM	1	139	0.38	0.60	0.28
SM	0.4	135	0.52	0.46	0.29
SM	1.6	149	0.08	0.90	0.31
HOM	0.4	142	0.66	0.32	0.31
HOM	1.6	157	0.28	0.70	0.32

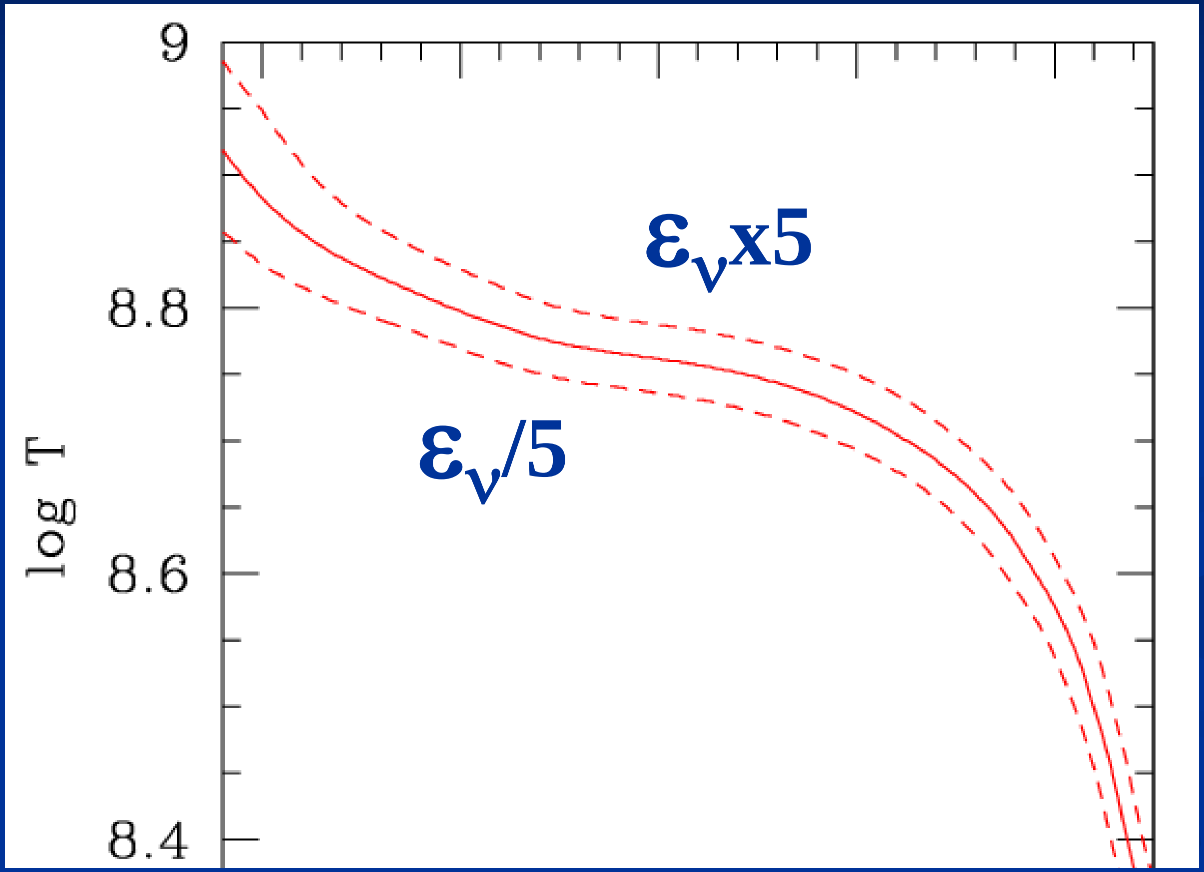
a) Enhancement factor of the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate. f = 1 corresponds to the Kunz et al. (2002) rate.
b) He-burning lifetime (Myr).
c) Final central mass fractions of C and O.
d) Location, in $M_{\odot}$, of the sharp discontinuity that marks the separation between the innermost low-C zone, corresponding to the maximum extension of the convective core, and the external layer built up by the shell-He burning occurred during the AGB phase.

C-burning, thermonuclear Sne & the mass limit for low-mass/massive stars

$^{12}C + ^{12}C \rightarrow ^{24}Mg^*$



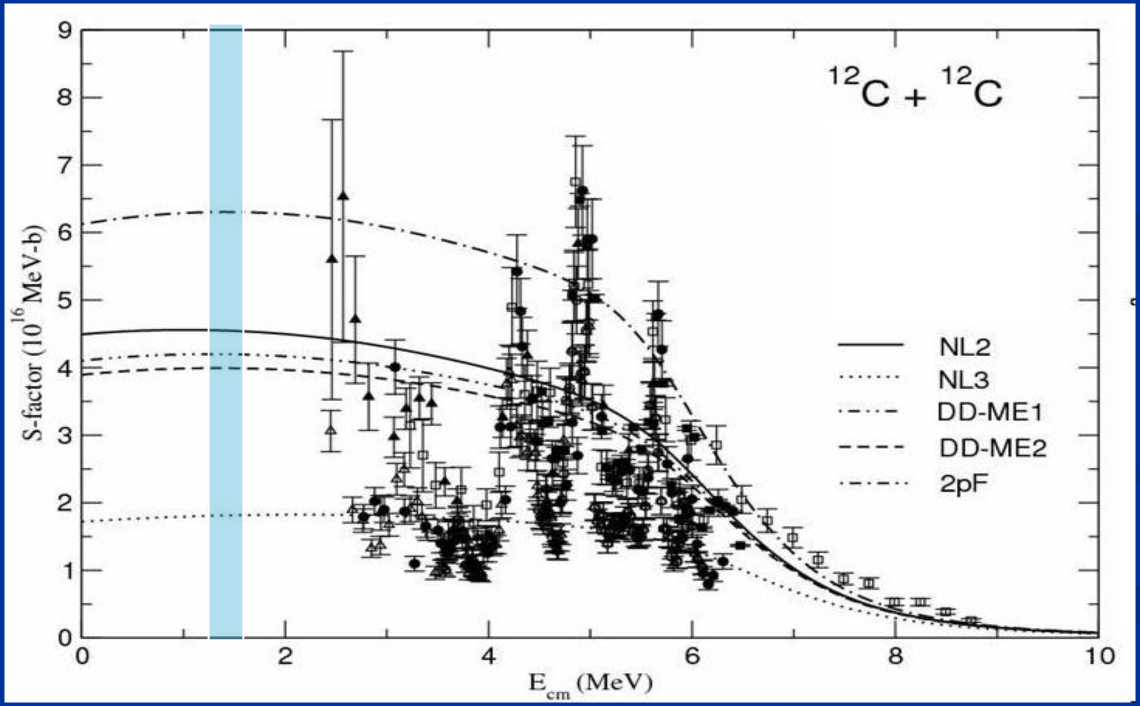
Varying ε_ν or $X(^{12}C)$



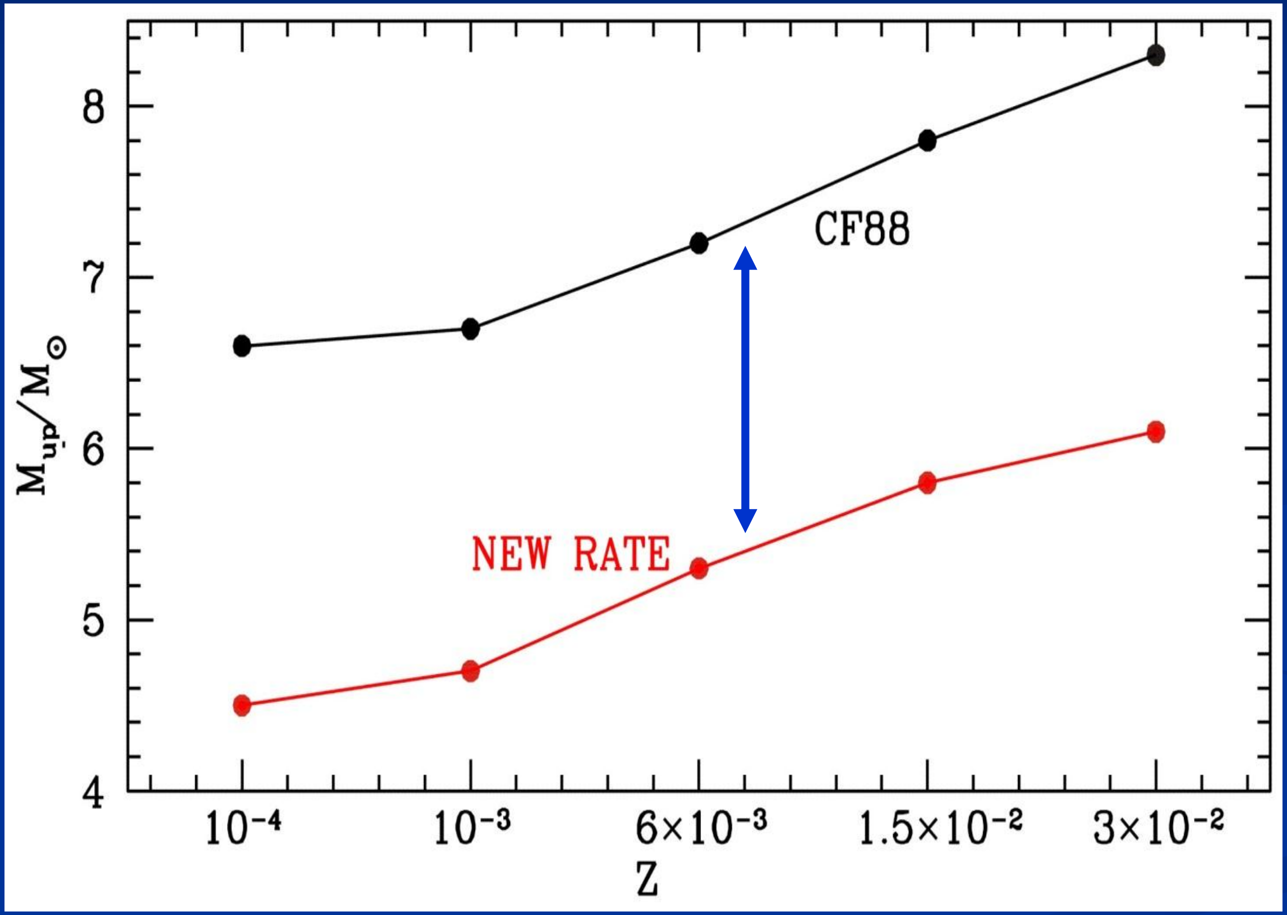
Equivalent to a variation of X(C) from 0.1 to 0.5, as implied by a ±60% variation of the $^{12}C+\alpha \rightarrow ^{16}O$ rate (Straniero et al. 2003).

Varying the $^{12}C+^{12}C$

A resonance near the Gamow peak (1.5 MeV) would significantly increase the rate, thus reducing the critical M_H and, in turn, M_{up} as well as M_{up}^*.

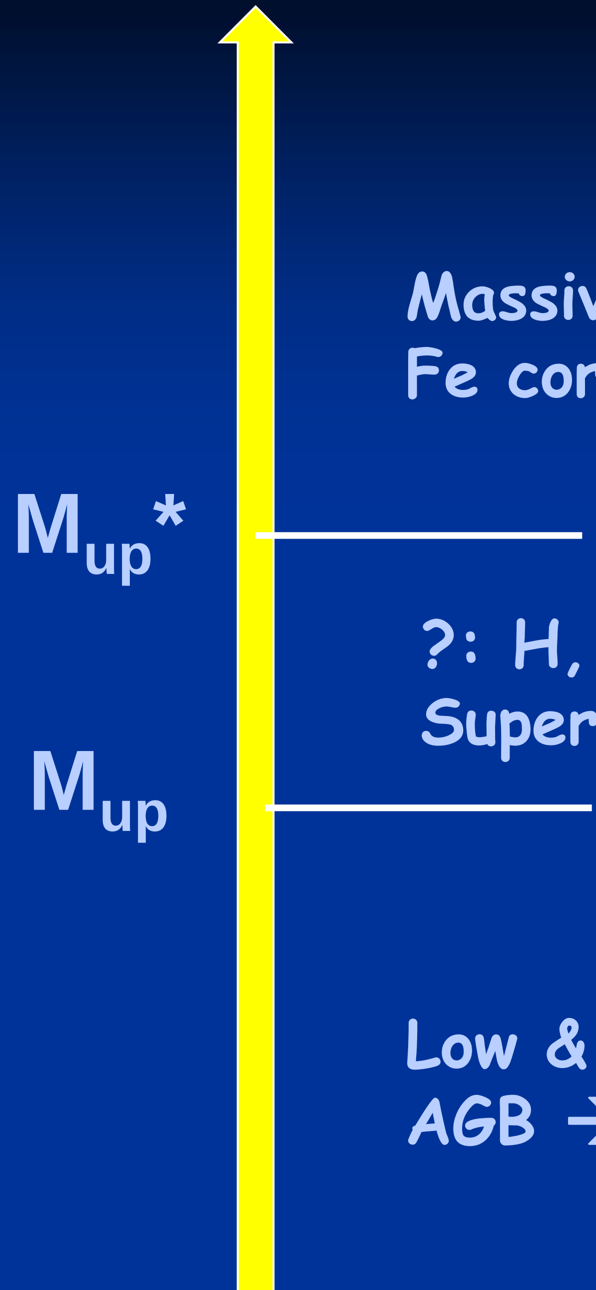


Varying the $^{12}C+^{12}C$



Z	CF88	VAR
0.0001	6.6	4.5
0.0010	6.7	4.7
0.0060	7.2	5.3
0.0149	7.8	5.8
0.0298	8.3	6.1

$\delta M_{up} \sim 2\ M_\odot$

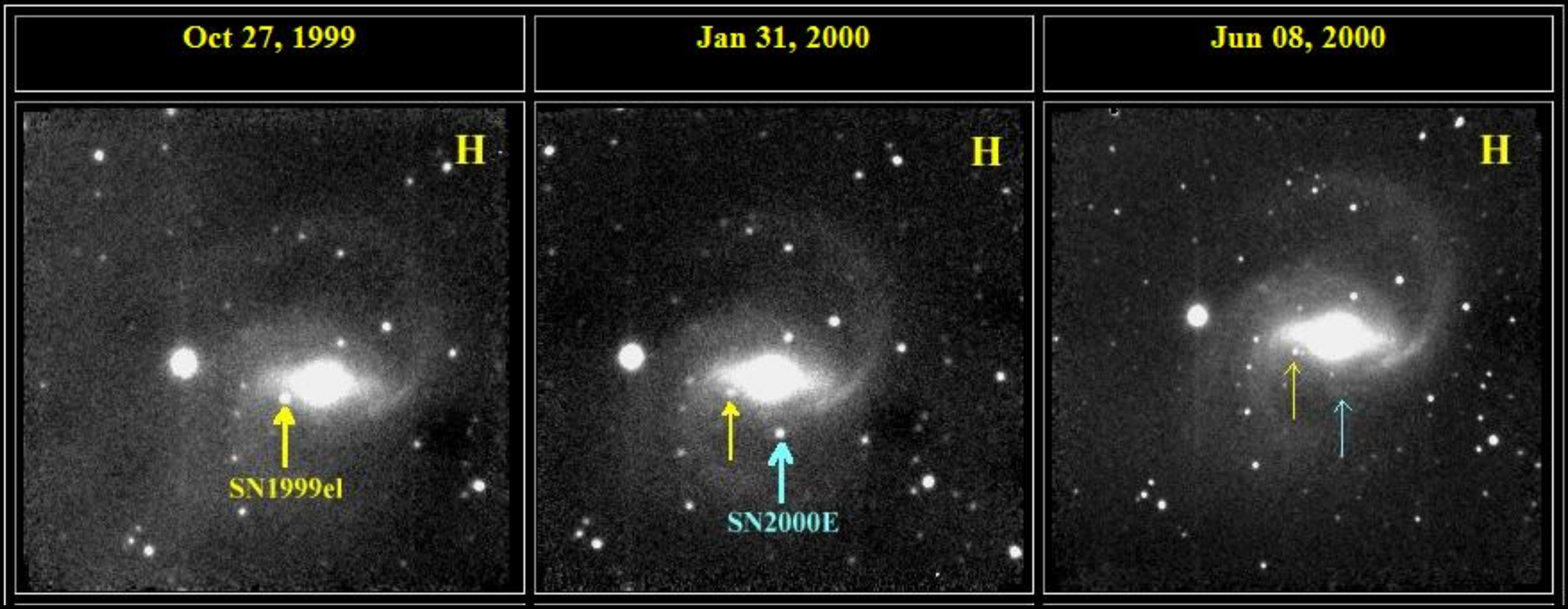


Massive stars: H, He, C, O, Ne, Si
Fe core → core collapse (SNE II,Ib,c)

?: H, He, C
Super AGB → O-Ne WD (SNE e-capture)

Low & intermediate mass: H, He,
AGB → C-O WD (SNE Ia)

LUNA MV - LNGS



SN1999el and SN2000E in NGC6951 as observed at the Campo Imperatore Observatory with the IR-camera@AZT24 telescope

Supernovae Ia

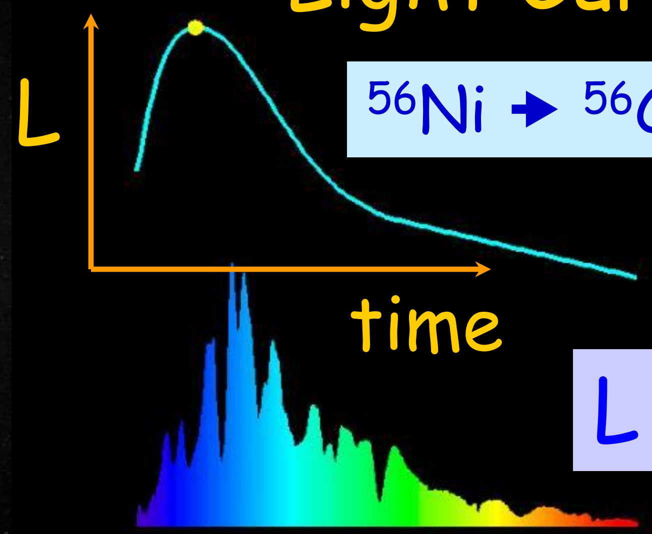
- Bright
- Homogeneous
- No evolutionary effects

Thermonuclear Explosion of a CO WD

$M \sim M_{Chandrasekhar}$

$(1.4\ M_{\odot})$

Light Curve



$^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$

$L \propto M_{Ni}$

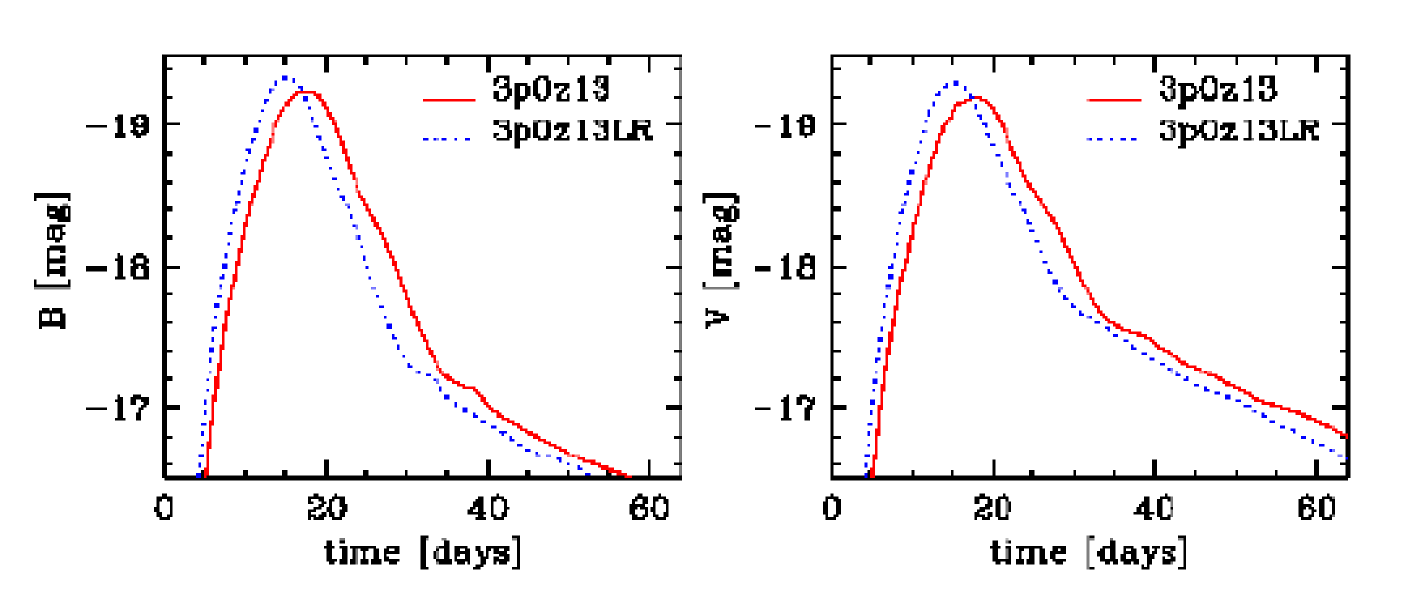
$^{12}C(\alpha,\gamma)^{16}O$ and the final mass of ^{56}Ni

TABLE 1

PROPERTIES OF THE MODELS

Initial Composition (1)	Model (2)	M_{MS} ($M_\odot$) (3)	M_{CO}^{TP} ($M_\odot$) (4)	C_{cen} (5)	M_{cen} ($M_\odot$) (6)	C/O_{Mch} (7)	^{56}Ni ($M_\odot$) (8)
$Z = 0.02$	1p5z22	1.5	0.55	0.21	0.27	0.75	0.589
$Y = 0.28$	3p0z22	3.0	0.57	0.21	0.28	0.76	0.584
	5p0z22	5.0	0.87	0.29	0.46	0.72	0.561
	7p0z22	7.0	0.99	0.28	0.70	0.60	0.516
$Z = 10^{-3}$	1p5z13	1.5	0.59	0.24	0.31	0.76	0.587
$Y = 0.23$	3p0z13	3.0	0.77	0.26	0.39	0.74	0.567
	5p0z13	5.0	0.90	0.29	0.58	0.66	0.541
	6p0z13	6.0	0.98	0.29	0.71	0.60	0.522
	Low Rate 3p0z13LR	3.0	0.76	0.51	0.38	1.22	0.620
$Z = 10^{-4}$	3p0z14	3.0	0.80	0.27	0.41	0.73	0.568
$Y = 0.23$	5p0z14	5.0	0.90	0.29	0.58	0.65	0.541
	6p0z14	6.0	0.99	0.28	0.72	0.59	0.511
$Z = 10^{-10}$	5p0z00	5.0	0.89	0.32	0.49	0.70	0.549
$Y = 0.23$	7p0z00	7.0	0.99	0.31	0.59	0.62	0.525

$\Delta M(^{56}Ni)=10\%$

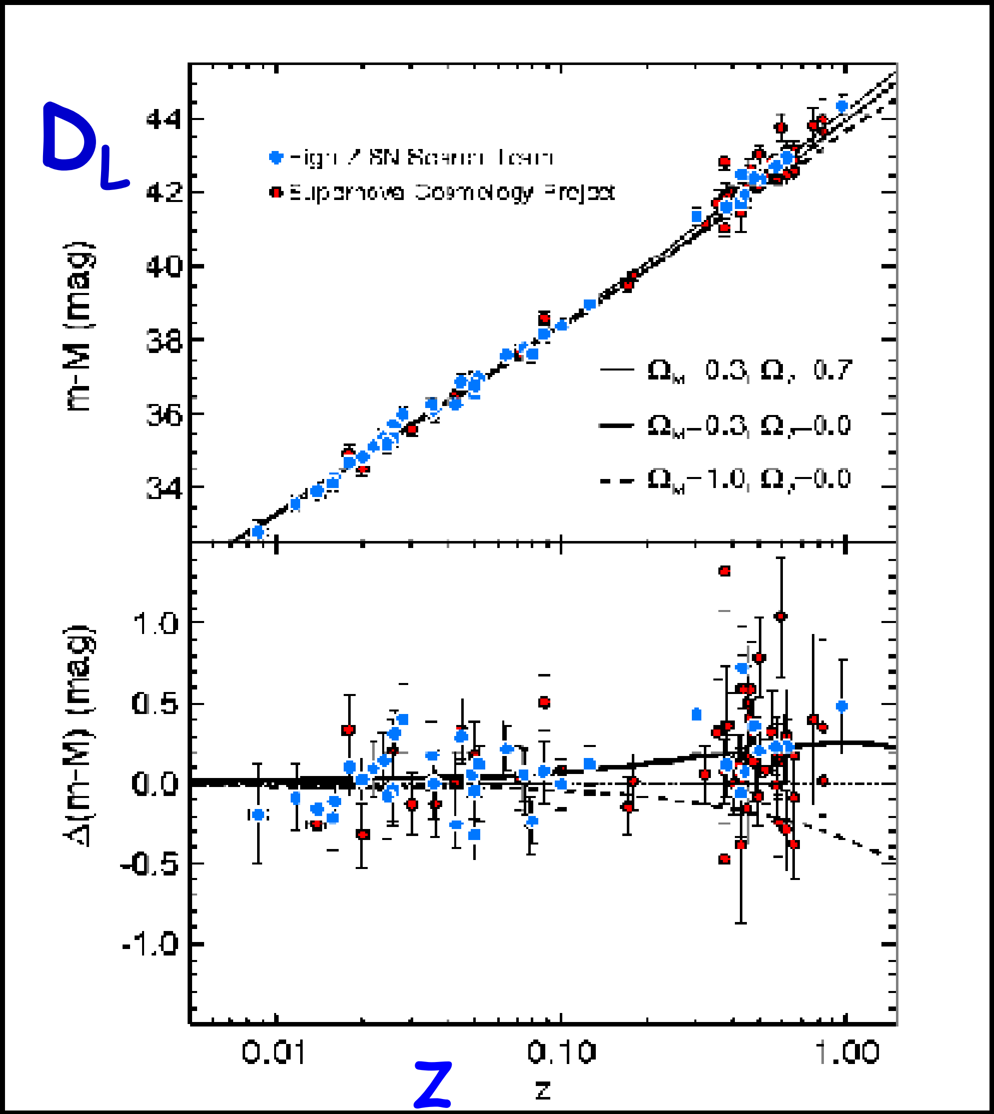


$^{12}C(\alpha,\gamma)^{16}O$	HIGH	LOW
M_V	-19.21	-19.30
Rise time	18.0 d	15.3 d

from
Dominguez, Hoflich, Straniero 2002

HIGH Rate C/O ↓

Observed: 18± 0.4 d



- **High-z Team**

  (Brian Schmidt & co)

- **Supernova Cosmology Project**

  (Saul Perlmutter & co.)

0.25 mag fainter than for an EMPTY Universe

Fainter → Further

The Universe is Accelerating

$$q_o = \frac{1}{2}\Omega_M - \Omega_\lambda$$

neutron sources and the synthesis of heavy elements

$^{13}C(\alpha,n)^{16}O$

$^{22}Ne(\alpha,n)^{25}Mg$

neutron captures (nTOF@CERN)