Massive stars

School on “The synthesis of the elements”

Granada (12-16 April 2010)

Alessandro Chieffi

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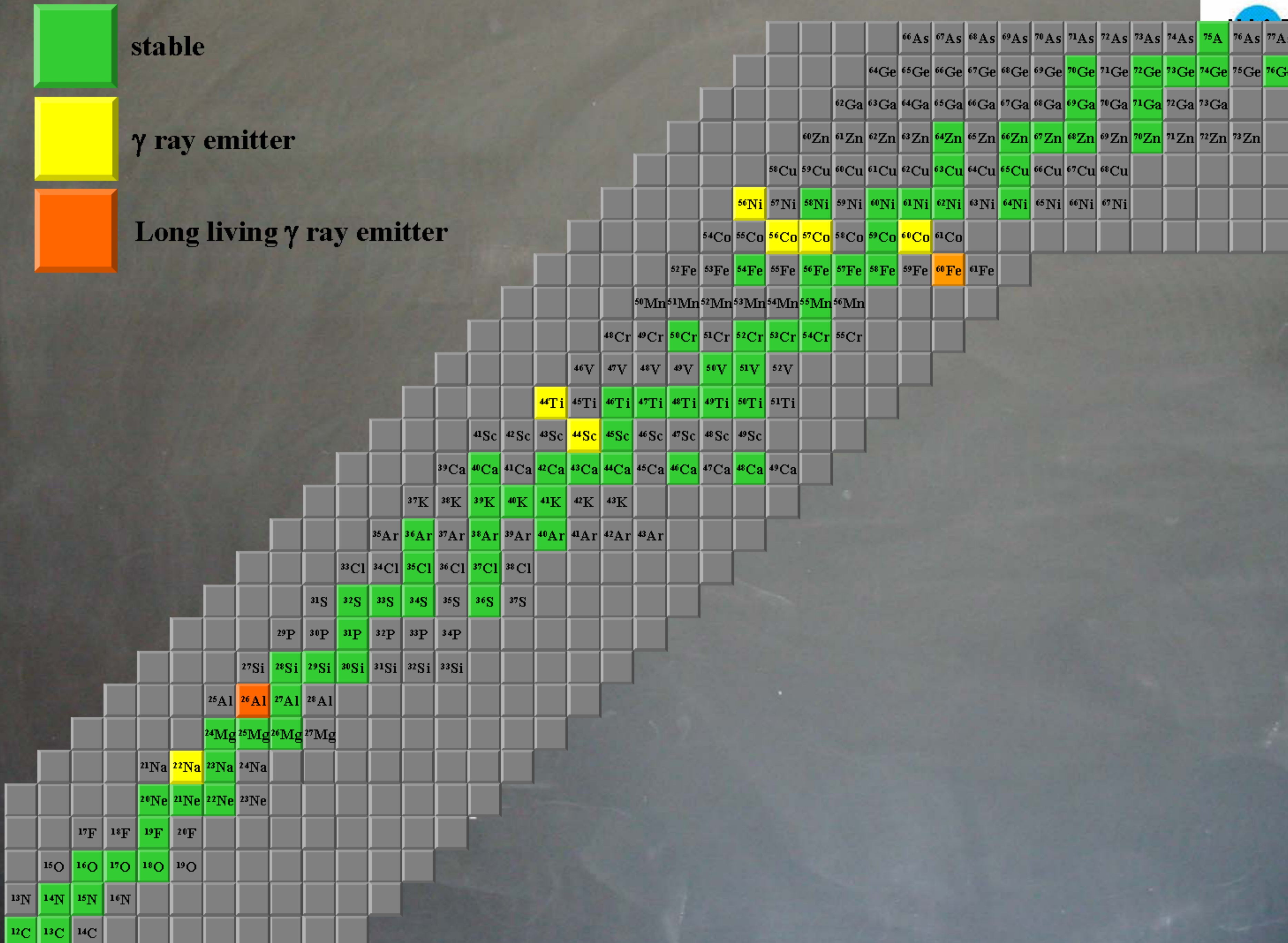
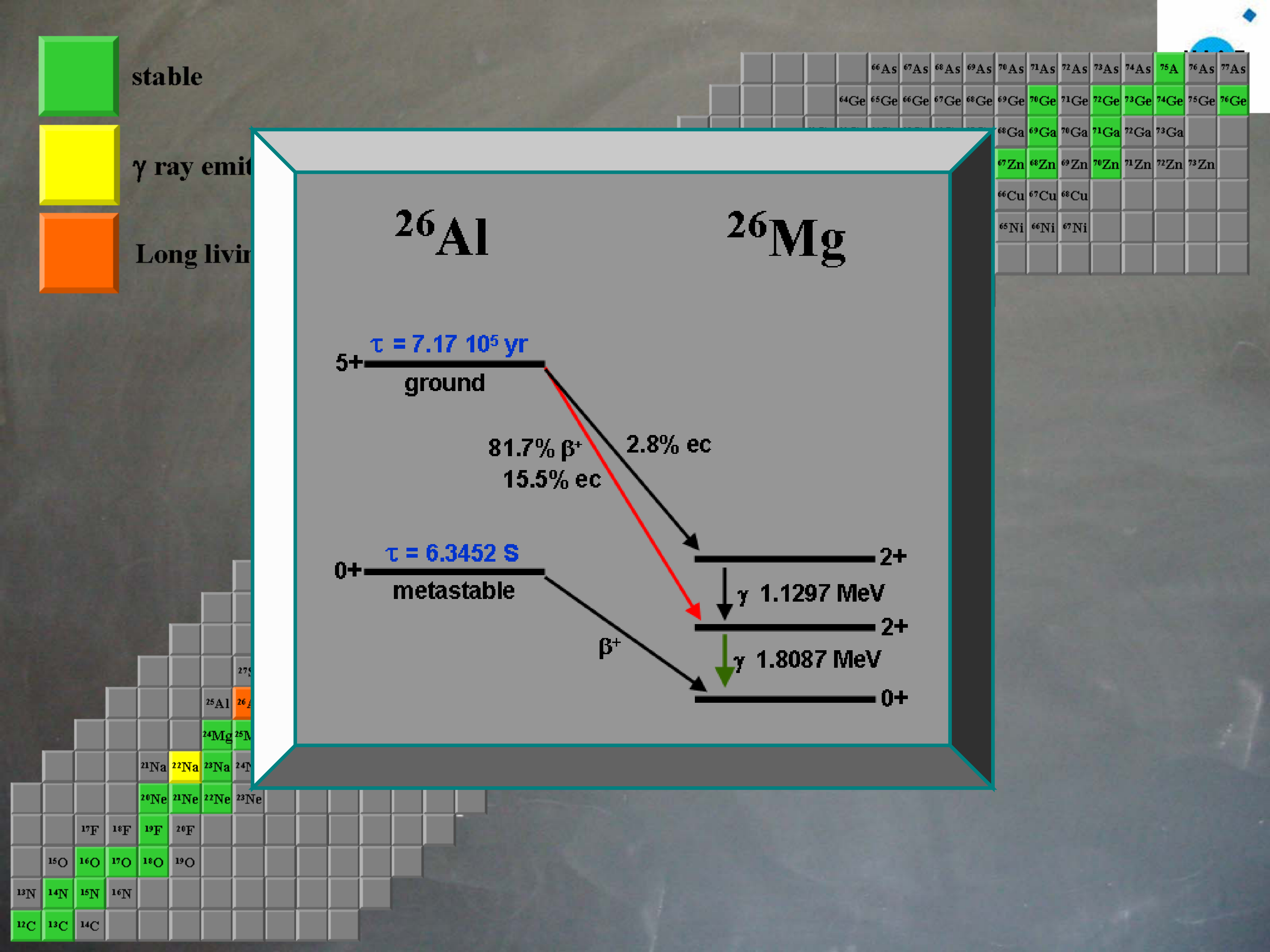
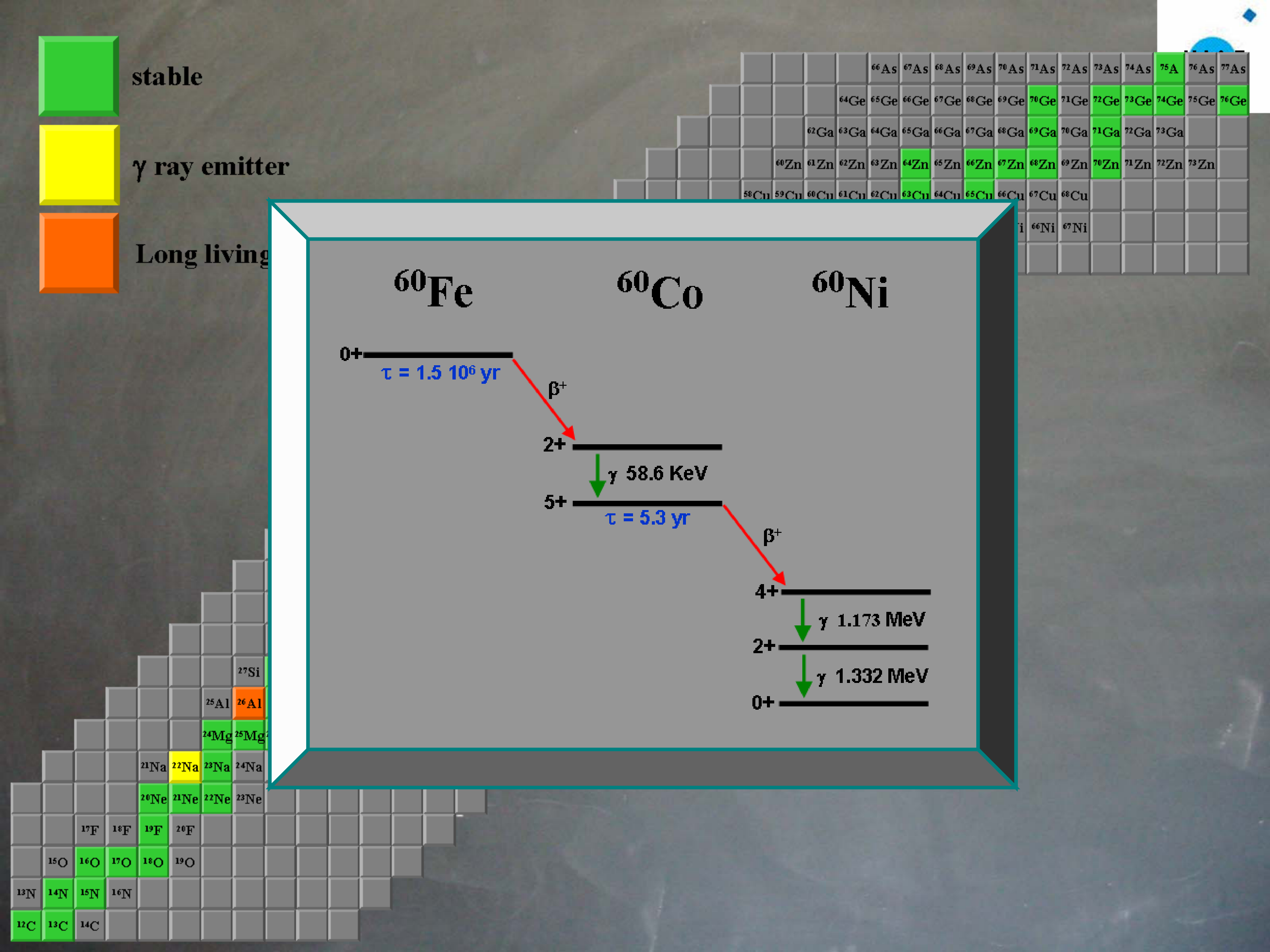
Part 5


stable
γ ray emitter
Long living γ ray emitter
66As 67As 68As 69As 70As 71As 72As 73As 74As 75A 76As 77As
64Ge 65Ge 66Ge 67Ge 68Ge 69Ge 70Ge 71Ge 72Ge 73Ge 74Ge 75Ge 76Ge
62Ga 63Ga 64Ga 65Ga 66Ga 67Ga 68Ga 69Ga 70Ga 71Ga 72Ga 73Ga
60Zn 61Zn 62Zn 63Zn 64Zn 65Zn 66Zn 67Zn 68Zn 69Zn 70Zn 71Zn 72Zn 73Zn
58Cu 59Cu 60Cu 61Cu 62Cu 63Cu 64Cu 65Cu 66Cu 67Cu 68Cu
56Ni 57Ni 58Ni 59Ni 60Ni 61Ni 62Ni 63Ni 64Ni 65Ni 66Ni 67Ni
54Co 55Co 56Co 57Co 58Co 59Co 60Co 61Co
52Fe 53Fe 54Fe 55Fe 56Fe 57Fe 58Fe 59Fe 60Fe 61Fe
50Mn 51Mn 52Mn 53Mn 54Mn 55Mn 56Mn
48Cr 49Cr 50Cr 51Cr 52Cr 53Cr 54Cr 55Cr
46V 47V 48V 49V 50V 51V 52V
44Ti 45Ti 46Ti 47Ti 48Ti 49Ti 50Ti 51Ti
41Sc 42Sc 43Sc 44Sc 45Sc 46Sc 47Sc 48Sc 49Sc
39Ca 40Ca 41Ca 42Ca 43Ca 44Ca 45Ca 46Ca 47Ca 48Ca 49Ca
37K 38K 39K 40K 41K 42K 43K
35Ar 36Ar 37Ar 38Ar 39Ar 40Ar 41Ar 42Ar 43Ar
33Cl 34Cl 35Cl 36Cl 37Cl 38Cl
31S 32S 33S 34S 35S 36S 37S
29P 30P 31P 32P 33P 34P
27Si 28Si 29Si 30Si 31Si 32Si 33Si
25Al 26Al 27Al 28Al
24Mg 25Mg 26Mg 27Mg
21Na 22Na 23Na 24Na
20Ne 21Ne 22Ne 23Ne
17F 18F 19F 20F
15O 16O 17O 18O 19O
13N 14N 15N 16N
12C 13C 14C

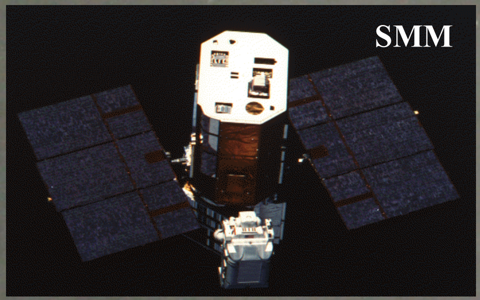


stable
γ ray emit
Long livin
26Al
26Mg
τ = 7.17 10^5 yr
5+
ground
81.7% β+
15.5% ec
2.8% ec
τ = 6.3452 S
0+
metastable
β+
2+
γ 1.1297 MeV
2+
γ 1.8087 MeV
0+


stable
γ ray emitter
Long living
60Fe
60Co
60Ni
0+
τ = 1.5 10⁶ yr
β+
2+
γ 58.6 KeV
5+
τ = 5.3 yr
β+
4+
γ 1.173 MeV
2+
γ 1.332 MeV
0+

Between 1979 and 2001 several experiments were carried out:

HEAO3



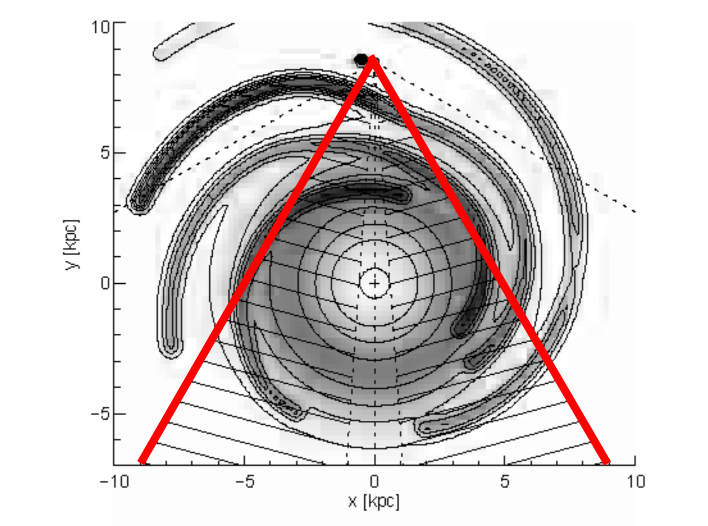


Fig. 1. Model of the free electron density in the galactic plane (Taylor & Cordes 1993), used as ^{26}Al source density distribution. Dotted lines represent −60°, −30°, −4°, 0°, 4°, 30° and 60° galactic longitude. Hatched areas illustrate the eastern/western parts of the inner galactic region.

Kretschmer et al. AA 412,47 (2003)

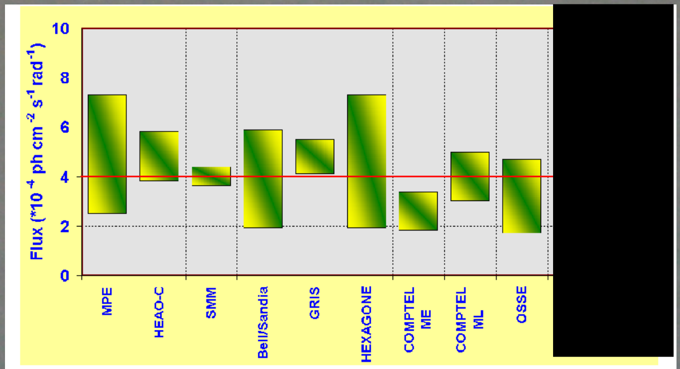
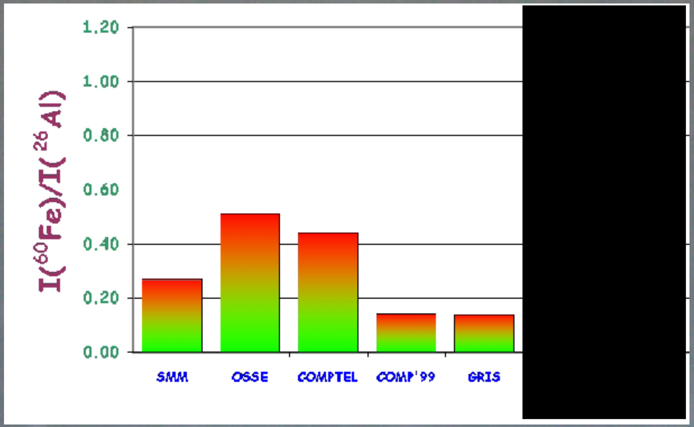


FIGURE 5: Comparison of the line fluxes for integrated ^{26}Al emission from the inner Galaxy, normalized for the central radian.

R. DIEHL Clemson 2005 Astronomy with Radioactivities V



On the basis of just the integrated flux towards the galactic center, it is not possible to choose among the various possible ^{26}Al sources:

Type II Supernovae $10<M<30$

WR stars $30<M<120$

Confined in the spiral arms of our Galaxy

Novae

Intermediate mass stars $1\text{-}3<M<7$

Confined within the disk of our Galaxy

THE ASTROPHYSICAL JOURNAL, **294**:591–598, 1985 July 15

ANGULAR DISTRIBUTION OF INTERSTELLAR ^{26}Al

MARK D. LEISING AND DONALD D. CLAYTON
Department of Space Physics and Astronomy, Rice University
Received 1984 October 26; accepted 1985 January 29

ABSTRACT

Although the detection by *HEAO 3* of ^{26}Al in the interstellar medium has profound consequences for nucleosynthesis, the origins of the ^{26}Al cannot be determined without information on its angular distribution.

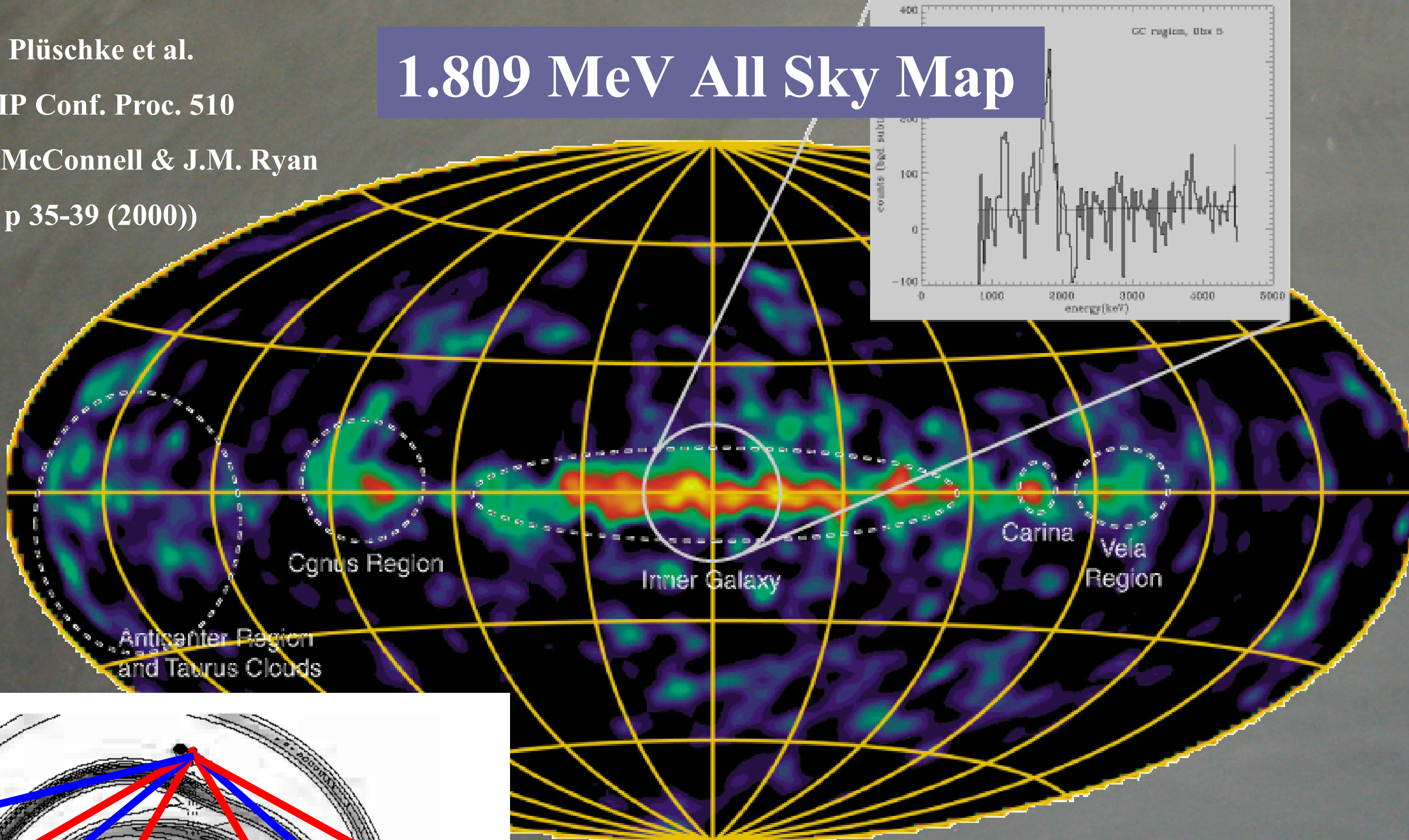
Plüschke et al.

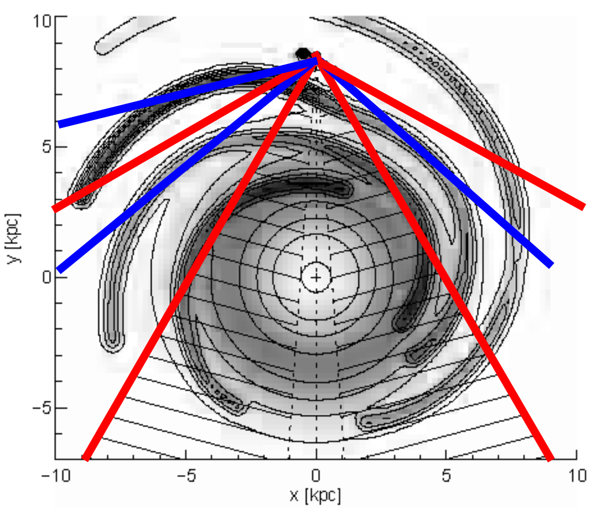
AIP Conf. Proc. 510

ed. M.L. McConnell & J.M. Ryan

p 35-39 (2000))

1.809 MeV All Sky Map





Kretschmer et al. AA 412,47 (2003)

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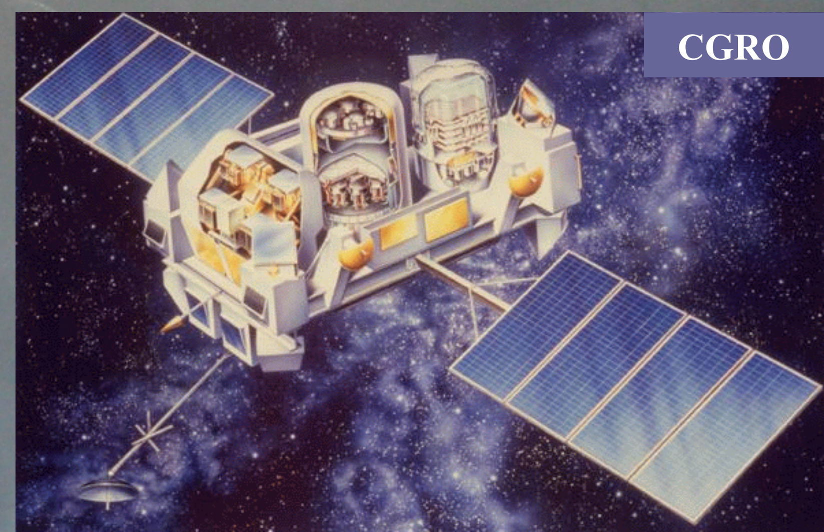


Astron. Astrophys. 344, 68–82 (1999)

ASTRONOMY AND ASTROPHYSICS

A multiwavelength comparison of COMPTEL 1.8 MeV ^{26}Al line data

J. Knödlseder[1], K. Bennett[5], H. Bloemen[3], R. Diehl[2], W. Hermsen[3], U. Oberlack[6], J. Ryan[4], V. Schönfelder[2], and P. von Ballmoos[1]

[1] Centre d'Etude Spatiale des Rayonnements, CNRS/UPS, B.P. 4346, F-31028 Toulouse Cedex 4, France
[2] Max-Planck-Institut für Extraterrestrische Physik, Postfach 1603, D-85740 Garching, Germany
[3] SRON-Utrecht, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands
[4] Space Science Center, University of New Hampshire, Durham, NH 03824, USA
[5] Astrophysics Division, ESTEC, ESA, 2200 AG Noordwijk, The Netherlands
[6] Astrophysics Laboratory, Columbia University, New York, NY 10027, USA

Received 7 July 1998 / Accepted 23 December 1998

The 53 GhZ free-free all-sky map marks the regions of ionized matter.

A strong ionizing flux (l<912 A) is necessary to mantain matter ionized

(otherwise it would recombine in 1 Myr)

Only stars more massive than, say, 15 M_O do produce a strong ionizing flux

hence

The correlation between the 53 GhZ free-free and the 1.809 MeV maps implies that they share the same spatial distribution amd therefore that ^{26}Al and ionizing photons are produced by the same stars

i.e. ^{26}Al mainly produced by stars more massive than 15 M_O

Knodelseder (1999 - ApJ 510, 915) found also that the scaling between the two fluxes is <u>CONSTANT</u> towards all longitudes and equal to:

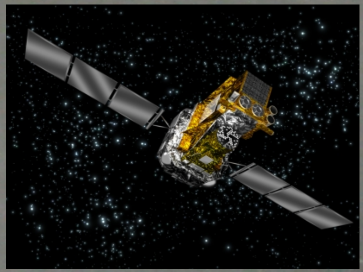
$Y_{26Al} = 10^{-4}$ M_O per O7 V ($\mathrm{Log}(Q_o)=49.05$)

$R_{GxL} = 1.25\ 10^{-11}$ $g_{1.8MeV}$ / $g_{<912A}$

RHESSI and INTEGRAL launched in 2002

Reuven Ramaty High Energy Solar Spectroscopic Imager

INTErnational Gamma-Ray Astrophysics Laboratory



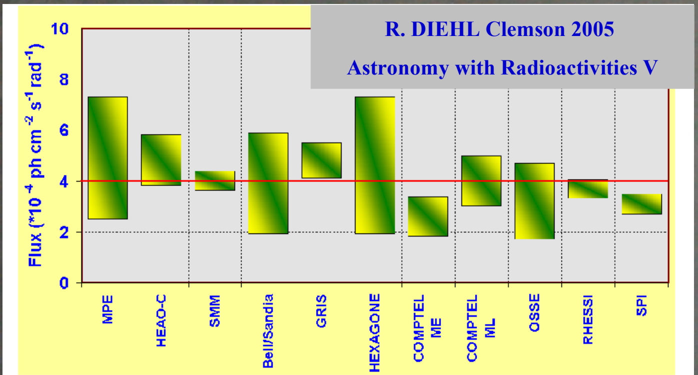
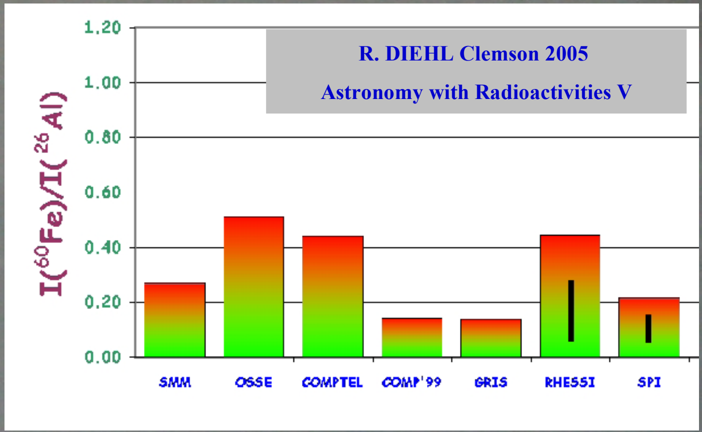


FIGURE 5: Comparison of the line fluxes for integrated ^{26}Al emission from the inner Galaxy, normalized for the central radian.

^{60}Fe/^{26}Al

RHESSI	0.17± 0.05
INTEGRAL	0.11± 0.03



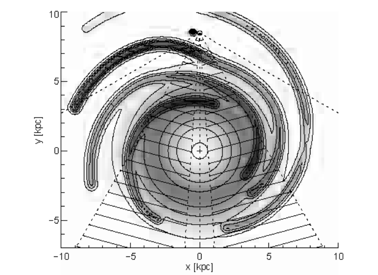
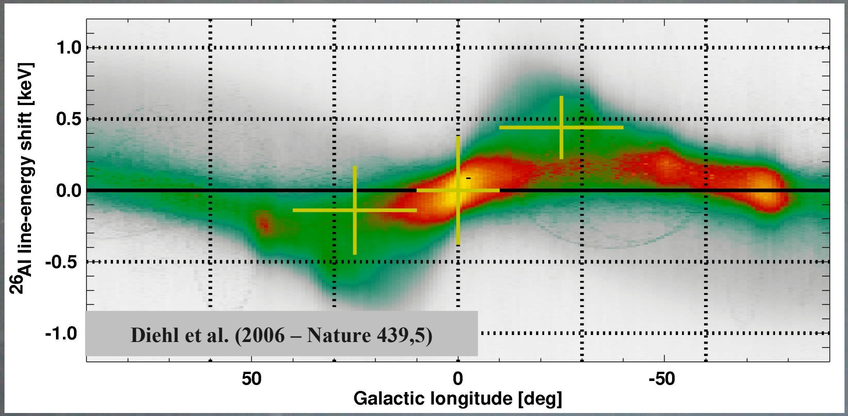


Fig. 1. Model of the free electron density in the galactic plane (Taylor & Cordes 1993), used as ^{26}Al source density distribution. Dotted lines represent −60°, −30°, −4°, 0°, 4°, 30° and 60° galactic longitude. Hatched areas illustrate the eastern/western parts of the inner galactic region.



Summary of the observational facts:

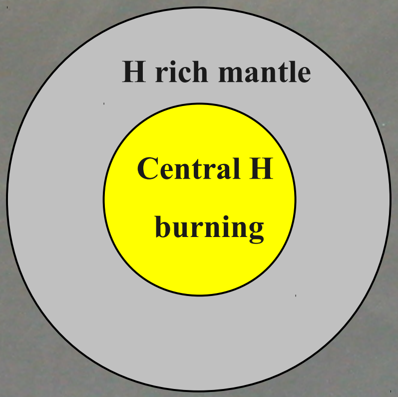
1) ^{26}Al is very probably produced by stars having M>15 M_O

2) There are roughly 1.25 10^{-11} $\gamma_{1.8MeV}$ per ionizing photon at all longitudes

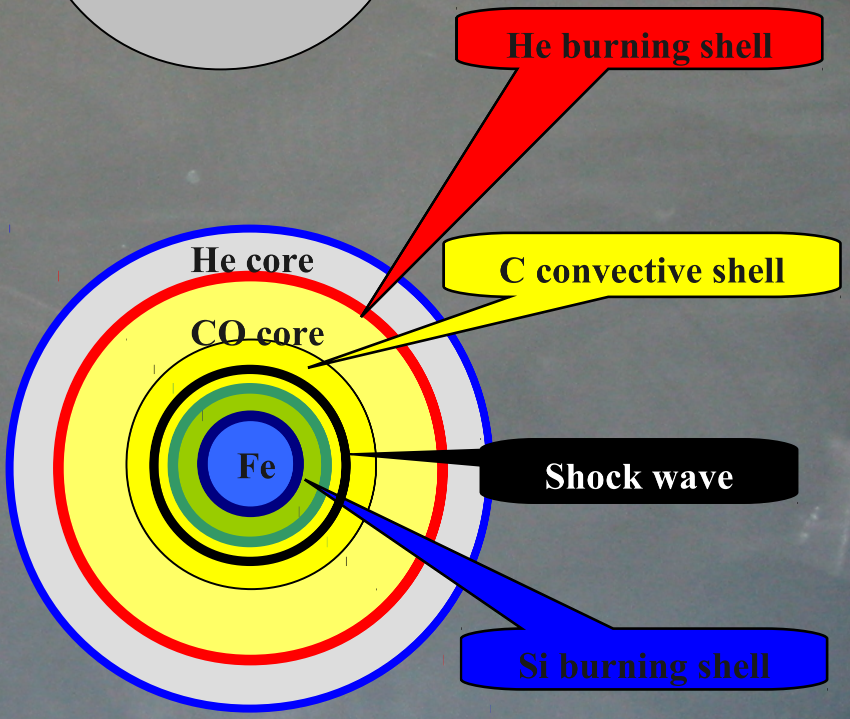
3) The ^{60}Fe/^{26}Al flux ratio is of the order of 0.14 ± 0.05 towards the Galactic center

4) Roughly 2.8 M_O of ^{26}Al are present in the Galaxy (± 30%)

^{26}Al production:



1) H convective core

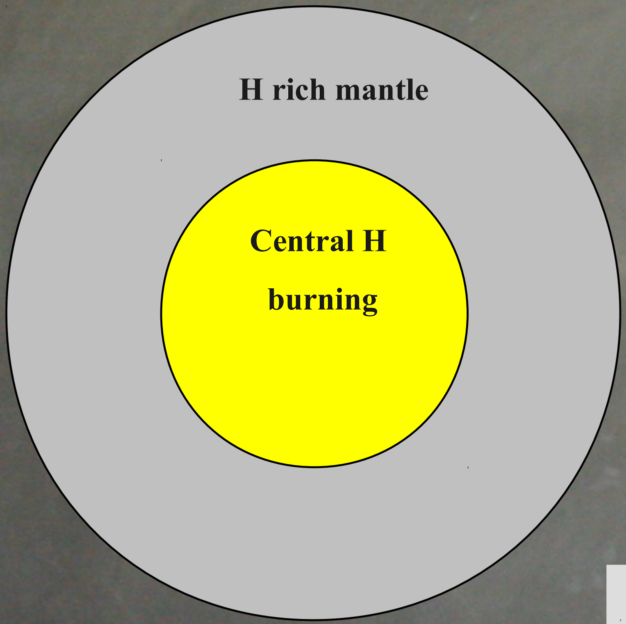


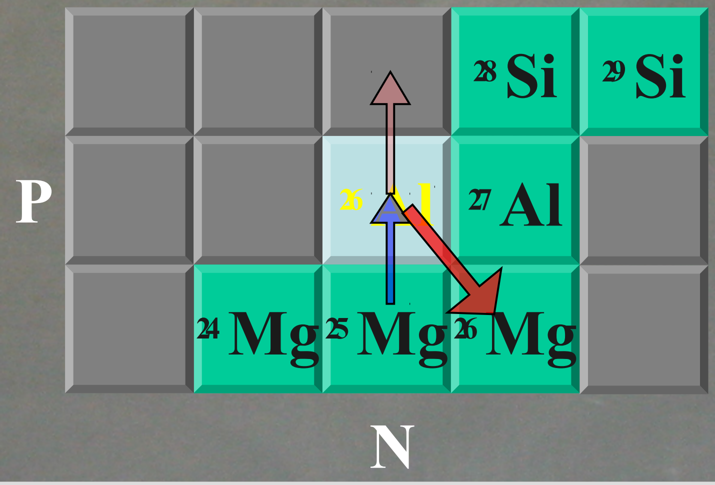
2) C (Ne/C) conv. shell

(when the star is in shell Si burning)

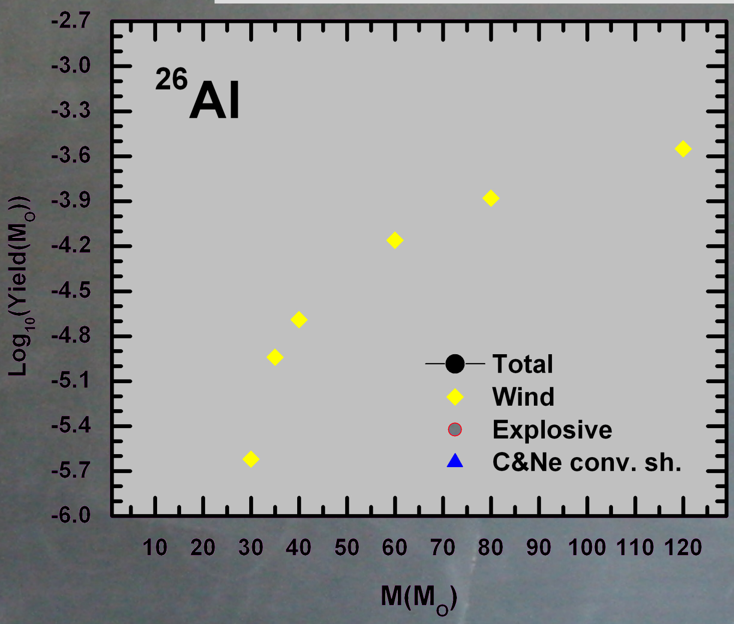
3) Explosive Ne burning

^{26}Al production in central H burning

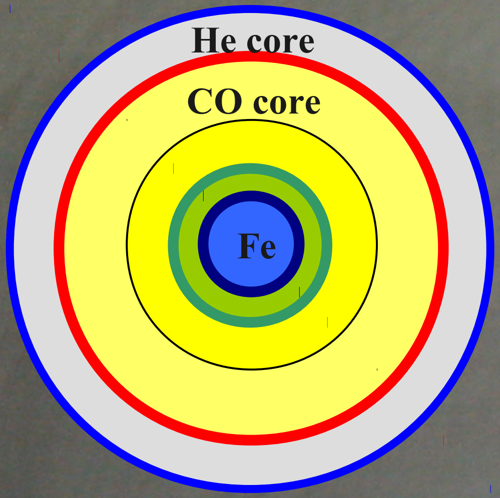


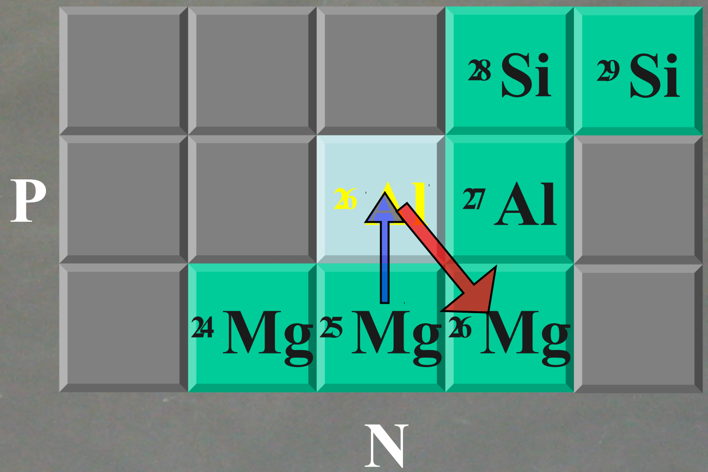


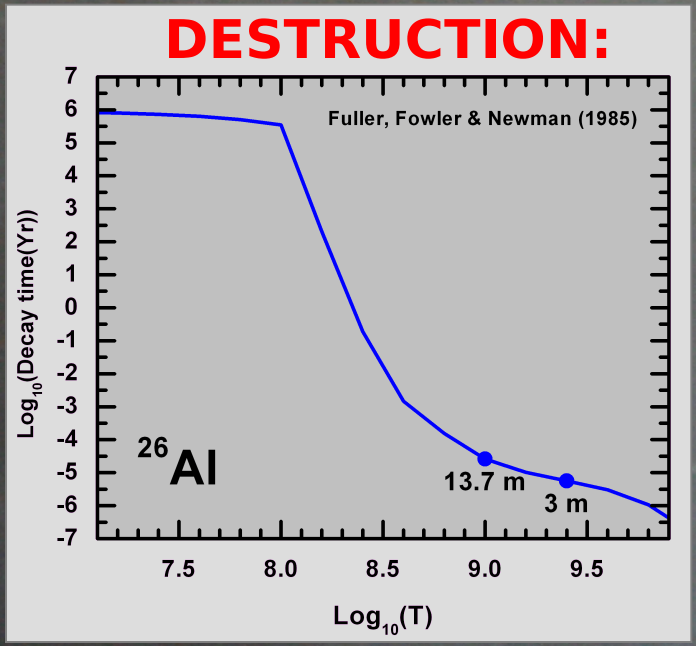
The ^{25}Mg is the initial one (usually scaled solar)

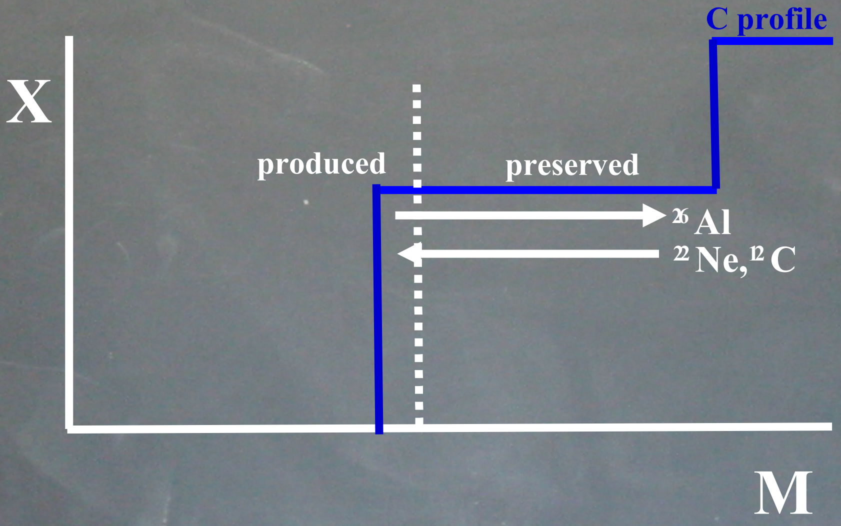


^{26}Al production in the C (Ne/C) convective shell

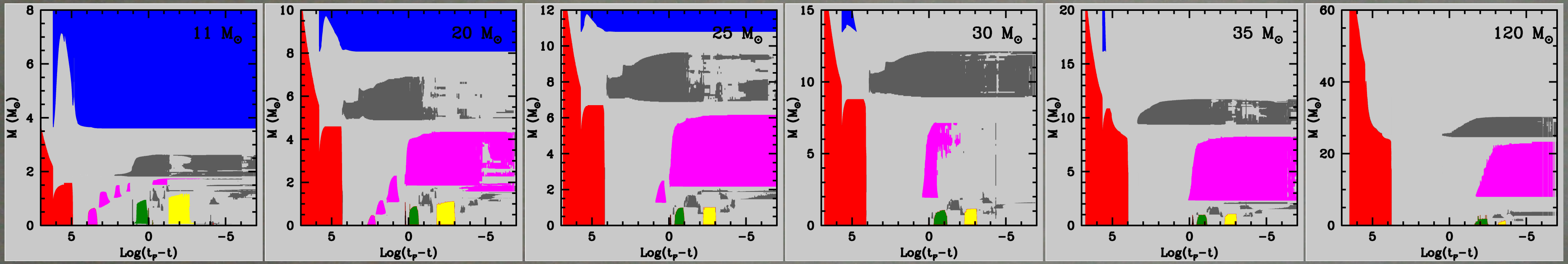


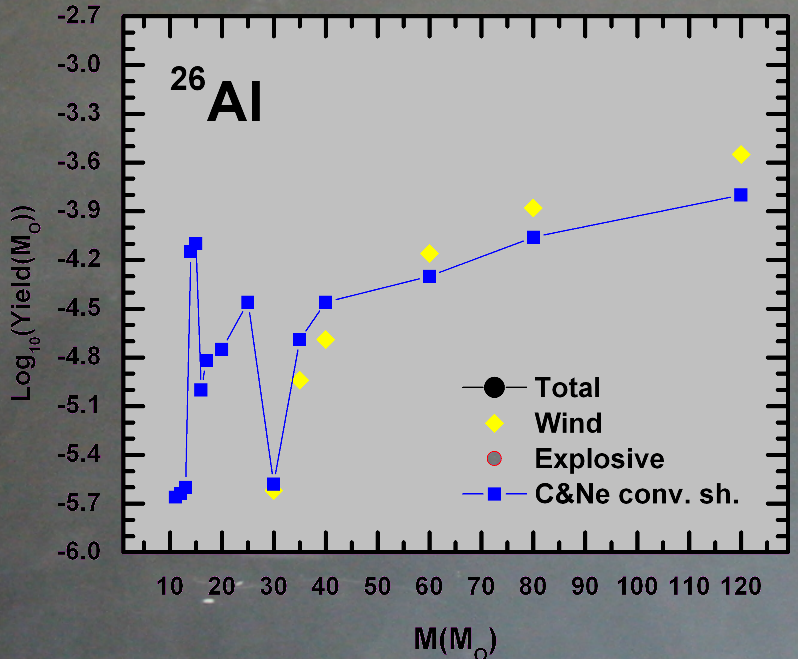






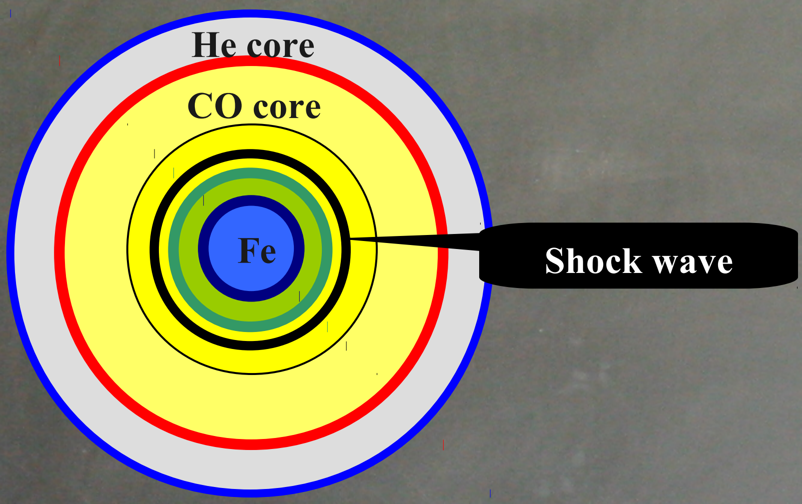
^{26}Al production in C (Ne/C) convective shell

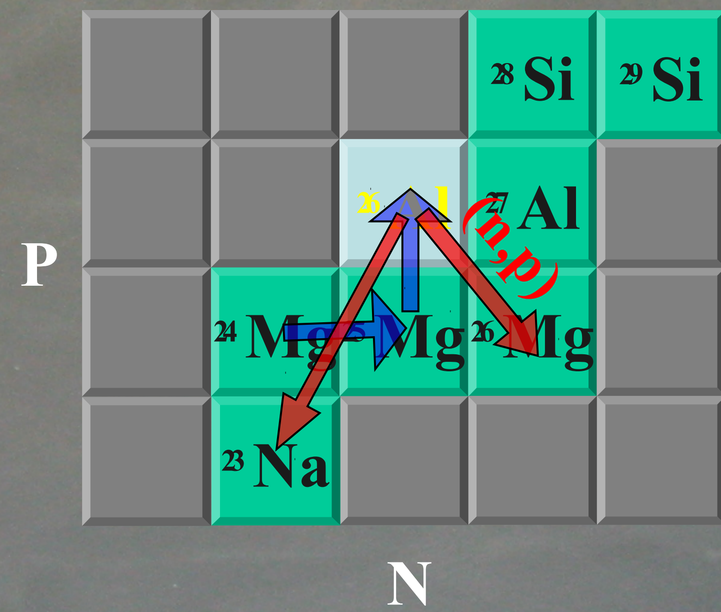


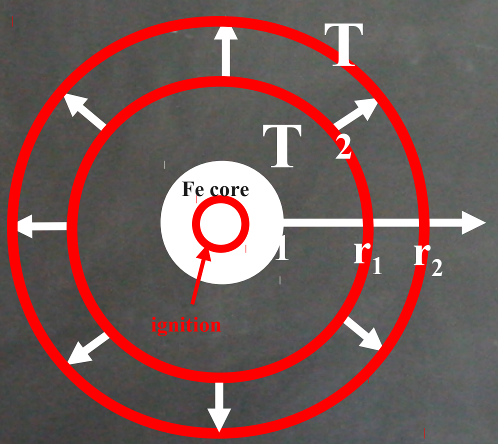


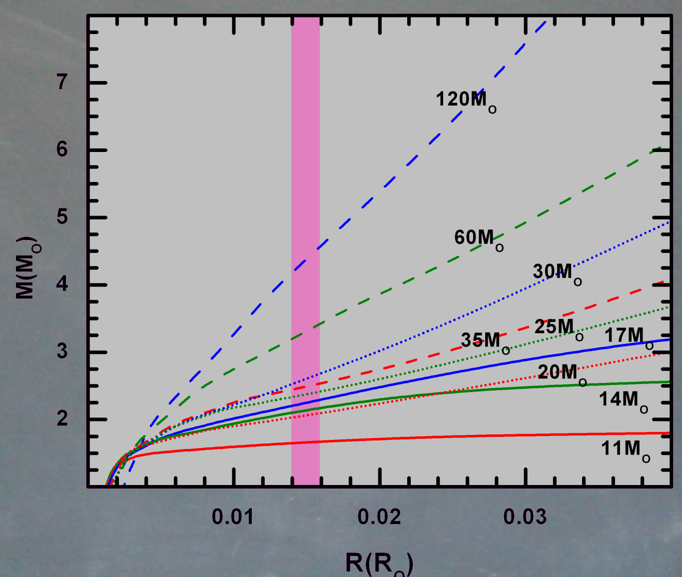
^{26}Al production by the explosive Ne burning

The synthesis of ^{26}Al occurs in the region where the peak temperature drops to $T_{peak} \approx 2.2\ 10^9$ K

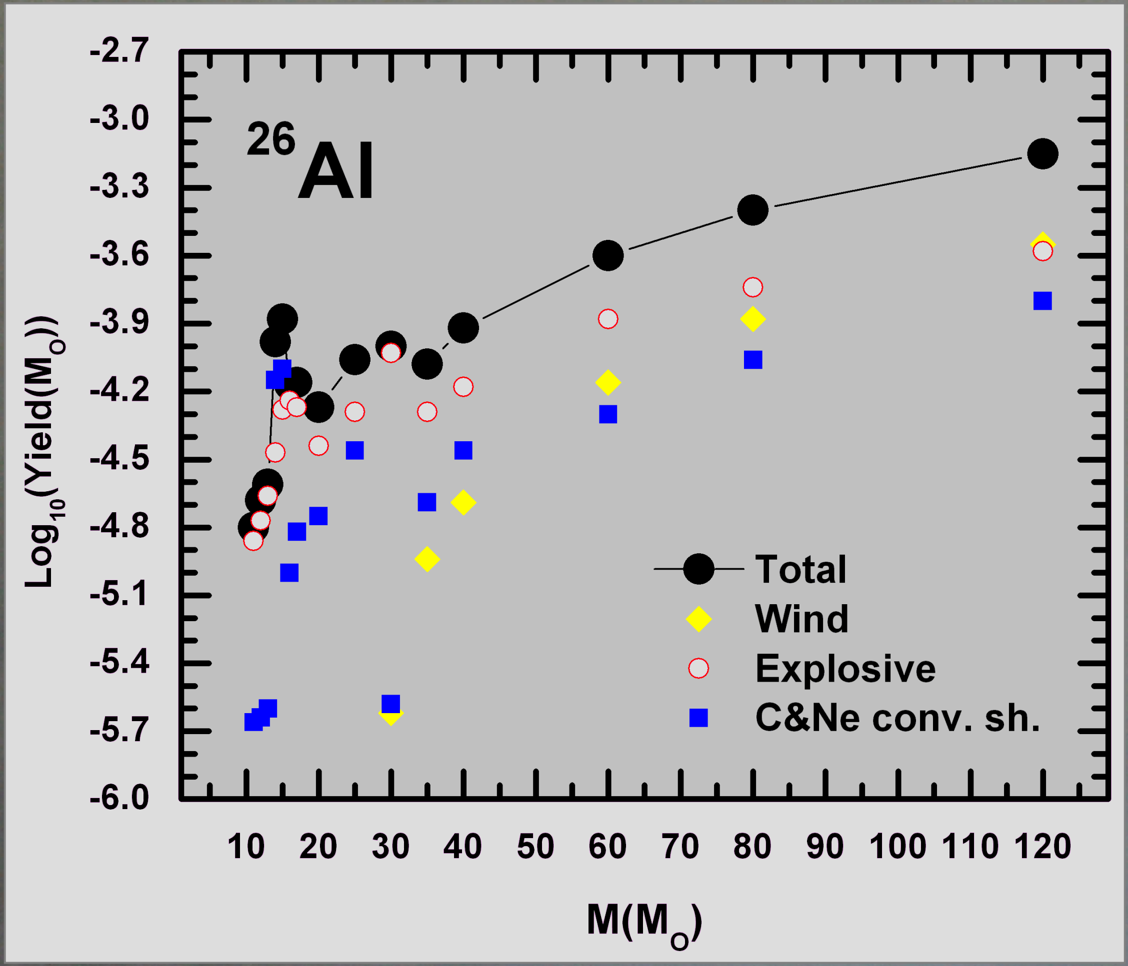




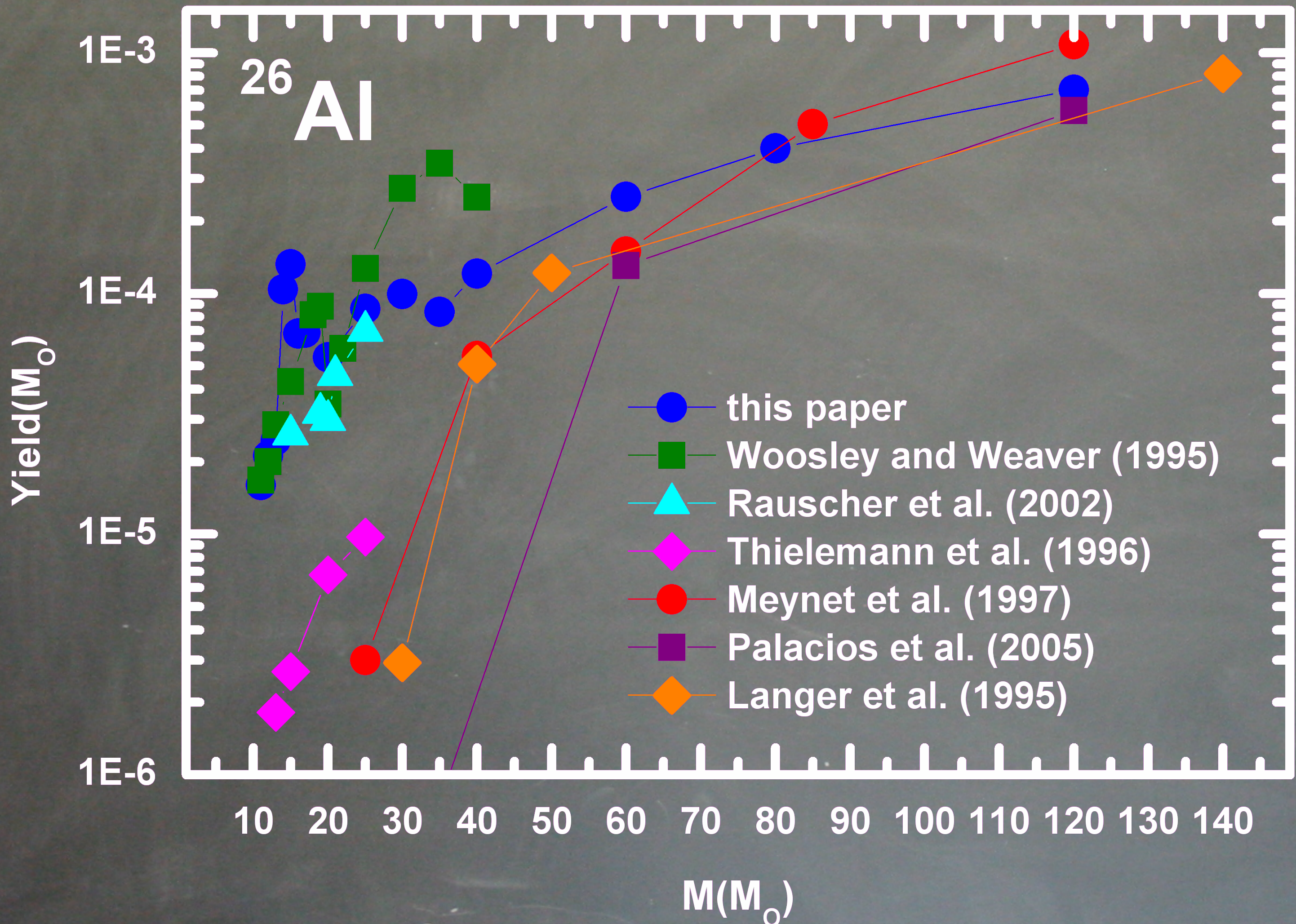




Total ^{26}Al yield as a function of the initial mass



H-burn	C(C/Ne) shell	Explosive Ne burn.
Semi secondary origin	Semi secondary origin	Primary origin



26Al
1E-3
1E-4
1E-5
1E-6
Yield(Mo)
this paper
Woosley and Weaver (1995)
Rauscher et al. (2002)
Thielemann et al. (1996)
Meynet et al. (1997)
Palacios et al. (2005)
Langer et al. (1995)
10 20 30 40 50 60 70 80 90 100 110 120 130 140
M(Mo)

Summary of the observational facts:

1) ^{26}Al is very probably produced by stars having $M>15\ M_{O}$

2) There are roughly $1.25\ 10^{-11}$ $\gamma_{1.8MeV}$ per ionizing photon at all longitudes

3) The $^{60}Fe/^{26}Al$ flux ratio is of the order of 0.14 ± 0.05 towards the Galactic center

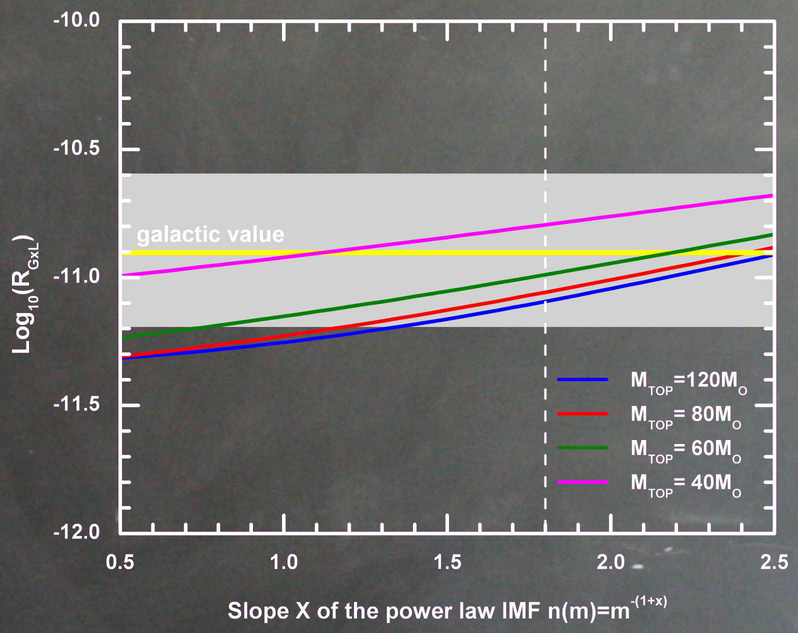
4) Roughly 2.8 M_{O} of ^{26}Al are present in the Galaxy ($\pm$ 30%)

By adopting:

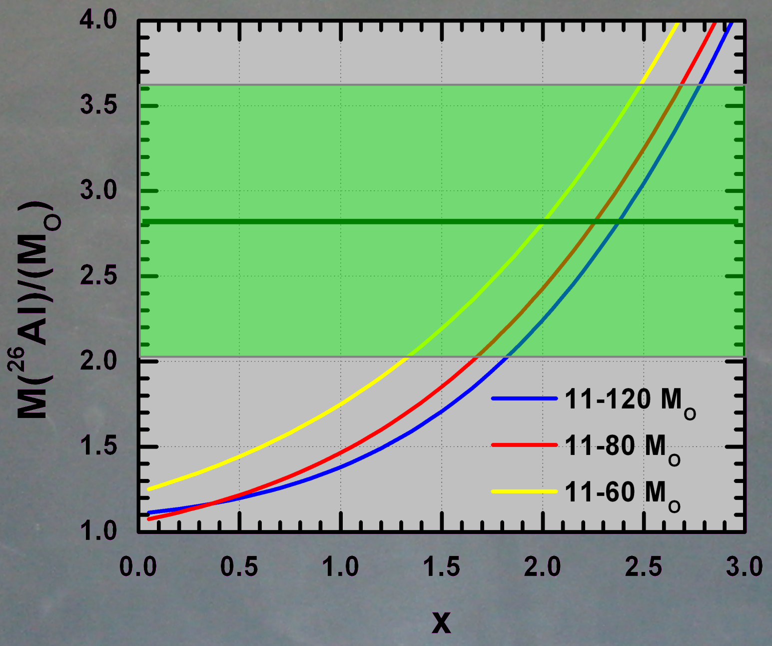
$M_{up'} = 11M_{O}$ - $M_{top} = 120M_{O}$

a Galactic Lyman continuum Luminosity $Q_{GAL} = 3.5\ 10^{53}$ photons/s

The galactic R_{GxL}



The galactic ^{26}Al



The galactic ^{26}Al

By adopting:

m_{up} =11M_o - M_{SNII} =35M_o - M_{top} = 120M_o

a Galactic Lyman continuum Luminosity Q_{GAL} = 3.5 10^{53} photons/s

$$\frac{dN}{dm} = km^{-(1+x)}$$

$$N_{m_1}^{m_2} = k\int_{m_1}^{m_2} \frac{dN}{dm}\,dm = k\,\frac{(m_2^{-x} - m_1^{-x})}{-x}$$

$$N_{m_1}^{m_2} = 1 \Rightarrow k = \frac{-x}{(m_2^{-x} - m_1^{-x})}$$

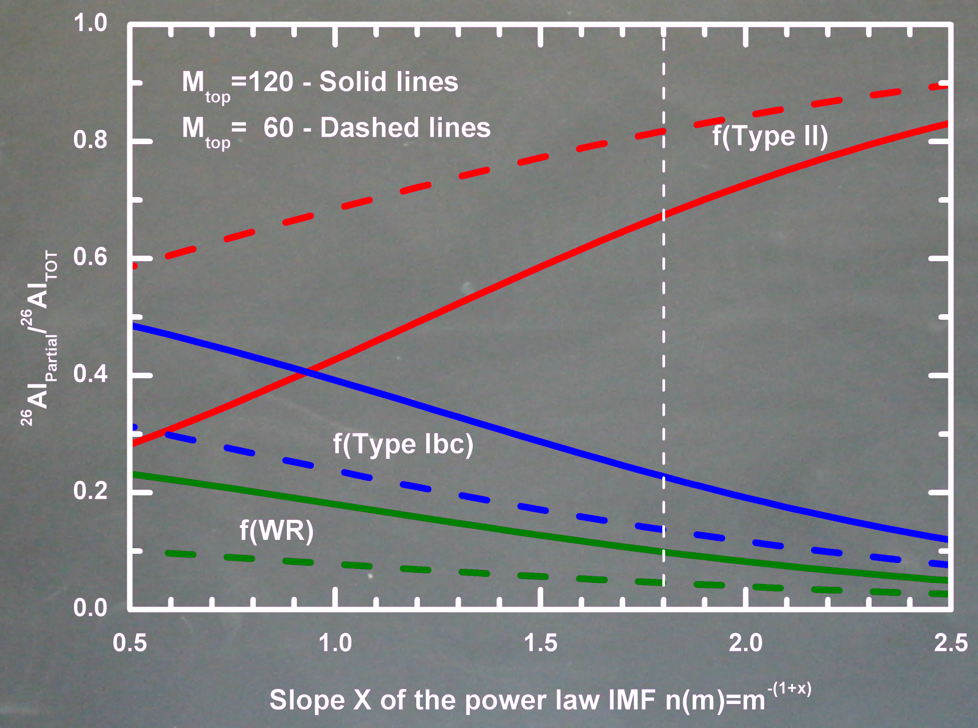
$$M_{m_1}^{m_2} = k\int_{m_1}^{m_2} m\,\frac{dN}{dm}\,dm = k\,\frac{(m_2^{-x+1} - m_1^{-x+1})}{-x+1}$$

$$Y(^{26}Al) = k\int_{m_1}^{m_2} Y_{^{26}Al}(m)\,\frac{dN}{dm}\,dm$$

$$\dot{M}(^{26}Al) = Y_{^{26}Al} \times SFR$$

$$Y_{^{26}Al} \times SFR = \frac{M_{GAL}(^{26}Al)}{\tau_{^{26}Al}}$$ **Steady state**

$$SFR = \frac{Q_{GAL}(ionizingflux)}{Q_{STAR}}(N_* / yr)$$

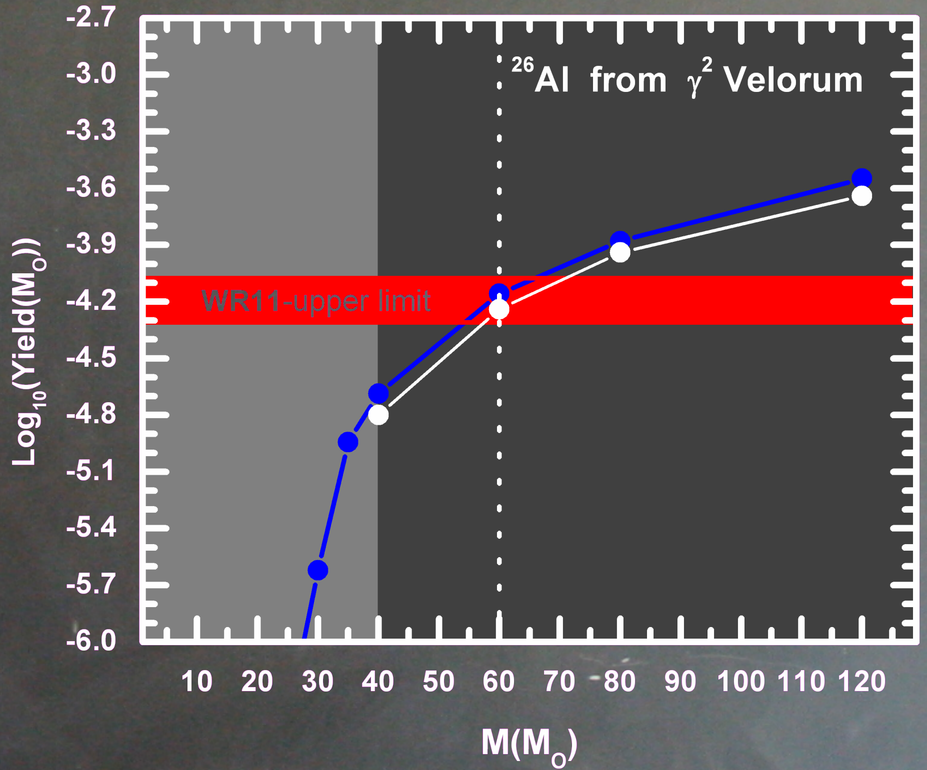


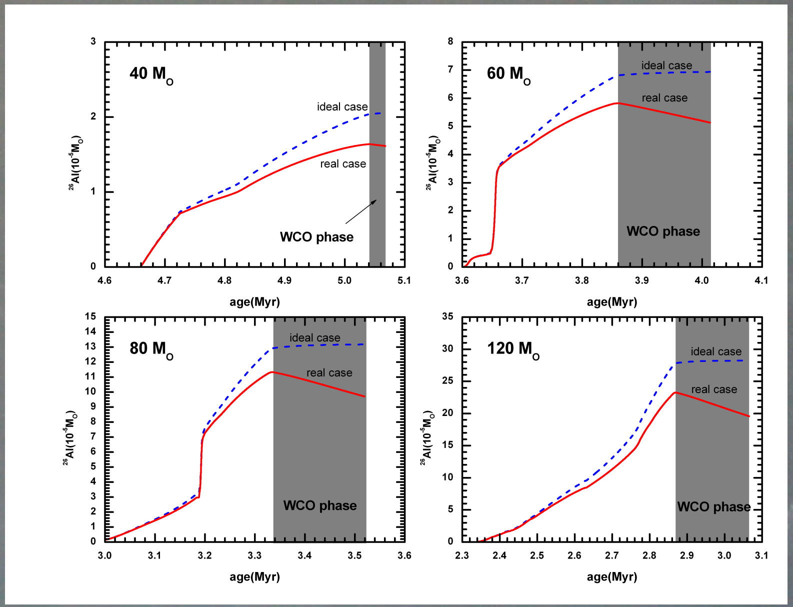
γ² Velorum

Binary system containing the closest WR(11) star
Main data taken from Schaerer et al. (1997) and Oberlack et al. (2000)

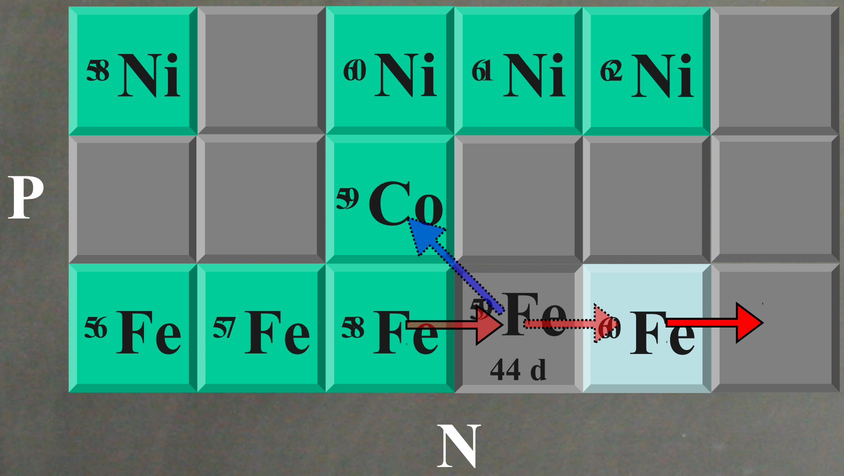
Distance: 258 pc - WC8 (9 $M_\odot$) - O8.5III (29 $M_\odot$)

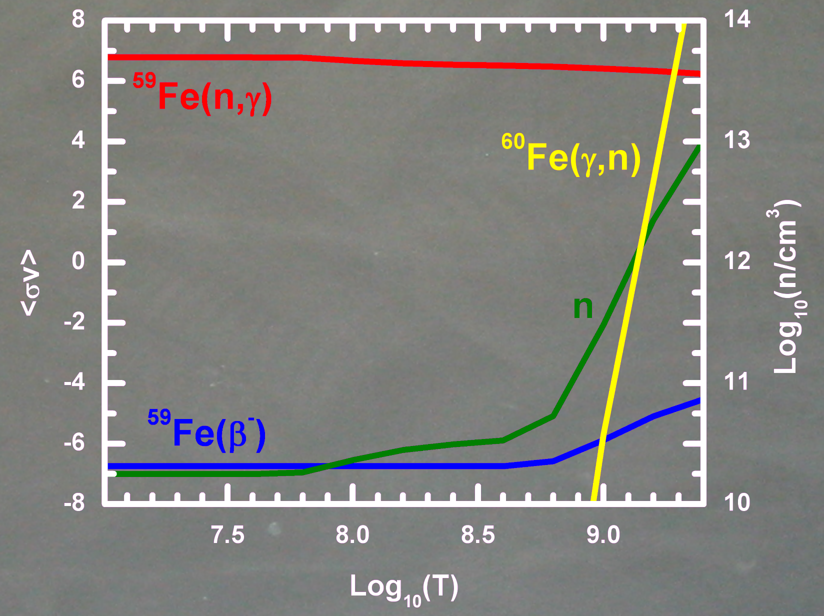
^{26}Al(Upper limit) => 6.3 10^{-5} (+2.1-1.4) $M_\odot$





^{60}Fe production: 1) basics

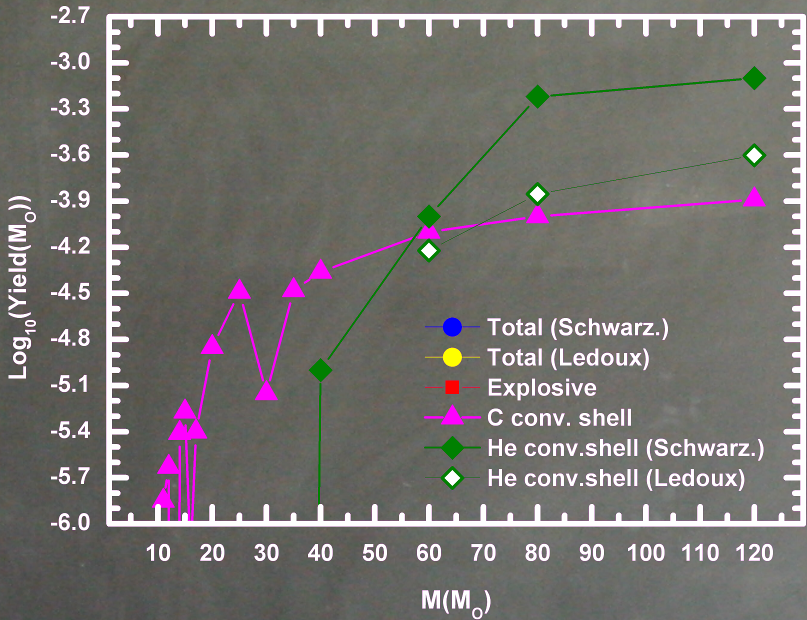


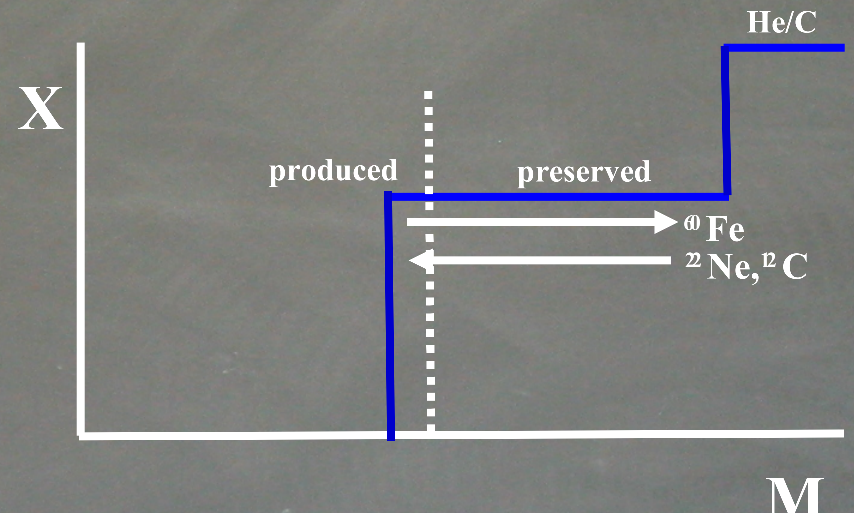


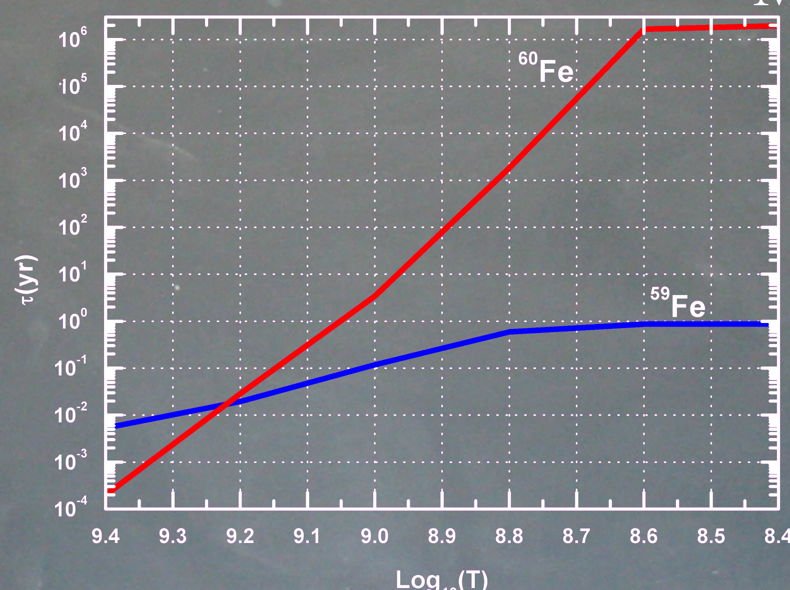
Main n donor → ^{22}Ne(α,n)^{25}Mg

Central He burning	$T < 3.5\ 10^8$ K	$\rho < 10^7$ n/cm^3	$\rho_{crit} = 10^{10}$ n/cm^3
Central C burning	$T < 10^9$ K	ρ = few 10^7 n/cm^3	$\rho_{crit} = 3\ 10^{11}$ n/cm^3
Shell He burning	$T > 4\ 10^8$ K	ρ => $6\ 10^{10}$ to 10^{12} n/cm^3	
Shell C burning	$T > 1.3\ 10^9$ K	ρ => $6\ 10^{11}$ to $2\ 10^{12}$ n/cm^3	
Shell Ne burning	$T > 1.8\ 10^9$ K	ρ => $6\ 10^{11}$ to $2\ 10^{12}$ n/cm^3	

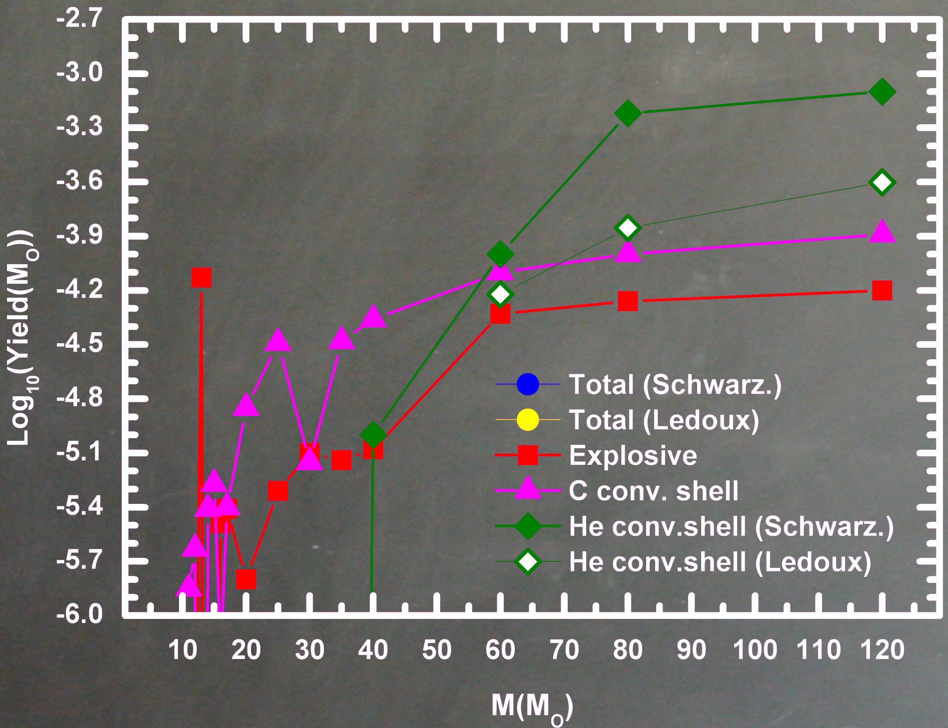
^{60}Fe production: 2) the He and C convective shells

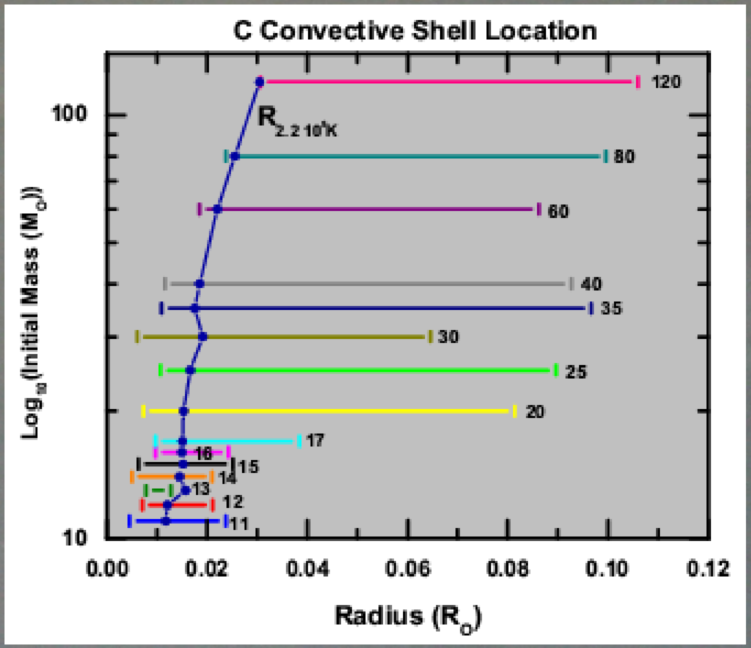




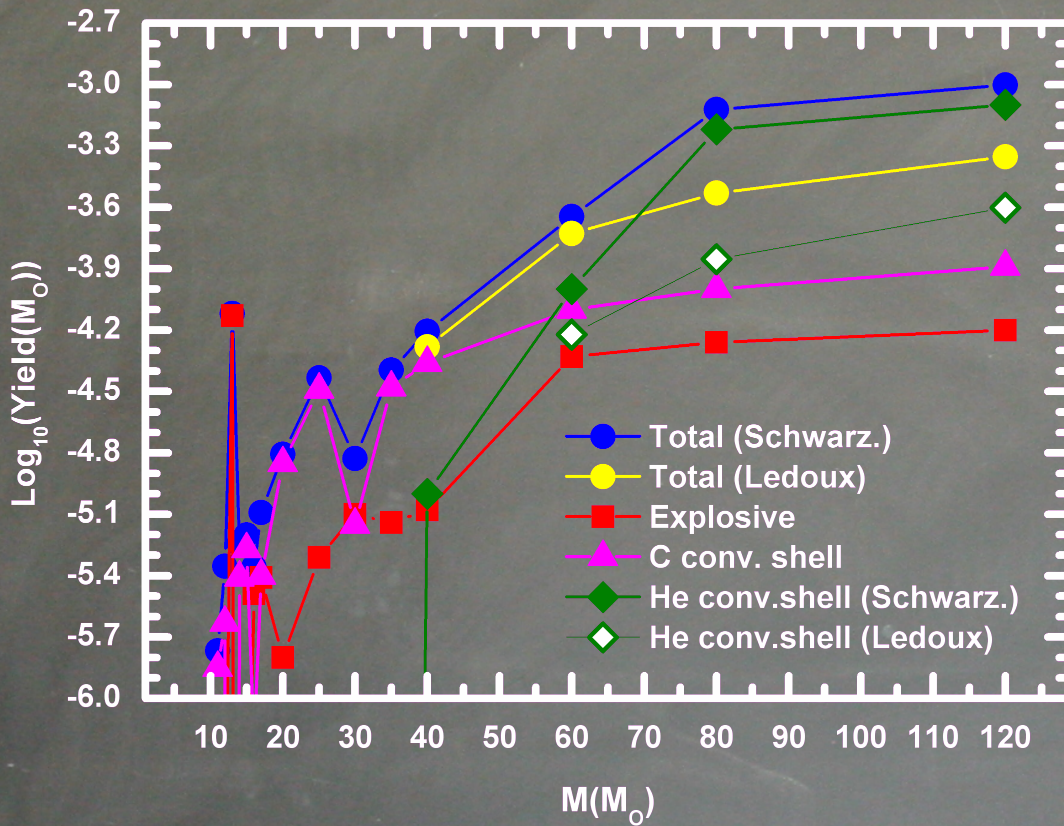


^{60}Fe production: 3) the Ne explosive contribution





The total ^{60}Fe production



$M < 60\ M_O$ Mainly produced by the C convective shell

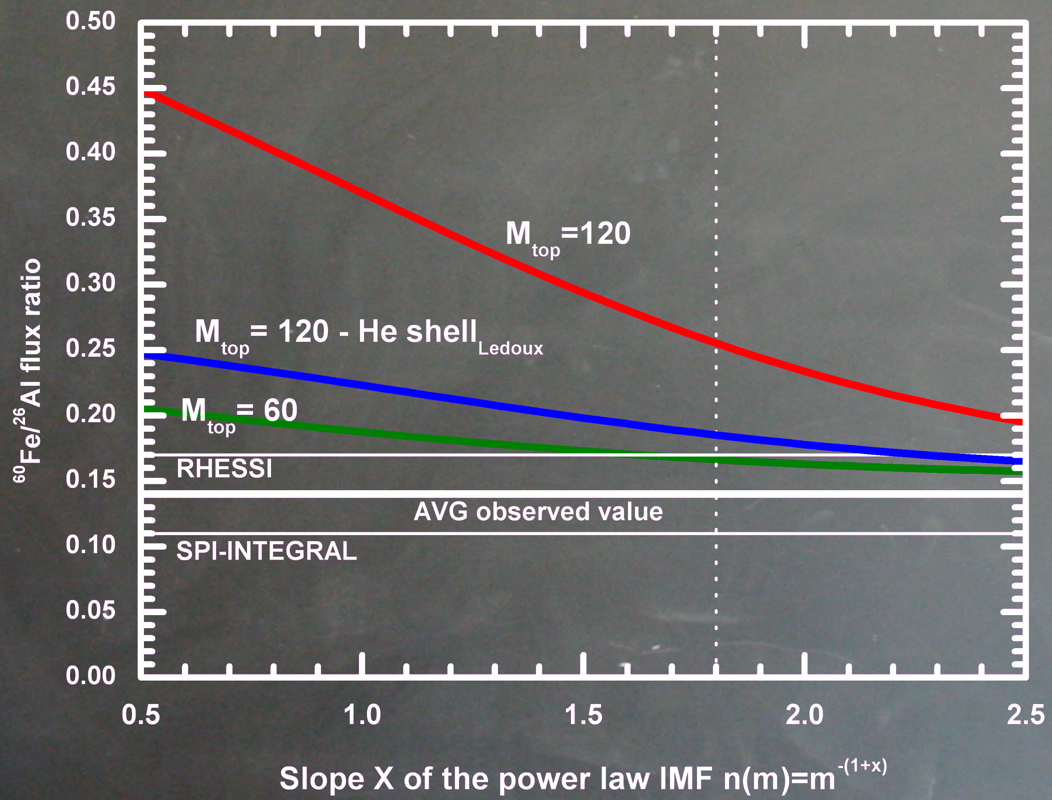
$M > 60\ M_O$ Mainly produced by the C convective shell (Ledoux criterion)

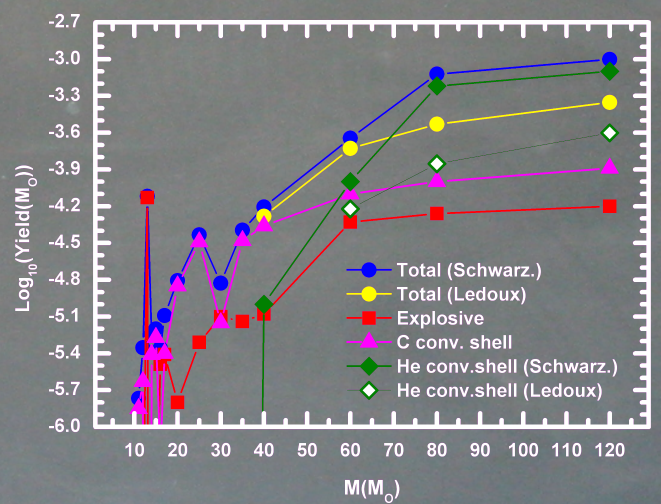
$M > 60\ M_O$ Mainly produced by the He convective shell (Schwarz. criterion)

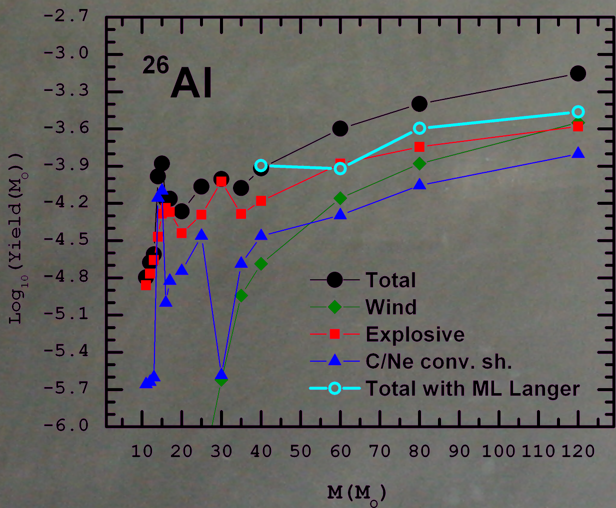
The galactic ^{60}Fe/^{26}Al flux ratio

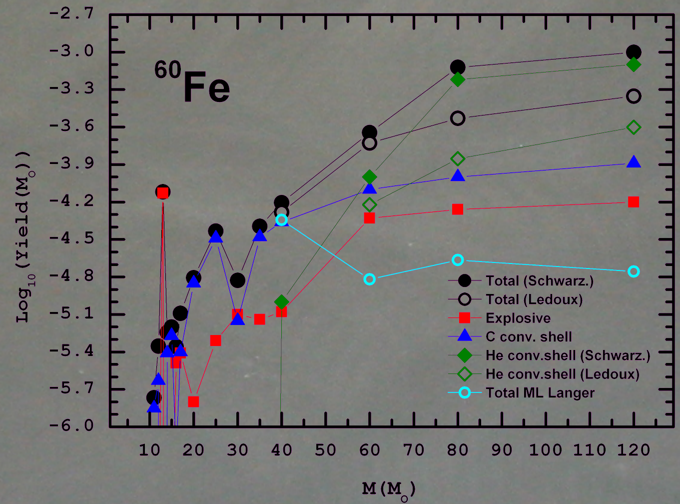
The ^{60}Fe/^{26}Al flux ratio is of the order of 0.14 ± 0.03 towards the Galactic center

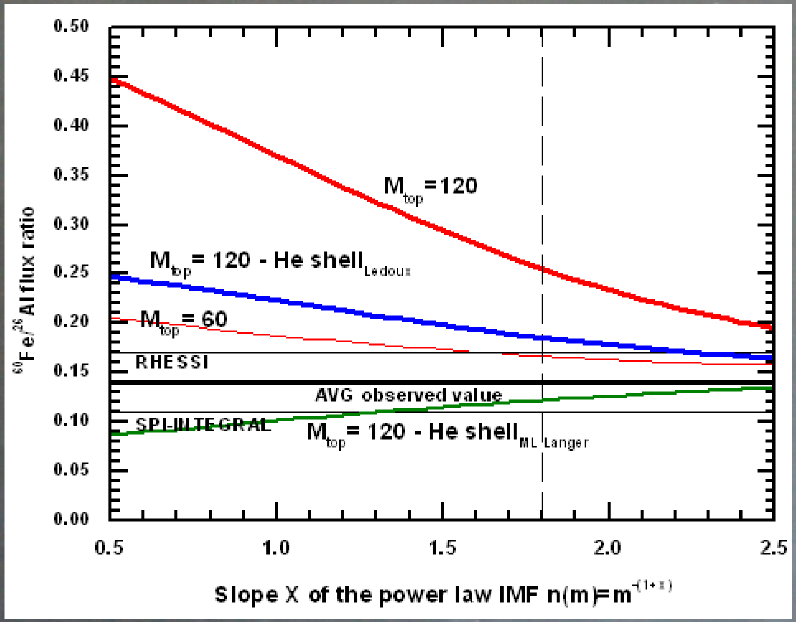
$$\frac{dN}{dm} = km^{-(1+x)} \qquad \frac{N(^{60}Fe)}{N(^{26}Al)} \propto \int_{M_{BOT}}^{M_{TOP}} \frac{y_{60}(m)}{y_{26}(m)} \frac{26}{60} m^{-(1+x)} dm$$






26Al
Log10 (Yield (Mo))
M (Mo)
Total
Wind
Explosive
C/Ne conv. sh.
Total with ML Langer


60Fe
Log10 (Yield (Mo))
M (Mo)
Total (Schwarz.)
Total (Ledoux)
Explosive
C conv. shell
He conv.shell (Schwarz.)
He conv.shell (Ledoux)
Total ML Langer


60Fe/26Al flux ratio
Mtop =120
Mtop = 120 - He shellLedoux
Mtop = 60
RHESSI
AVG observed value
SPI-INTEGRAL
Mtop = 120 - He shellML Langer
Slope X of the power law IMF n(m)=m-(1+x)

Summary & Conclusions

Observational:

^{26}Al is very probably produced by stars having $M>15\ M_{\odot}$

There are roughly $1.25\ 10^{-11}$ $n(\gamma_{1.8MeV})$/ (ionizing photon) at all longitudes

The $^{60}Fe/^{26}Al$ flux ratio is of the order of 0.14 ± 0.05 towards the Galactic center

Roughly $2.8\ M_{\odot}$ of ^{26}Al are present in the Galaxy ($\pm$ 30%)

Theoretical:

^{26}Al is mainly produced by the Ne explosive burning.

^{60}Fe is mainly produced by the C convective shell.

The observed (and quite constant) average number of $\gamma_{1.8MeV}$ per ionizing photon (R_{GxL}) is rather well reproduced.

The observed $^{60}Fe/^{26}Al$ flux ratio towards the center of our Galaxy is well reproduced if the Langer (1989) mass loss rate in the WNE,WCO is adopted.

Predictions for γ^2 Velorum are in agreement with the quoted upper limit.

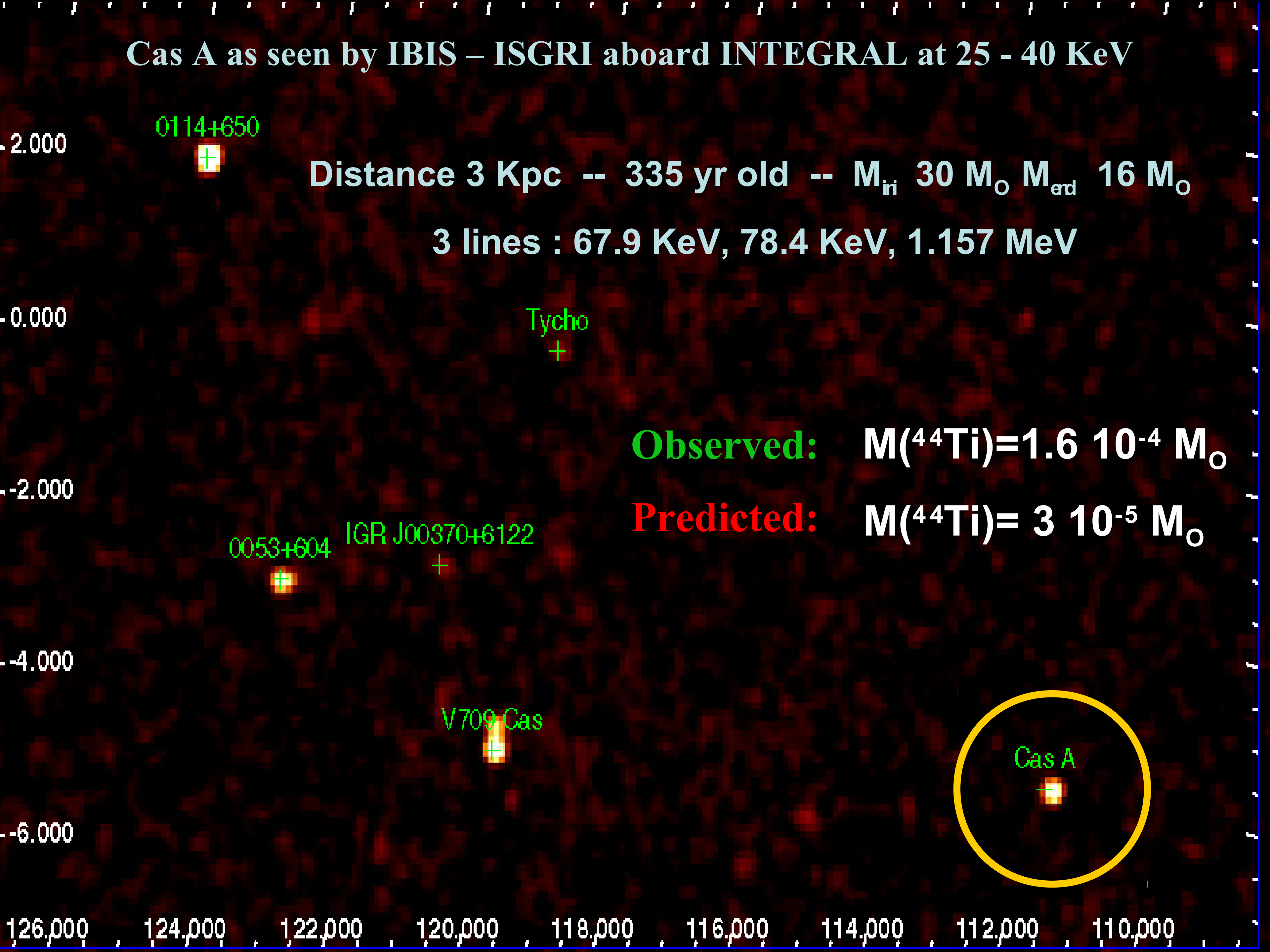
Cas A as seen by IBIS – ISGRI aboard INTEGRAL at 25 - 40 KeV

Distance 3 Kpc -- 335 yr old -- M_{ini} 30 M_O M_{end} 16 M_O

3 lines : 67.9 KeV, 78.4 KeV, 1.157 MeV

Observed: $M(^{44}Ti)=1.6\ 10^{-4}\ M_O$

Predicted: $M(^{44}Ti)= 3\ 10^{-5}\ M_O$

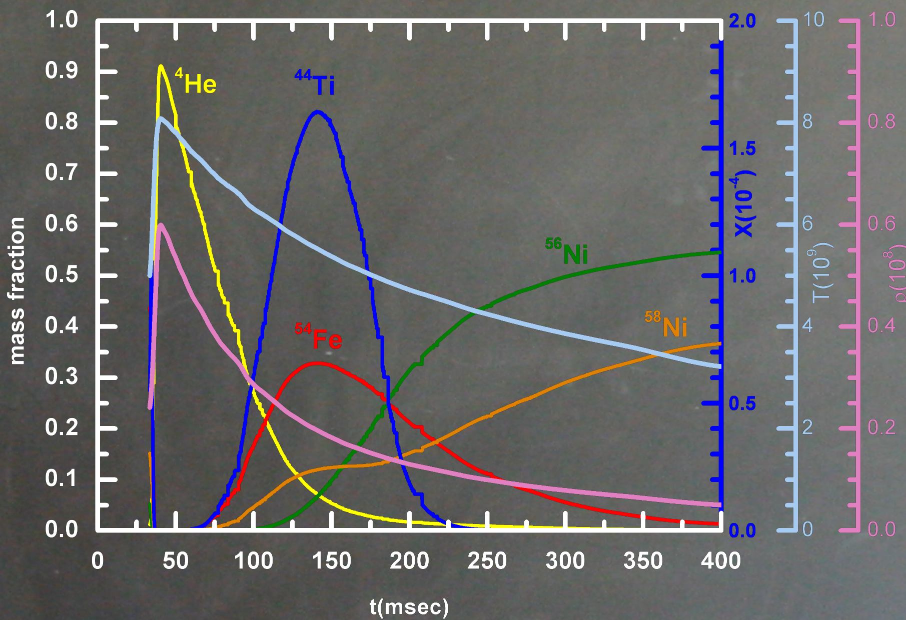


^{44}Ti

Not produced in a normal freeze out

$\tau_{cooling} \gg \tau_{build}$

($3\alpha \Rightarrow {}^{12}C(\alpha,\gamma){}^{16}O(\alpha,\gamma)\ldots$NSE)



Produced in the α-rich freeze-out of zones exposed to the complete explosive Si burning

$\tau_{cooling} \ll \tau_{build}$