Supernovae from massive stars

Events in which heavy elements are made that enrich the interstellar medium from which later stars form

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17 Jan 2006 SINP

A core collapse Supernova: Death of a massive star

These are violent explosions in the universe

Energy emitted (EM+KE) ~ few x 10^{51} erg.

(Compare the energy nuclear explosions ~ 1 MT ≈ 4×10^{22} erg)

The energy budget in neutrinos is ~ 3 $\times10^{53}$ erg (I.e. only 1% of the total energy is “visible”)

Type II, Ib, Ic Sne leave behind Neutron star or Black holes and have massive progenitors (> 8 M_{Solar})

Occur only in Spiral arms of galaxies (young population of stars)

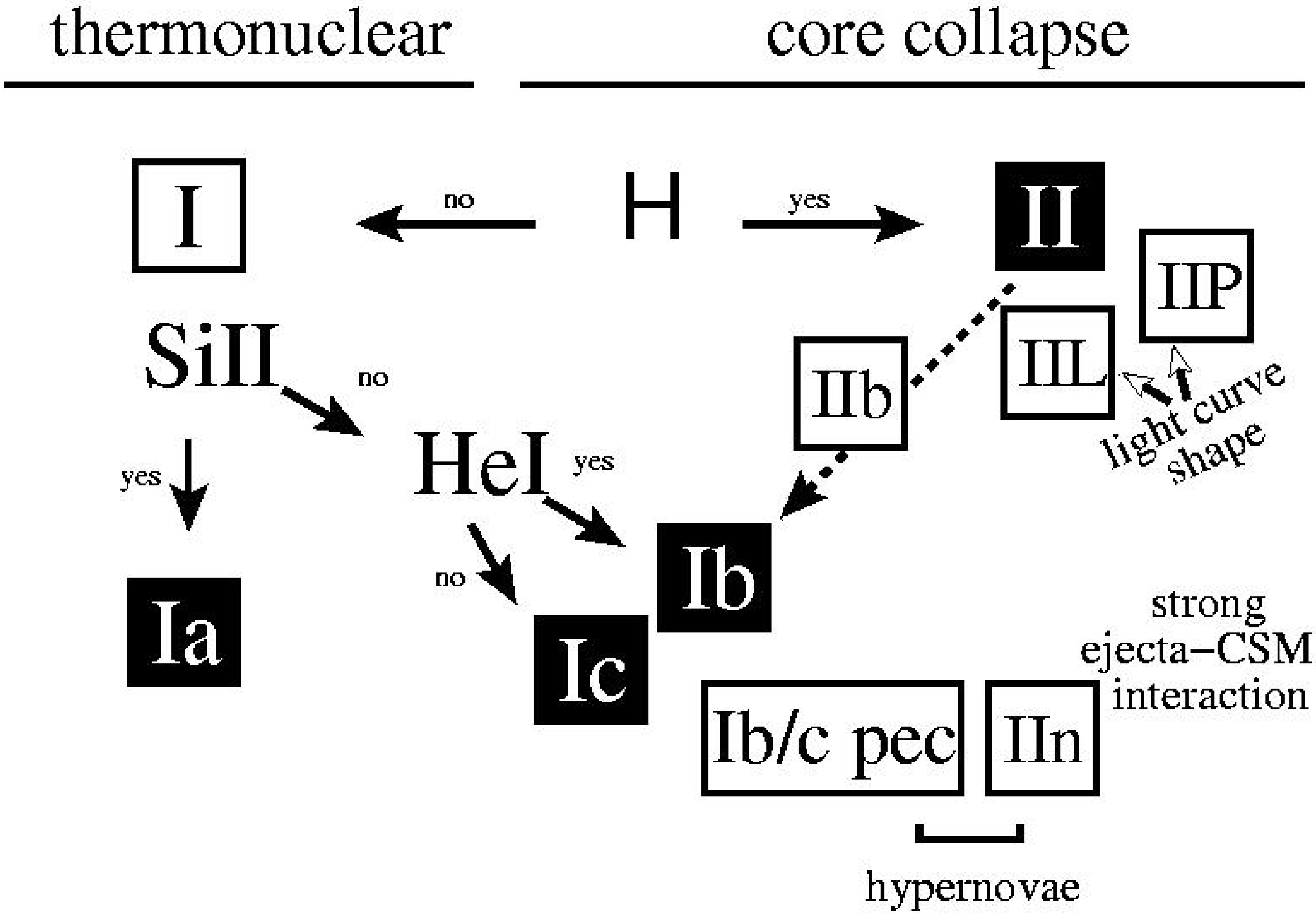
Energy scales of explosions

Chemical explosives	$\sim 10^{-6}$ MeV/atom
Nuclear explosives	~1MeV/nucleon
Novae explosions	few MeV/nucleon
Thermonuclear explosions	few MeV/nucleon
Core collapse supernovae	100 MeV/nucleon

Why study supernoave?

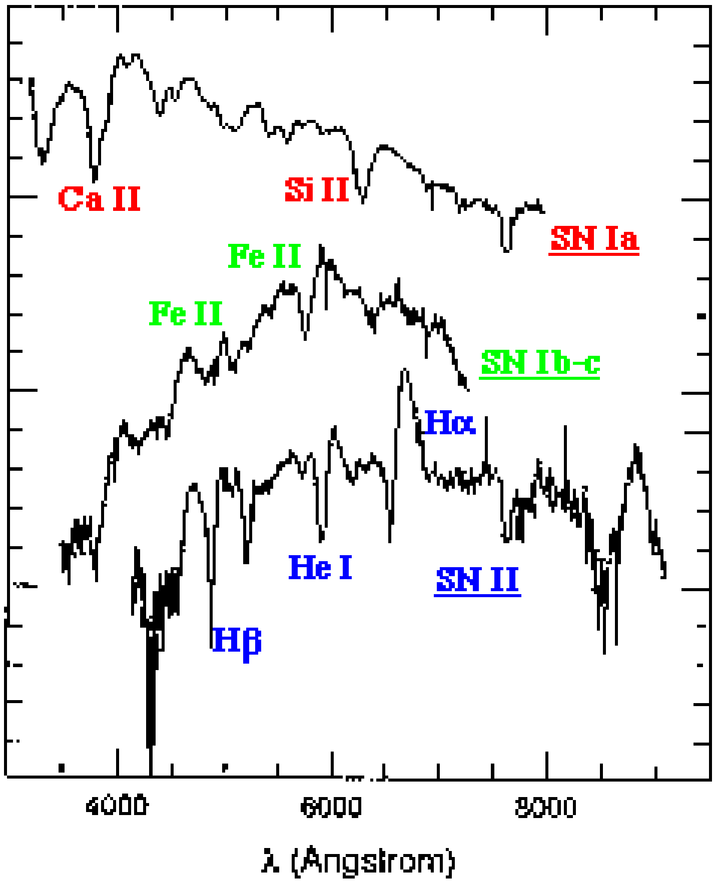
- **Enrich galaxy with heavy elements such as Iron, Calcium, Silicon, which are crucial to life.**
- **Influence formation of new stars.**
- **Are used to measure the geometry of the universe.**
- **Result of the stellar and influence galaxy evolution.**
- **Possible source of energetic cosmic rays.**

Different types of Supernovae



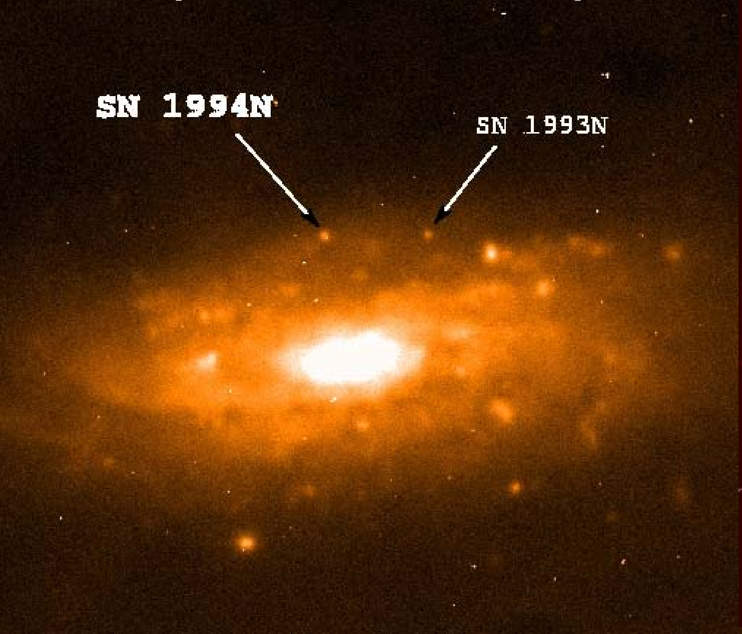
M. Turatto 2004

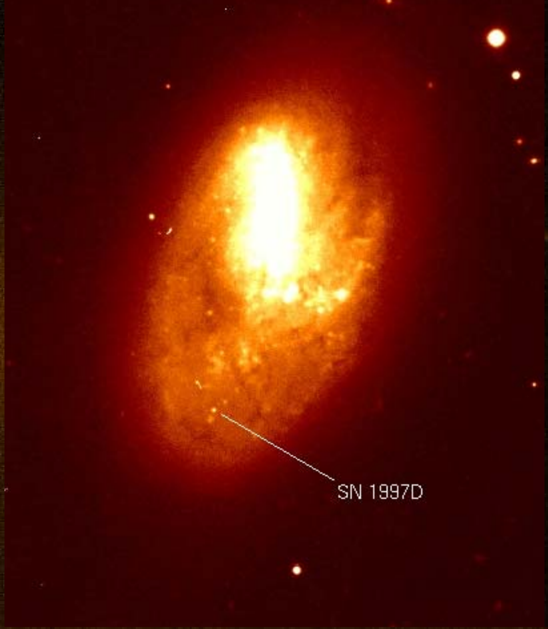
Spectra and SN Classification

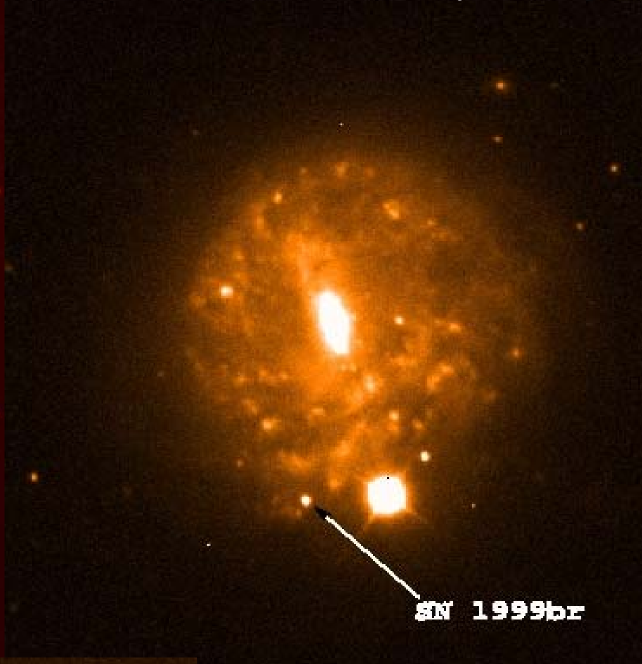


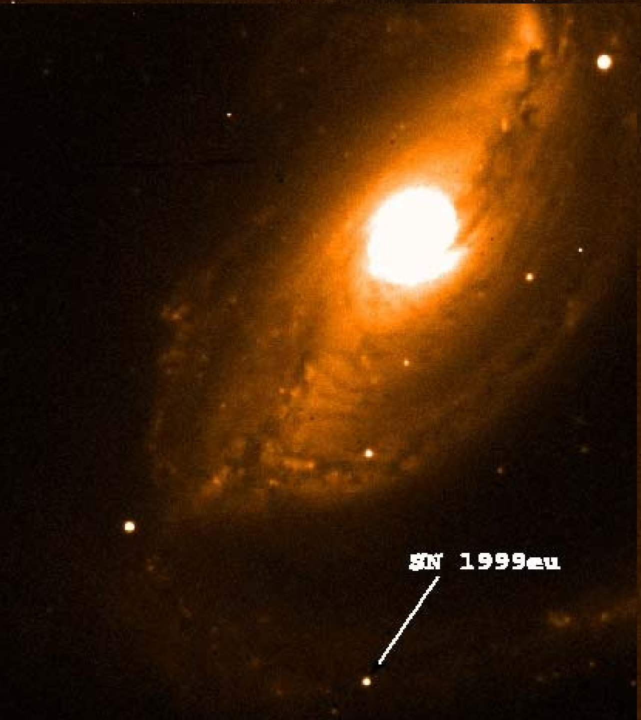
Ni poor SNII in Spiral Galaxies

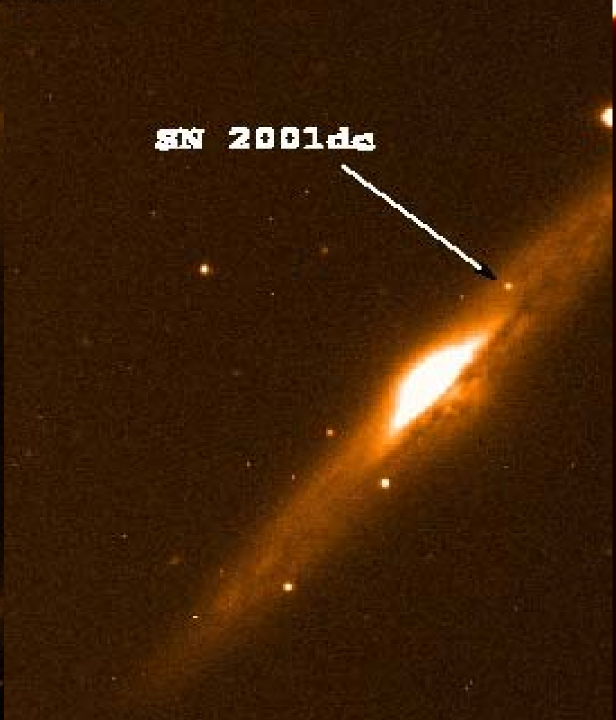
Courtesy: M. Turatto

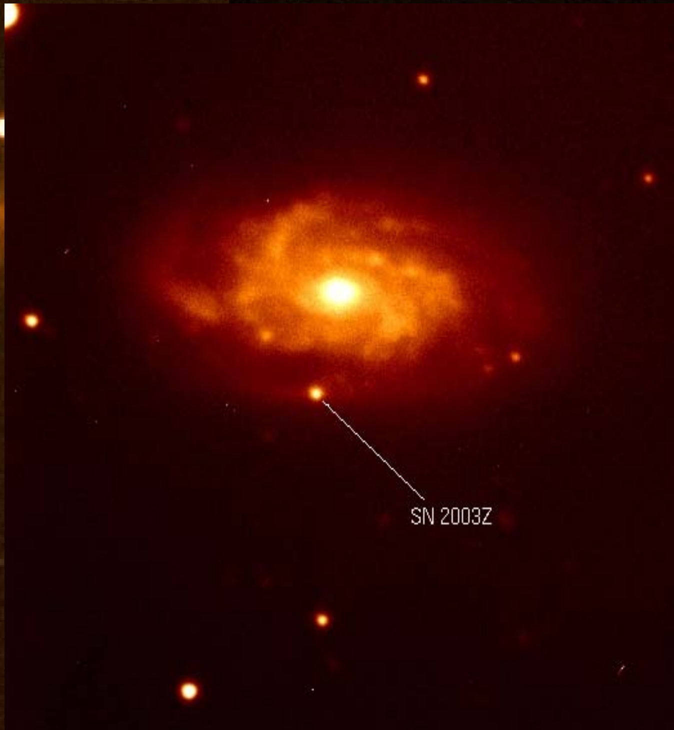




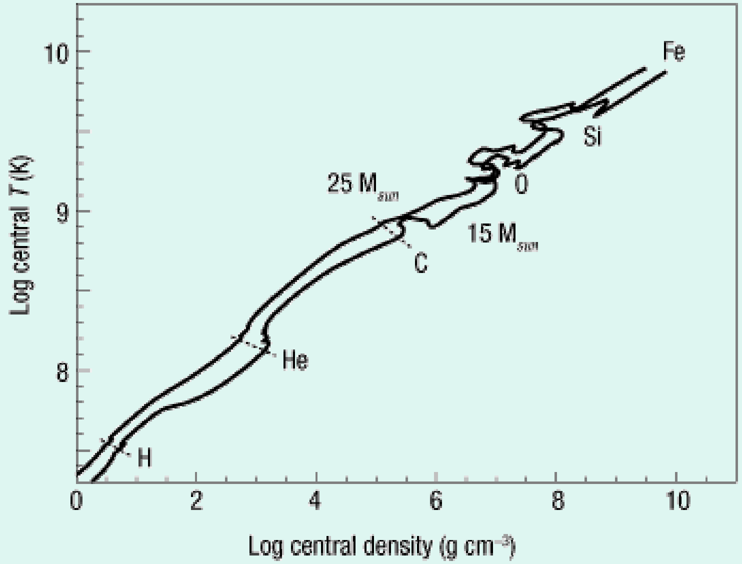








Endpoints of stellar evolution



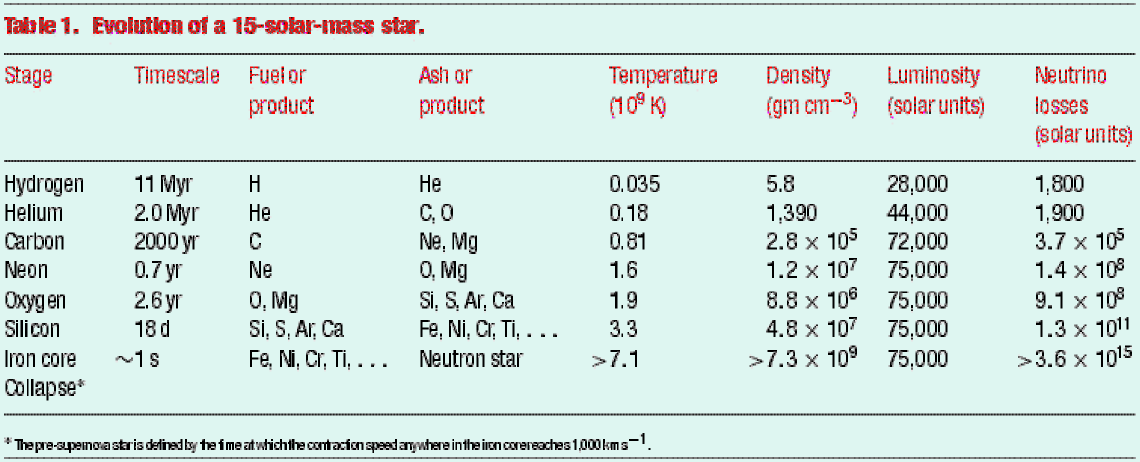


Table 1. Evolution of a 15-solar-mass star.

Stage	Timescale	Fuel or product	Ash or product	Temperature (10^9 K)	Density (gm cm^{-3})	Luminosity (solar units)	Neutrino losses (solar units)
Hydrogen	11 Myr	H	He	0.035	5.8	28,000	1,800
Helium	2.0 Myr	He	C, O	0.18	1,390	44,000	1,900
Carbon	2000 yr	C	Ne, Mg	0.81	2.8×10^5	72,000	3.7×10^5
Neon	0.7 yr	Ne	O, Mg	1.6	1.2×10^7	75,000	1.4×10^8
Oxygen	2.6 yr	O, Mg	Si, S, Ar, Ca	1.9	8.8×10^6	75,000	9.1×10^8
Silicon	18 d	Si, S, Ar, Ca	Fe, Ni, Cr, Ti, . . .	3.3	4.8×10^7	75,000	1.3×10^{11}
Iron core Collapse*	~1 s	Fe, Ni, Cr, Ti, . . .	Neutron star	>7.1	$>7.3 \times 10^9$	75,000	$>3.6 \times 10^{15}$

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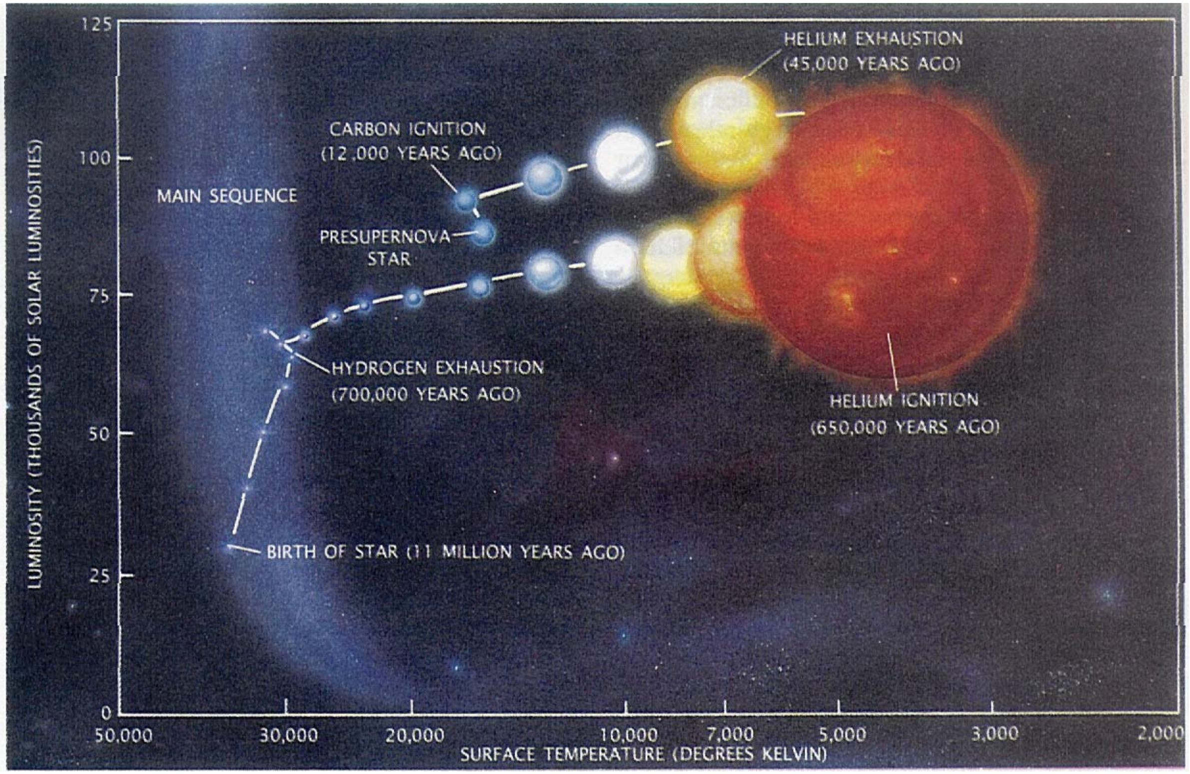
* The pre-supernova star is defined by the time at which the contraction speed anywhere in the iron core reaches 1,000 km s^{-1}.

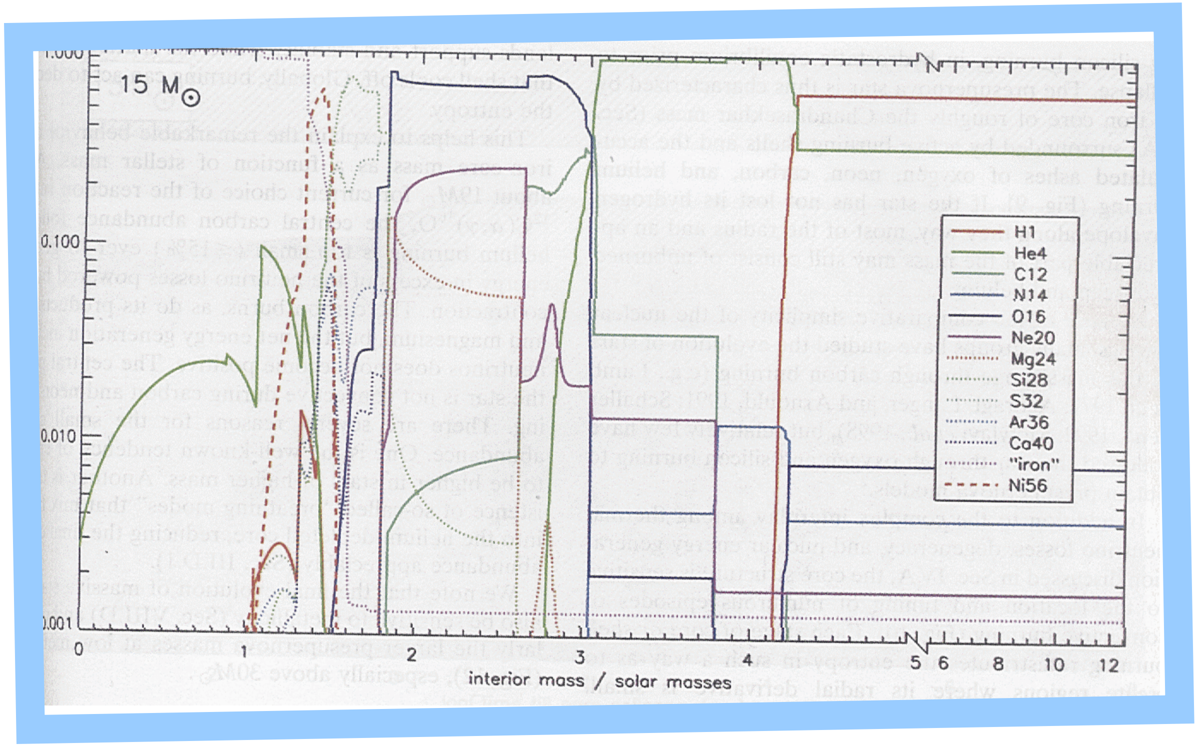
Woosley and Janka 2005

Temperature and Luminosity changes as a star evolves



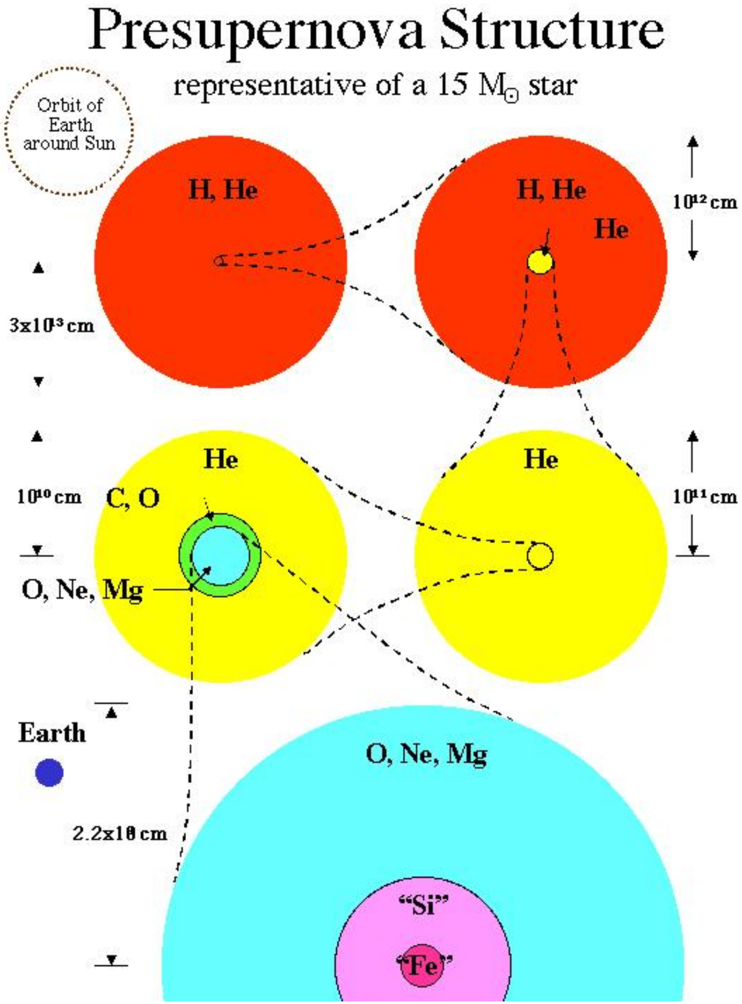
Woosley and Weaver 1989

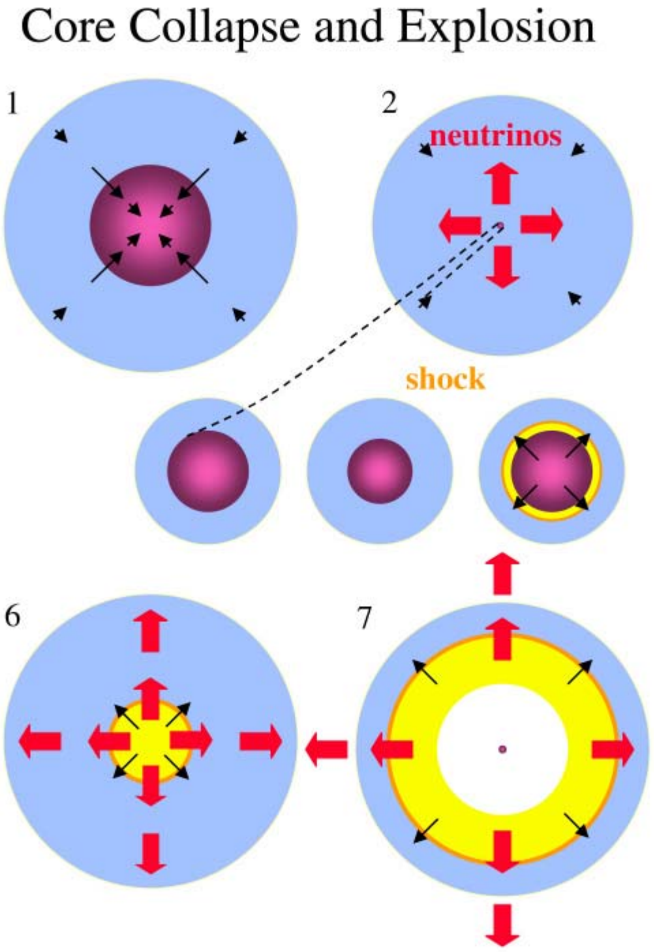
Interior composition of a massive star



Woosley etal 2002

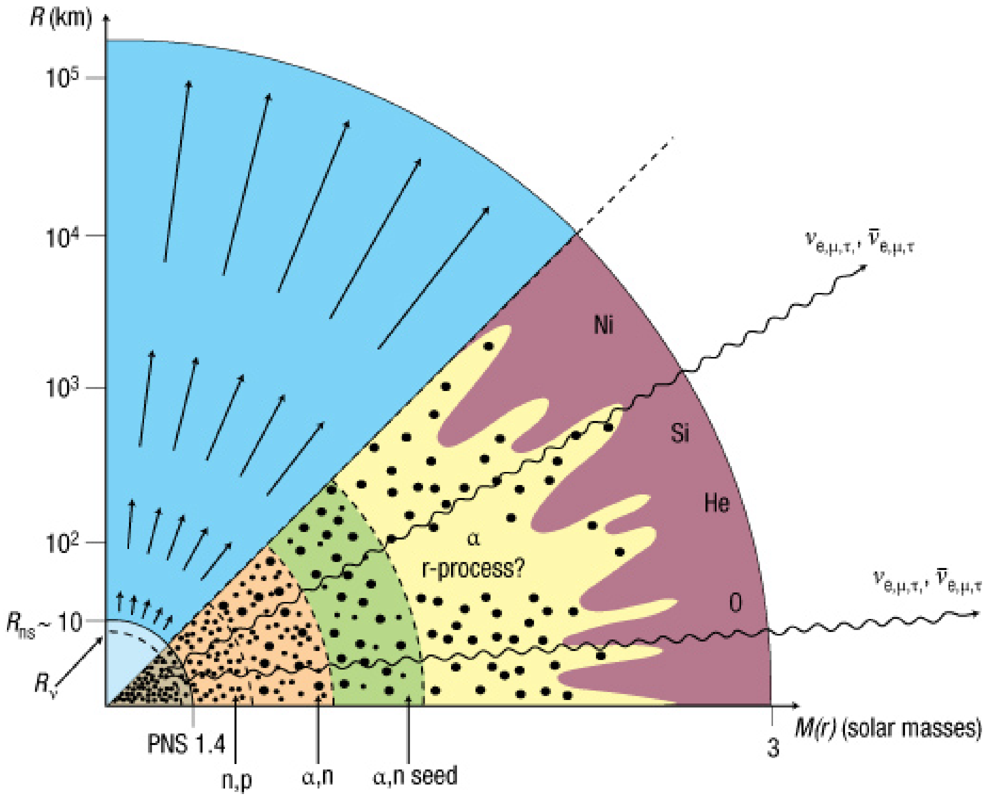
Internal structure of stars





C. Cardall

Neutrino cooling and neutrino-driven wind ($t \approx 10$ s)

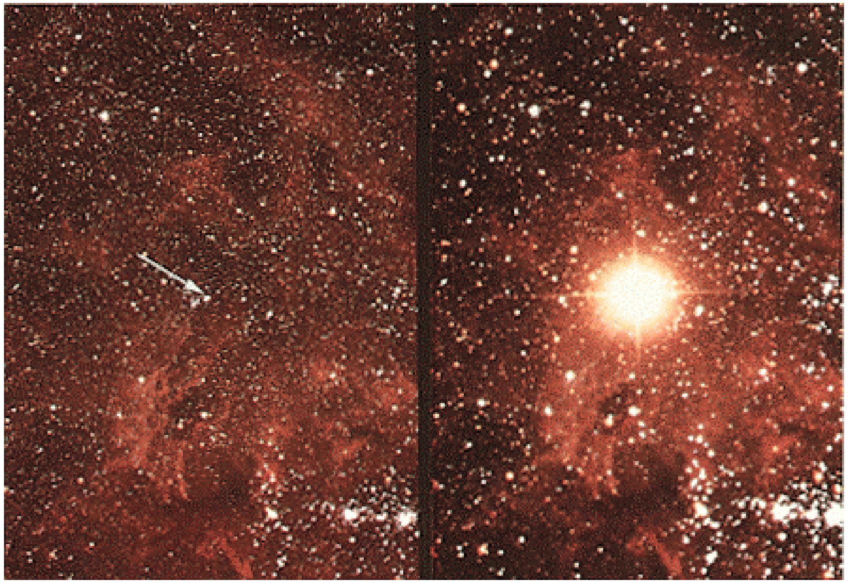


Woosley and Janka 2005

Important Core Collapse Supernovae

(SN1987A, 1993J, Crab, Caseopeia A SNRs)

SN 1987A

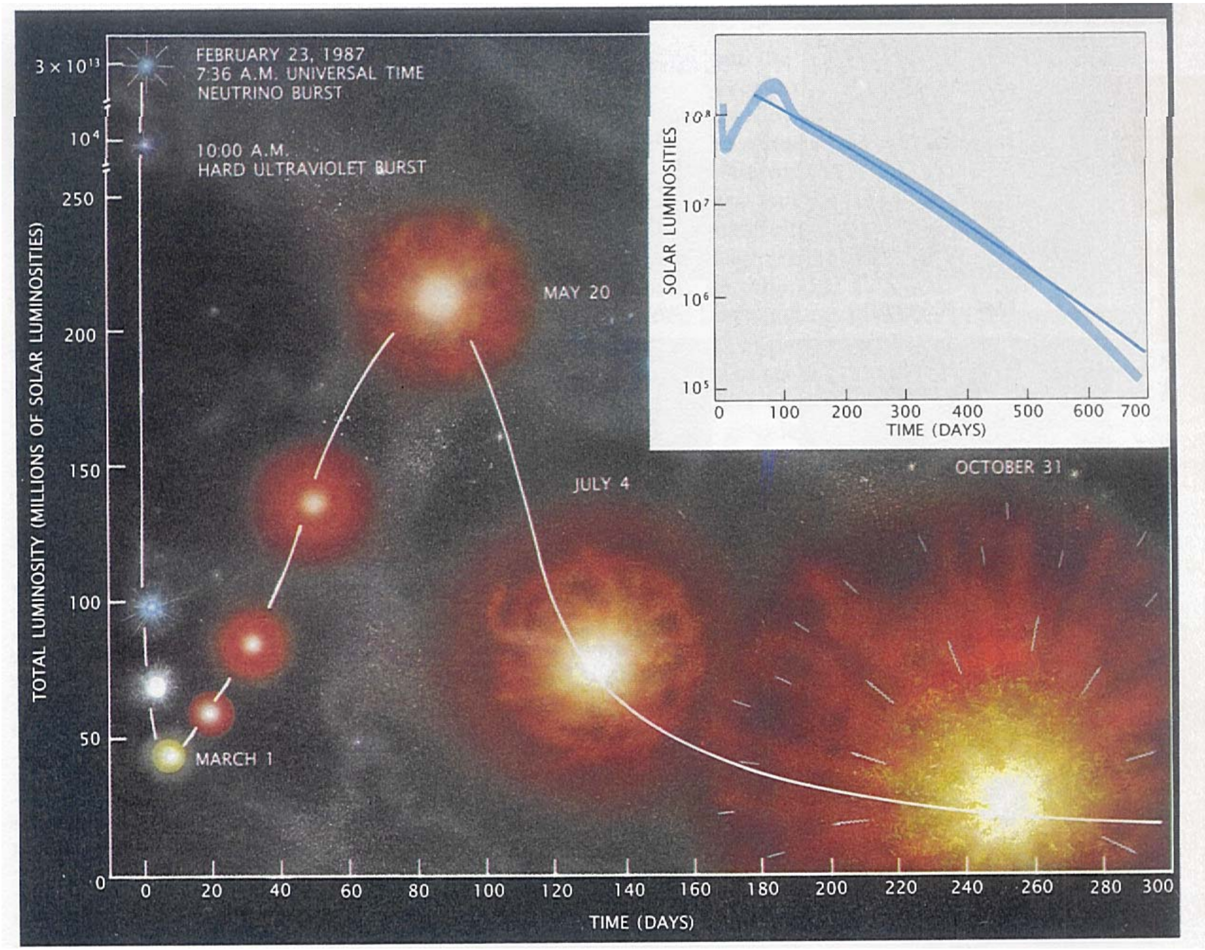


Before

After

David Malin

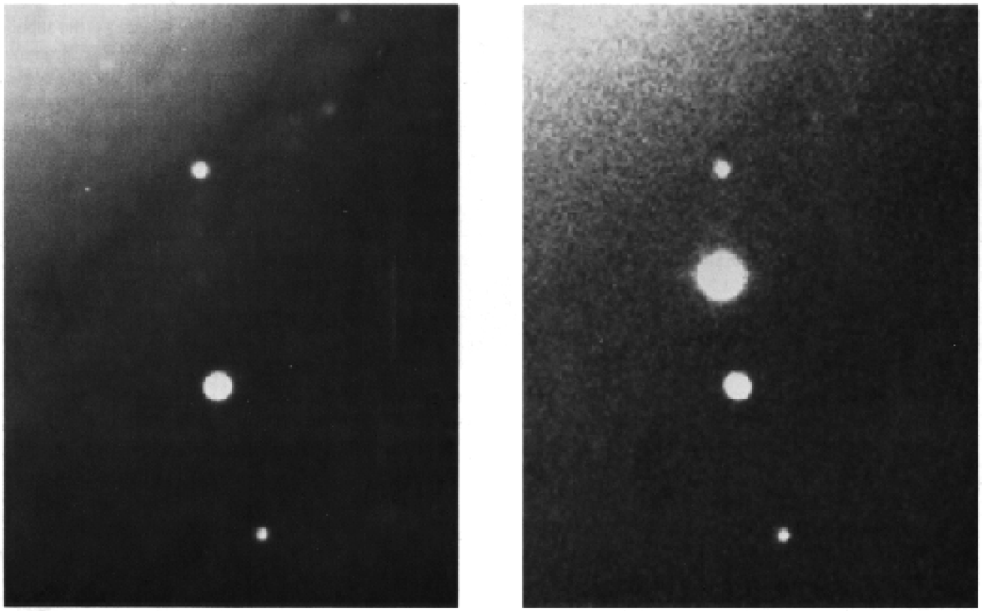
SN 1987A Light-Curve



Woosley and Weaver 1989

A supernova with identity crisis

Supernova 1993J



Spectrum showed hydrogen near maximum light but
Weakened to having strong helium line. Type II ⇒ Type Ib

Spectra of SN 1993J

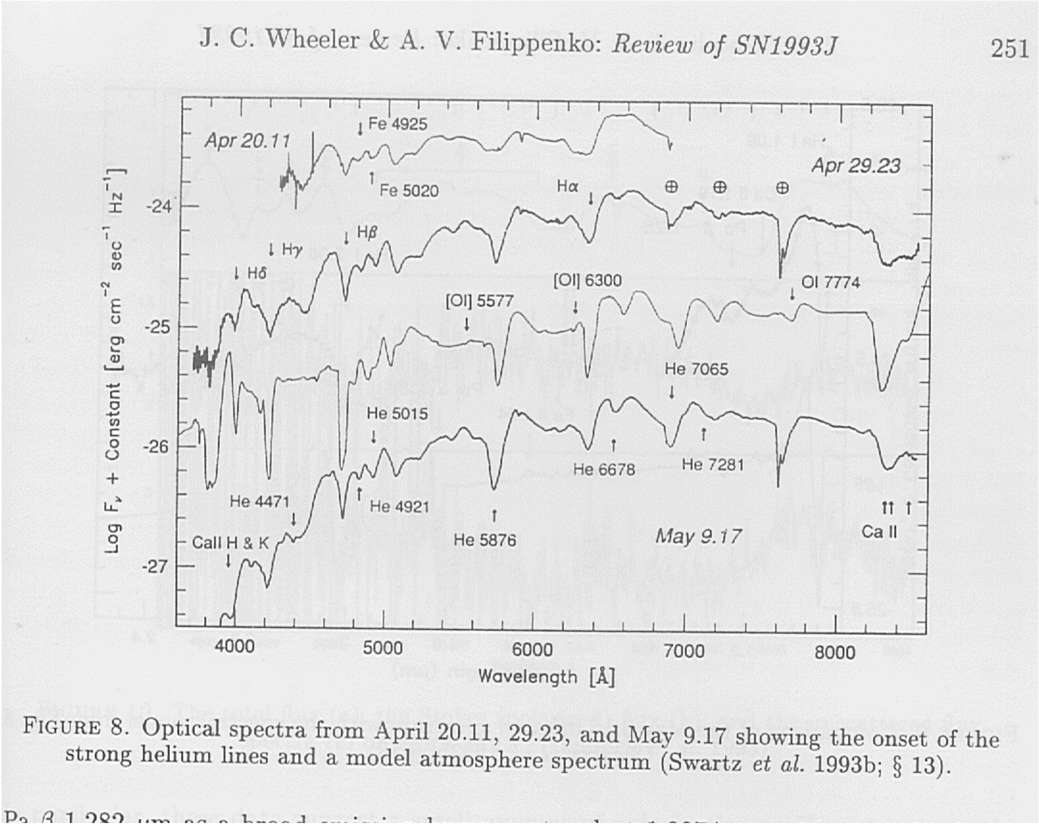
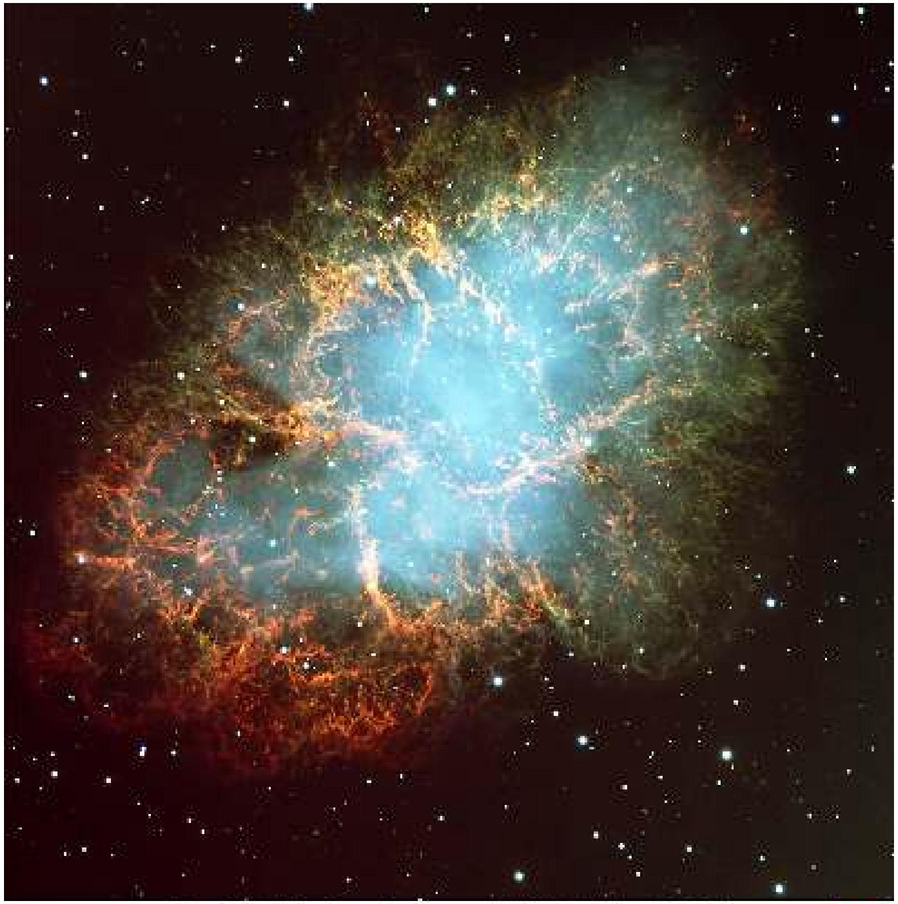

J. C. Wheeler & A. V. Filippenko: *Review of SN1993J* 251

FIGURE 8. Optical spectra from April 20.11, 29.23, and May 9.17 showing the onset of the strong helium lines and a model atmosphere spectrum (Swartz *et al.* 1993b; § 13).

Schartz et al 1993

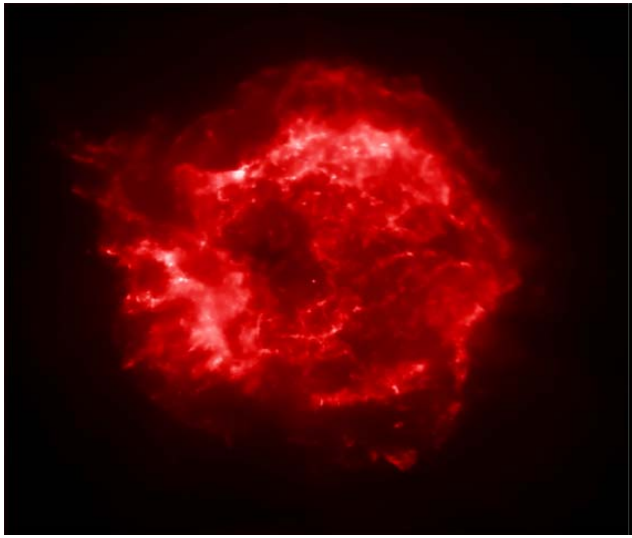


The Crab Nebula in Taurus (VLT KUEYEN + FORS2)

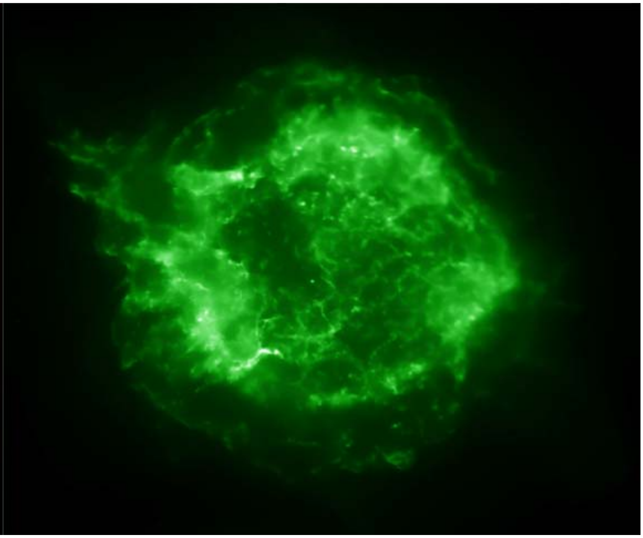
ESO PR Photo 40f/99 (17 November 1999)

© European Southern Observatory

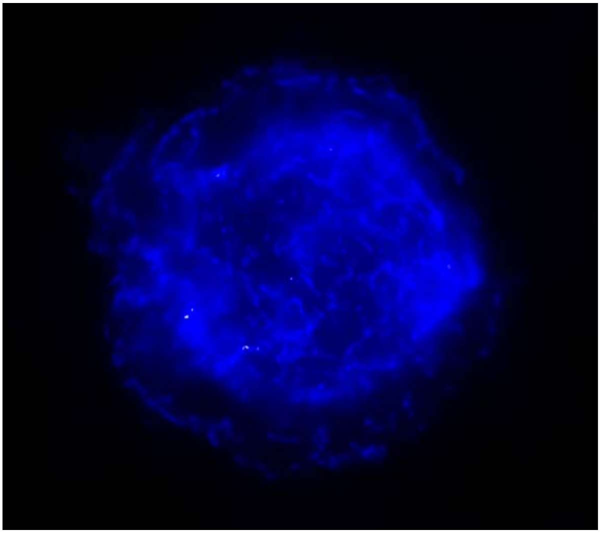
Cassiopeia A in X-ray bands observed by Chandra



0.3 -- 1.55 keV

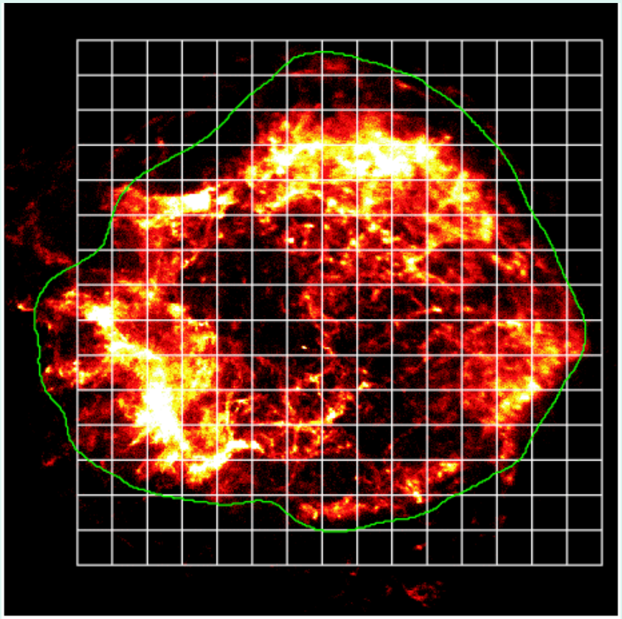


1.55 -- 3.34 keV

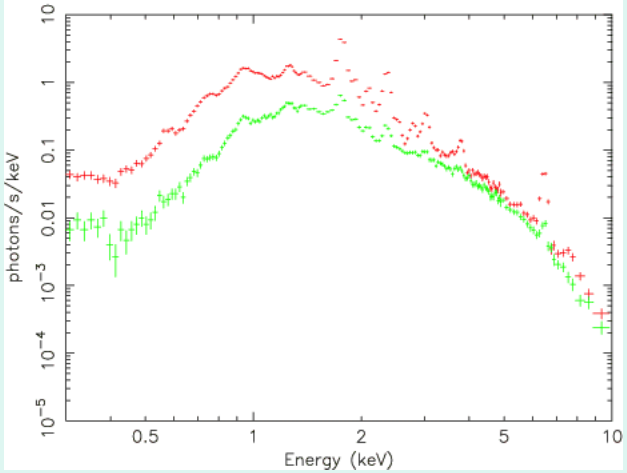


3.34 -- 10 keV

Cassiopeia A with XMM-Newton

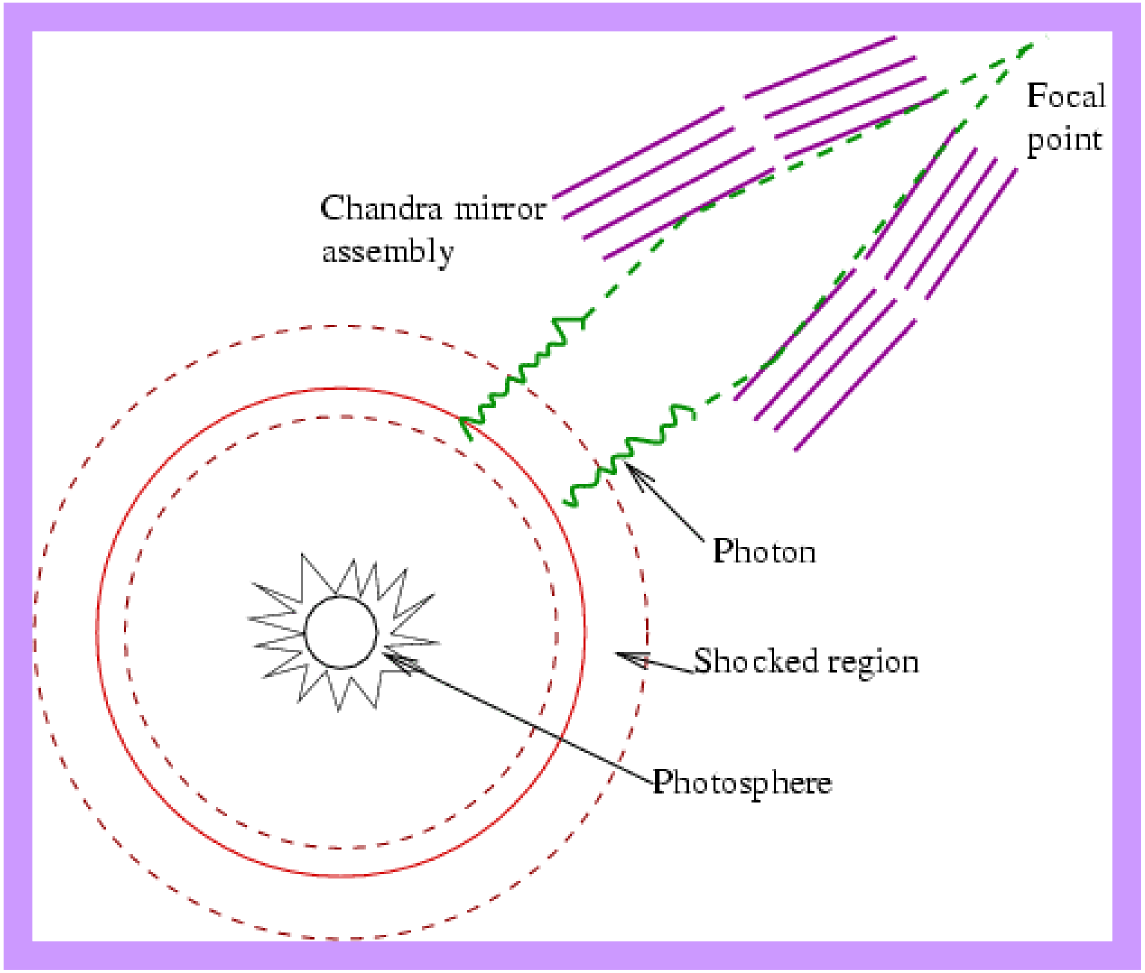


Chandra Image overlaid on the pixel Grid used in XMM Spectral analysis

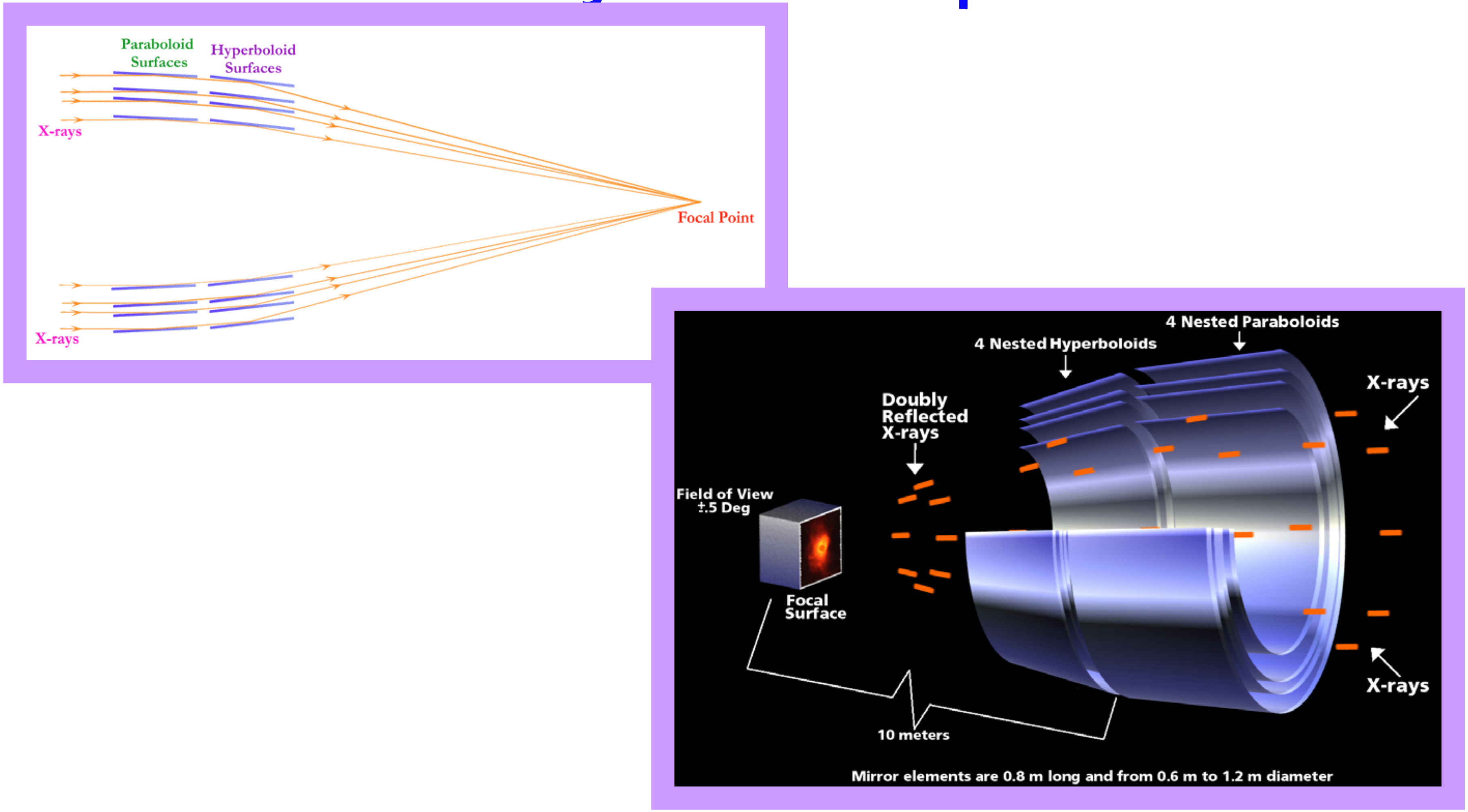


Willingale et al 2002

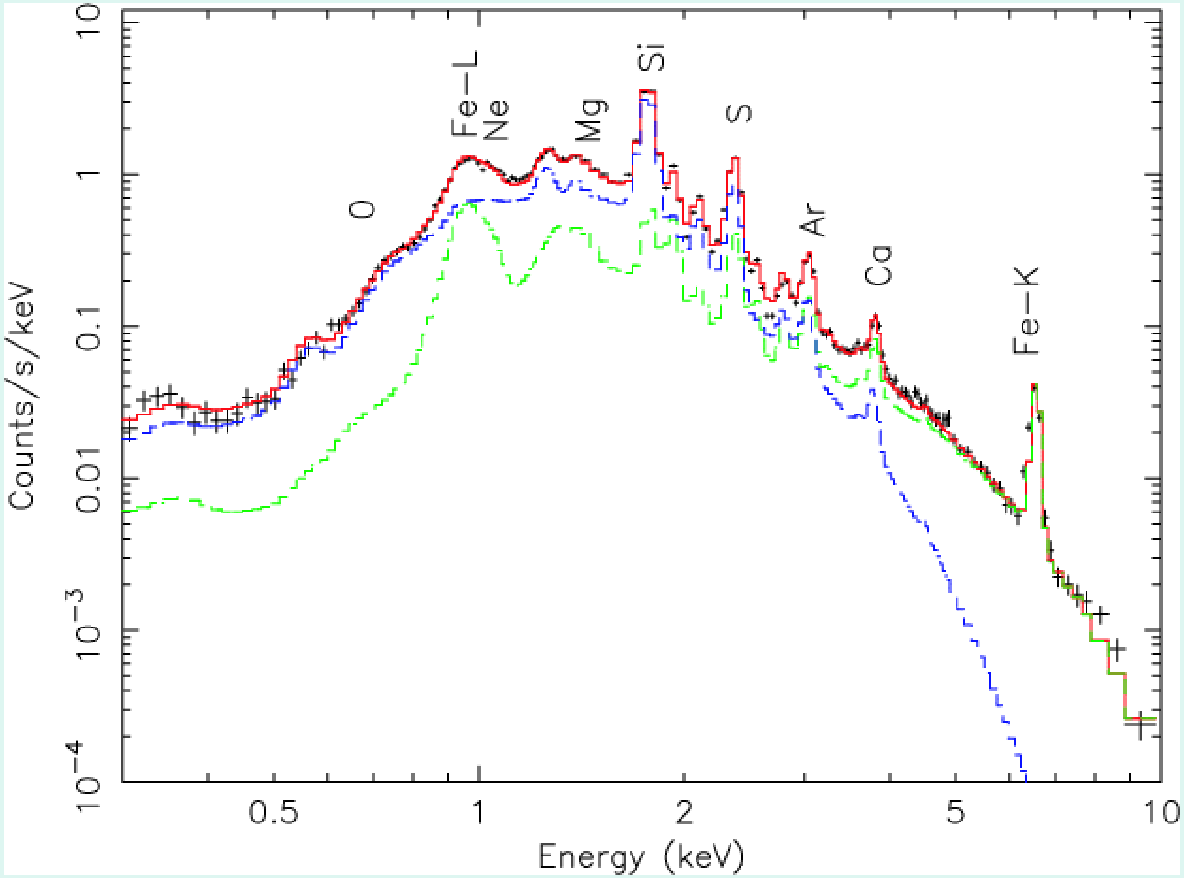
X-rays from the SN shock observed by space-borne telescopes



X-ray telescopes



Cassiopeia A X-ray spectrum



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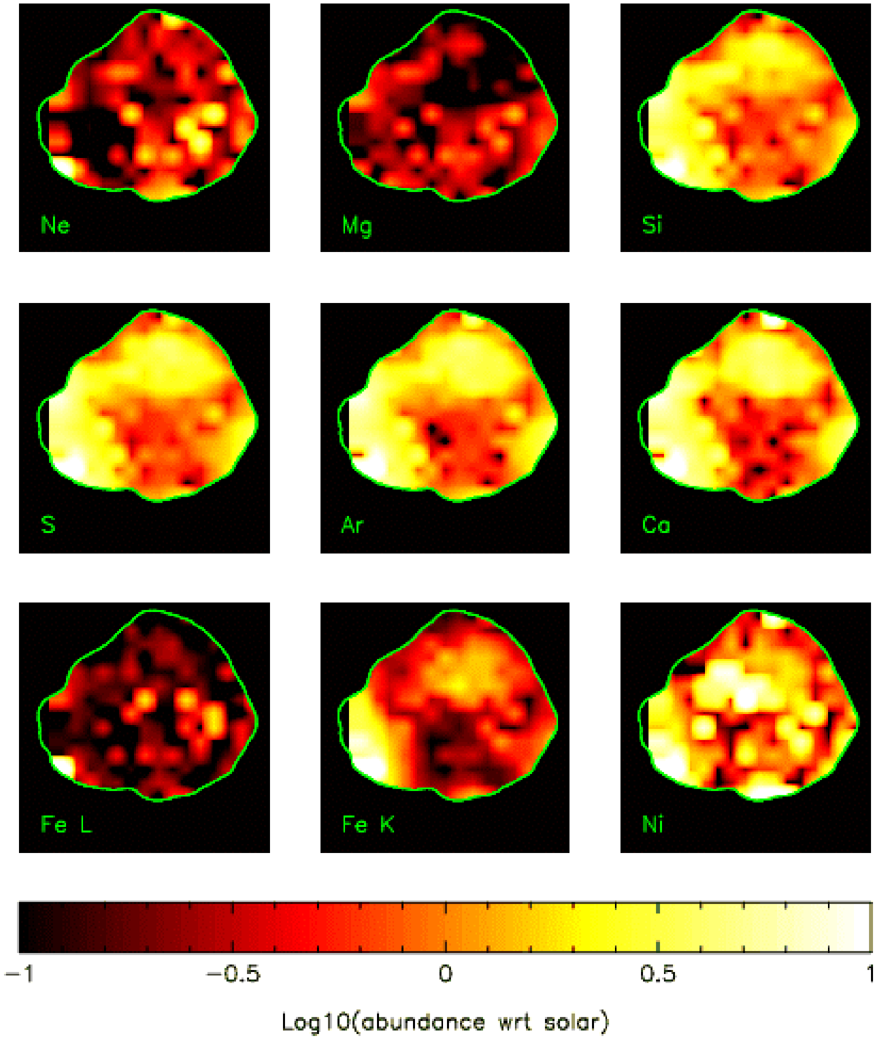
Cas A: Abundance maps



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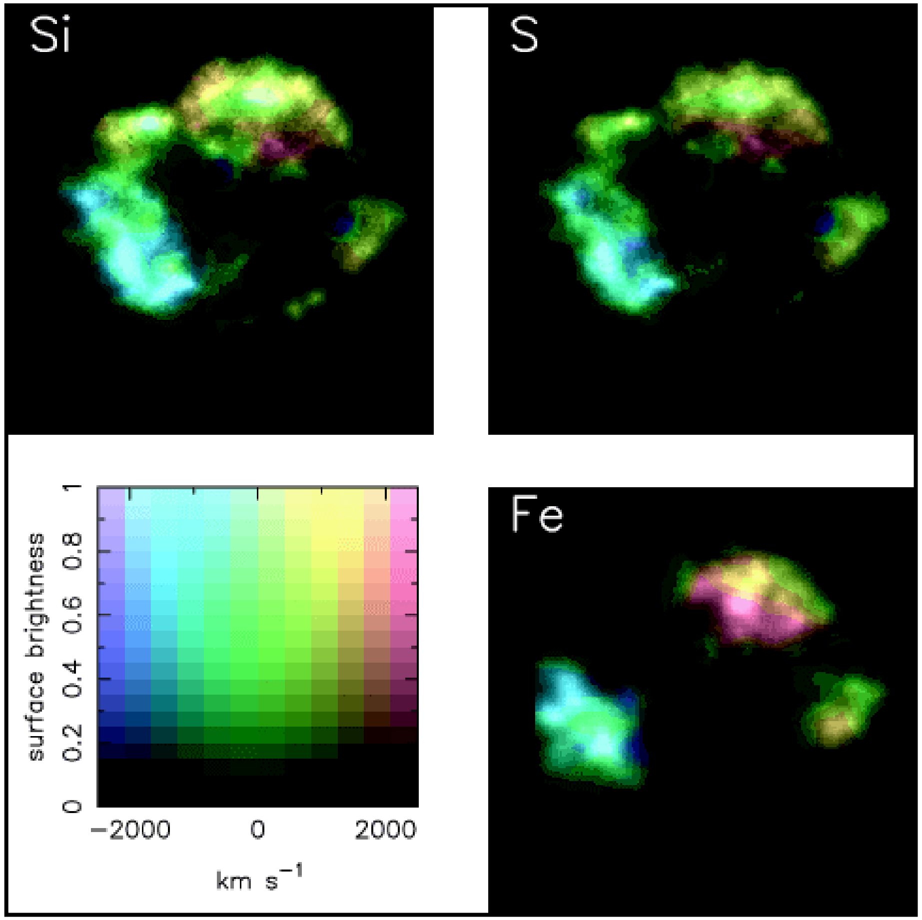
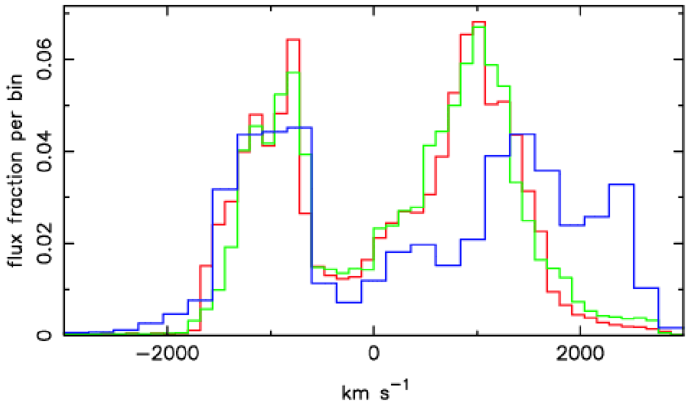
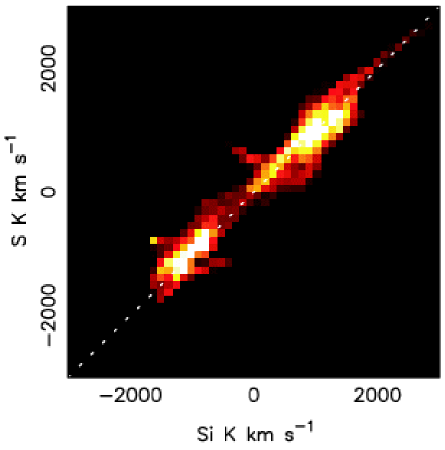
Doppler maps of Cas A from Si-K, S-K and Fe-K emission lines



Willingale et al 2002

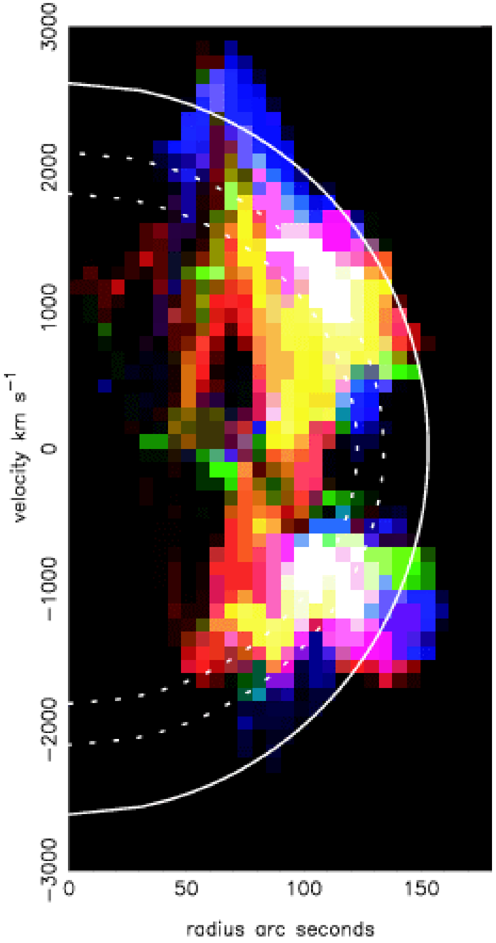
Cas A: Si-K , S-K and Fe-K fluxes vs Doppler velocity





Willingale et al 2002

Cas A: flux distributions of Si-K, S-K and Fe-K in radius velocity plane



Willingale et al 2002

Nuclear physics of precollapse

(Electron capture and beta decay)

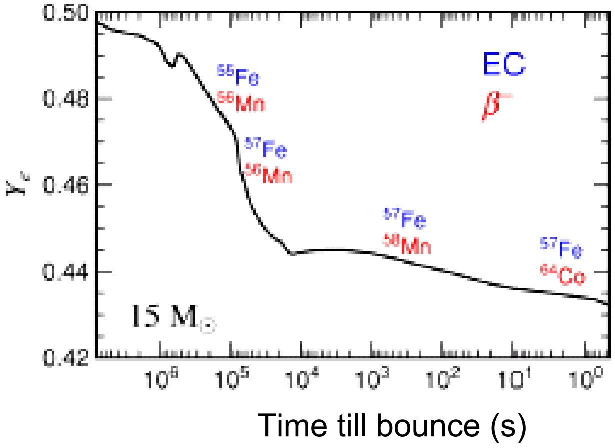
electron capture reduces the number of electrons
β-decay increases the number of electrons

changes Y_e=<Z/A>

both produce neutrinos; carry energy/entropy from the core

pressure Support affected

Langanke and Martinez-Pinedo



Nuclei in the fp-shell are Important: stable and unstable

Nuclear physics of precollapse

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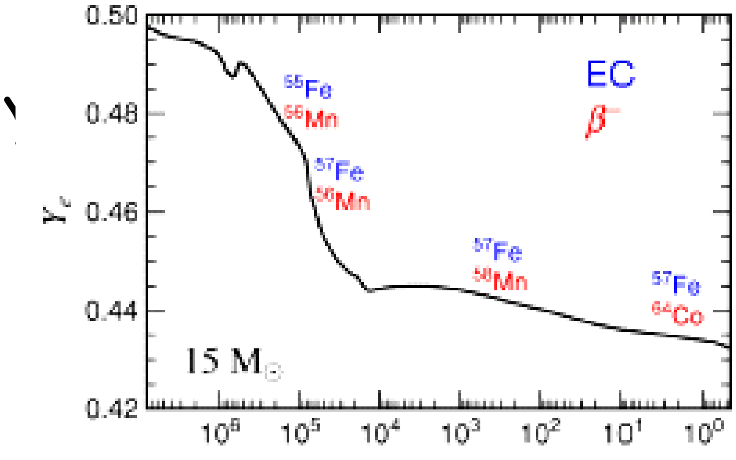


time till bounce

Langanke & Martinez-Pinedo

Up to pf shell nuclei (A~55-65) are important both stable and unstable

SN II (or CC): Collapse stage

Since neutrinos carry away entropy, composition is dominated by nuclei and not nucleons.

temperatures and densities are large enough to maintain nuclear statistical equilibrium (for given Y_e nuclei with highest binding are favored)

electron capture⇒Y_e decreases Þneutron-rich and heavy nuclei (β-decay)

nuclei with A~65-112, including N>40 and Z<40 (neutron shell-blocked nuclei)

EC and β-decay

Allowed transitions

- **Fermi** $\tau_{\pm}(i) = \Sigma\, \tau_{\pm}(i)$ **=>** $\Delta L = \Delta S = 0, \Delta T = 0, 1$
  0+ → 0+ (IAS dominates) Sum Rule: $\Sigma\beta^{-} - \Sigma\beta^{+} = N\text{-}Z$
- **β-decay**
- **Gamow-Teller** $\sigma\tau_{\pm} = \Sigma\, \sigma(i)\tau_{\pm}(i)$ => $\Delta L = 0, \Delta S = 1, \Delta T = 0, 1$
  $0^{+} \rightarrow 1^{+}$ **(Giant resonances) Sum Rule:** $\Sigma\beta^{-} - \Sigma\beta^{+} = 3(N\text{-}Z)$

- **EC and b-decay**

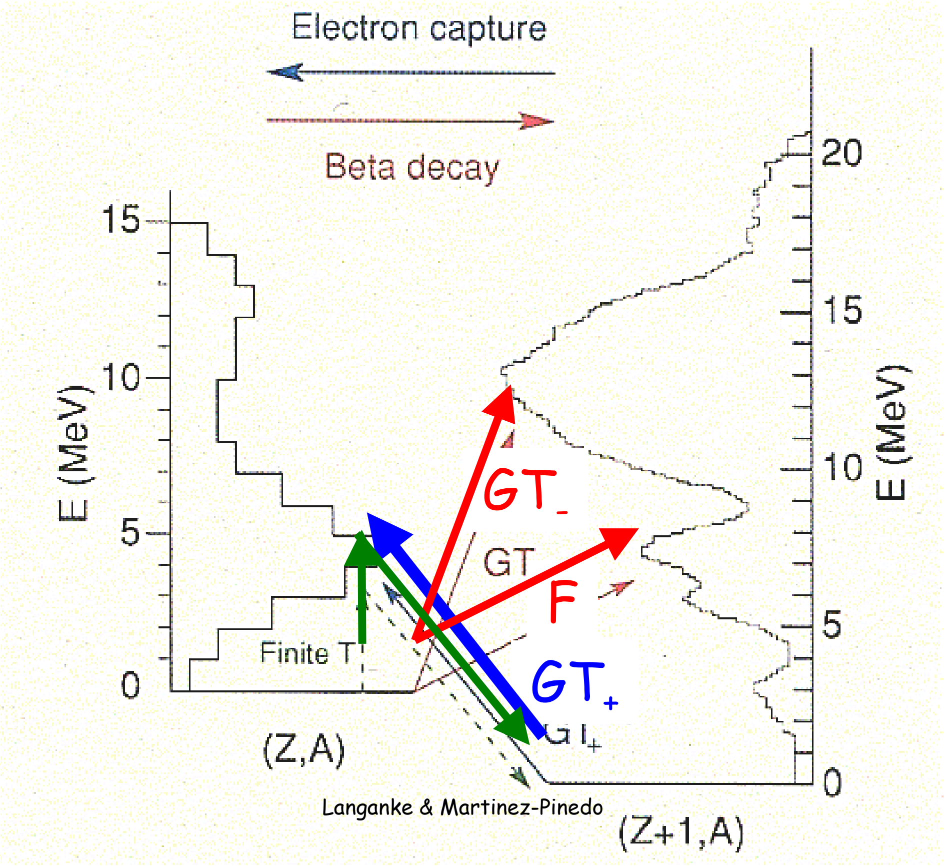
strength:

$$B(GT_{+}) = \sum_{i,f} \frac{n_i^p n_f^h}{(2j_i+1)(2j_f+1)} \boxed{\left|\left\langle f \middle| \vec{\sigma}\tau_{+} \middle| i \right\rangle\right|^2}$$

cross section in charge-exchange:

$$\frac{d\sigma}{d\Omega} = \left[\frac{\mu}{2\pi\hbar}\right]^2 \frac{k_f}{k_i} N_D \left|V_{\sigma\tau}\right|^2 \boxed{\left|\left\langle f \middle| \sum_k \sigma_k \tau_k \middle| i \right\rangle\right|^2}$$

EC and Beta-decay in stars



Langanke & Martinez-Pinedo

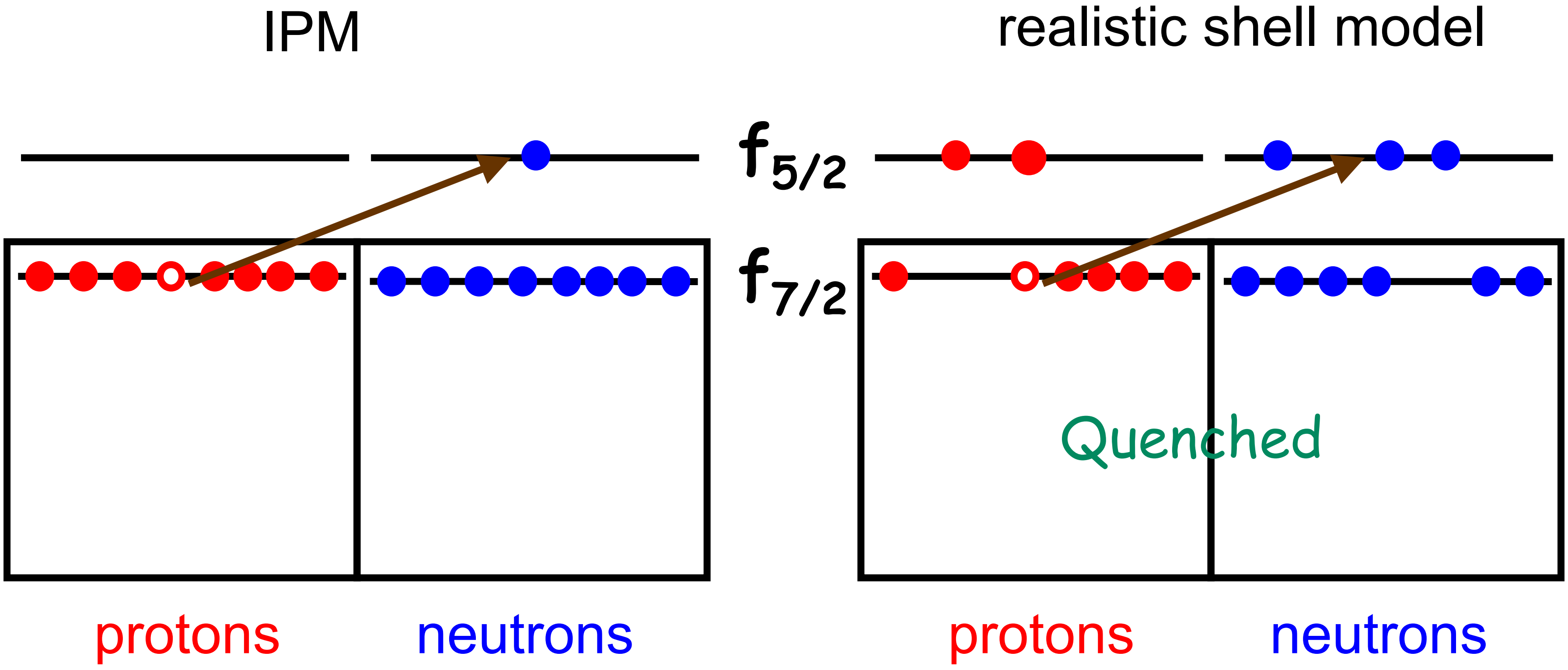
- Electrons in degenerate gas are sufficiently energetic to populate the GTR: GT_+
- F and GT_- outside the Q window; phase space for electron is blocked by electron gas
- due to finite temperature excited states are thermally populated and connect to low-lying states in the daughter with increased phase space (URCA reactions)

Estimating transition strengths

- Weak interaction rates by Fuller,Fowler,Newman (FFN) (1980-1985)
- Use experimental info from ground-state to low-lying excited states.
- Add collective strength via single particle representation determined via independent particle model (IPM)
- Experimental results [(p,n) and (n,p)] indicate:
- There is strong quenching for medium-heavy nuclei
- Fragmentation of strength
- Estimate strengths via Spectral Distribution Theory
- Make shell-model calculations
- Take into account residual interactions between valence nucleons

schematics

Example: $^{56}\mathrm{Ni}^{28+} \Rightarrow {}^{56}\mathrm{Co}^{27+}$



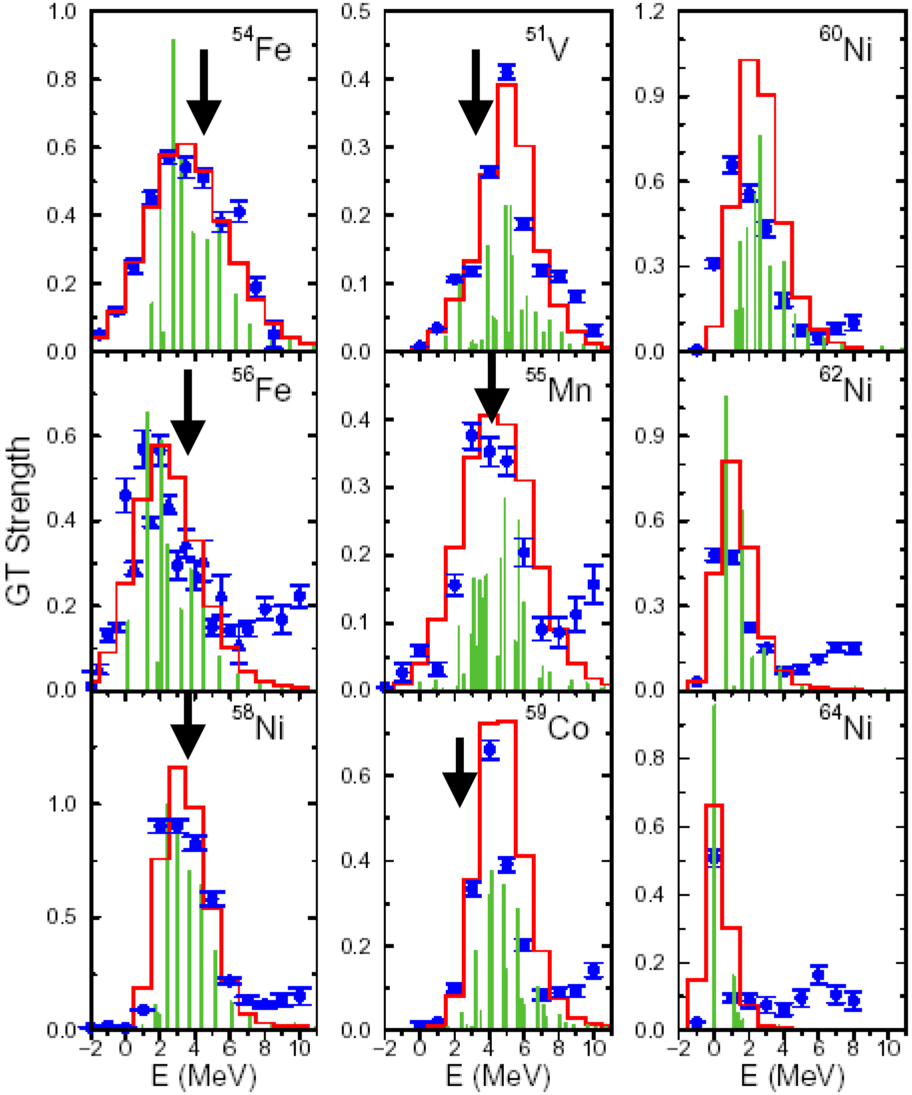
Large-scale shell-model calculations (A~55-65)

↓ : FFN (IPM model)

● : data (n,p) (TRIUMF)

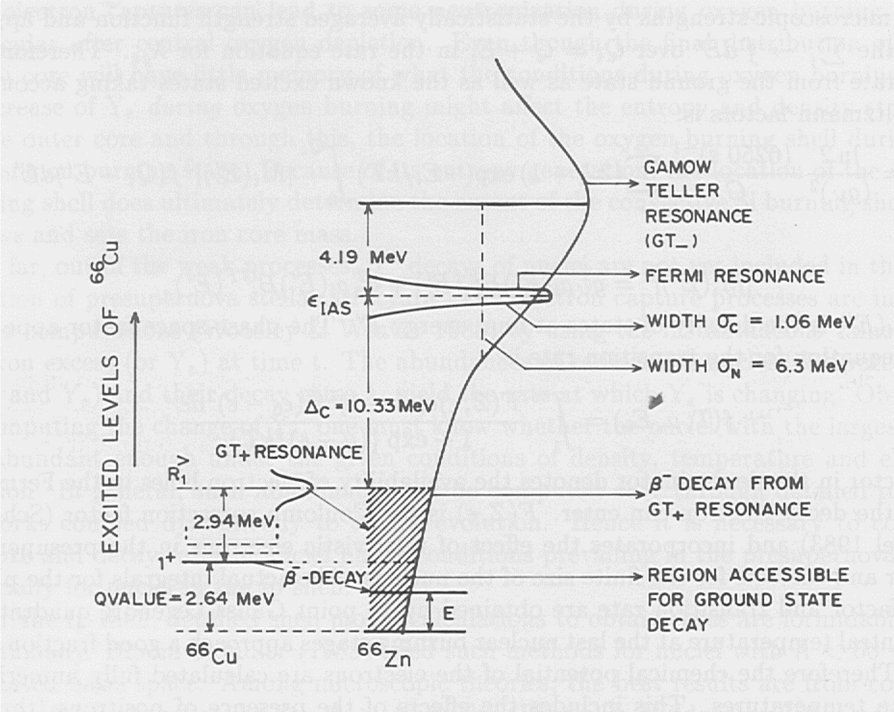
🟩 : Caurier et al. (1999) SM

🟥 : Caurier et al. folded with experimental resolution



Beta decay calculation of Cu66

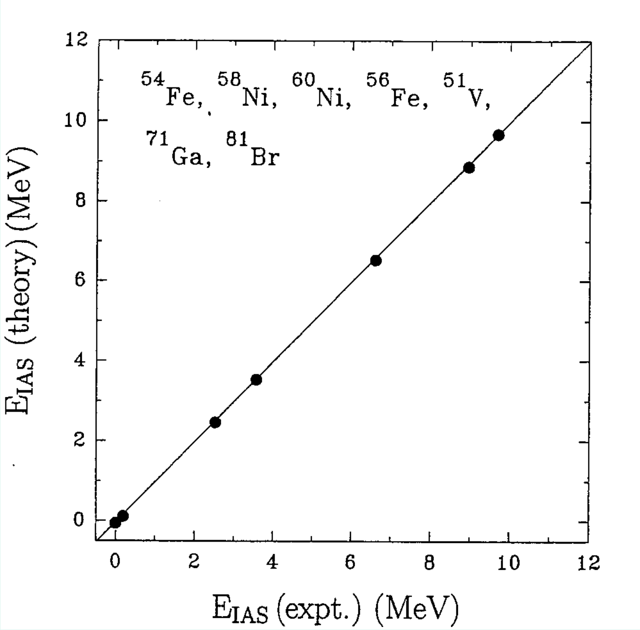
Using spectral distribution theory

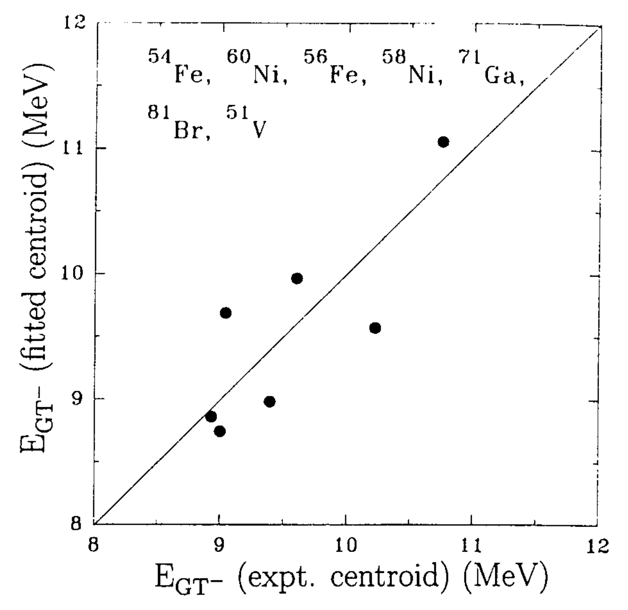


β^- - DECAY DIAGRAM FOR ^{66}Cu

Ray et al 1996
Kar et al 1998

Isobaric Analog States and Gamow-Teller transition centroids





$$E_{\mathrm{IAS}} = \Delta M_A - \Delta M_C - 0.7824 + \frac{1.728(Z_C - 1)}{R}\ \mathrm{MeV} \qquad (3)$$

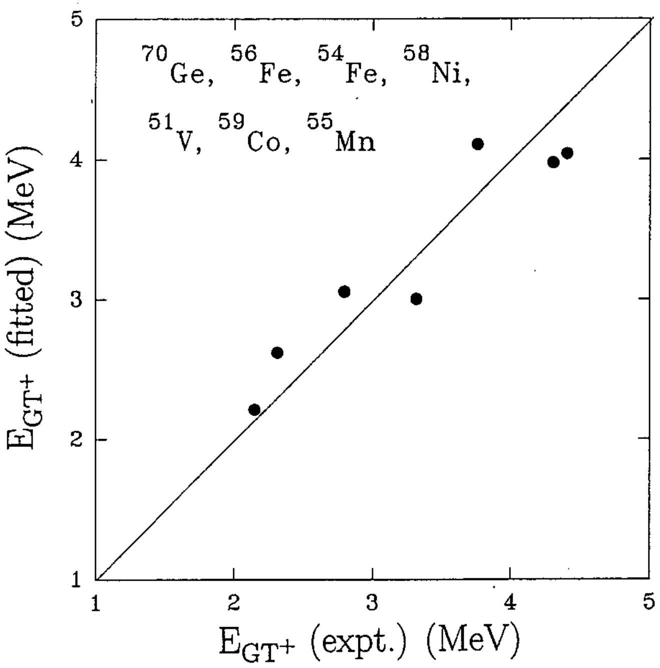
with

$$R = 1.12A^{1/3} + 0.78.$$

$$E_{\mathrm{GT}^-} - E_{\mathrm{IAS}} = 44.16A^{-1/3} - 76.1(N-Z)/A. \qquad (4)$$

Sutaria & Ray 1995

GT+ Centroids

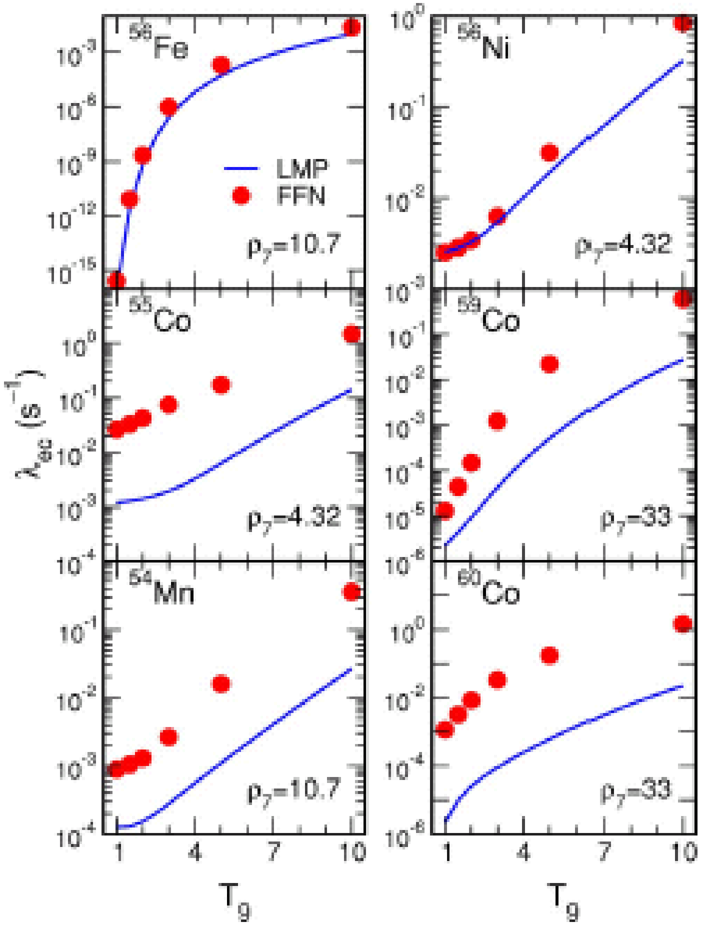


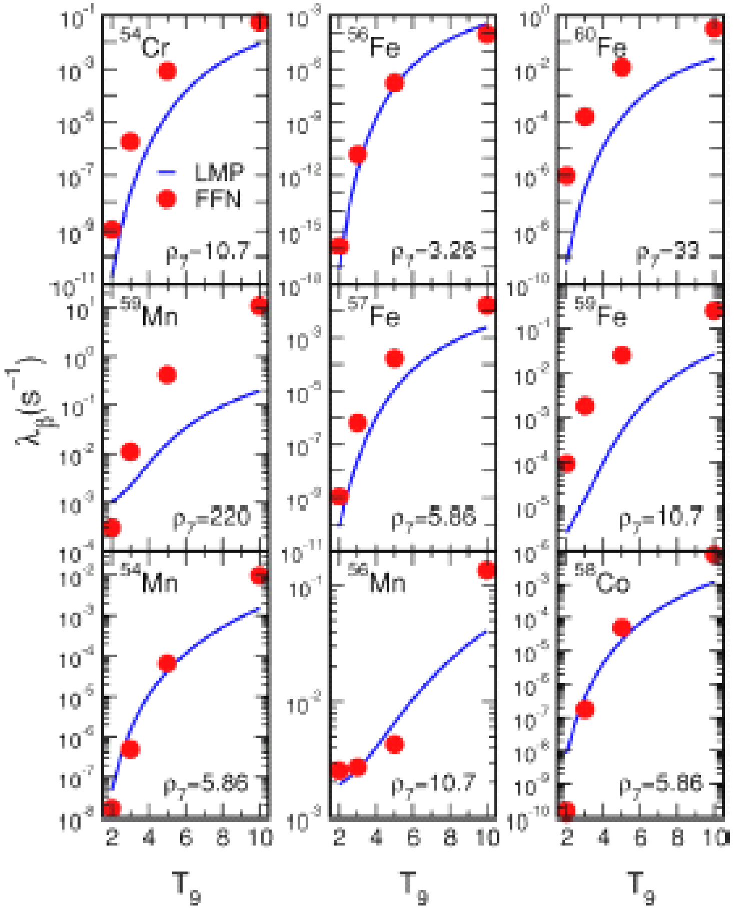
$$E_{GT^+} = 13.10A^{-1/3} - 11.28(N-Z)/A + 12A^{-1/2}\delta_{A_{odd}}. \tag{5}$$

Sutaria & Ray 1995

EC and Beta decay rates

EC



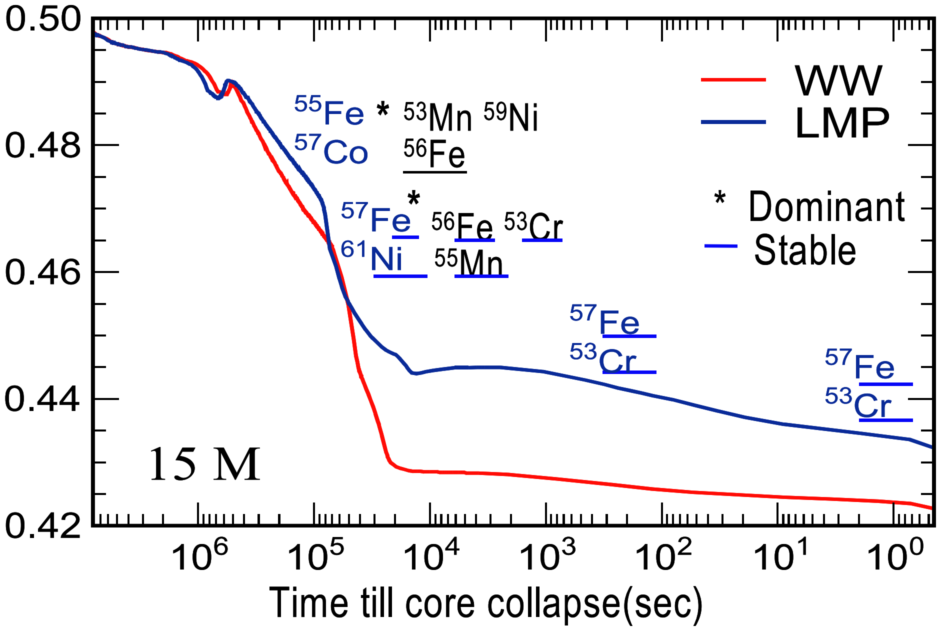


Beta Decay

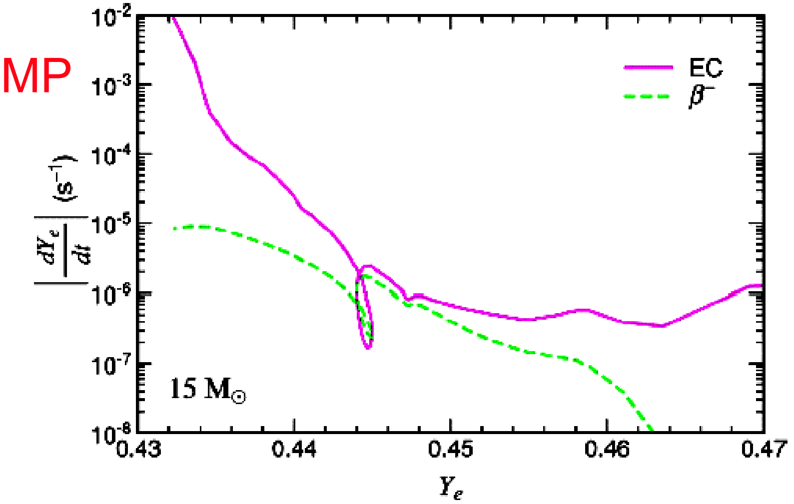
Martinez-Pinedo & Langanke (Shell-Model)

FFN ●

Effect of the rates on precollapse stage of SNII



LMP



WW: Woosley, Weaver (FFN)
LMP:Langanke, Martinez-Pinedo &
Heger, Langanke (SM)

Beta decay Counteracts Y_e reduction
But leads to Cooling, reduction of entropy

Neutrino emission during galactic stellar core collapse and signals in SK and SNO at 1 kpc

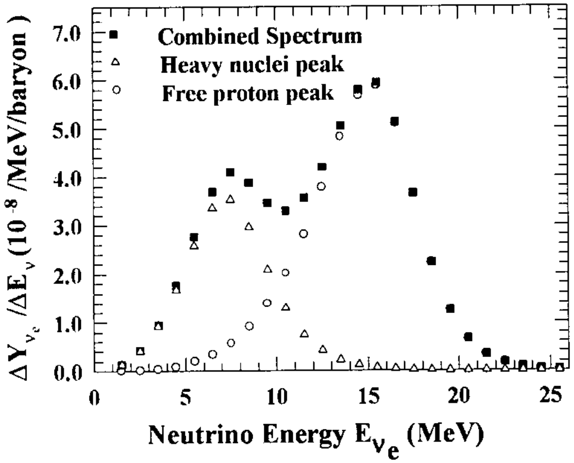


FIG. 1. "Snapshot" neutrino spectrum (change in electron fraction MeV^{-1} per baryon in a narrow density interval $\Delta\rho_{10} = 0.0002$ around mean one-zone $\rho_{10} = 9.8668\ \mathrm{g\,cm^{-3}}$ for a $15 M_\odot$ star and $|M_{\mathrm{GT}}|^2 = 1.2$ and later 0.1.

Sutaria & Ray 1997

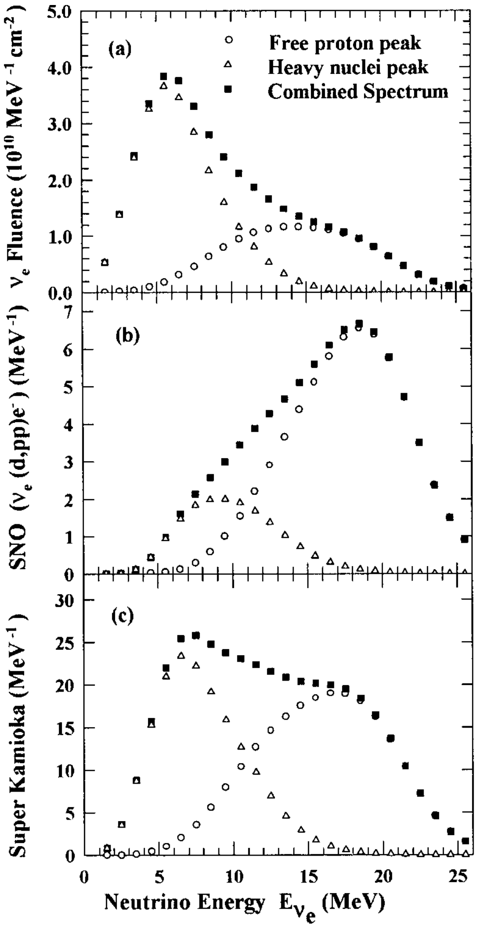
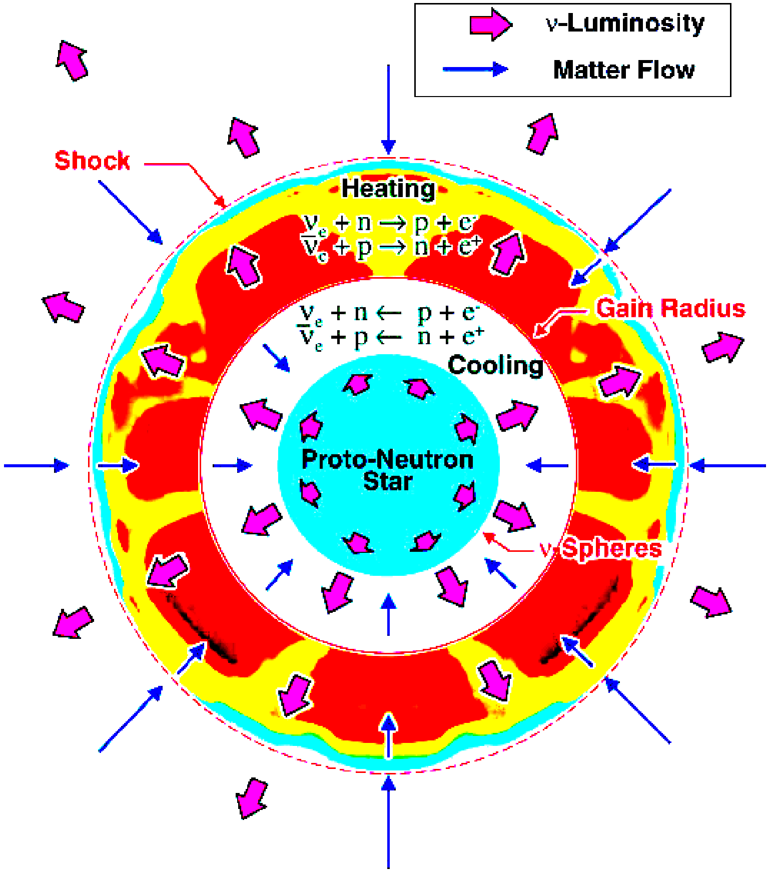


FIG. 2. (a) Cumulative neutrino fluence up to $\rho_{10} = 24.16\ \mathrm{g\,cm^{-3}}$, with $M = 15 M_\odot$, $D = 1$ kpc, and $|M_{\mathrm{GT}}|^2 = 1.2$ and later 0.1. (b) The spectrum in (a) folded with the detection cross section for c.c. reaction $\nu_e(d, pp)e^-$ in SNO. (c) The spectrum in (a) folded with the detection cross section for ν_e-e^- scattering in Super-Kamioka.

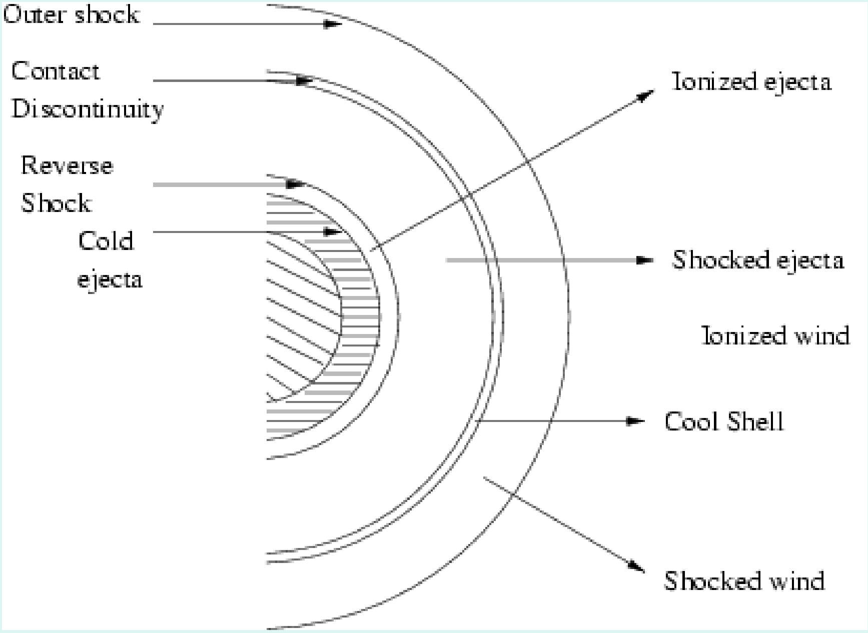
Stellar core bounce and explosion and neutrino emission



C. Cardall 2004

After the explosion

Polluters of the environment

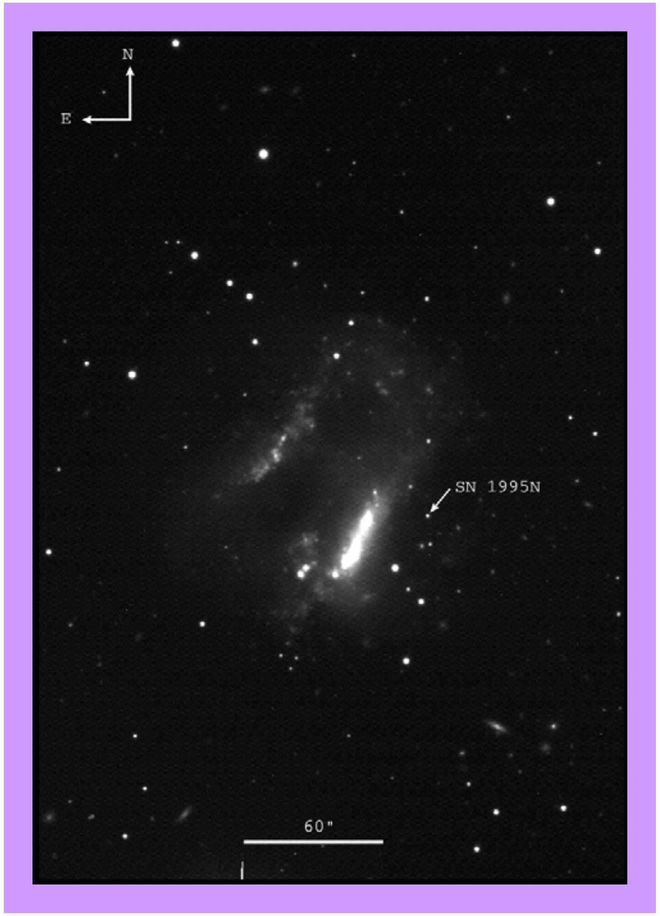


Supernova 1995N at an extragalactic distance

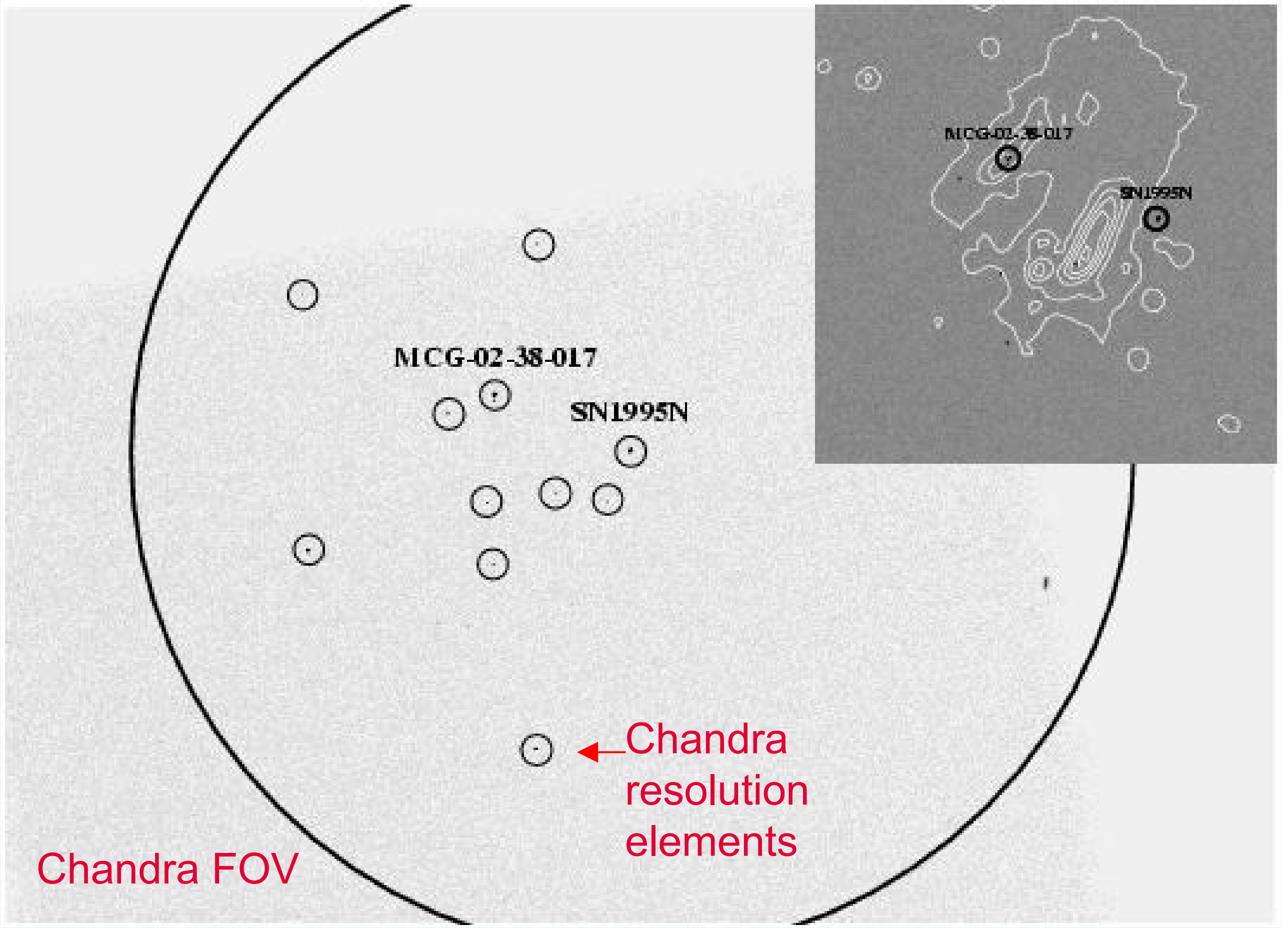
SN 1995N

Discovered on 1995 May 5

Parent Galaxy is at a distance D= 24 Mpc (MCG-02-38-017)



Extragalactic SN 1995N observed with Chandra and ASCA



Optical Contours Overlaid On Chandra image

Chandra resolution elements

Chandra FOV

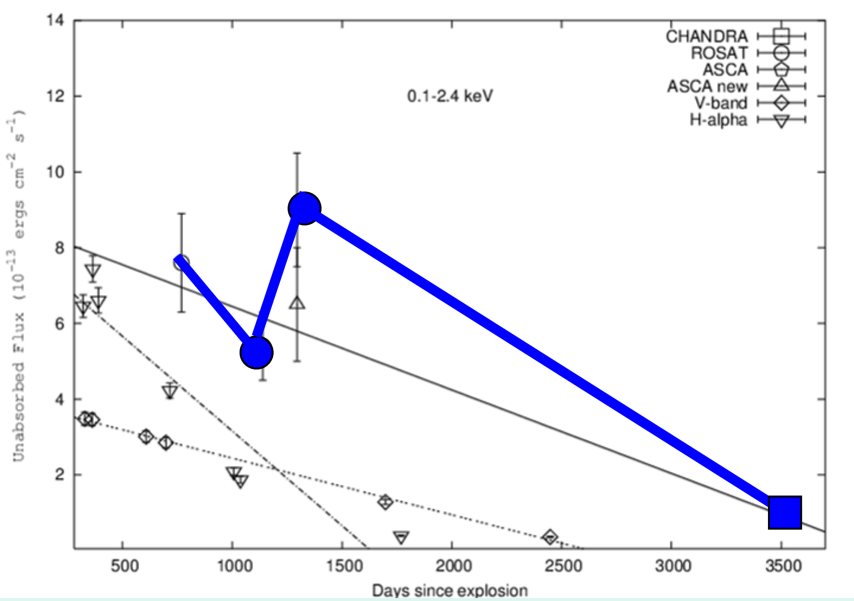
P. Chandra et al 2005

SN 1995N Chandra Observations (March 2004)

Total counts	758 counts
Temperature	2.35 keV
Absorption column Depth	1.5×10^{21} cm^{-2}
0.1-2.4 keV Unabsorbed flux	$0.6\text{-}1.0 \times 10^{-13}$ erg cm^{-2} s^{-1}
0.5-7.0 keV Unabsorbed flux	$0.8\text{-}1.3 \times 10^{-13}$ erg cm^{-2} s^{-1}
Luminosity (0.1-10 keV)	2×10^{40} erg s^{-1}

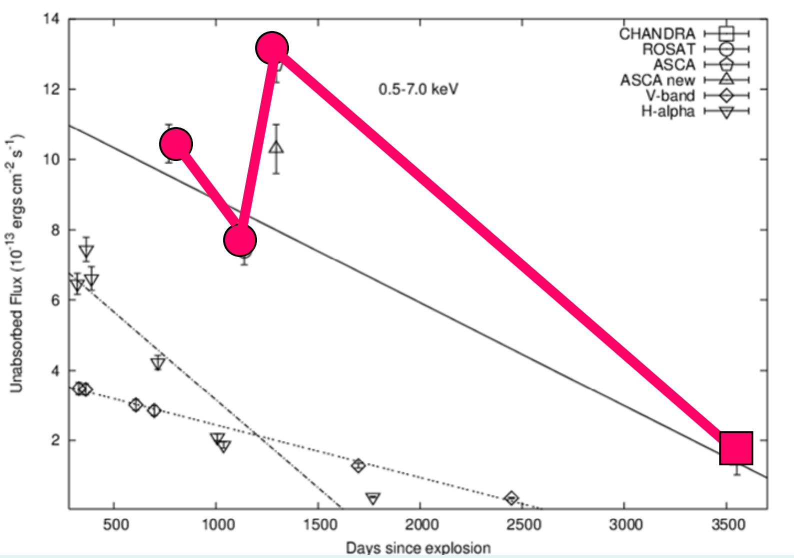
P. Chandra et al, 2005

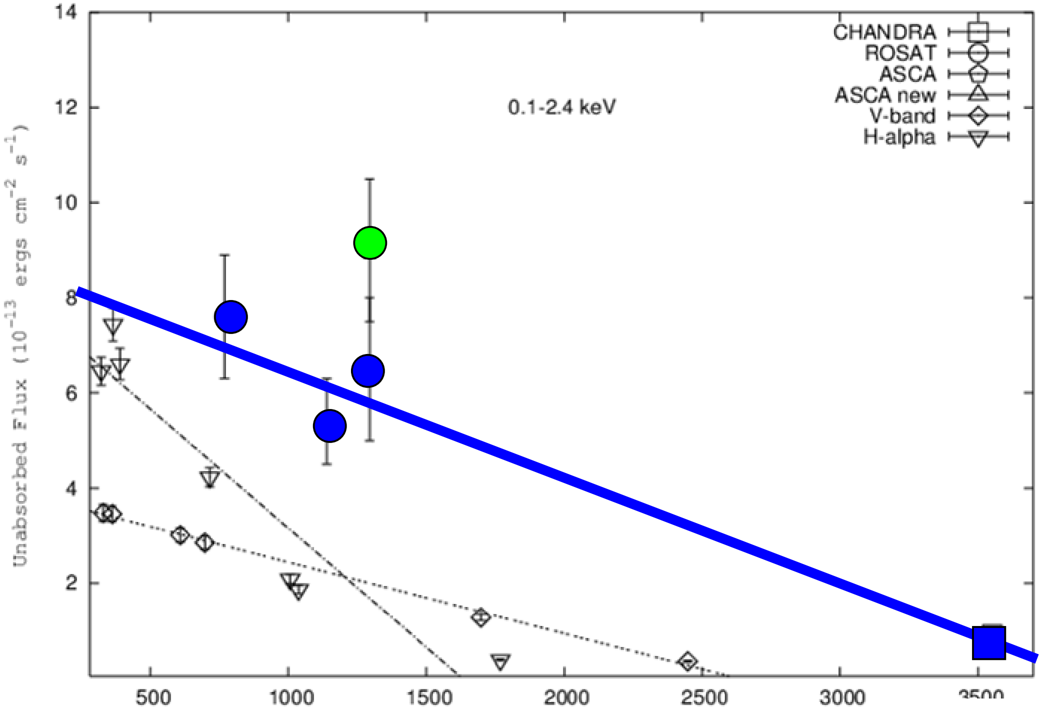
SN 1995N light curve with low angular resolution



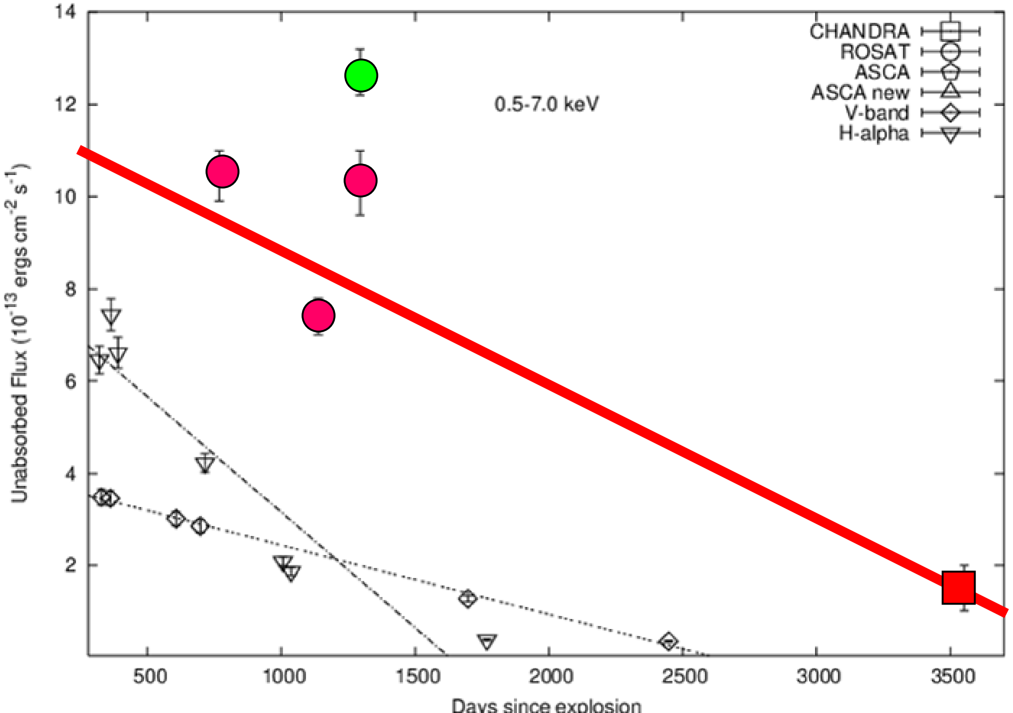
ROSAT BAND (0.1-2.4 keV)

ASCA BAND (0.5-7.0 keV)





ROSAT BAND (0.1-2.4 keV)

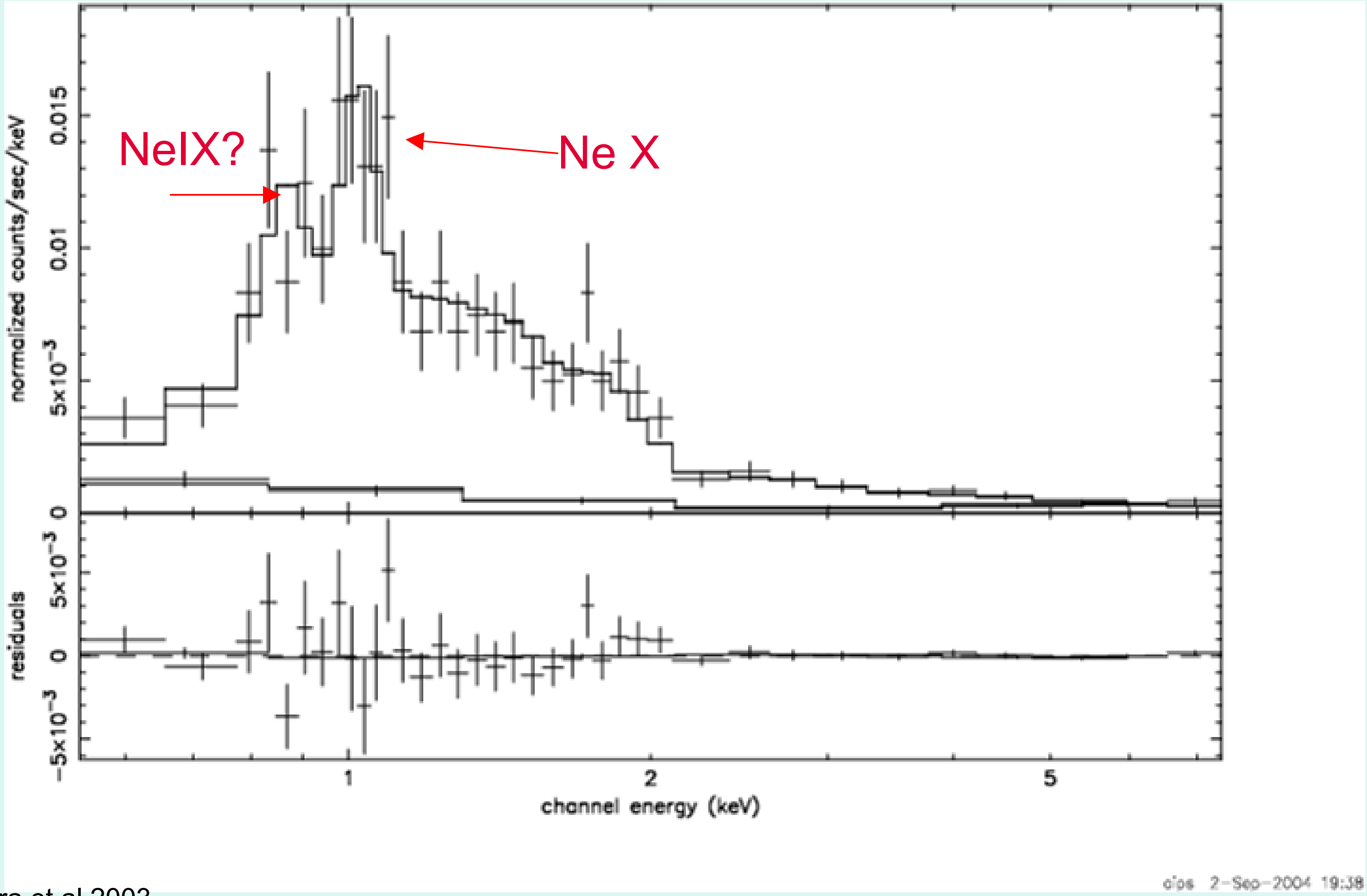


ASCA BAND (0.5-7.0 keV)

17 J

Poonam Chandra et al 2005

SN 1995N X-ray Spectrum with Chandra



NeIX?

Ne X

P. Chandra et al 2003

X-ray the innards of a massive star

(SN 1995N)

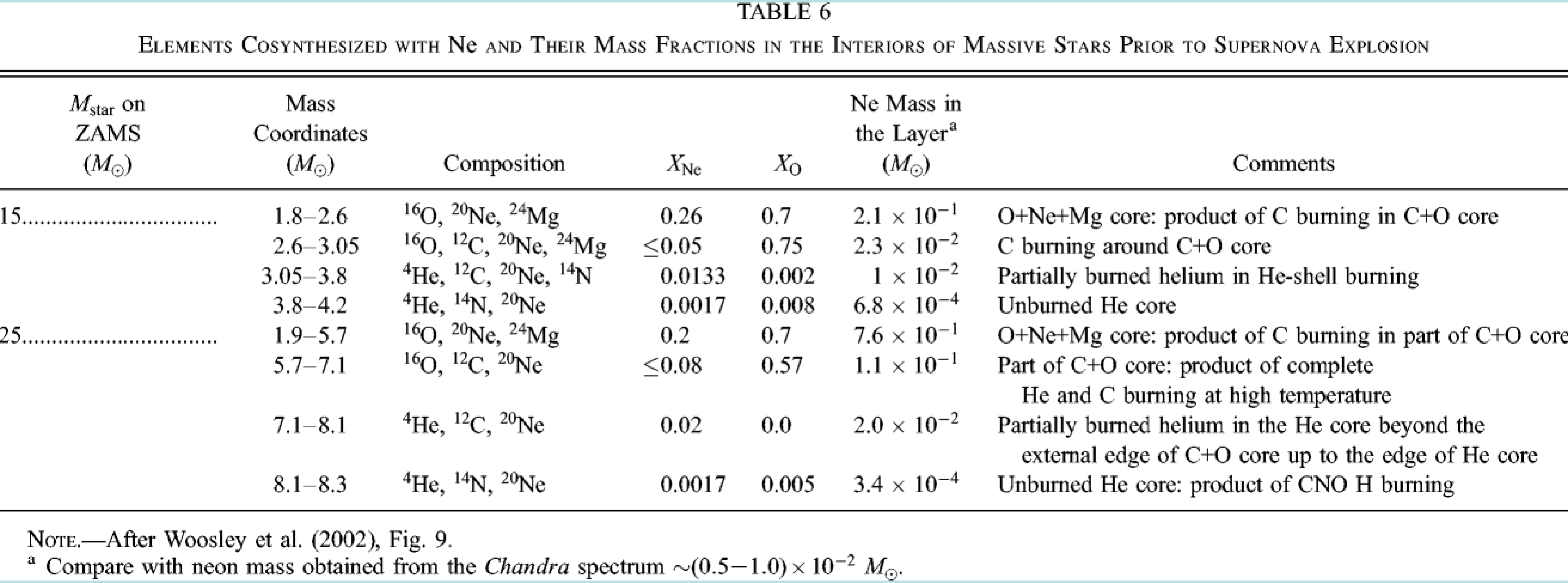


TABLE 6

Elements Cosynthesized with Ne and Their Mass Fractions in the Interiors of Massive Stars Prior to Supernova Explosion

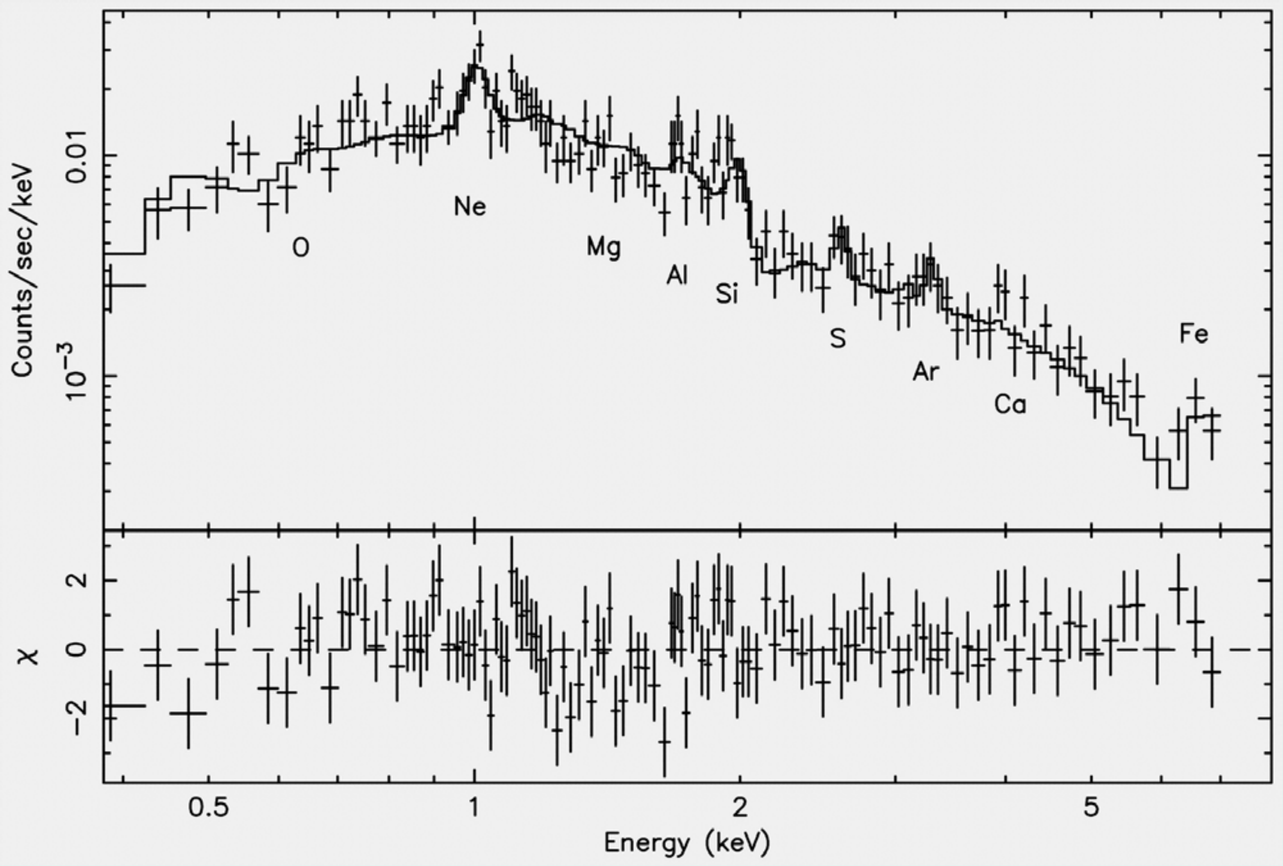
$M_{\rm star}$ on ZAMS ($M_\odot$)	Mass Coordinates ($M_\odot$)	Composition	$X_{\rm Ne}$	$X_{\rm O}$	Ne Mass in the Layer[a] ($M_\odot$)	Comments
15................................	1.8–2.6	^{16}O, ^{20}Ne, ^{24}Mg	0.26	0.7	2.1×10^{-1}	O+Ne+Mg core: product of C burning in C+O core
	2.6–3.05	^{16}O, ^{12}C, ^{20}Ne, ^{24}Mg	$\leq$0.05	0.75	2.3×10^{-2}	C burning around C+O core
	3.05–3.8	^{4}He, ^{12}C, ^{20}Ne, ^{14}N	0.0133	0.002	1×10^{-2}	Partially burned helium in He-shell burning
	3.8–4.2	^{4}He, ^{14}N, ^{20}Ne	0.0017	0.008	6.8×10^{-4}	Unburned He core
25................................	1.9–5.7	^{16}O, ^{20}Ne, ^{24}Mg	0.2	0.7	7.6×10^{-1}	O+Ne+Mg core: product of C burning in part of C+O core
	5.7–7.1	^{16}O, ^{12}C, ^{20}Ne	$\leq$0.08	0.57	1.1×10^{-1}	Part of C+O core: product of complete He and C burning at high temperature
	7.1–8.1	^{4}He, ^{12}C, ^{20}Ne	0.02	0.0	2.0×10^{-2}	Partially burned helium in the He core beyond the external edge of C+O core up to the edge of He core
	8.1–8.3	^{4}He, ^{14}N, ^{20}Ne	0.0017	0.005	3.4×10^{-4}	Unburned He core: product of CNO H burning

Note.—After Woosley et al. (2002), Fig. 9.

[a] Compare with neon mass obtained from the *Chandra* spectrum $\sim(0.5-1.0) \times 10^{-2}\ M_\odot$.

P. Chandra et al 2005

X-ray spectrum of SN 1998S



Pooley et al 2002

Elements synthesis in SN 1998S

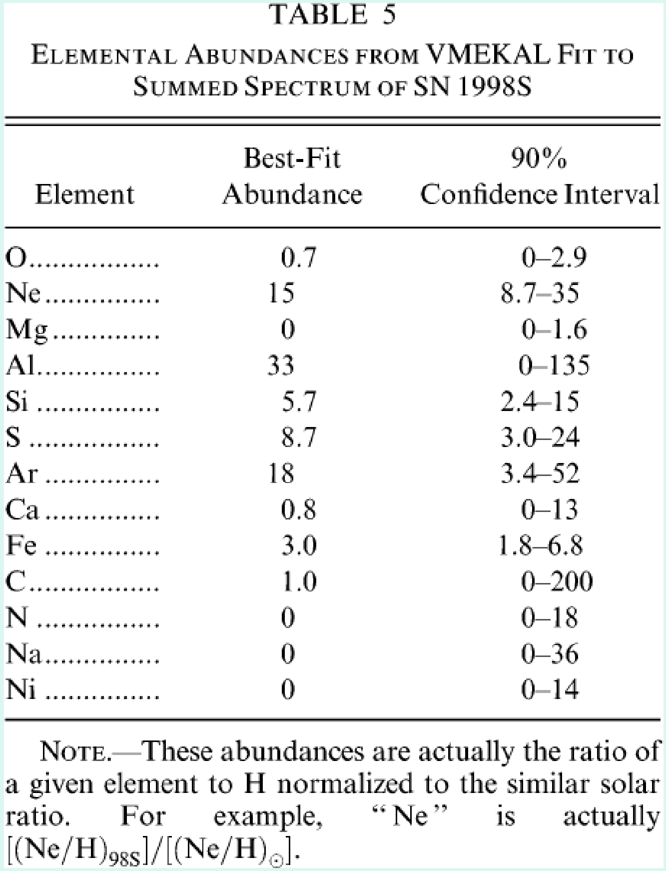


TABLE 5

ELEMENTAL ABUNDANCES FROM VMEKAL FIT TO SUMMED SPECTRUM OF SN 1998S

Element	Best-Fit Abundance	90% Confidence Interval
O	0.7	0–2.9
Ne	15	8.7–35
Mg	0	0–1.6
Al	33	0–135
Si	5.7	2.4–15
S	8.7	3.0–24
Ar	18	3.4–52
Ca	0.8	0–13
Fe	3.0	1.8–6.8
C	1.0	0–200
N	0	0–18
Na	0	0–36
Ni	0	0–14

NOTE.—These abundances are actually the ratio of a given element to H normalized to the similar solar ratio. For example, "Ne" is actually $[(\mathrm{Ne/H})_{98S}]/[(\mathrm{Ne/H})_{\odot}]$.

Pooley et al 2002

Abundance ratios and constraints on progenitor mass of SN 1998S

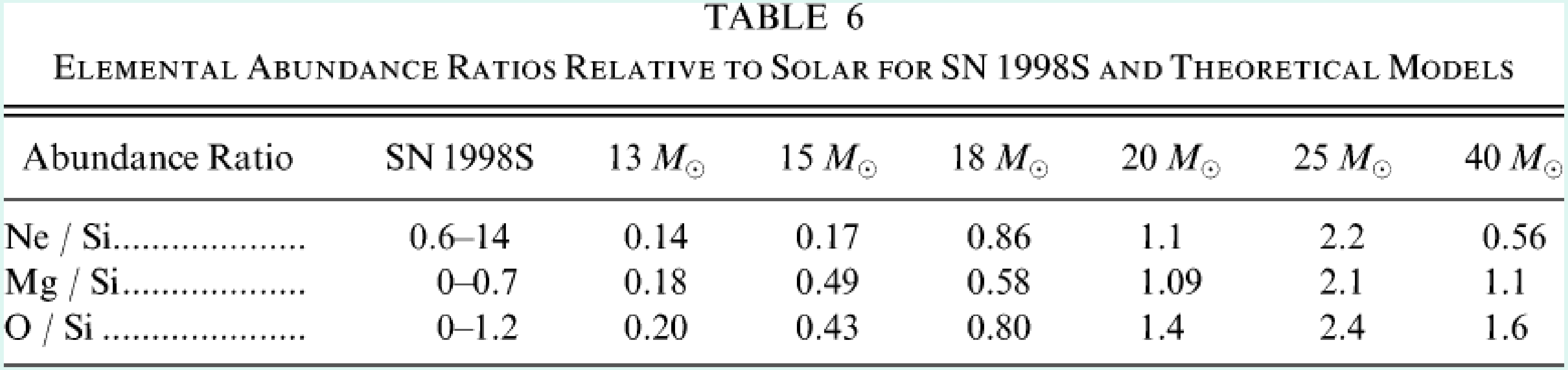


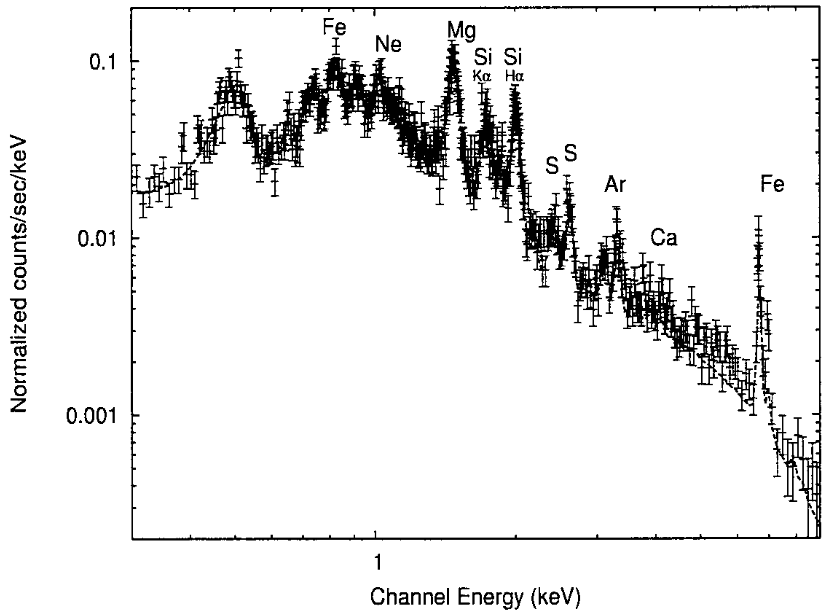
TABLE 6

ELEMENTAL ABUNDANCE RATIOS RELATIVE TO SOLAR FOR SN 1998S AND THEORETICAL MODELS

Abundance Ratio	SN 1998S	13 $M_\odot$	15 $M_\odot$	18 $M_\odot$	20 $M_\odot$	25 $M_\odot$	40 $M_\odot$
Ne / Si....................	0.6–14	0.14	0.17	0.86	1.1	2.2	0.56
Mg / Si....................	0–0.7	0.18	0.49	0.58	1.09	2.1	1.1
O / Si	0–1.2	0.20	0.43	0.80	1.4	2.4	1.6

D. Pooley et al 2002

XMM spectrum of SN1993J (synthetic)



Line	E_{rest} keV	Band keV	N_{line} counts	ΔE_N eV	ΔE_{cont} eV	ΔV km s^{-1}
Si-K	1.74	1.72-1.96	1900	2.5	2.4	425
S-K	2.31	2.29-2.58	600	1.6	2.5	475
Fe-K	6.40	6.20-6.92	110	14.0	1.8	600

Accepted observing proposal on XMM:
A.R. , P. Chandra et al, 2006

Summary

- Neutrino driven winds may be the site of r-process nucleosynthesis in supernova
- Weak interaction processes (EC and Beta decays are important for presupernova structure
- Many types of nuclear reactions are important in determining the composition of the debris
- Supernovae enrich the interstellar medium with heavy elements from which new stars form

Thanks !

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  Poonam Chandra
  Firoza Sutaria
  Sukhendu Sarkar
  Eric Schlegel
  Wolfgang Pitesch
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- Roger Chevalier
- Claes Fransson
- Ken'ichi Nomoto
- Bernd Aschenbach
- Stefan Immler
- Soumya Chakravarti

Nucleosynthesis in the r-process

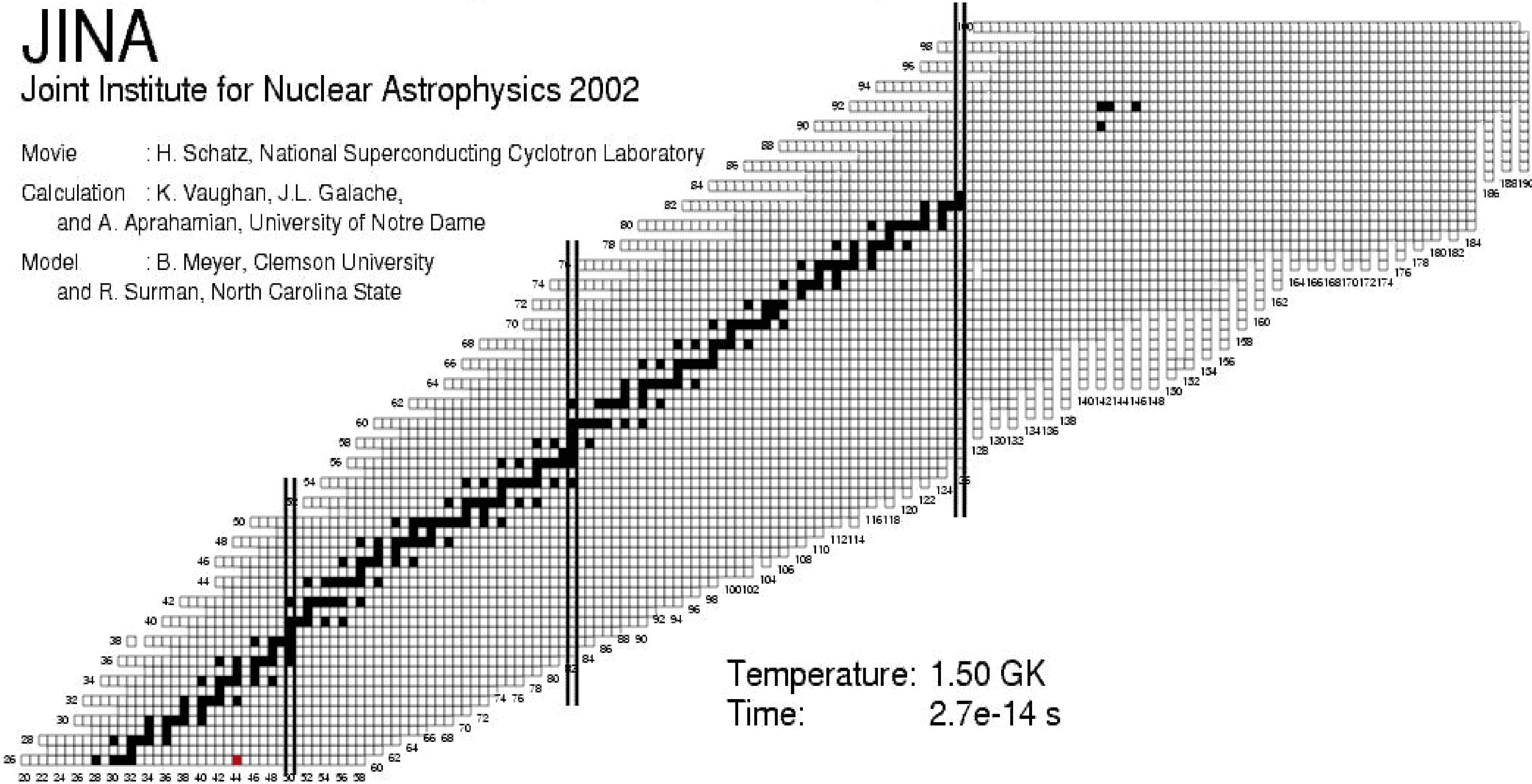
JINA

Joint Institute for Nuclear Astrophysics 2002

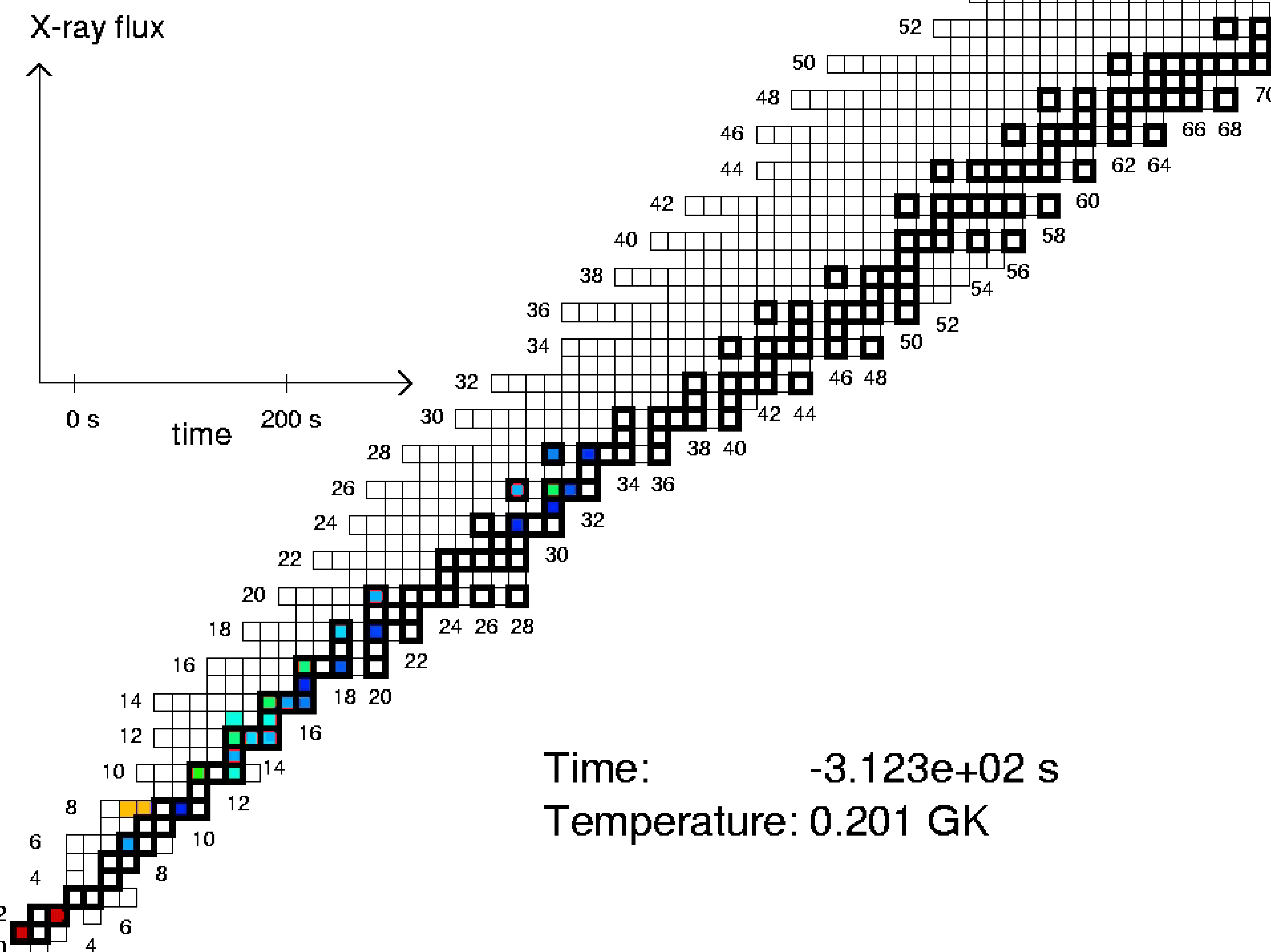
Movie : H. Schatz, National Superconducting Cyclotron Laboratory

Calculation : K. Vaughan, J.L. Galache,
and A. Aprahamian, University of Notre Dame

Model : B. Meyer, Clemson University
and R. Surman, North Carolina State



Temperature: 1.50 GK
Time: 2.7e-14 s


X-ray flux
0 s
time
200 s
Time: -3.123e+02 s
Temperature: 0.201 GK
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