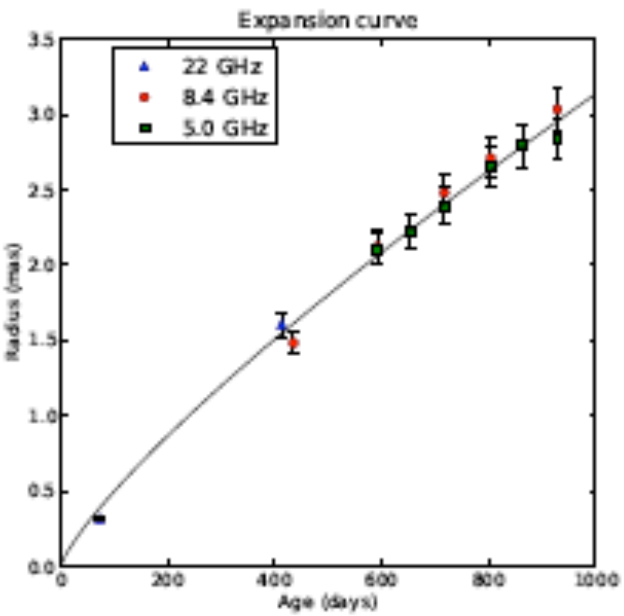
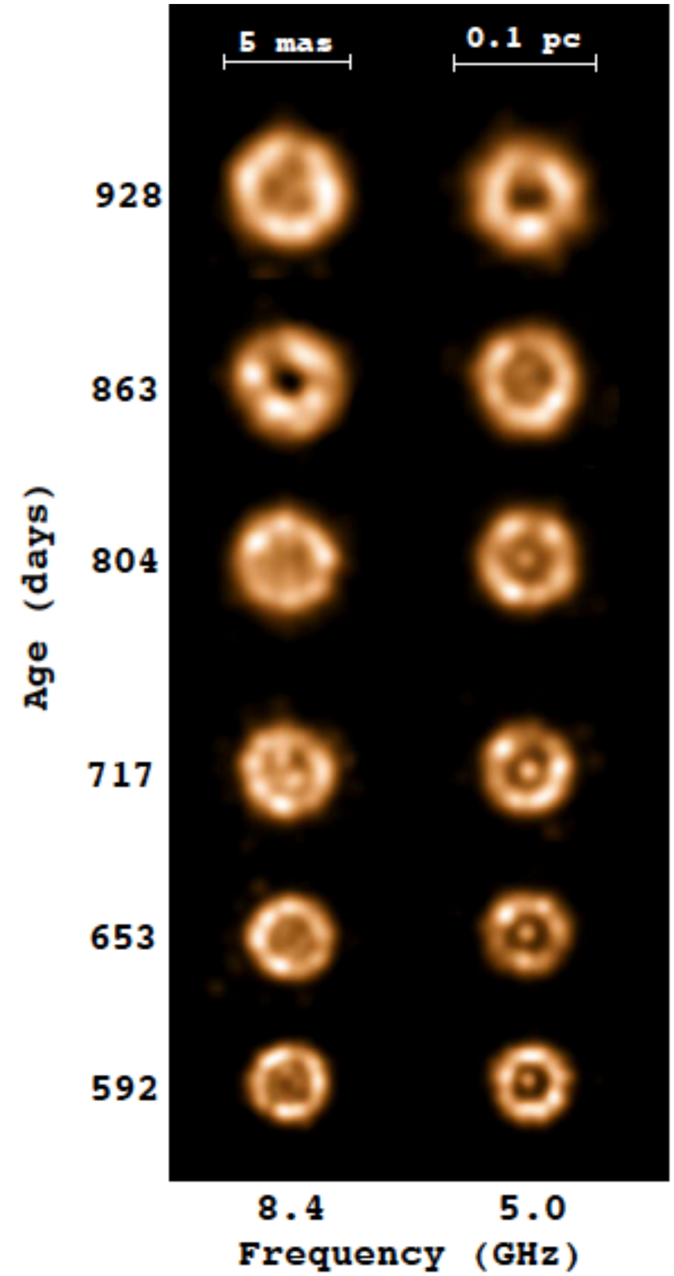
Super Nova and Super Nova Remnants

- Types of Super Nova
- Explosions
- Nucleosynthesis
- Physics of Supernova remnants
- Particle Acceleration
- Cosmology?

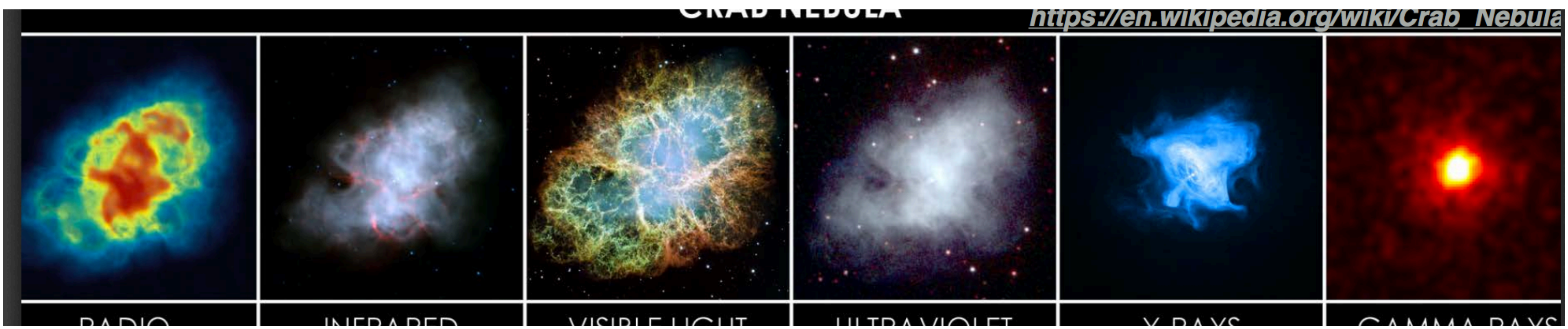




Radio images of SN2008 in M82 +Size vs time

SNR are multi-wavelength objects

- SNR appearance depends on SN and the surrounding medium and age –SNR diameter is not a proxy for age
- X-ray-primary shock physics, thermal content, ISM density, ejecta abundances
- Optical- secondary shock physics, densities and (occasionally) shock speed and abundances
- Radio- particle acceleration
- To understand SNRs as a class, high quality data are required at multiple wavelengths



Why Study Supernova Remnants?

Supernova explosion:
How is mass and energy distributed in the ejecta?
What was the mechanism of the supernova explosion?
What and (how much) elements were formed in the explosion, and how?
What are the characteristics of the compact stellar remnant?

Shock physics:
How is energy distributed between electrons, ions, and cosmic rays in the shock?
How do electrons and ions share energy behind the shock?

Interstellar medium: SN 'Control' the structure of the ISM- Yesterdays talk
What is the structure of the interstellar medium, and how does the shock interact with that structure?
How is the ISM enriched and ionized

Supernovae and Supernova Remnants

Supernovae

T~ 5000 K charcteristic kT of photospheric emission during early period

characteristic emission is optical and infrared

timescale ~ year

Supernova remnants

powered by expansion energy of supernova ejecta,

dissipated as the debris collides with interstellar material generating shocks

$T \sim 10^{6-7}$ K

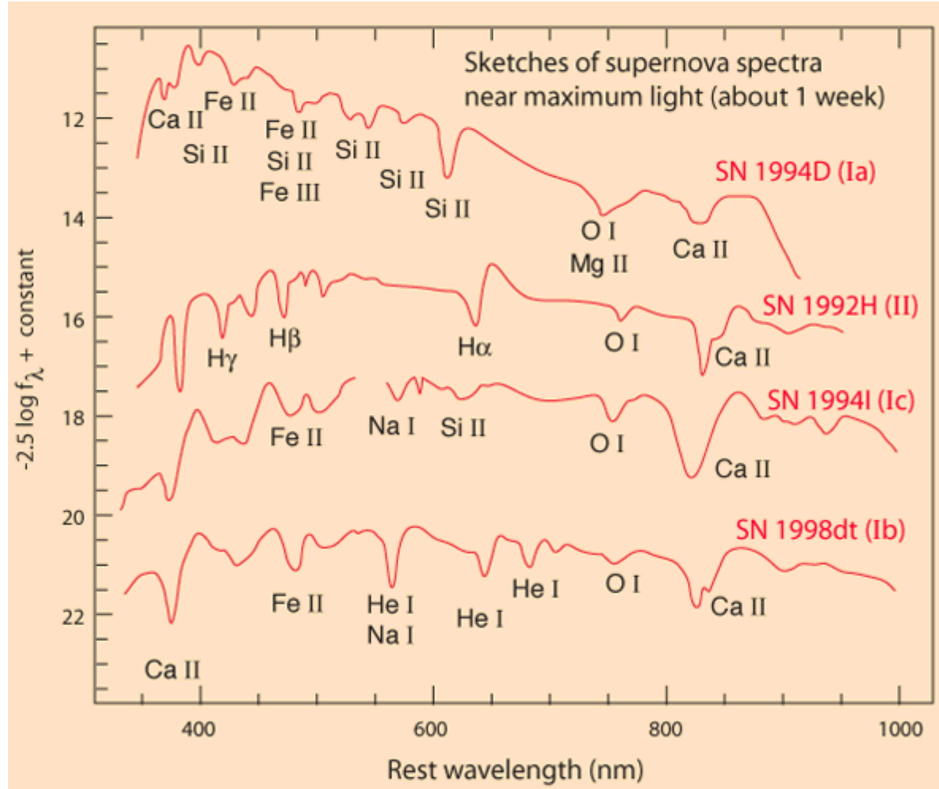
characteristic thermal emission is X-rays

timescale ~100-10,000 years

Supernova- See Ch 4 (sec 4.1-4.3 of Rosswog and Bruggen

- Supernova come in two types (I and II)
  - Type Ia is the explosion of a white dwarf pushed over the Chandrasekar limit- details are not understood
    - However they are used as a 'standard candle' for cosmology
  - Type Ib and II is the explosion of a massive star after it has used up its nuclear fuel
- Type I supernovae do not show hydrogen in their spectra. Type Ia supernovae reach peak luminosities of about 2×10^{43} erg/s
- Type II supernovae show hydrogen in their spectra. Their light curves are rather diverse, and their peak luminosities are around 10^{42} erg/s

- I – No H in spectrum
  - Ia : No He either, but characteristic Si absorption
  - Ib: He, as well as intermediate mass elements, O, Mg, Ca I
  - Ic: No He, but intermediate elements
- II – Strong H in spectrum
  - II-P : plateau in light curve
  - II-L: linear decline after maximum
  - IIn: narrow multiple H lines



Sketches of spectra from Carroll & Ostlie, data attributed to Thomas Matheson of National Optical Astronomy Observatory.

K. Long

Type Ia's

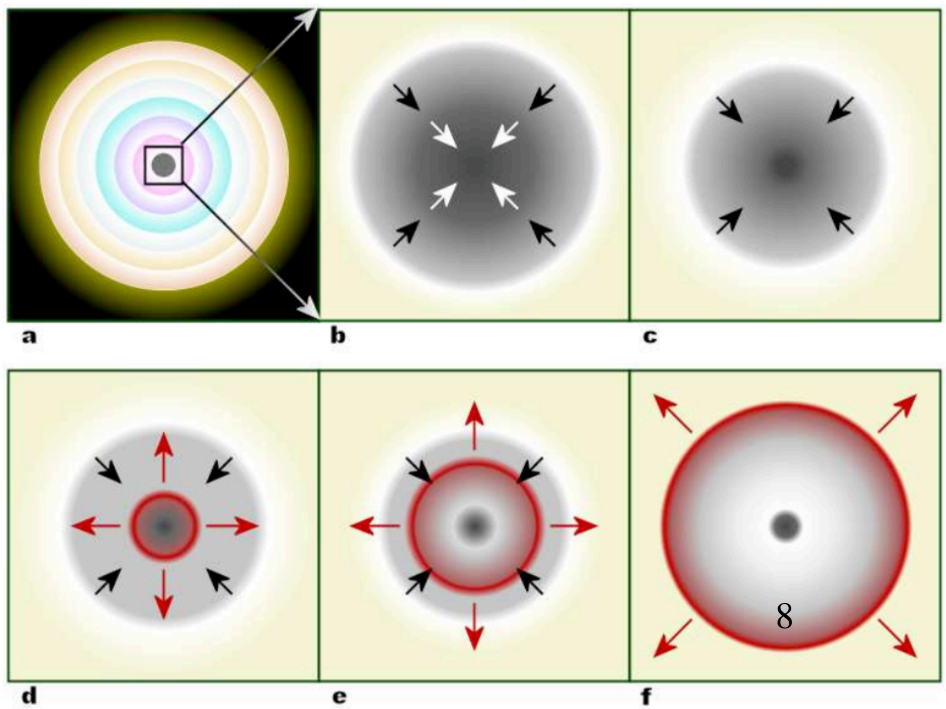
- Why a thermonuclear explosion of a white dwarf?
  - Kinetic energy of ejecta ~5×10^{17} erg/gm (~$1/2v^2$~$(10^4 \text{km/sec})^2$) is similar to nuclear burning energy of C/O to Fe (~1 Mev/ nucleon)
  - lack of remnant (e.g. NS or BH) or progenitor
  - occurence in elliptical galaxies with no star formation
- But (Rosswog and Bruggen pg 136)
  - No consensus on
    - mass of WD or its composition
    - origin of accreted material
    - exact explosion mechanism

Type IIs

- Collapse of a massive star- the cores mass 'burns' into iron nuclei has a maximum size determined by the Chandrasekhar limit, ~1.4 $M_{\odot}$.
- Natural from stellar evolution
- Leaves NS or BH or maybe no remnant
- However wide range of masses, metallicities, binarity etc make for wide range of properties

Luminosity at peak~10^{43}erg/s
total optical energy ~10^{49}erg.
several solar masses ejected at ~1%c
•The kinetic energy about10^{51}erg.

Lattimer-
http://www.astro.sunysb.edu/lattimer/AST301/lecture_snns.pdf



Types of Supernovae

Type Ia	Type II
• No H, He in spectrum	Both H, He in spectrum
• No visible progenitor (WD)	Supergiant progenitor
• Kinetic Energy: 10^{51} erg	Kinetic Energy: 10^{51} erg
• EM Radiation: 10^{49} erg	EM Radiation: 10^{48-49} erg
• Likely no neutrino burst ?	Neutrinos: 10^{53} erg
• Rate: 1/300 yr in Milky Way Rate:	1/50 yr in Milky Way
• Occur in spirals and ellipticals	Occur mainly in spiral galaxies
• No compact remnant	NS or BHs
• most of the explosion energy is	vast majority of the energy is in
in heavy element synthesis	neutrino emission
and kinetic energy of the ejecta	,

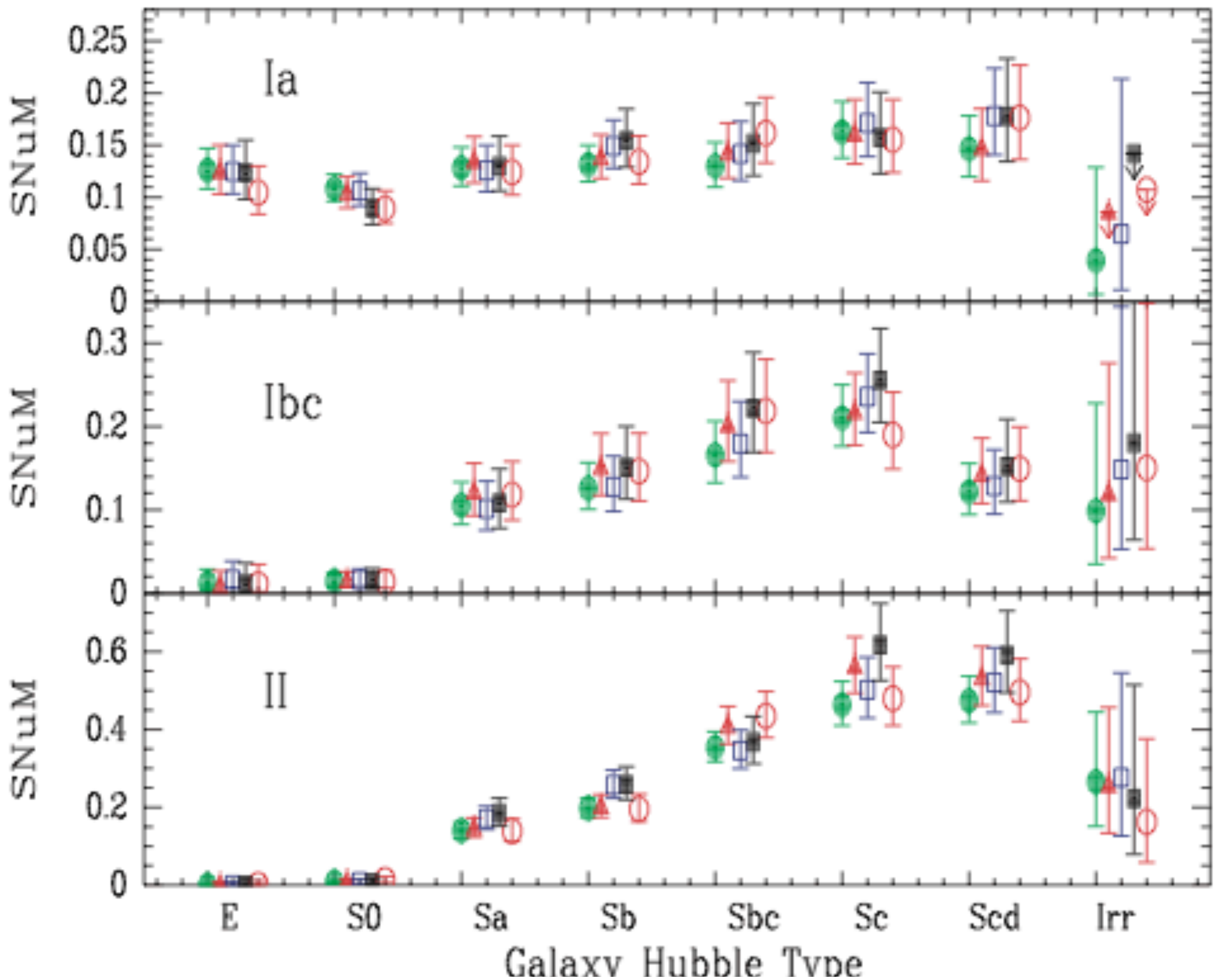
Type II events occur during the regular course of a massive star's evolution. a Type Ia supernova, needs several very specific events to push white dwarf over the Chandrasekhar limit.(adapted from Type Ia Supernovae and Accretion-Induced Collapse Ryan Hamerly)

SN Rates as a function of host galaxy type-

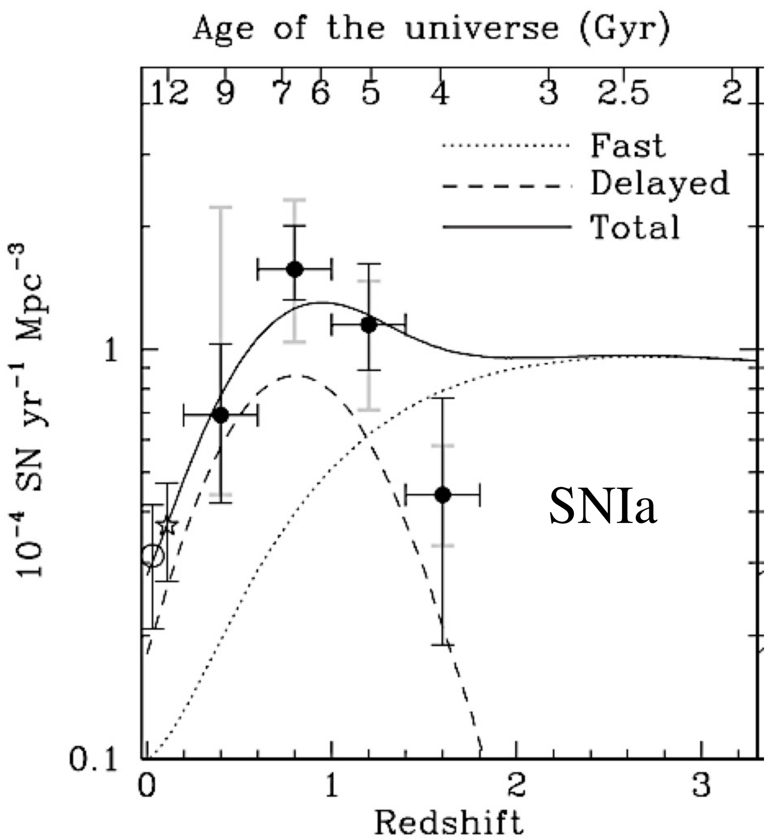
Type Ias appear in all types of galaxies

Type II and Ib primarily in star forming systems (e.g late type spirals)- by number

not corrected for mass of hosts

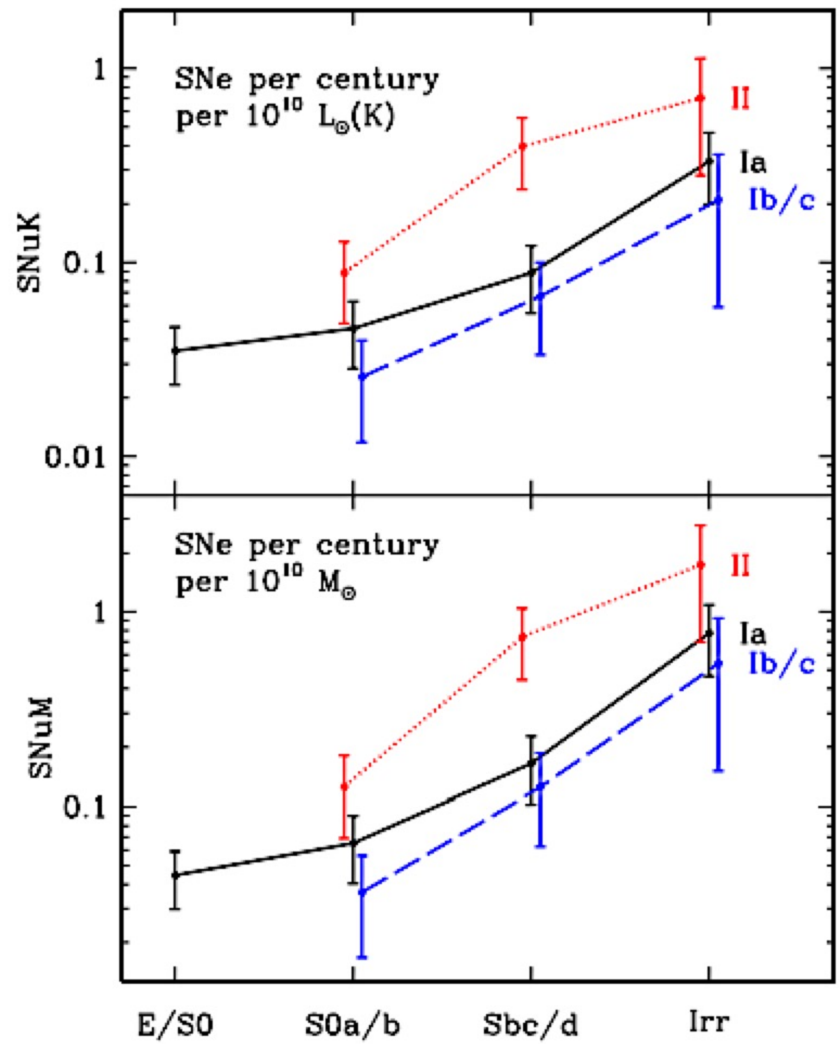


- The Ia SN rate per unit mass changes with galaxy morphology , colors and cosmic time
- it increases by a factor of about 4 from E' S0 to Sbc/d, up to a factor of about 17 in Irr galaxies
- Argues for 2 populations of SNIa (fast and slow)



SN Rate vs Time and Galaxy Properties

SNuK SN rate per $10^{10}L_K$ /century



Mannucci 2005

Lensing Result Today

RELICS: A Candidate z ~ 10 Galaxy Strongly Lensed into a Spatially Resolved Arc
Brett Salmon

THE ASTROPHYSICAL JOURNAL LETTERS, 864:L22 (6pp), 2018 September 1 Salmon et

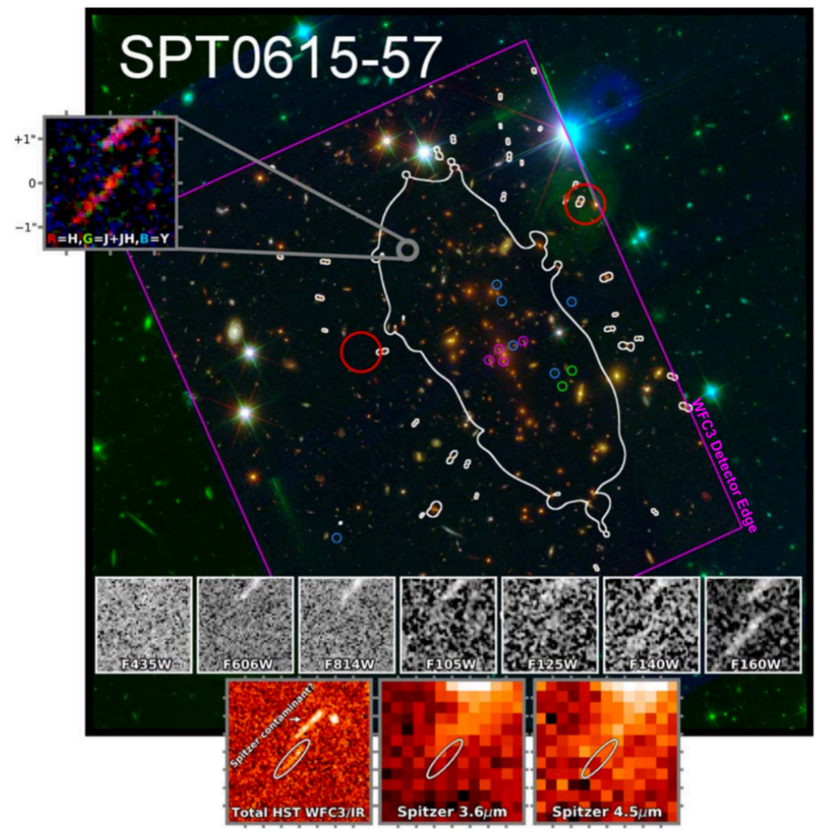


Figure 1. 3′.25 × 3′.25 color image of the *HST* RELICS cluster field SPT0615-57. The yellow circle marks the location of the $z \sim 10$ candidate SPT0615-JD1. T

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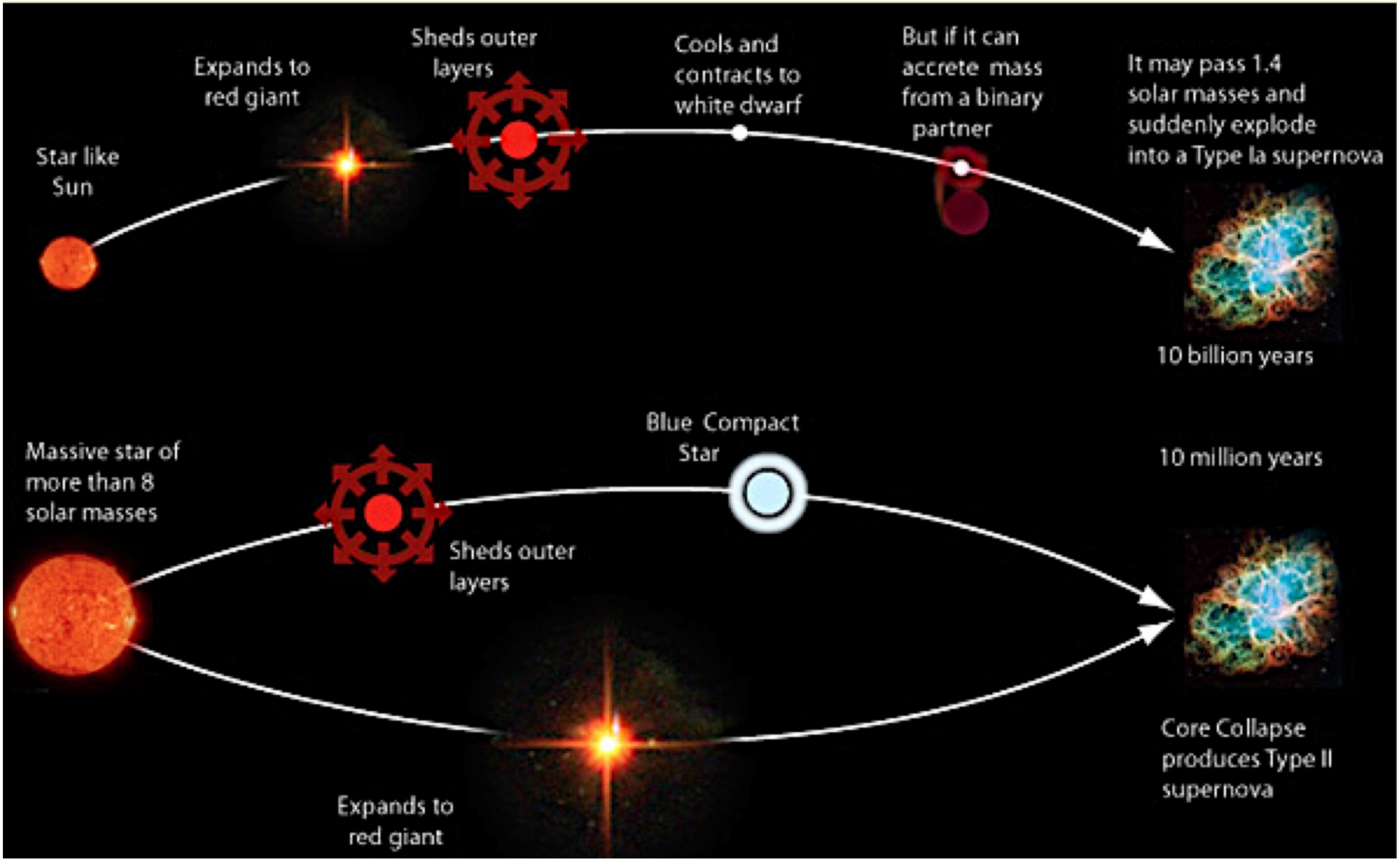
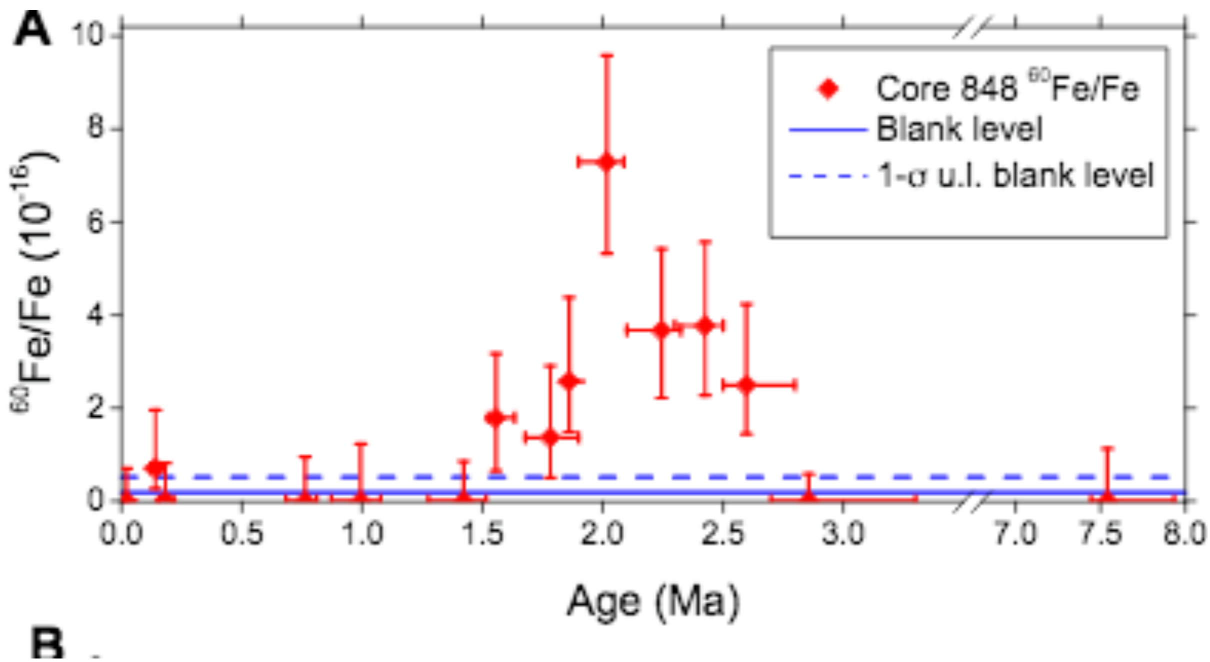
SN Scenario's



Time-Resolved Two Million Year Old Supernova Activity
Discovered in the Earth's Microfossil Record
1710.09573.pdf Peter Ludwig et al

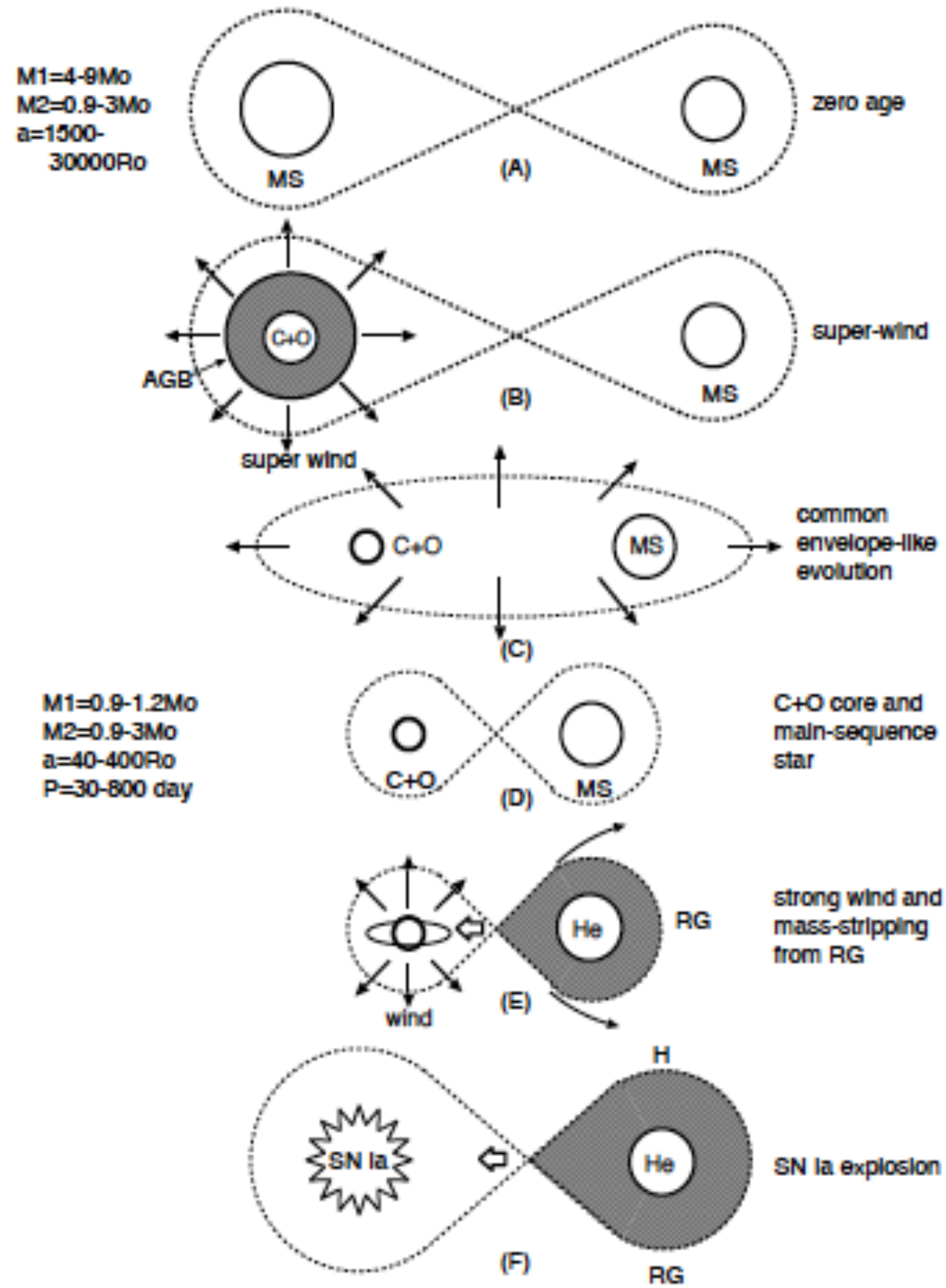
- a time-resolved ^{60}Fe signal
- ^{60}Fe is mostly produced during the evolution of massive stars



The Local Bubble is a low density cavity~150pc in diameter, in which the solar system presently finds itself.
It has been carved out by a succession of~20 supernovae over the last~10Ma ~3 SN in the past 3Ma at a distance of about 300 light years could be responsible for the deposition of an amount of 60Fe in the solar system as observed For a Review see G. Korschinek &T. Faestermann Science Direct 438,148 2019 https://doi.org/10.1016/j.nimb.2018.05.034

How to Get to a Type I

- Route to a type I is very complex and not well understood-single degenerate scenario – a white dwarf (WD) in a semi-detached binary system accreting mass from its secondary
- There maybe several evolutionary paths



'IGURE 2. An illustration of the WD+RG (symbiotic) channel to Type Ia supernovae.

Supernova Explosions

Ia Thermonuclear Runaway

• Accreting C-O white dwarf reaches Chandrasekhar mass limit, undergoes thermonuclear runaway (single degenerate model, double degenerate wide model, empirical model 50% of all SNe Ia explode during the first 100 Myr since the beginning of star formation (prompt SNe Ia), while the rest explodes with larger delays as long as the Hubble time)

• Results in total disruption of progenitor (no remnant NS or BH)
• Explosive synthesis of Fe-group plus some intermediate mass elements (e.g., Si)
• Uncertain mechanism and progenitor: probably a delayed detonation (flame transitions from subsonic to supersonic speed) or deflagration*
•Amount of Ni synthesized is not the same from object to object

➔**different ejecta mass**

➔**different explosion energies**

➔**asymmetries in the explosions**

➔**differences in the explosion physics**

Deflagration-

"Combustion" that propagates through a gas or across the surface of an explosive at subsonic speeds, driven by the transfer of heat.

- the relative yields produced by SNIa are sensitive to the propagation of the burning flame triggering the explosion (e.g. Iwamoto et al. 1999).
- Deflagration models predict that the flame propagates sub-sonically, which produces larger amounts of Ni and moderate amounts of intermediate elements.
- Delayed-detonation models, on the contrary, predict that the flame becomes supersonic below a specific density, which produces less Ni and more intermediate elements.
- Hitomi results indicated a diversity in SNIa explosions (with both deflagration and delayed-detonation models) was required to reproduce successfully all the average estimated X/ Fe ratios

Mernier et al 2017

Evidence for Two Distinct Populations of Type Ia Supernovae

- See the Hitomi paper discussed last week
- Type Ia supernovae (SNe Ia) have been used as standardizable candles for measuring cosmic expansion, but their progenitors are still elusive...
- SNIa with high-velocity ejecta are substantially more concentrated in the inner and brighter regions of their host galaxies than are normal-velocity SNe Ia ...
  - and are in larger and more luminous hosts...
- suggesting that high-velocity SNe Ia originate from younger and more metal-rich progenitors and are only found in galaxies with substantial chemical evolution.

Physics of SN Explosions (Woosley and Weaver 1986 Ann Rev Astro Astrophy 24,205

- Mass range for Type II SN bounded at lower end by most massive stars that can become white dwarfs ($8M_\odot$) and at upper by the most massive stars that can exist.
- Supernova physics relates some of the most complicated physical processes from the explosion mechanisms to nucleosynthesis, radiation transport, and shock physics
- SNe Ia are the main producer of iron in the universe. Their progenitors have long life times, compared to massive stars which become core-collapse supernovae.

Types II/Ib/Ic Core-Collapse of Massive Progenitor

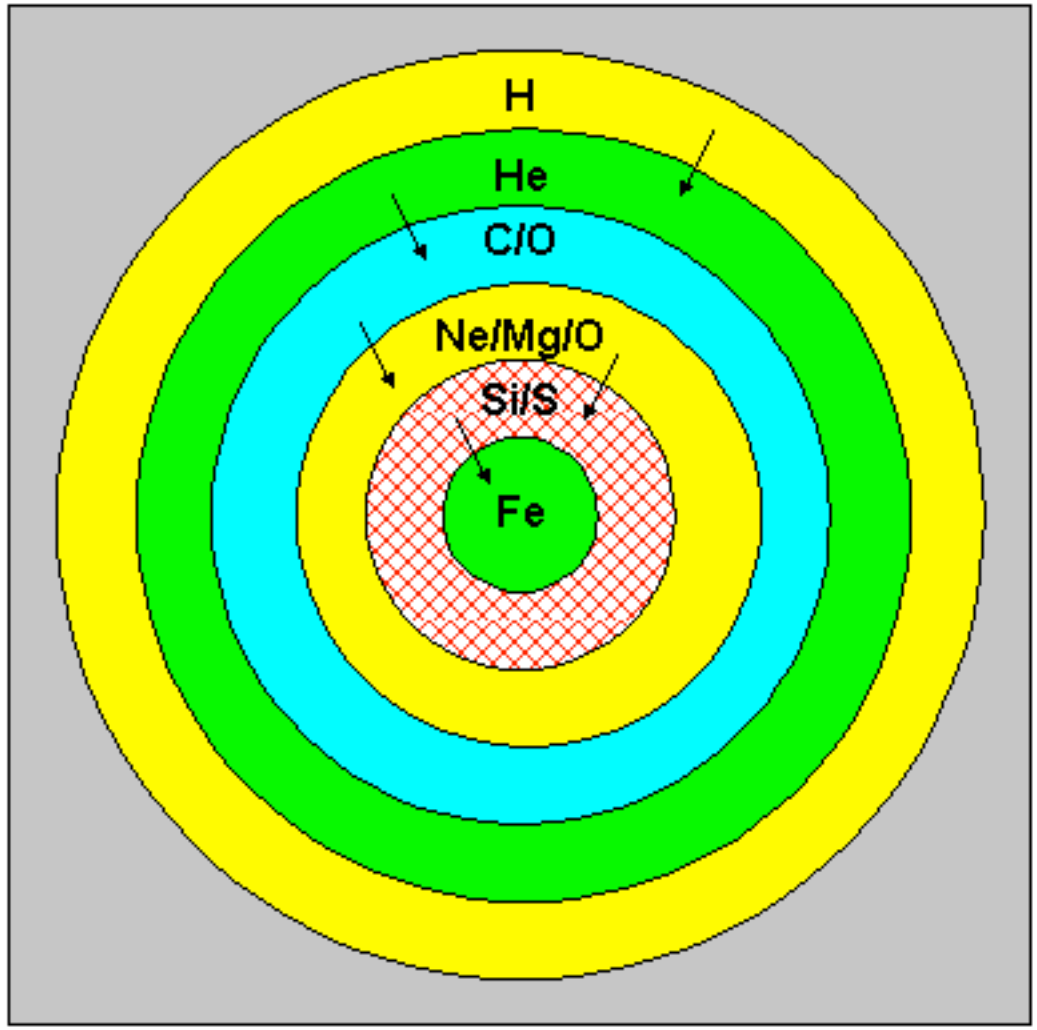
• Massive progenitor core forms neutron star or black hole

• Explosive nucleosynthesis products near core (Si and Fe) plus hydrostatically formed outer layers (O, Ne) are expelled

• **Most of the explosion energy is carried away by neutrinos**- Detection of neutrinos from SN 1987A confirmed basic physics Nobel prize 2002 (Cardall astro-ph 0701831)

• Uncertain explosion mechanism details involve neutrinos, probably large-scale shock instabilities, rotation, possibly magnetic fields

Supernova Explosions



Initially in core-collapse supernovae (type II) the energy comes from the gravitational energy freed in the collapse- later times from radioactive decay

SNIIa
see sec 4.2.3 of R+B

- $E_{kinetic}$~10^{51} erg<<$E_{binding}$~$3x10^{53}$
- Very difficult to make them explode in computer models

On the way to explosion

- Oxygen burning goes very fast (~2 weeks) Si even faster ~1 day.
- Photon energy leaks out very slowly (cross sections for interaction very large), neutrinos escape rapidly (during final collapse opacity high even for neutrinos)
- Once Fe core reaches Chandrasekar mass electrons are relativistic, and unstable to gravitational collapse.
- Core temperature extremely high- elements photo-disintegrate; this lowers pressure increasing runaway (R+B pg 129-130)
- Core collapses (v~r) and outer parts of star fall in supersonically
- ***Then things get hideously complicated*** …

Type II

- Mass motion ~10^{51} ergs (~$10M_{\odot}v^2_{ejecta}$)
  - SNIa v^2_{ejecta}=20,000km/s $M=0.25$-$1M_{\odot}$
  - SNII $M=4\ M_{\odot}$ $v_{ejecta}=5000$
  - Neutrino luminosity is ~$3x10^{53}$ ergs ($0.15M_{\odot}c^2$)

  photon luminosity ~10^{49}

4 Hans-Thomas Janka

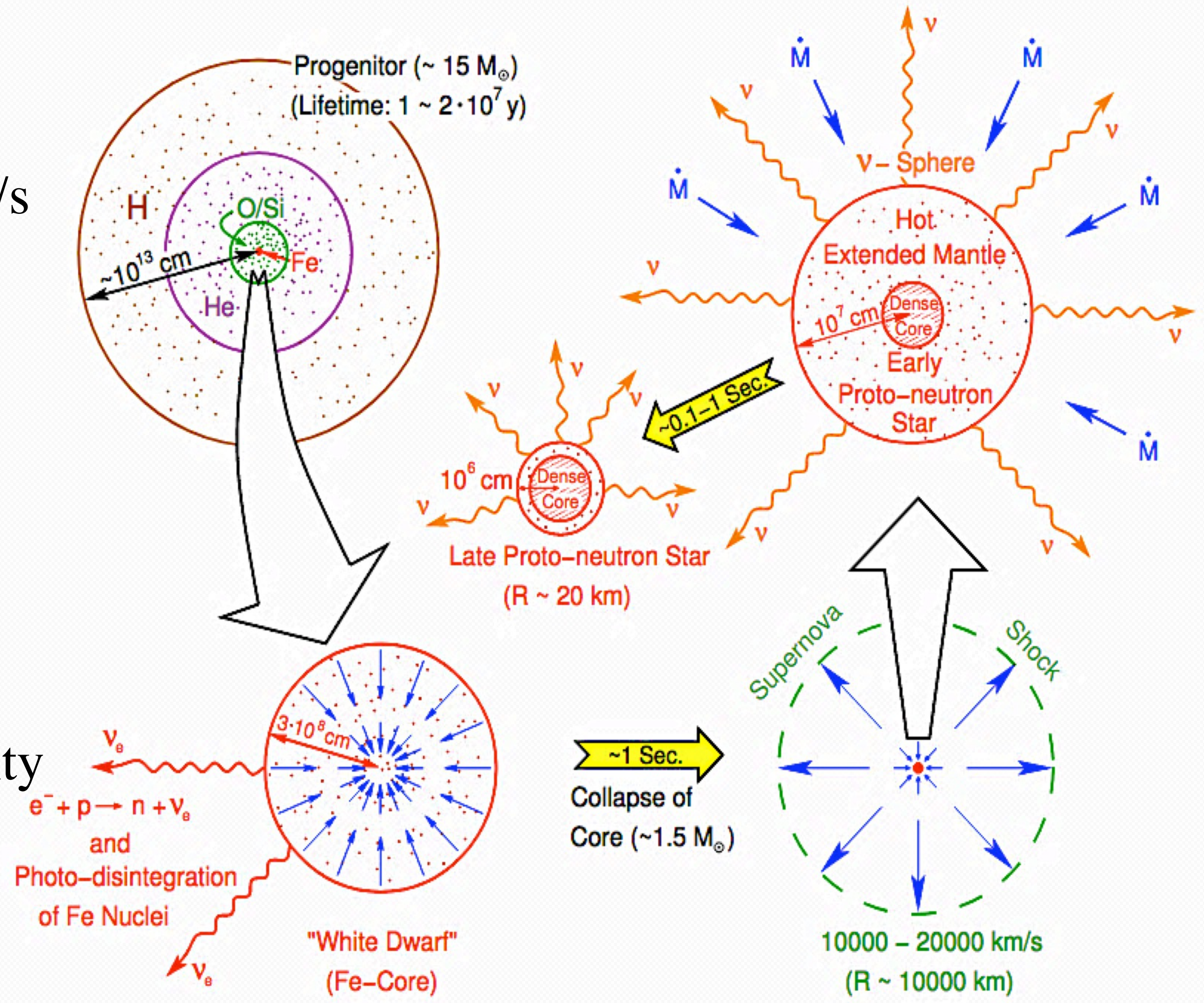
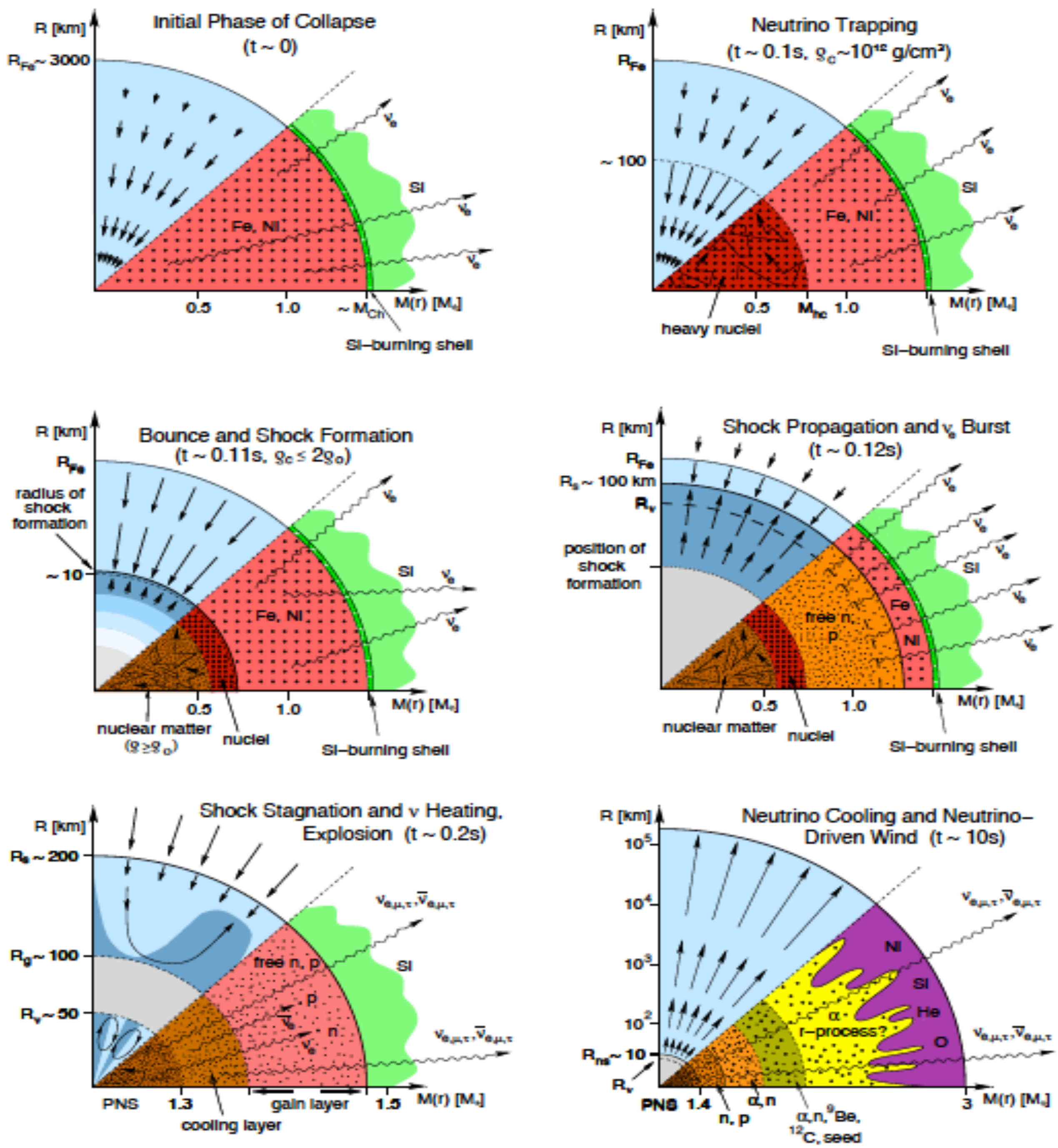


Fig. 2 Evolution of a massive star from the onset of iron-core collapse to a neutron star. The progenitor has developed a typical onion-shell structure with layers of increasingly heavier elements surrounding the iron core at the center (upper left corner). Like a white dwarf star, this iron core

- Present understanding of explosion of massive star (Janka et al 2017)
- importance of hydrodynamic instabilities in the supernova core during the very early moments of the explosion (the figure covers 0.1-10 sec)



SuperNova Optical Light Curves

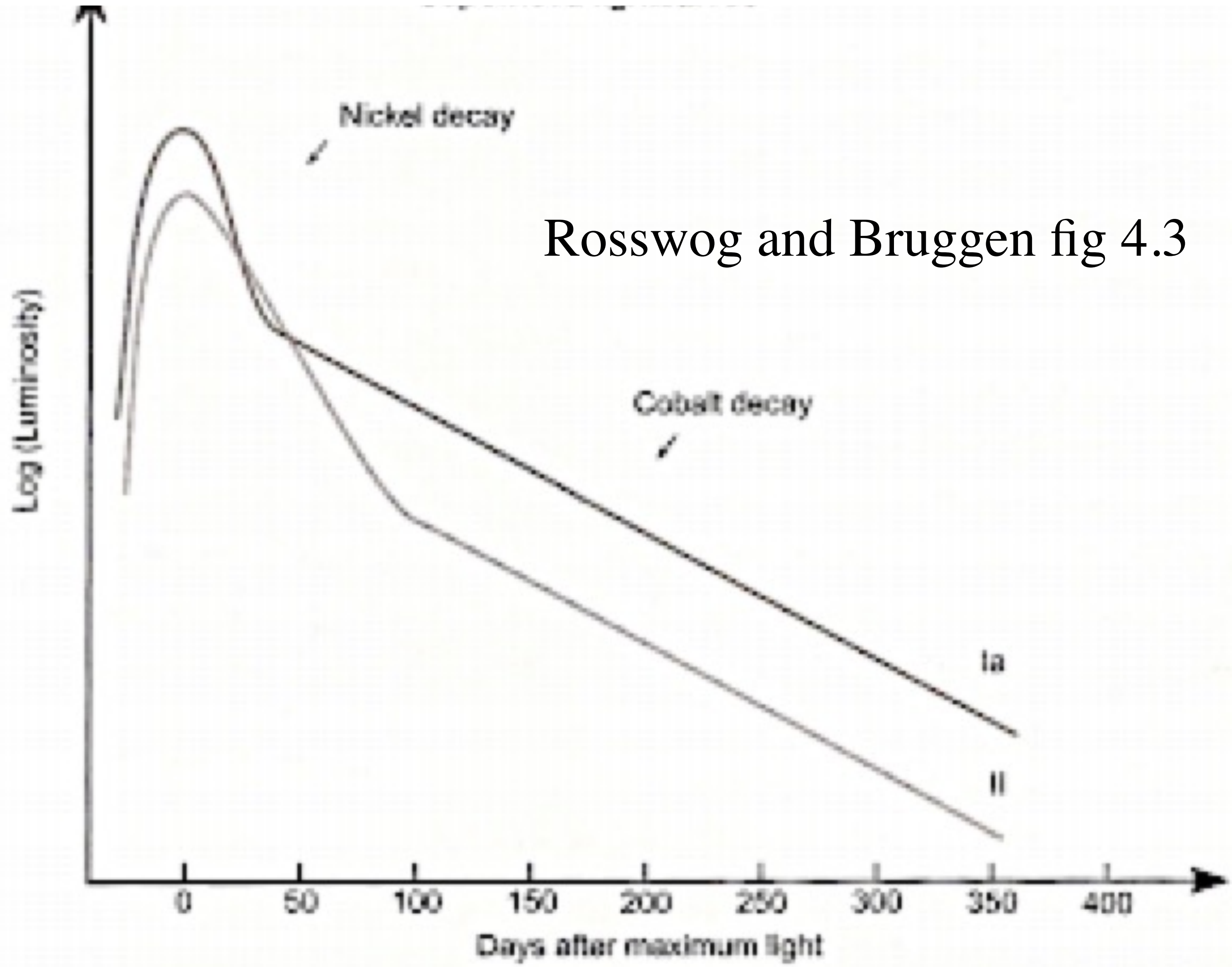


Figure 4.3 Supernovae light curves for Types Ia and II.

SN "Light Curves"

- For first ~1000 days the photon luminosity is driven by radioactive decay (type Ia)

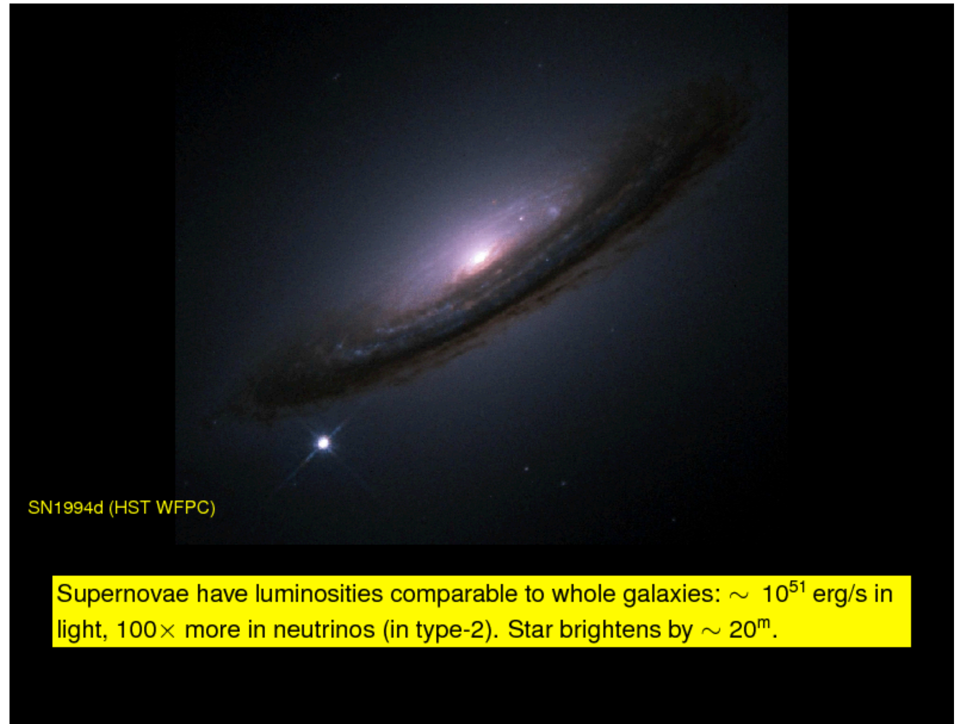
$Ni^{56} \Rightarrow Co^{56} \Rightarrow Fe^{56}$ (6.1 days and 77 day 1/2 life)

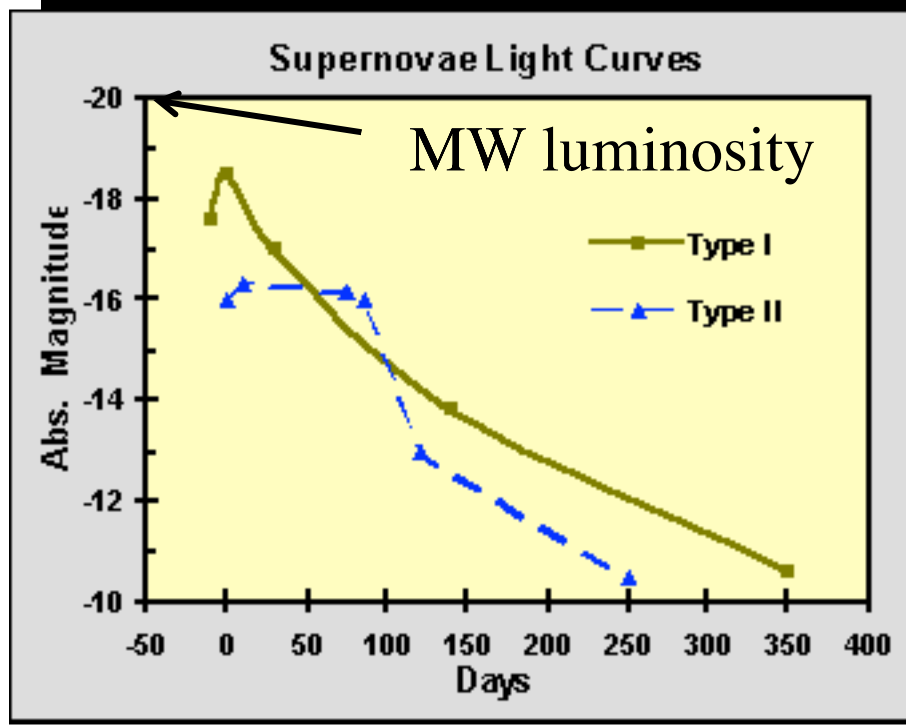
Velocities of gas seen in the optical is ~10^4 km/sec

$E \sim 1/2 M v^2 \sim 10^{51} M_\odot v_4^2$ ergs

Luminosity of SN ~ that of the host galaxy- can be seem to z>1

v_4 in units of 10^4 km/sec

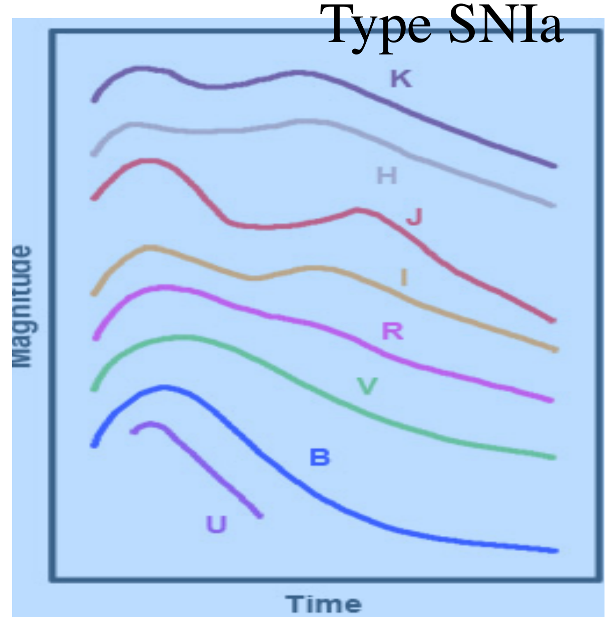


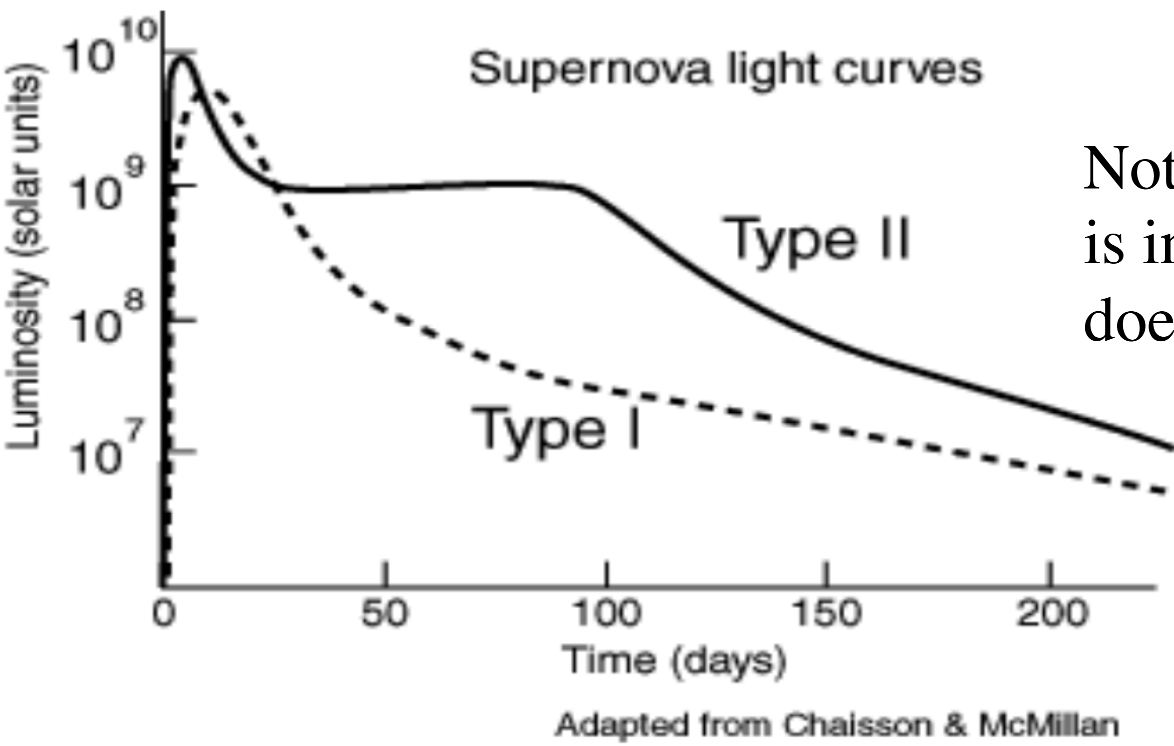


SuperNova Light Curves-http://astronomy.swin.edu.au/cosmos/T/Type+Ia+supernova+light+curves

- Shape and amplitude depends on color (physics of atmosphere and velocity of expansion)
- SN are 'typed' by the amplitude, shape and color of their light curves
- Optical spectra

Type SNIa





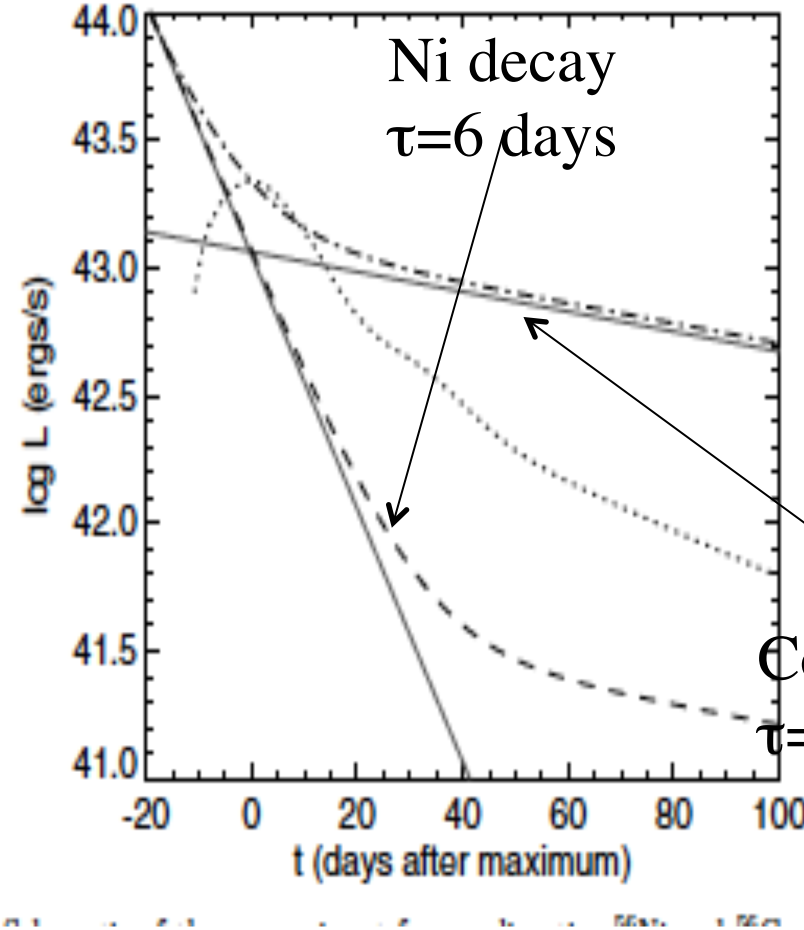
Notice absolute luminosity is in solar units and the graph does not specify the color

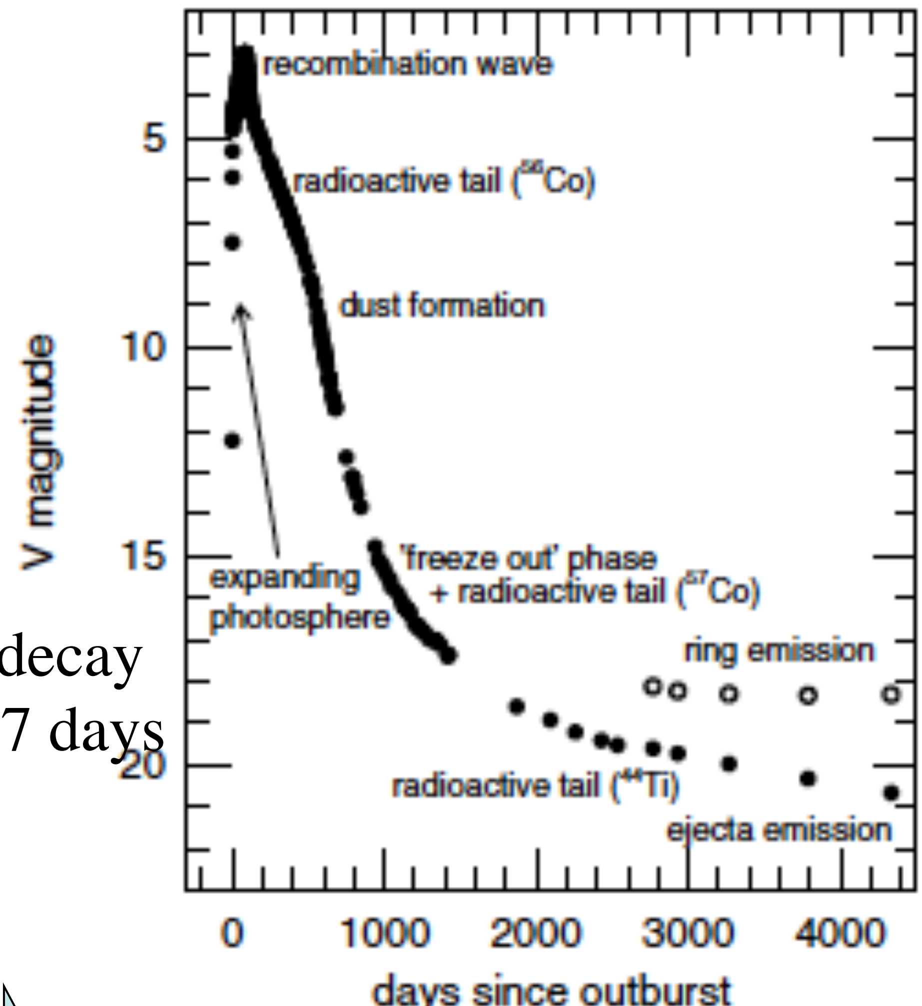
SN Light Curves

Type Ia

Bruno Leibundgut

Type II

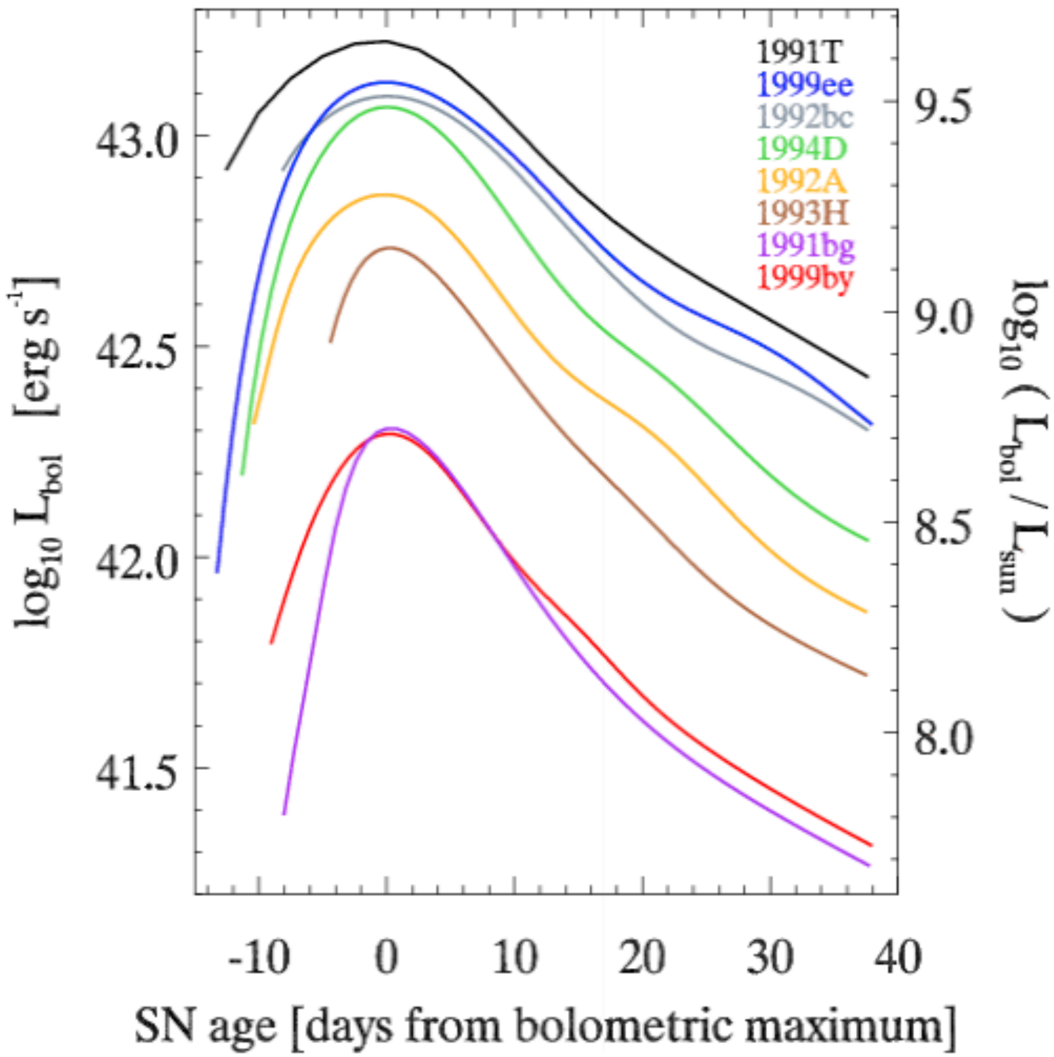




$^{56}Ni+e^-$ → $^{56}Co+\nu$; $^{56}Co+e$ → $^{56}Fe+\nu$

Type Ias

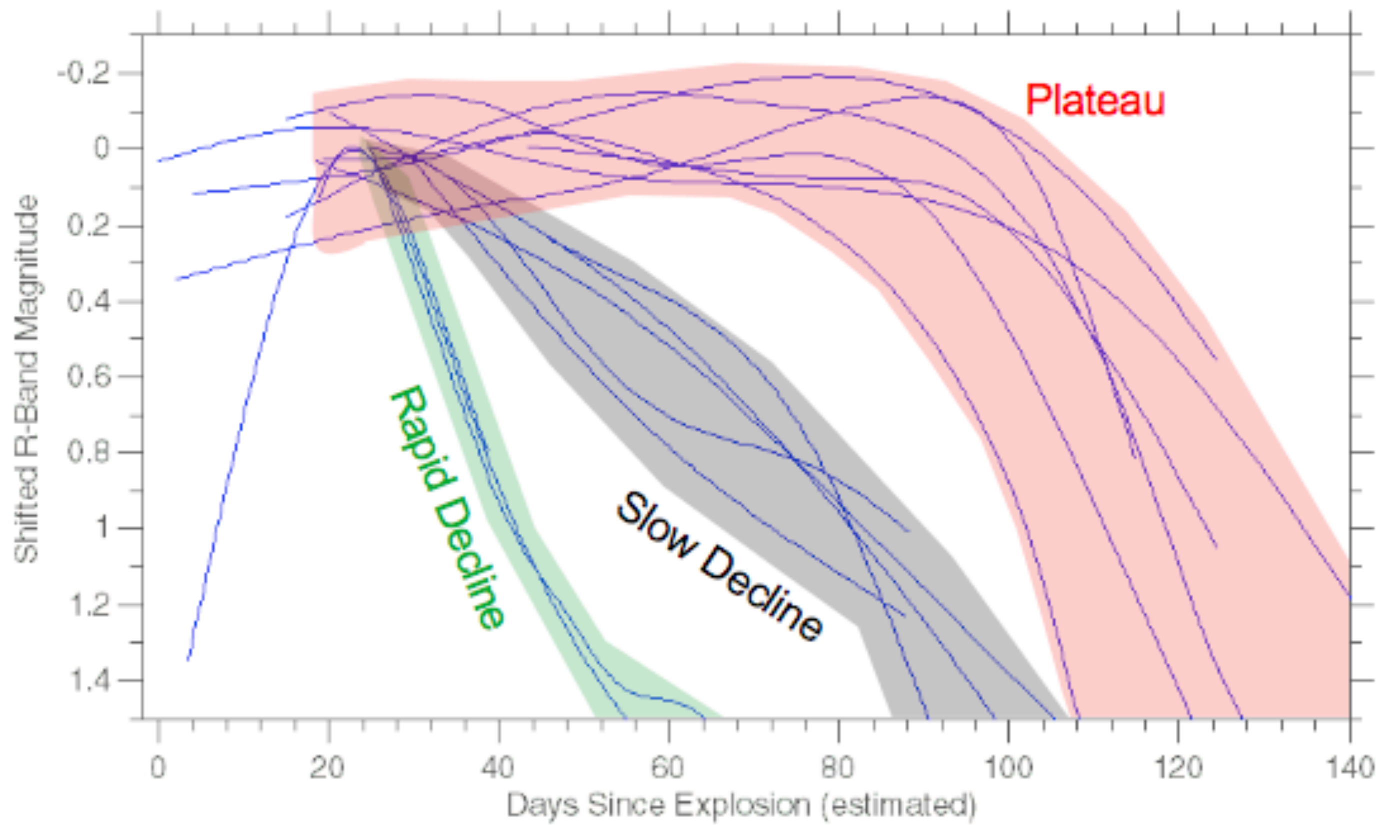
- From total luminosity derive M_{Ni} that has been synthesized and thus the amount of Fe that has been produced.
- SNe Ia :the main producer of iron in the universe. Their progenitors have long life times.
- L_{total}~$1.1x10^{50}$ ergs~ $0.6M_{\odot}$ of Ni
- Light curves are rather homogenous- suggesting little variation in the nature of the progenitor (?)
  - 2 possibilities
    - merger of 2 white dwarfs
    - or white dwarf collapse due to accretion



SN II

- Wide Variety of Light Curves- assume wide range of progenitors
- Type II supernovae - implosion-explosion events of a massive star. They show a characteristic plateau in their light curves a few months after explosion

This plateau is reproduced by models which assume that the energy comes from the expansion and cooling of the star's outer envelope as it is blown away



Neutrinos Carry Away Most of the Energy in type IIs

- Neutrino emissivity Cardall astro-ph 0701831
- for details see Janka 1702.08713.pdf

- Because of their low interaction cross sections neutrinos escape 'rapidly'
- Photons bounce around a lot and take days to escape

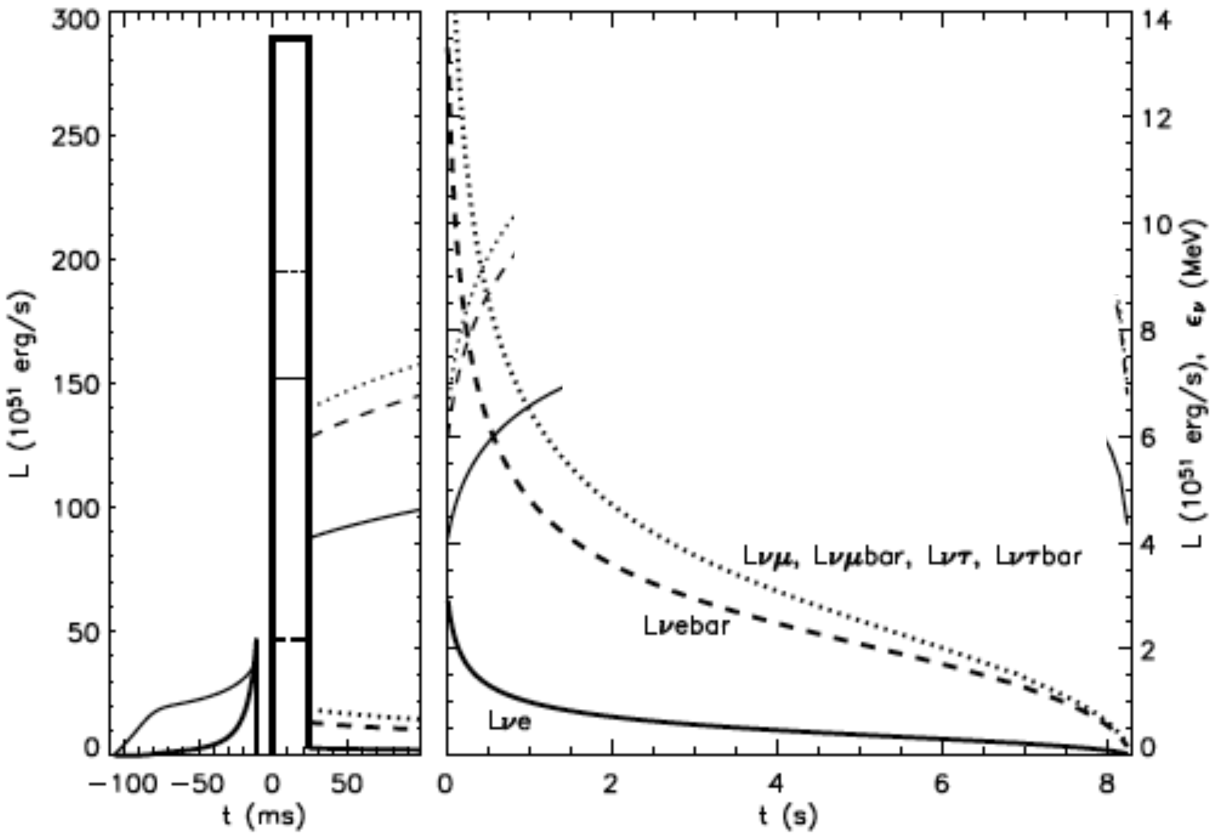


Figure 2. Crudely estimated neutrino luminosities (thick) Note the change in time and luminosity (but not energy) scales between the left and right panels. The left panel is a close-up of infall and bounce at $t = 0$.

Explosive Nucleosynthesis- Type IIs

Nuclear processing as the supernova shock wave propagates through the star (see Arnett 1996)

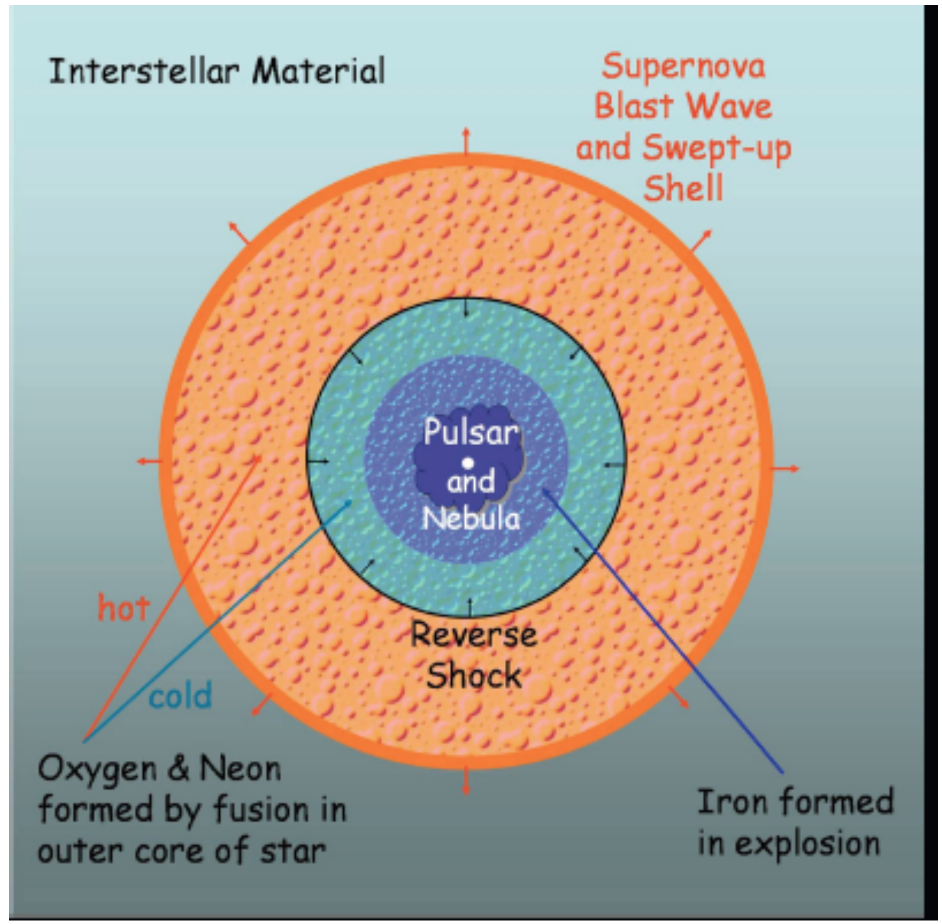
'α' products

C burning produces O, Ne, Mg, etc
T ~ 2 x 10^9 K

Ne burning produces O, Mg, etc
T ~ 2.3 x 10^9 K

O burning produces Si, S, Ar, Ca, etc
T ~ 3.5 x 10^9 K

Si burning produces Fe, Si, S, Ca, etc T ~ 5 x 10^9 K



stops at Fe, sort of

Physics of SN Explosions
(Woosley and Weaver 1986 Ann Rev Astro Astrophy 24,205

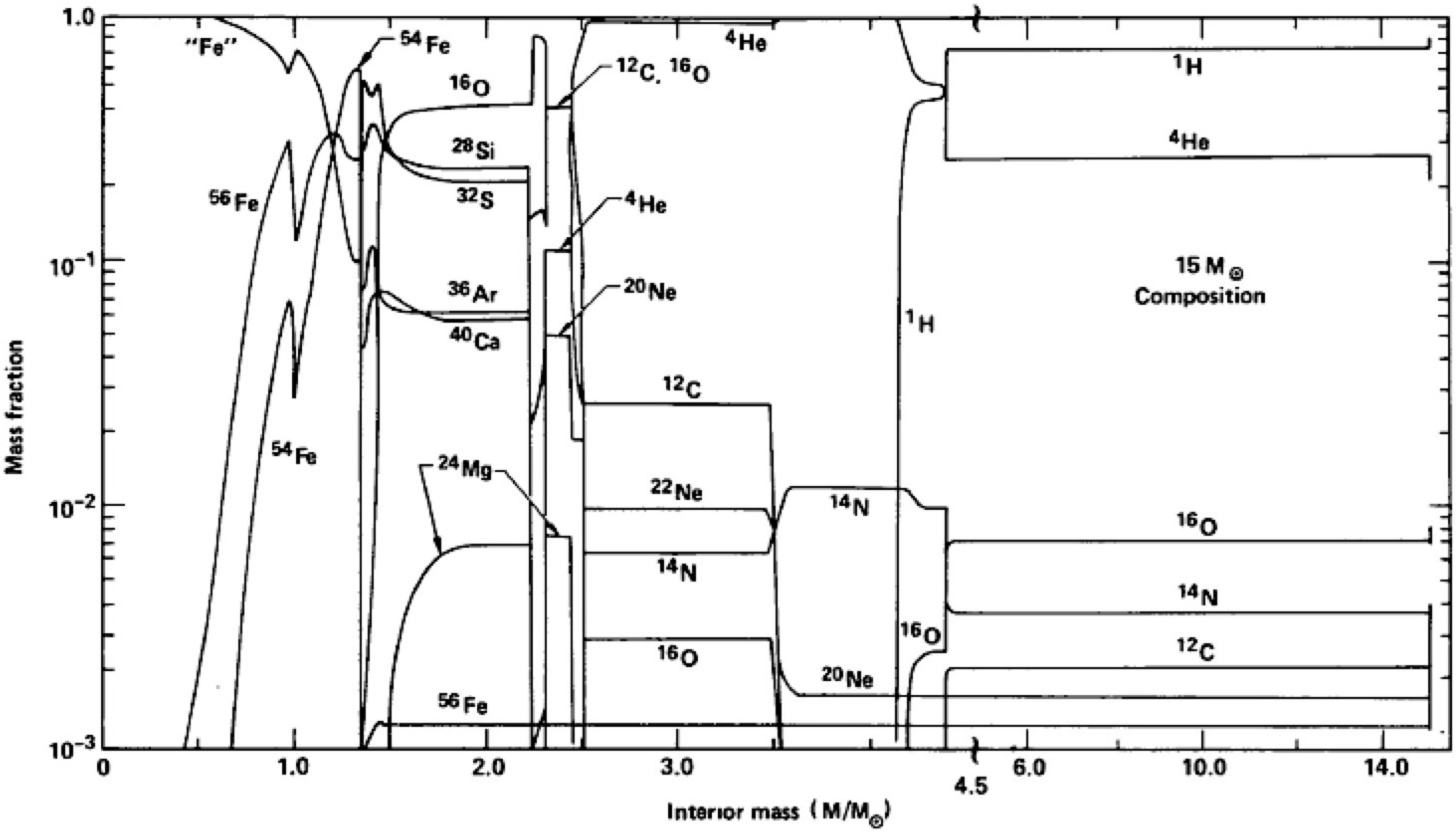


Figure 1 Structure and composition of a 15-$M_\odot$ presupernova star at a time when the edge of its iron core begins collapsing at 1000 km s^{-1}. Neutrino emission from electron capture

Distribution of material in pre-supernova $15M_\odot$ star- notice the layer cake type distribution

Type Ia- How the Explosion Occurs

- Deflagration wave
  - Deflagration-

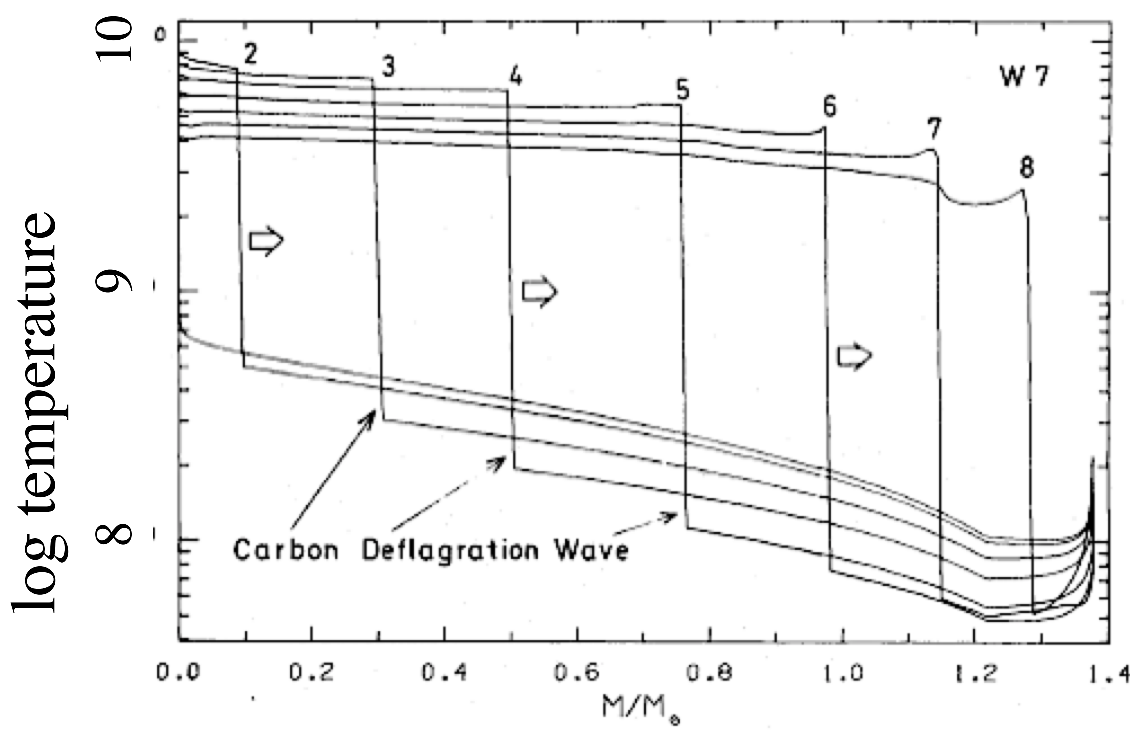
"Combustion" that propagates through a gas or across the surface of an explosive at subsonic speeds, driven by the transfer of heat.

In main sequence stars $T_c \sim 10^8$ K to ignite helium core burning- in SNIa $T_{core} \sim 10^{10}$ K

Detailed physics is still controversial!

Fundamental reason: nuclear burning rate in SnIa conditions $\sim T^{12}$

'flame' ~ 1cm thick, White dwarf has $r \sim 10^8$cm

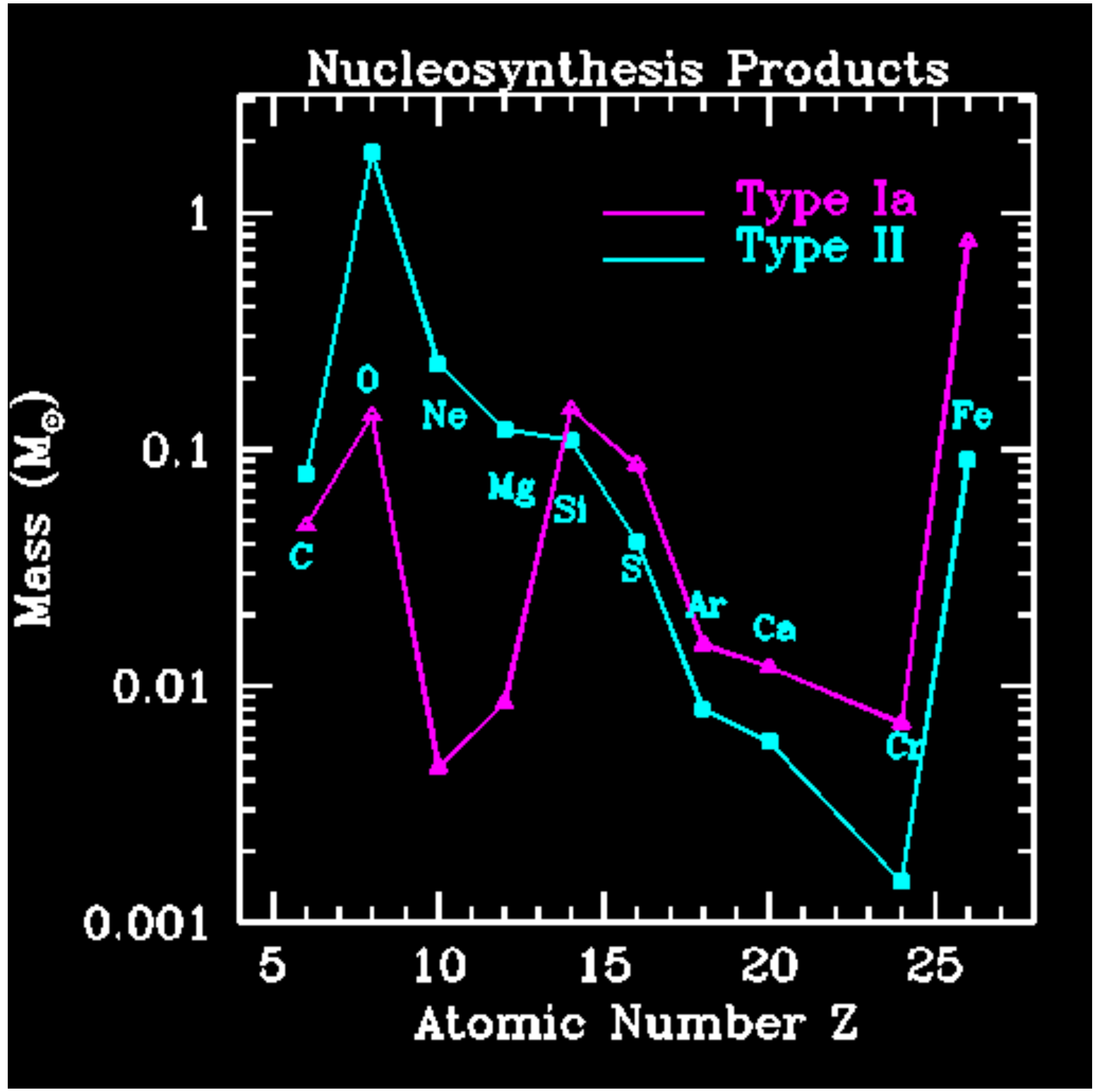


mass shell

Deflagration wave in WD
time steps are at 0, 0.6, 0.79, 0 .91, 1.03, 1.12, 1.18, 1.24 **sec**

Elemental Production in Type Is and IIs

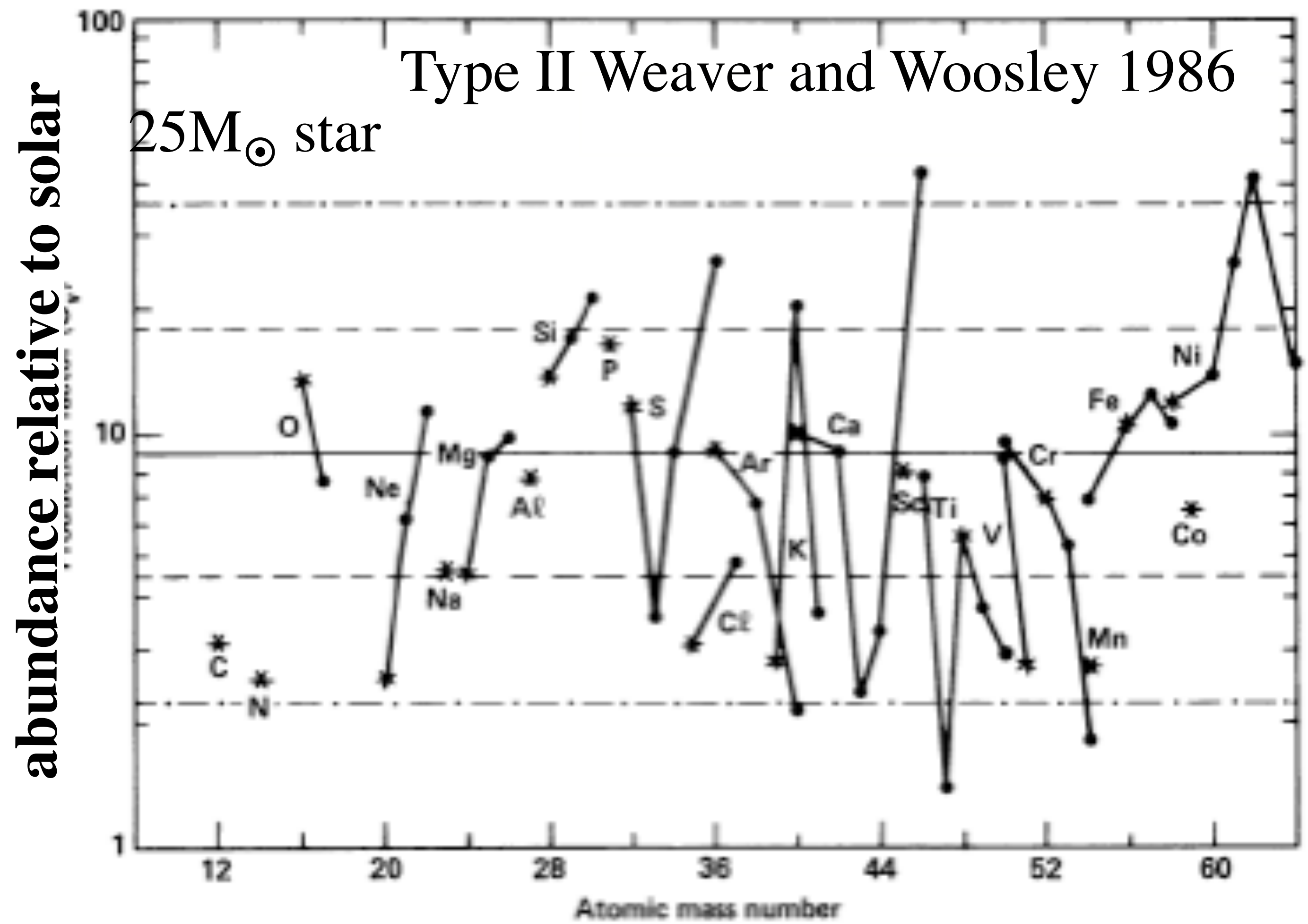
- To simplify
  - Type Is produce mostly Fe and a little Si and S
  - Type IIs produce O and α+O e.g. add a α particle to O^{16}
  - To get 'solar' composition need to add the sum of the two 'just right' and have the 'right' number of SN over cosmic times



Examples of Detailed Yields

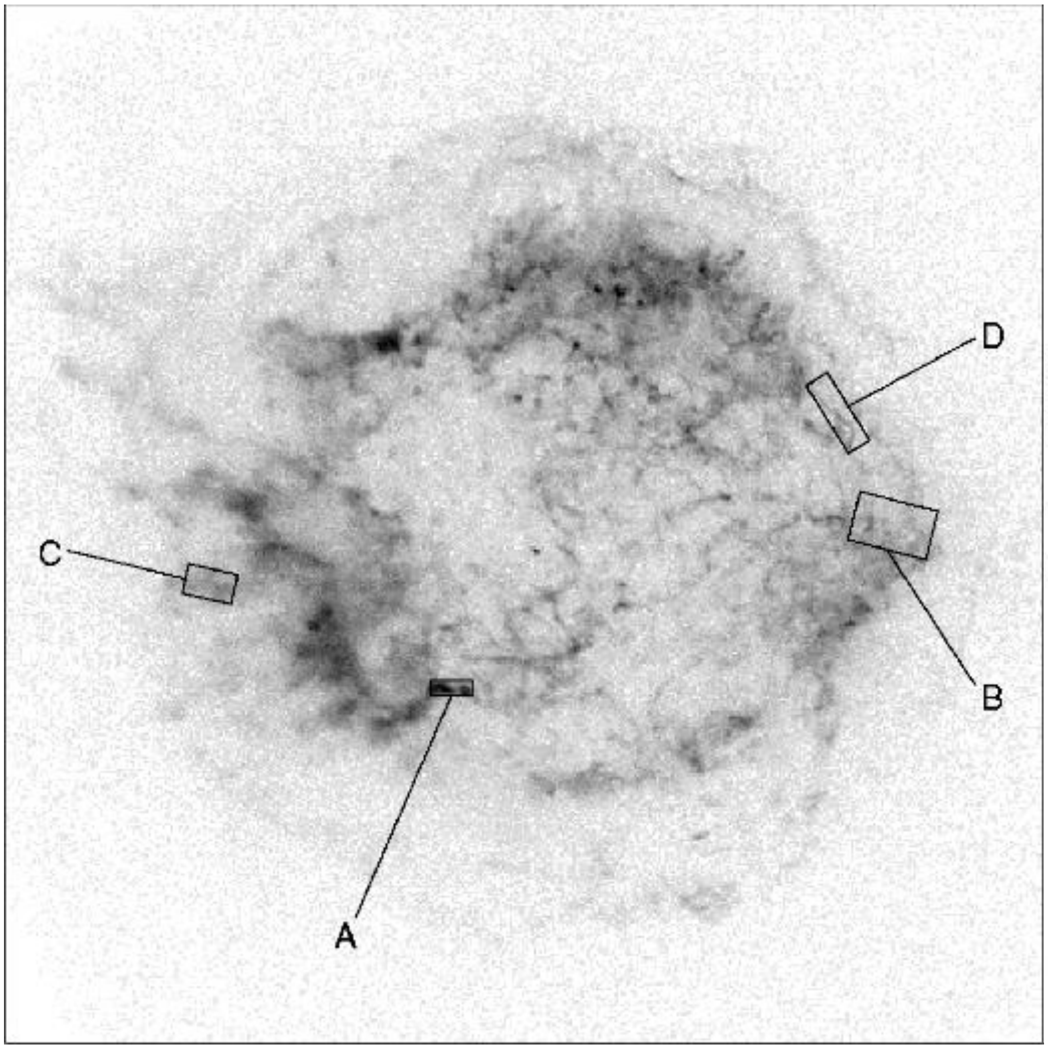
Different SN of different intial mass (Type II) have different yields.

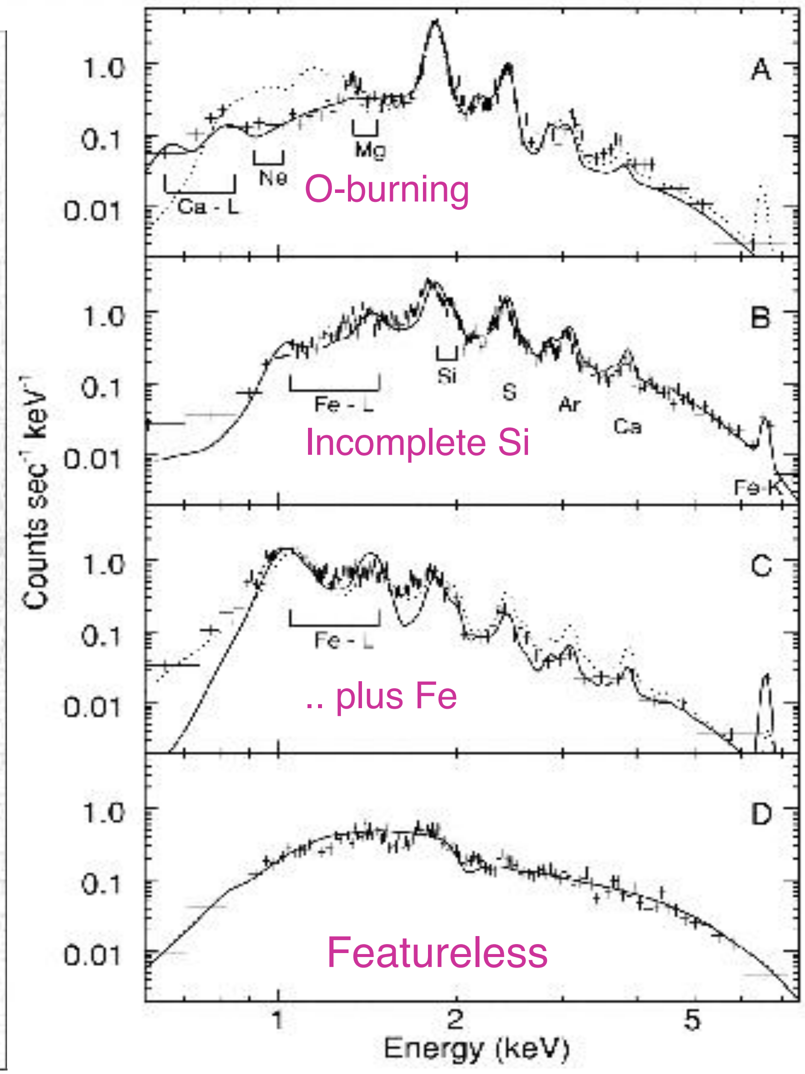
Net elememtal production due to type IIs requires summing over the initial mass function



igure 3 Isotopic nucleosynthesis in a 25-$M_\odot$ explosion. Final abundances in the ejecta are lotted for isotopes from ^{12}C to ^{64}Ni compared with their abundances in the Sun (Cameron

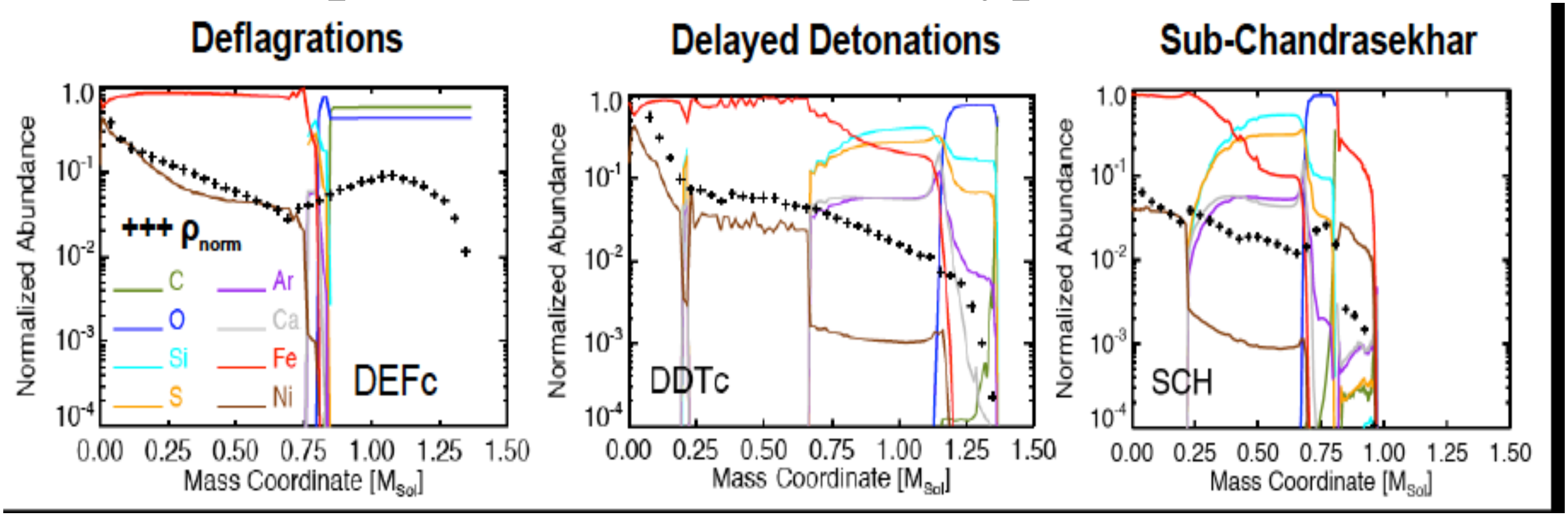
Cassiopeia A: Observations of Explosive Nucleosynthesis
Spectral/Spatial Decomposition





(Hughes et al. 2000 ApJ, 518, L109)

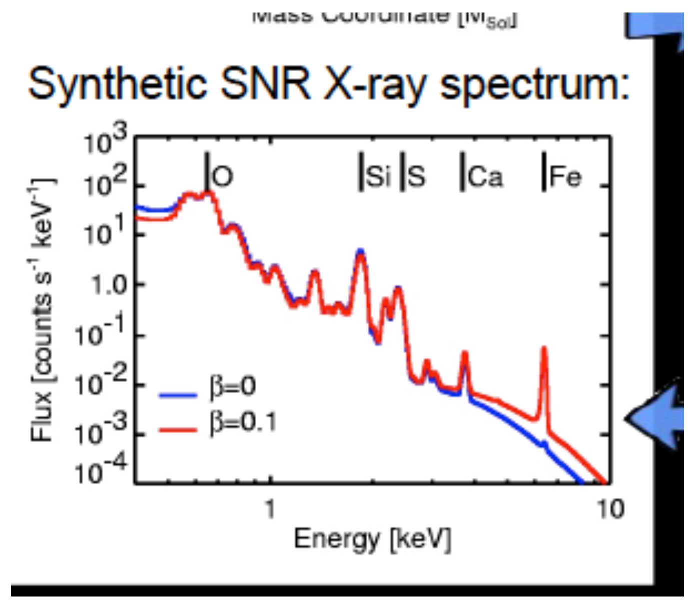
Examples of Yields from 3 Type Ia SN Models

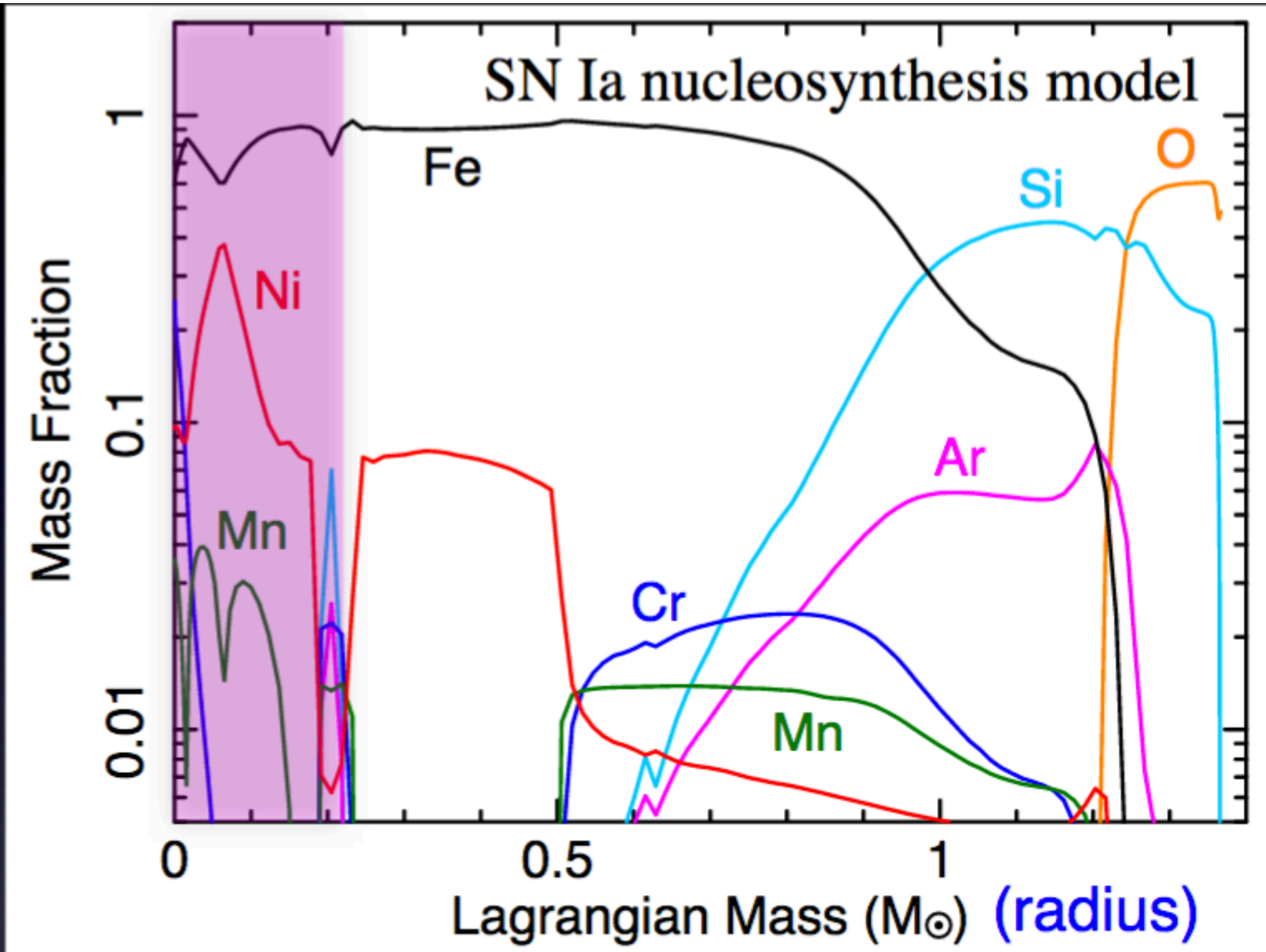


- Check of these yields against analysis of chemical abundance of SNR favors Delayed detonations.

C. Badenes et al 2006 fit in Tycho SN for $E_{kinetic}=1.16\cdot10^{51}$ erg,

- $M_{Fe}=0.8\ M_\odot$, $M_O=0.12\ M_\odot$, $M_{Si}=0.17\ M_\odot$, $M_S=0.13\ M_\odot$, $M_{Ar}=0.033\ M_\odot$, $M_{Ca}=0.038\ M_\odot$





Electron capture reactions ($p + e^{-} \rightarrow n + \nu_e$) increase abundances of *n*-rich elements.

Detailed Yield for a SNIa model

Abundances are relative to solar

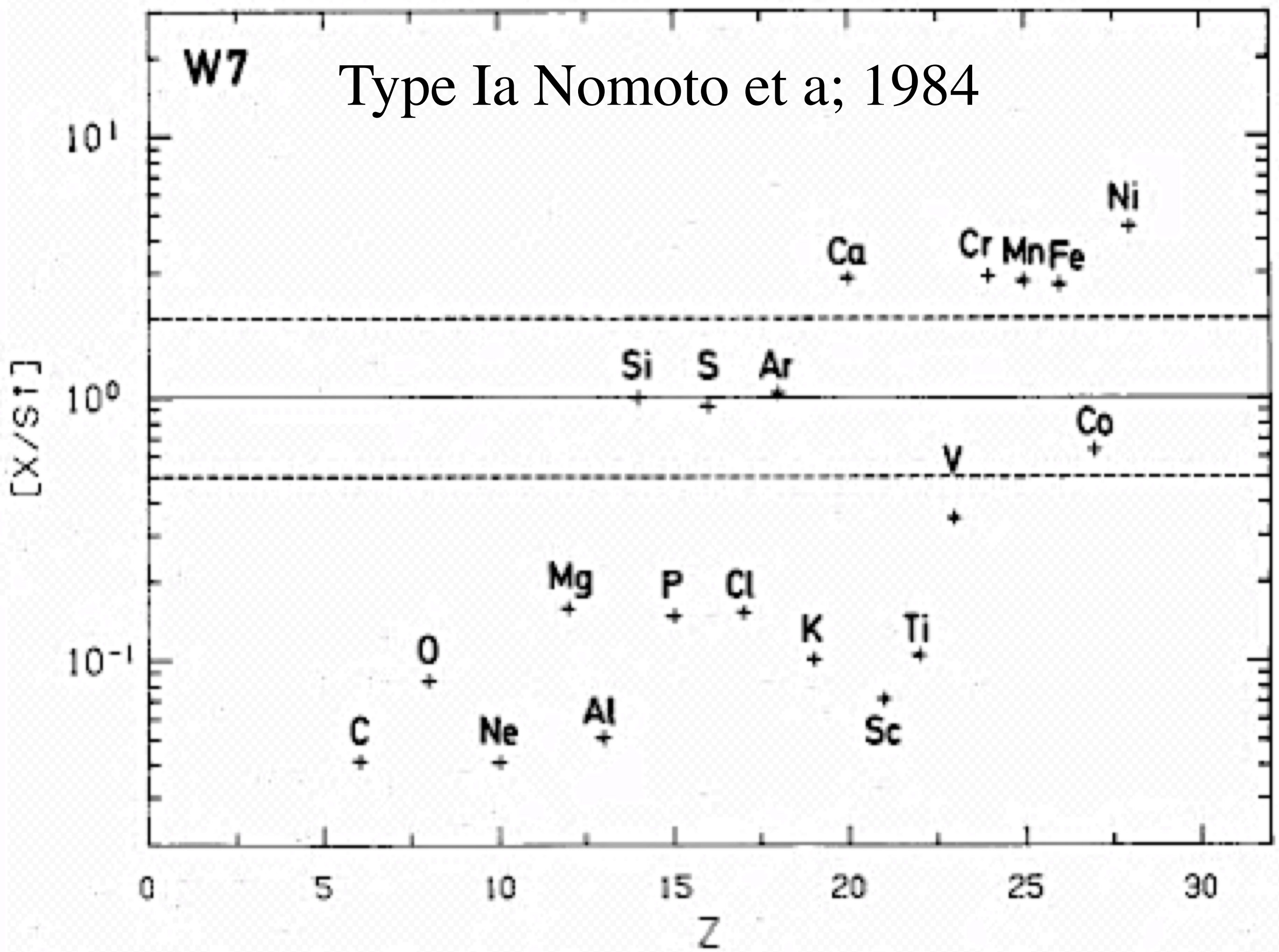
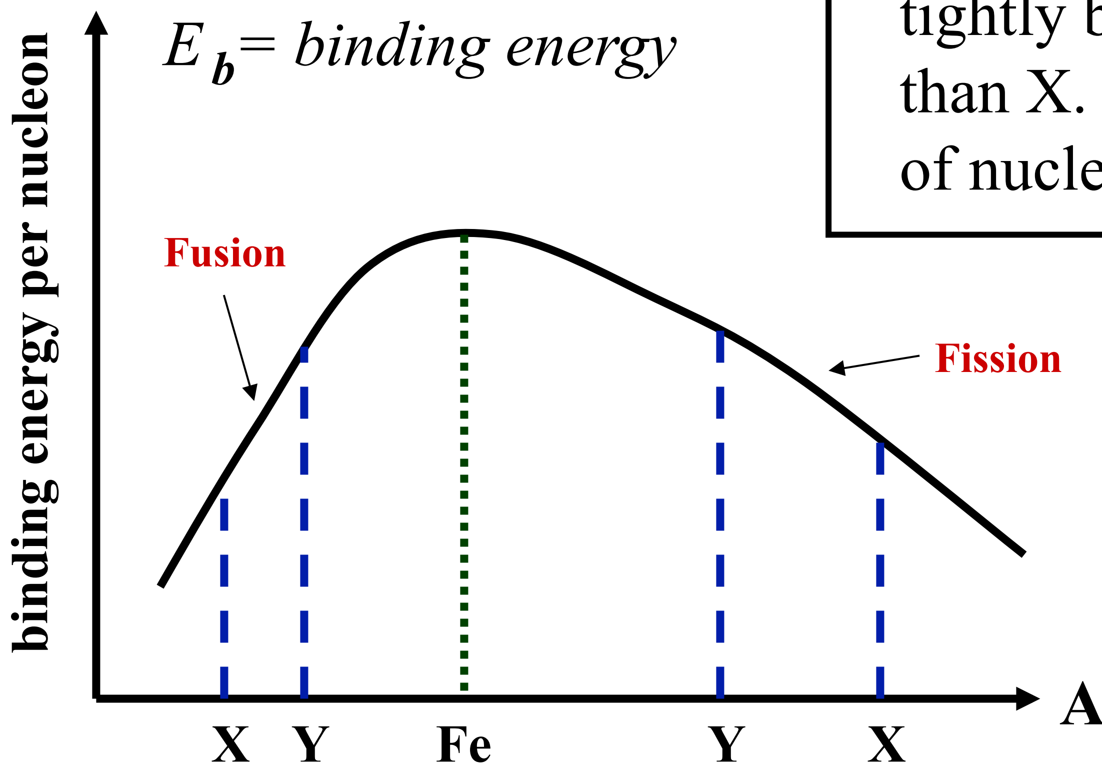


FIG. 10.—The abundances of elements relative to the solar values (W7). The ratio is normalized to Si.

Binding energy of Nuclei - why stellar burning stops generating energy

A=total no. nucleons
Z=total no. protons
E_b= *binding energy*

Change from X to Y emits energy since Y is more tightly bound per nucleon than X. This is a function of nucleon mass



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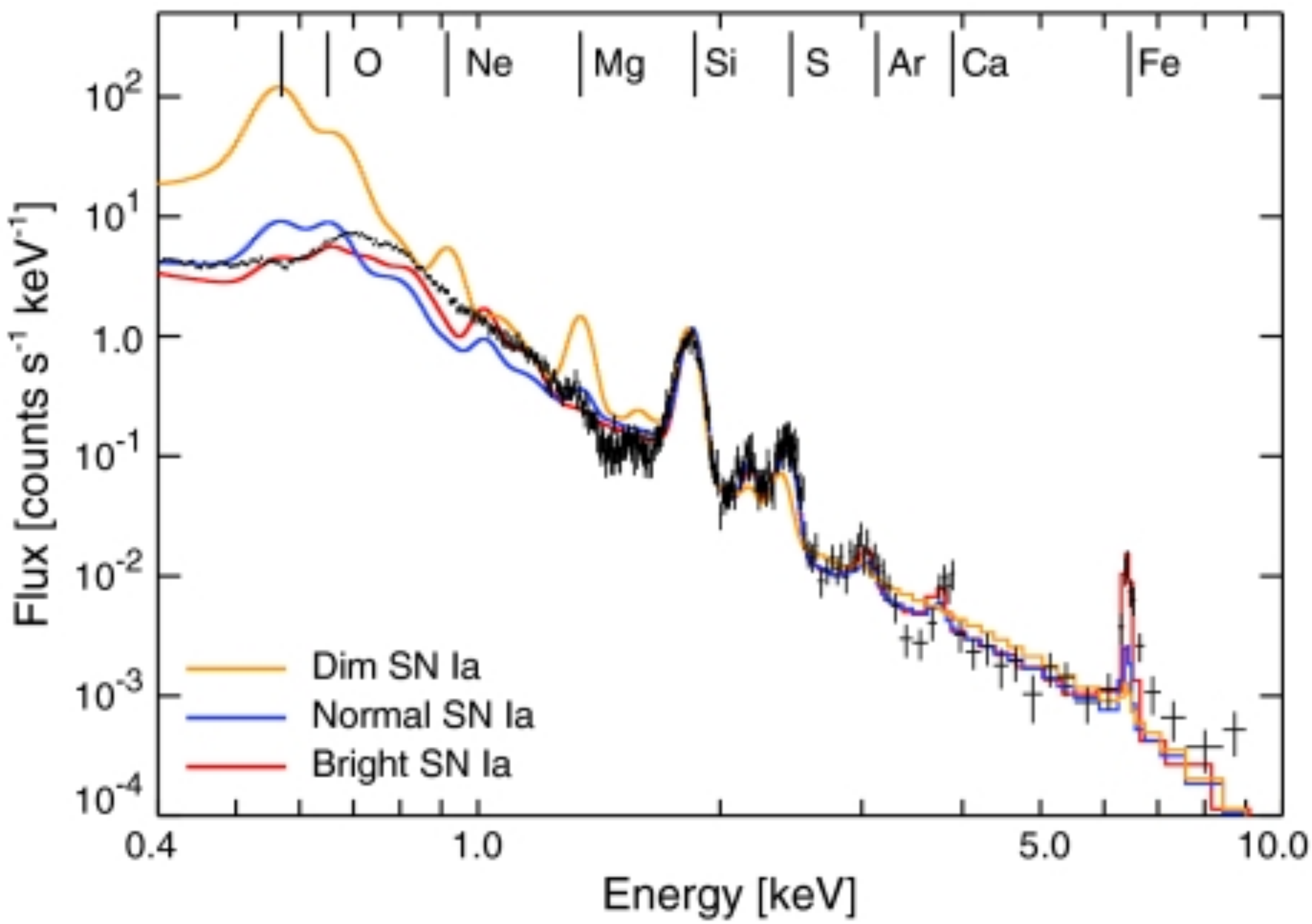
Comparison of Yields From Different Type Ia Models with X-ray Spectral data

C. Badenes

Proc Natl Acad Sci U S A. 2010 107(16): 7141–7146.



Supernova Remnants

Explosion by core-collapse of massive stars (II, Ib/c) or thermonuclear instability in accreting C+O white dwarf (Ia)

$\sim 10^{51}$ ergs kinetic energy released per explosion

Forward shock heats and compresses interstellar medium, accelerates particles

Reverse shock heats ejecta starting from outermost layer inward as ejecta expand

Low gas densities, short ages of 100-10^4 yr
ionizing plasma: ionization timescale = $n_{electron}$ x t_{shock}