Supernovae: Explosions, Remnants, Products

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- **Astronomers generally group supernovae into two broad classes: Type I and Type II. This lecture will provide an overview of these two classes including:**
  - **their outburst mechanisms**
  - **their distinguishing observational characteristics**
  - **their remnants**
  - **their contributions to nucleosynthesis**

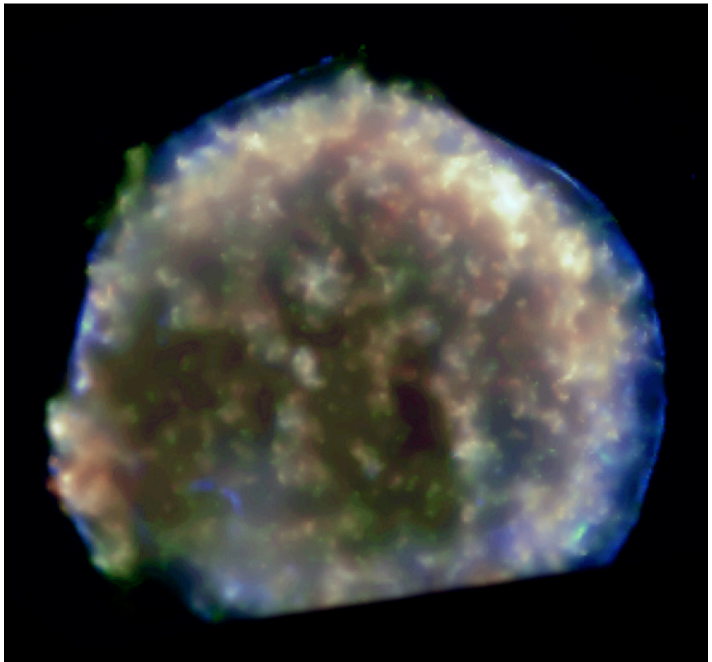
Discovery of a SNe Ia?

One evening when I was contemplating as usual the celestial vault, whose aspect was so familiar to me, I saw, with inexpressible astonishment, near the zenith, in Cassiopeia, a radiant star of extraordinary magnitude. Struck with surprise, I could Hardly believe my eyes.

Tycho Brahe,

November 1572

"Stella Nova" (1573), discovery chart

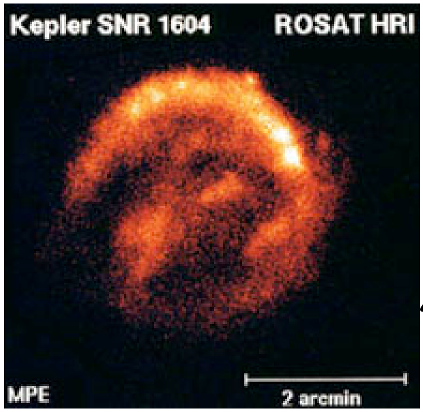


Tycho, SAO, Chandra

Historical Supernovae in our Galaxy

SN 1054 → Crab Nebula

Chaco Canyon Petroglyph



SN	Identification	SN Type
185	Historical descriptions	Ia ?
1006	Historical descriptions	Ia ?
1054	Crab Nebula	II ?
1572	Tycho Brahe	Ia
1604	Johannas Kepler	Ia
~1680	Cassiopeia A	II

- **The expected rate in the Milky Way is about 1 every 50 years, with SNe II being roughly 3 times more frequent than SNe Ia.**

Significance of Supernovae

High-Z Supernova Search Team, HST

Supernovae are the most spectacular of galactic events:

- They release $\approx 10^{51}$ ergs of light and kinetic energy.
- As the brightest objects in galaxies, they allow probes of the distance scale of the Universe.
- They enrich the Galaxy in "heavy" elements (heavier than helium) to levels of order 2 percent (Solar Abundance).
- They provide energy sufficient to power the acceleration of cosmic rays.
- They leave condensed remnants - neutron stars and black holes - whose presence in binary systems give rise to X-ray bursts and other high energy phenomena.

Significance of Supernovae

COBE

High-Z Supernova Search Team, HST

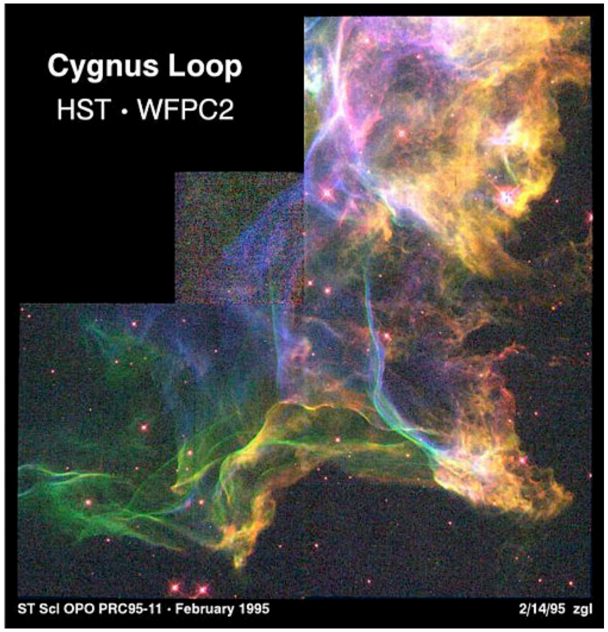
- SNe Ia contribute to the chemical enrichment of galaxies - synthesis of iron-peak elements.
- SNe Ia are crucial for cosmology: probes of the distance scale provide constraints upon the expansion and geometry (Ω_M, Ω_Λ) of the Universe and the nature of dark energy
- SNe II contribute to the chemical enrichment of galaxies - synthesis of the elements from oxygen to zinc and of heavy elements from krypton through uranium.

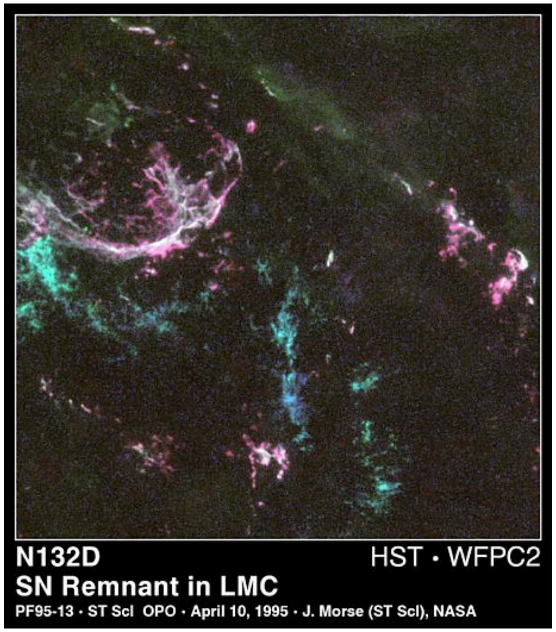
Supernovae

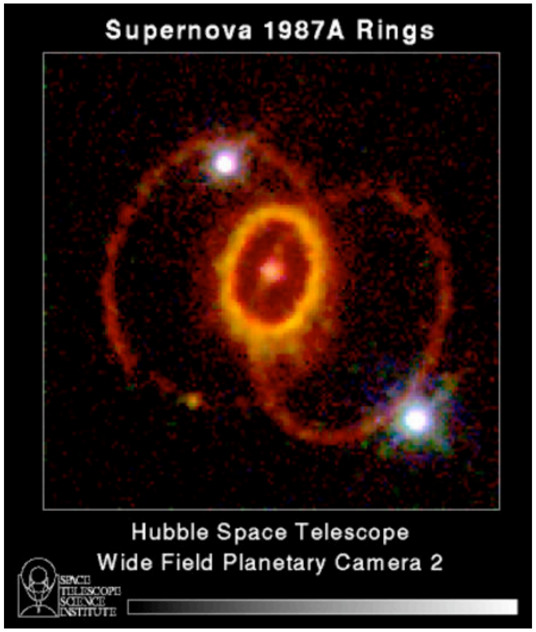
- Astronomical observations reveal the existence of two broad classes of supernovae: Types Ia and II.

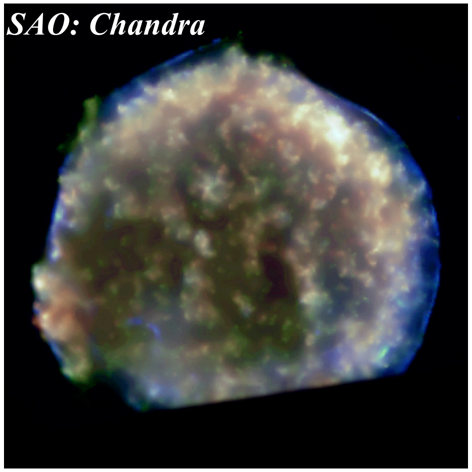
- Distinguishing features include:
  - Stellar Population:
    - Type II's in young populations (e.g. spiral arms of Spirals)
    - Type Ia's in older populations (e.g. Elliptical galaxies)
  - Supernova spectra:
    - Type II's are hydrogen rich (early ejecta of ~ Solar composition)
    - Type Ia spectra reveal absence of hydrogen in ejecta
  - Remnants:
    - Type II supernovae leave neutron star or black hole remnants
    - Type Ia supernovae leave no condensed remnants
  - Light curves

Supernovae and Supernova Remnants

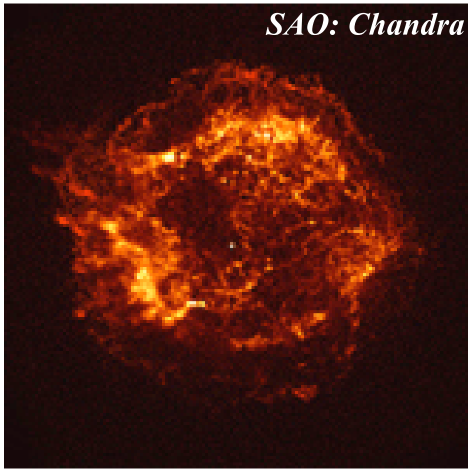








SN 1572: Tycho

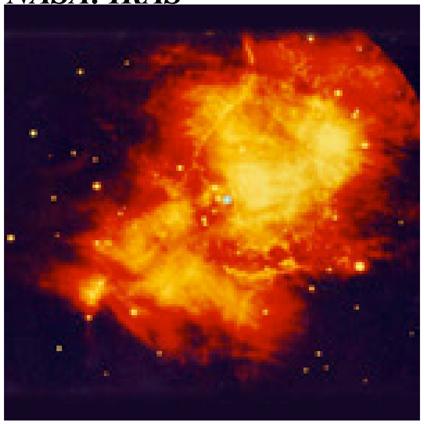


SN C1680: Cas A

Supernovae and Supernova Remnants

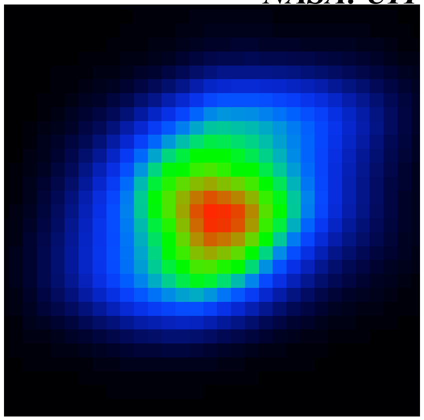
SNe 1054 Supernova Remnant (Crab Nebula in Taurus)

NASA: IRAS



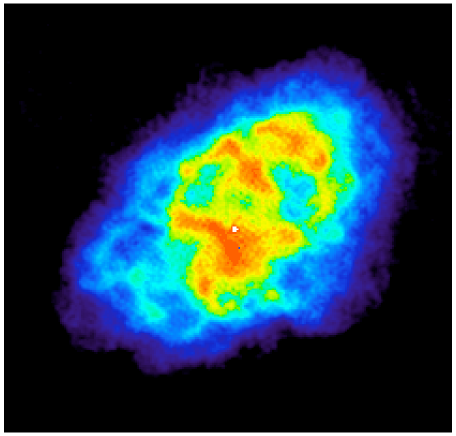
Infrared

NASA: UIT



Far UV

NRAO: 1992

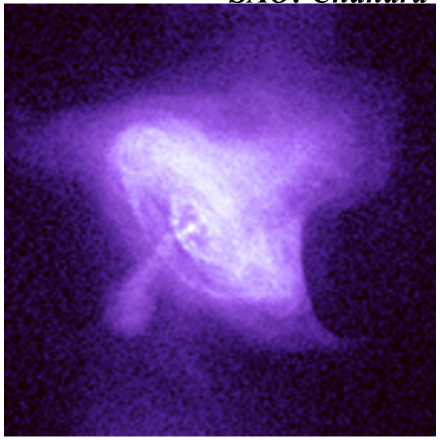


Radio

Malin/Pasakoff/Caltech

Optical

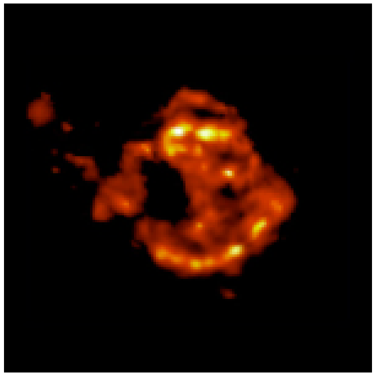
SAO: Chandra



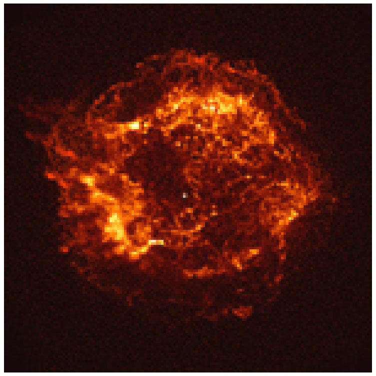
X-ray

Supernovae and Supernova Remnants

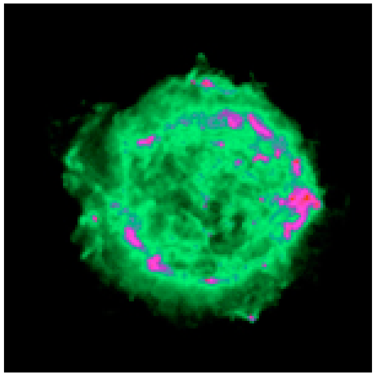
Cassiopeia Supernova Remnant
(estimated occurrence: 1680)



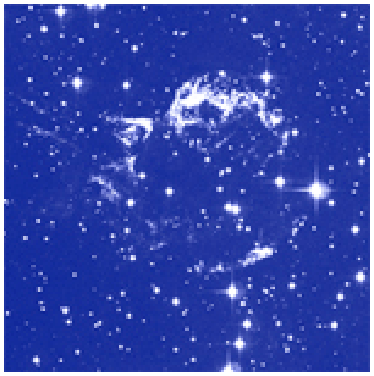
Cas A 1680 -Infrared



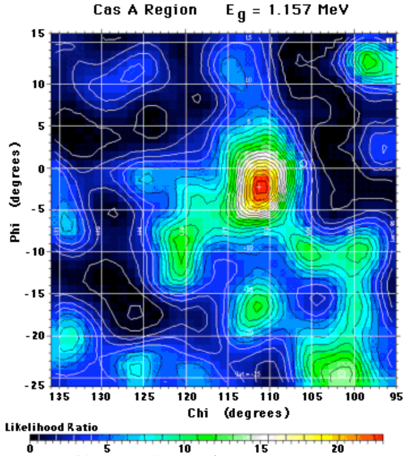
Cas A 1680 - X-ray



Cas A 1680 - Radio



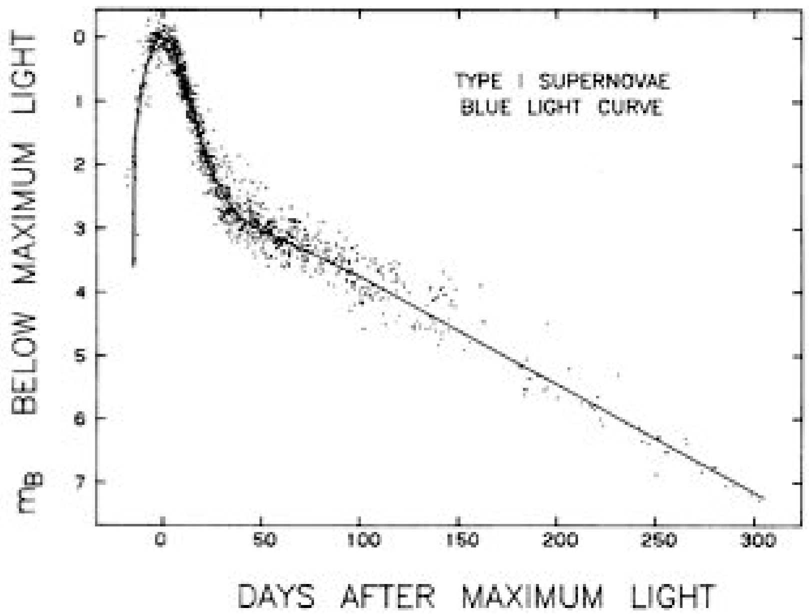
Cas A 1680 - Optical



Cas A 1680 - γ-ray

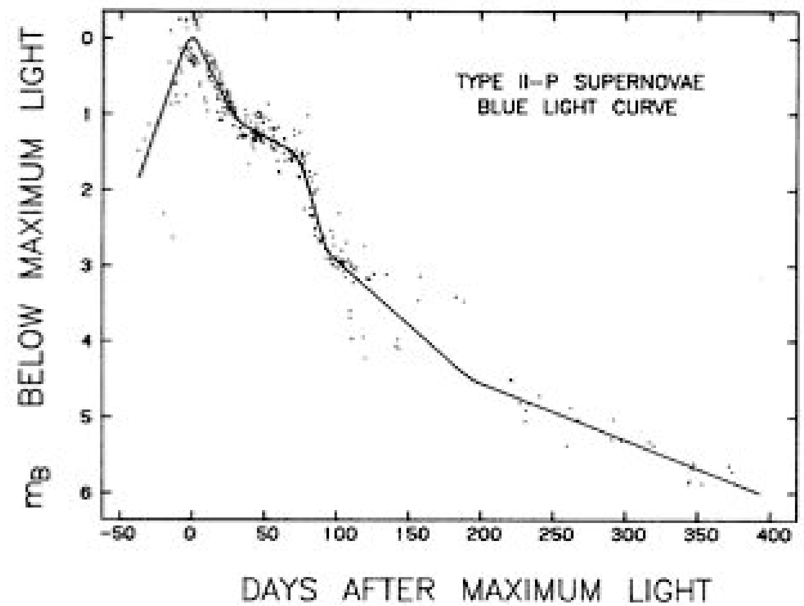
Supernova Light Curves: SNe Ia and SNe II

Doggett and Branch (ApJ 1985)



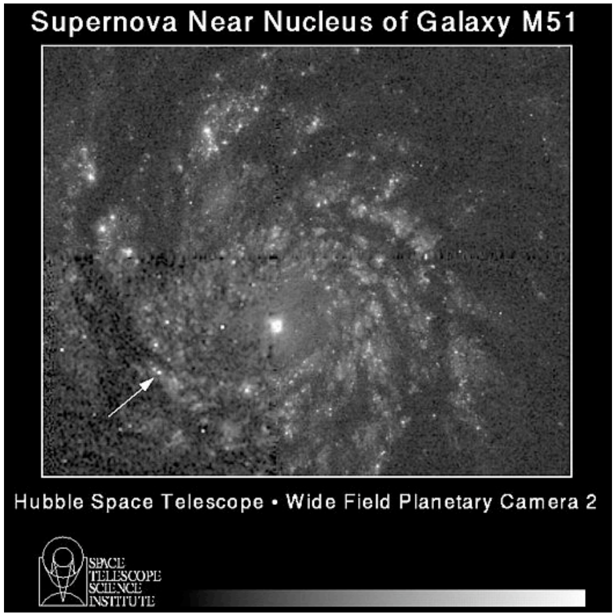
Type Ia Supernova Light Curve

Doggett and Branch (ApJ 1985)



Type II Supernova Light Curve

Supernova in Galaxies: Populations



SNe 1994I (Type II)

Elliptical Galaxy M87

High-z Supernova Search Team, HST, NASA

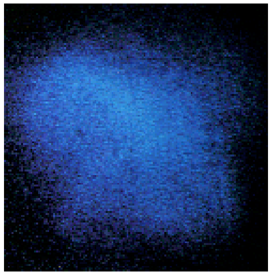
SNe 1994D (Type Ia)

SNe 1987A (Type II)

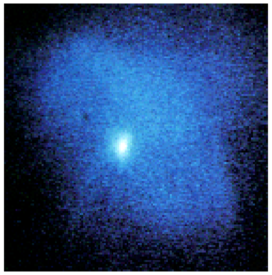
Large Magellanic Cloud

Supernova Remnants

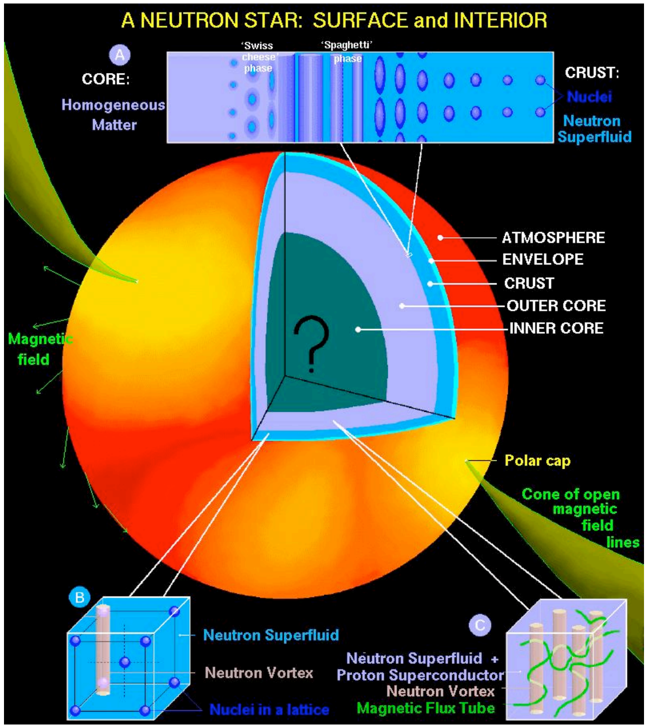
Crab Pulsar - Off



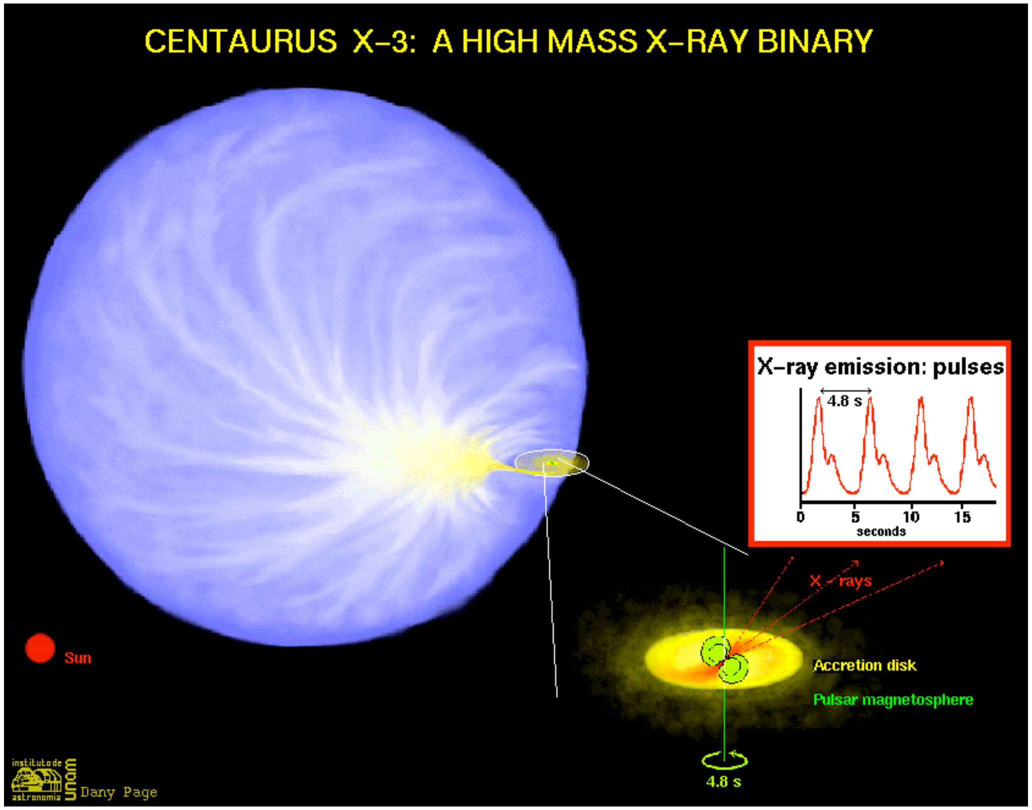
Crab Pulsar - On



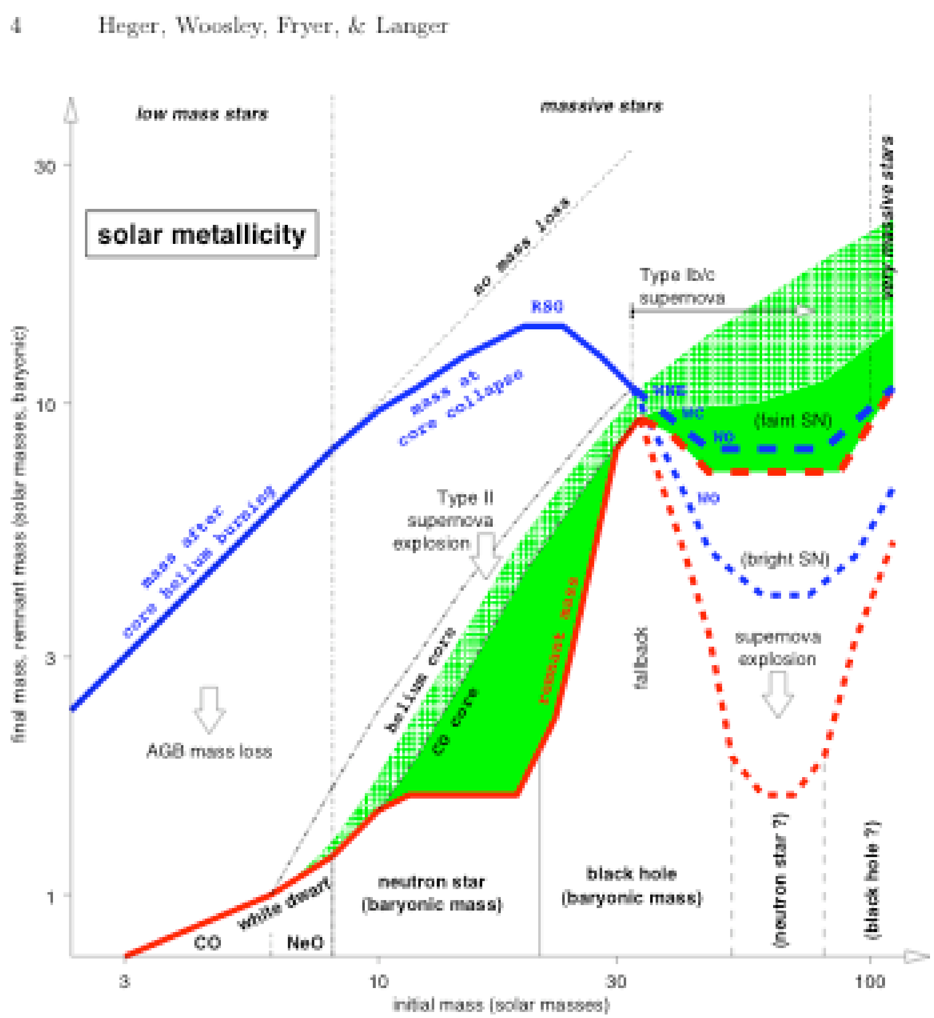
Einstein X-Ray Observatory



www.lsw.uni-heidelberg.de/~mcamenzi/NS_Mass.html



Stellar and Supernova Remnants



SNe Ia and SNe II Supernova Progenitors

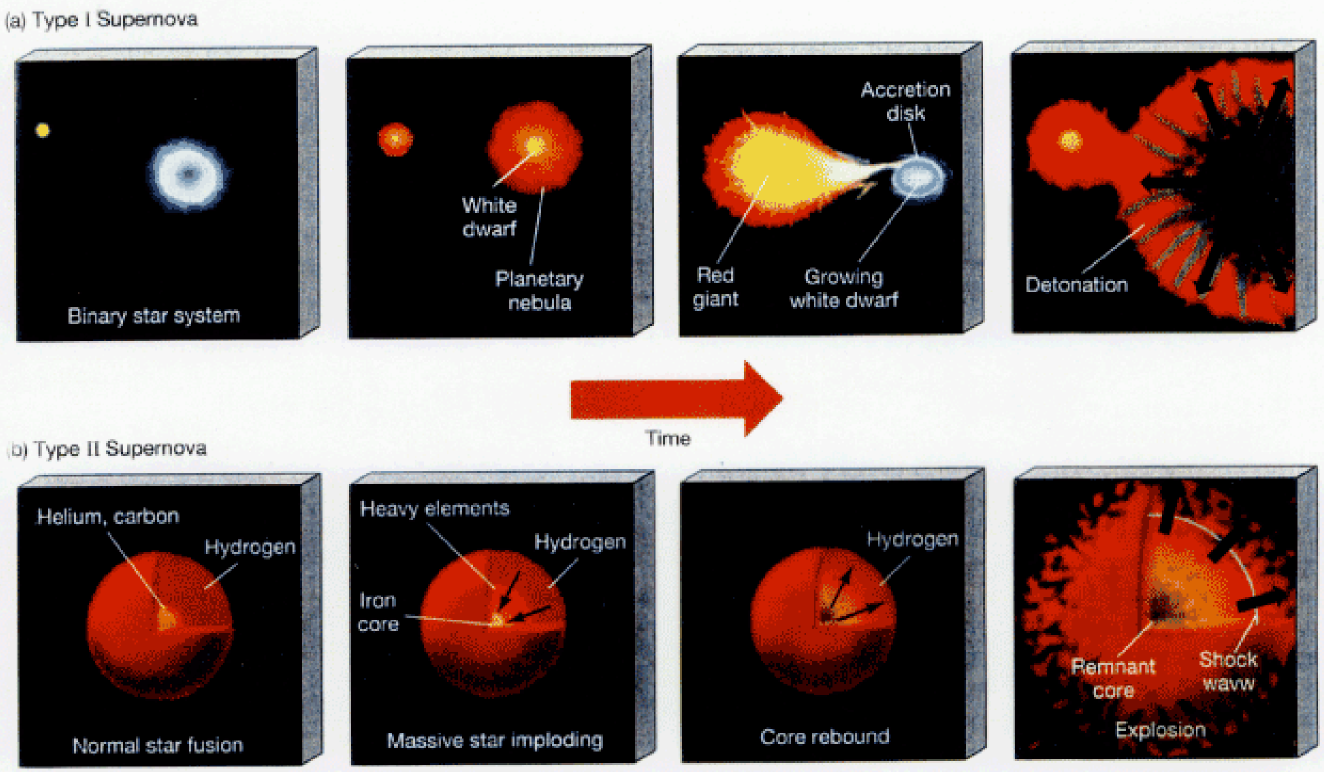
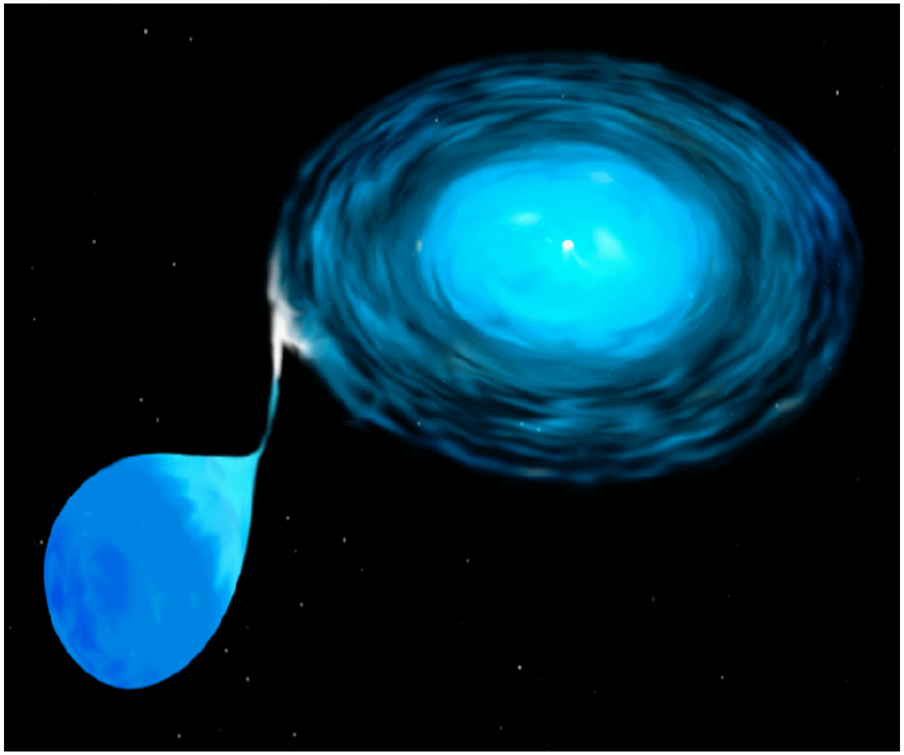


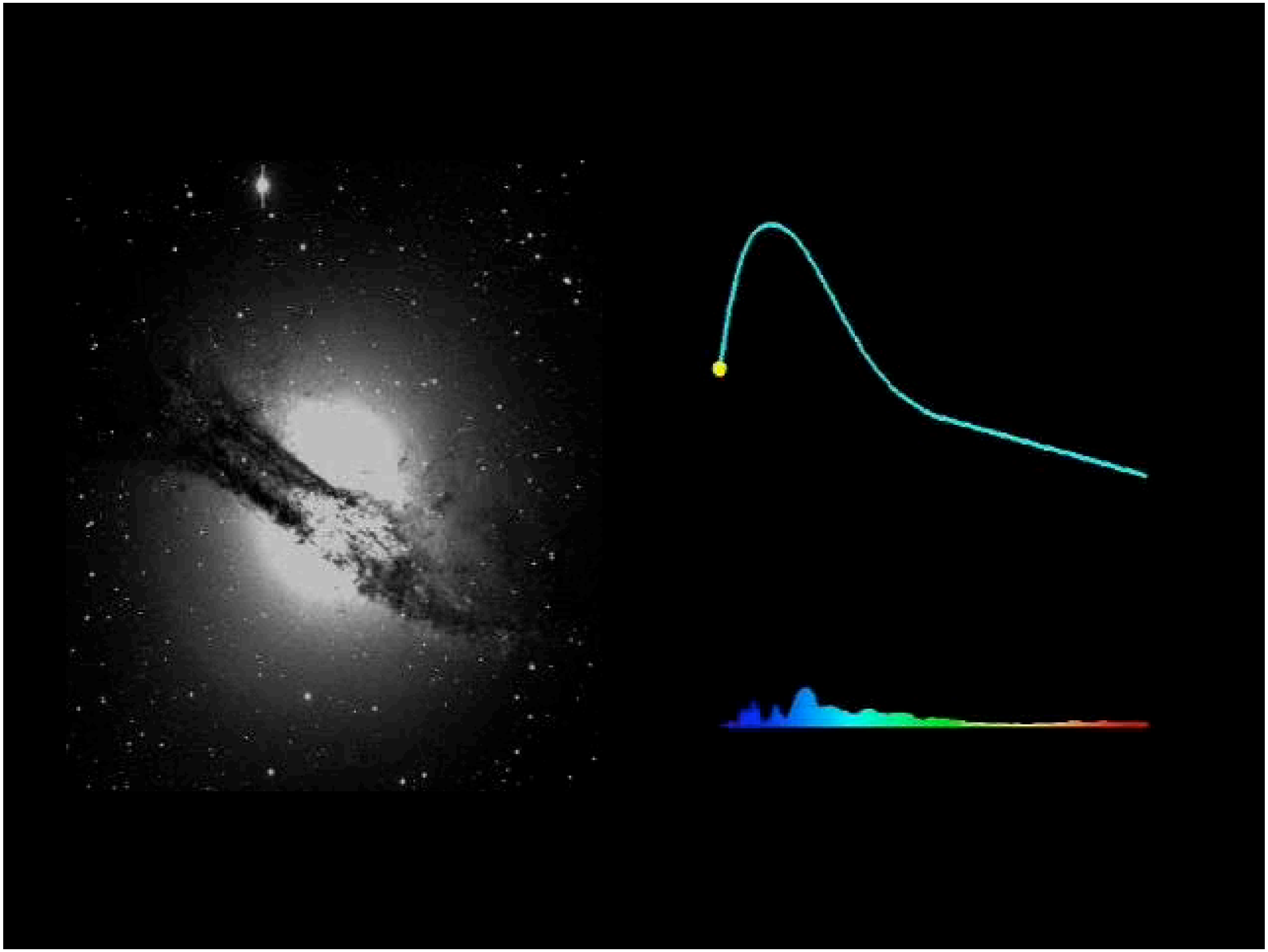
Figure 21.8 Type I and Type II supernovae have different causes. These sequences depict the evolutionary history of each type. (a) A Type I supernova usually results when a carbon-rich white dwarf pulls matter onto itself from a nearby red-giant companion. (b) A Type II supernova occurs when the core of a more massive star collapses, then rebounds in a catastrophic explosion.

Type Ia Supernovae: Theory

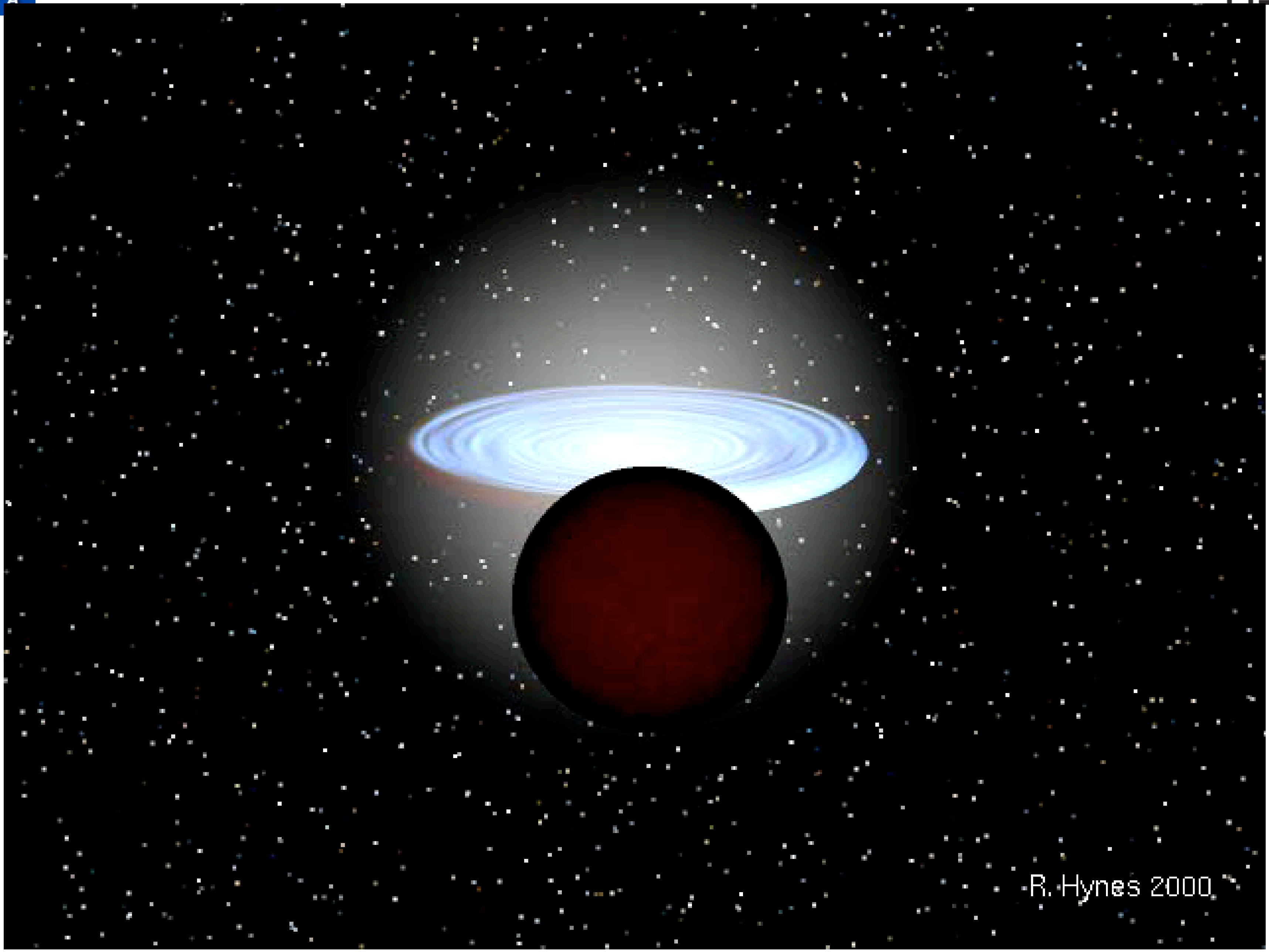


- "Standard model" (Hoyle & Fowler 1960):
  - SNe Ia are thermonuclear explosions of C+O white dwarf stars.
- Evolution to criticality:
  - Accretion from a binary companion leads to growth of the WD to the critical (Chandrasekhar) mass (1.4 solar masses).
- After ~1000 years of slow thermonuclear "cooking", a violent explosion is triggered at or near the center.
- Complete incineration occurs within two seconds, leaving no compact remnant.
- Nucleosynthesis contributions: 1/2 to 2/3 iron-peak nuclei. ($\tau_{nucleosynthesis} > 10^9$ yrs)
- **Their light curves are powered by the radioactive decay of ^{56}Ni. Their peak luminosities: $L_{max} \propto M(^{56}Ni)$.**

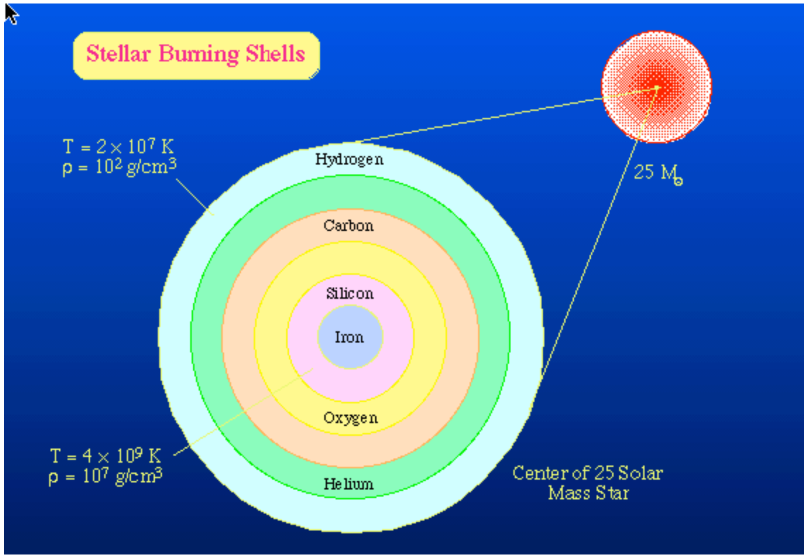
Light Curve and Spectrum of SNe Ia



Binary Origin of SNe Ia Progenitors

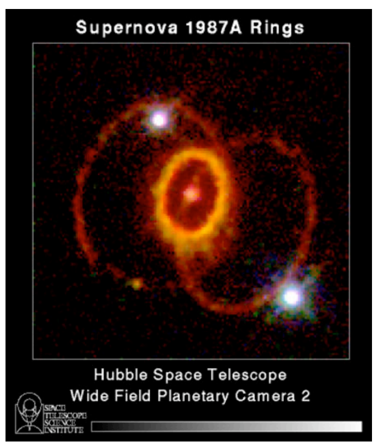


Type II Supernovae: Theory



Courtesy Mike Guidry: guidry@utk.edu

SNe1054: Crab Nebula



SNe1987A Hubble Image

- **"Standard model" (Hoyle & Fowler 1960):**
  - **SNe II are themproduct of the evolution of massive stars 10 < M < 100 $M_\odot$.**
- **Evolution to criticality:**
  - **A succession of nuclear burning stages yield a layered compositional structure and a core dominated by ^{56}Fe.**
  - **Collapse of the ^{56}Fe core yields a neutron star.**
  - **The gravitational energy is released in the form of neutrinos, which interact with the overlying matter and drive explosion.**
- **Remnants: Neutron star and black hole remnants are both possible SNe II remnants.**
- **Nucleosynthesis contributions: elements from oxygen to iron (formed as ^{56}Ni) and neutron capture products from krypton through uranium and thorium. ($\tau_{nucleosynthesis} < 10^8$ yrs)**

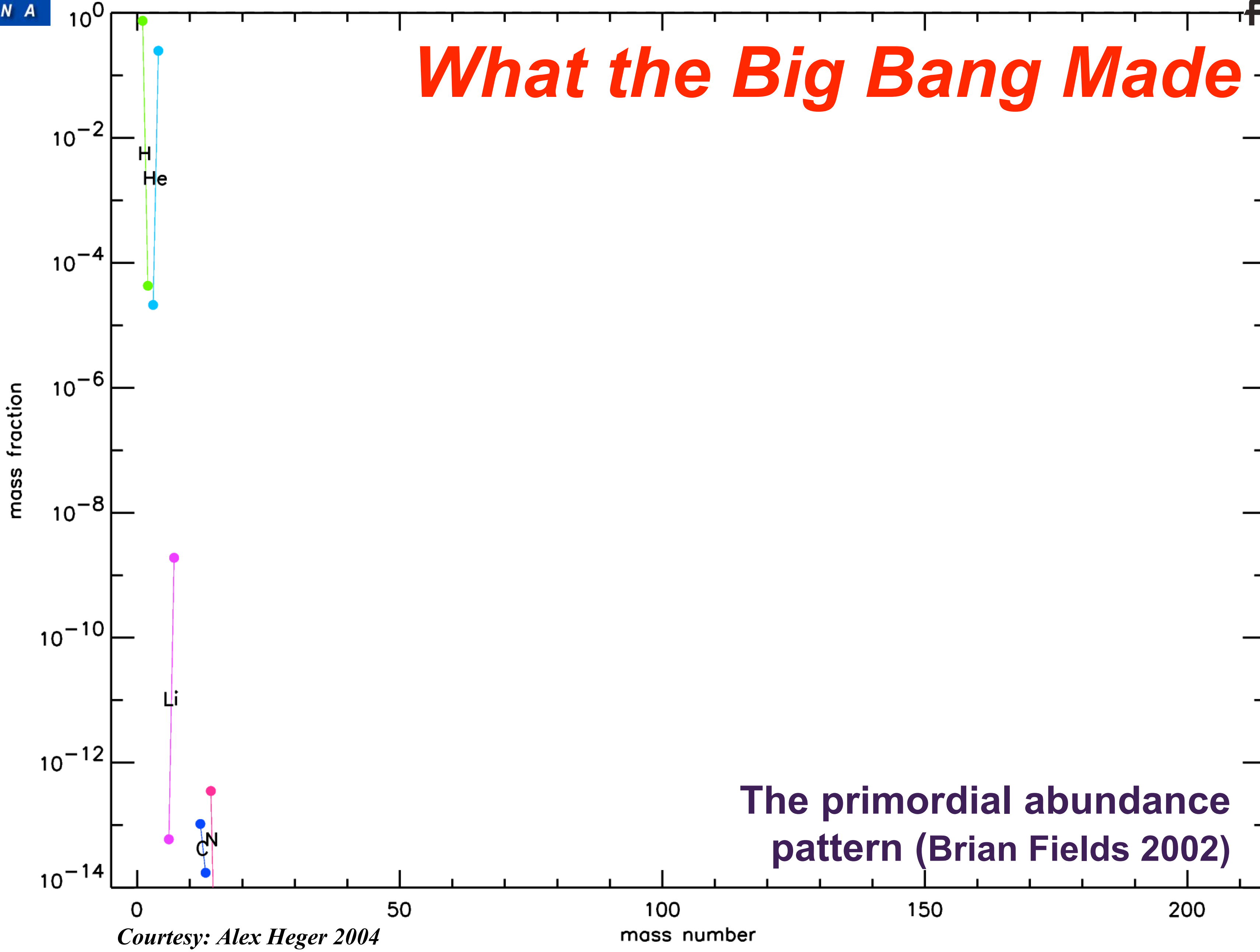
Nucleosynthesis and "Cosmic" Abundances

- The Universe emerged from the cosmological Big Bang with a composition consisting of hydrogen, helium, ^{2}D, ^{3}He, and ^{7}Li.

- Galaxies and the first stars within them were born with this primordial composition.

- The heavy elements with which we are familiar - from carbon to iron to uranium - are the products of nuclear processes associated with the evolution of stars and supernovae of Types Ia and II.

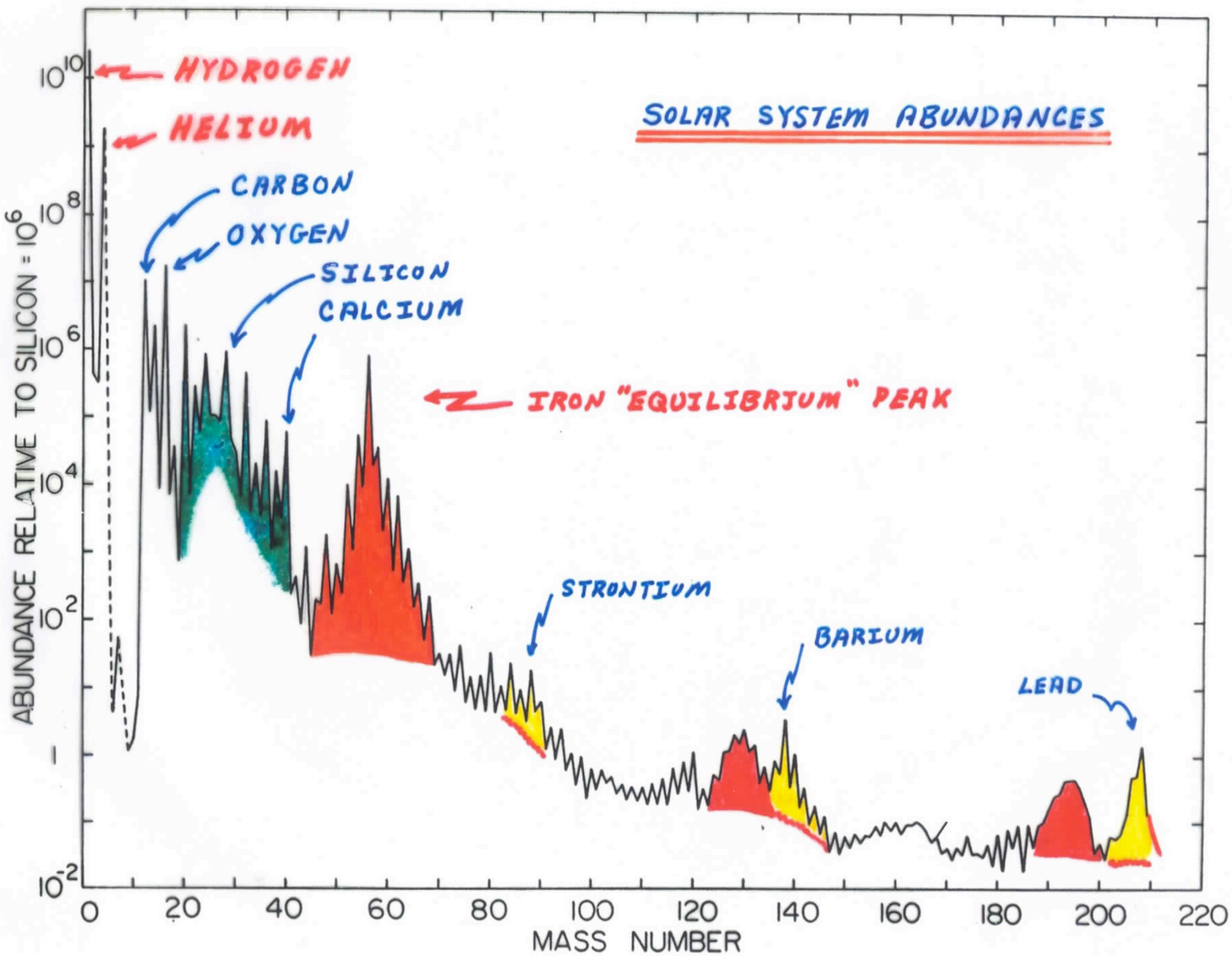
What the Big Bang Made



The primordial abundance pattern (Brian Fields 2002)

Courtesy: Alex Heger 2004

Cosmic Abundances of the Elements



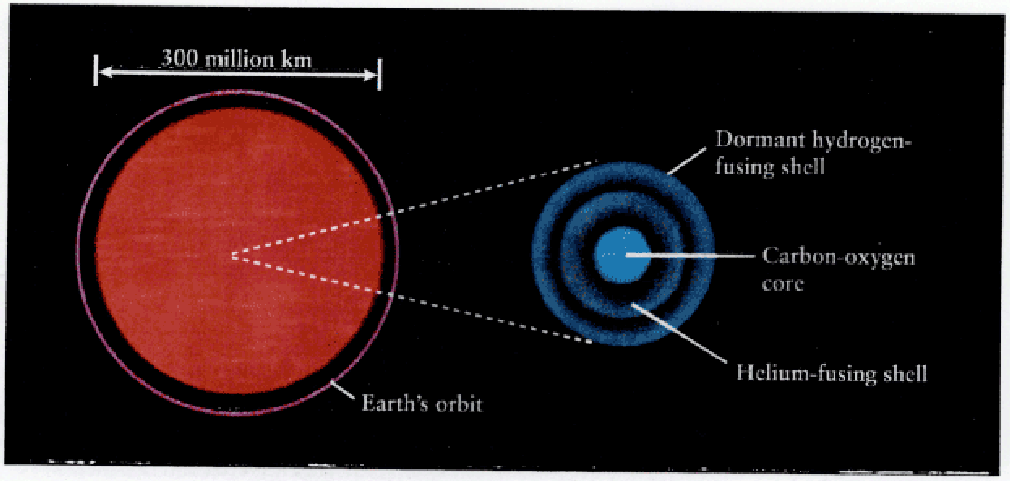
Nucleosynthesis Sites

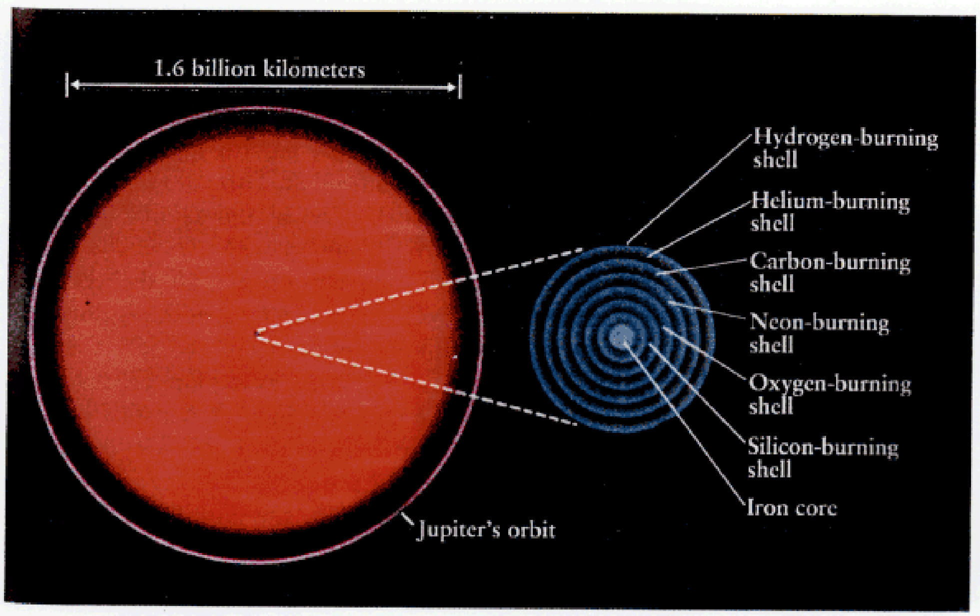
- Massive star ($M > 10\ M_{\odot}$) and SNe II synthesis of the nuclear species from oxygen to zinc, and the r-process heavy elements

- Red Giant ($1 < M < 10\ M_{\odot}$) synthesis of carbon and s-process elements

- SNe Ia synthesis of the 1/2-2/3 of the iron peak nuclei not produced by SNe II

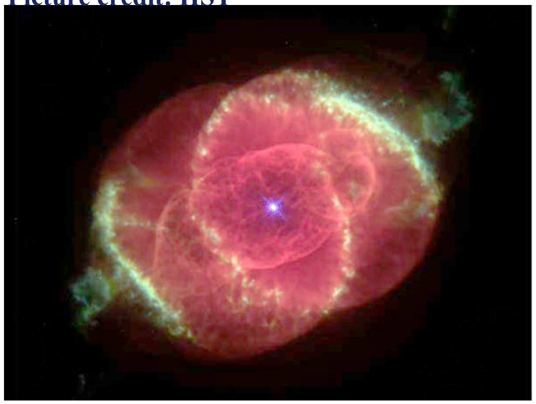
Stellar and Supernova Nucleosynthesis





Kaufmann "Universe" 1994

Picture credit: HST

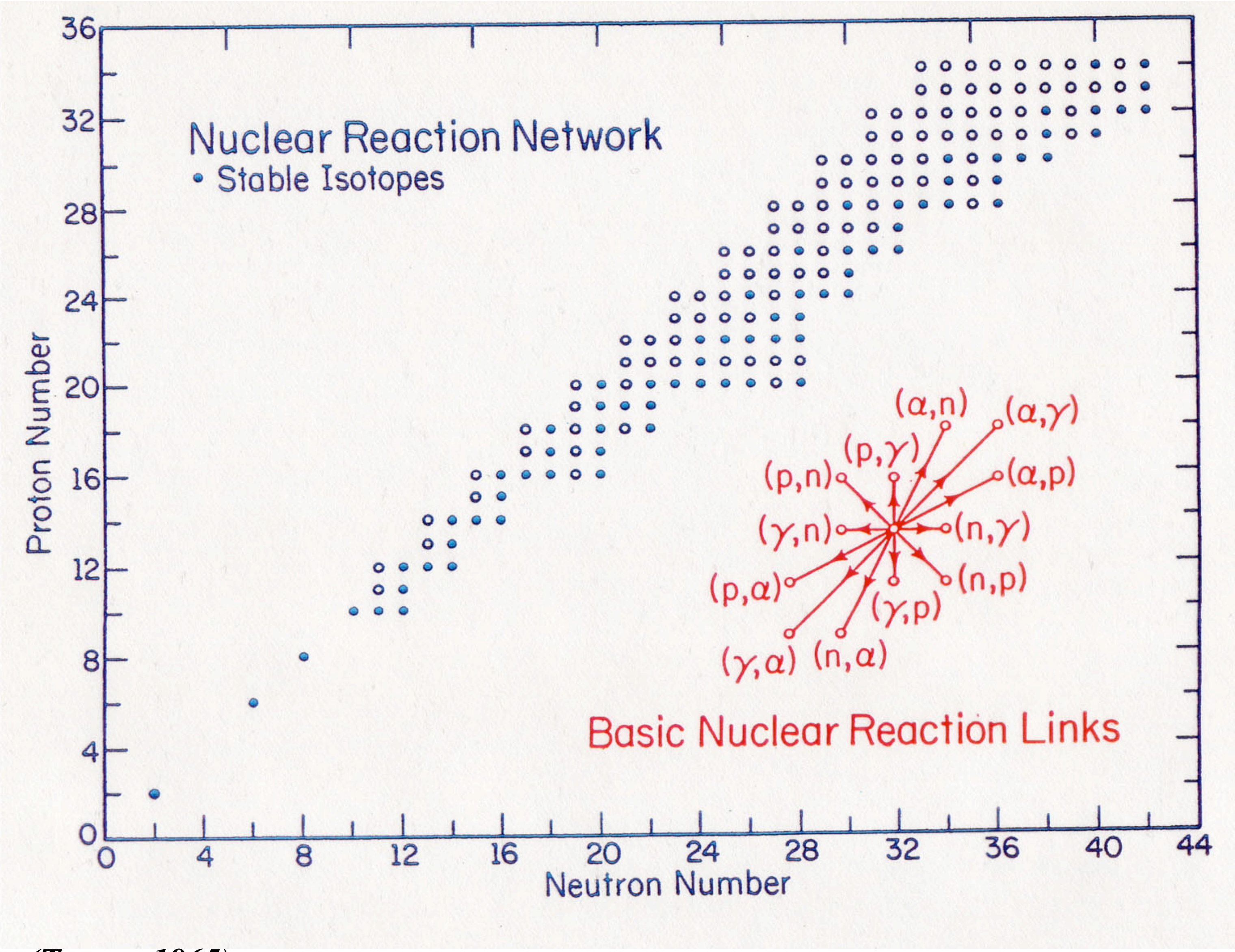


AGB Star - Planetary Nebula

High-Z Supernova Search Team, HST

Massive Star - SNII

Representative Nuclear Reaction Network



(Truran 1965)

^{56}Ni Production in "Explosive Nucleosynthesis"

- **Pre-explosion compositions involve primarily nuclei of Z ≡ N, viz: ^{12}C, ^{16}O, ^{28}Si ….**
- **Explosive burning at T≥ 5x10^{9} ^{o}K typically occurs on timescales ≤ seconds.**
- **Supernova nucleosynthesis sees reactions occurring on a dynamical timescale.**
- **Weak interactions proceed too slowly to convert any significant fraction of protons to neutrons.**

$$e^- + (Z, A) \rightarrow (Z\text{-}1, A) + \nu_e$$

- **It follows that the (in situ) iron-peak products of explosive nucleosynthesis in supernovae are proton-rich nuclei of Z≈N, viz. ^{44}Ti, ^{48}Cr, ^{52}Fe, ^{56}Ni, ^{60}Zn, and ^{64}Ge. Of these, ^{56}Ni is far the most abundant.**

Supernova Nucleosynthesis Sites

- Massive star ($M > 10\ M_\odot$) and associated SNe II synthesize most of the nuclear species from oxygen to zinc. The “intermediate mass” nuclei (oxygen through calcium) are found to be overproduced relative to “iron peak” nuclei by a factor ≈ 2-3.

- SNe Ia synthesize ≈ 1/2-2/3 of the iron peak nuclei (those not produced by SNe II) and small but critical concentrations of intermediate mass elements.

- Given that SNe Ia produce ≈ 0.6 $M_\odot$ per event while SNe II produce rather ≈ 0.1 $M_\odot$ per event, the ratio SNe II/ SNe Ia by number is ≈ 3 over Galactic history.

Supernova Ia Nucleosynthesis

- ❑ **Early studies of Type Ia models and associated nucleosynthesis focused on the "carbon detonation model" of Arnett (1969).**

- ❑ **We now recognize that this results in the burning of the entire core to ^{56}Ni, in disagreement with recent spectroscopic studies of SNe Ia ejecta which reveal the presence of intermediate mass elements.**

⇒ Not a Pure Detonation

552 Thermonuclear Reactions and Nucleosynthesis

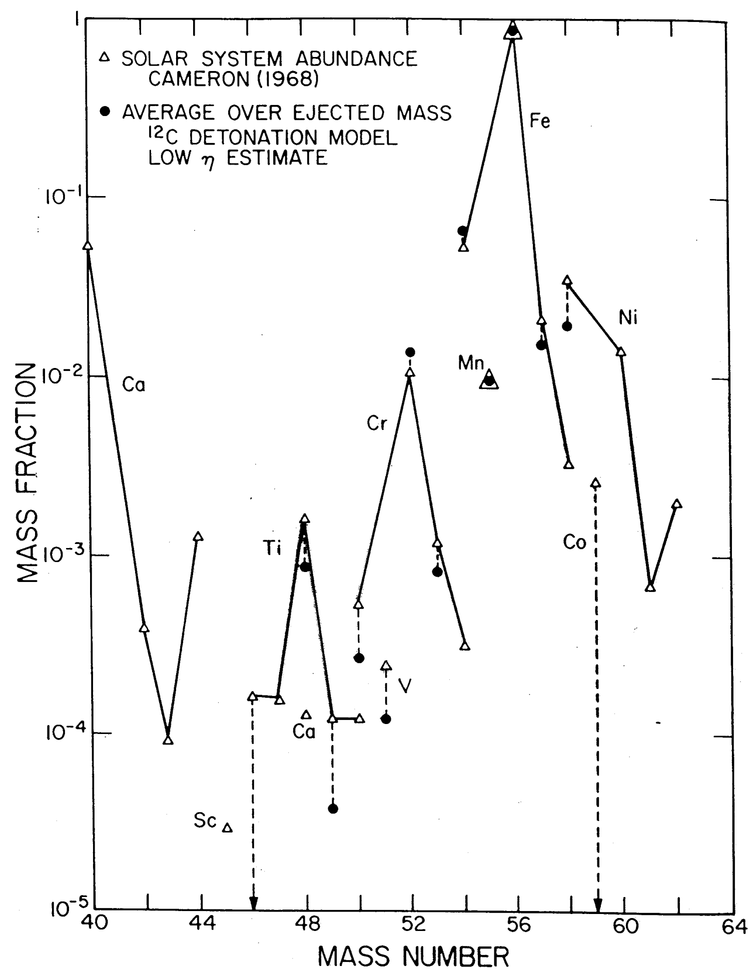
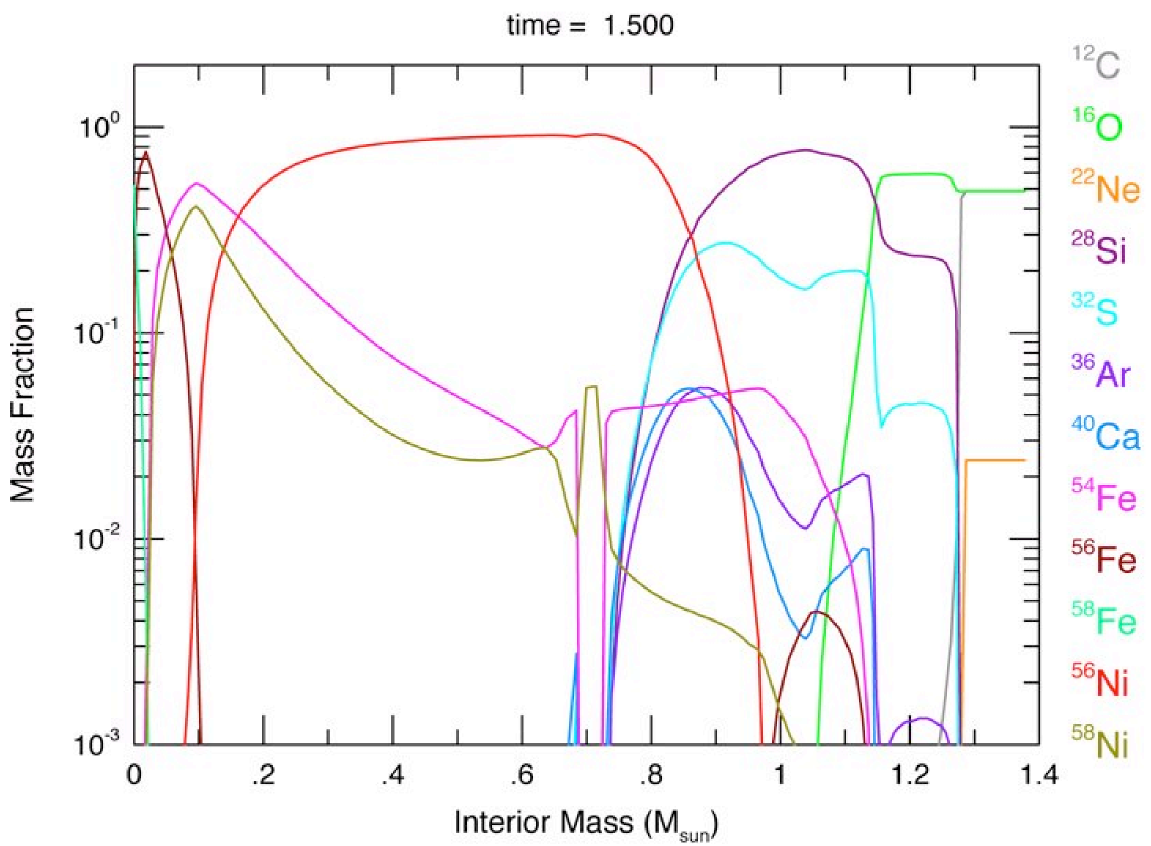


Figure 13. The nuclear abundances by mass produced in the mass zones ejected in the ^{12}C detonation model are compared to the solar system abundances. The two distributions are normalized at ^{56}Fe. The "low η" estimate of the neutron excess was employed.

(Truran, Arnett, and Woosley 1971)

Supernova Ia Nucleosynthesis

- Nearly all one-dimensional Chandrasekhar mass models of Type Ia supernovae produce most of their ^{56}Ni in a nuclear statistical equilibrium environment between the mass shells 0.2 M_{sun} and 0.8 M_{sun}.

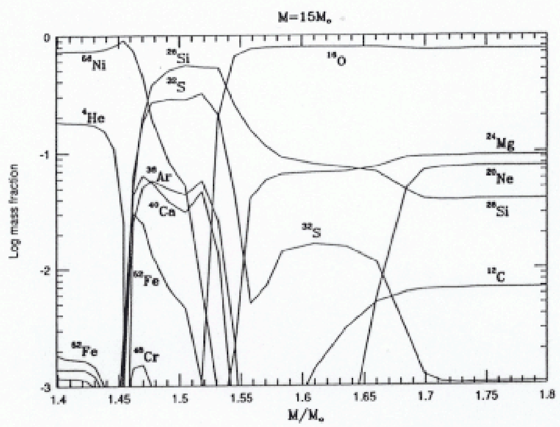


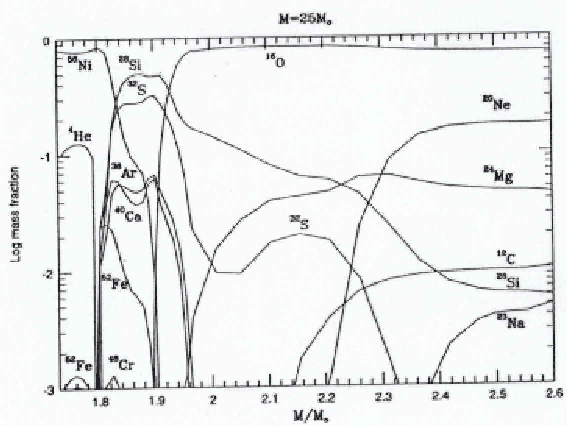
W7 model of Nomoto, Thielemann, & Yokoi (1984)

Supernova II Nucleosynthesis

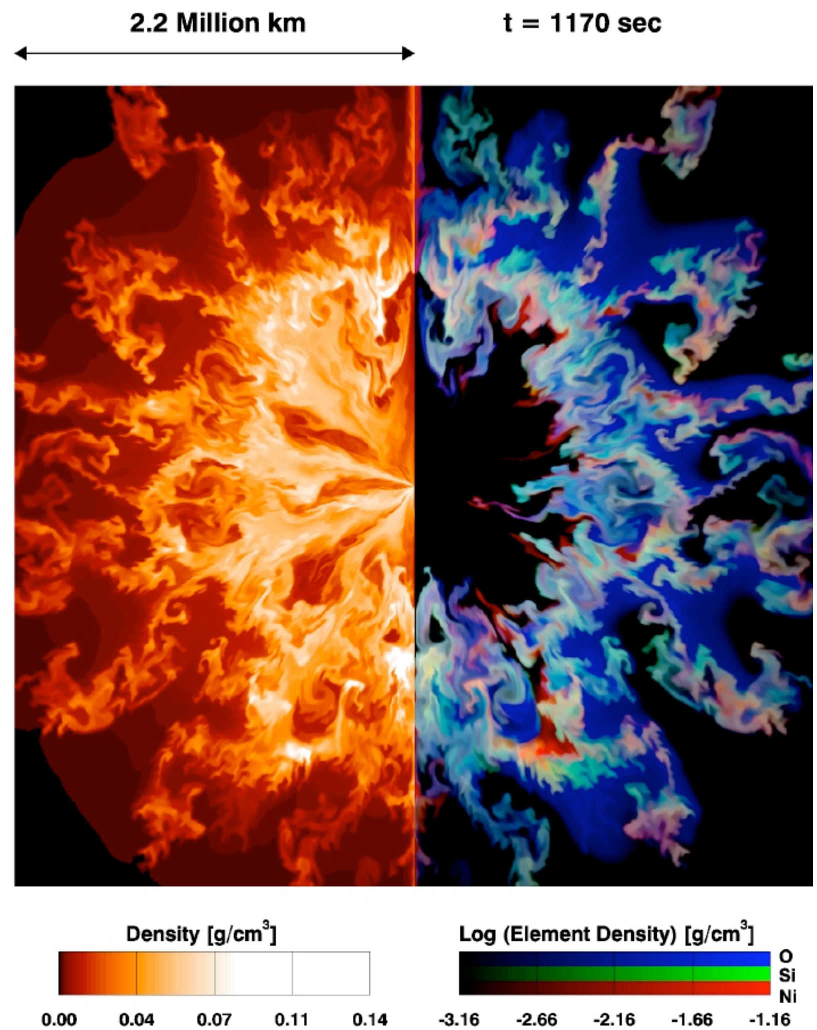
SNe II NUCLEOSYNTHESIS

(THIELEMANN, NOMOTO AND HASHIMOTO 1992)



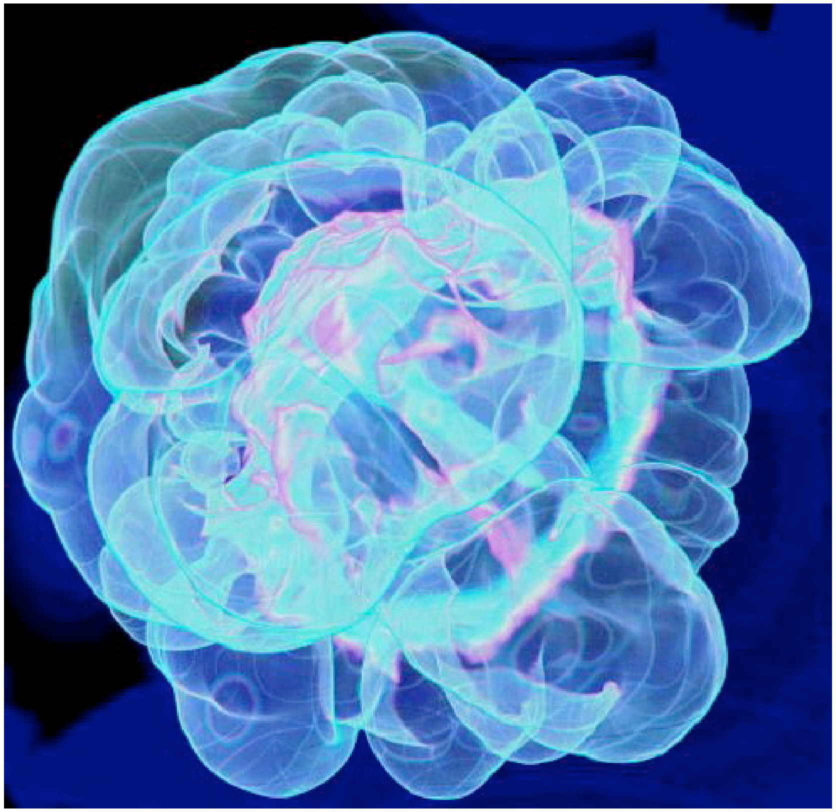


MASS FRACTIONS OF SEVERAL MAJOR NUCLEI AS THEY RESULT FROM POST-SHOCK SUPERNOVA PROCESSING



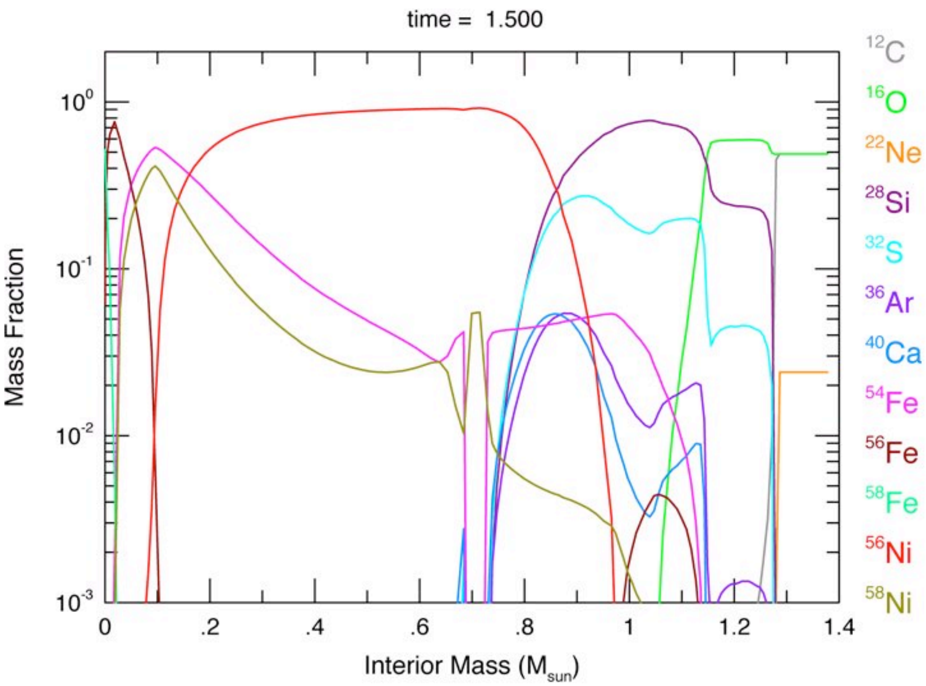
(Kifonidis et al. 2000)

Supernova Ia Nucleosynthesis



Off-center Deflagration Simulation

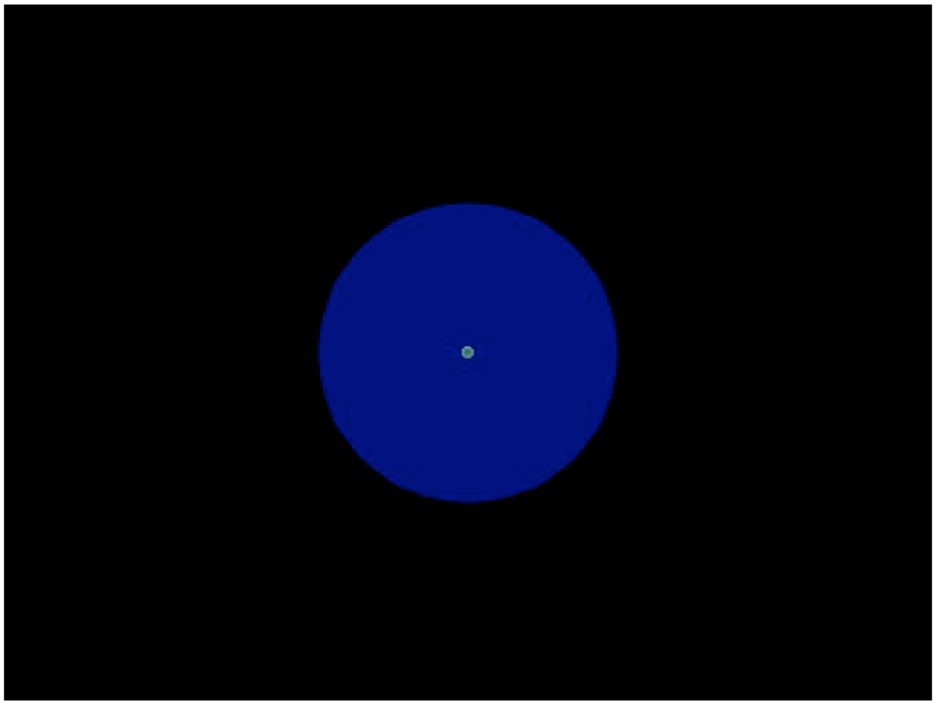
(Calder et al. 2004)



Evolution of Core Composition

(Timmes, Brown, Truran 2003)

SNe Ia: Deflagration and Nucleosynthesis



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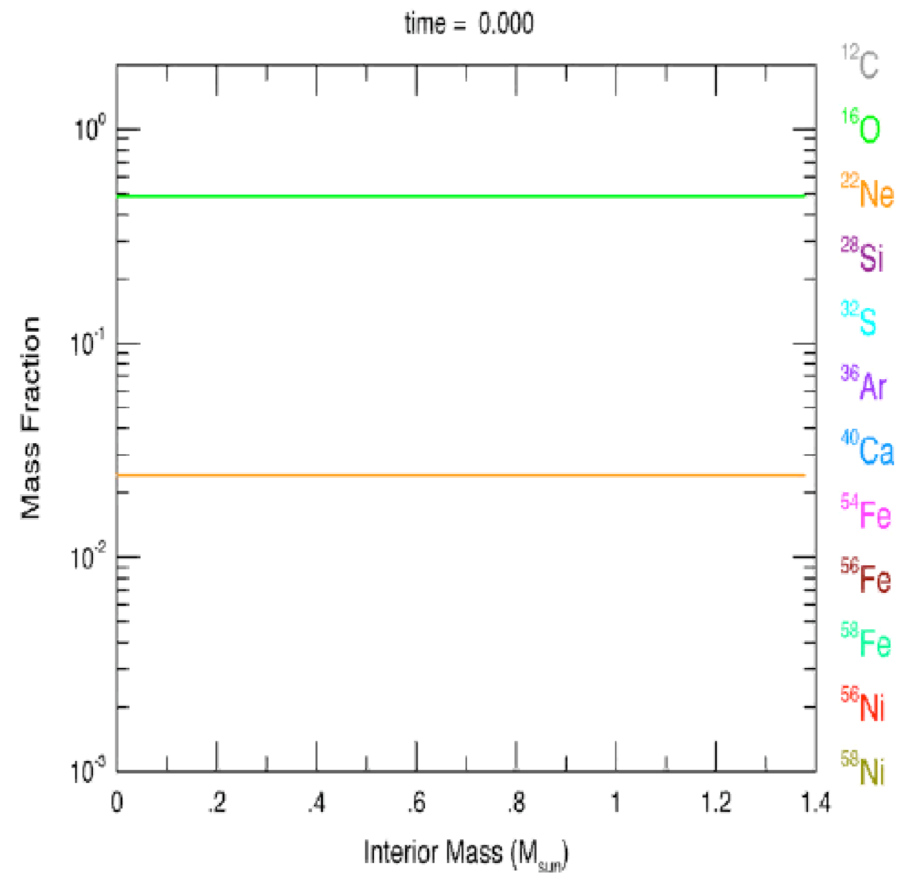

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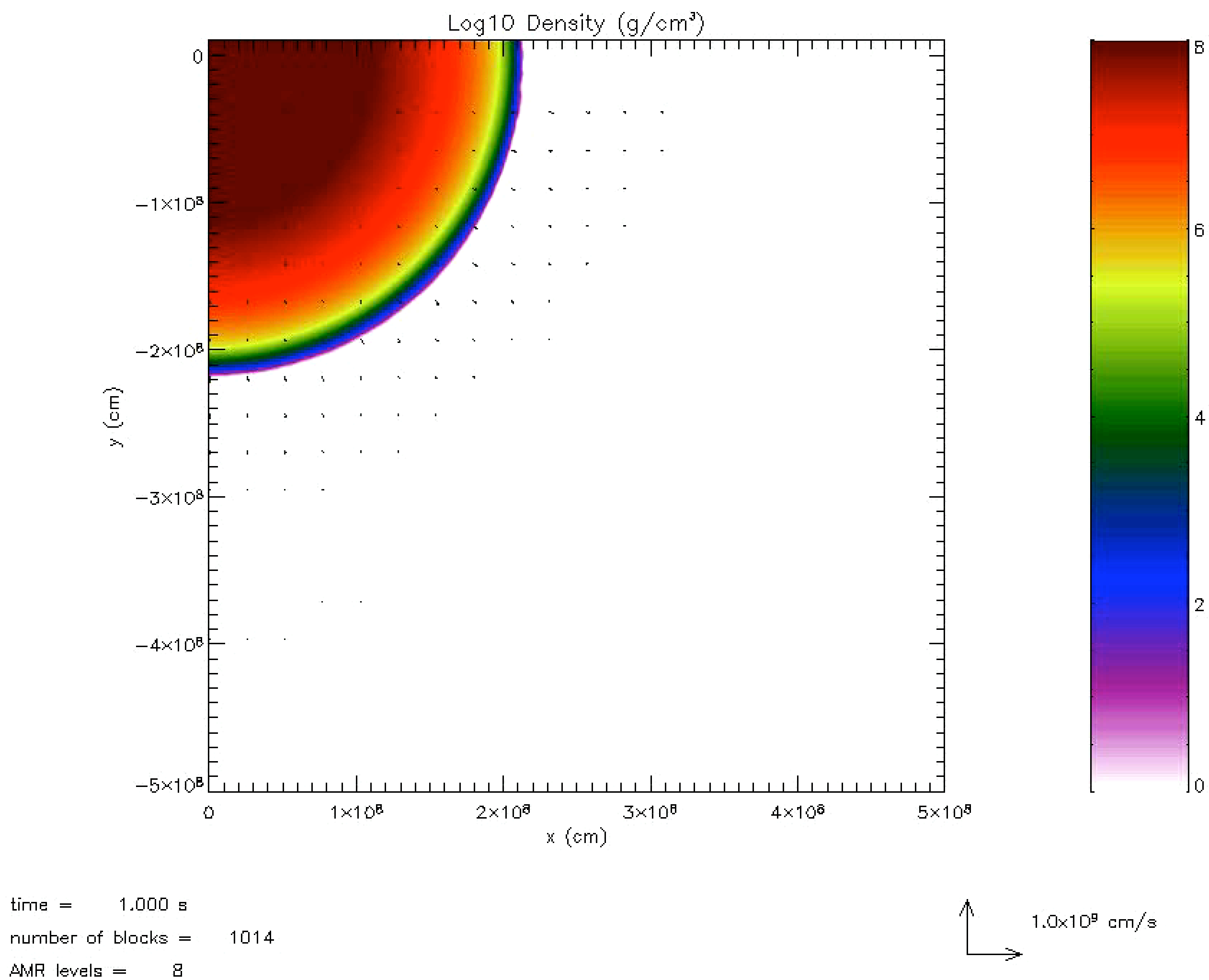
SNe Ia: Deflagration and Nucleosynthesis



Possible Consequences of Breakout

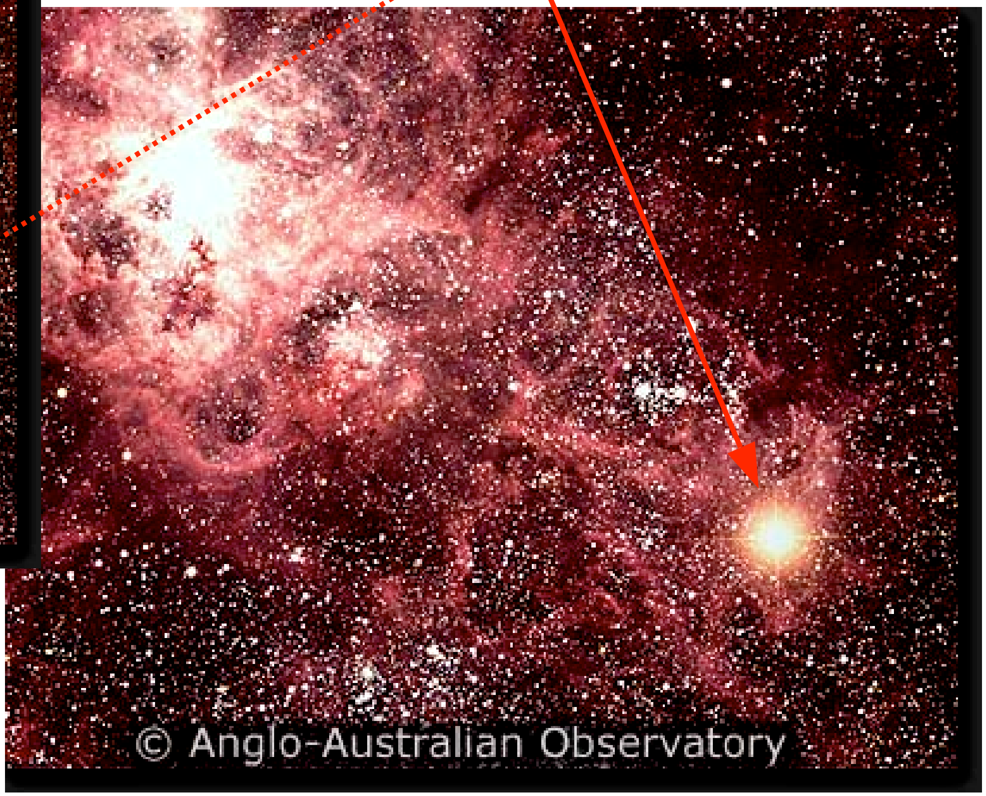
(Plewa et al 2004)

SN 1987A in the Large Magellanic Cloud

An Exciting Recent Supernova Event

30 Doradus Nebula prior to explosion of SN 1987A

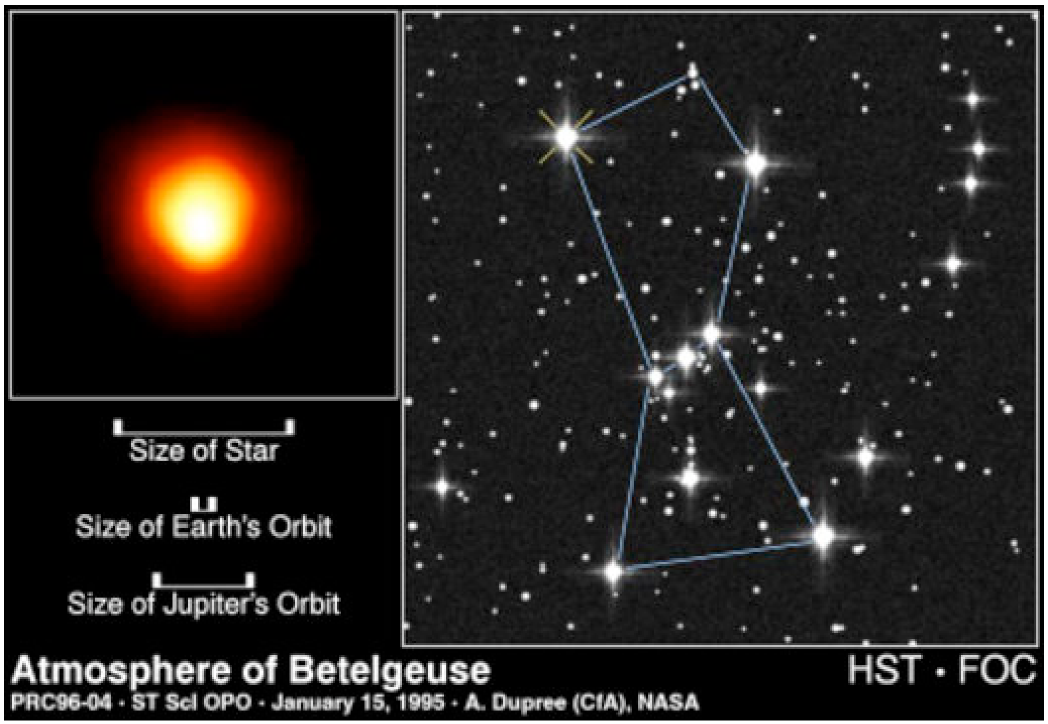
30 Doradus subsequent to explosion of SN 1987A



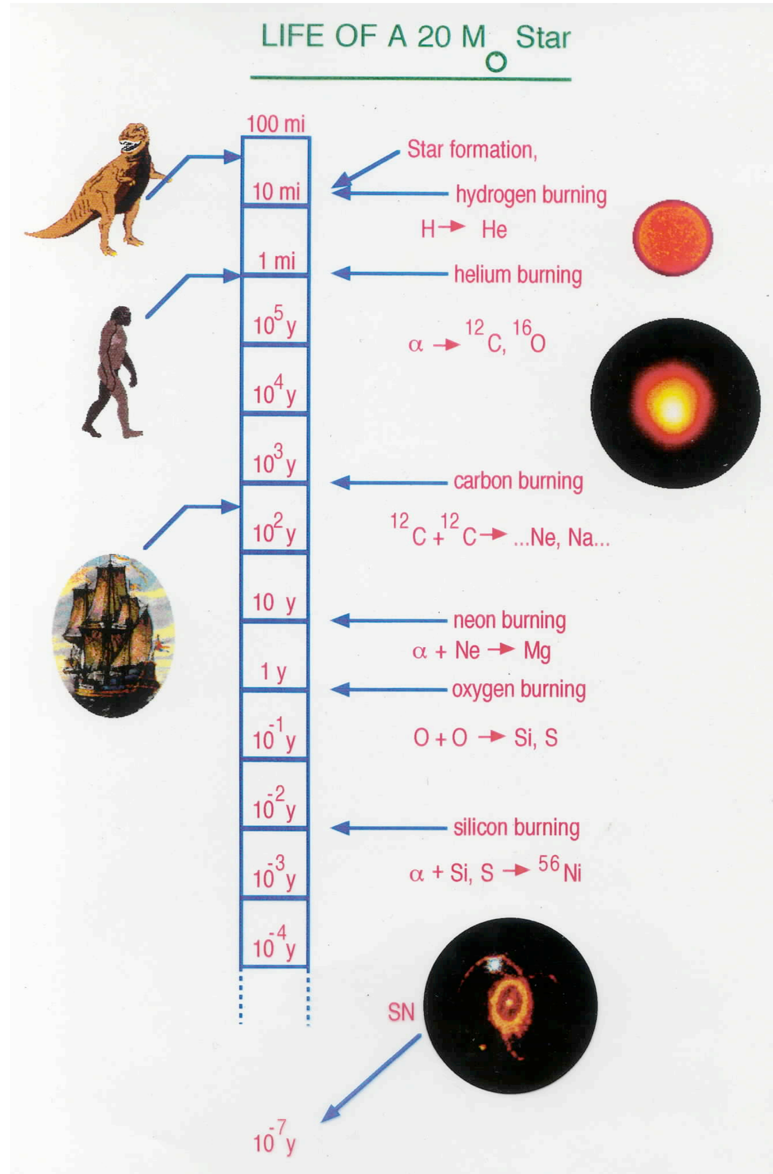
SN 1987A in the Large Magellanic Cloud

- SN 1987A, whose brightness at maximum was of order 10^9 $L_\odot$, was of great significance to supernova theorists:
  - It was the first local supernova since 1604 (Kepler).
  - The progenitor star was identified and found to be a massive star: M~ 20 $M_\odot$ and luminosity L ~ 20 $L_\odot$.
  - Most of its energy release (~ 3 x 10^{53} ergs) was in the form of neutrinos - which were detected.
  - The magnitude of this energy release confirmed the formation of a condensed remnant - a neutron star or black hole of mass ≥ 1.4 $M_\odot$.
  - Its light curve was powered by the decay of the ≈ 0.07 $M_\odot$ of 56Ni ejected as: $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$, confirmed by detection of γ-rays from ^{56}Co and ^{57}Co.
  - It ejected 5-6 $M_\odot$ of heavy elements - from oxygen to iron - and on to uranium and thorium.

SN 1987A in the Large Magellanic Cloud



*A likely supernova candidate for the next millenium: **Betelgeuse***



Courtesy: Ernst Rehm, ANL

SN 1987A in the Large Magellanic Cloud

The light curve of SN 1987A revealed the decay of nickel through cobalt to iron of approximately 0.07 $M_{\odot}$ of ejecta.

GAMMA-RAY EMISSION FROM RADIOACTIVE ISOTOPES 651

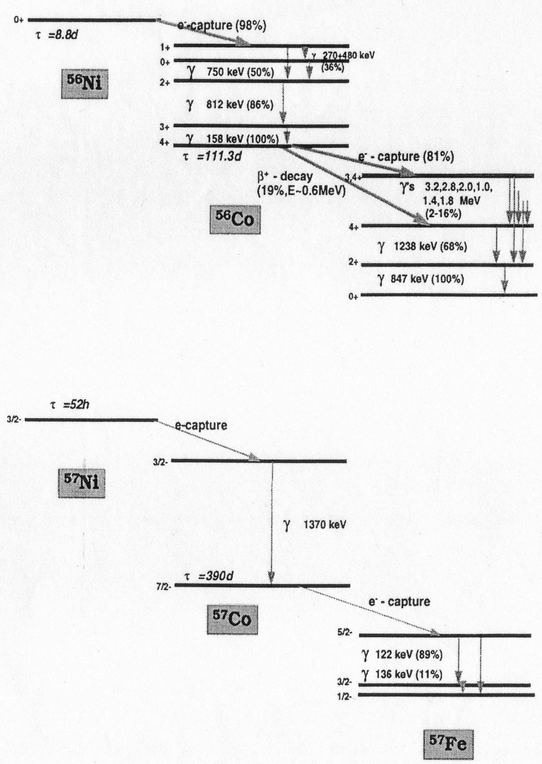
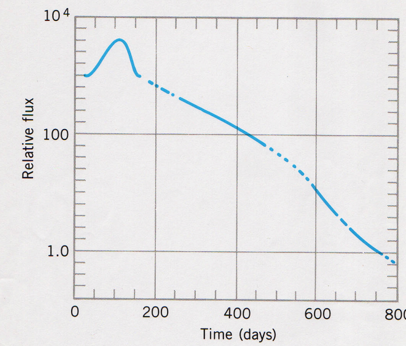


FIG. 11.—Decay of ^{56}Ni to ^{56}Fe and ^{57}Ni to ^{57}Fe, illustrating the most significant spin-parity levels and γ-ray photons. The most important transitions for γ-ray line astronomy and supernova diagnostics are marked with an asterisk.



Light curve of the Supernova from the first day of the visible outburst until May 16, 1988, some 800 days later.

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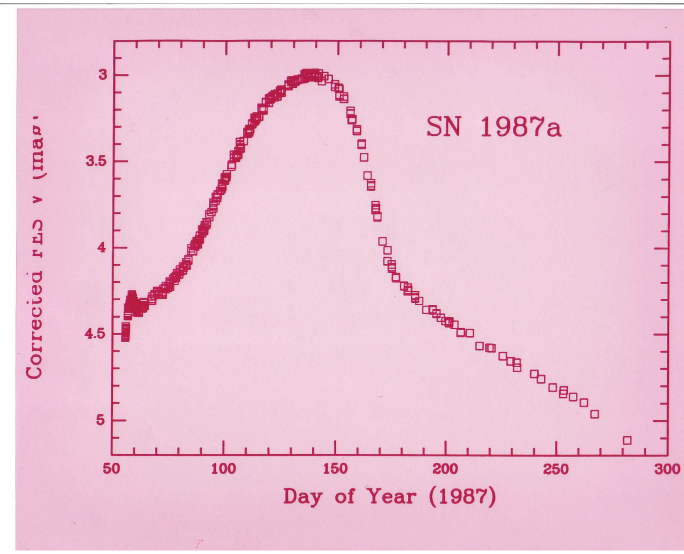

NASA: HST

Challenges in Supernova Theory

- Understanding Basic Mechanisms:
  - SNe Ia: evolution of burning front
  - SNe II: neutrino energy transport
- Nucleosynthesis:
  - production of oxygen to iron elements
  - site of the r-process of neutron capture
- Remnants:
  - powering of nebular remnants
  - black hole verses Neutron Star
- Population impact on SNe Ia lightcurves