



Jim Truran

Lecture III: Supernova Explosions

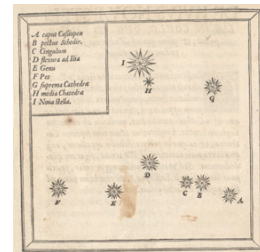
- ❑ Nuclear Energetics of Supernovae and Supernova Models
 - ❑ “core collapse” supernovae - SNe Type II
 - ❑ “thermonuclear” supernovae - SNe Type Ia

Summer School in Nuclear Physics
Laurence Berkeley National Laboratory
June 6-10, 2005

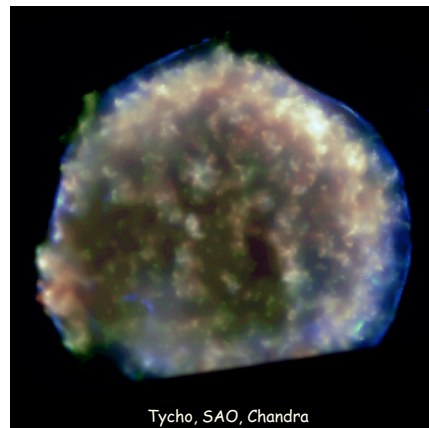
Discovery of a SNe Ia?

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

Significance of Supernovae



High-Z Supernova Search Team, HST

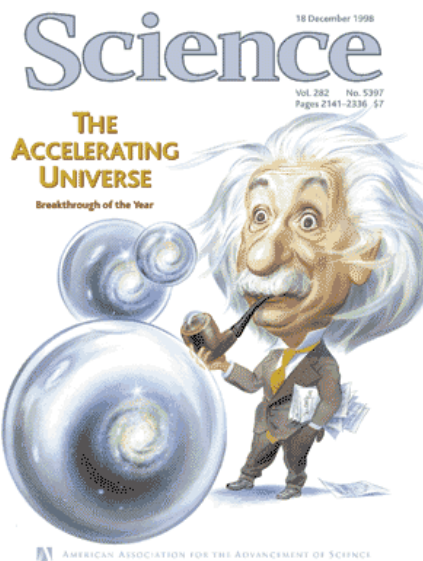


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Supernovae are the most spectacular of galactic events:

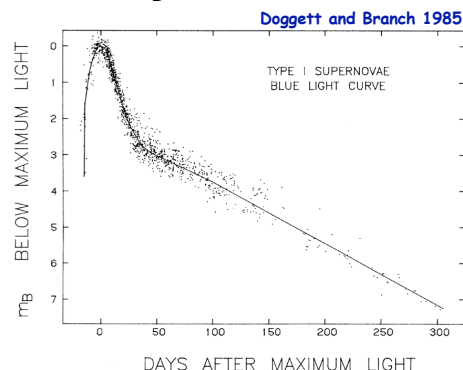
- ❑ They release $\approx 10^{51}$ ergs of light and kinetic energy.
- ❑ As the brightest objects in galaxies, they allow probes of the distance scale of the Universe.
- ❑ They enrich the Galaxy in “heavy” elements (heavier than helium) to levels of order 2 percent (Solar Abundance).
- ❑ They provide 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.
- ❑ 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.

Supernovae Ia and Cosmology



In 1998, SNe Ia played a major role in the “science breakthrough of the year:”

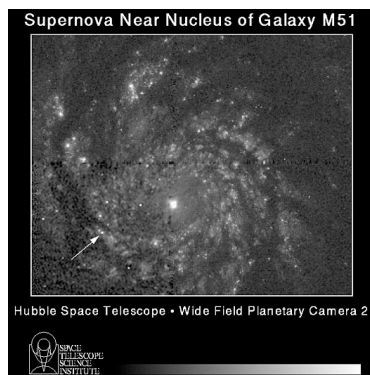
Using SNe Ia as distance indicators (standard candles), two groups of astronomers found strong indications for an accelerating cosmic expansion.



Type Ia and Type II Supernovae

- ❑ The two broad classes of supernovae exhibit a variety of distinguishing characteristics:
- ❑ Spectrum at Maximum Light
 - ❑ Type Ia spectra at maximum are devoid of hydrogen
 - ❑ Type II spectra at maximum are hydrogen rich (Solar)
- ❑ Stellar Population
 - ❑ Type II occur only in young populations: spirals/irregulars
 - ❑ Type Ia occur in old and young populations - and are the only supernovae seen in elliptical galaxies

Supernova in Galaxies: Populations



SNe 1994I (Type II)

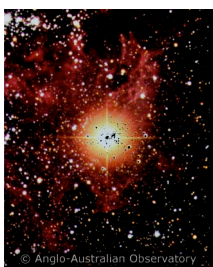


Elliptical Galaxy M87

High-z Supernova Search Team, HST, NASA



SNe 1994D (Type Ia)



SNe 1987A (Type II)



Large Magellanic Cloud

Type Ia and Type II Supernovae

- ❑ The two broad classes of supernovae exhibit a variety of distinguishing characteristics:
- ❑ Explosion Mechanism
 - ❑ Type Ia are “thermonuclear” supernovae, powered by energy release in burning ^{12}C and ^{16}O to iron-peak nuclei
 - ❑ Type II are “core collapse” supernovae, powered by the energy release in the formation of a neutron star or black hole remnant
- ❑ Energetics
 - ❑ Type Ia supernovae release 10^{51} ergs in light and kinetic energy
 - ❑ Type II supernovae release 10^{51} ergs in light and kinetic energy and $\approx 3 \times 10^{51}$ ergs in neutrinos

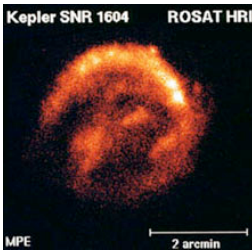
Type Ia and Type II Supernovae

- ❑ The two broad classes of supernovae exhibit a variety of distinguishing characteristics:
- ❑ Frequency of occurrence:
 - ❑ Type Ia occur about once per century in spirals, with a roughly comparable rate per unit mass in ellipticals
 - ❑ Type II occur about once per century in spirals
- ❑ Light Curves
 - ❑ Type Ia are extremely regular & the peak brightness is correlated with light curve shape ($L_{\text{MAX}} \approx 10^9 L_{\odot}$)
 - ❑ Type II are more irregular in their light curves with a somewhat lower peak brightness ($L_{\text{MAX}} \approx 10^8 L_{\odot}$)

SN 1054 → Crab Nebula

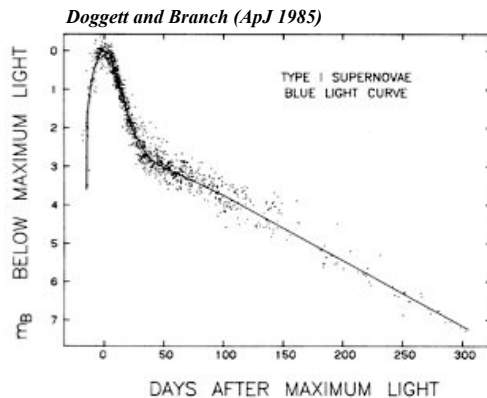


Chaco Canyon Petroglyph

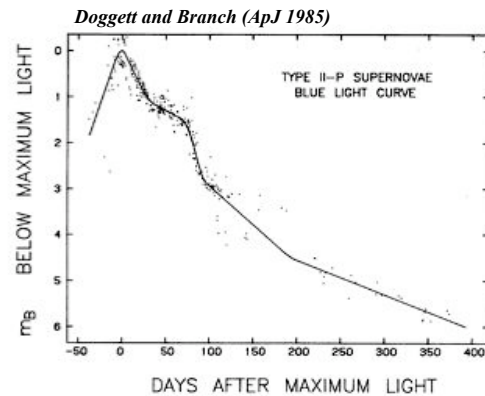


SN	Identification	SN Type
185	Historical descriptions	Ia ?
1006	Historical descriptions	Ia ?
1054	Crab Nebula	II ?
1572	Tycho Brahe	Ia
1604	Johannas Kepler	Ia
~1680	Cassiopeia A	II

- ❑ 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.



Type Ia Supernova Light Curve

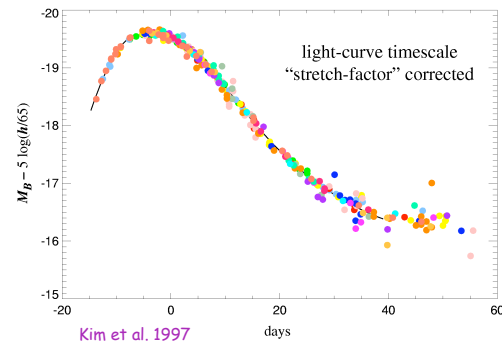
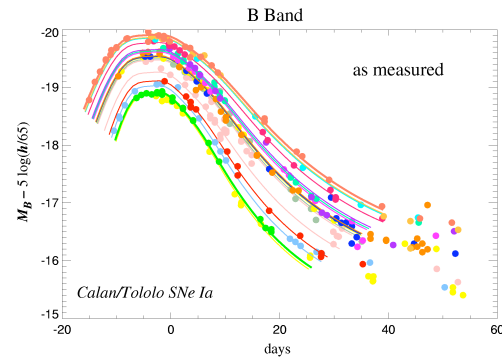
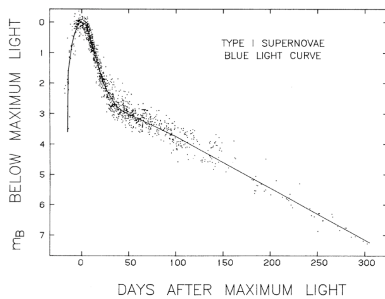


Type II Supernova Light Curve

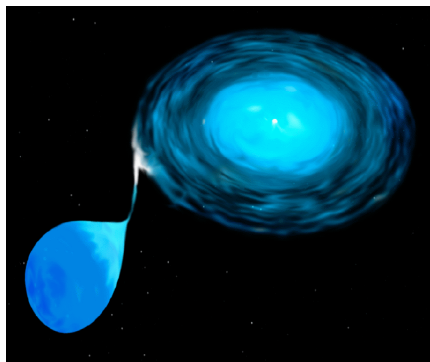
Brighter is Broader

❑ The Phillips relation compensates for the observed variation in peak luminosity to give a standard candle.

❑ Brighter SNe Ia decline more slowly.



Type Ia Supernovae: Theory



NASA STScI



High-Z Supernova Search Team, HST

❑ "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).

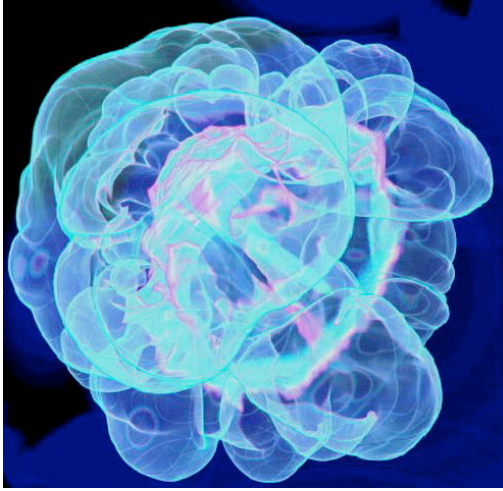
❑ After ~1000 years of slow thermonuclear "cooking", a violent explosion is triggered at or near the center.

❑ Complete incineration occurs within two seconds, leaving no compact remnant.

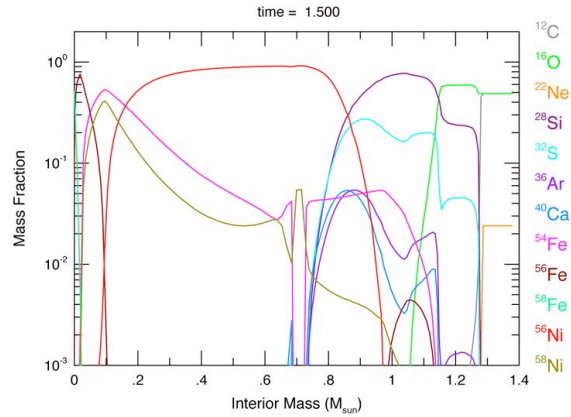
❑ Nucleosynthesis contributions: 1/2 to 2/3 iron-peak nuclei. ($\tau_{\text{nucleosynthesis}} > 10^9$ yrs)

❑ Their light curves are powered by the radioactive decay of ^{56}Ni . Their peak luminosities: $L_{\text{max}} \propto M(^{56}\text{Ni})$.

Supernova Ia Nucleosynthesis

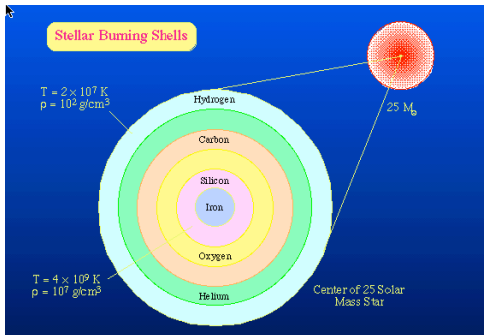


Off-center Deflagration Simulation
(Calder et al. 2004)

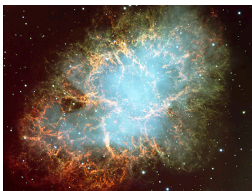


Evolution of Core Composition
(Timmes, Brown, Truran 2003)

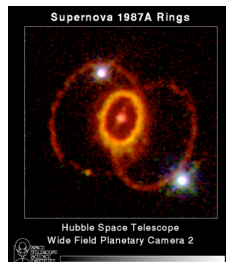
Type II Supernovae: Theory



Courtesy Mike Guidry: guidry@utk.edu



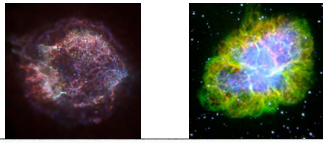
SN1054: Crab Nebula



SN1987A Hubble Image

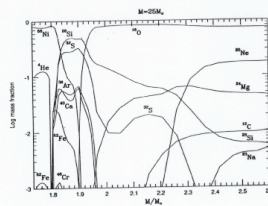
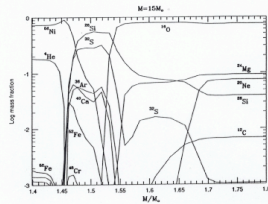
- ❑ "Standard model" (Hoyle & Fowler 1960):
 - ❑ SNe II are the product of the evolution of massive stars $10 < M < 100 M_{\odot}$.
- ❑ Evolution to criticality:
 - ❑ A succession of nuclear burning stages yield a layered compositional structure and a core dominated by ^{56}Fe .
 - ❑ Collapse of the ^{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. ($\tau_{\text{nucleosynthesis}} < 10^8 \text{ yrs}$)

Massive Stars and Type II Supernovae



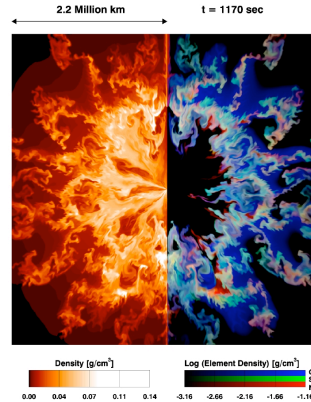
SNc II NUCLEOSYNTHESIS

(THEISELMANN, NOMOTO AND HASHIMOTO 1992)



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

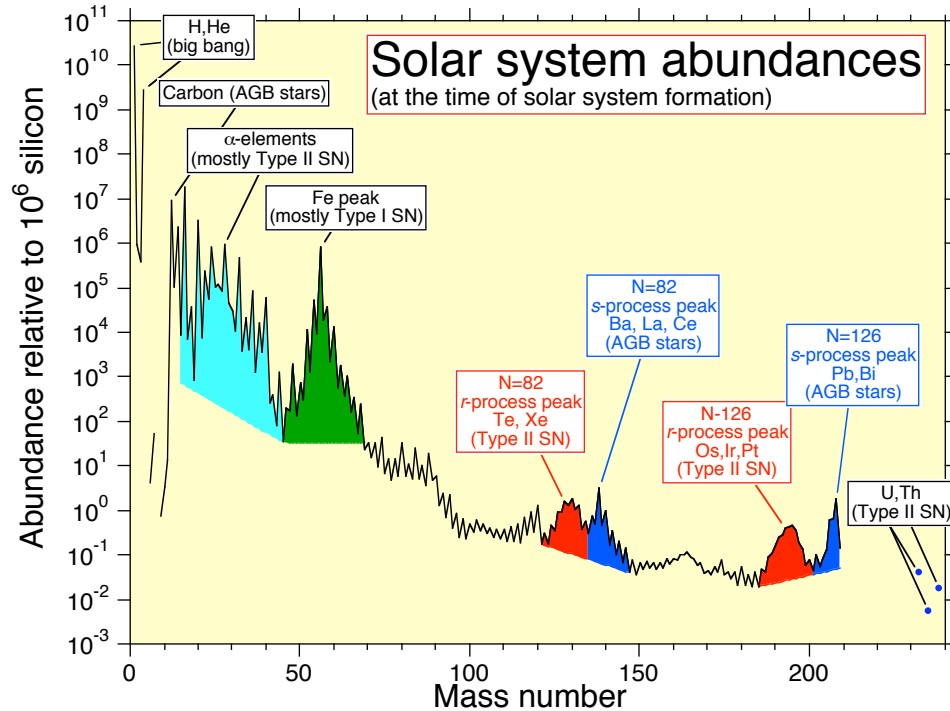
- ❑ Massive stars ($M > 10 M_{\odot}$) evolve through a sequence of burning stages to the formation of an iron core surrounded by shells of, respectively, silicon, oxygen, neon, carbon, and helium.
- ❑ The r-process heavy elements are also believed to be formed in these events.



(Kifonidis et al. 2000)

EXPLOSIVE NUCLEOSYNTHESIS

Cosmic Abundances



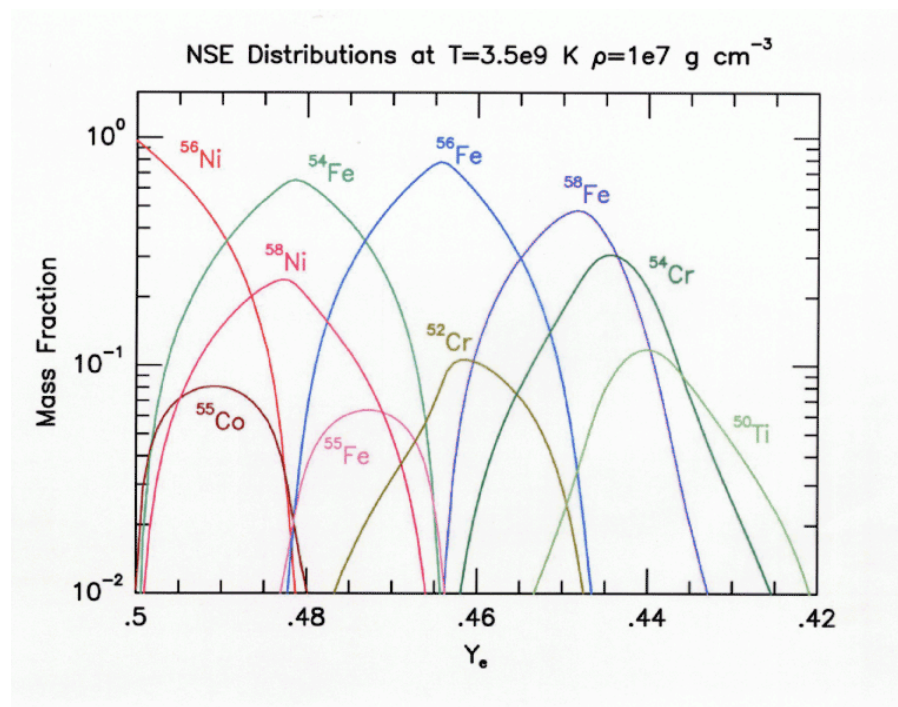
^{56}Ni Production in Nucleosynthesis

- ❑ Pre-explosion compositions involve largely nuclei of $Z \equiv N$, viz. ^{12}C , ^{16}O , ^{28}Si .
- ❑ Explosive burning at $T \geq 4 \times 10^9$ °K typically occurs on timescales $\leq$ seconds.
- ❑ Supernova nucleosynthesis sees reactions occurring on a dynamical timescale.
- ❑ Weak interactions proceed too slowly to convert any significant fraction of protons to neutrons.

⁵⁶Ni Production in Nucleosynthesis

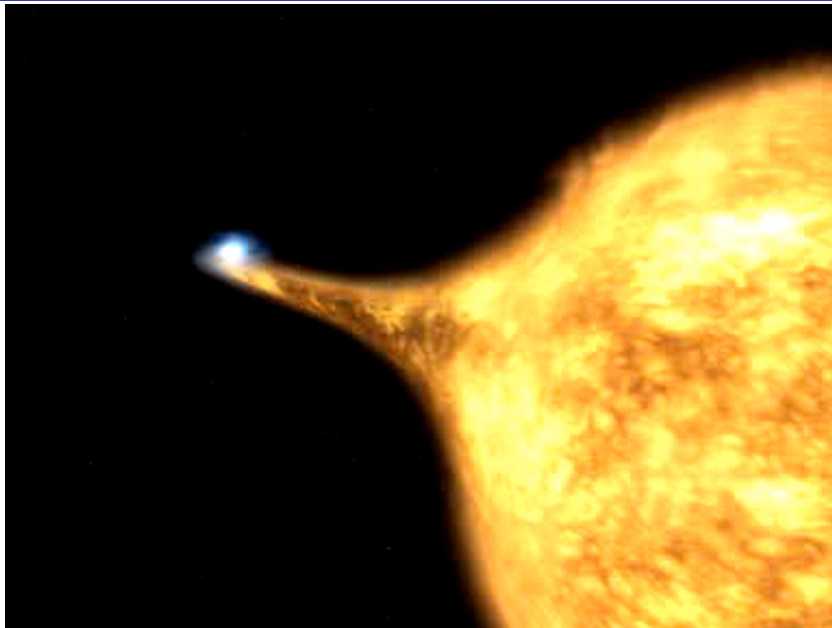
- ❑ Explosive ($T > 4 \times 10^9$ K) supernova incineration of ^{12}C , ^{16}O , and ^{28}Si yields proton-rich iron-peak product nuclei of $Z \approx N$ ($Y_e \approx 0.5$), viz. ^{44}Ti , ^{48}Cr , ^{52}Fe , ^{56}Ni , ^{60}Zn , and ^{64}Ge (Truran, Arnett, and Cameron 1967; Arnett, Truran, and Woosley 1971).
- ❑ Relatively small changes (decreases) in Y_e can, however, influence the emerging abundance patterns.
- ❑ Such increases in N/Z (or decreases in Y_e) can be introduced by weak interactions at higher densities – **or by the presence of the neutron rich isotope ^{22}Ne in the stellar matter.**

Nuclear Statistical Equilibrium Conditions

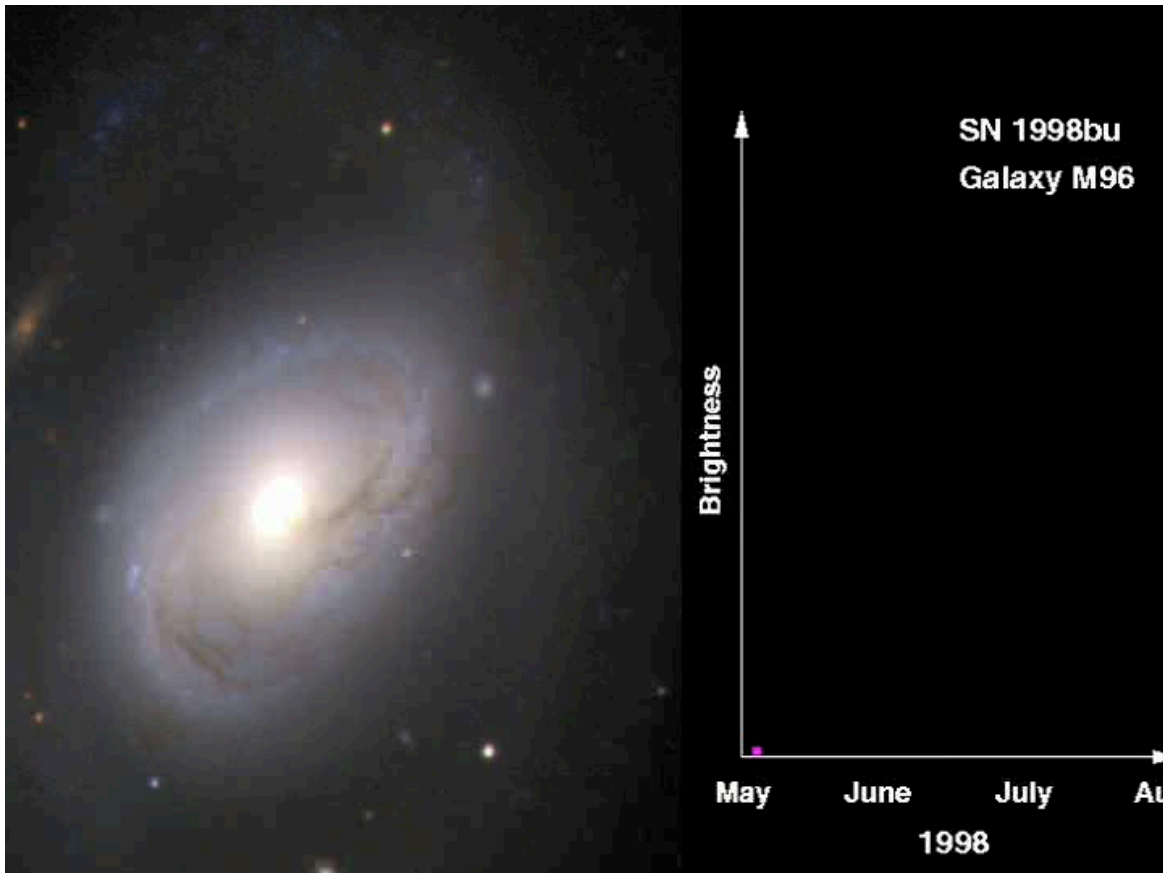


TYPE Ia SUPERNOVAE

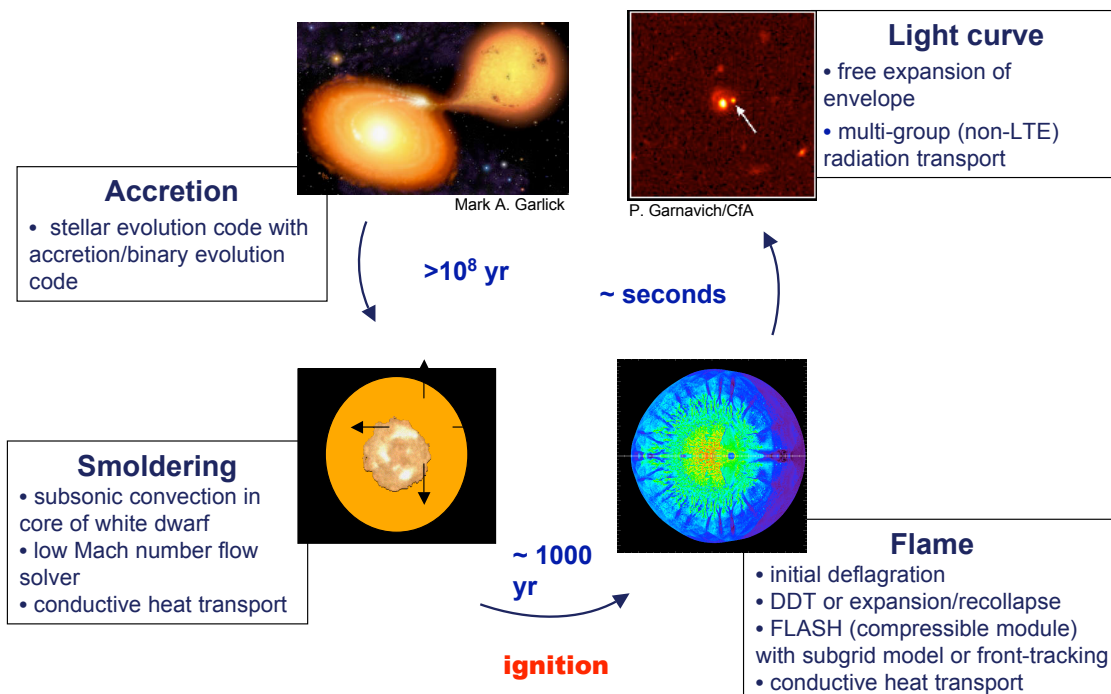
The Standard Model for SNe Ia



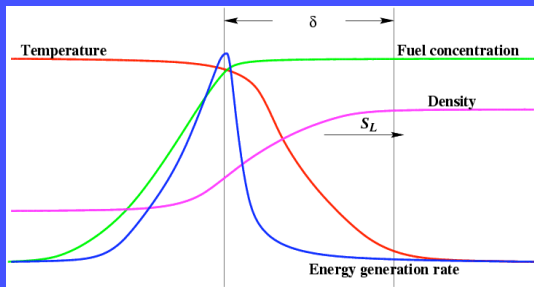
- White dwarf in a binary system
- Growth to the Chandrasekhar limit by mass transfer



Evolution Towards SN Ia



Main Characters: Deflagrations and Detonations



Deflagrations (“Flames”):

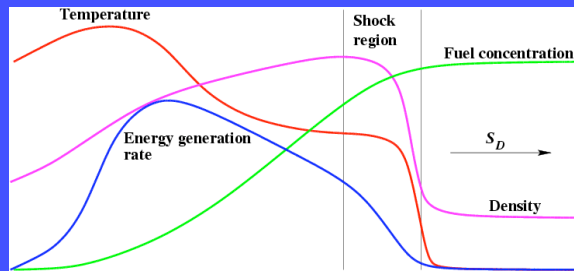
Subsonic burning fronts, propagating by heat conduction. Laminar flame speed and flame width (Timmes & Woosley 1992):

$$S_L \sim 0.001 u_{\text{sound}}, \quad d \sim 1 \mu\text{m} \dots 1 \text{ cm}$$

Detonations:

Supersonic burning fronts, propagating by shock heating. Detonation width and speed:

$$S_D \sim u_{\text{sound}}, \quad d \sim 0.1 \text{ mm} \dots 1 \text{ m}$$



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

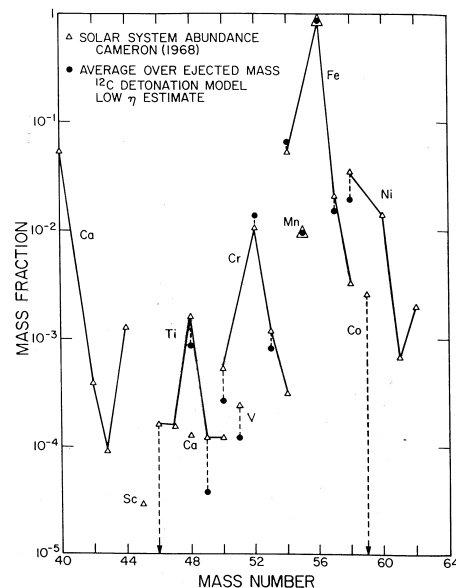
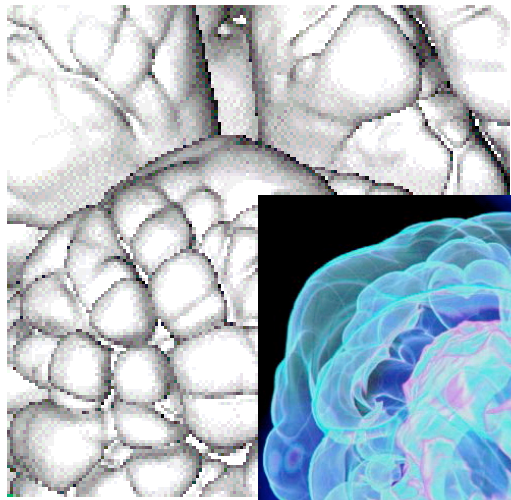


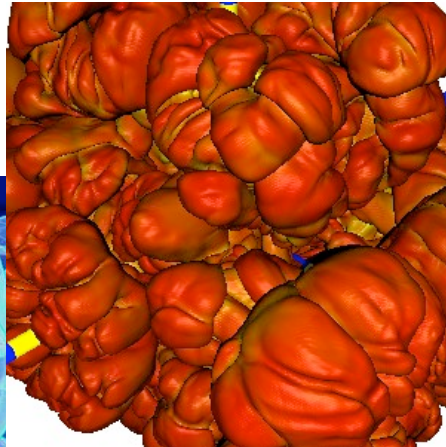
Figure 11. The nuclear abundances by mass produced in the mass zones ejected in the ^{12}C detonation model are compared to the solar system abundances. The two distributions are normalized at ^{56}Fe . The “low n” estimate of the neutron excess was employed.

(Truran, Arnett, and Woosley 1971)

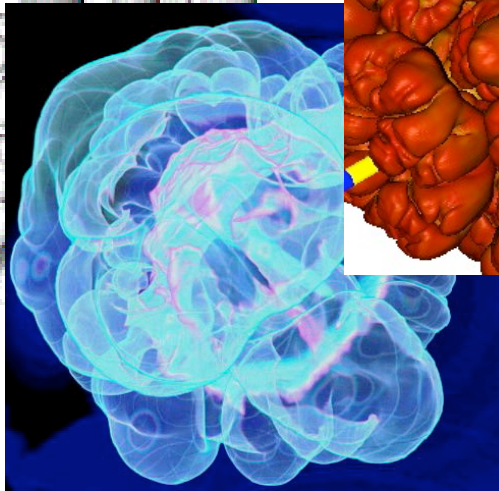
Deflagration Model: Flame Morphology



Gamezo et al. (2002)

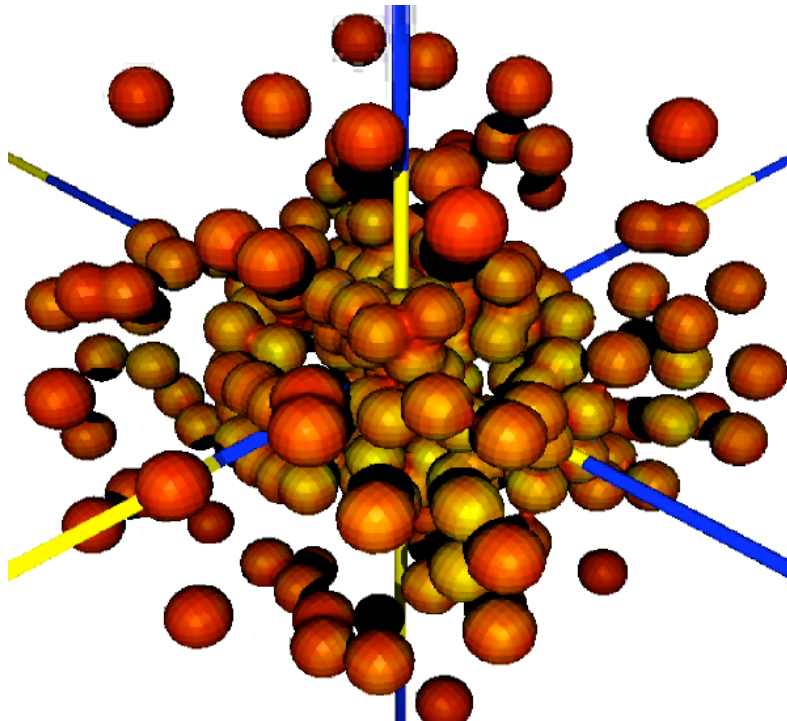


Reinecke et al. (2002)



FLASH (2003)

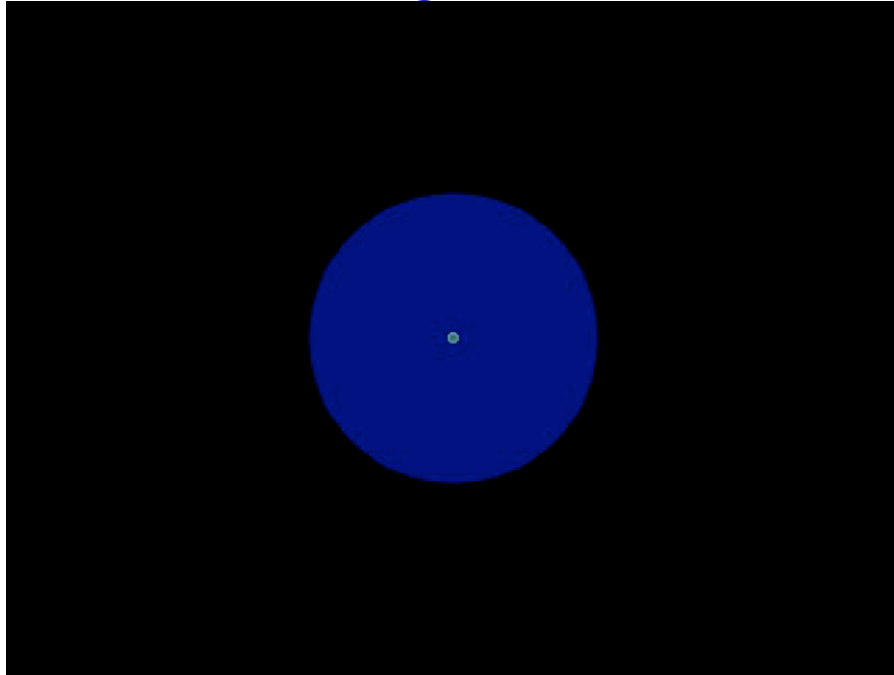
Multiple Point Spherical Ignition



(Roepke et al. 2004)

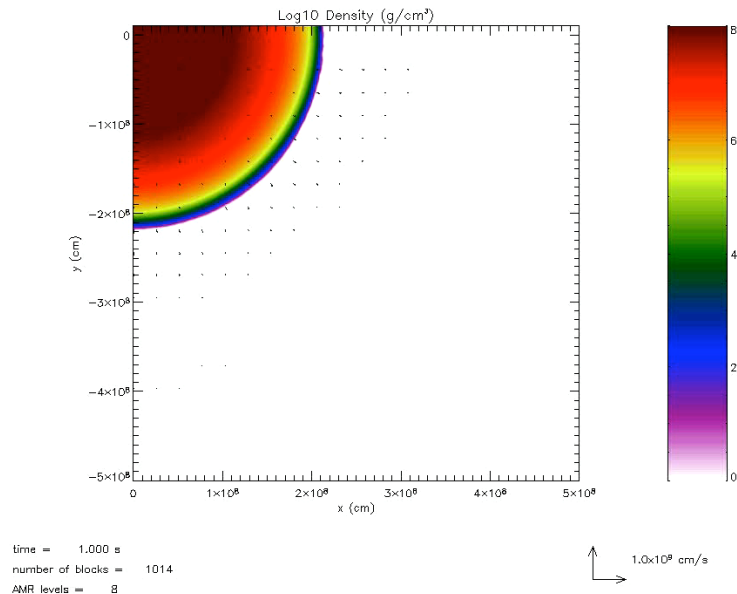
Consequences of Off-Center Ignition

Off-center Deflagration Simulation



Calder, Vladimirova, Plewa, Lamb, Robinson & Truran (2003)

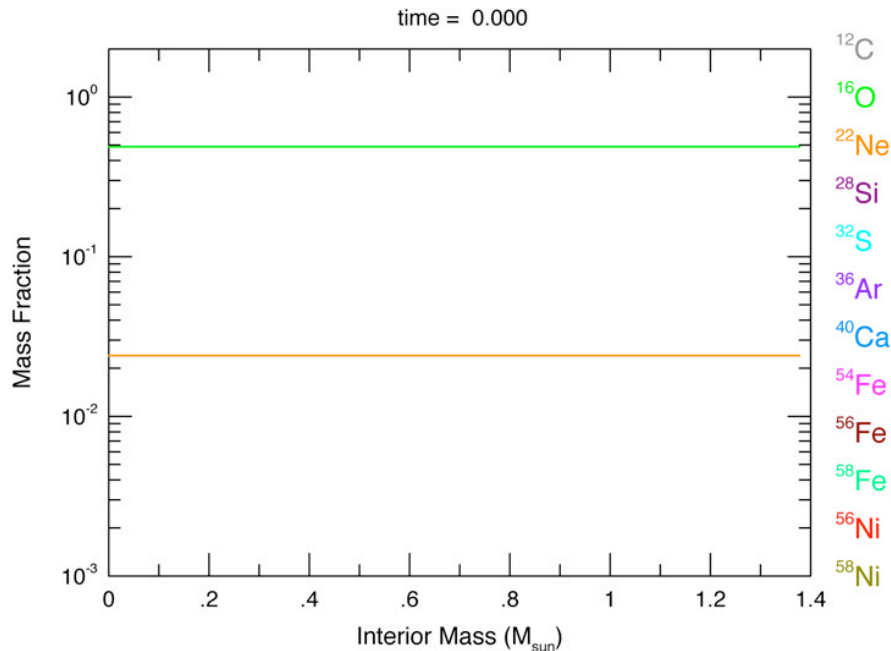
Consequences of Off-Center Ignition



Possible Consequences of Breakout



-

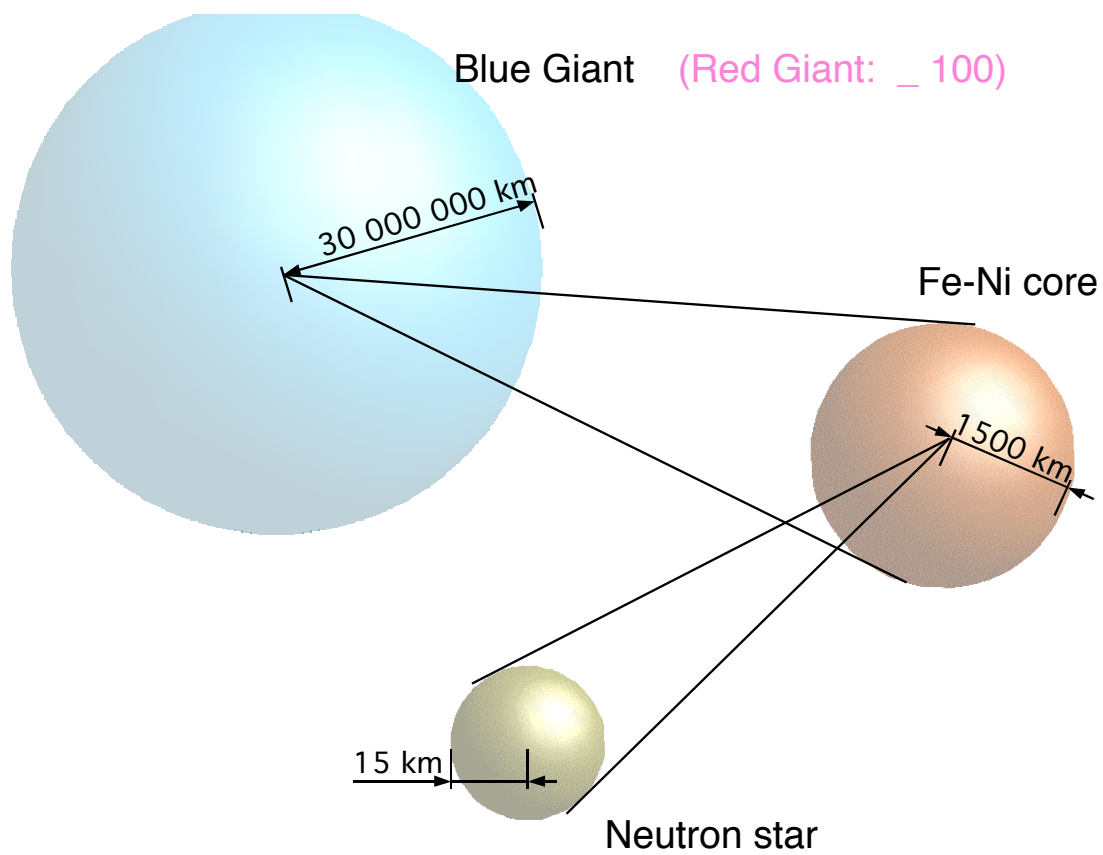


Evolution of Core Composition (Timmes, Brown, Truran 2003)

Conclusions: Metallicity Dependence

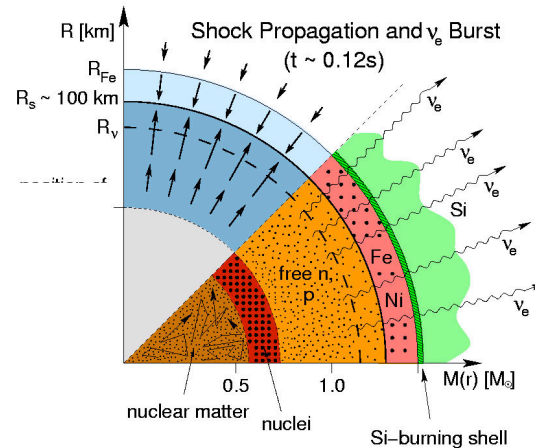
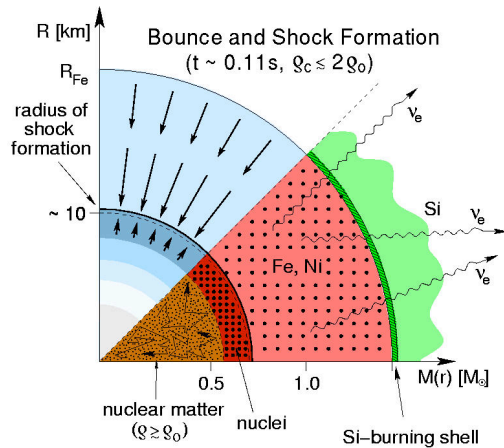
- ❑ The brightness of a Type Ia supernova at maximum is a function of the mass of ^{56}Ni produced.
- ❑ ^{56}Ni is formed in nuclear statistical equilibrium in matter characterized by a Y_e approaching 0.5 (e.g. $Z \approx N$)
- ❑ The critical region of formation in Type Ia events is that from ≈ 0.2 - 0.8 solar masses.
- ❑ The mass of ^{56}Ni formed in NSE in this critical region is sensitive to the initial composition of the star (^{22}Ne).
- ❑ The observed scatter in metallicity in the galactic disk, to values several times solar, introduces a scatter in peak brightness of order 30 percent.
- ❑ Metal rich galaxies (e.g. E galaxies) may be expected to have fewer bright SNe Ia.

TYPE II SUPERNOVAE



Core collapse supernovae:

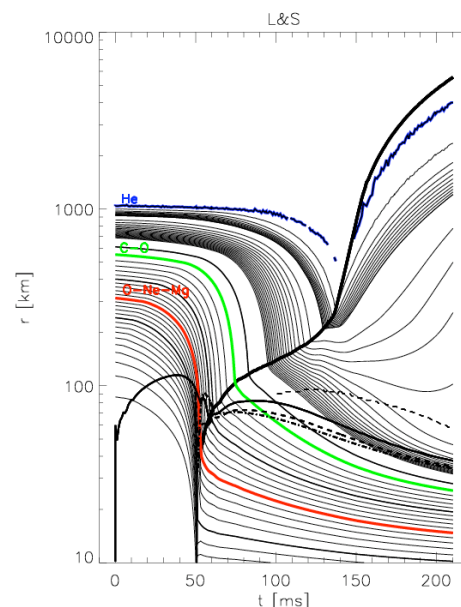
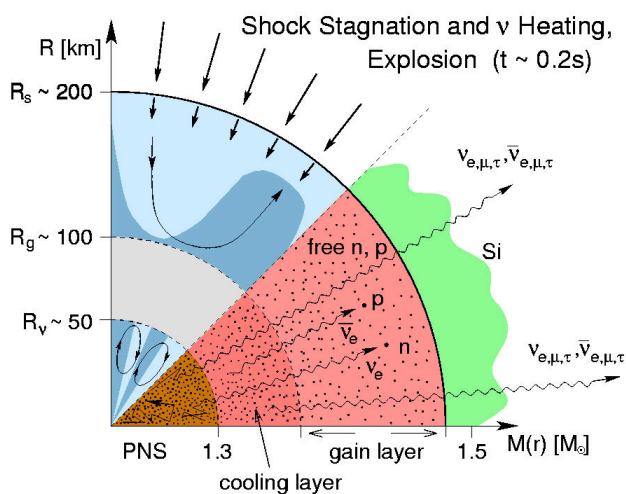
- Prompt explosion mechanism does not work (explored during the 1970's and 1980's; commonly accepted early 1990's)



- Shock wave forms close to sonic point ($M \sim 0.7 M_{\text{sun}}$)
initial energy: $(5 \dots 8) \times 10^{51}$ erg

- Severe energy losses during shock propagation (8 MeV/nucleon or 1.6×10^{51} erg/ $0.1 M_{\text{sun}}$)

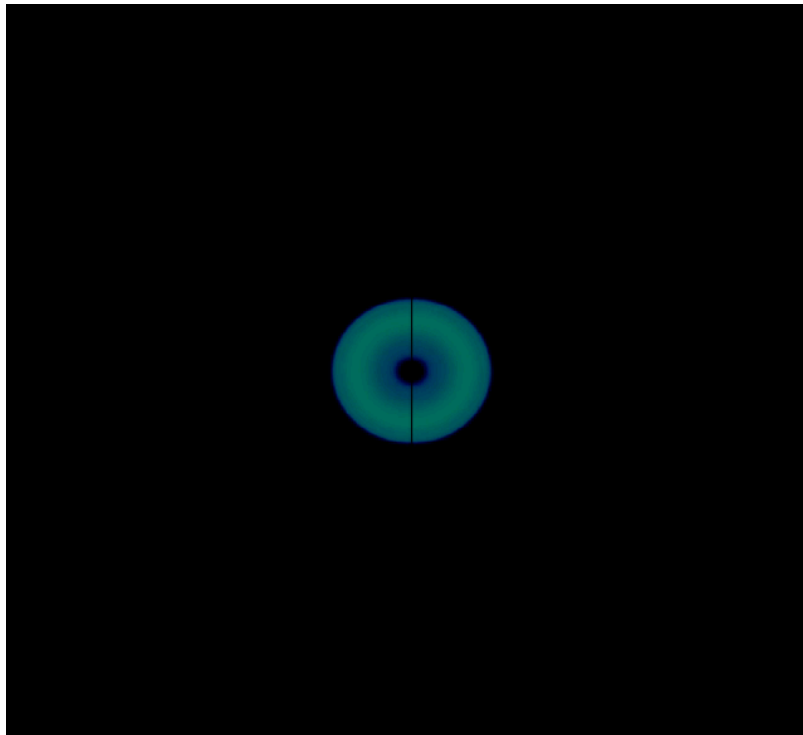
- Current paradigm: neutrino-driven delayed explosions (discovered through computer simulations by Wilson '82, and first analyzed by Wilson & Bethe '95)



In its simplest form: Seems to work for low-mass core only! (Kitaura et al '05)

- ❑ Observations imply: non-radial flow and mixing are common in core collapse supernovae
- ❑ Theoretical models based on delayed explosion mechanism predict non-radial flow and mixing due to:
 - ❑ **Ledoux convection** inside the **proto-neutron star** (deleptonization and neutrino diffusion)
 - ❑ **convection** inside **neutrino heated** hot **bubble** (neutrino energy deposition behind the shock)
 - ❑ **Rayleigh-Taylor instabilities** in **stellar envelope** (non-steady shock propagation; hot bubble)

Mixing in Type II Supernovae



SN 1987A in the Large Magellanic Cloud



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*





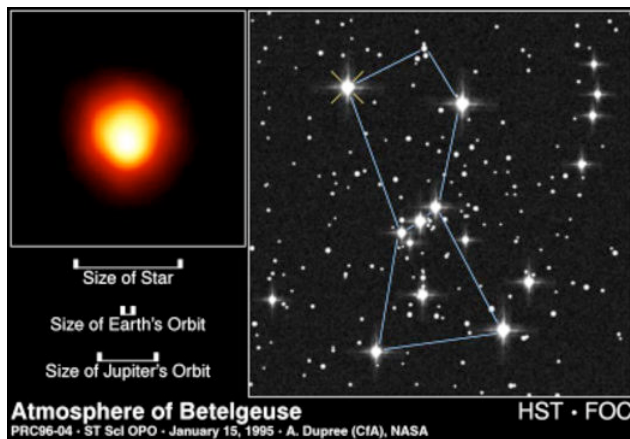
SN 1987A in the Large Magellanic Cloud



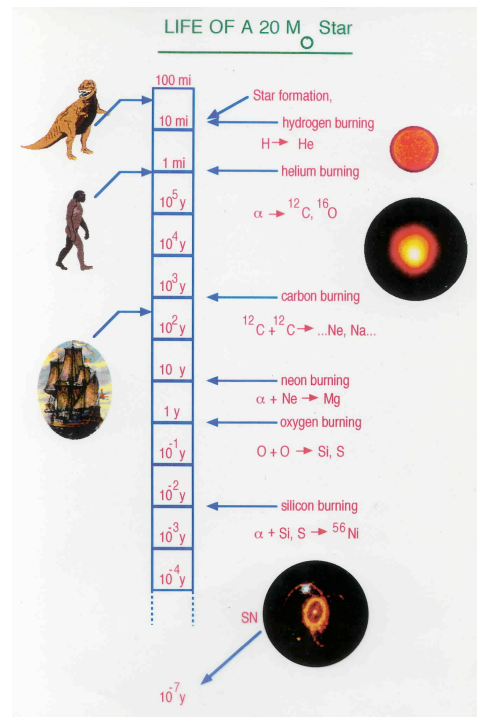
- ❑ SN 1987A, whose brightness at maximum was of order $10^9 L_{\odot}$, was of great significance to supernova theorists:
- ❑ It was the first local supernova since 1604 (Kepler).
- ❑ The progenitor star was identified and found to be a massive star: $M \sim 20 M_{\odot}$ and luminosity $L \sim 20 L_{\odot}$.
- ❑ Most of its energy release ($\sim 3 \times 10^{53}$ 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 $\geq 1.4 M_{\odot}$.
- ❑ Its light curve was powered by the decay of the $\approx 0.07 M_{\odot}$ of ^{56}Ni ejected as: $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$, confirmed by detection of γ -rays from ^{56}Co and ^{57}Co .
- ❑ It ejected $5\text{-}6 M_{\odot}$ of heavy elements - from oxygen to iron - and on to uranium and thorium.



SN 1987A in the Large Magellanic Cloud

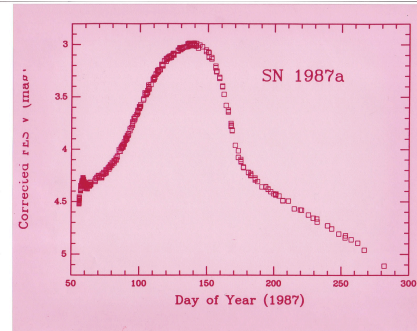
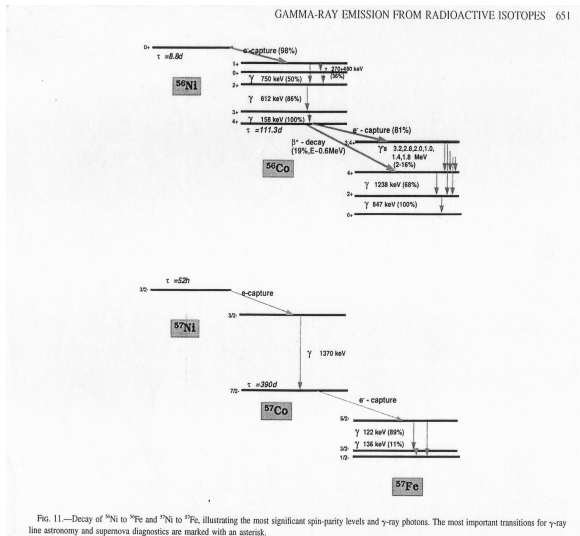
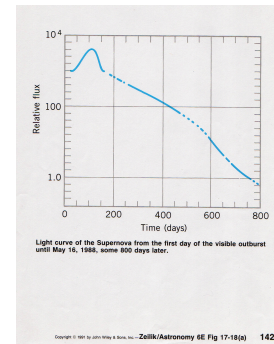


*A likely supernova candidate for the next millenium: **Betelgeuse***



Courtesy: Ernst Rehm, ANL

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



NASA: HST