Supernovae

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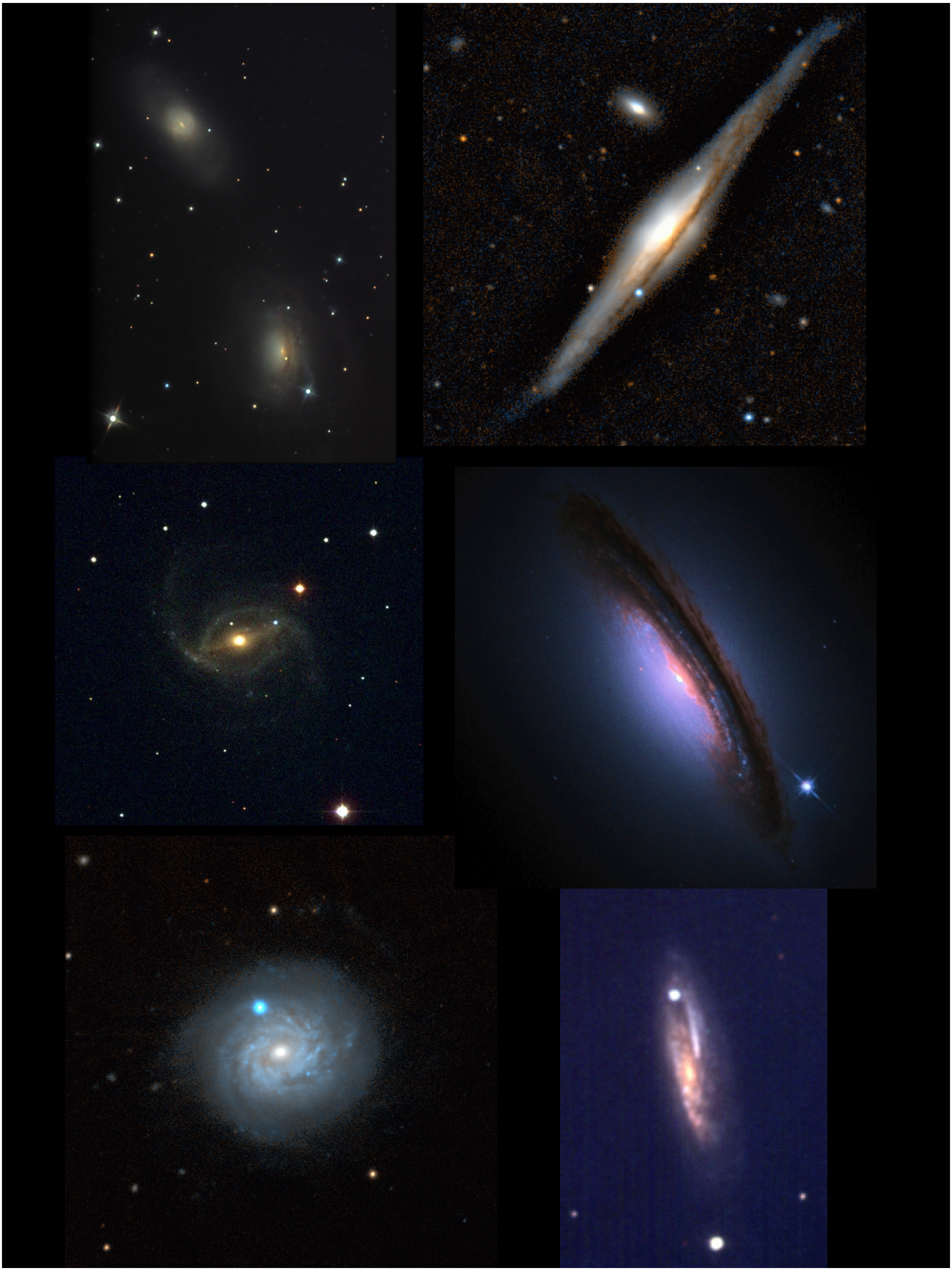
1. Supernovae
2. Supernova Remnants
3. Supernova 1987A

Why are supernovae interesting?

- They are the source of all elements in the universe (except H, He, Li)
- They influence the dynamics of interstellar gas and, hence, regulate star formation
- They produce extreme physical systems: neutron stars, black holes, gamma ray bursts



Supernovae

- Historical Supernovae
- Types of supernovae
- Supernova Light Curves
- Supernova Spectra
- Basic physics of thermonuclear supernovae
- Basic physics of core collapse supernovae

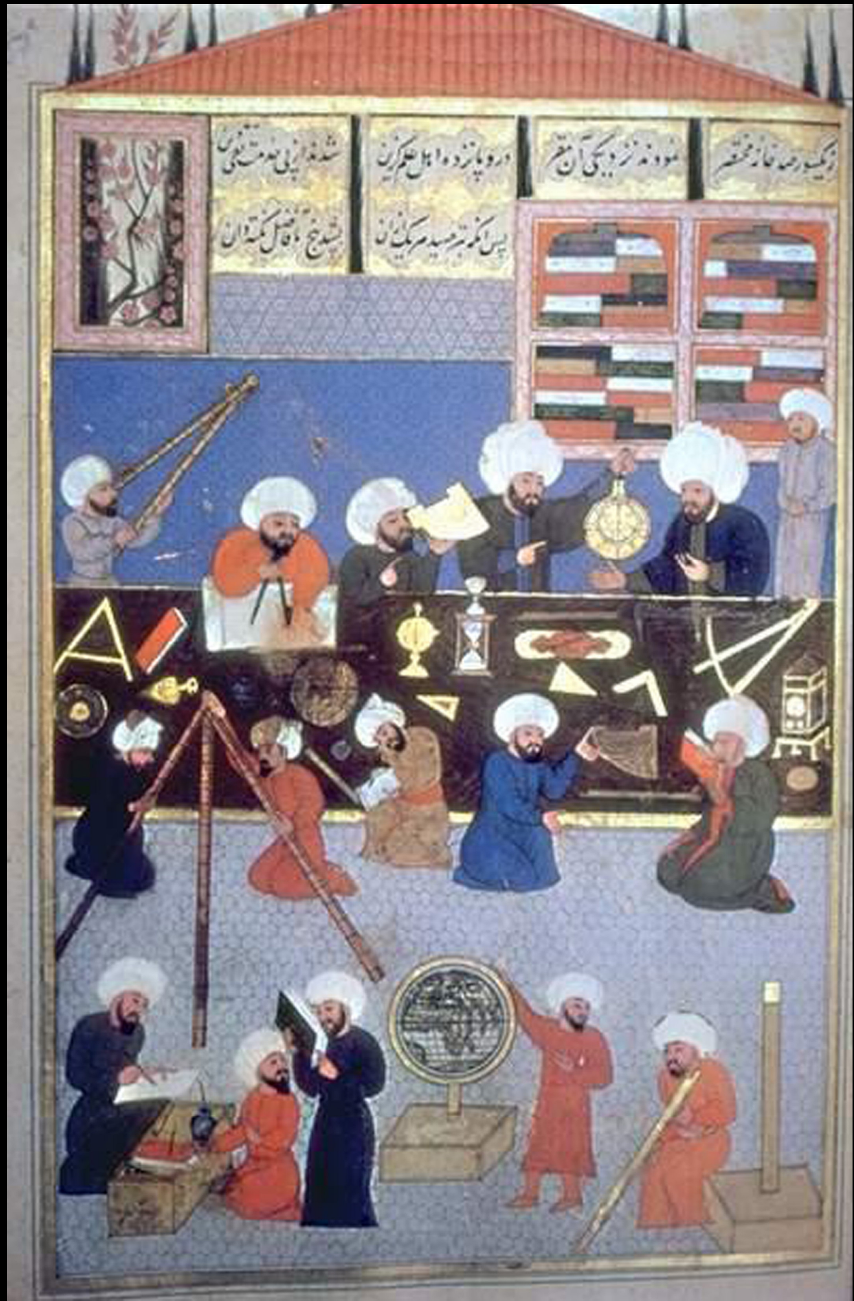
Supernova 1006

- April 30, 1006
- The brightest visible supernova in history – V = -10 (as bright as ¼ Moon)
- Remained visible for ~ 6 months
- Location: in constellation Scorpio
- Historical records: China, Japan, Korea, Europe, Egypt

Ali Ibn Ridwan

I will now describe a spectacular star which I saw at the beginning of my studies. This star appeared in the constellation Scorpio, in opposition to the Sun. The sun on that day was 15 degrees in Taurus and the star was in the 15th degree of Scorpio. It was 3 times as large as Venus. The sky was shining because of its light. The intensity of its light was a little more than a quarter of that of moonlight. It remained where it was and it remained in place until the Sun was in Virgo, when it disappeared at once. ...

Because the zodiacal sign Scorpio is a bad omen for the Islamic religion, people bitterly fought each other in great wars and many of their great countries were destroyed. Also many incidents happened to the king of Mecca and Medina. Drought, increase of prices and famine occurred, and countless thousands died by the sword as well as from famine and pestilence. When the star appeared, calamity and destruction occurred which lasted for many years afterwards."

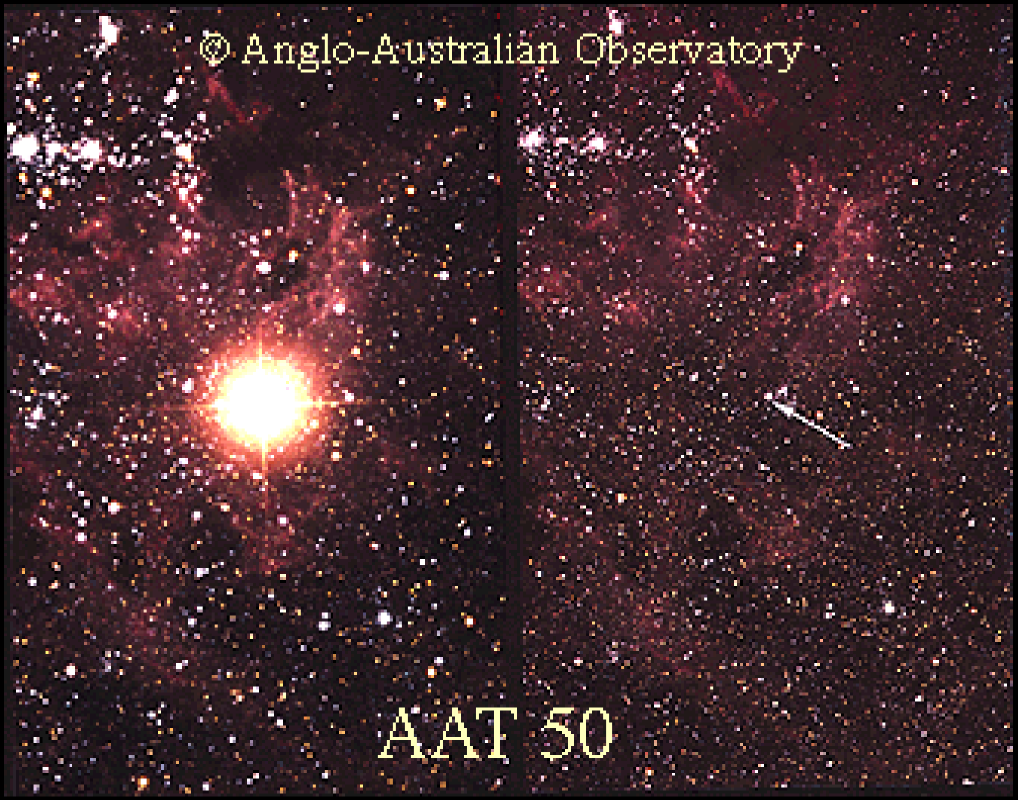


وانا ارسم لك فى هذا الموضع اثرا شاهدته فى
مبدا تعليمى ظهر هذا الاثر فى برج العقرب على
مقابلة الشمس وكانت الشمس يوميذ فى خمس
عشرة درجة من الثور والنيزك فى يه درجة من
العقرب وكان نيزكا عظيما مستدير الشكل يكون
عظمه قدر الزهرة مرتين ونصف او ثلاث مرات
وكان نوره يضئ منه الافق ويلمع لمعانا شديدا
ومقدار ضيائه ربع ضياء القمر واكثر قليلا ولم يزل
ظاهرا ويتحرك فى برجه بحركة معدل النهار الى ان
صارت الشمس الى تدسيه من برج السنبلة فبطل
دفعة واحدة وجميع ما ذكرته من امره هو
مشاهده وقد رصده من كان ايضا فى زمانى من
العلماء فكان على ما ذكرت سوا ومواضع الكواكب
فى وقت مبدا ظهوره على هذه الصفة. الشمس والقمر
يجتمعان فى برج الثور يه درجة زحل بالاسد يب
درجة ويا دقيقة المشترى فى السرطان يا درجة وكا
دقيقة المريخ بالعقرب كا ويط الزهرة بالجوزاء يب كج
عطارد بالثور ه يا الجوزهر بالقوس كج لج النيزك الذى
حدث بالعقرب يه درجة وطالع الاجتماع الذى كان فيه
فى وقت ظهور هذا النيزك على فسطاط مصر الاسد د ب
وعاشرة الثور بالحمل كو كز فلان العقرب برج كسوف ملة
الاسلام وقد انها حدث بالمسلمين بعضهم فى بعض حروب
عظيمة وحربت لهم بلدان عظيمة وخرج على ملك الحرمين
خارجى عظيم ووقع القحط والغلاء والوباء ومات بالسيف
والغلاء والوباء خلق لا يحصى عددهم والوف كثيرة جدا
وكان ذلك فى وقت ظهور النيزك واتصل البلاء والفساد بعد
ظهوره سنين كثيرة ونحن نستقصى ذلك فى المقالات لا .

HISTORICAL SUPERNOVAE

Date (AD)	Type	Magnitude at Max	Discovered by	Remnant
1006	I	-10	Chinese/Arabs	SN1006
1054	II	-5	China/Japan	Crab Nebula
1181	II	-1	China/Japan	3C58
1572	I	-4	Tycho Brahe	Tycho
1604	I	-3	Kepler	Kepler
ca. 1680	II	5 ?	Flamsteed	Cas A
1987	II	+2.9	Ian Shelton	SN1987A

SN1987A



- February 23, 1987
- The brightest supernova since SN1604 (Kepler)

Two Fundamentally Different Kinds of Supernovae

Thermonuclear (Type Ia)

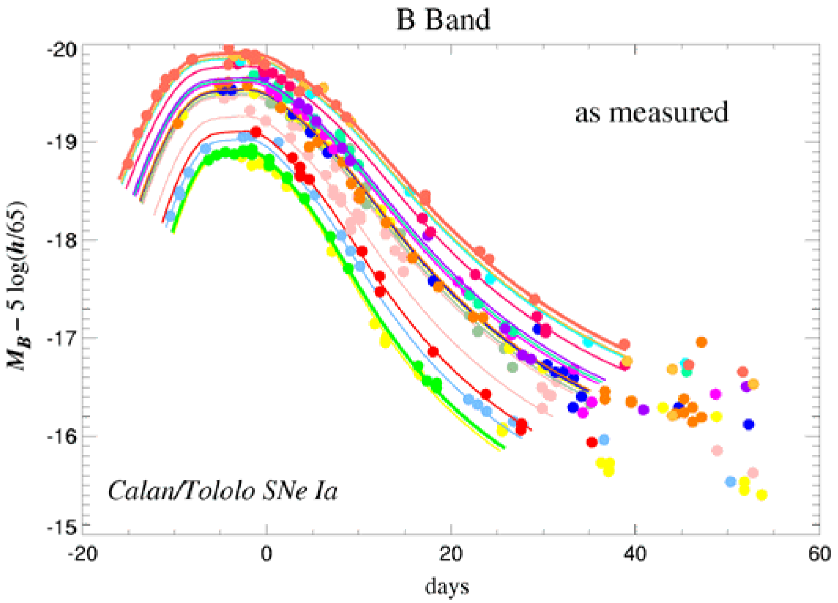
- Spectrum: no Hydrogen
- Explosion of white dwarf star in binary system
- Energy: fusion of C + O → Ni
- Blows apart completely
- Maximum luminosity ~ 10^9 Suns
- Occurs in Milky Way ~ 1/(100 years)

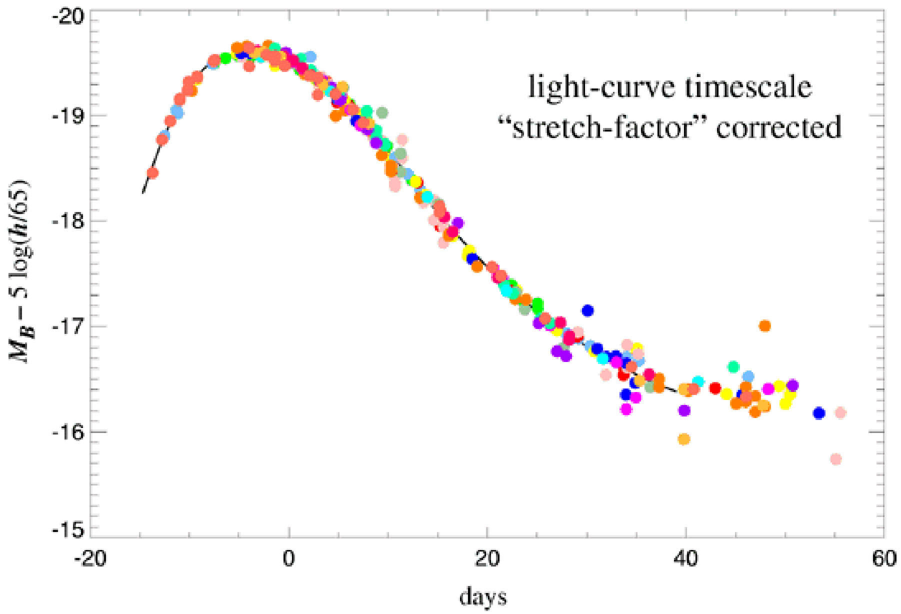
Core Collapse (Type II)

- Spectrum: Hydrogen
- Collapse of core of massive star (7 – 30 M_{Sun})
- Energy: gravity
- Forms neutron star
- Maximum luminosity ~ 10^9 Suns
- Occurs in Milky Way ~ 1/(100 years)

Thermonuclear Supernovae

Thermonuclear Supernovae: Light Curves

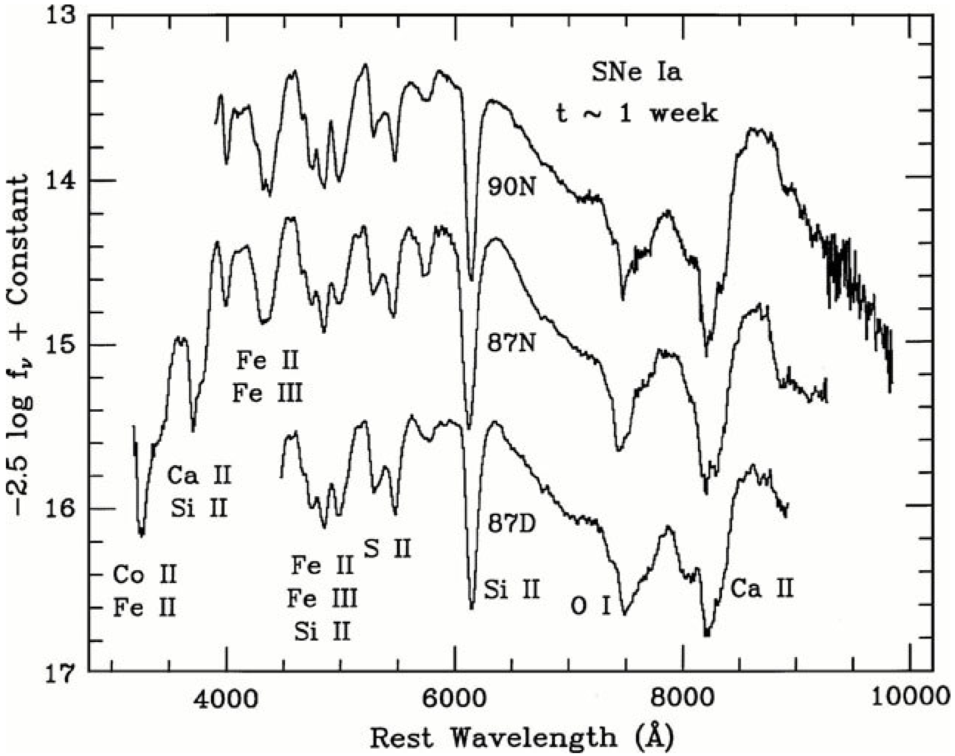




- **All have similar shapes.**
- **Luminous ones decay more slowly.**
- **Allowing for this correlation, light curves of all thermonuclear supernovae are nearly identical.**

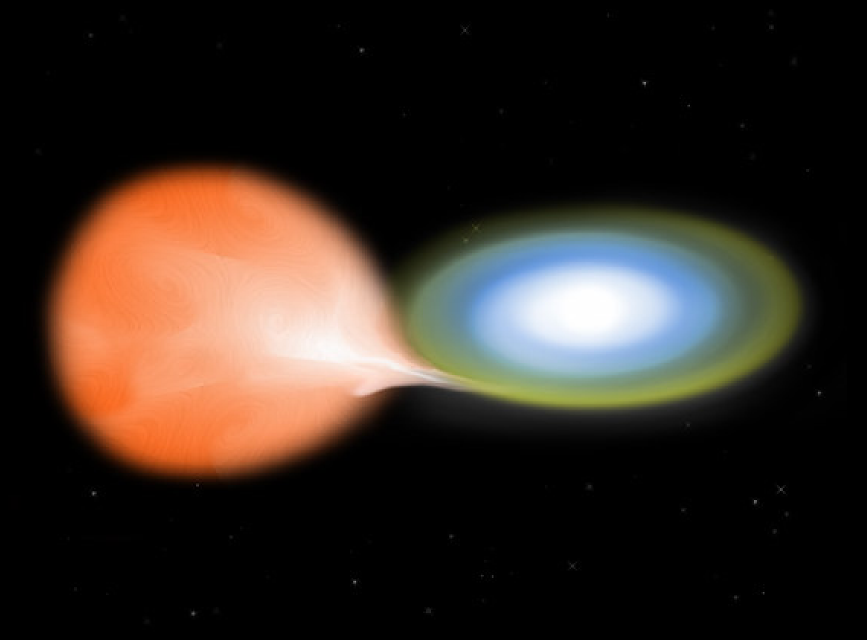
⇨ **Thermonuclear supernovae are excellent "standard candles" for measuring cosmic expansion**

Thermonuclear Supernova: Type Ia Spectrum



- No hydrogen lines
- SiII, CaII, OI, Fe absorption lines
- Spectra of all thermonuclear supernovae are very similar

Thermonuclear Supernovae: Physical Model

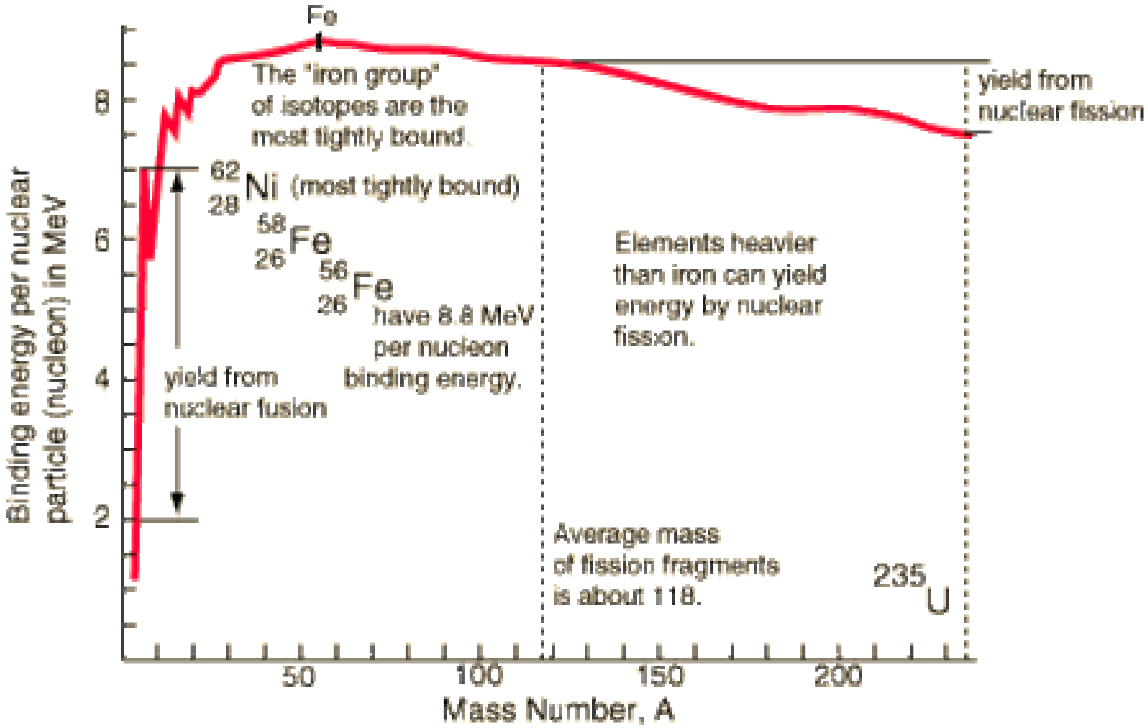


- Progenitor star: C, O, white dwarf (WD) star
- Mass: ~ 1.4 M_{Sun}
- Triggered by mass transfer from nearby companion (He) star
- Thermonuclear explosion (T ~ 10^9 K): ^{12}C, ^{16}O → ^{56}Ni
- WD star blows apart completely

1-zone model for thermonuclear supernovae

- The simplest possible physical model
- Neglect all radial structure (use average values)
- Estimates light curve correctly within factor 3.

Thermonuclear Energy



$M(^{16}O)/16 - M(^{56}Ni)/56 = 0.5 \times 10^{-3}$

Energy release $= 0.5 \times 10^{-3} \times 1.4\ M_{Sun}c^2$

$= 10^{51}$ ergs

Explosion Debris

Expansion Velocity:

$\frac{1}{2} E_0 = \frac{1}{2} MV^2$:

$E_0 = 10^{51}$ ergs, $M = 1.25\ M_{Sun}$ ⇨ $V \sim 5000$ km/s

$R = R_0 + Vt = 10^8$ cm $+ 4 \times 10^{13}$ cm [t/(1 day)]

Interior radiation temperature:

$\frac{1}{2} E_0 = aT_0^4\, 4\pi R_0^3/3 + 3/2 M/m_H kT$ ⇨ $T_0 = 2 \times 10^9$ K

Expansion cooling: $p_{rad} \sim \rho^{4/3}$ ⇨ $T_{rad} \sim R^{-1}$.

⇨ $T_{rad} \sim 5000$ K $[t/(1\ \text{day})]^{-1}$

Conclusion: Supernova will be invisible optically after 3 days, without an additional source of energy

So, why can we see supernovae? Answer: radioactive heating

$^{56}Ni \rightarrow {}^{56}Co + e^+$

t_{Ni} = 8.8 days,

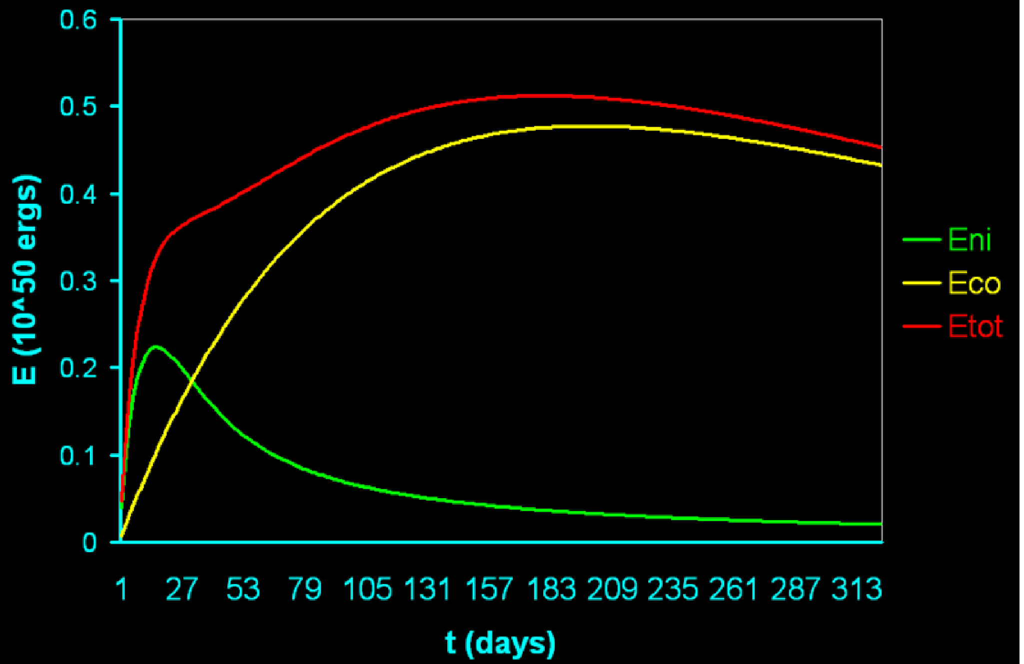
ΔE = 1.75 MeV

⇨ $E_{Ni} = 0.75 \times 10^{50}$ ergs $M_*/(1.4\ M_{Sun})$

$^{56}Co \rightarrow {}^{56}Fe + e^+$;

t_{Co} = 111 days, ΔE = 3.7 MeV

⇨ $E_{Co} = 1.6 \times 10^{50}$ ergs $M_*/(1.4\ M_{Sun})$



$$dE/dt = -E_0/t + E_{Ni}/t_{Ni} \exp(-t/t_{Ni}) + E_{Co}/t_{Co} \exp(-t/t_{Co})$$

Diffusion of radiation

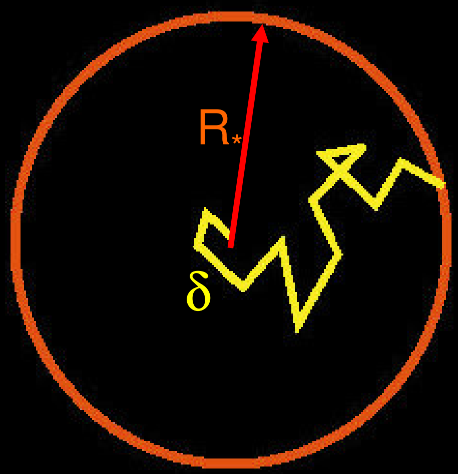
Optical depth: $\tau = n_e R_* \sigma_T$

$n_e = \frac{1}{2} M_*/(4/3\ \pi R_*^3\ m_H)$;

$\sigma_T = 6.6 \times 10^{-25}\ \mathrm{cm}^2$

⇨ $\tau = 8 \times 10^4\ M_*/(1.4\ M_{Sun})\ [t/(1\ \mathrm{day})]^{-2}$

⇨ Supernova is initially very opaque

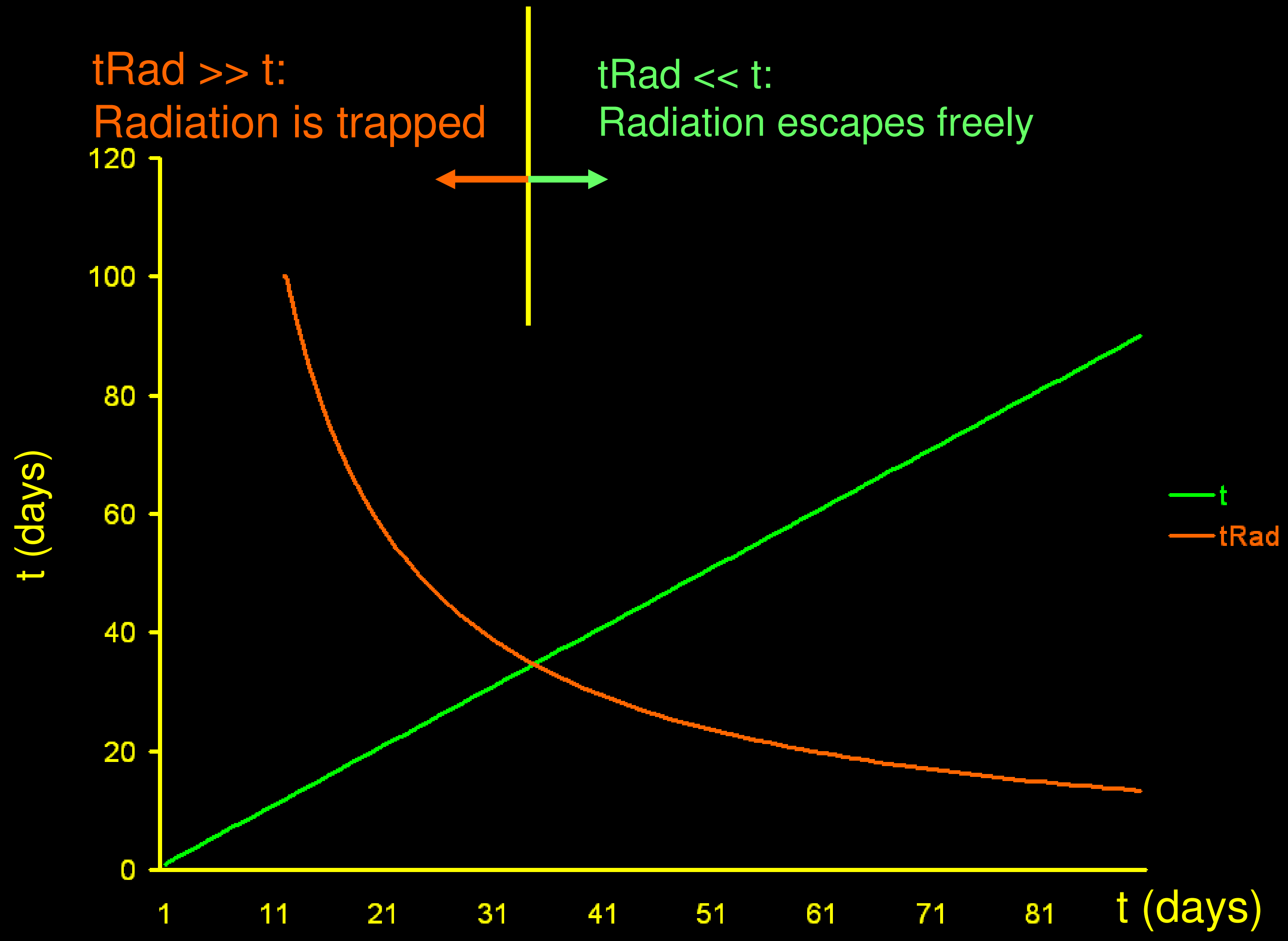


Radiation path length: $L = R_*^2/\delta = R_* \tau$

$\delta = (n_e \sigma_T)^{-1}$ (mean free path)

Diffusion time:

$t_{rad} = L/c = 1.2 \times 10^3\ [t/(1\ \mathrm{day})]^{-1}$ days



Radiation will escape when $t = t_{rad}$: ⇨ t_{esc} = 1 month

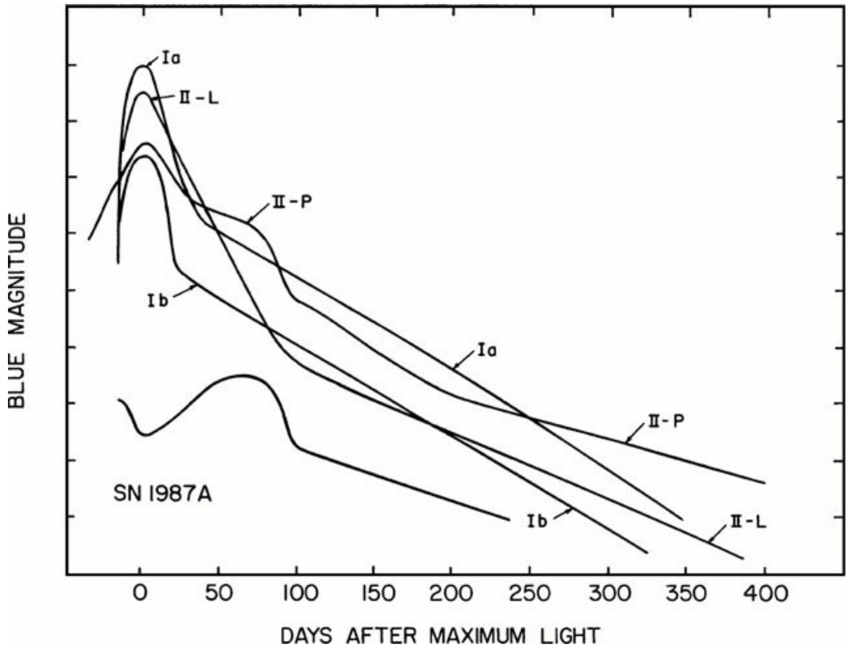
Maximum Luminosity: $L_{max} = E_{rad}/t_{esc} = 4 \times 10^9 L_{Sun}$

Unsolved Problems of Thermonuclear Supernovae

- What triggers the explosion?
- What causes the variation in the maximum luminosity? (Mass? C/O ratio?, opacity?)
- How do we account for the relationship between maximum luminosity and decay time?

Core Collapse (Type II) Supernovae (also Types Ib, Ic)

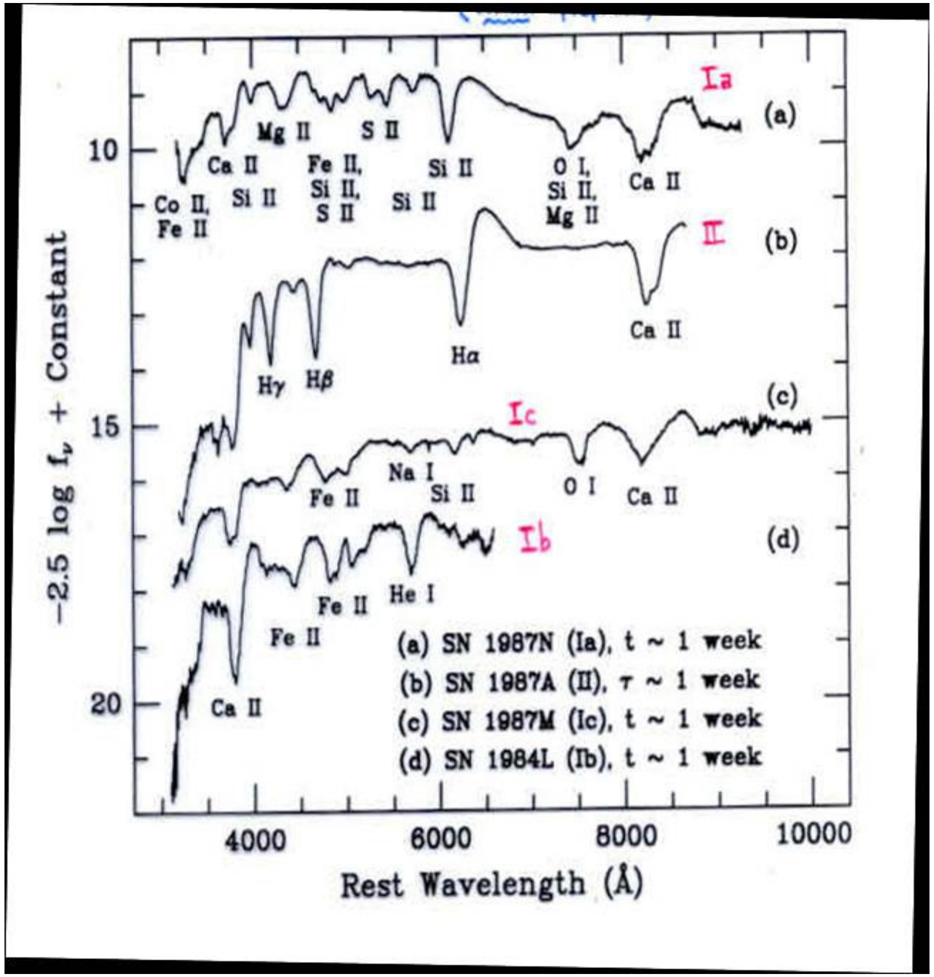
Light Curves



Compared to thermonuclear (Type Ia) supernovae), light curves of core collapse supernovae:

- Have much greater diversity
- Have lower maximum luminosity

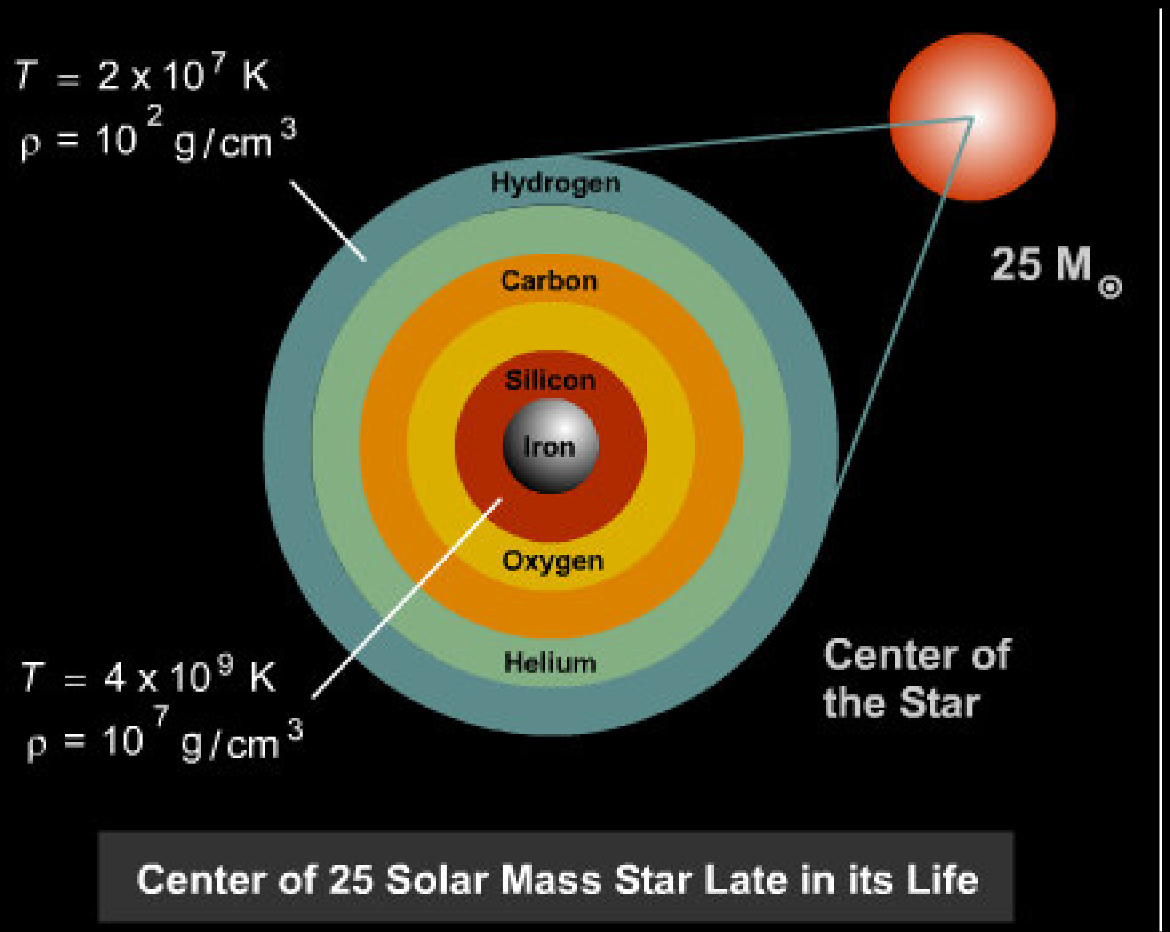
Spectra



Type I: no hydrogen lines

Type II: hydrogen lines

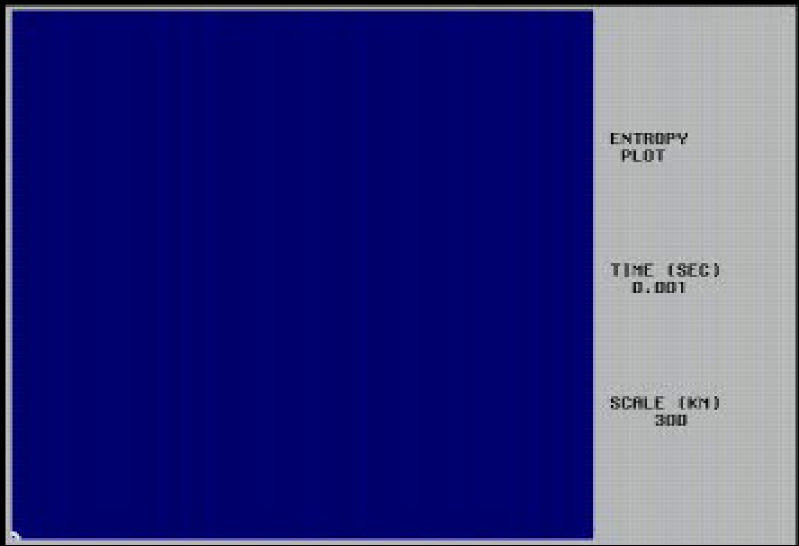
Core Collapse Supernova Progenitor Star

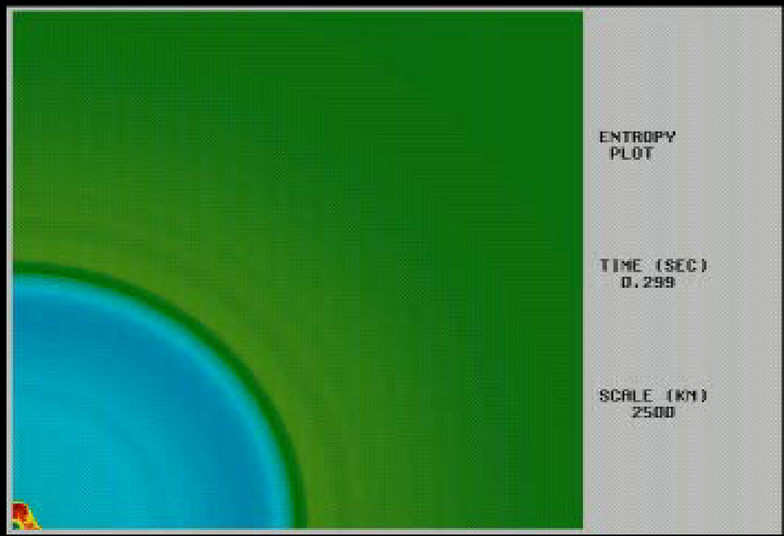


Core Collapse Supernova Energy Sources

- Core collapse:
  $E \sim GM^2/R \sim 0.1\ Mc^2 \sim 10^{53}$ ergs
  Neutrinos: t ~ 10s
- Radioactivity:
  $0.07\ M_{\odot}[^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe] \sim 10^{49}$ ergs.
  Light: t ~ 3 months
- Kinetic energy:
  $\sim 10\ M_{\odot}$, $V_{expansion} \sim 3000$ km/s $\sim 10^{51}$ ergs
  ~ 1% core collapse.
  X-rays: t ~ centuries.

Core collapse simulation





Supernova Nucleosynthesis

Pre-supernova stellar burning:

H → He: $T = 2 \times 10^7$ K

He → C, O: $T = 10^8$ K (thermonuclear progenitor)

O → Mg, Si: $T = 6 \times 10^8$ K

Si → Fe: $T = 10^9$ K (core collapse progenitor)

Supernova burning ($T = 3 \times 10^9$ K):

Thermonuclear SN: C, O → Si → He → Ni ("alpha process")

⇨ Si to Fe

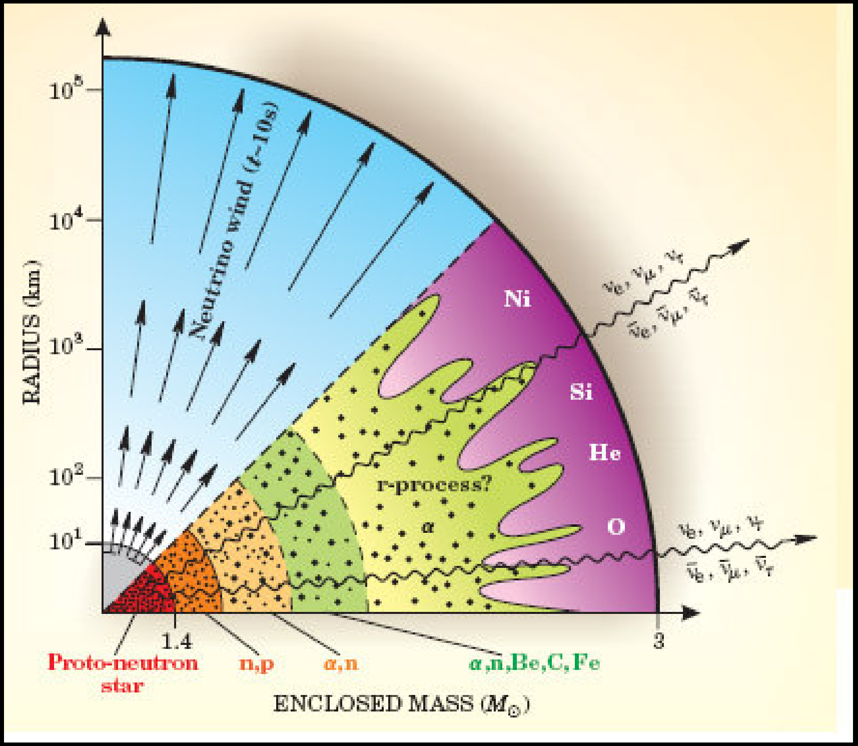
Core collapse SN: Si → Ni, and (for $\rho > 10^8$ g cm^{-3}):

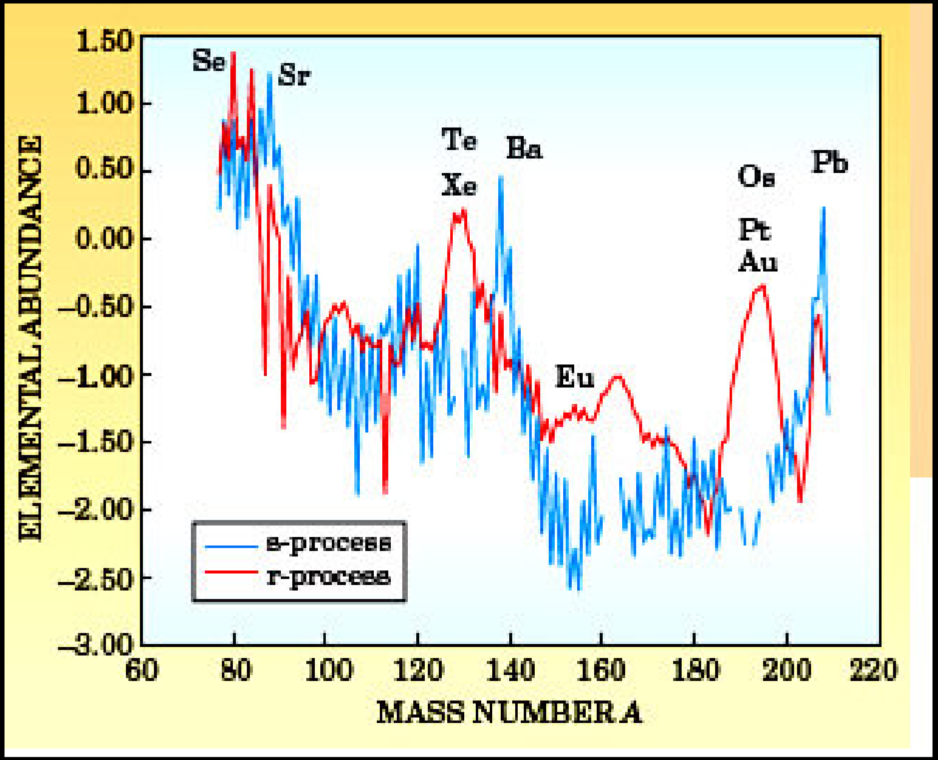
(A,Z) + e → (A, Z-1) → (A-1, Z-1) + n ("neutron drip")

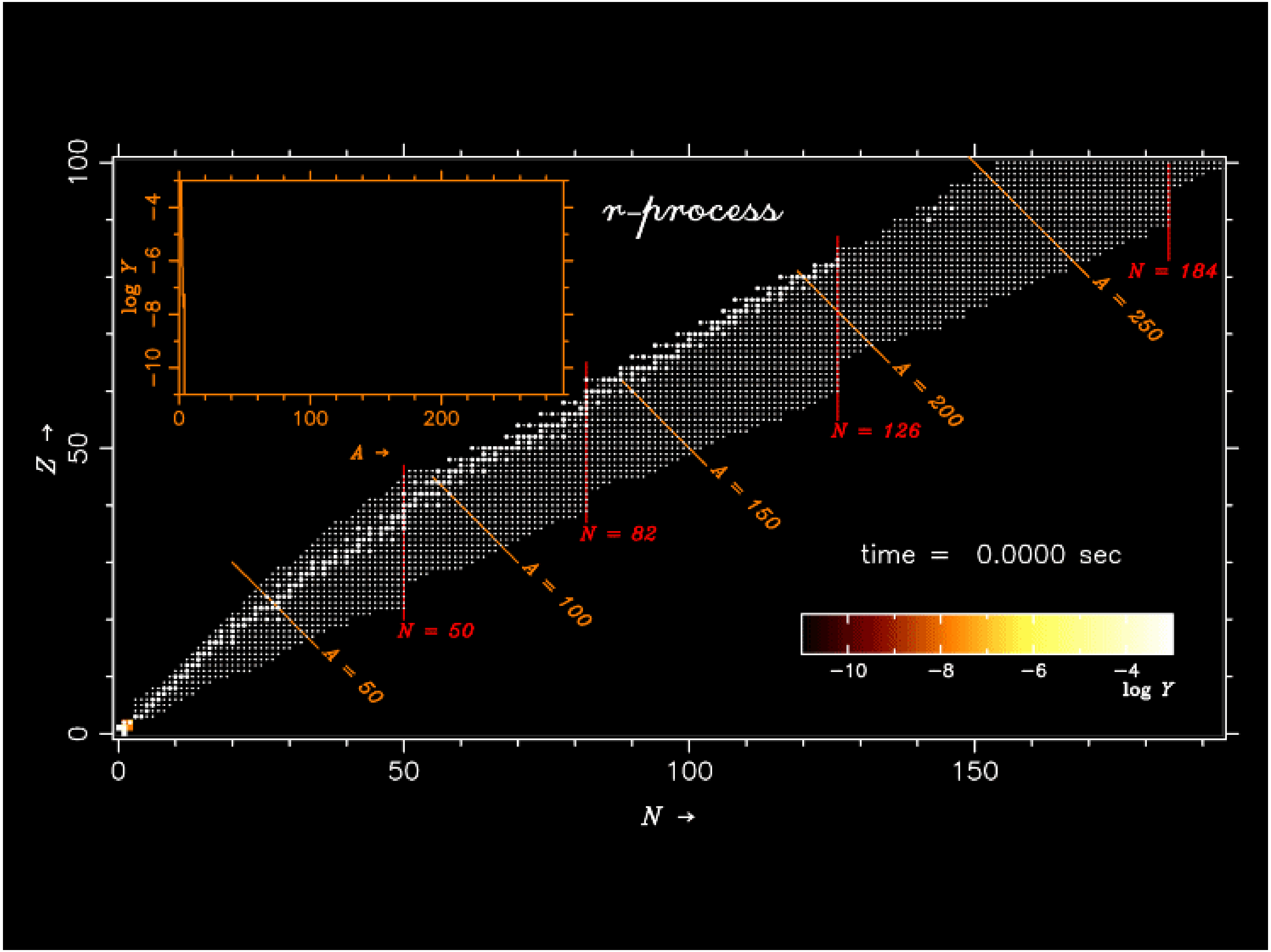
Si, Ni + n → all heavier elements ("r, s processes")

⇨ typical cosmic abundance ratios

Element abundances from supernova nucleosynthesis






r-process
time = 0.0000 sec
log Y
A →
N = 50
N = 82
N = 126
N = 184
A = 50
A = 100
A = 150
A = 200
A = 250
Z →
N →

Unsolved Problems of Core Collapse Supernovae

- Why is explosion energy about 10^{-2} of collapse energy?
- How do they explode?

  (Rotation? Magnetic field?)
- Relationship to gamma ray burst sources?