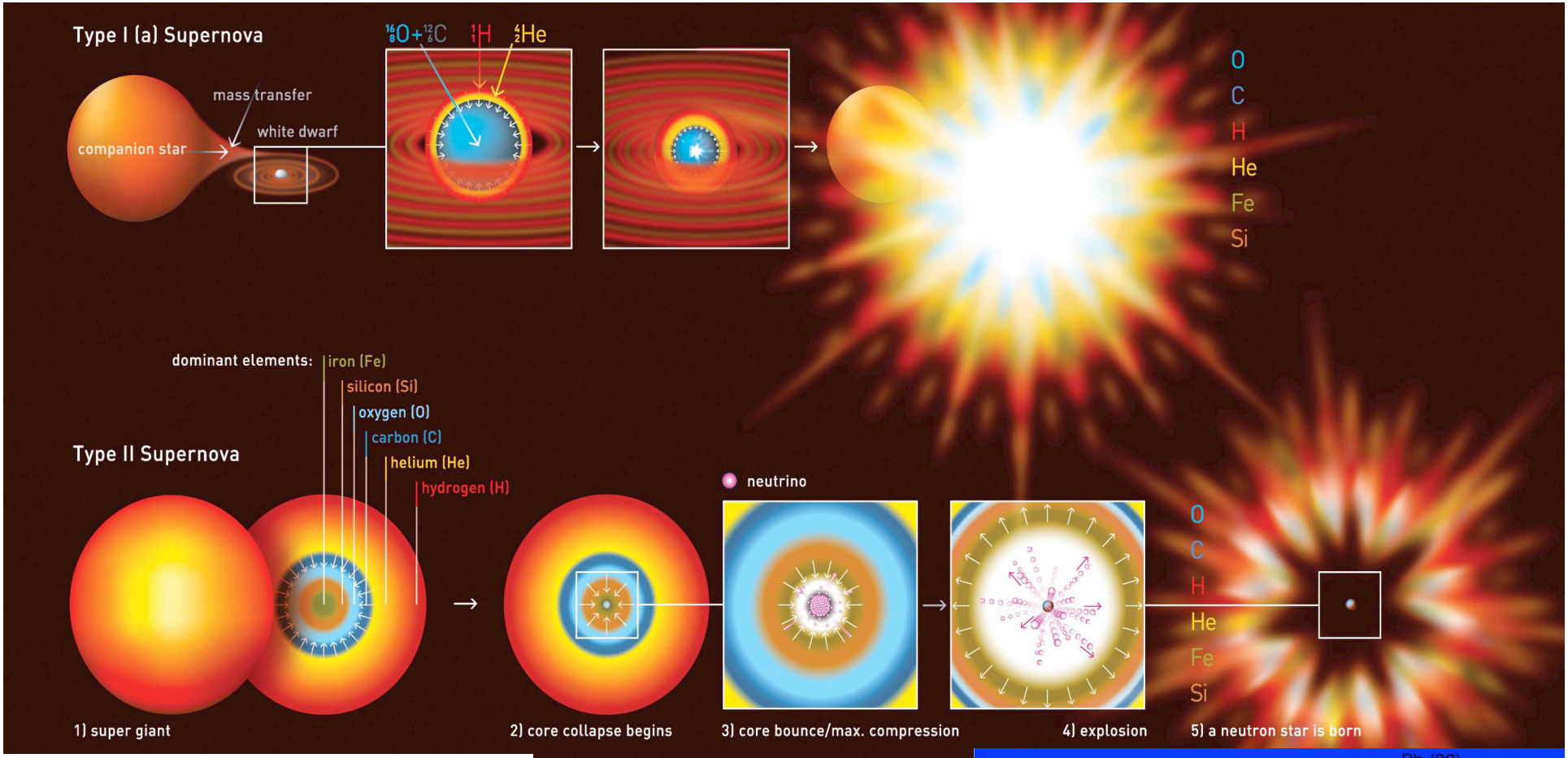
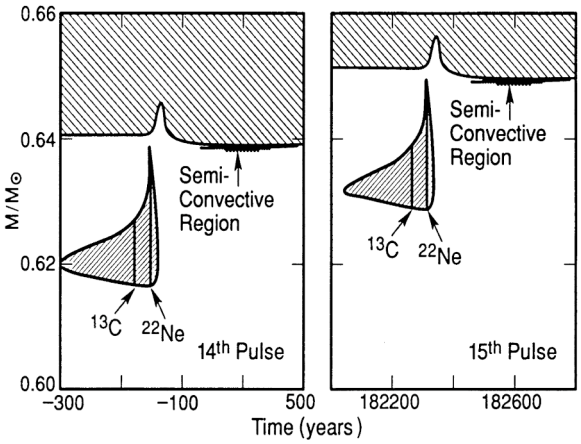
Supernovae

Type Ia: Thermonuclear

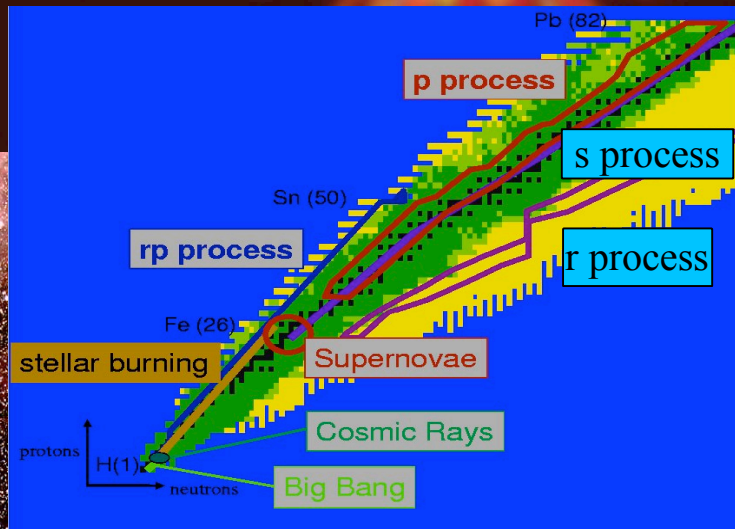
Core-Collapse

GRBs/Hypernovae


Type I (a) Supernova
mass transfer
white dwarf
companion star
O
C
H
He
Fe
Si
dominant elements:
iron (Fe)
silicon (Si)
oxygen (O)
carbon (C)
helium (He)
hydrogen (H)
Type II Supernova
neutrino
1) super giant
2) core collapse begins
3) core bounce/max. compression
4) explosion
5) a neutron star is born

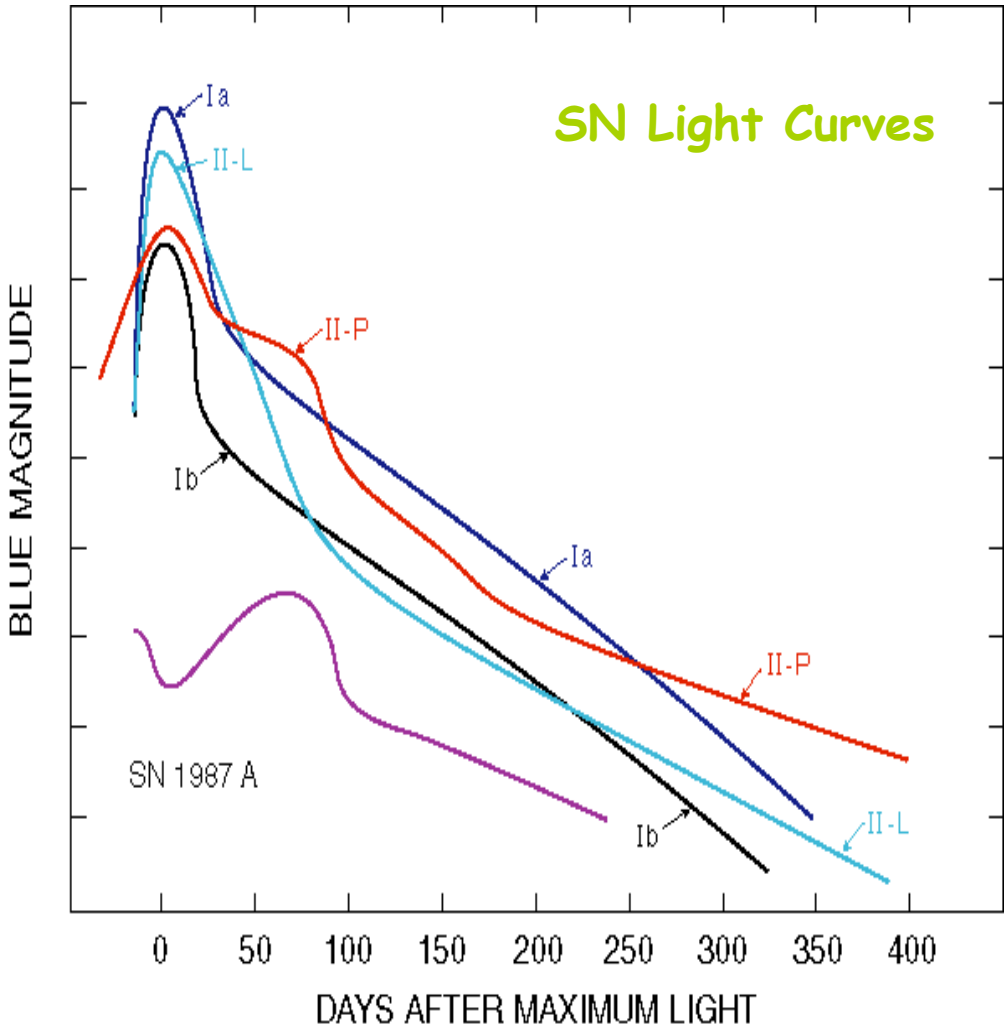

0.66
0.64
0.62
0.60
M/M⊙
Semi-
Convective
Region
13C
22Ne
14th Pulse
15th Pulse
−300
−100
500
182200
182600
Time (years)

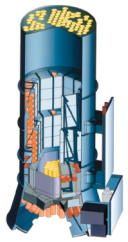
SN 1987A


Pb (82)
p process
s process
Sn (50)
rp process
r process
Fe (26)
stellar burning
Supernovae
Cosmic Rays
protons
H(1)
neutrons
Big Bang

Supernovae

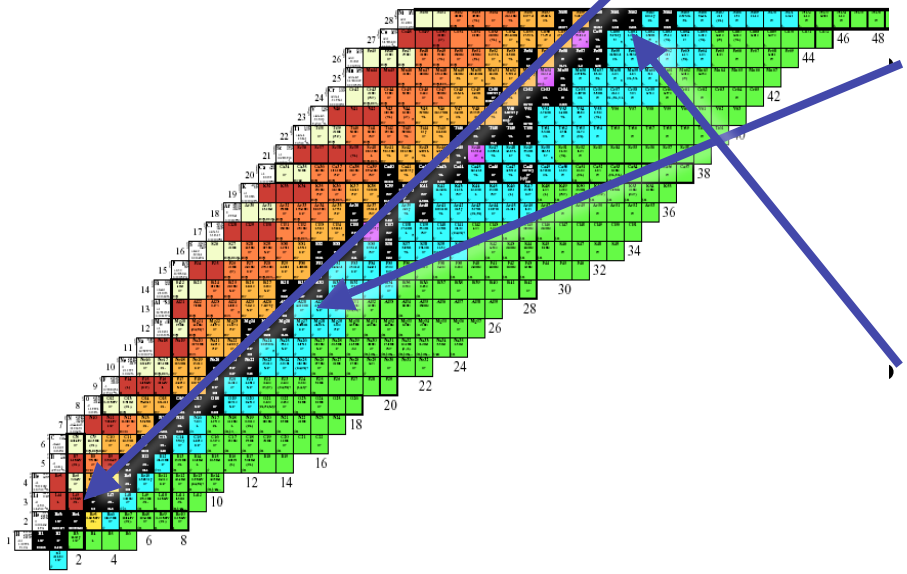
- Explosion of a Star
  - Explosive Nucleosynthesis -> Radioactive Energy
- Energy Release
  - Radioactive Heating
  - Progressive Transparency of Exploding Star
  - Recombination Radiation (stored ionizing energy of explosion)
- Types
  - Thermonuclear Supernovae (Type Ia)
  - Gravitational Collapse Supernovae (Types II, Ib/c)





Gamma-Rays and Positrons from SNe

Isotope	Mean Lifetime	Decay Chain	γ -Ray Energy (keV)
^{7}Be	77 d	$^{7}Be \rightarrow {}^{7}Li^{*}$	478
^{56}Ni	111 d	$^{56}Ni \rightarrow {}^{56}Co^{*} \rightarrow {}^{56}Fe^{*}+e^{+}$	158, 812; 847, 1238
^{57}Ni	390 d	$^{57}Co \rightarrow {}^{57}Fe^{*}$	122
^{22}Na	3.8 y	$^{22}Na \rightarrow {}^{22}Ne^{*} + e^{+}$	1275
^{44}Ti	89 y	$^{44}Ti \rightarrow {}^{44}Sc^{*} \rightarrow {}^{44}Ca^{*}+e^{+}$	78, 68; 1157
^{26}Al	1.04 10^{6}y	$^{26}Al \rightarrow {}^{26}Mg^{*} + e^{+}$	1809
^{60}Fe	2.0 10^{6}y	$^{60}Fe \rightarrow {}^{60}Co^{*} \rightarrow {}^{60}Ni^{*}$	59, 1173, 1332
e^{+}	.... 10^{5}y	$e^{+}+e^{-} \rightarrow Ps \rightarrow \gamma\gamma$..	511, 1811



!

- 511 keV, ^{7}Be -> Novae
  -> p-Captures, β^{+} Decays
  -> ^{19}F Production…

^{26}Al -> Reaction Path Details in Stars/SNe, ν-Process
-> Metal/Fe Ratio, Si/Fe

^{44}Ti, ^{56}Ni -> Most Stable Isotopes
^{56}Ni/^{4}He, Freeze-Out of NSE
-> Metal/Fe Ratio, Heavies/Fe

Type Ia Supernovae

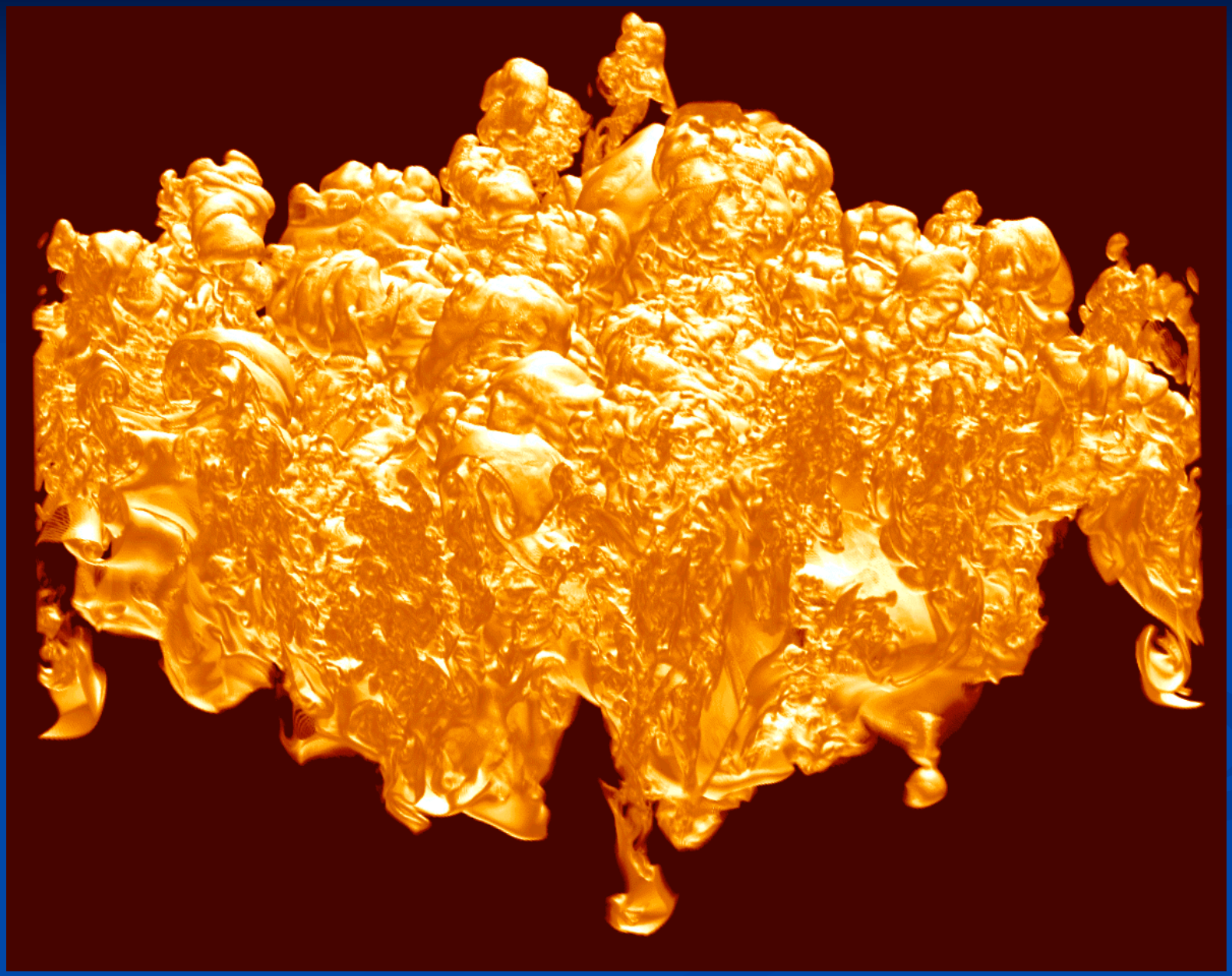
Thermonuclear Supernovae: Type Ia

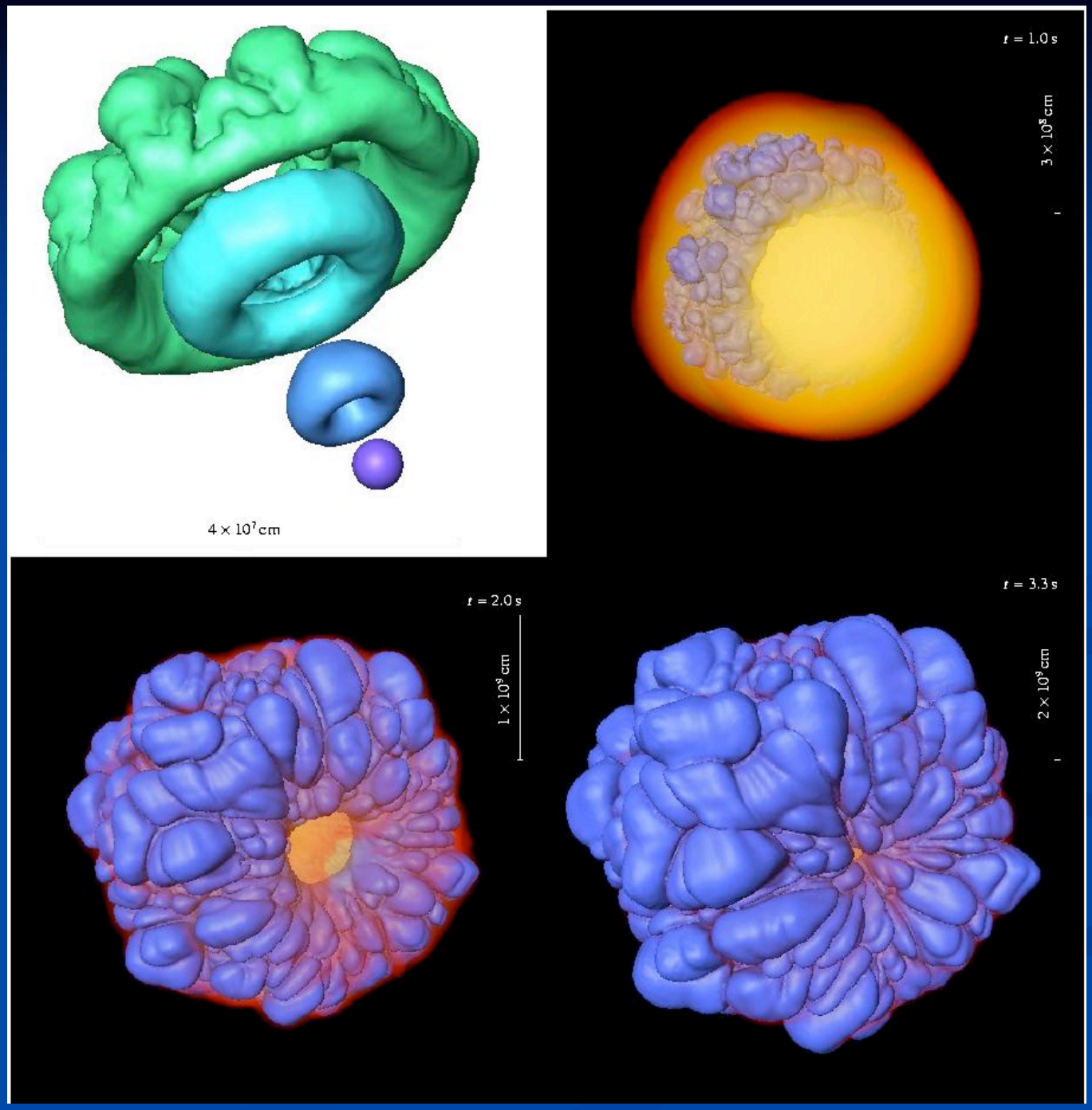
- Used for cosmology: “standardizable” and bright
- ~1 per 300 years in Milky Way
- C/O White Dwarf that achieves the Chandrasekhar mass
- Thermonuclear explosions of M_{Ch}
- ~10^{51} ergs of K.E.; ~10^{49} ergs in light
- Powered by radioactivity: ^{56}Ni - ^{56}Co - ^{56}Fe ; γ and e^+
- Q ~ 0.6 MeV/b ; 0.6×10^{18} erg/g x 1.4 x 2×10^{33} g = 1.7 x 10^{51} erg
- B.E. ~ 1/2 $m_e c^2 (M_{Ch}/m_p)$ ~ 0.7×10^{51} ergs
- E - B.E. ~ 10^{51} ergs; Energetics is marginal
- K.E. ~ 1/2 Mv^2 --> v ~ 10^9 cm/s = 10^4 km/s
- O/Mg/Ne white dwarfs - core collapse? AIC?

Thermonuclear Supernovae (cont.)

- $\Delta\tau$ ~ 1 second
- R ~ 4000 km
- V ~ 10^4 km/s
- Deflagration?
- Detonation? D ~ $((2\gamma^2 - 1)Q)^{1/2}$ ~ 10^9 cm/s
- DDT?
- Ignition?
- Progenitors (in fact, unknown!)
- ^{56}Ni - ^{56}Co - ^{56}Fe is the source of most Fe in the Universe
- Light curve powered by decay chain; does not redshift with expansion
- Peak powered by ^{56}Ni decay
- Mean lives: 8.8 and 111.3 days
- Total decay energy ~ 10^{49} ergs
- L_{peak} ~ 10^{43} ergs/s < 10^{10} L_{sun}
- Gamma-ray astronomy
- Major source of Fe peak (~50% or more?), but other elements as well

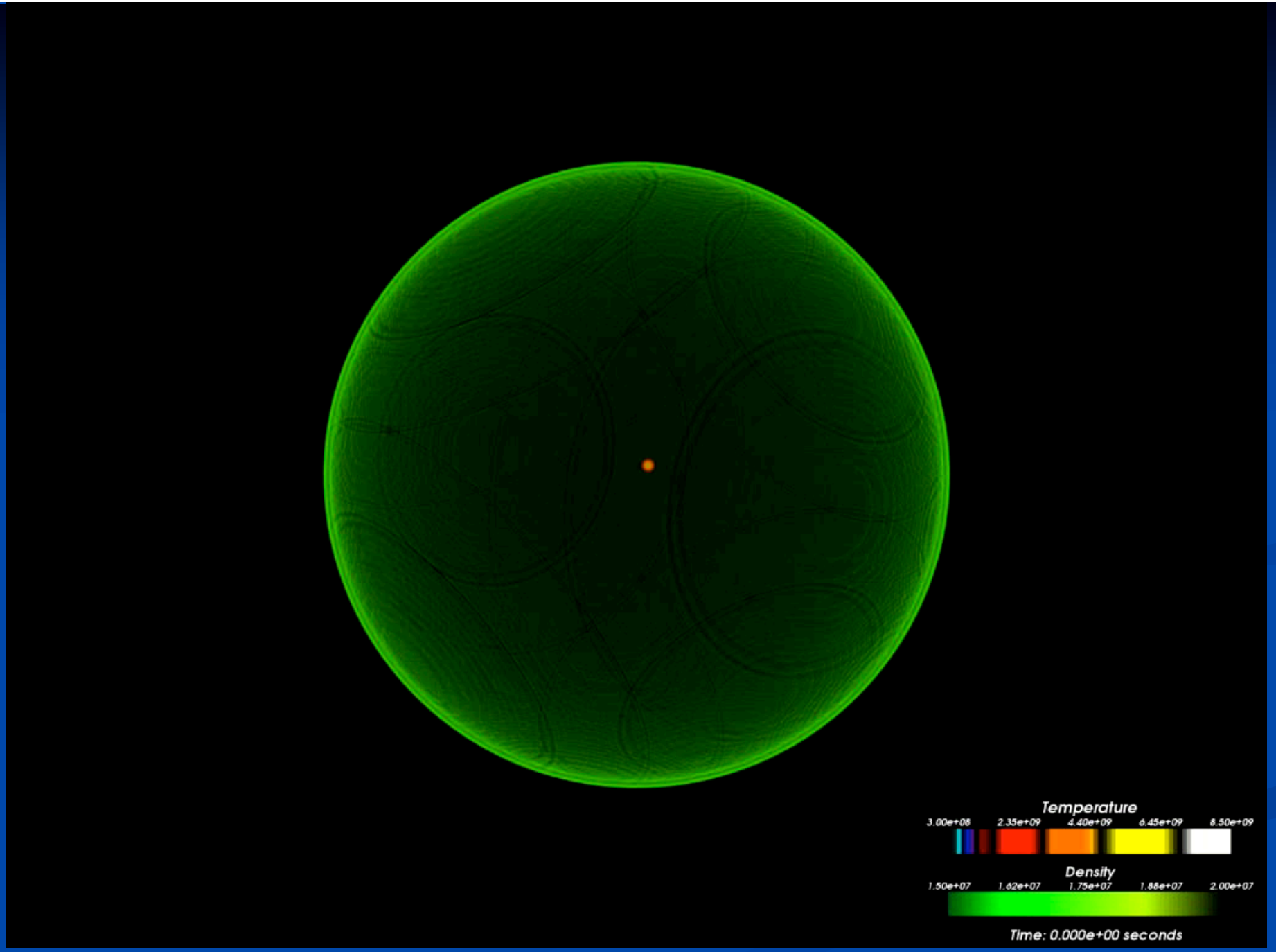
Turbulent Thermonuclear Flame Front




4×10^7 cm
t = 1.0 s
3×10^8 cm
t = 2.0 s
1×10^9 cm
t = 3.3 s
2×10^9 cm

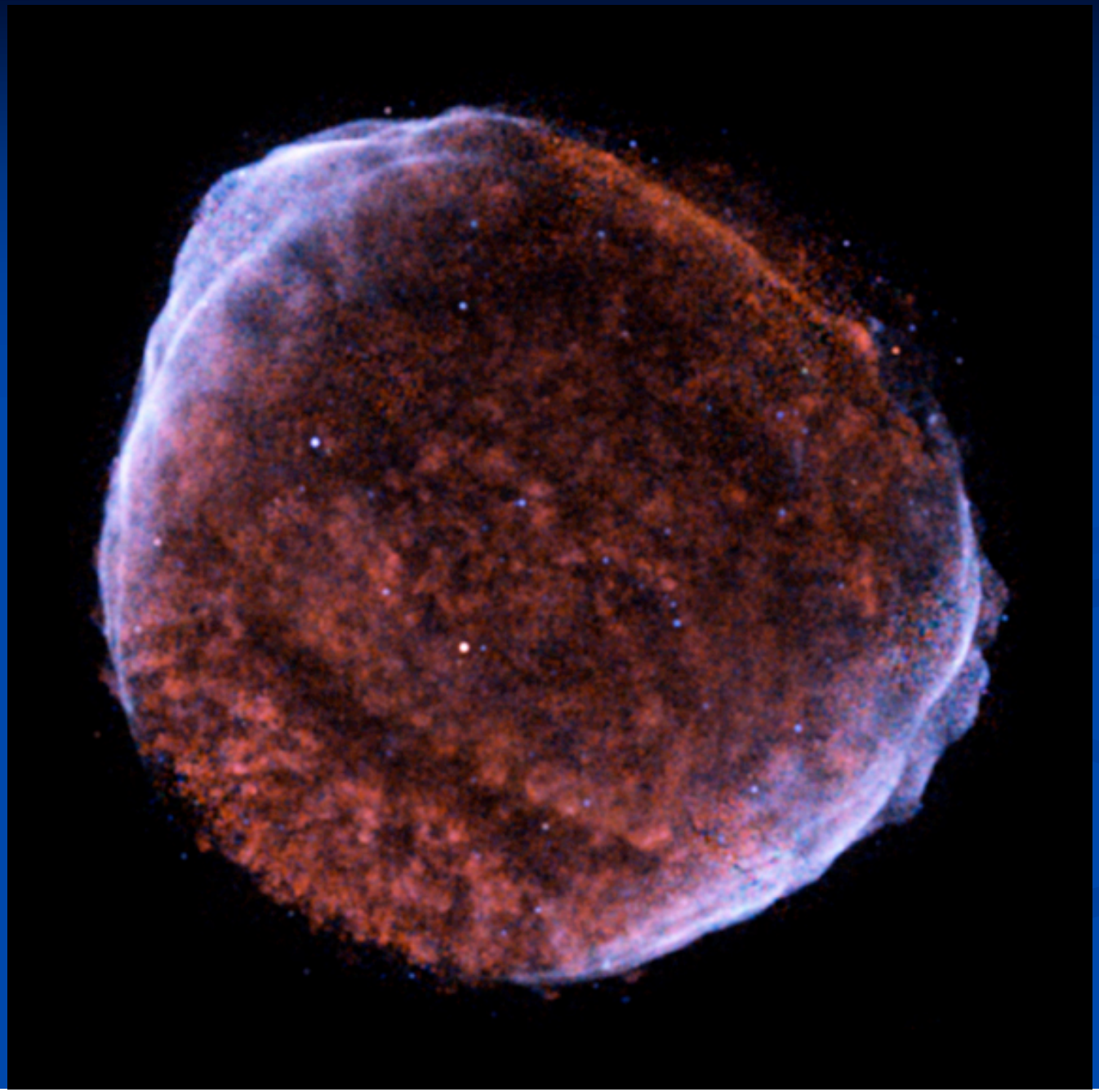
b0123d-400x45x120, ye=0.495, 8e8cm

T = (300+0) msec

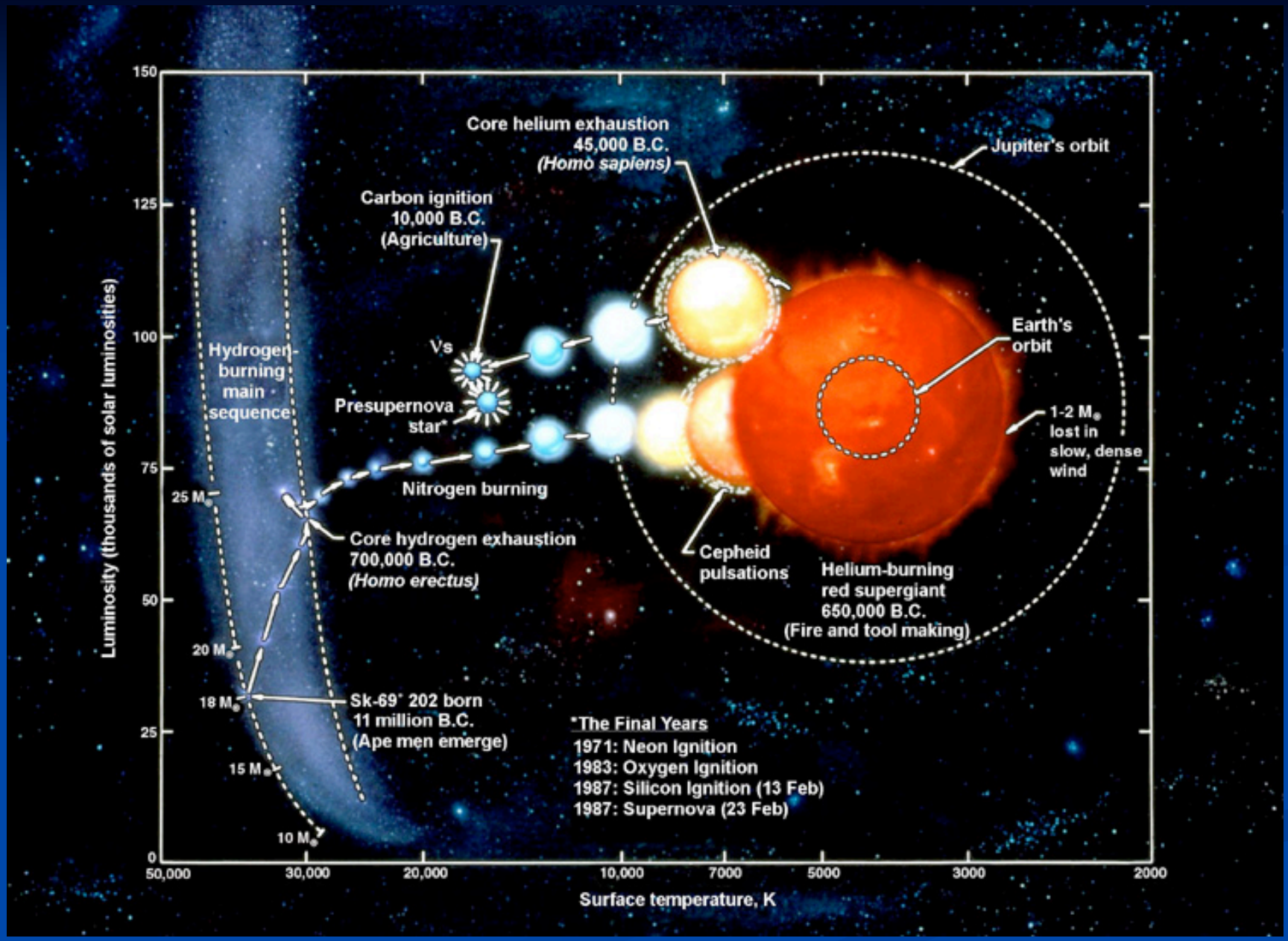


Flash Center, Off-Center Single-point Ignition

Type Ia: SN1006 (in X-rays)

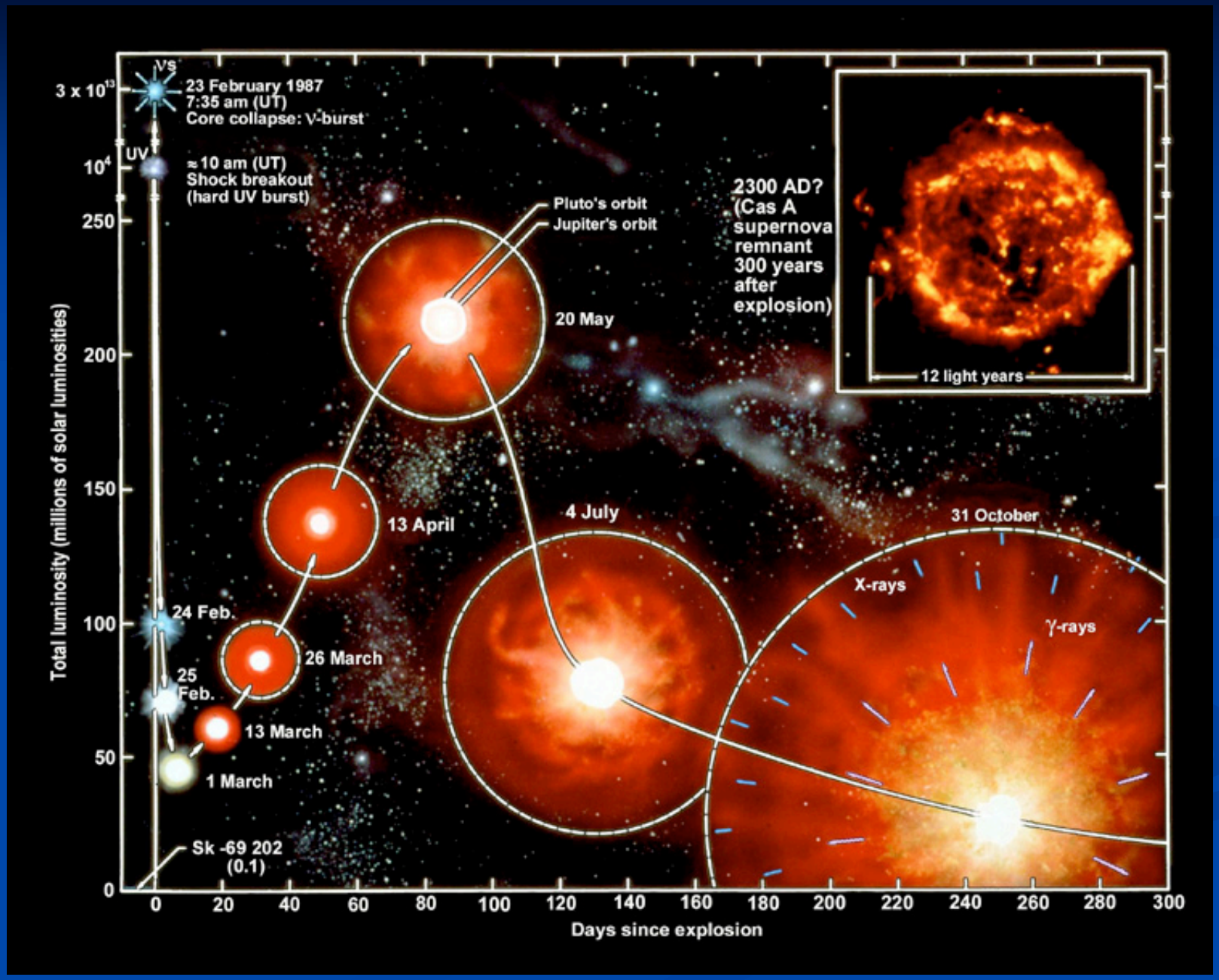


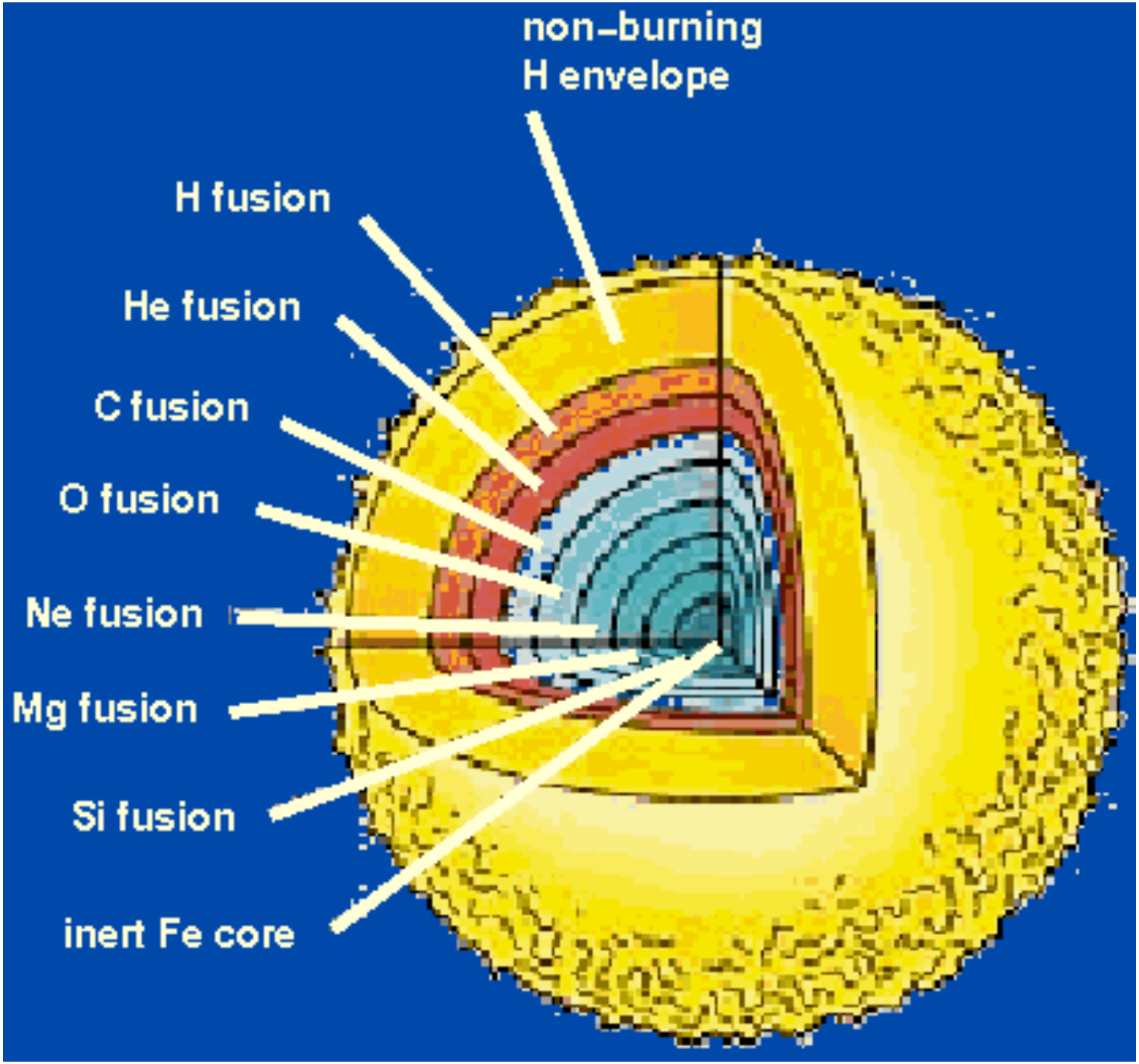
Core-Collapse Supernovae



Courtesy of Tom Weaver

Core-Collapse Supernova Light Curve: SN1987A




non-burning
H envelope
H fusion
He fusion
C fusion
O fusion
Ne fusion
Mg fusion
Si fusion
inert Fe core

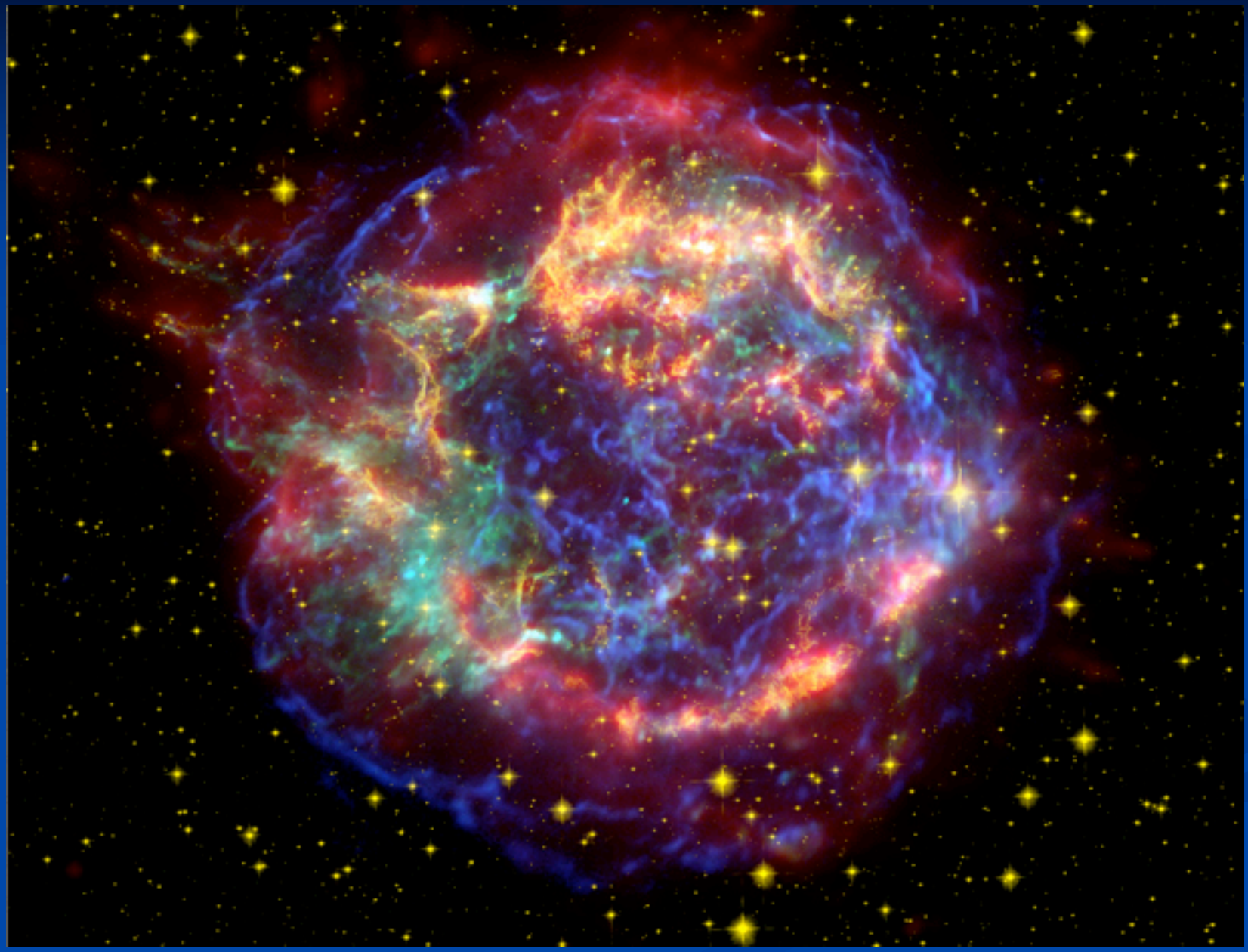
Core-Collapse Supernovae: Types IIp,L,n,b; Ib, Ic

- Gravitationally-powered; Neutrinos!?
- Most prevalent Type; 1 per 30-50 years in Milky Way
- Heterogeneous in energy, nucleosynthesis
- Collapse of M_{Ch} (!), but in the core of massive stars (> 8 M_{sun})
- Envelope at first oblivious - whole star does not collapse
- Core collapses in ~0.5 seconds
- Collapse speed ~ 7×10^4 km/s
- Bounce at nuclear density due to EOS stiffening --> shock wave!
- But shock stalls into accretion; Mdot ~ 100 to 0.1 M_{sun}/s (!)
- Must be revitalized: Neutrinos, MHD, acoustic?
- Birthplace of neutron stars (and stellar-mass black holes) - endpoints
- Explosion occurs in the proto-neutron star (PNS) mantle
- Binding energy of NS residue ~ $GM^2/2R \sim 3 \times 10^{53}$ ergs; (R ~ 10 km)
- Radiated as Neutrinos! ; L ~ 10^{53} ergs/s

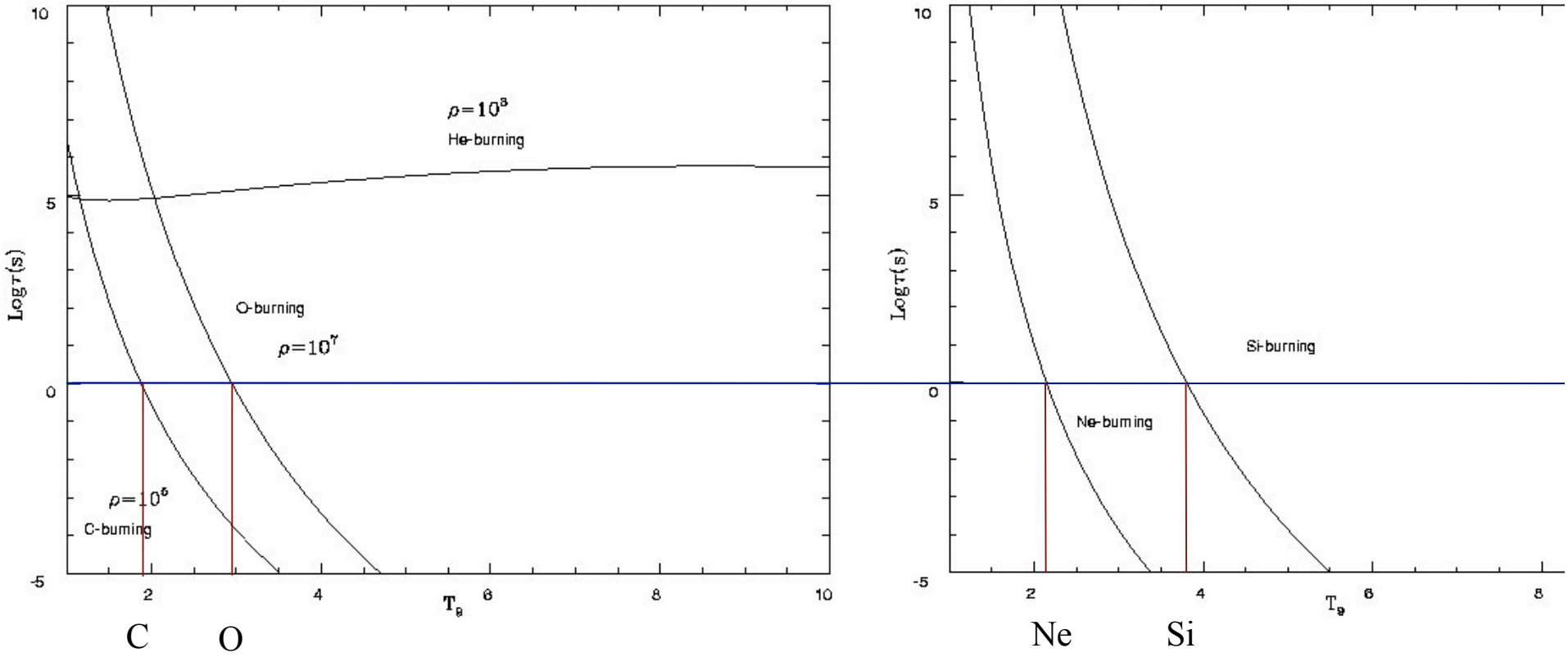
Core-Collapse Supernovae (cont.)

- L(photons) ~ $10^{7\text{-}10}$ L_{sun}
- L(neutrinos) ~ $10^{19\text{-}20}$ L_{sun} ! (neutrinos of all 6 species)
- SN1987A - 19 anti-electron neutrinos detected over ~10 s -- 50 kpc
- ^{56}Co gamma-rays detected from SN1987A! -- 50 kpc
- K.E. ~ 10^{51} ergs, but a few x 10^{50} - 10^{52} ergs (hypernovae; < 1%)
- Larger ejecta mass - lower v than Type Ias (v ~ $10^{3\text{-}4}$ km/s)
- ~$10^{48\text{-}49}$ ergs of light - shocked envelope; H recombination wave (Type IIp); ^{56}Co decay (SN1987A) - radioactive sources don't redshift away with expansion (crucial fact for Type Ias)
- Large initial radius - cooling of shocked envelope powers light curve
- Small initial radius (Wolf-Rayet, He core) - radioactive power
- GRB connection! (<0.5% of core collapses) ; rotation? MHD, BH?
- Source of O, Ne, Mg, S, Ca, Si, Fe peak, r-process elements

Supernova Remnant Cas A in X-rays



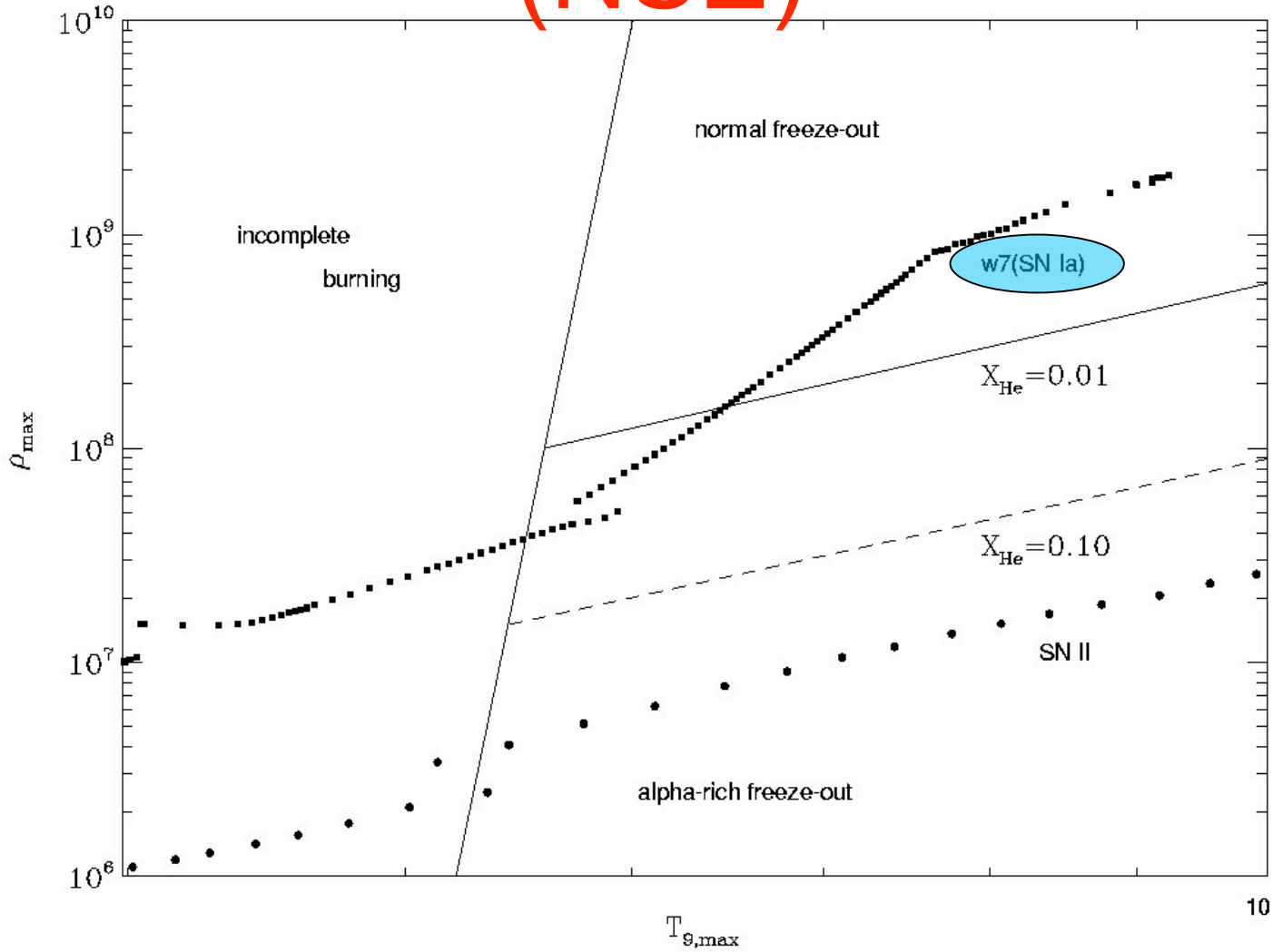
Explosive Burning



C O Ne Si

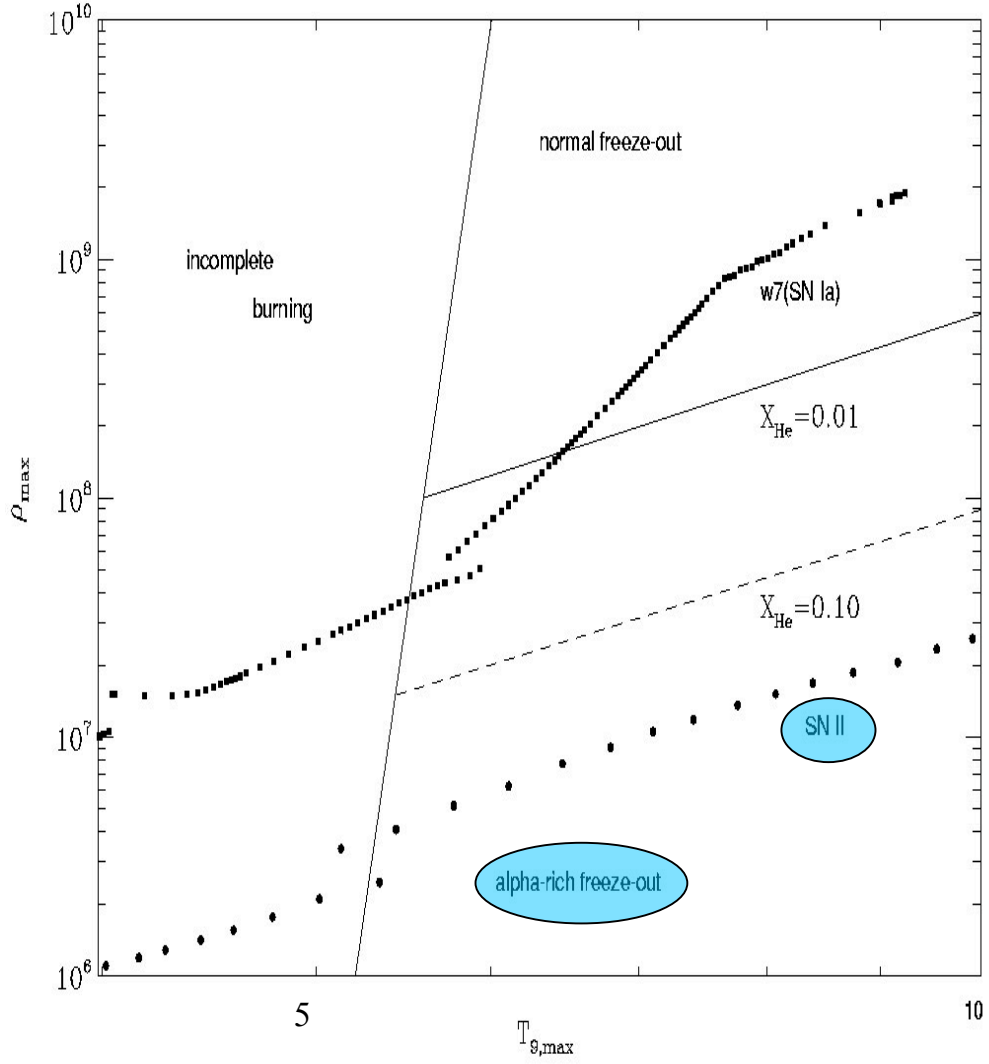
typical explosive burning process timescale order of seconds: fusion reactions (He, C, O) density dependent (He quadratic, C,O linear) photodisintegrations (Ne, Si) not density dependent

Complete chem. equilibrium (NSE)

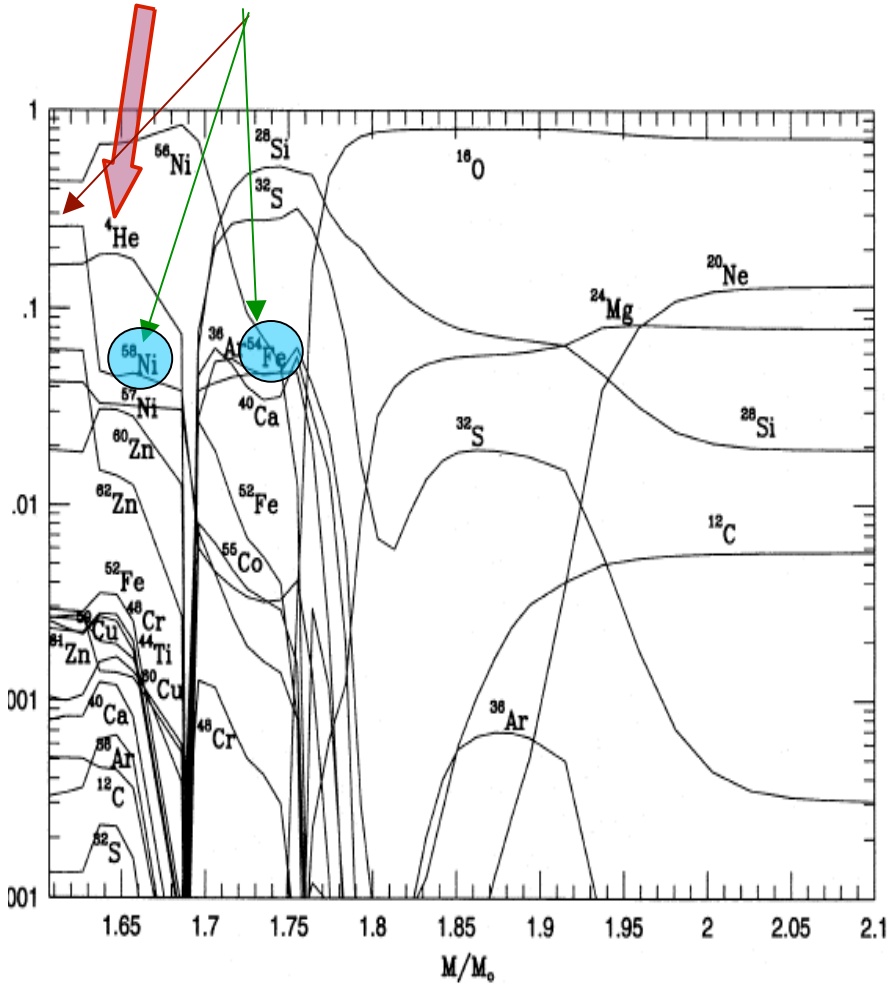


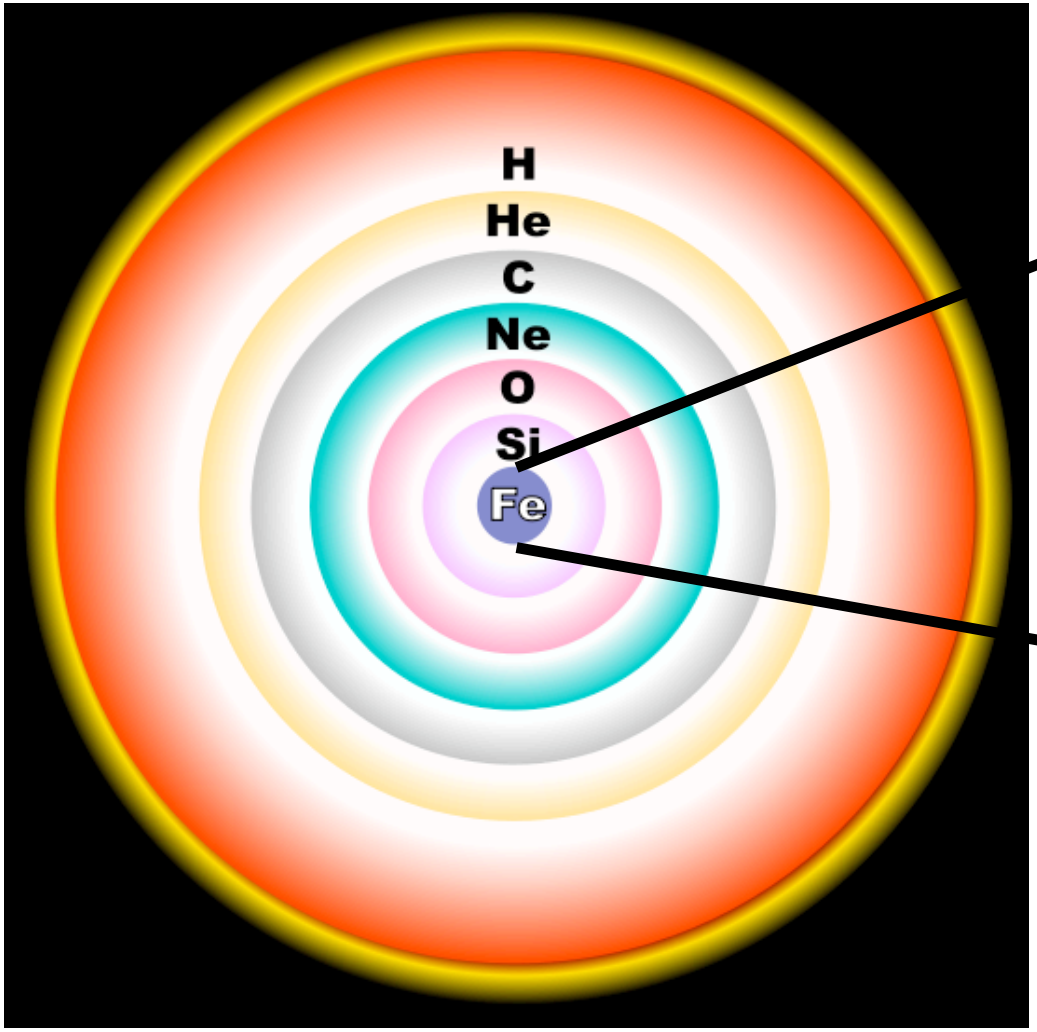
Si-burning in stellar evolution and expl. Si-burning at high densities lead to NSE!

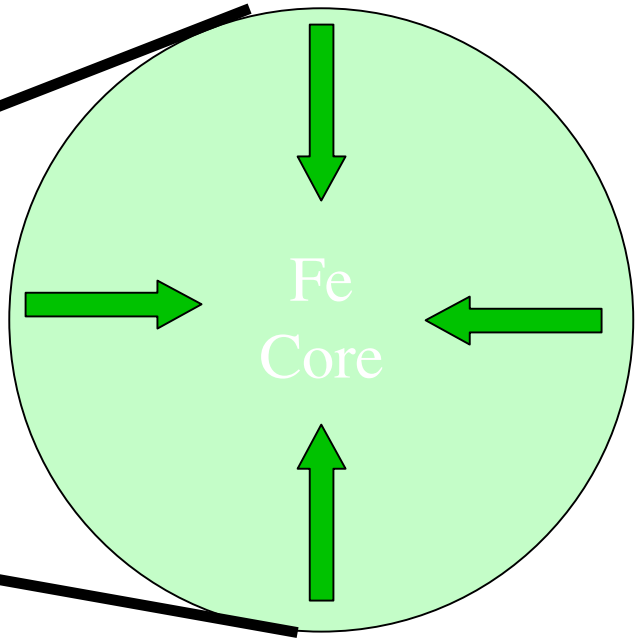
QSE and Freeze-out in Explosive Si-burning



disconnected light element (n,p,He) and Si-Fe QSE-cluster, high alpha-abundance prefers alpha-rich nuclei (^{58}Ni over ^{54}Fe), Y_e determines dominant QSE-isotope.







$1.4\ M_\odot$, R ~3000 km

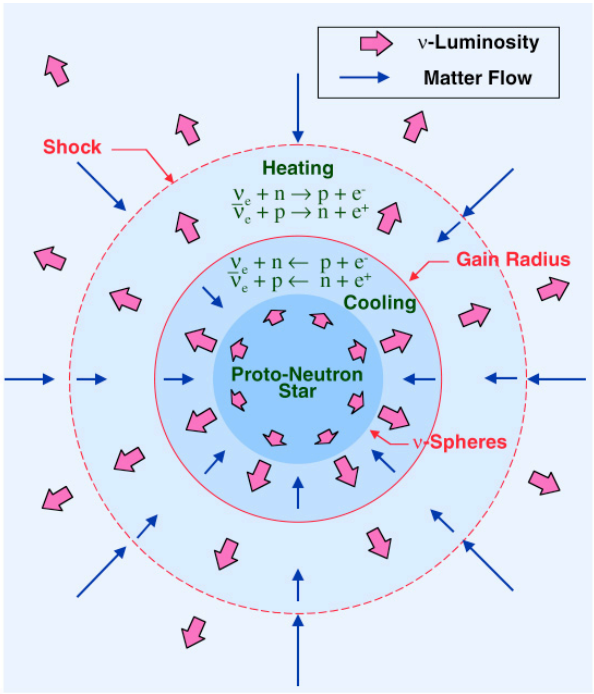
T_{dyn} ~ 250 ms

$M_{ZAMS} \gtrsim 8\ M_\odot$

R~ 30-60 km

PNS

Neutrino-driven Core Collapse Supernovae?



$\nu_e + n \leftrightarrow p + e^-$ heating

$\bar{\nu}_e + p \leftrightarrow n + e^+$

$\nu_e + A' \leftrightarrow A + e^-$ opacity

$\nu + N \leftrightarrow \nu + N$

$\nu + A \leftrightarrow \nu + A$

$\nu + e^- \leftrightarrow \nu + e^-$ thermalization

$e^+ + e^- \leftrightarrow \nu + \bar{\nu}$

$\nu = \nu_e, \nu_\mu, \nu_\tau$ source terms

$e^+ + e^- \leftrightarrow \nu + \bar{\nu}$

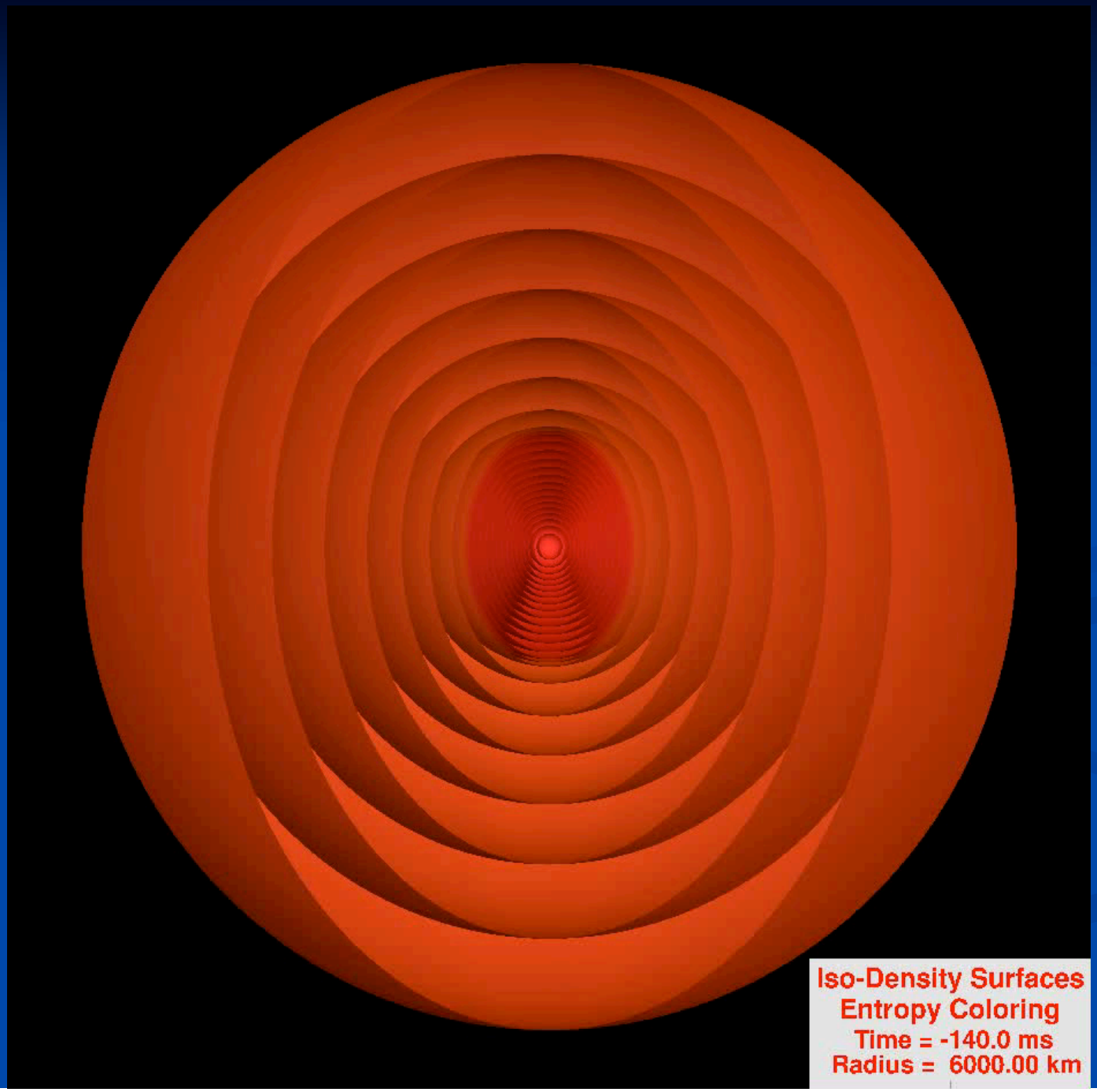
$\gamma + \gamma \leftrightarrow \nu + \bar{\nu}$

also

$e + \gamma \leftrightarrow e + \gamma + \nu + \bar{\nu}$

and

$\nu_e + \bar{\nu}_e \rightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$


Iso-Density Surfaces
Entropy Coloring
Time = -140.0 ms
Radius = 6000.00 km