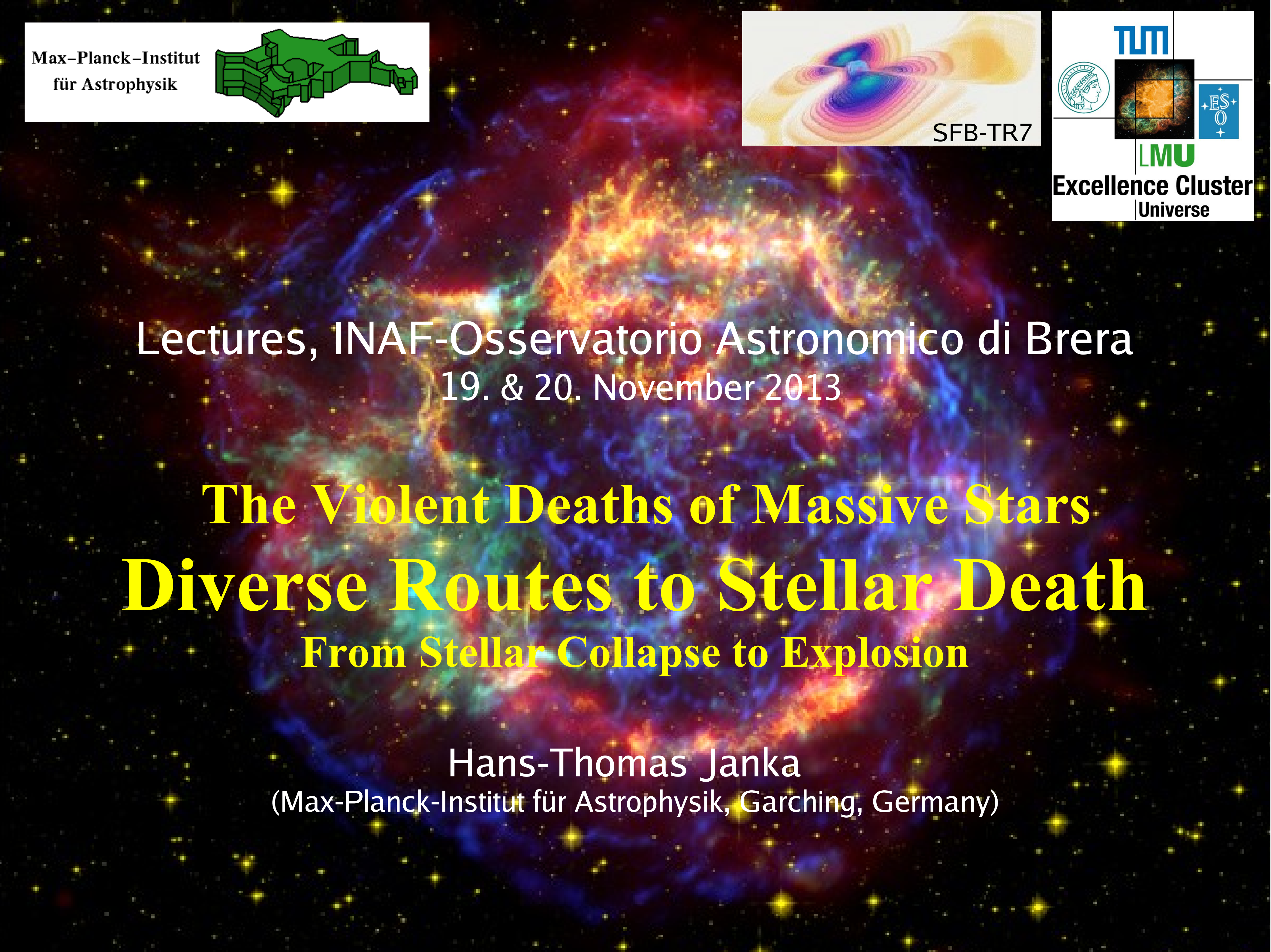

Max-Planck-Institut
für Astrophysik

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Lectures, INAF-Osservatorio Astronomico di Brera
19. & 20. November 2013

The Violent Deaths of Massive Stars
Diverse Routes to Stellar Death
From Stellar Collapse to Explosion

Hans-Thomas Janka
(Max-Planck-Institut für Astrophysik, Garching, Germany)

Contents

Lecture I:

- Supernovae: classification and phenomenology
- Basics of stellar evolution & death scenarios in overview
- White dwarfs and thermonuclear supernovae

Lecture II:

- Gravitational (core-collapse) supernovae: evolution stages
- SN modeling: some technical aspects
- Status of 2D and 3D SN modeling

Lecture III:

- Supernova models: Predictions of observable signals
- Neutron stars: birth and death
- Black holes and gamma-ray bursts: Sources of heavy elements

For concise reviews of much of what I will say, see

ARNPS 62 (2012) 407, arXiv:1206.2503
and
PTEP 2012, 01A309, arXiv:1211.1378

REVIEWS IN ADVANCE

Explosion Mechanisms of Core-Collapse Supernovae

Hans-Thomas Janka

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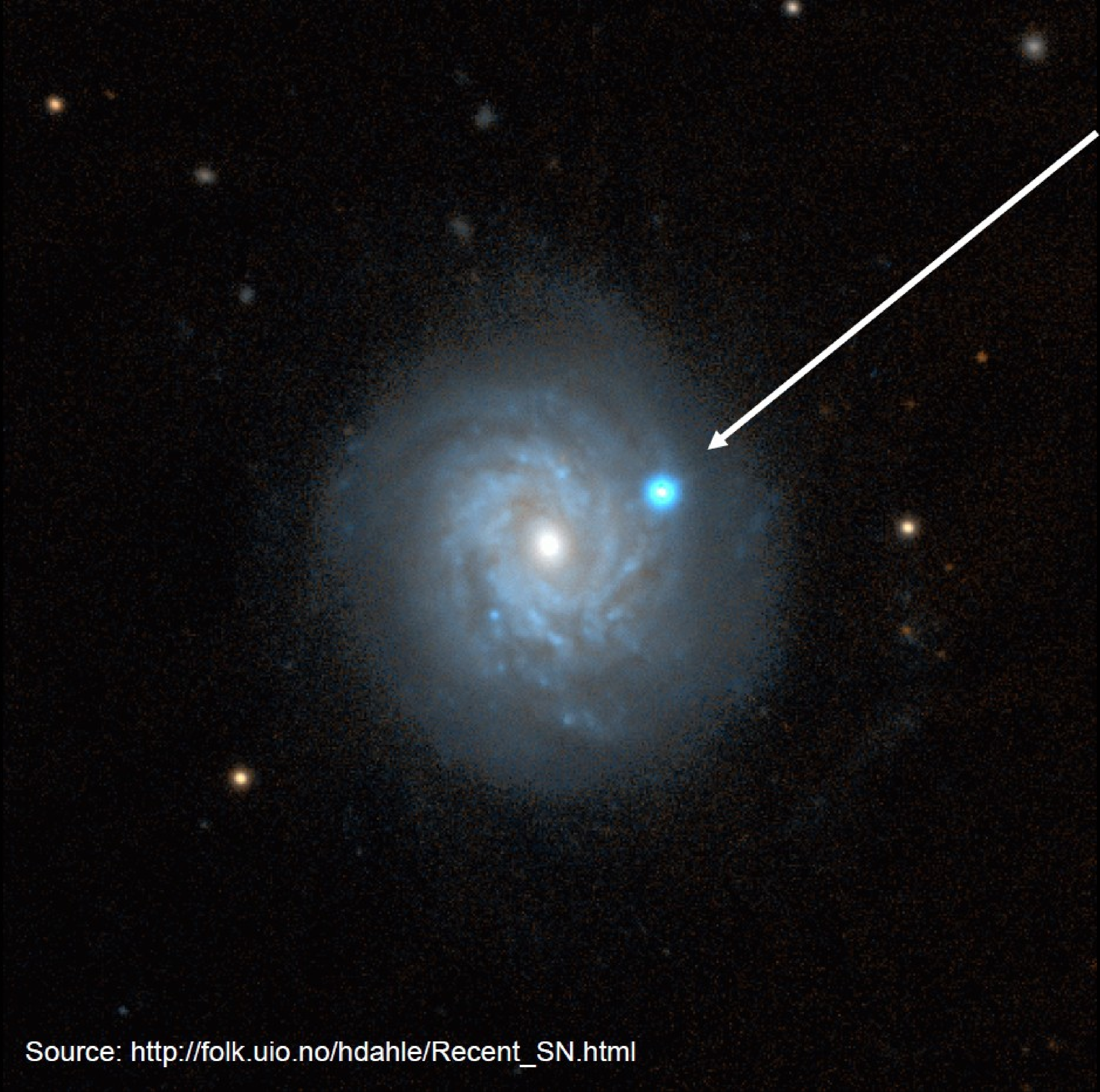
email: thj@mpa-garching.mpg.de

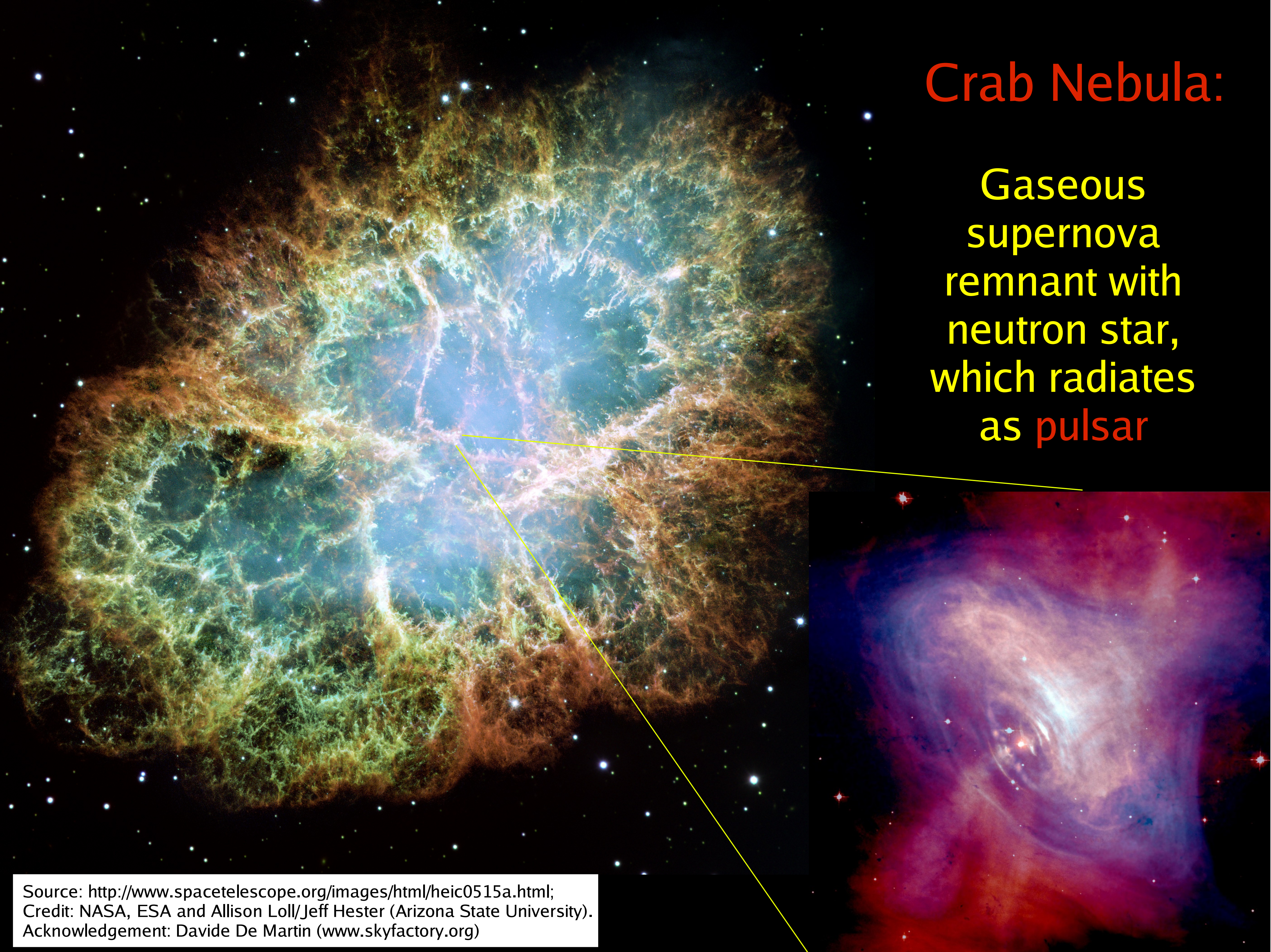
Supernova Phenomenology and Classification

SN 1994d



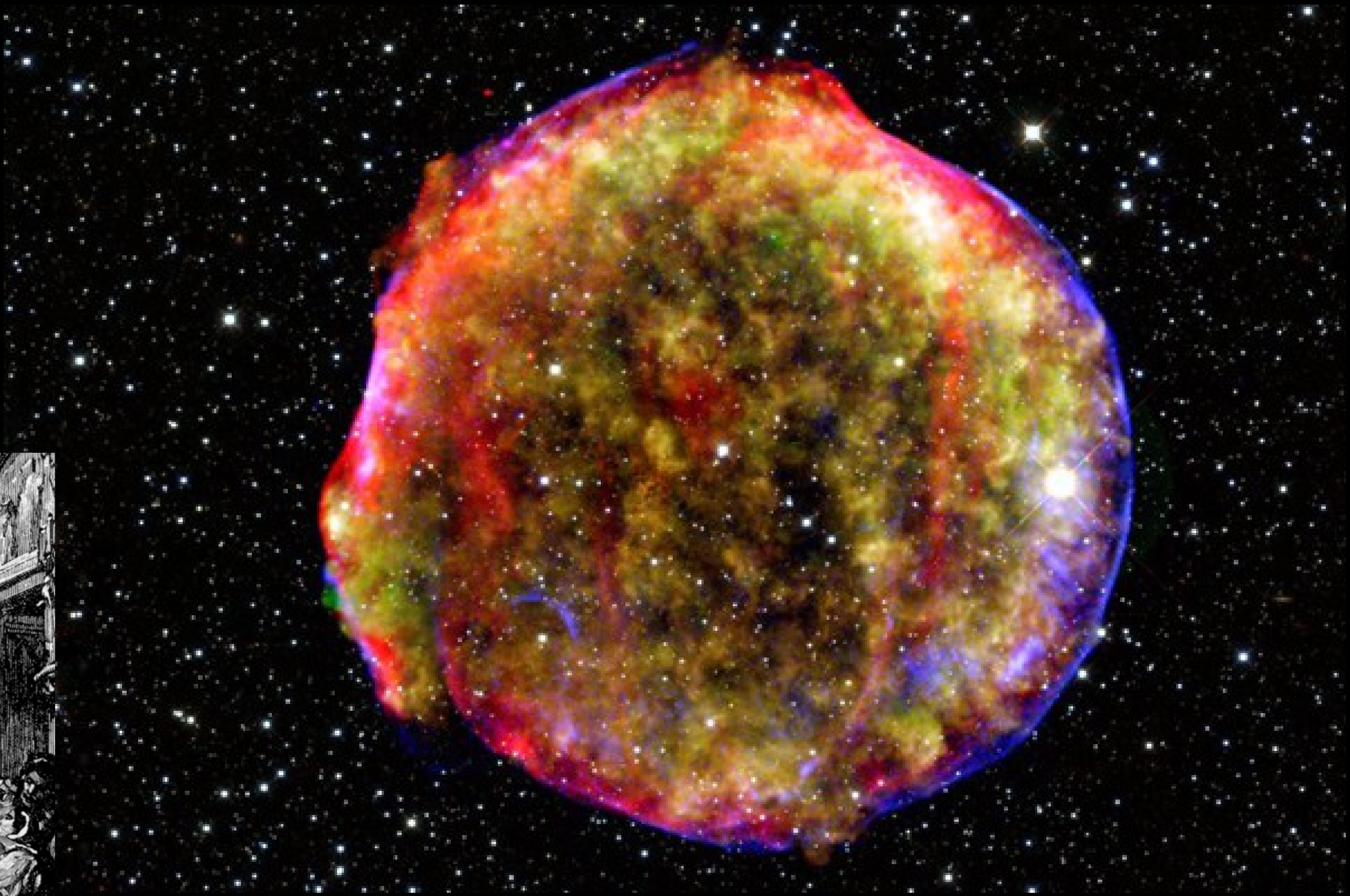
Crab Nebula:

Gaseous supernova remnant with neutron star, which radiates as pulsar



Source: http://www.spacetelescope.org/images/html/heic0515a.html;
Credit: NASA, ESA and Allison Loll/Jeff Hester (Arizona State University).
Acknowledgement: Davide De Martin (www.skyfactory.org)

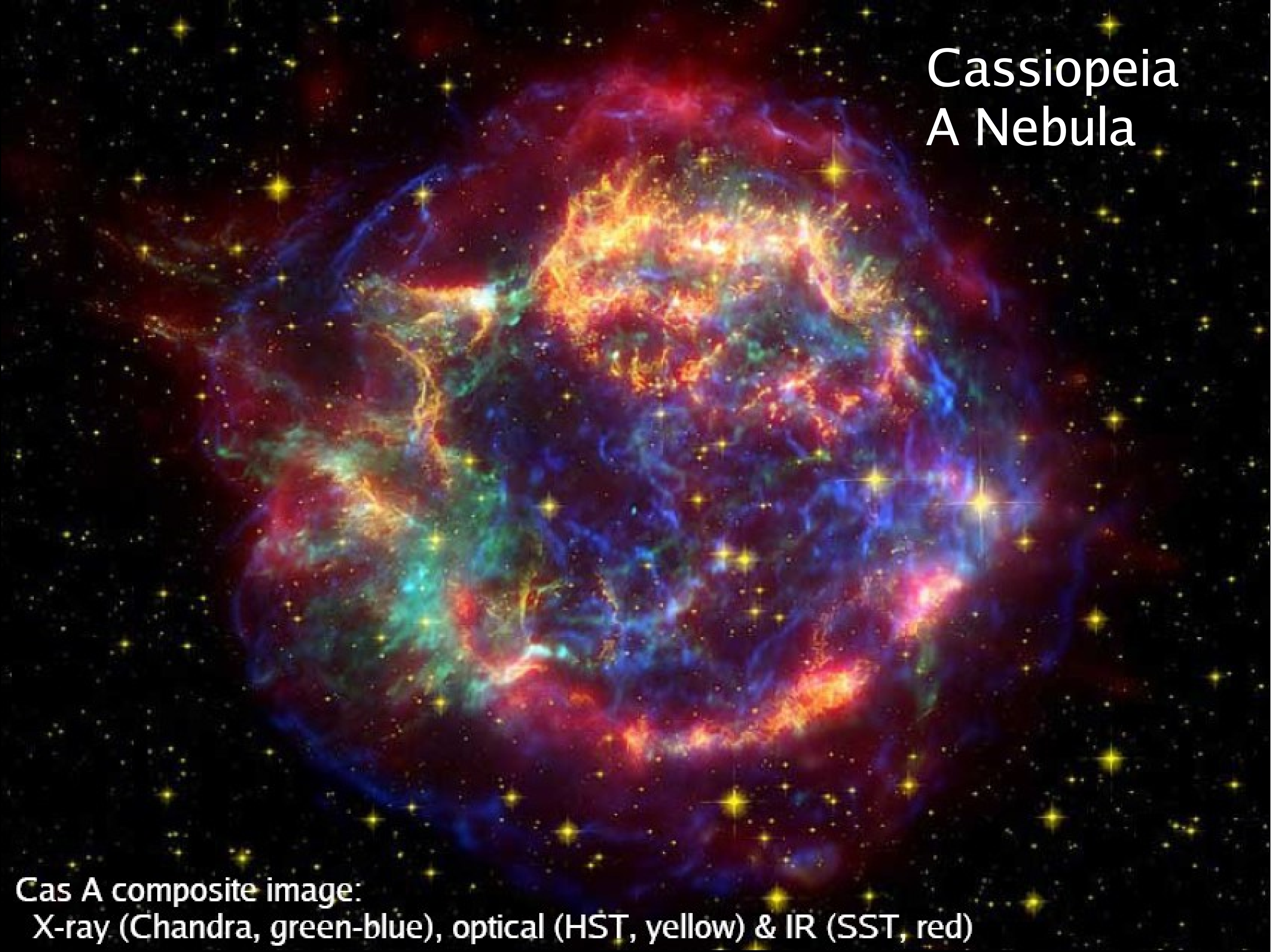
Tycho SNR



(CHANDRA satellite image)

1572: Tycho Brahe
observes "new star" that
remains visible for months

Cassiopeia A Nebula



Cas A composite image:
X-ray (Chandra, green-blue), optical (HST, yellow) & IR (SST, red)

Supernovae in the Universe

- 1–10 supernovae explode in the Universe every second
- ~2 per 100 years in the Milky Way (historical records of ~10 past events, several with visible remnants)
- Several 100 distant supernovae observed every year in surveys

- Energy release in radiation: 10^{49} erg
  Release of kinetic energy of ejected gas: 10^{51} erg
  (1 erg = 10^{-7} J; 10^{51} erg = 1 bethe)

- Hypernovae and gamma-ray bursts (GRBs) can release up to 100 times more energy, but occur only in < 1% of all core collapses!

Historically Reported Supernovae in the Milly Way Within the Past 1000 Years

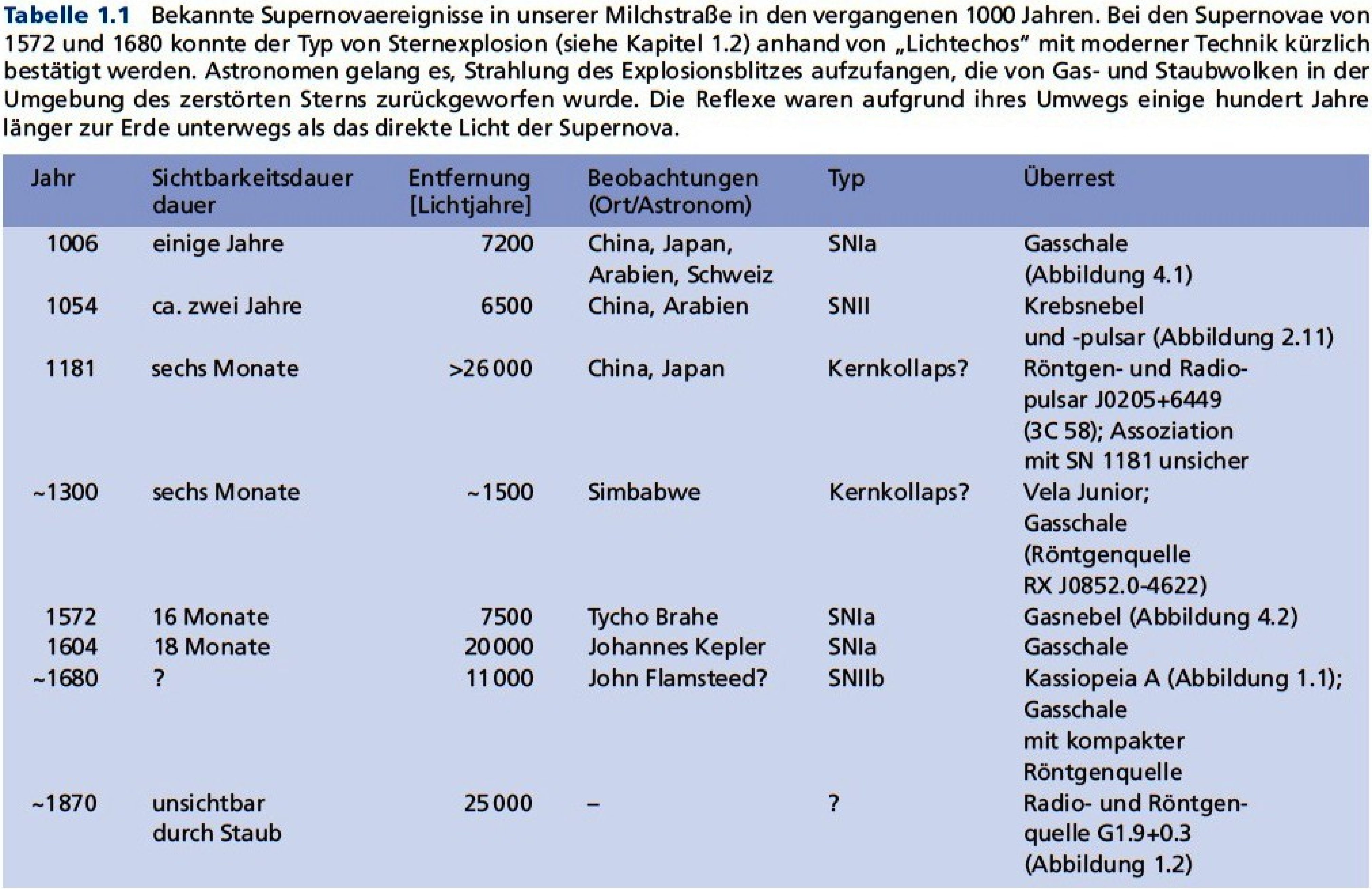


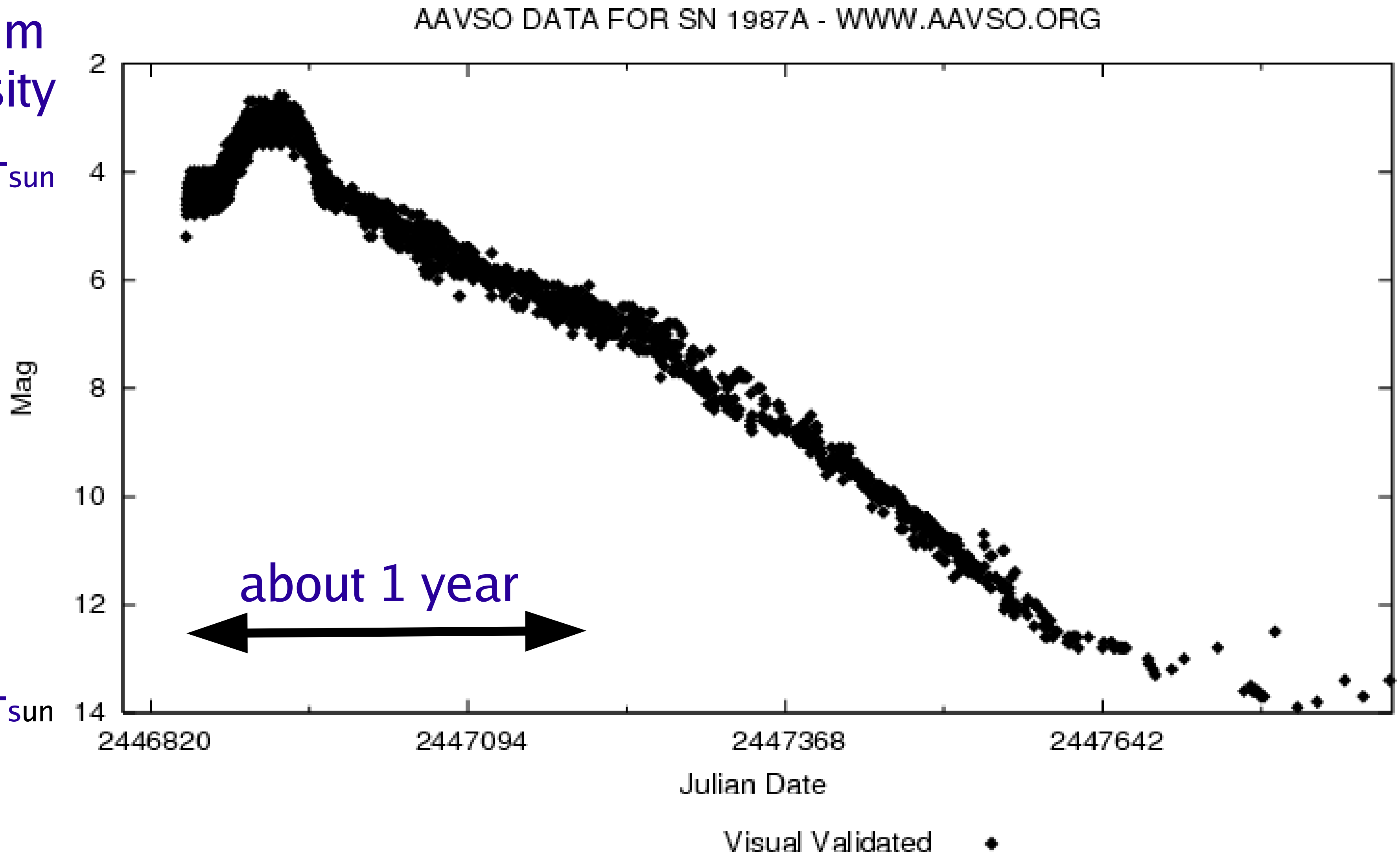
Tabelle 1.1 Bekannte Supernovaereignisse in unserer Milchstraße in den vergangenen 1000 Jahren. Bei den Supernovae von 1572 und 1680 konnte der Typ von Sternexplosion (siehe Kapitel 1.2) anhand von „Lichtechos" mit moderner Technik kürzlich bestätigt werden. Astronomen gelang es, Strahlung des Explosionsblitzes aufzufangen, die von Gas- und Staubwolken in der Umgebung des zerstörten Sterns zurückgeworfen wurde. Die Reflexe waren aufgrund ihres Umwegs einige hundert Jahre länger zur Erde unterwegs als das direkte Licht der Supernova.

Jahr	Sichtbarkeitsdauer dauer	Entfernung [Lichtjahre]	Beobachtungen (Ort/Astronom)	Typ	Überrest
1006	einige Jahre	7200	China, Japan, Arabien, Schweiz	SNIa	Gasschale (Abbildung 4.1)
1054	ca. zwei Jahre	6500	China, Arabien	SNII	Krebsnebel und -pulsar (Abbildung 2.11)
1181	sechs Monate	>26 000	China, Japan	Kernkollaps?	Röntgen- und Radiopulsar J0205+6449 (3C 58); Assoziation mit SN 1181 unsicher
~1300	sechs Monate	~1500	Simbabwe	Kernkollaps?	Vela Junior; Gasschale (Röntgenquelle RX J0852.0-4622)
1572	16 Monate	7500	Tycho Brahe	SNIa	Gasnebel (Abbildung 4.2)
1604	18 Monate	20 000	Johannes Kepler	SNIa	Gasschale
~1680	?	11 000	John Flamsteed?	SNIIb	Kassiopeia A (Abbildung 1.1); Gasschale mit kompakter Röntgenquelle
~1870	unsichtbar durch Staub	25 000	–	?	Radio- und Röntgenquelle G1.9+0.3 (Abbildung 1.2)

Sanduleak –69 202

Supernova 1987A 23. Februar 1987

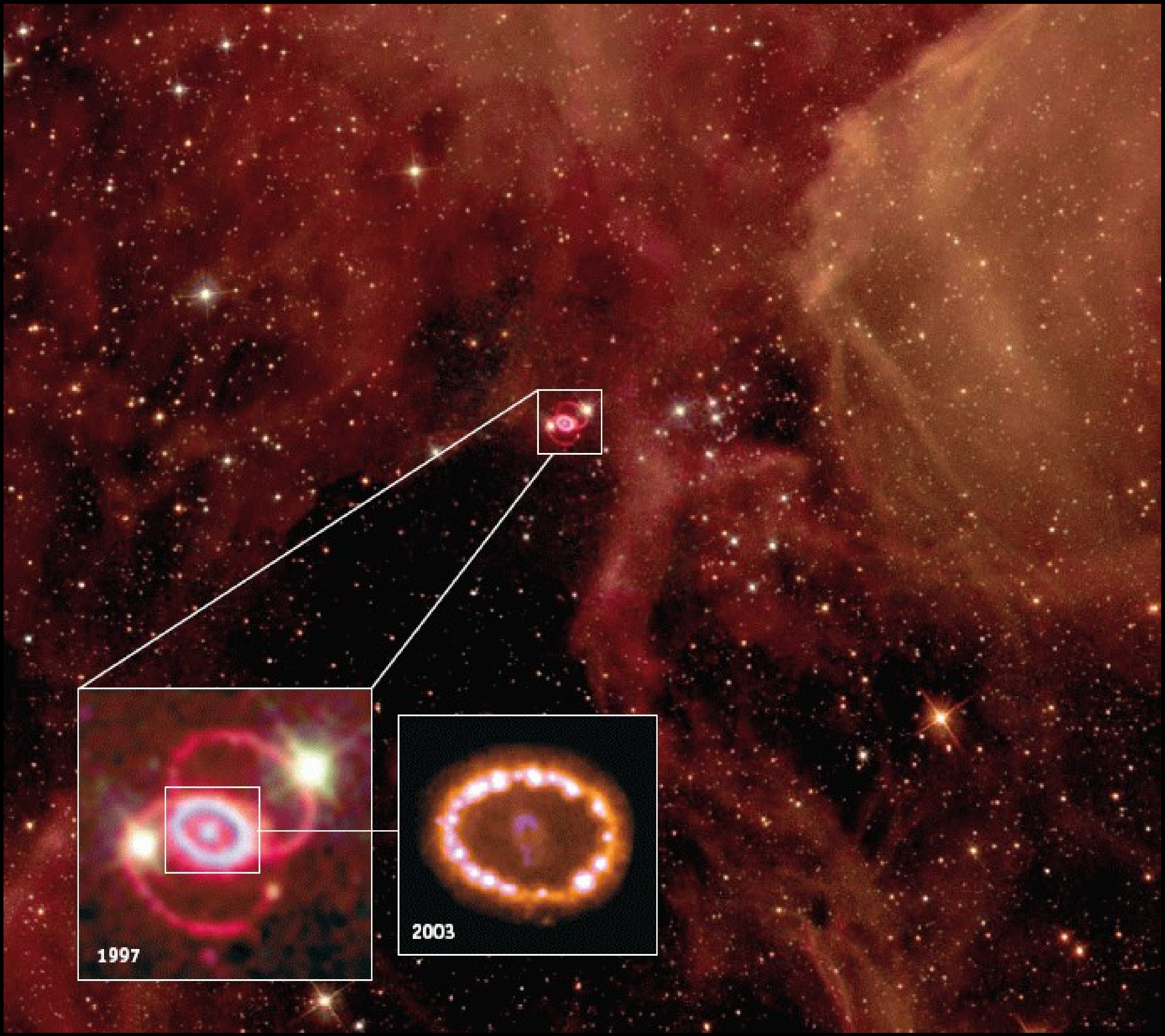
Supernova 1987A: Light Curve



Maximum Luminosity $\sim 2*10^8\ L_{sun}$

about 1 year

$\sim 10^4\ L_{sun}$

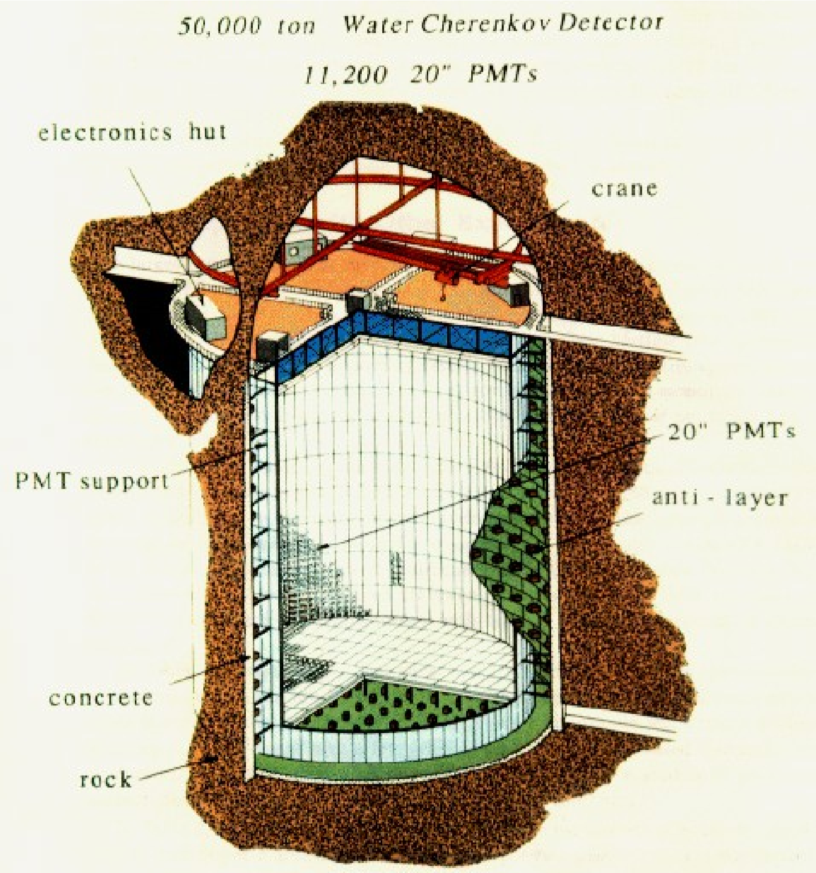


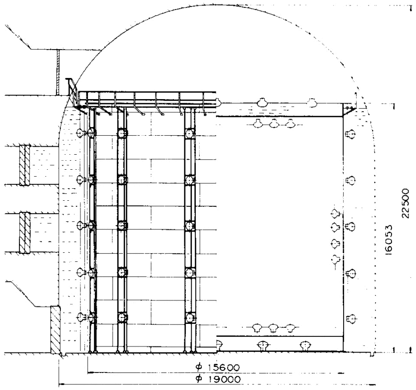
Supernova
1987A
as a
teenager

Supernova 1987A

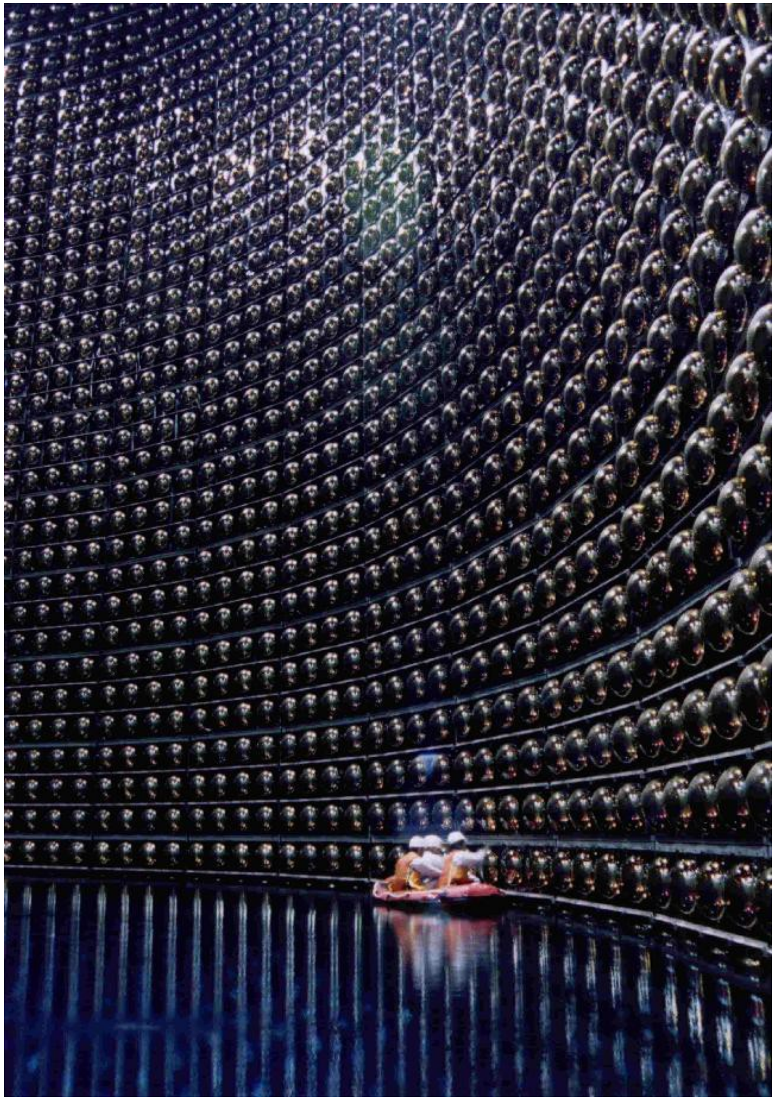
- Birthday: Februar 23rd, 1987
- Birth place: Large Magellanic Cloud
- Distance: about 170,000 lightyears
- Origin: blue supergiant star with about 20 solar masses
- Importance:
    - * only nearby supernova in the past 400 years that was visible to the naked eye
    - * unprecidented wealth of observational data
    - * first measurement of extragalactic neutrinos
    - * confirmation of neutron star birth theory
    - * unambiguous information about strongly turbulent processes during stellar explosions

Supernova 1987A

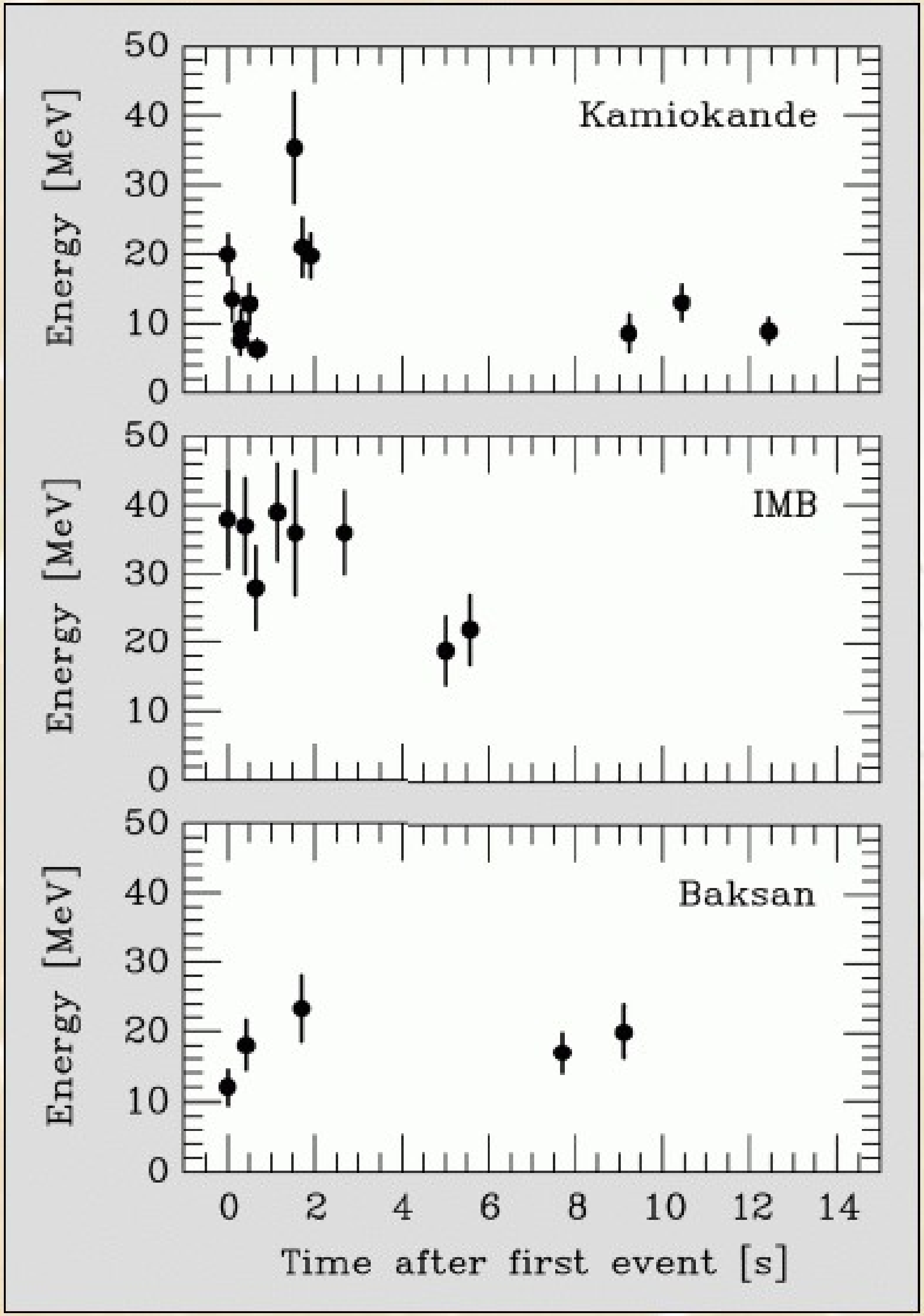




Two dozen (of 10^{58}) neutrinos were captured in underground laboratories!



Neutrino Burst of Supernova 1987A



Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ±50 ms

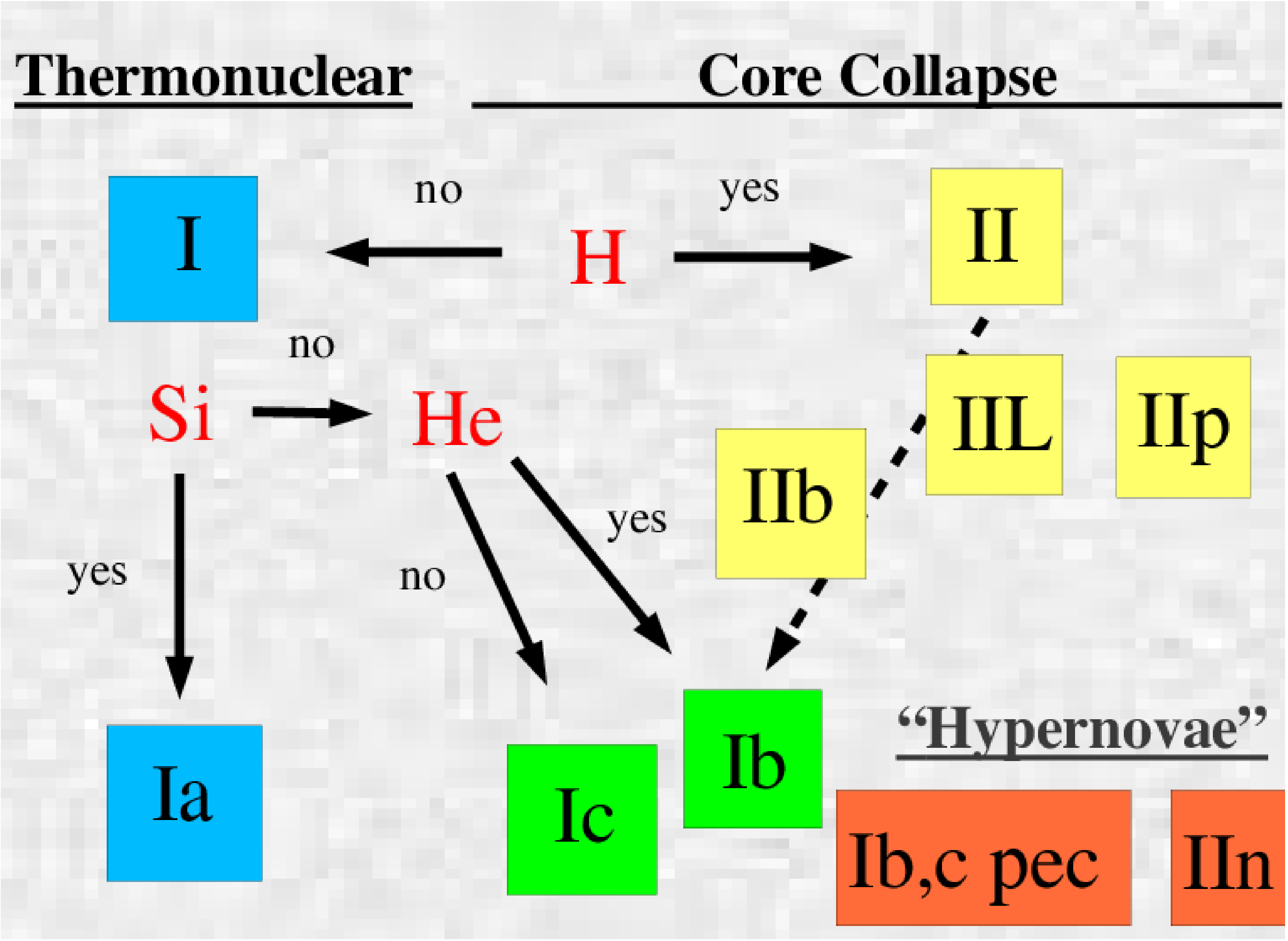
Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster ~ 0.7/day
Clock uncertainty +2/-54 s

Within clock uncertainties,
signals are contemporaneous

Supernova Classification Scheme

Thermonuclear	Core Collapse
Energy source: thermonuclear burning C, O ---> Si, Ni	Energy source: gravitational binding energy of compact remnant (NS, BH)

Supernova Classification Scheme



Thermonuclear

Core Collapse

I

no

H

yes

II

no

Si

He

IIL

IIp

IIb

yes

yes

no

Ia

Ic

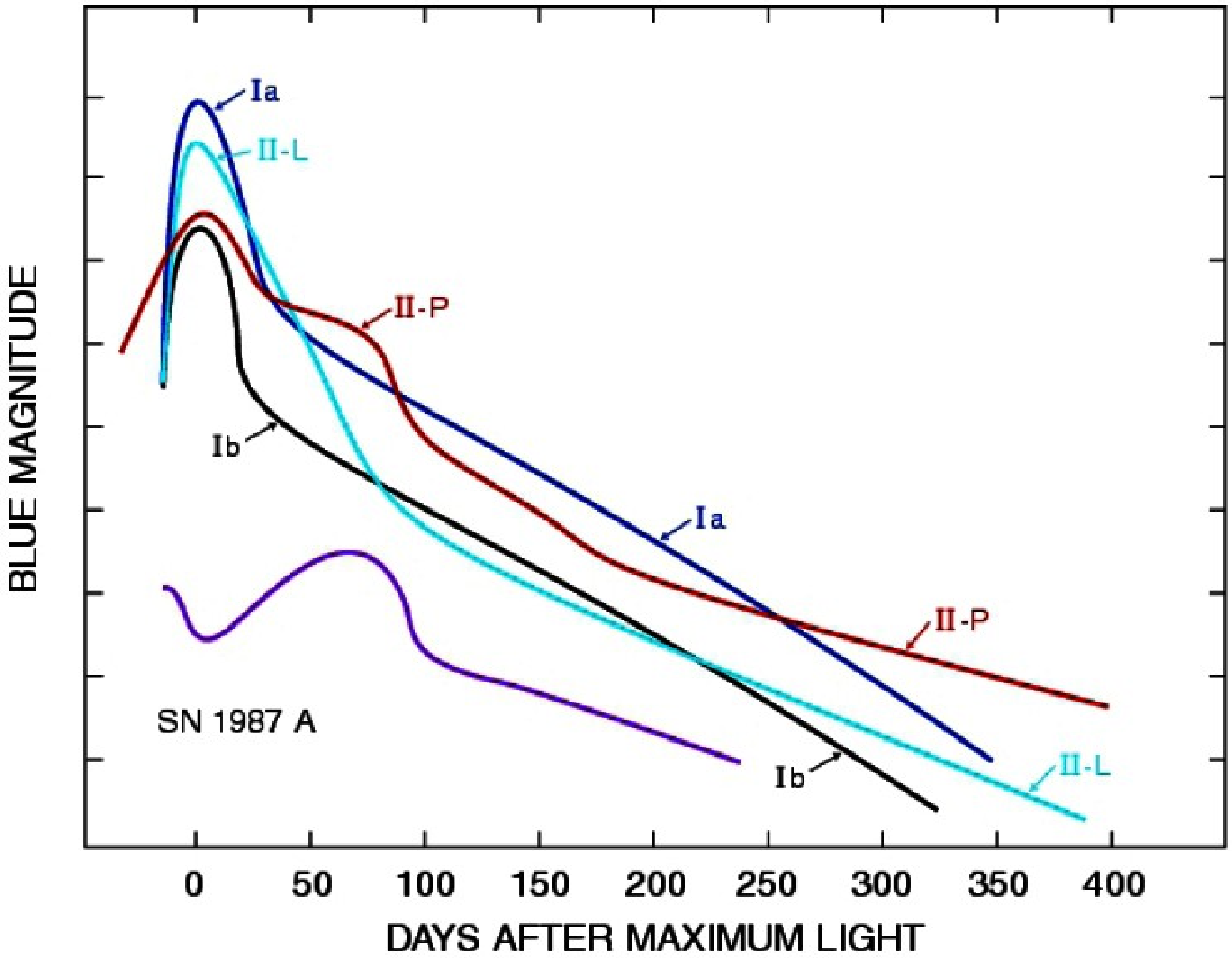
Ib

"Hypernovae"

Ib,c pec

IIn

Supernova Light Curves



Supernova light curves

pronounced maximum
after 2-3 weeks

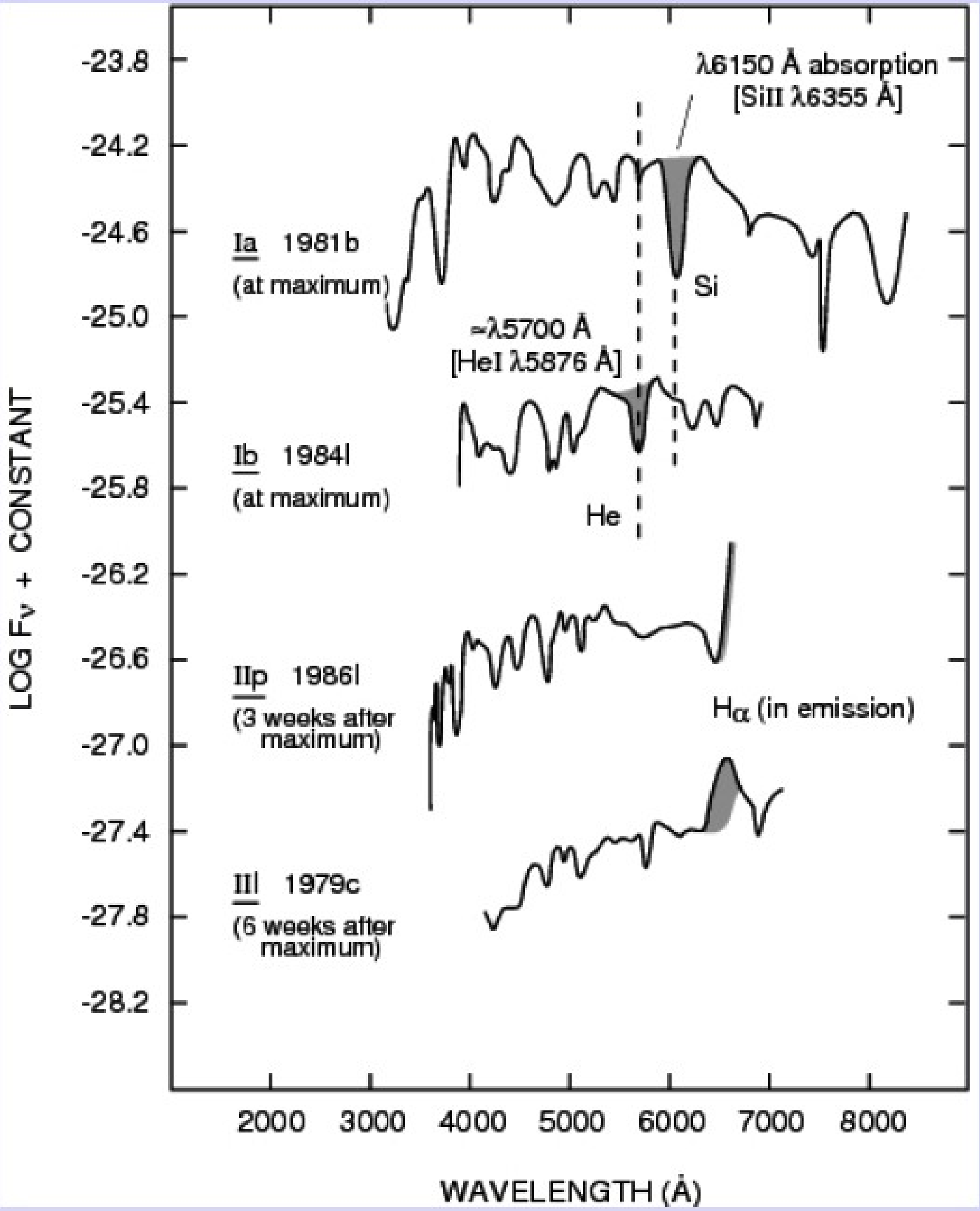
exponential tail
(radioactive decay of
^{56}Ni → ^{56}Co → ^{56}Fe)

maximum brightness
largest for SNe Ia

only SNe Ia form a (quite) homogeneous class
→ standard candles!?

→ possibility to measure expansion of universe

Supernova Spectra



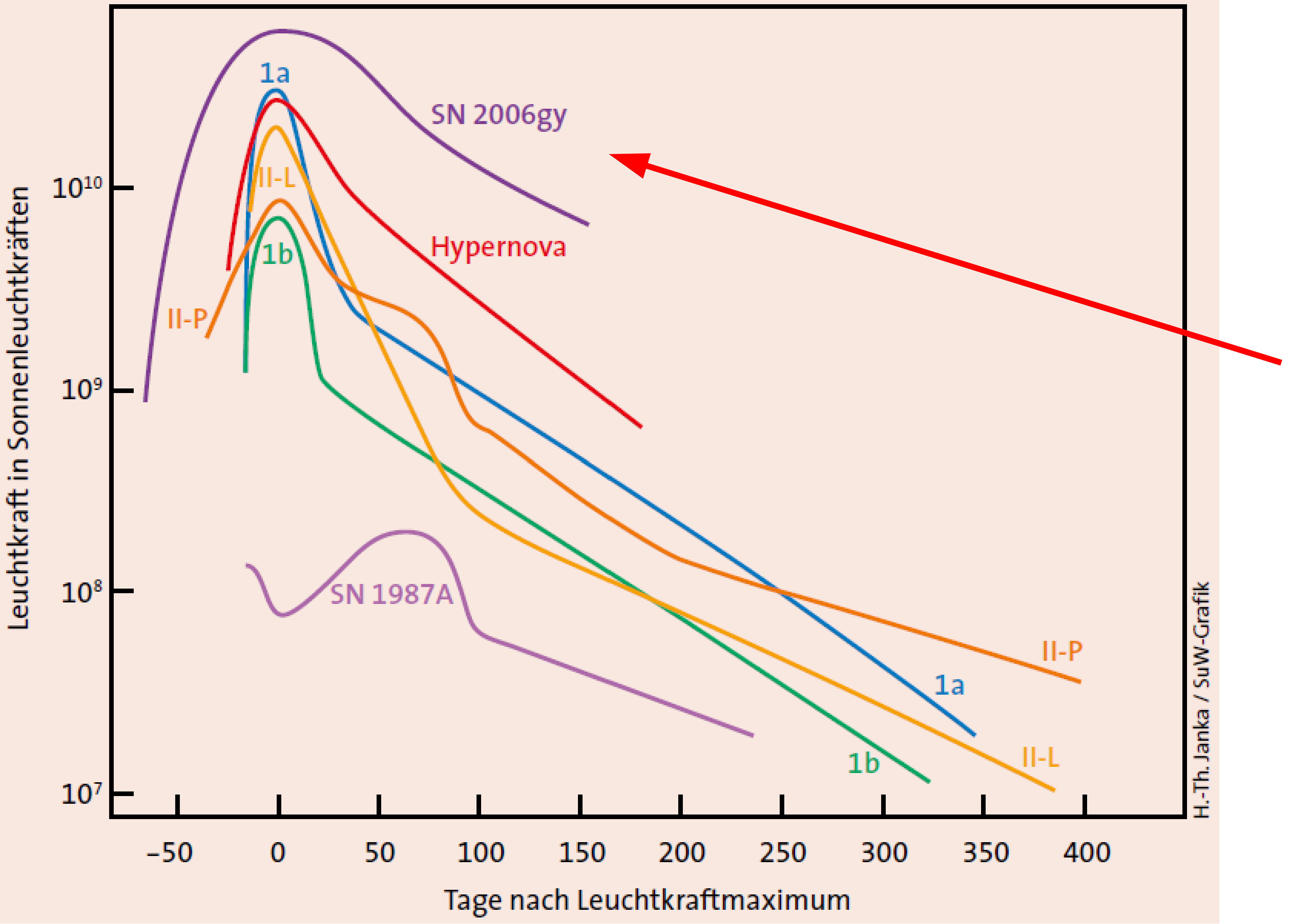
Supernova spectra

discriminate types
(no spectrum → no type!!)

provide information about

- stellar & explosive nucleosynthesis
- abundances and chemical stratification (tomography)
- stellar environment & progenitor star

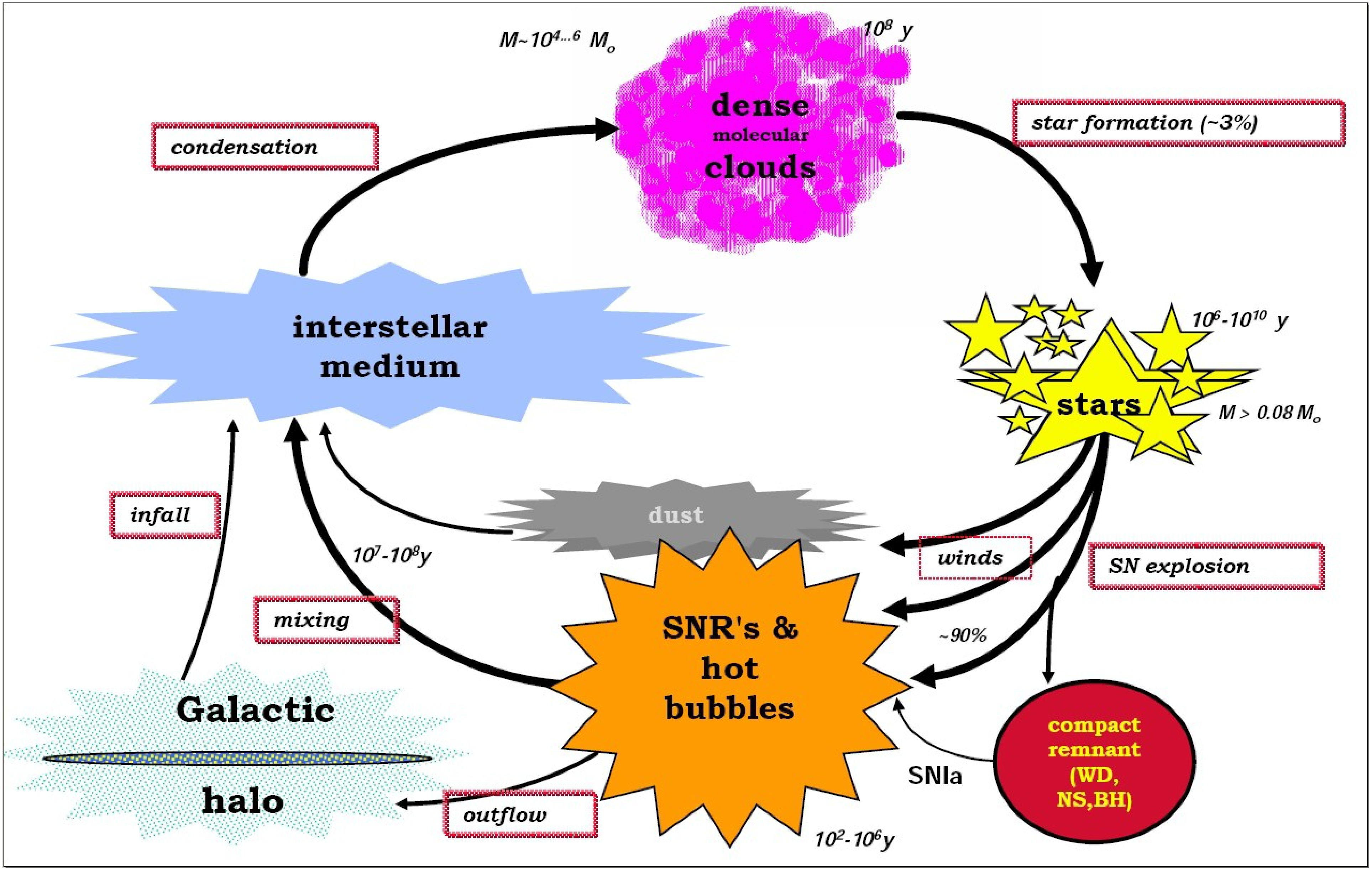
Superluminal Supernovae



Role of Supernovae

- strongest cosmic explosions
- sources of heavy elements
- driving force of cosmic cycle of matter
- sources of neutrinos and gravitational waves: fundamental physics
- acceleration of cosmic radiation
- birth sites of neutrons stars and black holes
-
-
-

SNe in the Cosmic Cycle of Matter



Supernova Types: Basic Differences

Thermonuclear Supernovae (Type Ia):	Core-Collapse Supernovae (Type II, Ib, Ic):
Low-mass stars (< 8–10 M_{sun})	Massive stars (> 8–10 M_{sun})
Highly evolved (old white dwarfs)	Extended envelopes (esp. Type II)
Binary systems	Single stars (binaries possible for Type Ib,c)
Thermonuclear burning C, O ---> Si, Ni	Nuclear burning by (shock) compression
Complete distruction of star	Compact remnants are left behind: neutron star or black hole

Fundamentals of Stellar Evolution

Stellar Evolution Equations

Assumed: spherical symmetry, Newtonian gravity, single star

Mass conservation:

$$\boxed{\frac{\partial M(r)}{\partial r} = 4\pi r^2 \rho(r) \qquad (1)}$$

with ρ being the mass density, $M(r)$ the enclosed mass,

and $M(R_*) = M_*$.

Hydrostatic equilibrium:

$$\boxed{\rho \frac{\mathrm{d}^2 r}{\mathrm{d}t^2} = -\frac{\partial P(r)}{\partial r} - \frac{GM(r)\rho(r)}{r^2} = 0 \qquad (2)}$$

with $P = P_{\rm gas} + P_\gamma \; (+P_\nu + P_B + P_{\rm turb} + P_{\rm deg} + ...)$ and $P(R_*) = 0$.

In general: $P = P(\rho, T, \text{composition})$.

Energy equation:

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{e}{\rho}\right) - P\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{1}{\rho}\right) = T\frac{\mathrm{d}s}{\mathrm{d}t} = \dot{\varepsilon} - \frac{1}{4\pi r^2\rho}\,\frac{\partial L_\gamma}{\partial r}\ ,$$

or

$$\frac{\partial}{\partial r}L_\gamma(r) = 4\pi r^2\rho(r)\left(\dot{\varepsilon} - T\,\frac{\mathrm{d}s}{\mathrm{d}t}\right) \qquad (3)$$

with e being the internal energy density, L_γ the "luminosity", $\dot{\varepsilon} = \dot{\varepsilon}_{\mathrm{nuc}} - \dot{\varepsilon}_\nu - \dot{\varepsilon}_{\mathrm{x}}$, and $\dot{\varepsilon}_{\mathrm{grav}} \equiv -T(\mathrm{d}s/\mathrm{d}t)$ ("gravothermal energy source term" associated with expansion or contraction of mass).

Total energy conservation:

Integrate Eq. (3) over volume, using Eq. (2), to obtain for change of internal, gravitational, and nuclear energy:

$$\frac{\mathrm{d}}{\mathrm{d}t}(E_{\mathrm{i}} + E_{\mathrm{grav}} + E_{\mathrm{nuc}}) = -(L_\gamma + L_\nu) \qquad (3a)$$

Energy transport:

- by radiative transfer
- by convection
- by heat conduction (irrelevant in ordinary stars)

Consider radiative transfer by diffusion for $\lambda_{\rm mfp} \ll h_P = |{\rm d}r/{\rm d}\ln P|$ (pressure scale height).

Fick's law:

$$F_\gamma = \frac{L_\gamma}{4\pi r^2} = -D\nabla e_\gamma = -\frac{1}{3}c\lambda_{\rm mfp}\frac{\partial e_\gamma}{\partial r} \ ,$$

with $e_\gamma = a_\gamma T^4$, $\lambda_{\rm mfp} = (\kappa\rho)^{-1}$ (κ: "opacity") follows

$$\boxed{\frac{\partial T}{\partial r} = -\frac{3\kappa\rho(r)L_\gamma(r)}{16\pi a_\gamma c r^2 T^3} \qquad (4)}$$

Virial theorem:

Perform integration $\int_0^{R_*} \mathrm{d}r\, 4\pi r^3 [Eq.\ (2)]$, using ideal gas EoS,

$$P = (\Gamma - 1)e \quad \text{with} \quad \Gamma \equiv \left(\frac{\partial \ln P}{\partial \ln \rho}\right)_s ,$$

to obtain relation between internal and gravitational energy for star in mechanical equilibrium:

$$\boxed{E_{\mathrm{grav}} = -3(\Gamma - 1)E_{\mathrm{i}} \ . \qquad (5)}$$

With total energy $E_{\mathrm{tot}} = E_{\mathrm{i}} + E_{\mathrm{grav}}$ one gets for $\Gamma \neq \frac{4}{3}$:

$$\boxed{E_{\mathrm{i}} = -\frac{E_{\mathrm{tot}}}{3\Gamma - 4} \ . \qquad (5a)}$$

Normal stars have $\Gamma = \frac{5}{3}$. When such stars lose energy, $\mathrm{d}E_{\mathrm{tot}}/\mathrm{d}t = -L$, they become hotter ("negative specific heat")!

Basic Principles of Stellar Evolution

Radiating and evolving stars become hotter
(have “negative specific heat”)

Scaling relations:

From stellar structure equations one obtains by linearization (use $M(r) = 0$, $L_\gamma(r) = 0$ for $r = 0$, $P(R_*) = 0$, and $P = \overline{P}$, $\rho = \bar{\rho}$):

$$\frac{P}{M} \sim \frac{M}{R^4}\,, \qquad \frac{R}{M} \sim \frac{1}{R^2\rho}\,, \qquad \frac{T}{M} \sim \frac{L}{R^4T^3}$$

$$\frac{L}{M} \sim \varepsilon_{\mathrm{nuc}} \sim \rho^\lambda T^\nu$$

and in particular, with the use of $P \propto \rho T/\mu$ (μ: mean molecular weight):

$$\boxed{\frac{T^3}{\rho} \propto M^2\,, \qquad L \propto \mu^4 M^3\,, \qquad \tau_{\mathrm{nuc}} \sim \frac{M}{L} \propto M^{-2}}$$

with τ_{nuc} being the nuclear burning timescale.

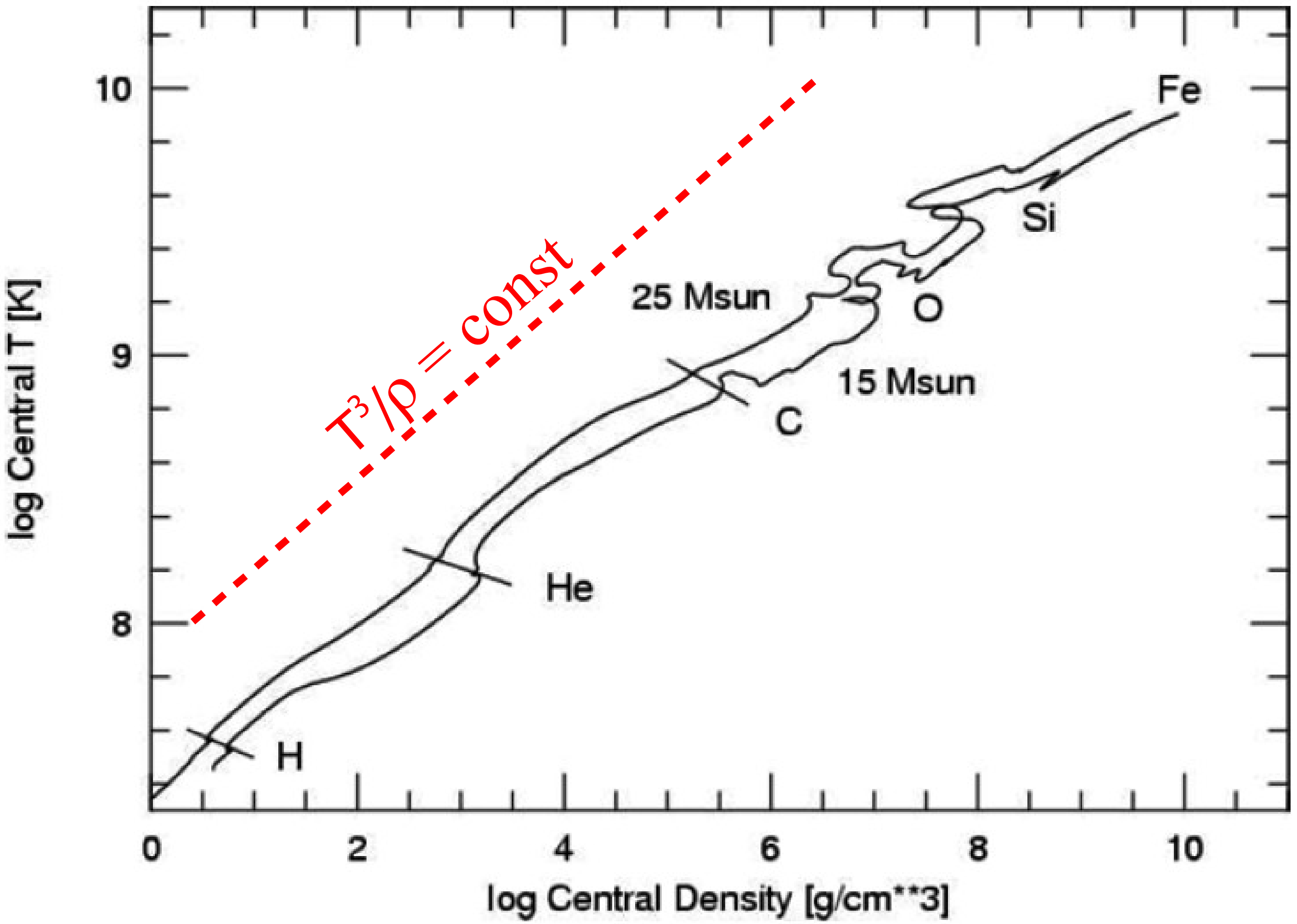
- More massive stars evolve faster and live shorter!

Basic Principles of Stellar Evolution

$$T^3/\rho \sim M^2$$

* As star contracts and its density grows, T increases like $\rho^{1/3}$
* For given density, stars with larger mass M are hotter

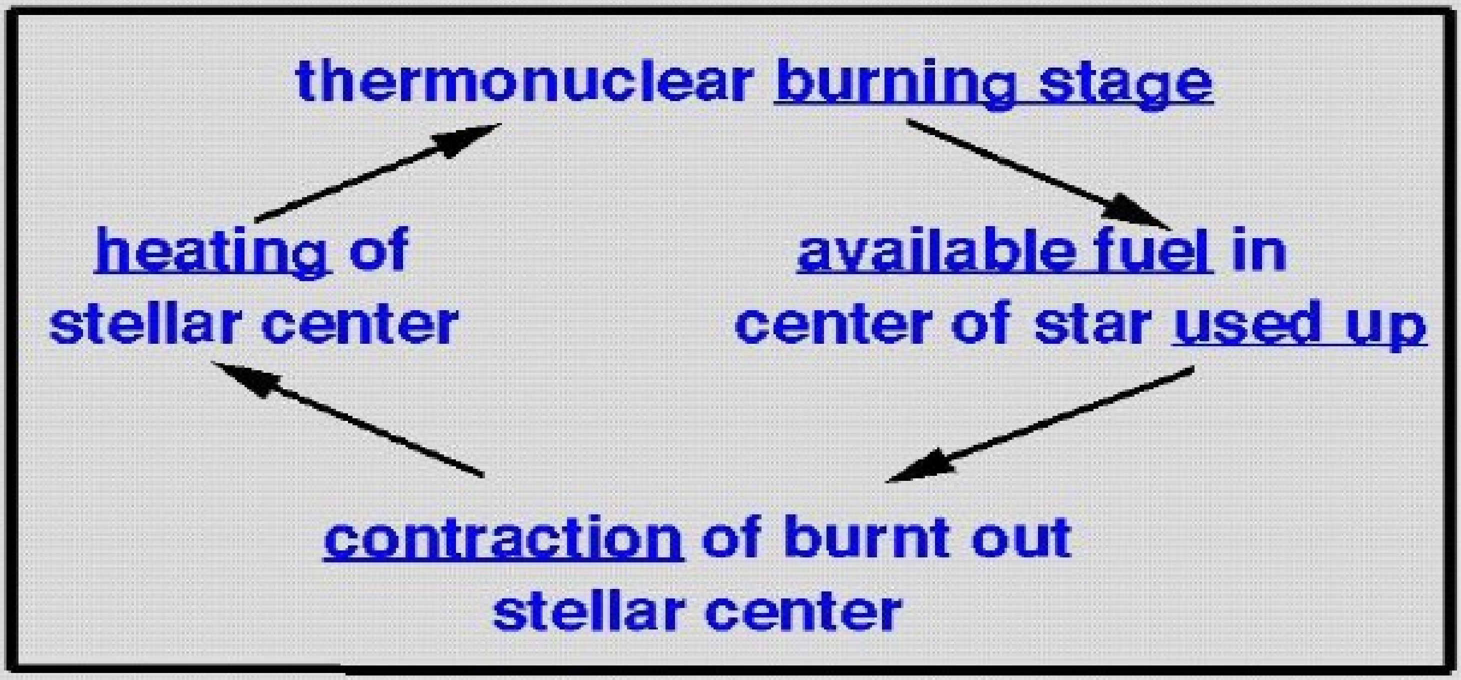
Evolution Tracks of Massive Stars



- Central density increases roughly like 3rd power of central temperature

Evolution towards gravitational collapse

- depending on stellar mass:
  number of thermonuclear burning stages



thermonuclear burning stage

available fuel in center of star used up

contraction of burnt out stellar center

heating of stellar center

- every burning stage: central burning + shell burning

- stars with $M > 8 - 10\ M_{Sun}$ experience all physically possible burning stages

Stellar Burning Stages

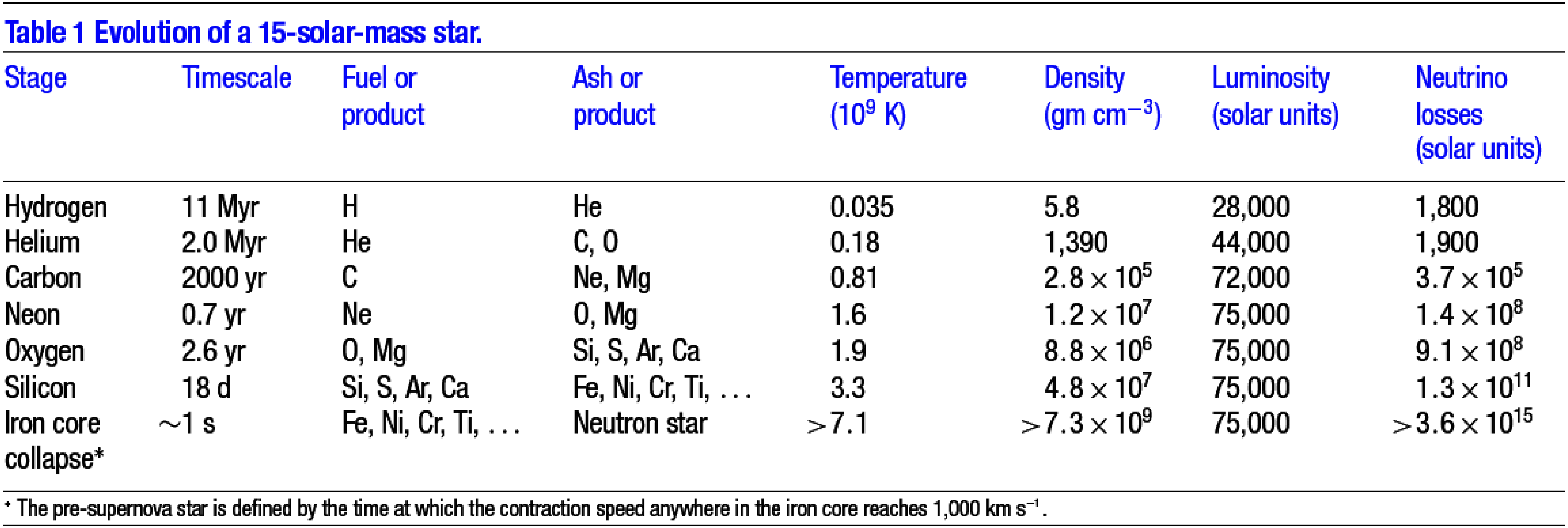


Table 1 Evolution of a 15-solar-mass star.

Stage	Timescale	Fuel or product	Ash or product	Temperature (10^9 K)	Density (gm cm^{-3})	Luminosity (solar units)	Neutrino losses (solar units)
Hydrogen	11 Myr	H	He	0.035	5.8	28,000	1,800
Helium	2.0 Myr	He	C, O	0.18	1,390	44,000	1,900
Carbon	2000 yr	C	Ne, Mg	0.81	2.8×10^5	72,000	3.7×10^5
Neon	0.7 yr	Ne	O, Mg	1.6	1.2×10^7	75,000	1.4×10^8
Oxygen	2.6 yr	O, Mg	Si, S, Ar, Ca	1.9	8.8×10^6	75,000	9.1×10^8
Silicon	18 d	Si, S, Ar, Ca	Fe, Ni, Cr, Ti, . . .	3.3	4.8×10^7	75,000	1.3×10^{11}
Iron core collapse*	$\sim$1 s	Fe, Ni, Cr, Ti, . . .	Neutron star	>7.1	$>7.3 \times 10^9$	75,000	$>3.6 \times 10^{15}$

* The pre-supernova star is defined by the time at which the contraction speed anywhere in the iron core reaches 1,000 km s^{-1}.

(Woosley & Janka, Nature Physics 1. 2005)

Basic Principles of Stellar Evolution

$$\tau_{nuc} \sim M^{-2}$$

More massive stars evolve faster and live shorter

Stellar Equations of State

Grenzfall	Zustandsgleichung	ND	D
NR	$P = \frac{2}{3}\varepsilon$	$P = nk_BT$	$P \sim (Y_F\rho)^{5/3}$
ER	$P = \frac{1}{3}\varepsilon$	$P = nk_BT$ (Jüttner 1915)	$P \sim (Y_F\rho)^{4/3}$

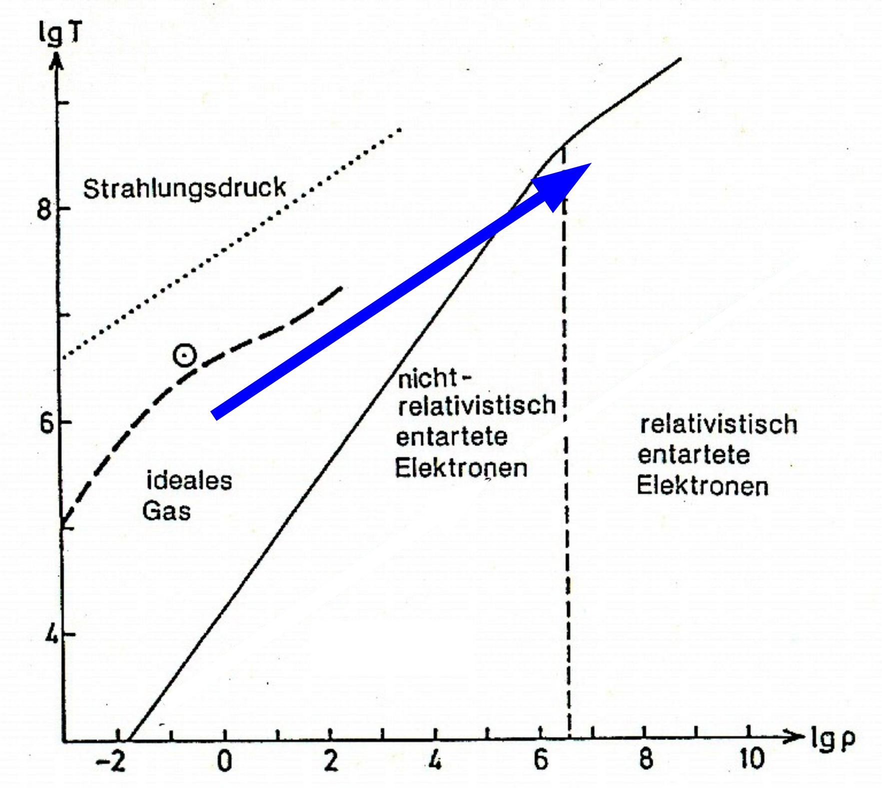
Onset of degeneracy:

$\varepsilon_{\text{Fermi}} / kT > 1$

- NR gas: $\varepsilon_{\text{Fermi}}/T \sim \rho^{2/3}/T$
- ER gas: $\varepsilon_{\text{Fermi}}/T \sim \rho^{1/3}/T$

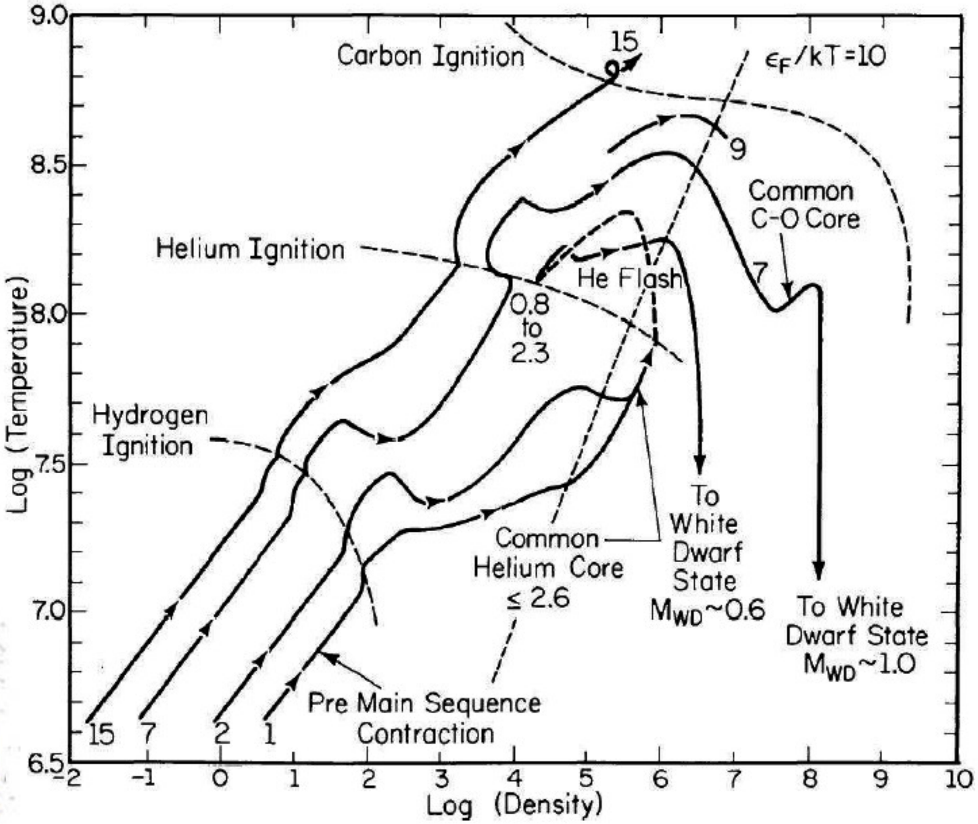
$$P = P_{\text{gas}} + P_{\text{deg}} + P_{\text{photons}}$$

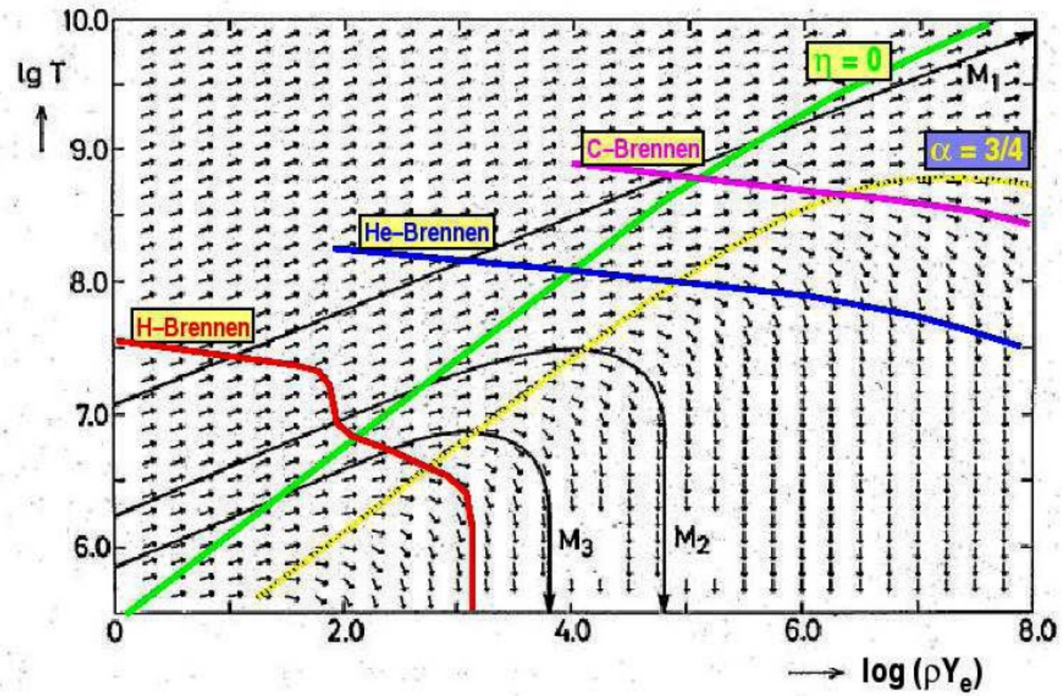
- Stellar gas is in different regimes of equation of state properties as stars evolve
- Normal stars: gas behaves like classical Boltzmann gas (P_{gas})
- As temperature and density rises, the stellar gas can become degenerate and relativistic (P_{deg})



Stellar Evolution towards Degeneracy

- When stellar gas becomes degenerate: further contraction does not lead to strong heating
- Stars cool at nearly fixed density
- Maximum central density and burning stage depends on stellar mass





Stellar Evolution towards Degeneracy

Stars reach limiting burning stage and become degenerate:

$0.013\ M_{sun} < M < 0.08\ M_{sun}$: deuterium burning
$0.08\ M_{sun} < M < 0.5\ M_{sun}$: hydrogen burning
$0.5\ M_{sun} < M < 7\text{–}8\ M_{sun}$: hydrogen and helium burning

$M < 8\ M_{sun}$: final stage of evolution is a white dwarf

before they reach the central carbon burning

Chandrasekhar Mass Limit for WDs

$$M_{\mathrm{Ch}} = 1.457(2Y_{\mathrm{e}})^2 \mathrm{M}_{\odot}$$

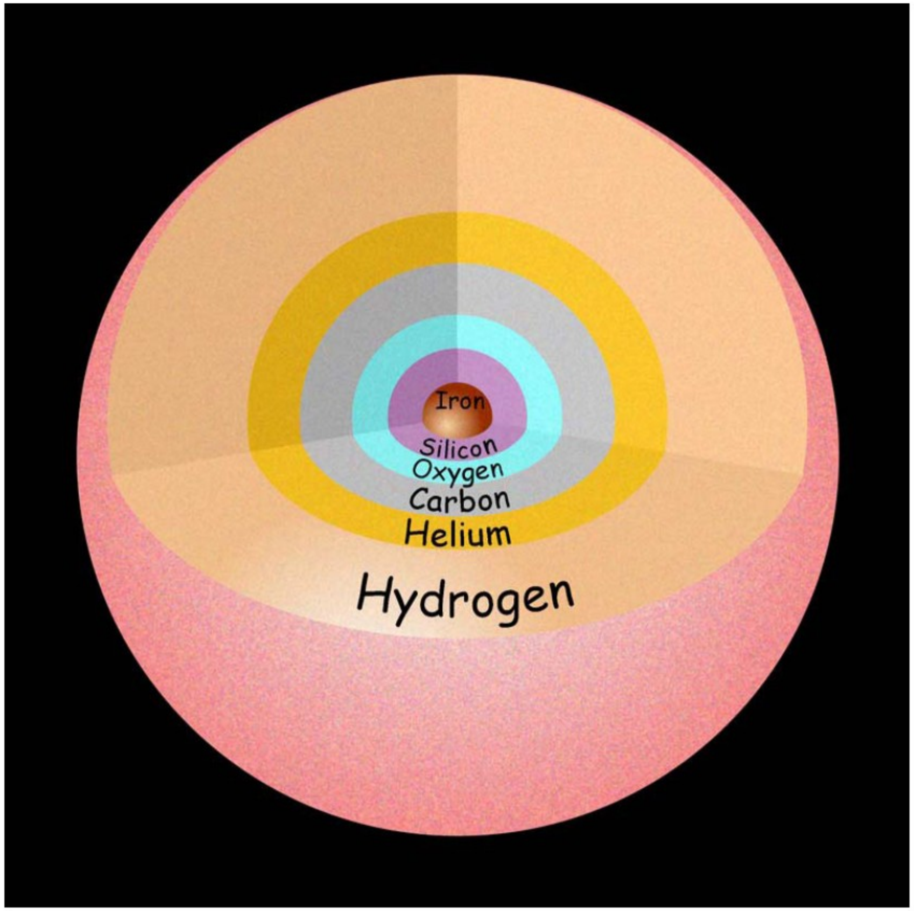
Chandrasekhar-Mass:

Maximum mass for a stable equilibrium of a cold star whose pressure is dominated by fully degenerate, ultrarelativistic fermions.
For $M > M_{\mathrm{Ch}}$ gravitational instability and collapse occurs.

Final Stages of Stellar Evolution

- $M > 8\ M_{sun}$: stars develop onion shell structure before they undergo gravitational collapse
- $M > 10\ M_{sun}$: iron cores formed
- $M = 8–25\ M_{sun}$: **neutron star** and supernova explosion
- $M > 25\ M_{sun}$: **black hole** and (sometimes) hypernova explosion

Onion-shell structure



Final Stages of Stellar Evolution

- Stars with $M_* > 8\ M_{sun}$: approach gravitational instability:
  Hydrostatic (mechanical) equilibrium breaks down

  -----------> collapse of stellar core to neutron star or black hole

- Mechanical equilibrium impossible when adiabatic index of EoS

$$\boxed{\Gamma_{EoS} = (\partial \ln P/\partial \ln \rho)_s < \Gamma_{crit} = 4/3 + \delta_{GR} - \delta_{rot} + \delta_{\nu loss}}$$

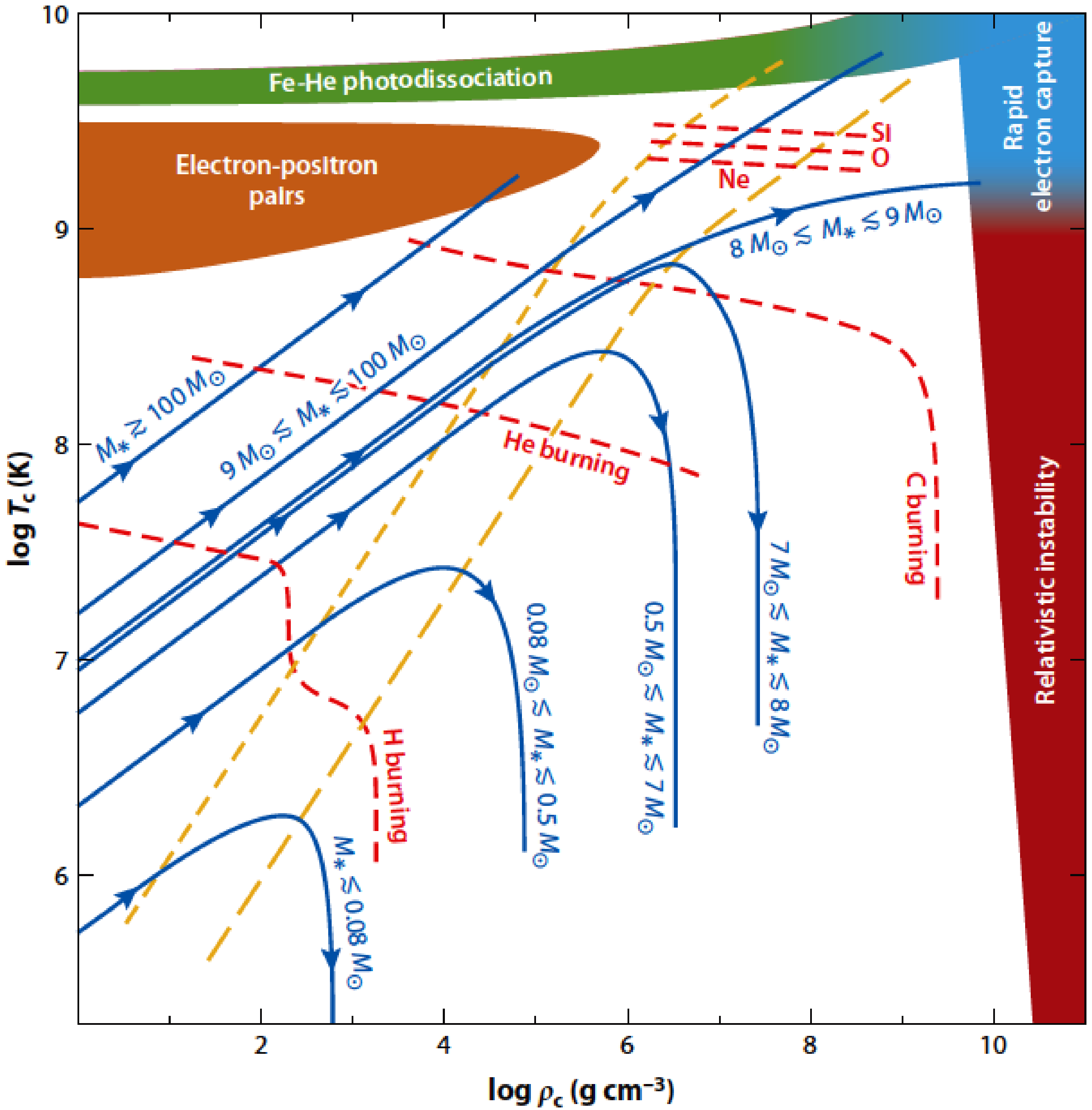
(Reason: for $\Gamma_{EoS} = (4/3 + \varepsilon)$ with $\varepsilon < 0$ stabilizing pressure gradient increases less steeply with density than destabilizing gravitational force: $P/R \propto \rho^{5/3+\varepsilon}$; $GM/R^2 \propto \rho^{5/3}$)

Final Stages of Massive Star Evolution

Stars with ~8–9 M_{sun} develop degenerate ONeMg cores
—> collapse by
rapid e-capture

Stars with ~9–100 M_{sun} develop Fe cores
—> collapse by nuclear
photodisintegration

Stars with > 100 M_{sun} approach gravitational instability before O-burning
—> collapse by
e^+e^- pair fomation



(Janka, ARNPS 62. 2012)

Final Stages of Massive Star Evolution

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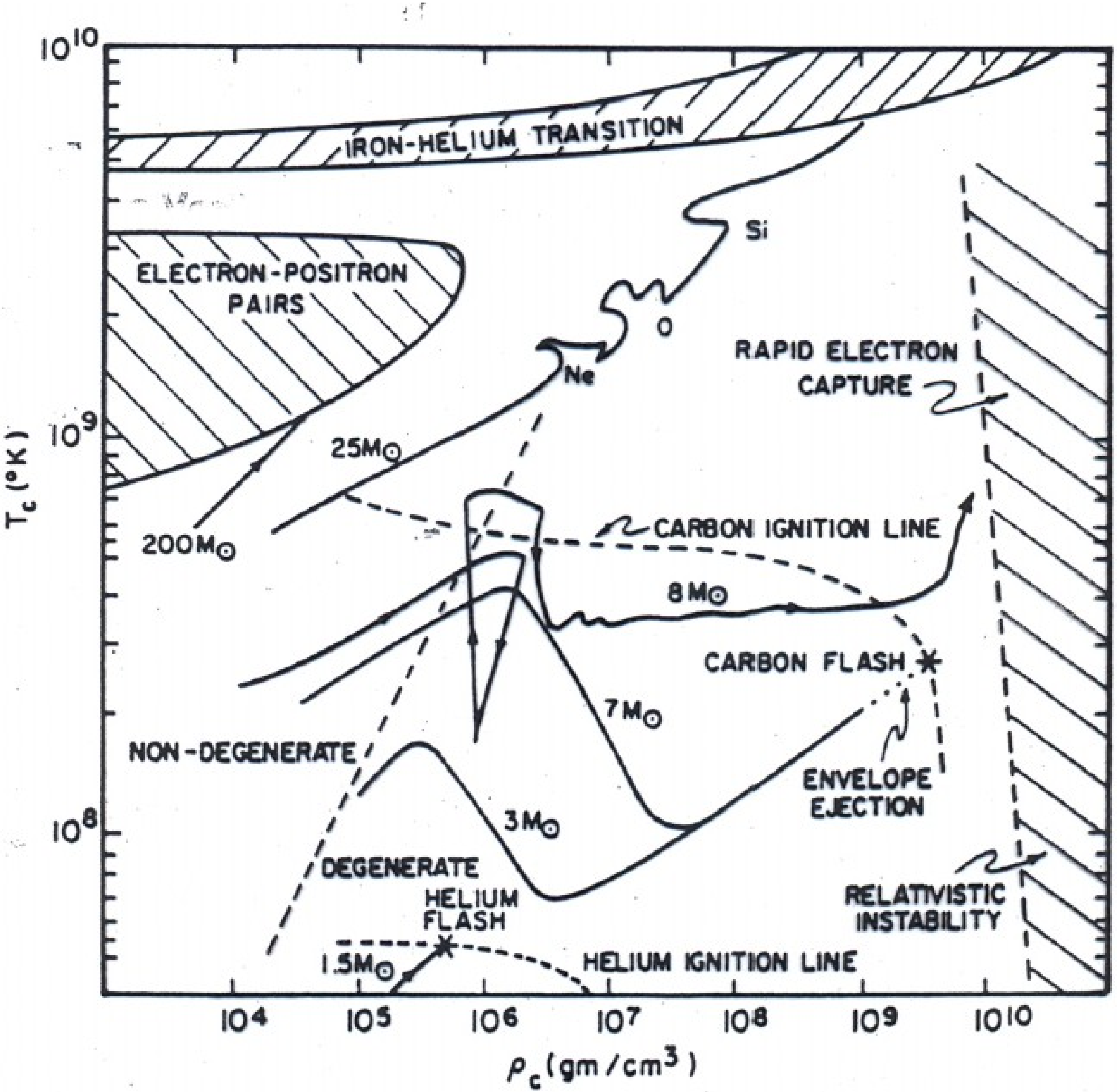
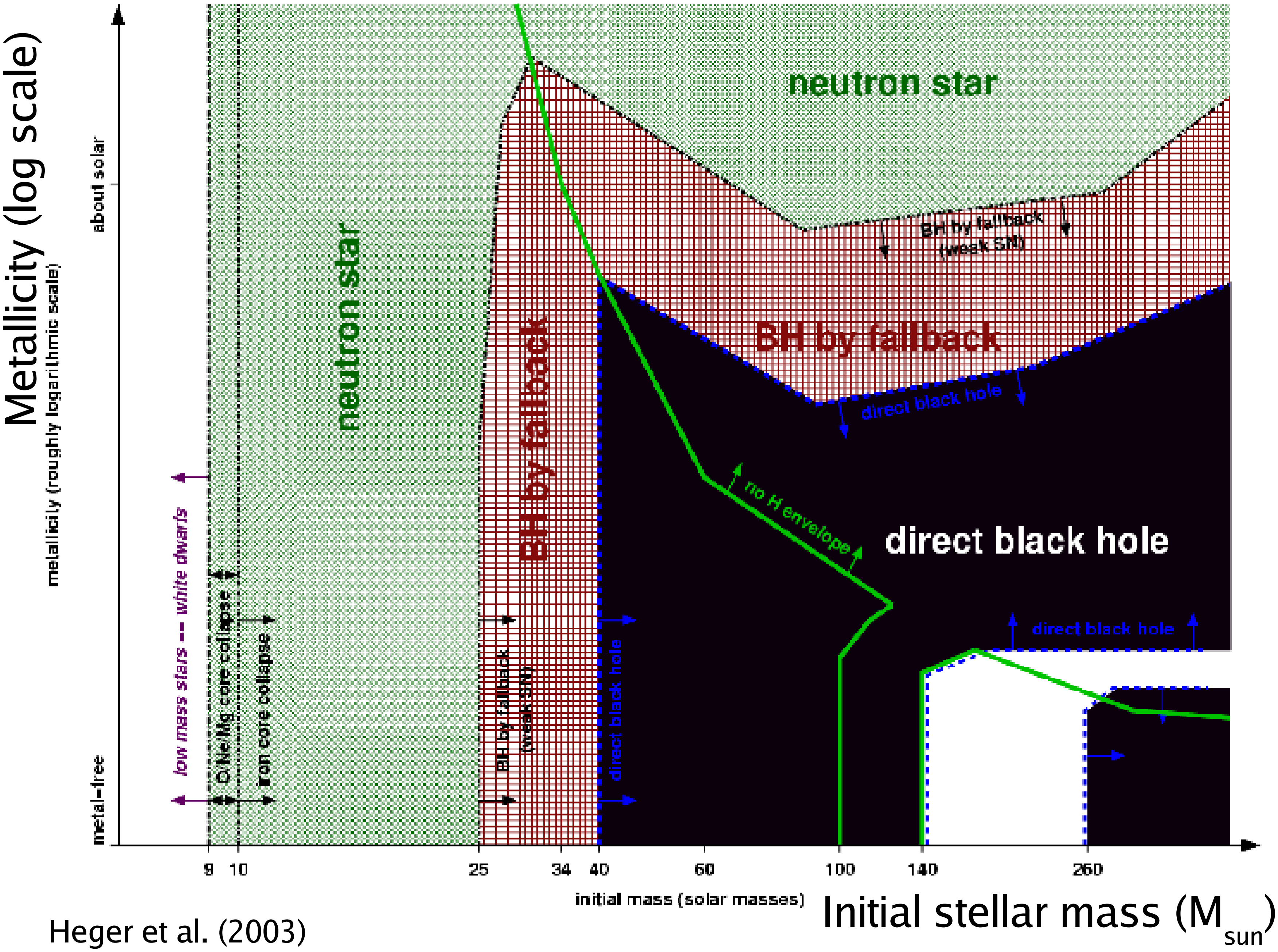


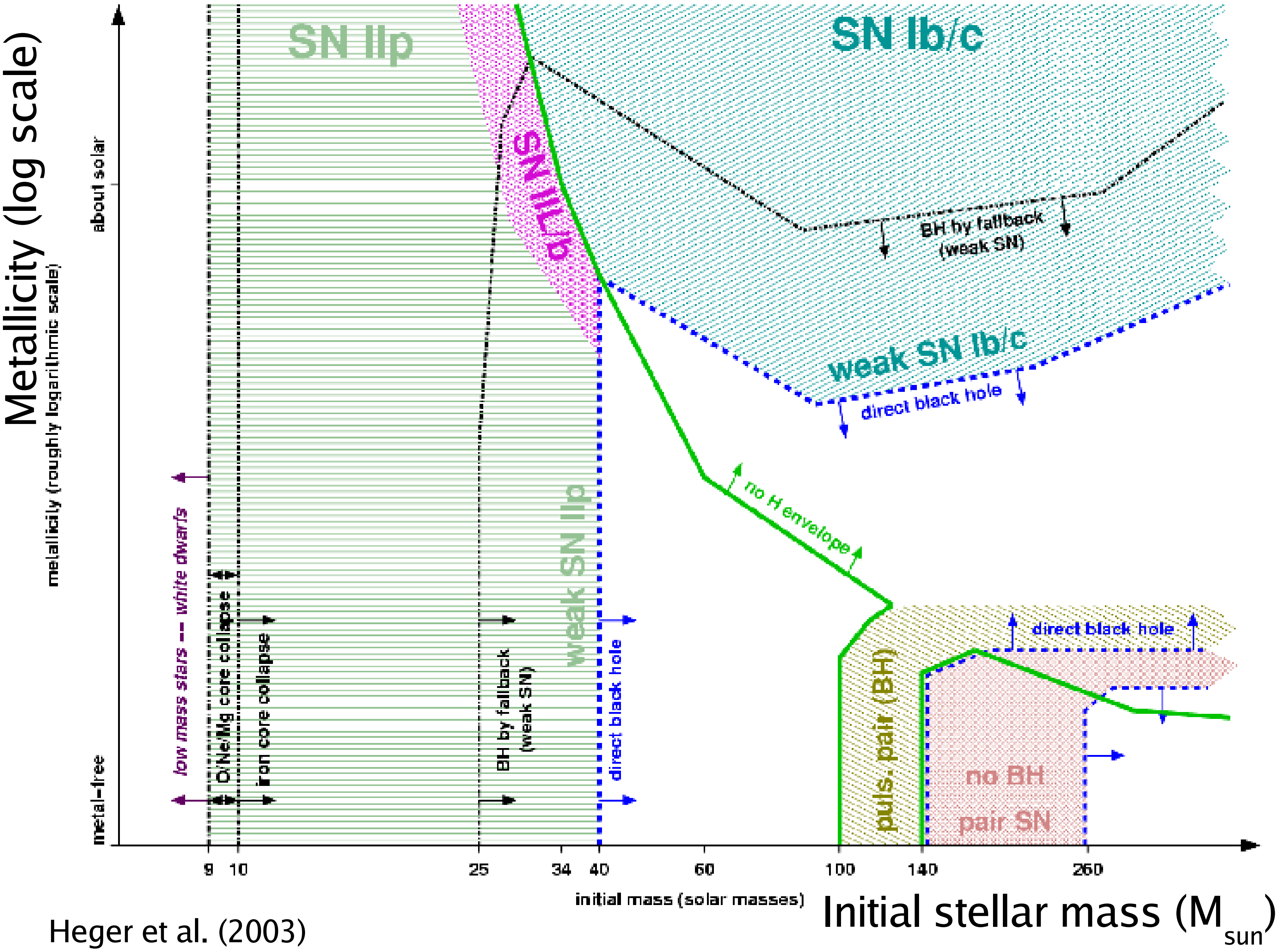
(Wheeler et al. 1990)

Core Collapse Events and Remnants



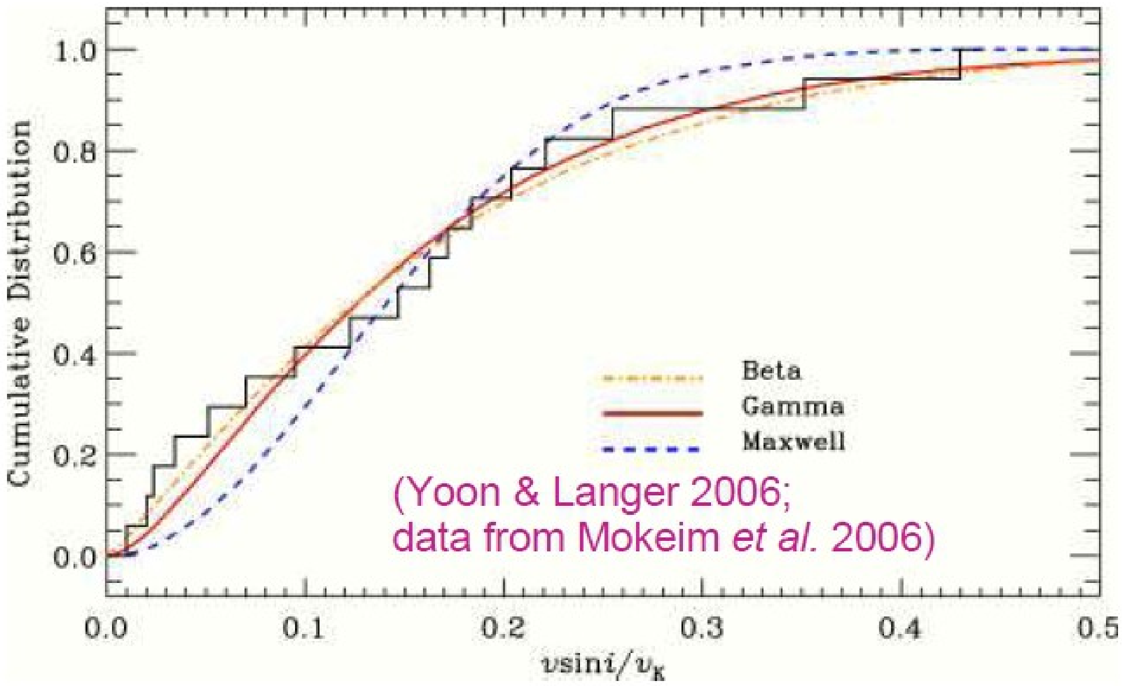
Heger et al. (2003)

Core Collapse Events and Remnants



Heger et al. (2003)

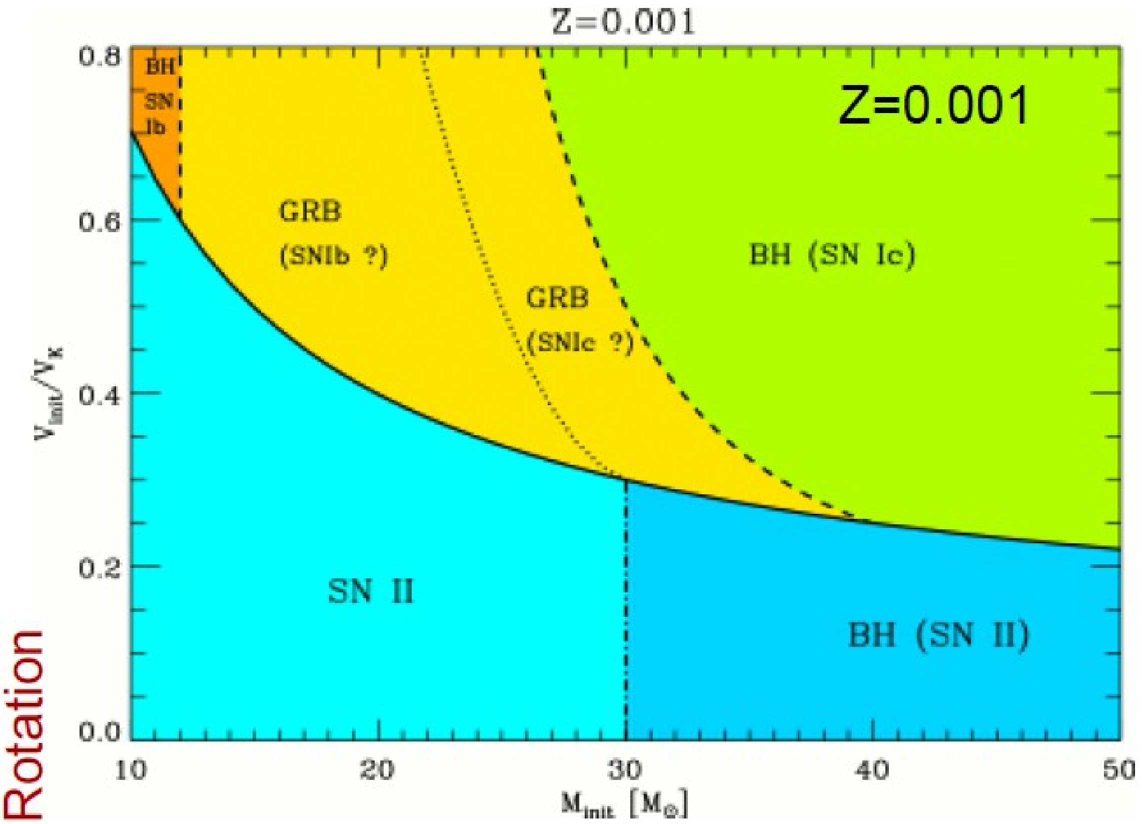
Black Holes and GRBs from Rotating Stars



(Yoon & Langer 2006;
data from Mokeim *et al.* 2006)

A small fraction of single stars is born rotating rapidly

The fastest rotators evolve chemically homogeneously, become WR stars on the MS, and may lose less angular momentum.

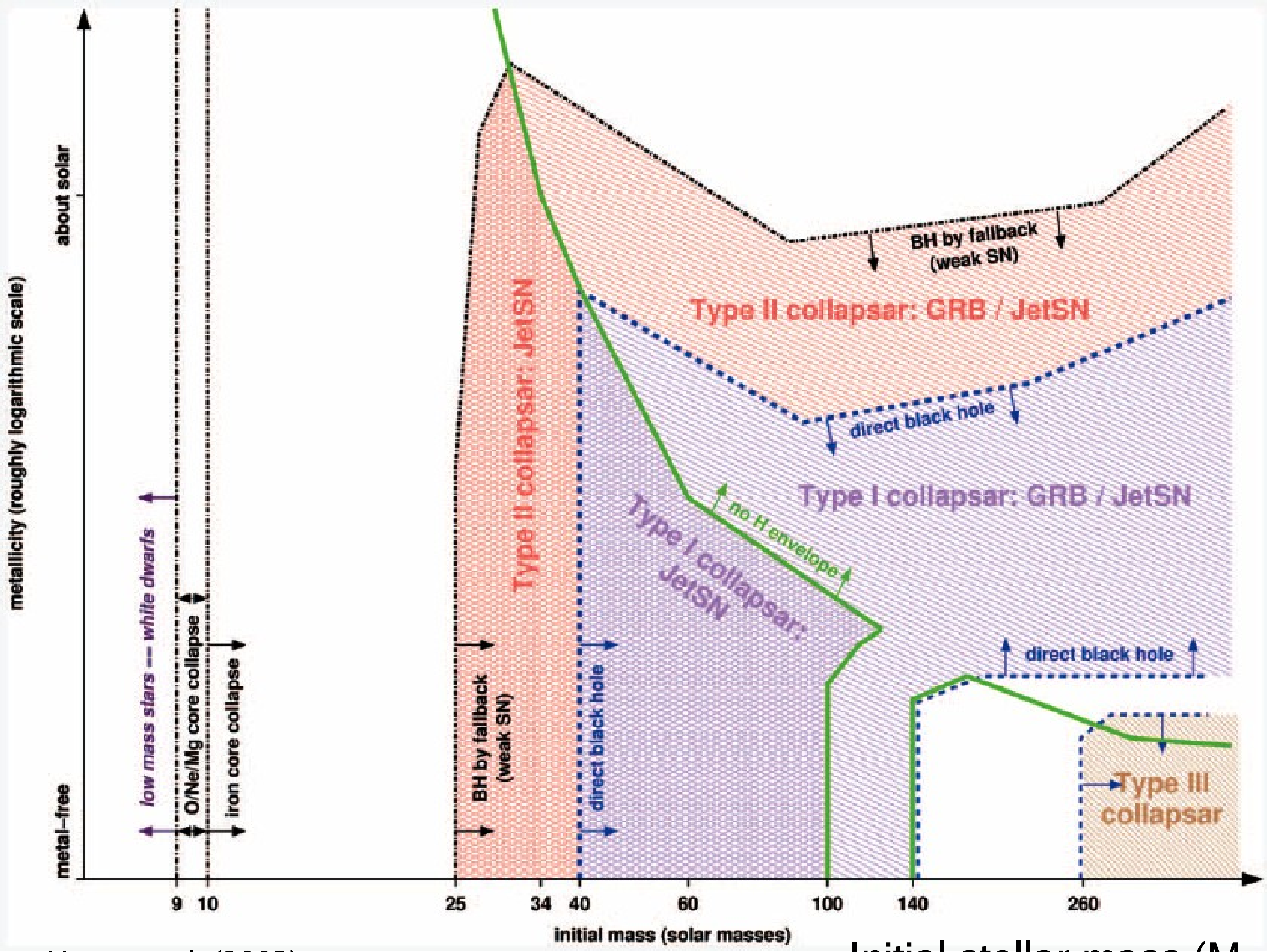


(Yoon & Langer 2006)

Rotation

A. Heger (2011)

Core Collapse Events and Remnants



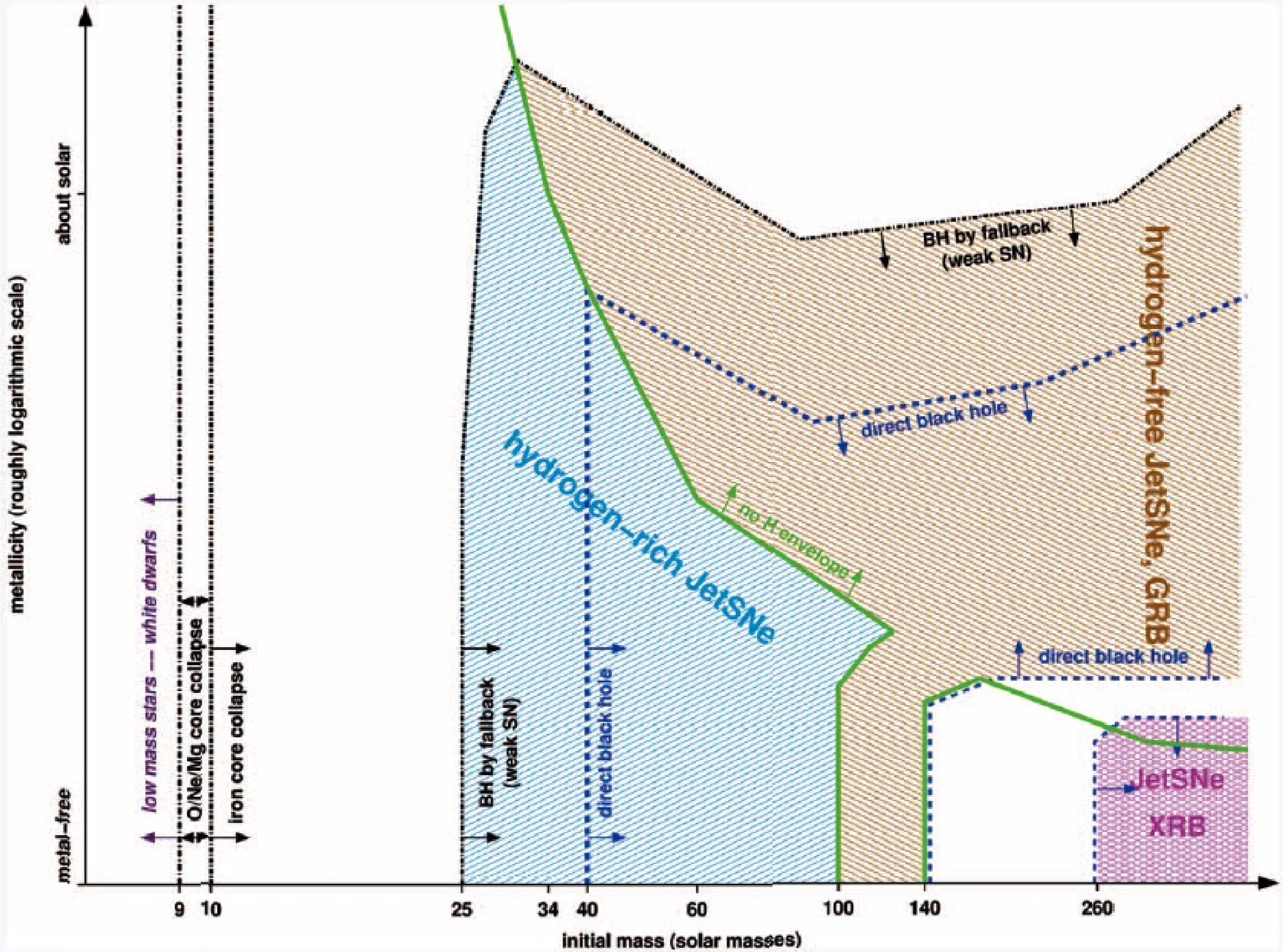
Metallicity (log scale)

Initial stellar mass (M_{sun})

Heger et al. (2003)

Core Collapse Events and Remnants

Metallicity (log scale)



Heger et al. (2003)

Initial stellar mass (M_{sun})

Core-Collapse Events

A heterogeneous class with growing diversity

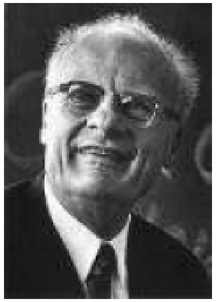
- Observational diversity: Large variability due to structure of stellar mantle and envelope at time of explosion, also on environment!
- Intrinsic explosion differences: Events also differ largely in energy and Ni production <--------> different explosions mechanisms?

- Determining factors of stellar evolution:
  - * mass of progenitor star
  - * "metallicity" (i.e., heavy element abundances of stellar gas at formation)
  - * binary effects
  - * mass loss during stellar evolution
  - * stellar rotation and magnetic fields
- These factors decide about:
  - * neutron star (NS) or black hole (BH) formation in collapse;
  - * explosion mechanism, explosion energy, & Ni production;
  - * lightcurve and spectral properties <—> SN classes;
  - * anisotropy of explosion

Things that blow up

supernovae

- CO white dwarf ➔ Type Ia SN, E≈1Bethe
- MgNeO WD, accretion ➔ AIC, faint SN
- “SAGB” star (AGB, then SN) ➔ EC SN
- “normal” SN (Fe core collapse) ➔ Type II SN
- WR star (Fe CC) ➔ Type Ib/c
- “Collapsar”, GRB ➔ broad line Ib/a SN, “hypernova”
- Pulsational pair SN ➔ multiple, nested Type I/II SN
- Very massive stars ➔ pair SN,≲100B (1B=10^{51} erg)
- Very massive collapsar ➔ IMBH, SN, hard transient
- GR He instability ➔ >100 B SN+SMBH, or 10,000 B
- Supermassive stars ➔ ≳100000 B SN or SMBH



1B=10^{51} erg

MASS

A. Heger (2011)