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WE Heraeus Summer School on Nuclear Astrophysics in the Cosmos

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Stellar Evolution and Death
Models and Modeling

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Contents

Lecture I :

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

Lecture II :

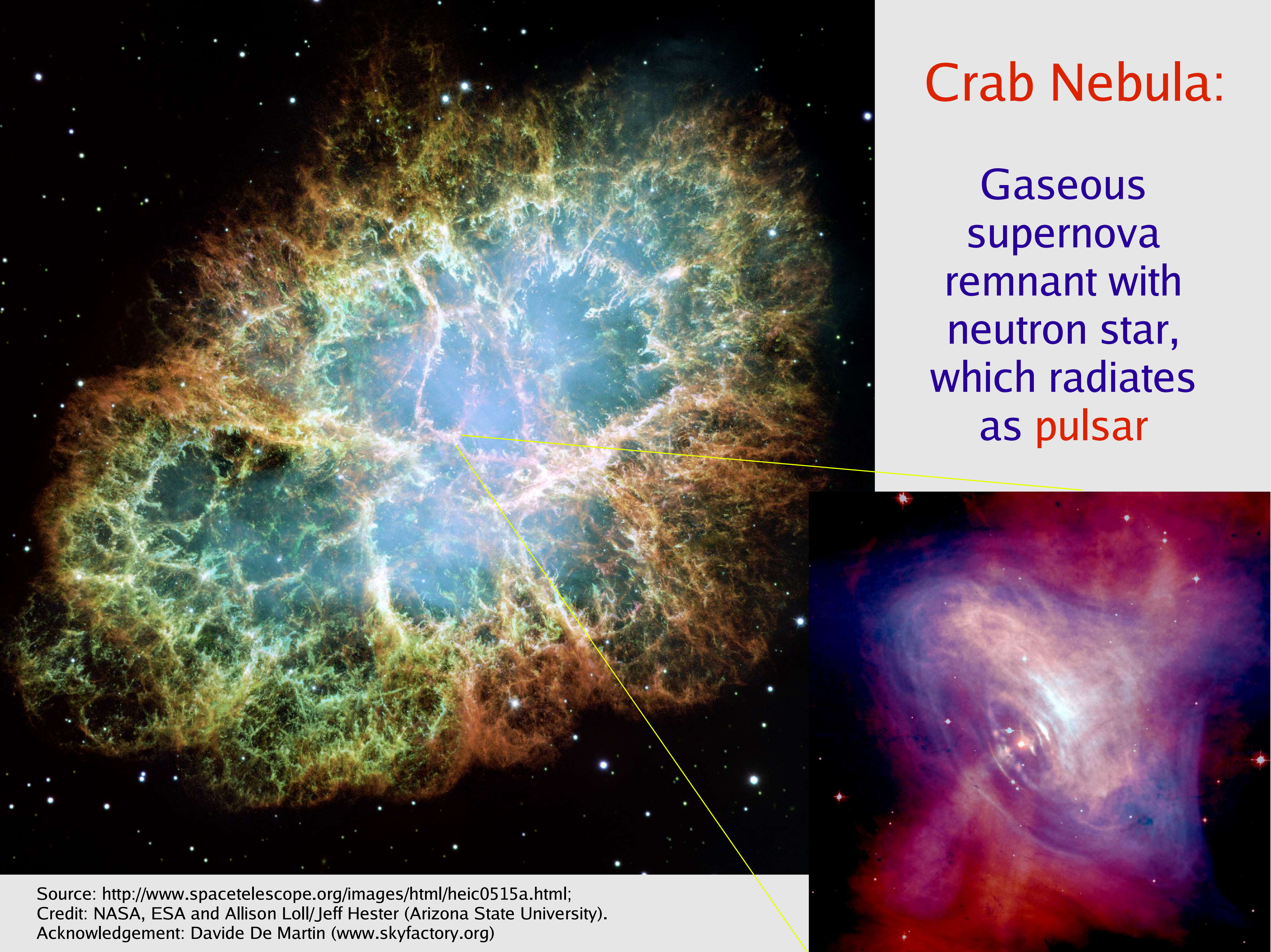
- Gravitational (core-collapse) supernovae: evolution stages
- Neutron stars and their birth
- Black holes and gamma-ray bursts
- Observable signals: neutrinos, gravitational waves, heavy elements

Supernova Phenomenology and Classification

SN 1994d

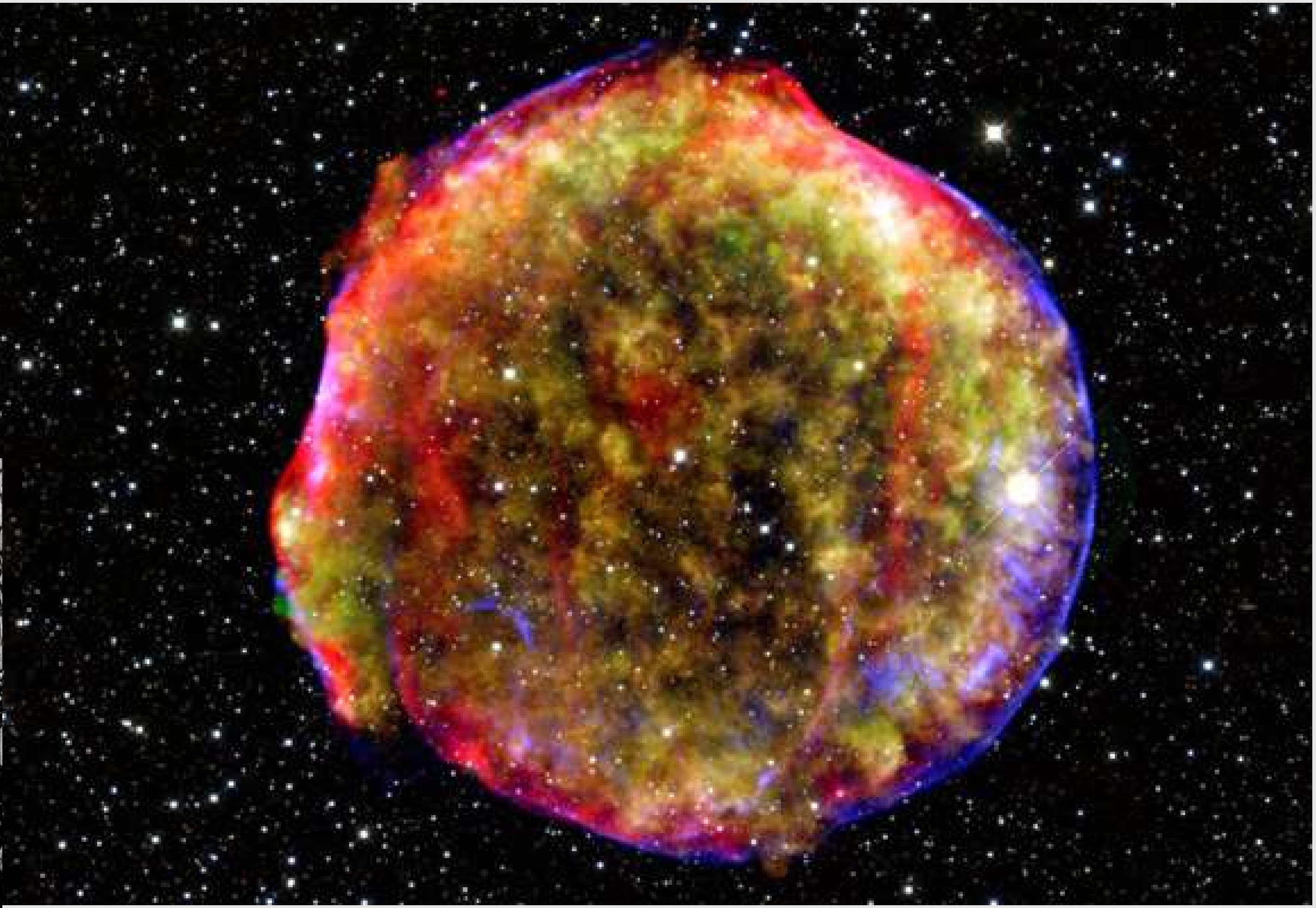
Crab Nebula:

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)

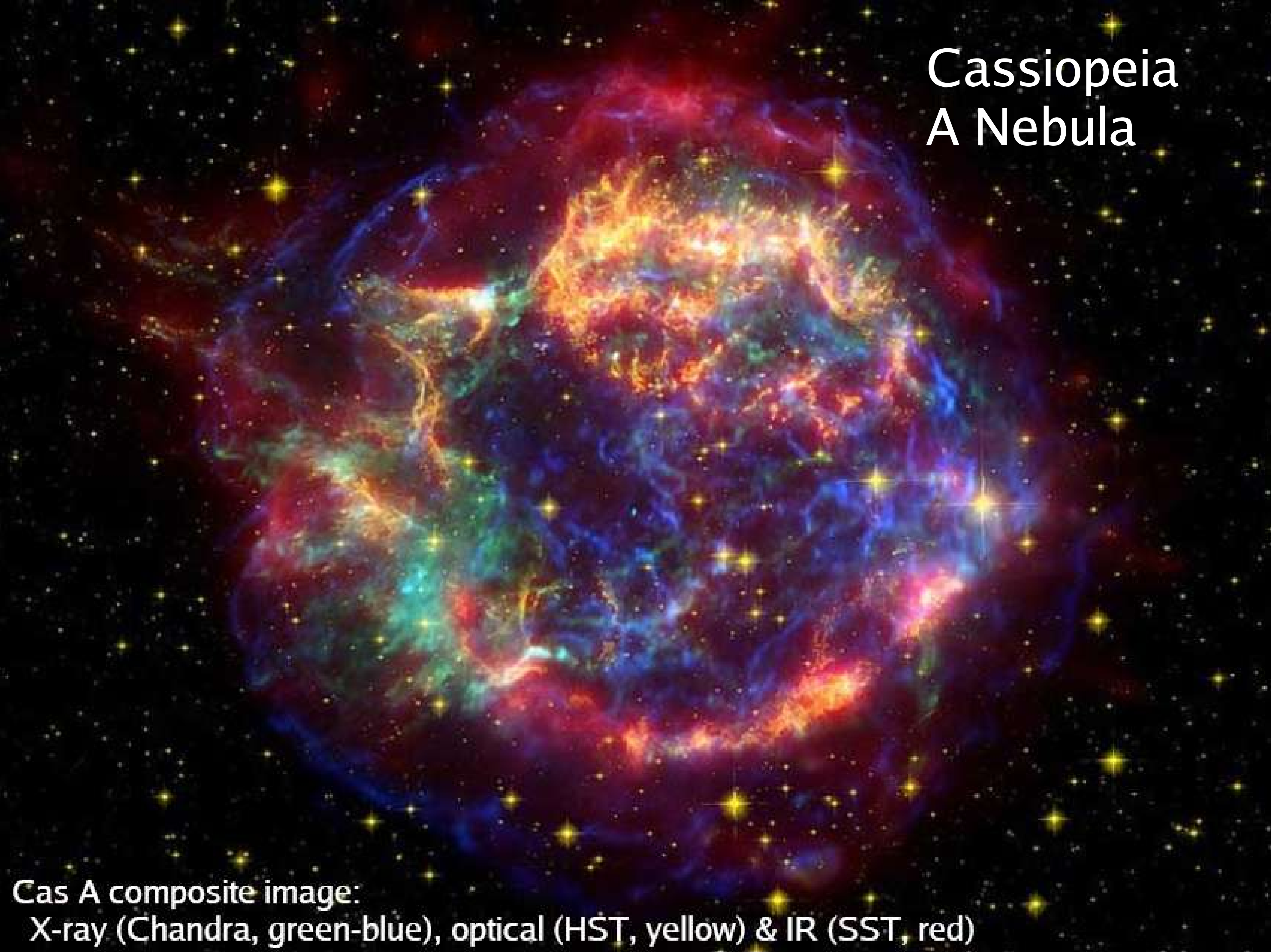
Supernova Remnant Tycho



(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 = 1 B;
  1 bethe equals about 10^{28} mid-sized H-bombs!)

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

Historical Supernovae

Supernovae in the Milky Way during the last millenium

date	visible for	distance	observed in/by
1006	some years	6 500	far east, Arabia, St.Gallen
1054	about 2 years	7 100	far east, Arabia
1181	6 months	26 000	China, Japan
~1300	?	650	? (RX J0852-4642)
1572	16 months	23 000	Tycho Brahe
1604	about 1 year	32 000	Johannes Kepler
~1680	?	11 000	Flamsted ? (Cas A)
23.2.1987	>18 years	160 000	Ian Shelton

Number of observed extragalactic supernovae: > 3100 (since 1885)

Supernova Classification Scheme

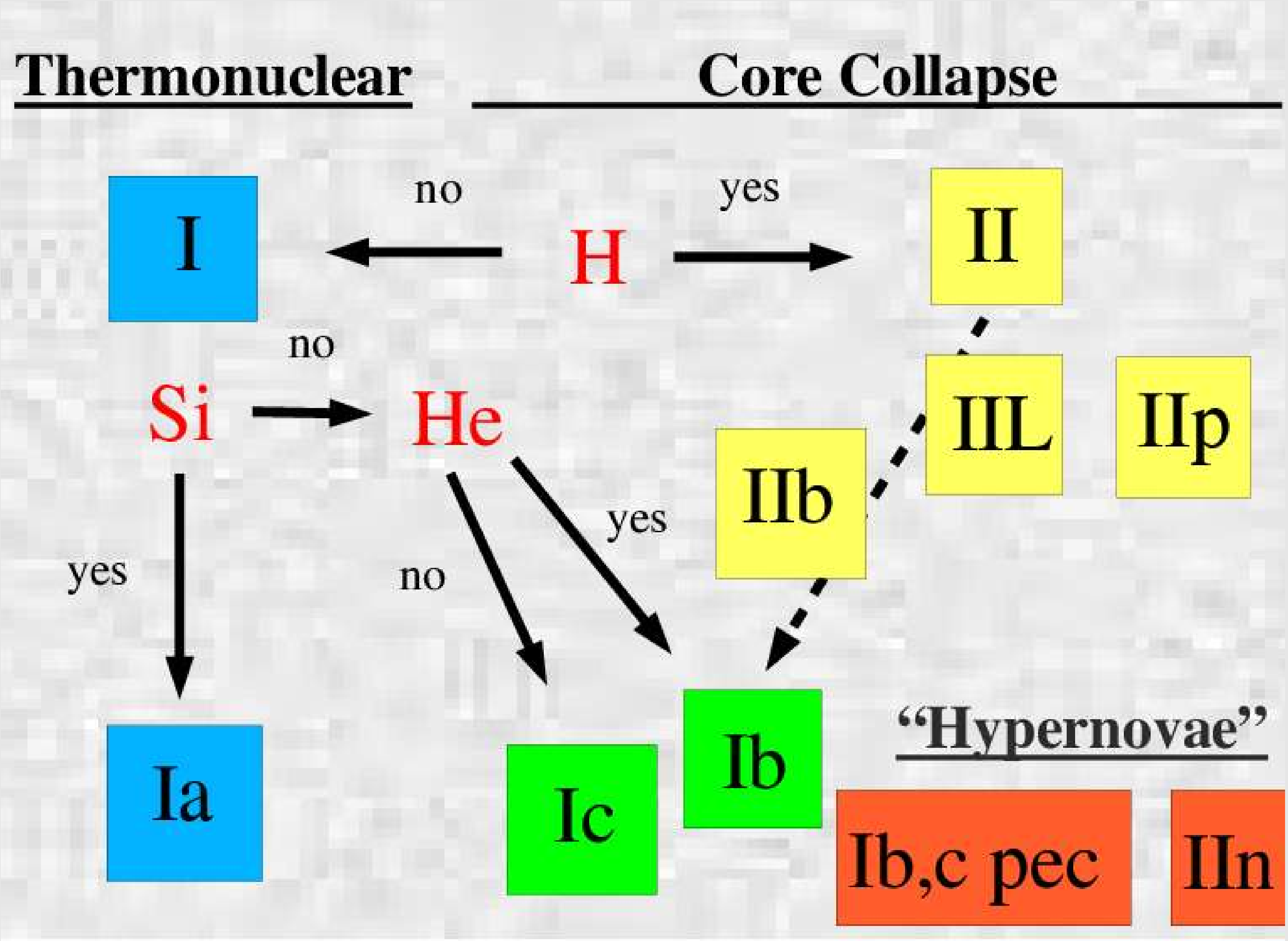
Thermonuclear

Energy source:
thermonuclear burning
C, O ---> Si, Ni

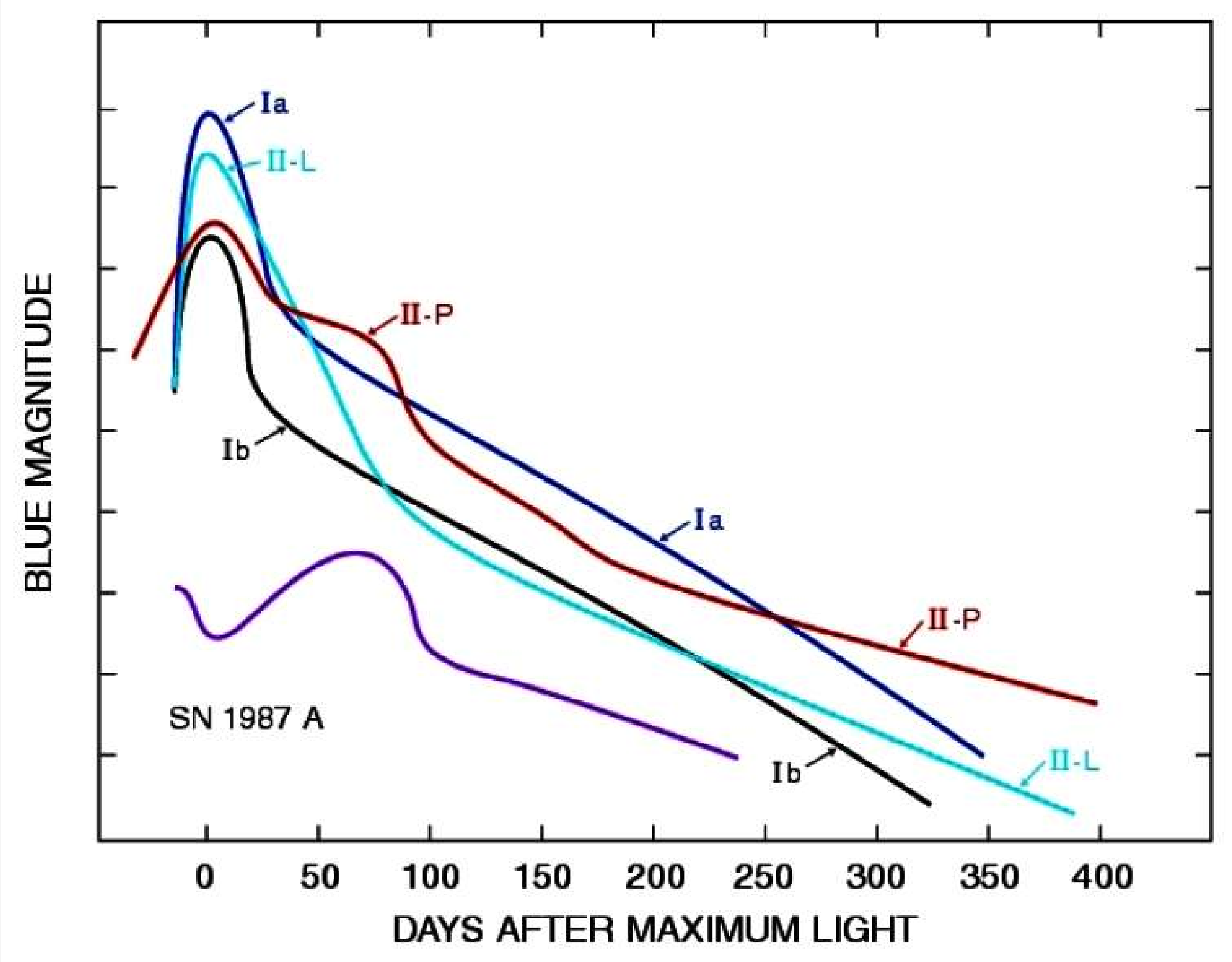
Core Collapse

Energy source:
gravitational binding
energy of compact
remnant (NS, BH)

Supernova Classification Scheme



Supernova Lightcurves



Supernova light curves

pronounced maximum
after 2-3 weeks

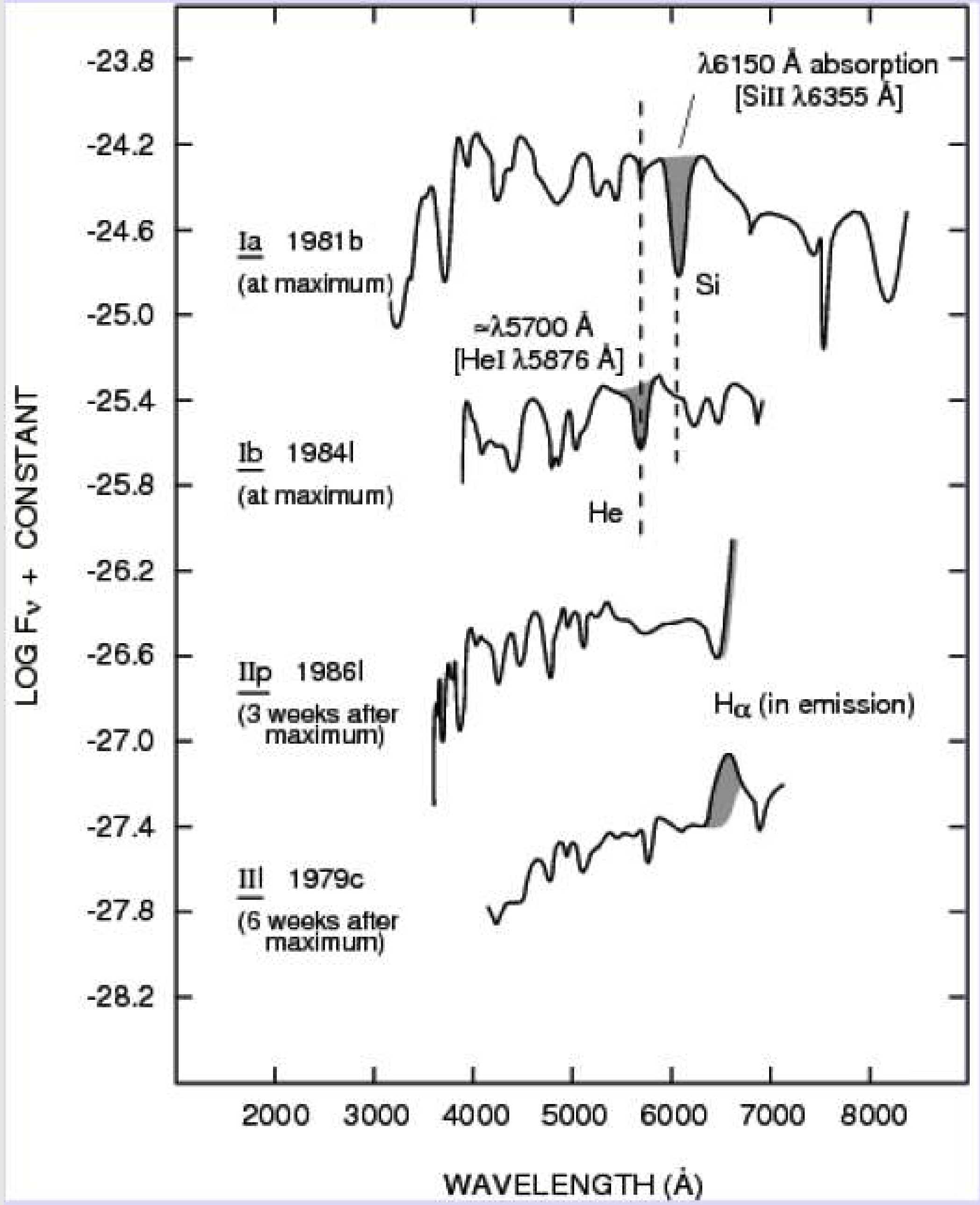
exponential tail
(radioactive decay of
^{56}Ni → ^{56}Co → ^{56}Fe)

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

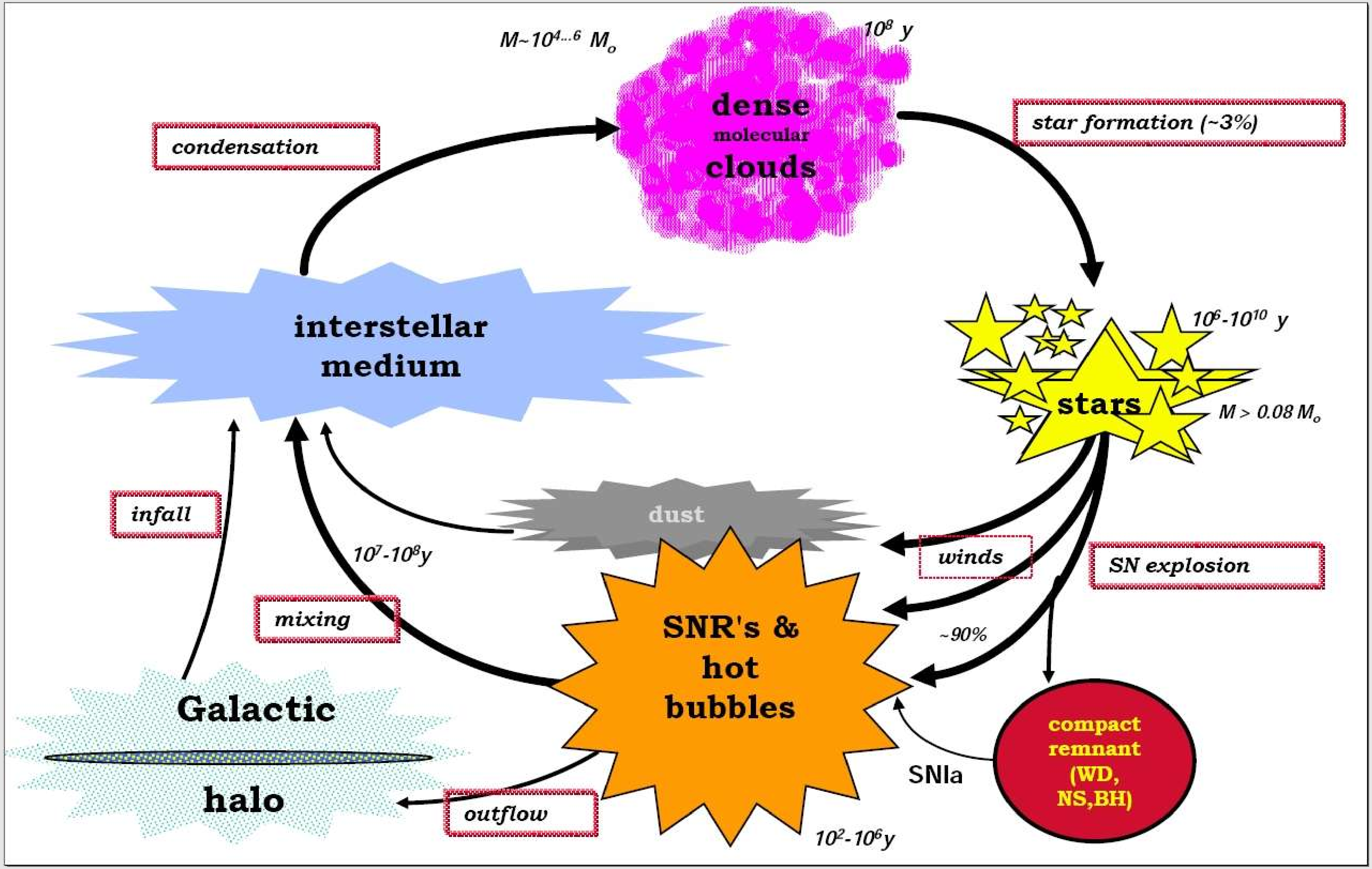
discriminate types
(no spectrum → no type!!)

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

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



$M \sim 10^{4...6}\ M_o$

dense molecular **clouds**

10^8 y

condensation

star formation (~3%)

interstellar medium

stars

10^6-10^{10} y

$M > 0.08\ M_o$

infall

dust

winds

SN explosion

10^7-10^8y

mixing

~90%

SNR's & hot bubbles

compact remnant (WD, NS,BH)

SNIa

Galactic halo

outflow

10^2-10^6y

Supernova Types: Summary

Thermonuclear	**Core Collapse**
(Type Ia)	(Type II, Ib, Ic)
Stars of low mass (< 8 M_{sun})	massive stars (> 8 M_{sun})
highly evolved (white dwarfs)	extended envelopes (espec. Type II)
explosive C+O burning	gravitational collapse
	nuclear burning by compression
binary stars	single stars; binary stars for Type Ib,c
complete disruption	compact remnant (NS, BH)

Stellar Evolution

Stellar Evolution Equations

Assumed: spherical symmetry, Newtonian gravity, single star

Mass conservation:

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

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

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

Hydrostatic equilibrium:

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

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

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

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 $\lambda_{\mathrm{mfp}} \ll h_P = |\mathrm{d}r/\mathrm{d}\ln P|$ (pressure scale height).

Fick's law:

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

with $e_\gamma = a_\gamma T^4$, $\lambda_{\mathrm{mfp}} = (\kappa\rho)^{-1}$ (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:

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

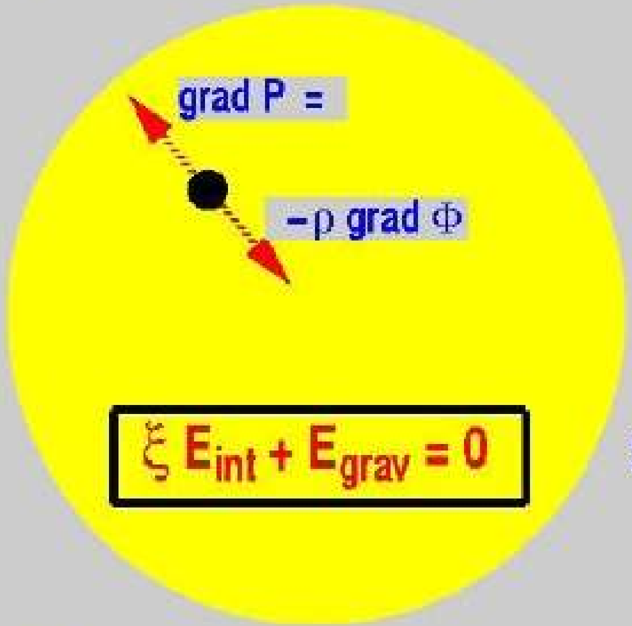
With total energy $E_{\mathrm{tot}} = E_{\mathrm{i}} + E_{\mathrm{grav}}$ one gets for $\Gamma \neq \frac{4}{3}$:

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

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

stellar evolution mostly hydrostatic, i.e pressure and gravitational forces are in equilibrium



$$\boxed{\xi E_{int} + E_{grav} = 0}$$

virial theorem

$\xi := 3P/\rho u$ ideal gas: $P = (\gamma-1)\rho u$ --> $\xi = 3(\gamma-1)$

relativ. Fermi gas: $P = 1/3\,\rho u$ --> $\xi = 1$

total energy:

$$\boxed{W := E_{int} + E_{grav} = (1-\xi)\,E_{int} = (\xi-1)/\xi\,E_{grav}}$$

if $\xi = 1$ --> $W = 0$!

gas: finite temperature --> star radiates

energy conservation:

$$\boxed{dW/dt + L = 0}$$

luminosity

$$\boxed{L = (\xi-1)\,dE_{int}/dt = -(\xi-1)/\xi\,dE_{grav}/dt}$$

if $L > 0$ --> $dE_{grav}/dt < 0$ <--> contraction --> $dE_{int}/dt > 0$

contraction with $\gamma = 5/3$ $(\xi = 2)$:

50% of liberated energy are radiated away

50% of liberated energy heat the star

--> star has 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 $P = \overline{P}$, $\rho = \bar{\rho}$):

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

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

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

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

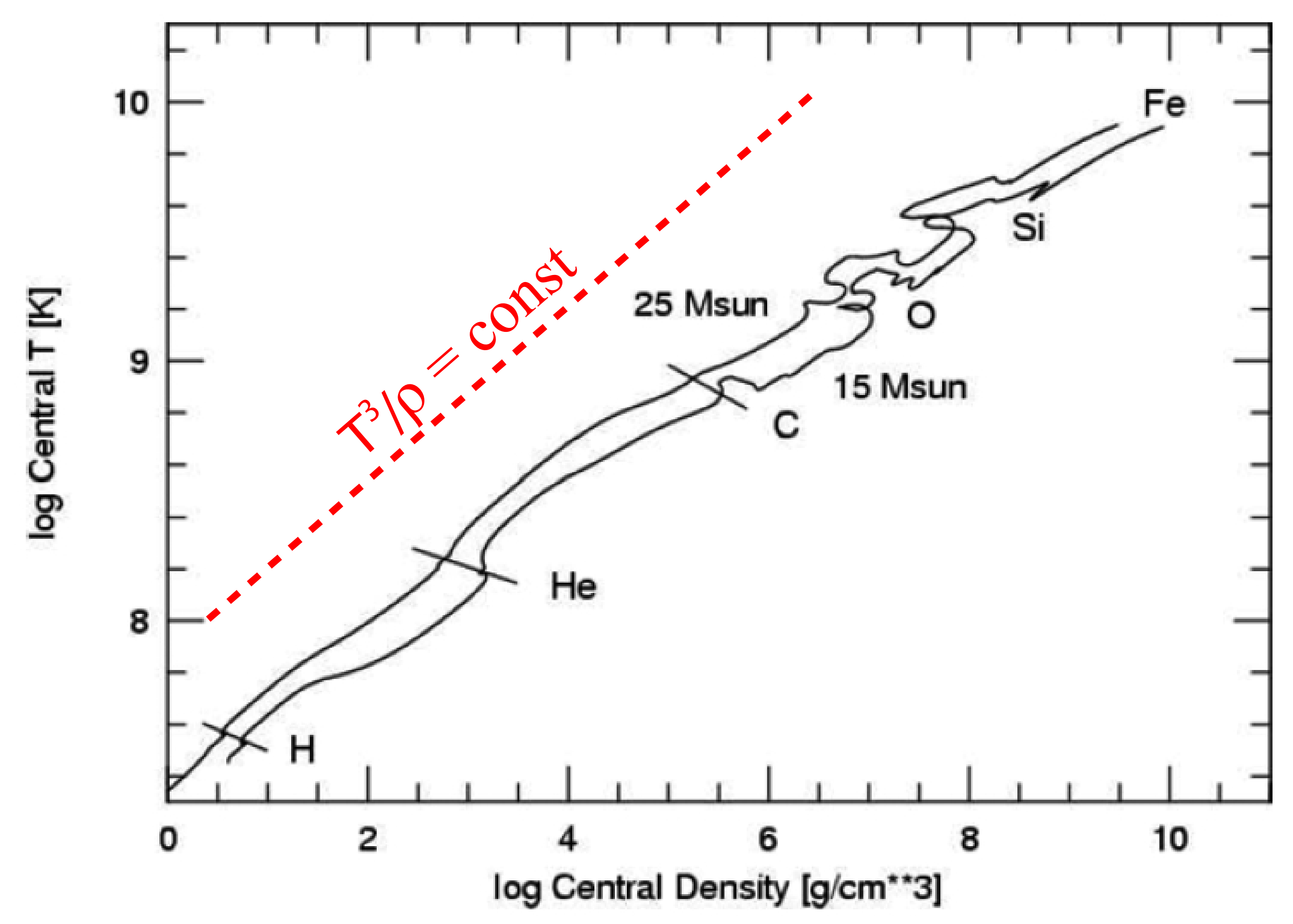
with τ_{nuc} being the nuclear burning timescale.

Basic Principles of Stellar Evolution

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

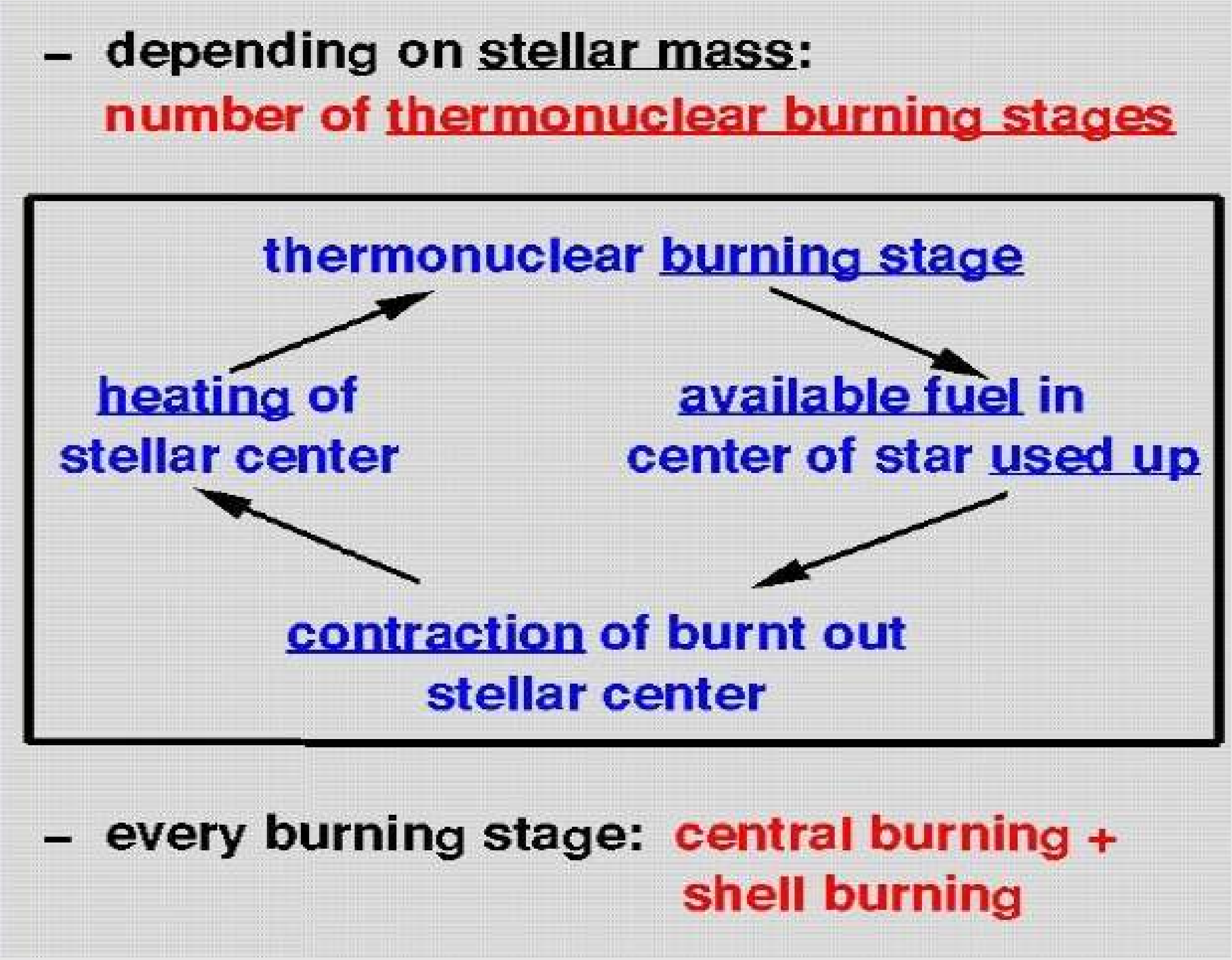
- As star contracts and its density grows, T increases like $\rho^{1/3}$
- For given density, stars with larger mass M are hotter

Evolution Tracks of Massive Stars



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

Stellar Burning Cycles



- depending on stellar mass:
  number of thermonuclear burning stages

thermonuclear burning stage

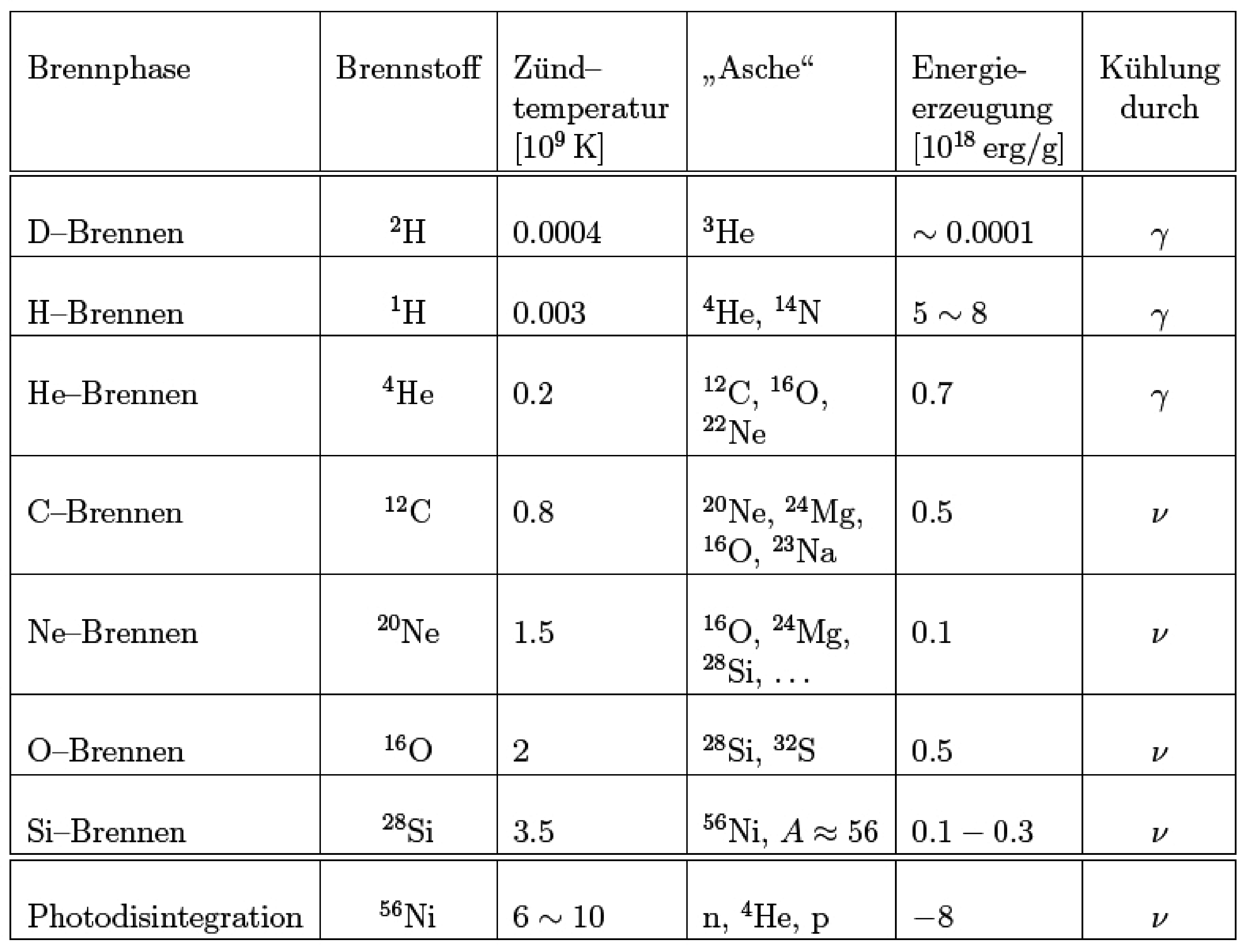
available fuel in center of star used up

contraction of burnt out stellar center

heating of stellar center

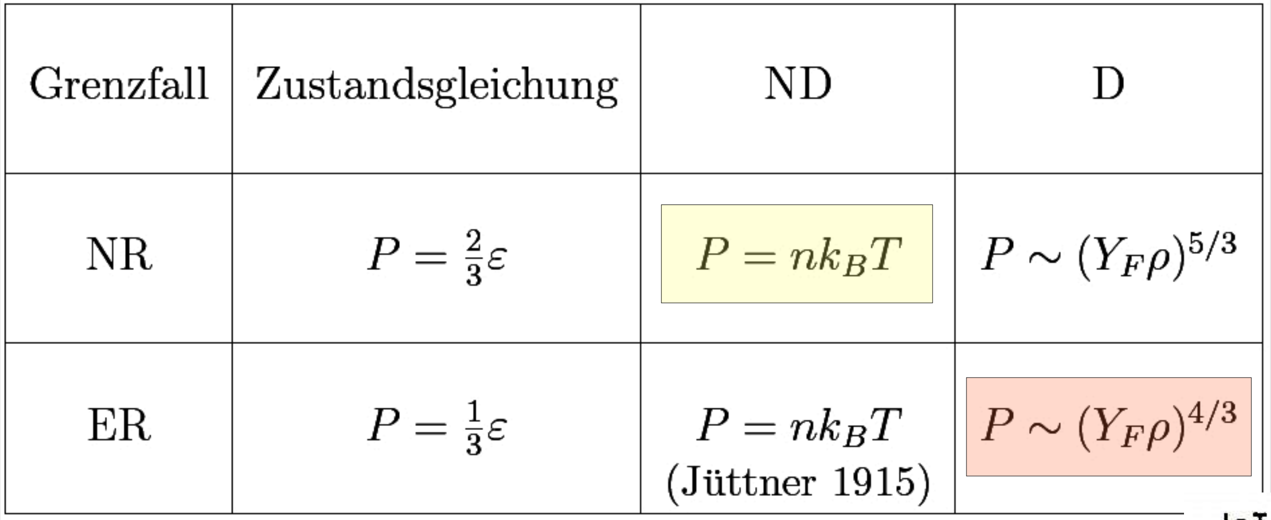
- every burning stage: central burning + shell burning

Stellar Burning Conditions



Brennphase	Brennstoff	Zünd–temperatur $[10^9$ K$]$	„Asche“	Energie-erzeugung $[10^{18}$ erg/g$]$	Kühlung durch
D–Brennen	^{2}H	0.0004	^{3}He	~ 0.0001	γ
H–Brennen	^{1}H	0.003	^{4}He, ^{14}N	$5 \sim 8$	γ
He–Brennen	^{4}He	0.2	^{12}C, ^{16}O, ^{22}Ne	0.7	γ
C–Brennen	^{12}C	0.8	^{20}Ne, ^{24}Mg, ^{16}O, ^{23}Na	0.5	ν
Ne–Brennen	^{20}Ne	1.5	^{16}O, ^{24}Mg, ^{28}Si, …	0.1	ν
O–Brennen	^{16}O	2	^{28}Si, ^{32}S	0.5	ν
Si–Brennen	^{28}Si	3.5	^{56}Ni, $A \approx 56$	$0.1 - 0.3$	ν
Photodisintegration	^{56}Ni	$6 \sim 10$	n, ^{4}He, p	-8	ν

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)	$P \sim (Y_F\rho)^{4/3}$

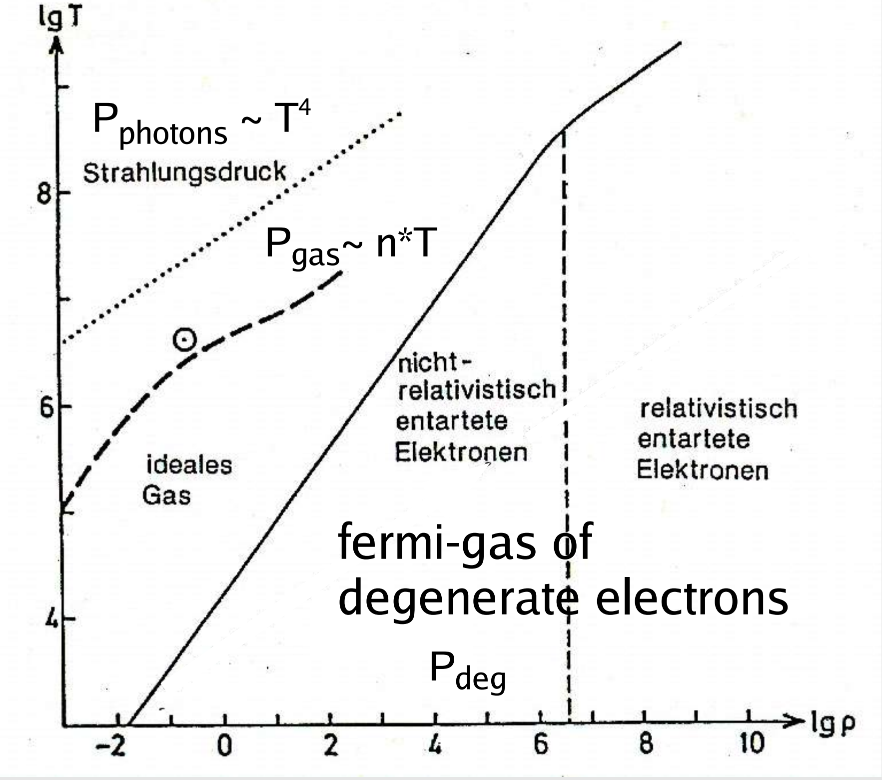
Onset of degeneracy for fermions:

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

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

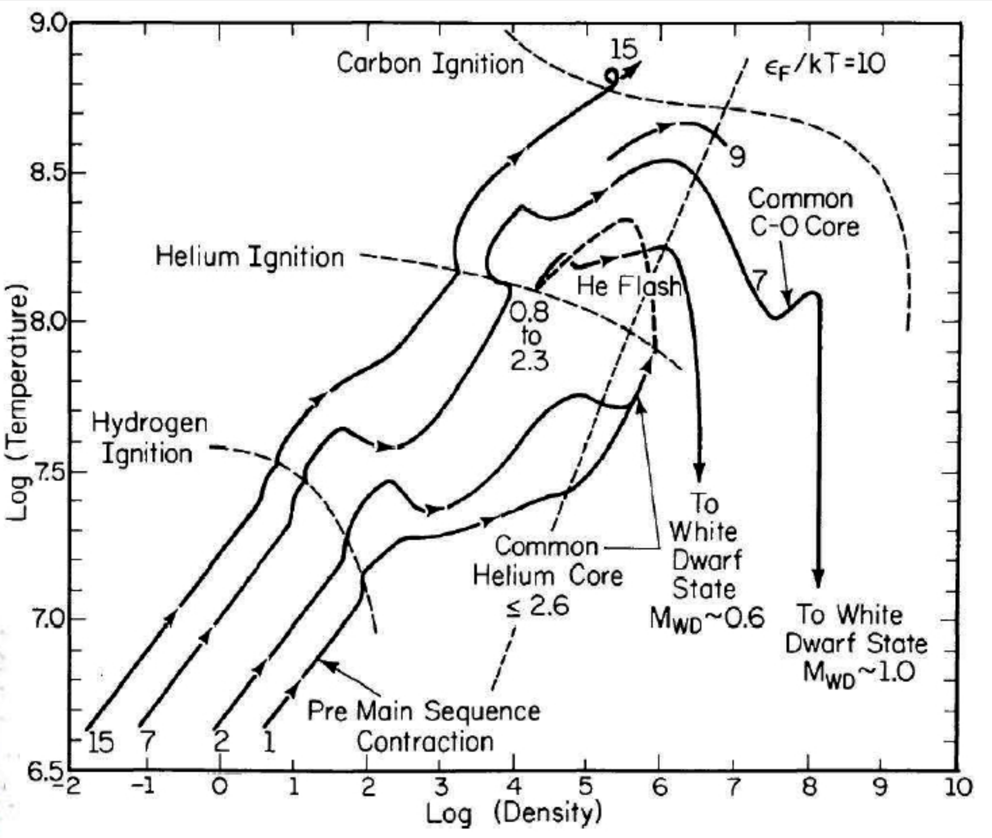
$$P = P_{\text{gas}} + P_{\text{deg}} + P_{\text{photons}}$$

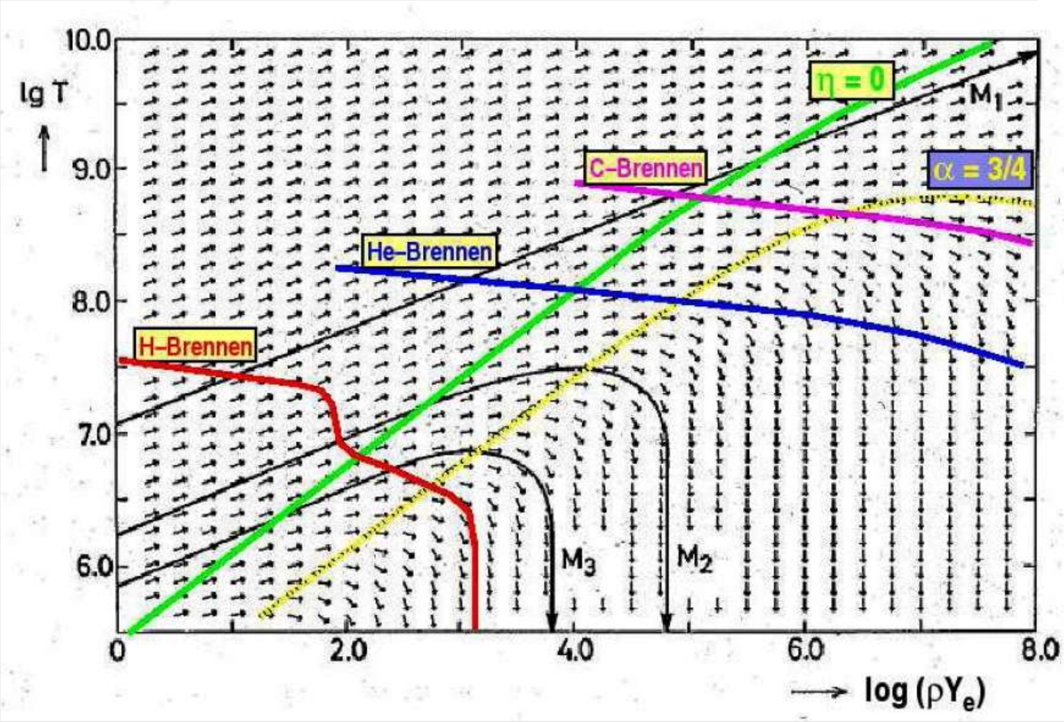
- Stellar gas attains different regimes of equation of state properties as stars evolve
- Normal stars: gas behaves like classical Boltzmann gas (P_{gas})
- As temperature and density rises, the electrons can become relativistic and degenerate (P_{deg})



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

$M < {\sim}8\ M_{sun}$: final stage of evolution is a **white dwarf** and planetary nebula before stars reach the central carbon burning

White Dwarfs and Planetary Nebula

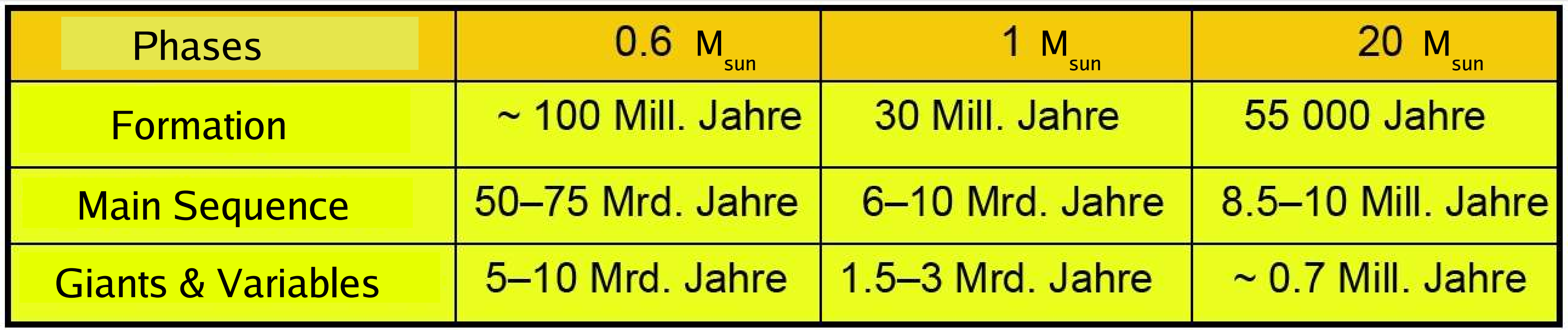
Ant Nebula

NGC 3132

Basic Principles of Stellar Evolution

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

More massive stars evolve faster and live shorter



Phases	0.6 M_{sun}	1 M_{sun}	20 M_{sun}
Formation	~ 100 Mill. Jahre	30 Mill. Jahre	55 000 Jahre
Main Sequence	50–75 Mrd. Jahre	6–10 Mrd. Jahre	8.5–10 Mill. Jahre
Giants & Variables	5–10 Mrd. Jahre	1.5–3 Mrd. Jahre	~ 0.7 Mill. Jahre

(Mill. Jahre = million years; Mrd. Jahre = billion years)

Stellar Burning Stages of Stars with $M > 10\ M_{sun}$

Stars with more than ~9–10 solar masses reach all possible stages of nuclear burning

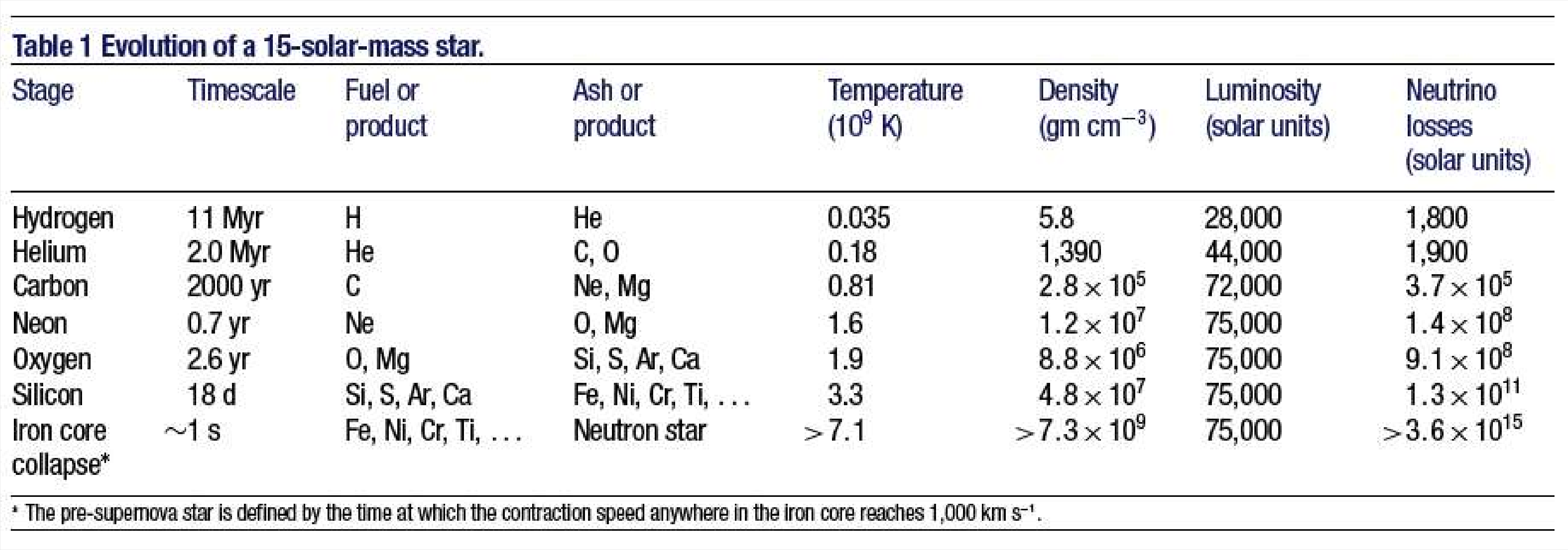


Table 1 Evolution of a 15-solar-mass star.

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*	~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}.

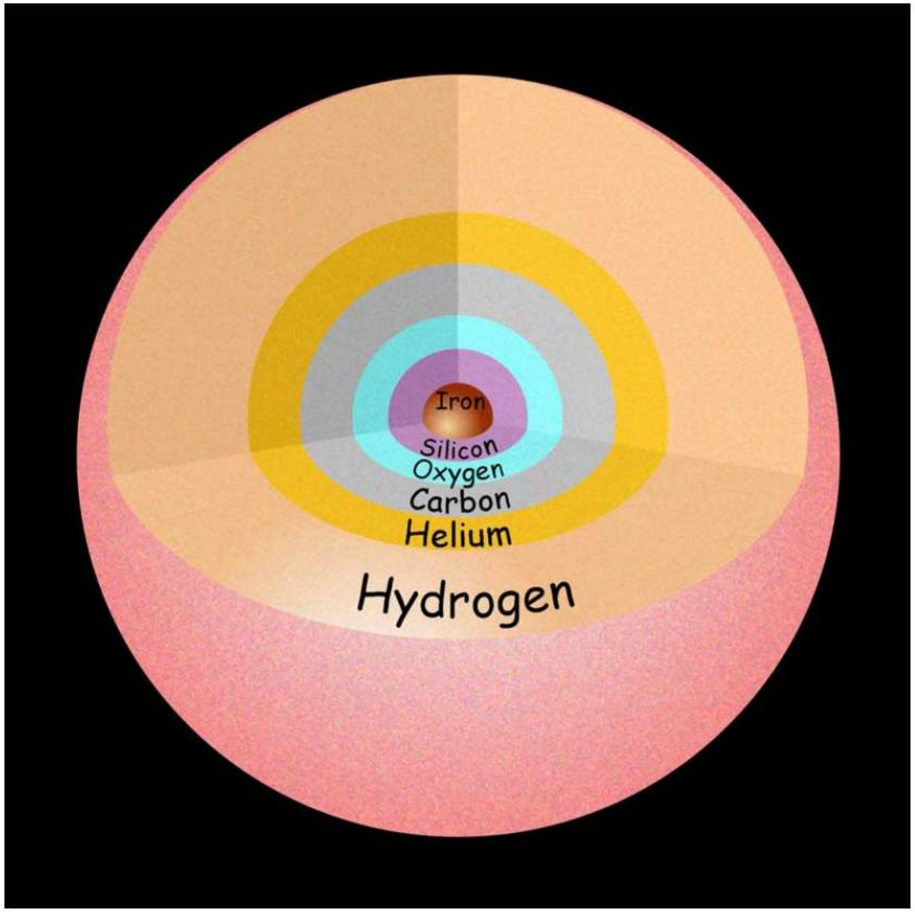
Final Stages of Stellar Evolution

- $M > \sim 8\ M_{sun}$:
  stars develop electron-degenerate cores and onion shell structure before the core undergoes a gravitational collapse

- $\sim 8\ M_{sun} < M < \sim 9\text{–}10\ M_{sun}$:
  O-Ne-Mg cores are formed

- $M > \sim 9\text{–}10\ M_{sun}$:
  iron cores are formed

Onion Shell Structure



Chandrasekhar Mass Limit

Self-gravitating configurations supported by pressure of relativistic electrons (fermions) have a maximum mass for stable hydrostatic equilibrium:

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

Final Stages of Stellar Evolution

- White dwarfs/stellar cores with M_* ---> M_{Ch} approach gravitational instability:

  Hydrostatic (mechanical) equilibrium breaks down

  -----------> contraction,
  possibly collapse to neutron star

- Mechanical equilibrium impossible when “effective” adiabatic index

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

Reason: for $P = (\Gamma_{eff} - 1)e = K\rho^{\Gamma eff}$ with $\Gamma_{eff} = \Gamma_{EoS} + \varepsilon < 4/3$, the pressure gradient increases less steeply than the gravitational force: $P/R \propto \rho^{5/3+\varepsilon}$; $GM/R^2 \propto \rho^{5/3}$

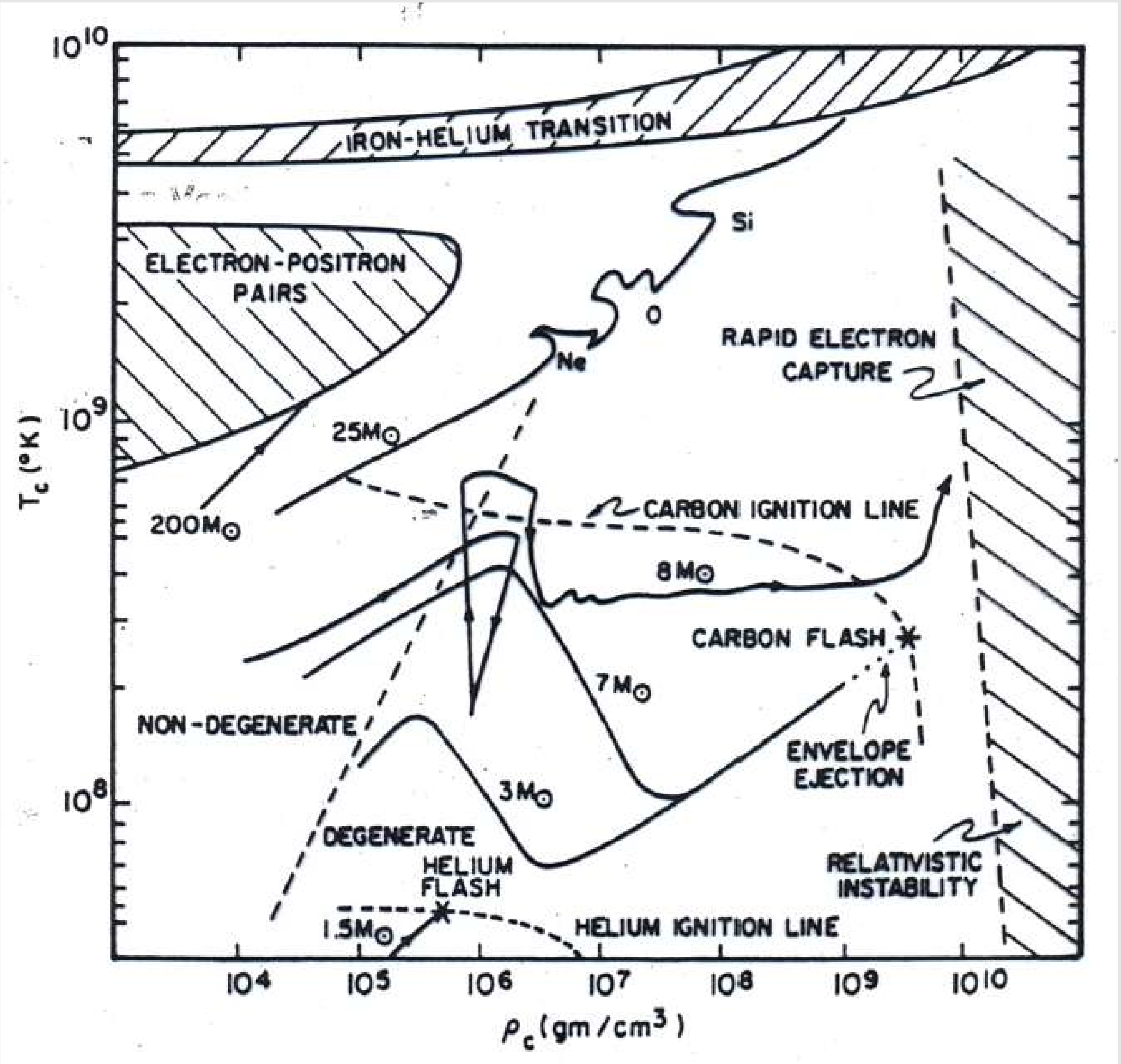
- Neutrino losses (electron captures) and general relativistic corrections destabilize, nucleon pressure and rotation help stabilizing

Final Stages of Massive Star Evolution

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

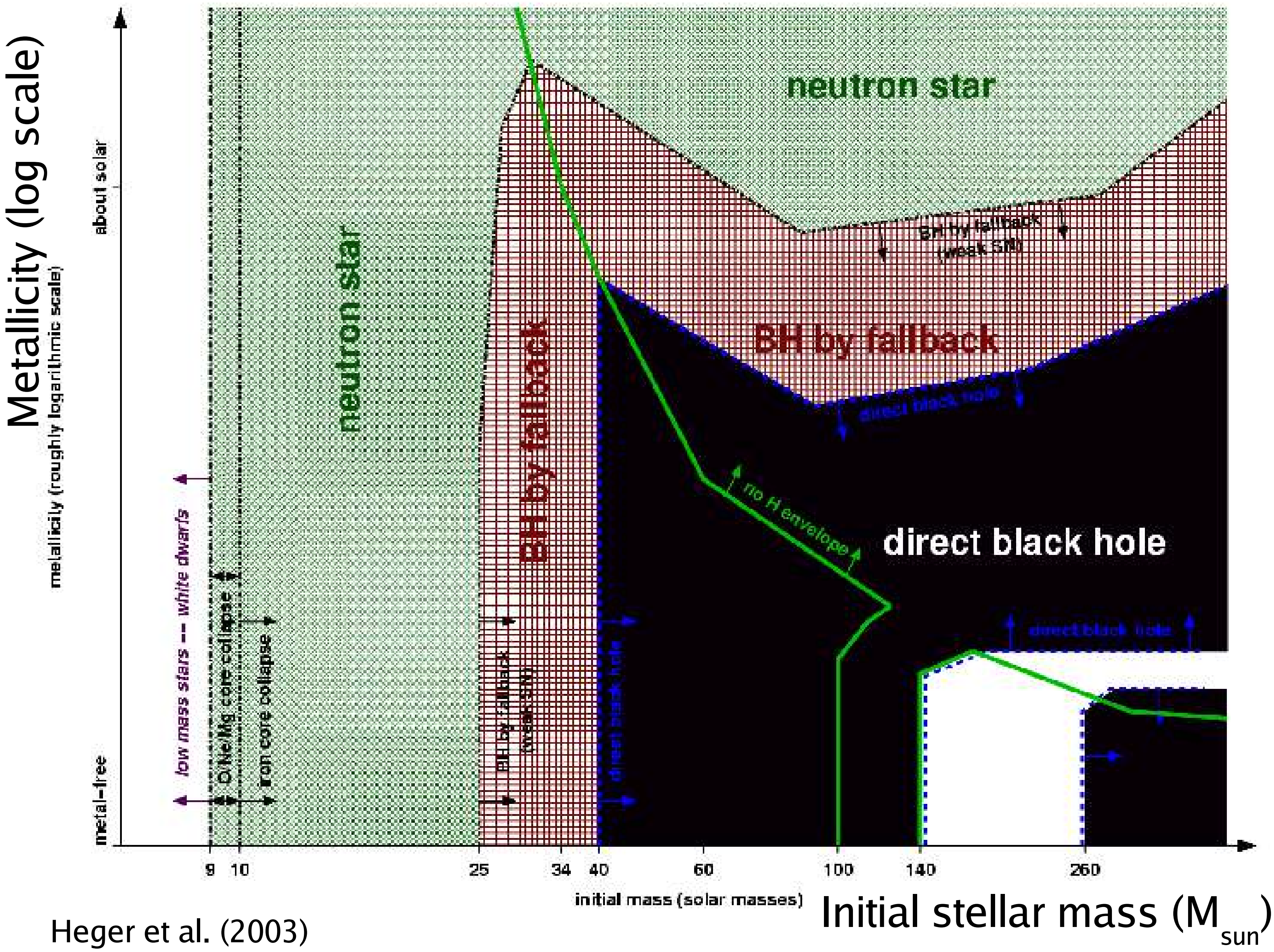
Stars with ~9–100 $M_{\rm sun}$ develop Fe cores
—> collapse by nuclear
photodisintegration

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



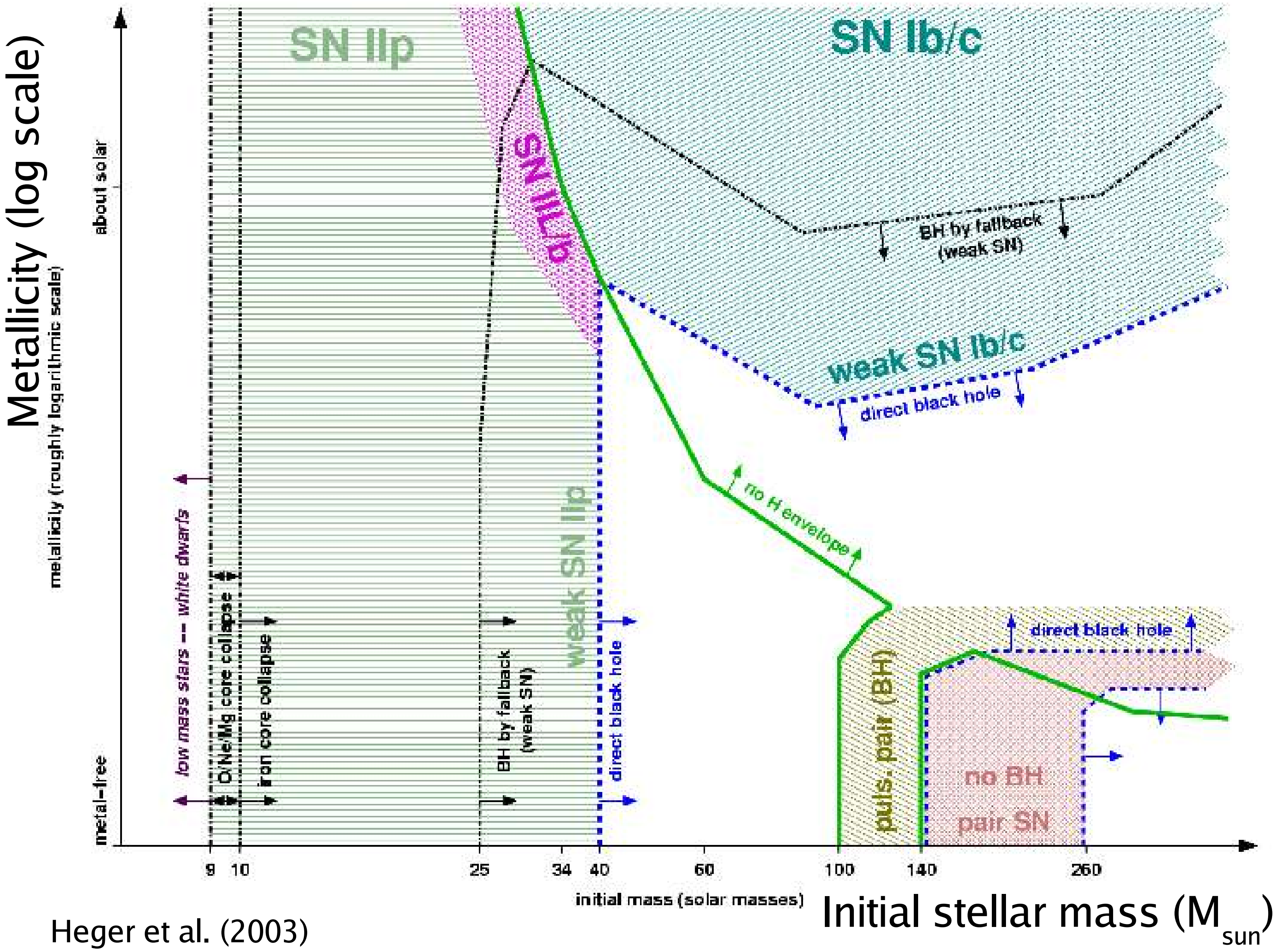
(Wheeler et al. 1990)

Core Collapse Events and Remnants



Heger et al. (2003)

Core Collapse Events and Remnants



Heger et al. (2003)

Core-Collapse Events

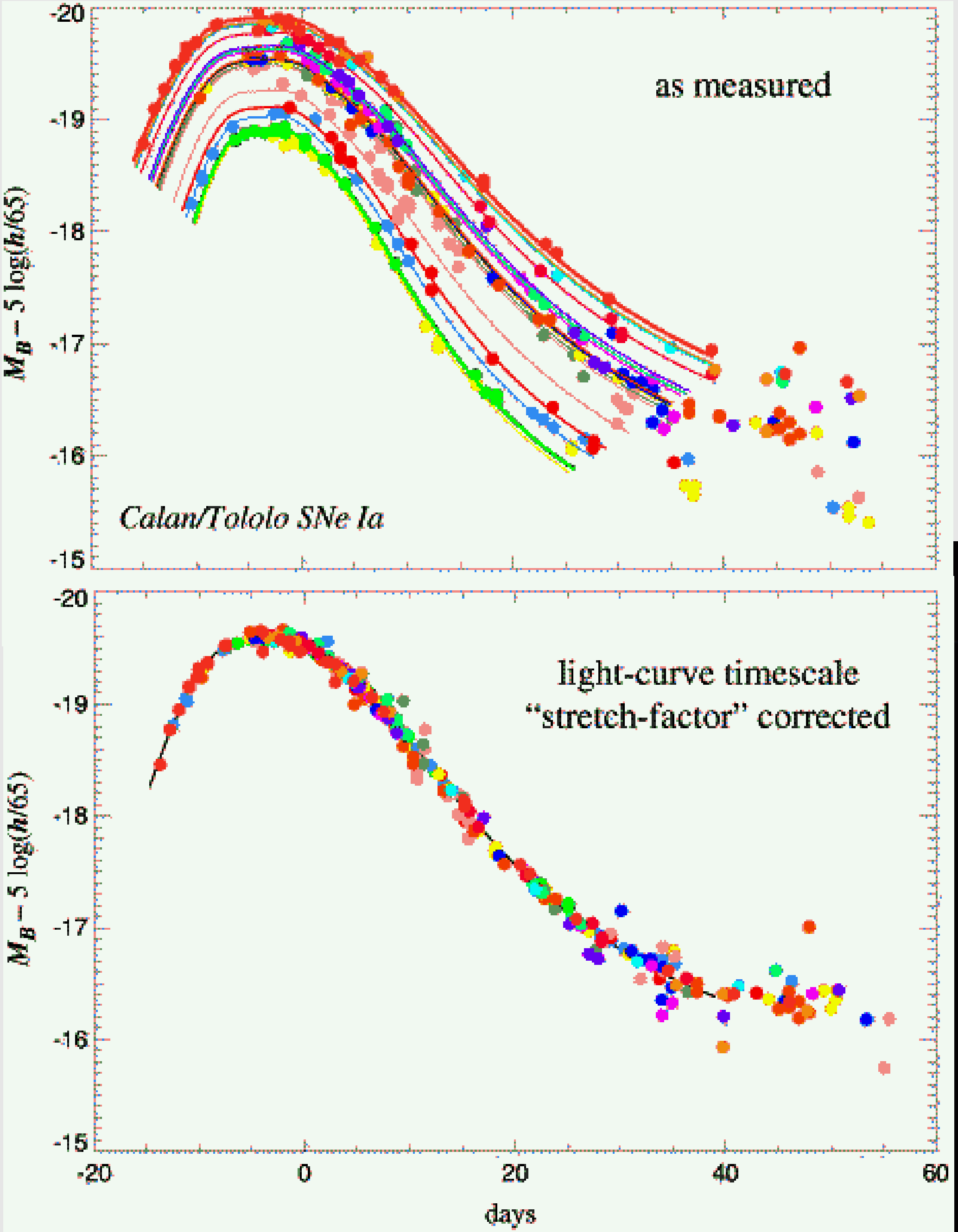
A heterogeneous class with growing diversity

- Observational diversity: Large variability due to structure of stellar mantle and envelope at time of explosion
- Intrinsic explosion differences: Events also differ largely in energy and Ni production
- 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 whether:
  - * neutron star (NS) or black hole (BH) forms in collapse;
  - * explosion mechanism, explosion energy, & Ni production;
  - * lightcurve and spectral properties <—> SN classes;
  - * anisotropy of explosion

Thermonuclear (Type Ia) Supernovae

Standard candles for measuring the universe

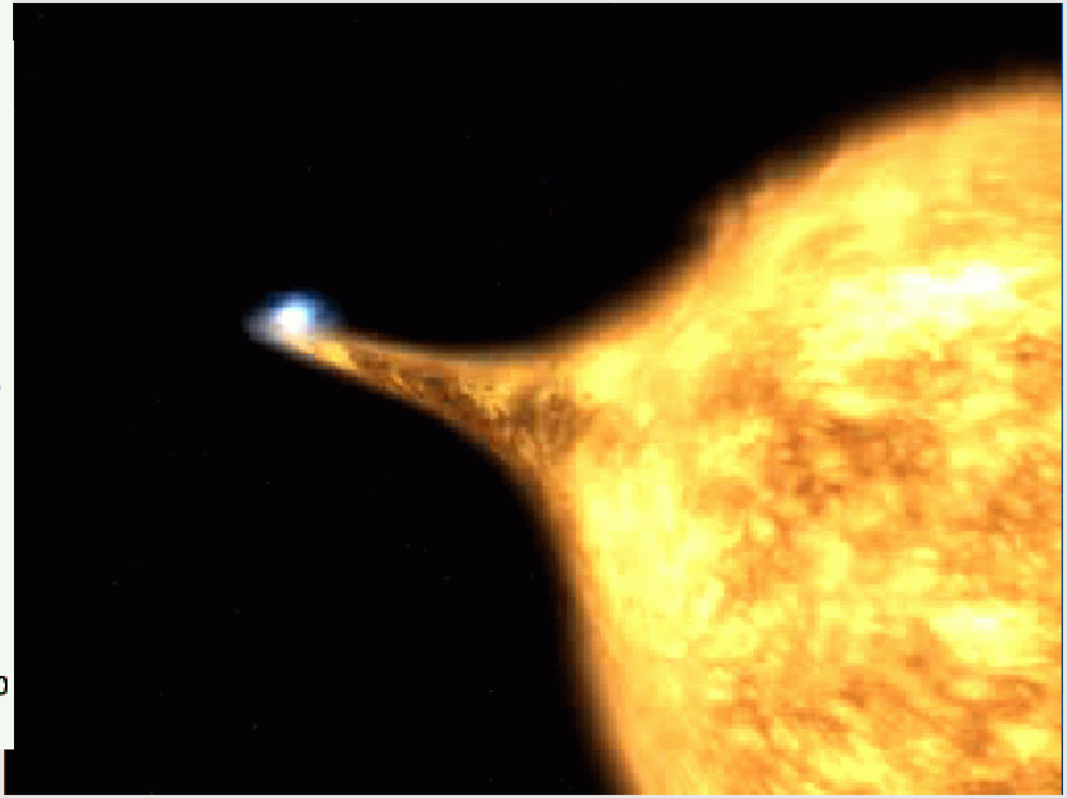
Type Ia Supernovae



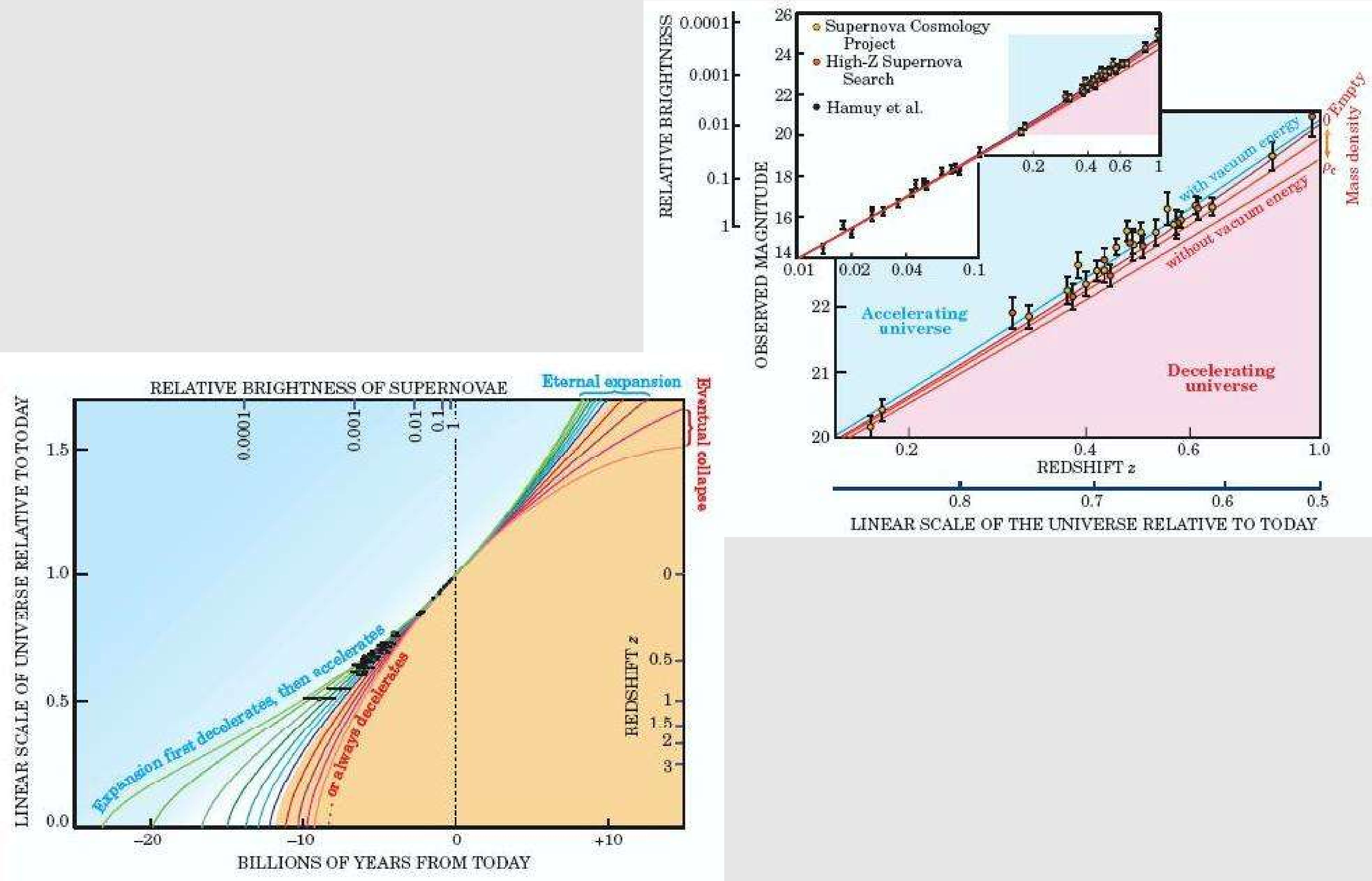
Recalibration with Phillips relation

Exploding accreting white dwarfs in binary systems

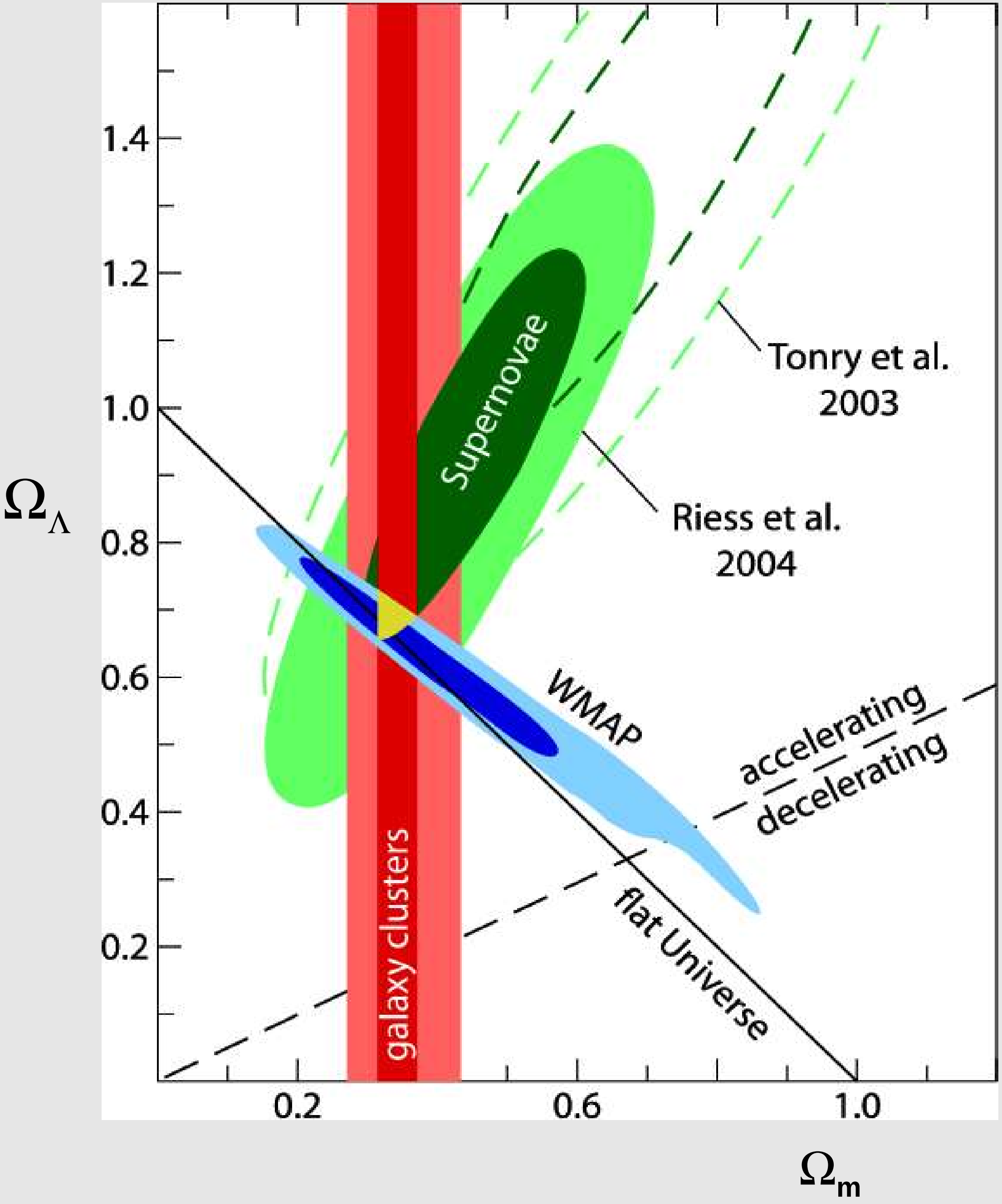
"standard candles"



Type Ia SNe and Cosmology



Observational Constraints of Cosmic Parameters



WMAP results from Spergel et al. 2003

REFLEX results from Schuecker et al. 2003 (three weeks before WMAP publication)

Hydrodynamics Equations

- mass conservation:

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \vec{v})$$

non-linear term => turbulence

- momentum balance:

$$\frac{\partial \vec{v}}{\partial t} = \boxed{-(\vec{v}\nabla) \cdot \vec{v}} - \frac{\nabla P}{\rho} + \vec{f}$$

- species balance:

$$\frac{\partial (\rho X_i)}{\partial t} = -\nabla \cdot (\rho X_i \vec{v}) - \rho \omega_{X_i}, \qquad i = 1, \ldots, N$$

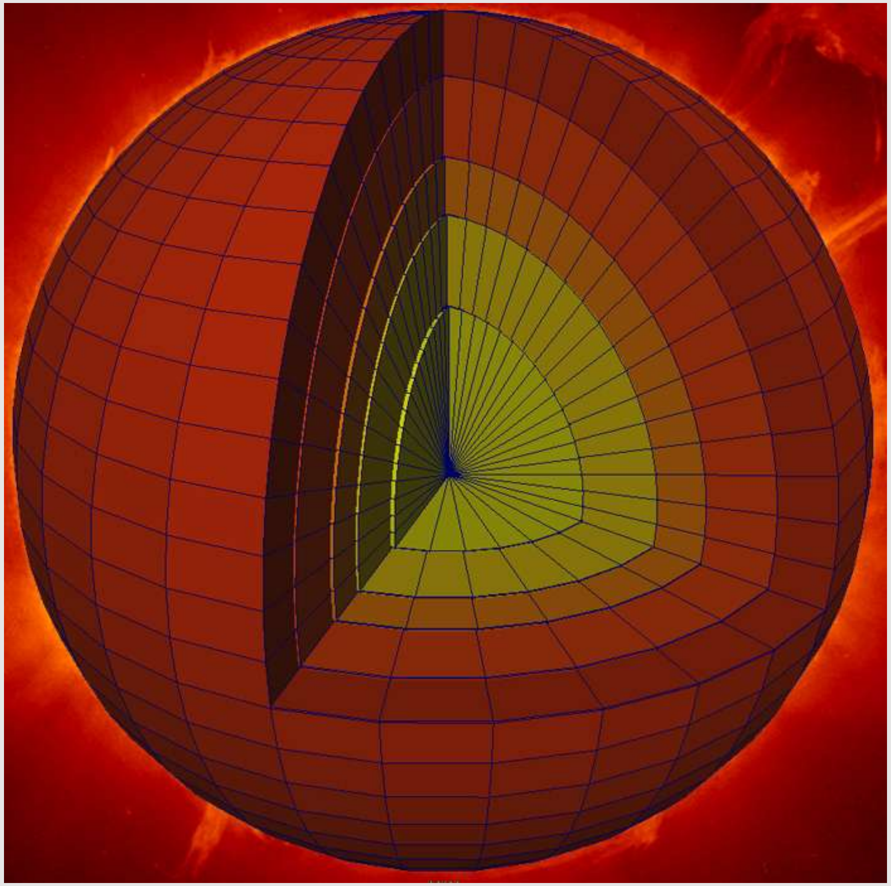
- energy balance:

$$\frac{\partial (\rho e_{\mathrm{tot}})}{\partial t} = -\nabla \cdot (\rho e_{\mathrm{tot}} \vec{v}) - \nabla (P \vec{v}) + \rho \vec{v} \cdot \vec{f} + \rho S$$

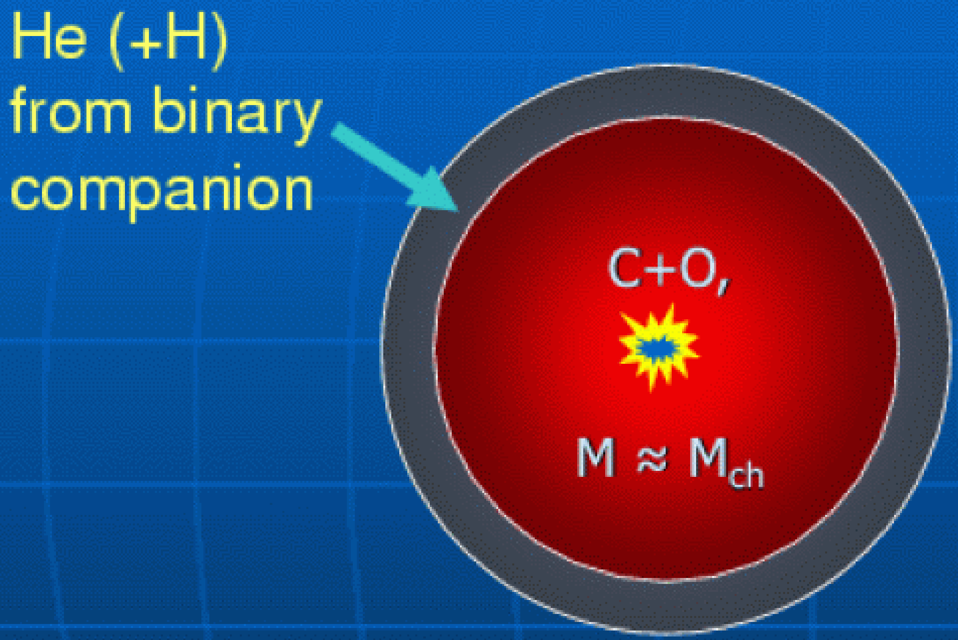
- closed by EoS

Supernova Ia Simulations

- Multi-dimensional (3D)
- Nuclear burning
- Long evolution timescales
- Turbulence: large scale differences!
- Extremely CPU intense



How does the model work?



He (+H) from binary companion

C+O,

$M \approx M_{ch}$

Density ~ 10^9 - 10^{10} g/cm

Temperature: a few 10^9 K

Radii: a few 1000 km

Explosion energy:

Fusion C+C, C+O, O+O → "Fe"

Laminar burning velocity:

$U_L \sim 100$ km/s $<< U_S$

Too little is burned!

Shocks & Burning Fronts

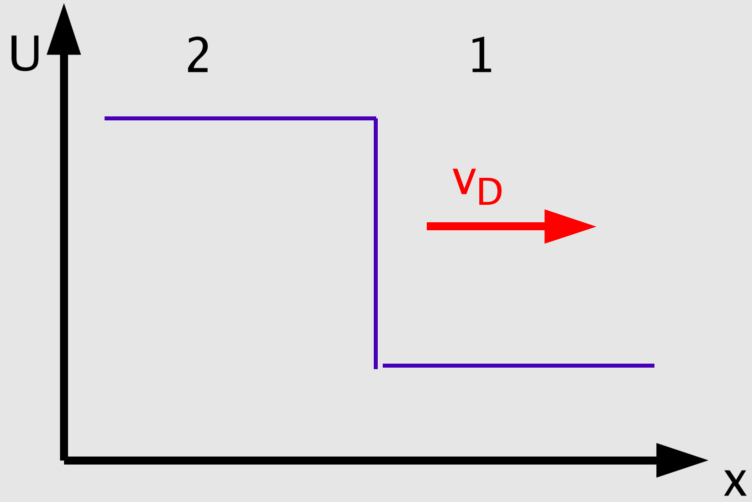
Shock jump conditions --- Rankine-Hugoniot conditions:

$$-v_D\,(\mathbf{U}_2 - \mathbf{U}_1) = \mathbf{F}_2 - \mathbf{F}_1$$

oder komponentenweise

$$\boxed{\begin{aligned} v_D\,[\rho] &= [\rho u] \\ v_D\,[\rho u] &= [\rho u^2 + p] \\ v_D\,[\rho e] &= [(\rho e + p) u] \end{aligned}}\;,$$

wobei $[A] \equiv A_2 - A_1$ gilt.



In system comoving with shock front,
i.e. where $v_D = 0$:

$$\boxed{\begin{aligned} \rho_1 u_1 &= \rho_2 u_2 \\ \rho_1 u_1^2 + p_1 &= \rho_2 u_2^2 + p_2 \\ u_1(\rho_1 e_1 + p_1) &= u_2(\rho_2 e_2 + p_2) \end{aligned}}$$

Shocks & Burning Fronts

shock wave: continuity of all fluxes

- Rayleigh line:

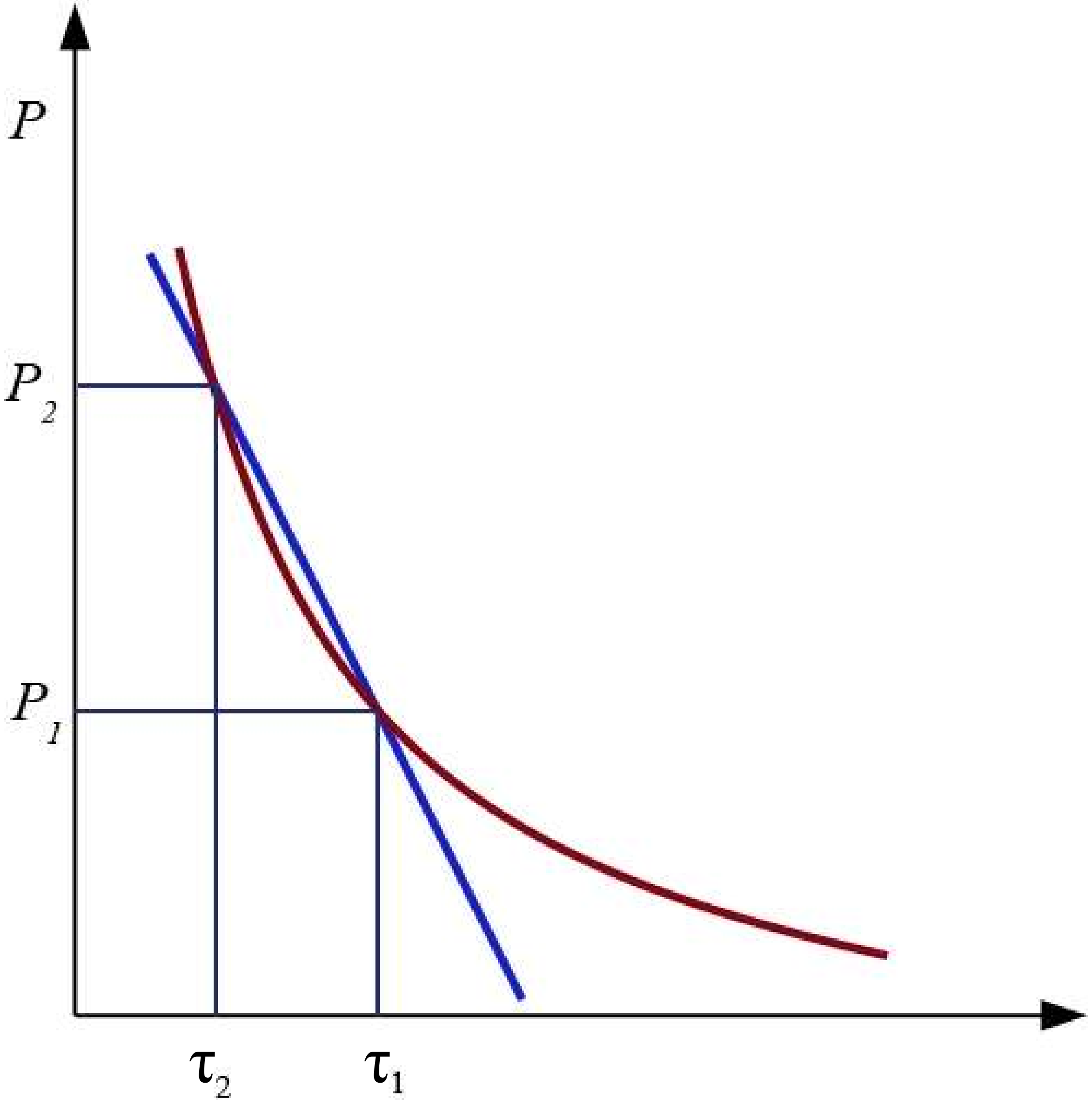
$$(\rho_1 v_{1,n})^2 = (\rho_2 v_{2,n})^2 = \frac{P_1 - P_2}{\tau_2 - \tau_1}$$

- shock adiabatic:

$$e_{\text{int},1} - e_{\text{int},2} = \frac{P_1 + P_2}{2}(\tau_1 - \tau_2)$$

$$\tau = 1/\rho$$

jump conditions for state variables over shock:



Shocks & Burning Fronts

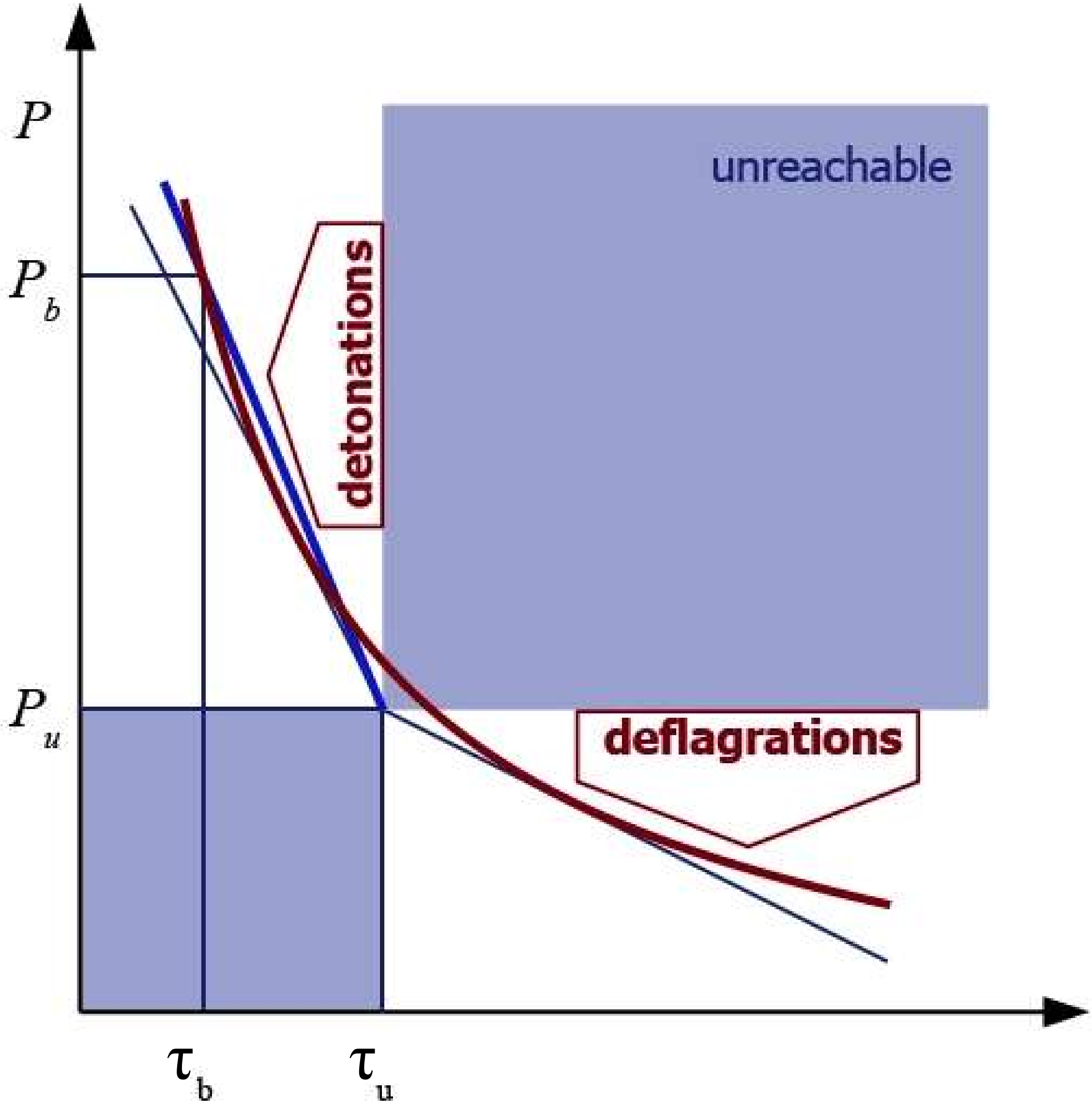
combustion wave:

- **Rayleigh line:**

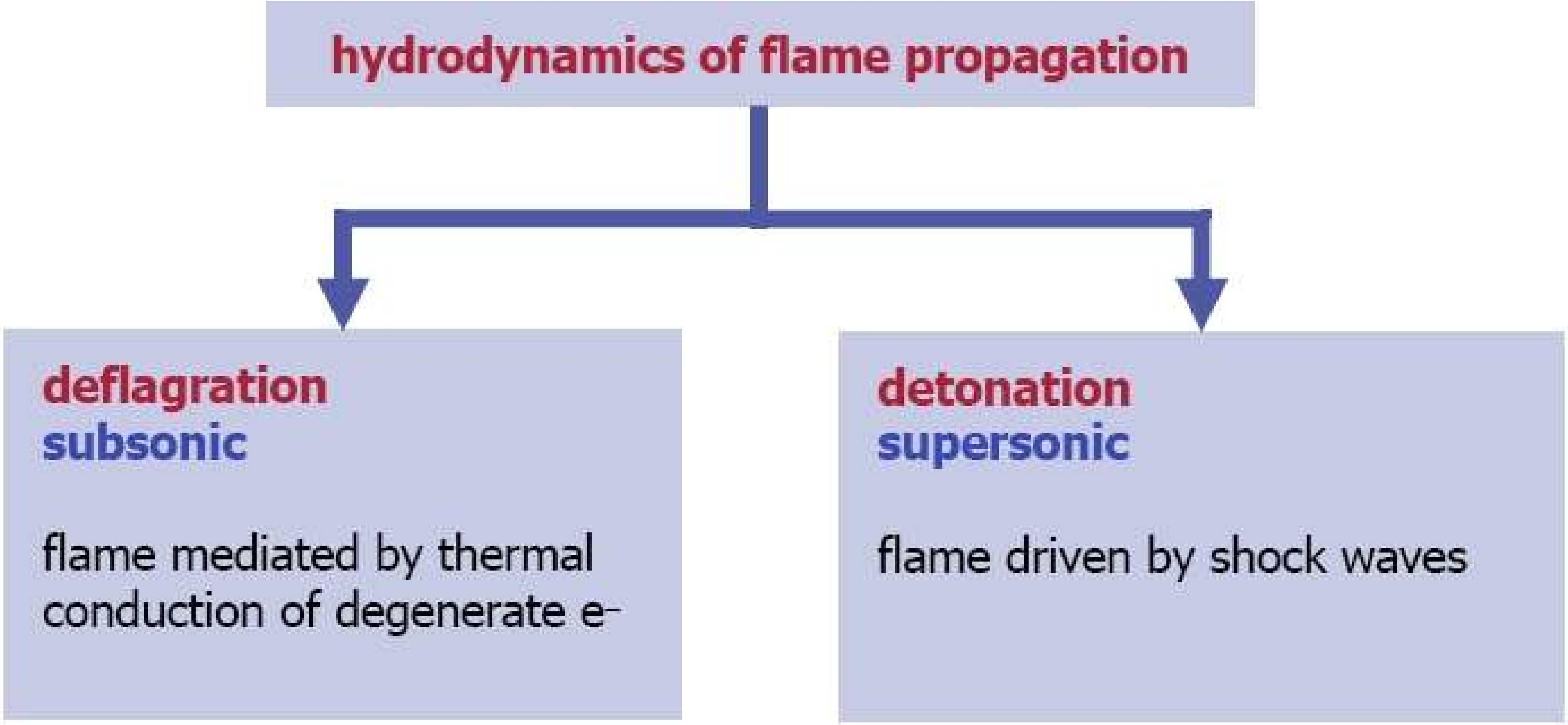
$$(\rho_u v_{u,n})^2 = (\rho_b v_{b,n})^2 = \frac{P_u - P_b}{\tau_b - \tau_u}$$

- **Hugoniot adiabatic:**

$$e_{\mathrm{int},u} - e_{\mathrm{int},b} = \boxed{\Delta h_0} + \frac{P_u + P_b}{2}(\tau_u - \tau_b)$$



Shocks & Burning Fronts



hydrodynamics of flame propagation

deflagration
subsonic

flame mediated by thermal conduction of degenerate e-

detonation
supersonic

flame driven by shock waves

What is the mode of nuclear burning in SNe Ia?

"Detonation":

(Super-) Sonic front;

heating to ignition by a shock wave.

"Deflagration":

Subsonic front;

heating to ignition by heat diffusion.

Strong Si-lines at maximum light:

Pure detonations are excluded!

(But possibly at lower densities???)

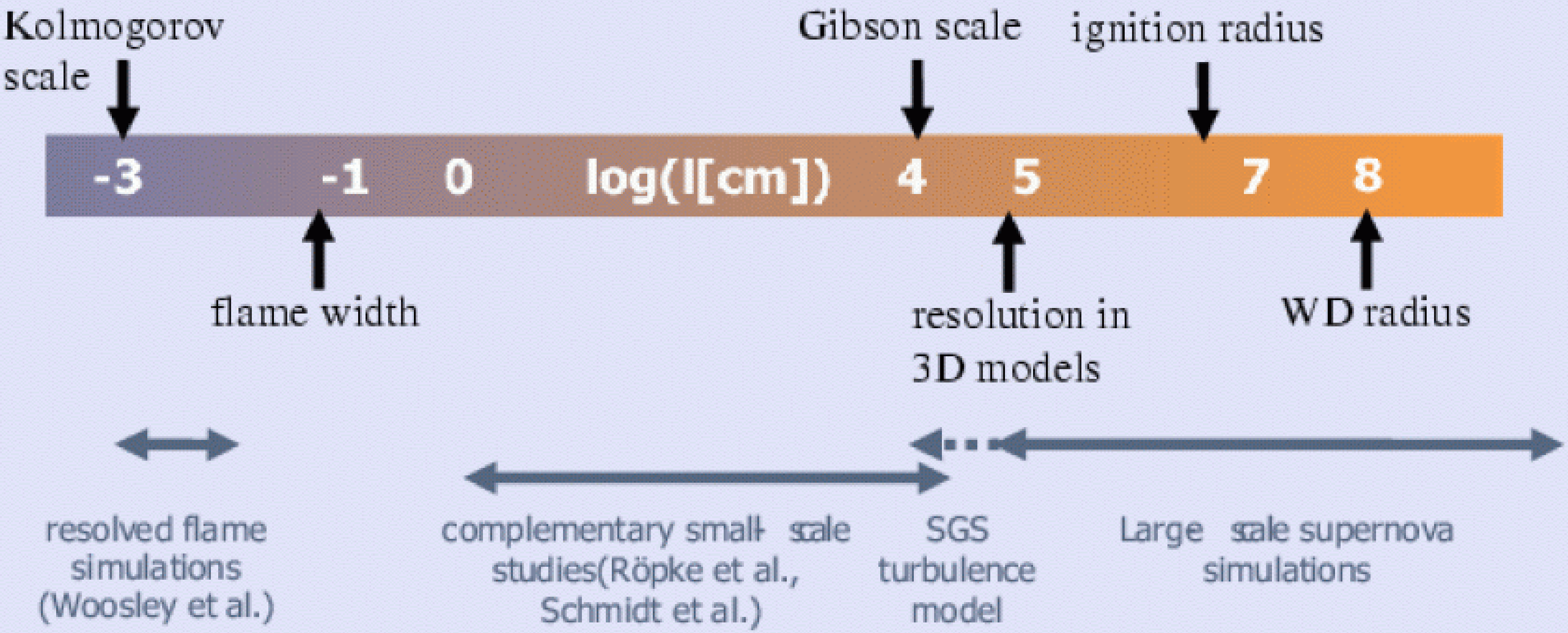
The physics of turbulent combustion

- Everydays experience: *Turbulence increases the burning velocity.*
- In a star: Reynoldsnumber ~ 10^{14} !
- In the limit of strong turbulence: $U_B \sim V_T$!
- Physics of thermonuclear burning is very similar to premixed chemical flames.

Relevant length scales in simulations of SN Ia explosions

beginning of the explosion:

flamelet regime



Kolmogorov scale

Gibson scale

ignition radius

-3 -1 0 log(l[cm]) 4 5 7 8

flame width

resolution in 3D models

WD radius

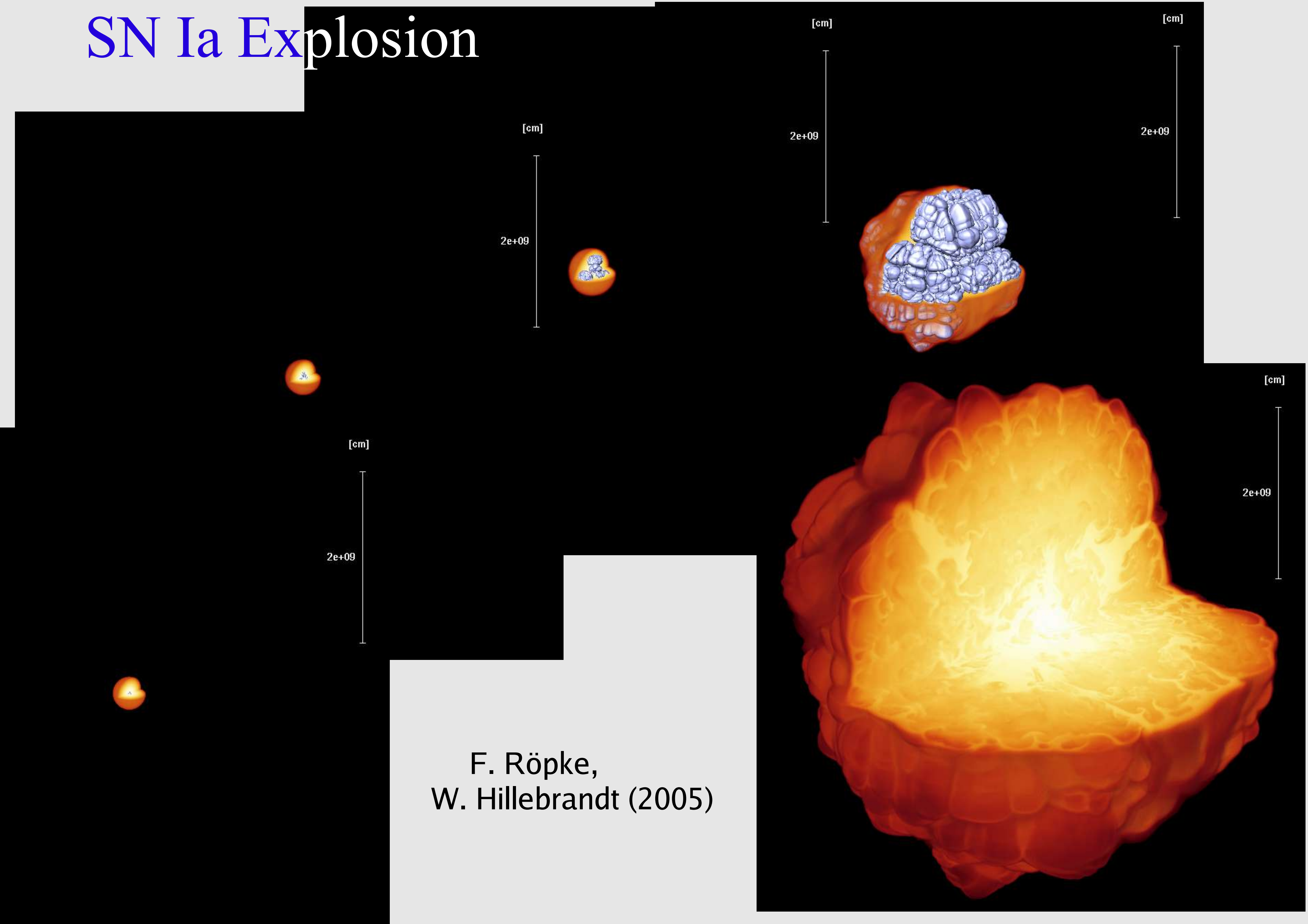
resolved flame simulations (Woosley et al.)

complementary small-scale studies(Röpke et al., Schmidt et al.)

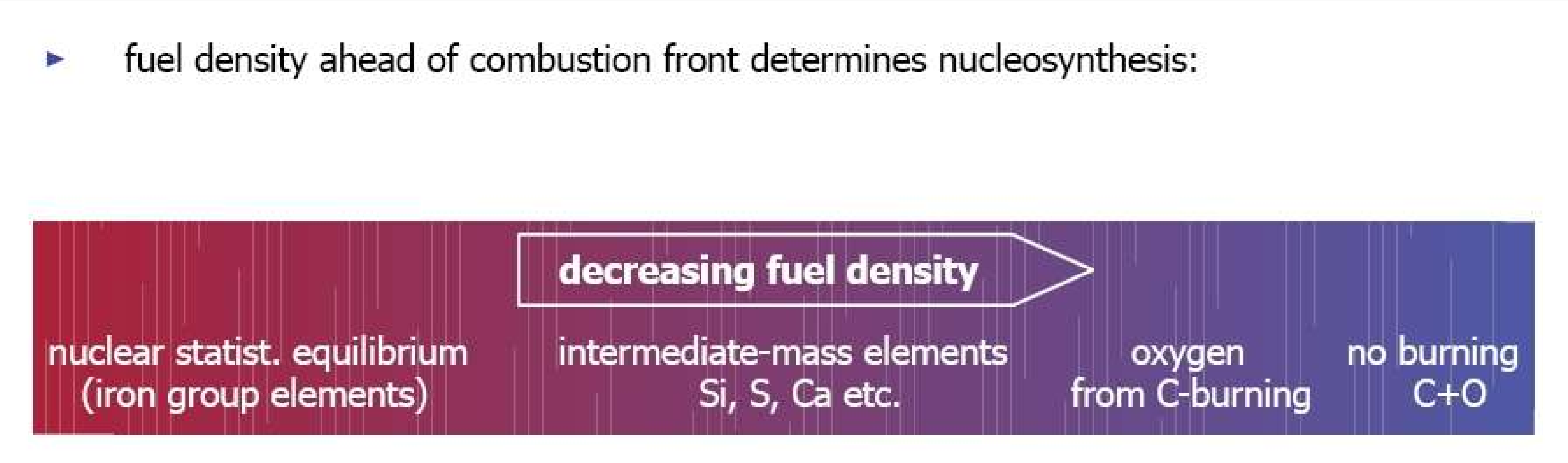
SGS turbulence model

Large scale supernova simulations

SN Ia Explosion



F. Röpke,
W. Hillebrandt (2005)



- fuel density ahead of combustion front determines nucleosynthesis:

decreasing fuel density

nuclear statist. equilibrium
(iron group elements)

intermediate-mass elements
Si, S, Ca etc.

oxygen
from C-burning

no burning
C+O

Deflagration allows pre-expansion of WD

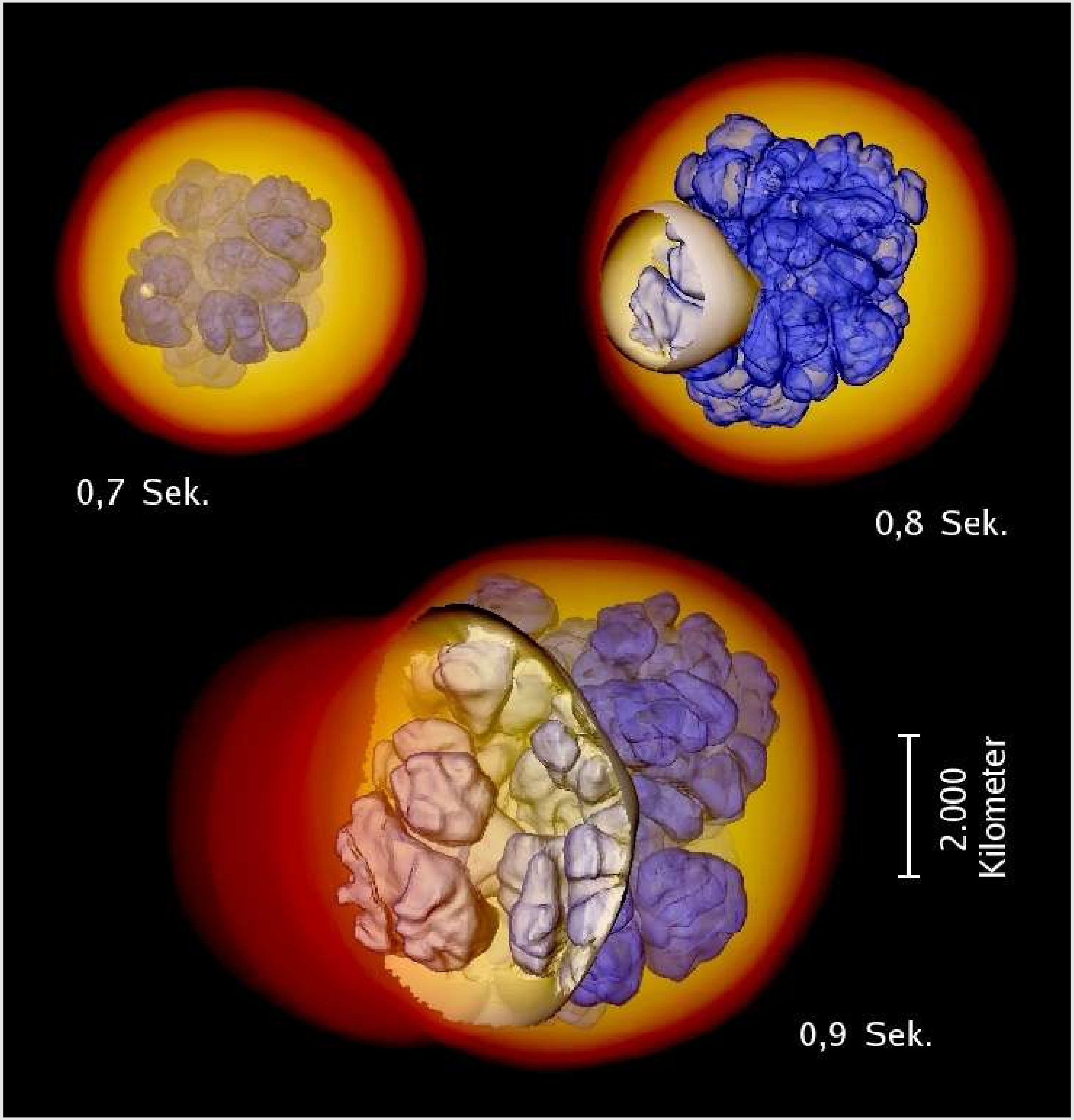
-------> leaves too much unburned C, O

====> pure deflagrations are also not possible for all SNIa !

Type Ia Supernovae – Achievements and Insights

- Deflagration models explode.
- Explosion energy ~$0.8*10^{51}$ ergs (a bit low), too much unburned C+O.
- Need of deflagration to detonation transition.
- Explosion energy and produced Ni depends on ignition conditions but not on composition.
- Brightness depends on amount of Ni produced, but only weakly on C+O composition.

Deflagration to Detonation Transition



Röpke
(2008)

Type Ia Supernovae –
Open Questions and Problems

- Are there different types of progenitors?
  Progenitor systems have not been observed yet !
  ("single degenerate" and "double degenerate" scenarios.)
- How does thermonuclear ignition of white dwarf start?
- Where and how does transition from deflagration to detonation occur?
- What is the reason for the Phillips relation?
  Are there any systematic uncertainties?

Contents

Lecture I :

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

Lecture II :

- Gravitational (core-collapse) supernovae: evolution stages
- Neutron stars and their birth
- Black holes and gamma-ray bursts
- Observable signals: neutrinos, gravitational waves, heavy elements

Core Collapse Events

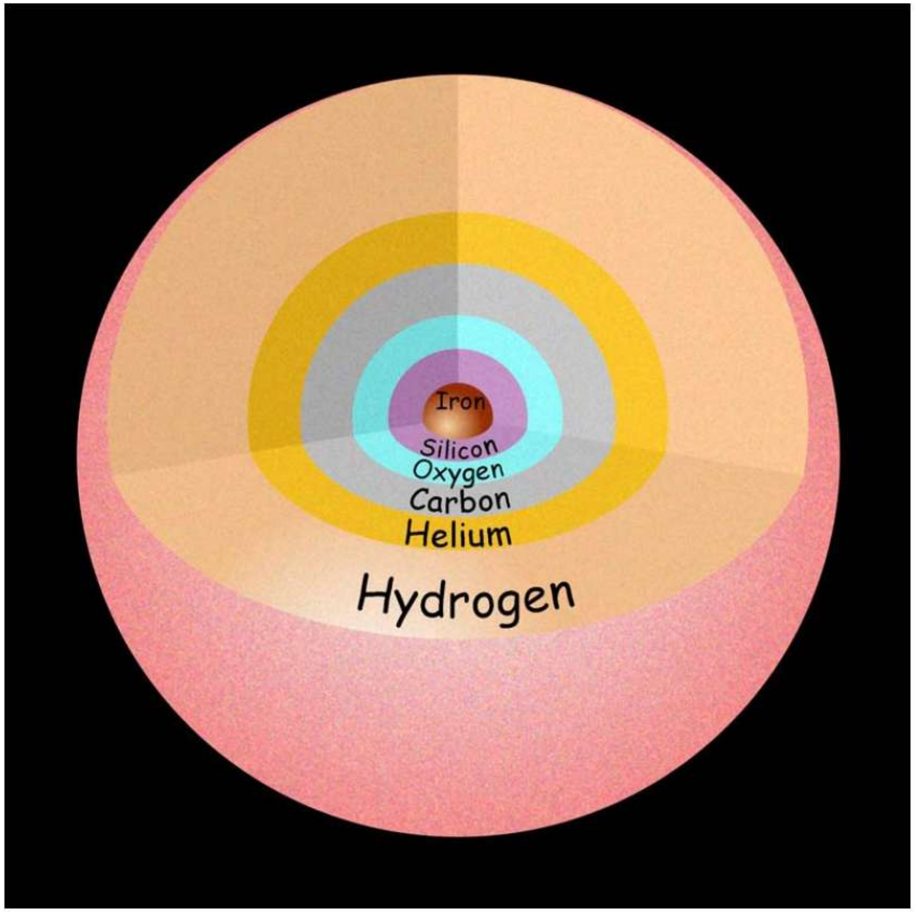
Final Stages of Stellar Evolution

- $8\ M_{sun} < M < 9\ M_{sun}$: onion shell structure with O-Ne-Mg core
- $9\ M_{sun} < M < 100\ M_{sun}$: onion shell structure with iron core

Gravitational collapse :

- $M = 8–25\ M_{sun}$: neutron star and supernova explosion
- $M > 25\ M_{sun}$: black hole and (sometimes) hypernova explosion and gamma-ray burst

Zwiebelschalen-Struktur

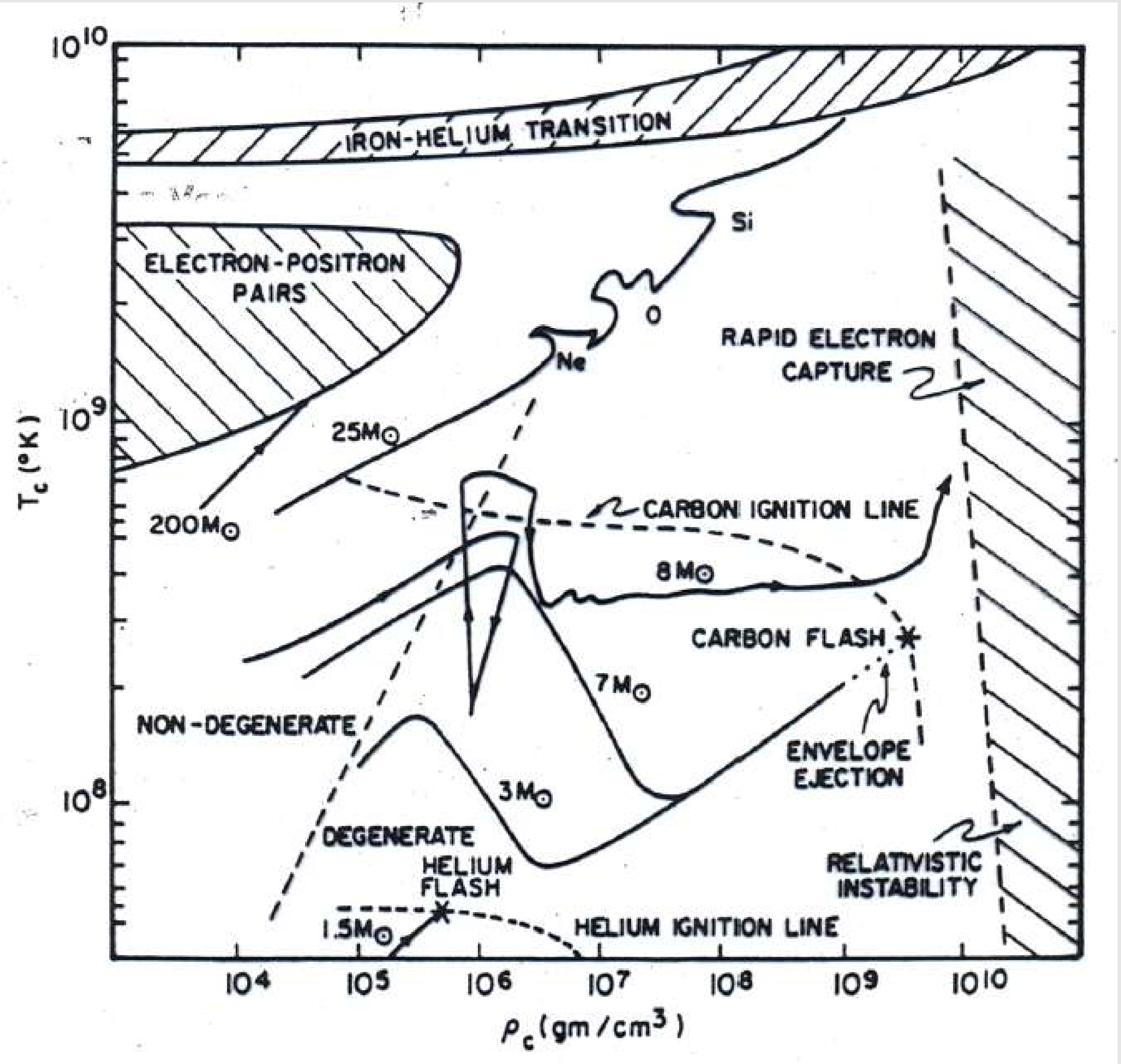


Final Stages of Massive Star Evolution

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

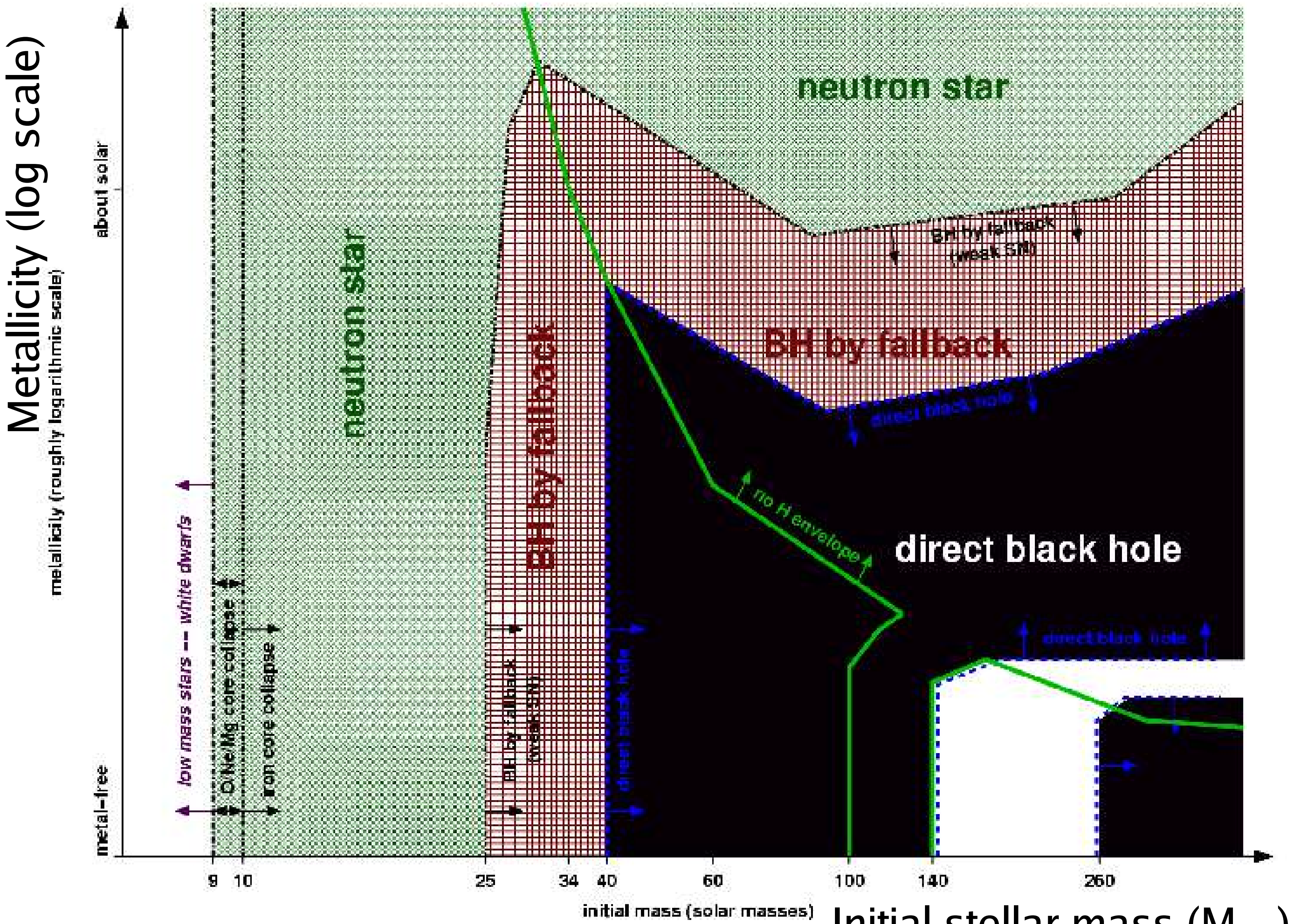
Stars with ~9–100 M_{sun} develop Fe cores
—> collapse by nuclear
photodisintegration

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



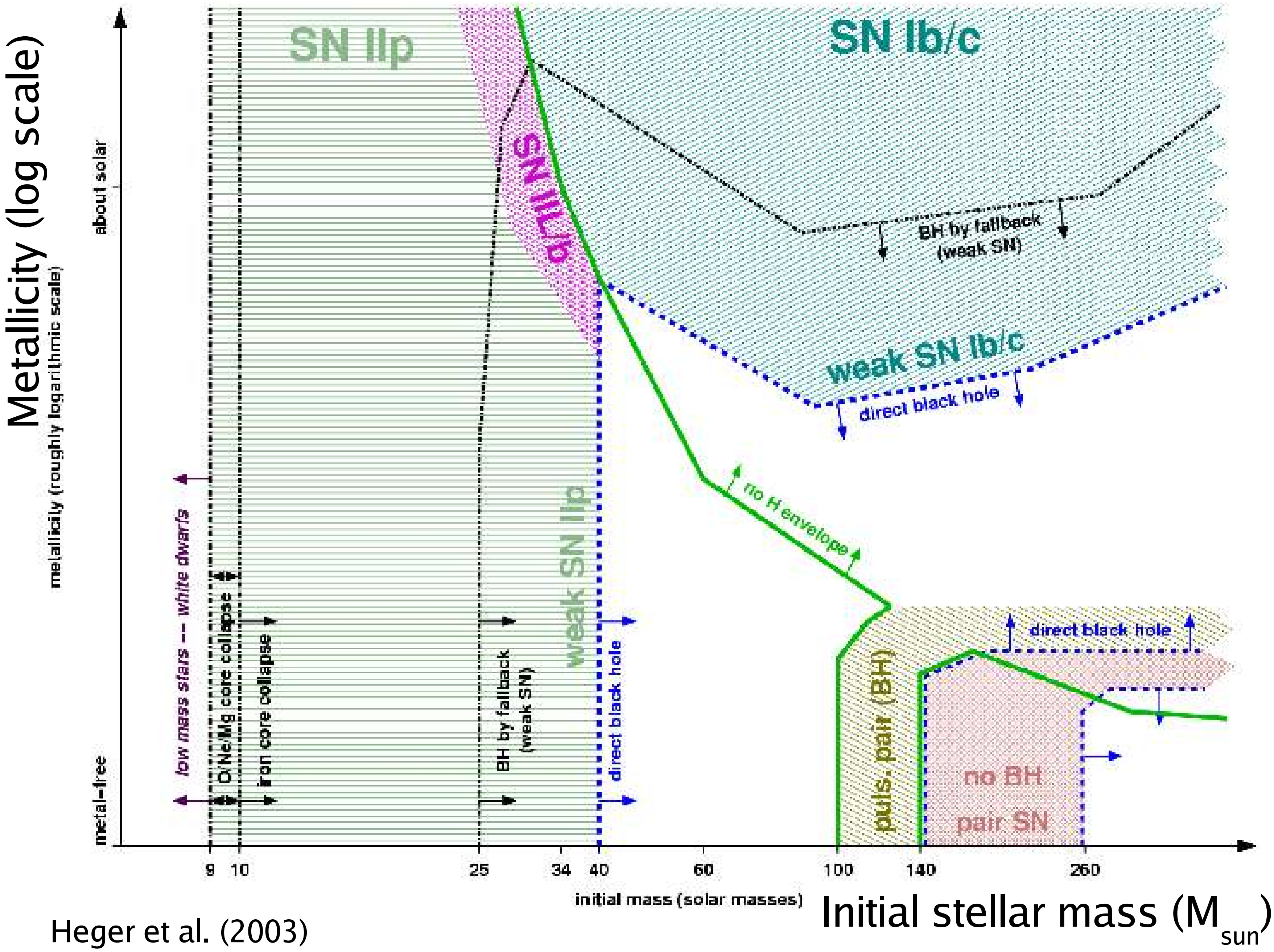
(Wheeler et al. 1990)

Core Collapse Events and Remnants



Heger et al. (2003)

Core Collapse Events and Remnants



Heger et al. (2003)

Core-Collapse Events

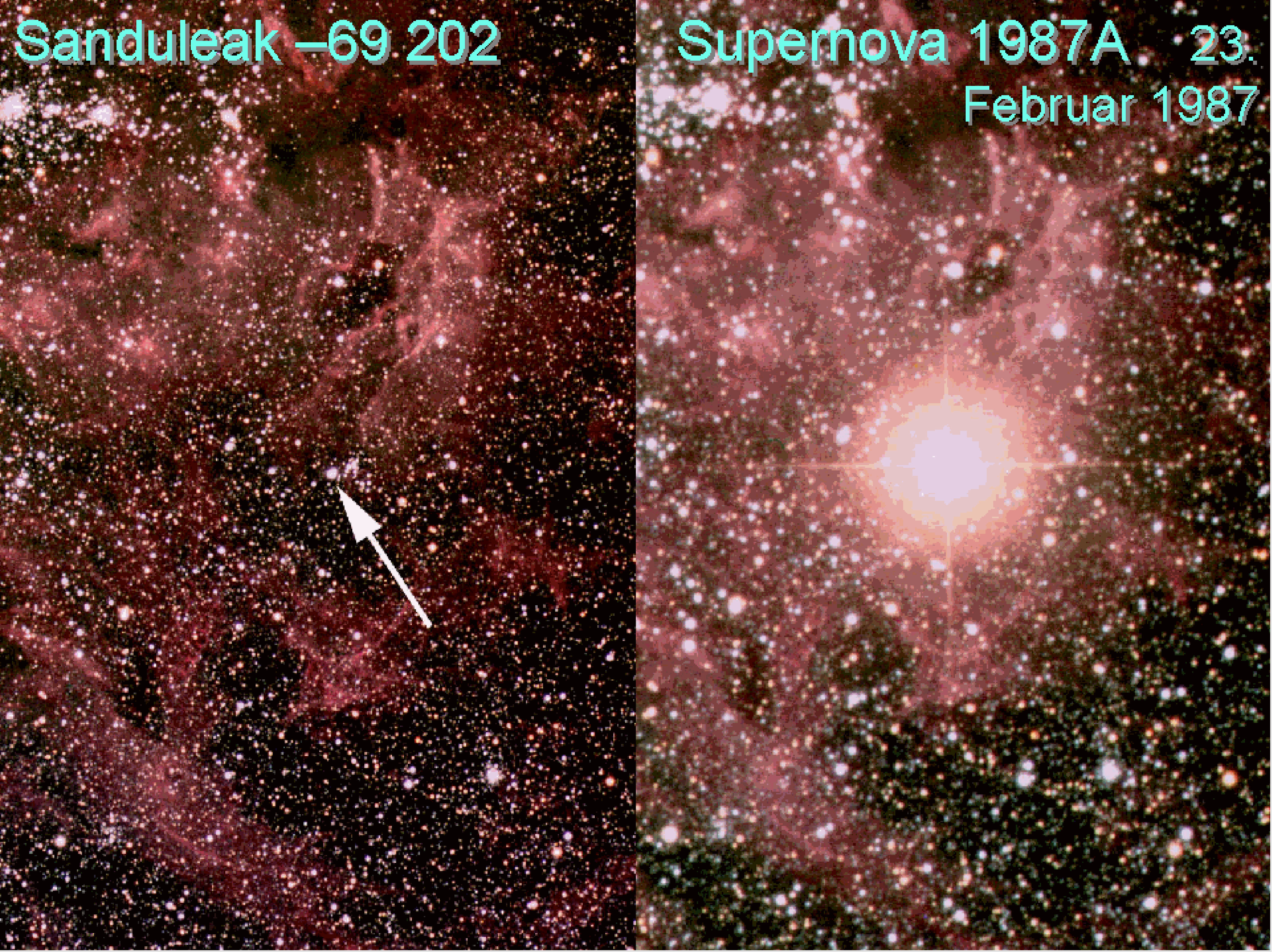
A heterogeneous class with growing diversity

- Observational diversity: Large variability due to structure of stellar mantle and envelope at time of explosion
- Intrinsic explosion differences: Events also differ largely in energy and Ni production
- 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 whether:
  - * neutron star (NS) or black hole (BH) forms in collapse;
  - * explosion mechanism, explosion energy, & Ni production;
  - * lightcurve and spectral properties <—> SN classes;
  - * anisotropy of explosion

"Ordinary" Supernovae

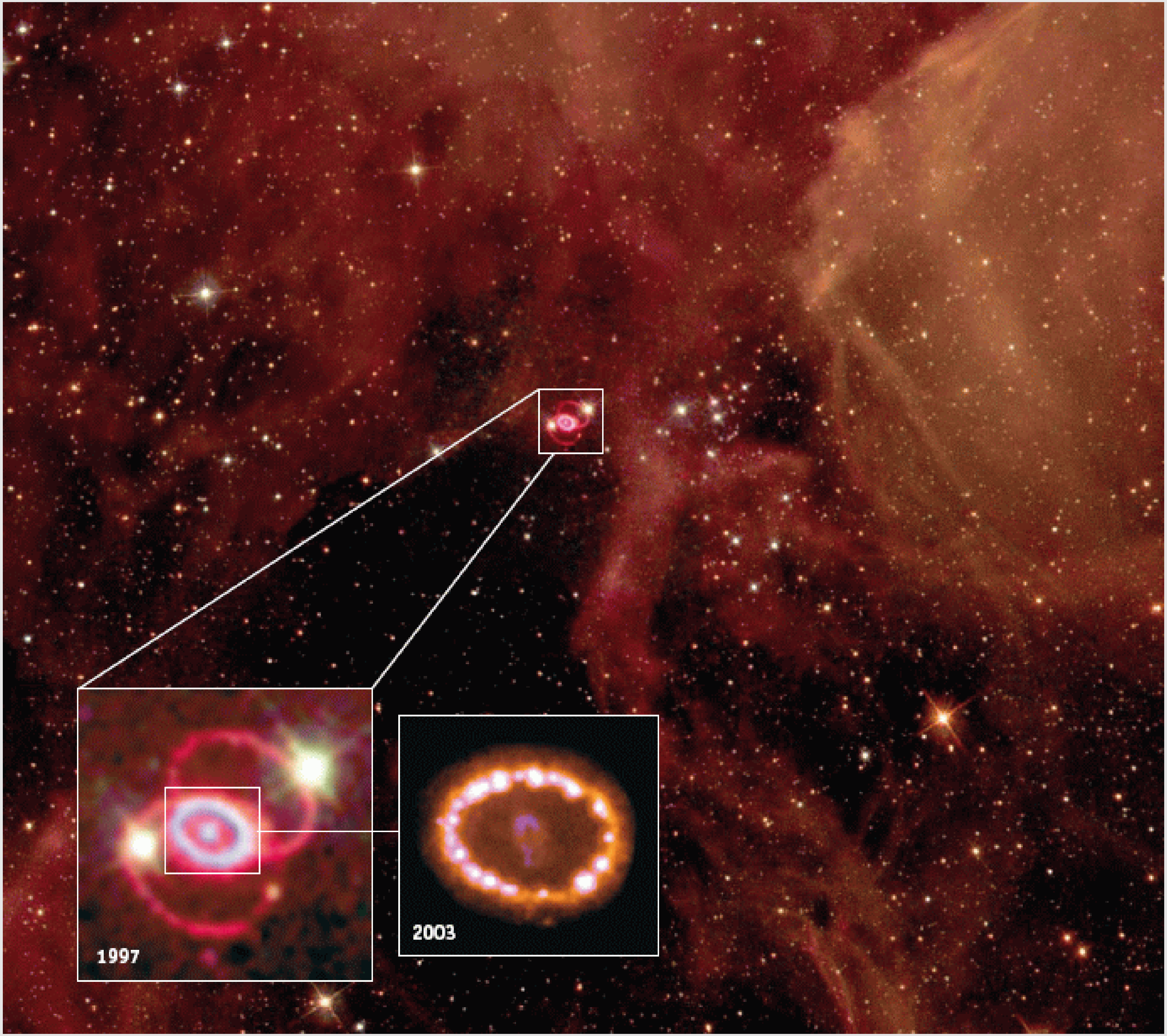
Gravitational collapse and explosions of stars

with $8\ M_{sun} < M_* < 100\ M_{sun}$


Sanduleak –69 202
Supernova 1987A
23. Februar 1987

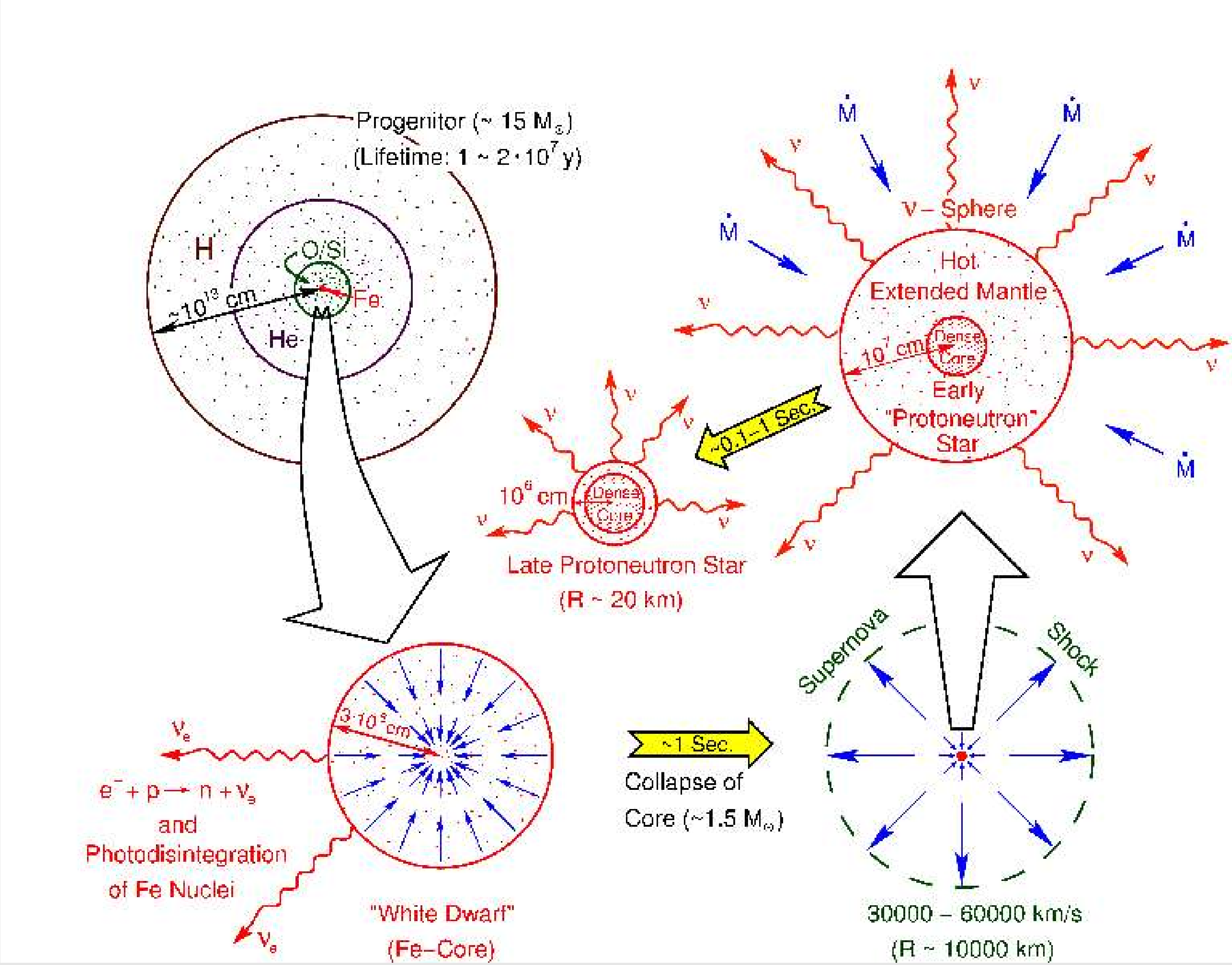
Supernova 1987A

- 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
  - * unambiguous information about strongly turbulent processes during stellar explosions



Supernova 1987A as a teenager

Stellar Collapse & Explosion



(adapted from A. Burrows)

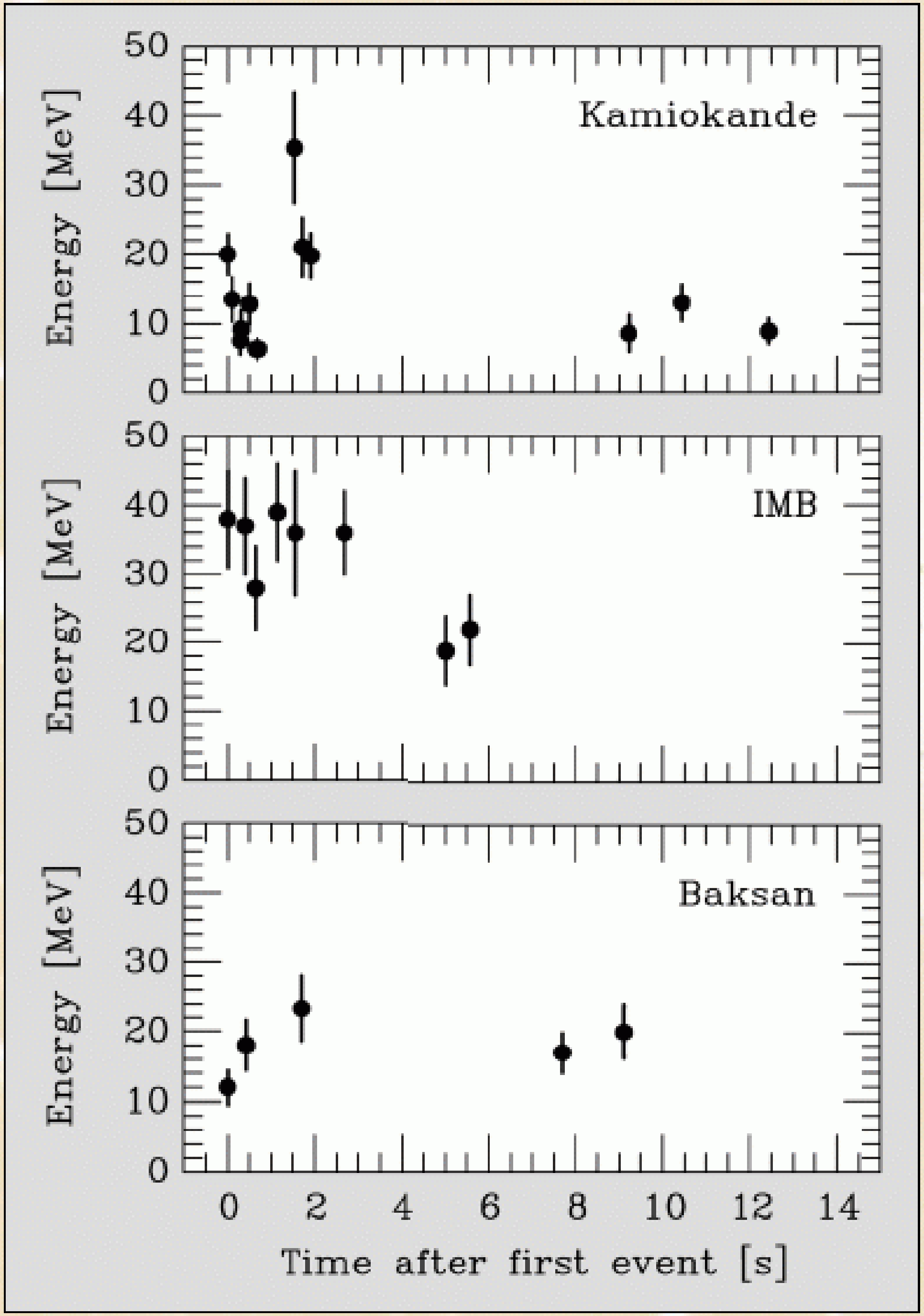
energy sources for a core collapse supernova explosion

gravitational binding energy (SNe II, Ib, Ic)
formation of a compact object of ~1 solar mass
with a radius ~10km

$$E_b \approx 3 \times 10^{53} \left(\frac{M}{\mathrm{M}_\odot}\right)^2 \left(\frac{R}{10\,\mathrm{km}}\right)^{-1} \text{ ergs}$$

Neutrino energy $E_\nu = E_b$
$\approx$ 100 × E_{kin} of SN explosion
$\approx 10^{51}$ erg = 10^{44} J

Neutrino Burst of Supernova 1987A



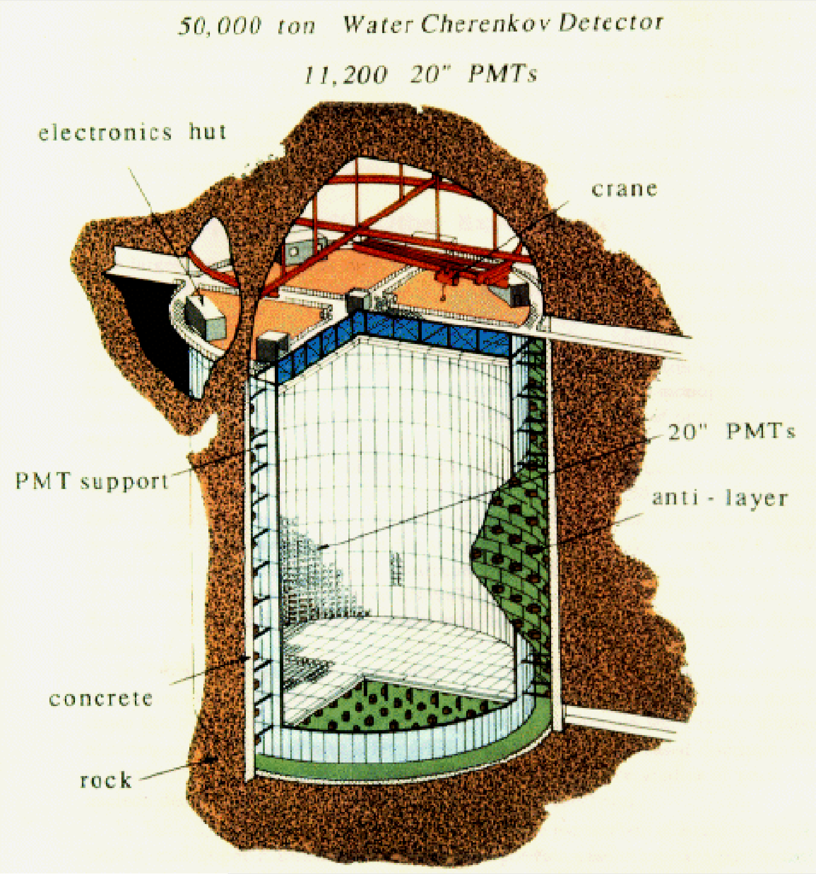
Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

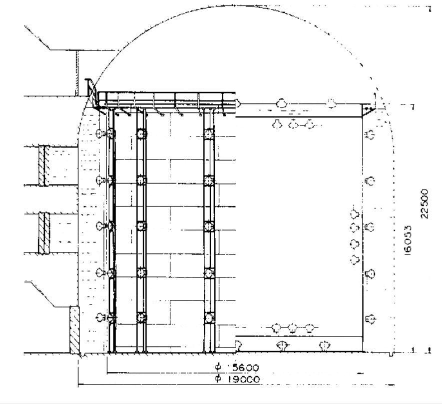
Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ±50 ms

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

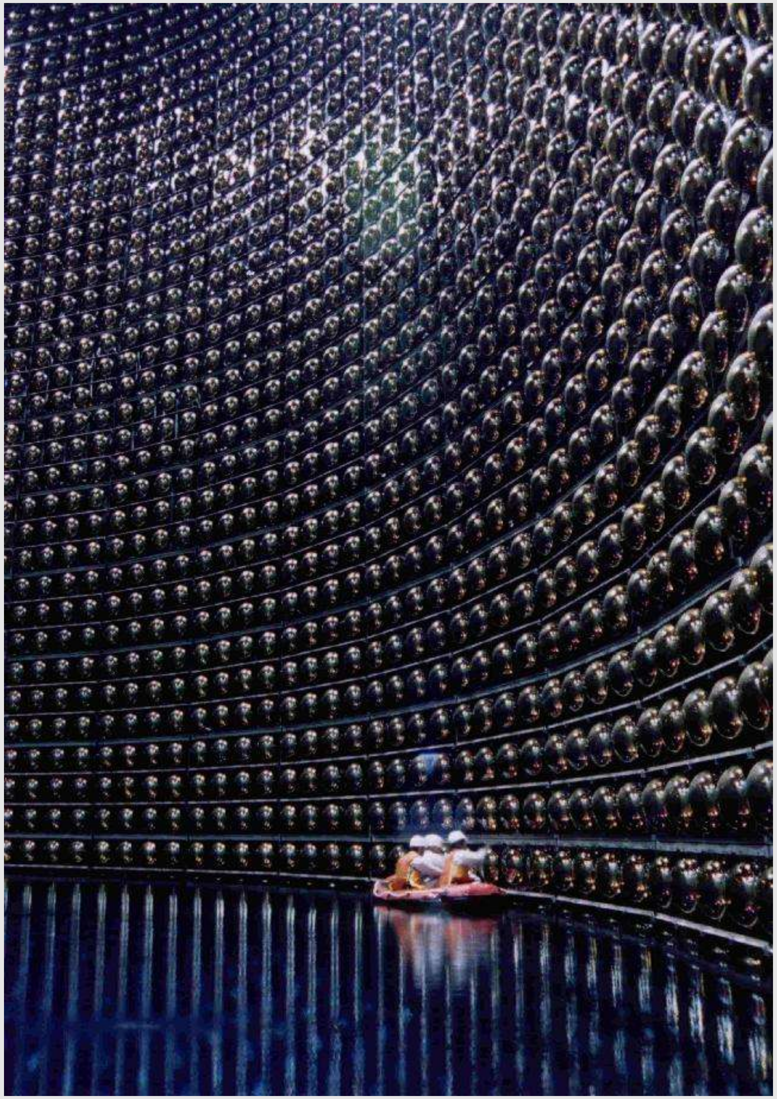
Within clock uncertainties, signals are contemporaneous

Supernova 1987A

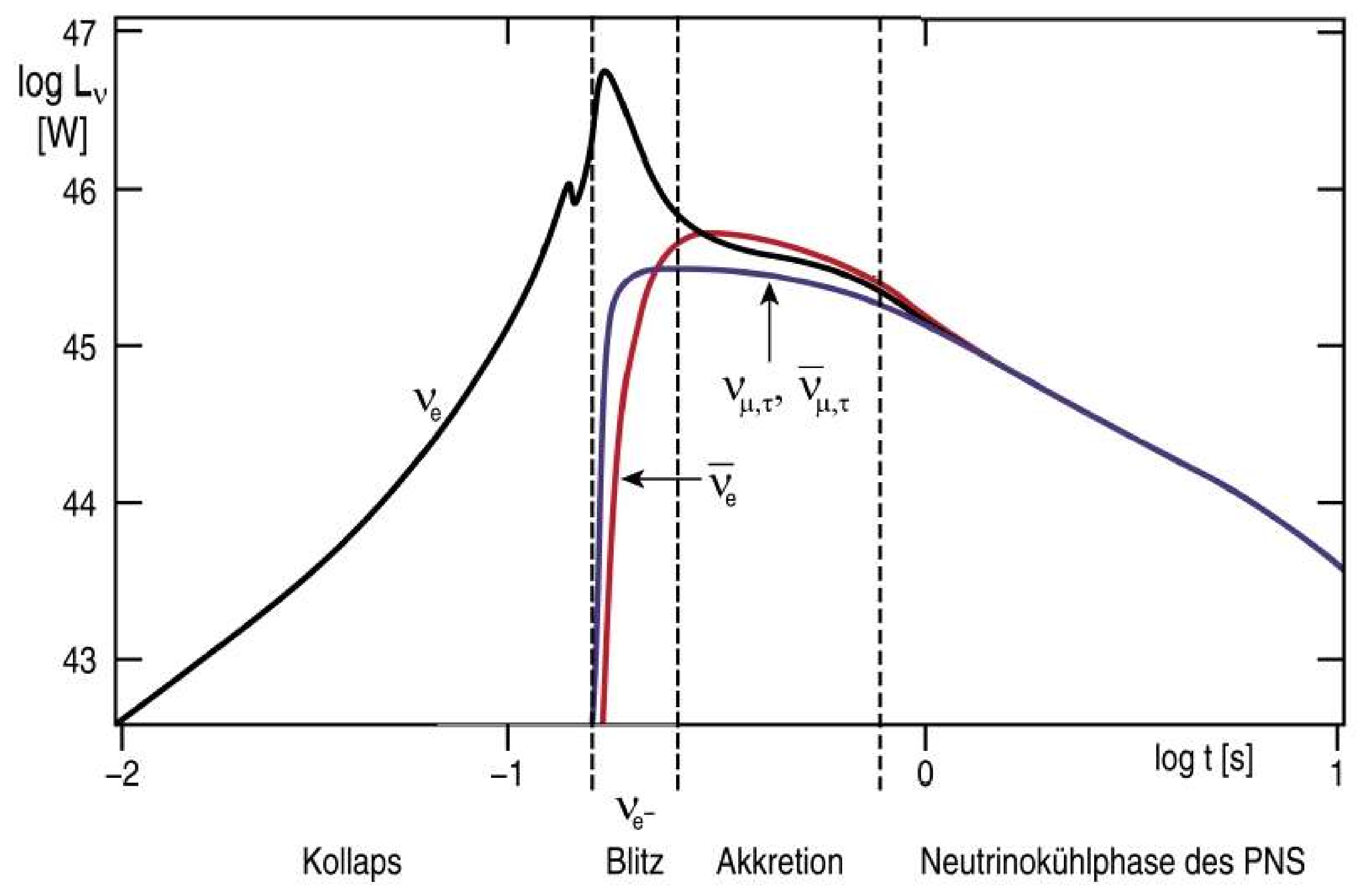




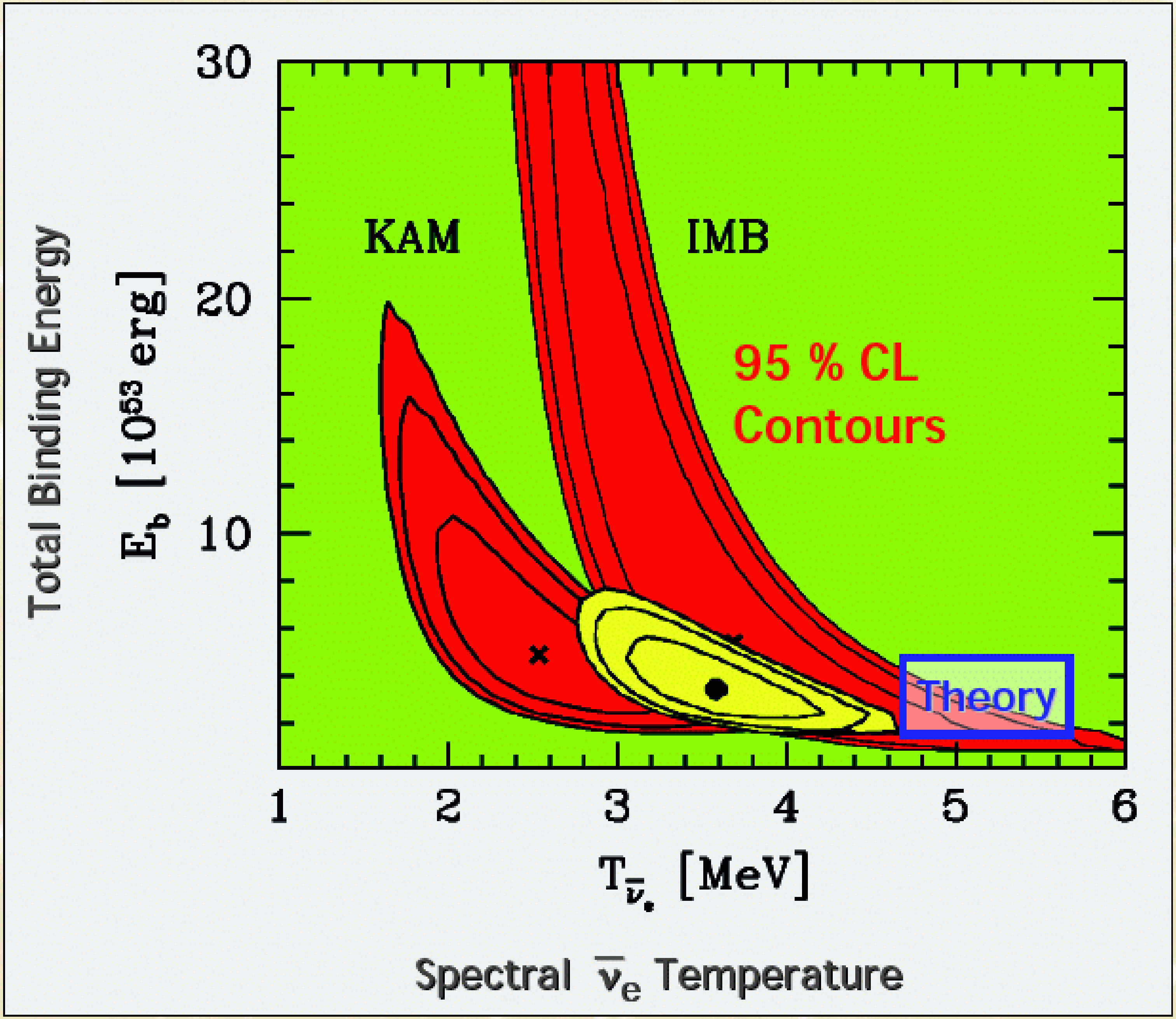
Two dozen (of 10^{58}) neutrinos were captured in underground laboratories!



Neutrino Luminosities (schematic)



Interpreting SN 1987A Neutrinos



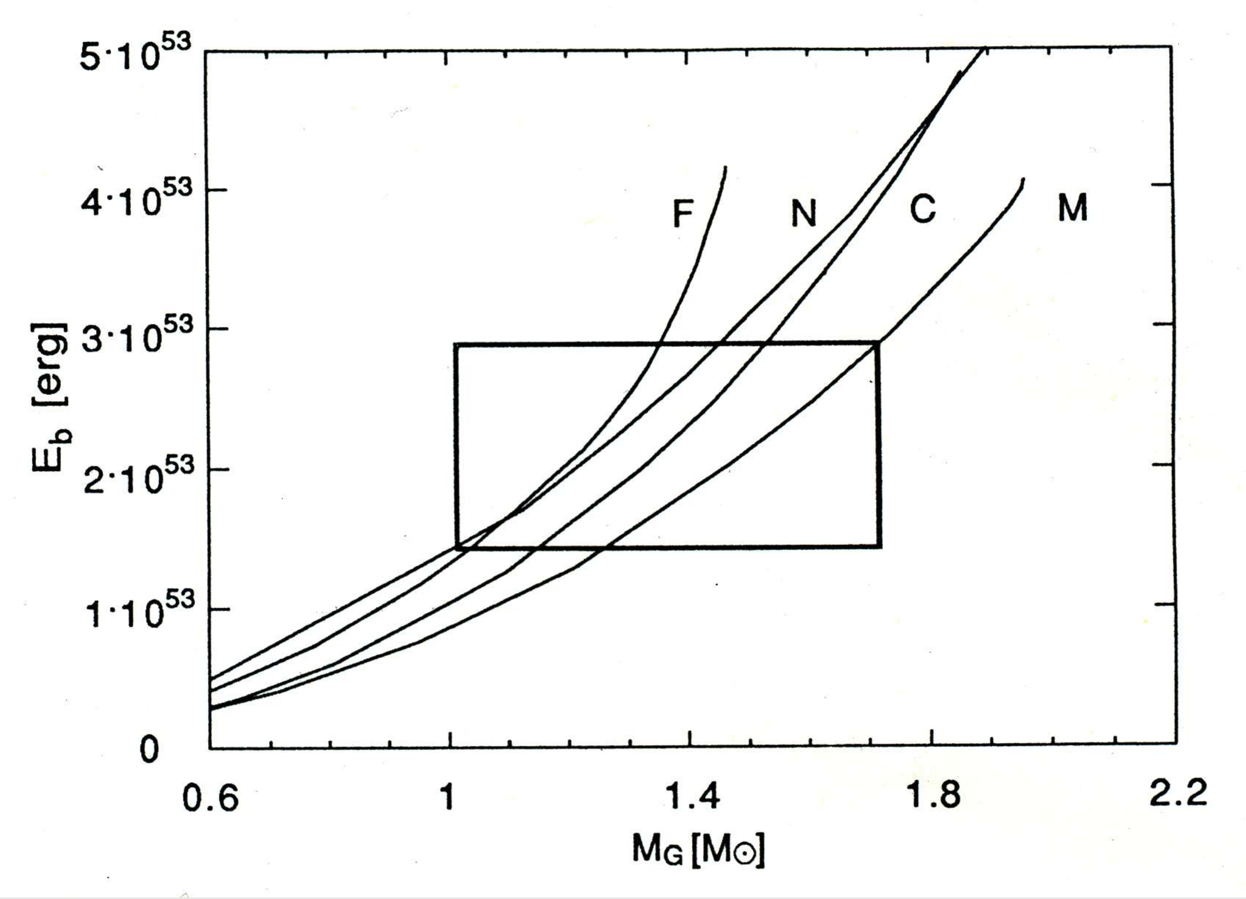
Jegerlehner, Neubig & Raffelt, PRD 54 (1996) 1194

Assume thermal spectra and equipartition of energy between the six degrees of freedom ν_e, ν_μ, ν_τ and their antiparticles

SN 1987A: Neutrino Signal

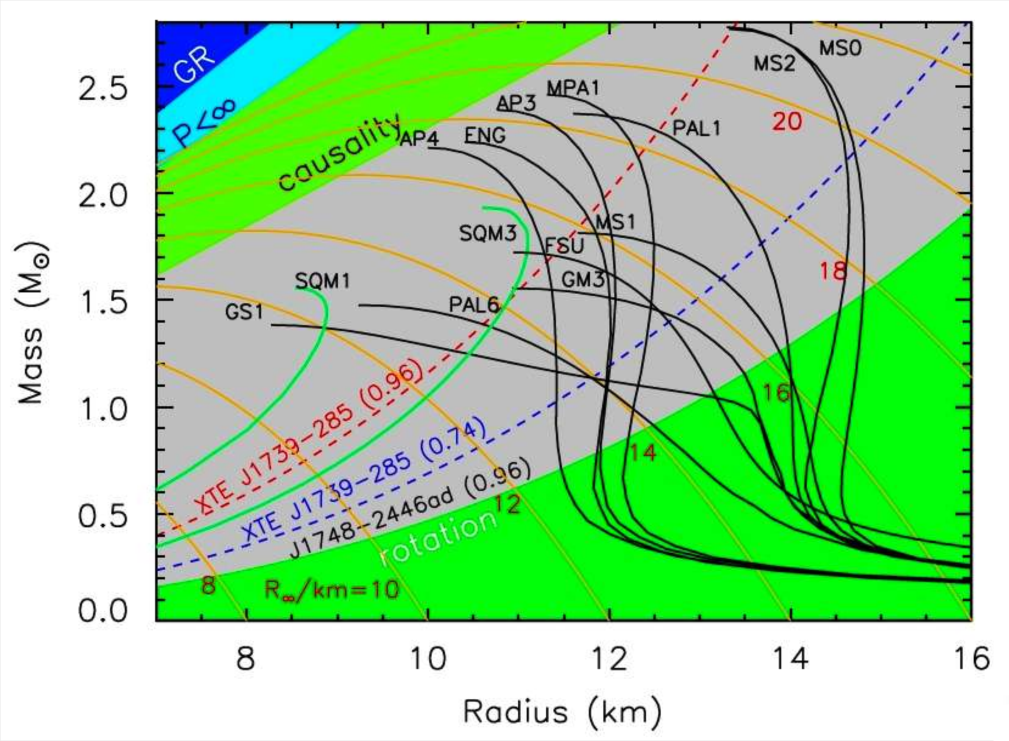
- Neutrino signal was used to constrain properties of neutrinos and other particles that may be produced in the SN core (e.g. axions)
- Neutrinos were used as probe of fundamental physics
- Neutrinos provided evidence for neutron star formation

Neutrino signal contains information about the nuclear EoS!

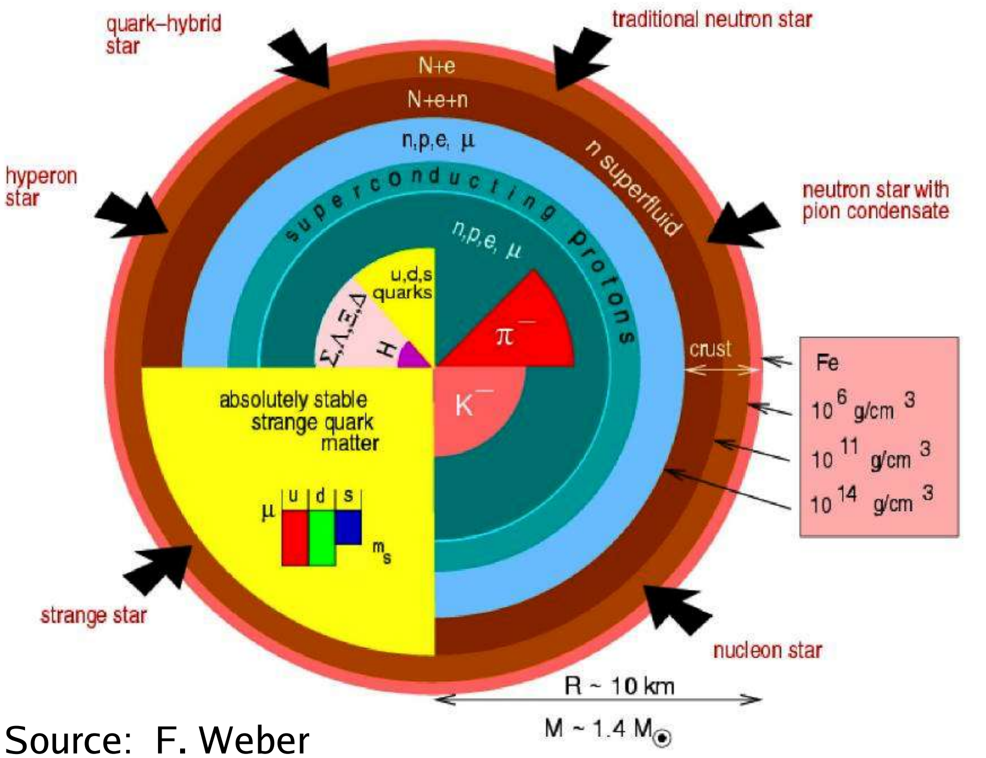


(Suzuki, PhD Thesis 1990)

Neutron Star Equations of State



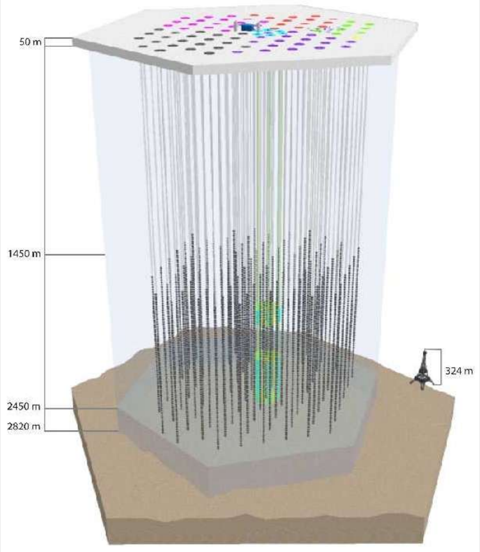
Lattimer & Prakash, Phys. Rep. 442 (2007)



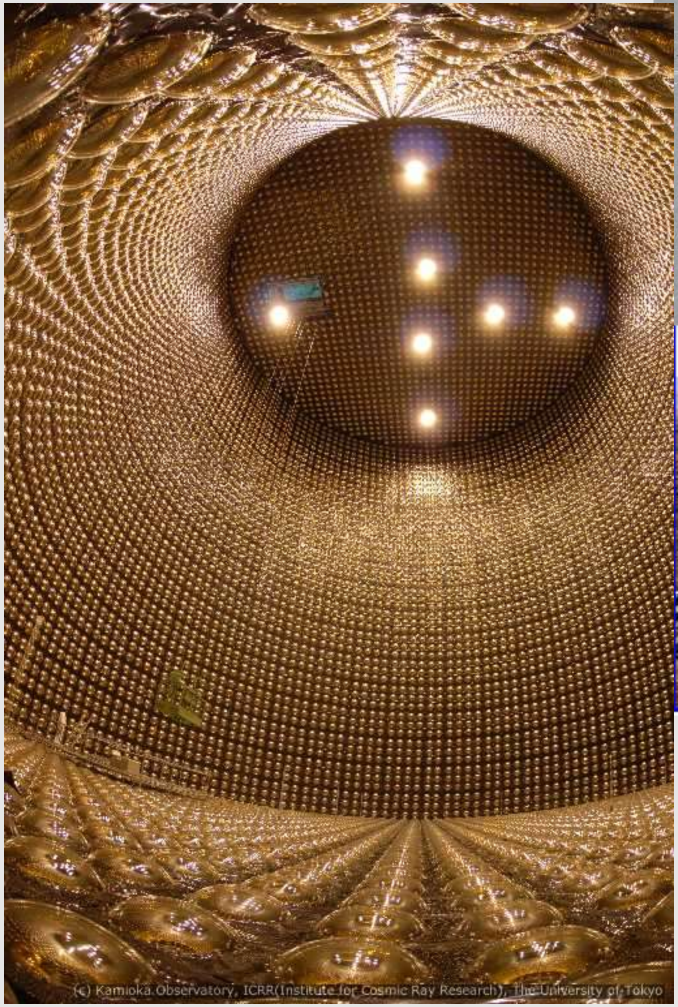
Source: F. Weber

Detecting Core-Collapse SN Signals

IceCube



Superkamiokande

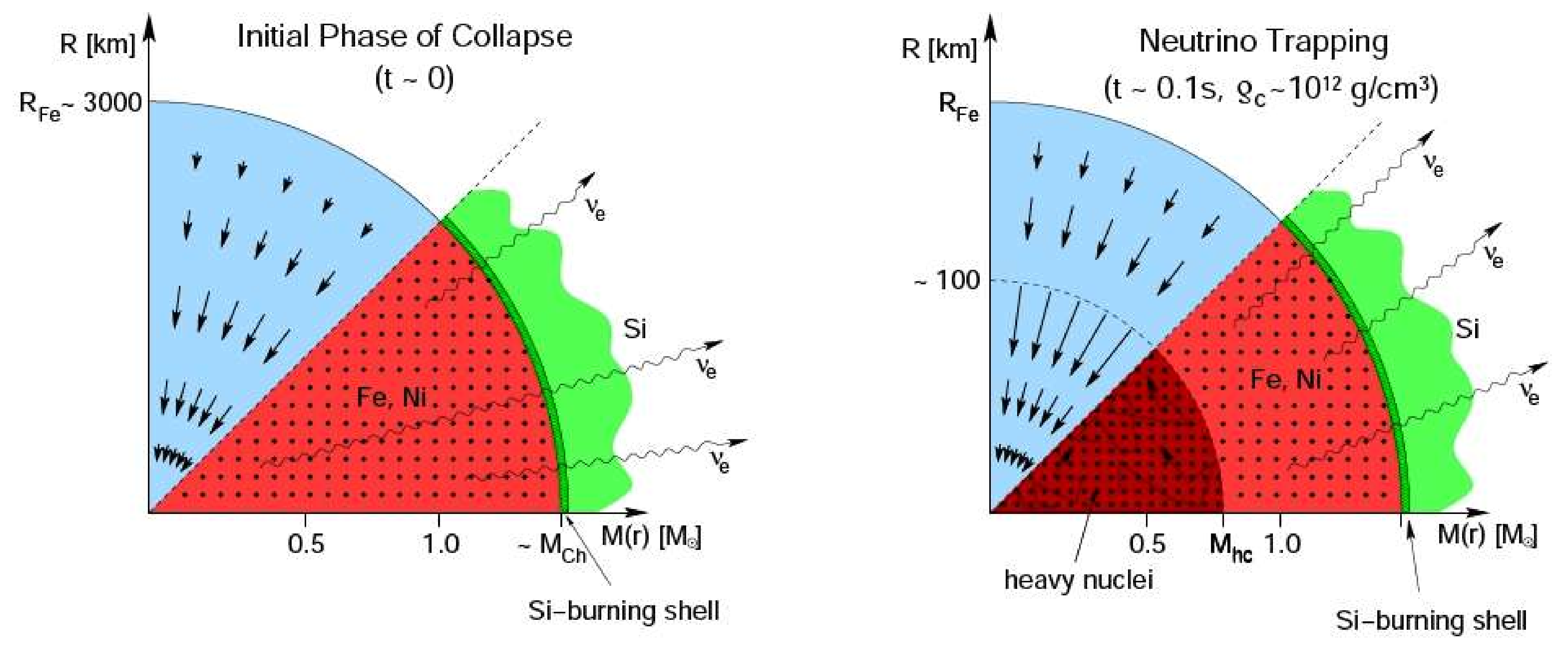

(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

LIGO

VIRGO

What happens in the Supernova Core?

Stellar core collapse

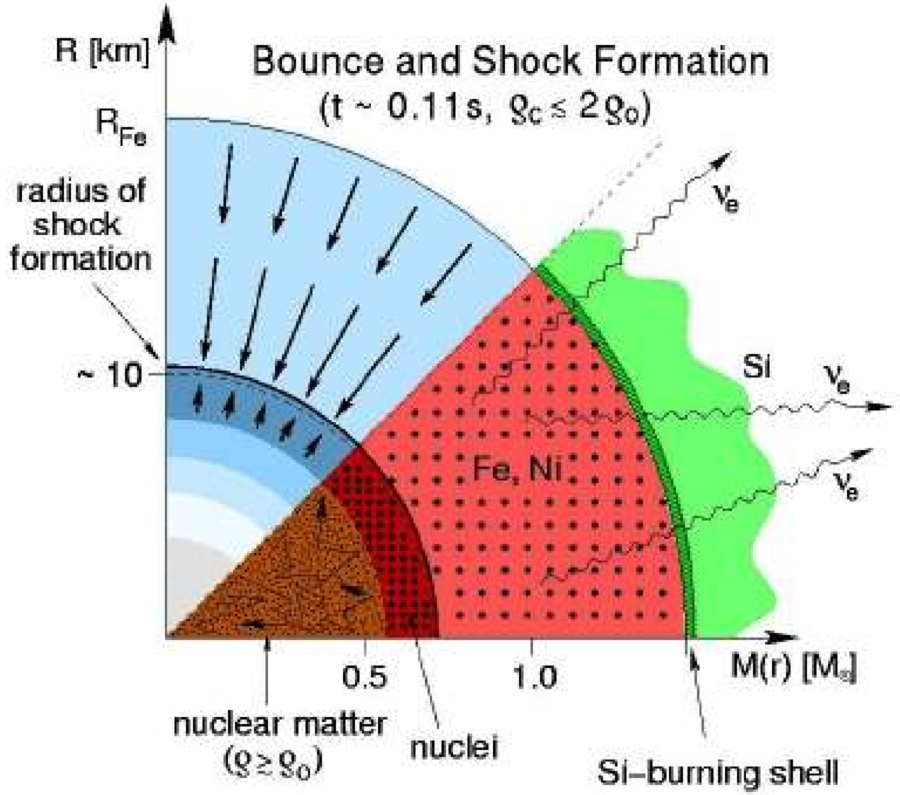


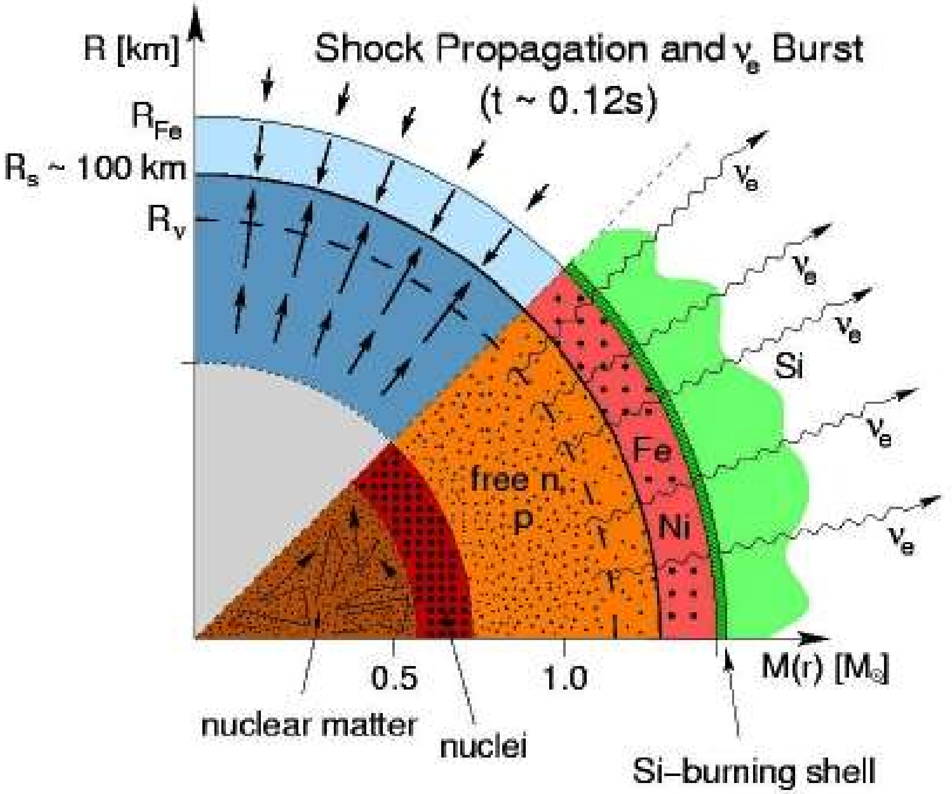
- Neutrinos produced by electron captures escape: no β-equilibrium
  -----> deleptonization, neutronization of stellar gas
- Little entropy change -----> collapse proceeds nearly adiabatically
- Initially neutrinos escape freely
- For densities > ~ 1/100 of nuclear matter: neutrinos get trapped (diffusion timescale becomes longer than collapse timescale)

Core collapse supernovae:

- prompt explosion mechanism does not work

(explored during the 1970's and 1980's; commonly accepted early 1990's)



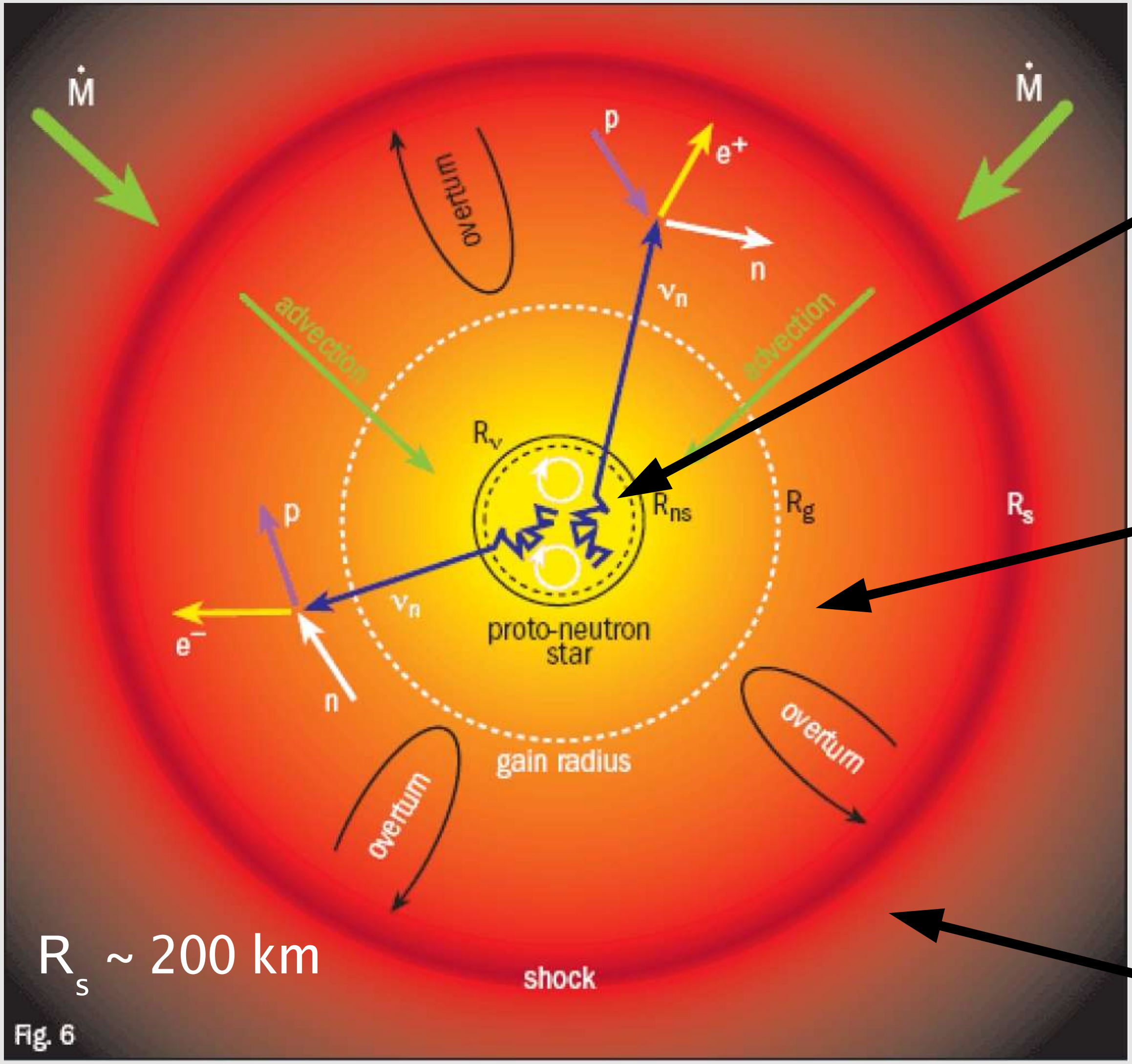


shock wave forms close to sonic point (M ~ 0.5 M_{sun})
initial energy: (5 ... 8) x 10^{51} erg

severe energy losses during shock propagation (8 MeV/nucleon or 1.6 x 10^{51} erg/0.1M_{sun})

Core collapse supernovae: neutrino-driven delayed explosion

(Wilson ´82, Bethe & Wilson '85)



$R_s \sim 200$ km

Fig. 6

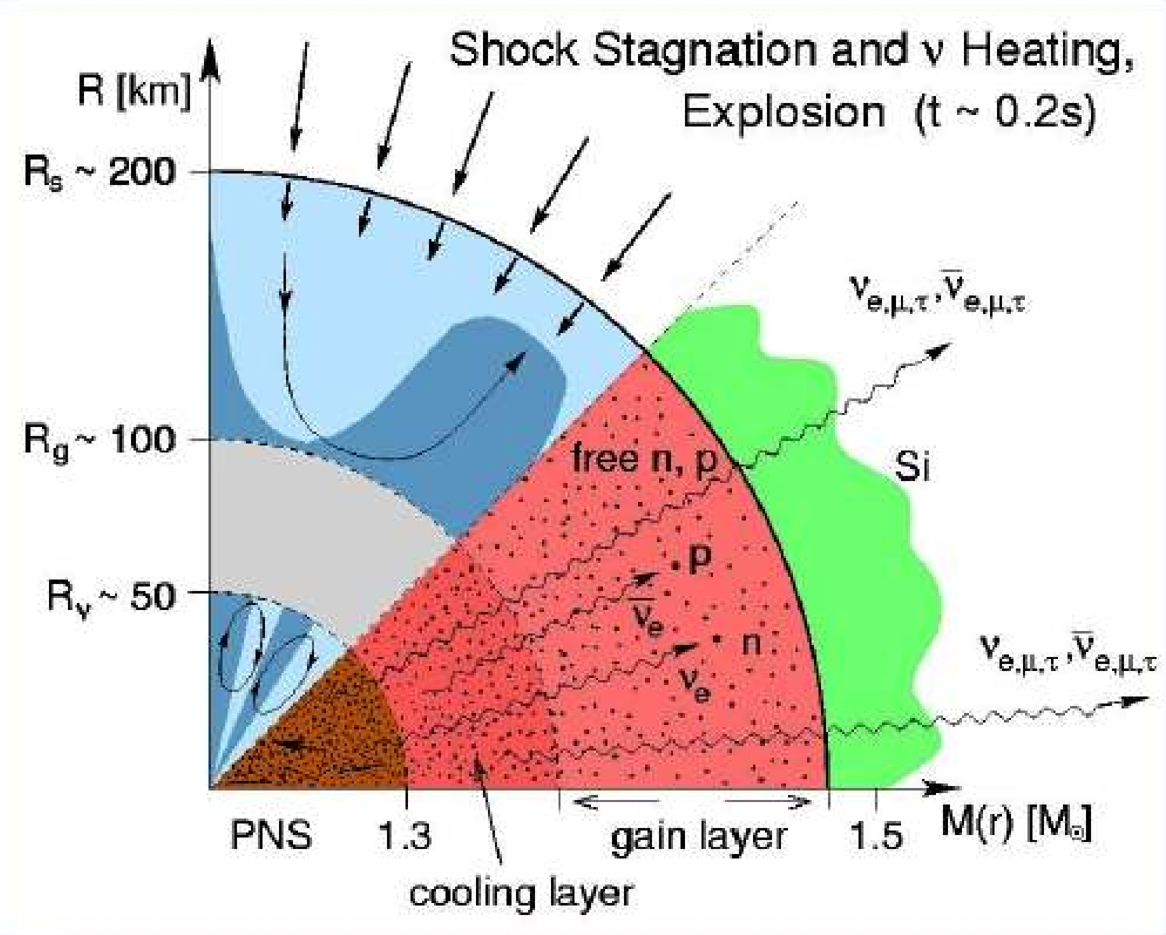
neutrinos diffuse out of opaque proto-neutron star ($\tau_\nu \sim 1$)

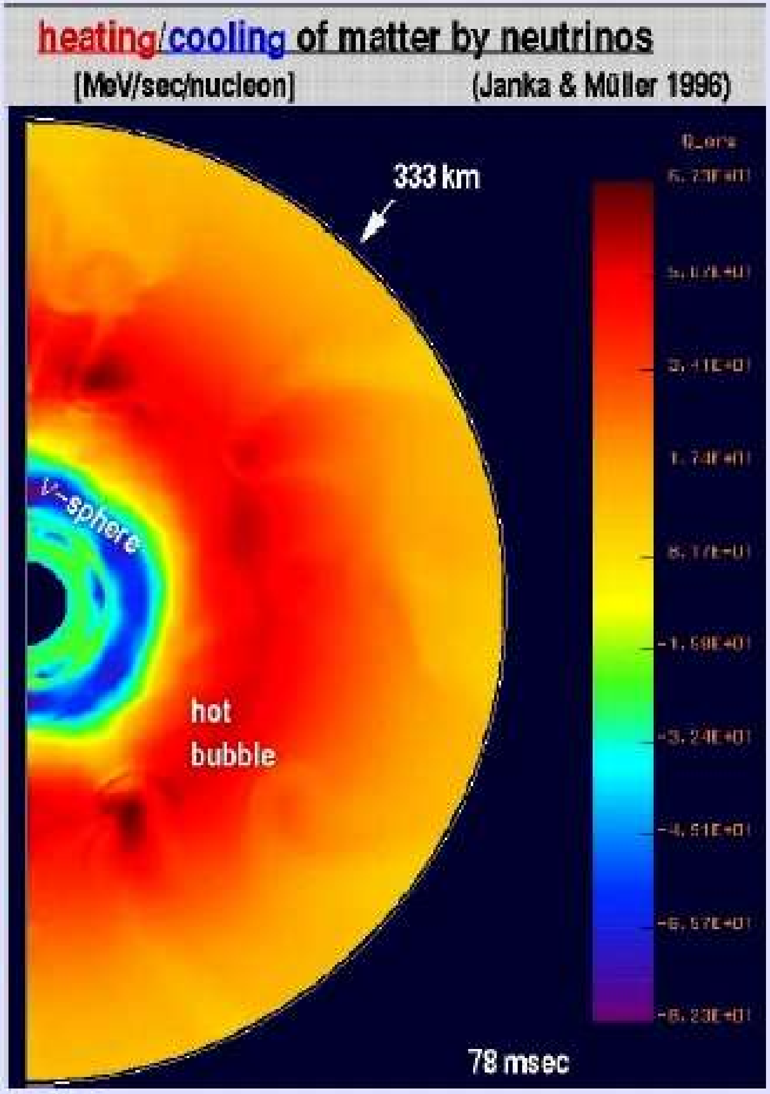
neutrinos heat matter in semi-transparent ($\tau_\nu \sim 1$) post-shock region ---> convection with coexisting downflows and rising hot bubbles sets in

neutrinos stream freely through stellar envelope ($\tau_\nu << 1$)

current paradigm: neutrino driven delayed explosions

(discovered through computer simulations by Wilson '82, and first analyzed by Wilson & Bethe '85)





Neutrino Heating of SN Shock

$$\nu_\mathrm{e} + n \longleftrightarrow e^- + p$$

$$\bar{\nu}_\mathrm{e} + p \longleftrightarrow e^+ + n$$

$$Q^+_{\nu_\mathrm{e},\bar{\nu}_\mathrm{e}} \cong 110 \cdot \frac{L_{\nu,52}\langle\epsilon^2_{\nu,15}\rangle}{r_7^2\langle\mu\rangle} \cdot \left\{ \begin{matrix} Y_n \\ Y_p \end{matrix} \right\} \left[\frac{\mathrm{MeV}}{\mathrm{s}\cdot\mathrm{nucleon}}\right]$$

$$Q^-_{\nu_\mathrm{e},\bar{\nu}_\mathrm{e}} \cong 2.4 \left(\frac{T}{1\mathrm{MeV}}\right)^6 \cdot \left\{ \begin{matrix} Y_p \\ Y_n \end{matrix} \right\} \left[\frac{\mathrm{MeV}}{\mathrm{s}\cdot\mathrm{nucleon}}\right]$$

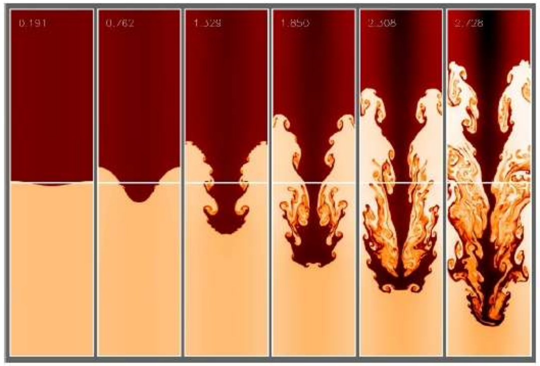
$$\begin{aligned} L_\nu &= 4\pi r^2 \frac{2\pi c}{(hc)^3} \int d\epsilon_\nu d\mu_\nu \epsilon_\nu^3 \mu_\nu f, \\ \langle\epsilon_\nu^2\rangle &= \frac{\int d\epsilon_\nu d\mu_\nu \epsilon_\nu^5 f}{\int d\epsilon_\nu d\mu_\nu \epsilon_\nu^3 f}, \\ \langle\mu\rangle &= \frac{\int d\epsilon_\nu d\mu_\nu \epsilon_\nu^3 \mu_\nu f}{\int d\epsilon_\nu d\mu_\nu \epsilon_\nu^3 f} \\ &= \frac{L_\nu}{4\pi r^2 c u_\nu}, \end{aligned}$$

$$Q_\mathrm{net} = Q^+_{\nu_\mathrm{e},\bar{\nu}_\mathrm{e}} - Q^-_{\nu_\mathrm{e},\bar{\nu}_\mathrm{e}} = \mathrm{const}\left[T_\nu^6 (R_\nu/2r)^2 - T^6\right]$$

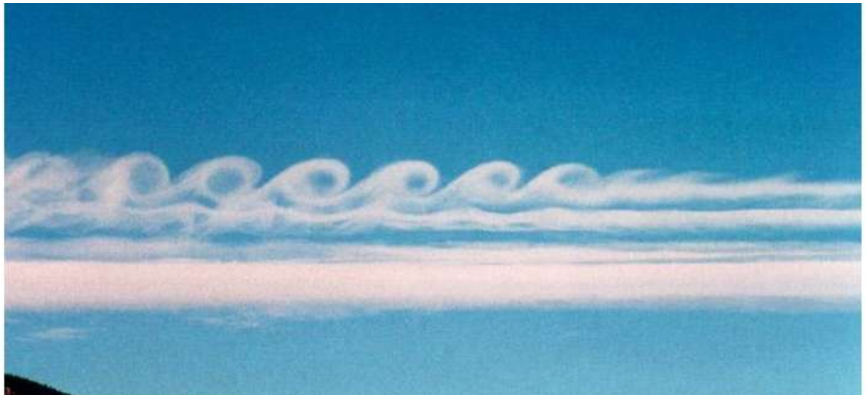
Neutrino heating around neutron star dominates over cooling because $T(r) \propto r^{-1}$

Hydrodynamical Instabilities

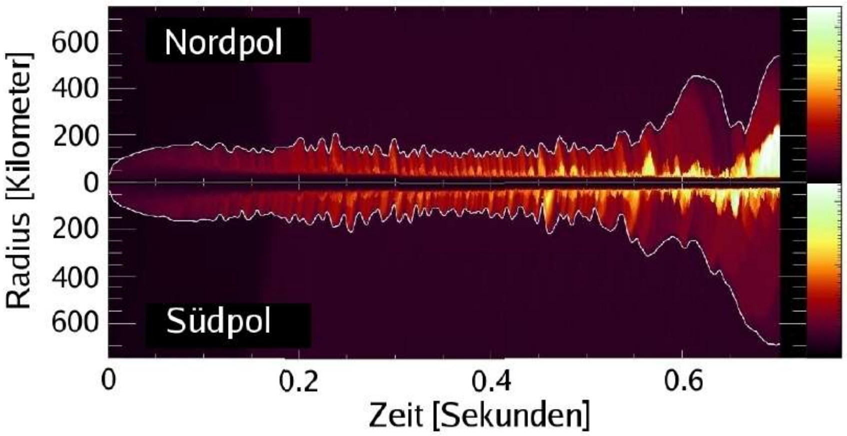
Rayleigh-Taylor instability



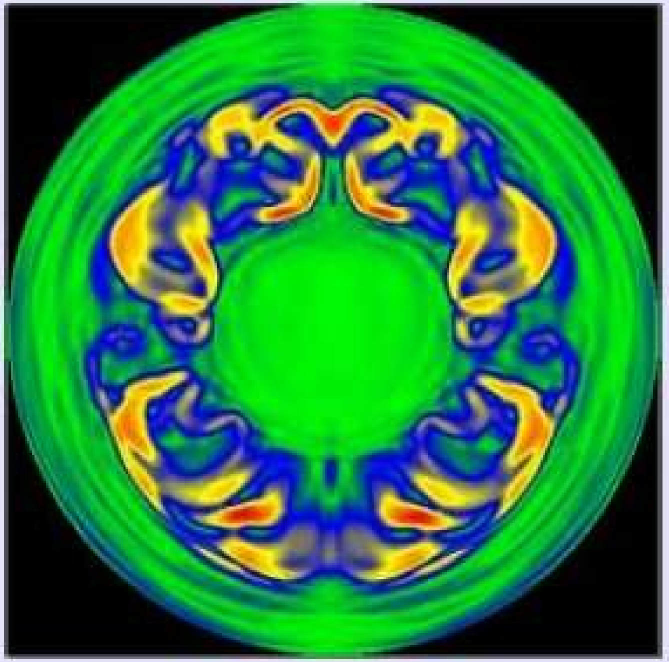
Kelvin-Helmholtz instability



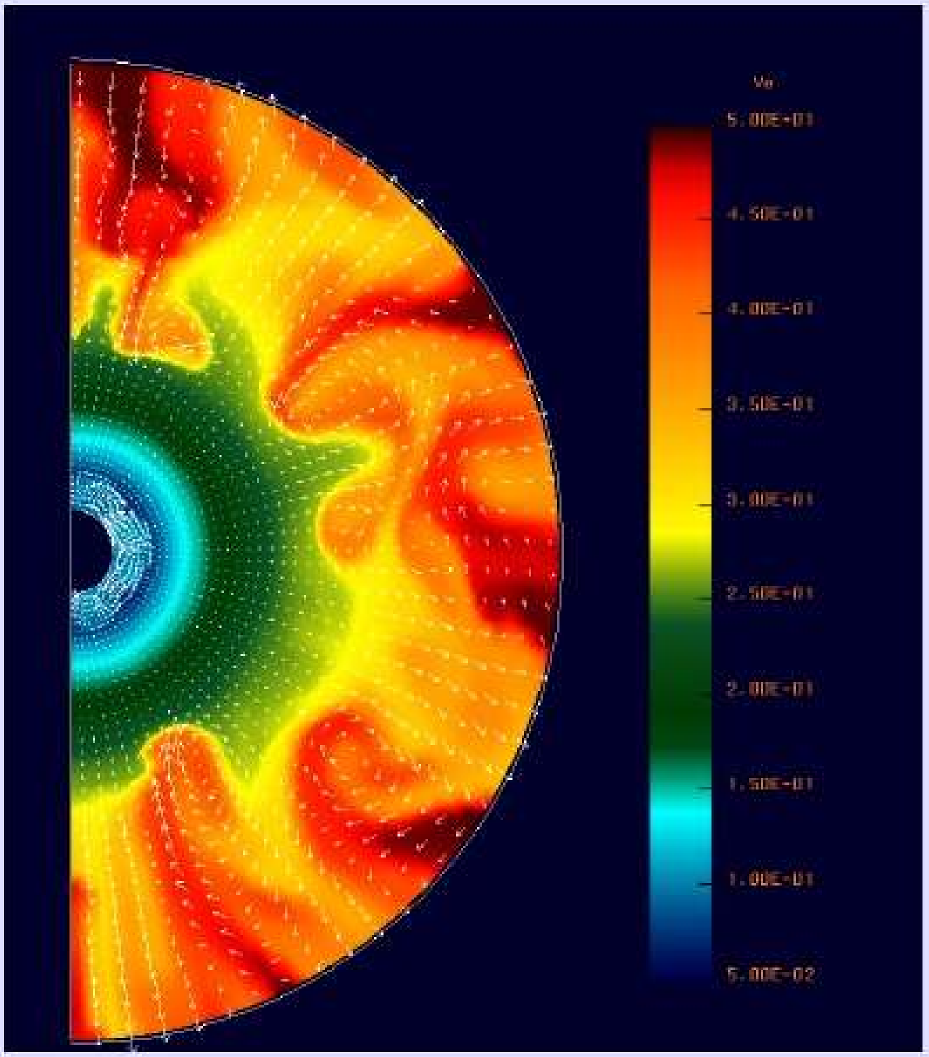
standing accretion shock instability (SASI)



Core collapse supernovae need multidimensional modeling !



Ledoux convection inside proto-neutron star due to negative lepton and entropy gradients (Keil, Janka & Müller '96)

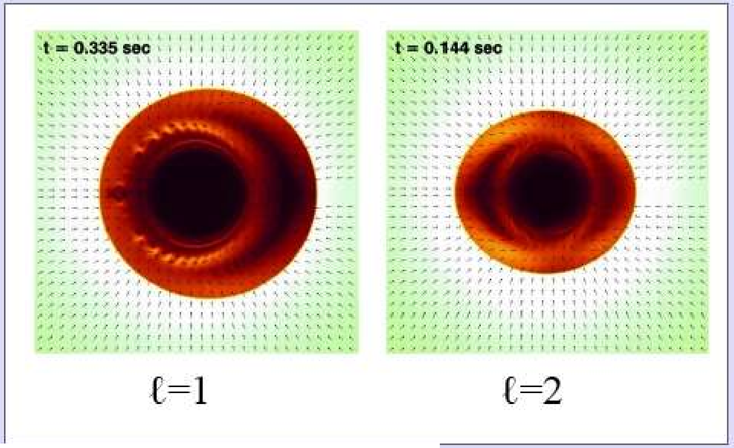


Convection in the surface layers of the proto-neutron star and in the hot bubble 78 msec after core bounce (Janka & Müller '96)

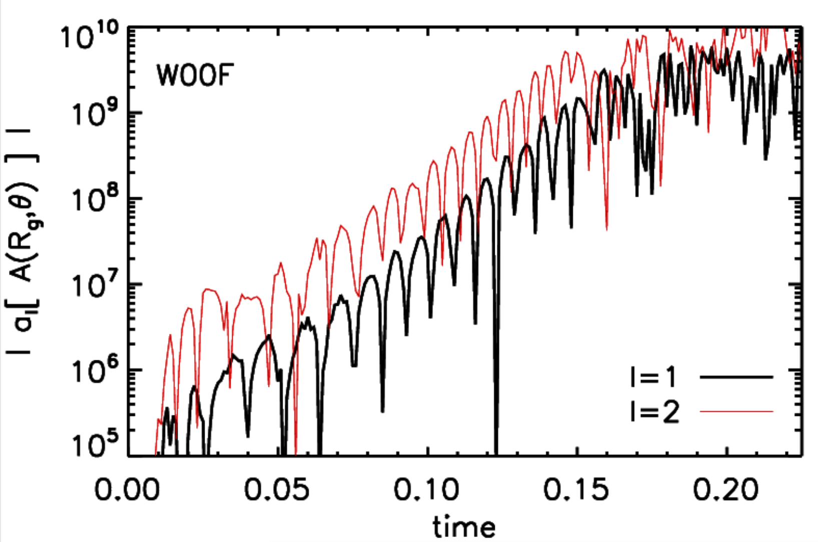
SASI in SN Cores

"Standing Accretion Shock Instability"

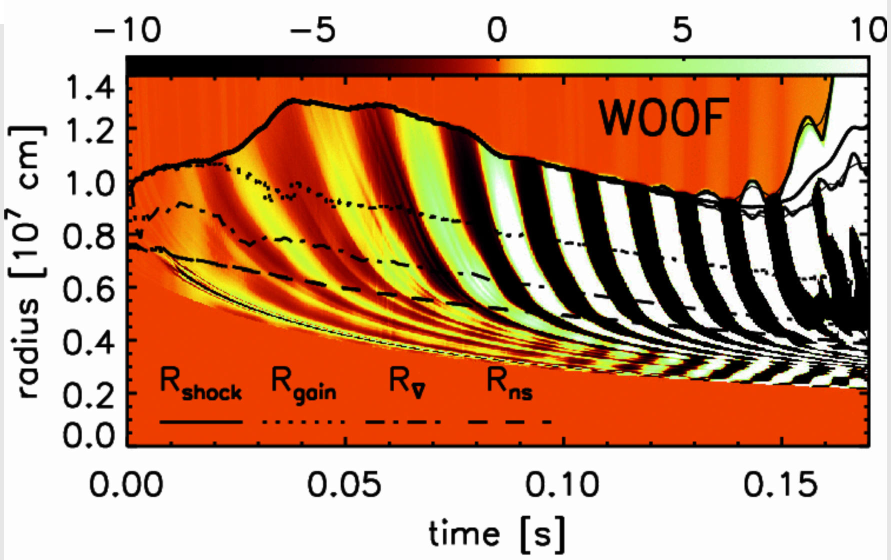
(Blondin et al. 2003)

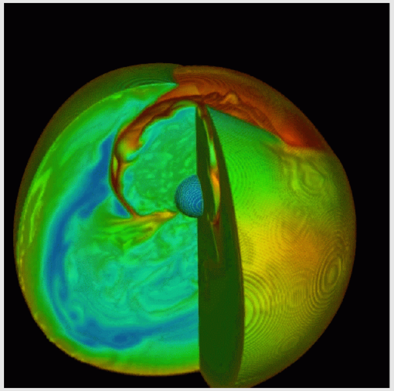


- occurs also when convection is suppressed or weak
- grows in oscillatory way
- Dipole and quadrupole modes grow fastest ====> global asymmetry
- is caused by an “advective-acoustic feedback cycle”
- seen in 2D as well as 3D simulations



Scheck et al., A&A (2008)

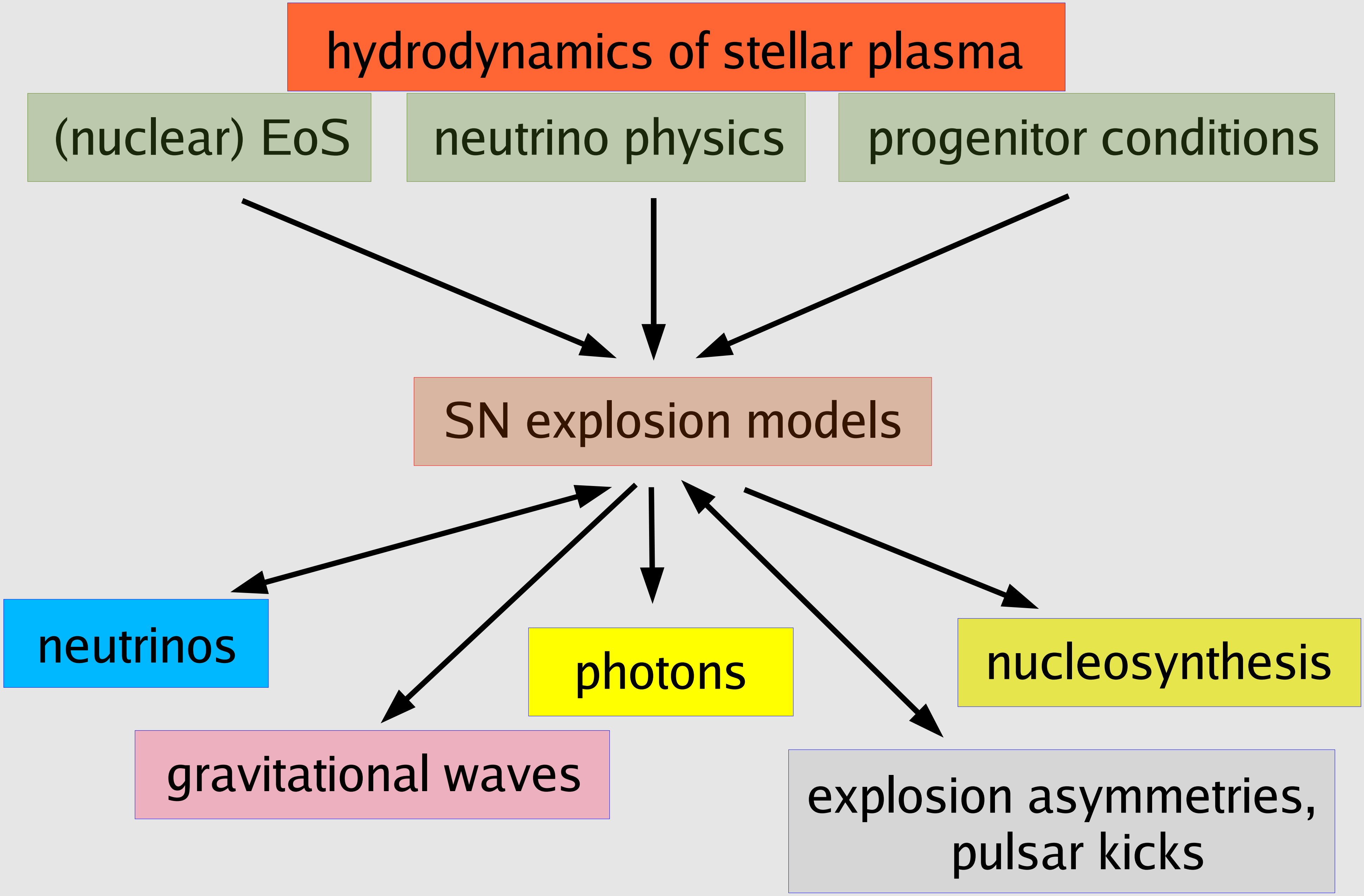




ondin & Mezzacappa 2006)

Modeling Stellar Collapse and Explosion

Supernova Modeling: Input & Output



hydrodynamics of stellar plasma

(nuclear) EoS

neutrino physics

progenitor conditions

SN explosion models

neutrinos

gravitational waves

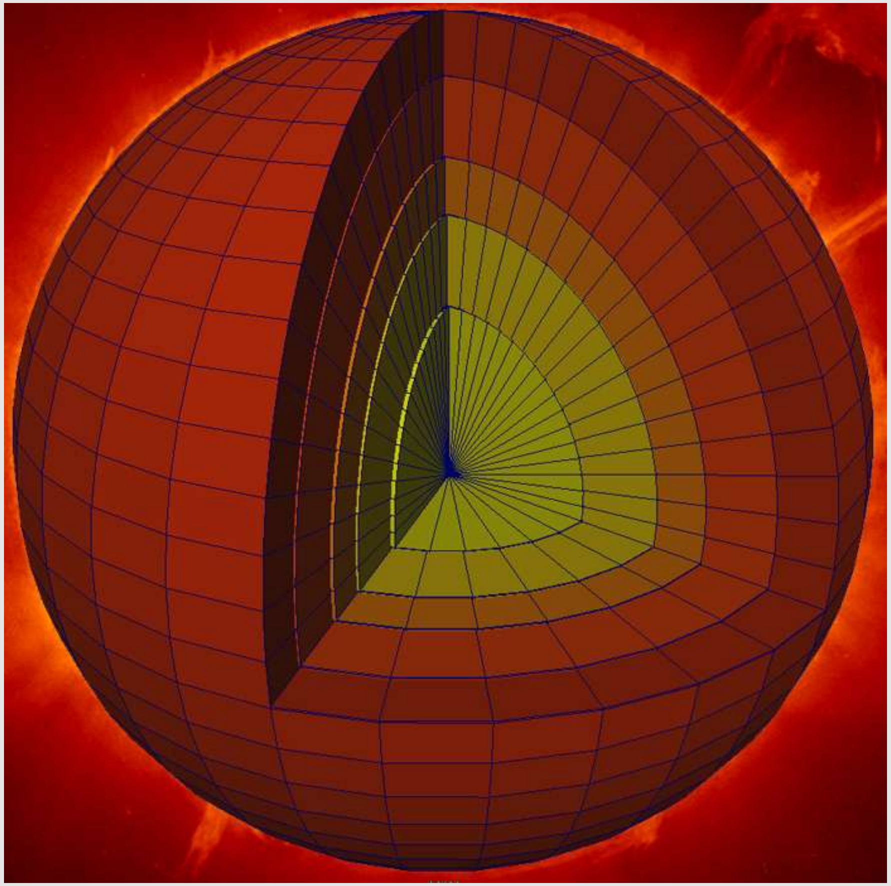
photons

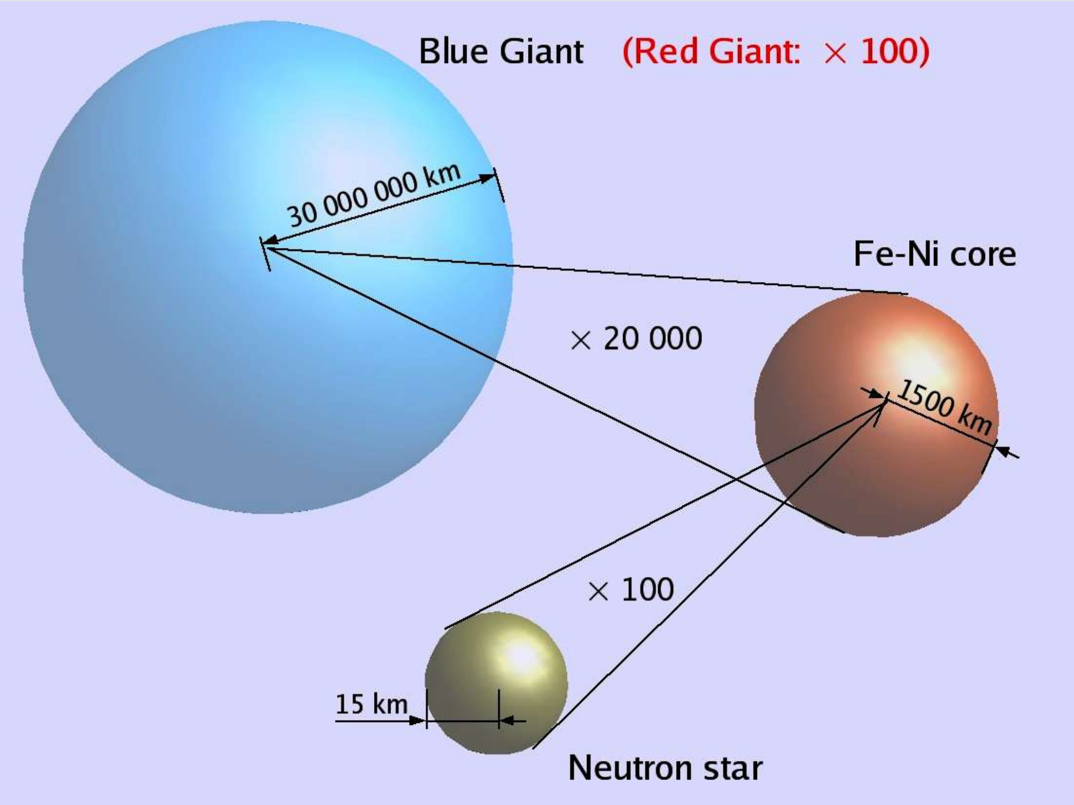
nucleosynthesis

explosion asymmetries,
pulsar kicks

Supernova Simulations

- multi-dimensional
- complex microphysics
- long evolution timescales
- large radial scale difference
- extremely CPU intense





Neutrino Reactions in Supernovae

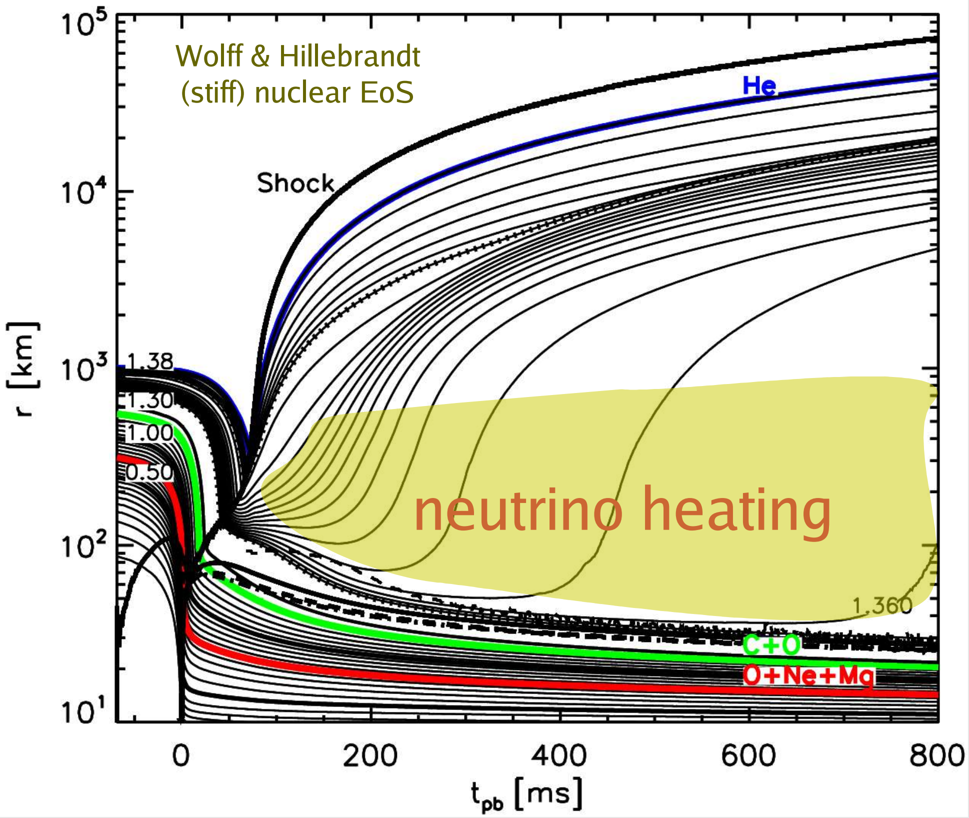
Beta processes:	• $e^- + p \rightleftharpoons n + \nu_e$ • $e^+ + n \rightleftharpoons p + \bar{\nu}_e$ • $e^- + A \rightleftharpoons \nu_e + A^*$
Neutrino scattering:	• $\nu + n, p \rightleftharpoons \nu + n, p$ • $\nu + A \rightleftharpoons \nu + A$ • $\nu + e^\pm \rightleftharpoons \nu + e^\pm$
Thermal pair processes:	• $N + N \rightleftharpoons N + N + \nu + \bar{\nu}$ • $e^+ + e^- \rightleftharpoons \nu + \bar{\nu}$
Neutrino-neutrino reactions:	• $\nu_x + \nu_e, \bar{\nu}_e \rightleftharpoons \nu_x + \nu_e, \bar{\nu}_e$ $(\nu_x = \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \text{ or } \bar{\nu}_\tau)$ • $\nu_e + \bar{\nu}_e \rightleftharpoons \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

Recent Results of Simulations

SN Simulations: $M_{star} \sim 8...10\ M_{sun}$

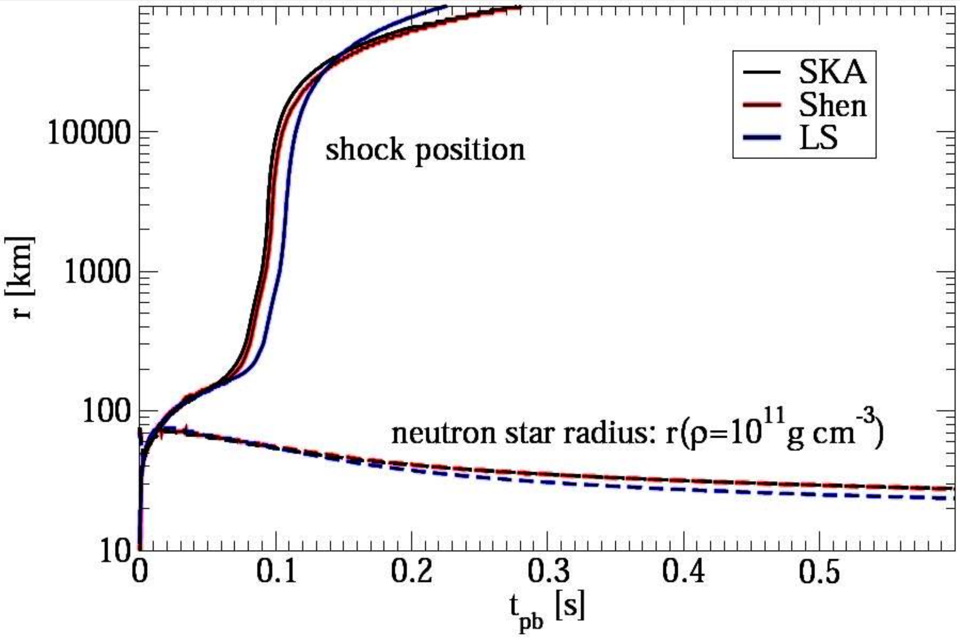
"Electron-capture supernovae"
or "ONeMg core supernovae"

- No prompt explosion !
- Mass ejection by "neutrino-driven wind"
  (like Mayle & Wilson 1988
  and similar to AIC of WDs;
  see Woosley & Baron 1992, Fryer et al. 1999;
  Dessart et al. 2006)
- Explosion develops in similar way for soft nuclear EoS (i.e. compact PNS) and stiff EoS (less compact PNS)



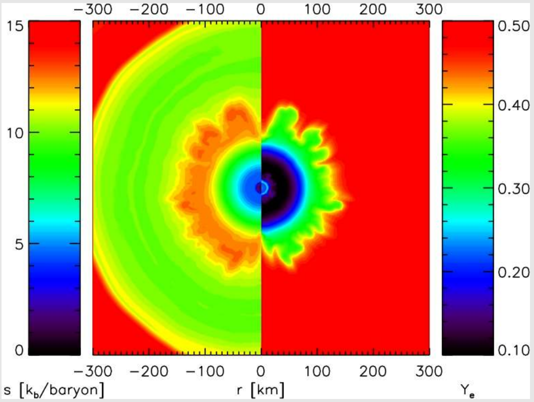
Kitaura et al., A&A 450 (2006) 345;
Janka et al., A&A 485 (2008) 199

Convection is not necessary for launching explosion but occurs in NS and in neutrino-heating layer

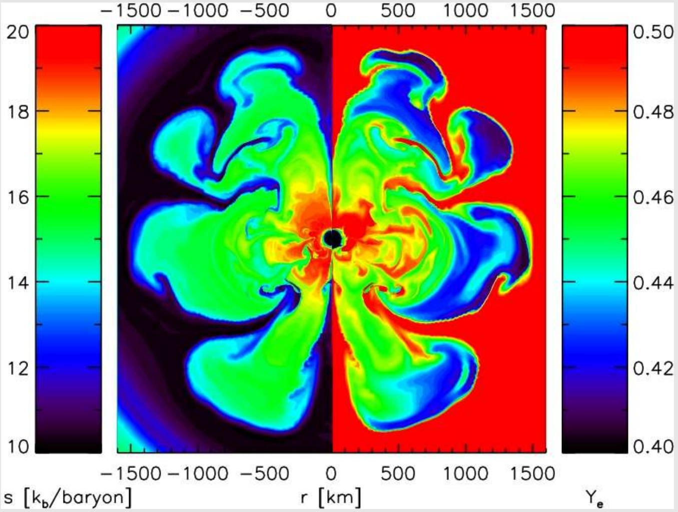


SN Simulations: $M_{star} \sim 8...10\ M_{sun}$

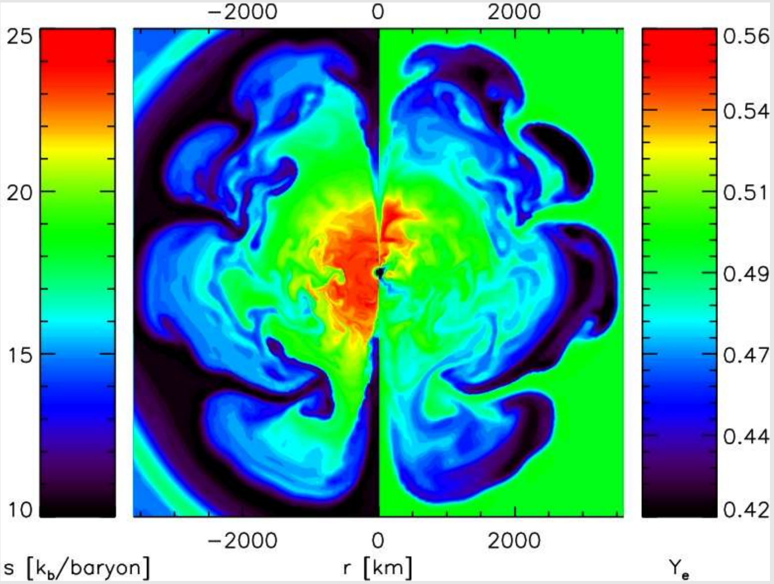
Convection leads to slight increase of explosion energy and causes explosion asymmetries



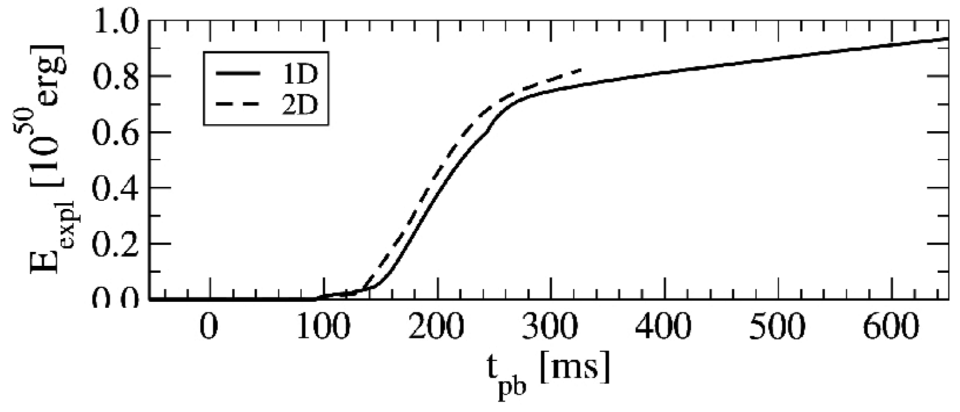
t = 0.097 s after core bounce



t = 0.144 s after core bounce



t = 0.262 s after core bounce

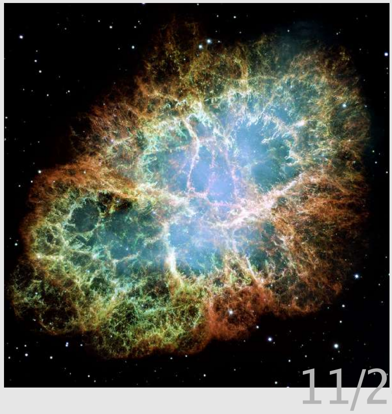


Müller et al. (in preparation)

Low explosion energy and ejecta composition – little Ni, C, O – of CRAB (SN1054) is compatible with ONeMg core explosion

(Nomoto et al., Nature, 1982;
Hillebrandt, A&A, 1982)

Might also explain other low-luminosity supernovae (e.g. SN1997D, 2008S, 2008HA)

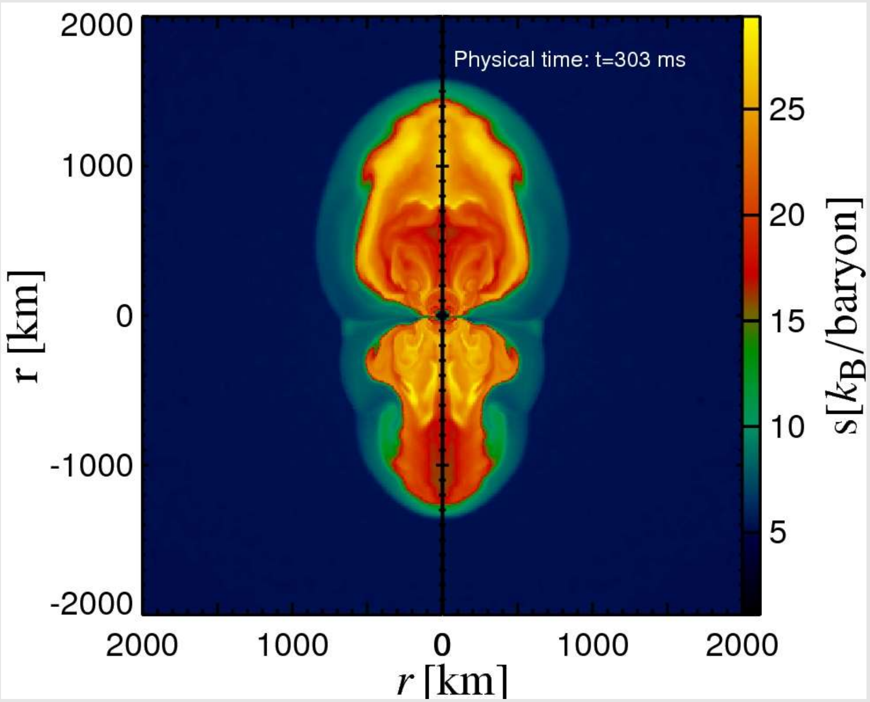


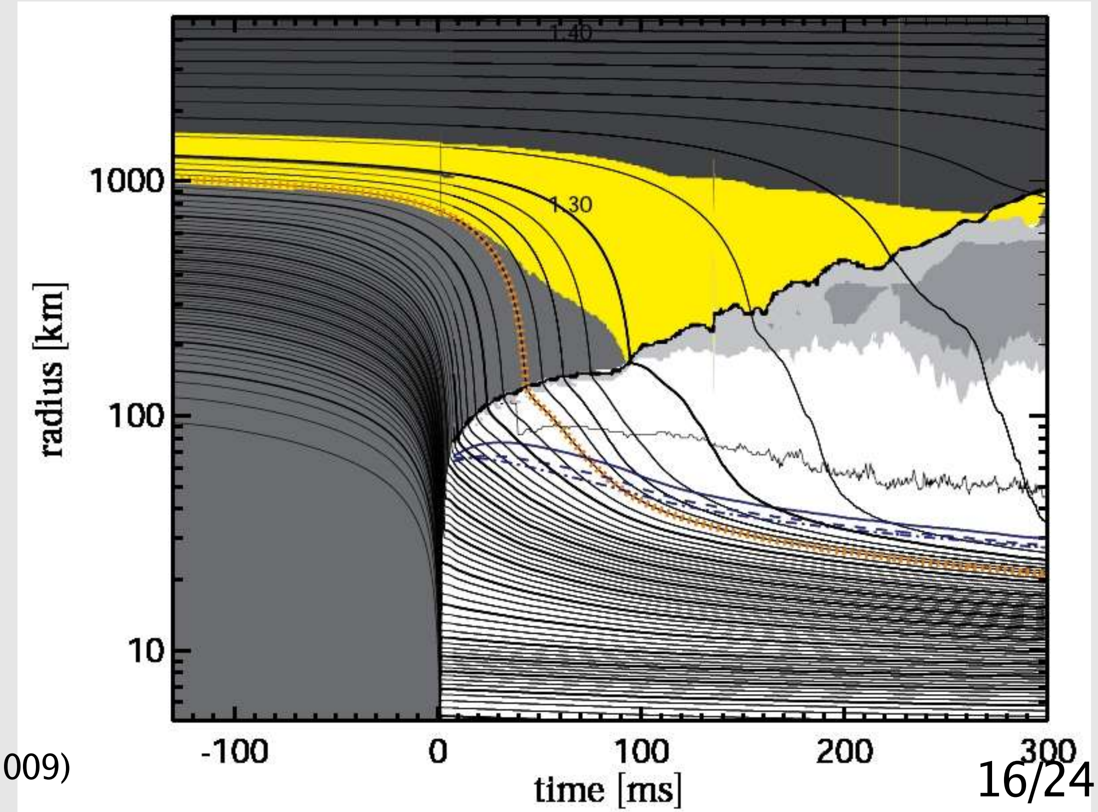
2D SN Simulations: $M_{star} \sim 11\ M_{sun}$

For explosions of stars with $M > 10\ M_{sun}$ multi-dimensional effects (nonradial hydrodynamic instabilities) are crucial !

Low-mode nonradial (dipole, l=1, and quadrupole, l=2) "standing accretion shock instability" ("SASI"; Blondin et al. 2003) develops and pushes shock to larger radii

===> This stretches residency time of matter in neutrino heating layer and thus increases neutrino energy deposition;
Initiation of globally aspherical explosion by neutrino heating even without rotation

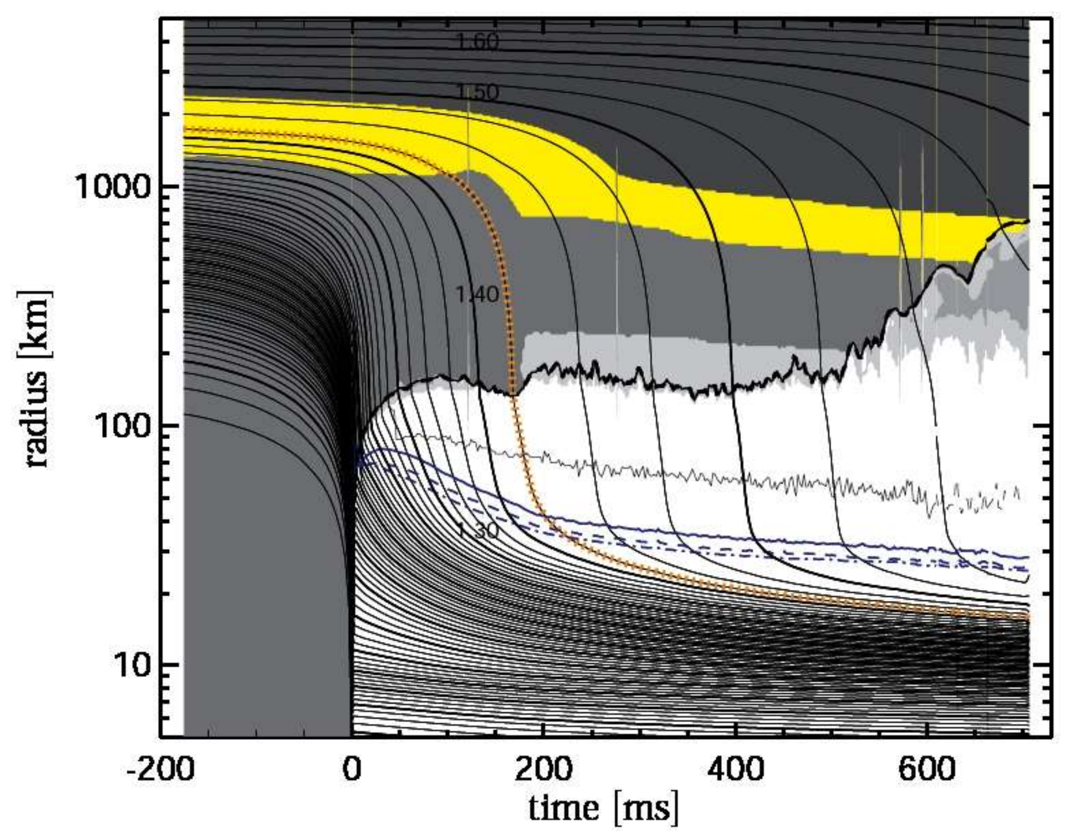


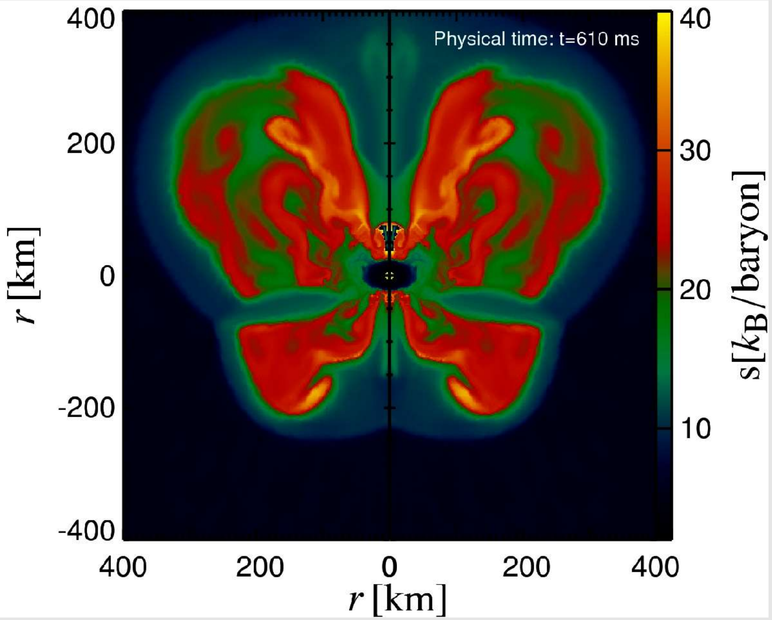


Buras et al., A&A 457 (2006) 281; Marek & Janka, ApJ (2009)

2D SN Simulations: $M_{\text{star}} = 15\ M_{\text{sun}}$

Violent SASI oscillations,
ν-driven explosion sets in
at t ~ 600 ms after bounce



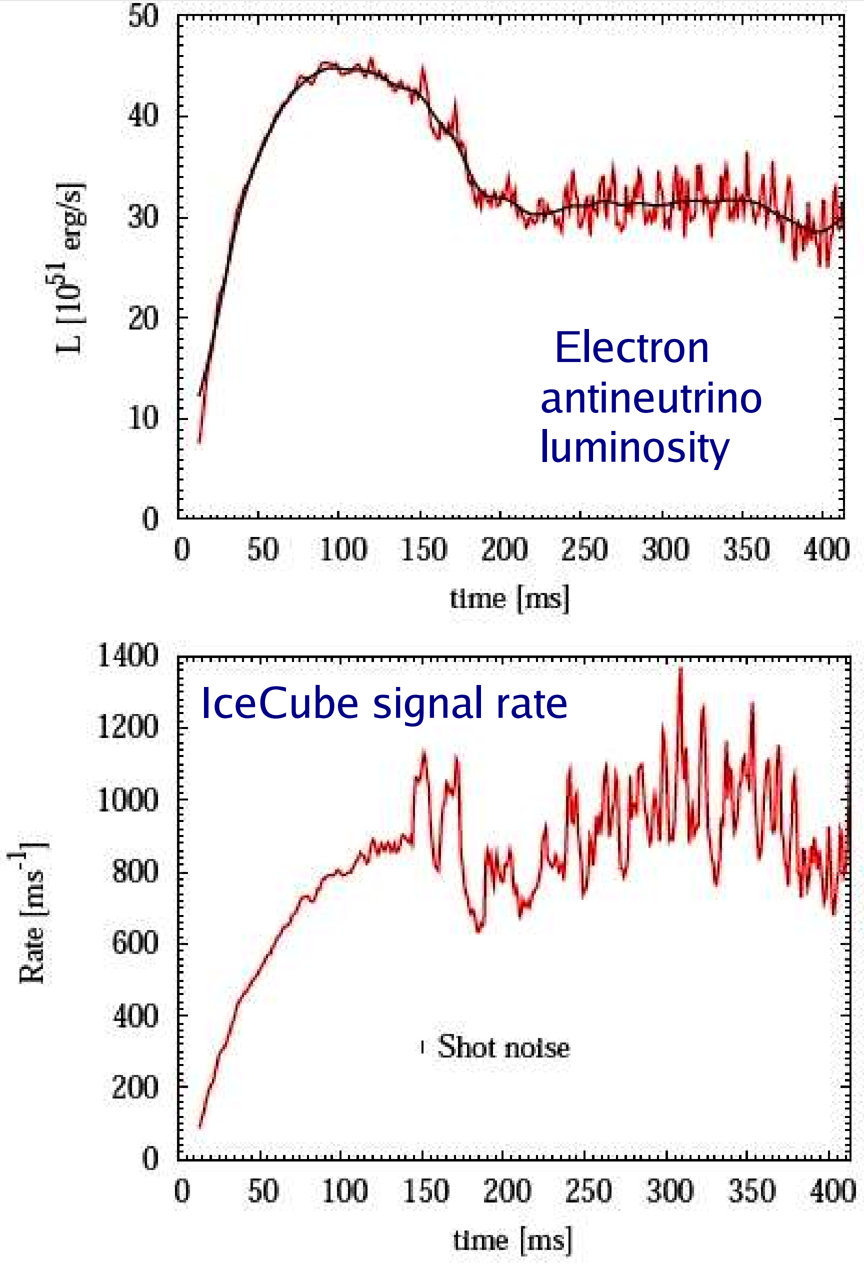


(Marek, PhD Thesis 2007;
Marek & THJ, ApJ, 2009)

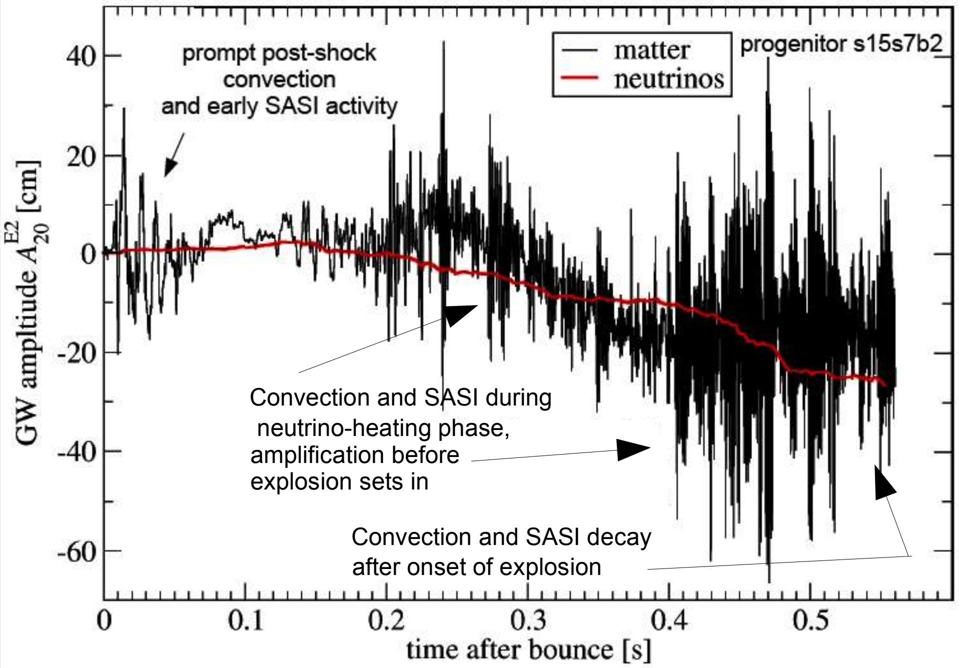
Consequences and Implications of SASI in Stellar Explosions

- Charactersitic neutrino signal modulations
- Gravitational wave signals
- Neutron star kicks
- Asymmetric mass ejection & large-scale radial mixing

Neutrinos and Gravitational Waves



Lund et al., PRD, sumitted; arXiv:1006.1889

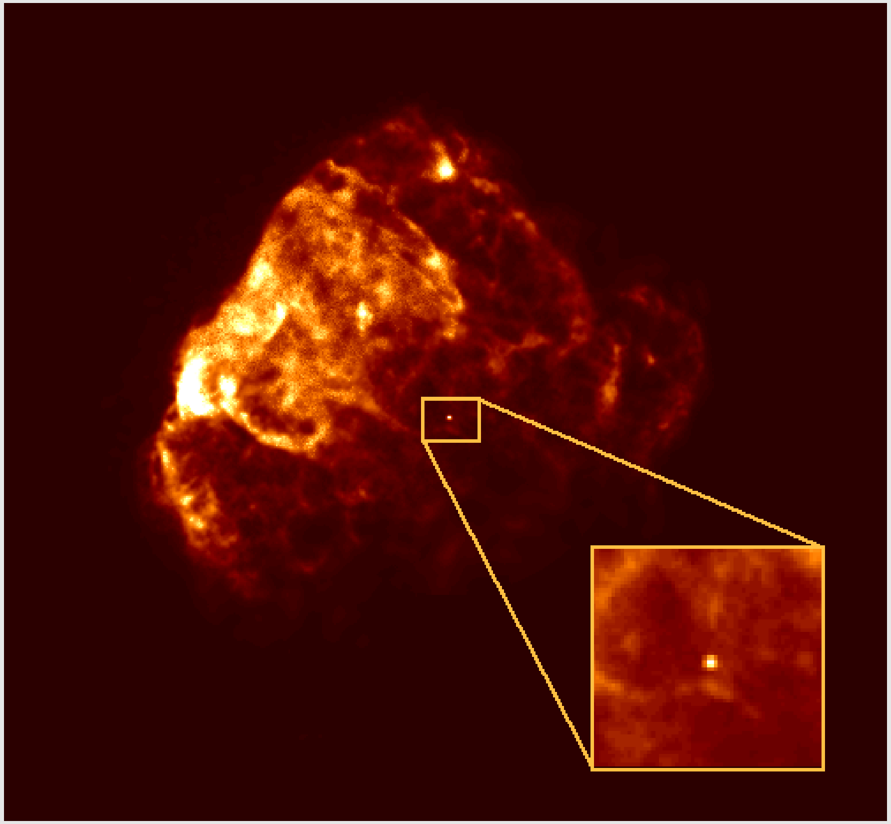


(Müller, Marek & THJ, in preparation)

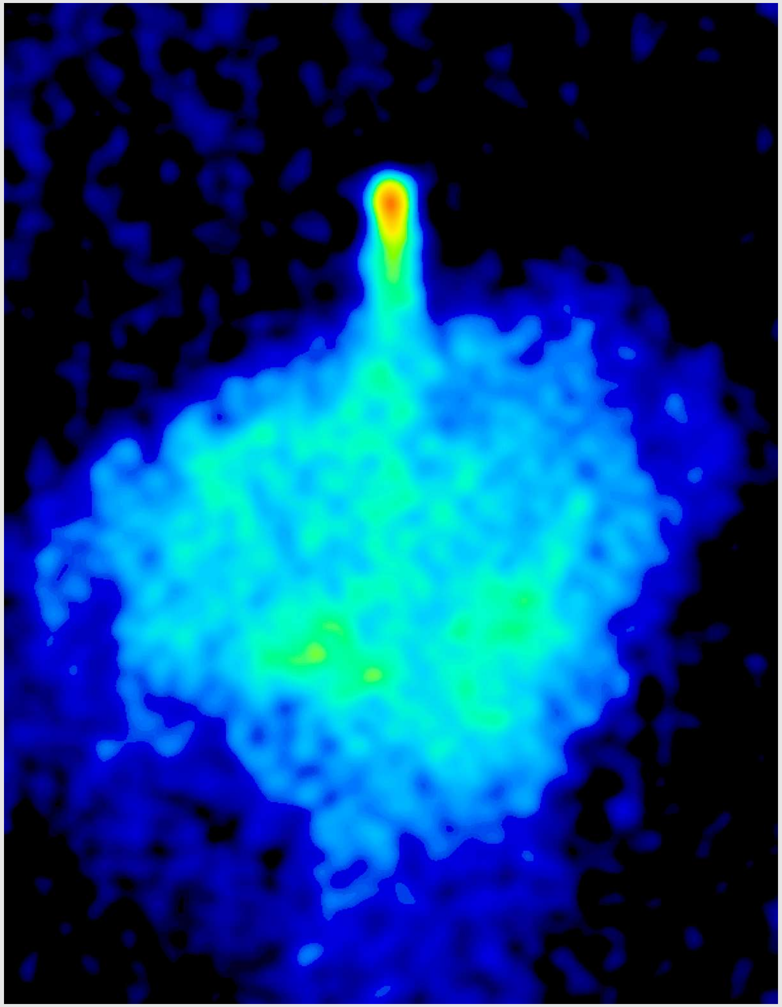
For a galactic supernova:

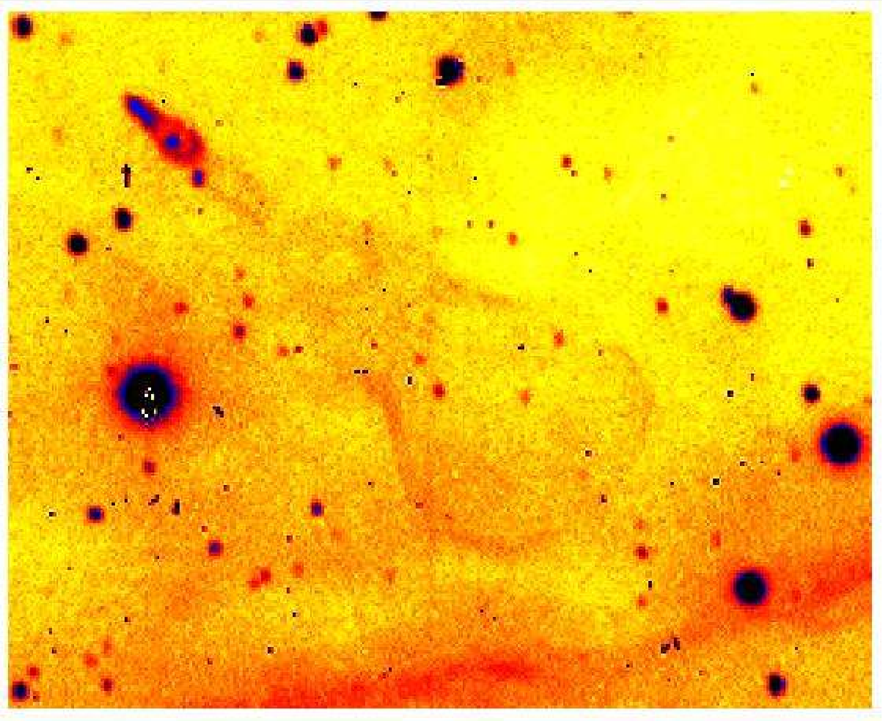
- Variations of neutrino emission clearly detectable with ICECUBE
- Gravitational waves should be observable with advanced LIGO and VIRGO

Neutron Star Kicks



Puppis A

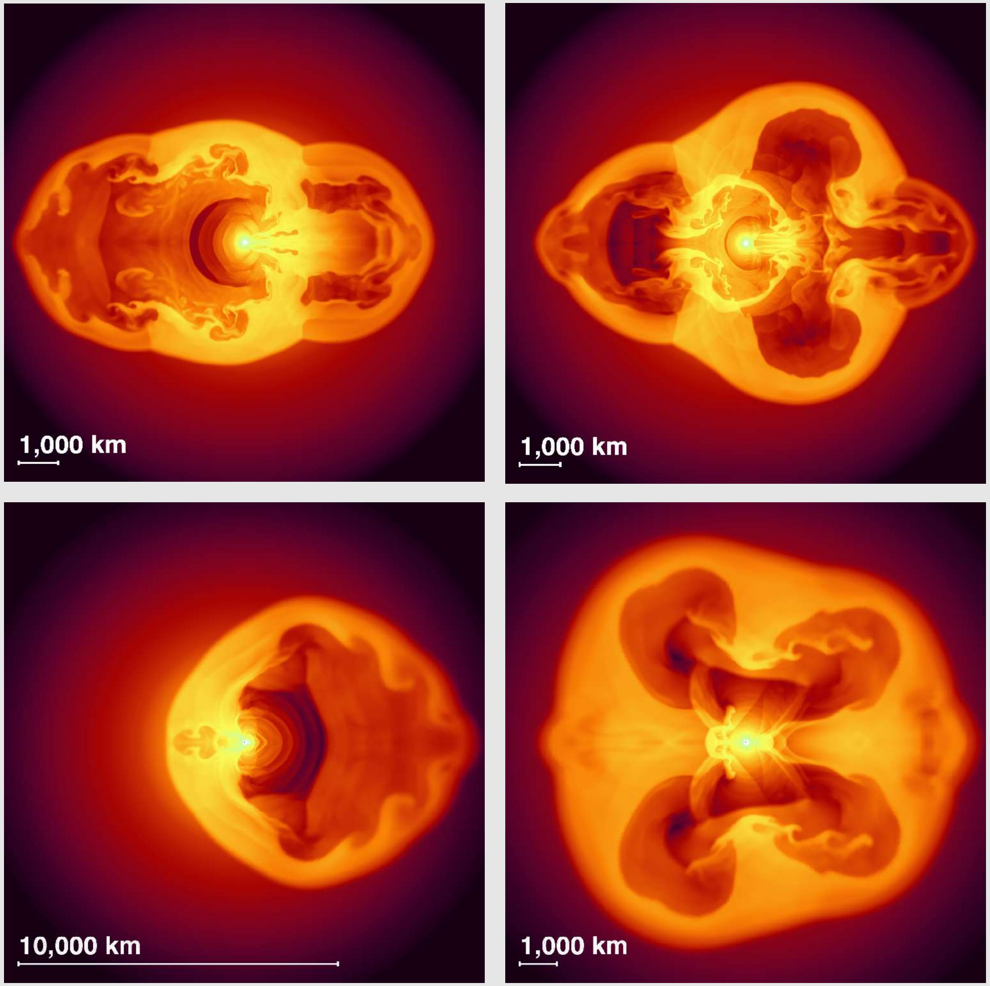


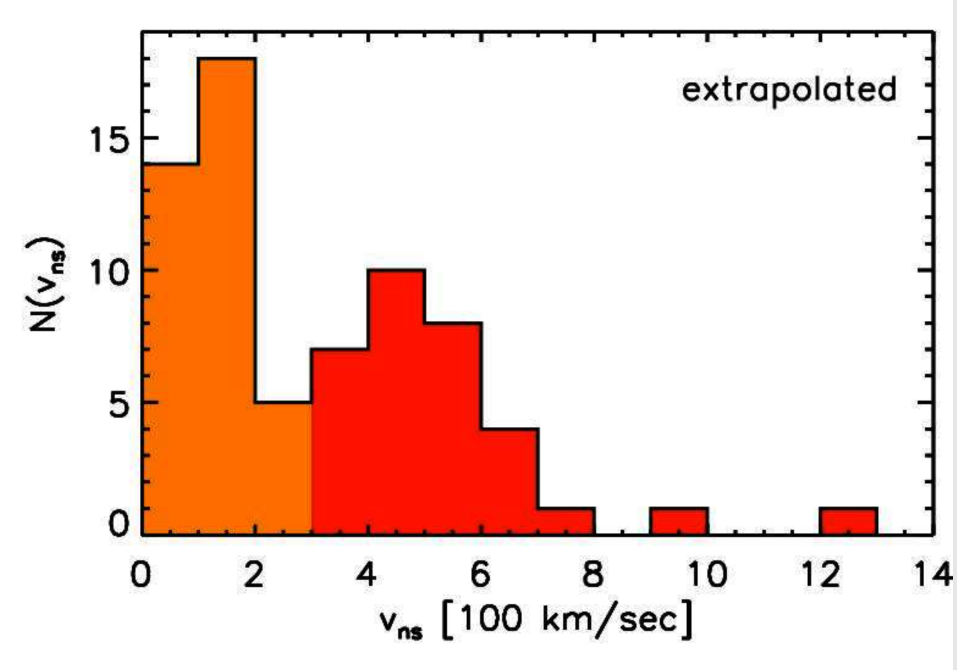


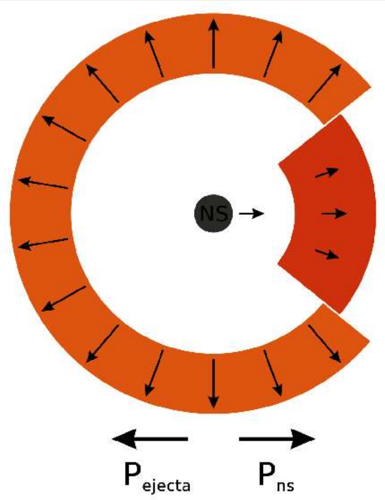
Guitar
Nebula

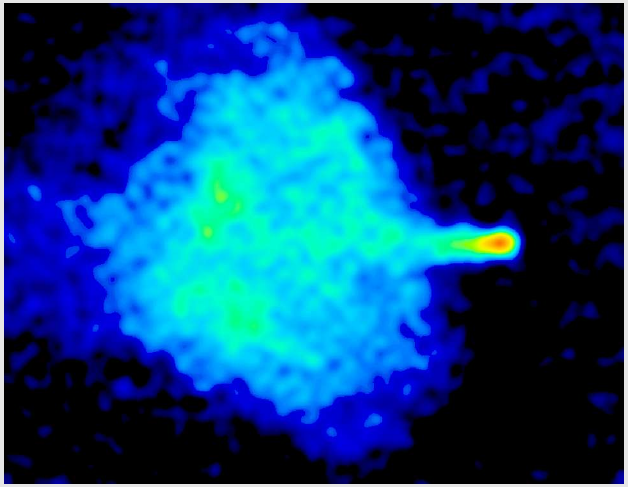
Neutron Star Recoil

- Stochastic and chaotic growth of instabilities
====> different explosion asymmetries
- NS receives kick by hydrodynamic recoil
- NS velocities up to v_{NS} > 1000 km/s in 2D







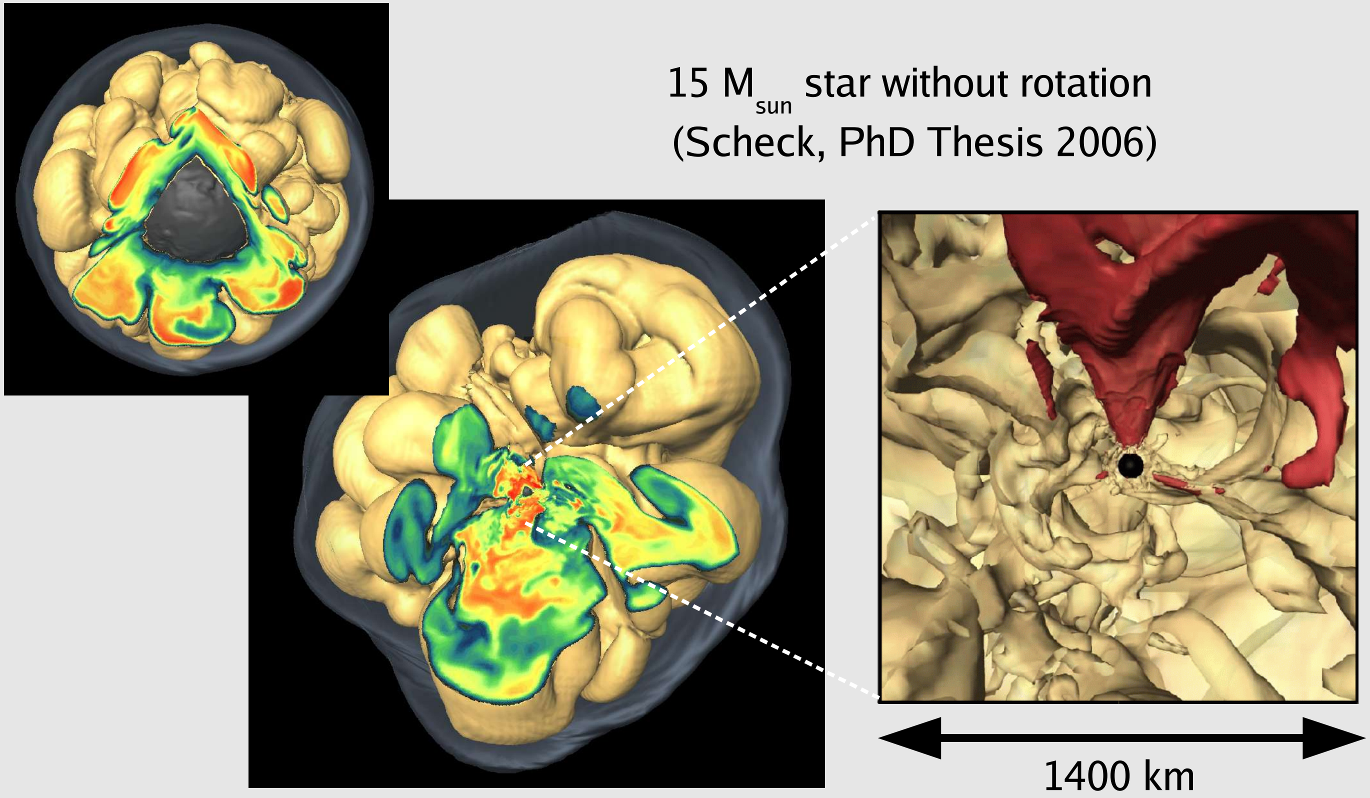


Scheck et al. (PRL, 2004), Scheck et al. (A&A, 2006)

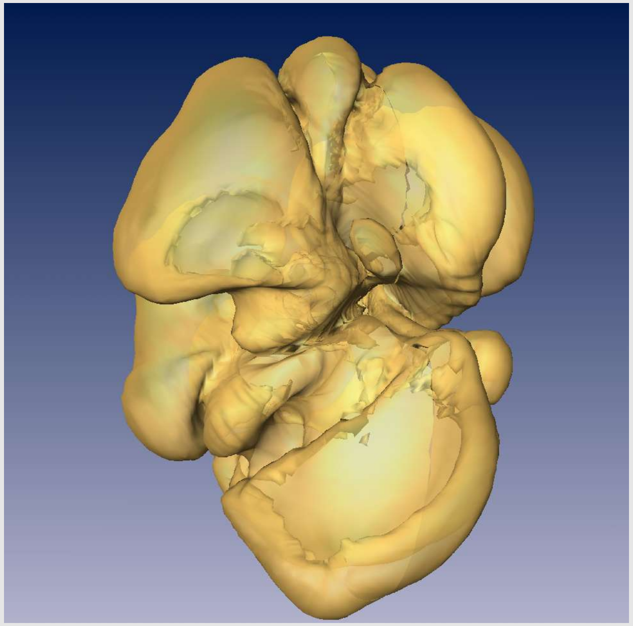
Supernova Asymmetries

Parametric Explosion Studies in 3D

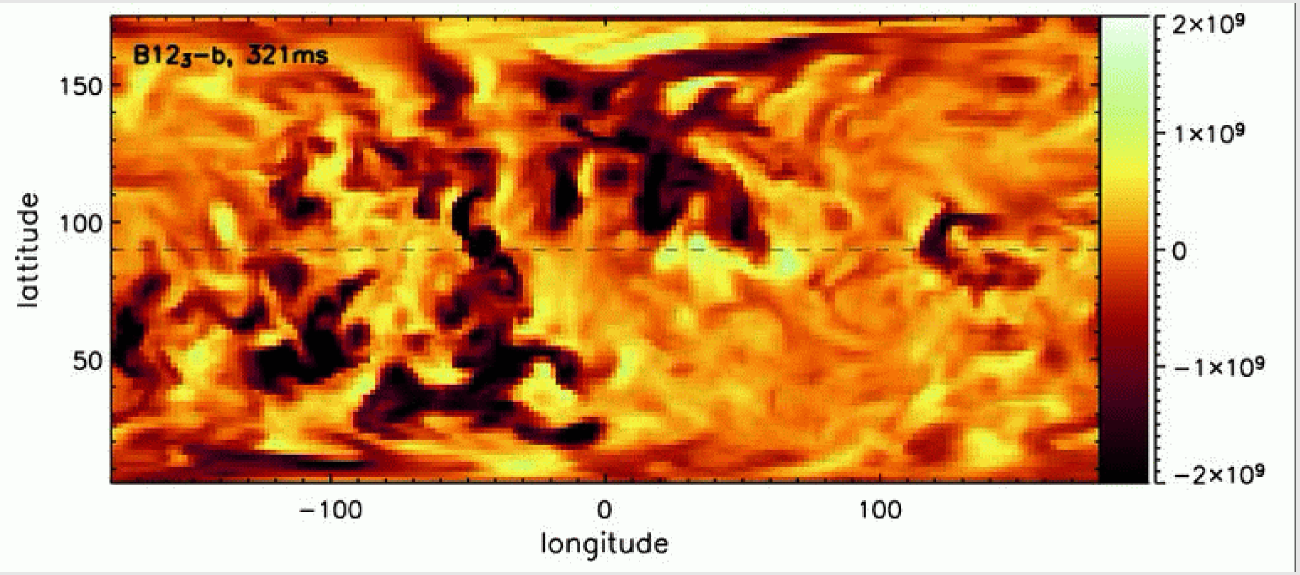
- Explosions in 3D show also very large asymmetries
- Accretion flow to neutron star develops l = 1 mode also in 3D
- Should produce neutron star kicks similar to 2D



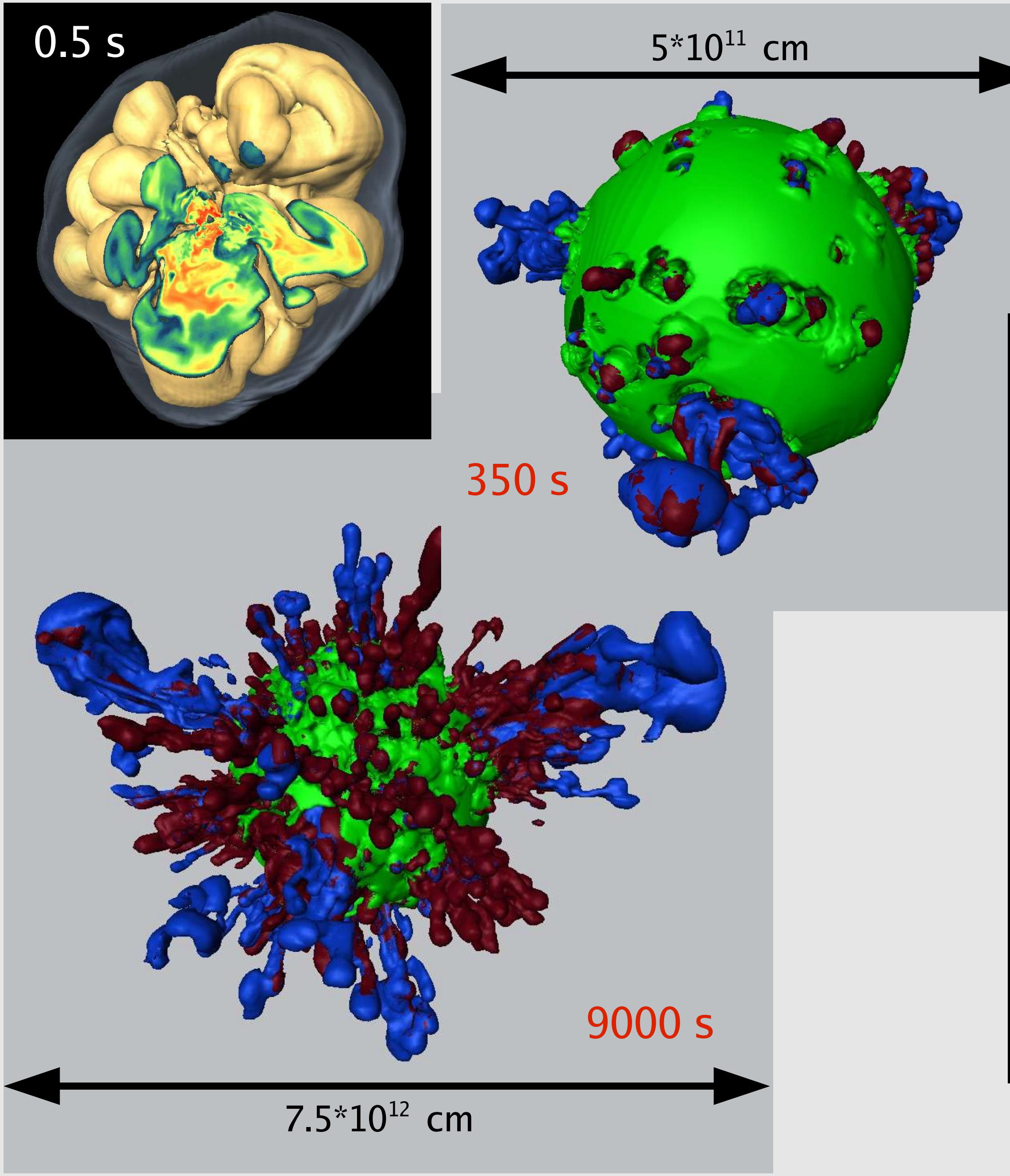
15 M_{sun} star without rotation (Scheck, PhD Thesis 2006)



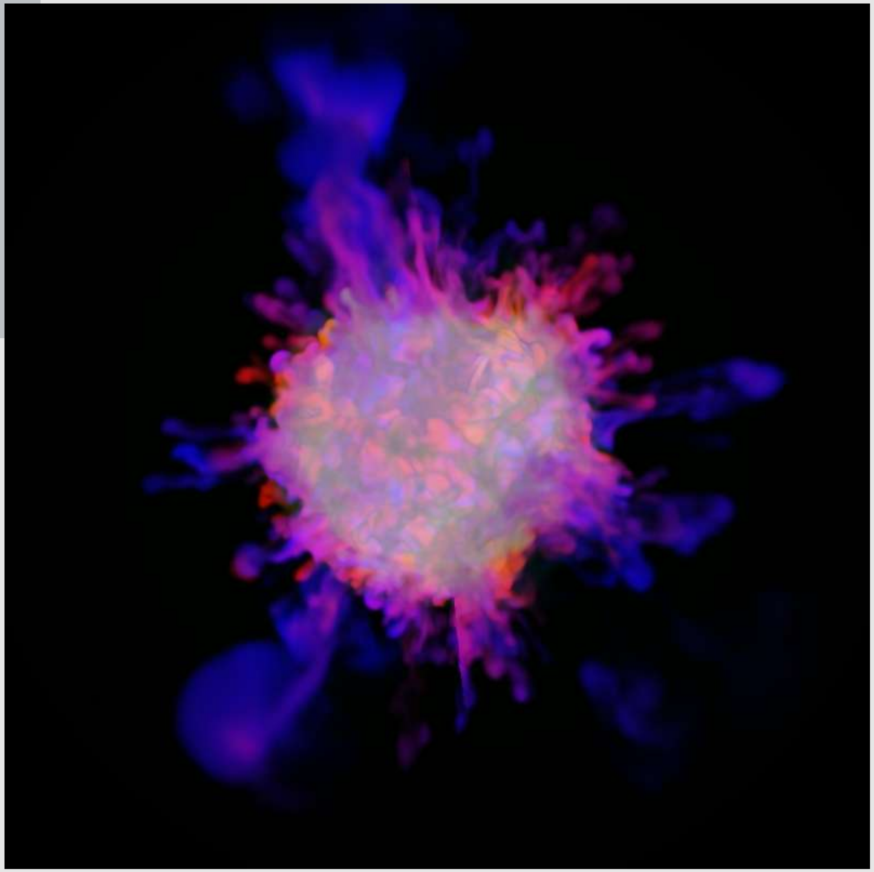
3D with rotation (Scheck, PhD Thesis 2006)



Mixing Instabilities in 3D SN Models



green: carbon
red: oxygen
blue: nickel

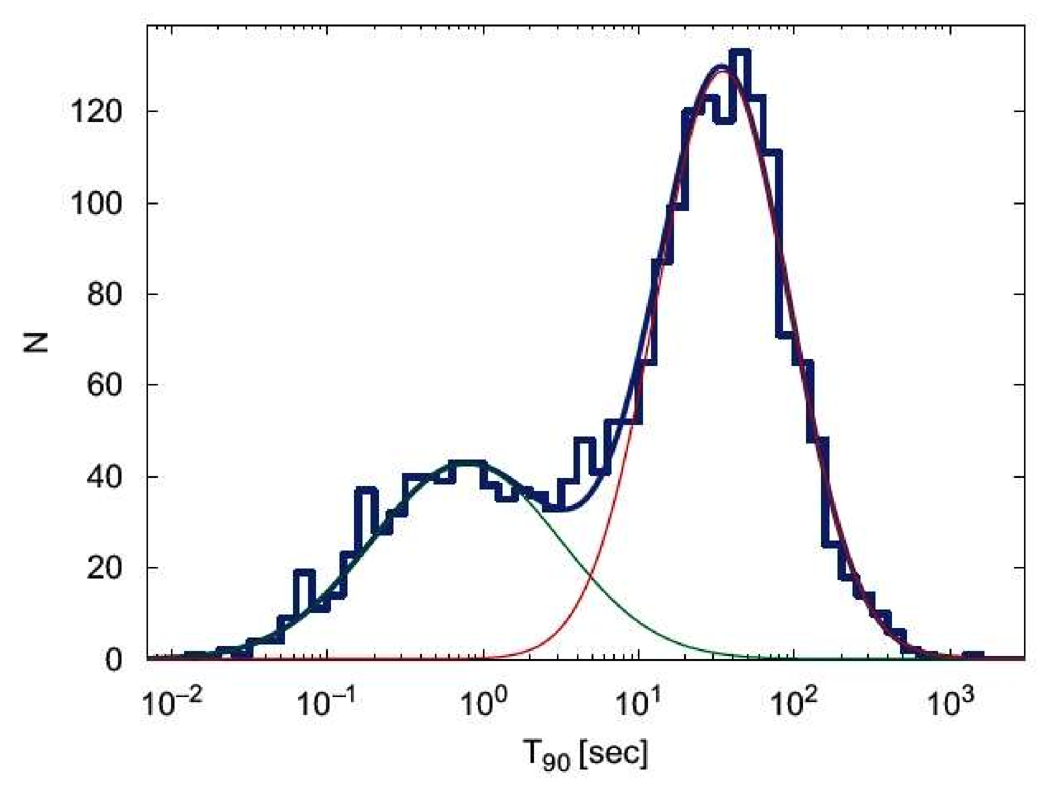


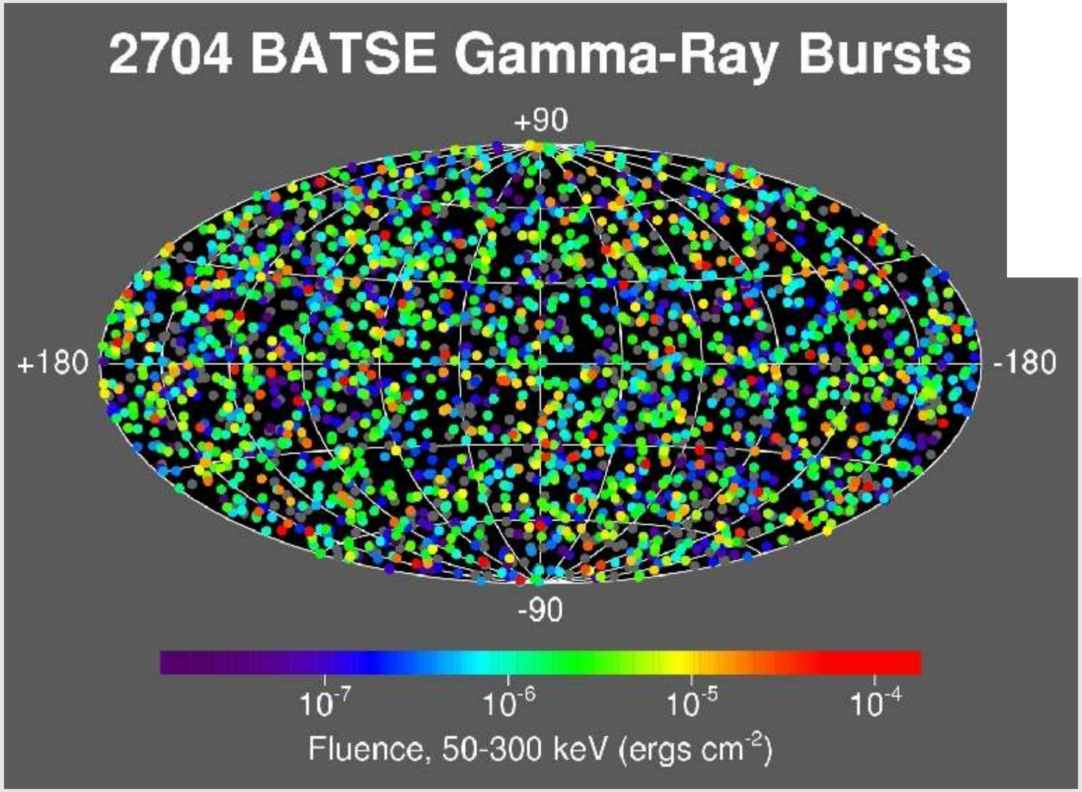
(Hammer, Janka, Müller, submitted)

Gamma-Ray Bursts (GRBs) and Black Hole Formation

GRB Phenomenology I

- Isotropic on sky
- Bimodal distribution

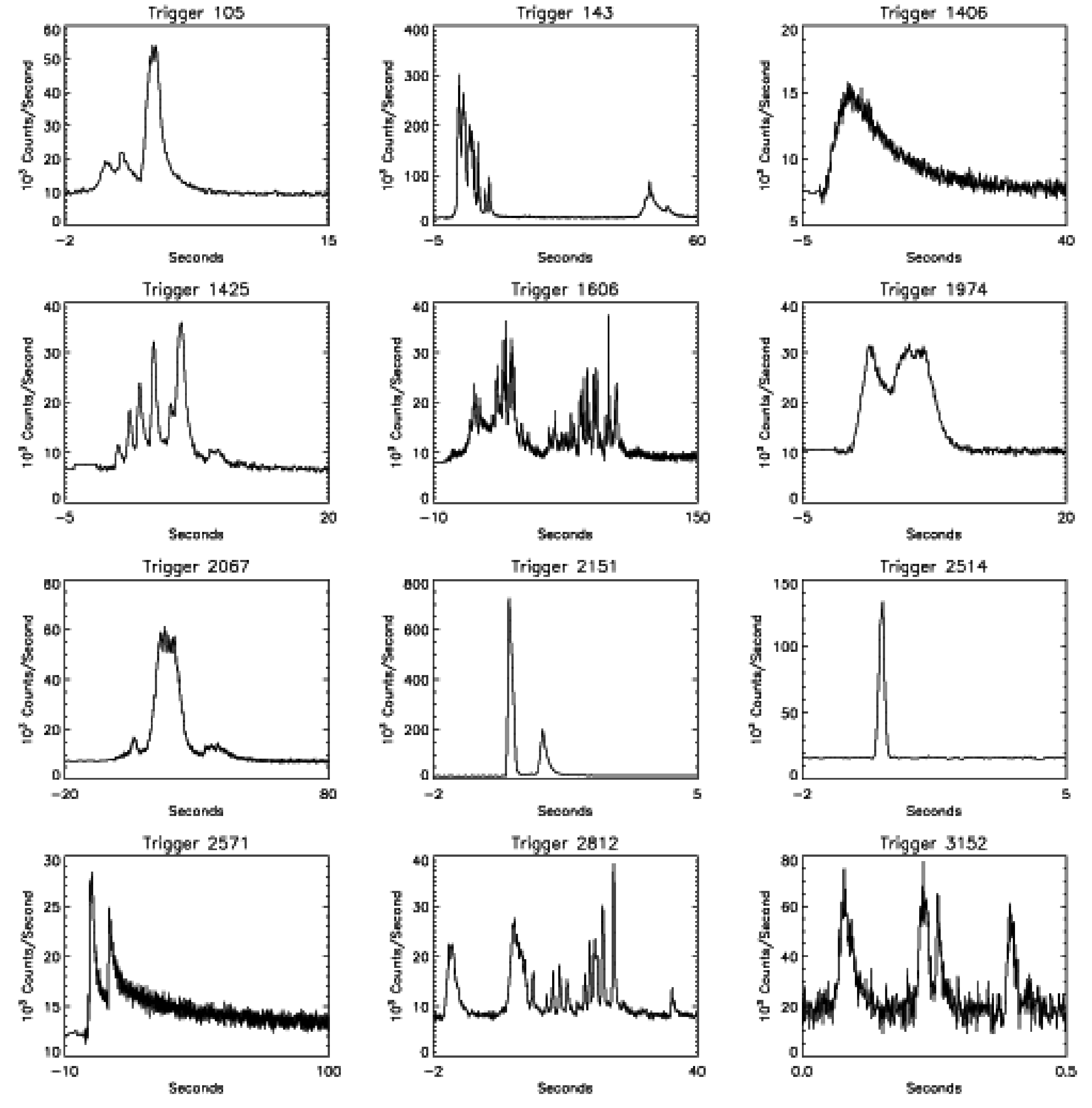




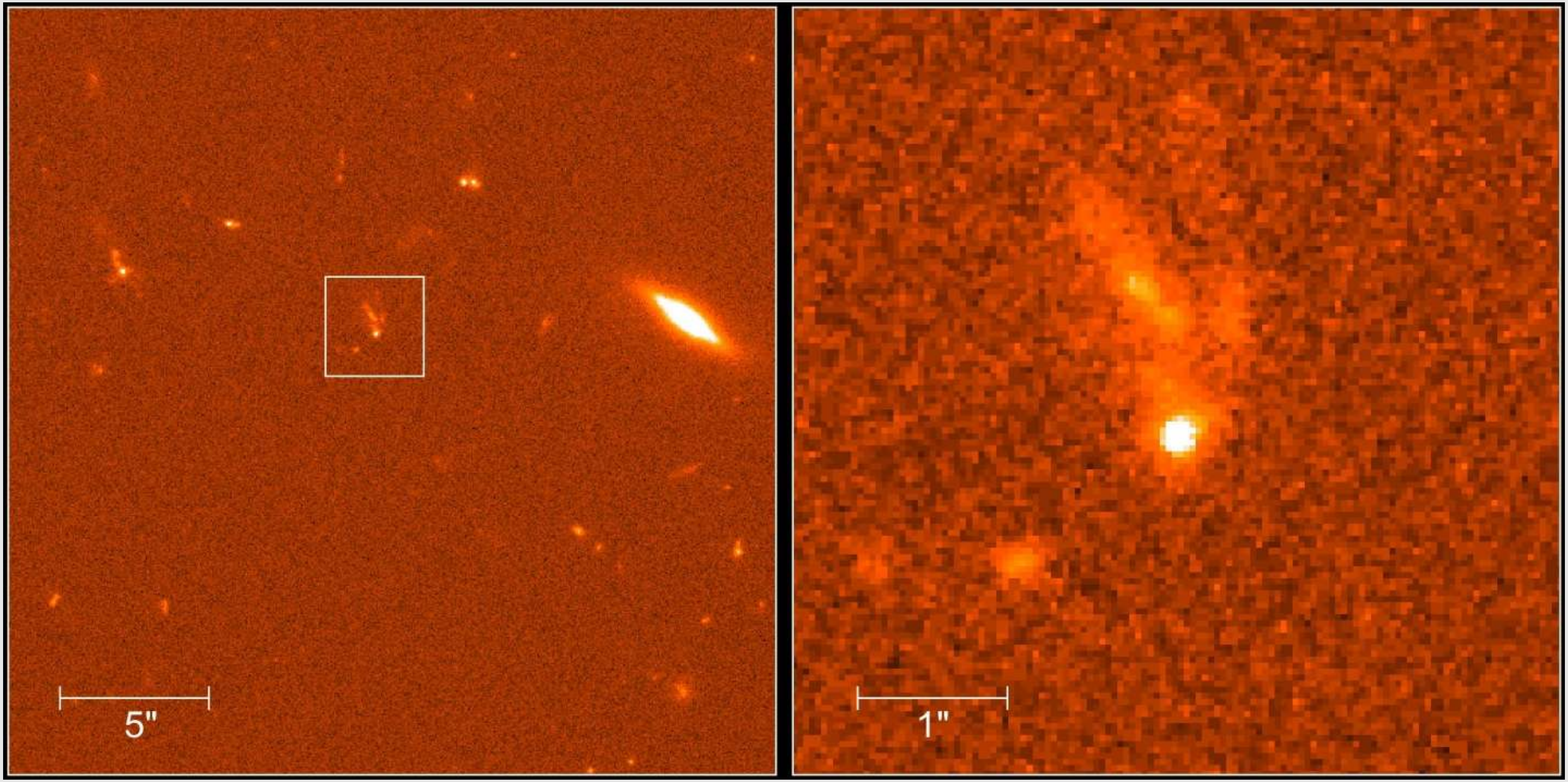
Observed GRBs show
bimodality
Two types of bursts:
long, soft and short, hard

GRB Phenomenology II

- High variability
- Fast time modulation
- Afterglows (AGs) seen at cosmological distances (z > 1)

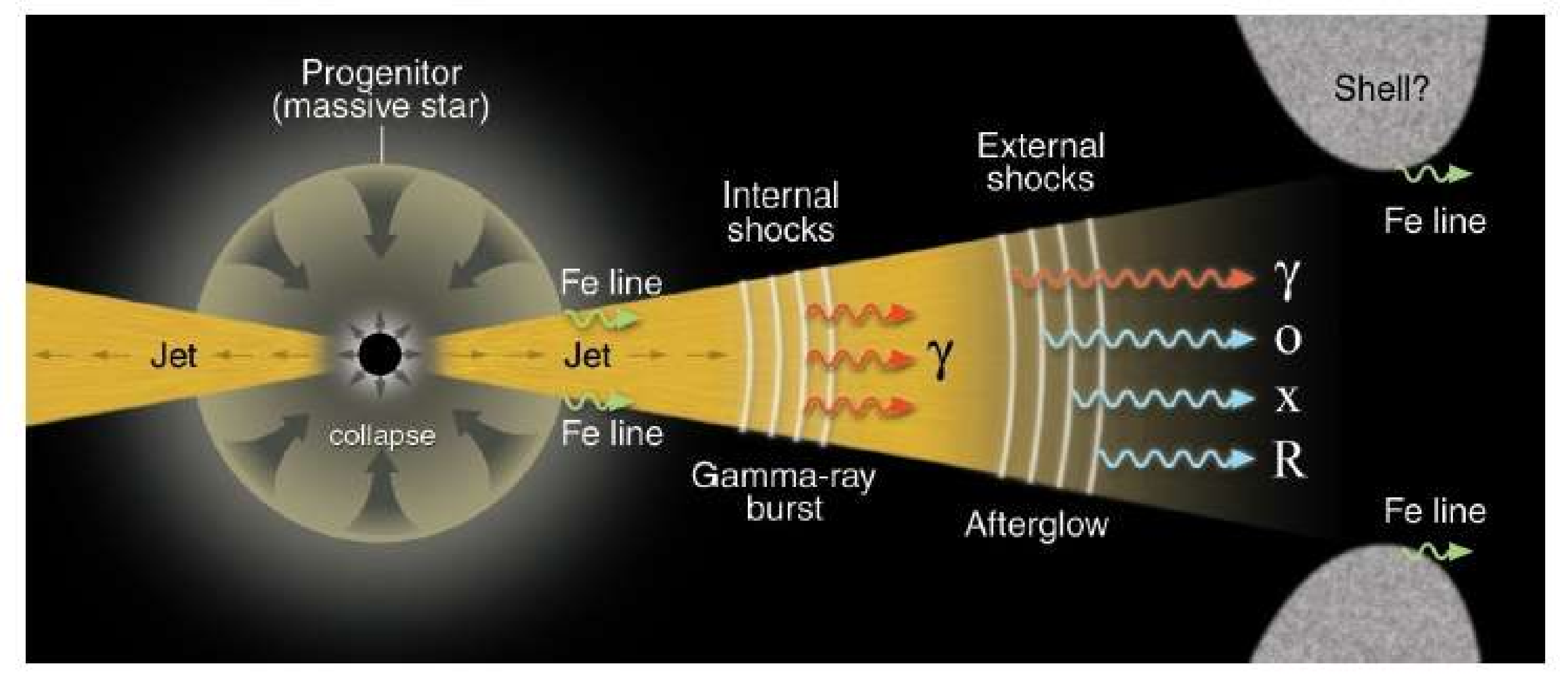


GRB-Supernova Associations



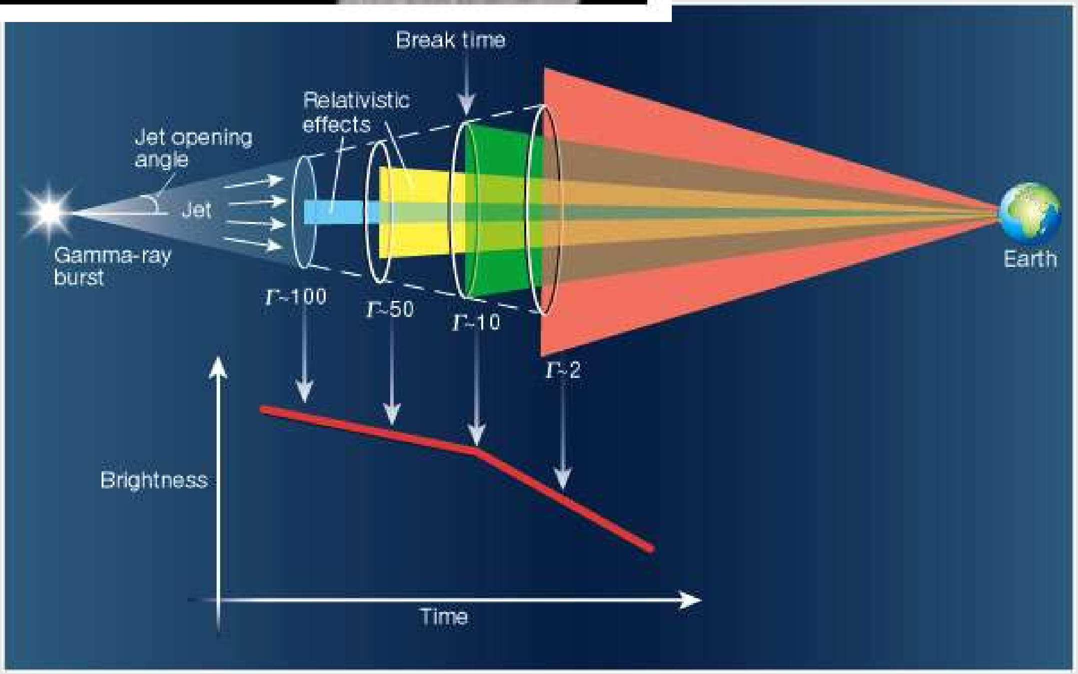
GRB 990123

GRB and Afterglow Scenarios



Meszaros (2002)

Woosley (2005)



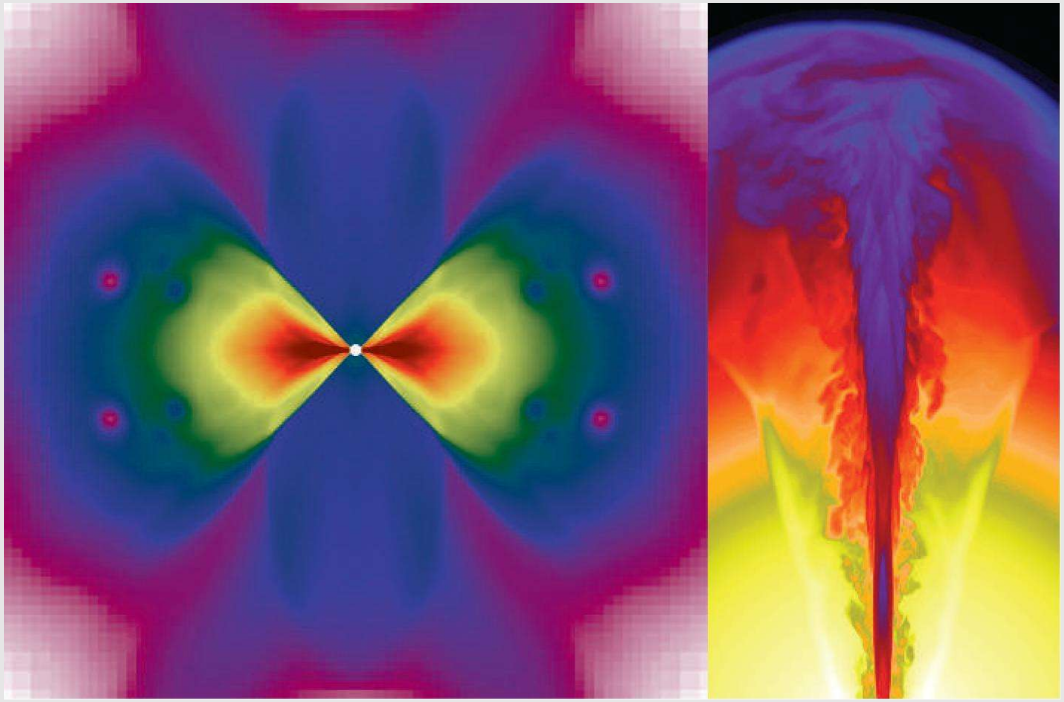
Associated with massive star explosions ("GRB-SNe"): SN bumps, GRB located in star formation regions, direct SN/GRB associations

Jets (opening angles: 1°–5°)

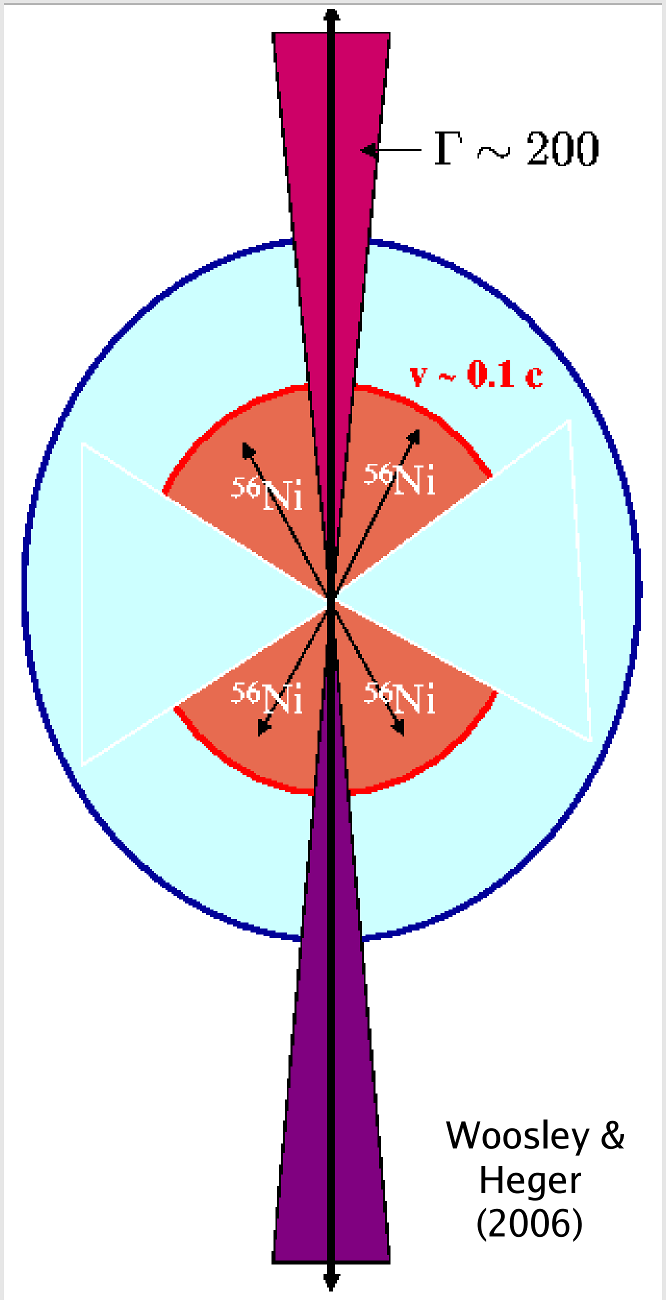
Energies: 10^{50}–10^{51} erg in gamma rays, similar in AG

Gamma-Ray Bursts and Hypernovae

- Occur in rare cases of very rapidly rotating, very massive stars with sufficient mass loss until collapse
- Black hole formation (?)
- BH accretion and ejection of very narrow, ultrarelativistic GRB jet, can be accompanied by hypernova explosion
- Jet is driven by magnetohydrodynamic (MHD) effects and/or neutrino-antineutrino annihilation
- Extremely energetic stellar explosion by MHD mechanism or viscous energy release in accretion disk



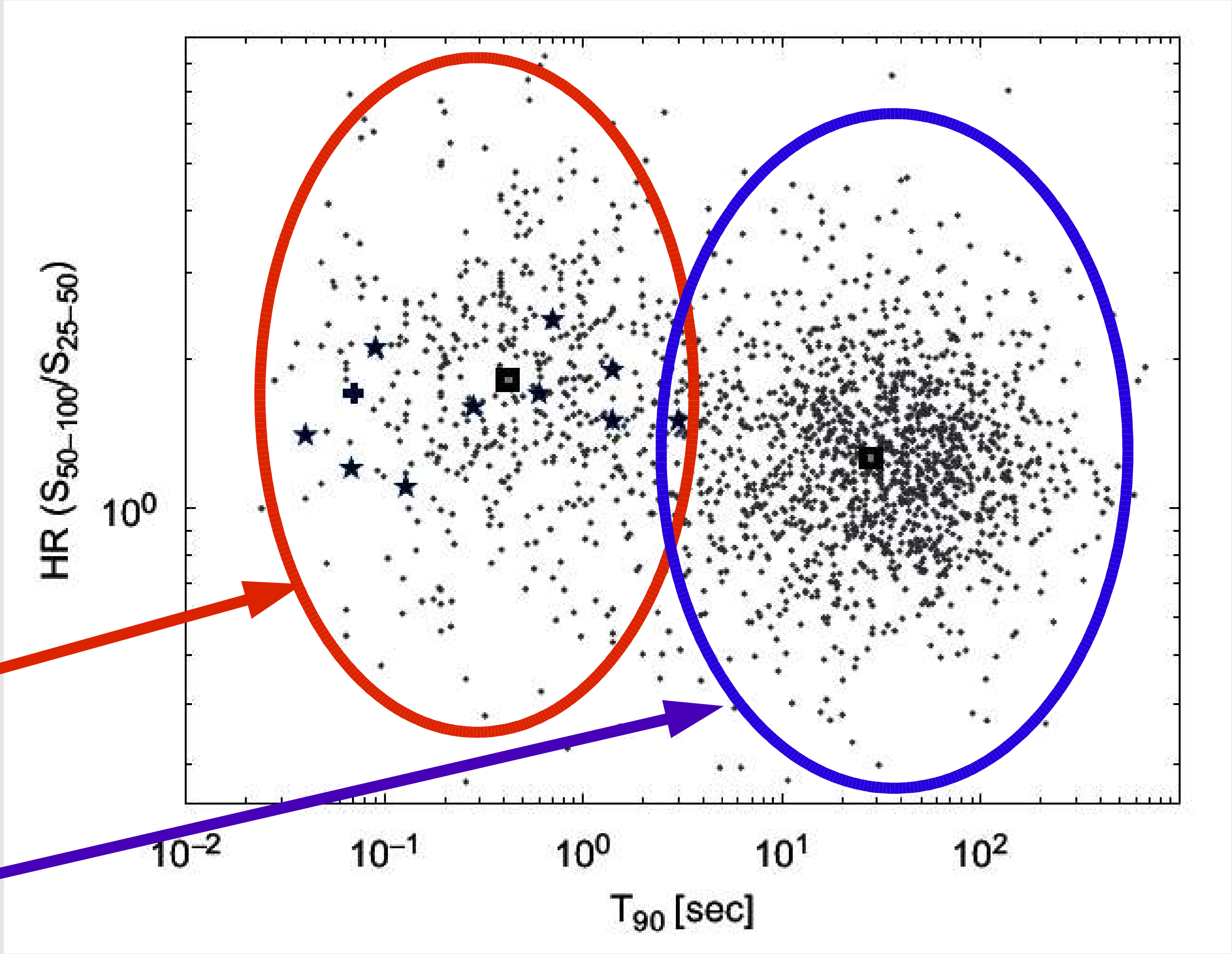
Zhang & Woosley (2005)



Woosley & Heger (2006)

Short GRBs

- Spectrally harder
- ~100 less energetic
- ~10 with unambiguously determined redshifts



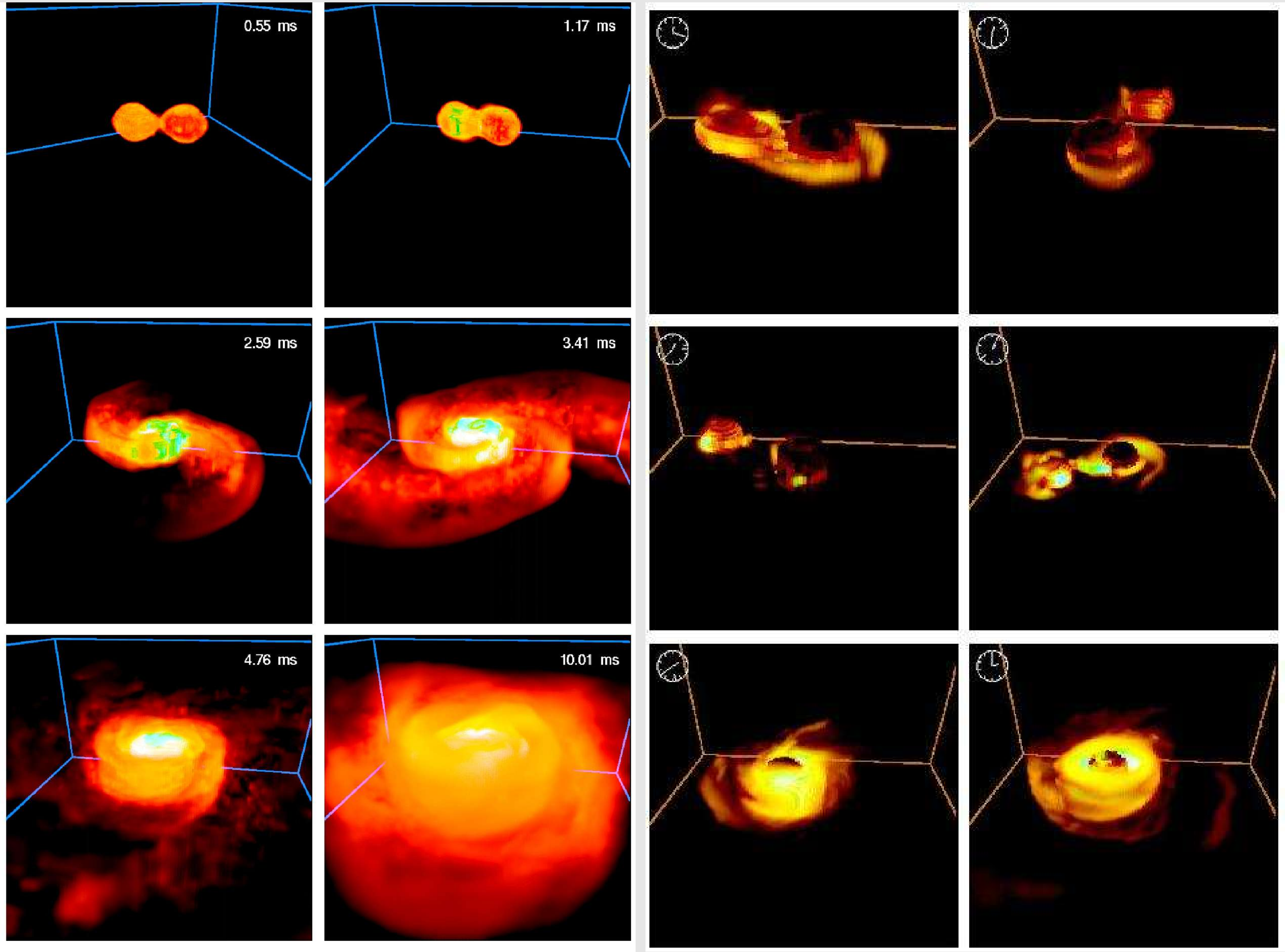
Short GRBs

Long GRBs

Nakar (2007)

Short GRBs: NS+NS/BH Mergers

- Short GRBs seem to originate from compact binary mergers (<10 sGRBs with known redshifts)
- BH formation and accretion
- γ-energies about 1% of long-GRBs



Ruffert et al.
Rosswog et al.
Oechslin et al.
Shibata et al.