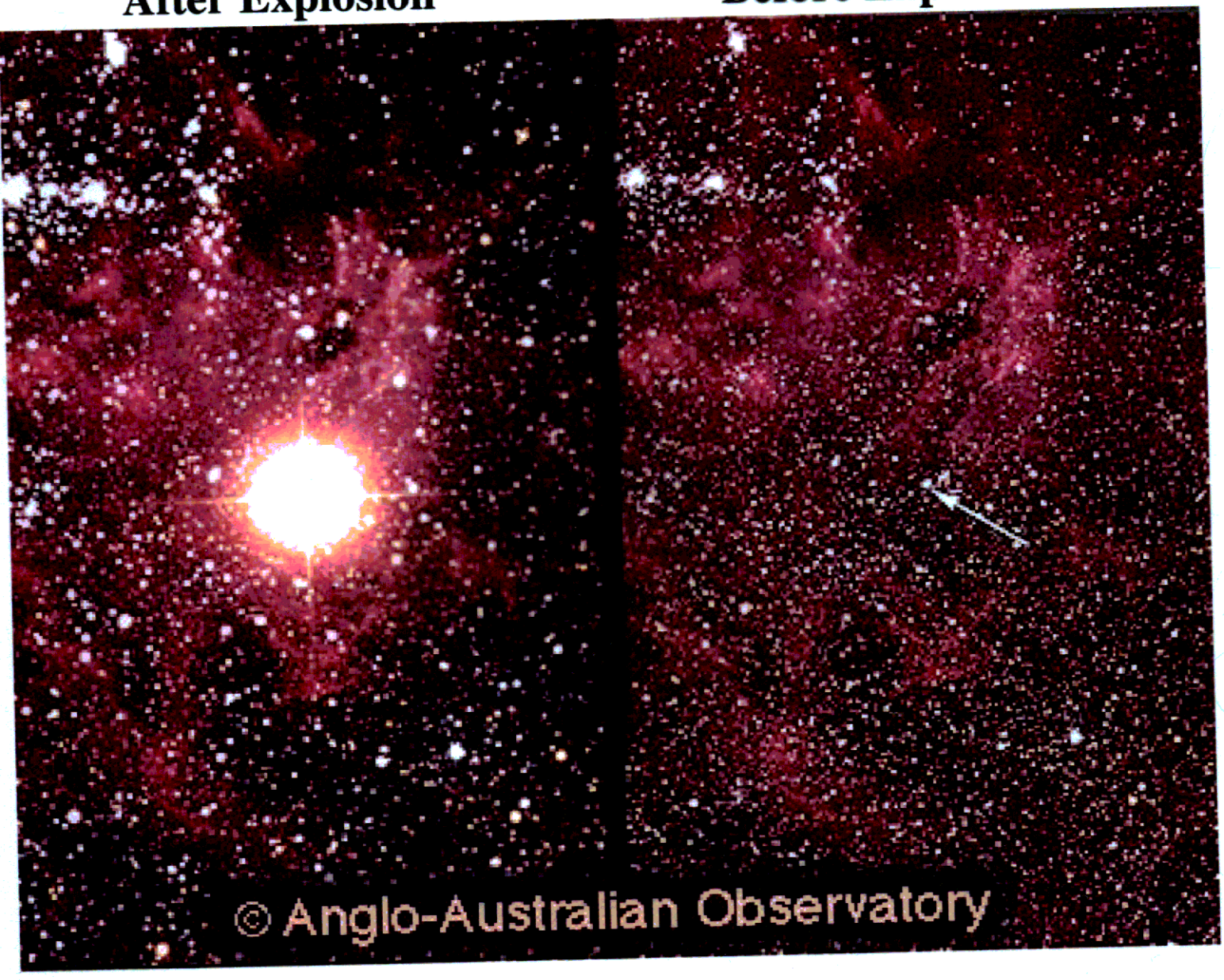
Supernova 1987A

Before and After Shots

After Explosion **Before Explosion**



Why Do Astrophysicists Care?

Hot Explosions and Cool Physics!

Supernovae are one of the biggest explosions in the universe.

10^{51} ergs of Kinetic Energy!!!

Temperatures beyond 100 MeV!
Densities above 10^{14} g/cc!

→ New, Untested Physics!
Neutrino Physics, General Relativity,
Matter at Nuclear Densities...

History

Theory

MASS EJECTION FROM SUPERNOVA

Recently, Arnett (1967) published a paper demonstrating that massive stars $\geq 10\ M_\odot$ do not eject sufficient mass by the mechanism of neutrino heat transport to result in a major explosion of the star. This disagrees with the original formulation by Colgate and White (1966; hereinafter referred to as "CW"), and the following Note discusses the problem. The problem is important to cosmological considerations because the existence of relativistic gravitational collapse beyond the state of the classical neutron star depends upon the lack of major mass ejection by massive stars. Conversely, all stars undergoing non-relativistic collapse according to the mechanism of CW may manage to eject sufficient mass so that the residual neutron star is stable.

Colgate ApJ 153,335

ON SUPERNOVA HYDRODYNAMICS

Recently, Colgate (1968) has criticized an investigation of gravitational collapse of non-rotating massive stars by the author (Arnett 1967) in which energy transport by electron-type neutrinos and antineutrinos was found to be much less efficient in massive stars ($M_{\text{core}} \gtrsim 8\ M_\odot$) than estimated by Colgate and White (1966; hereinafter referred to as "CW"). Mathematical models of these stars would not explode by this mechanism. The purpose of this Note is to reply to Colgate's criticisms and point out some weaknesses in the analysis given in CW.

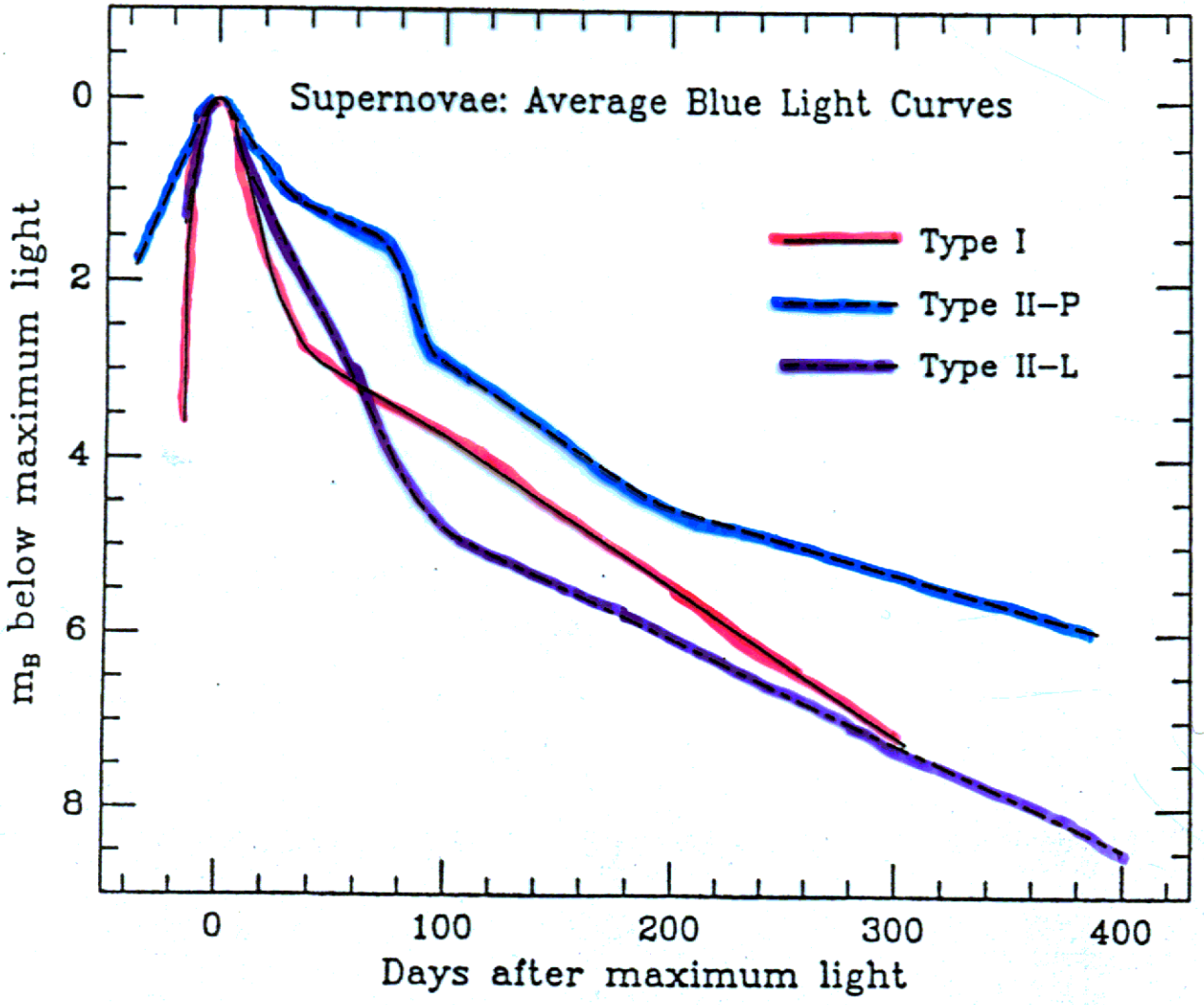
Arnett ApJ 153, 341

2 Mechanisms

1) Thermonuclear Explosion of WD

2) Core Collapse of Massive Star

Typical Light curves



Type II

Formation Sites:

Spirals (some irregulars)

Spectra:

<u>Hydrogen</u>

Light Curves:

most have "plateaus"

Neutrinos!

1987A

Type II Spectra

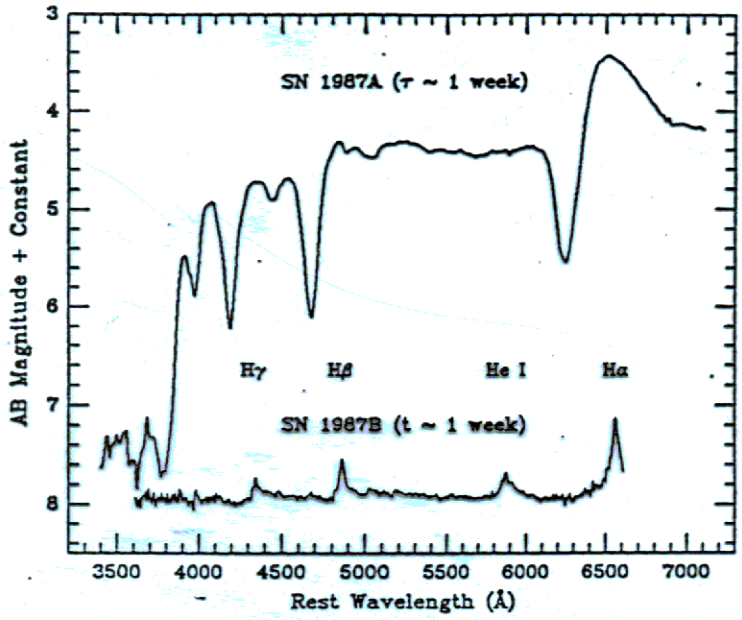


Figure 5: Early-time spectra of SNe 1987A and 1987B. The spectrum of SN 1987B was provided by Dr. R. P. Harkness.

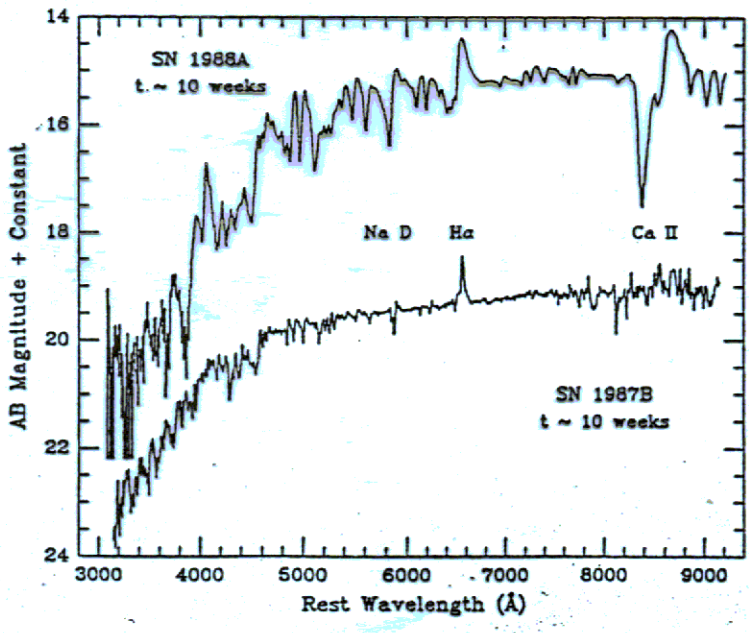


Figure 6: Spectra of SNe 1988A and 1987B at comparable phases. The near-IR ($\lambda \gtrsim 7700$ Å) region of SN 1987B is noisy due to incomplete removal of CCD interference fringes.

Type Ia

Formation Sites:

All types of Galaxies

Spectra:

No H; O, S, Si, Mg

Large Ejection Velocities

Light Curve:

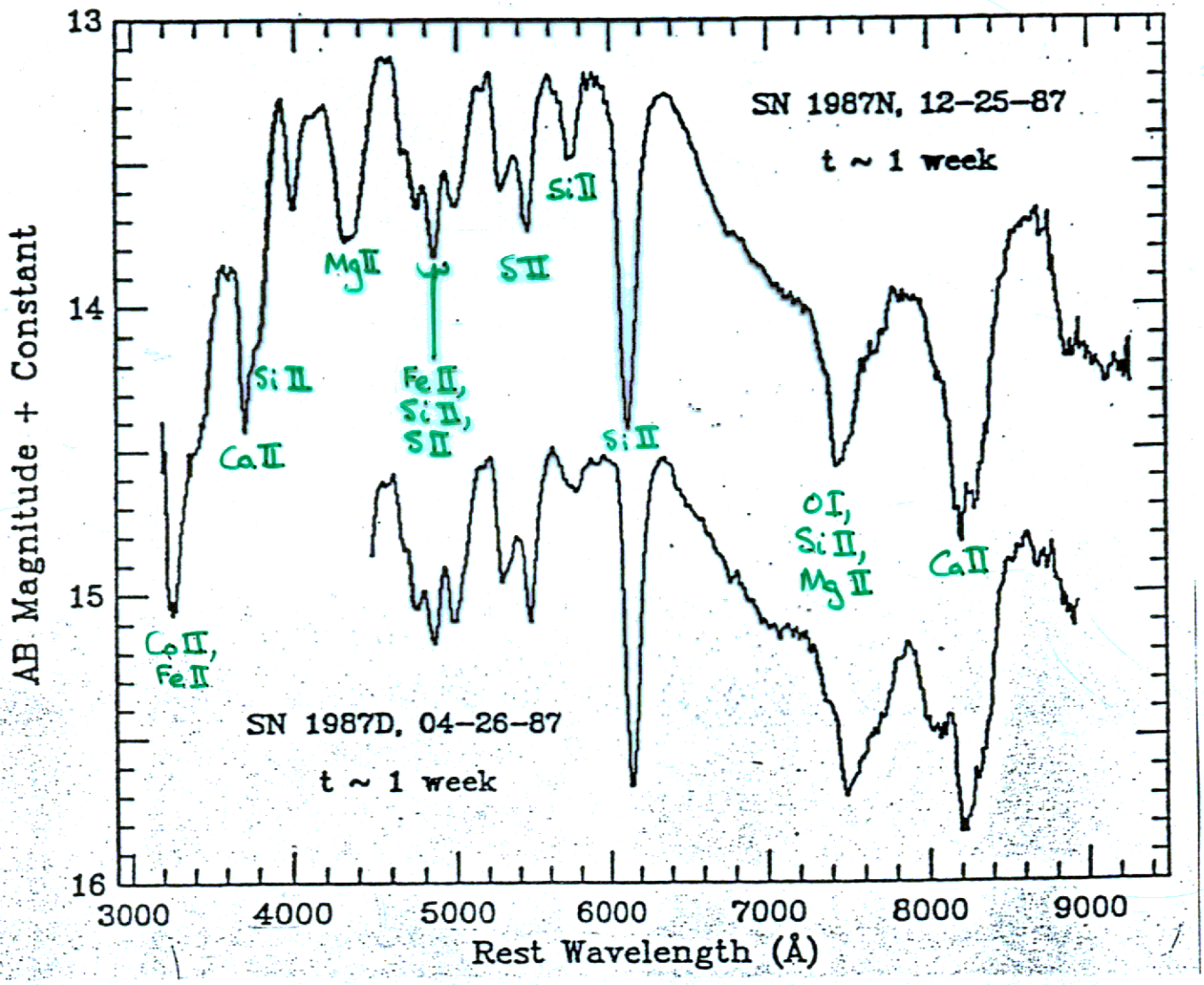
Rapid Decline

Exponential Tail

$\Rightarrow$ WD progenitor

Type Ia Spectra

Si !!! No H



Type Ib + Ic

Formation Sites:

Late Type Galaxies Sb, Sc

Spectra:

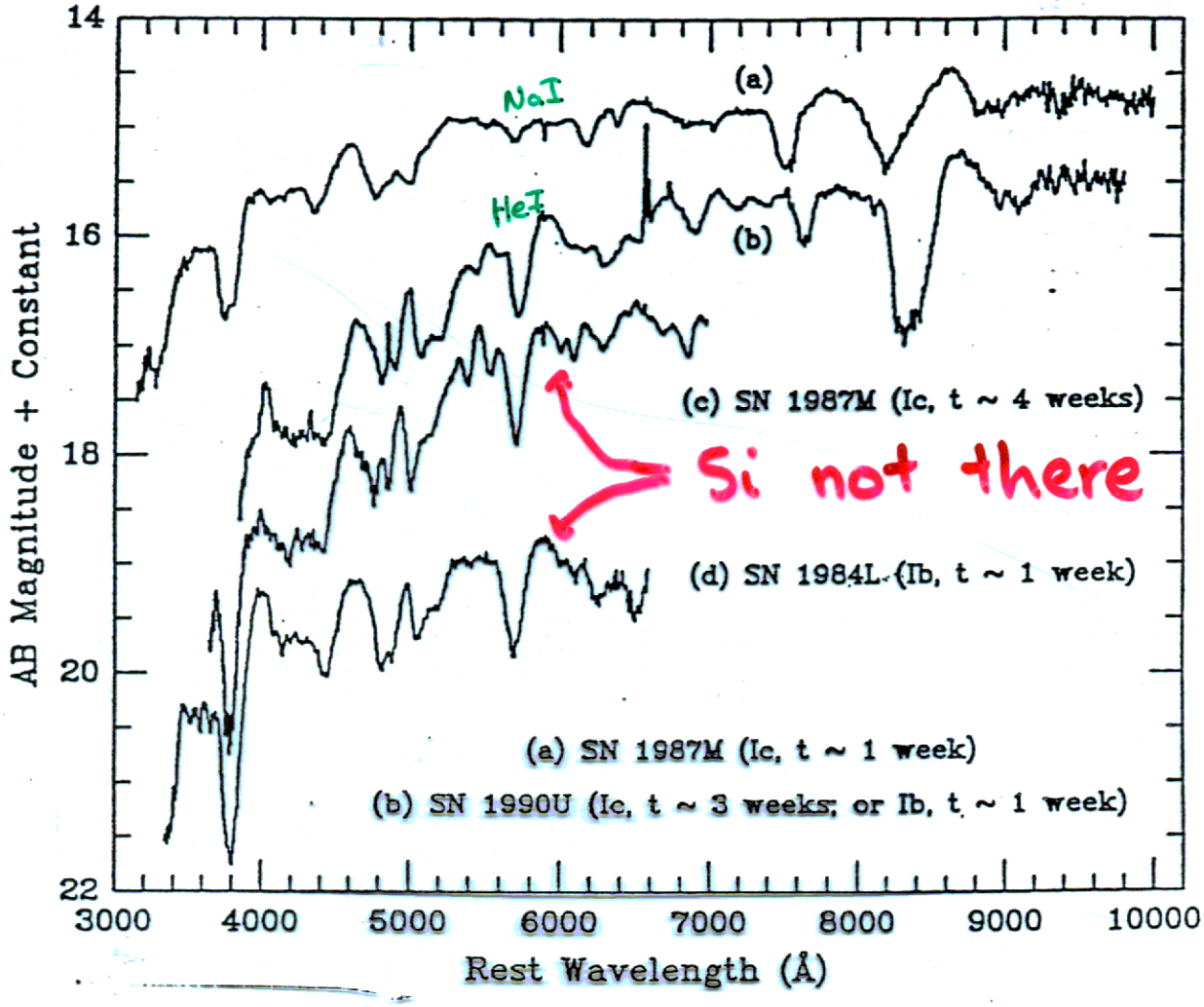
No or weak Si

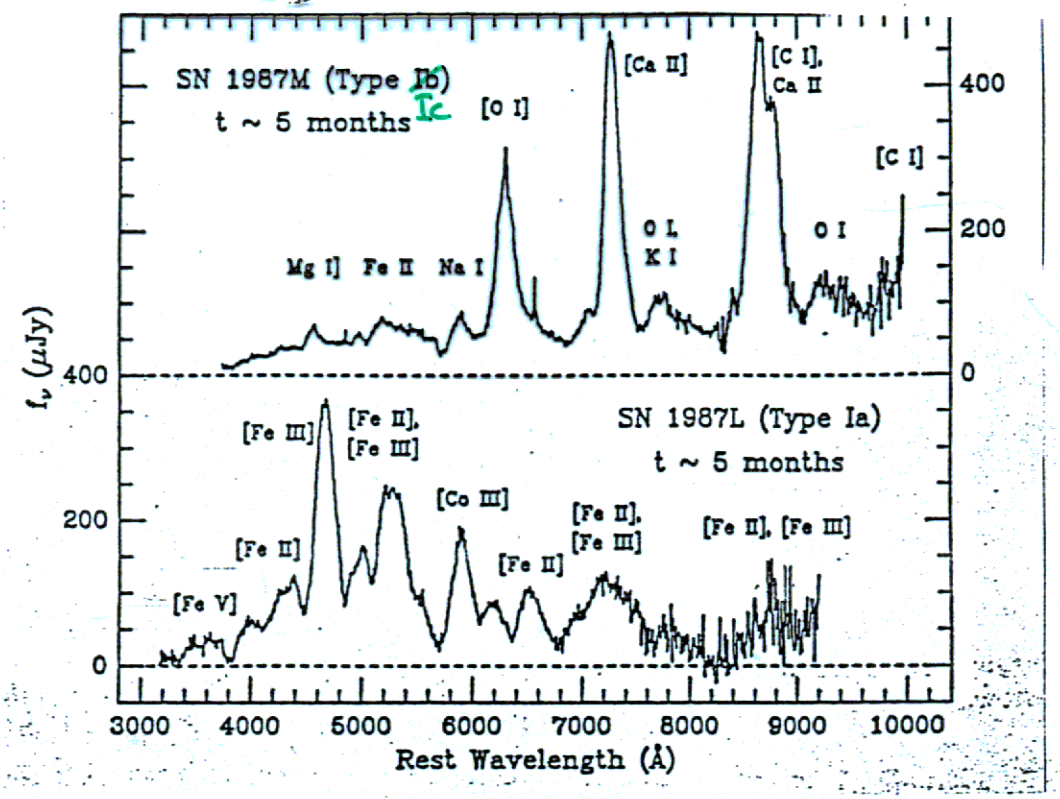
Type Ib	Type Ic
HeI Strong	HeI not Strong

Light Curve:

Like Type Ia

Type Ib + Ic Spectra

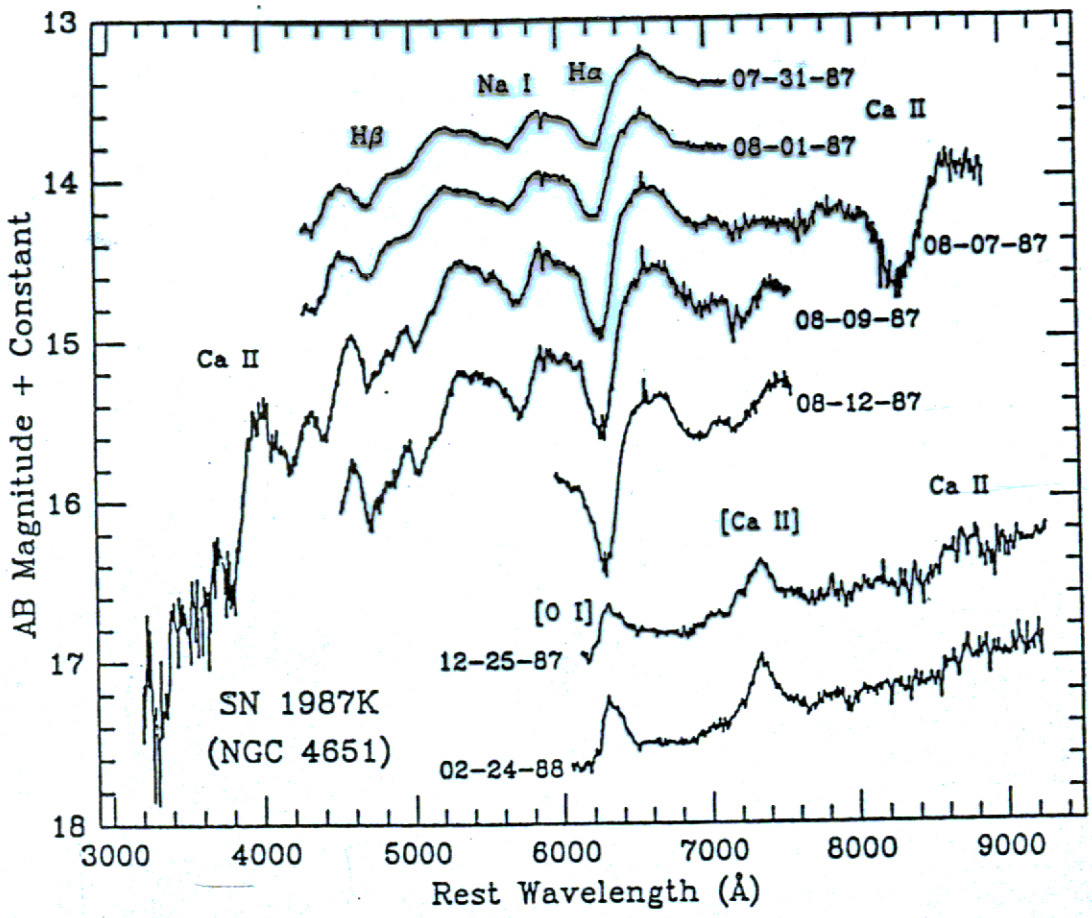




* News Flash *

Type II becomes Ib

1987K, 1993J

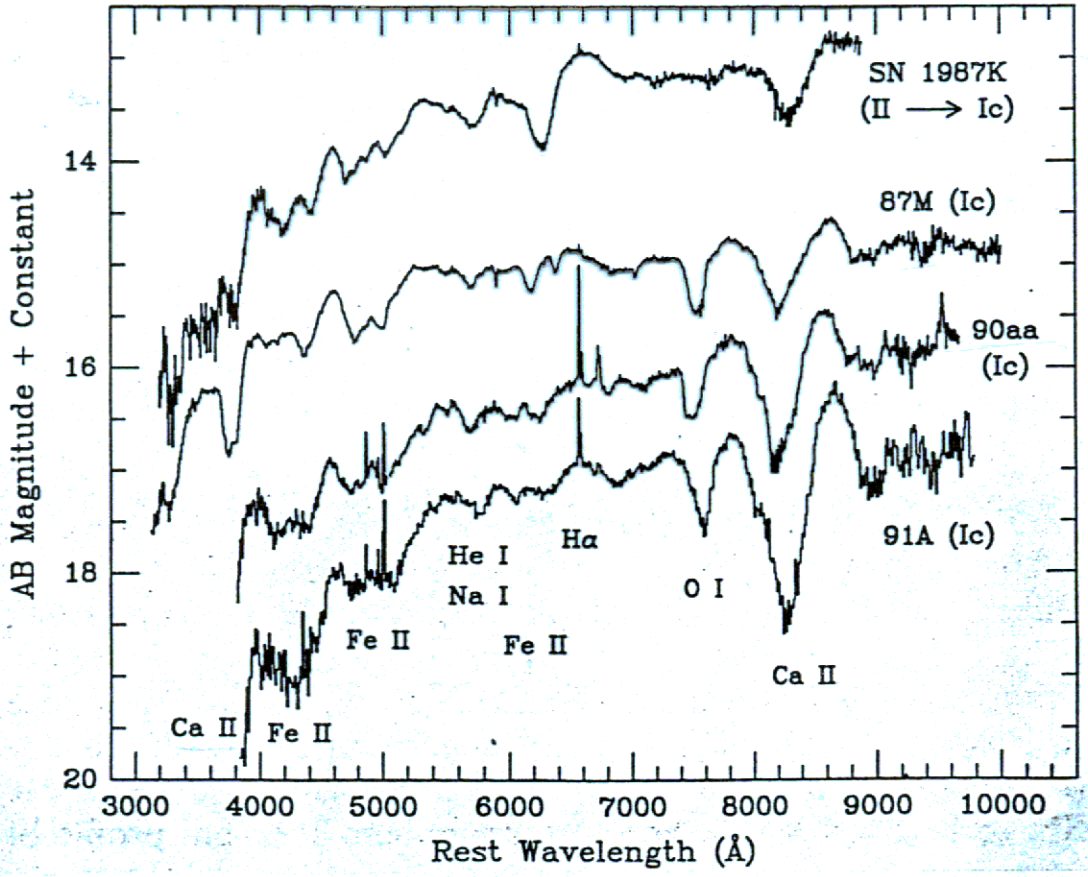


Filippenko AJ 96, 1941

The Plot Thickens

Type I's with Hα

1990aa, 1991A



Filippenko ApJL 384 L37

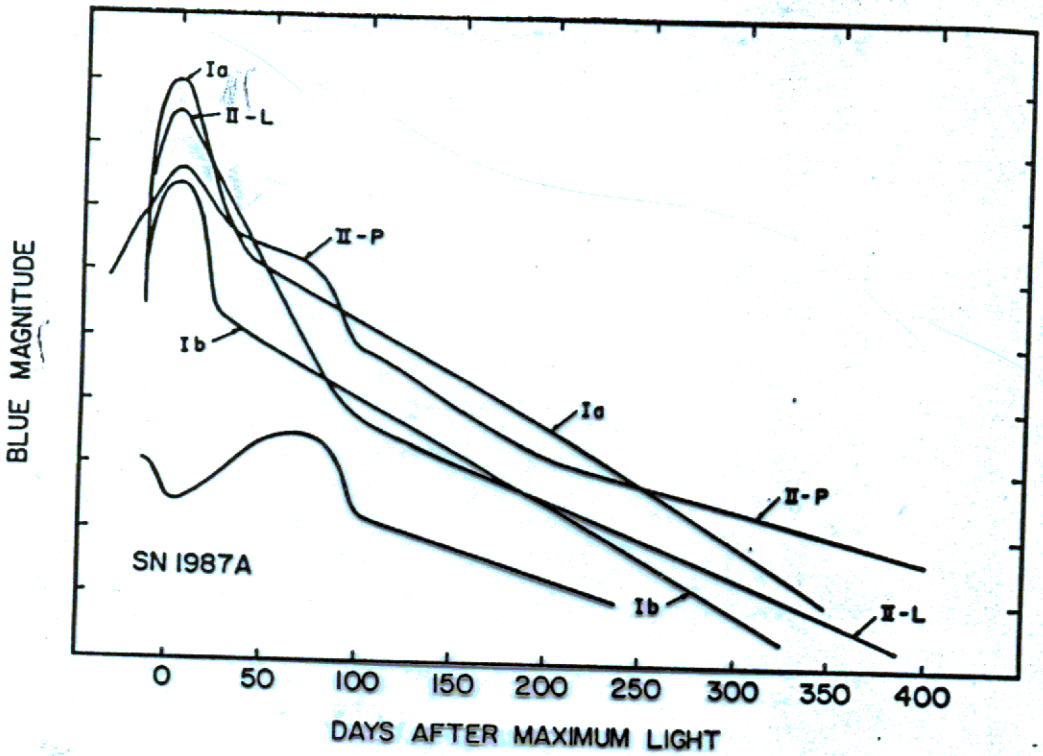


Figure 3 Schematic light curves for SNe of Types Ia, Ib, II-L, II-P, and SN 1987A. The curve for SNe Ib includes SNe Ic as well, and represents an average. For SNe II-L, SNe 1979C and 1980K are used, but these might be unusually luminous. From Wheeler 1990; reproduced with permission.

NIEMEYER, HILLEBRANDT, & WOOSLEY

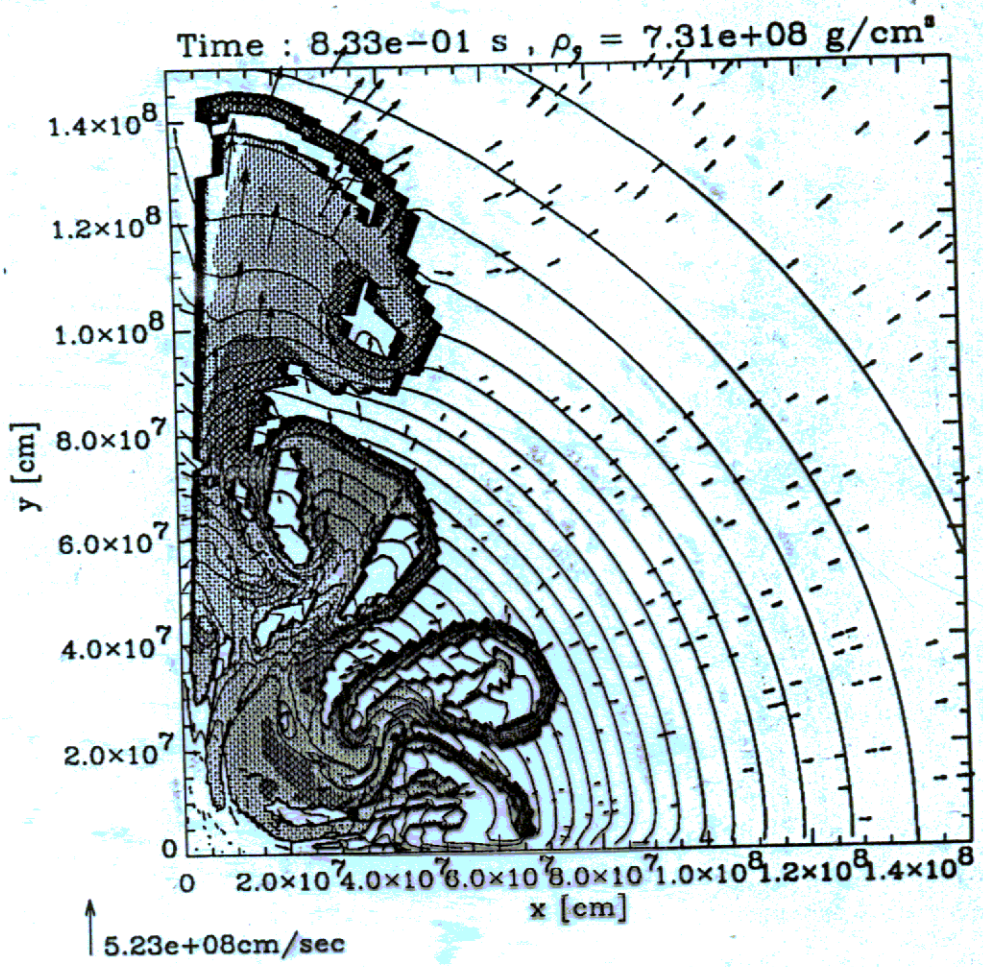
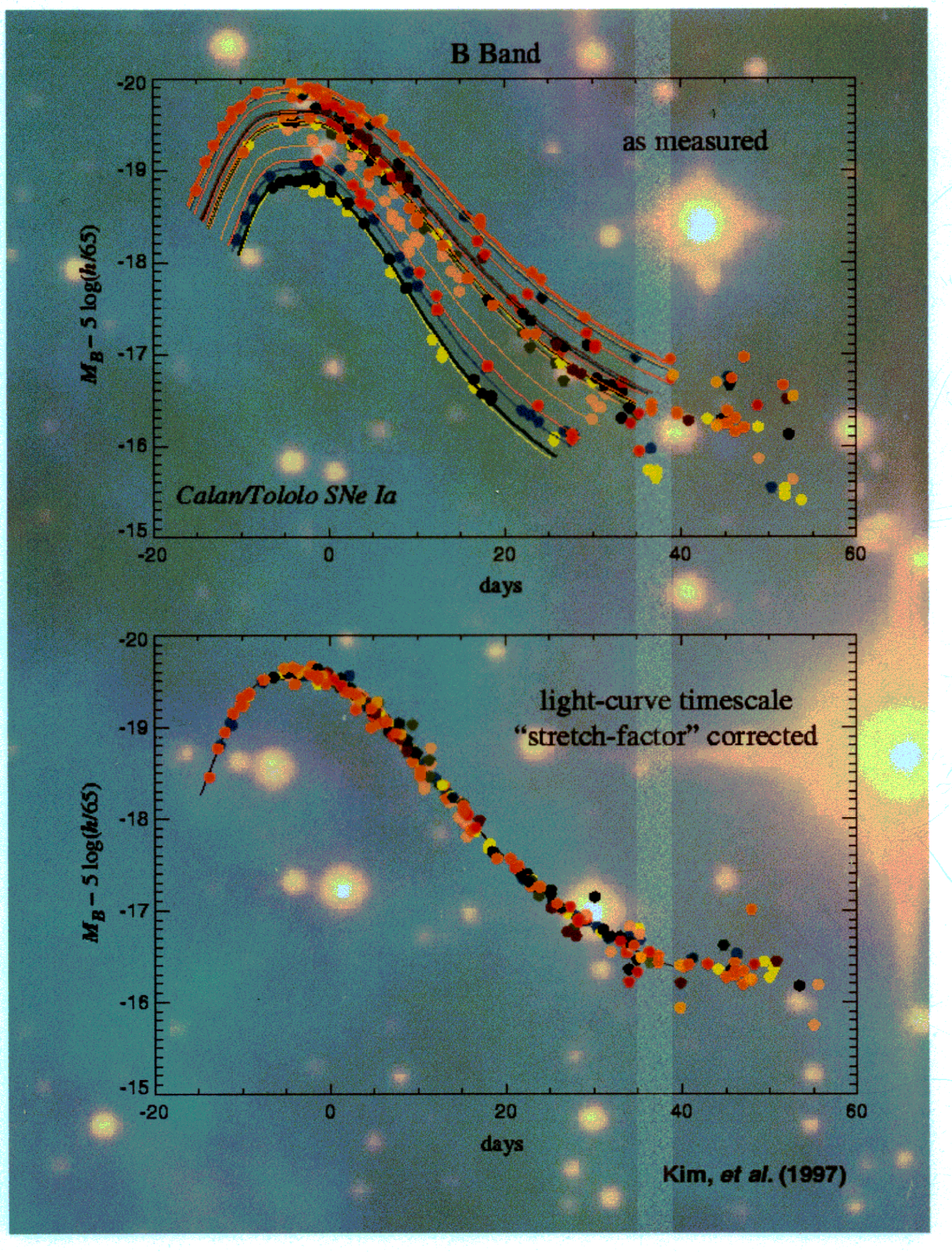
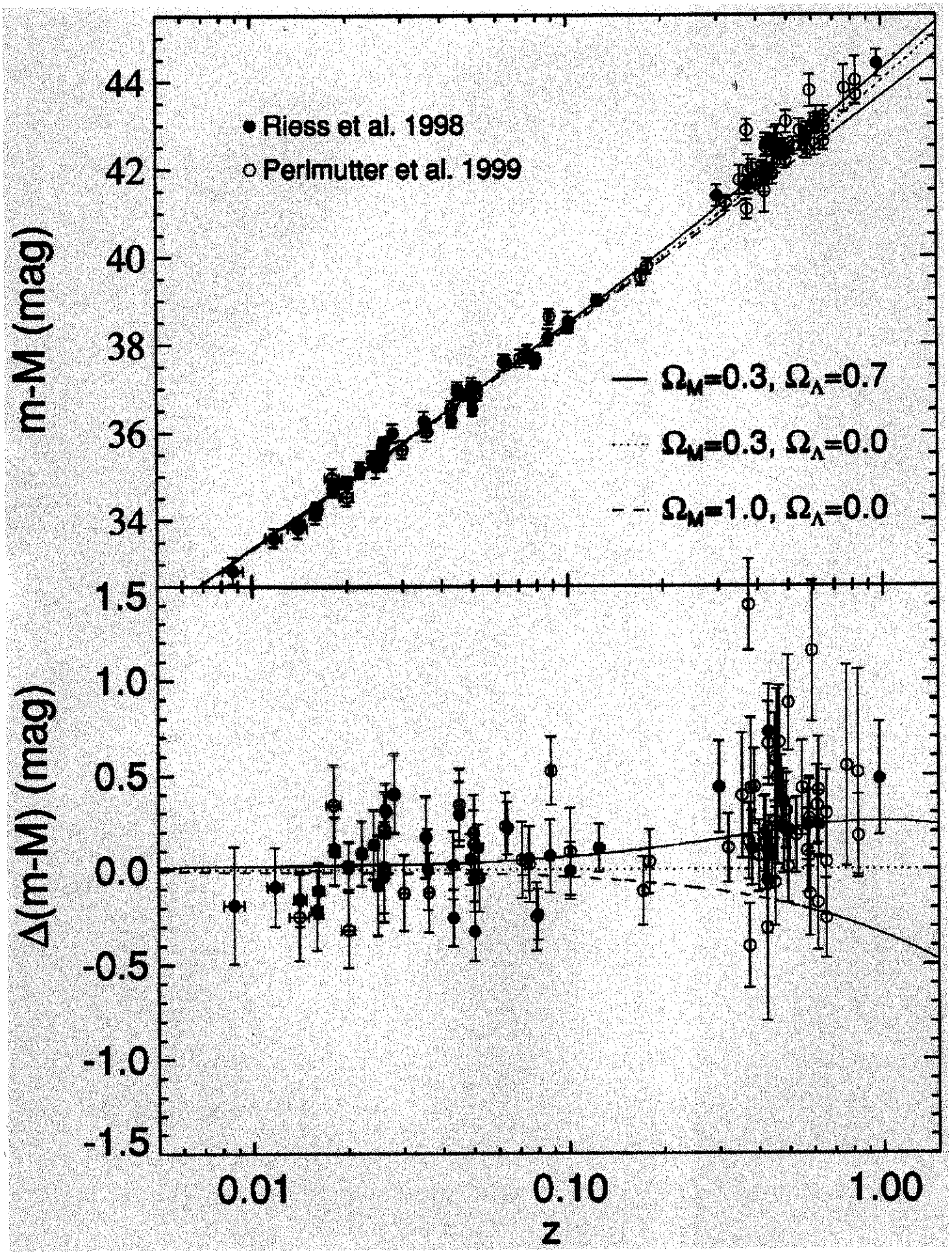


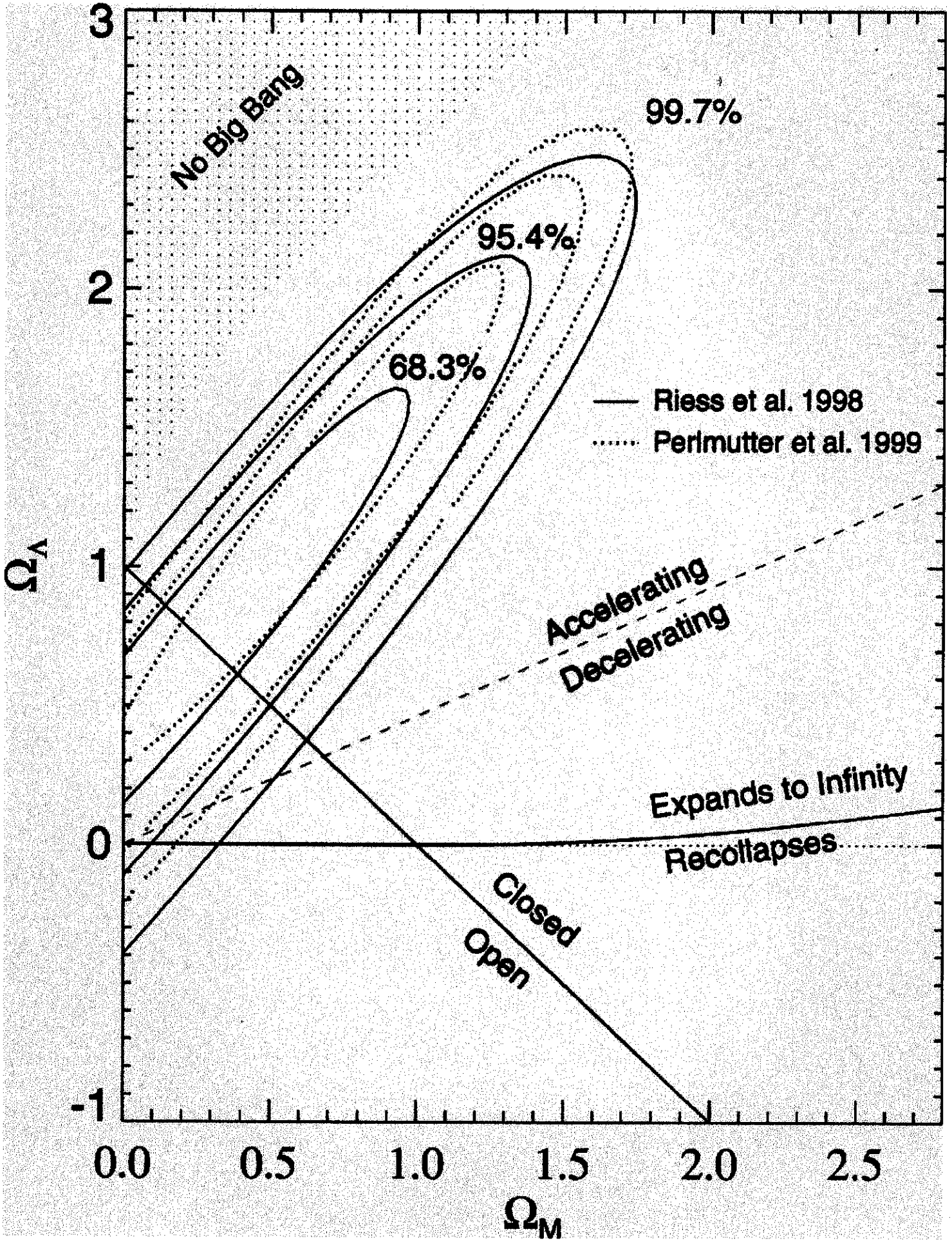
FIG. 3.—$\delta\rho = 3 \times 10^7$ g cm^{-3}; $\dot{S}_{max} = 1.3 \times 10^{19}$ ergs g^{-1} s^{-1}

"Despite 25 years of intensive investigation, the basic physics whereby a carbon-oxygen core of nearly the Chandrasekhar mass explodes as a Type Ia SN is still debated. One may conclude that it is a hard problem."

Delayed Detonation
pulsational Detonation
pulsational Deflagration
convective Deflagration...


B Band
as measured
Calan/Tololo SNe Ia
$M_B - 5\log(h/65)$
days
light-curve timescale
"stretch-factor" corrected
$M_B - 5\log(h/65)$
days
Kim, et al. (1997)


Riess et al. 1998
Perlmutter et al. 1999
Ω_M=0.3, Ω_Λ=0.7
Ω_M=0.3, Ω_Λ=0.0
Ω_M=1.0, Ω_Λ=0.0
m-M (mag)
44
42
40
38
36
34
Δ(m-M) (mag)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
0.01
0.10
1.00
z


No Big Bang
99.7%
95.4%
68.3%
Riess et al. 1998
Perlmutter et al. 1999
Accelerating
Decelerating
Expands to Infinity
Recollapses
Closed
Open
Ω_Λ
Ω_M
3
2
1
0
-1
0.0
0.5
1.0
1.5
2.0
2.5

What is a Core-Collapse Supernova?

(For the SN afficinado,
Core Collapse SN $\equiv$ Type Ib/c, II SN)

- Death of a Massive Star
- Explosion Powered by the Gravitational Energy Released during the collapse of a Massive Stellar core down to a Neutron Star

$$E_{explosion} = \frac{G M_{core}^2}{R_{NS}} - \frac{G M_{core}^2}{R_{before\ collapse}}$$

$$\approx 6 \times 10^{53} \text{ ergs !!!}$$

for $M_{core} = 1.5 M_\odot = 3 \times 10^{33}$ g

$R_{NS} = 10$ Km

$R_{before\ collapse} = 1000$ Km

Supernova Collapse

Temperature and Density of the Core becomes so High that:

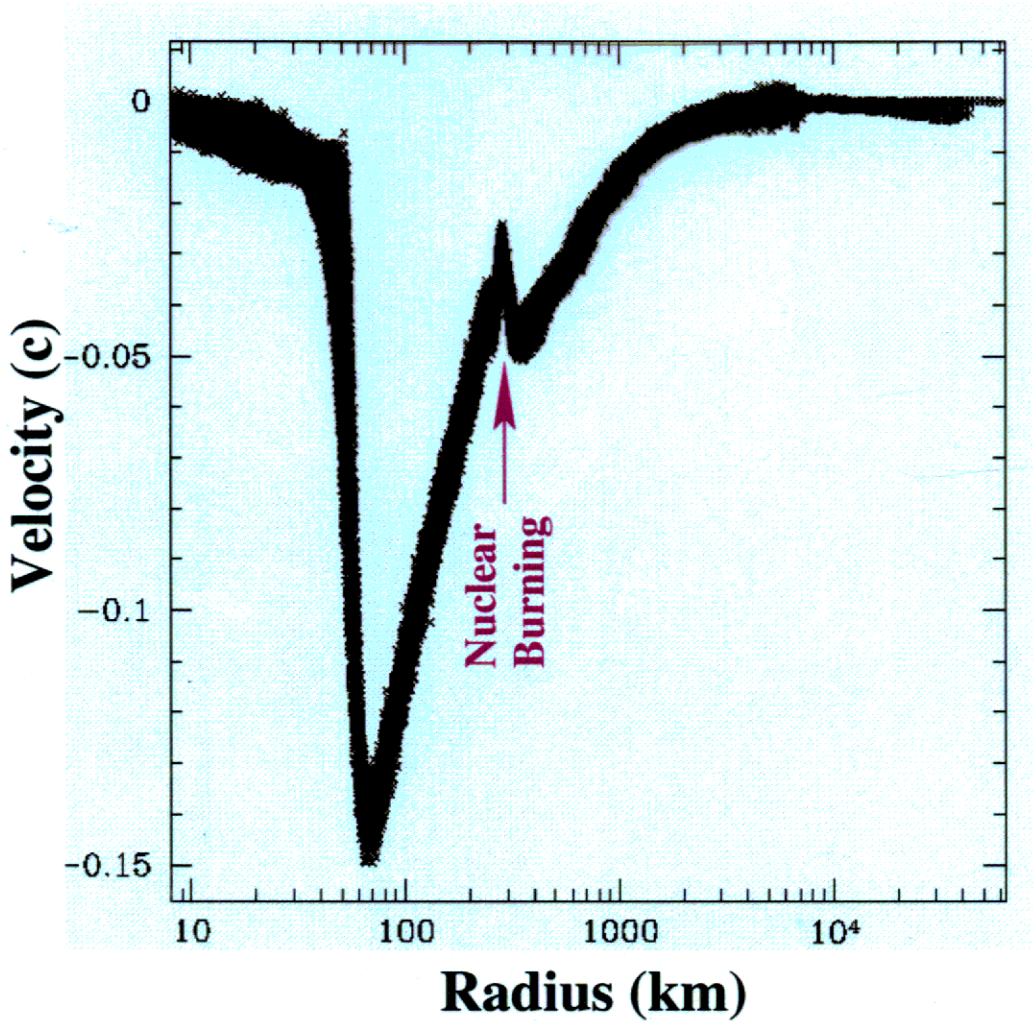
Iron Dissociates into α-particles

Electrons Capture onto Protons

$$e + p \rightarrow n + \nu_e$$

→ **Pressure in Core Decreases**

→ **Core Collapses nearly at Free-Fall!!!**

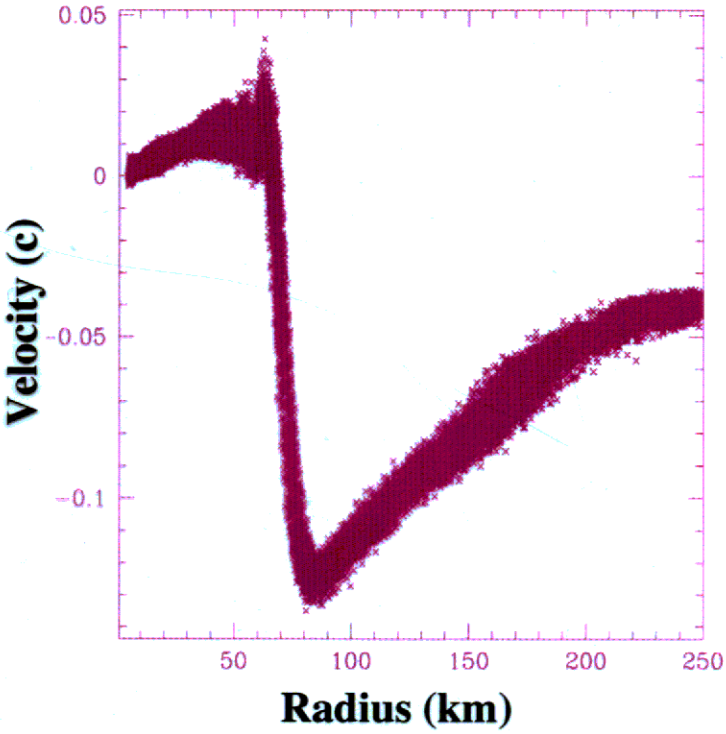


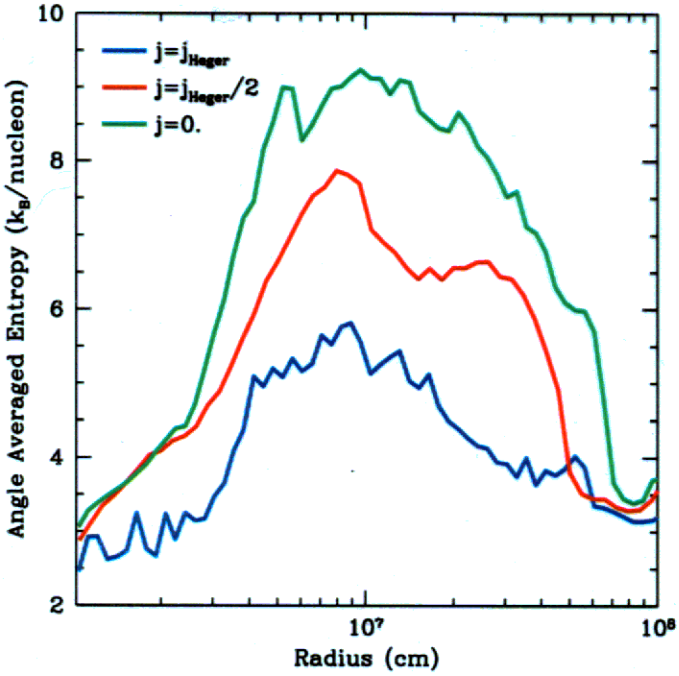
Core Bounce and Stall of the Shock

Core Reaches Nuclear Densities

→ Nuclear Forces, Neutron Degeneracy Increase Pressure

→ Bounce!





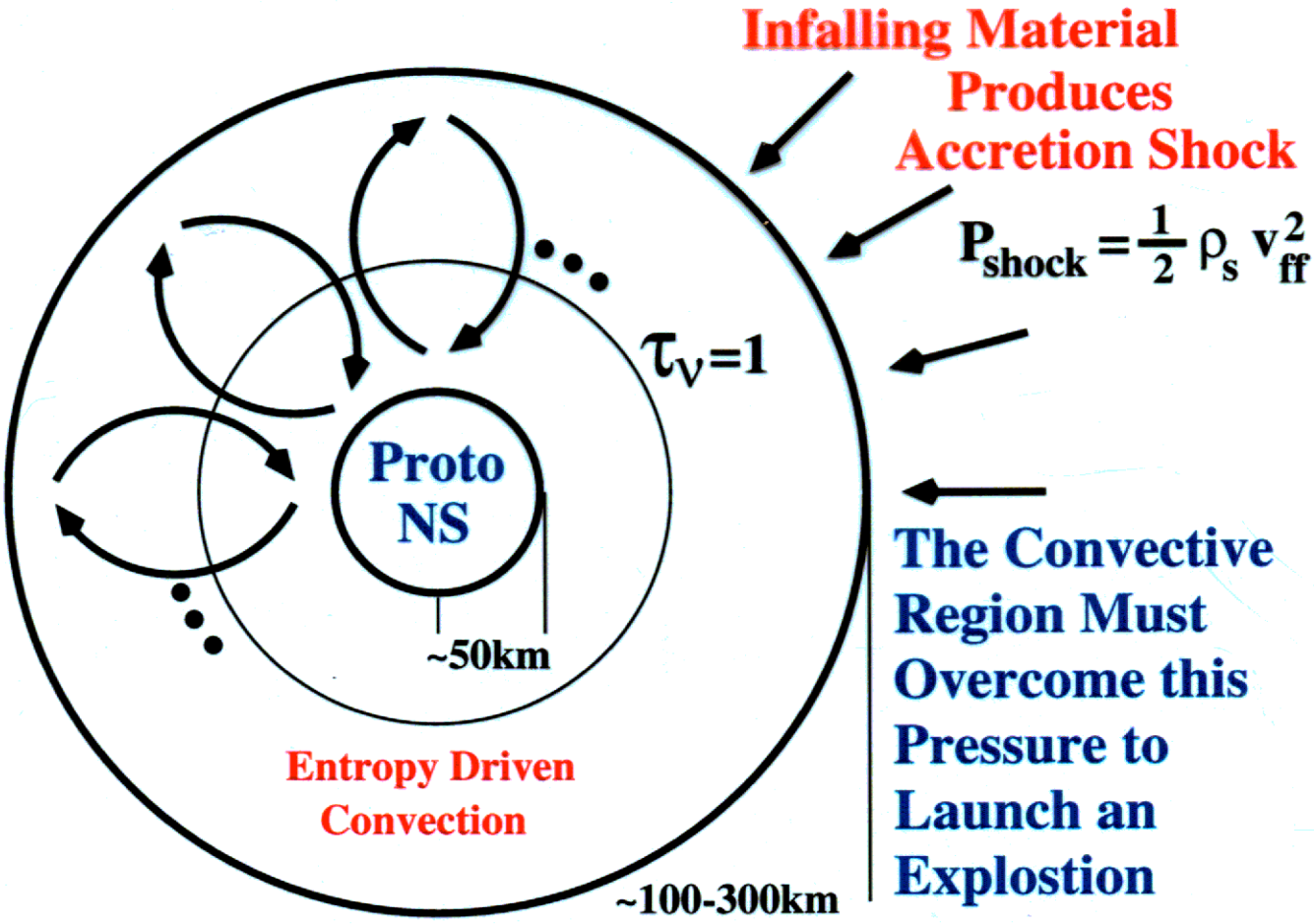
Neutrino Emission and Dissociation Stall Shock

However, the Shock Leaves Behind an Unstable Entropy Gradient which Seeds Convection!

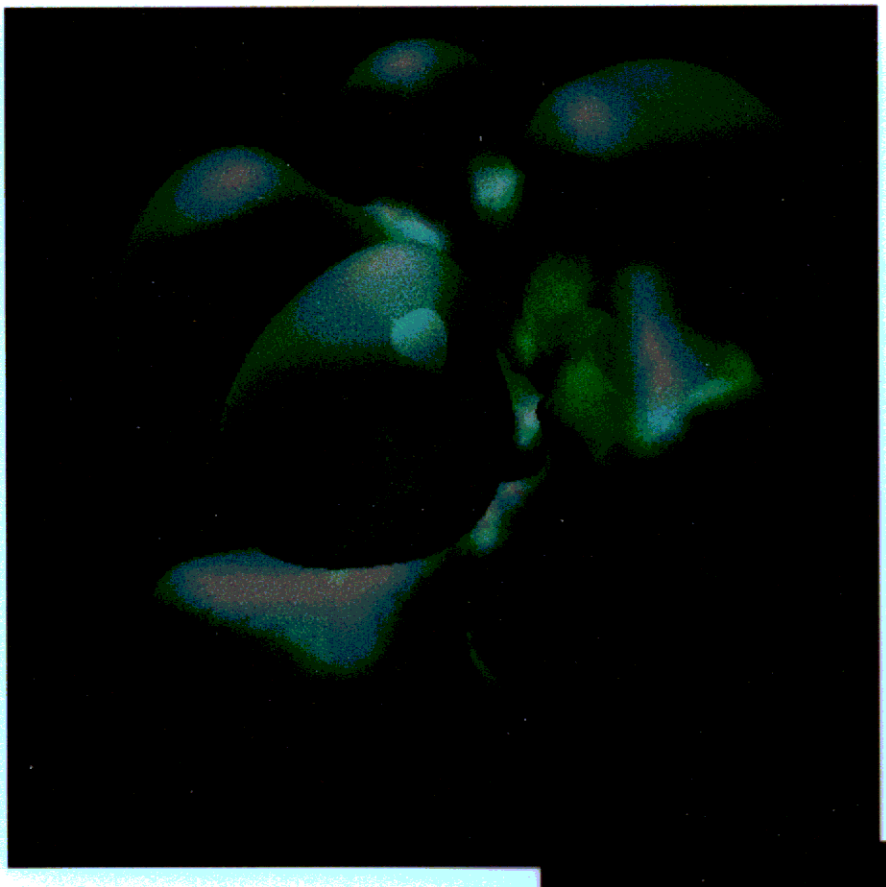
Convection Enhanced Supernovae

- Neutrino Heated Material Rises, Cooling Adiabatically Before Losing Its Energy Via Neutrino Emission

- Infalling Material Convects Down to the Proto-Neutron Star. It Does NOT Pile Up at the Accretion Shock.



3D Core–Collapse Supernovae



Iso–Surface Plot
(V_{rad}=1000 km/s)

15 Solar Mass
Collapse

T=75ms
After Bounce

300,000 particles

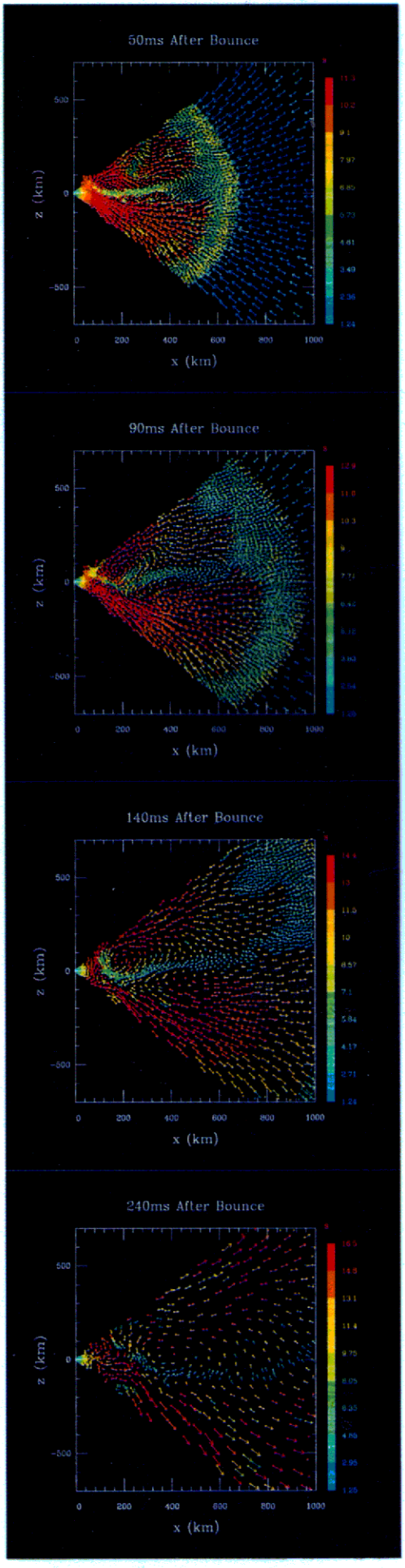
2.9 FOE Explosion

1 Million Particles

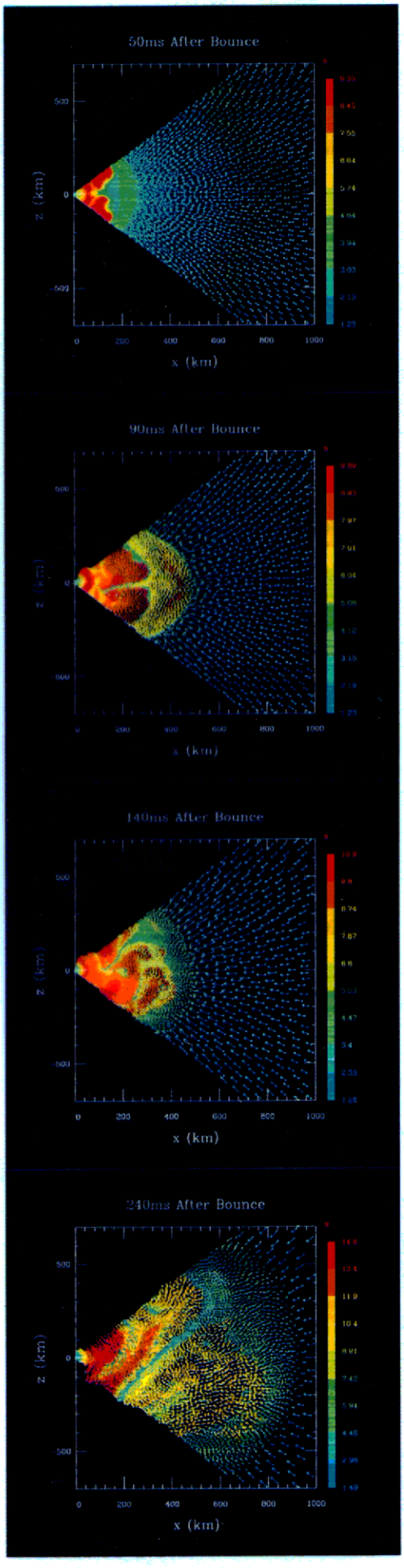
2.8 FOE Explosion

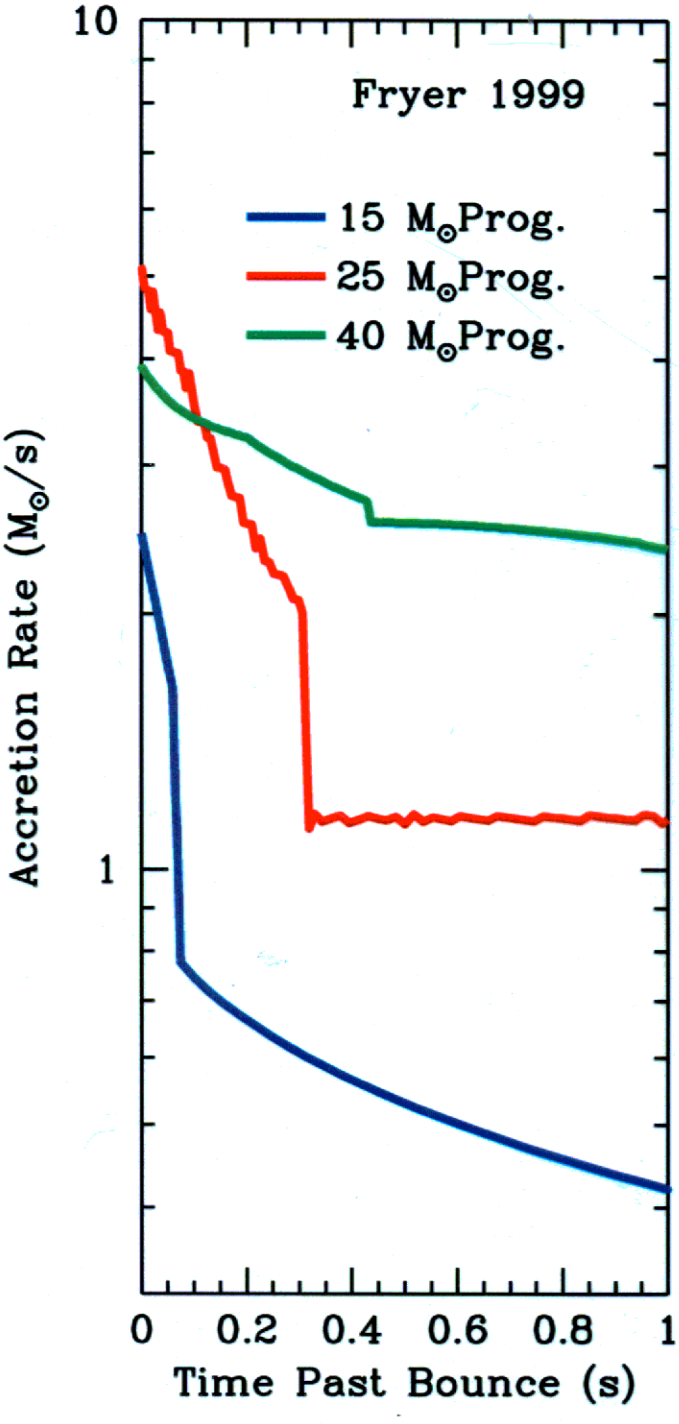
Remnant Mass
Identical

15 Solar Mass Progenitor



25 Solar Mass Progenitor





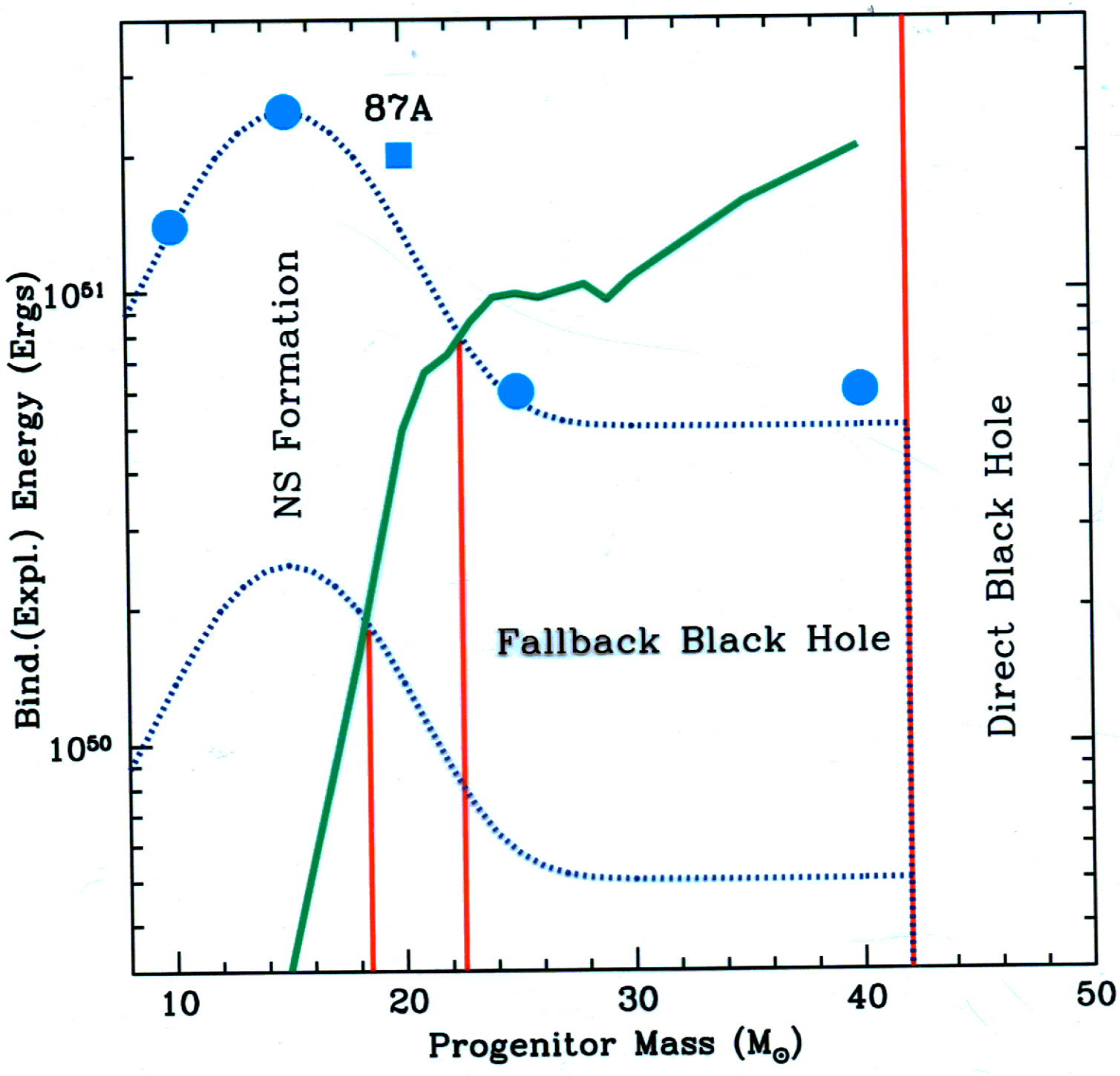
$$P_{Shock} \approx \frac{1}{2}\rho v_{ff}^2$$

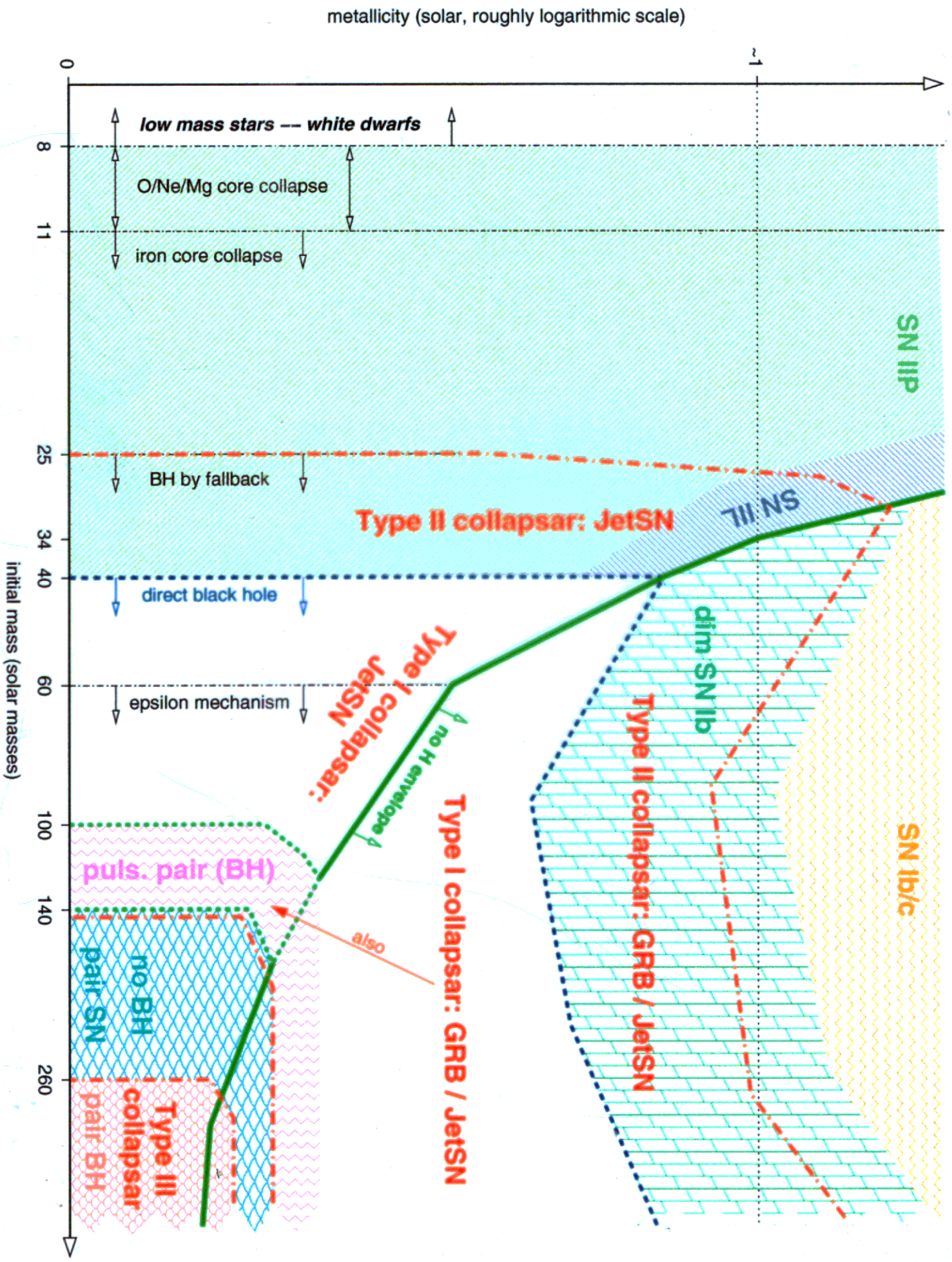
$$\approx \frac{(2GM_{encl})^{1/2}}{8\pi R_S^{2.5}}\dot{M}_S$$

Massive Stars Have Higher Infall Rates →Requires More Energy To Explode

Burrows & Goshy 1993

Fryer '99


87A
NS Formation
Fallback Black Hole
Direct Black Hole
Bind.(Expl.) Energy (Ergs)
10^{51}
10^{50}
10
20
30
40
50
Progenitor Mass ($M_\odot$)


metallicity (solar, roughly logarithmic scale)
0
~1
initial mass (solar masses)
8
11
25
34
40
60
100
140
260
low mass stars -- white dwarfs
O/Ne/Mg core collapse
iron core collapse
BH by fallback
direct black hole
epsilon mechanism
SN IIP
SN IIL
Type II collapsar: JetSN
Type I collapsar: JetSN
no H envelope
dim SN Ib
Type II collapsar: GRB / JetSN
SN Ib/c
Type I collapsar: GRB / JetSN
also
puls. pair (BH)
pair SN
no BH
Type III collapsar
pair BH