Supernova Neutrinos and Nucleosynthesis

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Neutrinos & Dark Matter 2009
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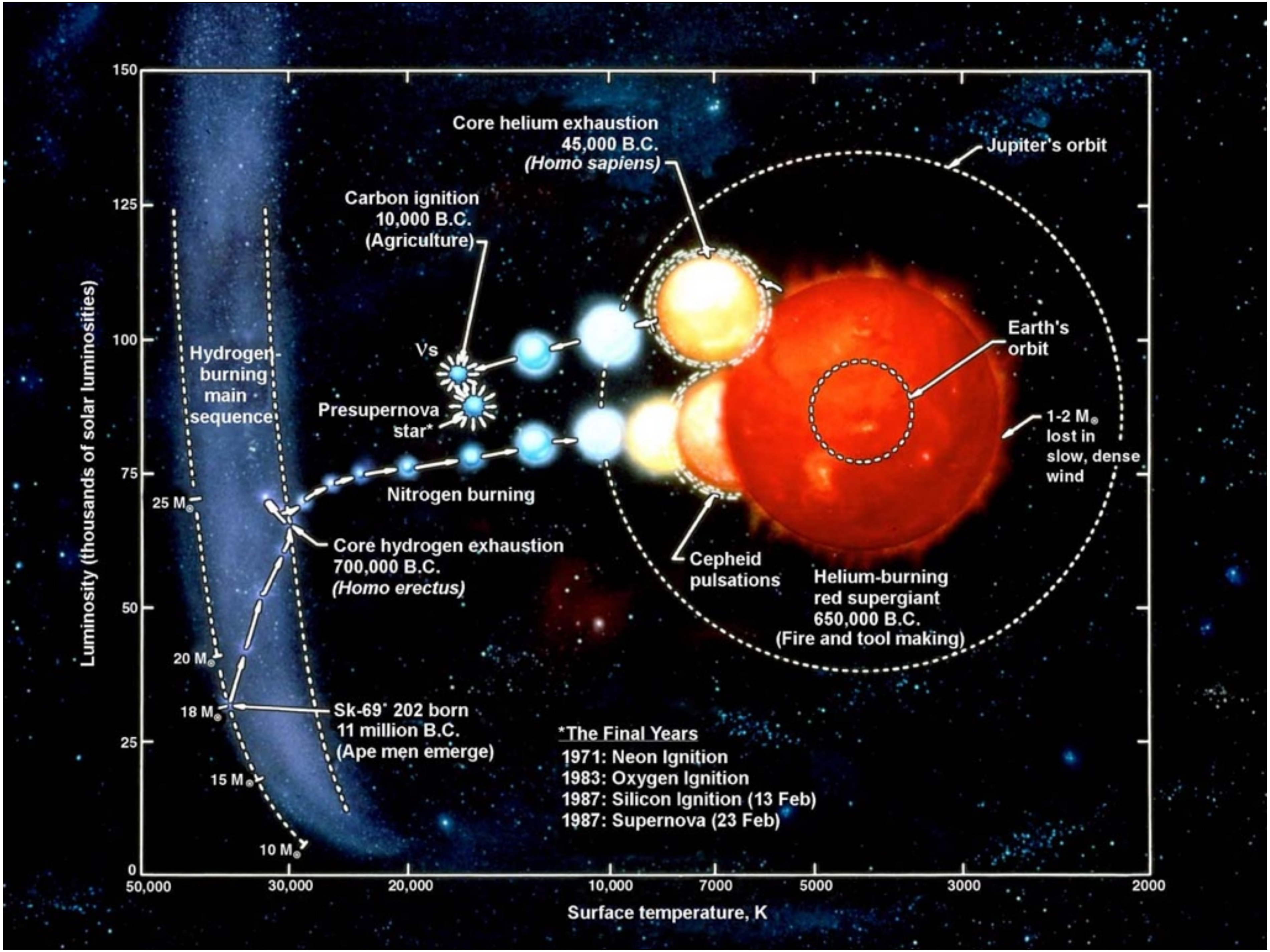
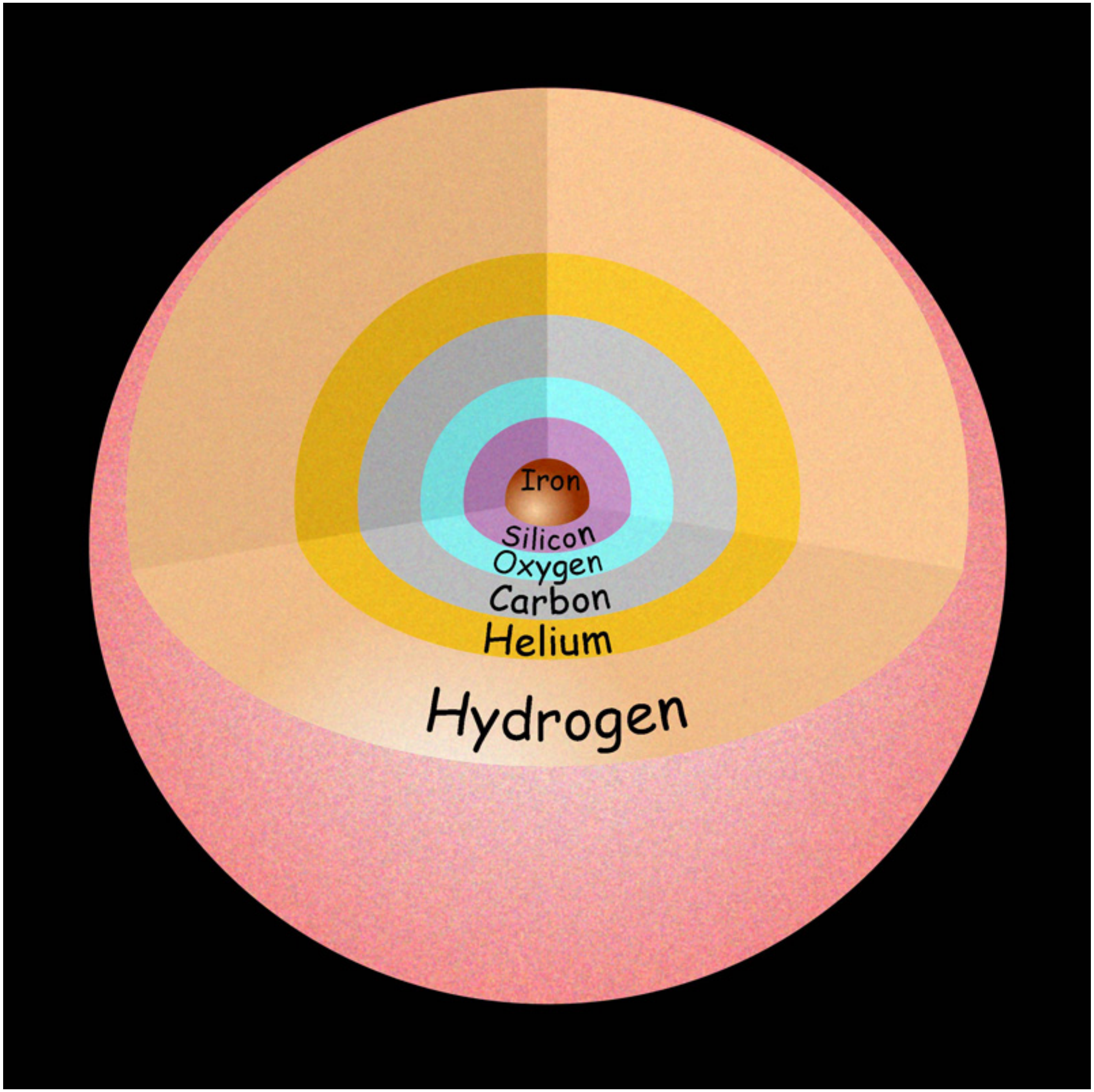
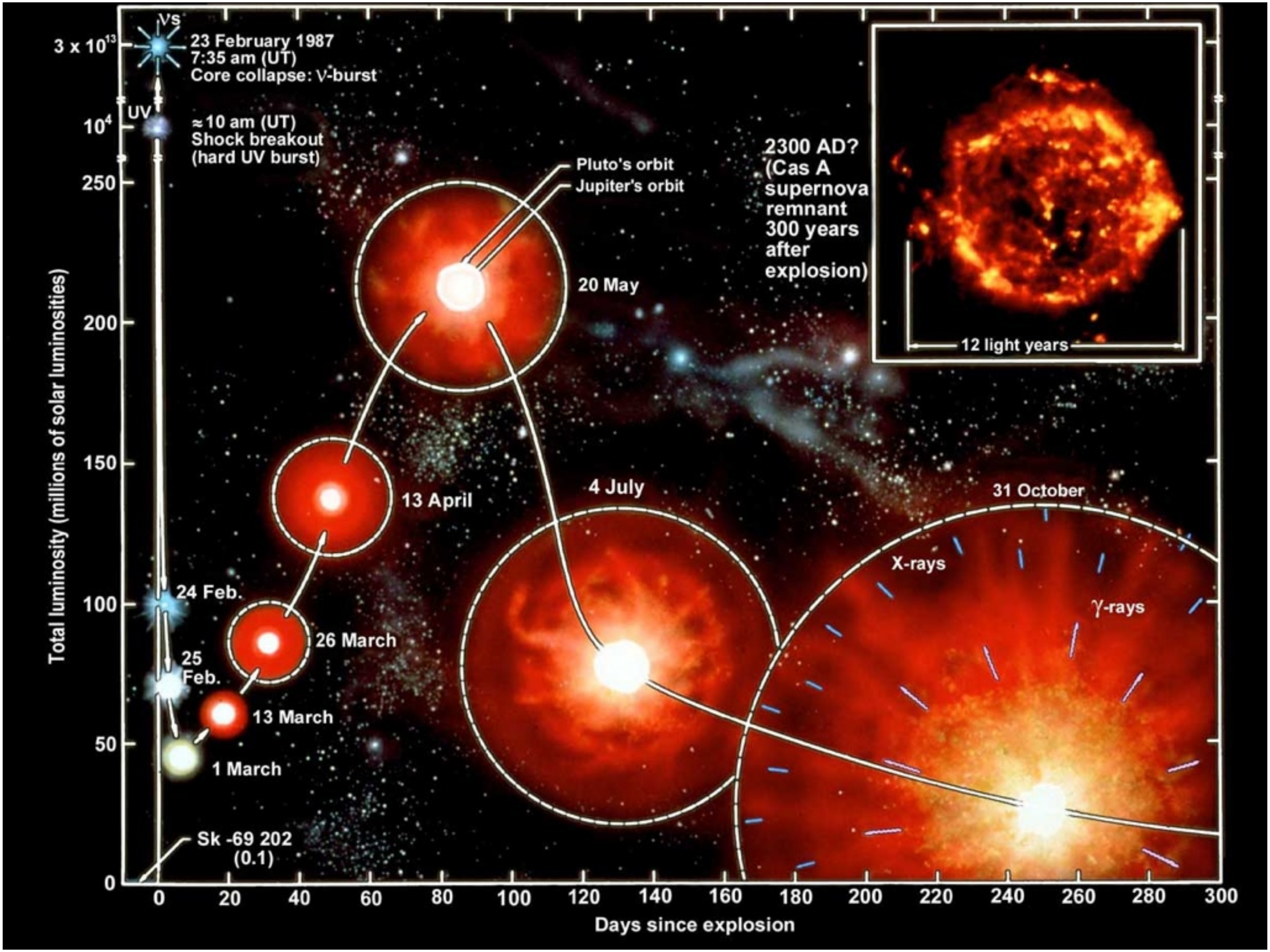


Core helium exhaustion
45,000 B.C.
(Homo sapiens)
Jupiter's orbit
Carbon ignition
10,000 B.C.
(Agriculture)
Vs
Earth's orbit
Hydrogen-burning main sequence
Presupernova star*
1-2 M⊙ lost in slow, dense wind
Nitrogen burning
25 M⊙
Core hydrogen exhaustion
700,000 B.C.
(Homo erectus)
Cepheid pulsations
Helium-burning red supergiant
650,000 B.C.
(Fire and tool making)
20 M⊙
18 M⊙
Sk-69° 202 born
11 million B.C.
(Ape men emerge)
15 M⊙
10 M⊙
*The Final Years
1971: Neon Ignition
1983: Oxygen Ignition
1987: Silicon Ignition (13 Feb)
1987: Supernova (23 Feb)
Luminosity (thousands of solar luminosities)
150
125
100
75
50
25
0
50,000
30,000
20,000
10,000
7000
5000
3000
2000
Surface temperature, K



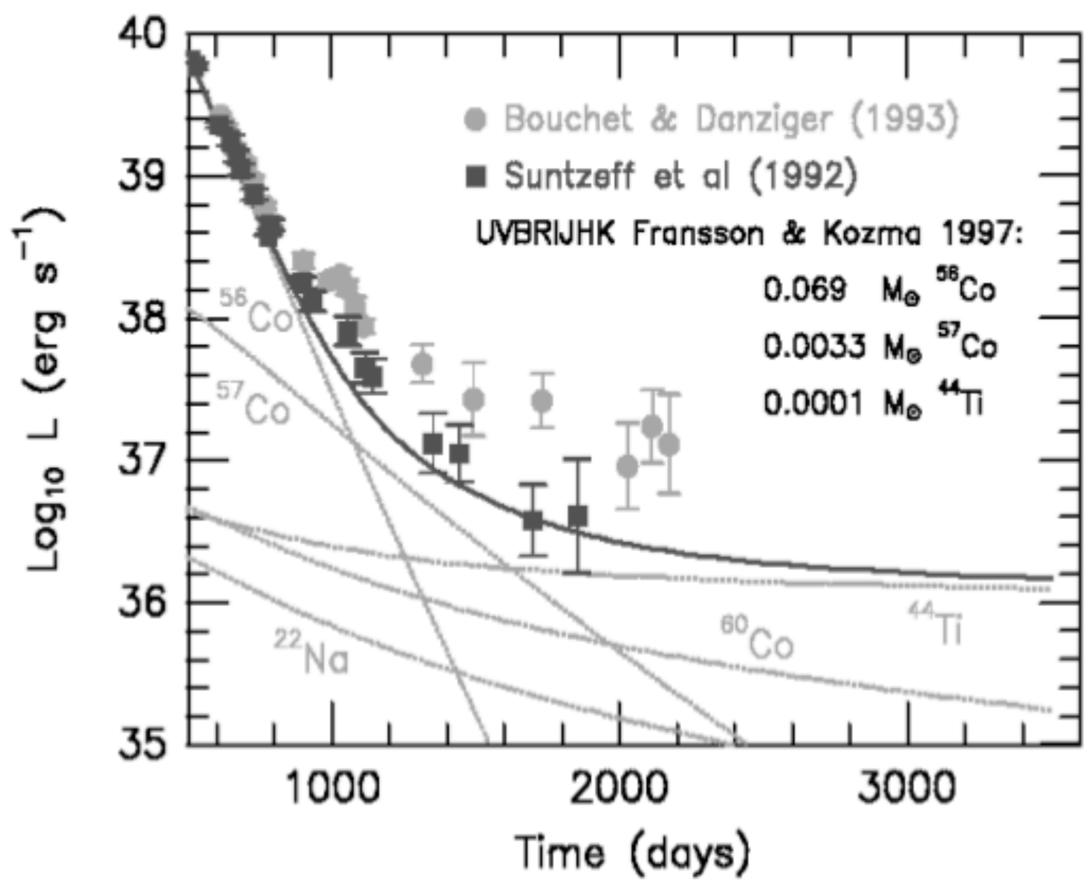
Iron
Silicon
Oxygen
Carbon
Helium
Hydrogen

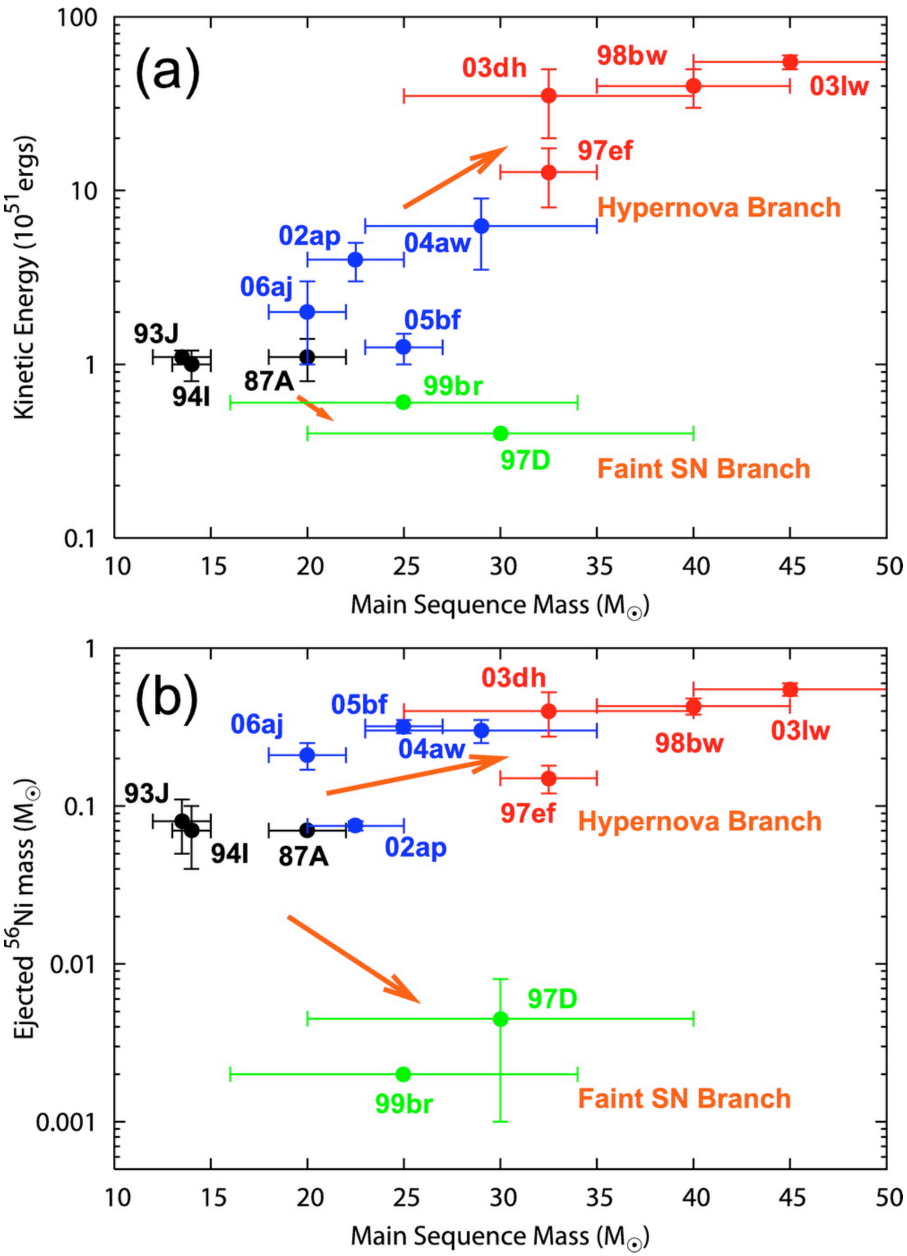


Total luminosity (millions of solar luminosities)
Days since explosion
3 x 10^13
10^4
250
200
150
100
50
0
-20 0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300
νs
23 February 1987
7:35 am (UT)
Core collapse: ν-burst
UV
≈10 am (UT)
Shock breakout
(hard UV burst)
Pluto's orbit
Jupiter's orbit
2300 AD?
(Cas A
supernova
remnant
300 years
after
explosion)
12 light years
20 May
13 April
4 July
31 October
X-rays
γ-rays
24 Feb.
26 March
25
Feb.
13 March
1 March
Sk -69 202
(0.1)

The Energy from Radioactivity in SN1987A

- Early Light Curve Dominated by ^{56}Ni and ^{57}Co Radioactivity (Gamma-Ray Lines Detected by SMM and OSSE, respectively)
- Late Light Curve Power Source Unknown: ~10^{-4} M_o of ^{44}Ti? Pulsar?
- Detection by INTEGRAL Possible, if ^{44}Ti Source





Tominaga et al. (2007)

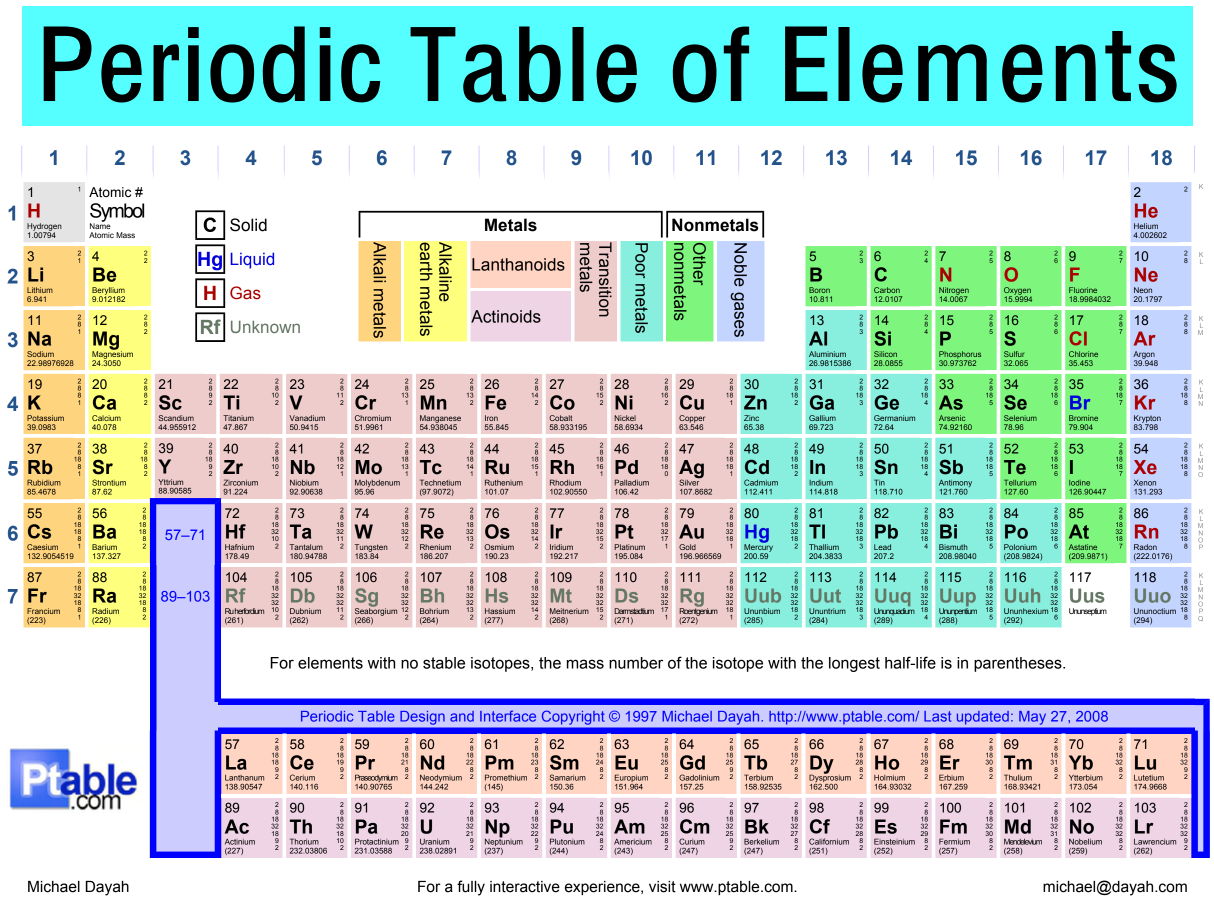
normal SNe

$M \sim 12\text{–}25\, M_\odot$

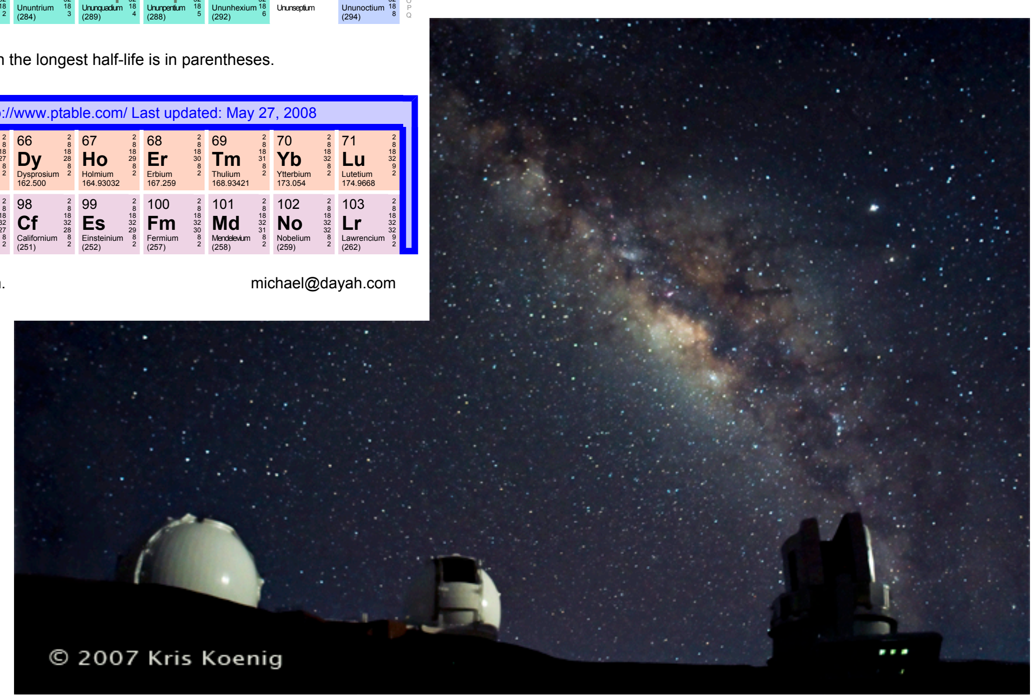
HNe

$M \sim 25\text{–}50\, M_\odot$

faint SNe unimportant for nucleosynthesis



stars make “metals” after the big bang



observations of metal abundances by Keck, VLT, Subaru

Stellar sources for early chemical evolution

massive stars $M \gtrsim 8\,M_\odot \Rightarrow \tau \lesssim 30$ Myr

core-collapse SNe: neutron stars, black holes

low- and intermediate-mass stars

$M \sim 1\text{–}8\,M_\odot,\ \langle M\rangle \sim 2\,M_\odot \Rightarrow \tau \sim 1$ Gyr

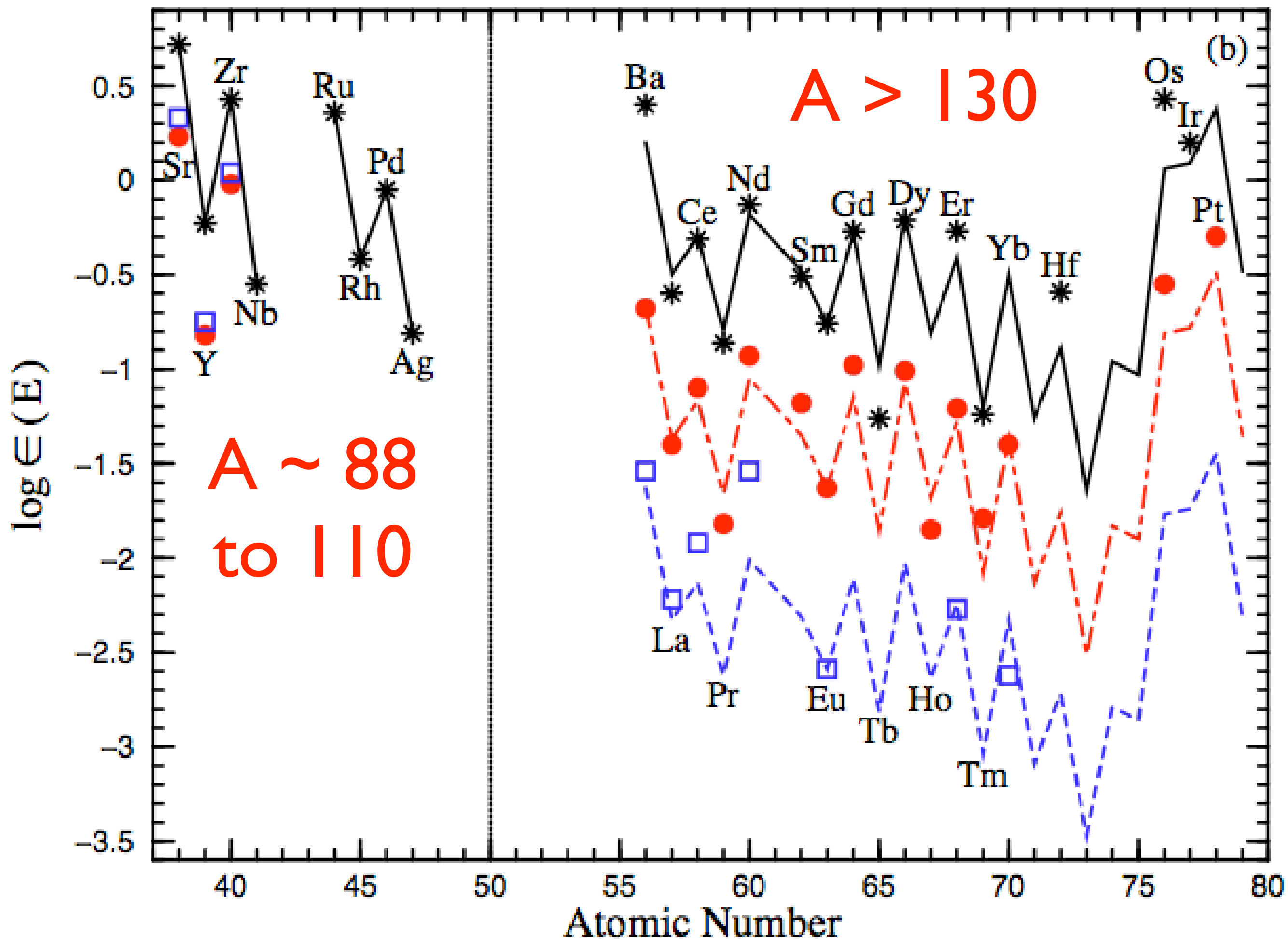
AGB: s-process (A > 70), white dwarfs

WDs in binaries: SNe Ia (Fe group, A ~ 56)

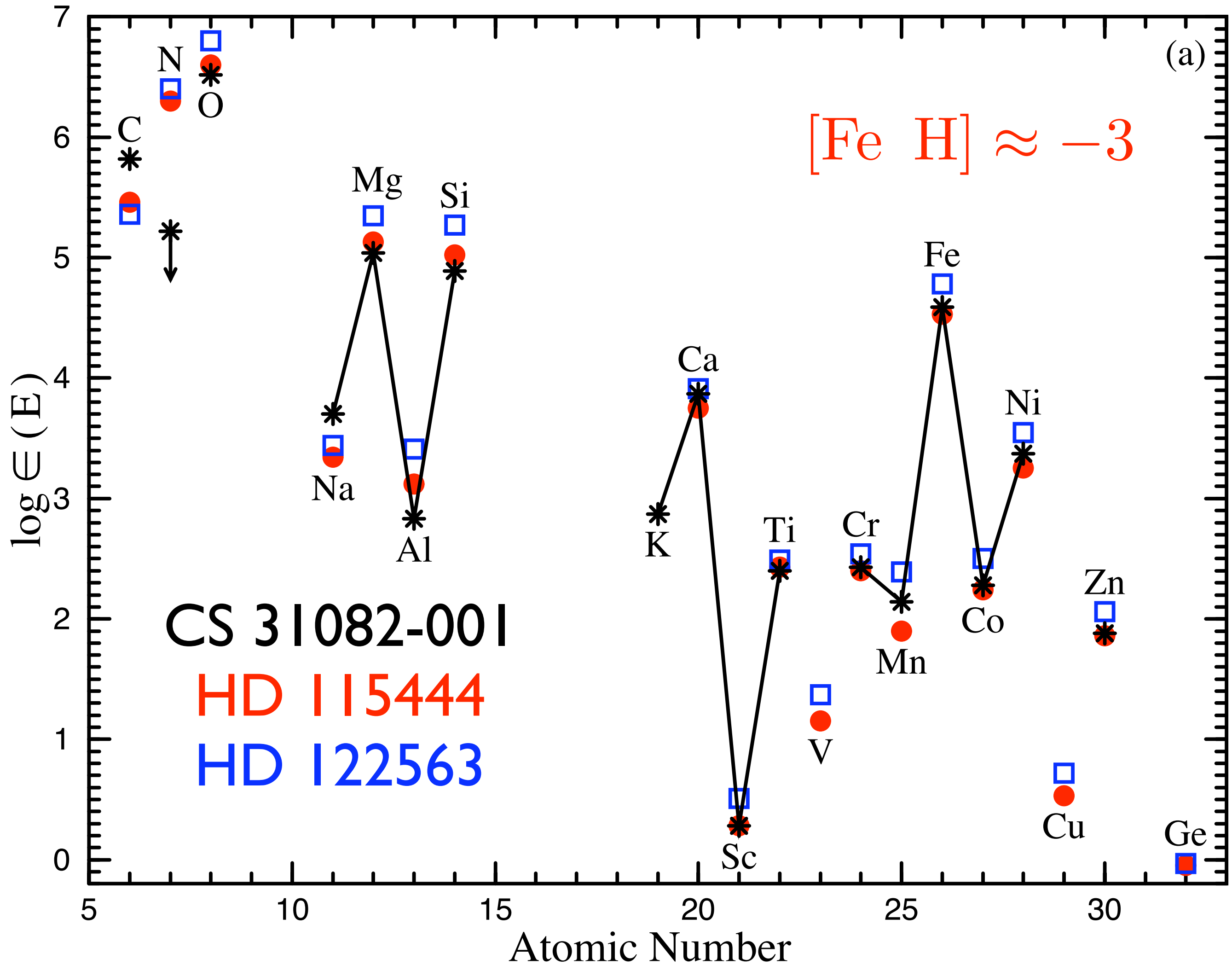
CCSNe over 10 Gyr: ~1/3 of solar Fe

➡ early (first Gyr): $[\mathrm{Fe/H}] \lesssim -1.5$

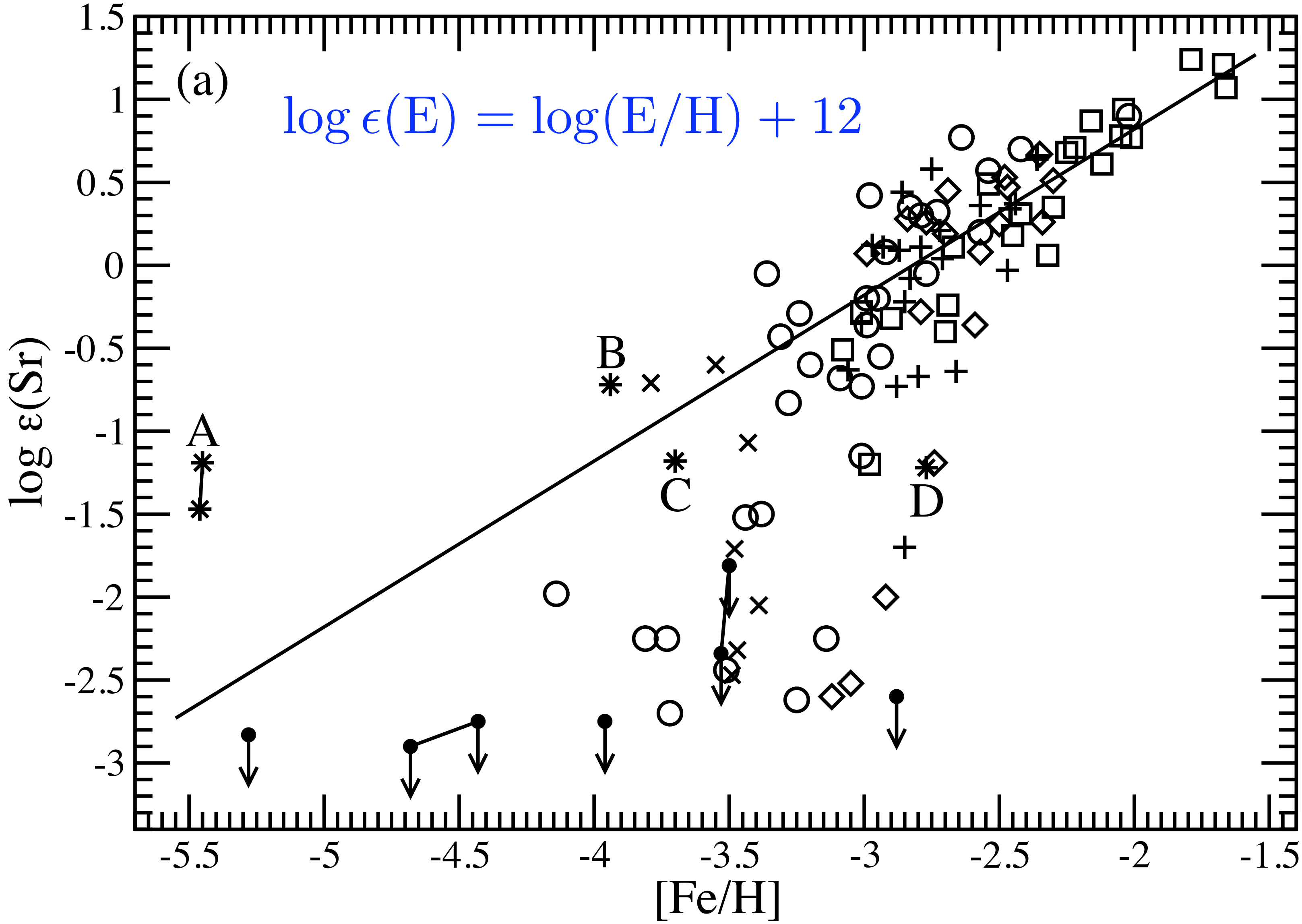
Observations of Sr- & Ba-like elements
(Westin et al. 2000; Hill et al. 2002)



Fe-like elements (A < 70)



Evolution of Sr with Fe

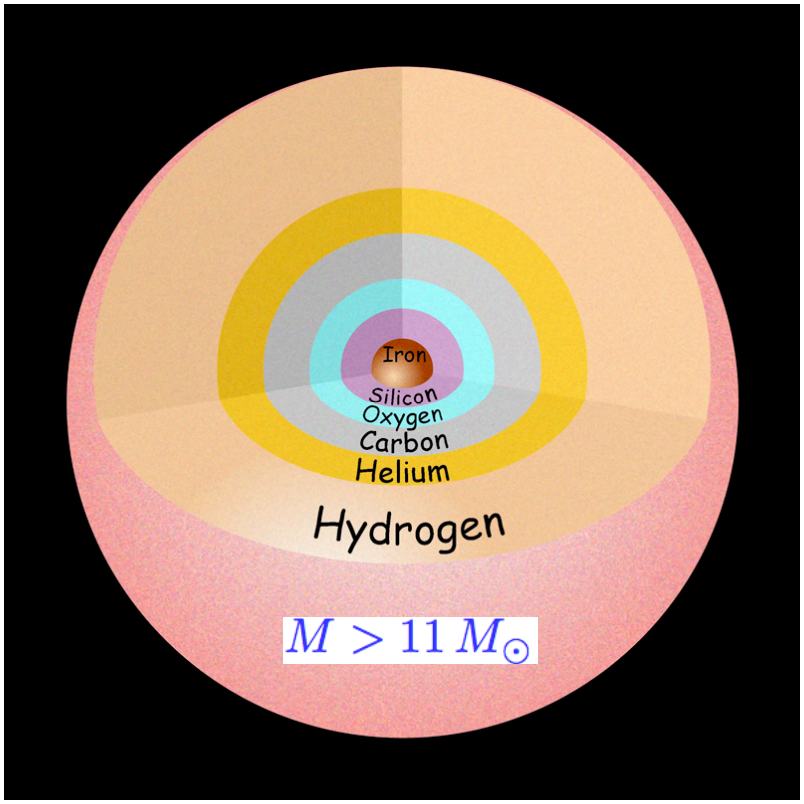


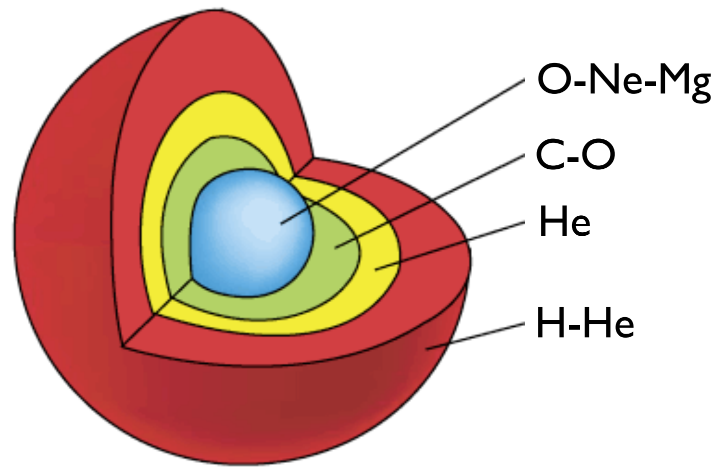
Summary of observations

- wide variations in the ratio of elements between different groups
- Ba-like elements decoupled from Fe-like elements
- there must be an Fe source producing no Sr or Ba

→ three distinct types of sources

Three types of core-collapse SNe for nucleosynthesis





$M \sim 8\text{–}11\, M_\odot$

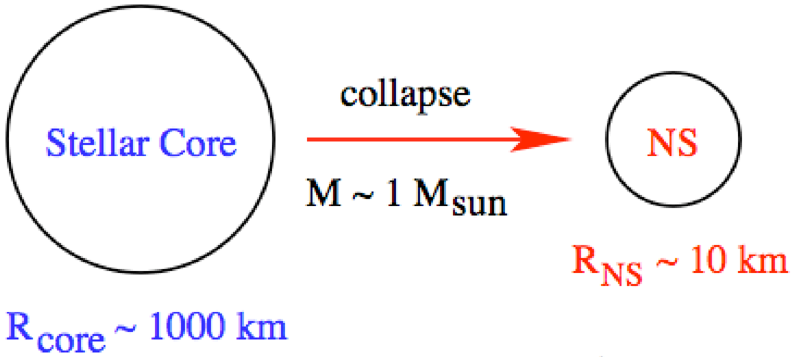
low-mass SNe: NS

$M \sim\ 12\text{–}25\, M_\odot$ normal SNe: NS

$M \sim\ 25\text{–}50\, M_\odot$ hypernovae (HNe): BH

Characteristics of stellar sources

sources	nucleosynthesis	remnants
low-mass SNe	no Fe-like elements	NS
normal SNe	Fe-like elements	NS
HNe	Fe-like elements	BH



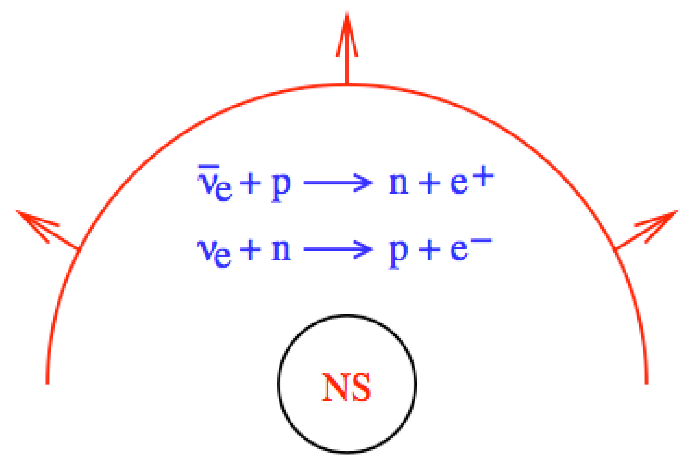
Supernovae as a neutrino phenomenon

$$e^+ + e^- \to \nu + \bar{\nu},\ \ N + N \to N + N + \nu + \bar{\nu}$$

$$\frac{GM^2}{R_{NS}} \sim 3 \times 10^{53}\ \mathrm{erg} \Rightarrow \nu_e,\ \bar{\nu}_e,\ \nu_{\mu(\tau)},\ \bar{\nu}_{\mu(\tau)}$$

production of Sr-like elements in the neutrino-driven wind

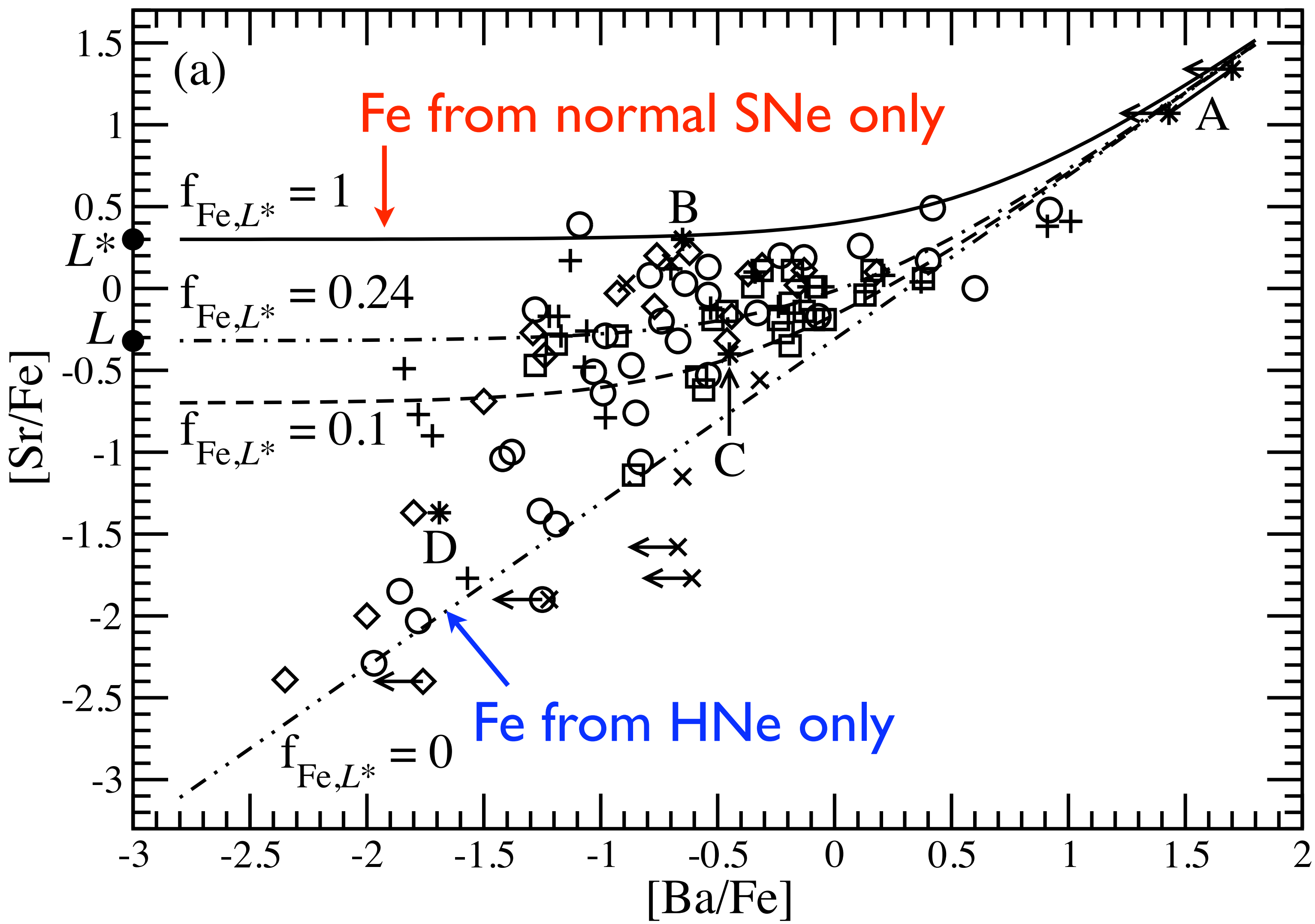
(Woosley & Hoffman 1992)



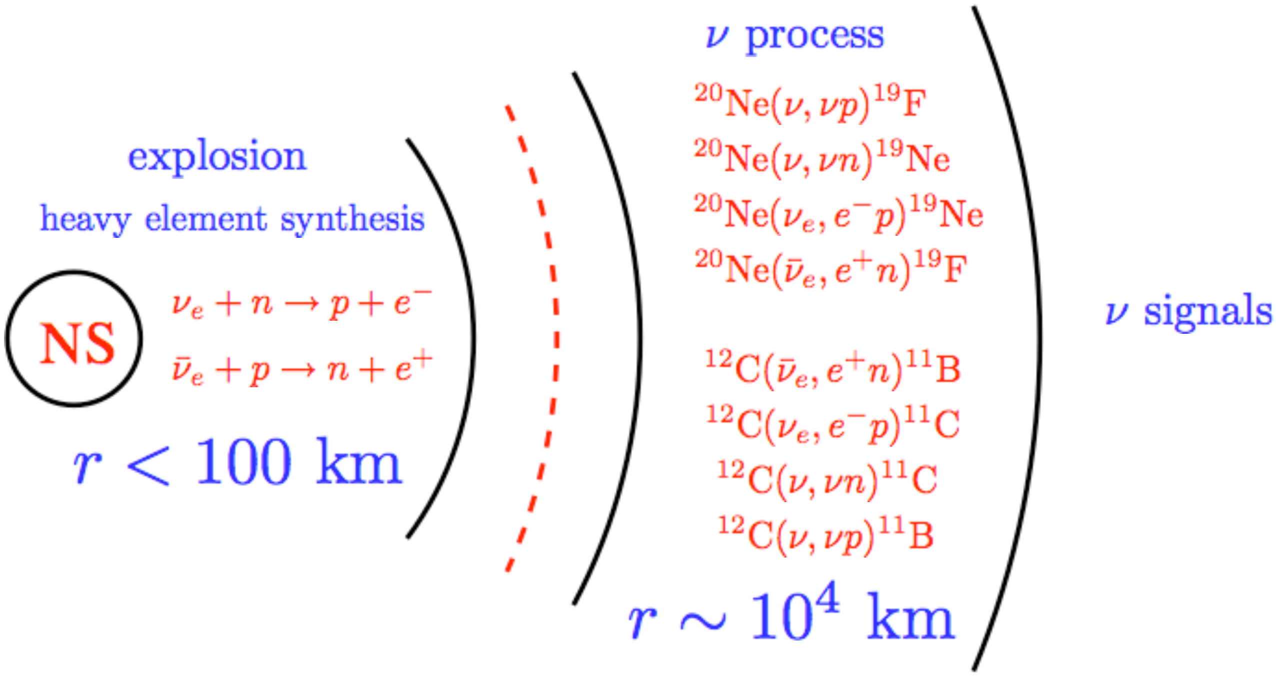
Stellar sources for elements

sources	Fe-like elements	Sr-like elements	Ba-like elements
low-mass SNe	No	Yes	Yes
normal SNe	Yes	Yes	No
HNe	Yes	No	No

3-component model (Qian & Wasserburg 2008)



Interplay between supernova and neutrino Physics



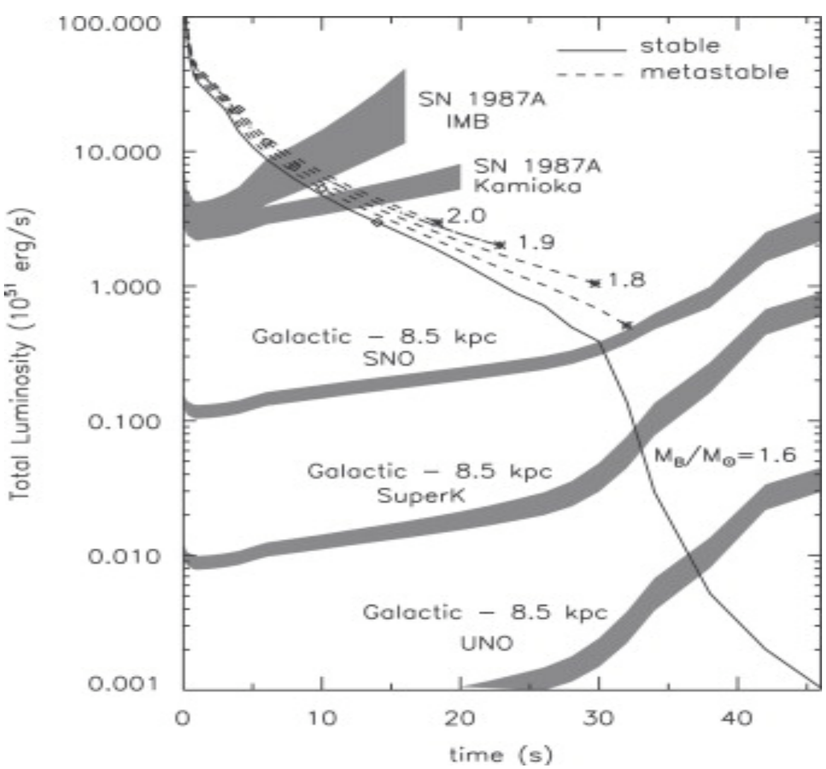
How to use neutrino signals to identify various CCSNe?

progenitor dependences of neutrino emission

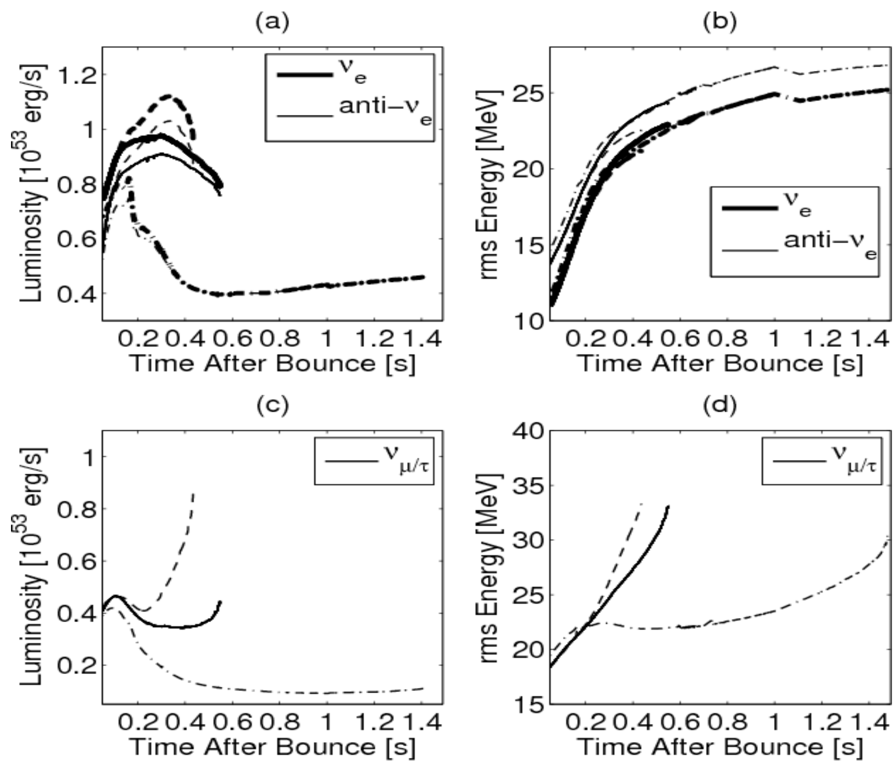
- core size, accretion →

  final NS mass: low-mass & normal SNe

  BH formation: HNe & faint SNe



Pons et al. 2001



Fischer et al. 2009

progenitor dependences of neutrino flavor evolution

- density profile →

positions and adiabaticity of MSW resonances

modulation by shock propagation

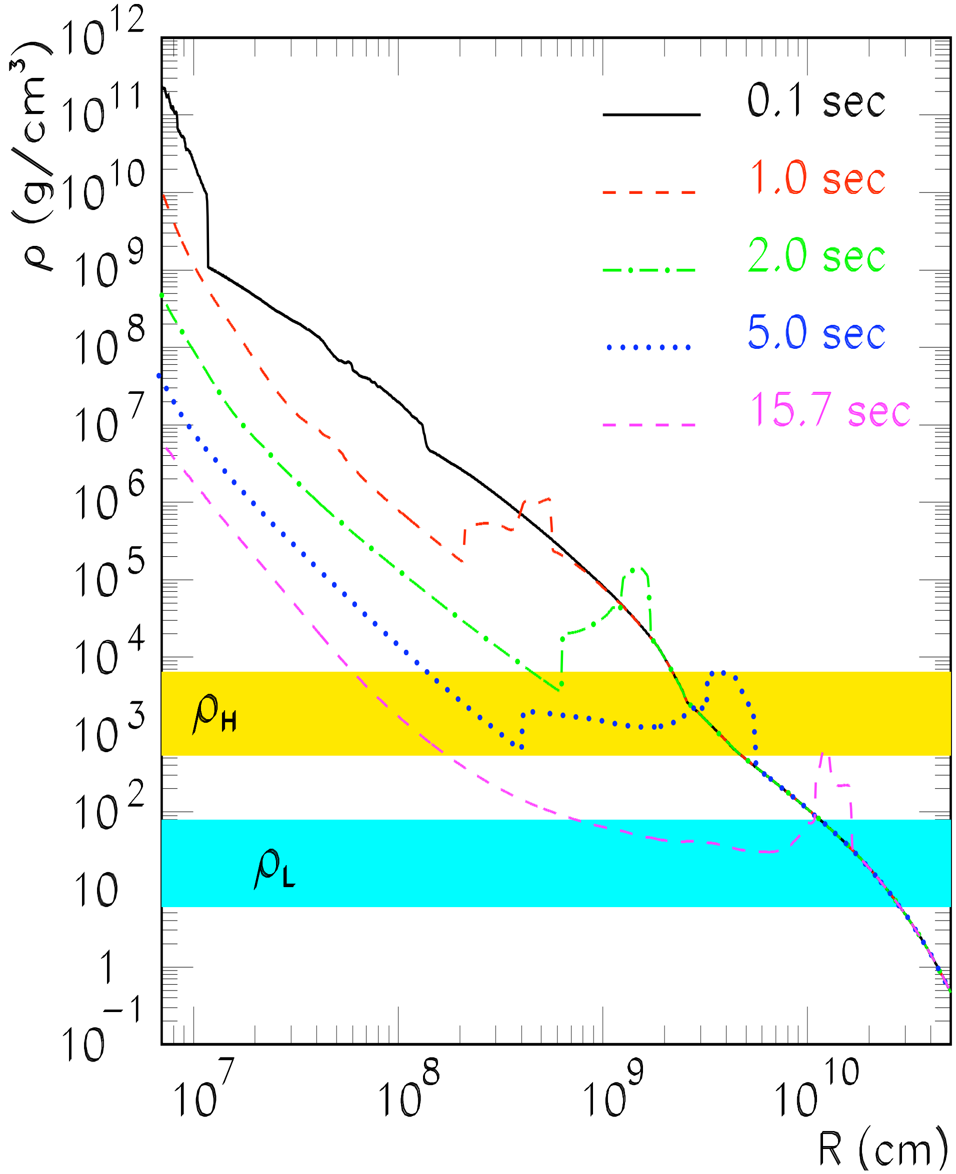
(Schirato & Fuller 2002)

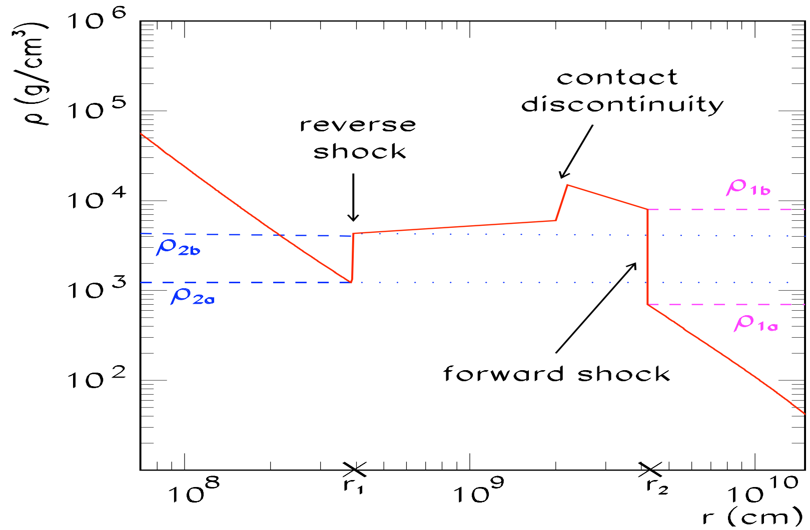
comparison with neutrino density:

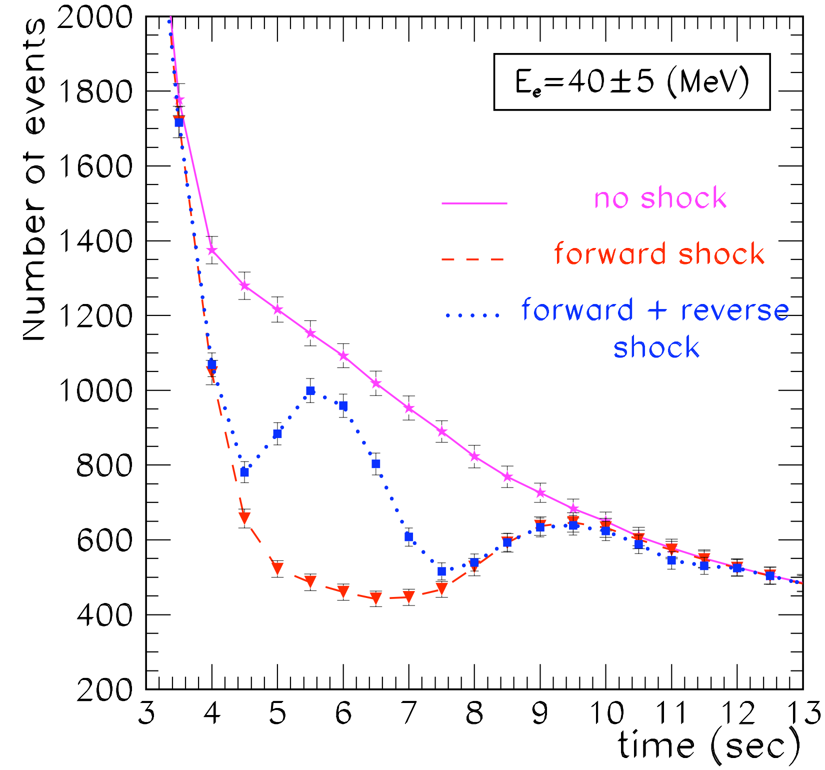
collective oscillations

(Pantaleone 1992;
Kostelecky & Samuel 1993;
Duan et al. 2006-09;
Raffelt & collaborators 2006-09)

Tomas et al. 2004



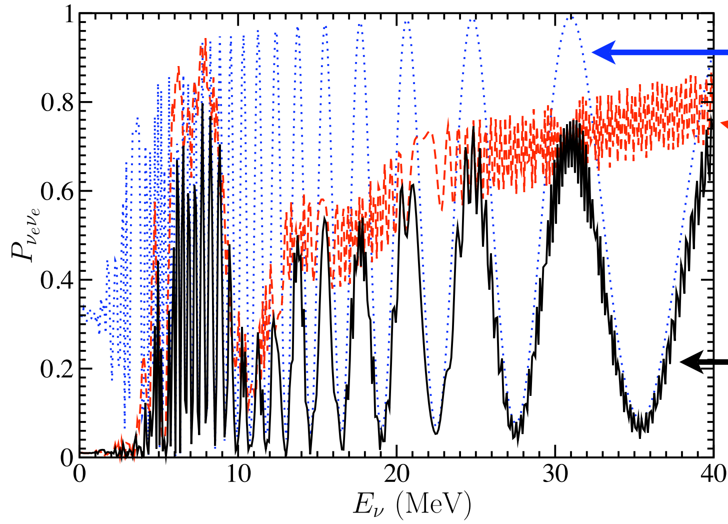




Example of 3-neutrino mixing including self-interaction

neutronization burst from an O-Ne-Mg core-collapse SN

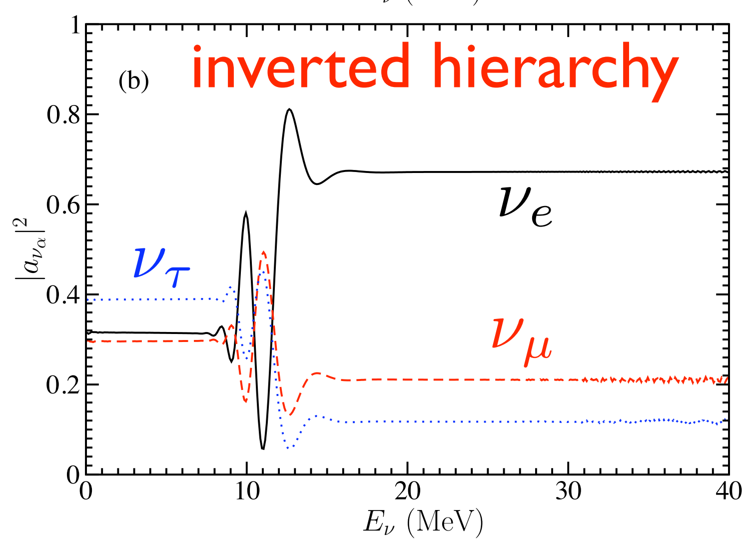
Duan, Fuller, Carlson, & Qian, PRL 100, 021101 (2008)

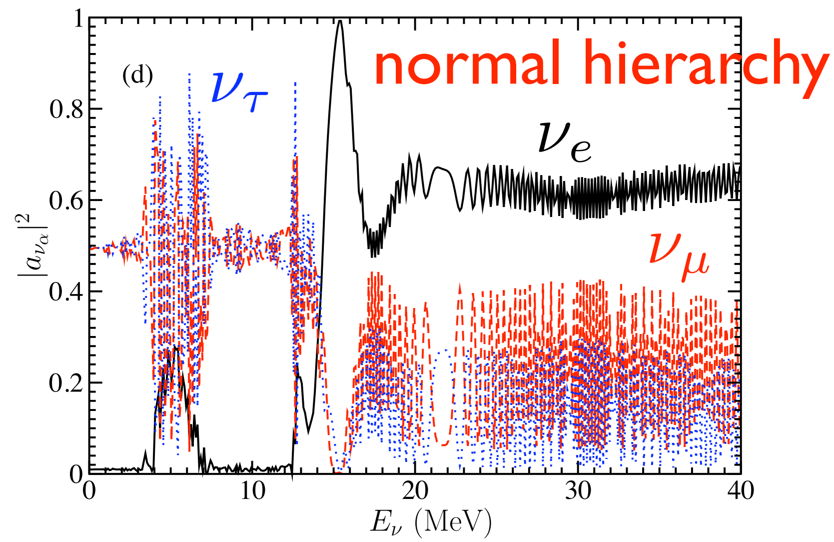


2-neutrino solar scale

2-neutrino atmospheric scale (normal hierarchy)

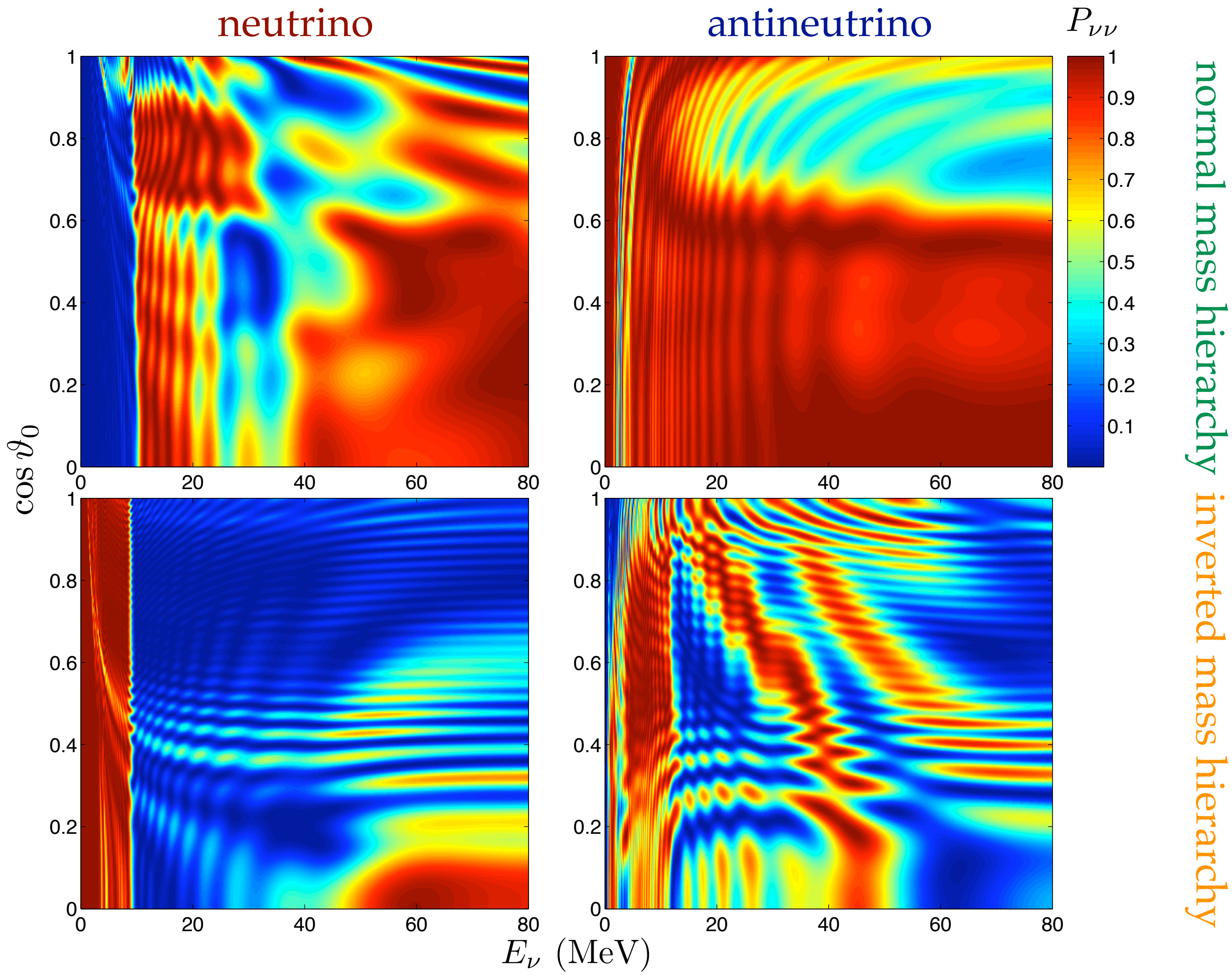
3-neutrino (matter effect only, normal hierarchy)



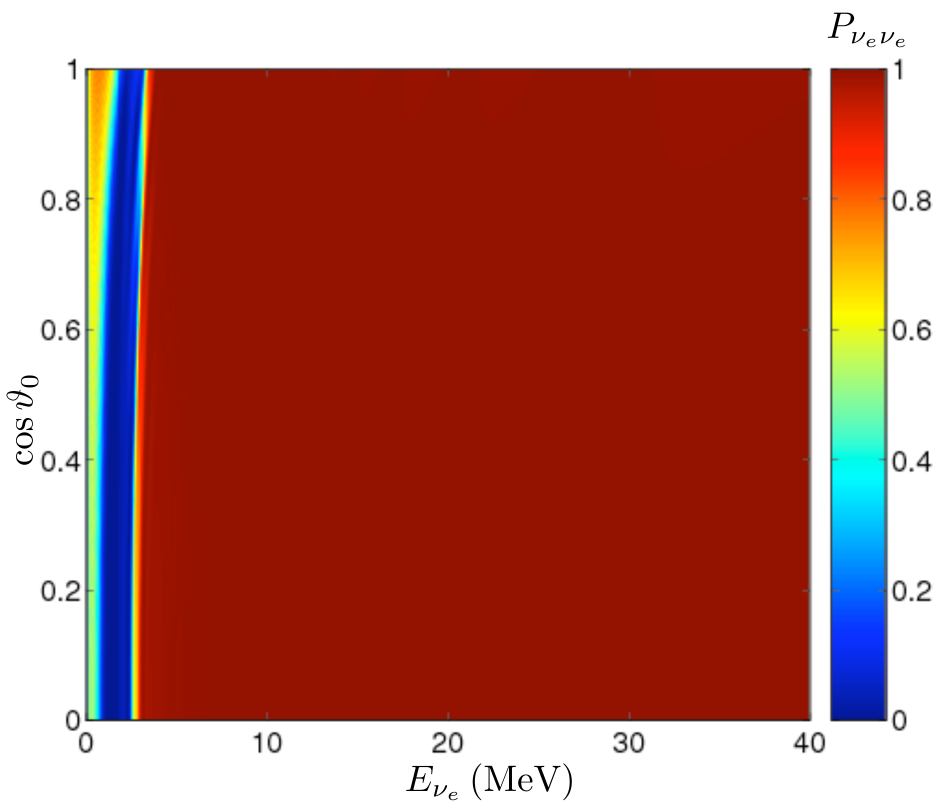


Survival Probability at $r = 225$ km

$$\delta m^2 \equiv m_3^2 - m_1^2 \to \pm 3 \times 10^{-3}\ \mathrm{eV}^2,\ \ \theta_\mathrm{v} \to 0.1$$

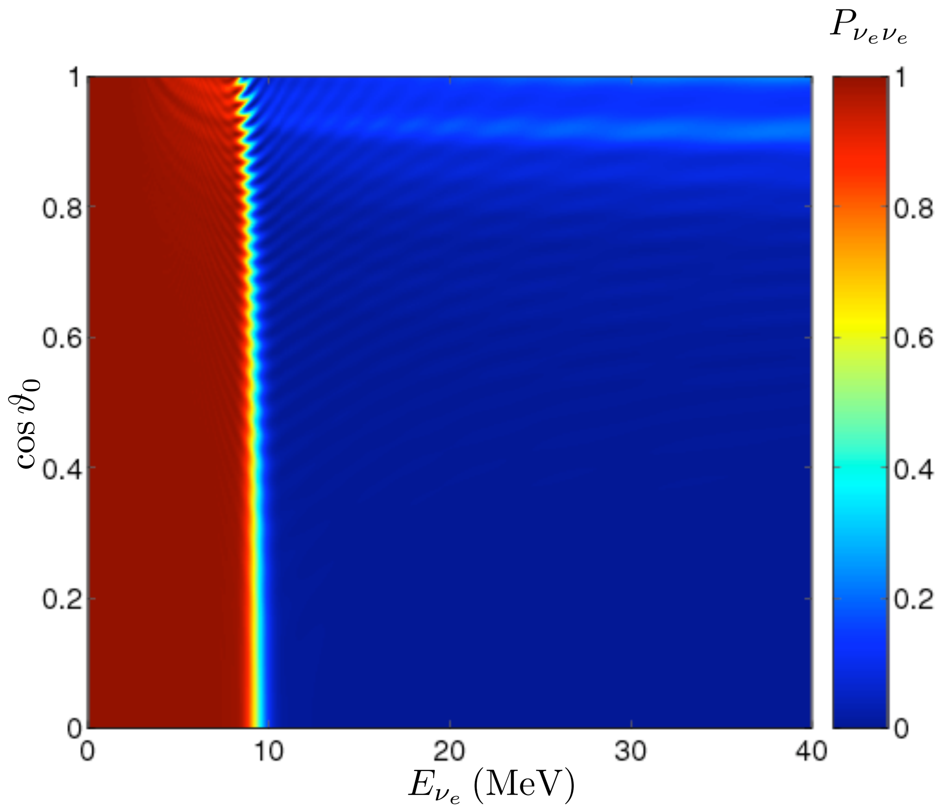


Survival Probability at $r = 250$ km



normal mass hierarchy

$\theta_{\rm v} = 0.01$



inverted mass hierarchy

$\theta_{\rm v} = 10^{-9}$

(Duan, Fuller, Carlson, & Qian 2006, 2007)

Other important issues

- convection, rotation, magnetic field →

  asymmetry in explosion, neutrino emission & flavor evolution

  (Kneller, McLaughlin, & Brockman 2008)

- how to put it all together?

  self-consistent model of stellar evolution, core collapse, explosion, nucleosynthesis, neutrino emission & flavor evolution