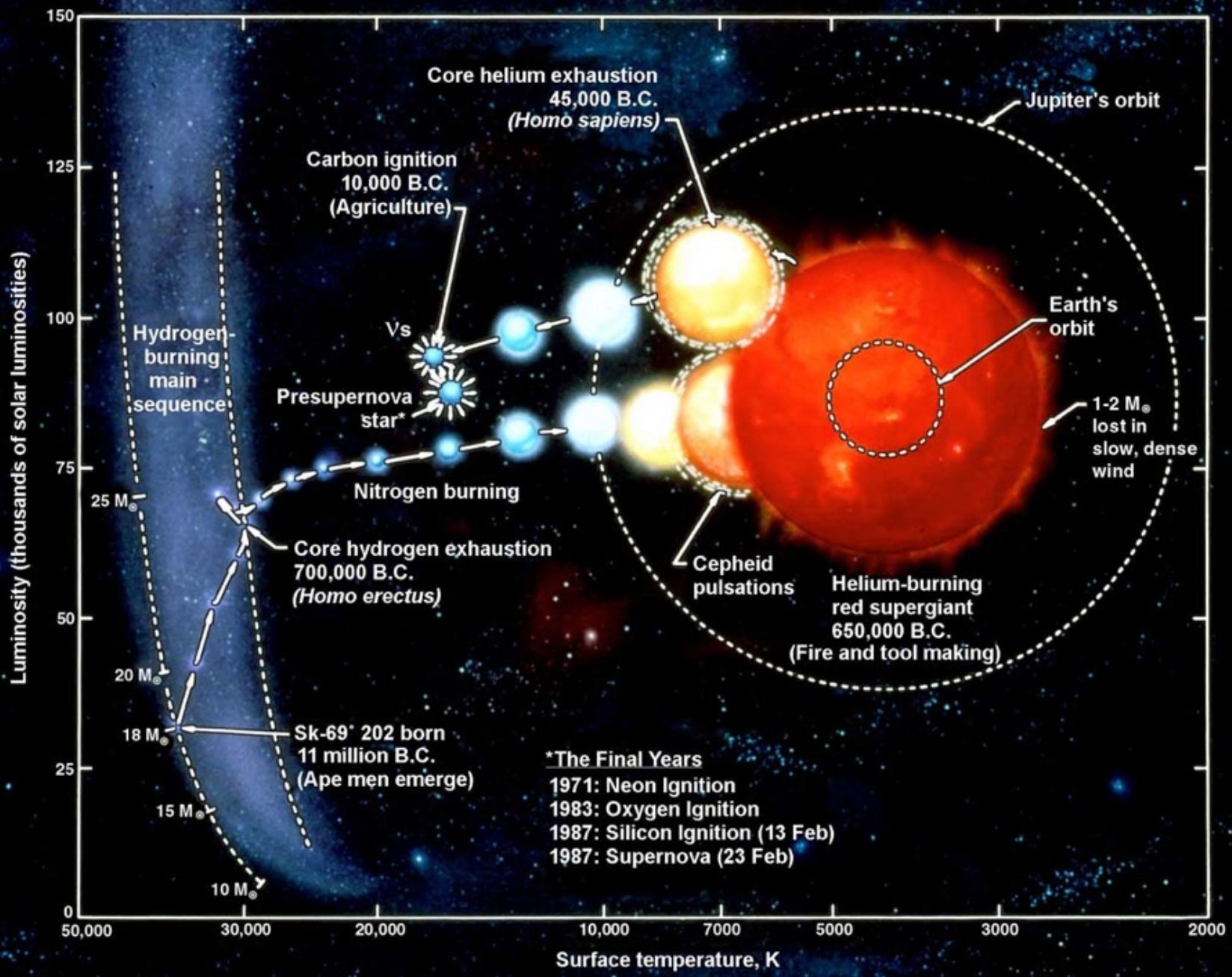
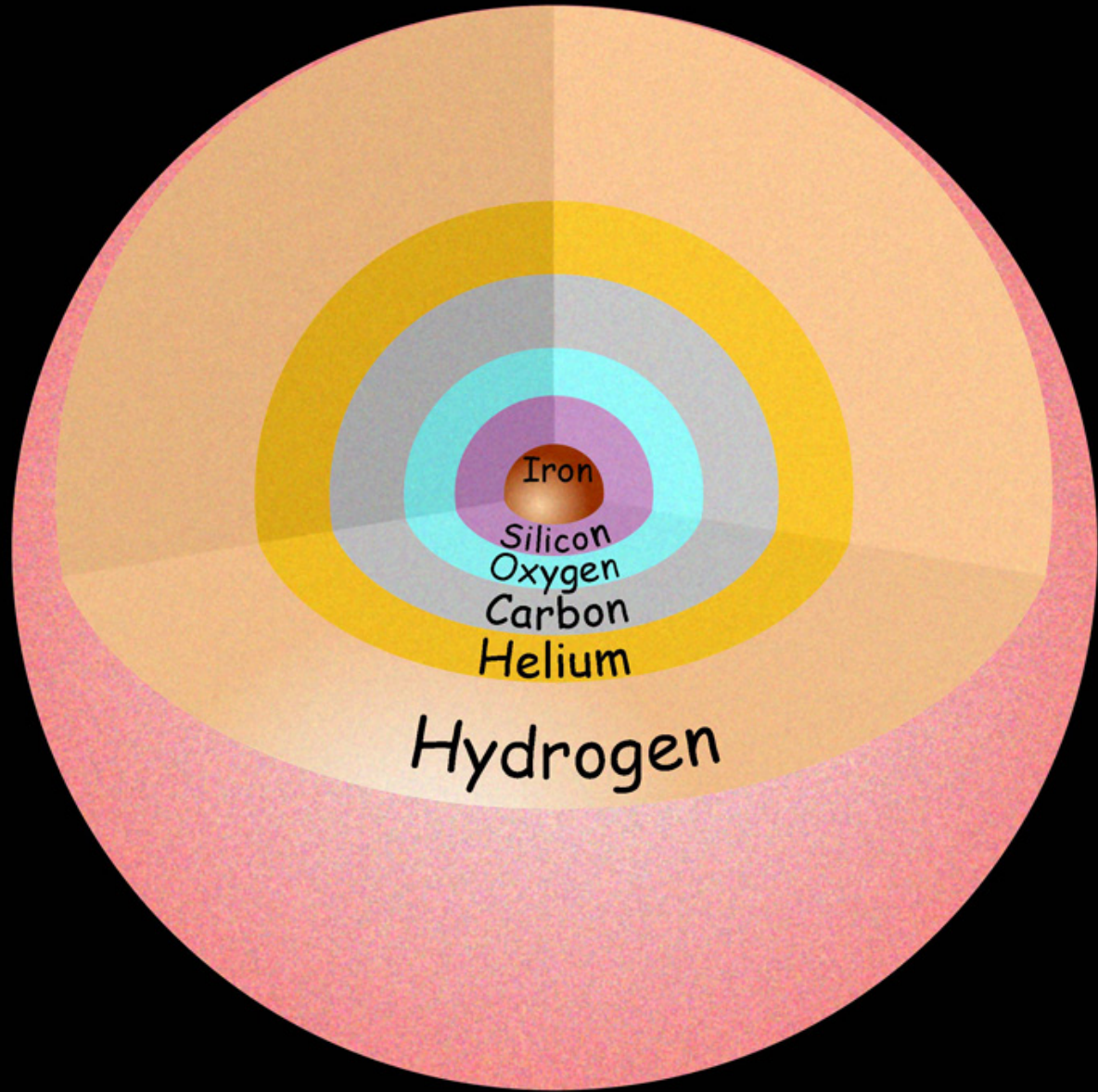


Supernova Neutrinos and Nucleosynthesis

Yong-Zhong Qian
University of Minnesota

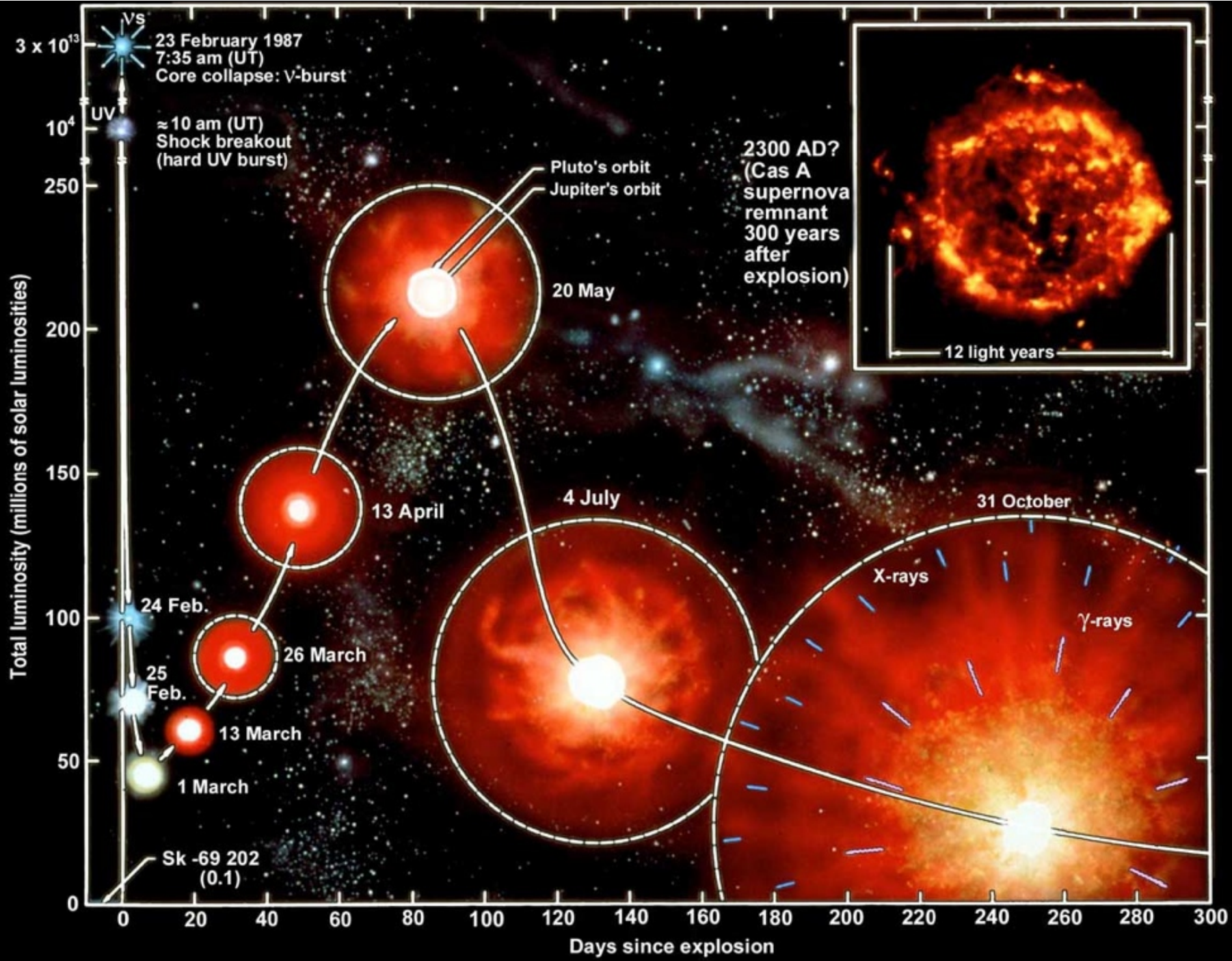
Neutrinos & Dark Matter 2009
September 2, 2009





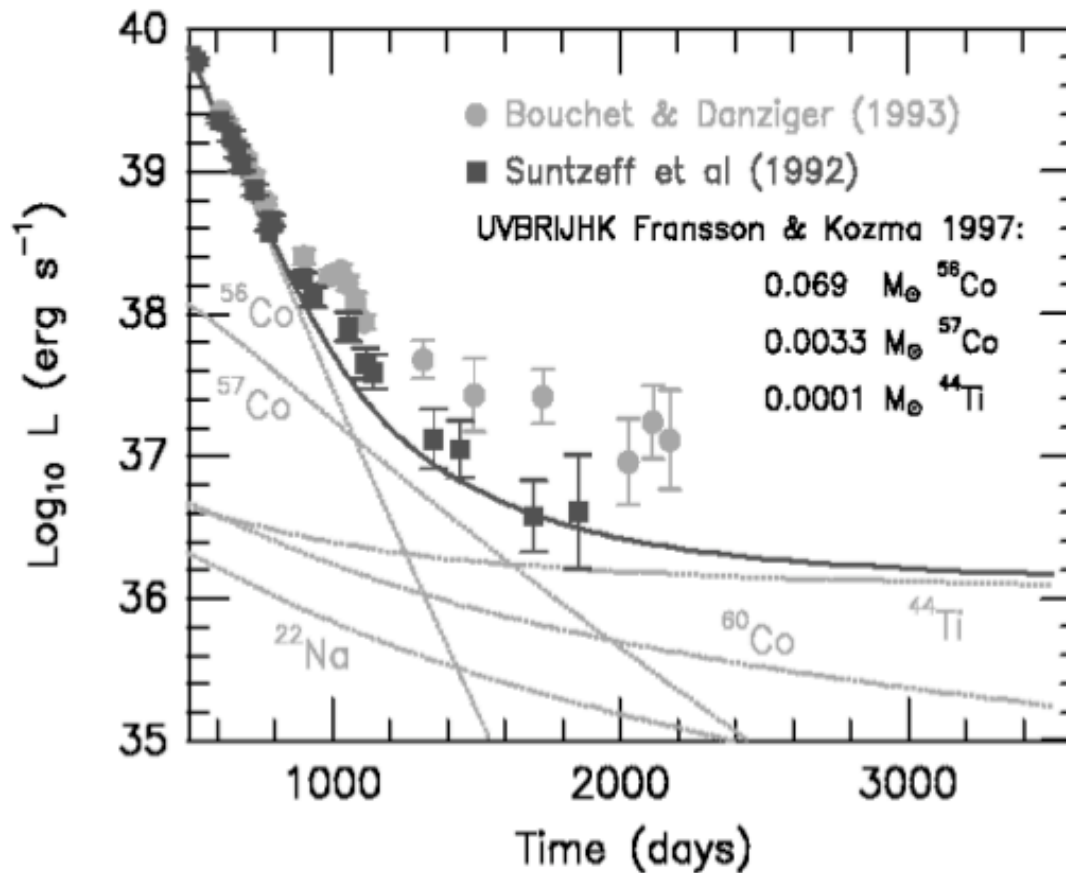
Hydrogen

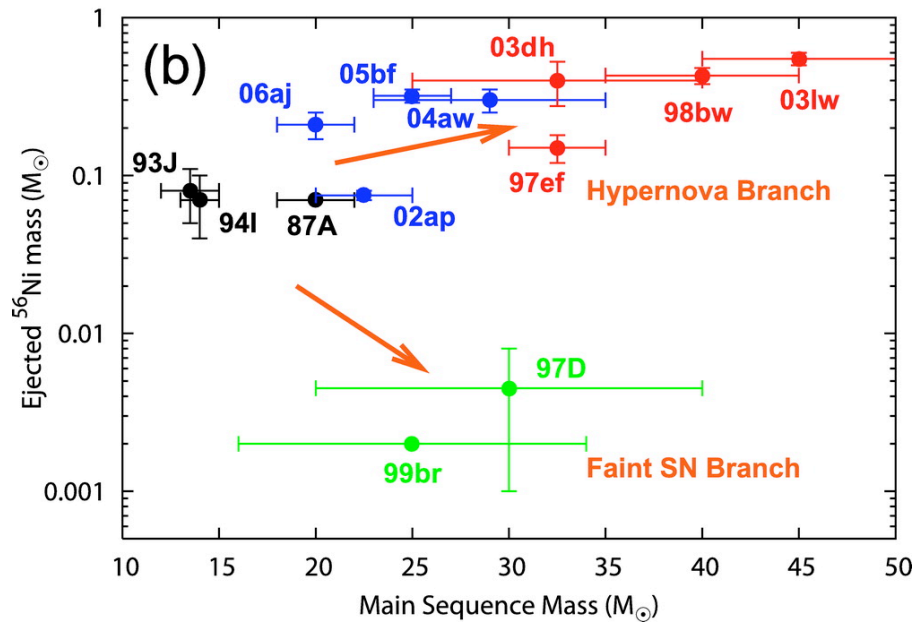
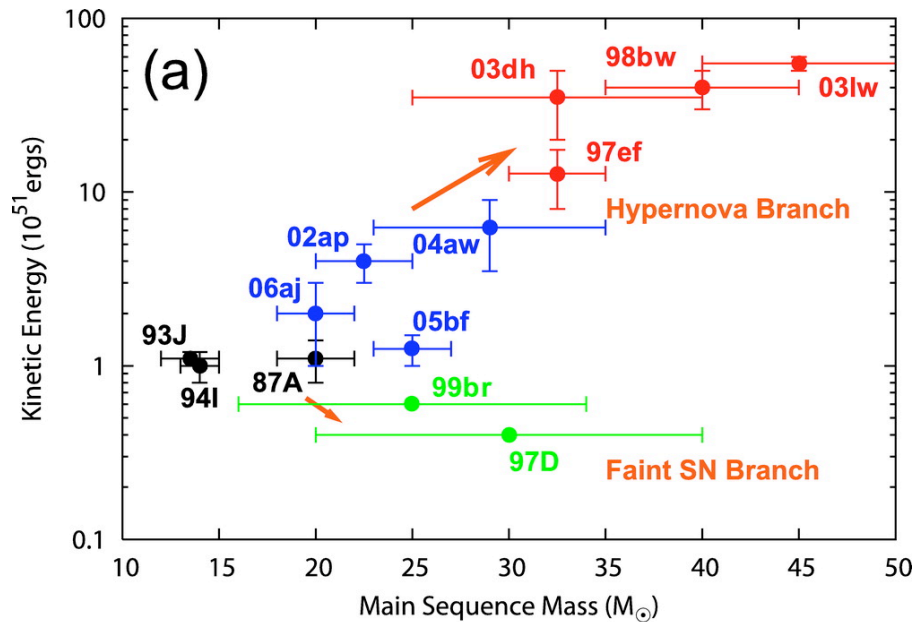
Iron
Silicon
Oxygen
Carbon
Helium



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: $\sim 10^{-4} M_{\odot}$ 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

Periodic Table of Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H Hydrogen 1.00794	2 He Helium 4.002602																
3 Li Lithium 6.941	4 Be Beryllium 9.012182																
5 Na Sodium 22.98976928	6 Mg Magnesium 24.3050																
7 K Potassium 39.0983	8 Ca Calcium 40.078	9 Sc Scandium 44.955912	10 Ti Titanium 47.887	11 V Vanadium 50.9415	12 Cr Chromium 51.9961	13 Mn Manganese 54.938045	14 Fe Iron 55.845	15 Co Cobalt 58.933195	16 Ni Nickel 58.6934	17 Cu Copper 63.546	18 Zn Zinc 65.38	19 Ga Gallium 69.723	20 Ge Germanium 72.64	21 As Arsenic 74.92160	22 Se Selenium 78.96	23 Br Bromine 79.904	24 Kr Krypton 83.798
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.96	43 Tc Technetium (97.9072)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.293
55 Cs Cesium 132.9054519	56 Ba Barium 137.327	57-71 Lanthanoids	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.222	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98040	84 Po Polonium (209)	85 At Astatine (209)	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium (226)	89-103 Actinoids	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (277)	109 Mt Meitnerium (268)	110 Ds Darmstadtium (271)	111 Rg Roentgenium (272)	112 Uub Ununbium (285)	113 Uut Ununtrium (284)	114 Uuq Ununquadium (289)	115 Uup Ununpentium (288)	116 Uuh Ununhexium (282)	117 Uus Ununseptium	118 Uuo Ununoctium (294)

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

Periodic Table Design and Interface Copyright © 1997 Michael Dayah. <http://www.ptable.com/> Last updated: May 27, 2008

57 La Lanthanum 138.90547	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.967
89 Ac Actinium (227)	90 Th Thorium 232.03806	91 Pa Protactinium 231.03688	92 U Uranium 238.02891	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

stars make
“metals” after
the big bang



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Michael Dayah

For a fully interactive experience, visit www.ptable.com.

michael@dayah.com

observations of
metal abundances by
Keck, VLT, Subaru

Stellar sources for early chemical evolution

massive stars $M \gtrsim 8 M_{\odot} \Rightarrow \tau \lesssim 30 \text{ Myr}$

core-collapse SNe: neutron stars, black holes

low- and intermediate-mass stars

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

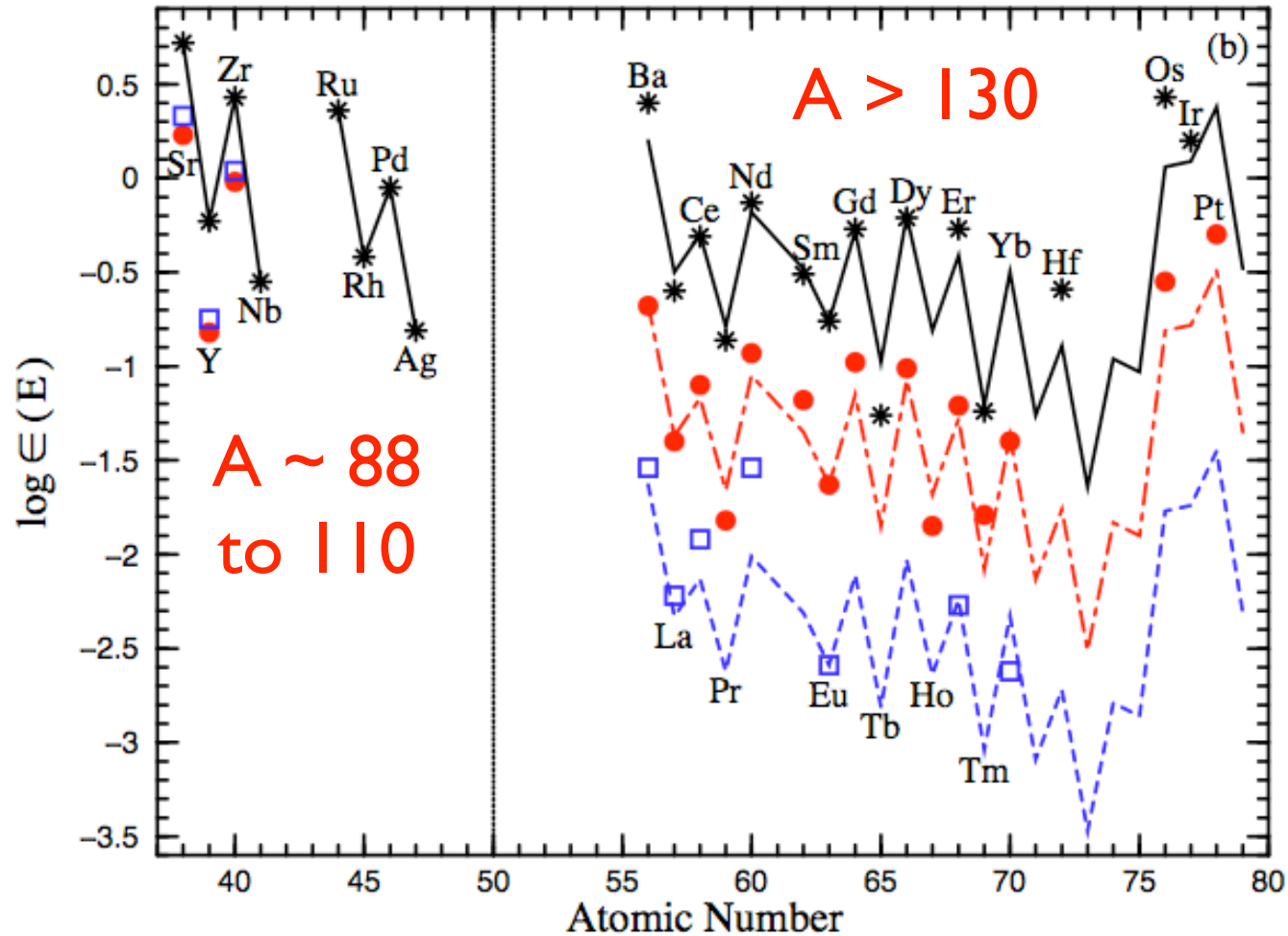
AGB: s-process ($A > 70$), white dwarfs

WDs in binaries: SNe Ia (Fe group, $A \sim 56$)

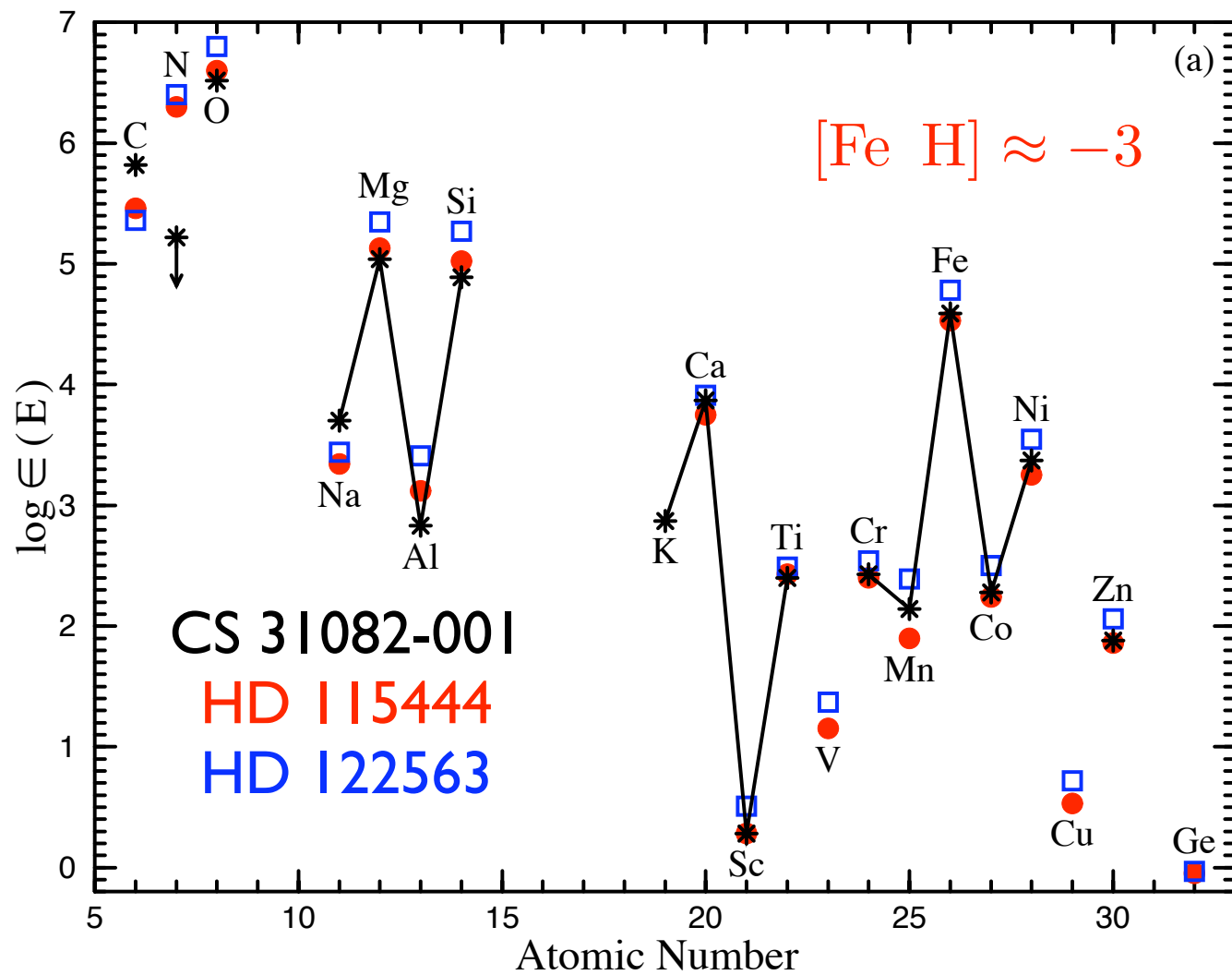
CCSNe over 10 Gyr: $\sim 1/3$ of solar Fe

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

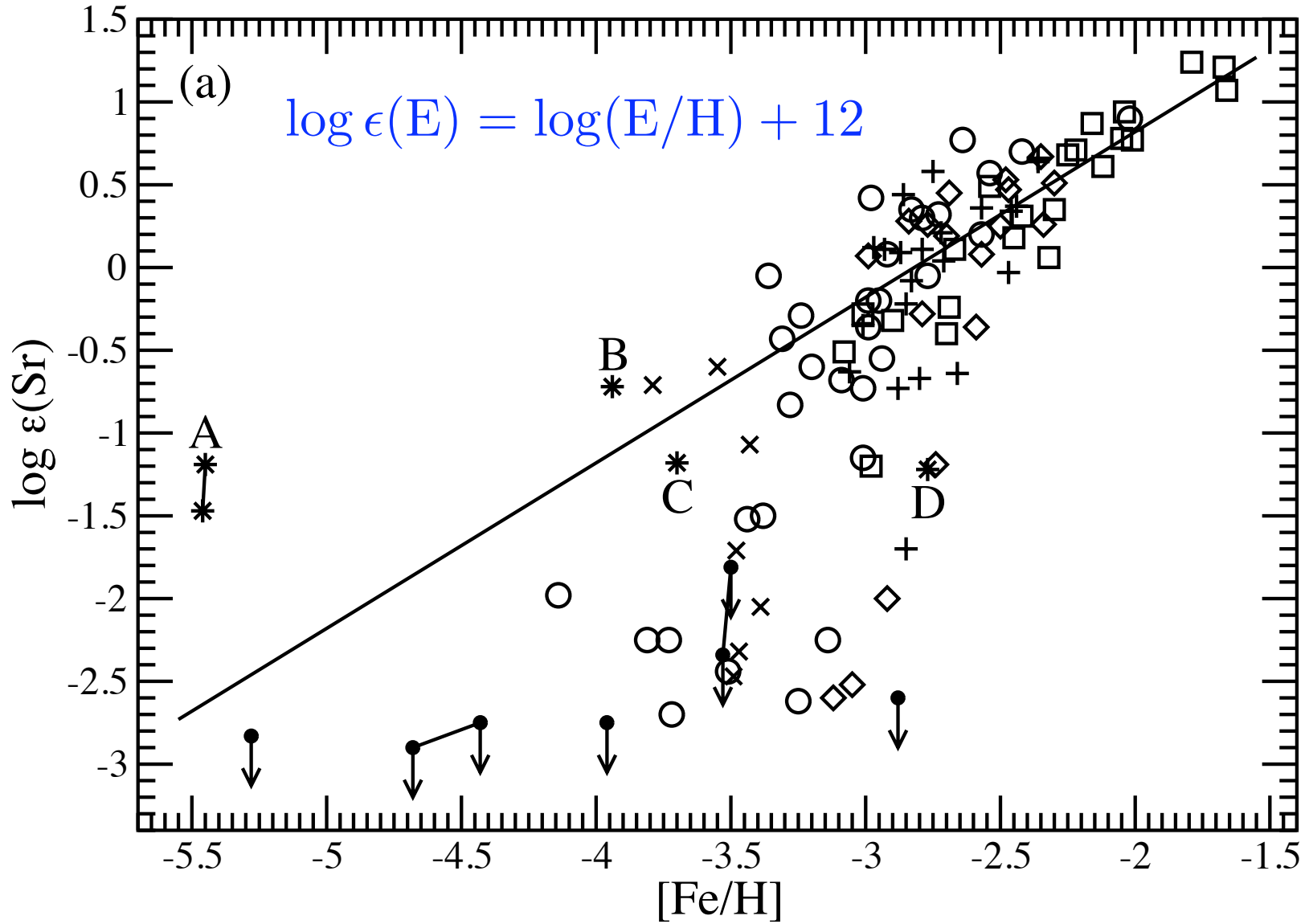
Observations of Sr- & Ba-like elements
(Westin et al. 2000; Hill et al. 2002)



Fe-like elements ($A < 70$)



Evolution of Sr with Fe

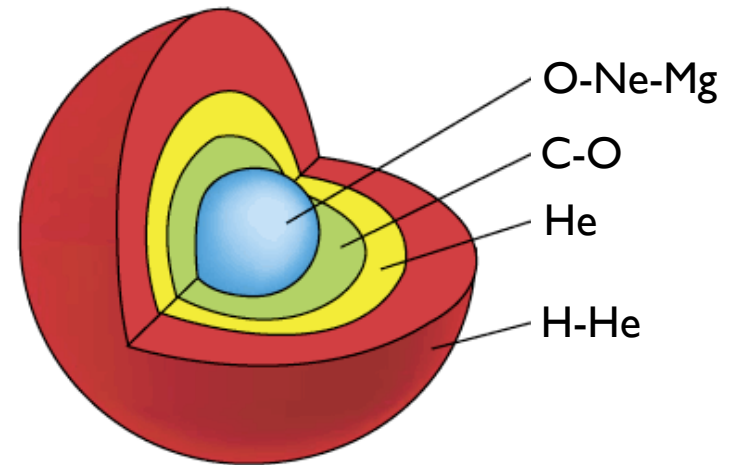
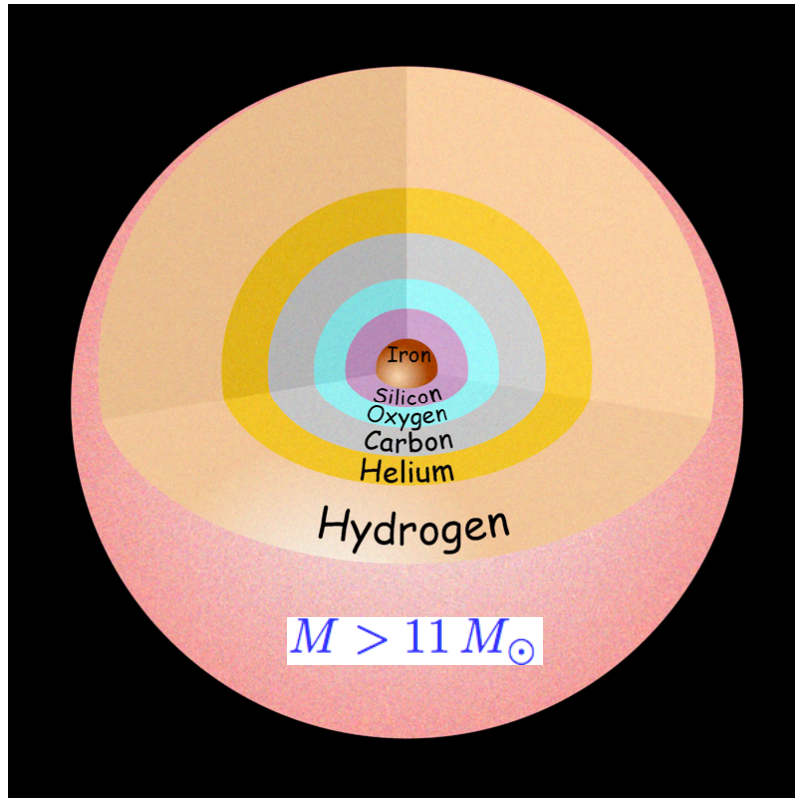


Summary of observations

- 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



$$M \sim 8-11 M_{\odot}$$

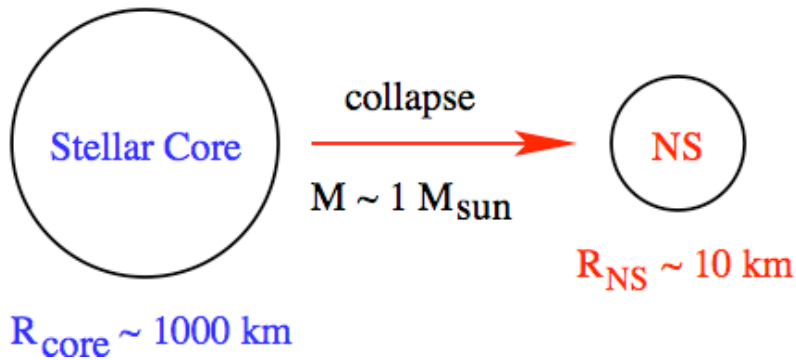
low-mass SNe: NS

$M \sim 12-25 M_{\odot}$ normal SNe: NS

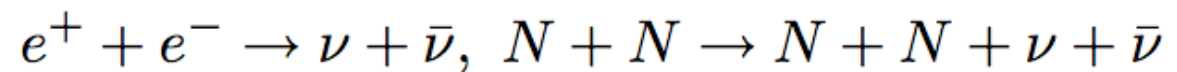
$M \sim 25-50 M_{\odot}$ hypernovae (HNe): BH

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



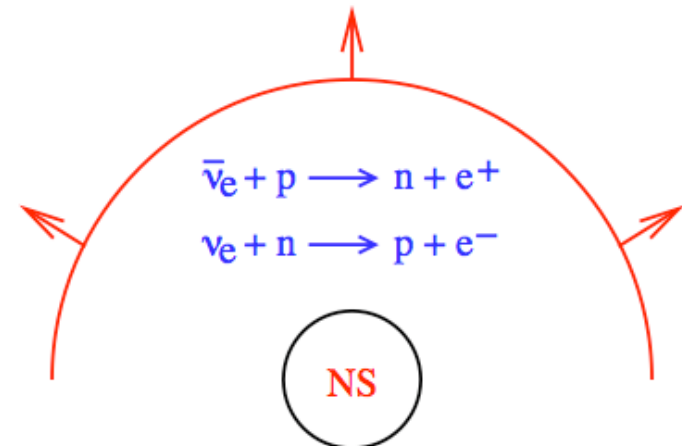
Supernovae as a neutrino phenomenon



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

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

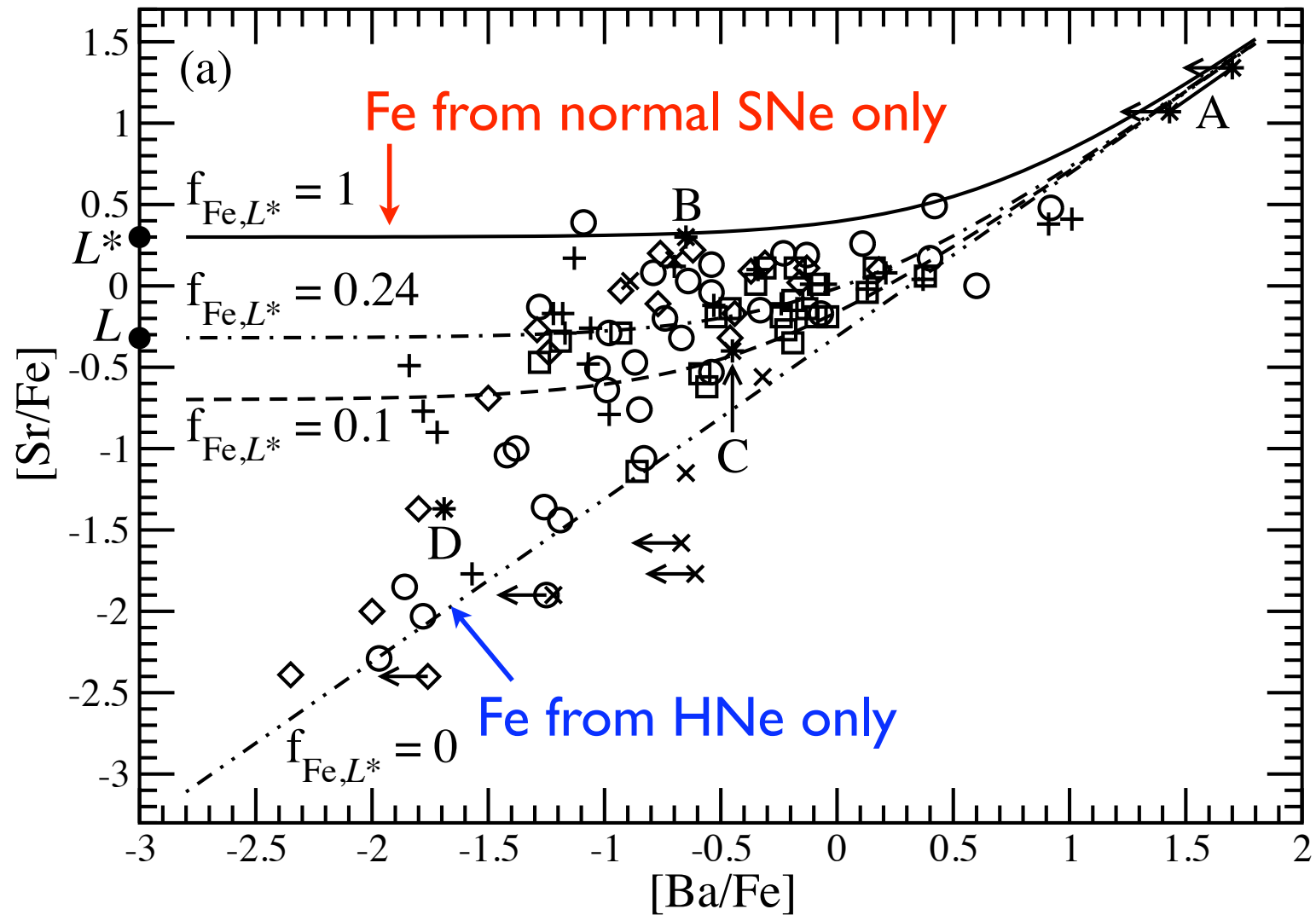
(Woosley & Hoffman 1992)



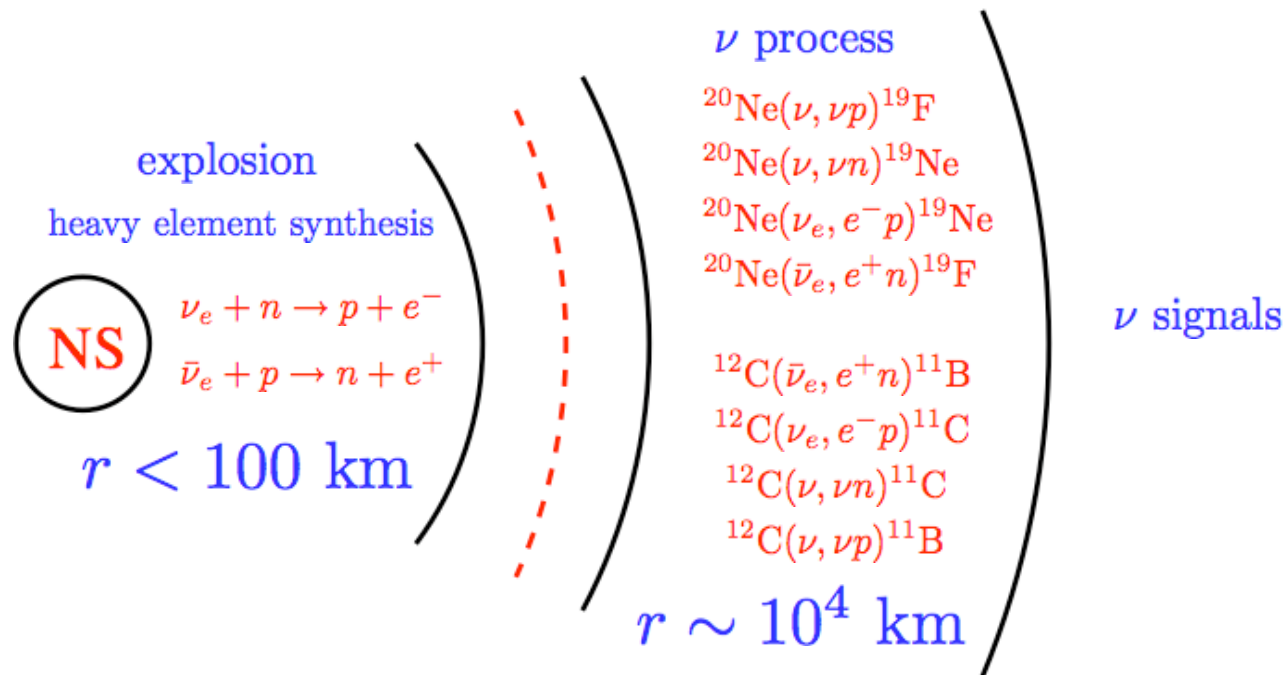
Stellar sources for elements

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



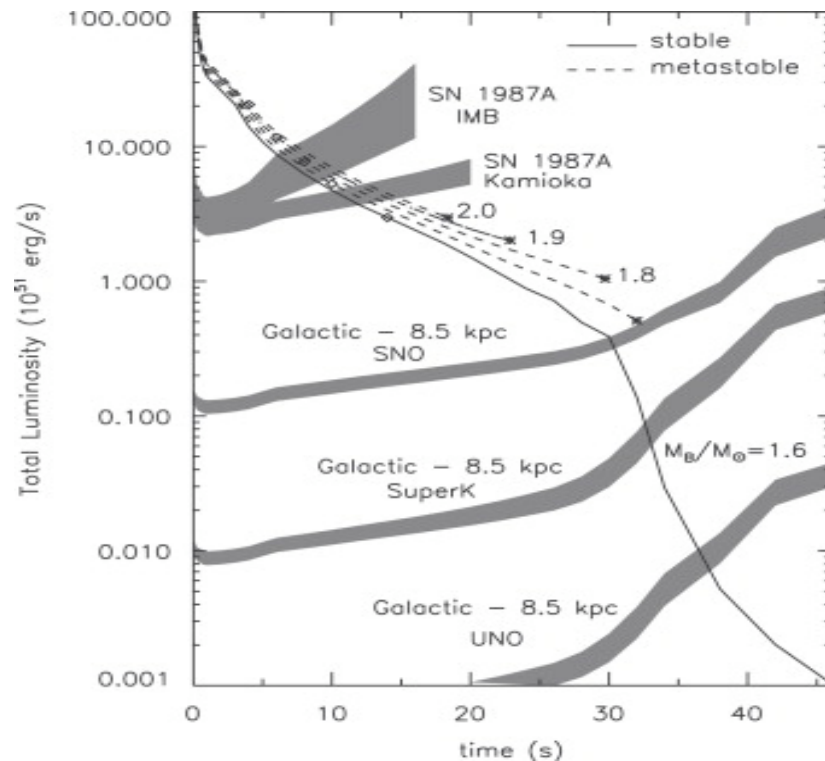
How to use neutrino signals to identify various CCSNe?

progenitor dependences of neutrino emission

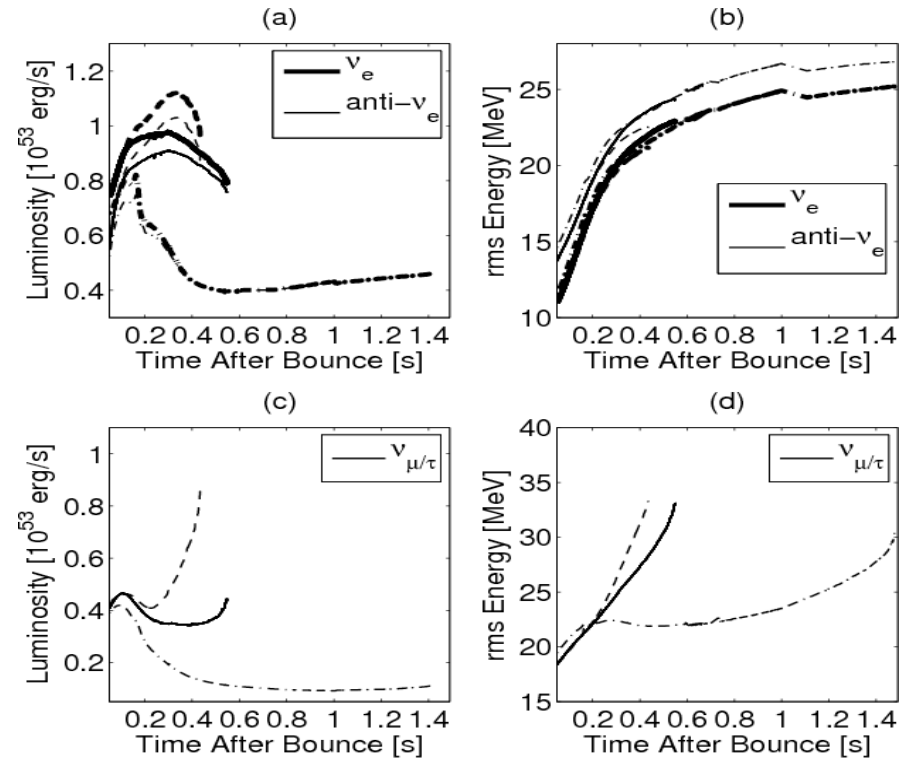
☀ core size, accretion →

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

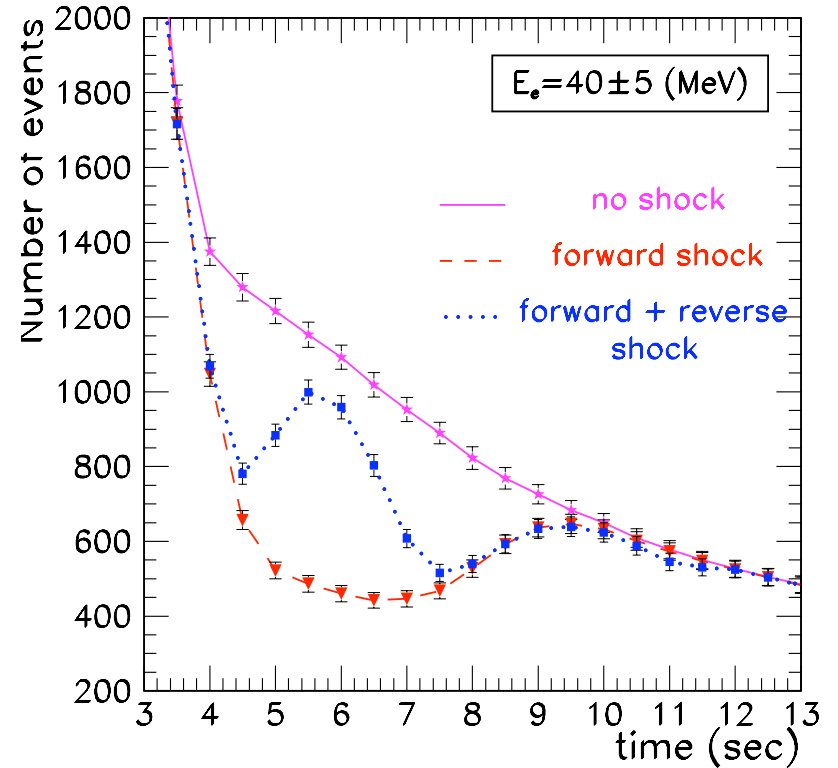
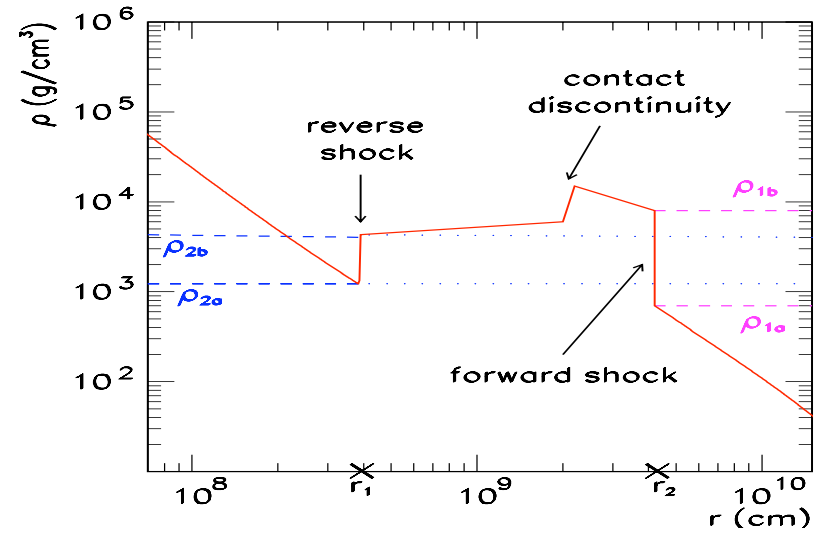
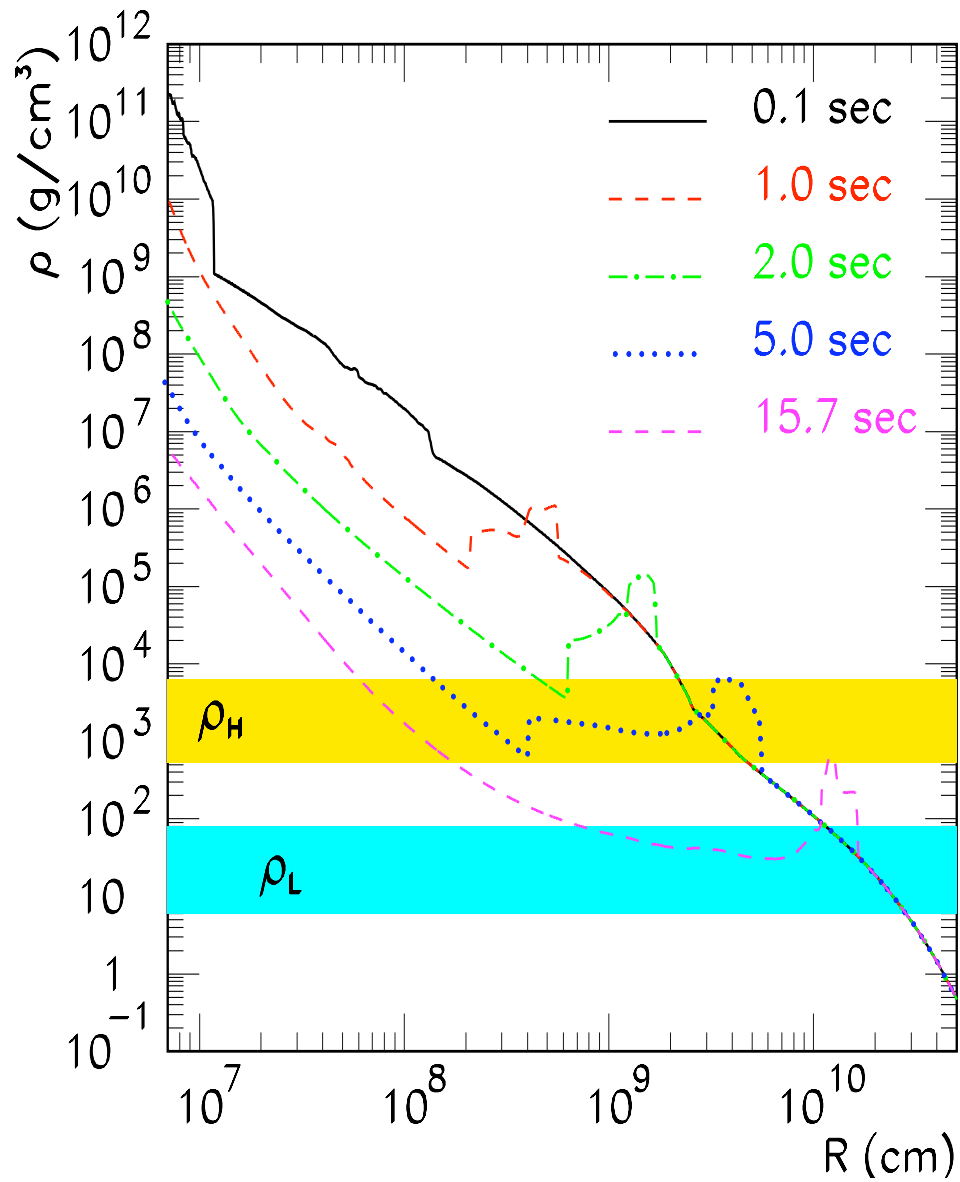
(Pantaleone 1992;

Kostelecky & Samuel 1993;

Duan et al. 2006-09;

Raffelt & collaborators 2006-09)

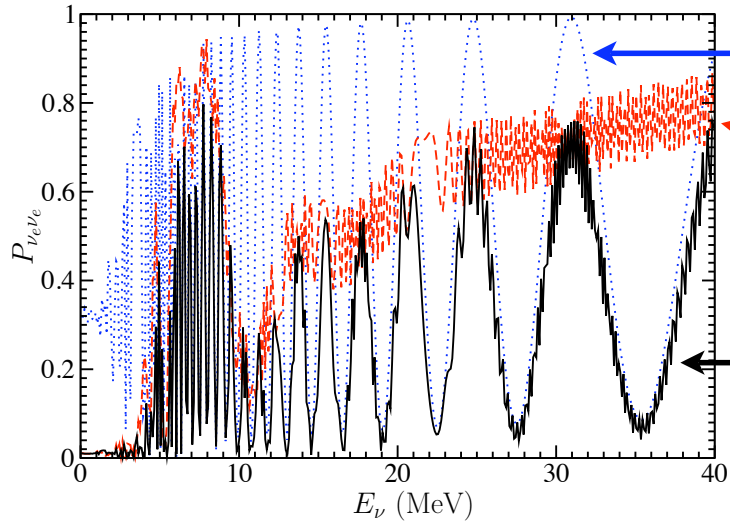
Tomas et al. 2004



Example of 3-neutrino mixing including self-interaction

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

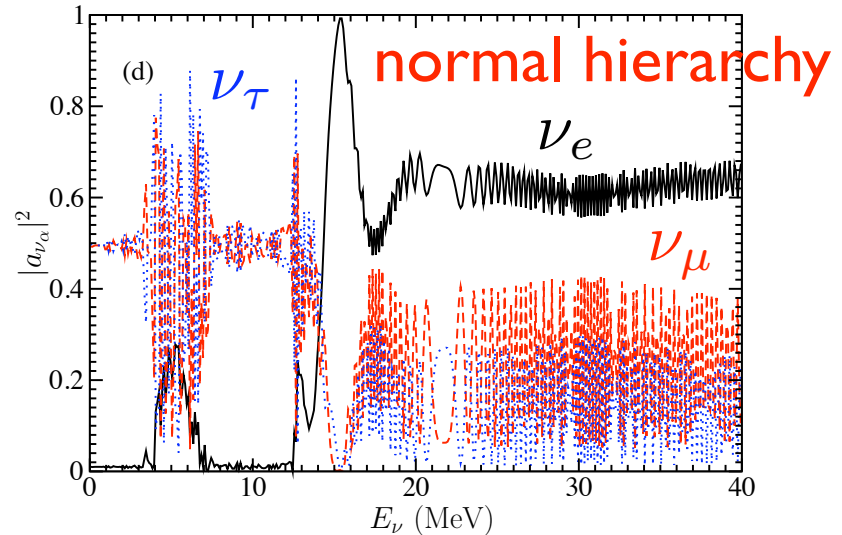
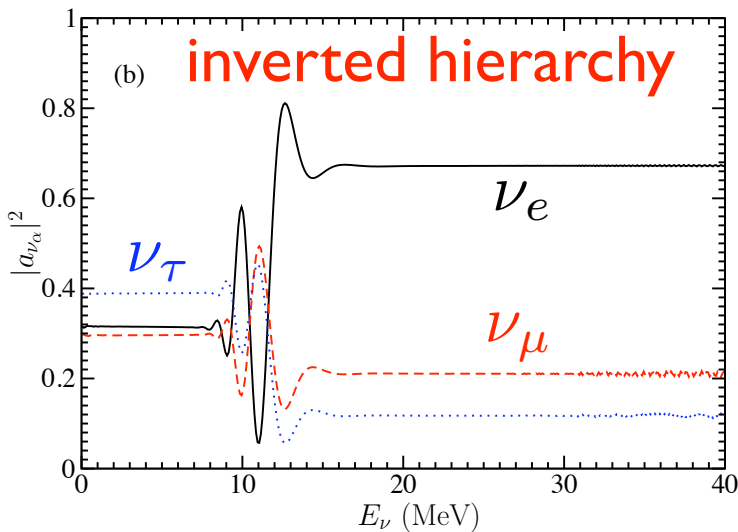
Duan, Fuller, Carlson, & Qian, PRL 100, 021101 (2008)



2-neutrino solar scale

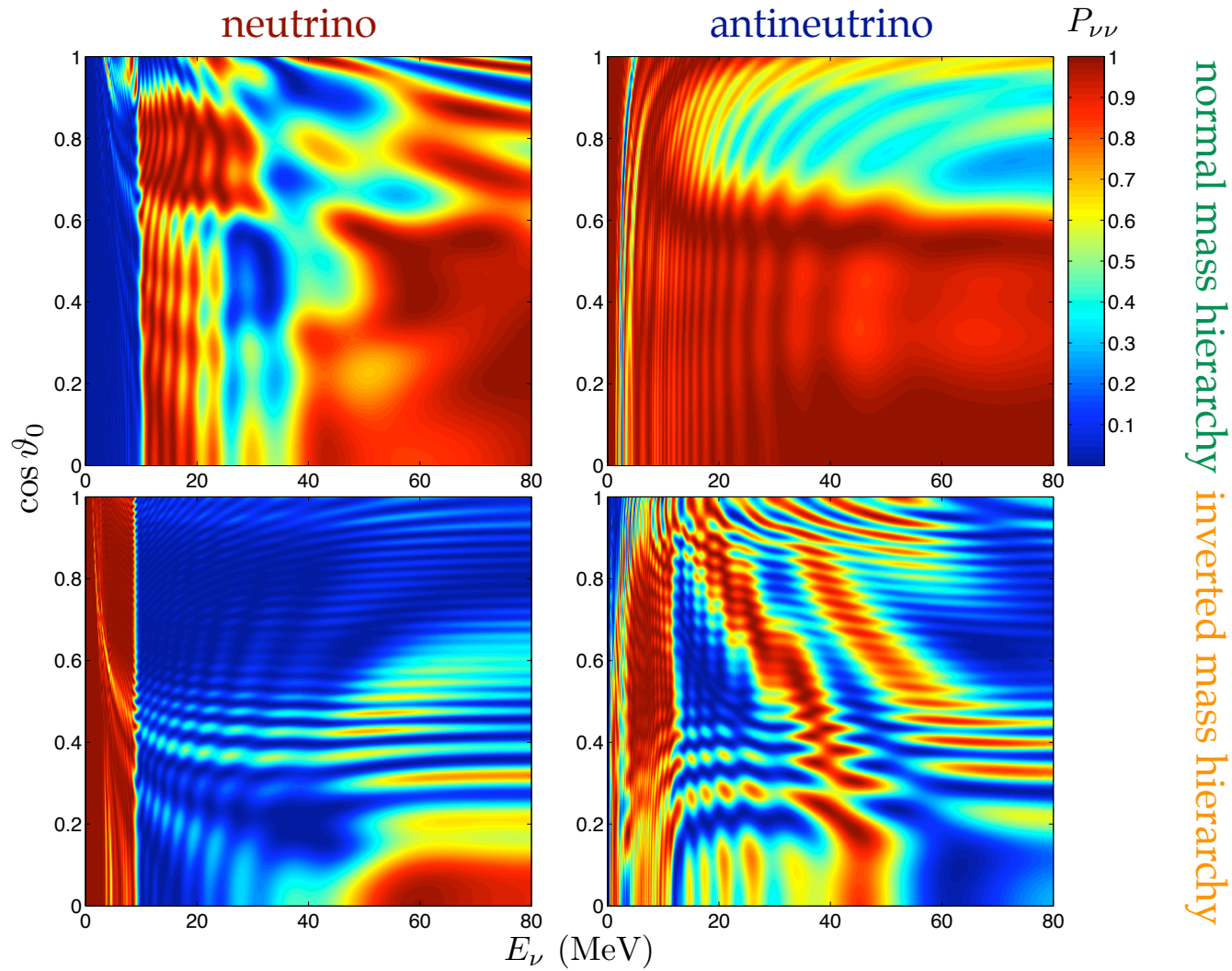
2-neutrino atmospheric scale (normal hierarchy)

3-neutrino (matter effect only, normal hierarchy)

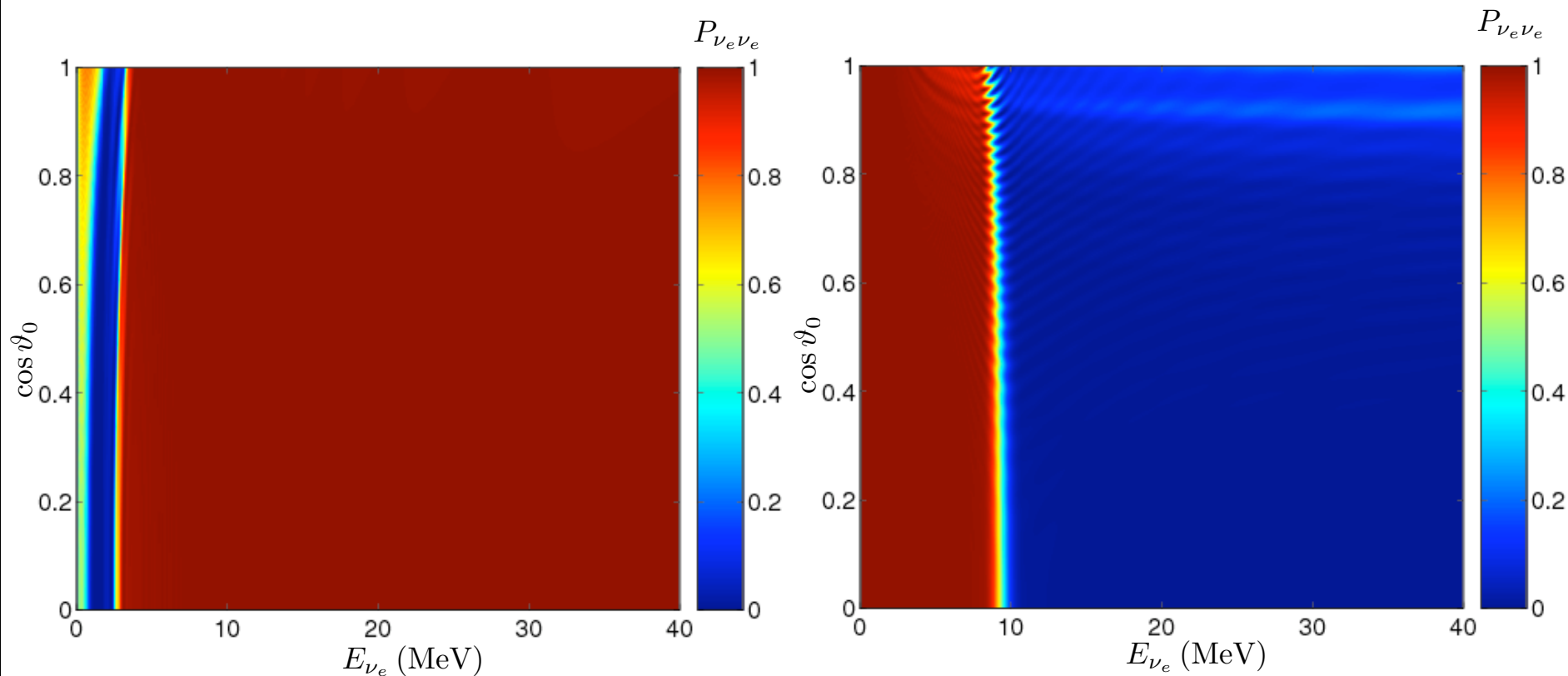


Survival Probability at $r = 225$ km

$$\delta m^2 \equiv m_3^2 - m_1^2 \rightarrow \pm 3 \times 10^{-3} \text{ eV}^2, \theta_v \rightarrow 0.1$$



Survival Probability at $r = 250$ km



normal mass hierarchy

$$\theta_{\nu} = 0.01$$

inverted mass hierarchy

$$\theta_{\nu} = 10^{-9}$$

(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