Neutrinos, Nucleosynthesis, and Core-Collapse Supernovae

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Outline

- varieties of core-collapse supernovae (CCSNe): theory & observations
- varieties of CCSNe: their neutrinos & nucleosynthesis
- neutrino signals with & without oscillations
- what can we learn from neutrino signals: CCSN physics & neutrino properties

How to Become a Star

Virial theorem for a contracting gas cloud

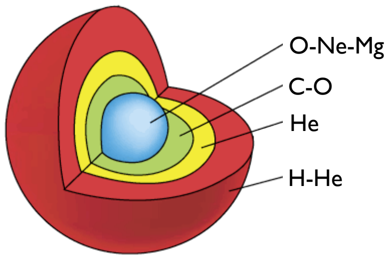
$$T_c + \frac{\hbar^2}{2m_e d^2} \sim \frac{GMm_p}{R}$$

$$\left(\frac{M}{m_p}\right) d^3 \sim R^3 \Rightarrow$$

$$T_c \sim \frac{GMm_p}{R} - \frac{\hbar^2}{2m_e}\left(\frac{M}{m_p}\right)^{2/3} \frac{1}{R^2}$$

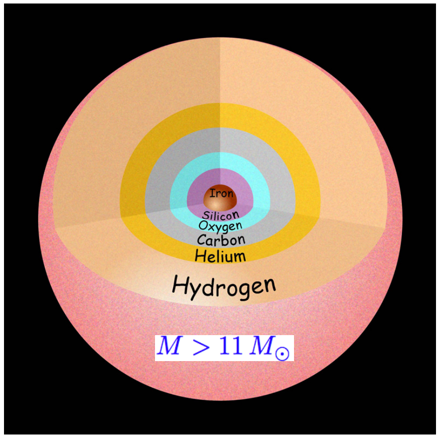
$$\Rightarrow T_{c,\max} \propto M^{4/3}$$

Four types of core-collapse SNe



$M \sim 8\text{–}11\, M_\odot$

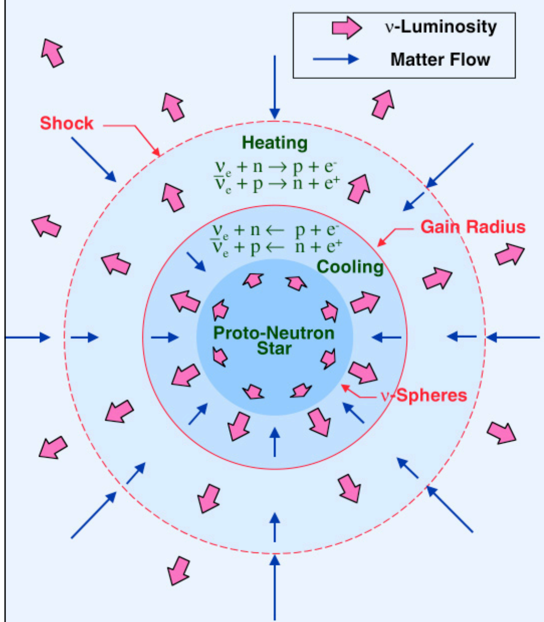
low-mass SNe: NS



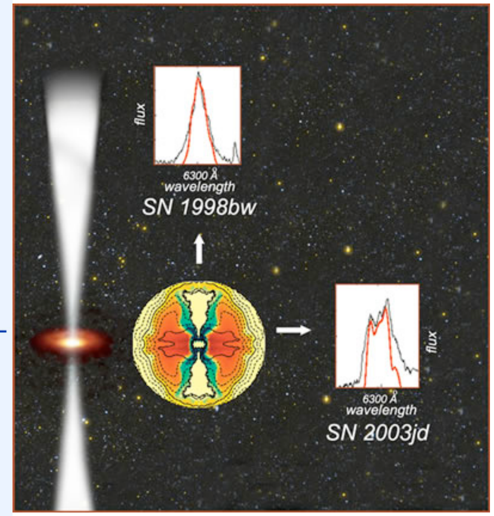
$M \sim\ 12\text{–}25\, M_\odot$ normal SNe: NS

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

low-mass & normal SNe:
neutrino-driven

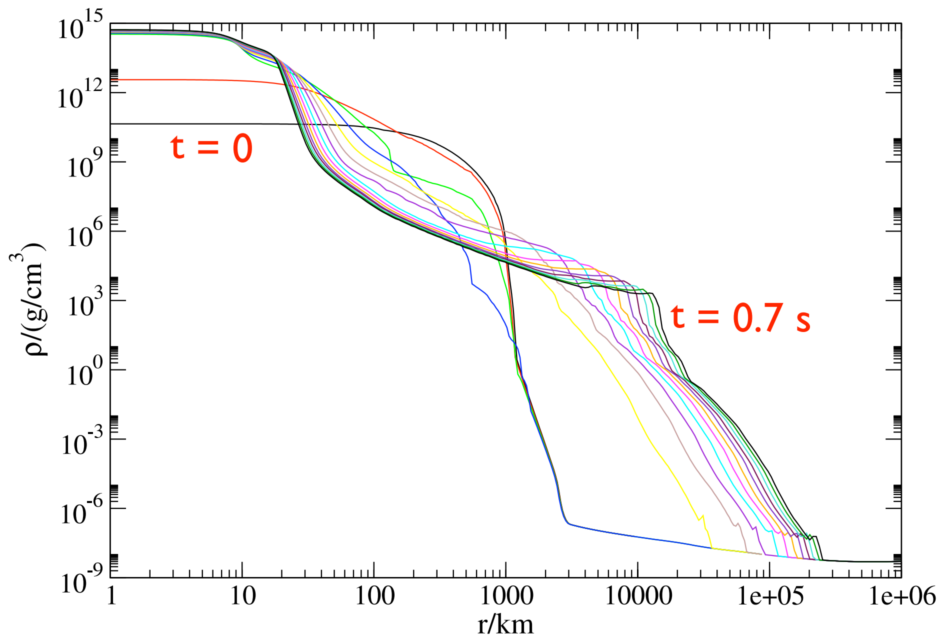


HNe: strong jets

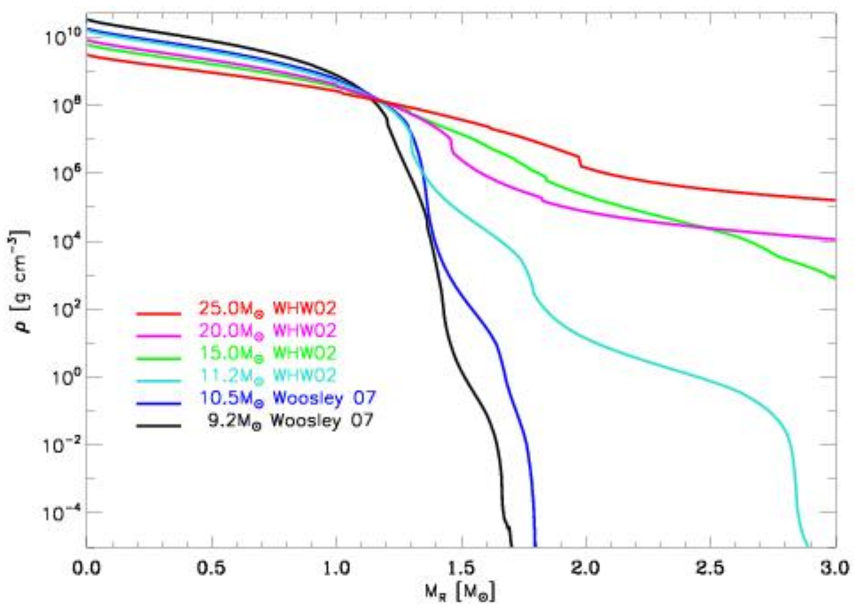


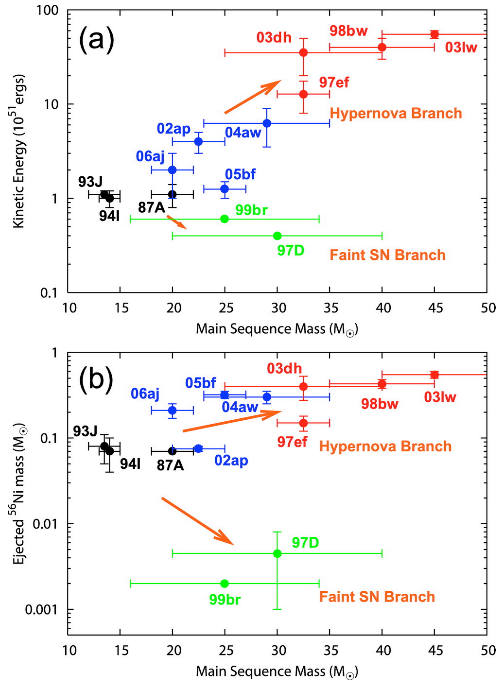
faint SNe: weak jets

low-mass SNe (Janka et al. 2008)



Density profiles of CCSN progenitors





Tominaga et al. (2007)

normal SNe

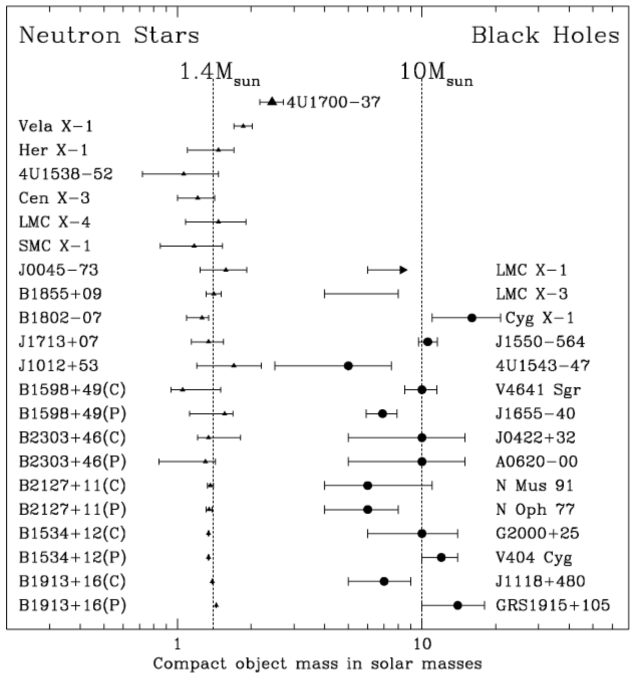
$M \sim 12\text{–}25\ M_\odot$

HNe

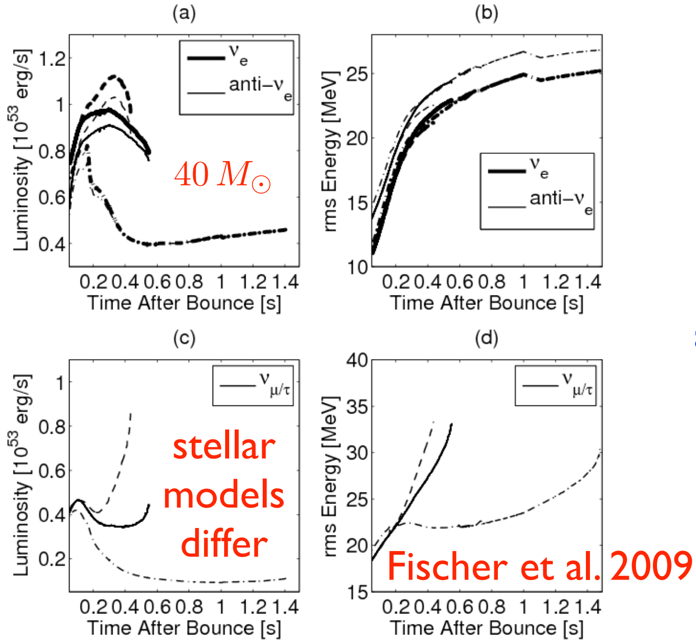
$M \sim 25\text{–}50\ M_\odot$

faint SNe

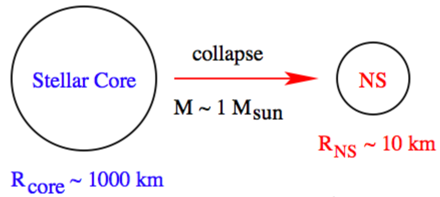
$M \sim 25\text{–}50\ M_\odot$


Neutron Stars
Black Holes
1.4M_sun
10M_sun
4U1700-37
Vela X-1
Her X-1
4U1538-52
Cen X-3
LMC X-4
SMC X-1
J0045-73
B1855+09
B1802-07
J1713+07
J1012+53
B1598+49(C)
B1598+49(P)
B2303+46(C)
B2303+46(P)
B2127+11(C)
B2127+11(P)
B1534+12(C)
B1534+12(P)
B1913+16(C)
B1913+16(P)
LMC X-1
LMC X-3
Cyg X-1
J1550-564
4U1543-47
V4641 Sgr
J1655-40
J0422+32
A0620-00
N Mus 91
N Oph 77
G2000+25
V404 Cyg
J1118+480
GRS1915+105
1
10
Compact object mass in solar masses

signature of BH formation: interruption of ν signals



followed by neutrino emission from accretion disk around BH?



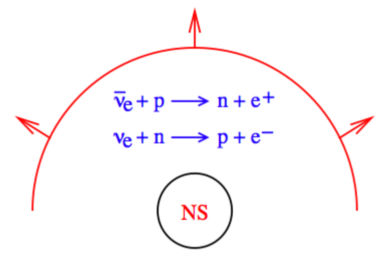
Supernovae as a neutrino phenomenon

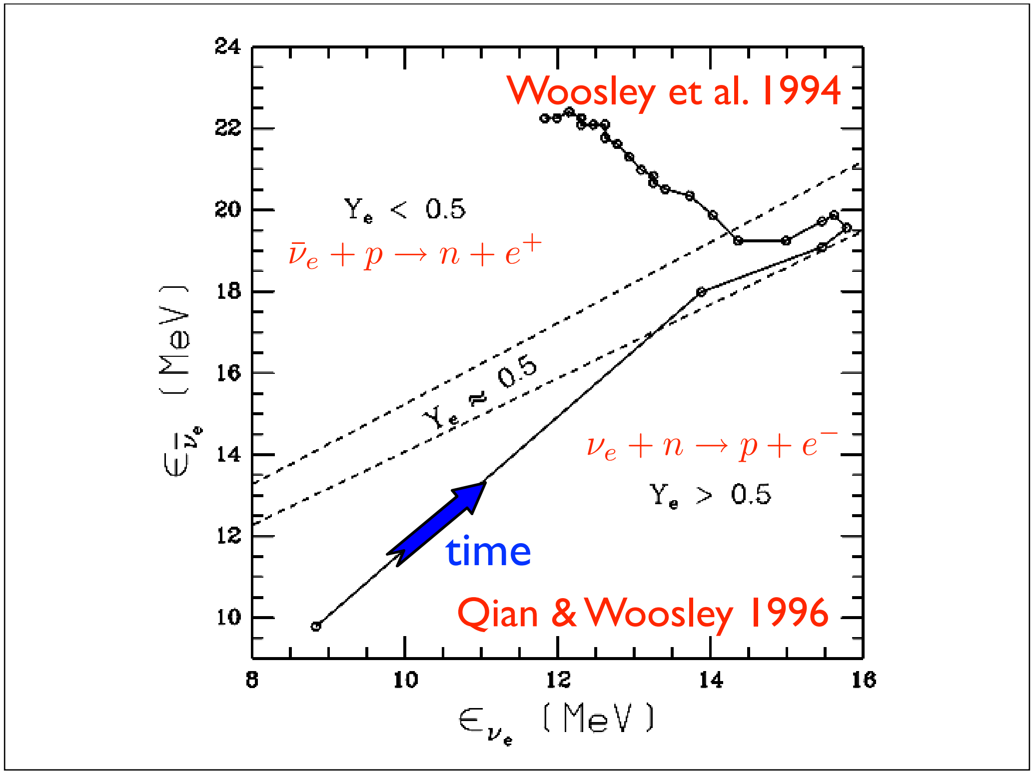
$$e^+ + e^- \to \nu + \bar{\nu},\ N + N \to N + N + \nu + \bar{\nu}$$

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

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

(Woosley & Hoffman 1992; Arcones & Montes 2011)

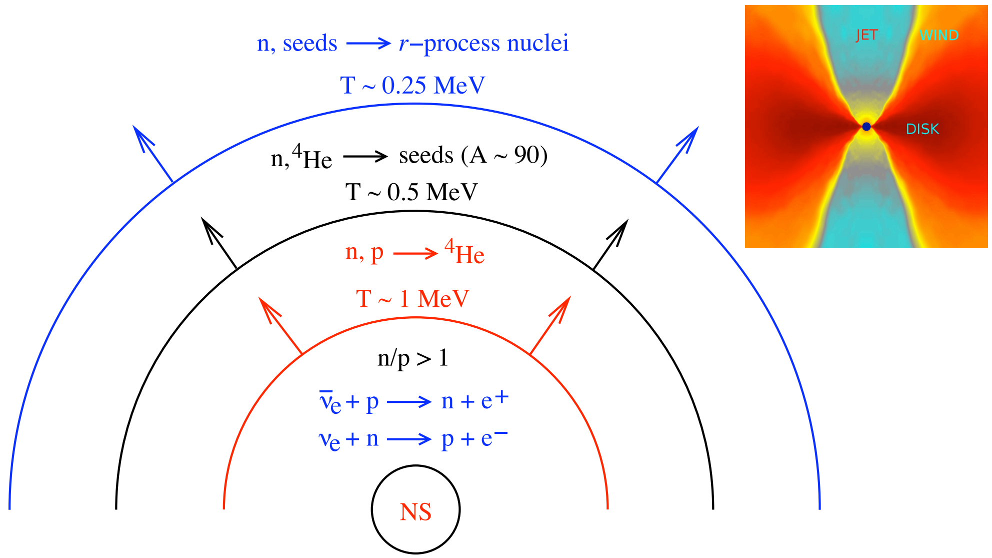




Woosley et al. 1994
$Y_e < 0.5$
$\bar{\nu}_e + p \rightarrow n + e^+$
$Y_e \approx 0.5$
$\nu_e + n \rightarrow p + e^-$
$Y_e > 0.5$
time
Qian & Woosley 1996
$\epsilon_{\bar{\nu}_e}$ (MeV)
ϵ_{ν_e} (MeV)

r−Process in Neutrino−driven Wind or accretion disk wind?

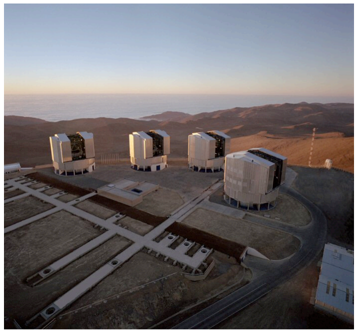
(e.g., Woosley & Baron 1992; Meyer et al. 1992; Woosley et al. 1994)



CCSN sources for elements

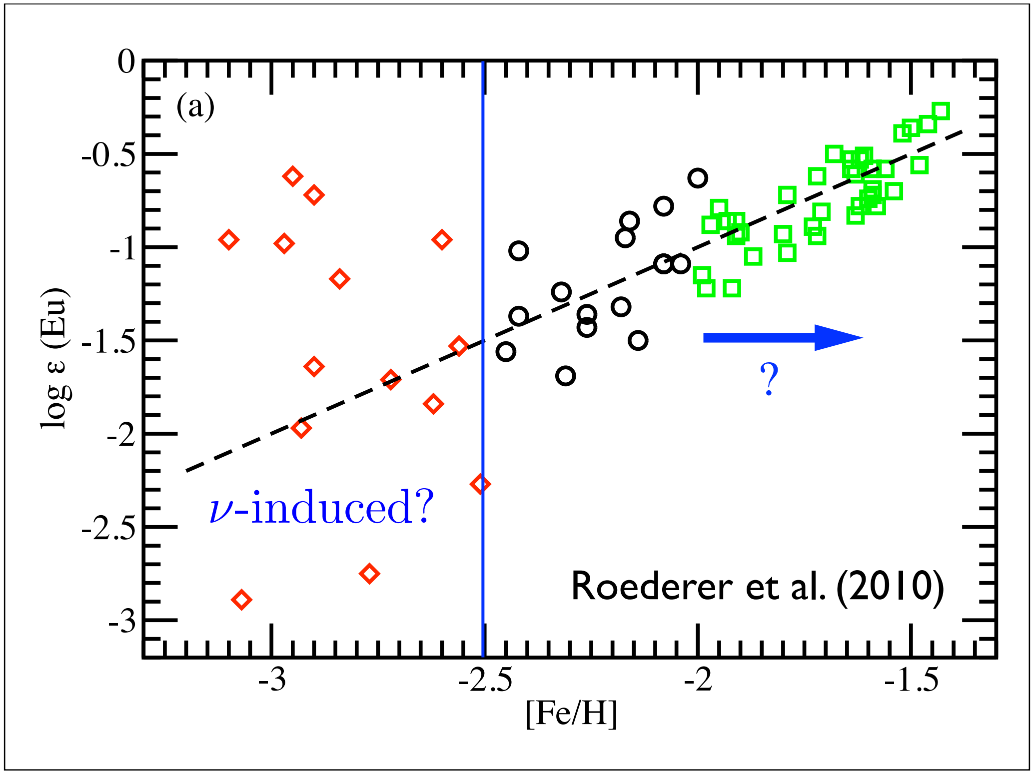
sources	Fe-like elements	Sr-like elements	Ba-like elements
low-mass SNe	No	Yes	?
normal SNe	Yes	Yes	?
HNe	Yes	No	?

Elemental abundances in metal-poor stars



Johnson 2002; Honda et al. 2004; Aoki et al. 2005; Francois et al. 2007; Cohen et al. 2007

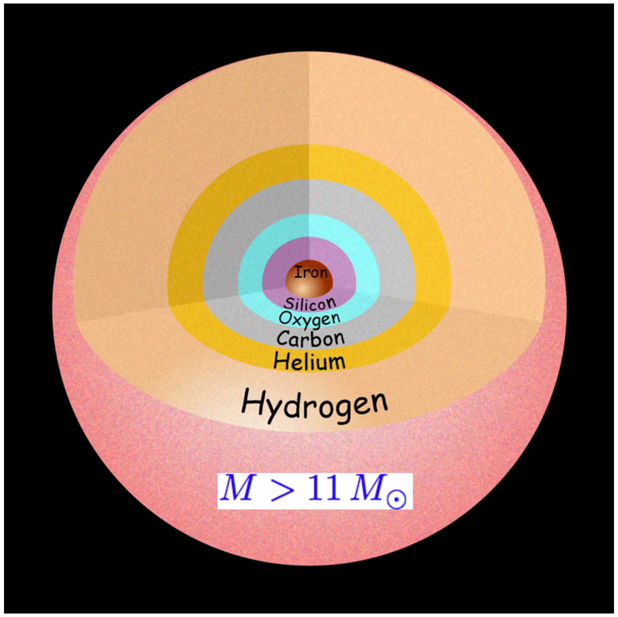
- Fe-like elements (A ~ 23 to 70)
  Na, Mg, Al, Si, ..., Fe, ..., Zn
- Sr-like elements (A ~ 88 to 110)
  Sr, Y, Zr, ..., Ag
- Ba-like elements (A > 130)
  Ba, ..., Eu, ..., Pt, ..., Th, ..., U, ...

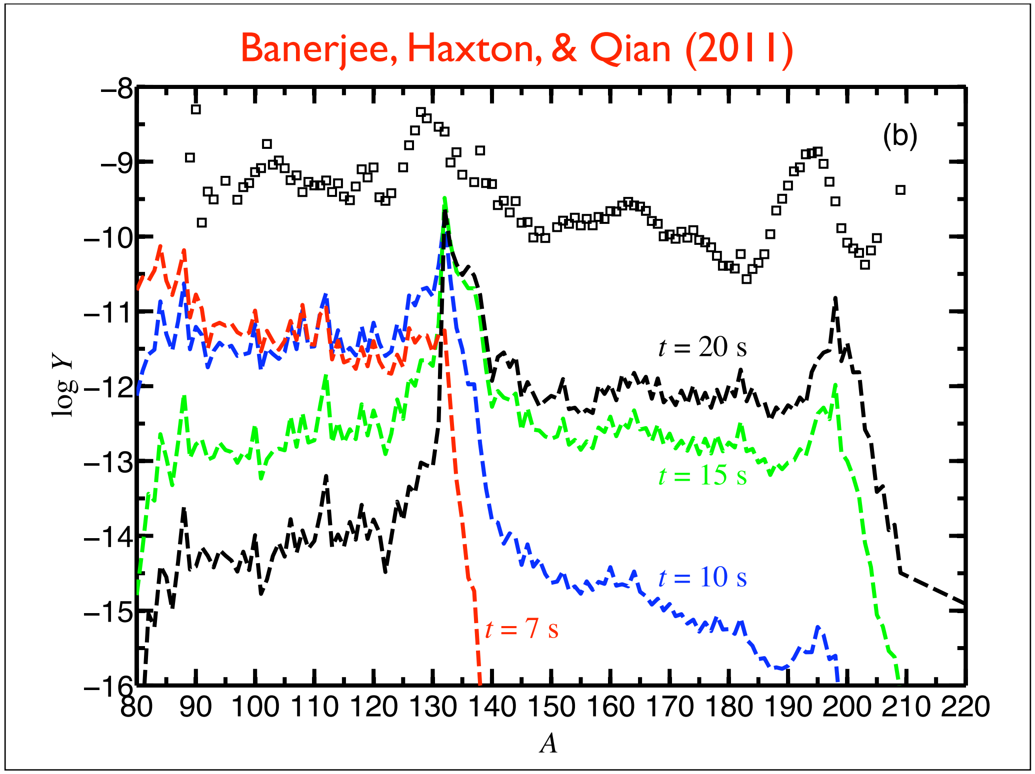


(a)
log ε (Eu)
[Fe/H]
ν-induced?
?
Roederer et al. (2010)

Neutrino-induced r-process in He shell

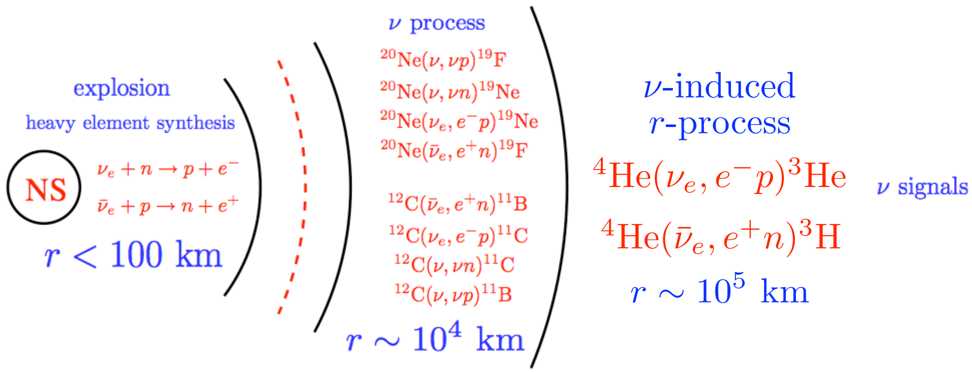
(Epstein, Colgate, & Haxton 1988)

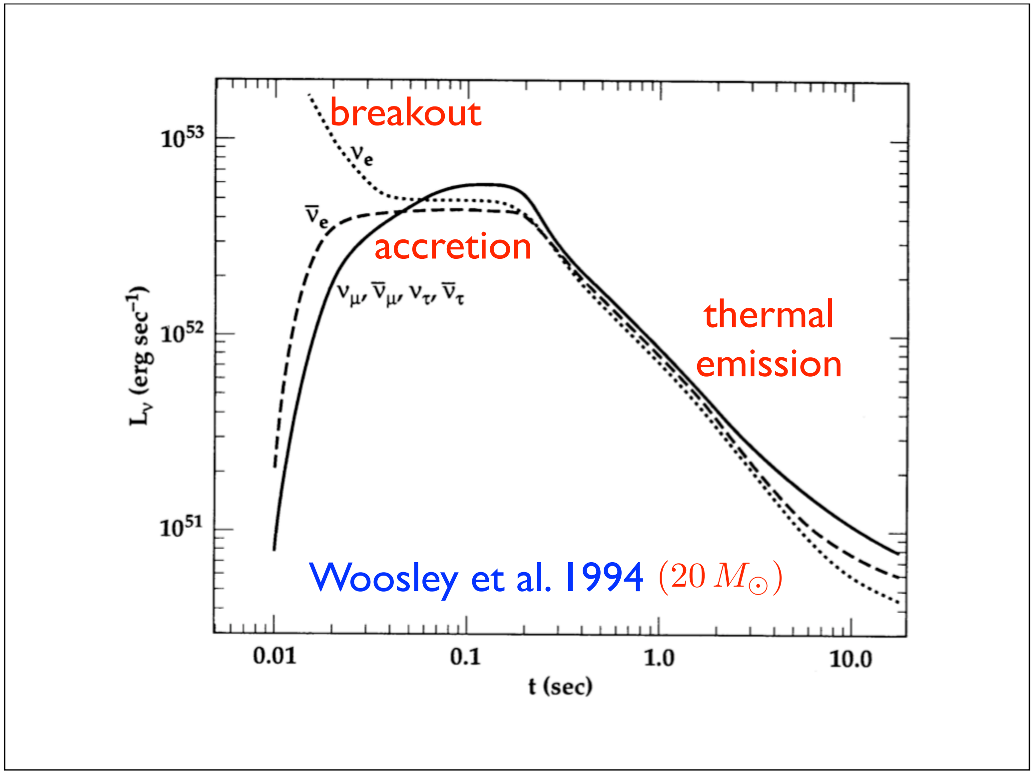




Banerjee, Haxton, & Qian (2011)
(b)
log Y
A
t = 20 s
t = 15 s
t = 10 s
t = 7 s
−8
−9
−10
−11
−12
−13
−14
−15
−16
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220

Interplay between Supernova and Neutrino Physics




breakout
accretion
thermal
emission
ν_e
$\bar{\nu}_e$
$\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$
10^{53}
10^{52}
10^{51}
L_ν (erg sec^{-1})
0.01
0.1
1.0
10.0
t (sec)
Woosley et al. 1994 $(20\,M_\odot)$

CCSN physics & neutrinos without oscillations

existing neutrino detectors: Super-K, IceCube

$$\bar{\nu}_e + p \rightarrow n + e^+$$

- duration of accretion phase

  → progenitors, neutrino-driven explosion

- termination of thermal emission

  → black hole formation

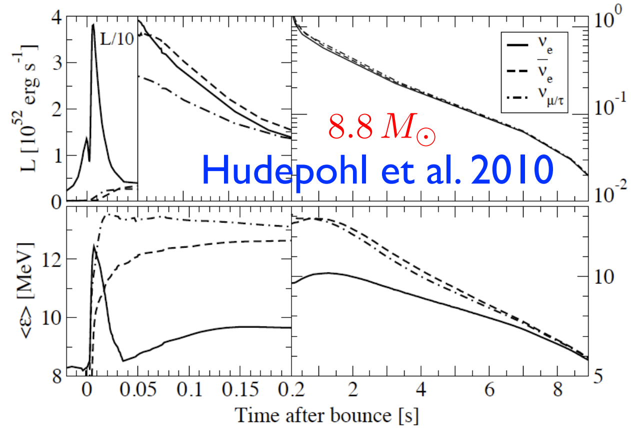
  progenitors

  nuclear equation of state

CCSN physics & neutrinos with oscillations

hierarchy of average neutrino energies

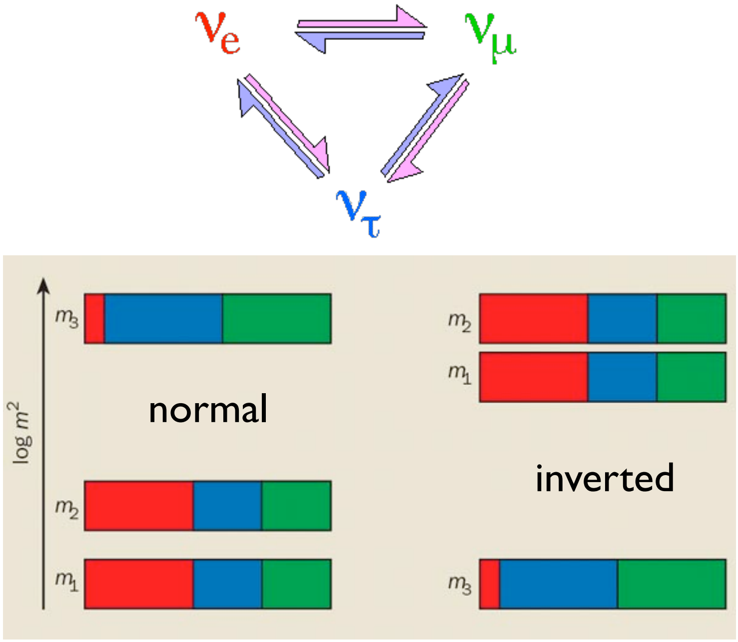
$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_{\mu,\tau}} \rangle, \ \langle E_{\nu_{\mu,\tau}} \rangle \approx \langle E_{\bar{\nu}_{\mu,\tau}} \rangle$



sensitive to neutrino opacities!

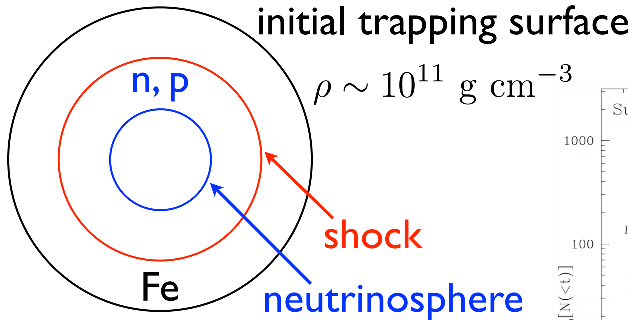
(Martinez-Pinedo et al. 2012; Roberts & Reddy 2012)

Three-Neutrino Mixing



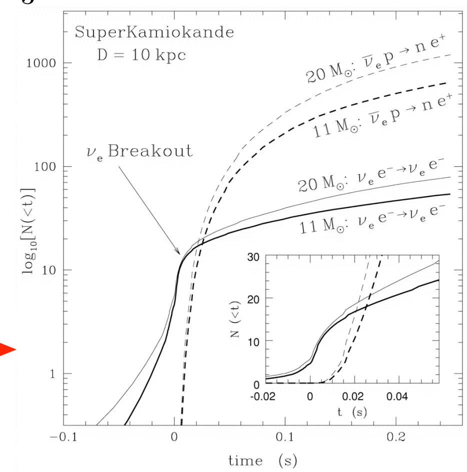
“neutronization” pulse at shock breakout

$e^- + p \to n + \nu_e \Rightarrow$ predominantly ν_e



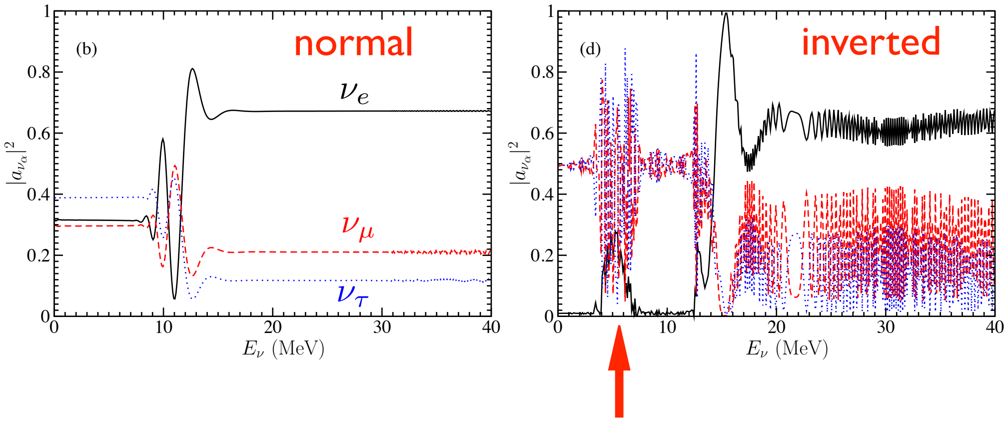
without oscillations

(Thompson et al. 2003)



neutronization neutrino signal from low-mass CCSNe

(Duan et al. 2007; Cherry et al. 2010, 2011, 2012)



need sensitivity to low-energy ν_e

liquid argon: $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$

progenitor dependences of neutrino flavor evolution

density profile →

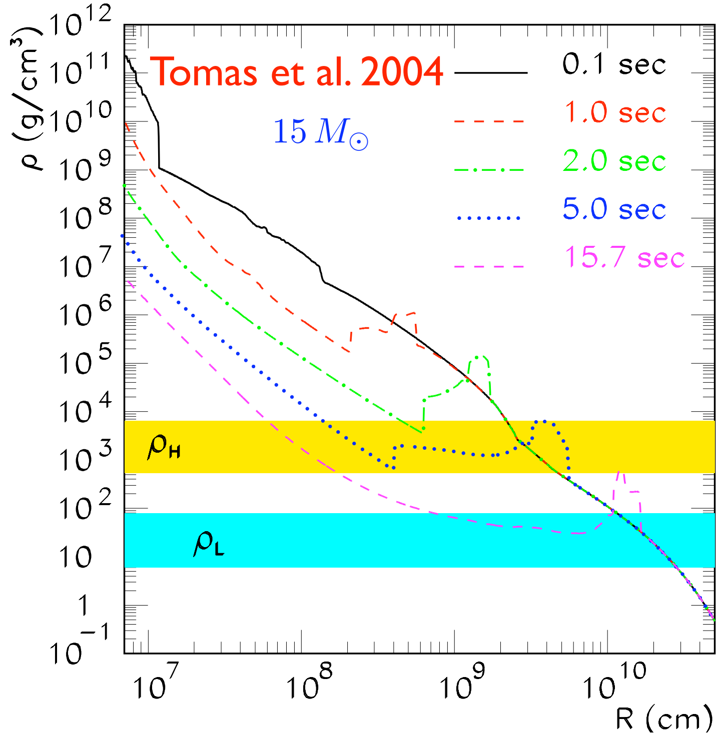
positions and adiabaticity of MSW resonances

modulation by shock propagation

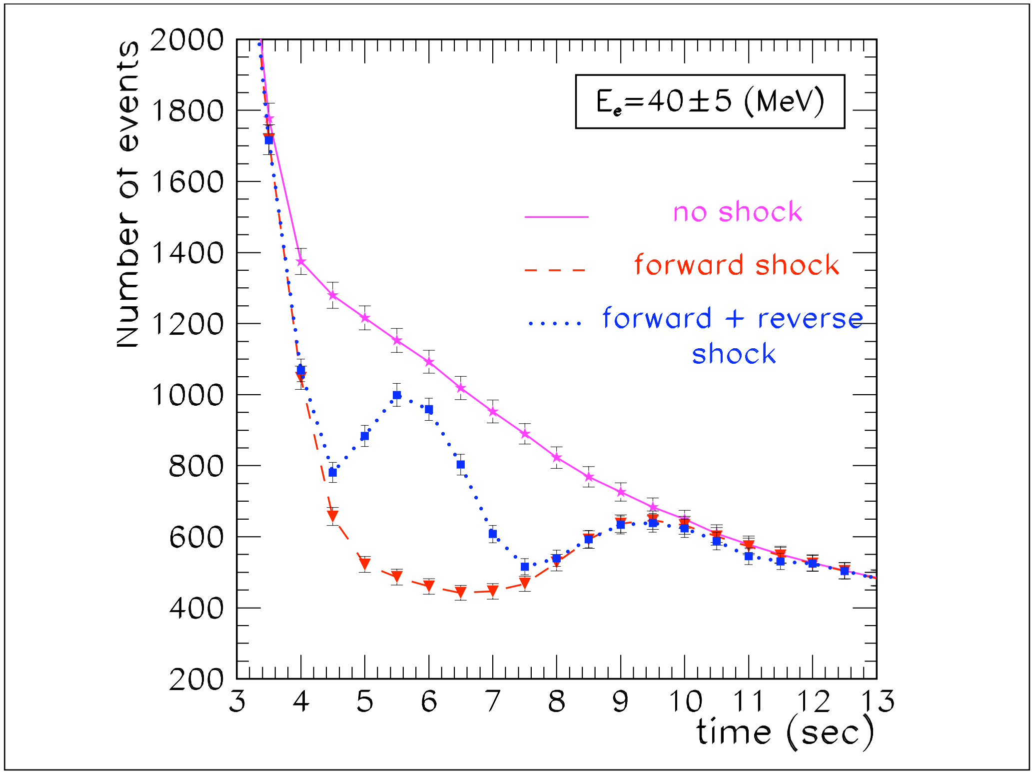
(Schirato & Fuller 2002)

comparison with neutrino density:
collective oscillations due to neutrino self-interaction

(Pantaleone 1992; Kostelecky & Samuel 1993;
Duan et al. 2006 & subsequent works;
Raffelt & collaborators; Mirizzi & collaborators)



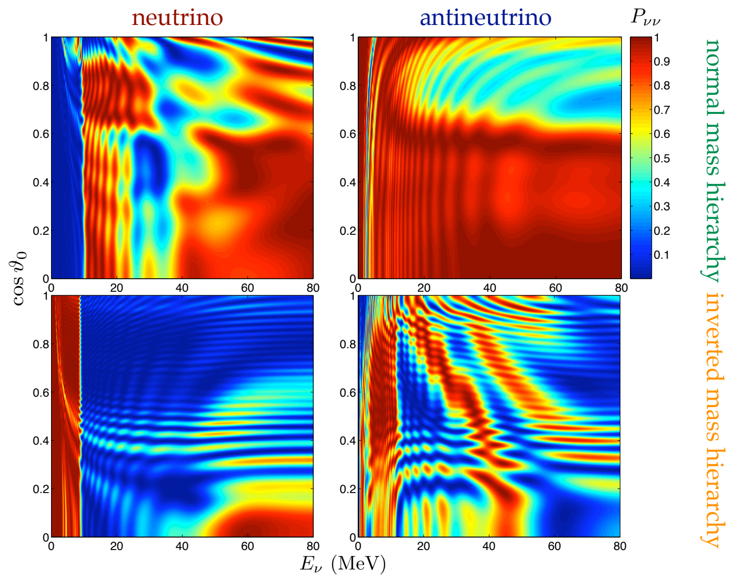
Tomas et al. 2004
15 $M_\odot$
0.1 sec
1.0 sec
2.0 sec
5.0 sec
15.7 sec
ρ_H
ρ_L
ρ (g/cm^3)
R (cm)
10^{12}
10^{11}
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^7
10^8
10^9
10^{10}

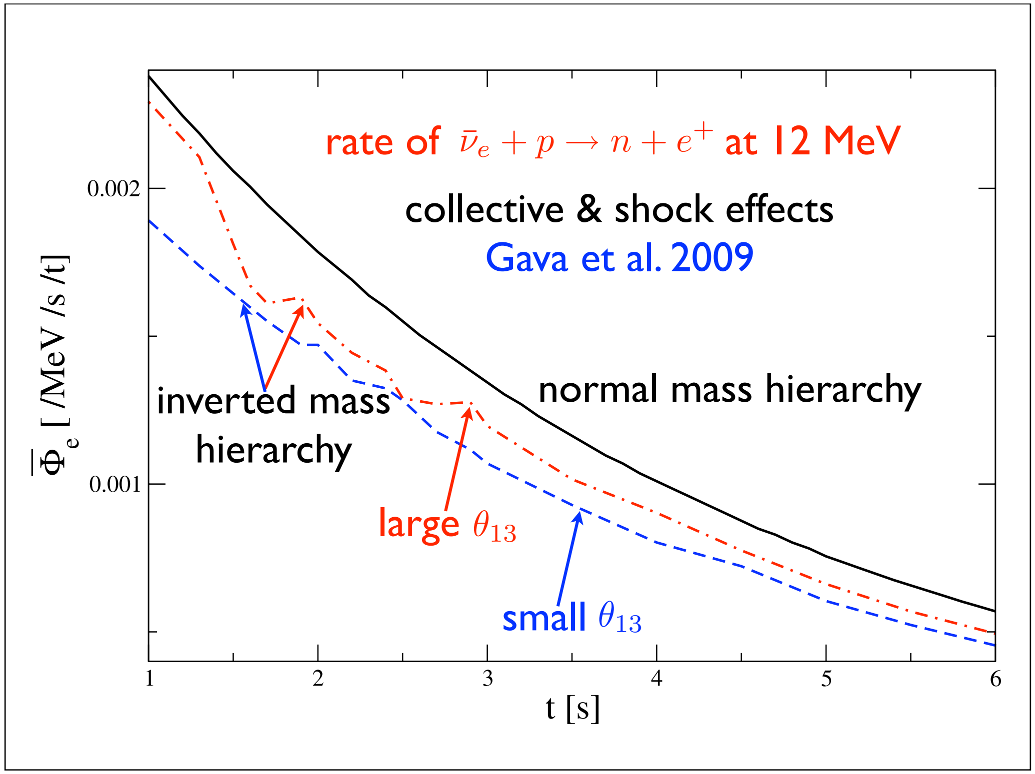


Number of events
time (sec)
E_e=40±5 (MeV)
no shock
forward shock
forward + reverse shock
2000
1800
1600
1400
1200
1000
800
600
400
200
3
4
5
6
7
8
9
10
11
12
13

Survival Probability at $r = 225$ km

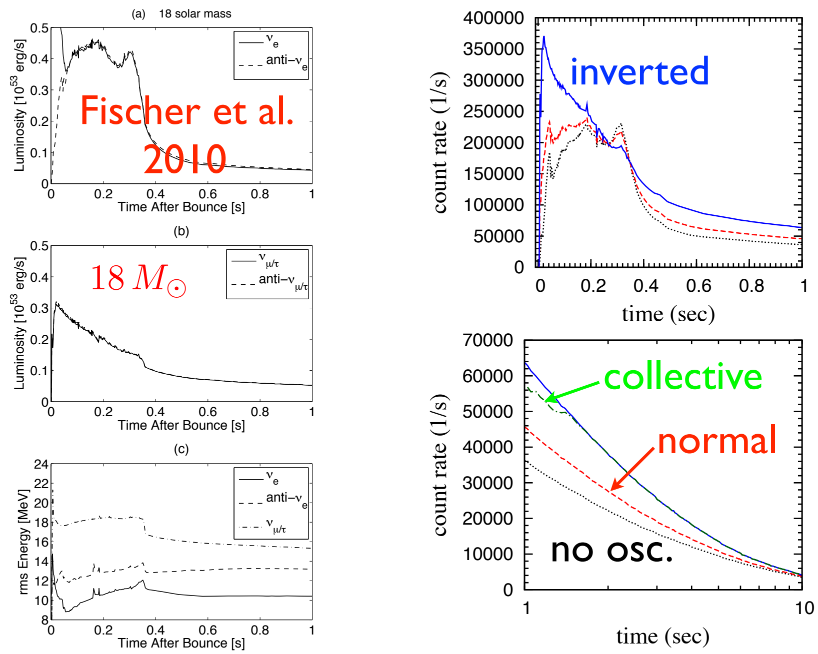
(Duan et al. 2007)





rate of $\bar{\nu}_e + p \rightarrow n + e^+$ at 12 MeV
collective & shock effects
Gava et al. 2009
normal mass hierarchy
inverted mass hierarchy
large θ_{13}
small θ_{13}
$\overline{\Phi}_e$ [/MeV /s /t]
0.002
0.001
t [s]
1
2
3
4
5
6

$\bar{\nu}_e + p \rightarrow n + e^+$ in IceCube (Wu et al. 2012)



Summary: supernovae and their neutrino signals

- interruption of neutrino signals reveals BH formation
  - → progenitor density structure (accretion rate)
  - nuclear equation of state (phase transition)
- rich interplay among progenitor structure, shock propagation, neutrino emission & flavor evolution

  "neutronization" pulse at shock breakout relatively simple to study as a probe of neutrino properties

  bulk emission of "thermal" neutrinos gives potential probes of supernova physics & neutrino properties (systematic study of collective & shock effects needed)
- templates of neutrino signals important for study of relic/diffuse supernova neutrino background