Supernova Neutrinos

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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

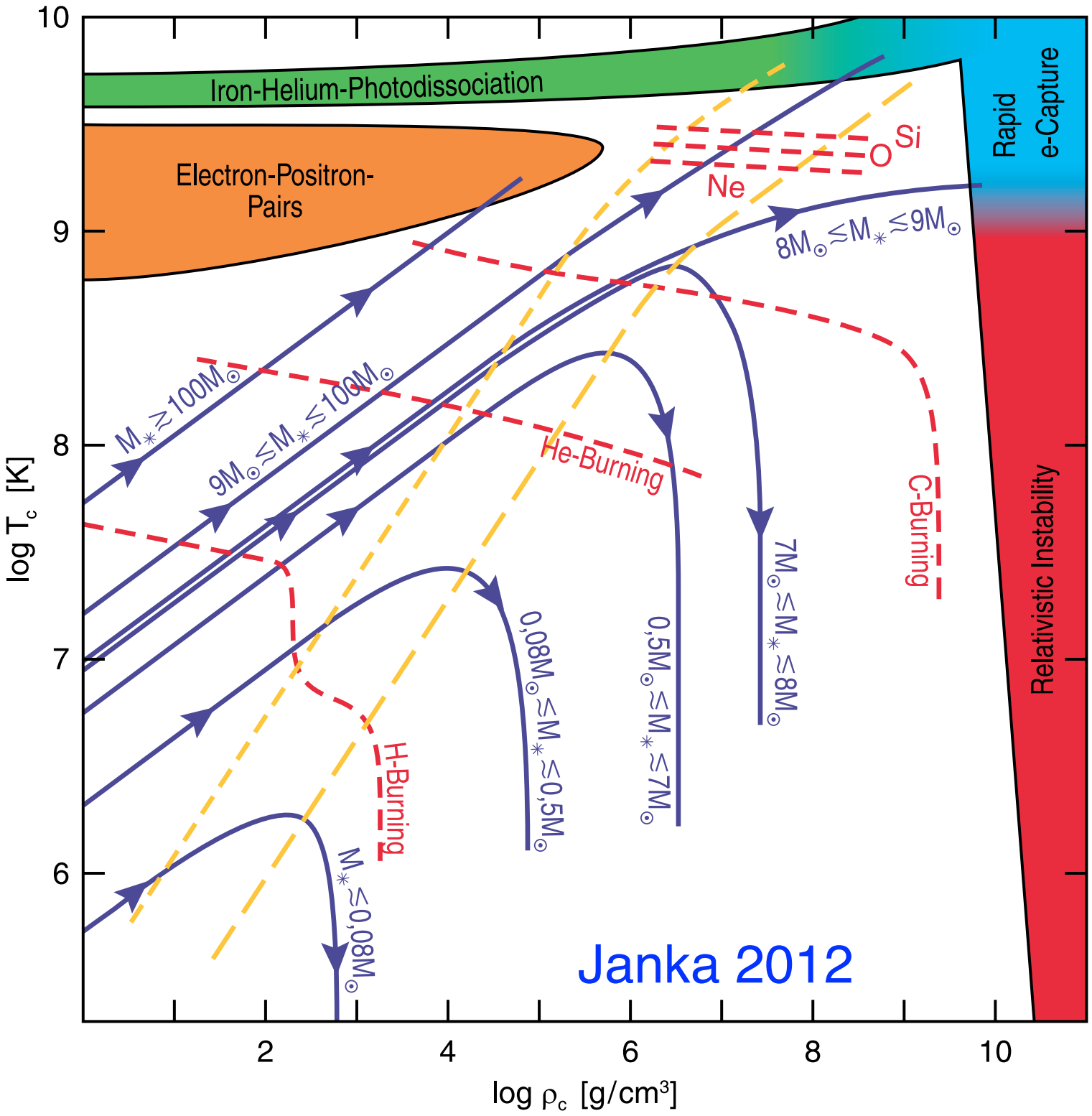
Virial theorem for a contracting gas cloud

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

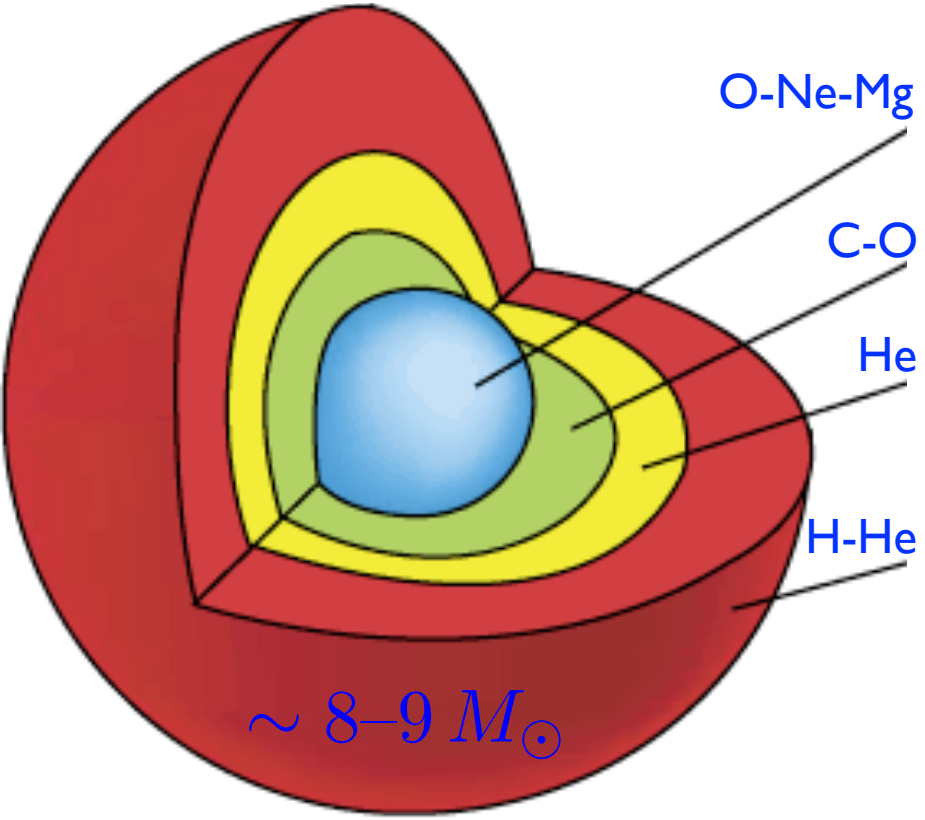
$$\left(\frac{M}{m_p}\right) d^3 \sim R^3 \Rightarrow$$

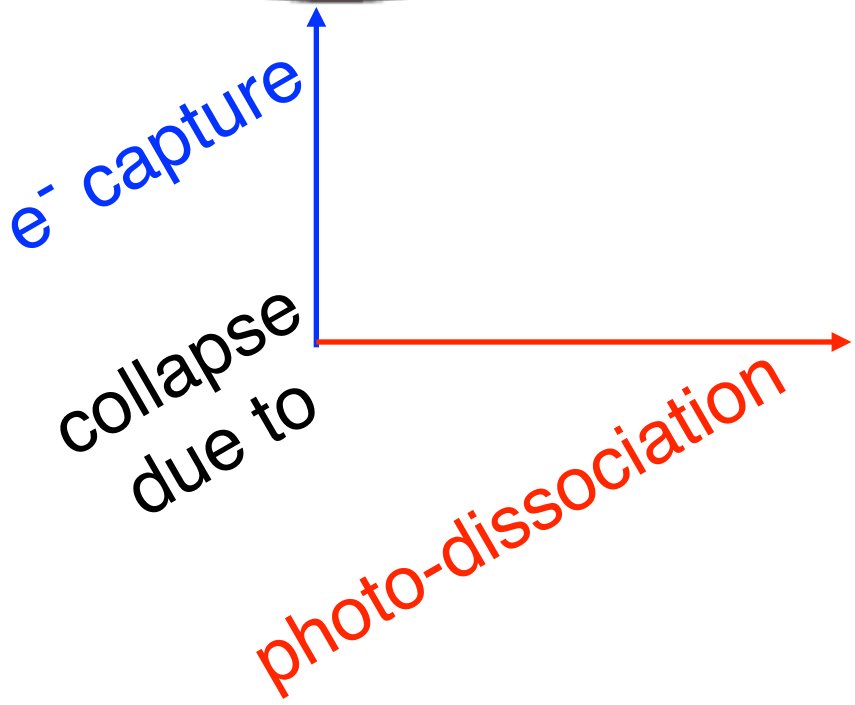
$$T_c \sim \frac{GMm_p}{R} - \frac{\hbar^2}{2m_e}\left(\frac{M}{m_p}\right)^{2/3} \frac{1}{R^2}$$

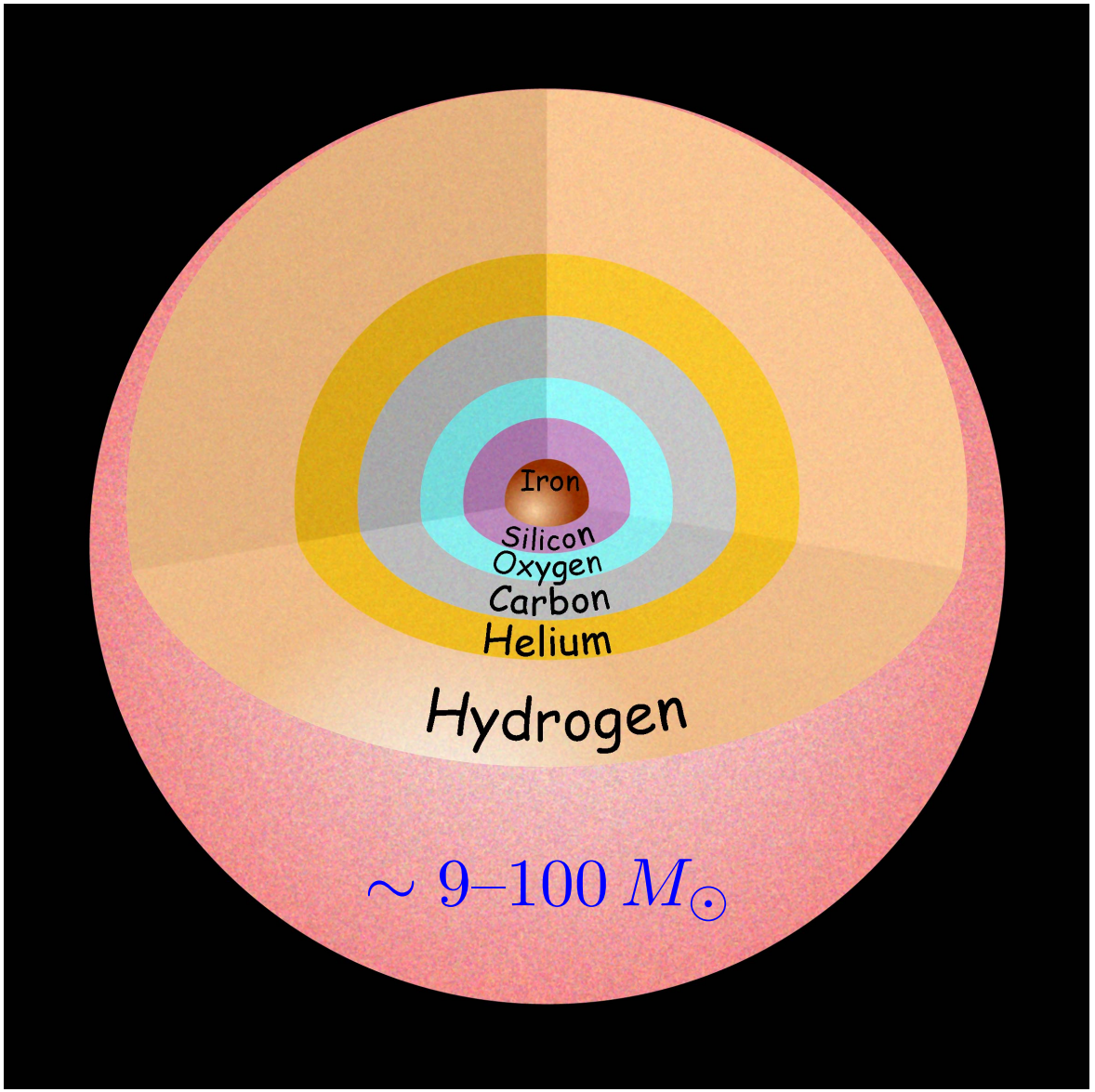
$$\Rightarrow T_{c,\max} \propto M^{4/3}$$

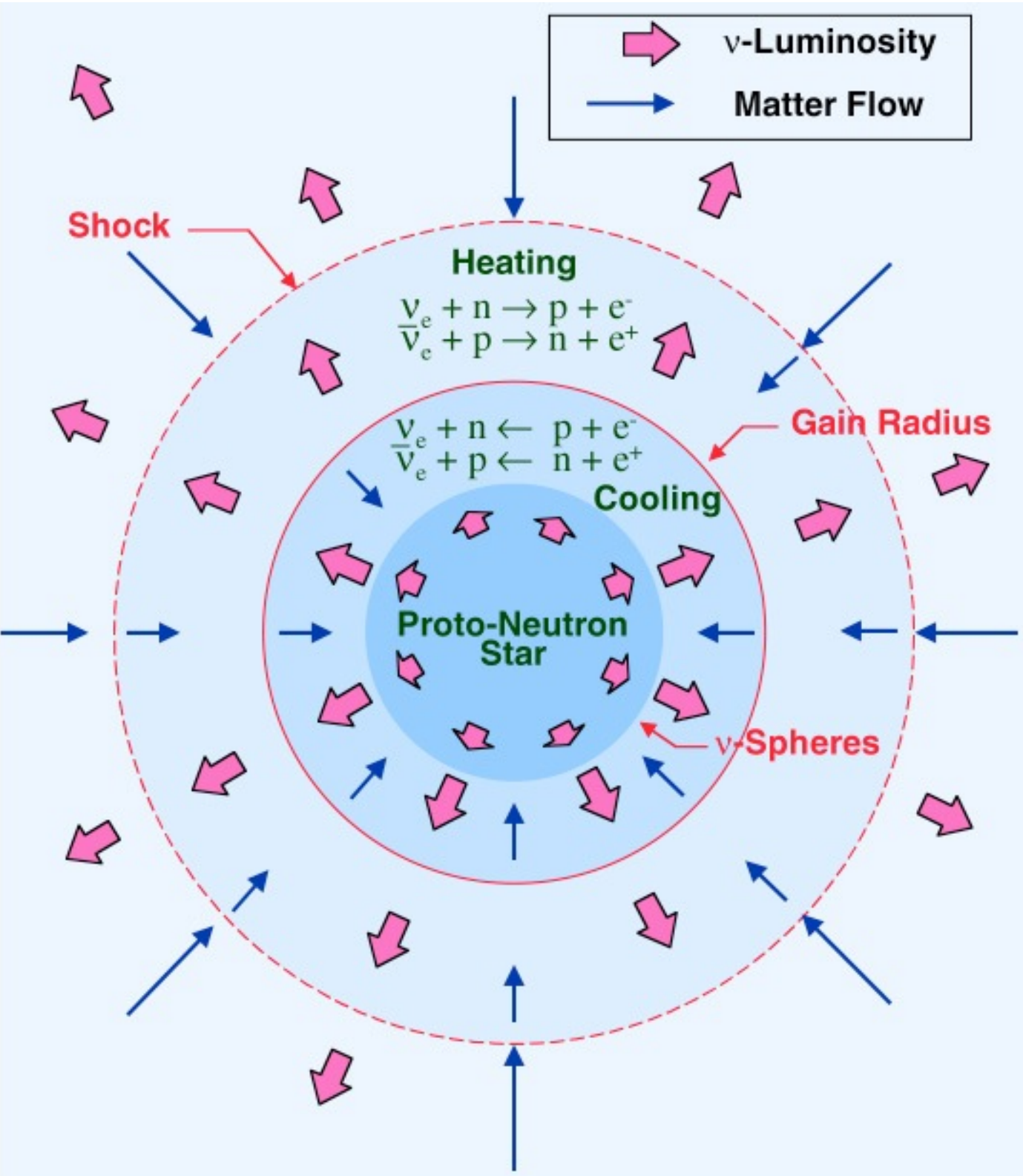

Iron-Helium-Photodissociation
Electron-Positron-
Pairs
Rapid
e-Capture
Relativistic Instability
O
Si
Ne
8M⊙≲M∗≲9M⊙
M∗≳100M⊙
9M⊙≲M∗≲100M⊙
He-Burning
C-Burning
7M⊙≲M∗≲8M⊙
0,08M⊙≲M∗≲0,5M⊙
0,5M⊙≲M∗≲7M⊙
H-Burning
M∗≲0,08M⊙
Janka 2012
log Tc [K]
log ρc [g/cm³]
10
9
8
7
6
2
4
6
8
10

"Onion-Skin" Structure of Pre-SN Stars









$$\dot{q}_{\nu N} \propto \frac{L_\nu}{\langle E_\nu \rangle} \frac{\langle E_\nu \sigma_{\nu N} \rangle}{r^2}$$

$$\dot{q}_{eN} \propto n_e \langle E_e \sigma_{eN} \rangle$$

$$\propto T^6$$

gain radius r_g

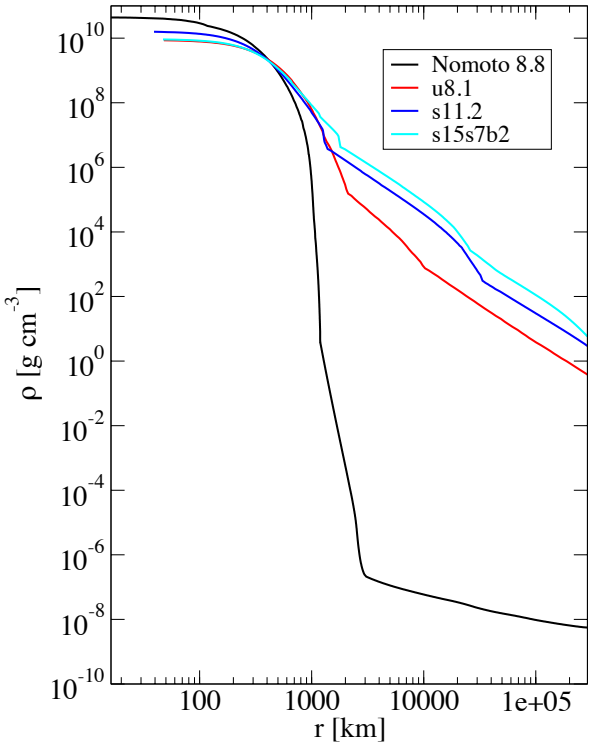
$$\dot{q}_{\nu N}(r_g) = \dot{q}_{eN}(r_g)$$

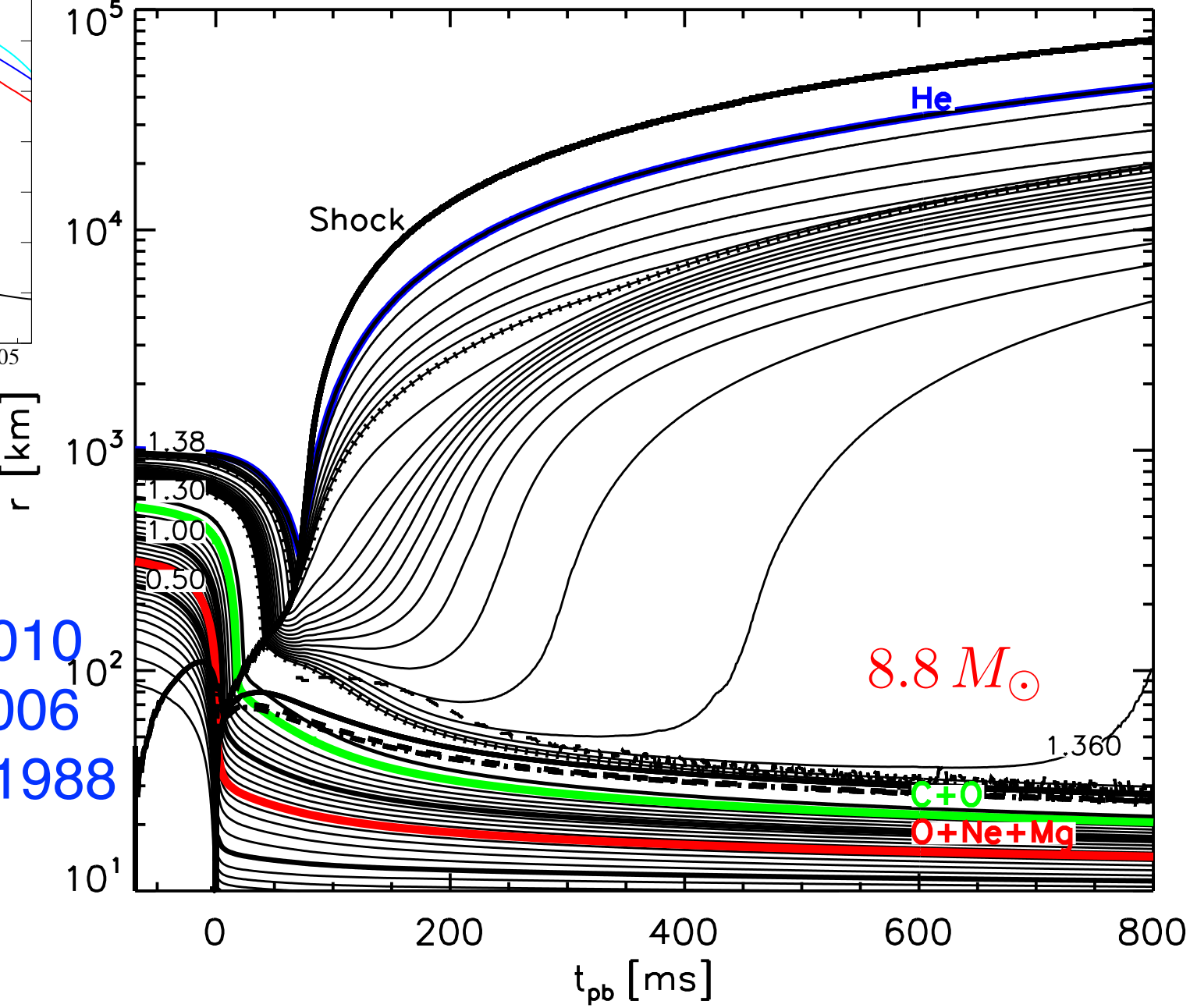
outside gain radius

$$\dot{q}_{\nu N}(r) > \dot{q}_{eN}(r)$$

Bethe & Wilson 1985

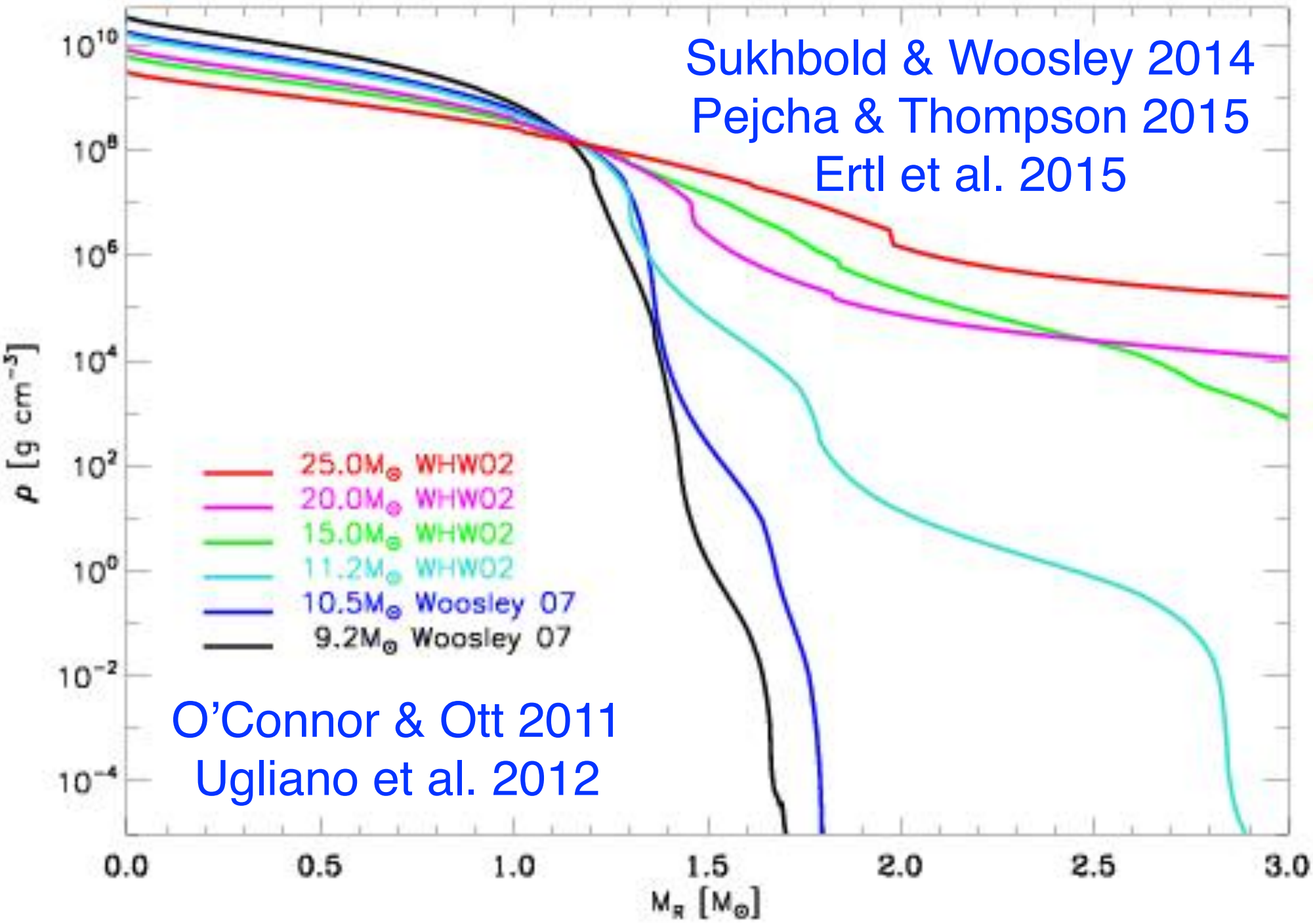
Neutrino-Driven Explosion of a Low-Mass SN

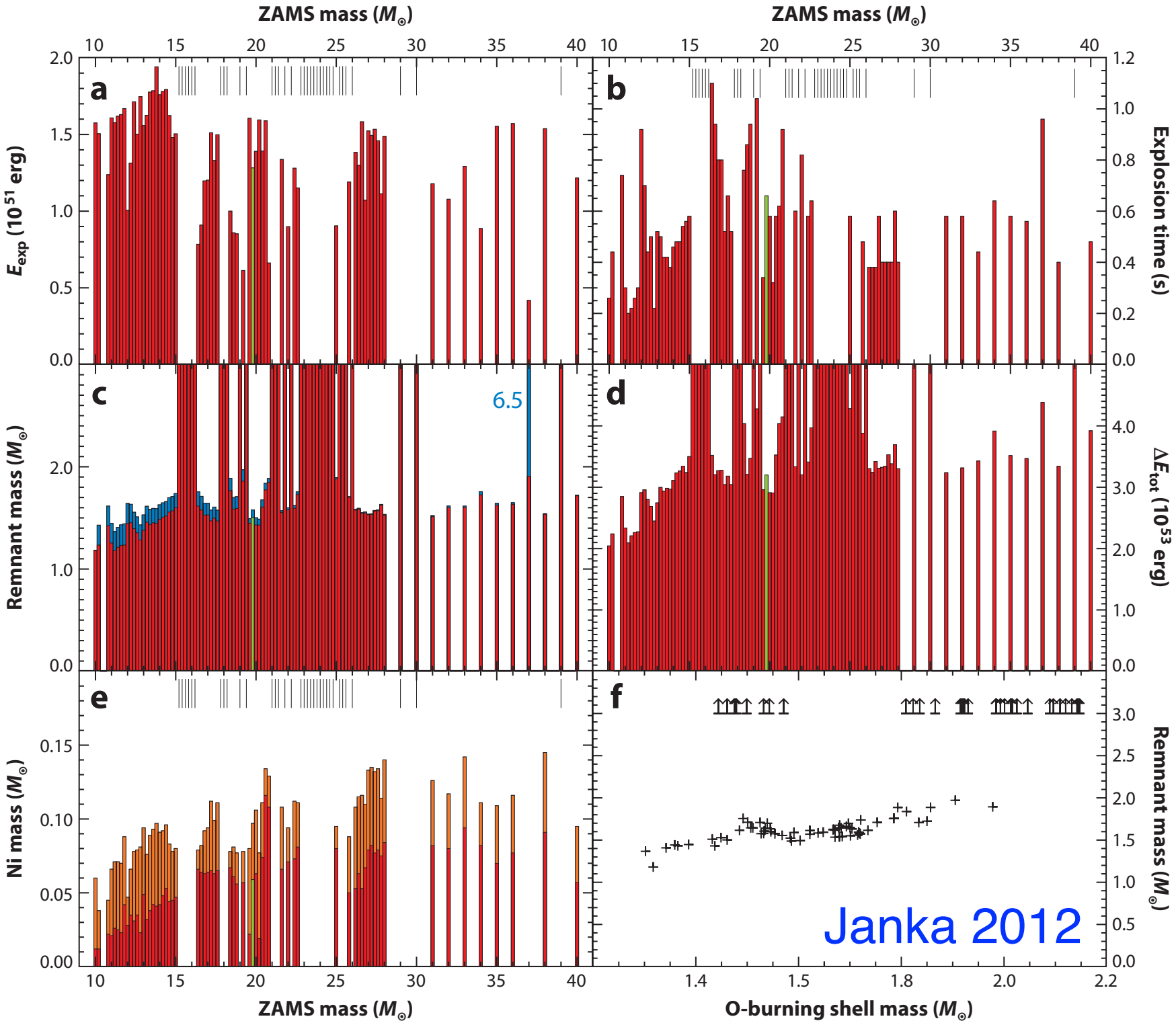




Janka 2012
Fischer et al. 2010
Kitaura et al. 2006
Mayle & Wilson 1988

Compactness & Explodability




ZAMS mass ($M_\odot$)
ZAMS mass ($M_\odot$)
a
b
c
d
e
f
6.5
E_{exp} (10^{51} erg)
Explosion time (s)
Remnant mass ($M_\odot$)
ΔE_{tot} (10^{53} erg)
Ni mass ($M_\odot$)
Remnant mass ($M_\odot$)
ZAMS mass ($M_\odot$)
O-burning shell mass ($M_\odot$)
Janka 2012

Light Curve of SN 1987a

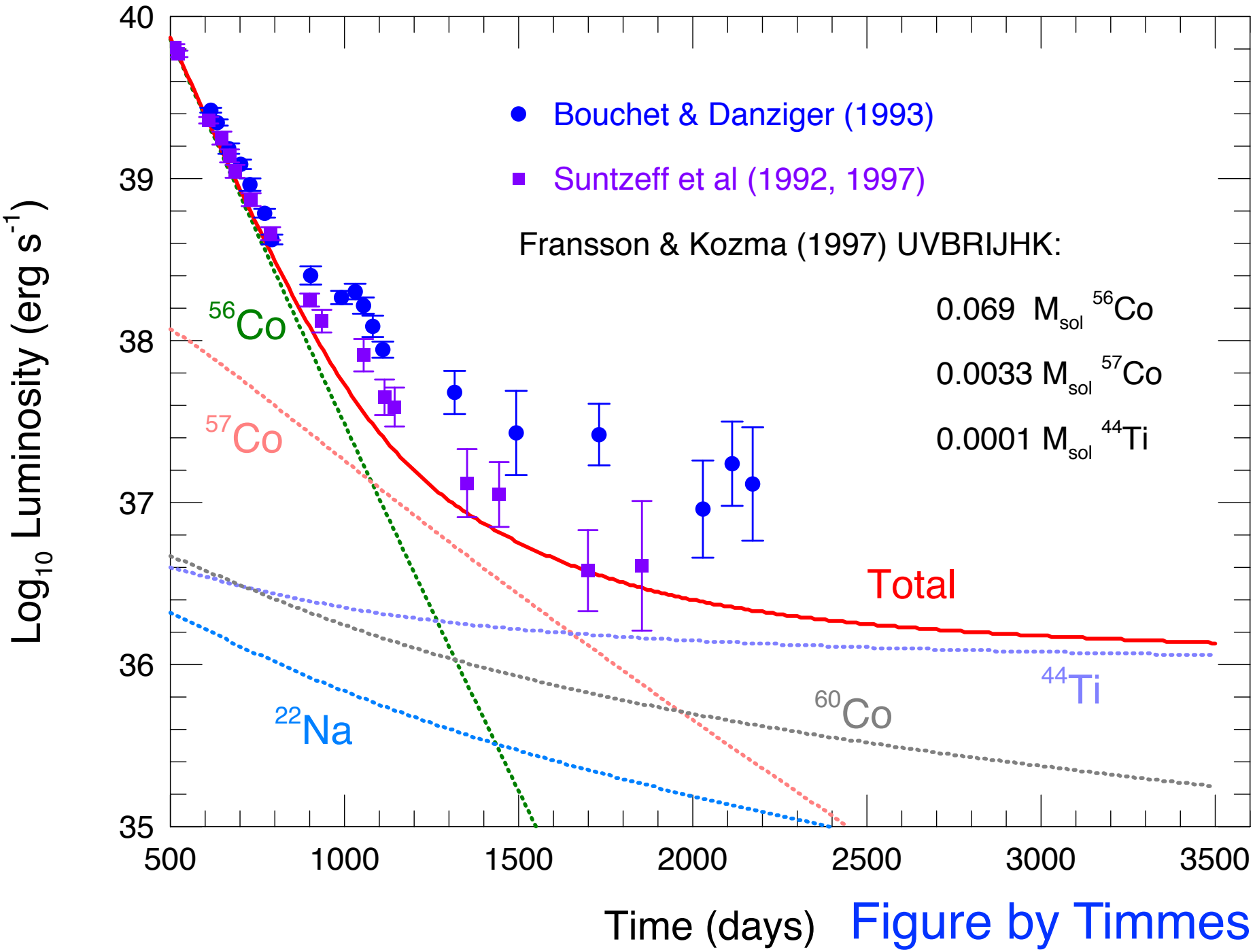
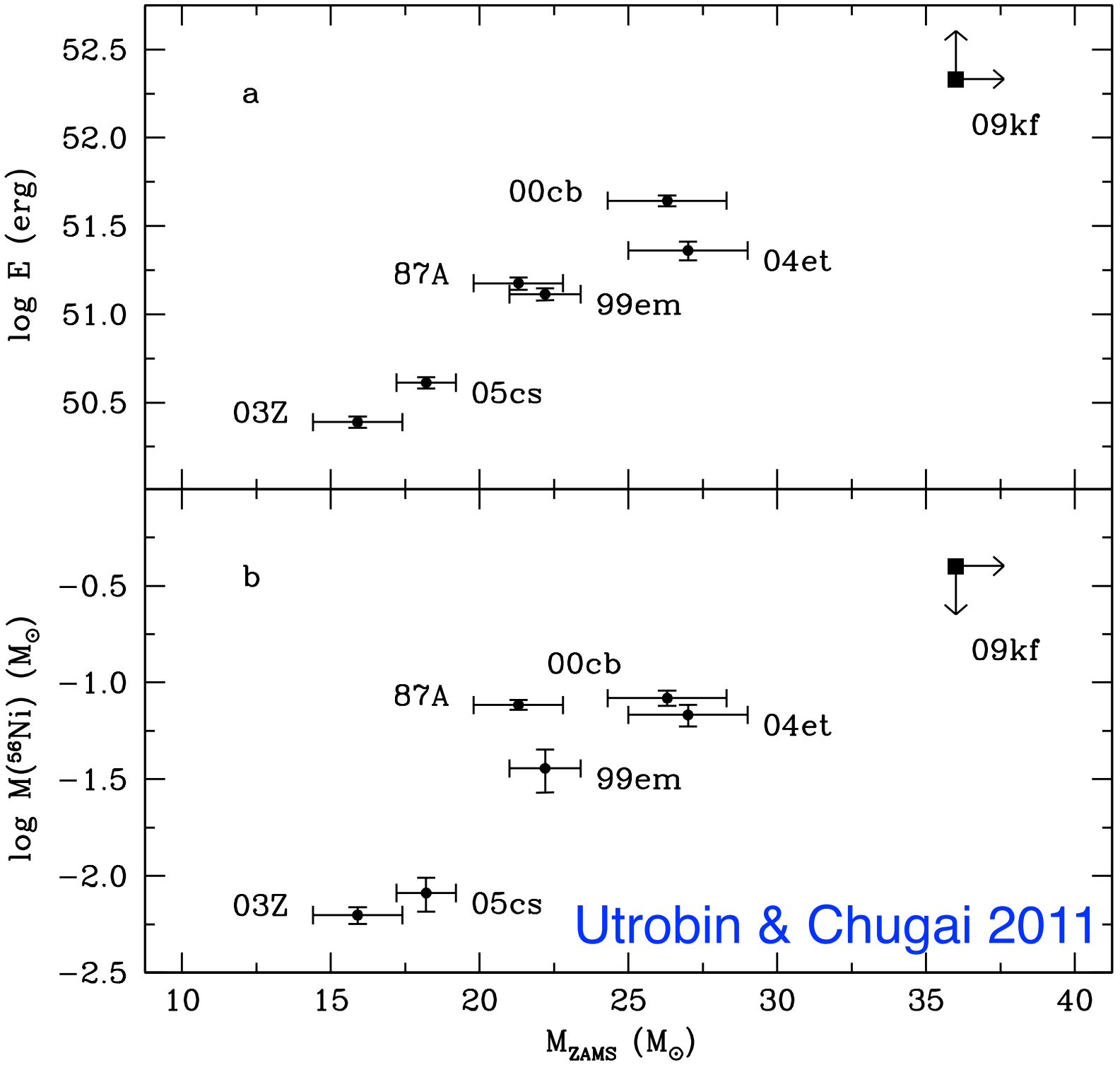
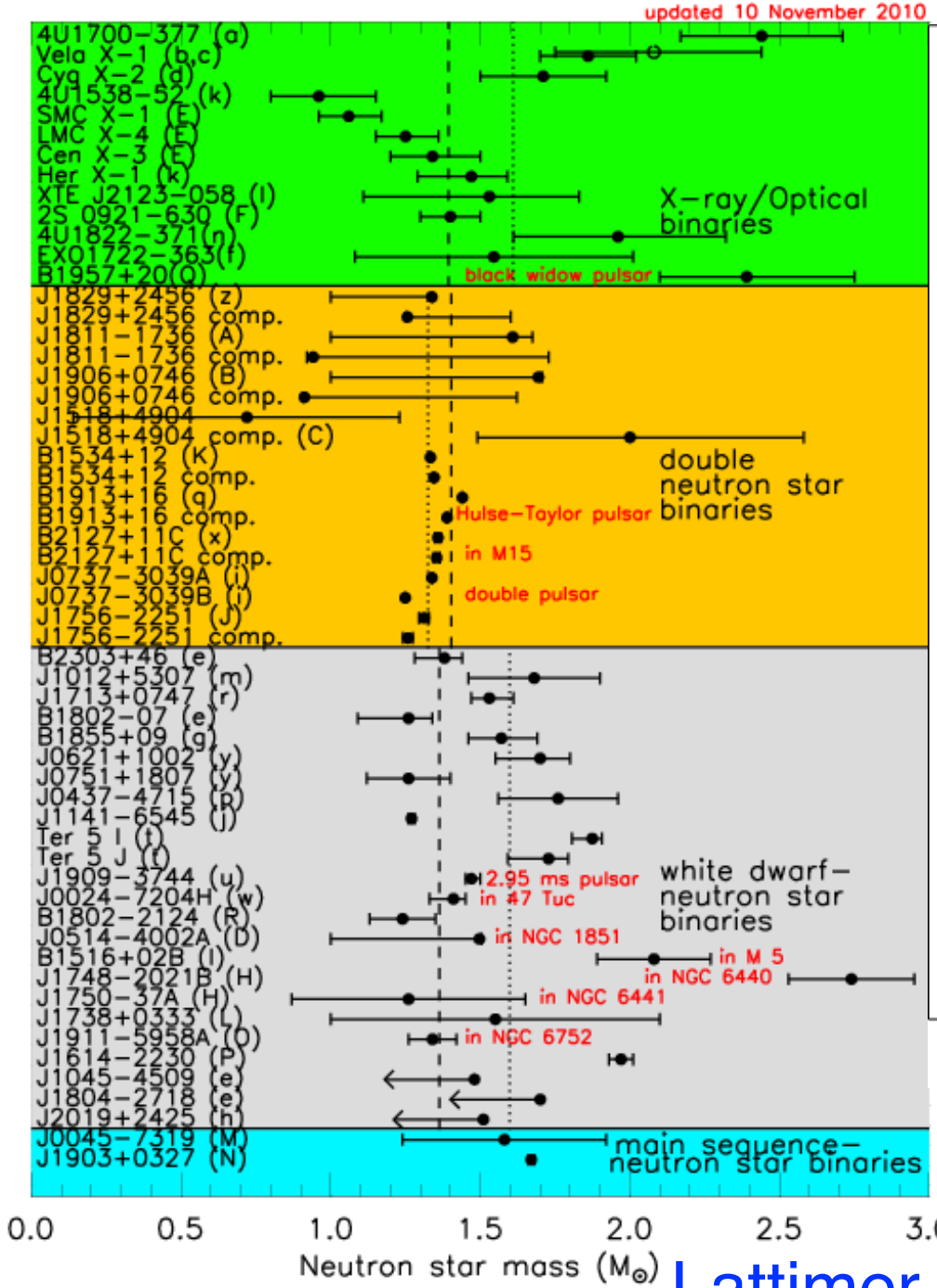


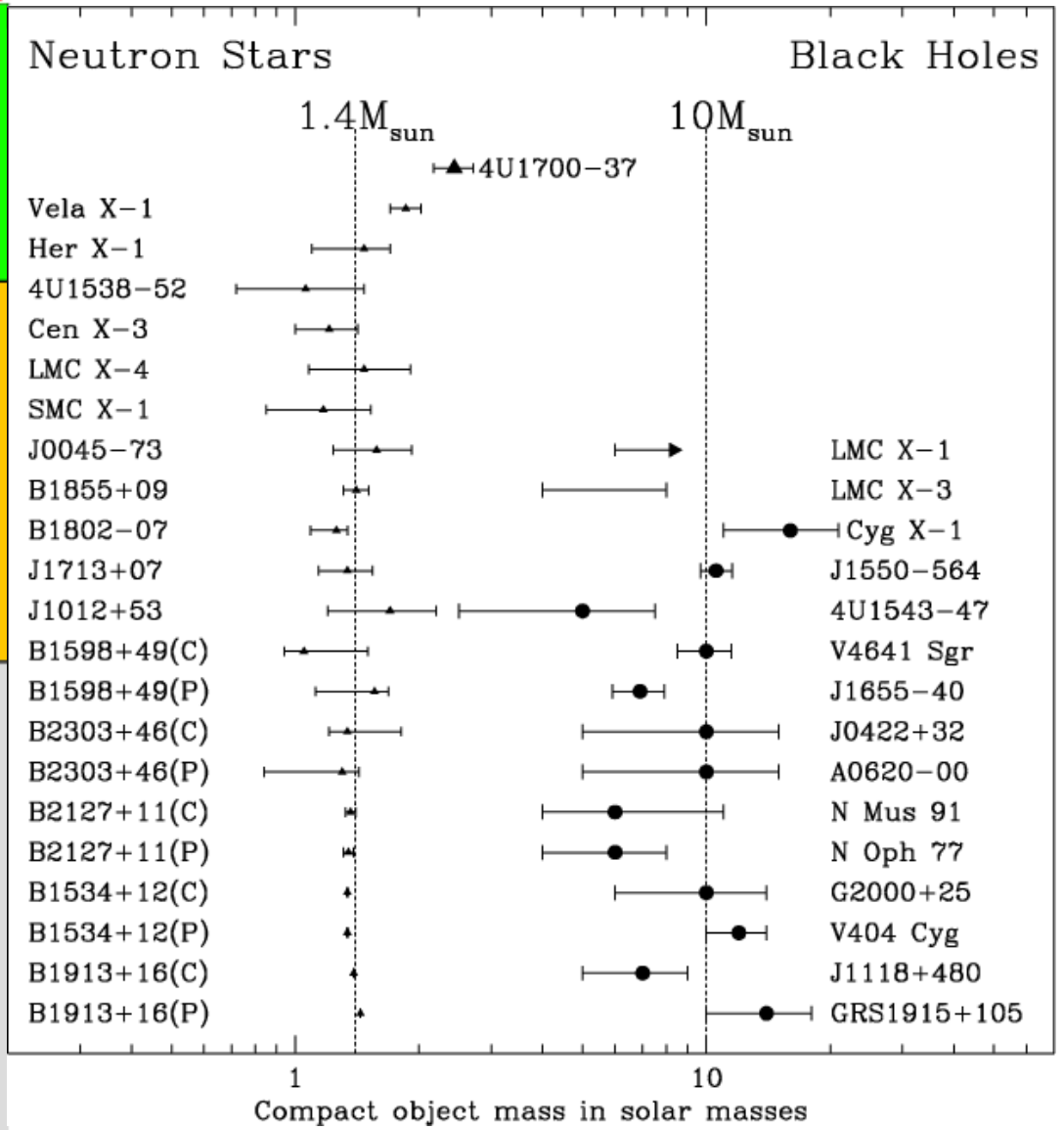
Figure by Timmes


a
b
log E (erg)
log M(56Ni) (M⊙)
M_ZAMS (M⊙)
52.5
52.0
51.5
51.0
50.5
−0.5
−1.0
−1.5
−2.0
−2.5
10
15
20
25
30
35
40
09kf
00cb
04et
87A
99em
05cs
03Z
Utrobin & Chugai 2011

Neutron Star & Black Hole Masses

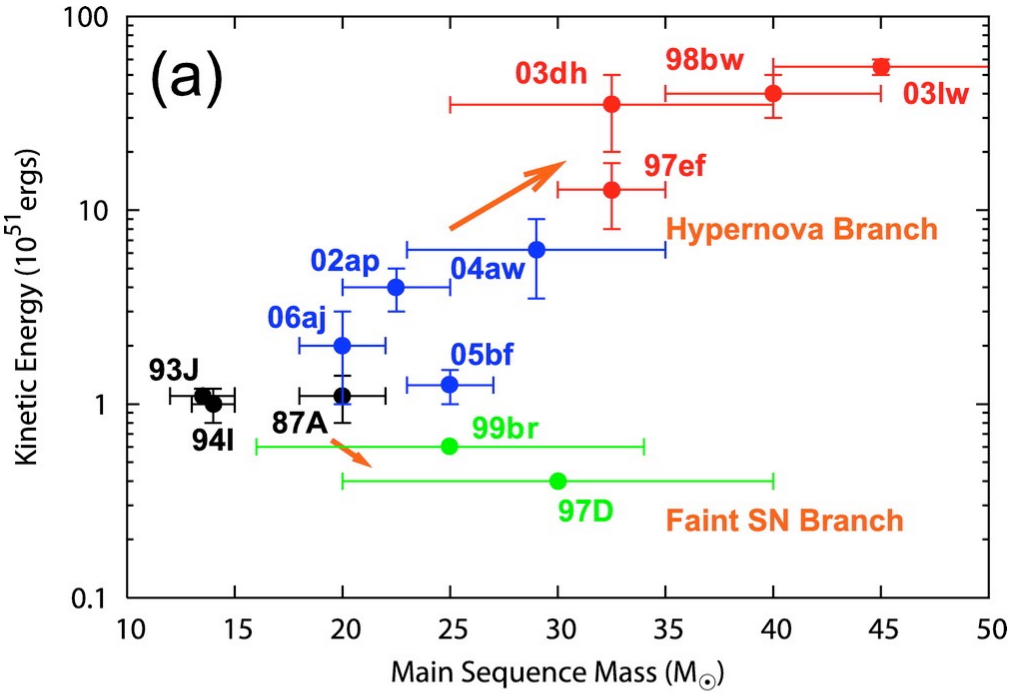


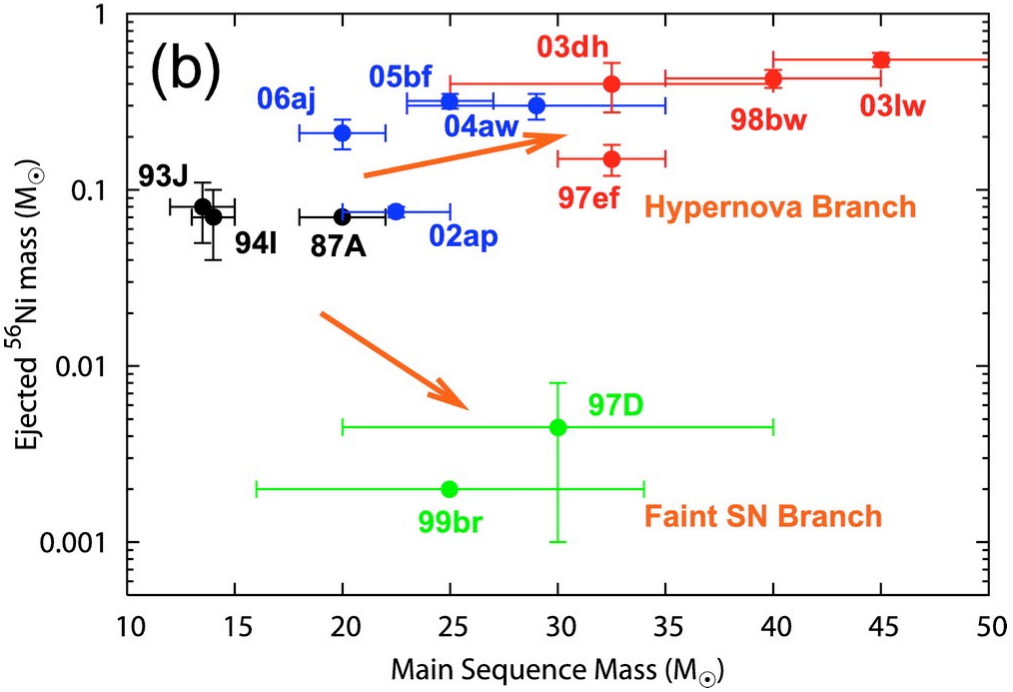
Lattimer 2010

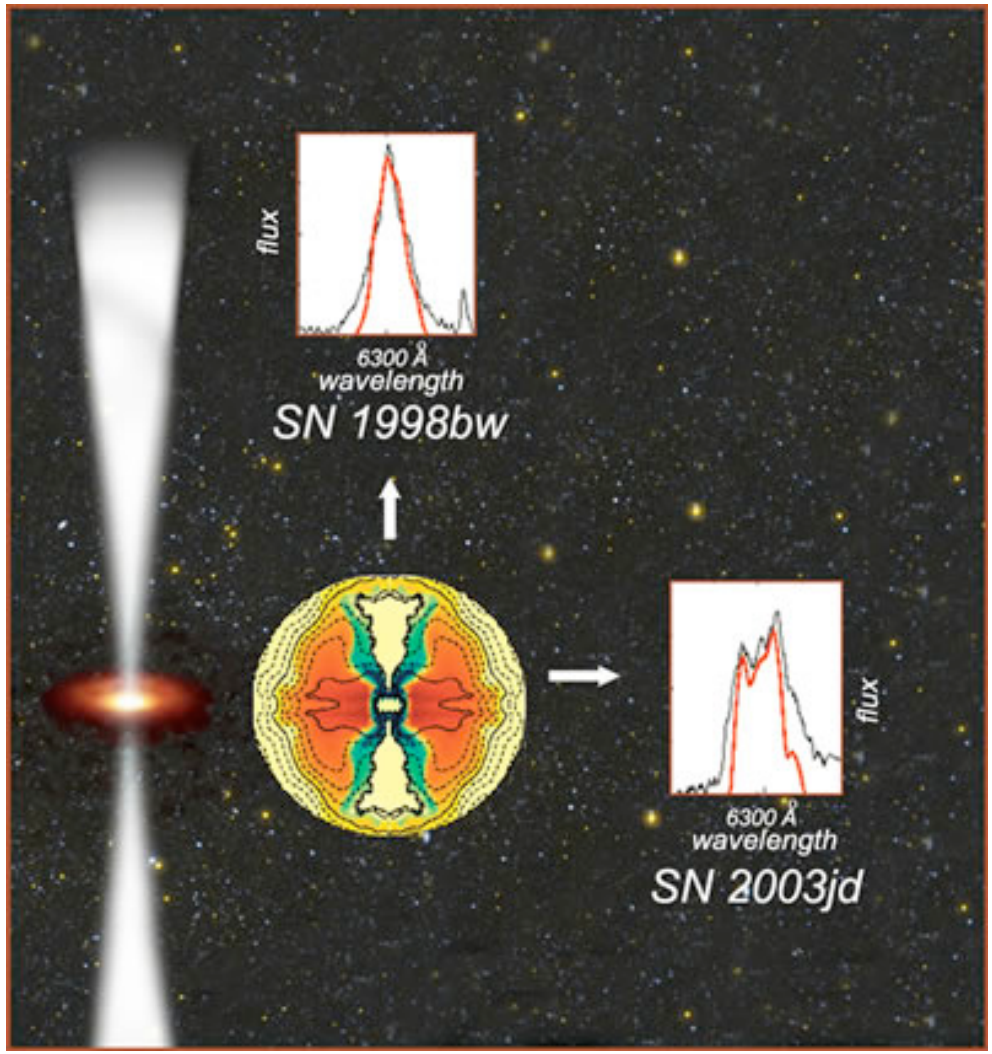


Clark et al. 2002

black hole formation & hypernovae

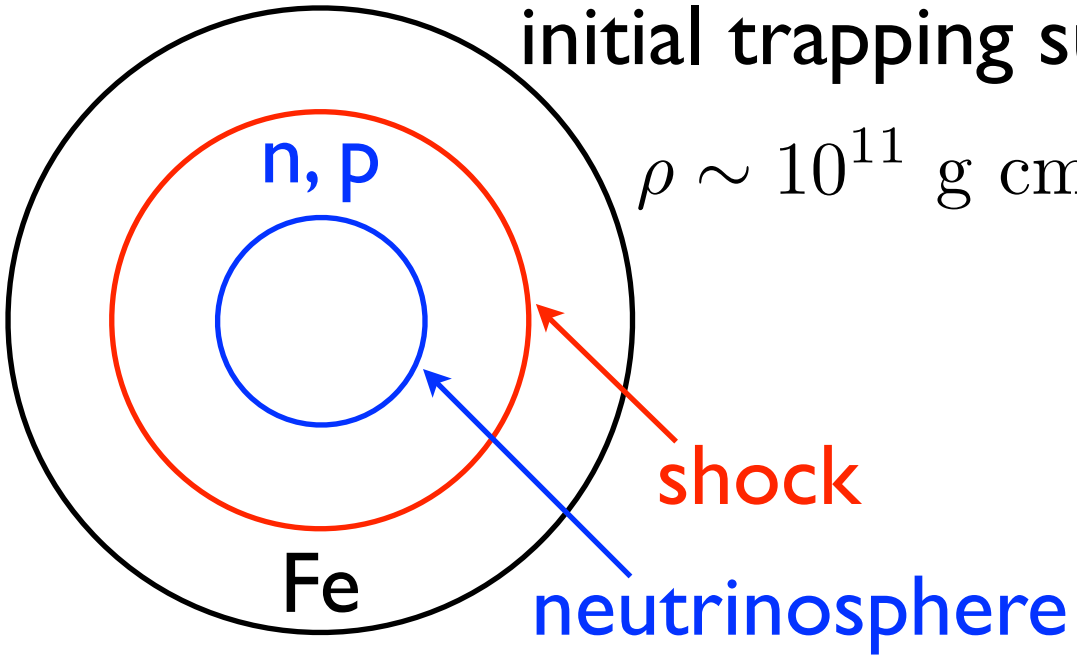




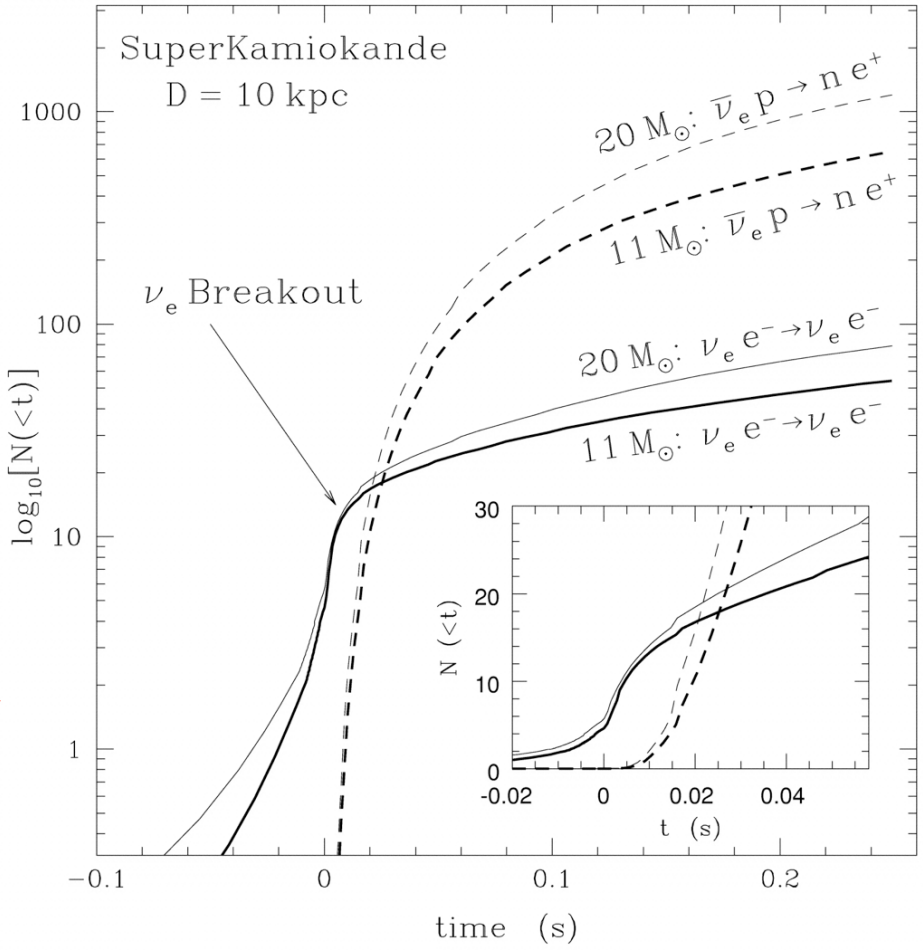


"neutronization" pulse at shock breakout

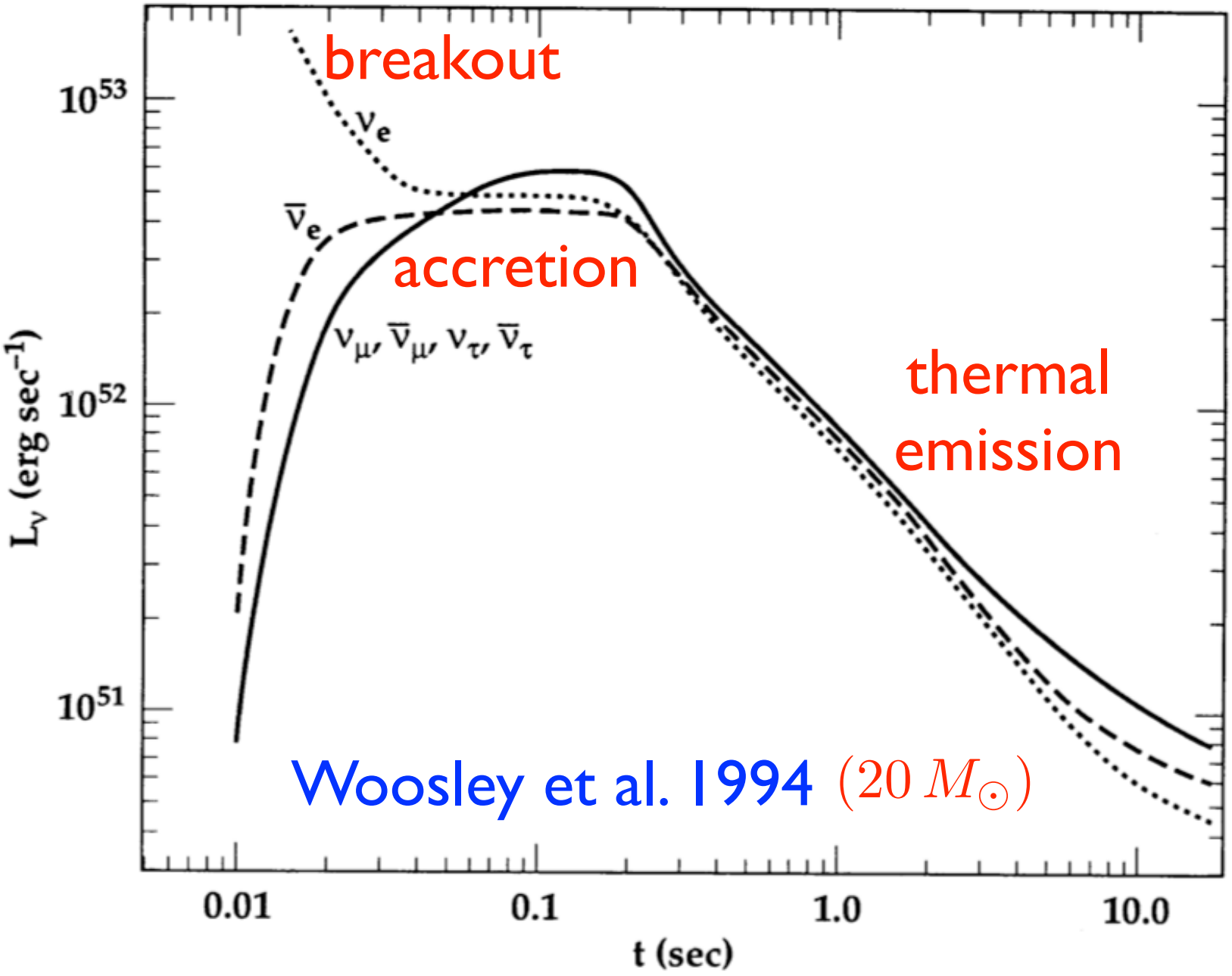
$$e^- + p \rightarrow n + \nu_e \Rightarrow \text{predominantly } \nu_e$$



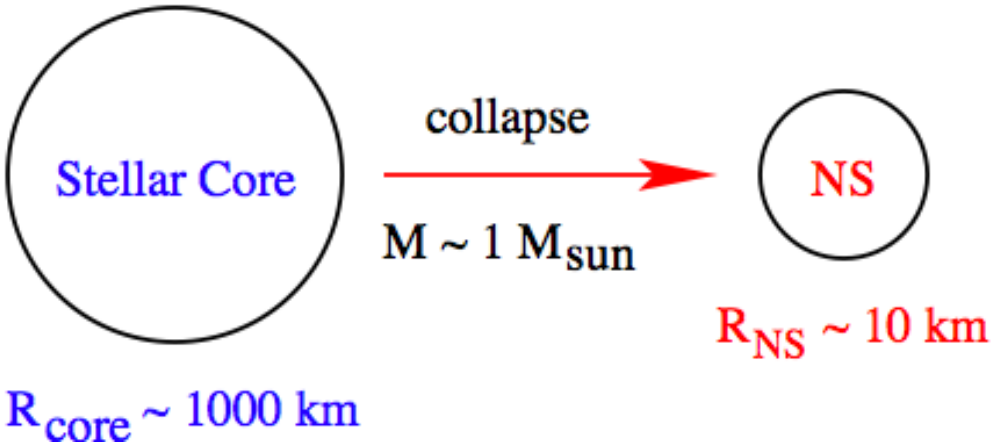
without oscillations



(Thompson et al. 2003)


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 $(20\,M_\odot)$

Neutrino Emission from Proto-NS Cooling



$$e^+ + e^- \rightarrow \nu + \bar{\nu}$$

$$N + N \rightarrow N + N + \nu + \bar{\nu}$$

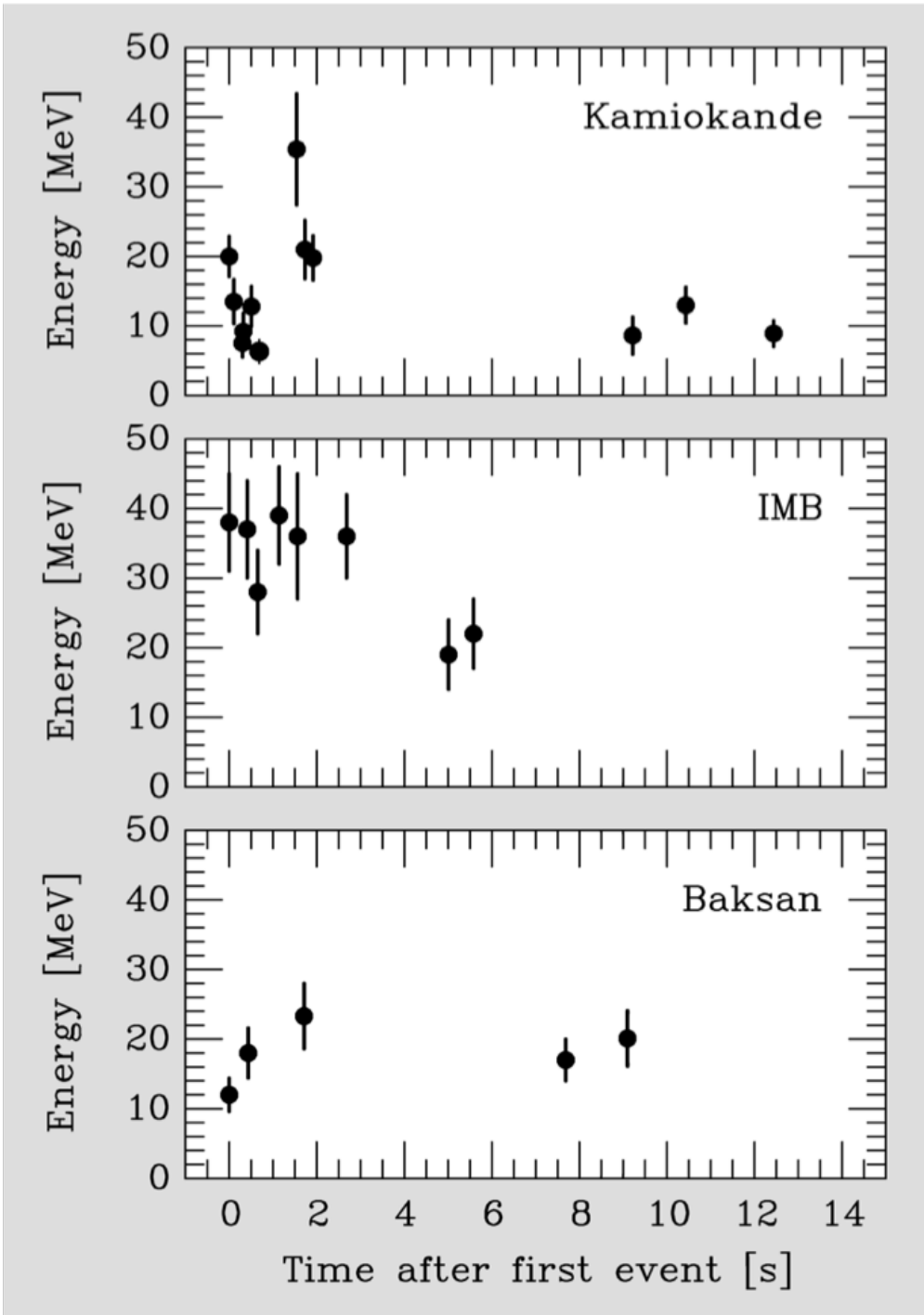
$$\frac{GM^2}{R_{\rm NS}} \sim 3 \times 10^{53}\ {\rm erg}$$

$$\Rightarrow \nu_e,\ \bar{\nu}_e,\ \nu_\mu,\ \bar{\nu}_\mu,\ \nu_\tau,\ \bar{\nu}_\tau$$

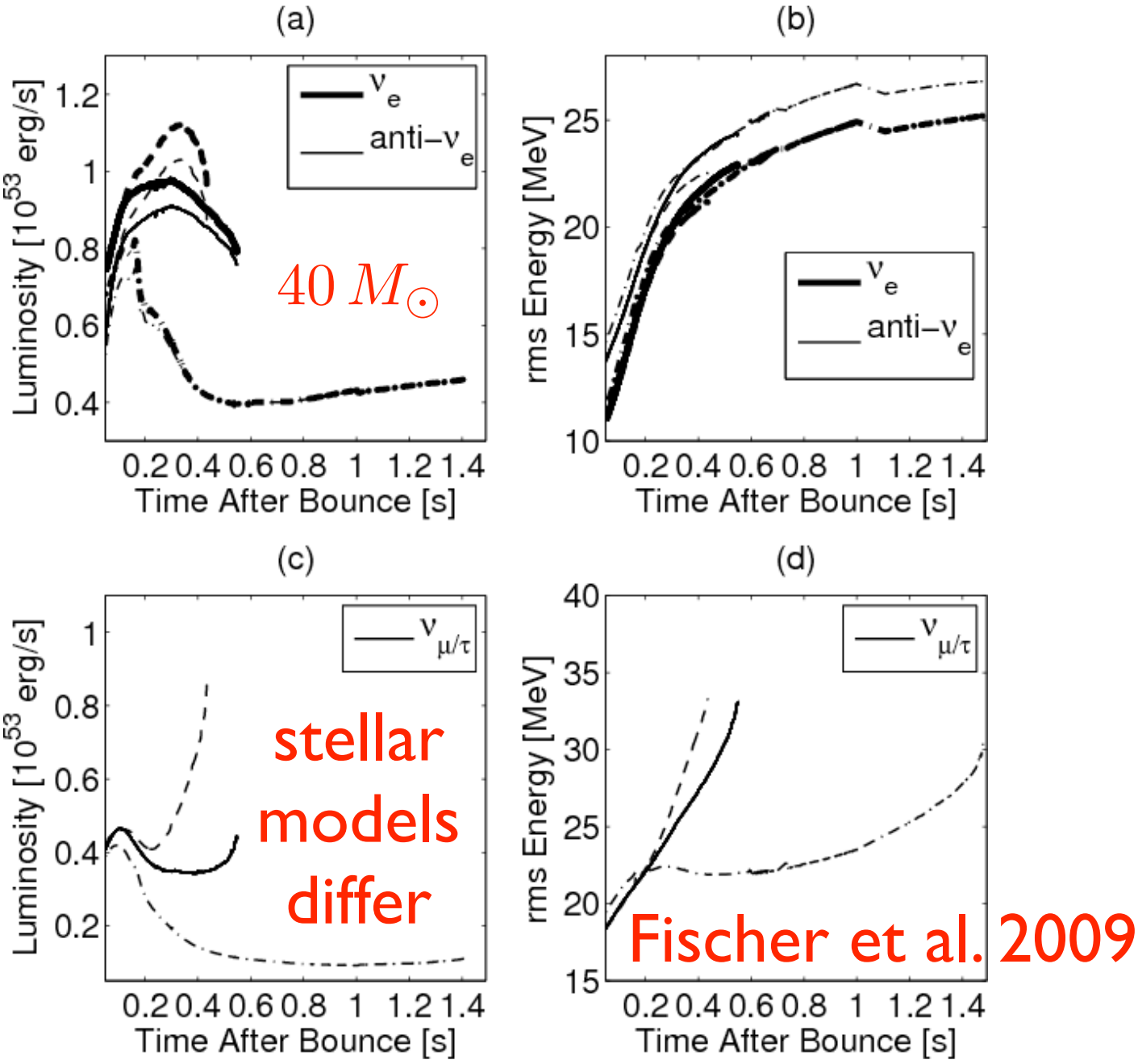
for a Galactic SN at ~10 kpc

~10^4 events in SK due to

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



signature of BH formation: interruption of ν signals



followed by neutrino emission from accretion disk around BH?

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

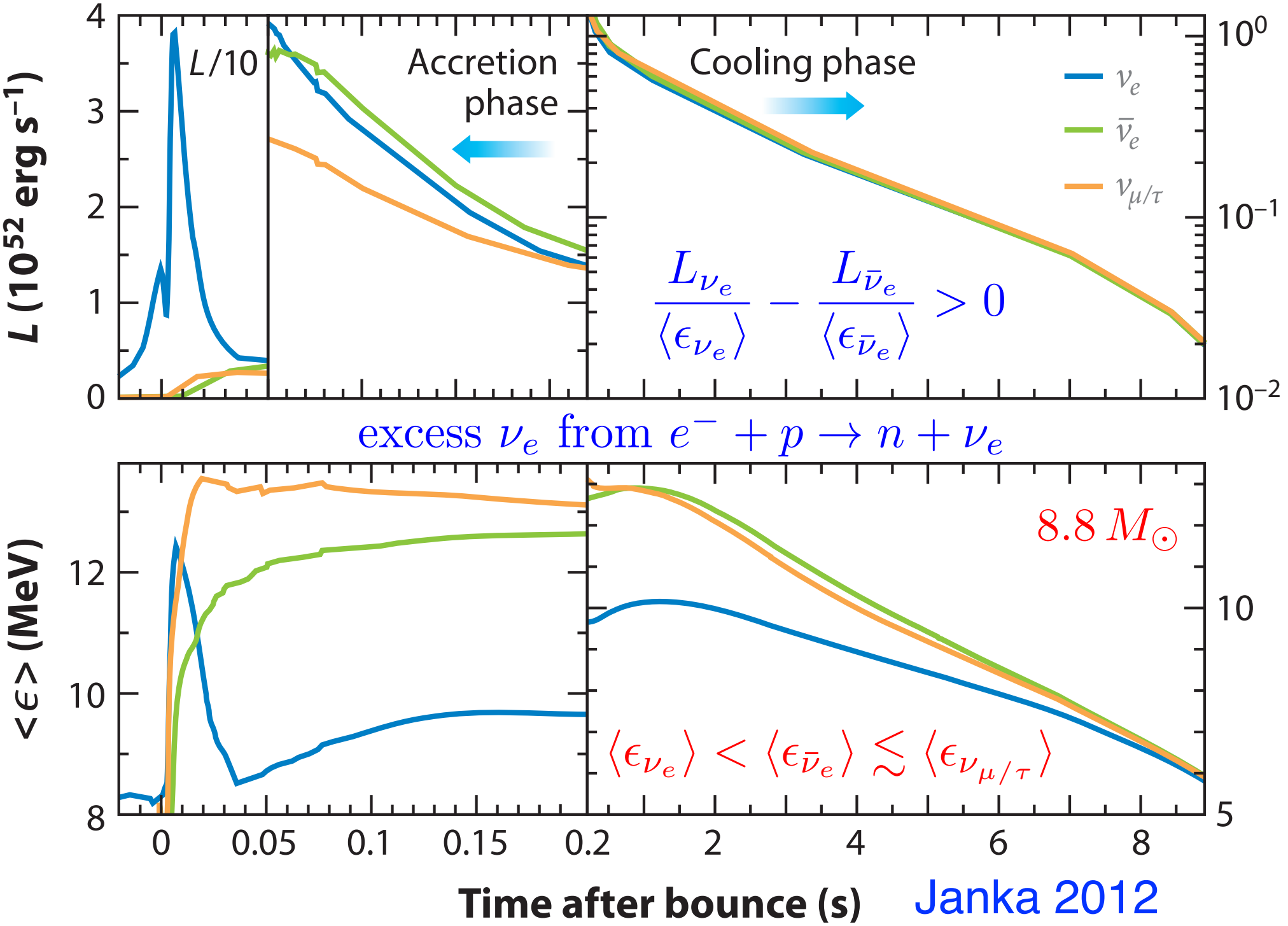
- termination of thermal emission

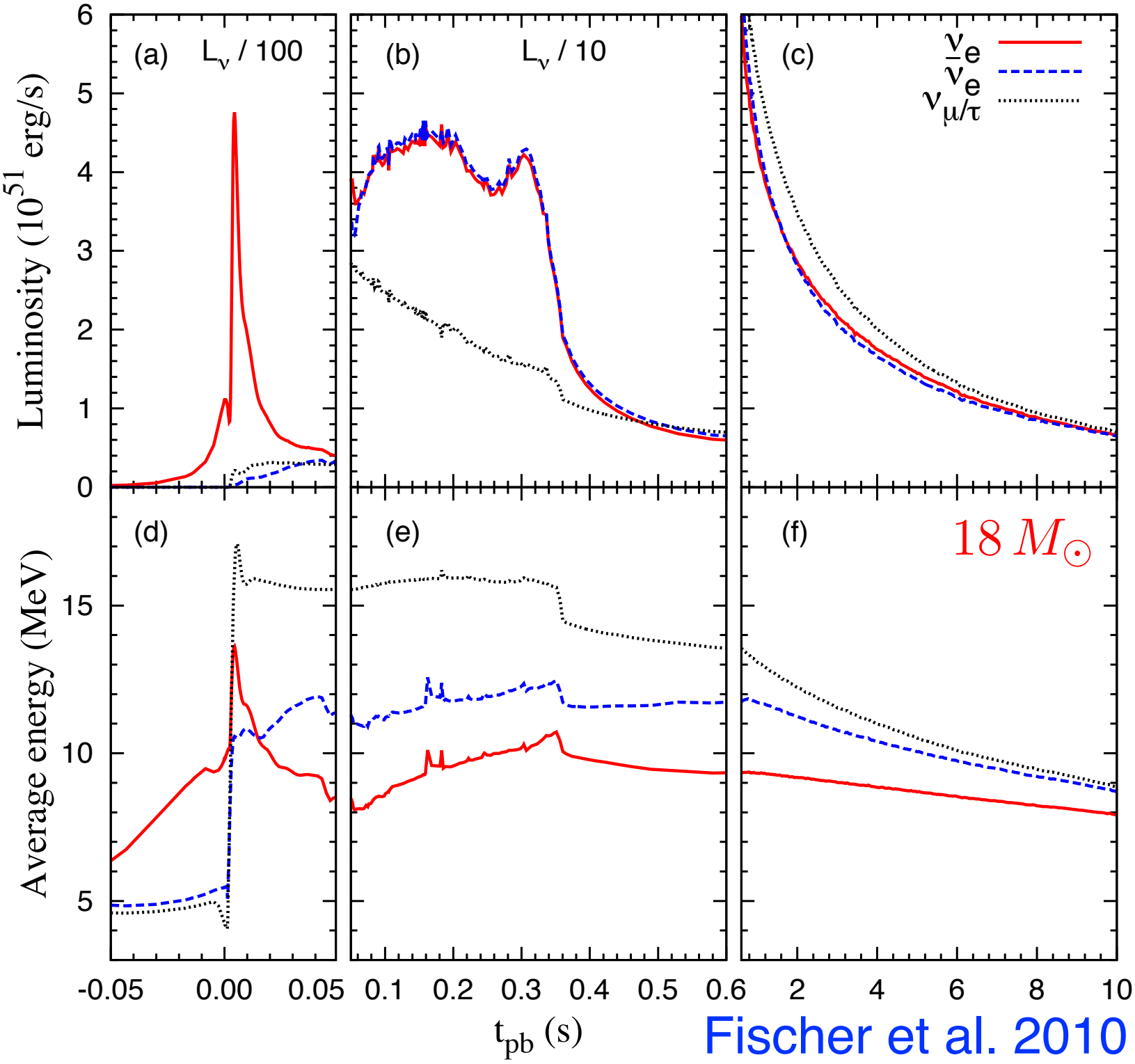
  → black hole formation

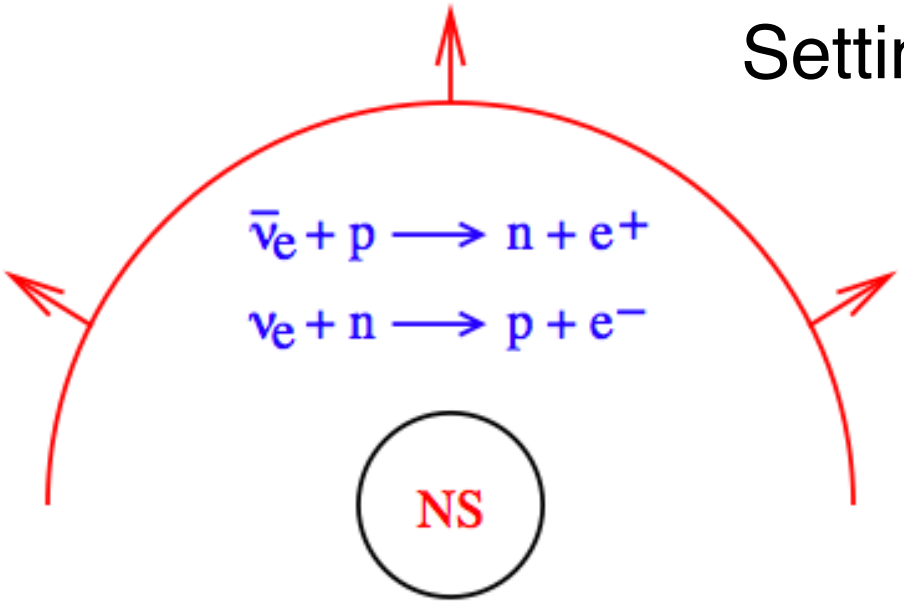
  progenitors

  nuclear equation of state

Neutrino Emission from a Low-Mass SN




(a) L_ν / 100
(b) L_ν / 10
(c)
ν_e
ν̄_e
ν_μ/τ
(d)
(e)
(f)
18 M⊙
Luminosity (10^51 erg/s)
Average energy (MeV)
t_pb (s)
Fischer et al. 2010



Setting n/p in the Neutrino-Driven Wind

$$n/p > 1 \Rightarrow Y_e < 0.5$$

Qian et al. 1993
Qian & Woosley 1996
McLaughlin et al. 1996
Horowitz & Li 1999

$$\sigma_{\nu N} \propto (E_\nu \mp \Delta_{np})^2$$

$$\lambda_{\bar{\nu}_e p} = \frac{L_{\bar{\nu}_e}}{4\pi r^2} \frac{\langle \sigma_{\bar{\nu}_e p} \rangle}{\langle E_{\bar{\nu}_e} \rangle} \propto L_{\bar{\nu}_e} \left(\frac{\langle E^2_{\bar{\nu}_e} \rangle}{\langle E_{\bar{\nu}_e} \rangle} - 2\Delta_{np} \right)$$

$$\lambda_{\nu_e n} = \frac{L_{\nu_e}}{4\pi r^2} \frac{\langle \sigma_{\nu_e n} \rangle}{\langle E_{\nu_e} \rangle} \propto L_{\nu_e} \left(\frac{\langle E^2_{\nu_e} \rangle}{\langle E_{\nu_e} \rangle} + 2\Delta_{np} \right)$$

$$\frac{\langle E^2_{\bar{\nu}_e} \rangle}{\langle E_{\bar{\nu}_e} \rangle} - \frac{\langle E^2_{\nu_e} \rangle}{\langle E_{\nu_e} \rangle} > 4\Delta_{np} \approx 5.2 \text{ MeV} \Rightarrow \frac{n}{p} > 1$$

Neutrino Opacities!

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

progenitor dependences of neutrino flavor evolution

density profile 

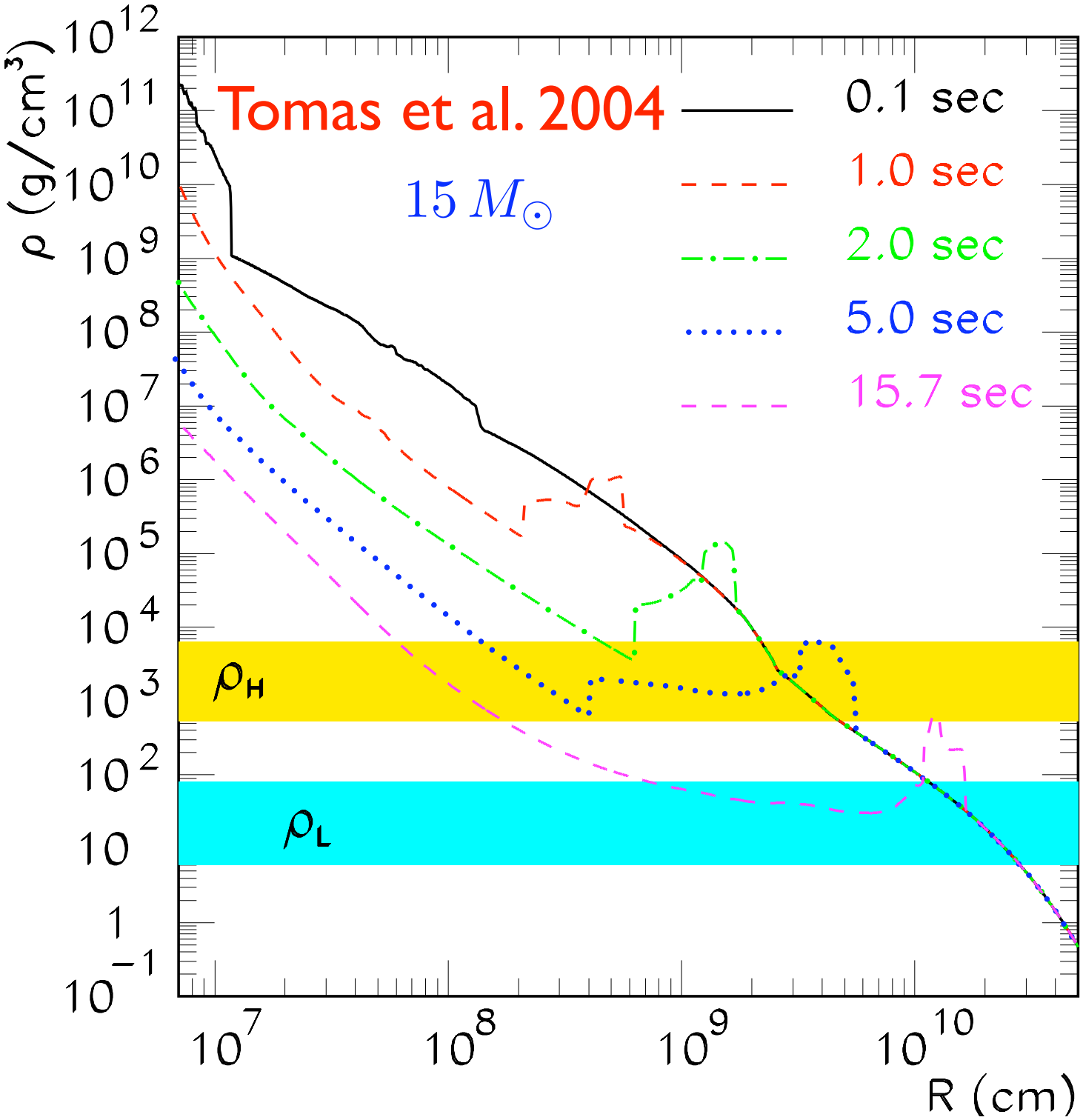
positions and adiabaticity of MSW resonances

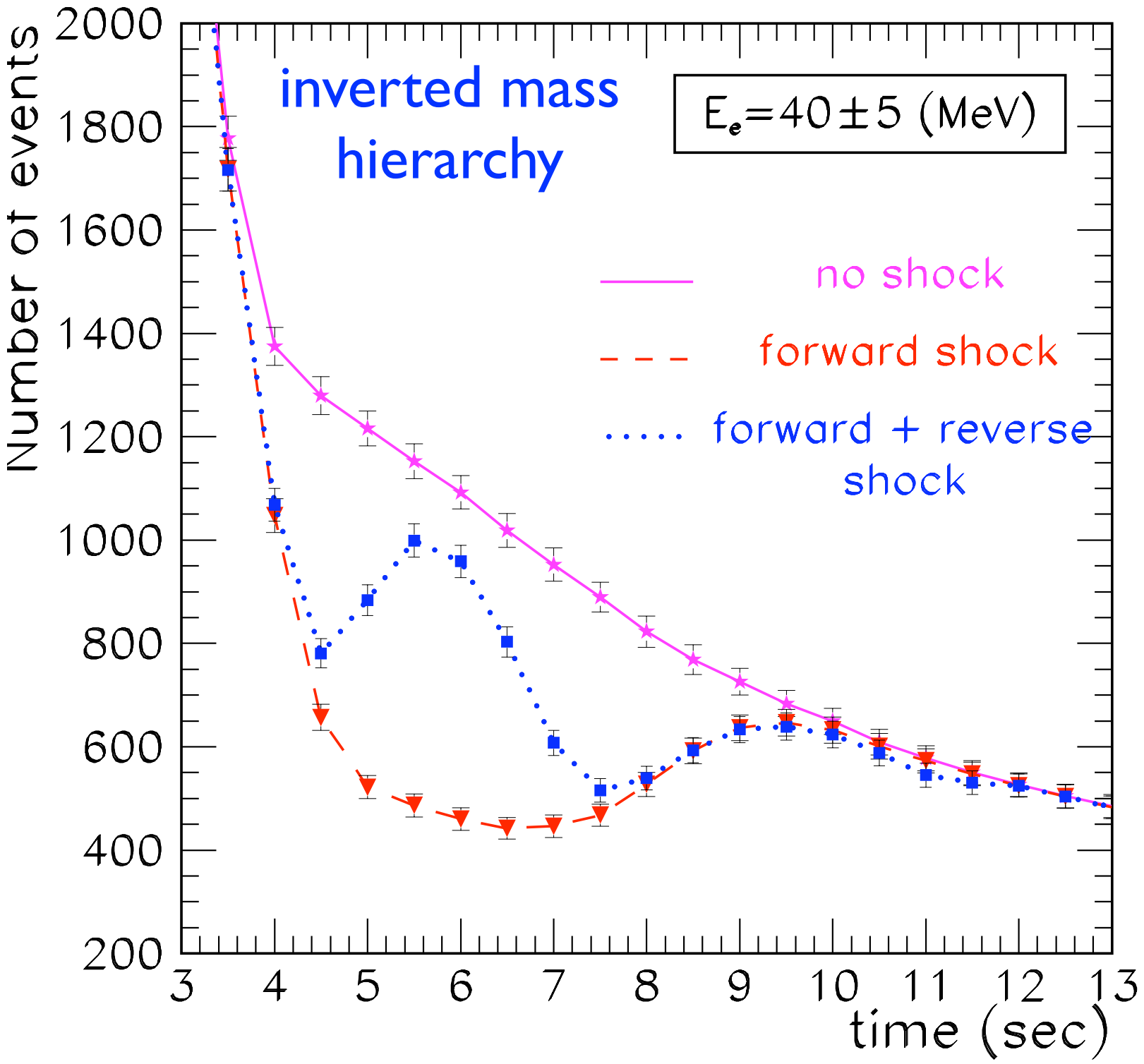
modulation by shock propagation

(Schirato & Fuller 2002)

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

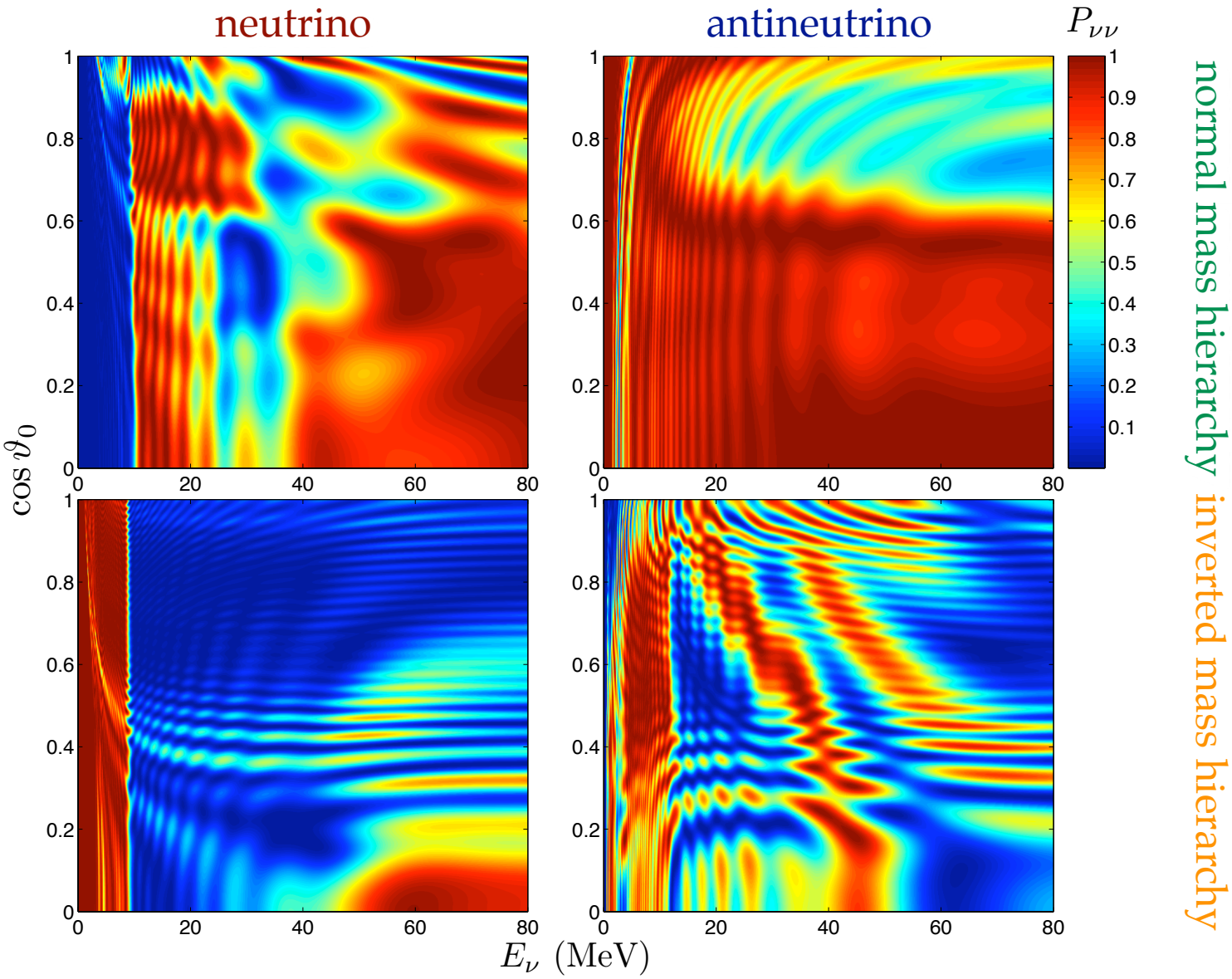
(Pantaleone 1992; Kostelecky & Samuel 1993;
Duan et al. 2006 & subsequent works;
Raffelt & collaborators; Mirizzi & collaborators)


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}

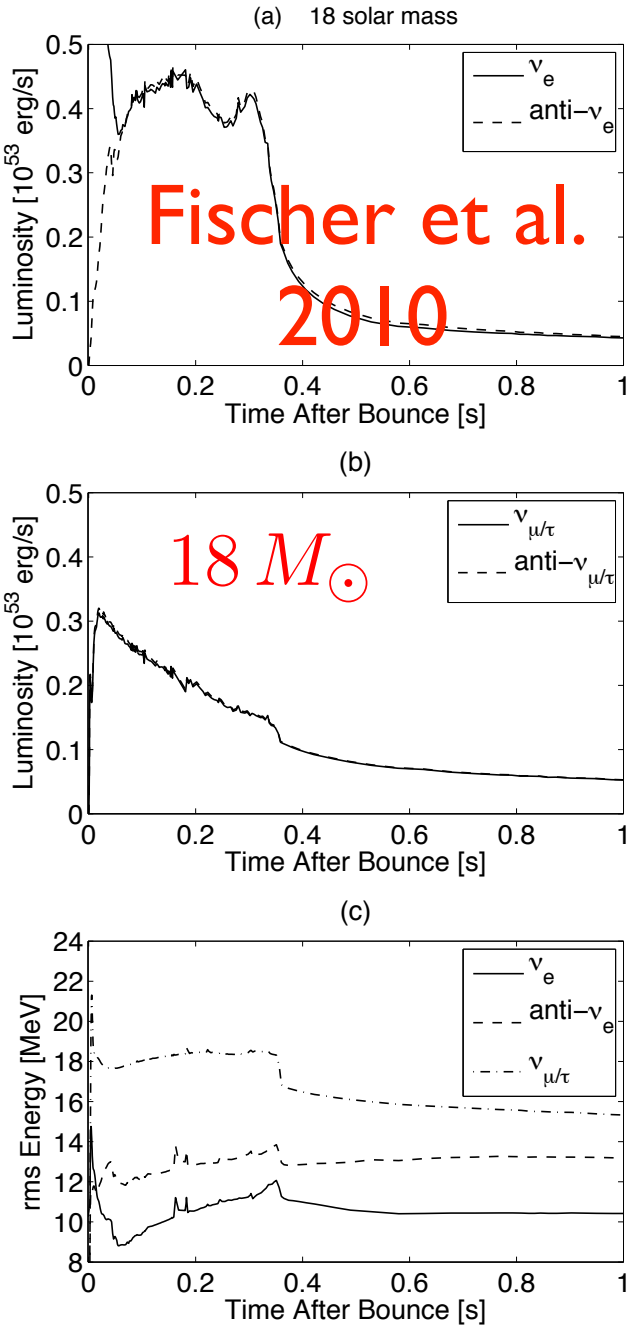

inverted mass hierarchy
E_e=40±5 (MeV)
no shock
forward shock
forward + reverse shock
Number of events
time (sec)
2000
1800
1600
1400
1200
1000
800
600
400
200
3
4
5
6
7
8
9
10
11
12
13

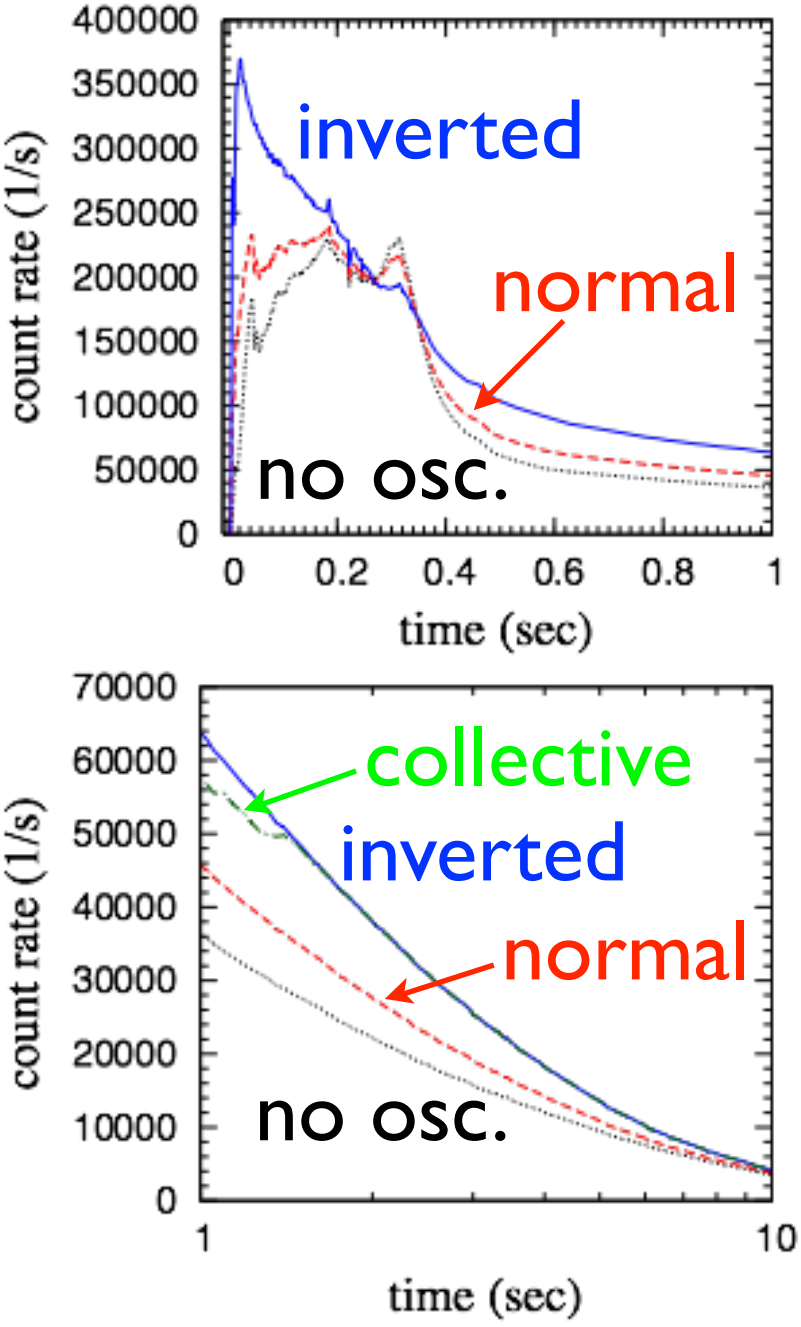
Survival Probability at $r = 225$ km

(Duan et al. 2006)

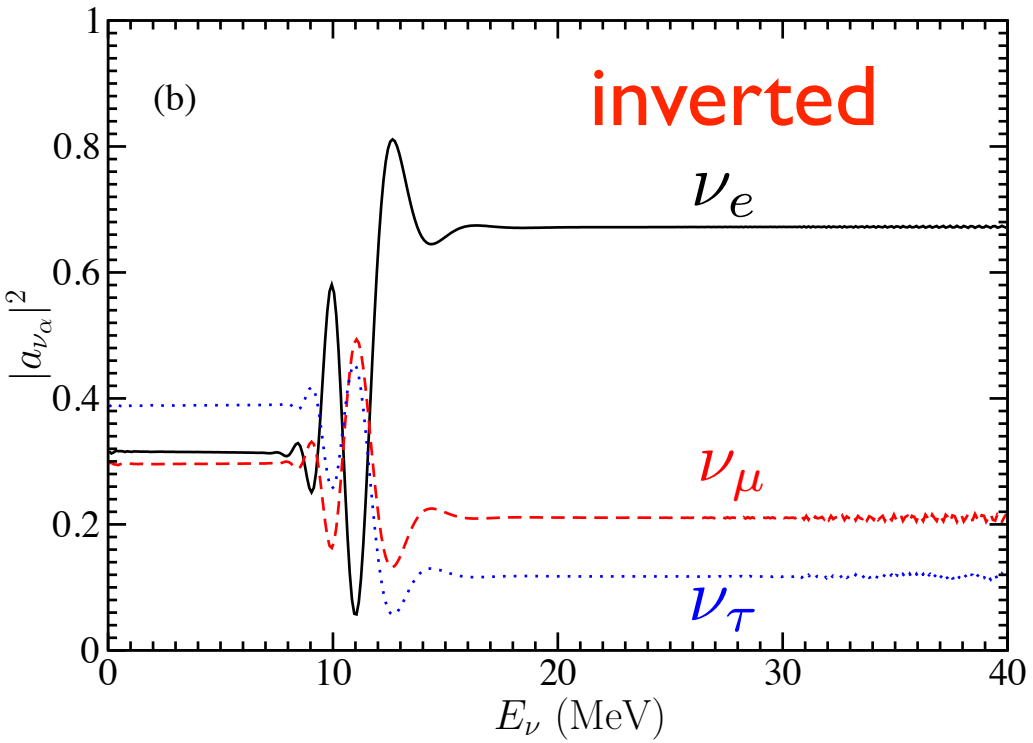


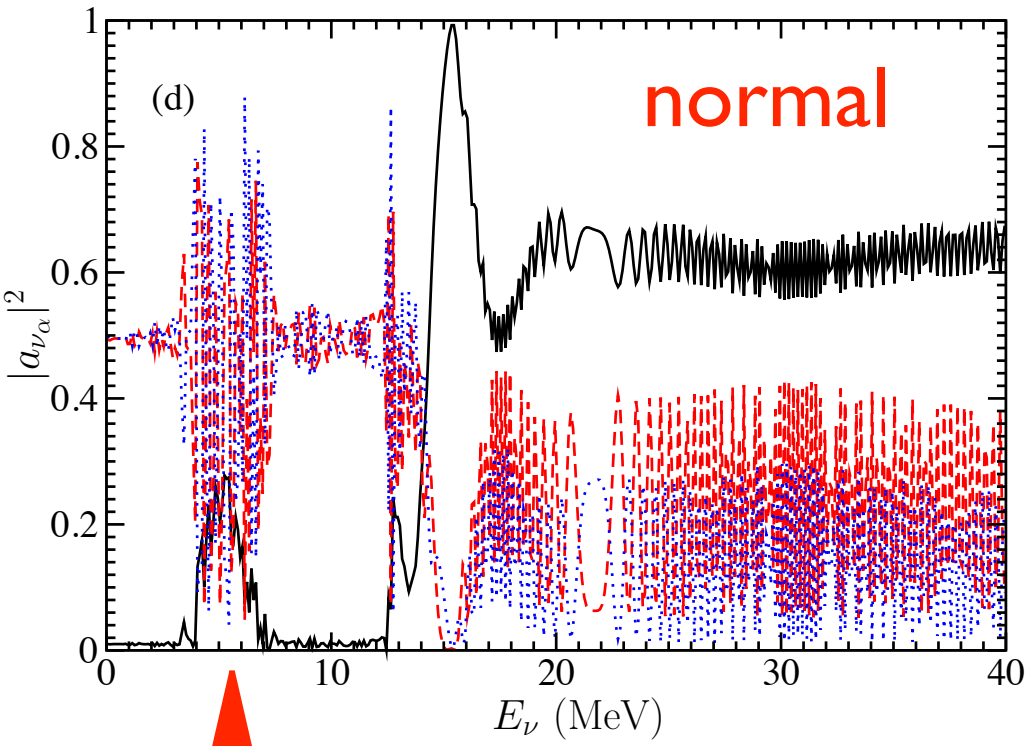
$\bar{\nu}_e + p \rightarrow n + e^+$ in IceCube (Wu et al. 2015)





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

Summary: supernovae and their neutrino signals

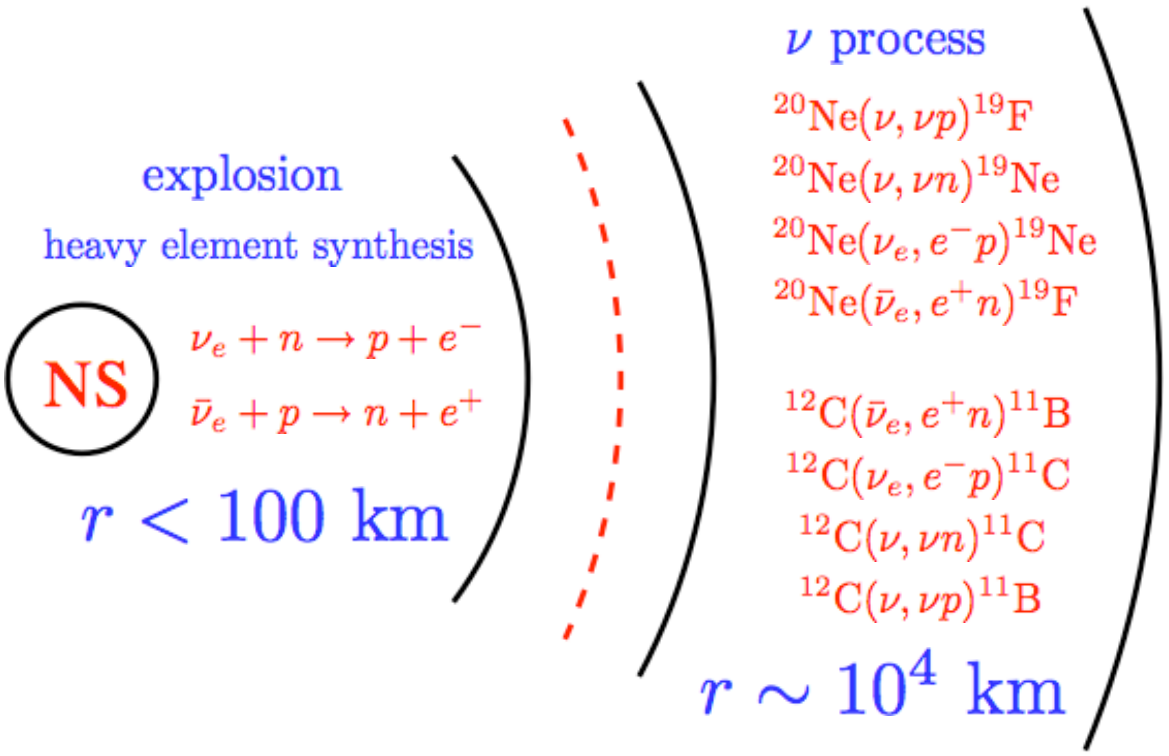
- interruption of neutrino signals reveals BH formation
  → progenitor density structure (accretion rate)
  nuclear equation of state (phase transition)
- rich interplay among progenitor structure, shock propagation, neutrino emission & flavor evolution

"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

Interplay between Supernova and Neutrino Physics



ν-induced
r-process

$^4\mathrm{He}(\nu_e, e^- p)^3\mathrm{He}$

$^4\mathrm{He}(\bar{\nu}_e, e^+ n)^3\mathrm{H}$

$r \sim 10^5$ km

ν signals

LHC, RHIC, FAIR

nuclear EOS, NS properties

LIGO

gravitational waves from NS mergers

NOvA, PINGU, DUNE, JUNO

neutrino mass hierarchy, CP violation

SuperK, IceCube, JUNO

SN neutrino detection

FRIB, HIRFL-CSR

nuclear properties far from stability

Astronomical Surveys (APOGEE, GAIA)

elemental abundances in stars