Effects of eV-Scale Sterile Neutrinos on Supernova Explosion & Nucleosynthesis

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Outline

- Stellar Evolution & Core Collapse
- Neutrino-Driven Supernova Explosion
- Electron Fraction Ye & Nucleosynthesis in the Neutrino-Driven Wind
- Active-Sterile Neutrino Mixing in SNe
- Treatment of Evolution of Ye in the Wind
- Effects on Nucleosynthesis & Explosion
- Discussion

How to Become a Star

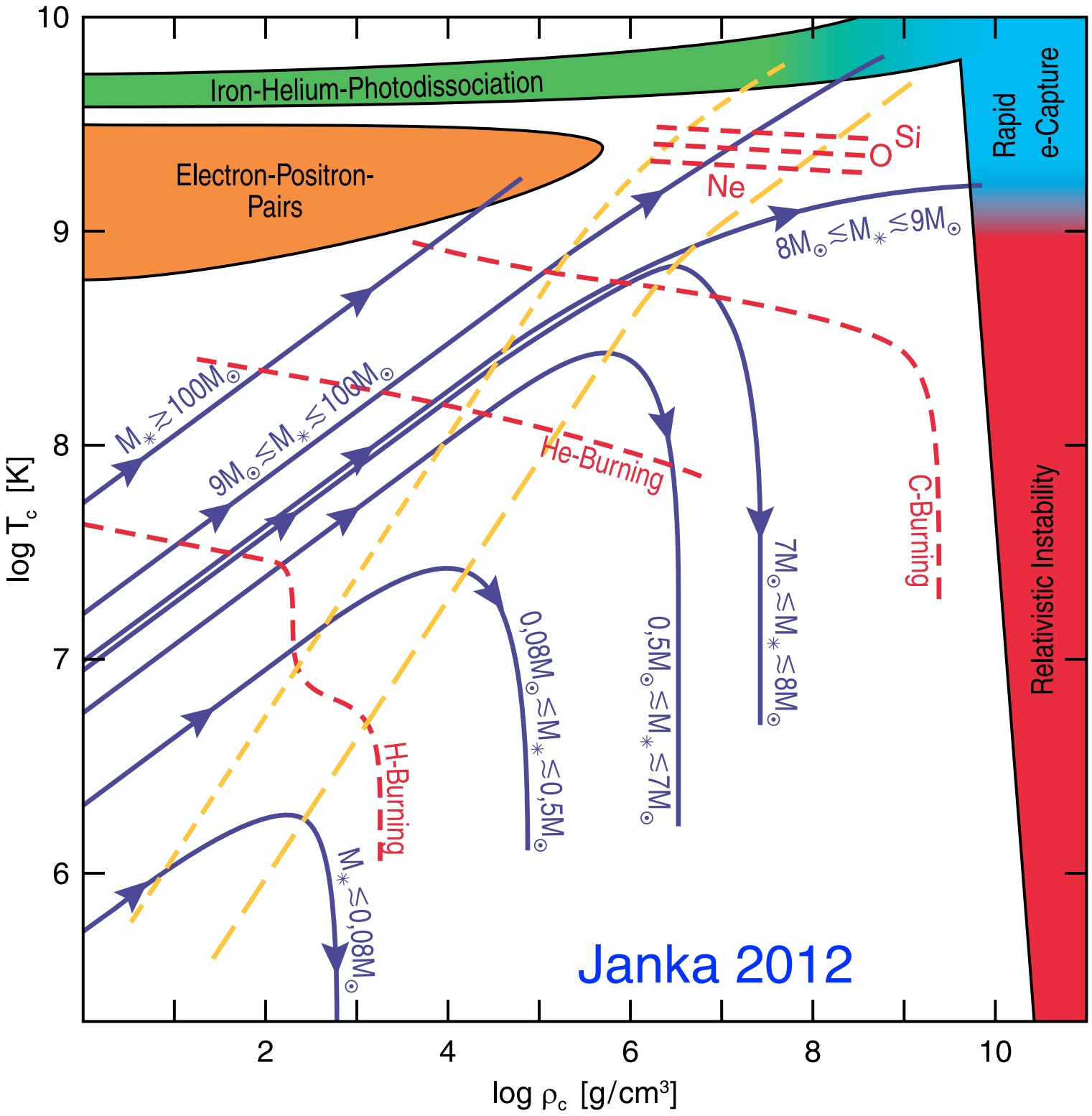
Virial theorem for a contracting gas cloud

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

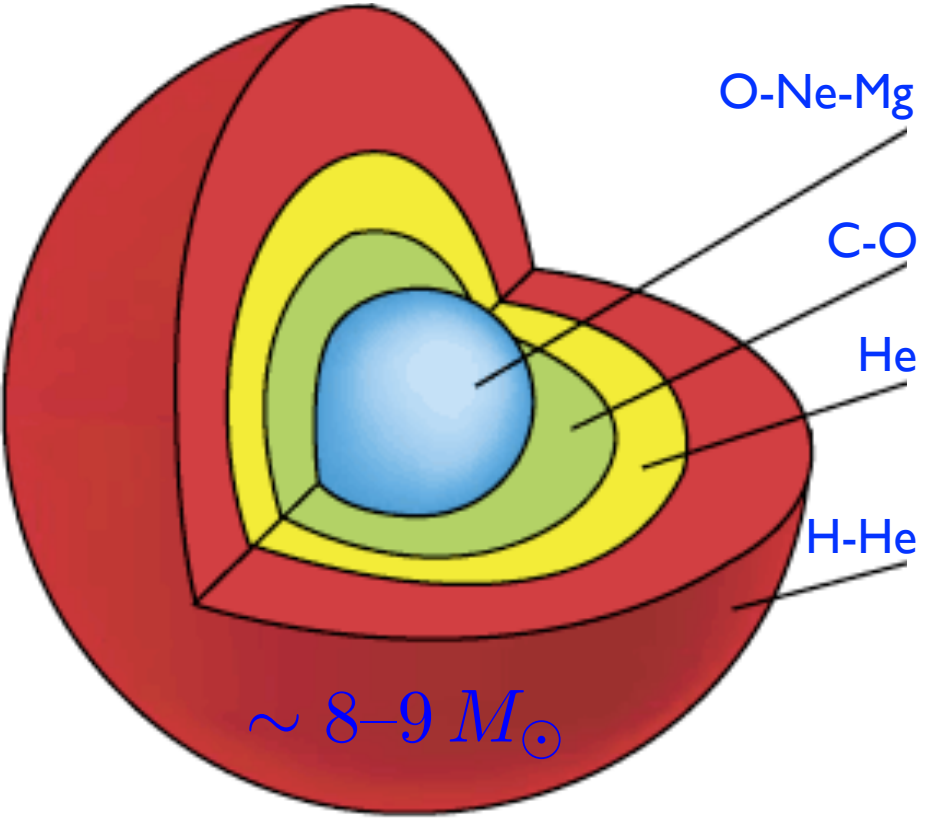
$$\left(\frac{M}{m_p}\right) d^3 \sim R^3 \Rightarrow$$

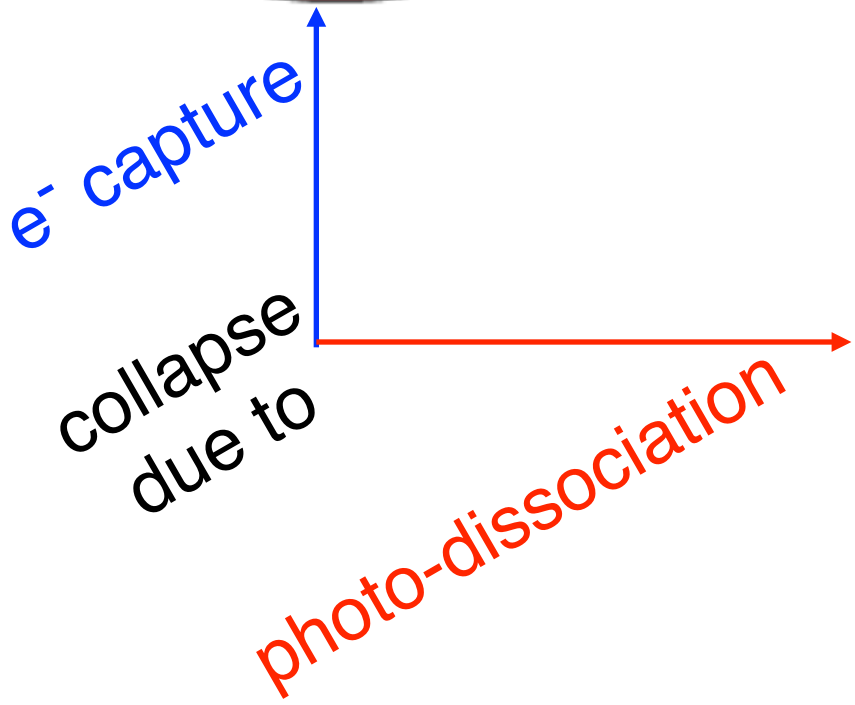
$$T_c \sim \frac{GMm_p}{R} - \frac{\hbar^2}{2m_e}\left(\frac{M}{m_p}\right)^{2/3} \frac{1}{R^2}$$

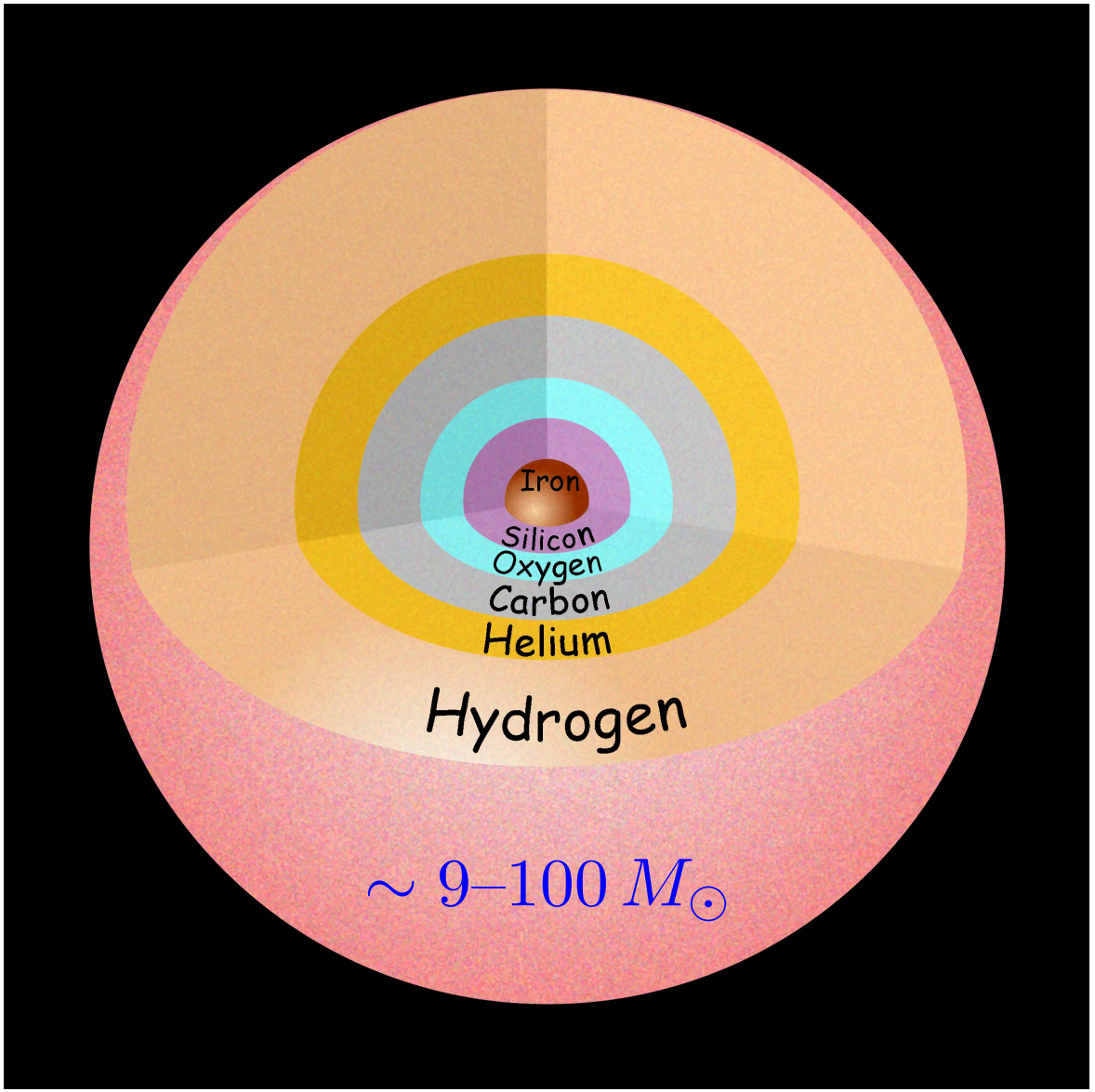
$$\Rightarrow T_{c,\max} \propto M^{4/3}$$

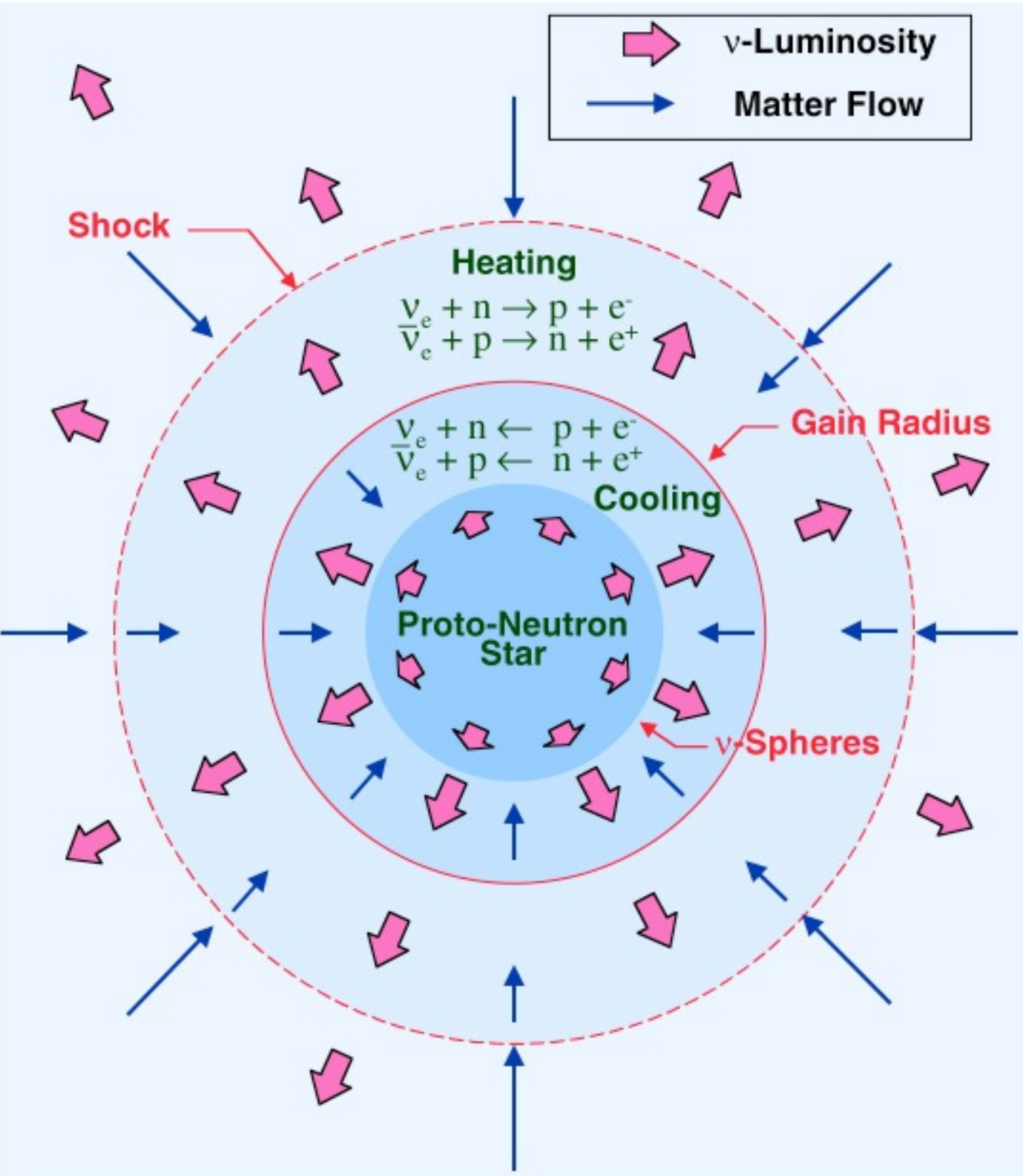

Iron-Helium-Photodissociation
Electron-Positron-
Pairs
Rapid
e-Capture
Relativistic Instability
O
Si
Ne
8M⊙≲M∗≲9M⊙
M∗≳100M⊙
9M⊙≲M∗≲100M⊙
He-Burning
C-Burning
7M⊙≲M∗≲8M⊙
0,08M⊙≲M∗≲0,5M⊙
0,5M⊙≲M∗≲7M⊙
H-Burning
M∗≲0,08M⊙
Janka 2012
log Tc [K]
log ρc [g/cm³]
10
9
8
7
6
2
4
6
8
10

"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

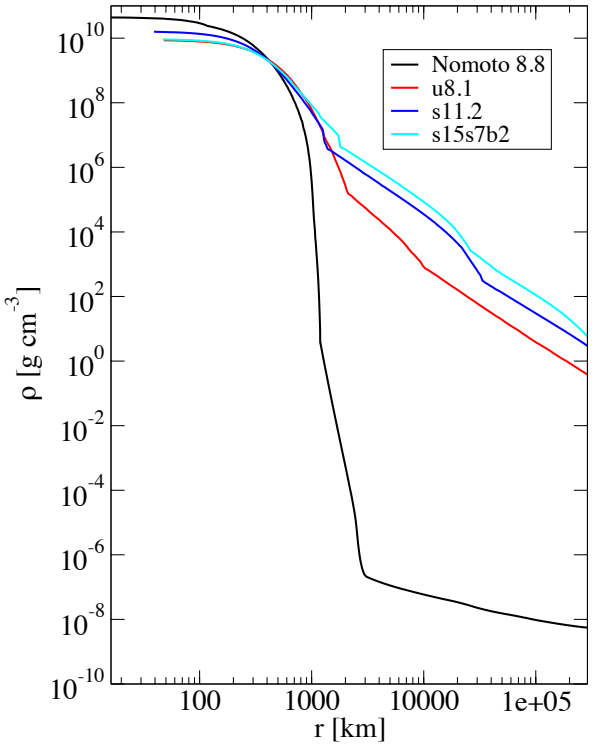
$$\dot{q}_{\nu N}(r_g) = \dot{q}_{eN}(r_g)$$

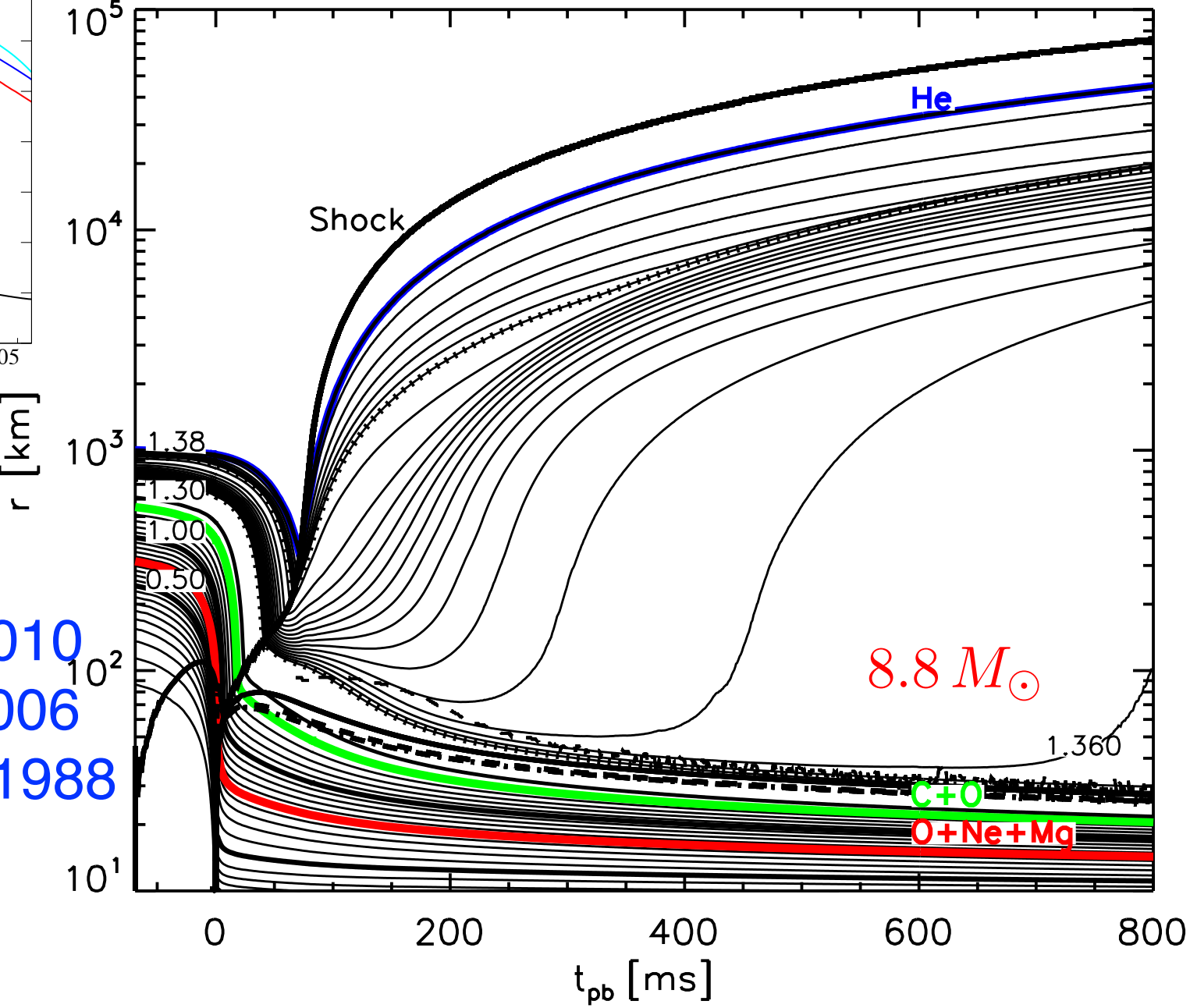
outside gain radius

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

Bethe & Wilson 1985

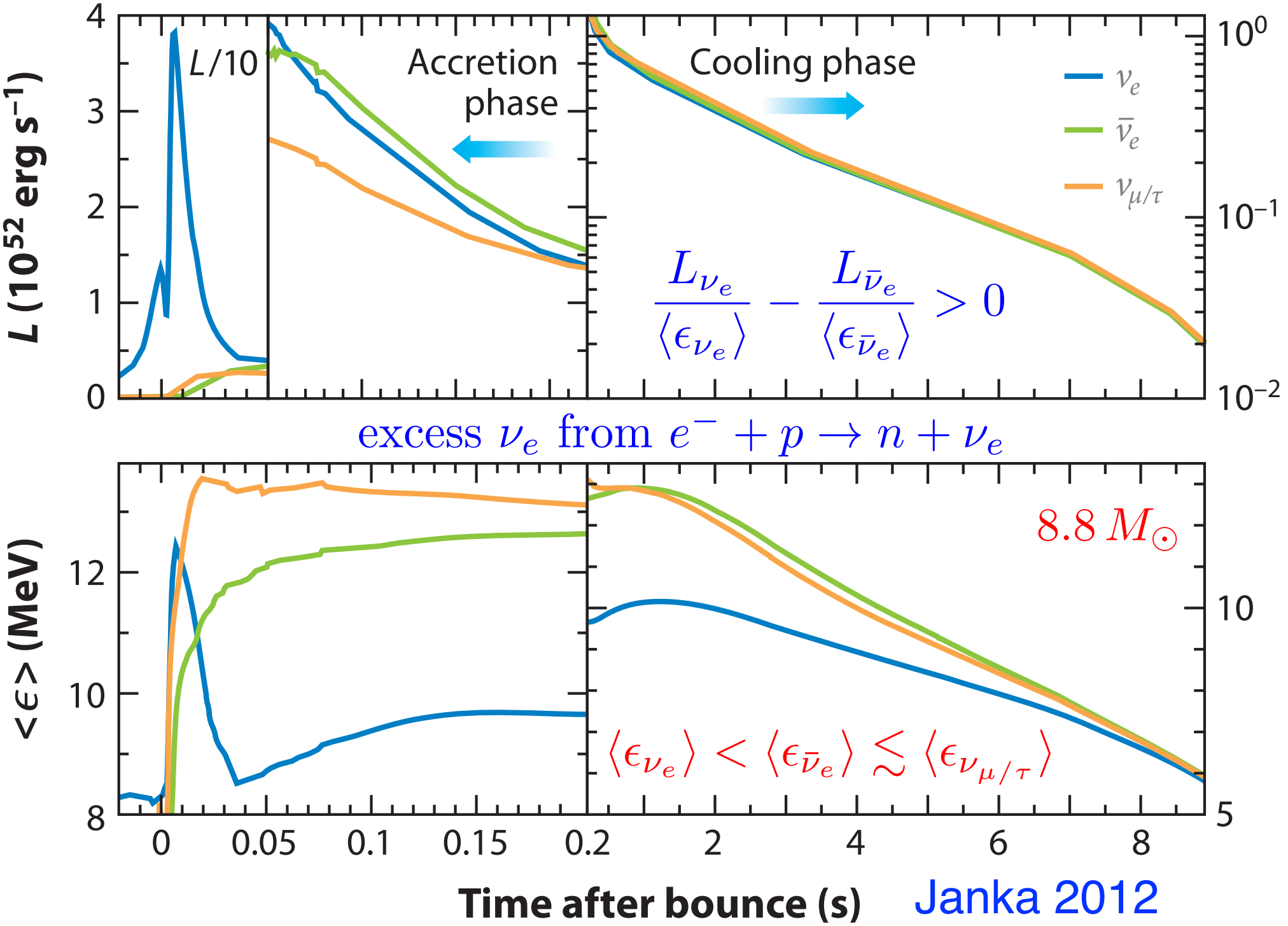
Neutrino-Driven Explosion of a Low-Mass SN

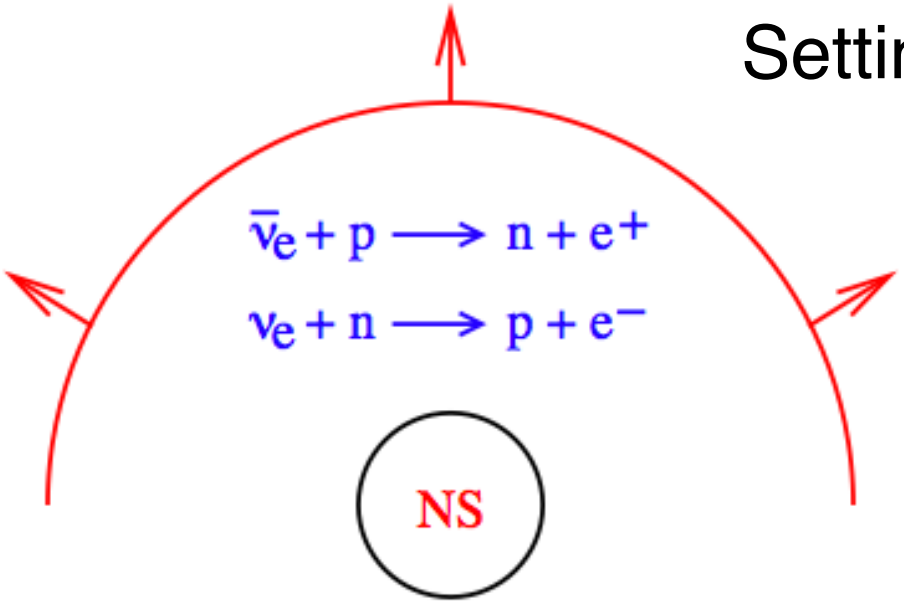




Janka 2012
Fischer et al. 2010
Kitaura et al. 2006
Mayle & Wilson 1988

Neutrino Emission from a Low-Mass SN





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

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

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

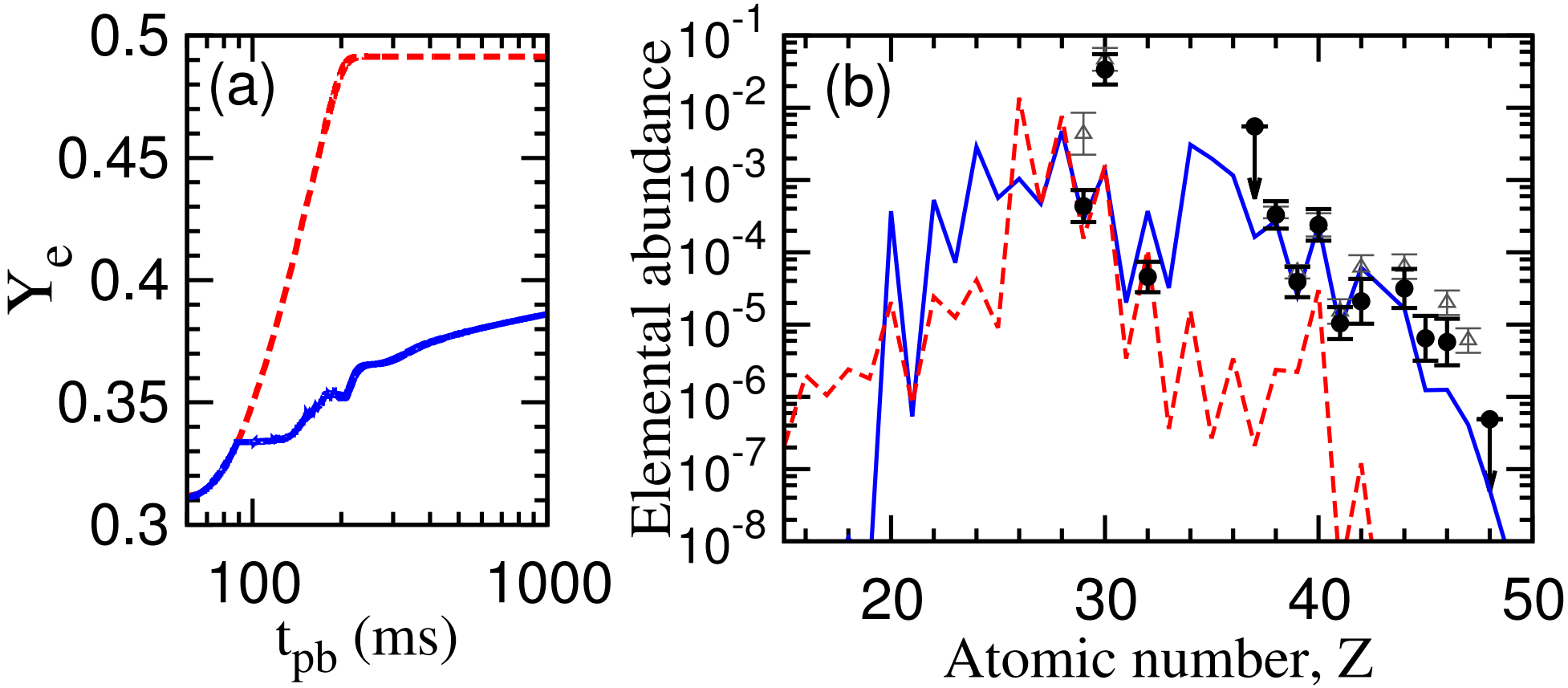
$$\lambda_{\nu_e n} = \frac{L_{\nu_e}}{4\pi r^2} \frac{\langle \sigma_{\nu_e n} \rangle}{\langle E_{\nu_e} \rangle} \propto L_{\nu_e} \left(\frac{\langle E^2_{\nu_e} \rangle}{\langle E_{\nu_e} \rangle} + 2\Delta_{np} \right)$$

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

Neutrino Opacities!

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

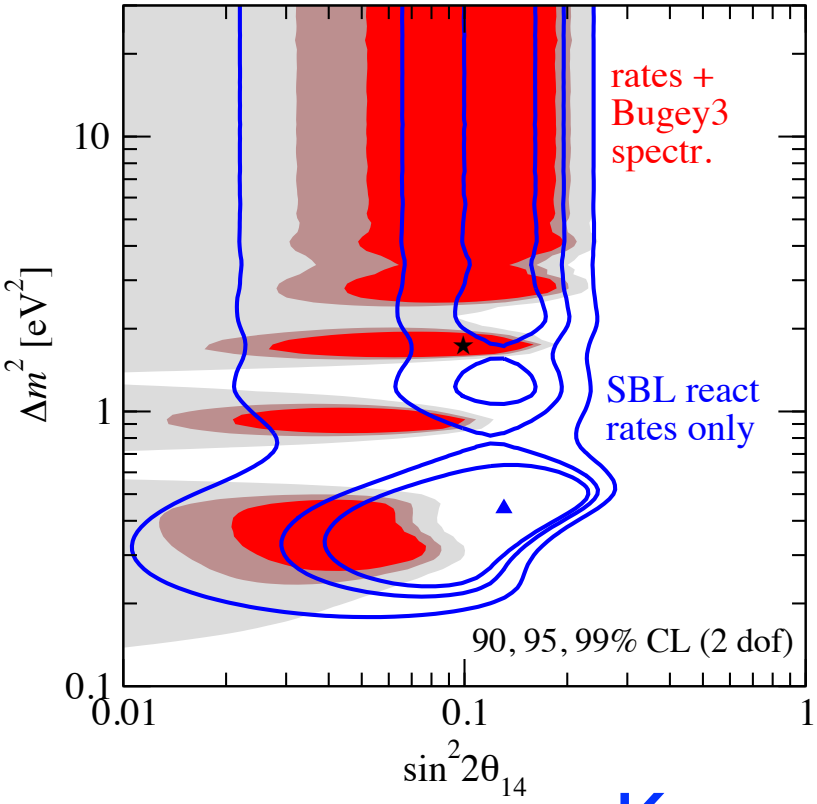
Example Evolution of Ye & Nucleosynthesis in the Wind (Wu, Fischer, Huther, Martinez-Pinedo, Qian 2014)

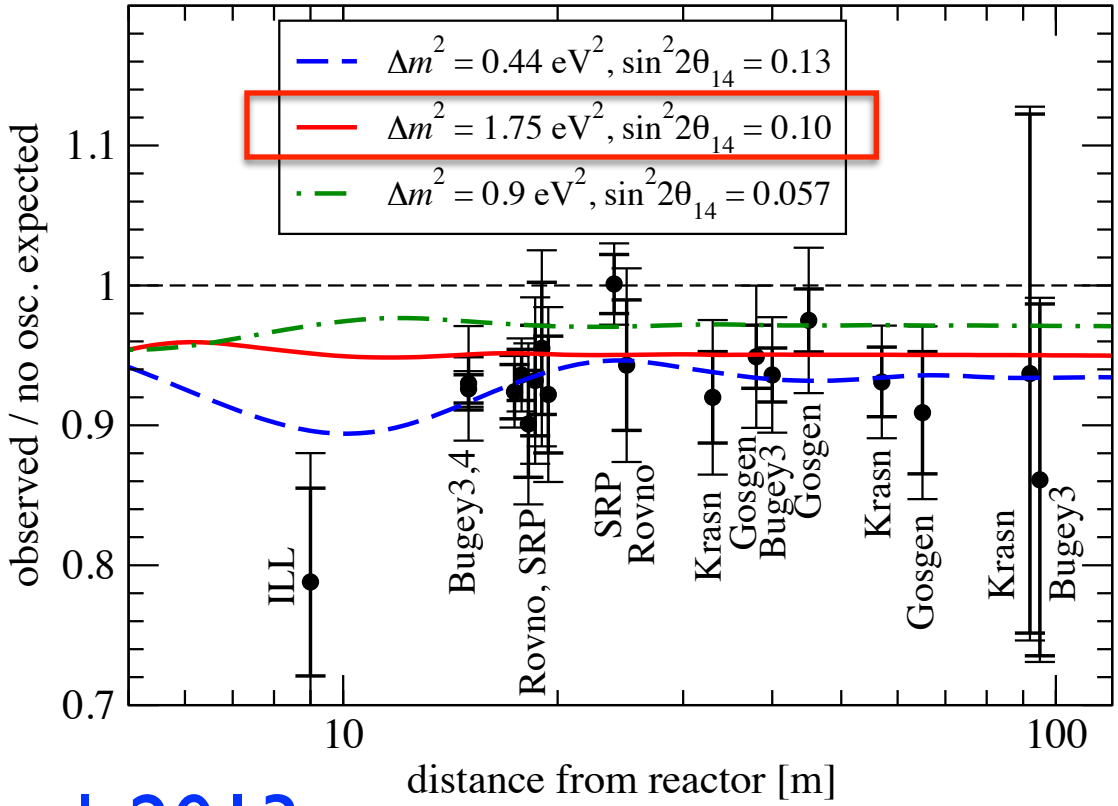


Indications for eV-Scale Sterile Neutrinos

LSND, Mini-BooNE, Gallium anomaly

reactor antineutrino anomaly (Mention et al. 2011)





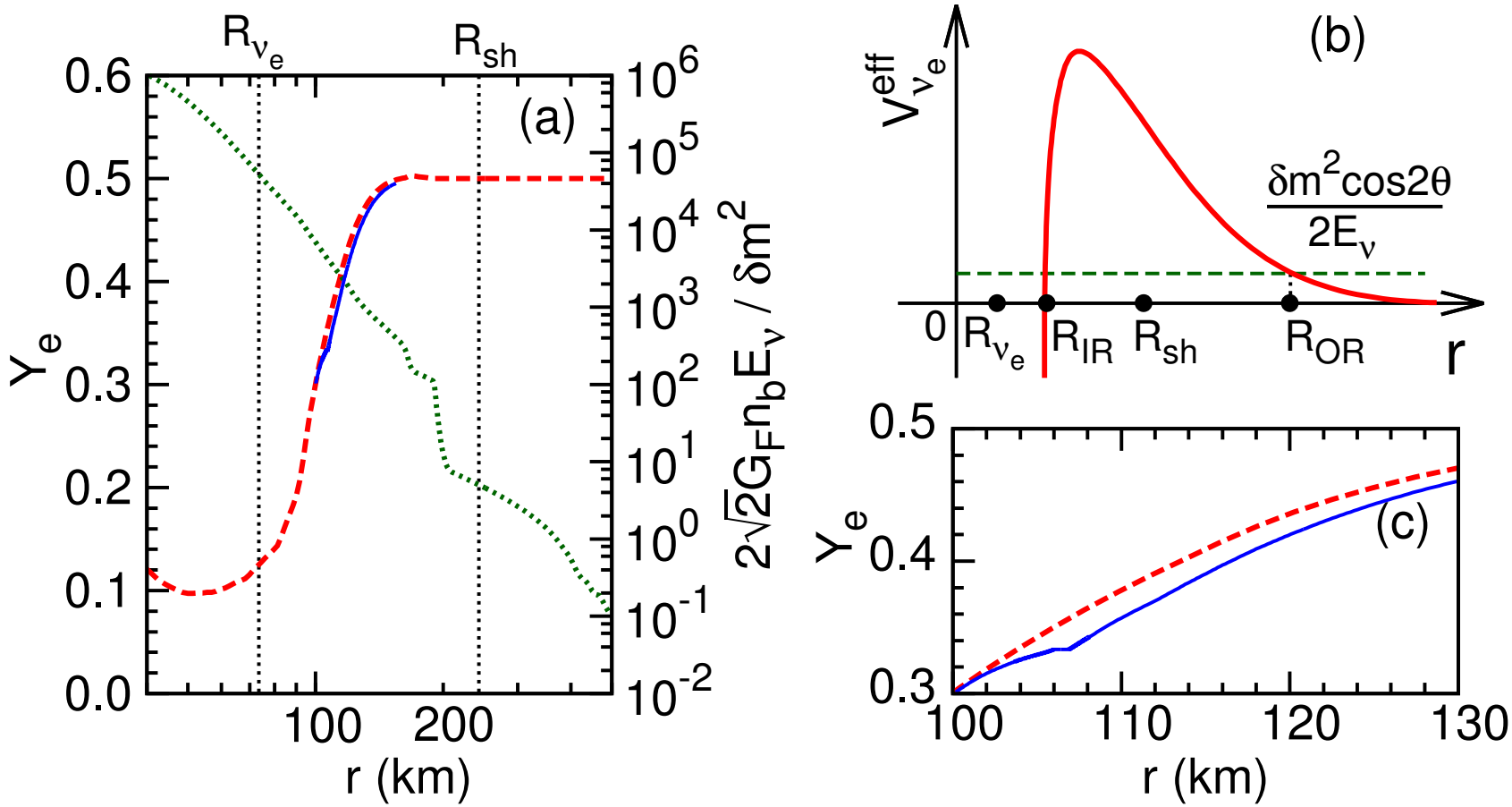
Kopp et al. 2013

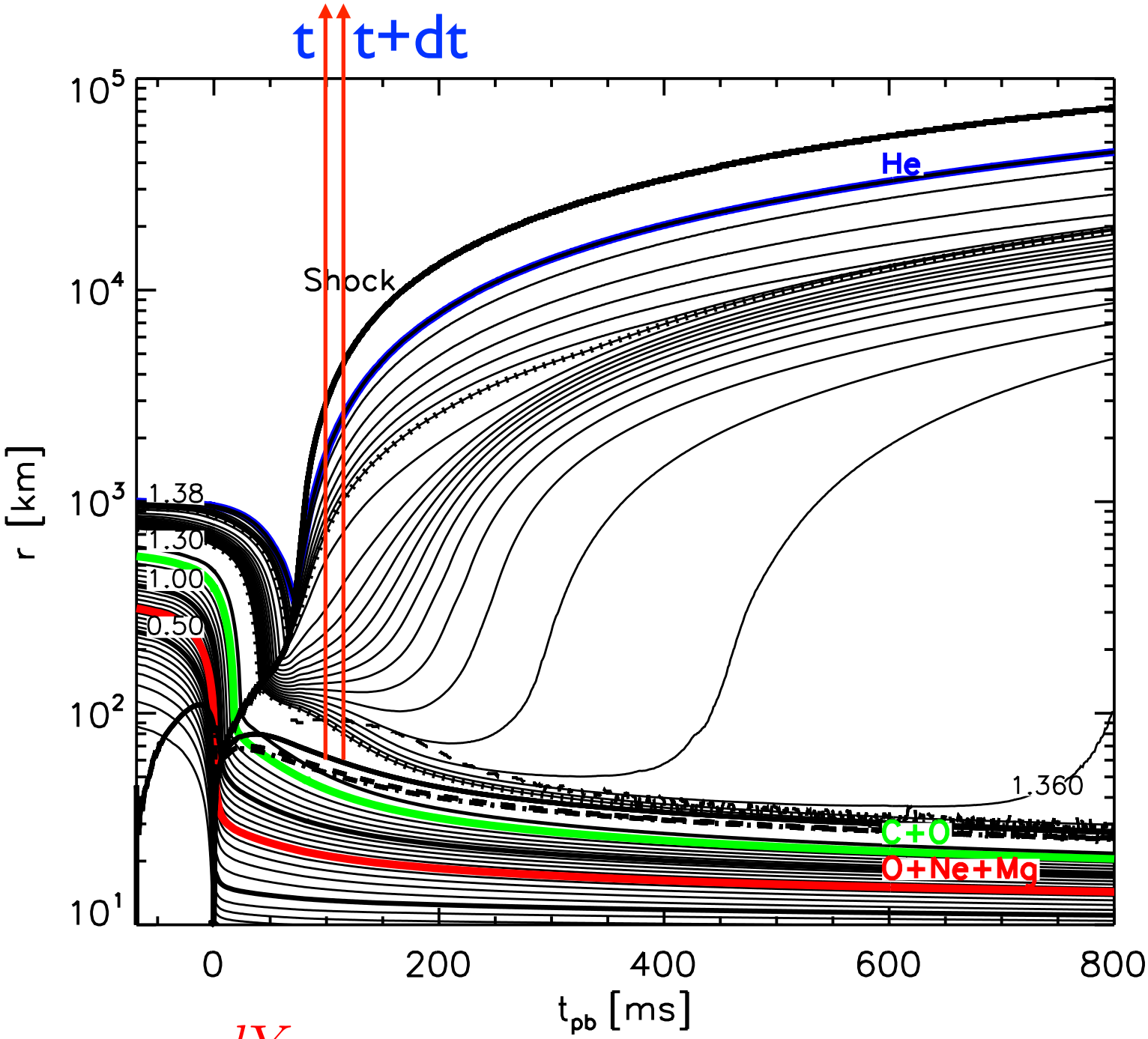
cosmology → $\delta m^2 > 0$

Active-Sterile Neutrino Mixing in SNe

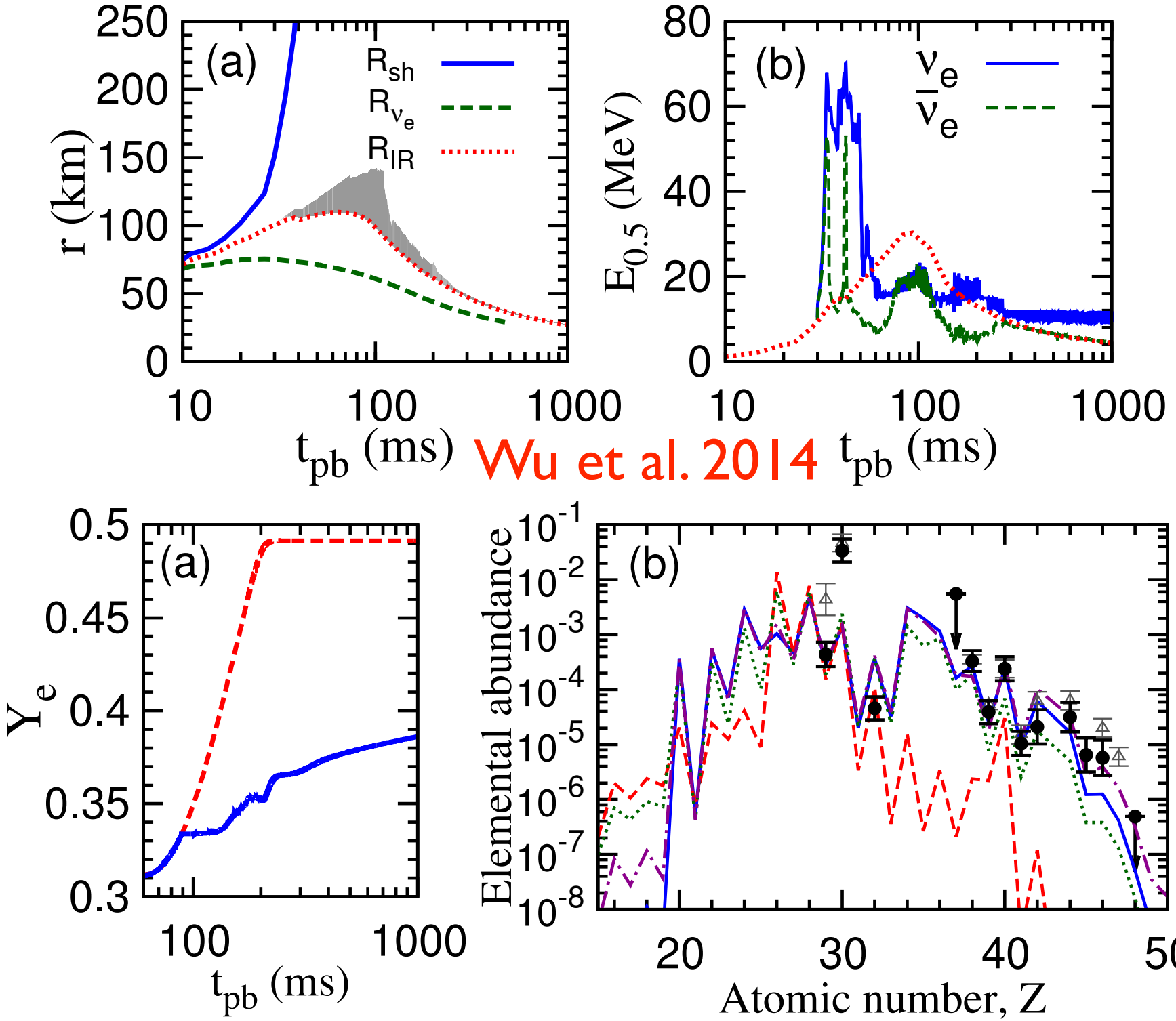
(Kainulainen et al. 1991; Nunokawa et al. 1997; Fetter et al. 2003; Tamborra et al. 2012; Wu et al. 2014)

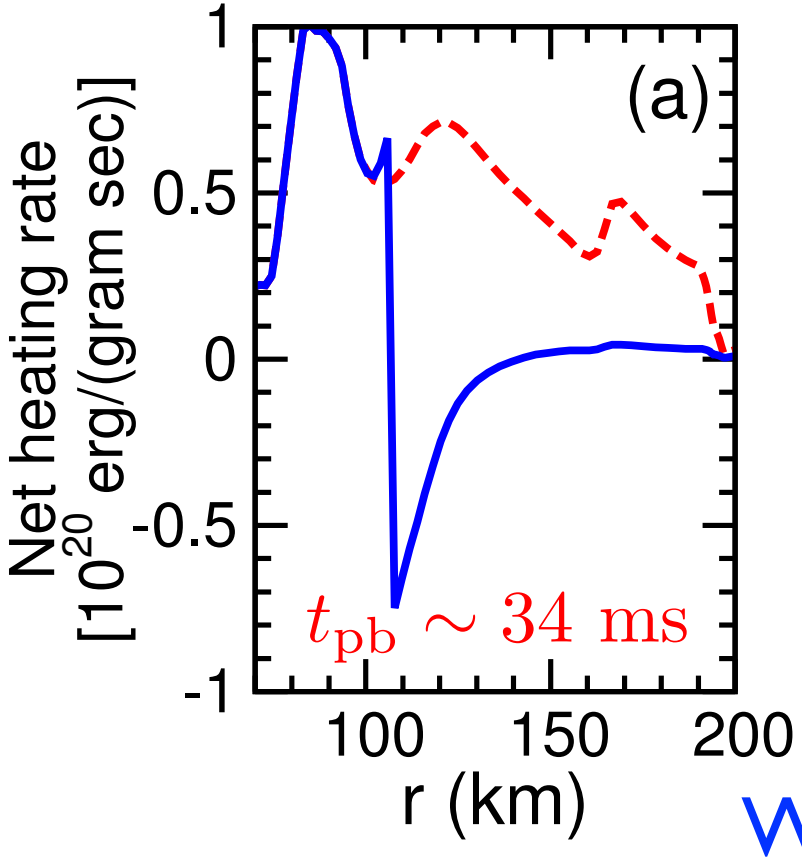
$$\frac{\delta m^2}{2E_\nu}\cos 2\theta = \pm\frac{3\sqrt{2}}{2}G_F n_b\left(Y_e - \frac{1}{3}\right)$$

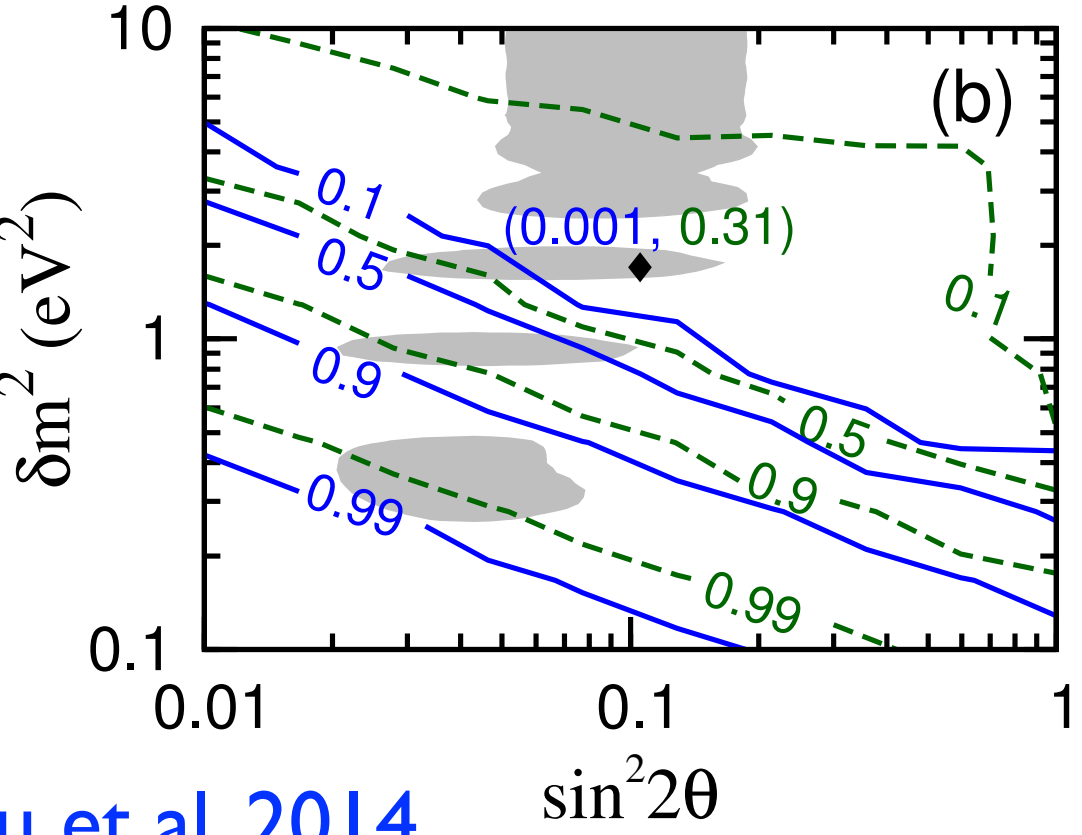




for $r_i(t)$, $\dfrac{dY_{e,i}}{dt} = \lambda_{\nu_e n}(r_i)Y_{n,i}(t) - \lambda_{\bar{\nu}_e p}(r_i)Y_{p,i}(t)$


(a)
R_{sh}
R_{ν_e}
R_{IR}
r (km)
250
200
150
100
50
0
10
100
1000
t_{pb} (ms)
(b)
ν_e
$\bar{\nu}_e$
$E_{0.5}$ (MeV)
80
60
40
20
0
10
100
1000
t_{pb} (ms)
Wu et al. 2014
(a)
Y_e
0.5
0.45
0.4
0.35
0.3
100
1000
t_{pb} (ms)
(b)
Elemental abundance
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
20
30
40
50
Atomic number, Z





Wu et al. 2014

$$\dot{q}_{\nu N} \propto \langle E_\nu \sigma_{\nu N} \rangle \propto \int E_\nu^{3+\alpha} \exp(-E_\nu/E_0) dE_\nu$$

$$\lambda_{\nu N} \propto \langle \sigma_{\nu N} \rangle \propto \int E_\nu^{2+\alpha} \exp(-E_\nu/E_0) dE_\nu$$

Other Issues

- self-consistent treatment of SN dynamics
- flavor evolution with neutrino background
- effects on SN neutrino signals
- potential conflicts with CMB & BBN
- global analyses of neutrino experiments