artistic view of elemental distribution from SN1987A (Feb. 23, 1987) based on Hubble

Neutrino properties

–

role for (*r*-process) nucleosynthesis

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Russbach, March, 2013

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- F.-K. Thielemann

Scopes

- Introduction

  (nucleosynthesis patterns)

- Evolution of (proto)neutron stars (PNS)

  (mass ejection and nucleosynthesis of heavy elements?)

- Neutrino emission during PNS deleptonization

  (luminosities/spectra, neutrino opacity/reaction rates, EOS impact)

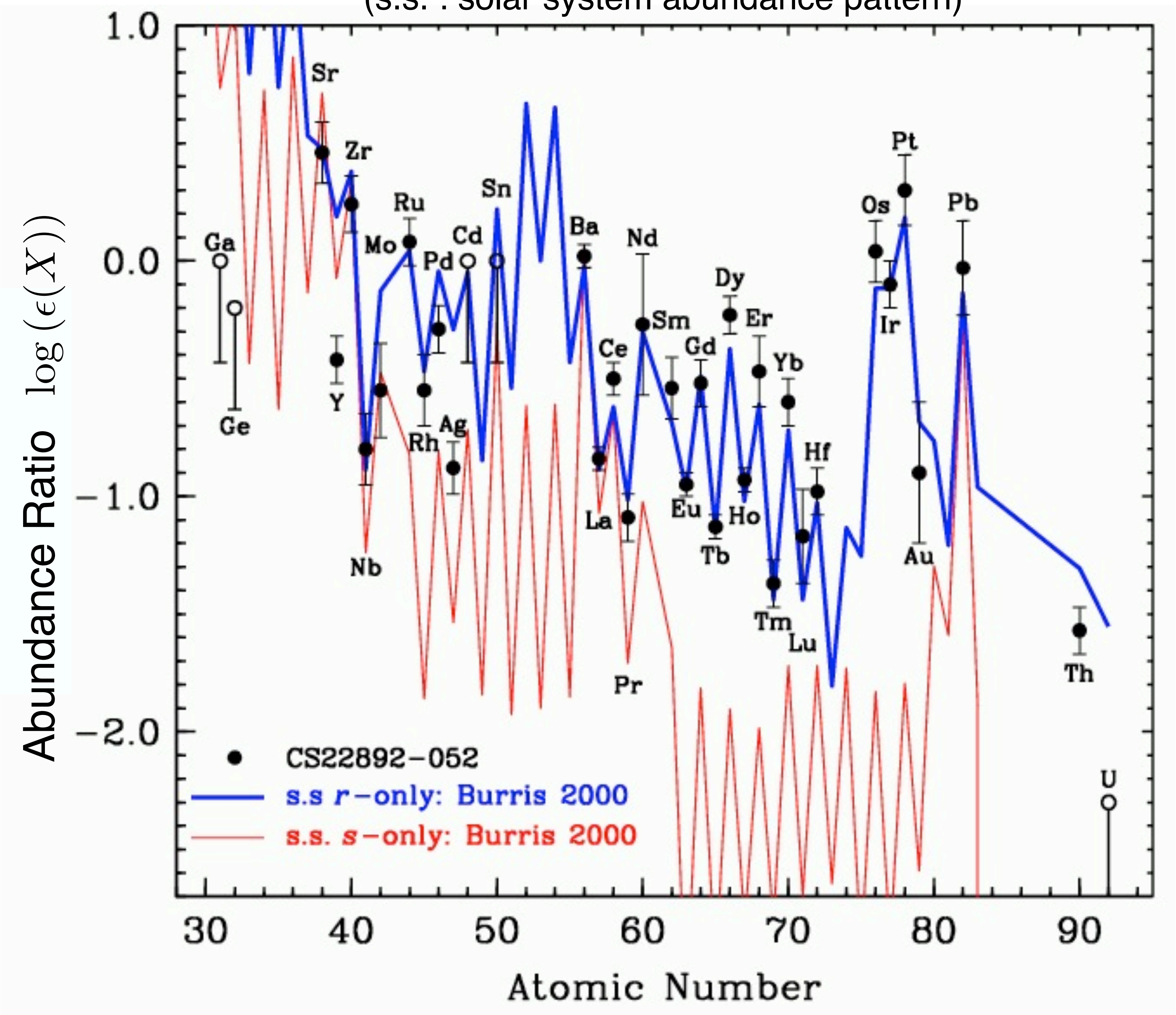
- Some nucleosynthesis results from recent models

- Summary and conclusions

Introduction

Cosmic fingerprints from heavy-elements

(s.s. : solar system abundance pattern)



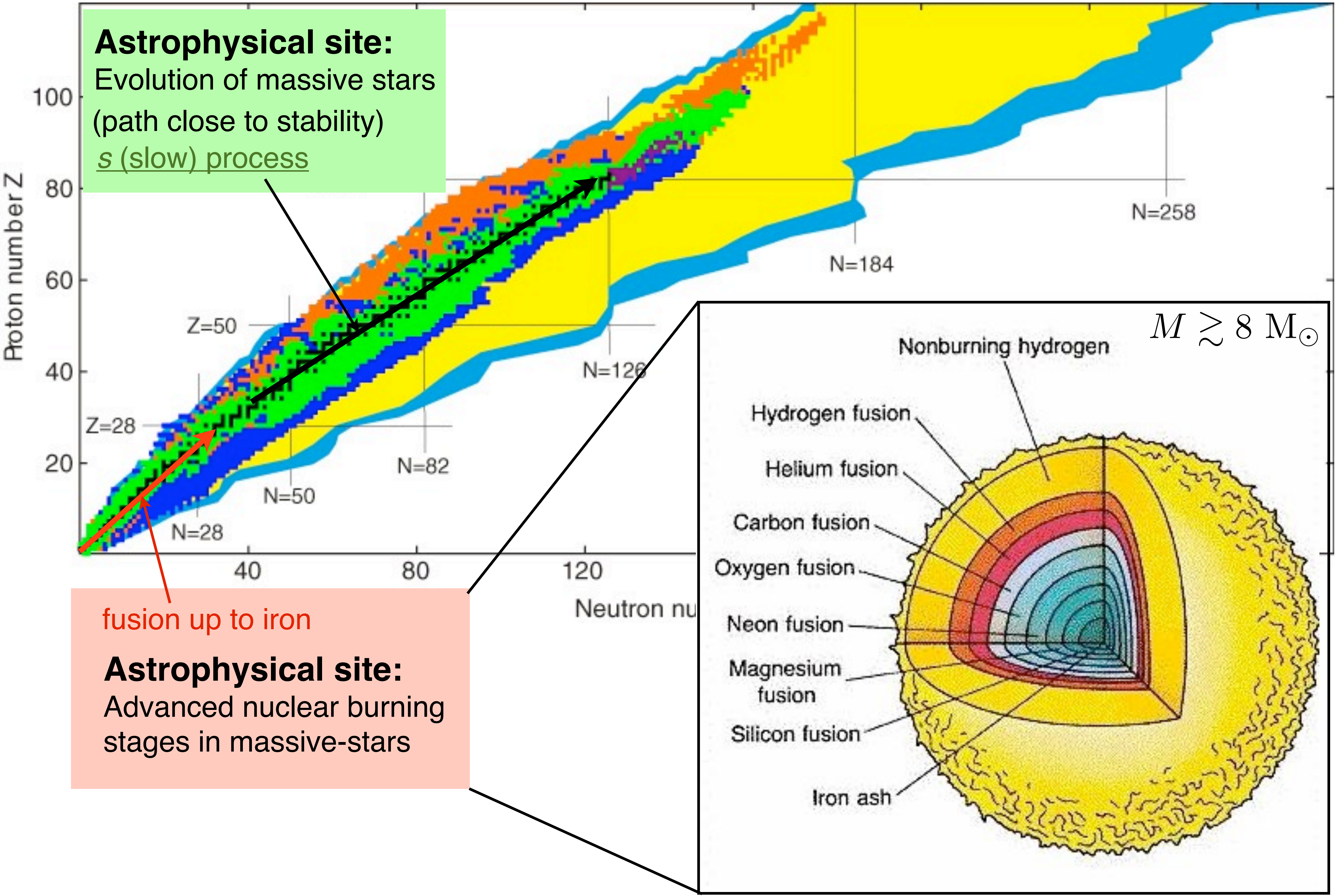
CS22892–052: metal-poor star

(metallicity ~ age)

- Robust enrichment of heavy *r*-process elements (Z > 52) and poor in iron [Eu/Fe] > 1.0 (*r*-II stars)
- Consistent with solar *r*-process abundance

$$\left\{\log\left(\epsilon(X)\right) = \log\left(\frac{N_X}{N_H}\right) + 12\right\}$$

Relation to nuclear physics

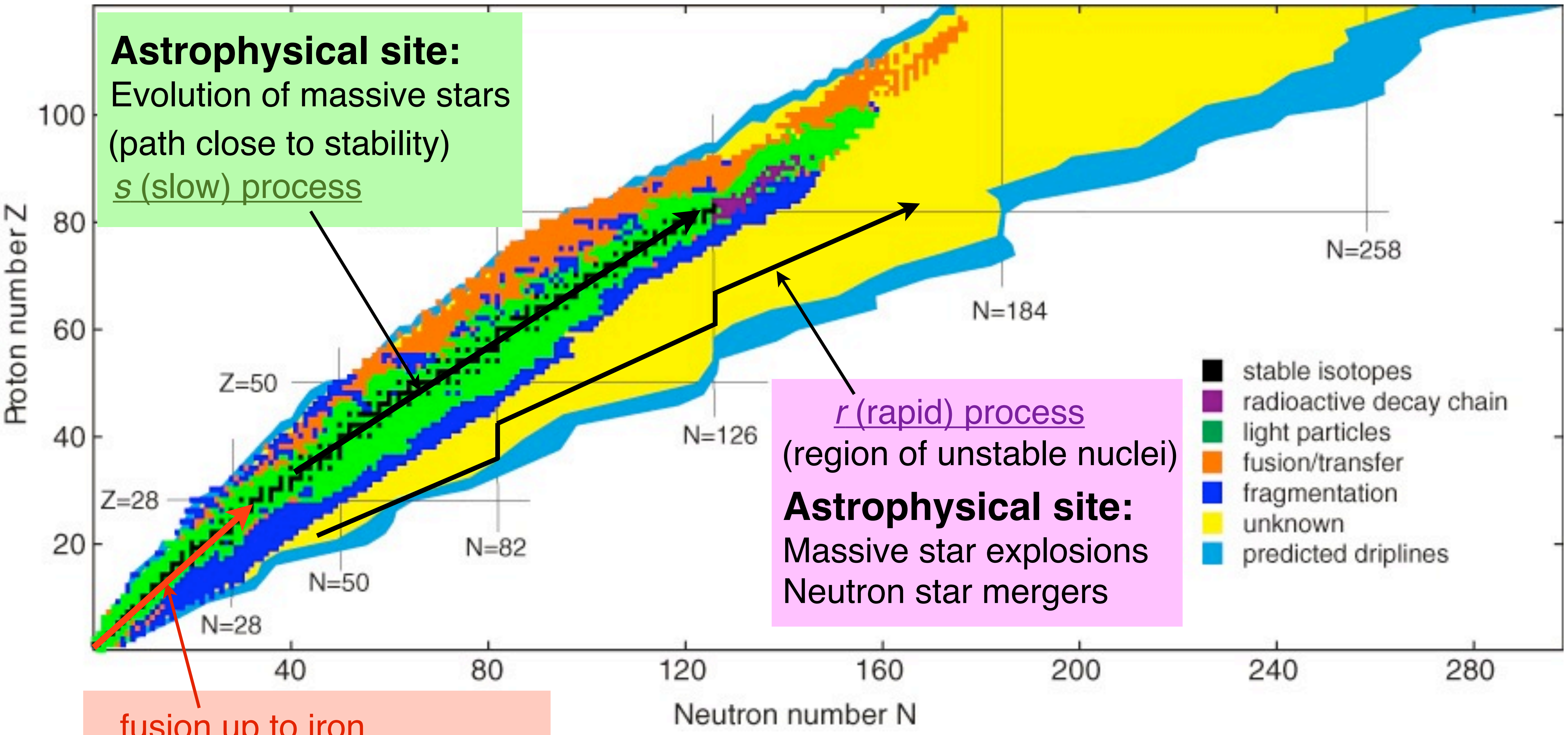


Astrophysical site:
Evolution of massive stars
(path close to stability)
s (slow) process

fusion up to iron

Astrophysical site:
Advanced nuclear burning stages in massive-stars

Relation to nuclear physics



Astrophysical site:
Evolution of massive stars
(path close to stability)
s (slow) process

r (rapid) process
(region of unstable nuclei)

Astrophysical site:
Massive star explosions
Neutron star mergers

fusion up to iron

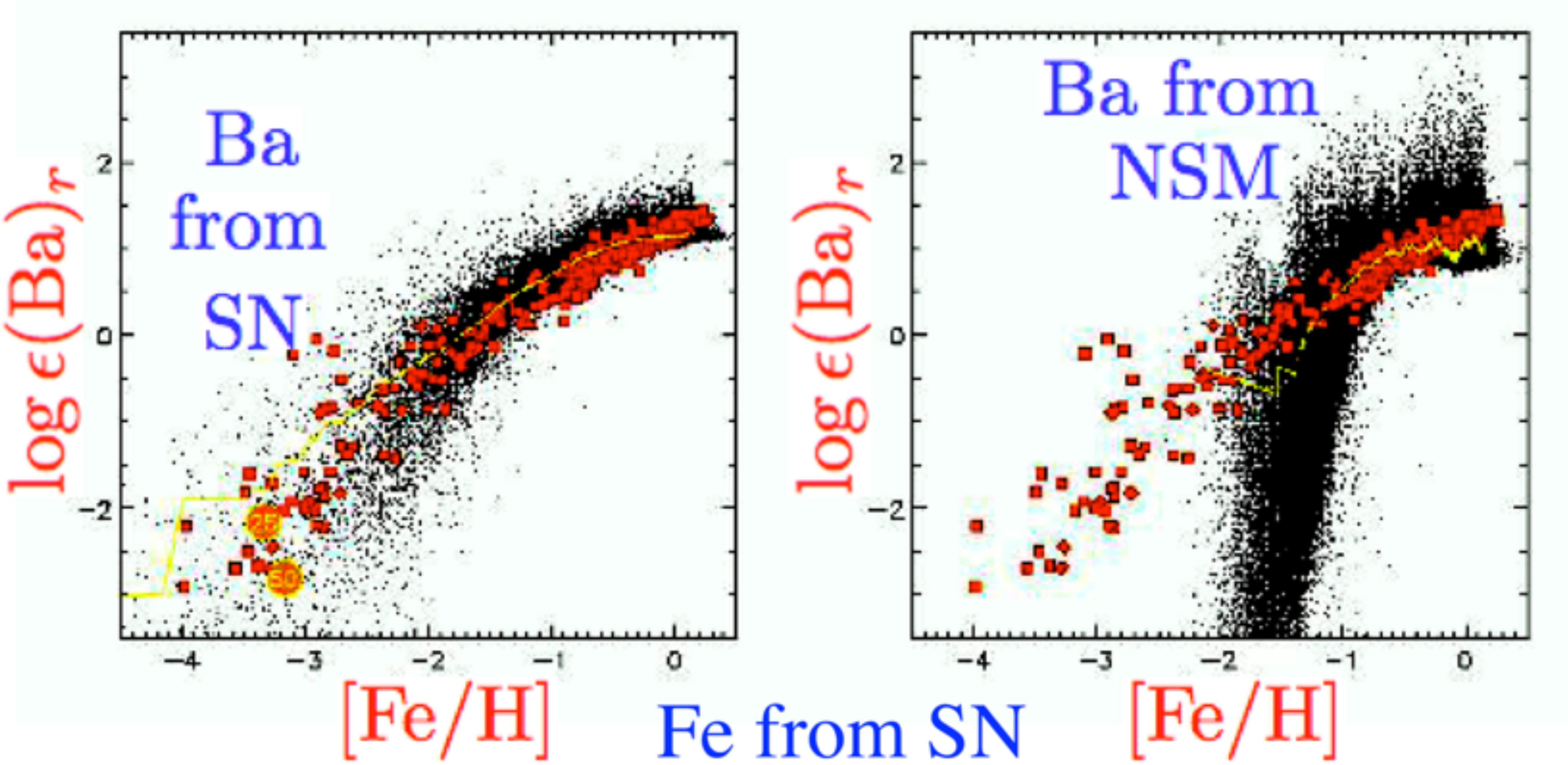
Astrophysical site:
Advanced nuclear burning
stages in massive-stars

There’s a problem. . .

Chemical evolution of the Galaxy

Qian, (2000), ApJ, 534, 67
Argast et al., (2004) A&A 416, 997

Early Galaxy ← Today



Note at low metallicity:

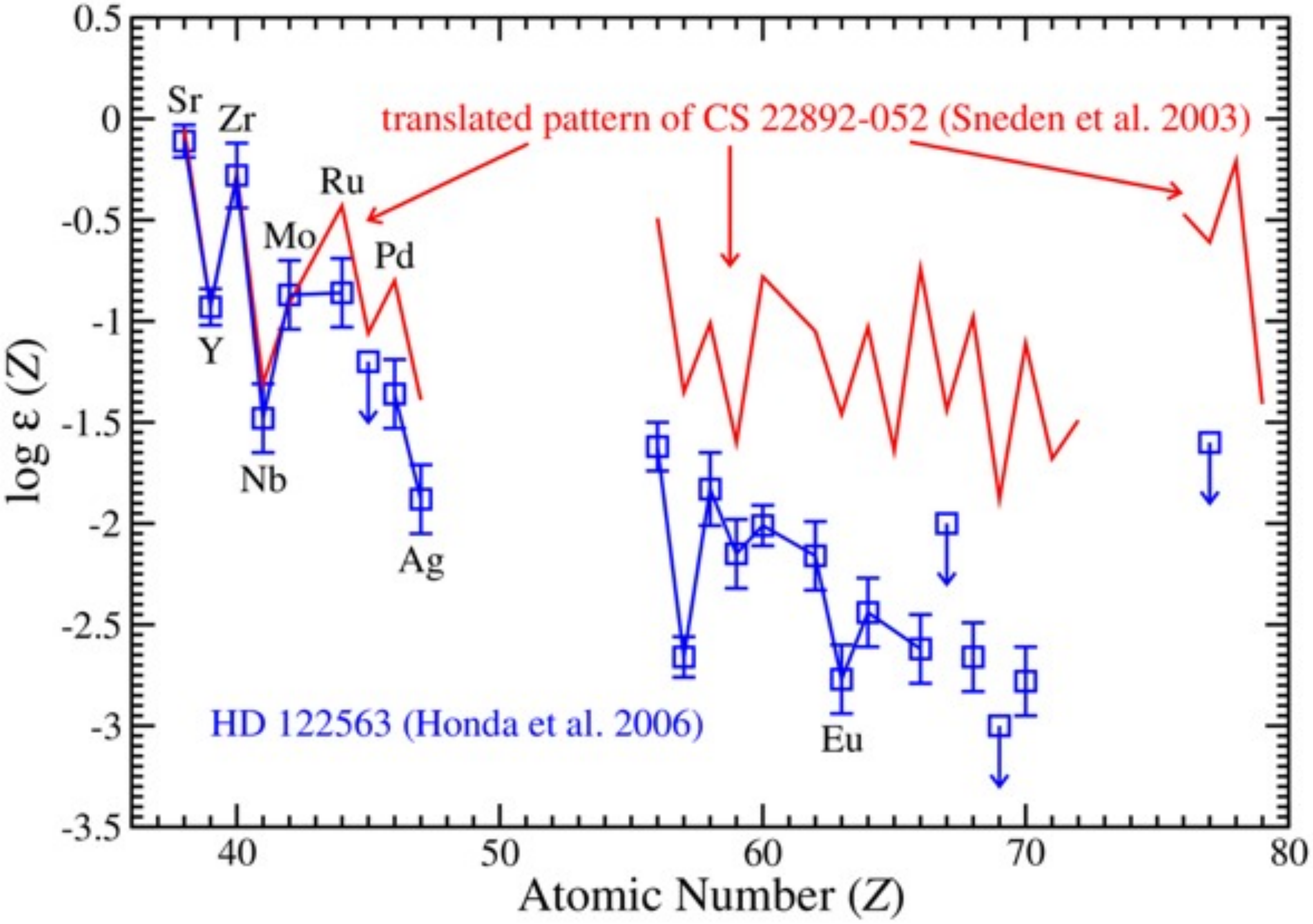
massive star-explosions primary site (still under debate)

neutron star mergers take too long

current SN models: no strong ($Z > 50$) *r*–process!

The origin of these heavy elements is still a mystery

Cosmic fingerprints from heavy-elements



There is hope . . .

There is another class of observations:

(Honda et al. 2006)

- Poor in heavy neutron-capture elements (Z>47)
- large abundances of light neutron-capture elements (38<Z<47, Sr, Y, Zr)
- **Production of light and heavy neutron-capture elements seems intrinsically decoupled: 2 different (astrophysical) sites?**

Astrophysical scenario discovered (?)

neutrino-driven winds from core-collapse supernova explosions/ (proto)neutron stars

Protoneutron star (PNS) evolution
–
Deleptonization phase

But first: ejection of the stellar mantle

- PNS born in the event of core-collapse supernova explosion
- Supernova explosion associated with shock expansion
- “**direct**” ejection of stellar mantle;

  outer layers of progenitor star

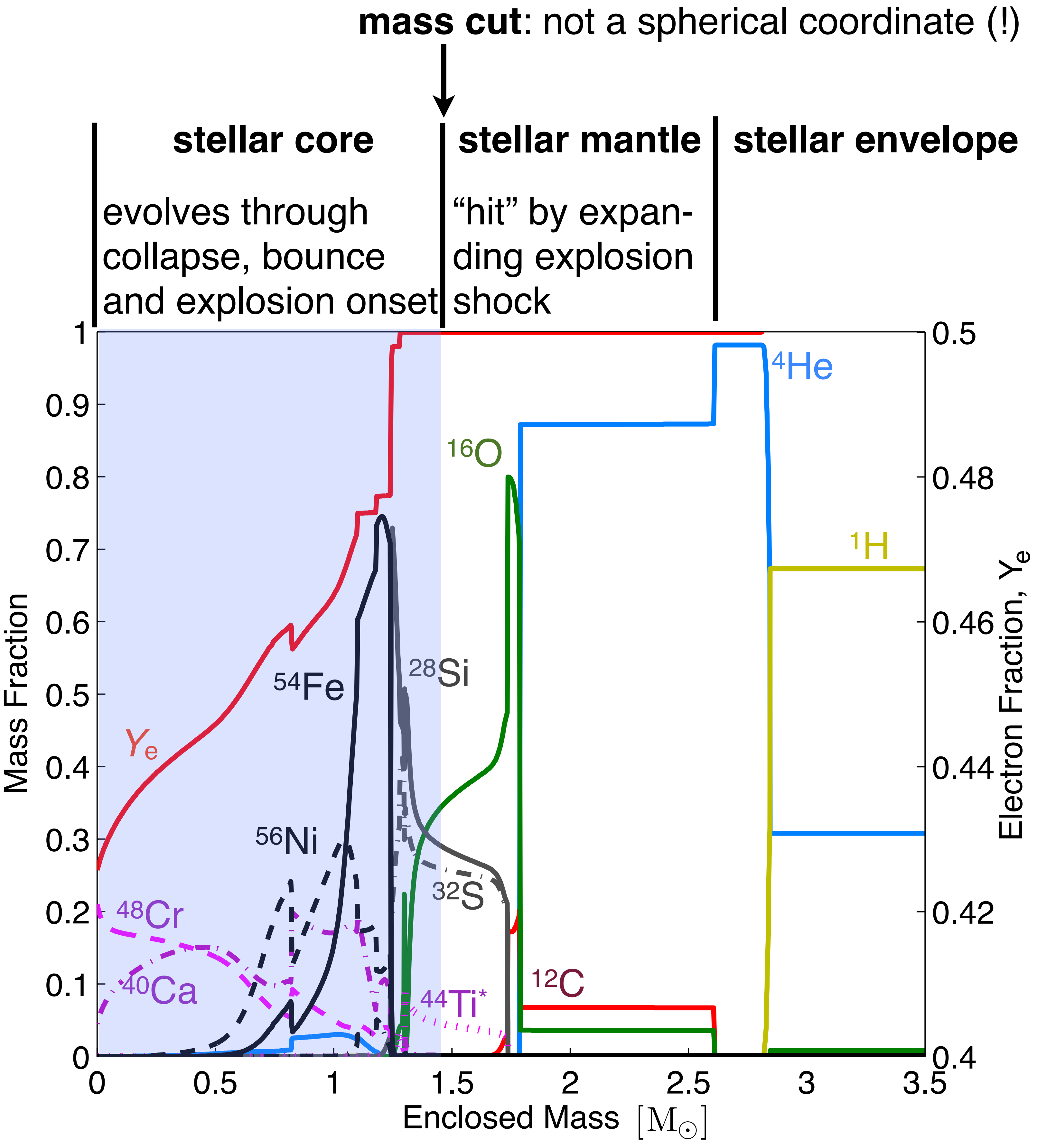
  ^{16}O, ^{12}C, ^{4}He,...

  ^{28}Si, ^{40}Ca, ^{44}Ti, Fe-group nuclei depends on details of explosion and progenitor composition

  (in particular, on temperature at shock front, Y_e, and progenitor composition)

$11.2\ \mathrm{M}_\odot$ progenitor

(Woosley, et al., (2002) Rev Mod Phys. 74)



mass cut: not a spherical coordinate (!)

stellar core

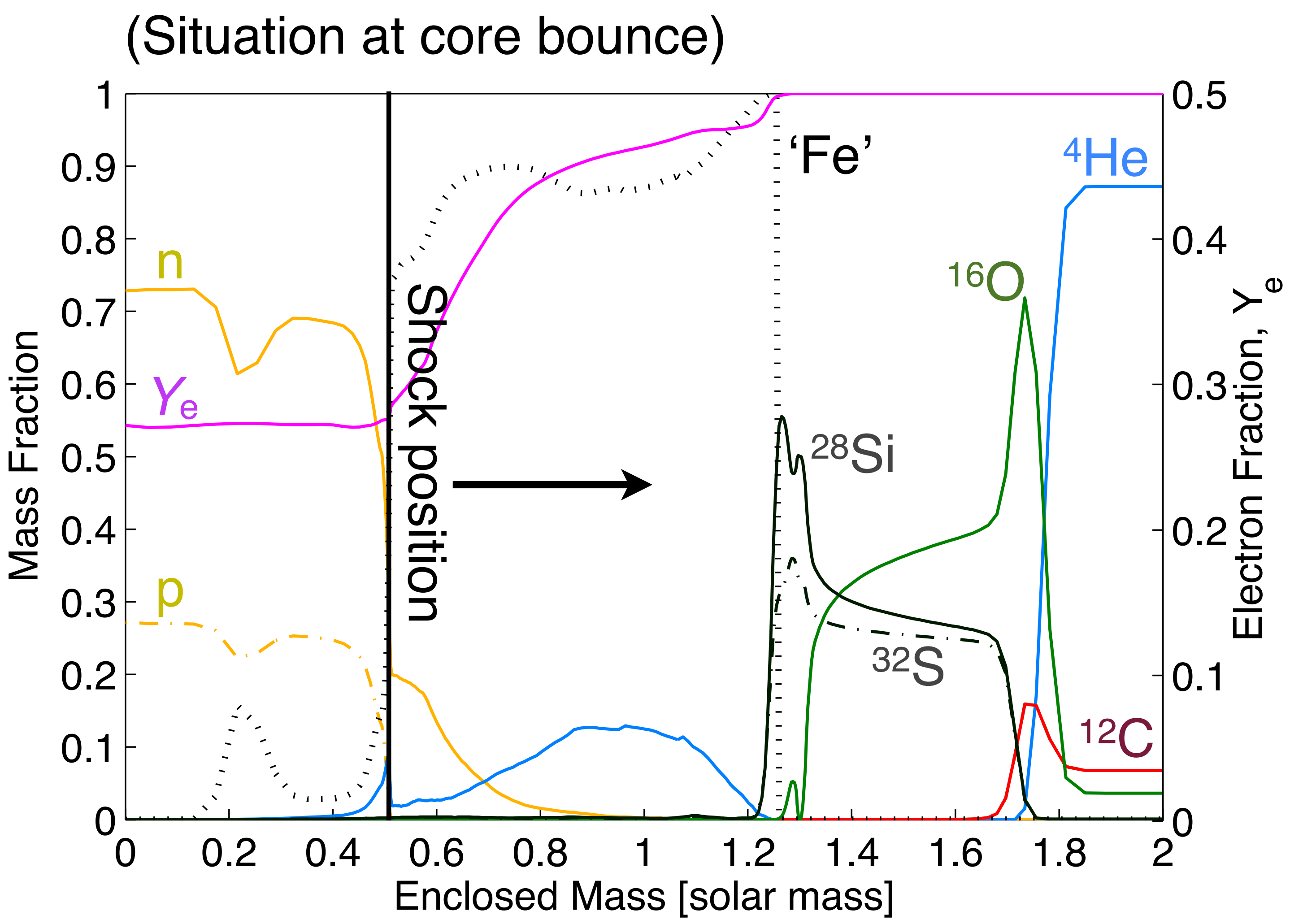
evolves through collapse, bounce and explosion onset

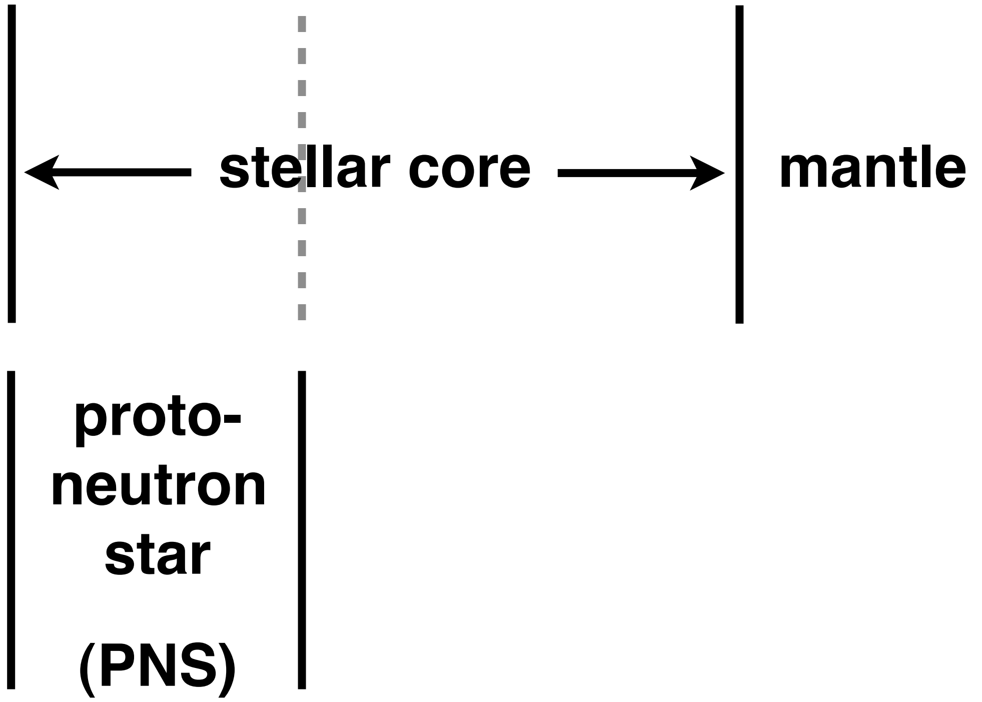
stellar mantle

“hit” by expanding explosion shock

stellar envelope

Early shock propagation – high temperatures destroy ‘most’ nuclei




stellar core

mantle

proto-neutron star

(PNS)

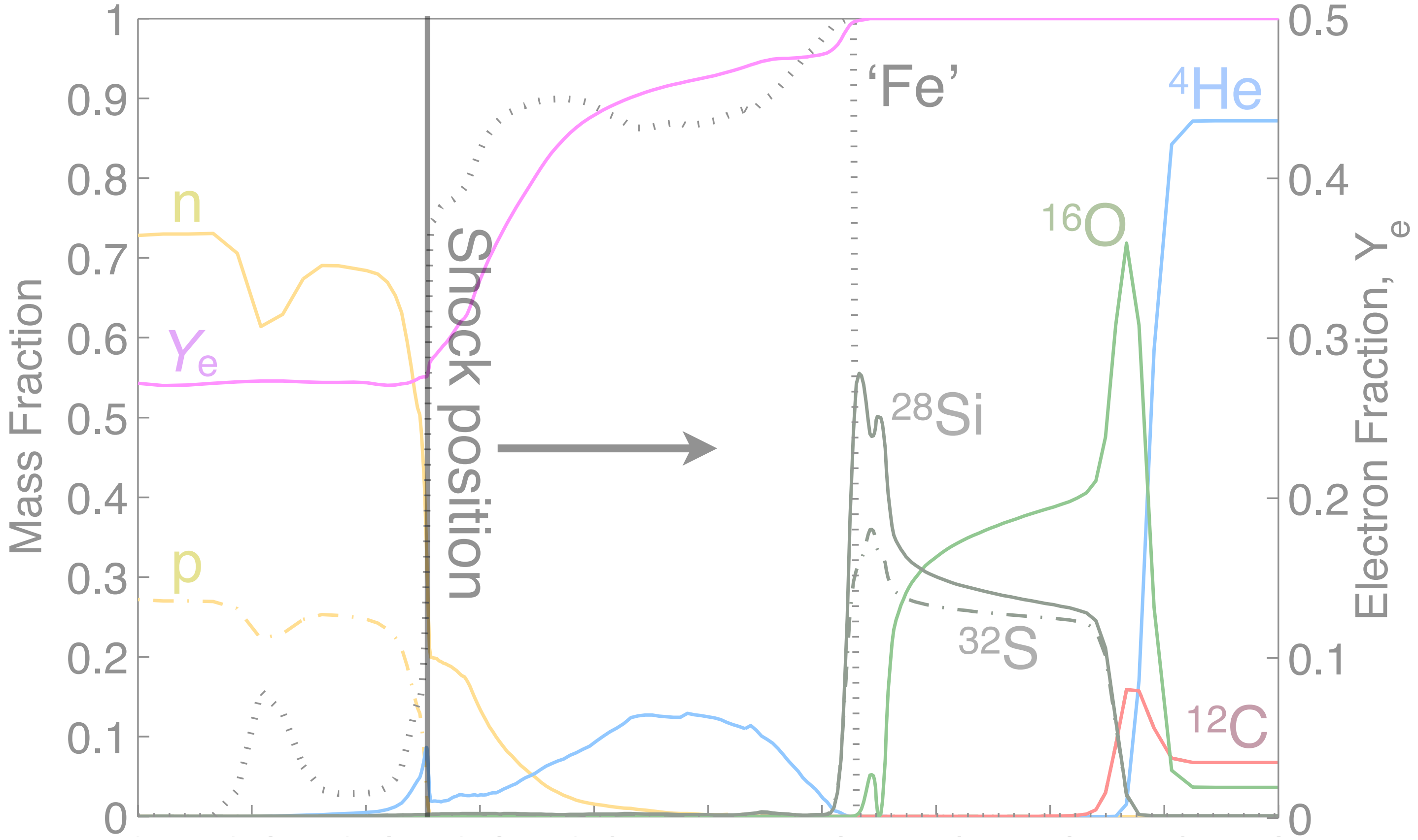
Early shock propagation – high temperatures destroy ‘most’ nuclei

Explosive Si-burning ($Y_e \approx 0.5$)

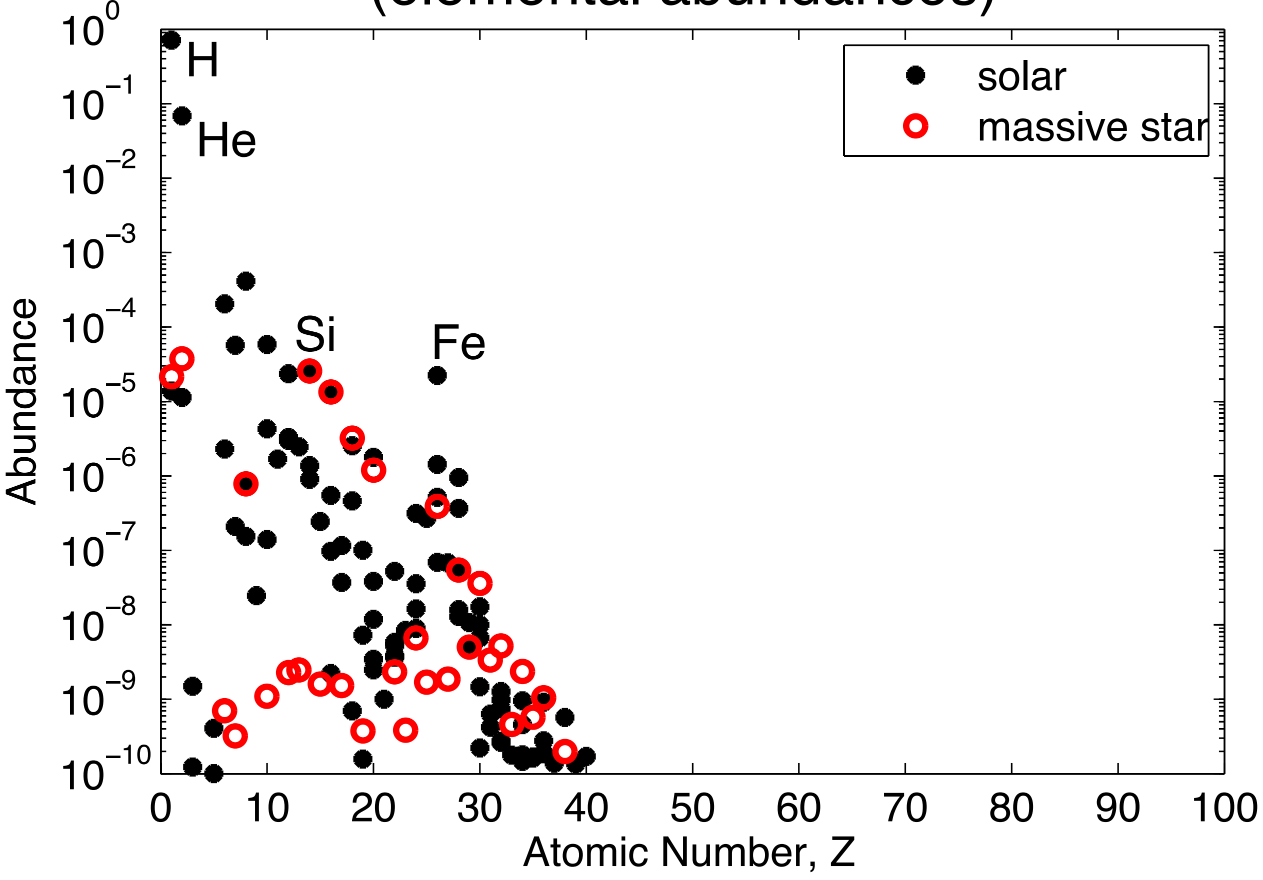
Nucleosynthesis outcome highly stellar model dependent

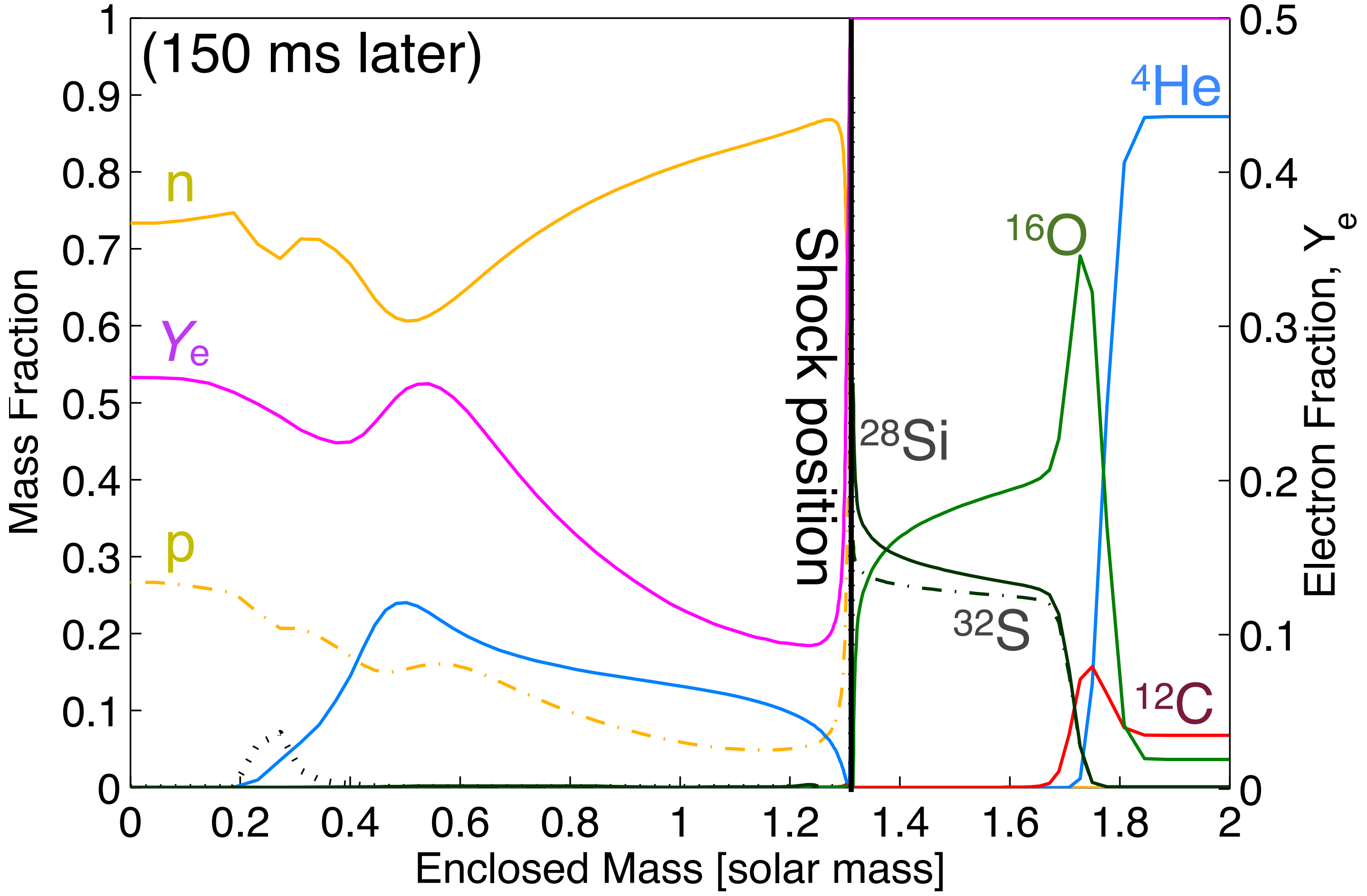
Sharp drop at Z≥35–40 (no heavy elements produced)

(at core bounce)



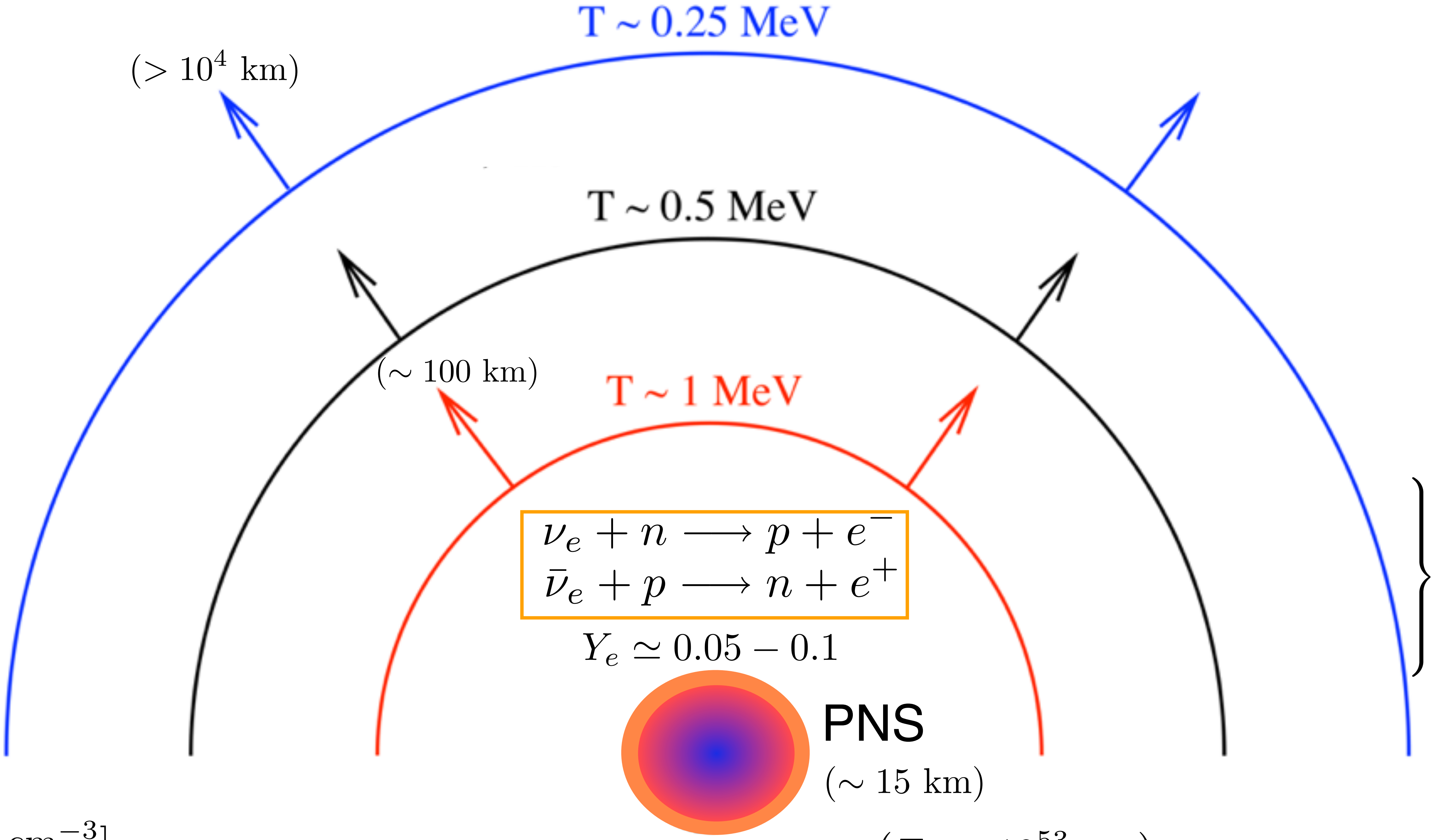
(elemental abundances)





After the explosion onset. . .

Supernova shock propagates to increasingly larger radii



T ~ 0.25 MeV

$(> 10^4 \text{ km})$

T ~ 0.5 MeV

$(\sim 100 \text{ km})$

T ~ 1 MeV

$$\boxed{\begin{array}{l} \nu_e + n \longrightarrow p + e^- \\ \bar{\nu}_e + p \longrightarrow n + e^+ \end{array}}$$

$Y_e \simeq 0.05 - 0.1$

PNS

$(\sim 15 \text{ km})$

$T = 5 - 30 \text{ MeV} \ (E_\nu \sim 10^{53} \text{ erg})$

< 10

10^6

10^{10}

10^{14}

$\rho \ [\text{g} \cdot \text{cm}^{-3}]$

low-mass
outflow:
“*ν*-driven
wind”

Y_e fix !

neutrino heating

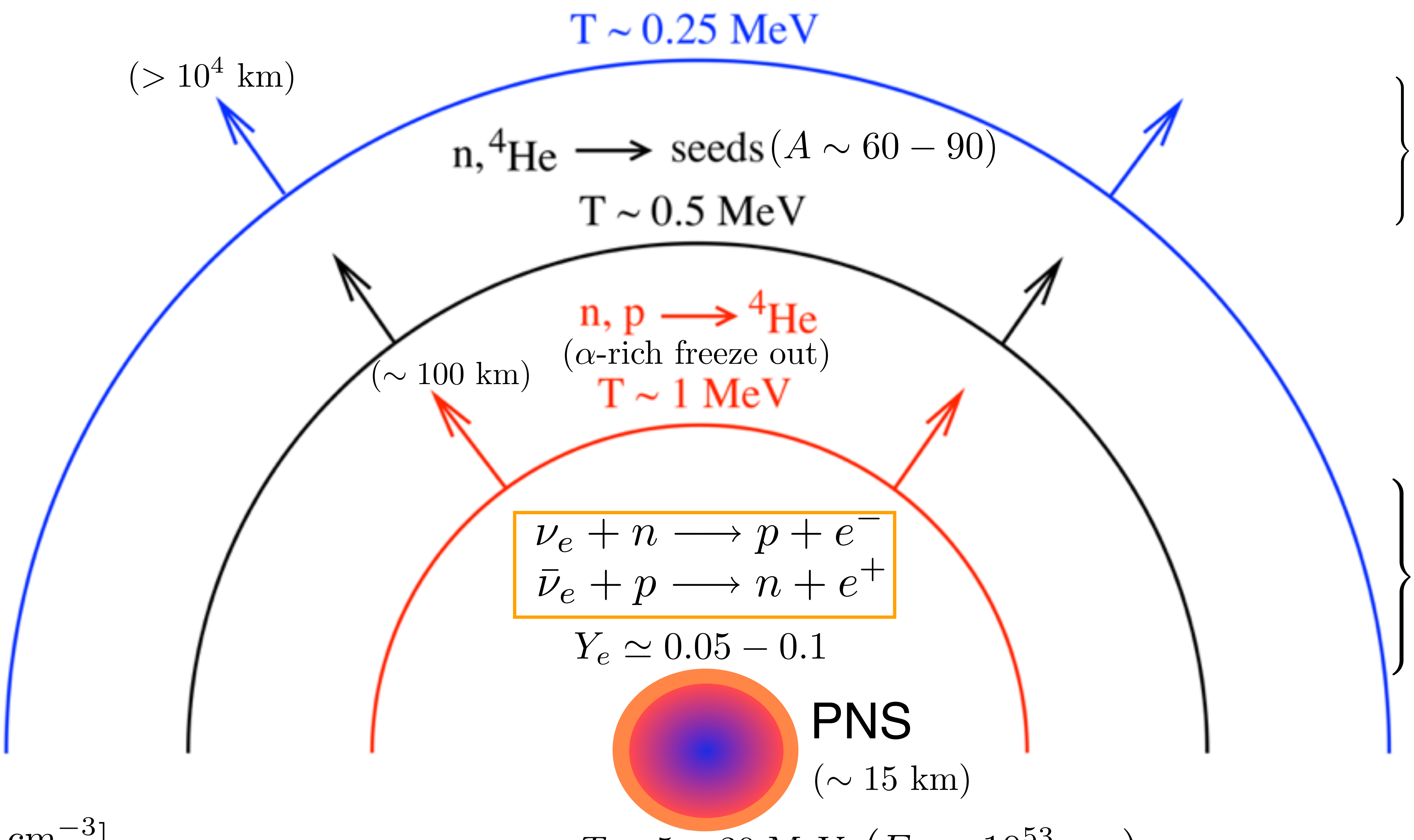
static proto-
neutron star
(PNS)

Schematic picture of “late”– time mass ejection

proton rich ($Y_e > 0.5$)
vp process

neutron rich ($Y_e < 0.5$)
neutron-capture process

formation of heavy nuclei (?)



T ~ 0.25 MeV

< 10

($> 10^4$ km)

n, ^{4}He $\longrightarrow$ seeds ($A \sim 60 - 90$)

seed nuclei

T ~ 0.5 MeV

low-mass outflow: “*v*-driven wind”

10^6

(~ 100 km)

n, p $\longrightarrow$ ^{4}He
(α-rich freeze out)
T ~ 1 MeV

Y_e fix !

10^{10}

$$\boxed{\begin{array}{l} \nu_e + n \longrightarrow p + e^- \\ \bar{\nu}_e + p \longrightarrow n + e^+ \end{array}}$$

neutrino heating

$Y_e \simeq 0.05 - 0.1$

PNS
(~ 15 km)

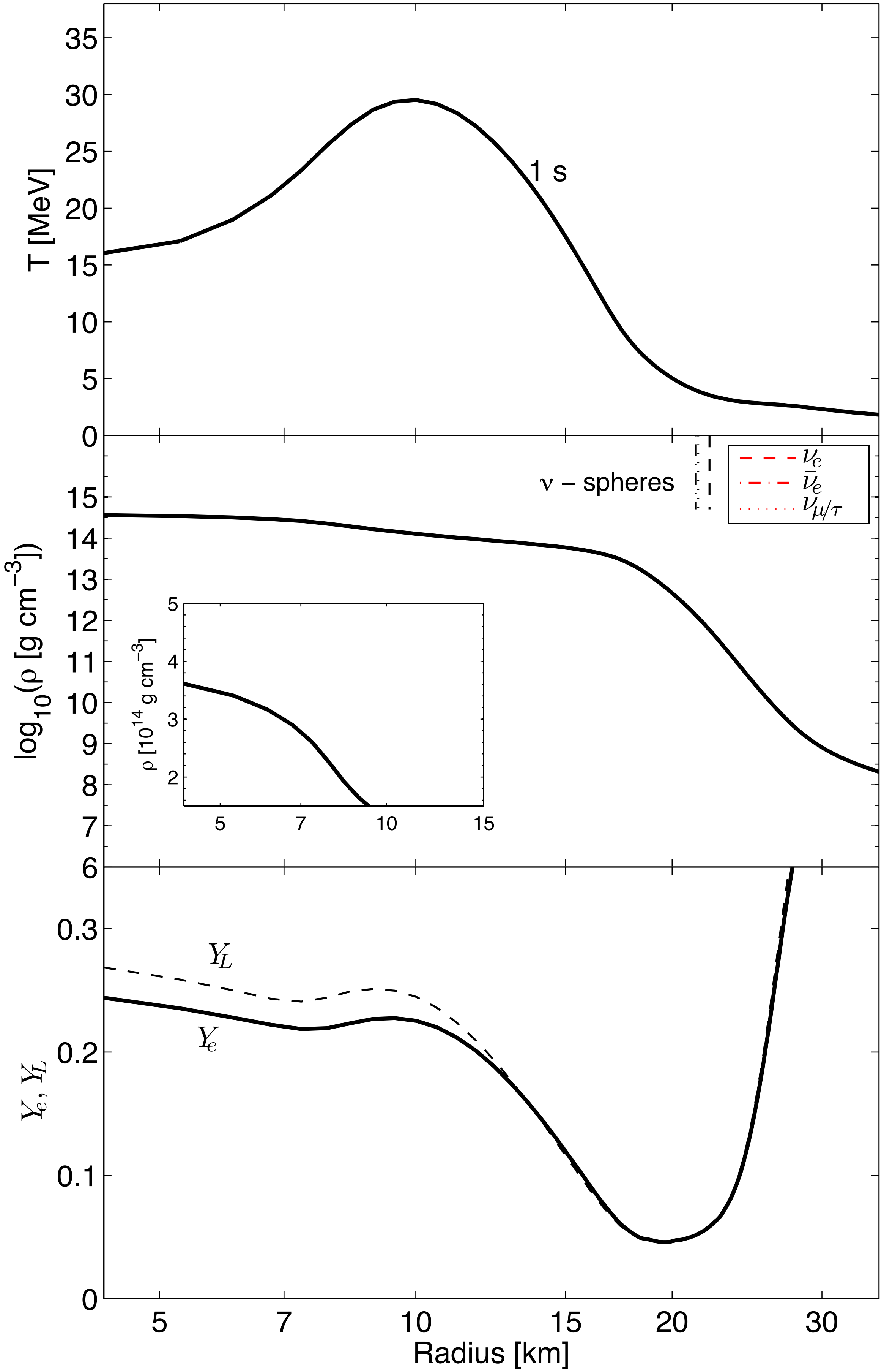
static proto-neutron star (PNS)

10^{14}

$\rho\ [\mathrm{g \cdot cm^{-3}}]$

$T = 5 - 30$ MeV $\left(E_\nu \sim 10^{53}\ \mathrm{erg}\right)$

PNS evolution during deleptonization



$(11.2\ \mathrm{M}_\odot$ progenitor$)$

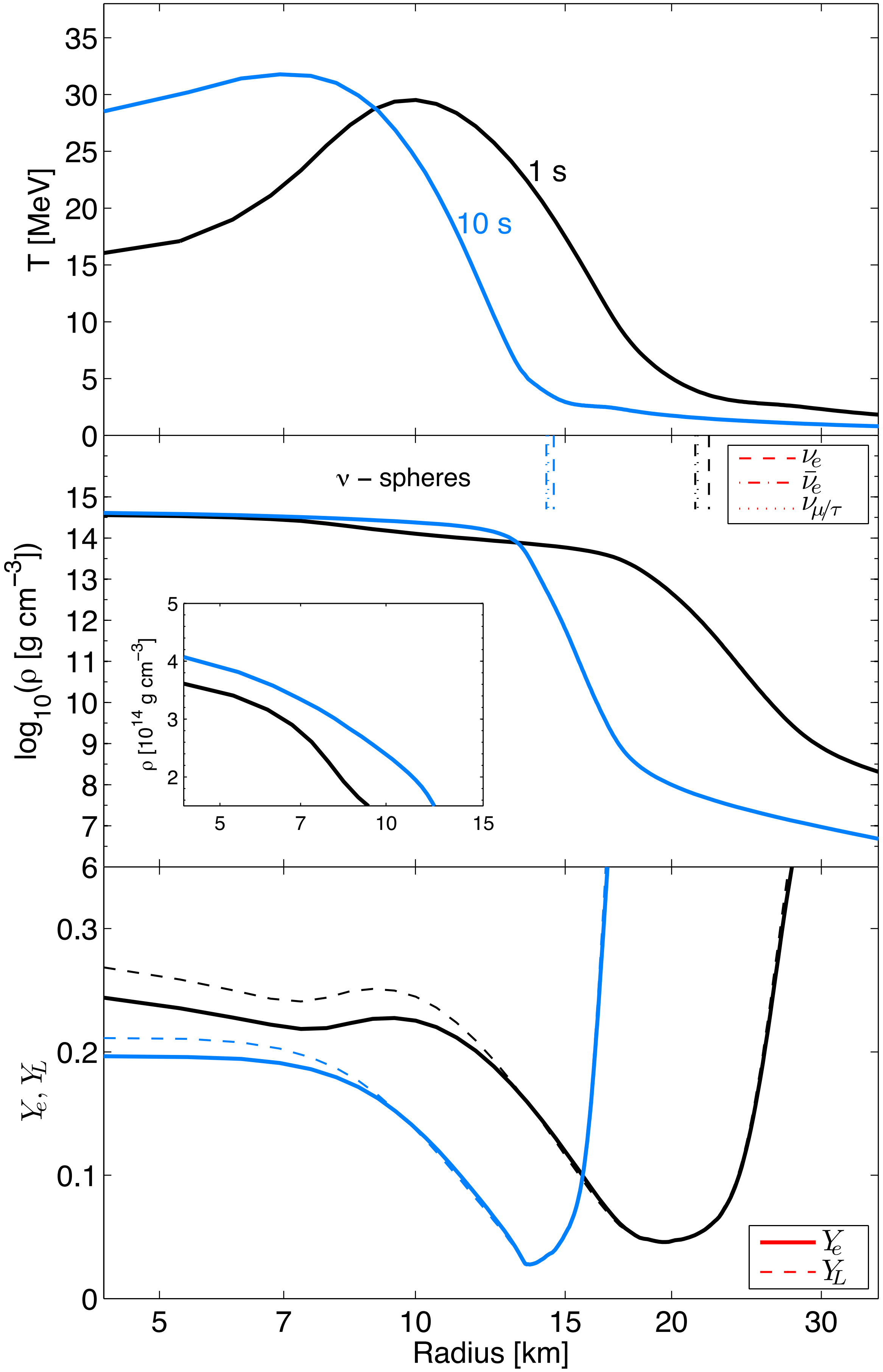
- Non-monotonous *T*–profile; large neutron excess ($Y_e \sim 0.05$); relic from supernova history
- Sharp density gradient at PNS surface; important for *ν*–decoupling
- Still substantial abundance of neutrinos trapped inside PNS; $Y_L = Y_e + Y_{\nu_e} - Y_{\bar{\nu}_e}$

$$\rho|_{R_{\nu_e}} \simeq 5 \times 10^{11}\ \mathrm{g\ cm^{-3}}$$

$$\rho|_{R_{\nu_{\mu/\tau}}} \simeq 10^{12}\ \mathrm{g\ cm^{-3}}$$

(neutrino decoupling)

PNS evolution during deleptonization



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- Substantial PNS contraction due to loss of pressure support; central density & T rise
- Steepening of the density profile at the PNS surface
- ν–decoupling shifts to higher density BUT remain at T~5 MeV; Y_e and Y_L drop continuously

$$\rho|_{R_{\nu_e}} \simeq 10^{12}\ \text{g cm}^{-3}$$

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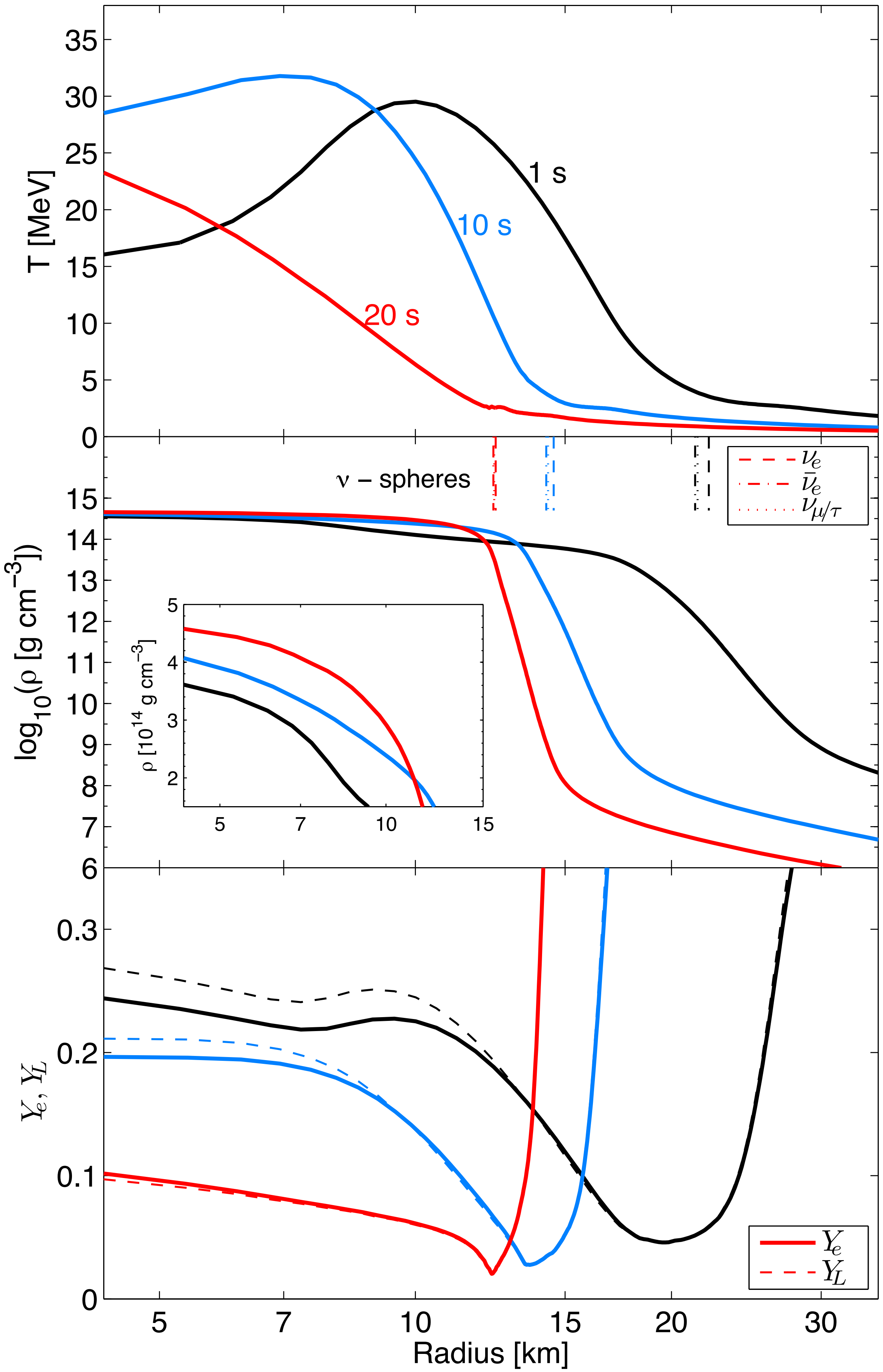
(neutrino decoupling)

PNS evolution during deleptonization



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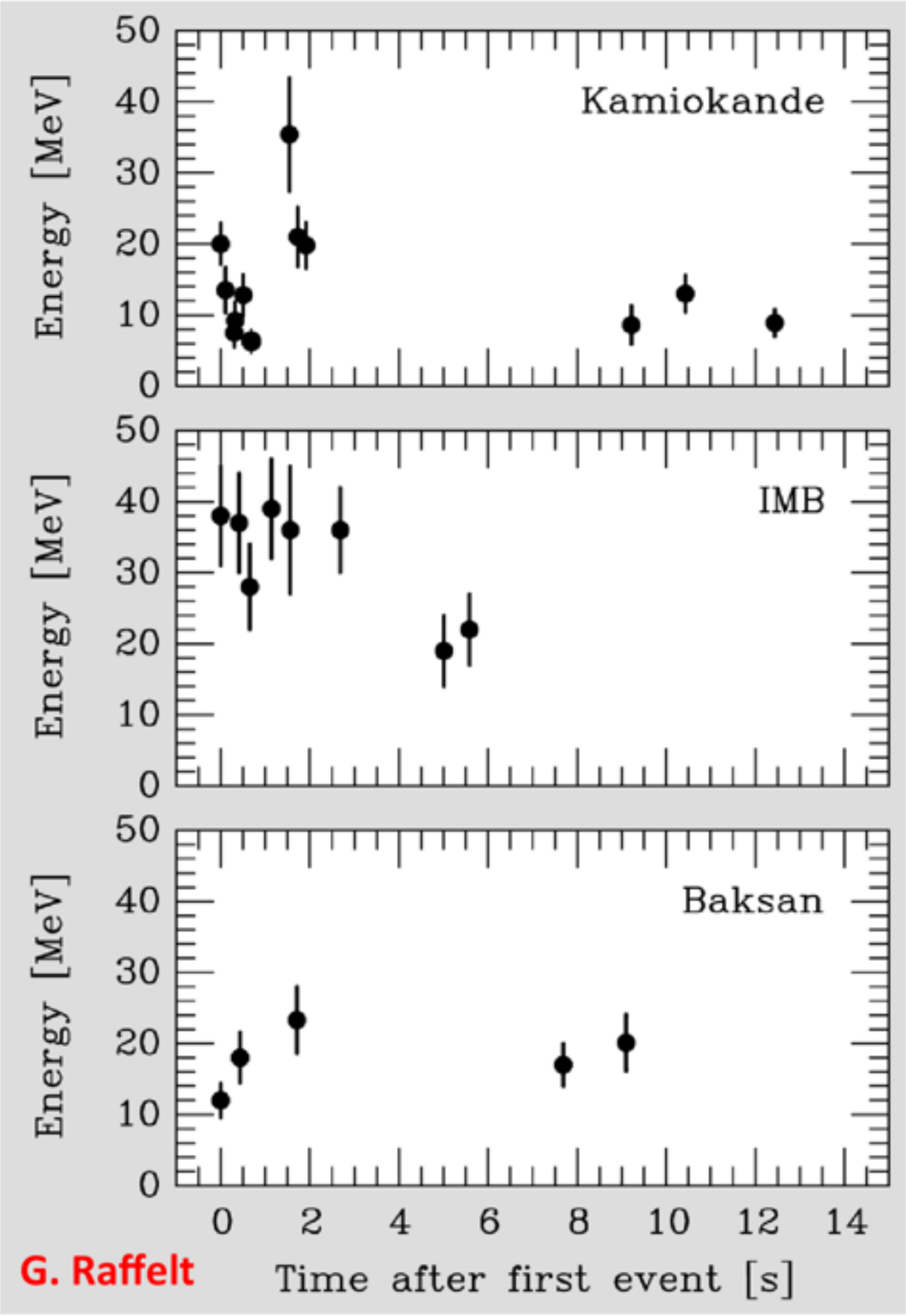
- Substantial PNS contraction due to loss of pressure support; central density & *T* rise
- Steepening of the density profile at the PNS surface
- *ν*–decoupling shifts to higher density BUT remain at *T*~5 MeV; Y_e and Y_L drop continuously
- Continuous contraction BUT now central *T* starts to decrease; Y_ν —> 0 (!)
- Average *ν*–decoupling ~10^{14} g cm^{-3}

Neutrino emission during PNS deleptonization

Neutrinos from SN1987A



SN rates:

1SN s^{-1} $universe^{-1}$

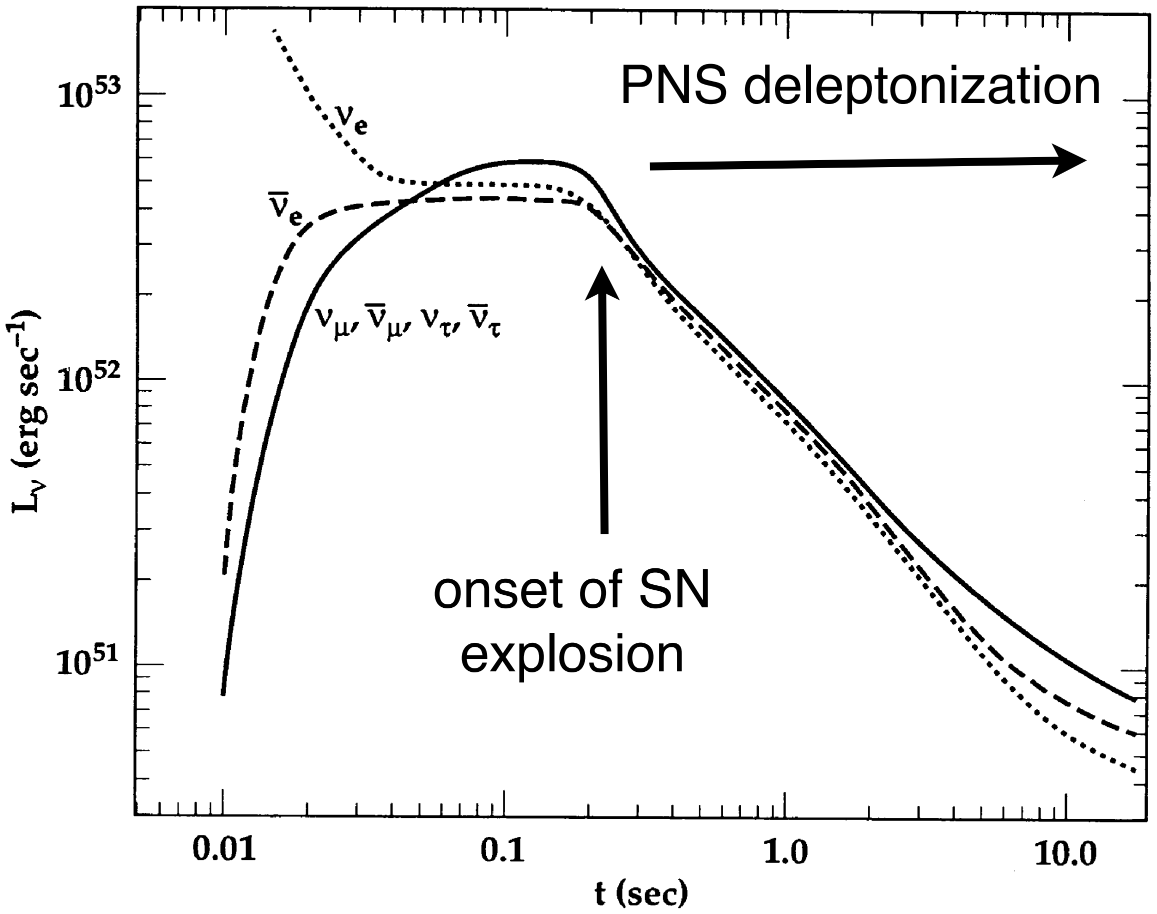
1SN $year^{-1}$ 10^6 pc^{-1}

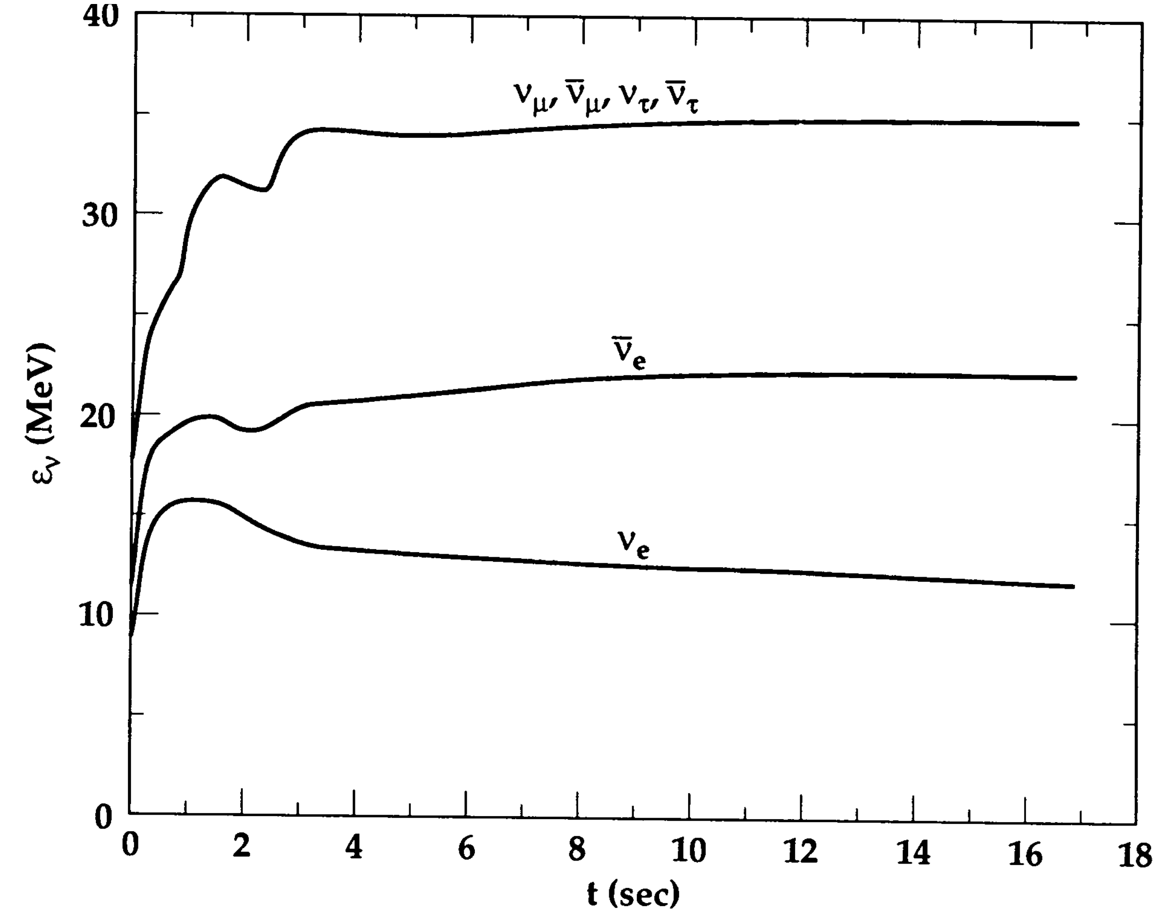
1SN 100 $years^{-1}$ Milky Way^{-1}

Insights from SN1987A (large Magellanic Cloud):

- Progenitor star $18\ \mathrm{M}_\odot$
- Confirmation of the basic model
- Stellar collapse to a (proto) neutron star ~3 *x* 10^{53} erg
- 99% emitted in neutrinos over ~10 seconds
- Explosion energy (kinetic energy of ejecta at stellar surface) ~10^{51} erg

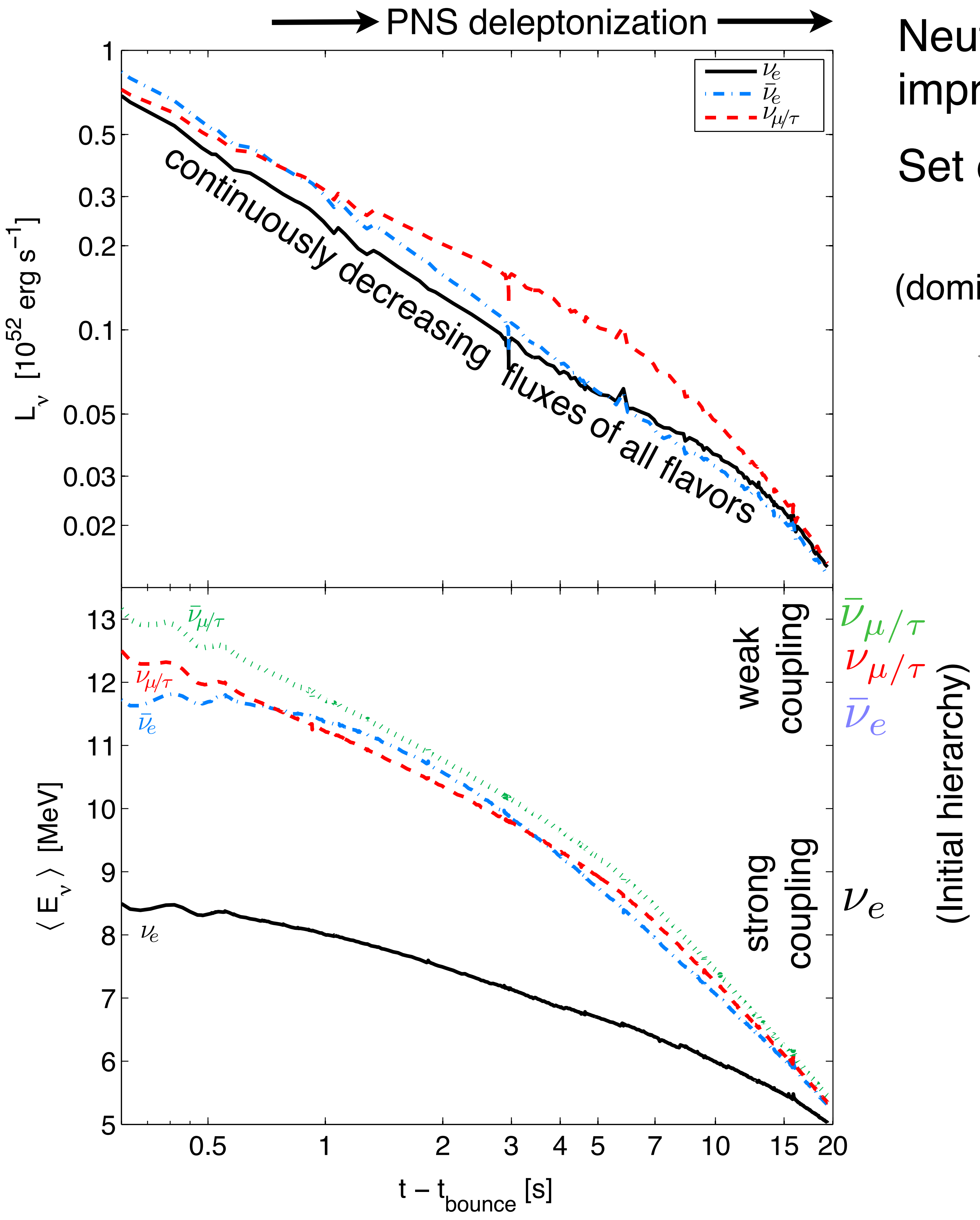
Some historical remark: the early 1990s





- Woosley et al. (1994) ApJ 433, 229 (first complete “modern” simulation incl. neutrino transport)
- Continuously decreasing neutrino fluxes; flavor differences depend on details of weak rates
- Problem with average energies
- Unphysically high entropy per baryon (~300 k_B)
- Increasing neutron excess of ejected matter and strong *r*–process (*A*=195, 3rd peak)

Current state-of-the-art



Neutrino transport and input physics improved over the years. . .

Set of weak processes considered:

charged current reactions

(dominant energy exchange; strong coupling to matter)

$$\{\ e^- + \langle A, Z\rangle \ \leftrightarrows\ \langle A, Z-1\rangle + \nu_e\ \}$$

$$e^- + p \ \leftrightarrows\ n + \nu_e$$

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

elastic scattering

(momentum exchange; largest opacity)

$$\{\ \nu + \langle A, Z\rangle \ \leftrightarrows\ \langle A, Z\rangle + \nu\ \}$$

$$\nu + N \ \leftrightarrows\ \nu' + N$$

inelastic scattering

(thermalization of *ν*–spectra)

$$\nu + e^\pm \ \leftrightarrows\ \nu' + e^\pm$$

pair processes

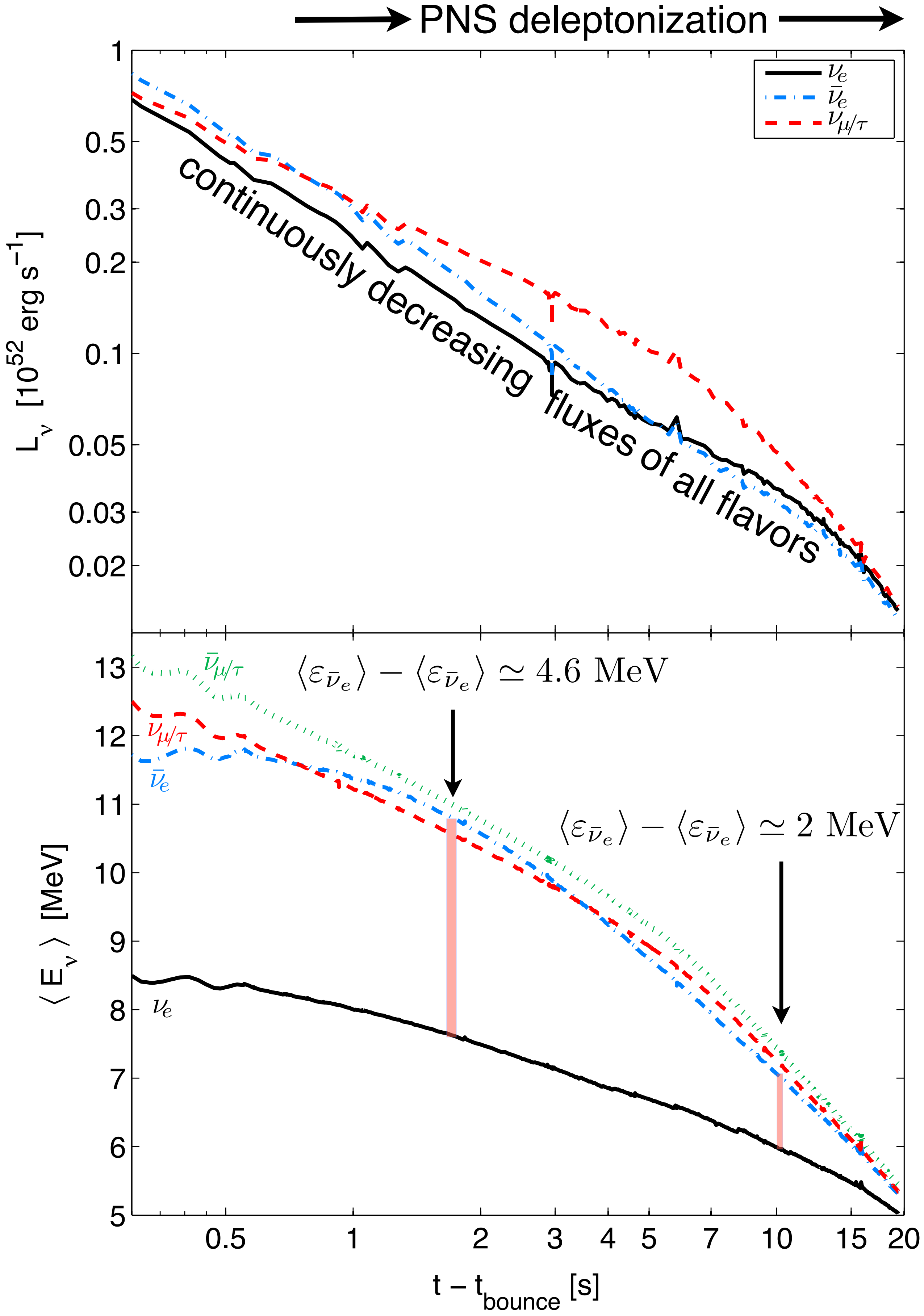
(production of heavy flavor *ν*'s)

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

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

$$\nu_e + \bar{\nu}_e \ \leftrightarrows\ \nu_{\mu/\tau} + \bar{\nu}_{\mu/\tau}$$

Neutrino luminosities and average energies



Continuously reducing spectral differences between all neutrino species.

Relevance for nucleosynthesis:

(Qian et al. (1996), ApJ 471, 331)

$$L_{\nu_{\mu/\tau}} > L_{\nu_e} \simeq L_{\bar\nu_e} \qquad \langle E_{\nu_{\mu/\tau}}\rangle \simeq \langle E_{\bar\nu_e}\rangle > \langle E_{\bar\nu_e}\rangle$$

$$\langle\varepsilon_{\bar\nu_e}\rangle - \langle\varepsilon_{\nu_e}\rangle \begin{cases} \gtrsim 5\ \mathrm{MeV} & (Y_e < 0.5)\ \text{neutron rich} \\ < 5\ \mathrm{MeV} & (Y_e > 0.5)\ \text{proton rich} \end{cases}$$

$$\left(\langle\varepsilon_\nu\rangle = \langle E_\nu^2\rangle / \langle E_\nu\rangle \right)$$

Dominant weak processes:

$$\bar\nu_e + p \longrightarrow n + e^+ \qquad \text{(neutron rich)}$$

$$\nu_e + n \longrightarrow p + e^- \qquad \text{(proton rich)}$$

What determines the magnitude of spectral differences?

Charged-current weak rates in supernova simulations

- Neutrino opacity/reaction rate (charged-current weak processes): $\nu_e + n \longrightarrow e^- + p$

$$1/\lambda(E_{\nu_e}) = \frac{G_F^2 V_{ud}^2}{\pi(\hbar c)^7}(g_V^2 + 3g_A^2)\int \frac{d^3p_e}{(2\pi)^3}(1 - F_e(E_e))\, S(q_0, q)$$

$$q_0 = E_\nu - E_e\ , \qquad q = |\mathbf{p}_\nu - \mathbf{p}_e|$$

$$1/\lambda_\nu(E_\nu) \simeq \frac{G_F^2 V_{ud}^2}{\pi(\hbar c)^7}(g_V^2 + 3g_A^2)\, p_e\, E_e(1 - F_e(E_e))\frac{n_n - n_p}{1 - e^{\beta(\mu_p^0 - \mu_n^0)}}$$

(zero-momentum transfer approximation)

Reddy et al., (1998) PRD 58, 013009

Bruenn, S.W. (1985) ApJS 58, 77

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(zero-momentum transfer approximation)

- Description of weak processes based on free-Fermi gas model

(μ_n^0, μ_p^0) (free Fermi-gas chemical potentials)

- Supernova equations of state (EOS) are based on interacting nucleons and treat them as quasi-particles that move in a potential, *U_N* (!)

$$\begin{aligned} \mu_n^0 &= \mu_n - U_n - m_n \\ \mu_p^0 &= \mu_p - U_p - m_p \end{aligned}$$

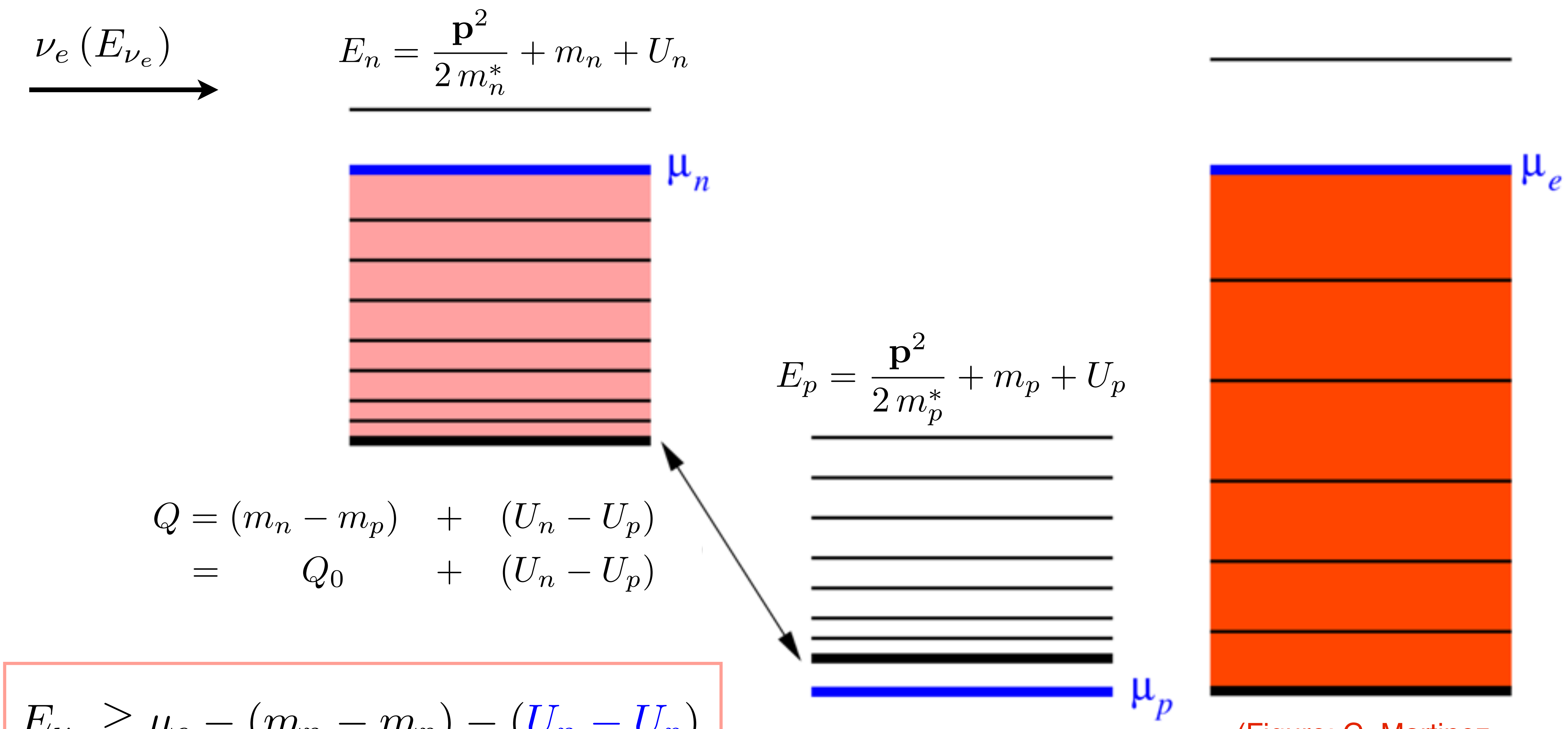
(U_n, U_p) (nucleon self energies)

Reddy et al., (1998) PRD 58, 013009

Bruenn, S.W. (1985) ApJS 58, 77

Weak rates consistent with the equation of state

- Similar situation as in heavy neutron rich nucleus: $\nu_e + n \longrightarrow e^- + p$



$$E_n = \frac{\mathbf{p}^2}{2\,m_n^*} + m_n + U_n$$

$$E_p = \frac{\mathbf{p}^2}{2\,m_p^*} + m_p + U_p$$

$$\begin{aligned} Q &= (m_n - m_p) \quad + \quad (U_n - U_p) \\ &= \qquad Q_0 \qquad + \quad (U_n - U_p) \end{aligned}$$

$$\boxed{E_{\nu_e} \gtrsim \mu_e - (m_n - m_p) - ({\color{blue}U_n - U_p})}$$

(Figure: G. Martinez-Pinedo)

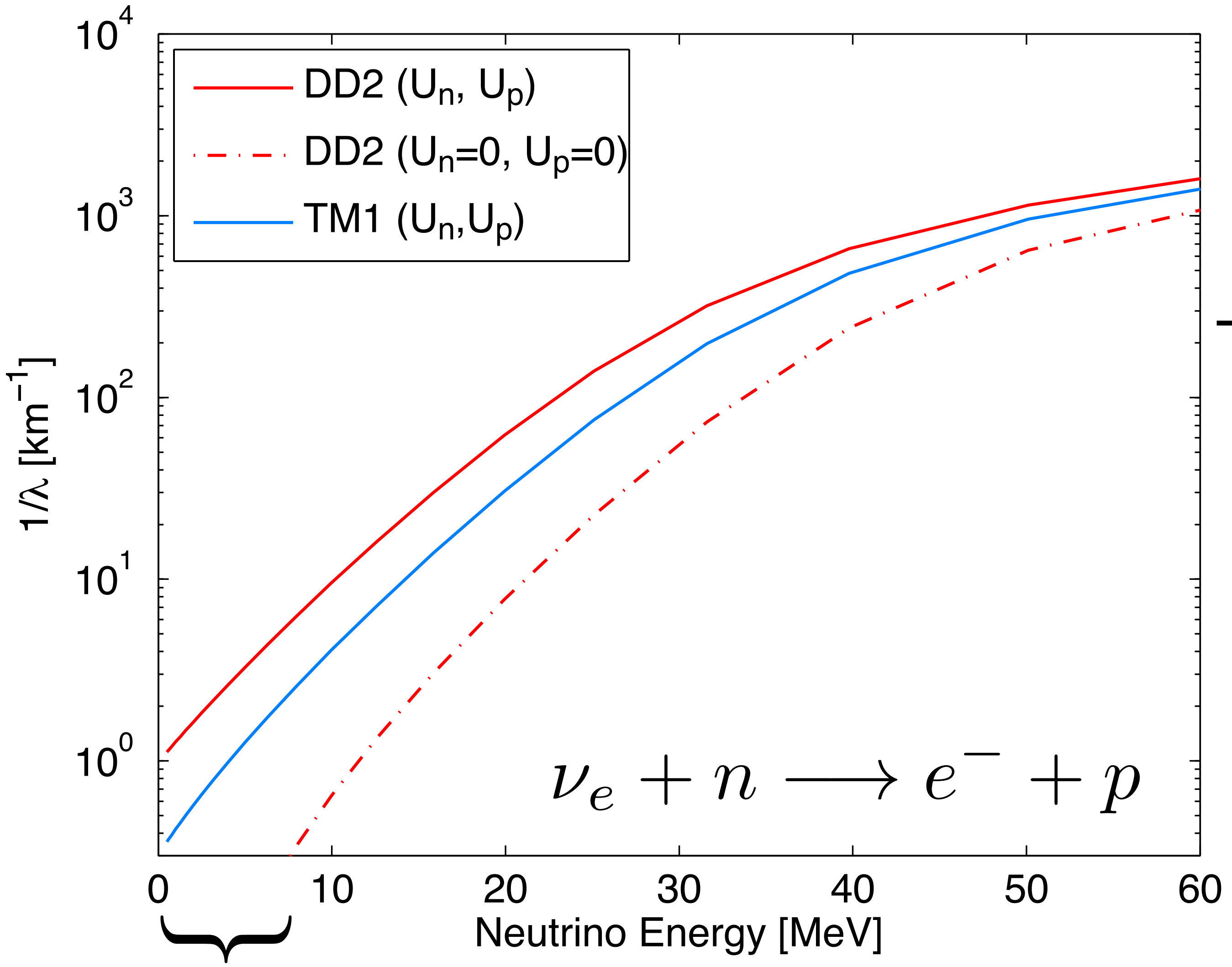
$(\mu_e \simeq 50 - 100\ \mathrm{MeV})$

$(U_n - U_p \simeq 1 - 10\ \mathrm{MeV})$

Martinez-Pinedo & T.F., et al. (2012) PRL,109, 251104

Roberts et al., (2012) PRC 86, 065803

Neutrino opacity consistent with the EOS



$$\nu_e + n \longrightarrow e^- + p$$

$$\sim (U_n - U_p)$$

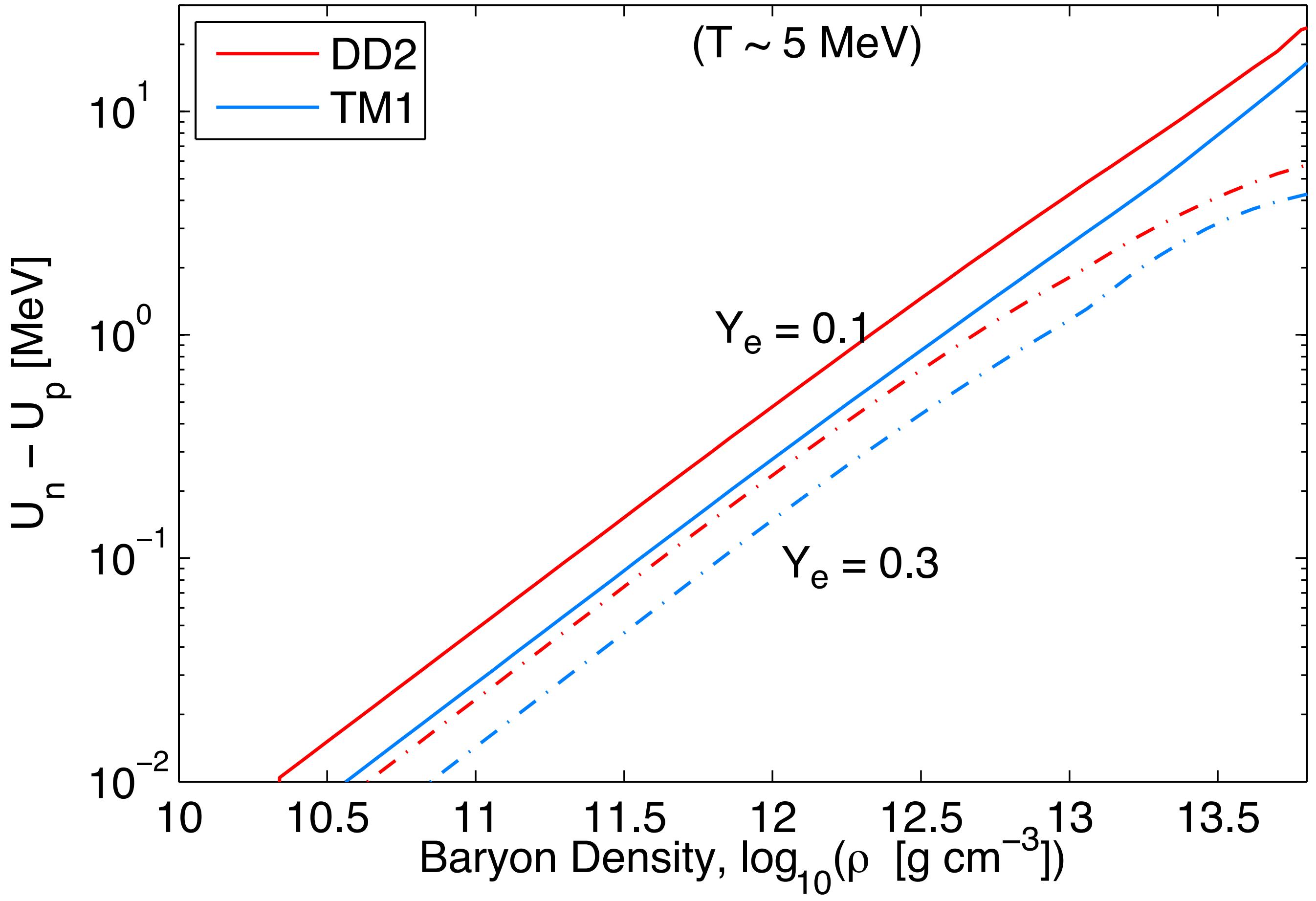
— — consistent description (DD2 , TM1)

-·-· inconsistent description (DD2)

Large suppression of low-energy neutrinos

$$E_{\nu_e} = E_{e^-} - (m_n - m_p) - (U_n - U_p)$$

Differences between DD2 and TM1 are due to different values of nucleon self-energies



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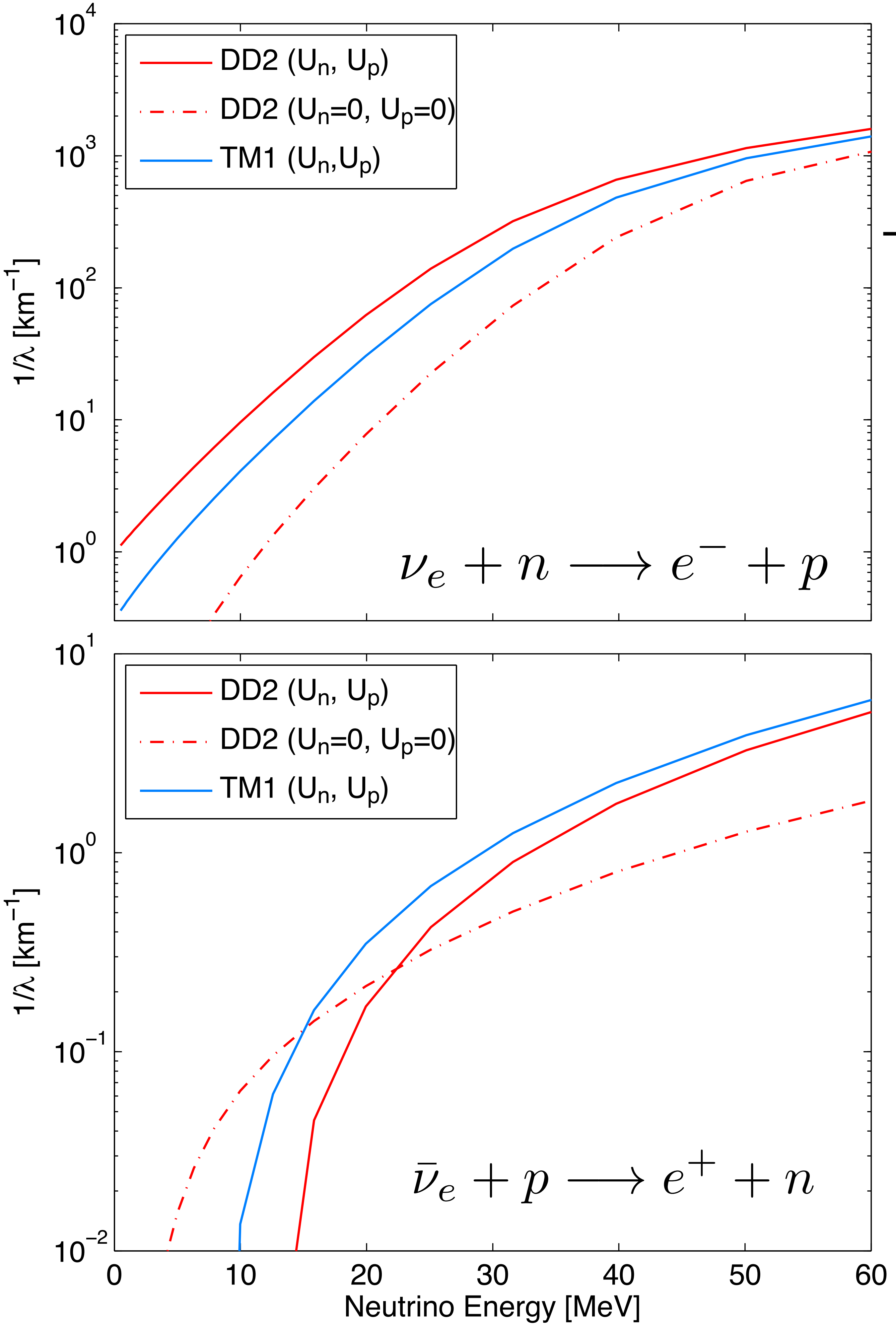

consistent description (DD2 , TM1)

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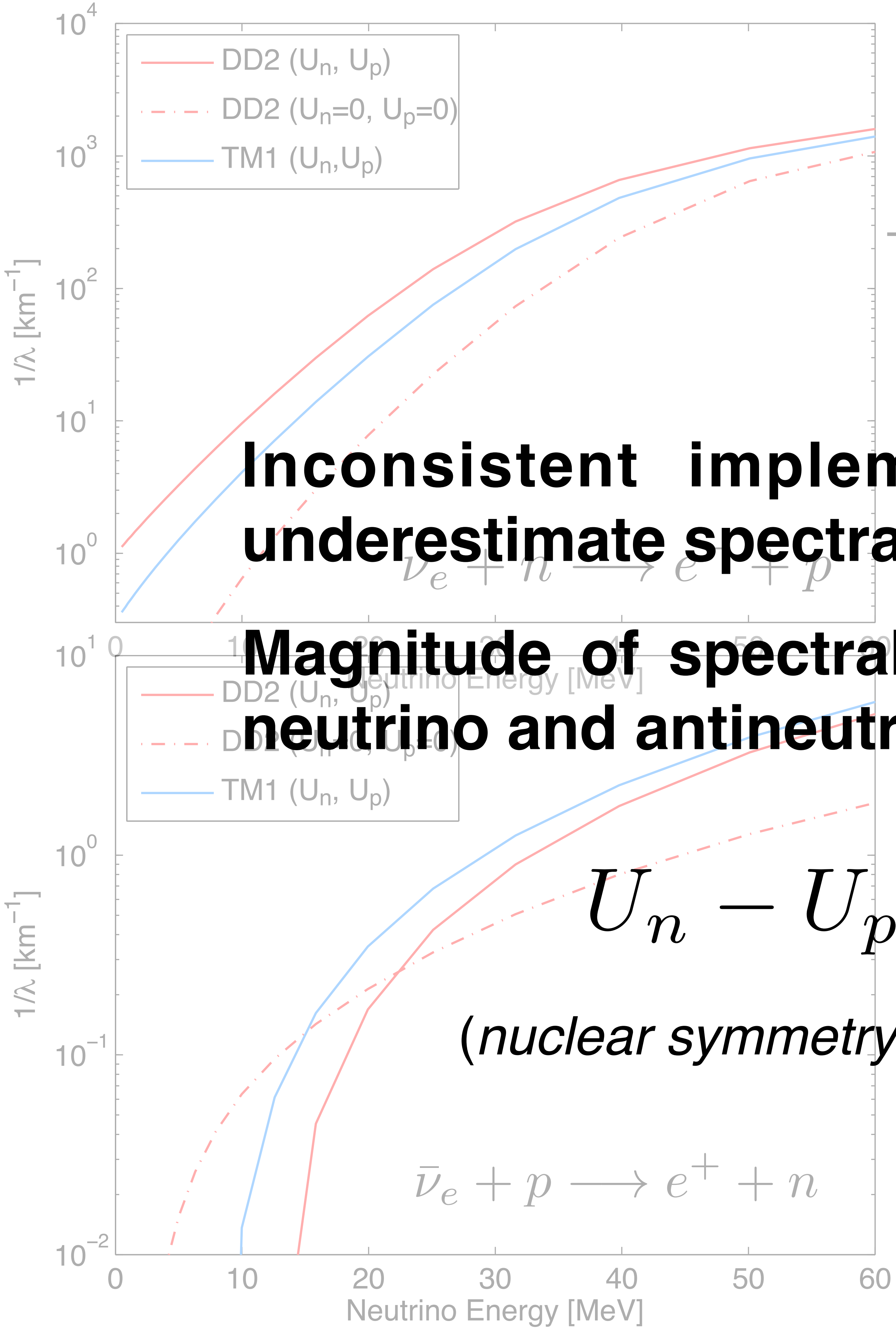
Overestimated low-energy anti neutrinos

$$E_{\bar{\nu}_e} = E_{e^+} + (m_n - m_p) + (U_n - U_p)$$

Neutrino opacity consistent with the EOS



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Overestimated low-energy anti neutrinos

$$E_{\bar{\nu}_e} = E_{e^+} + (m_n - m_p) + (U_n - U_p)$$

Inconsistent implementation: tends to underestimate spectral differences

Magnitude of spectral differences between neutrino and antineutrino given by:

$$U_n - U_p \sim S_B^F(\rho)$$

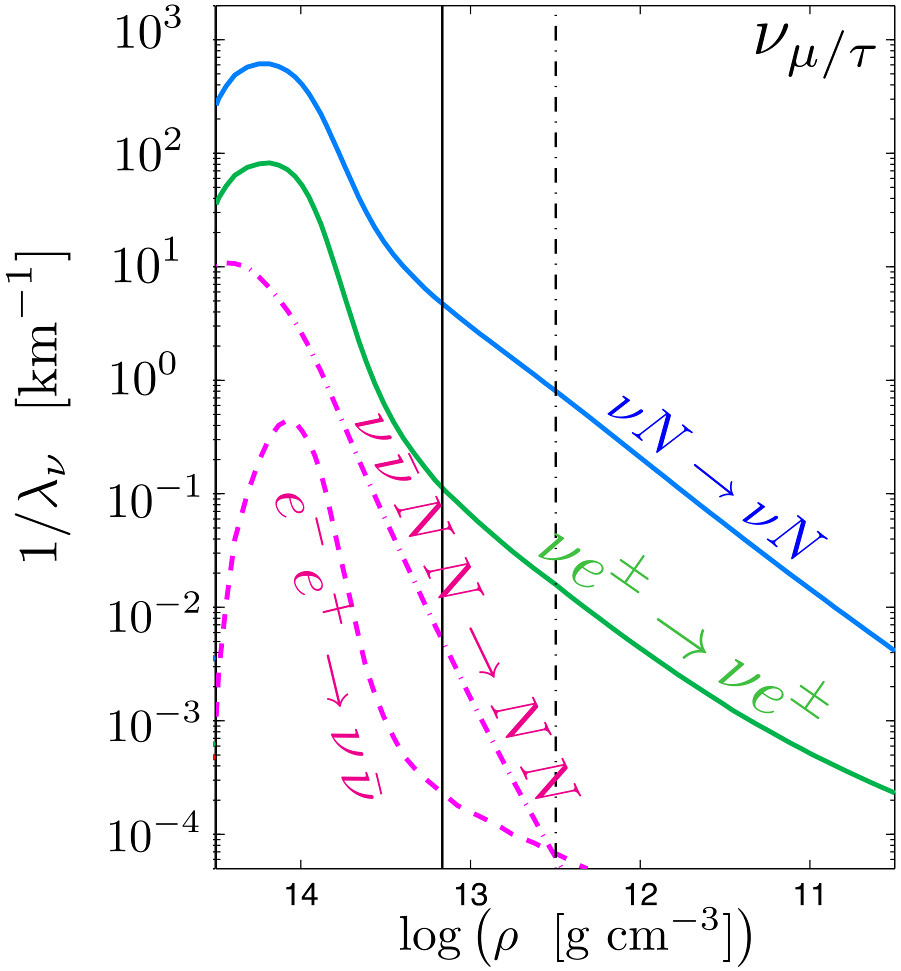
(*nuclear symmetry energy*; EOS quantity)

Opacity during deleptonization

Neutrino energy integration:

$$\frac{1}{\lambda_\nu}\ \left[\frac{1}{\mathrm{km}}\right] \propto \int E^2 dE \frac{1}{\lambda_\nu}(E) f_\nu(E)$$

(Note: no charged-current processes for μ-neutrinos)



⟵ PNS ⟶

1 second after explosion onset

TF et al.,(2012)
PRD 85, 083003

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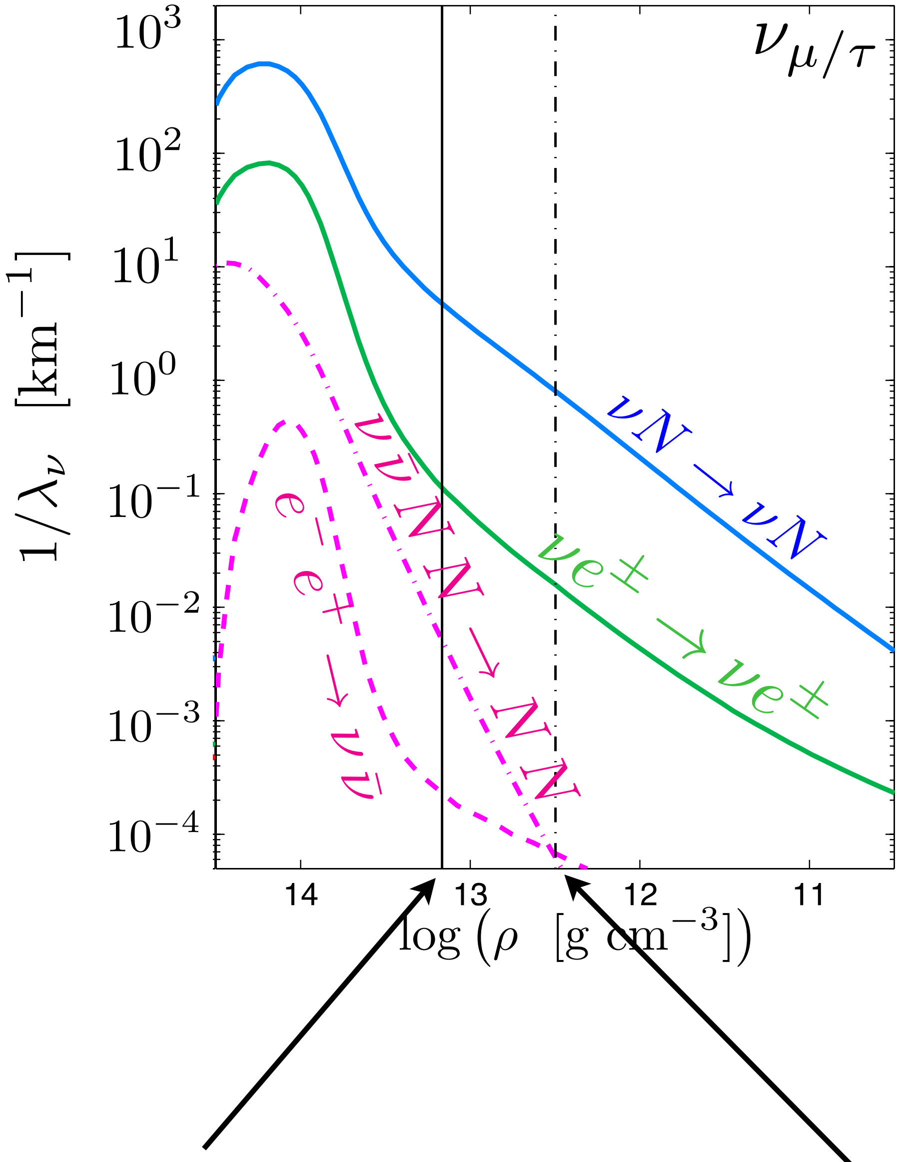


1 second after explosion onset

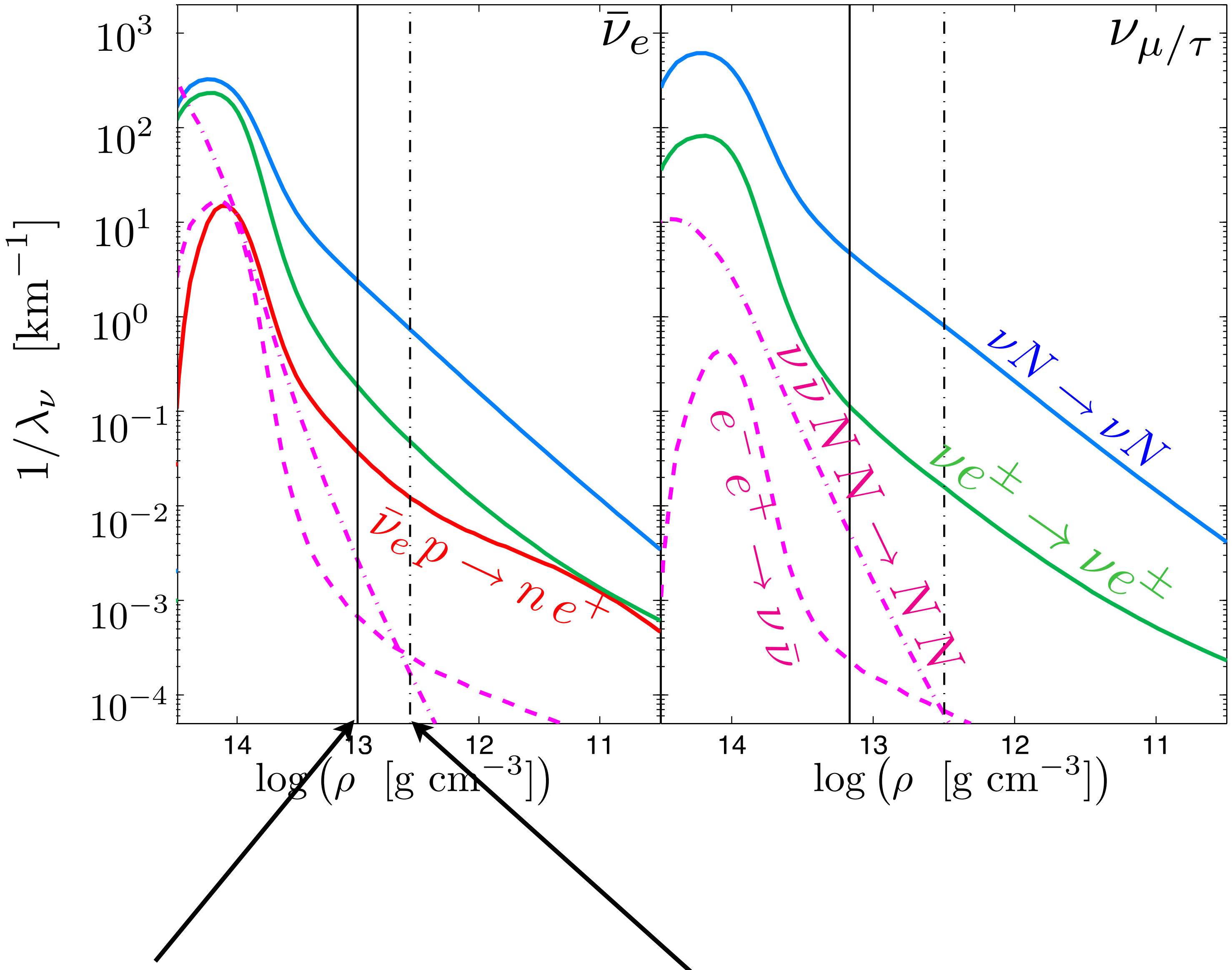
Neutrinospheres: last energy exchange last scattering

Largest opacity: scattering on nucleons (elastic process)

Largest energy exchange: scattering on $e^{\pm}$

TF et al.,(2012)
PRD 85, 083003

Opacity during deleptonization



last energy exchange

last scattering

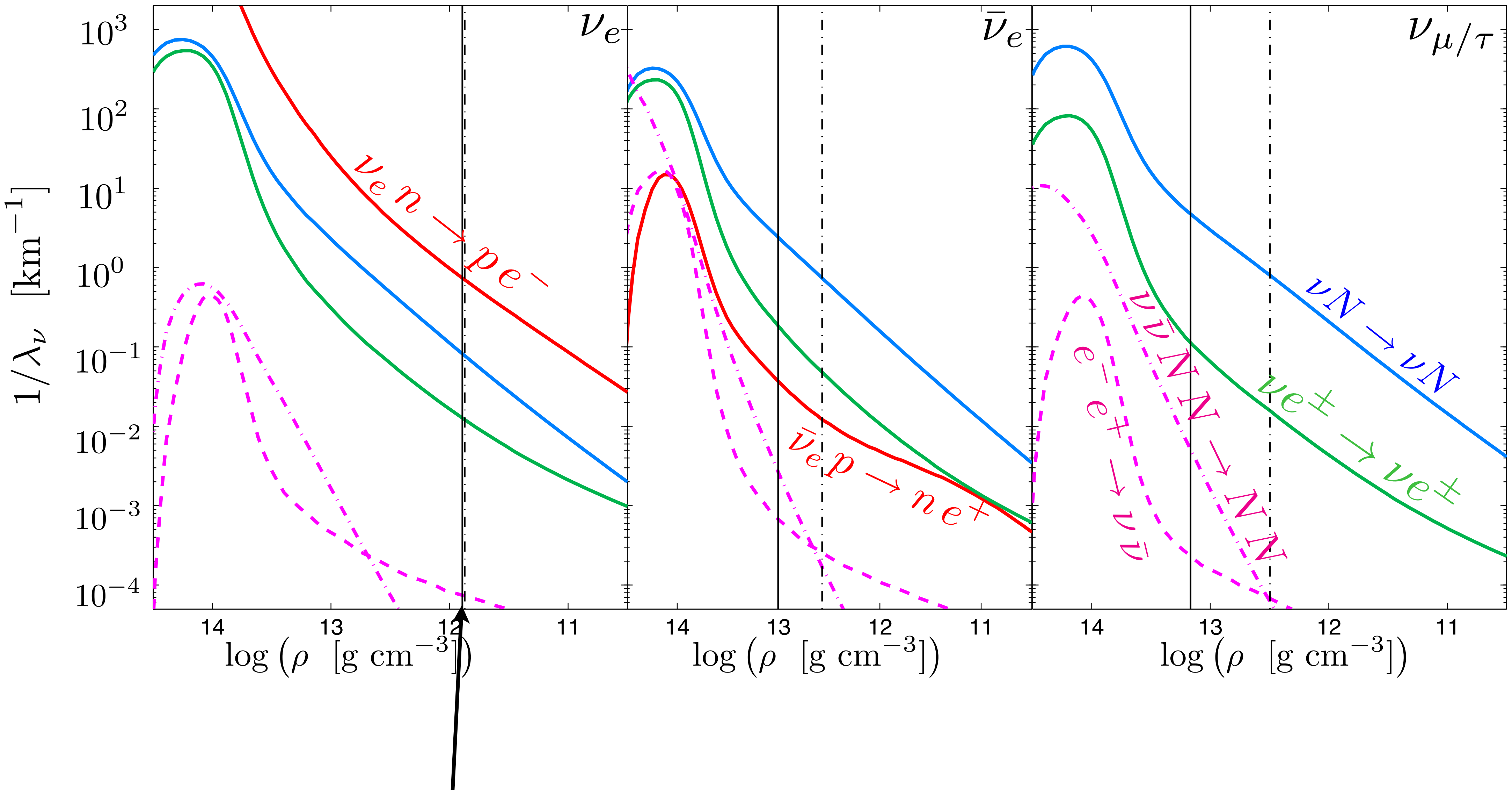
1 second after
explosion onset

Largest opacity: scattering on nucleons (elastic process)

Largest energy exchange: scattering on $e^\pm$ ~ absorption on protons

TF et al.,(2012)
PRD 85, 083003

Opacity during deleptonization



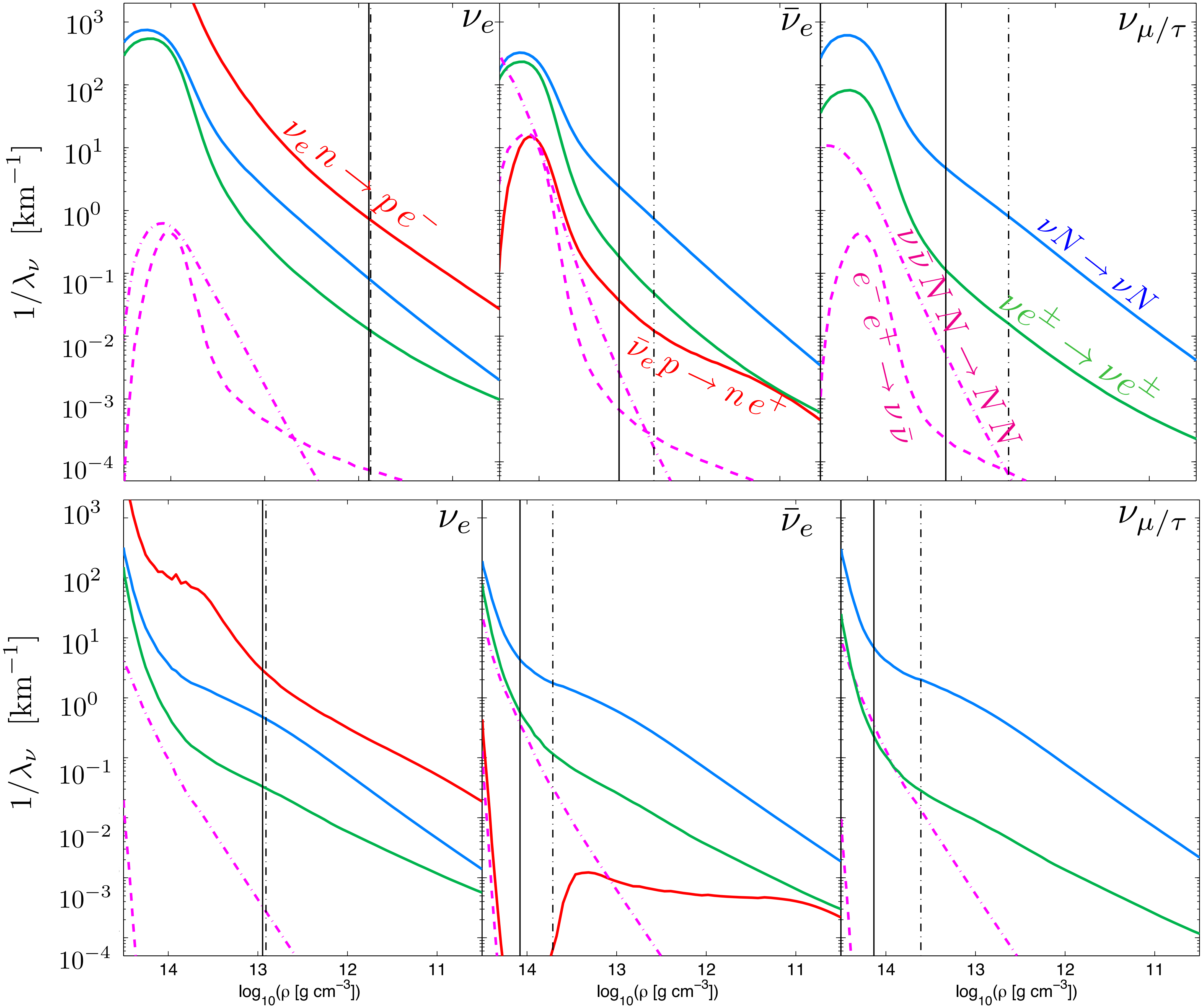
1 second after explosion onset

last energy exchange ~ last scattering

Largest opacity: absorption on neutrons (inelastic process)

TF et al.,(2012)
PRD 85, 083003

Opacity during deleptonization



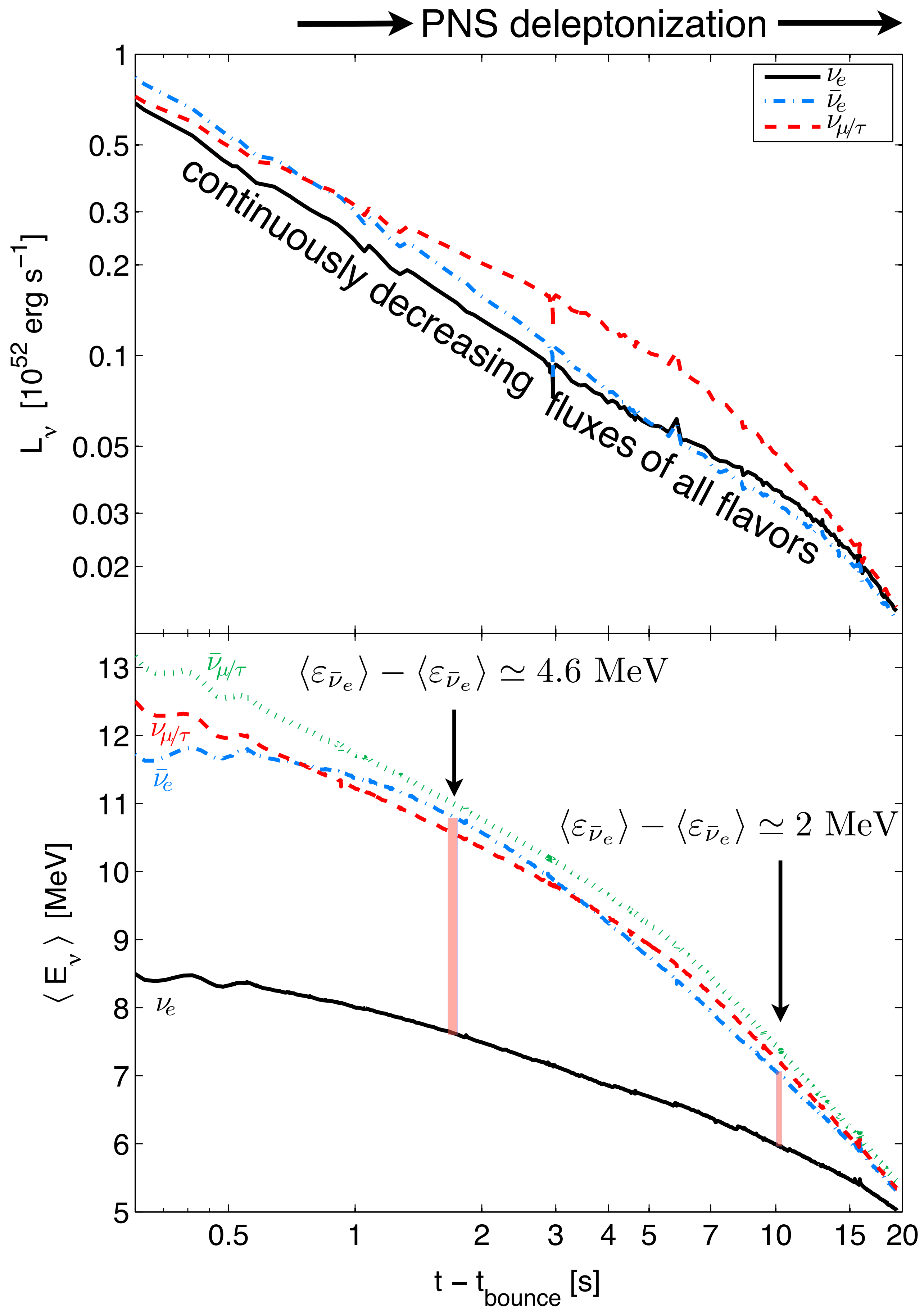
1 second after explosion onset

10 second after explosion onset

TF et al.,(2012)
PRD 85, 083003

Some nucleosynthesis results

Neutrino luminosities and average energies



Continuously reducing spectral differences between all neutrino species.

Relevance for nucleosynthesis:

(Qian et al. (1996), ApJ 471, 331)

$$L_{\nu_{\mu/\tau}} > L_{\nu_e} \simeq L_{\bar{\nu}_e} \qquad \langle E_{\nu_{\mu/\tau}} \rangle \simeq \langle E_{\bar{\nu}_e} \rangle > \langle E_{\bar{\nu}_e} \rangle$$

$$\langle \varepsilon_{\bar{\nu}_e} \rangle - \langle \varepsilon_{\nu_e} \rangle \begin{cases} \gtrsim 5 \text{ MeV} & (Y_e < 0.5) \\ & \text{neutron rich} \\ < 5 \text{ MeV} & (Y_e > 0.5) \\ & \text{proton rich} \end{cases}$$

$$\left(\langle \varepsilon_\nu \rangle = \langle E_\nu^2 \rangle / \langle E_\nu \rangle \right)$$

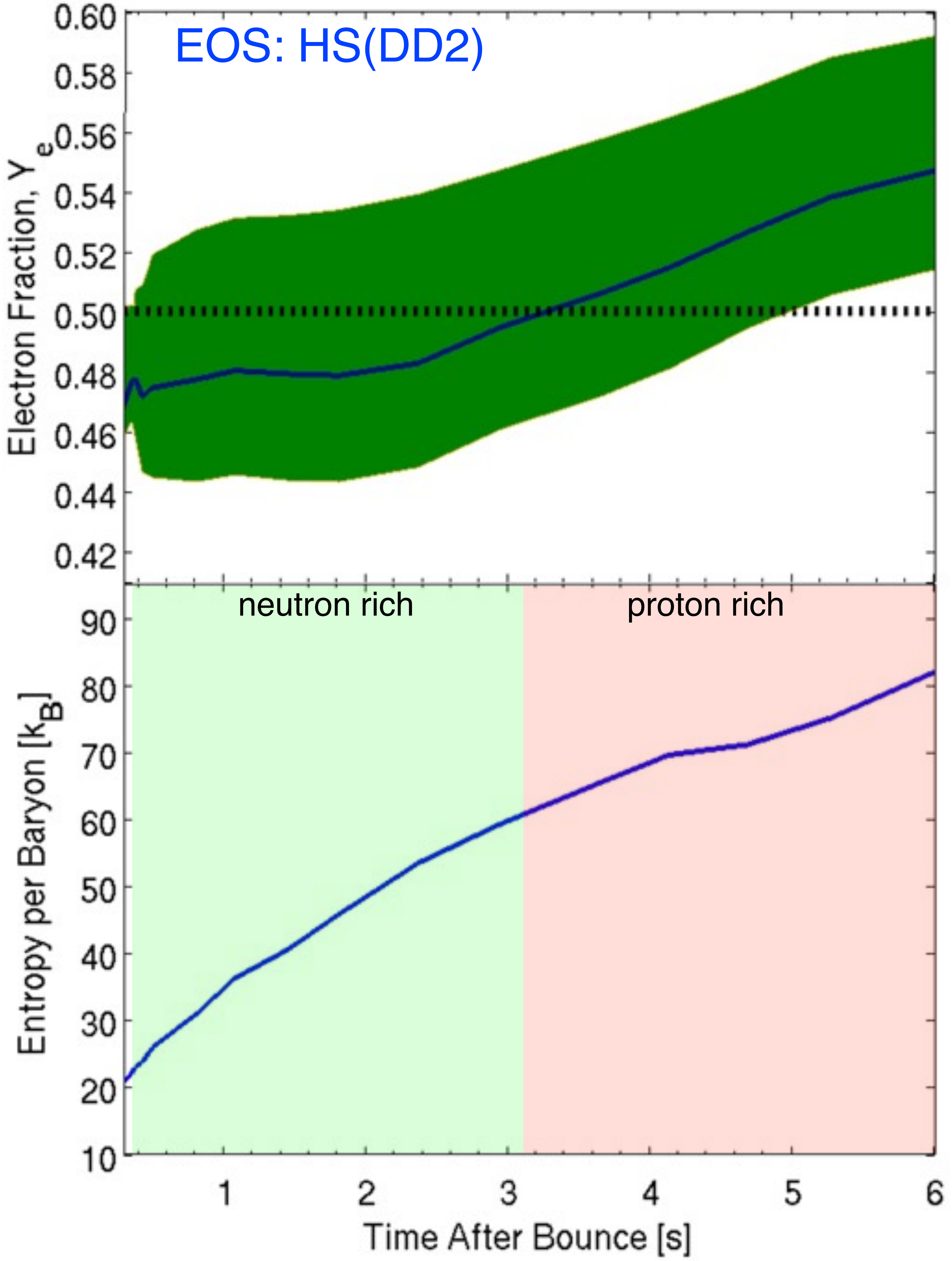
Dominant weak processes:

$$\bar{\nu}_e + p \longrightarrow n + e^+ \qquad \text{(neutron rich)}$$

$$\nu_e + n \longrightarrow p + e^- \qquad \text{(proton rich)}$$

What determines the magnitude of spectral differences?

Nucleosynthesis relevant conditions



Early ν-driven wind phase:
neutron-rich ejecta

Late phase:
ejecta become proton rich

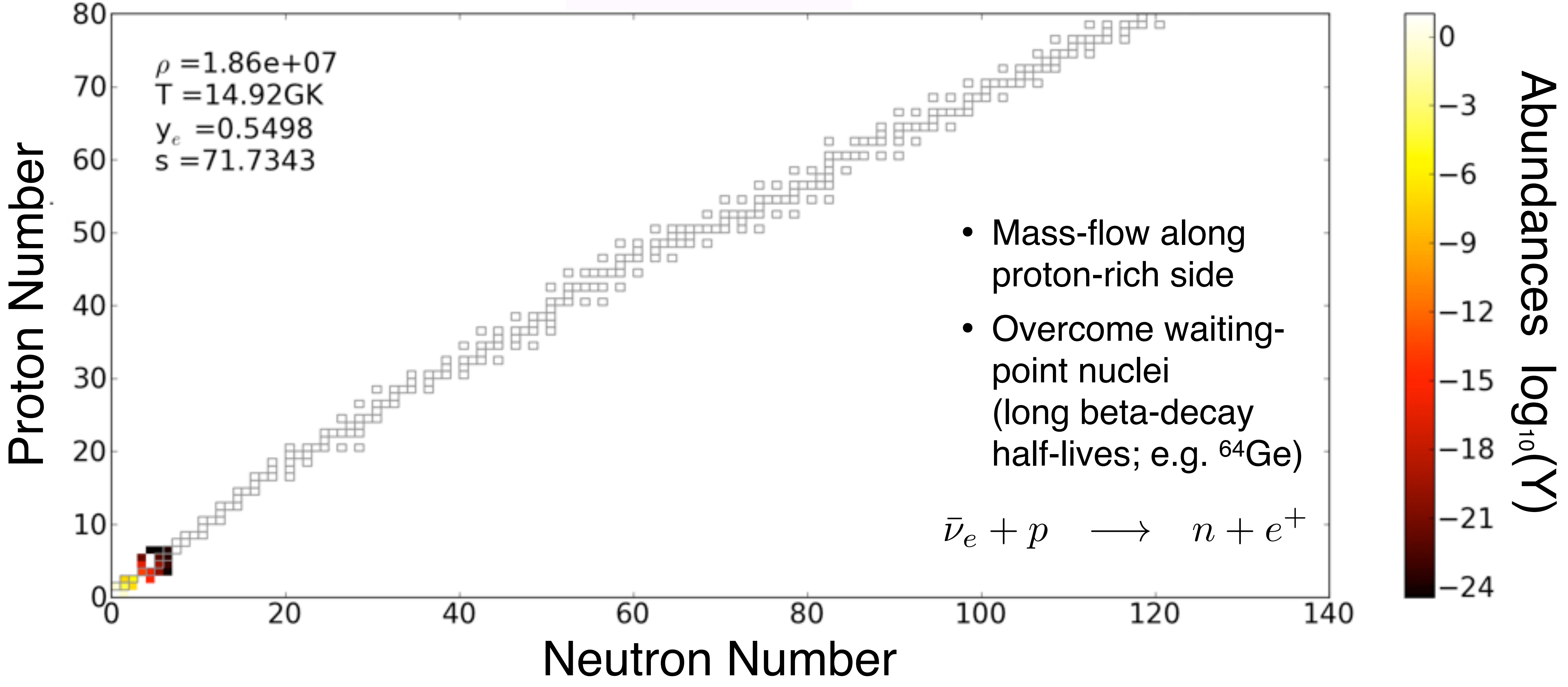
- For the tested EOS, we find
  early phase: $Y_e \approx 0.48$ (0.44 – 0.54)
  late phase: $Y_e > 0.50$ (0.49 – 0.62)
- Moderate entropy per baryon
  early phase: S~20–65 k_B
  late phase: S~65–120 k_B
- Model uncertainties (±10%):

  weak rates, nuclear symmetry energy, weak magnetism, inelastic processes,

  reverse shock, ν-oscillations . . .

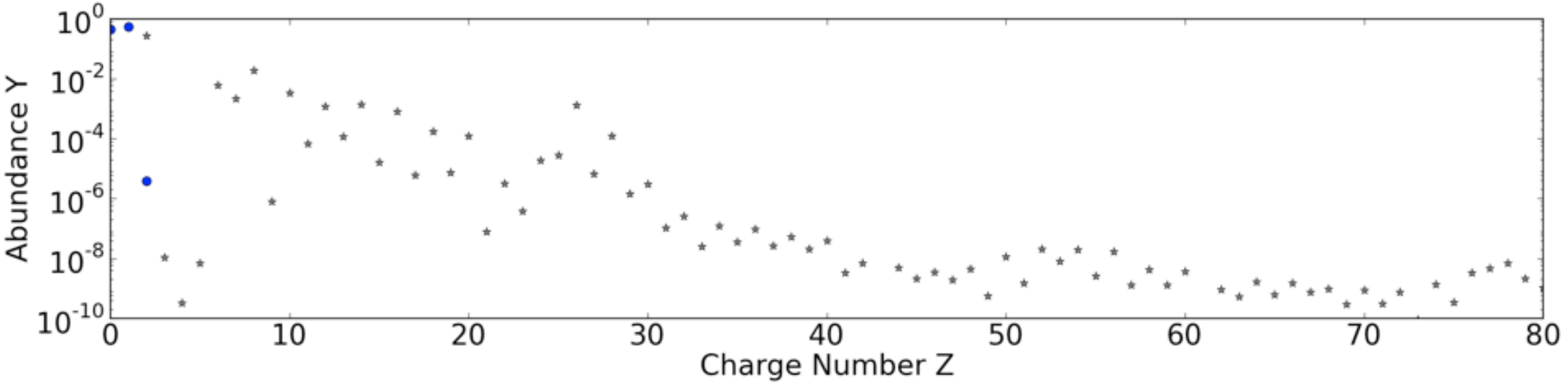
  luminosity/energy enhancement from late-phase fall back

Nucleosynthesis in proton rich conditions: *νp* process



- Mass-flow along proton-rich side
- Overcome waiting-point nuclei (long beta-decay half-lives; e.g. ^{64}Ge)

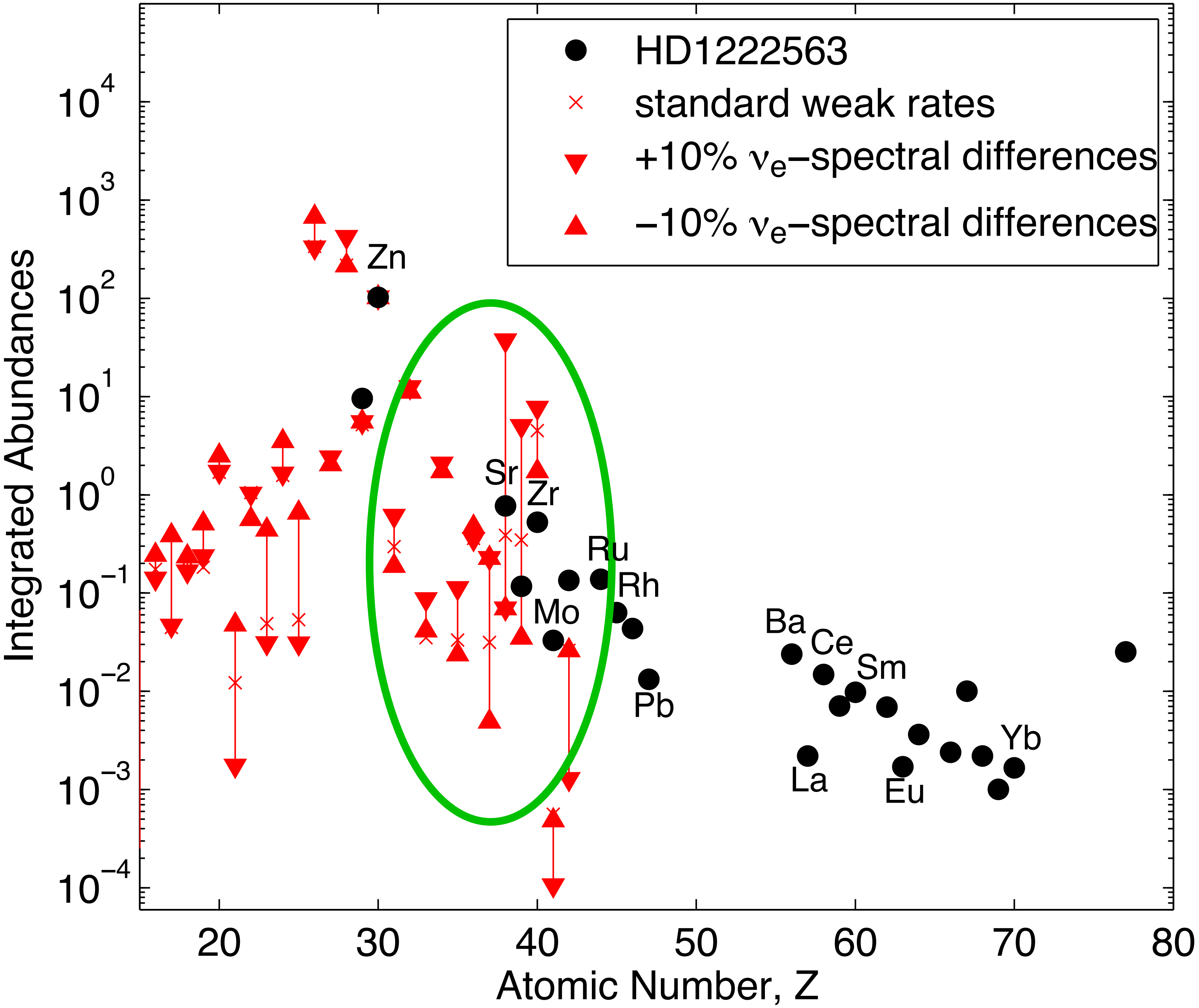
$$\bar{\nu}_e + p \longrightarrow n + e^+$$



Integrated nucleosynthesis analysis

Elemental abundances:

(gauged to ^{60}Zn)



- Production of light neutron-capture elements
- Consistent with observations: (Honda stars: poor in heavy neutron-capture elements (Z>45) but large abundances of light neutron-capture elements 38<Z<45 ,Sr, Y, Zr)
- Proton-rich ejecta: ***vp process***

Mass-flow along proton-rich side

Overcome waiting-point nuclei (long beta-decay half-lives; e.g. ^{64}Ge)

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

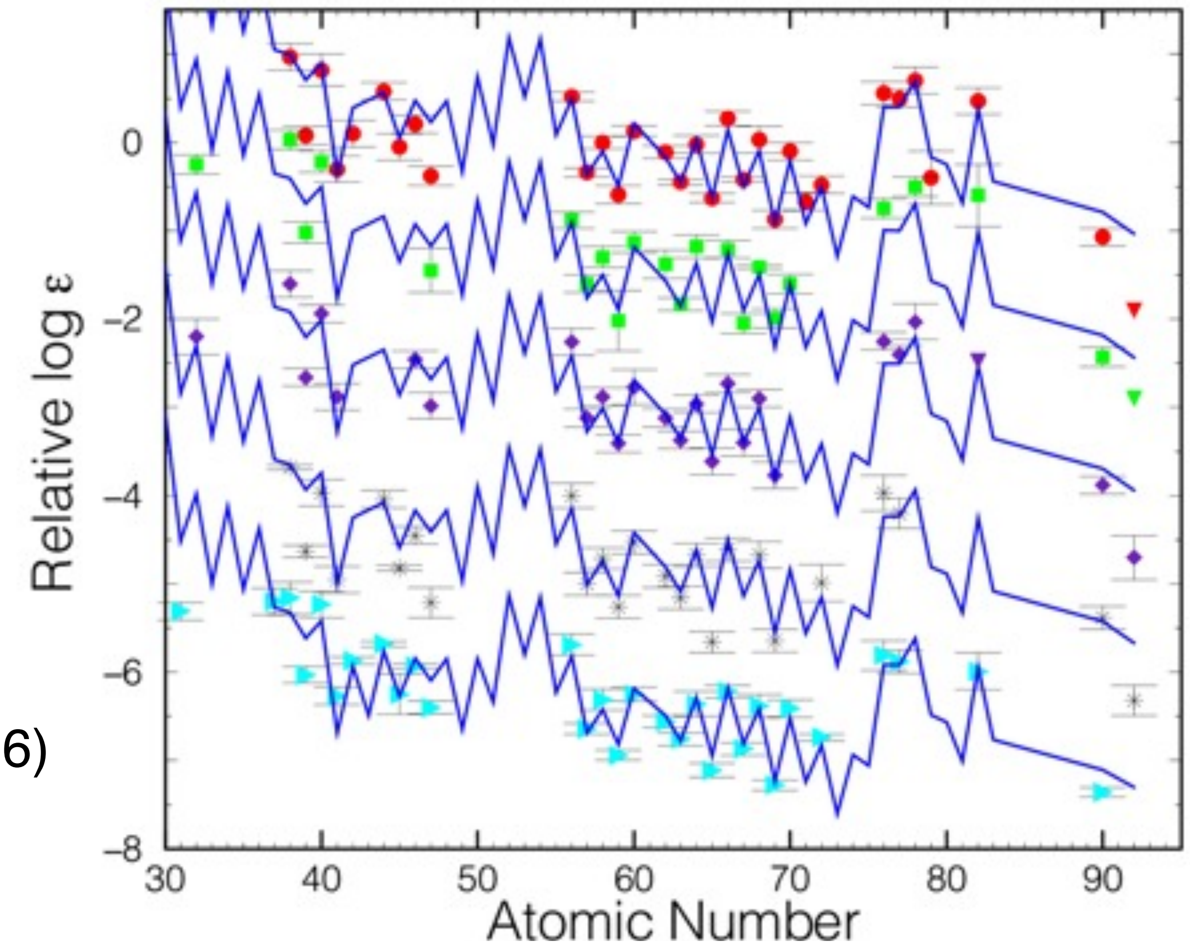
Summary and Conclusions

Summary and Conclusions I

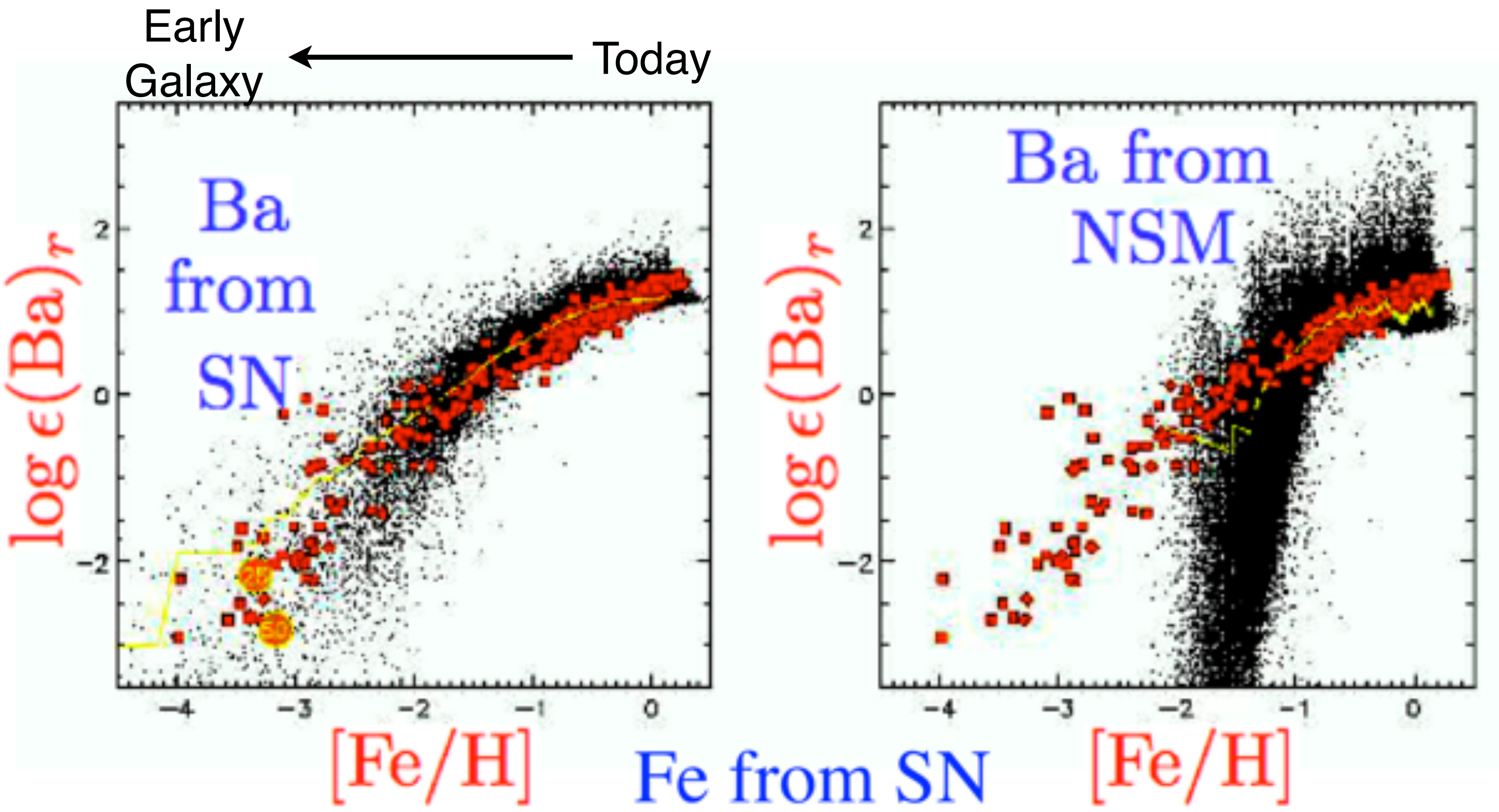
- Observations of strong *r* process in metal-poor stars)
  (young stars/early Galaxy)

—— solar *r* abundance (rescaled)

● ● ● ● ● ● observations (Cowan & Sneden 2006)



- Standard supernova models cannot explain the strong *r* process (*A* ~ 195)
  (low metallicity/early evolution of the Galaxy)



Qian, (2000), ApJ, 534, 67
Argast et al., (2004) A&A 416, 997

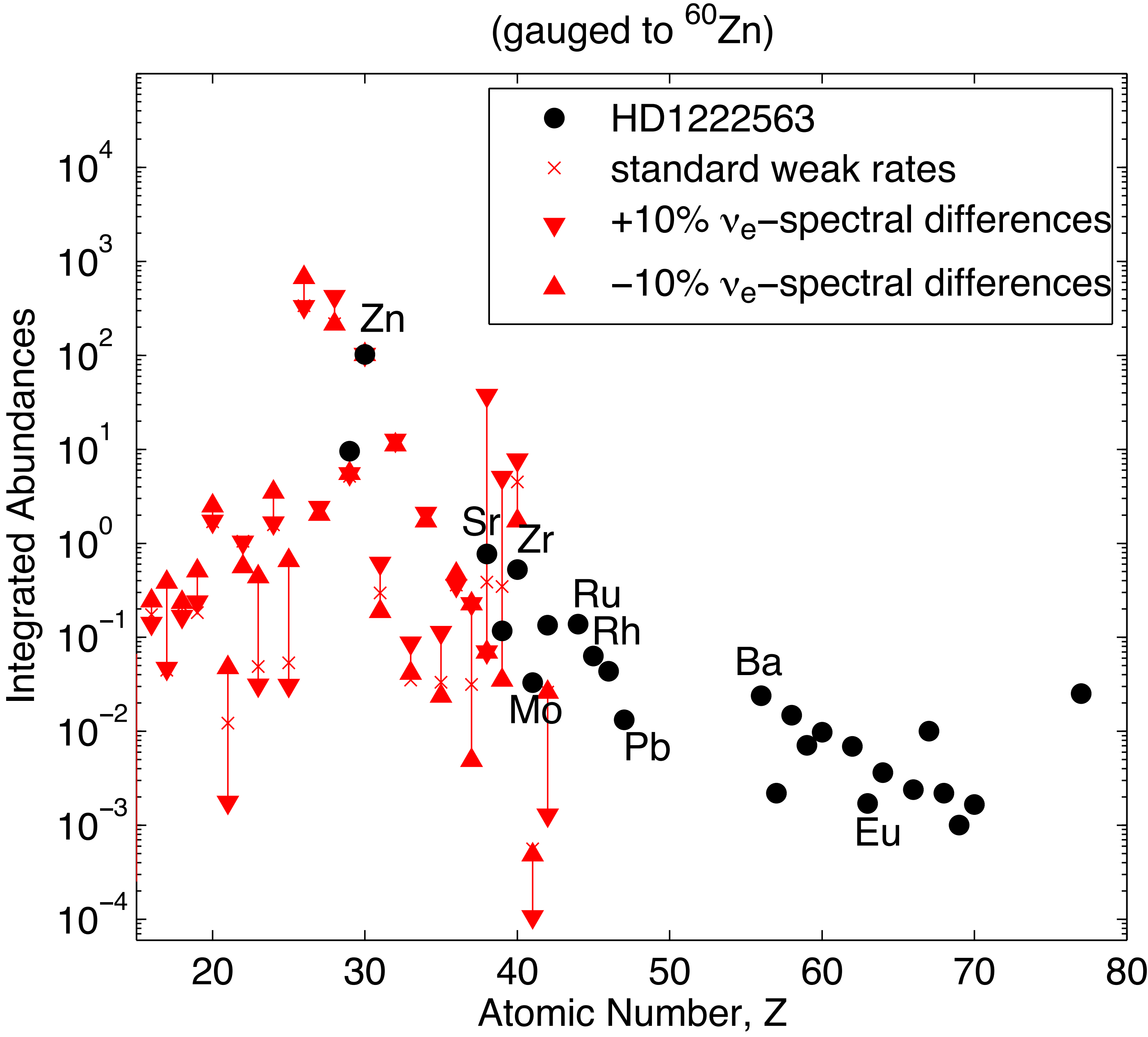
Summary and Conclusions II

- Production site for light neutron-capture (38<Z<45) elements found:

  neutrino driven winds from protoneutron stars (Electron-capture supernovae)

  slightly neutron rich, $Y_e \sim 0.45\text{-}0.47$

  moderately high entropy per baryon (50–100 k_B)



- No production of heavy *r*-process elements (Z>45), not enough free neutrons available (!)

Thanks for your attention