Neutrinos and the Origin of the Elements

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INT Program on Astrophysical Neutrinos and the Origin of the Elements
July 26, 2023

Fischer, Guo, Langanke, Martinez-Pinedo, Qian, & Wu 2023

N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

NSF

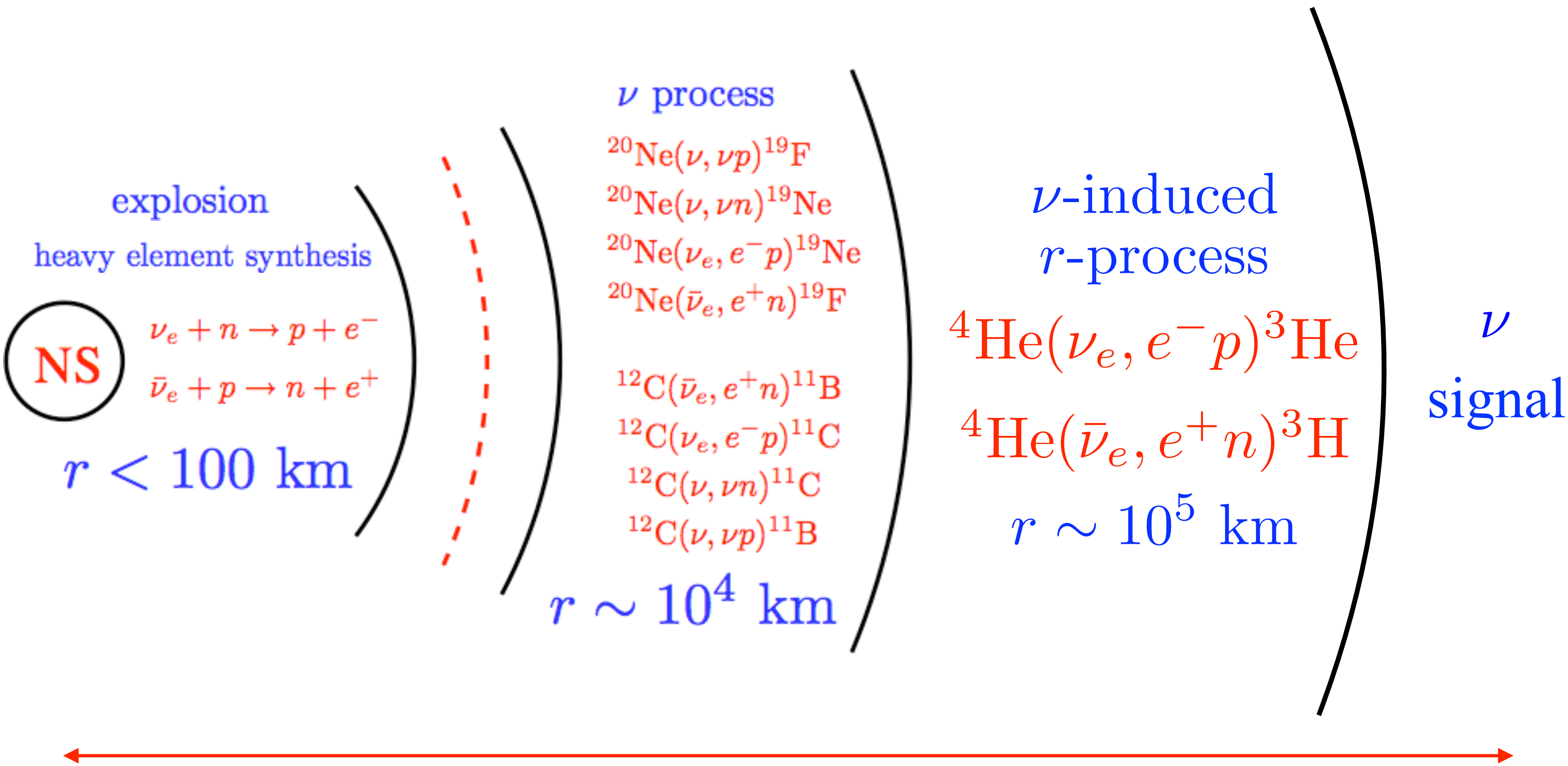
core-collapse supernovae & neutron star mergers
as laboratories of neutrino physics

neutrinos dominate or play important roles in
dynamics and nucleosynthesis

same nuclear physics input
EoS, neutrino opacities, neutrino oscillations,
nuclear reaction rates

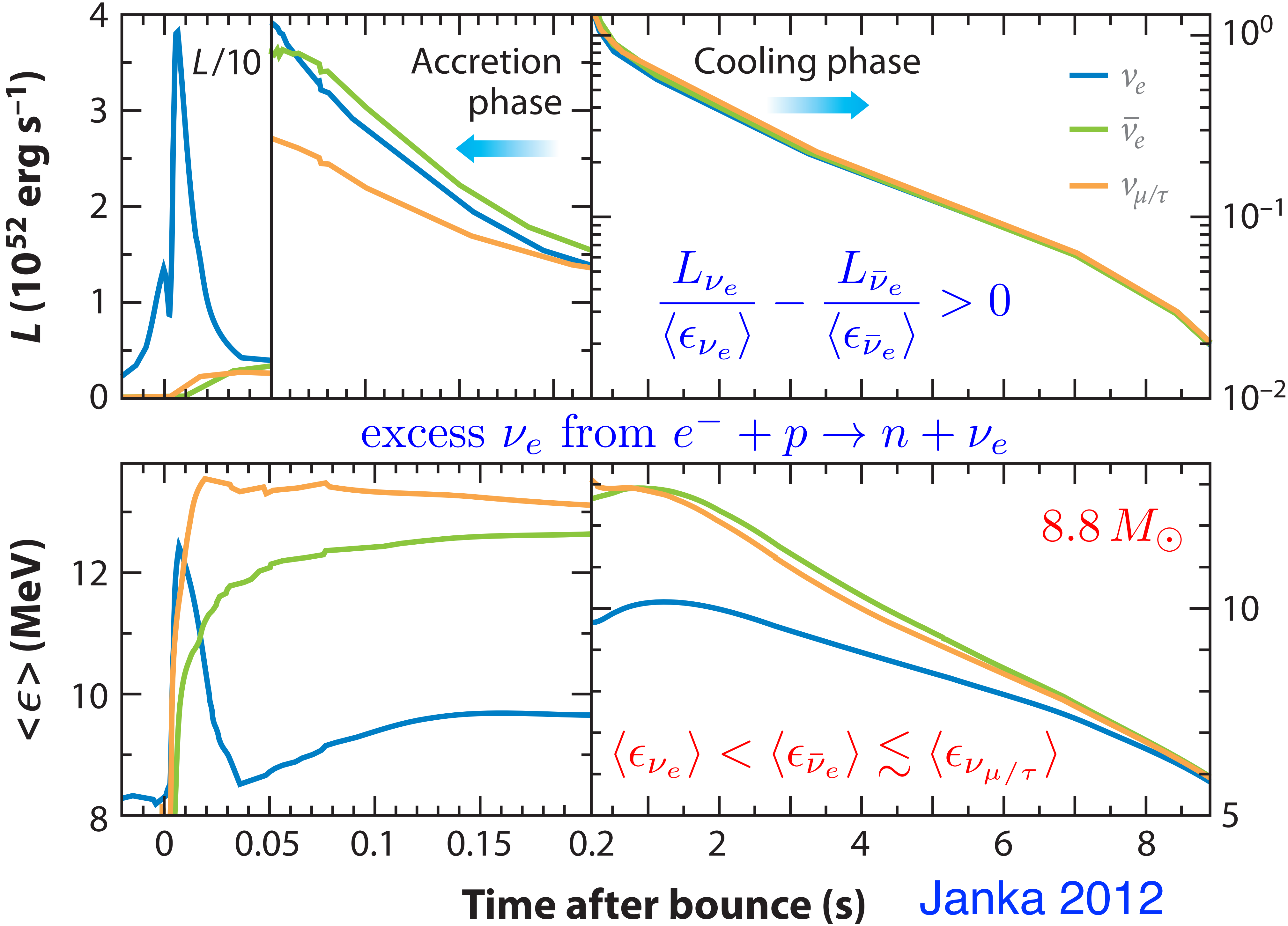
parallel multi-messenger observables
neutrinos, light curve, gamma rays, gravitational waves,
chemical enrichments

neutrino processes in typical core-collapse supernovae

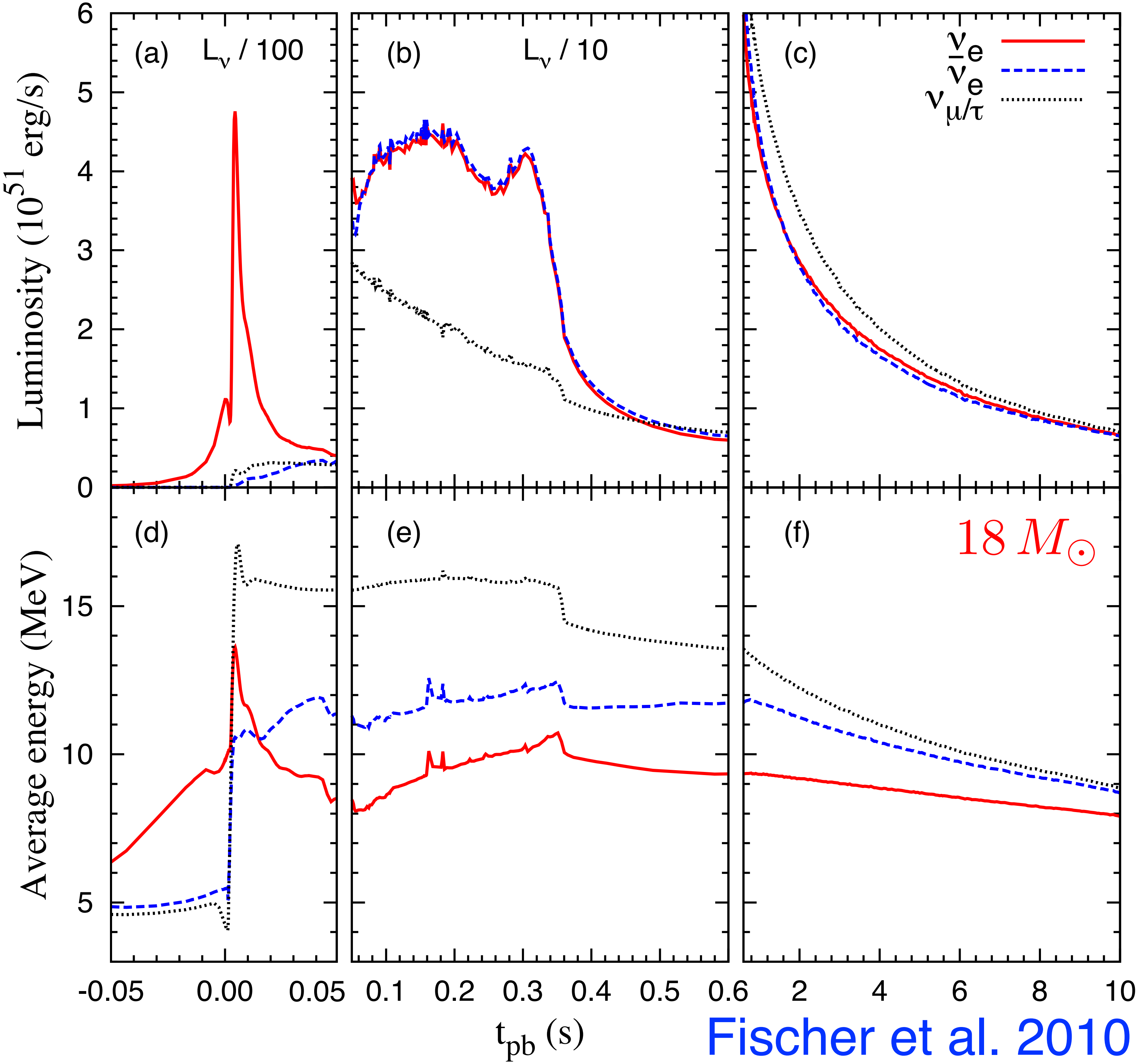


neutrino interactions & oscillations

Neutrino Emission from a Low-Mass SN

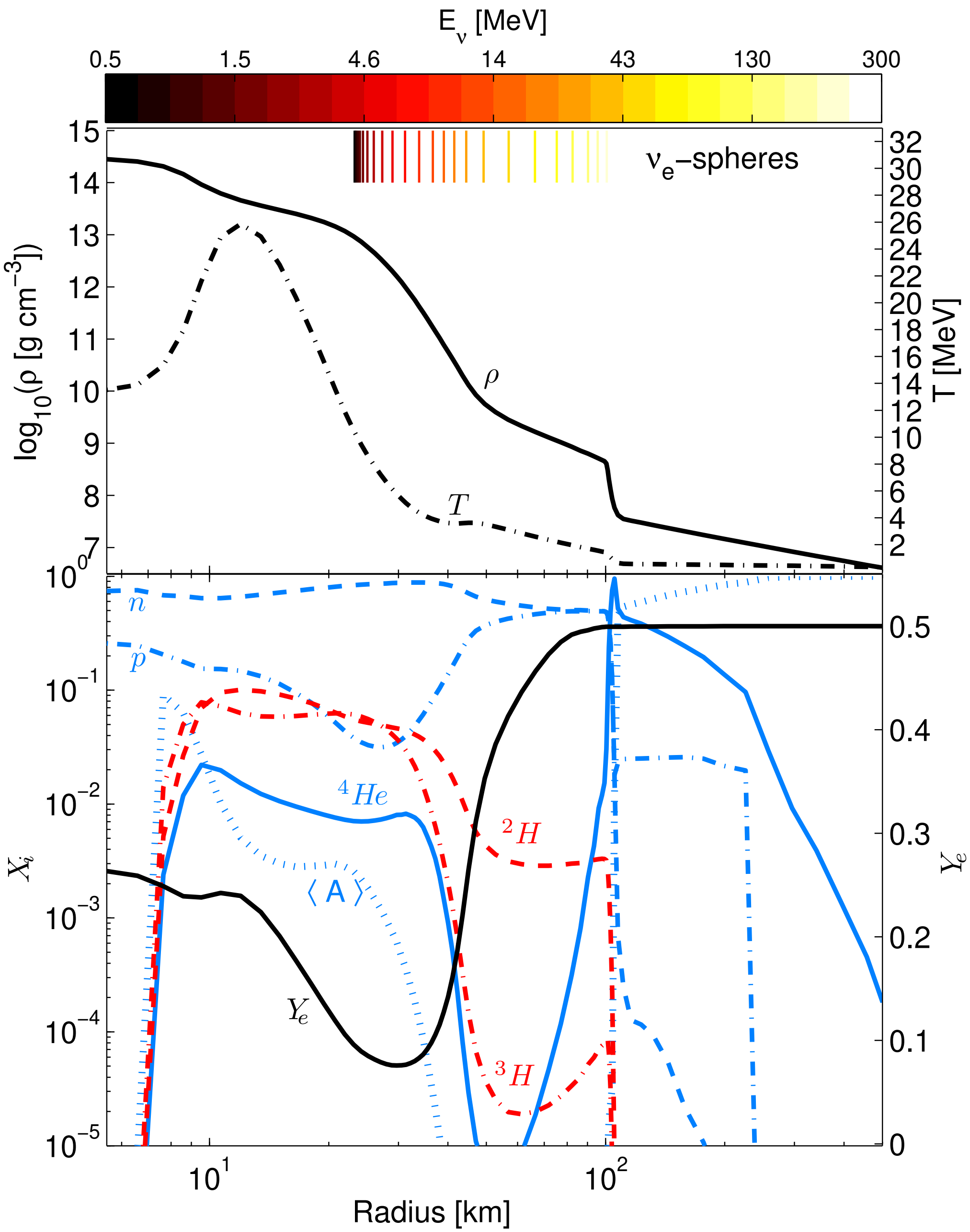


Janka 2012

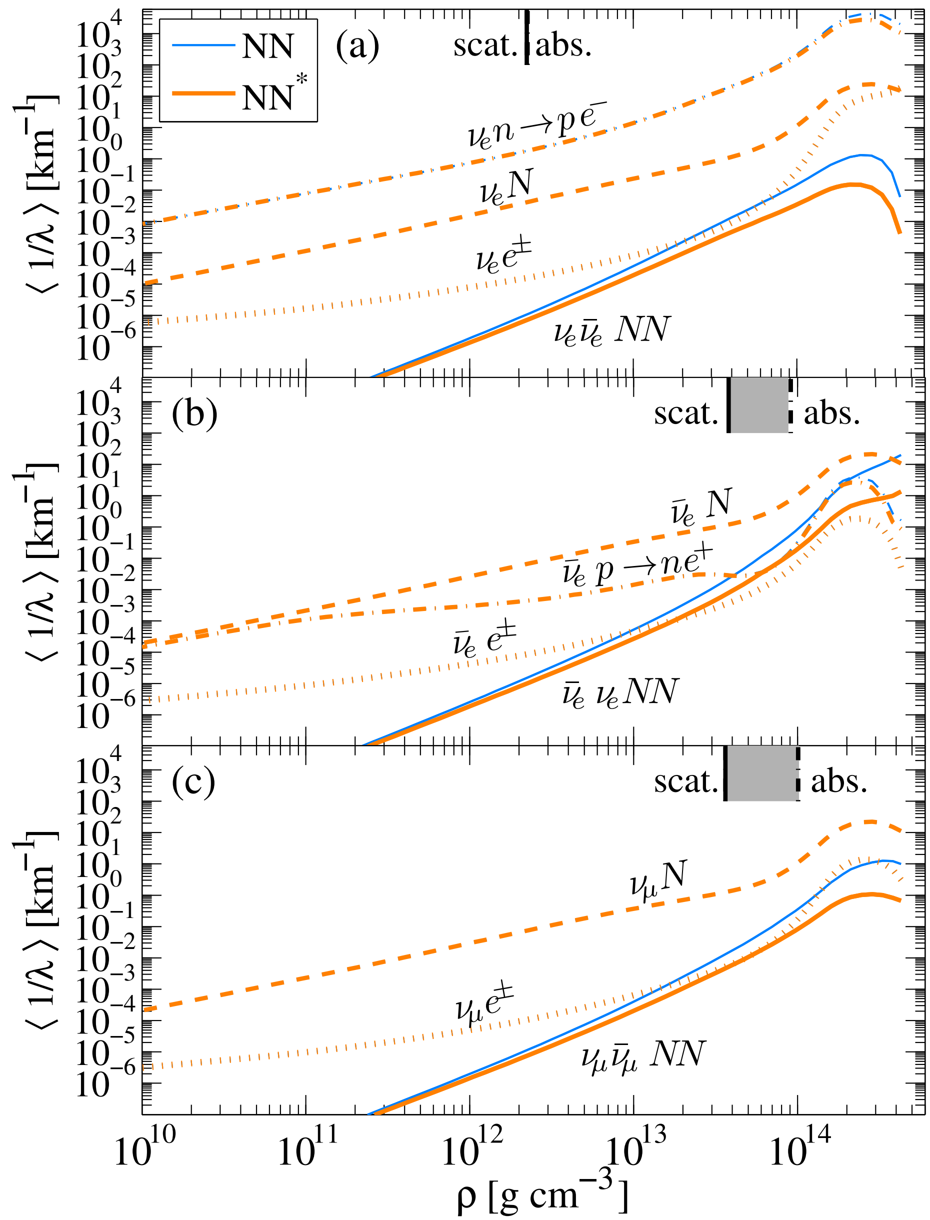


Fischer et al. 2010

neutrino decoupling from protoneutron star

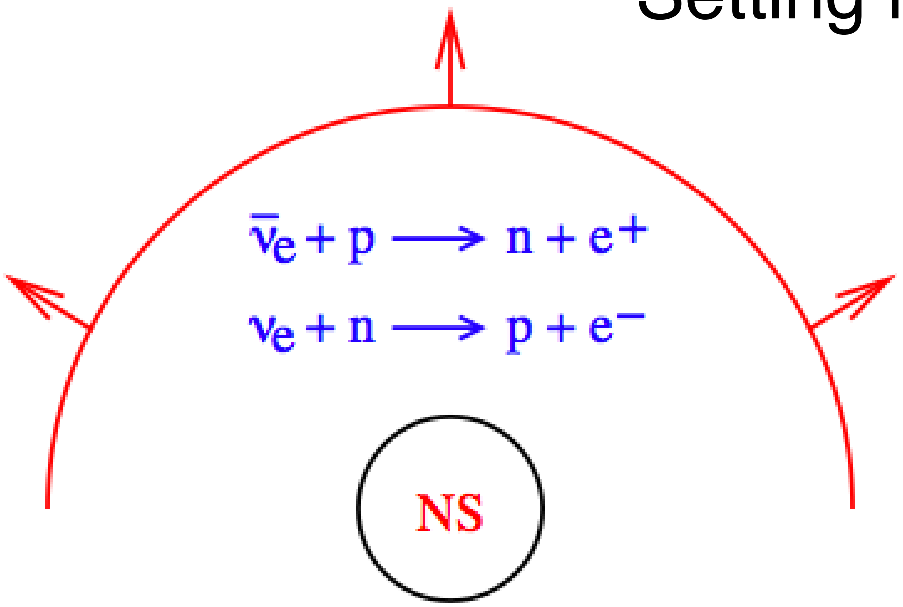


Fischer et al. 2014



Fischer 2016

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

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

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

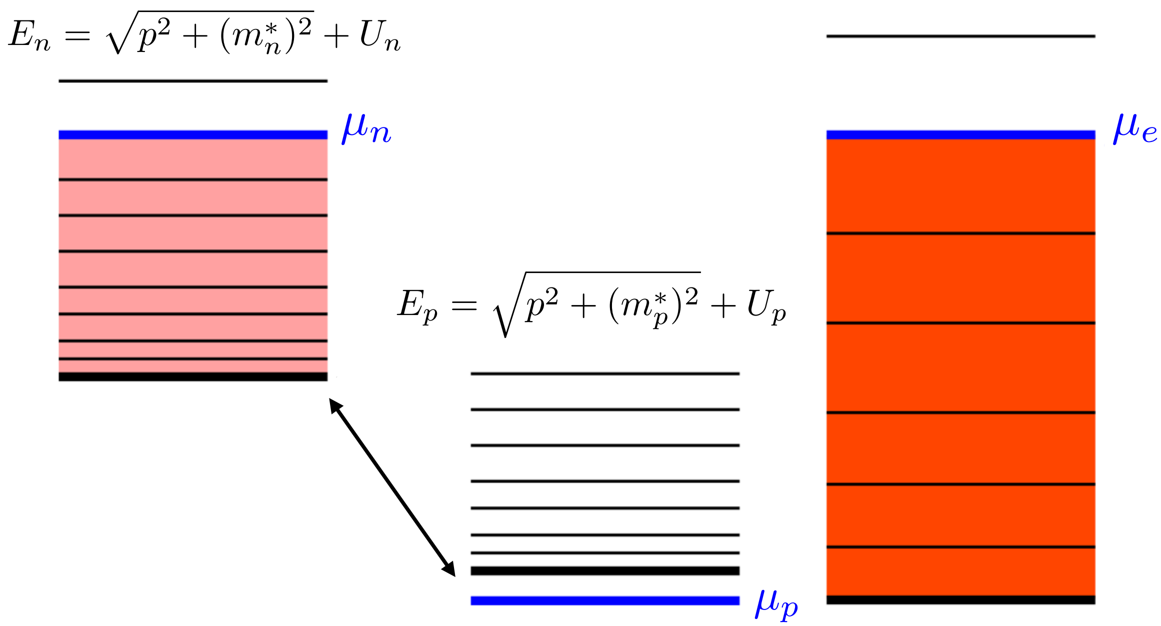
$$\lambda_{\nu_e n} = \frac{L_{\nu_e}}{4\pi r^2} \frac{\langle \sigma_{\nu_e n} \rangle}{\langle E_{\nu_e} \rangle} \propto L_{\nu_e} \left(\frac{\langle E^2_{\nu_e} \rangle}{\langle E_{\nu_e} \rangle} + 2\Delta_{np} \right)$$

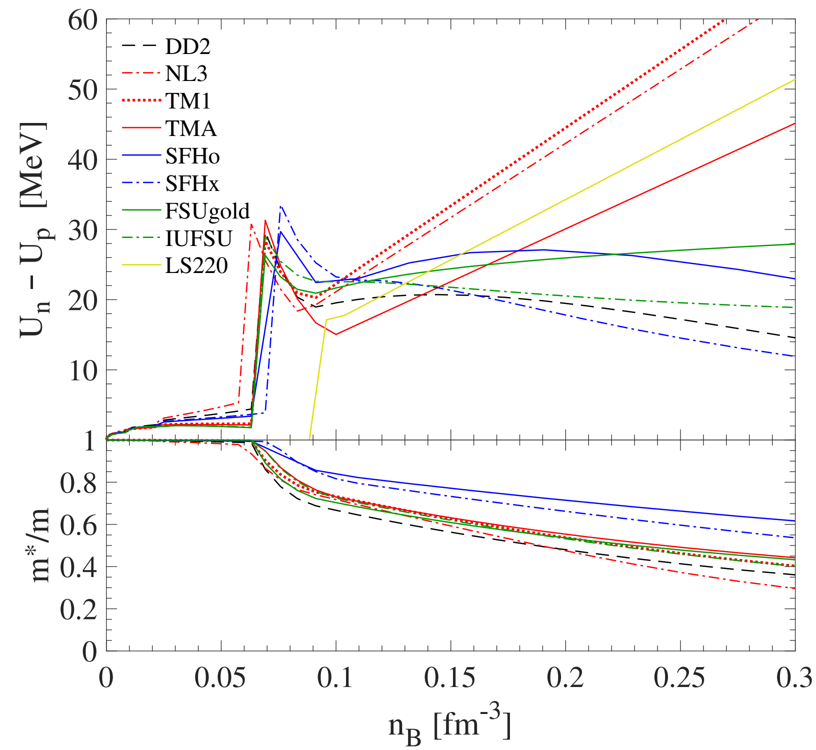
$$\frac{\langle E^2_{\bar{\nu}_e} \rangle}{\langle E_{\bar{\nu}_e} \rangle} - \frac{\langle E^2_{\nu_e} \rangle}{\langle E_{\nu_e} \rangle} > 4\Delta_{np} \approx 5.2 \text{ MeV} \Rightarrow \frac{n}{p} > 1$$

medium effects on neutrino opacities

$$\nu_e + n \to p + e^-, \; \bar{\nu}_e + p \to n + e^+$$

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

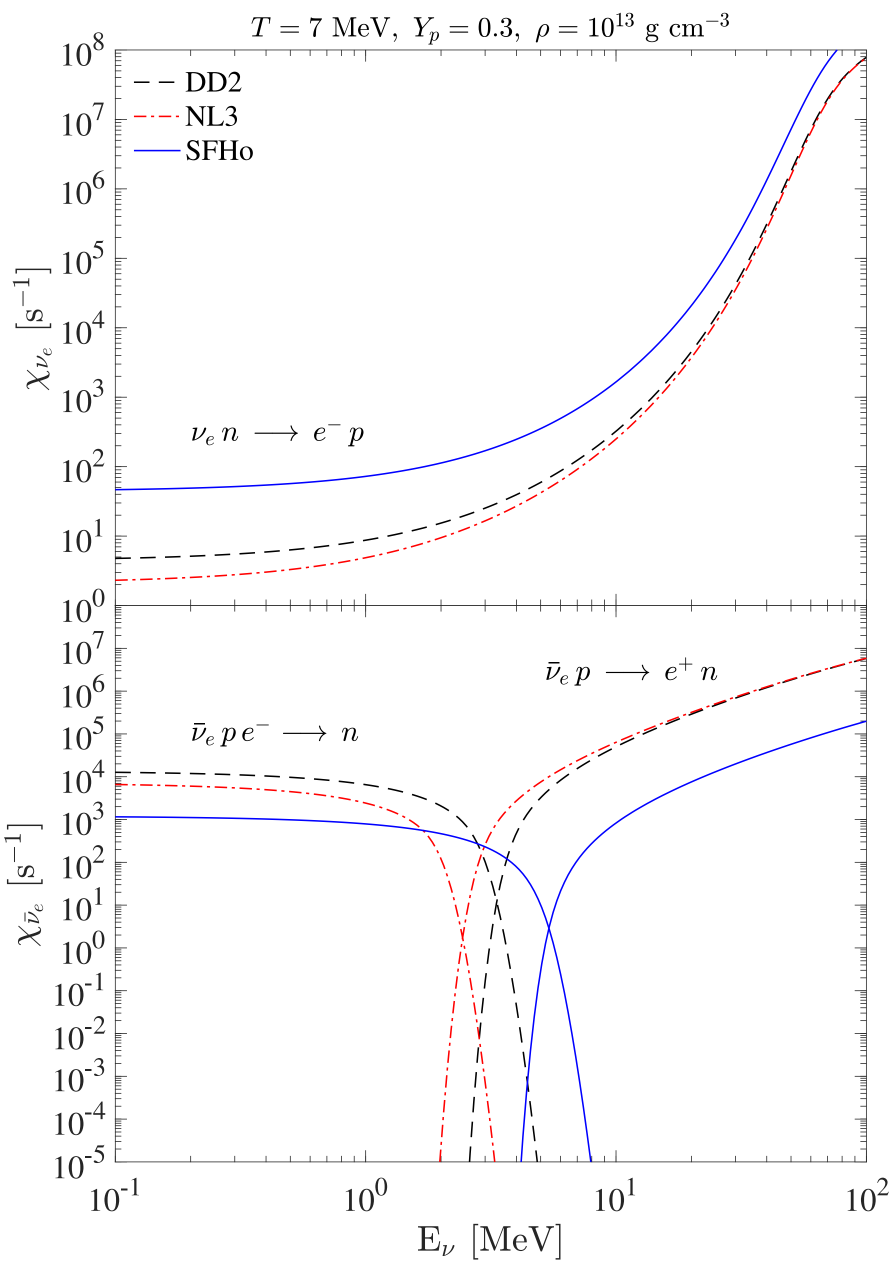


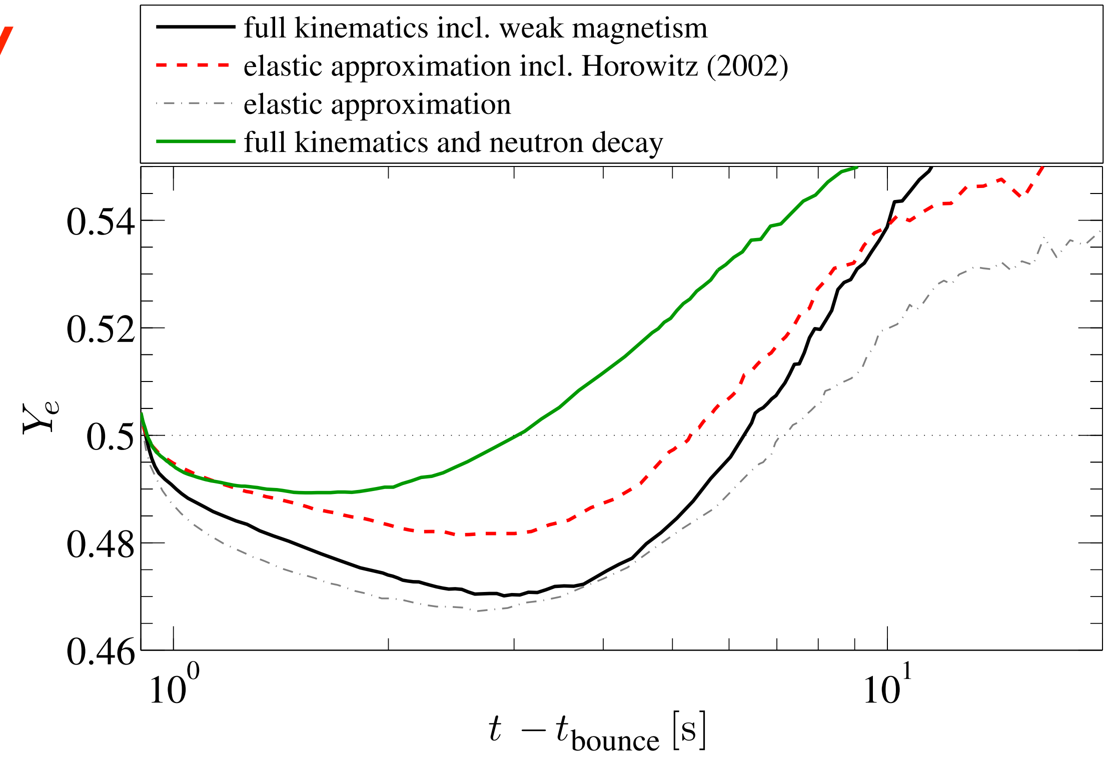


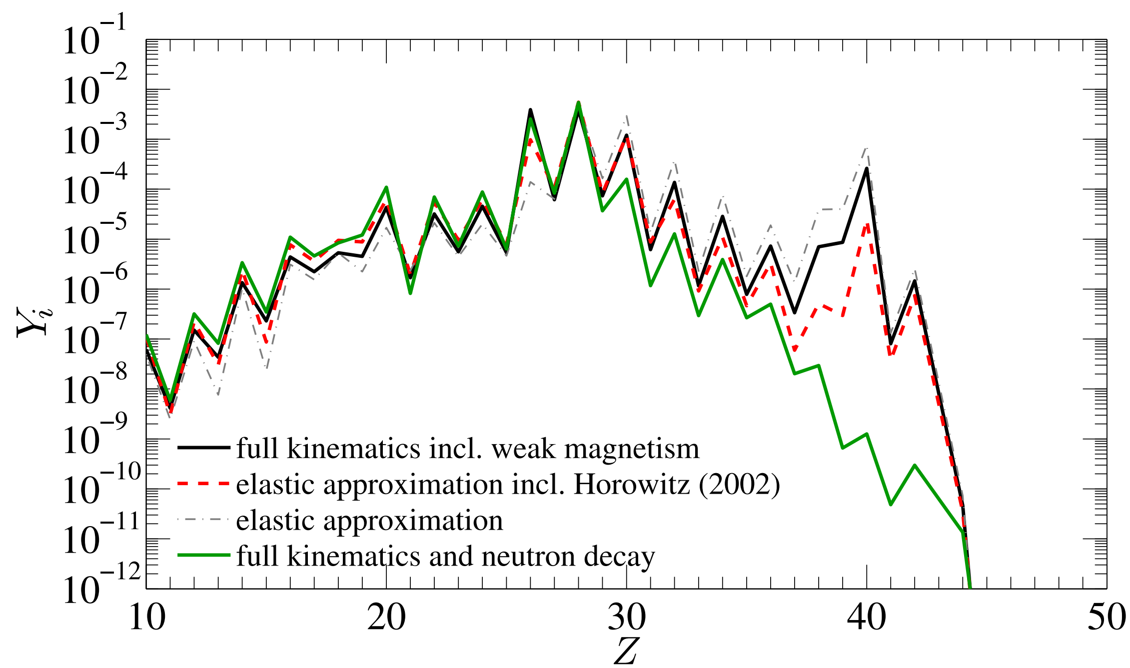
see new treatment
in talk by Ermal Rrapaj

$T = 7$ MeV, $Y_e = 0.3$

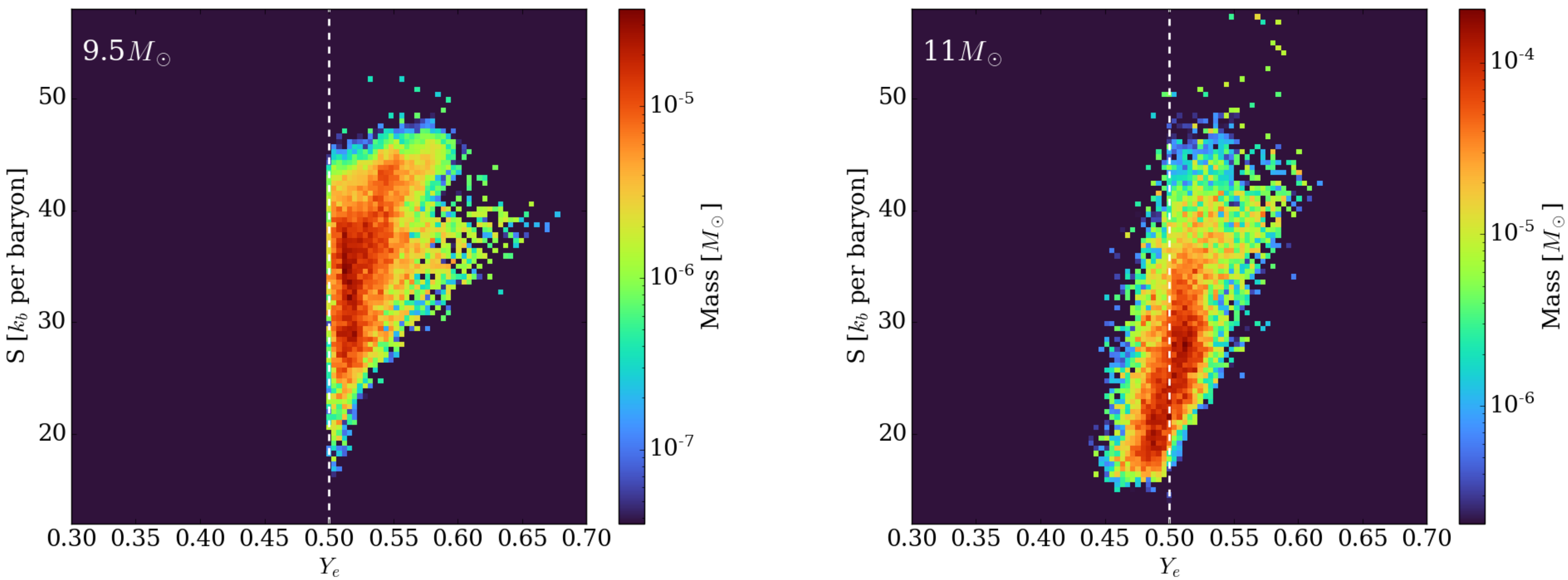
effects of inverse n decay



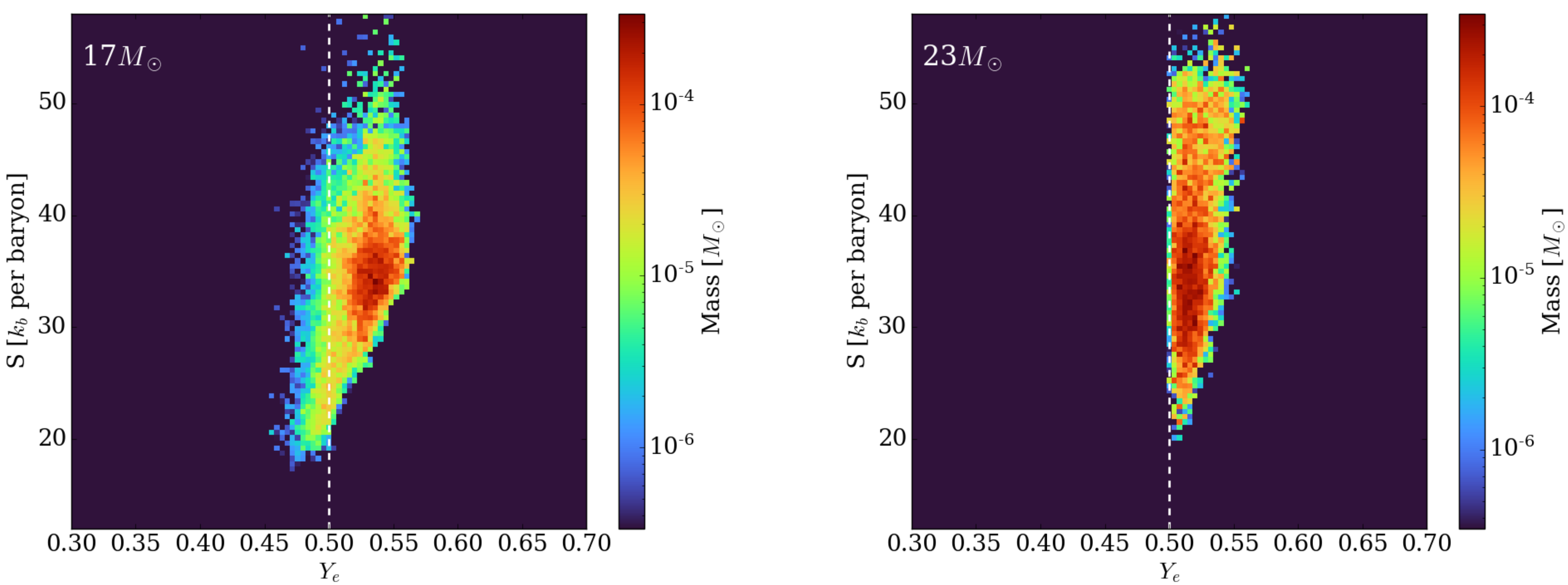


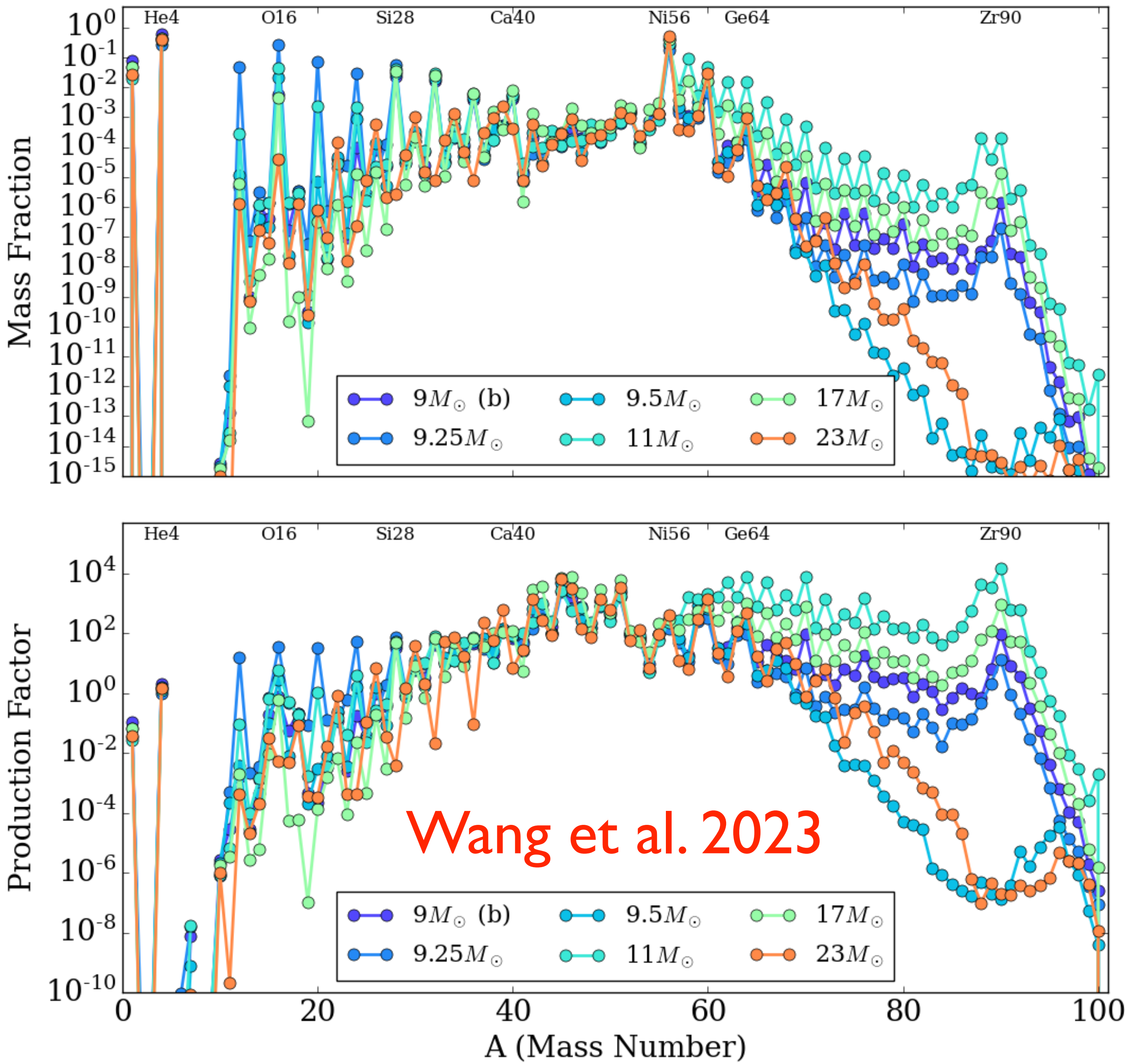


Fischer et al. 2020



neutrino-driven winds in 3D models (Wang et al. 2023)

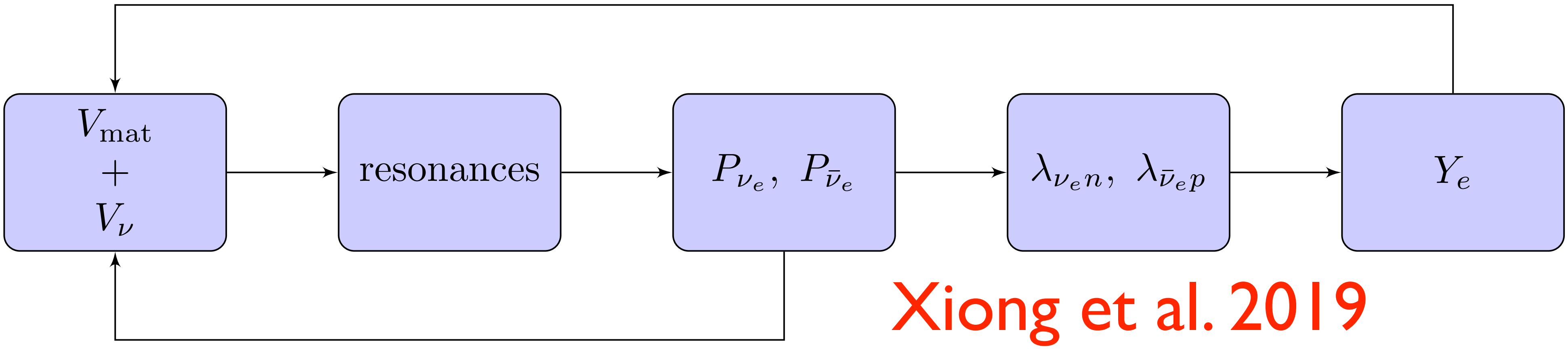



He4
O16
Si28
Ca40
Ni56
Ge64
Zr90
Mass Fraction
Production Factor
A (Mass Number)
9$M_\odot$ (b)
9.25$M_\odot$
9.5$M_\odot$
11$M_\odot$
17$M_\odot$
23$M_\odot$
Wang et al. 2023

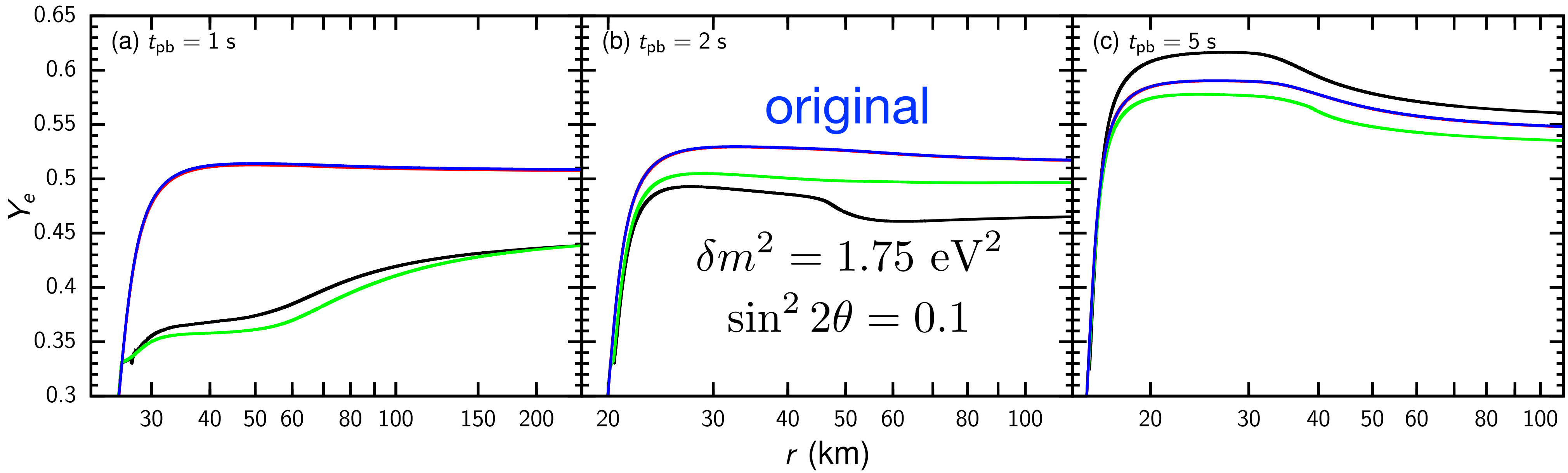
self-consistent treatment of flavor oscillations in the winds

$\nu_e \rightleftharpoons \nu_s$ & $\bar{\nu}_e \rightleftharpoons \bar{\nu}_s$: importance of feedback

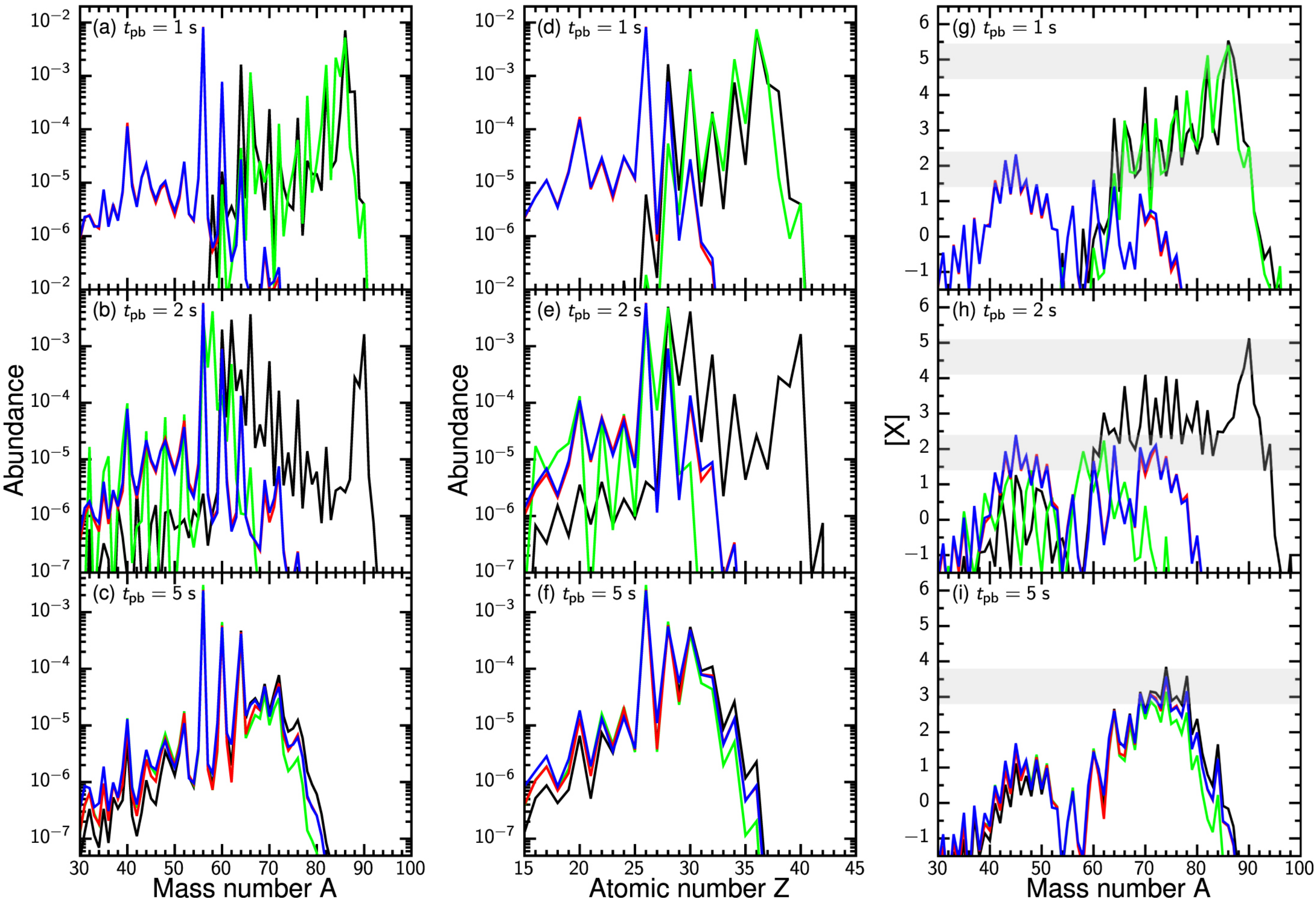
e.g., McLaughlin et al. 1999; Tamborra et al. 2012



Xiong et al. 2019

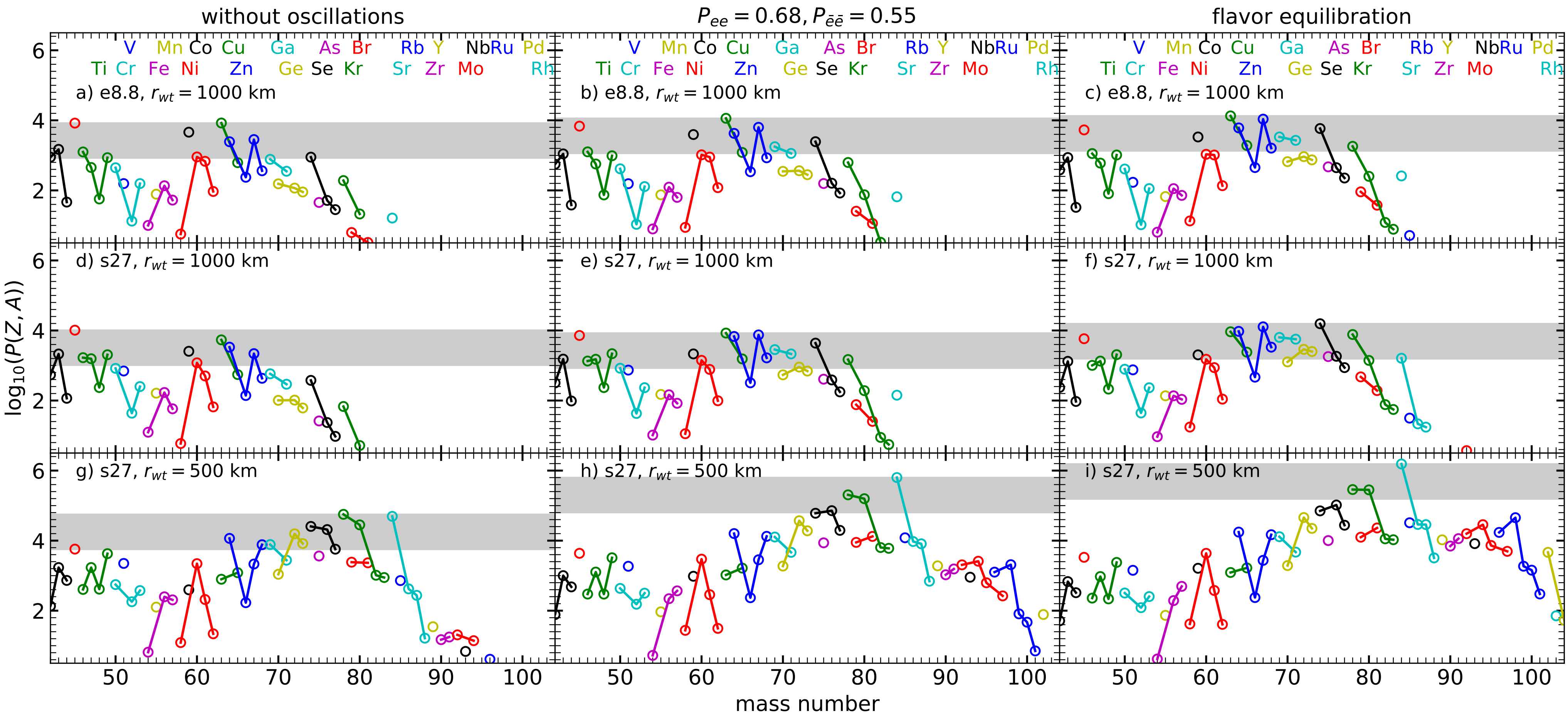


Xiong et al. 2019



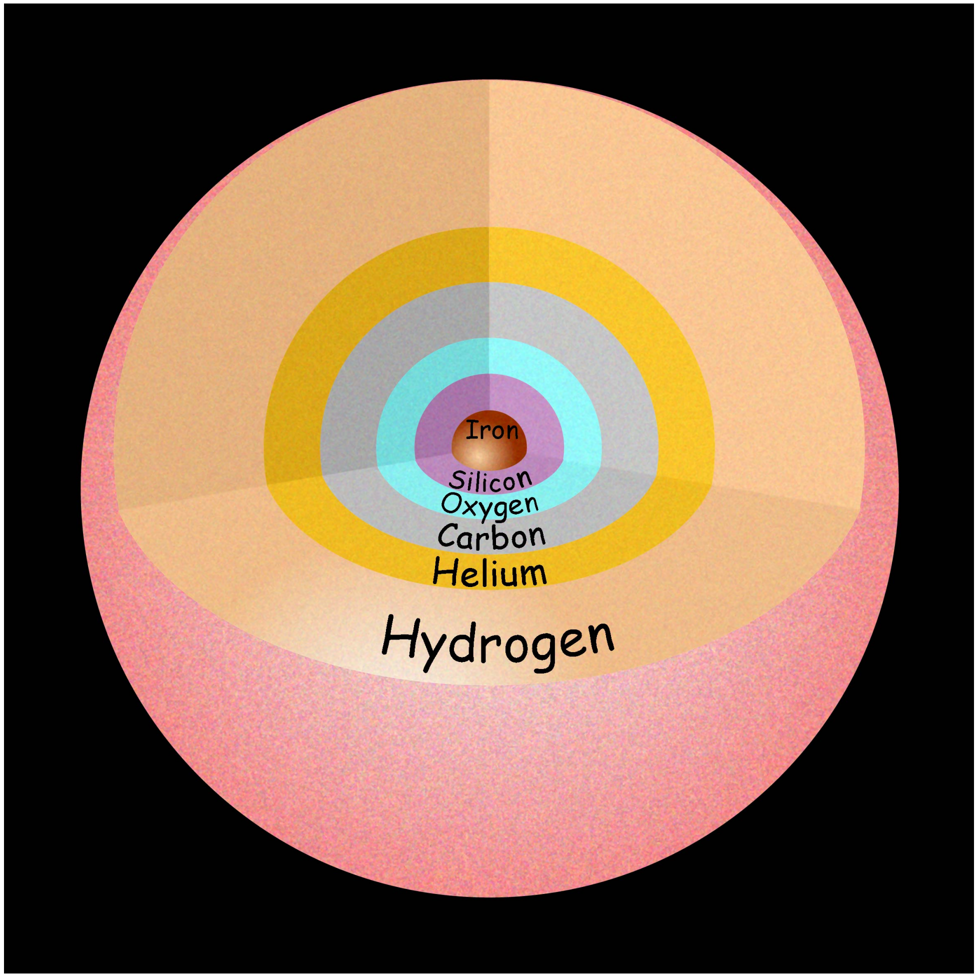
potential effects of fast flavor oscillations

Xiong et al. 2020

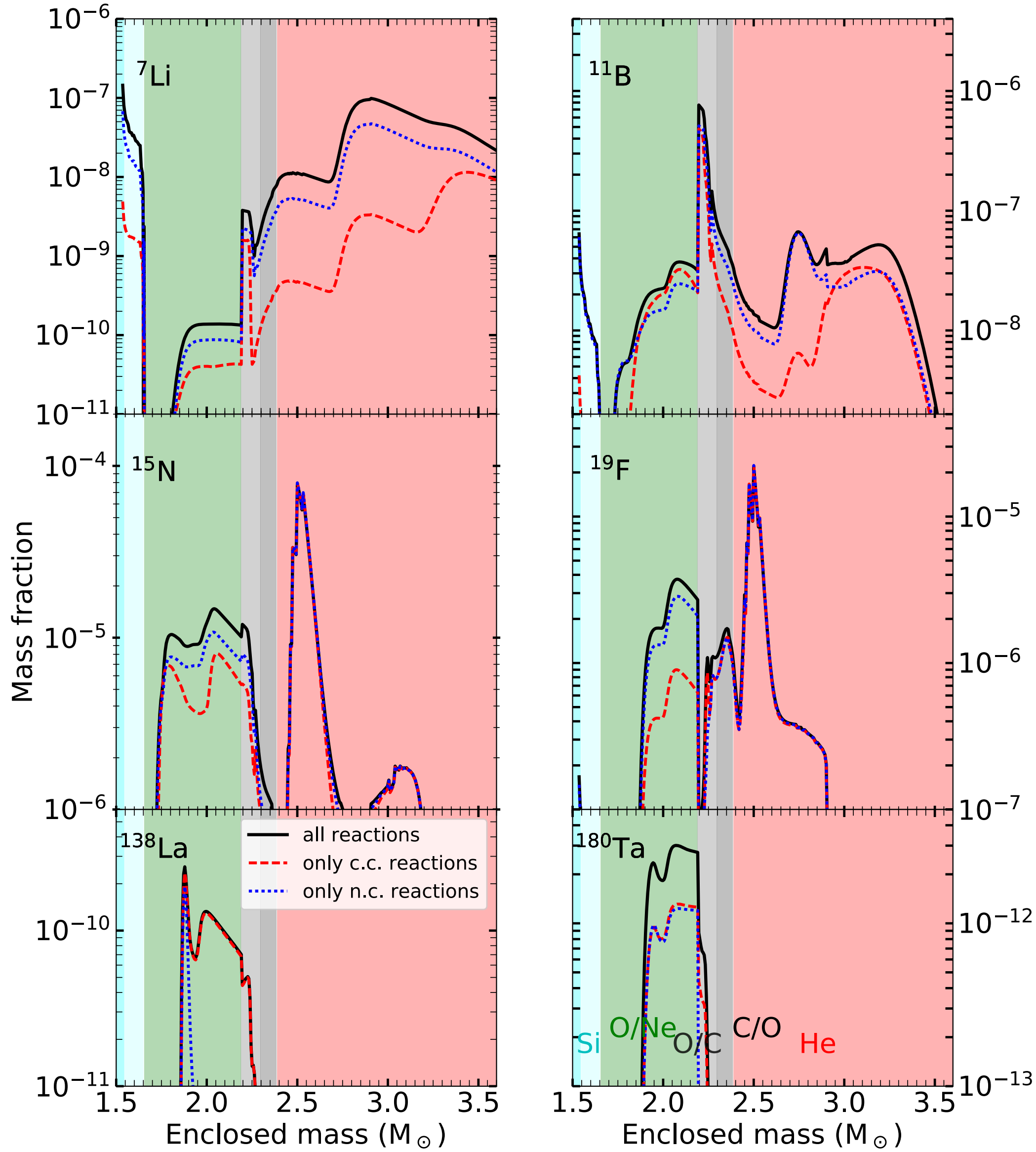


neutrino process

Woosley et al. 1990



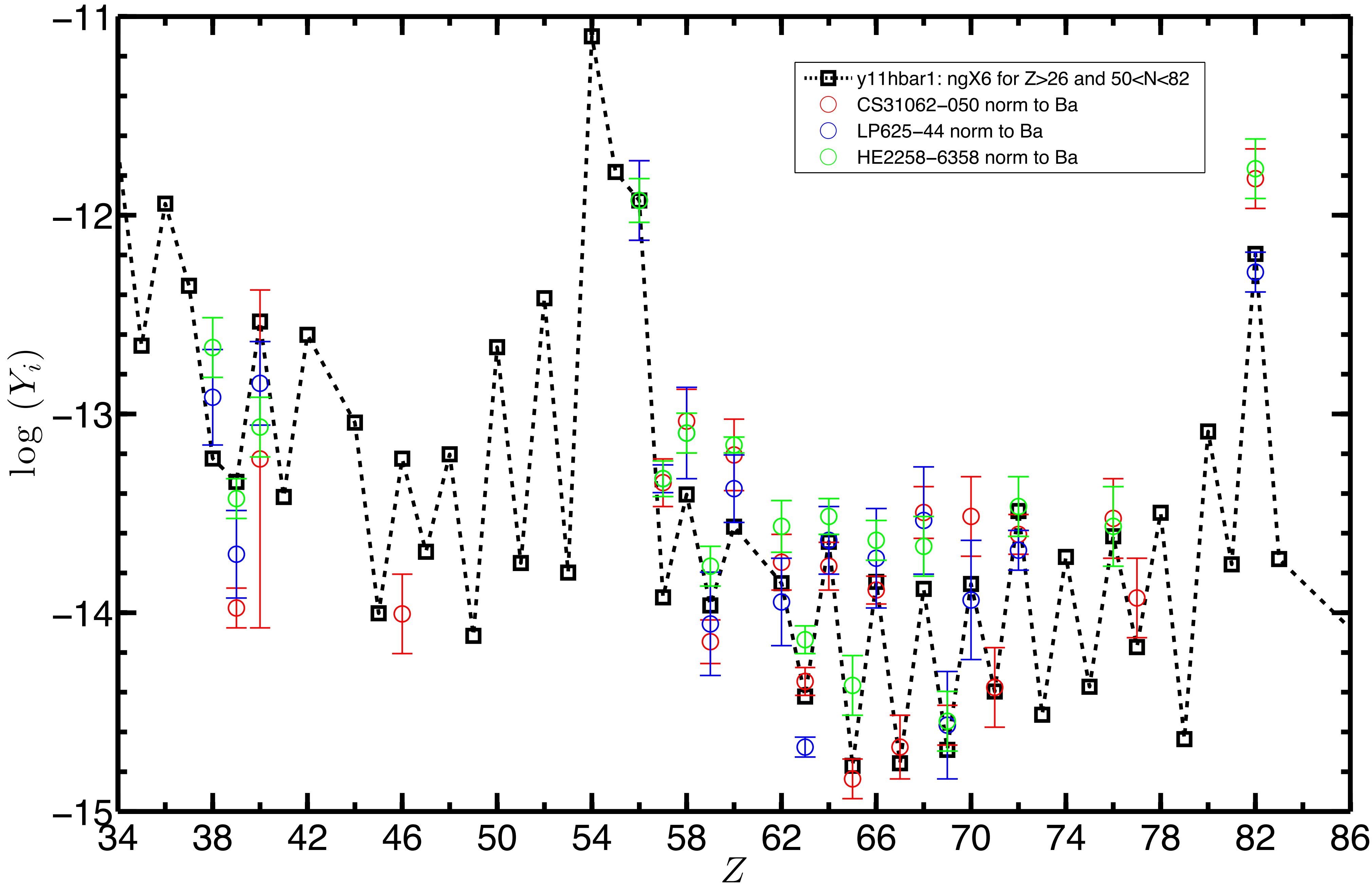
Sieverding et al. 2018



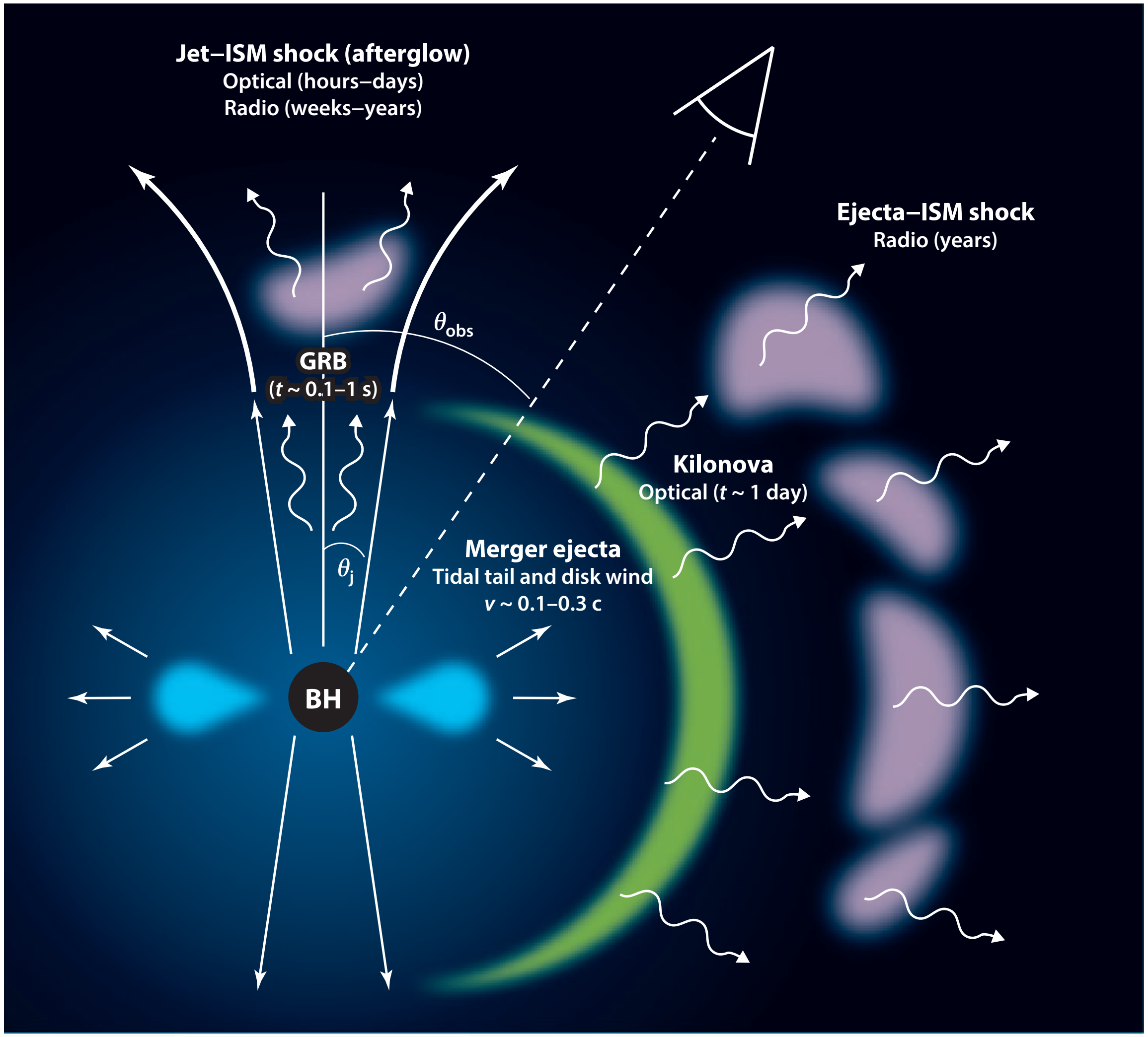
neutrino-induced n-capture process in He shell

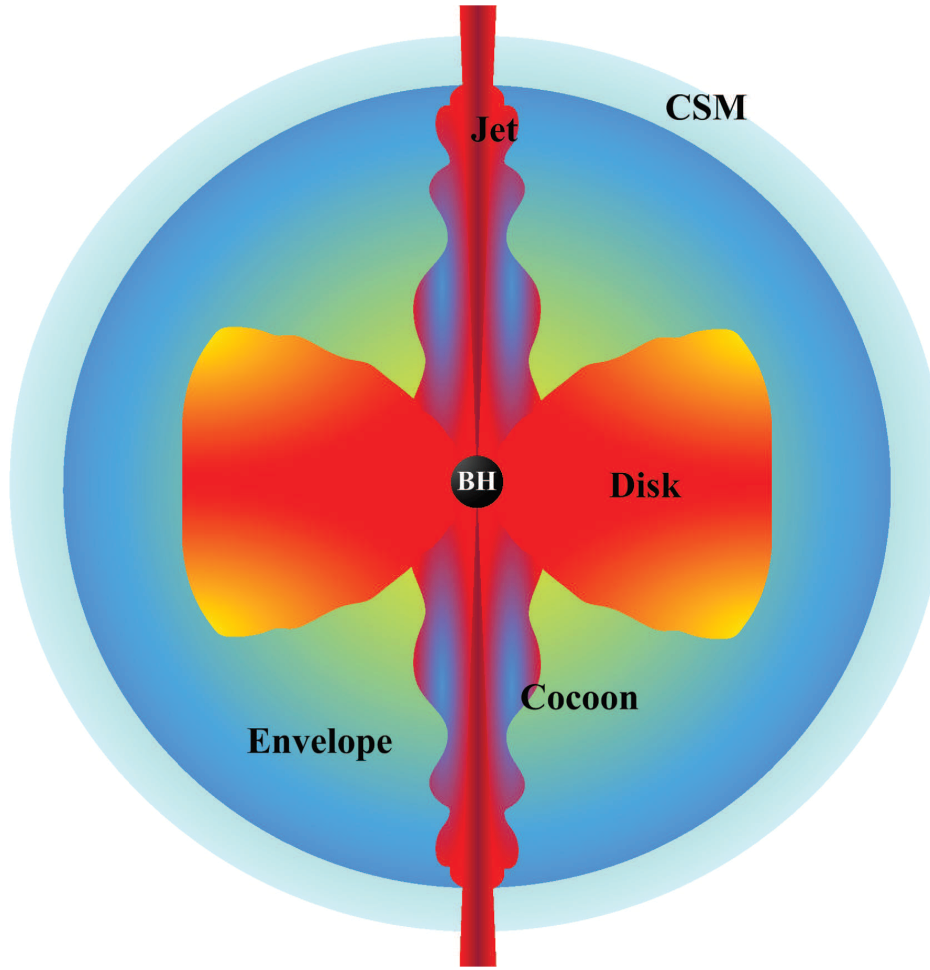
Epstein et al. 1988; Banerjee et al. 2011, 2016

Banerjee, Qian, Heger, & Haxton 2016



jets, accretion disks, gamma-ray bursts, & nucleosynthesis

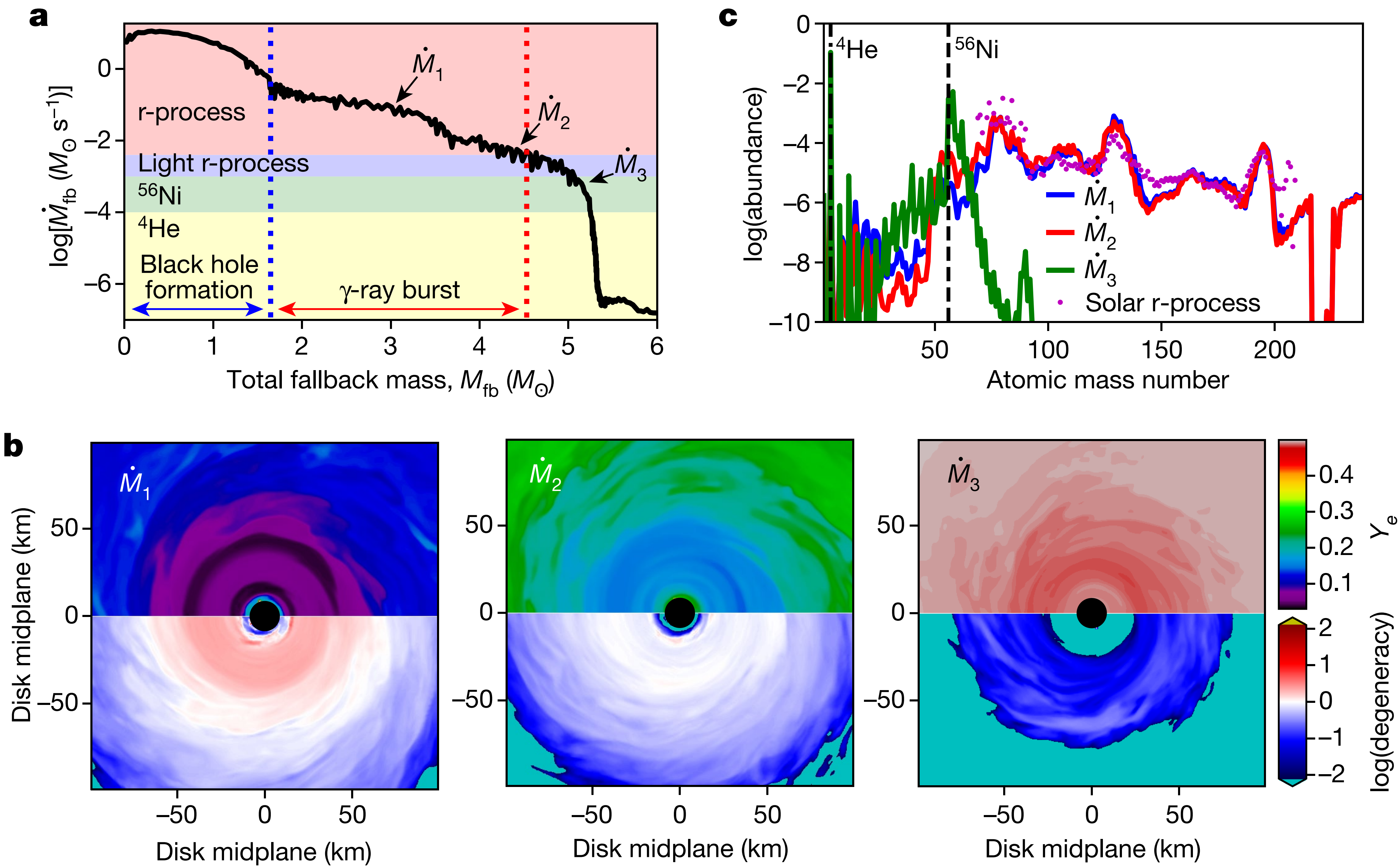




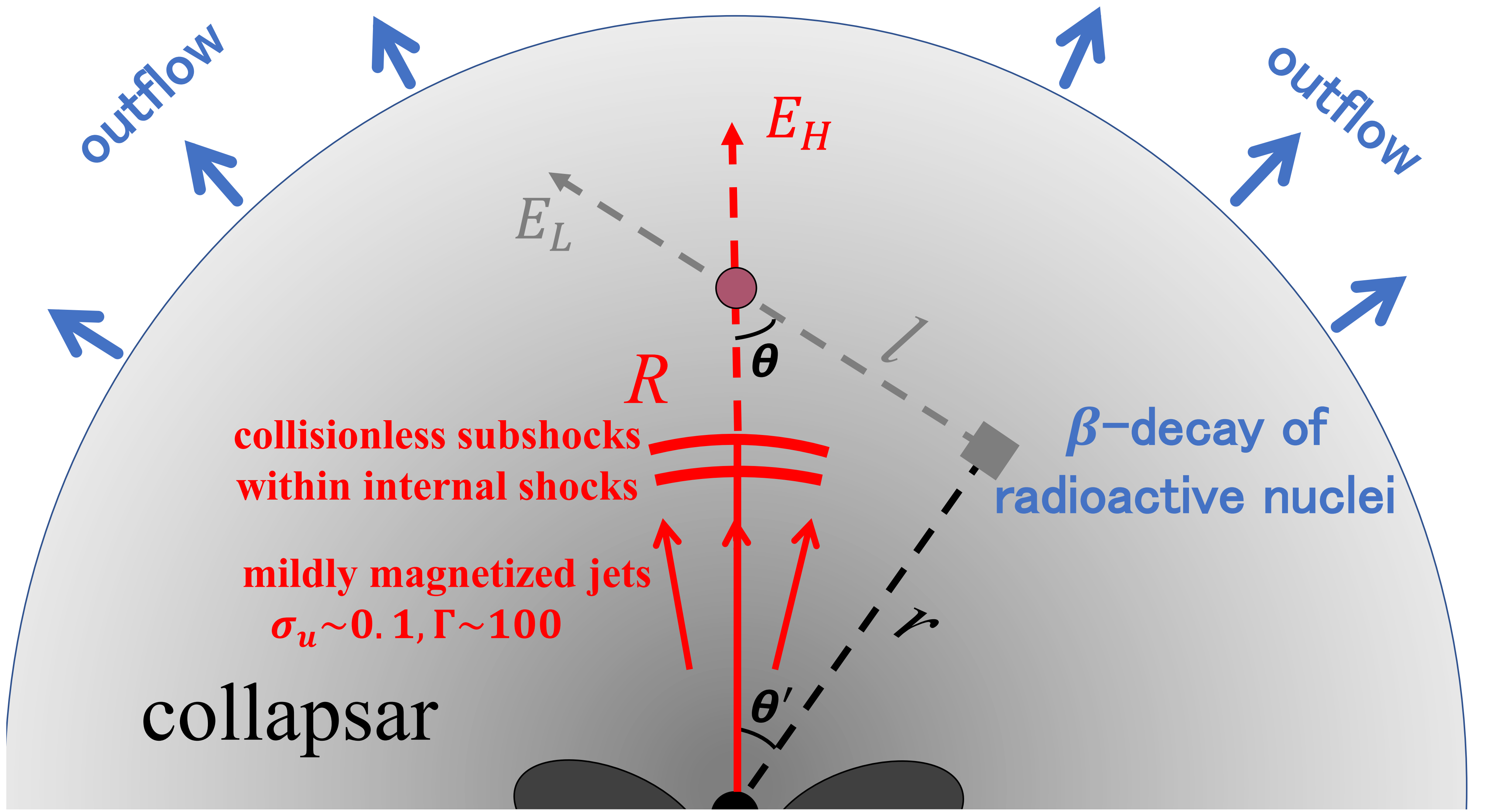
neutron star merger

collapsar

r-process in collapsars (Siegel et al. 2019)



Guo, Qian, & Wu 2023



r-process in collapsars (Siegel, Barnes, & Metzger 2019)

High-Energy Neutrino Production

collision of slow and rapid jets with $\Gamma \sim 250$–500

→ mildly relativistic shock

shock acceleration of protons up to 10^6 GeV

$pp,\ p\gamma$ reactions produce $\pi^\pm,\ K^\pm$

$$\pi^+ \to \mu^+ + \nu_\mu,\ \pi^- \to \mu^- + \bar{\nu}_\mu$$

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu,\ \mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

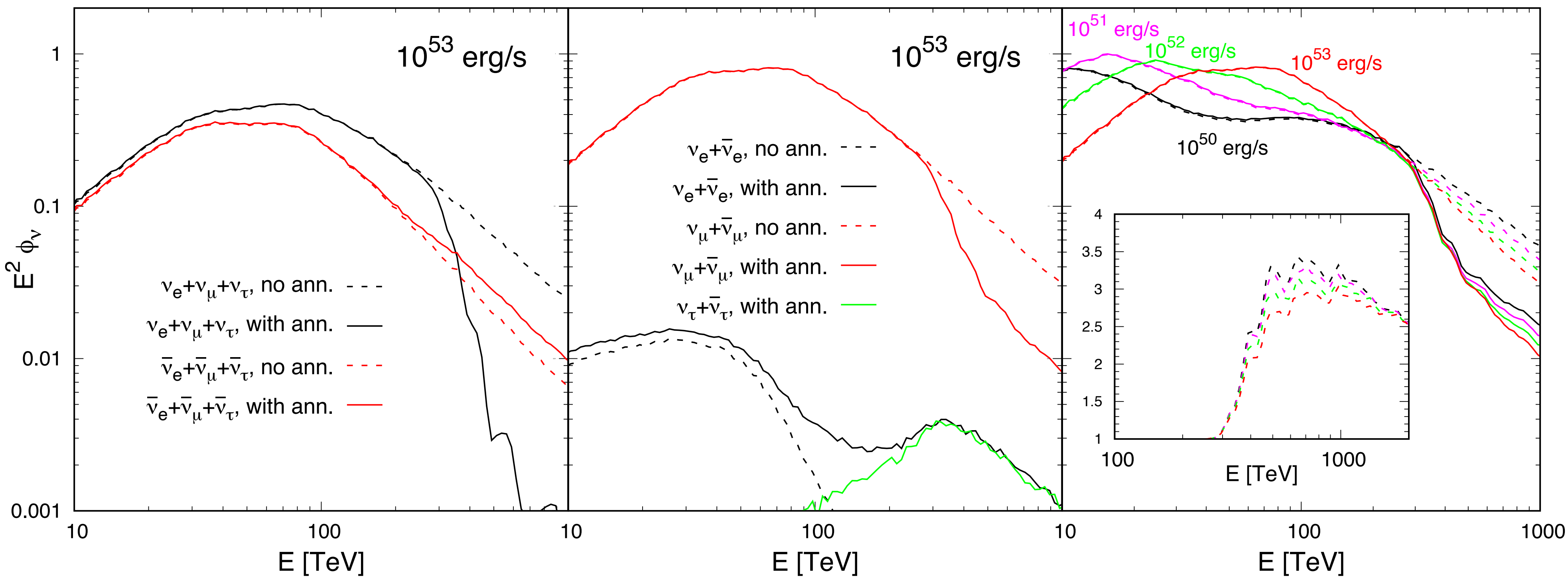
$$E_\nu \sim 0.05 \Gamma E_p$$

Annihilation of HE ν_μ by LE $\bar{\nu}_\mu$ Converted from β-Decay $\bar{\nu}_e$

$$2E_L E_H (1 - \cos\theta) = M_Z^2$$

$$\Rightarrow E_{H,\mathrm{min}} = \frac{M_Z^2}{4E_{L,\mathrm{max}}} \approx 260\ \mathrm{TeV}$$

Guo, Qian, & Wu 2023

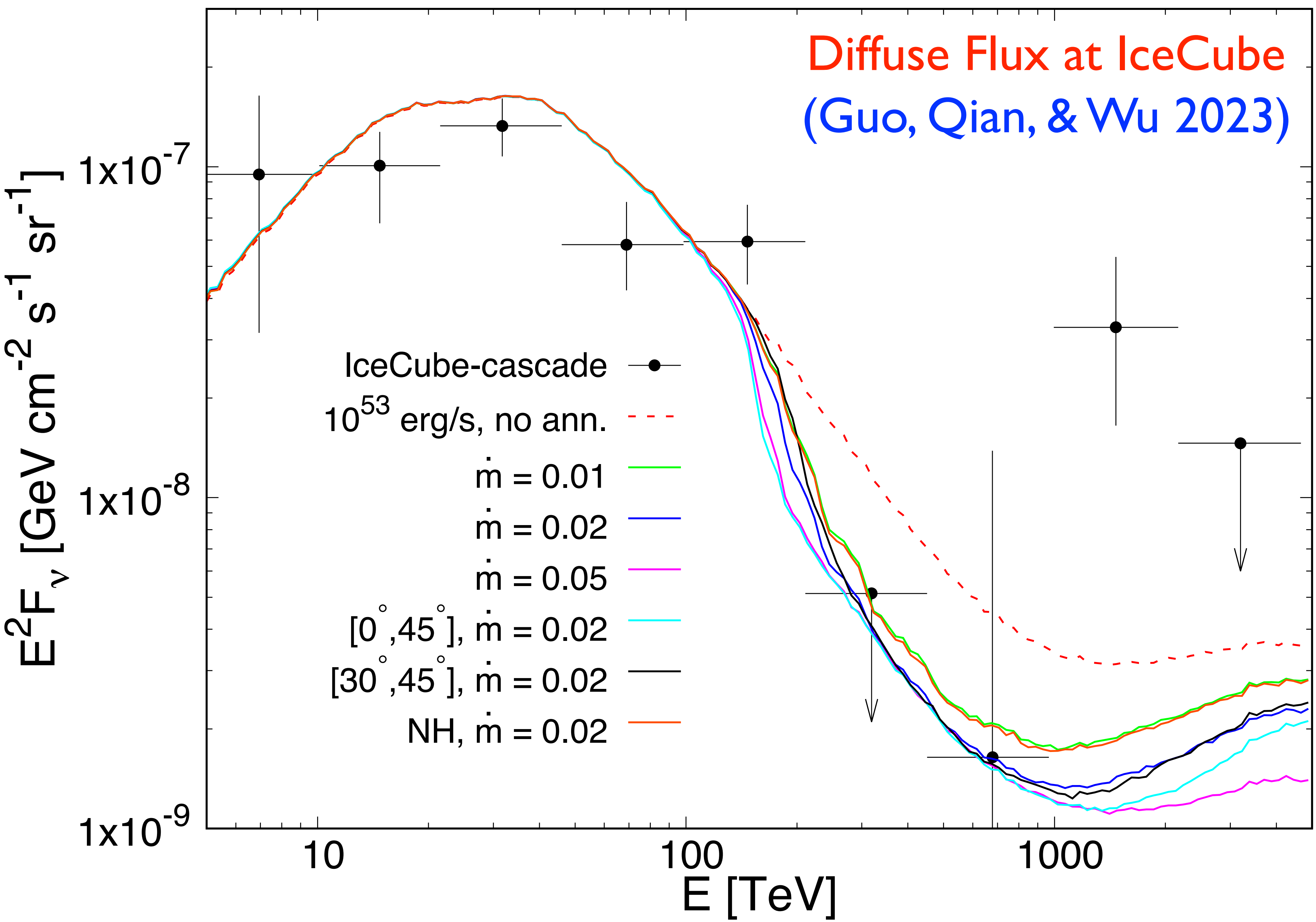


initial proton spectrum $E_p^{-2}\exp(-E_p/E_{p,\max})$

cooling of $\pi^\pm, K^\pm$ by synchrotron radiation

and $\pi^\pm/K^\pm + \gamma \to \pi^\pm/K^\pm + e^+ + e^-$

annihilation of HE ν_μ by LE $\bar{\nu}_\mu$ converted from β-decay $\bar{\nu}_e$



Diffuse Flux at IceCube
(Guo, Qian, & Wu 2023)
IceCube-cascade
10^53 erg/s, no ann.
ṁ = 0.01
ṁ = 0.02
ṁ = 0.05
[0°,45°], ṁ = 0.02
[30°,45°], ṁ = 0.02
NH, ṁ = 0.02
1x10^-7
1x10^-8
1x10^-9
10
100
1000
E [TeV]
E^2F_ν [GeV cm^-2 s^-1 sr^-1]

core-collapse supernovae & neutron star mergers
as laboratories of neutrino physics

neutrinos dominate or play important roles in
dynamics and nucleosynthesis

same nuclear physics input
EoS, neutrino opacities, neutrino oscillations,
nuclear reaction rates

parallel multi-messenger observables
neutrinos, light curve, gamma rays, gravitational waves,
chemical enrichments