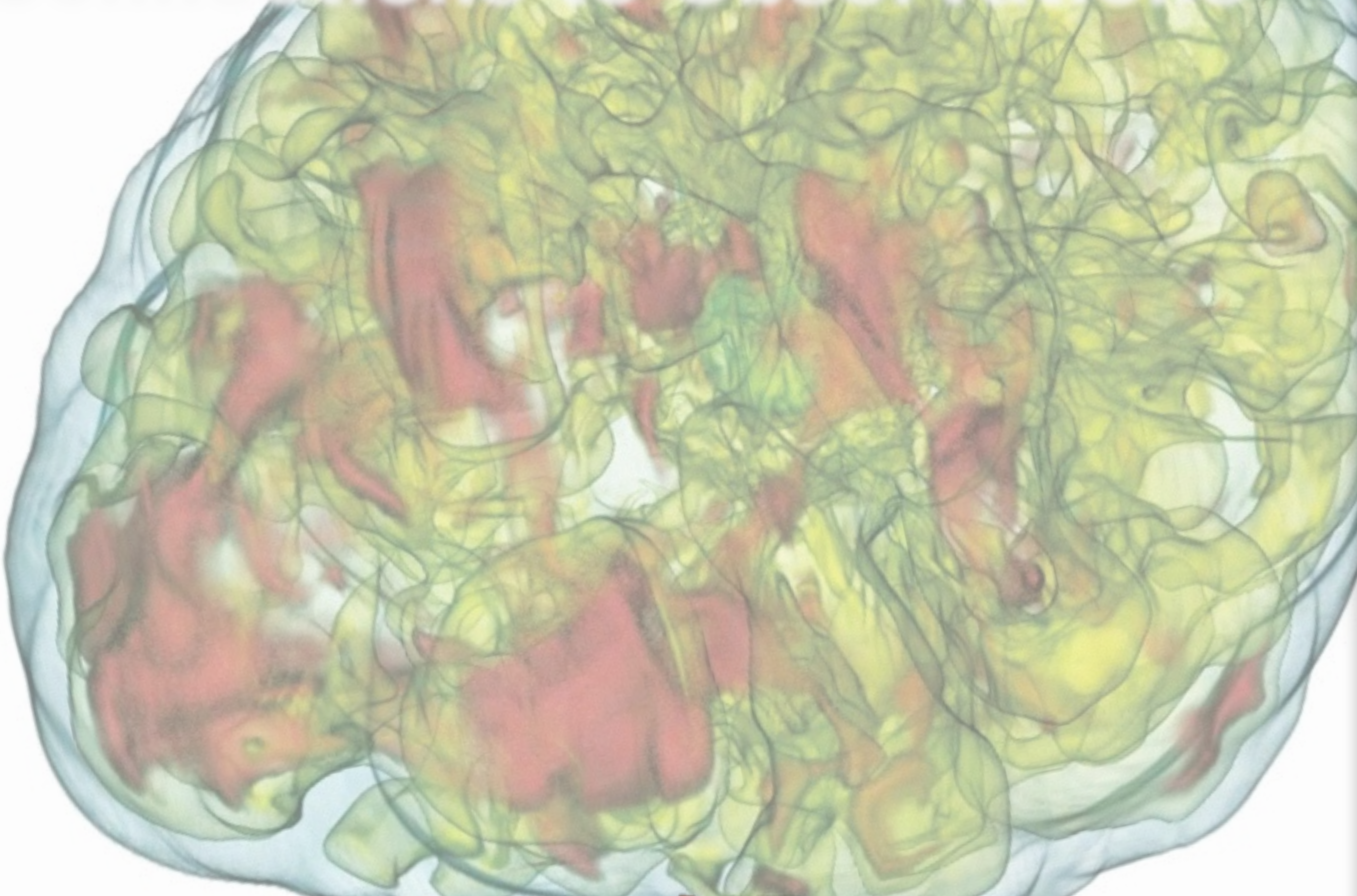
Neutrinos From Core-Collapse Supernovae: 2D & 3D Simulations and Connections to Observations



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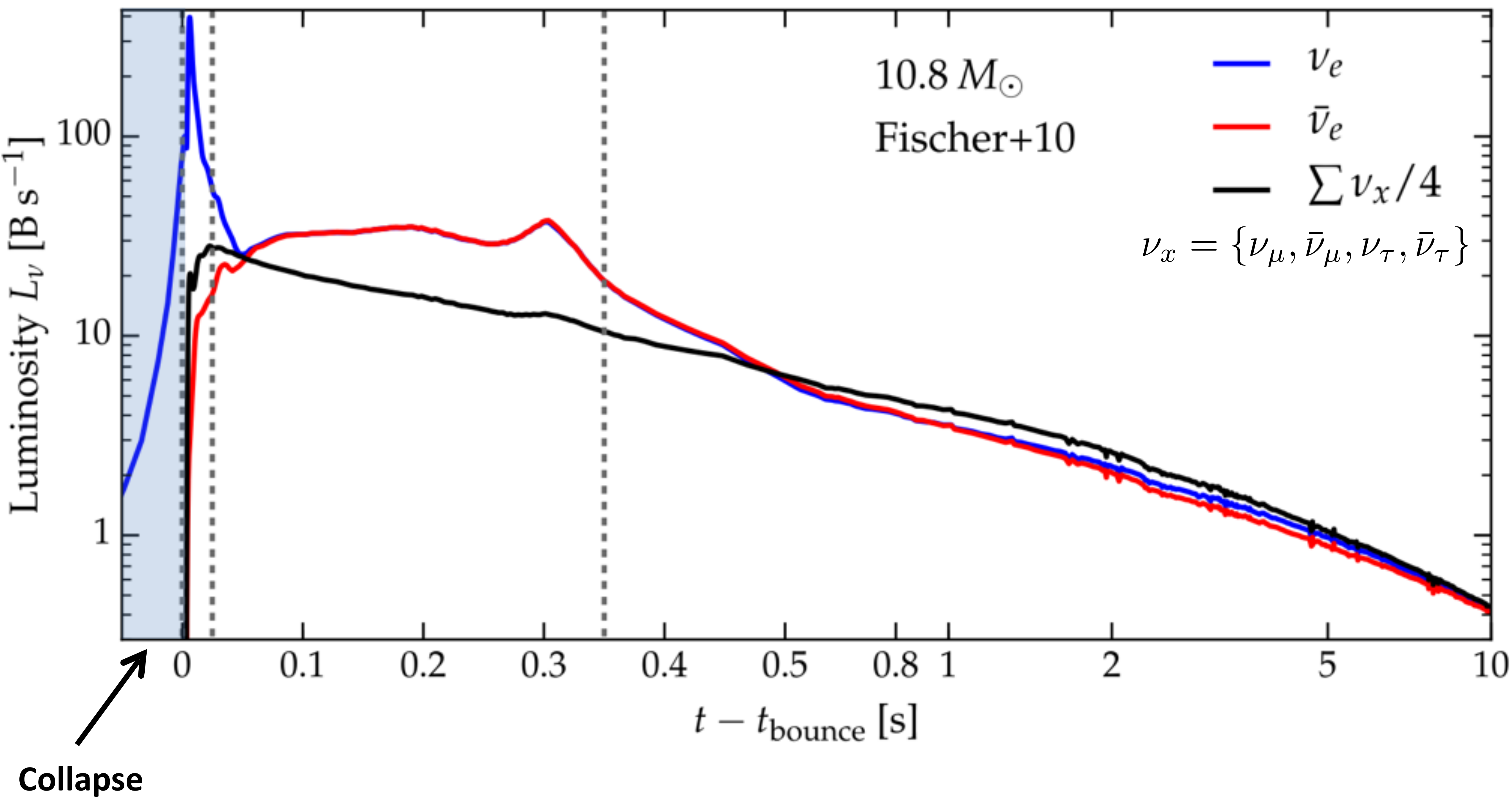
Supernova neutrino "light curves"



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

Collapse: neutrino trapping

$$\lambda_\nu = \frac{1}{\sigma_A n_A}$$

$$n_A = \frac{\rho}{A m_u}$$

$$\sigma_A = \frac{1}{16}\sigma_0 \left(\frac{E_\nu}{m_e c^2}\right)^2 A^2 \left[1 - \frac{Z}{A} + \left(4\sin^2\theta_W - 1\right)\frac{Z}{A}\right]^2$$

During stellar core collapse, the neutrino opacity is dominated by coherent scattering on nuclei.

Freedman, PRD **9**, 1389 (1974)

$$\lambda_\nu \approx 100\,\text{km} \left(\frac{\rho}{3\times10^{10}\ \text{g cm}^{-3}}\right)^{-5/3} \left(\frac{A}{56}\right)^{-1} \left(\frac{Y_e}{26/56}\right)^{2/3} \propto \rho^{-5/3}$$

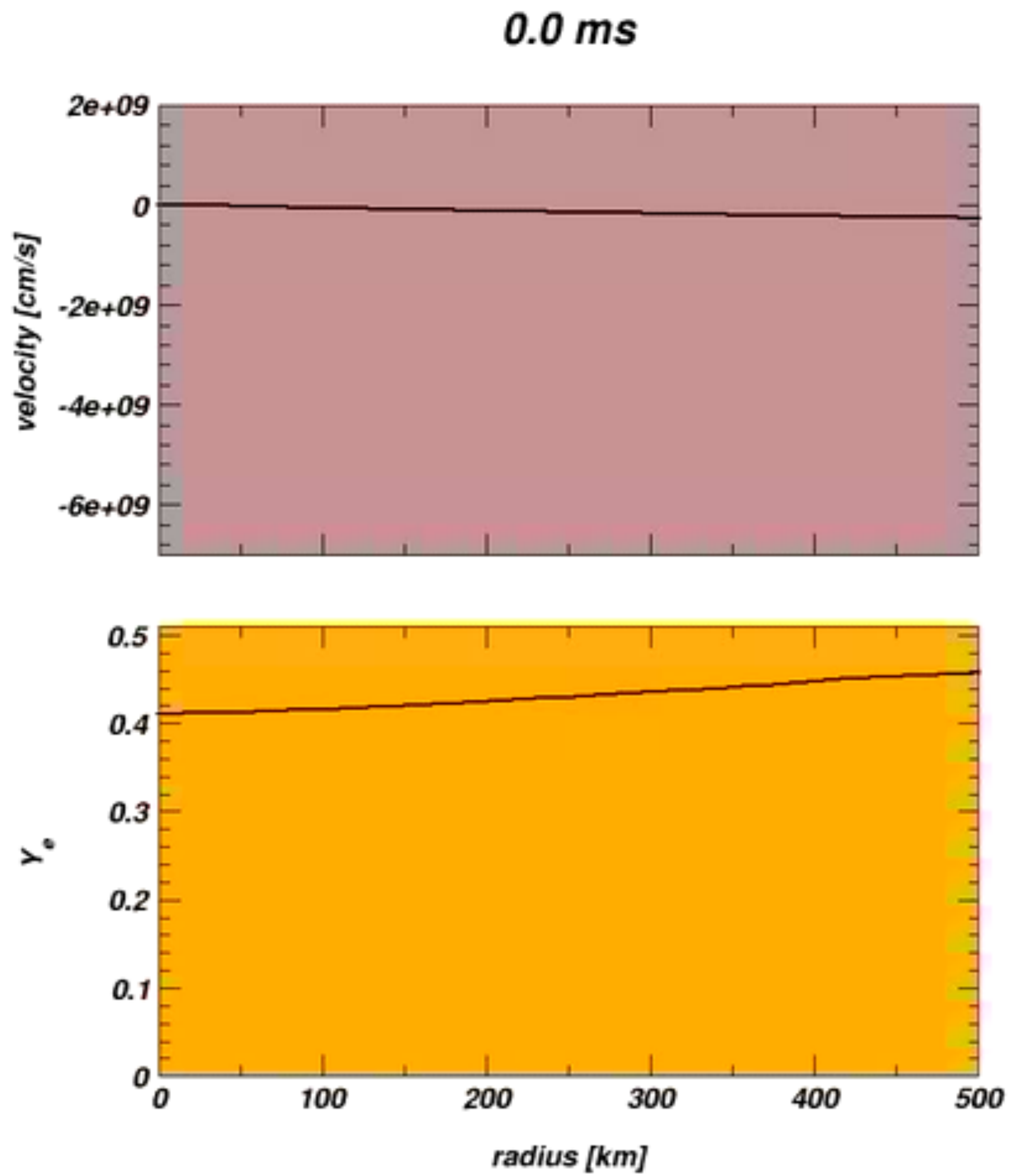
$$R_\text{core} \approx \left(\frac{3M_\text{core}}{4\pi\rho}\right)^{1/3} \approx 270\ \text{km} \left(\frac{\rho}{3\times10^{10}\ \text{g cm}^{-3}}\right)^{-1/3} \left(\frac{Y_e}{26/56}\right)^{2/3} \propto \rho^{-1/3}$$

Arnett, ApJ **218**, 815 (1977)

Electron-neutrino mean free path decreases much more rapidly with density than does the size of the core, and the neutrinos become trapped in the core.

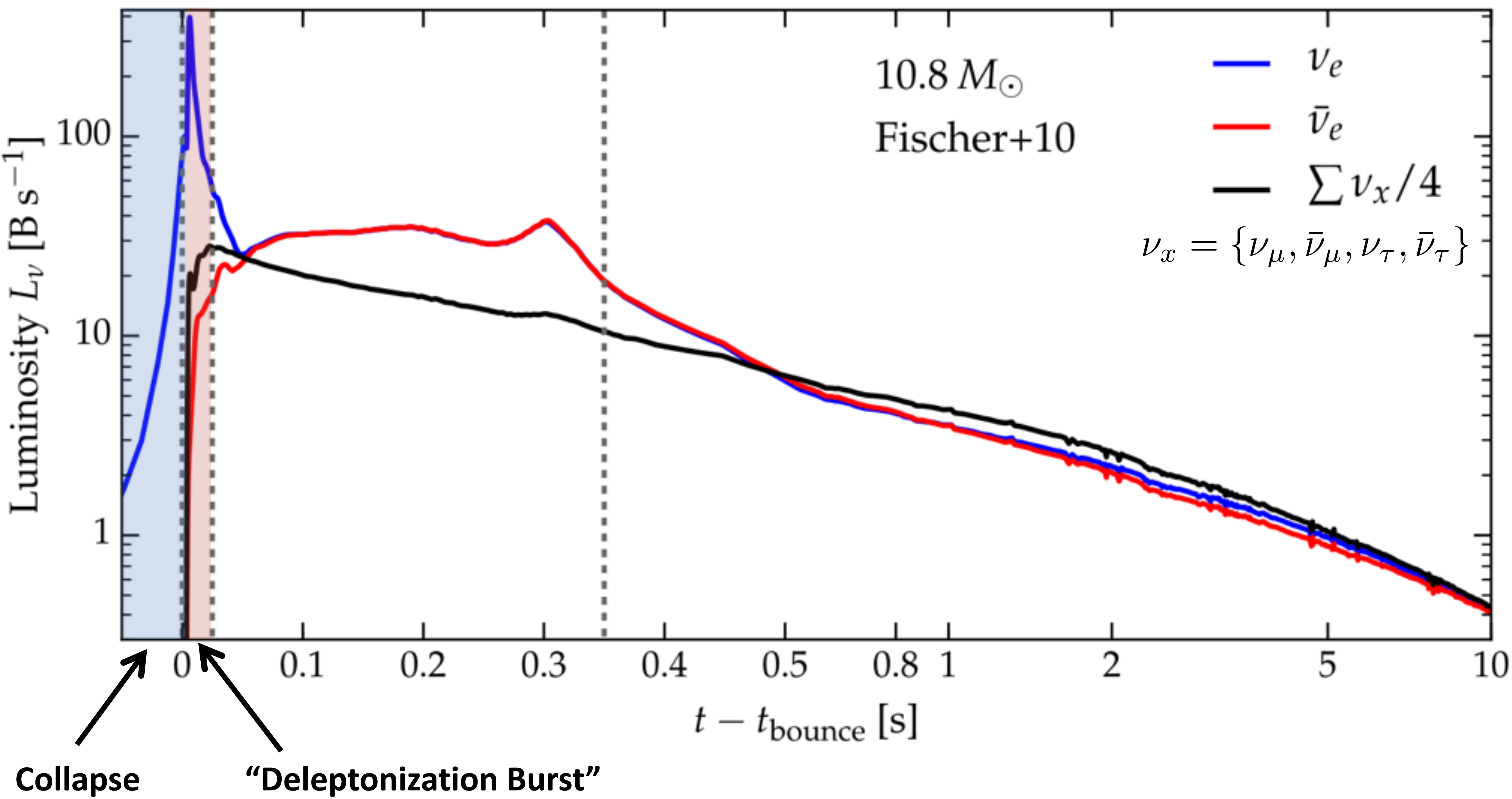
Degenerate electron-neutrino Fermi sea develops (E_F > 100 MeV)

Spherically symmetric collapse and shock propagation



AGILE-Boltztran

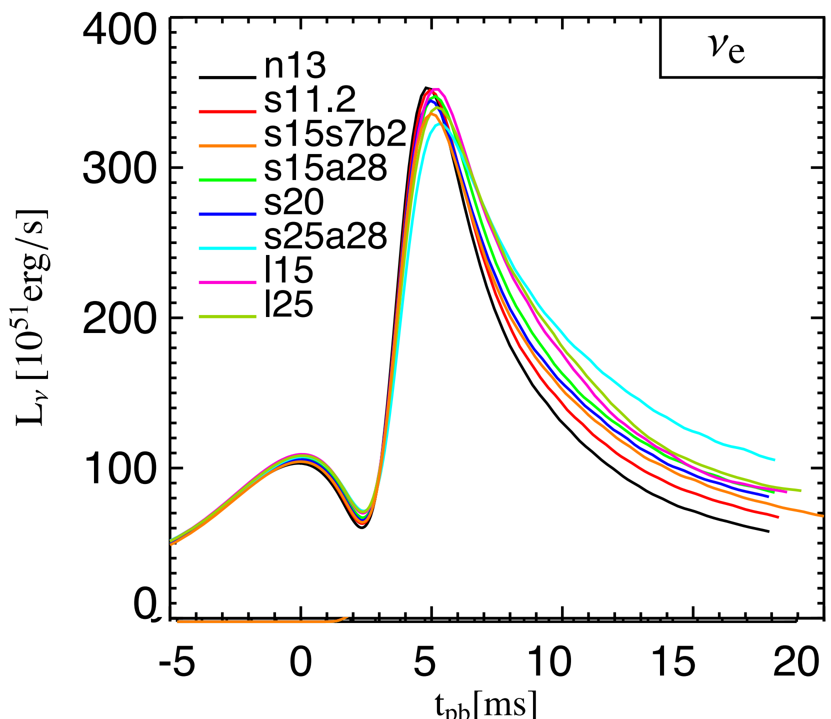
Supernova neutrino "light curves"



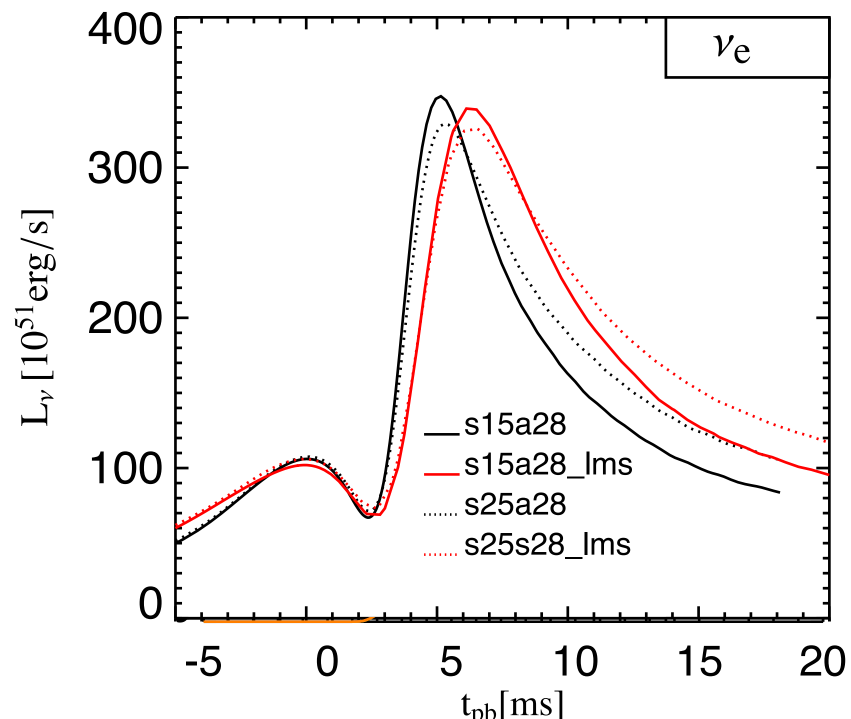
$$e^- + p \rightarrow n + \nu_e$$

The neutronization burst is insensitive to a lot.

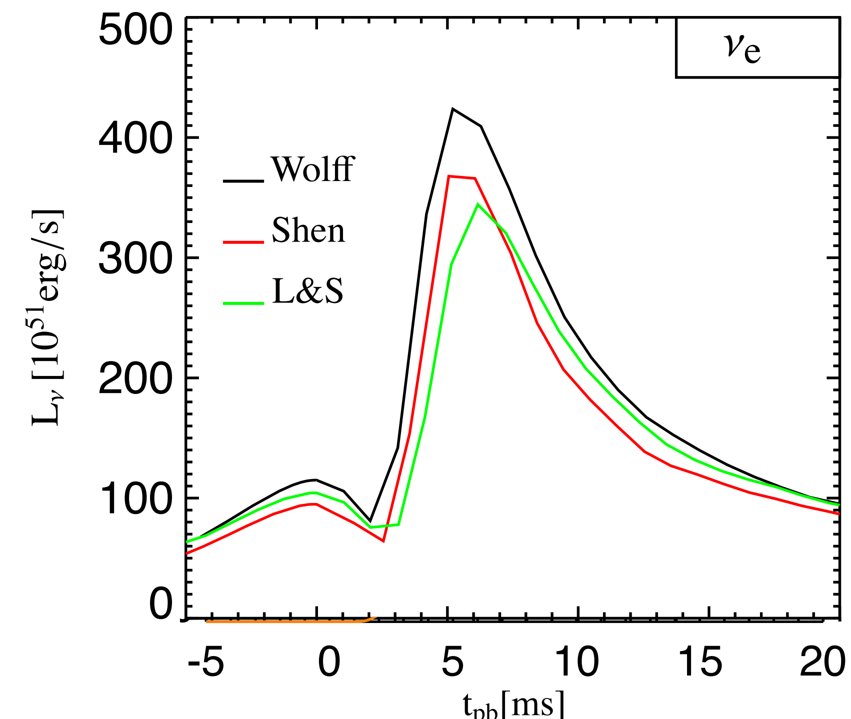
Kachelrieß+ 2005



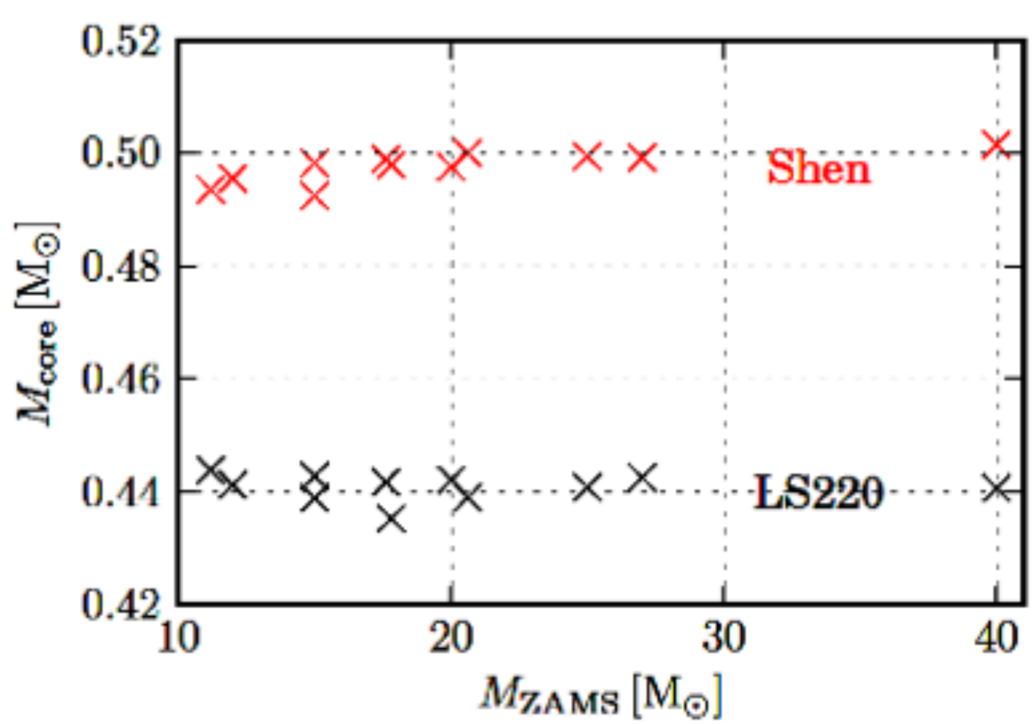
✗ progenitor mass



✗ e- capture in collapse



✔ EOS



Changes trapped lepton fraction
and
free proton fraction

L. Hüdepohl, PhD Thesis (2013)

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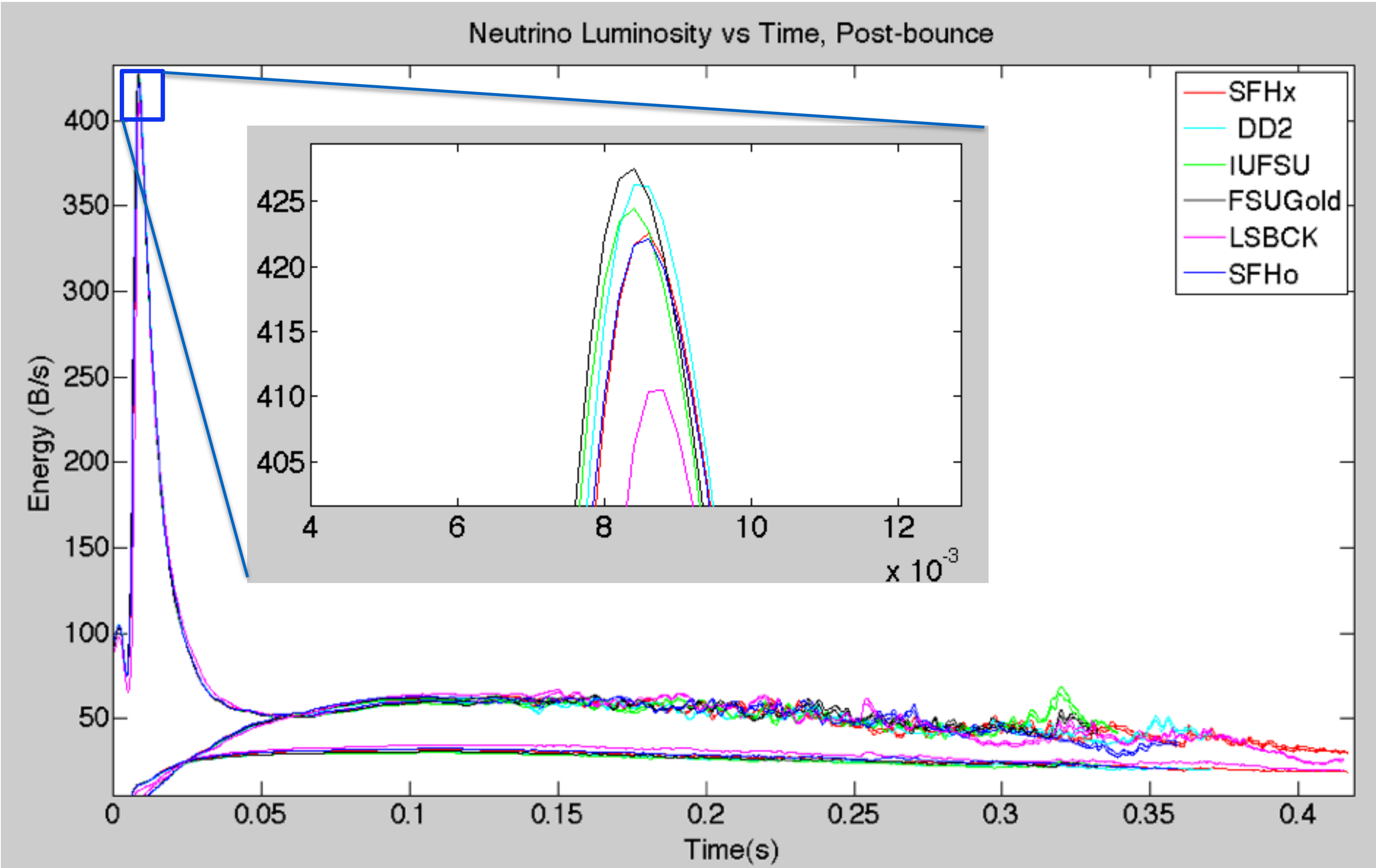
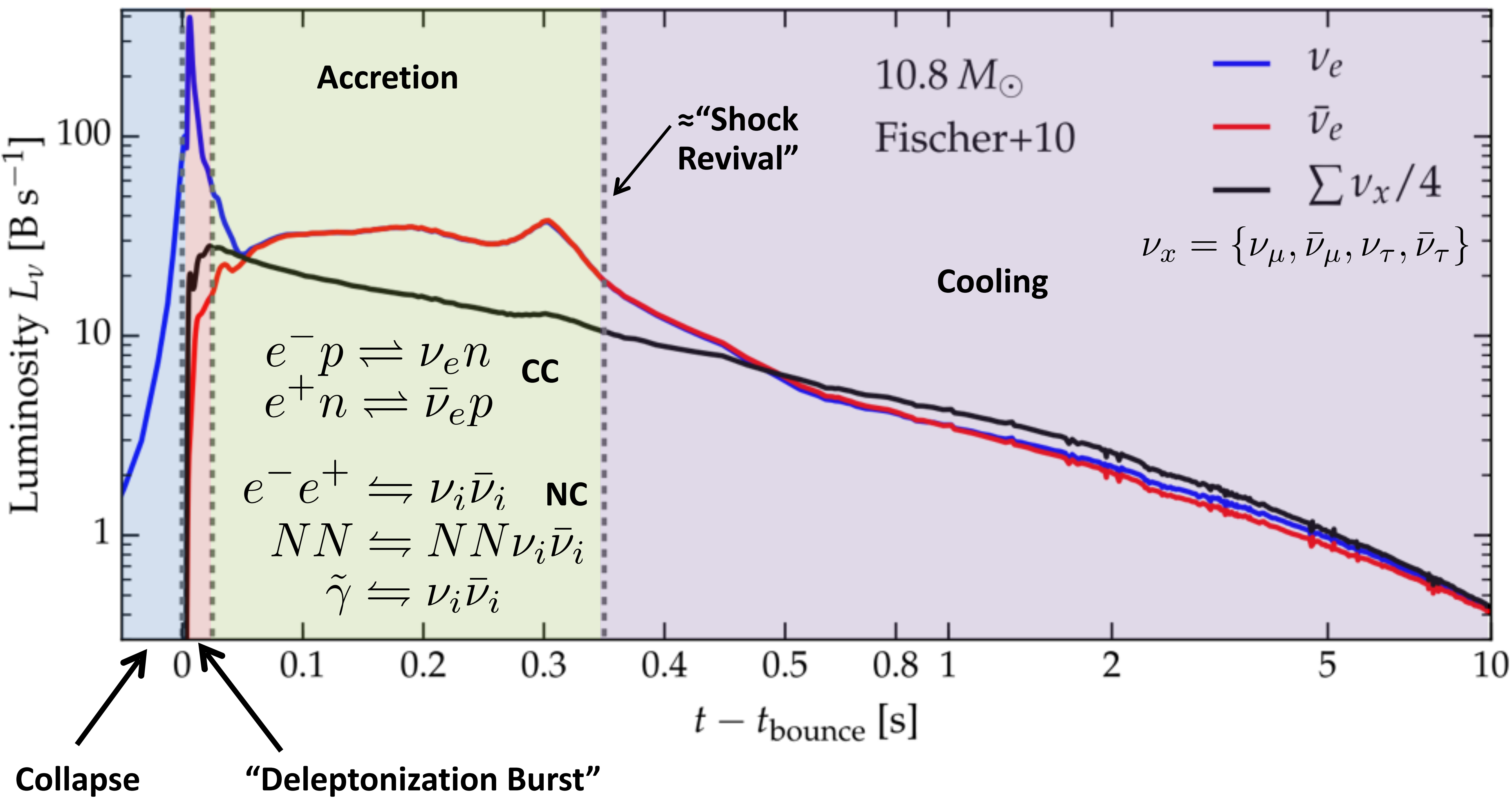
...but, modern EOS's have much smaller differences.



R. Landfield, PhD thesis (U. Tennessee)

Supernova neutrino "light curves"



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

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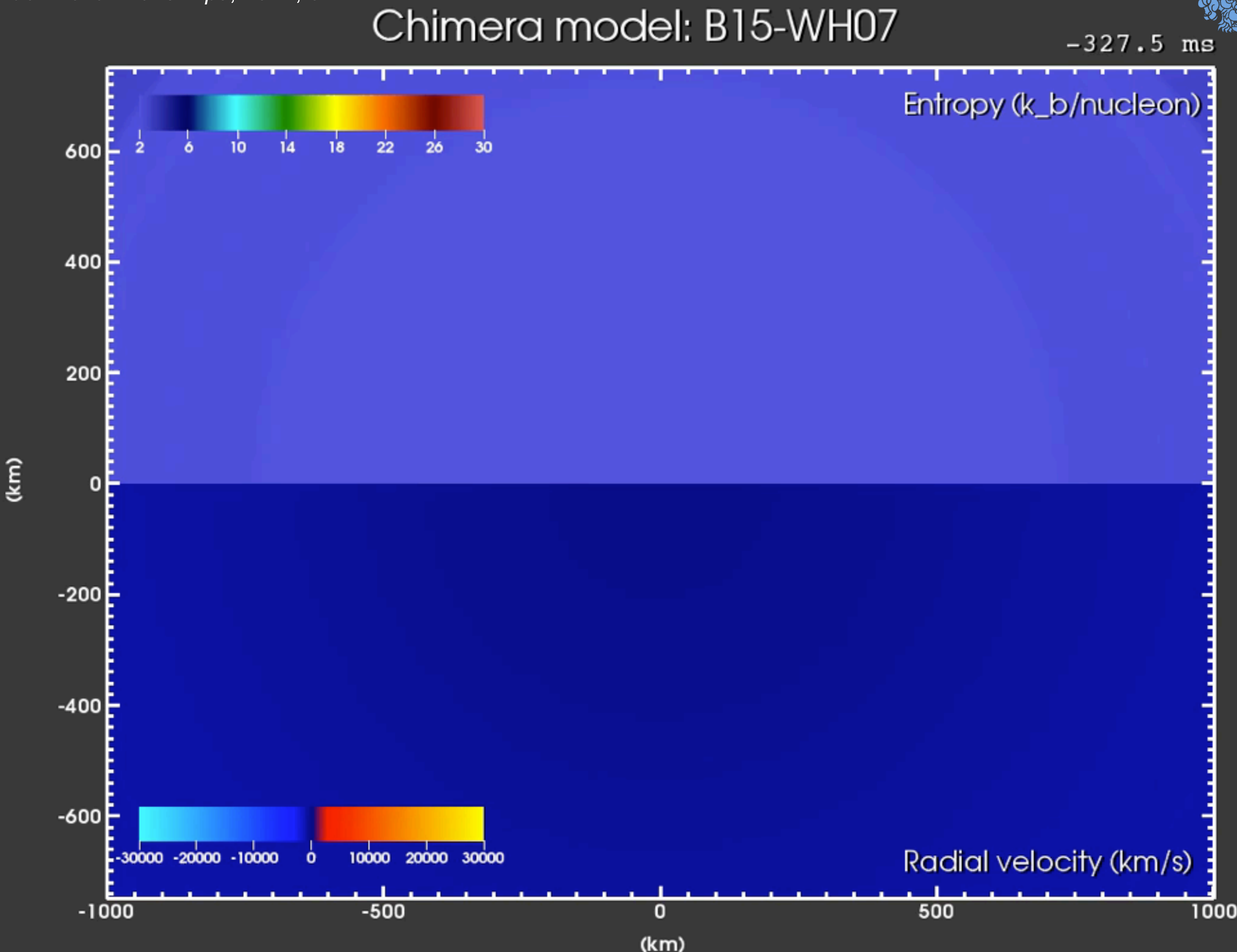
Bruenn et al. 2013. *ApJ*, **767L**, 6B.

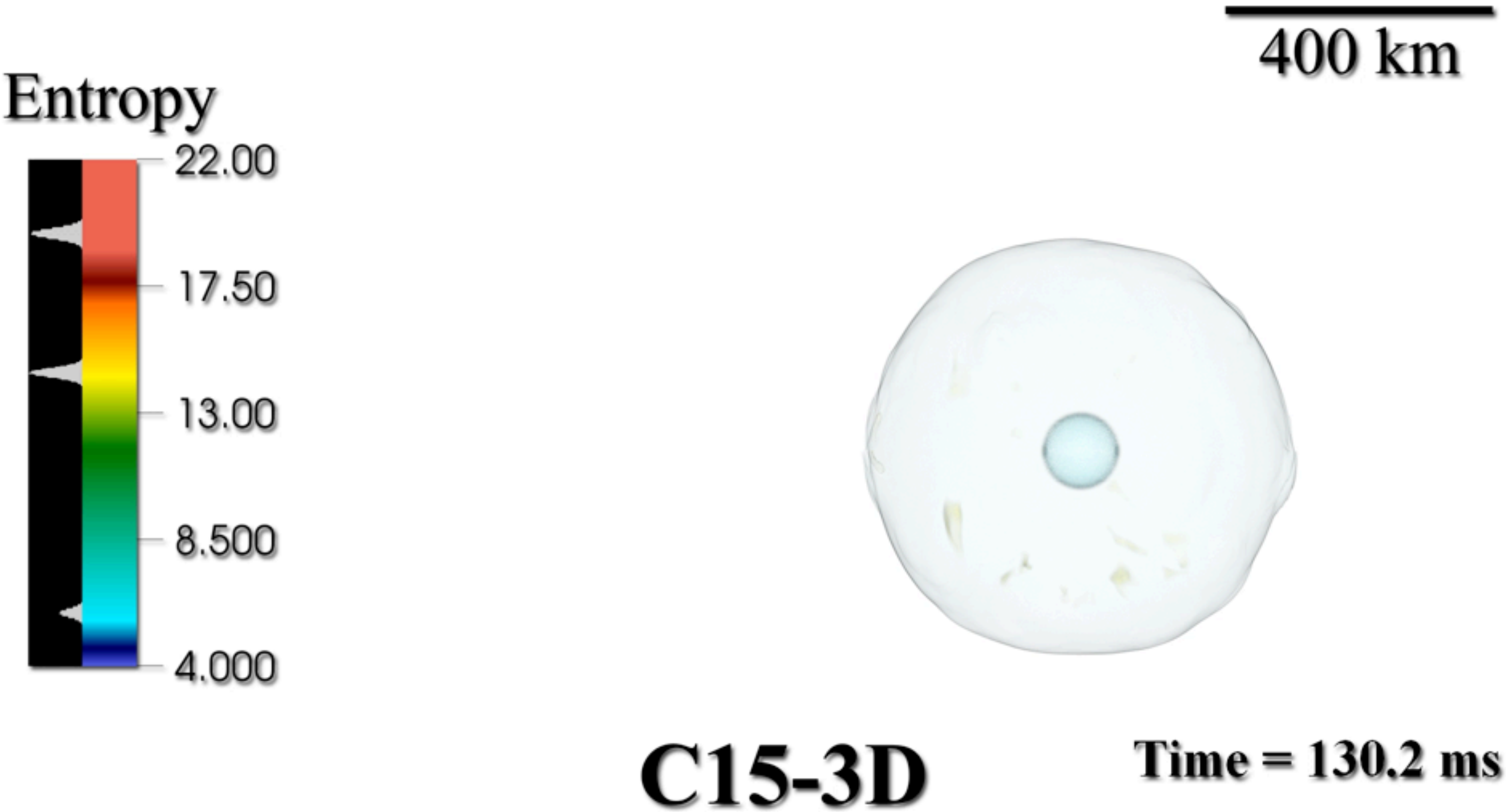


15 solar mass 3D run

~6 months on ~48,000 cores

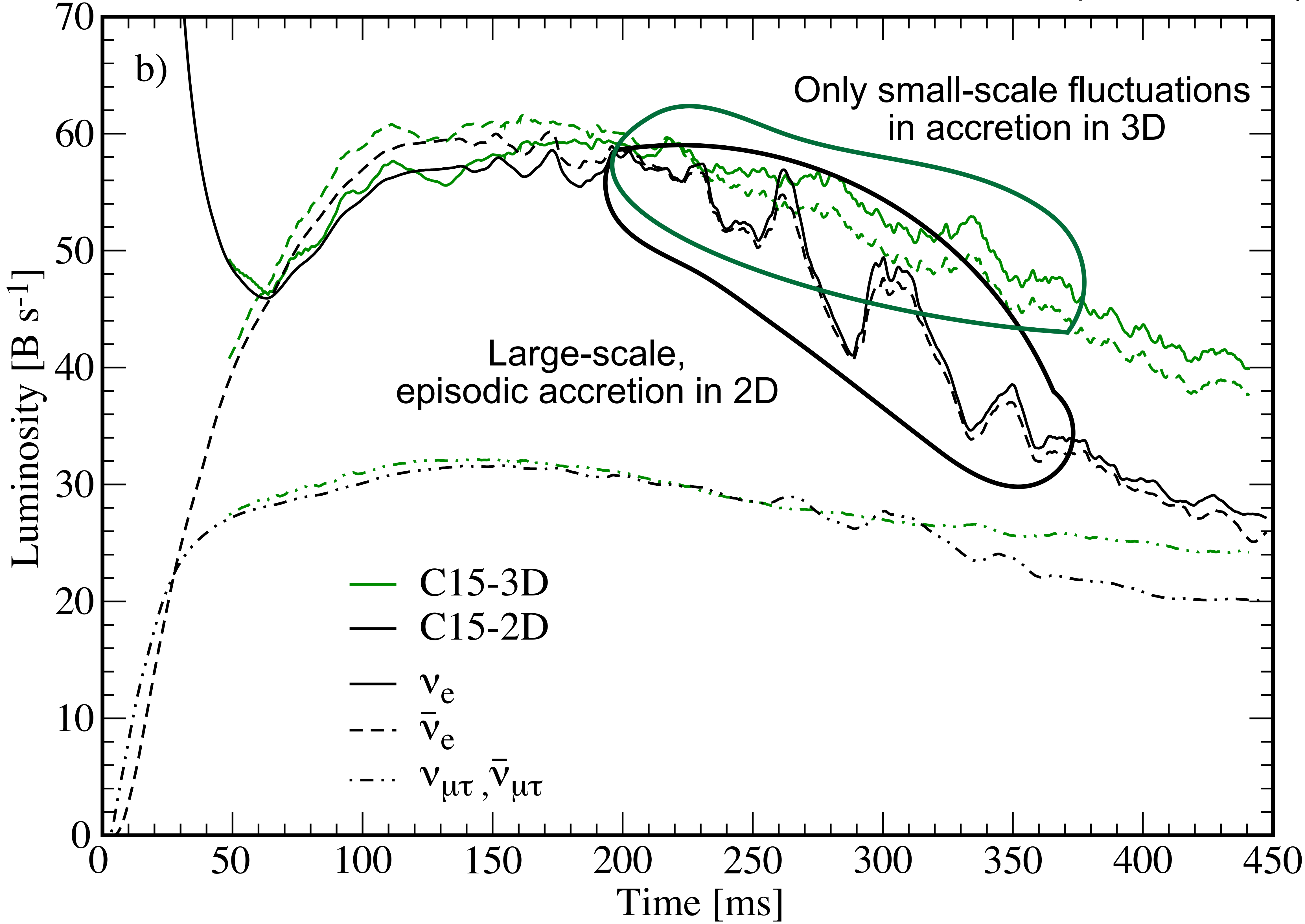
- 15 solar mass WH07 progenitor
- 540 radial zones covering inner 11000 km
- 180 phi zones (2 degree resolution)
- 180 theta zones in "constant mu" grid, from 2/3 degree at equator to one 8.5 degree zone at pole.
- “Full” opacities
- 0.1% density perturbations (10-30 km) applied at 1.3 ms after bounce in transition from 1D.

Lentz et al. *ApJL* **807**, L31 (2015)



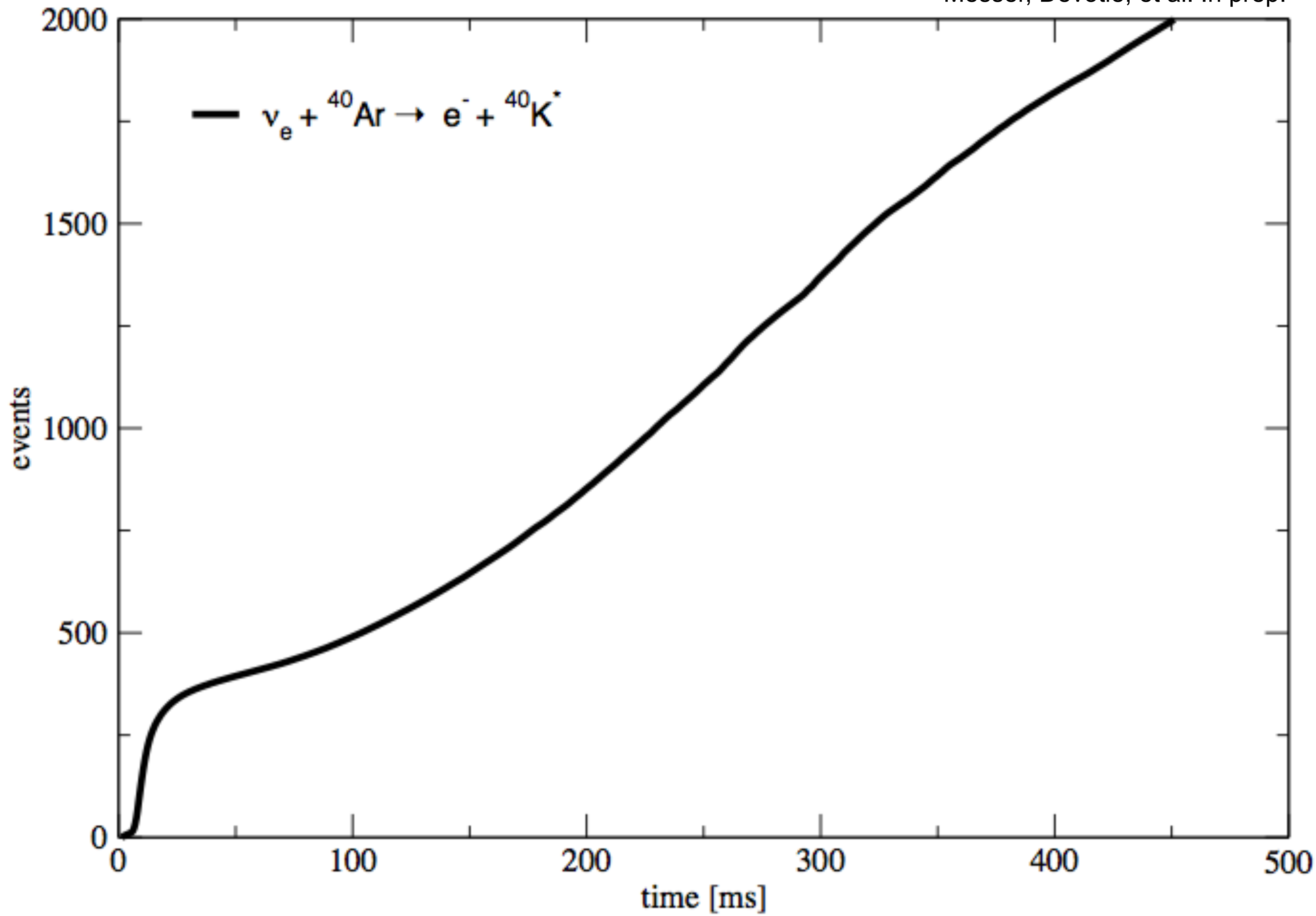
3D vs 2D luminosities

Lentz et al. *ApJL* **807**, L31 (2015)



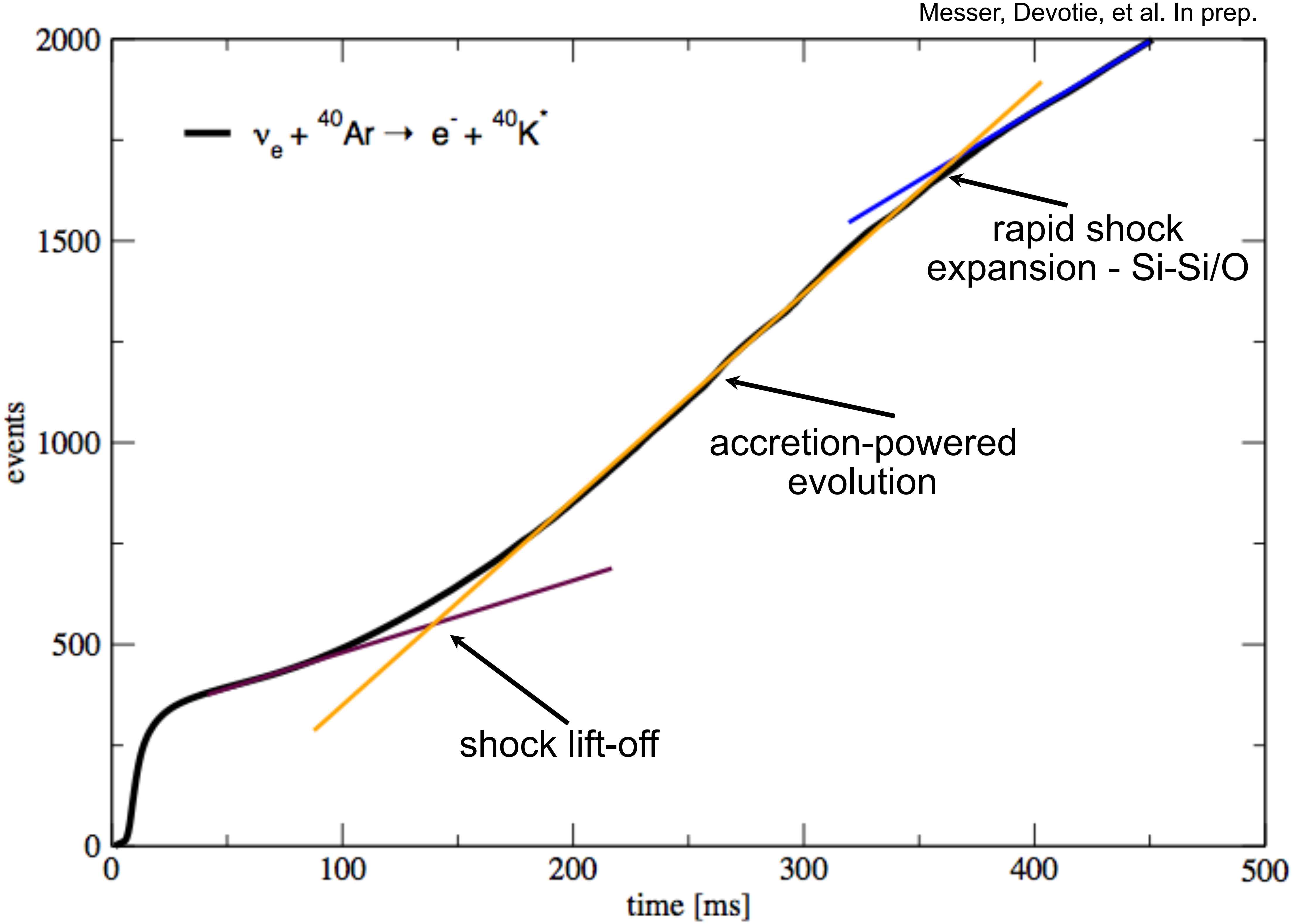
2D - ν_e total counts vs. time

Messer, Devotie, et al. In prep.



C15-2D, angle-averaged, SNOwGLoBES Ar17kt, 10 kpc

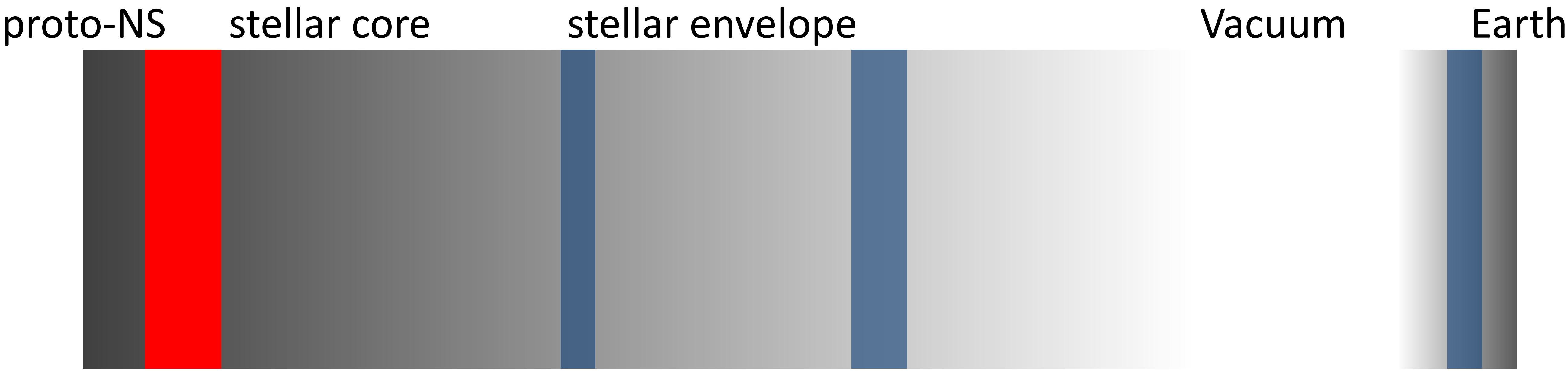
2D - ν_e total counts vs. time



C15-2D, angle-averaged, SNOwGLoBES Ar17kt, 10 kpc

Supernova neutrino oscillations

(see, e.g., Mirizzi+15, Duan+10 for reviews)



$\mu \gg \lambda$	$\omega_{31} \simeq \lambda$	$\omega_{21} \simeq \lambda$
$10^9 - 10^7\,\mathrm{g\,cm^{-3}}$	$10^3\,\mathrm{g\,cm^{-3}}$	$1 - 10\,\mathrm{g\,cm^{-3}}$
$r \lesssim 10^3\,\mathrm{km}$	MSW	MSW
	H Resonance	L Resonance

Collective osc.

(likely)
suppressed in accretion phase e.g. Chakraborty+ 2011, but see previous talk

(figure inspired by C. Lunardini)

3 flavor oscillations with ν_x and anti-ν_x

$$F_e = \frac{1}{4\pi R^2}[p_{ee}\Phi_e + (1 + p_{ee})\Phi_x]$$

$$F_\mu + F_\tau = \frac{1}{4\pi R^2}[(1 - p_{ee})\Phi_e + (1 + p_{ee})\Phi_x]$$

$$\bar{F}_e = \frac{1}{4\pi R^2}[\bar{p}_{ee}\bar{\Phi}_e + (1 - \bar{p}_{ee})\bar{\Phi}_x]$$

$$\bar{F}_\mu + \bar{F}_\tau = \frac{1}{4\pi R^2}[(1 - \bar{p}_{ee})\bar{\Phi}_e + (1 + \bar{p}_{ee})\bar{\Phi}_x]$$

general three-flavor expressions from J. Kneller (2015, private communication)

SN ν oscillations: simplest scenario

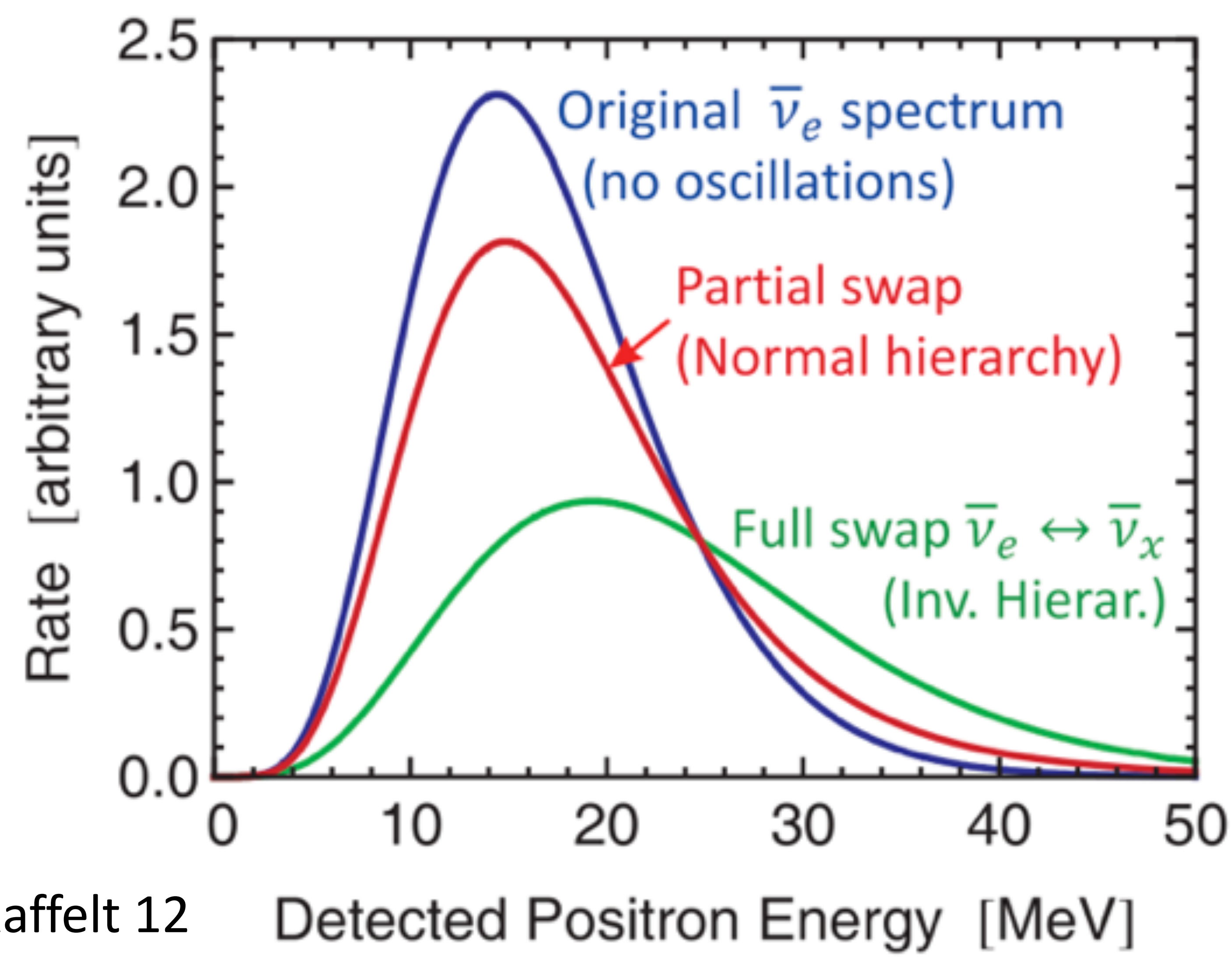
(see, e.g., Mirizzi+15, Duan+10 for reviews)

- No self-induced oscillations, no Earth effects, adiabatic evolution

Survival probabilities:

Normal Hierarchy: $(P_{ee}, \bar{P}_{ee}) = (0, \cos^2\theta_{12})$

Inverted Hierarchy: $(P_{ee}, \bar{P}_{ee}) = (\sin^2\theta_{12}, 0)$



Raffelt 12

Complications:

- Shock
  - non-adiabaticity when H resonance reached
- turbulence (see J. Kneller's talk…maybe…)

3 flavor oscillations with ν_x and anti-ν_x

NH **Normal hierarchy**

$$F_e = \frac{1}{4\pi R^2}[\Phi_x]$$

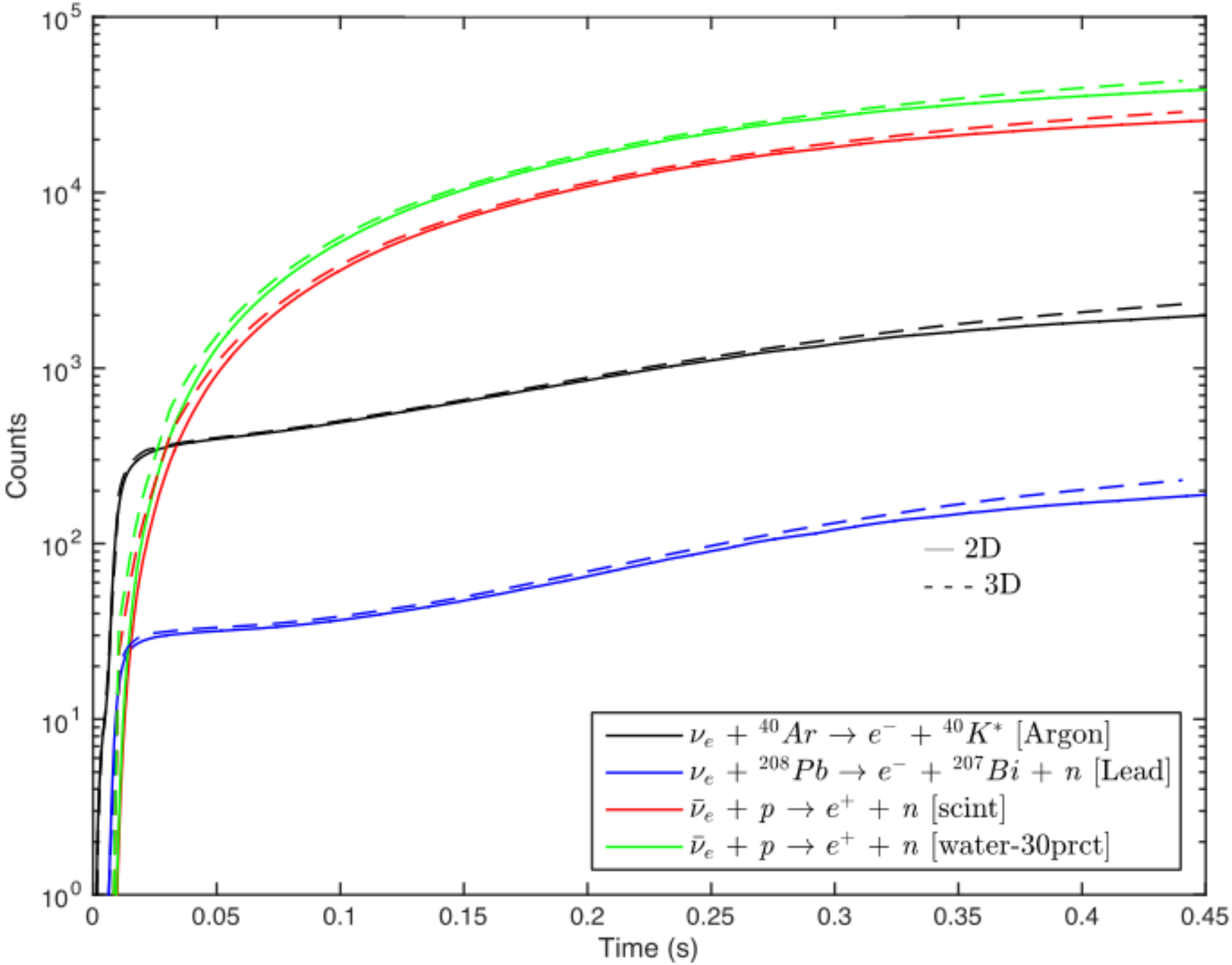
$$F_\mu + F_\tau = \frac{1}{4\pi R^2}[\Phi_e + \Phi_x]$$

$$\bar{F}_e = \frac{1}{4\pi R^2}[\cos^2(\theta_{12})\bar{\Phi}_e + \sin^2(\theta_{12})\bar{\Phi}_x]$$

$$\bar{F}_\mu + \bar{F}_\tau = \frac{1}{4\pi R^2}[\sin^2(\theta_{12})\bar{\Phi}_e + (1+\cos^2(\theta_{12}))\bar{\Phi}_x]$$

N.B. Φ_x **is <u>half</u> of the nu_x flux (i.e. half of** $[\Phi_\mu + \Phi_\tau]$**)**

Dominant channels - no osc.



Messer, Devotie, et al. In prep.

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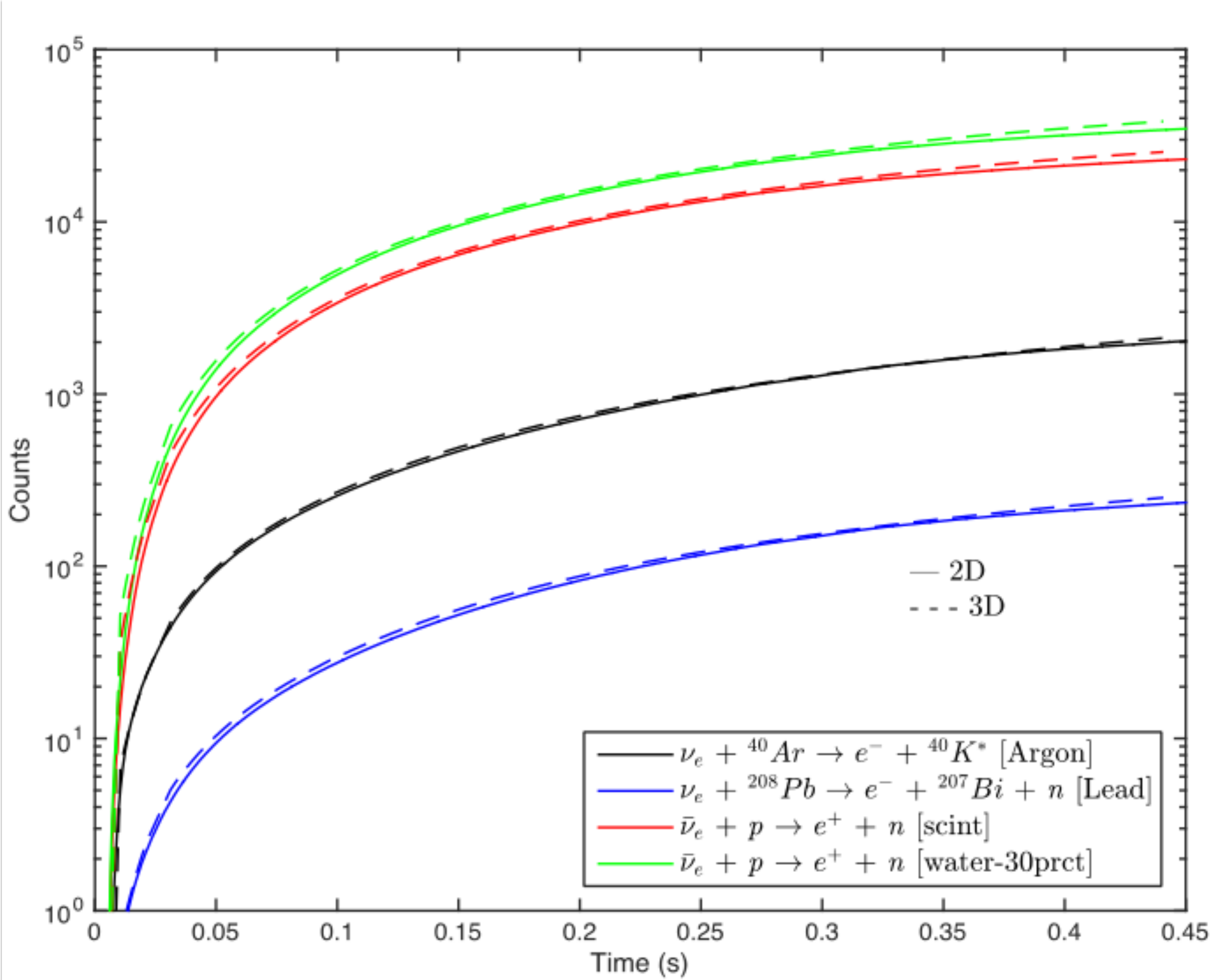
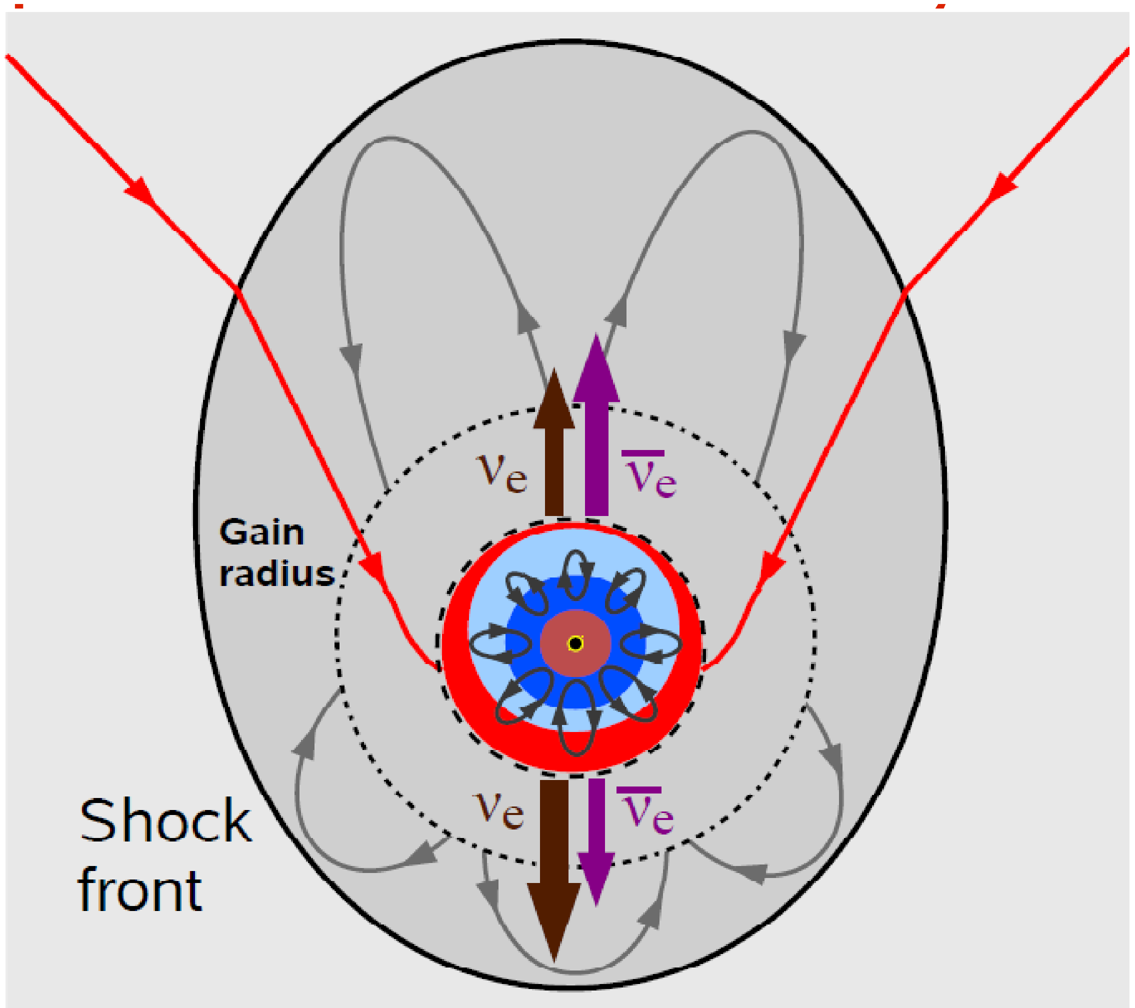
Dominant channels - w/ oscillations, NH



Messer, Devotie, et al. In prep.

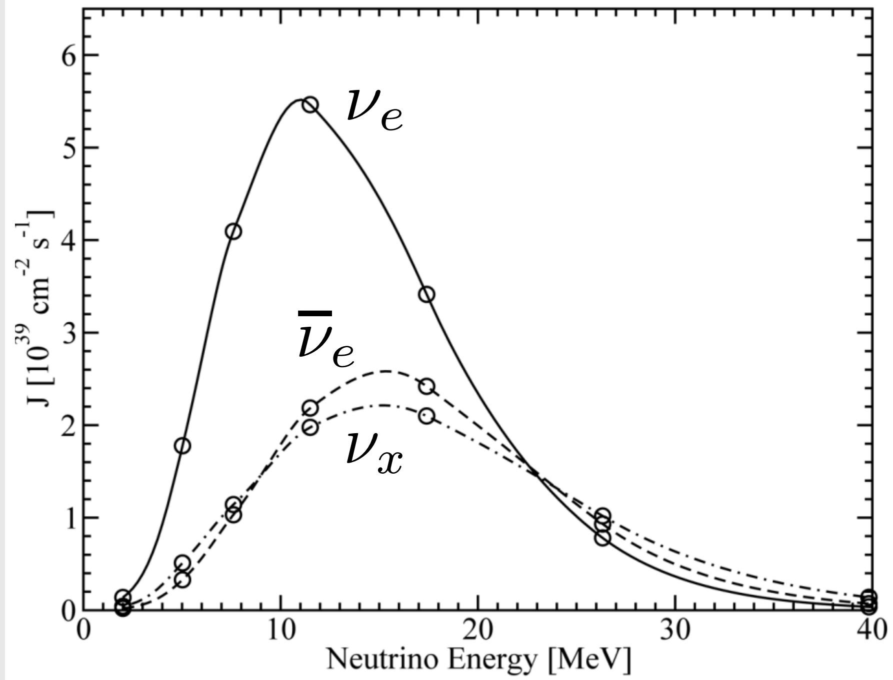
LESA

from Tamborra (FOE2015, NCSU)

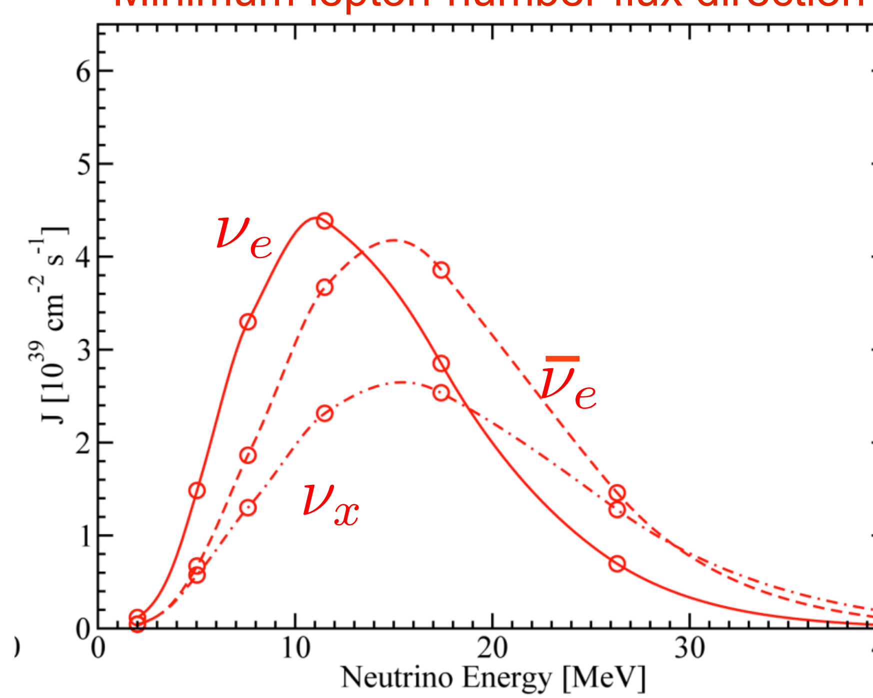


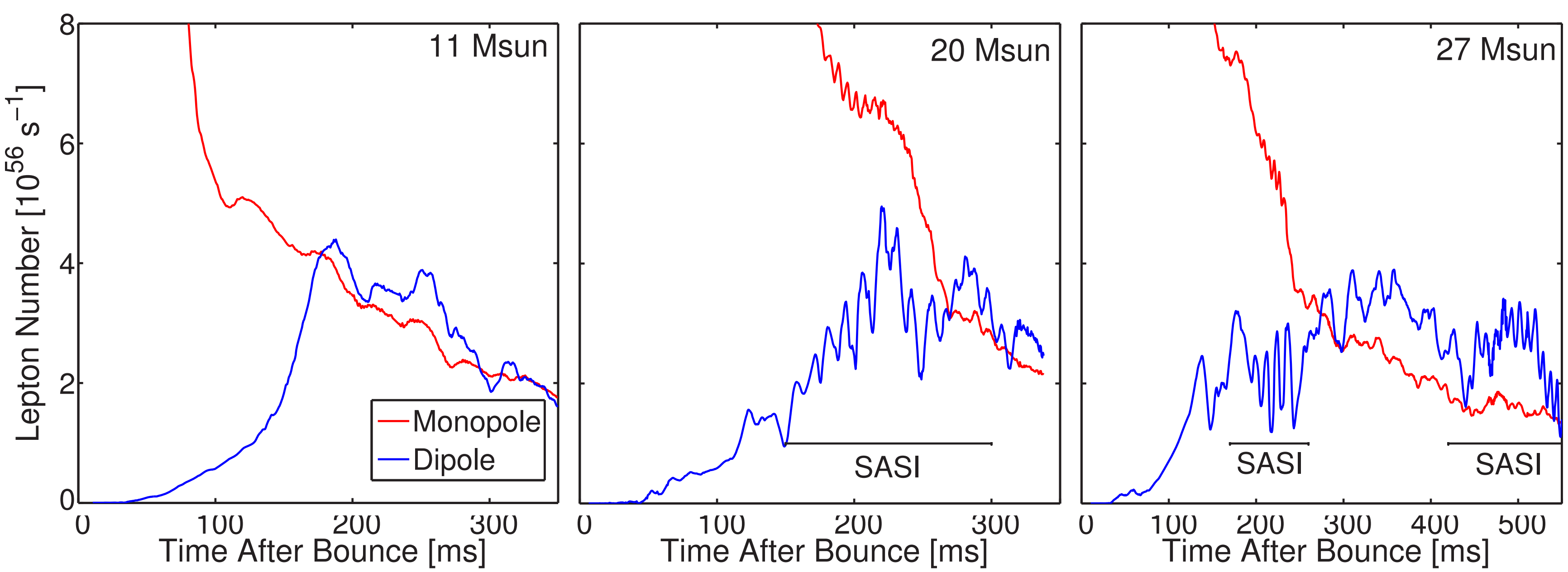
$$\dot{q} \propto \frac{\sigma_0}{r^2}\left(L_{\nu_e}\left\langle\epsilon^2_{\nu_e}\right\rangle Y_n + L_{\bar{\nu}_e}\left\langle\epsilon^2_{\bar{\nu}_e}\right\rangle Y_p\right)$$

Maximum lepton-number flux direction



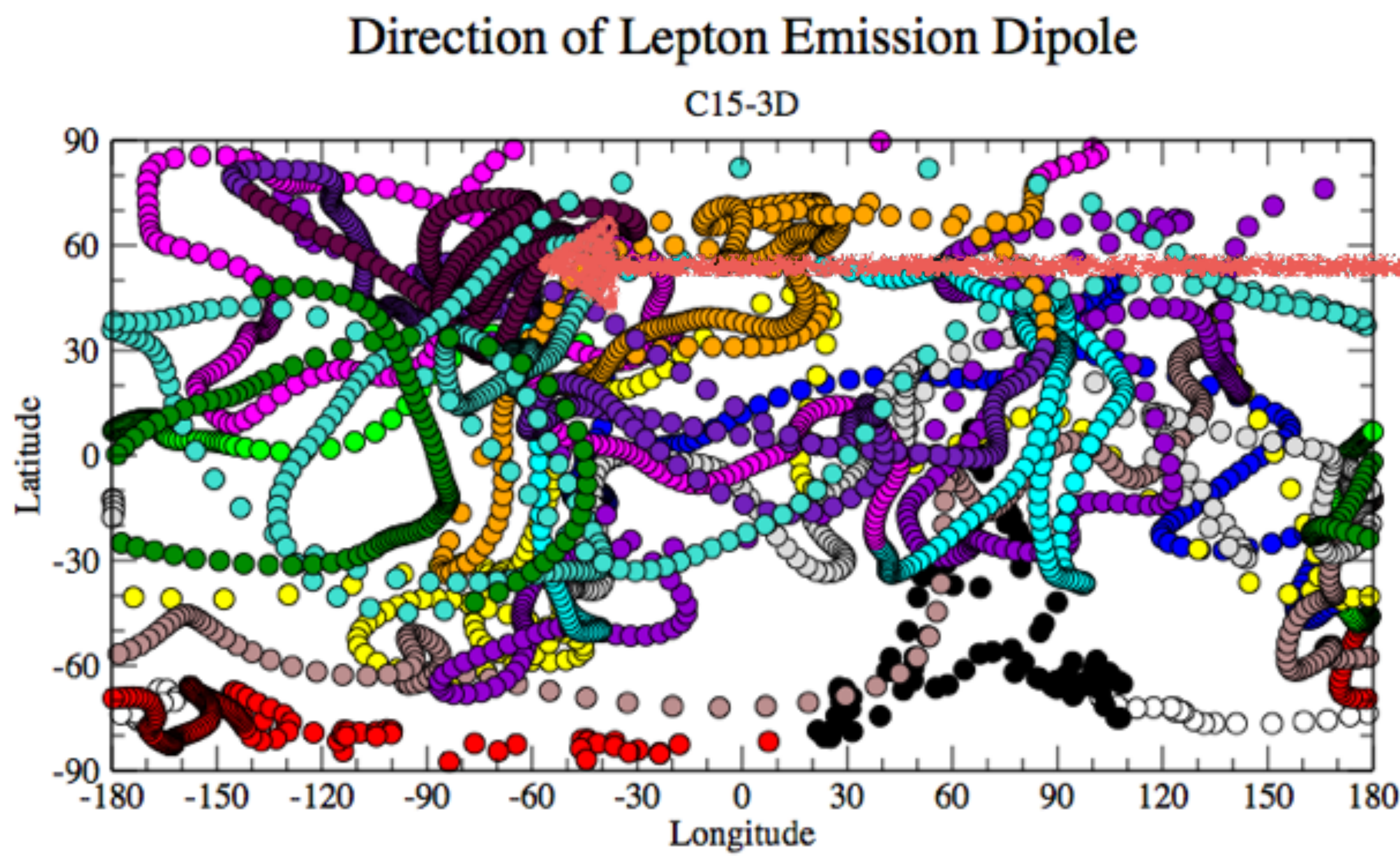
Minimum lepton-number flux direction



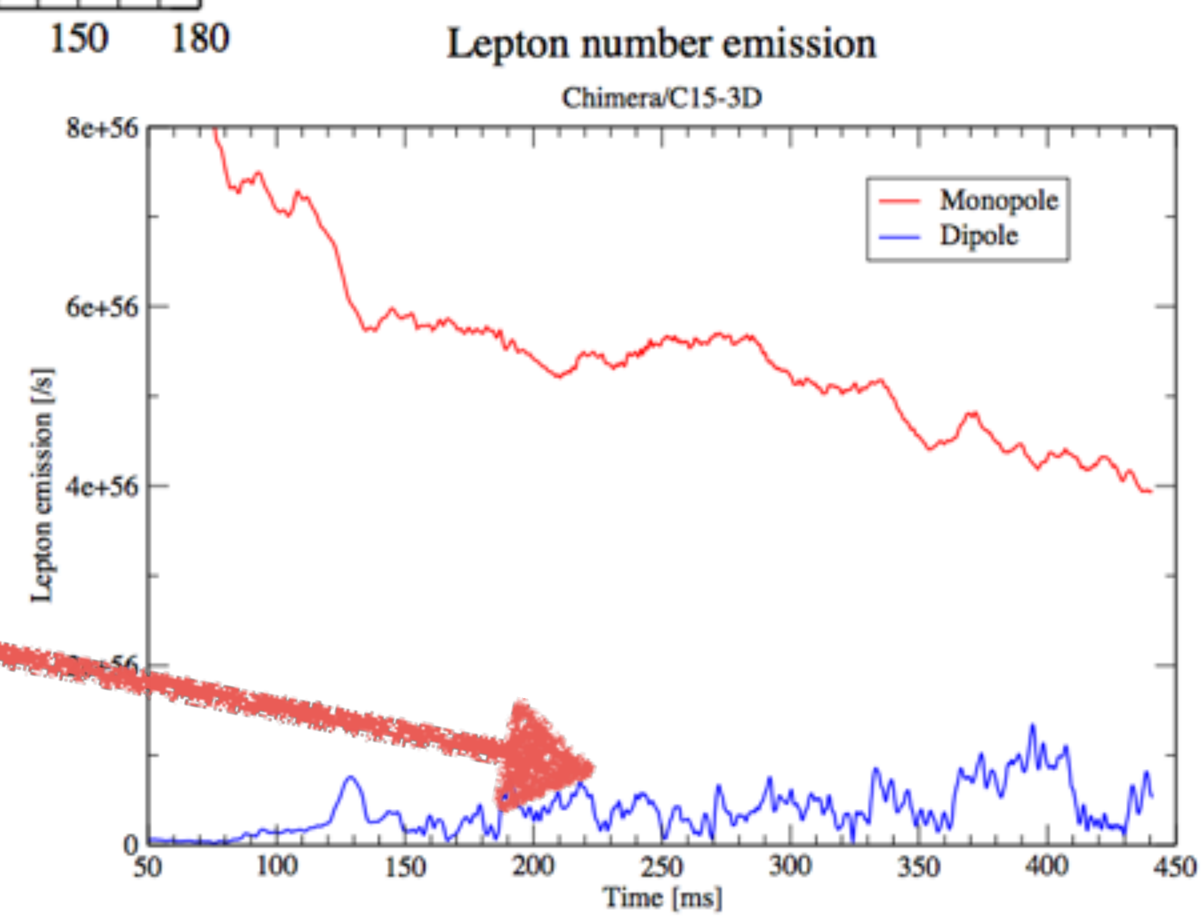


Is the LESA a generic instability?

CHIMERA C-15 3D model



Dipole relatively long-lived, but perhaps not "persistent"



Dipole present, but relatively weak

Summary

- Multi-dimensional core-collapse supernova simulations with high-fidelity neutrino transport necessarily cover the collapse and accretion epochs, extending little into the PNS cooling epoch.
- Multi-D effects can modulate the neutrino signal in multiple flavors on 10 ms time scales.
- 1D PNS cooling calculations available now. Extension to multi-D can happen, but how long?
- Collective effects are important at late (or earlier?) times, but definitive calculations will require quantum kinetic simulations (cf. George’s putatively never-ending slide from this morning).
- LESA-like effects are seen in CHIMERA simulations, but the robustness is an open question.