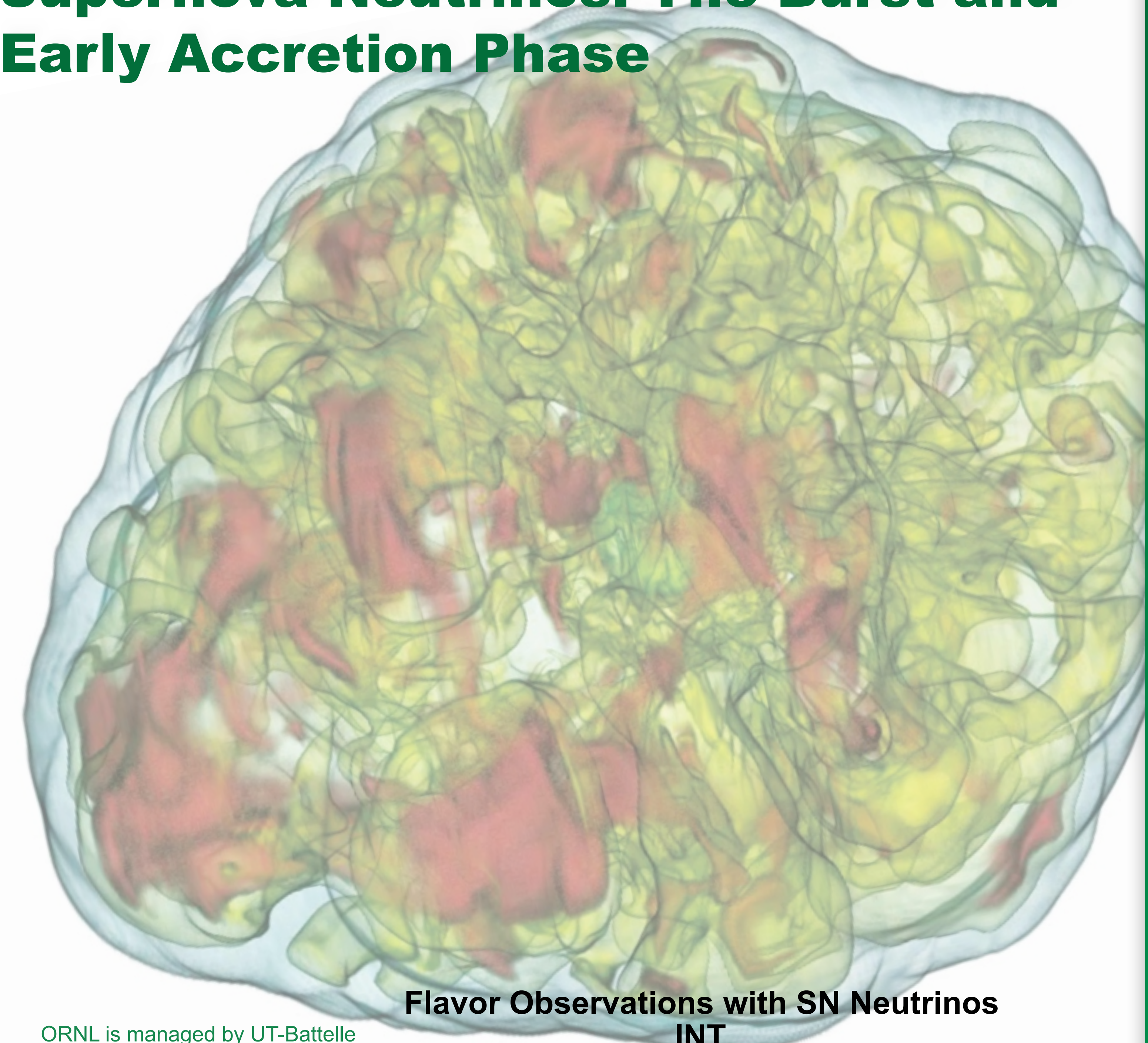
Supernova Neutrinos: The Burst and Early Accretion Phase



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Flavor Observations with SN Neutrinos
INT
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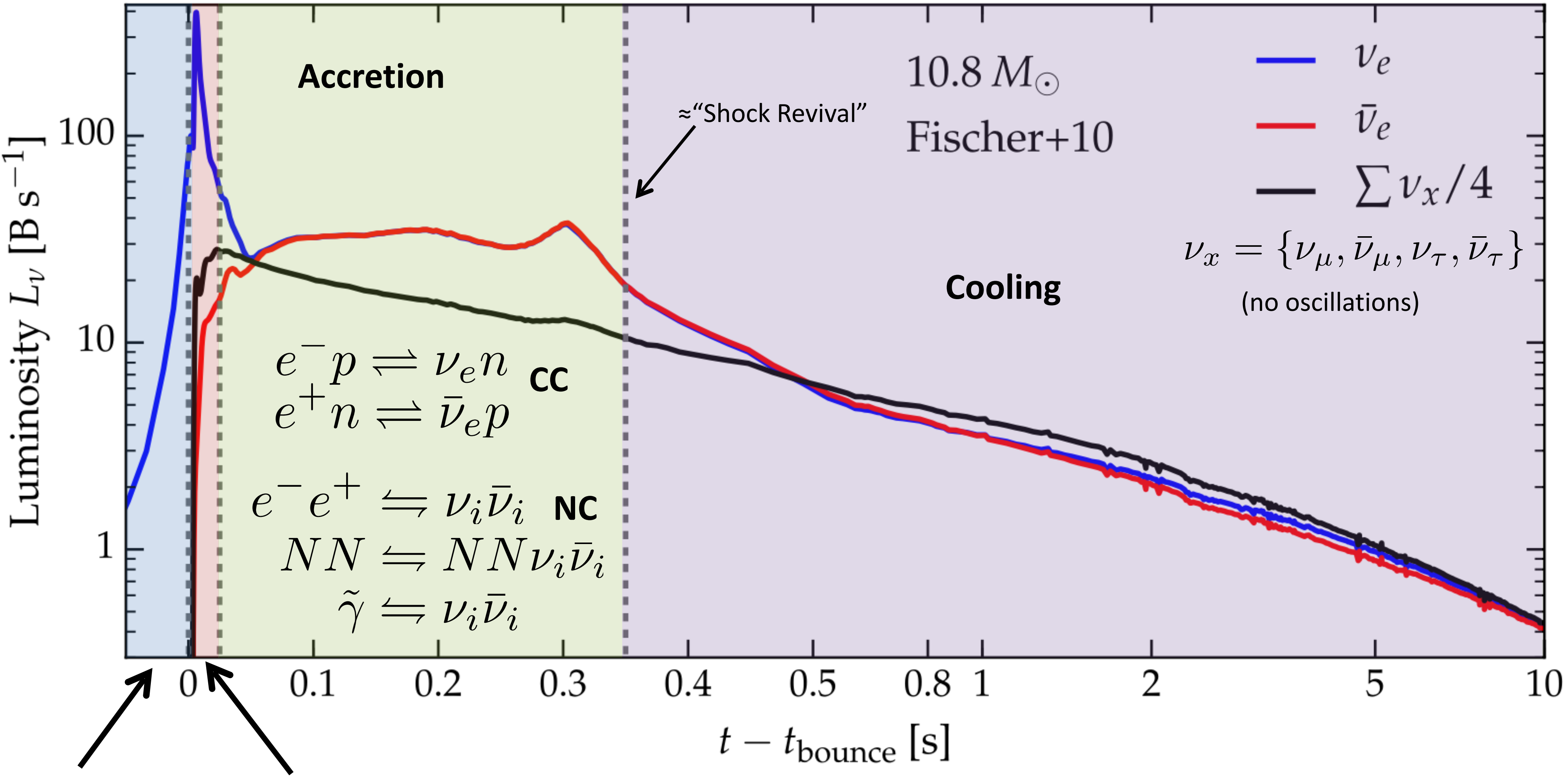
Supernova neutrino “lightcurves”



Collapse

“Deleptonization Burst”

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

Neutrino trapping

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

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

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

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

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

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

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

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

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)

Important neutrino emissivities/opacities

Bruenn, *Ap.J. Suppl*. (1985)
- Nucleons in nucleus independent. (N>40 --> e capture shut off)
- No energy exchange in nucleonic scattering.

“Standard” Emissivities/Opacities

$$e^- + p,A \leftrightarrow \nu_e + n,A'$$

Langanke, ..., Messer, et al. PRL, **90**, 241102 (2003)
- Include correlations between nucleons in nuclei.

$$e^+ + e^- \leftrightarrow \nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau}$$

$$\nu + n,p,A \rightarrow \nu + n,p,A$$

Reddy, Prakash, and Lattimer, PRD, **58**, 013009 (1998)
Burrows and Sawyer, PRC, **59**, 510 (1999)
- (Small) Energy is exchanged due to nucleon recoil.
- Many such scatterings.

$$\nu + e^-,e^+ \rightarrow \nu + e^-,e^+$$

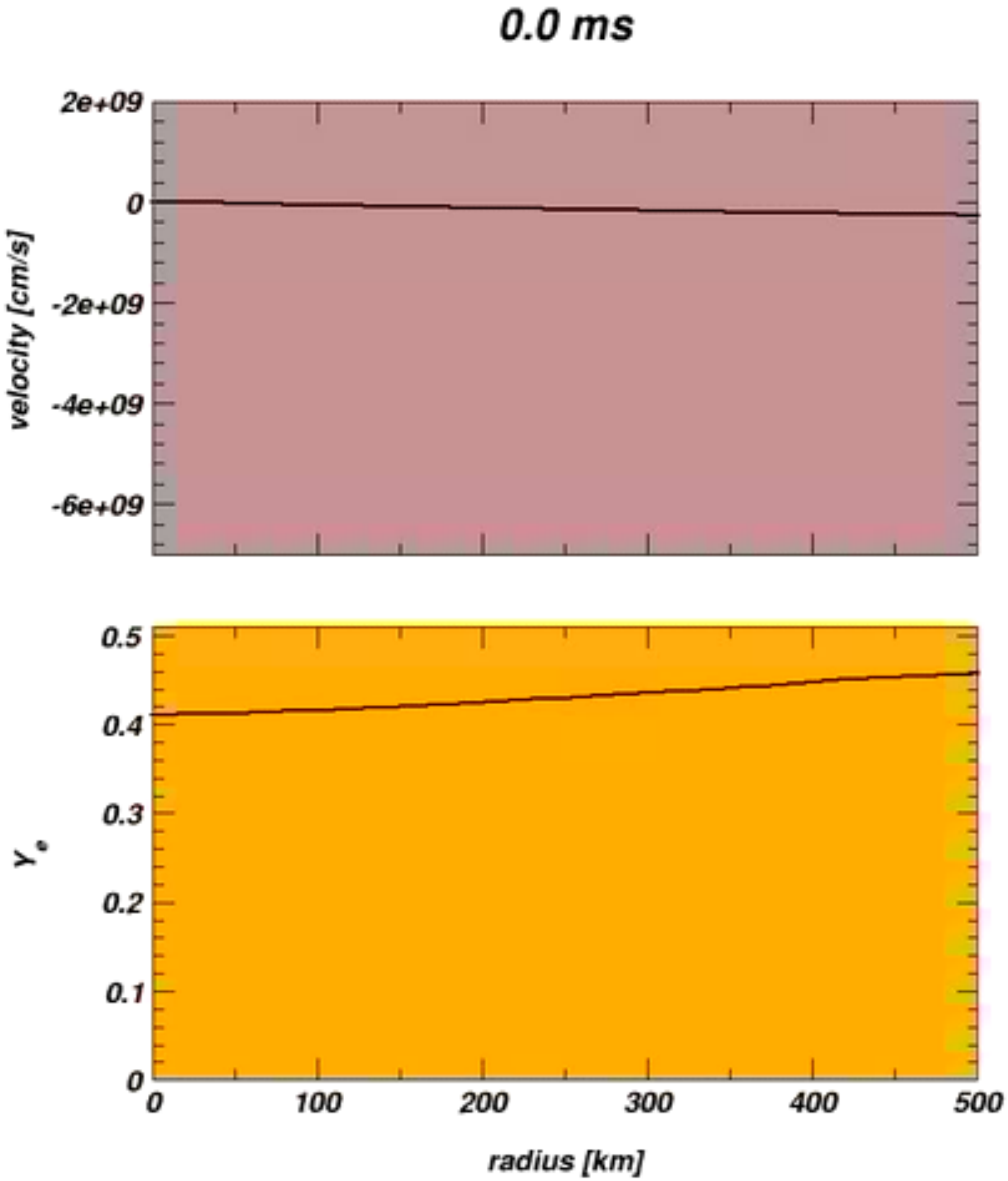
$$N + N \leftrightarrow N + N + \nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau}$$

Hannestad and Raffelt, *Ap.J.* **507**, 339 (1998)
Hanhart, Phillips, and Reddy, *Phys. Lett. B*, **499**, 9 (2001)
- “softer” source of neutrino-antineutrino pairs vs. e^+e^-

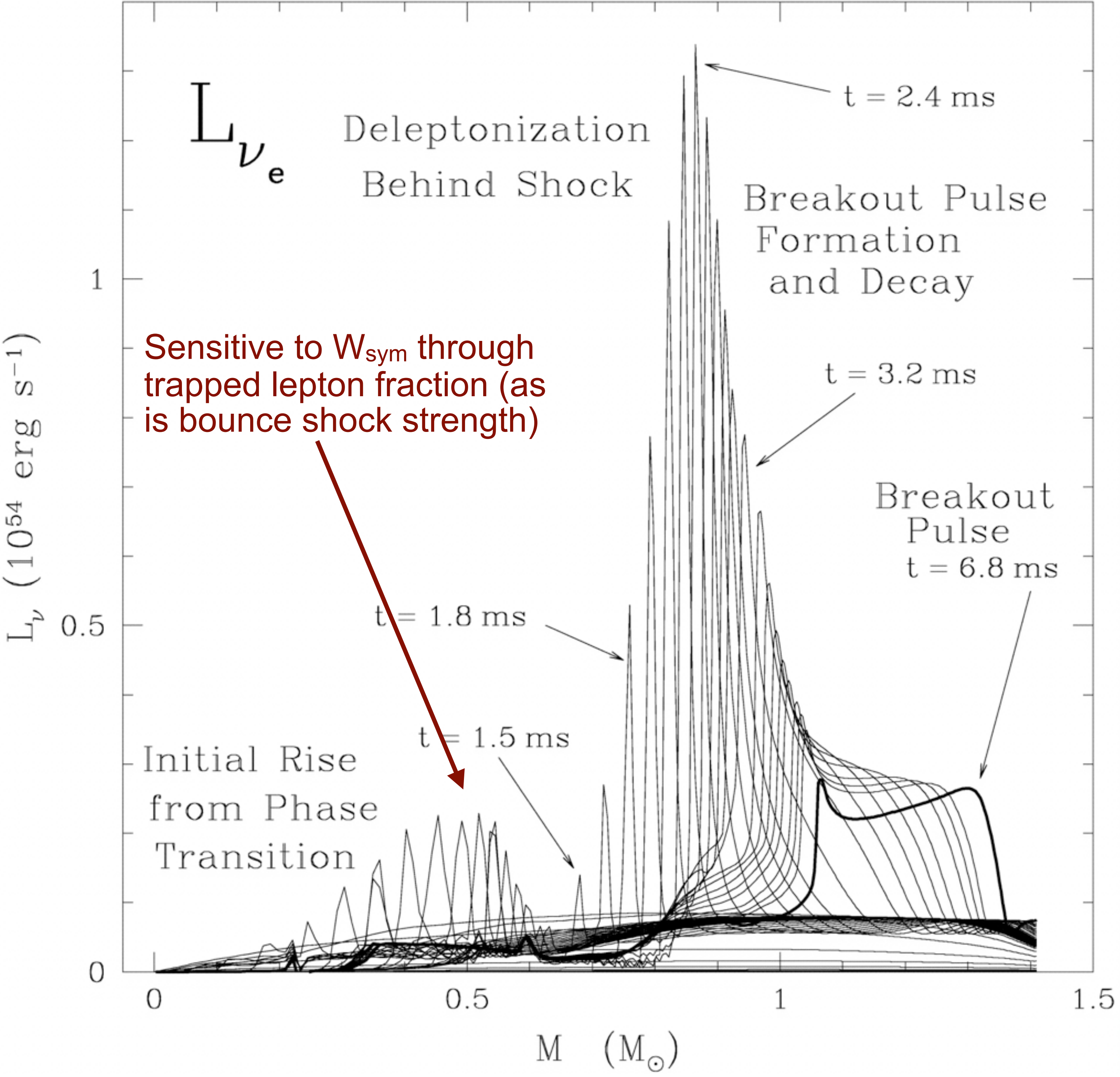
$$\nu_e + \bar{\nu}_e \leftrightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$$

Janka et al. PRL, **76**, 2621 (1996)
Buras et al. *Ap.J.*, **587**, 320 (2003)

Spherically symmetric collapse and shock propagation



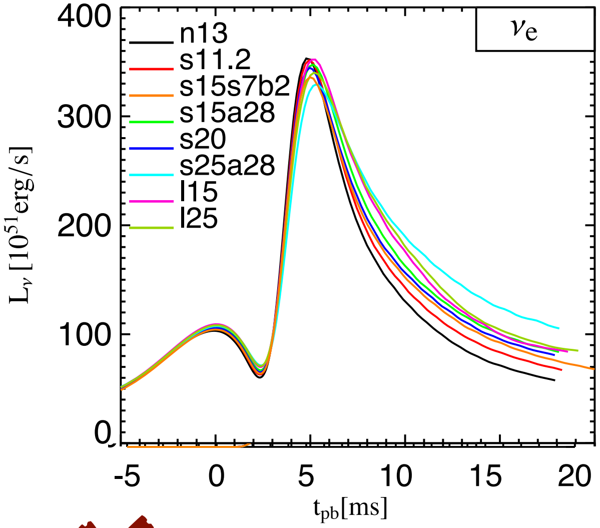
Thompson, Burrows, & Pinto *ApJ* 592:434-456, 2003



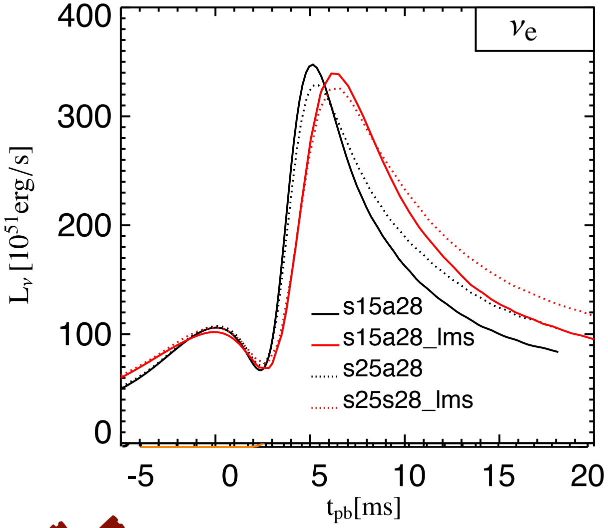
Sensitive to W_{sym} through trapped lepton fraction (as is bounce shock strength)

The neutronization burst is insensitive to a lot.

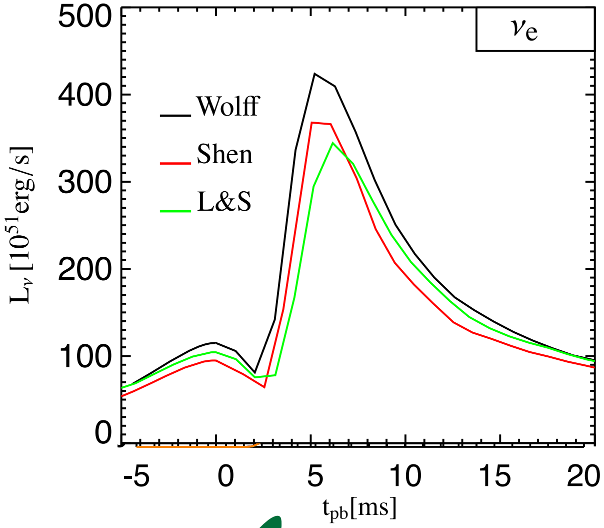
Kachelrieß+ 2005



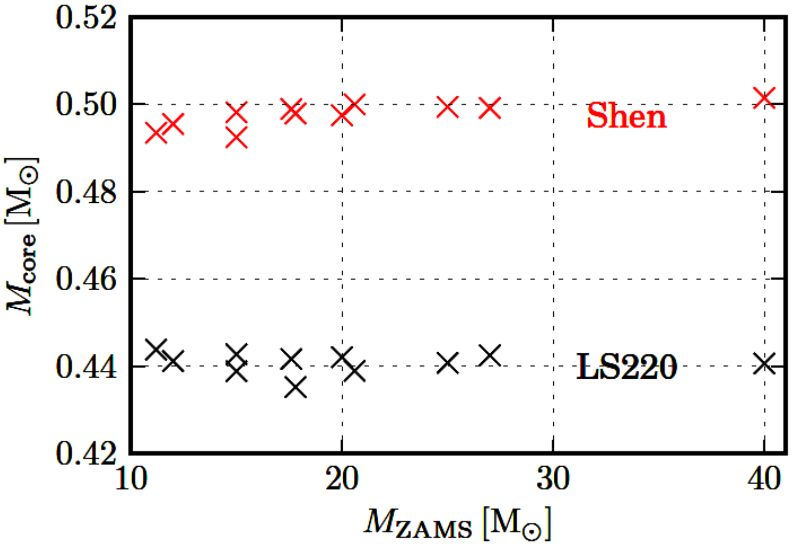
✗ progenitor mass



✗ e- capture in collapse



✔ EOS



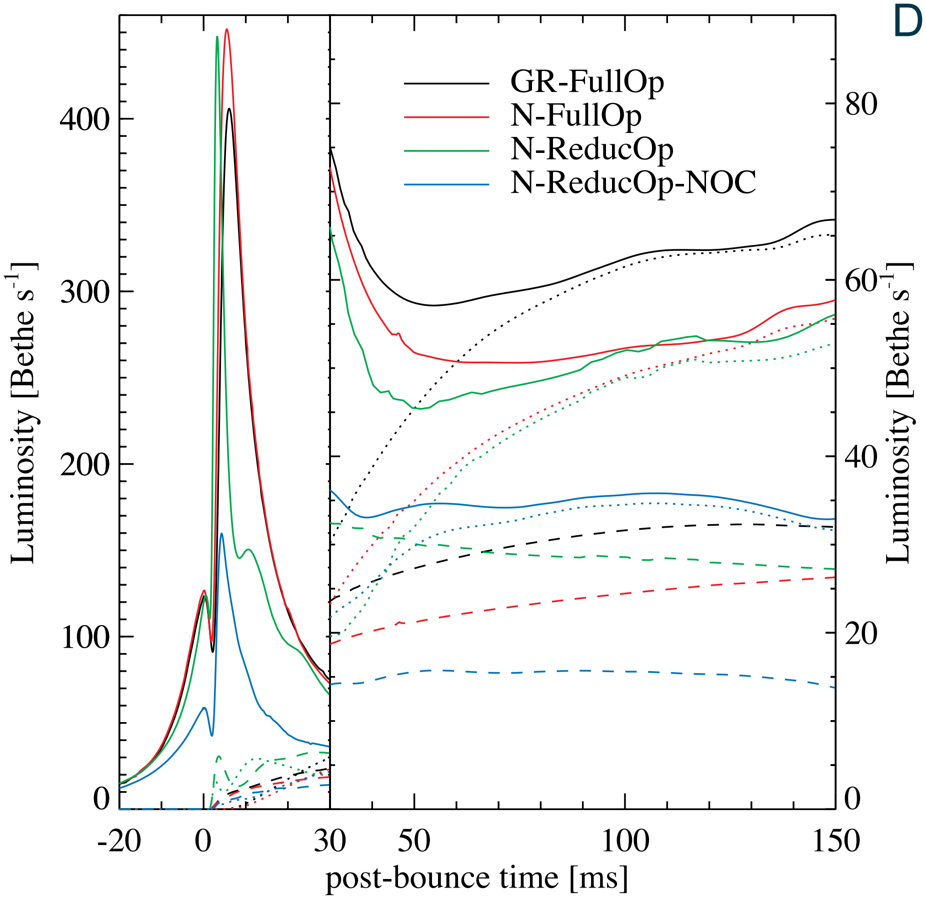
Changes trapped lepton fraction
and
free proton fraction

L. Hüdepohl, PhD Thesis (2013)

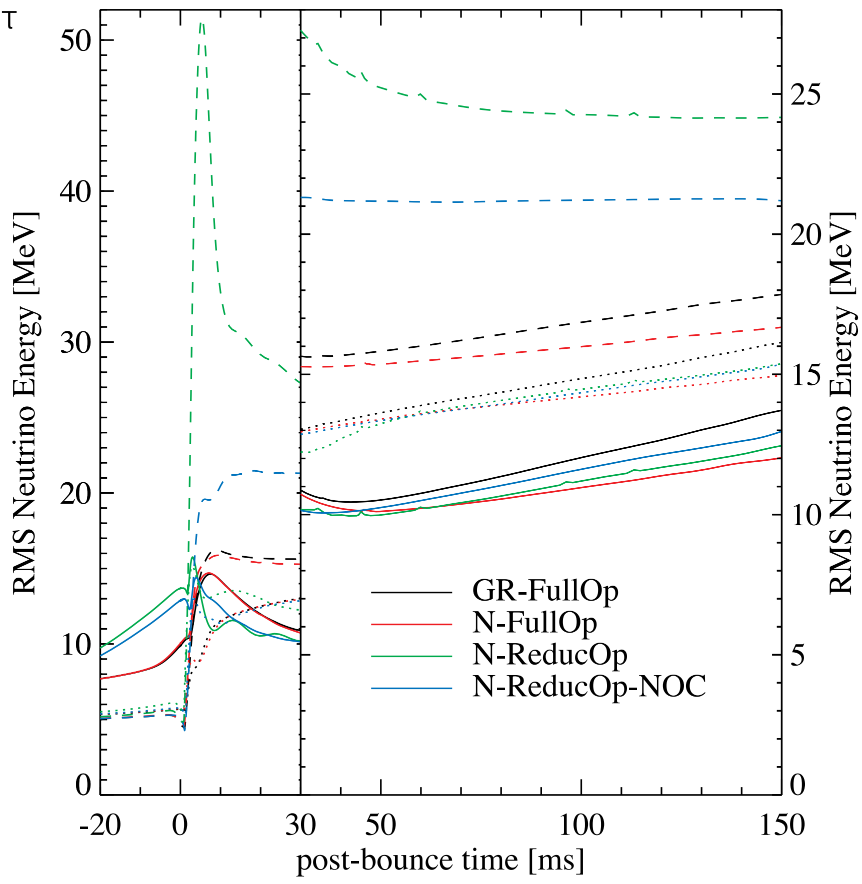
Lentz et al. (2012) ApJ, 760, 94

Solid: ν_e
Dotted: $\bar{\nu}_e$
Dashed: $\nu_{\mu\tau}$

Luminosity



RMS Energy

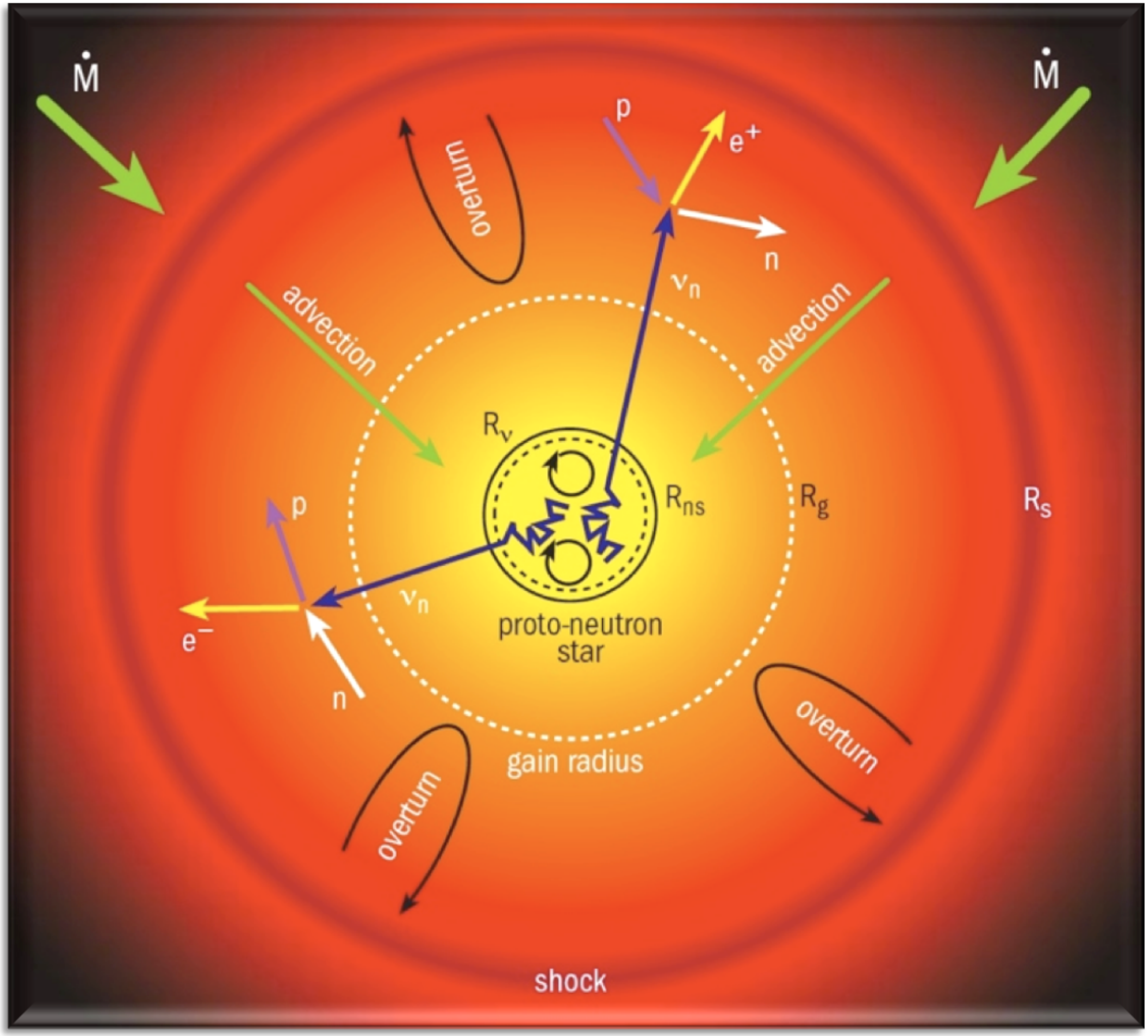


GR: Higher luminosity, harder spectrum

ReducOp opacities: Narrower breakout burst

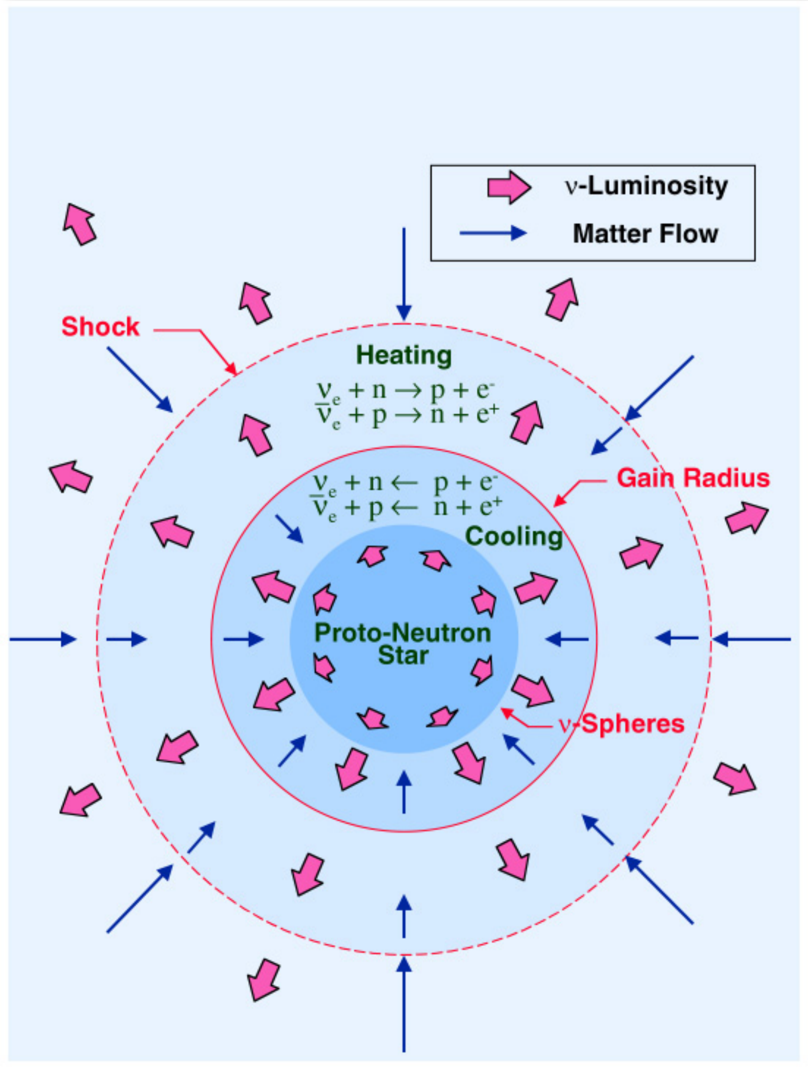
No Observer Corrections: **Reduced breakout burst and reduced luminosity in accretion phase**

Post-bounce profile



Hillebrandt & Janka 2006 (Sci Am)

Neutrino heating in the gain region



Neutrino heating depends on neutrino luminosities, spectra, and angular distributions.

$$\dot{\epsilon} = \frac{X_n}{\lambda_0^a}\frac{L_{\nu_e}}{4\pi r^2}\langle E_{\nu_e}^2\rangle\langle\frac{1}{\mathcal{F}}\rangle + \frac{X_p}{\lambda_0^a}\frac{L_{\bar{\nu}_e}}{4\pi r^2}\langle E_{\bar{\nu}_e}^2\rangle\langle\frac{1}{\mathcal{F}}\rangle$$

➠ *Must compute neutrino distribution functions.*

$$f(t,r,\theta,\phi,E,\theta_p,\phi_p)$$

Multifrequency
Multiangle

$$E_R(t,r,\theta,\phi,E) = \int d\theta_p\, d\phi_p\, f$$

$$F_R^i(t,r,\theta,\phi,E) = \int d\theta_p\, d\phi_p\, n^i f$$

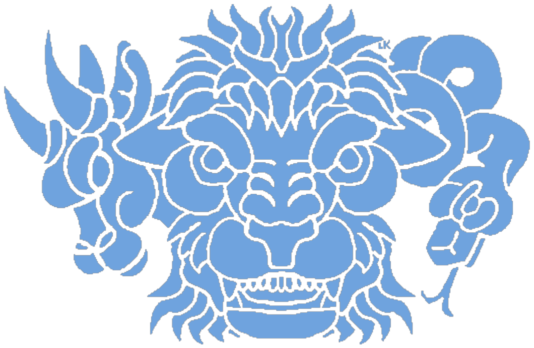
Multifrequency
(*solve for lowest-order multifrequency angular moments: energy and momentum density/frequency*)

Requires a closure prescription:

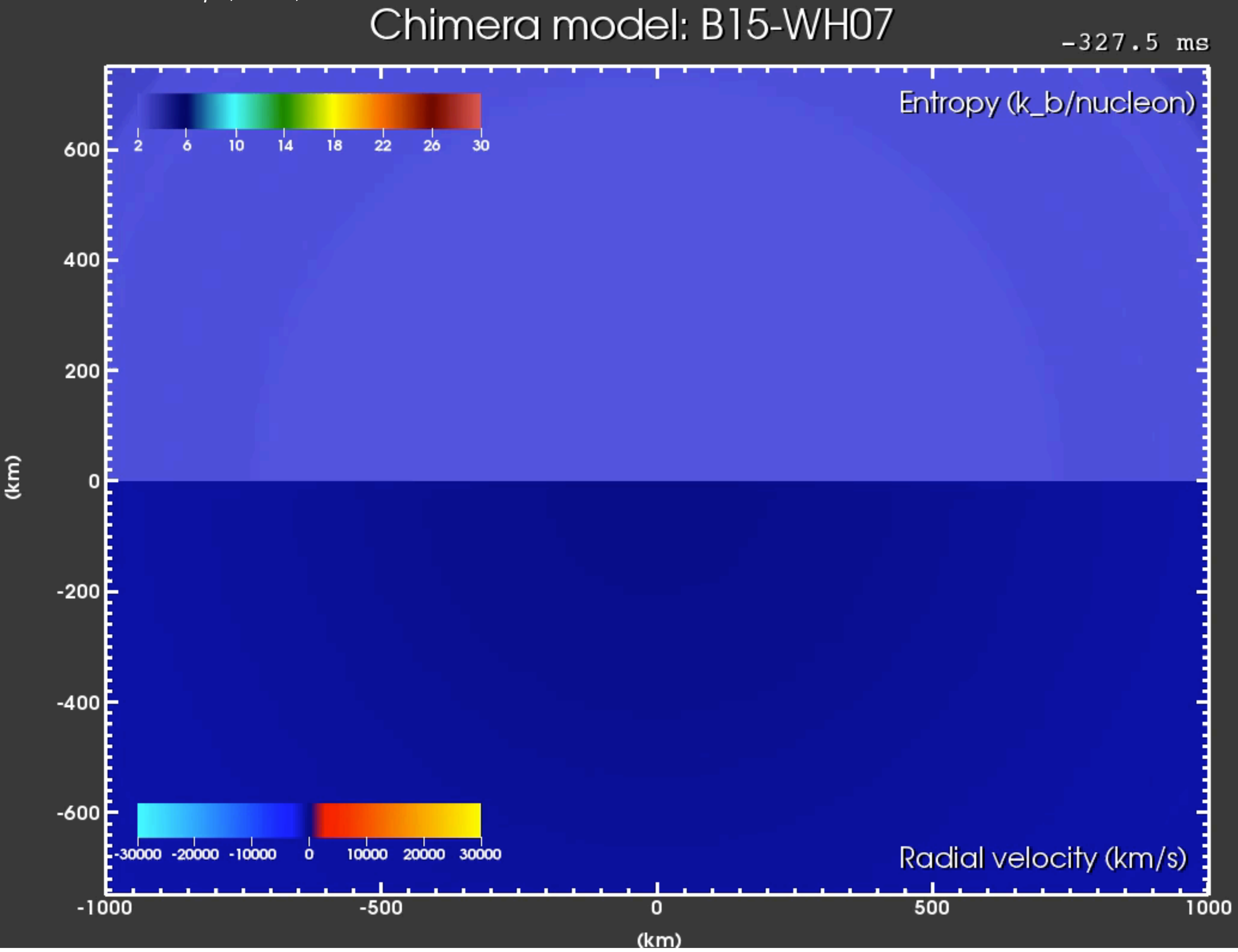
- MGFLD
- MGVEF/MGVET

CHIMERA

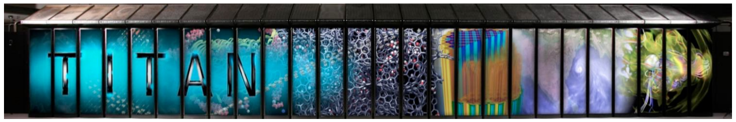
- “Ray-by-ray-**Plus**” MGFLD Neutrino Transport
  - O(v/c), GR time dilation and redshift, GR aberration
- PPM Hydrodynamics (finite-volume)
  - GR time dilation, effective gravitational potential
  - adaptive radial grid
- Lattimer-Swesty EOS + low-density BCK EOS
  - K=220 MeV
  - low-density EOS (BCK+NSE solver) “bridges” LS to network
- Nuclear (Alpha) Network
  - 14 alpha nuclei between helium and zinc
- Effective Gravitational Potential
  - Marek et al. A&A, 445, 273 (2006)
- Neutrino Emissivities/Opacities
  - “Standard” + Elastic Scattering on Nucleons + Nucleon–Nucleon Bremsstrahlung



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



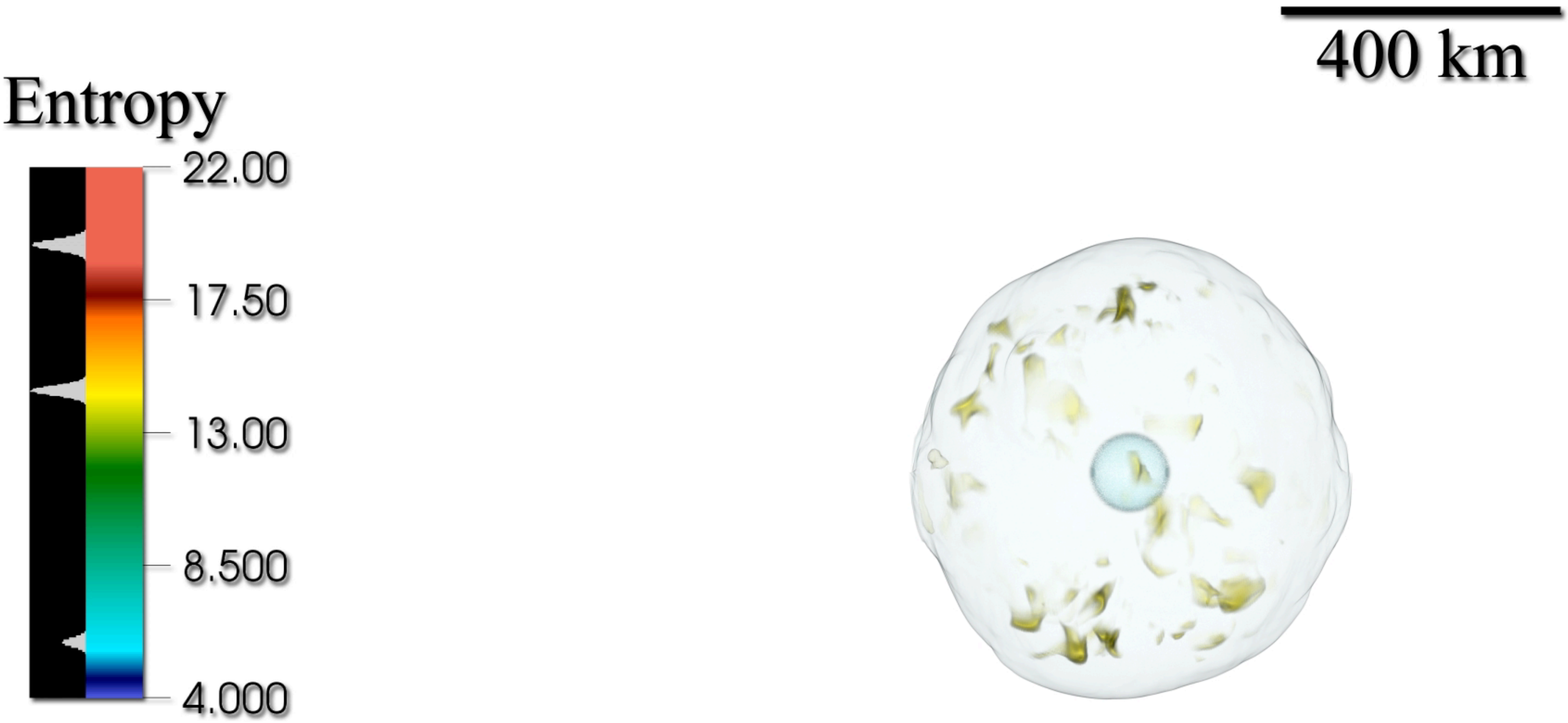
15 solar mass 3D run



~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)

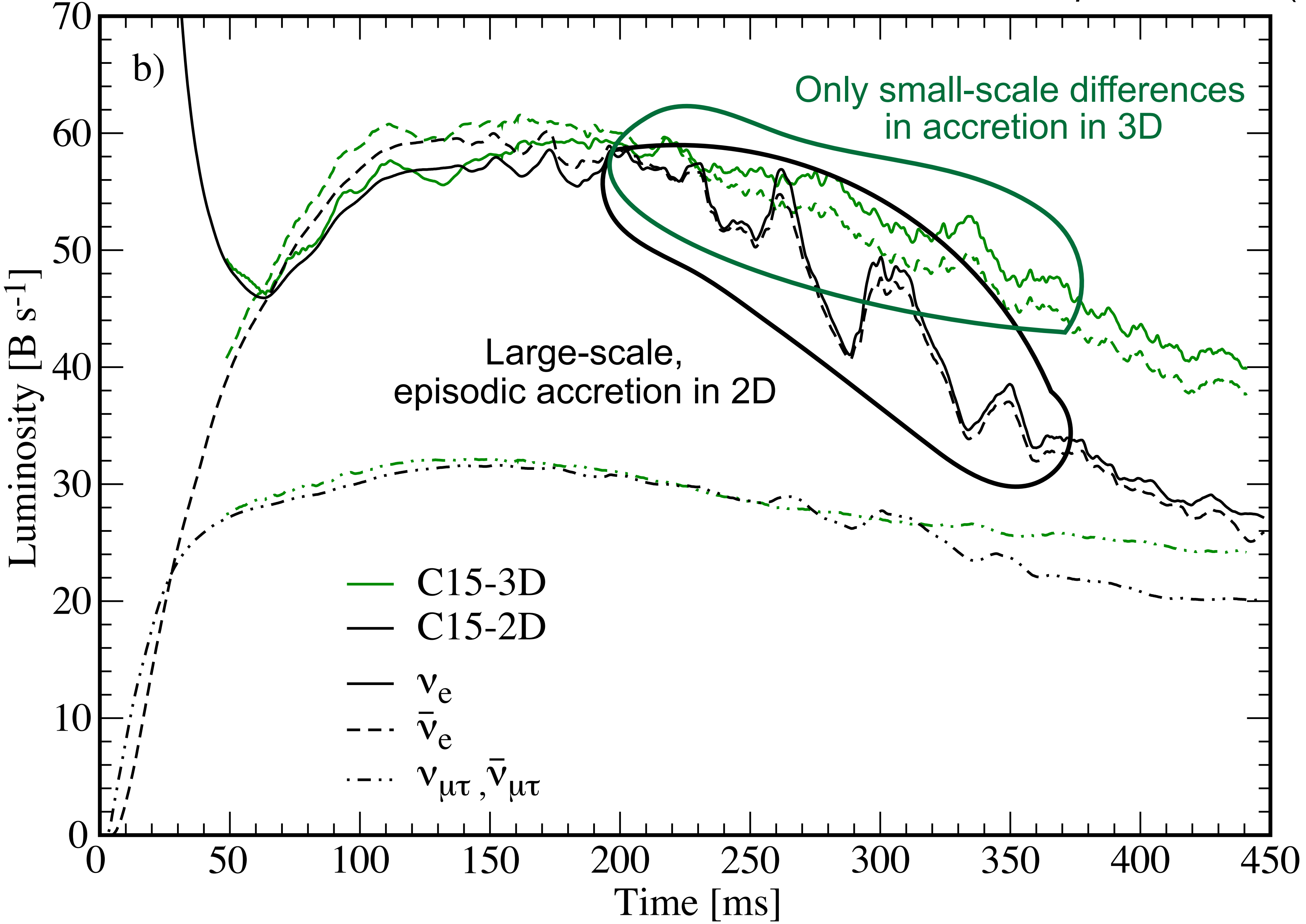


C15-3D

Time = 136.9 ms

3D vs 2D luminosities

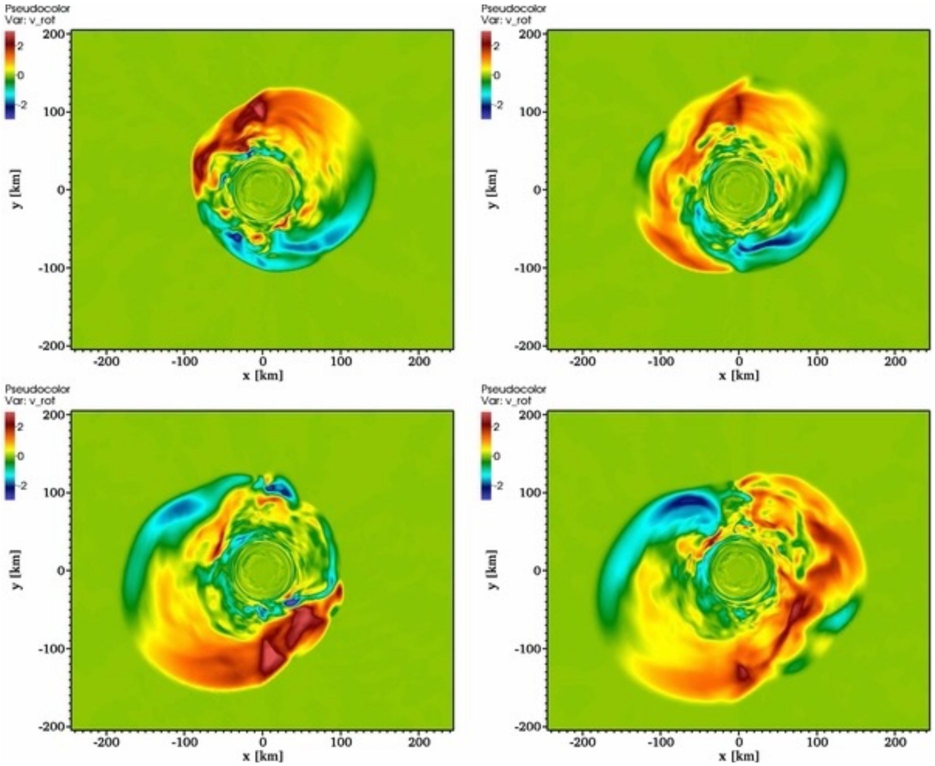
Lentz et al. *ApJL* **807**, L31 (2015)



Only small-scale differences in accretion in 3D

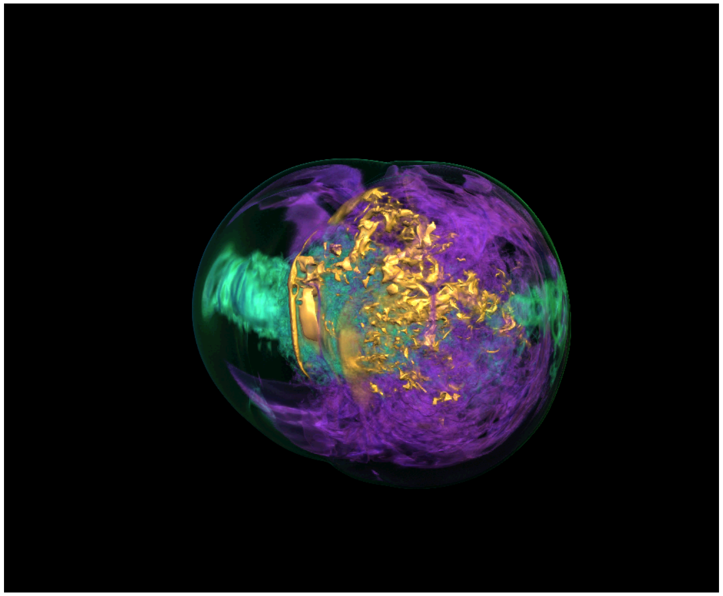
Large-scale, episodic accretion in 2D

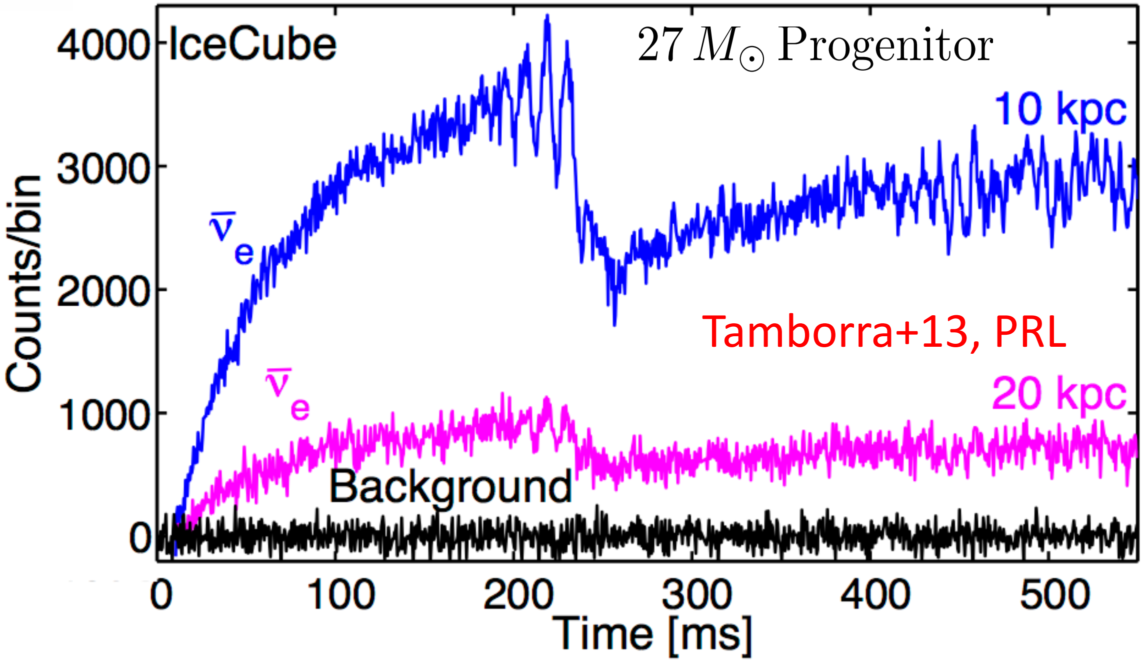
Probing multi-D supernova dynamics



Hanke+13, ApJ

- Neutrino-driven convection & standing accretion shock instability (SASI) can *both* modulate neutrino signal.





Tamborra+13, PRL

Time scales

$$t_{diff} = \tau L/c$$

$$\tau \approx 3$$

$$L \approx 50 km$$

$$\rightarrow t_{diff} \approx 0.5 ms$$

- Typical for accretion phase
  - during cooling, optical depth increases faster than typical extent of source — t_{diff} increases

$$t_{conv} \approx 10 - 20 ms$$

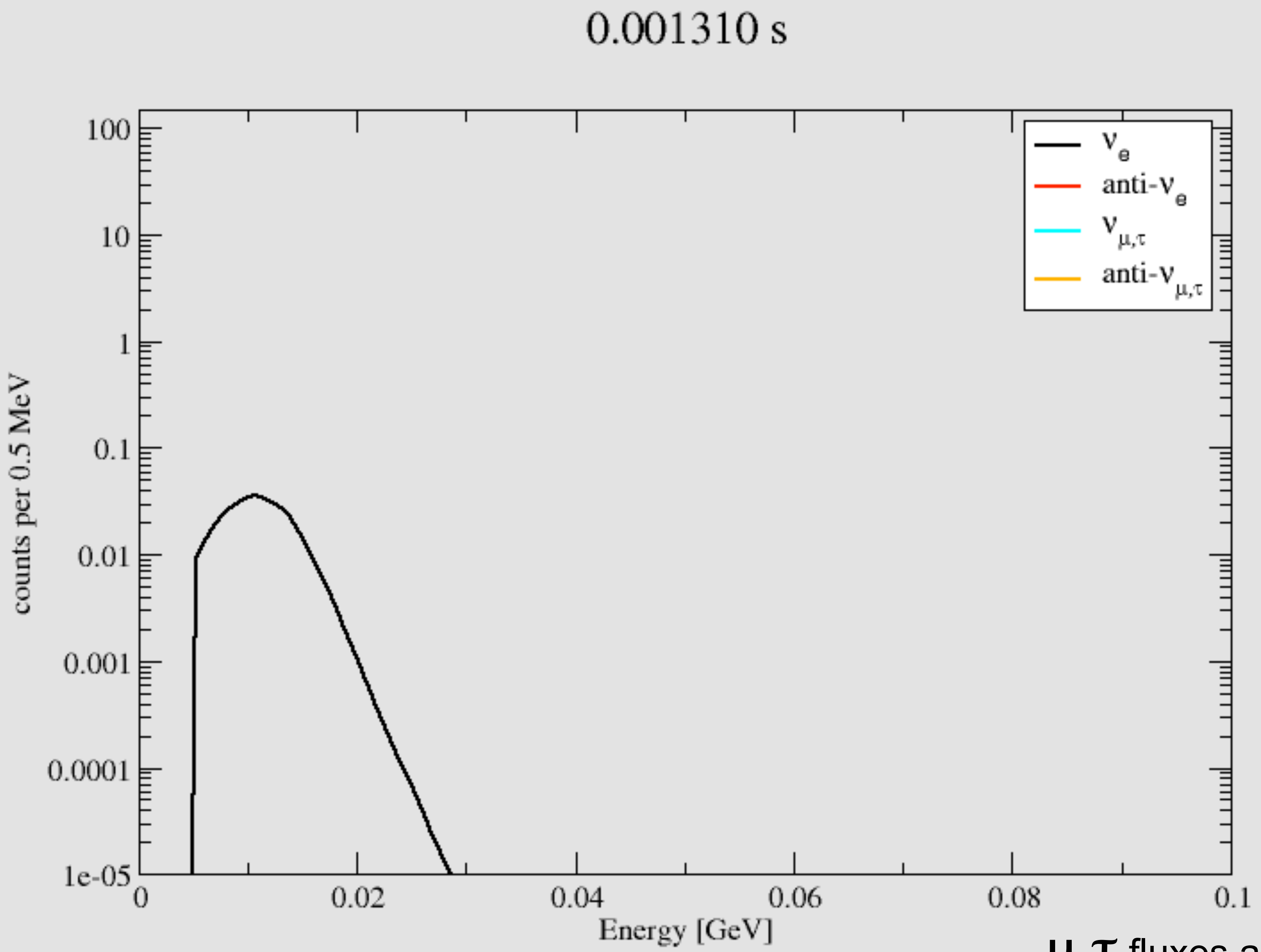
- cf. luminosity variability shown earlier

$$f_{SASI} \approx tens - 100 Hz$$

$$t_{SASI} \approx 10 - 100 ms$$

- LESA timescale > SASI

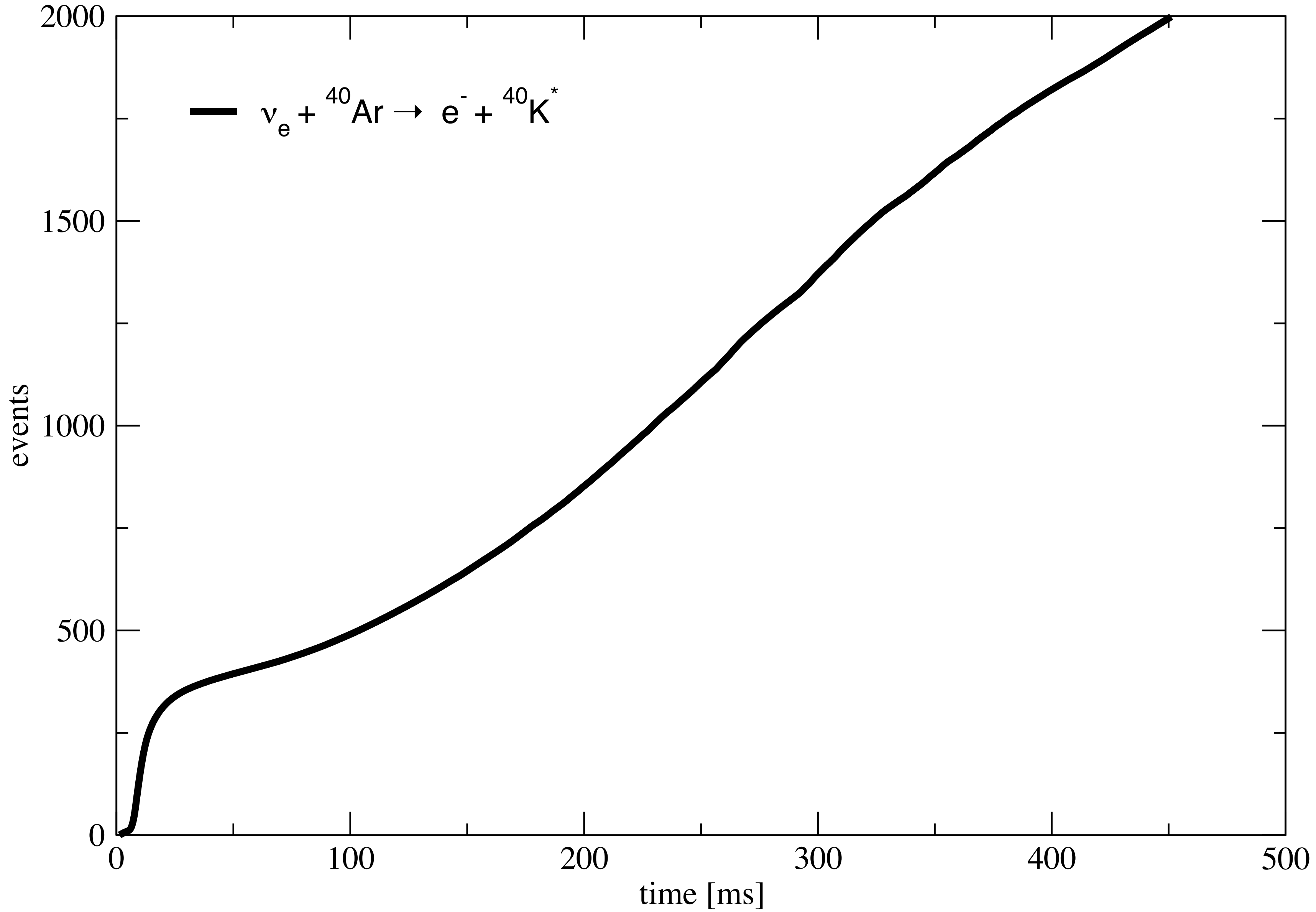
Multi-flavor detection



μ,τ fluxes are 0.5x

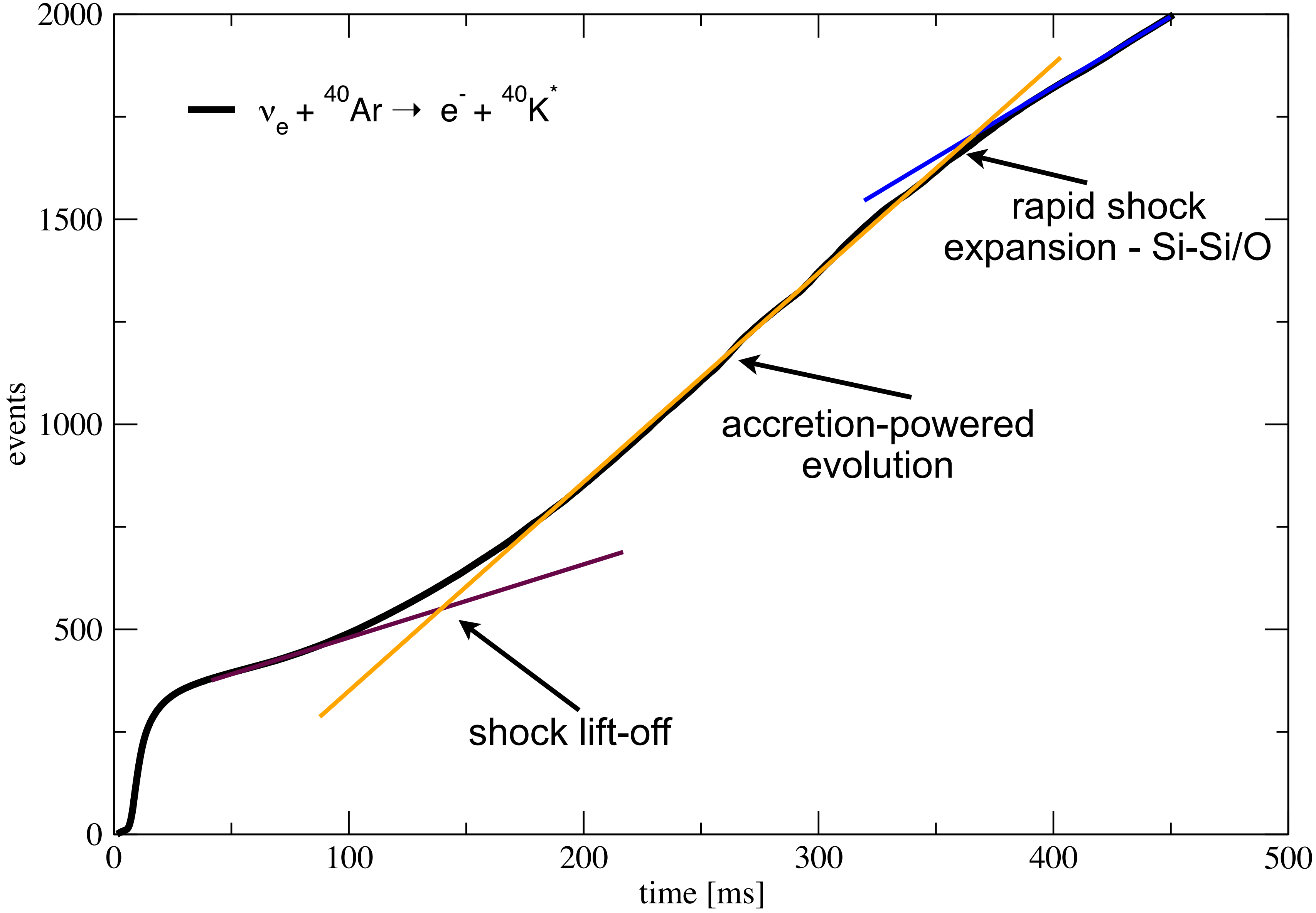
C15-2D, angle-averaged, SNOwGLoBES Ar17kt, 10 kpc

2D - ν_e total counts vs. time



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

2D - ν_e total counts vs. time



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

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

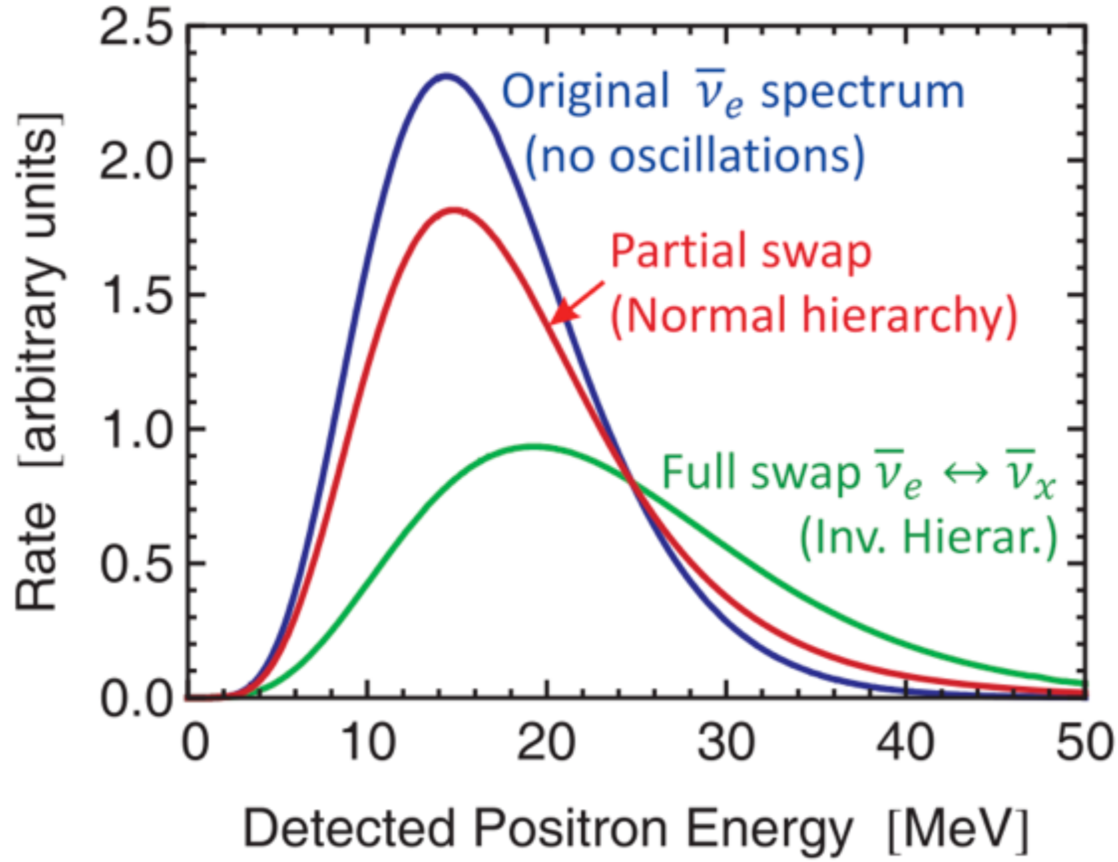
(see, e.g., Mirizzi+15, Duan+10 for reviews)

- 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

3 flavor oscillations with ν_x and anti-ν_x

NH Normal hierarchy

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

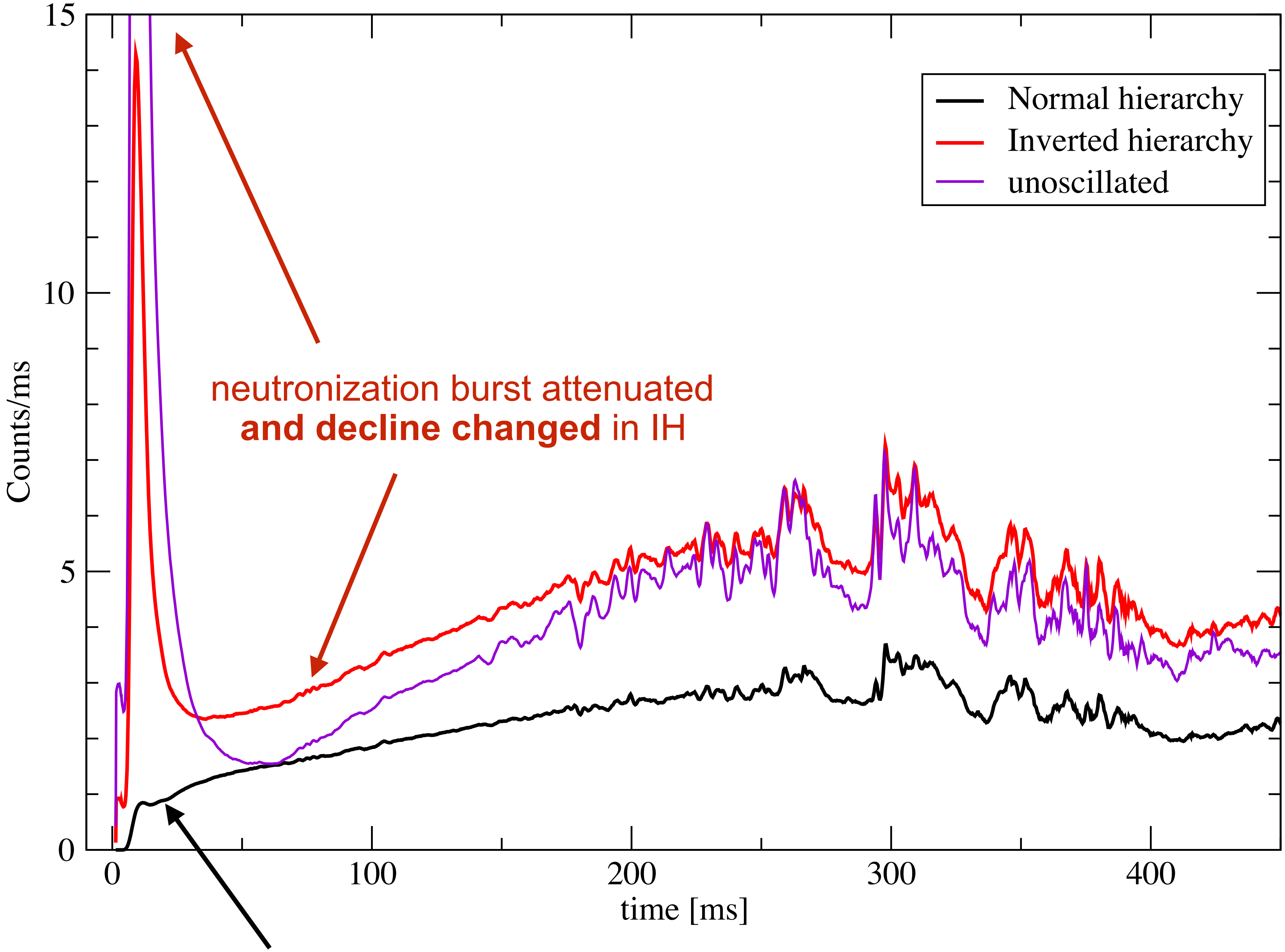
$$F_\mu + F_\tau = \frac{1}{4\pi R^2}[\Phi_e + \Phi_x]$$

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

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

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

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



neutronization burst attenuated **and decline changed** in IH

neutronization burst disappears in NH

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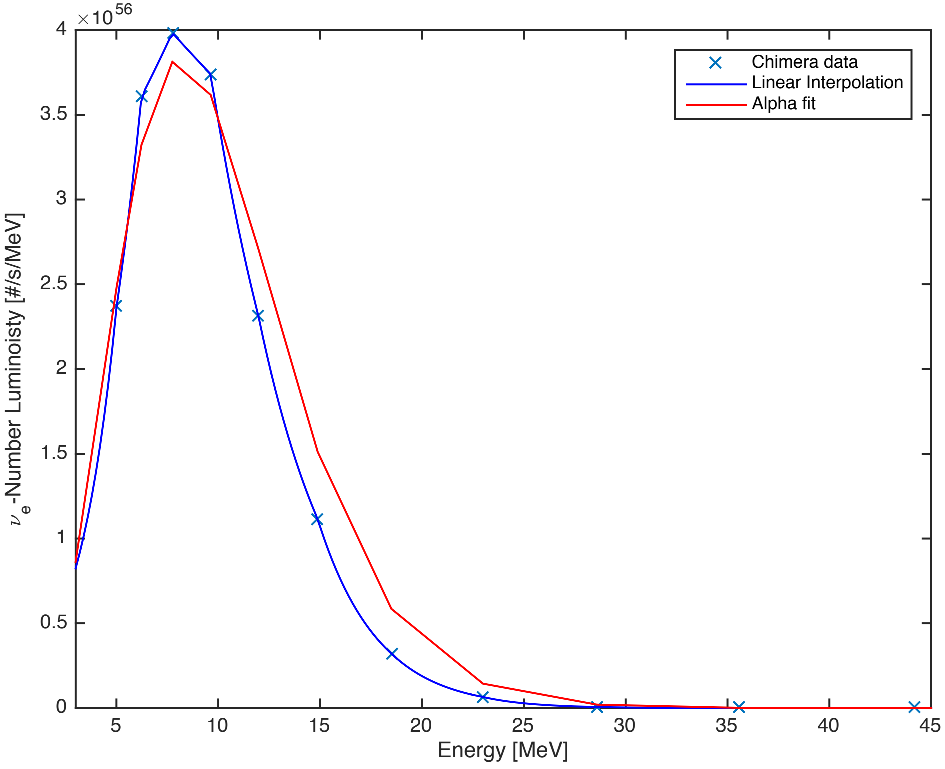
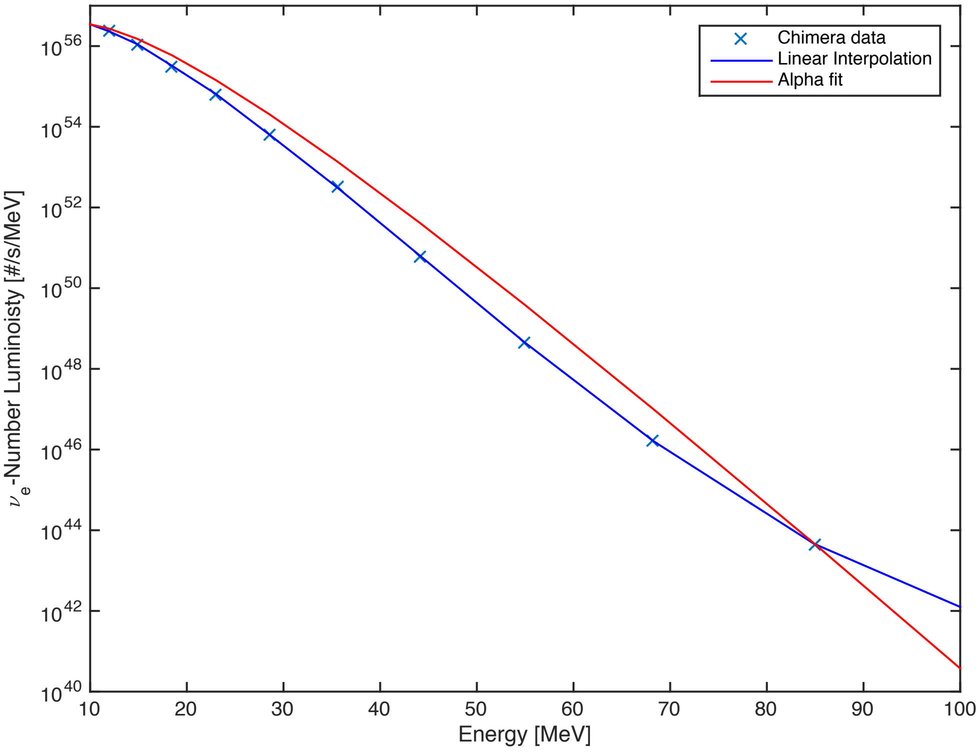
The alpha fit during accretion

- Alpha fit (Keil+03) reproduces mean energy fairly well
- But, at early times…
  - overestimates much of higher-energy tail
  - underestimates maximum spectral flux
- What effect, e.g., for discerning hardening from accretion luminosity cut-off?
  - Typical simulations produce O(thousands) timesteps with 20 neutrino bins —> 3-4 MB/line-of-sight for L_{num}





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.
- Collective effects are important at late times, but definitive calculations may require quantum kinetic simulations.
- Time-independent, spherically symmetric fits are convenient, but lose information.