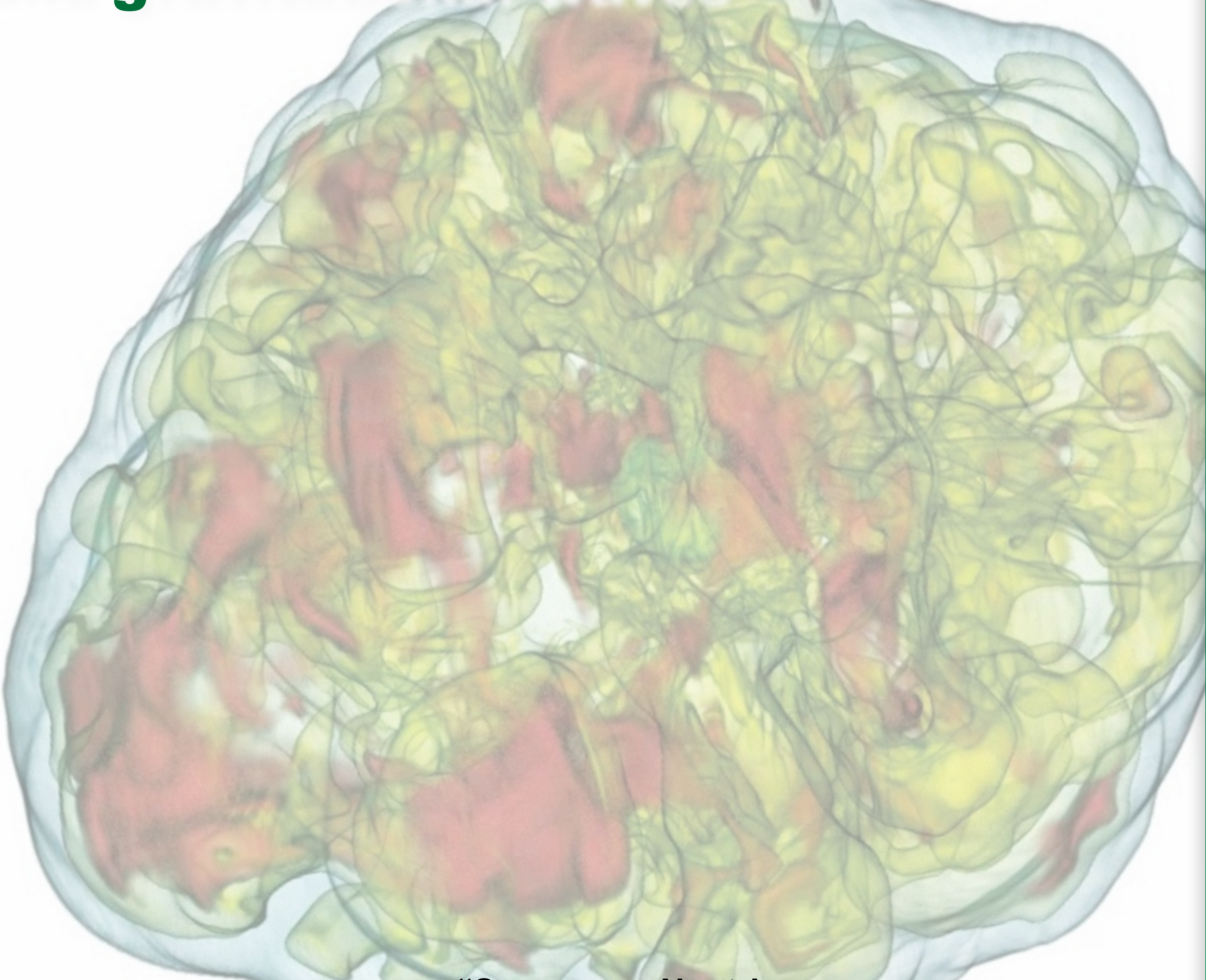
Supernova models: neutrino signals and gravitational waves



Bronson Messer

Scientific Computing & Theoretical Physics Groups
Oak Ridge National Laboratory

Department of Physics & Astronomy
University of Tennessee

"Supernova Neutrino Observations: What can we learn and do?" (SNOBS)
10 Oct 2017

ORNL is managed by UT-Battelle for the US Department of Energy

mitp Mainz Institute for Theoretical Physics

Oak Ridge National Laboratory

Acknowledgements

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TEAMS - Towards Exascale Astrophysics of Mergers and Supernovae

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Project Number: 17-SC-20-SC

ECP EXASCALE COMPUTING PROJECT

ExaStar

Multi-physics Stellar Astrophysics Simulations at the Exascale

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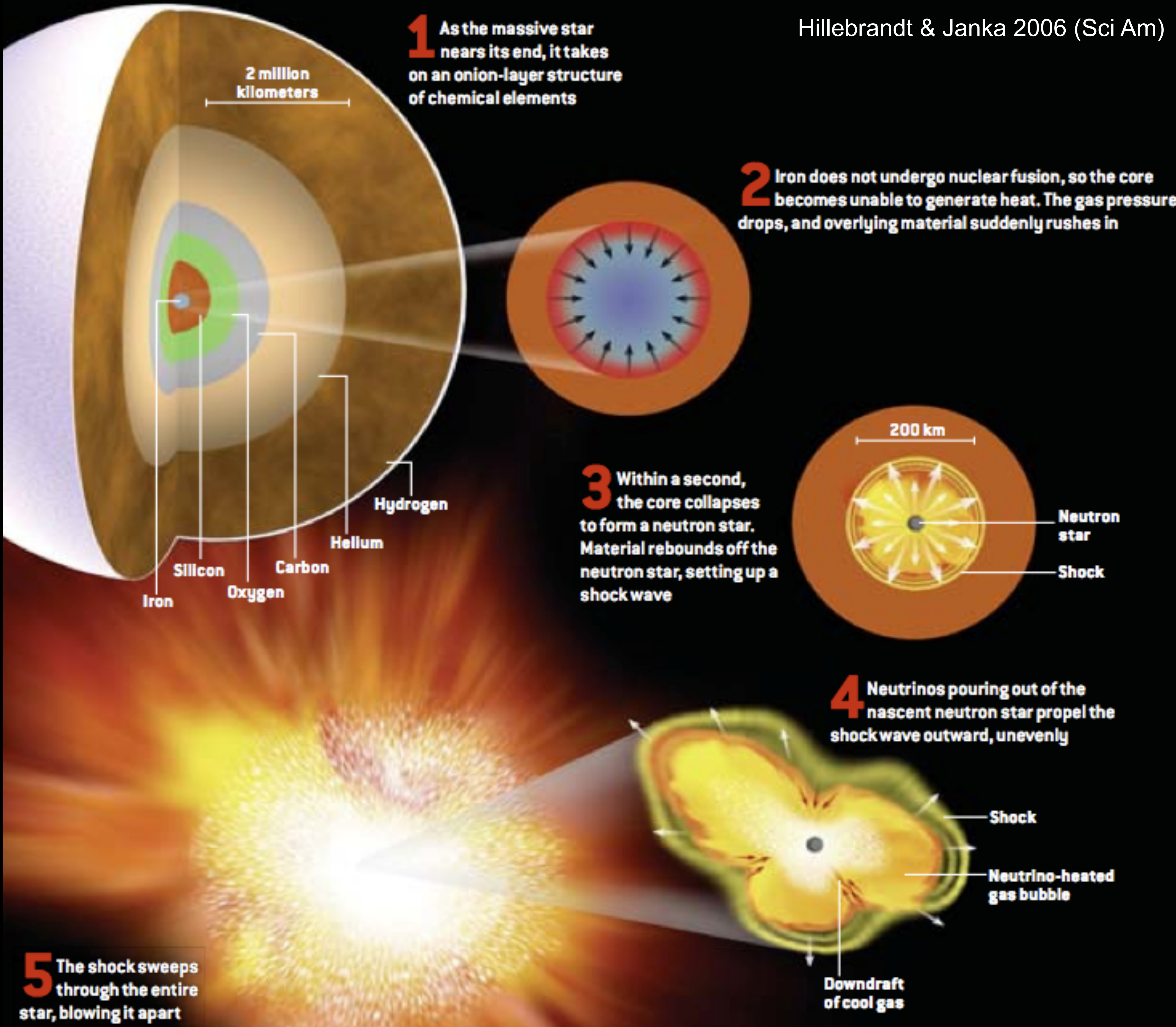
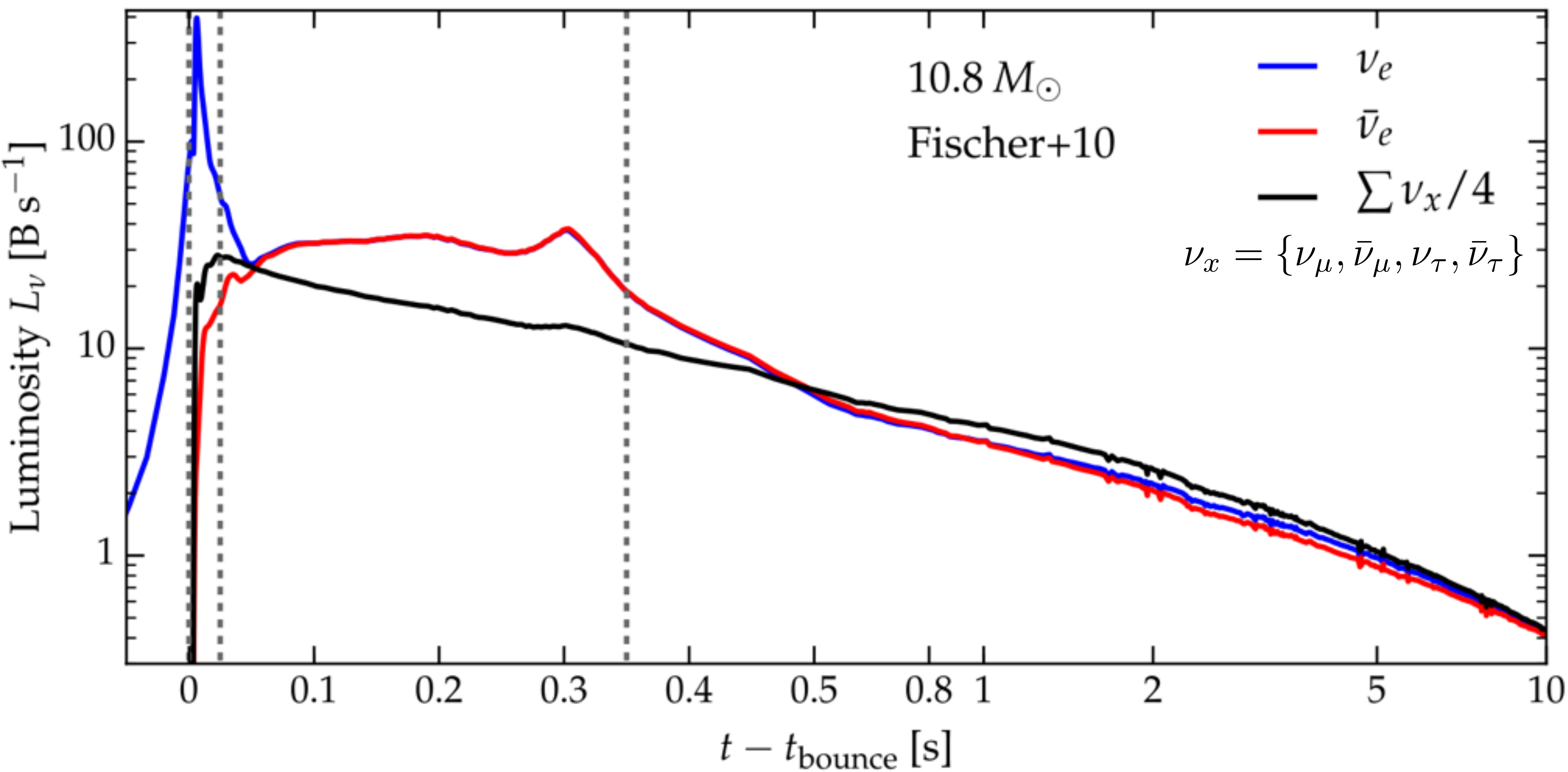

Hillebrandt & Janka 2006 (Sci Am)
1 As the massive star nears its end, it takes on an onion-layer structure of chemical elements
2 million kilometers
Hydrogen
Helium
Carbon
Oxygen
Silicon
Iron
2 Iron does not undergo nuclear fusion, so the core becomes unable to generate heat. The gas pressure drops, and overlying material suddenly rushes in
200 km
3 Within a second, the core collapses to form a neutron star. Material rebounds off the neutron star, setting up a shock wave
Neutron star
Shock
4 Neutrinos pouring out of the nascent neutron star propel the shock wave outward, unevenly
Shock
Neutrino-heated gas bubble
Downdraft of cool gas
5 The shock sweeps through the entire star, blowing it apart

Supernova neutrino "light curves"



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

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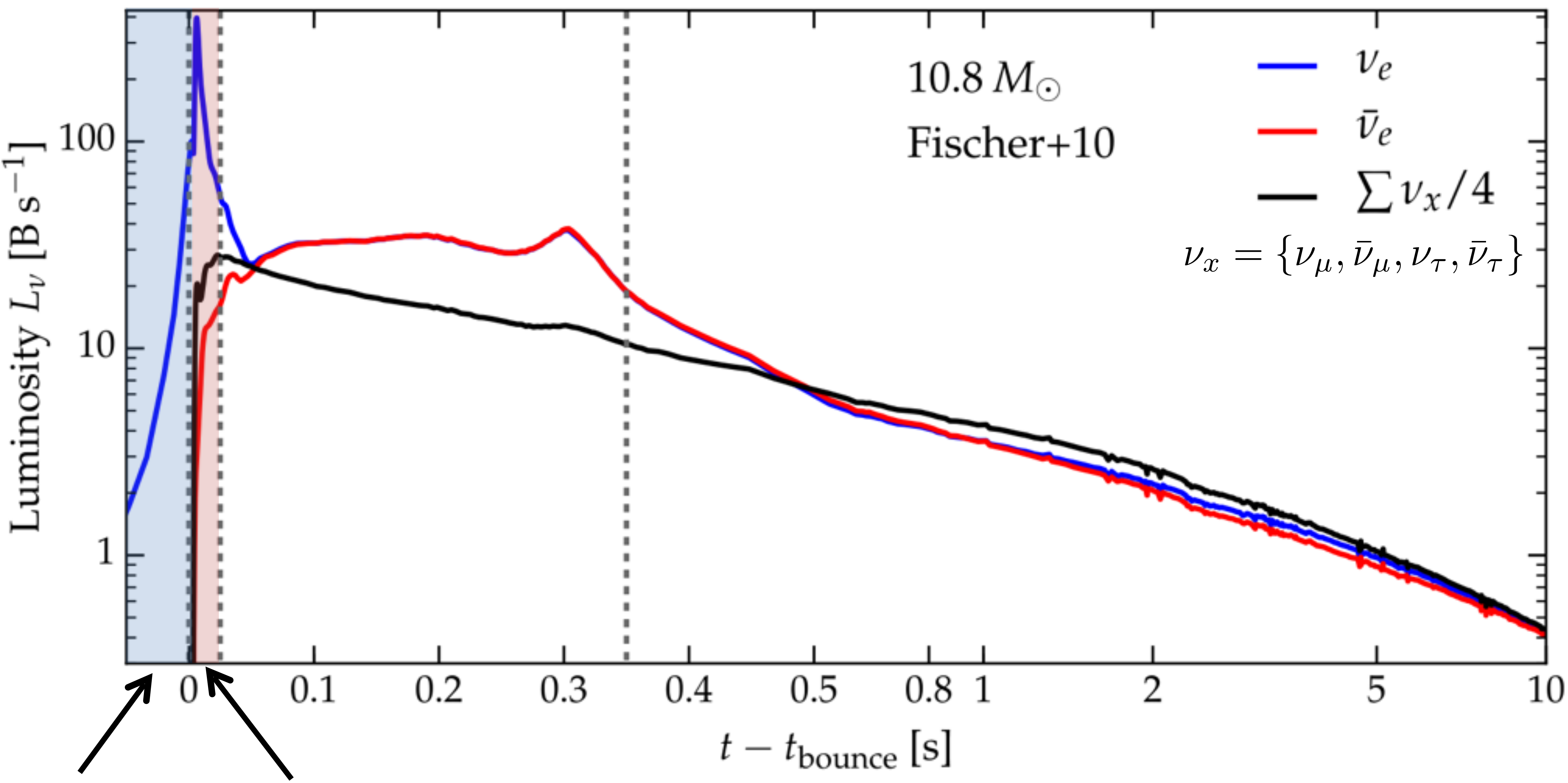
Supernova neutrino "light curves"



Collapse

"Deleptonization Burst"

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

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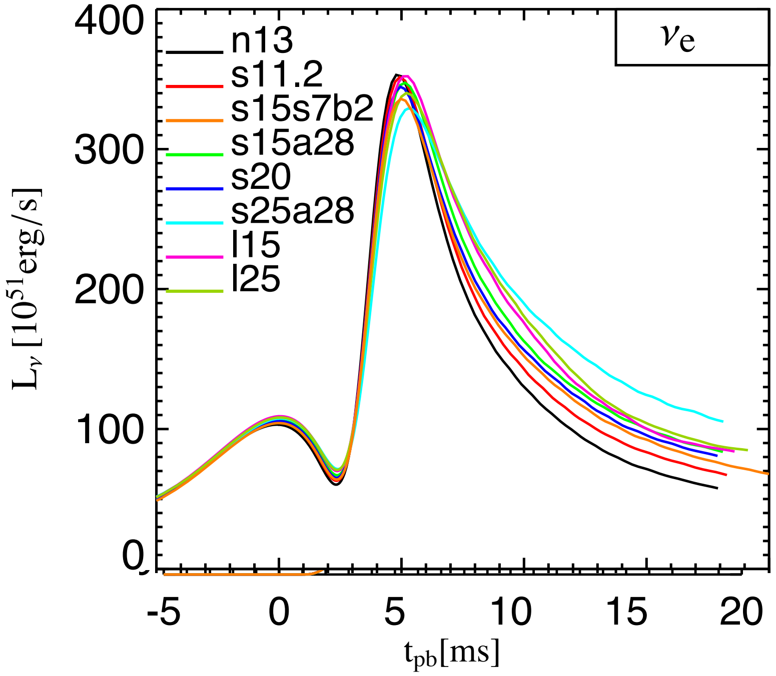
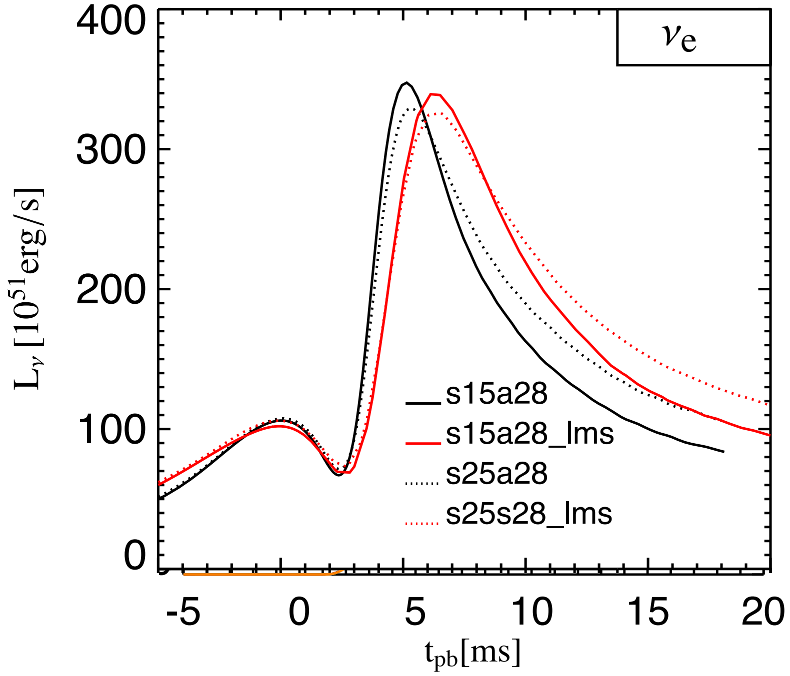
The neutronization burst is insensitive to a lot.

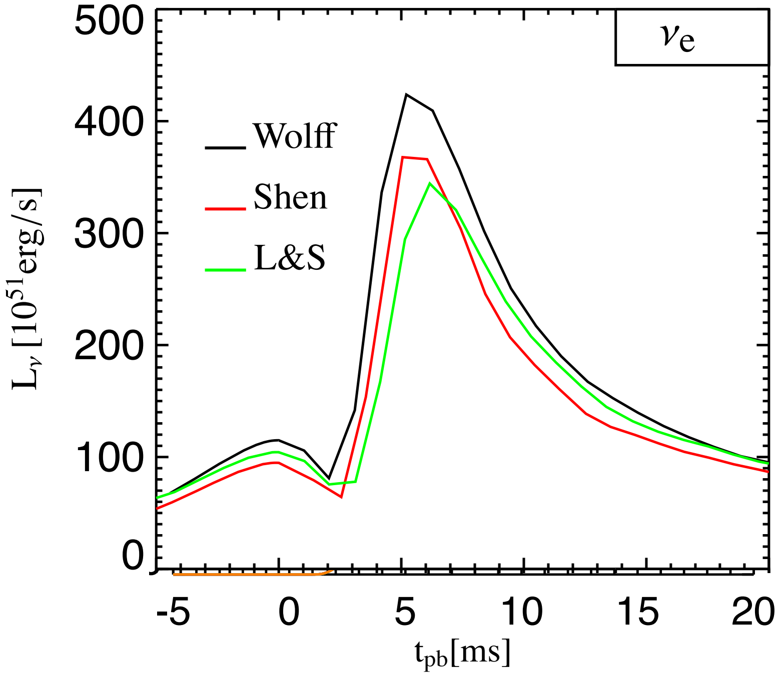
Kachelrieß+ 2005



progenitor mass



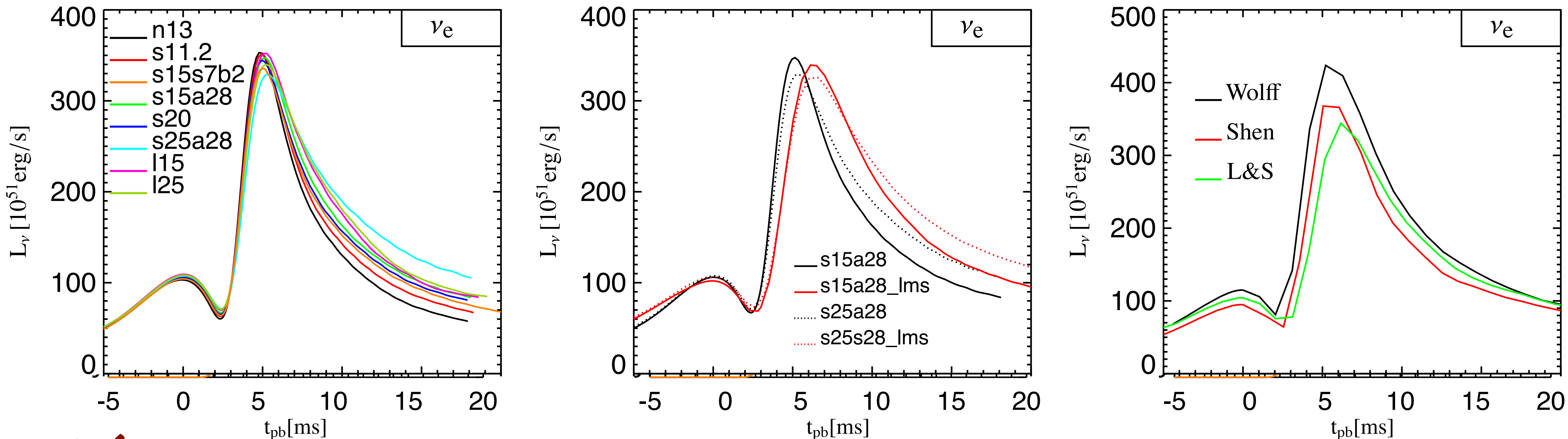
e- capture in collapse



EOS

The neutronization burst is insensitive to a lot.

Kachelrieß+ 2005



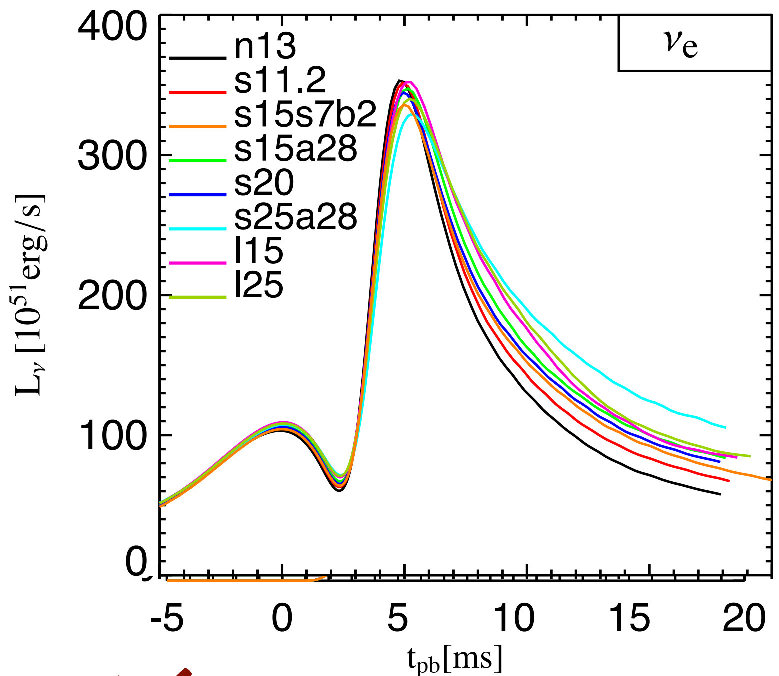
progenitor mass

e- capture in collapse

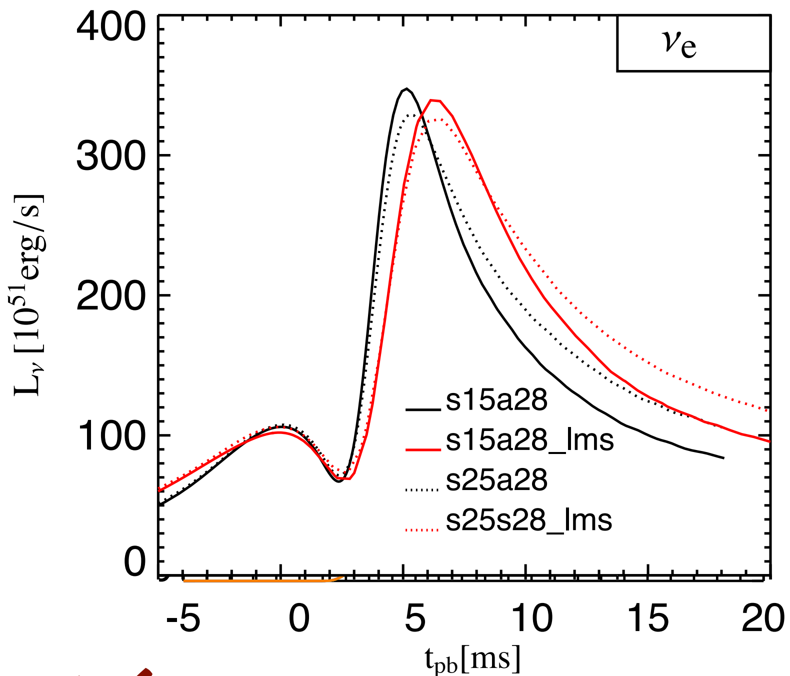
EOS

The neutronization burst is insensitive to a lot.

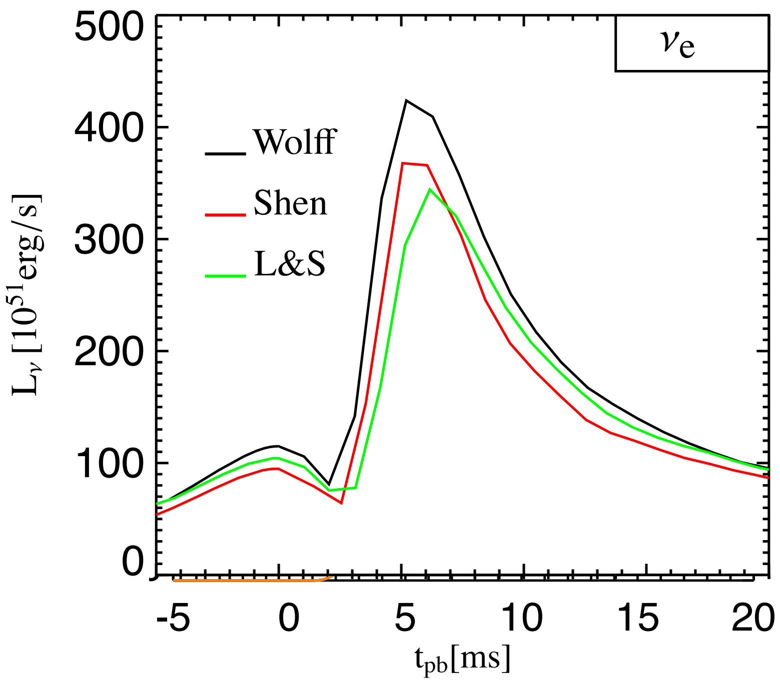
Kachelrieß+ 2005



✗ progenitor mass



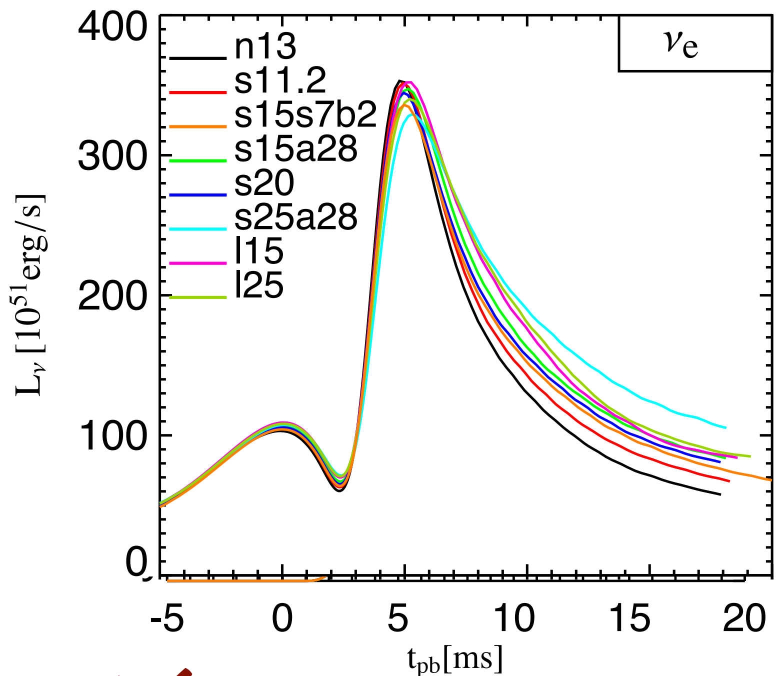
✗ e- capture in collapse

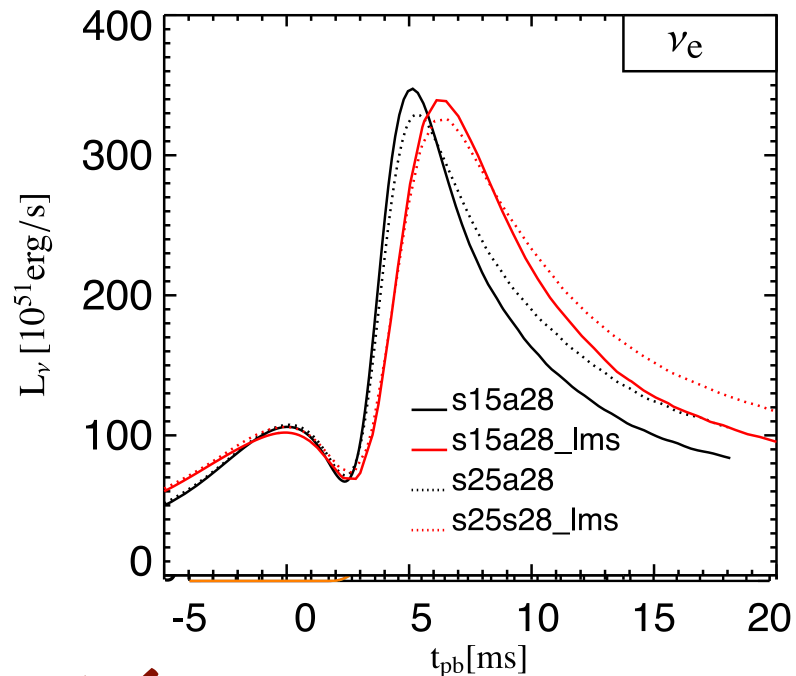


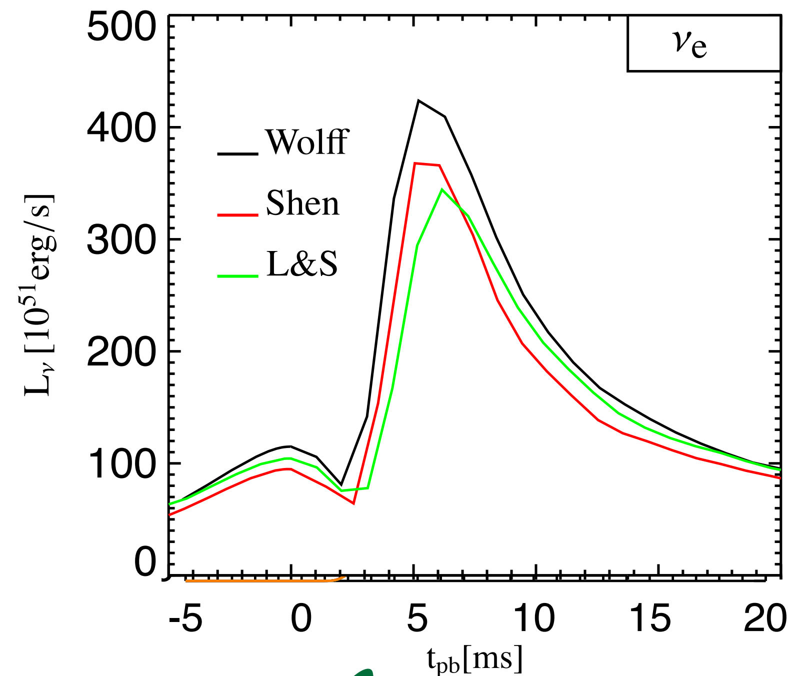
EOS

The neutronization burst is insensitive to a lot.

Kachelrieß+ 2005



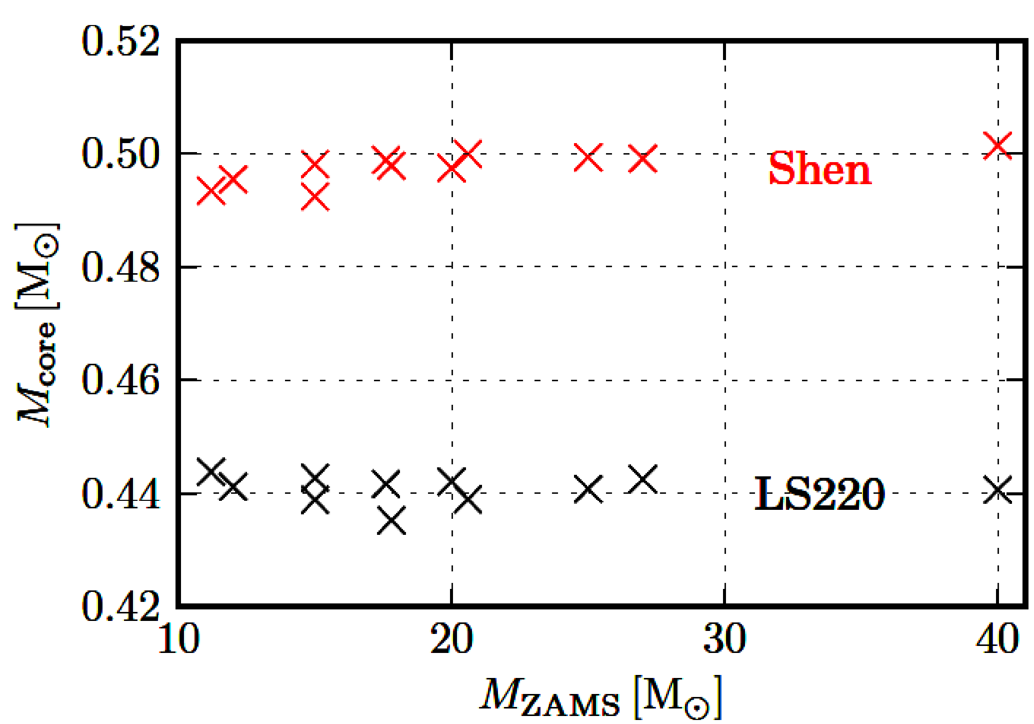




✗ progenitor mass

✗ e- capture in collapse

✔ EOS



Changes trapped lepton fraction
and
free proton fraction

L. Hüdepohl, PhD Thesis (2013)

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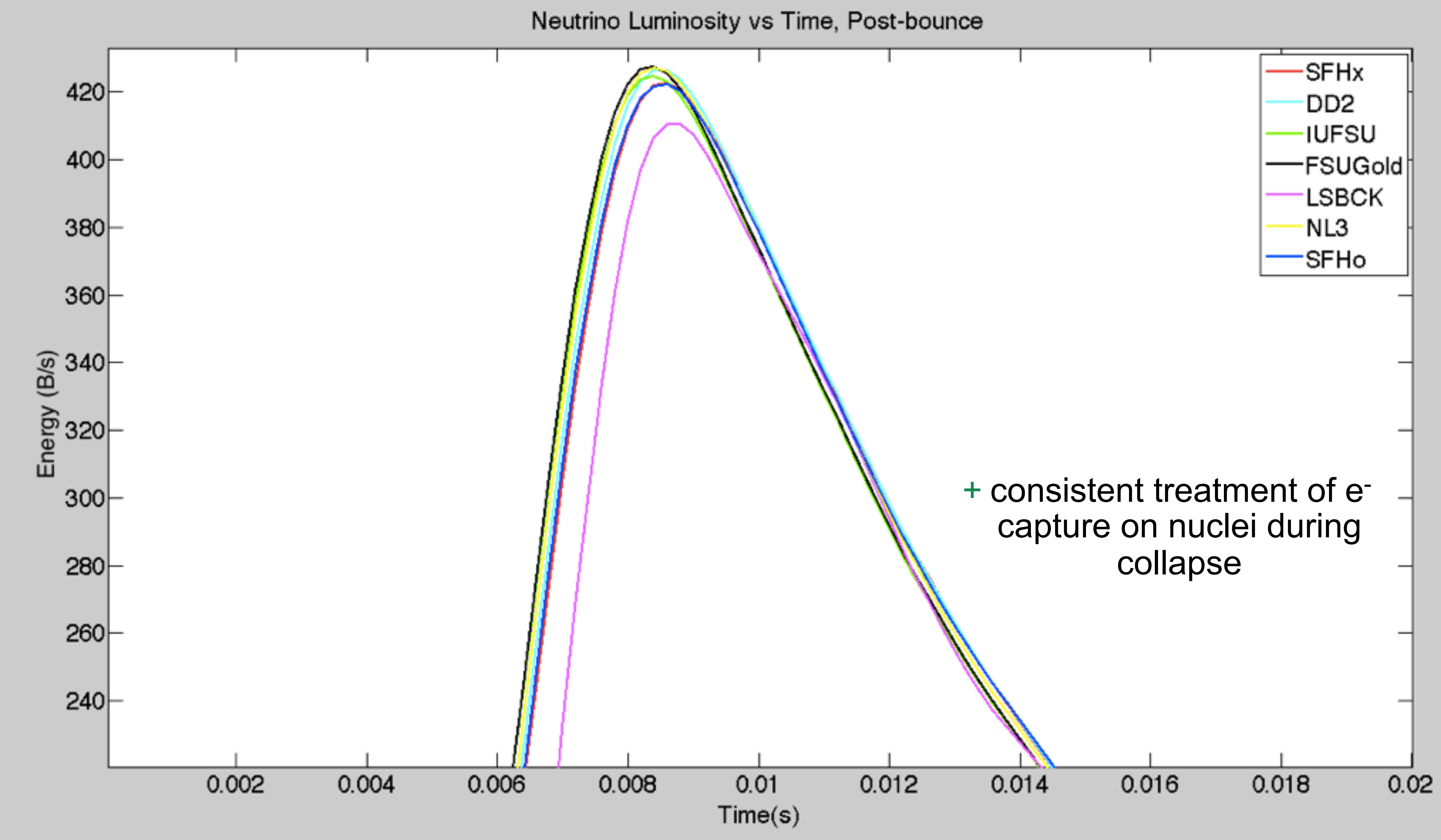
...but, modern EOS's have much smaller differences.



+ consistent treatment of e^- capture on nuclei during collapse

R. Landfield, PhD thesis (2017, U. Tennessee)

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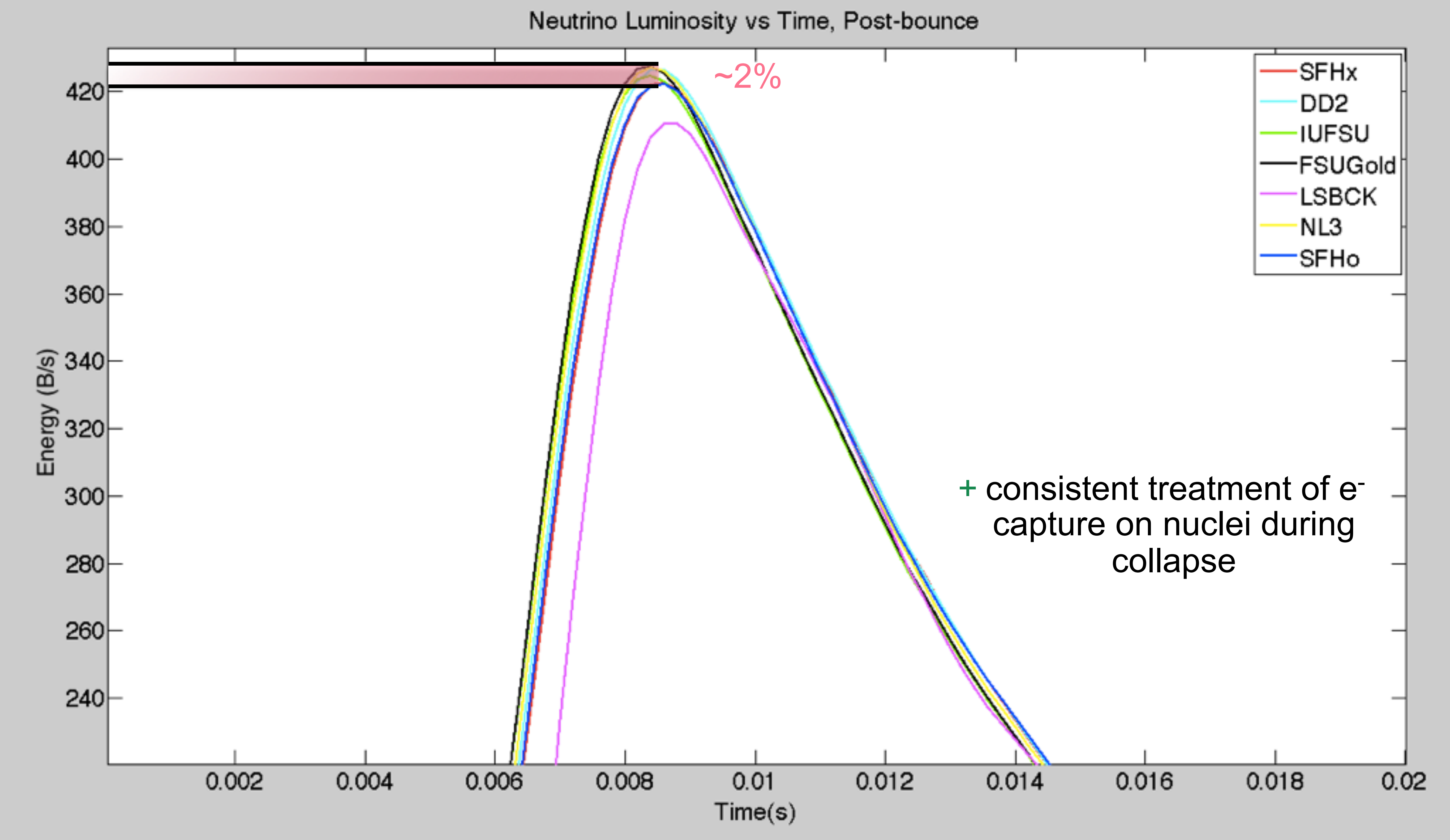
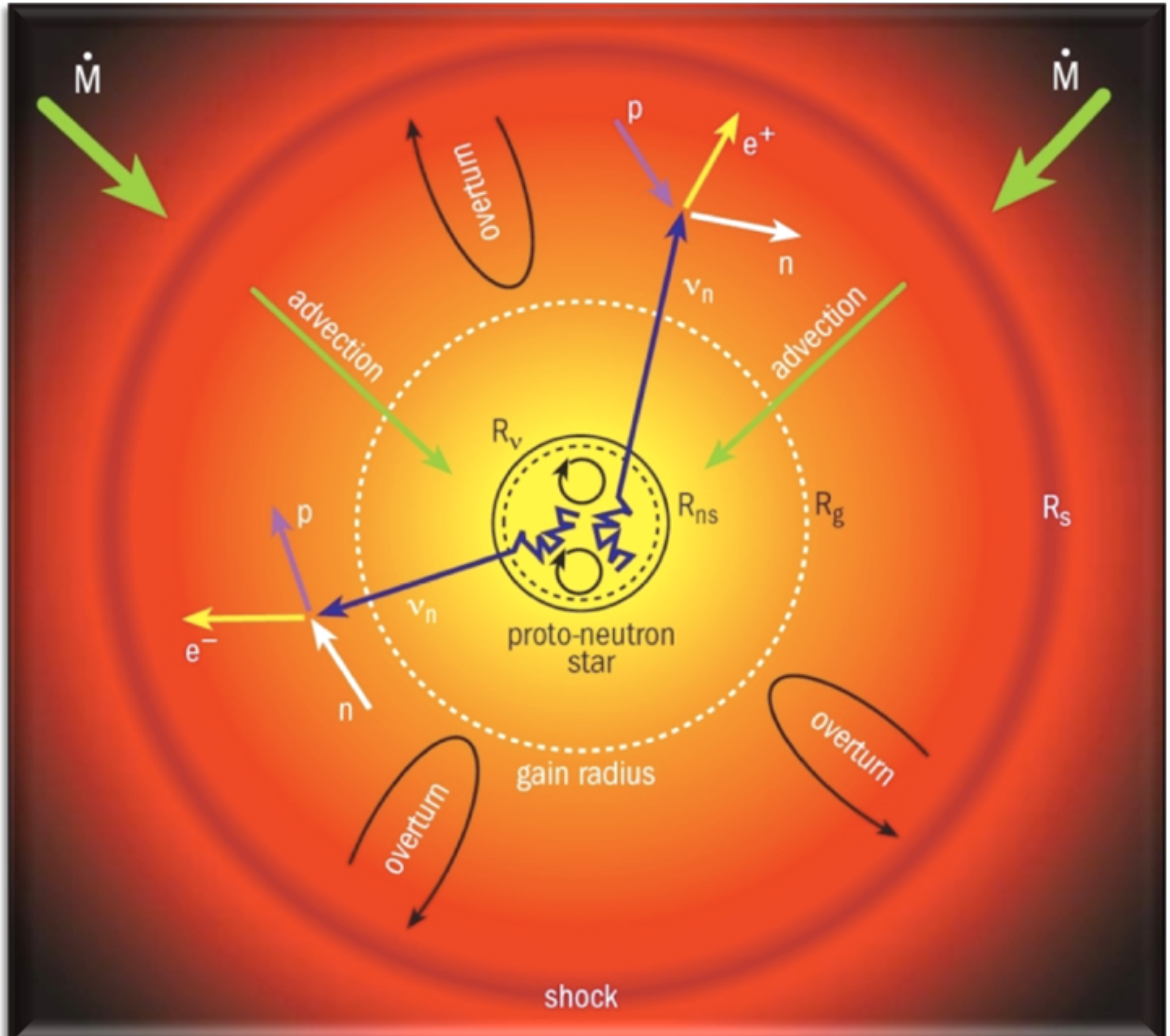
...but, modern EOS's have much smaller differences.



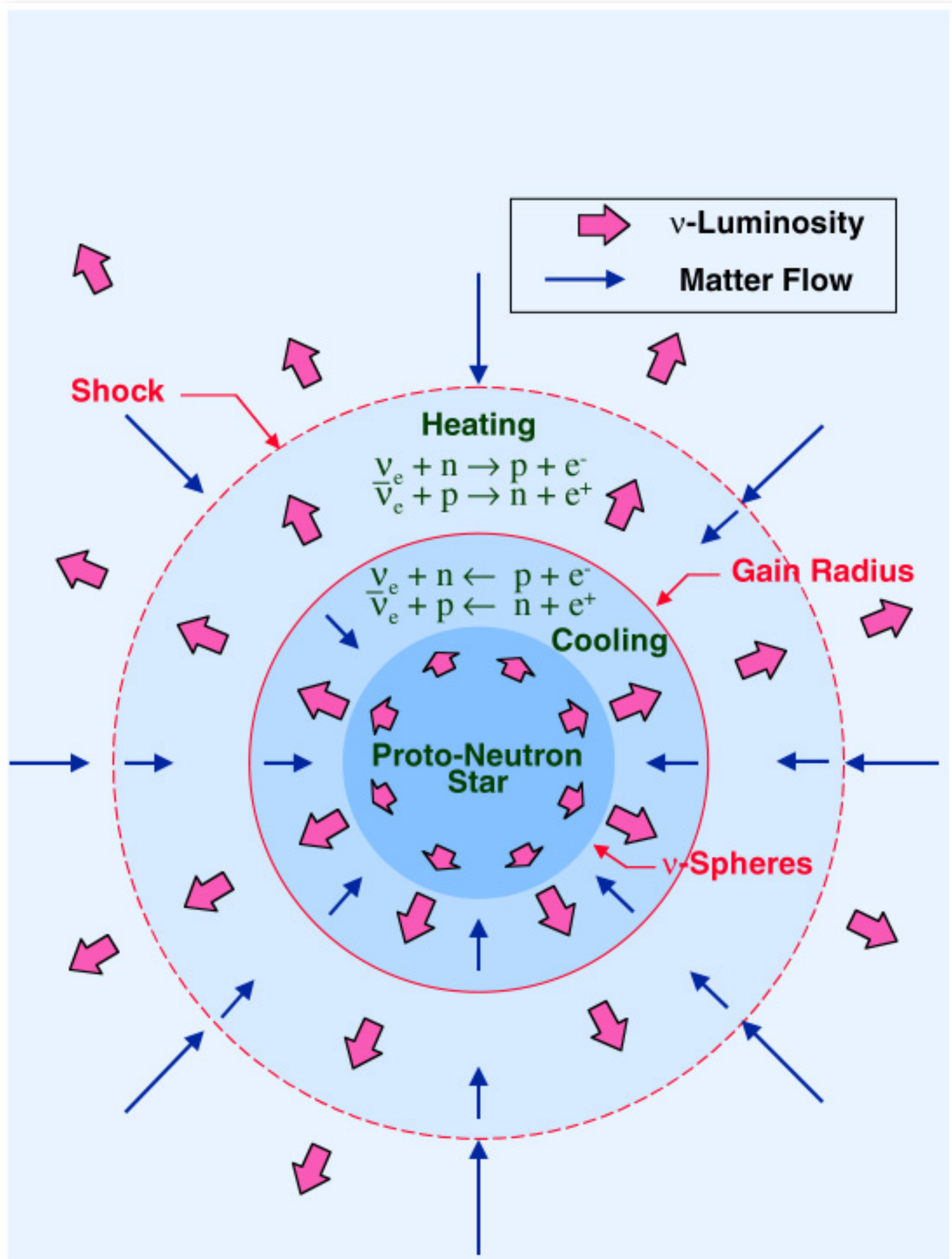
R. Landfield, PhD thesis (2017, U. Tennessee)

Post-bounce profile



Hillebrandt & Janka 2006 (Sci Am)

Neutrino heating in the gain region



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

$$\dot{\epsilon} = \frac{X_n}{\lambda_0^a}\frac{L_{\nu_e}}{4\pi r^2}\langle E_{\nu_e}^2\rangle\langle\frac{1}{\mathcal{F}}\rangle + \frac{X_p}{\bar{\lambda}_0^a}\frac{L_{\bar{\nu}_e}}{4\pi r^2}\langle E_{\bar{\nu}_e}^2\rangle\langle\frac{1}{\bar{\mathcal{F}}}\rangle$$

➠ *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

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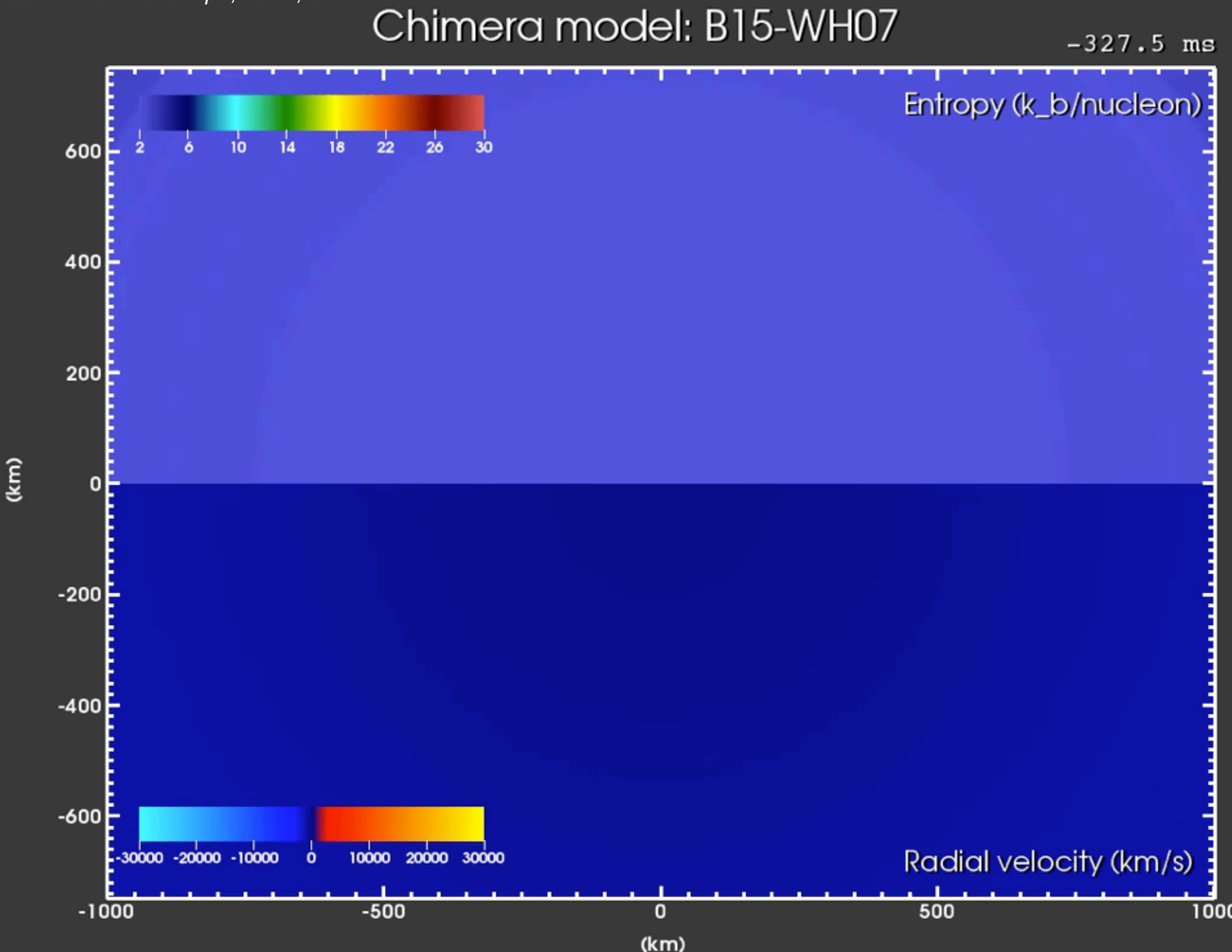
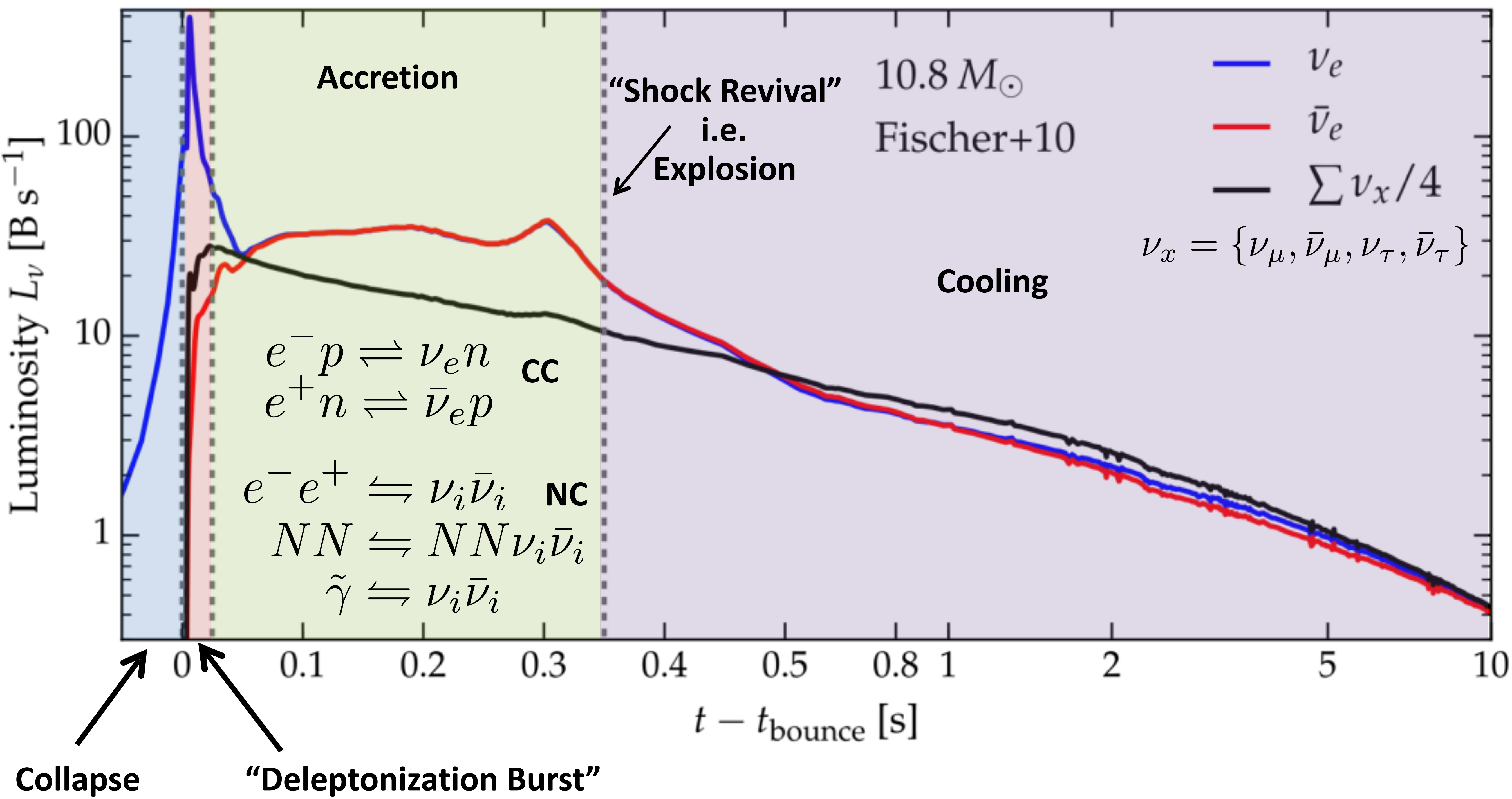
Bruenn et al. 2013. *ApJ*, **767L**, 6B.



Supernova neutrino “light curves”



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

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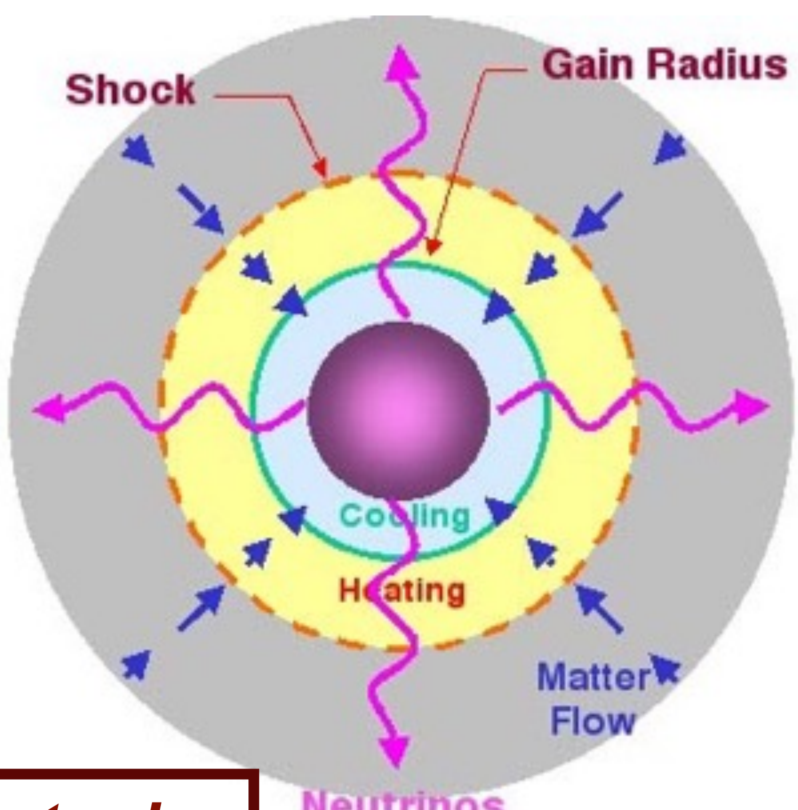
Many 2D simulations have been performed in the past few years by several groups.

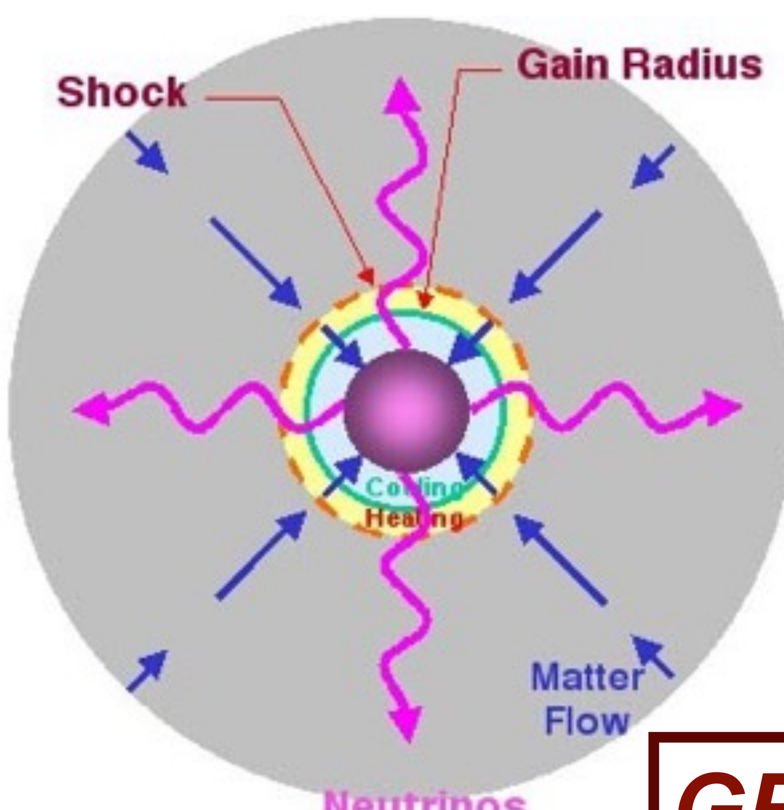
adapted from O'Connor & Couch (2016)

Explosions!

Reference	Gravity	EOS	Grid	ν Treatment	s12 Exp?	s12 t_{exp} [s]	s15 Exp?	s15 t_{exp} [s]	s20 Exp?	s20 t_{exp} [s]	s25 Exp?	s25 t_{exp} [s]
Bruenn et al. (2013)	GREP	LS220	Spherical	MGFLD RxR+	Yes	0.236	Yes	0.233	Yes	0.208	Yes	0.212
Hanke (2014)	GREP	LS220	Spherical	VEF RxR+	Yes	0.79	Yes	0.62	Yes	0.32	Yes	0.40
O'Connor & Couch (2016)	GREP	LS220	Cylindrical	MG M1	No	–	Yes	0.737	Yes	0.396	Yes	0.350
Dolence et al. (2015)	NW	H. Shen	Cylindrical	MGFLD	No	–	No	–	No	–	No	–
Suwa et al. (2014)	NW	LS220	Spherical	IDSA RxR	Yes	0.425	No	–	No	–	N/A	N/A
O'Connor & Couch (2016)	NW	LS220	Cylindrical	MG M1	No	–	No	–	No	–	No	–
Burrows et al.(2016)	GREP	LS220	Spherical	MG M1	Yes	~.310	Yes	~.370	Yes	~.410	Yes	~.340

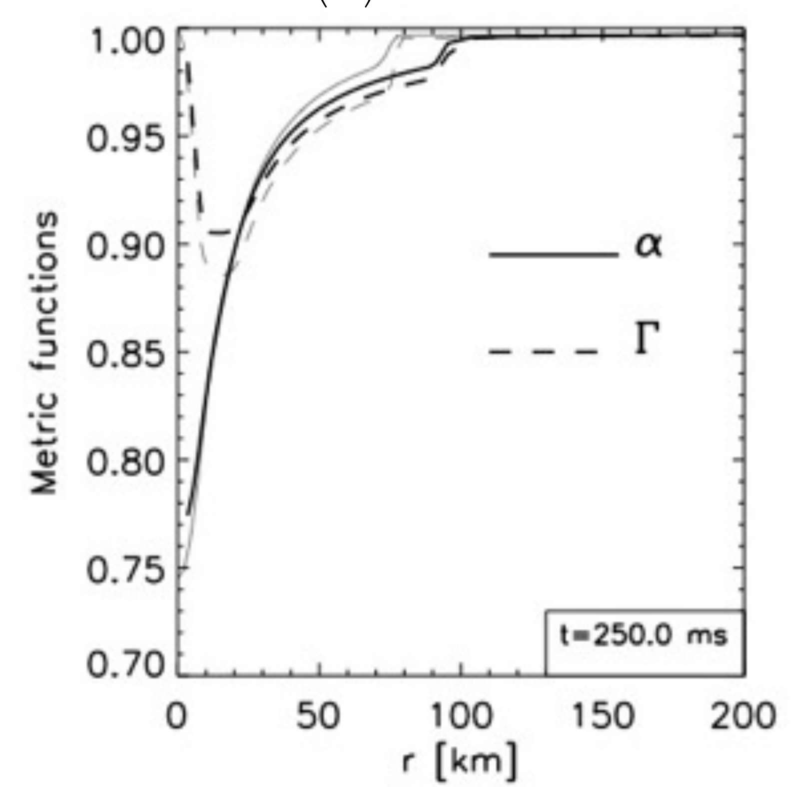


Newtonian



GR

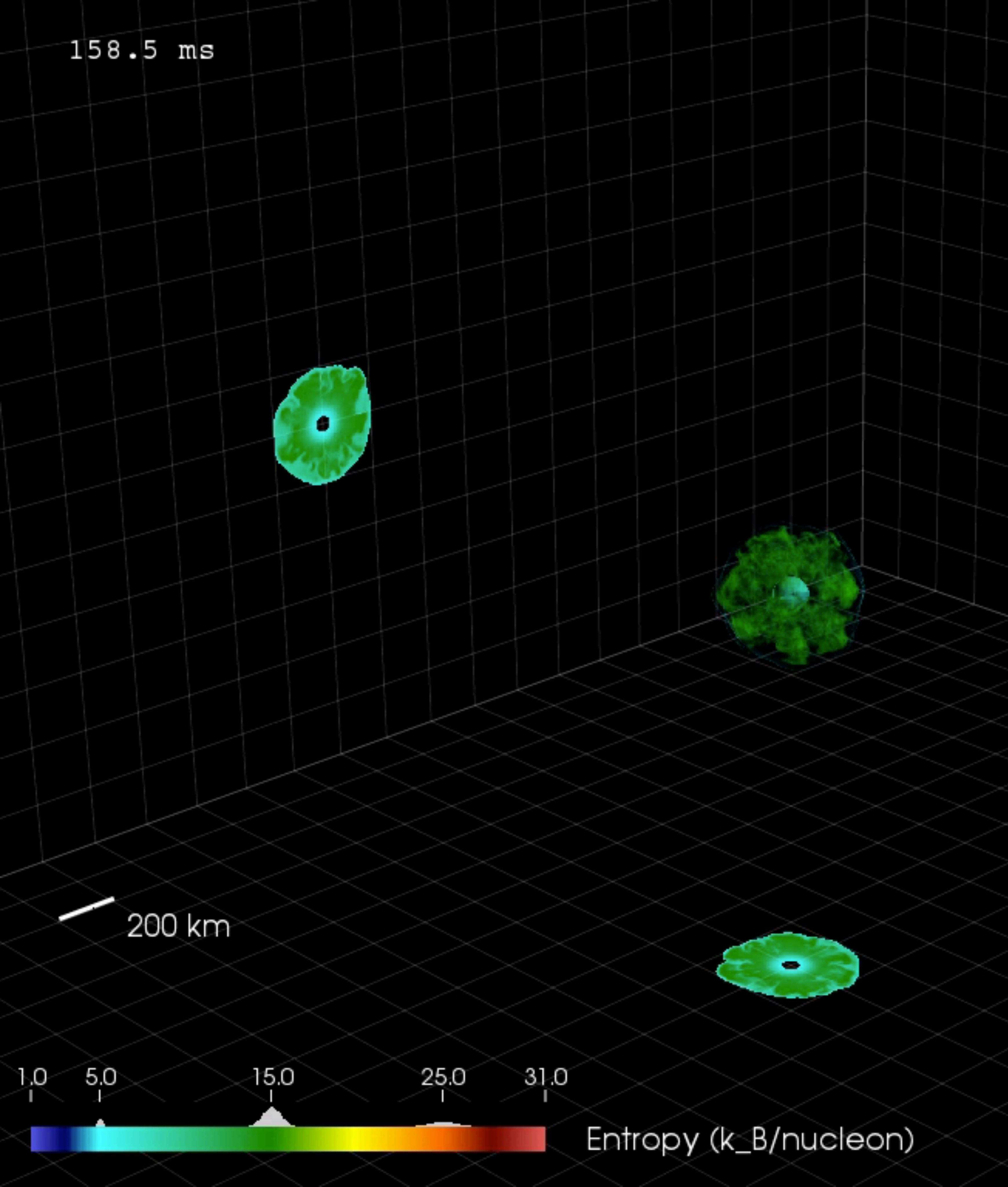
$$ds^2 = -\alpha^2 dt^2 + \left(\frac{r'}{\Gamma}\right)^2 da^2 + r^2\left(d\theta^2 + \sin^2\theta d\varphi^2\right)$$



15 solar mass 3D run

~6 months on ~48,000 cores

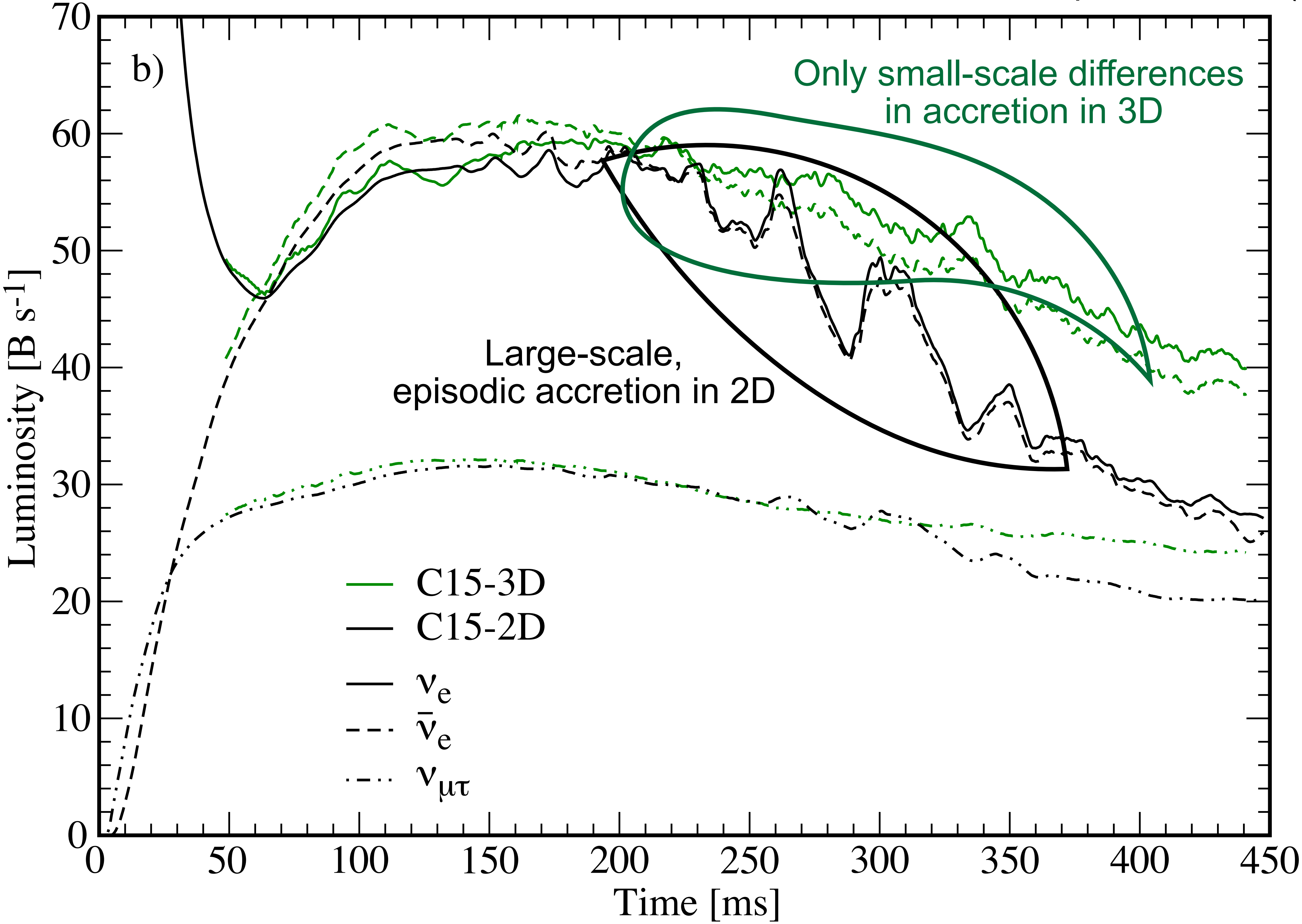
- 15 solar mass WH07 progenitor
- 540 radial zones covering inner 11000 km
- 180 phi zones (2 degree resolution)
- 180 theta zones in "constant mu" grid, from 2/3 degree at equator to one 8.5 degree zone at pole.
- “Full” opacities
- 0.1% density perturbations (10-30 km) applied at 1.3 ms after bounce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



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

3D vs 2D luminosities

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



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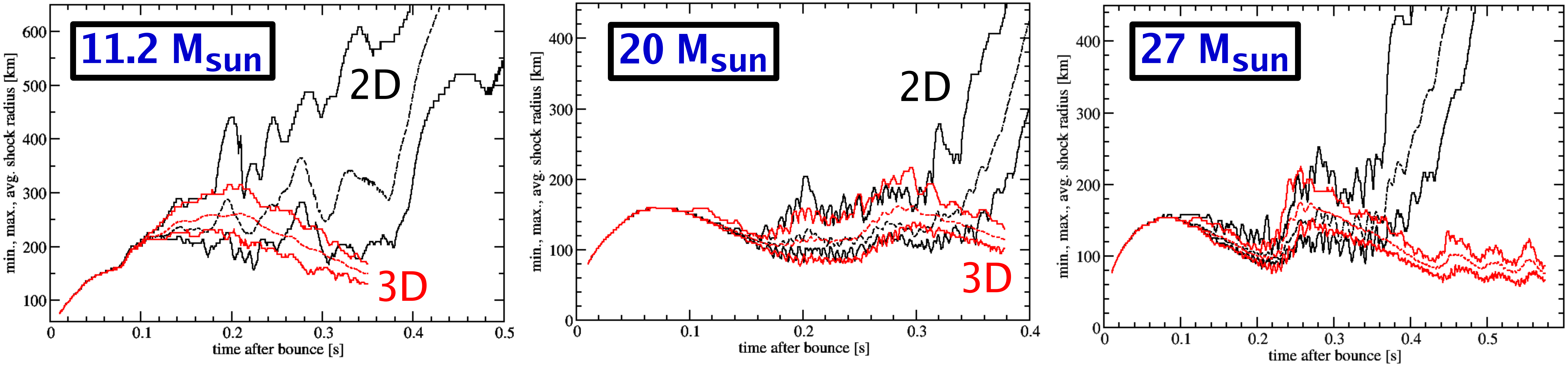
3D vs 2D continued

Florian Hanke, PhD project (2014), MPA



but…

$$\frac{d\sigma_0}{d\Omega} = \frac{G_F^2\epsilon^2}{4\pi^2}\left[c_v^2(1+\cos\theta) + c_a^2(3-\cos\theta)\right], \quad (1)$$

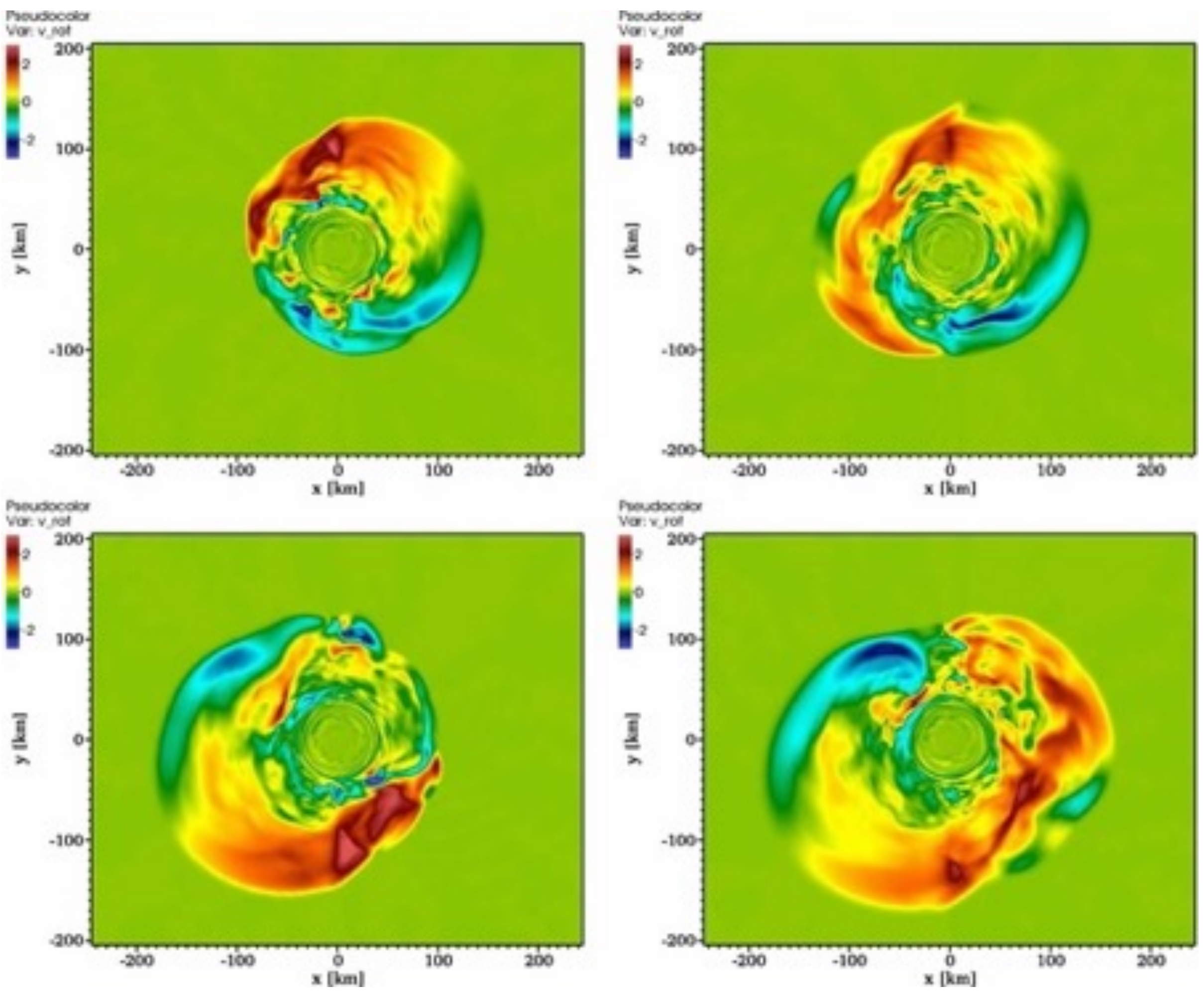
$$\sigma_0^t = \int_{4\pi} d\Omega\, \frac{d\sigma_0}{d\Omega}(1-\cos\theta) = \frac{2G_F^2\epsilon^2}{3\pi}\left(c_v^2 + 5c_a^2\right). \quad (2)$$

$$c_a = \frac{1}{2}(\pm g_a - g_a^s), \quad (3)$$

$g_a = 1.26$
$g_a^s = -0.2$

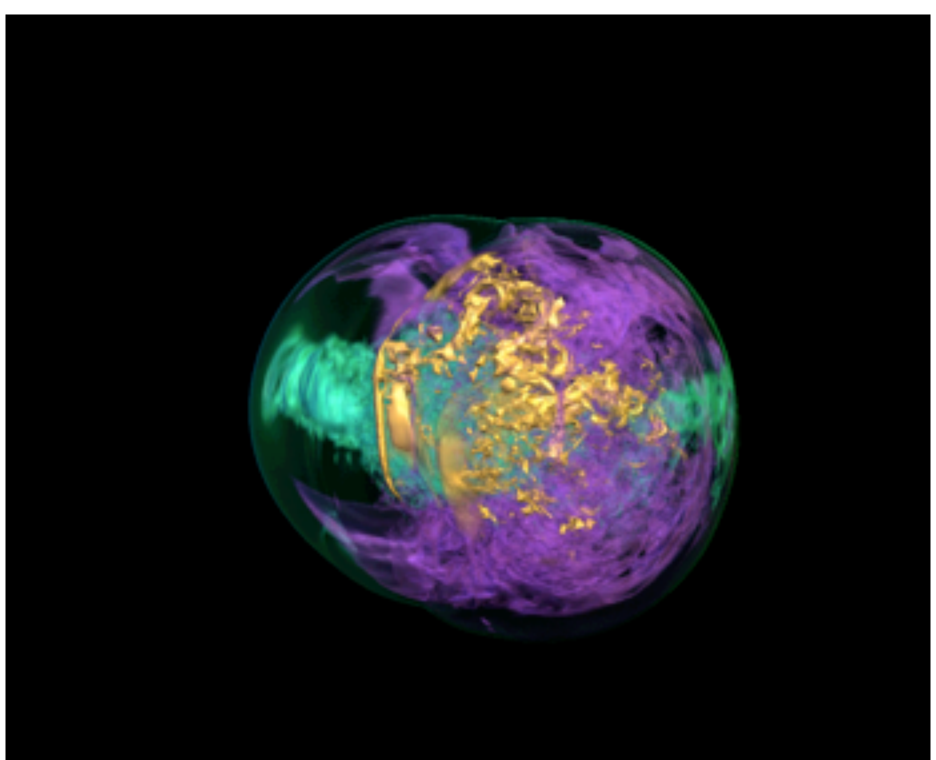
Effective reduction of neutral-current neutrino-nucleon scattering by ~15%

Probing multi-D supernova dynamics

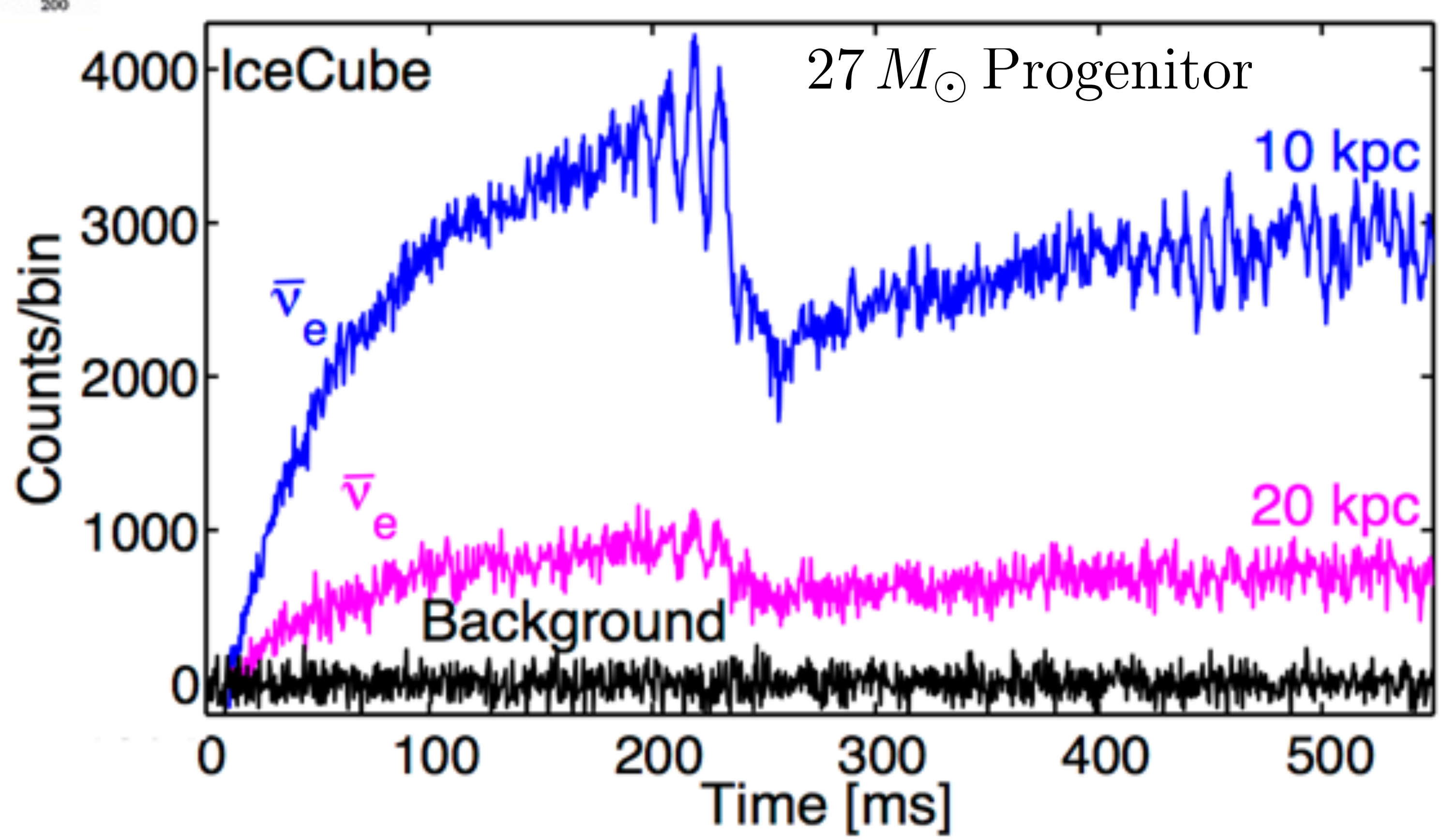


Hanke+ (2013), ApJ

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

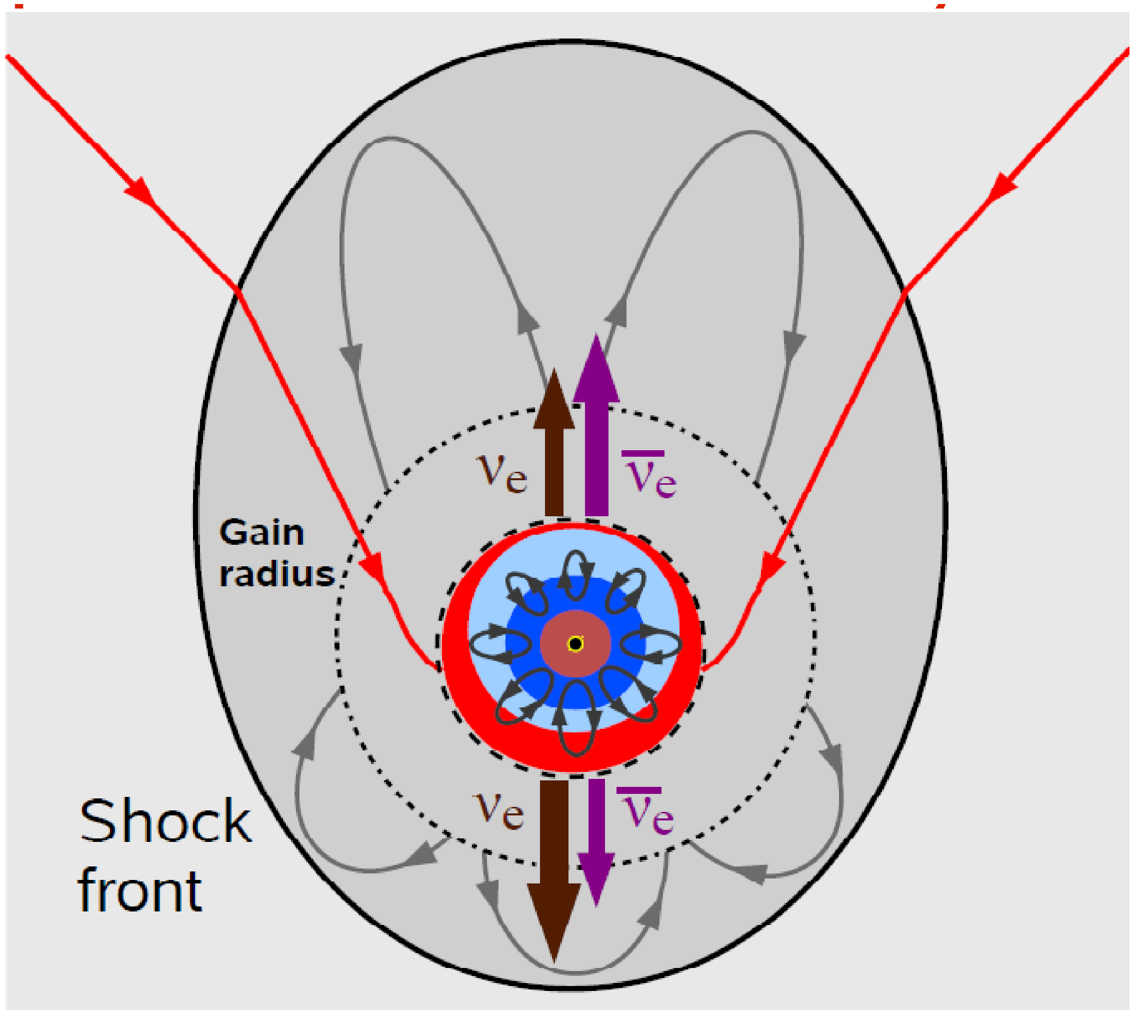


Tamborra+ (2013), PRL

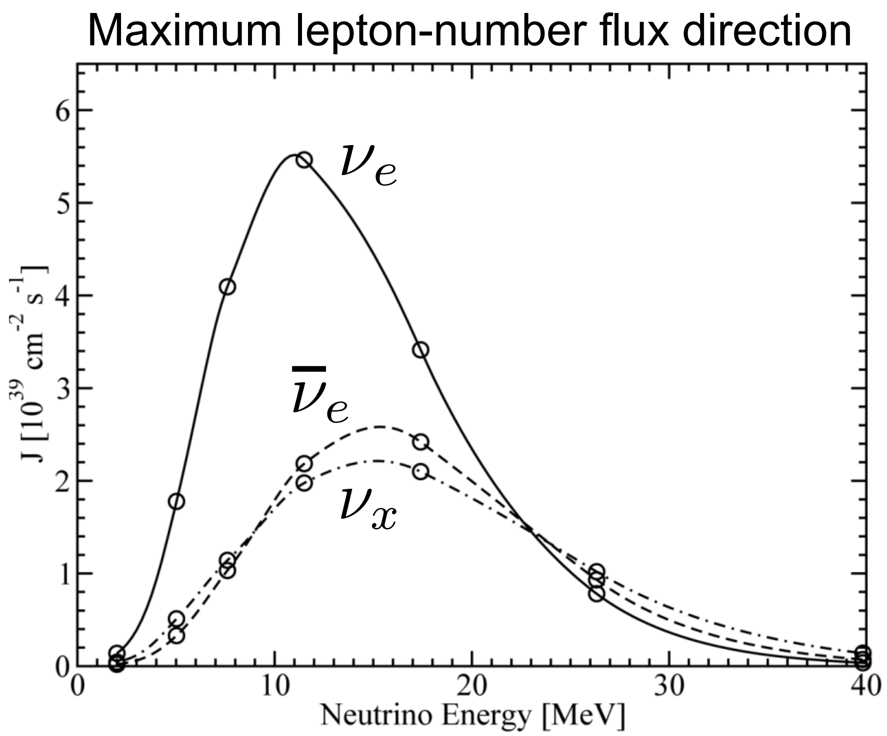


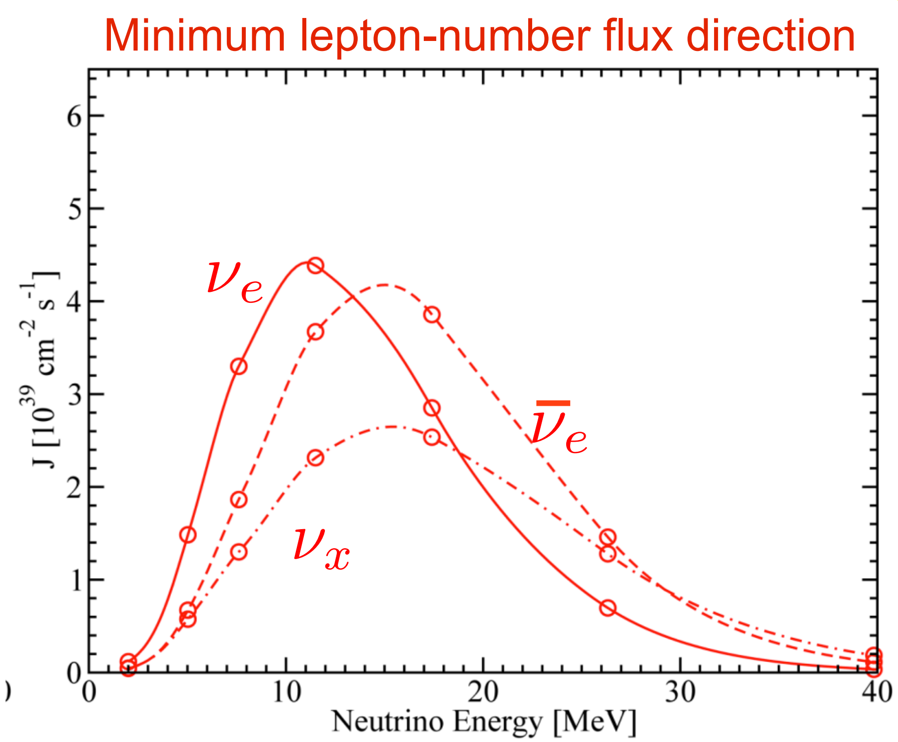
LESA

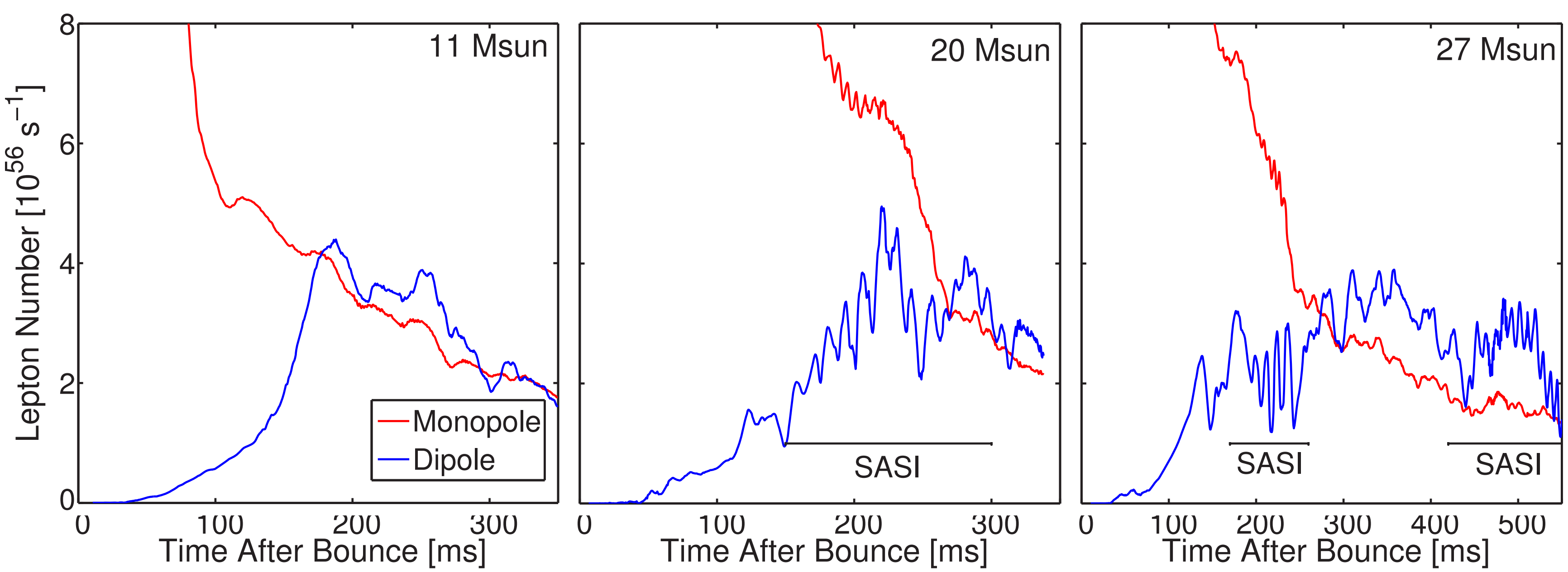
from Tamborra (FOE2015, NCSU)



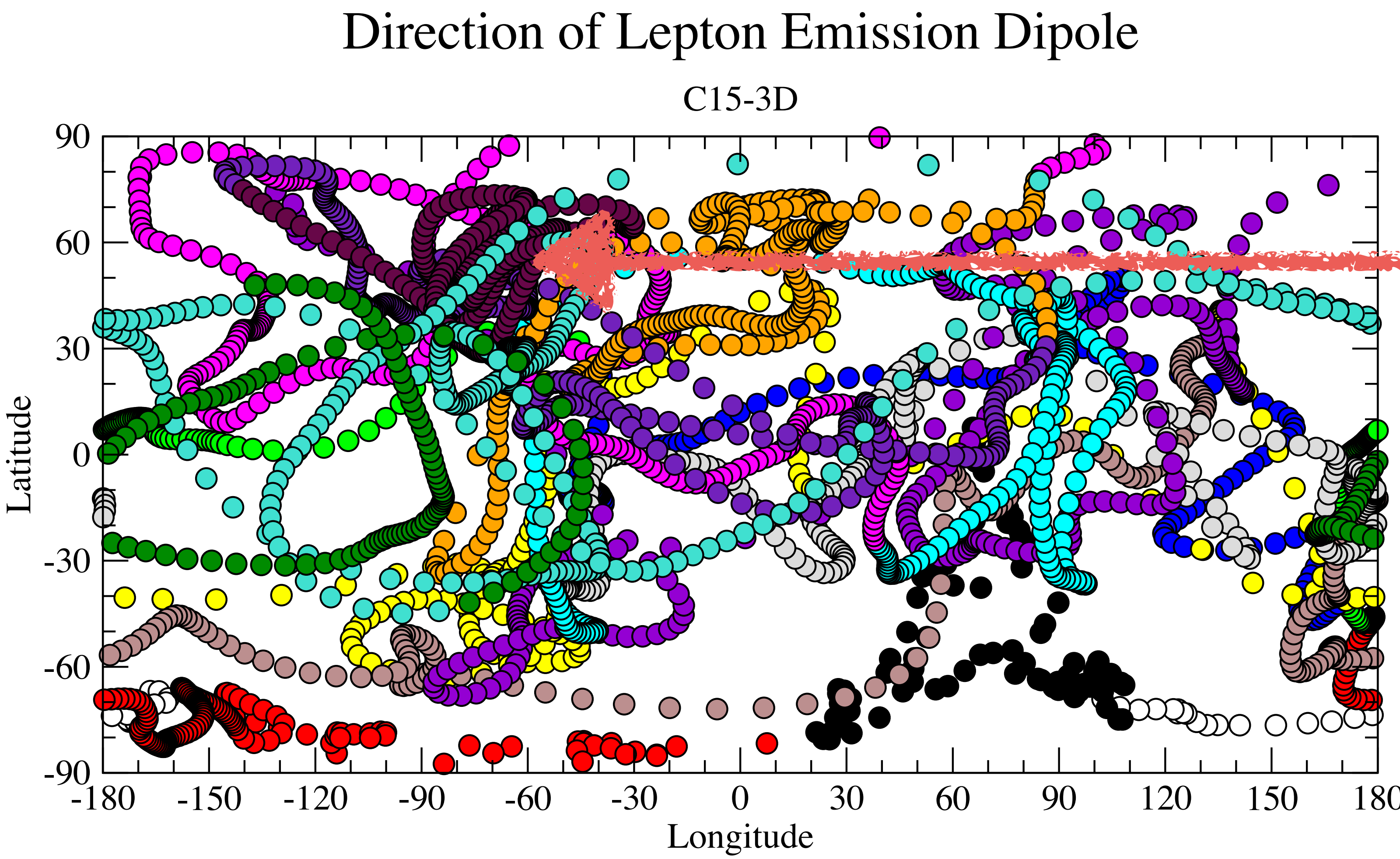
$$\dot{q} \propto \frac{\sigma_0}{r^2}\left(L_{\nu_e}\left\langle\epsilon_{\nu_e}^2\right\rangle Y_n + L_{\bar{\nu}_e}\left\langle\epsilon_{\bar{\nu}_e}^2\right\rangle Y_p\right)$$







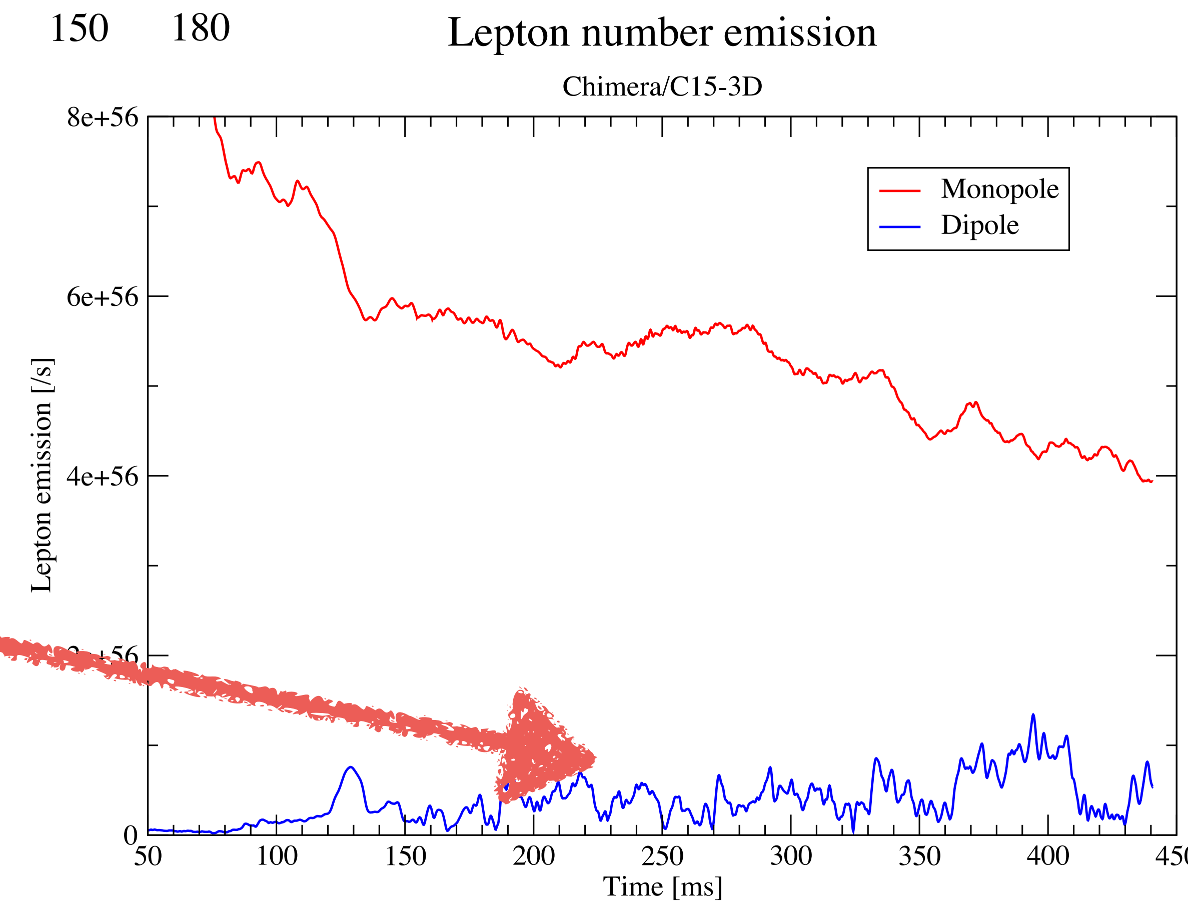
Is the LESA a generic instability?



CHIMERA C-15 3D model

Dipole relatively long-lived,
but not “persistent”

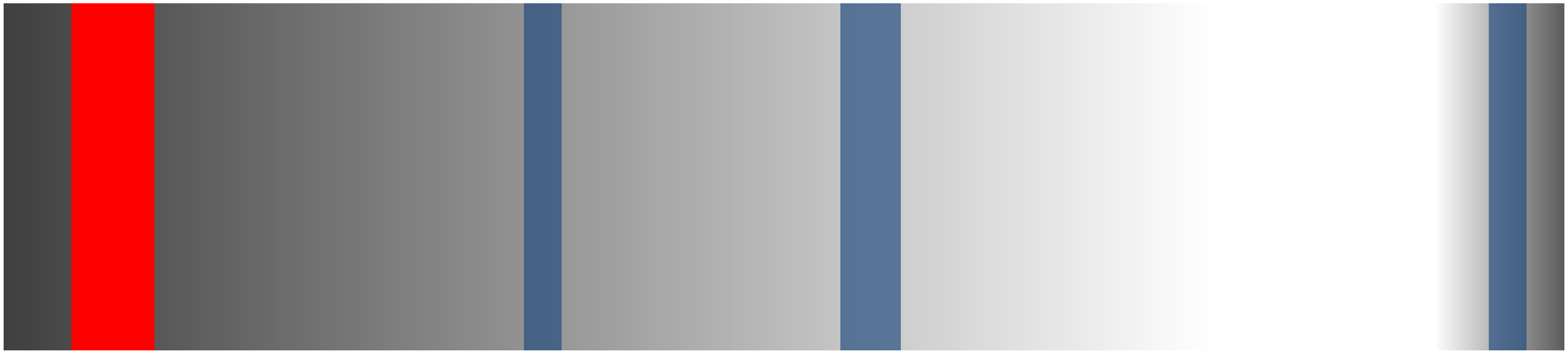
Dipole present, but relatively weak



Supernova neutrino oscillations

(see, e.g., Mirizzi+ (2015), Duan+ (2010) for reviews)

proto-NS | stellar core | stellar envelope | Vacuum | Earth



$\mu \gg \lambda$

$10^9 - 10^7\,\mathrm{g\,cm^{-3}}$

$r \lesssim 10^3\,\mathrm{km}$

Self-Induced

(likely?)
suppressed in accretion phase e.g. Chakraborty+ (2011)

$\omega_{31} \simeq \lambda$

$10^3\,\mathrm{g\,cm^{-3}}$

MSW
H Resonance

$\omega_{21} \simeq \lambda$

$1 - 10\,\mathrm{g\,cm^{-3}}$

MSW
L Resonance

$\omega_{21} \simeq \lambda$

$1 - 10\,\mathrm{g\,cm^{-3}}$

MSW
L Resonance

(figure inspired by C. Lunardini)

SN ν oscillations: simplest scenario

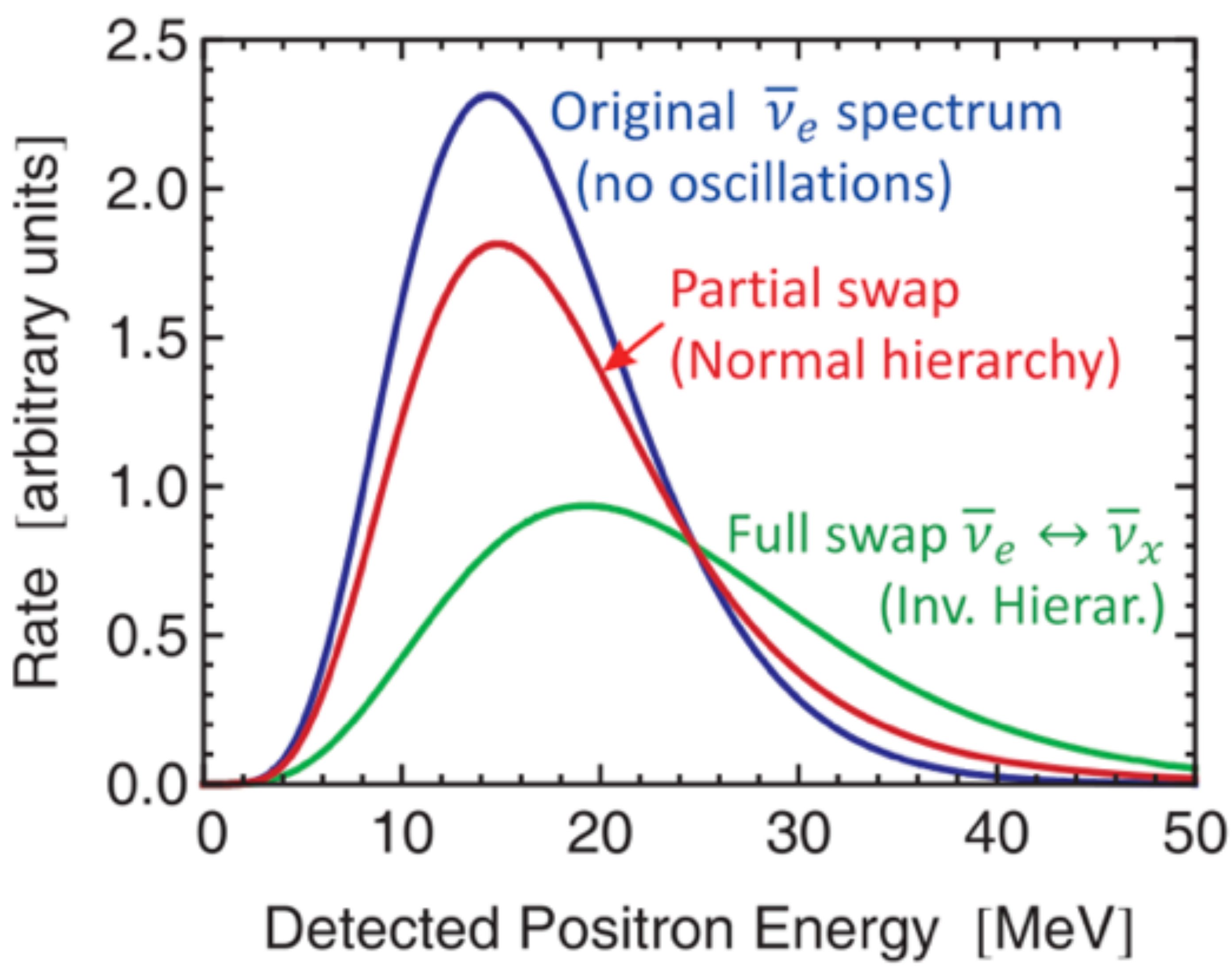
(see, e.g., Mirizzi+ (2015), Duan+ (2010) for reviews)

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



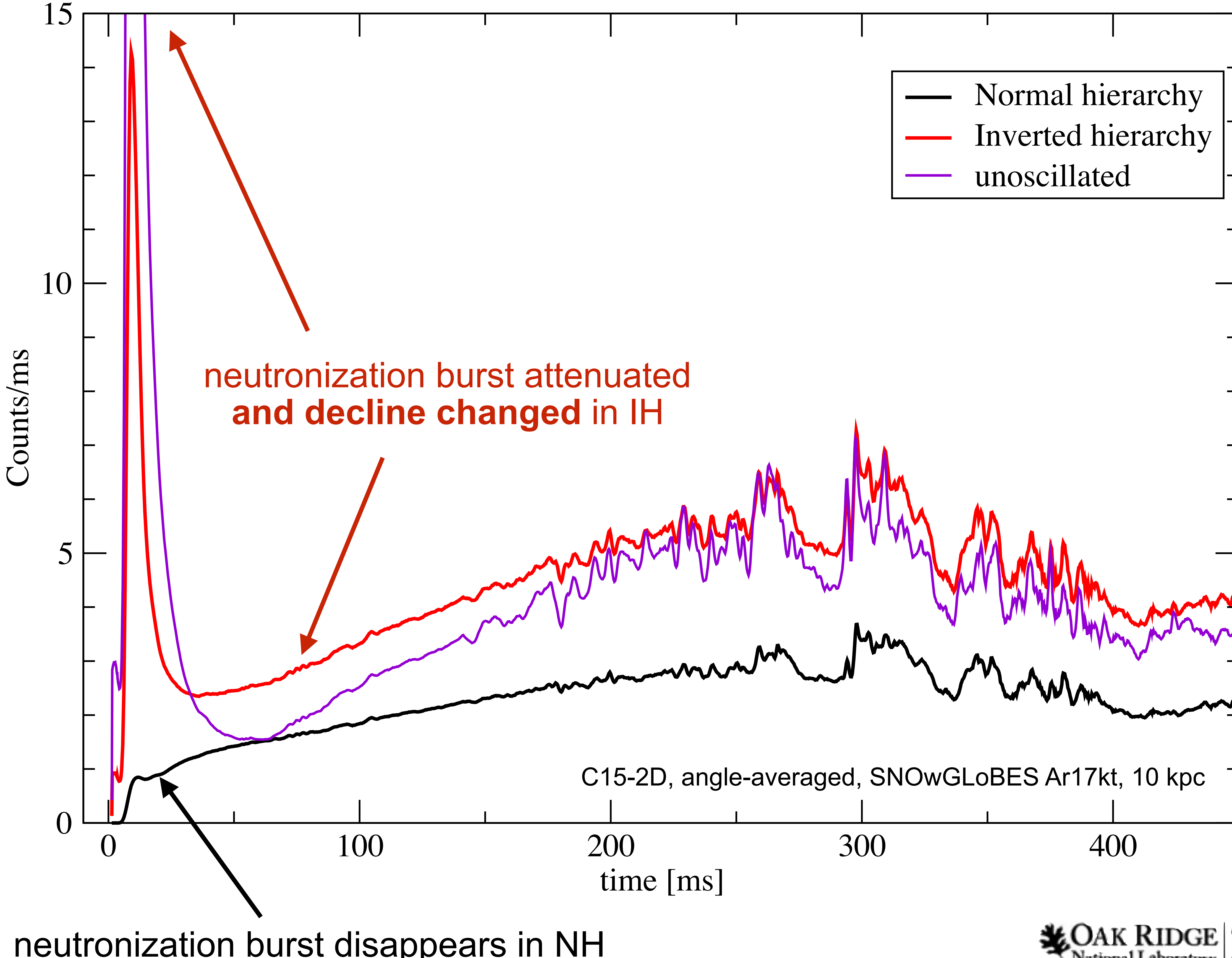
Raffelt (2012)

Complications:

Shocks (non-adiabaticity when H resonance reached), turbulence

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

Messer, Devotie, et al (submitted)



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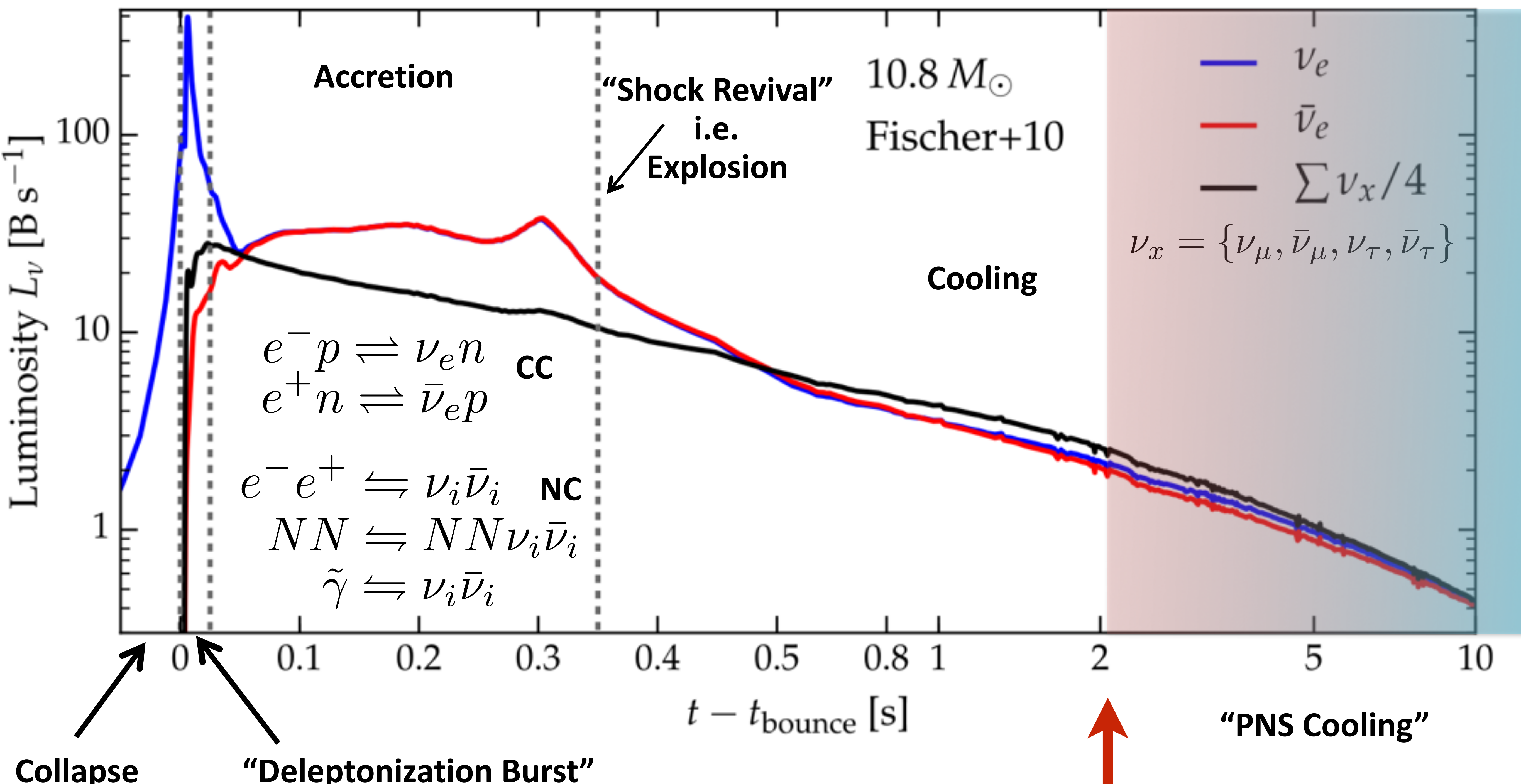
Supernova neutrino “light curves”



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

Approximate temporal extent of modern SN models

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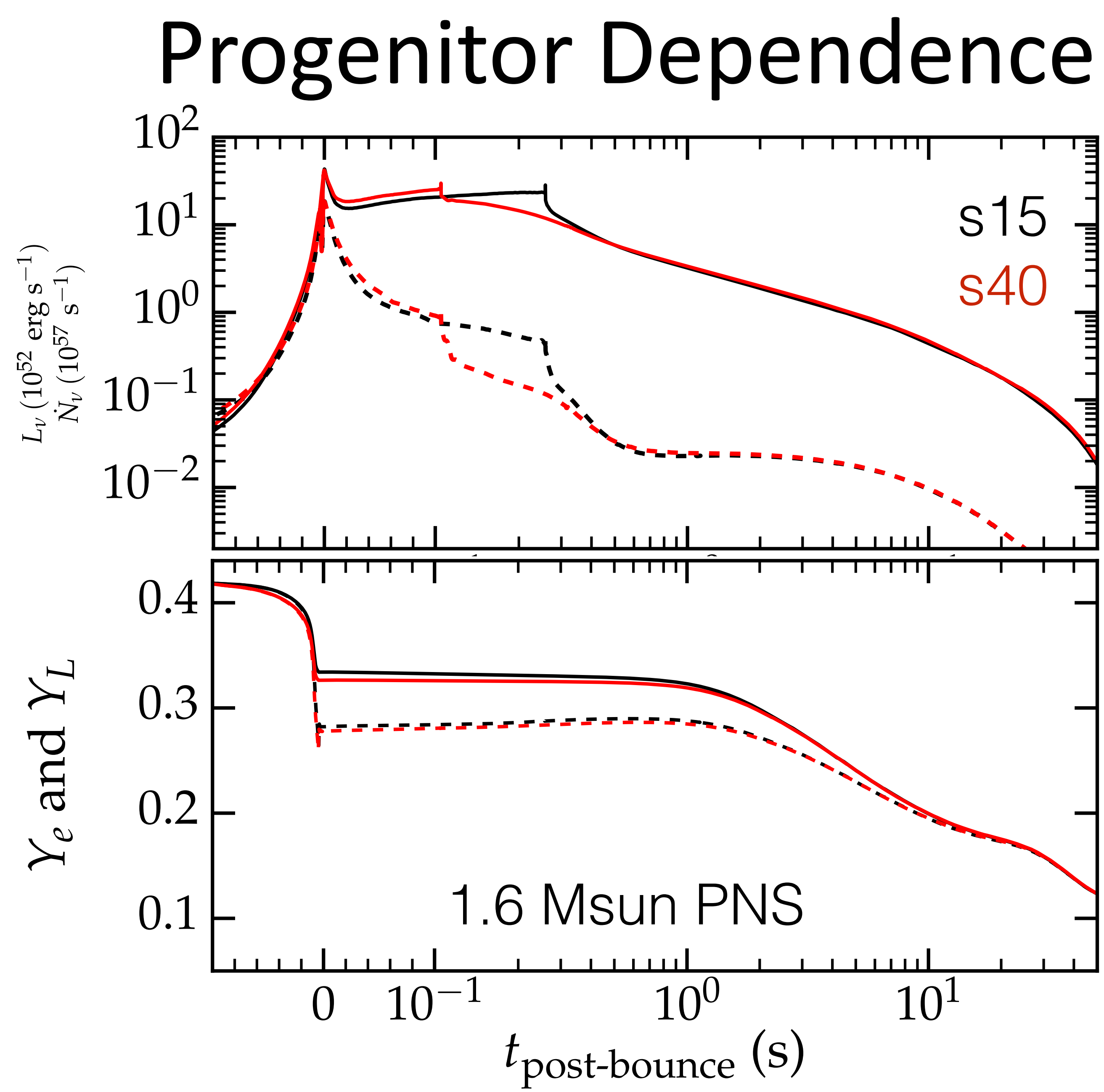
PNS cooling

- The long term neutrino cooling signal is not particularly sensitive to progenitor structure for fixed remnant mass L. Roberts (MSU)

- But, like the SN models preceding them, PNS cooling models need accurate treatments of macro- and microphysics. In particular,
  - convection
  - neutrino opacities
  - nuclear correlations at high density



L. Roberts (MSU)

See also, e.g.:
Burrows & Lattimer (1986), Pons+(1999), Keil+(2003), Fischer+(2010,2012), Hüdepohl+(2010), Nakazato+(2013), Mirizzi+(2015)

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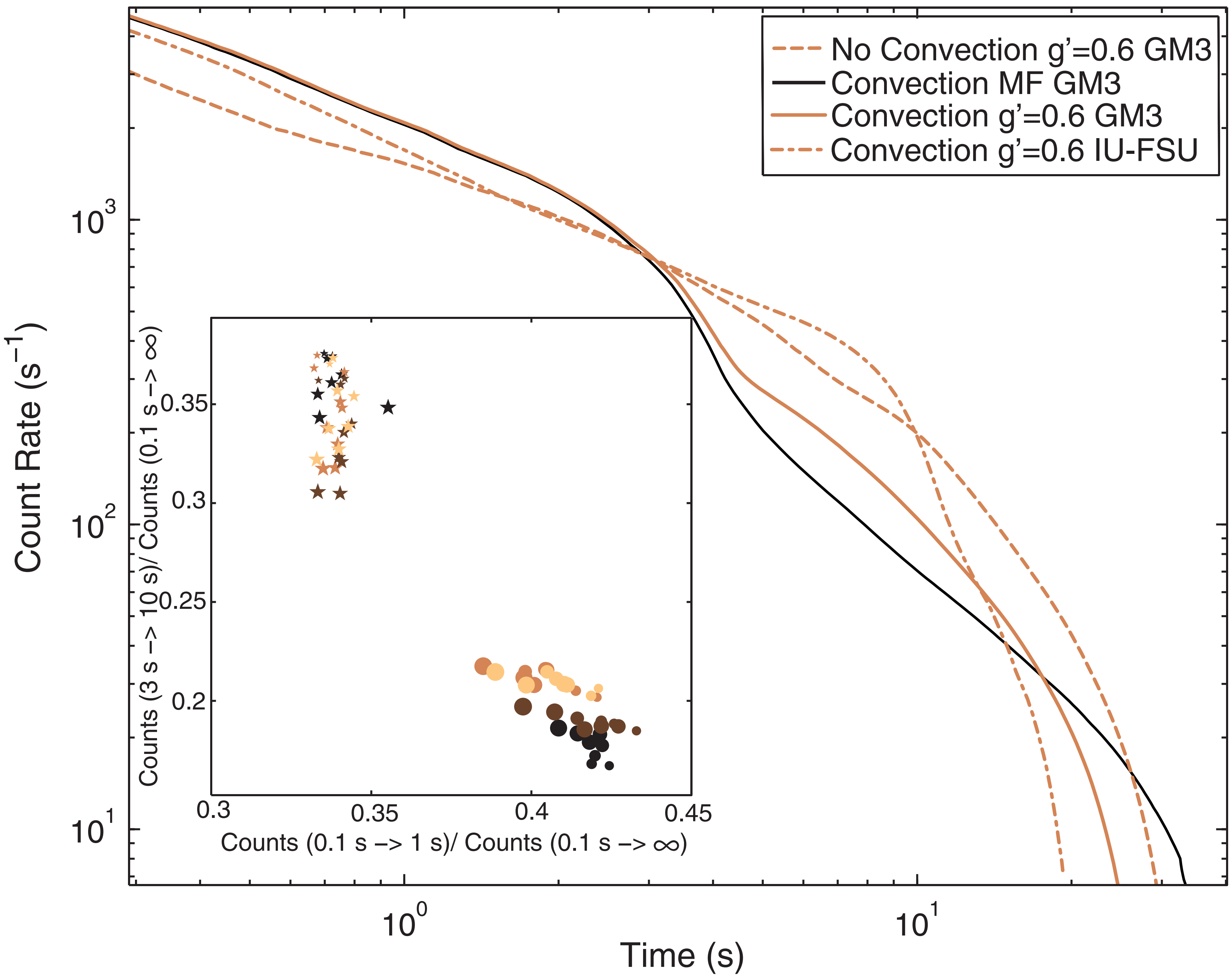
PNS cooling

- PNS convection significantly impacts the neutrino cooling timescale, produces a break in the neutrino emission
- Neutrino opacities especially important to the late time cooling timescale
  - In particular, nuclear correlations can also leave a signature on the tail of the neutrino signal

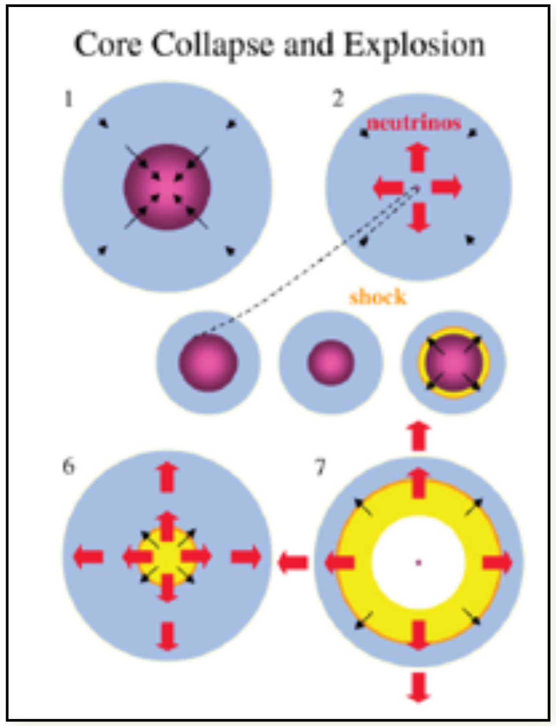
L. Roberts (MSU)

Roberts+(2012)

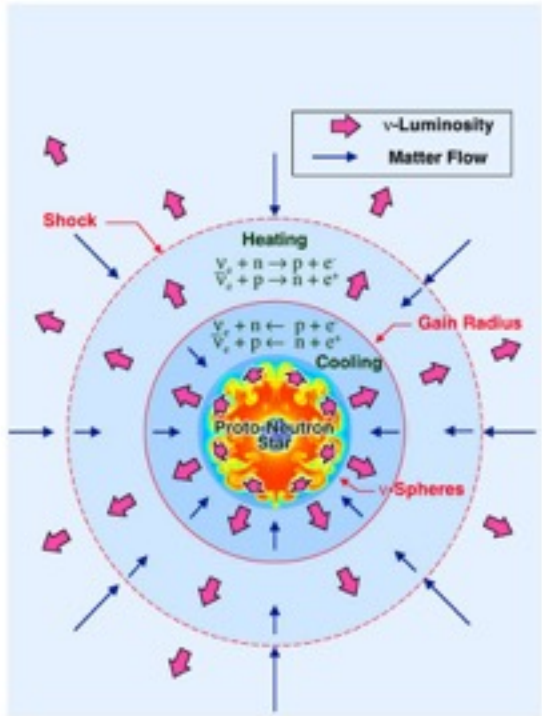


cf. cooling calculations of Bollig+ at http://wwwmpa.mpa-garching.mpg.de/ccsnarchive/archive.html

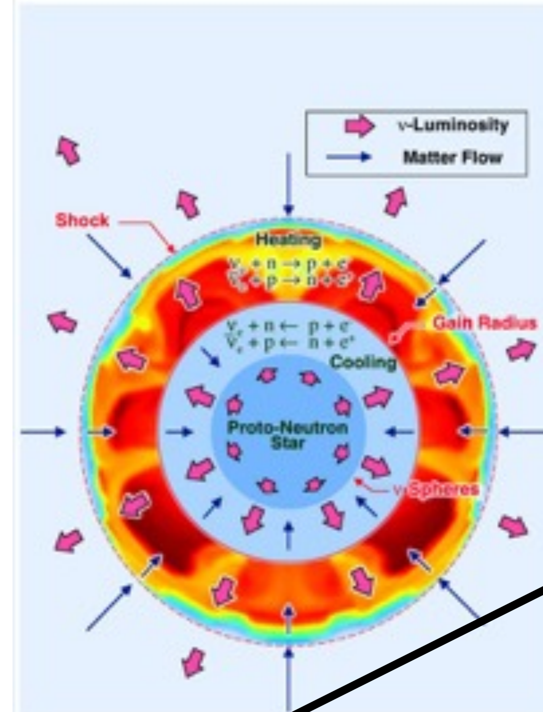
Neutrino-driven CCSNe: Sources of gravitational waves



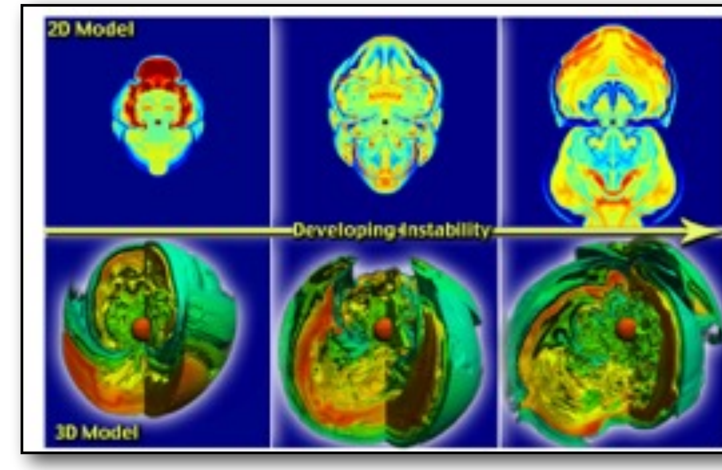
Stellar Core Bounce



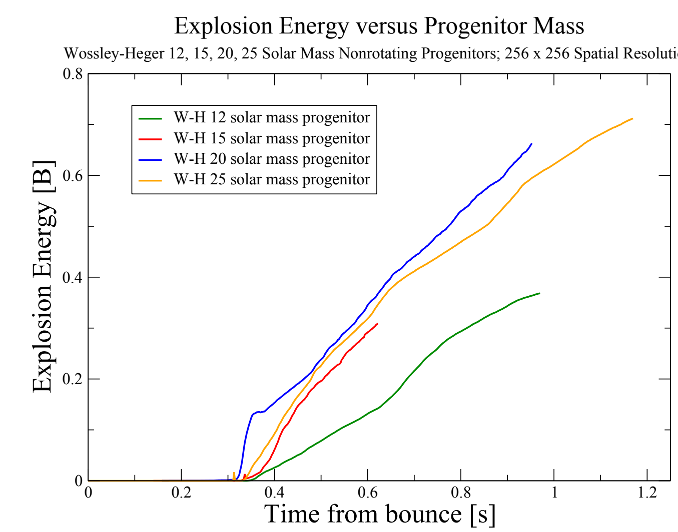
Proto-Neutron Star (PNS) Instabilities

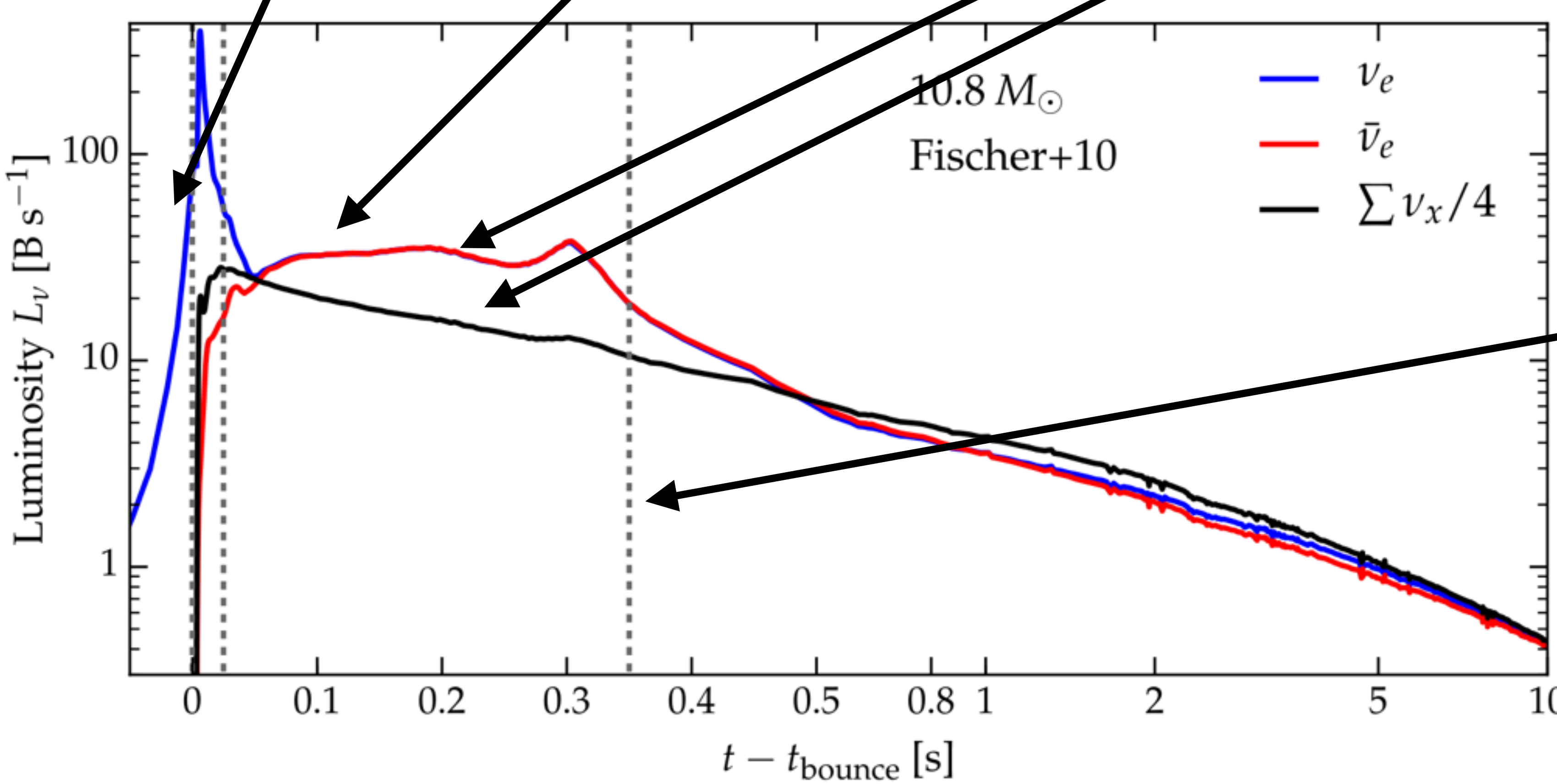


Post-Shock Region Neutrino-Driven Convection



Standing Accretion Shock Instability (SASI)





Explosion

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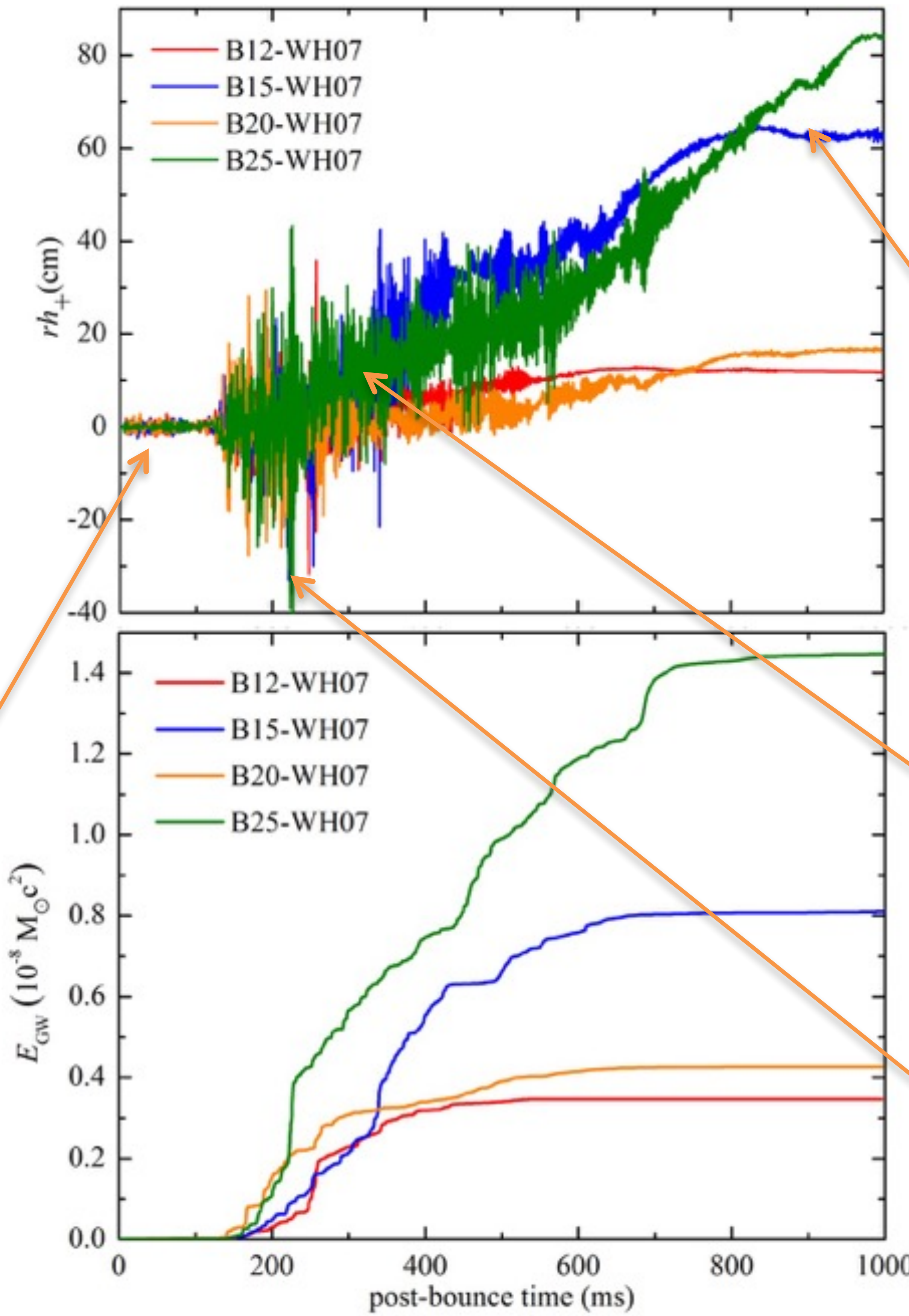
Gravitational wave signals: 2D amplitudes



Explosion Induced GW
Source: Ejected Matter

PNS Instabilities
Induced GW

Source: PNS

Neutrino-Driven Convection
and SASI-induced GW
Source: PNS

Modulated by SASI
N.B. Low-Frequency Envelope

A. Mezzacappa

Yakunin et al. 2015 PRD **92** 084040

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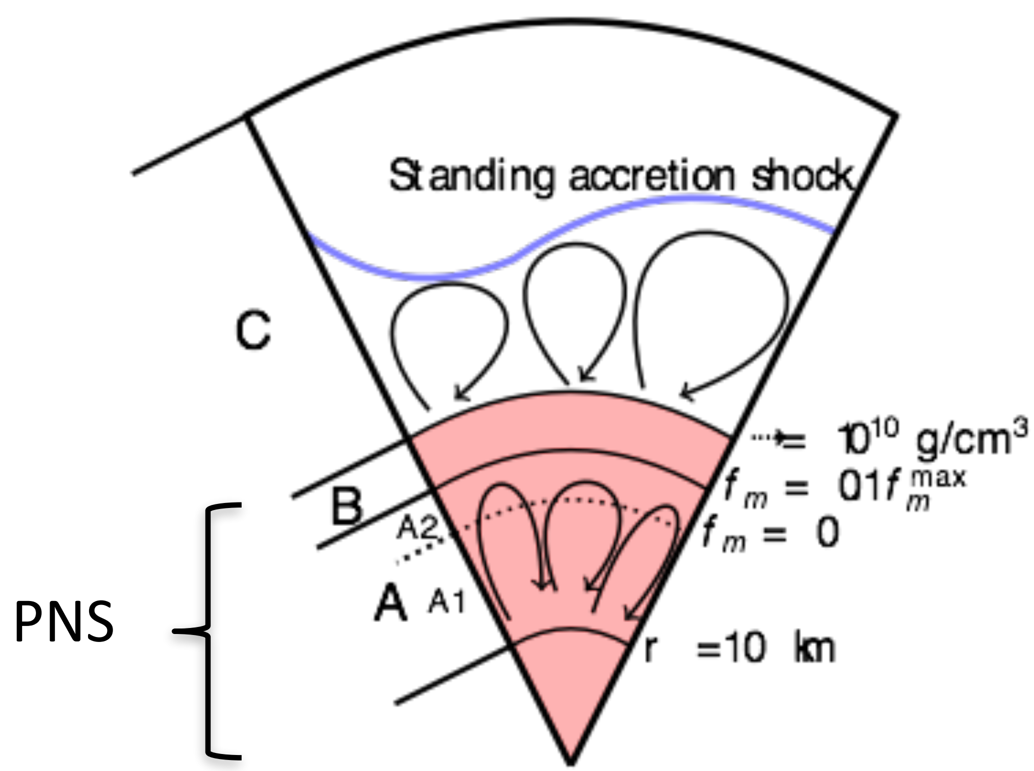
Gravitational wave signal: Source analysis

(5) SASI-Induced Modulation (Low Frequency)



Andresen et al. 2017 arXiv:1607.05199

Sources of Gravitational Radiation

(1) PNS convection in region A.

(2) Acoustic waves in the PNS initiated by PNS convection.

(3) Deceleration of infalling convective plumes.

(4) Excitation of PNS g-modes by these down flows (2D) or by PNS convection (3D).

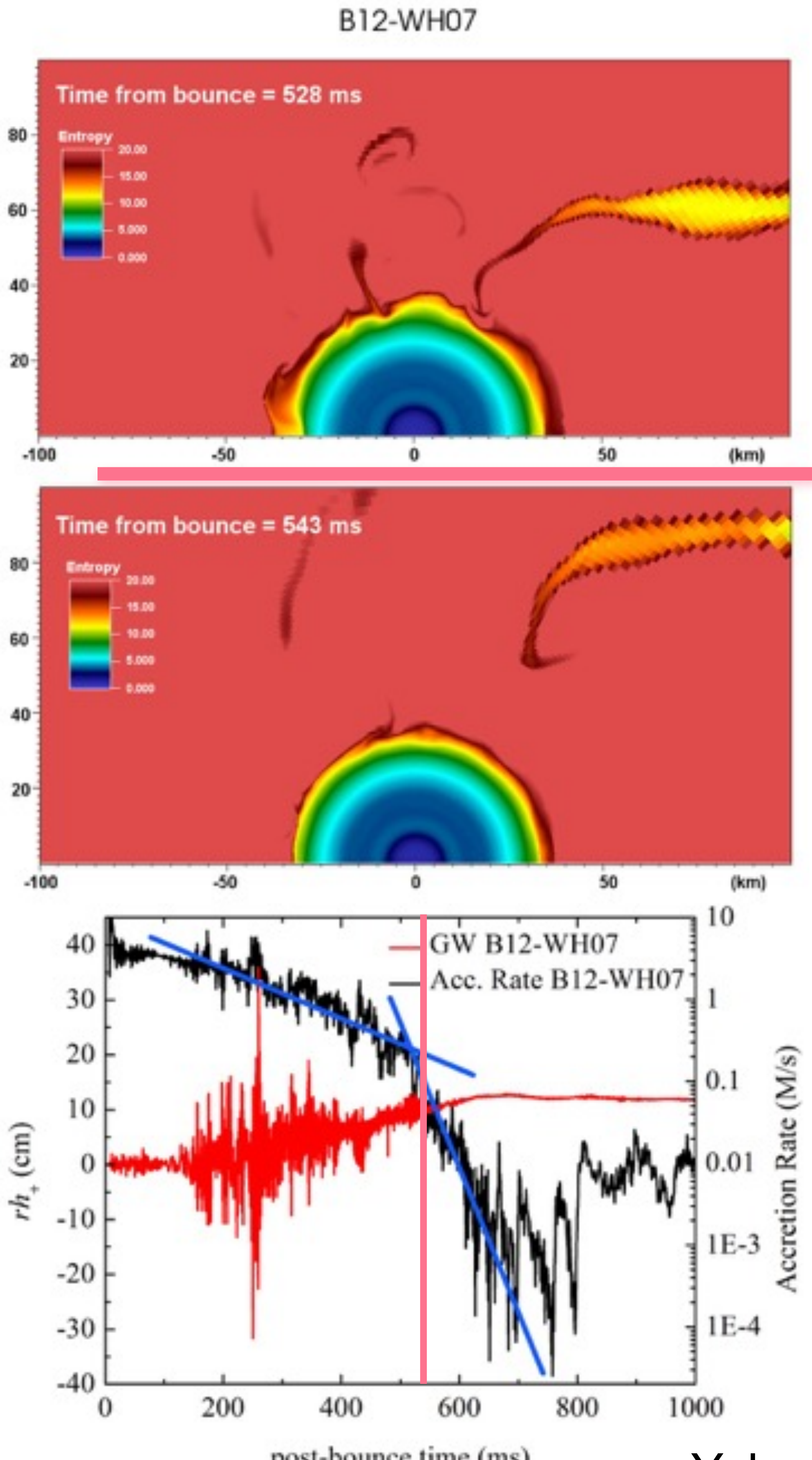
- Marek, Janka, and Mueller, *A&A* **496**, 475 (2009)
- Murphy, Ott, and Burrows *Ap.J.* **707** 1173 (2009)
- Mueller, Janka, and Marek *Ap.J.* **766**, 43 (2013)

g-Mode Frequency (Brunt-Vaisala Frequency)

$$f_p = \frac{N}{2\pi} = \frac{1}{2\pi}\frac{GM}{R^2}\sqrt{\frac{(\Gamma-1)m_n}{\Gamma k_b T}}\left(1-\frac{GM}{Rc^2}\right)^{3/2}$$

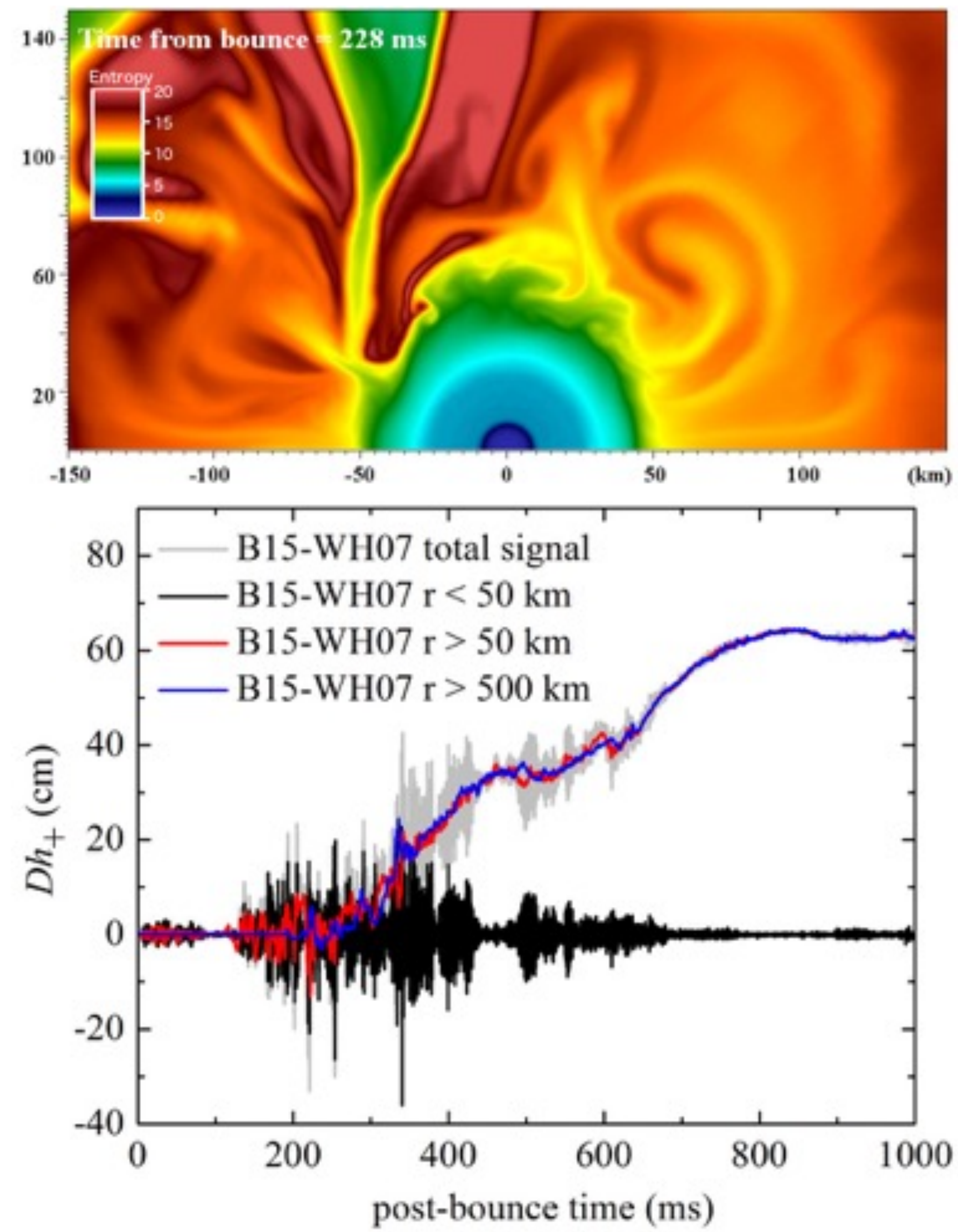
The late-time, high-frequency GW is given by the g-mode frequency in B (A2) for the 2D (3D) case.

GW amplitude: Correlation with accretion



533 ms

Cessation of accretion corresponds to cessation of high-frequency component of GW amplitude.



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A. Mezzacappa

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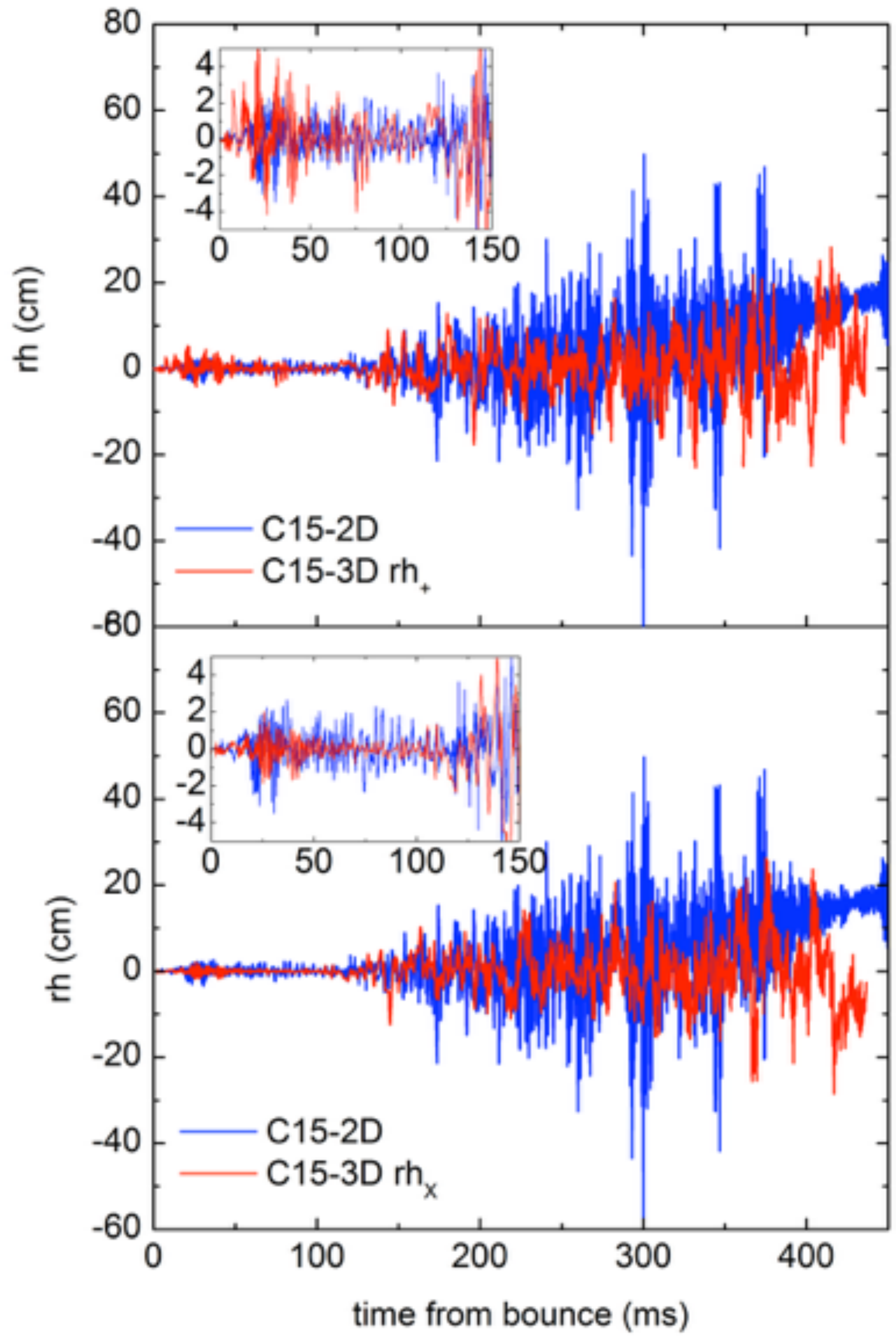
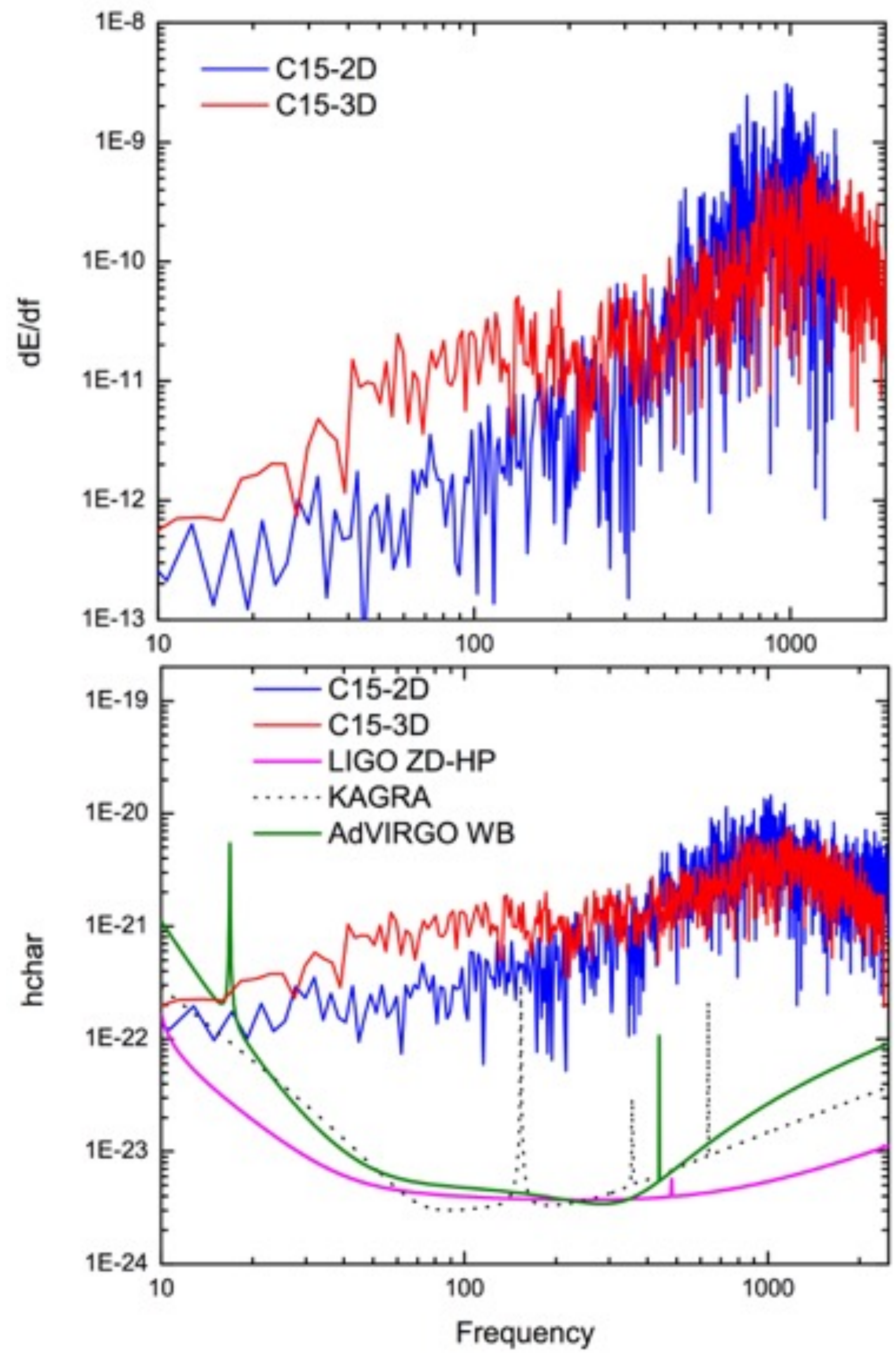
Gravitational Wave Signals: 2D vs. 3D





Yakunin et al. 2017, arXiv:1701.07325v1

But, see also Andresen et al. 2017 arXiv:1607.05199.

Summary

- **Modern multi-dimensional core-collapse supernova simulations with high-fidelity neutrino transport routinely explode.**
- **But, differences in:**
  - –2D vs 3D,
  - –the treatment of gravity,
  - –neutrino microphysics,
  - –and other effects (e.g. the level to which pre-shock flows are different from purely radial),

  can make qualitative and quantitative differences (including non-explosion).
- **Multi-D effects can modulate the neutrino signal in multiple flavors on 10 ms time scales.**
- **The ability to answer questions regarding collective flavor transformations with fully-integrated simulations will require methods and implementations for quantum transport.**
- **CCSNe simulations with high-fidelity neutrino transport necessarily cover the collapse and accretion epochs, extending little into the PNS cooling epoch.**
- **Neutrino emission and GW emission both occur in and above the outer precincts of the PNS during the explosion and post-explosion epochs, providing real multi-messenger correlation possibilities.**