Summary of the Astrophysics Session

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Equation of state

Equation of state

The nuclear equation of state should be stiff enough to support a star of 2 $M_\odot$ and have a small enough symmetry energy to give the star a radius of about 11-13 km. The vast majority of candidate EOSs do not meet these requirements, including one with a QCD phase change that would give a secondary neutrino burst. A notable exception is LS220. New equations of state are being released based on different calculational methods and using a range of nuclear species. At least one of these meets these requirements.

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Explosion mechanism

Equation of state

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Explosion mechanism

There is wide agreement that neutrino heating, aided by the stationary accretion shock instability (SASI) and convection, may well be able to revive the stalled shock. There remain differences over how long it takes to revive the shock, and whether the mechanism will prove more robust in 3D. Collective neutrino flavor mixing does not appear to affect the explosion mechanism.

Neutrino emission

Neutrino emission

Plots of neutrino luminosities and average energies have been produced by various groups. Differences in transport physics—including interactions, relativistic effects, and solver approximations—have noticeable effects.

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Neutrinos and nucleosynthesis

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Neutrinos and nucleosynthesis

Neutrinos affect nucleosynthesis by setting the neutron/proton ratio and by altering the numbers of free neutrons and protons available for capture by heavier nuclei. Recent simulations indicate that neutrinos produce a proton-rich environment that would rule out the *r* process but produce observationally feasible abundances of intermediate mass nuclei. If neutron-rich conditions somehow obtain, collective neutrino oscillations make things worse for the *r* process. Multi-angle calculations of collective oscillations are needed to get nucleosynthesis effects right because the radius at which flavor transformations occur matters; the single-angle approximation gets this wrong even if it gives decent answers at infinity.

From neutrino signal to astrophysics

From neutrino signal to astrophysics

Differences between nuclear equations of state may be detectable in Super-Kamiokande. The characteristic frequencies of the SASI may be extractable thanks to the time resolution of IceCube, provided the supernova is within 1-2 kpc.

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Explosion mechanism and some proto neutron star evolution (~10 seconds)

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Proto neutron star evolution (10s of seconds)

- Spherical symmetry, more heavily approximated multiphysics

Flavor mixing outside the proto neutron star (stationary)

Different types of simulations address the different phases of neutrino emission.

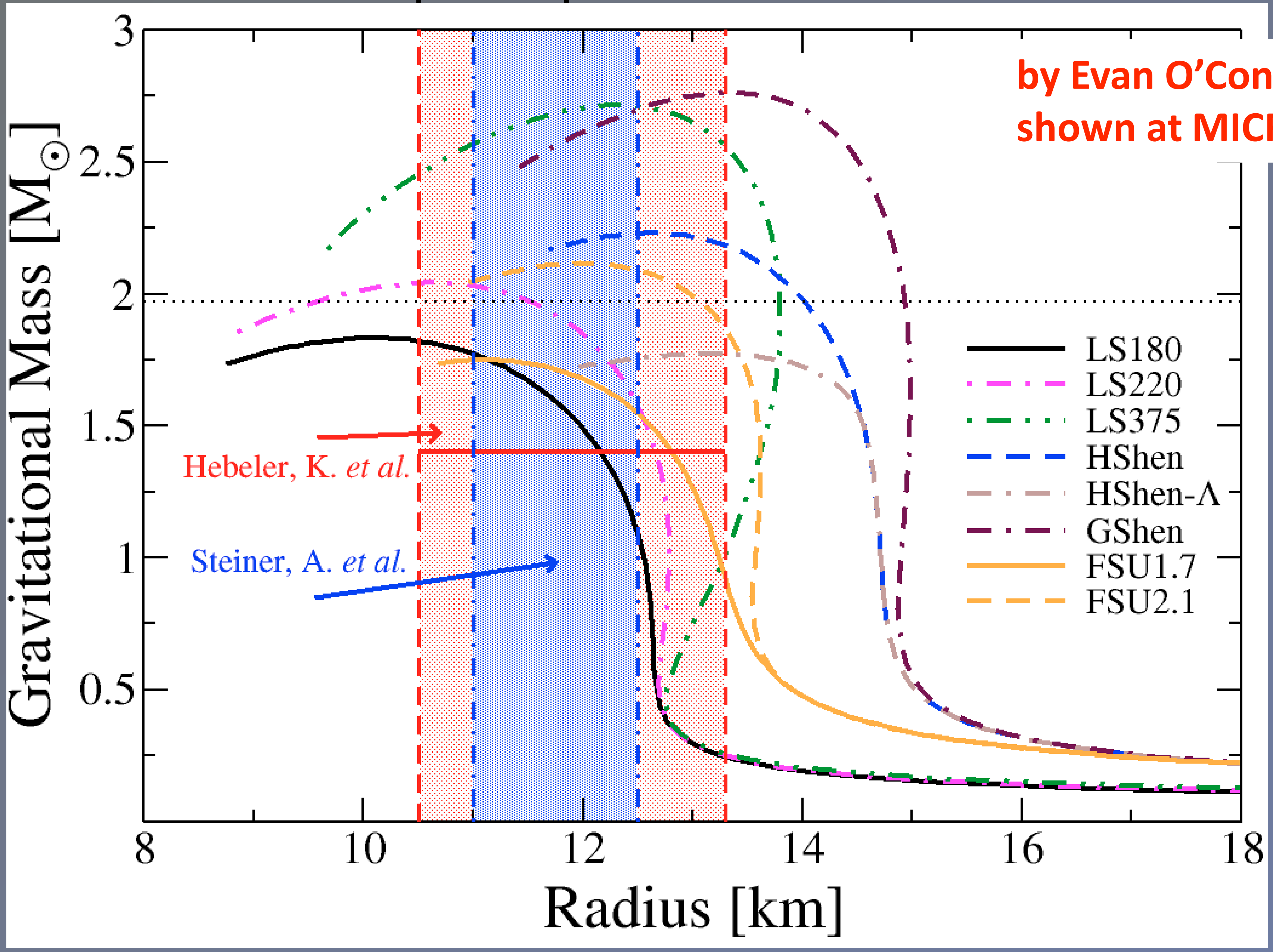
- Explosion mechanism (~1 second)
  - Multidimensional, multiphysics
- Explosion mechanism and some proto neutron star evolution (~10 seconds)
  - Spherical symmetry, multiphysics
- Proto neutron star evolution (10s of seconds)
  - Spherical symmetry, more heavily approximated multiphysics
- Flavor mixing outside the proto neutron star (stationary)
  - Spherical symmetry, neutrinos only, “free streaming” only; high resolution in neutrino energy and in rare cases angles

Equation of state

C. Ott

Constraints on the Nuclear EOS (5)

- Application to core-collapse supernova EOS:

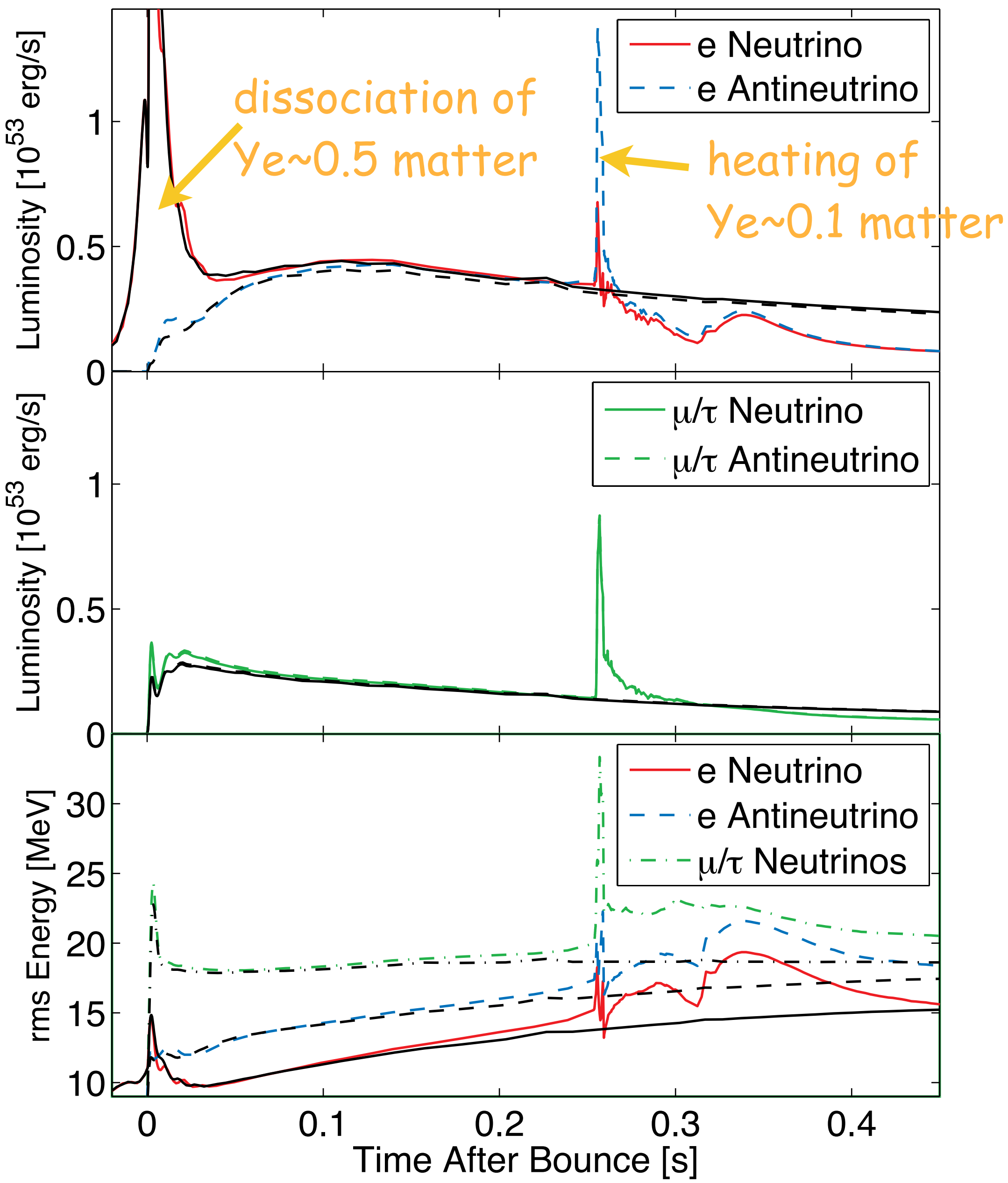


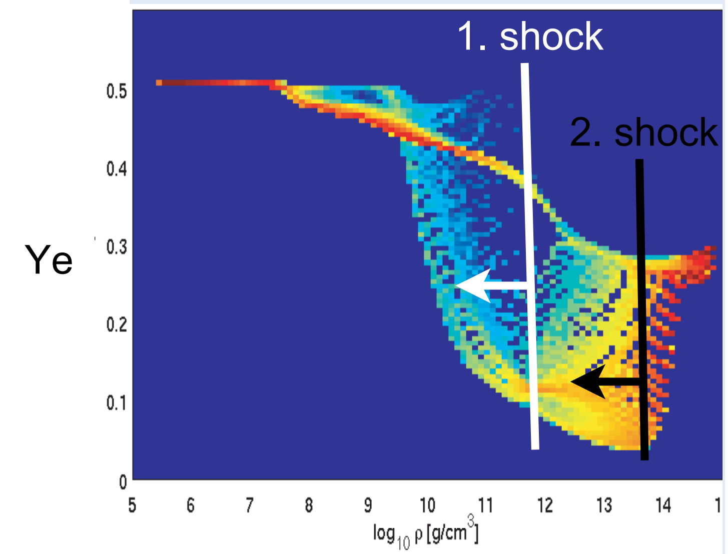
- **No CCSN EOS consistent with observations** (but true error bar uncertain)
- **LS220 only EOS consistent with theory; LS180 clearly ruled out.**

M. Liebendörfer

QCD phase transition induced explosions

UNI BASEL





- Second neutrino peak in all flavours, dominated by anti-ν's
- Step up in neutrino rms energies

(Sagert, Fischer et al., PRL 2009)

G. Shen

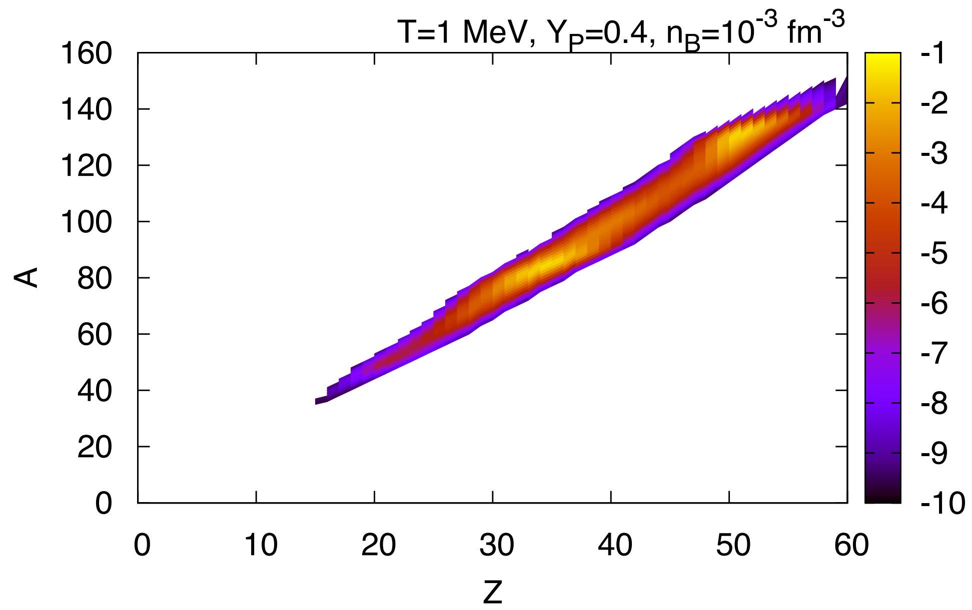
New Astrophysical Equations of State

- For simulations of supernovae, neutron star mergers, black hole formation...
- Cover density n, temperature T, and proton fraction Yp over large range (calculated at 180,000 points) $0<Yp<0.56$, $0<T<80$ MeV, $10^{-8}<n<1.6$ fm^{-3}.
- Almost all realistic SN simulations use
  - J.M. Lattimer, F.D. Swesty – liquid droplet model + skyrme force
  - H. Shen, H. Toki, K. Oyamatsu, K. Sumiyoshi - relativistic mean field model in Thomas-Fermi approximation and variational cal.
- Recently, nuclear statistical model + uniform matter at high density
  - M. Hempel, J. Schaffner-Bielich

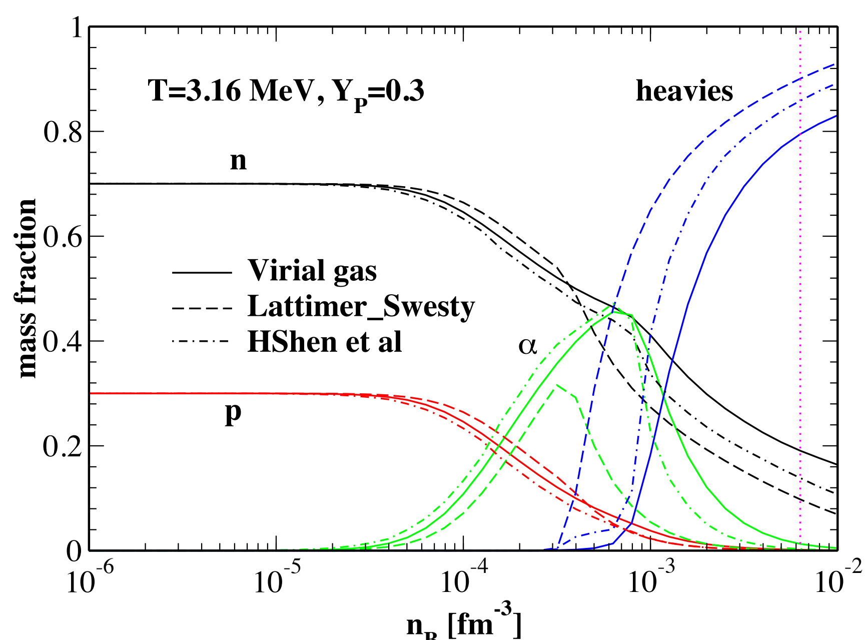
- Our EOSs use extensive relativistic mean field calculations at high densities and virial + nuclear statistical model at low densities.
  EOS tables at http://cecelia.physics.indiana.edu/gang_shen_eos/

G. Shen

Composition: nucleons, alphas, heavy nuclei



- The previous two EOS used single average nucleus approximation.
- In our EOS, mass distribution of heavy nuclei is often multi peaked Gaussian distribution.
- This may greatly influence the infall phase of supernova, particularly lepton capture rate: eg, Juodagalvis et al, 2010.



<-- Virial+ NSE | RMF -->

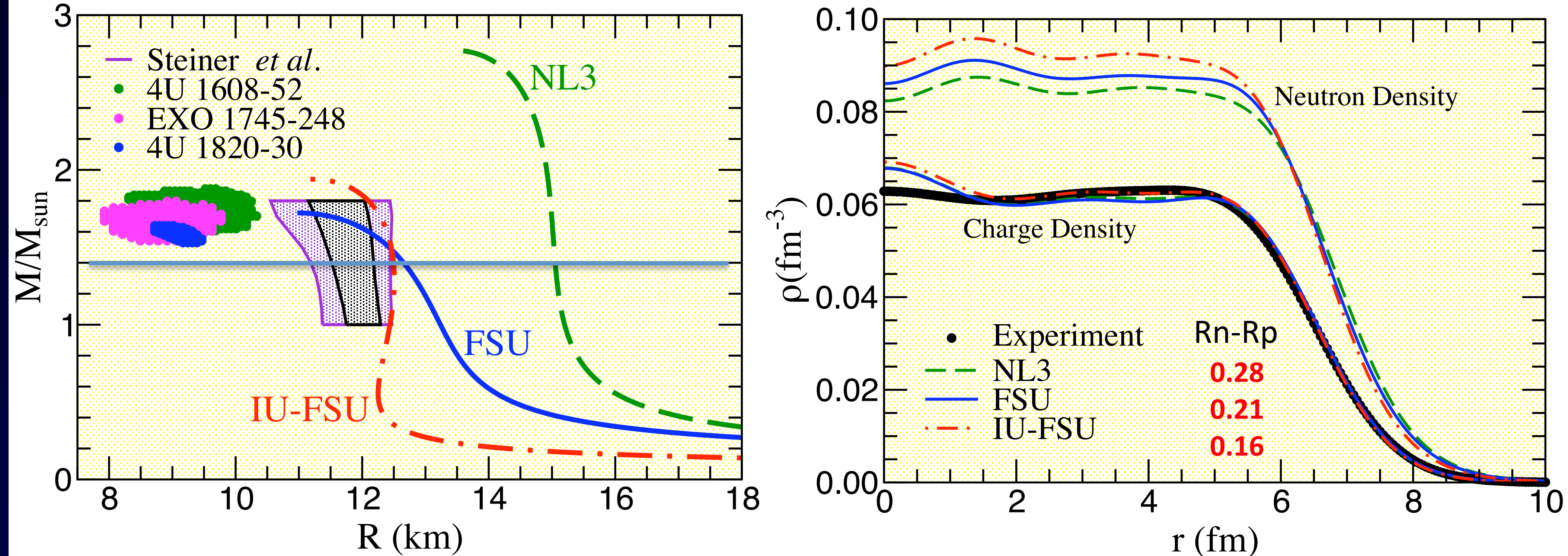
- Attractive interactions between alphas and nucleons increase mass fraction of alpha
- The change in composition may influence the position of neutrino sphere and neutrino spectrum,

  eg, Arcones et al, 2008

G. Shen

Models	NL3	FSUGold	IU-FSU
$n_0E'_{sym}(n_0)$ [MeV]	39.4	20.2	15.7

- Neutron star radius and neutron radius in Pb208



PREX: 1% in Rn

A larger $E'_{sym}(n_0)$ indicates a bigger radius for 1.4 solar mass neutron star and a bigger neutron radius in 208Pb.

Fattoyev, Horowitz, Piekarewicz, Shen (2010)

Explosion mechanism

C. Ott

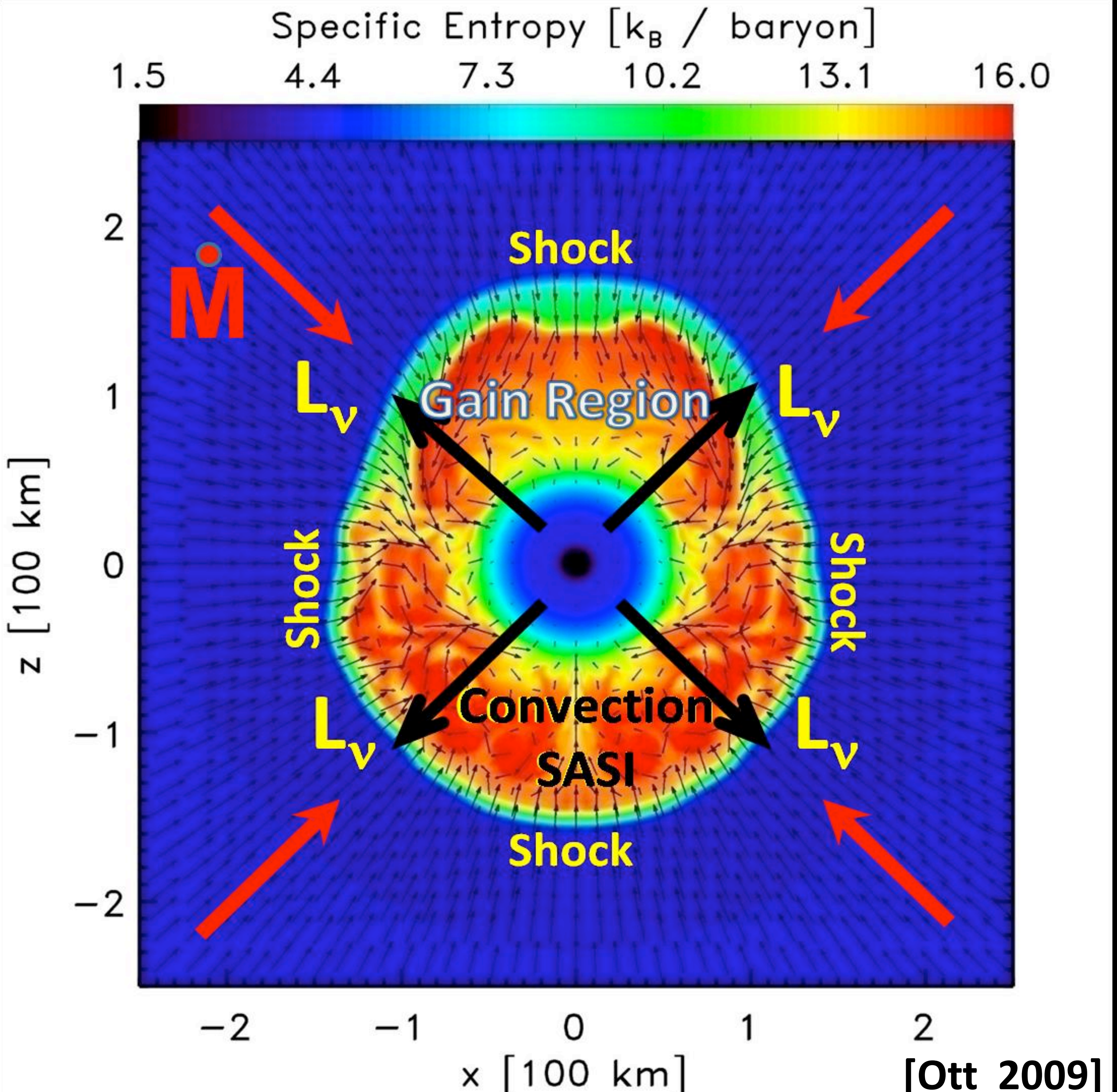
Some Recent Core-Collapse Supernova Models

Community Overview

- **MPA Garching**:
  Buras et al. '06ab, Kitaura et al. '06, Scheck et al. '06, '08, Marek et al. '09ab, Wongwathanarat et al. '10, Hüdepohl et al. '10, **B. Müller et al. '10,** E. Müller et al. '10, Obergaulinger & Janka '11
- **ORNL/Florida Atlantic**: Bruenn et al. '09, Yakunin et al. '10, Endeve et al. '10
- **Basel**:
  Liebendörfer et al. '09, Scheidegger et al. '10, Fischer et al. '09, Sagert et al. '09, Fischer et al. '10, Kaeppeli et al. '09
- **LANL**: Fryer & Young '07, Fryer & Warren '02, '04
- **Princeton/Jerusalem/Caltech**:
  Burrows et al. '06, '07ab, Livne et al. '04,'07, Dessart et al. '06ab,'07,'08 Ott et al. '06, '08, Murphy & Burrows '08, Nordhaus et al. '10, Brandt et al. '11
- **Princeton/LBNL**: Nordhaus et al. '10, Rantsiou et al. '11
- **Tokyo**:
  Kotake et al. '11, Suwa et al. '10, '11, Takiwaki et al. '09, Iwakami et al. '08,'09
- **Kyoto**: Shibata et al. '06, Sekiguchi et al. '10ab, '11
- **Caltech**: Dasgupta et al. '11, O'Connor & Ott '10,'11, Ott et al. '11

C. Ott

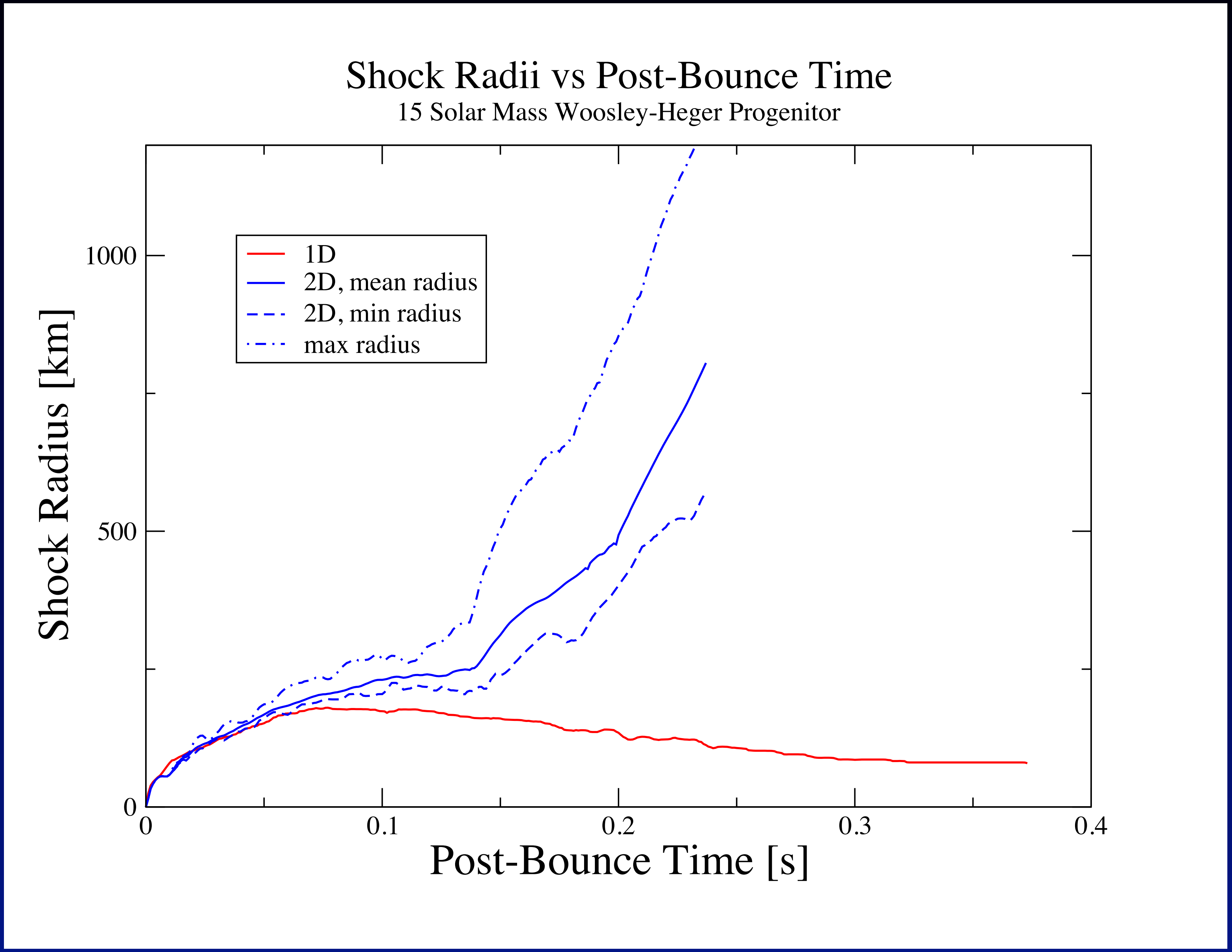
Neutrino Mechanism



[Ott 2009]

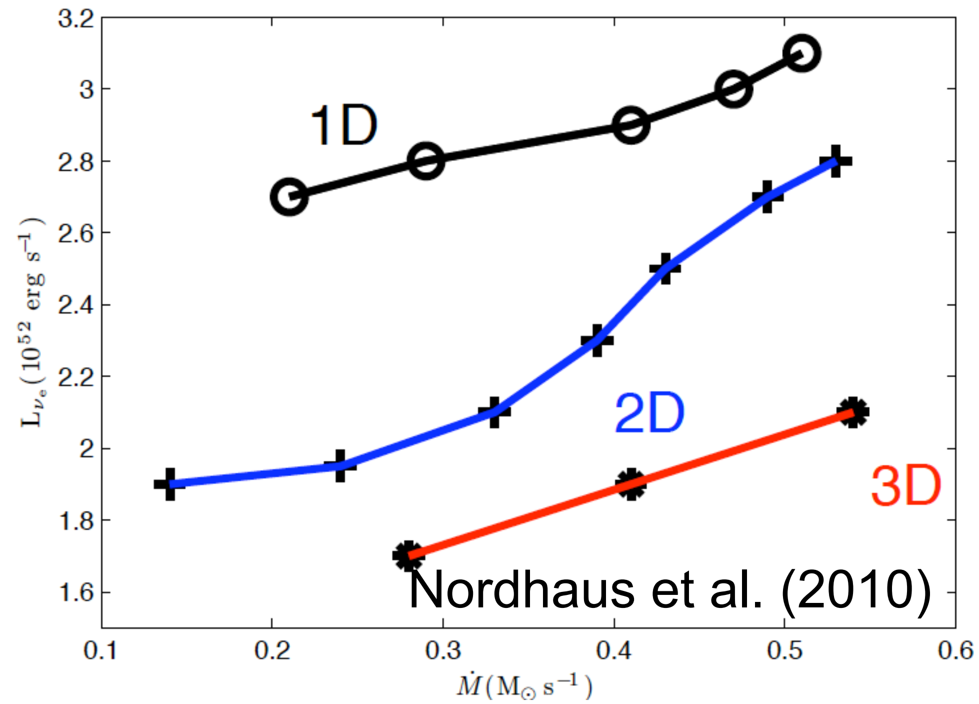
S. Bruenn

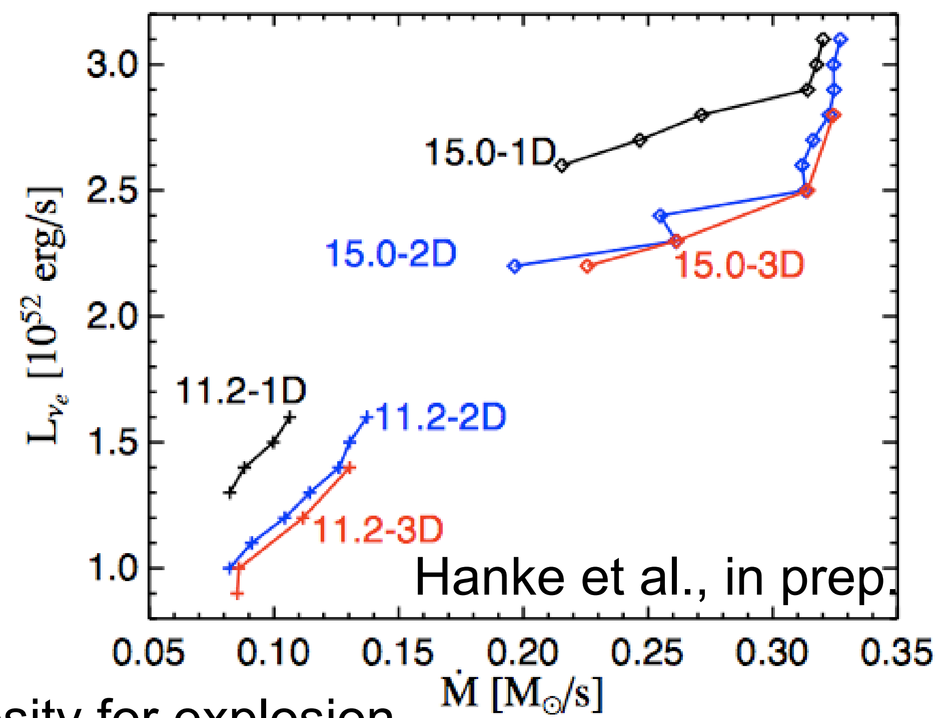
Shock Radii: 1D vs 2D



B. Müller

Outlook





"Critical" luminosity for explosion

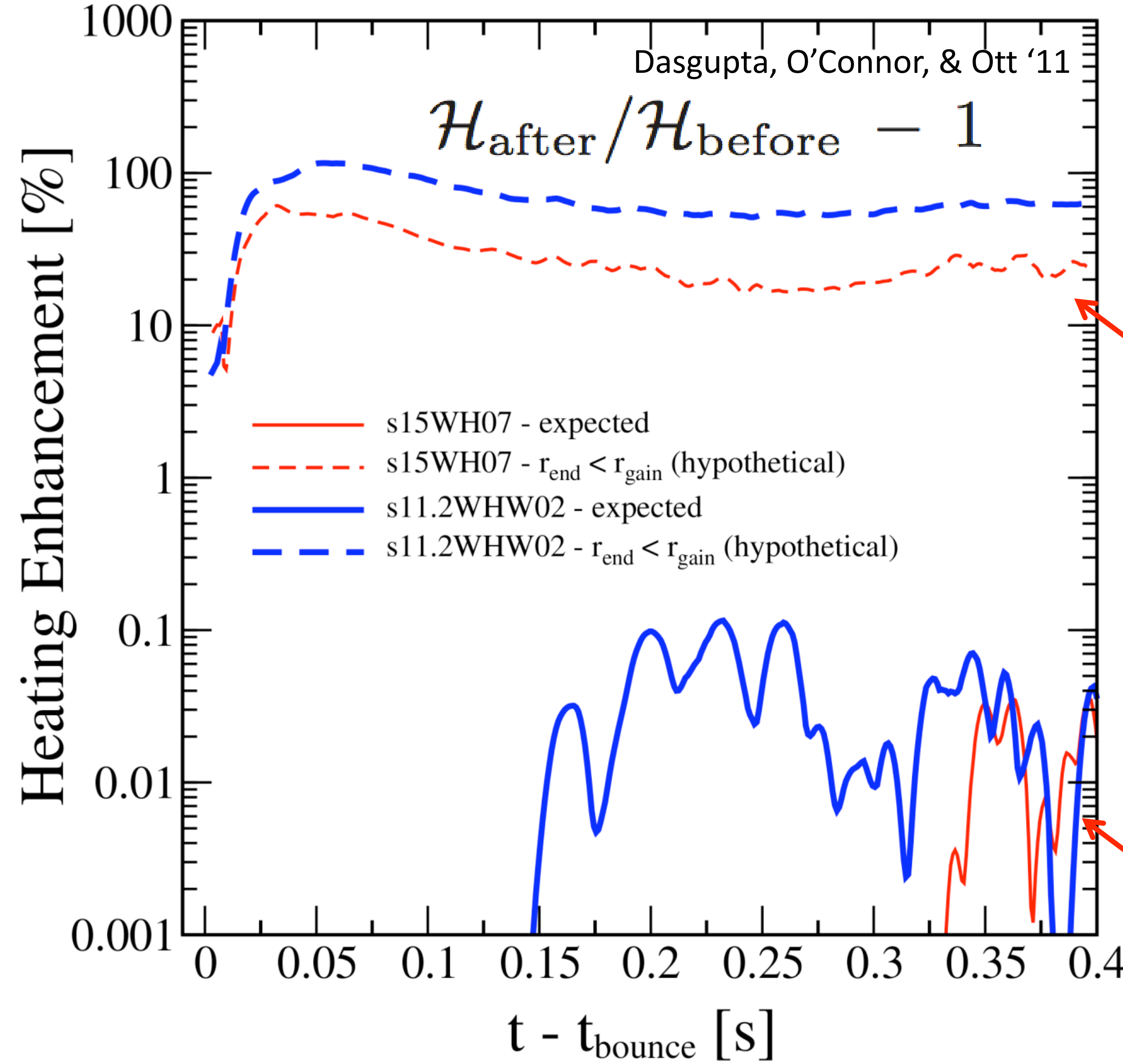
- Non-spherical motion of matter & anisotropic neutrino emission intimately tied to model dynamics (time of explosion, strength of SASI & convection)
- SASI (presence of sloshing or spiral mode) & convection in turn possibly strongly dependent on heating conditions, neutron star compactness, etc.
- Impact of dimensionality (3D vs. 2D) not yet well understood
- Self-consistent 3D simulations required!

C. Ott

Heating Enhancement

[work with Basudeb Dasgupta and Evan O'Connor, arXiv:1106.1167]

Progenitors:
11.2 M_{Sun}
15 M_{Sun}
Woosley et al. '02



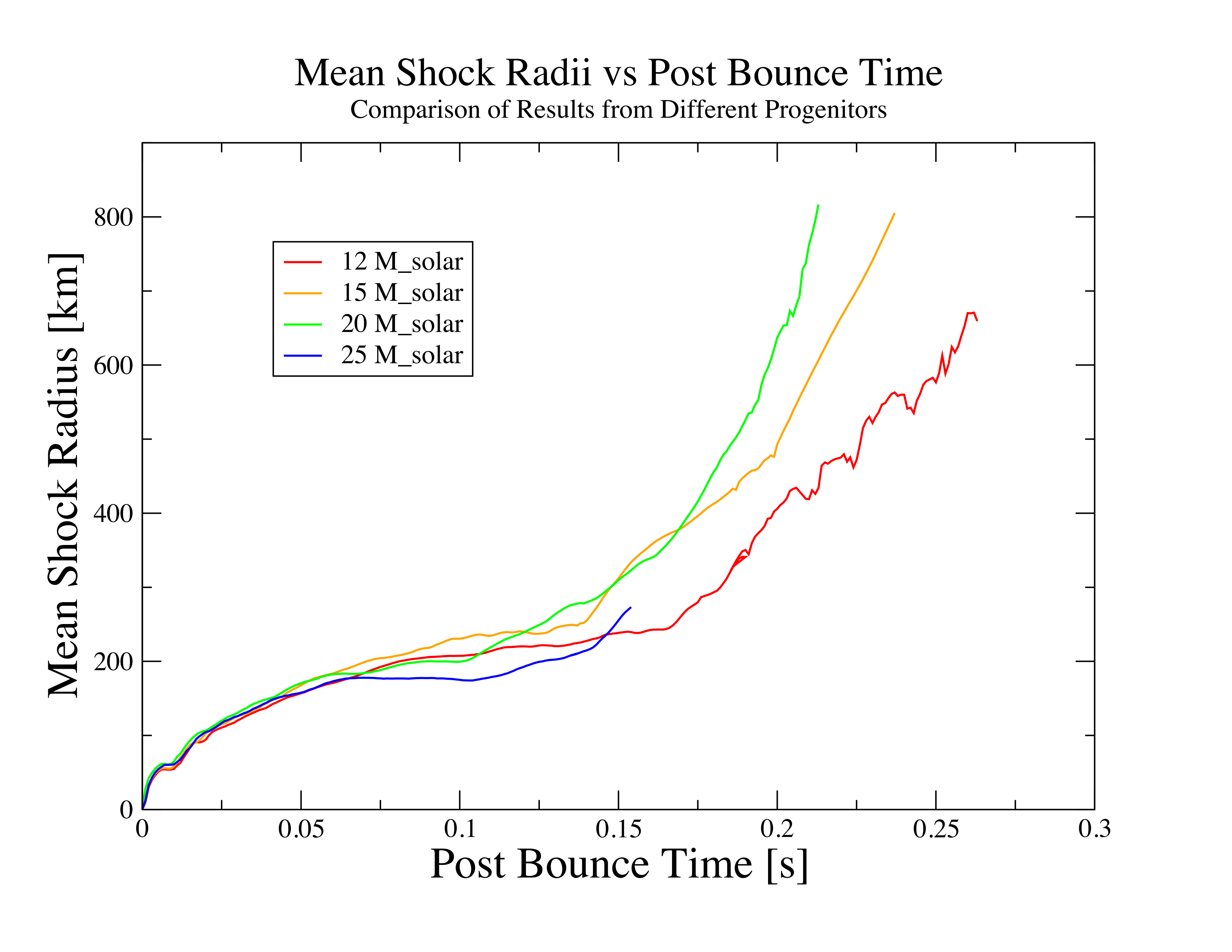
most optimistic guess

results from actual calculations

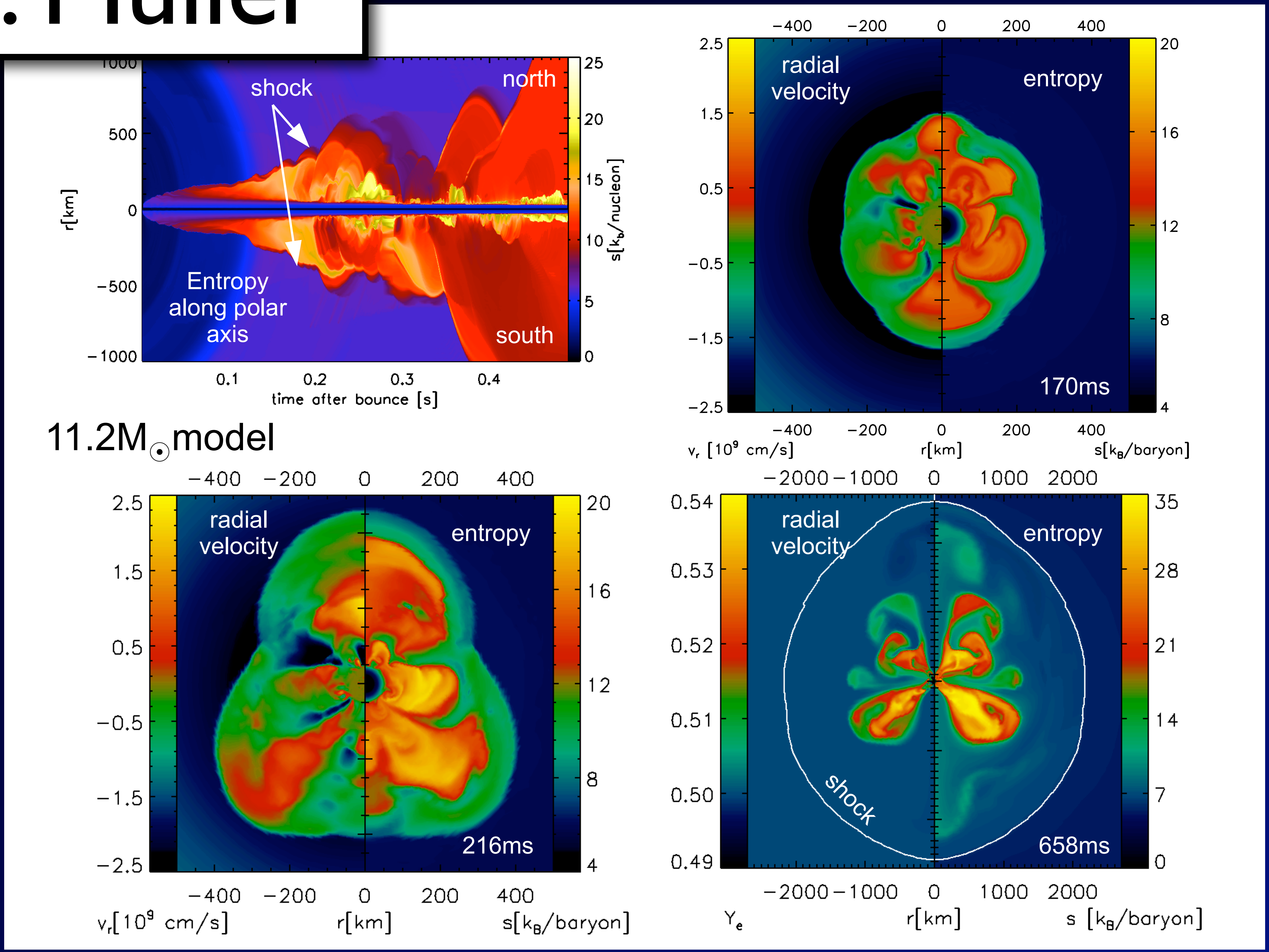
See also
Suwa et al. '11

S. Bruenn

Shock Radii vs Time from Different Progenitors

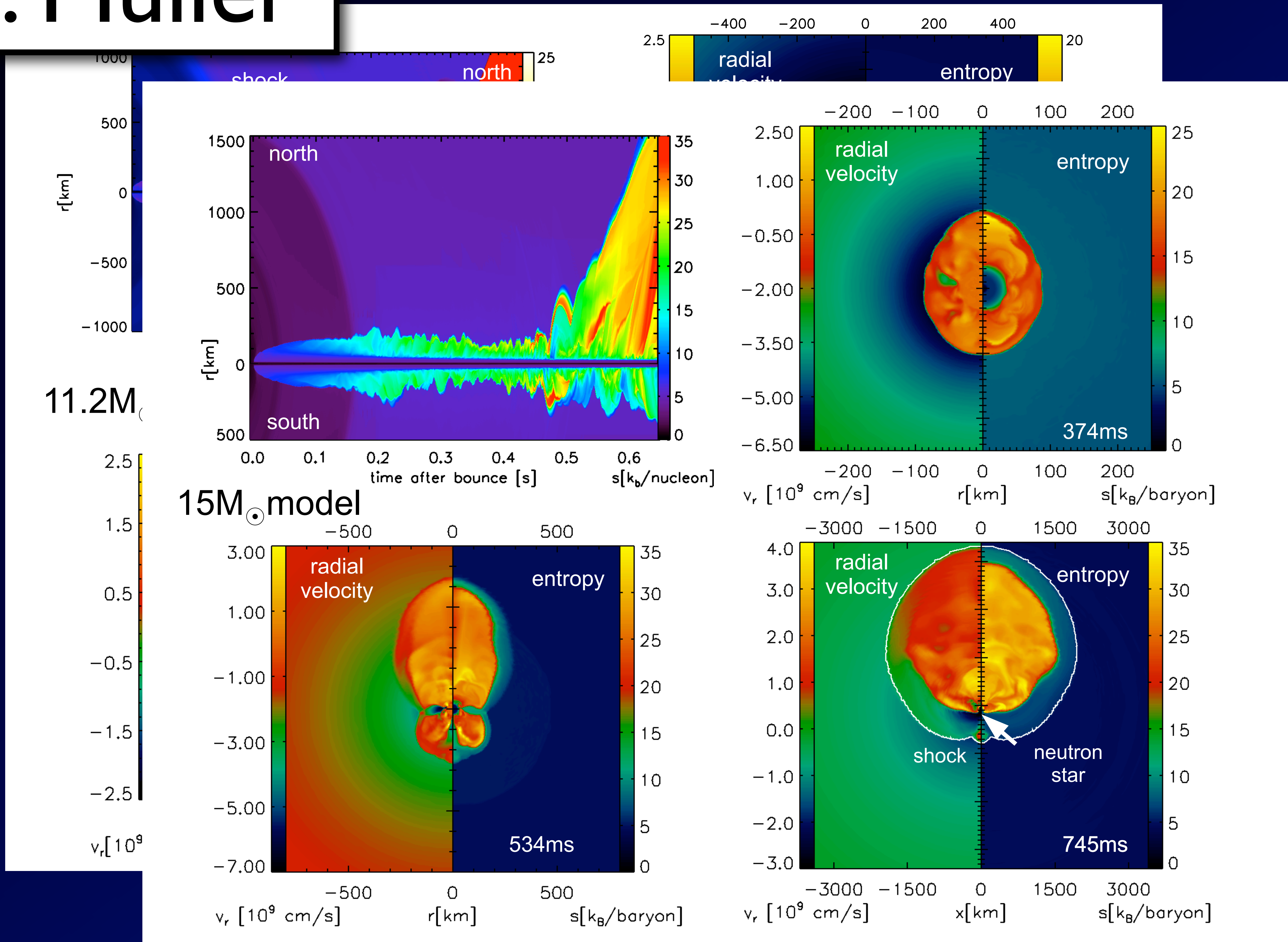


B. Müller



11.2M$_\odot$ model

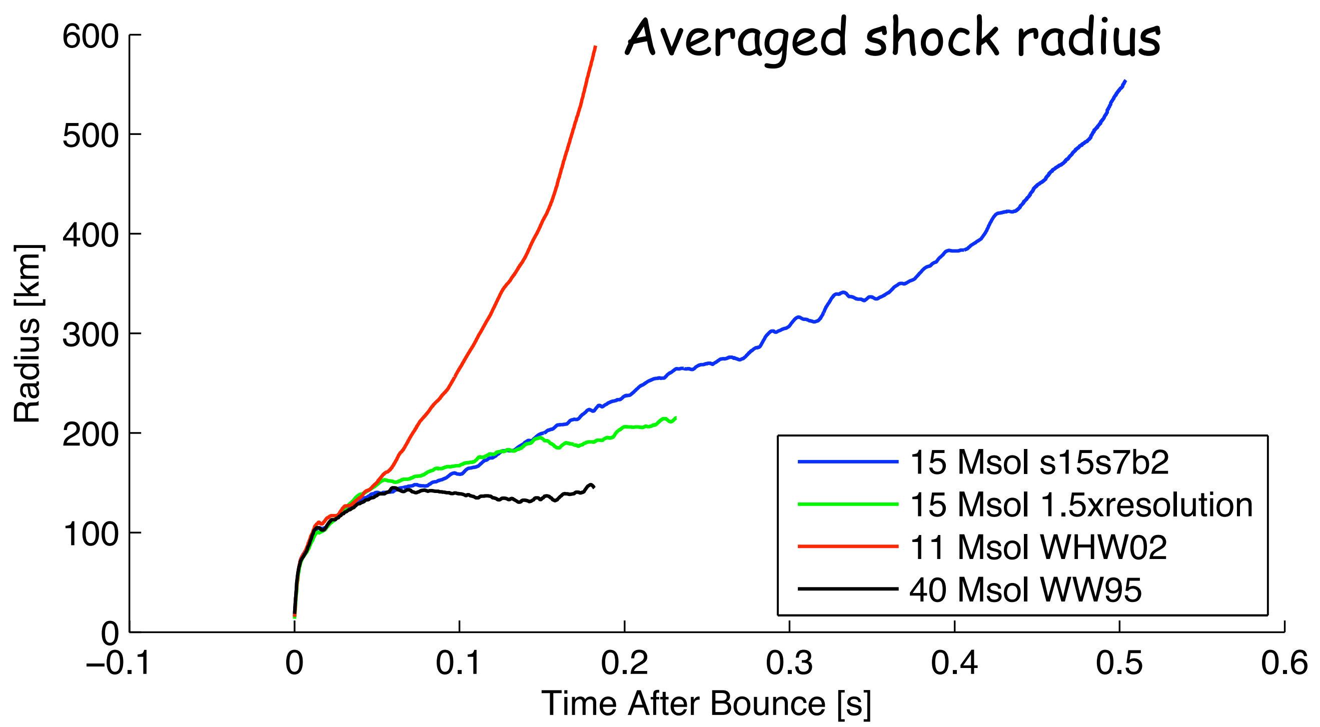
B. Müller



11.2M
15M$_\odot$ model
north
south
r[km]
time after bounce [s]
s[k_b/nucleon]
radial velocity
entropy
374ms
534ms
745ms
shock
neutron star
v_r [10^9 cm/s]
r[km]
x[km]
s[k_B/baryon]

M. Liebendörfer

3D supernova model with IDSA



• The 11 solar mass progenitor run shows positive velocities and produces an explosion

• The 15 solar mass progenitor has not (yet) developed positive velocities, even if the shock radius increases.

Runs more optimistic than (Marek & Janka 2009) 2D models.

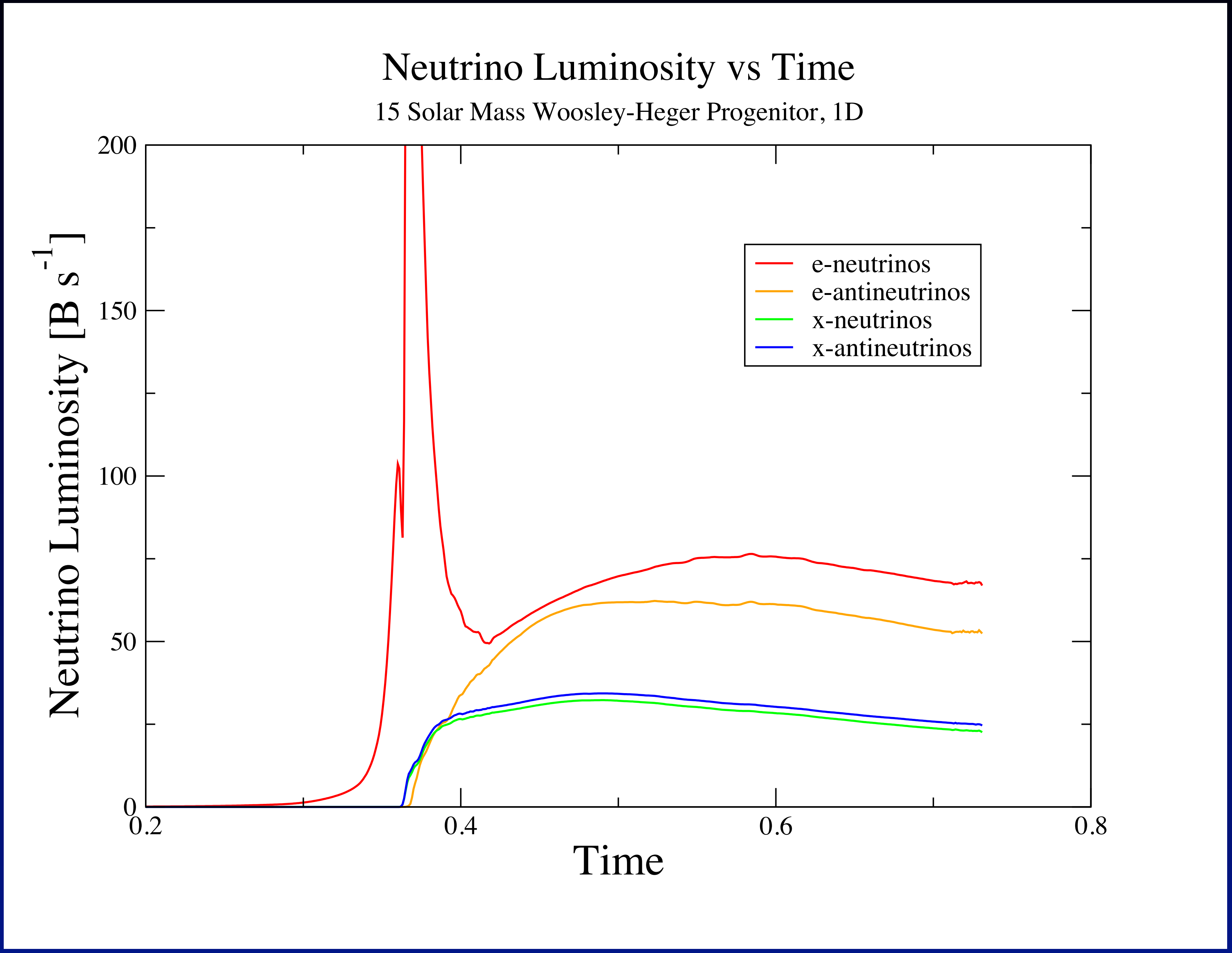
Runs more pessimistic than (Hix et al. 2010) 2D models.

Convergence test: blue run perhaps still too optimistic?

Neutrino emission

S. Bruenn

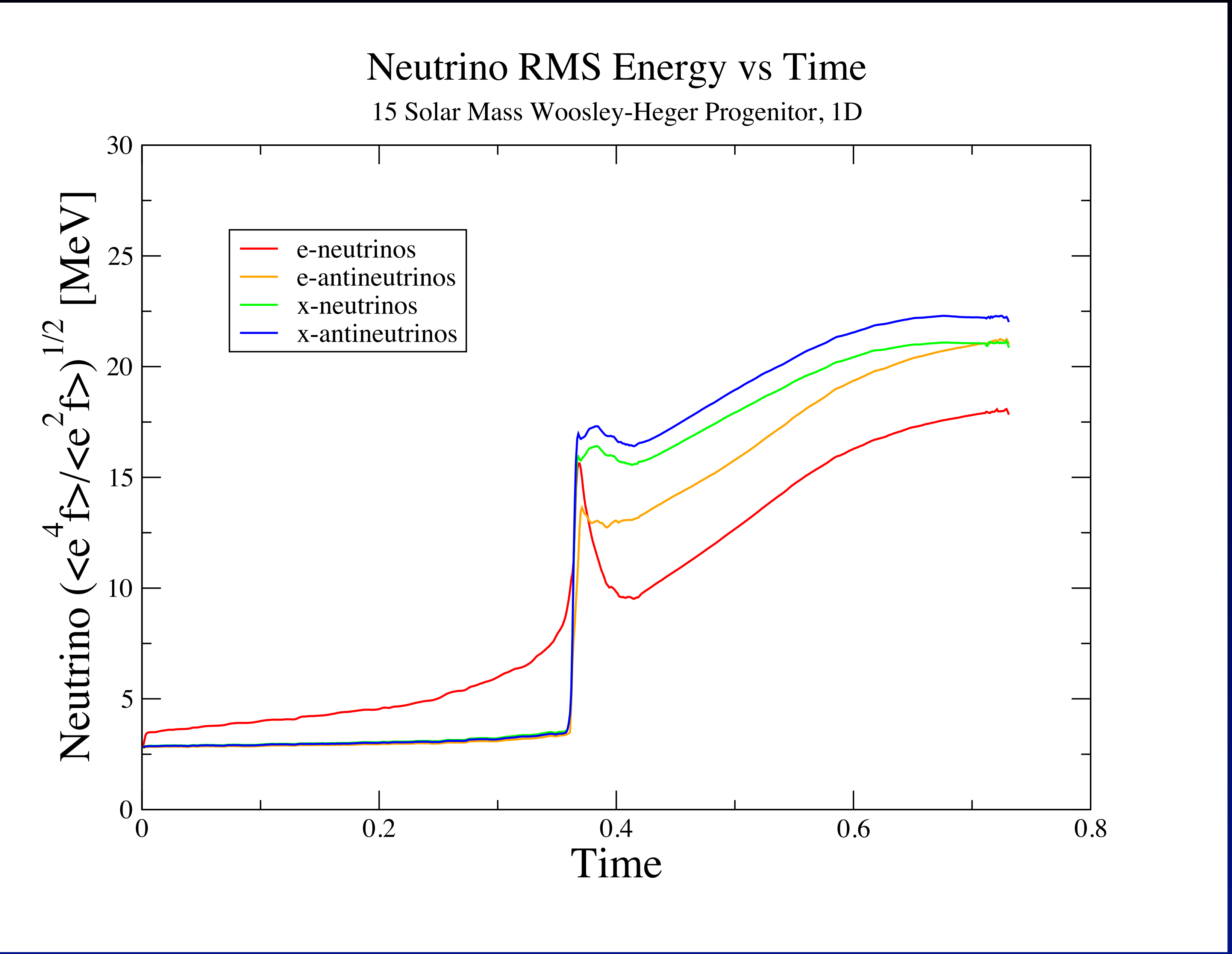
Neutrino Luminosities



S. Bruenn

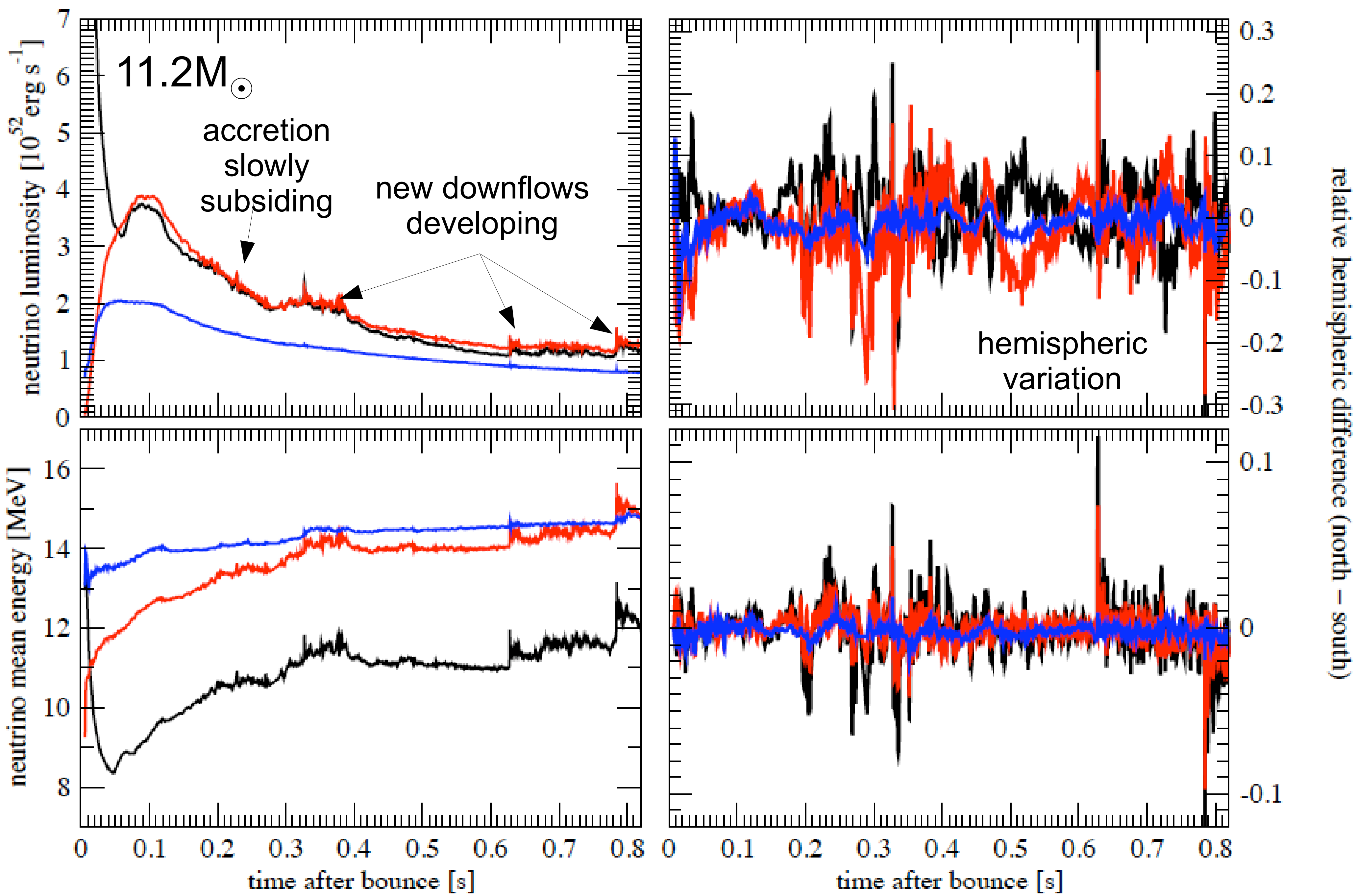
Neutrino Luminosities

Neutrino RMS Energies $(\langle \epsilon^4 f \rangle / \langle \epsilon^2 f \rangle)^{1/2}$



B. Müller

Translating the dynamics into the ν-signal



B. Müller

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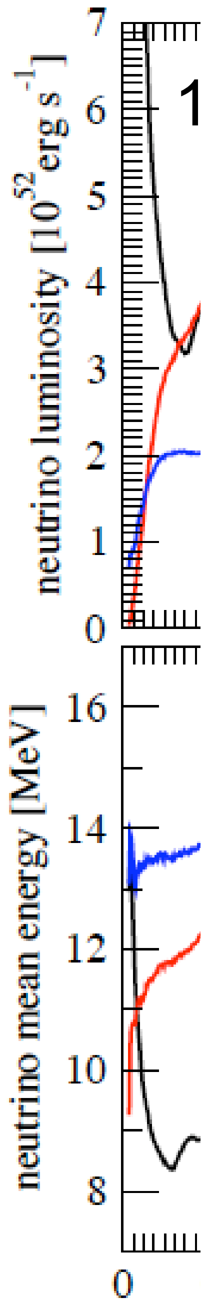

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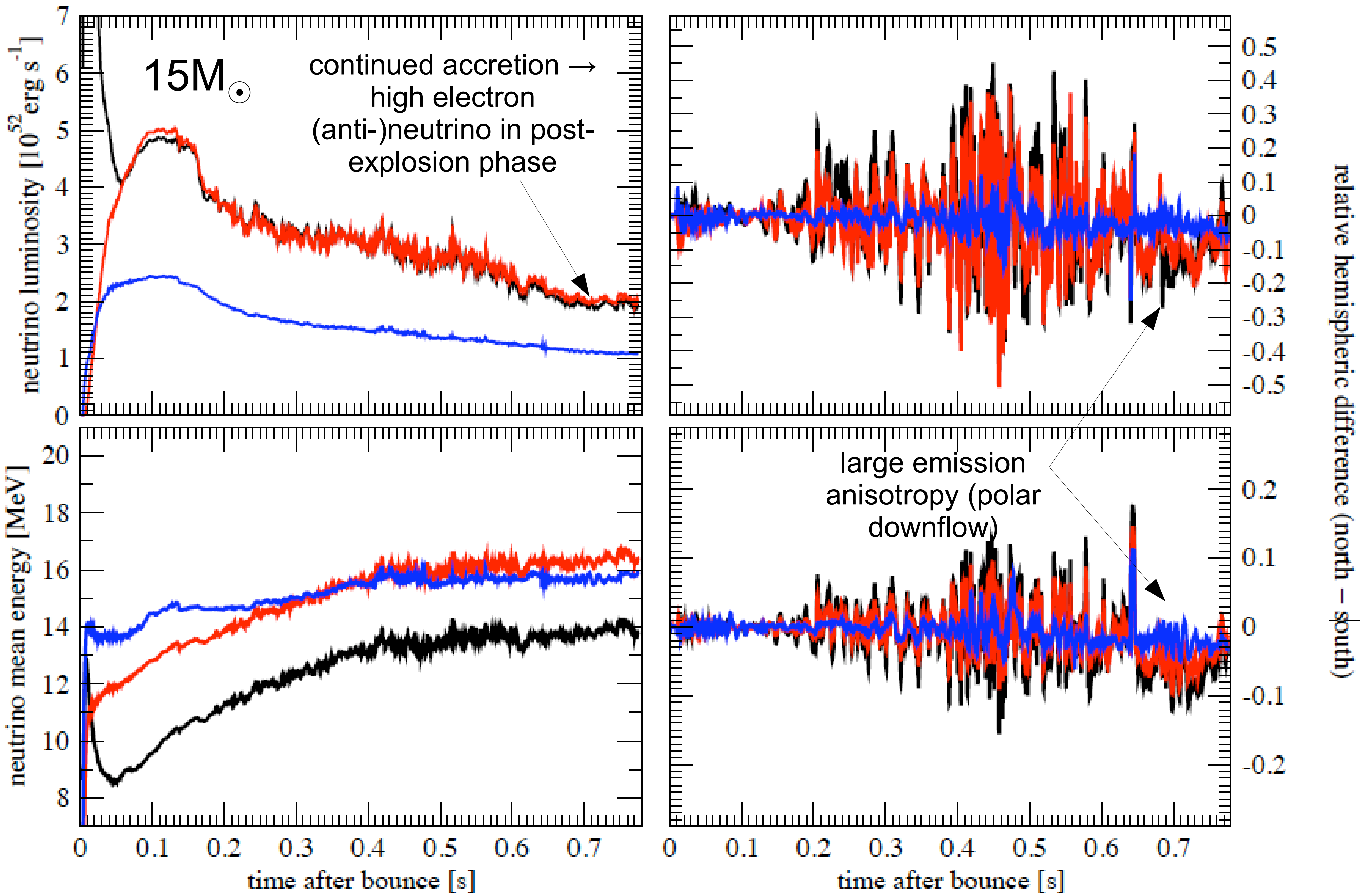
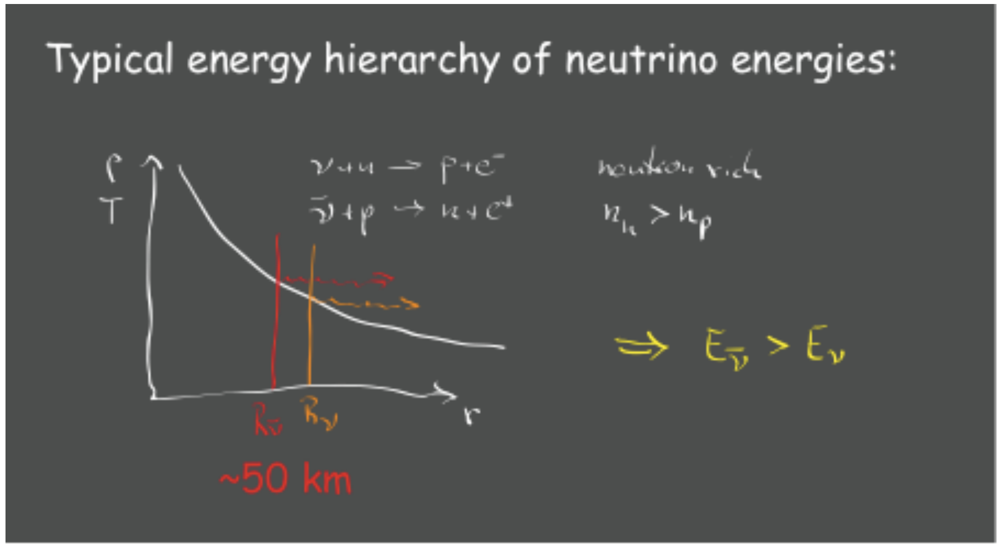
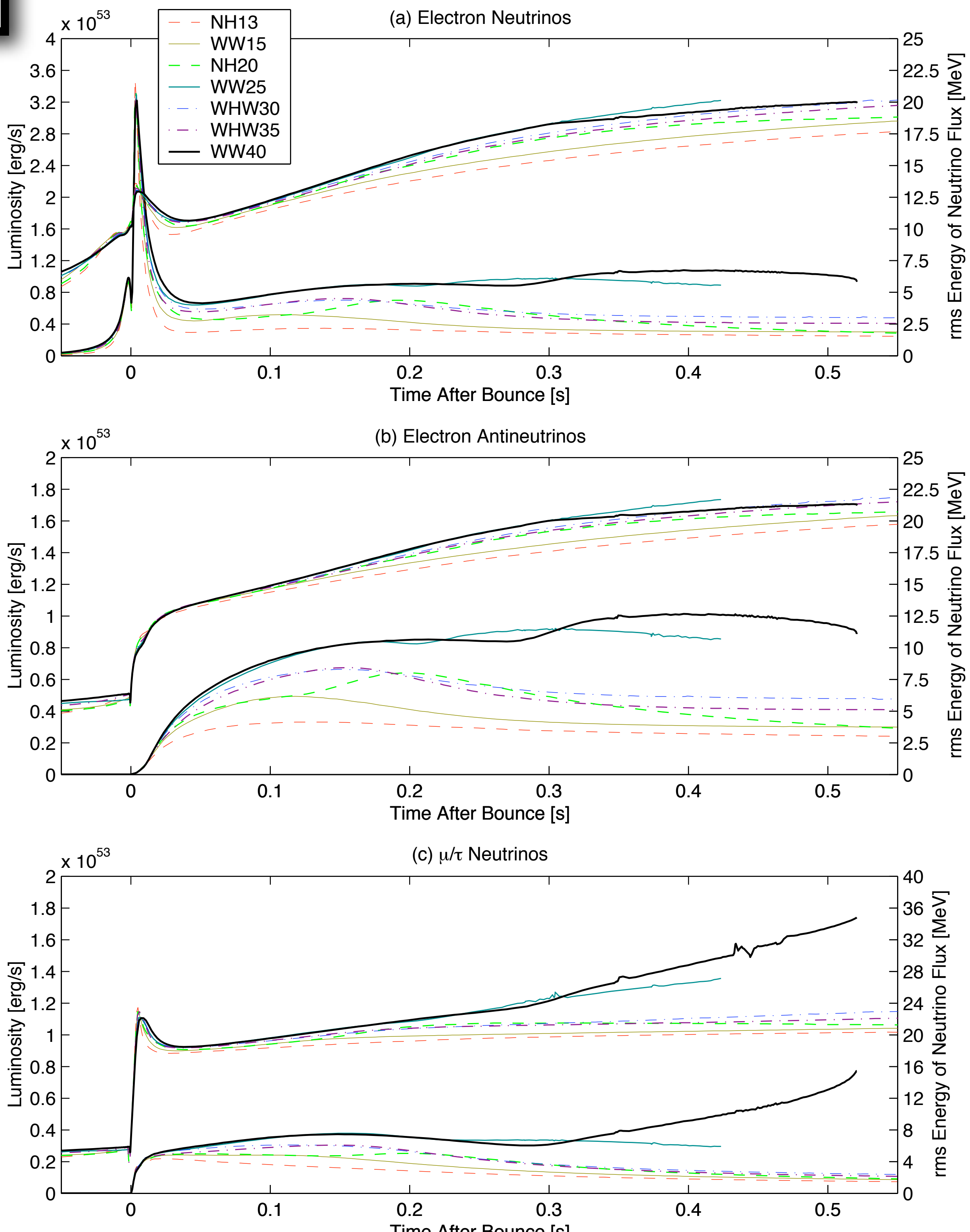


M. Liebendörfer

Neutrinos from the postbounce phase

The neutrino luminosities reflect the accretion rate and the thermodynamic conditions at the neutrinospheres

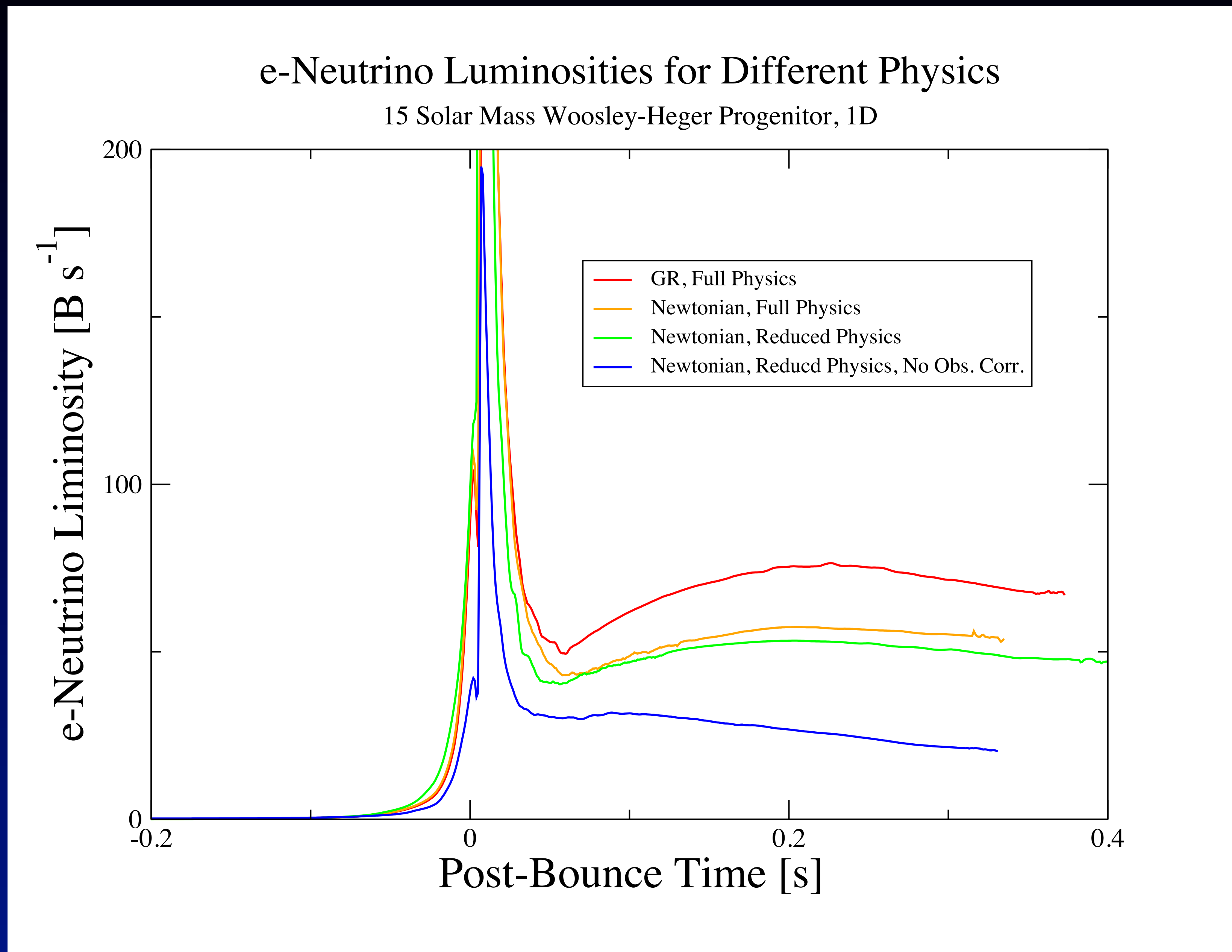




(Liebendörfer et al. 2003)

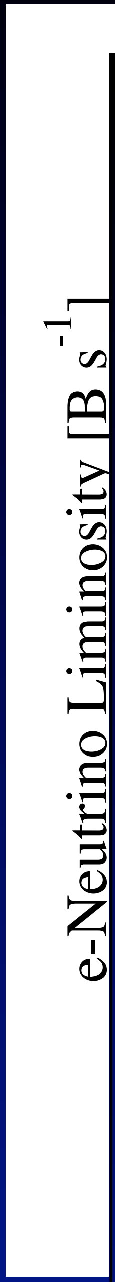
S. Bruenn

ino Luminosities, Effect of Included Physics

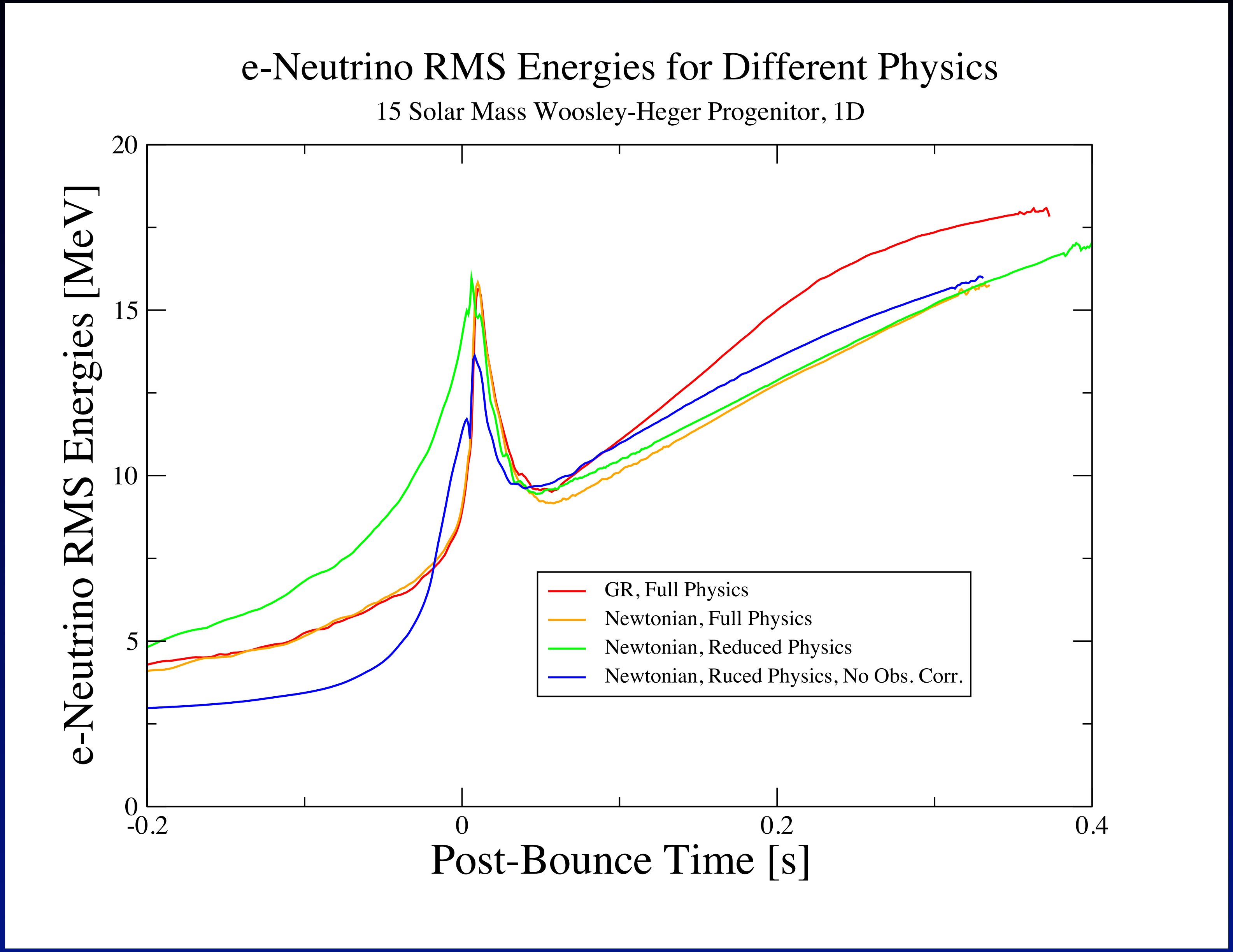


S. Bruenn

...rino Luminosities, Effect of Included Physics

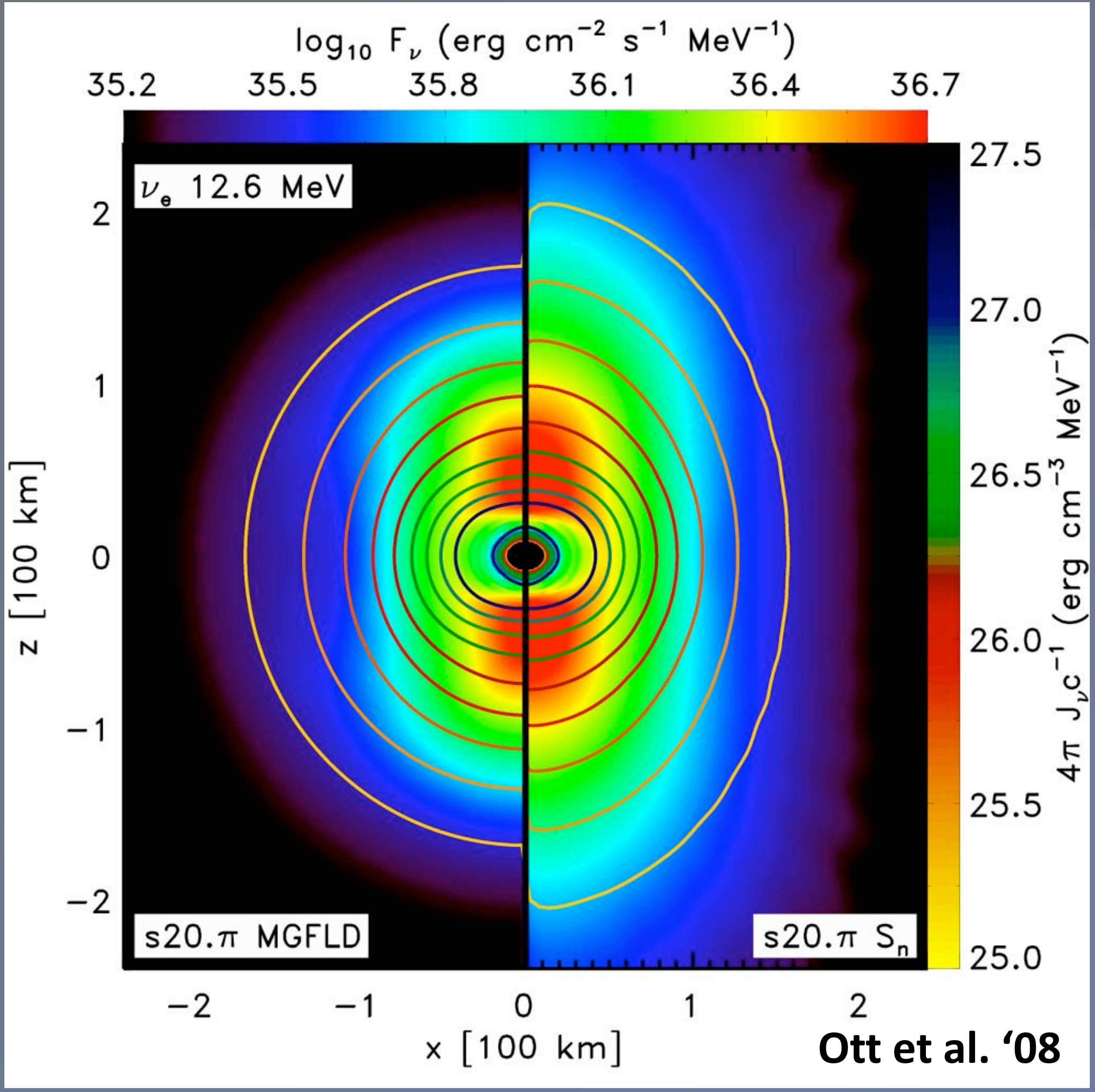


Neutrino RMS Energies ($\langle\epsilon^4 f\rangle/\langle\epsilon^2 f\rangle)^{1/2}$, Effect of Included Physics



C. Ott

Why do we care? (2)



Ott et al. '08

- Here: Radiation field asymmetries due to rotation.

Neutrinos and nucleosynthesis

R. Surman

stages of heavy element synthesis | impact of ν

(1) free neutrons and protons

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

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

ν can set the neutron to proton ratio, n/p

n/p determines the subsequent nucleosynthesis

(2) assembly of alpha particles

$$p,\ n \rightarrow \alpha\text{'s} + \text{excess } p \text{ or } n$$

(3) assembly of seed nuclei

$$\alpha\text{'s} + \text{excess } p \text{ or } n \rightarrow \text{iron peak nuclei} + \text{remaining } p \text{ or } n$$

(4) free nucleon capture on seeds

$$\text{iron peak nuclei} + \text{remaining } p \text{ or } n \rightarrow \text{heavy nuclei}$$

R. Surman

stages of heavy element synthesis | impact of ν

(1) free neutrons and protons

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

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

(2) assembly of alpha particles

$$p,\ n \rightarrow \alpha\text{'s} + \text{excess } p \text{ or } n$$

ν can continue to convert the excess *p* or *n*

this alters the free nucleons available for capture onto seeds

(3) assembly of seed nuclei

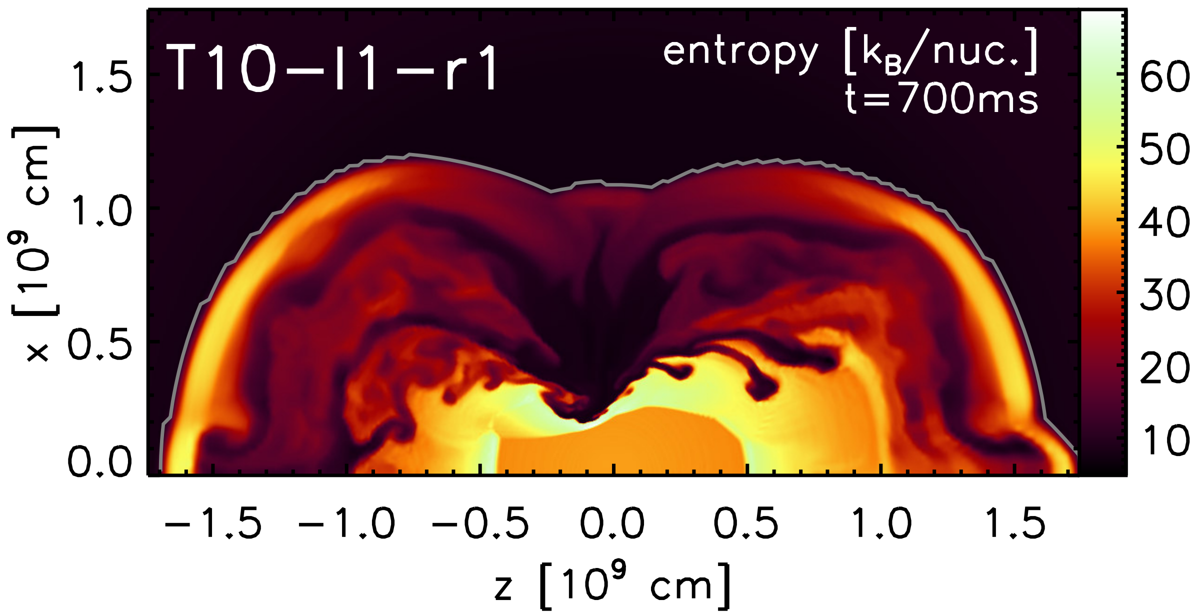
$$\alpha\text{'s} + \text{excess } p \text{ or } n \rightarrow \text{iron peak nuclei} + \text{remaining } p \text{ or } n$$

(4) free nucleon capture on seeds

$$\text{iron peak nuclei} + \text{remaining } p \text{ or } n \rightarrow \text{heavy nuclei}$$

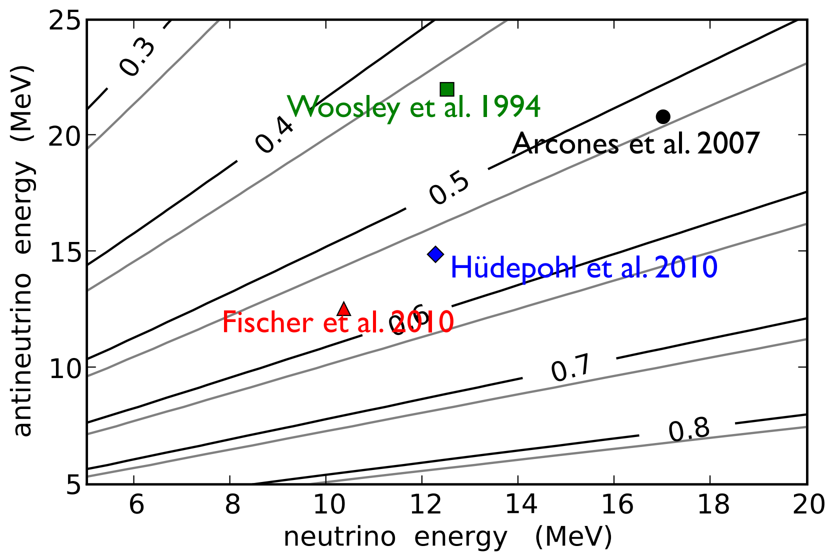
A. Arcones

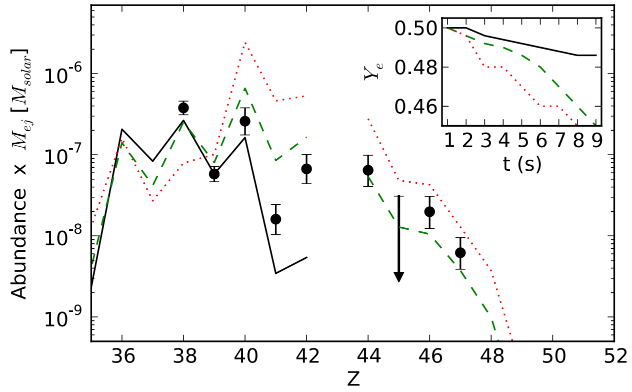
Conclusions



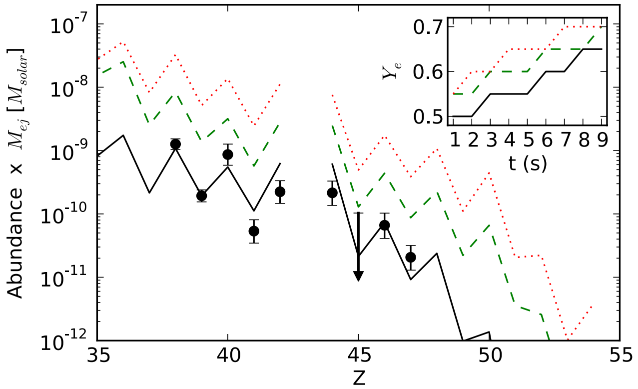
Neutrino-driven wind:
- no r-process,
- lighter heavy elements (Sr,Y,Zr)
- nucleosynthesis depends on Y_e

Uncertainties on neutrino spectra and Y_e





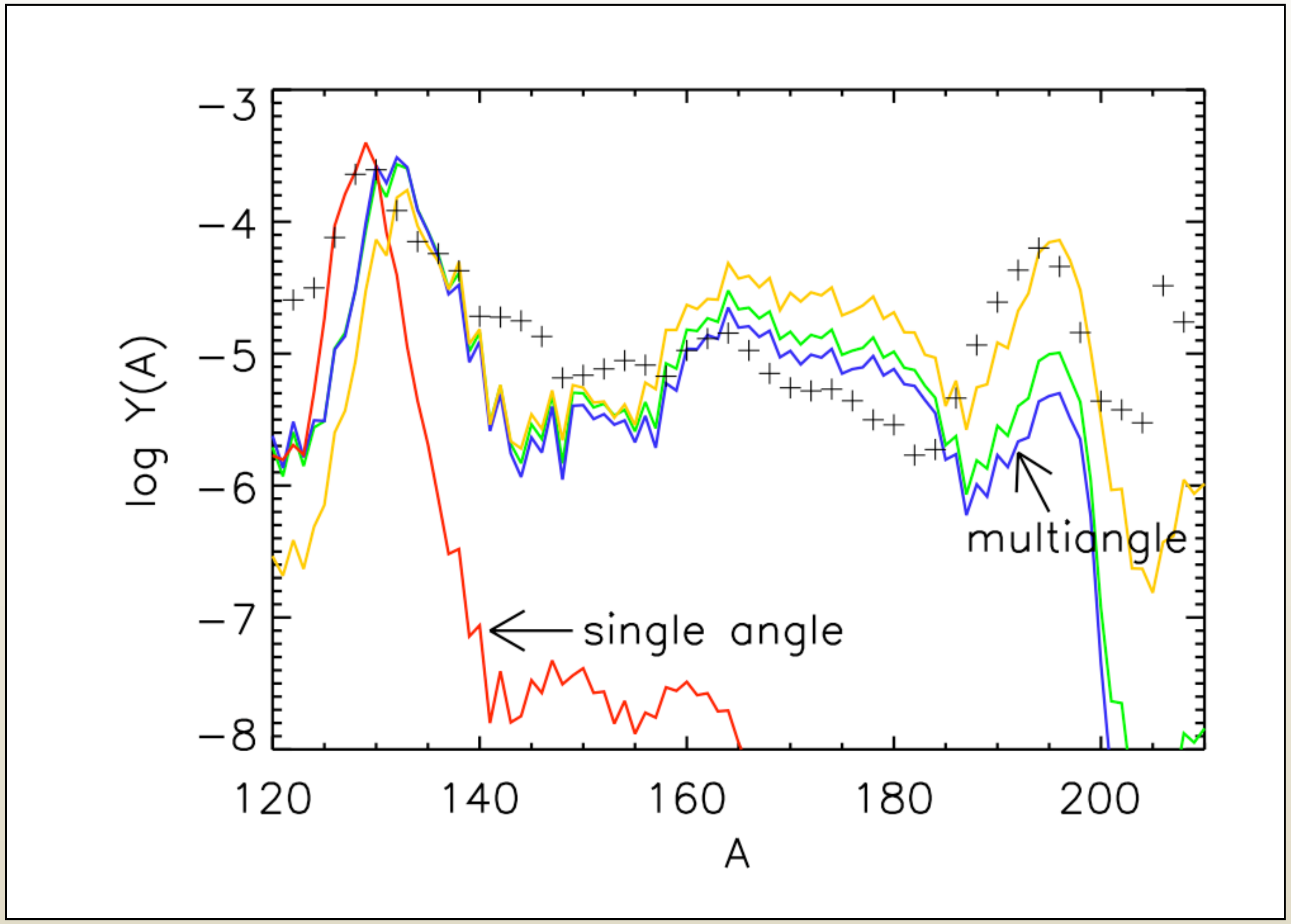
neutron rich



proton rich

R. Surman

a full neutrino oscillation + *r*-process calculation



No ν for $T_9 < 9$

No oscillations

Multiangle ν oscillation calculation

Single angle ν oscillation calculation

$s/k = 200$

$\tau = 18$ ms

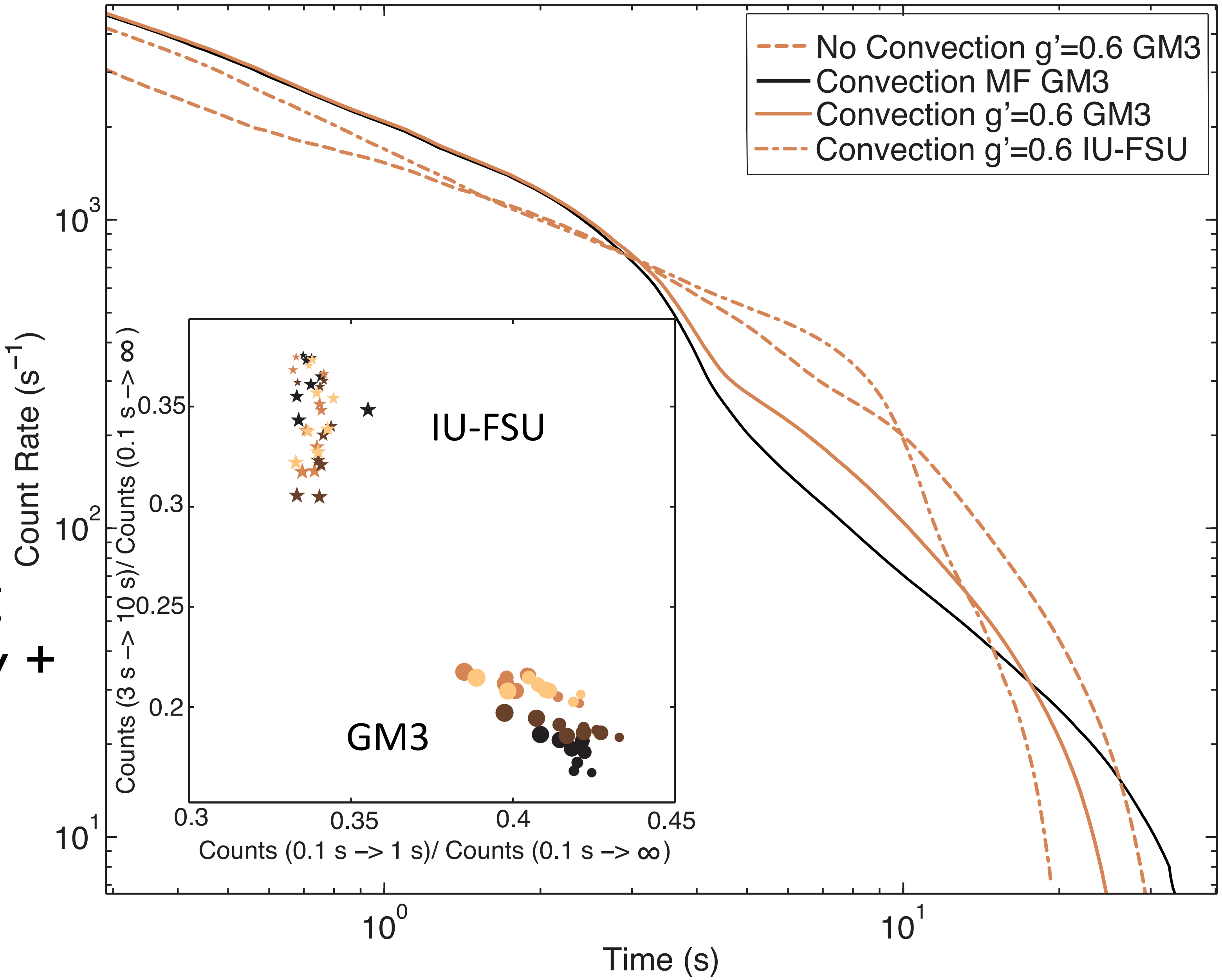
Duan, Friedland, McLaughlin, & Surman, J Phys G, 38, 035201 (2011)

From neutrino signal to astrophysics

G. Shen

Observable signatures of convective transport

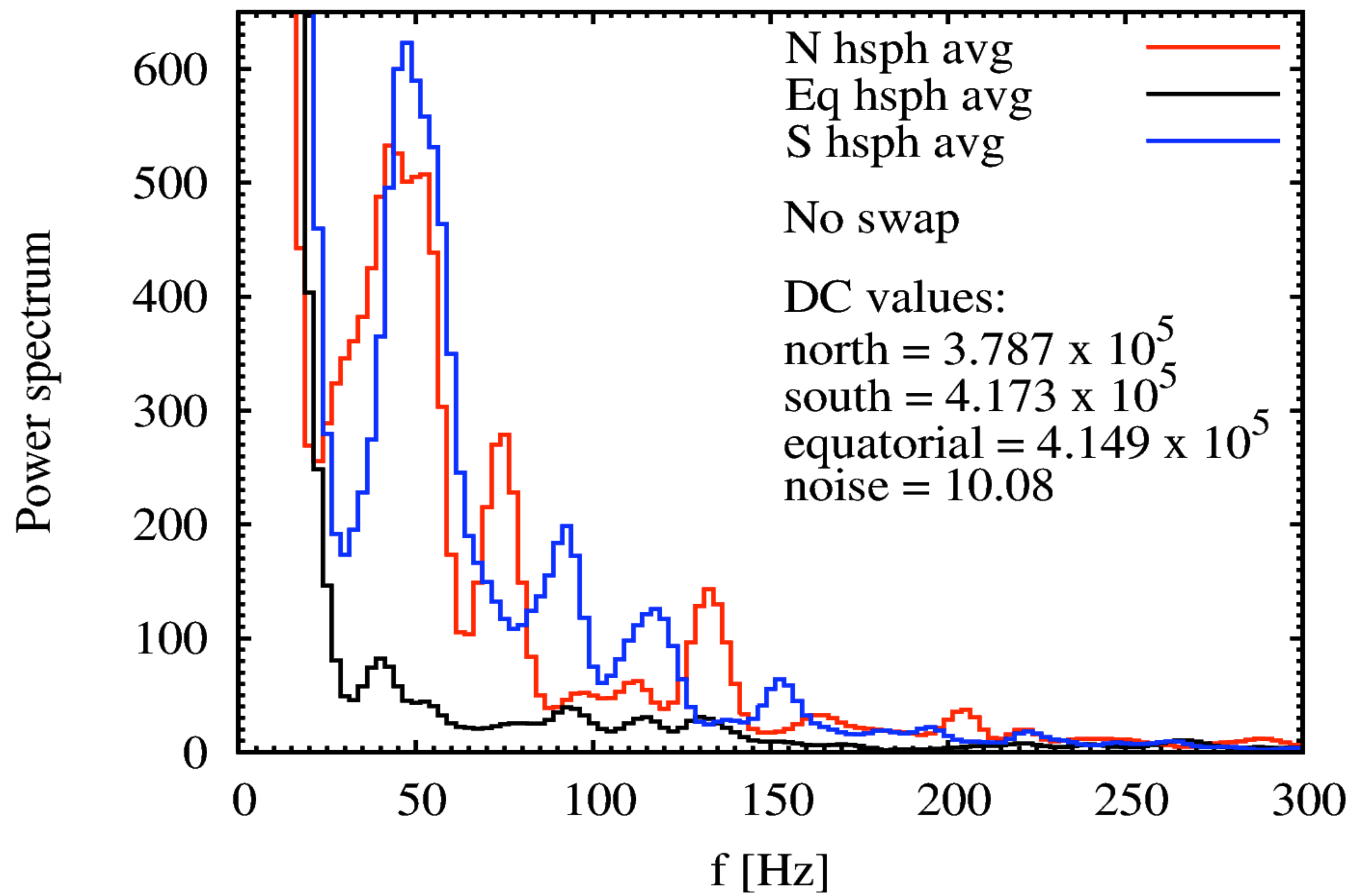
- Count rate in Super-Kamiokande for galactic supernova at 10 kpc.
- Varying mixing length + opacity + PNS masses do not change the conclusion.



Roberts, Shen, Cirigliano, Pons, Reddy, Woosley (2011)

T. Lund

Results - 2D

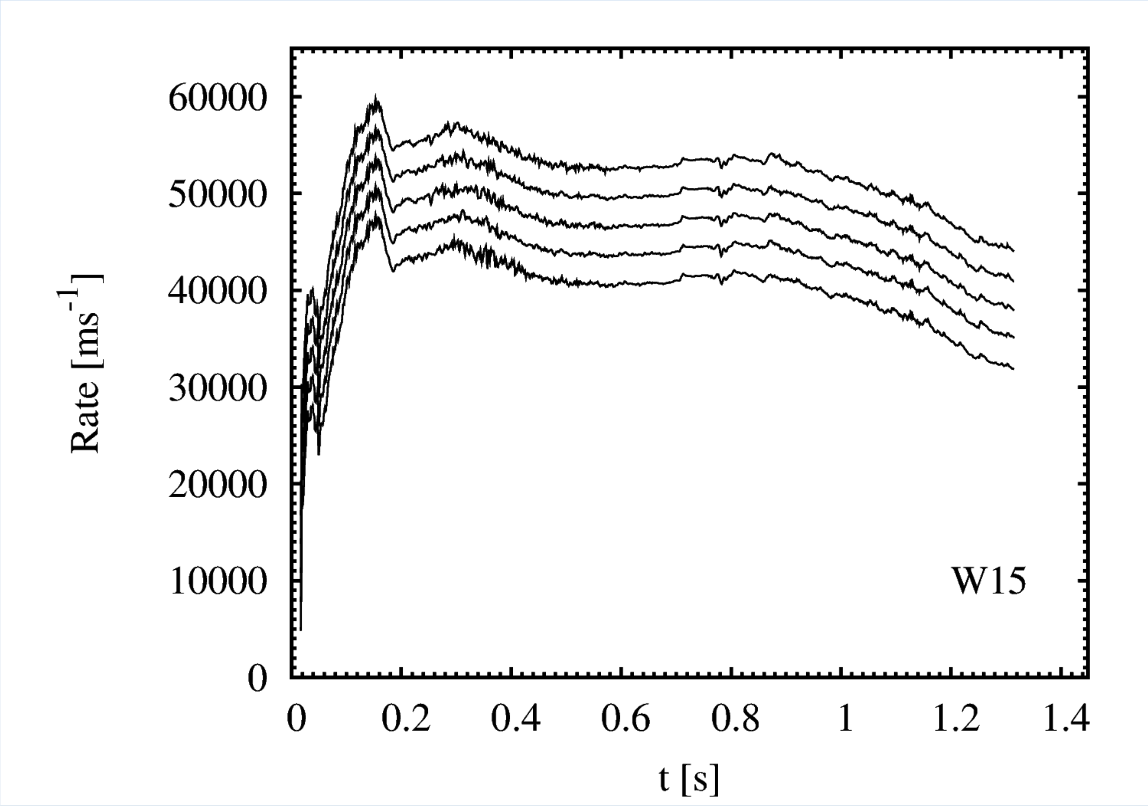


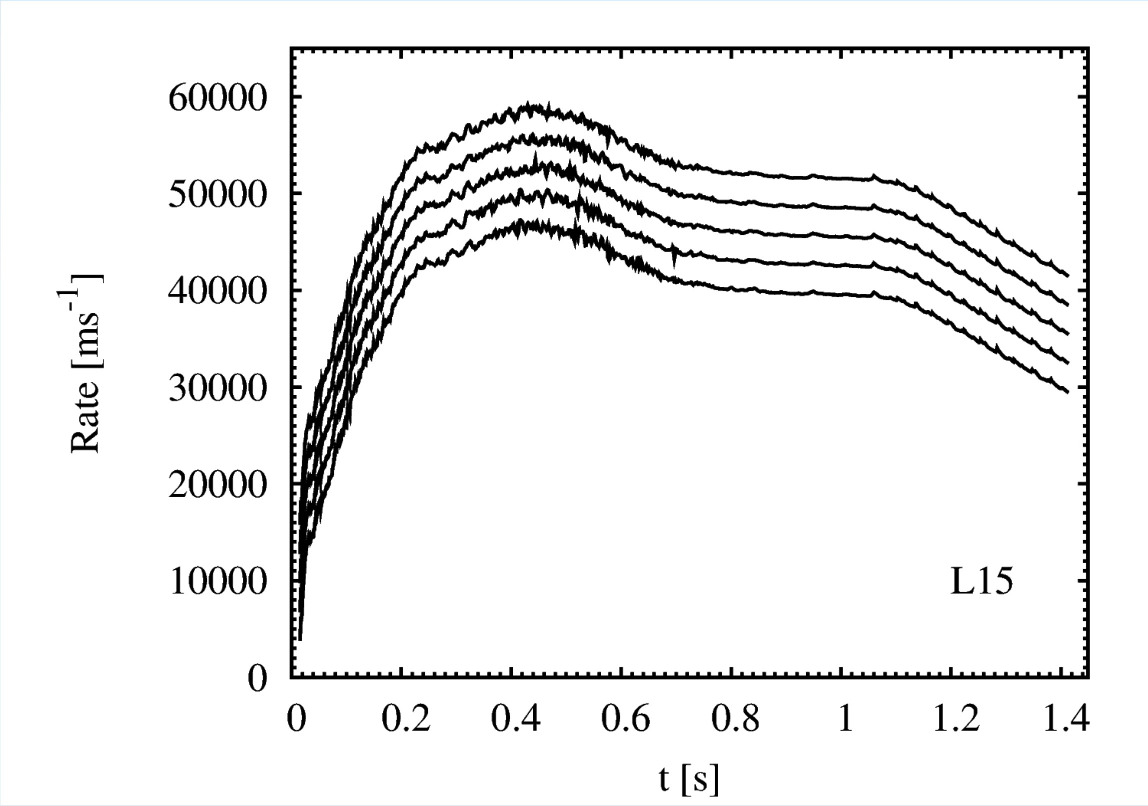
15 M_{sun}, LS EoS

[Lund et al, 2010.]

T. Lund

Rates in 3D



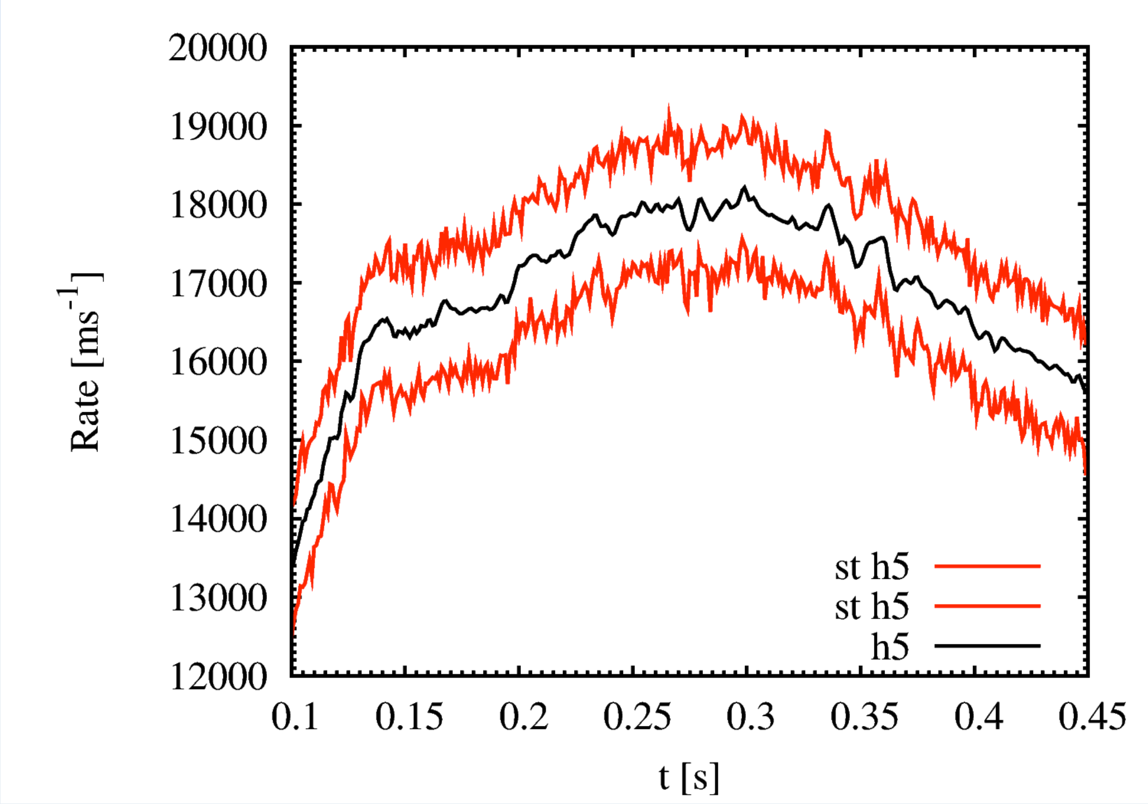


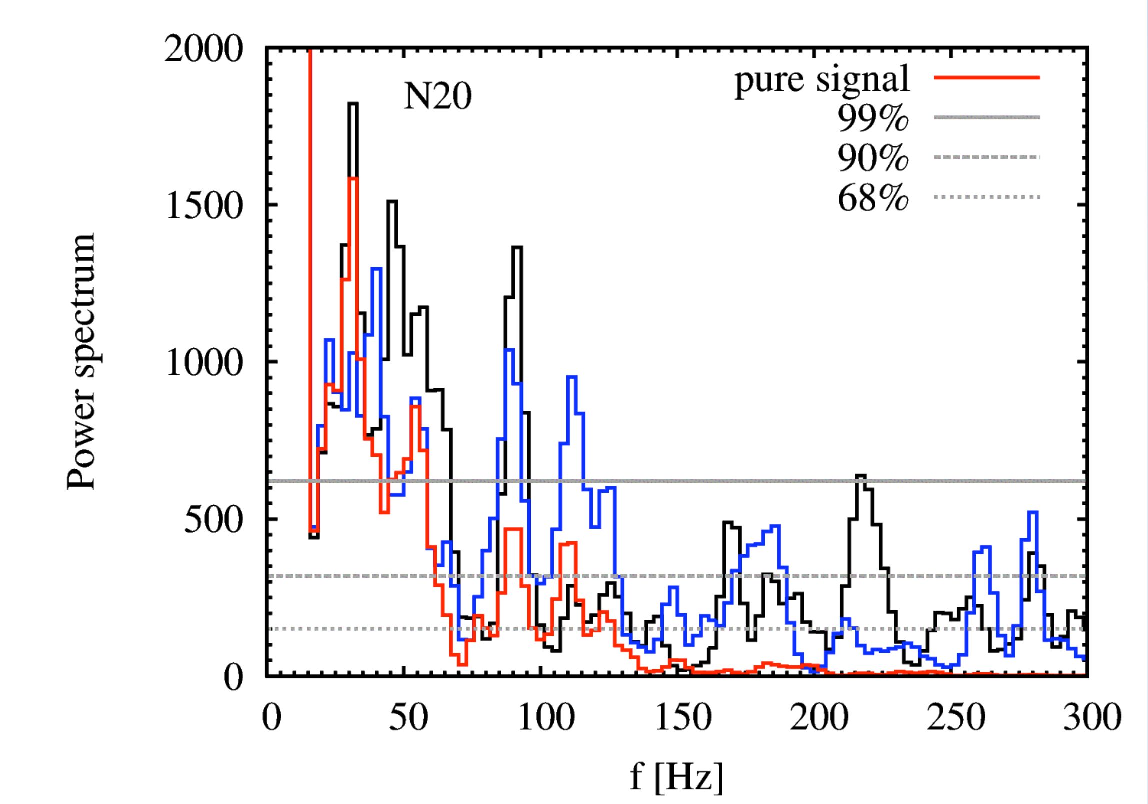
At 1 kpc

[Lund et al, 2011, *in preparation*.]

T. Lund

Stastistical effects





N20 at 2 kpc

Equation of state

Equation of state

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Explosion mechanism

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Explosion mechanism

There is wide agreement that neutrino heating, aided by the stationary accretion shock instability (SASI) and convection, may well be able to revive the stalled shock. There remain differences over how long it takes to revive the shock, and whether the mechanism will prove more robust in 3D. Collective neutrino flavor mixing does not appear to affect the explosion mechanism.

Neutrino emission

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Neutrinos and nucleosynthesis

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Neutrinos and nucleosynthesis

Neutrinos affect nucleosynthesis by setting the neutron/proton ratio and by altering the numbers of free neutrons and protons available for capture by heavier nuclei. Recent simulations indicate that neutrinos produce a proton-rich environment that would rule out the *r* process but produce observationally feasible abundances of intermediate mass nuclei. If neutron-rich conditions somehow obtain, collective neutrino oscillations make things worse for the *r* process. Multi-angle calculations of collective oscillations are needed to get nucleosynthesis effects right because the radius at which flavor transformations occur matters; the single-angle approximation gets this wrong even if it gives decent answers at infinity.

From neutrino signal to astrophysics

From neutrino signal to astrophysics

Differences between nuclear equations of state may be detectable in Super-Kamiokande. The characteristic frequencies of the SASI may be extractable thanks to the time resolution of IceCube, provided the supernova is within 1-2 kpc.