Nuclei in the Cosmos XI, Heidelberg 2010

Models and direct observables of core-collapse supernovae

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- Ingredients of core-collapse supernova models
- Walk through scenario with brand-new 3D models
- Sensitivity of observables to input physics

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J. Schaffner-Bielich
S. Scheidegger
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Observable extreme conditions

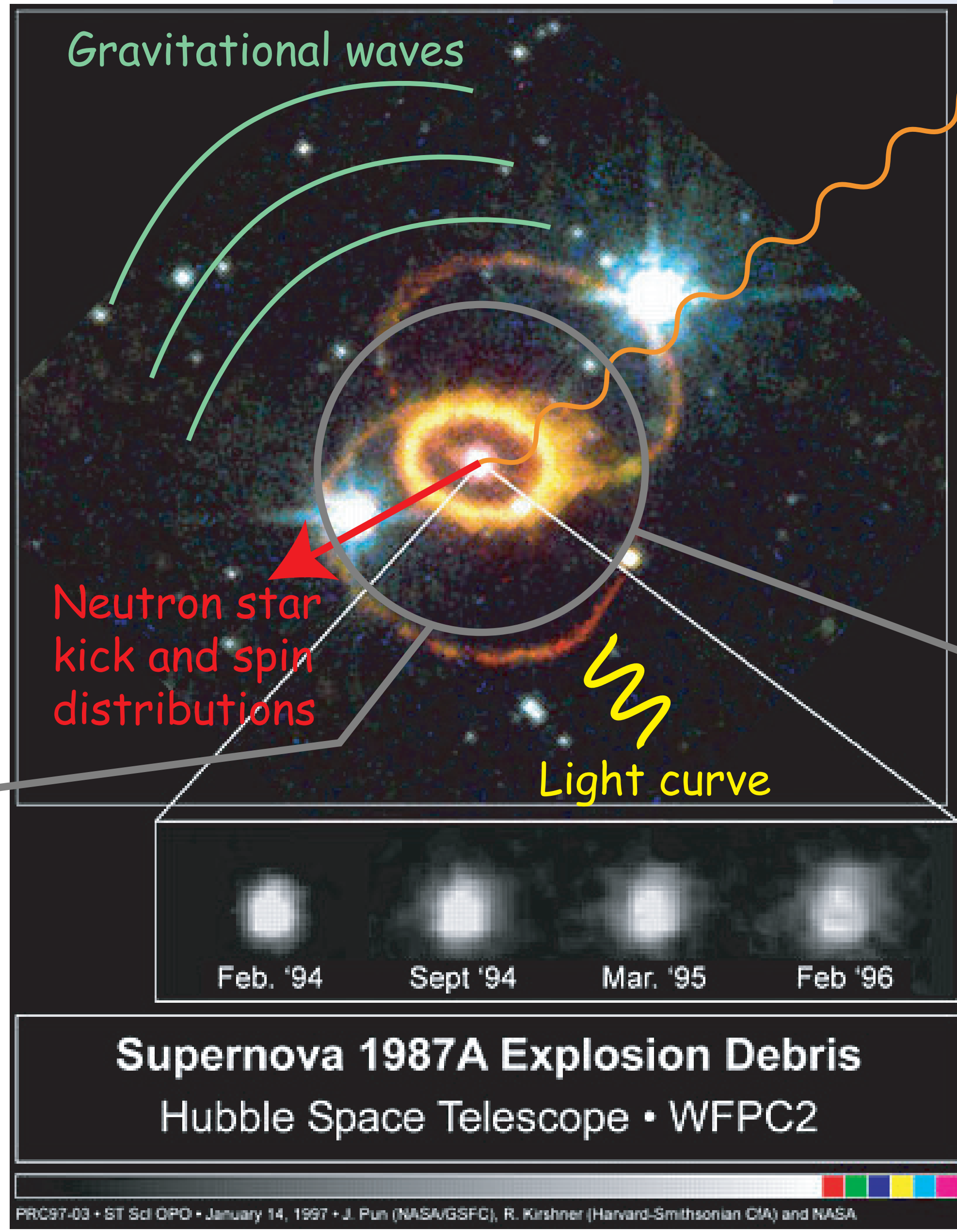
Huge energy scale:
1e+53 erg neutrinos
1e+48 erg elmag
1e+41 erg visible.

Energy from mass-defect by gravitational binding

(Baade, Zwicky, 1934)

Indirect observation of ejecta:

- contamination of metal-poor stars by SN ejecta.
- galactic evolution.
- solar abundance.



Immediate neutrino signal from innermost region.

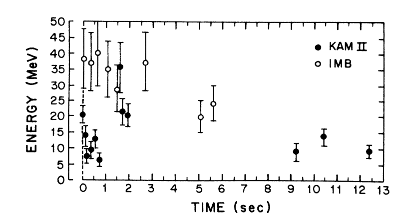


FIG. 15. Scatter plot of energy and time of the 12 events in the burst sample observed in Kamiokande-II, and the 8 events in the burst sample observed in the IMB detector. The earliest event in the sample of each detector has, arbitrarily but not unreasonably, been assigned $t=0$.

Hirata et al. 1988

Direct observation of ejecta:

- elemental composition and velocity distribution from spectra.
- asymmetry from polarization.

Ingredients for a minimum SN model

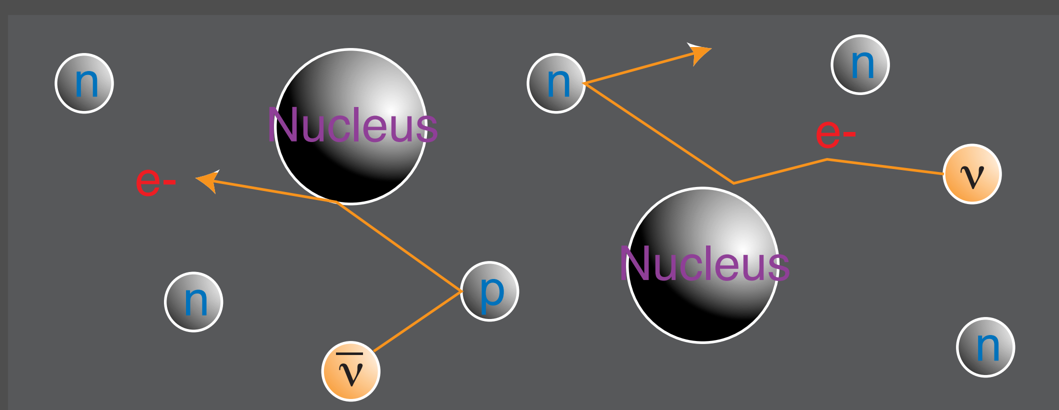
Conservation laws:

- Baryon number
- Lepton number
- Energy
- Momentum
- Magnetic flux

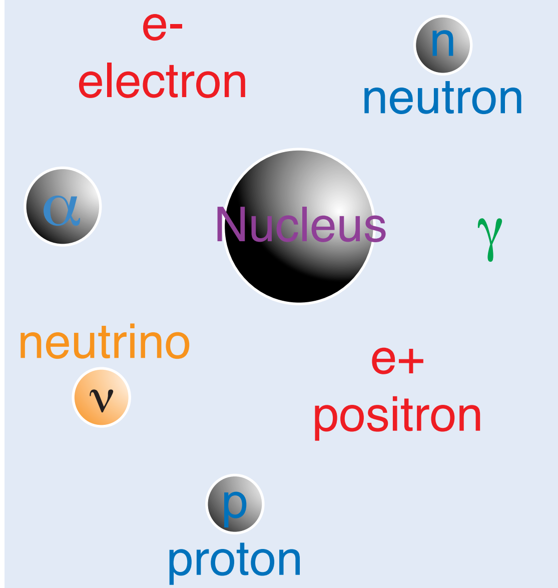
Conditions:

- Nuclear statistical equilibrium (NSE)
- Charge neutrality
- Detailed balance
- div(B) = 0

Radiative transfer of neutrinos:



- Main composition:



- Weak interactions:

$$e^- + p \longleftrightarrow n + \nu$$

$$e^+ + n \longleftrightarrow p + \bar{\nu}$$

Microscopic input physics

Weak interactions between neutrinos and matter
(Bruenn, ApJS 58, 1985 and Refs. therein)

Coherent scattering of neutrinos on nuclei
$$\nu + (A,Z) \rightleftharpoons \nu + (A,Z)$$
Ion-ion correlations (Itoh 1975)

Neutrino-electron scattering
$$\nu + e \rightleftharpoons \nu + e$$

Electron/neutrino capture on nuclei
$$\nu_e + (A,Z) \rightleftharpoons e^- + (A,Z+1)$$

Electron/neutrino capture on nucleons
$$\nu_e + n \rightleftharpoons e^- + p$$
$$\bar{\nu}_e + p \rightleftharpoons e^+ + n$$

Neutrino-nucleon scattering
$$\nu + N \rightleftharpoons \nu + N$$

Pair creation/annihilation
$$e^- + e^+ \rightleftharpoons \nu + \bar{\nu}$$
Nucleon-Nucleon bremsstrahlung (Thompson et al. 2002)
Electron-ν pair annihilation --> muon-ν pair creation (Buras et al. 2003)

Cool collapse

Equation of state:
- charge neutrality
- nuclear statistical equilibrium (NSE)
- finite temperature

- Liquid drop (Lattimer-Swesty 1991)
- Rel. Mean Field (Shen et al. 1998)

Hot postbounce

Solving the Boltzmann equation

$$\frac{\partial F}{\alpha c \partial t} + \frac{\partial\left(4\pi r^2 \alpha \rho \mu F\right)}{\alpha \partial m} + \Gamma\left(\frac{1}{r} - \frac{\partial \alpha}{\alpha \partial r}\right)\frac{\partial\left[\left(1-\mu^2\right)F\right]}{\partial \mu}$$

$$+ \left(\frac{\partial \ln \rho}{\alpha c \partial t} + \frac{3}{r}\frac{u}{c}\right)\frac{\partial\left[\mu\left(1-\mu^2\right)F\right]}{\partial \mu}$$

$$+ \left[\mu^2\left(\frac{\partial \ln \rho}{\alpha c \partial t} + \frac{3}{r}\frac{u}{c}\right) - \frac{1}{r}\frac{u}{c} - \mu\Gamma\frac{\partial \alpha}{\alpha \partial r}\right]\frac{1}{E^2}\frac{\partial\left(E^3 F\right)}{\partial E}$$

$$= \frac{j}{\rho} - \tilde{\chi}F + \frac{1}{h^3 c^4}E^2\int d\mu' R_{is}\left(\mu,\mu',E\right)F\left(\mu',E\right)$$

$$- \frac{1}{h^3 c^4}E^2 F\int d\mu' R_{is}\left(\mu,\mu',E\right)$$

$$+ \frac{1}{h^3 c^4}\left[\frac{1}{\rho} - F\left(\mu,E\right)\right]\int E'^2 dE' d\mu' \tilde{R}^{in}_{nes}\left(\mu,\mu',E,E'\right)F\left(\mu',E\right)$$

$$- \frac{1}{h^3 c^4}F\left(\mu,E\right)\int E'^2 dE' d\mu' \tilde{R}^{out}_{nes}\left(\mu,\mu',E,E'\right)\left[\frac{1}{\rho} - F\left(\mu',E'\right)\right]$$

$$\frac{\partial Y_e}{\partial t} = -\frac{2\pi m_B}{h^3 c^2}\int E^2 dE d\mu\left(\frac{j}{\rho} - \tilde{\chi}F\right) \qquad \frac{\partial e}{\partial t} = \ldots \qquad \frac{\partial u}{\partial t} = \ldots$$

(Mezzacappa & Bruenn 1993, Liebendörfer 2000, Liebendörfer et al. 2004)

Evolution of specific neutrino distr. function:

F(t,m,μ,E) = f(t,r,μ,E)/ρ

=> 3D implicit problem

Comoving metric:

$$ds^2 = -\alpha^2 dt^2 + \left(\frac{1}{\Gamma}\frac{\partial r}{\partial a}\right)^2 + r^2\left(d\vartheta^2 + \sin^2\vartheta d\varphi^2\right)$$

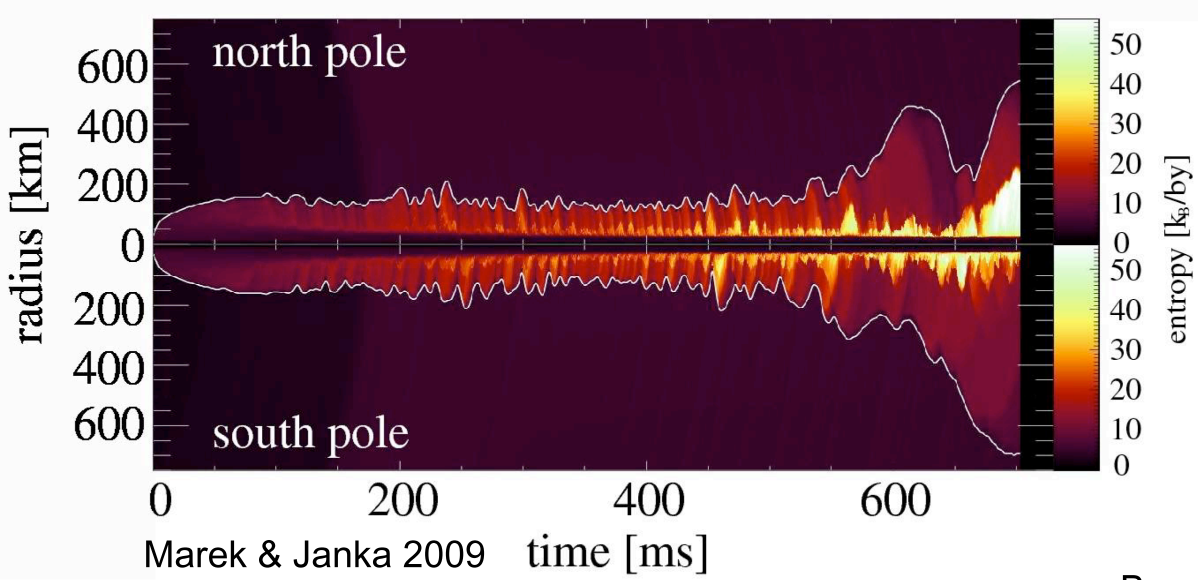
Stress-energy tensor:

$$\begin{aligned} T^{tt} &= \rho\left(1+e+J\right) \\ T^{ta} = T^{at} &= \rho H \\ T^{aa} &= p + \rho K \\ T^{\vartheta\vartheta} = T^{\varphi\varphi} &= p + \frac{1}{2}\rho\left(J-K\right) \end{aligned}$$

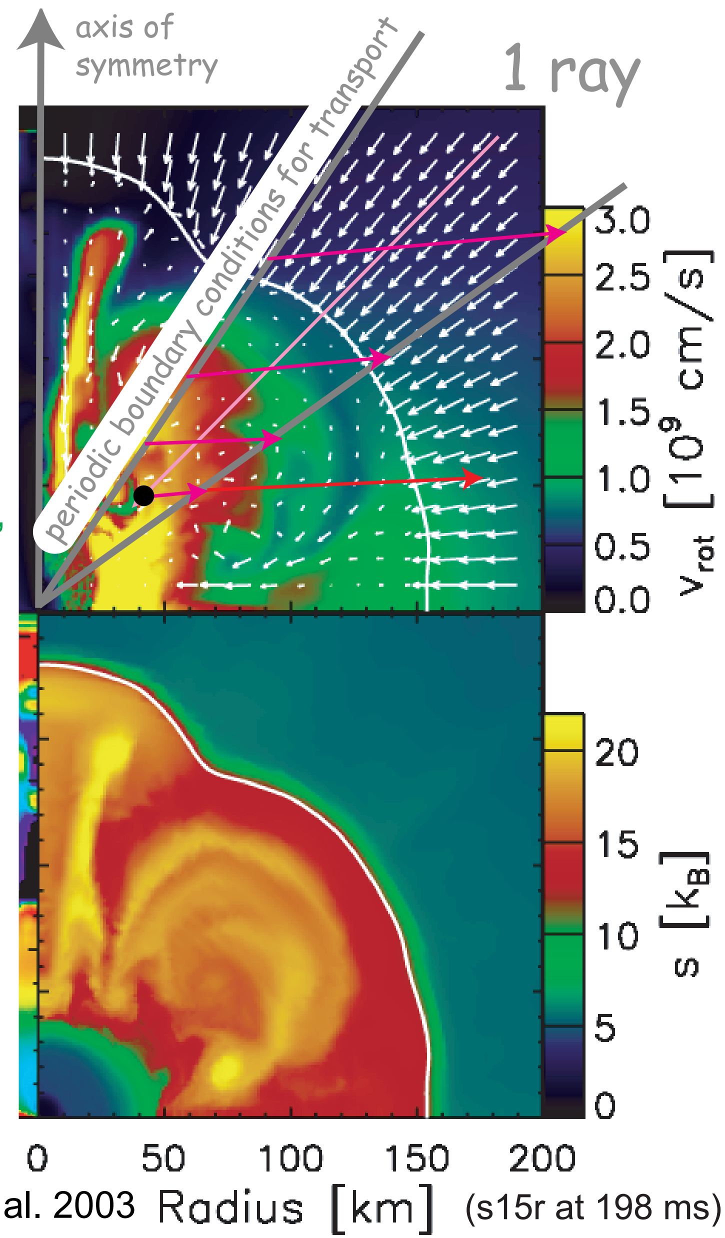
Spectral ν-transport in axisymmetry

Ray-by-ray approach
(still computationally expensive -->
only few runs available)

- Standing Accretion Shock Instability (SASI) perturbs shock radius
- Extended postbounce phase before weak explosion for 11 Ms and 15 Ms models



Marek & Janka 2009

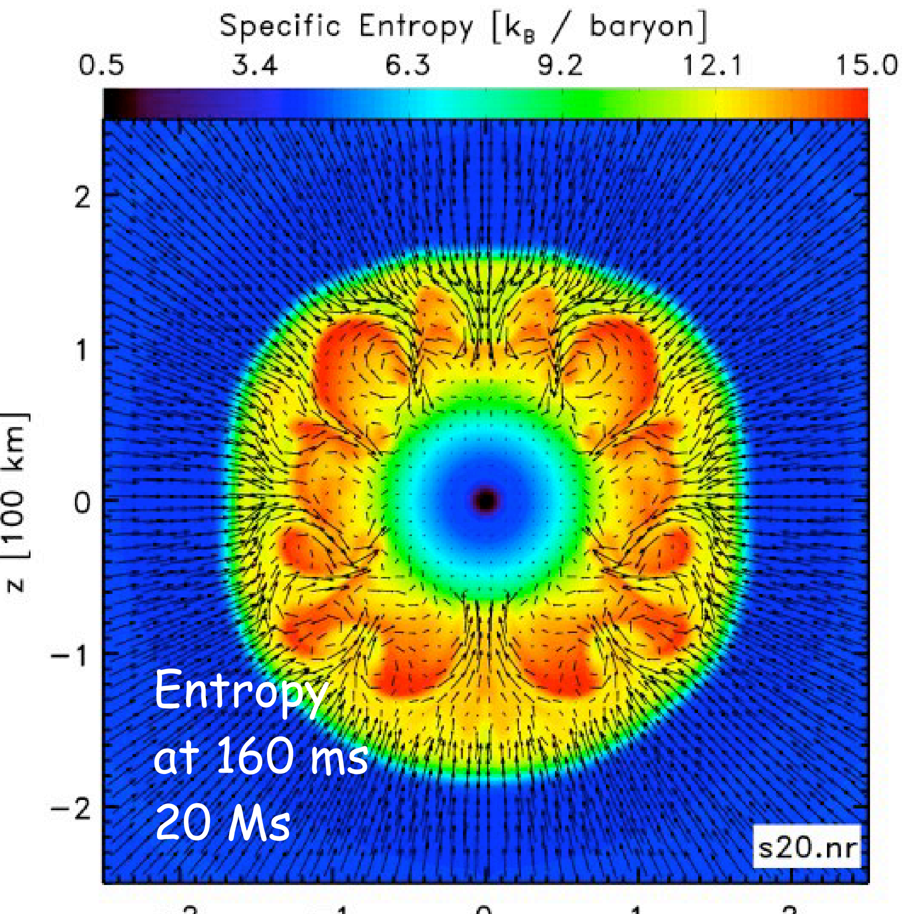


Buras et al. 2003 (s15r at 198 ms)

Convergence in 2D not yet demonstrated

Explosion at 1200 ms by acoustic mechanism:

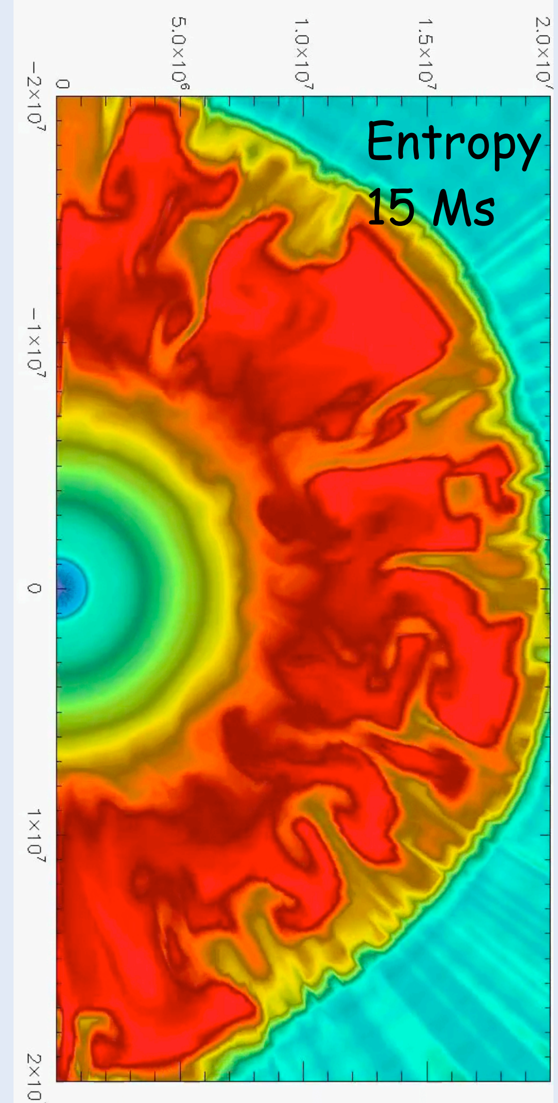
- to be confirmed by other groups Burrows et al. 2006
- coupling to higher modes? Weinberg & Quataert 2008



Ott et al. 2008

Alternative approaches:

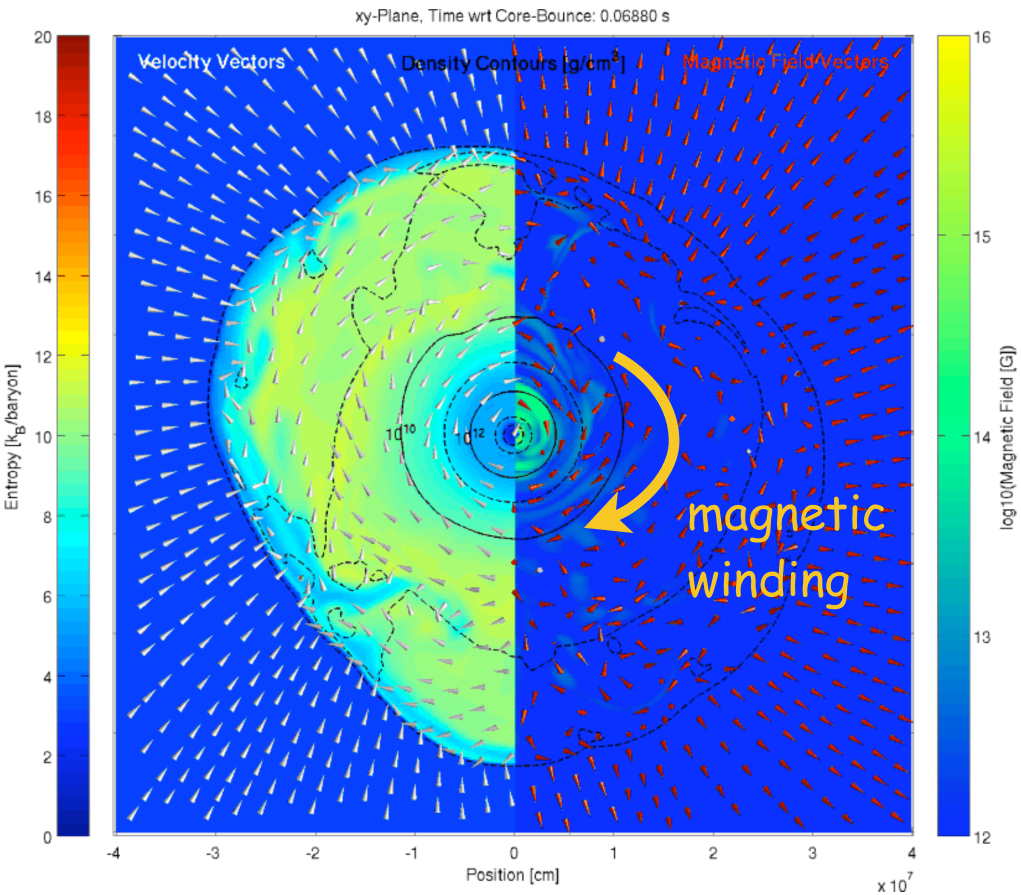
Livne et al. (2004)
Walder et al. (2004)
Myra & Swesty (2005/9)
Bruenn et al. 2007
Dessart et al. (2007)

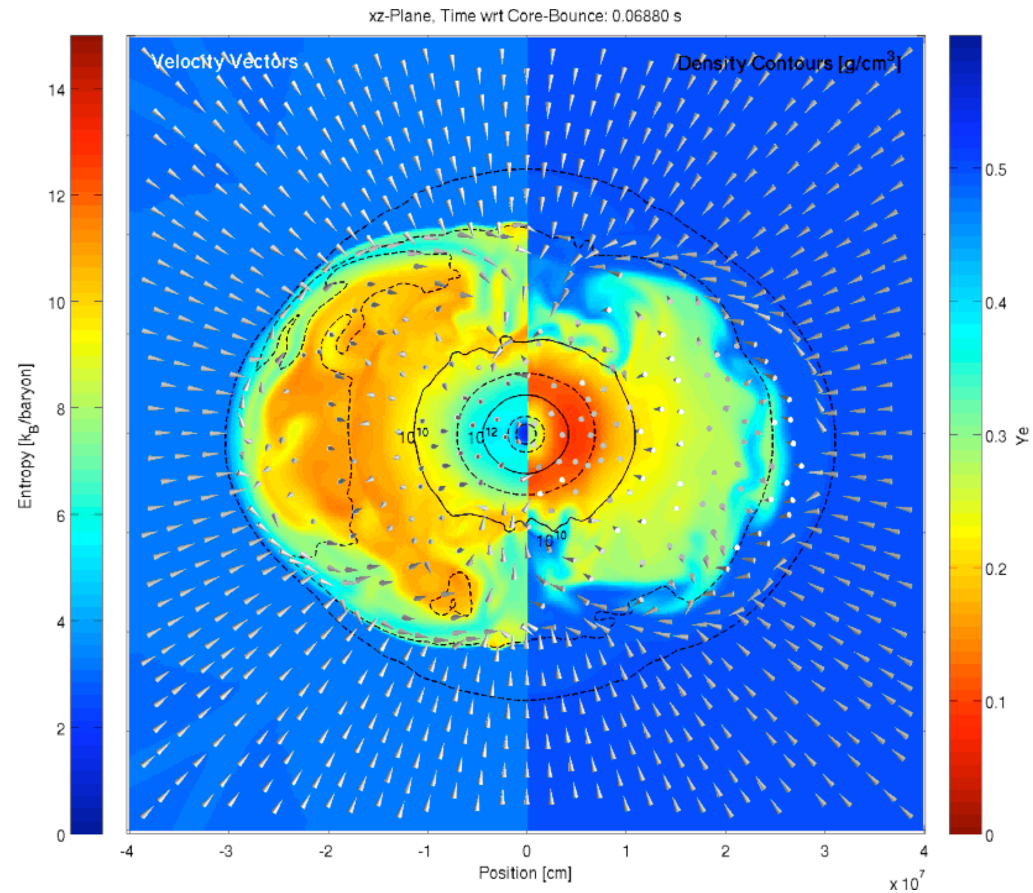


Explosion ~400ms?

Messer et al. 2008

For constraints: 3D models are necessary!





- Convective turnover in 2D is restricted to toroidal shapes!
- Tube-shaped downstreams and broad upflows cannot be modelled in 2D.
- Fluid instabilities and coupling to magnetic are intrinsically 3D.

There is no perfect transport algorithm...

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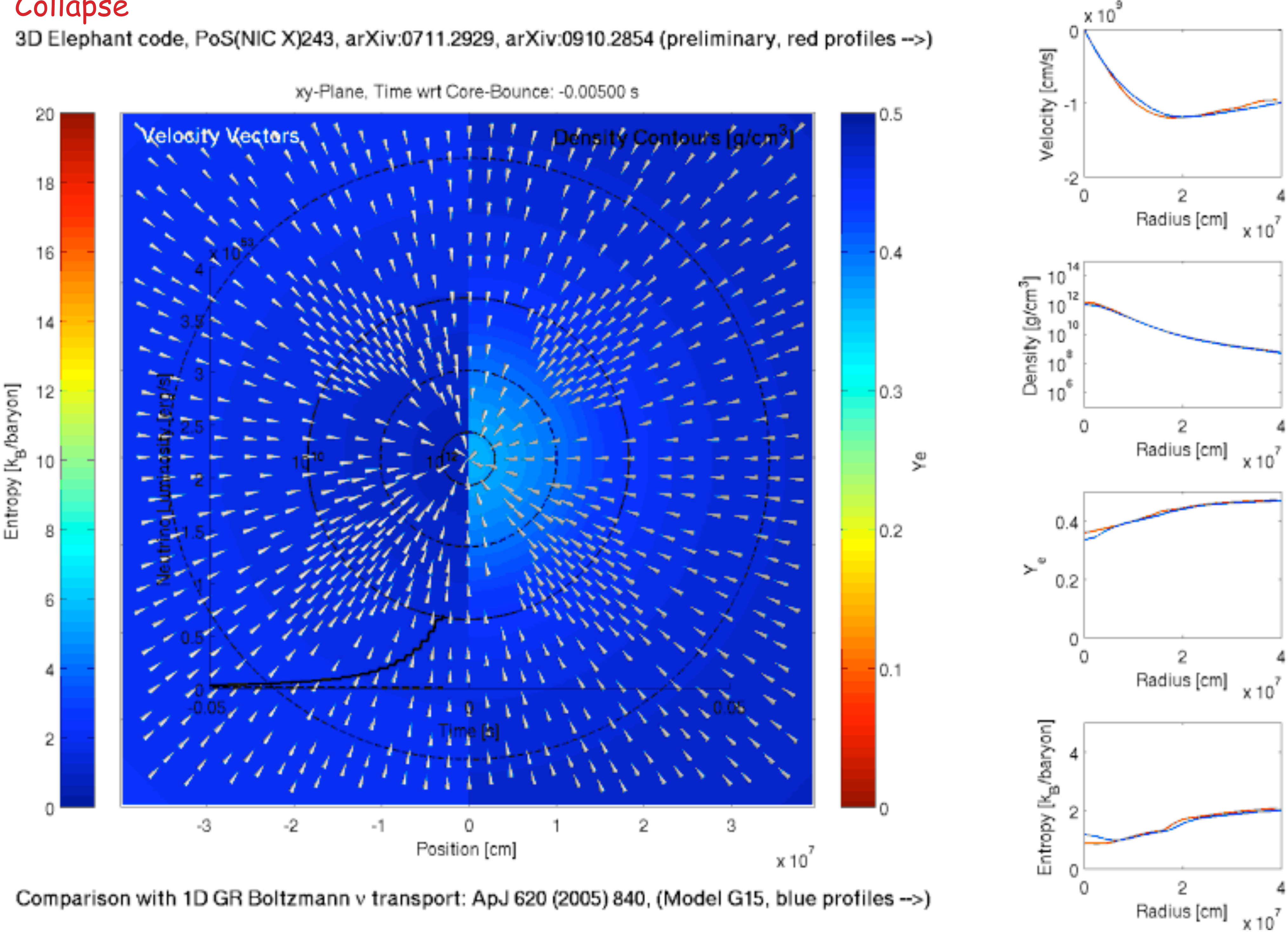
	Diffusive regime	Semi-transparent	Transparent regime
Boltzmann solver	Truncation errors in flux		Inefficient ang. resol.
Flux-limited diffusion		Flux-factor estimated	Flux-factor unknown
Ray-tracing	Short mean free path	Limited by reaction rates	

New three-dimensional simulations based on the
Isotropic Diffusion Source Approximation (IDSA)
Liebendörfer, Whitehouse, Fischer (2009)

- Variable Eddington Factor method
  successful in 2D but very computationally expensive!
  (Rampp & Janka, Buras et al. 2002-5)
- Grey diffusion in one regime and grey transparent elsewhere
  successful in 3D but not accurate enough!
  (e.g. Fryer & Warren 2004)
- Multi-Group Flux-Limited diffusion
  difficulty of local flux limiters & multi-D
  (e.g. Arnett 1966, Bruenn 1985,...)

Collapse

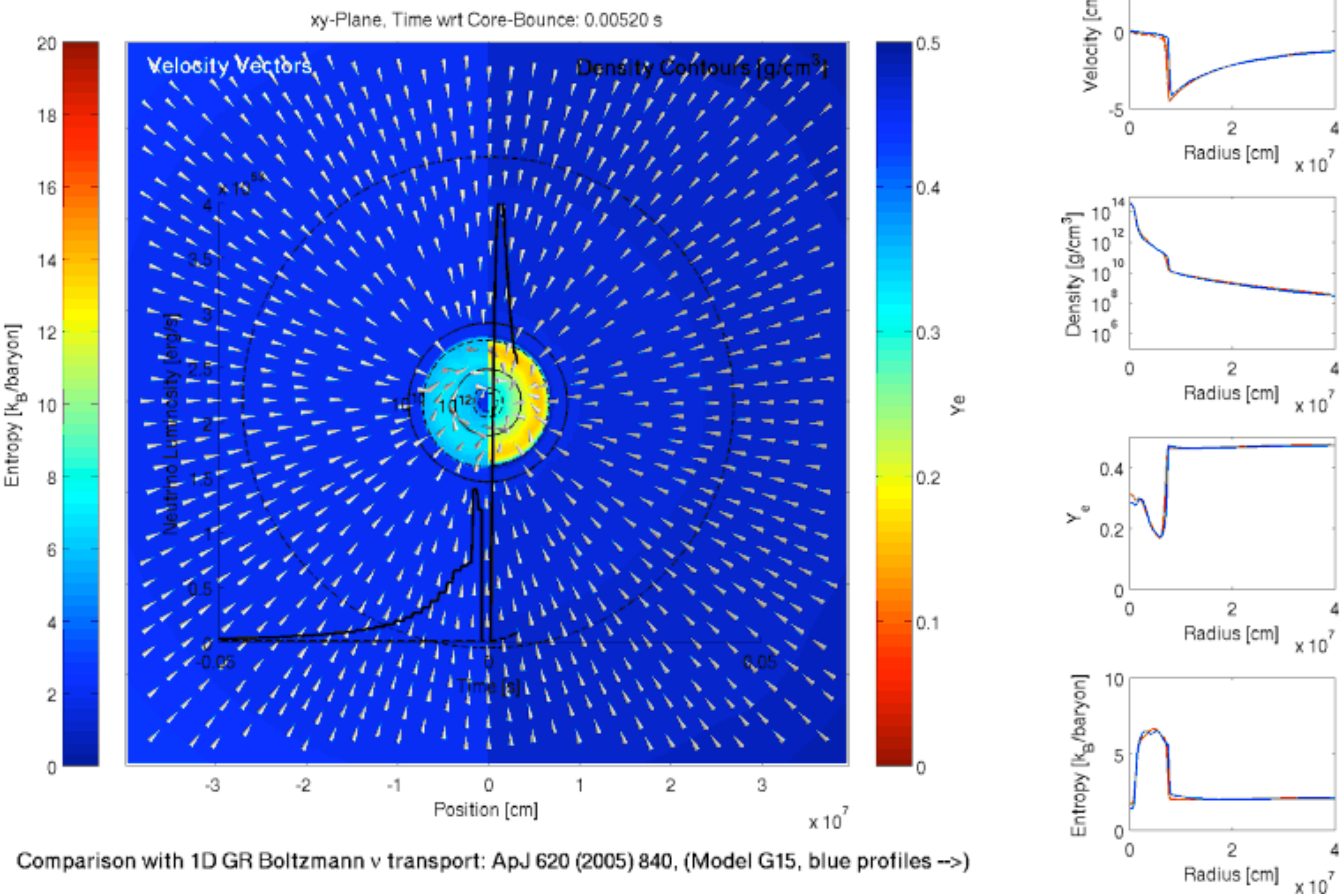
3D Elephant code, PoS(NIC X)243, arXiv:0711.2929, arXiv:0910.2854 (preliminary, red profiles -->)



Comparison with 1D GR Boltzmann ν transport: ApJ 620 (2005) 840, (Model G15, blue profiles -->)

Bounce and electron neutrino peak signal

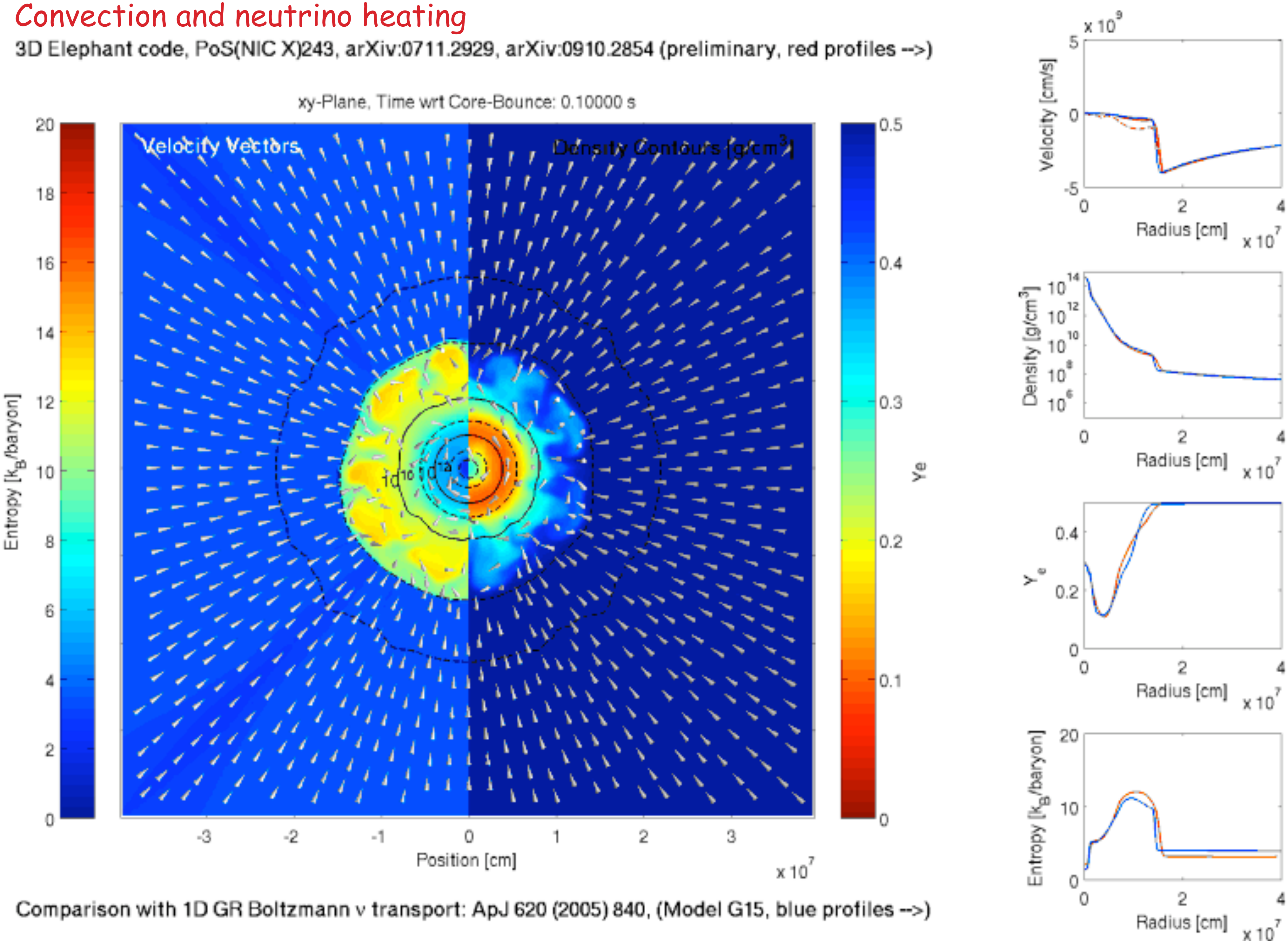
3D Elephant code, PoS(NIC X)243, arXiv:0711.2929, arXiv:0910.2854 (preliminary, red profiles -->)



Comparison with 1D GR Boltzmann ν transport: ApJ 620 (2005) 840, (Model G15, blue profiles -->)

Convection and neutrino heating

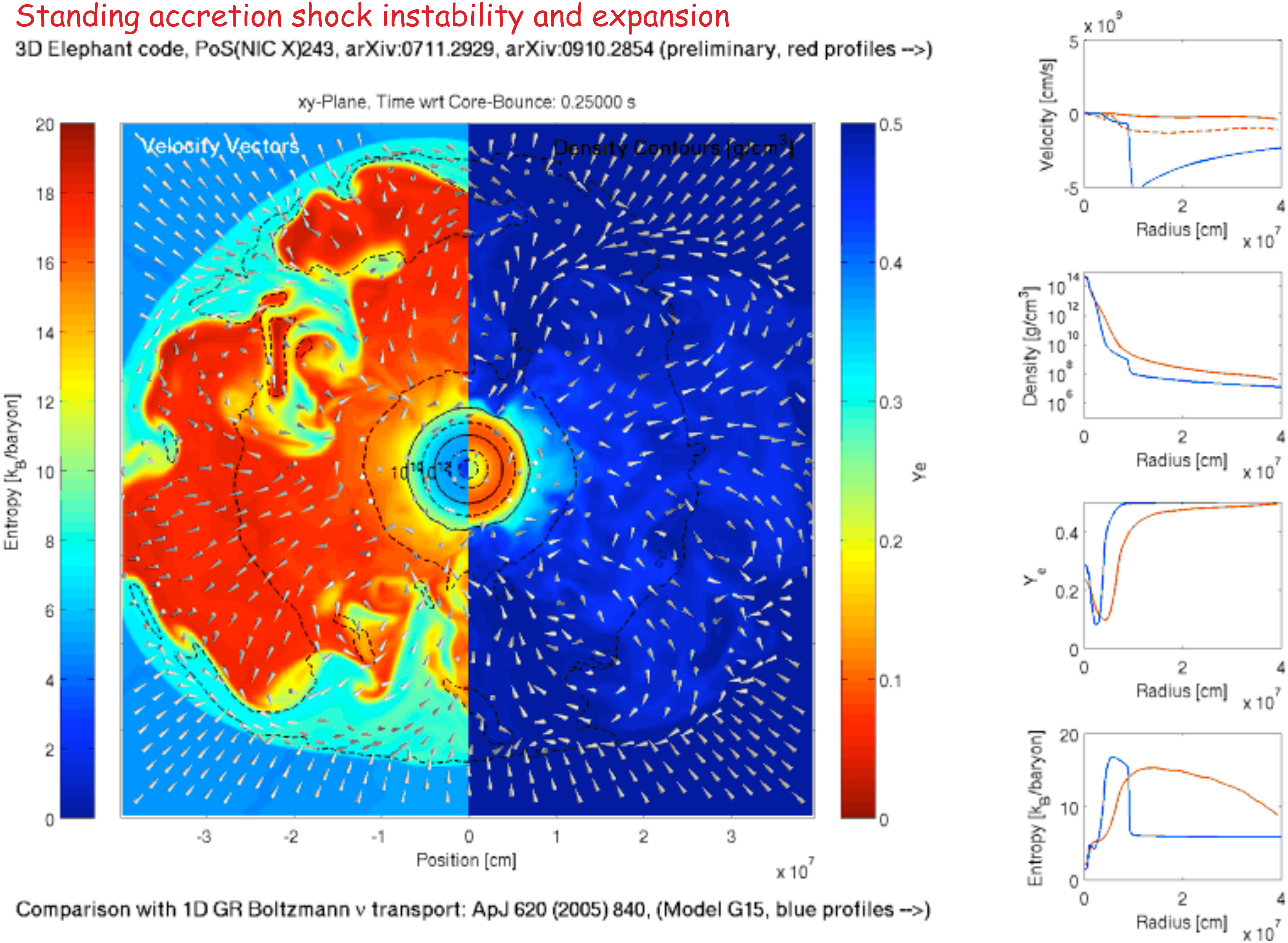
3D Elephant code, PoS(NIC X)243, arXiv:0711.2929, arXiv:0910.2854 (preliminary, red profiles -->)



Comparison with 1D GR Boltzmann ν transport: ApJ 620 (2005) 840, (Model G15, blue profiles -->)

Standing accretion shock instability and expansion

3D Elephant code, PoS(NIC X)243, arXiv:0711.2929, arXiv:0910.2854 (preliminary, red profiles -->)



Comparison with 1D GR Boltzmann ν transport: ApJ 620 (2005) 840, (Model G15, blue profiles -->)

Magneto-rotational explosion mechanism

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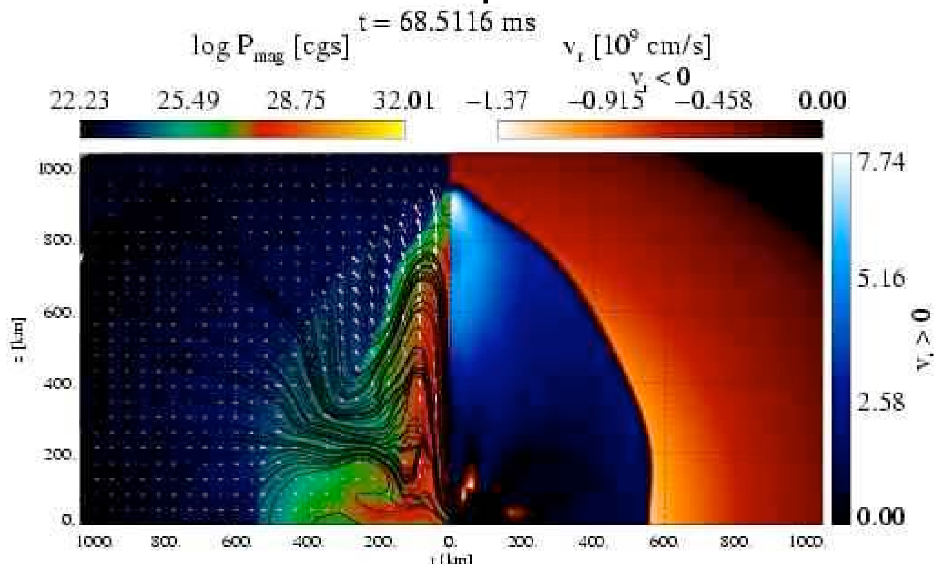
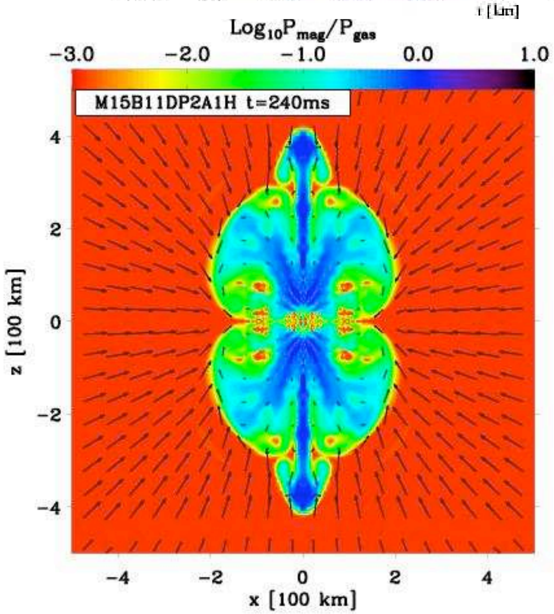
Recent MHD collapse simulations with a neutron star

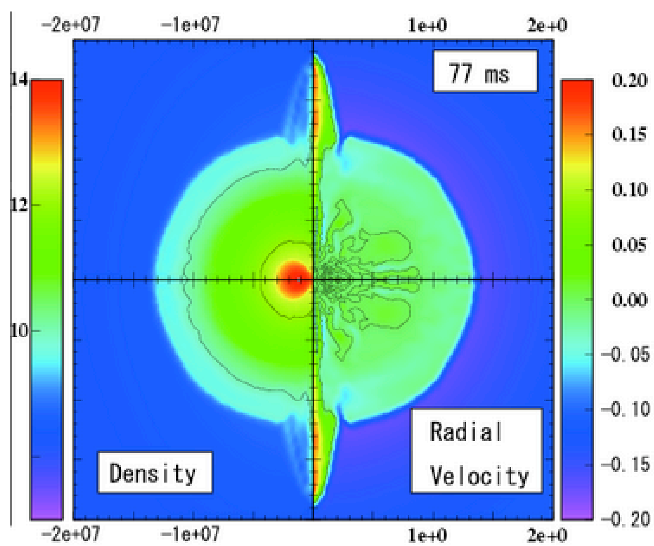


Obergaulinger et al. 2006, T/W=0.23%, B=1E+13 G

Takiwaki et al. 2007, T/W=1%, B=1E+10 G



Burrows et al. 2007, 2π rad/s, 1E+11 G



Pioneering efforts:

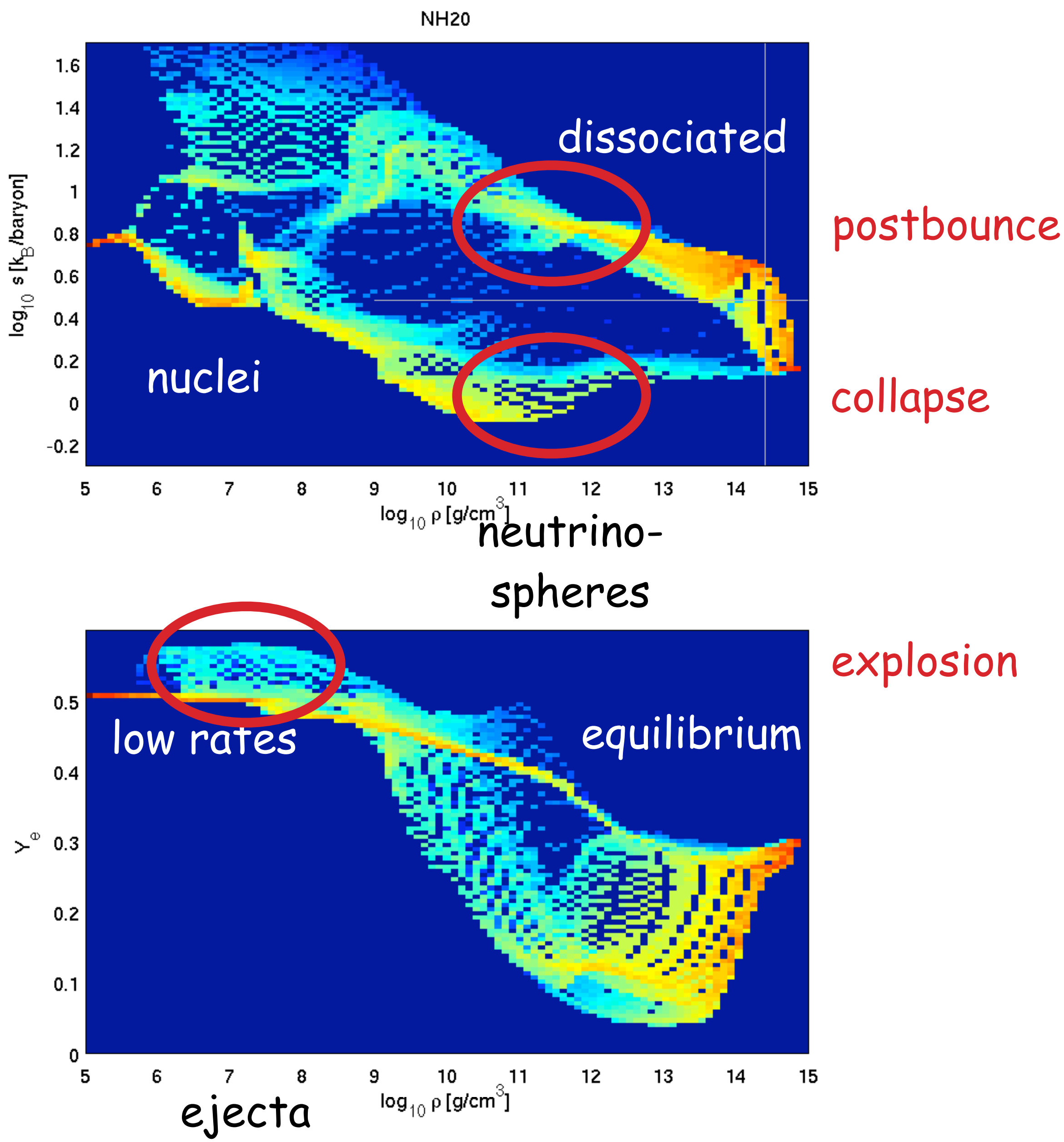
Leblanc & Wilson 1970
Bisnovatyi-Kogan 1971/76
Kundt 1976
Meier et al. 1976
Müller & Hillebrandt 1979
…
MacFadyen & Woosley 1999

Collapsar model (accretion into BH)

Modelling challenge:

- Weak initial field
- Short collapse
- Long growth time

Sensitivity of Observables to Input Physics



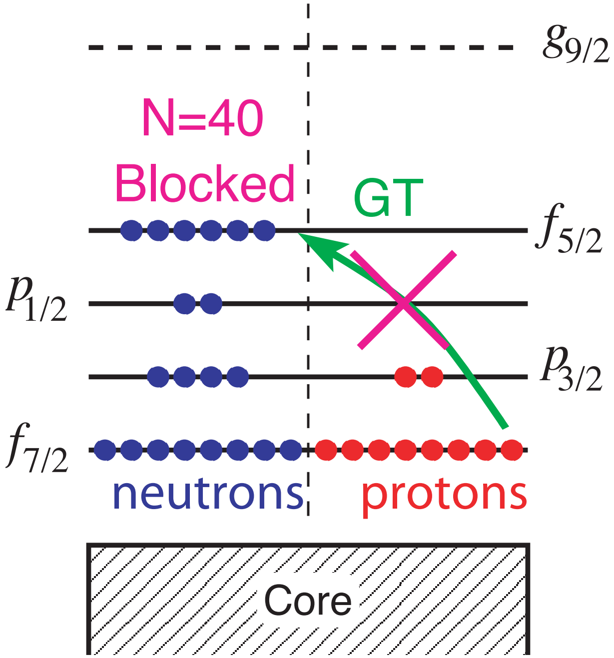
Models depend on:

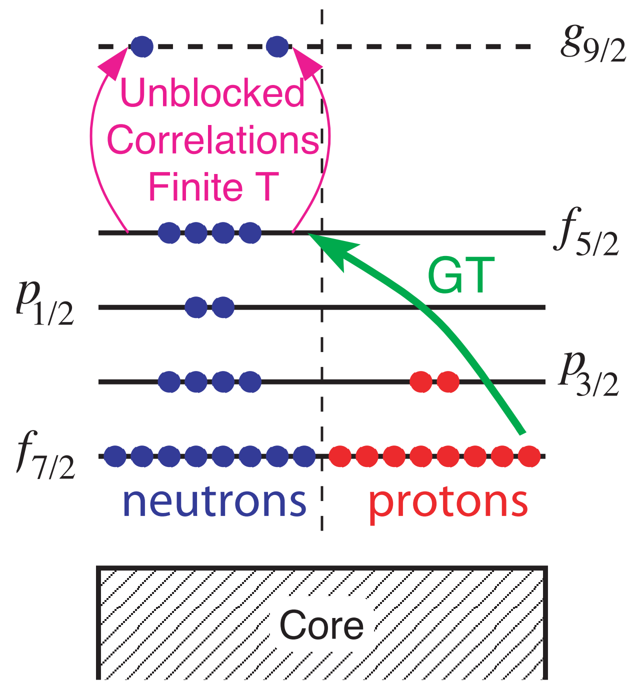
- Nucl. physics and weak interactions
- Progenitor models
- Equation of State (dynamics, comp., microscopic struct.)

observable through:

- neutrino signature
- gravitational waves
- nucleosynthesis

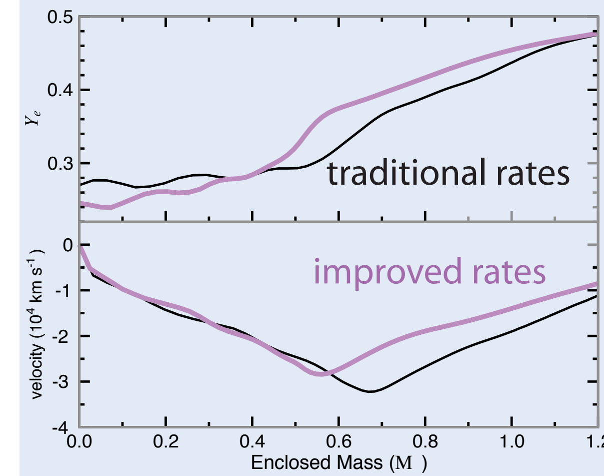
Nuclear Structure and Weak Interactions





(Martinez-Pinedo & Langanke 2002)

Electron fraction and velocity profile as function of enclosed mass before bounce



(Langanke et al. 2003)

- Traditional input physics:

Electron capture reactions blocked for neutrino-rich heavy nuclei

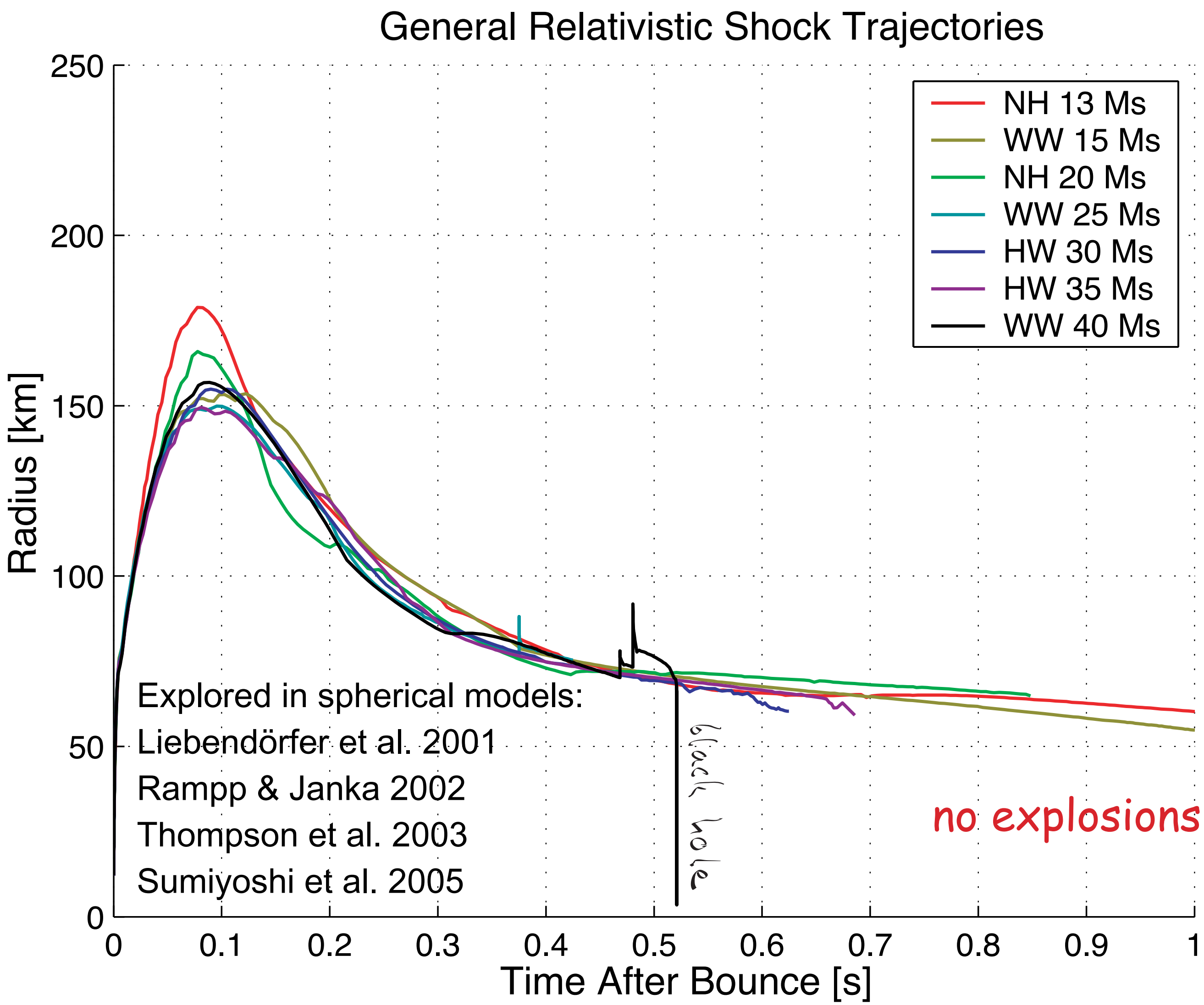
- Most recent input physics:

Electron captures on heavy nuclei proceed and dominate!

(Hix et al. 2003, Marek et al. 2006)

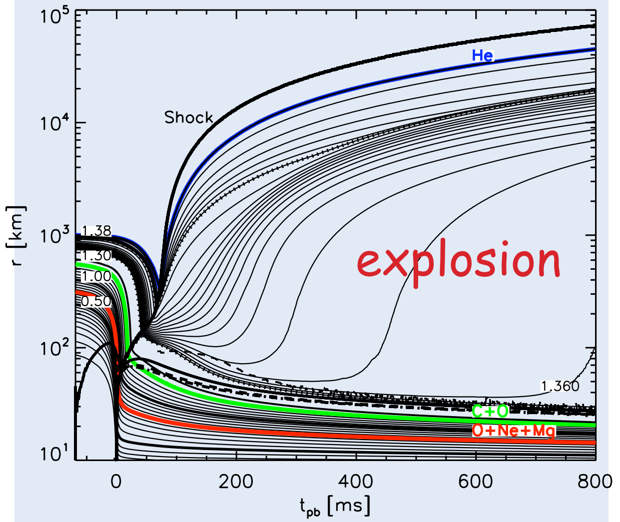
- the treatment of nuclear structure in n-rich nuclei causes 20% differences in shock formation!

Influence of the Progenitor Model



ONeMg core: Recurrent detailed investigations

Hillebrandt, Nomoto, Wolff 1984
Mayle, Wilson 1988
Kitaura, Janka, Hillebrandt 2006
Janka et al. 2008
Fischer et al. 2009



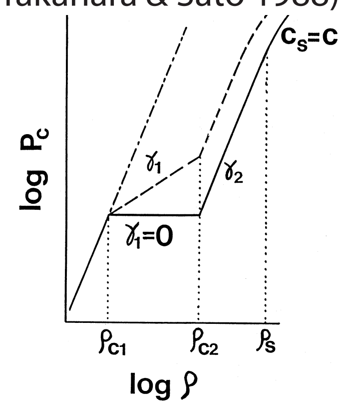
Kitaura, Janka, Hillebrandt 2006

Influence of the Equation of State

- early discussion, revived by SN1987A neutrinos
  (e.g. Migdal et al. 1979, Takhara & Sato 1985-88, Mishustin et al. 2003)

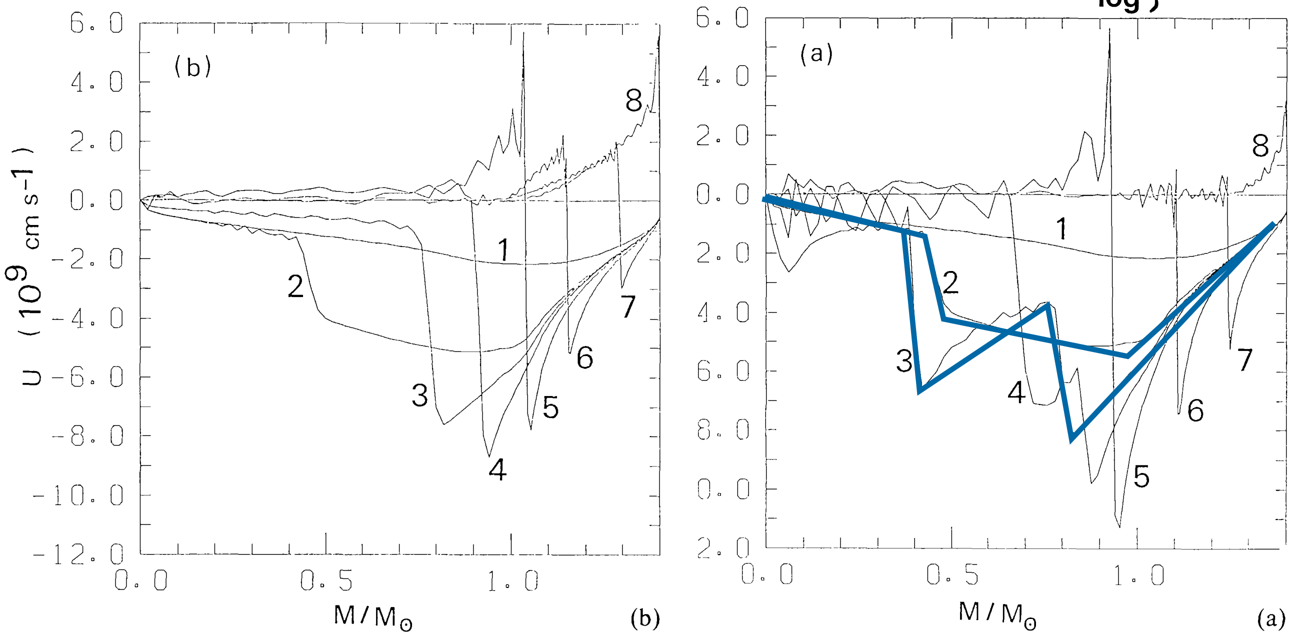
- investigations with parameterised equations of state and GR hydrodynamics

(Takahara & Sato 1988)



- more realistic EoS's and GR hydro-dynamics (Gentile et al. 1993)

(Takahara & Sato 1986)



- select phase transition at or immediately after core bounce

- a second shock forms

- catches up with first shock

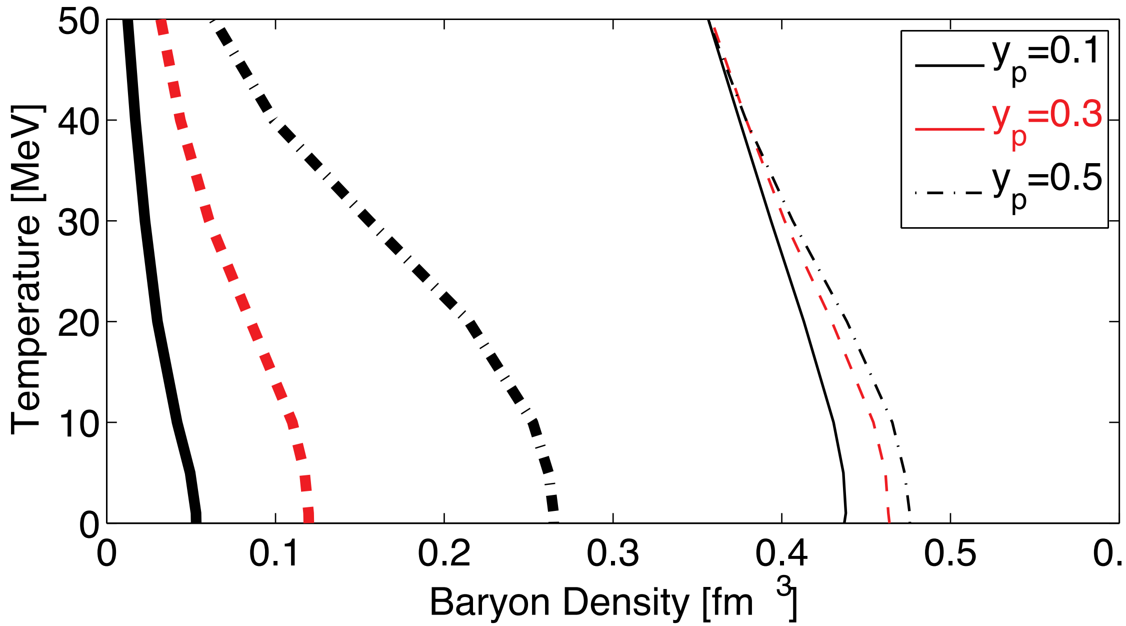
--> Is this observable?

T. Fischer
M. Hempel
G. Pagliara
I. Sagert
J. Schaffner-Bielich

(see also Nakazato et al. 2008)

Simple Model for QCD Phase Transition

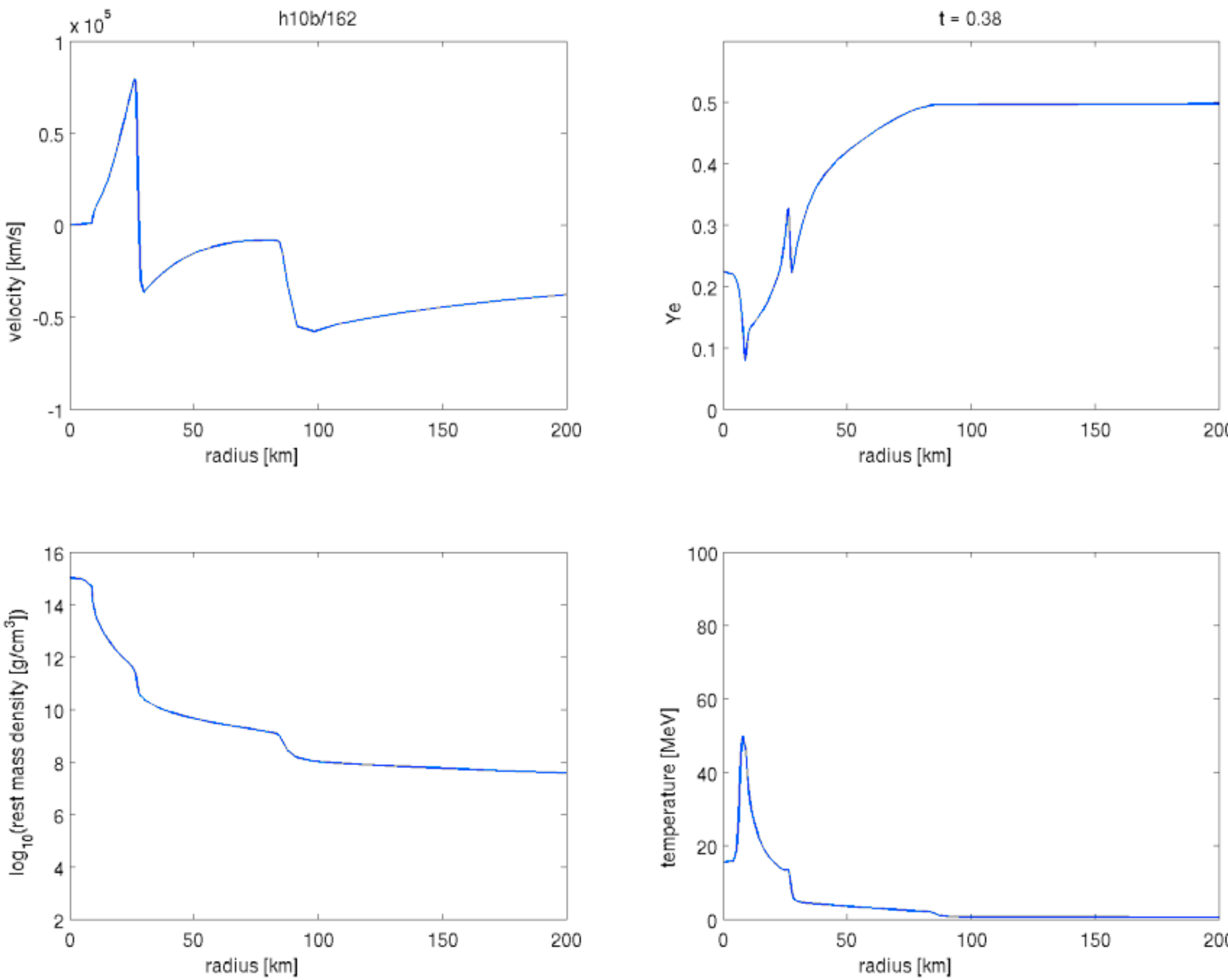
- state-of-the-art GR Boltzmann neutrino transport
- Shen et al. 1998 equation of state for hadronic phase
- MIT bag model for quark phase, choosing parameters for early phase transition: $B^{1/4}$=162-165 MeV, ms=100 MeV
- Mixed phase according to Gibbs construction (mechanical and chemical equilibrium, ν's trapped)



(Sagert, Fischer et al., PRL 2009)

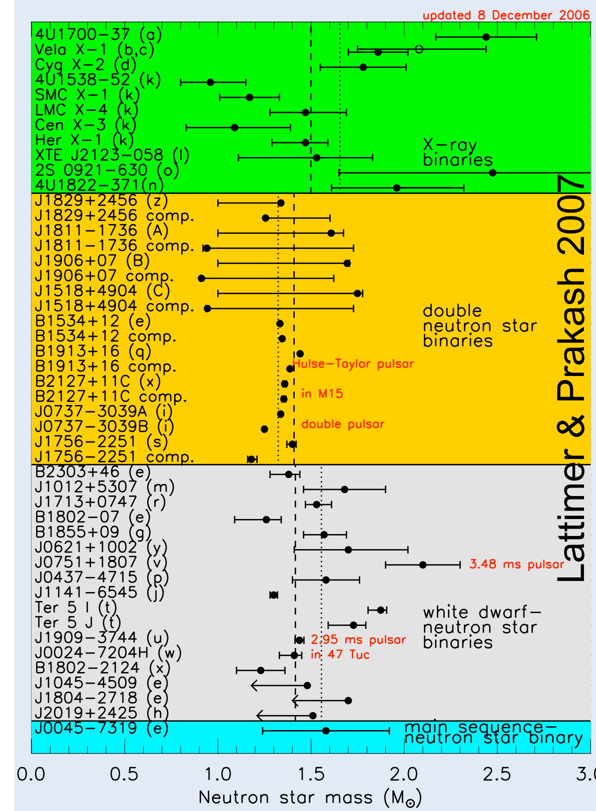
- compatible with heavy ion data
  - isospin-asymmetric
  - weak equilibrium allows for strange quarks
- 'just' compatible with neutron star data:
  - 162 supports 1.56 Ms
  - 165 supports 1.50 Ms

Second shock formation and acceleration



(Sagert, Fischer et al., PRL 2009)

- Suggests neutron star mass clustering



- Pockets with low Ye ejected, r-process?

ν-signature of phase transition

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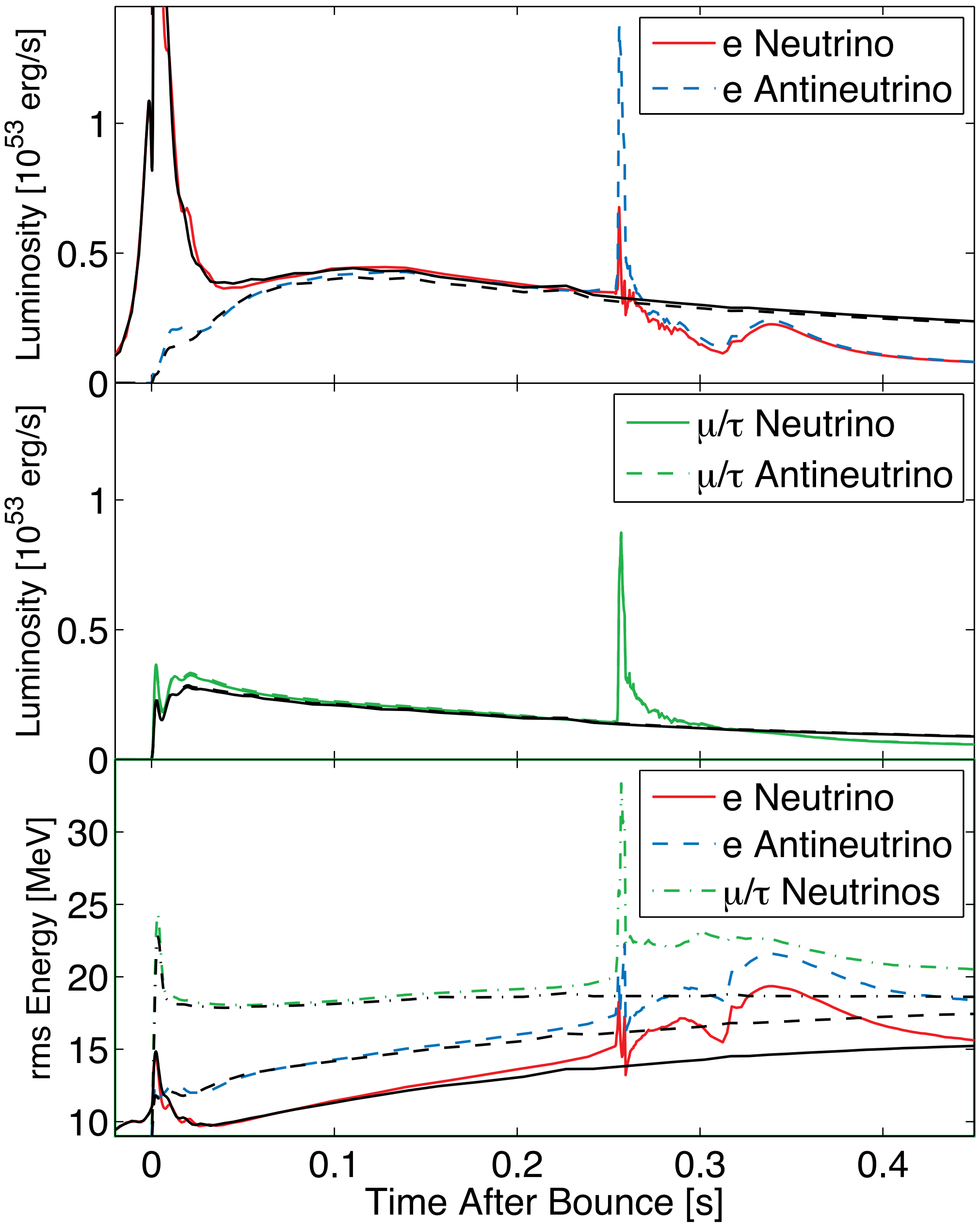
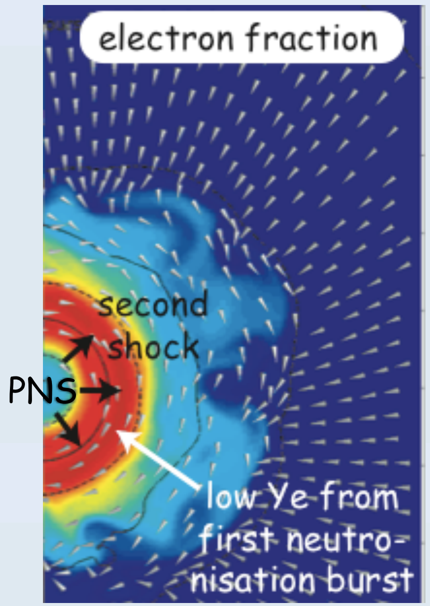


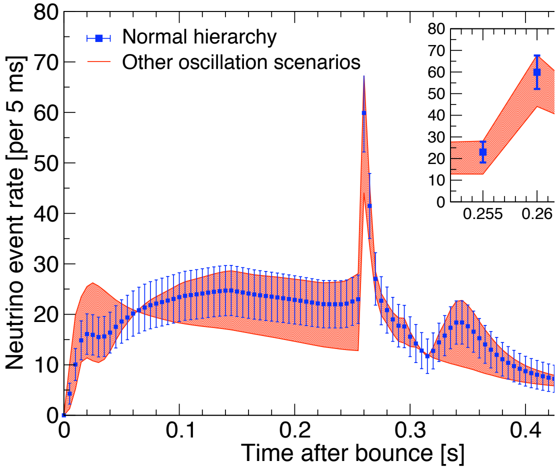


- Second neutrino peak in all flavours, dominated by anti-ν's
- Step up in neutrino rms energies

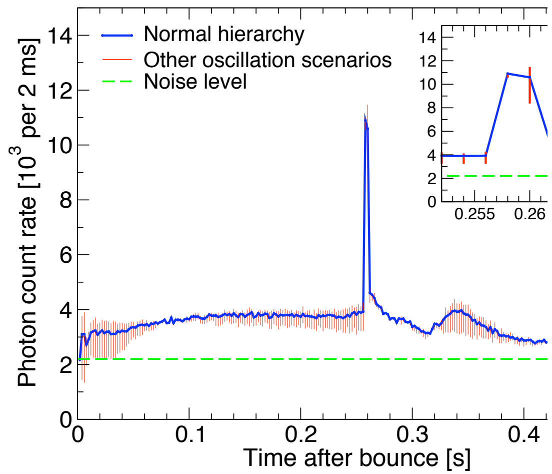
(Sagert, Fischer et al., PRL 2009)

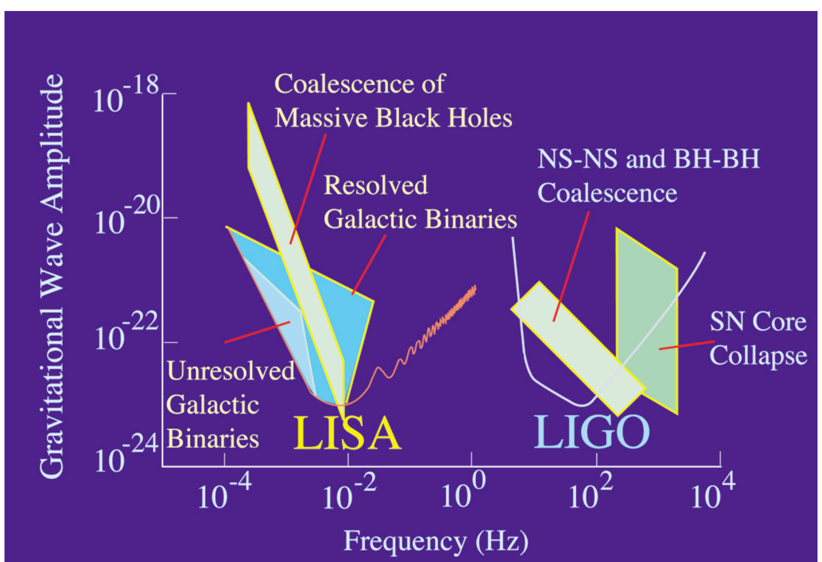
SN as QCD/Nucl. physics laboratory

Super-Kamiokande



IceCube





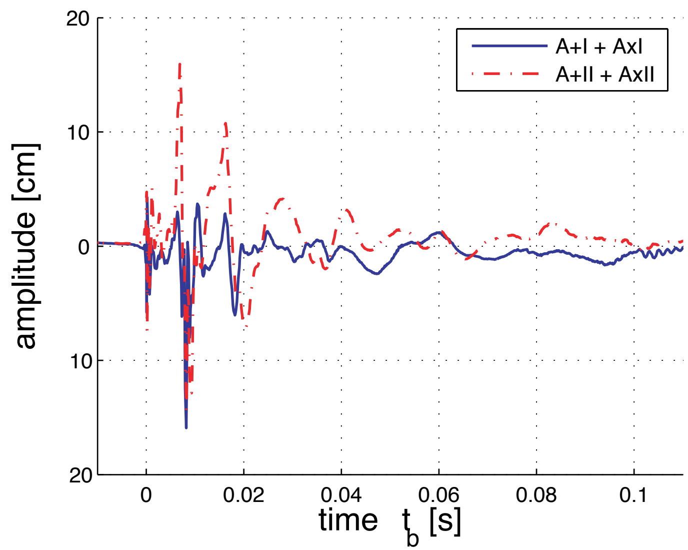
Neutrino signature from QCD phase transition in proto-neutron star

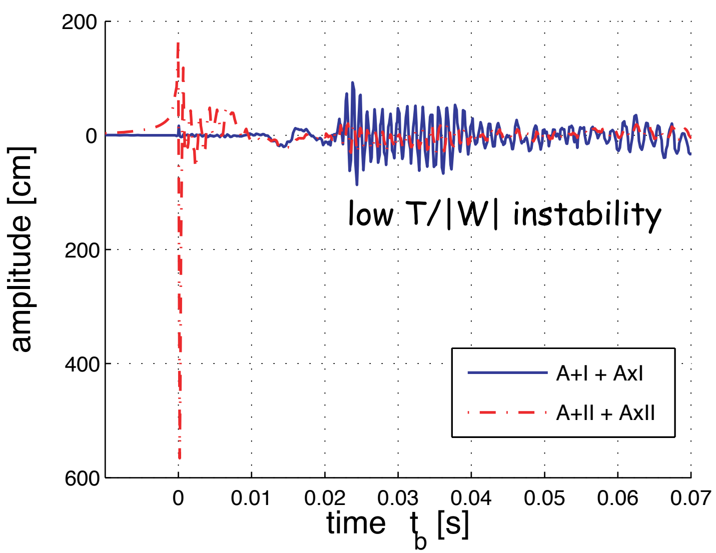
(Sagert, Fischer et al., PRL 2009, Dasgupta et al. arXiv:0912.2568)

Gravitational wave signal from 3D dynamics

These phenomena depend significantly on the thermodyn. features of the EoS

Gravitational waves in 3D





Scheidegger et al. 2008, in qualitative agreement with Ott et al. 2007

Slowly rotating 15Ms progenitor according to
(Heger, Woosley & Spruit 2005)

Fast rotating 15Ms progenitor
$\Omega \sim 2\pi$ rad/ps

--> imprint of bounce and rotation rate

Galactic supernova
- could (LIGO)
- should (Adv. LIGO)

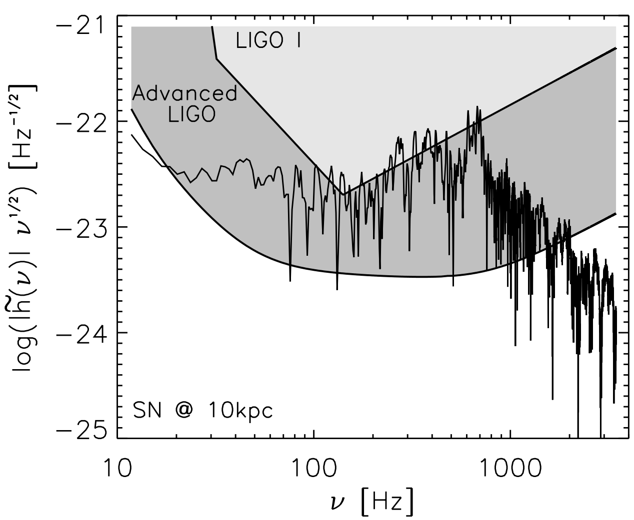
bee seen by GW detectors

LIGO, Livingston. Michelson Interferometer Other detectors: VIRGO, GEO600,TAMA300,AIGO,..

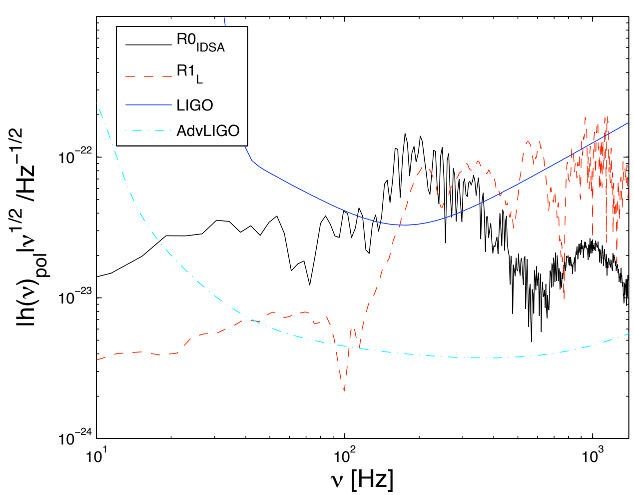
Large 3D GW parameter study

- Linear dependency of bounce signal on rotation rate confirmed. Dimmelmeier et al. 2008
- Confirmation of low-T/|W| instability for $\beta > 2.3\%$.
- Location and size of convectively unstable layer and postbounce neutrinos are key to the GW signal.
- No sensitivity to compressibility of equation of state, but to central Ye (asymmetry energy).

Müller et al. 2004



Scheidegger et al. CQG 2010



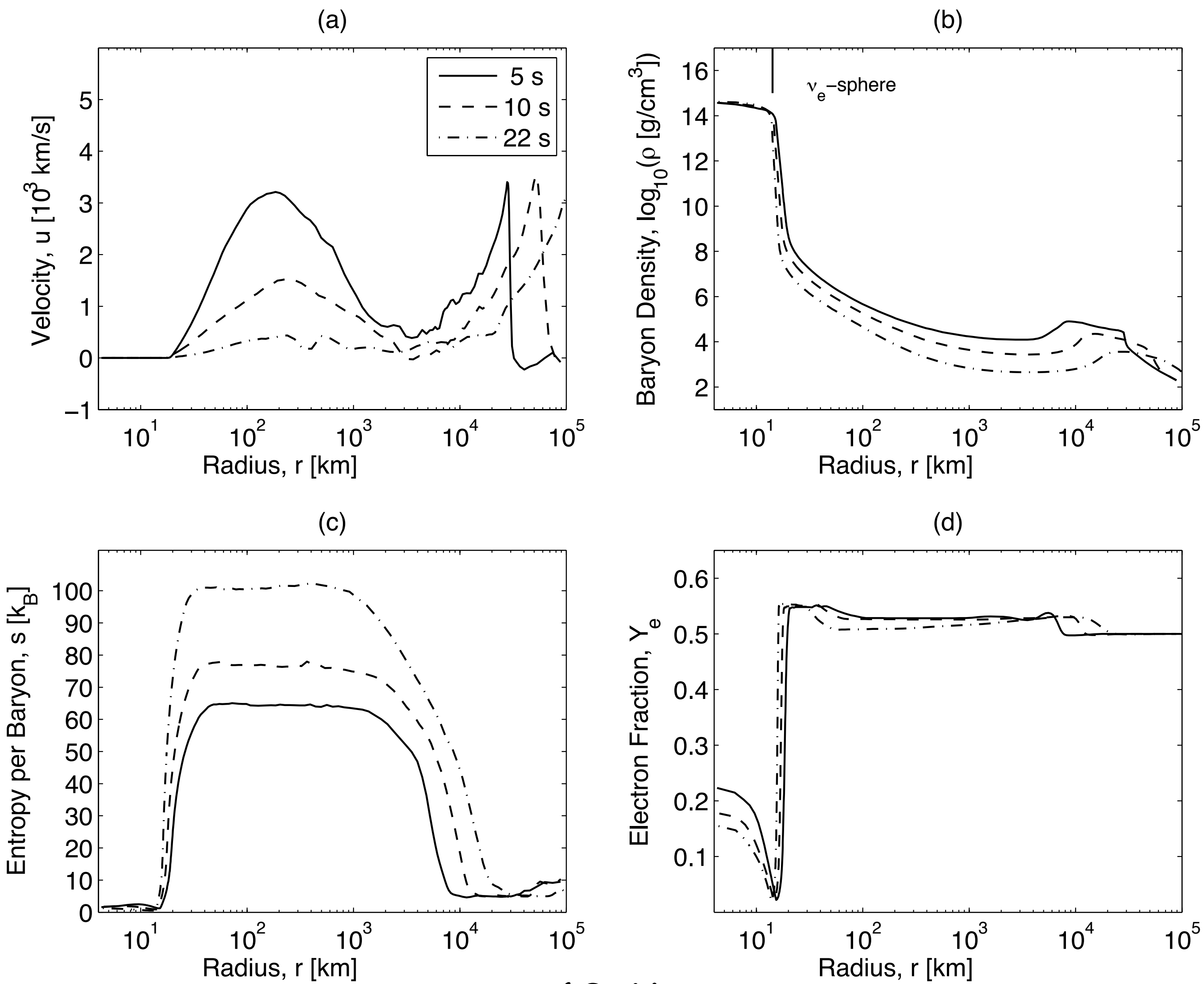
25 different models:

- different EoS
  LS K=180-375, Shen
- rotation rates
  0.3-4π rad/s
- magnetic field
  10^9 - 10^12 G

GW emission sensitive to $\rho r^2 \sim 10$km

Scheidegger et al. A&A 2010

Postexplosion phase: Boltzmann ν-transp.



18 Msun

Improvements allow for the first time for 1D simulations to run ~20s after bounce

Studies of explosions of 10 and 18 Msun progenitors based on enhanced ν rates.

ν-wind has rather high Ye (>~0.5), no r-process!

see Qian & Woosley. 1996
Fischer et al., arXiv:0908.1871
(confirmed in Hüdepohl et al. 2010)

Summary

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Spherically symmetric models with general relativistic Boltzmann neutrino transport speed up to tpb=20s:

- neutrino signal tells about thermodynamic conditions at neutrinospheres
- different explosion scenarios can be distinguished
- the QCD phase-transition induced explosion mechanism would lead to characteristic ν signal
- ν-wind for low mass progenitors, no r-process in spherical symmetry

Three-dimensional models gain terrain:

- Necessary to establish constraints on microscopic input physics and to investigate magnetic fields
- IDSA is an efficient transport approximation and compares well with Boltzmann results in 1D
- IDSA enables first 3D prediction of GW signal with spectral neutrino treatment and low T/W instability

Next galactic supernova: A high-density physics laboratory!

Next steps:

- long term 3D postbounce evolution
- different EoS for phase transition
- comparison with axisymmetry
- magnetic fields
- neutrino oscillations