Neutrino transport for 3D supernova models

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with
- T. Fischer
- R. Käppeli
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- U.-L. Pen
- S. Scheidegger
- F.-K. Thielemann
- S. C. Whitehouse

- Introduction to the core-collapse explosion mechanism
- Neutrino transport in core-collapse supernova models
- Efficient ν-transport approximation for 3D MHD models

The cosmic kitchen...

The cosmic kitchen...

The cosmic kitchen...

Supernova Observables

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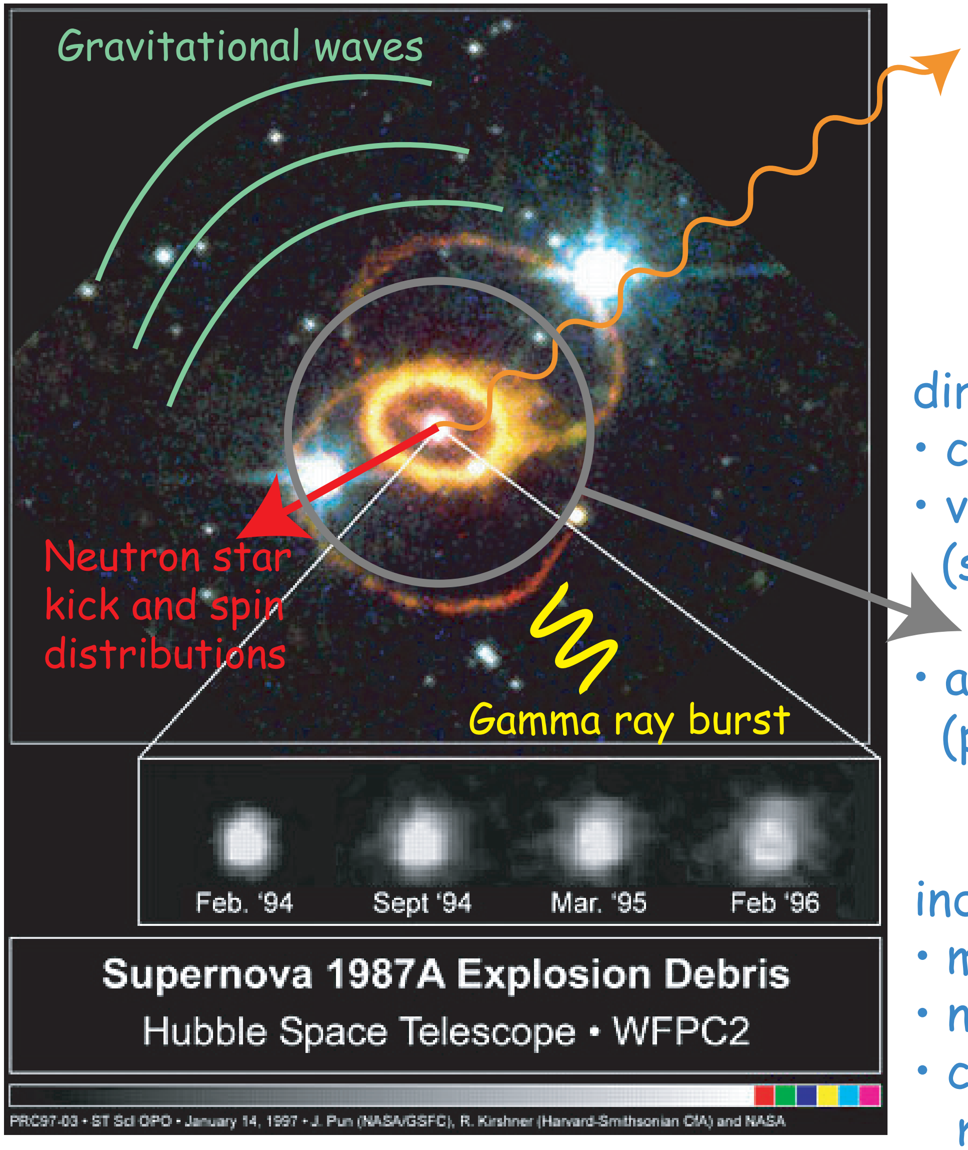


PRC97-03 • ST ScI OPO • January 14, 1997 • J. Pun (NASA/GSFC), R. Kirshner (Harvard-Smithsonian CfA) and NASA

neutrino signal from interior

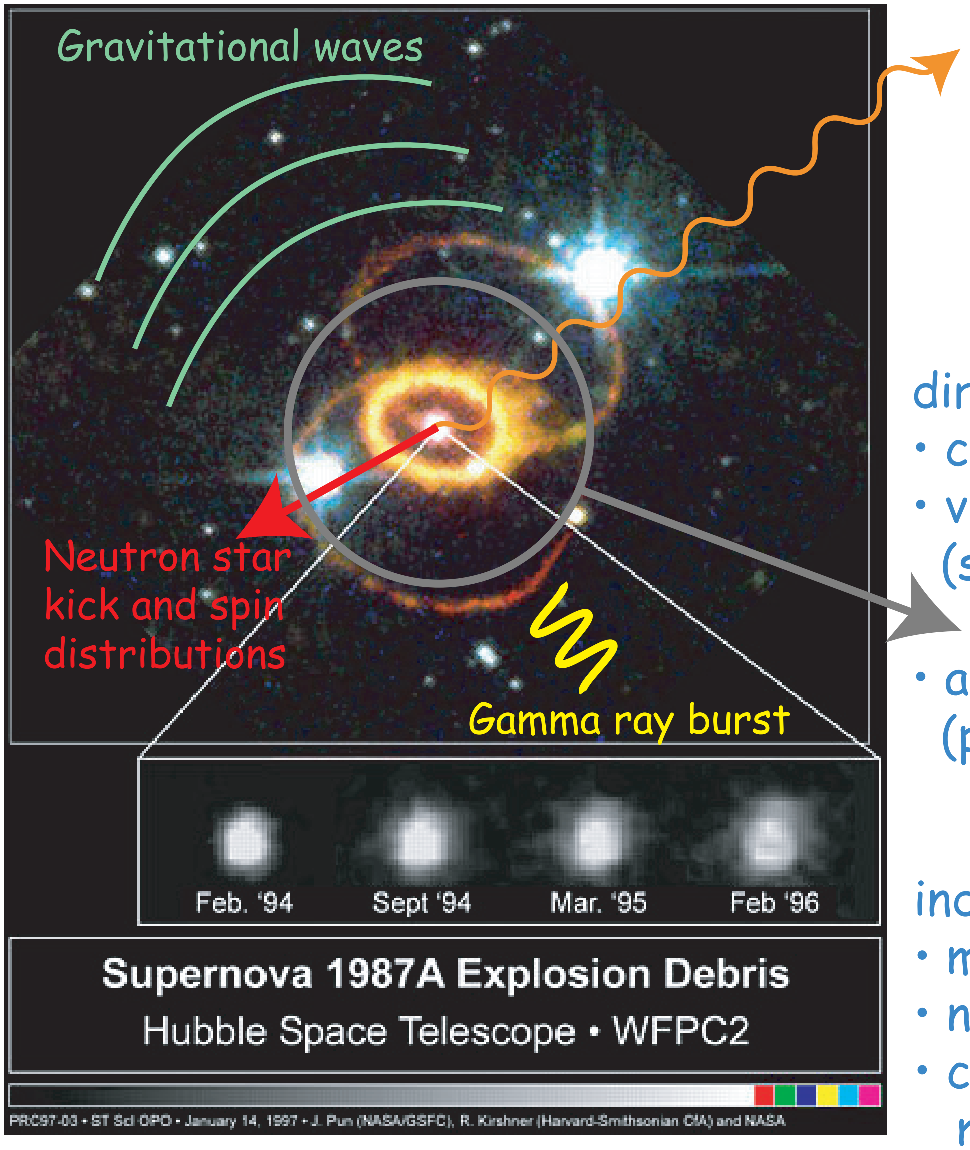
direct ejecta:

- composition
- velocity (spectra)
- asymmetry (polarization)

indirect ejecta

- mixing with ISM
- new star formation
- contamination of metal-poor stars

Supernova Observables



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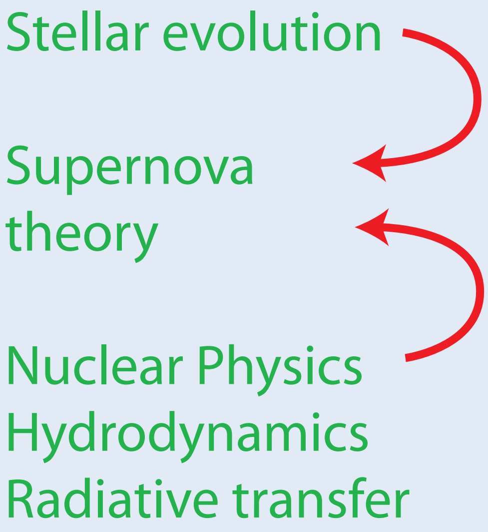
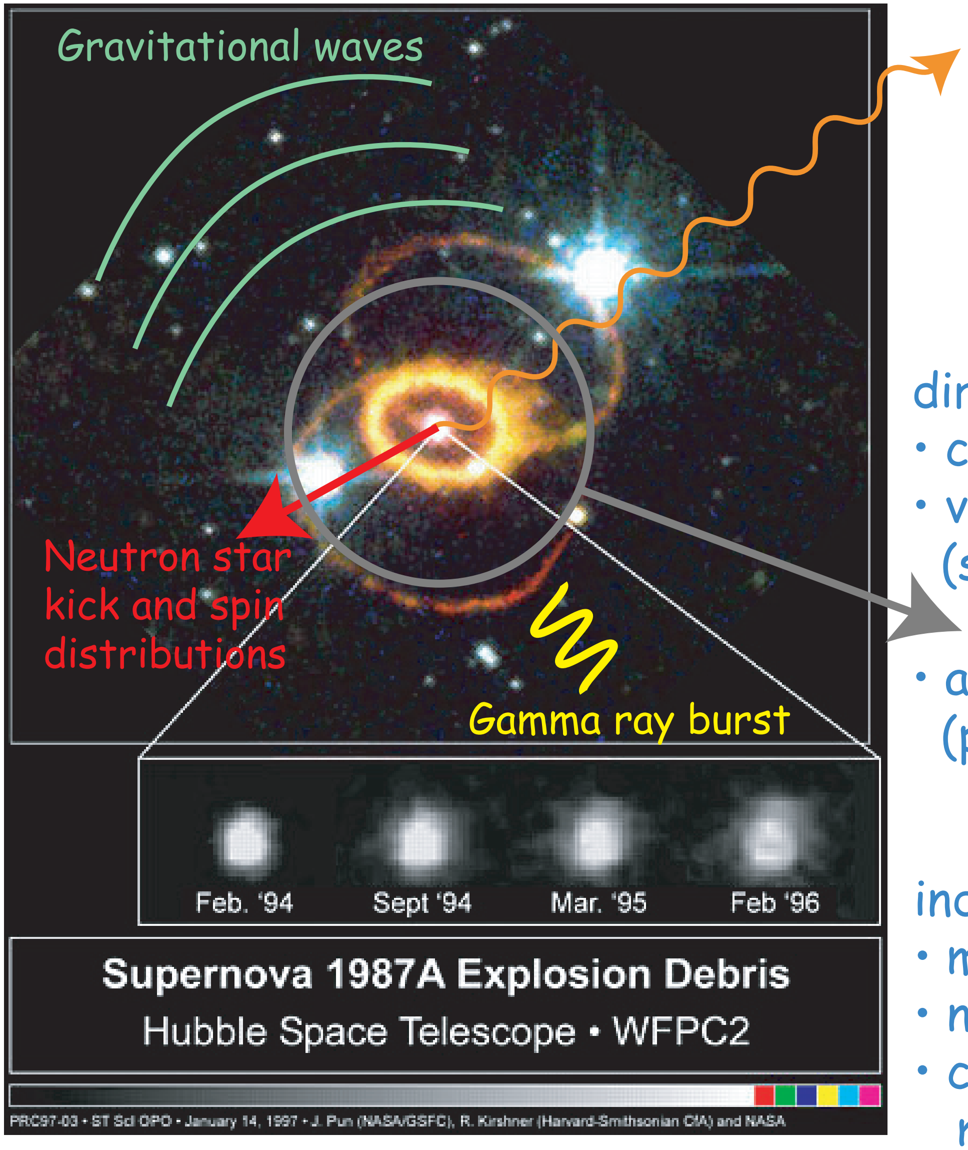


Stellar evolution

Supernova theory

Nuclear Physics
Hydrodynamics
Radiative transfer

Supernova Observables



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Cosmology

Galactic evolution

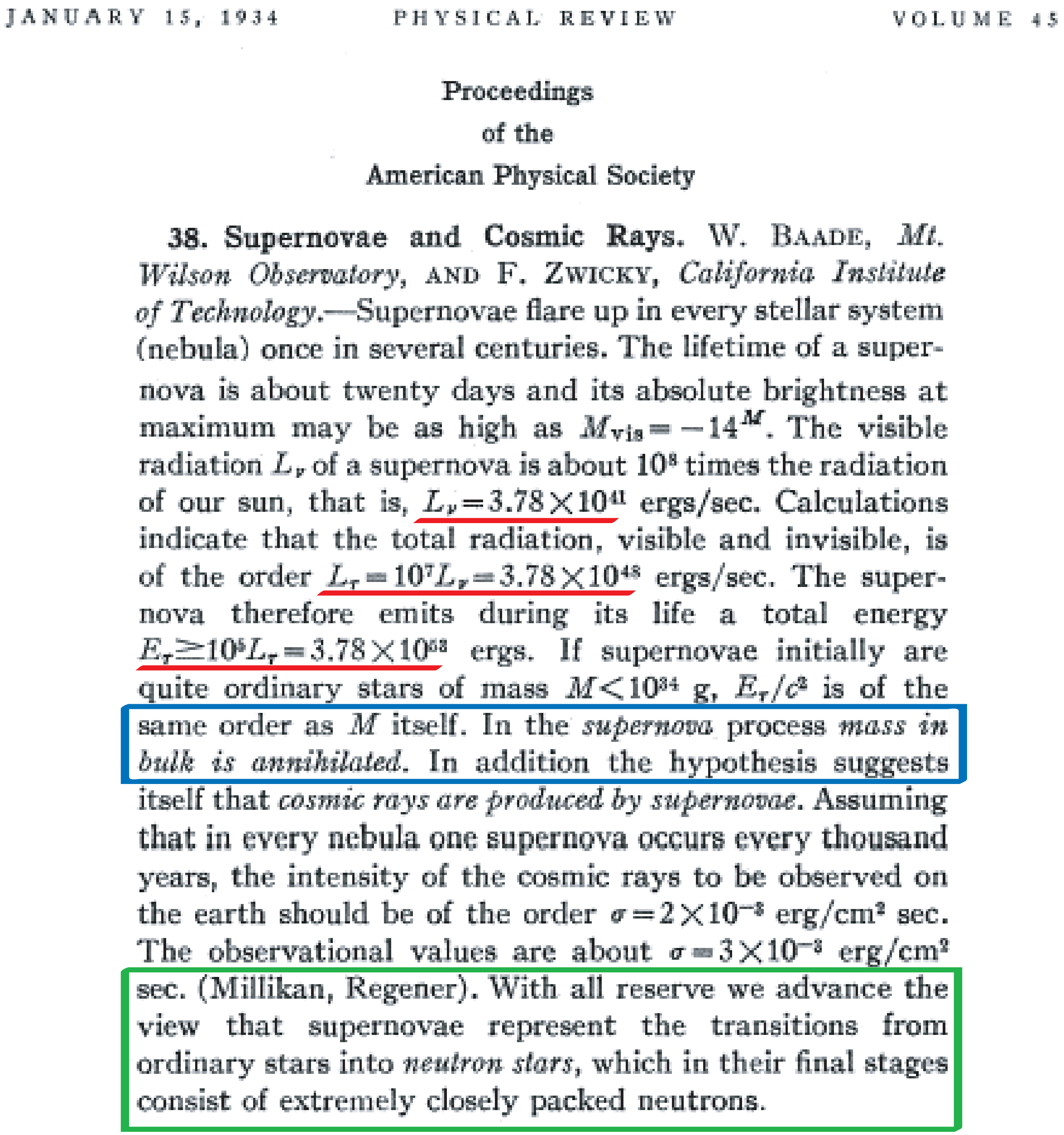
Stellar evolution

Supernova theory

Nuclear Physics
Hydrodynamics
Radiative transfer

Make extreme conditions of matter observable...

Core collapse supernova



JANUARY 15, 1934 PHYSICAL REVIEW VOLUME 45

Proceedings
of the
American Physical Society

38. Supernovae and Cosmic Rays. W. Baade, *Mt. Wilson Observatory,* and F. Zwicky, *California Institute of Technology.*—Supernovae flare up in every stellar system (nebula) once in several centuries. The lifetime of a supernova is about twenty days and its absolute brightness at maximum may be as high as $M_{\mathrm{vis}} = -14^M$. The visible radiation L_ν of a supernova is about 10^8 times the radiation of our sun, that is, $L_\nu = 3.78\times 10^{41}$ ergs/sec. Calculations indicate that the total radiation, visible and invisible, is of the order $L_\tau = 10^7 L_\nu = 3.78\times 10^{48}$ ergs/sec. The supernova therefore emits during its life a total energy $E_\tau \geq 10^5 L_\tau = 3.78\times 10^{53}$ ergs. If supernovae initially are quite ordinary stars of mass $M < 10^{34}$ g, E_τ/c^2 is of the same order as M itself. In the *supernova* process *mass in bulk is annihilated.* In addition the hypothesis suggests itself that *cosmic rays are produced by supernovae.* Assuming that in every nebula one supernova occurs every thousand years, the intensity of the cosmic rays to be observed on the earth should be of the order $\sigma = 2\times 10^{-3}$ erg/cm² sec. The observational values are about $\sigma = 3\times 10^{-3}$ erg/cm² sec. (Millikan, Regener). With all reserve we advance the view that supernovae represent the transitions from ordinary stars into *neutron stars,* which in their final stages consist of extremely closely packed neutrons.

Huge Energies

- neutrinos:
~1e+53 erg

- mechanical:
~1e+51 erg

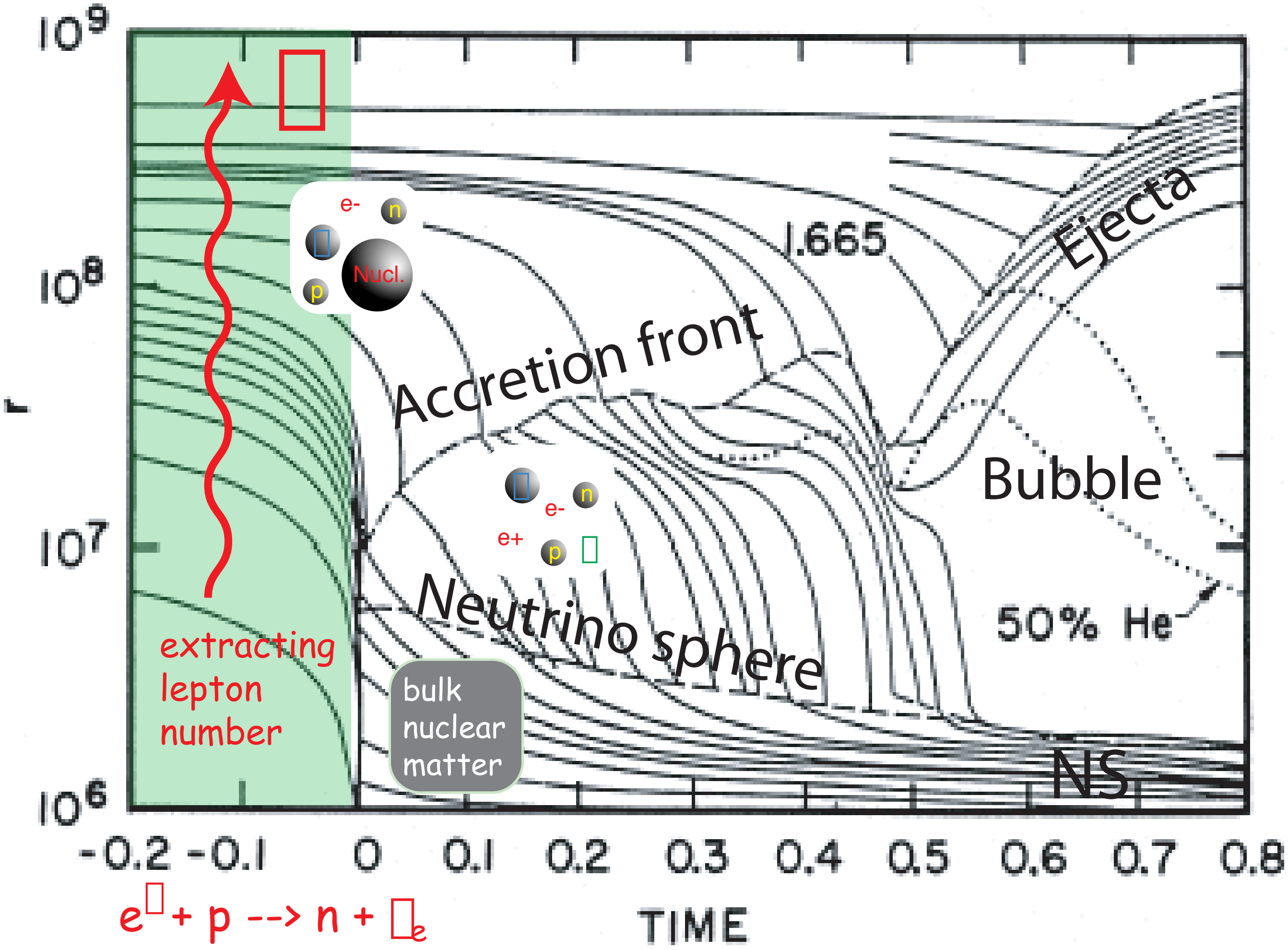
- electro-magn.:
~1e+48 erg elmag

- visible:
~1e+41 erg visible

56Ni -> 56Co ->56Fe
~6d ~110d

Delayed explosion: 4 phases

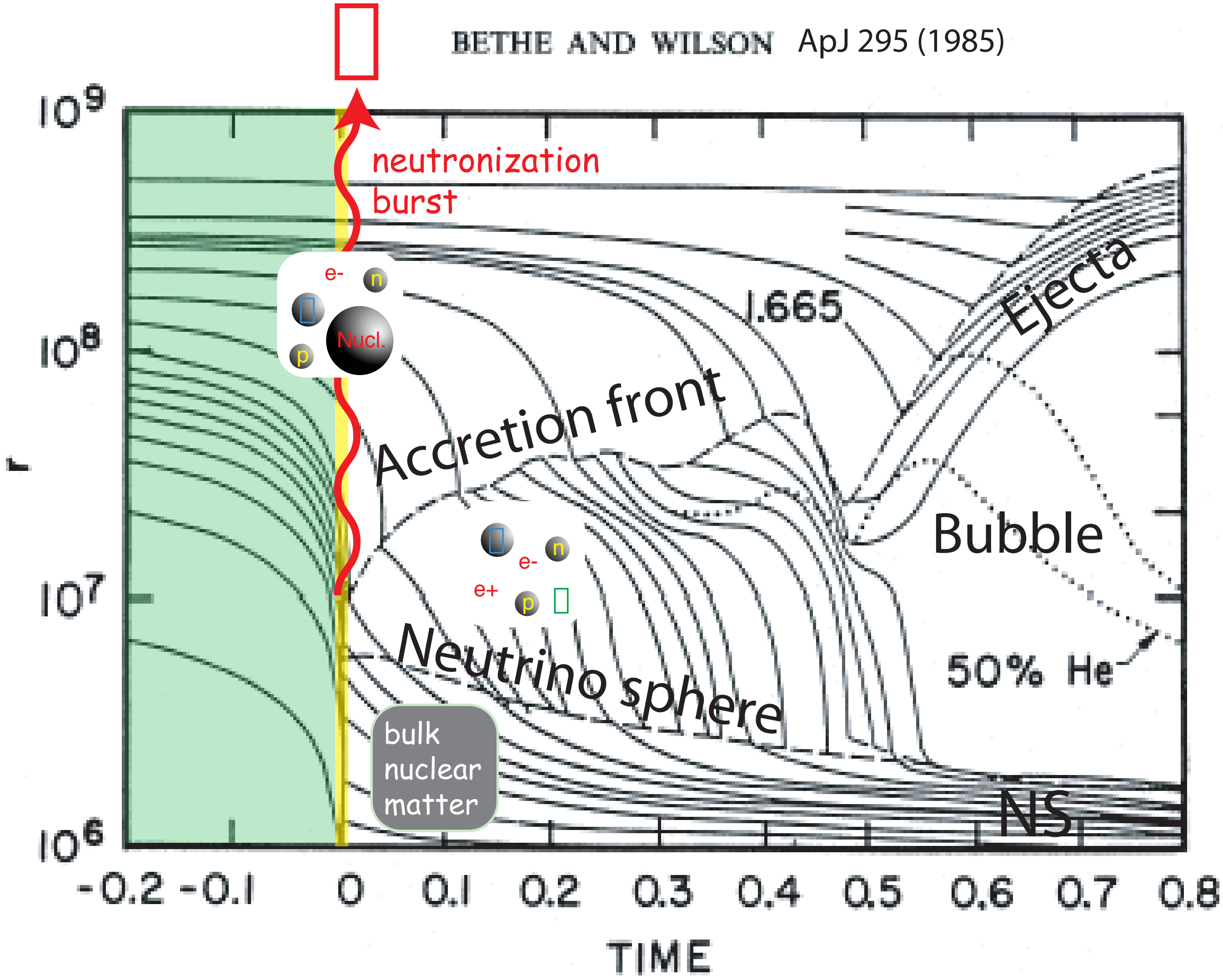
BETHE AND WILSON ApJ 295 (1985)



Colgate & White, ApJ 143 (1966)

1) Collapse

Delayed explosion: 4 phases



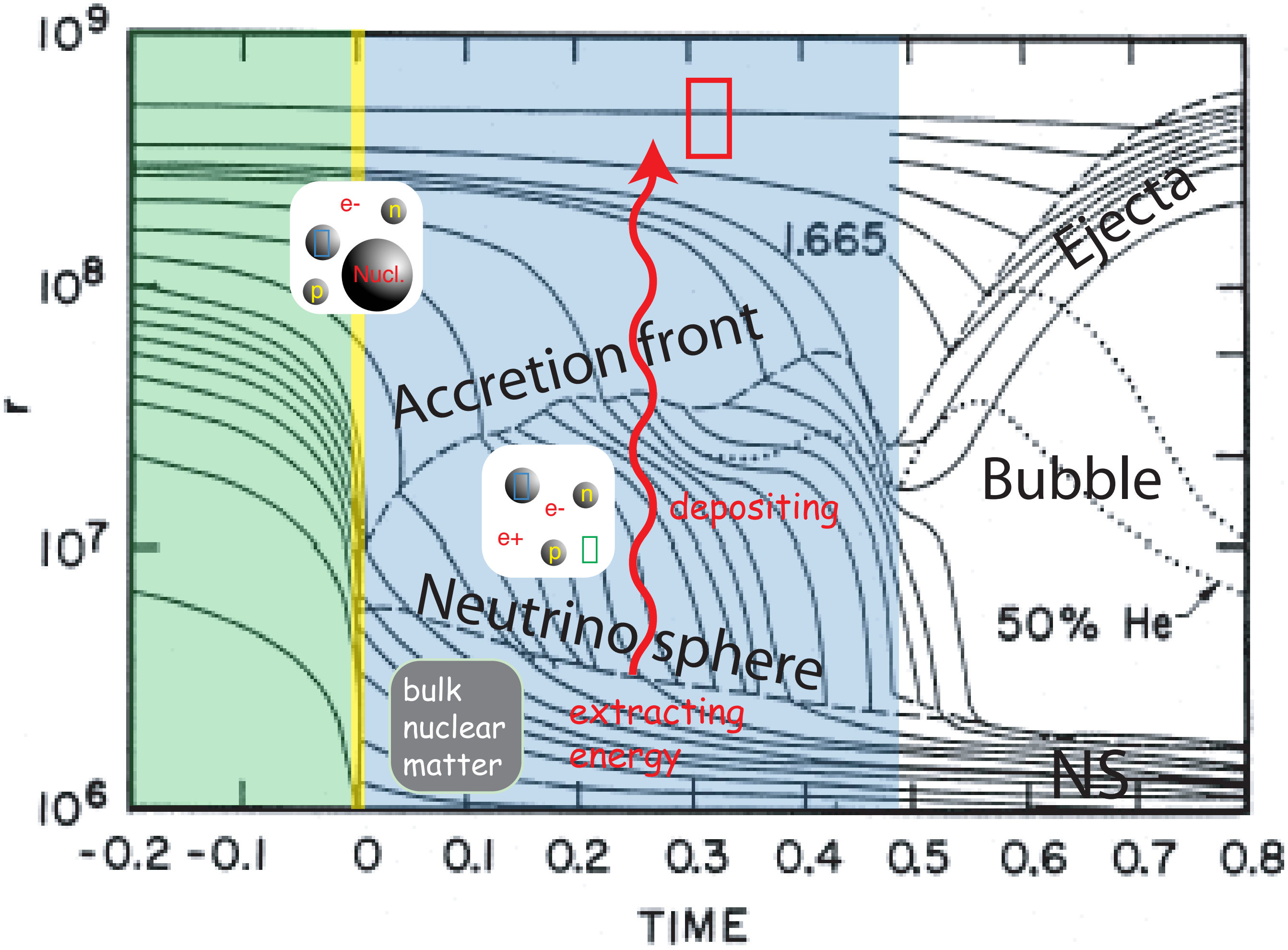
Colgate & White, ApJ 143 (1966)

1) Collapse

2) Bounce

Delayed explosion: 4 phases

BETHE AND WILSON ApJ 295 (1985)



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1) Collapse

2) Bounce

3) Accretion

Delayed explosion: 4 phases

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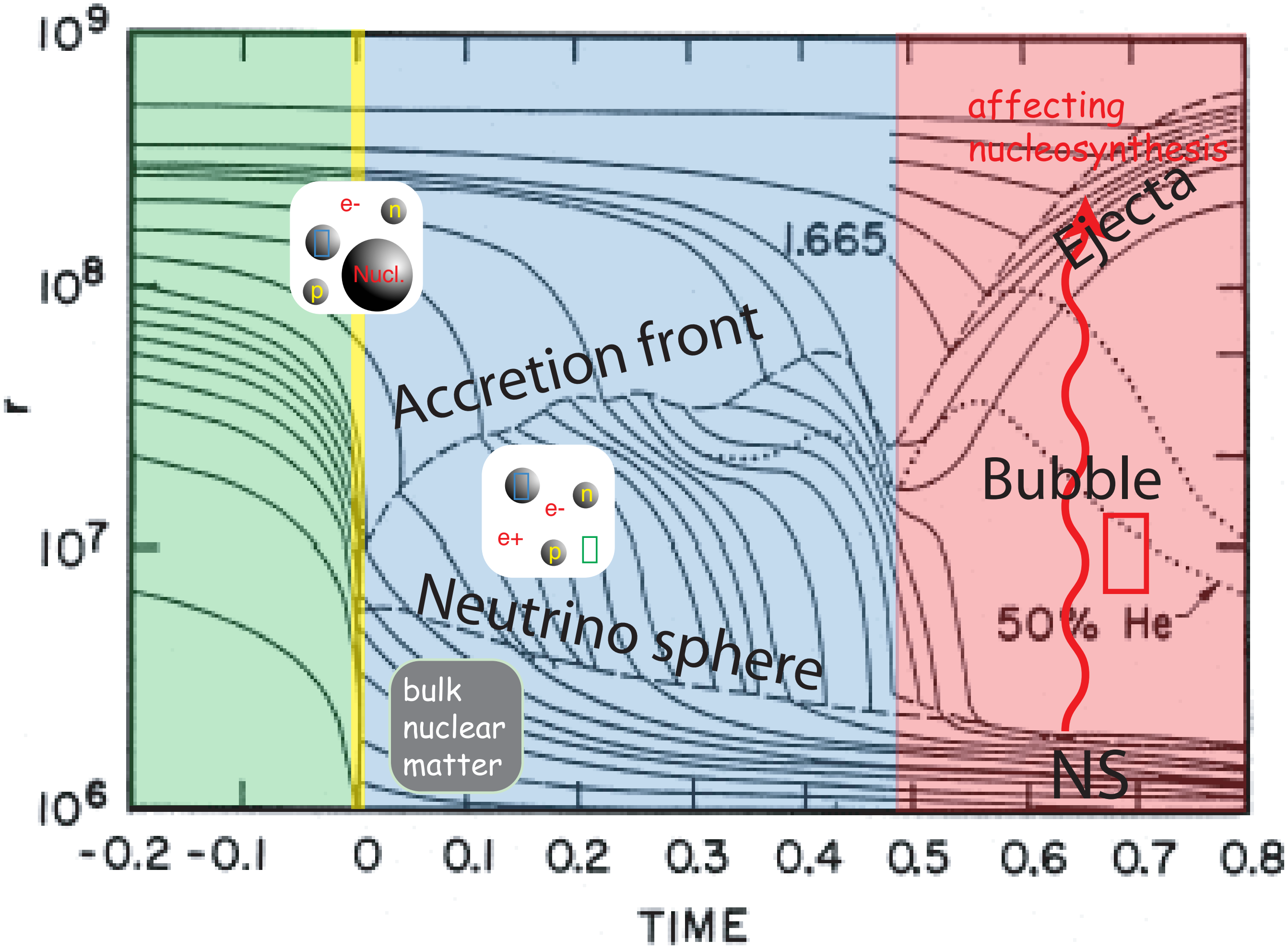


Colgate & White, ApJ 143 (1966)

1) Collapse

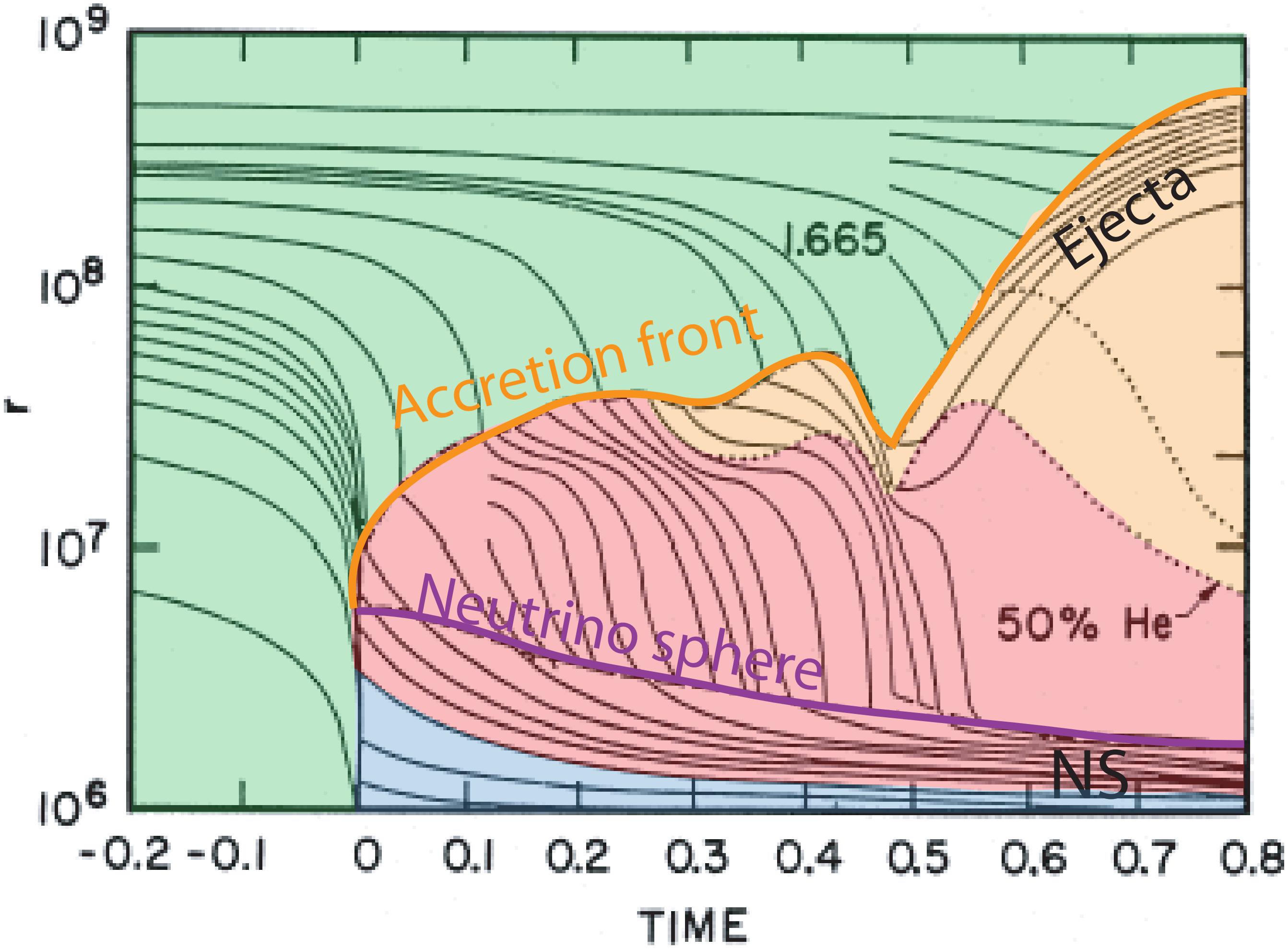
2) Bounce

3) Accretion

4) Explosion

Overview matter conditions

BETHE AND WILSON ApJ 295 (1985)



Colgate & White, ApJ 143 (1966)

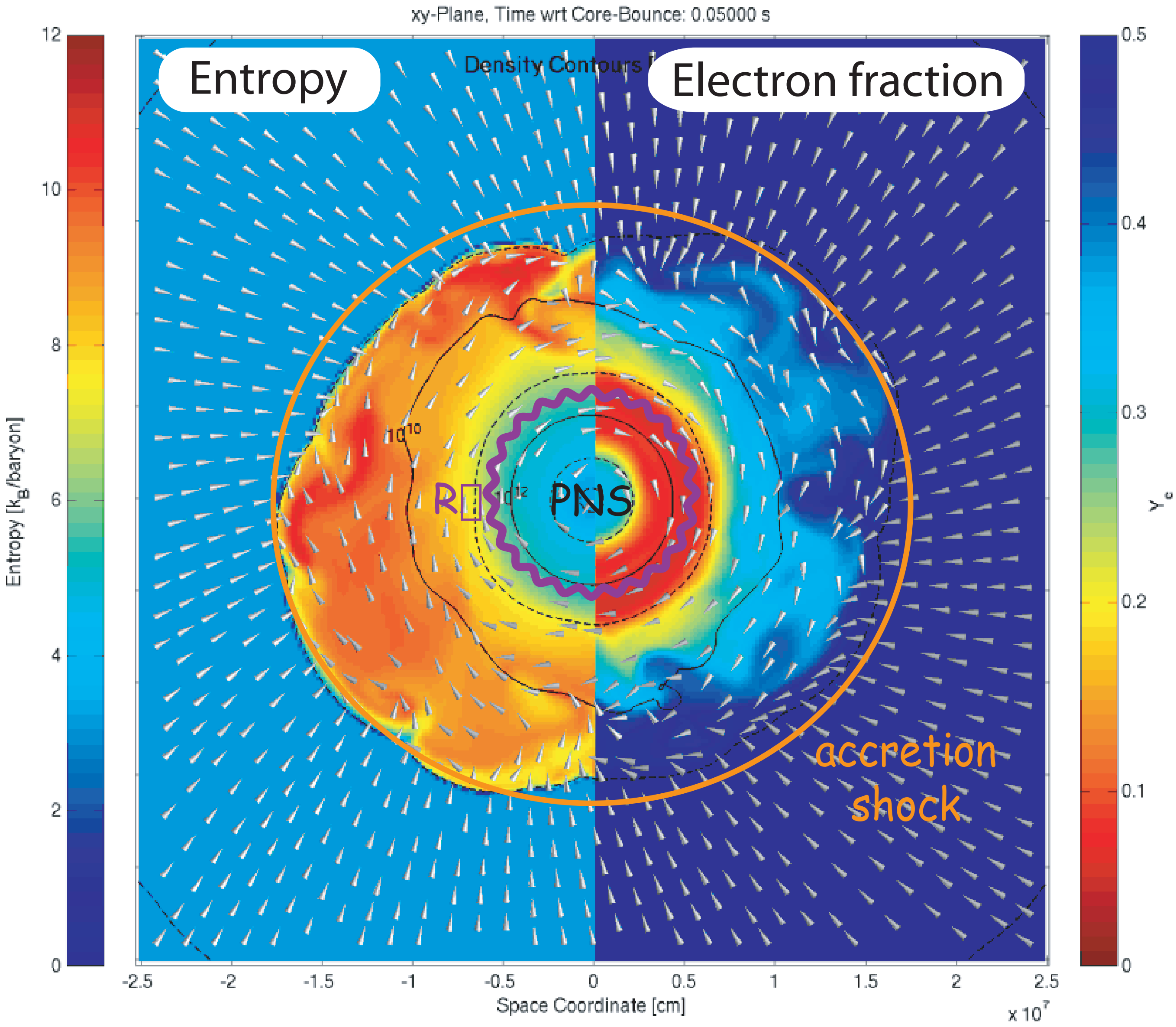
1) Ensemble
of nuclei

2) Cool bulk
nuclear matter

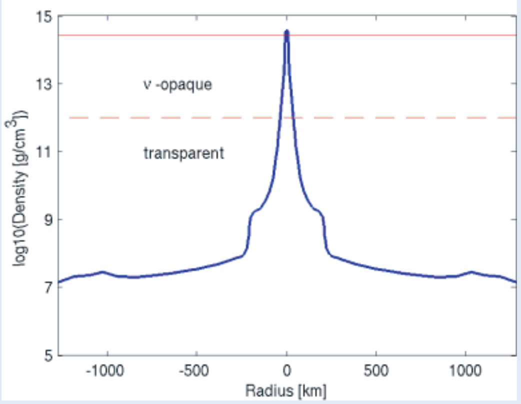
3) Hot dissociated

4) Freeze-out
of nuclei

Complex 3D surface-phenomenon

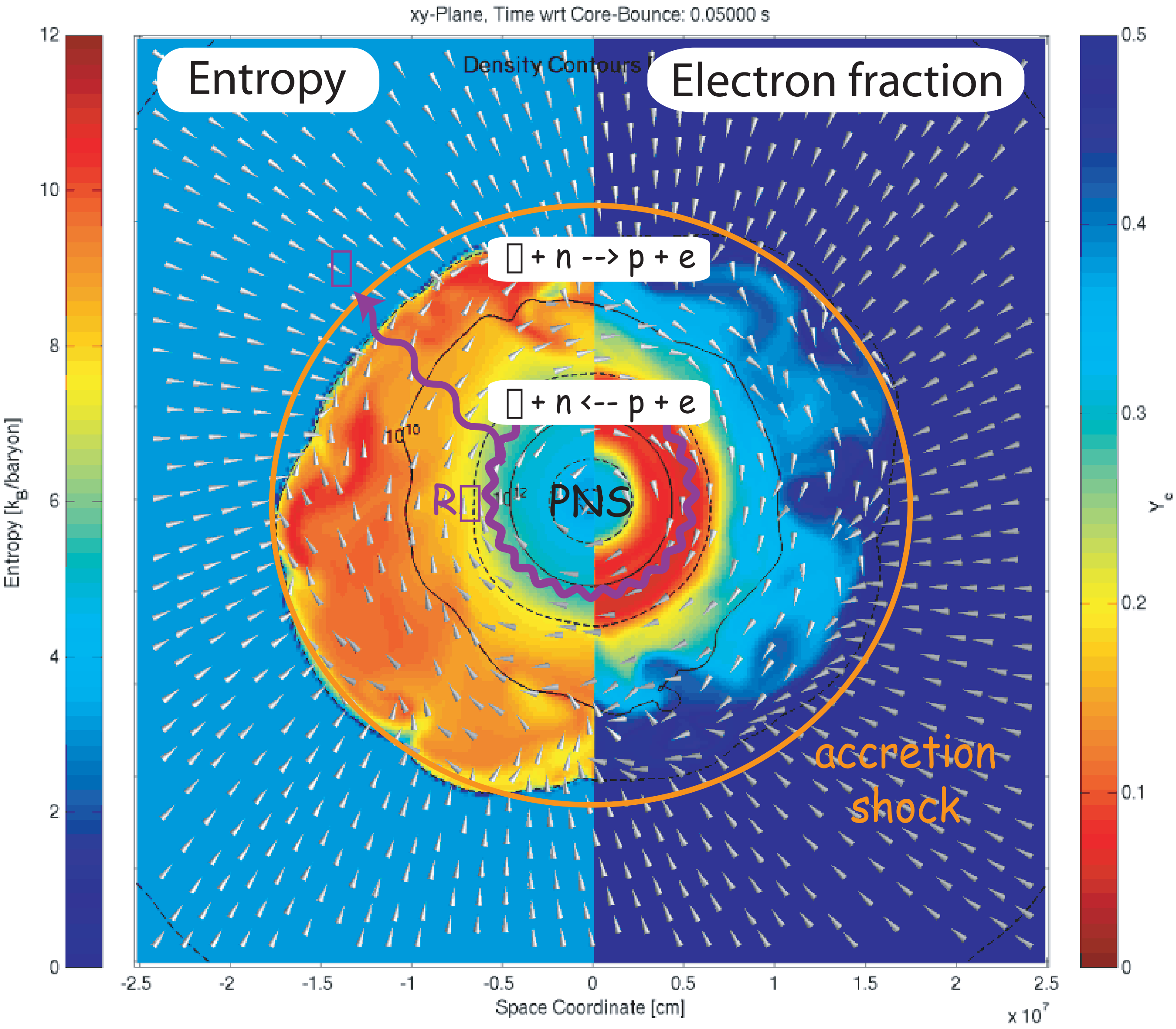


- The supernova explosion takes place on the surface of the protoneutron star



- The transport of lepton number and energy by neutrinos plays a key role for the dynamical evolution

Complex 3D surface-phenomenon



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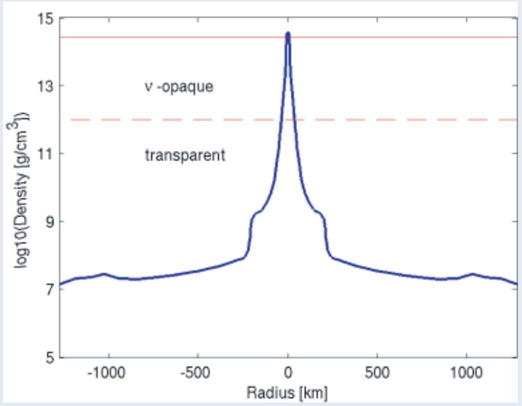

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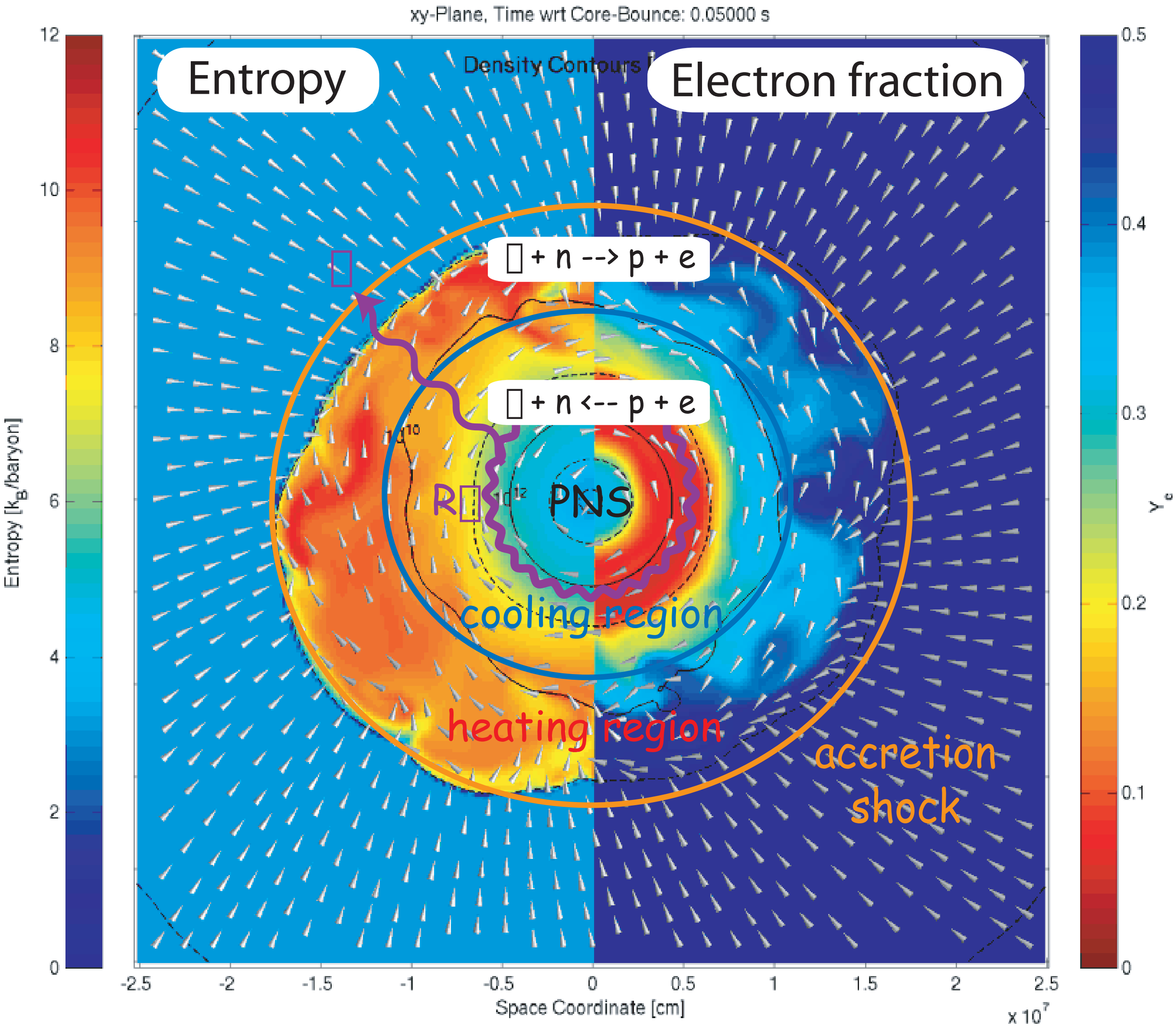

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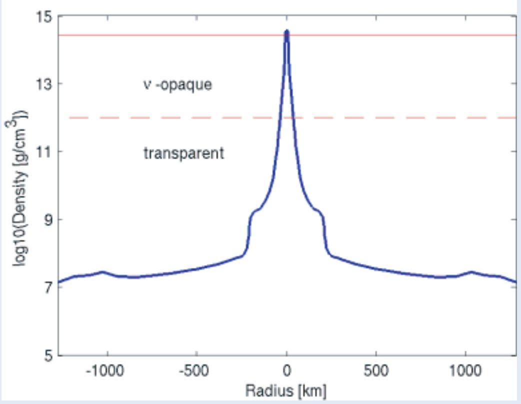


- The transport of lepton number and energy by neutrinos plays a key role for the dynamical evolution

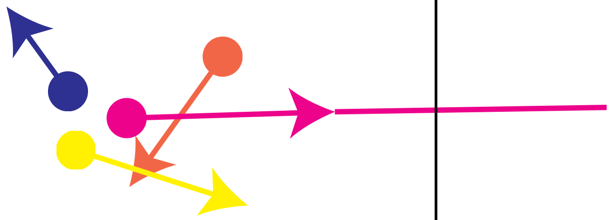
Neutrino-matter interactions

Bruenn (1985)
Raffelt (2001)

Description: Number Sphere | Energy Sphere | Transport Sphere

High matter density

Emission &
Absorption



Can be Pauli-
blocked in
diffusive
regime

Low matter density

Production/Annihilation

Electron or Positron capture

$$\nu_e + n \rightleftharpoons e^- + p$$
$$\bar{\nu}_e + p \rightleftharpoons e^+ + n$$
$$\nu_e + (A,Z) \rightleftharpoons e^- + (A,Z+1)$$

NN bremsstrahlung (Thompson et al. 2002)

□e pair --> □□ pair (Buras et al. 2003)

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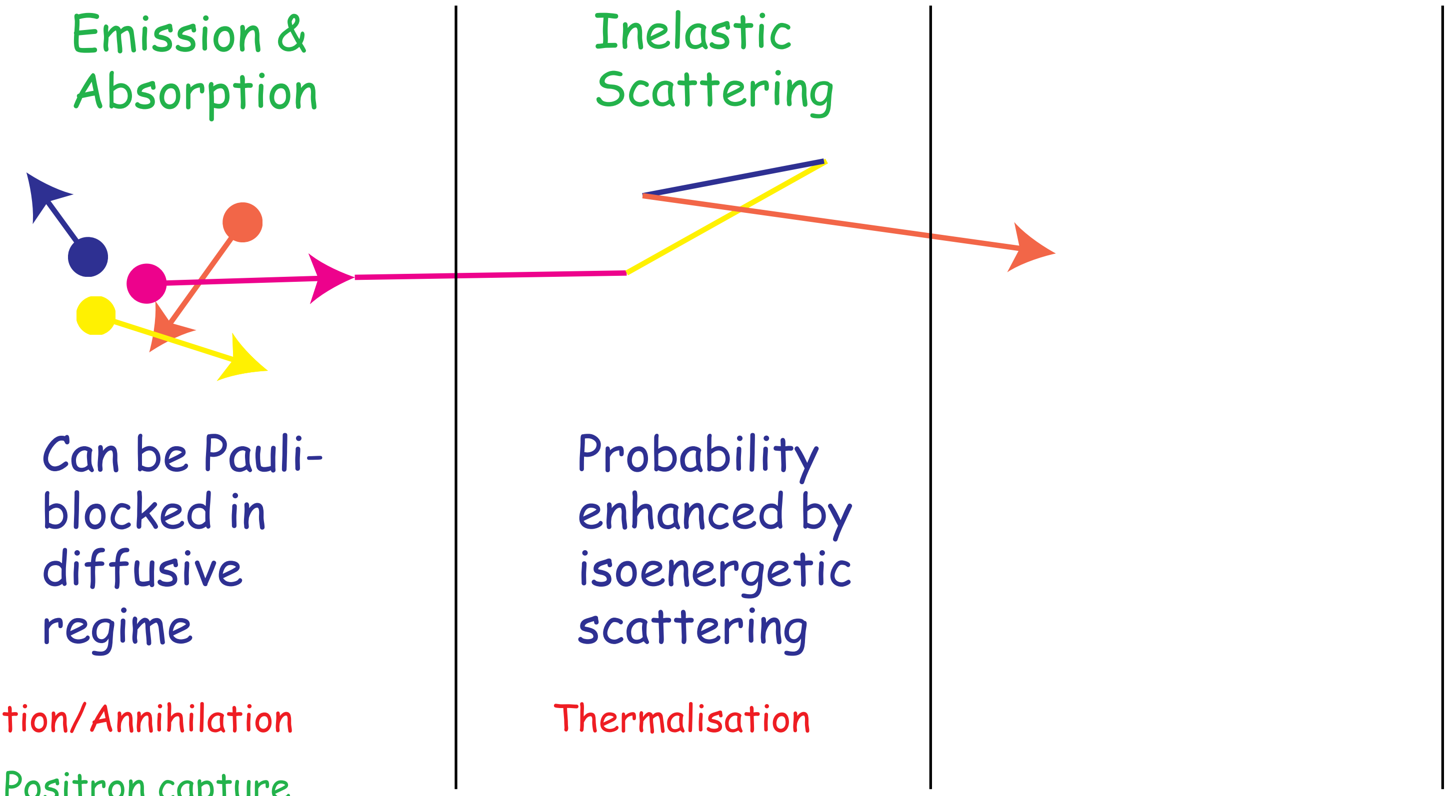

Description:

Number Sphere

Energy Sphere

Transport Sphere

High matter density

Low matter density

Emission & Absorption

Can be Pauli-blocked in diffusive regime

Inelastic Scattering

Probability enhanced by isoenergetic scattering

Production/Annihilation

Thermalisation

Electron or Positron capture

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Neutrino-electron scattering

$$\nu + e \rightleftharpoons \nu + e$$

Inelastic neutrino-nucleus scattering

Neutrino-matter interactions

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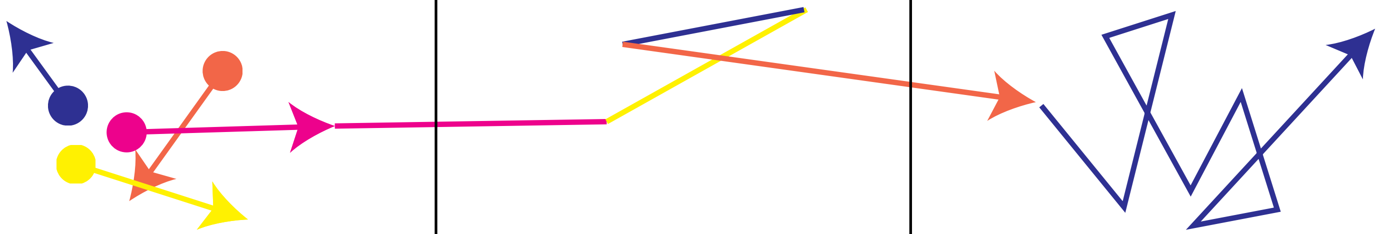
Description:

Number Sphere

Energy Sphere

Transport Sphere

High matter density



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Thermalisation

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$$\nu + e \rightleftharpoons \nu + e$$

Inelastic neutrino-nucleus scattering

Isoenergetic Scattering

Strong energy dependence, ~E^2

Scattering

Elastic coherent scattering of neutrinos on nuclei

$$\nu + (A,Z) \rightleftharpoons \nu + (A,Z)$$

Neutrino-nucleon scattering

$$\nu + N \rightleftharpoons \nu + N$$

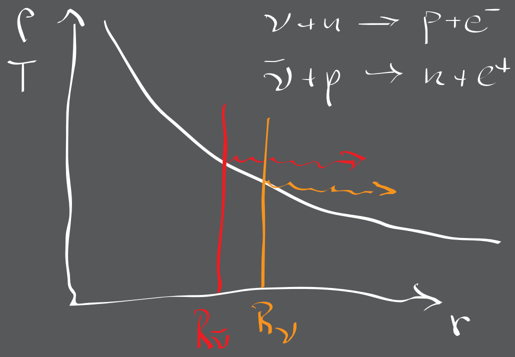
Low matter density

Streaming

Different luminosity contributions

- Luminosity composed of two parts:

2) neutrinos of cooling protoneutron star



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

$\bar\nu + p \rightarrow n + e^+$

neutron rich

$n_n > n_p$

$\Rightarrow E_{\bar\nu} > E_\nu$

- Classical hierarchy among neutrino energies reflects teperature at neutrinospheres

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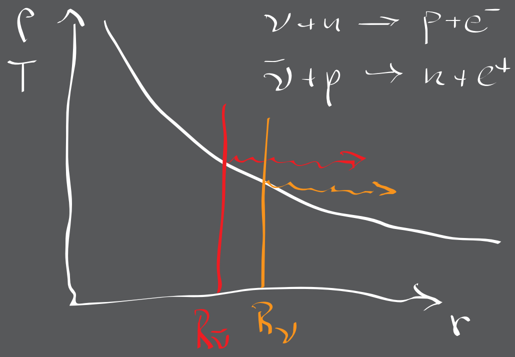

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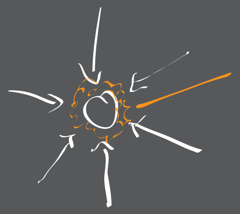
1) neutrinos from accretion flow



compression of degenerate electron gas

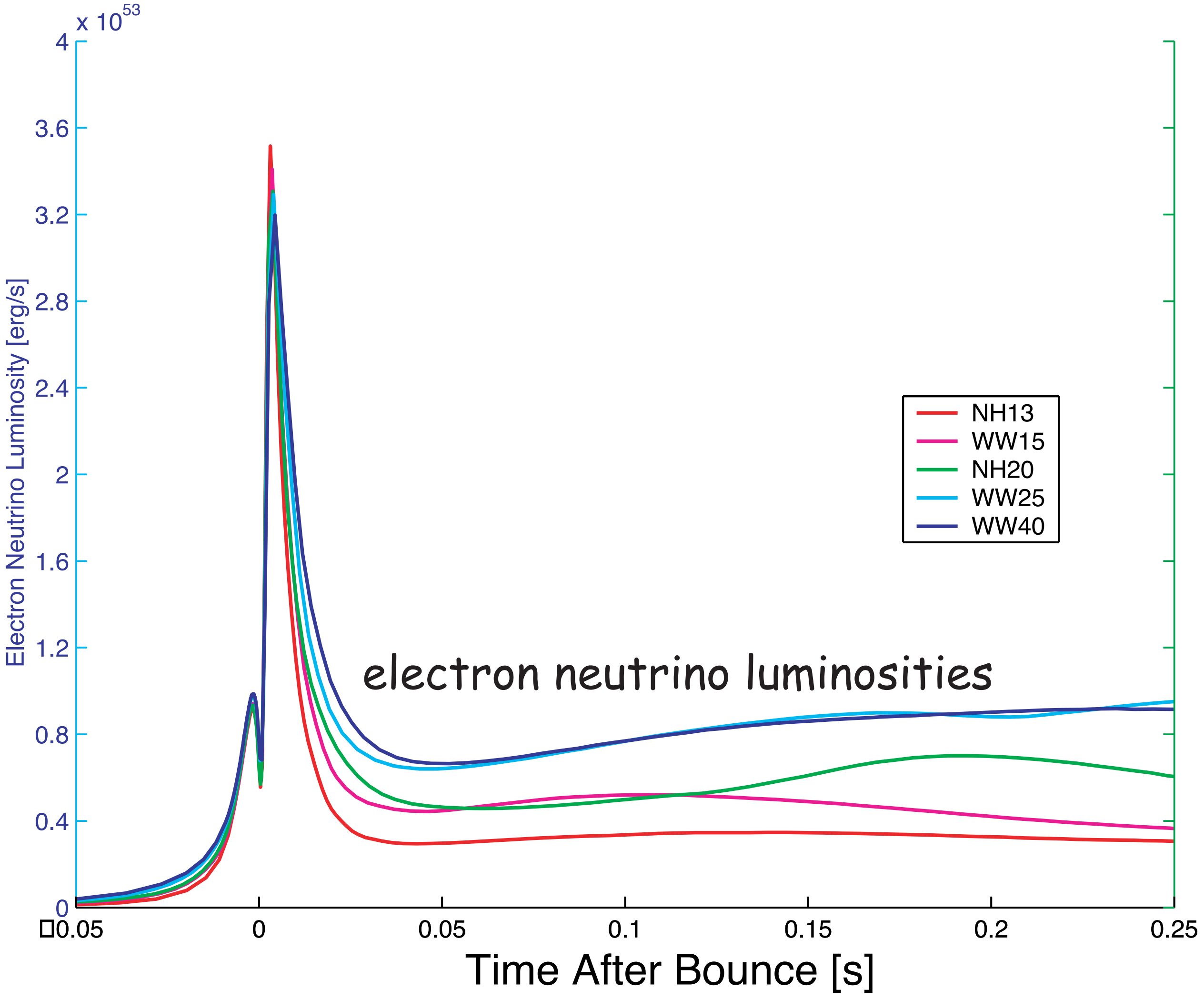
$\Rightarrow e^- + p \rightarrow n + \nu$

- Classical hierarchy among neutrino energies reflects teperature at neutrinospheres

- large accretion rate

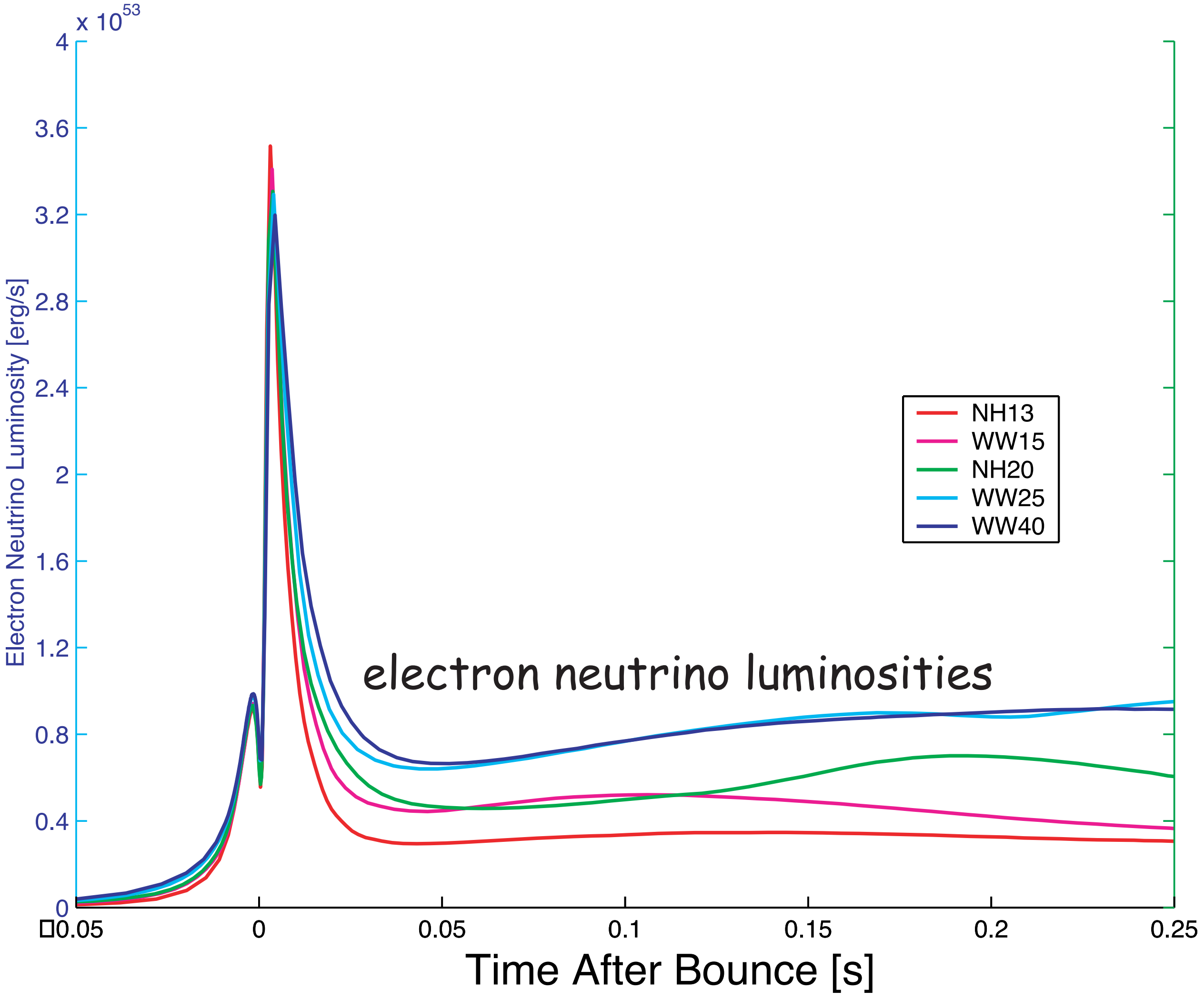
--> Lnu ~ Lnubar

Neutrino signal



- initially similar luminosities
- differences appear in accretion phase
- >50% accretion lumin.
- density profiles in outer progenitor layers very different

Neutrino signal



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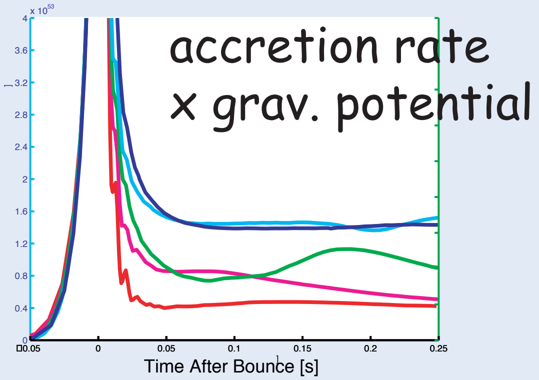
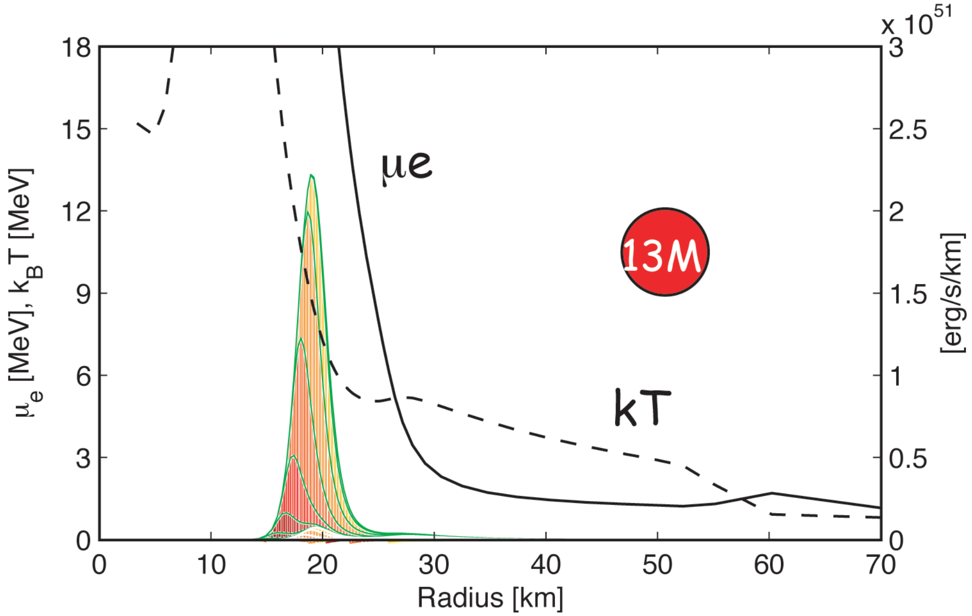


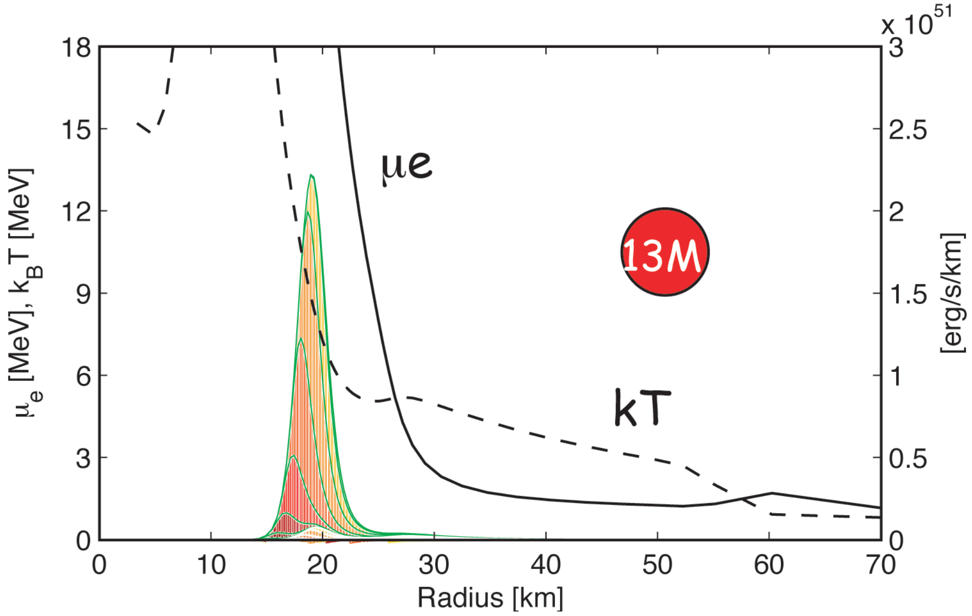
accretion rate
x grav. potential

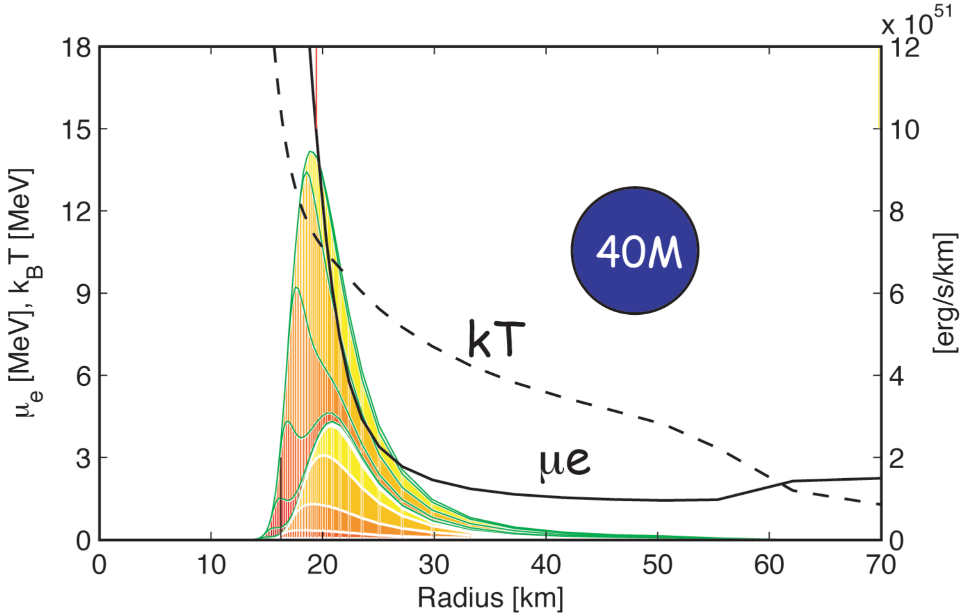
PNS evolution & □(□/□) properties



- low mass proto-neutron star (PNS)
  --> incompressible accretion

PNS evolution & □(□/□) properties





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- PNS close to maximum mass
  --> hot layers pushed inward

PNS evolution & □(□/□) properties

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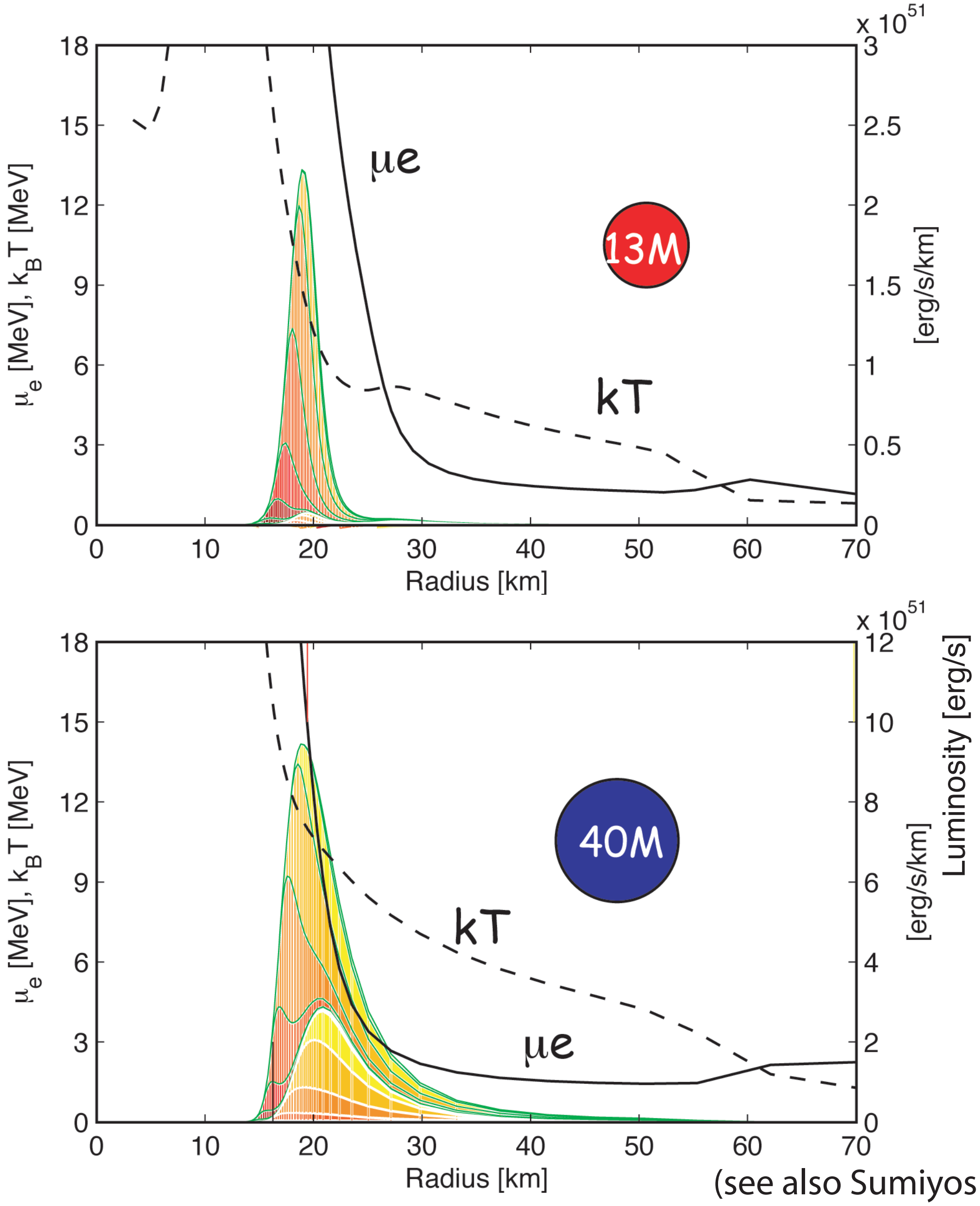
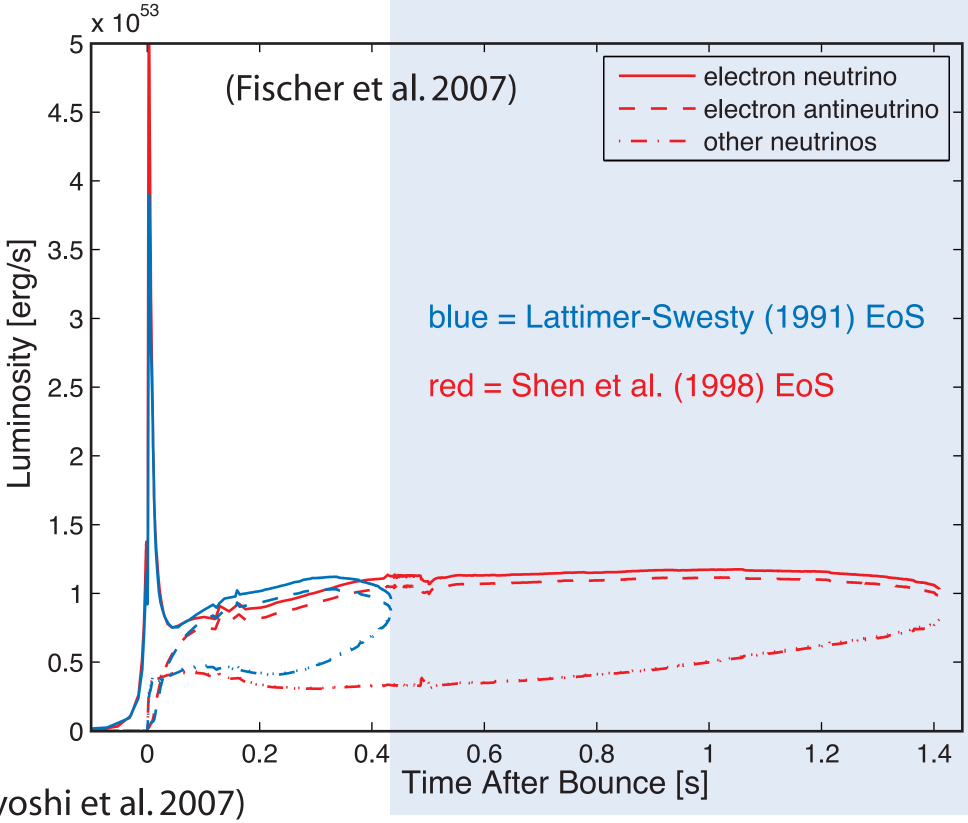




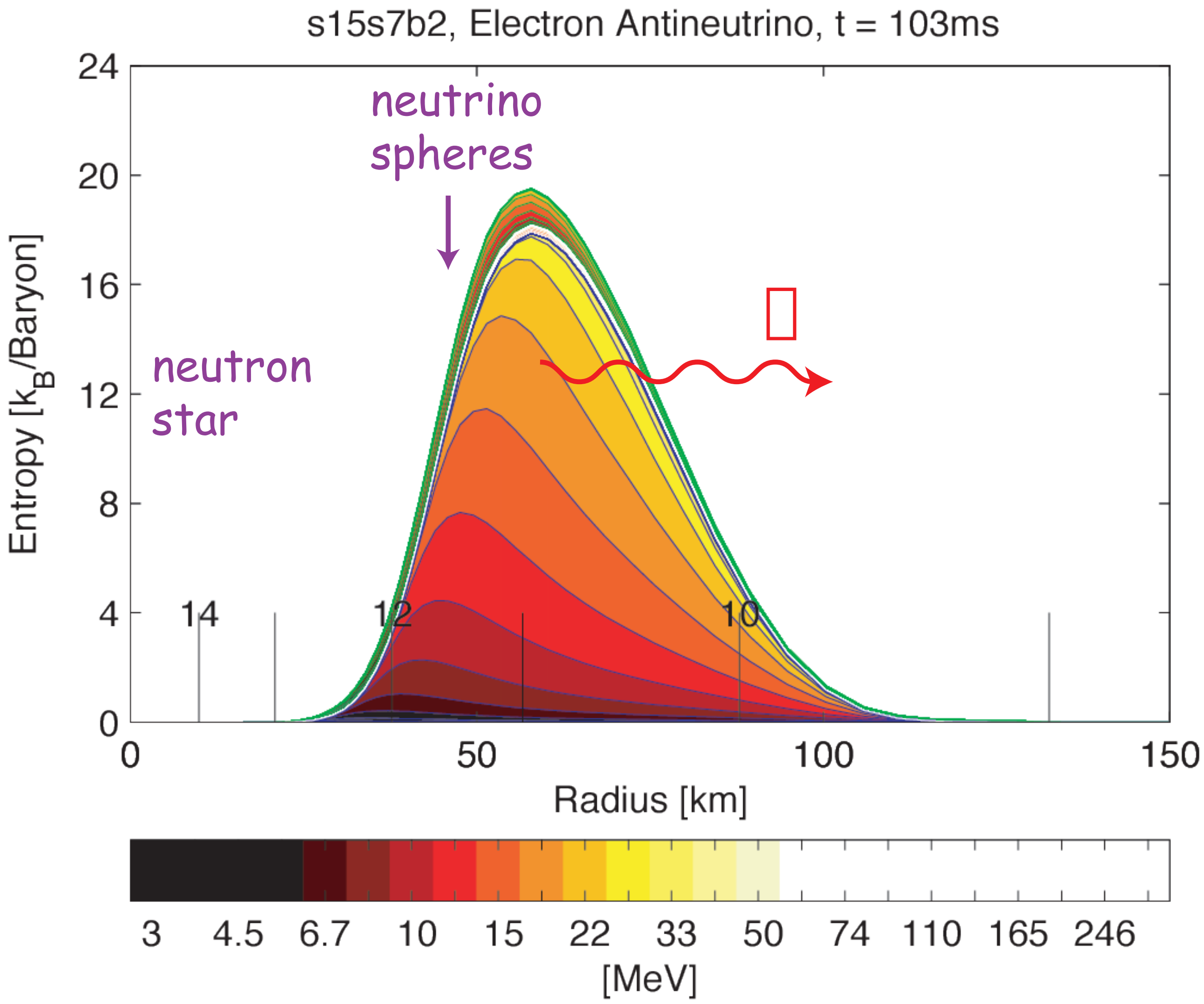
(Fischer et al. 2007)

blue = Lattimer-Swesty (1991) EoS

red = Shen et al. (1998) EoS

(see also Sumiyoshi et al. 2007)

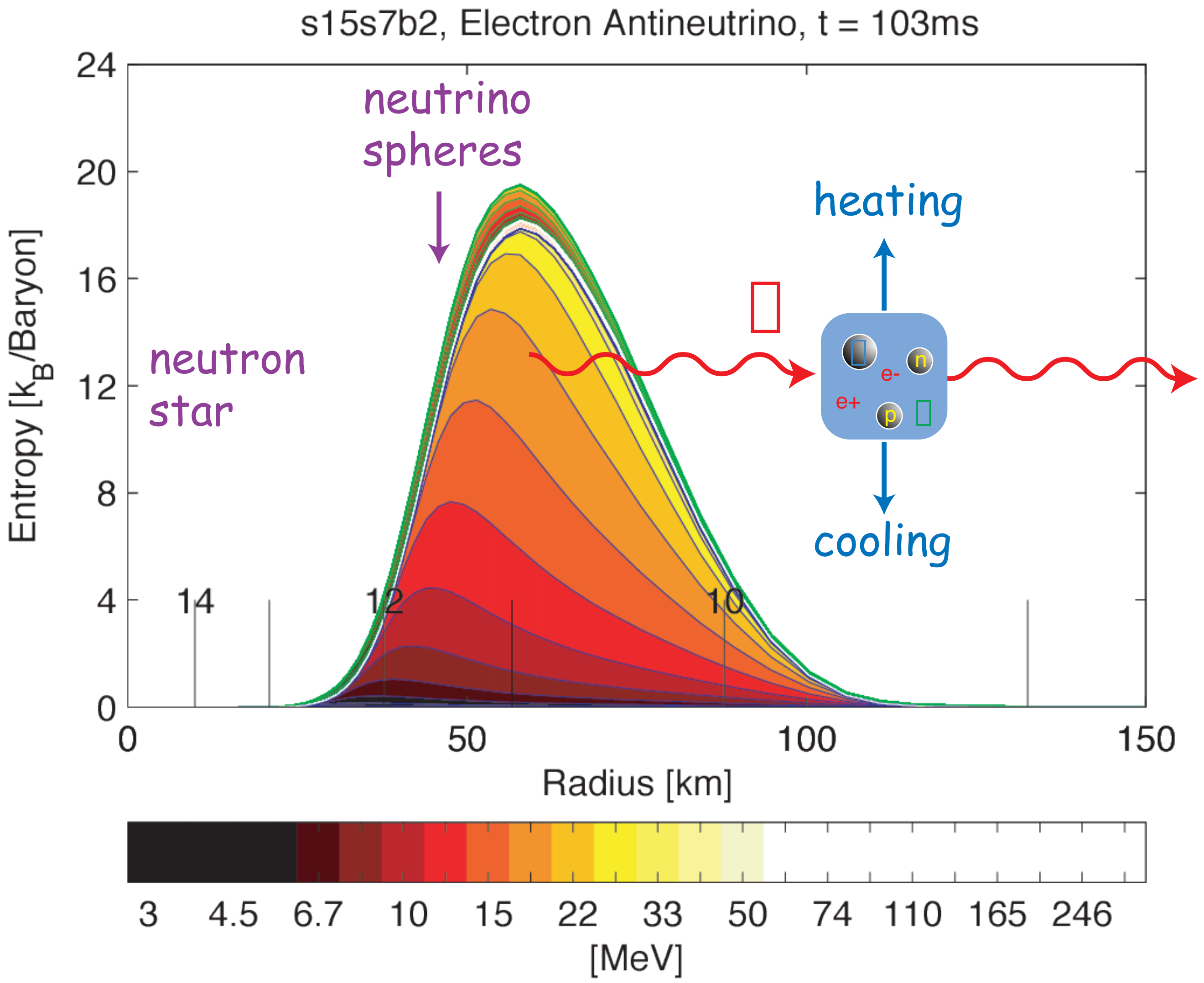
Neutrino heating



(Liebendörfer et al. 2003/4)

- neutrino cooling and neutrino heating are competing

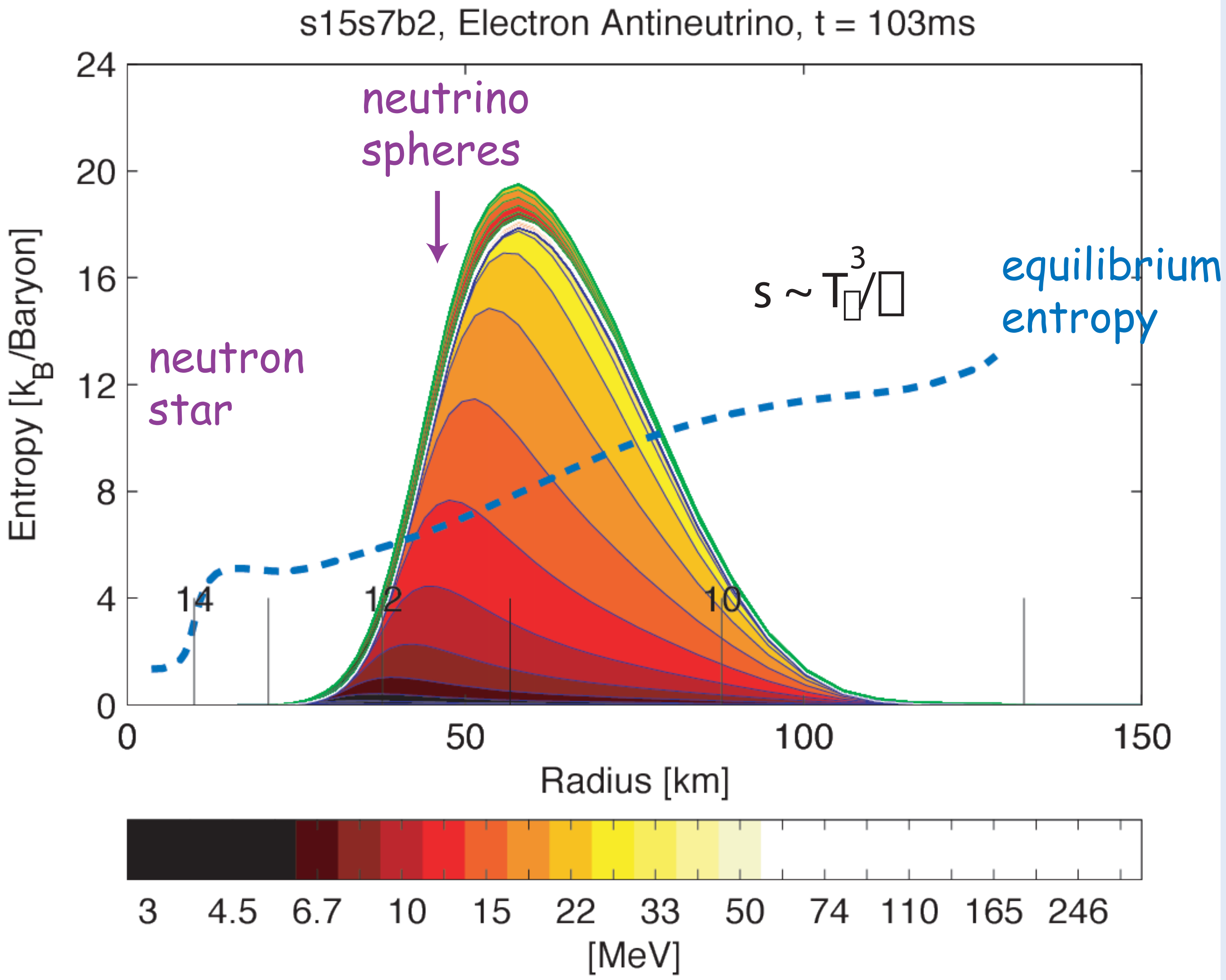
Neutrino heating



(Liebendörfer et al. 2003/4)

- neutrino cooling and neutrino heating are competing
- for given luminosity and density profiles there is an equilibrium entropy as function of radius

Neutrino heating



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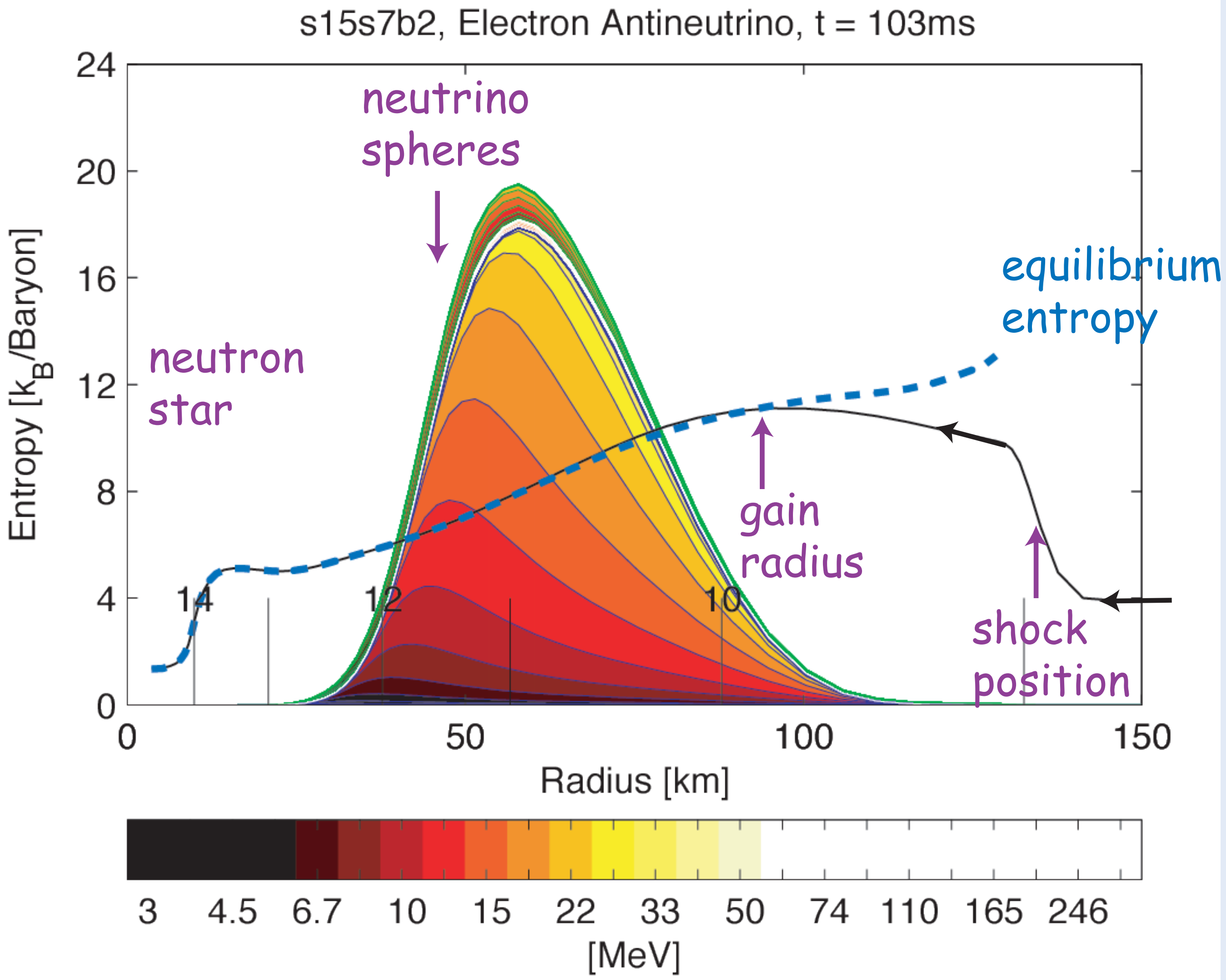

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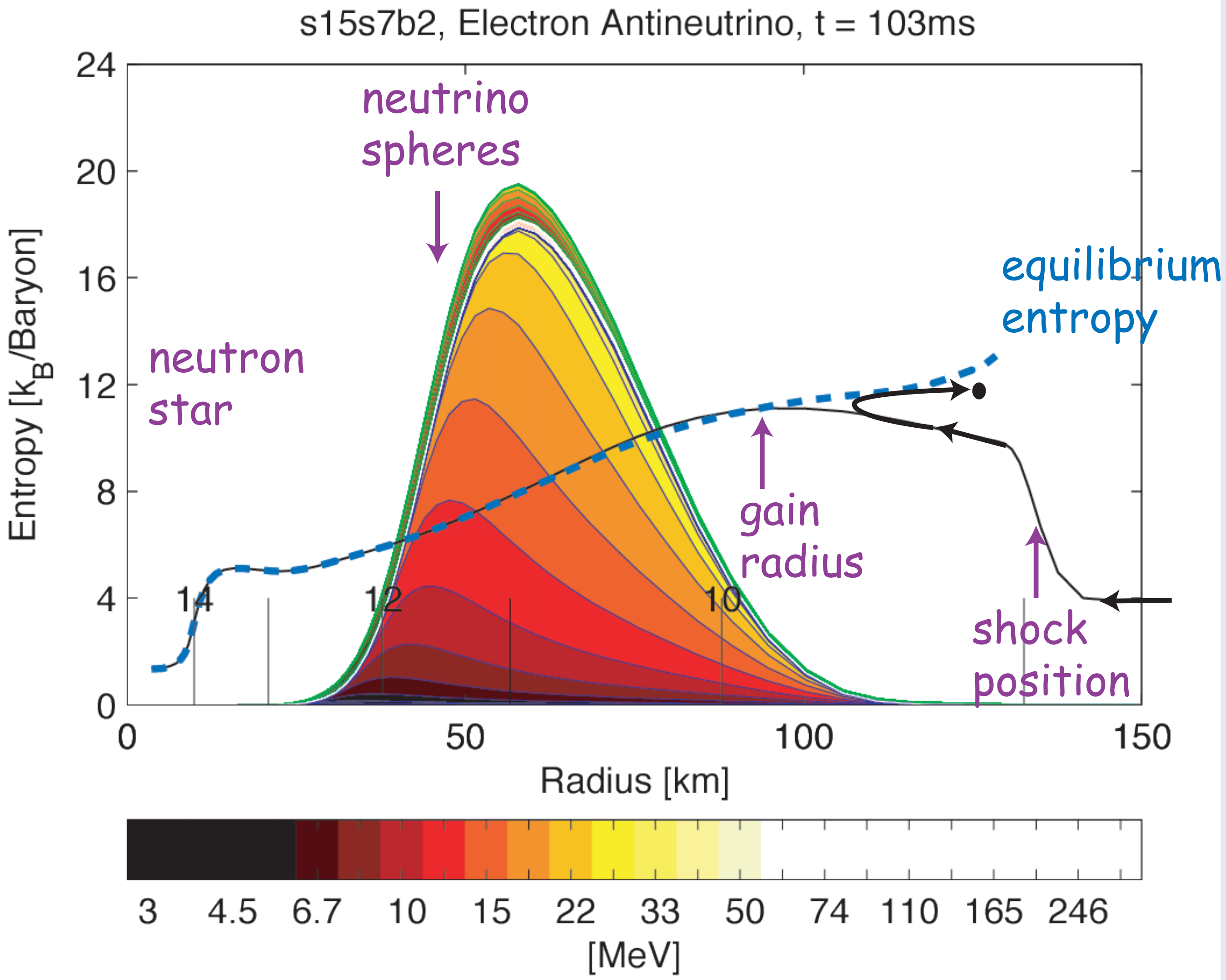
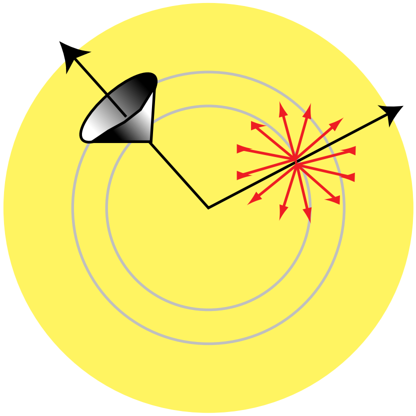


(Liebendörfer et al. 2003/4)

- neutrino cooling and neutrino heating are competing
- for given luminosity and density profiles there is an equilibrium entropy as function of radius
- heating more efficient in multi-D than in spherical symmetry!
  (Herant et al. 1994,
  Burrows, Hayes & Fryxell 1995
  Janka & Mueller 1996
  Buras et al. 2003)

Boltzmann neutrino transport



Direct calculation of the neutrino distribution function in spherical symmetry:

f(time,radius,angle,energy)

- GR implicit hydrodynamics
- GR implicit Boltzmann transport

Nuclear equation of state (Lattimer & Swesty, Shen)

Selection of weak interactions:

$$p + e^- \rightleftarrows n + \nu_e$$
$$n + e^+ \rightleftarrows p + \bar{\nu}_e$$
$$(A,Z) + e^- \rightleftarrows (A, Z-1) + \nu_e$$

$$\nu + N \rightleftarrows \nu + N$$
$$N + N \rightleftarrows N + N + \nu + \bar{\nu}$$

$$\nu + (A,Z) \rightleftarrows \nu + (A,Z)$$
$$\nu + e^\pm \rightleftarrows \nu + e^\pm$$

$$e^+ + e^- \rightleftarrows \nu + \bar{\nu}$$

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

- radial dependence
- treat different □ energy groups separately
- angular dependence even in spherical symmetry

=> 3D implicit problem

=> computationally expensive!

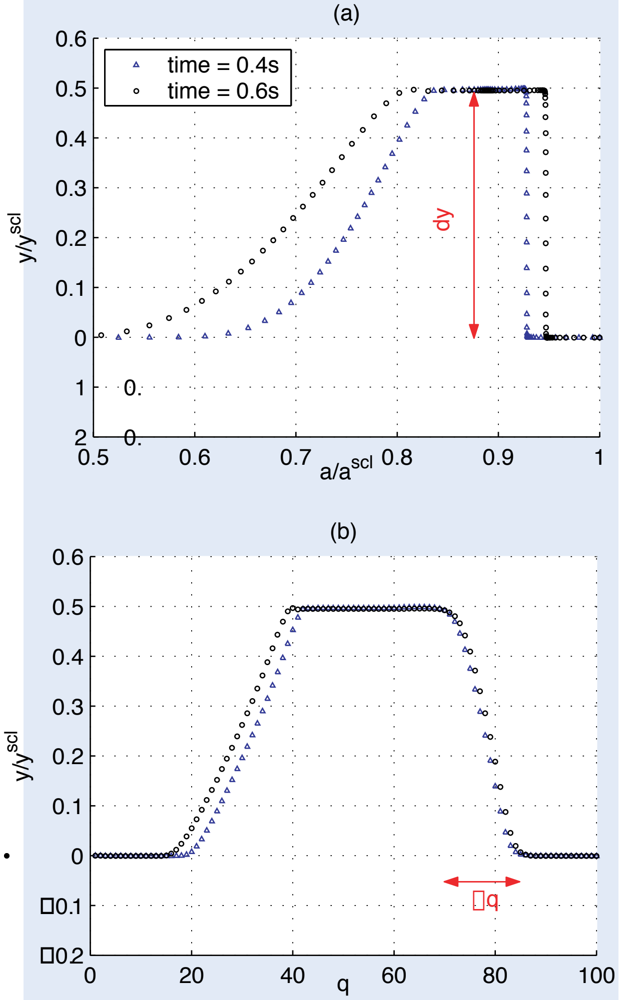
Solving the Boltzmann equation

$$
\begin{aligned}
&\frac{\partial F}{\alpha c\partial t} + \frac{\partial\left(4\pi r^2\alpha\rho\mu F\right)}{\alpha\partial m} + \Gamma\left(\frac{1}{r} - \frac{\partial\alpha}{\alpha\partial r}\right)\frac{\partial\left[\left(1-\mu^2\right)F\right]}{\partial\mu}\\
+&\left(\frac{\partial\ln\rho}{\alpha c\partial t} + \frac{3}{r}\frac{u}{c}\right)\frac{\partial\left[\mu\left(1-\mu^2\right)F\right]}{\partial\mu}\\
+&\left[\mu^2\left(\frac{\partial\ln\rho}{\alpha c\partial t} + \frac{3}{r}\frac{u}{c}\right) - \frac{1}{r}\frac{u}{c} - \mu\Gamma\frac{\partial\alpha}{\alpha\partial r}\right]\frac{1}{E^2}\frac{\partial\left(E^3F\right)}{\partial E}\\
=&\ \frac{j}{\rho} - \tilde{\chi}F + \frac{1}{h^3c^4}E^2\int d\mu' R_{is}\left(\mu,\mu',E\right)F\left(\mu',E\right)\\
-&\ \frac{1}{h^3c^4}E^2F\int d\mu' R_{is}\left(\mu,\mu',E\right)\\
+&\ \frac{1}{h^3c^4}\left[\frac{1}{\rho} - F\left(\mu,E\right)\right]\int E'^2dE'd\mu'\tilde{R}^{in}_{nes}\left(\mu,\mu',E,E'\right)F\left(\mu',E\right)\\
-&\ \frac{1}{h^3c^4}F\left(\mu,E\right)\int E'^2dE'd\mu'\tilde{R}^{out}_{nes}\left(\mu,\mu',E,E'\right)\left[\frac{1}{\rho} - F\left(\mu',E'\right)\right]
\end{aligned}
$$

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

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

on adaptive mesh



Results agree in all groups

Comparison of spherically symmetric simulations:
Oak Ridge/Basel group and Garching group

Liebendörfer, Rampp, Janka, Mezzacappa, ApJ 620 (2005)

Summary on spherically symmetric simulations:

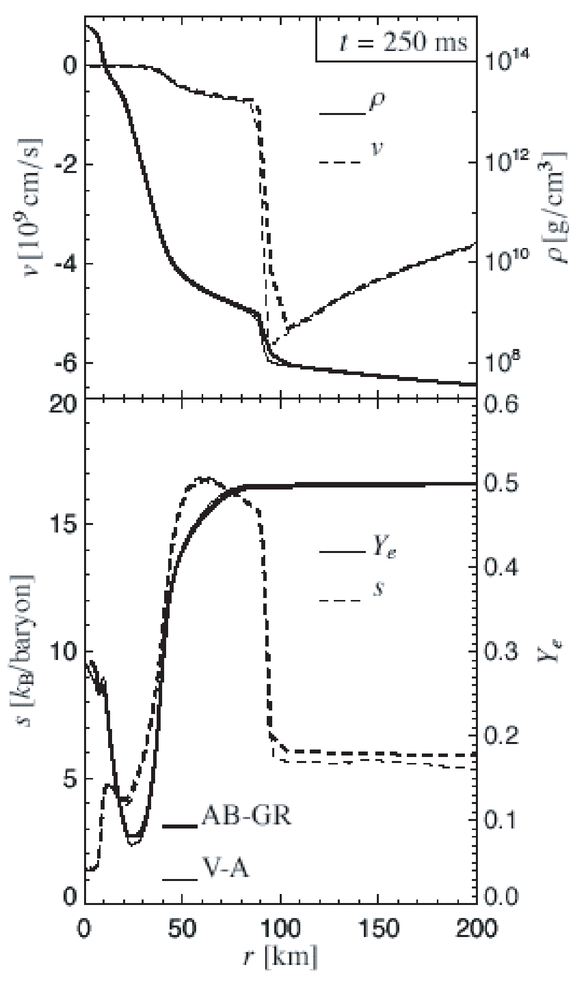
-> No explosions obtained (exception ONeMg core)

-> Transport approximations and
GR effects not responsible for failures

(Liebendörfer et al. 2001, Rampp & Janka 2002,
Thompson et al. 2003, Sumiyoshi et al. 2005)

datafiles.tar.gz of simulation in ApJ electronic edition

excellent agreement:



(Marek et al., A&A 2006)

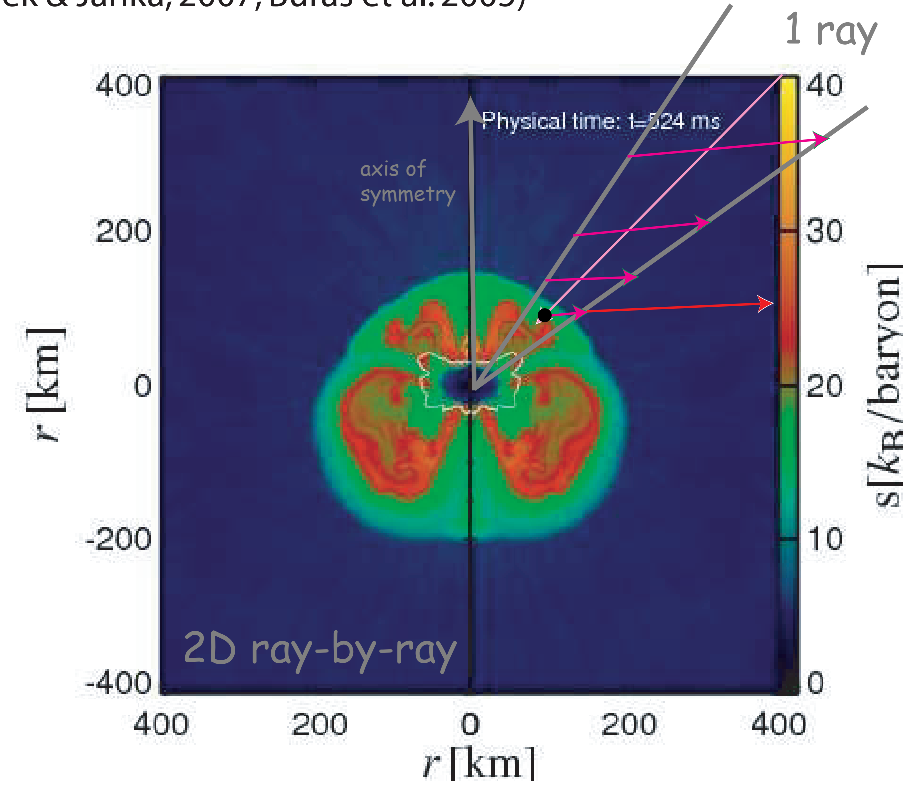
Axisymmetric supernova models

- Standing accretion shock instability (SASI)

  (Blondin & Mezzacappa 2003
  Foglizzo et al. 2007)

- Delayed neutrino-driven supernova explosions aided by the standing accretion-shock instability

  (Marek & Janka, 2007; Buras et al. 2005)



- Features of the Acoustic Mechanism of Core-Collapse Supernova Explosions

  (Burrows et al. 2006)

Accretion flow induces very strong g-mode oscillations

Heating by dissipation of emitted sound waves

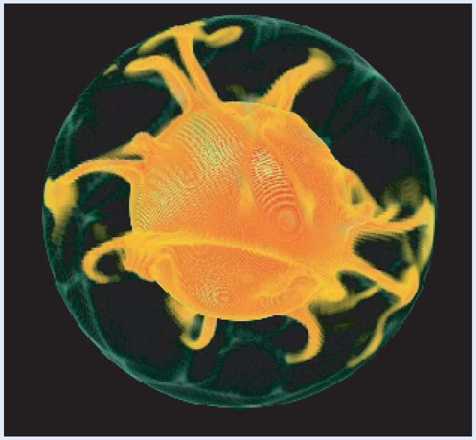
Open questions:

a) coupling to higher modes suppressed by low resolution
(Quataert et al. 2008)

b) g-mode oscillations weaker in models of other groups
(Kotake et al. 2007)

More degrees of freedom!

- how restrictive is axisymmetry?
- convective turnover is always toroidal
- narrow downflow restricted to cones instead of tubes



Shijie Zhong 2005

Effects from magnetic fields?

Leblanc & Wilson 1979, Symbalisty 1984:
Unphysically strong magnetic field leading to jets

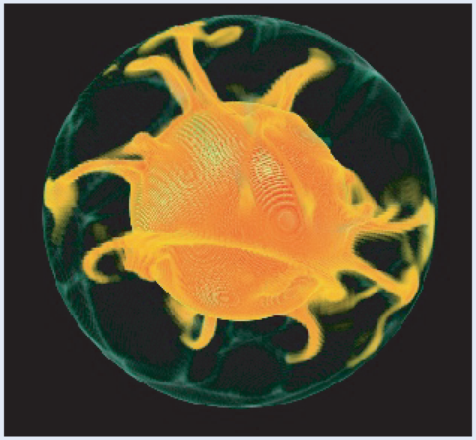
Bisnovatyi-Kogan 197x, Akiyama et al. 2003
Ardeljan et al. 2004:
Magnetic field growth and MRI until magnetic pressure becomes relevant

Thompson, Quataert, Burrows 2005:
Magneto-Rotational Instability as source of viscosity, leading to additional heating

Kotake et al. 2004:
Magentic field leading to asymmetries in the propagation of the shock front

see. e.g. Kotake, Sato, Takahashi (2005)

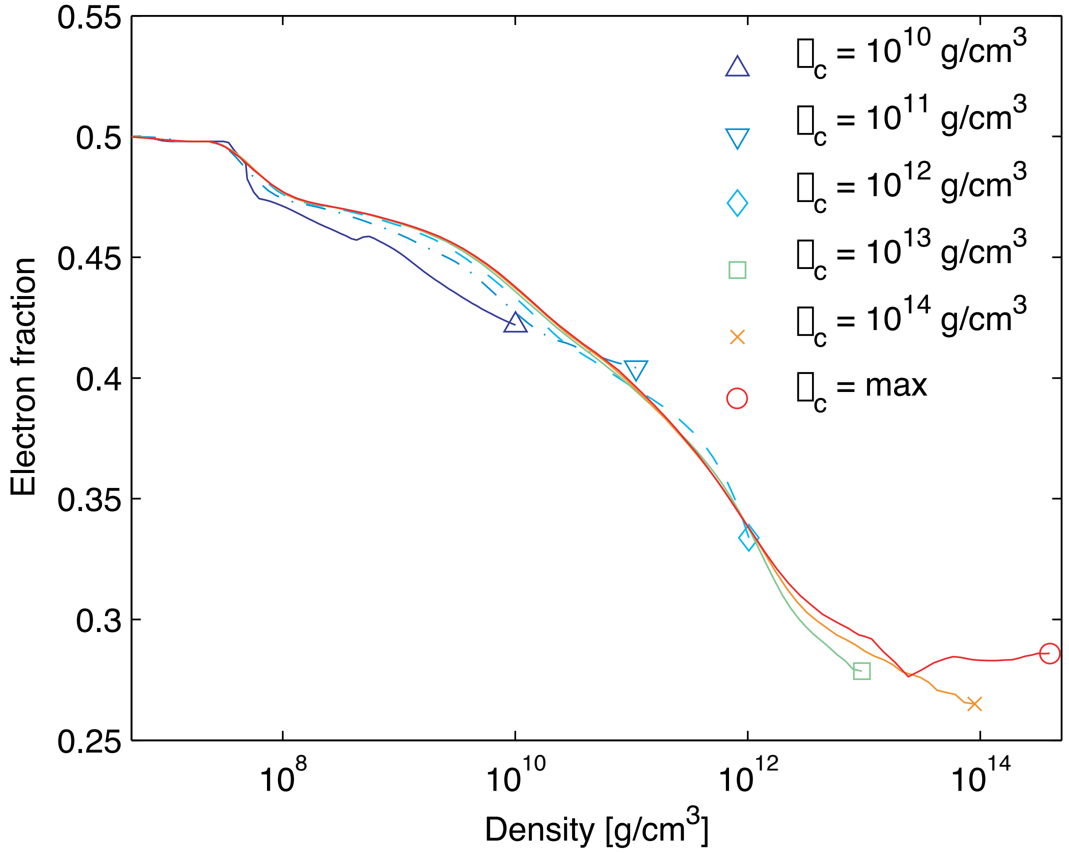
- how restrictive is axisymmetry?
- convective turnover is always toroidal
- narrow downflow restricted to cones instead of tubes



Shijie Zhong 2005

Parameterised ν-physics before bounce

Electron fraction in spherical runs can be parameterised



Entropy changes and neutrino stress can be derived:

$$\frac{\Delta s}{\Delta t} = -\frac{\Delta Y_e}{\Delta t}\frac{\mu_e - \mu_n + \mu_p - E_\nu^{esc}}{T},$$

(~10MeV)

(Liebendörfer 2005)

3D MHD

(Liebendörfer, Pen, Thompson 2006)

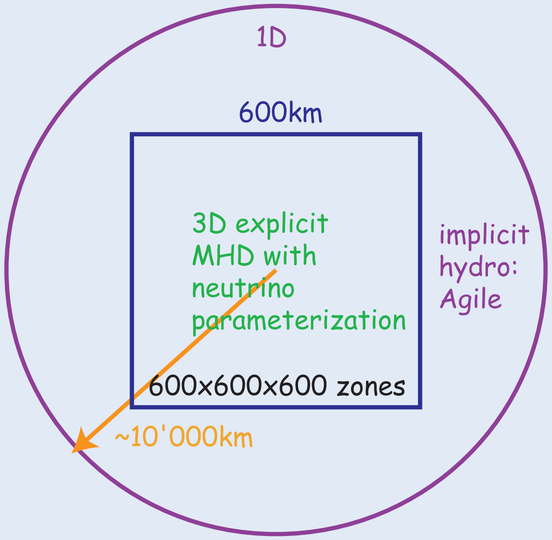
Lattimer-Swesty EOS

(Lattimer & Swesty 1991)

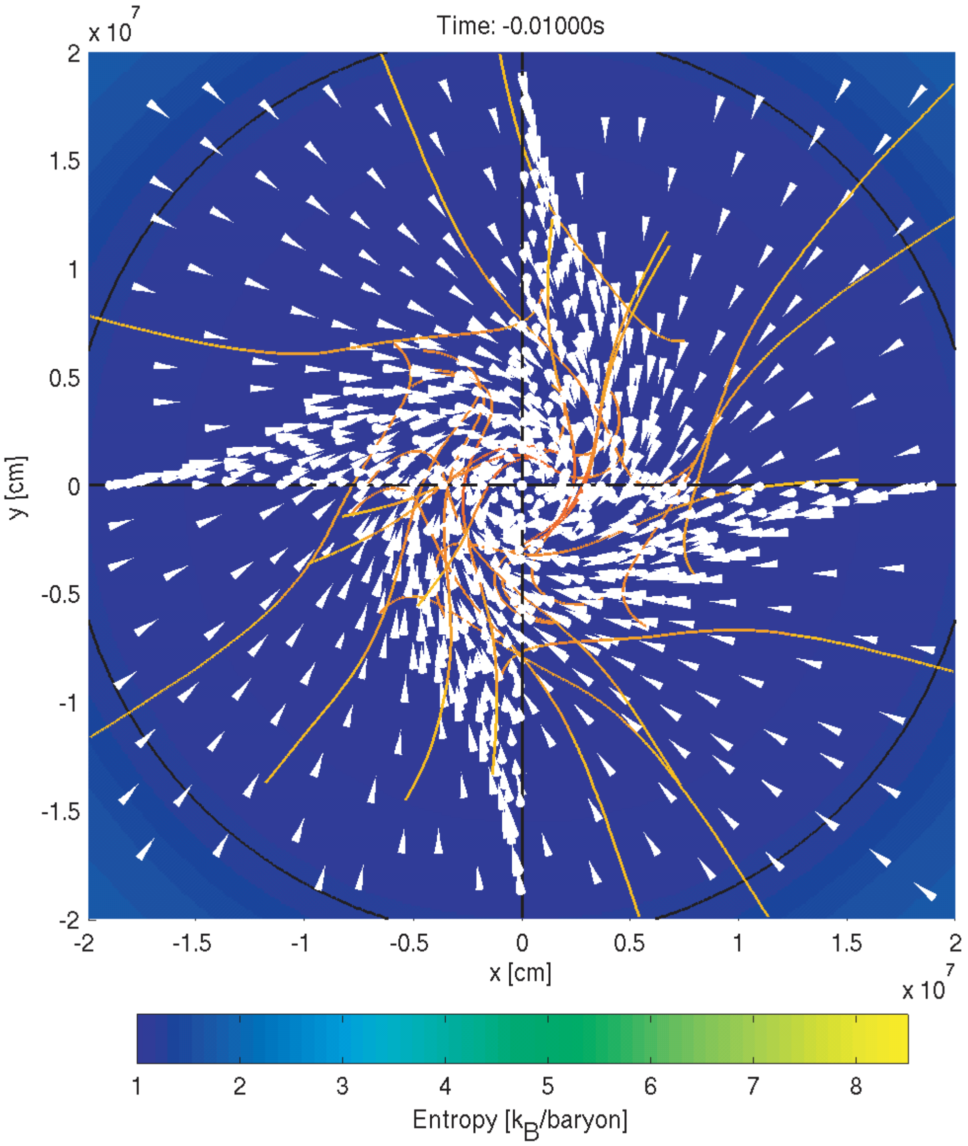
Effective GR potential

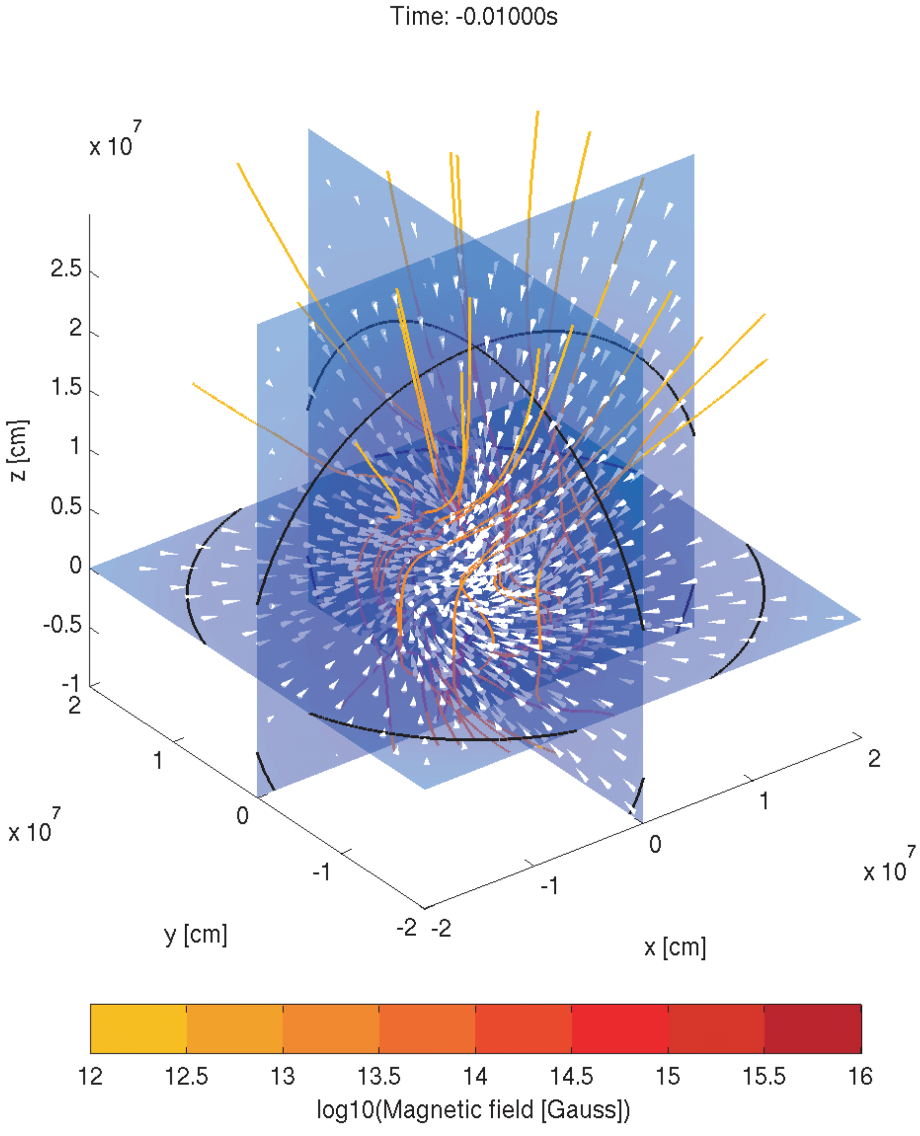
(Marek et al. 2006)

Fully parallelised

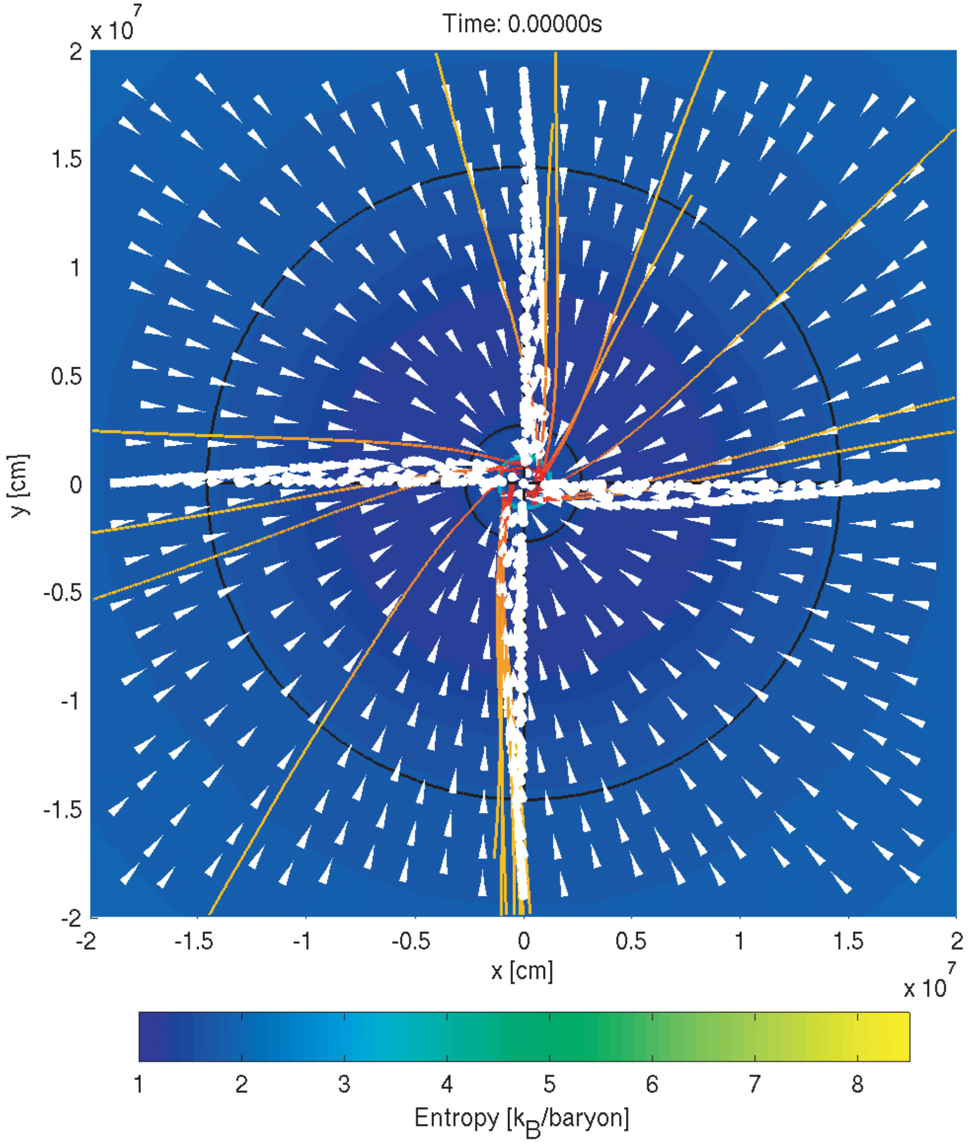


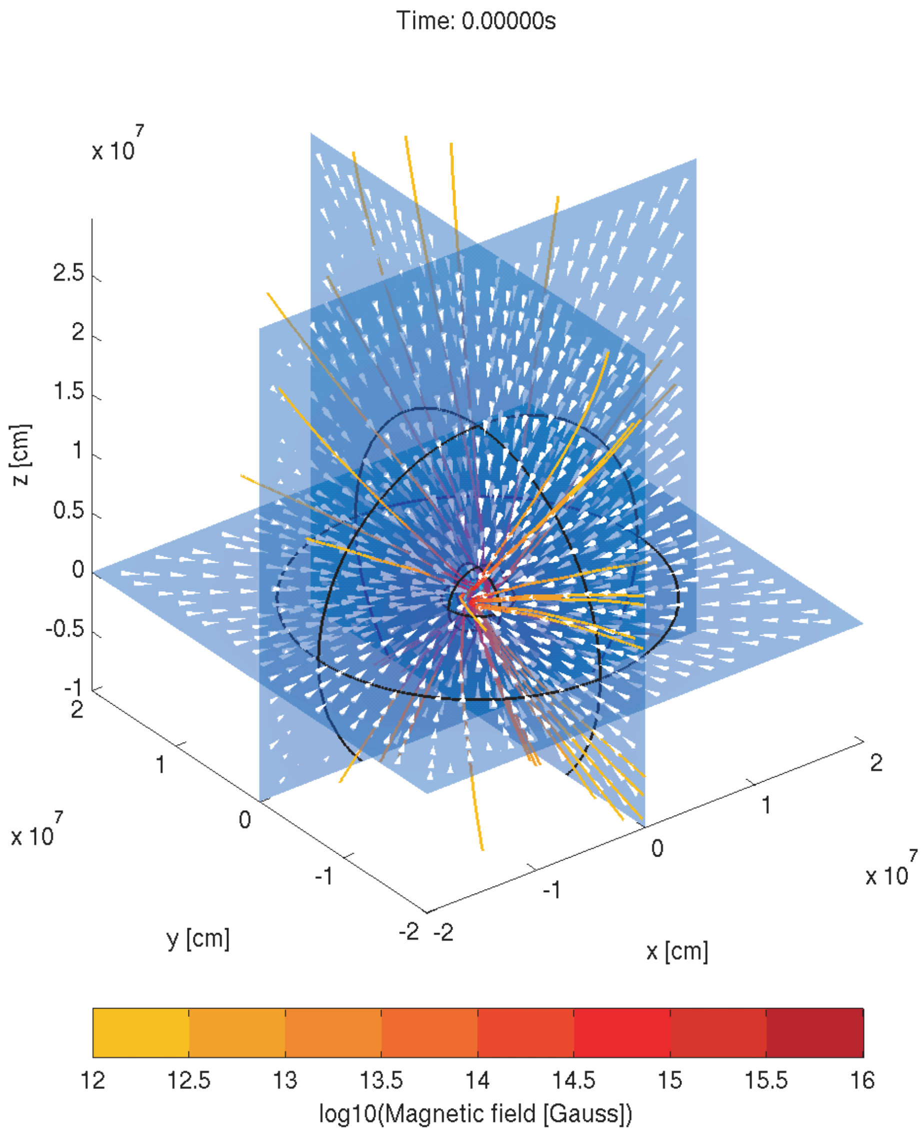
3D MHD & parameterized □'s





3D MHD & parameterized ν's





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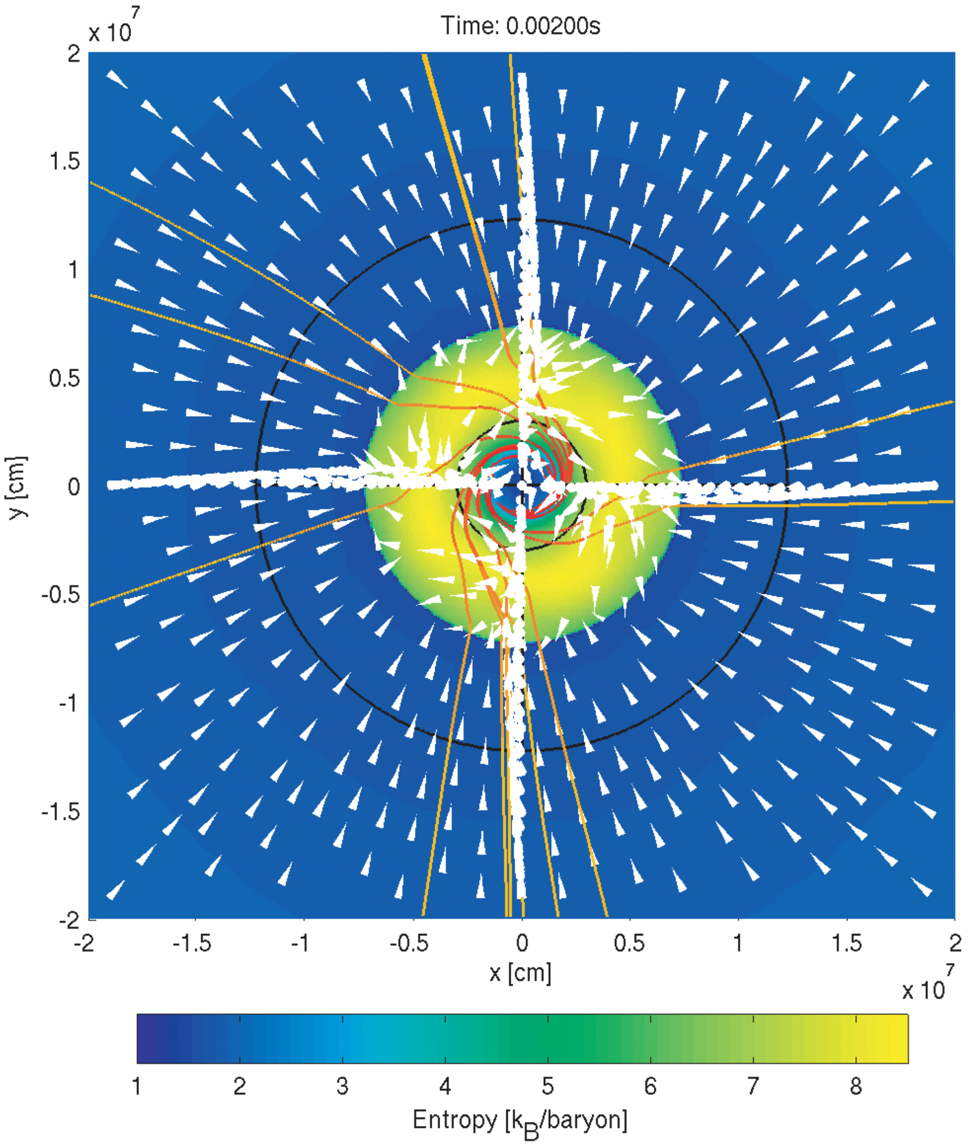

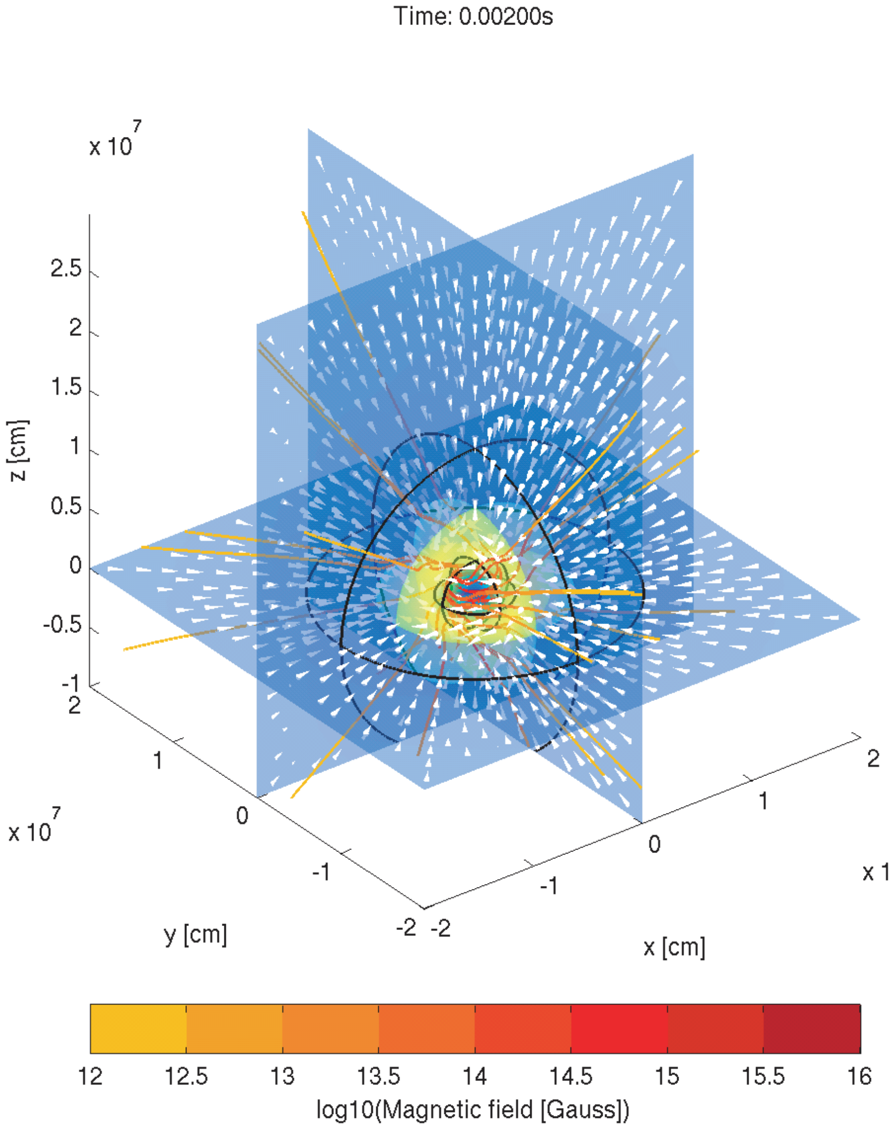

3D MHD without □-burst

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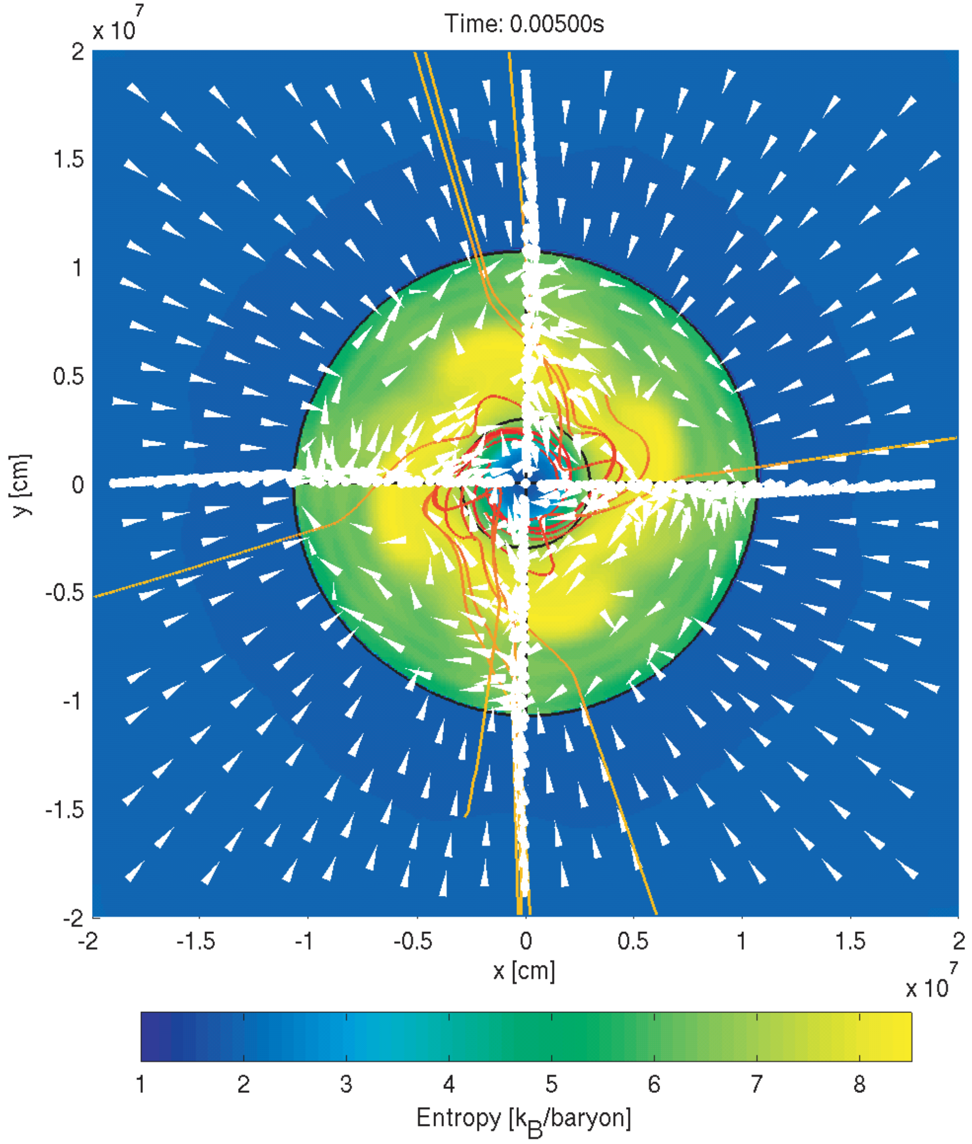
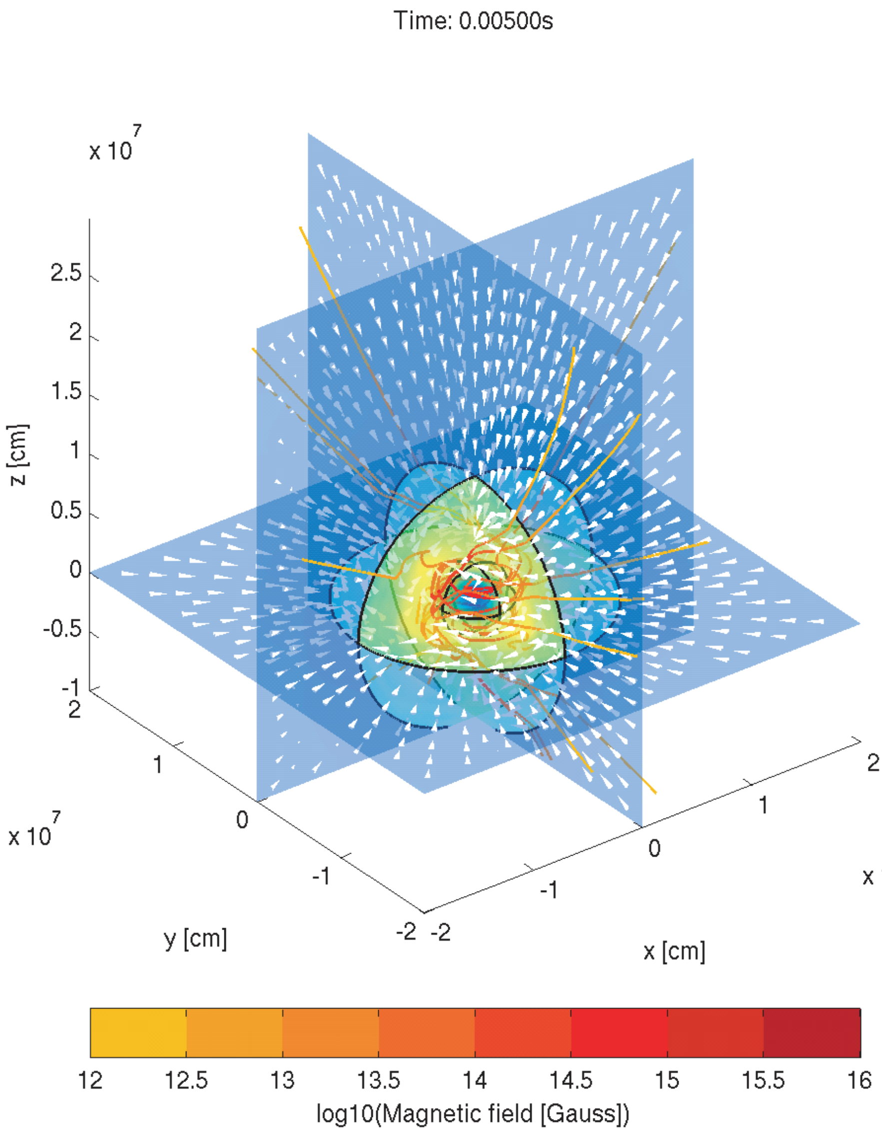
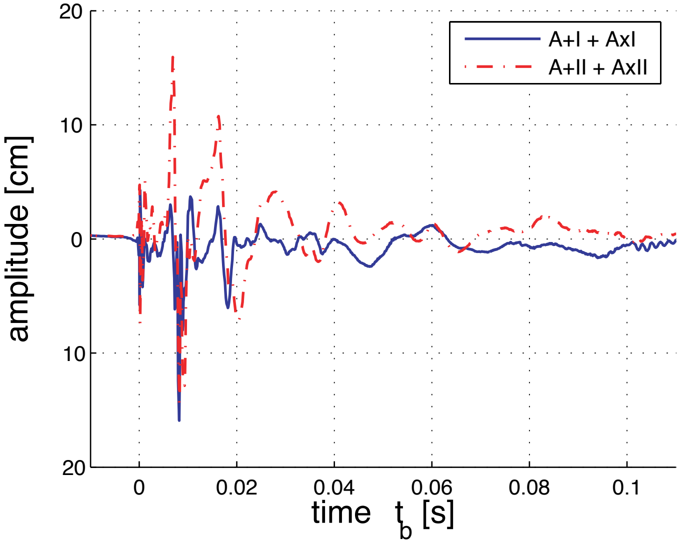


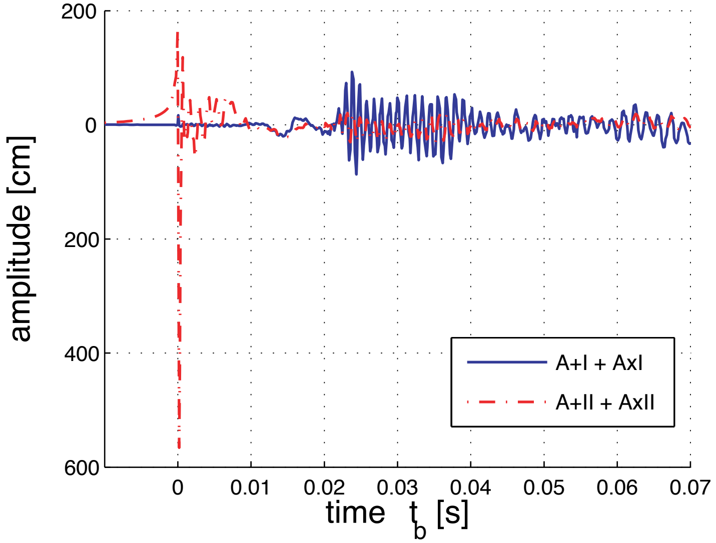


Prediction of Gravitational Wave Signal



Slowly rotating 15Ms progenitor according to

(Heger, Woosley & Spruit 2005)

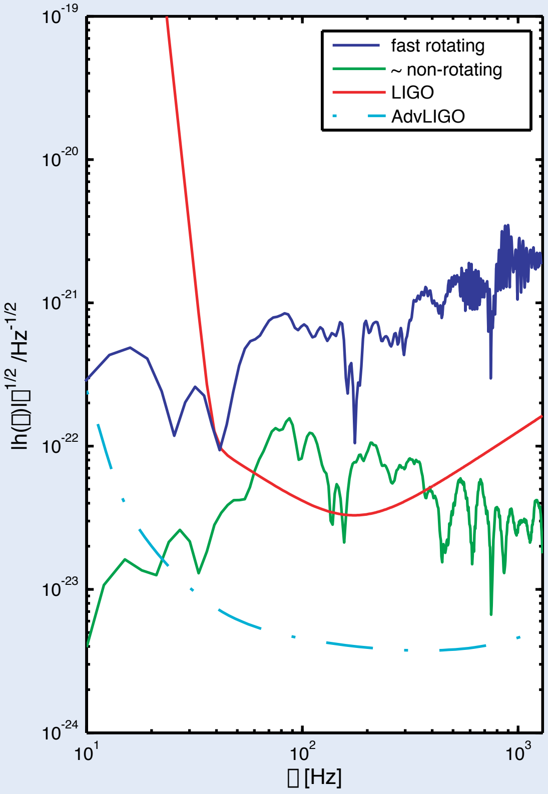


Fast rotating 15Ms progenitor

□ ~ 2□ rad/ps

--> imprint of bounce and rotation rate

(Scheidegger, Fischer, Whitehouse, Liebendoerfer 2007/8, see also Ott et al. 2007)



Galactic supernovae

-- could (LIGO)

-- should (Adv. LIGO)

be detectable

Too simple for post bounce phase...

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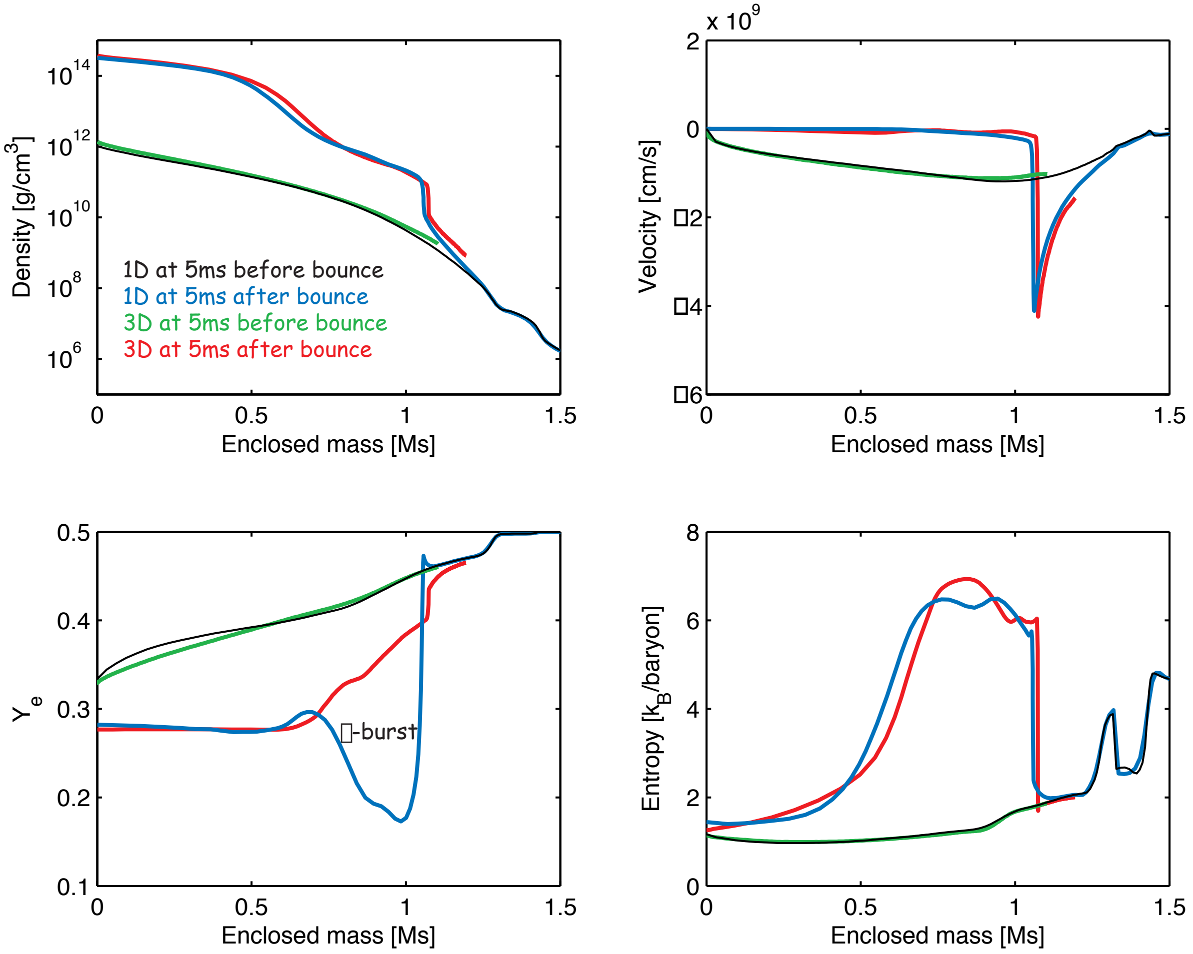
- Parameterization of electron fraction templates
- Comparison 1D GR Boltzmann <--> 3D approximations



3D MHD

(Liebendörfer, Pen, Thompson 2006)

Lattimer-Swesty EOS

(Lattimer & Swesty 1991)

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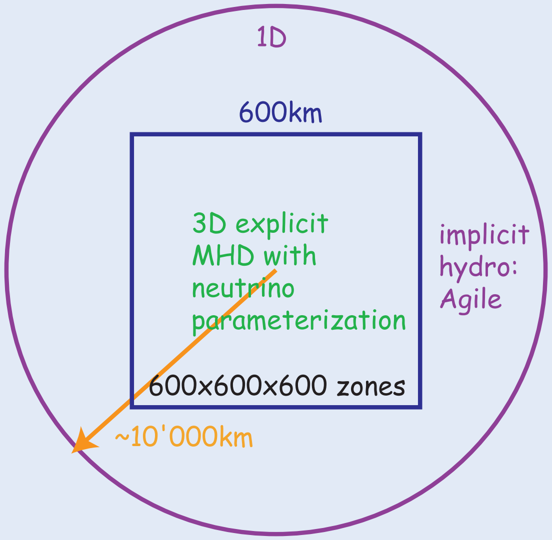
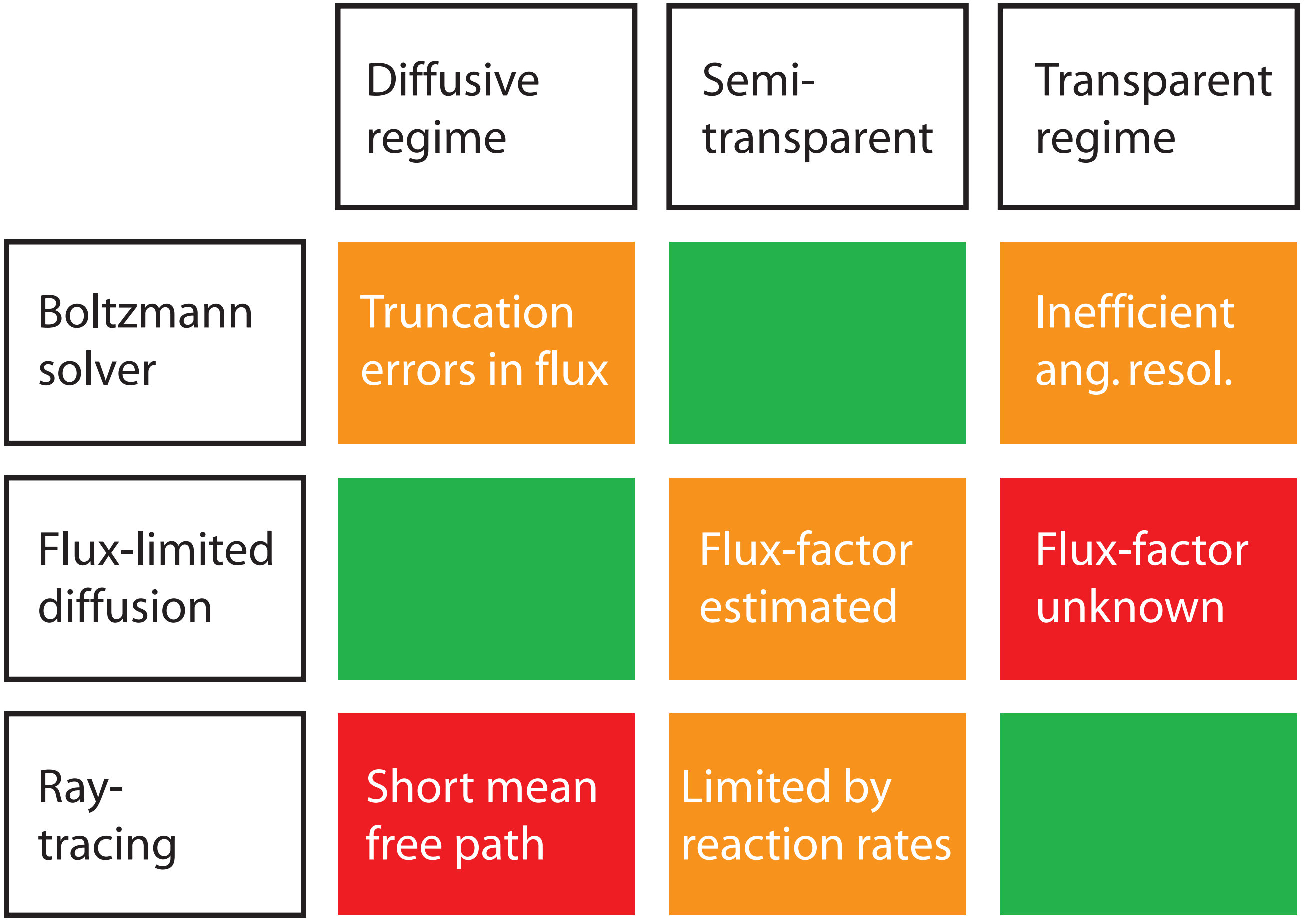


There is no perfect transport algorithm...



	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	🟩

The ideal algorithm combines the three green fields!
However, it might be too complicated. Alternatives:

There is no perfect transport algorithm...

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The ideal algorithm combines the three green fields!
However, it might be too complicated. Alternatives:

- Variable Eddington Factor method
  successful in 2D but very computationally expensive!
  (Buras et al. 2003-5)
- Grey diffusion in one regime and grey transparent elsewhere
  successful in 3D but not accurate enough!
  (e.g. Fryer & Warren 2004)
- Linear combination of grey/spectral diffusion & spectral free streaming
  (e.g. Imshennik & Nadyozhin 1972, Yudin & Nadyozhin 2008 + extension)

Spectral neutrino transport after bounce

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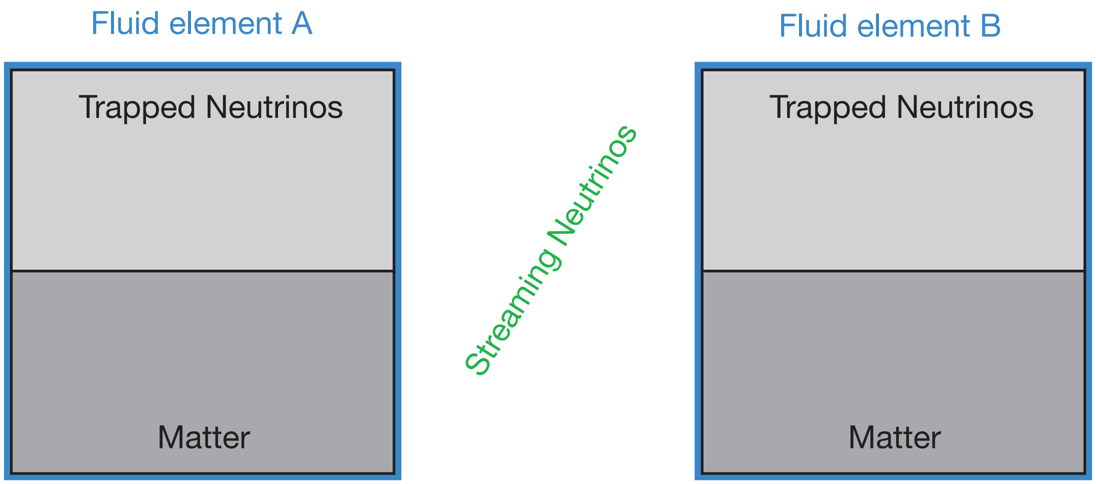
$D(f) = j - \square * f$

$f = f(\text{trapped}) + f(\text{streaming}) = ft + fs$

Different approx.
for trapped & streaming
neutrino components!

Isotropic
Diffusion
Source
Approximation

(Liebendörfer,
Whitehouse,
Fischer 2007)


Fluid element A

Trapped Neutrinos

Matter

Streaming Neutrinos

Fluid element B

Trapped Neutrinos

Matter

Spectral neutrino transport after bounce

D(f) = j - □*f

f = f(trapped) + f(streaming) = ft + fs

D(ft) = j - □*ft - □ (1)

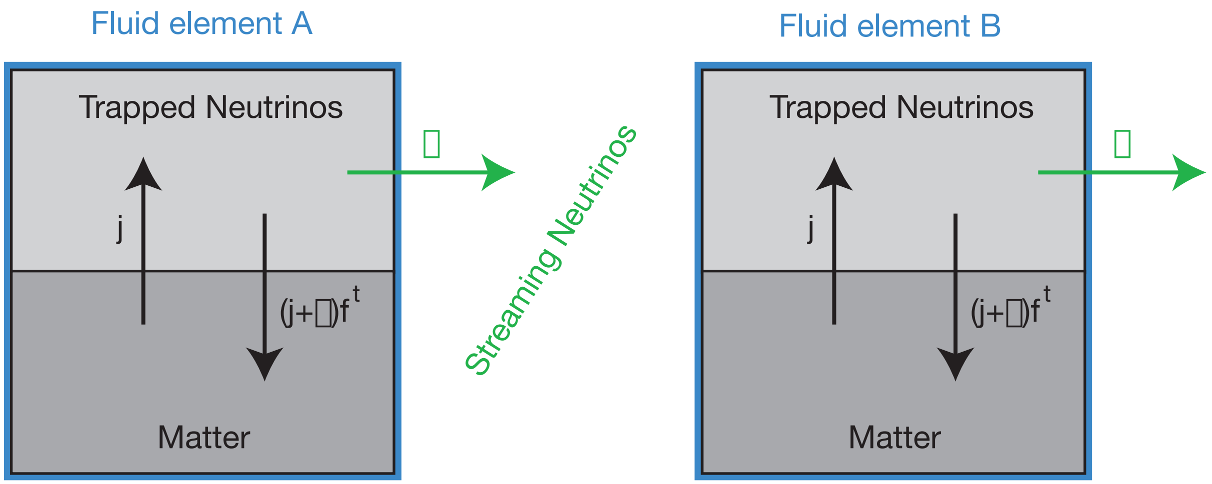
D(fs) = - □*fs + □ (2)

Different approx.
for trapped & streaming
neutrino components!

□ determined by diffusion limit of (1)

I sotropic
D iffusion
S ource
A pproximation

(Liebendörfer,
Whitehouse,
Fischer 2007)



Spectral neutrino transport after bounce

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Different approx.
for trapped & streaming
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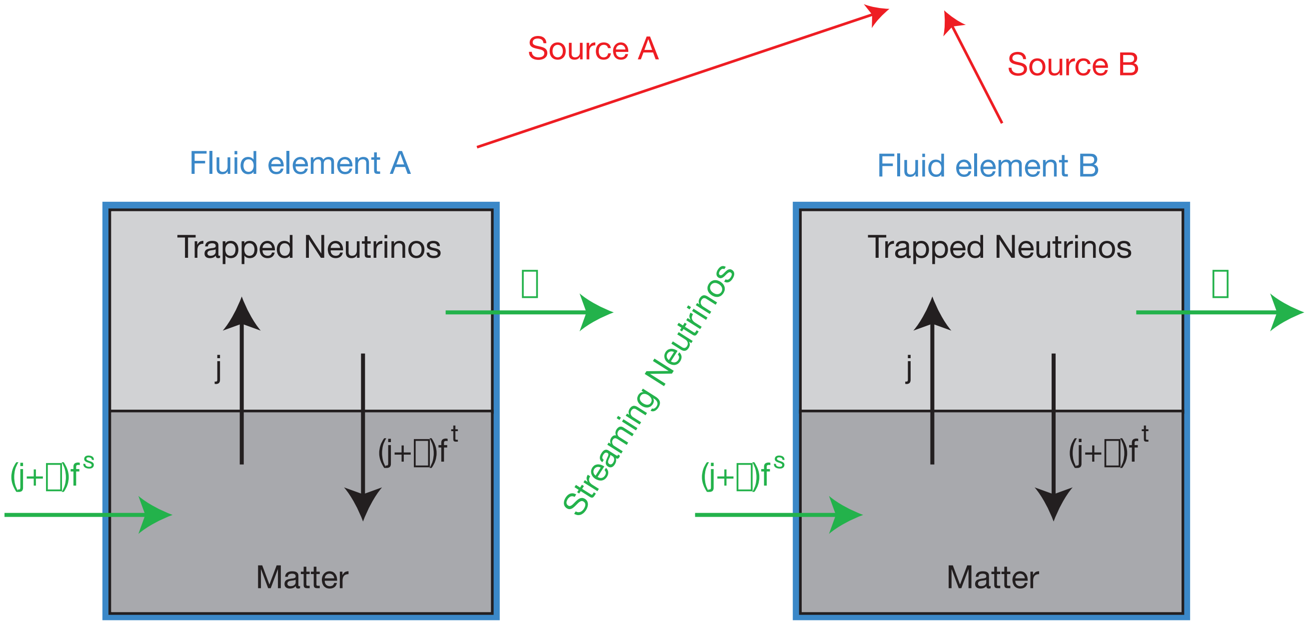
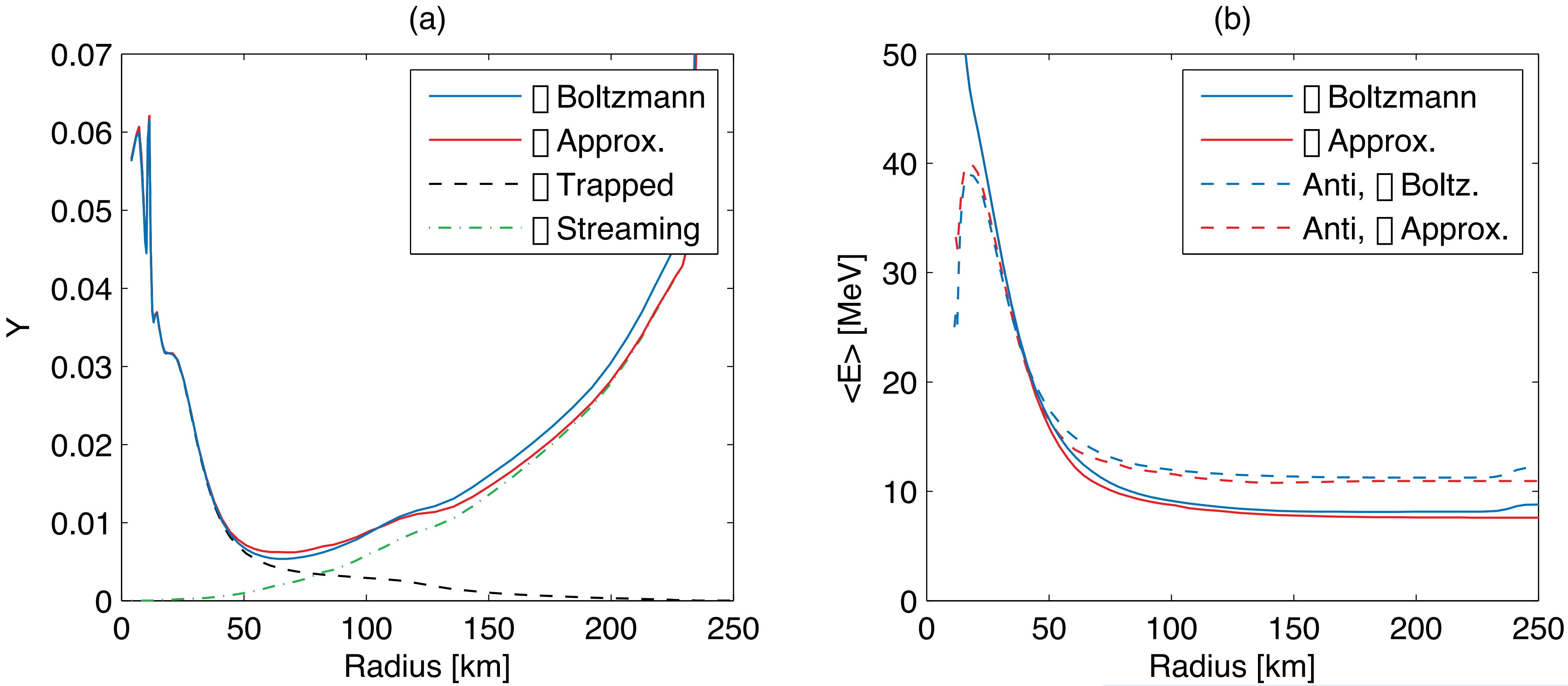
Stationary state approx. for (2) --> Poisson Eq.



Isotropic
Diffusion
Source
Approximation

(Liebendörfer,
Whitehouse,
Fischer 2007)

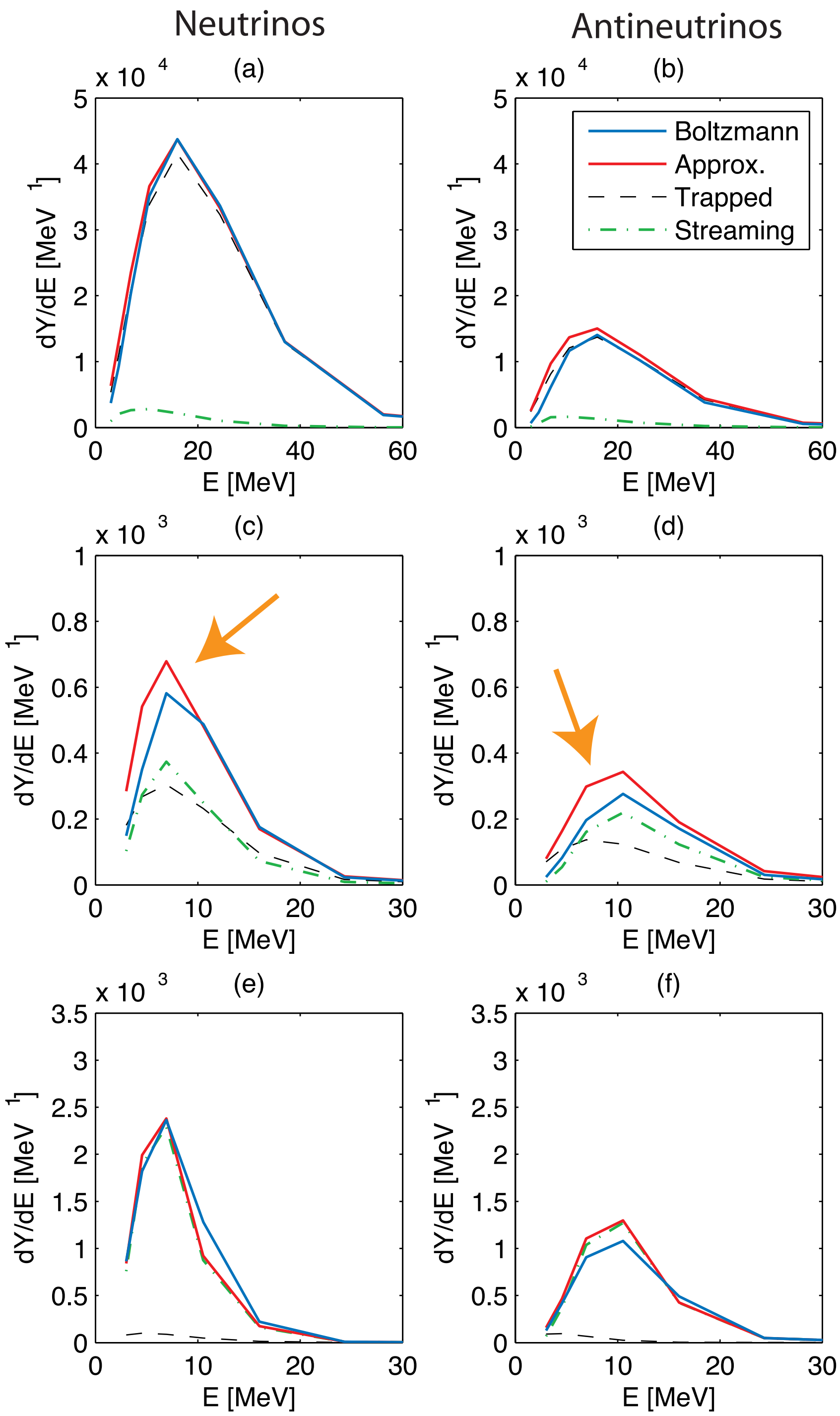
IDSA <--> Boltzmann



- *trapped neutrinos at center*
- *transition to streaming neutrinos toward surface*
- *sum of both compared to Boltzmann simulation*

Net neutrino
abundance and
mean energy

Spectra



R = 40 km
(trapped)

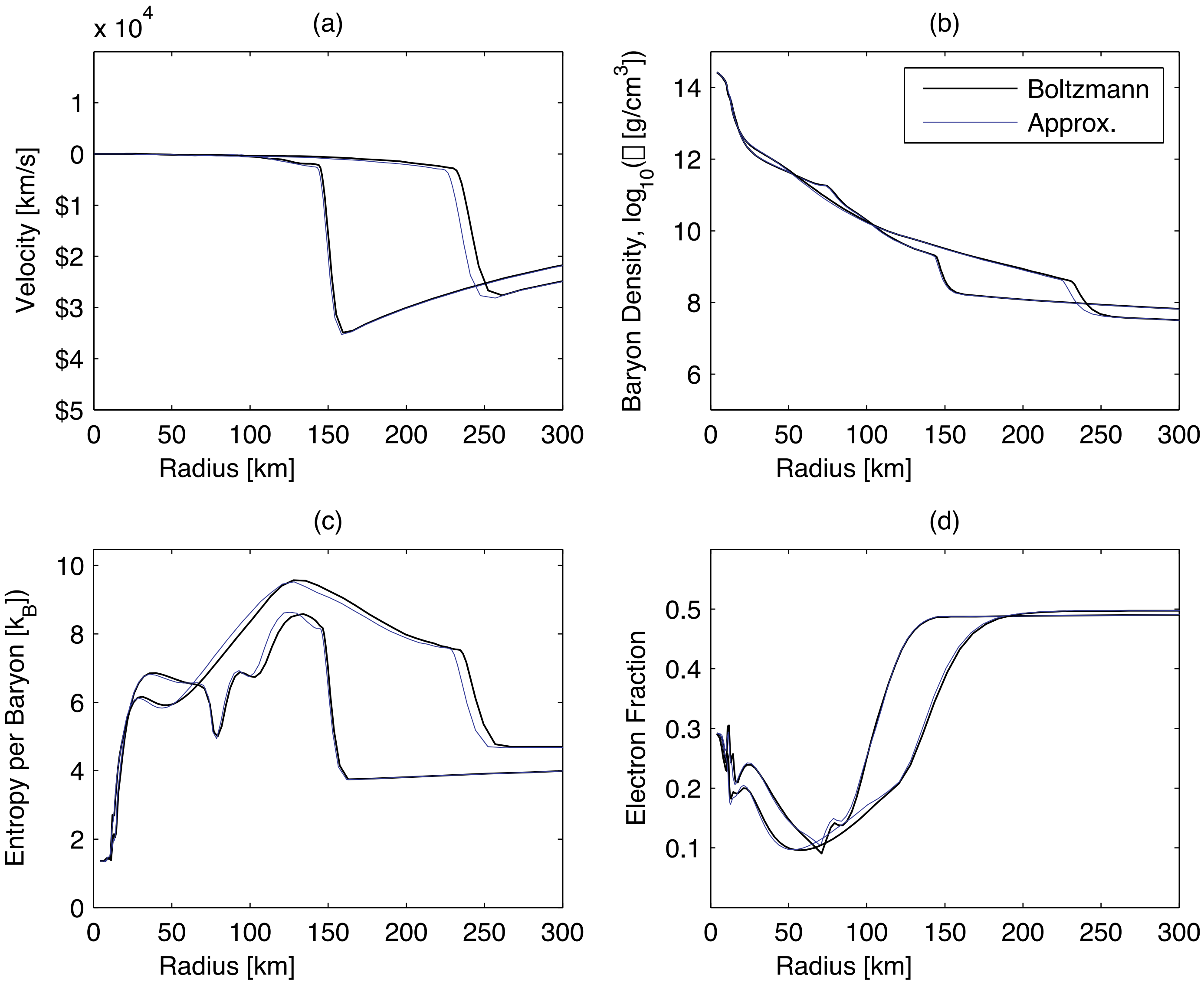
R = 80 km
(semi-transp.)

R = 160 km
(transparent)

In this comparison the trapped particle distribution function is assumed to be thermal.

--> overestimation at low energy

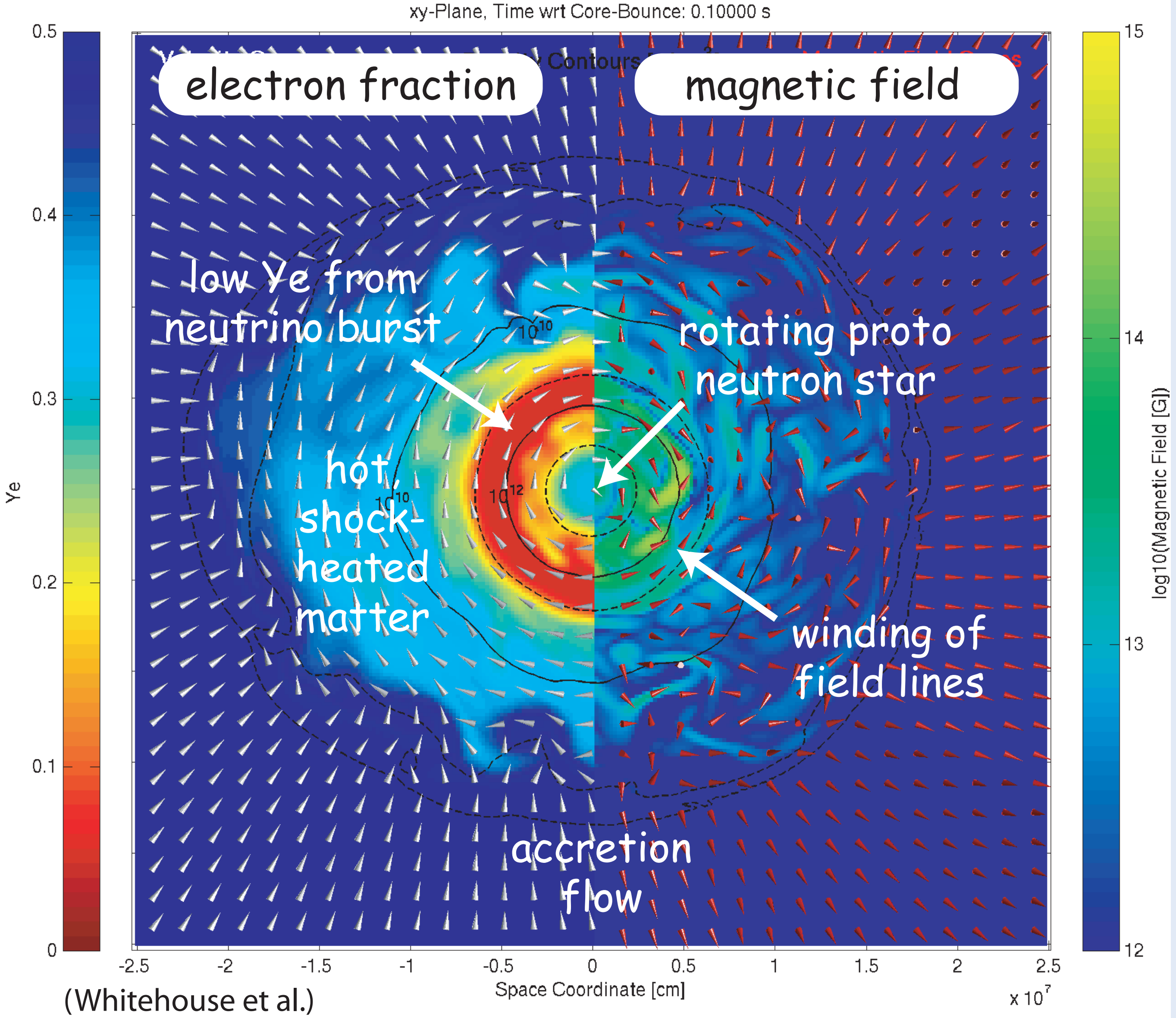
IDSA <--> Boltzmann



(Liebendörfer, Whitehouse, Fischer 2007)

Neutrino heating
and
shock expansion

Conclusion



(Whitehouse et al.)

- Neutrino- and grav. wave signal are sensitive to PNS
  --> equation of state
  --> thermal profile
  --> weak interaction rates

- SN explosion is surface effect on protoneutron star
  --> extended accretion phase
  --> energy deposition behind shock with fluid instabilities

- fluid instabilities and poss. magnetic field effects are essentially three-dimensional

- 3D models with spectral ν-transport and magnetic fields make first steps