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Investigating SN dynamics and magnetic fields in 3D

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with
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- U.-L. Pen
- S. Scheidegger
- F.-K. Thielemann
- S. C. Whitehouse

- Introduction stellar core collapse
- Neutrino transport in core-collapse supernova models
- Efficient -transport approximations for 3D MHD models

The cosmic kitchen...

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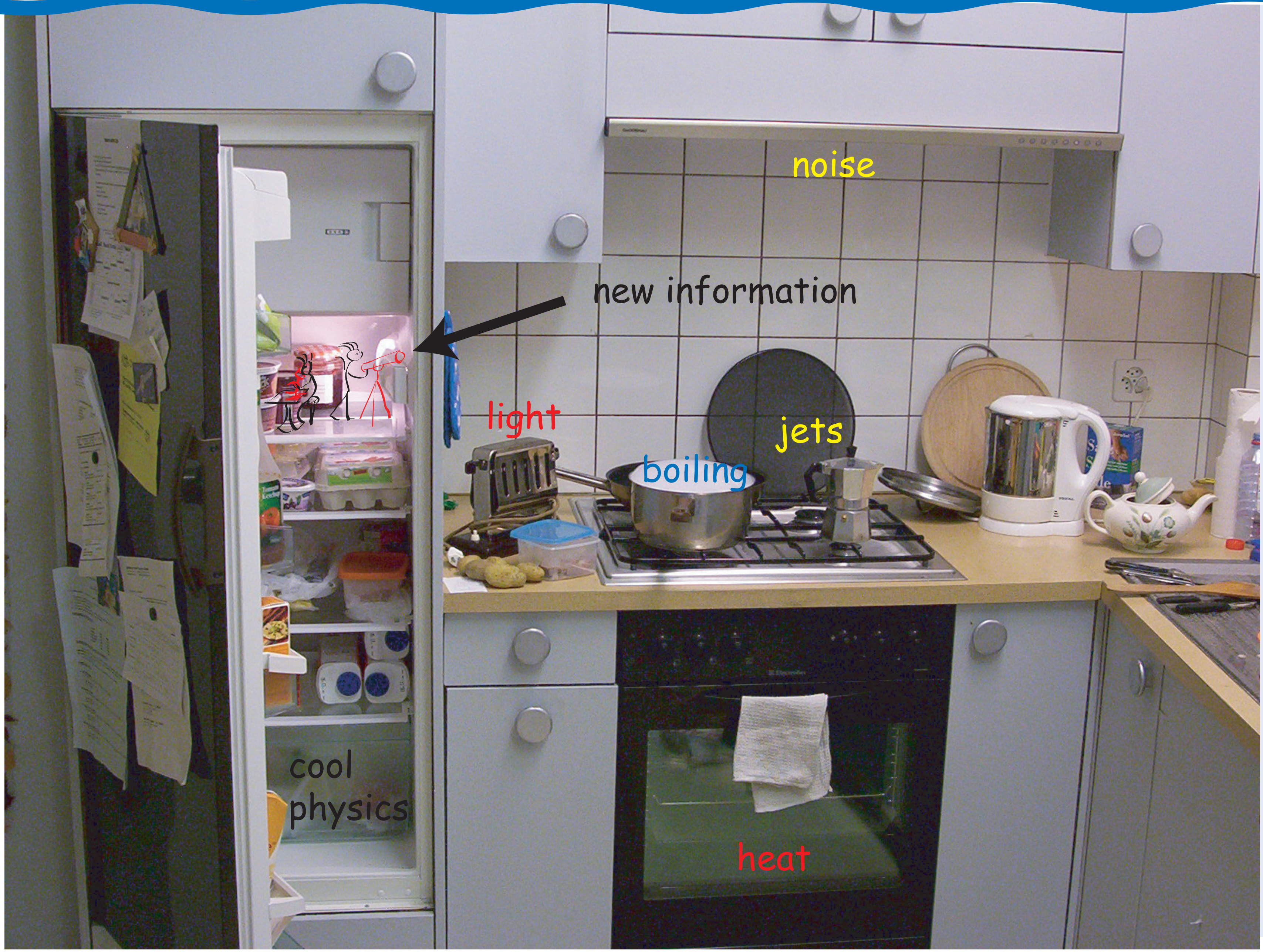
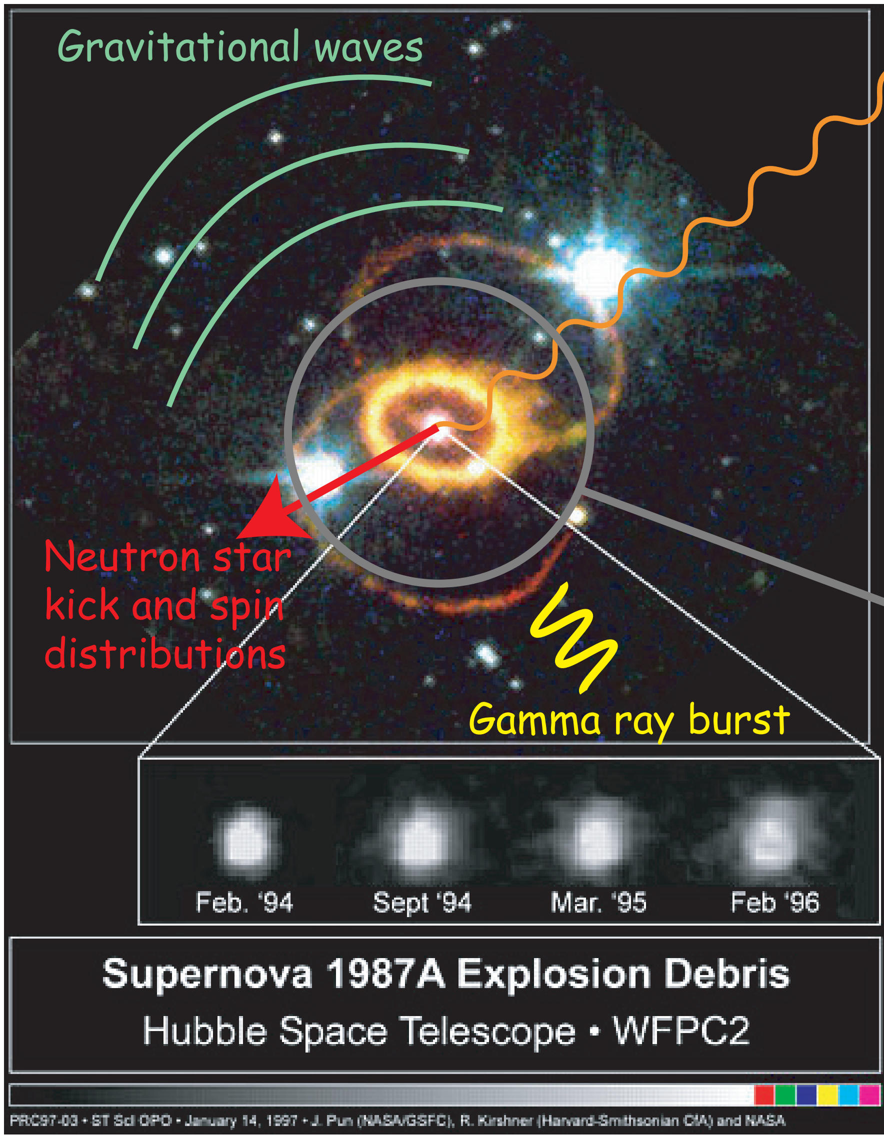


Supernova Observables

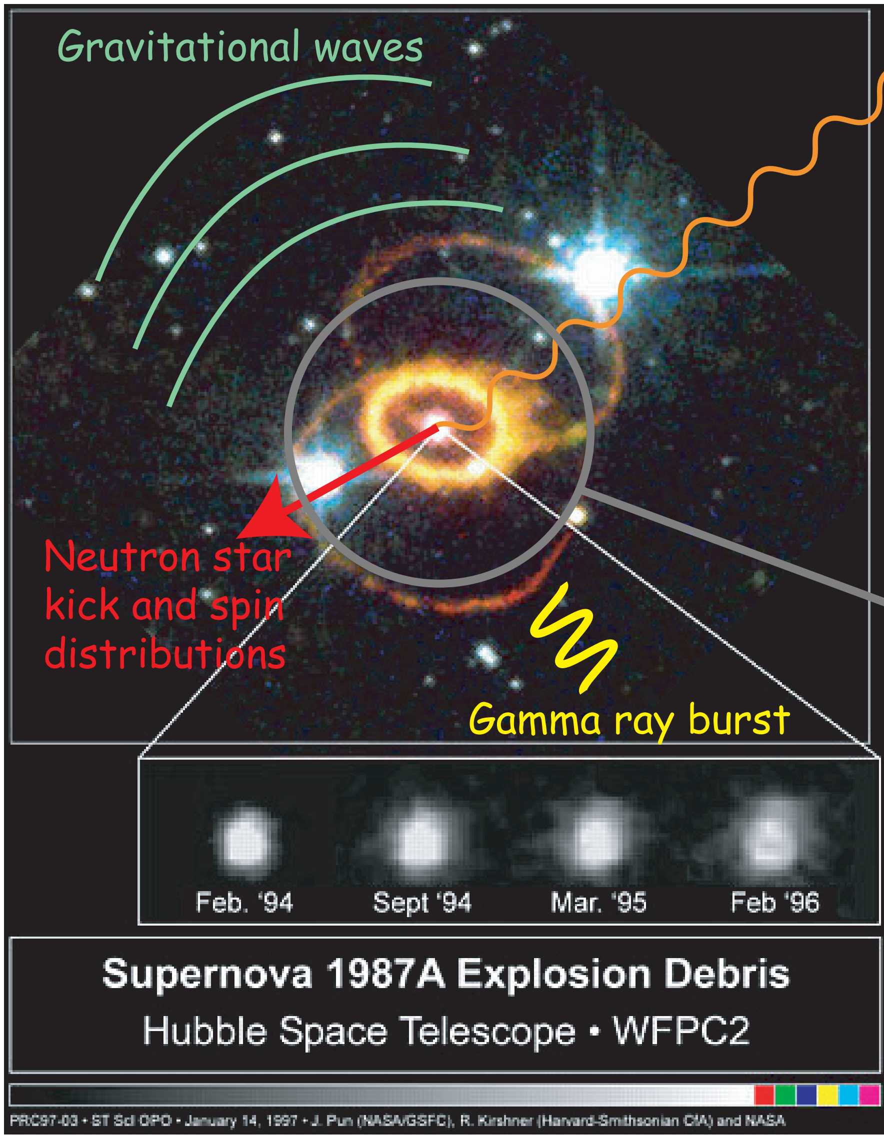


neutrino signal from interior

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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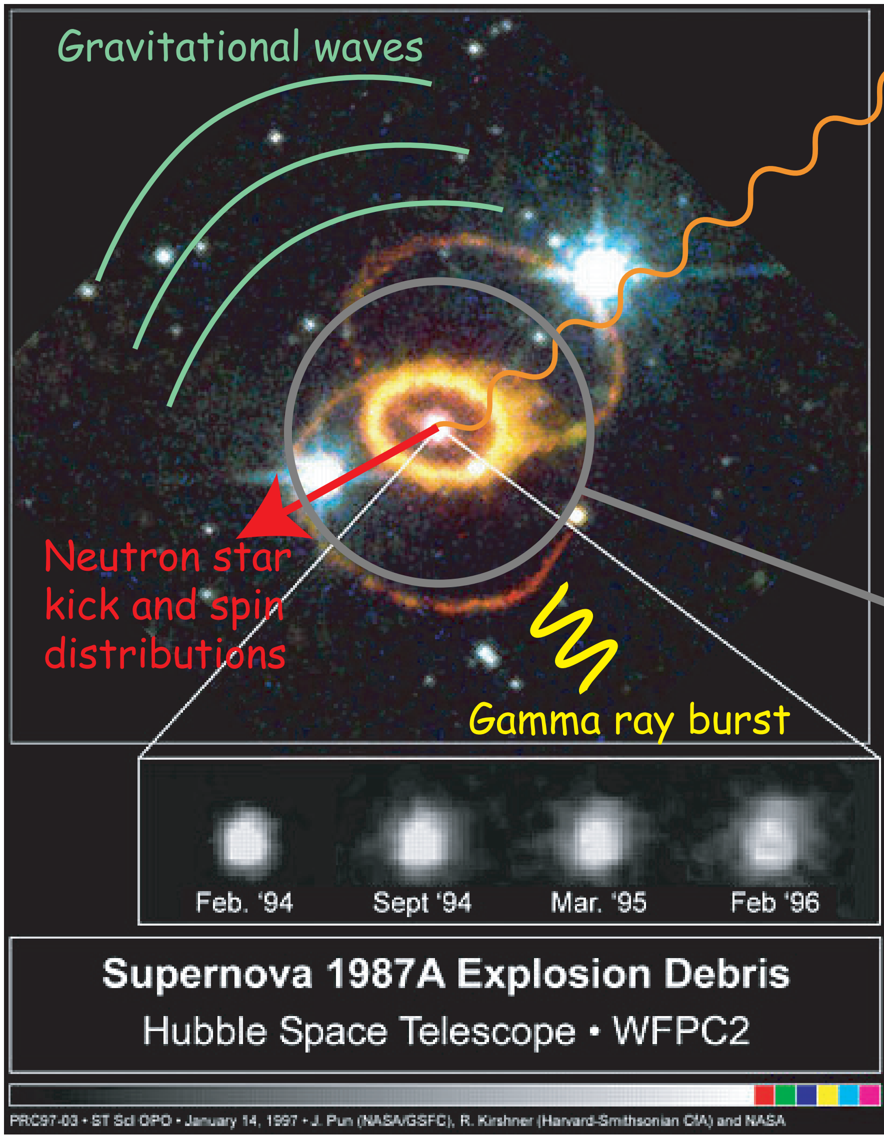
Stellar evolution

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 $M_{\text{vis}} = -14^M$. 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.

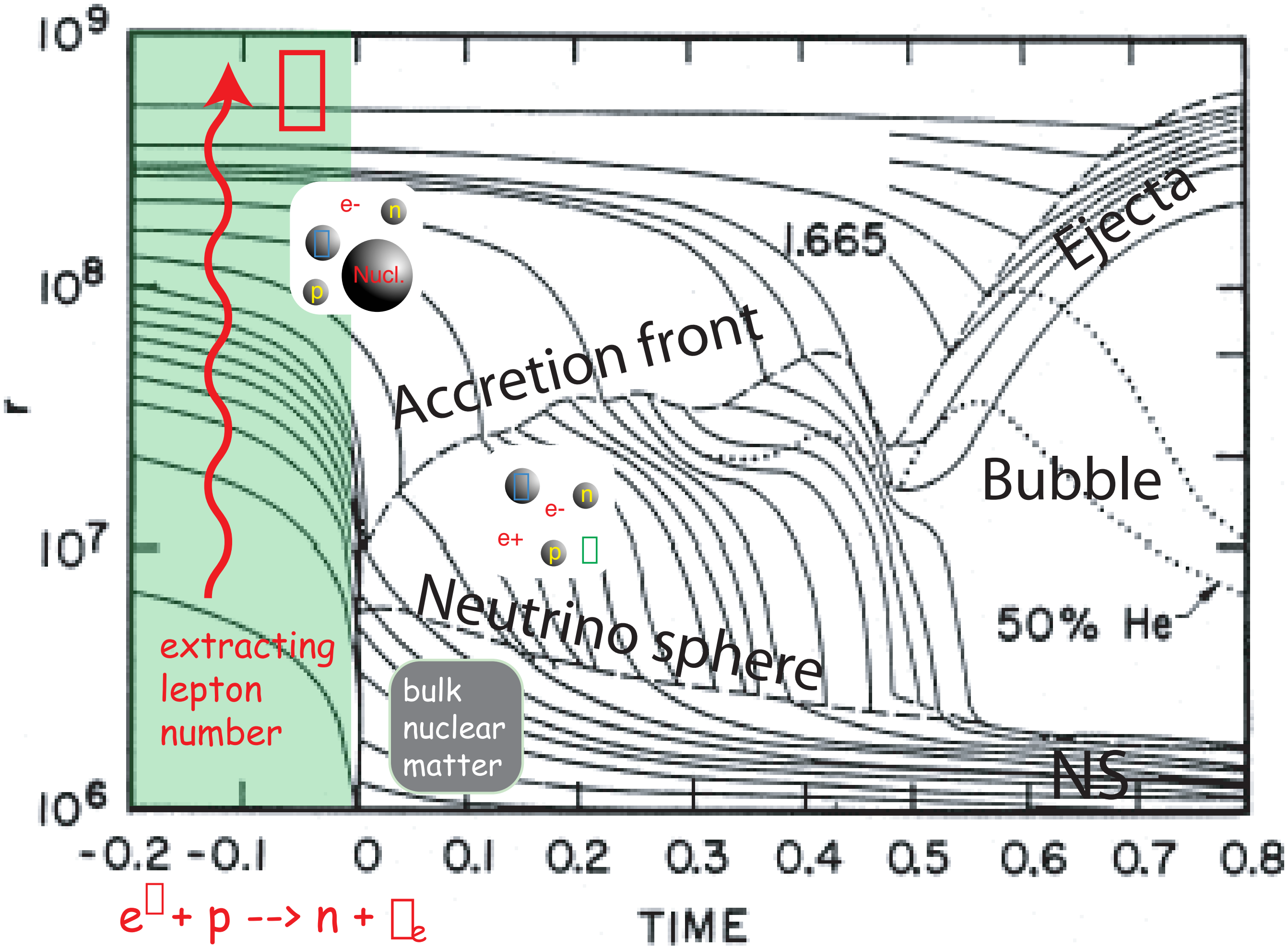
Huge Energies

- 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)

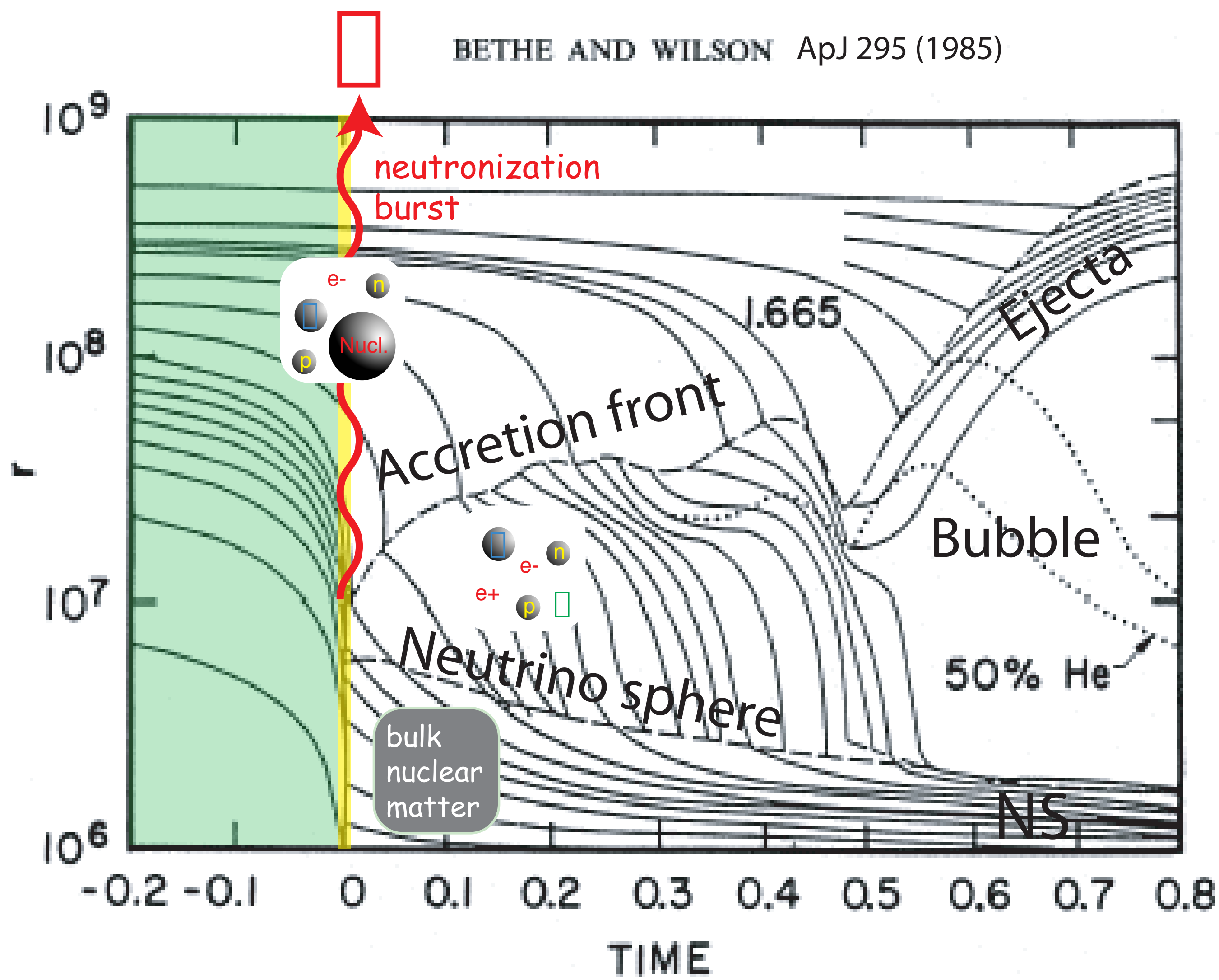


$e^{-} + p \rightarrow n + \nu_e$

Colgate & White, ApJ 143 (1966)

1) Collapse

Delayed explosion: 4 phases



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1) Collapse

2) Bounce

Delayed explosion: 4 phases

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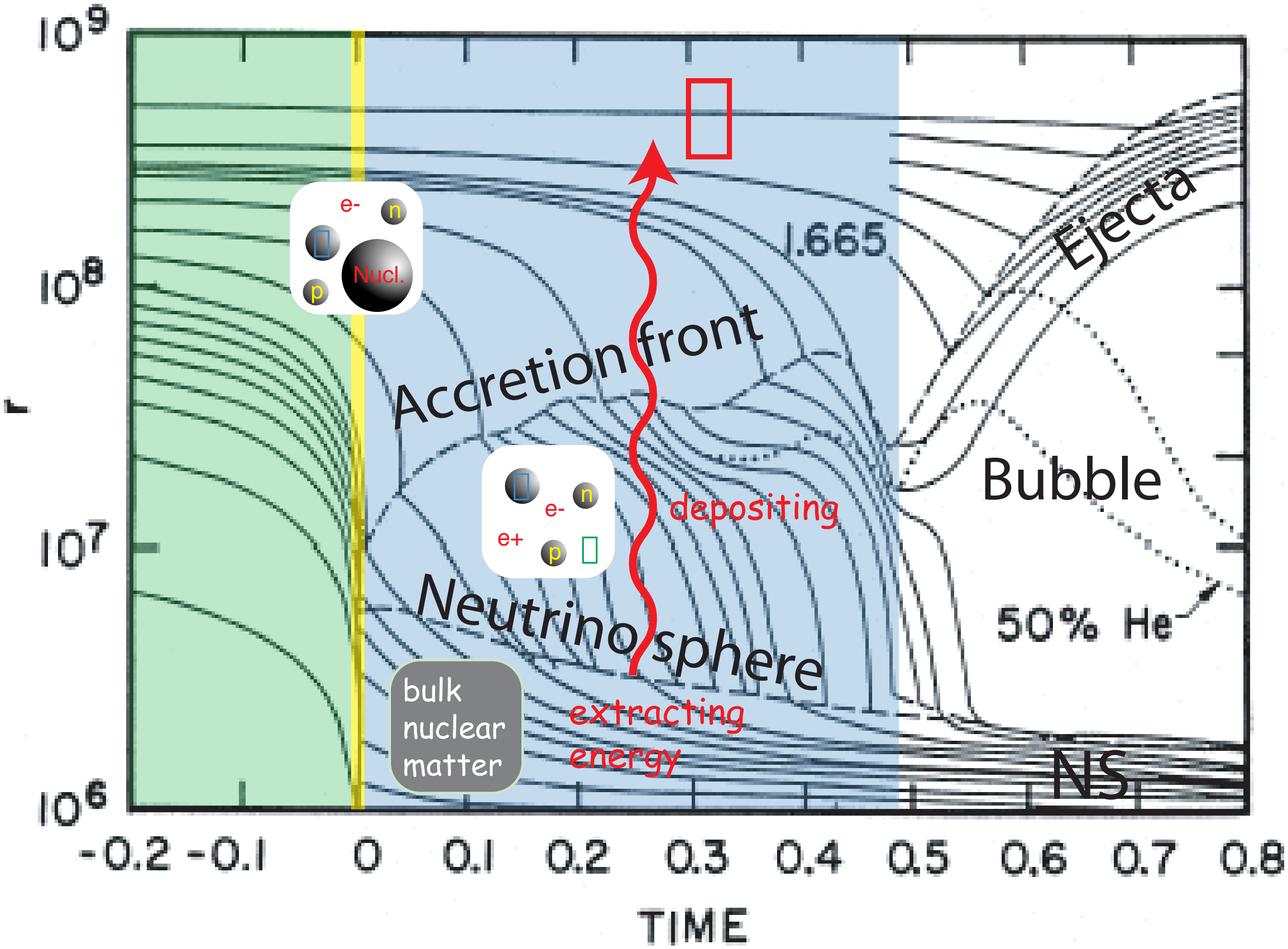

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1) Collapse

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3) Accretion

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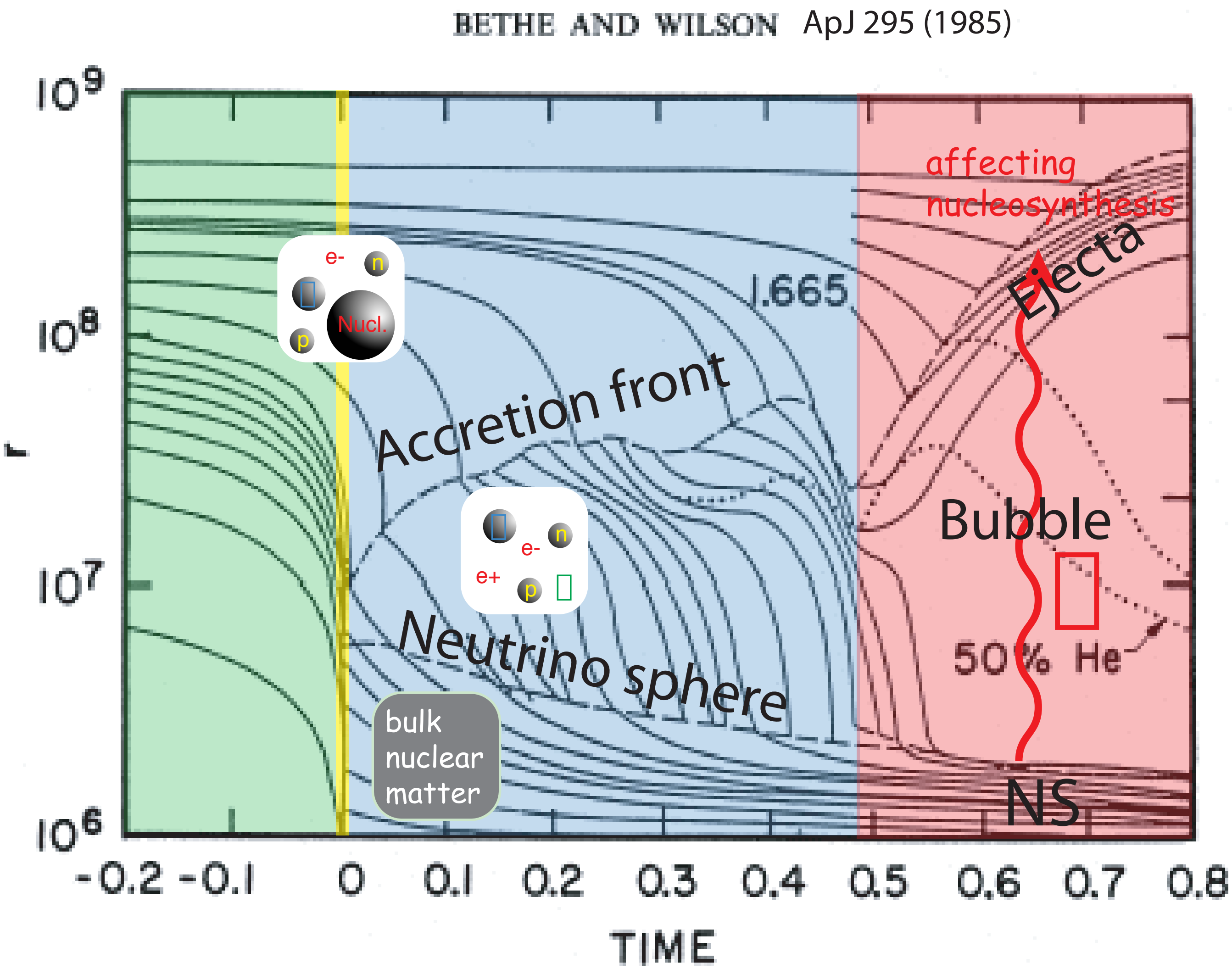


Colgate & White, ApJ 143 (1966)

1) Collapse

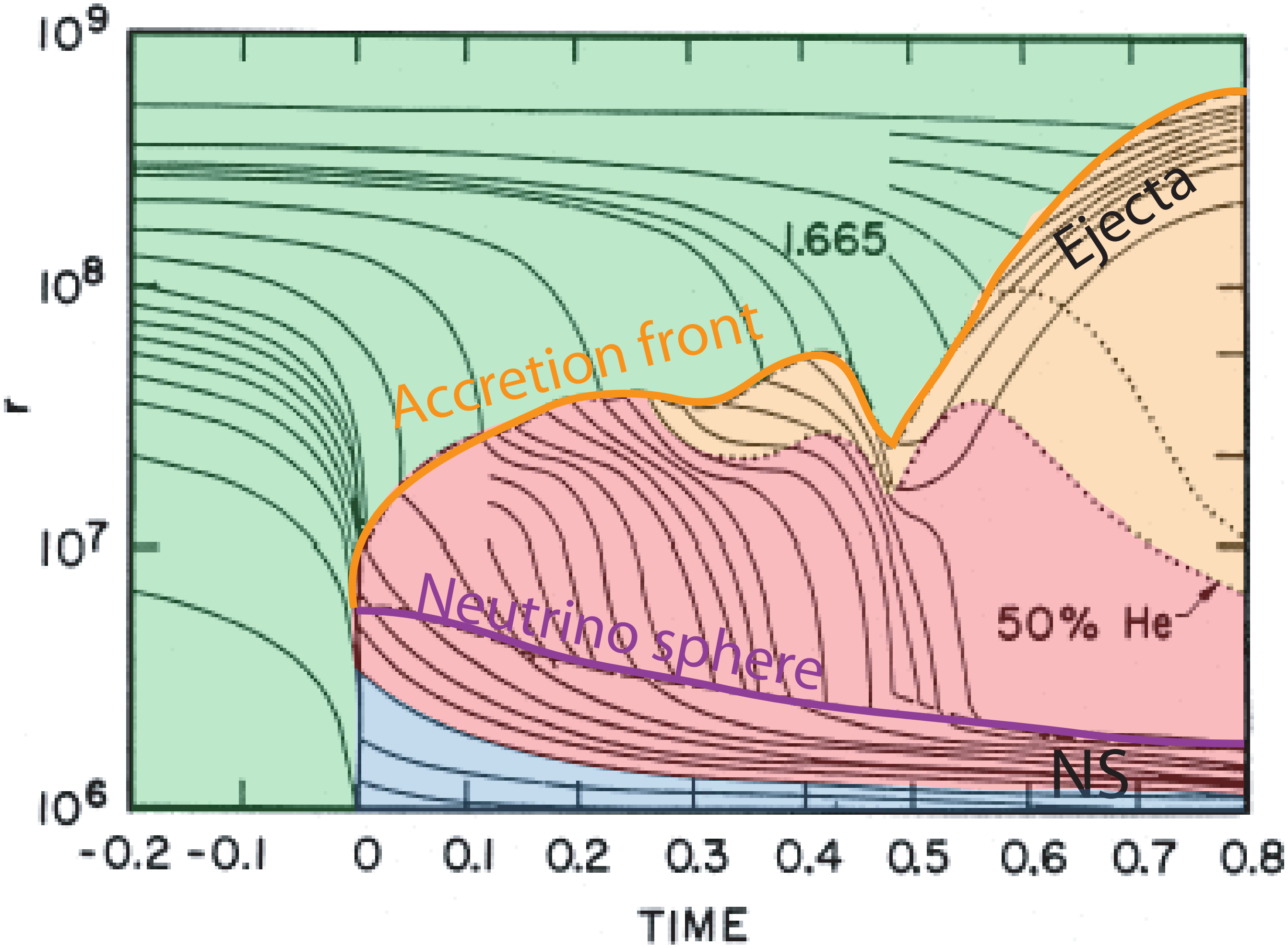
2) Bounce

3) Accretion

4) Explosion

Overview matter conditions

BETHE AND WILSON ApJ 295 (1985)



Colgate & White, ApJ 143 (1966)

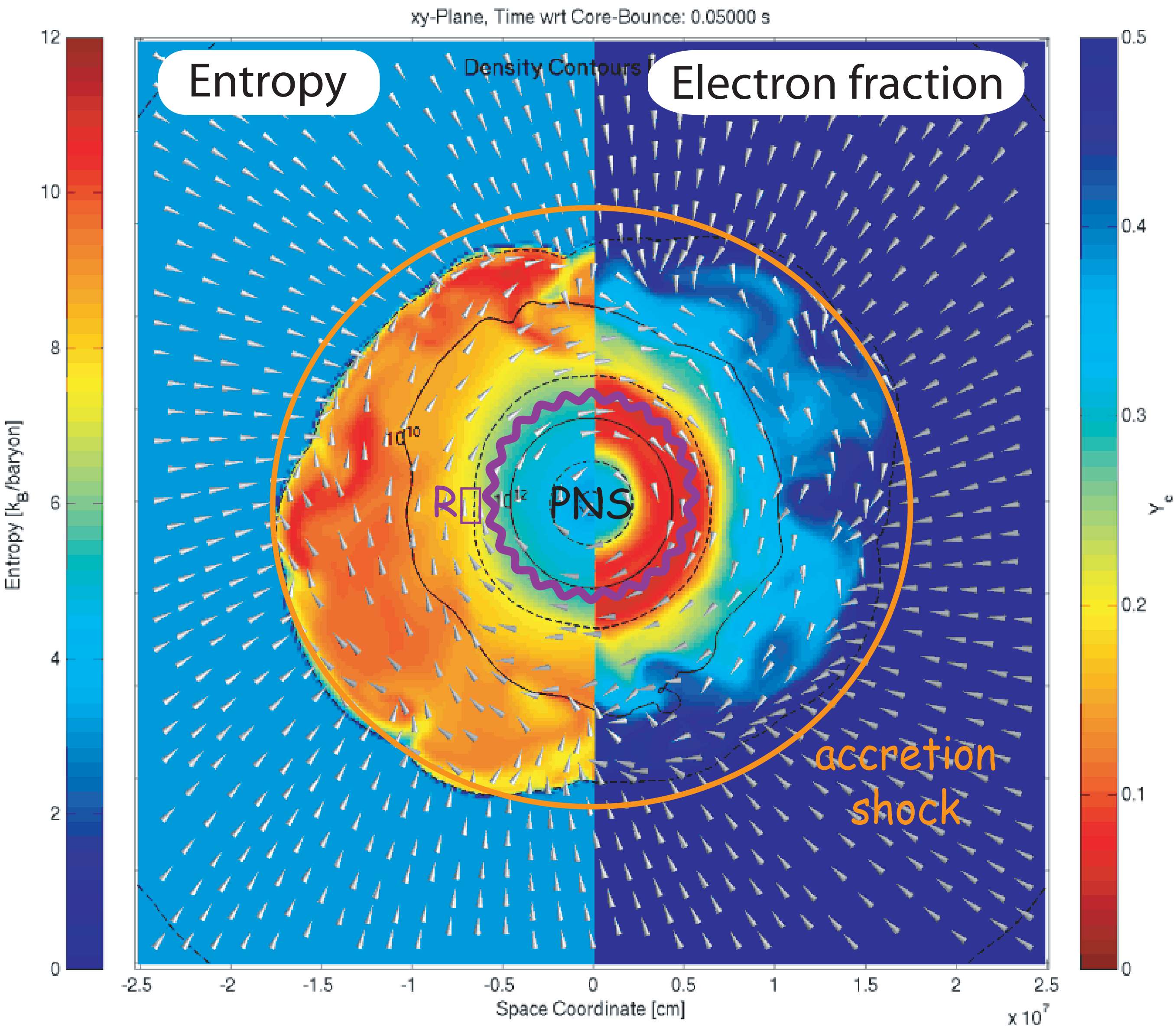
1) Ensemble of nuclei

2) Cool bulk nuclear matter

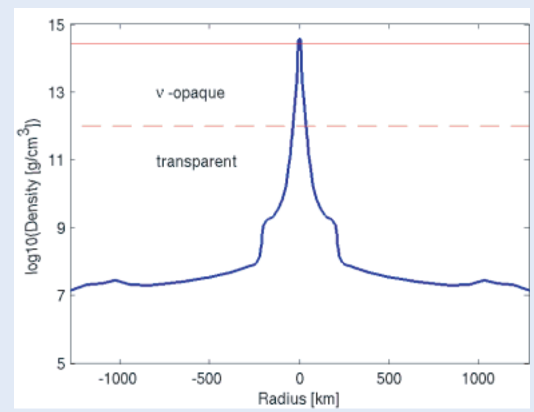
3) Hot dissociated

4) Freeze-out of nuclei

Complex 3D surface-phenomenon

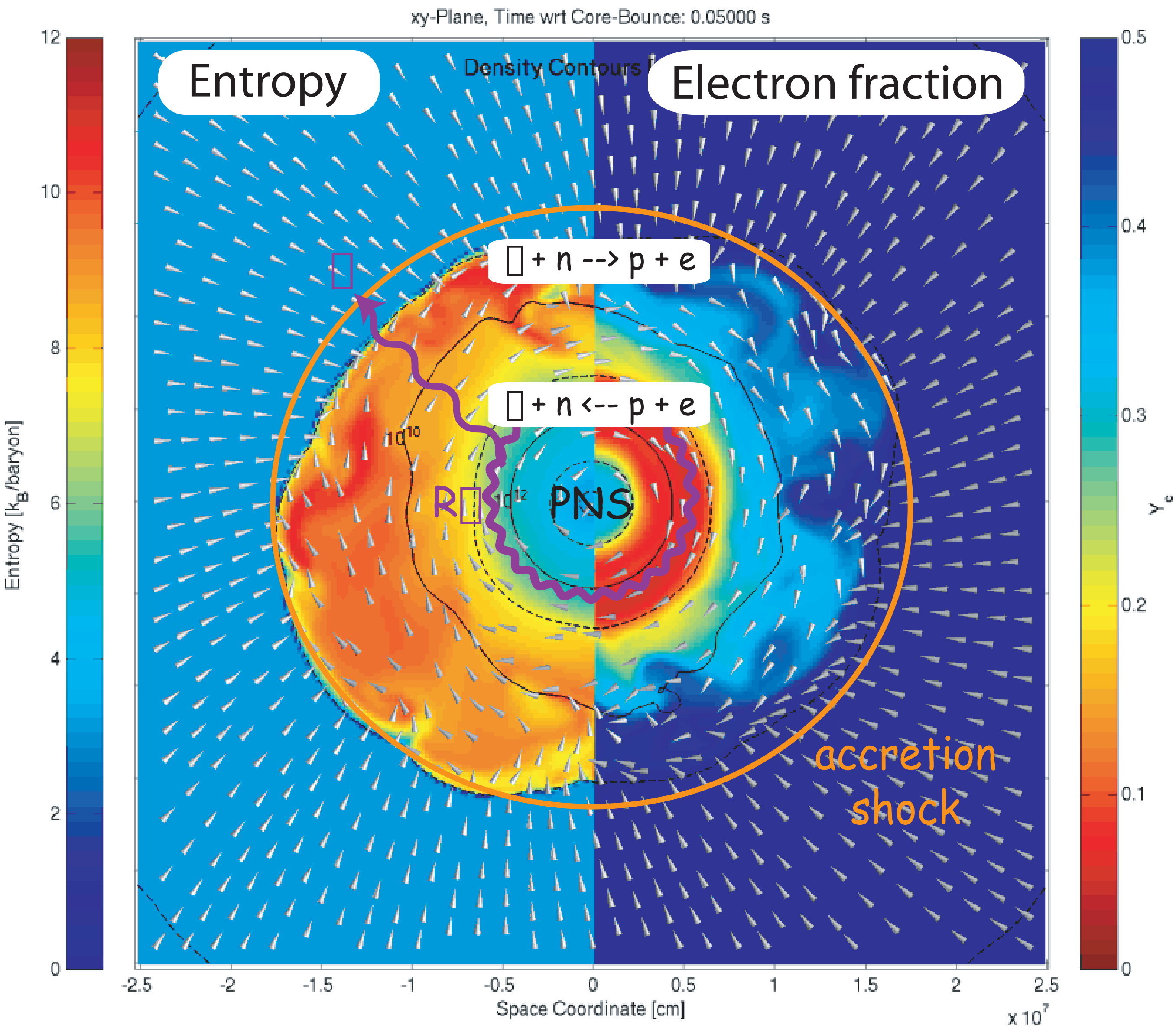


• The supernova explosion takes place on the surface of the protoneutron star



• 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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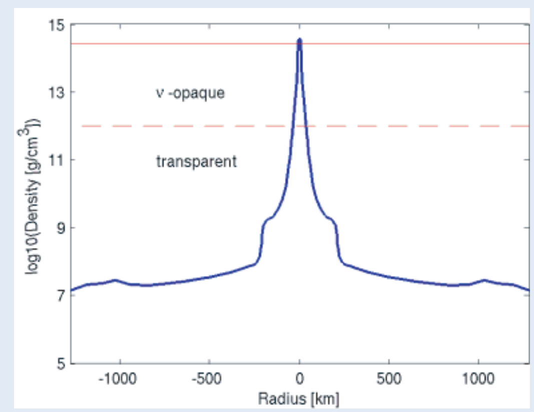

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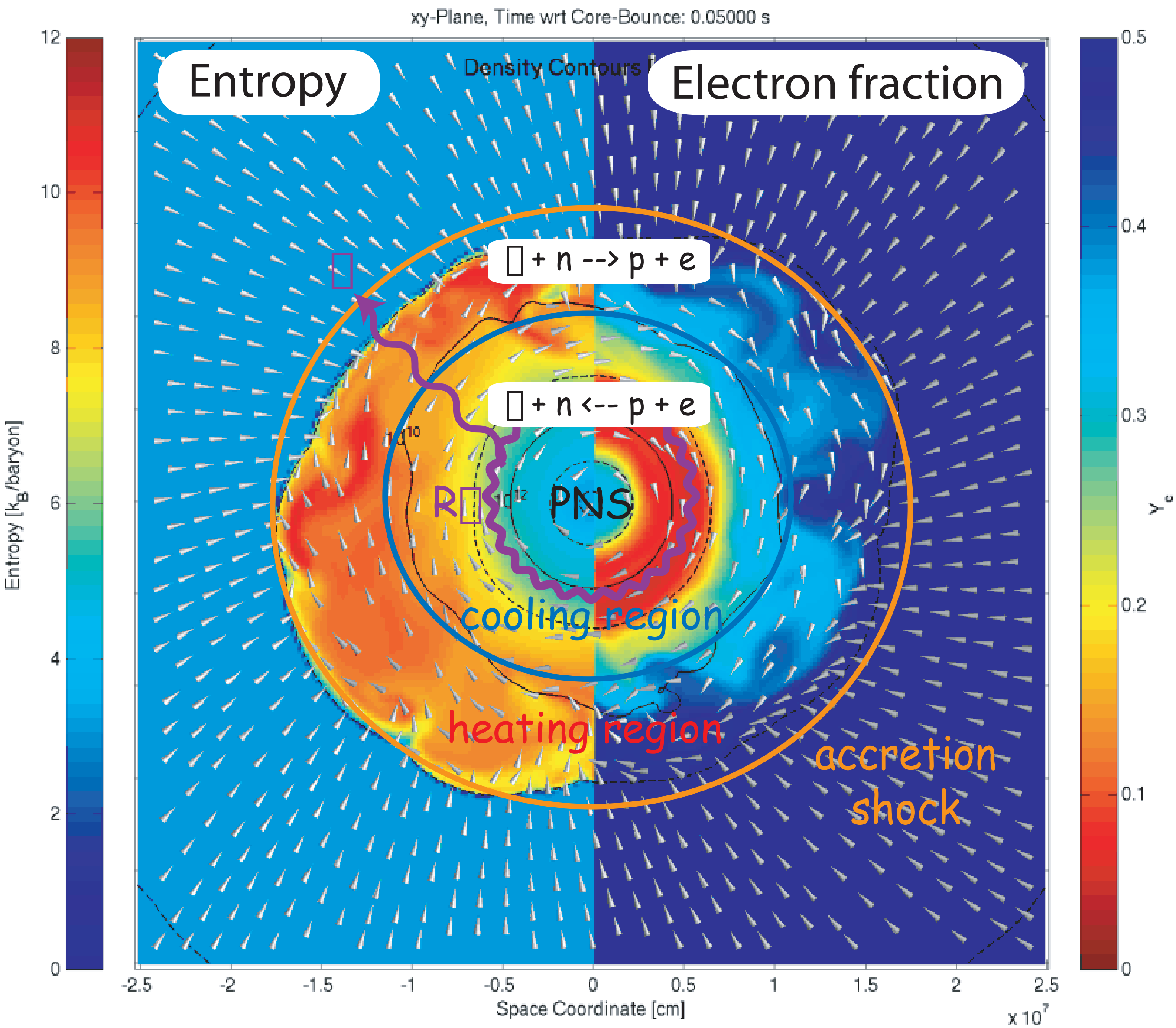

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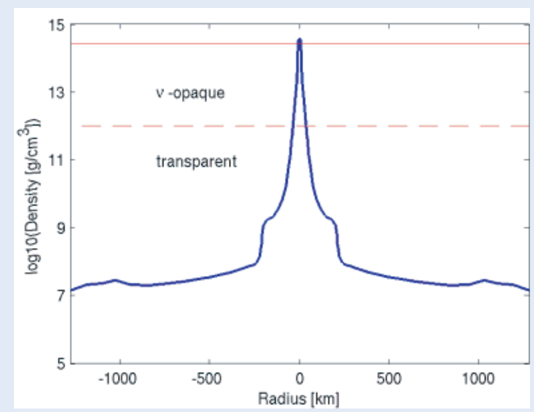

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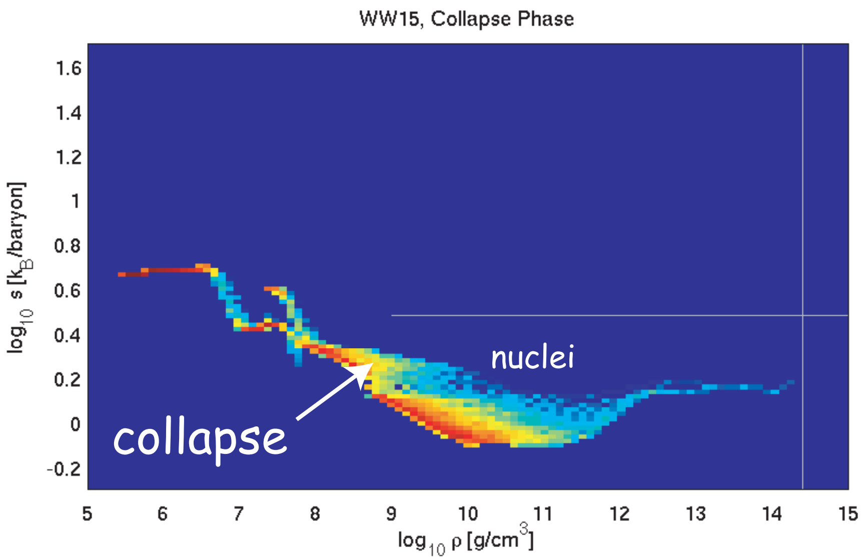
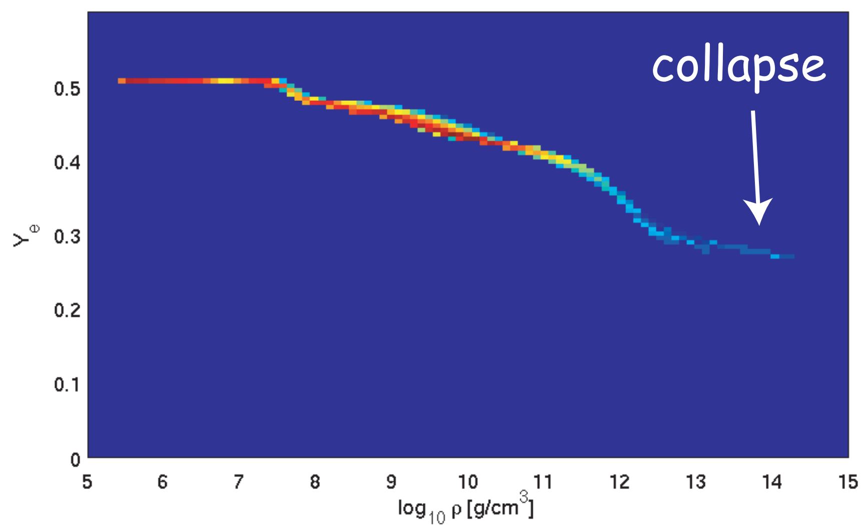
Conditions in (,s,Ye)-space

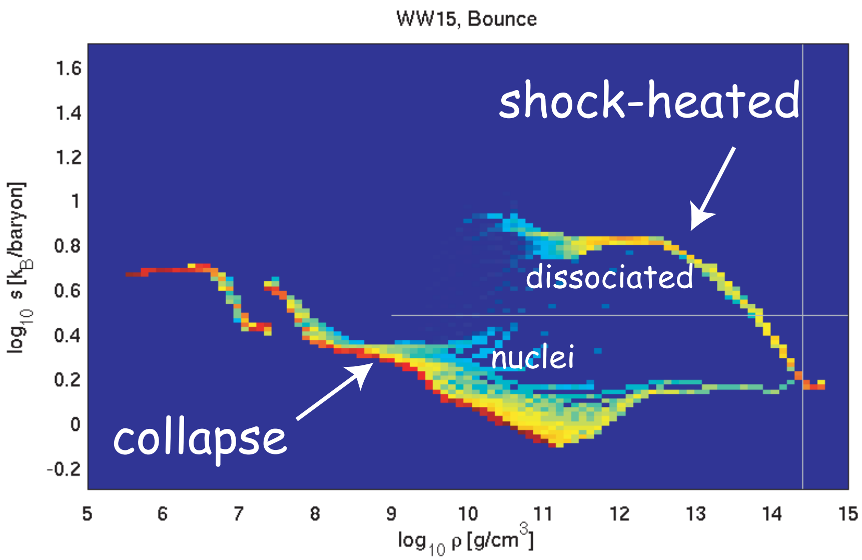


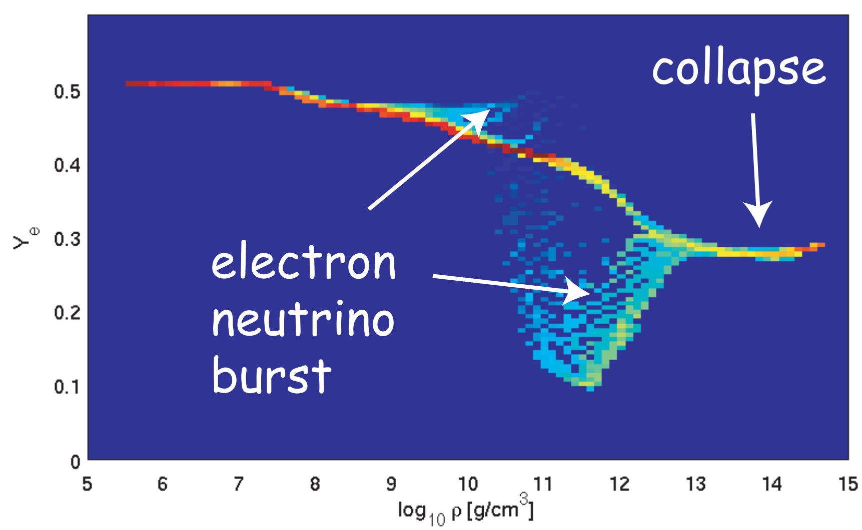


Collapse Phase:

- deleptonization along narrow trajectory
- slight entropy increase

Conditions in (ρ,s,Ye)-space





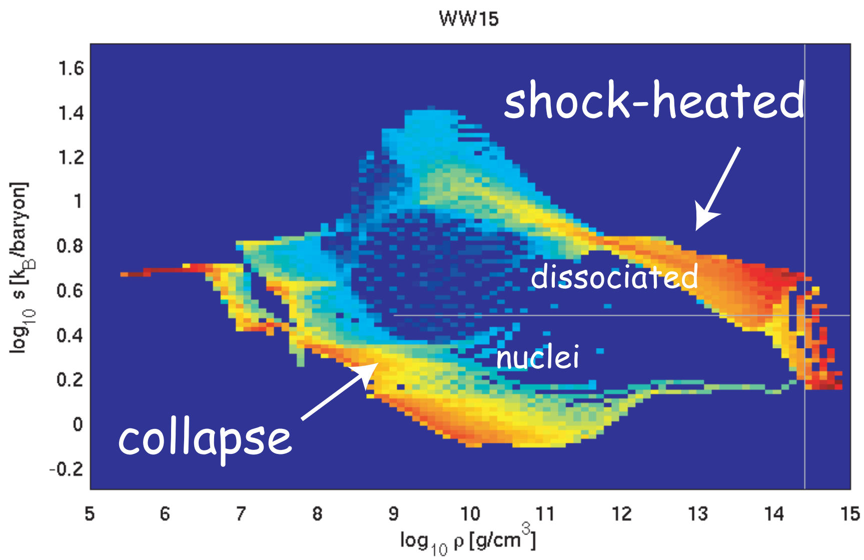
Collapse Phase:

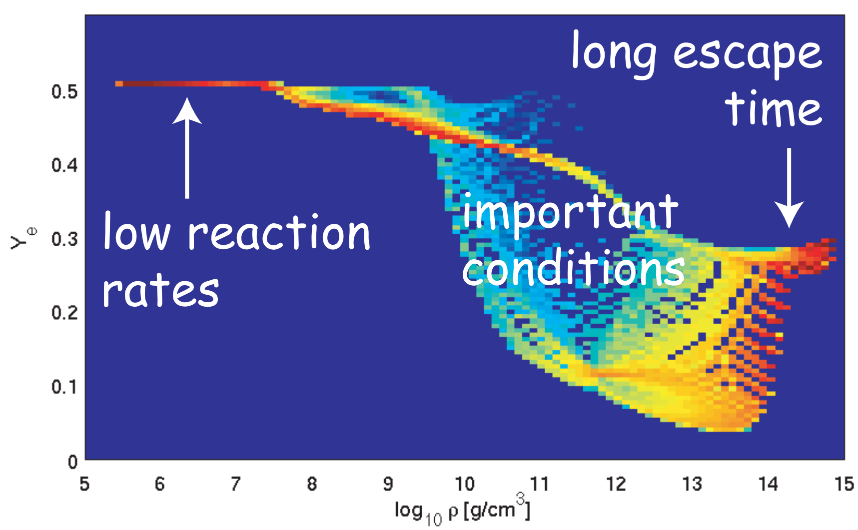
- deleptonization along narrow trajectory
- slight entropy increase

Postbounce Phase:

- jump to dissociated nucleon plasma

Relevant □-matter interactions





Collapse Phase:

- deleptonization along narrow trajectory
- slight entropy increase

Postbounce Phase:

- jump to dissociated nucleon plasma
- electron fraction: Ye decrease

e + p --> n + □

Neutrino-matter interactions

Bruenn (1985)
Raffelt (2001)

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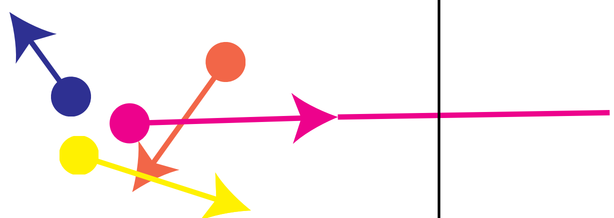
Description: Number Sphere Energy Sphere Transport Sphere

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)

Neutrino-matter interactions

Bruenn (1985)
Raffelt (2001)

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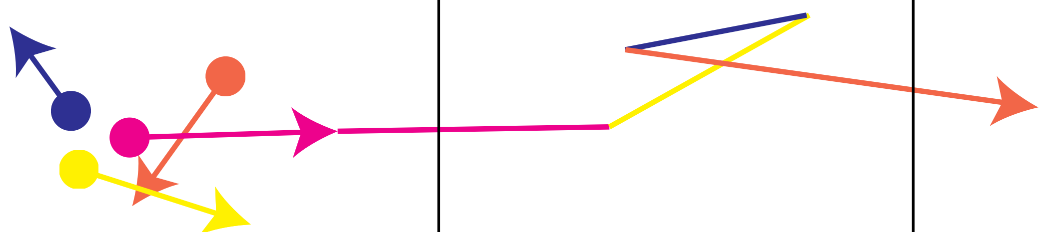
Description: Number Sphere | Energy Sphere | Transport Sphere

High matter density

Emission & Absorption

Inelastic Scattering



Can be Pauli-blocked in diffusive regime

Probability enhanced by isoenergetic scattering

Low matter density

Production/Annihilation

Thermalisation

Electron or Positron capture

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Neutrino-electron scattering

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

Inelastic neutrino-nucleus scattering

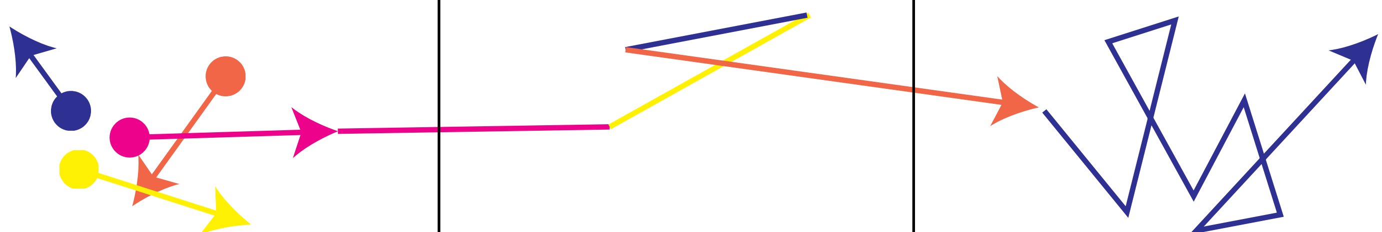
Neutrino-matter interactions

Bruenn (1985)
Raffelt (2001)

Description: Number Sphere | Energy Sphere | Transport Sphere

High matter density

Emission & Absorption	Inelastic Scattering	Isoenergetic Scattering



Can be Pauli-blocked in diffusive regime	Probability enhanced by isoenergetic scattering	Strong energy dependence, ~E^2

Low matter density

Production/Annihilation | Thermalisation | Scattering | Streaming

Electron or Positron capture

$$\nu_e + n \rightleftharpoons e^- + p$$
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Neutrino-electron scattering

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

Inelastic neutrino-nucleus scattering

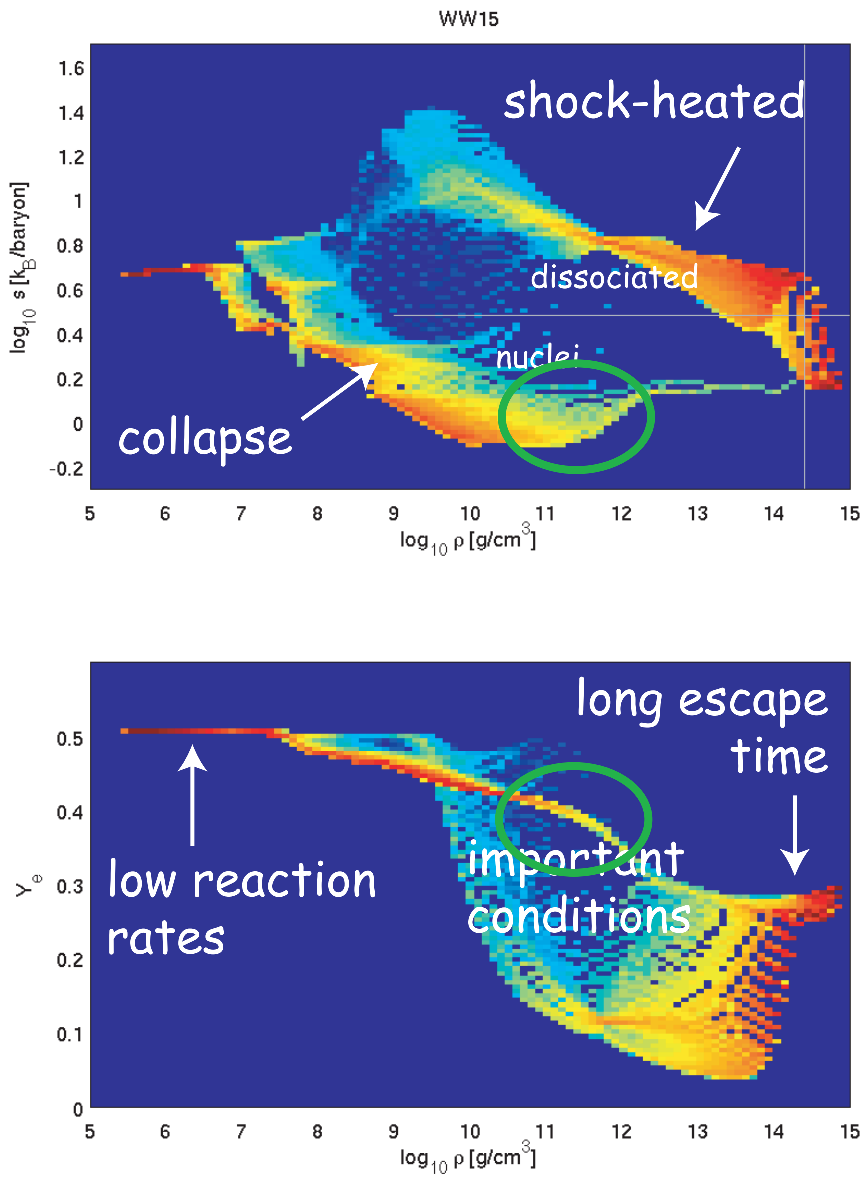
Elastic coherent scattering of neutrinos on nuclei

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

Neutrino-nucleon scattering

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

-sensitivity: 1. Collapse phase



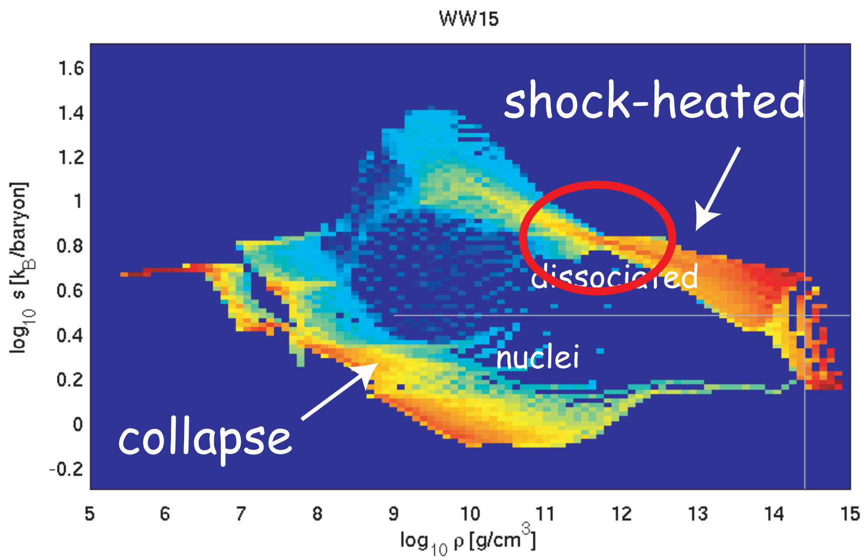
The conditions around the neutrino spheres are marked in

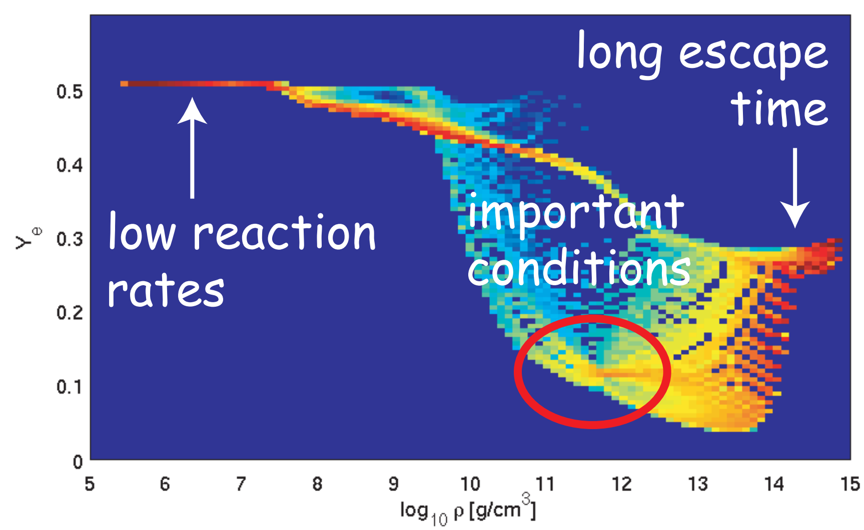
green ... collapse

red ... postbounce

orange ... explosion

□-sensitivity: 3. Explosion mechanism





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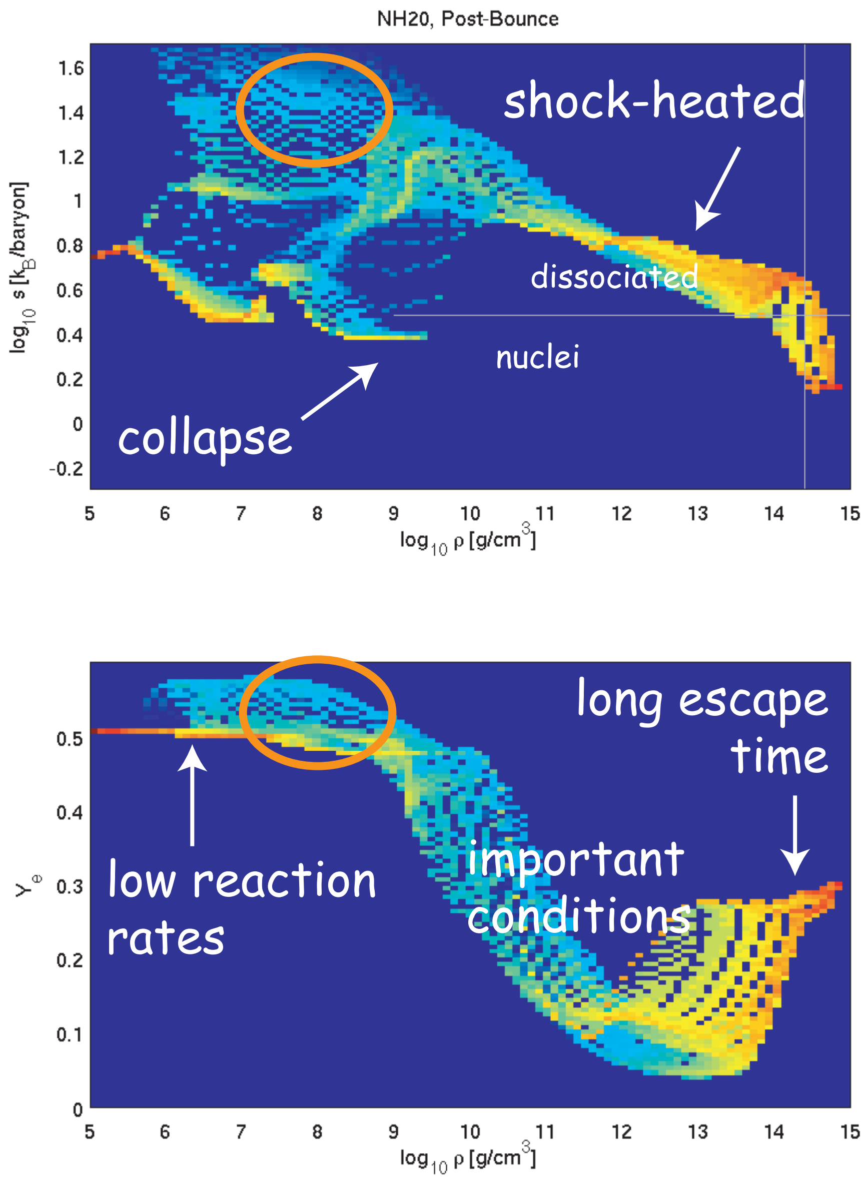
How to handle the multi-dimensional non-local coupling of neutrinos with fluid instabilities?

-sensitivity: 2. Explosion phase



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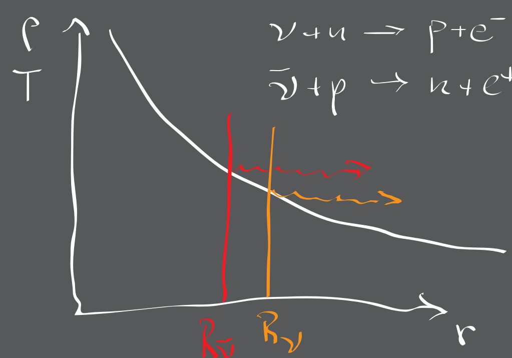
Different luminosity contributions

- Luminosity composed of two parts:

2) neutrinos of cooling protoneutron star



$\nu + n \to p + e^-$ neutron rich

$\bar\nu + p \to n + e^+$ $n_n > n_p$

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

- Classical hierarchy among neutrino energies reflects teperature at neutrinospheres

Different luminosity contributions

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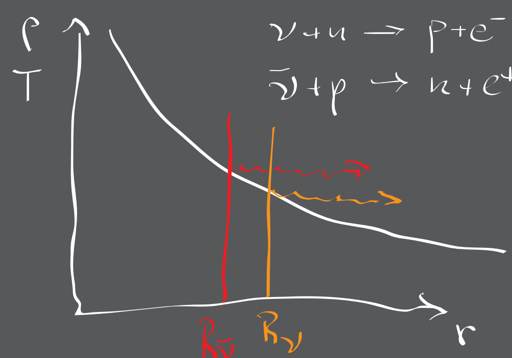


$\nu + n \rightarrow p + e^-$

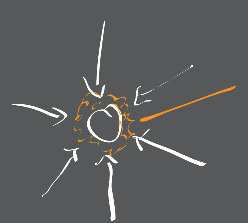
$\bar\nu + p \rightarrow n + e^+$

neutron rich

$n_n > n_p$

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

1) neutrinos from accretion flow



compression of degenerate electron gas

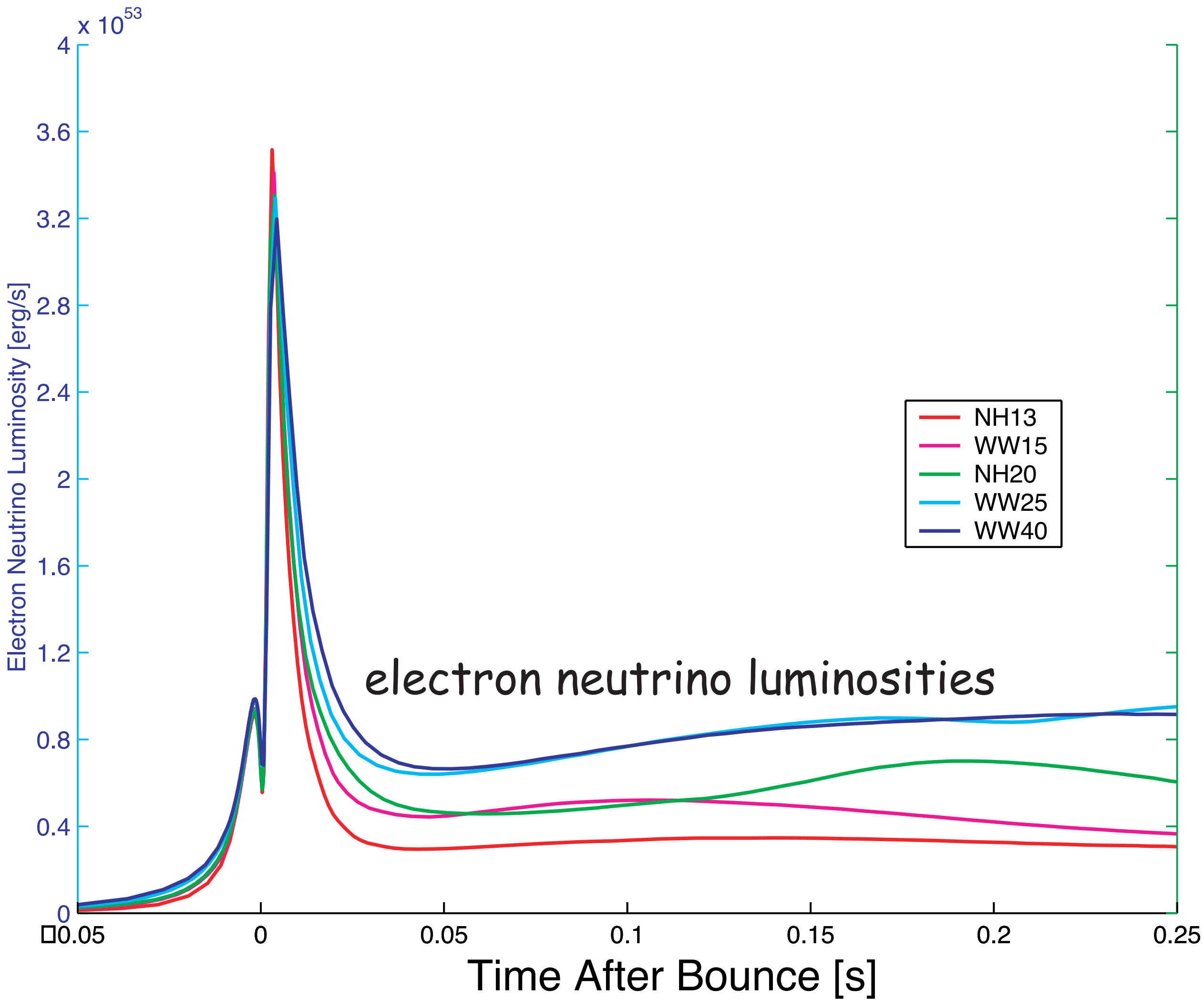
$\Rightarrow e^- + p \rightarrow n + \nu$

- Classical hierarchy among neutrino energies reflects teperature at neutrinospheres

- large accretion rate

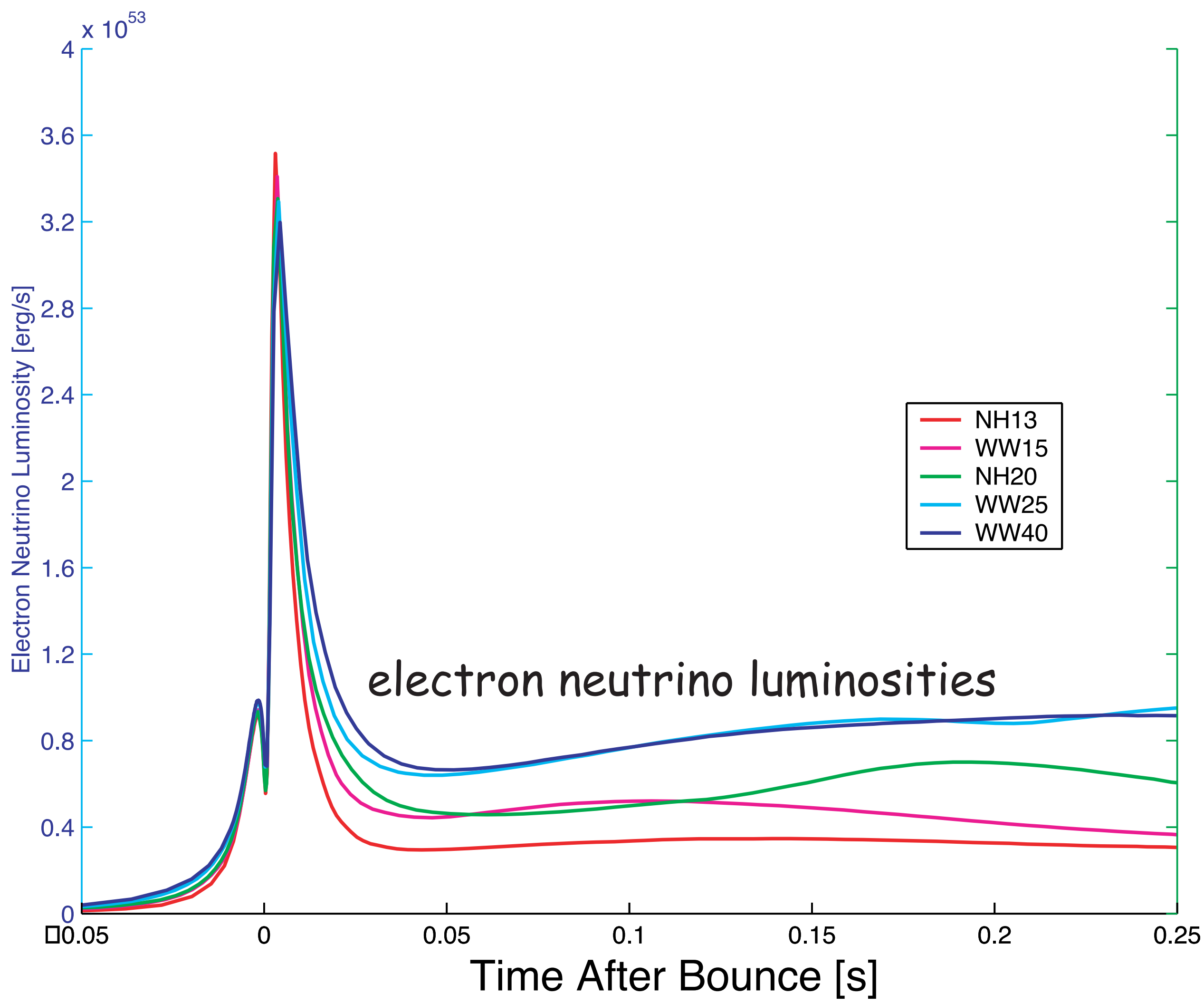
--> Lnu ~ Lnubar

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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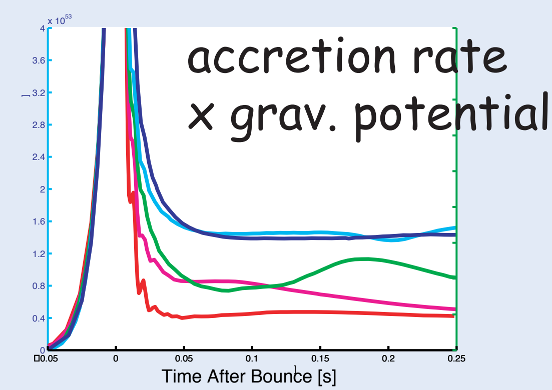
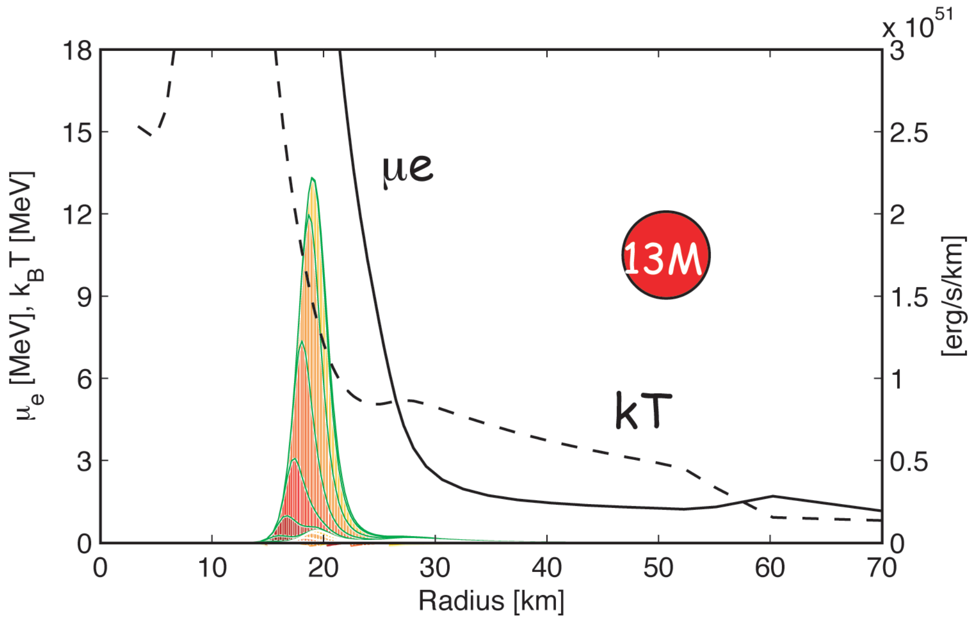
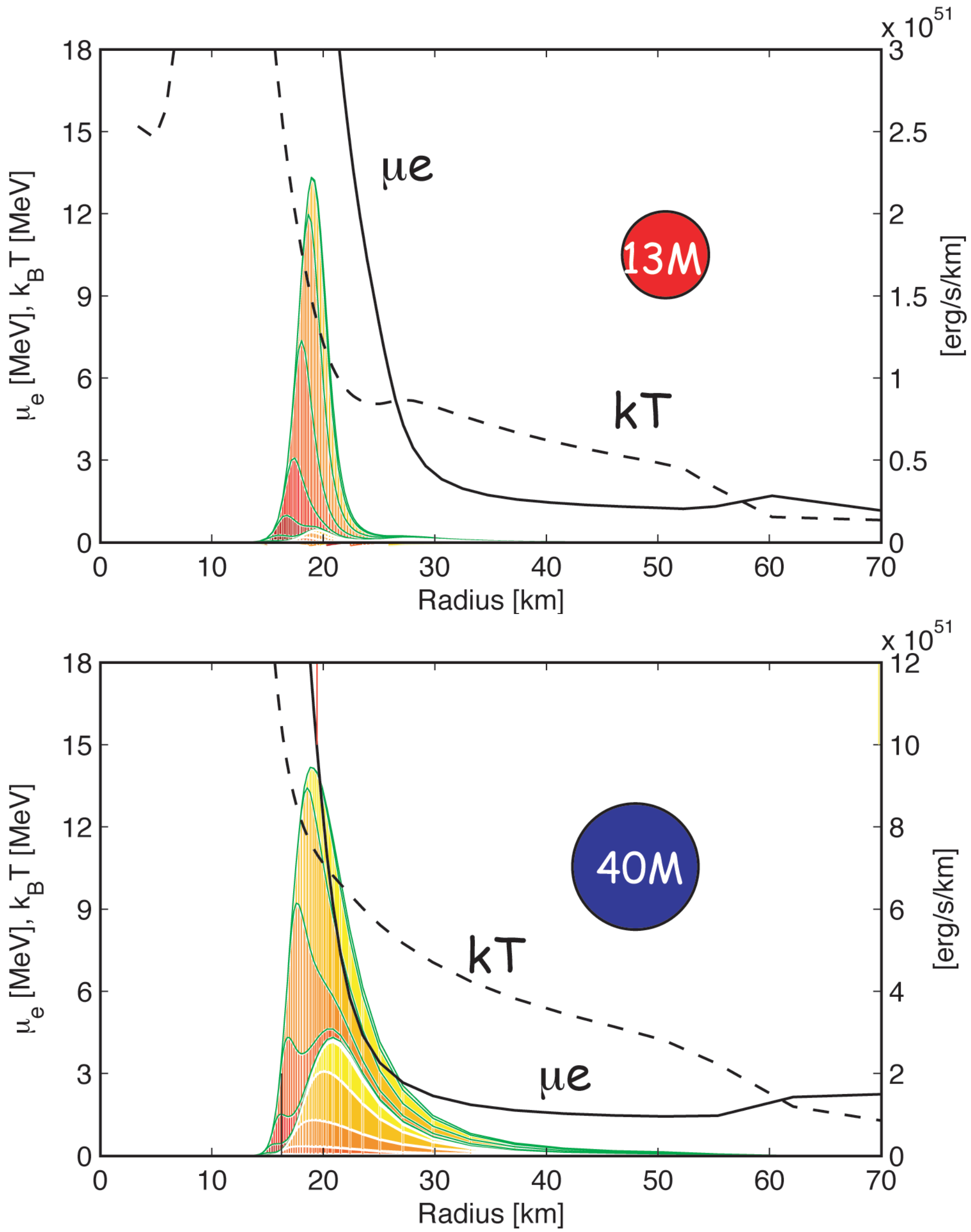


PNS evolution & (/) properties



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

PNS evolution & □(□/□) properties



- low mass proto-neutron star (PNS)
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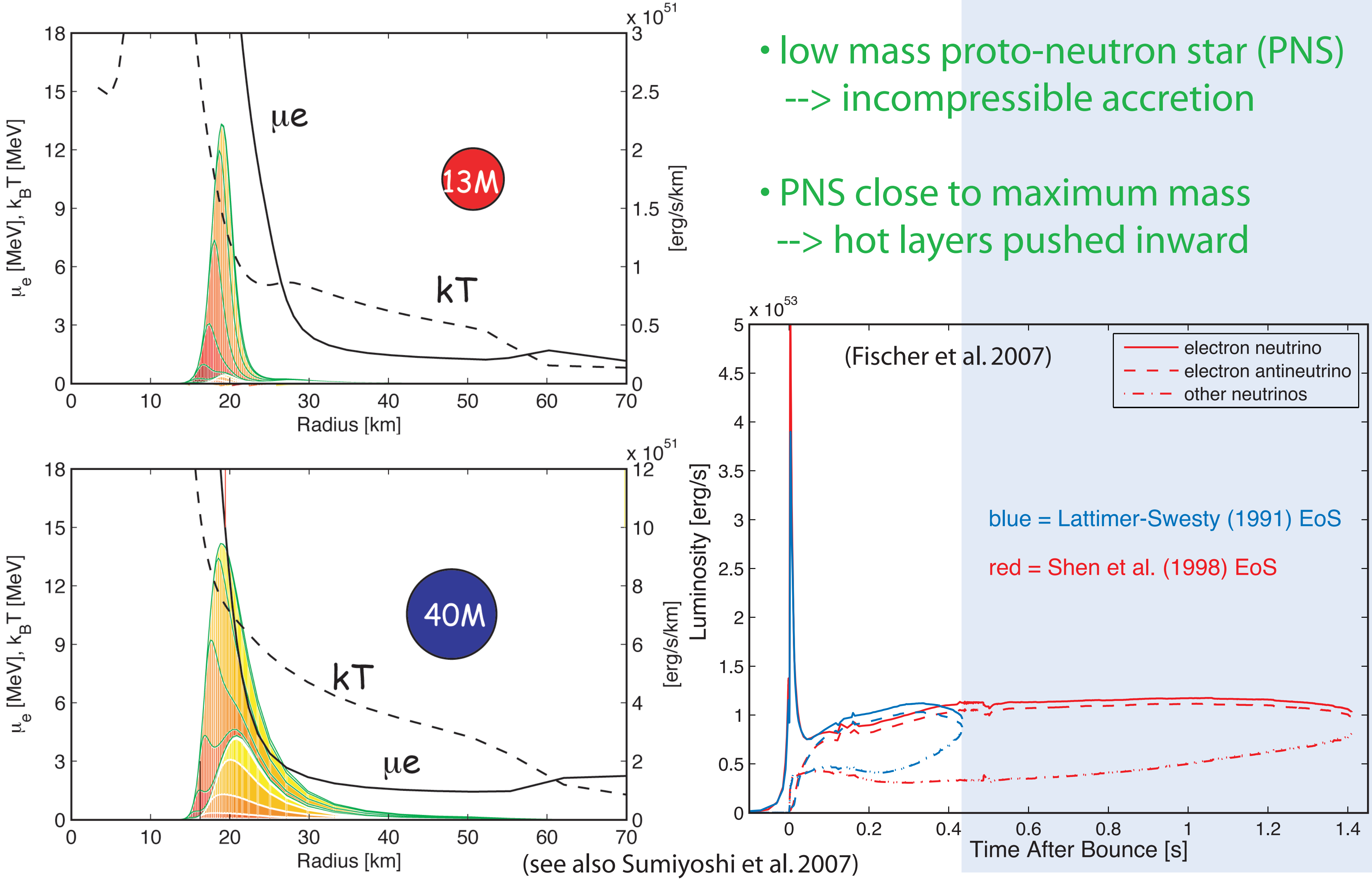
- PNS close to maximum mass
  --> hot layers pushed inward

PNS evolution & (/) properties



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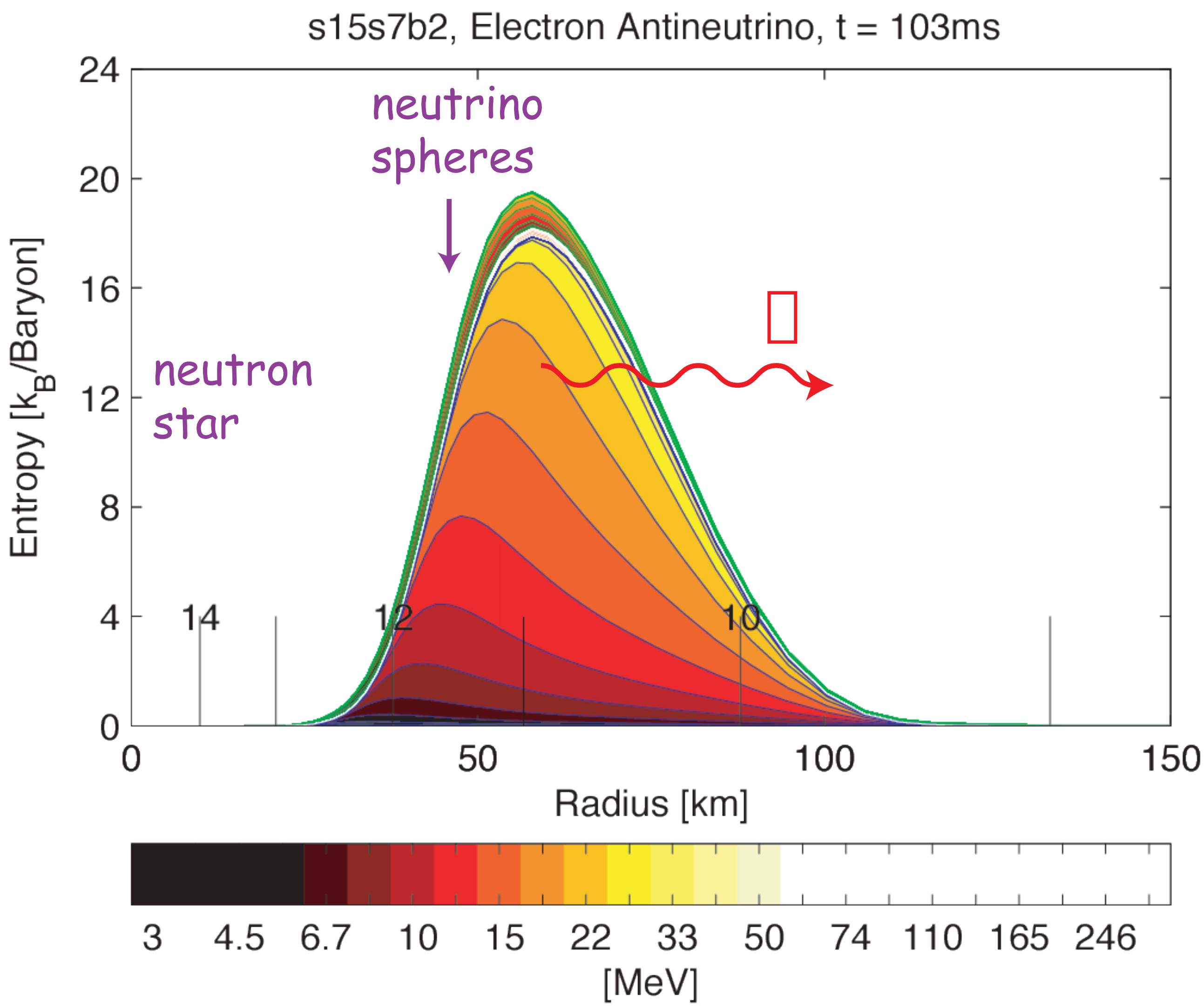
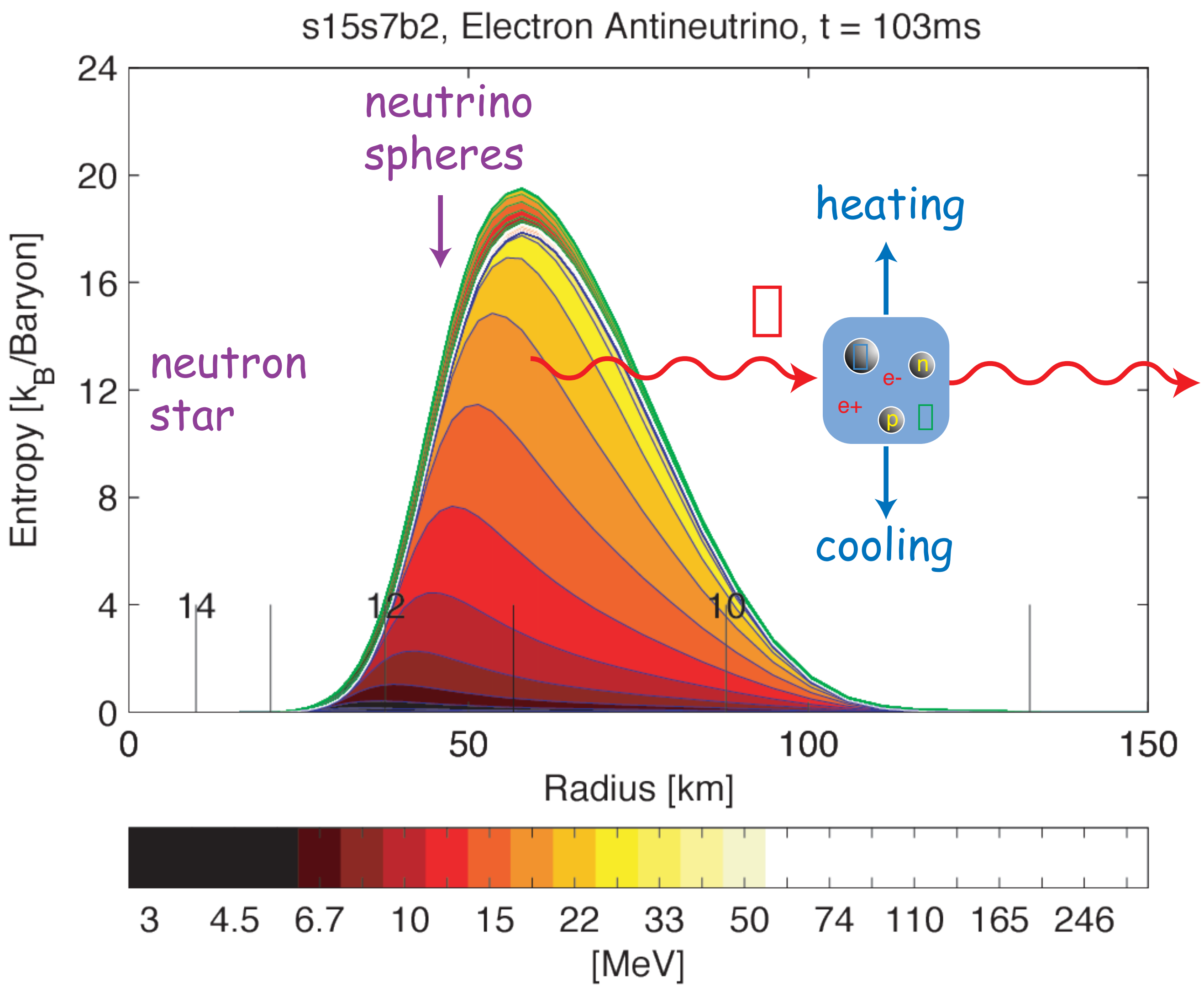
Neutrino heating



(Liebendörfer et al. 2003/4)

- neutrino cooling and neutrino heating are competing

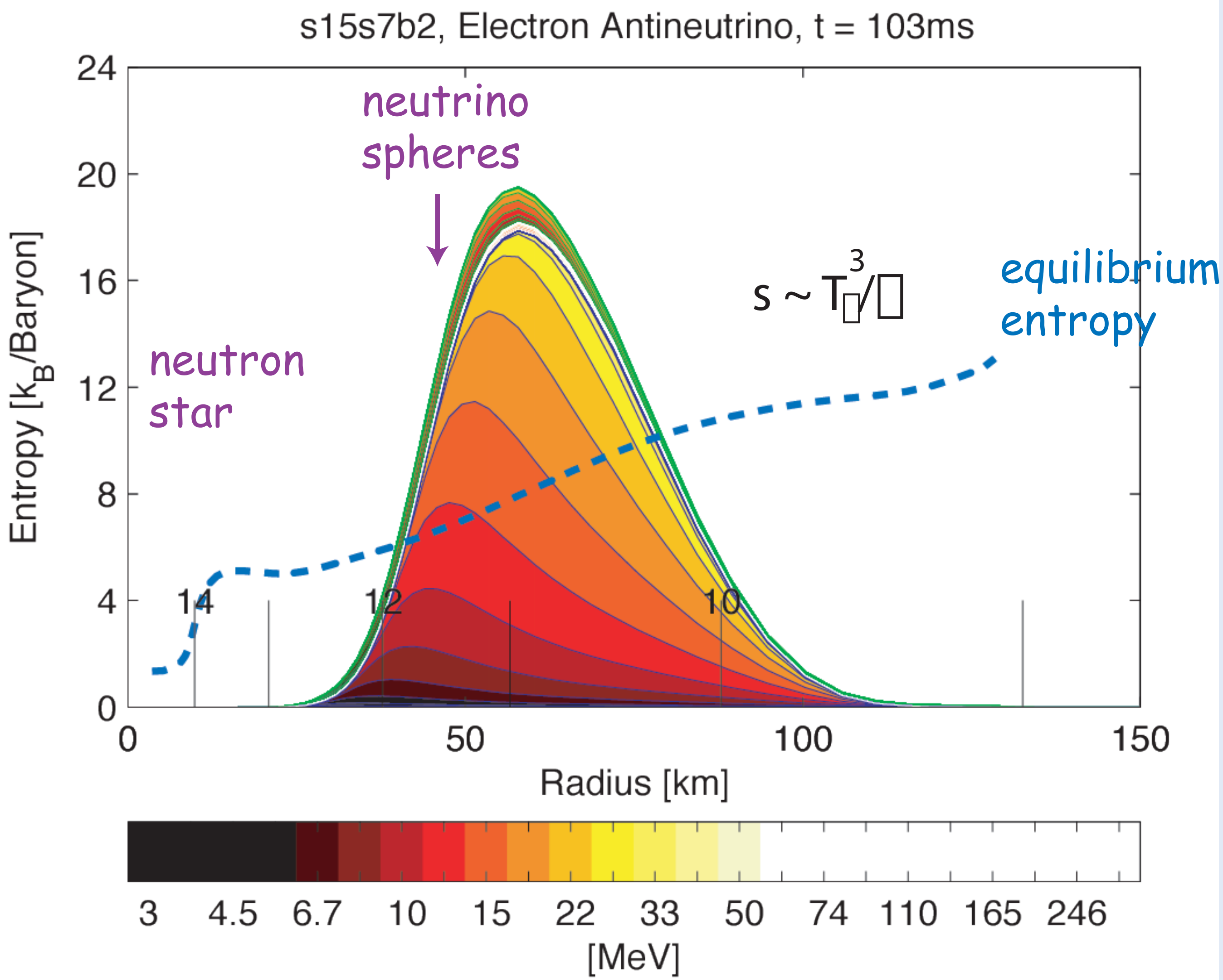
Neutrino heating



(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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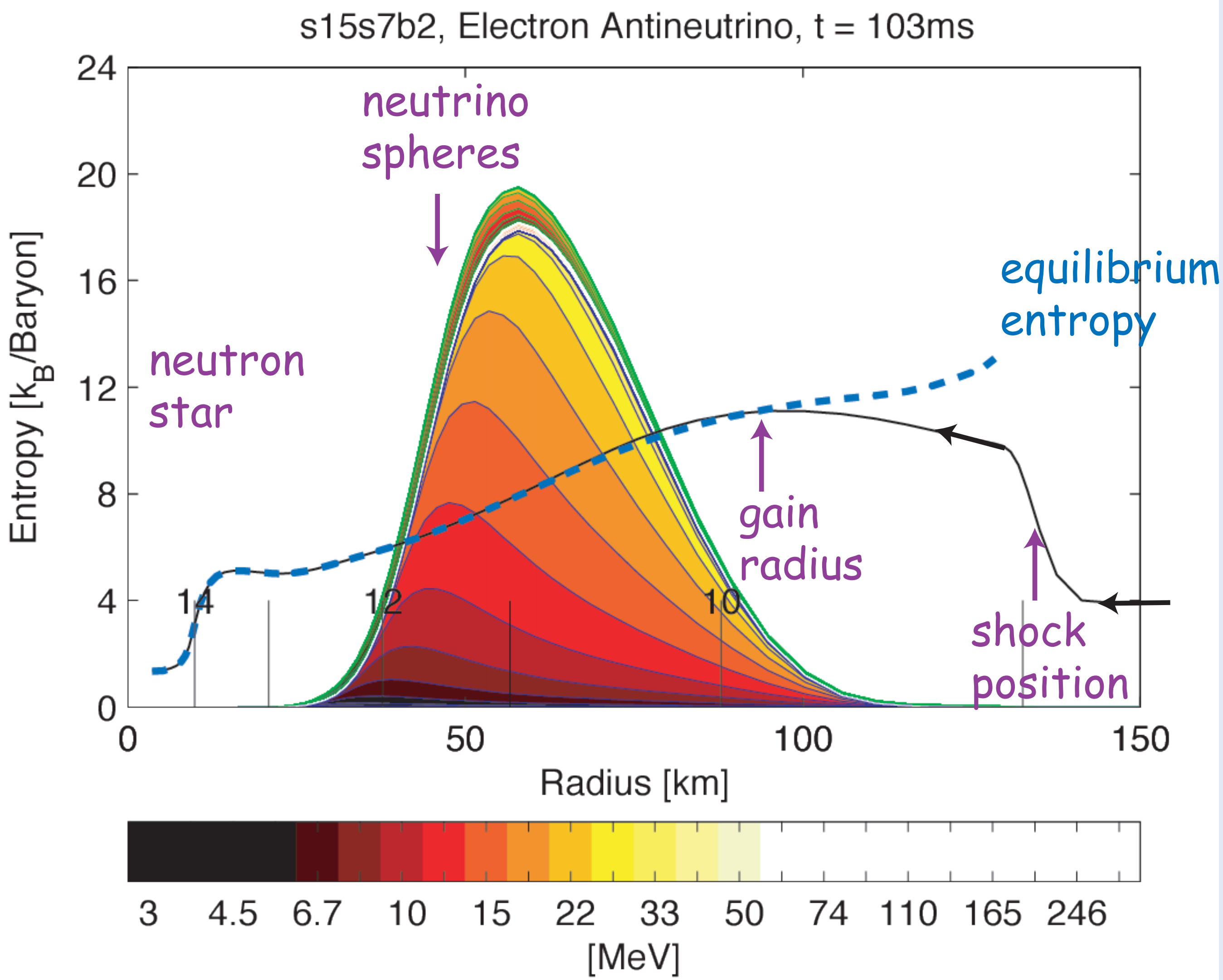

(Liebendörfer et al. 2003/4)

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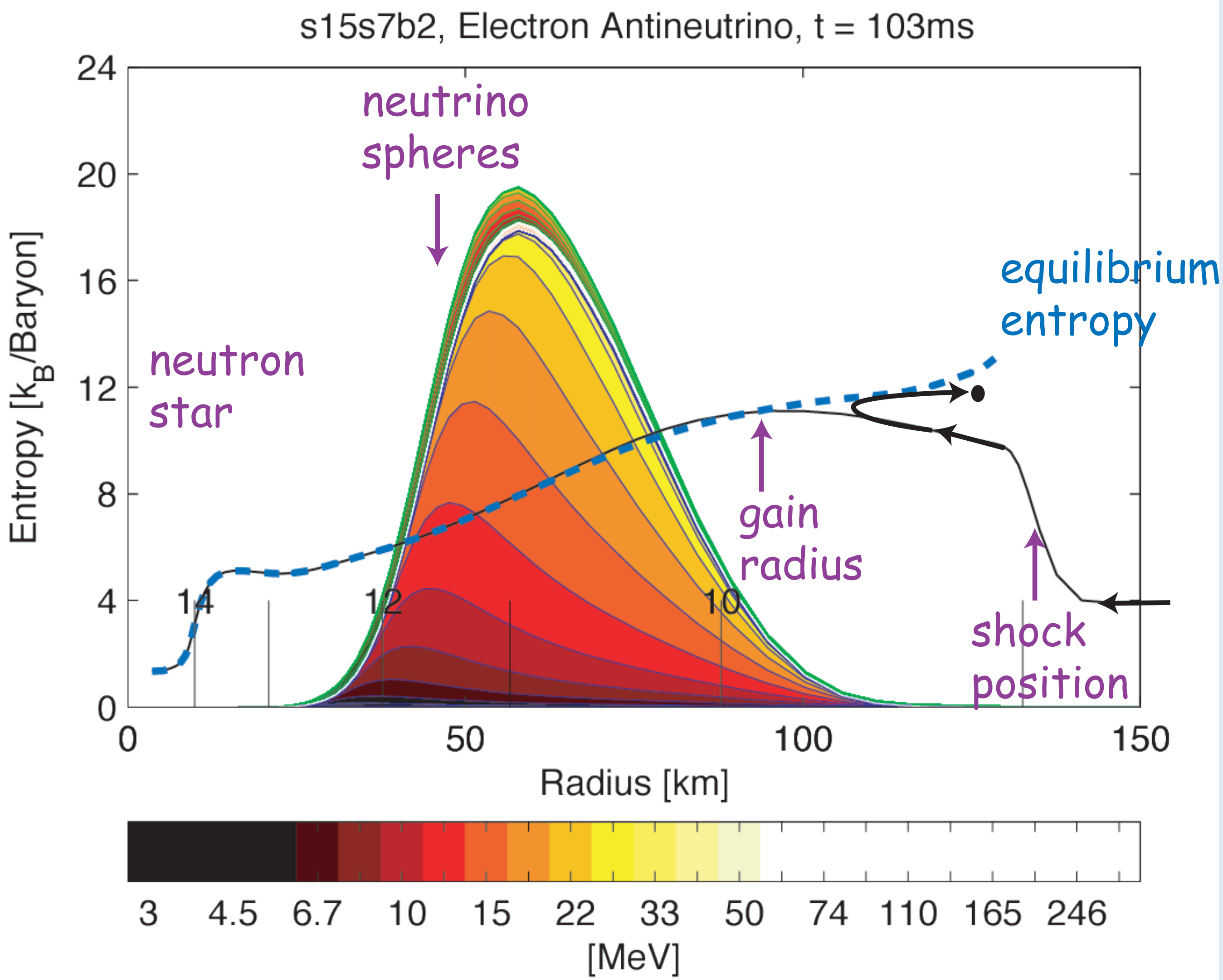
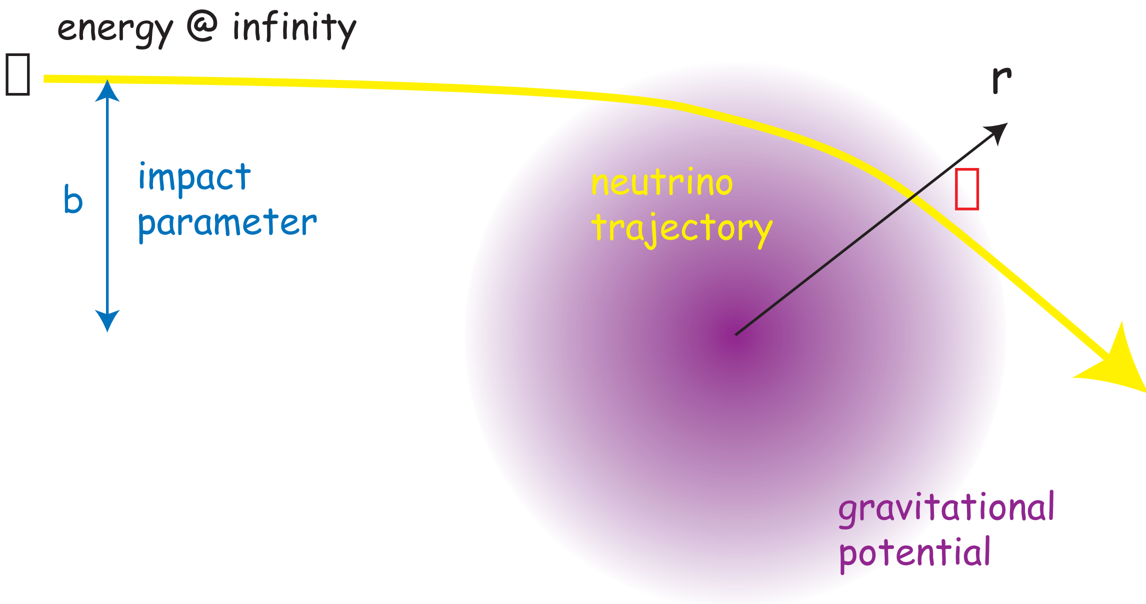
Neutrino heating



(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
- 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)

Spherical Boltzmann transport



distribution function $f(t, r, \mu, \varepsilon)$

$$\frac{\partial f}{\alpha \partial t} + \mu \Gamma \frac{\partial f}{\partial r} \approx \Omega(f)$$

Comoving metric:

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

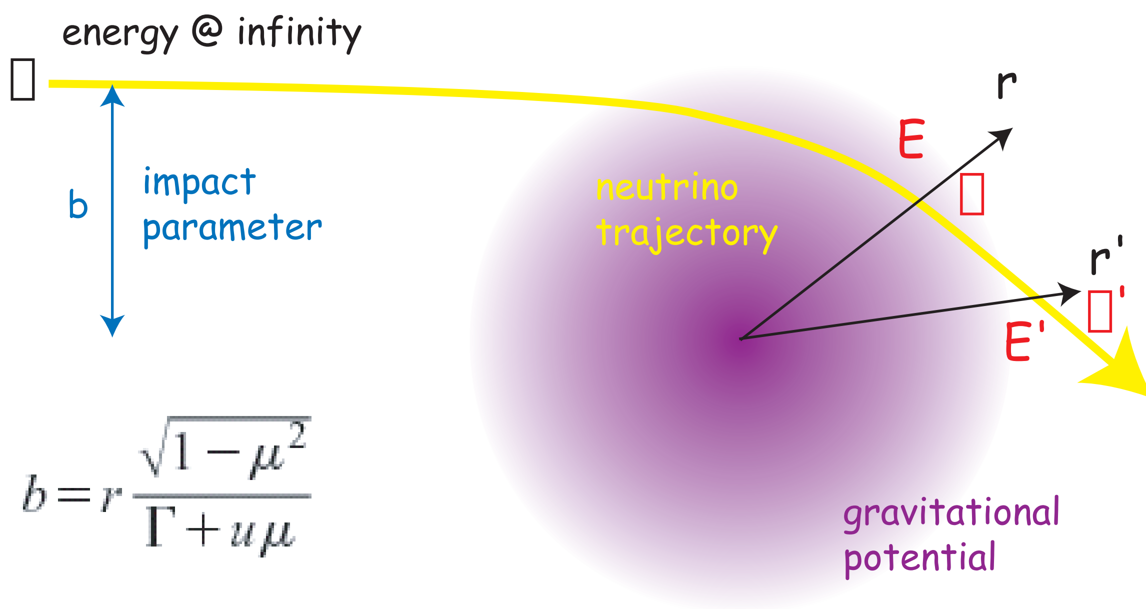
Stress-energy tensor:

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

Radiation moments:

$$\begin{aligned} J &= \frac{4\pi}{(hc)^3} \int F d\mu E^2 dE \\ H &= \frac{4\pi}{(hc)^3} \int F \mu d\mu E^2 dE \\ K &= \frac{4\pi}{(hc)^3} \int F \mu^2 d\mu E^2 dE \end{aligned}$$

Spherical Boltzmann transport



$$b = r\frac{\sqrt{1-\mu^2}}{\Gamma + u\mu}$$

$$\varepsilon = (\Gamma + u\mu)E.$$

distribution function $f(t, r, b, \varepsilon)$

$$\frac{\partial f}{\alpha \partial t} + \mu \Gamma \frac{\partial f}{\partial r} \approx \Omega(f)$$

partial derivatives at constant b, ε

(comoving frame --> Lindquist, Ann. Phys. 1966)

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Comoving metric:

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

Stress-energy tensor:

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

Radiation moments:

$$\begin{aligned} J &= \frac{4\pi}{(hc)^3}\int F d\mu E^2 dE \\ H &= \frac{4\pi}{(hc)^3}\int F \mu d\mu E^2 dE \\ K &= \frac{4\pi}{(hc)^3}\int F \mu^2 d\mu E^2 dE \end{aligned}$$

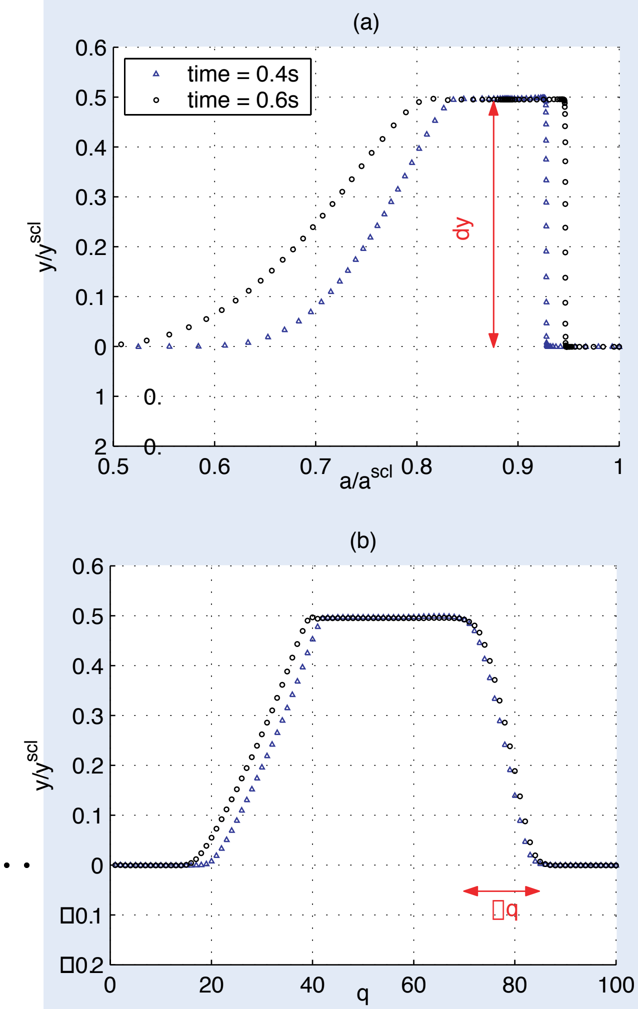
Solving the Boltzmann equation

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

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

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

on adaptive mesh



Results agree in all groups

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

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

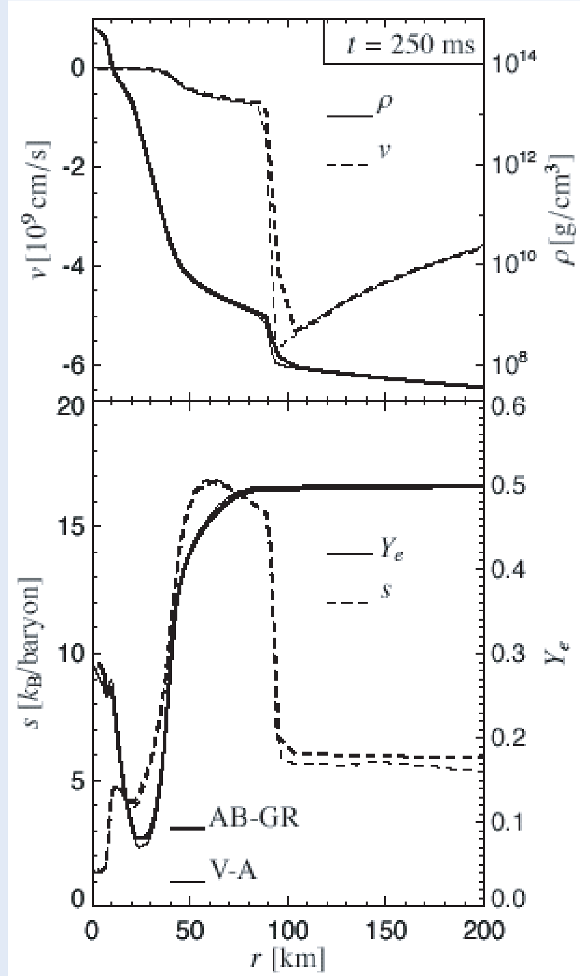
Summary on spherically symmetric simulations:

-> 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)

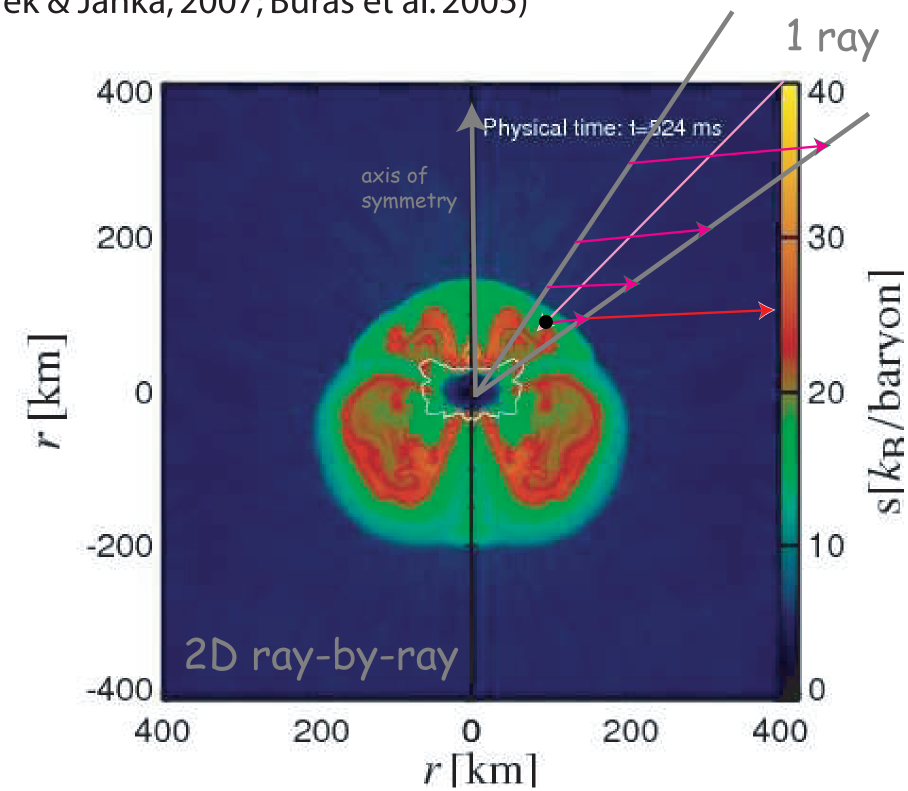
Axisymmetric supernova models

- 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

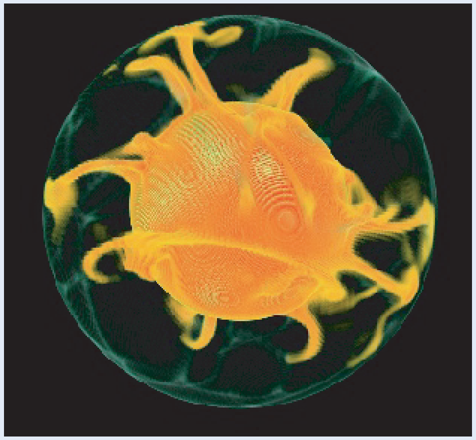
Open questions:

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

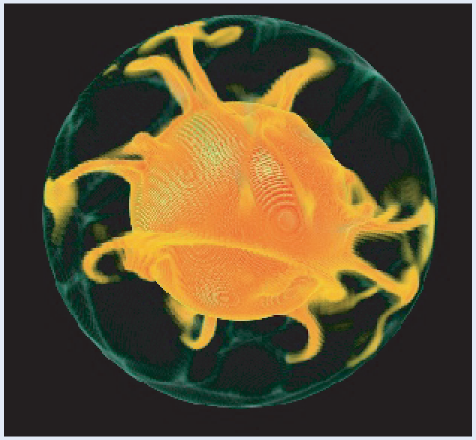
Bisnovatyi-Kogan 197x, Akiyama et al. 2003
Ardeljan et al. 2004:
Magnetic field growth and MRI until magnetic pressure becomes relevant

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)

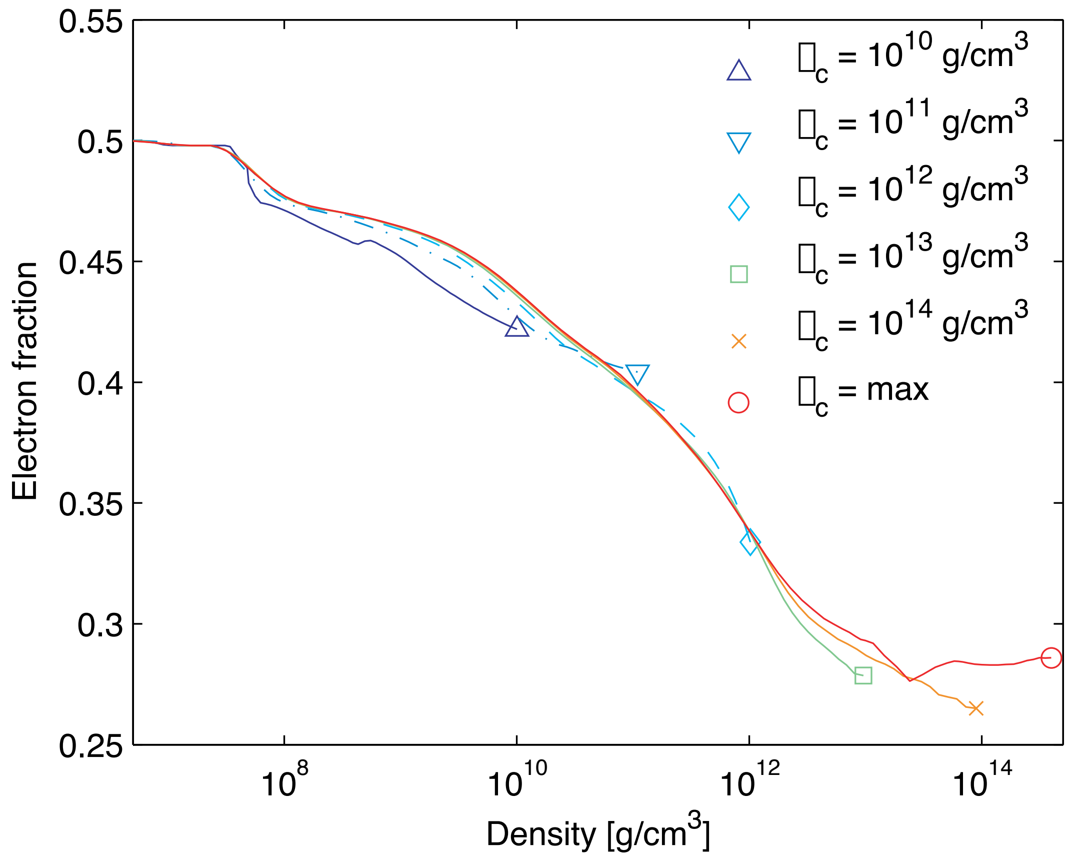
- how restrictive is axisymmetry?
- convective turnover is always toroidal
- narrow downflow restricted to cones instead of tubes



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)

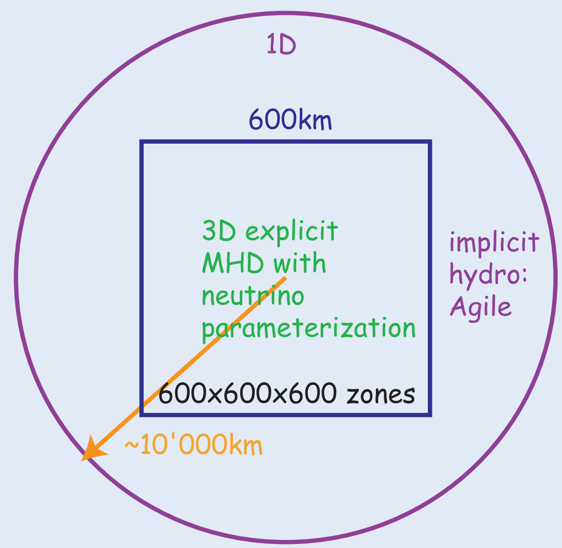
Lattimer-Swesty EOS

(Lattimer & Swesty 1991)

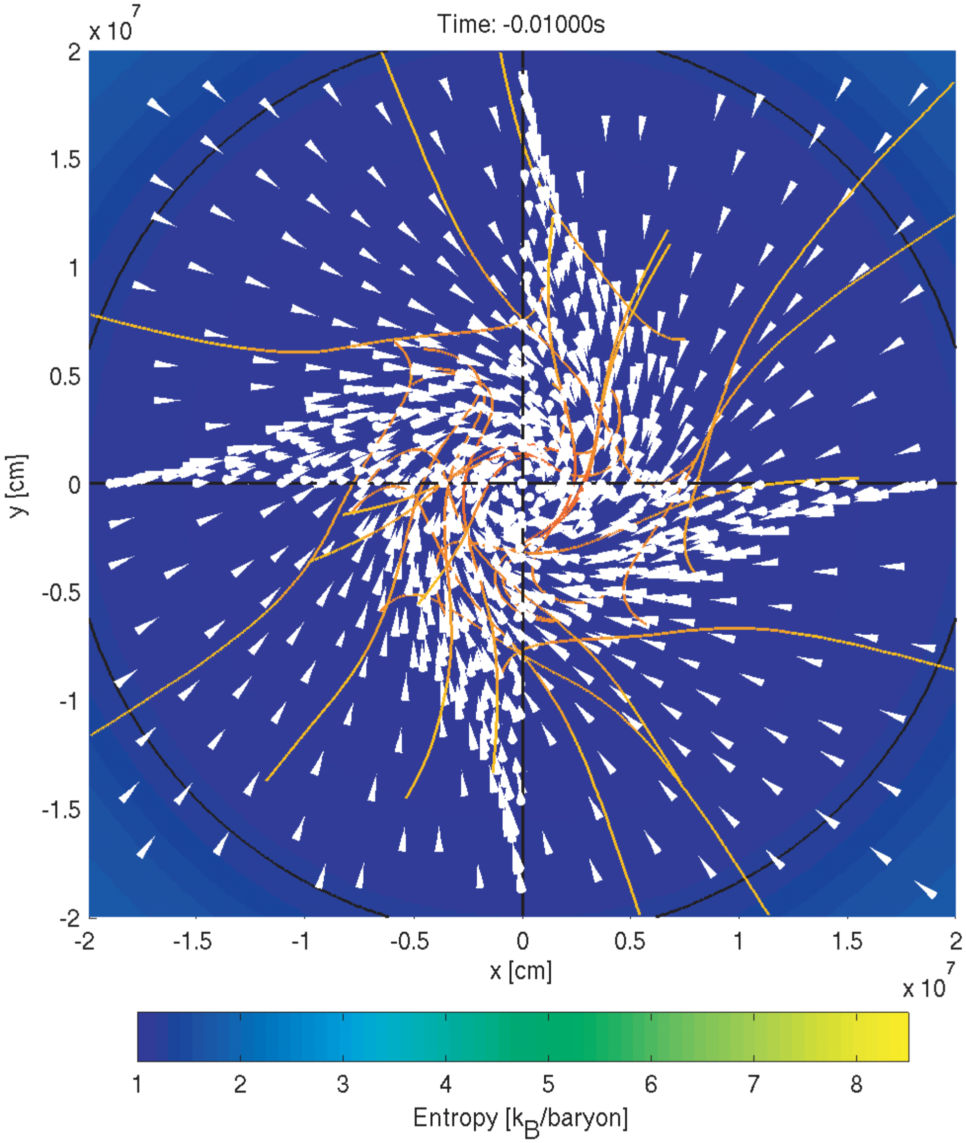
Effective GR potential

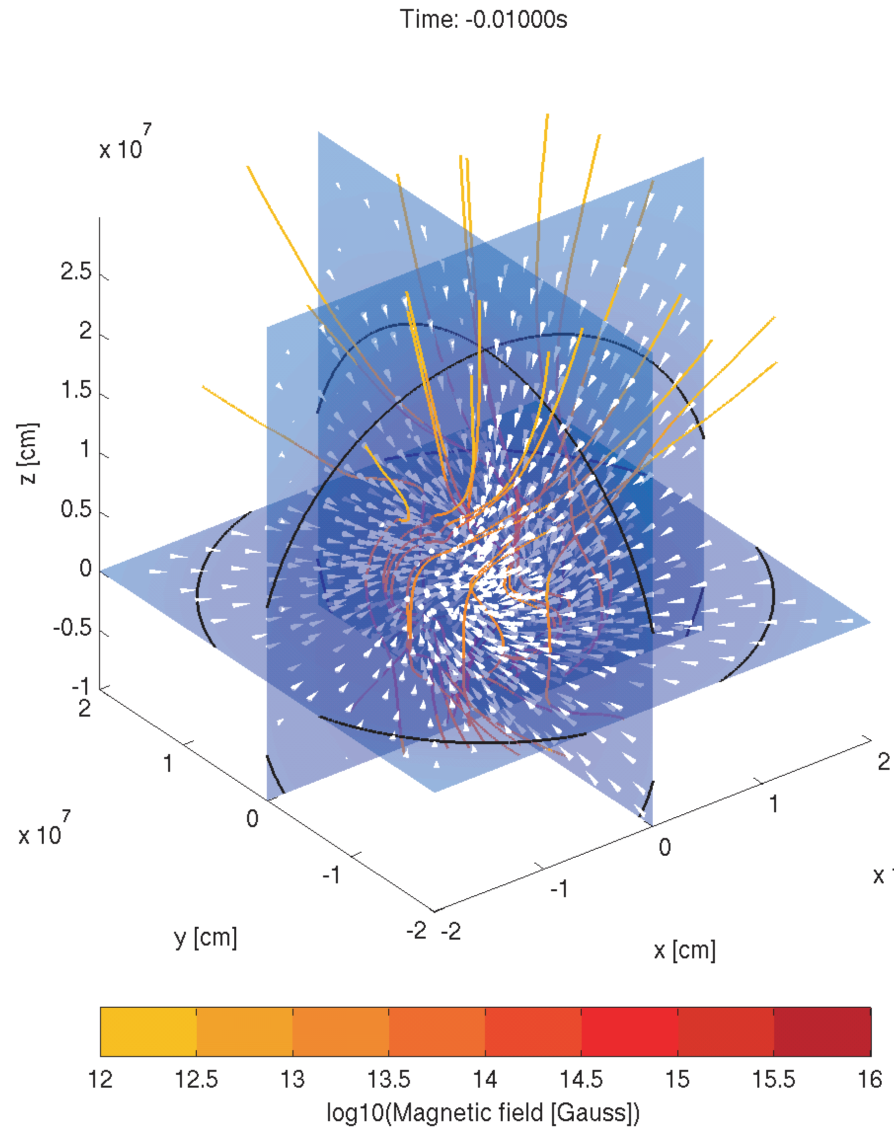
(Marek et al. 2006)

Fully parallelised



3D MHD & parameterized □'s





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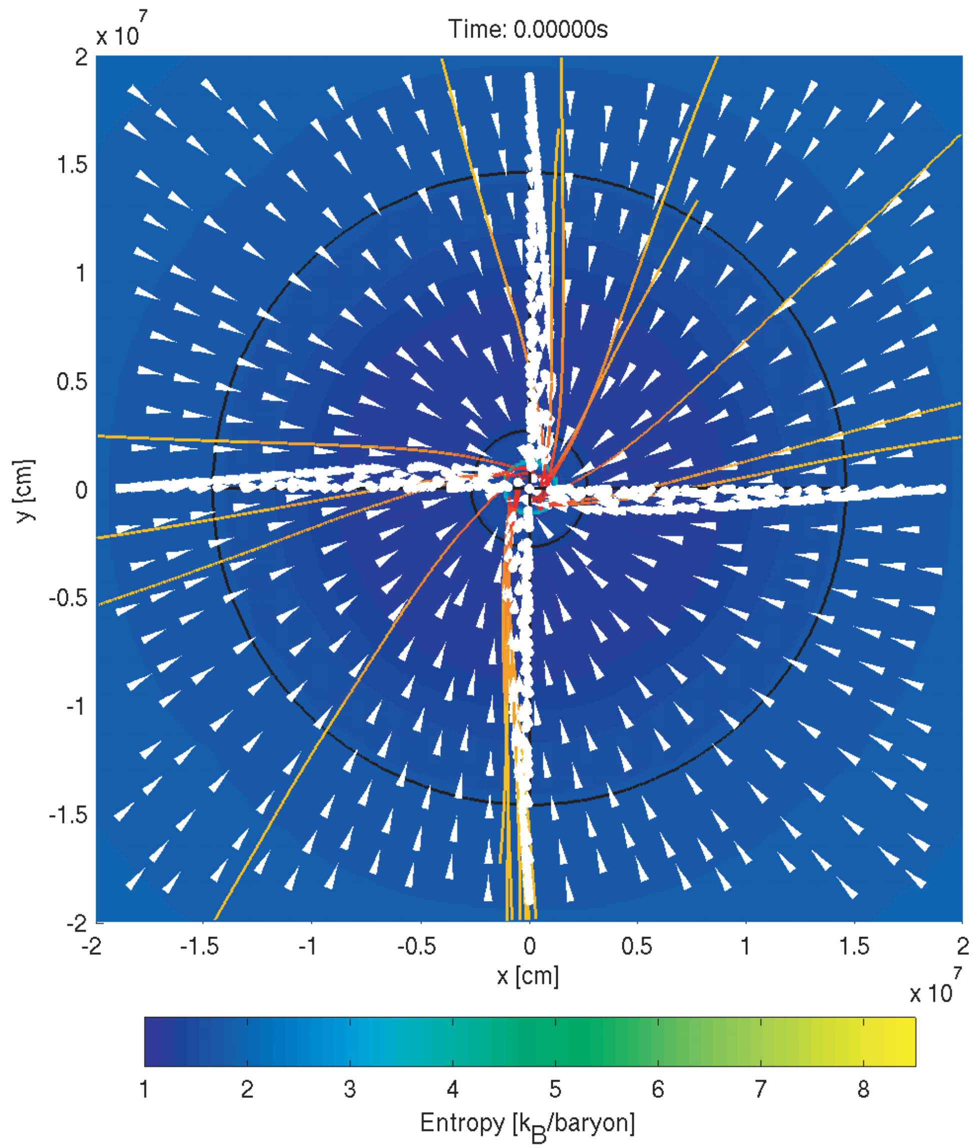

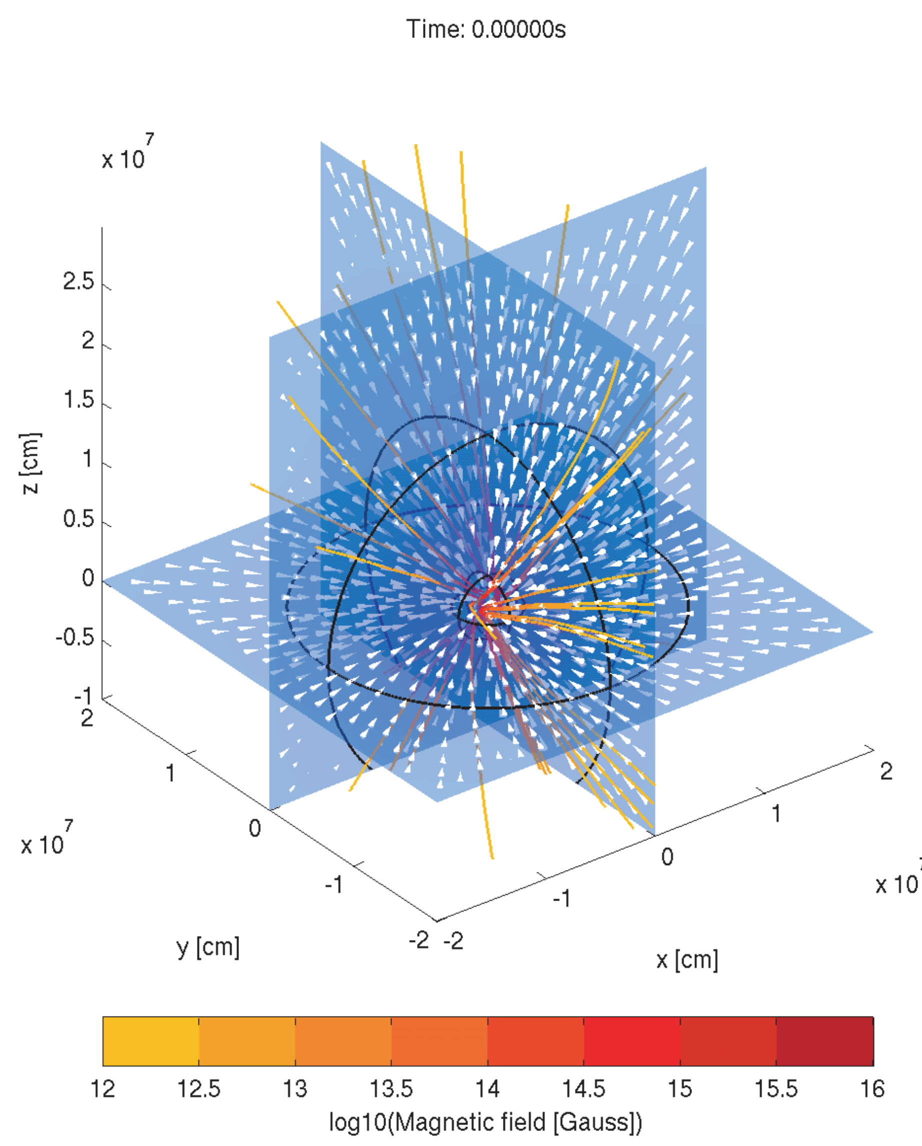

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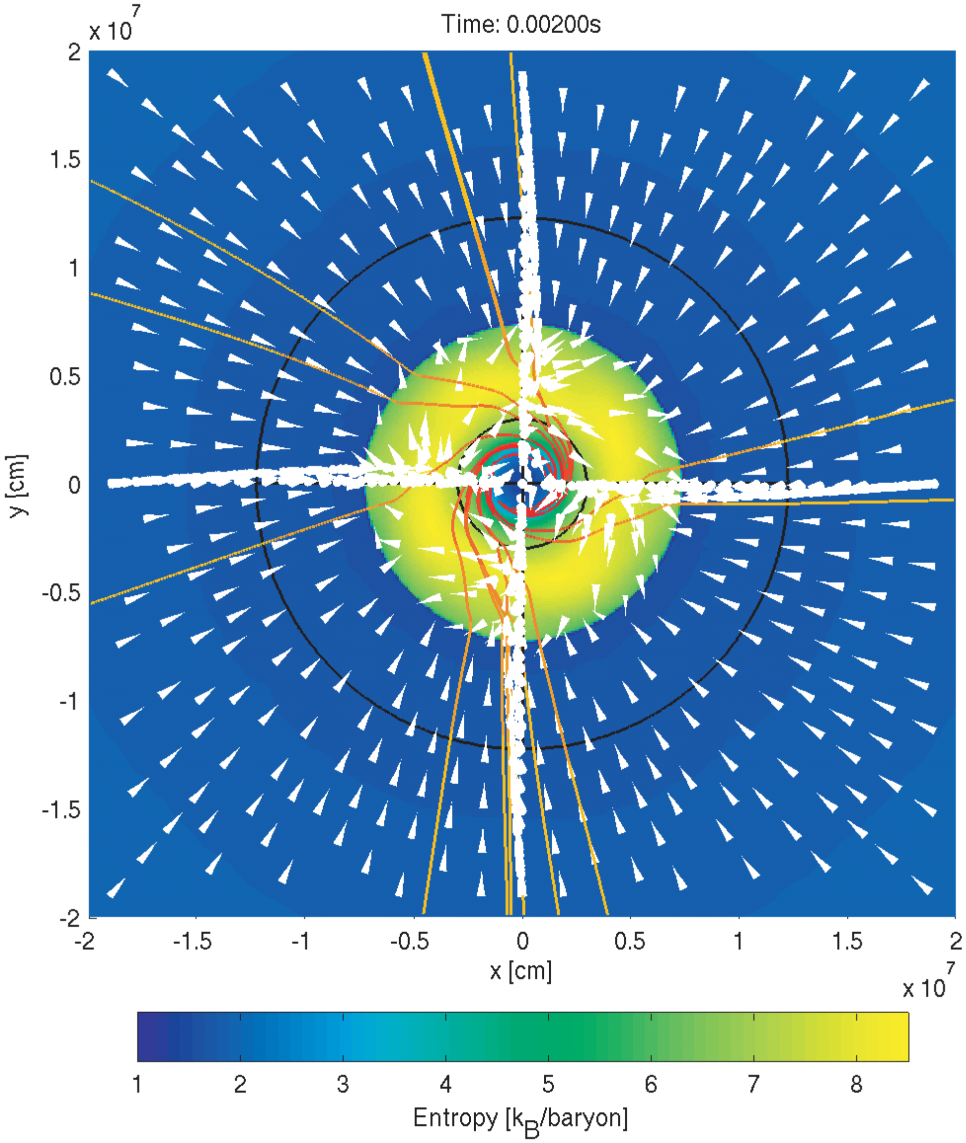
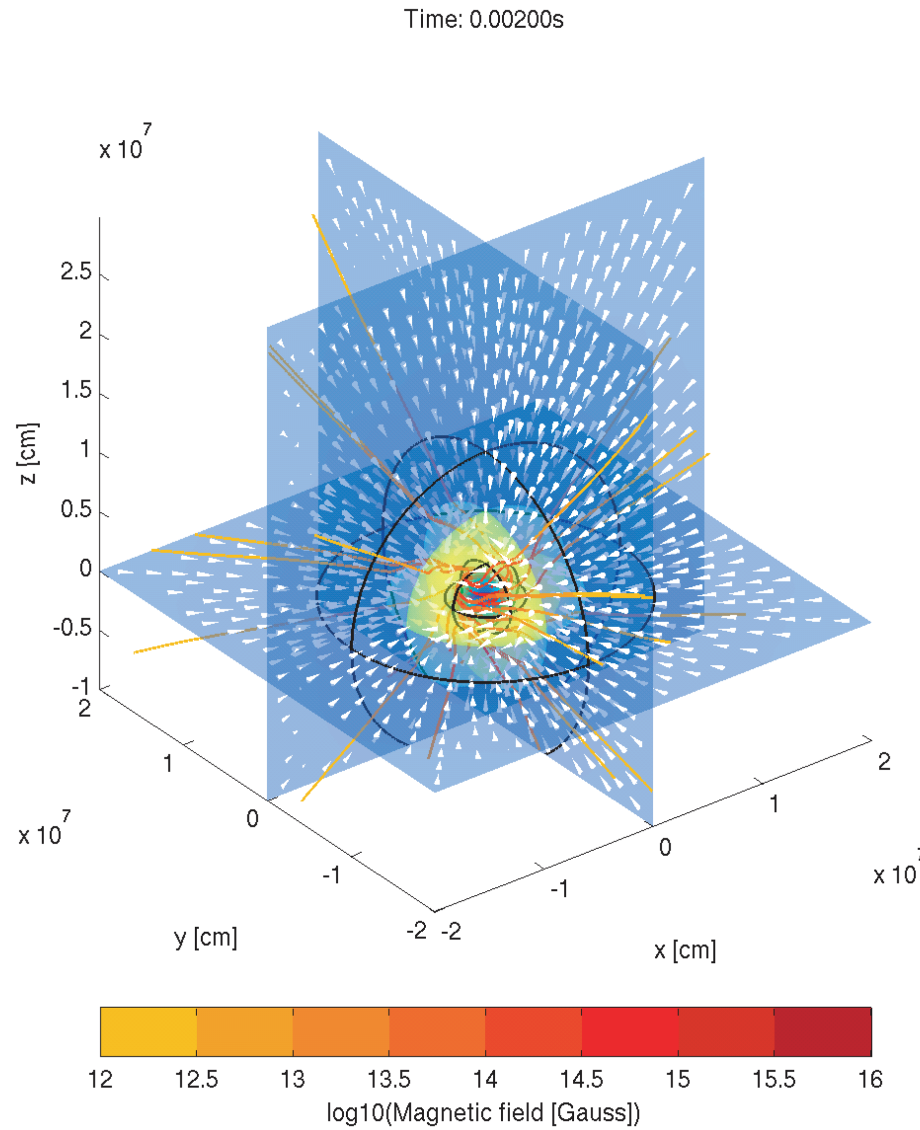
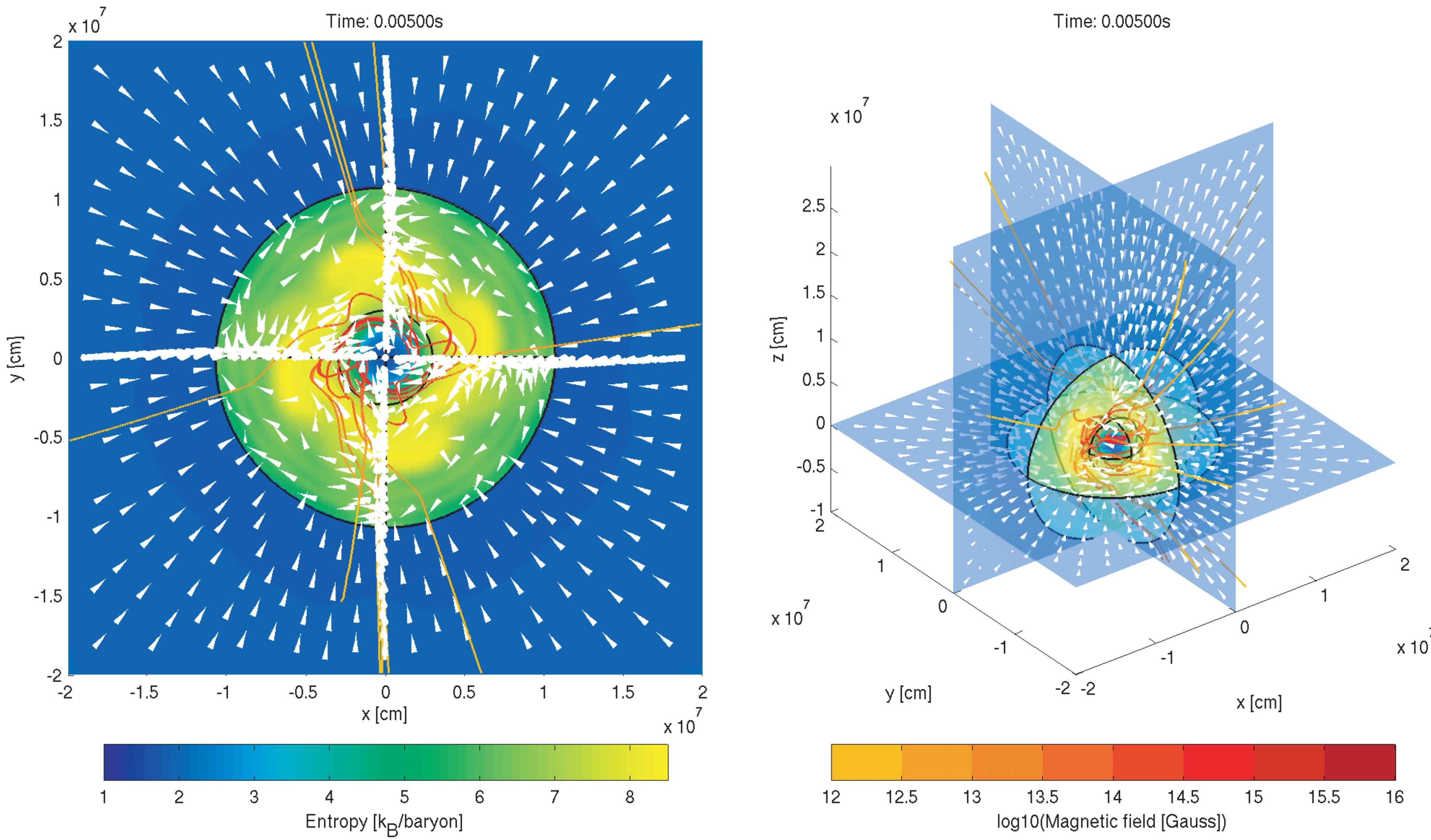


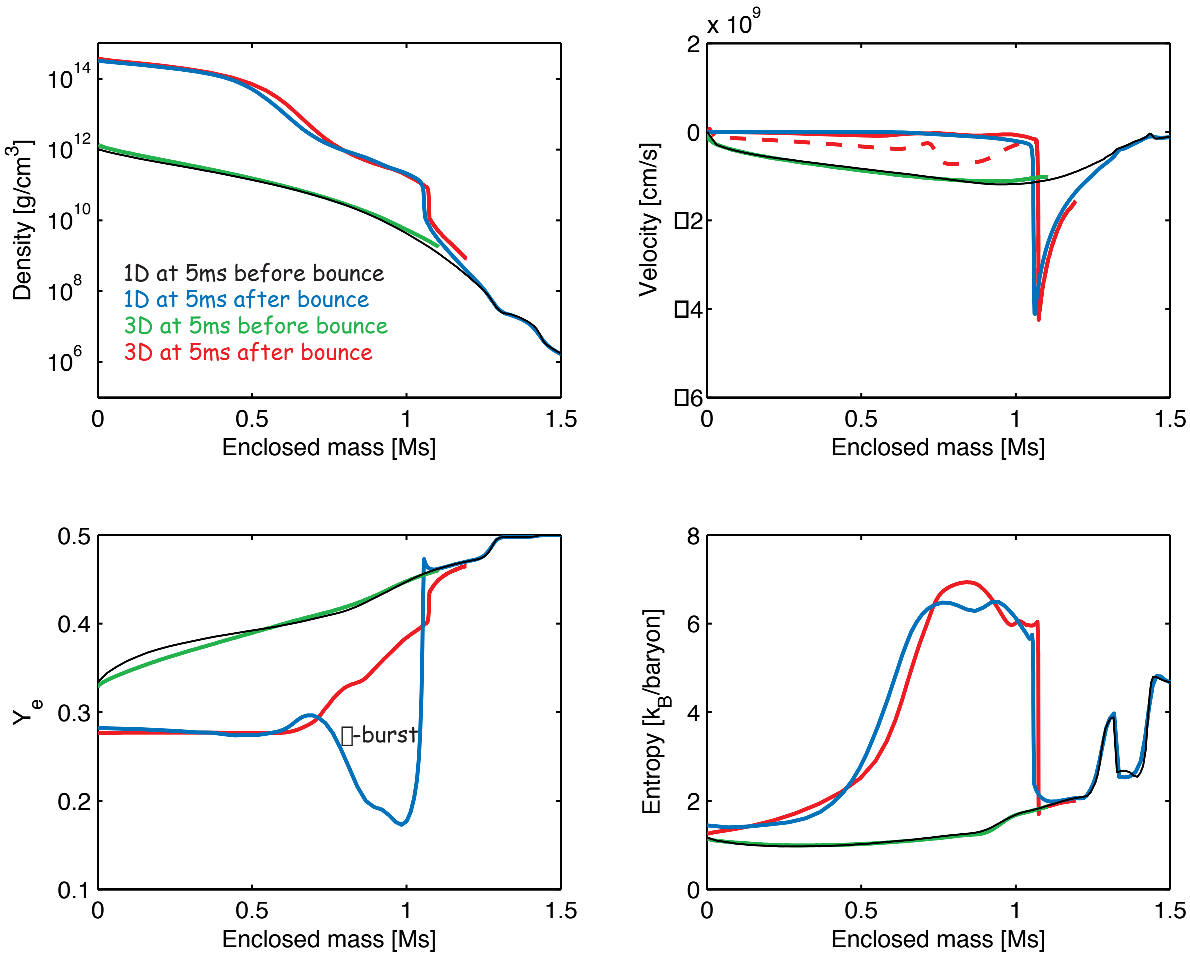


3D MHD without -burst



Too simple for postbounce phase

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



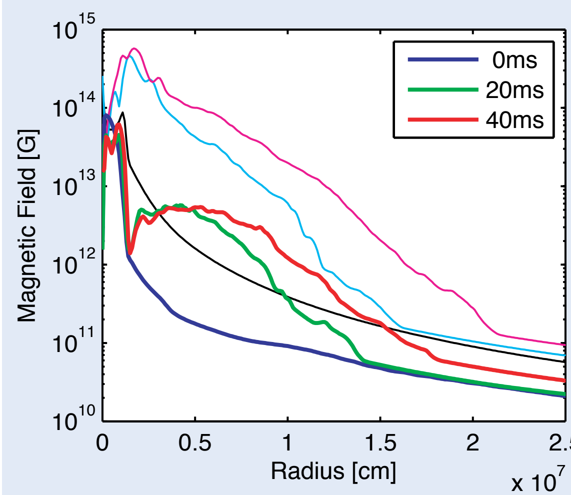
(Liebendörfer, Pen, Thompson, Nucl. in the Cosmos IX proceedings, 2006)

Evolution of magnetic field:

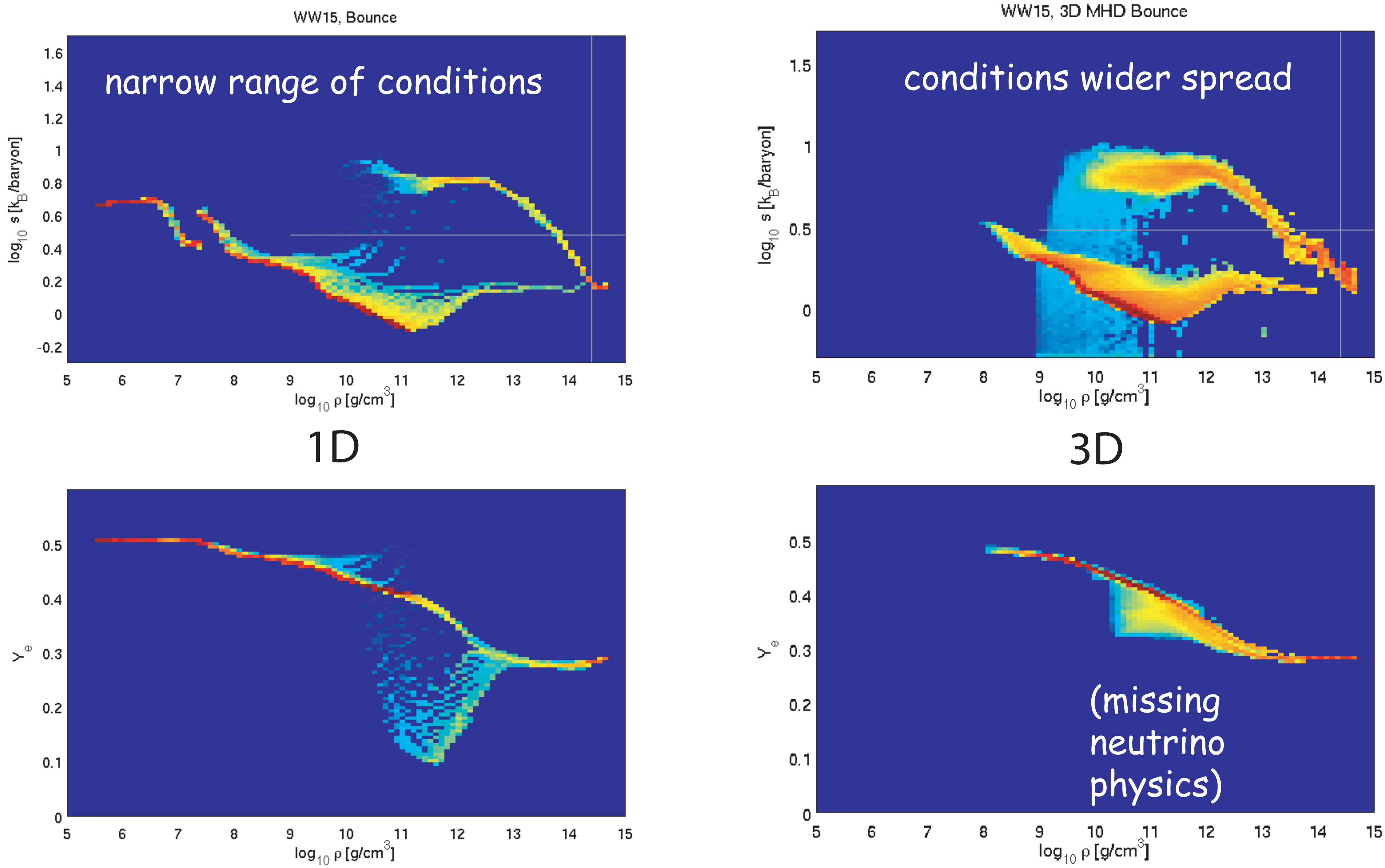
(Maeder & Meynet 2003-5)

A) 5x10^9 G toroidal
@ 5x10^7 g/cm^3
period ~100s
(Heger et al. 2005)

B) 5x10^9 G poloidal
@ 5x10^7 g/cm^3
period: 1s



How to compare multi-D: Statistics?



Limitations of Numerical Transport

Boltzmann transport:

- One fluid elemement contains
  4 □ types x 20 energies x 100 angles = 8000 variables
- At a resolution of 1000^3 zones
  --> 64TB per time step

Hydrodynamics:

- One fluid element contains ~10 variables
- At a resolution of 1000^3 zones
  --> 80GB per step

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Compression of Fermi-gas:

$$\frac{dF}{dt} - \frac{1}{3E^2}\frac{\partial}{\partial E}\left(E^3\rho F\right)\frac{d}{dt}\left(\frac{1}{\rho}\right) - \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{c\lambda}{3}\frac{\partial F}{\partial r}\right) = \left(\frac{dF}{dt}\right)_{collision}$$

de pdV diffusion = interactions

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difficult energy-terms must not be neglected!

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de pdV diffusion = interactions

Diffusion limit:

$$\frac{\lambda}{3}\frac{\partial F}{\partial r} \ll F, \qquad \frac{H}{cJ} \sim 10^{-4}, \qquad H = \int_{-1}^{+1} F(\mu)\,\mu d\mu$$

Hydrodynamics:

- One fluid element contains ~10 variables
- At a resolution of 1000^3 zones
  --> 80GB per step

difficult energy-terms must not be neglected!

Inaccurate fluxes in diffusion-regime due to large cancellations in angle integral!

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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...

	Diffusive regime	Semi-transparent	Transparent regime
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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:

- 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,...)

SN model minimum requirements

- shock-proof hydrodynamics
  - energy conservation for dissipation on small scales
- radial GR effects (as in TOV equation)
- transport of electron neutrino and antineutrino
  - hydrodynamic limit of neutrino gas (pdV term!)
  - comoving-frame diffusion limit
  - spectral decoupling in semi-transparent regime
  - non-local determination of flux factor
- emission of m/t neutrinos and antineutrinos
- equation of state
  - advection of composition at low density
  - nuclear statistical equilibrium at high density
- dominant weak interactions in each phase
  - accurate detailed balance
  - implicit finite differencing to obtain equilibria

- Good approximations can be more accurate if the full problem is computationally very challenging
- But, it is difficult to quantify their accuracy without a solution of the full problem

Spectral neutrino transport after bounce

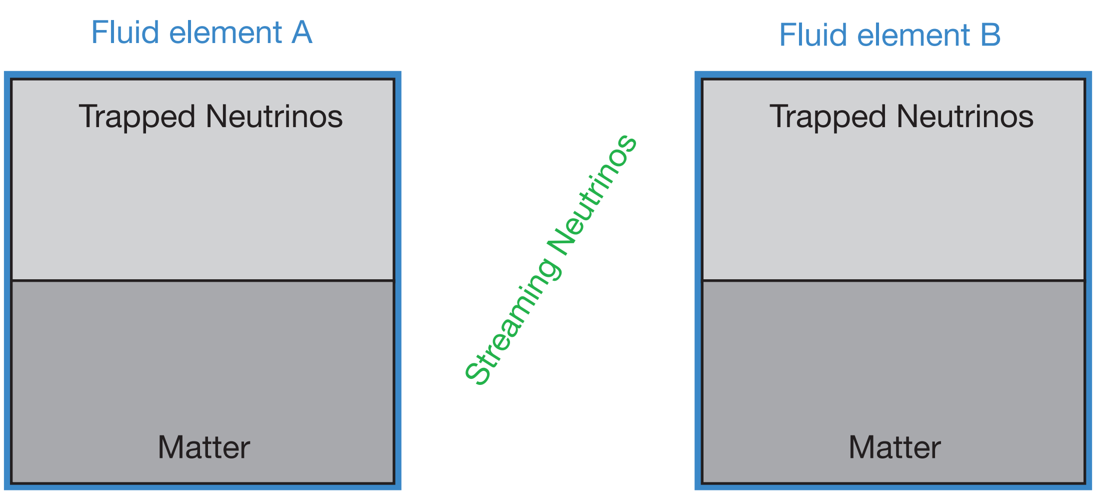
$D(f) = j - \square * f$

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

Different approx.
for trapped & streaming
neutrino components!

I sotropic
D iffusion
S ource
A pproximation

(Liebendörfer,
Whitehouse,
Fischer 2007)



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
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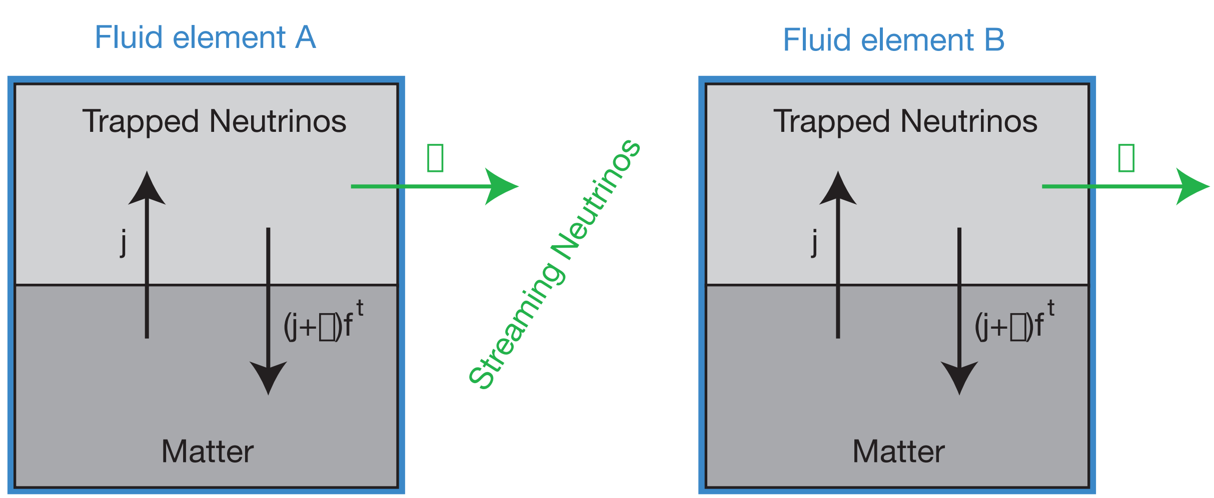
□ determined by diffusion limit of (1)



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Different approx.
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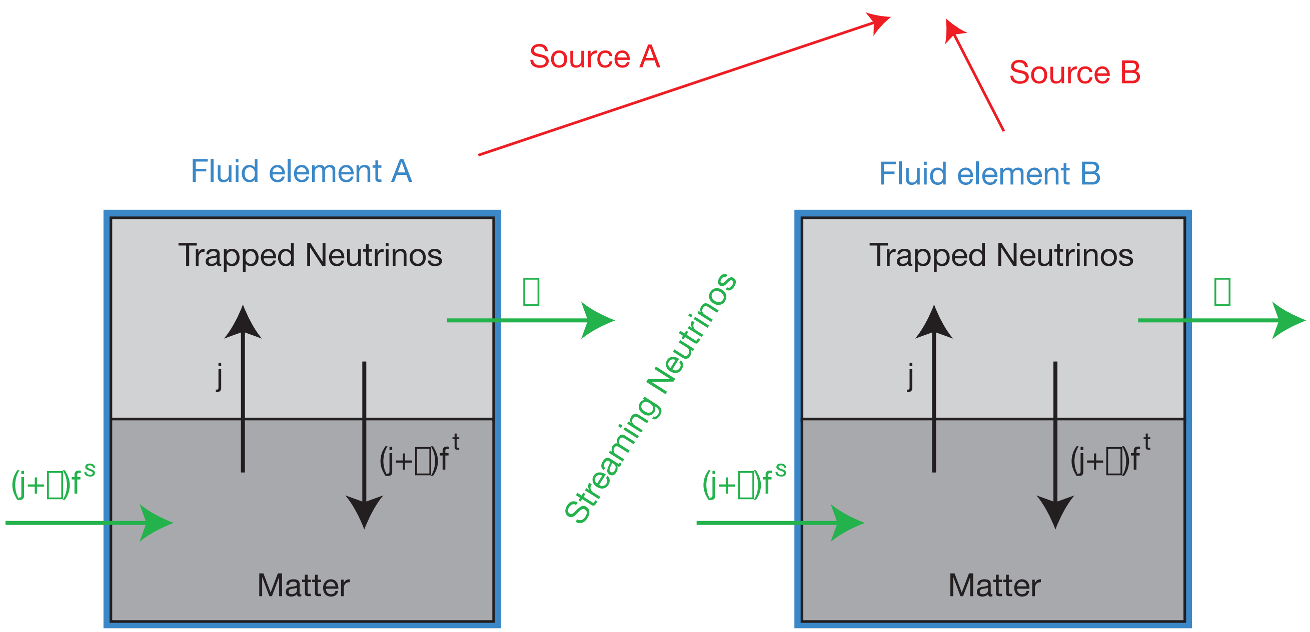
□ determined by diffusion limit of (1)
Stationary state approx. for (2) --> Poisson Eq.



I sotropic
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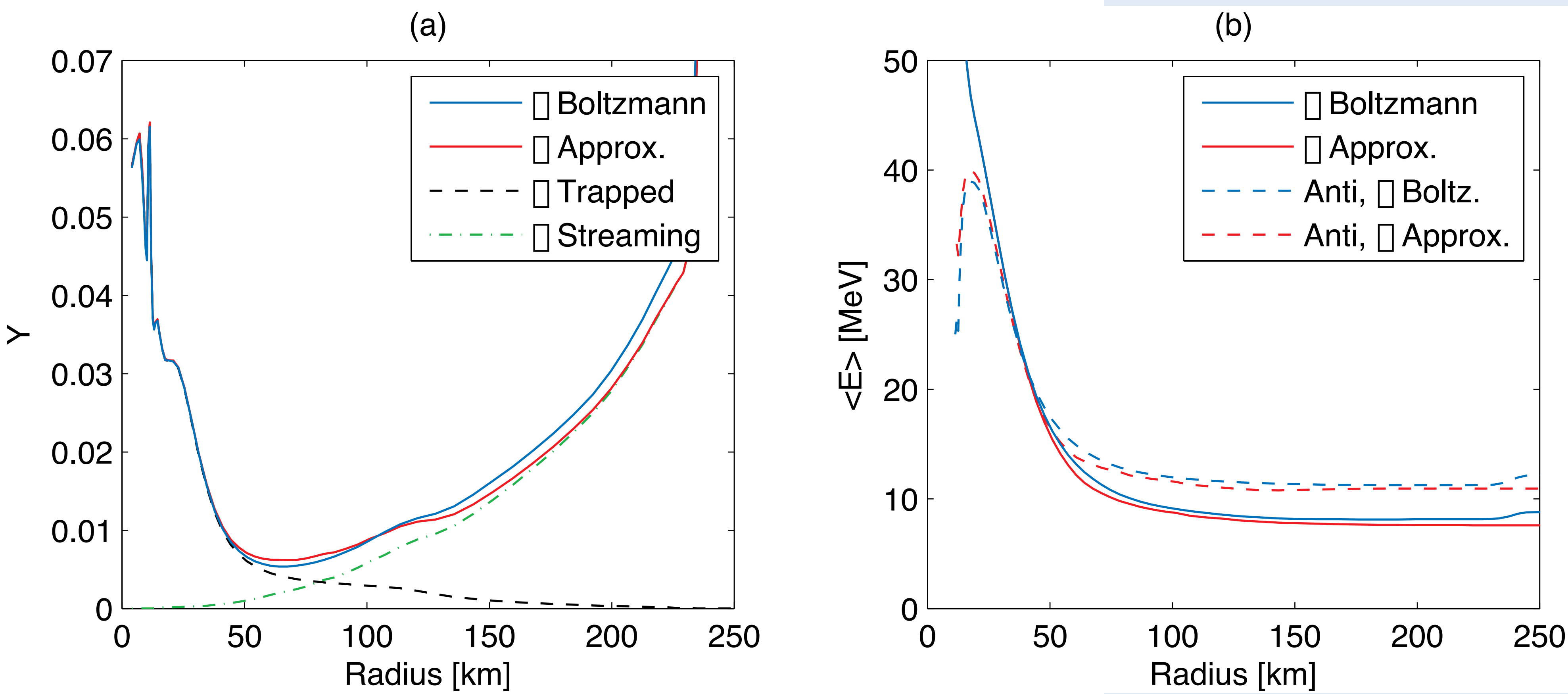
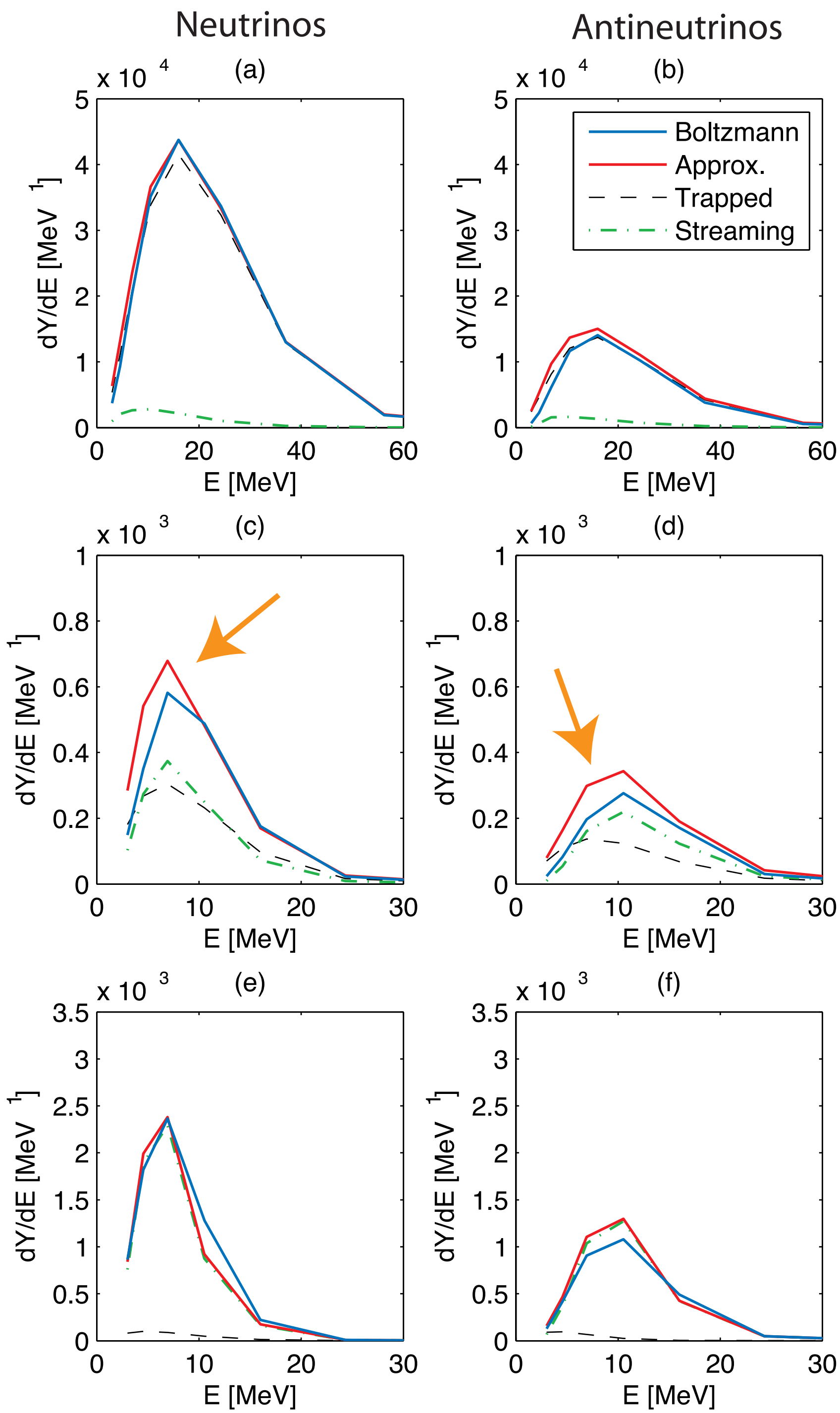
(Liebendörfer, Whitehouse, Fischer 2007)

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



R = 40 km
(trapped)

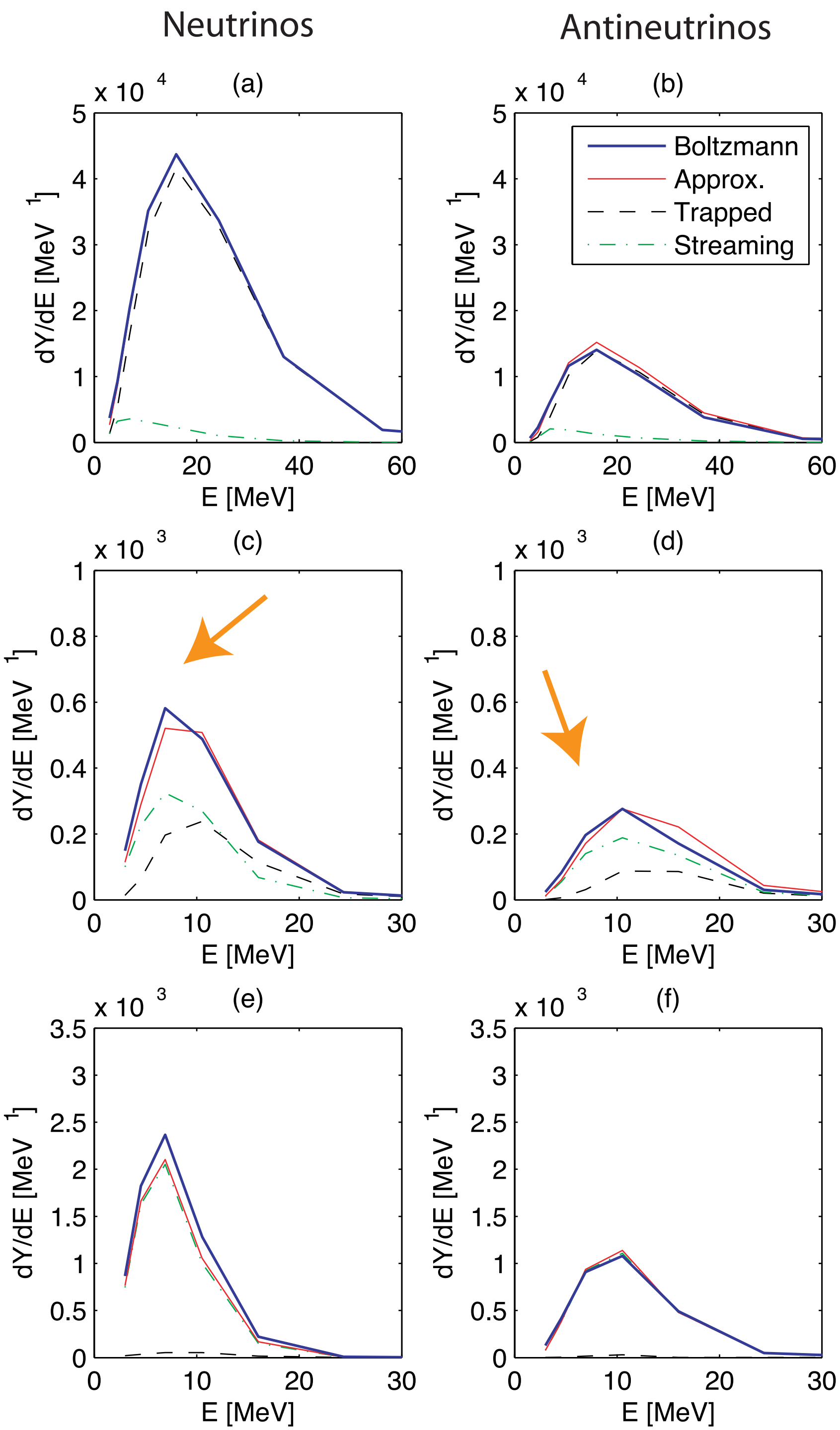
R = 80 km
(semi-transp.)

R = 160 km
(transparent)

Spectra

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

--> overestimation at low energy



R = 40 km
(trapped)

R = 80 km
(semi-transp.)

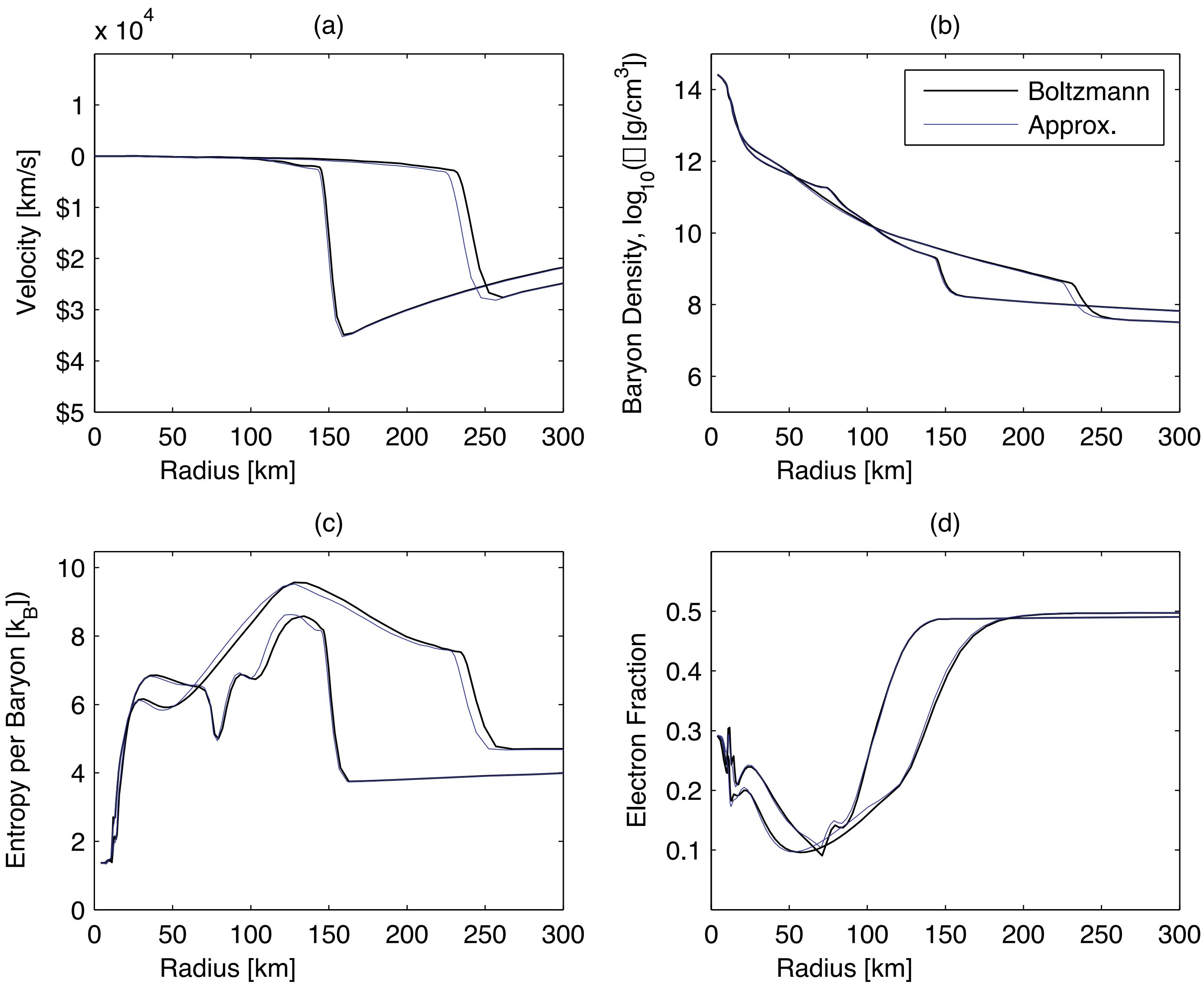
R = 160 km
(transparent)

Spectra

In this comparison the trapped particle distribution function is spectral.

--> agreement is better!

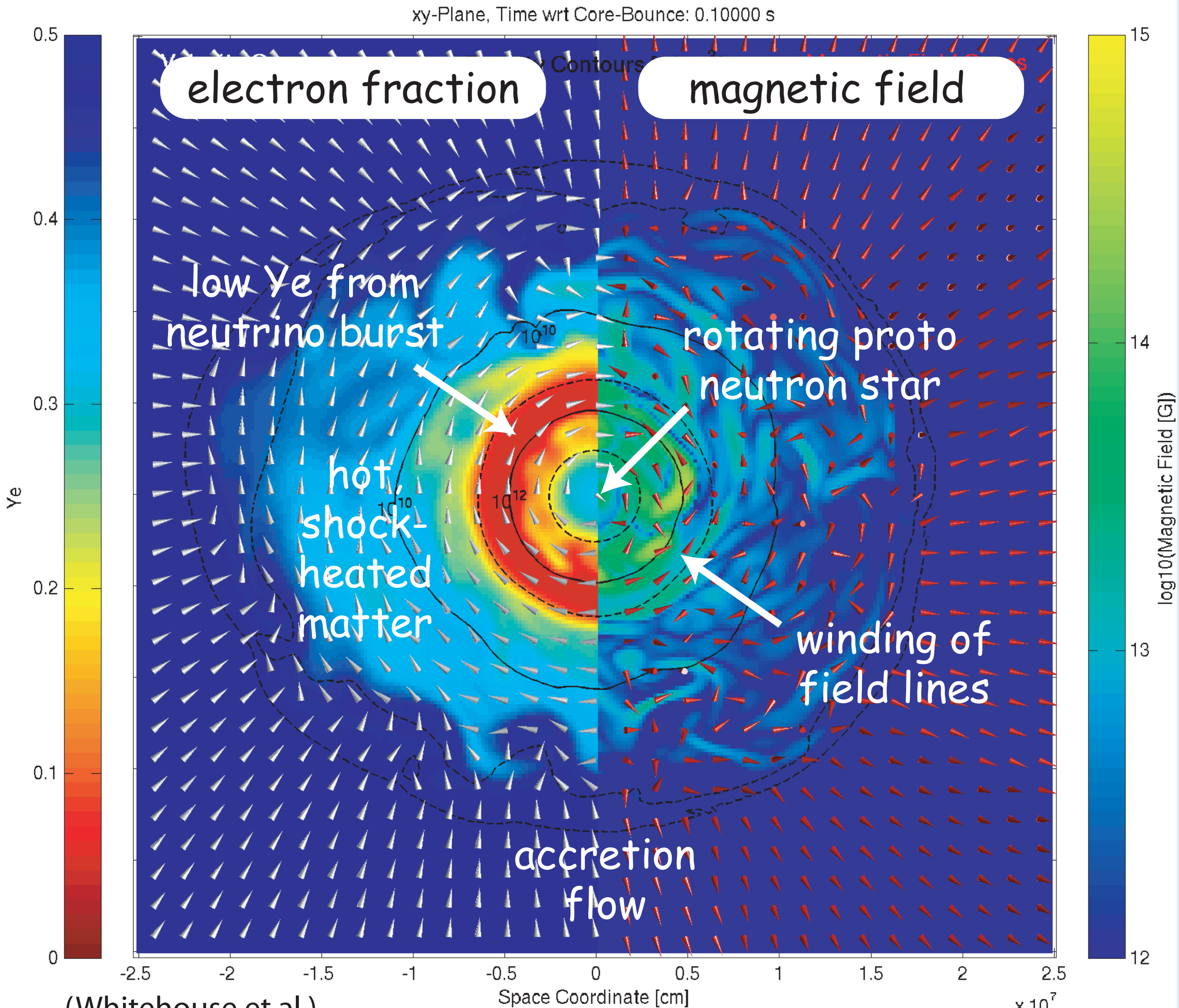
IDSA <--> Boltzmann



(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 []-transport and magnetic fields make first steps