Havse 2011 Hamburg

Microphysics of Supernova Core

M. Liebendörfer
University of Basel

- Matter and neutrinos in the collapse phase
- Matter and neutrinos in the postbounce phase
- New 3D models of 11 Ms, 15 Ms and 40 Ms progenitor

R. Cabezon
M. Hempel
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F.-K. Thielemann
N. Vasset
S. C. Whitehouse

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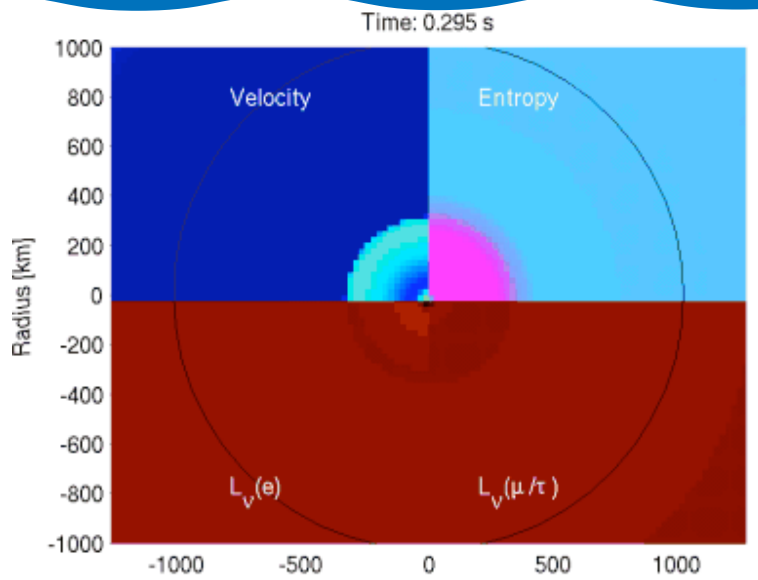
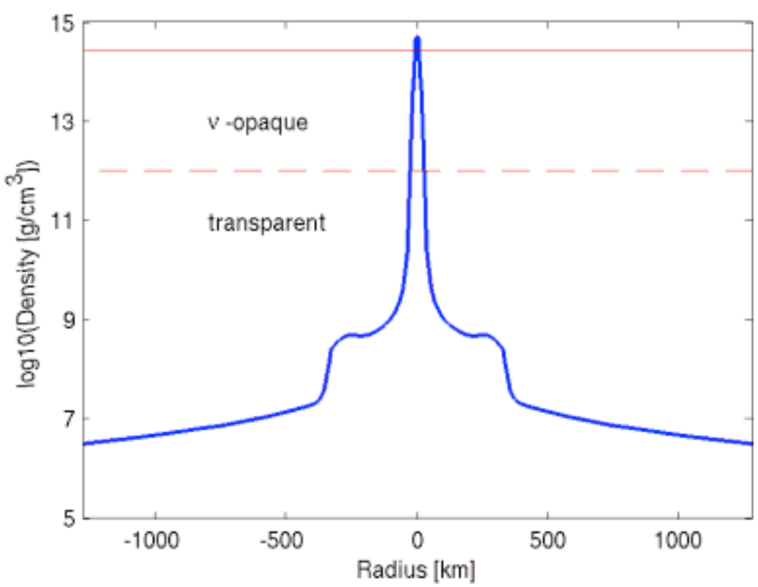
The Explosion Mechanism(s)





Keep in mind: The explosion is only a surface effect on the protoneutron star!

Different supernova explosion mechanisms suggested:

- prompt hydrodynamic
- delayed, ν-driven
- magneto-rotational
- acoustic
- magetoviscous/sonic
- phase transition in NS

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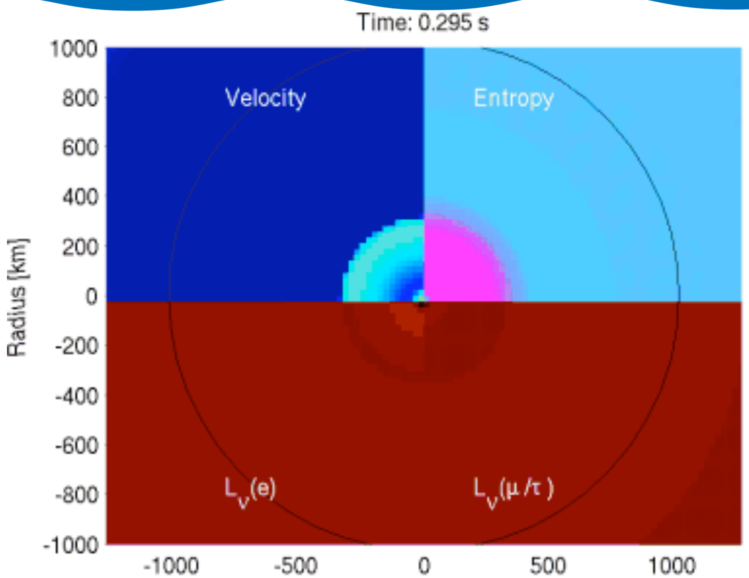

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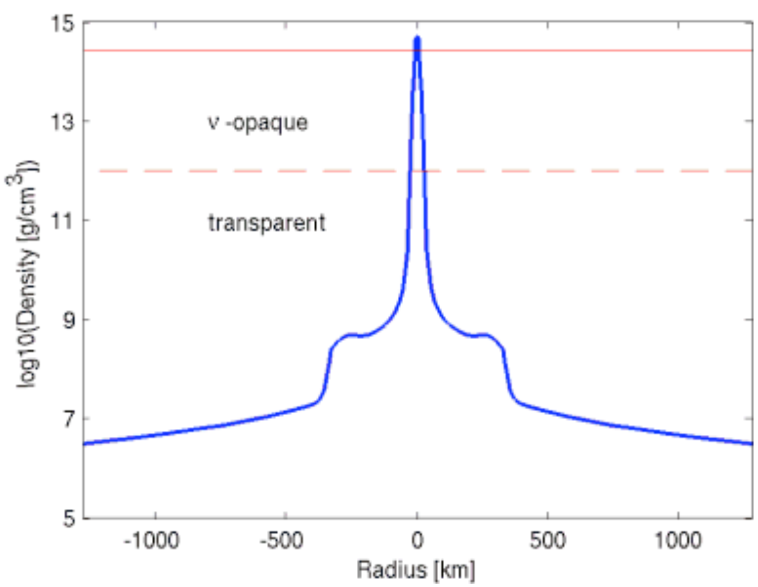

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  (e.g. Baron et al. 1985)
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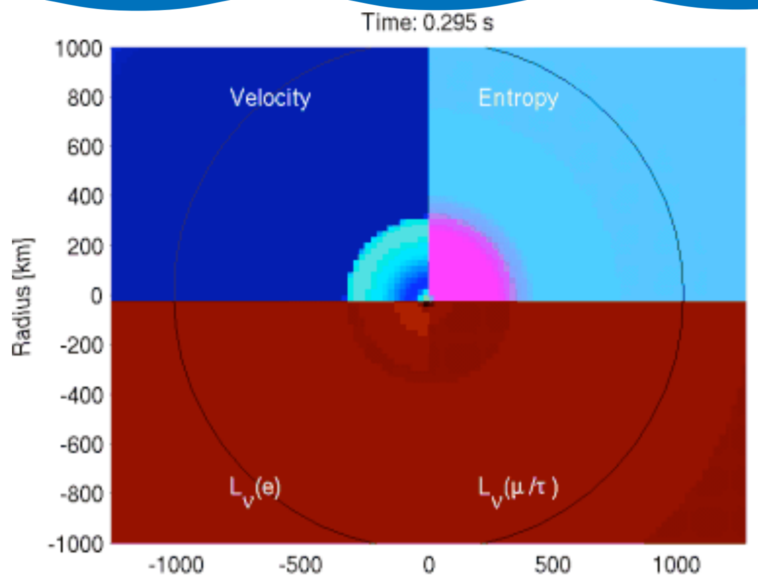

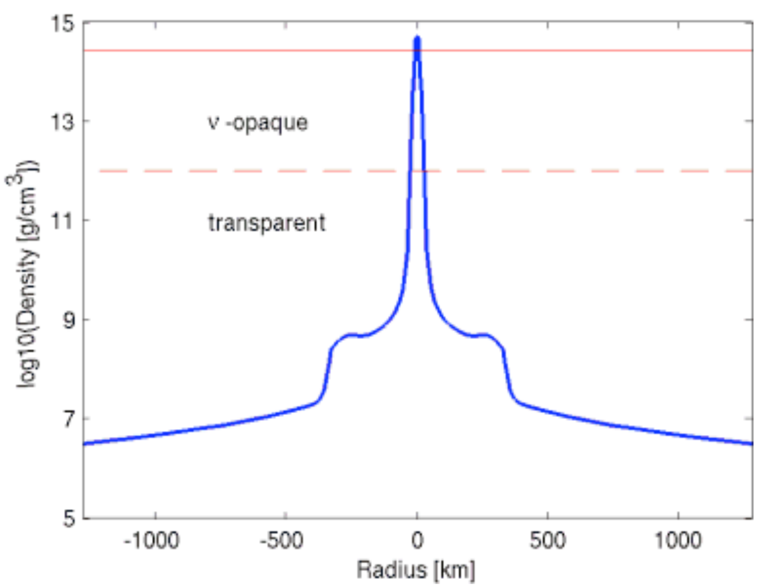

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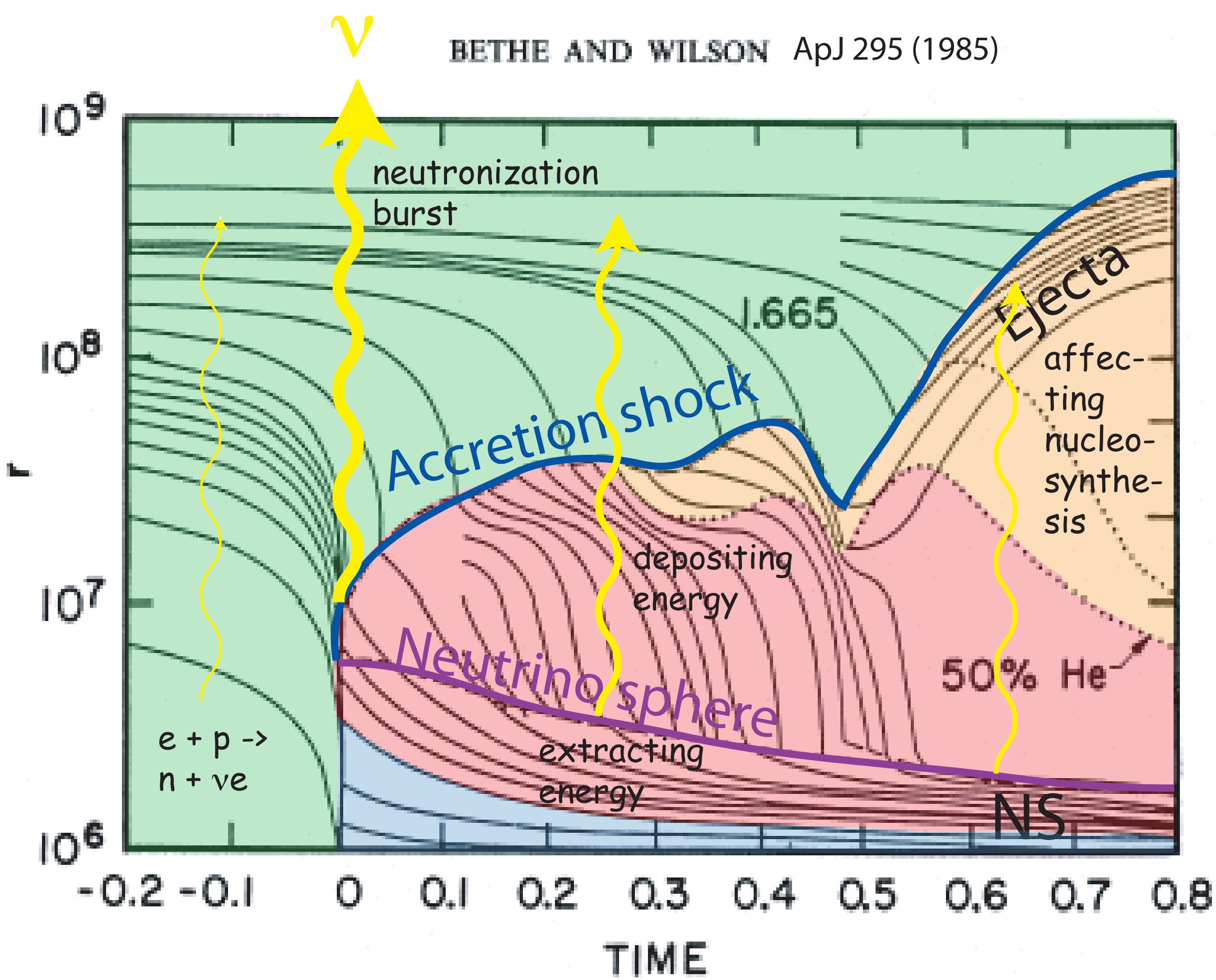
Matter conditions



collapse phase || postbounce accretion phase | explosion phase
bounce

Ensemble of nuclei

Cool bulk nuclear matter

Hot dissociated matter

Freeze-out of nuclei

Neutrino-matter interactions

Bruenn (1985)
Raffelt (2001)

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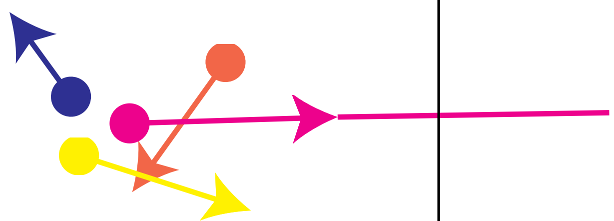
Description: Number Sphere | Energy Sphere | Transport Sphere

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)
νe pair --> νμ pair (Buras et al. 2003)

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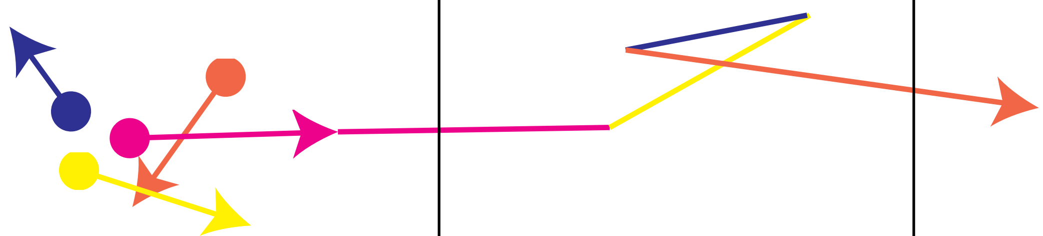
Emission & Absorption

Inelastic Scattering



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Probability enhanced by isoenergetic scattering

Production/Annihilation

Thermalisation

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

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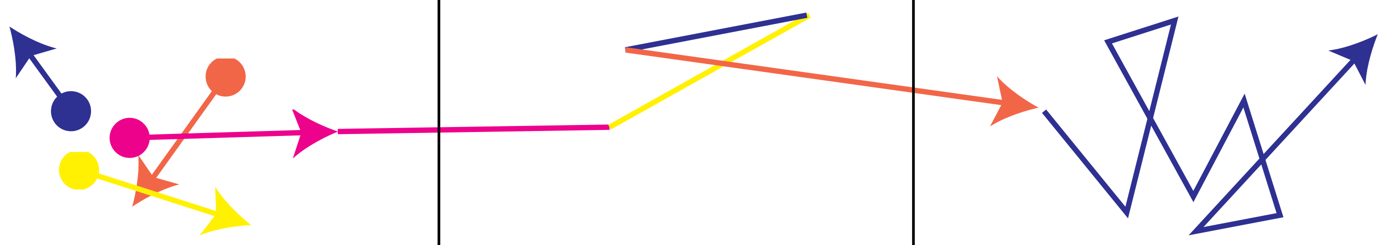

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$$\nu + e \rightleftharpoons \nu + e$$

Inelastic neutrino-nucleus scattering

Isoenergetic Scattering

Strong energy dependence, ~E^2

Scattering

Elastic coherent scattering of neutrinos on nuclei

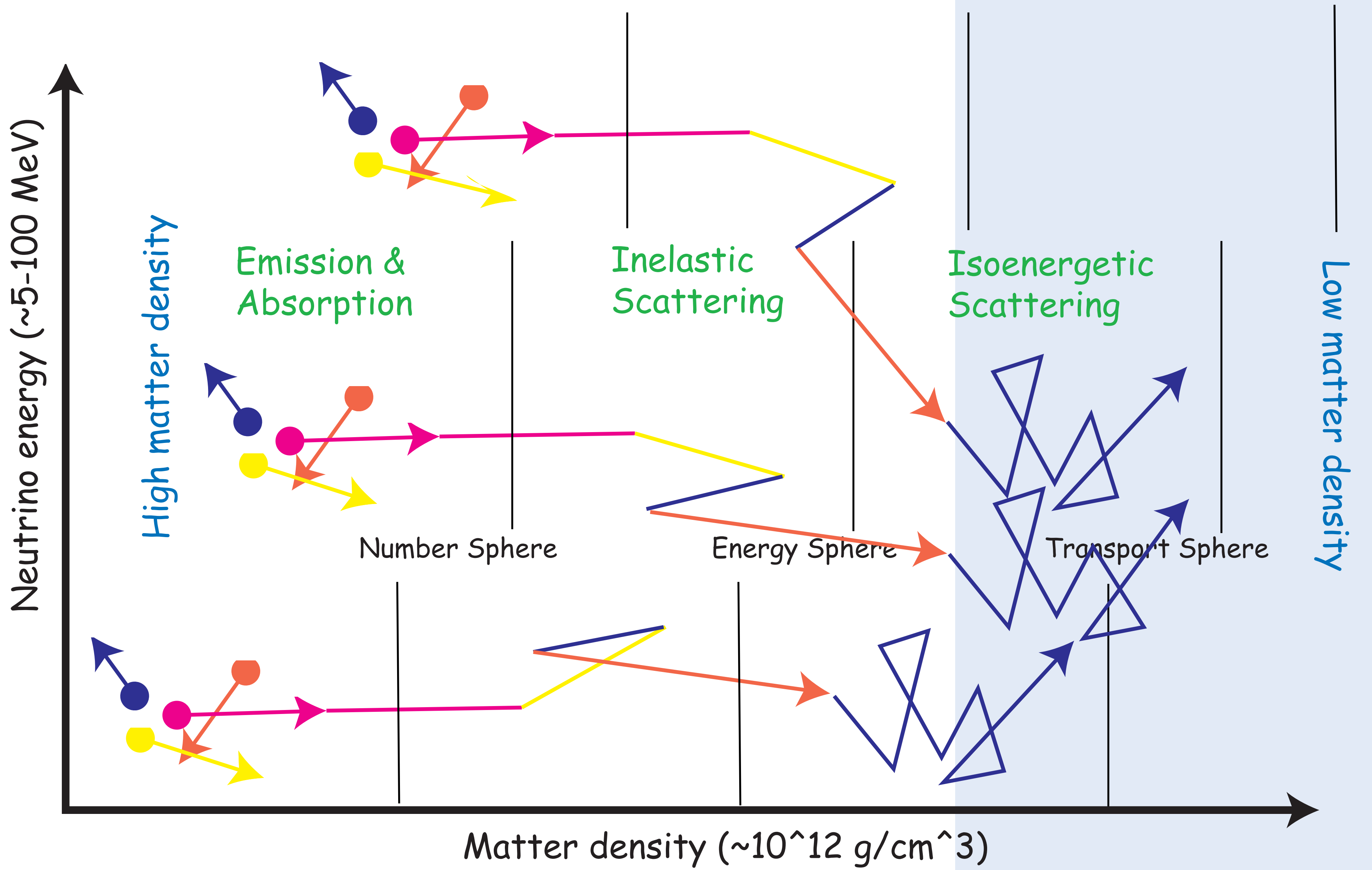
$$\nu + (A,Z) \rightleftharpoons \nu + (A,Z)$$

Neutrino-nucleon scattering

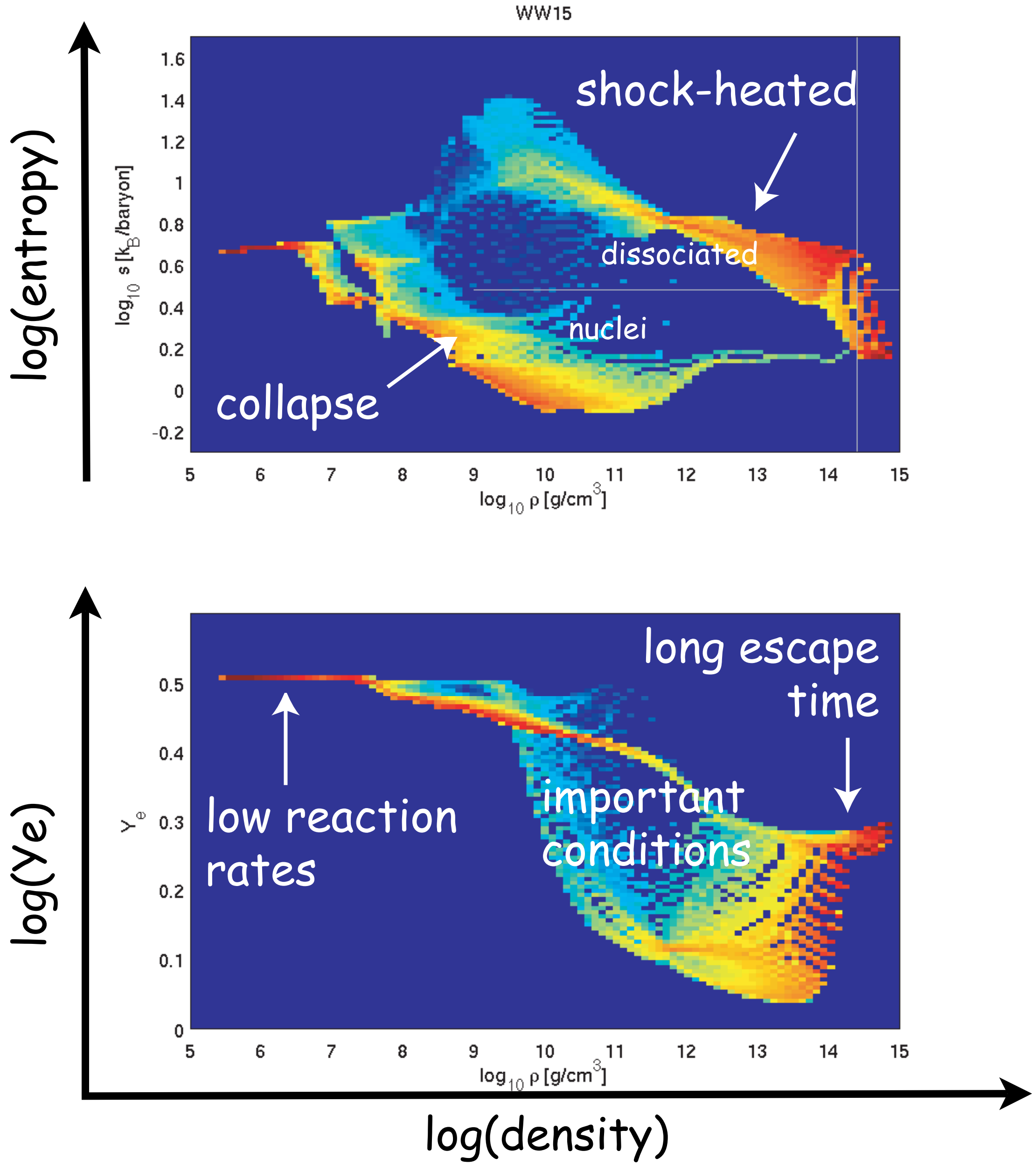
$$\nu + N \rightleftharpoons \nu + N$$

Streaming

Energy-dependent neutrino transport



Relevant ν-matter interactions



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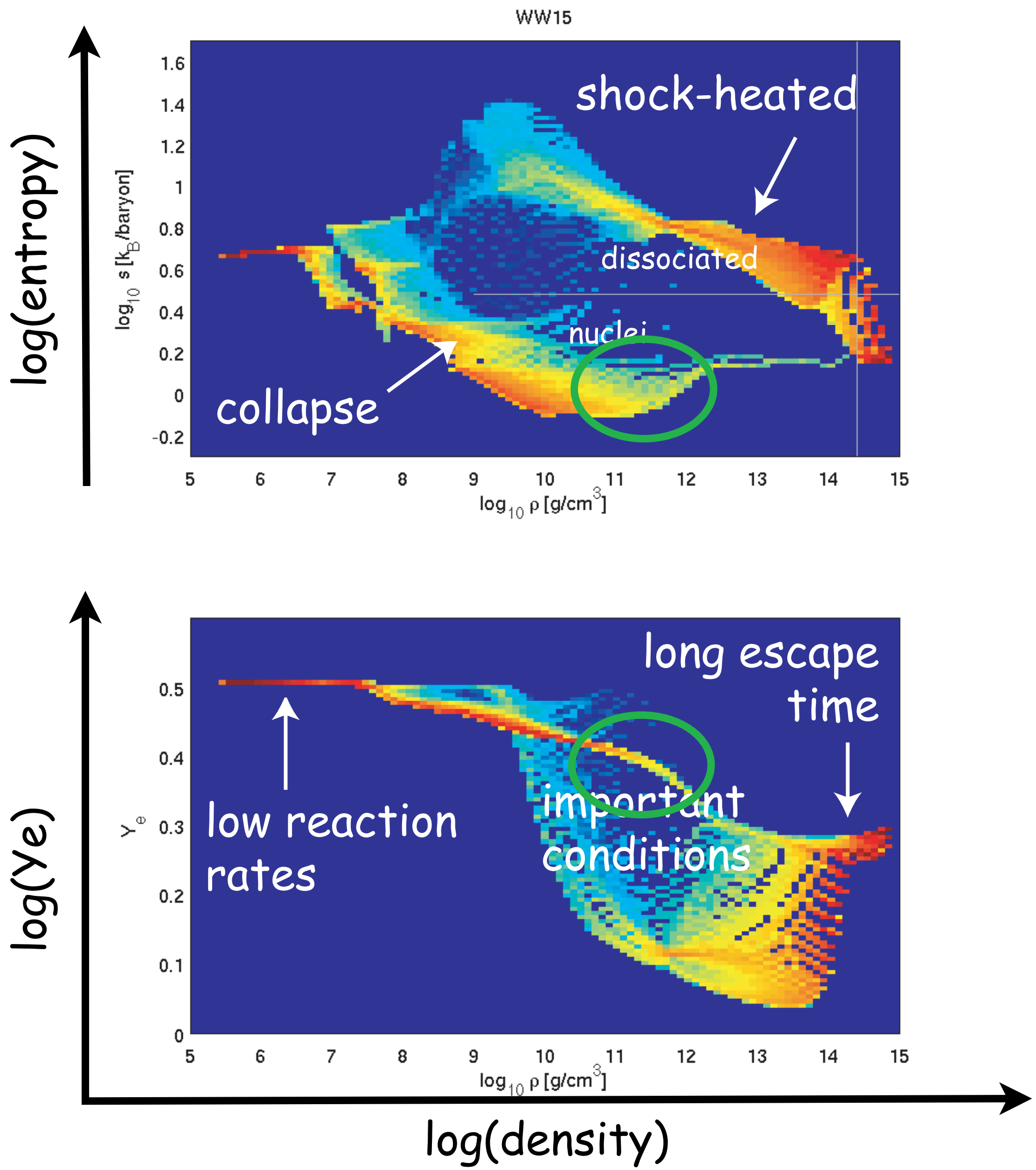

The conditions around the neutrino spheres are marked in

green ... collapse

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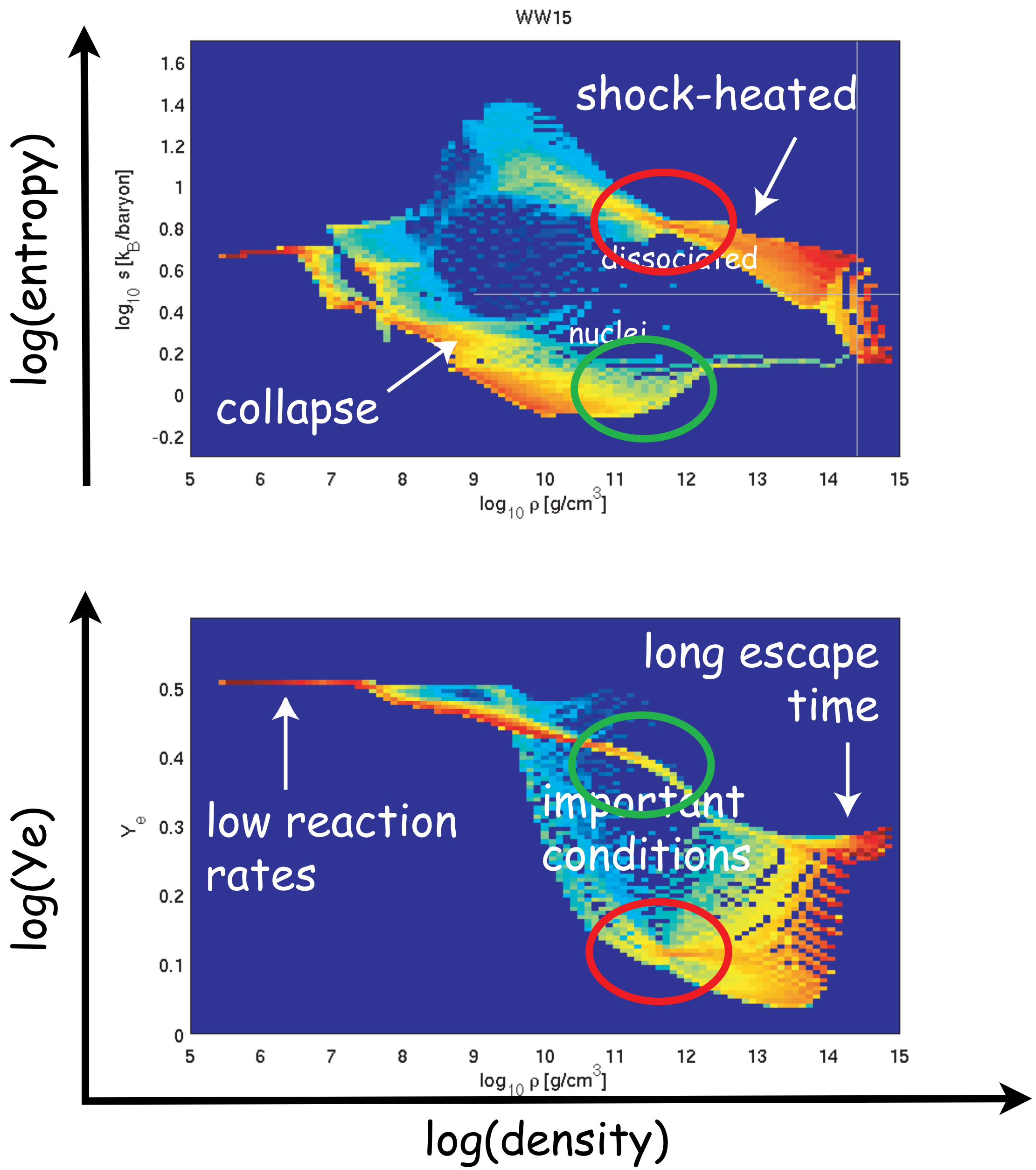


The conditions around the neutrino spheres are marked in

green ... collapse

red ... postbounce

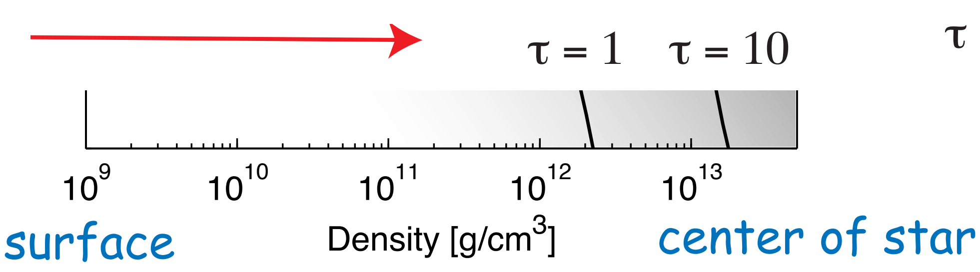
Physics for the collapse phase

Bethe (1990)
mean free path:

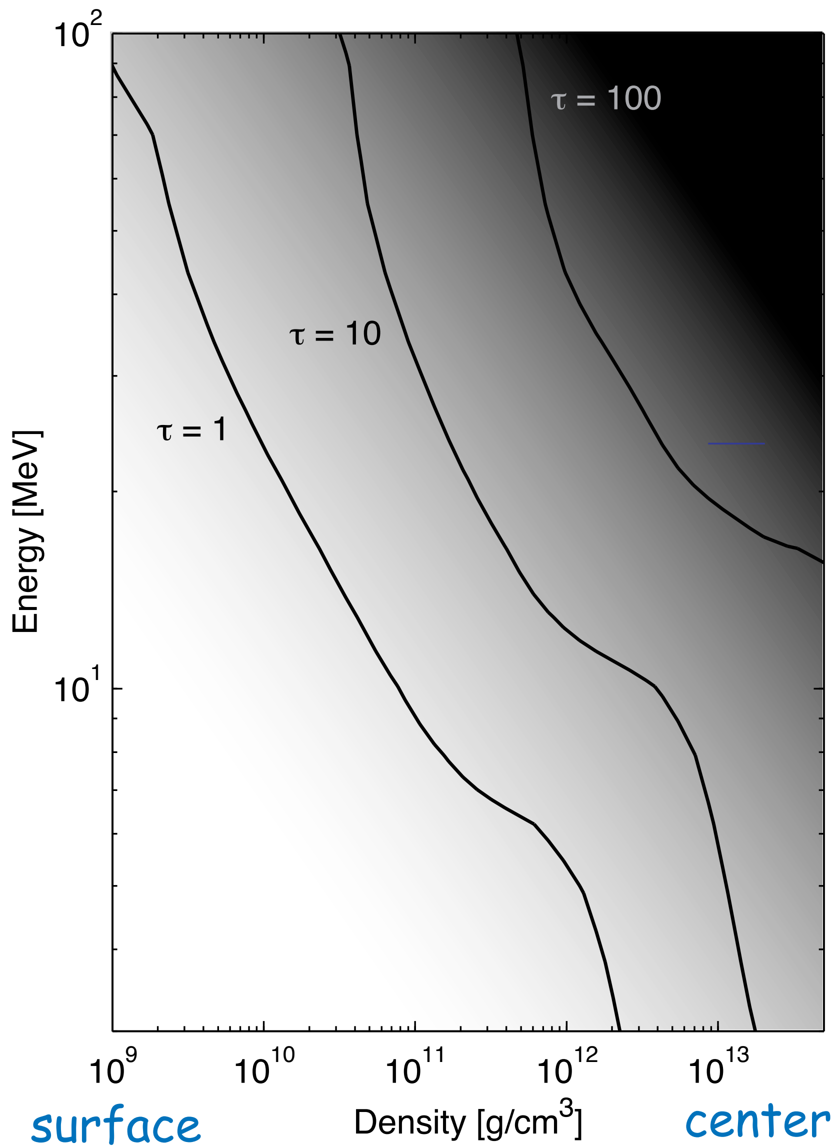
$$\lambda_\nu = 1.0 \times 10^8 \rho_{12}^{-1} [(N^2/6A) X_h + X_n]^{-1} \epsilon_\nu^{-2} \text{ cm} .$$

Optical depth:

$$\tau = \int dr/\lambda$$



Deleptonization



surface — center of star

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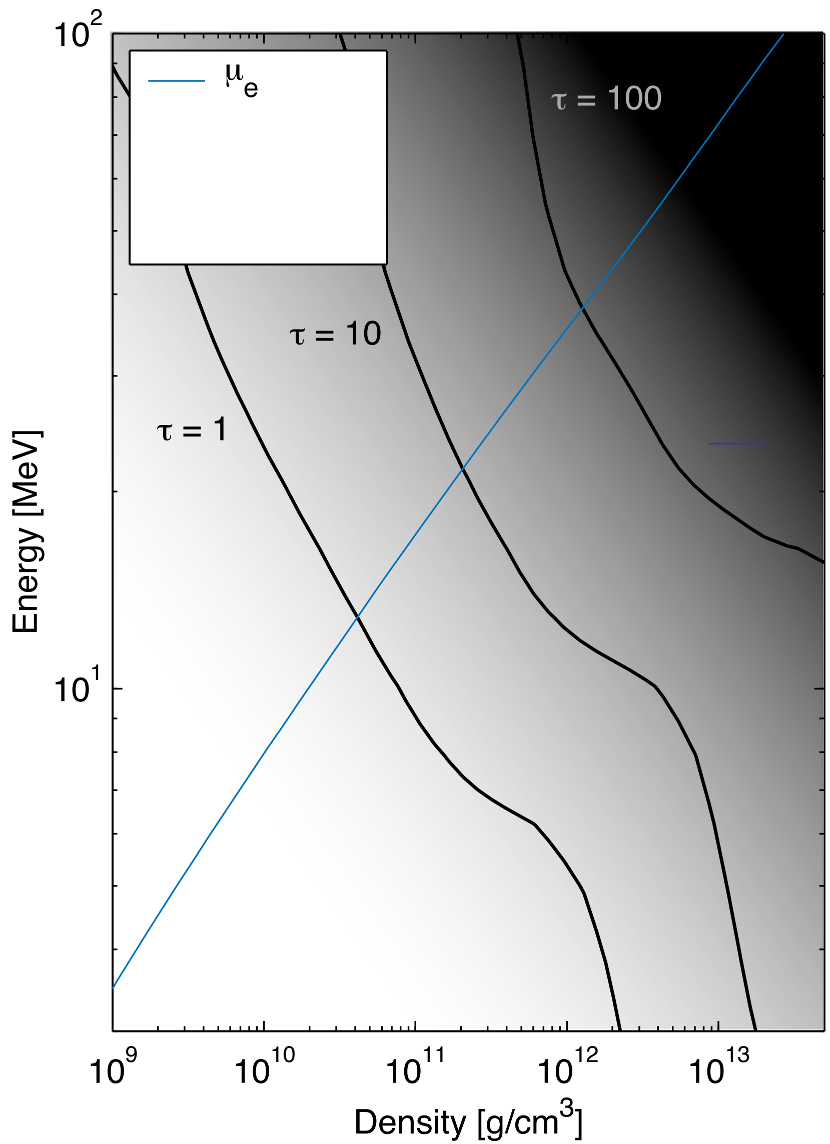

(Martinez-Pinedo, Liebendoerfer, Frekers, 2006)

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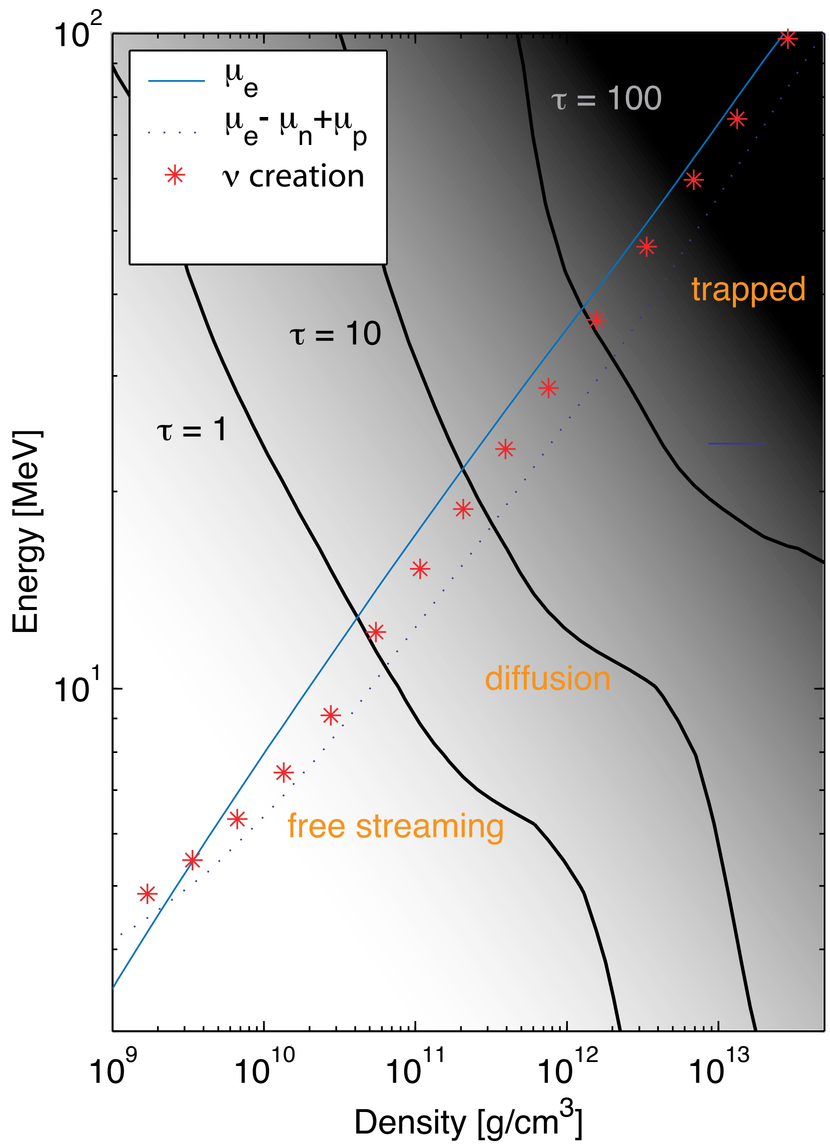

$$\mu_\nu \sim \mu_e - \mu_n + \mu_p$$

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

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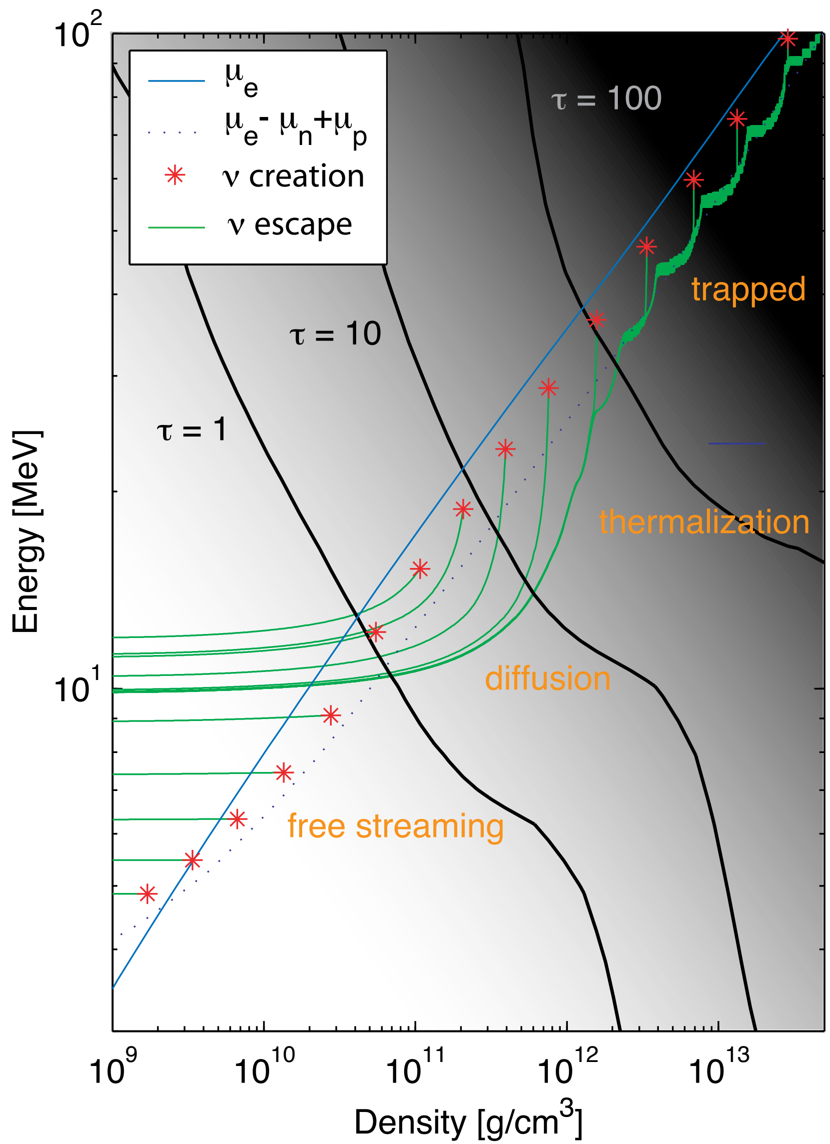

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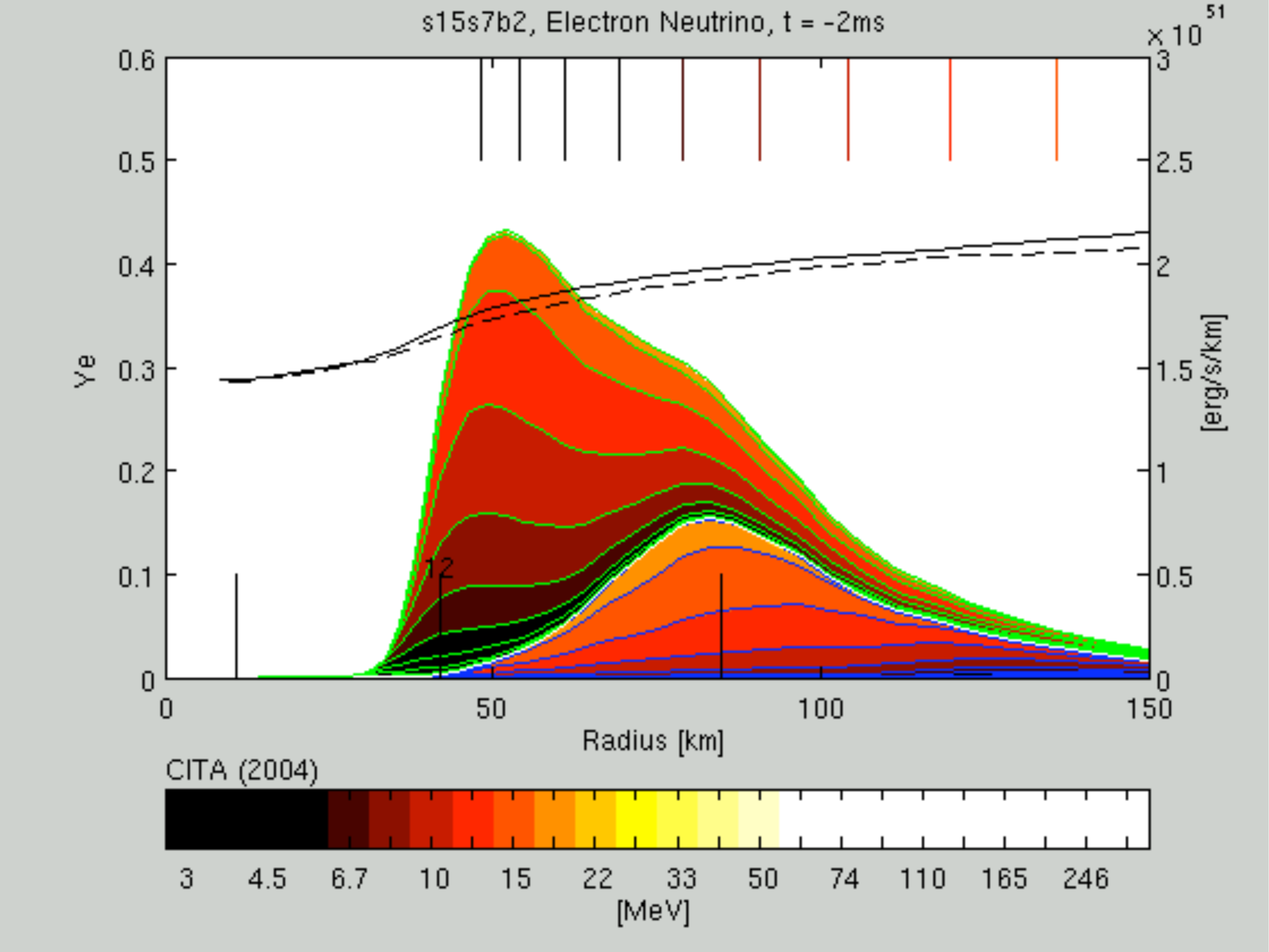
ν's escape directly:
-> entropy decrease

ν's thermalise:
-> entropy increase

Histogram of electron neutrino emission

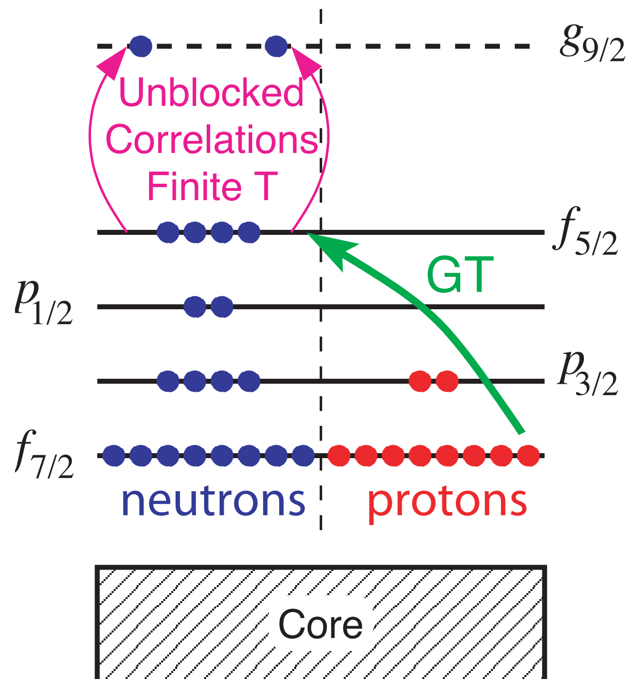


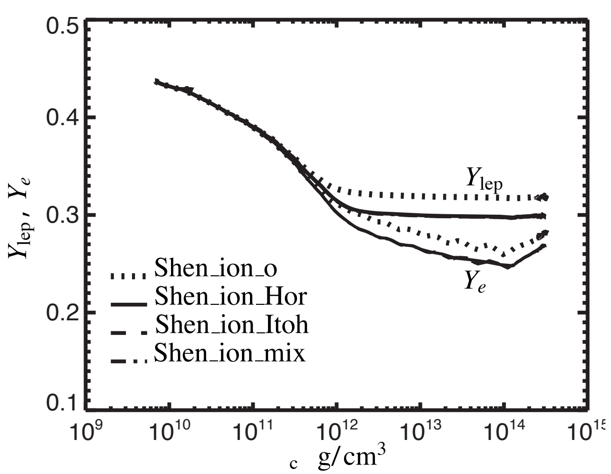
Physics for the collapse phase

Electron capture rates
- ensemble of nuclei with individual rates

Thermalisation
- neutrino-electron scattering, inelastic scattering with nuclei

Opacity
- coherent scattering
- ion-ion correlations
- clustering in phase transition
- unresolved: how to scatter on ensemble of nuclei?





Langake et al. 2003, Hix et al. 2003, Martinez-Pinedo, Liebendörfer, Frekers 2006

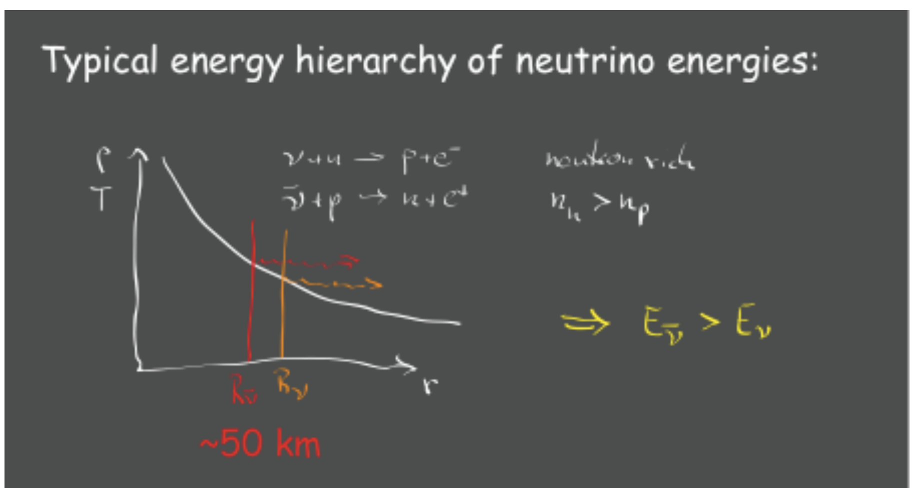
Myra & Bludman, Bruenn 1989, Langanke et al. 2008

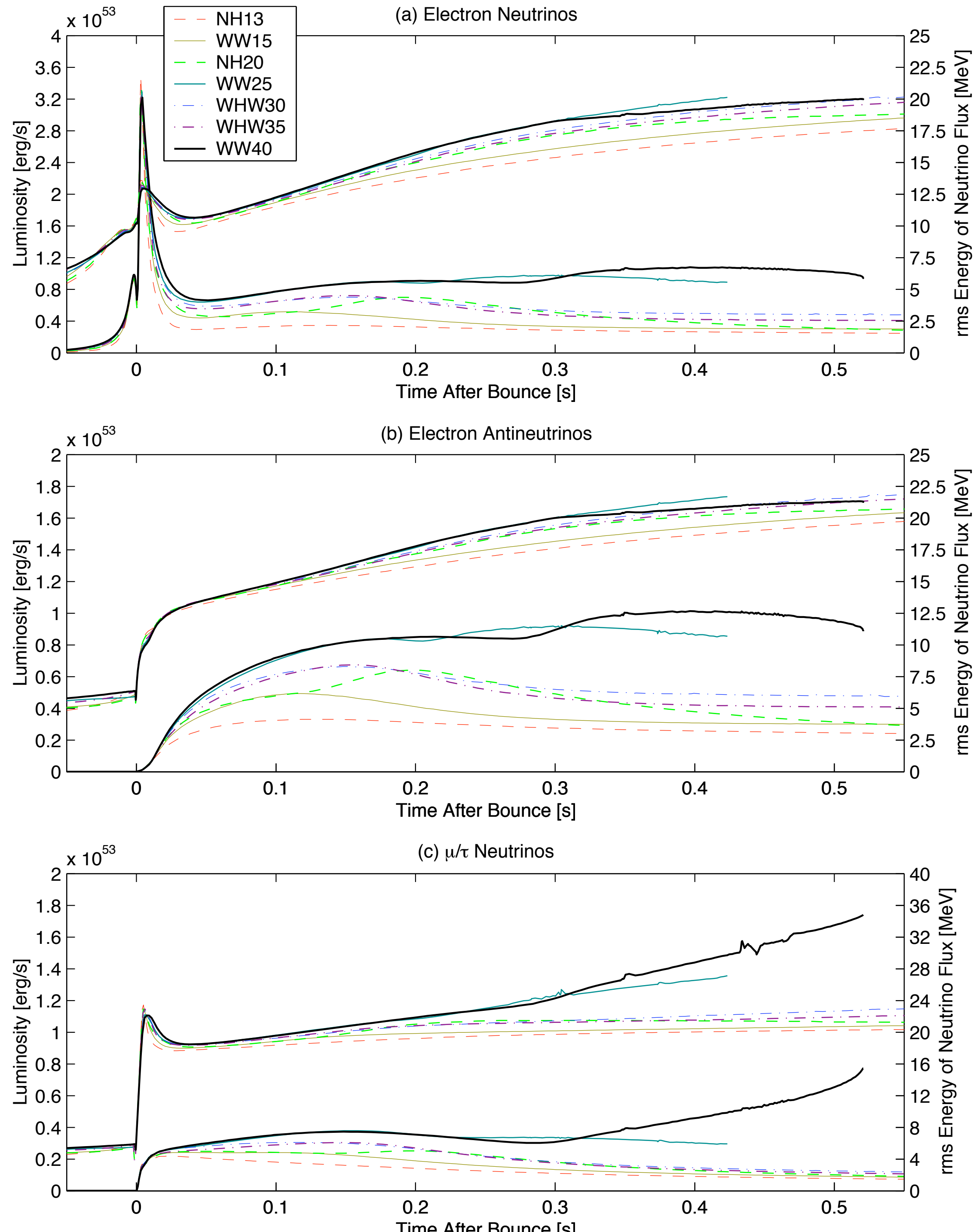
Itoh 1975, Horowitz 1997, Bruenn & Mezzacappa 1997, Watanabe 2004, Horowitz et al. 2004, Botvian & Mishustin 2005, Marek et al. 2005

Structure and dynamics of nuclei are key!

Neutrinos from the postbounce phase

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





(Liebendörfer et al. 2003)

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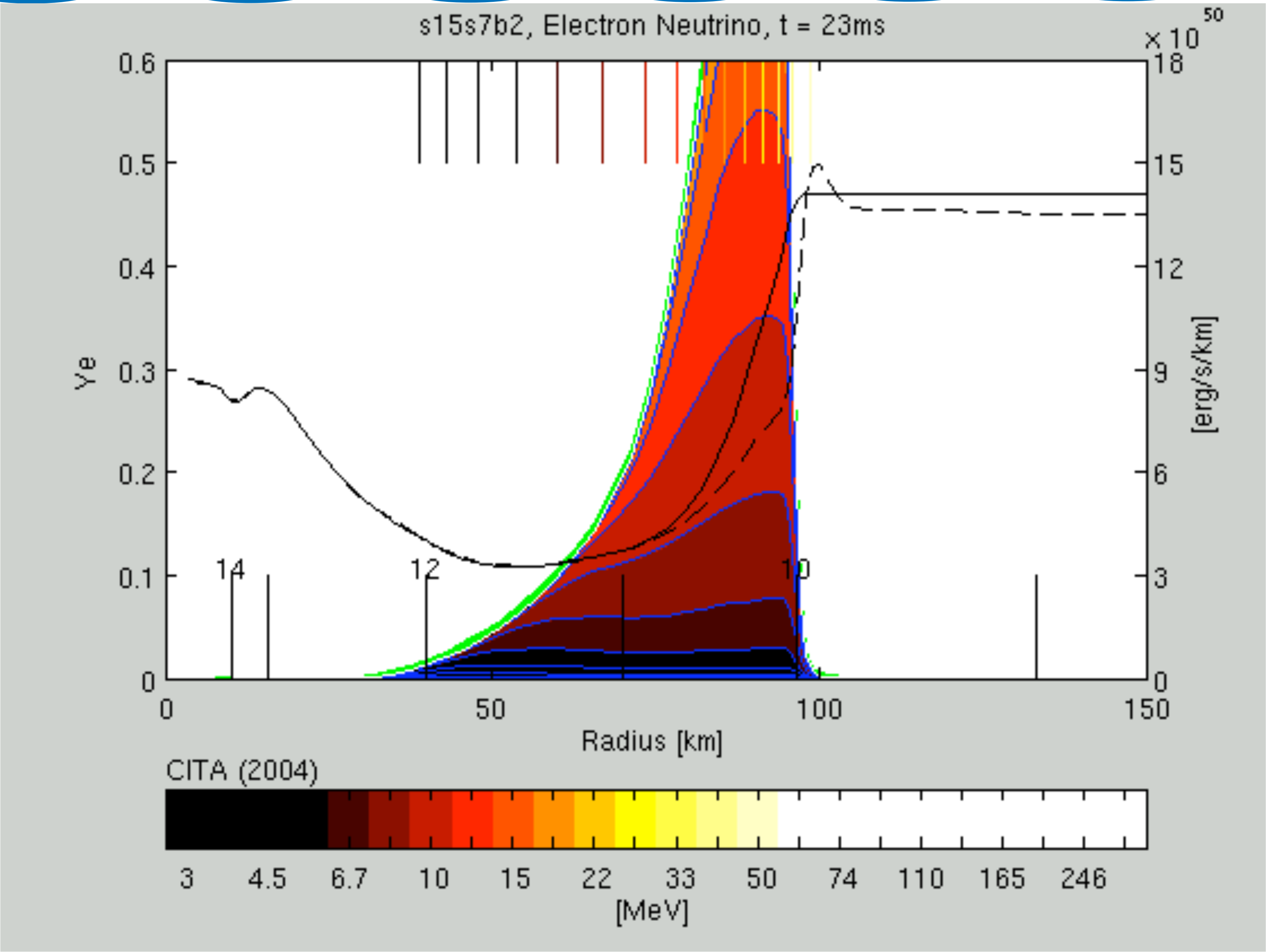
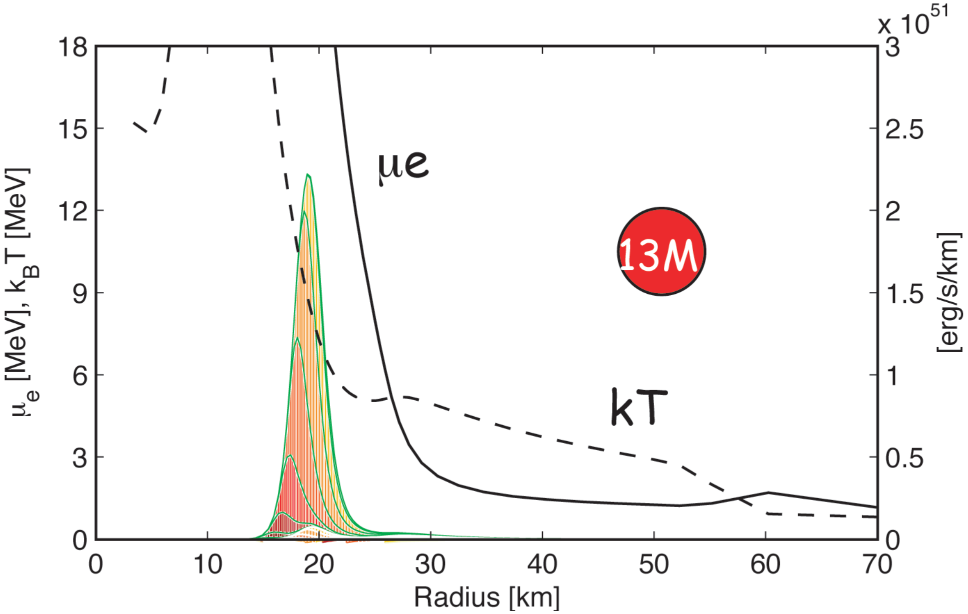
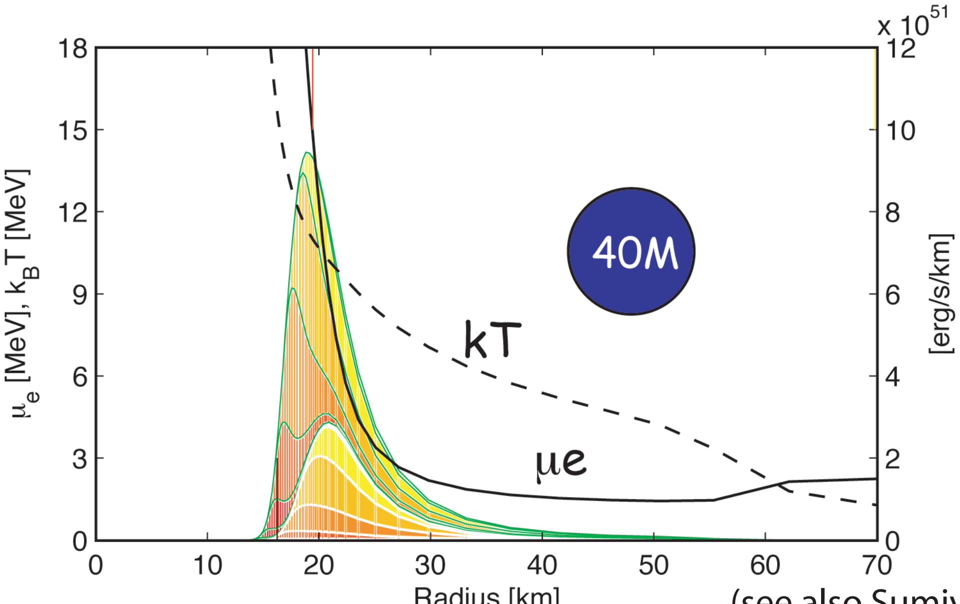


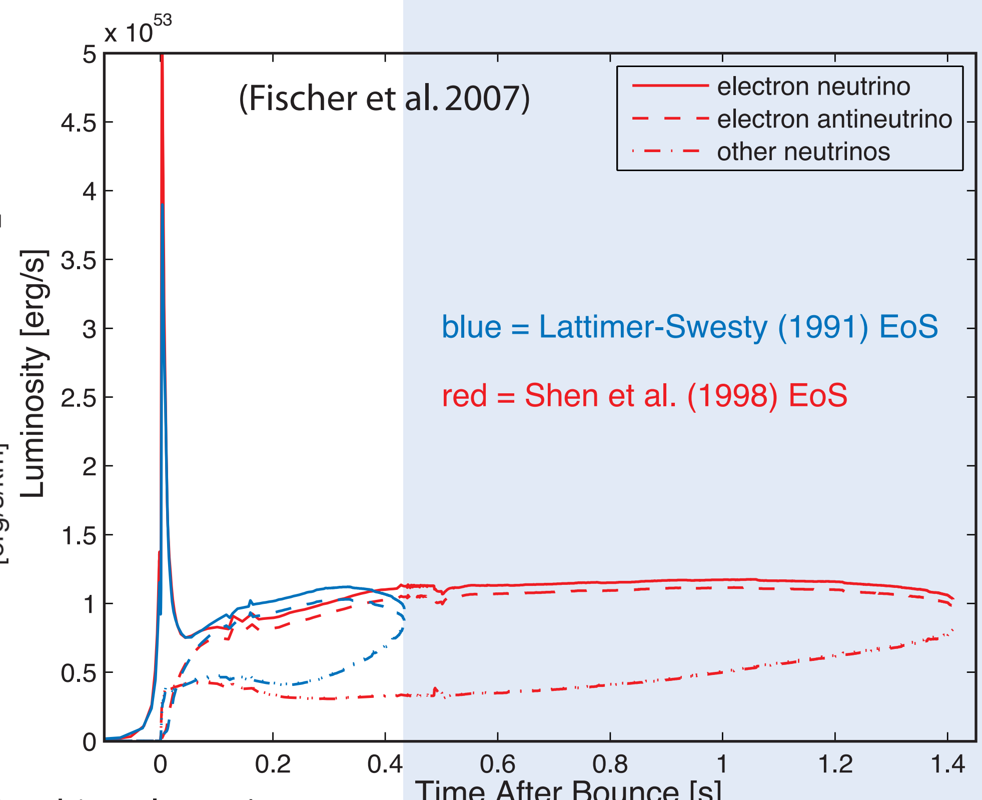
PNS evolution & ν(μ/τ) properties



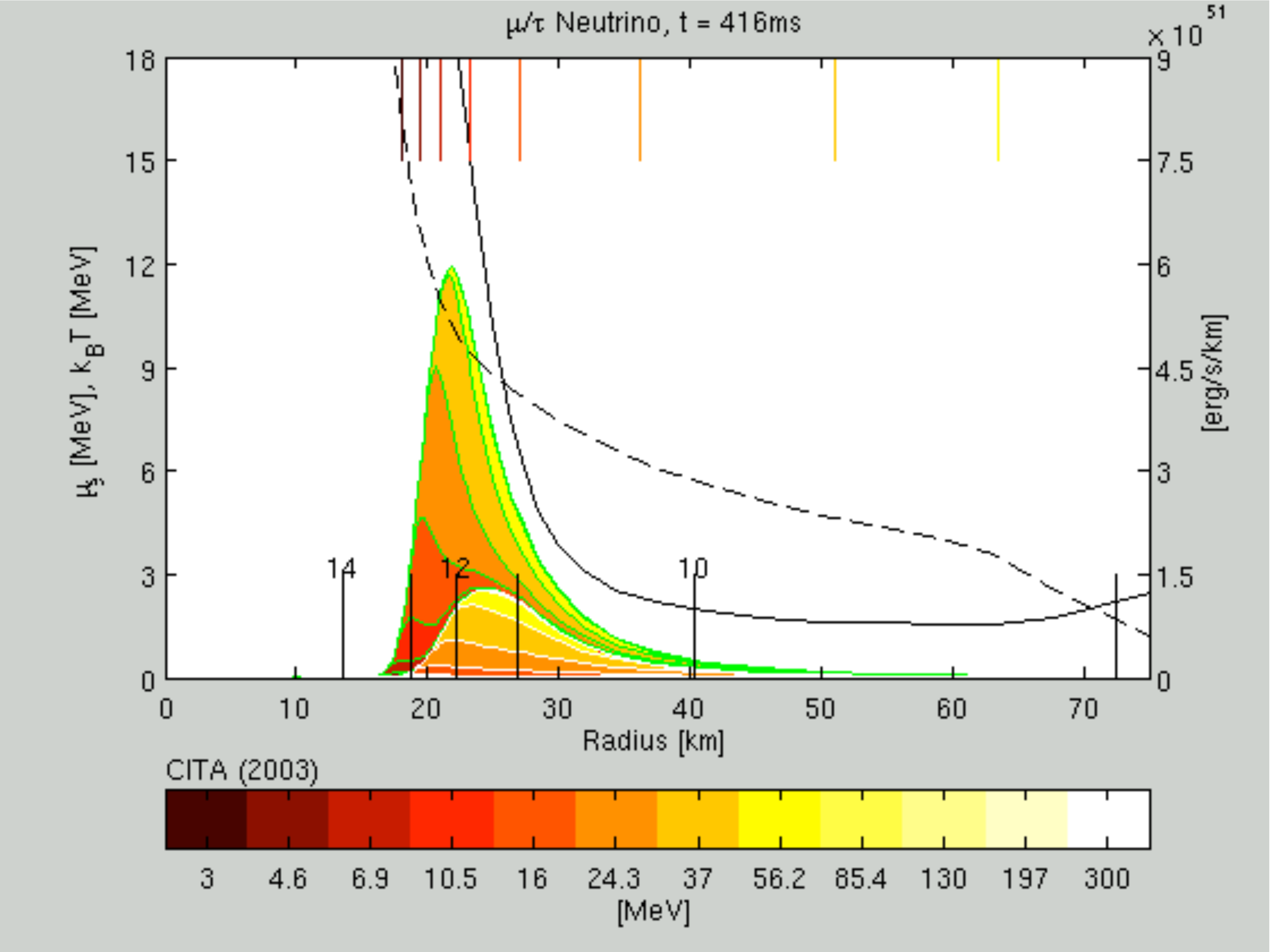


(see also Sumiyoshi et al. 2007)

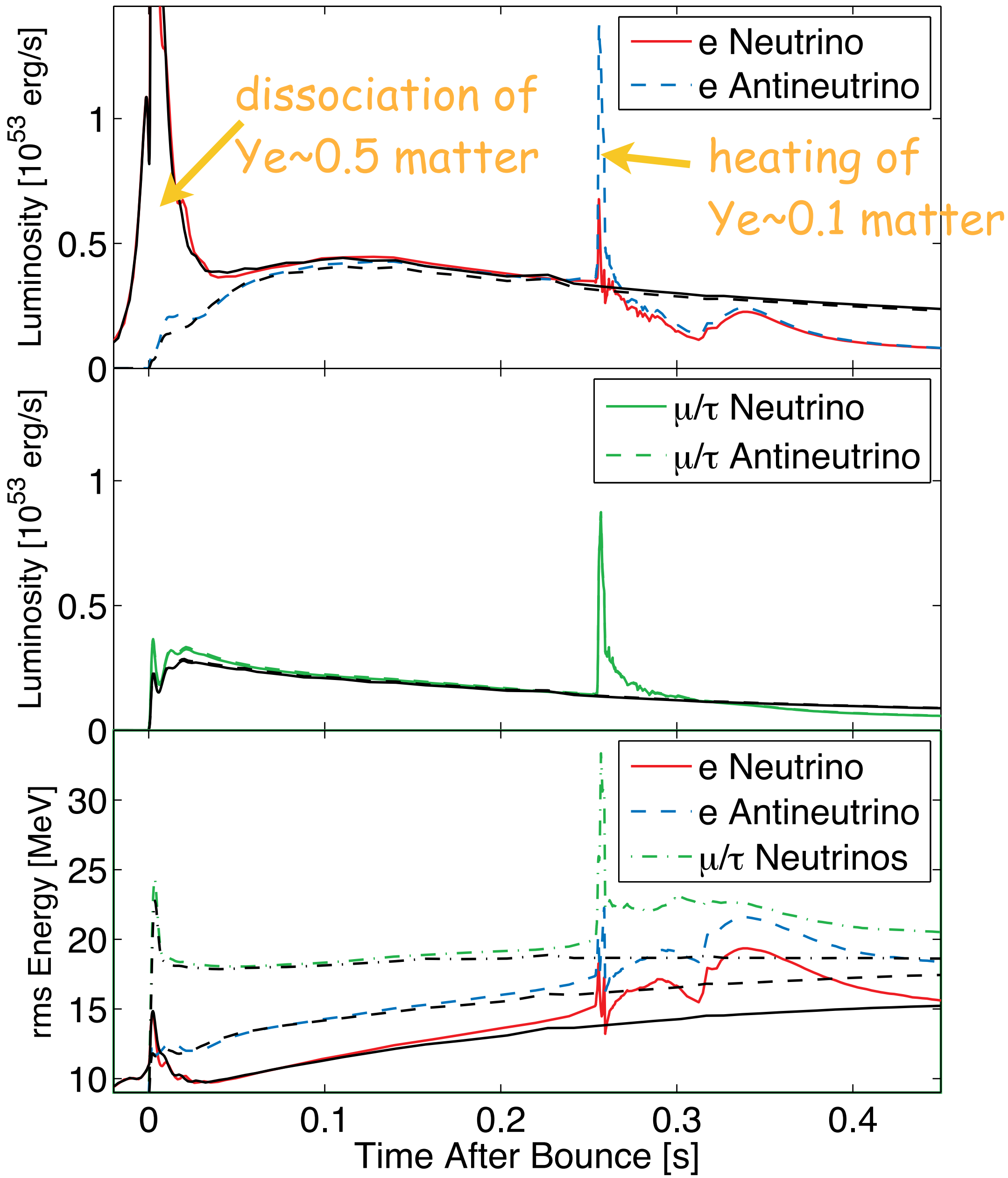
- low mass proto-neutron star (PNS) --> incompressible accretion
- PNS close to maximum mass --> hot layers pushed inward

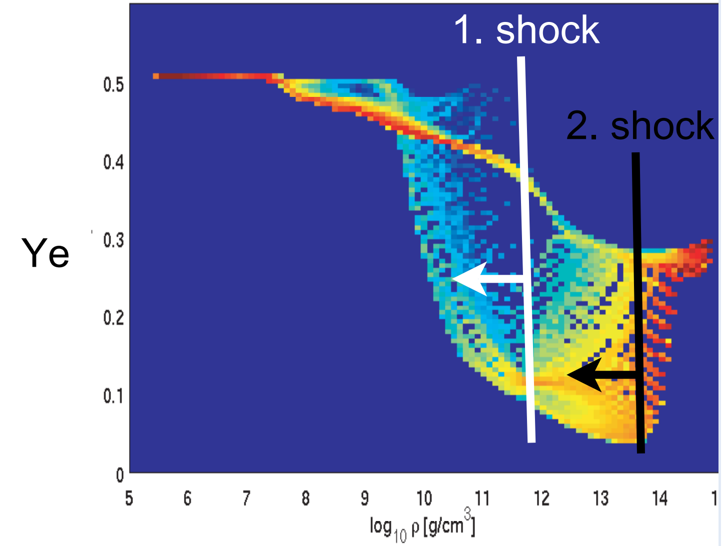


Histogram of μ/τ neutrino emission



QCD phase transition induced explosions

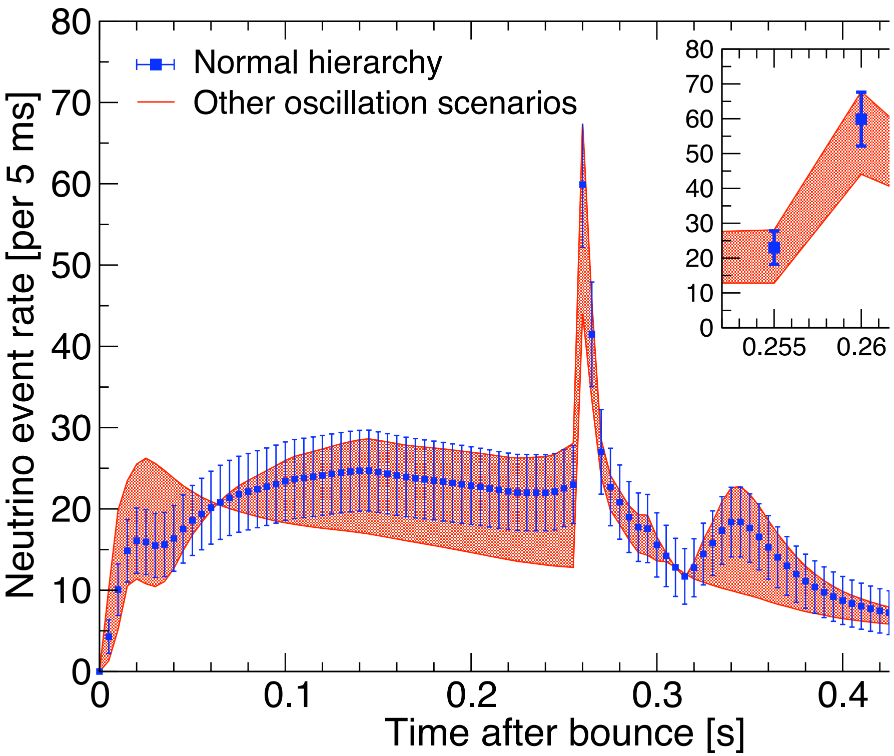


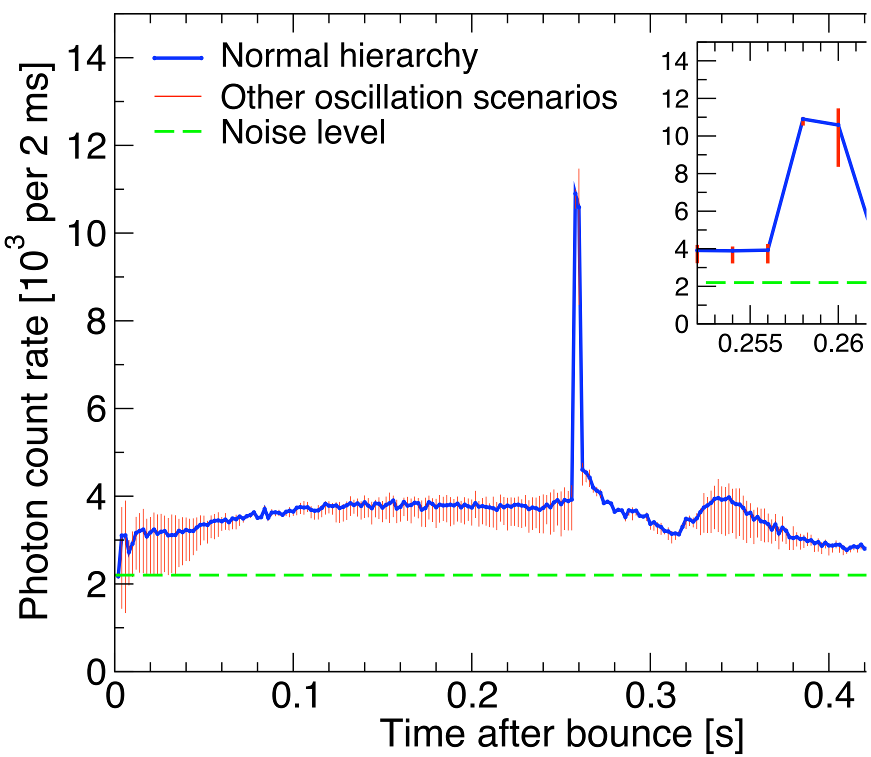


- Second neutrino peak in all flavours, dominated by anti-ν's
- Step up in neutrino rms energies

(Sagert, Fischer et al., PRL 2009)

SN as high-density physics laboratory

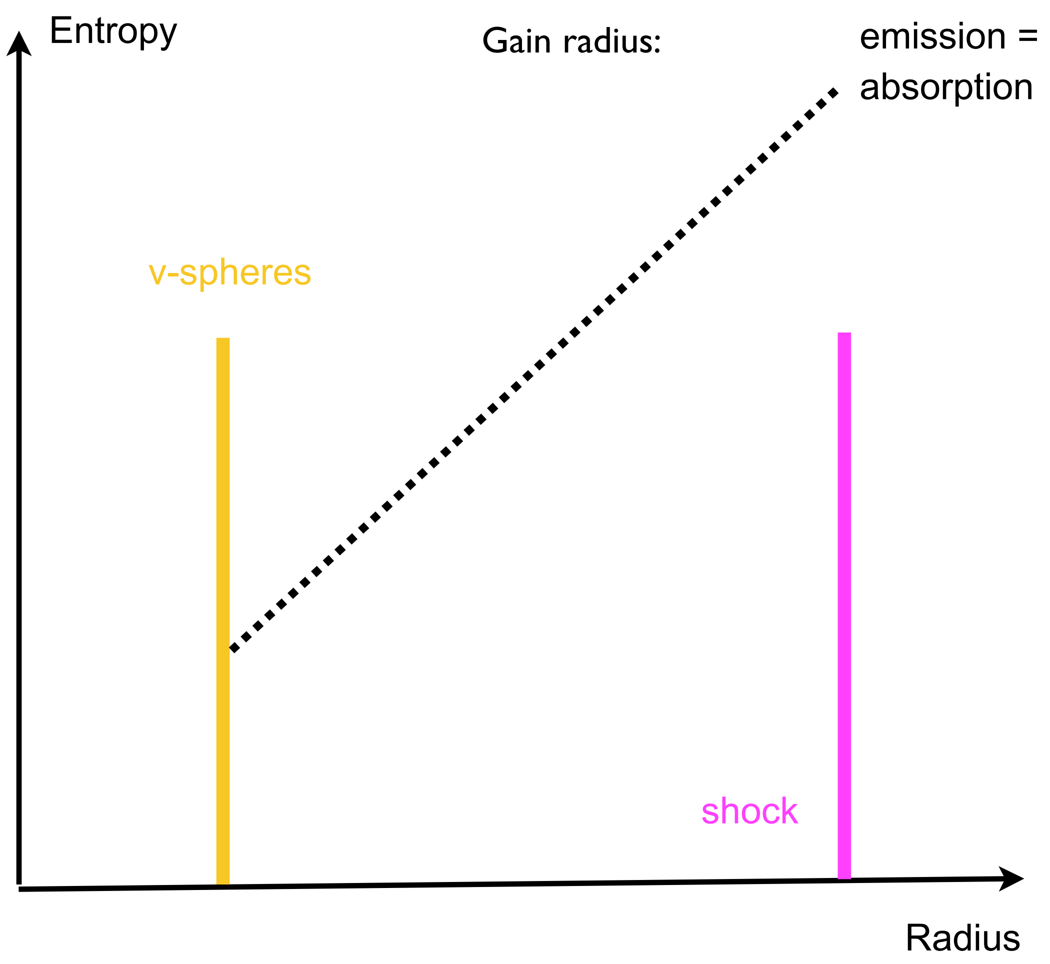




Neutrino signature from early QCD phase transition in proto-neutron star (EOS not compatible with 1.97 Ms neutron star! (Demorest et al. 2010))

(Dasgupta et al. 2010)

Physics for the postbounce phase



There are no heavy nuclei between the neutrinosphere and the shock!

Key input:
- high-density EOS
- fluid instabilities
- neutrino transport, (and oscillations?)
- magnetic fields

Fluid overturn is essential for ν–heating efficiency

(Herant et al. 1994)

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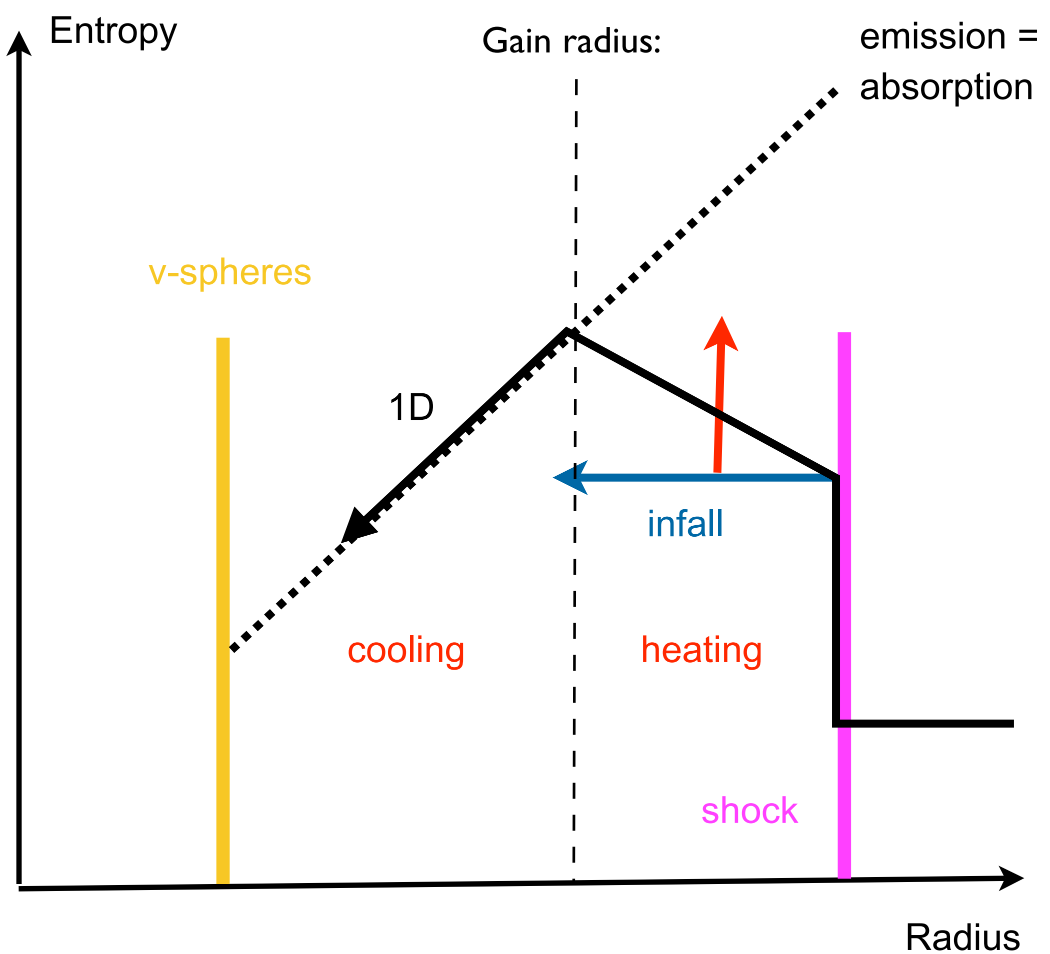

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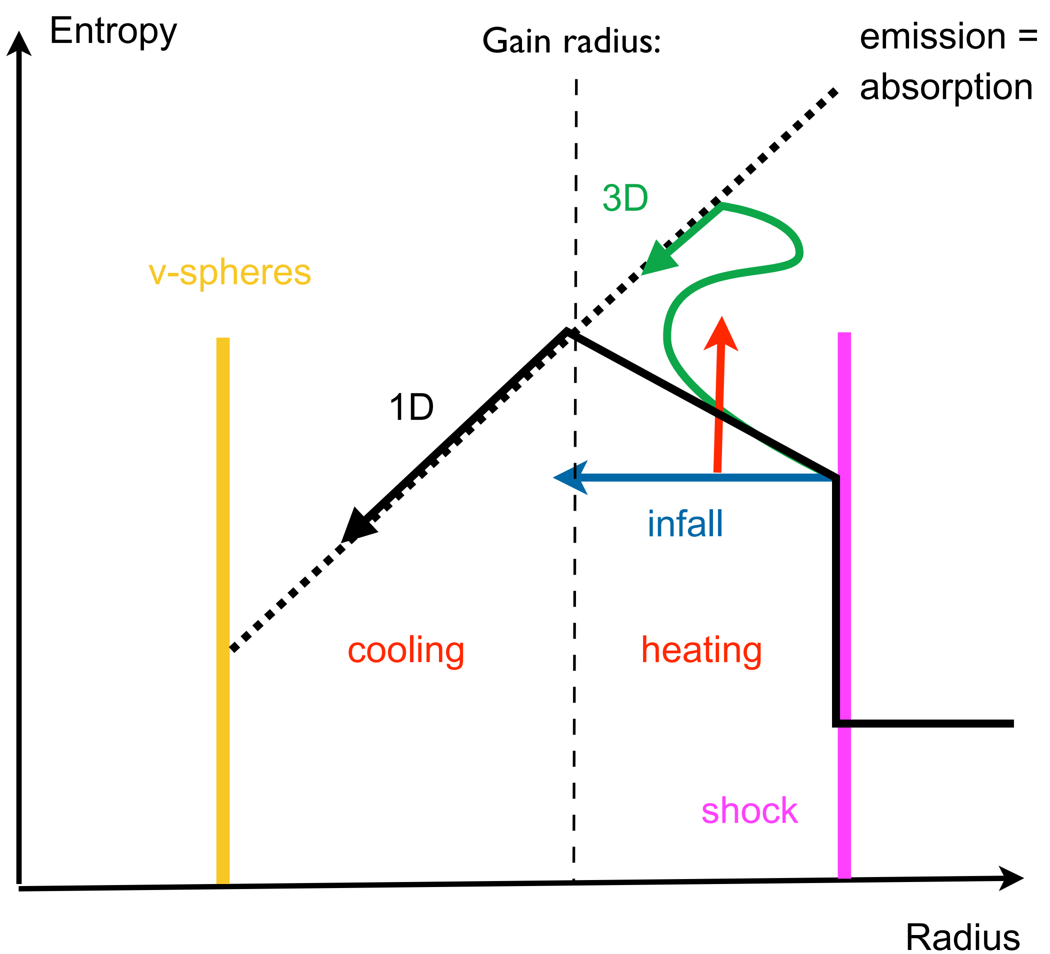

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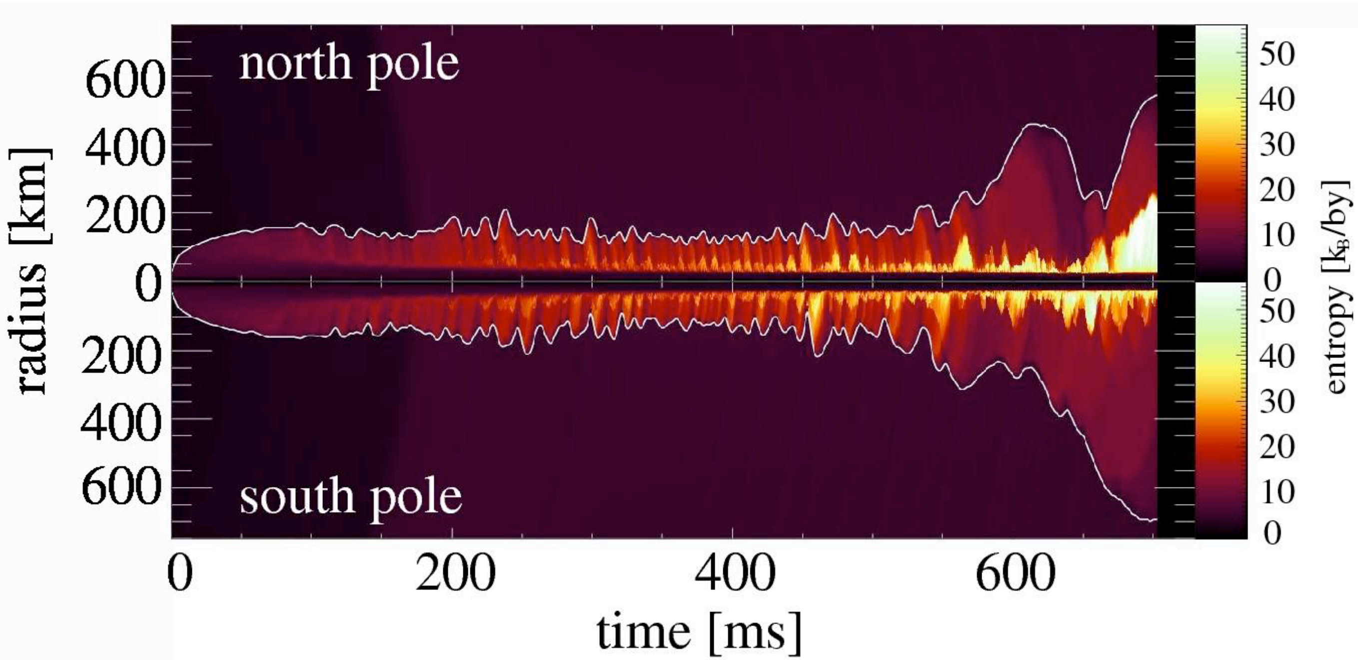
2D Models in axisymmetry



Marek & Janka 2009

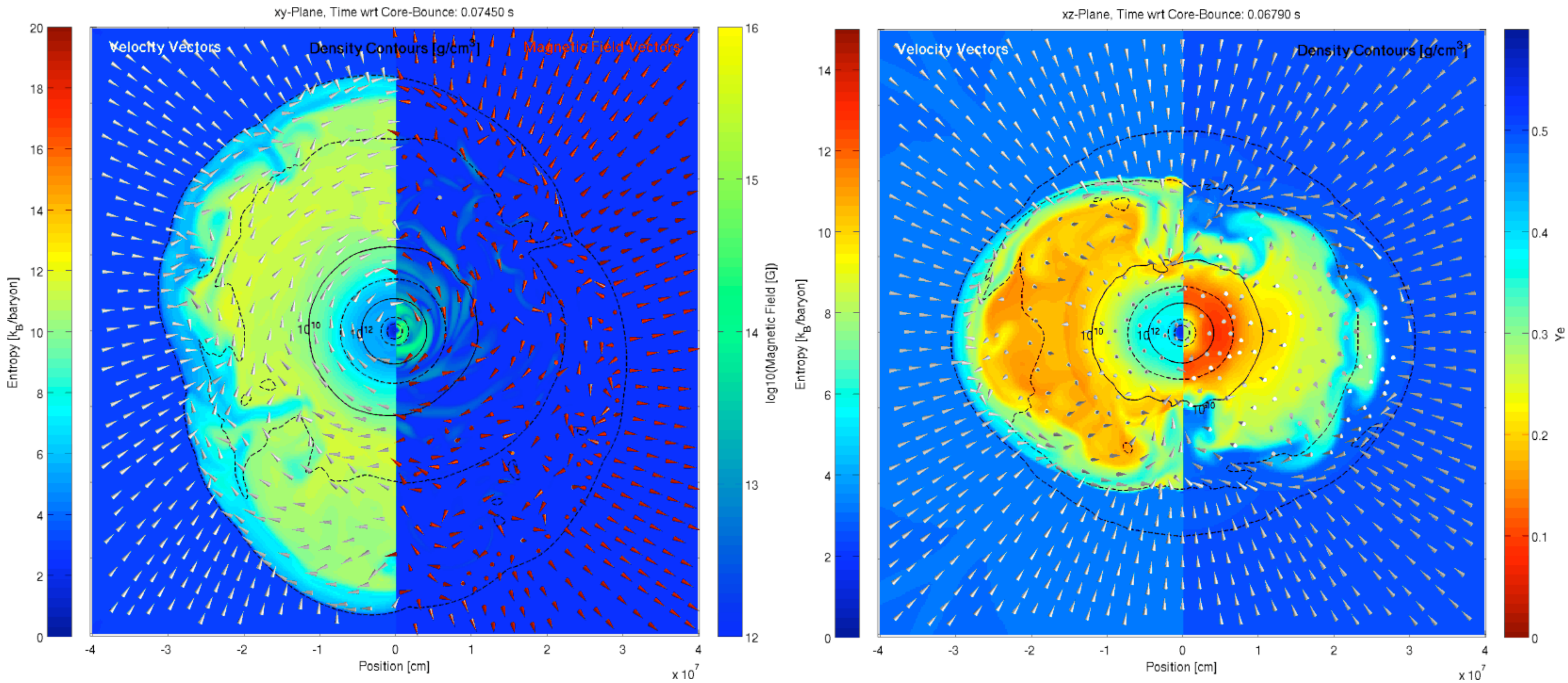
- Spectral neutrino transport
- Ray-by-ray approach couples transport in angular wedges to 2D hydrodynamics

Talks by

- Steve Bruenn
- Christian Ott
- Bernhard Müller
- Thomas Janka

- Neutrino heating
- Standing Accretion Shock Instability
- Input physics
- Asymmetries
- Grid/Coordinates
- Relativity / O(v/c)

FISH code: 3D magneto-hydrodynamics



- 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.

Käppeli et al. arXiv:0910.2854

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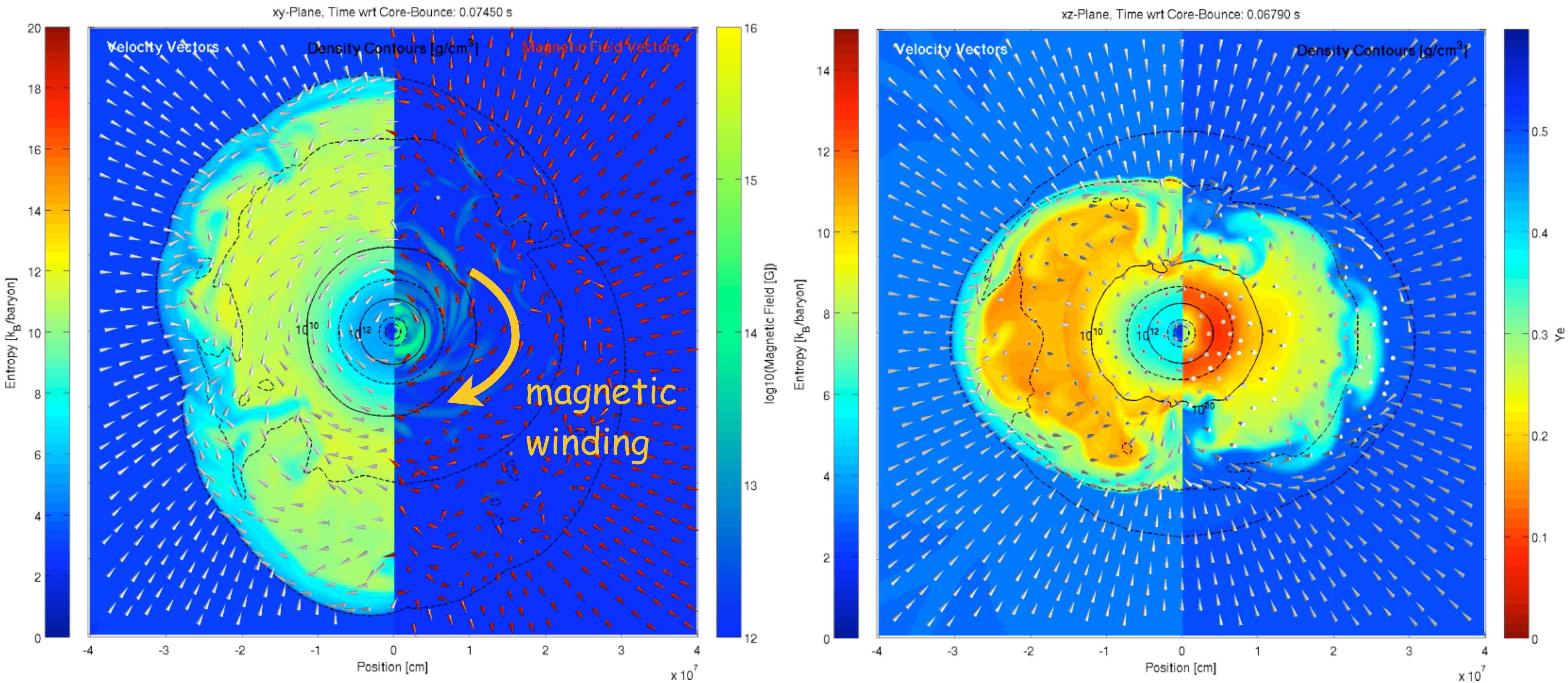

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Solving the Boltzmann equation

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

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

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

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

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

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

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

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

(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:

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

Stress-energy tensor:

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

Pitfalls of multi-D Boltzmann ν-transport

Boltzmann transport:

- One fluid elemement contains
  4 ν 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
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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

Hydrodynamics:

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difficult energy-terms must not be neglected!

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  --> 64TB per time step

Hydrodynamics:

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

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

difficult energy-terms must not be neglected!

Diffusion limit:

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

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

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:

Interpolate from diffusive regime to transparent regime:

- Multi-Group flux-limited diffusion

Flux factor unknown in transparent regime!

- New: Isotropic diff. source approximation

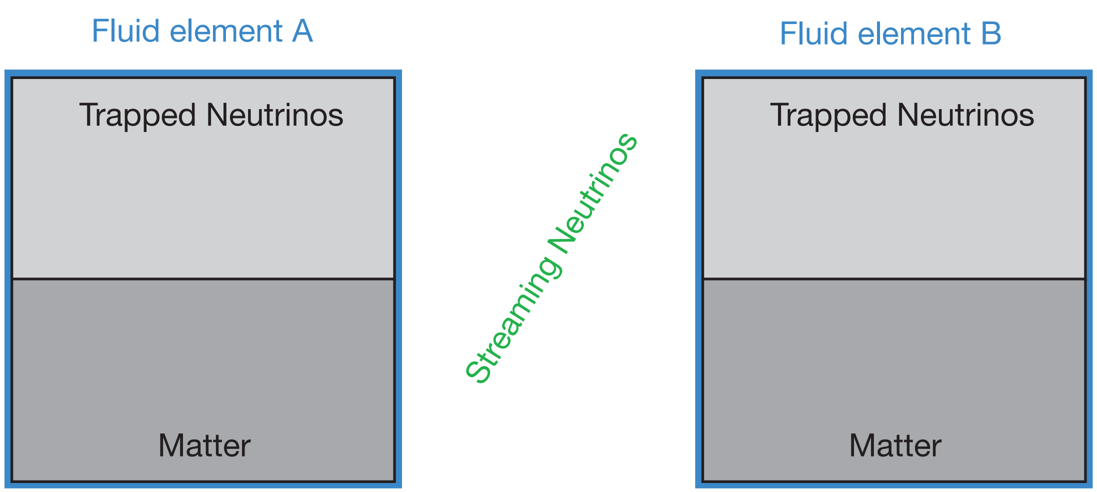
f = f(trapped) + f(streaming), separate evolution Eqs.

Isotropic Diffusion Source Approximation

$D(f) = j - \chi^{*}f$

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

Different approx.
for trapped & streaming
neutrino components!



Liebendörfer et al. 2009

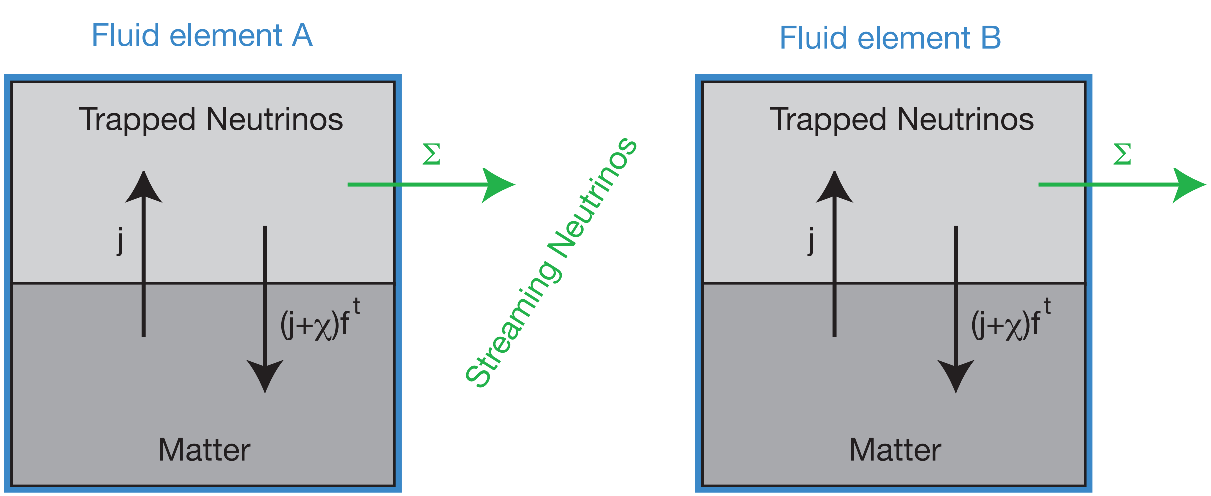
Isotropic Diffusion Source Approximation

$D(f) = j - \chi^* f$
$f = f(\text{trapped}) + f(\text{streaming}) = ft + fs$

$D(ft) = j - \chi^* ft - \Sigma \qquad (1)$
$D(fs) = - \chi^* fs + \Sigma \qquad (2)$

Different approx. for trapped & streaming neutrino components!

Σ determined by diffusion limit of (1)



- implicit local weak interaction solver
- advection-diffusion problem

Liebendörfer et al. 2009

Isotropic Diffusion Source Approximation

$D(f) = j - \chi^* f$

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

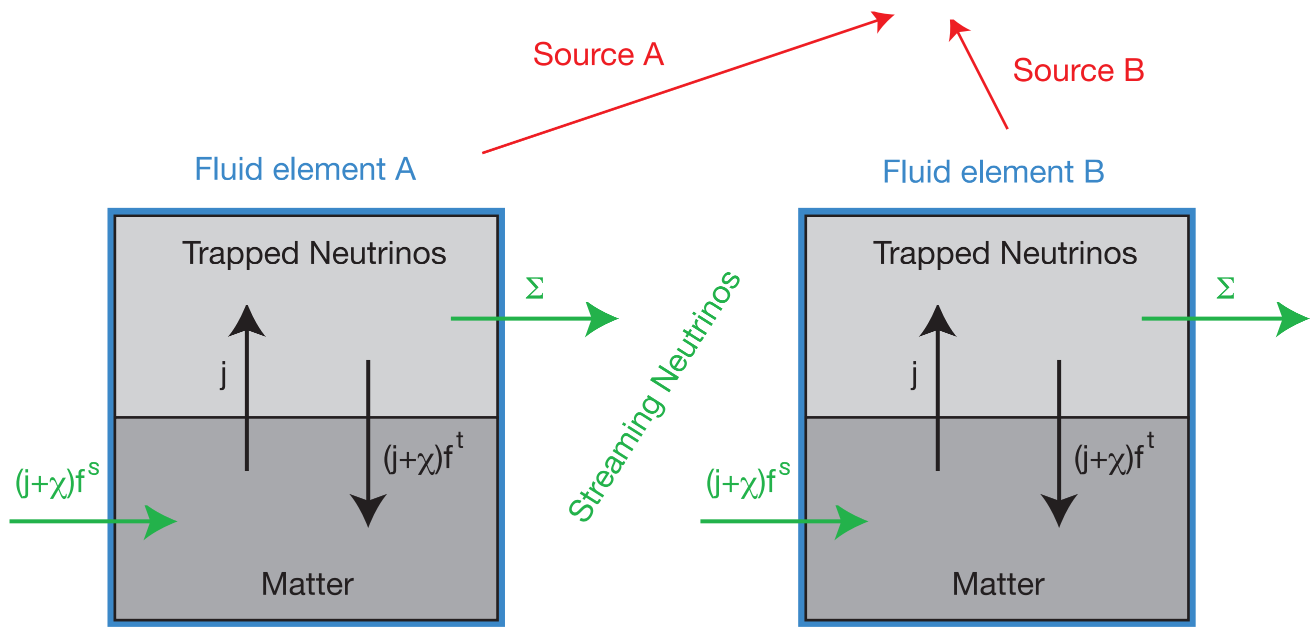
$D(ft) = j - \chi^* ft - \Sigma$ (1)

$D(fs) = -\chi^* fs + \Sigma$ (2)

Different approx. for trapped & streaming neutrino components!

Σ determined by diffusion limit of (1)

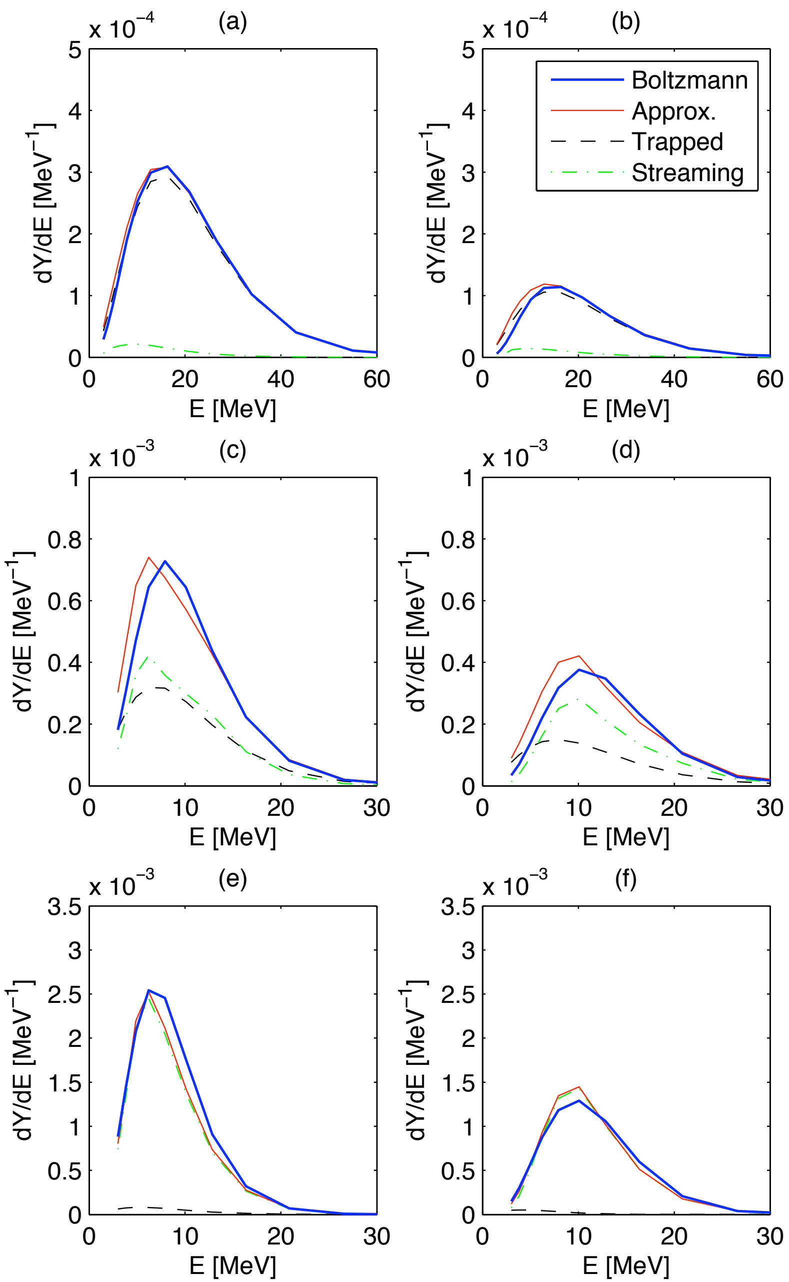
Stationary state approx. for (2) --> Poisson Eq.



- implicit local weak interaction solver
- advection-diffusion problem
- 20+1 Poisson solves per step
- Geometrical analysis of neutrino-spheres

Liebendörfer et al. 2009

Comparison of IDSA Spectra



at 40 km radius
(trapped regime)

Trapped neutrinos dominate spectrum

at 80 km radius
(semi-transparent)

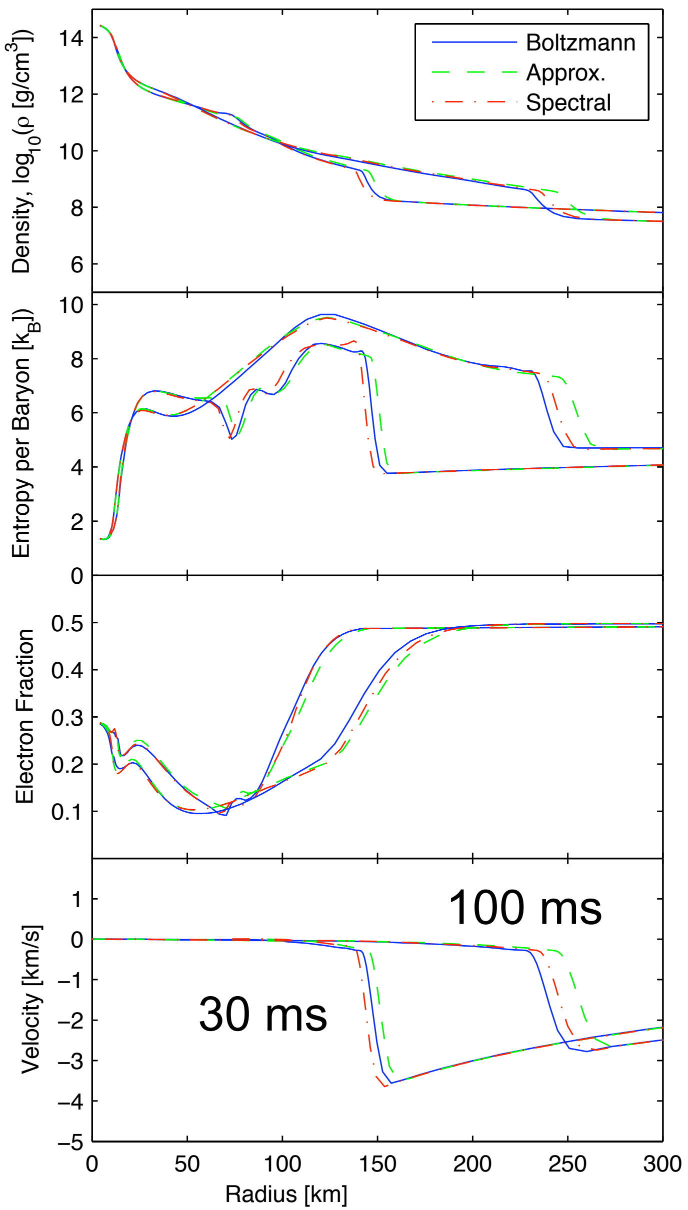
Trapped *and* streaming neutrinos form spectrum

at 160 km radius
(free streaming)

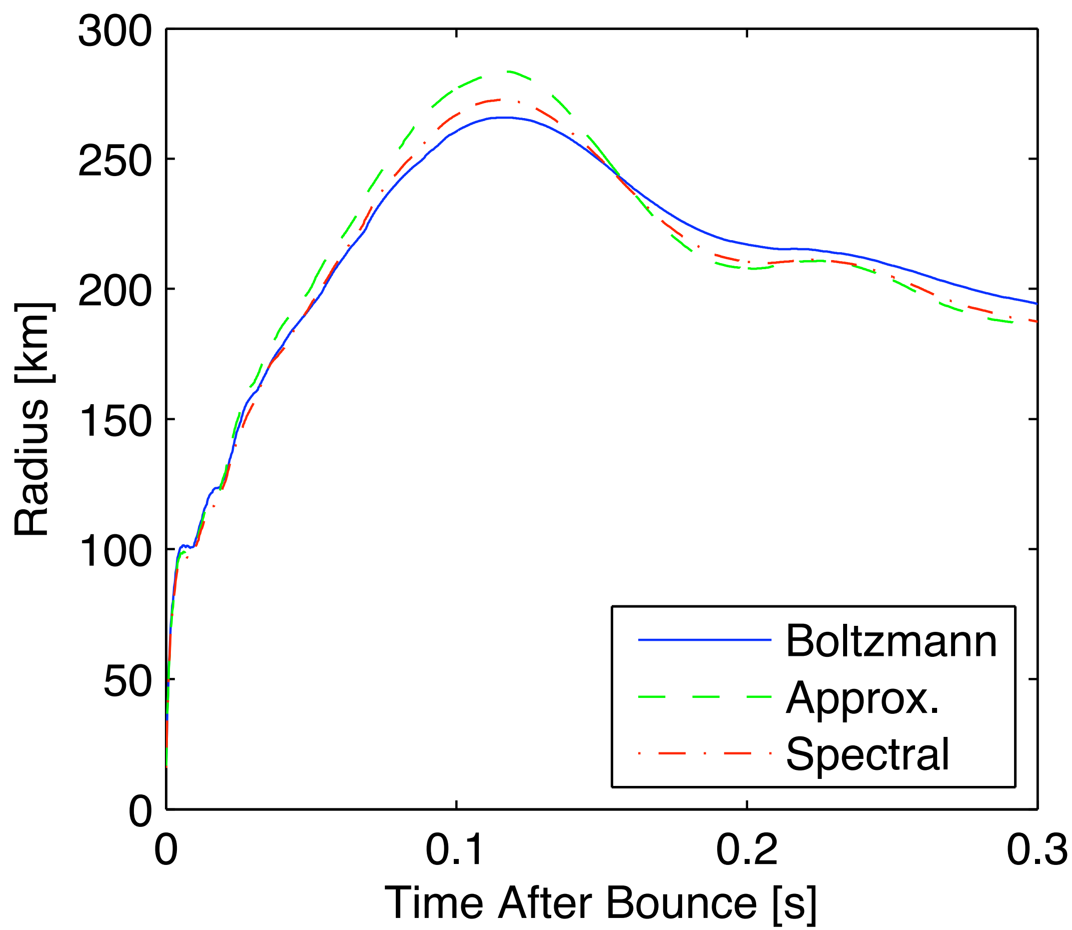
Streaming neutrinos dominate spectrum

Comparison of Hydrodynamical Evolution

UNI BASEL



Evolution of shock radius as function of time

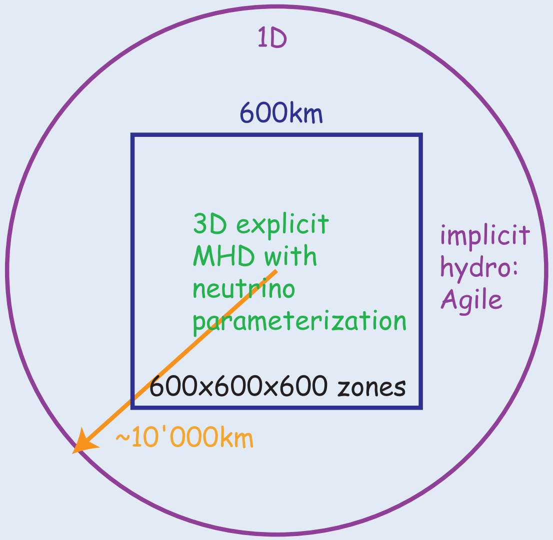


prel. Agile & IDSA available by email
to matthias.liebendoerfer at unibas.ch

From FISH to ELEPHANT...

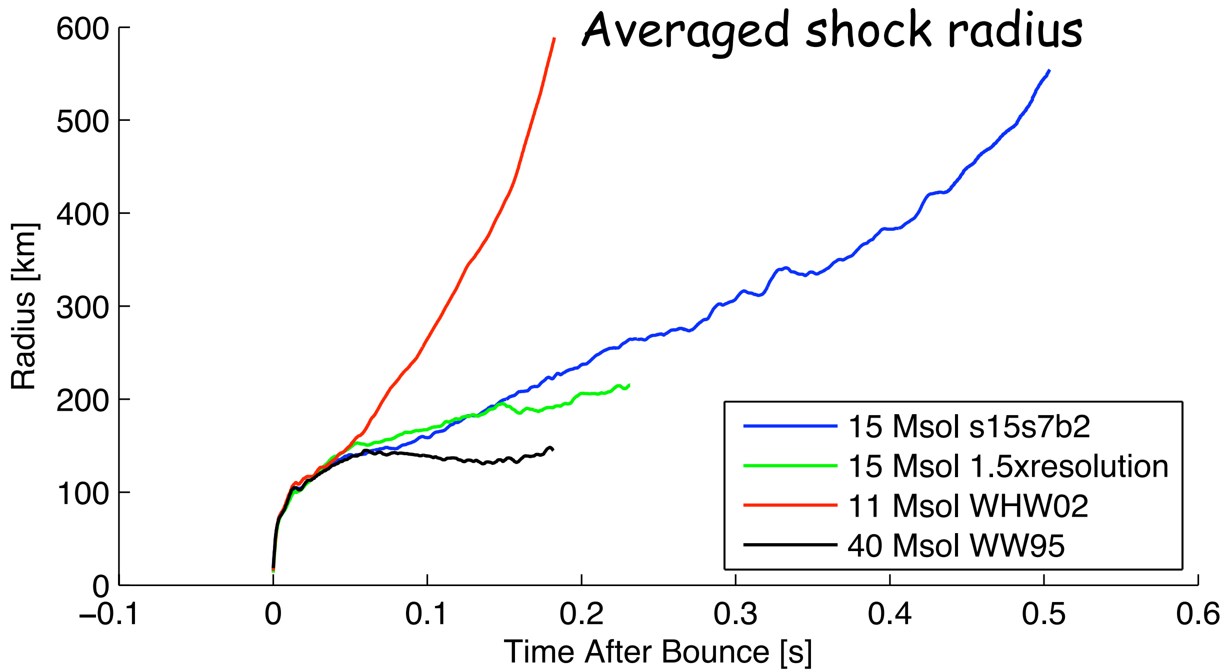
Elegant parallel hydrodynamics with
approximate neutrino transport

- Lattimer-Swesty EoS
- Effective GR potential
- constrained div(B)
- 2nd order TVD
- IDSA for e-flavour ν's
- Leakage for μ/τ ν's



(Whitehouse/Käppeli et al.)

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.

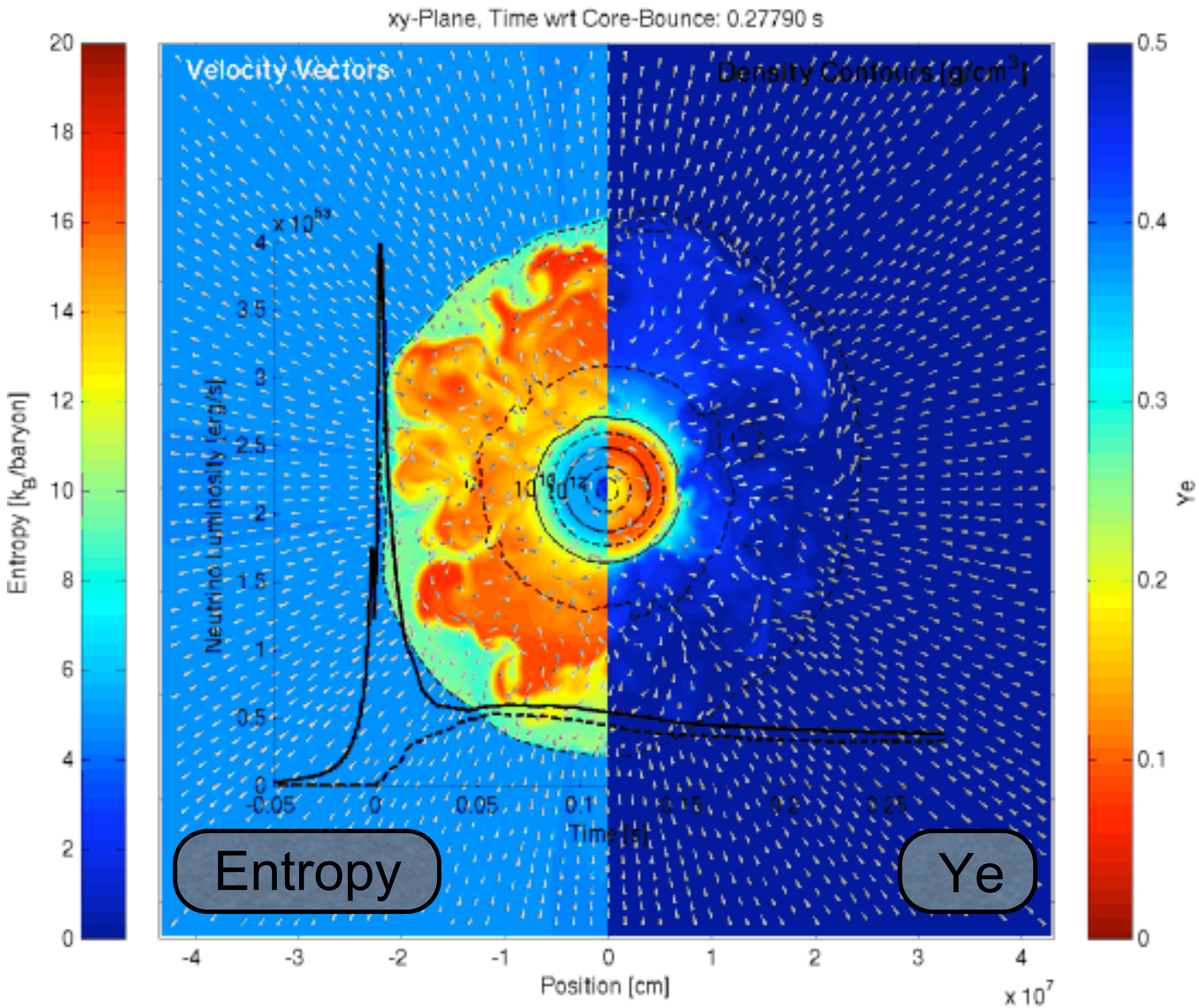
Runs more pessimistic than (Hix et al. 2010) 2D models.

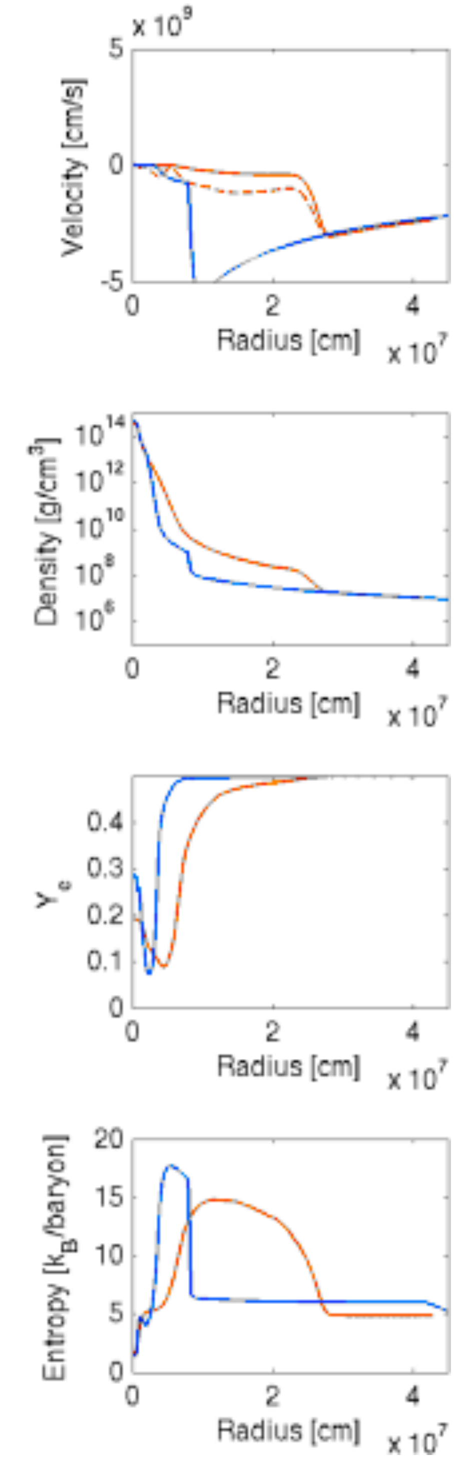
Convergence test: blue run perhaps still too optimistic?

Entropy

Ye

3D Elephant code, PoS(NIC X)243, arXiv:0711.2929, arXiv:0910.2854 (s15s7b2, red profiles -->)





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