Neutrinos in Core Collapse Supernovae

M. Liebendörfer
CITA, University of Toronto

- Part I: Neutrinos in Core collapse

- Intermezzo to bridge 40ms after bounce
  where neutrinos are less important:
  Boltzmann neutrino transport

- Part II: Neutrinos in the Postbounce phase

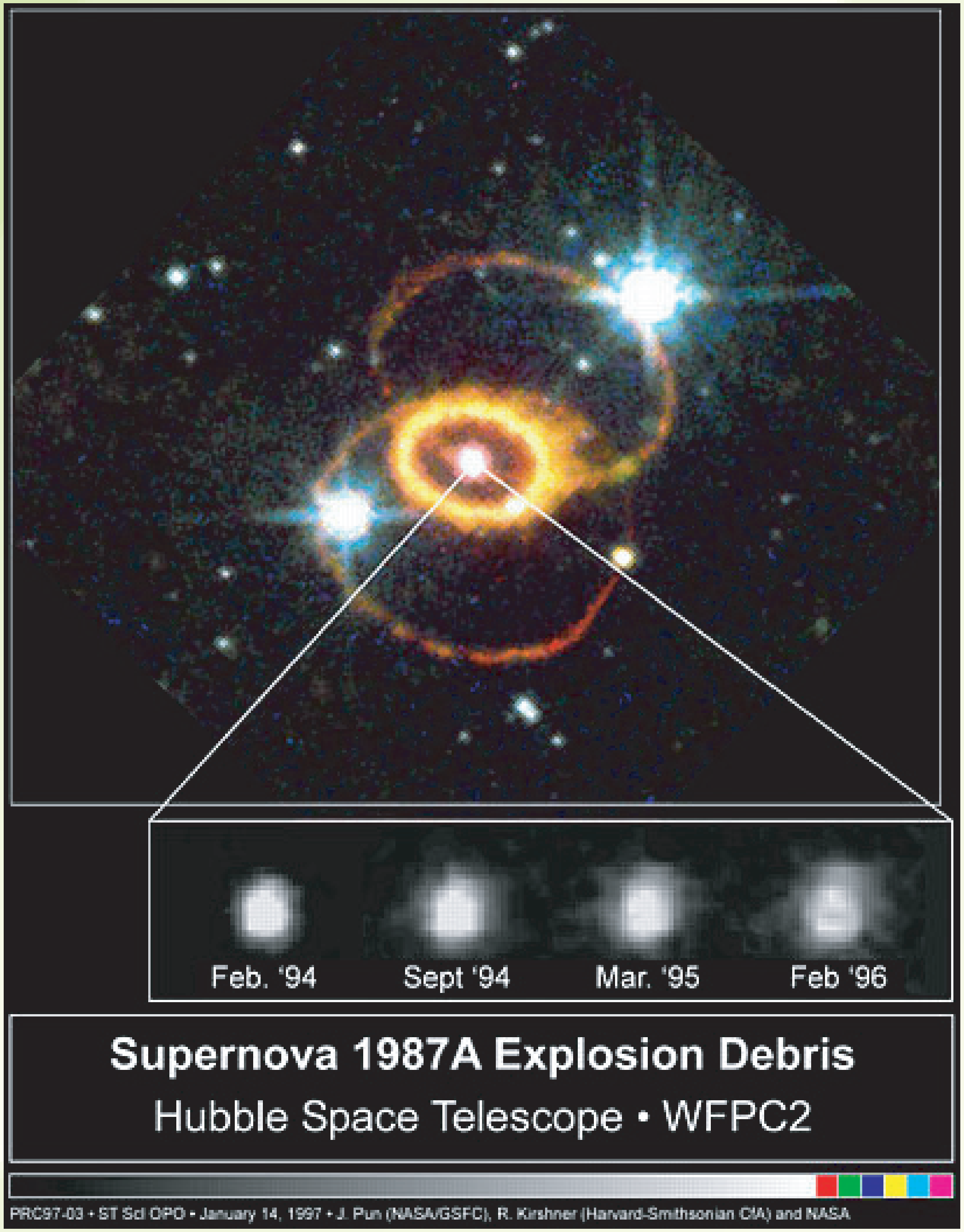
Dubna 2005

Observation of extreme conditions in the universe

Supernovae have been observed for ~1000 years.
Chinese Astron., 1060 a.D.

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

Annihilation of mass-energy by gravitational binding.
Baade, Zwicky, 1934



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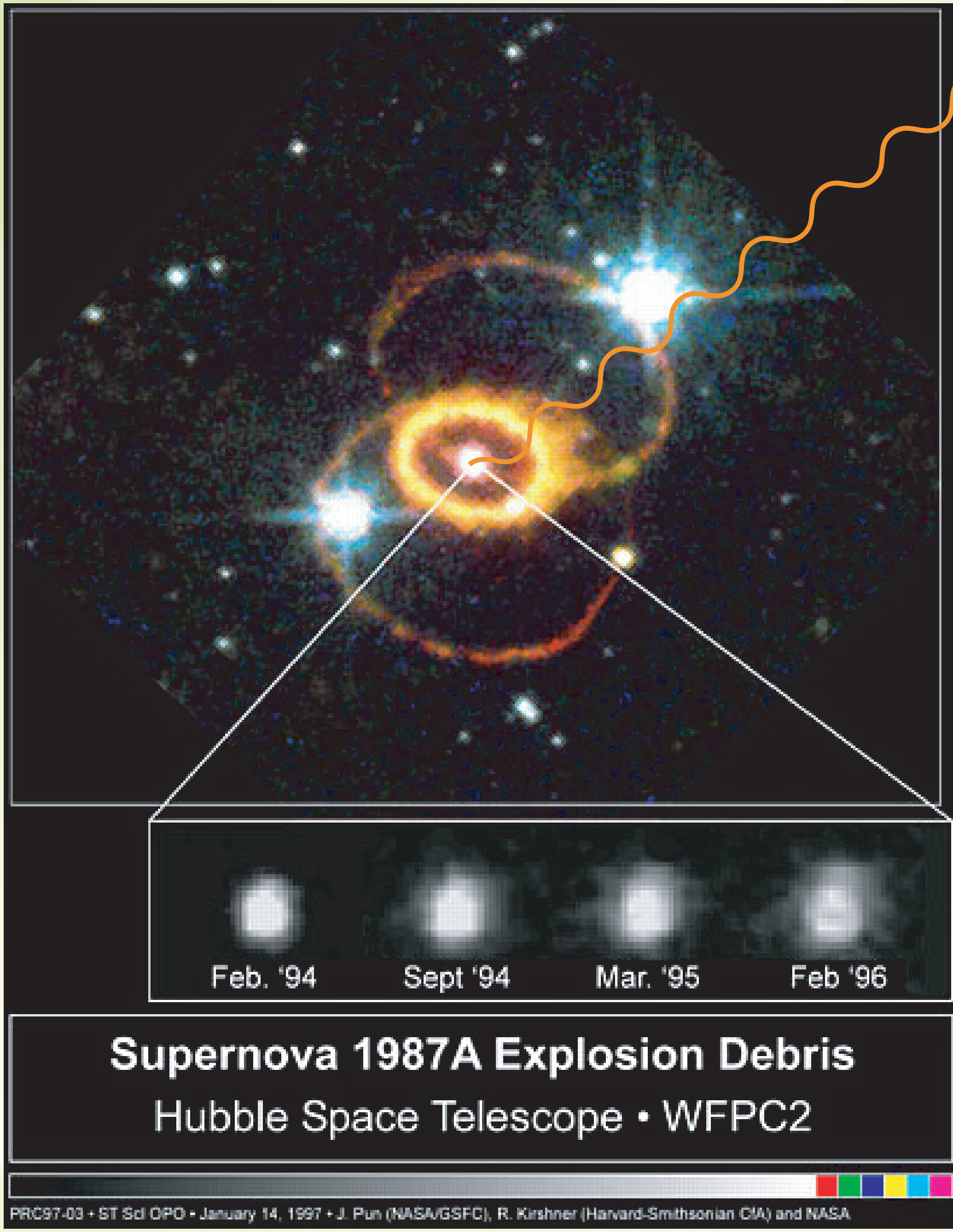
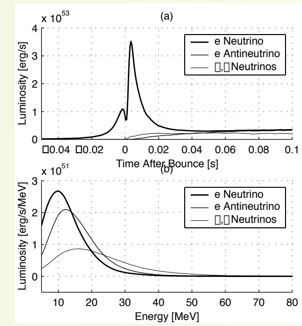


Immediate neutrino signal from innermost region.



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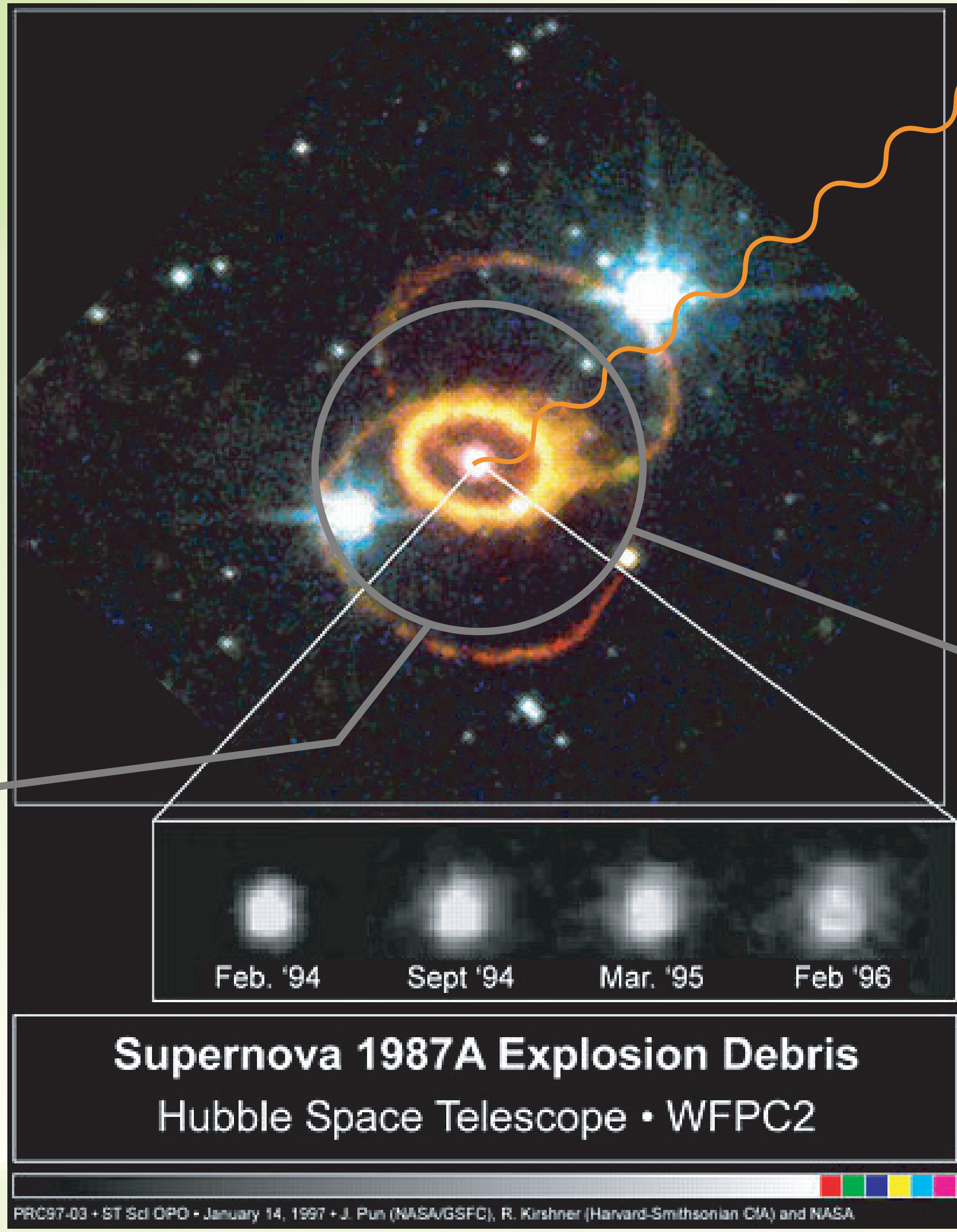

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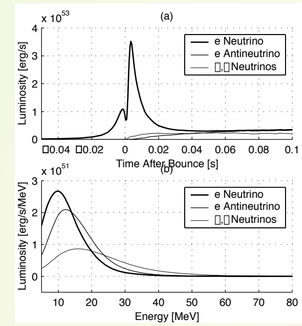

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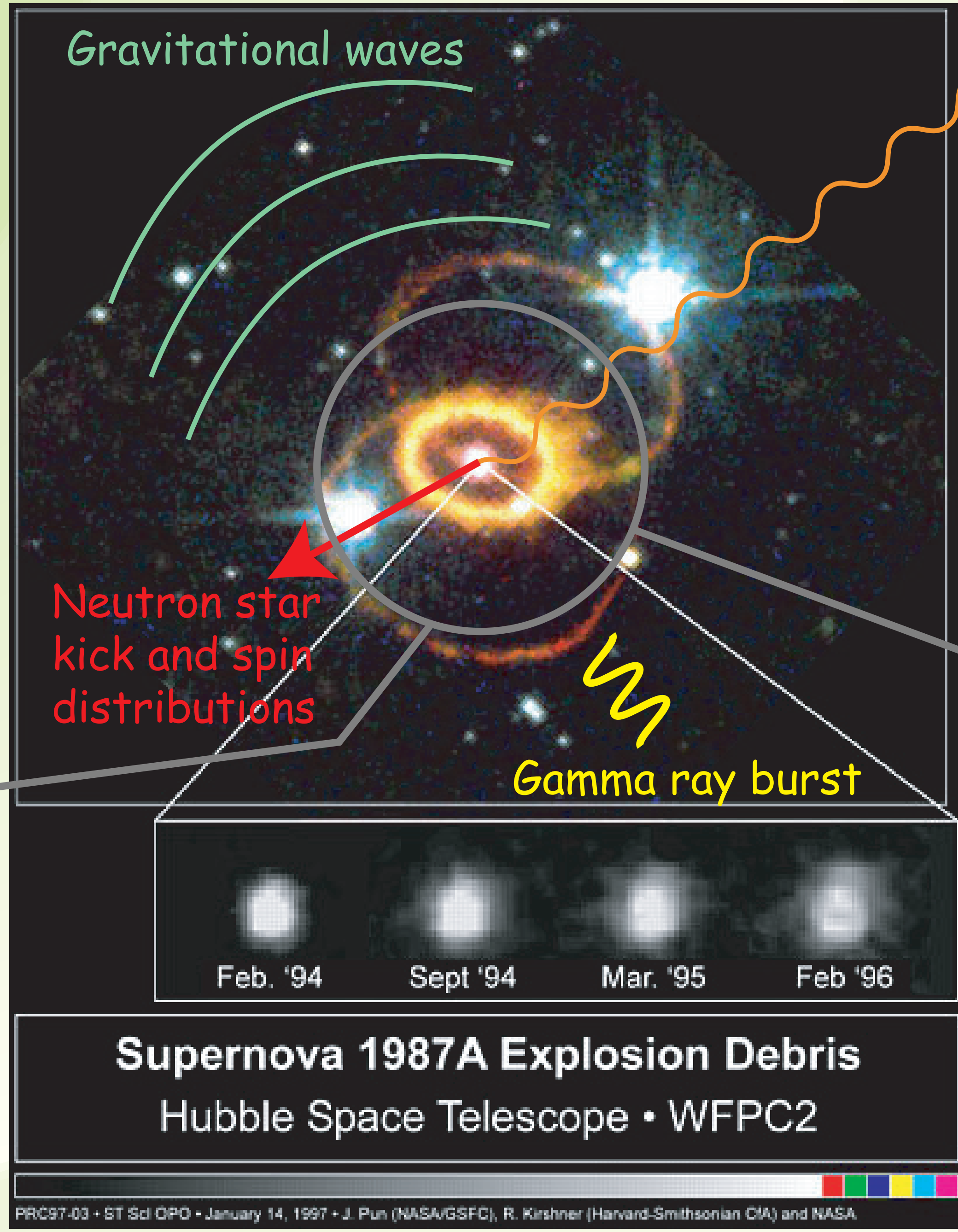

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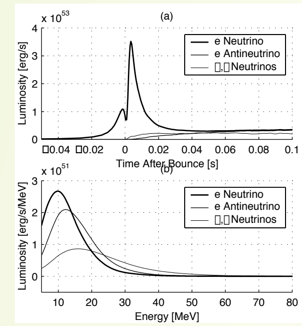

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1 density   2 temperature or entropy   3 electron fraction Ye=np/(np+nn)

For example

(e-) + p <==> n + ve	reduces Ye	reduces entropy
(e+) + n <==> p + vebar	increases Ye	reduces entropy

2 degrees of freedom: weak equilibrium & thermal balance

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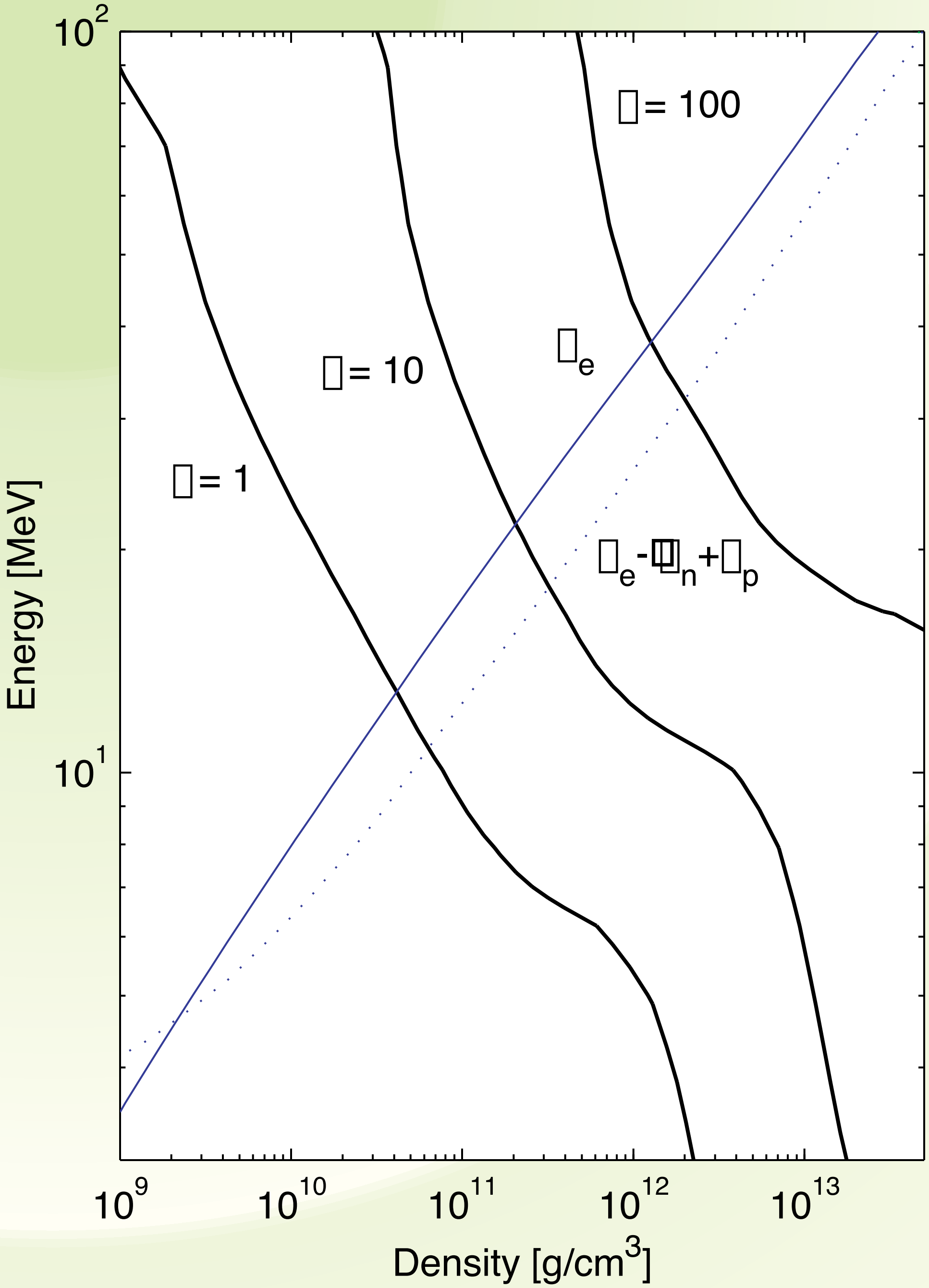
(c) They are responsible for the explosion in the v-driven mechanism (distorted view! - actually they are responsible for the failure:

- without neutrinos, Chandrasekhar mass ~ Ye^2 ~ 1.2 solar Masses
- homologous collapse, bounce, dissociation & explosion!)

Regions of semi-transparent neutrino transport



Bethe 1990:

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

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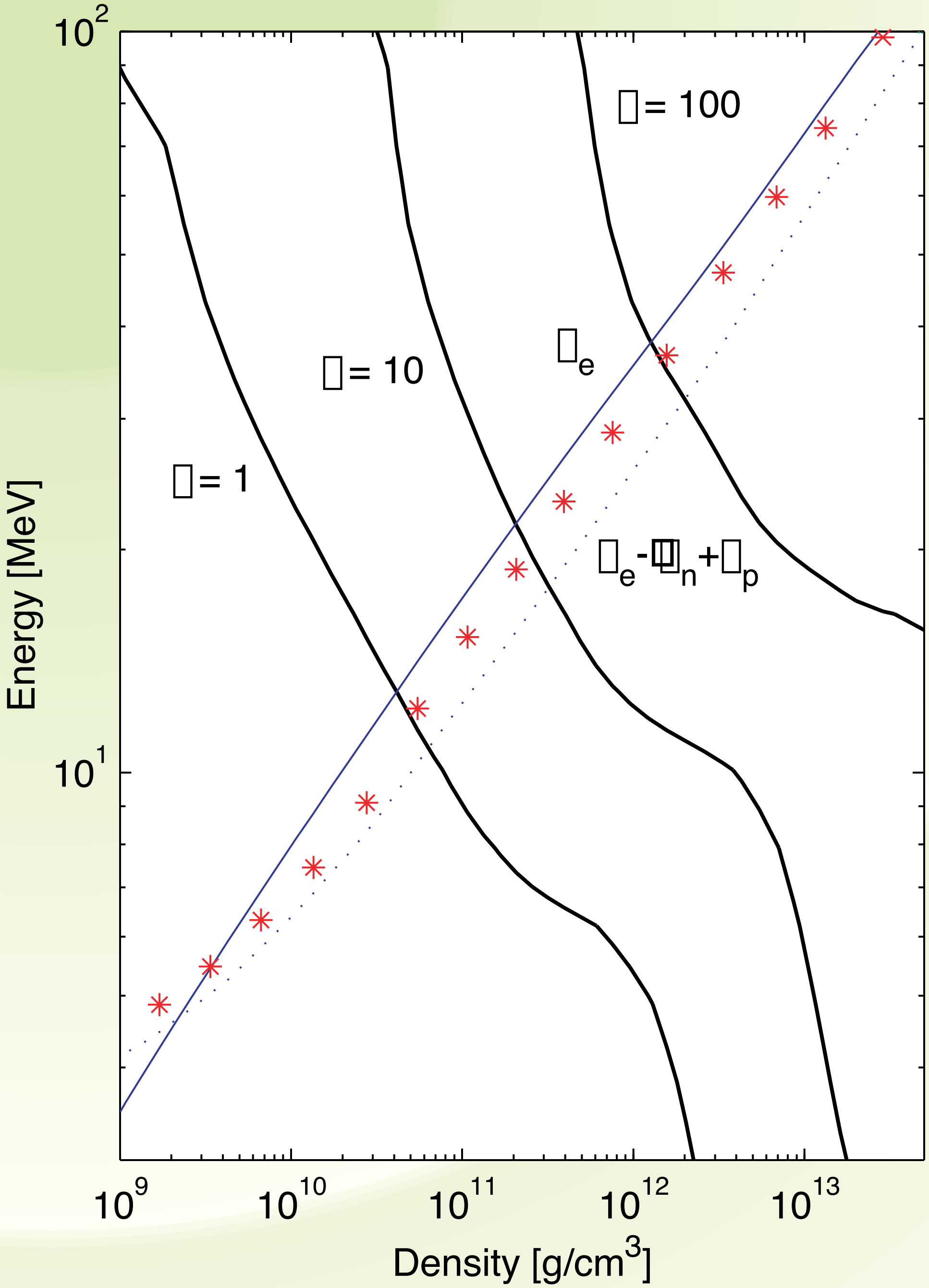

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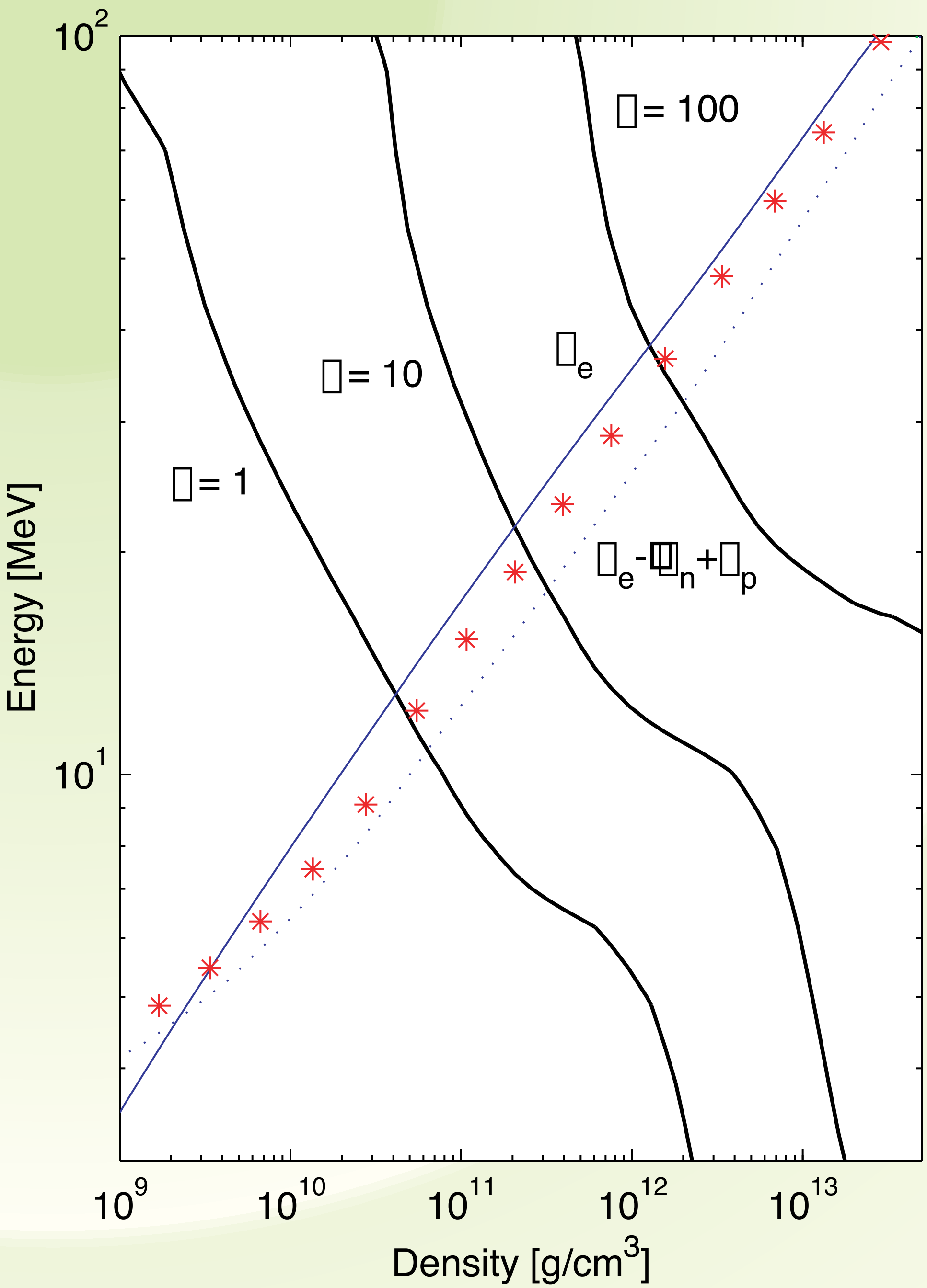

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~ 4pi/3 (170 km)^3

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& instable!

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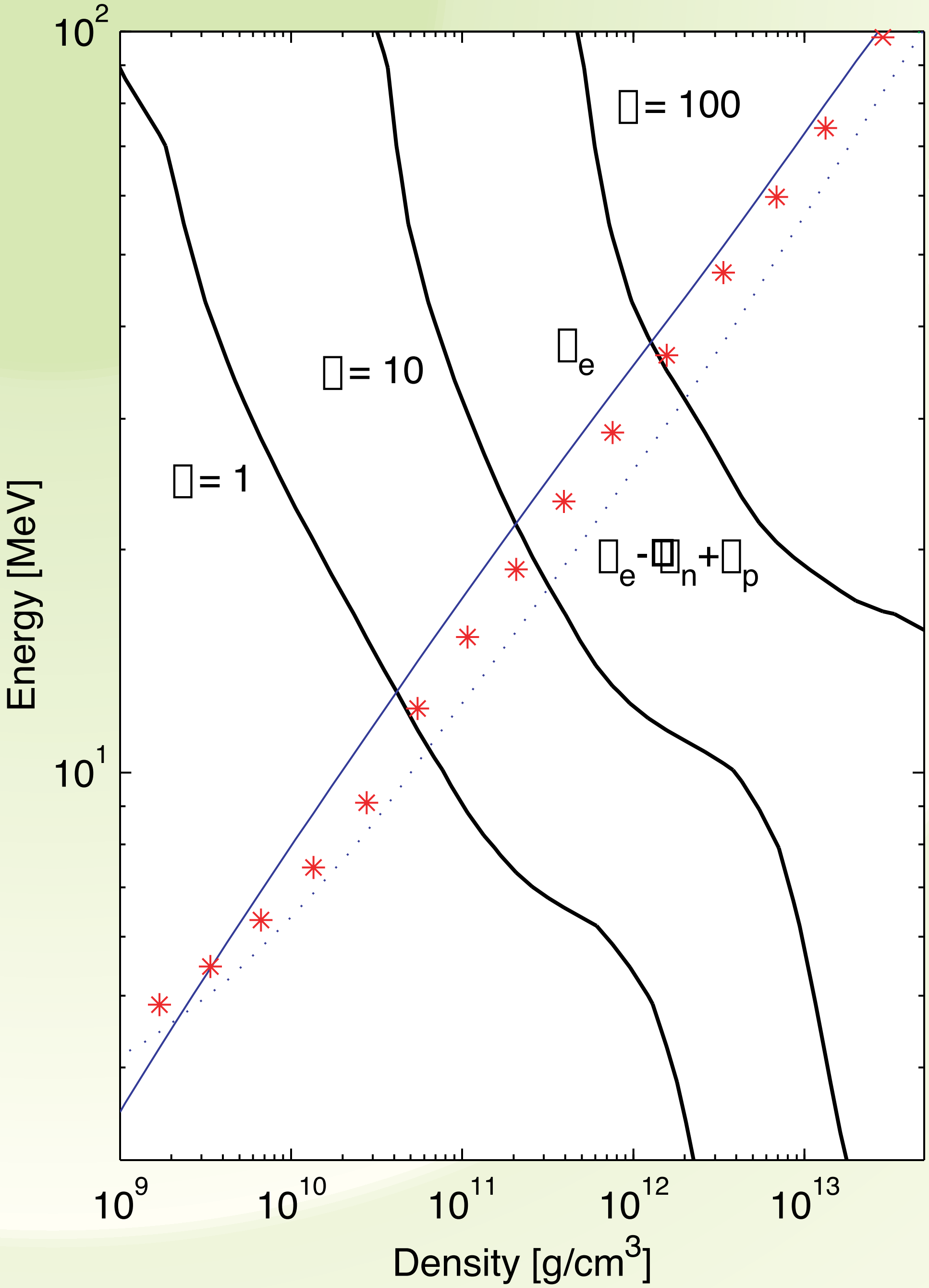

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time scale:

1/sqrt(G*10^11 g/cm^3)
~ 12 ms

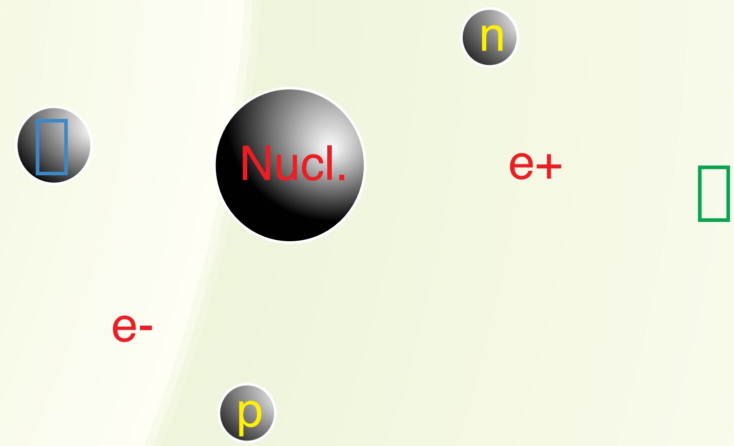
fast!

--> relativistic effects

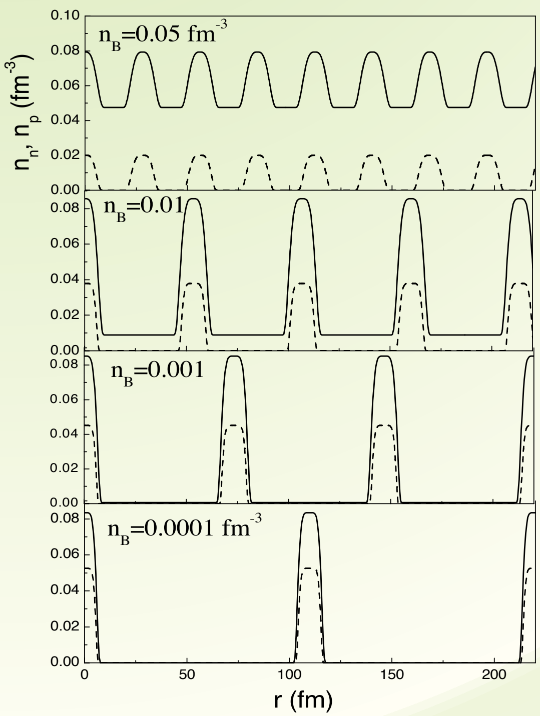
The Equation of State

Lattimer & Swesty equation of state (1991)
for hot dense matter, with

- representative nucleus in NSE
- free alpha particles
- free neutrons and protons
- electrons, positrons and photons



relativistic Brückner-Hartree-Fock



(from Shen, PRC65, 2002)

Compressible liquid drop model,
parametrized by

- bulk incompressibility
- bulk and surface symmetry energies
- symmetric matter surface tension
- nucleon effective mass

with phase transition to uniform nuclear matter

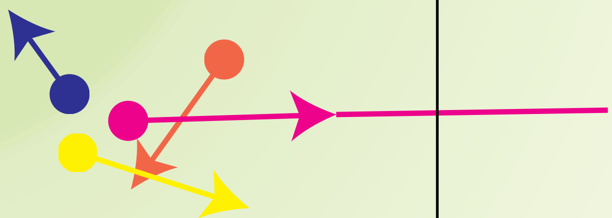
Bruenn, ApJS 58, 1985
Raffelt (2001)

Neutrino Interactions

Description:

Number Sphere

Emission & Absorption



Can be Pauli-blocked in diffusive regime

High matter density

Low matter density

Type Energy Direction

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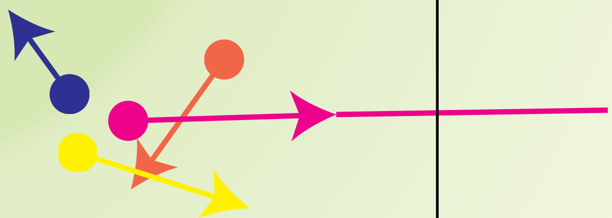

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Type   Energy   Direction

Neutrino absorption on nucleons

$$\nu_e + n \rightleftharpoons e^- + p$$
$$\bar{\nu}_e + p \rightleftharpoons e^+ + n$$

Neutrino absorption on nuclei

$$\nu_e + (A,Z) \rightleftharpoons e^- + (A, Z+1)$$

Neutrino production from pair annihilation

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

Nucleon-Nucleon bremsstrahlung (Thompson et al. 2002)

Electron-□ pair annihilation --> muon-□ pair creation (Buras et al. 2003)

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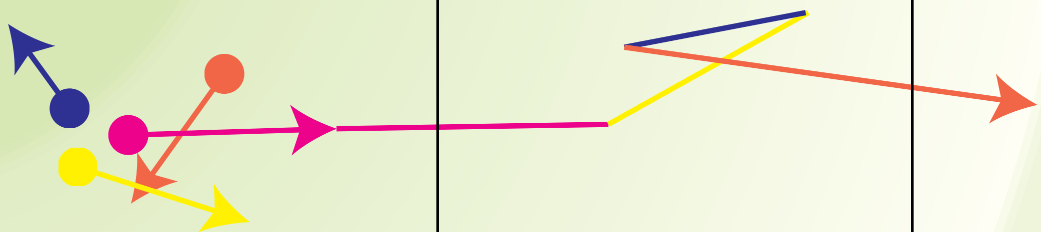
Emission & Absorption

Inelastic Scattering



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Probability enhanced by isoenergetic scattering

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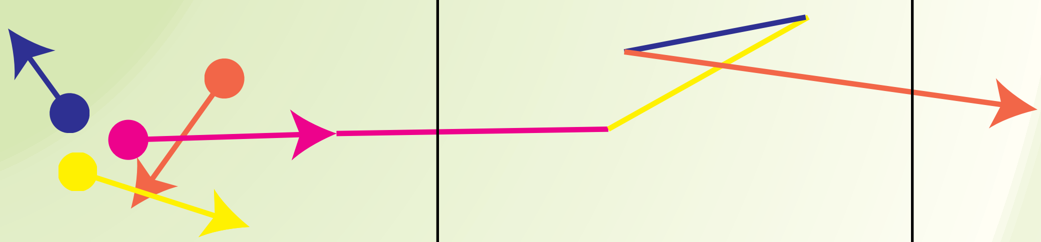

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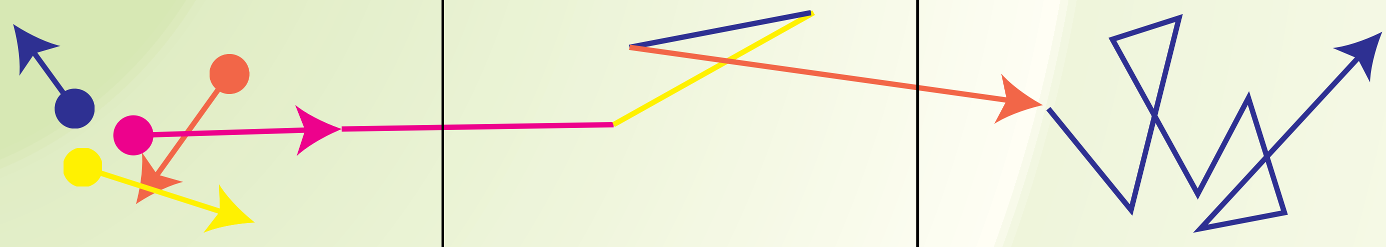

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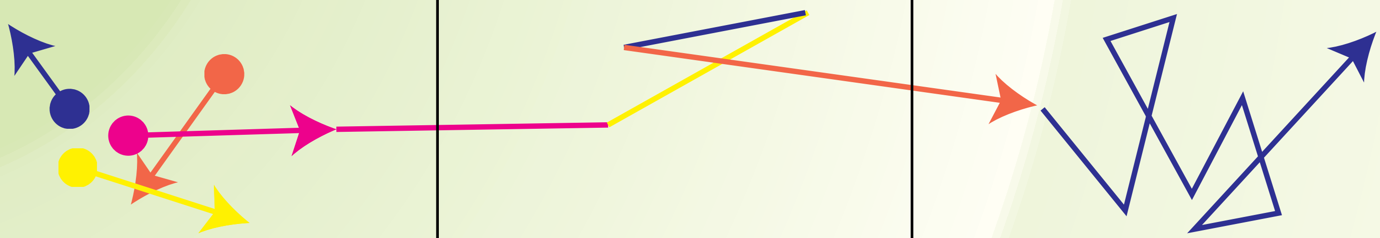
Emission & Absorption | **Inelastic Scattering** | **Isoenergetic Scattering**



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Inelastic neutrino-nucleus scattering

Inelastic coherent scattering of neutrinos on nuclei

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Stellar evolution

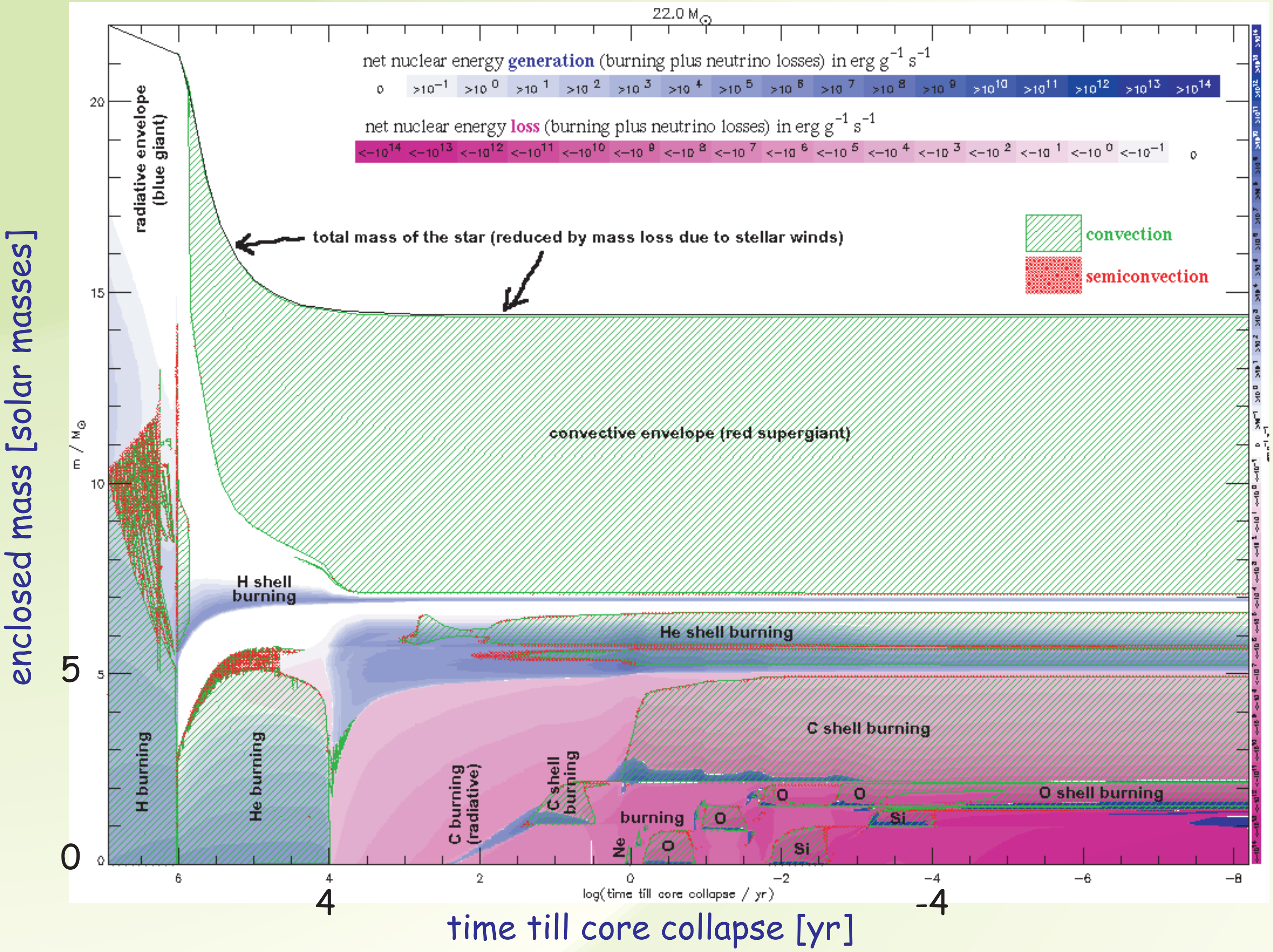

FIG. 6 Energy history of a 22 M star as a function of time till core collapse. The y-axis defines the included mass from the center. Hydrogen and helium core and shell burning are major energy sources. In the later burning stages, following oxygen core burning, neutrino losses related to weak processes in the stellar interior become increasingly important and can dominate over the nuclear energy production. Convection plays an important role in the envelope outside the helium burning shell, but also in shells during oxygen and silicon burning (from Heger and Woosley, 2001).

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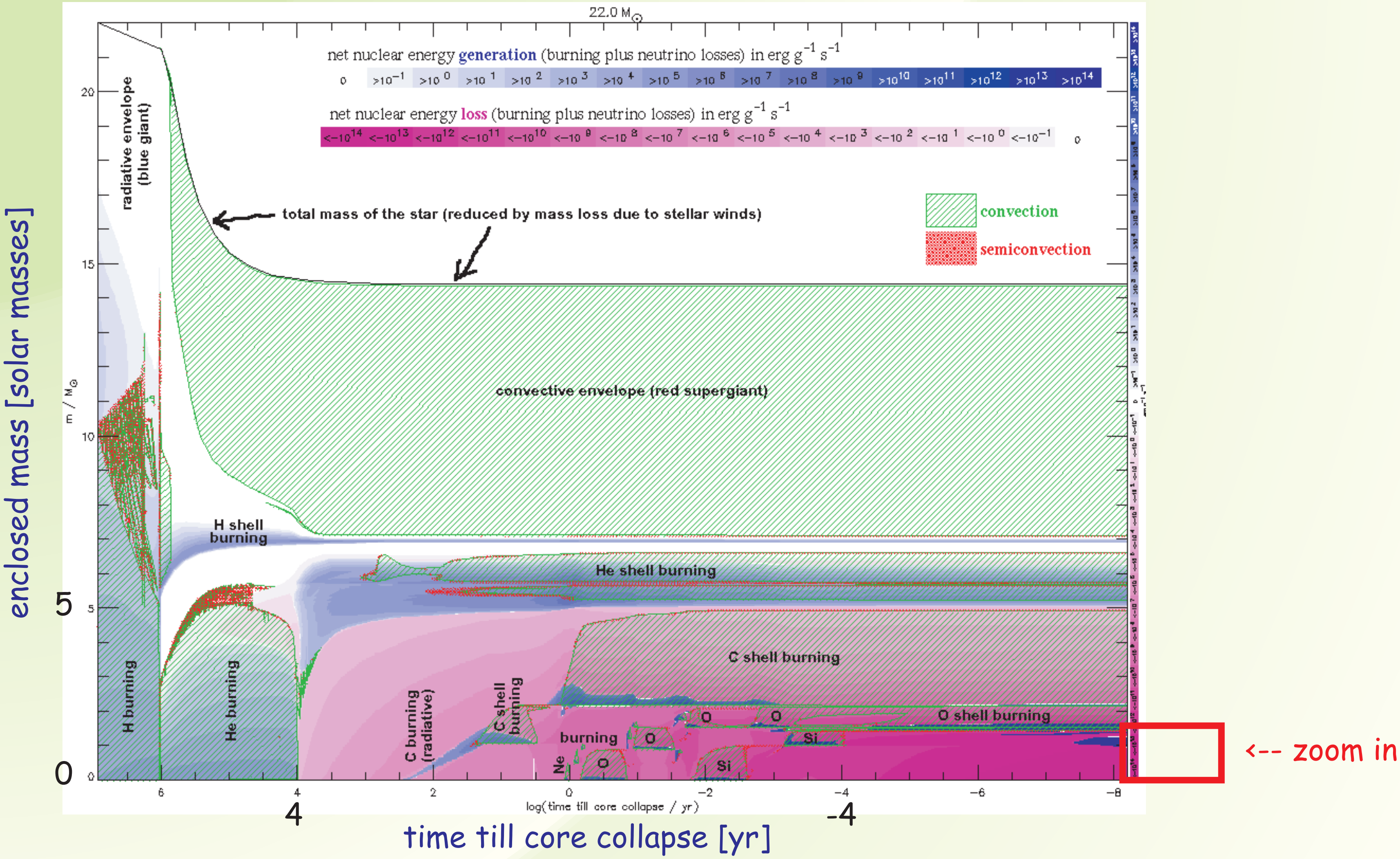

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Core collapse

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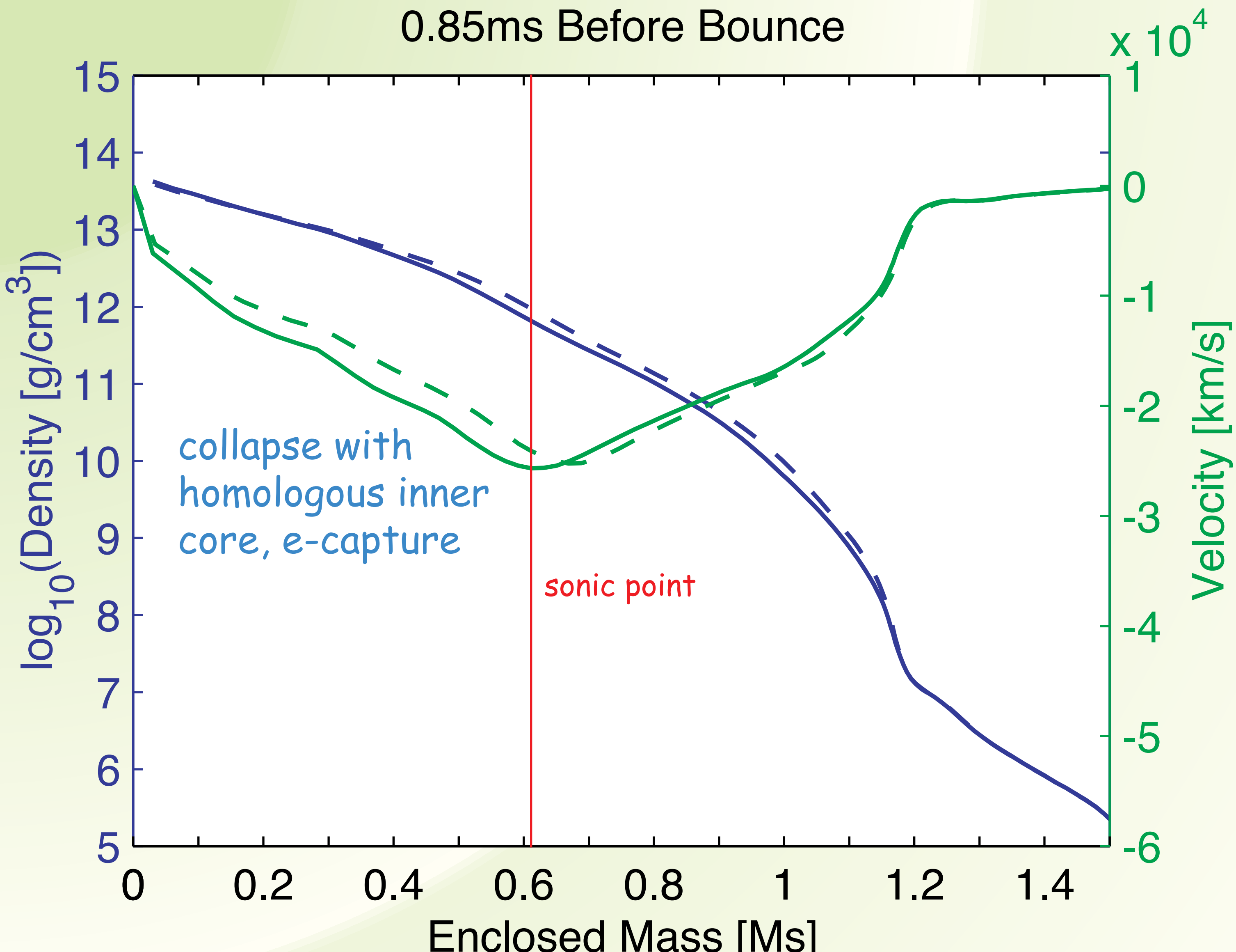

dashed = Newtonian
solid = general relativistic

Core collapse

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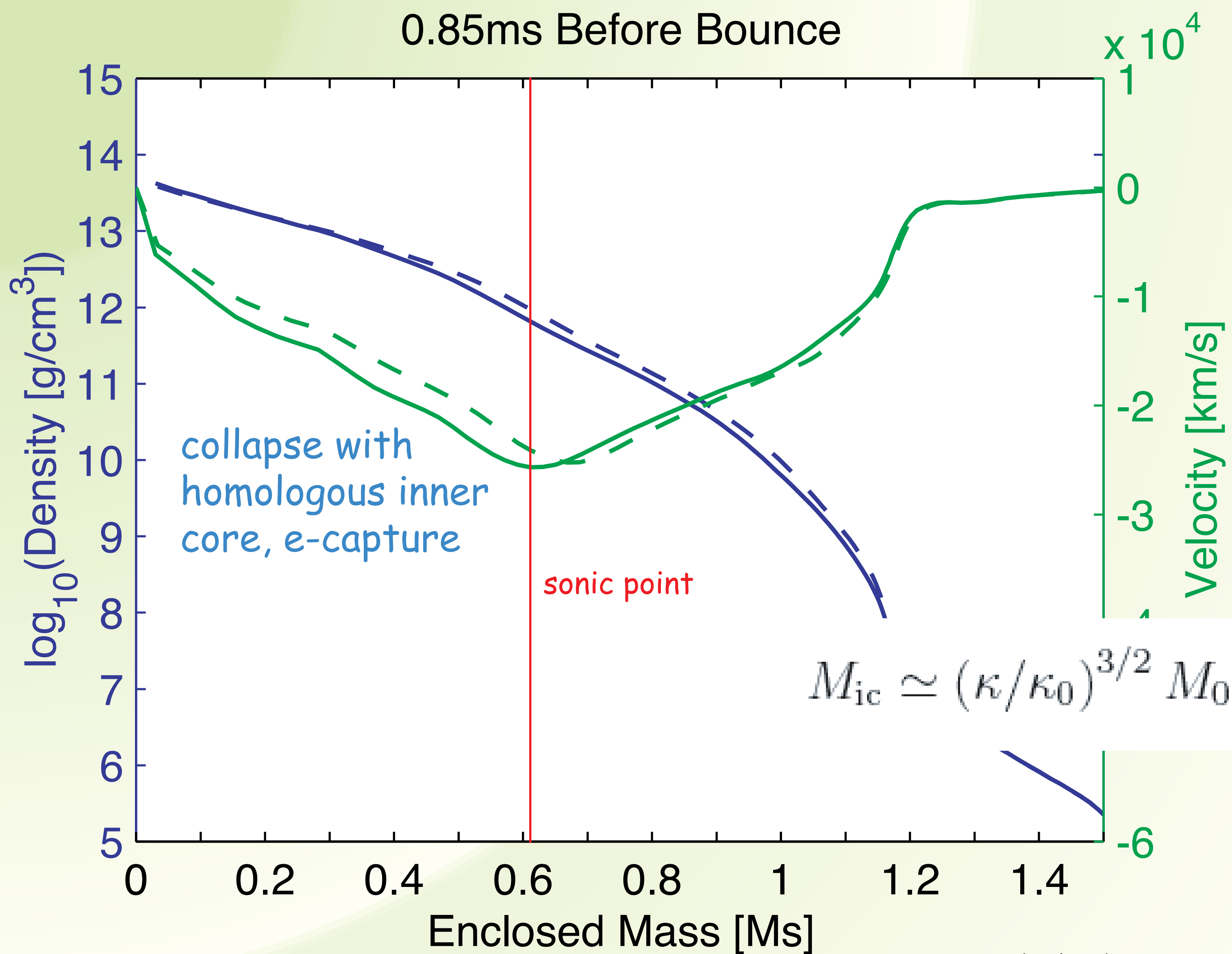

$$M_{\rm ic} \simeq (\kappa/\kappa_0)^{3/2}\, M_0,$$

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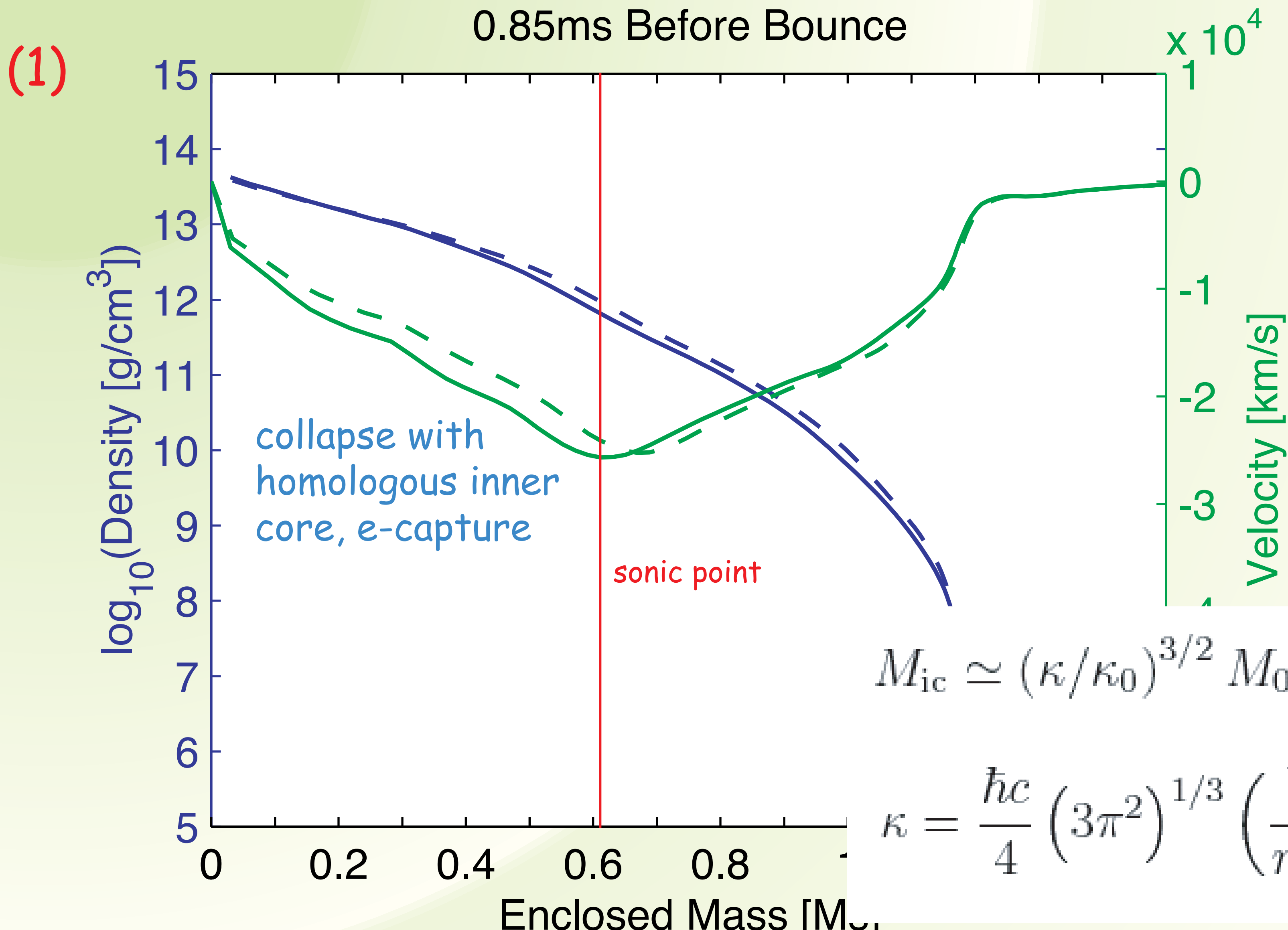
Core collapse



$$M_{\rm ic} \simeq (\kappa/\kappa_0)^{3/2}\, M_0,$$

$$\kappa = \frac{\hbar c}{4}\left(3\pi^2\right)^{1/3}\left(\frac{Y_e}{m_B}\right)^{4/3},$$

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Core collapse

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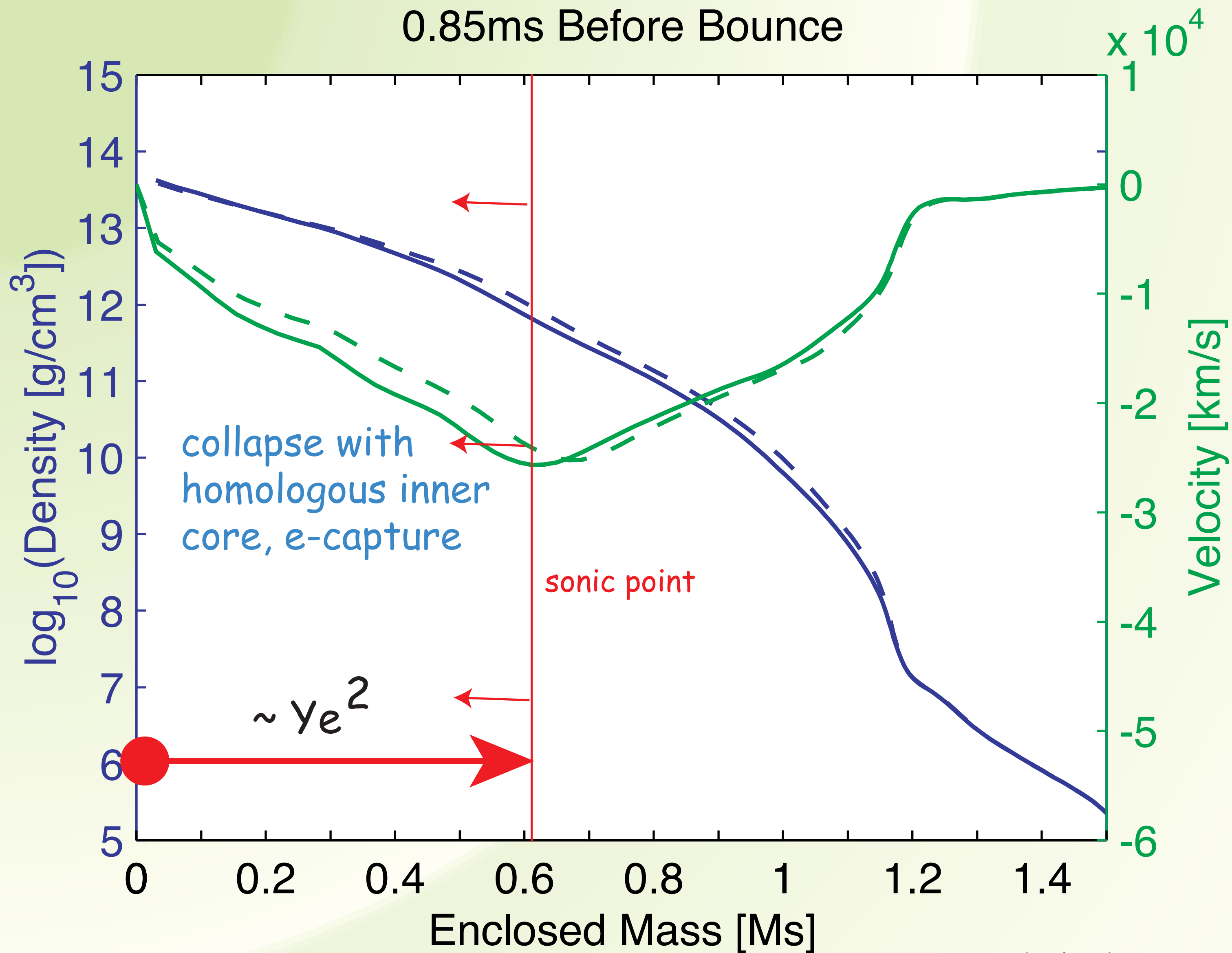

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Bounce

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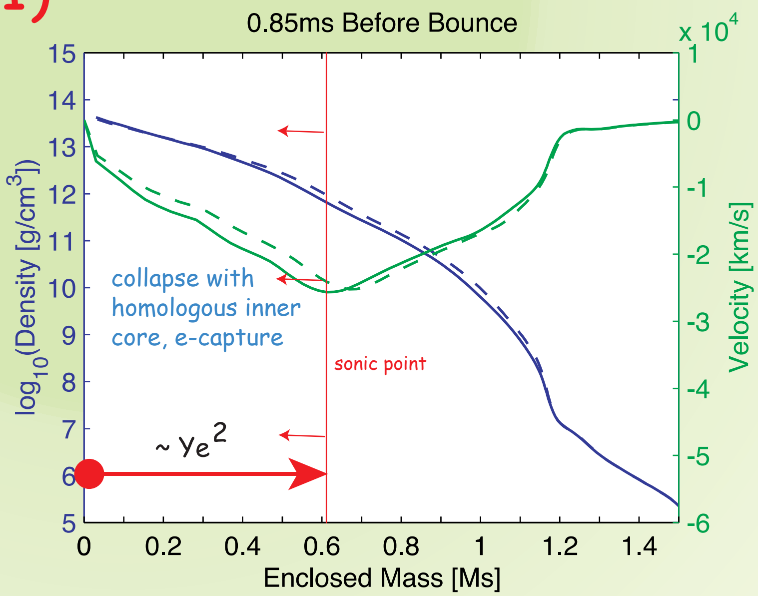

(2)

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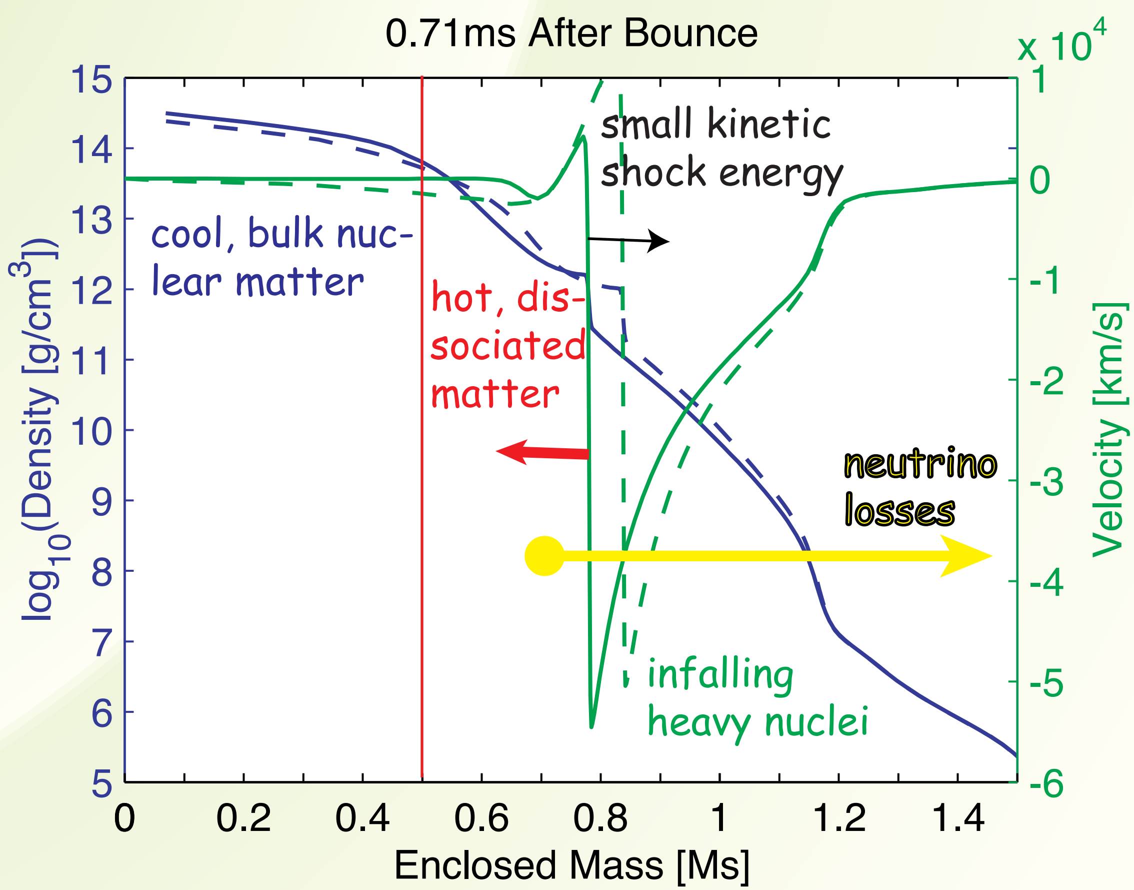
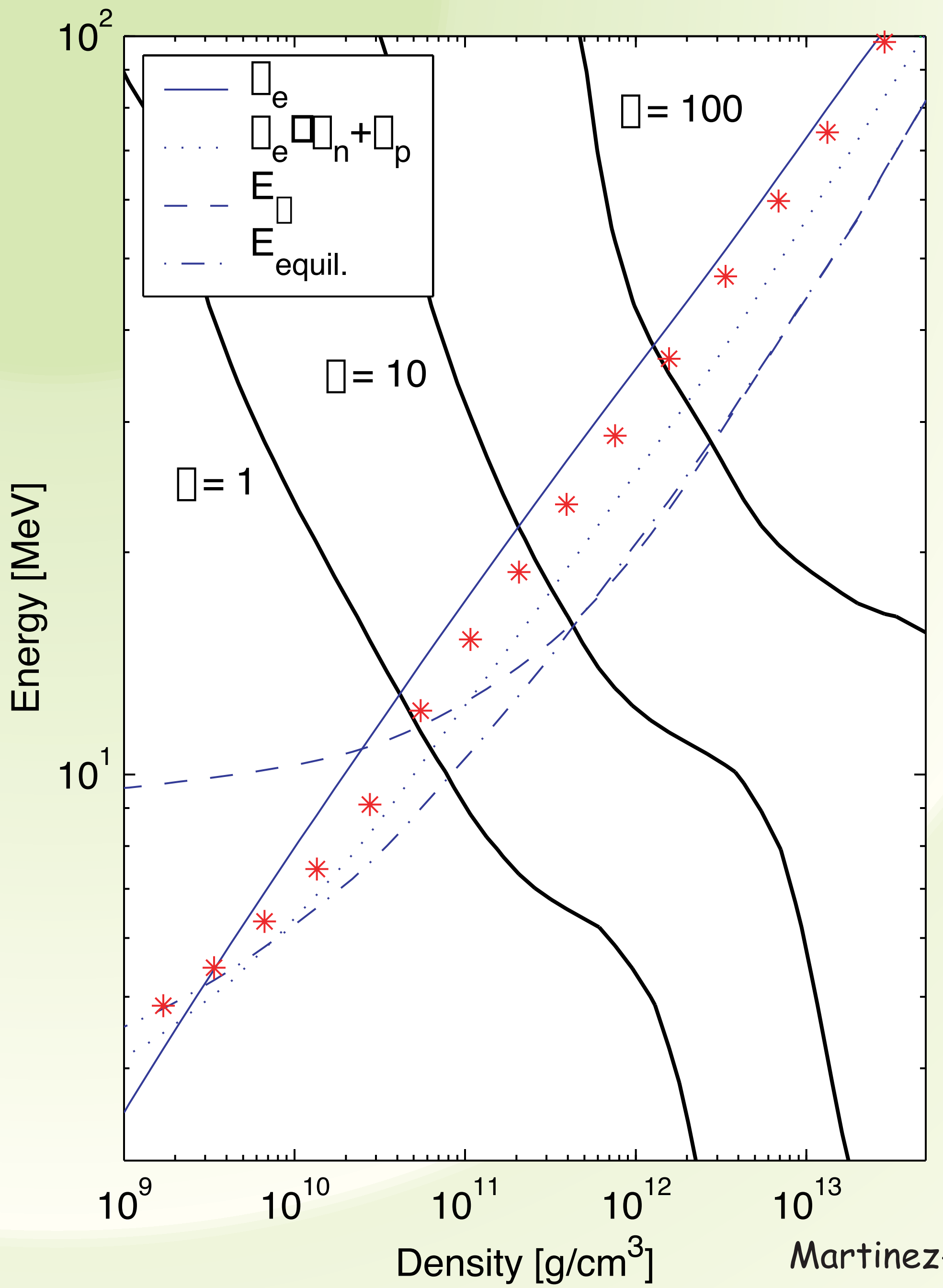


- Bounce at nuclear density
- Dynamic bounce-shock
- Dissociation of infalling material costs ~10^51 erg per 0.1 Ms
- Neutrino losses from ~5ms after bounce on
- Conversion to accretion shock

Neutrino escape from core collapse



Martinez-Pinedo et al., astro-ph/0412091

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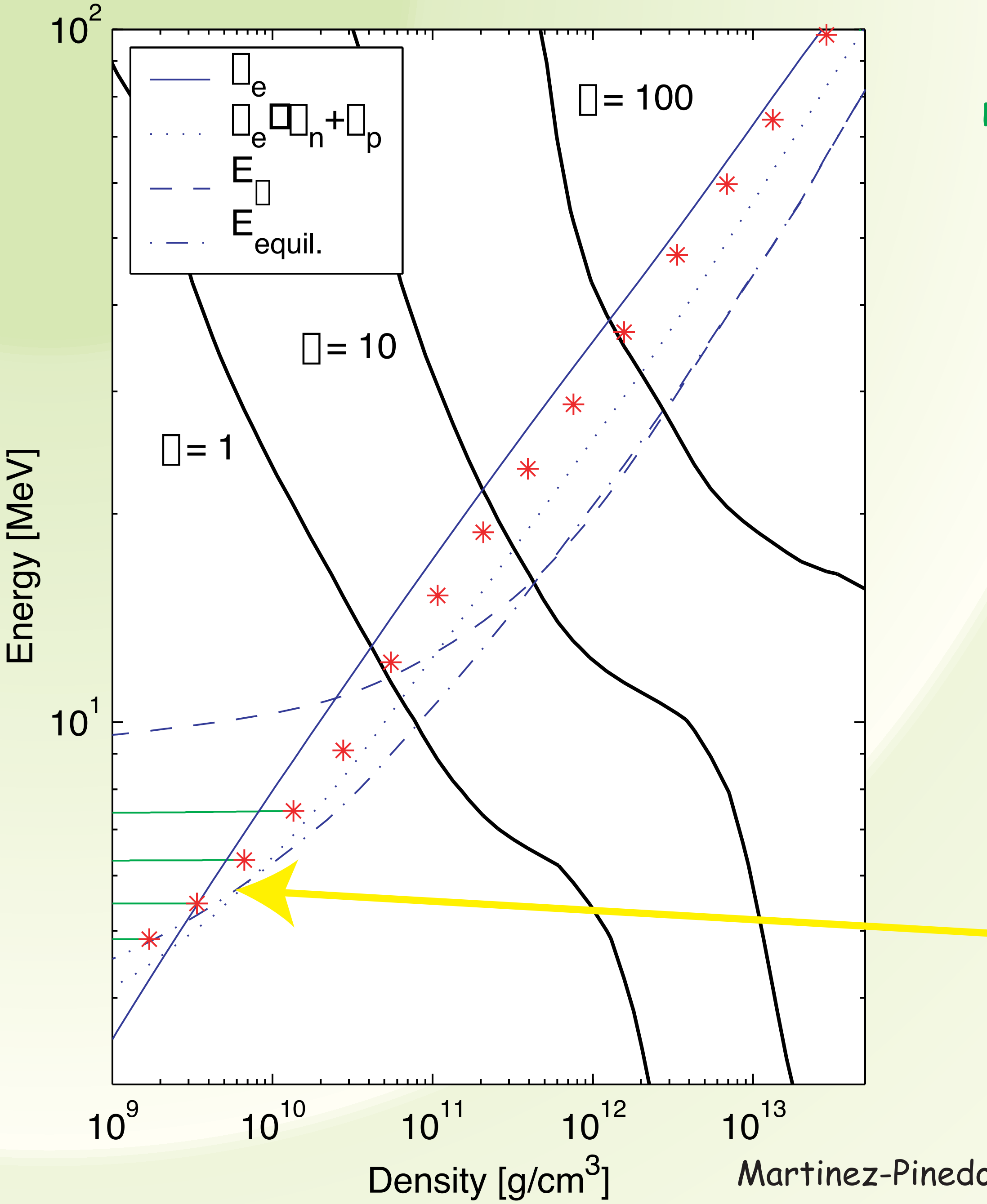

neutrinos are:

free streaming

productions rate is relevant

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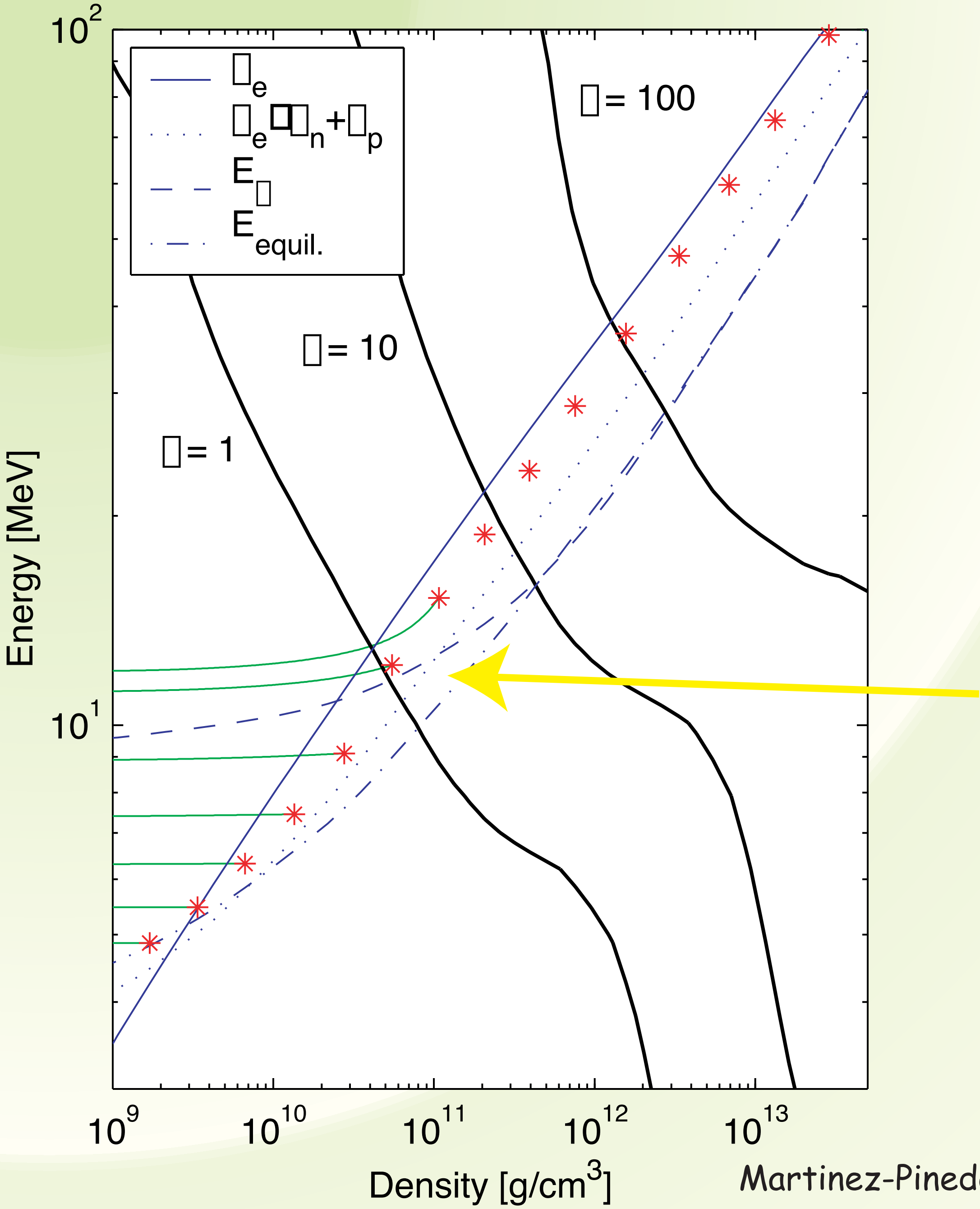

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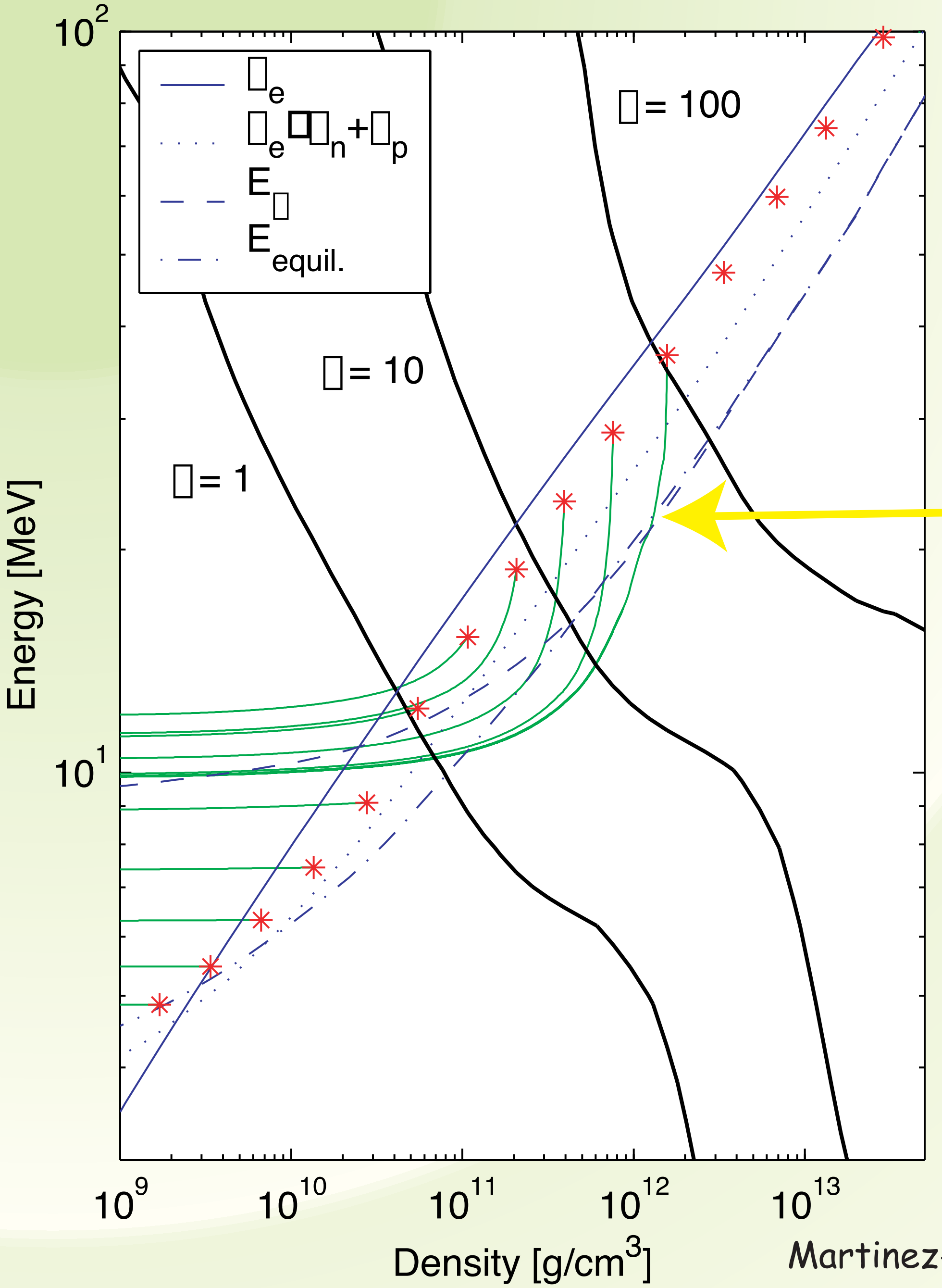

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thermalizing
thermalization time scale is relevant

diffusing
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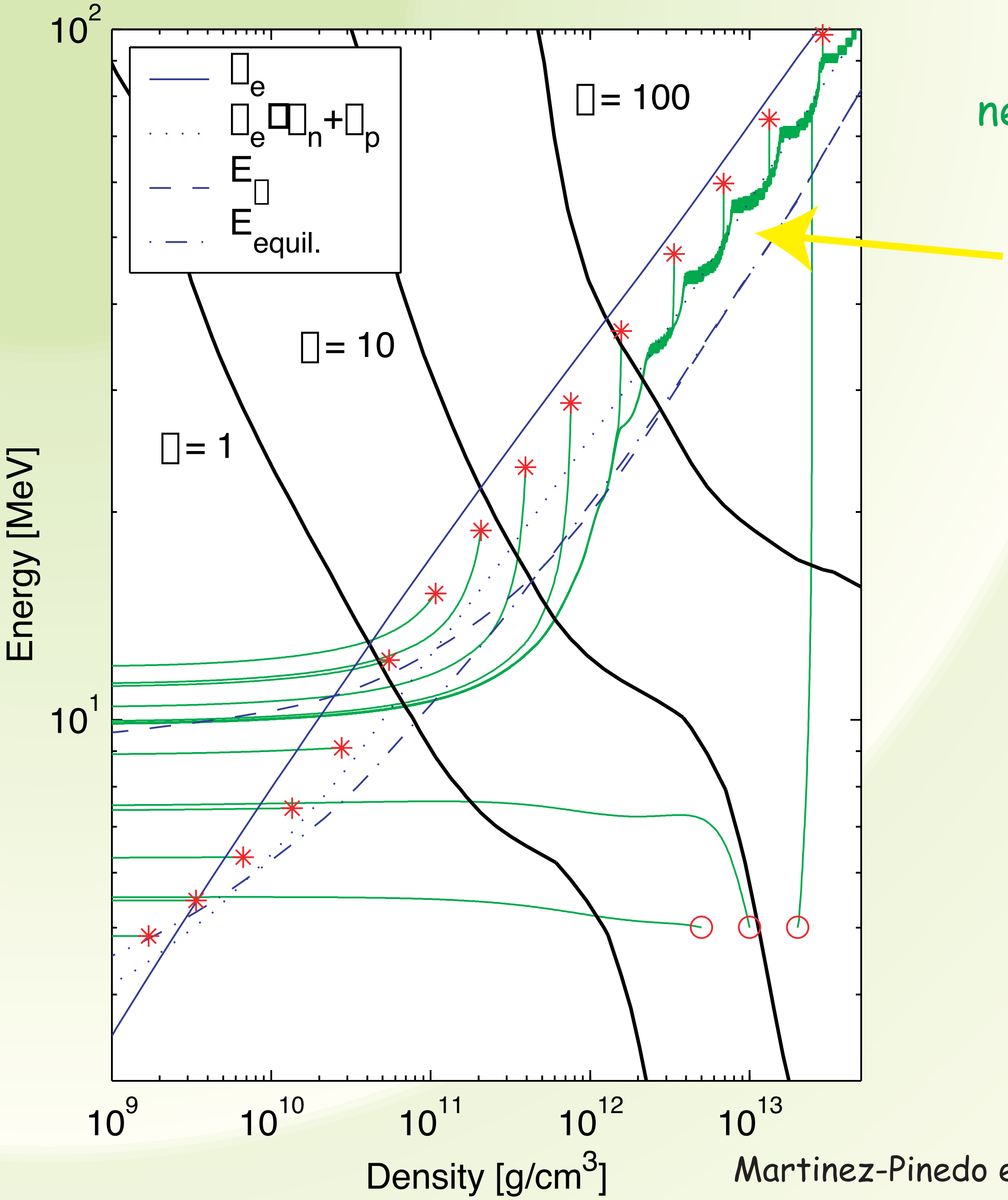

neutrinos are:

trapped and degenerate
Fermi surface is relevant

thermalizing
thermalization time scale
is relevant

diffusing
opacities and neutrino energies
are relevant

free streaming
productions rate is relevant

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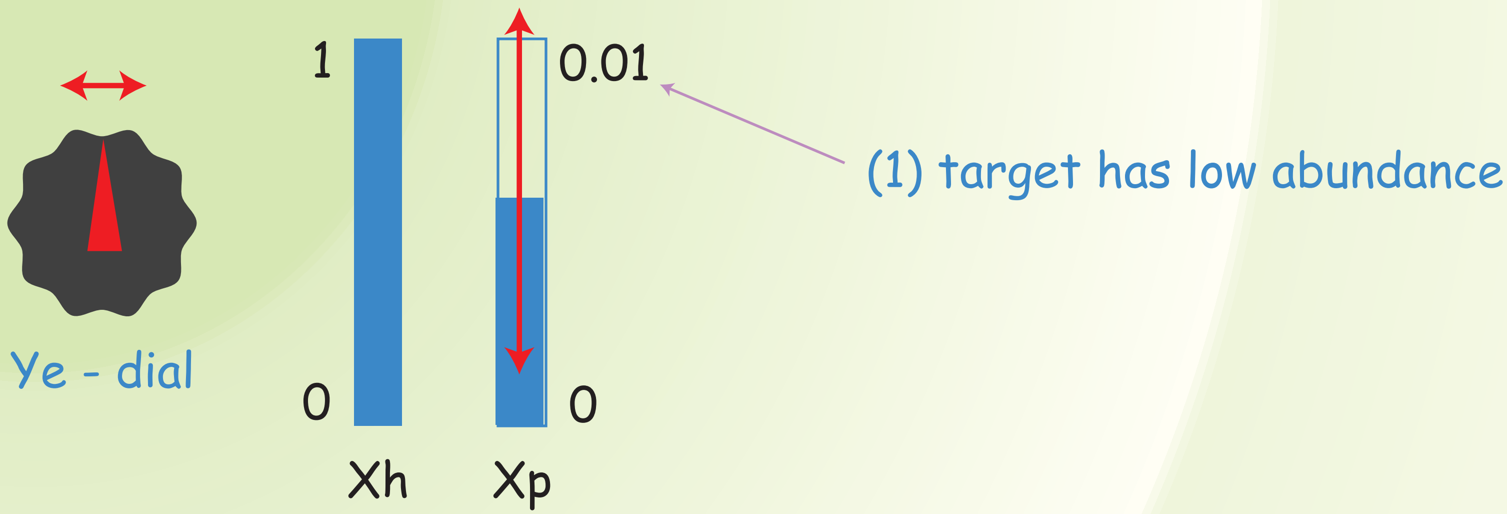
Electron Capture in Core Collapse



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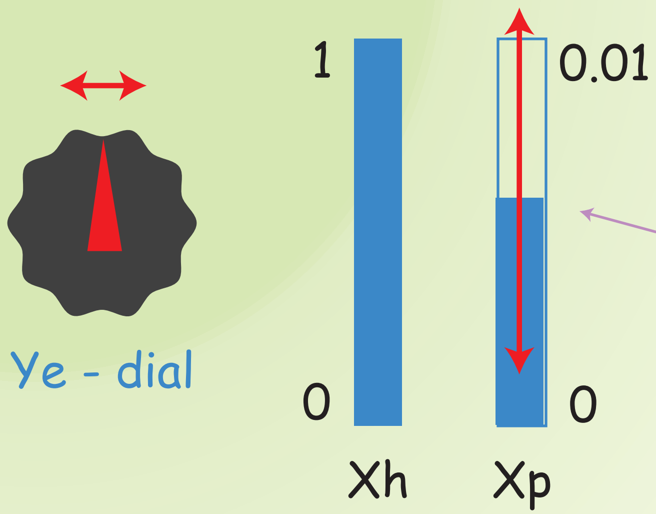

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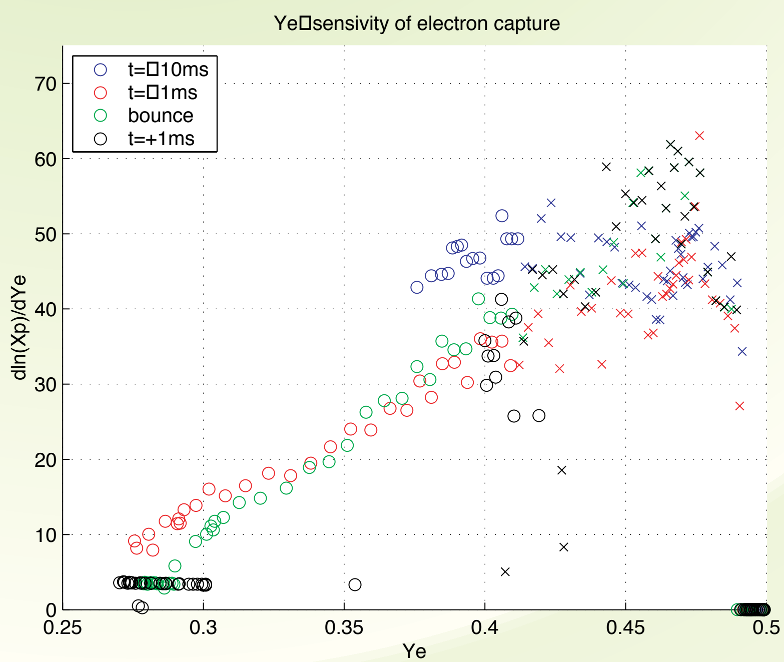
(2) abundance is sensitive to Ye



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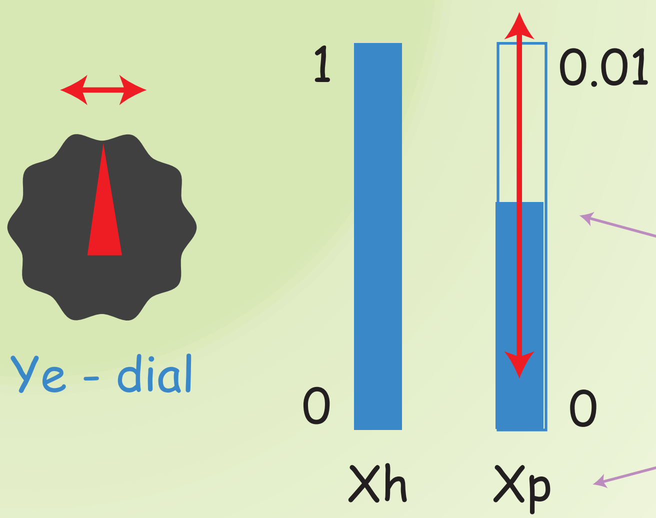
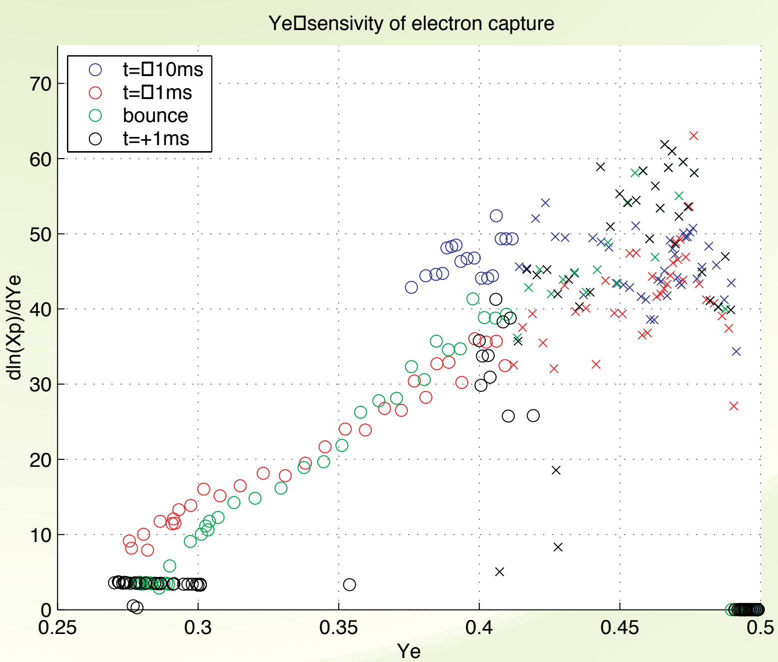


Messer et al. 200X

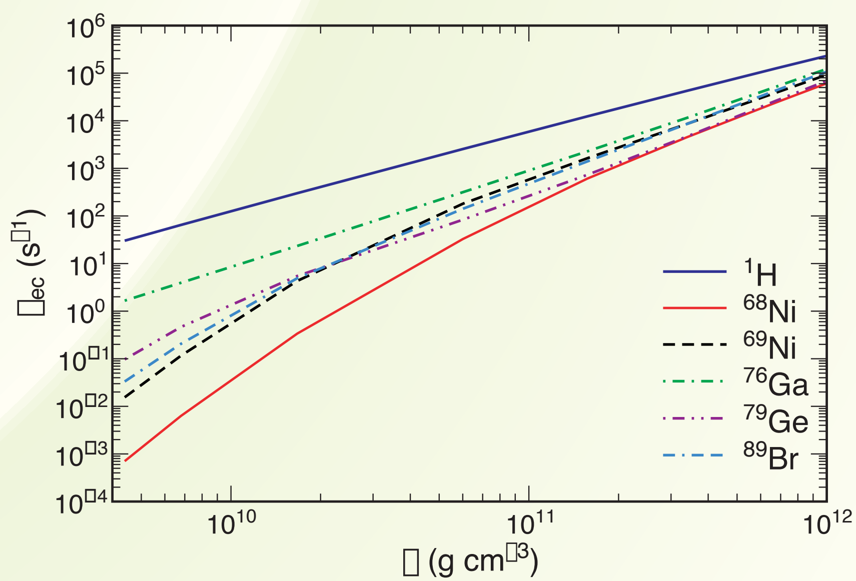
(1) target has low abundance

(2) abundance is sensitive to Ye

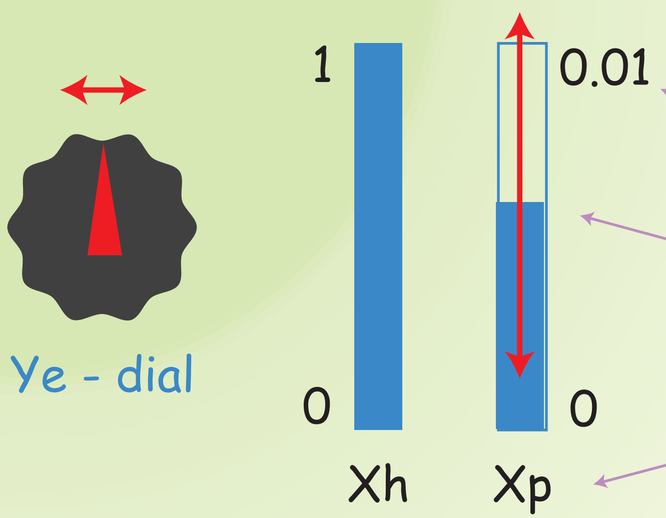
(3) the reaction dominates



Martinez-Pinedo et al. 2004



Electron Capture in Core Collapse



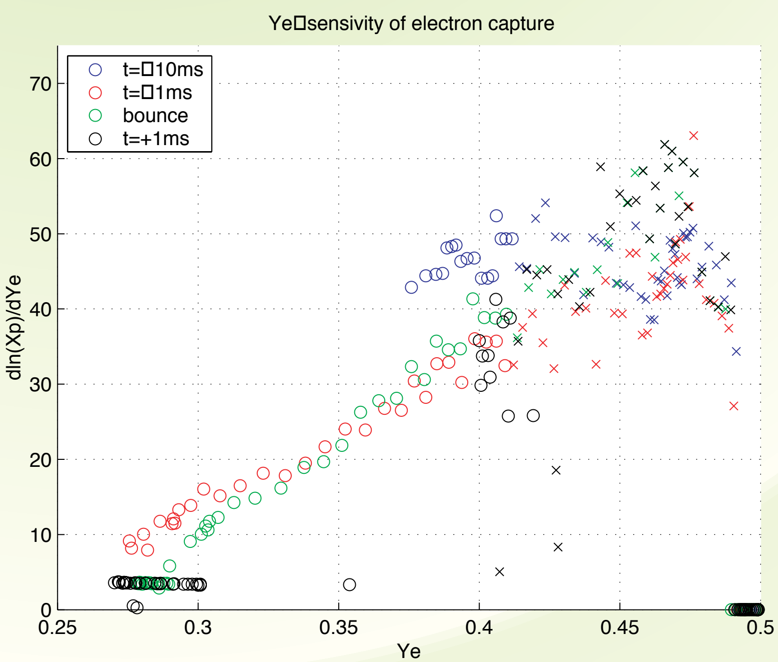
Convergence of Ye and sonic point if:

Messer et al. 200X

(1) target has low abundance

(2) abundance is sensitive to Ye

(3) the reaction dominates



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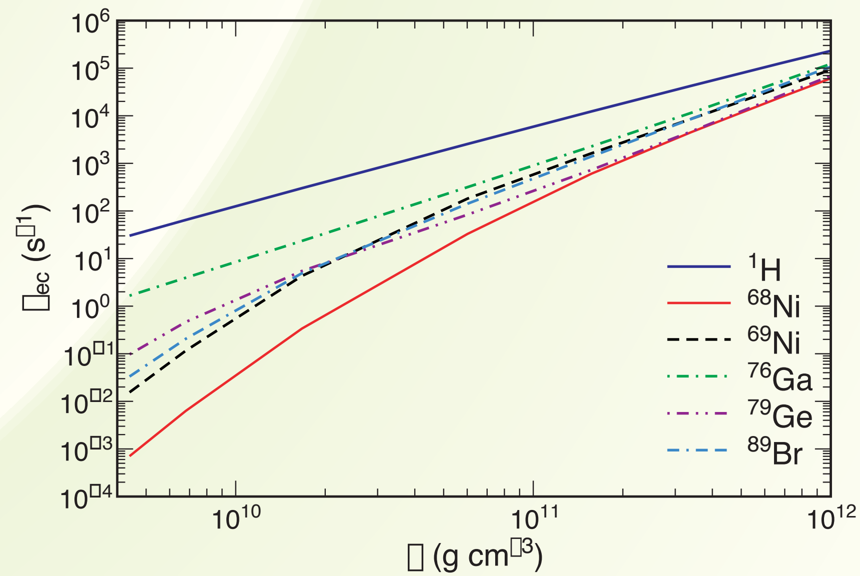


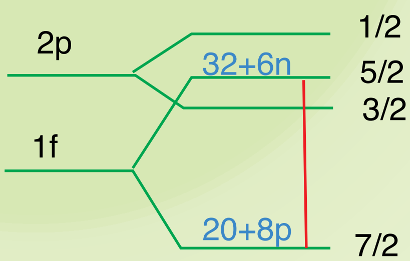
high Ye -> large Xp -> increased e-capture

low Ye -> negligible Xp -> slowed e-capture

=> norm Ye-trajectory during collapse

Input Physics Improvements

Old standard e capture rates:
(independent particle model)



New improved e capture rates
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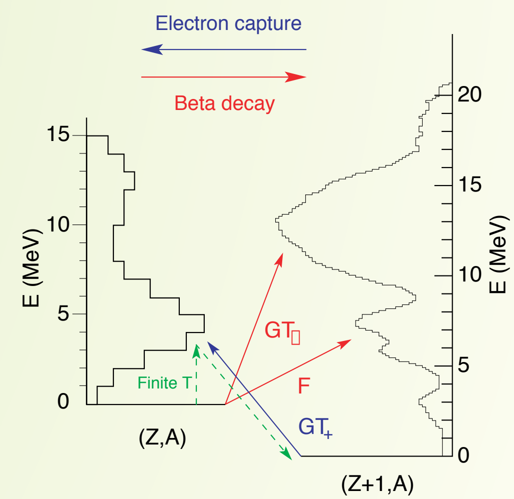

Langanke & Martinez-Pinedo, 2002

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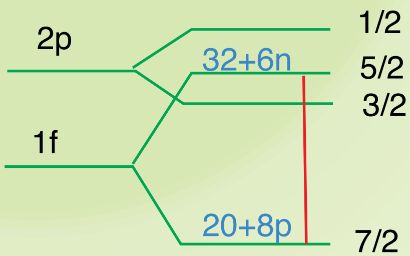
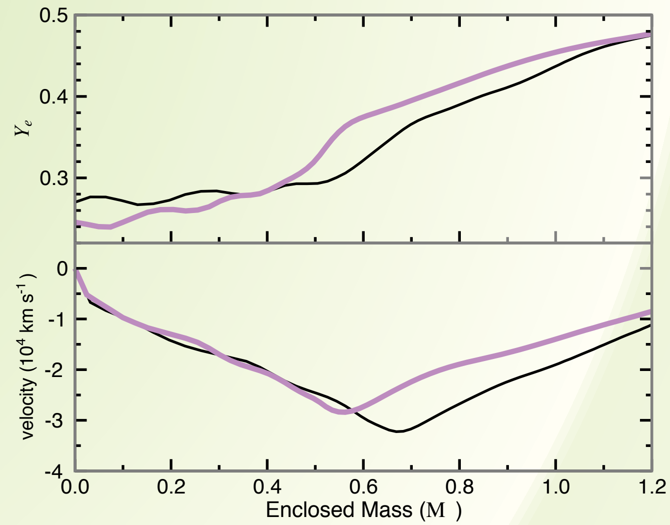
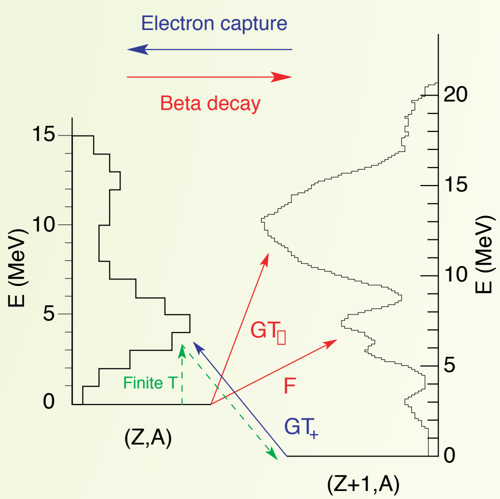




Langanke et al., Hix et al. 2003



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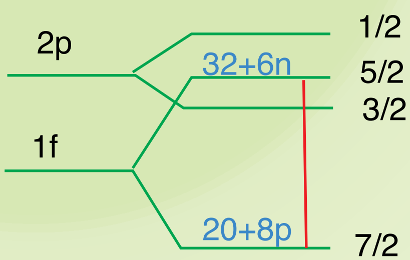

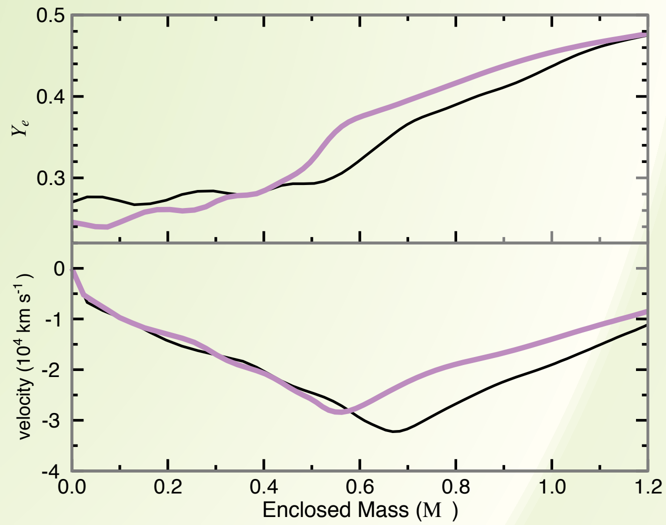

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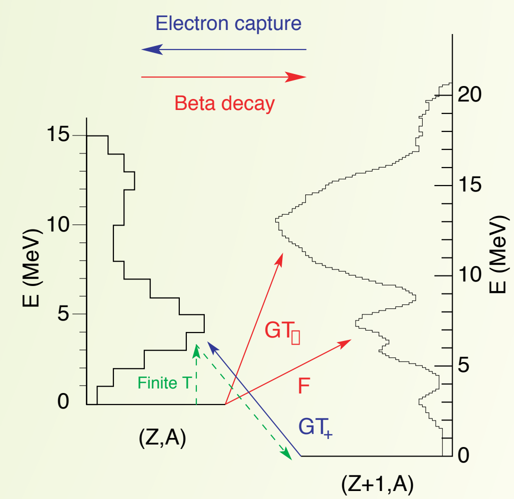

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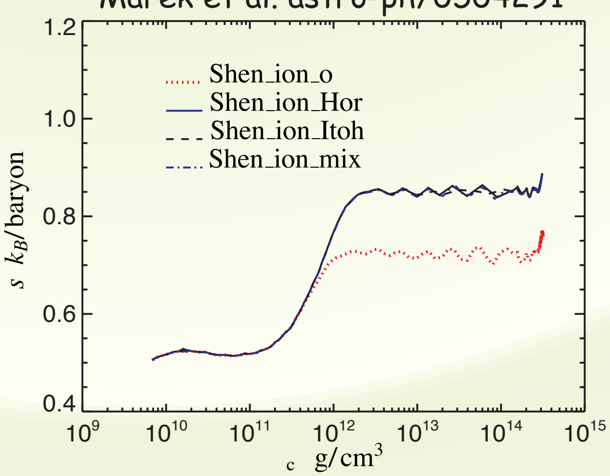
Marek et al. astro-ph/0504291



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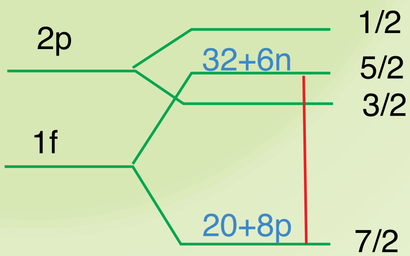

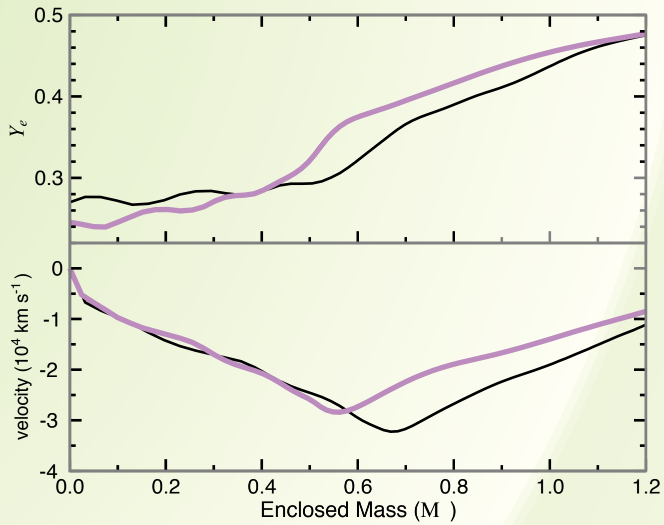

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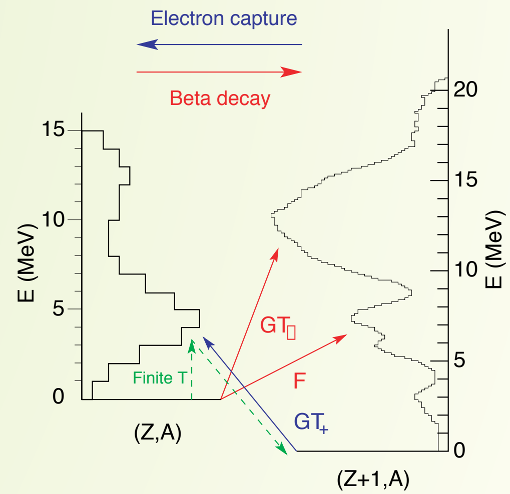

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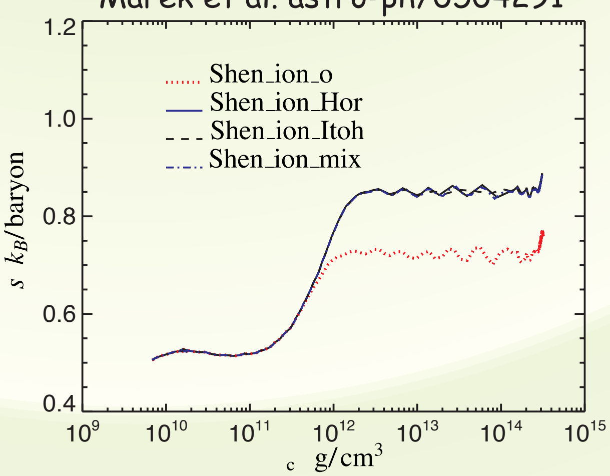

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Inelastic scattering of neutrinos on nuclei
--> thermalization

Bruenn & Haxton 1991

have not been updated so far!

Part I: Summary

- Chandrasekhar mass
- evolves by e-capture, diffusion, thermalization
- all three processes show(ed) potential for improvement
- e-capture on free protons provides deleptonization if alternative channels are closed
  --> convergence to "norm" trajectory
- most recent input physics predicts faster deleptonization by continued e-capture on nuclei
- bounce at twice nuclear density
- dissociation at the shock and neutrino losses lead to a stalled shock, no hydrodynamic prompt explosions
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GR Hydrodynamics Equations

Metric in spherical symmetry:

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

lapse function

enclosed baryon number

sphere radius def. by area

coordinate time

Lorenz factor in nonrel. limit

parameterized sphere

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Stress-energy tensor:

$$T^{tt} = \rho(1 + e + J),$$
$$T^{ta} = T^{at} = H,$$
$$T^{aa} = p + \rho K,$$
$$T^{\vartheta\vartheta} = T^{\varphi\varphi} = p + \frac{1}{2}\rho(J - K). \quad (2)$$

baryon density

internal fluid energy per baryon

radiation energy per baryon

energy transport

radiation stress

fluid pressure

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Conservation quantities:

$$\frac{1}{D} = \frac{\Gamma}{\rho}, \quad (3)$$

← 1/"density"

$$\tau = \Gamma(e + J) + \frac{2}{\Gamma + 1}\left(\frac{1}{2}u^2 - \frac{m}{r}\right) + uH, \quad (4)$$

← "total energy"

(internal: $\Gamma(e + J)$; kinetic: $\frac{1}{2}u^2$; potential: $\frac{m}{r}$)

$$S = u(1 + e + J) + \Gamma H. \quad (5)$$

← "radial momentum"

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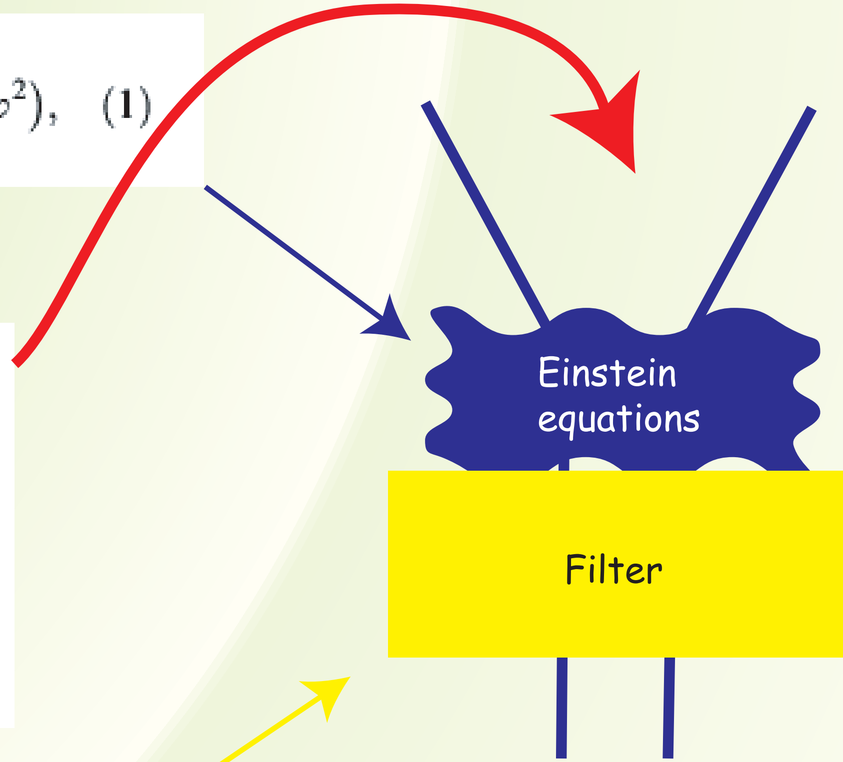

"continuity equation"

$$\frac{\partial}{\partial t}\left(\frac{1}{D}\right) = \frac{\partial}{\partial a}\left(4\pi r^2 \alpha u\right), \quad (6)$$

$$\frac{\partial \tau}{\partial t} = -\frac{\partial}{\partial a}\left[4\pi r^2 \alpha(up + u\rho K + \Gamma\rho H)\right], \quad (7)$$

"energy equation"

Neutrino Transport

Metric in spherical symmetry:

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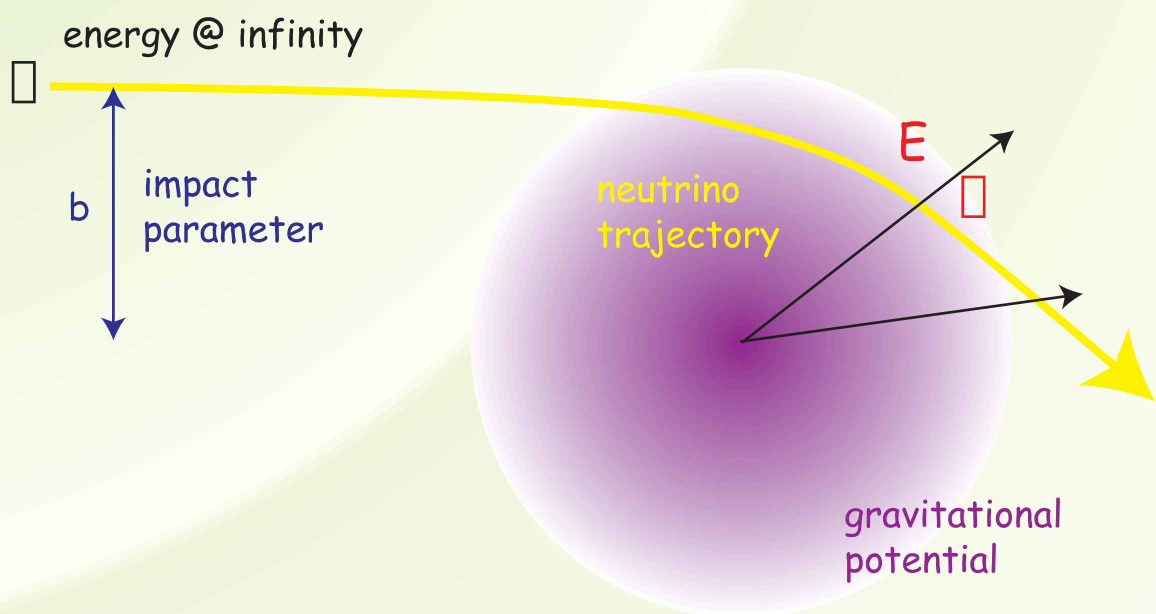
in comoving coordinates:
[Lindquist, Ann. Phys., 1966; etc.]



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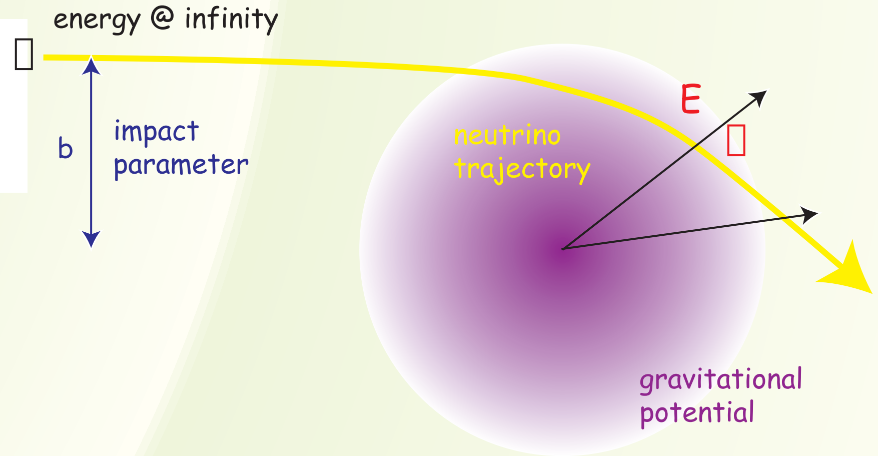

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[Lindquist, Ann. Phys., 1966; etc.]

$$C_t + D_a + D_\mu + D_E + O_\mu + O_E = C_c, \qquad (15)$$

with

Lagrangian time derivative

$$C_t = \frac{\partial F}{\alpha \partial t}, \qquad (16)$$

spatial advection

$$D_a = \frac{\mu}{\alpha}\frac{\partial}{\partial a}\left(4\pi r^2 \alpha \rho F\right), \qquad (17)$$

angular advection

$$D_\mu = \Gamma\left(\frac{1}{r} - \frac{1}{\alpha}\frac{\partial \alpha}{\partial r}\right)\frac{\partial}{\partial \mu}\left[\left(1-\mu^2\right)F\right], \qquad (18)$$

gravitational frequency shift

$$D_E = -\mu\Gamma\frac{1}{\alpha}\frac{\partial \alpha}{\partial r}\frac{1}{E^2}\frac{\partial}{\partial E}\left(E^3 F\right), \qquad (19)$$

Doppler frequency shift

$$O_E = \left[\mu^2\left(\frac{\partial \ln \rho}{\alpha \partial t} + \frac{3u}{r}\right) - \frac{u}{r}\right]\frac{1}{E^2}\frac{\partial}{\partial E}\left(E^3 F\right), \qquad (20)$$

angular aberration

$$O_\mu = \left(\frac{\partial \ln \rho}{\alpha \partial t} + \frac{3u}{r}\right)\frac{\partial}{\partial \mu}\left[\mu\left(1-\mu^2\right)F\right], \qquad (21)$$

collision term

$$C_c = \frac{j}{\rho} - \chi F. \qquad (22)$$

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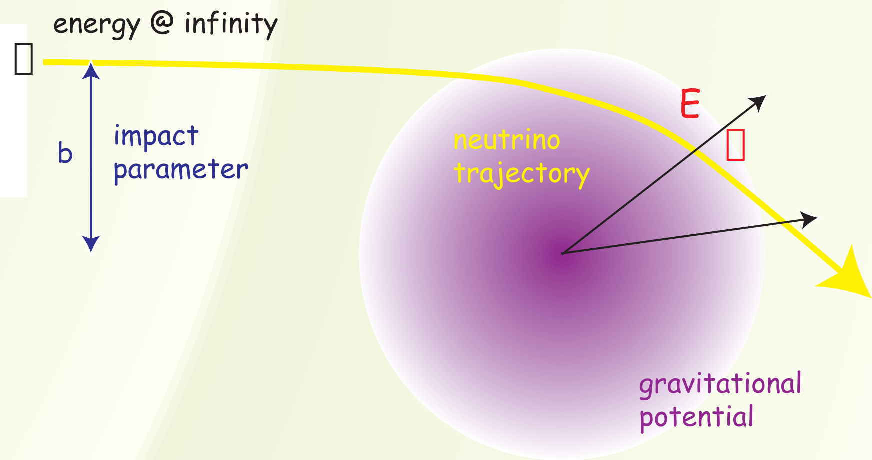

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- large contrast in densities and energies (10^53 ergs versus 10^51 ergs)

- large contrast in time scales of processes (1km/c~3E-6s versus 1s)

Microscopic Transport --- Macroscopic Properties

Interest in time evolution of macroscopic quantities,
e.g. the evolution of neutrino energy:

Laboratory frame:

$$\frac{\partial}{\partial t}\int(\Gamma+u\mu)FE^{3}dE\,d\mu.$$

time derivative

expectation value

Many cancellations among partial derivatives because □ is conserved along phase flow!

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$$\frac{\partial f_{i'}}{\partial t} + c\ \frac{f_{i'} - f_{i'-1}}{dx_{i'}} = 0.$$

Strongly simplyfied for the example:
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$$=-\sum_{i=1}^{n}g_{i'}f_{i'}+\sum_{i=0}^{n-1}g_{i'+1}f_{i'}$$

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... as function of expectation value

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evolution of macroscopic property...

macroscopic operator inherits finite differencing from advection term

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time derivative

expectation value

Many cancellations among partial derivatives because □is conserved along phase flow!

Cancellations don't happen in discretized world!

Discretized transport equation:

$$\frac{\partial f_{i'}}{\partial t}+c\,\frac{f_{i'}-f_{i'-1}}{dx_{i'}}=0.$$

$$\frac{\partial}{c\partial t}\sum_{i=1}^{n} g_{i'}f_{i'}dx_{i'}=\sum_{i=1}^{n} g_{i'}\frac{\partial f_{i'}}{c\partial t}dx_{i'}=-\sum_{i=1}^{n} g_{i'}(f_{i'}-f_{i'-1})$$

evolution of macroscopic property...

$$=-\sum_{i=1}^{n} g_{i'}f_{i'}+\sum_{i=0}^{n-1}g_{i'+1}f_{i'}$$

macroscopic operator inherits finite differencing from advection term

$$=\sum_{i=1}^{n}\frac{g_{i'+1}-g_{i'}}{dx_{i'}}f_{i'}dx_{i'}-\left(g_{n'+1}f_{n'}-g_{0'+1}f_{0'}\right).$$

Chain rule and integration by parts in discrete space!

... as function of expectation value

Comparison of Methods

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

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

includes datafiles.tar.gz with different conditions at different time slices during simulations.

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--> very good agreement!

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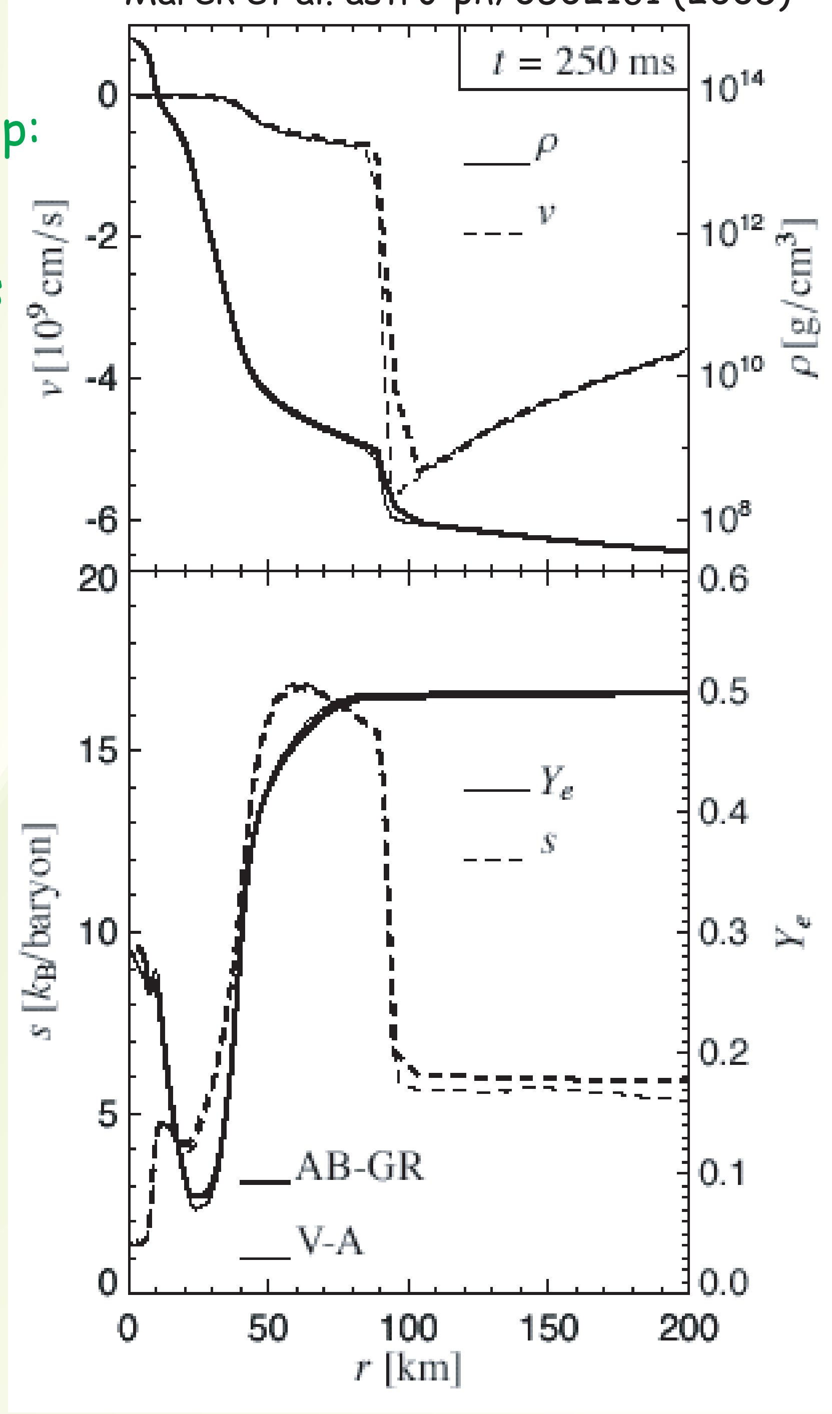

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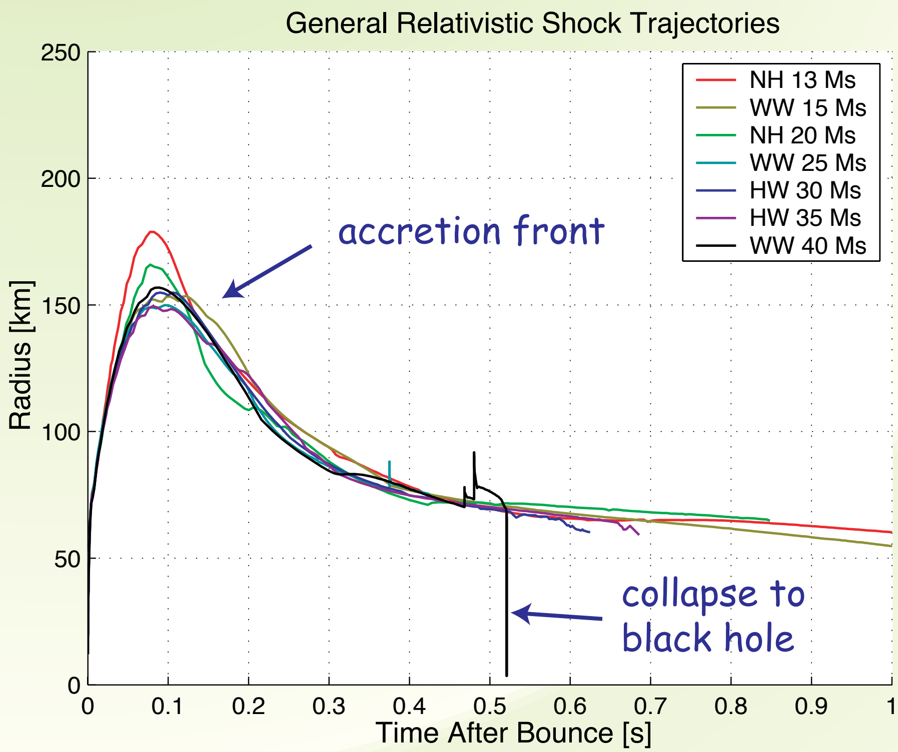

no explosions for progenitors >11 Msol!

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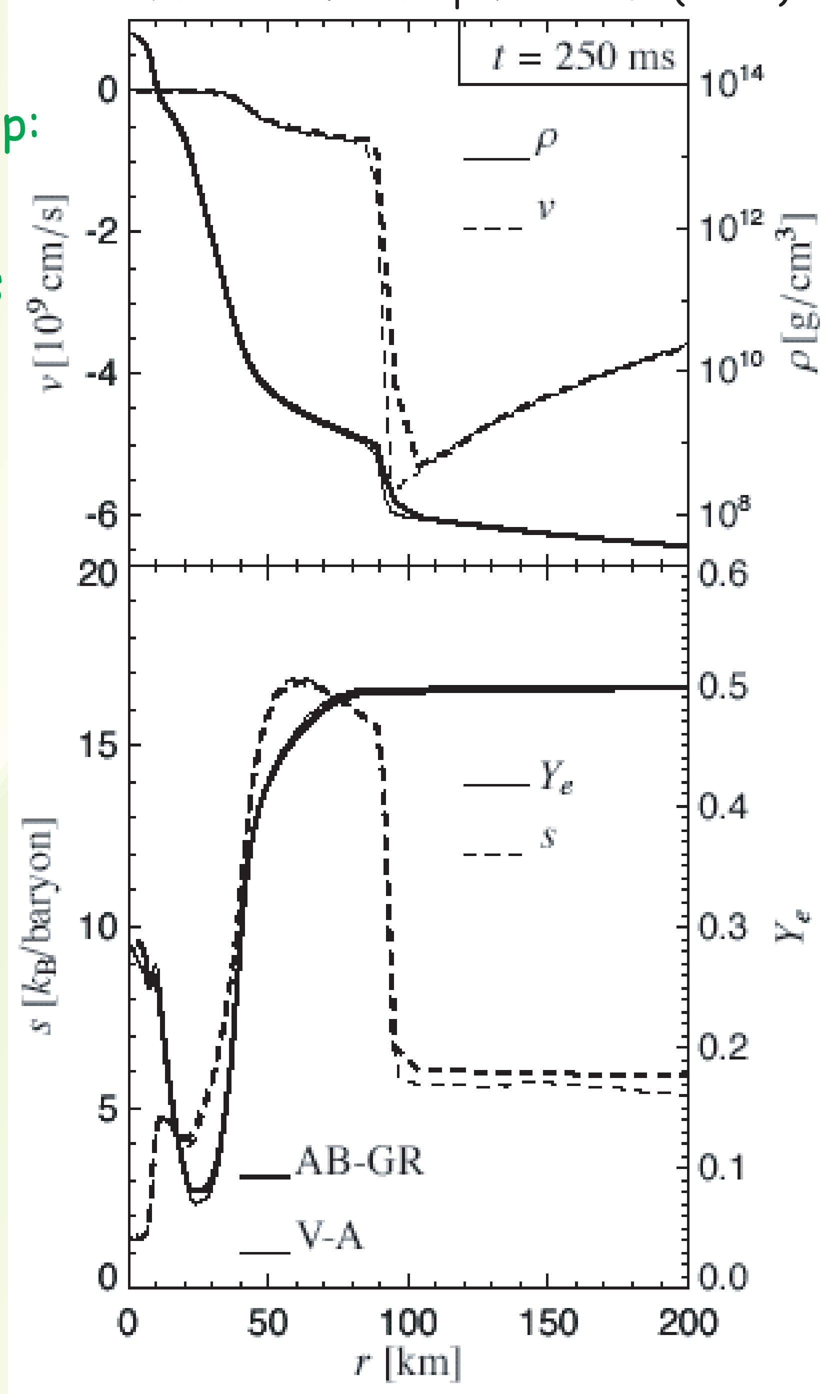

Why do explosions not occur automatically?

(1) electron capture during collapse

(2) dissociation of infalling material

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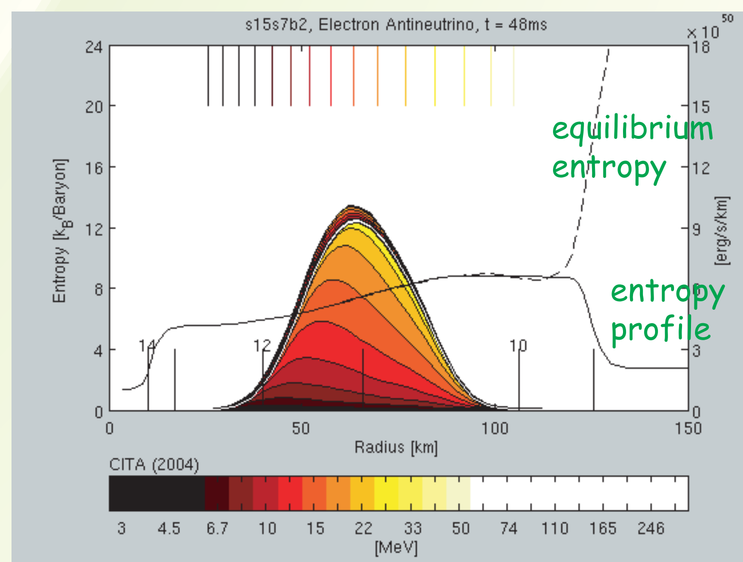
=> neutrino cooling determines
compactification and inflow

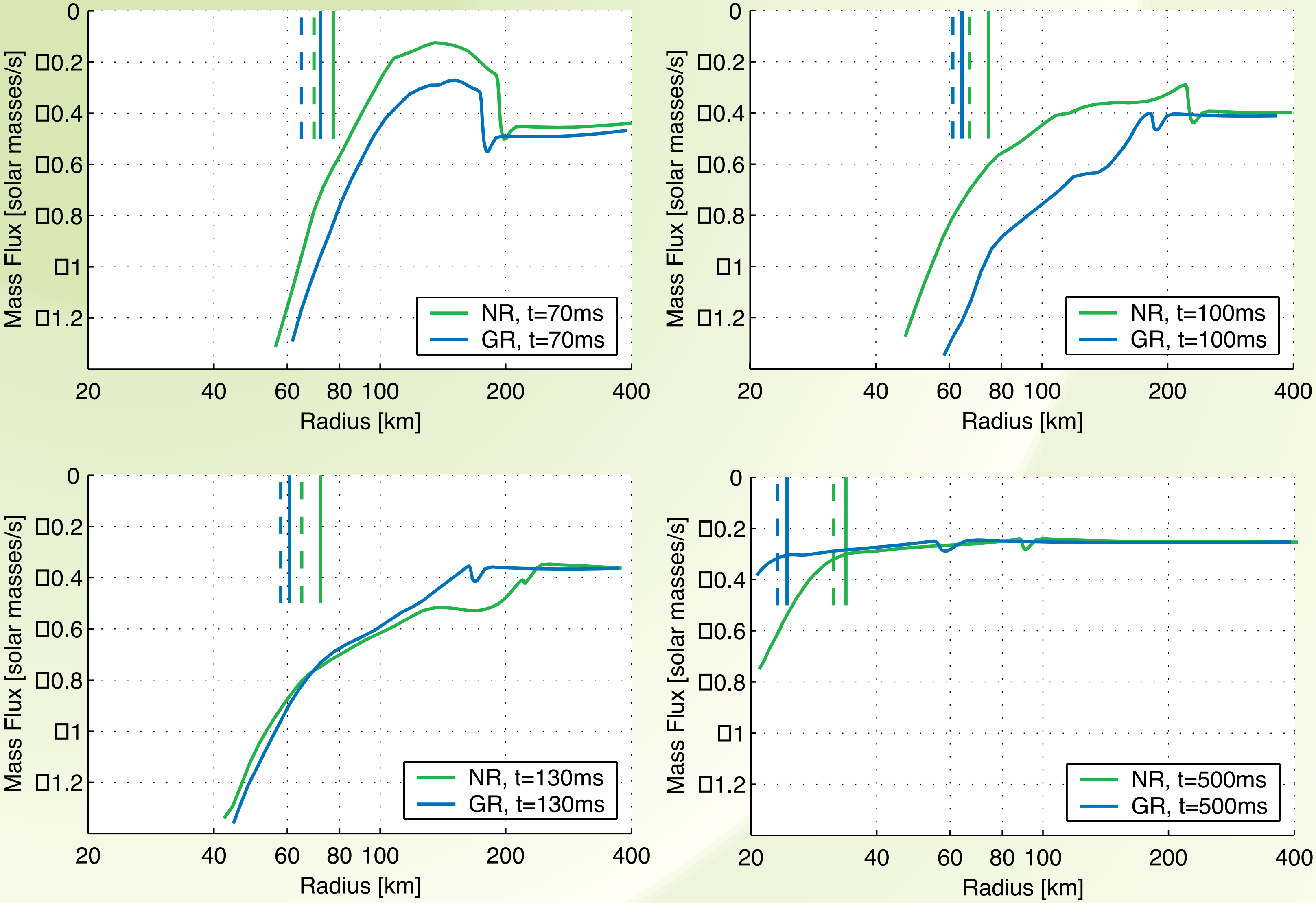
waiting for
equilibrium
--> Ye(equil.)
--> S(equil.)

48ms after bounce



Cooling...

Liebendörfer et al. 2001

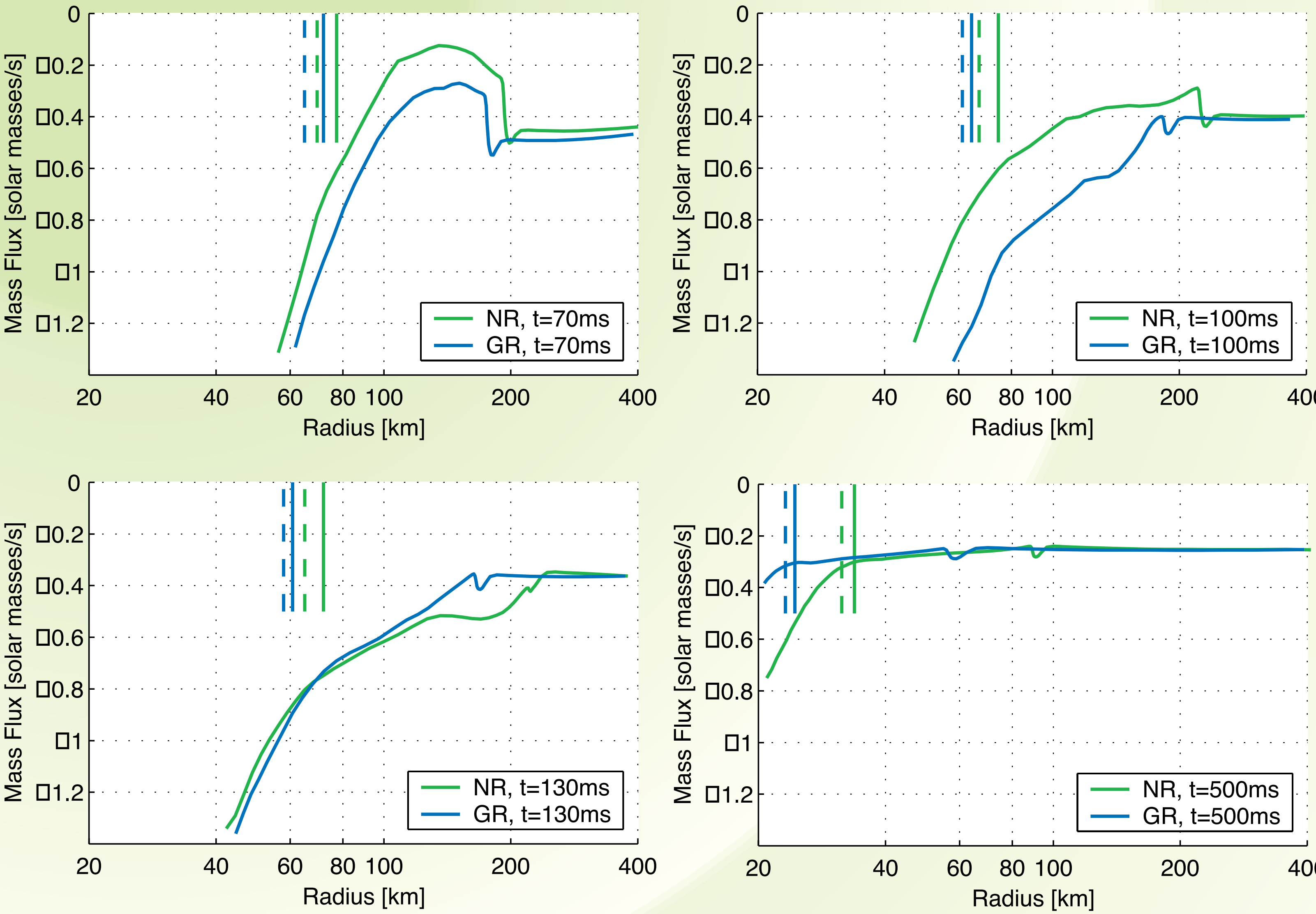


"It must be suspected that excessive neutrino emission in the cooling layer, causing mass and energy loss from the gain layer, may have been the main reason why spheri cally symmetric simulations ulti-mately failed to produce explosions"

Janka 2001

Four reasons, and then?

Liebendörfer et al. 2001



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(1) electron capture during collapse

(2) dissociation of infalling material

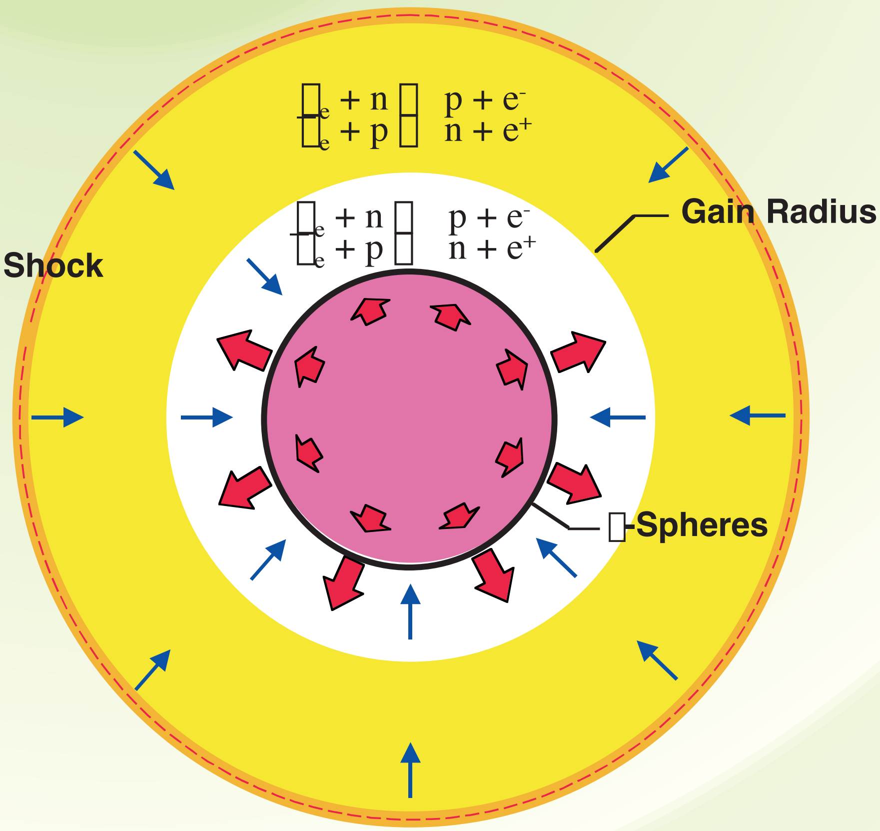
(3) neutrino cooling

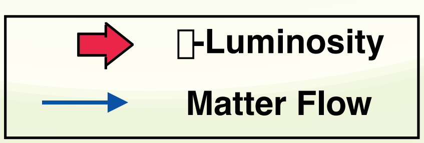
(4) fast accretion in heating region

A side-effect? A surface-effect?

"It is important to note that one is not obliged to unbind the inner core ... as well; the explosion is a phenomenon of the outer mantle at ten times the radius (50-200 kilometers)."

Burrows & Thompson 2002





matter in -
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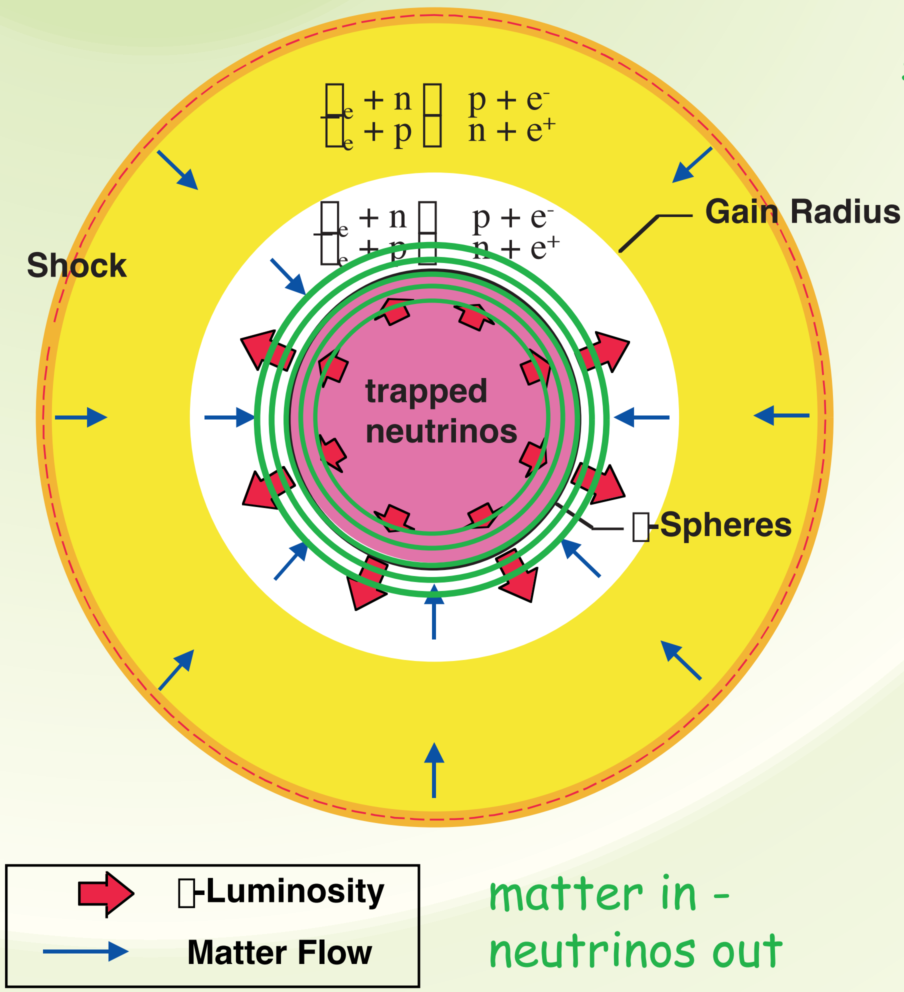

Extended layer with high neutrino opacities at subnuclear densities (roughly 10^12 g/cm^3)

It shields the region with the history of core collapse and many uncertainties in microscopic physics input from the surface on a long neutrino diffusion time scale

This layer is convectively unstable in simulations that explode (e.g. Wilson & Mayle '93, Herant et al. '94) and convectively stable in simulations that don't (Buras et al. '03)

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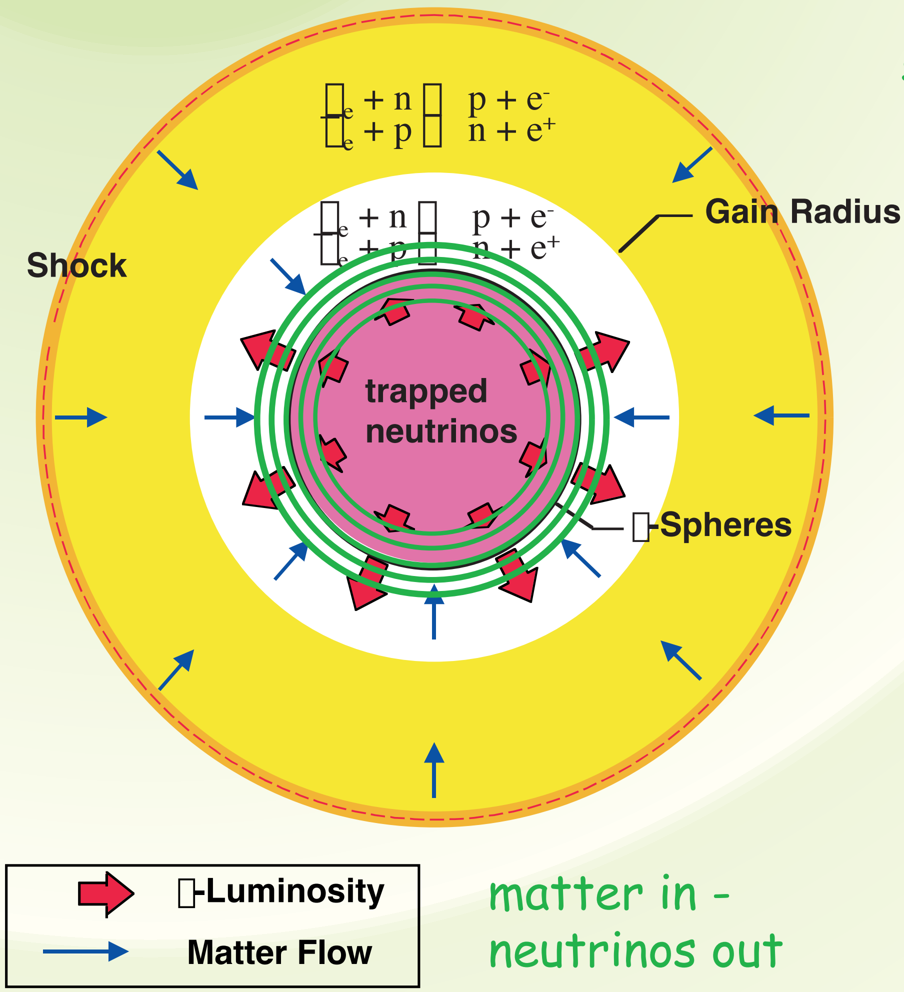

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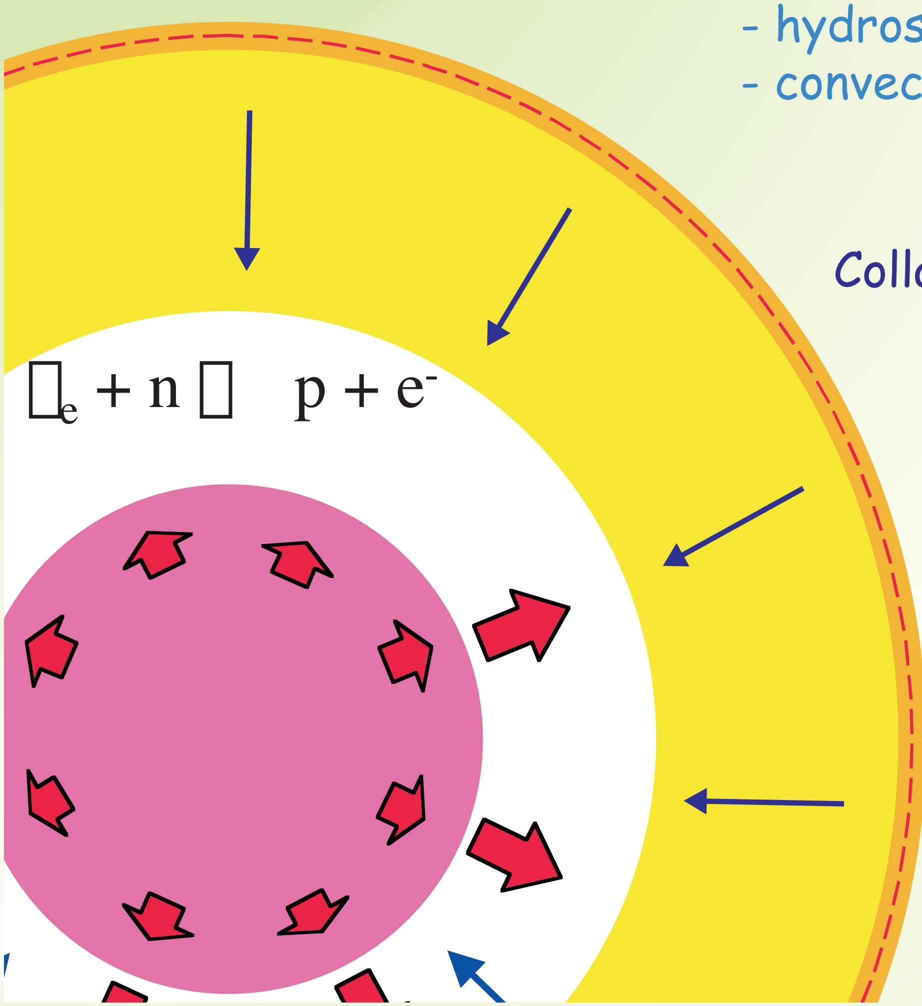
==> Reason number 5:
Stability of the protoneutron star around the neutrinospheres

Feedback in a strongly coupled one-dimensional region

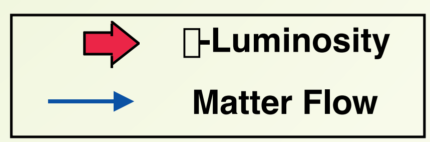
Postbounce situation:

- hot shock-heated matter
- free nucleons and alphas
- hydrostatic structure
- convectively instable



Collapse phase:

- cold matter, S~1kB/baryon
- heavy nuclei
- dynamical infall
- rotational?



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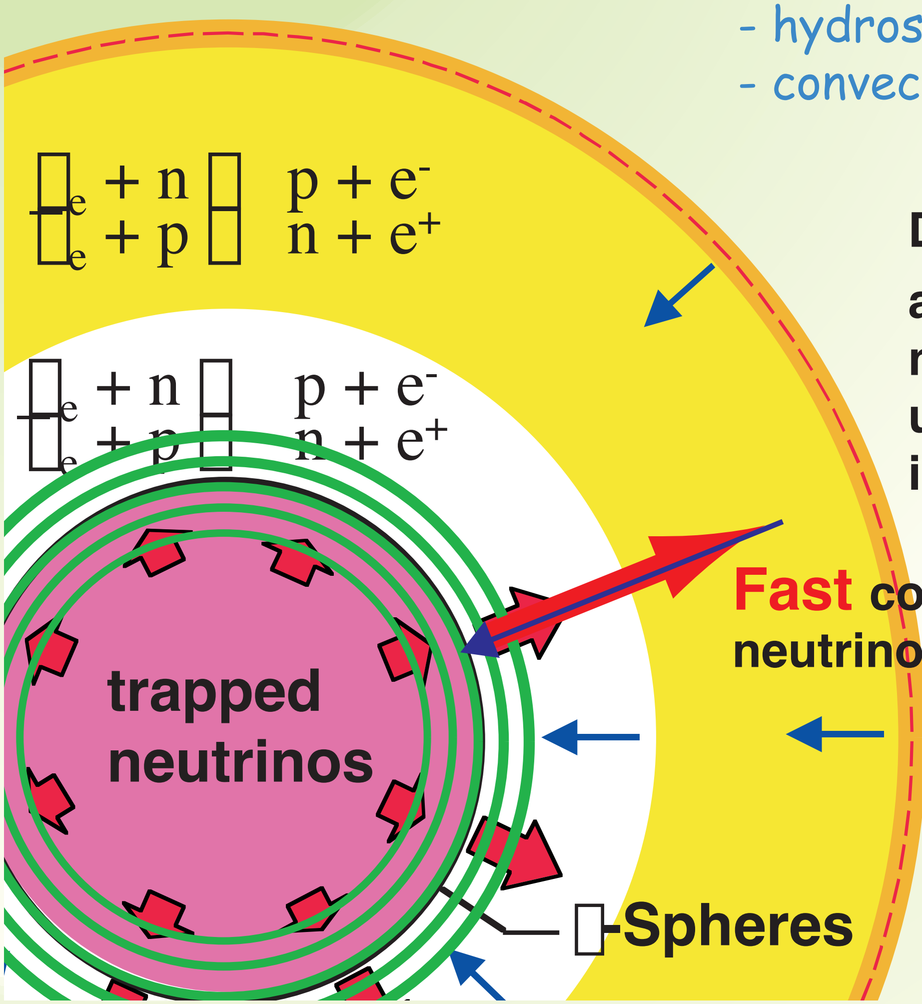
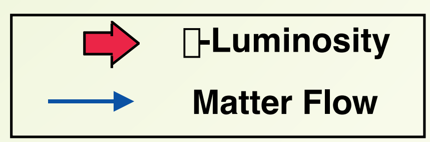


Delayed feedback via accretion is constrained: neutrino outflow couples unambiguously to matter inflow

Fast coupling via neutrino transport

Situation in spherical symmetry



matter in - neutrinos out

Feedback in a strongly coupled multi-dimensional region

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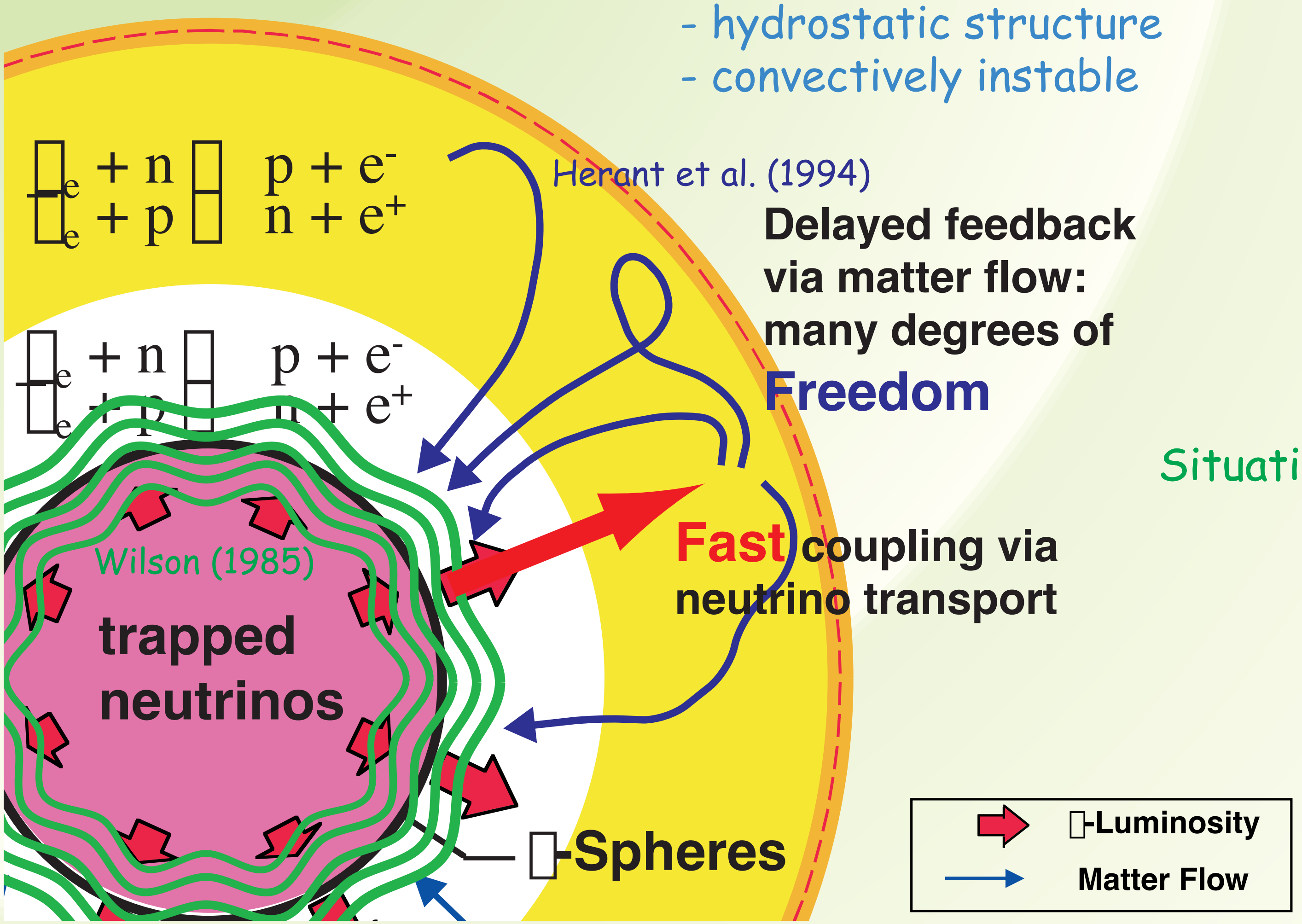

Situation in more dimensions

matter in -
neutrinos out

Feedback in a strongly coupled multi-dimensional region

Postbounce situation:

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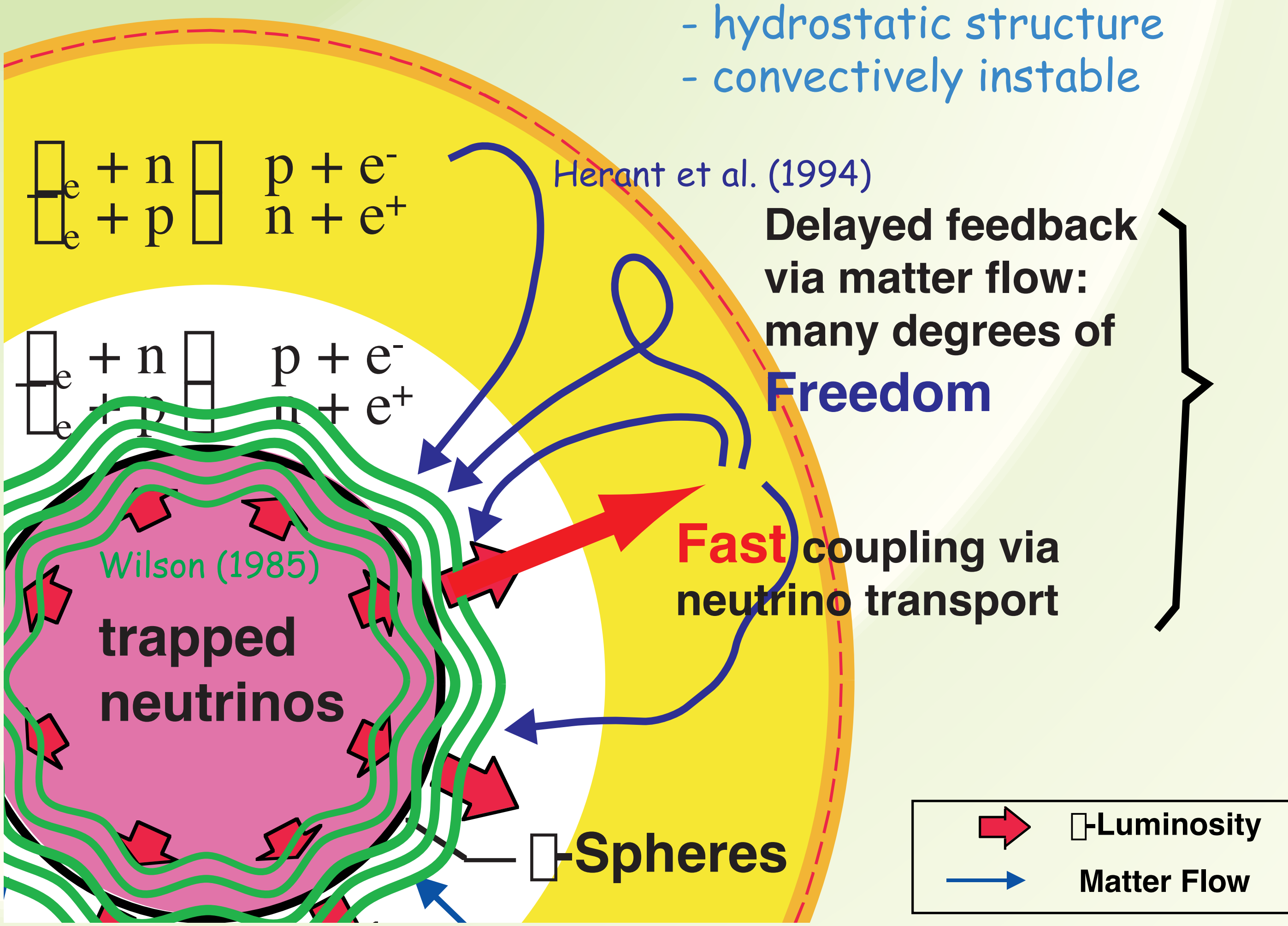


Very difficult global transport problem

Buras et al. (2003)
Livne et al. (2004)
Walder et al. (2004)
Cardall & Mezzacappa (2003)
Fryer & Warren (2004)
Myra & Swesty (2005)

matter in - neutrinos out

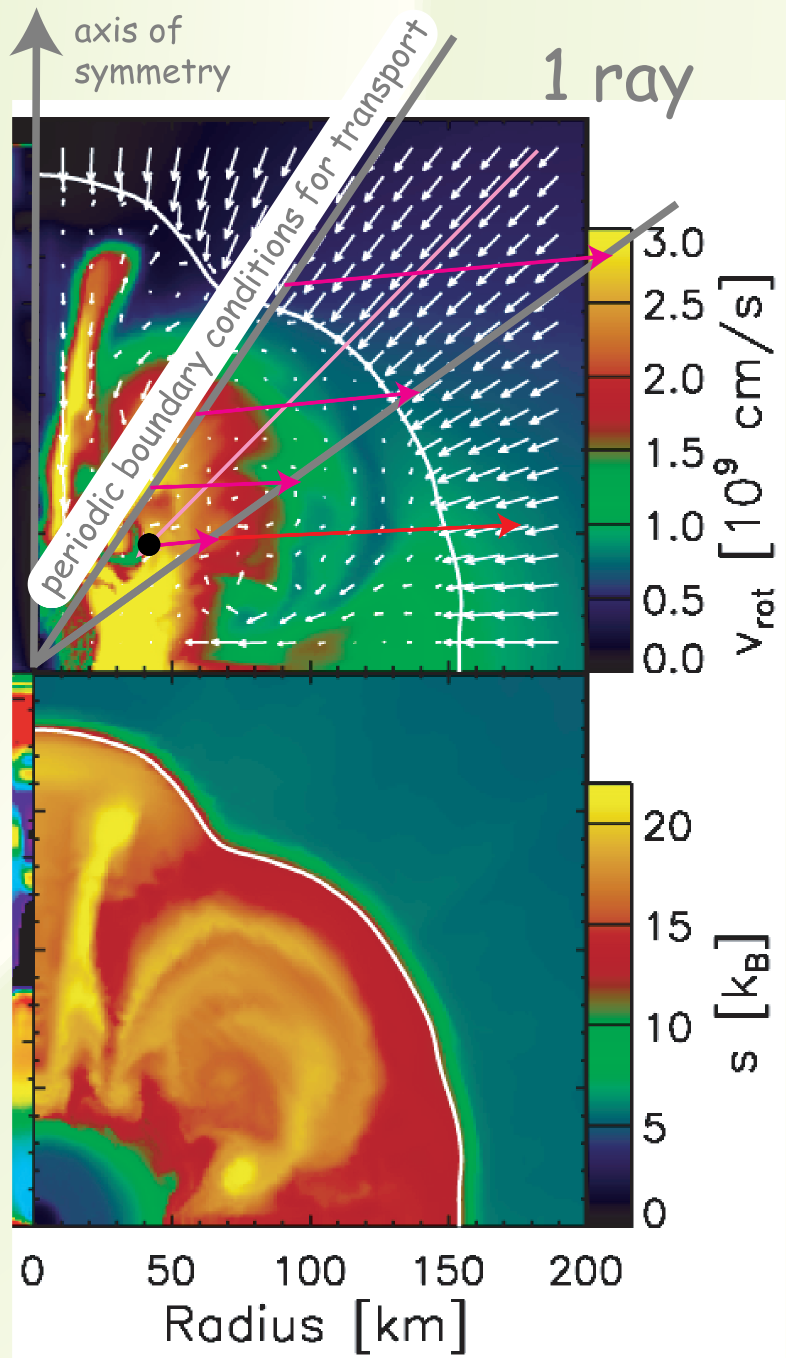
Convective turnover in the heating region

2D + ray-by-ray

Improved models of stellar core collapse and still no explosions: what is missing?

R. Buras, M. Rampp, H.-Th. Janka, K. Kifonidis, Phys. Rev. Lett., 2003

Snapshots of the stellar structure for the rotating model s15r at 198 ms after shock formation. The panels display the rotational velocity (top) and the entropy (in kB per nucleon) as functions of radius. The arrows indicate the velocity field, the white line marks the shock front.



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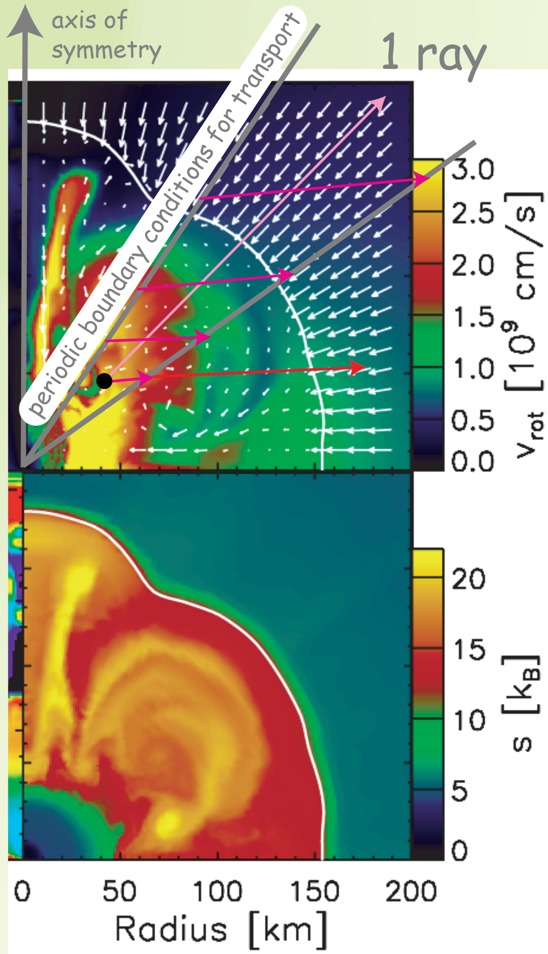

2D MGFLD

R. Walder, A. Burrows, C.D. Ott, E. Livne, I. Lichtenstadt, M. Jarrah, astro-ph/0412187

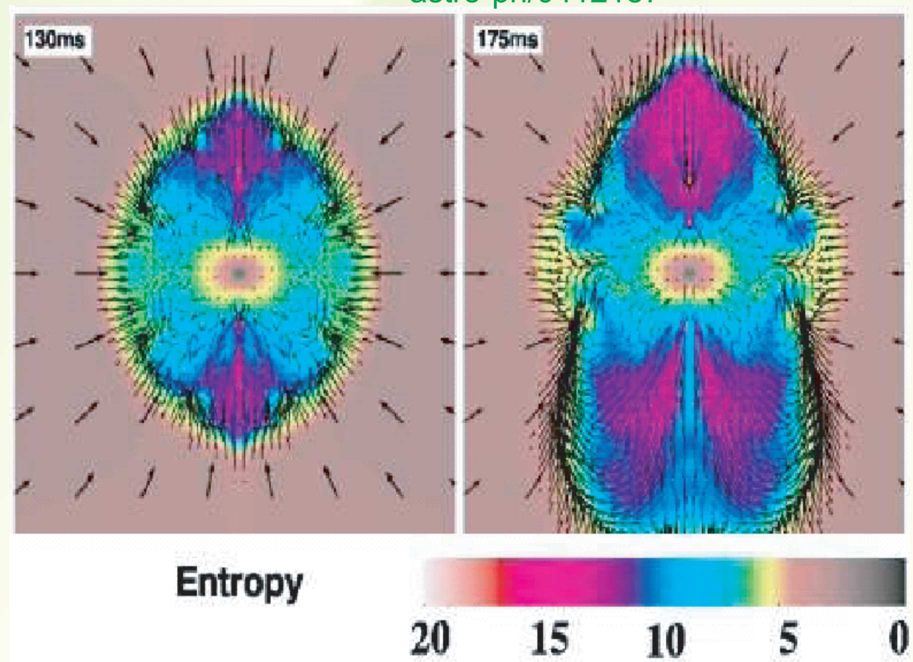

Fig. 4.— Color map of the entropy (per baryon per Boltzmann's constant), with the r-z velocities (arrows) superposed, of the fast rotating model A ($\Omega = 2.68$ s^{-1}). Shown is the inner 600 km on a side at times 40 ms (upper left panel), 85 ms (upper right panel), 130 ms (lower left panel), and 175 ms (lower right panel) after bounce. The entropy in the polar direction is about a factor of two higher than in the equatorial regions at the same radius.

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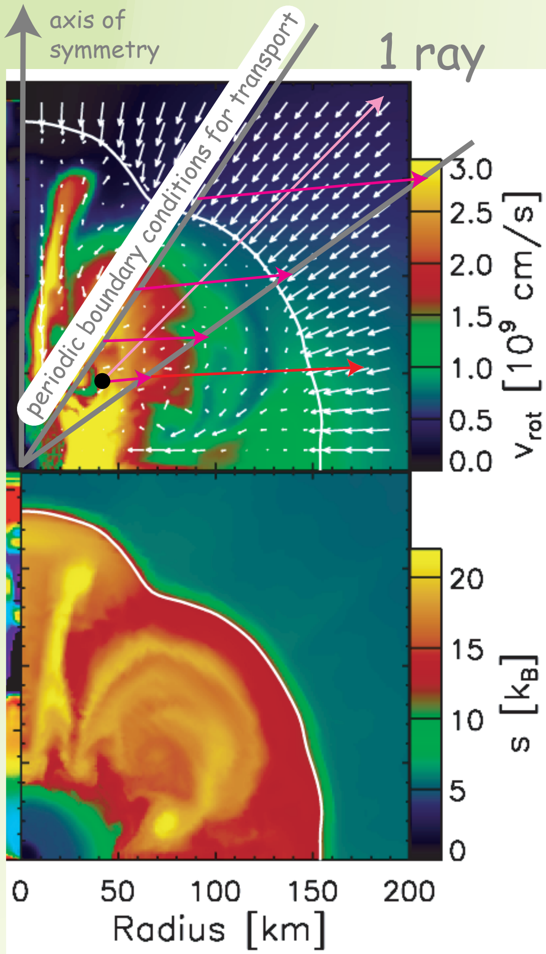

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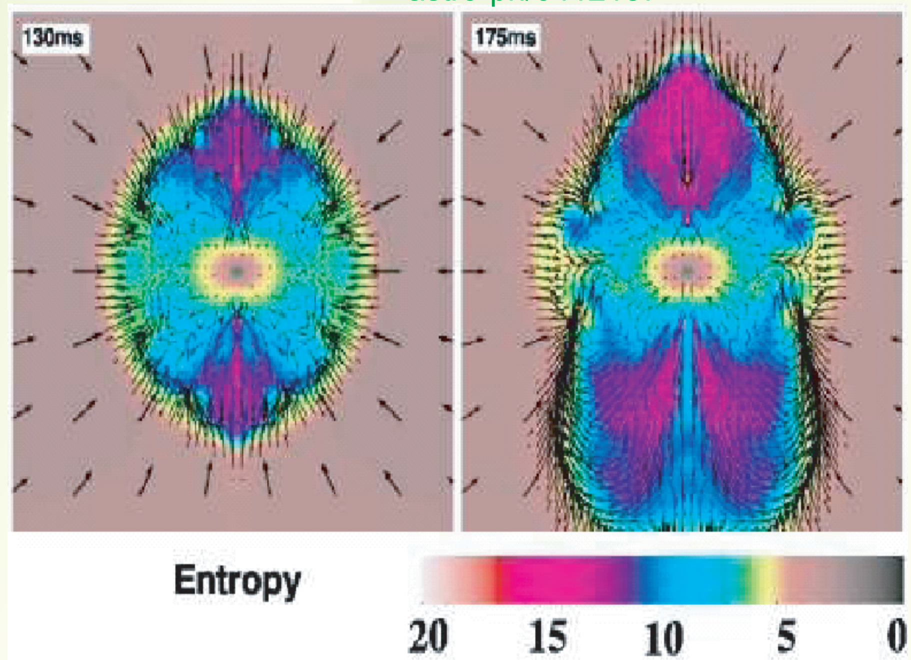

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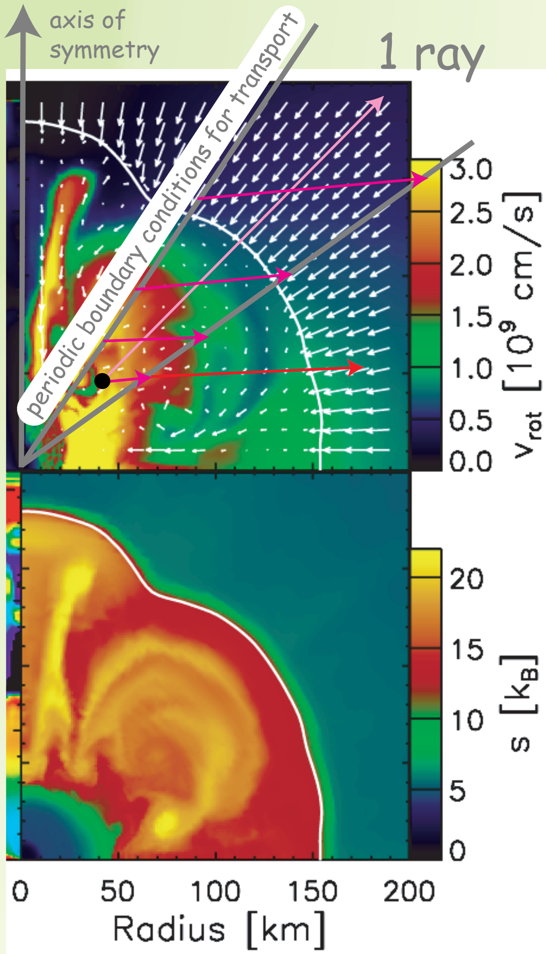

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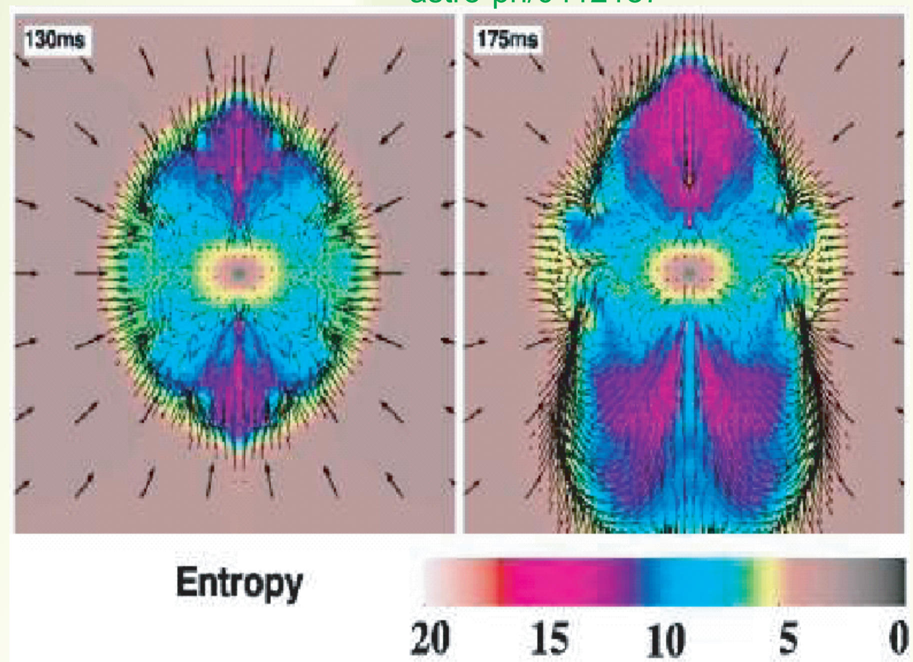

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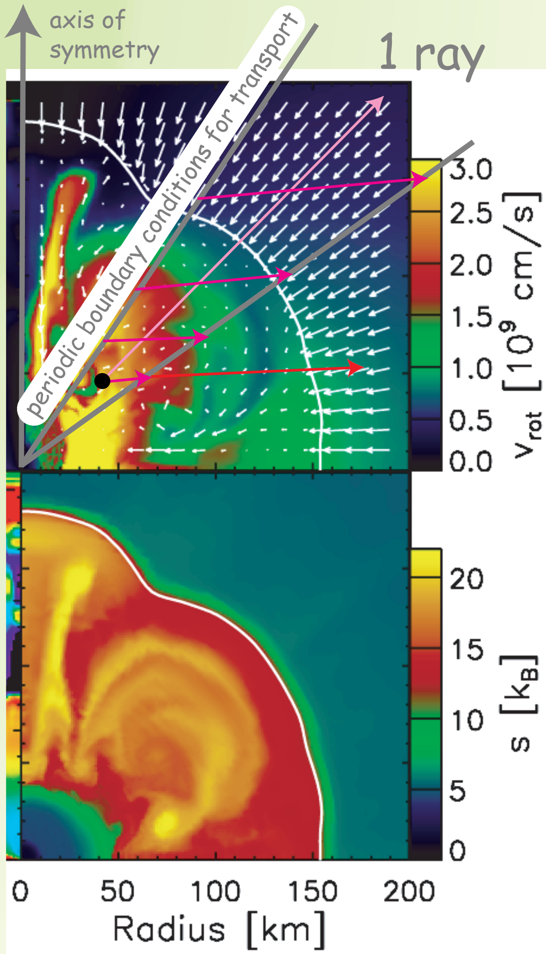

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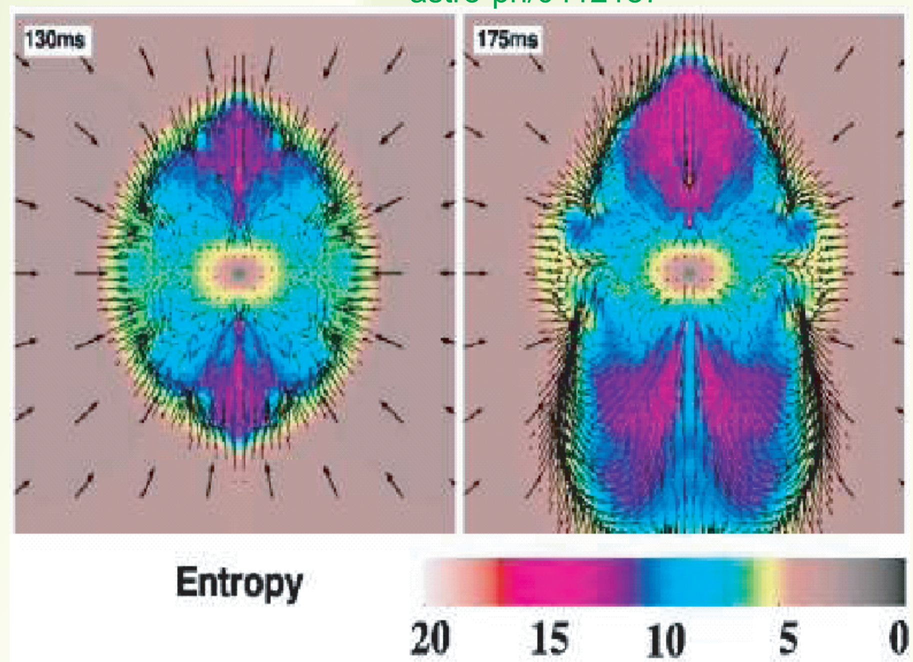

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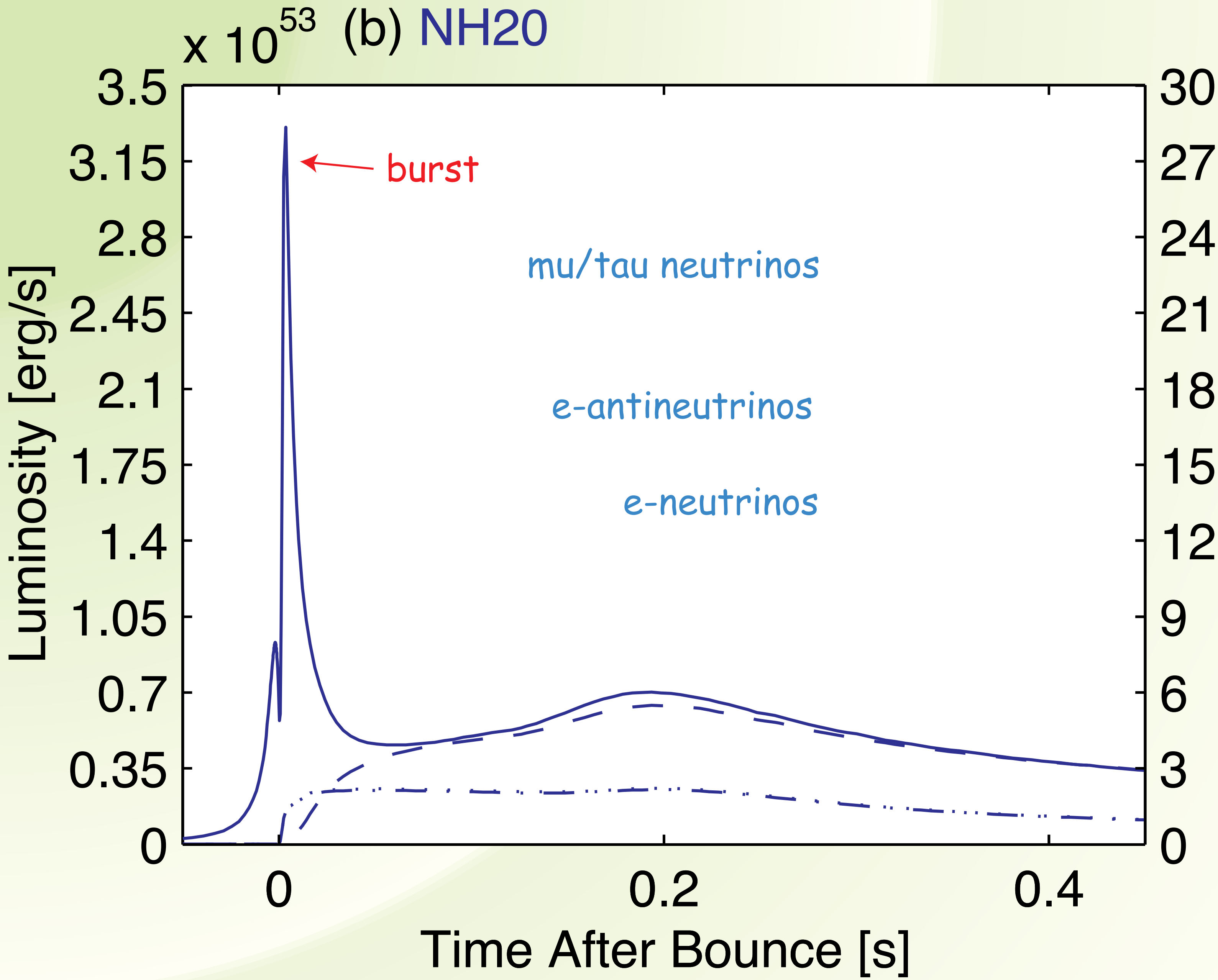
Parameterized neutrino physics

- Scheck et al., PRL, 2003
- Liebendörfer et al., Nucl. Phys. A, 2005, astro-ph/0504072

Neutrino luminosities and spectra



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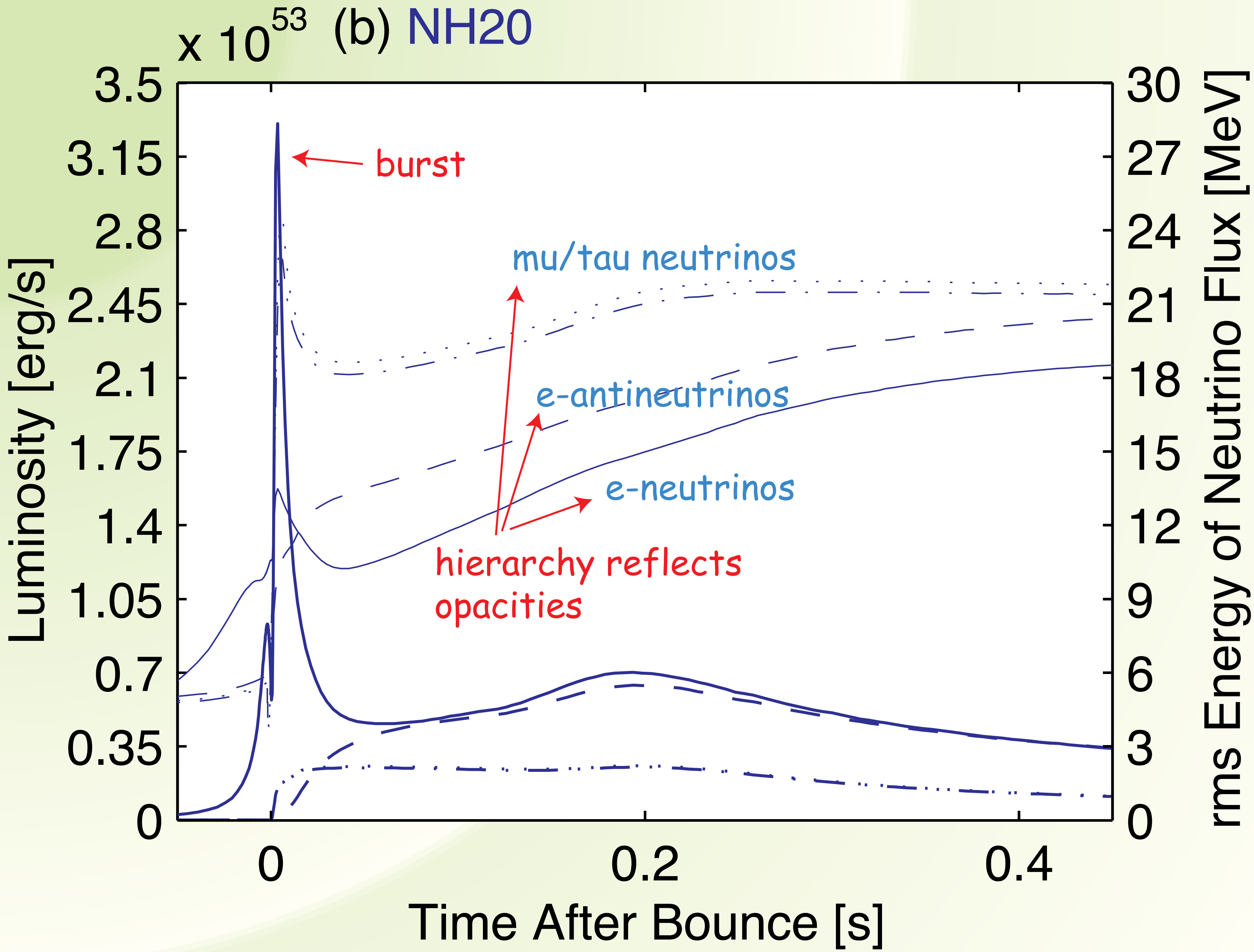

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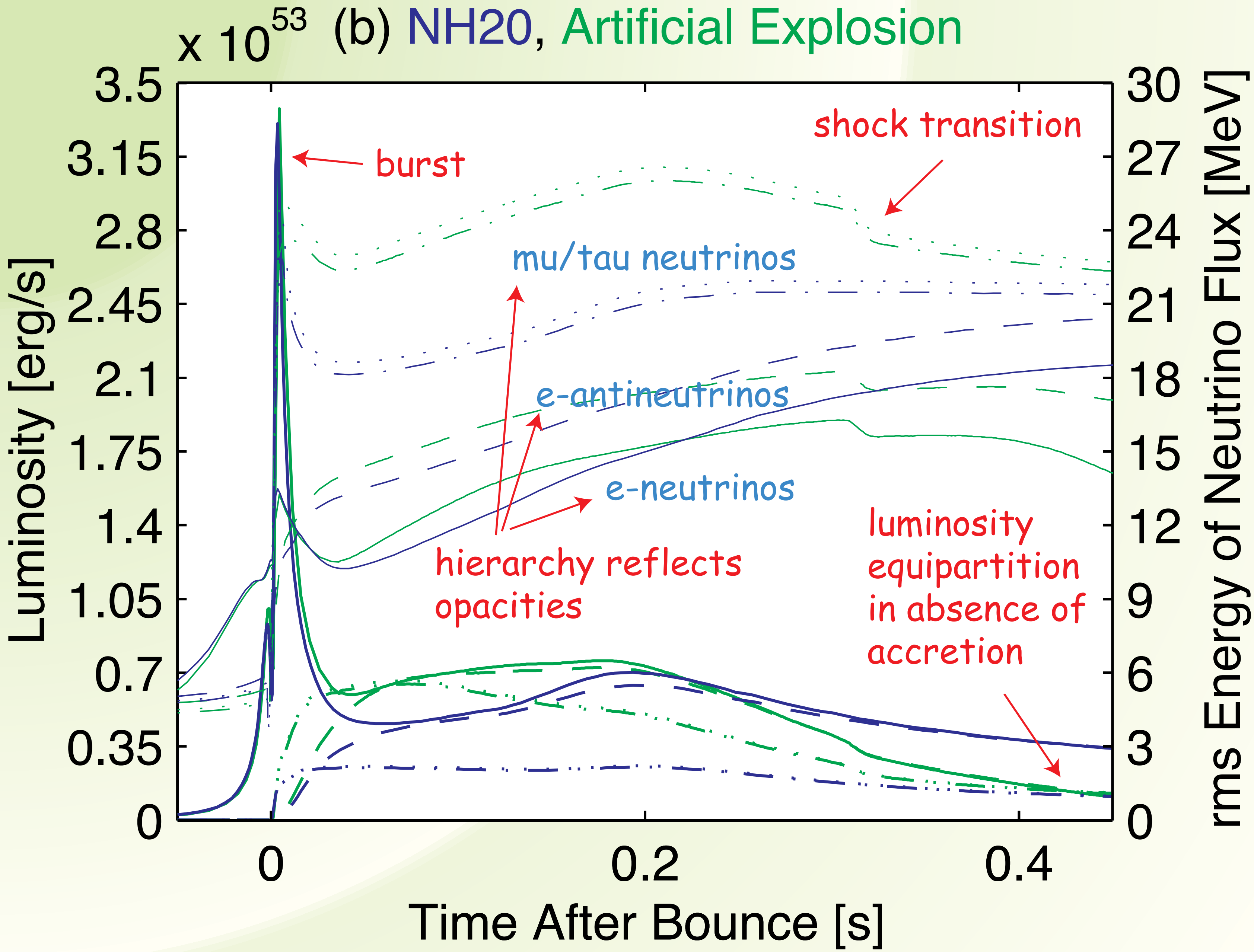


Accretion determines neutrino luminosities and spectra

Energy available from accretion:

~ 2/3 Accretion rate at neutrinosphere
times
Gravitational potential at neutrinosphere

~ 1/3 core diffusion luminosity

Equipartition in the luminosities only after reduction of the accretion luminosities

40M

25M

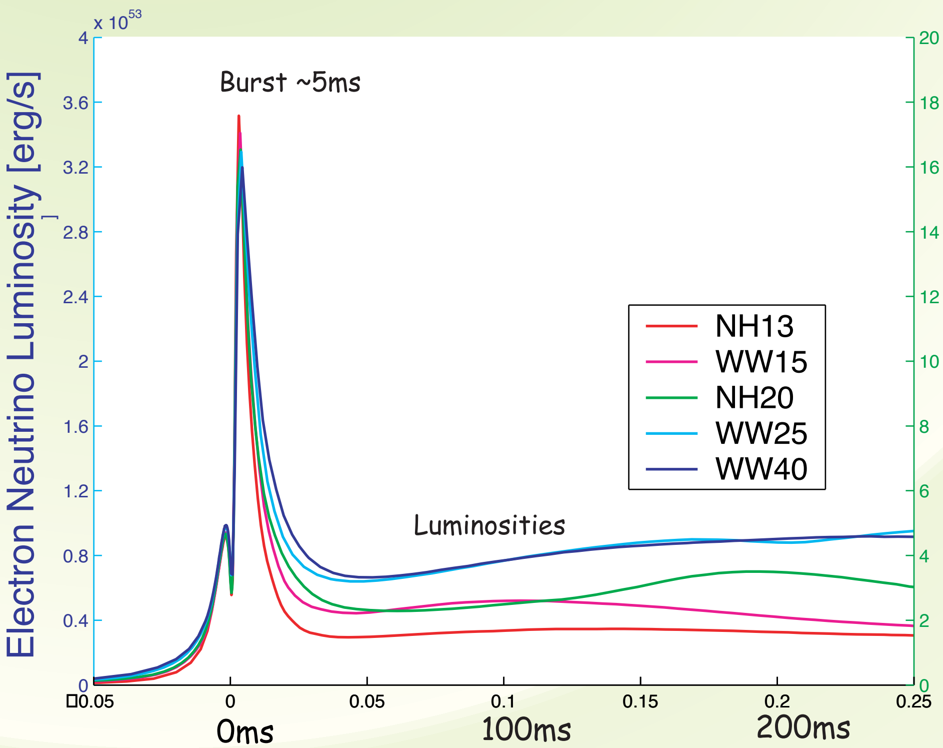
15M

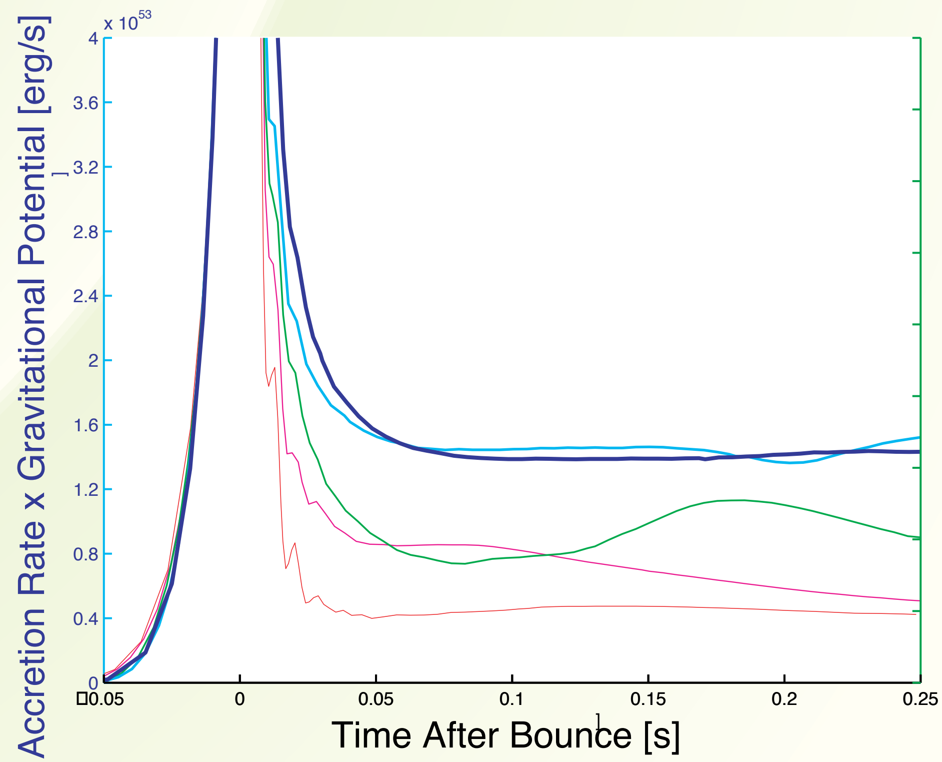
20M

13M

Woosley & Weaver '95

Nomoto & Hashimoto '88





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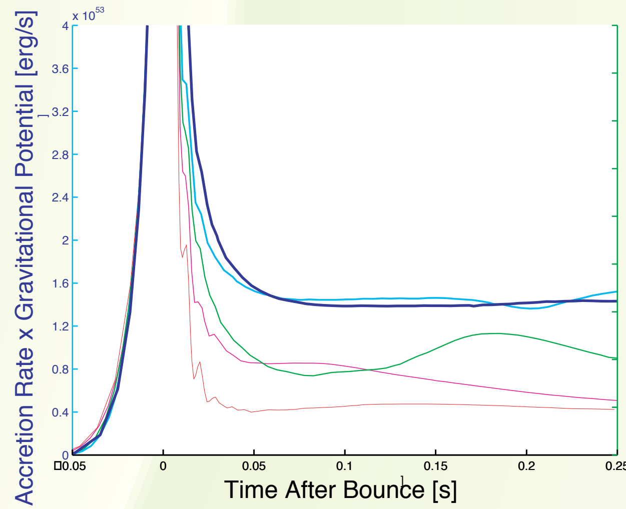

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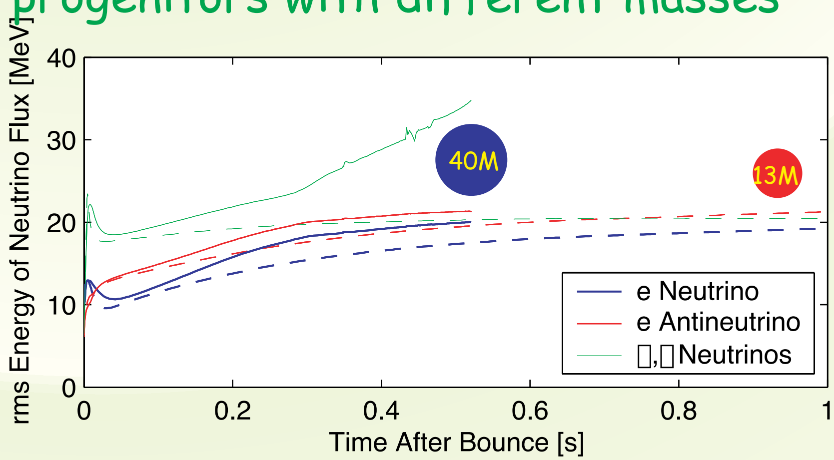
Different thermodynamic conditions deep in progenitors with different masses



Enclosed Mass at Radius 100 km
as Function of Time

(s)	13*M* Model	40*M* Model
0.0	0.90	0.88
0.1	1.19	1.57
0.2	1.25	1.77
0.3	1.28	1.89
0.4	1.31	2.02
0.5	1.33	2.20
1.0	1.42	-

Liebendörfer et al. 2004

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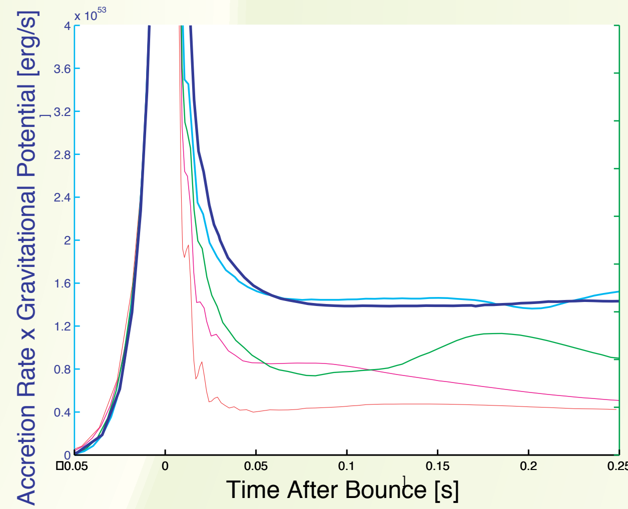

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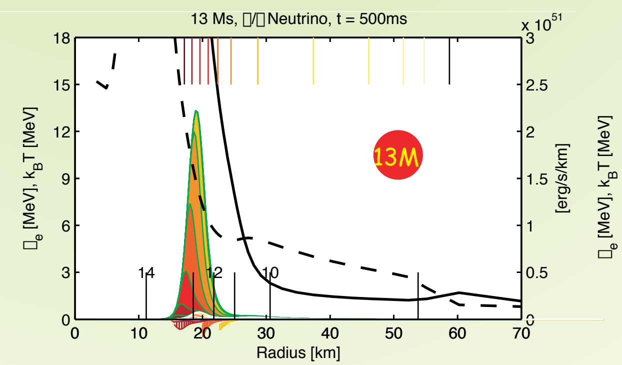

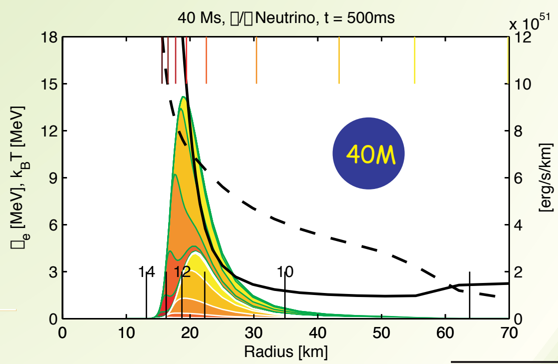

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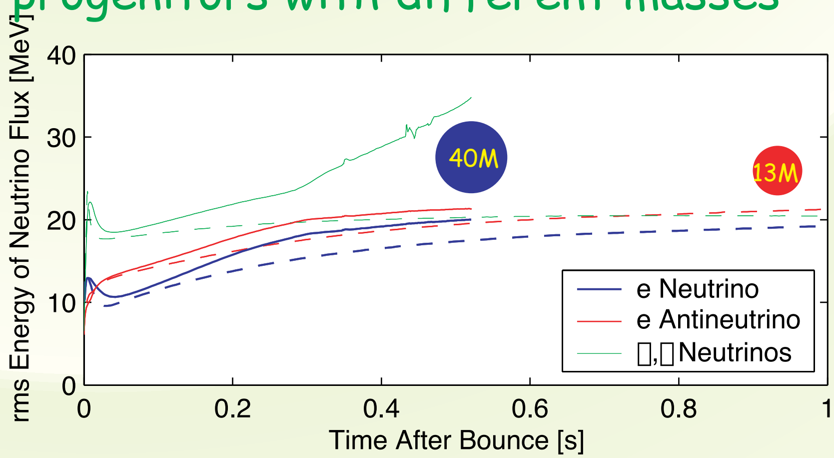

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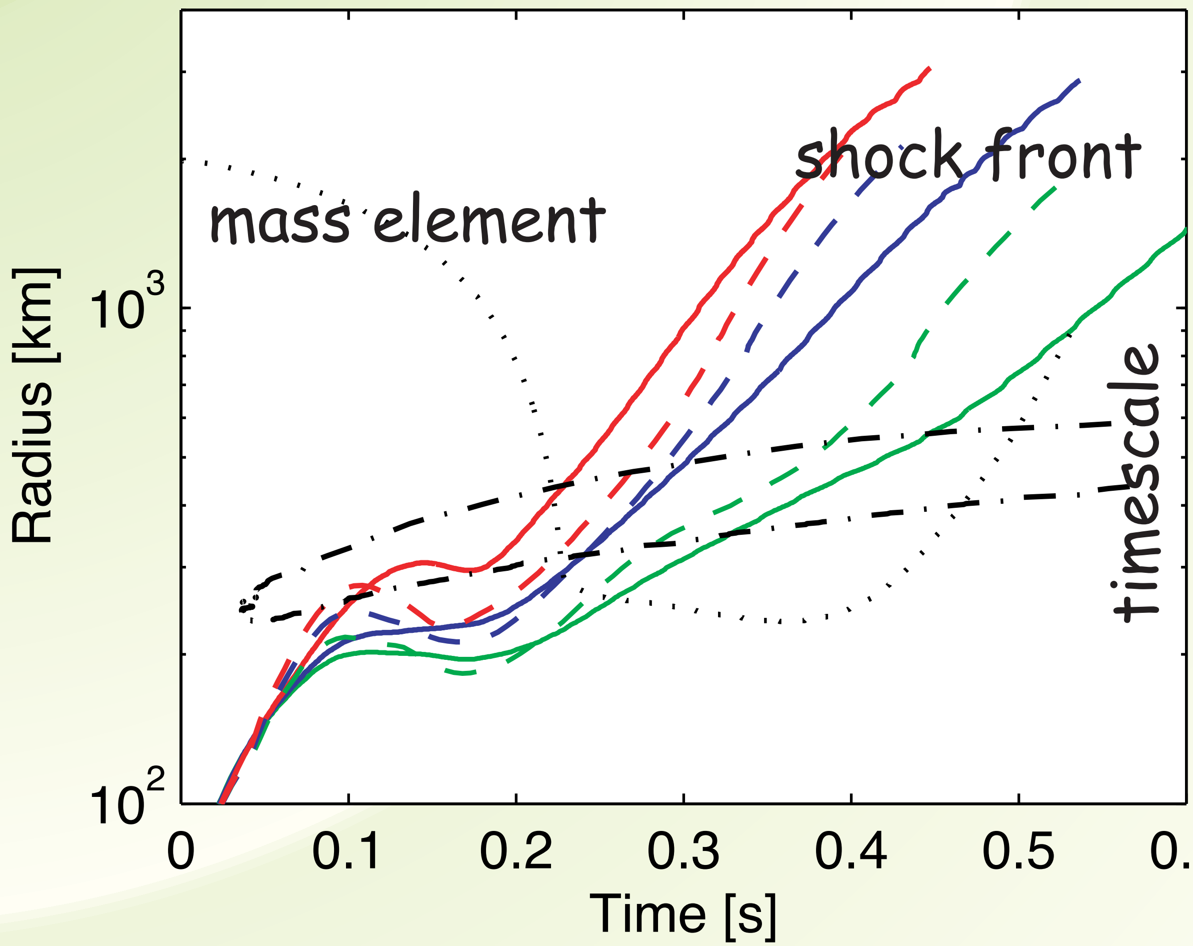
Luminosities and spectra determine explosion

Fröhlich et al., astro-ph/0410208

Explosions of 20 solar mass of Nomoto & Hashimoto forced with
- lowest angular resolution in neutrino transport (efficient & overestimates heating)
- parametrized scattering of neutrinos on free nucleons (0%-60%)

--> still self-consistent in the sense of energy and lepton number conservation



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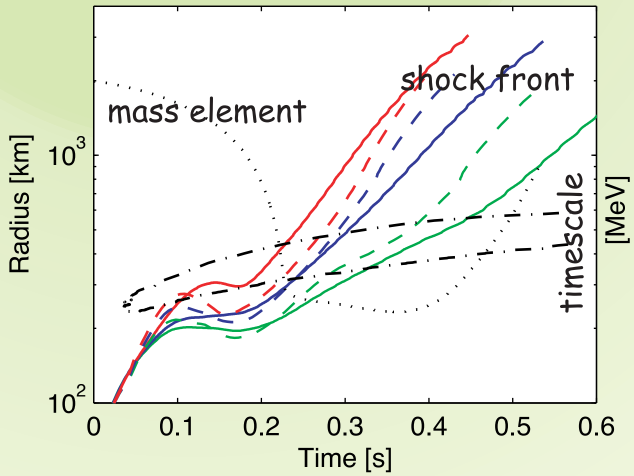

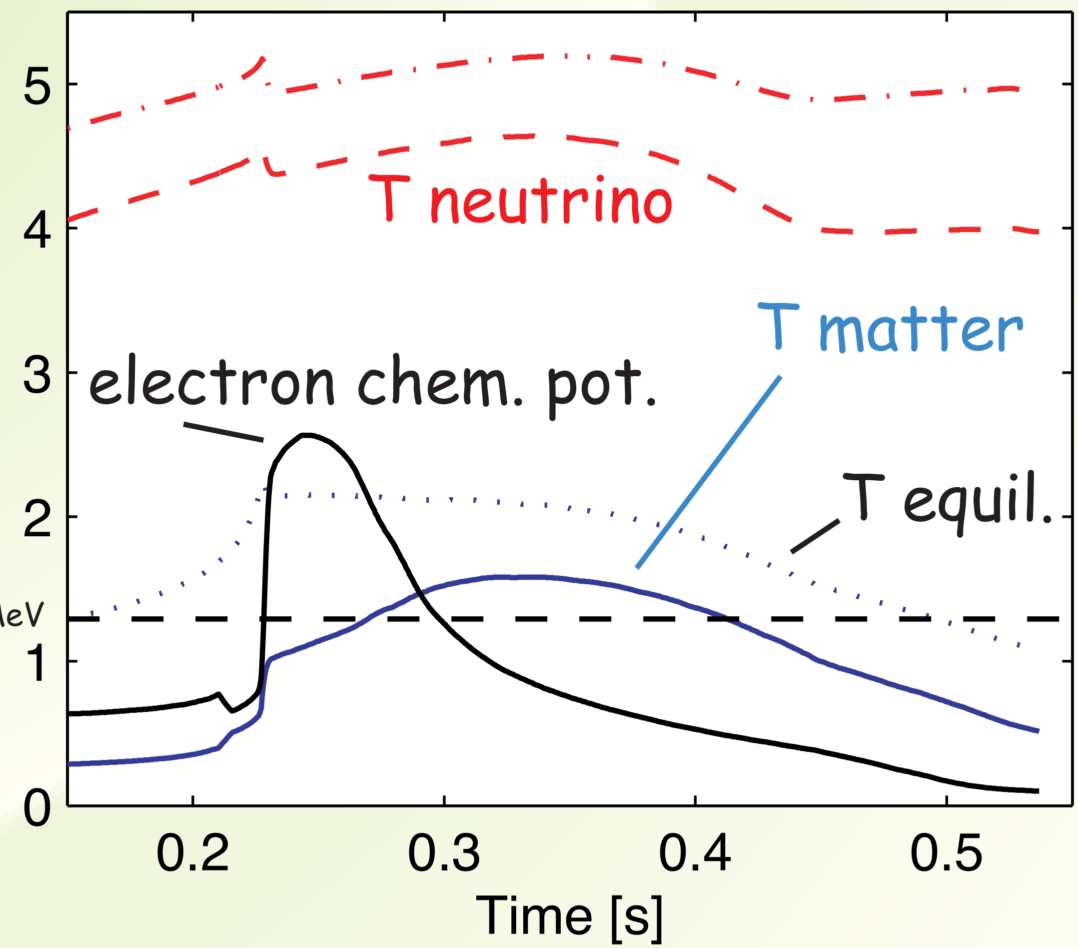

Proton favored!

Luminosities and spectra determine explosion

Fröhlich et al., astro-ph/0410208

Explosions of 20 solar mass of Nomoto & Hashimoto forced with
- lowest angular resolution in neutrino transport (efficient & overestimates heating)
- parametrized scattering of neutrinos on free nucleons (0%-60%)

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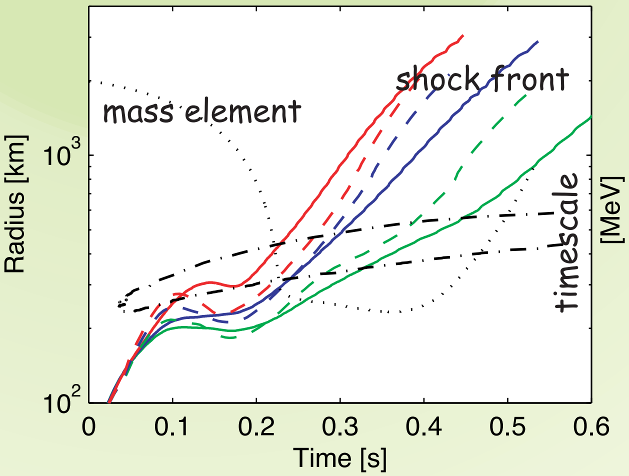

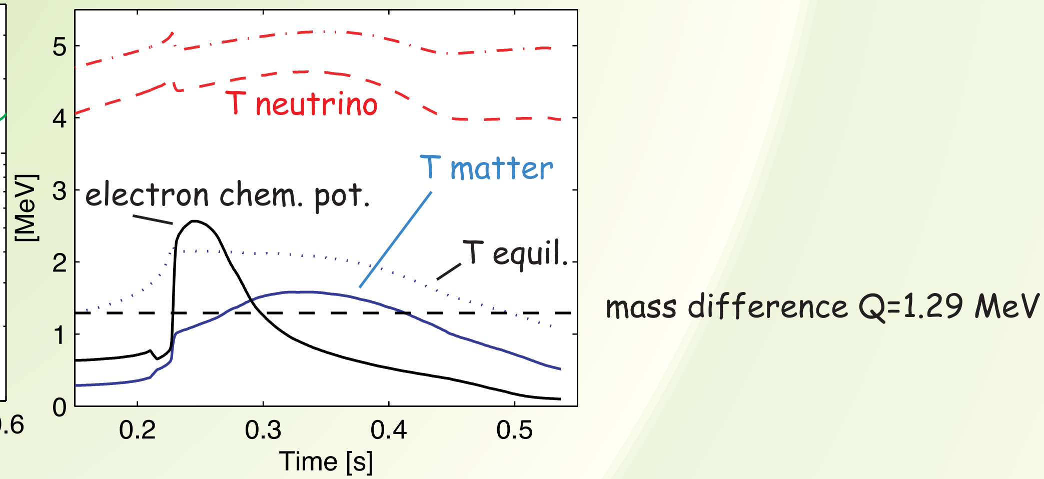

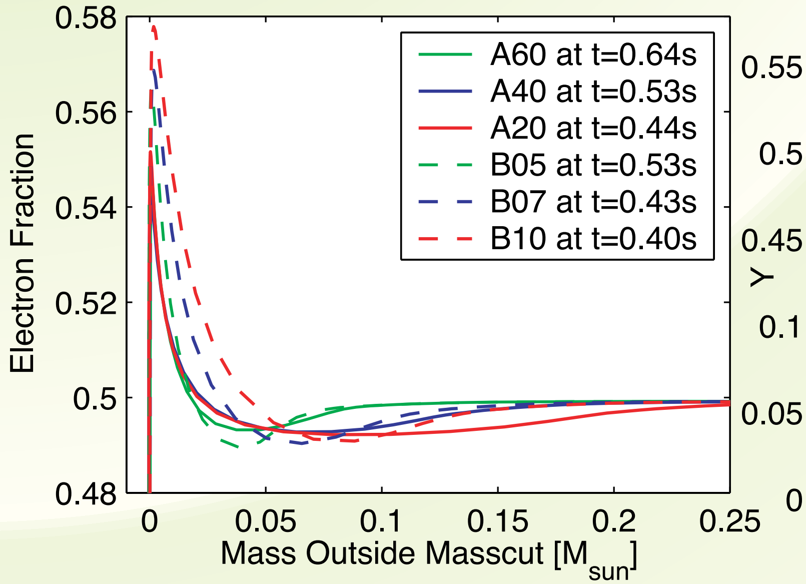

As the electron degeneracy becomes removed in the neutrino heated expanding ejecta, the electron fraction exceeds 0.5, driven by the mass difference between neutron and proton.

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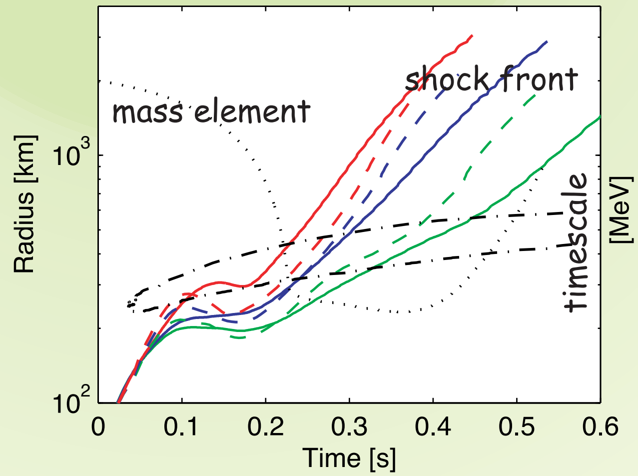

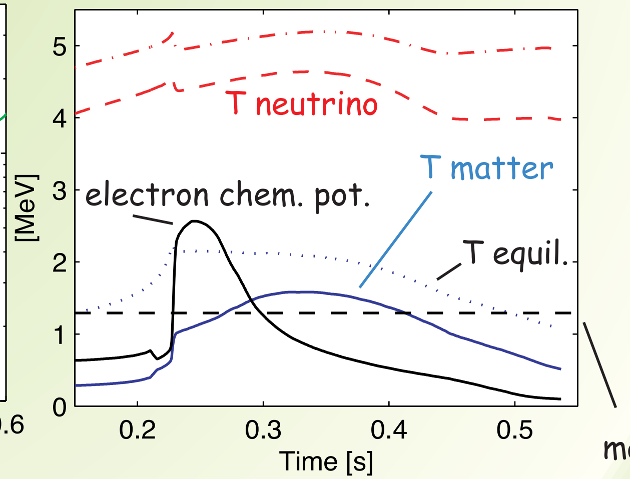

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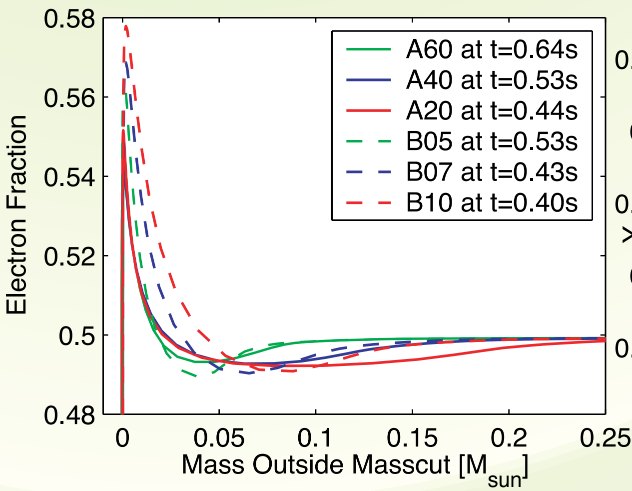
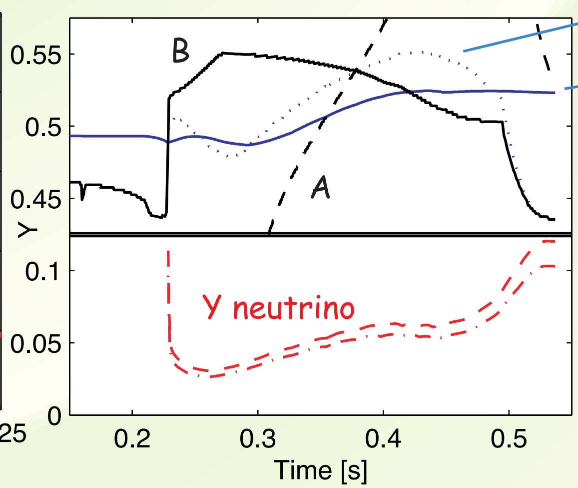


Hauser et al. 200X



A: equilibrium Ye with emission only (Beloborodov 2003)

B: equilibrium Ye with absorption only (Qian & Woosley 1996)

Are magnetic fields a relevant ingredient?

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

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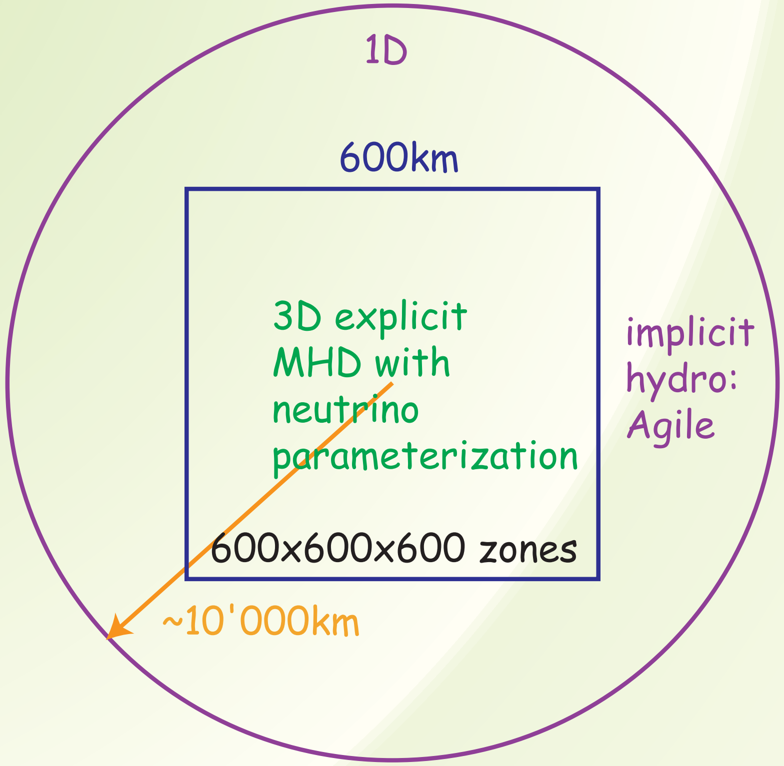
Heger, Woosley, Spruit:
Progenitor field estimate 5x10^9 G, almost no rotation?

Work in progress: 3D MHD simulations

Liebendörfer, Pen, Thompson, Nucl. Phys. A 758 (2005)



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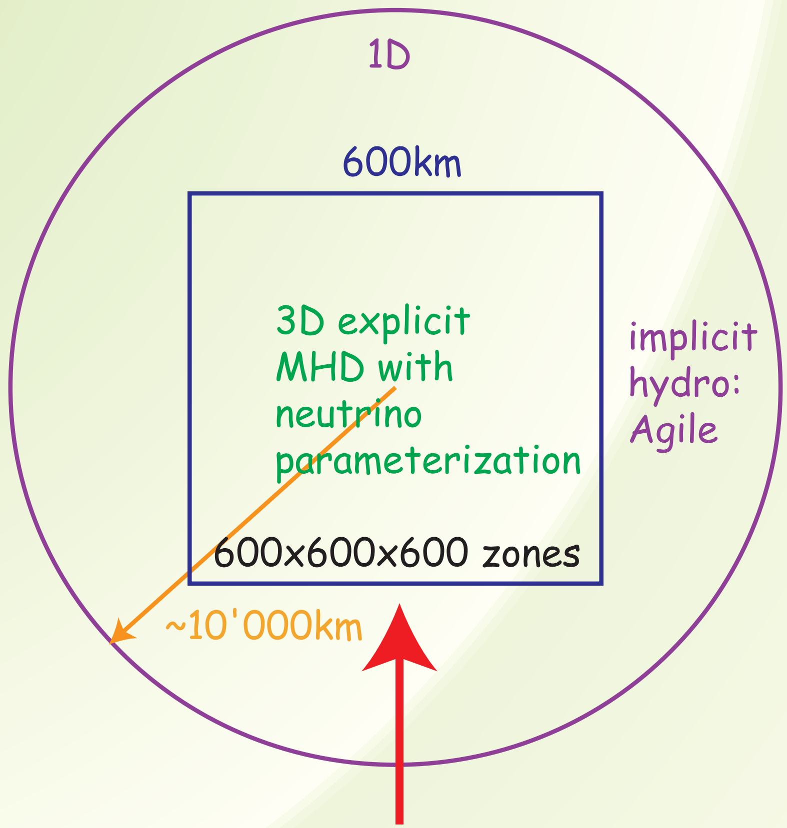

compare resolution to pixels
on 600 laptop screens!

Work in progress: 3D MHD simulations

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Done

3D MHD (Pen, Arras, Wong 2003)

new parallelization: cubic
domain decomposition

second order TVD

velocity decomposition
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(~Trac, Pen 2004)

divergence free
magnetic field

rough fix for magnetic
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Parameterization of
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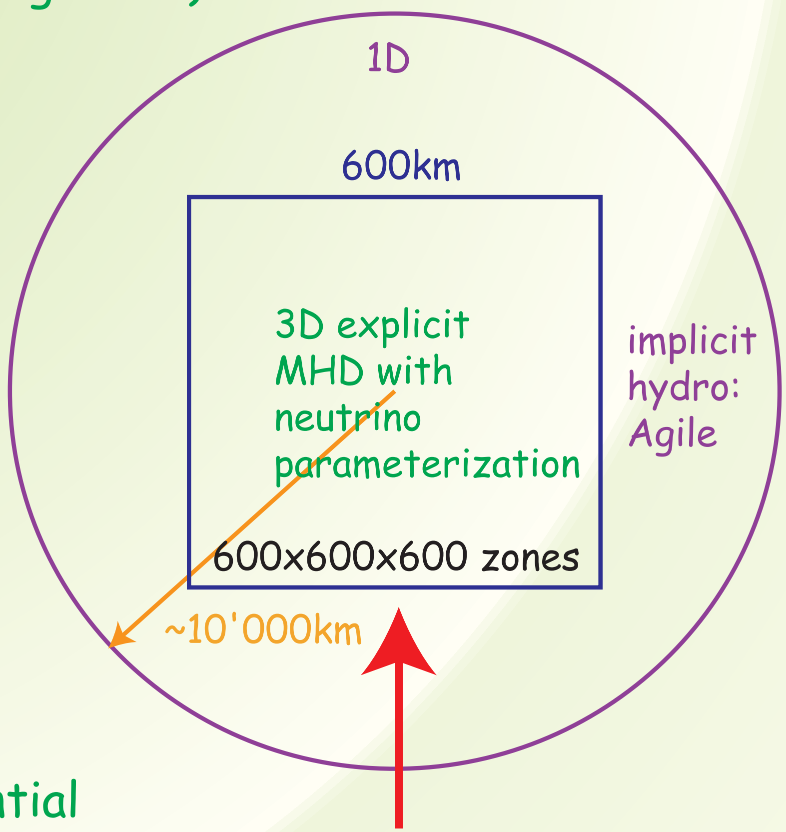

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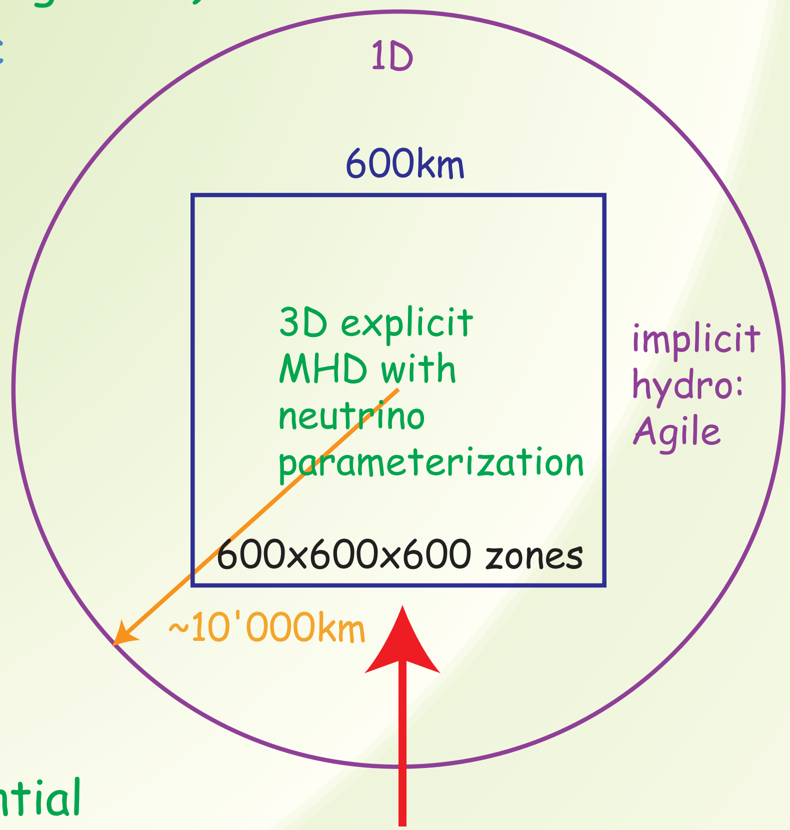

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Todo

evolution of magnetic field and rotation on boundary

keep entropy of PNS over longer time scale

implement neutrino cooling

improve analysis and continue testing

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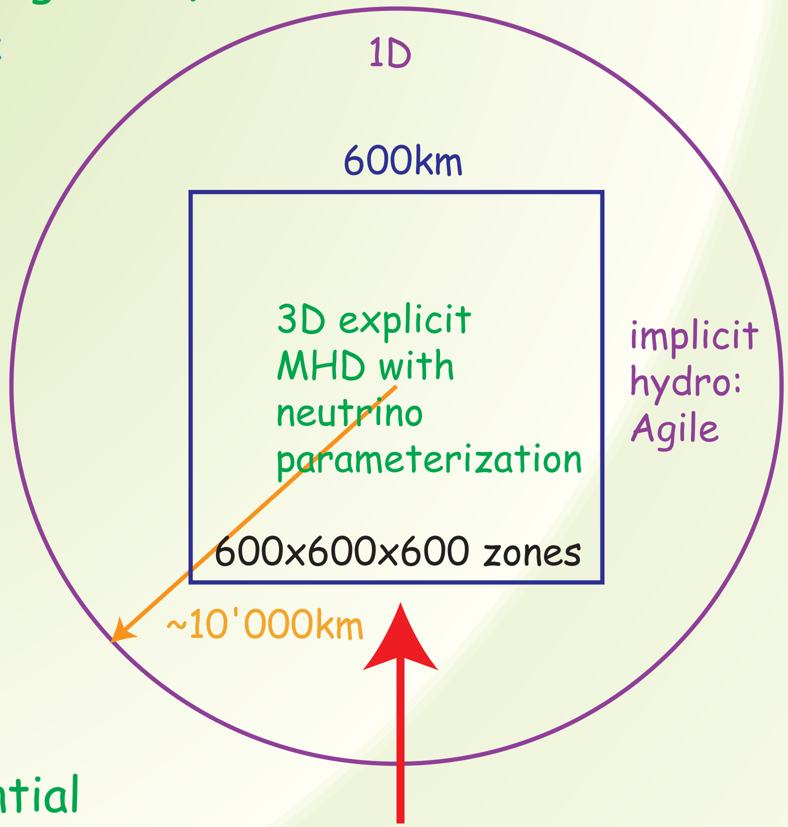

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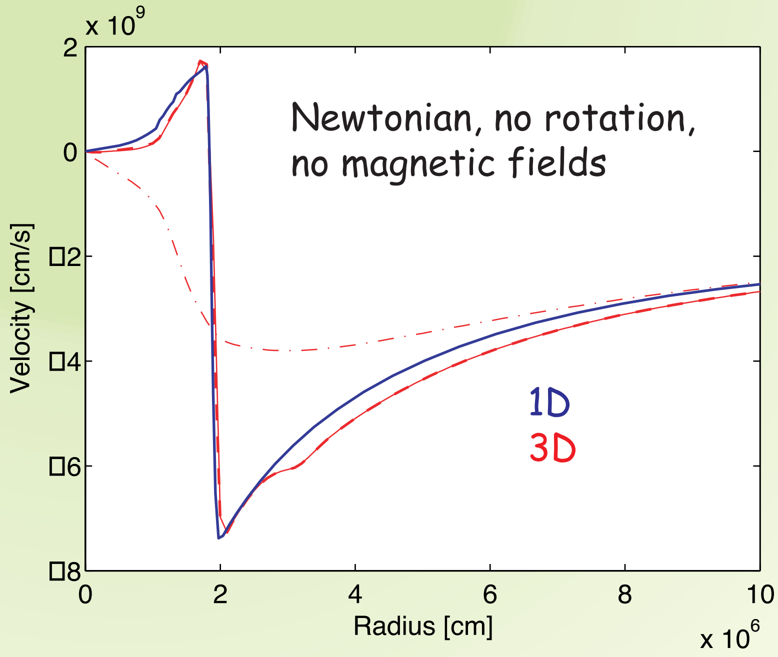
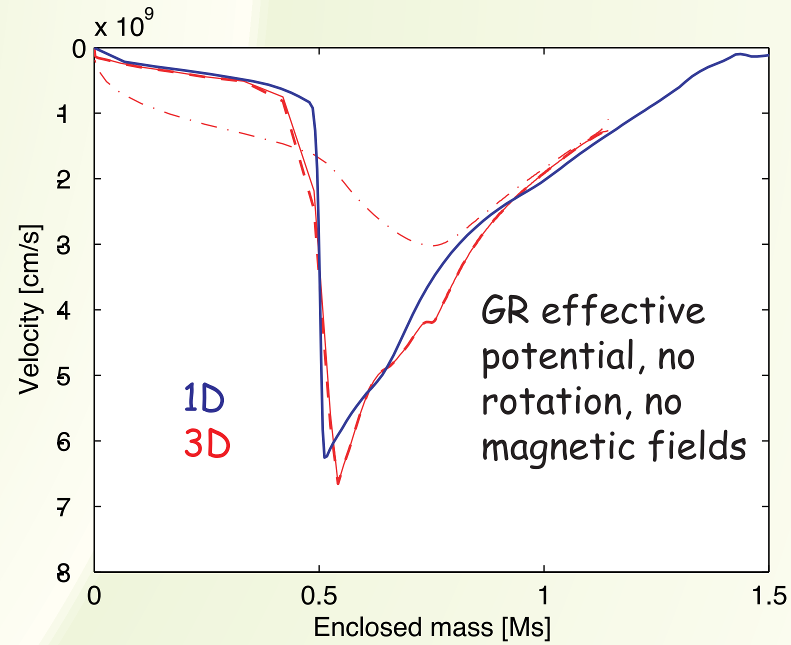
Efficiency:
7 days on 64 processors for progenitor stage to 20ms postbounce.

Work in progress: 3D MHD simulations

N13 (Nomoto, Hashimoto 1988)



G15 (Woosley, Weaver 1995)



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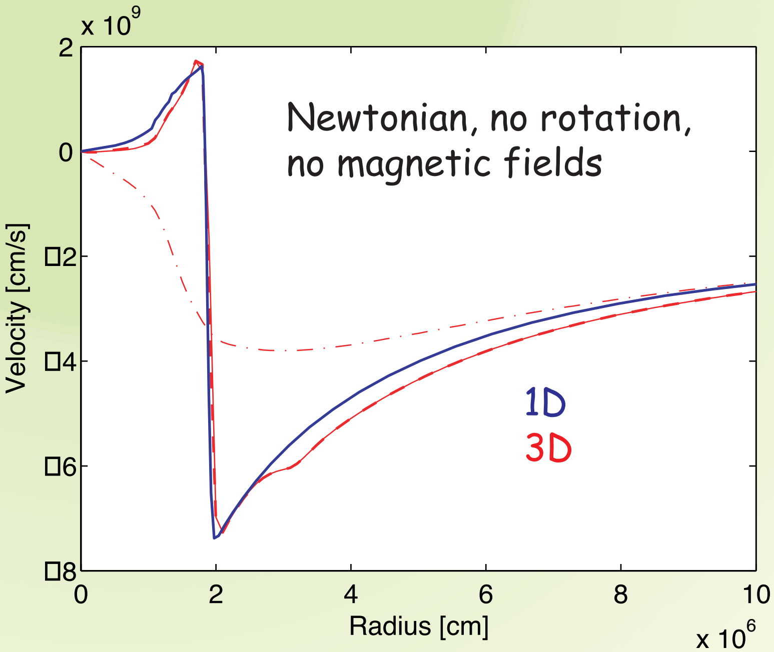

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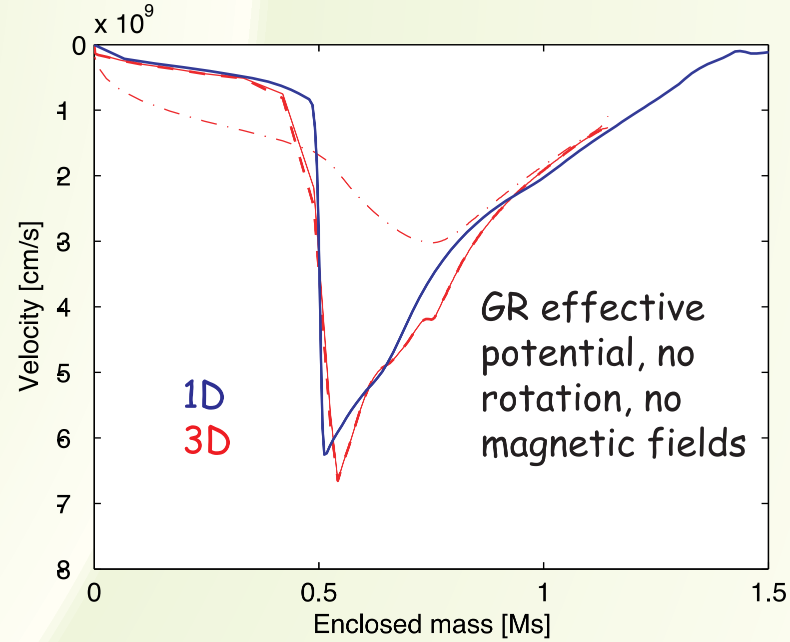

With rotation & magnetic fields

poloidal

initial conditions:

$$\Omega(r) = \Omega_0 \times \frac{{R_0}^2}{r^2 + R_0^2},$$

Omega = 31 rad/s

Ro = 100km

Bo = 10^12 Gauss

toroidal

Work in progress: 3D MHD simulations

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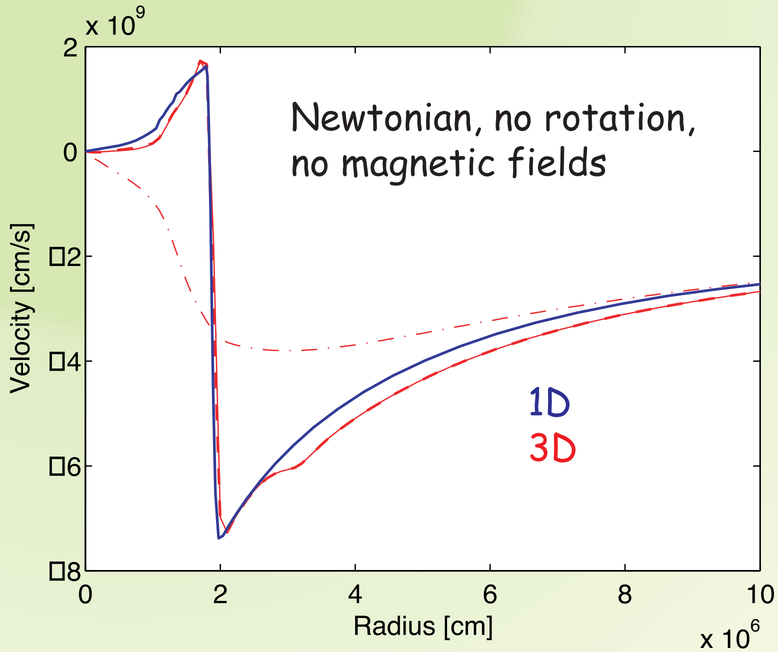

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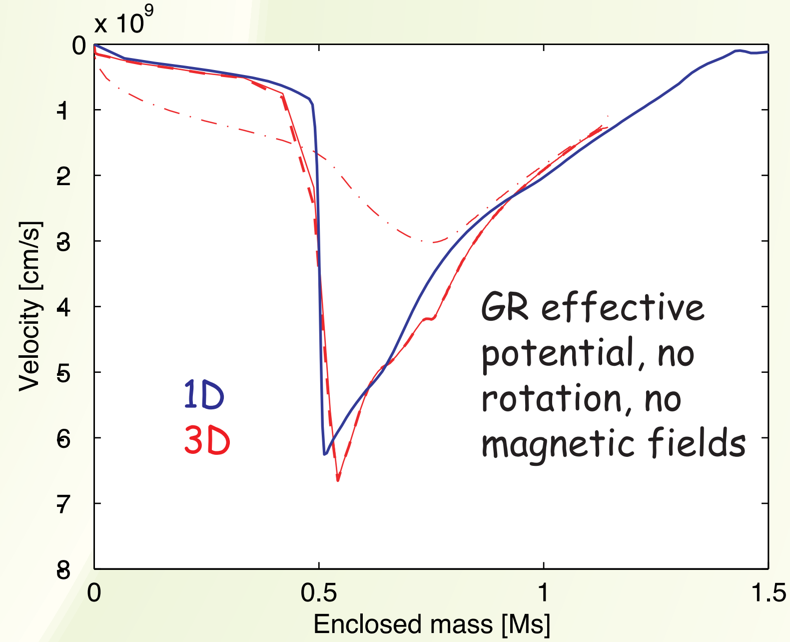

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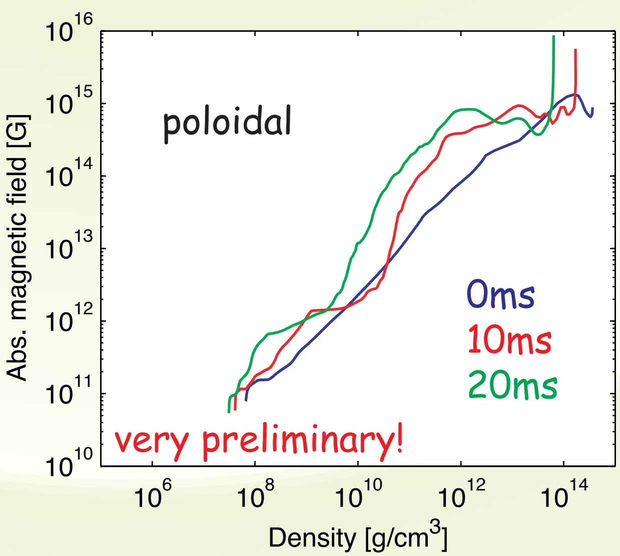

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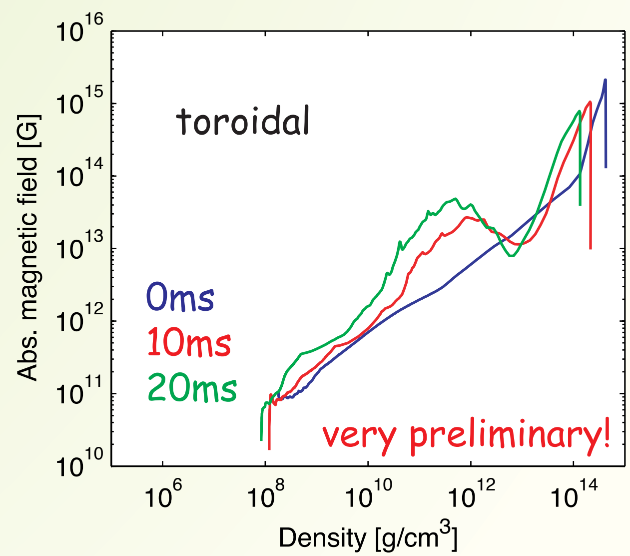

Part II: Summary

- neutrinos determine and couple dynamics in the hot mantle of the protoneutron star
- neutrinos influence the explosive nucleosynthesis
- neutrinos carry important information about the physics under extreme conditions to the Galactic observer

1D
- established and reliable
- explore input physics changes
- reasonable computation time

2D
- current edge of research
- does the SN mechanism work as suggested?

3D
- explore dynamical instabilities
- explore role of magnetic fields