EoS Workshop ANL 2008

Observables of the High-Density Equation of State in Supernovae

M. Liebendörfer
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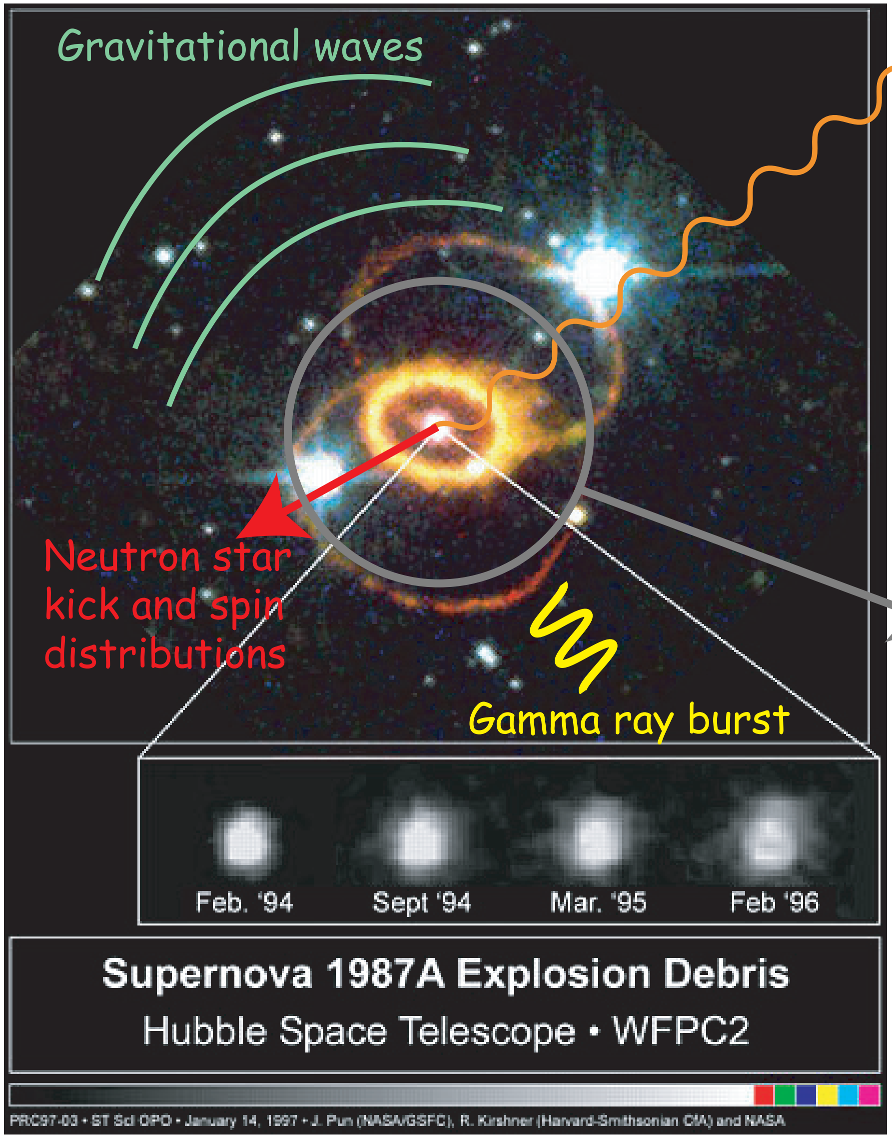
- The core-collapse supernova neutrino signature
- Imprints of the compressibility of the neutron star and an early QCD phase transition to quark matter
- Gravitational waves from stellar core collapse with different equation of state incompressibilities

with

- T. Fischer
- M. Hempel
- A. Mezzacappa
- G. Pagliara
- I. Sagert
- J. Schaffner-Bielich
- S. Scheidegger
- F.-K. Thielemann
- S. Whitehouse

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

Cosmology

Galactic evolution

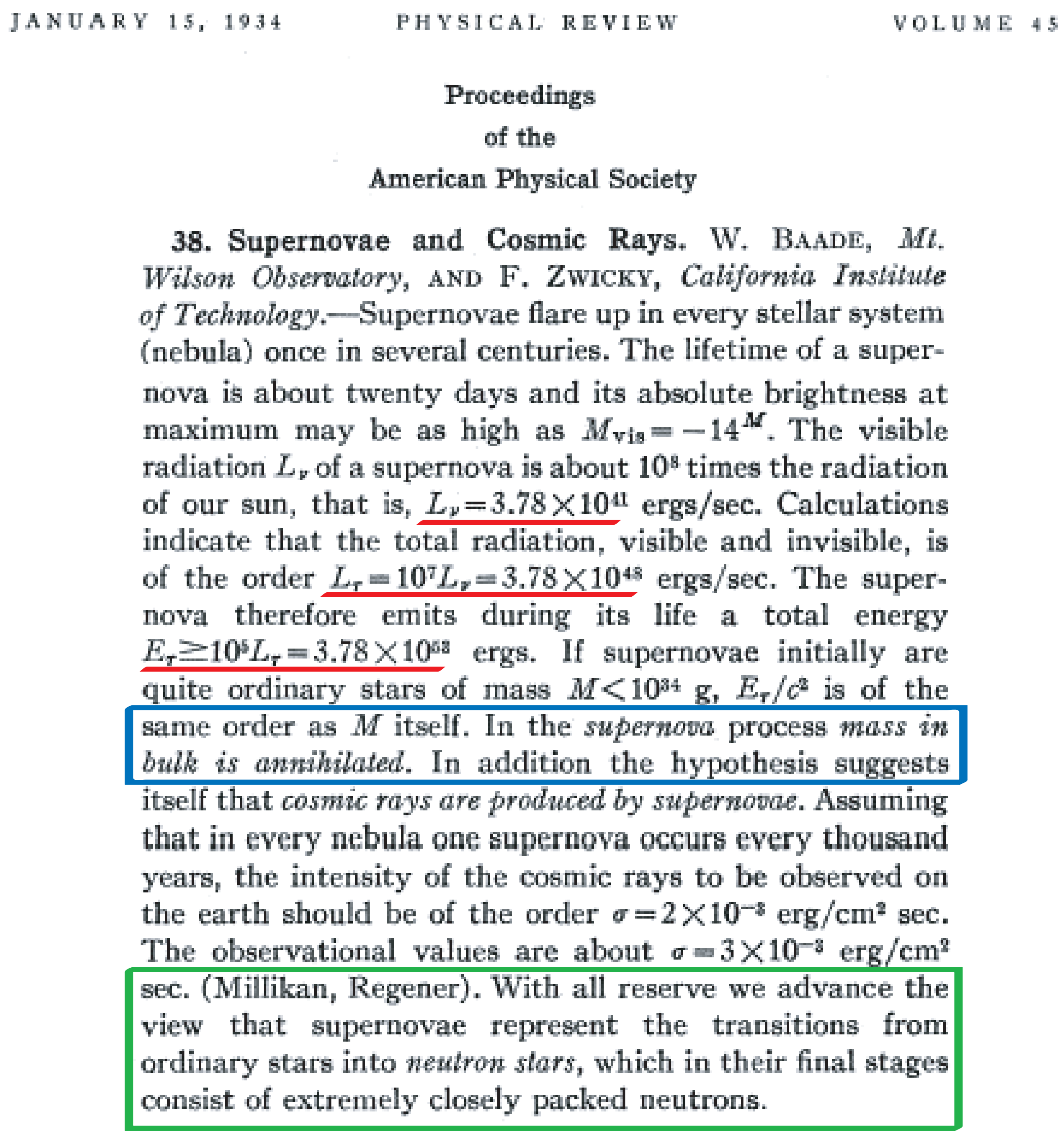
Stellar evolution

Supernova theory

Nuclear Physics
Hydrodynamics
Radiative transfer

Make extreme conditions of matter observable...

Core collapse supernova



JANUARY 15, 1934 PHYSICAL REVIEW VOLUME 45

Proceedings
of the
American Physical Society

38. Supernovae and Cosmic Rays. W. BAADE, *Mt. Wilson Observatory,* AND F. ZWICKY, *California Institute of Technology.*—Supernovae flare up in every stellar system (nebula) once in several centuries. The lifetime of a supernova is about twenty days and its absolute brightness at maximum may be as high as $M_{\mathrm{vis}}=-14^{M}$. The visible radiation L_ν of a supernova is about 10^8 times the radiation of our sun, that is, $L_\nu=3.78\times10^{41}$ ergs/sec. Calculations indicate that the total radiation, visible and invisible, is of the order $L_\tau=10^7L_\nu=3.78\times10^{48}$ ergs/sec. The supernova therefore emits during its life a total energy $E_\tau\geq10^6L_\tau=3.78\times10^{53}$ 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 $\sigma=2\times10^{-3}$ erg/cm² sec. The observational values are about $\sigma=3\times10^{-3}$ 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.

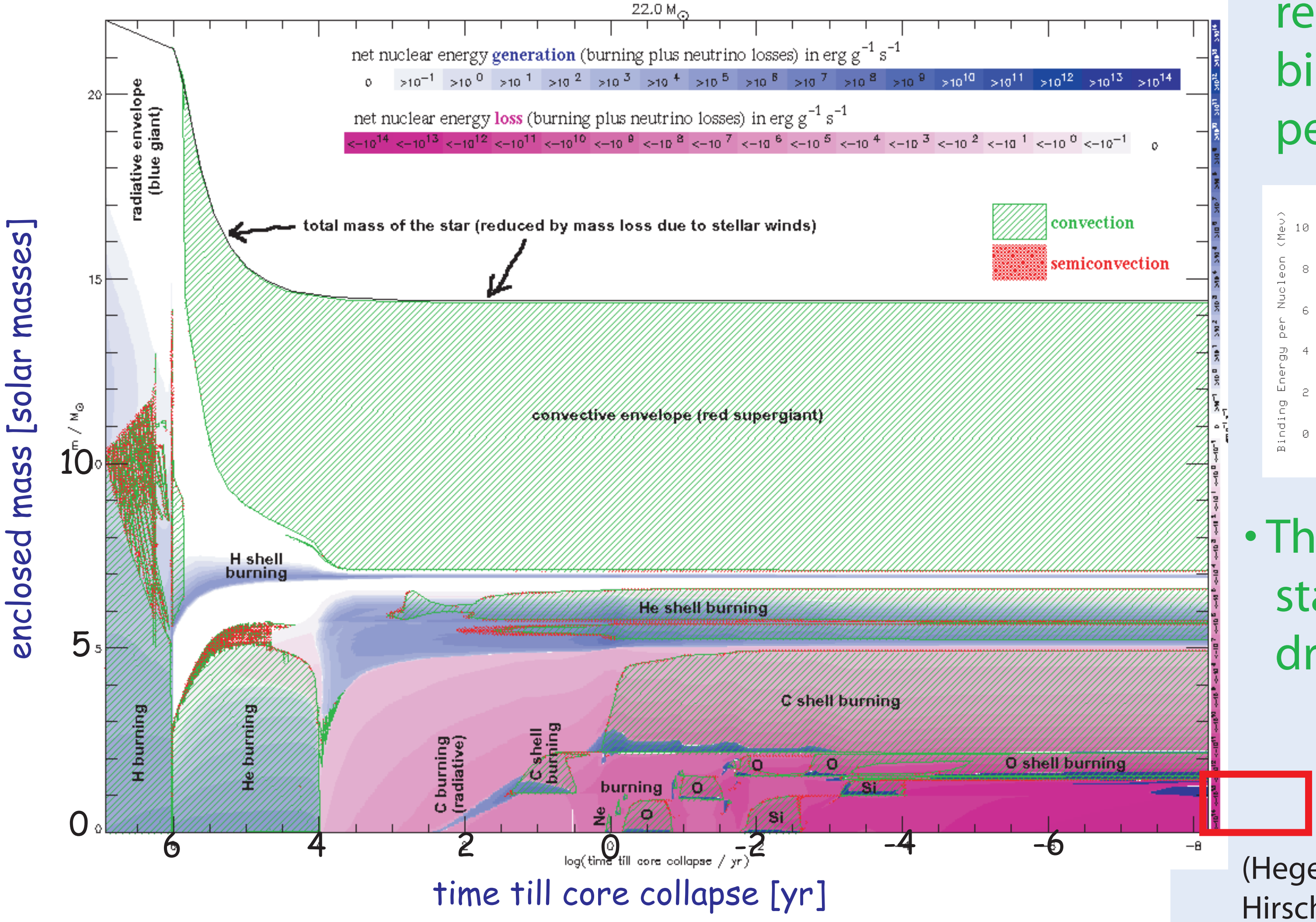
Huge Energies

- neutrinos:
  ~1e+53 erg
- mechanical:
  ~1e+51 erg
- electro-magn.:
  ~1e+48 erg elmag
- visible:
  ~1e+41 erg visible

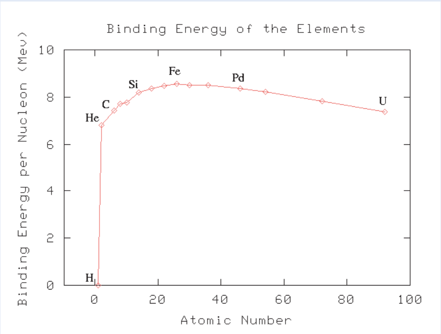
56Ni -> 56Co ->56Fe
~6d ~110d

Iron core collapse

Overview of burning phases in stellar evolution



- Fusion in core reaches maximum binding energy per baryon



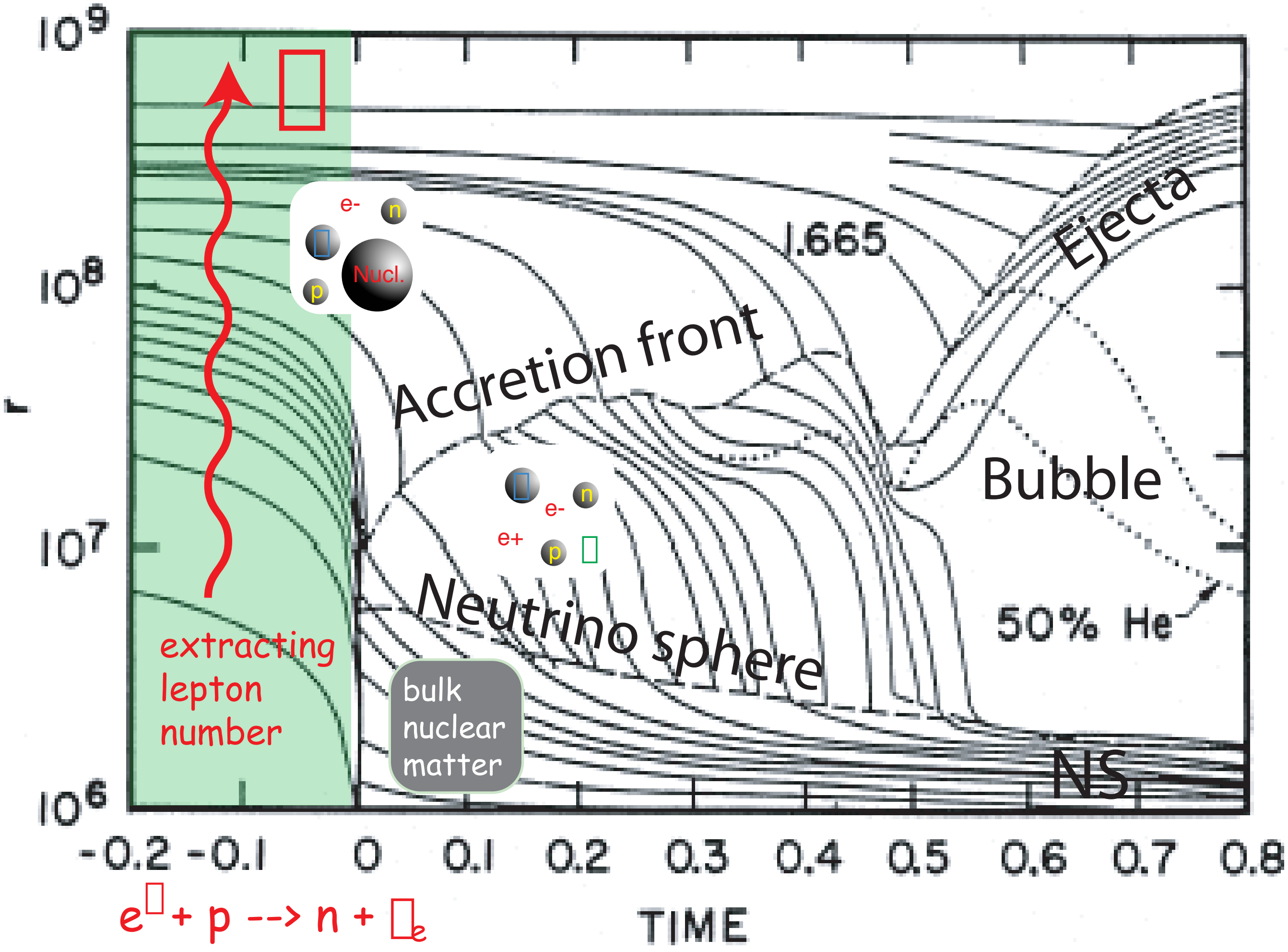
- There is a maximum stable mass: Chandrasekhar mass

stellar core collapse
<-- happens here!

(Heger & Woosley 2002, see also Hirschi, Meynet, Maeder 2005)

Delayed explosion: 4 phases

BETHE AND WILSON ApJ 295 (1985)

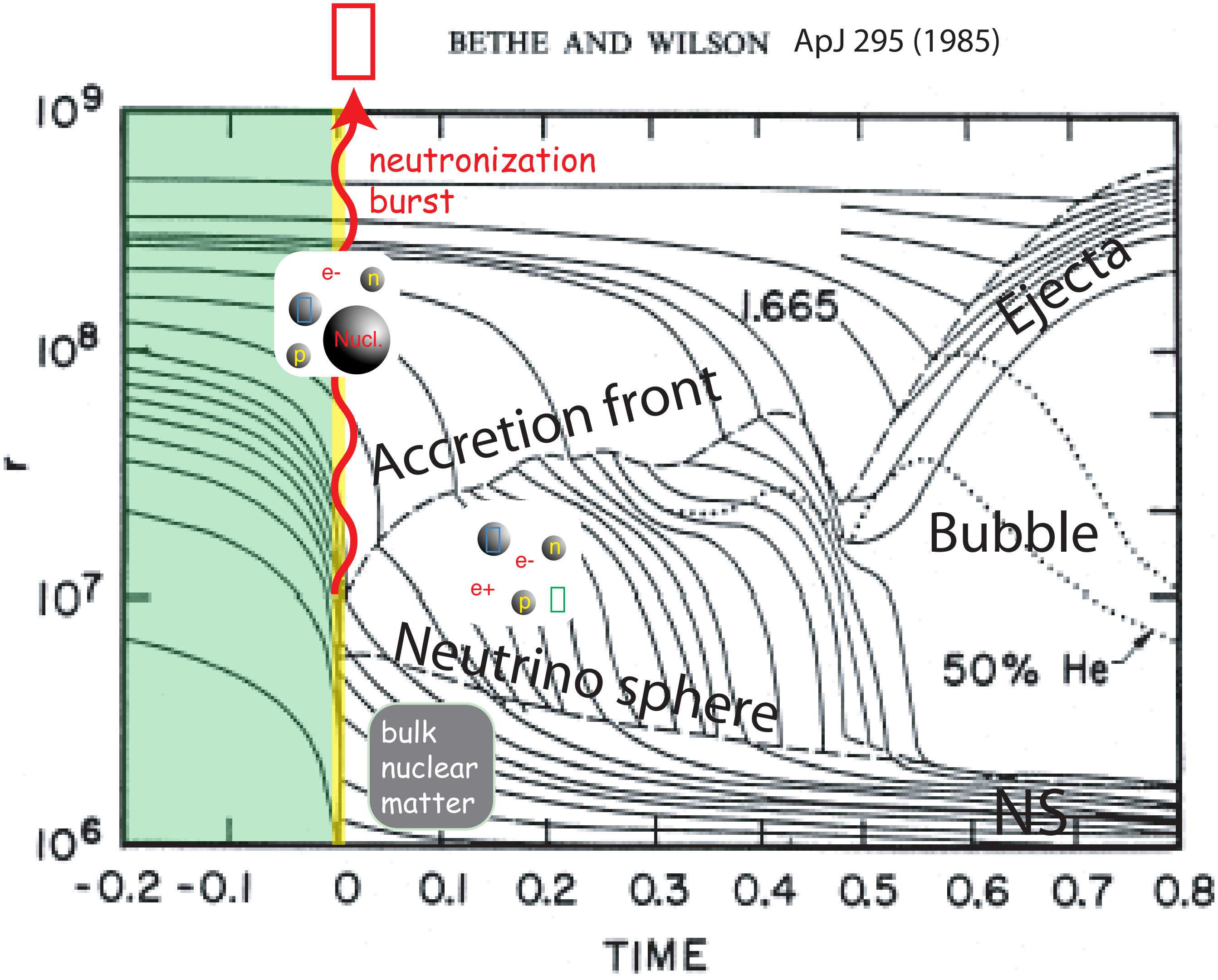


$e^{\square} + p \dashrightarrow n + \square_e$

Colgate & White, ApJ 143 (1966)

1) Collapse

Delayed explosion: 4 phases



BETHE AND WILSON ApJ 295 (1985)

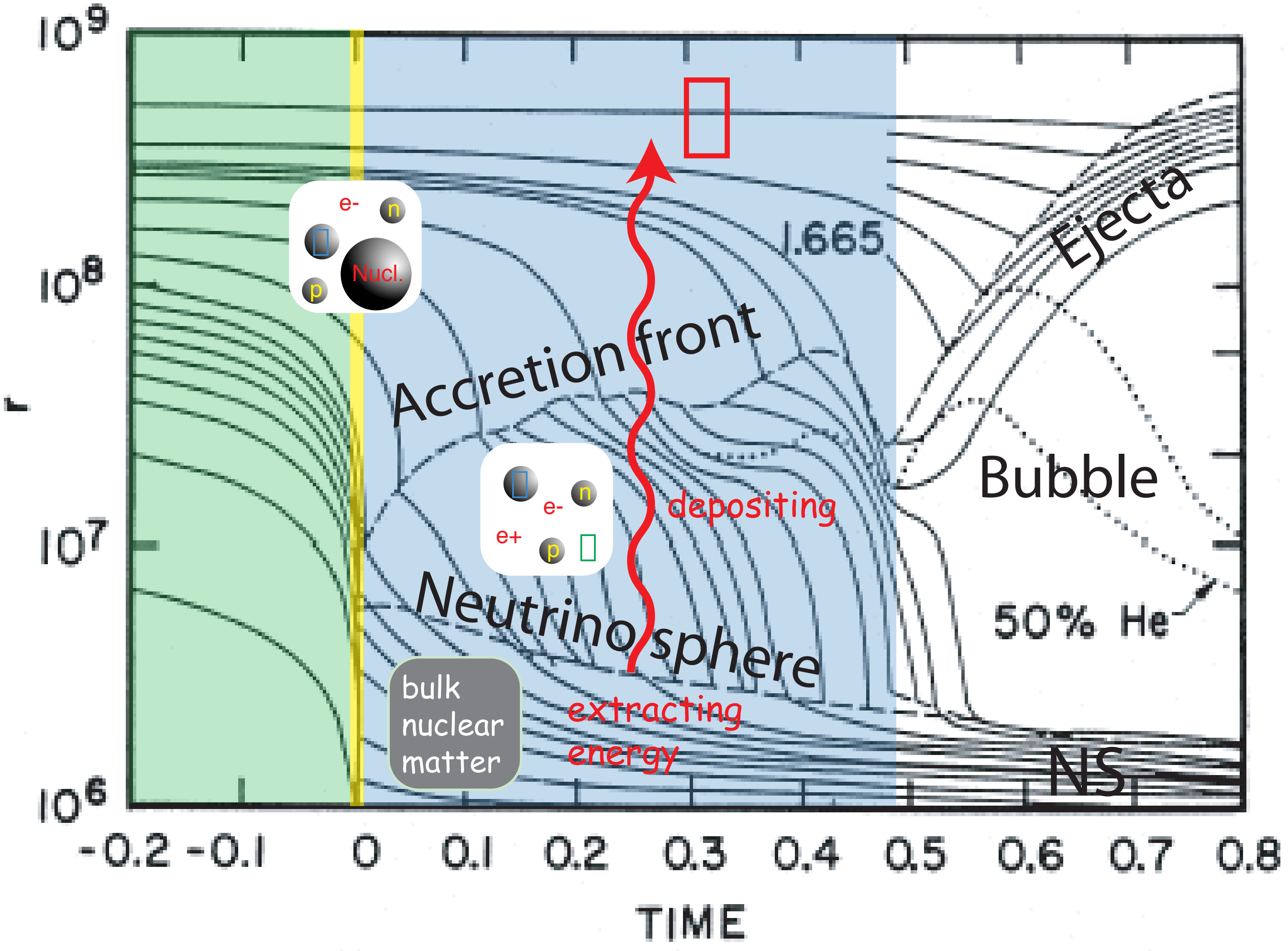
Colgate & White, ApJ 143 (1966)

1) Collapse

2) Bounce

Delayed explosion: 4 phases

BETHE AND WILSON ApJ 295 (1985)



Colgate & White, ApJ 143 (1966)

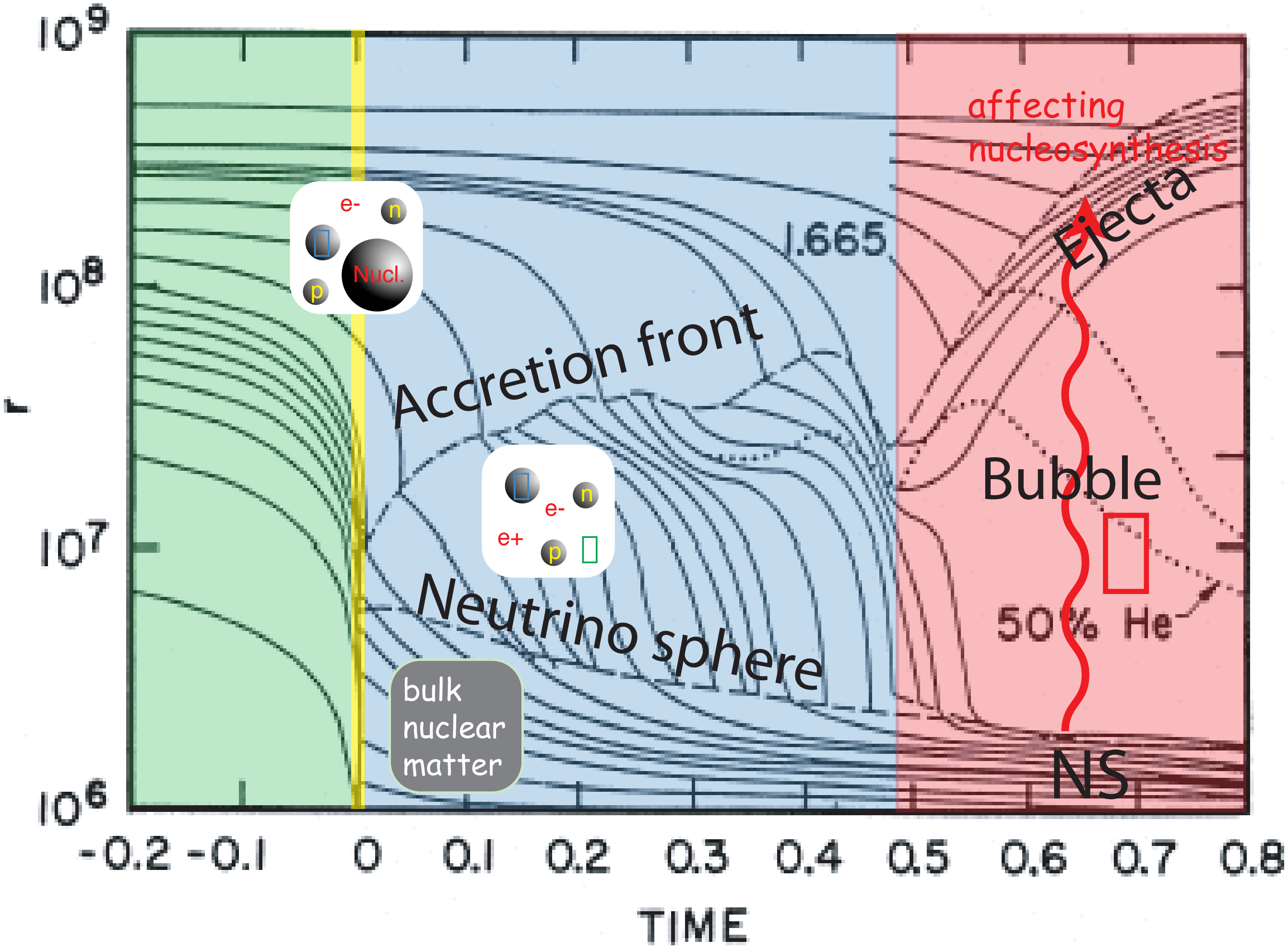
1) Collapse

2) Bounce

3) Accretion

Delayed explosion: 4 phases

BETHE AND WILSON ApJ 295 (1985)



Colgate & White, ApJ 143 (1966)

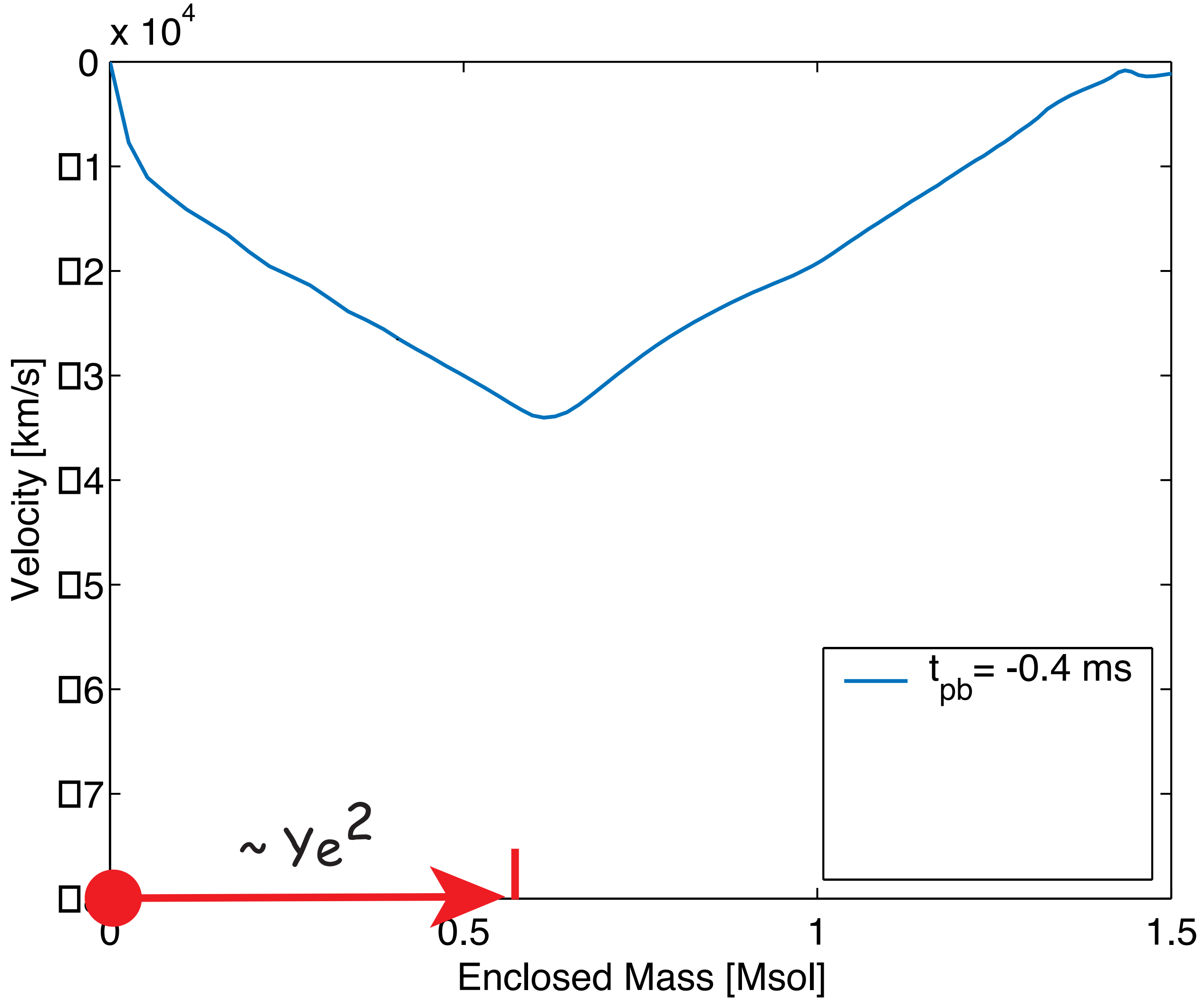
1) Collapse

2) Bounce

3) Accretion

4) Explosion

Neutronization during collapse



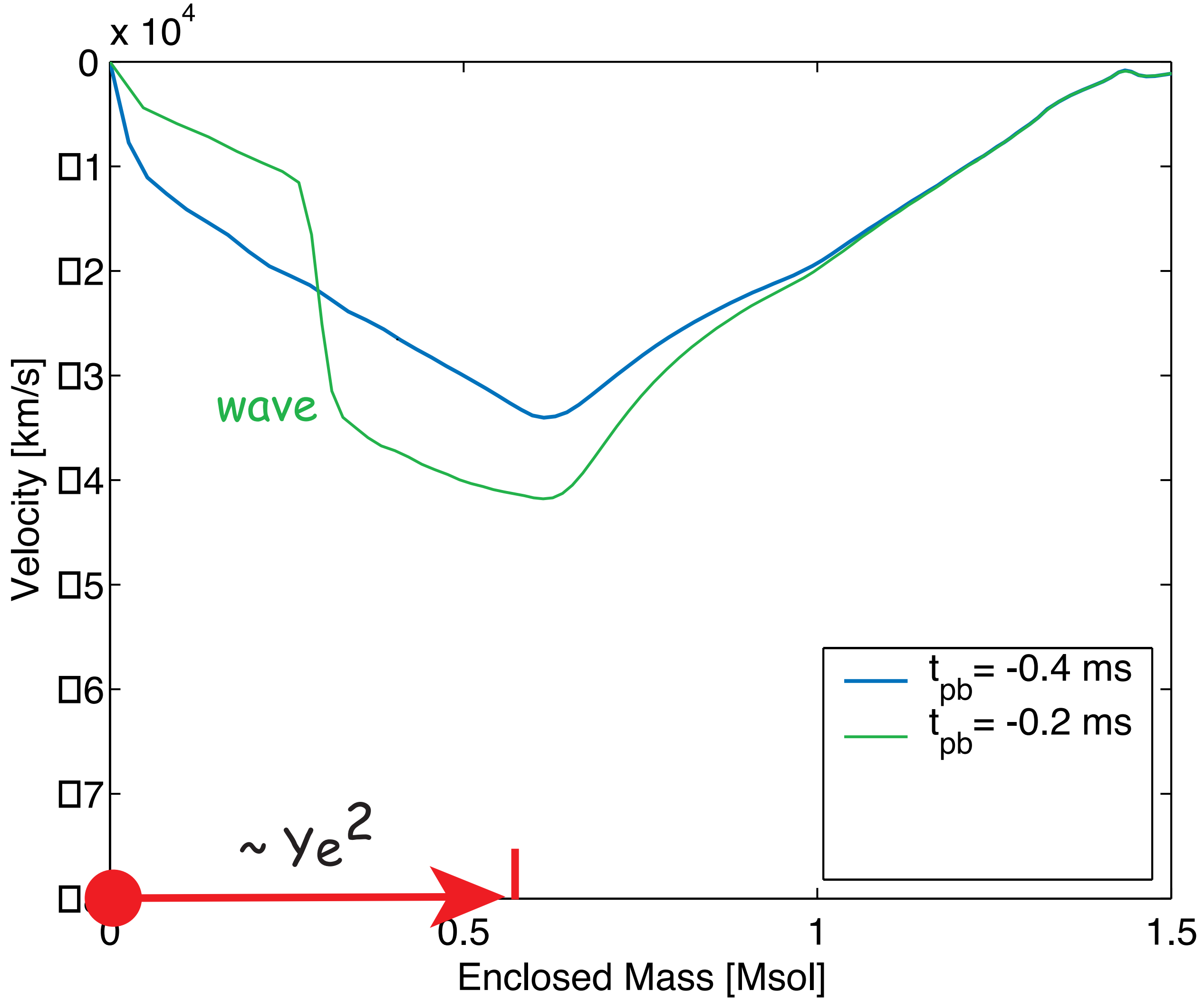
- causally connected collapse of iron core
- lower density in outer layers --> lower sound speed
- retarded infall of outer layers

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

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

(Goldreich & Weber 1980)

Neutronization during collapse



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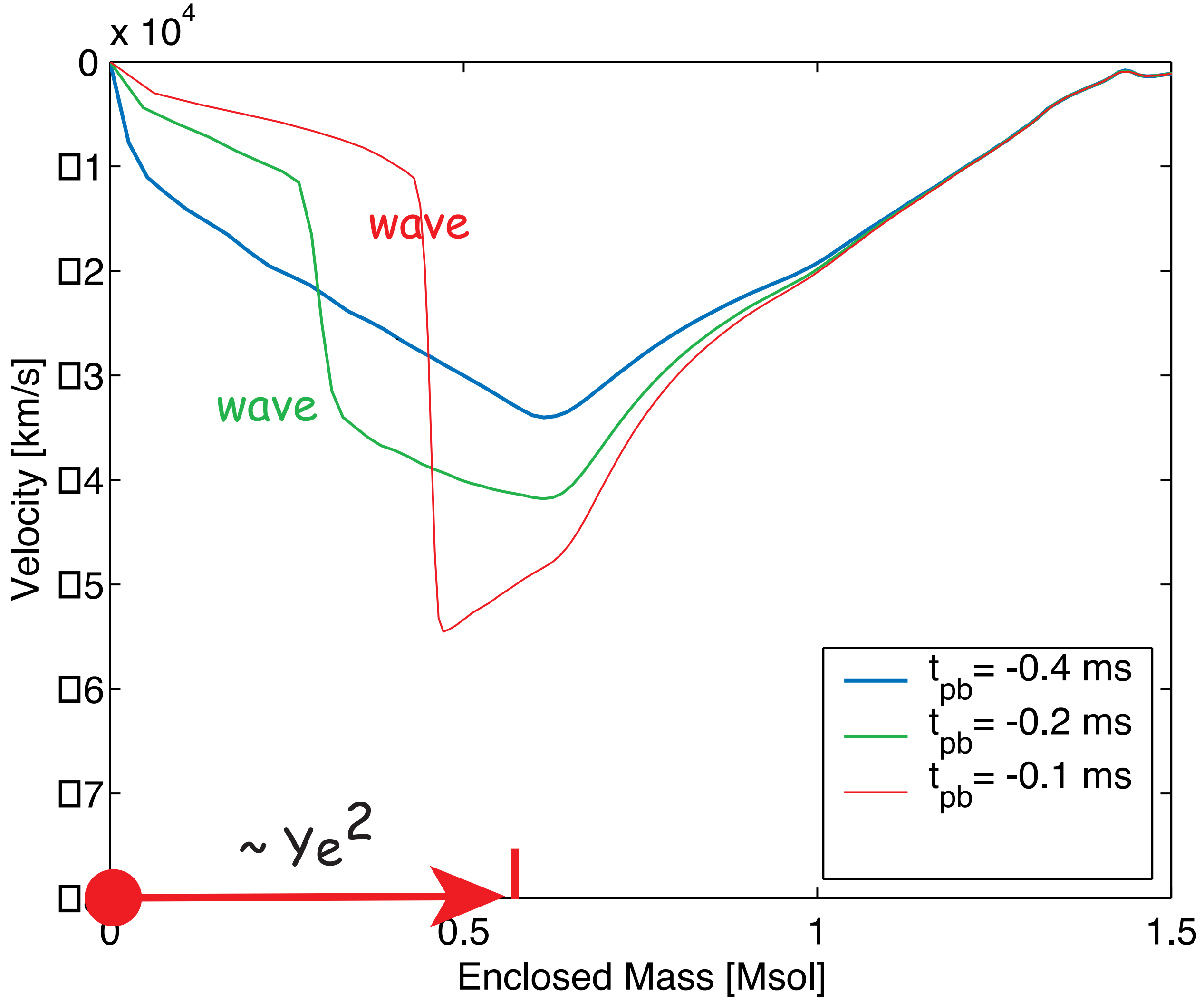

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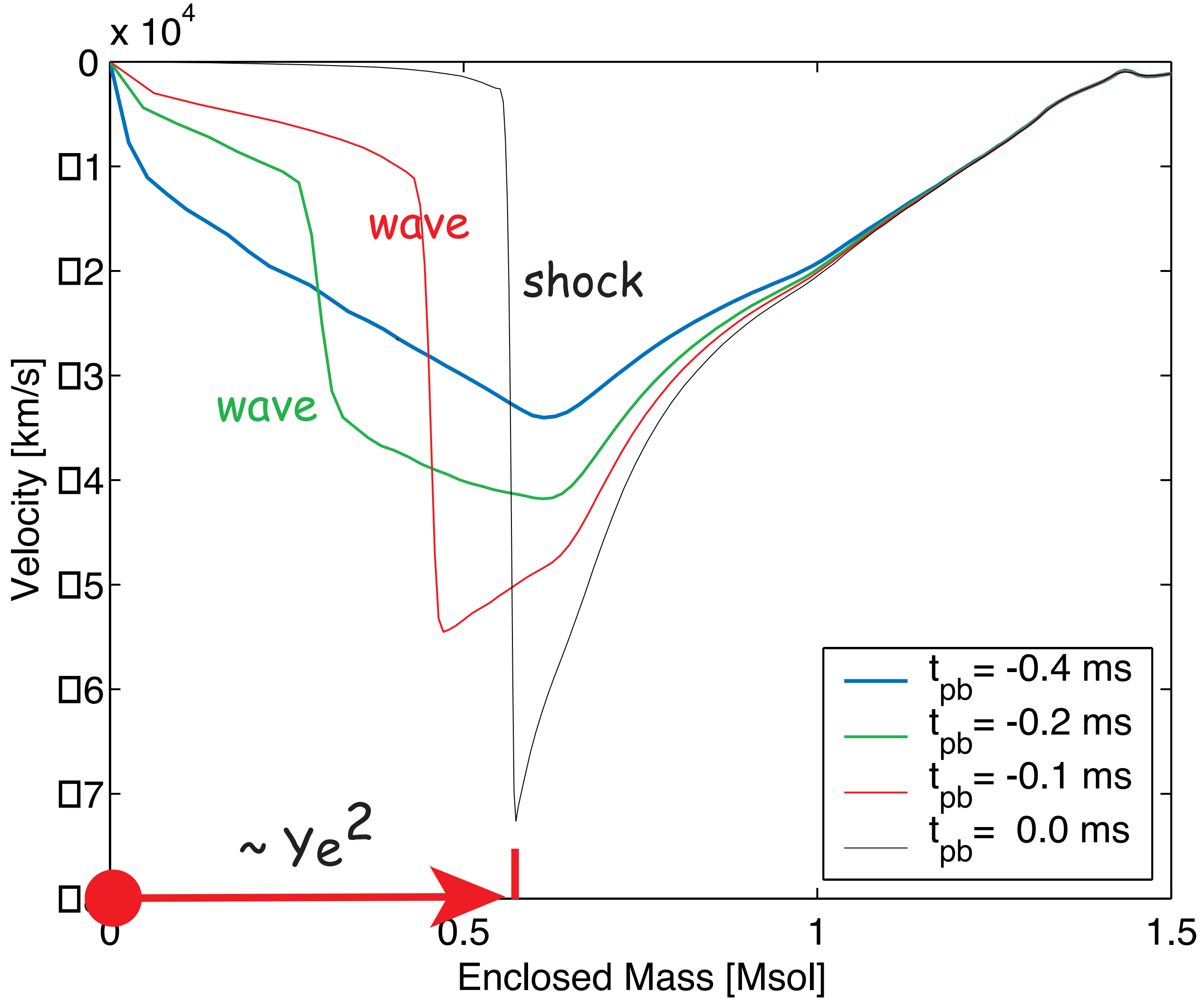

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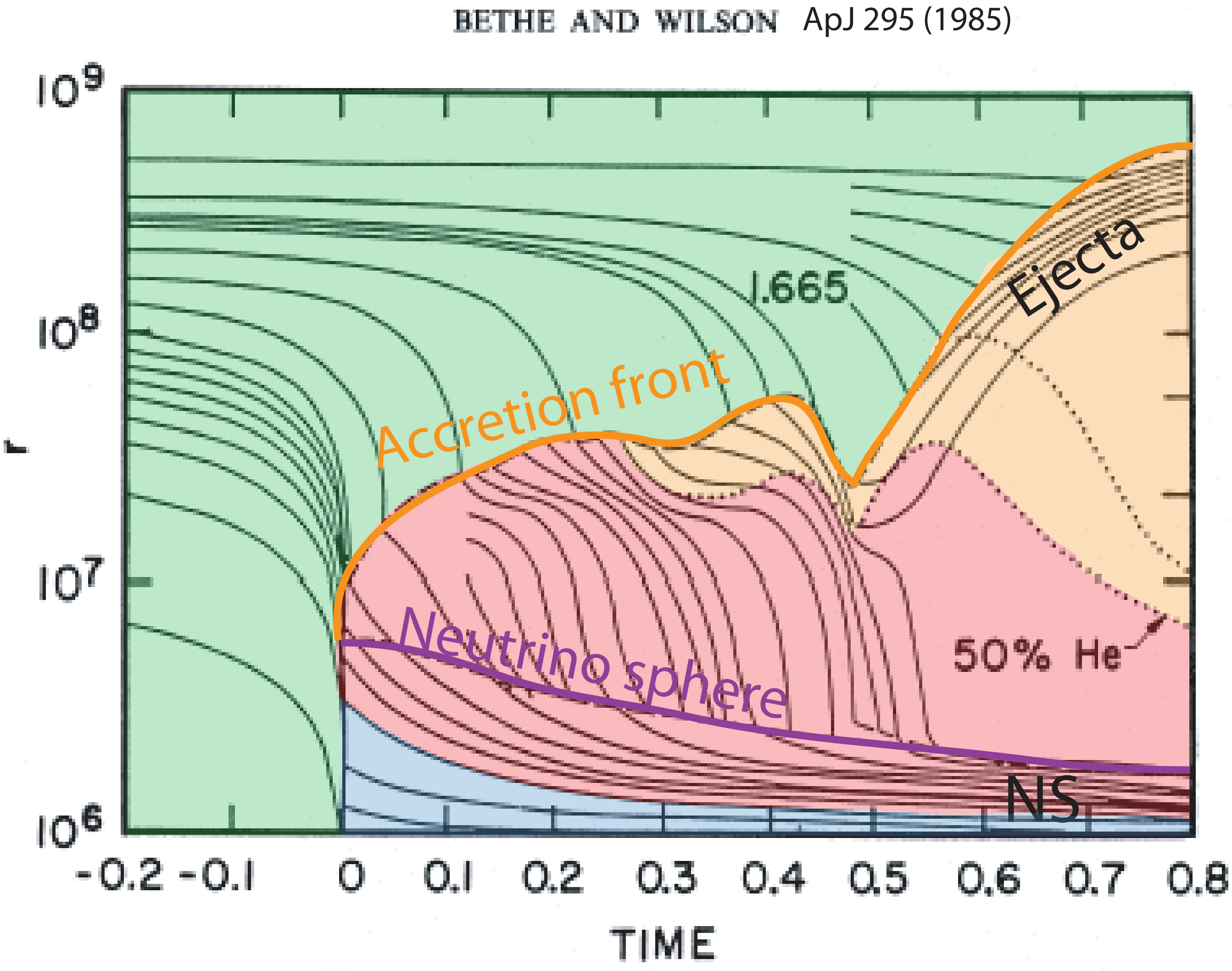
Overview matter conditions



Colgate & White, ApJ 143 (1966)

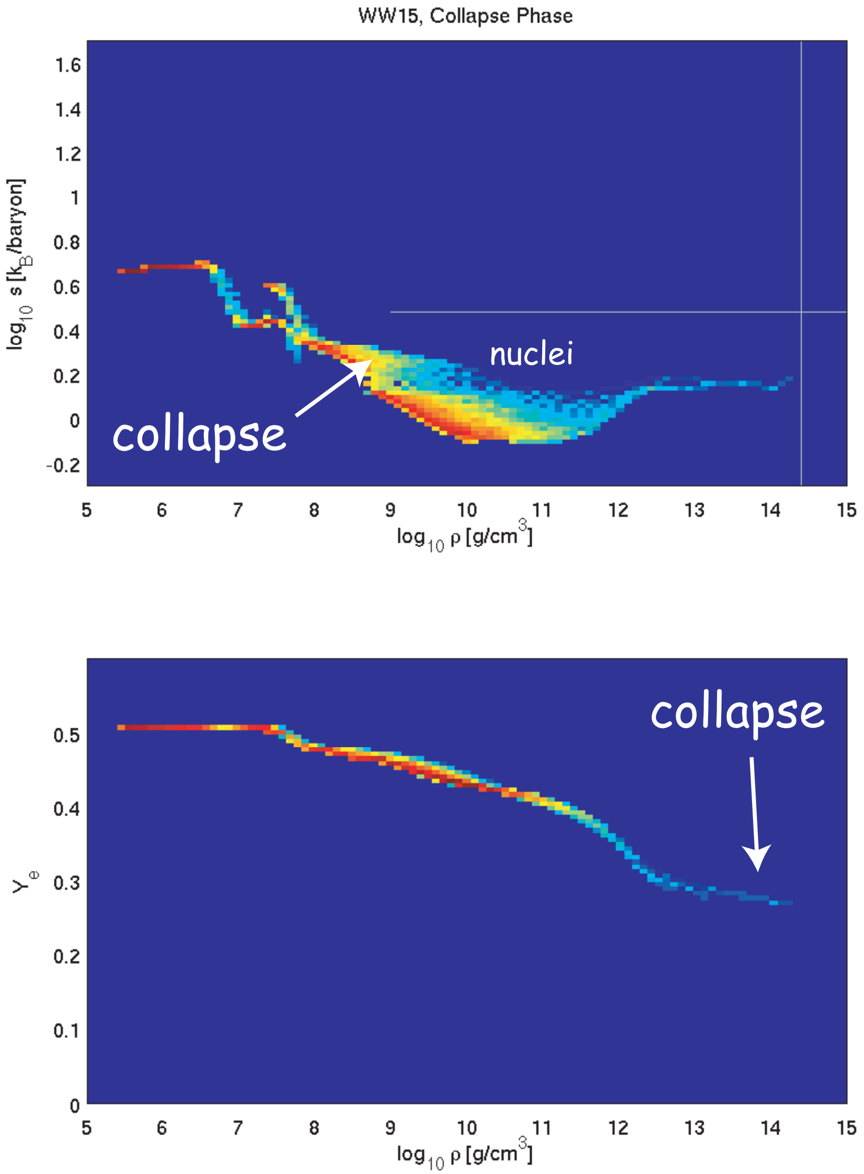
1) Ensemble of nuclei

2) Cool bulk nuclear matter

3) Hot dissociated

4) Freeze-out of nuclei

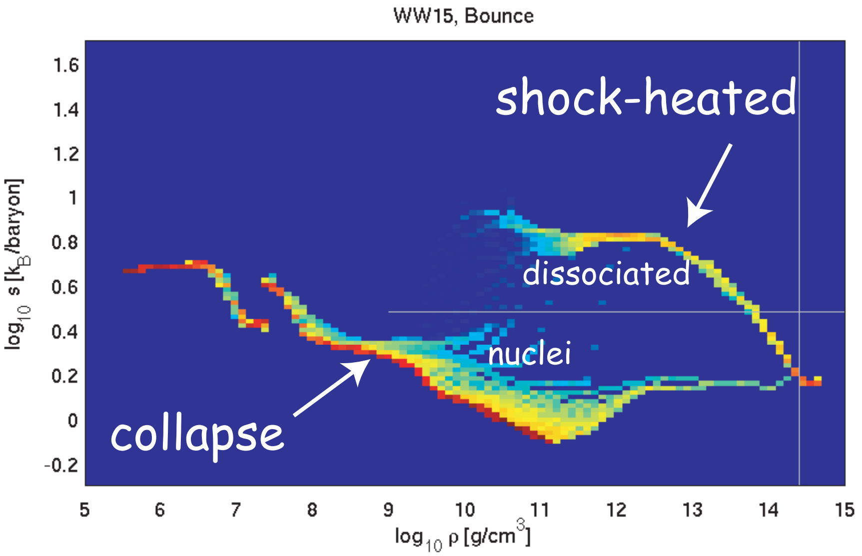
Conditions in (ρ,s,Ye)-space

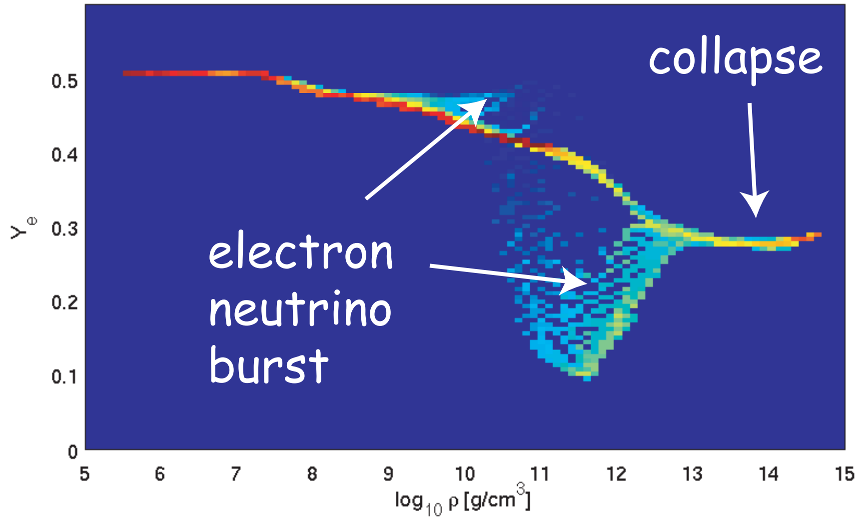


Collapse Phase:

- deleptonization along narrow trajectory
- slight entropy increase

Conditions in (ρ,s,Ye)-space





Collapse Phase:

- deleptonization along narrow trajectory
- slight entropy increase

Postbounce Phase:

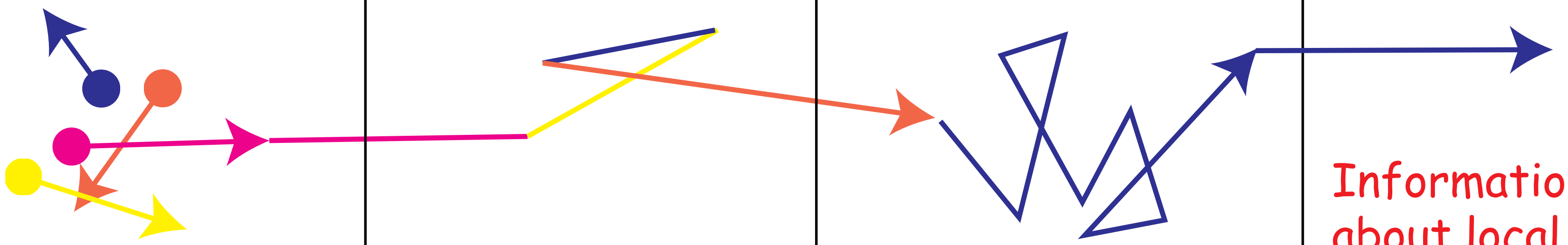
- jump to dissociated nucleon plasma

Neutrino-matter interactions

Bruenn (1985)
Raffelt (2001)

Number Sphere | Energy Sphere | Transport Sphere

High matter density



Production & Annihilation

Pauli-blocked in diffusive regime

Inelastic Scattering

Enhanced by elastic scattering

Elastic Scattering

Strong energy dependence, ~E^2

Free streaming

Information about local conditions carried to observer

Electron or Positron capture

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

NN bremsstrahlung (Thompson et al. 2002)
□e pair --> □□ pair (Buras et al. 2003)

Neutrino-electron scattering

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

Inelastic neutrino-nucleus scattering

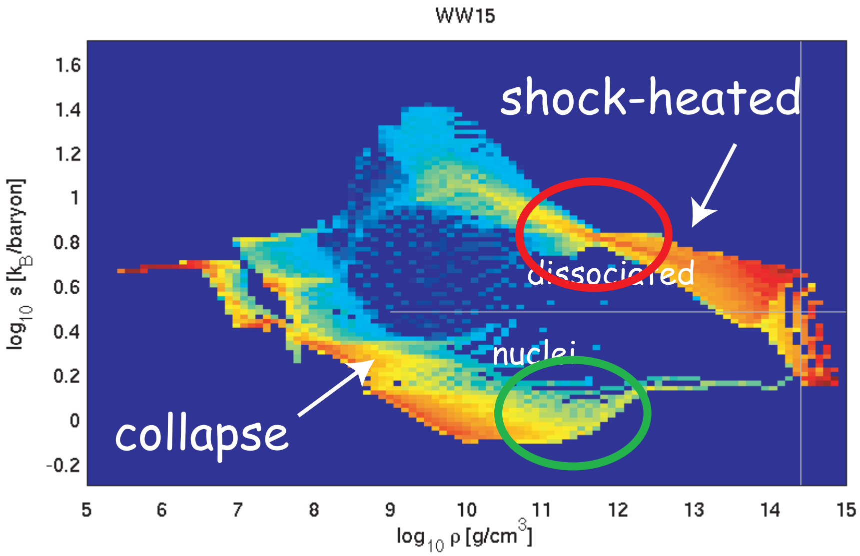
Elastic coherent scattering of neutrinos on nuclei

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

Neutrino-nucleon scattering

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

Relevant ν-matter interactions

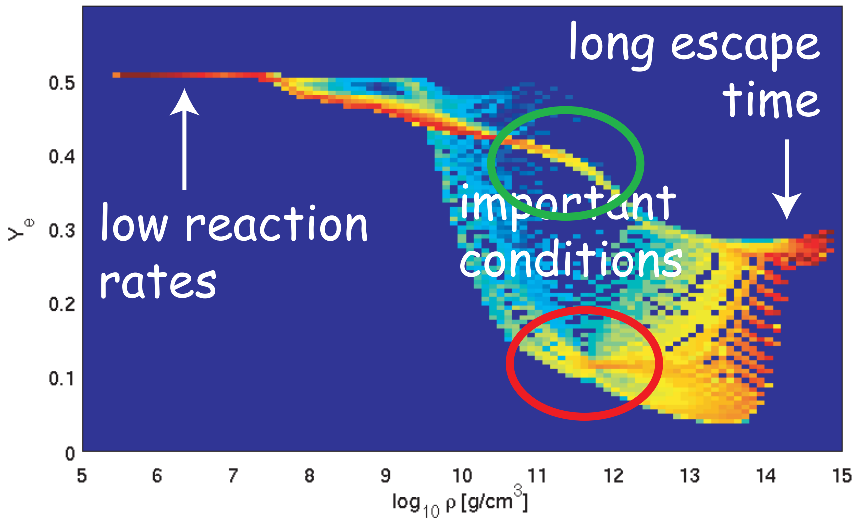


shock-heated

dissociated

nuclei

collapse



long escape time

low reaction rates

important conditions

The conditions around the neutrino spheres are marked in

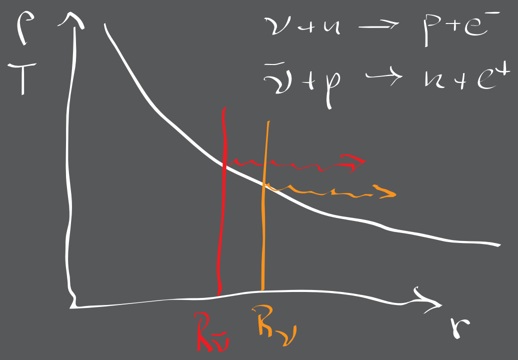
green ... collapse

red ... postbounce

Different luminosity contributions

- Luminosity composed of two parts:

2) neutrinos of cooling protoneutron star



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

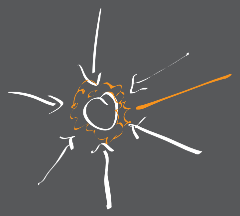
$\bar{\nu} + p \rightarrow n + e^+$

neutron rich

$n_n > n_p$

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

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

Solving the Boltzmann equation

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

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

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

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

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

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

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

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

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

Evolution of specific neutrino distr. function:

F(t,m,□,E) = f(t,r,□,E)/□

=> 3D implicit problem

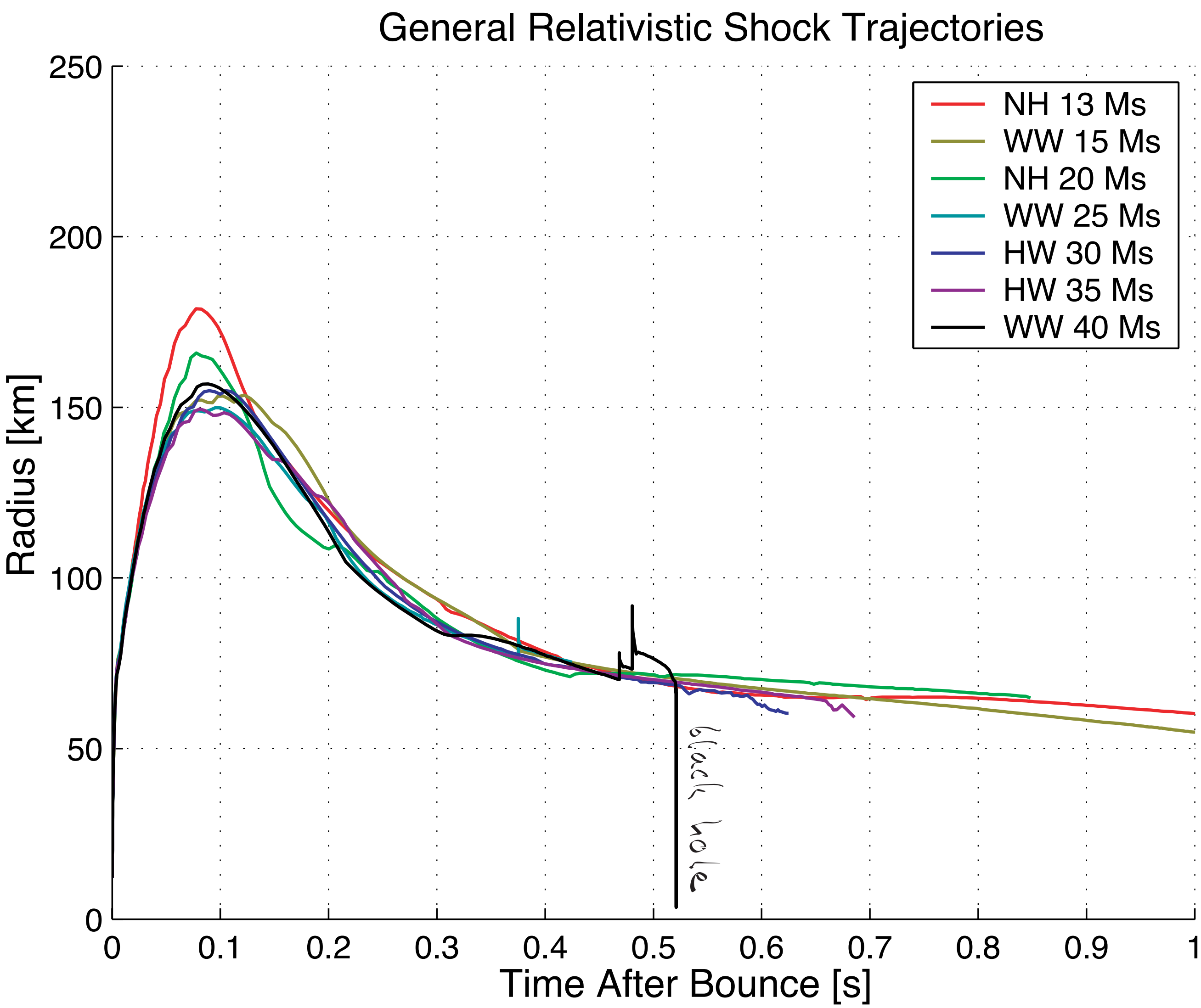
Comoving metric:

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

Stress-energy tensor:

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

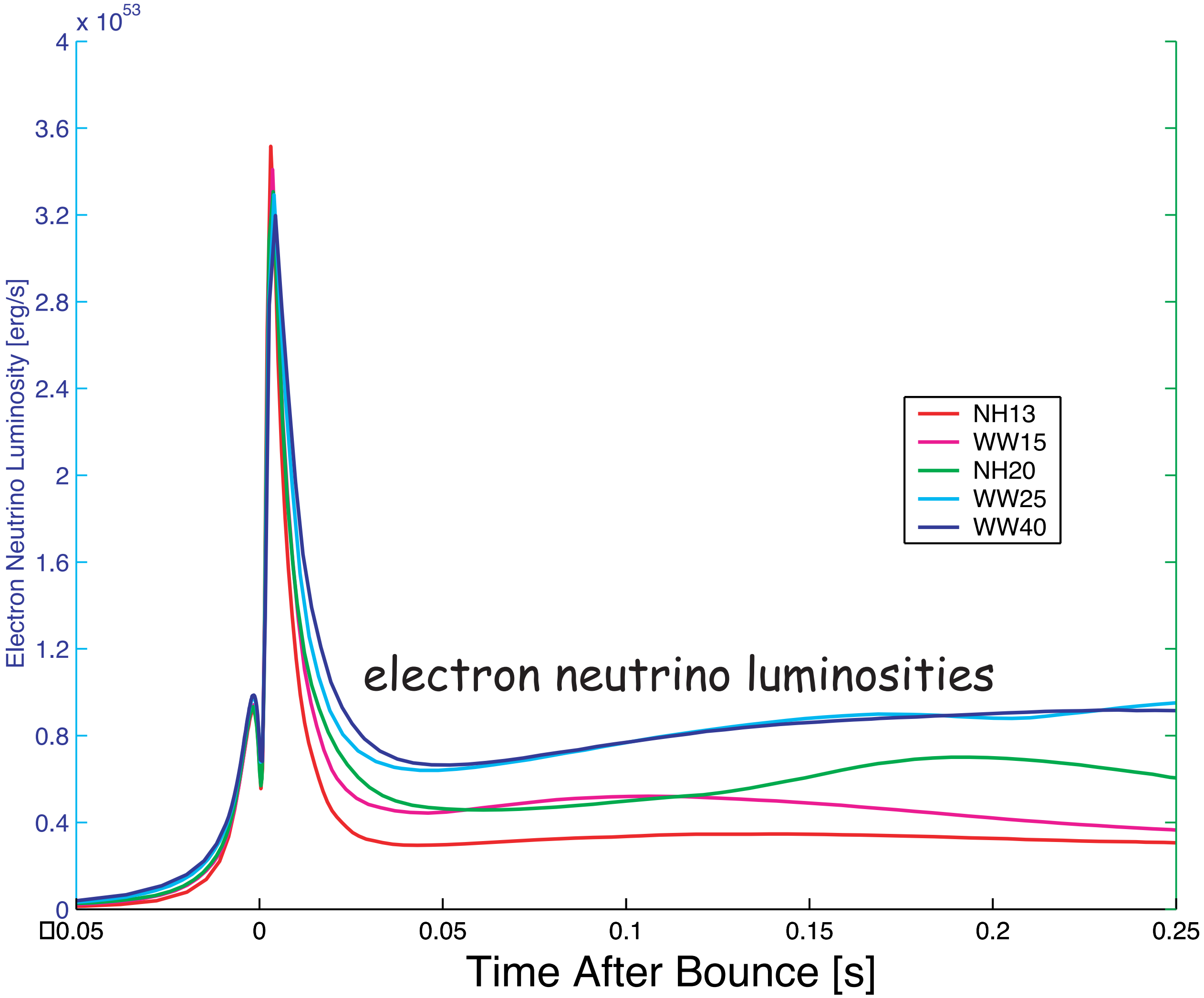
Modeling in spherical symmetry



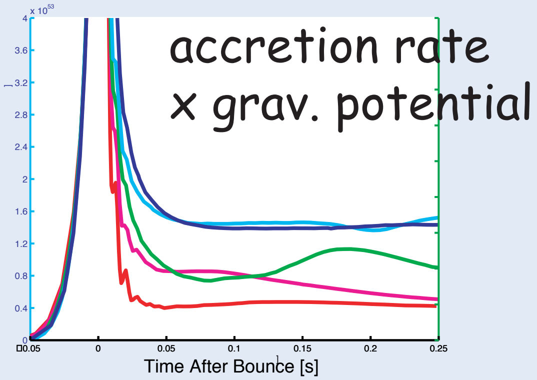
(Liebendörfer, Mezzacappa, Messer, Hix, Martinez-Pinedo, Thielemann, 2003)

- Trajectories of the accretion front for different progenitor stars 13Msol<M<40Msol
- calculated with Agile-Boltztran
- 40 Msol model forms a black hole
- 13 Msol model more optimistic
- no explosions obtained

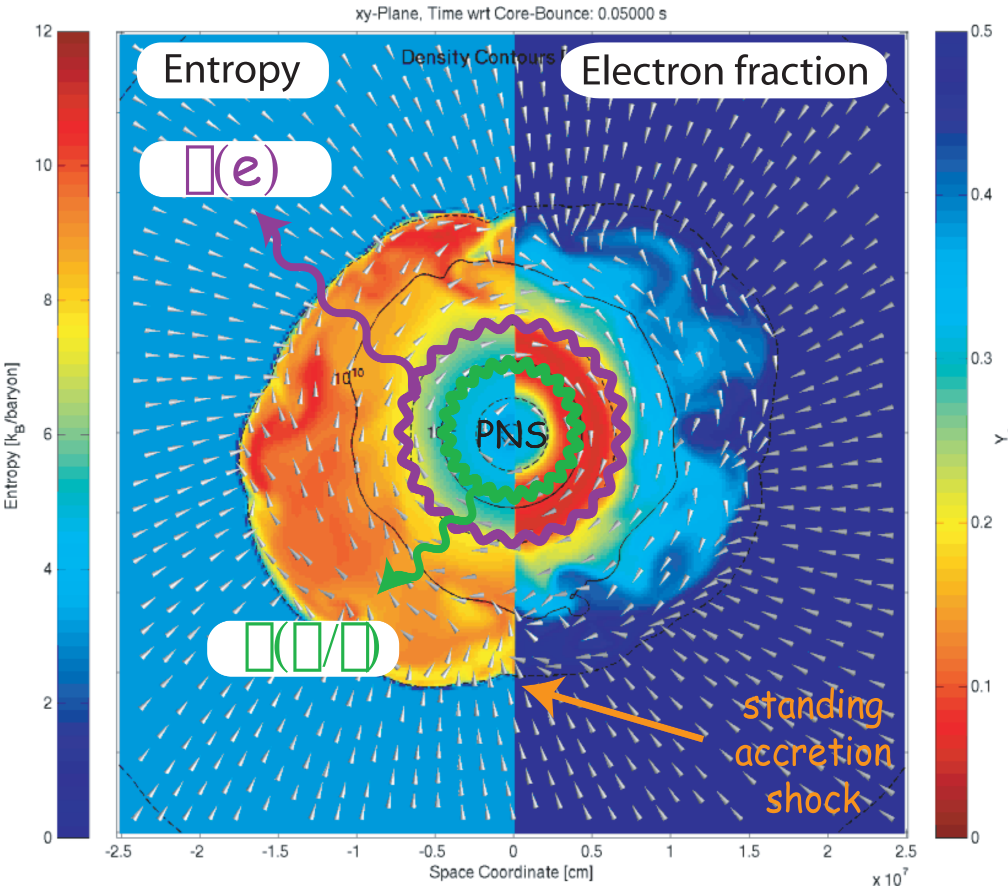
Neutrino signal

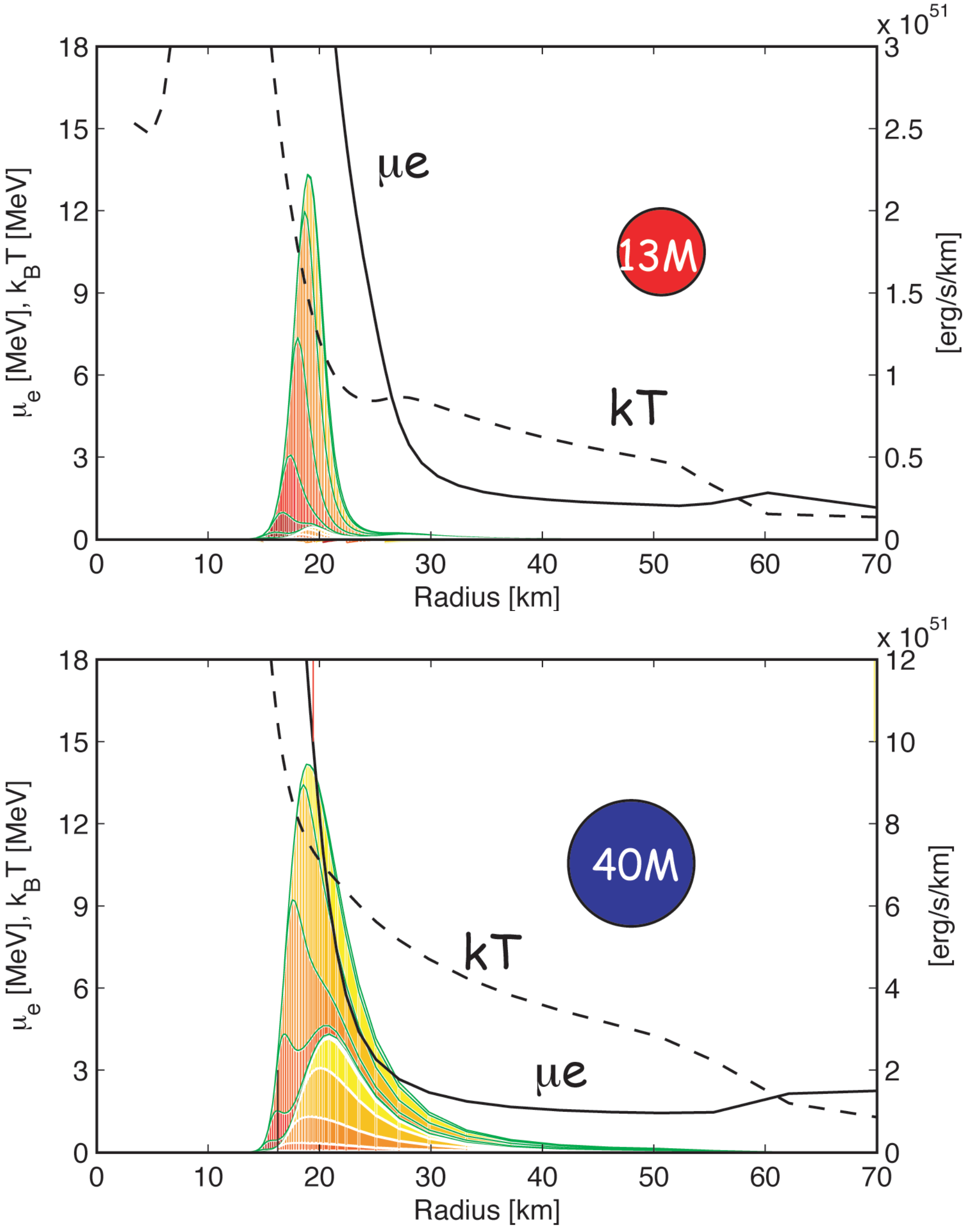


- initially similar luminosities
- differences appear in accretion phase
- >50% accretion lumin.
- density profiles in outer progenitor layers very different



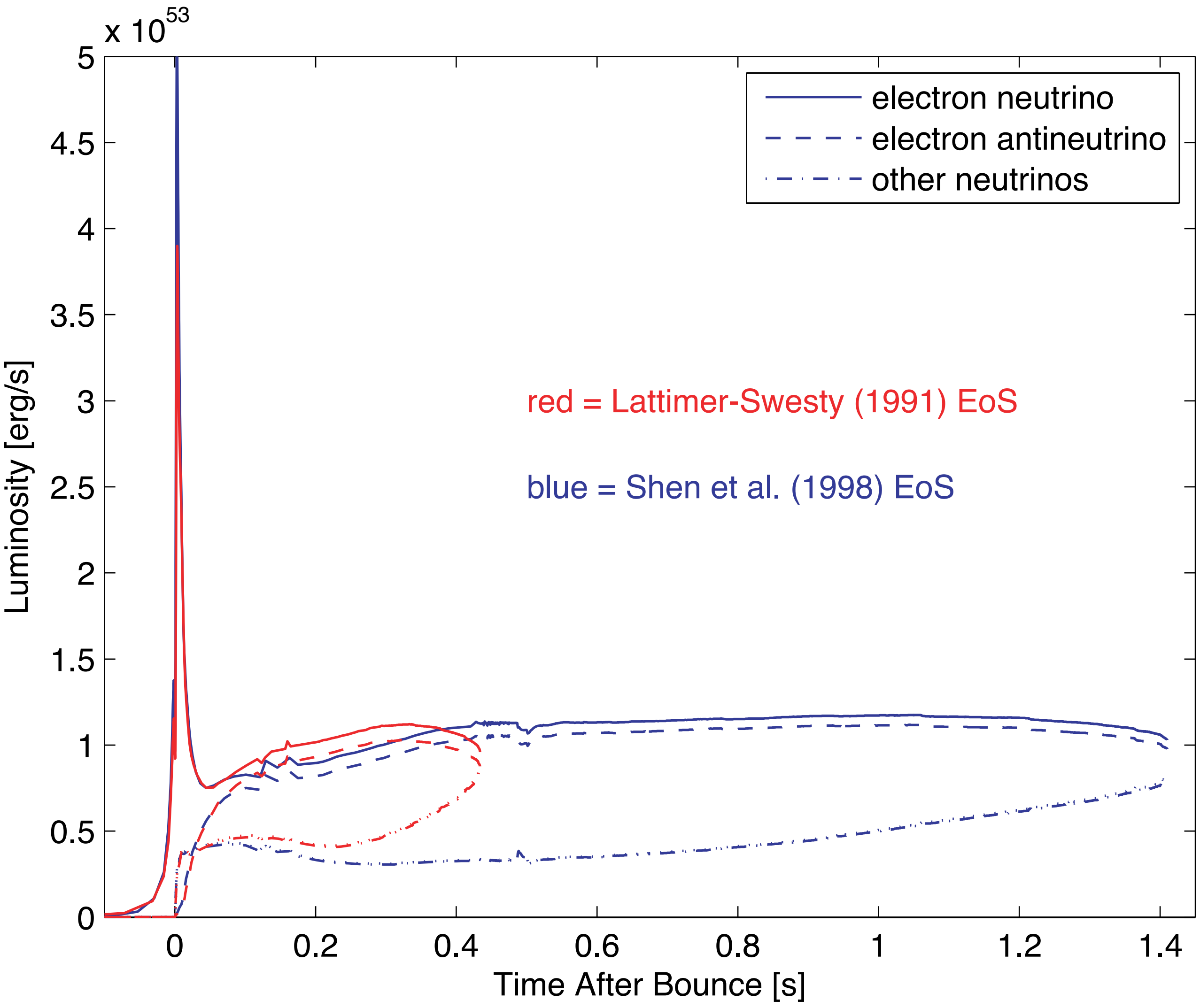
□(□/□) signal from PNS evolution





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

Sensitivity with respect to EoS



(Fischer et al. 2008, similar Sumiyoshi et al. 2007)

- Collapse, bounce, and postbounce evolution til black hole formation
- The quasi-static compression of the protoneutron star is reflected in mu/tau neutrino luminosities
- The different stiffness of the EoS causes very different delay times until BH formation

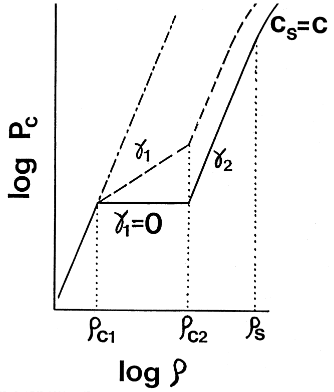
Signals of QCD phase transition?

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

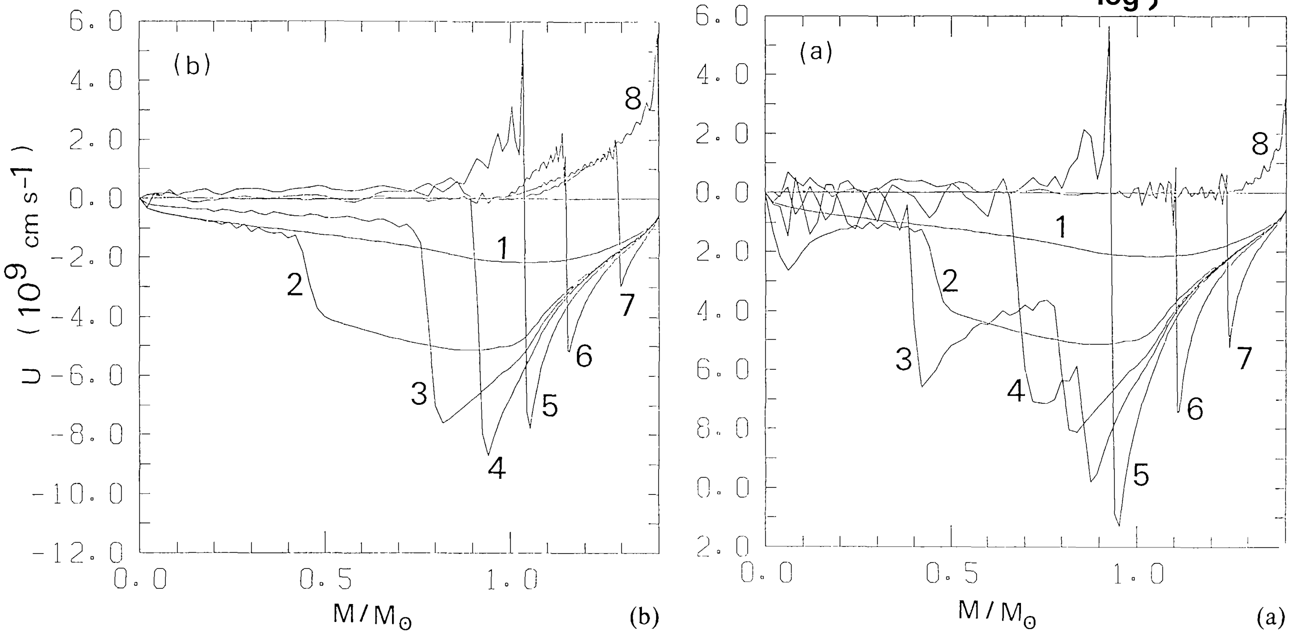
- investigations with parameterised equations of state and GR hydrodynamics

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

(Takahara & Sato 1988)



(Takahara & Sato 1986)



- select phase transition at or immediately after core bounce

- a second shock forms

- catches up with first shock

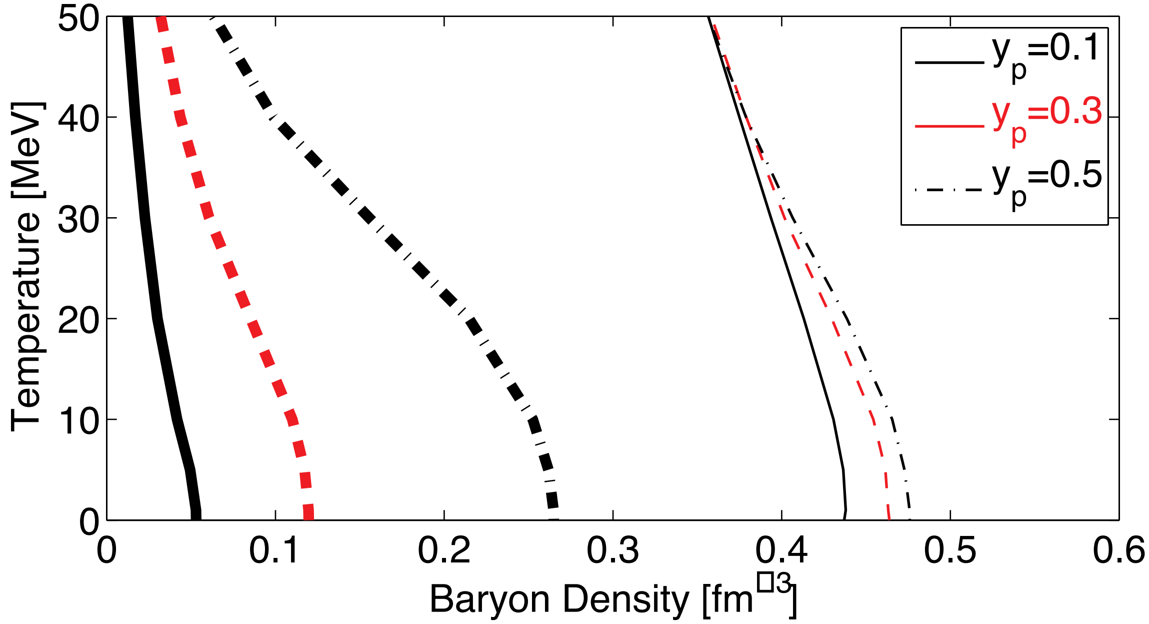
--> Is this observable?

- weak interactions and neutrinos neglected

- simulations only to few ms postbounce

Simple model for phase transition

- GR Boltzmann neutrino transport as discussed above
- Shen et al. 1998 equation of state for hadronic phase
- MIT bag model for quark phase, choosing parameters for early phase transition: B=162-165 MeV, ms=100 MeV
- Mixed phase according to Gibbs construction (mechanical and chemical equilibrium, □'s trapped)



(I. Sagert et al, T. Fischer et al. 2008, submitted)

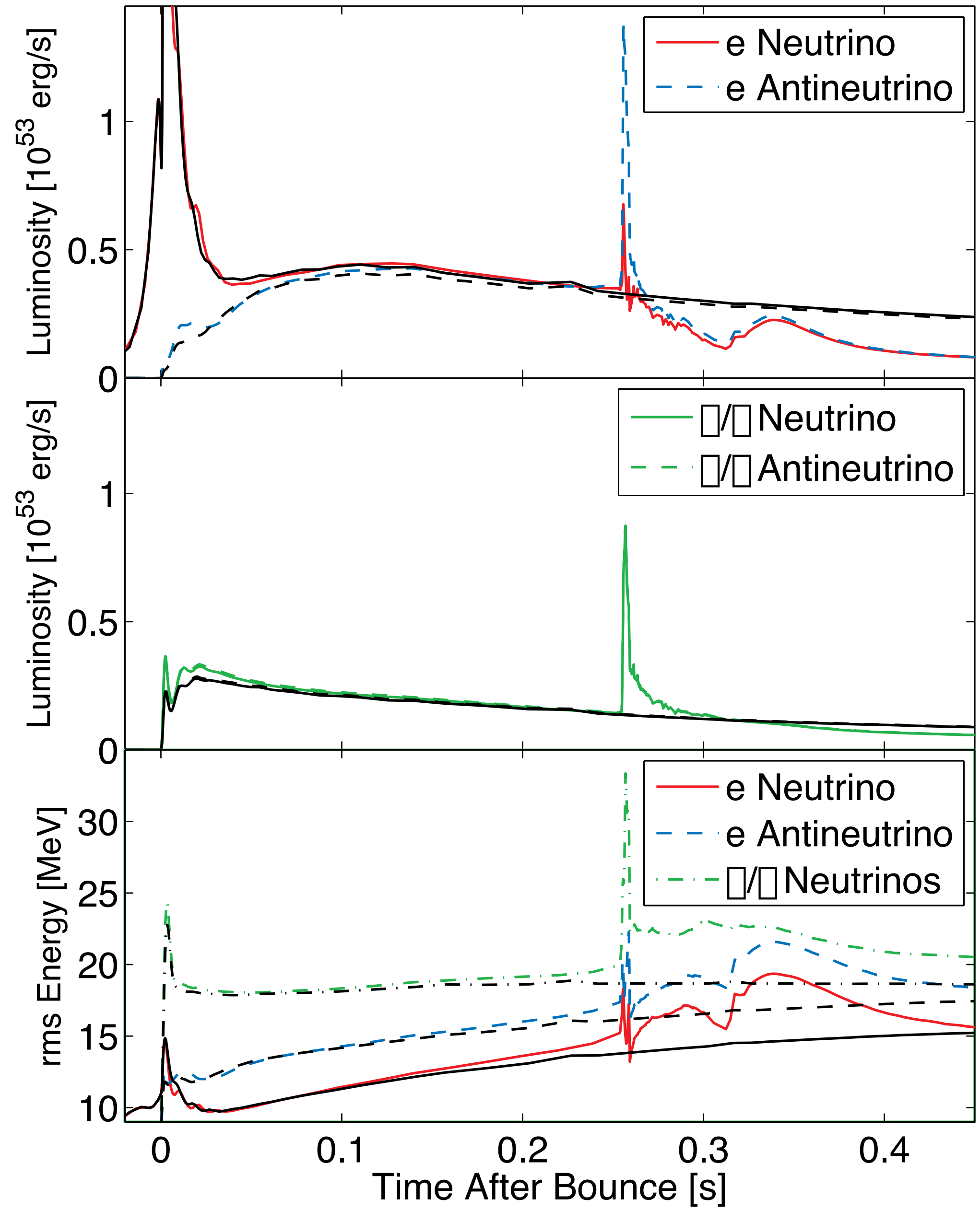
- compatible with heavy ion data

  - isospin-asymmetric
  - weak equilibrium allows for strange quarks

- 'just' compatible with neutron star data:

  - 162 supports 1.56 Ms
  - 165 supports 1.50 Ms

Neutrino signature of phase transition

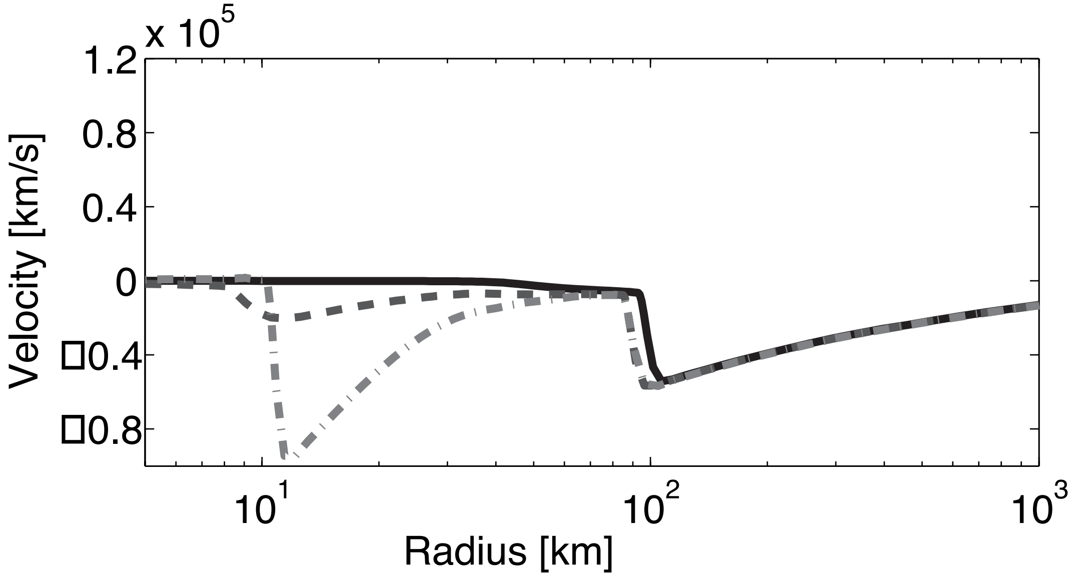


Shown is a simulation of a10 Ms star containing quark matter (B=162) compared to one with hadronic matter only (black lines)

- strong second neutrino burst in all flavours
- electron anti-neutrinos dominate
- step up in neutrino rms energies

(I. Sagert et al., T. Fischer et al. 2008)

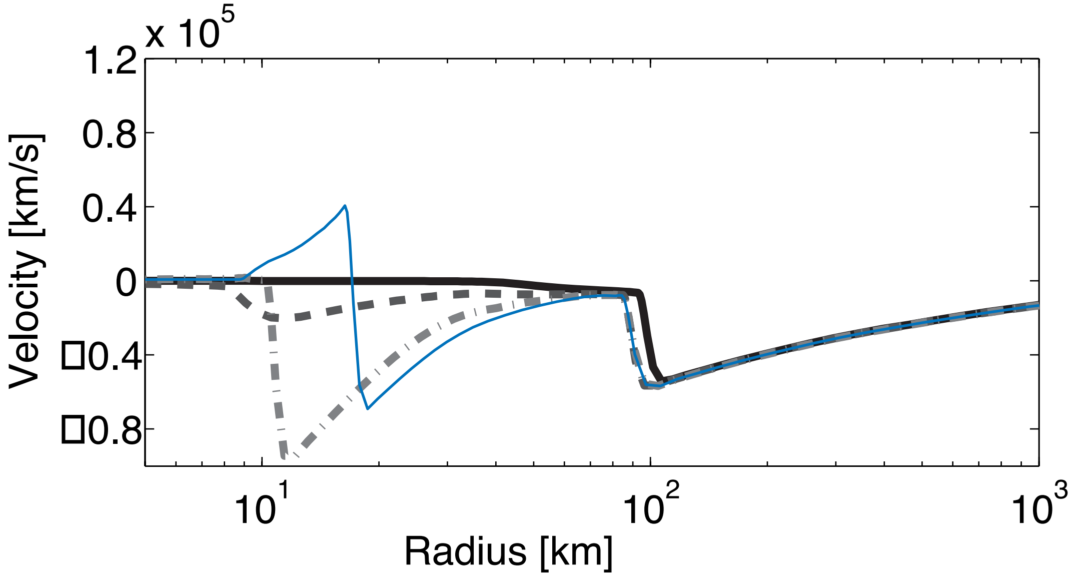
Different dynamical stages

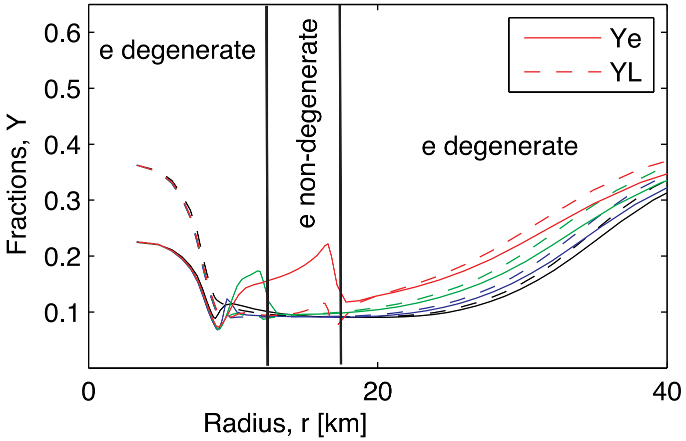


- collapse
- conversion to quark phase from inside out
- shrinking mixed phase
- second accretion shock propagating outward
- shock propagates with mixed-hadronic phase boundary

(Sagert et al., Fischer et al. 2008)

Different dynamical stages



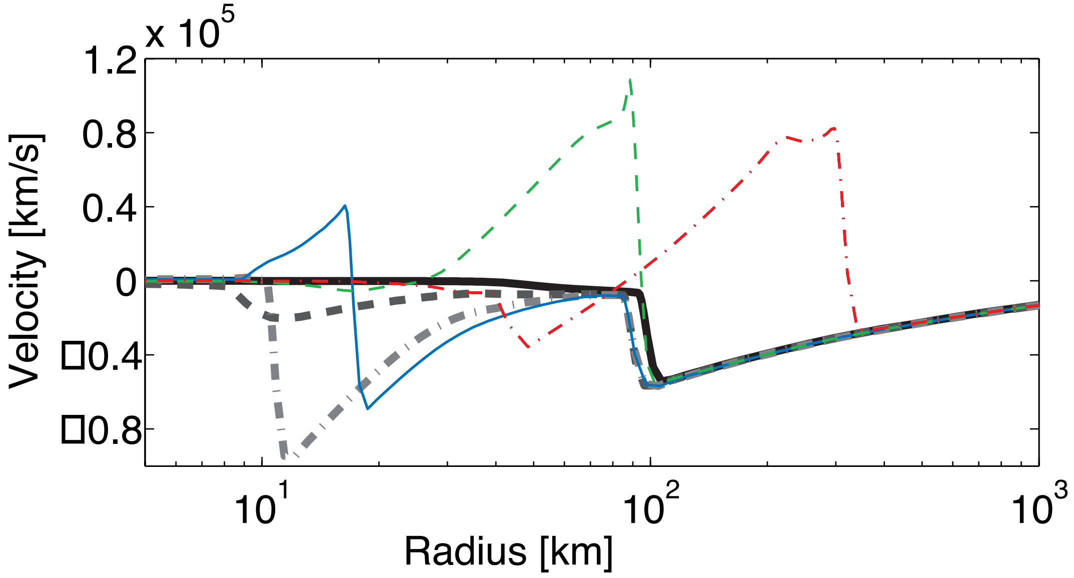


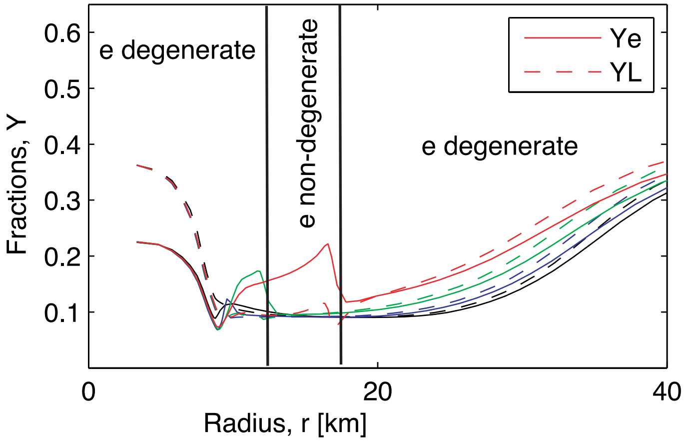
- deleptonised matter becomes non-degenerate
- weak equilibrium steps to larger Ye
- pressure increases

- collapse
- conversion to quark phase from inside out
- shrinking mixed phase
- second accretion shock propagating outward
- shock propagates with mixed-hadronic phase boundary
- accr. shock detaches from phase boundary to reach □-spheres in the hadronic phase

(Sagert et al., Fischer et al. 2008)

Different dynamical stages





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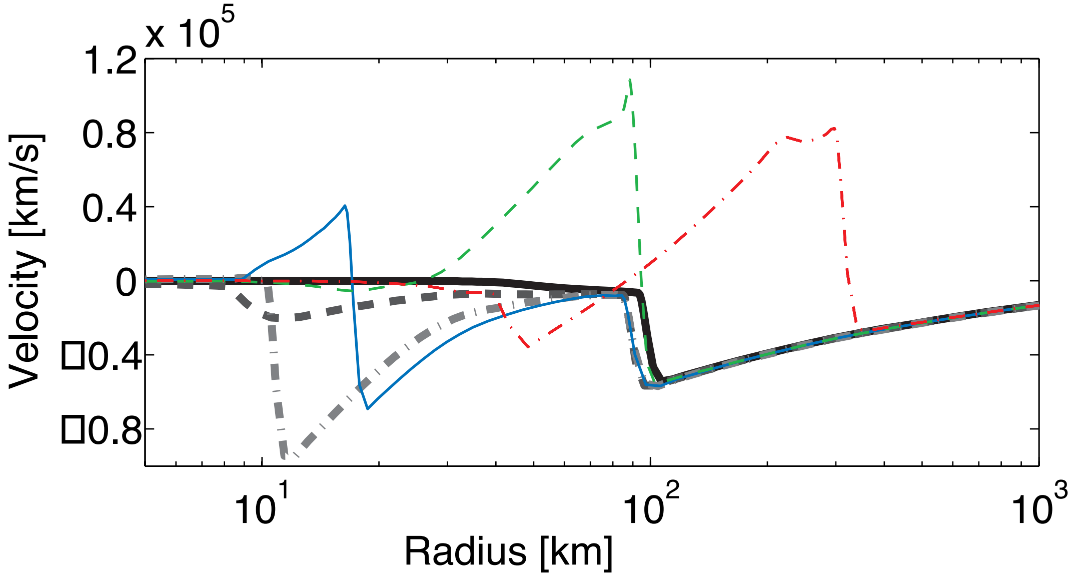
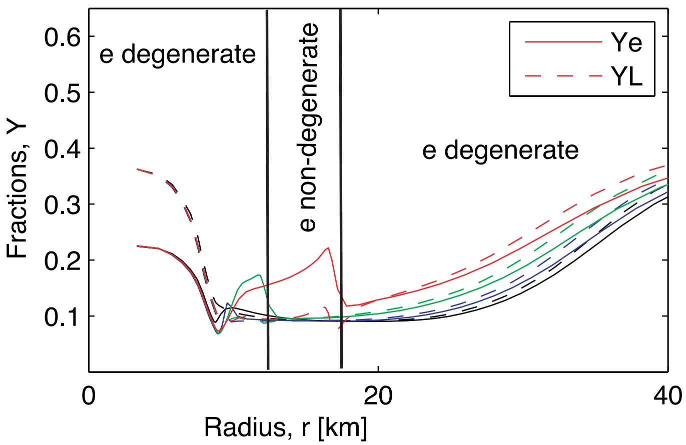
- second accretion shock propagating outward
- shock propagates with mixed-hadronic phase boundary
- accr. shock detaches from phase boundary to reach □-spheres in the hadronic phase
- shocked matter acelerates and triggers explosion

(Sagert et al., Fischer et al. 2008)

Different dynamical stages





- deleptonised matter becomes non-degenerate
- weak equilibrium steps to larger Ye
- pressure increases
- emission of anti-neutrino dominates when neutrino spheres are reached

- collapse
- conversion to quark phase from inside out
- shrinking mixed phase
- second accretion shock propagating outward
- shock propagates with mixed-hadronic phase boundary
- accr. shock detaches from phase boundary to reach ν-spheres in the hadronic phase
- shocked matter acelerates and triggers explosion

(Sagert et al., Fischer et al. 2008)

Bag constant & progenitor variations

Larger bag constant
--> longer postbounce accretion time
--> more massive protoneutron star
--> deeper gravitational potential
--> larger peak luminosity in second neutrino burst
--> larger explosion energies

Prog. [M]	B [MeV]	t_{pb} [ms]	M_Q [M]	M_{mixed} [M]	M_{PNS} [M]	E_{expl} [10^{51} erg]
10	162	255	0.850	0.508	1.440	0.44
10	165	448	1.198	0.161	1.478	1.64
15	162	209	1.146	0.320	1.608	0.42
15	165	330[a]	1.496	0.116	1.700	unknown[b]

[a] moment of black hole formation
[b] black hole formation before positive explosion energy is achieved

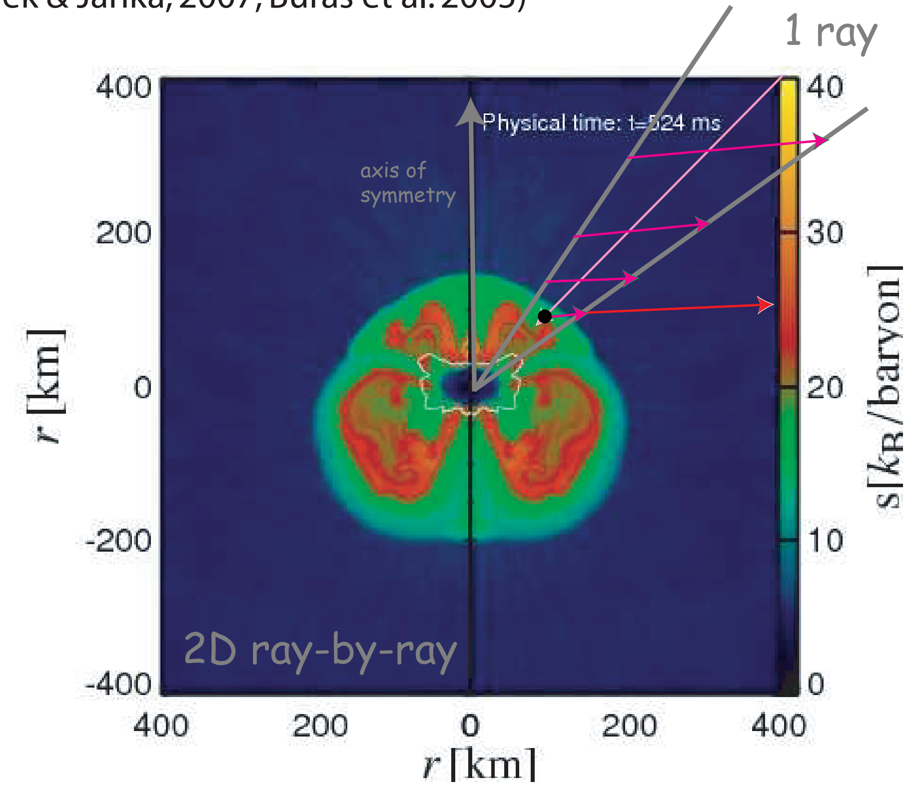
- Is tuning of parameters or the model of the quark phase possible to reproduce SN1987A?
- How do more massive progenitors explode?
- Weak □-driven explosion followed by phase transition?
- Some models eject low-Ye matter --> a possible site for the r-process?

(I. Sagert et al., T. Fischer et al. 2008)

Or in combination with...

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

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



- Standing accretion shock instability (SASI)

(Blondin & Mezzacappa 2003
Foglizzo et al. 2007)

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

(Burrows et al. 2006)

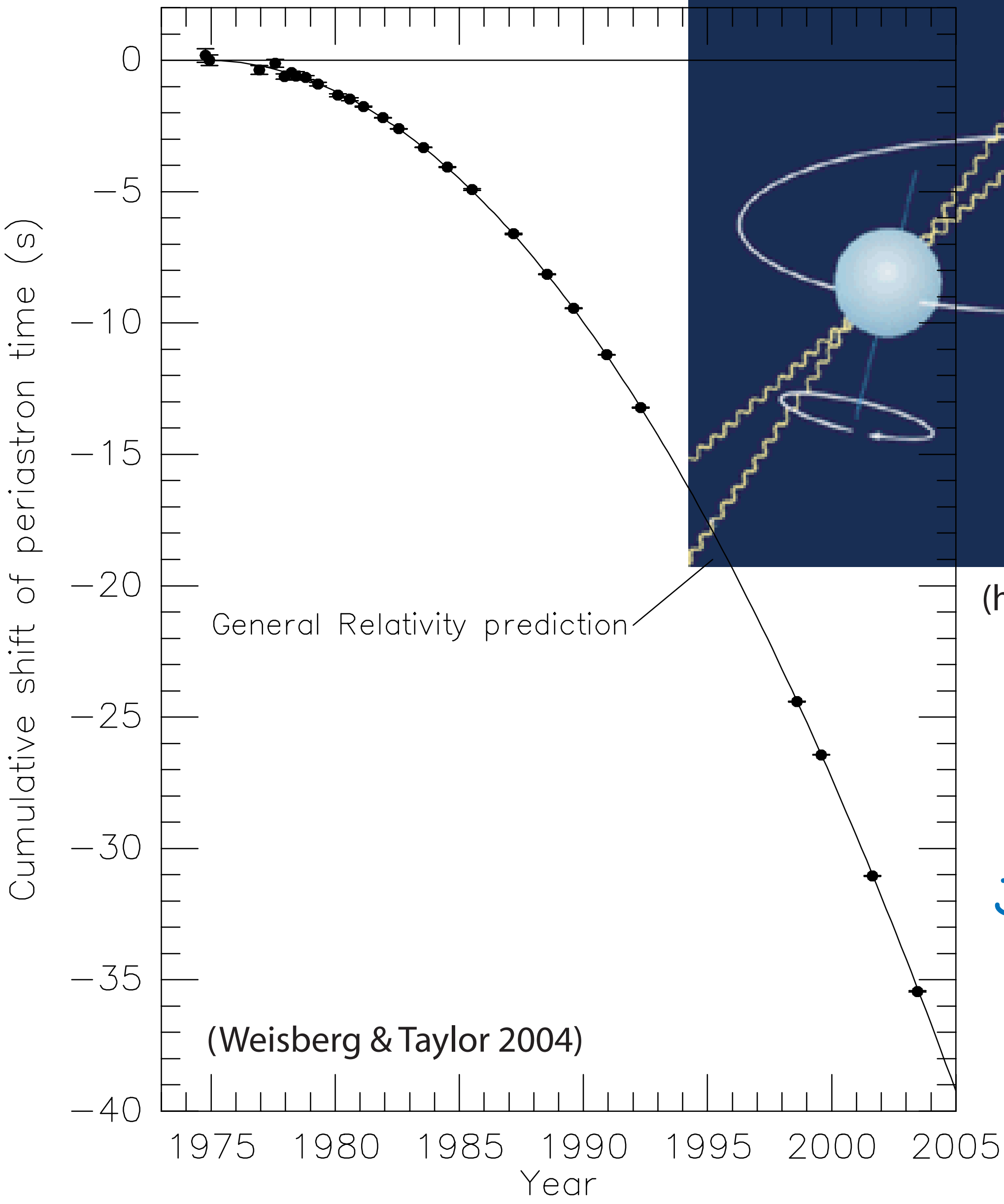
Heating by dissipation of emitted sound waves

- Magneto-rotational explosion mechanisms and collapsar model

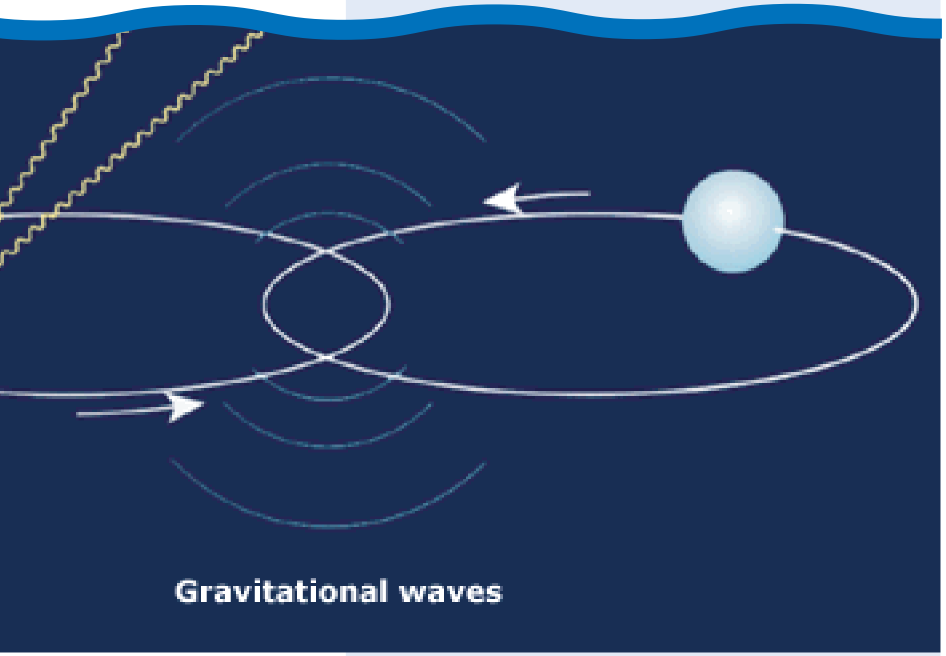
(Bisnovatyi-Kogan 1976,
Leblanc & Wilsons 1979,
MacFadyen & Woosley 1999)

Explosion after black hole formation

Gravitational Waves



(Weisberg & Taylor 2004)



(http://nobelprize.org)

Nobel prize
1993
Joseph Taylor
Russell Hulse

Pulsar B1913+16
- precision mass measurement
- slowdown measured
- compared to GR prediction

--> agreement to within 0.2% !

Prediction of Gravitational Wave Signal

Numerous 3D hydrodynamics simulations of stellar core-collapse in Numerical Relativity community:

- based on simple polytropic equation of state
- neutrino physics neglected
- prediction of GW signal: type I-III wave forms

In the mean time improved by using a microscopic equation of state and development of parameterisation scheme for deleptonisation during collapse:

- parameterise Ye as function of density from 1D
- estimate ds from dYe
- estimate luminosity and □-stress from int(dYe)

(Liebendörfer 2005)

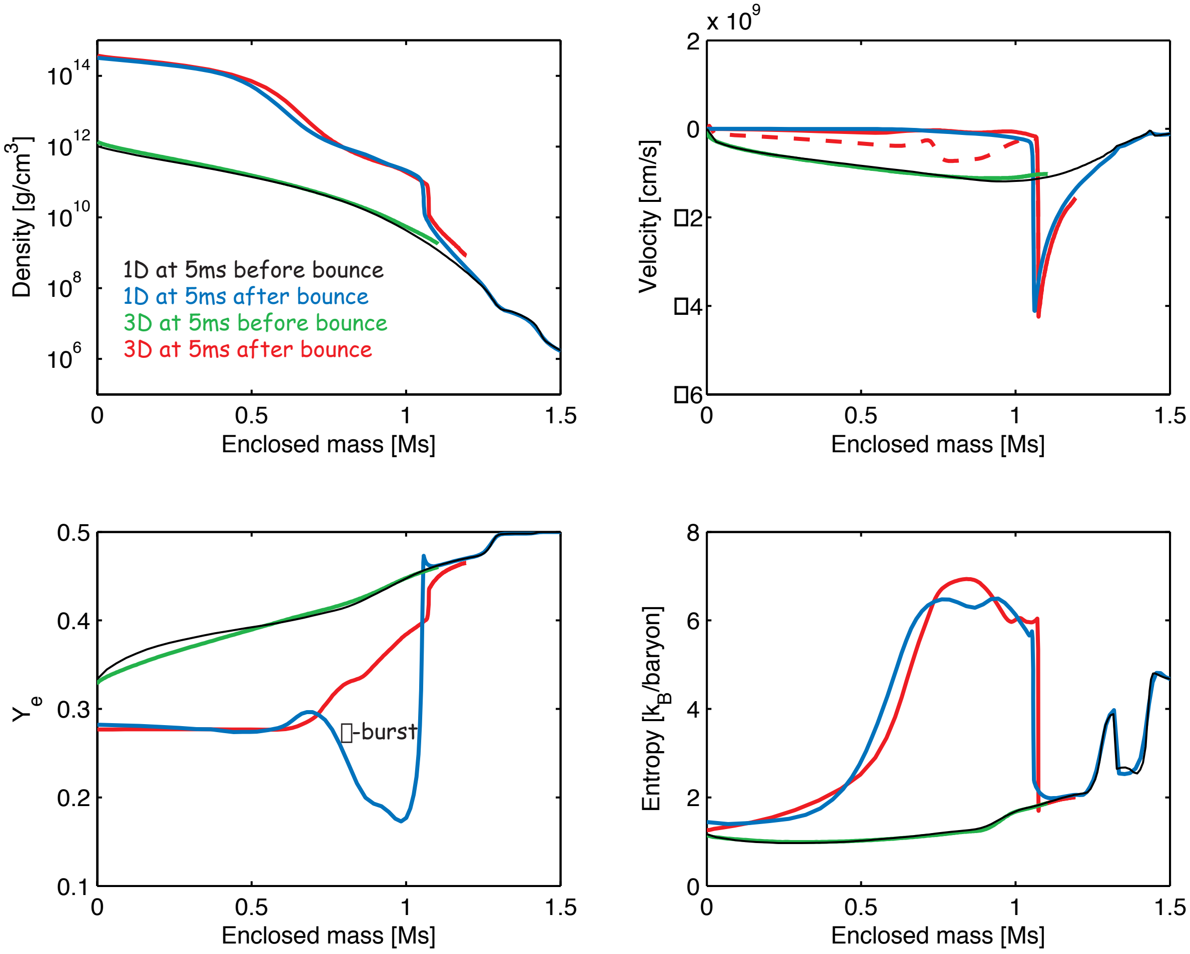
- Only type I GW signals have been found!

(Dimmelmeier et al. 2007,
Ott et al. 2007,
Scheidegger et al. 2007)

3D Magneto-Hydrodynamics

UNI BASEL

- Parameterization of weak interactions for collapse phase
- Comparison 1D GR Boltzmann <--> 3D approximations



(Liebendörfer, Pen, Thompson, PoS(NIC-IX)132, 2006)

3D MHD

(Pen, Arras, Wong 2003)

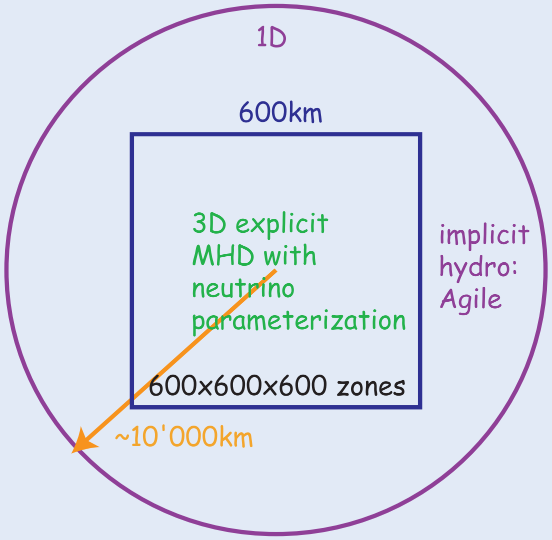
Lattimer-Swesty EOS

(Lattimer & Swesty 1991)

Effective GR potential

(Marek et al. 2006)

Fully parallelised



1D

600km

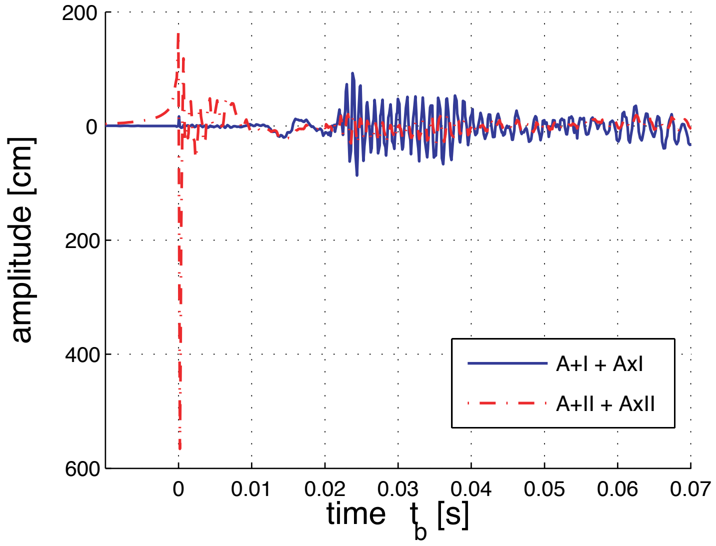
3D explicit
MHD with
neutrino
parameterization

implicit
hydro:
Agile

600x600x600 zones

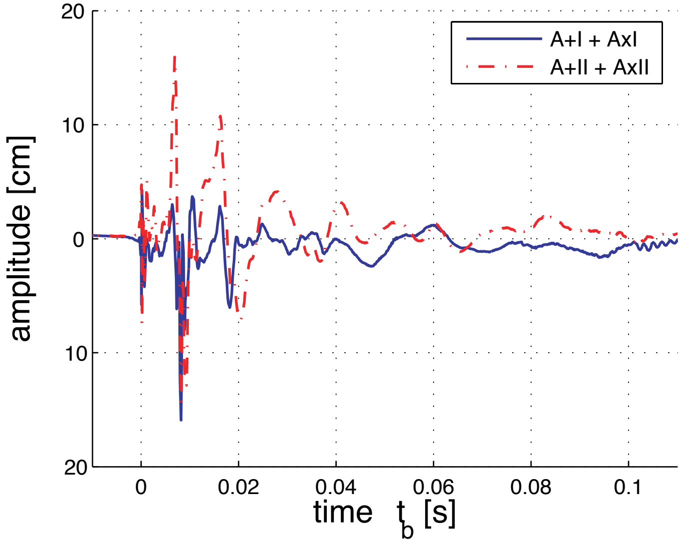
~10'000km

Prediction of Gravitational Wave Signal



Fast rotating 15Ms progenitor
□ ~ 2□ rad/ps
--> imprint of bounce and rotation rate

(see Ott et al. 2007)

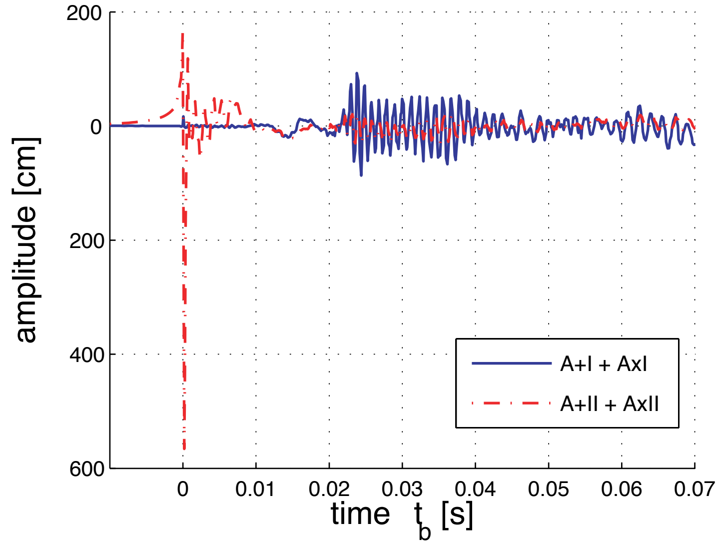


Slowly rotating 15Ms progenitor according to

(Heger, Woosley & Spruit 2005)

(Scheidegger et al. 2007/8)

Prediction of Gravitational Wave Signal



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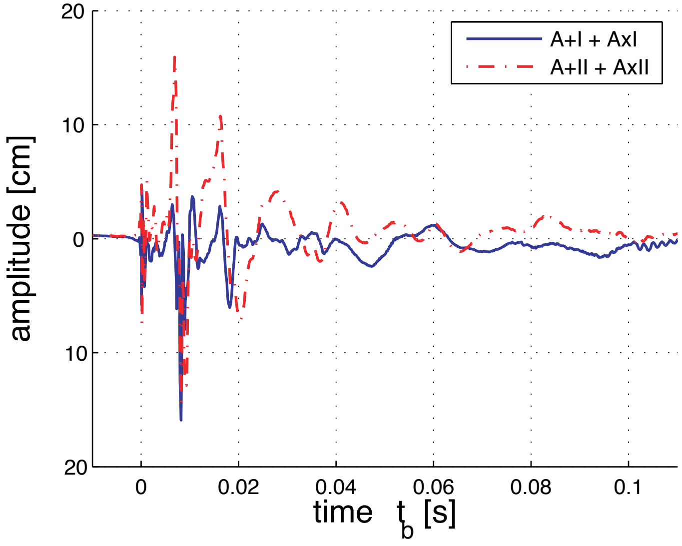

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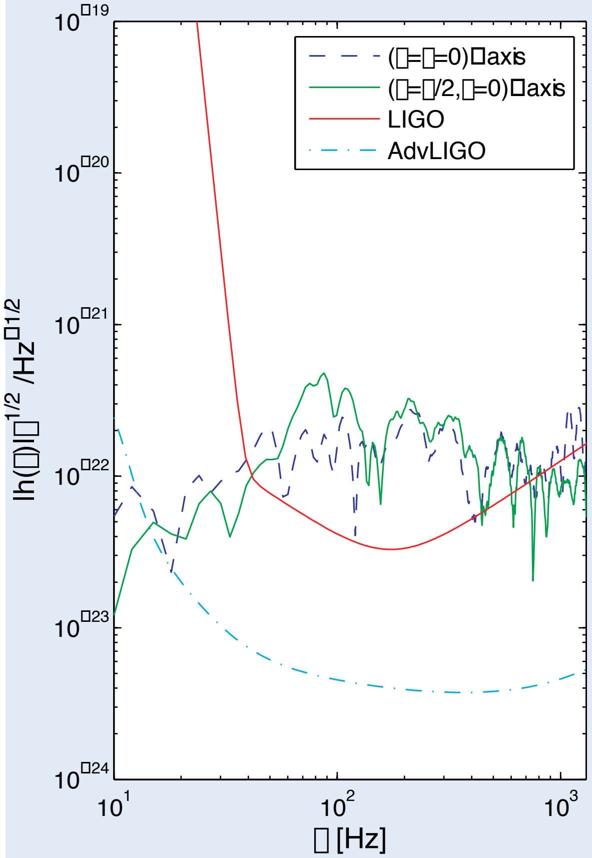
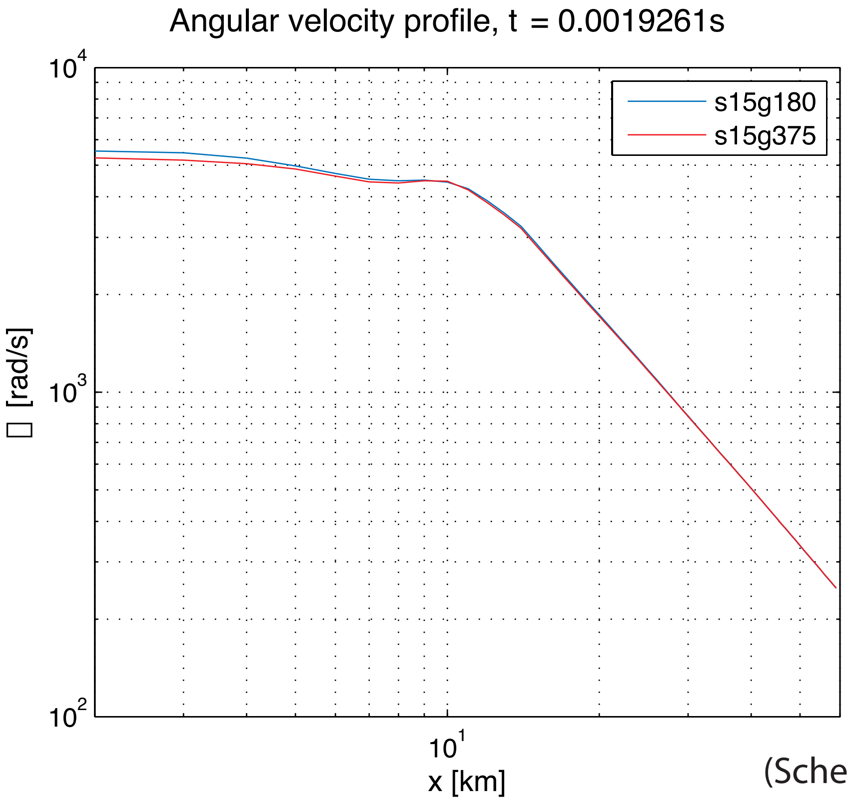


Galactic supernovae
-- could (LIGO)
-- should (Adv. LIGO)
be detectable

Incompressibility & Rotation

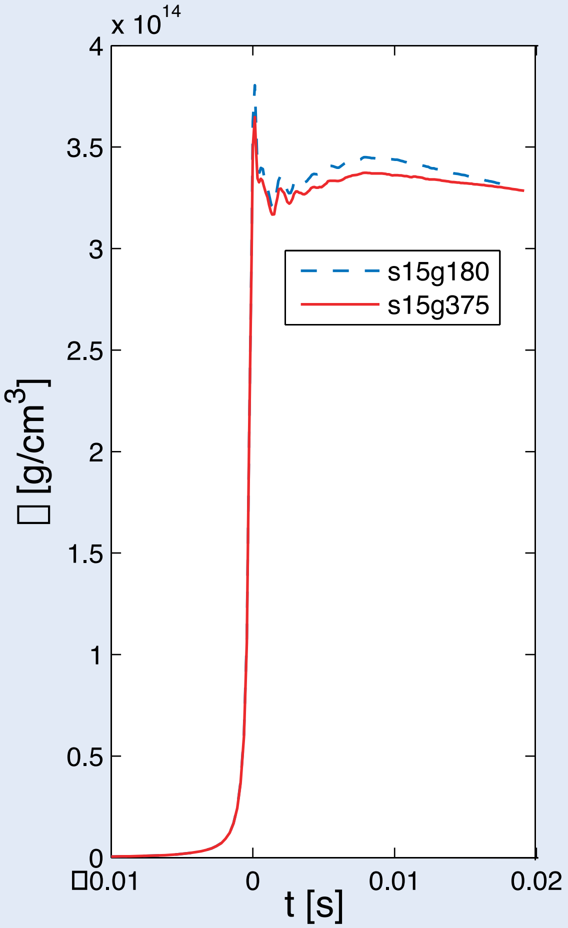
Two runs based on Lattimer-Swesty (1991) EoS
with incompressibility K=180 MeV and K=375 MeV:

--> *stiffer core becomes less dense*
--> *angular velocity is smaller*

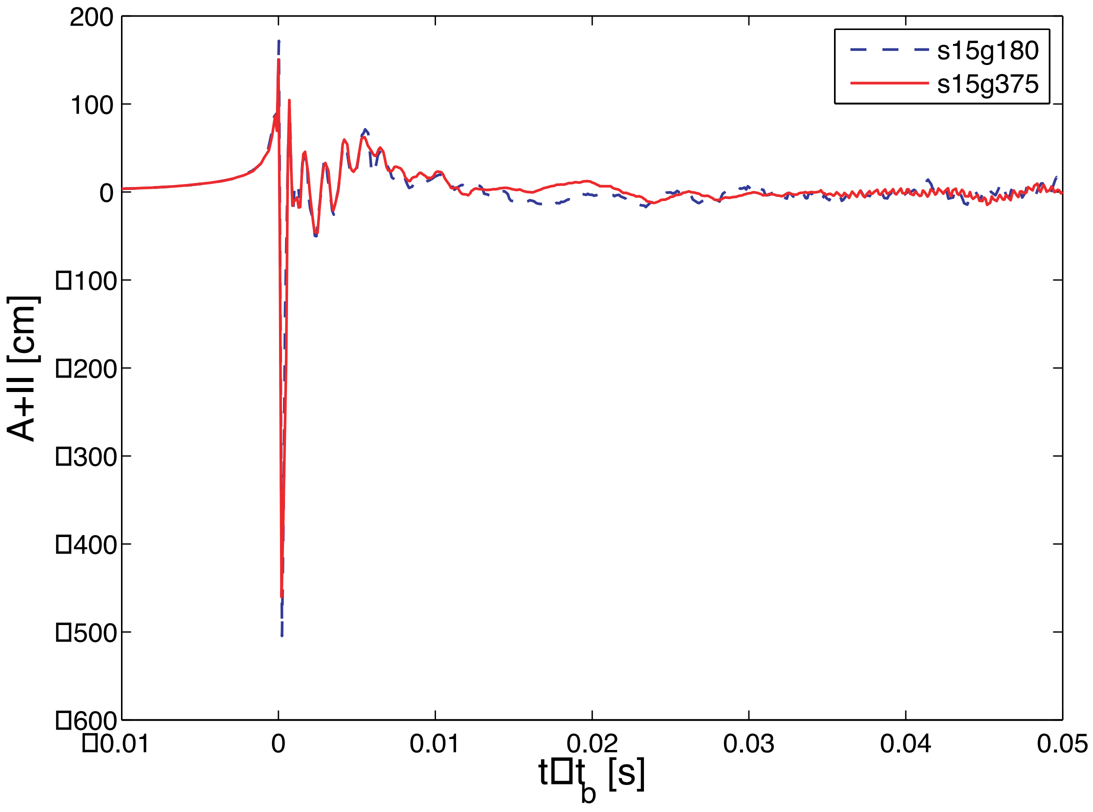


(Scheidegger et al. 200X)

Central density:



Impact of EoS on GW emission



- the direct impact is small!
- Is there an indirect impact on fluid instabilities that produce larger variations in GW emission?

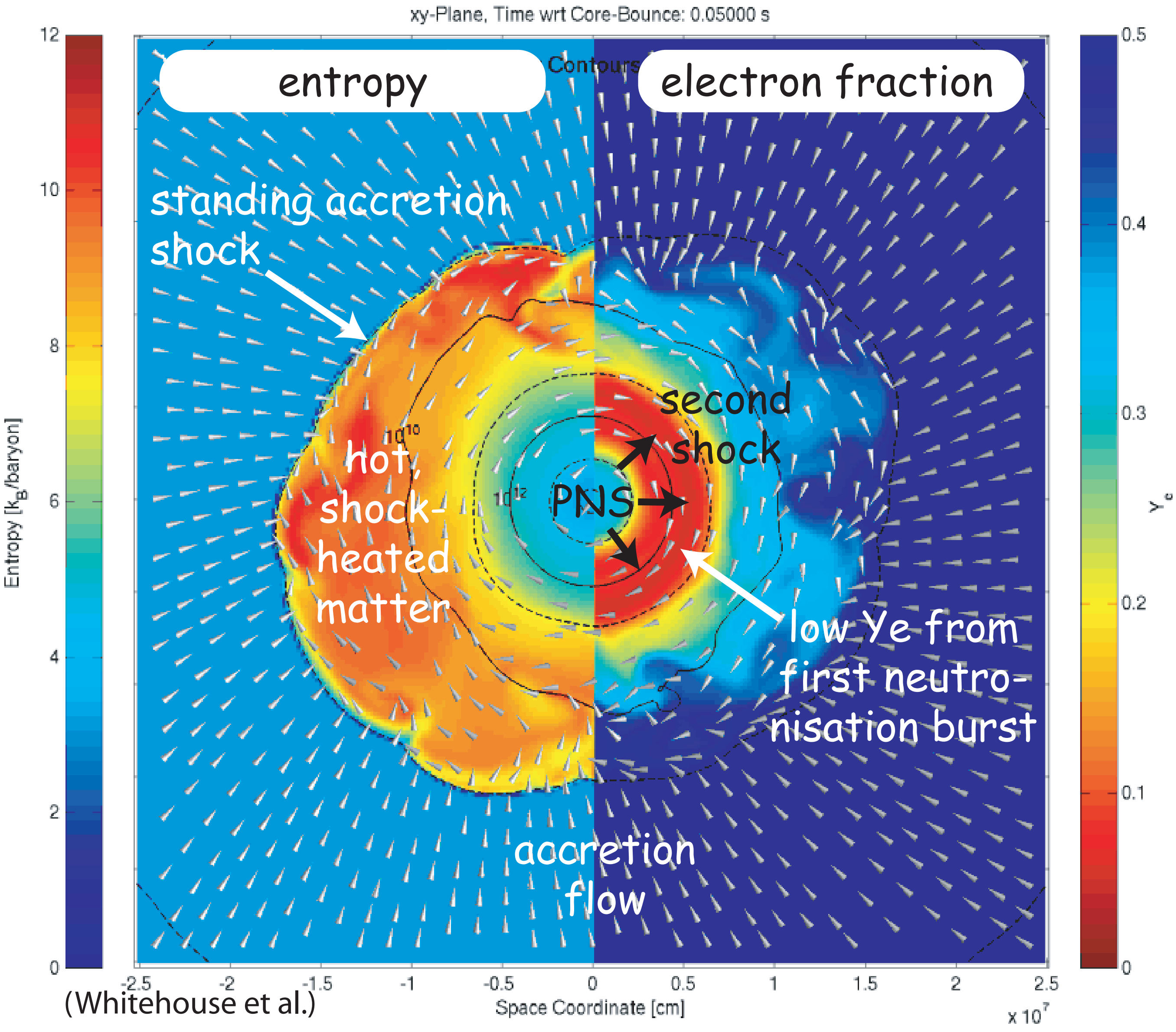
Run1 --> K=180 MeV
Run2 --> K=375 MeV

Maximum density:
Run1 --> □=3.8E14 g/cm3
Run2 --> □=3.6E14 g/cm3

Maximum Amplitude (A+II at bounce):
Run1 --> A=506 cm
Run2 --> A=406 cm

Characteristic frequency:
Run1 --> fc = 657 Hz
Run2 --> fc = 565 Hz

Conclusions



(Whitehouse et al.)

- Neutrinosignal reflects PNS compressibility and accretion rate, sensitive to
  --> equation of state
  --> PNS thermal profile
  --> weak interaction rates

- Select bag constant for early QCD phase transition to quark matter
  --> second accretion shock
  --> anti-neutrino burst
  --> shift in rms energies
  --> triggers explosion

- 3D models to study EoS compressibility in GW signal
  --> small effect @ bounce
  --> larger @ postbounce fluid instabilities and phase trans.?