Compschool, Copenhagen 2009

Core-Collapse Supernovae

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University of Basel

- Collapse phase: Dynamics & ν-interactions
- Postbounce phase: ν-transport & explosion mechanisms
- Models: Approximations & prediction of observables

Large cancellation effects in the total energy budget:

- Huge energy in!
- Huge energy out!
- The rest makes the supernova!

- Leading order contributions from many fields of physics possible...

Discussed Explosion Mechanisms

1) ~~Prompt explosion mechanism, E(bounce)~~

(e.g. Baron et al. 1985)

2) Neutrino-driven explosion mechanism, E(therm.)

(Colgate 1966, Arnett, Bruenn, Burrows, Mezzacappa … Marek &Janka 2009)

3) Magneto-rotational explosion mechanism, E(rot.)

(Bisnovatyi-Kogan 1976, Leblanc & Wilson 1979, ...)

4) Acoustic explosion mechanism, E(osc.)

(Burrows et al. 2006)

5) Magneto-sonic/viscous expl. mech., E(buoyancy)

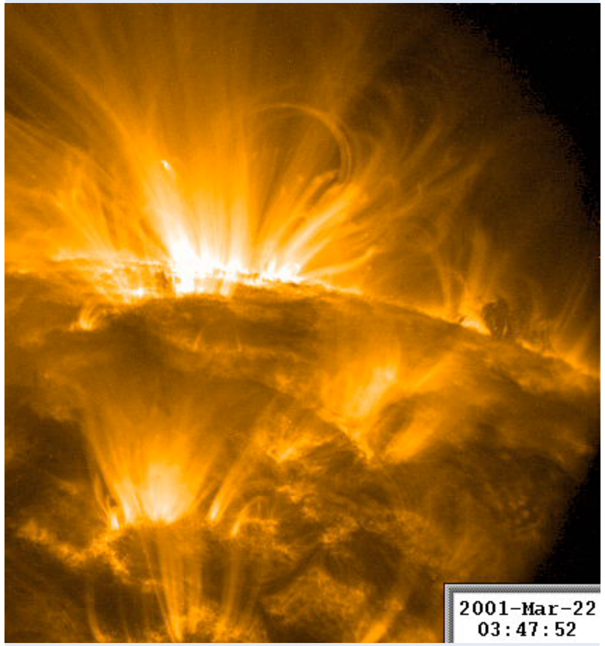
(Akiyama et al. 2003, Thompson et al. 2003, Socrates et al. 2005)

6) Phase transition induced expl. mech., E(compact)

(Migdal et al. 1971, … Sagert et al. 2009)

Energy scales:

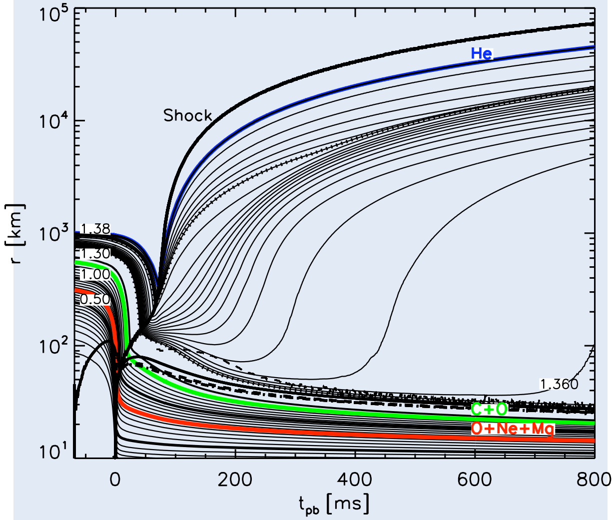
- Gravitational
  ~3E+53 erg
- Explosion
  ~1E+51 erg



Exception 1: ONeMg core

Recurrent detailed investigations:

Hillebrandt, Nomoto, Wolff 1984
Mayle, Wilson 1988
Kitaura, Janka, Hillebrandt 2006
Janka et al. 2008



Fischer et al. 2009

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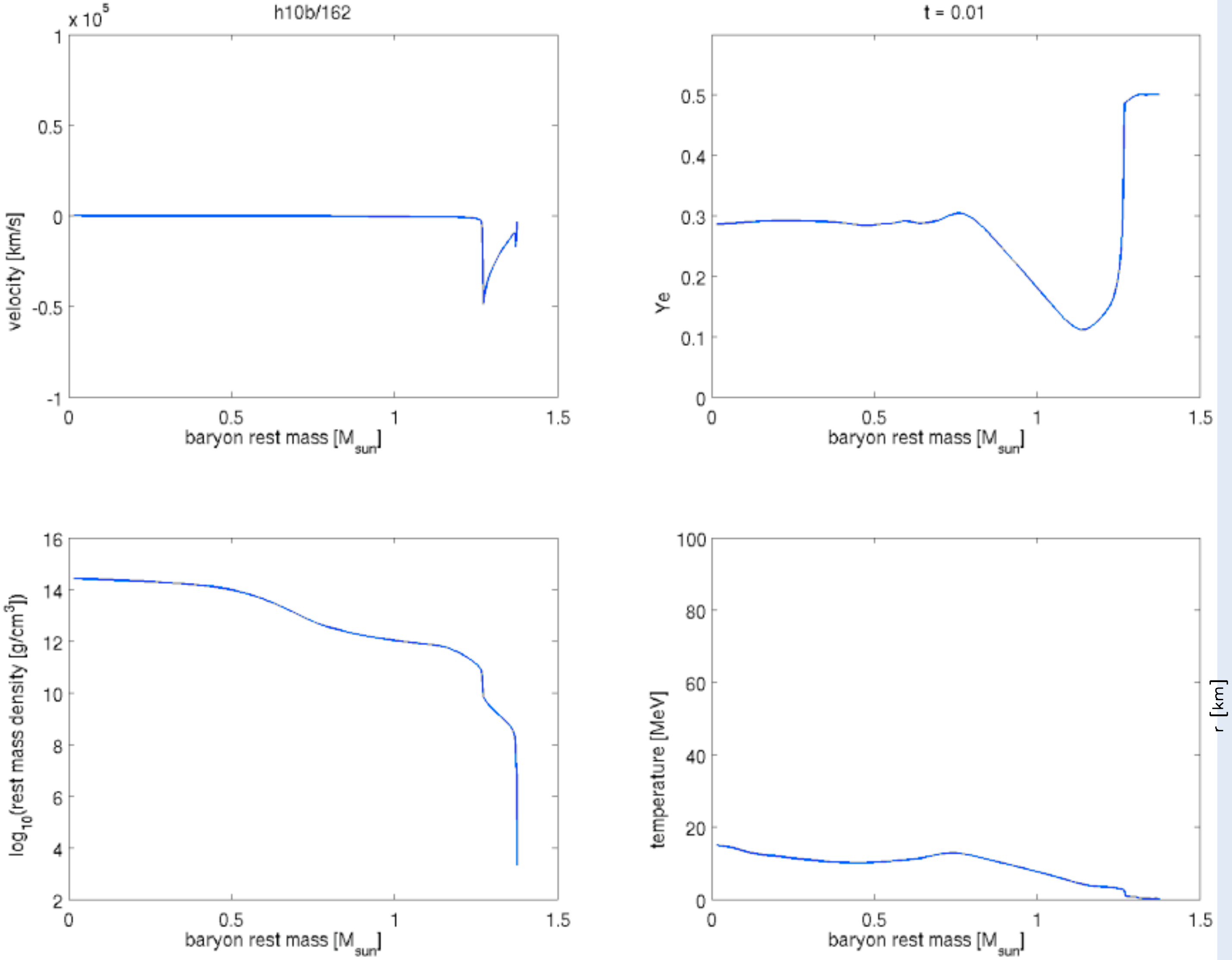

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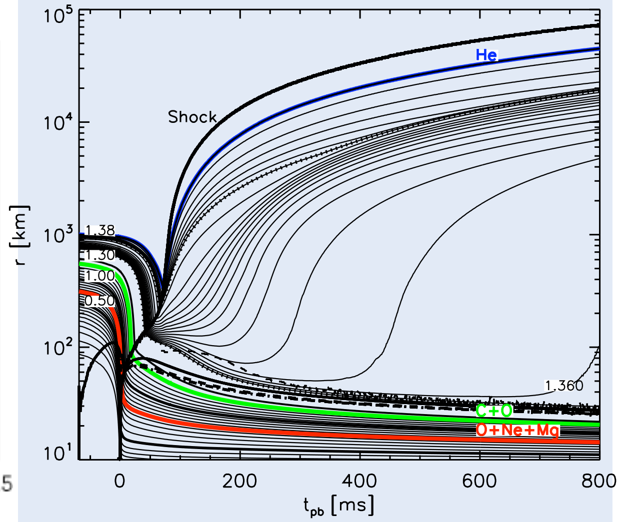
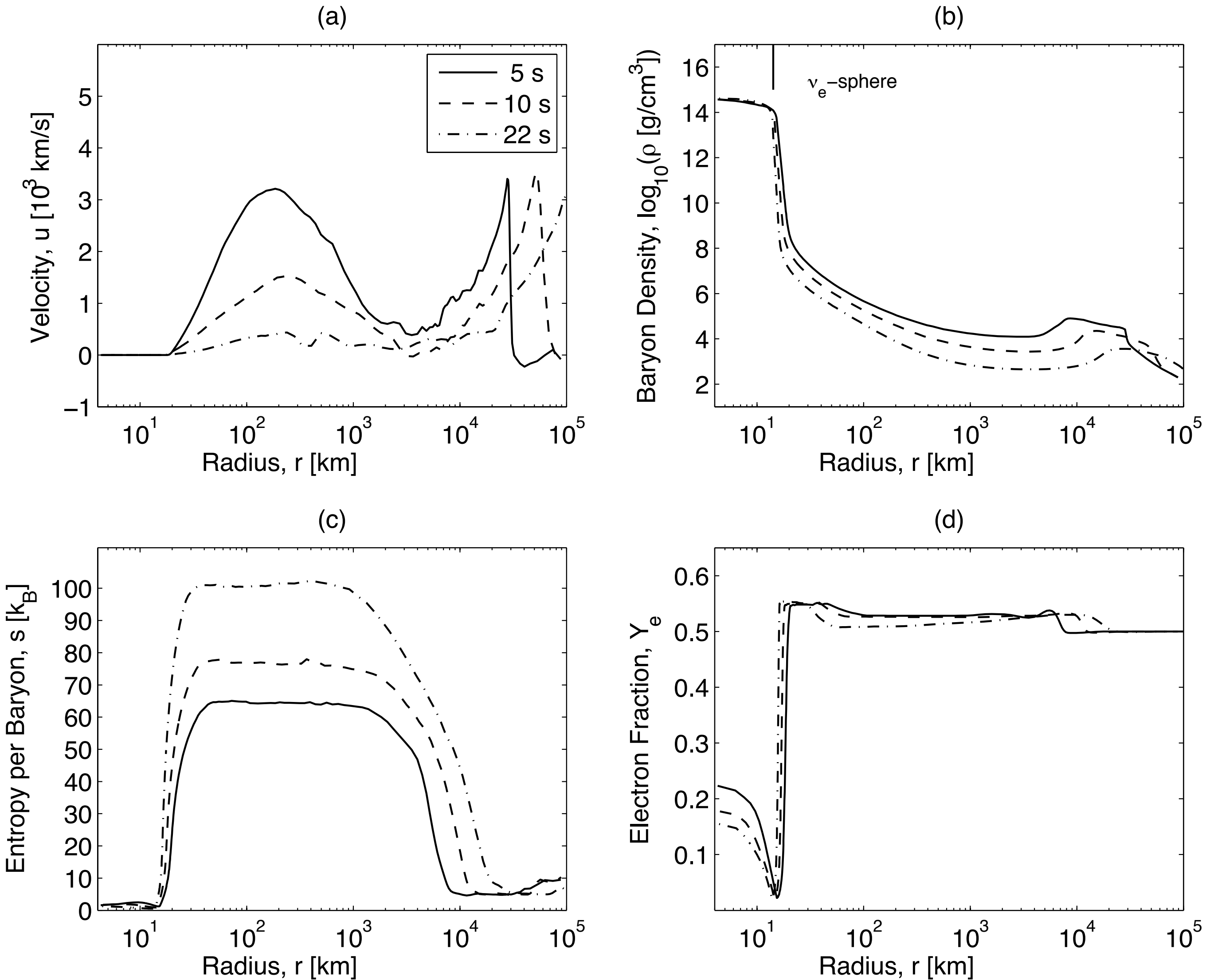


Neutrino wind phase



18 Msun

Improvements of Agile-Boltztran allow for the first time for simulations to ~20s postbounce time.

Studies of explosions of 10 and 18 Msun progenitors based on enhanced ν rates.

ν-wind has rather high Ye (>~0.5)

Fischer et al. 2009

The νp-process in p-rich ejecta

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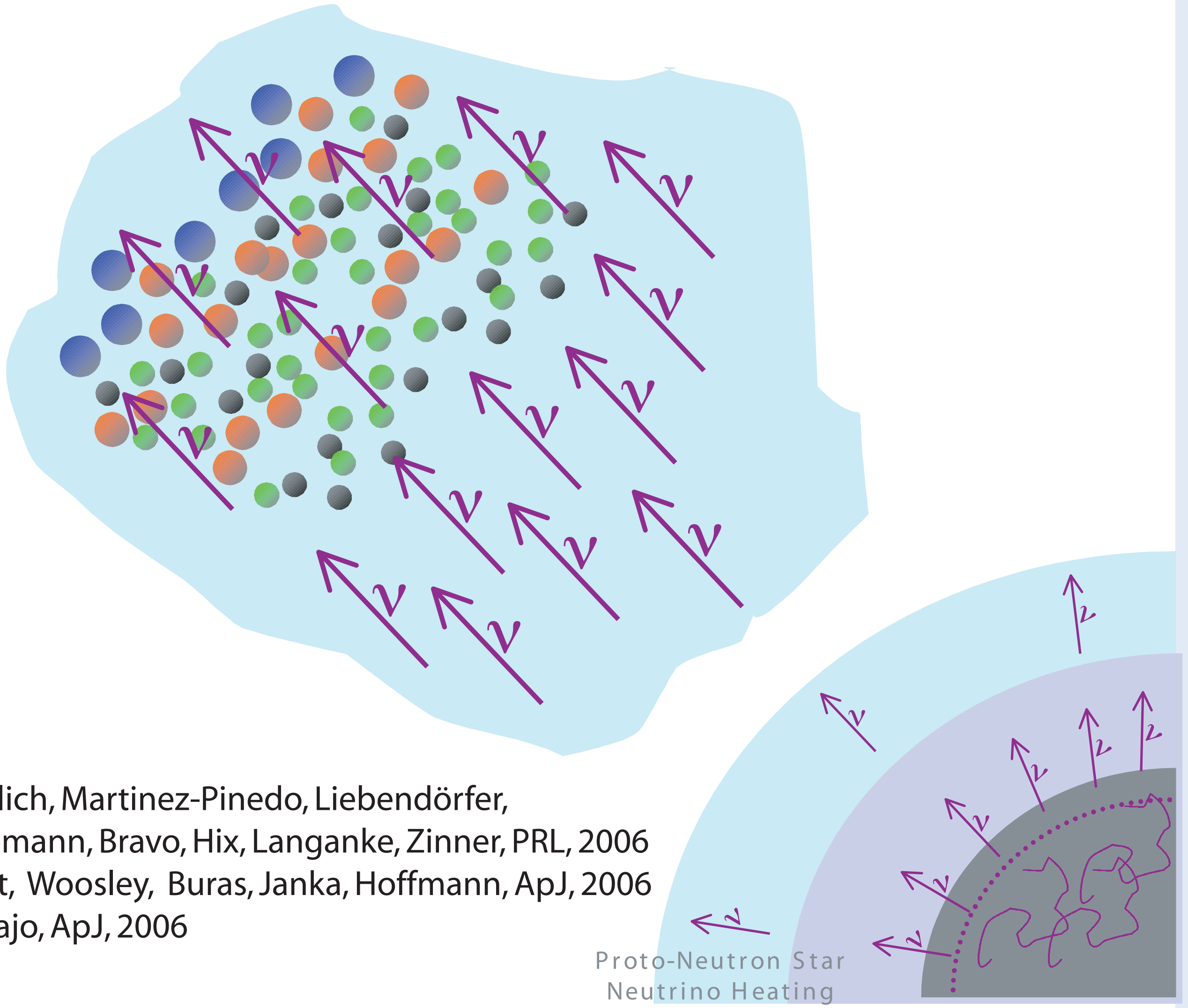
An interesting nucleosynthesis process:



Proto-Neutron Star
Neutrino Heating
of Shock Region from Inside

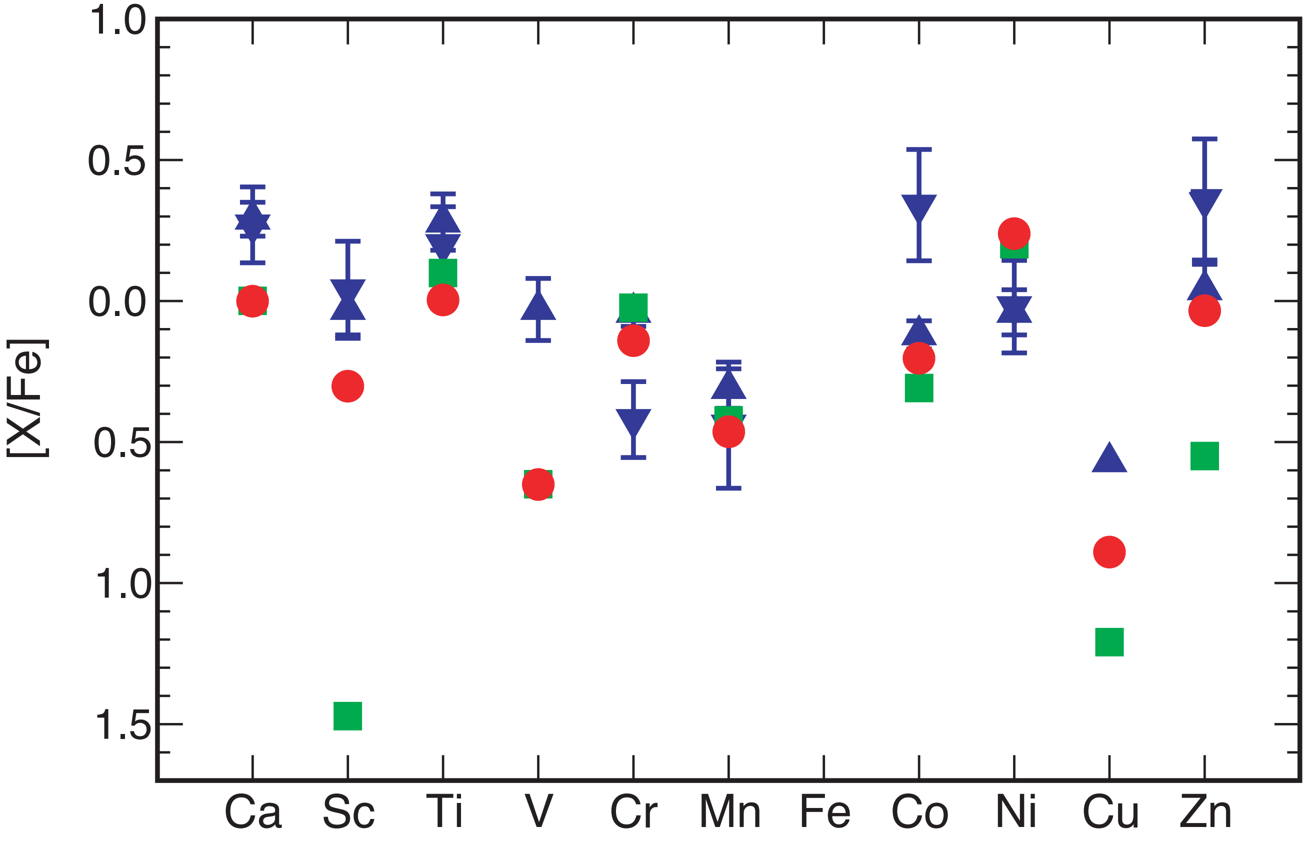
- Fröhlich, Martinez-Pinedo, Liebendörfer, Thielemann, Bravo, Hix, Langanke, Zinner, PRL, 2006
- Pruet, Woosley, Buras, Janka, Hoffmann, ApJ, 2006
- Wanajo, ApJ, 2006

- Similar luminosities of neutrinos and anti-neutrinos
- Hot expanding ejecta with low electron chemical potential

Proton to neutron mass difference favours protons

Nucleosynthesis in p-rich ejecta

Comparison of elemental overabundances with observations from metal-poor and extremely metal-poor stars

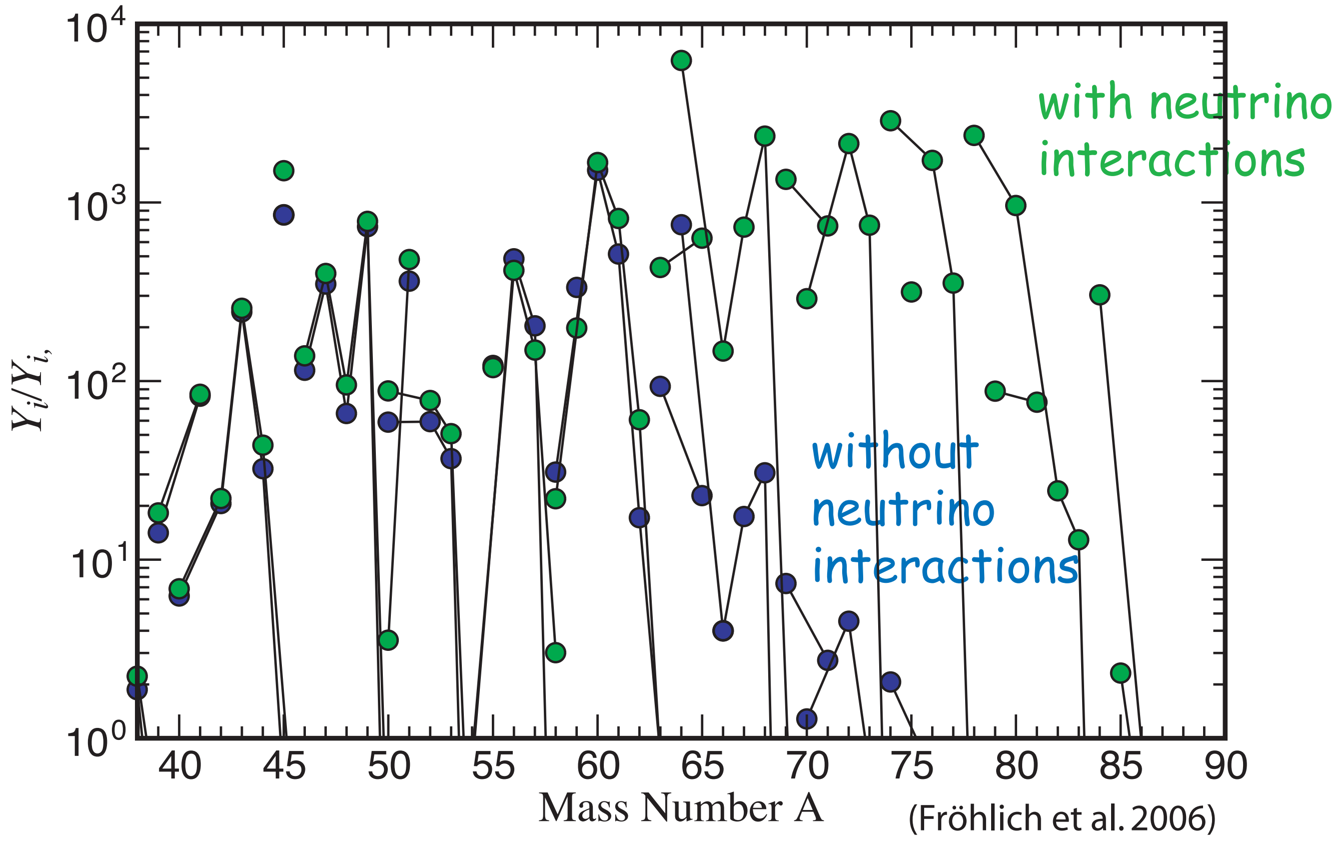


- improved agreement with observation by nucleosynthesis in proton-rich environment of
Sc
Cu
Zn

▼ Cayrel et al.
▲ Gratton & Sneden
■ Thielemann et al.
● Fröhlich et al.

(See also Umeda & Nomoto 2005)

Step 2: The νp-process



(Fröhlich et al. 2006)

1) 64Ge has T1/2=64, This is larger than the expansion time scale ~10s

2) antineutrinos are captured on free protons and produce neutrons for (n,p) reactions replacing beta decay-->the flow continues!

3) Responsible for Sr differences in HE 0107-6240, HE 1327-2326? (Frebel et al. 2006)

Nuclei up to A~80 are produced when the neutrino-nucleon interactions are consistently included in the network!

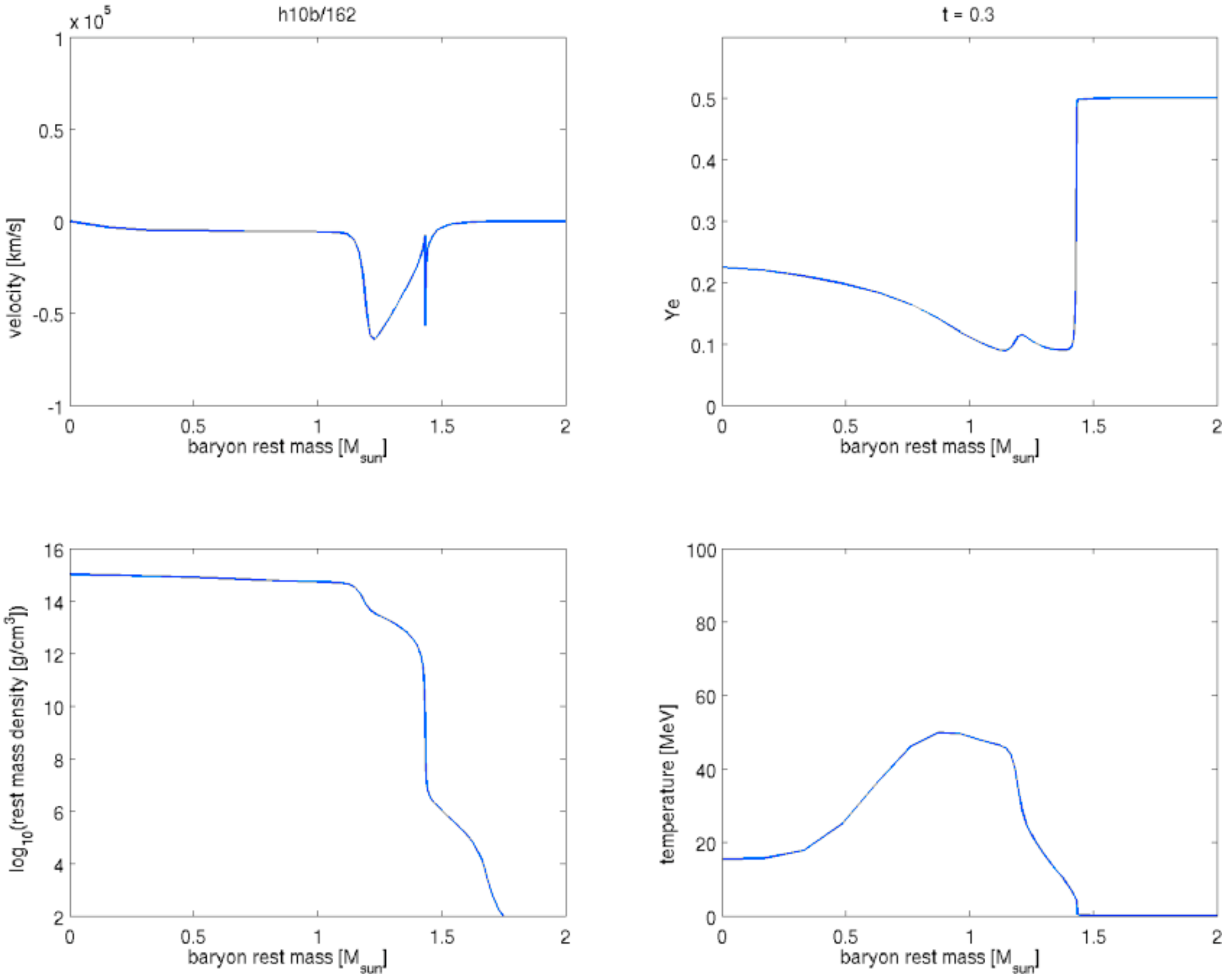
--> New nucleosynthesis process

Phase Transition in Proto-Neutron Star

- neutron star collapse
- conversion to quark phase from inside out
- shrinking mixed phase
- second accretion shock propagating out
- shock moves with mixed-hadronic phase boundary
- accretion shock detaches from phase boundary to reach ν-spheres in the hadronic phase
- shocked matter accelerates and triggeres explosion

(Sagert, Fischer et al., PRL 2009)

Phase Transition in Proto-Neutron Star



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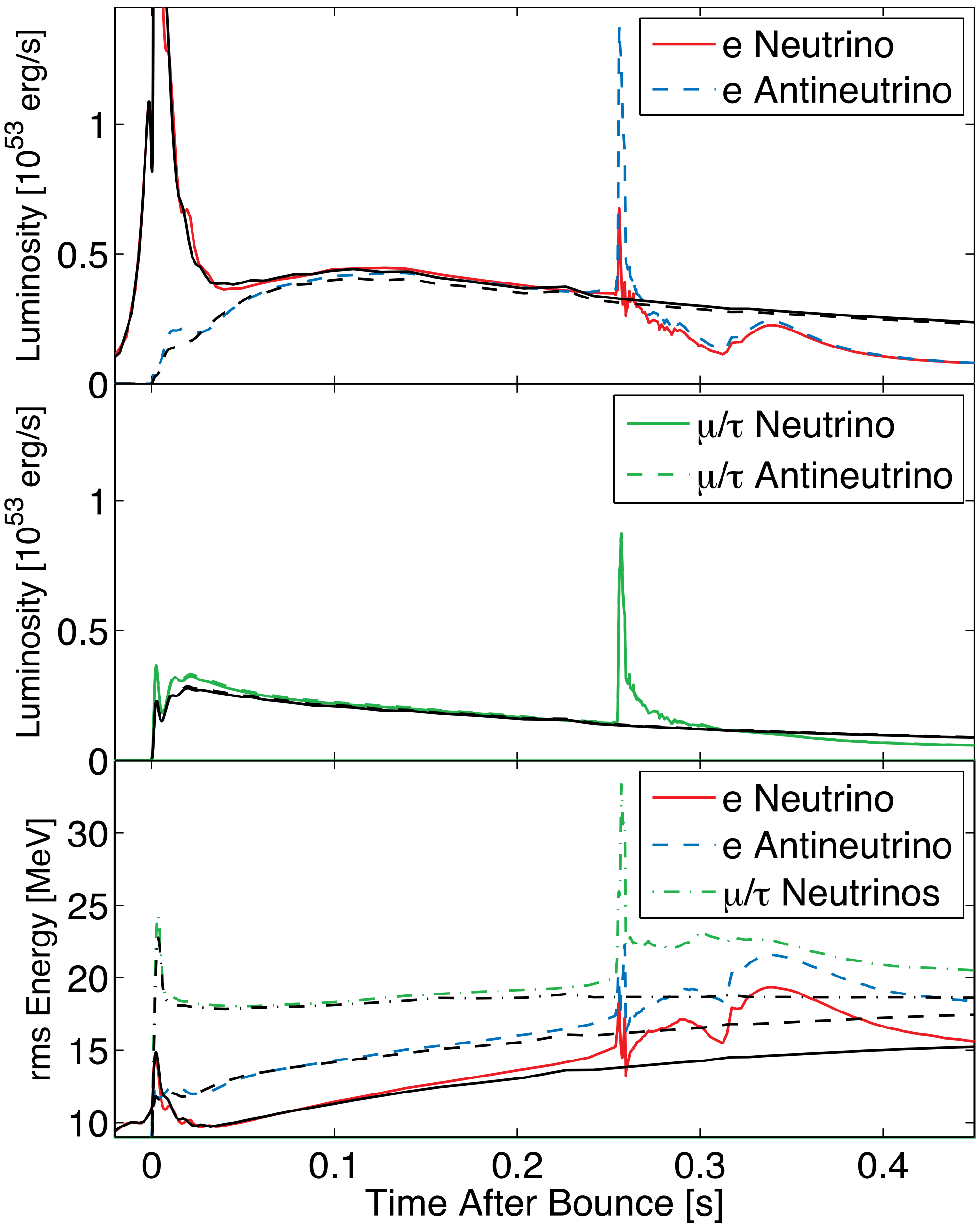
ν-signature of phase transition



Shown is a simulation of a10 Ms star containing quark matter ($B^{1/4}$=162) compared to one with hadronic matter only (black lines)

- Strong and narrow second neutrino peak in all flavours

- Step up in neutrino rms energies

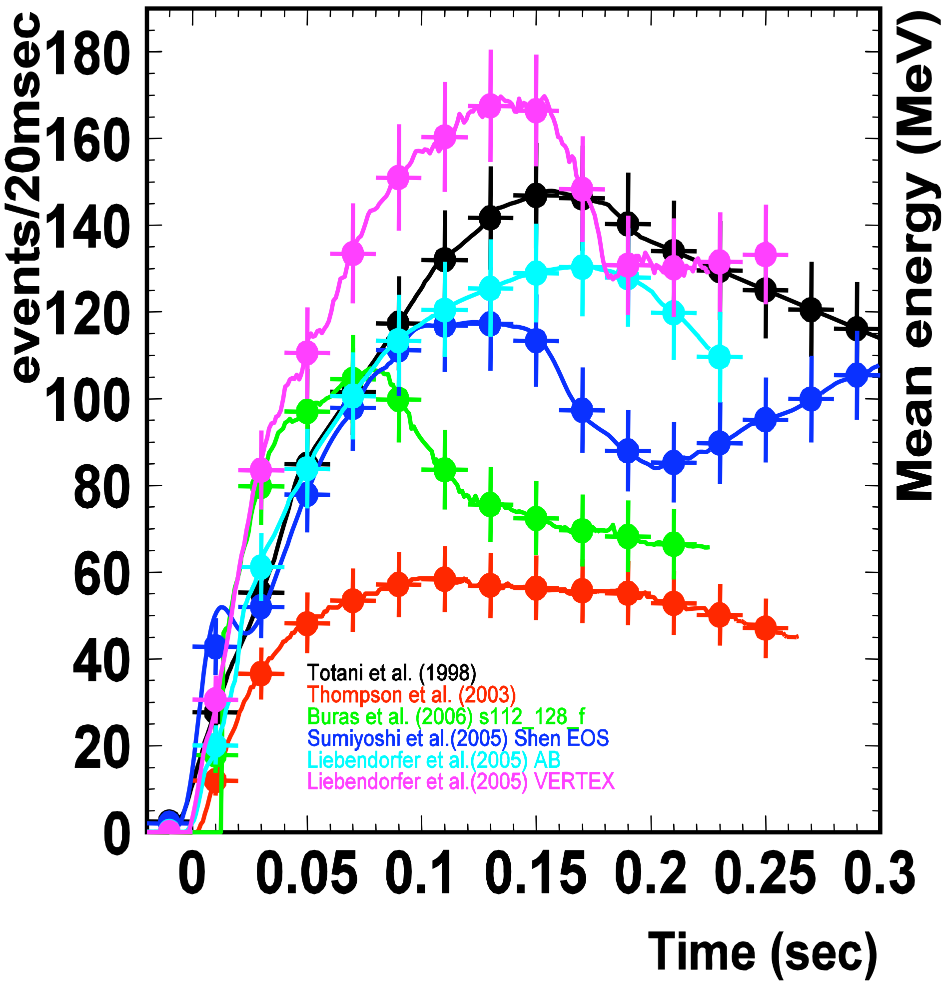
(I. Sagert et al., T. Fischer et al. 2008)

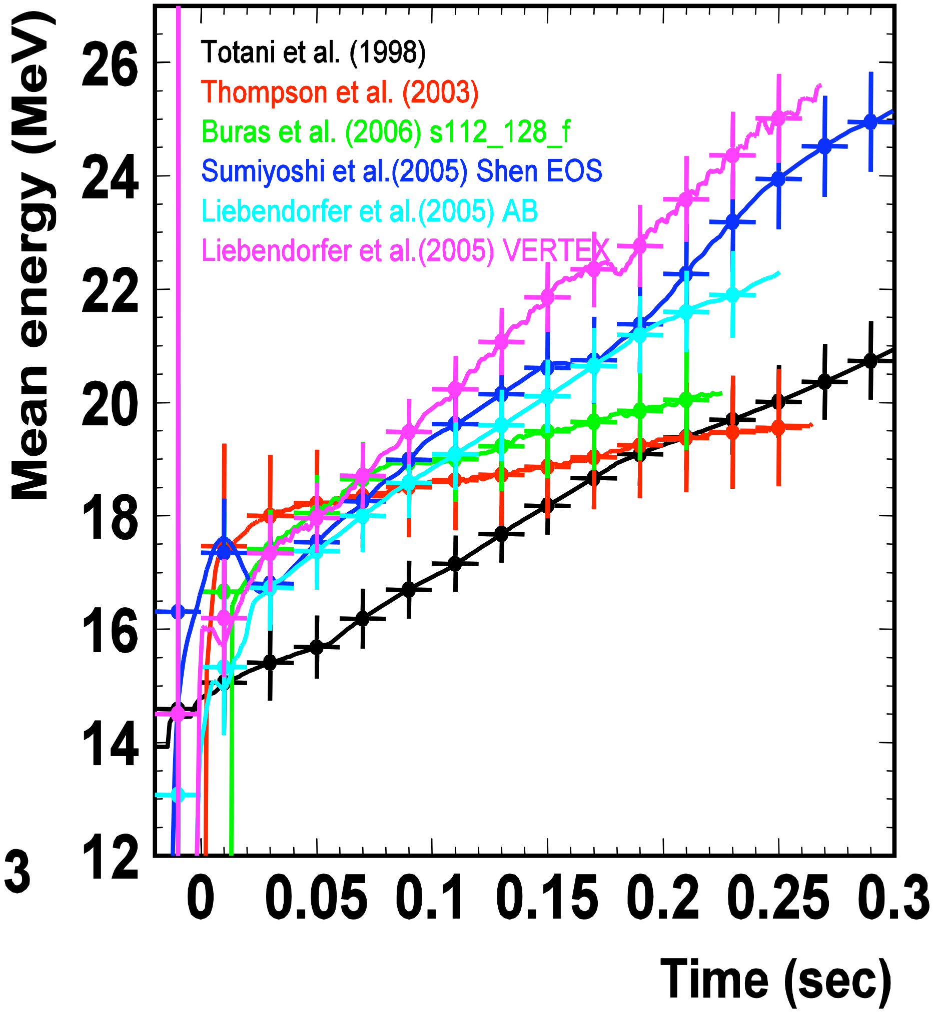
Sensitivity of SK for time variation measurement

Assuming a supernova at 10kpc, expected statistical error is plotted.

Time variation of event rate

Time variation of mean energy





Enough statistics to test those models

Transparency from M. Nakahata,
20 years after SN1987A, Feb. 2007

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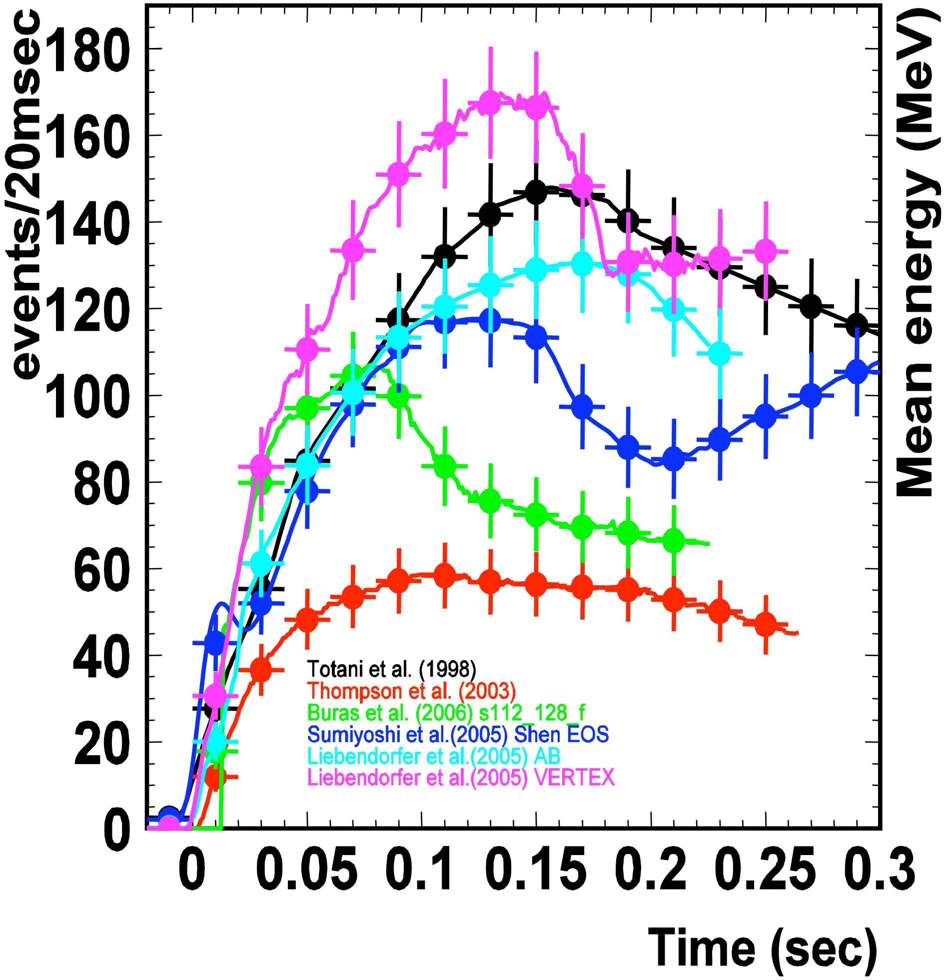
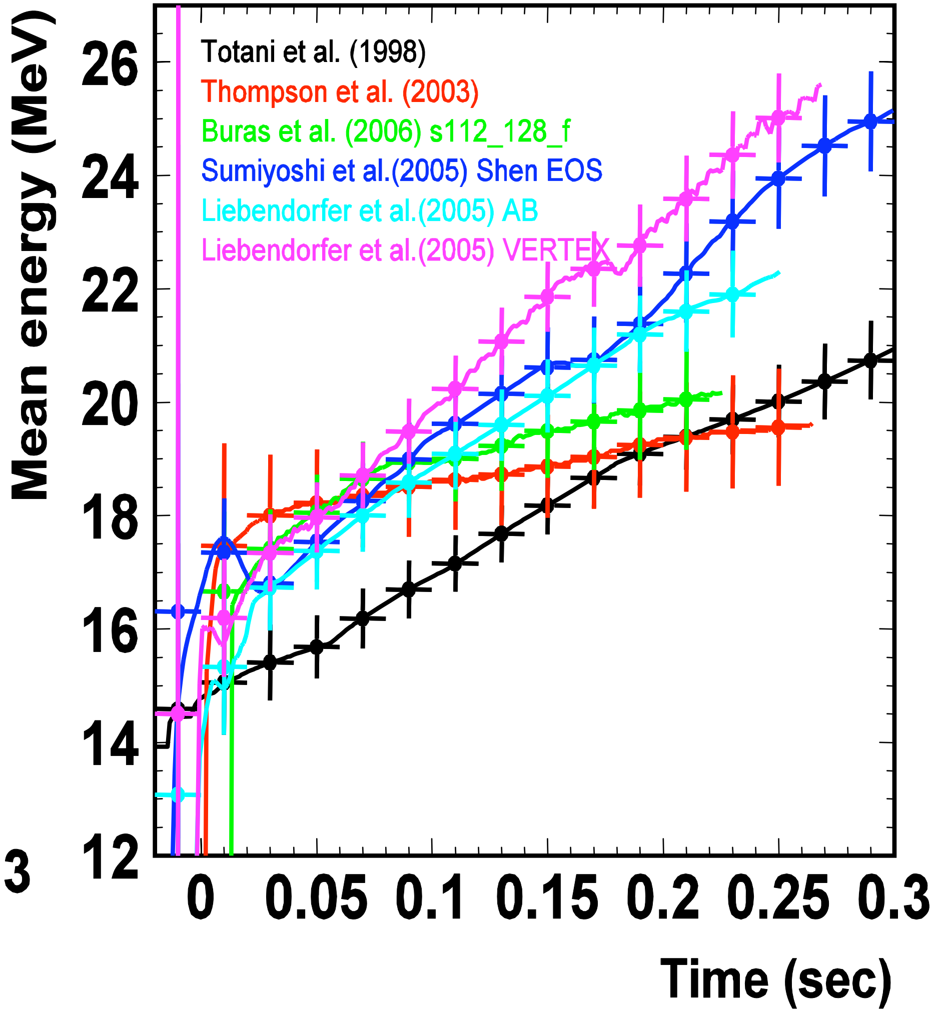


Time variation of mean energy



Enough statistics to test those models

yes, but difficult to detect narrow peak!

(pers. comm. S. Horiuchi, S. Kawagoe)

Transparency from M. Nakahata,
20 years after SN1987A, Feb. 2007

No/weak explosions: What is missing?

Accretion phase with standing accretion shock (spherical or not) or fallback from weak explosion

⇩

Proto-neutron star (PNS) reaches critical density and reconfigures

⇩

Shock wave propagates toward the PNS surface

⇩

Shock accelerates at the density cliff at the edge of the PNS and catches up with the first shock

⇩

Outflow behind the shock leads to a large gain radius so that the explosion becomes unavoidable

- similar neutron star masses at birth
- transient neutrino signal with anti-neutrino dominance
- ejected low-Ye pocket (r-process?)

⇩

Quark matter in neutron stars

(Sagert, Fischer et al., PRL 2009)

Spectral ν-transport in axisymmetry

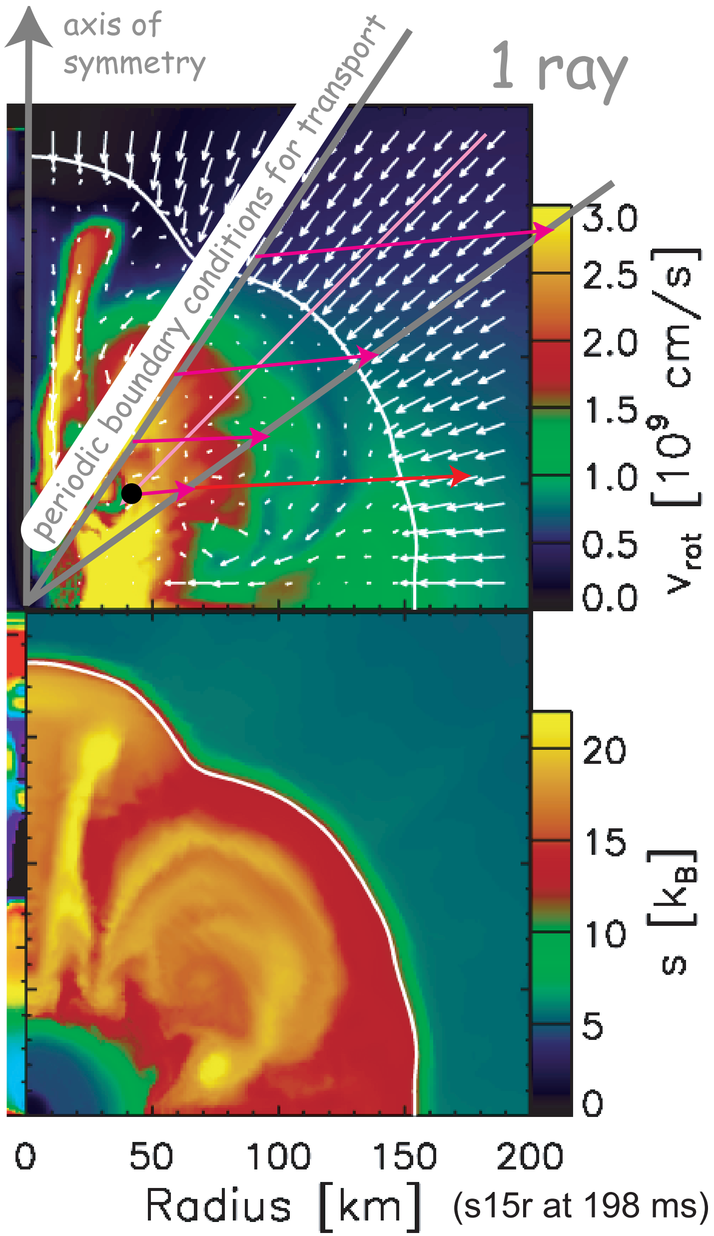
2D + ray-by-ray

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

Several alternative approaches:

Livne et al. (2004)
Walder et al. (2004)
Myra & Swesty (2005)
Bruenn et al. (2007)
Dessart et al. (2007)
Ott et al. (2008)
Swesty & Myra (2009)



(s15r at 198 ms)

Example Garching group:

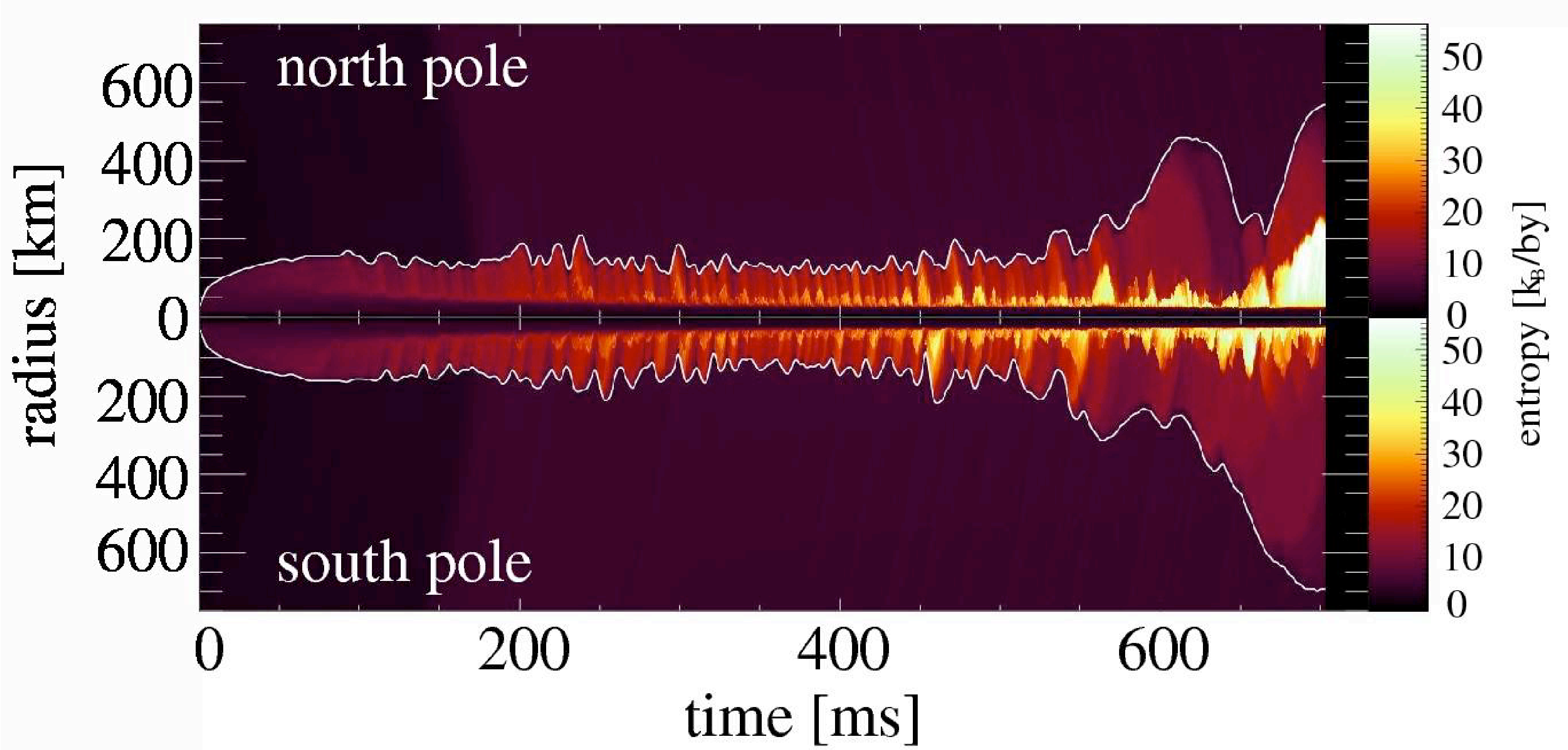
- couple 1D solution to 2D hydrodynamics in angular segments
- explosion for 11Ms, and for 15Ms (Marek & Janka 2007)
- advantage of reliable 1D transport
- disadvantage of large computation time and neglected tangential transport

...produces weak delayed explosions

- Standing Accretion Shock Instability (SASI) perturbs shock radius   Blondin, Mezzacappa 2003, Foglizzo et al. 2007
- Extended postbounce phase before weak explosion

Full problem only affordable for few selected runs

Marek & Janka 2009



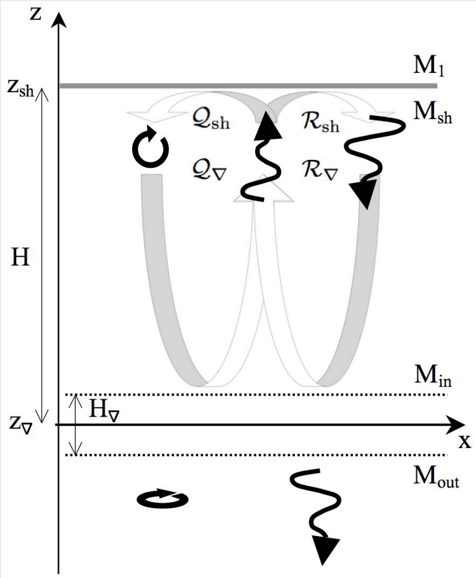
Standing Accretion Shock Instability

- Seen in simulations without ν physics: sloshing and spiral modes

Blondin & Mezzacappa 2003

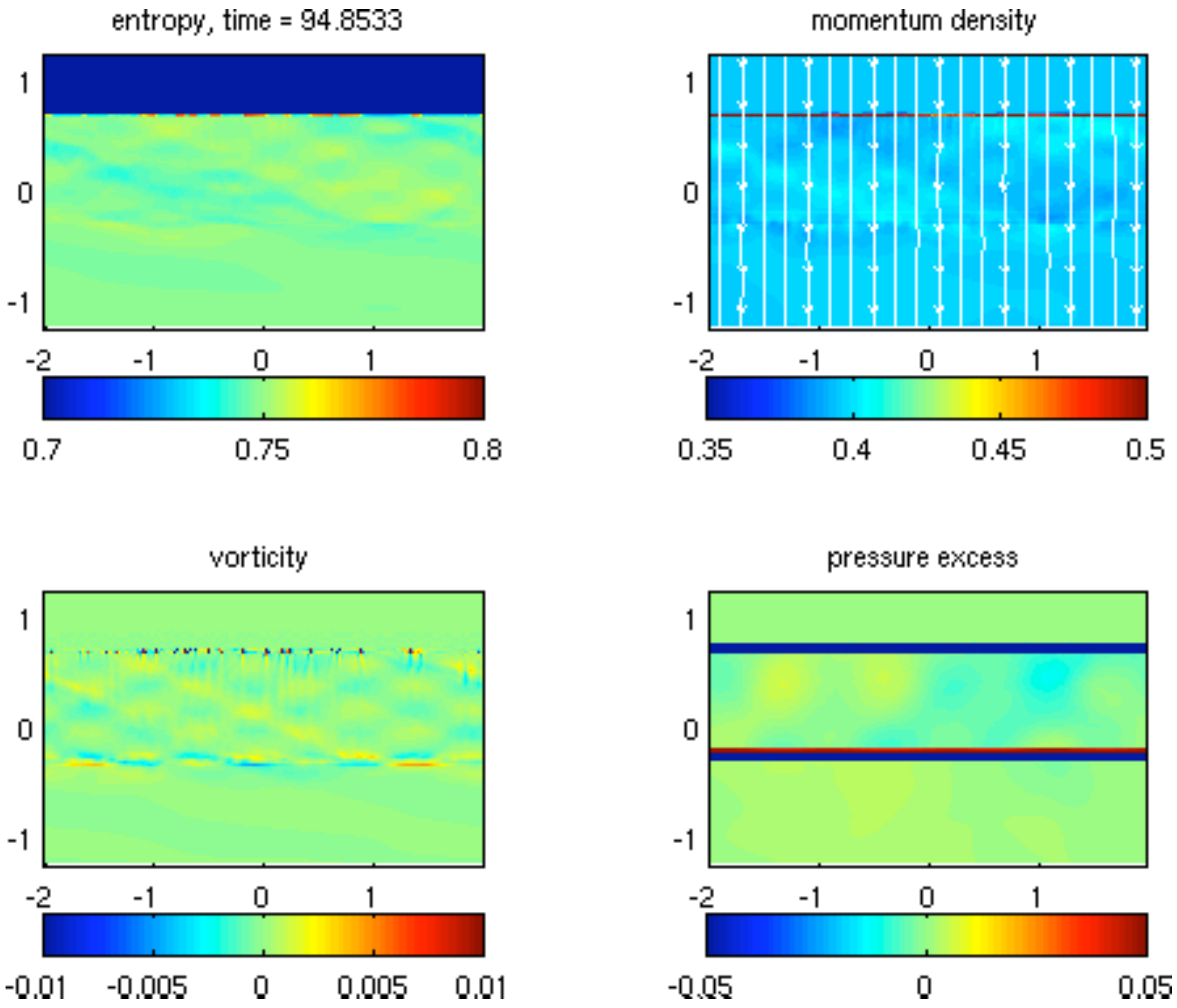
- Advective-acoustic instability (SASI)

Foglizzo et al. 2005/9



Why not convective turnover à la Herant et al. 1994 ?

Standing Accretion Shock Instability



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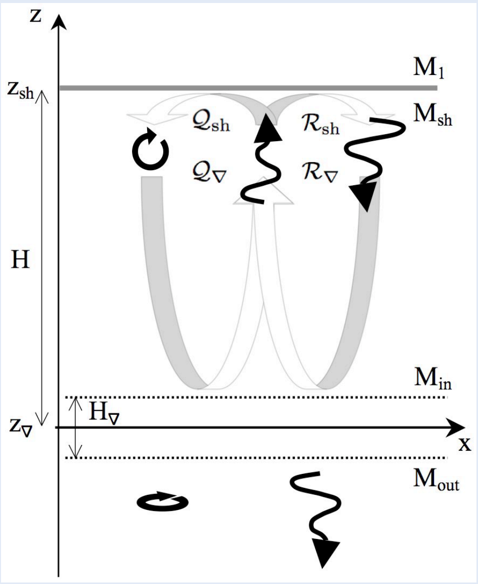
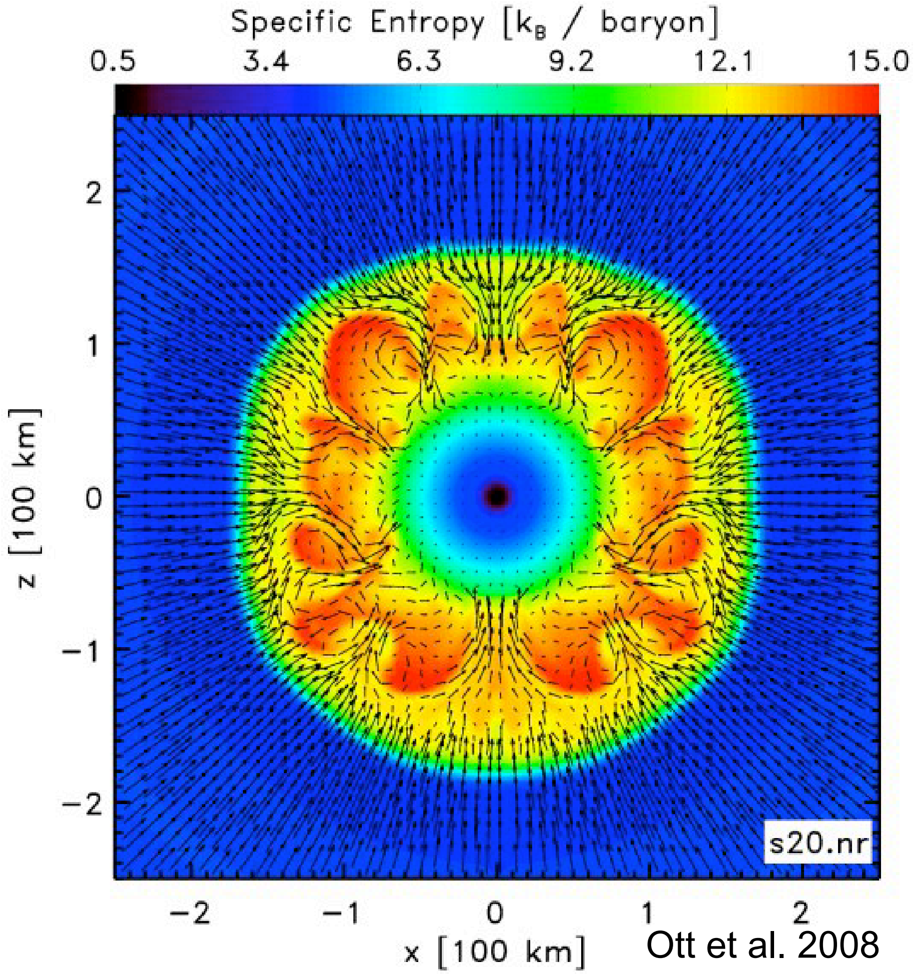


Why not convective turnover à la Herant et al. 1994 ?

Convergence in 2D not yet demonstrated

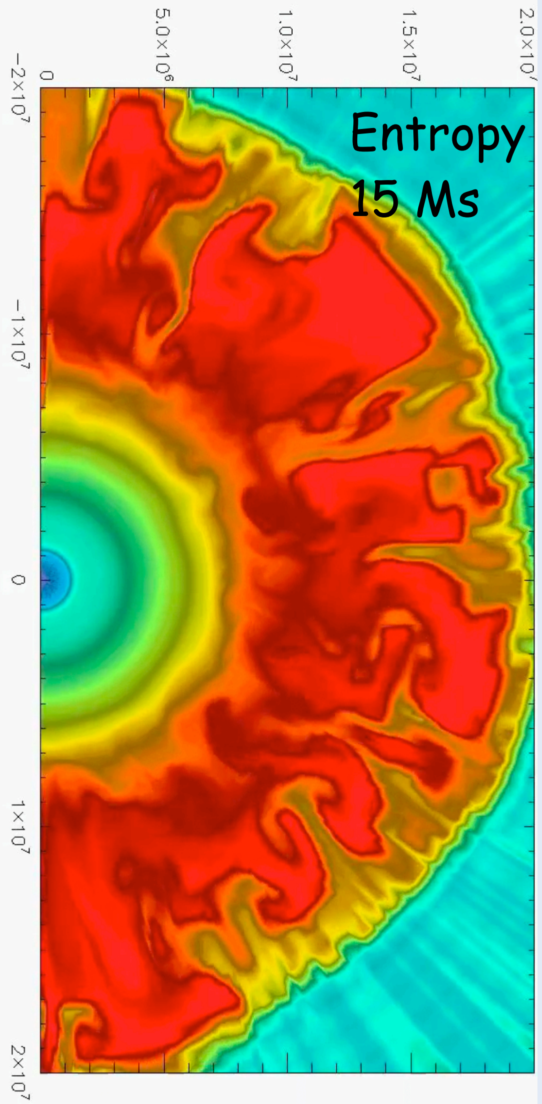
Explosion at 1200 ms by acoustic mechanism:

- unconfirmed by other groups Burrows et al. 2006
- coupling to higher modes? Weinberg & Quataert 2008



Ott et al. 2008

Entropy
at 160 ms
20 Ms



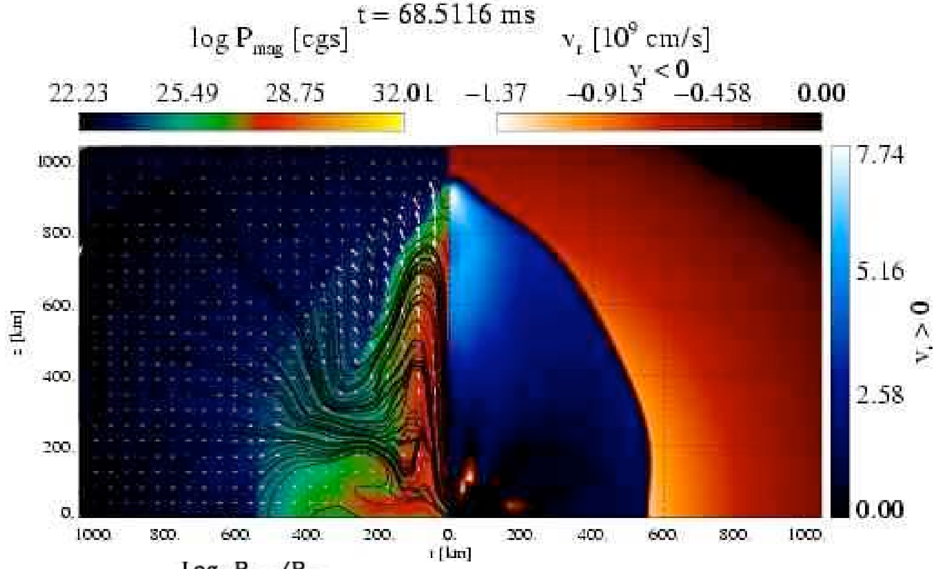
Entropy
15 Ms

Explosion ~400ms?

Messer et al. 2008

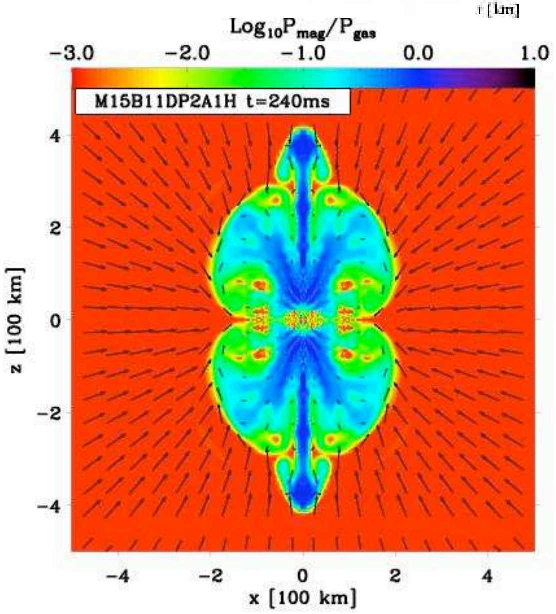
Magneto-rotational explosion mechanism

Recent MHD collapse simulations with a neutron star

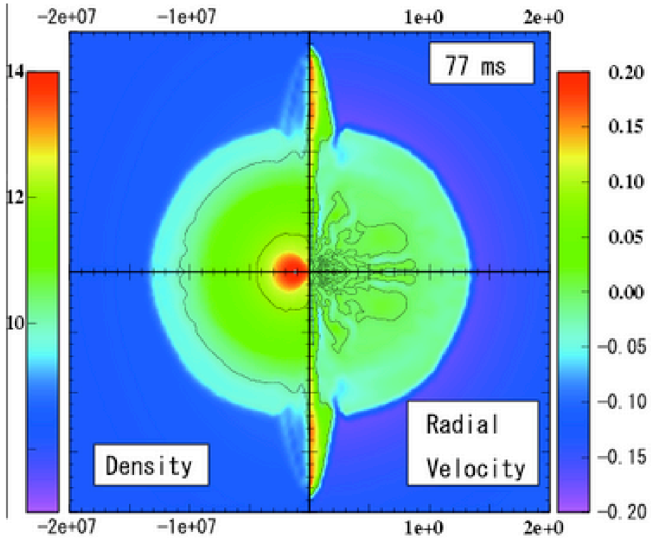


Obergaulinger et al. 2006, T/W=0.23%, B=1E+13 G

Takiwaki et al. 2007, T/W=1%, B=1E+10 G



Burrows et al. 2007, 2π rad/s, 1E+11 G



Pioneering efforts:

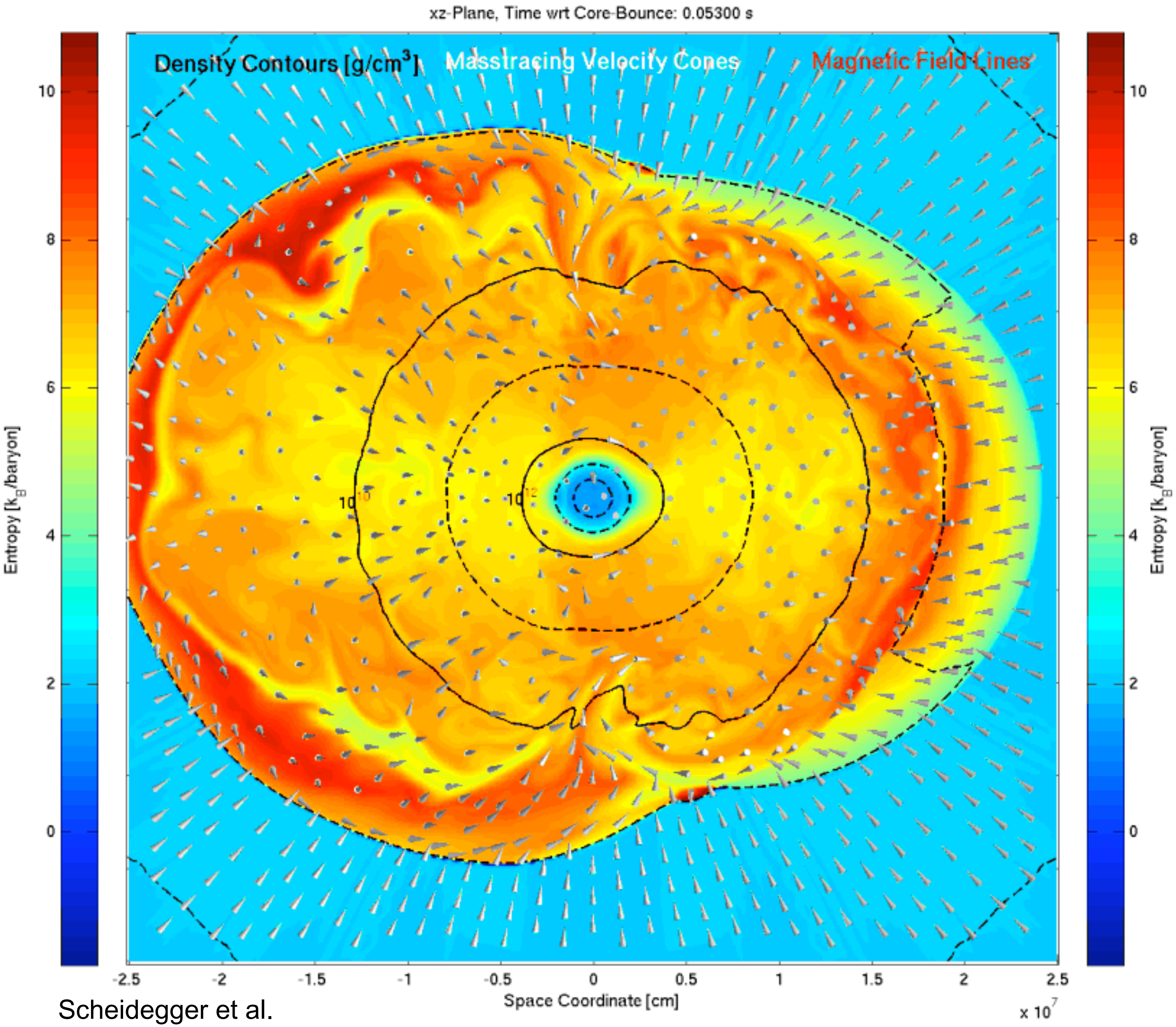
Leblanc & Wilson 1970
Bisnovatyi-Kogan 1971/76
Kundt 1976
Meier et al. 1976
Müller & Hillebrandt 1979
…
MacFadyen & Woosley 1999

Collapsar model (accretion into BH)

Modelling challenge:

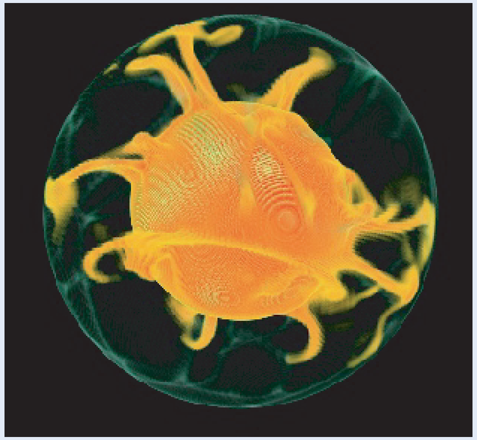
- Weak initial field
- Short collapse
- Long growth time

From axisymmetry to 3D



Scheidegger et al.

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

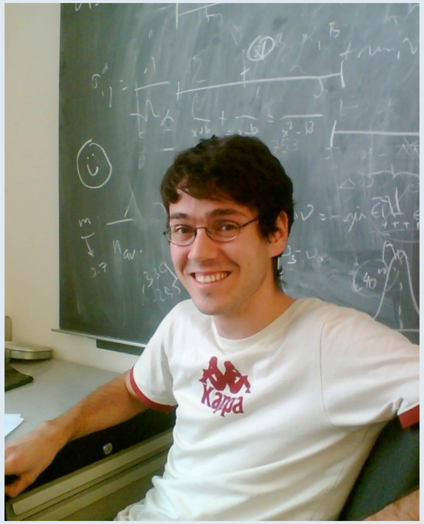


Shijie Zhong 2005

3D Magneto-Hydrodynamics

Elegant parallel hydrodynamics with
approximate neutrino transport

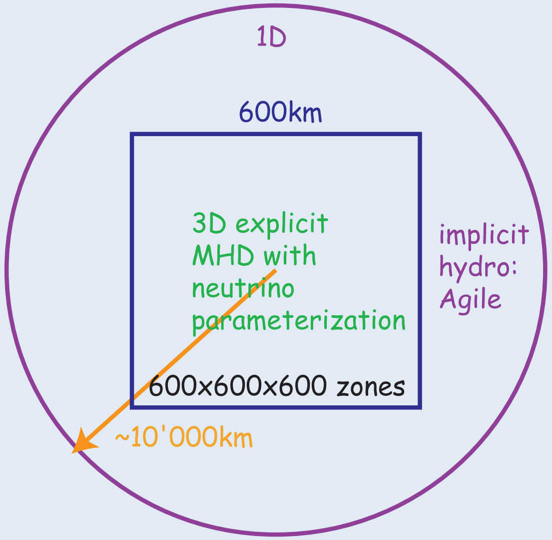
Dr. Stuart C. Whitehouse
Roger Käppeli



3D Magneto-Hydrodynamics

Elegant parallel hydrodynamics with
approximate neutrino transport

- Lattimer-Swesty EoS
- Effective GR potential
- constrained transport
- 2nd order TVD
- e-flavour neutrinos



1D

600km

3D explicit
MHD with
neutrino
parameterization

600x600x600 zones

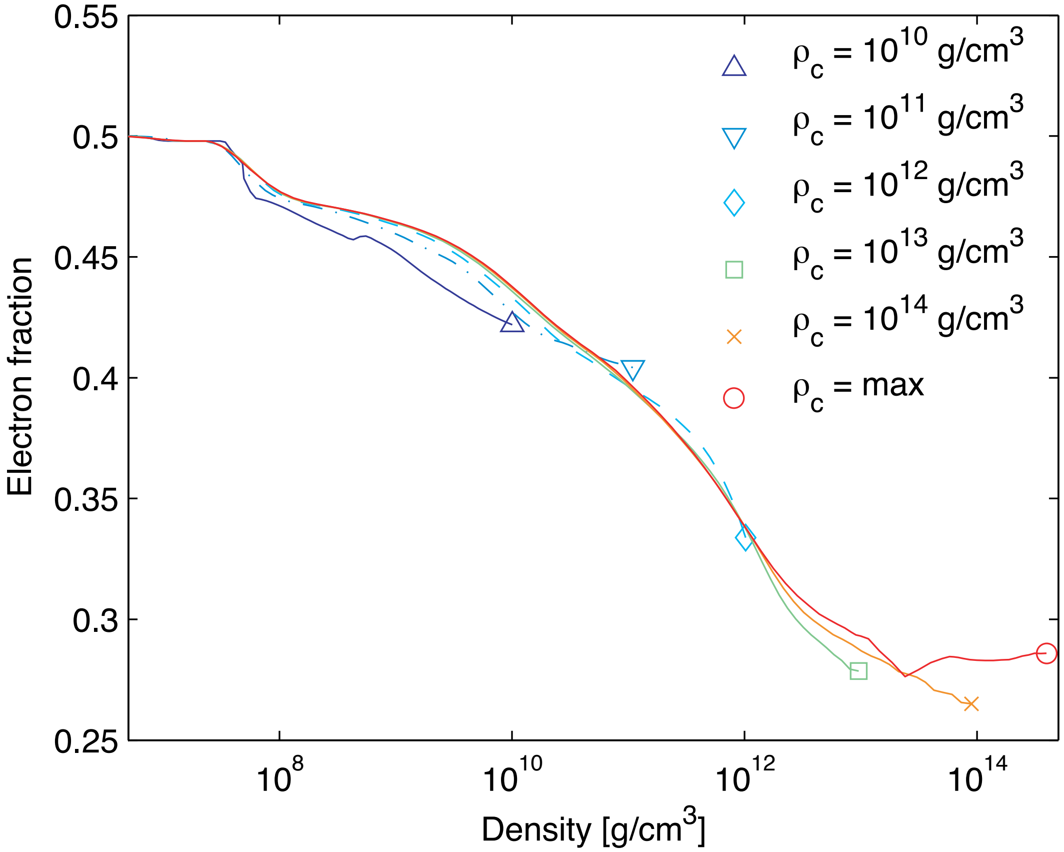
implicit
hydro:
Agile

~10'000km

(Liebendörfer, Pen, Thompson 2006)

Parameterised ν-physics before bounce

Electron fraction in spherical runs can be parameterised



Entropy changes and neutrino stress can be derived:

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

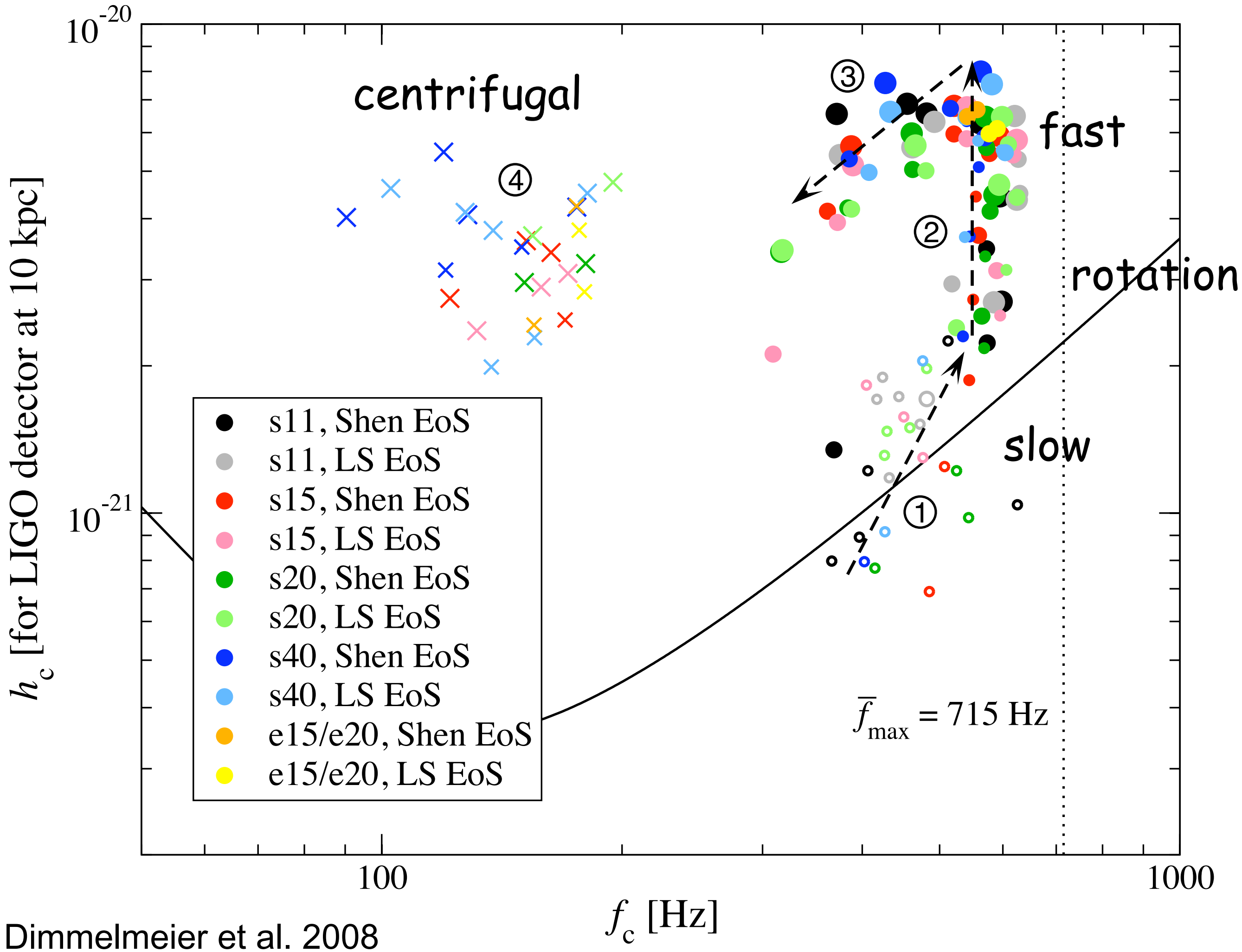
(~10MeV)

- Simple to implement (compared to neutrino transport...)
- Computationally very efficient!
- Performs well for collapse and bounce
- Not applicable in postbounce phase!

Liebendörfer 2005

Gravitational waves in 2D models

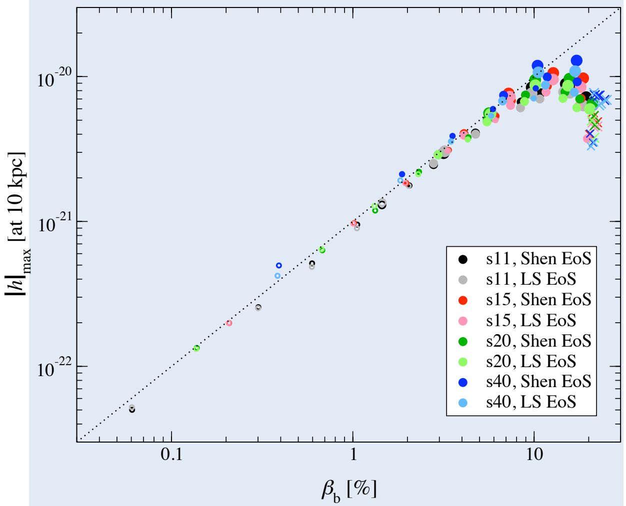
Many different runs have been analysed based on neutrino parameterisation scheme and nuclear EoS:



Dimmelmeier et al. 2008

Only type I signals found!

Dimmelmeier et al. 2008

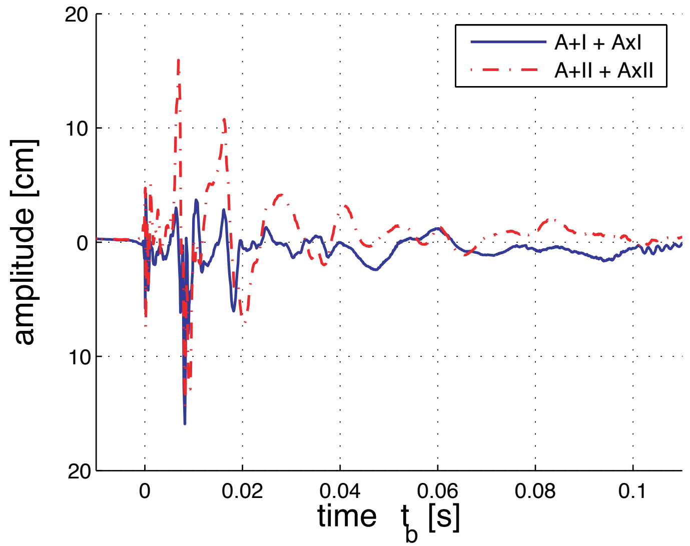


Linear imprint of core rotation rate on GW

Recent reviews on GW from core-collapse supernovae:

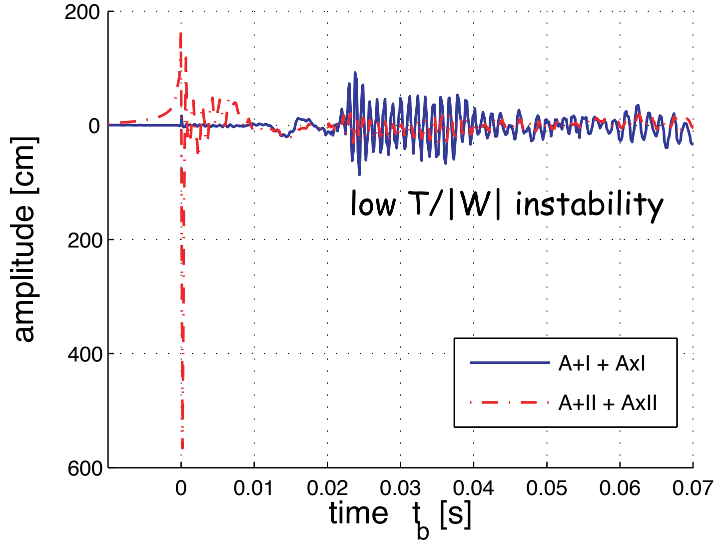
- Kotake, Sato, Takahashi 2005
- Ott 2009

Gravitational waves in 3D



Slowly rotating 15Ms progenitor according to

(Heger, Woosley & Spruit 2005)

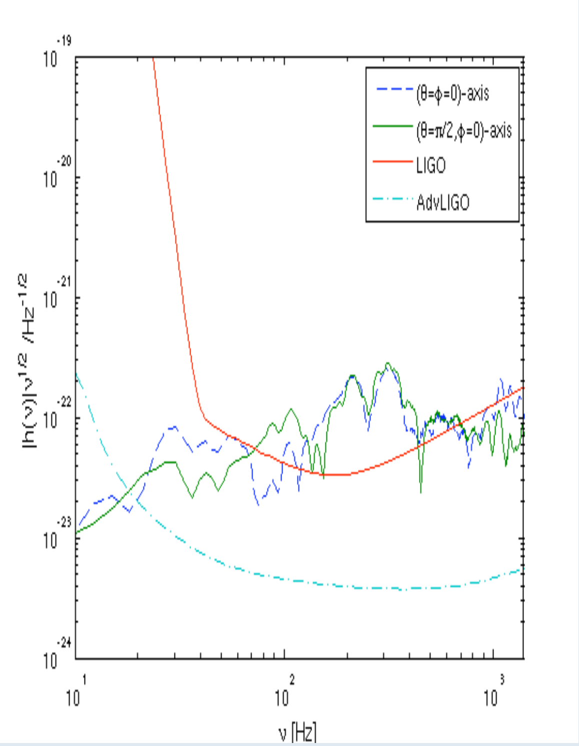


Fast rotating 15Ms progenitor

$\Omega \sim 2\pi$ rad/ps

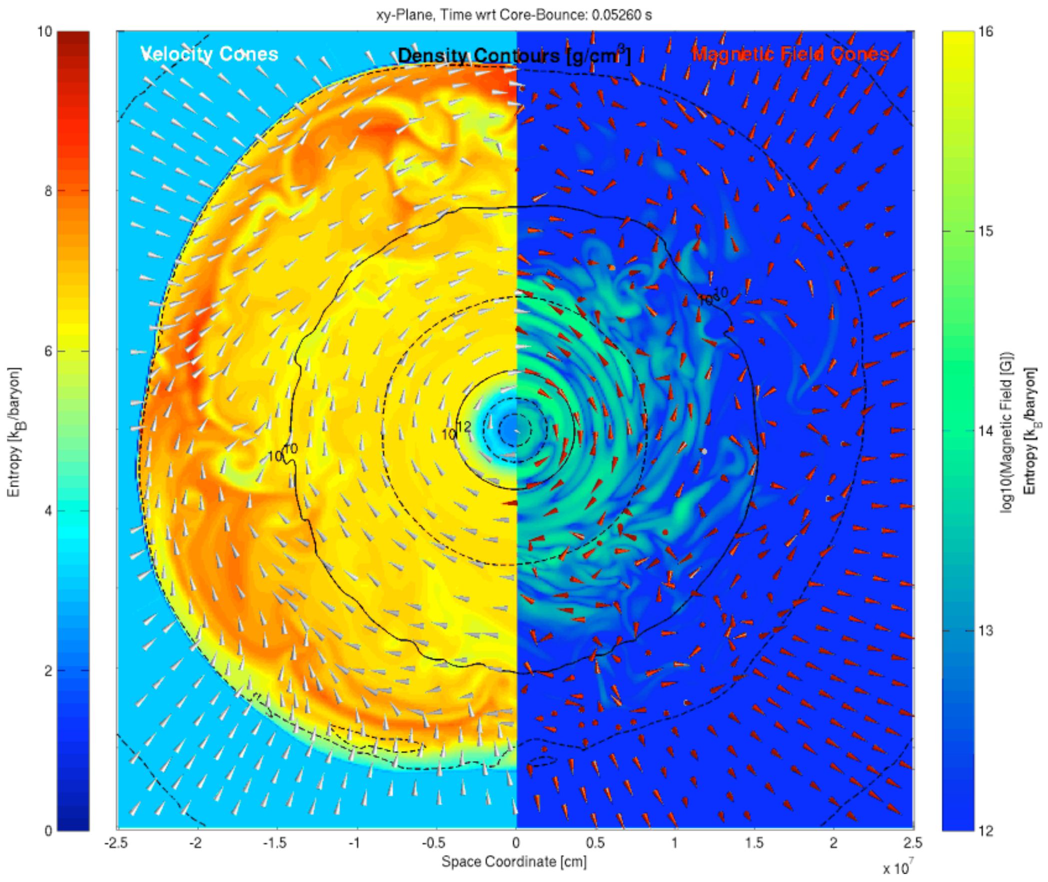
--> imprint of bounce and rotation rate

Scheidegger et al. 2009, in qualitative agreement with Ott et al. 2007

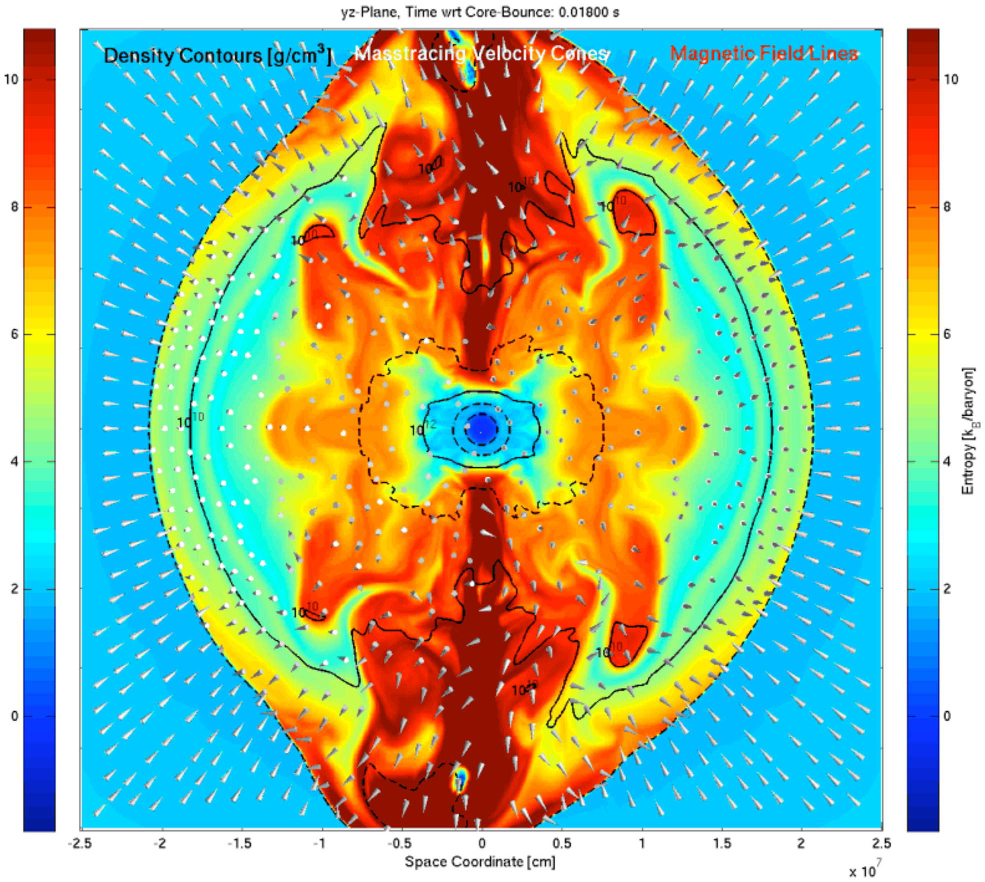


Galactic supernovae
-- could (LIGO)
-- should (Adv. LIGO)
be detectable

Experimental 3D magneto-rotational runs



Setup with weak toroidal field
--> winding
Liebendörfer et al. 2006



Setup with poloidal field as in Burrows et al. 2007,
--> jet
Käppeli, Scheidegger et al.

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
- At a resolution of
  1000^3 zones
  --> 80GB per step

Solving the Boltzmann equation

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

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

(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:

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  --> 64TB per time 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

Hydrodynamics:

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

difficult energy-terms must not be neglected!

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

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

Diffusion limit:

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

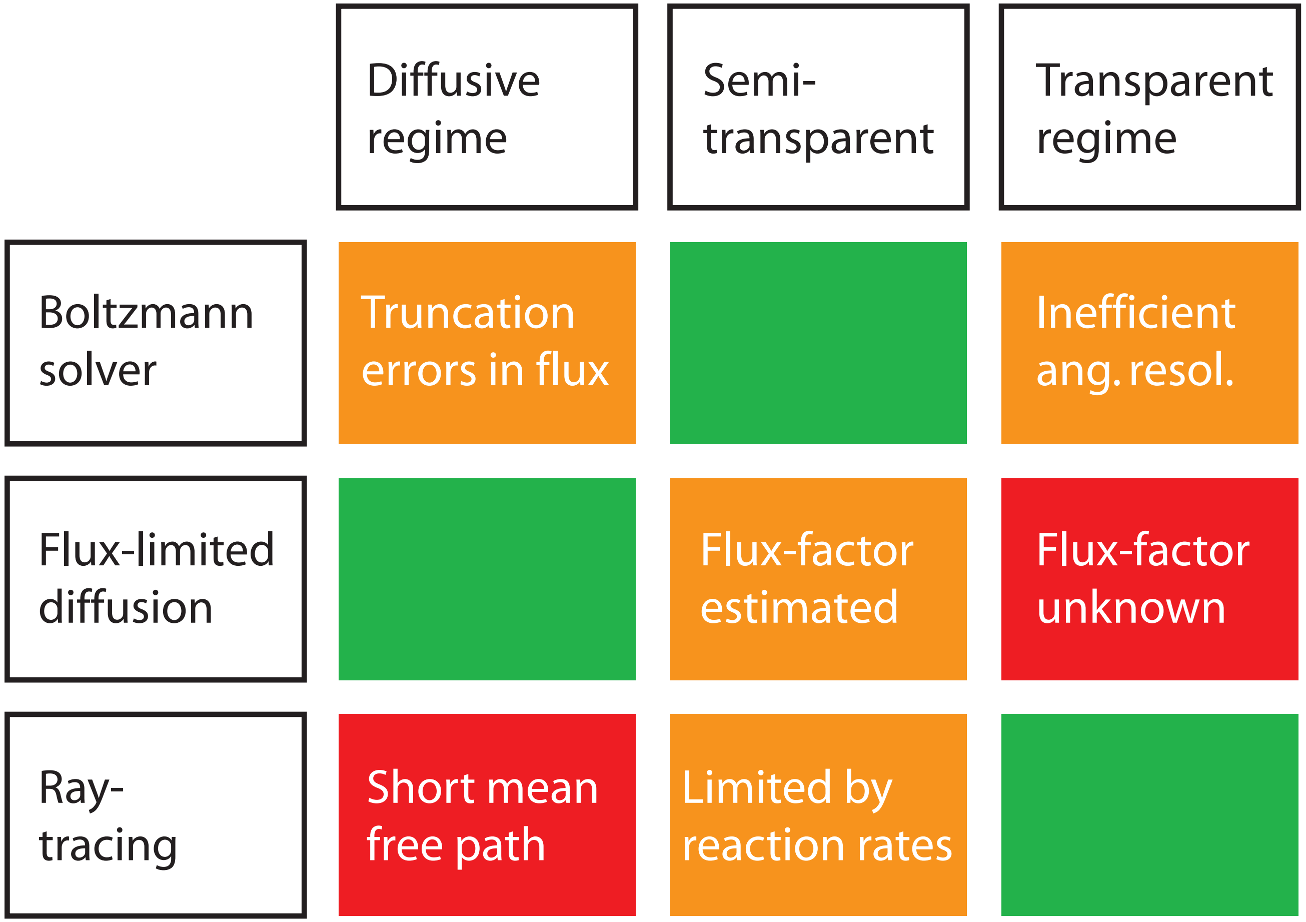
Hydrodynamics:

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

difficult energy-terms must not be neglected!

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

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:

- Variable Eddington Factor method
  successful in 2D but very computationally expensive!
  (Rampp & Janka, Buras et al. 2002-5)
- Grey diffusion in one regime and grey transparent elsewhere
  successful in 3D but not accurate enough!
  (e.g. Fryer & Warren 2004)
- Multi-Group Flux-Limited diffusion
  difficulty of local flux limiters & multi-D
  (e.g. Arnett 1966, Bruenn 1985,...)

… and 3D neutrino transport?

Fryer & Warren 2002/4,
Scheck et al. 2003

… and 3D neutrino transport?

Efficiency and accuracy?

Fryer & Warren 2002/4,
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Efficiency and accuracy?

Neutrino transport dominates calculation time:

--> Implement all relevant physics to leading order!

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- Accurate diffusion limit

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Neutrino transport dominates calculation time:

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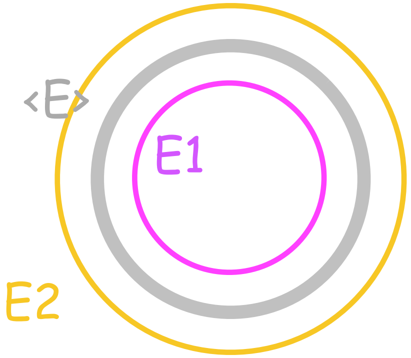
- Thermodynamics of trapped particles (pdV-term)
- Accurate diffusion limit
- Spectral lepton- and energy flux



Fryer & Warren 2002/4,
Scheck et al. 2003

('grey' schemes)

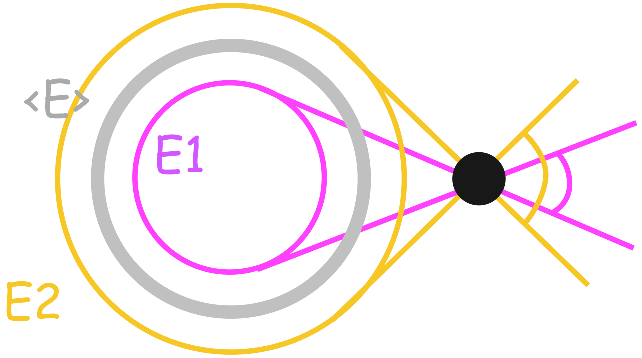
… and 3D neutrino transport?

Efficiency and accuracy?

Neutrino transport dominates calculation time:

--> Implement all relevant physics to leading order!

- Thermodynamics of trapped particles (pdV-term)
- Accurate diffusion limit
- Spectral lepton- and energy flux
- Non-local (geometric) ν propagation directions



Grey transport and 'local' MGFLD miss some geometry!

Fryer & Warren 2002/4,
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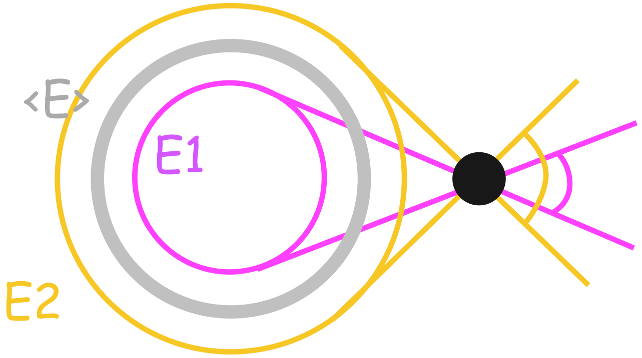

Grey transport and
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Fryer & Warren 2002/4,
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('grey' schemes)

Separation into
- trapped particles
- streaming particles

Different evolution approximations for these components (adaptive algorithm)

Spectral neutrino transport after bounce

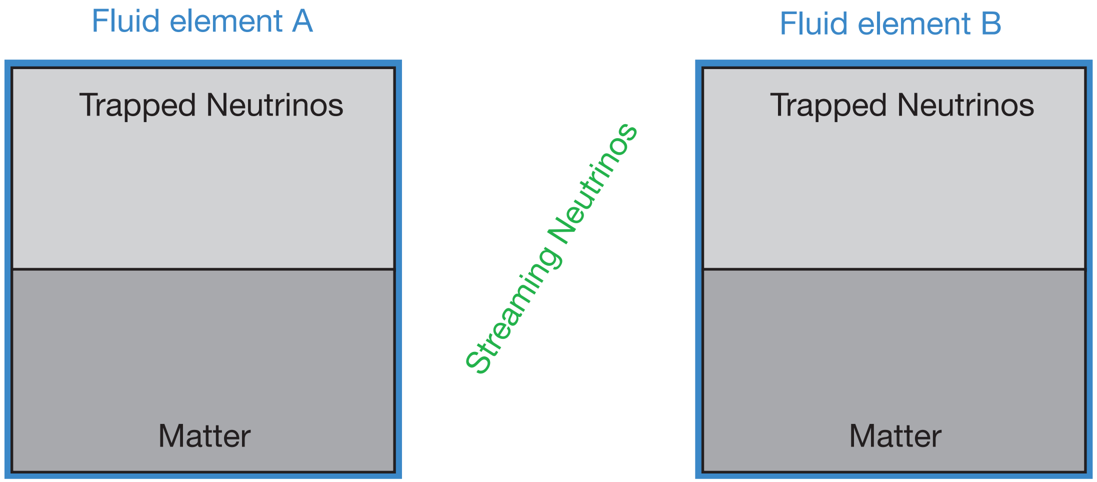
$D(f) = j - \chi^* f$

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

Different approx.
for trapped & streaming
neutrino components!

Isotropic
Diffusion
Source
Approximation

(Liebendörfer,
Whitehouse,
Fischer 2007)



Spectral neutrino transport after bounce

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

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

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

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

Different approx.
for trapped & streaming
neutrino components!

Σ determined by diffusion limit of (1)

I sotropic
D iffusion
S ource
A pproximation

(Liebendörfer,
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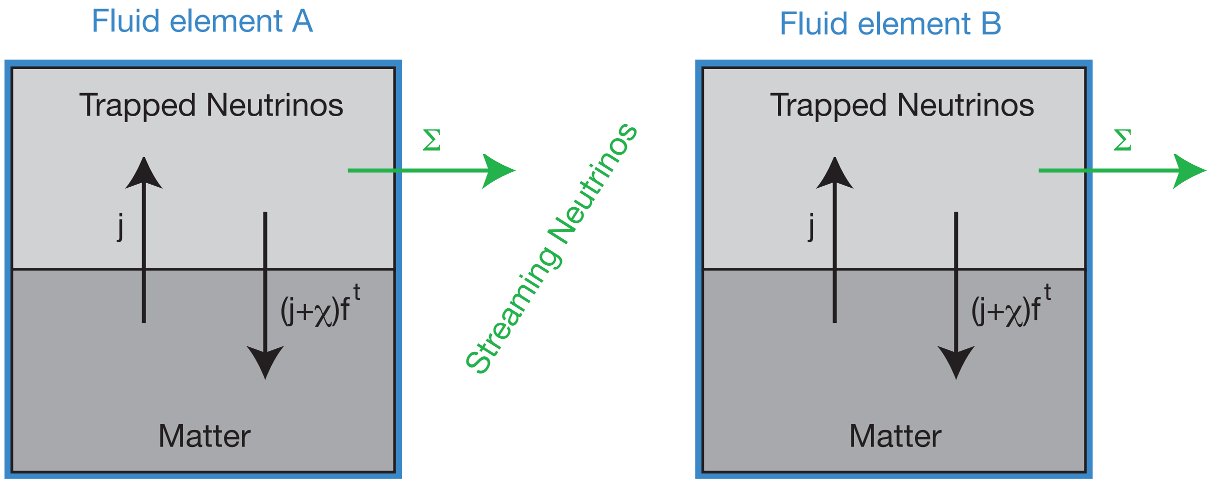

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S ource
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Whitehouse,
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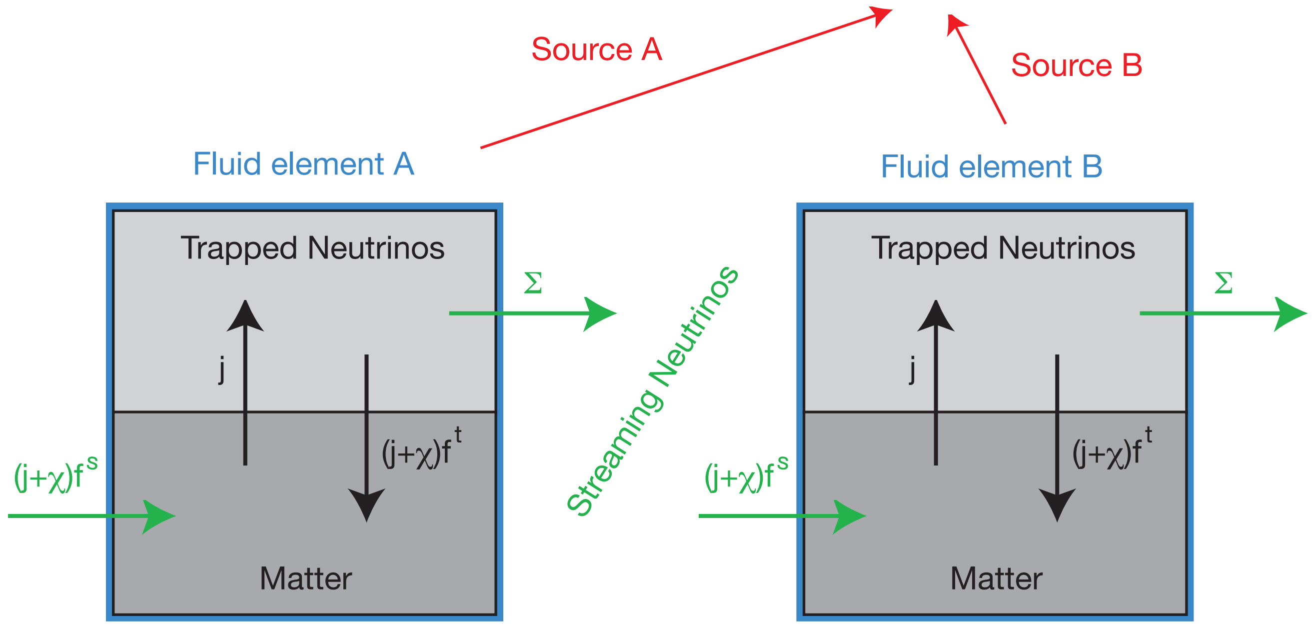
Σ determined by diffusion limit of (1)

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



Source A

Source B

Fluid element A

Fluid element B

Trapped Neutrinos

Matter

j

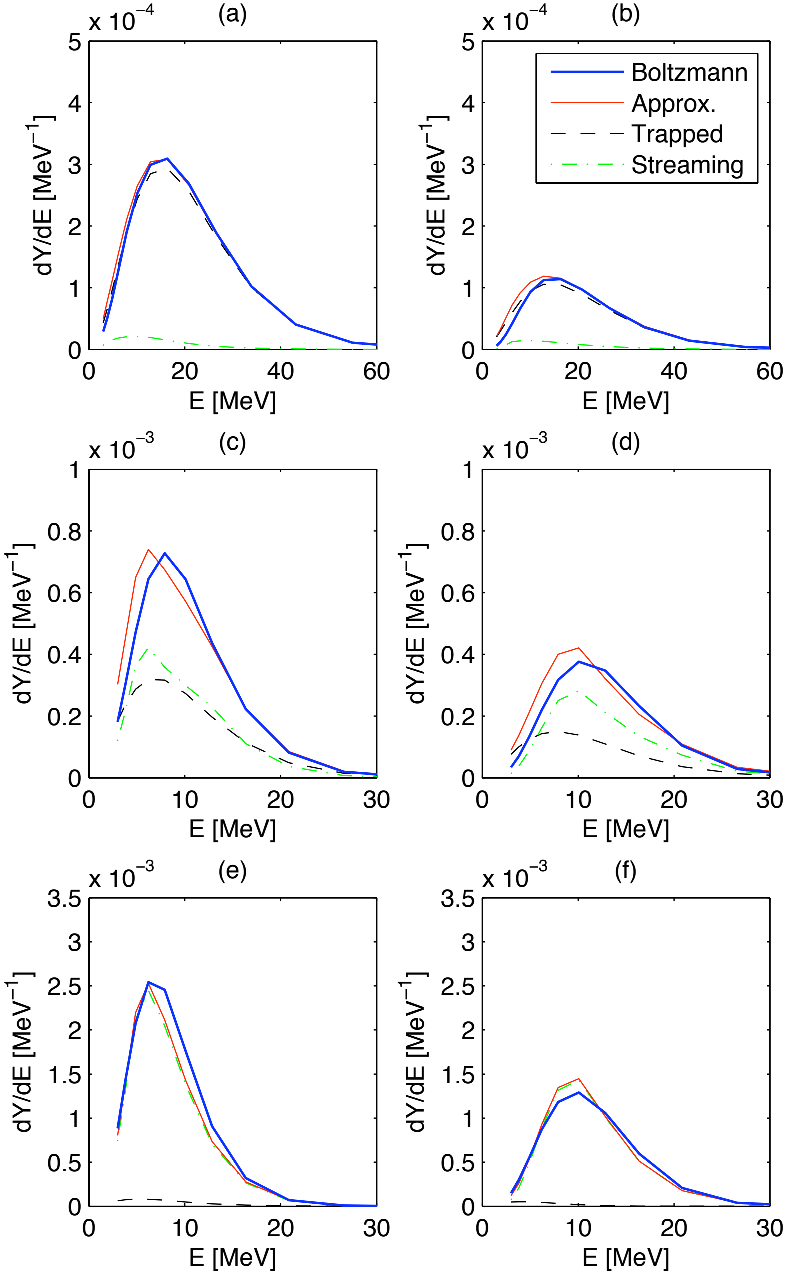
$(j+\chi)f^t$

$(j+\chi)f^s$

Σ

Streaming Neutrinos

Comparison of IDSA Spectra



at 40 km radius
(trapped regime)

Trapped neutrinos dominate spectrum

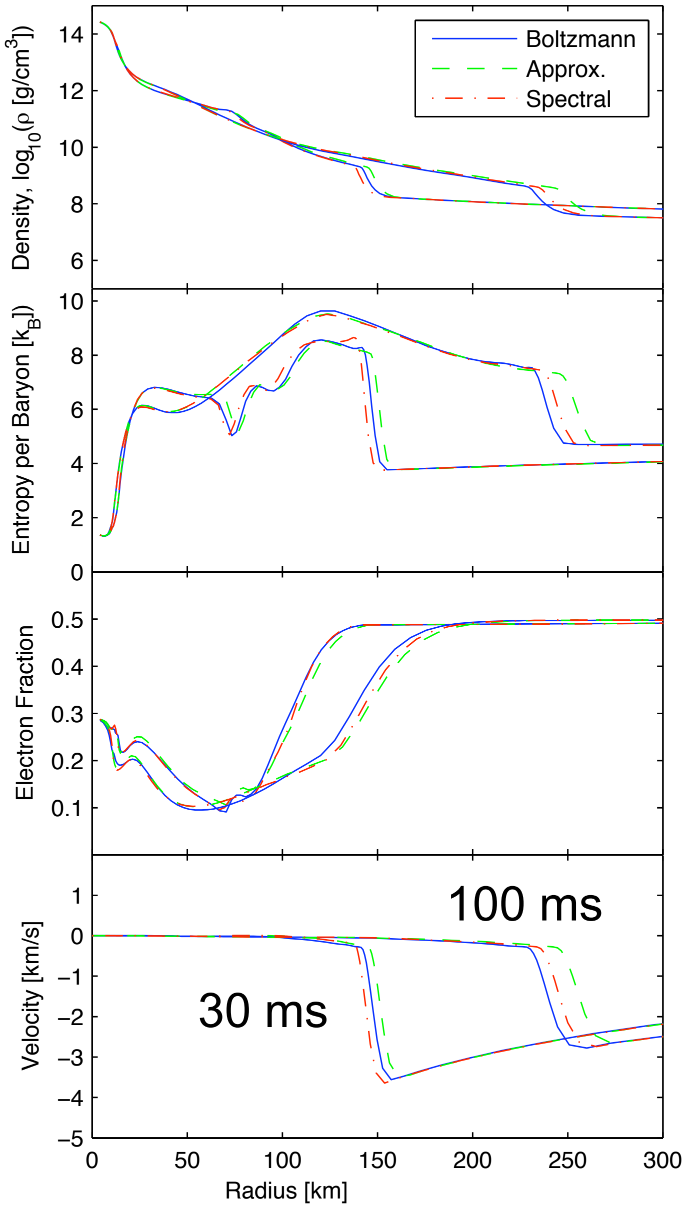
at 80 km radius
(semi-transparent)

Trapped *and* streaming neutrinos form spectrum

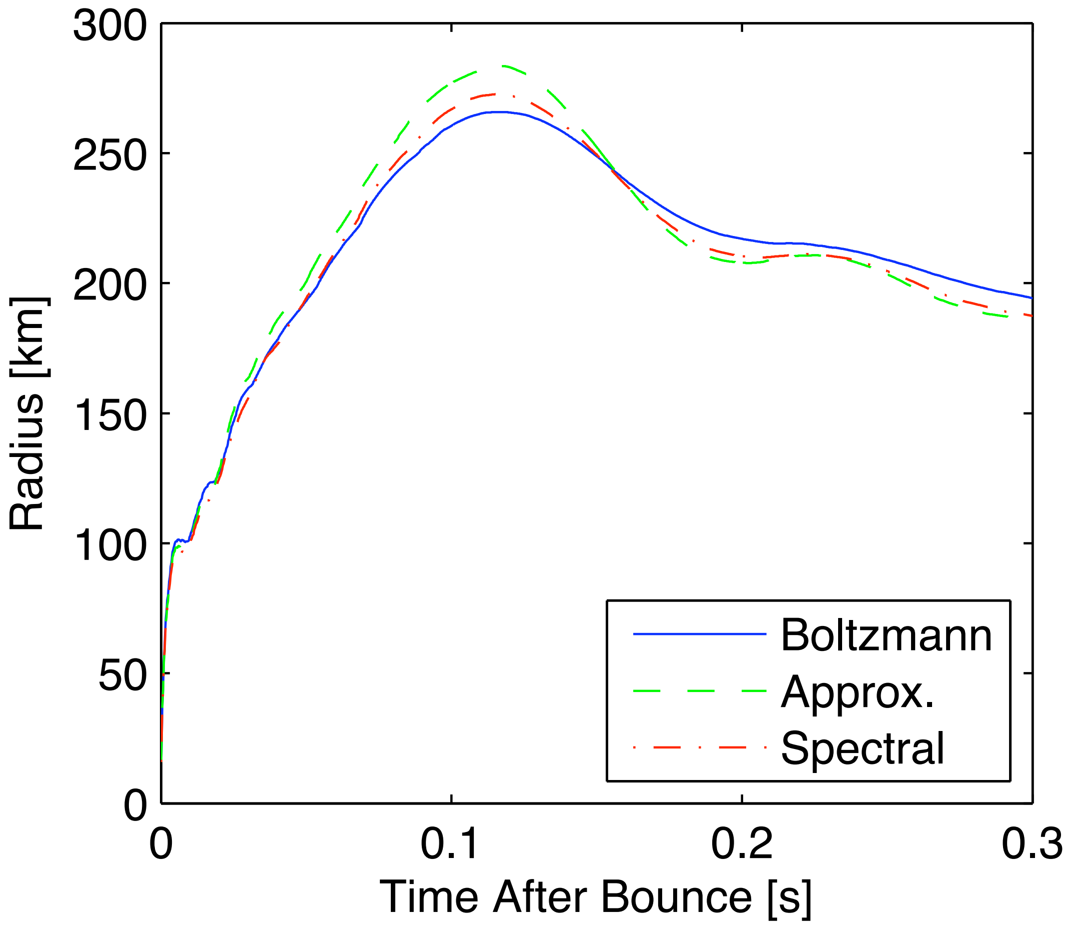
at 160 km radius
(free streaming)

Streaming neutrinos dominate spectrum

Comparison of Hydrodynamical Evolution

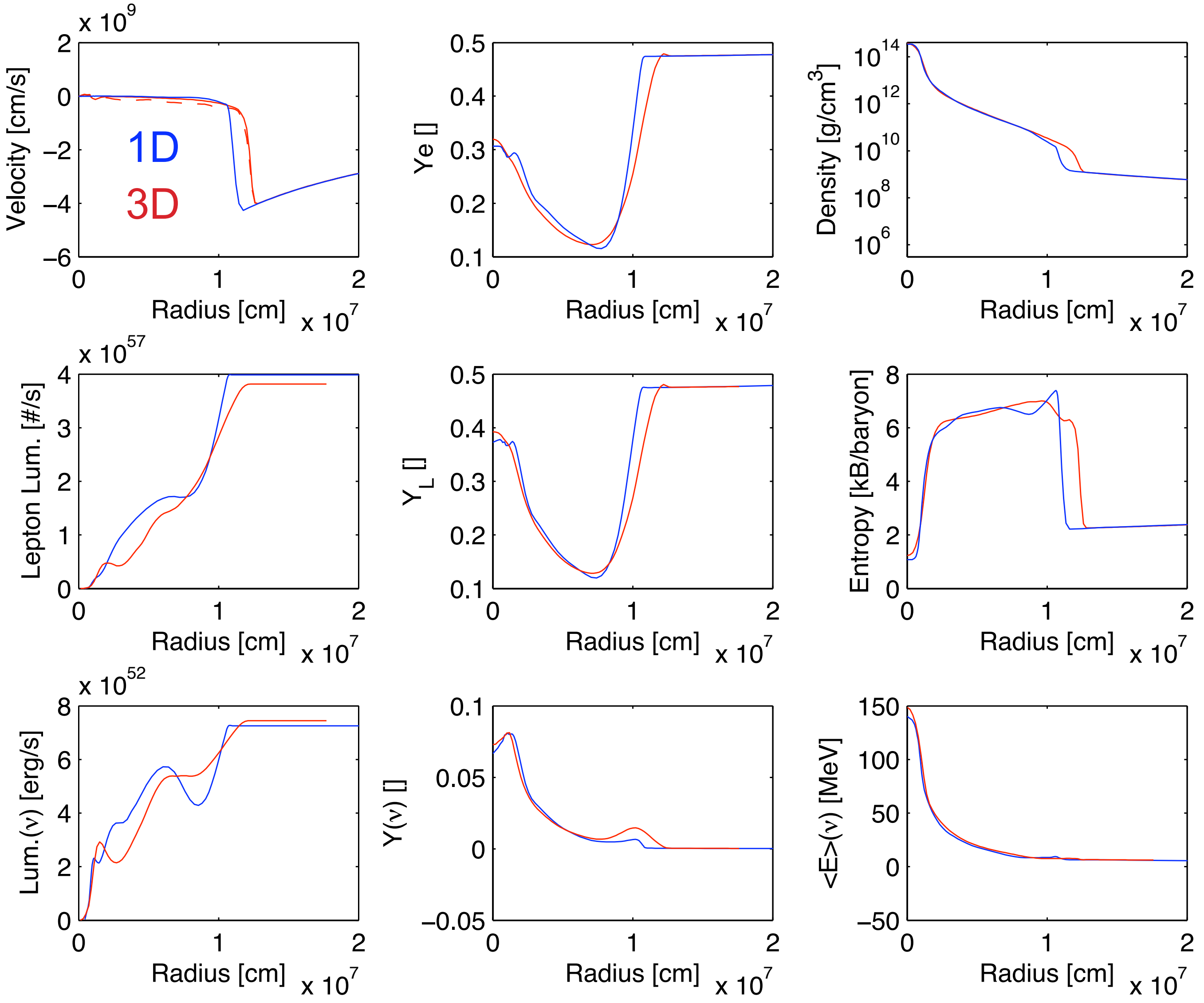


Evolution of shock radius as function of time



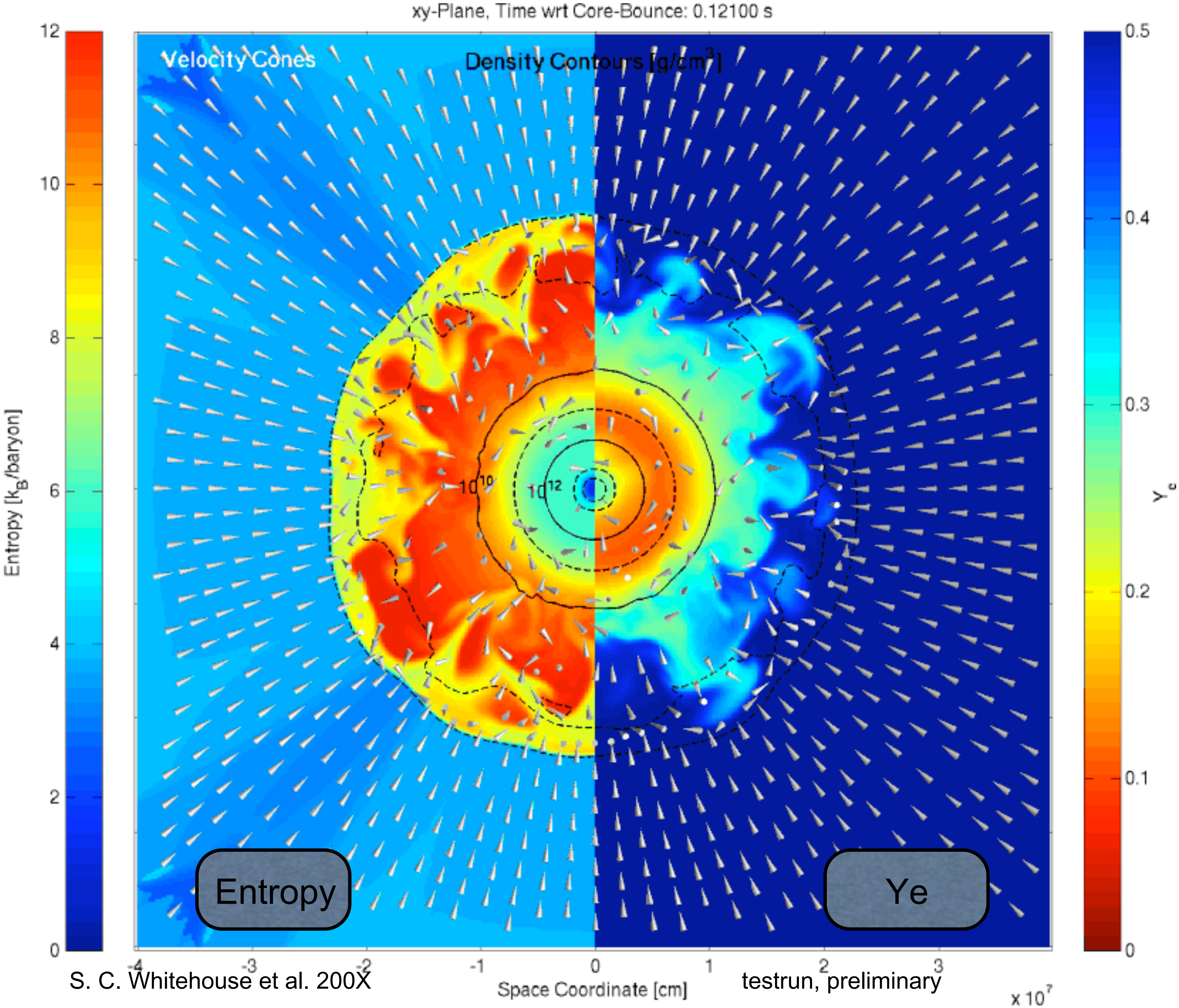
Good agreement!

Checking the 3D Elephant code...



20 ms postbounce, same input physics

- Production at Swiss Natl. Supercomp. Cent. (240’000 CPUh/month)



S. C. Whitehouse et al. 200X

testrun, preliminary

Physics <--> Model <--> Observation

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Spherical Symmetry:

- Excellent ν-transport with detailed input physics
- 5 different codes give consistent results!

Bruenn et al. 2001, Liebendörfer et al. 2001-5, Rampp & Janka 2000-2, Thompson et al. 2003, Sumiyoshi et al. 2005-7

- No explosions obtained for most progenitors, exploring neutrino interactions & nuclear physics

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Axisymmetry:

- ray-by-ray or MGFLD ν-transport
- computationally very expensive

Buras et al. 2003/5, Walder et al. 2004, Bruenn et al. 2006, Marek & Janka 2007, Ott et al. 2008

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Three-dimensional:

- ν-transport approximations
- enable 3D flow pattern & magnetic fields

Fryer & Warren 2002/4, Scheck et al. 2003,
Ott et al. 2007, Scheidegger et al. 2008, Iwakami et al. 2008

- No explosions obtained for most progenitors, exploring neutrino interactions & nuclear physics

- Some explosions obtained, results not yet converged --> likely and less likely explosion mechanisms

- Phenomenology --> predictive power, coming up...