Compschool, Copenhagen 2009

UNI BASEL

Core-Collapse Supernovae

M. Liebendörfer
University of Basel

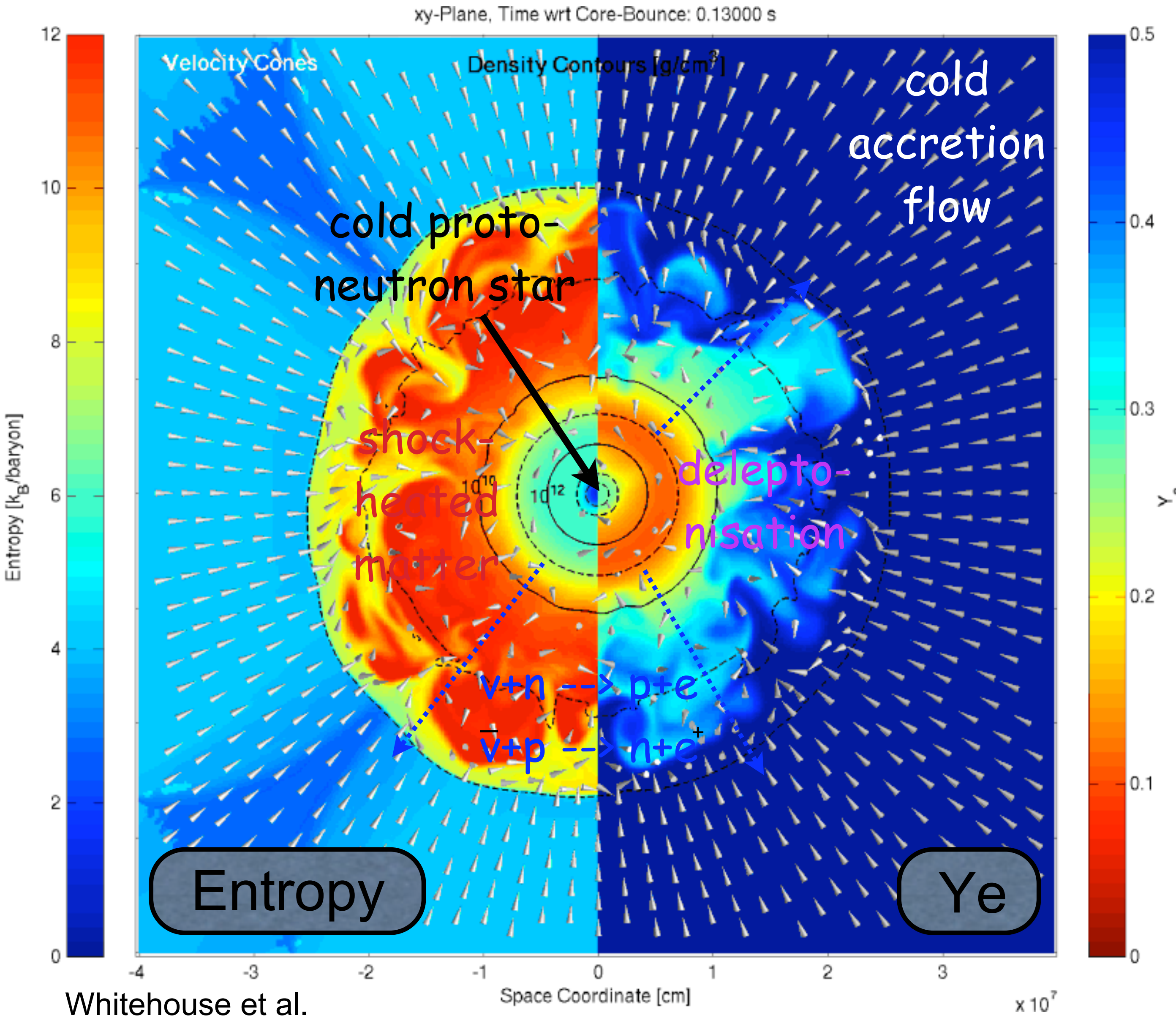
- Collapse phase: Dynamics & ν-interactions
- Postbounce phase: ν-transport & explosion mechanisms
- Models: Approximations & prediction of observables

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...

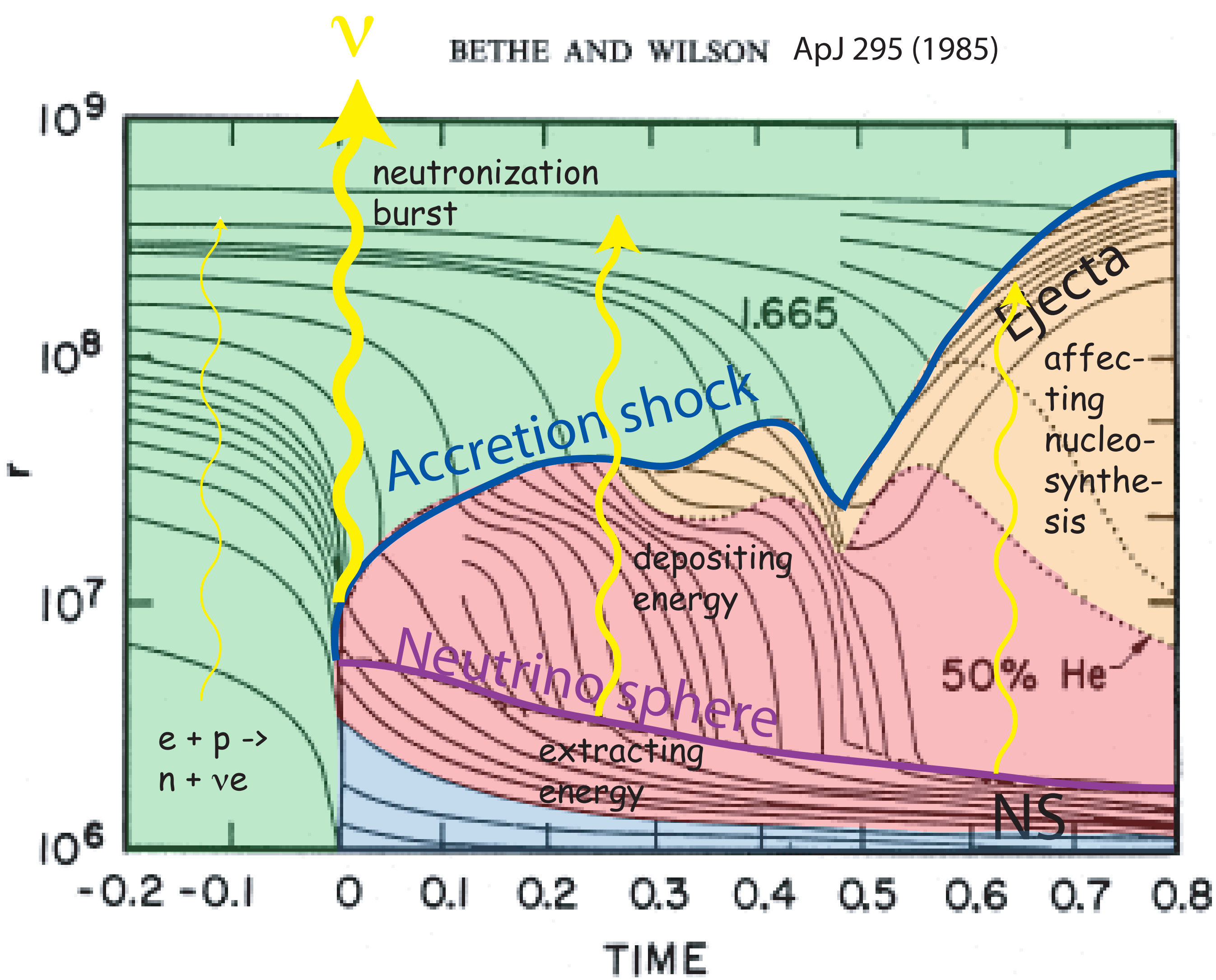
The Supernova Problem



Whitehouse et al.

- How does the collapse of single stars lead to explosions that outshine a galaxy?
- Which new physics is observable in the extreme conditions of matter during the explosion?
- Does the nucleosynthesis of heavy elements explain the abundances on Earth, the Sun and distant stars?

Delayed explosion: 4 phases



collapse phase || postbounce accretion phase | explosion phase
bounce

Ensemble of nuclei

Cool bulk nuclear matter

Hot dissociated matter

Freeze-out of nuclei

(-->movie)

Discussed Explosion Mechanisms

Energy scales:

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

Discussed Explosion Mechanisms

1) Prompt explosion mechanism, E(bounce)

(e.g. Baron et al. 1985)

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(Burrows et al. 2006)

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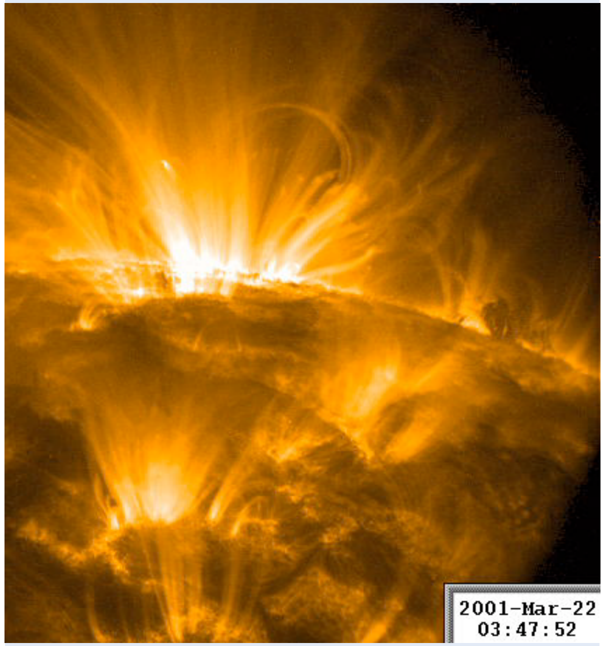

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(Akiyama et al. 2003, Thompson et al. 2003, Socrates et al. 2005)

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

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

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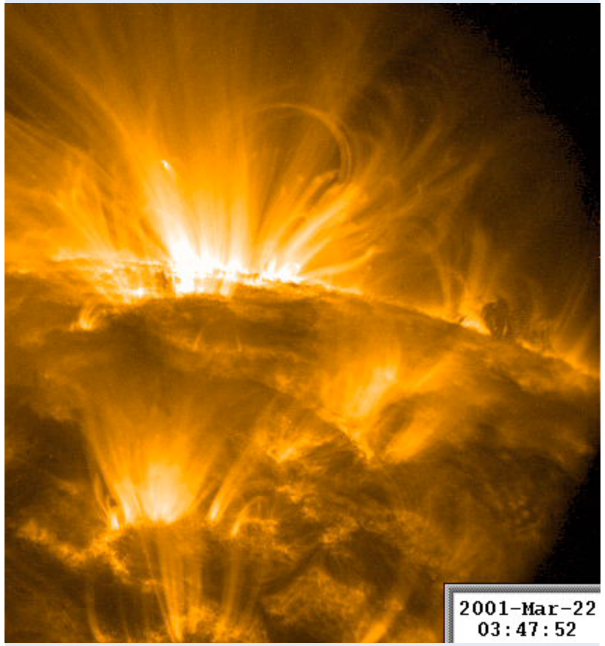

Input <--> Model <--> Observation

Physics	Modelling challenges	Observations
Reaction network	• uncertainties • stiff partial diff'eqs.	
Magneto-hydrodynamics	• resolution • time scales	
Gravity	• NR: elliptic equations • GR: metric/horizons	
Radiative transfer	• dimensionality • non-locality	

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Observations

- Lightcurve
- Polarisation
- Spectra/abundances
- Event rates
- Galactic Evolution
- NS kick & spin
- neutrino signal
- Grav. wave signal
- GRB's

Transient searches

Input <--> Model <--> Observation

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Observations:

Lightcurve
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Spectra/abundances
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Transient searches

→ Quality must match!

Solving the Boltzmann equation

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

$$= \frac{j}{\rho} - \tilde{\chi} F$$

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

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

Evolution of specific neutrino distr. function:

$F(t,m,\mu,E) = f(t,r,\mu,E)/\rho$

=> 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:

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

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

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

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

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Finite differencing of time evolution

Forward differencing:
evaluate slope with current state vector

Backw. differencing:
evaluate slope with future state

Let's see...

Explicit finite differencing

Forward differencing: evaluate slope with current state vector

- simple
- accurate for small time steps
- limited by charac-teristic time scale

Go faster...

Explicit finite differencing

Forward differencing: evaluate slope with current state vector

- simple
- inaccurate for large time steps
- even catastrophic!

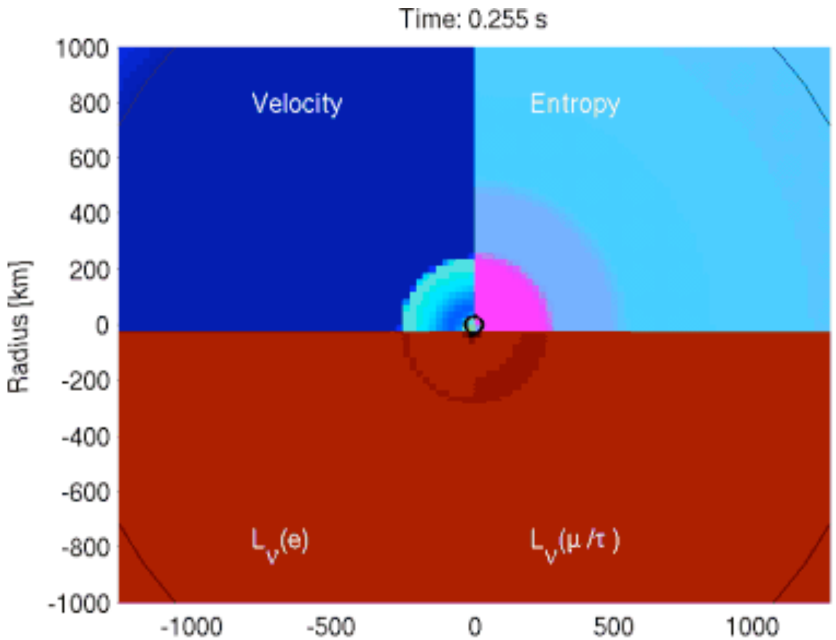
Think...

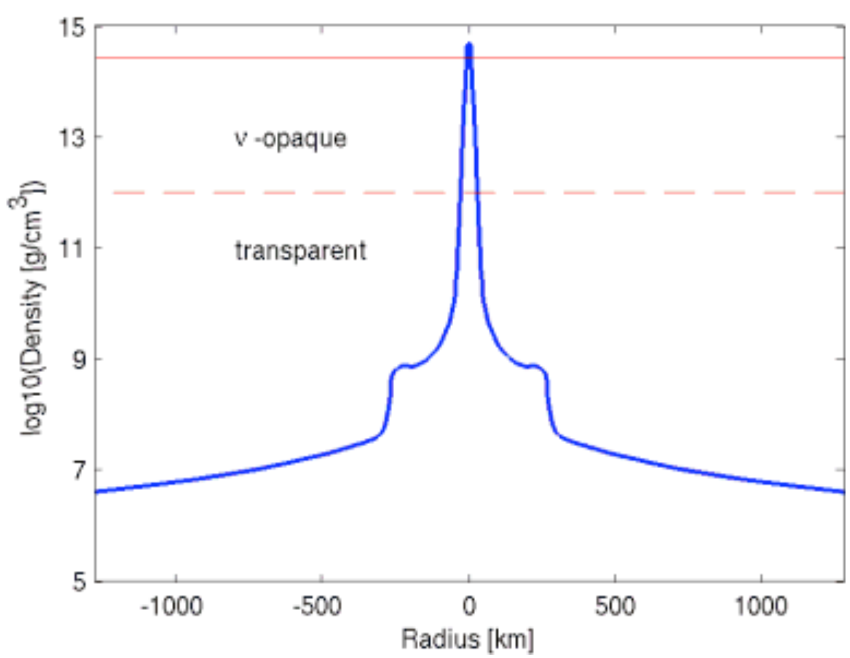
Implicit finite differencing

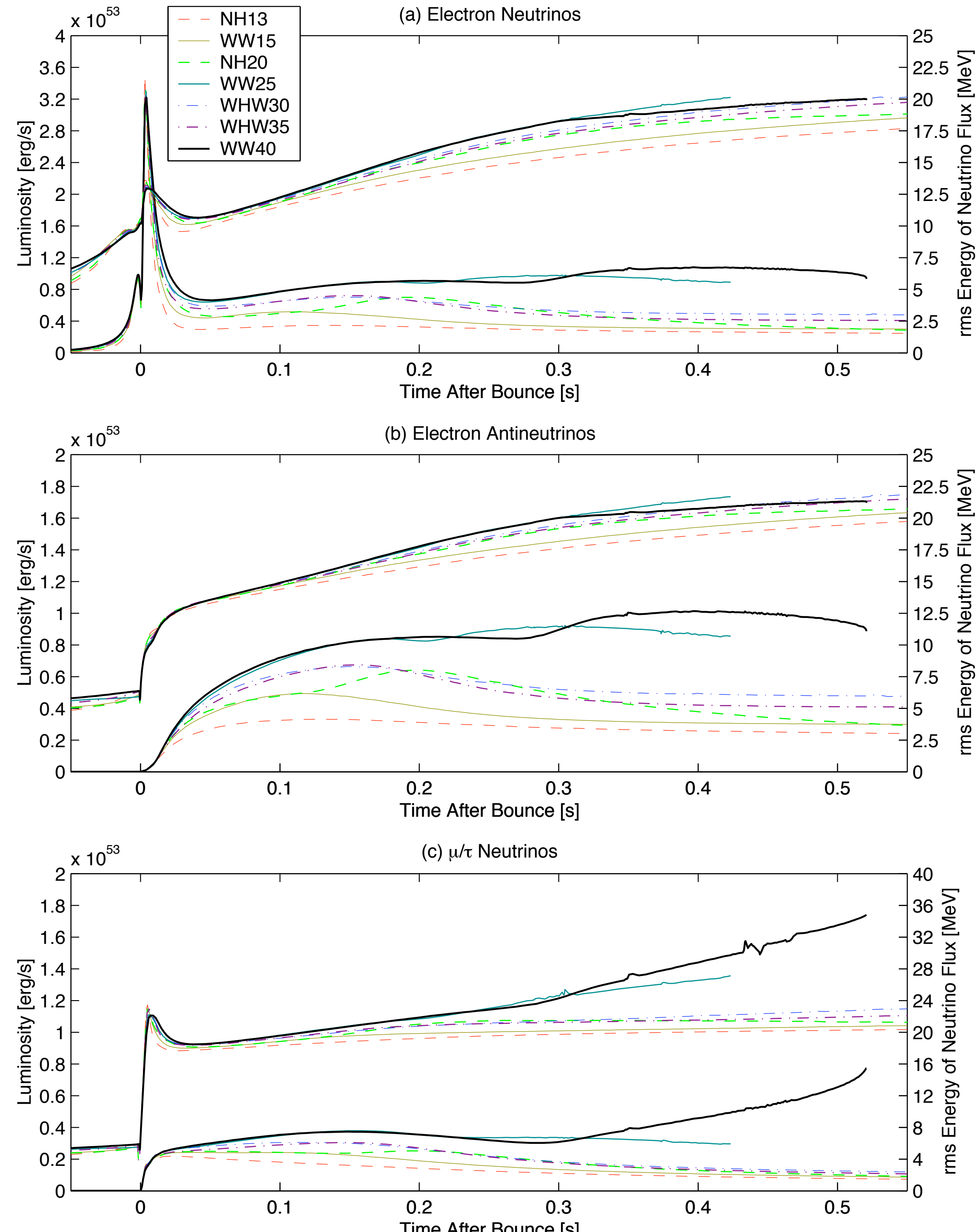
Backw. differencing: evaluate slope with future state vector

- Long time steps possible
- Follows ‘average’ evolution

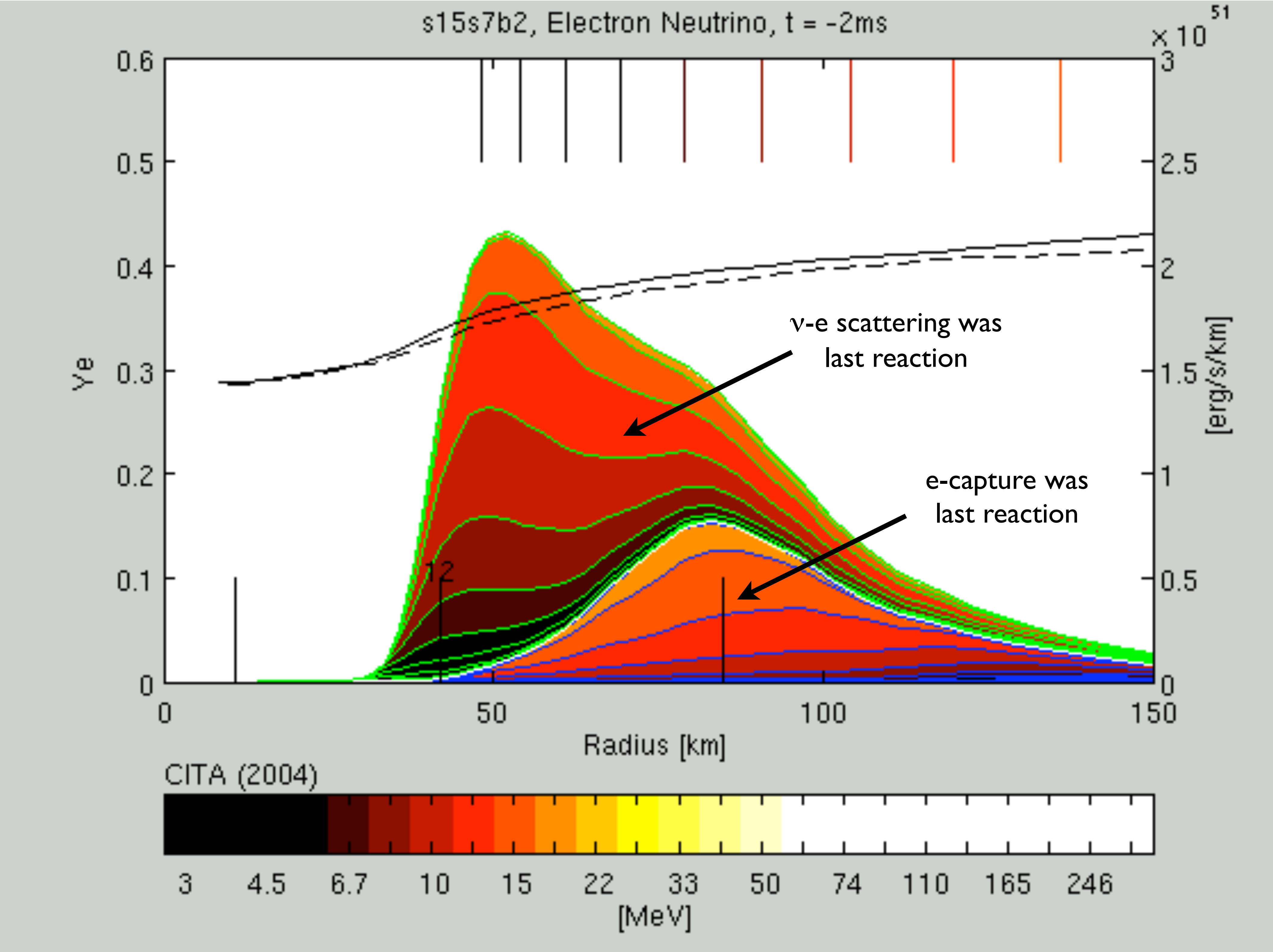
- nonlinear system
- computationally expensive!

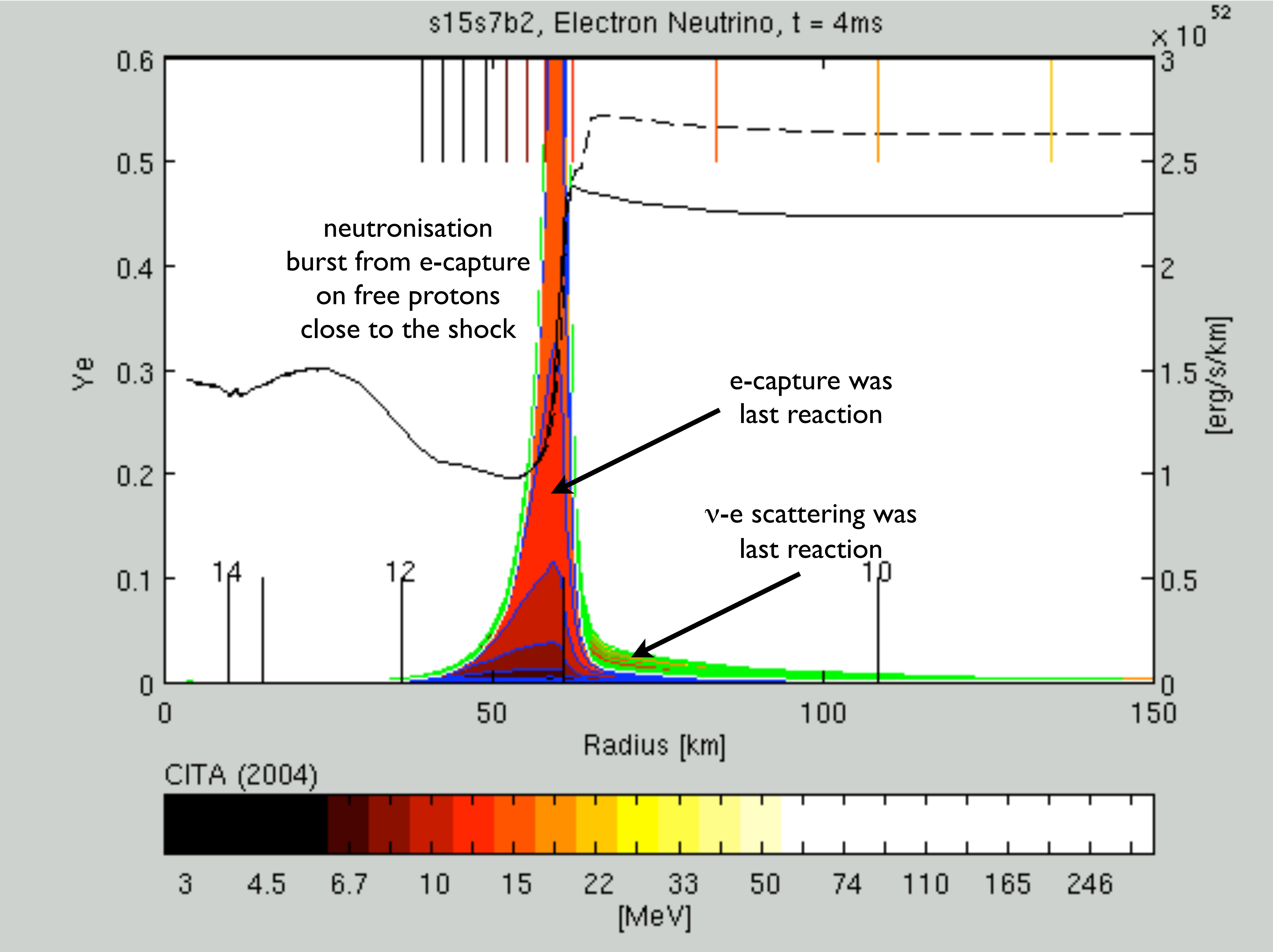




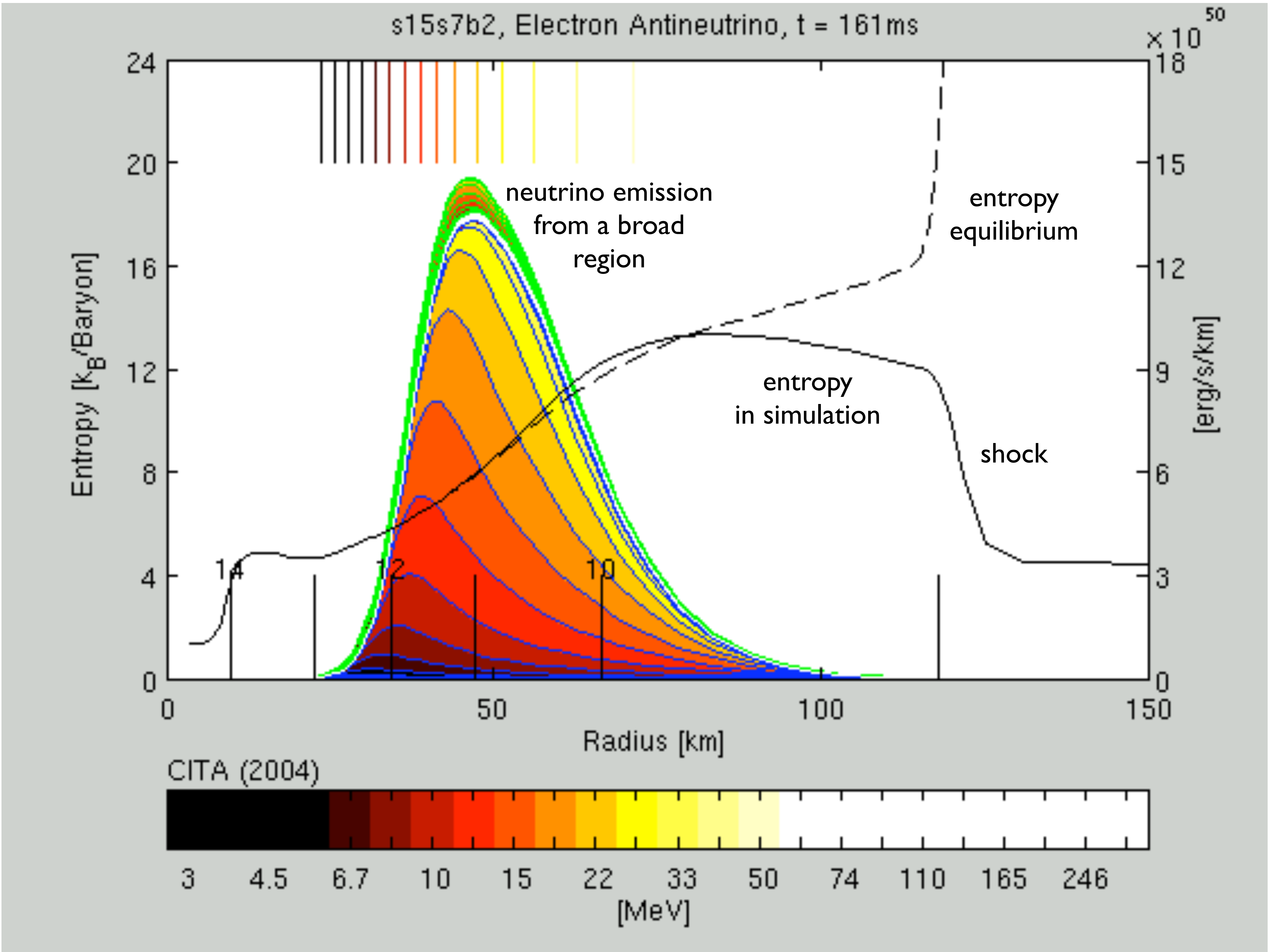


(Liebendörfer et al. 2003)

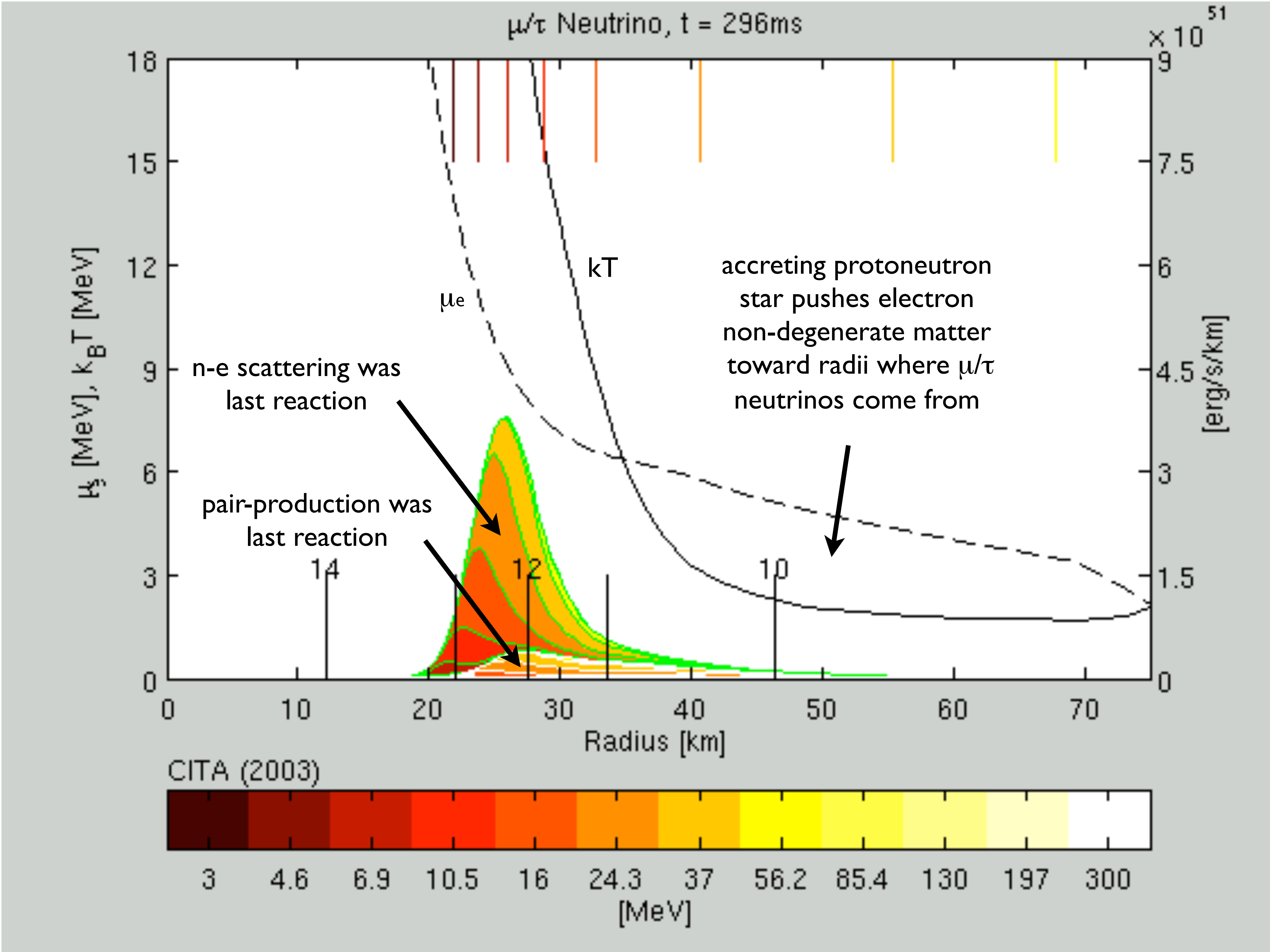

s15s7b2, Electron Neutrino, t = -2ms
×10^51
Ye
[erg/s/km]
Radius [km]
ν-e scattering was last reaction
e-capture was last reaction
12
CITA (2004)
3 4.5 6.7 10 15 22 33 50 74 110 165 246
[MeV]



s15s7b2, Electron Neutrino, t = 4ms
× 10^52
Ye
[erg/s/km]
Radius [km]
neutronisation burst from e-capture on free protons close to the shock
e-capture was last reaction
ν-e scattering was last reaction
14
12
10
CITA (2004)
3
4.5
6.7
10
15
22
33
50
74
110
165
246
[MeV]



s15s7b2, Electron Antineutrino, t = 161ms
×10^50
Entropy [K_B/Baryon]
[erg/s/km]
24
20
16
12
8
4
0
18
15
12
9
6
3
0
neutrino emission
from a broad
region
entropy
equilibrium
entropy
in simulation
shock
14
12
10
0
50
100
150
Radius [km]
CITA (2004)
3
4.5
6.7
10
15
22
33
50
74
110
165
246
[MeV]



μ/τ Neutrino, t = 296ms
× 10^51
μ_ν [MeV], k_BT [MeV]
[erg/s/km]
kT
μe
accreting protoneutron star pushes electron non-degenerate matter toward radii where μ/τ neutrinos come from
n-e scattering was last reaction
pair-production was last reaction
14
12
10
Radius [km]
CITA (2003)
3
4.6
6.9
10.5
16
24.3
37
56.2
85.4
130
197
300
[MeV]

Comparison among independent groups

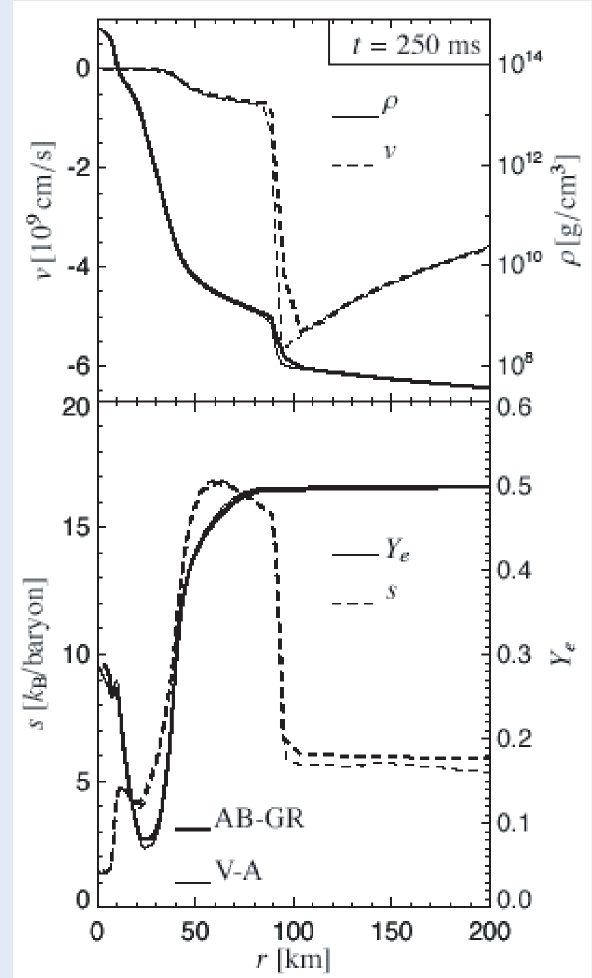
(datafiles.tar.gz in ApJ electronic edition)

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

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

Explosions only in exceptional cases!

excellent agreement:



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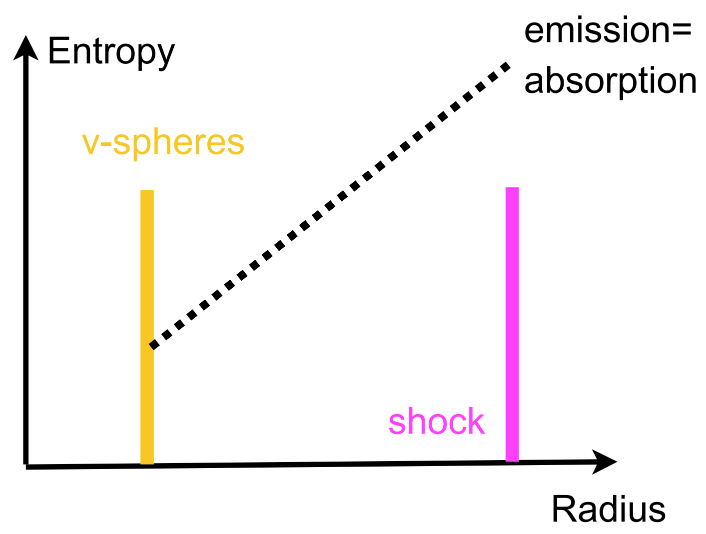
Problem 1: Exposure to heating limited by high infall velocity



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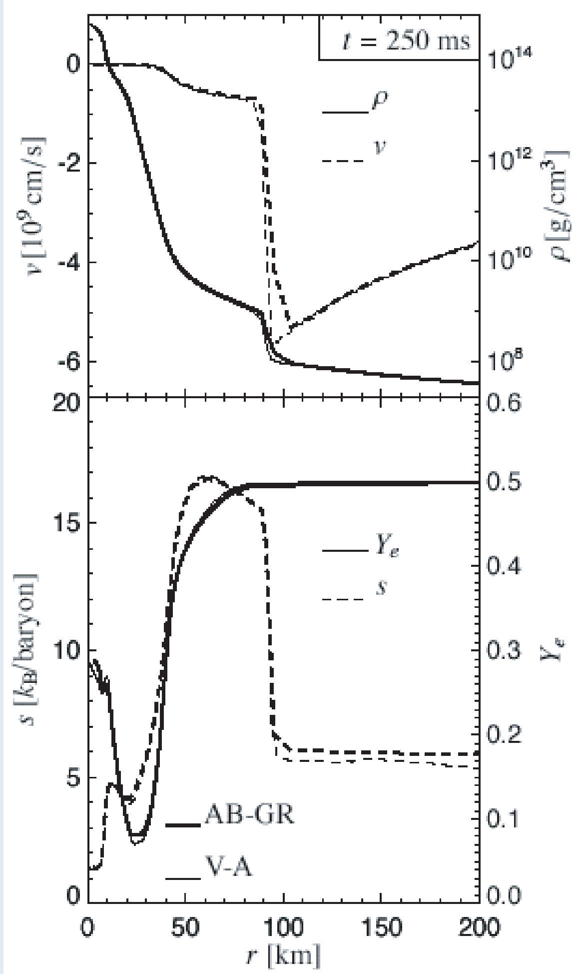

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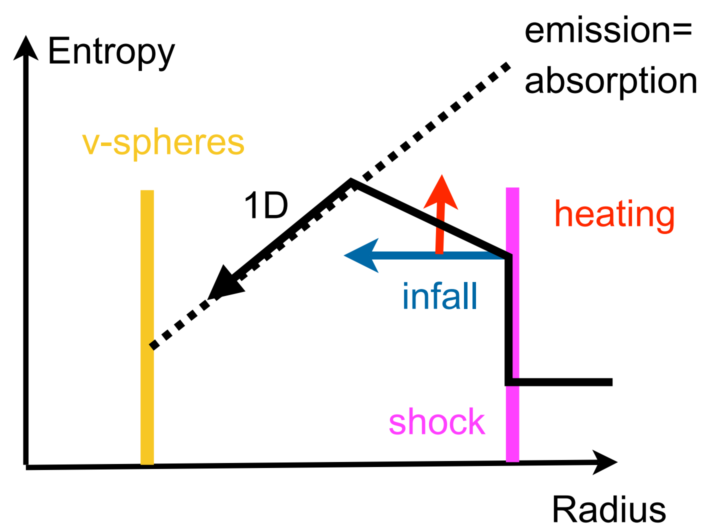

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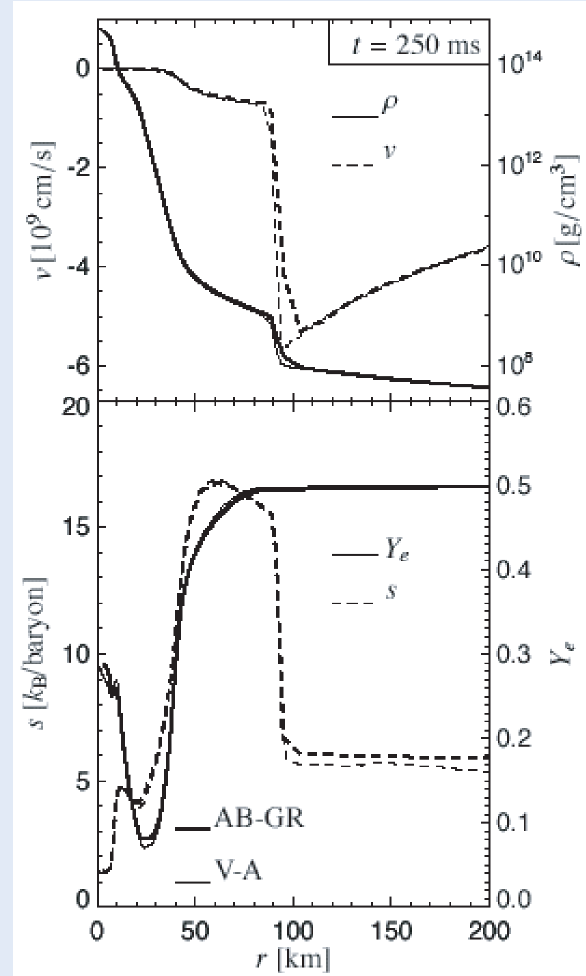

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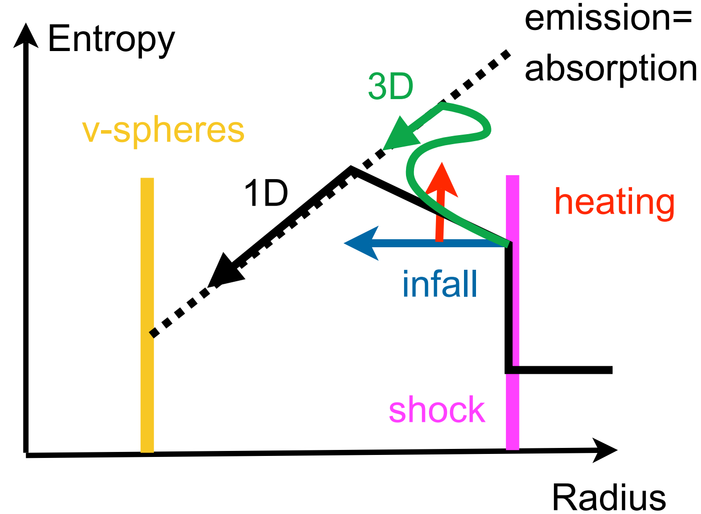

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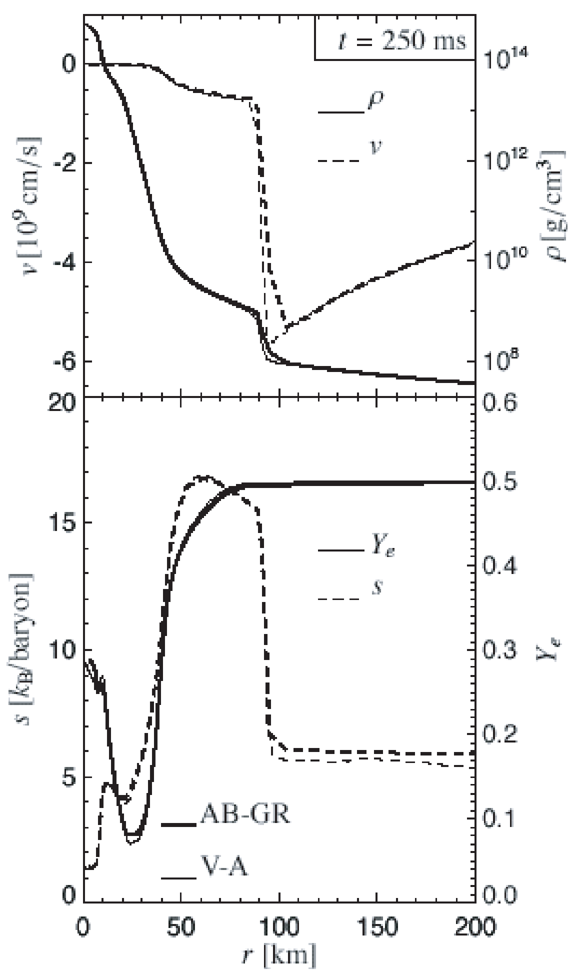

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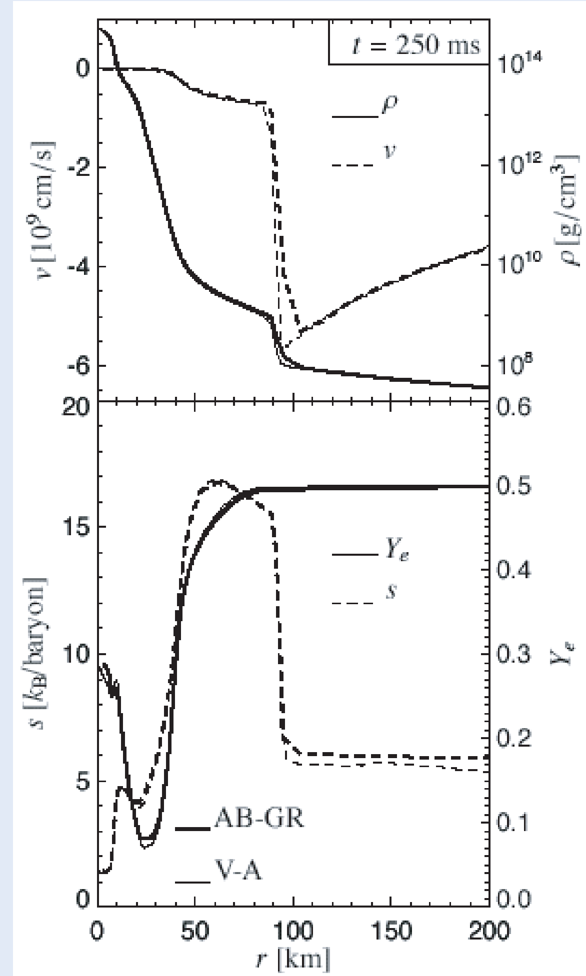

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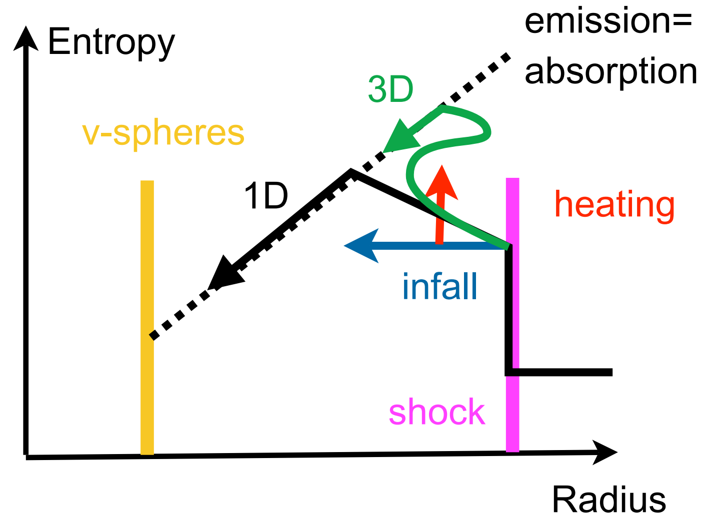

Problem 2: Accretion (-luminosity) shuts off after onset of explosion