Supernovae Part 3

Stellar Core Collapse and Bounce

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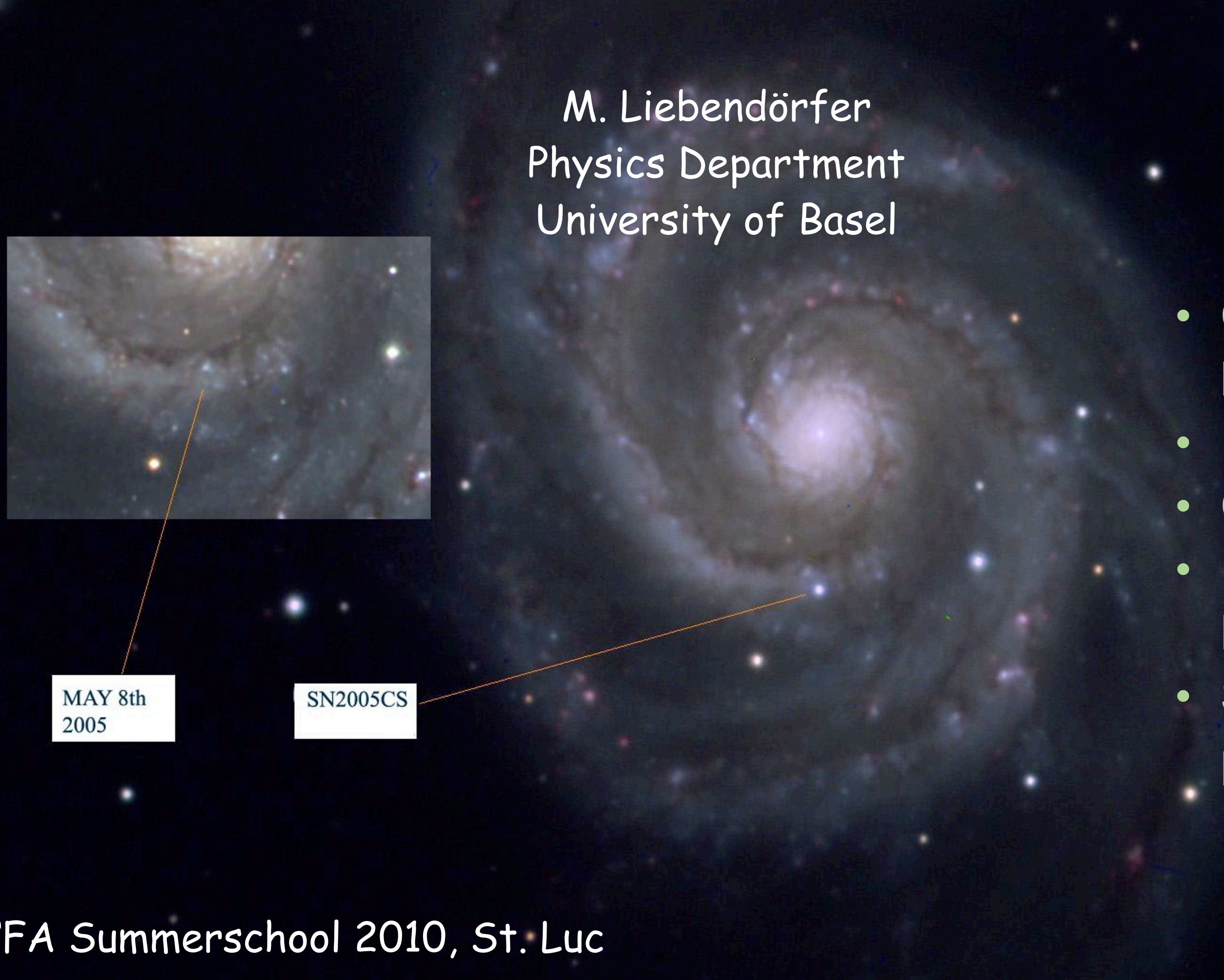
University of Basel



- Collapse and bouce phases
- Deleptonisation
- Core convergence
- Neutrino luminosities
- Sensitivity to input physics

SCFA Summerschool 2010, St. Luc

Supernova mechanism

for 1.4 M_sol:

Density [g/cm^3] ρ	Radius [km] $R=\left(\frac{3M}{4\pi\rho}\right)^{\frac{1}{3}}$	free fall time scale [s] $\tau = (G\rho)^{-\frac{1}{2}}$
10^{9}	873	0,123
10^{10}	405	0.039
10^{11}	188	0.012
10^{12}	87	0.004
10^{13}	41	1.2×10^{-3}
10^{14}	19	0.387×10^{-3}

- progenitor core that collapses within ~1s: 10'000 km
- this is ~ up to O-layer

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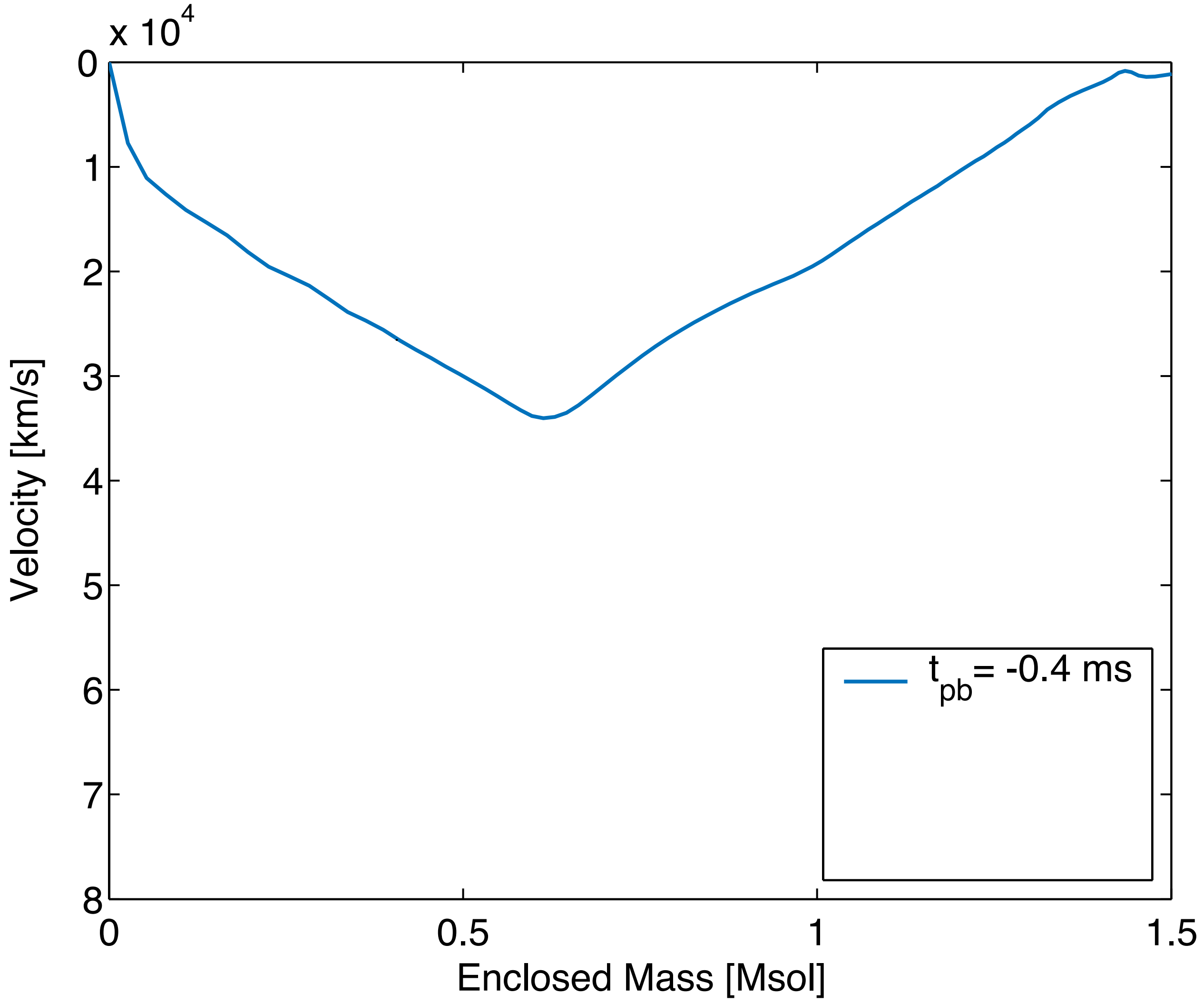
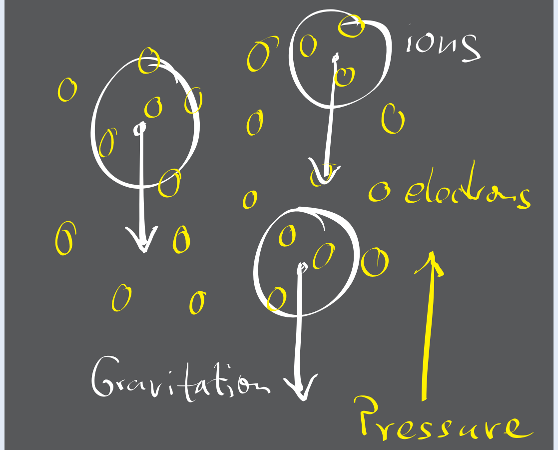
- progenitor core that collapses within ~1s: 10'000 km
- this is ~ up to O-layer
- neutrino sphere: location where a neutrino has the probability to make one more interaction before escape
- neutrino transport relevant in compact region

The collapse phase





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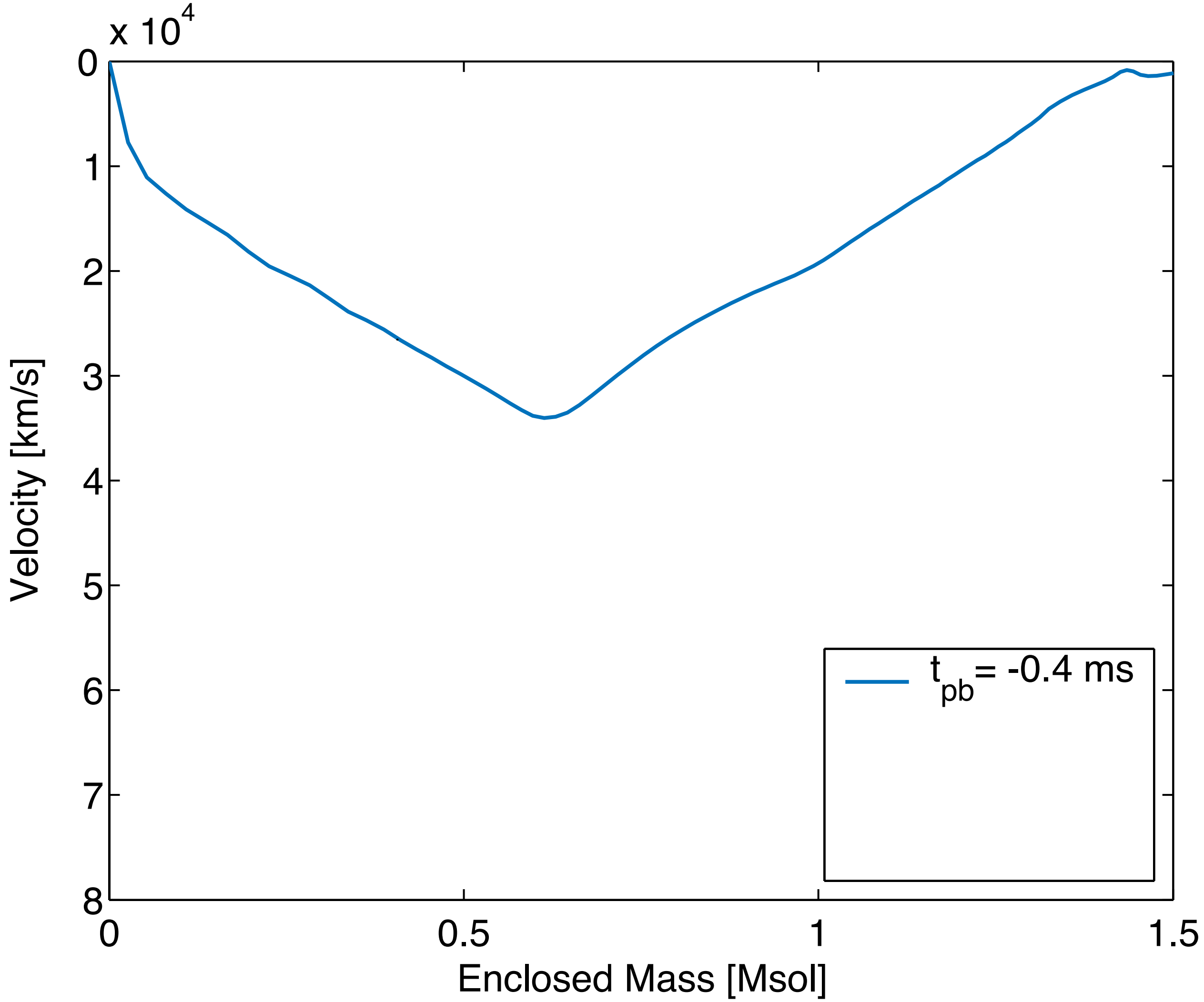
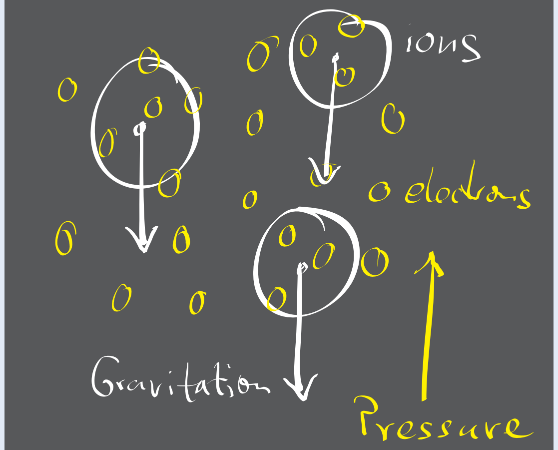
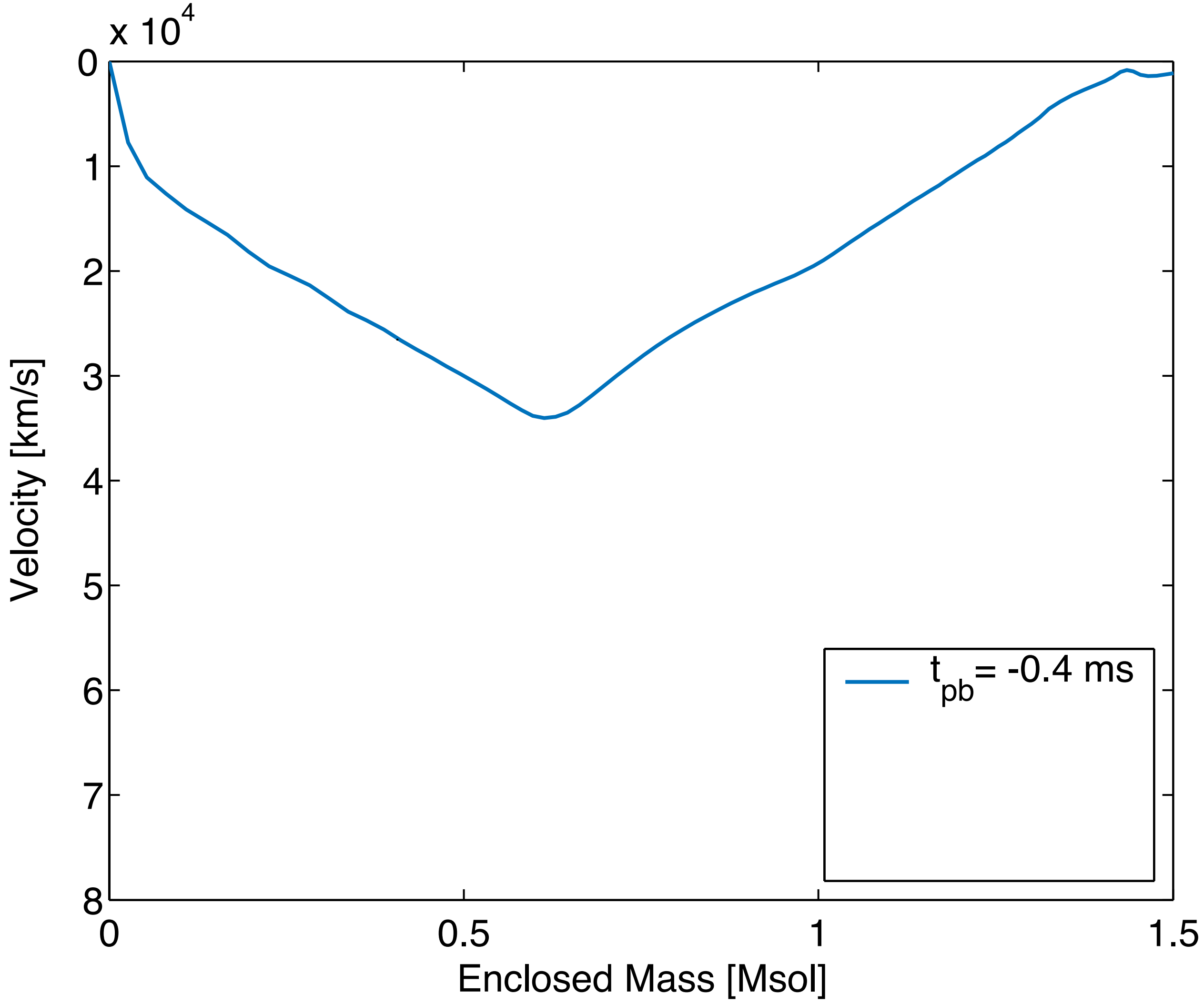
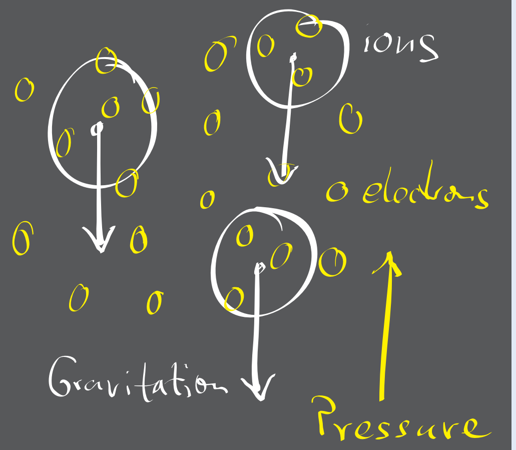




electron fraction
Ye = ne/nbaryon

The collapse phase





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Fermi gas $p = \varkappa \rho^{\gamma}$

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

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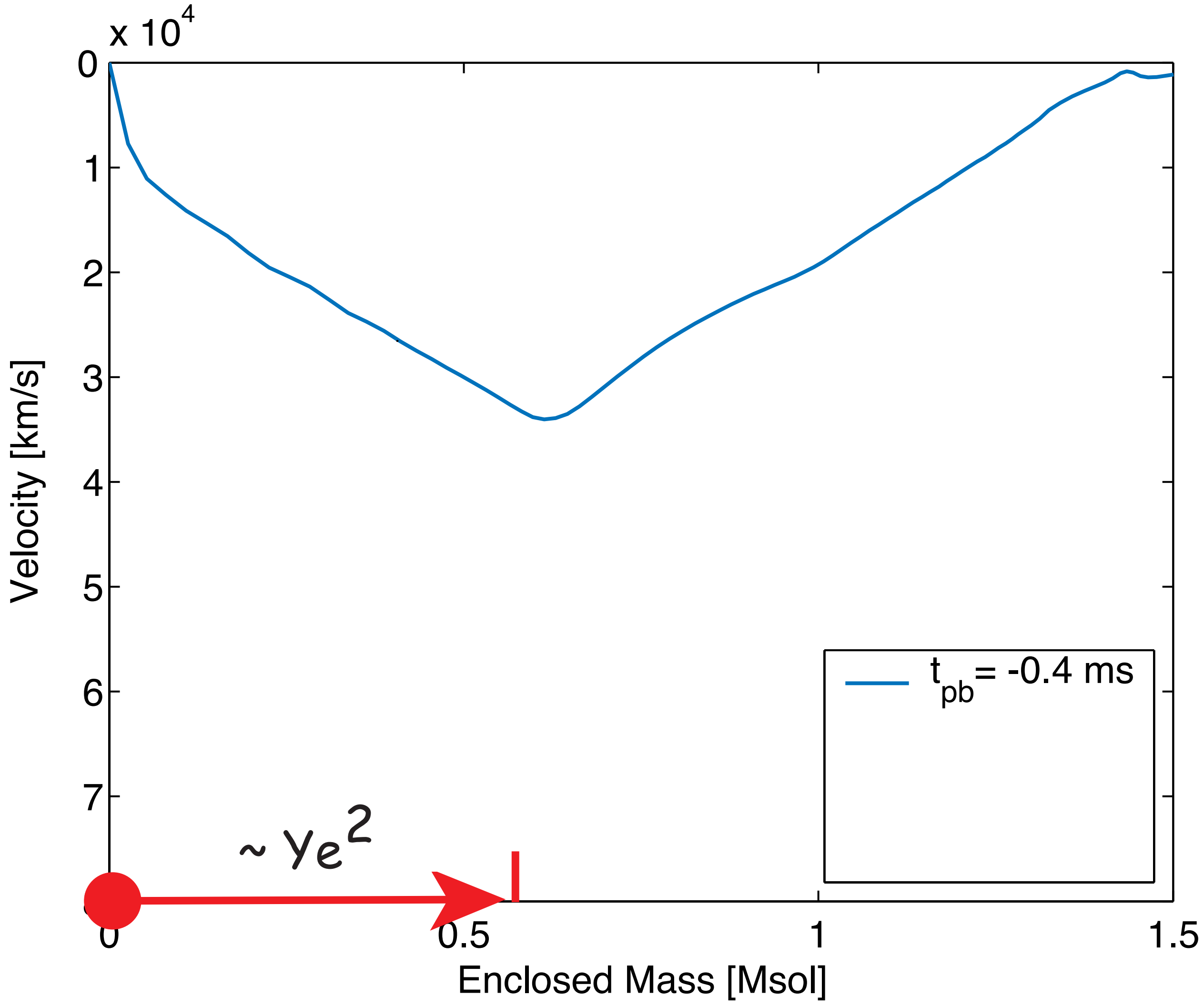

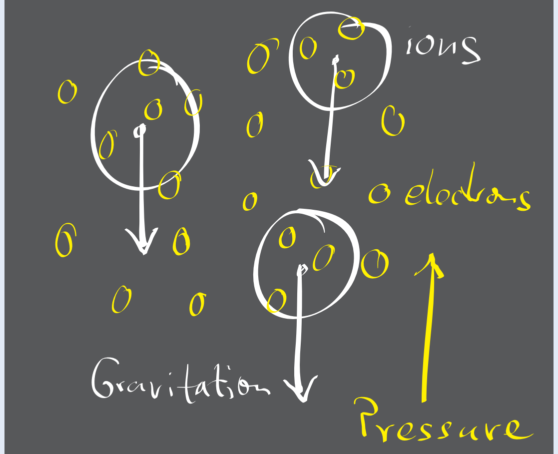

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homologous collapse:

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

(Goldreich & Weber 1980)

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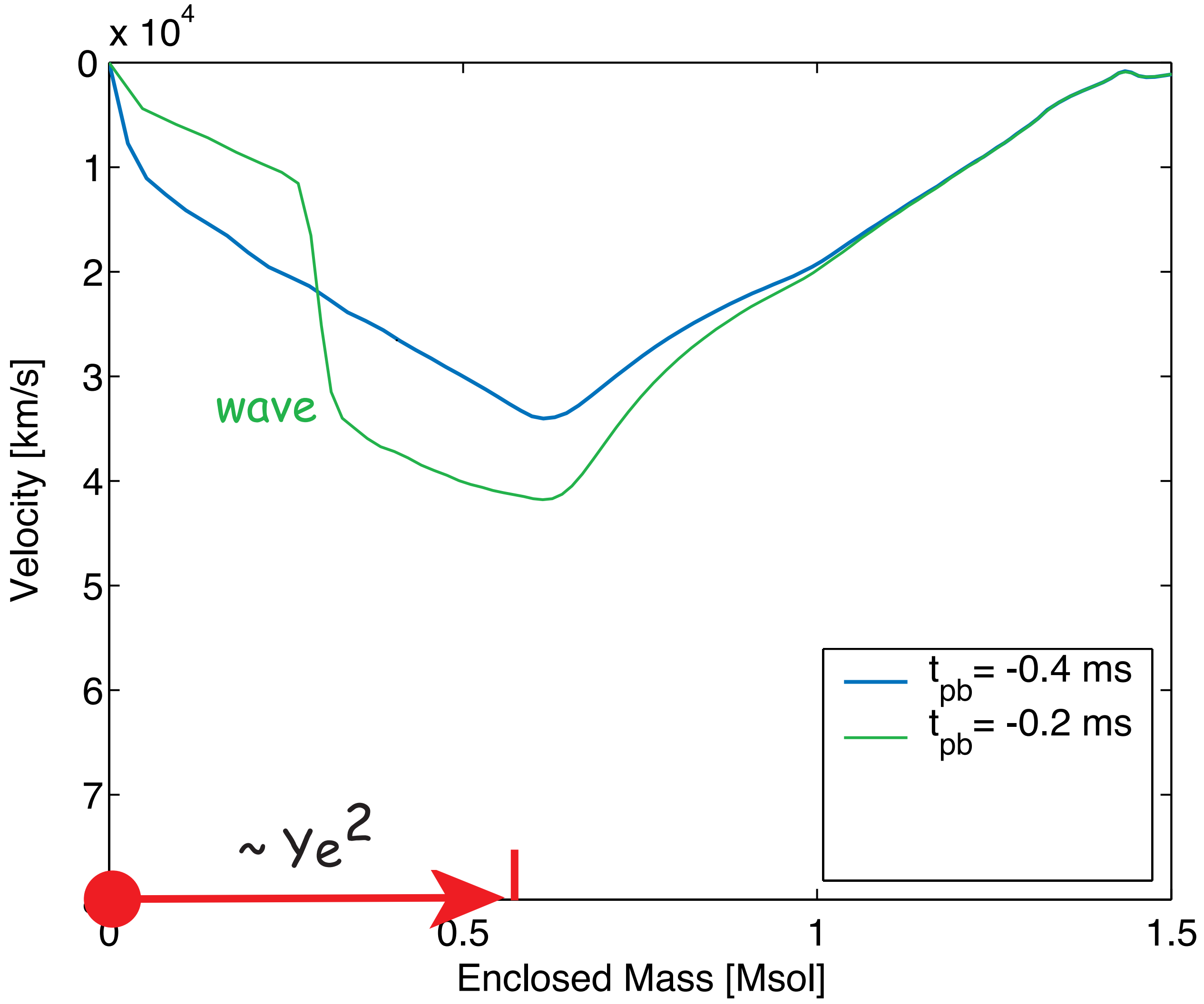

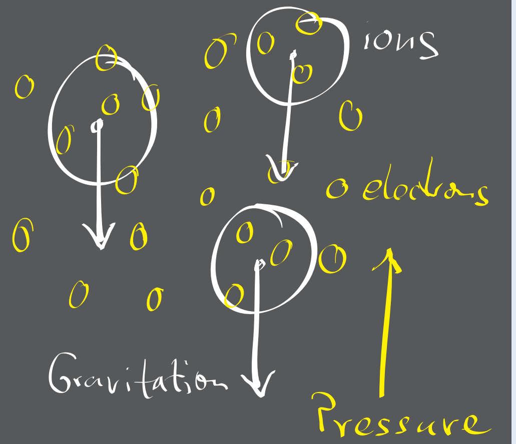

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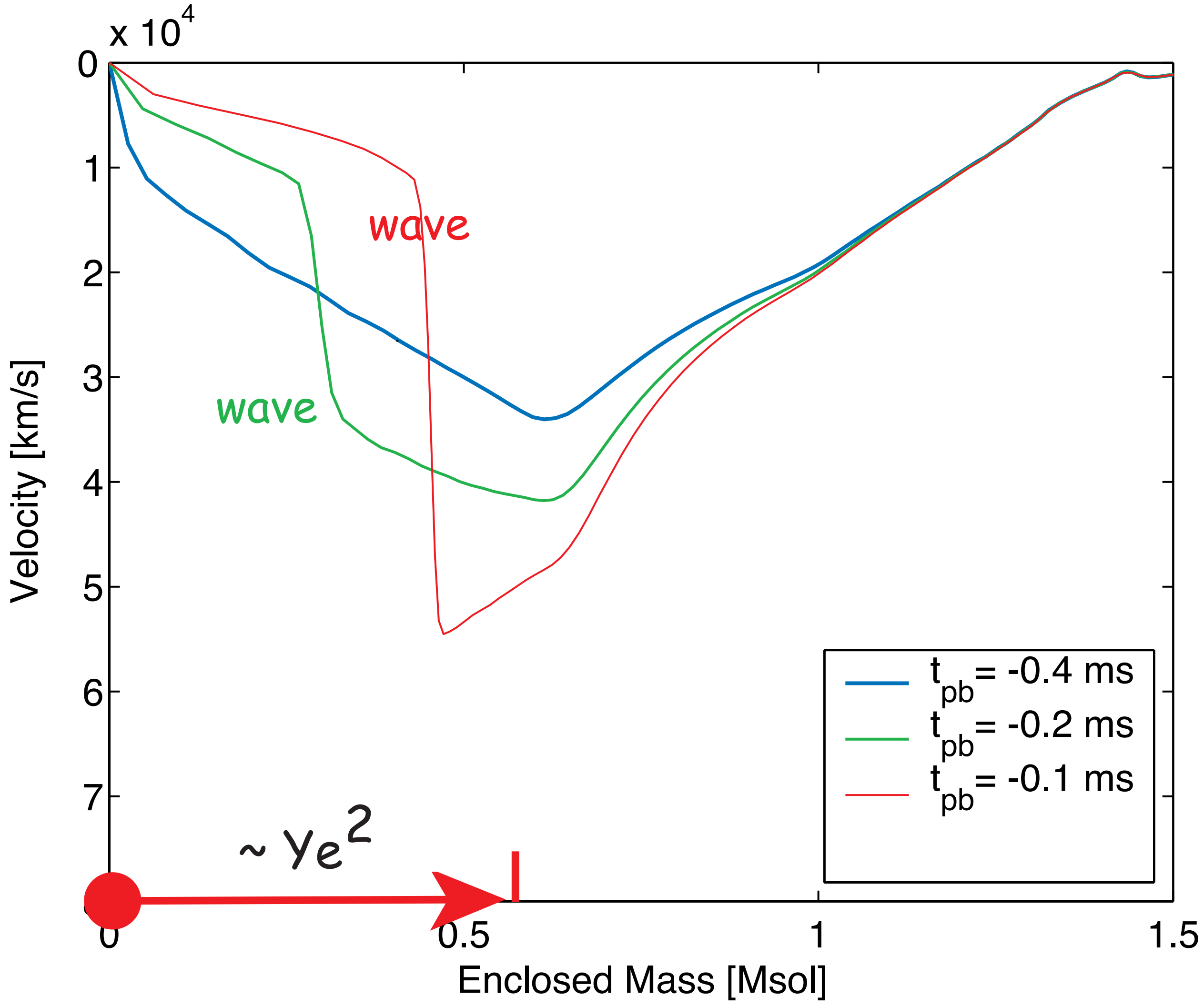

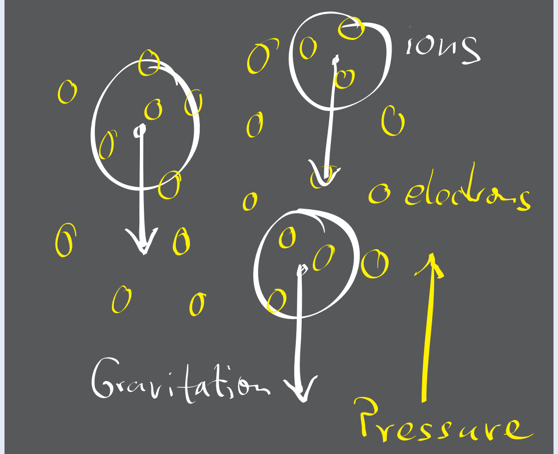

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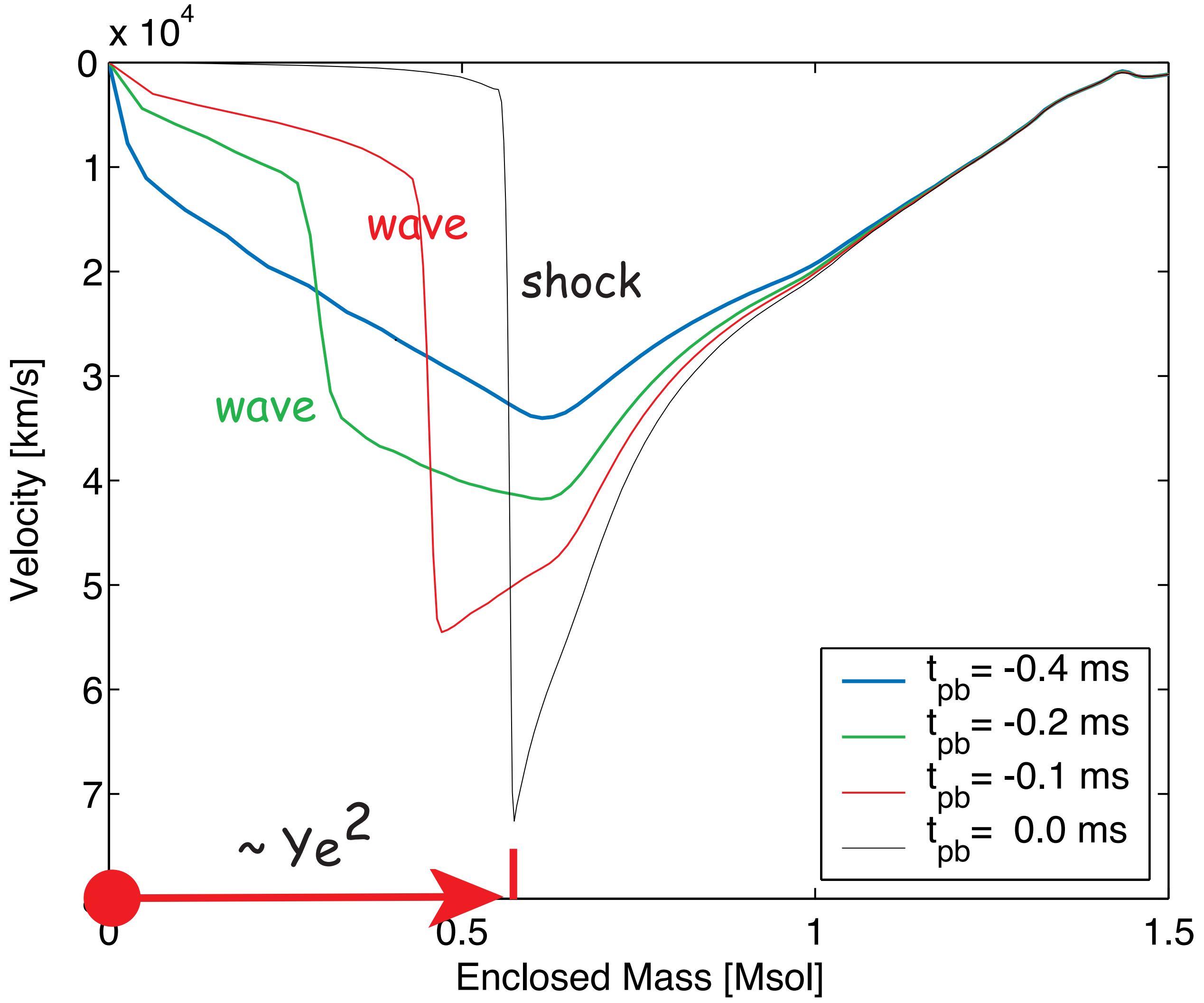

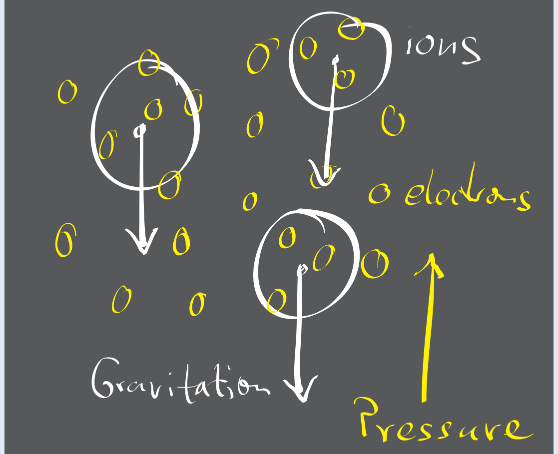

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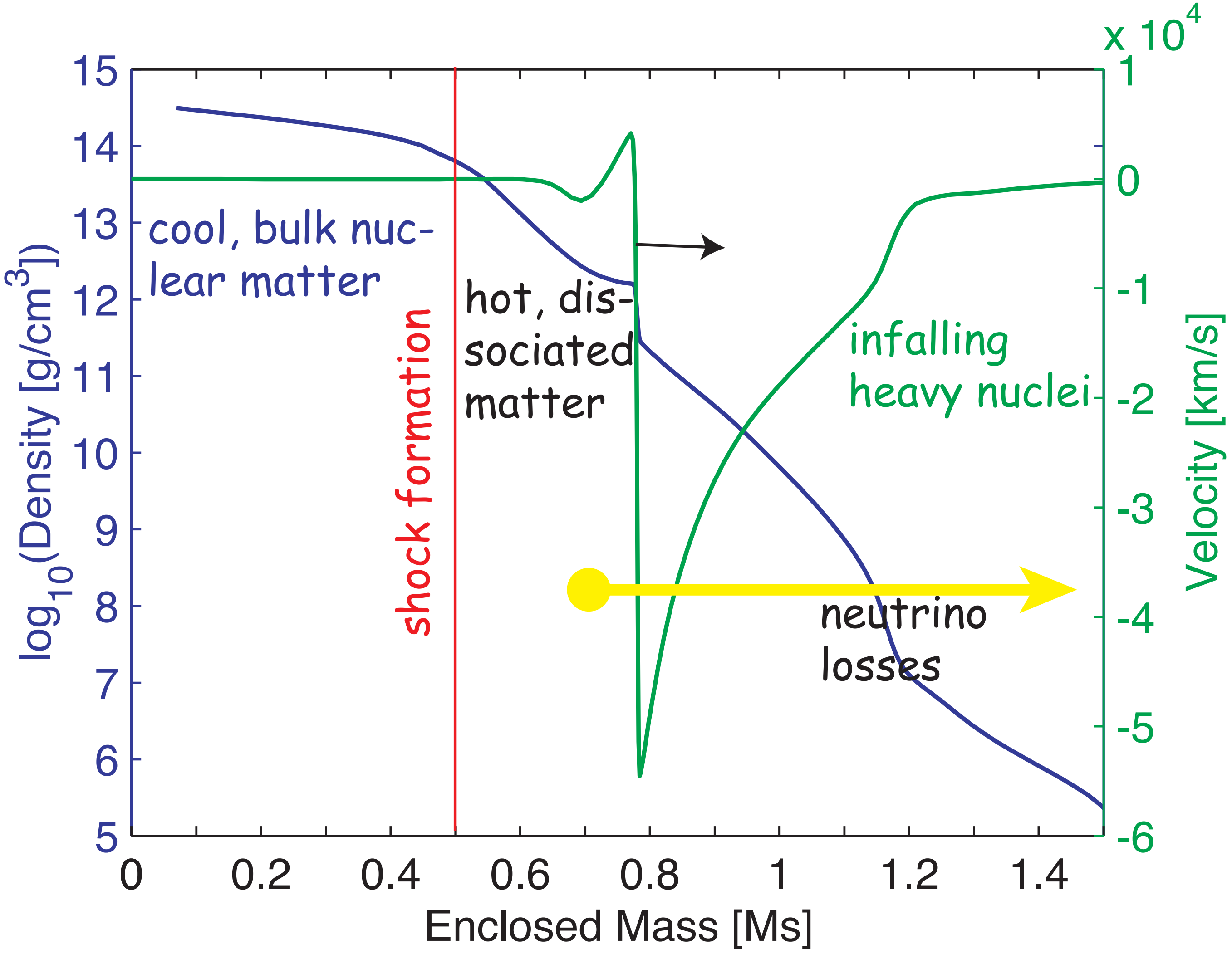
Bounce: Shock Energy Losses

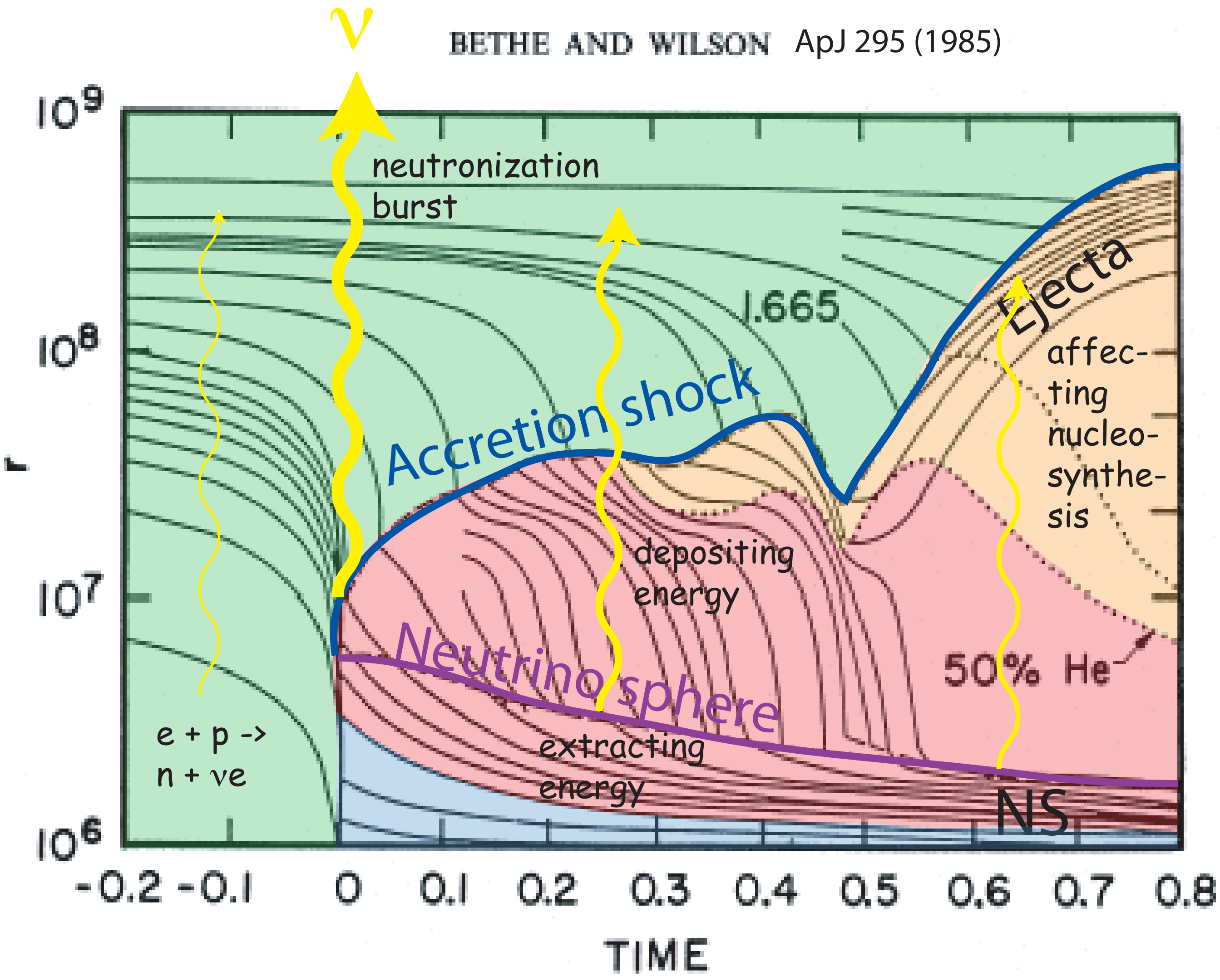
Within 2-4 milliseconds after bounce:



- dissociation losses and neutrino losses exhaust shock energy
- it was thought that a very strong shock could directly expel outer layers
- cannot be produced in simulations with neutrino transport
- robust result because electron captures on free protons limit uncertainties

Delayed explosion: 4 phases

BETHE AND WILSON ApJ 295 (1985)



collapse phase || postbounce accretion phase | explosion phase
bounce

Ensemble of nuclei

Cool bulk nuclear matter

Hot dissociated matter

Freeze-out of nuclei

(-->movie)

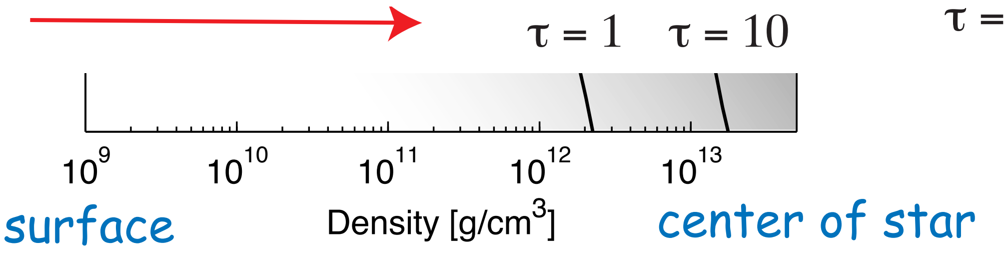
Deleptonization

Bethe (1990)
mean free path:

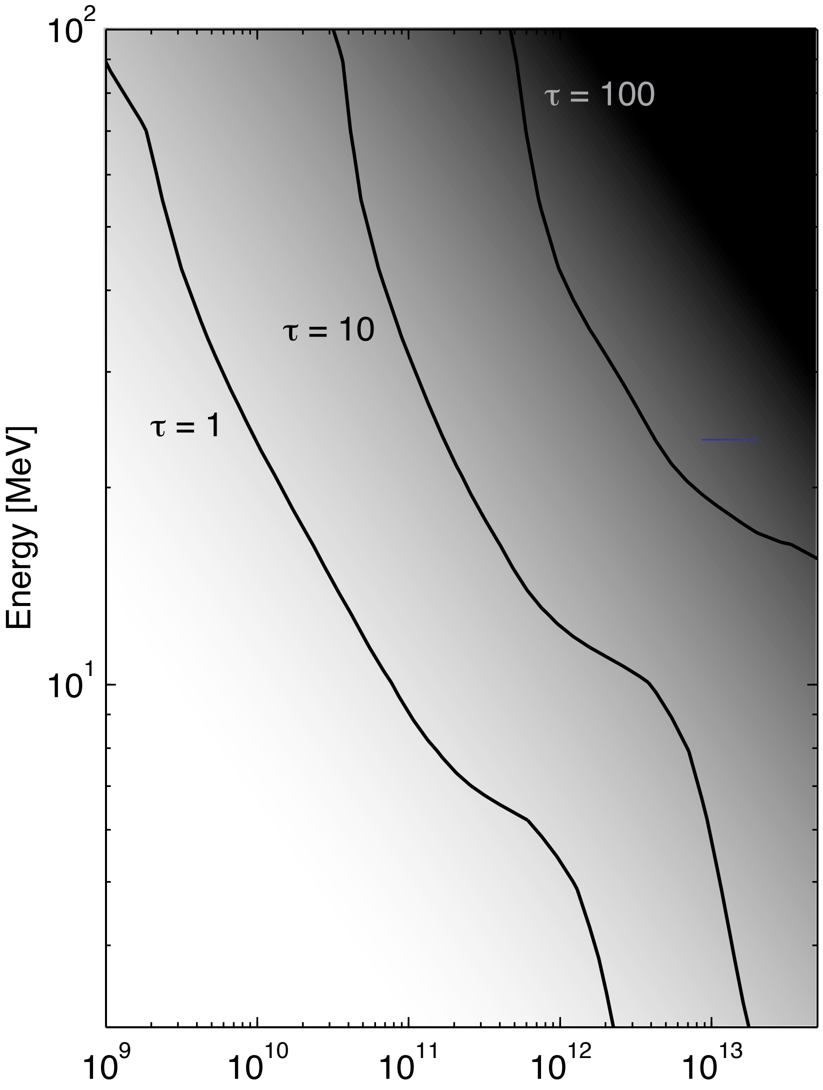
$$\lambda_\nu = 1.0 \times 10^8 \rho_{12}^{-1} [(N^2/6A)X_h + X_n]^{-1} \varepsilon_\nu^{-2} \text{ cm} .$$

Optical depth:

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



Deleptonization



surface

center of star

Bethe (1990)
mean free path:

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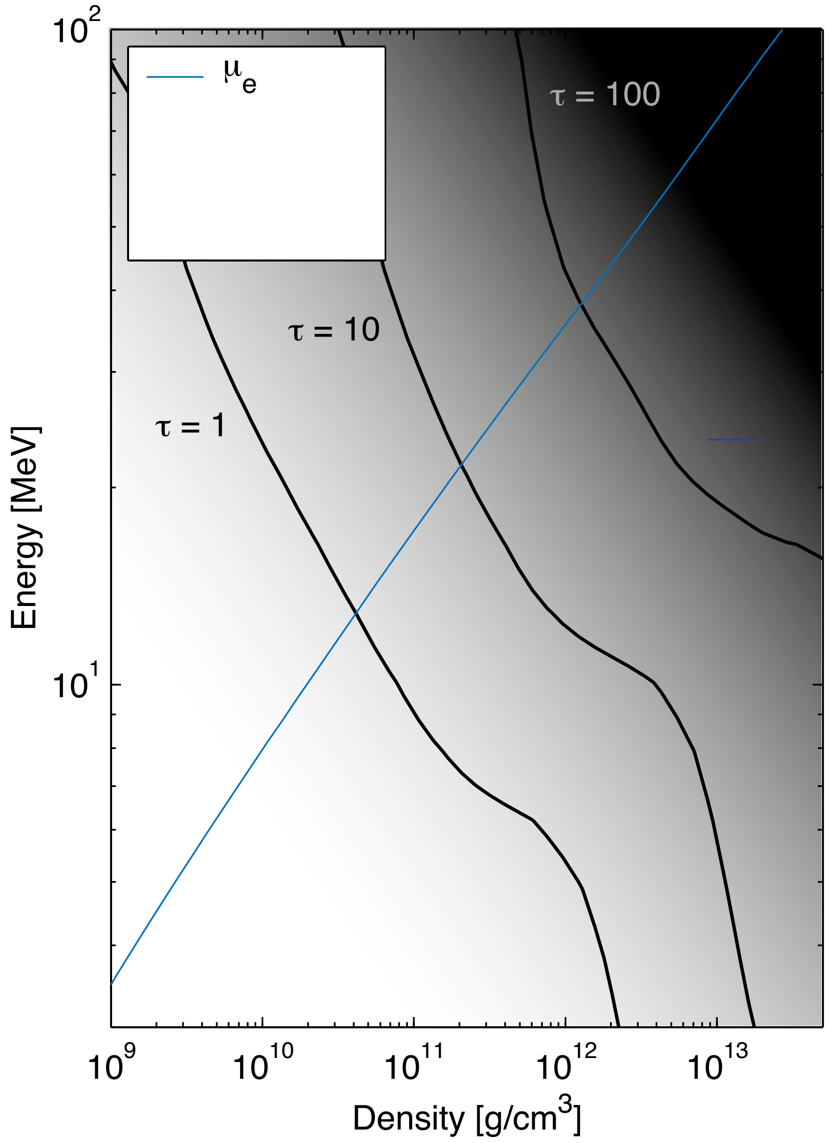
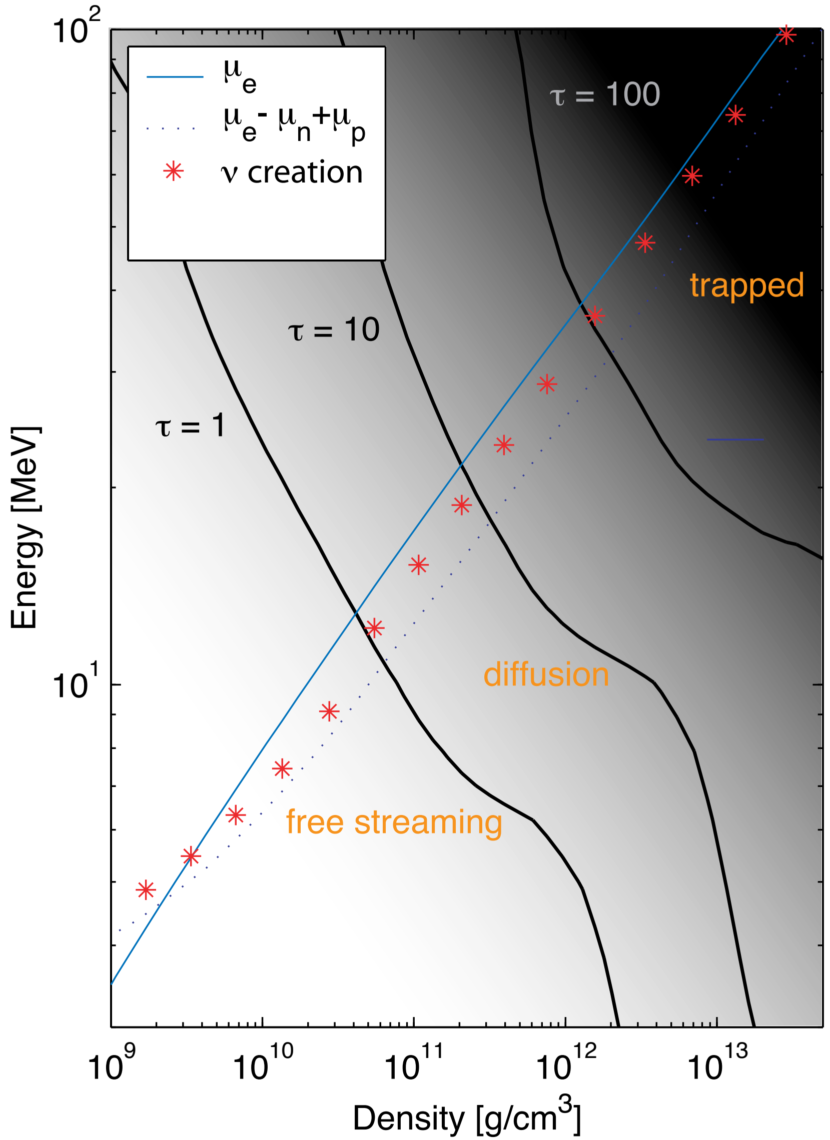


(Martinez-Pinedo, Liebendoerfer, Frekers, 2006)

Deleptonization



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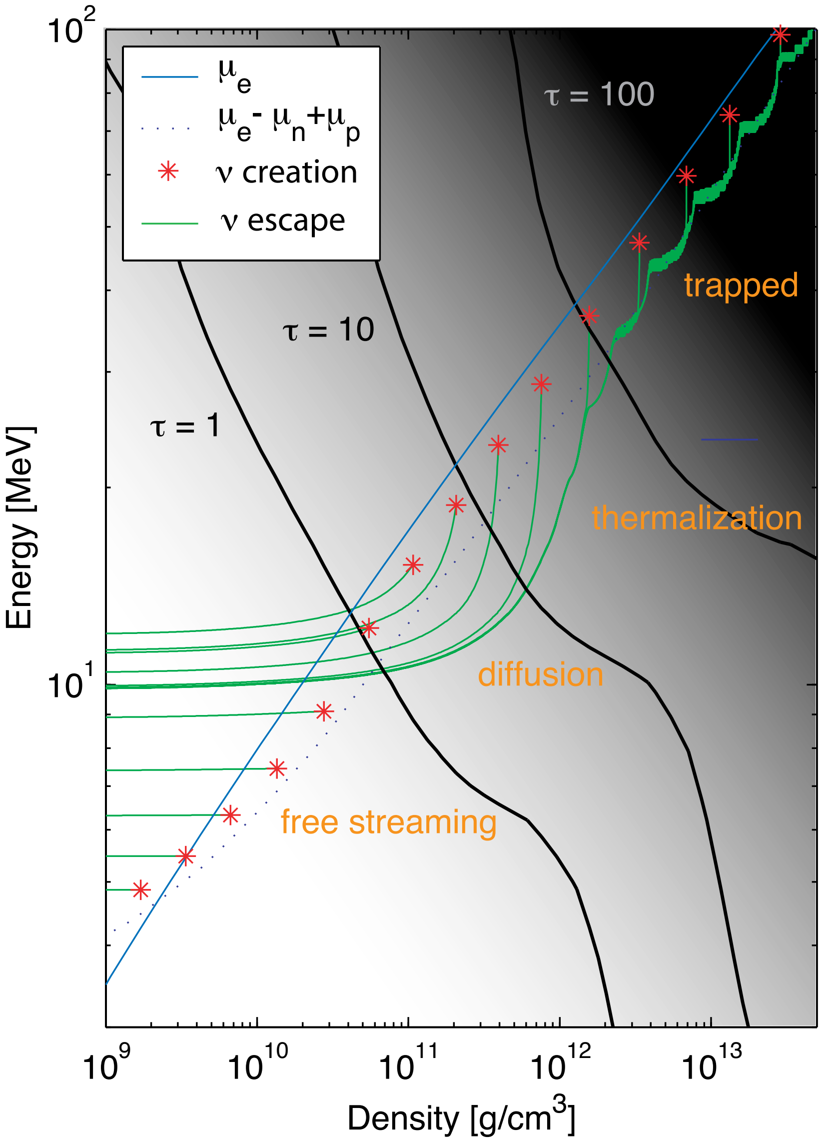

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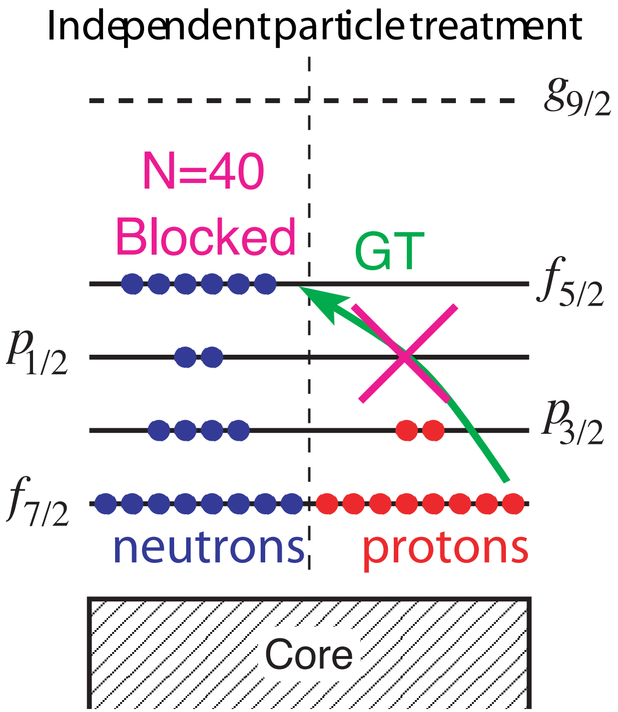
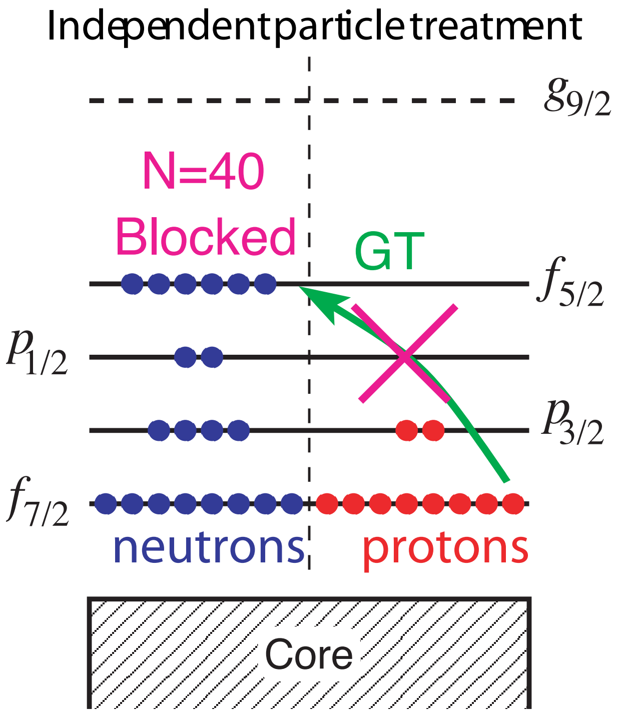
More neutrinos from electron capture

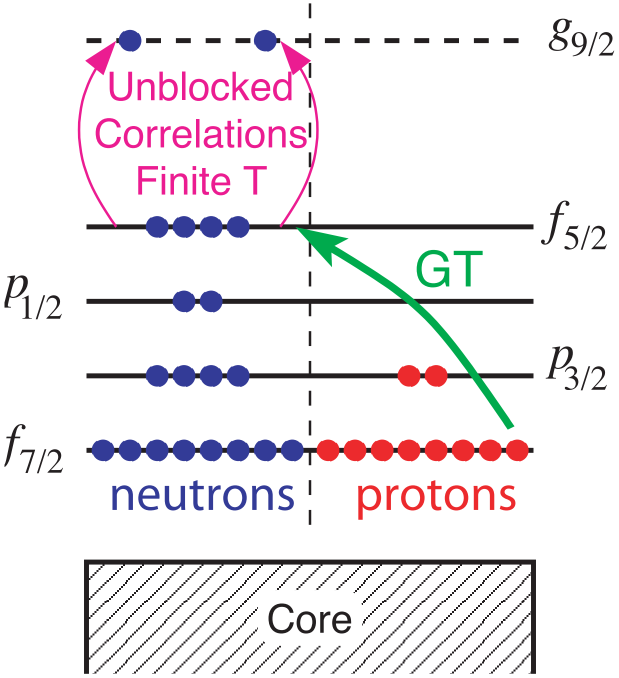


- Traditional input physics:

Electron capture reactions blocked for neutrino-rich heavy nuclei

More neutrinos from electron capture





(Martinez-Pinedo & Langanke 2002)

- Traditional input physics:

Electron capture reactions blocked for neutrino-rich heavy nuclei

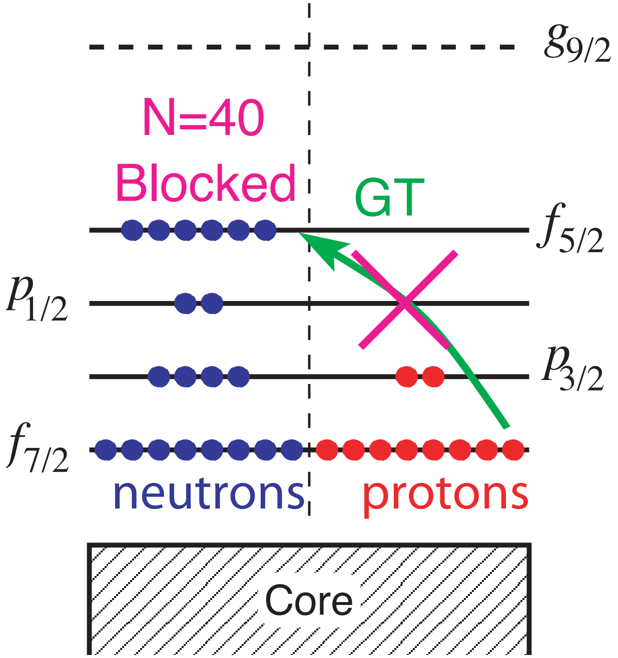
- Most recent input physics:

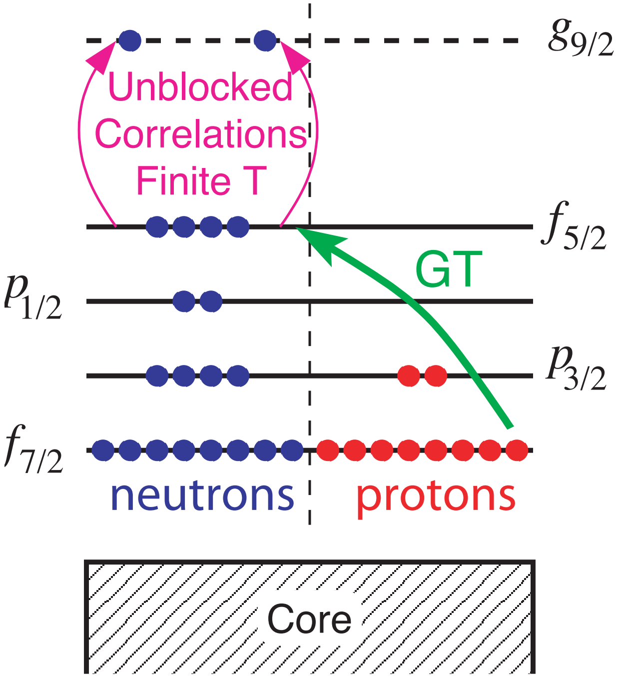
Electron captures on heavy nuclei proceed and dominate!

(Hix et al. 2003, Marek et al. 2006)

More neutrinos from electron capture

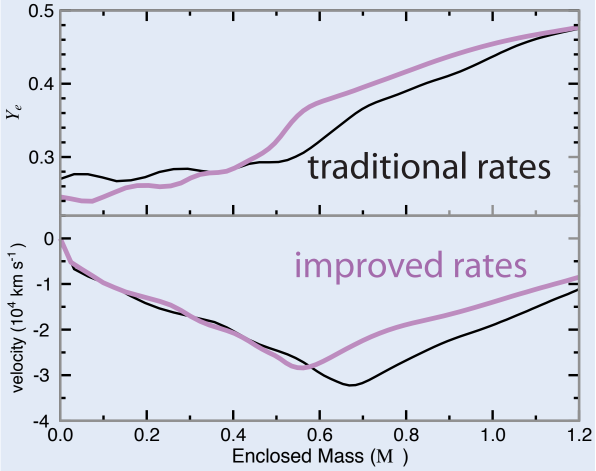
Independent particle treatment





(Martinez-Pinedo & Langanke 2002)

Electron fraction and velocity profile as function of enclosed mass before bounce



(Langanke et al. 2003)

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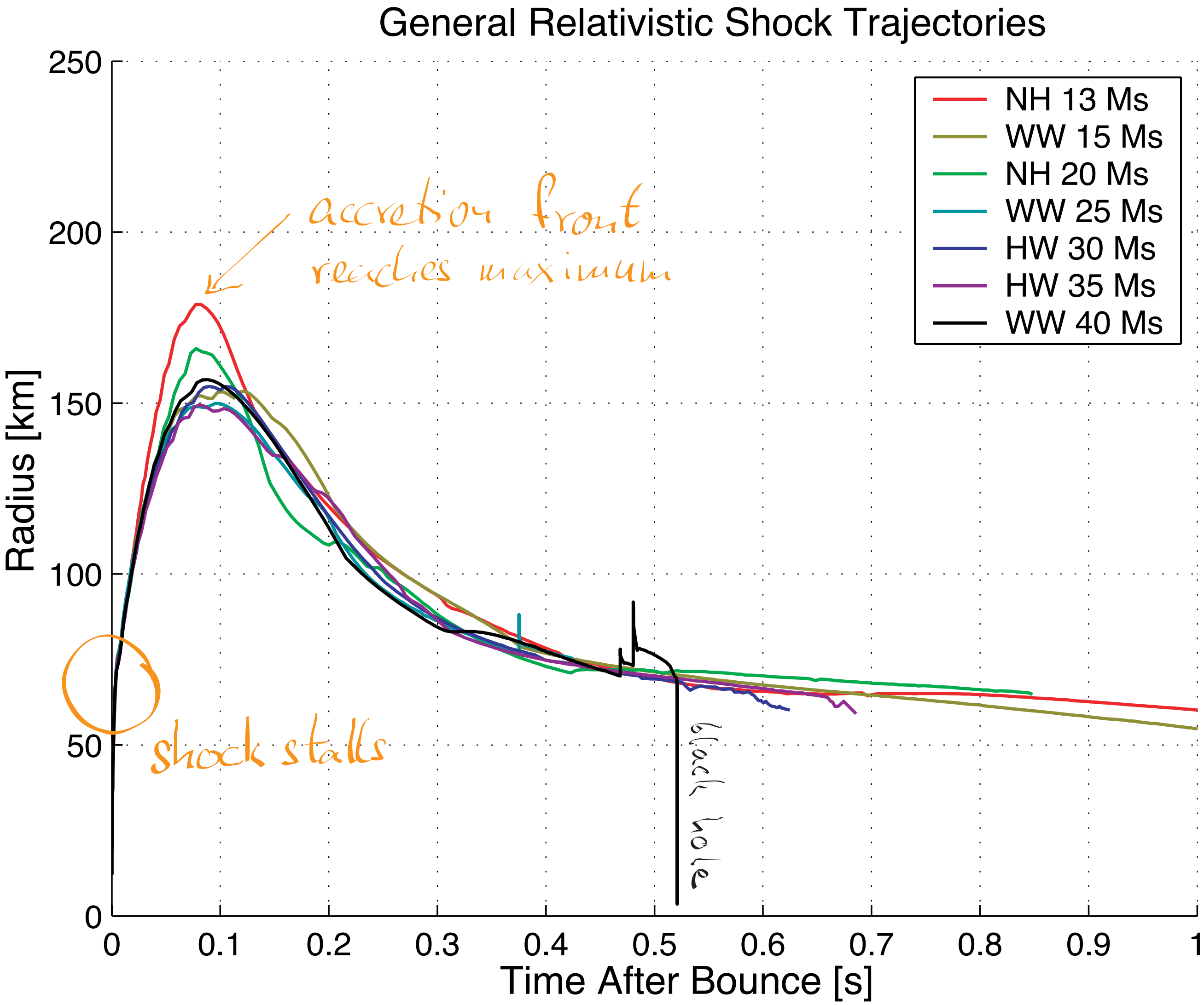
- the treatment of nuclear structure in n-rich nuclei causes 20% differences in shock formation!

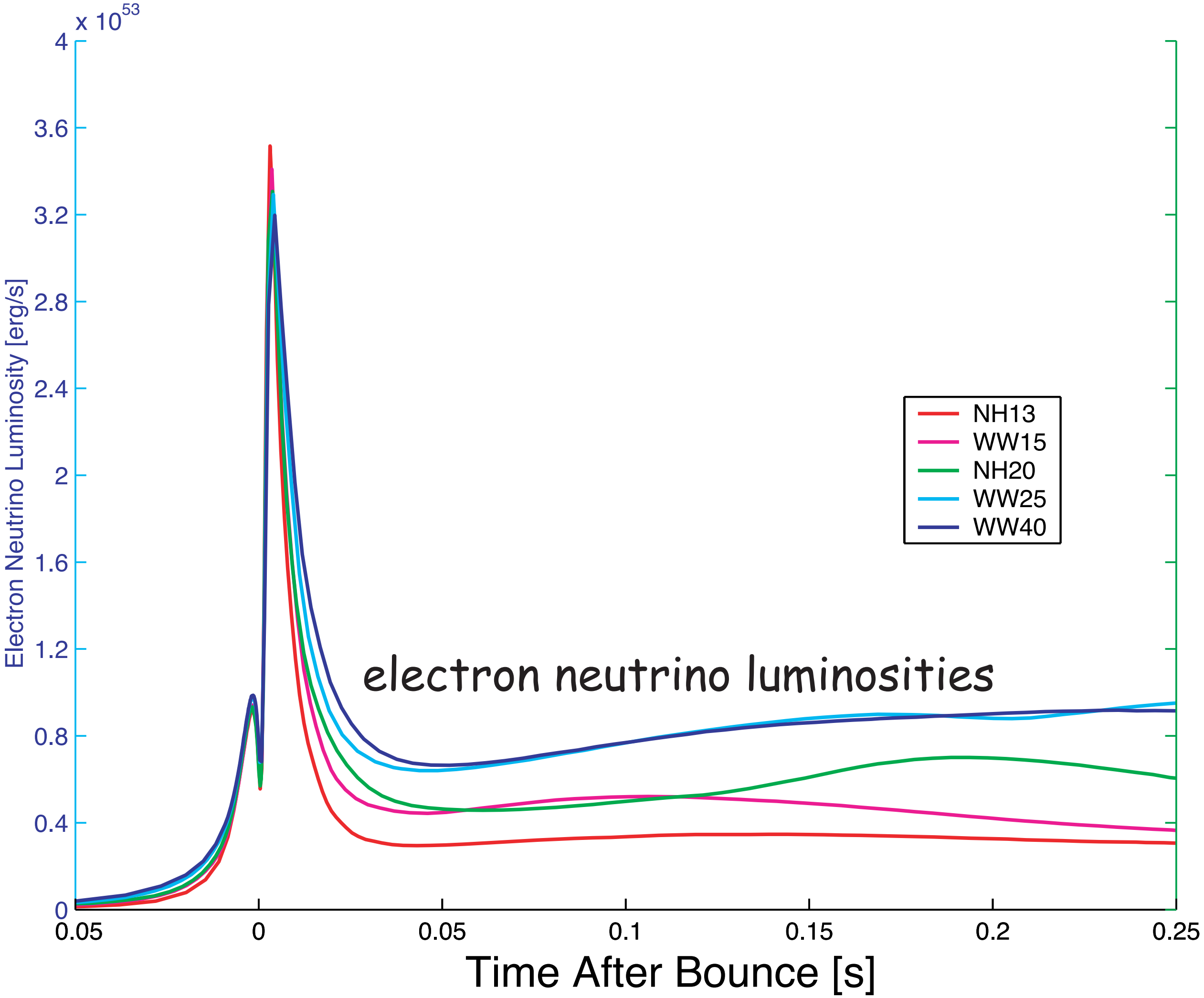
Modeling: accretion front



- 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
- all other models are VERY similar, why?

Modeling: neutrino signal

UNI
BASEL



electron neutrino luminosities

- initially similar luminosities

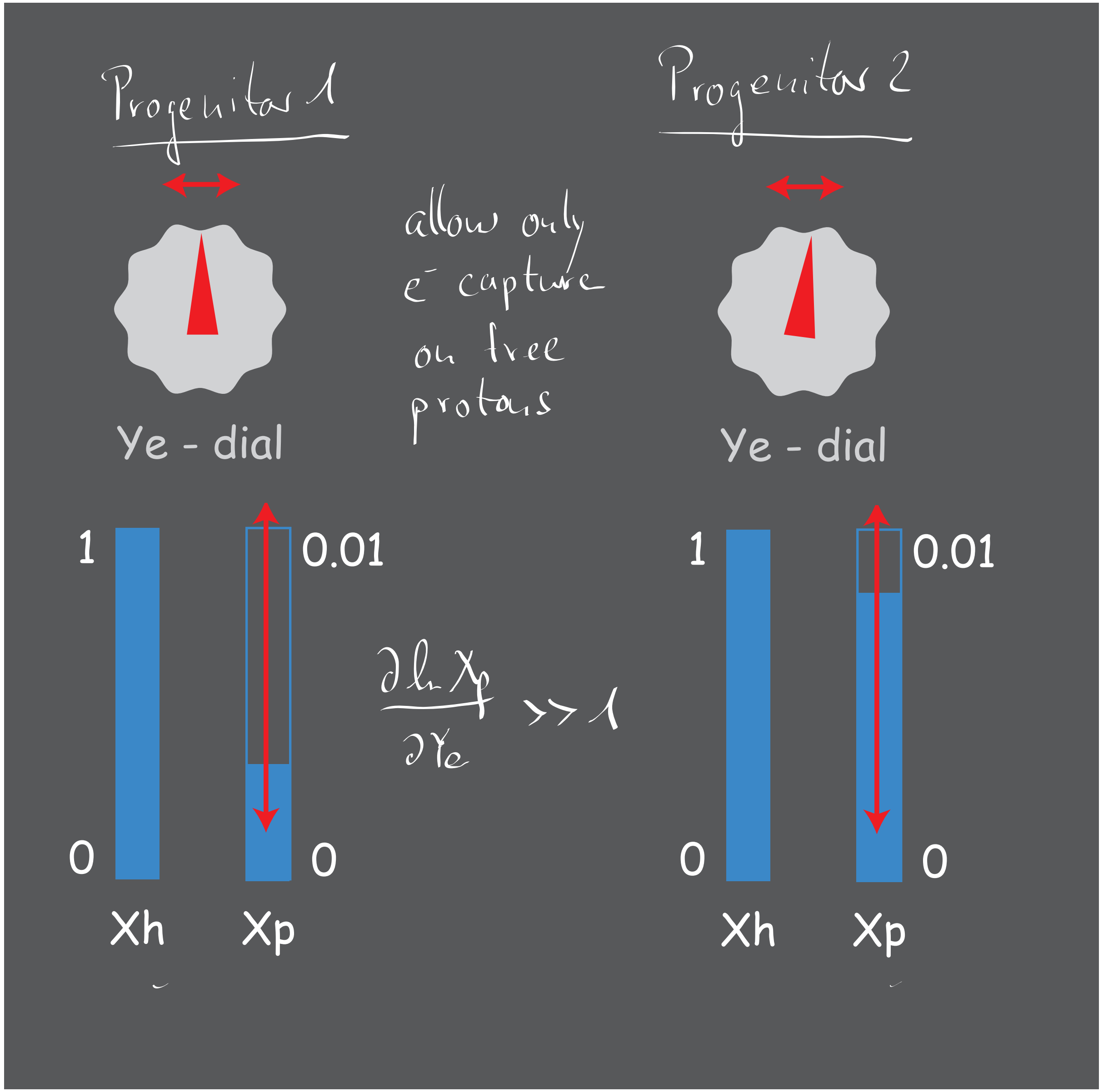
Physics: deleptonization

Progenitor 1

allow only
e^- capture
on free
protons

Progenitor 2

Physics: deleptonization



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$$\frac{\partial \ln X_p}{\partial Y_e} \gg 1$$

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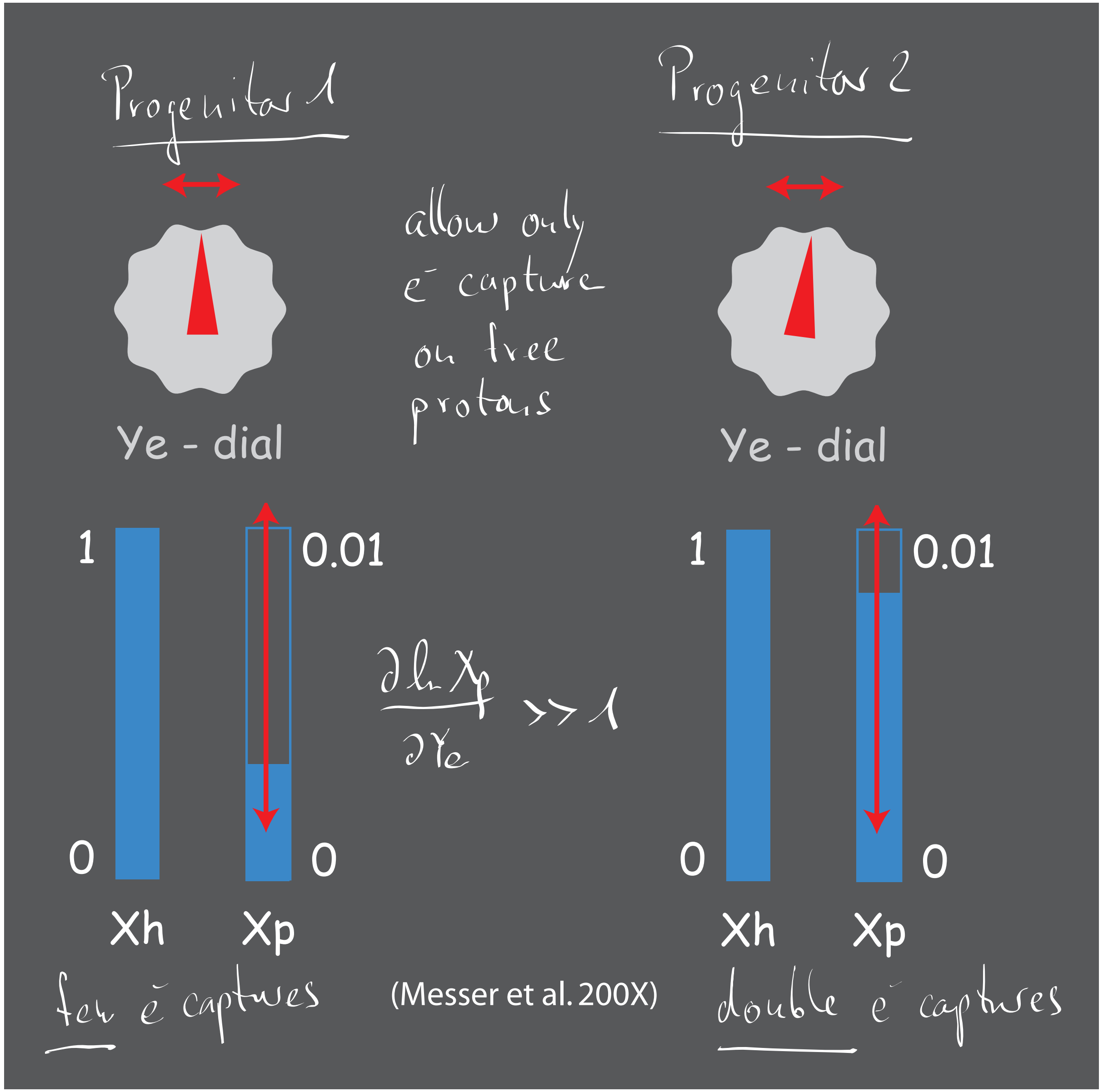

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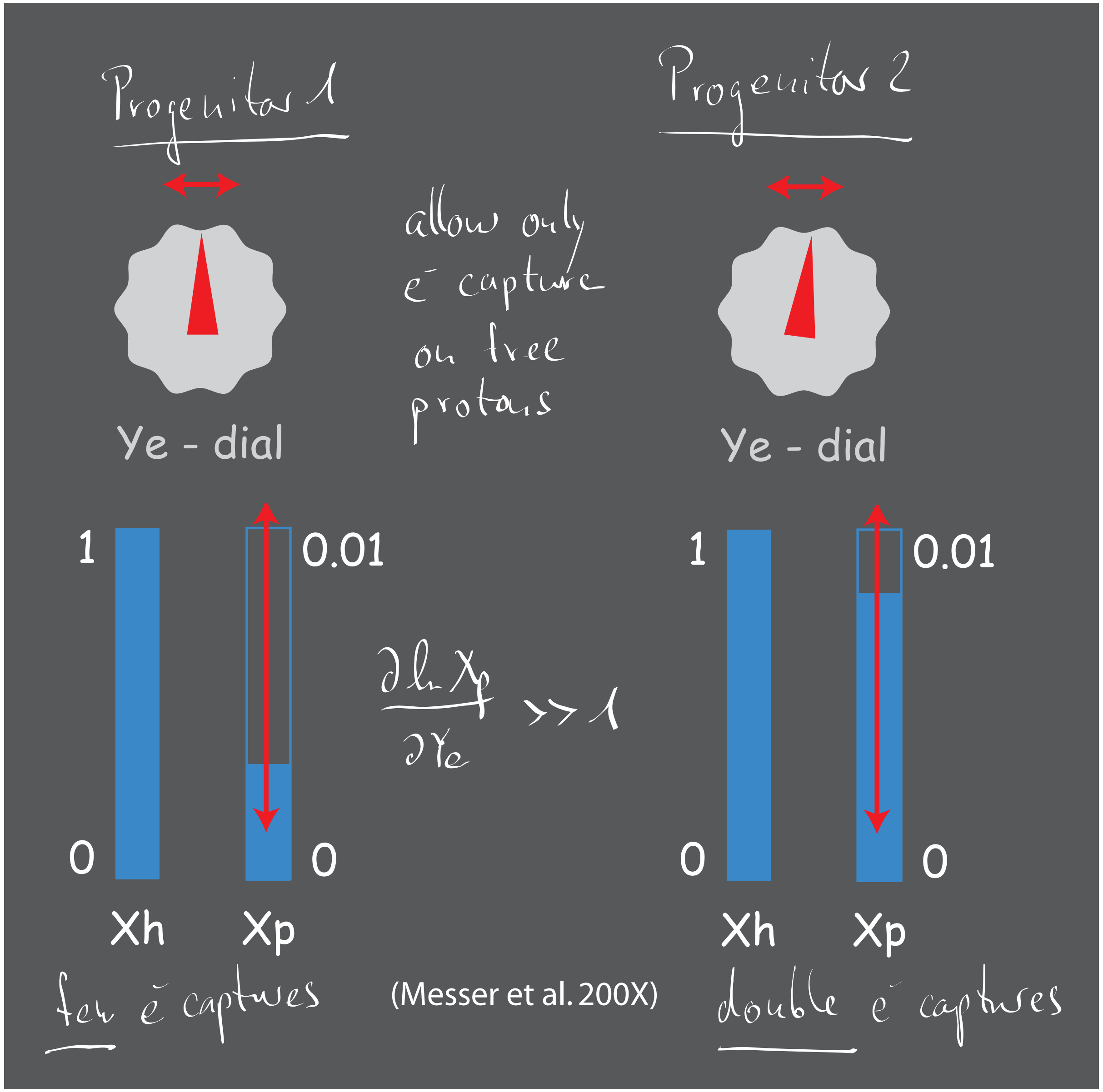
few e^- captures

double e^- captures

(Messer et al. 200X)

Physics: deleptonization



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(Messer et al. 200X)

different progenitors, but:

- approx. same Chandrasekhar mass at onset of collapse
- upper limit of Ye by e-capture on free protons
- converging deleptonization
- same bounce density

=> same bounce dynamics!

Why no explosion?

Iron core: 1.2 - 1.4 $M_\odot$

Inner core at bounce: 0,45 - 0,65 $M_\odot$

(Langanke et al. 2003
Hix et al. 2003)

best

very optimistic

1) deleptonization

2) dissociation

Hillebrandt & Müller 1981:	25 Msol
Rampp & Janka 2000:	15 Msol
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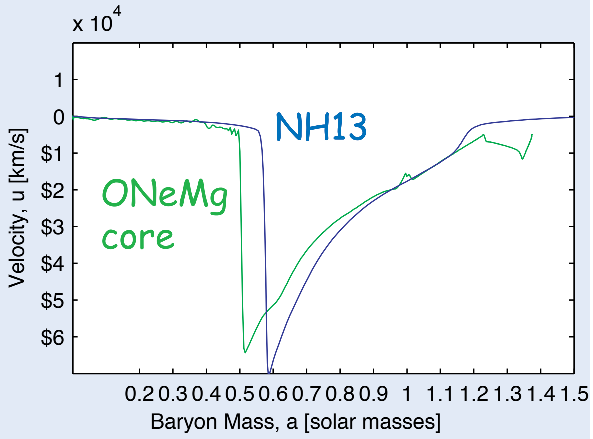
ONeMg core 2004:	9 Msol



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$\rightarrow \sim 10^{51}$ erg per 0.1 $M_\odot$ dissocitation

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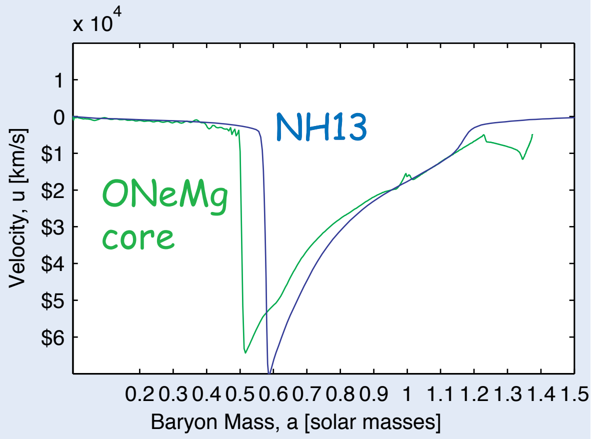

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→ ~10^{51} erg per 0.1 $M_\odot$ dissocitation

hydrodynamic shock must stall

unless input physics is dramatically different.

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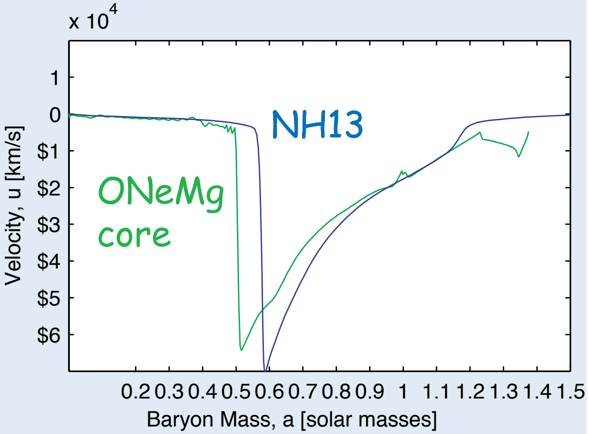
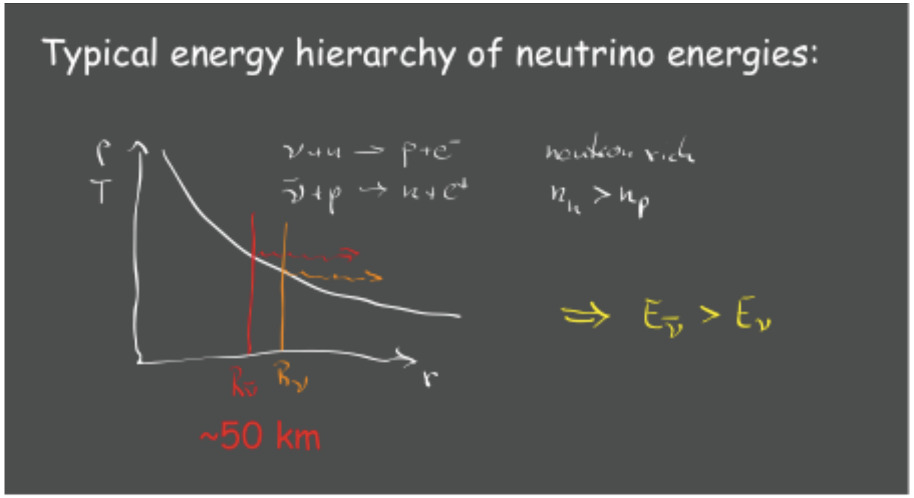
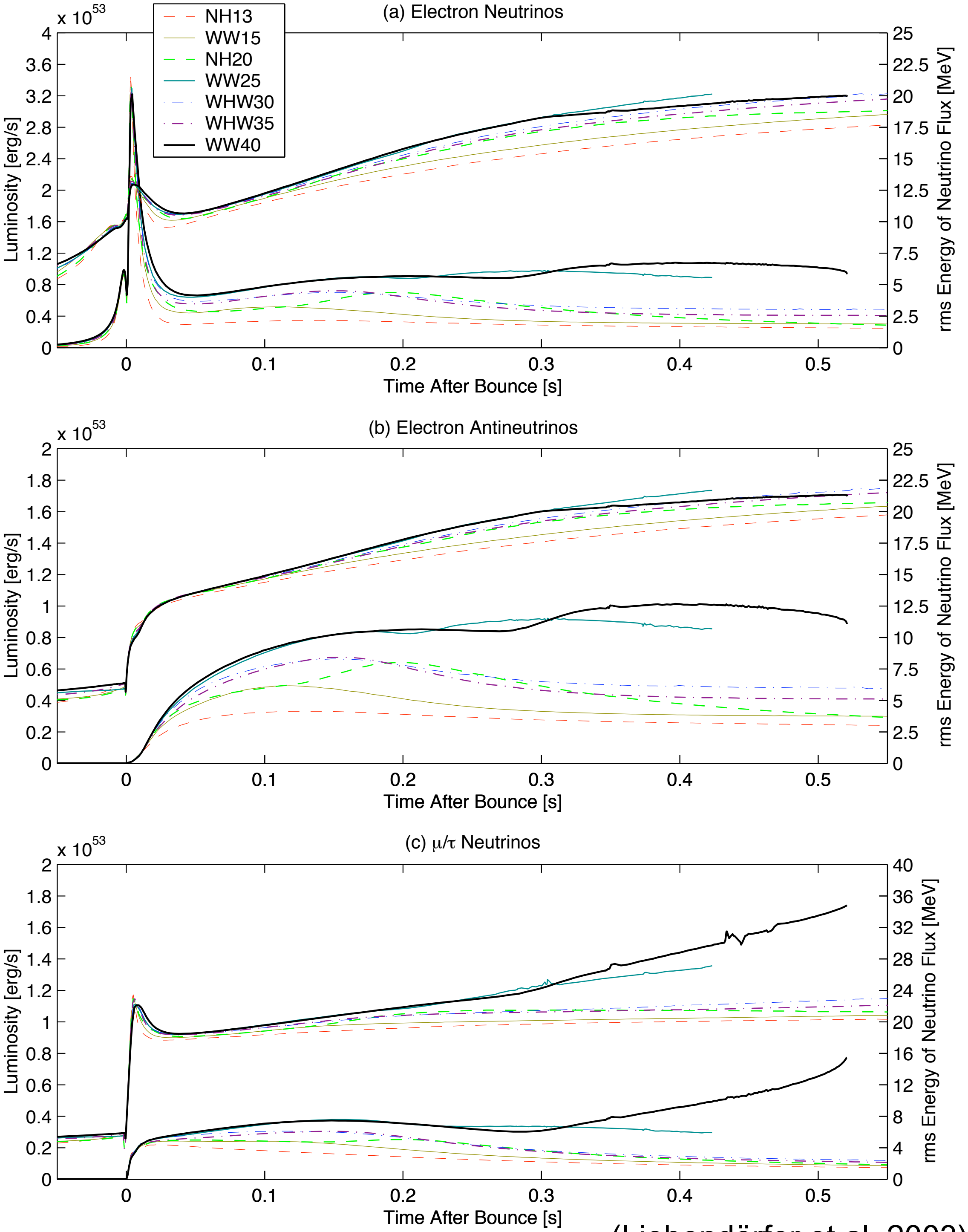


Neutrino Luminosities

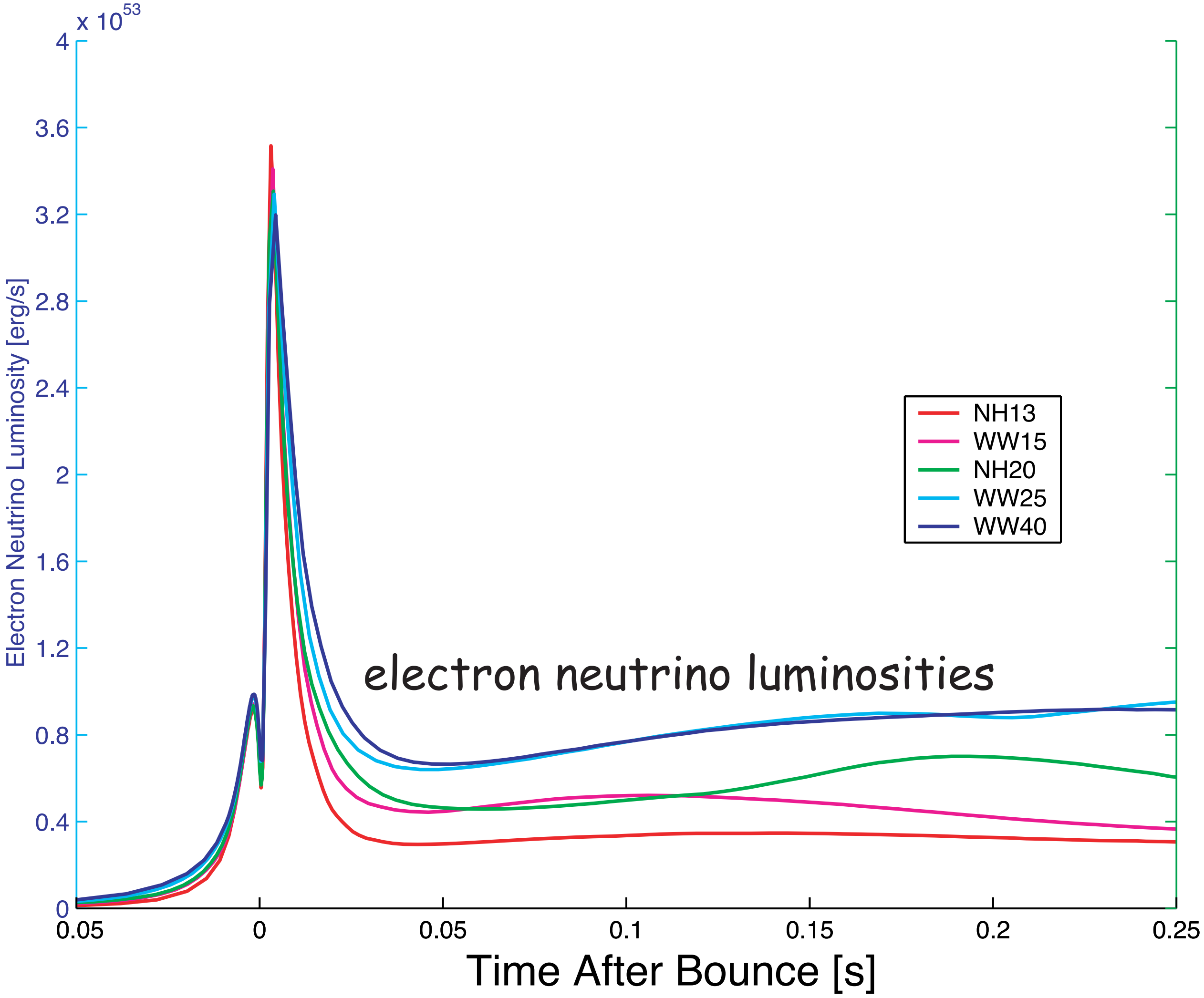
The neutrino luminosities reflect the accretion rate and the thermodynamic conditions at the neutrinospheres





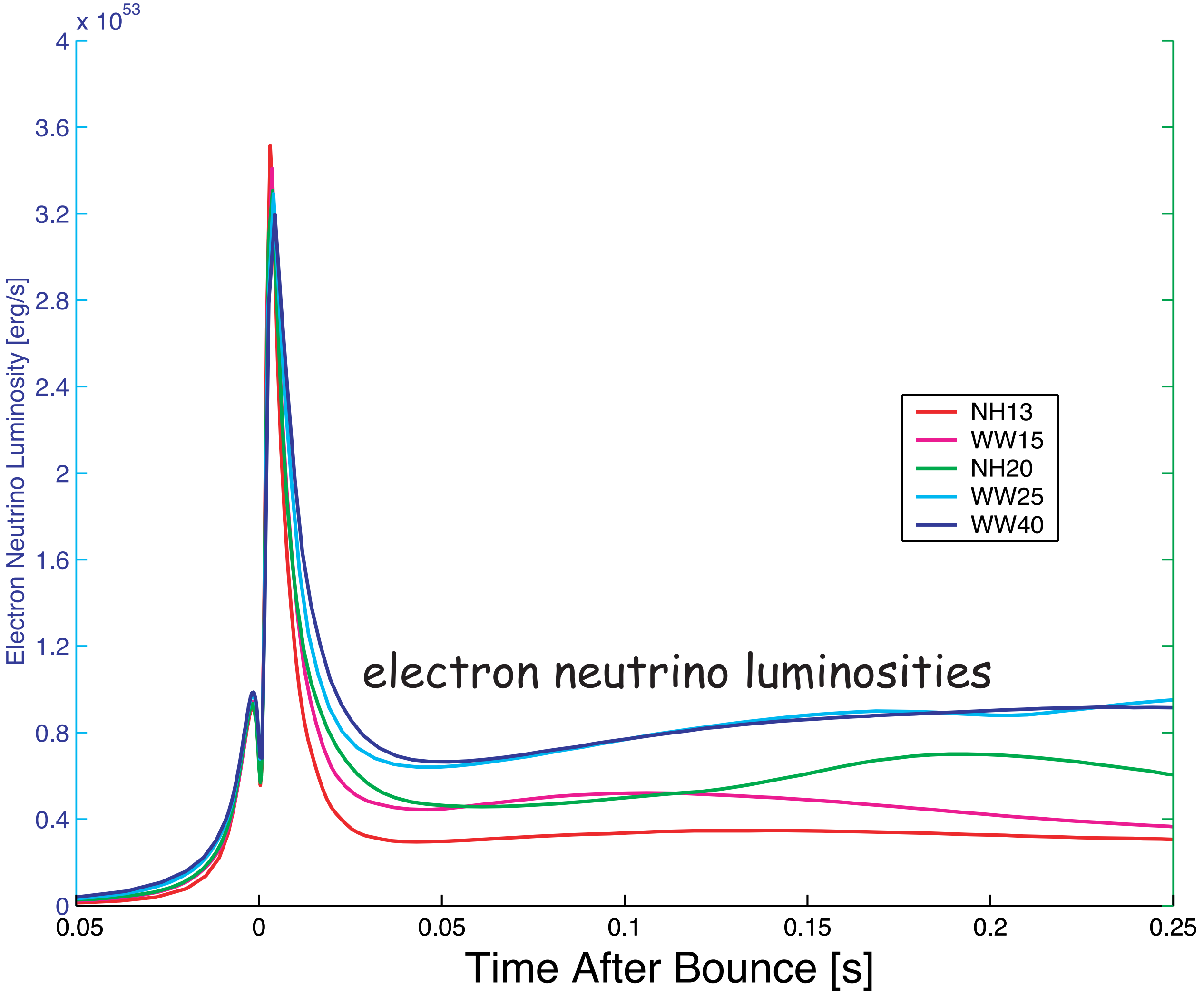
(Liebendörfer et al. 2003)

Neutrino signal



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

Neutrino signal



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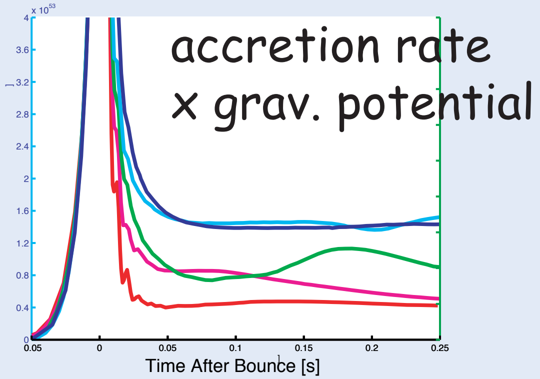
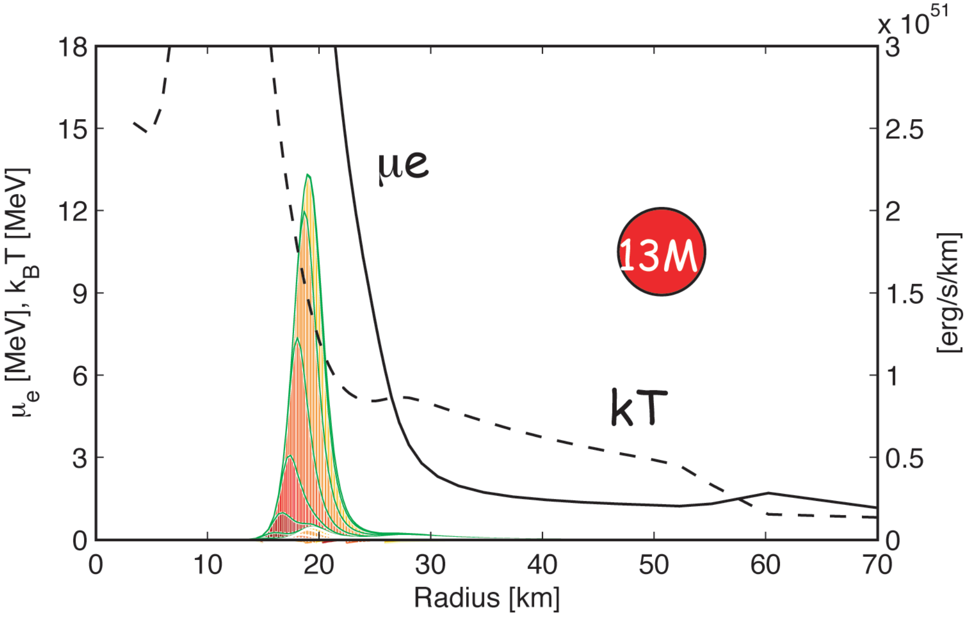


PNS evolution & ν(μ/τ) properties



- low mass proto-neutron star (PNS)
  --> incompressible accretion

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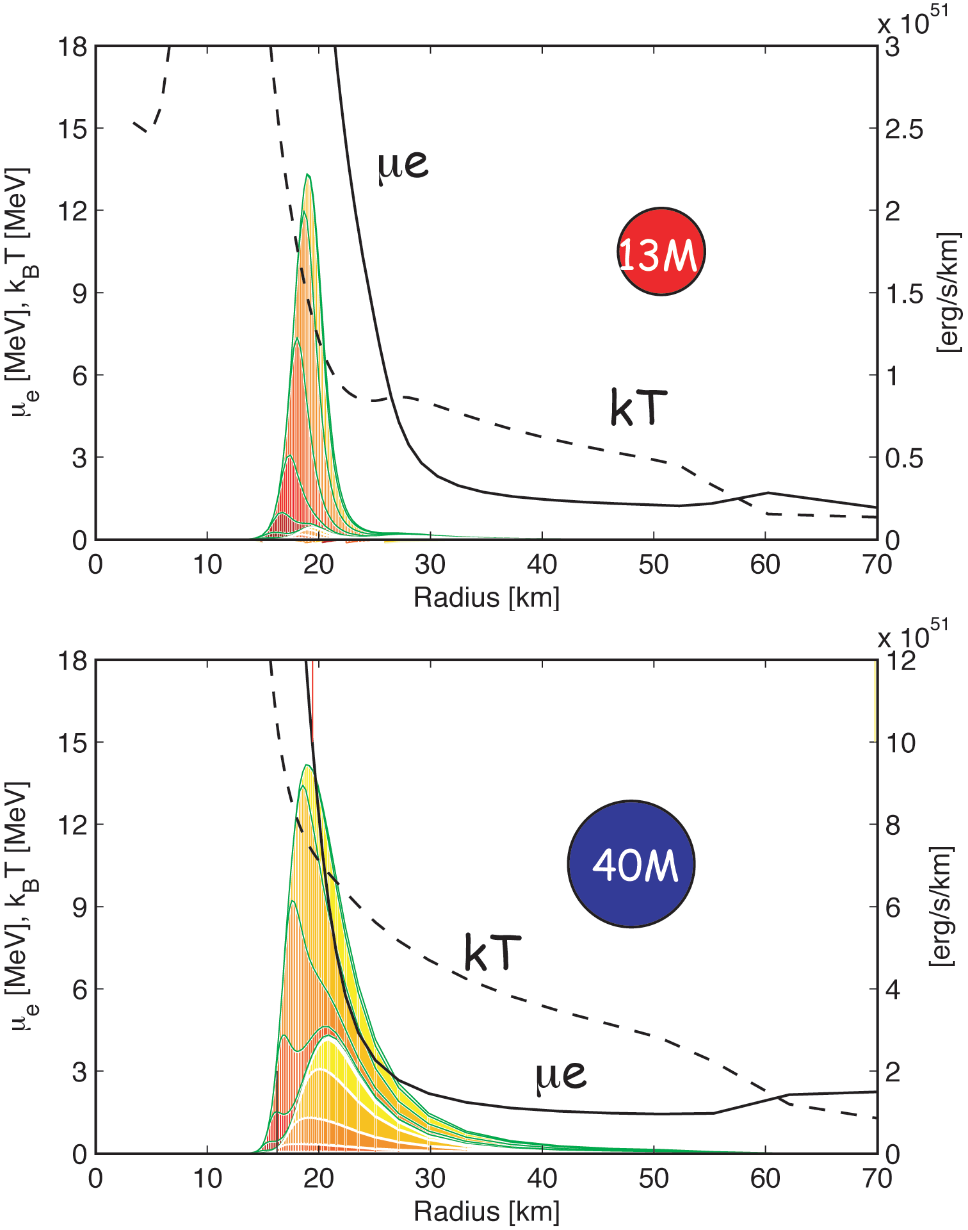

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- PNS close to maximum mass
  --> hot layers pushed inward

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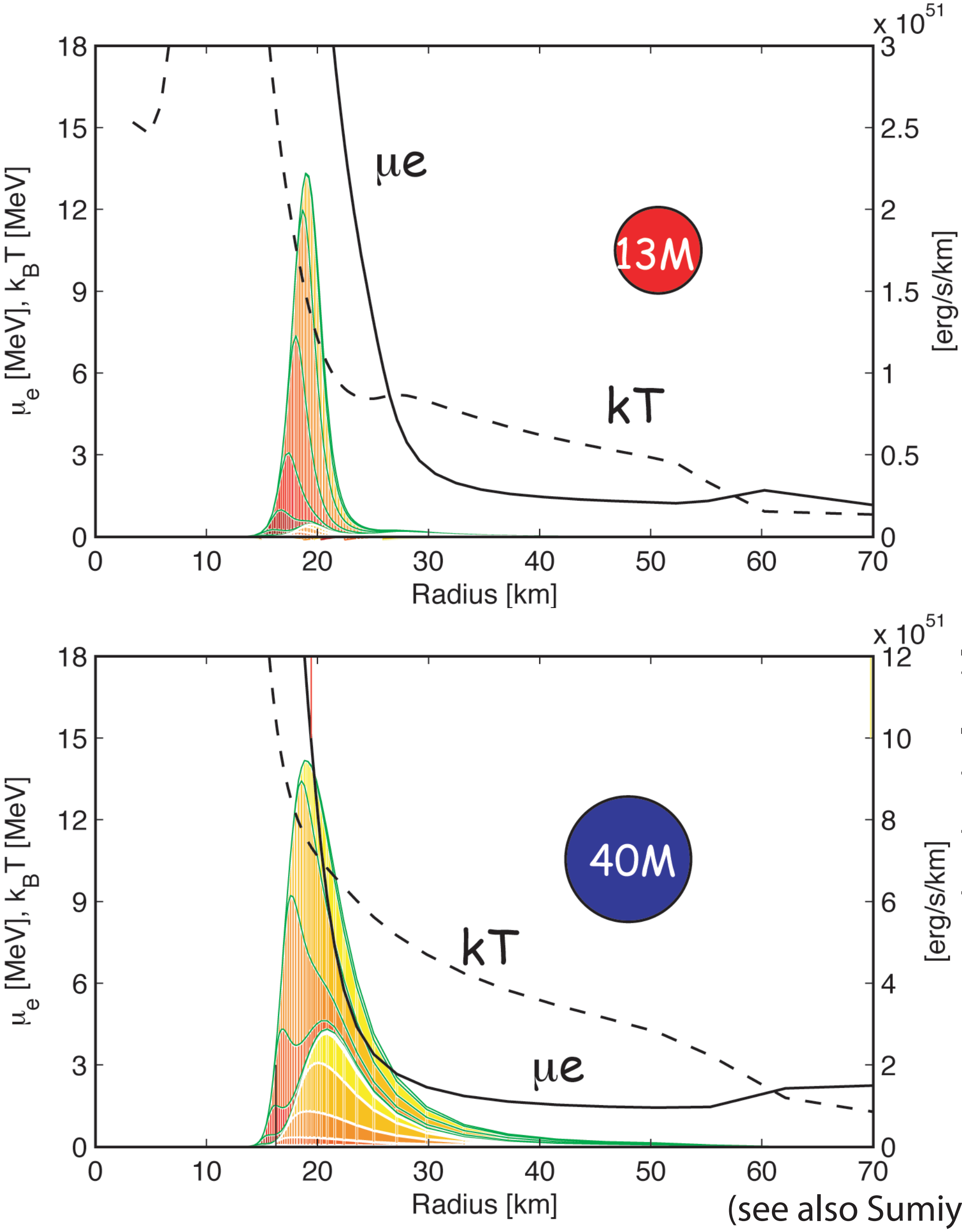
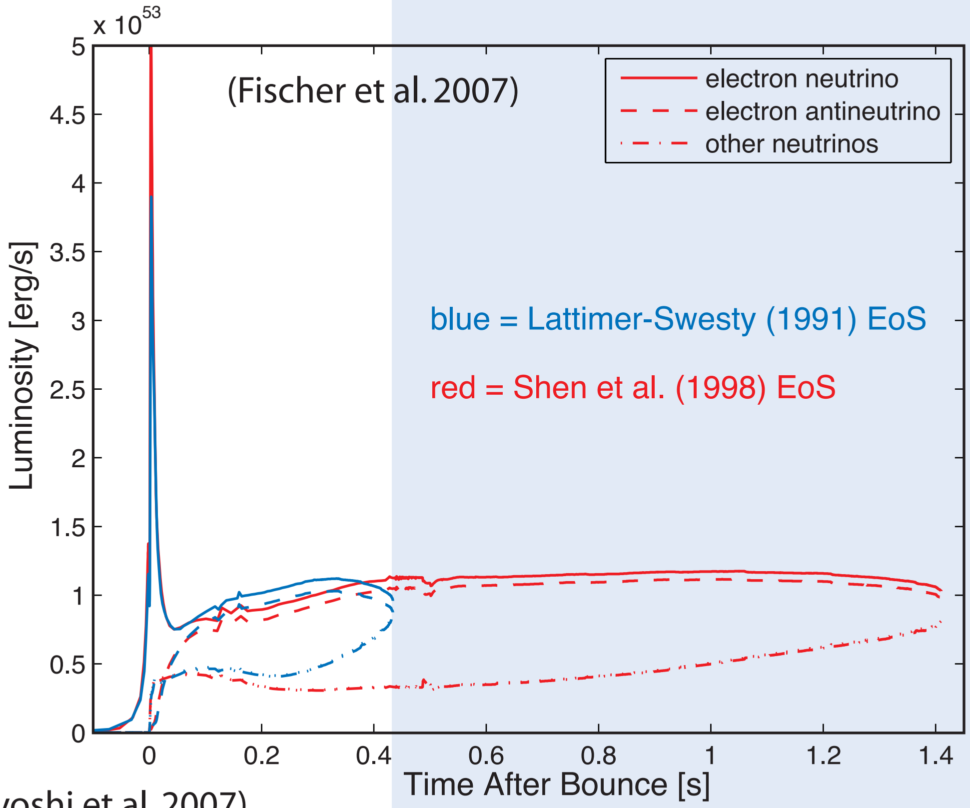


(see also Sumiyoshi et al. 2007)

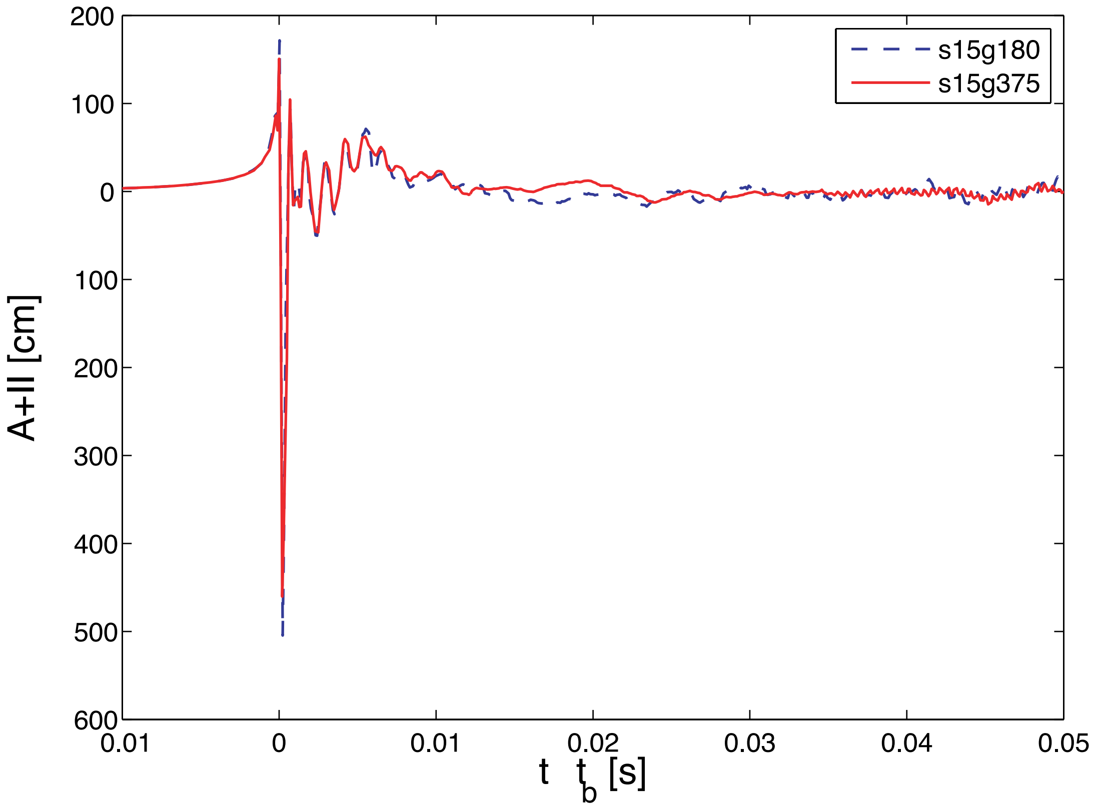


(Fischer et al. 2007)

blue = Lattimer-Swesty (1991) EoS

red = Shen et al. (1998) EoS

Testing equation of state at bounce?



- the direct impact is small!
- Is there an indirect impact on fluid instabilities that produce larger variations in GW emission?
- GW from QCD phase transition? (e.g. Yasutake et al. 2007, Abdikamalov et al. 2007)

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

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

Influence of Equation of State

Dynamics/Structure

binding energy per baryon
--> different temperature
--> different pressure
--> different composition -->

Compositional

different constituents
--> different neutrino-matter interactions
--> different freeze-out?
--> different fragmentation -->

Microscopic Structure

different arrangements of scattering centers
--> different coherence effects in neutrino-matter interactions
--> different binding energy? -->

References:

(e.g. Baron et al. 1985, Bruenn 1989, Martinez-P., Liebend., Frekers 2006, Sumiyoshi et al. 2005, Marek and Janka 2007, Fischer et al. 2007)

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Influence of Equation of State

Dynamics/Structure

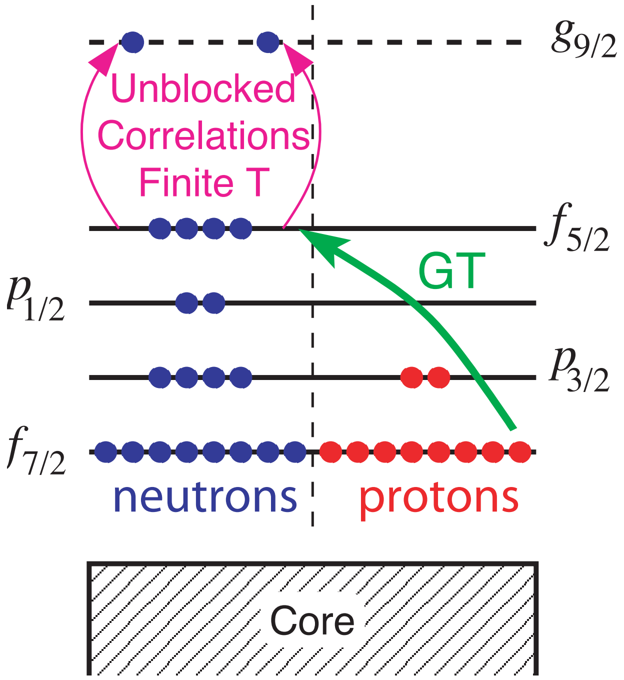
binding energy per baryon
--> different temperature
--> different pressure
--> different composition -->

Compositional

different constituents
--> different neutrino-matter interactions
--> different freeze-out?
--> different fragmentation -->

Microscopic Structure

different arrangements of scattering centers
--> different coherence effects in neutrino-matter interactions
--> different binding energy? -->



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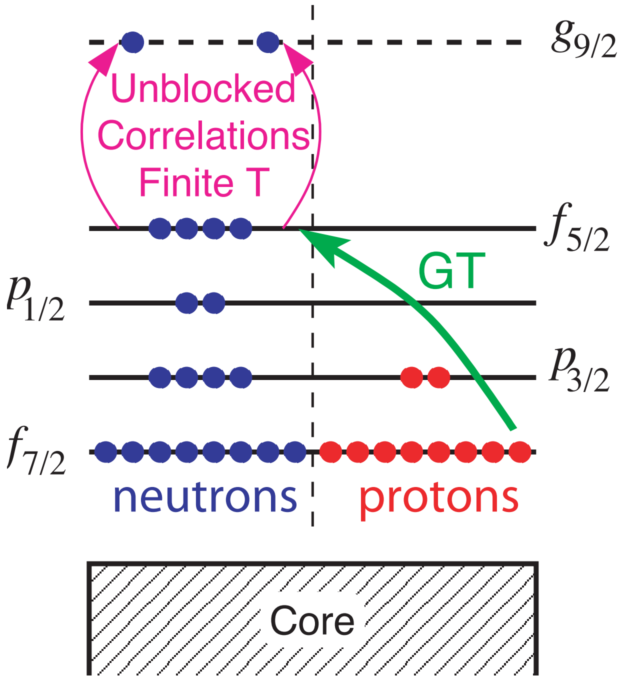

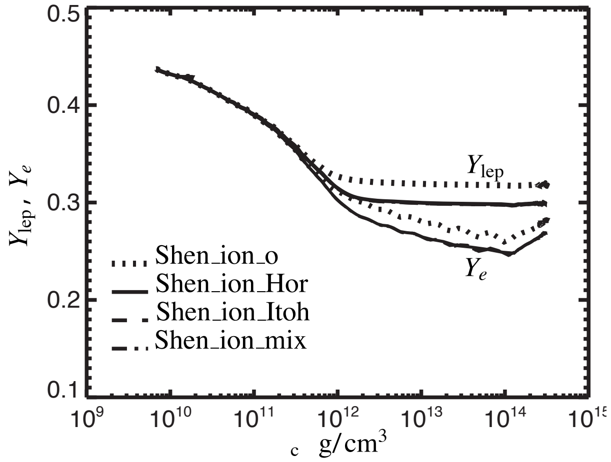

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