Compschool, Copenhagen 2009

UNI BASEL

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!

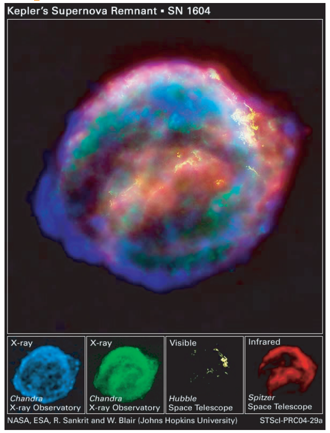
- Leading order contributions from many fields of physics possible...

Historical supernovae

Table 1. Summary of the historical supernovae, and the source of their records

date	length of visibility	remnant	Historical Records: Chinese	Japanese	Korean	Arabic	European
AD1604	12 months	G4·5+6·8	few	–	many	–	many
AD1572	18 months	G120·1+2·1	few	–	two	–	many
AD1181	6 months	3C58	few	few	–	–	–
AD1054	21 months	Crab Nebula	many	few	–	one	–
AD1006	3 years	SNR327.6+14.6	many	many	–	few	two
AD393	8 months	–	one	–	–	–	–
AD386?	3 months	–	one	–	–	–	–
AD369?	5 months	–	one	–	–	–	–
AD185	8 or 20 months	–	one	–	–	–	–

(Green & Stephenson 2003)



Kepler, det. ~20d before maximum (Mars, Jupiter)

Tycho, day-light visibility

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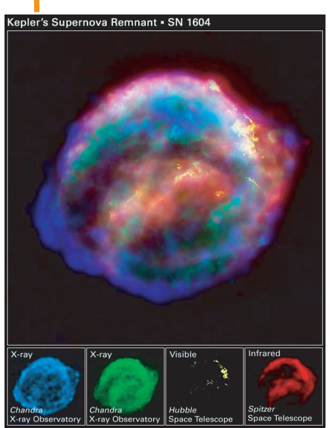

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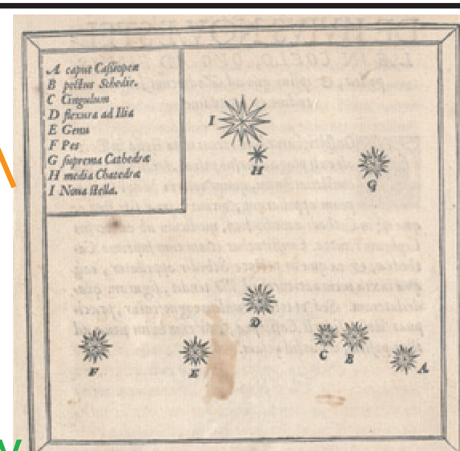

Change of fixed star!

Tycho, day-light visibility

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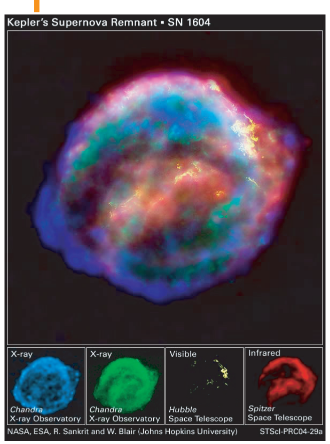
St. Gallen



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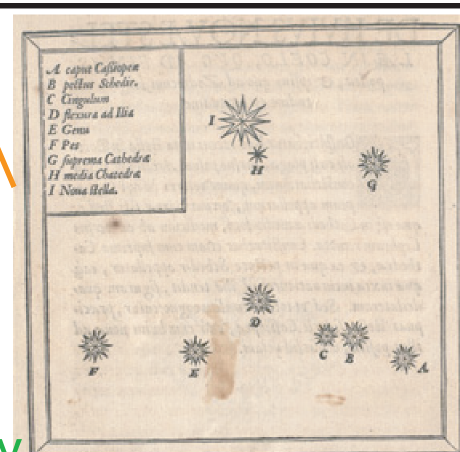

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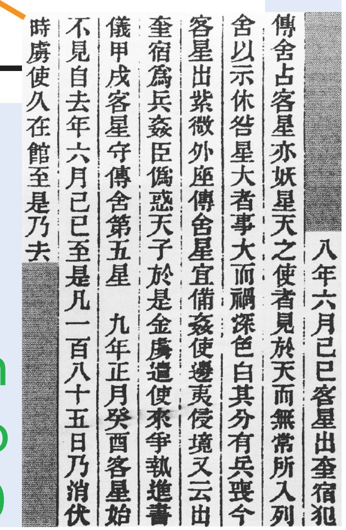
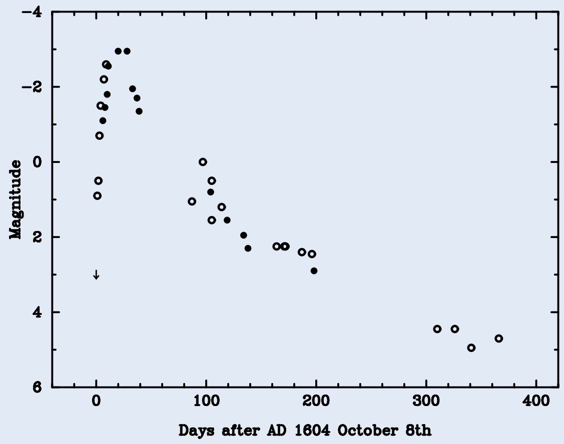
Change of fixed star!



八年六月己巳客星出奎宿犯
傳舍占客星亦妖星天之使者見於天而無常所入列
舍以示休咎星大者事大而禍深色白其分有兵喪今
客星出紫微外座傳舍星宜備姦使邊夷侵境又云出
奎宿爲兵姦臣僞惑天子於是金虜遣使來爭執進書
儀甲戌客星守傳舍第五星　九年正月癸酉客星始
不見自去年六月己巳至是凡一百八十五日乃消伏
時虜使久在館至是乃去

Wenxian Tongkao AD 1280

Supernova Lightcurve

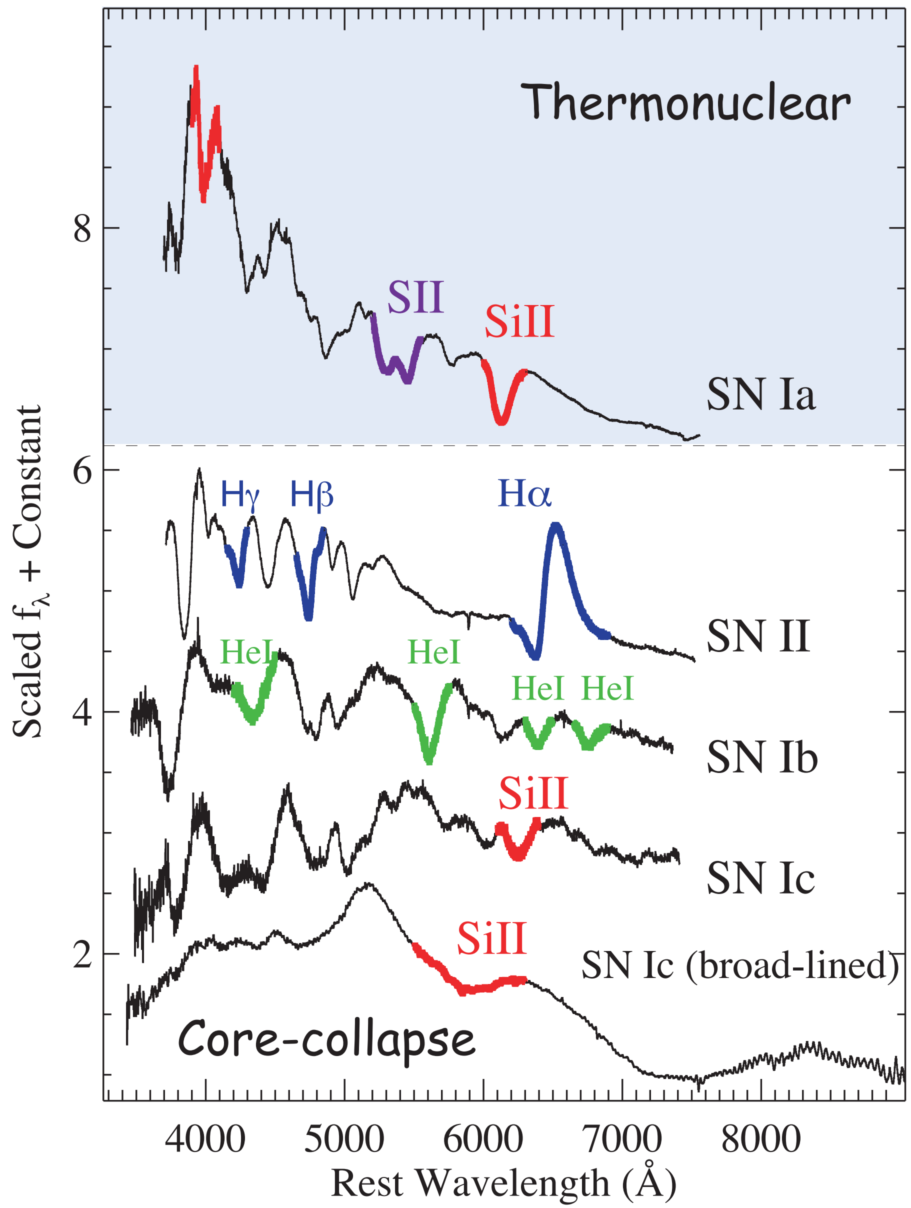


Lightcurve SN 1604
European o
Korean •

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

Early 'measurement' of radio-active half-life...

Supernova Lightcurve



Examples:

SN1994D

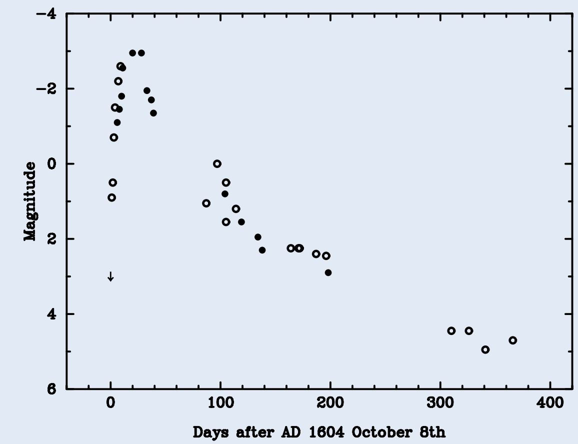
SN1999em

SN2004gq

SN2004gk

SN1998bw
GRB980425

(Modjaz 2008)



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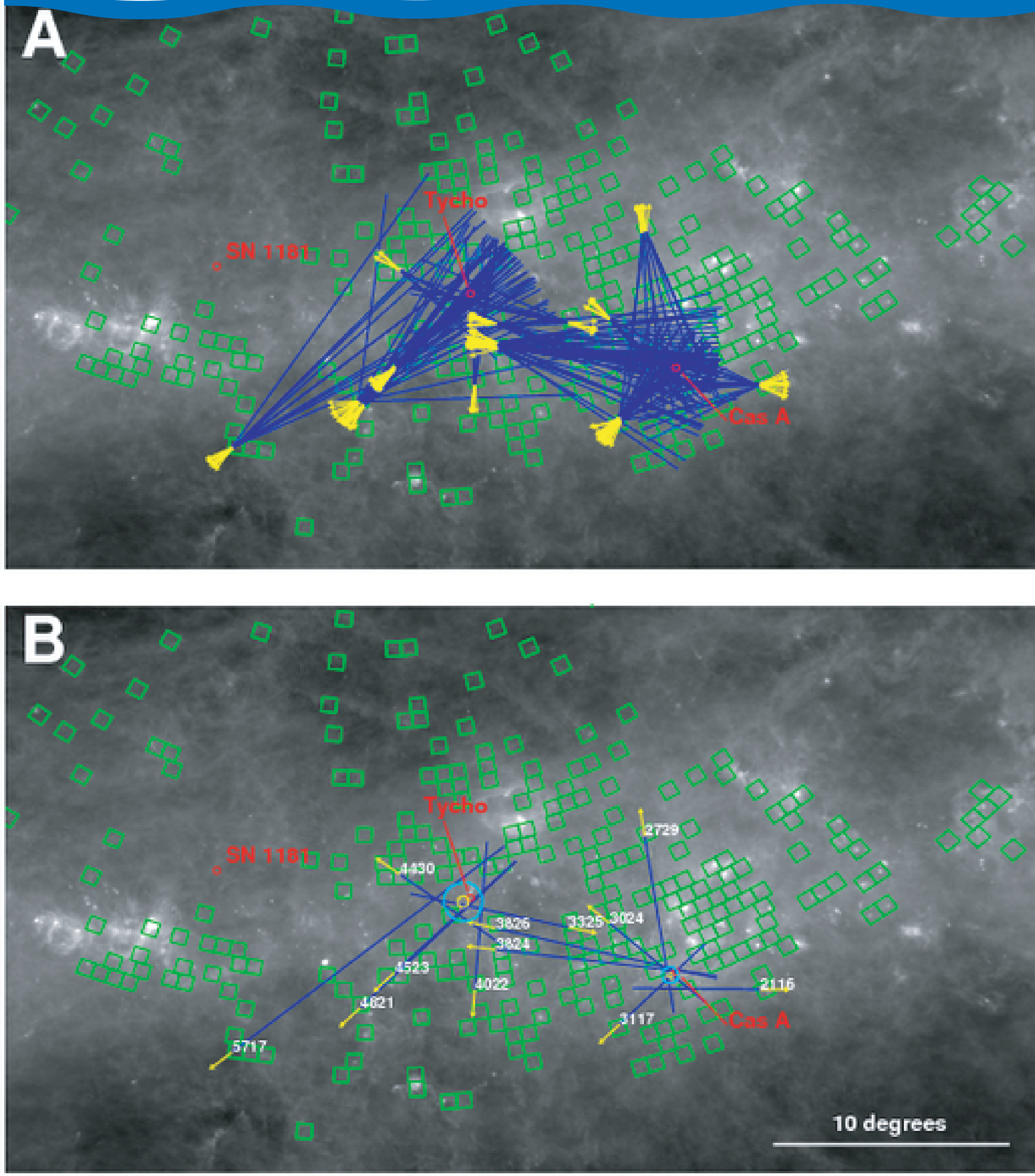
Echoes from Cass A & Tycho



No echoes seen from SN1181?

- Search in Milky Way: historical supernovae?
- Challenge: large solid angle for search
- green = 2 epochs available
- 2 clusters found
- deviations ~10 deg due to dust sheet orientation in A

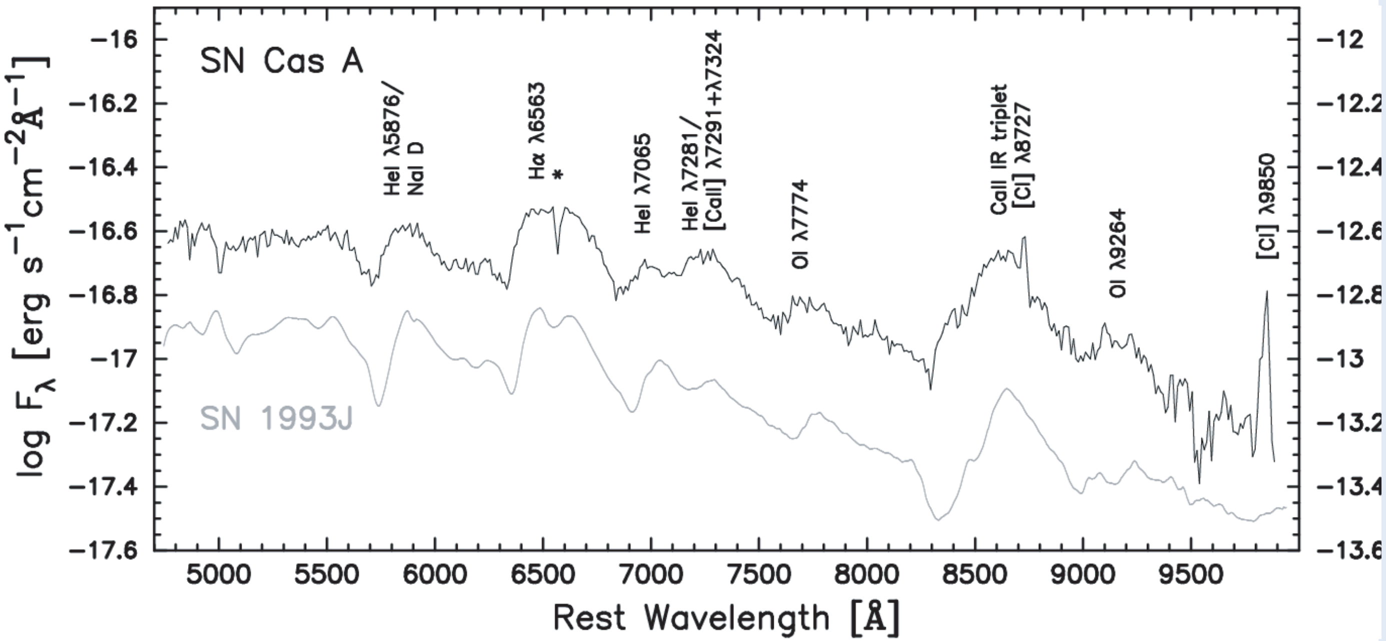
--> average vector in B

(Rest et al., ApJL 681, 2008)

Cas A Supernova was of Type IIb

... We present an optical spectrum of the Cassiopeia A supernova near maximum brightness, obtained from observations of a scattered light echo --- more than three centuries after the direct light of the explosion swept Earth. The spectrum shows that Cassiopeia was a type IIb supernova...

- very faint at Earth
- no widespread record
- type controversial



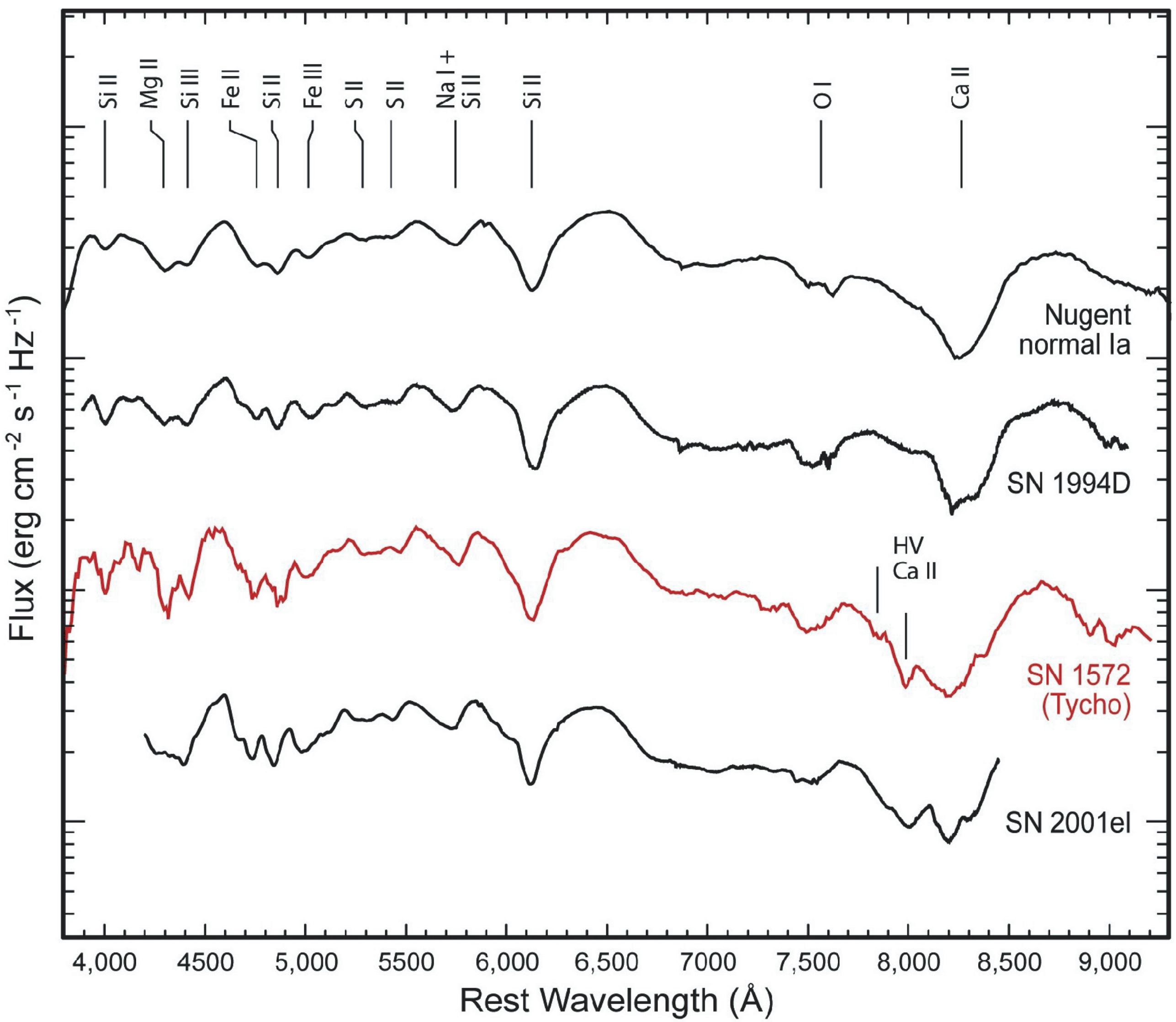
--> echo unambigously from supernova

--> weak He lines

--> similar to optically bright prototype SN1993J

(Krause et al., Sci 320, 2008)

Tycho's SN was of type Ia



- clearly SN origin
- absence of hydrogen
- prominent Si II
- ejecta v=12000 km/s

--> typical SN Ia

comparison with 90d time-averaged spectra

(Krause et al., Nature, arXiv:0810.5106)

Where does the Energy come from?

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 $M_{vis} = -14^M$. The visible radiation L_ν of a supernova is about 10^8 times the radiation of our sun, that is, $L_\nu = 3.78 \times 10^{41}$ ergs/sec. Calculations indicate that the total radiation, visible and invisible, is of the order $L_\tau = 10^7 L_\nu = 3.78 \times 10^{48}$ ergs/sec. The supernova therefore emits during its life a total energy $E_\tau \geq 10^5 L_\tau = 3.78 \times 10^{53}$ 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 $\sigma = 2 \times 10^{-3}$ erg/cm² sec. The observational values are about $\sigma = 3 \times 10^{-3}$ 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

Mass defects...

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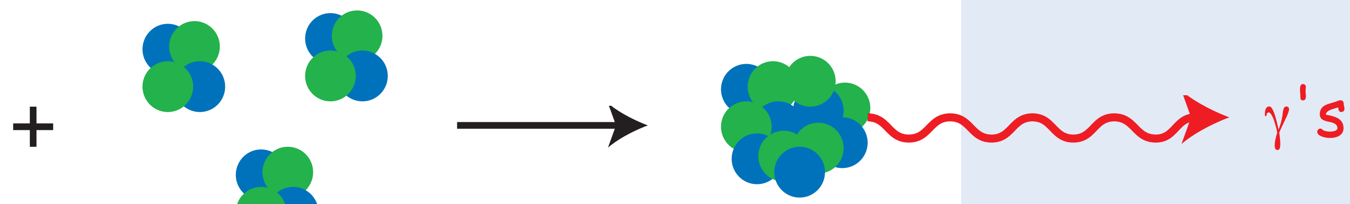
... of nuclei

strong-
& electro-
weak
interaction



3 m(He) > m(C)

Energies: keV-MeV

Mass defects...

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strong-
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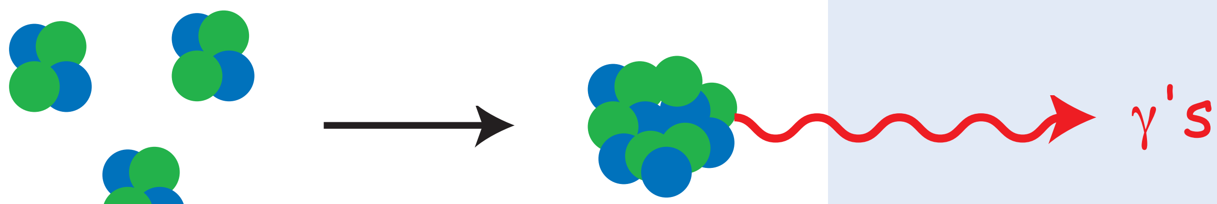
+



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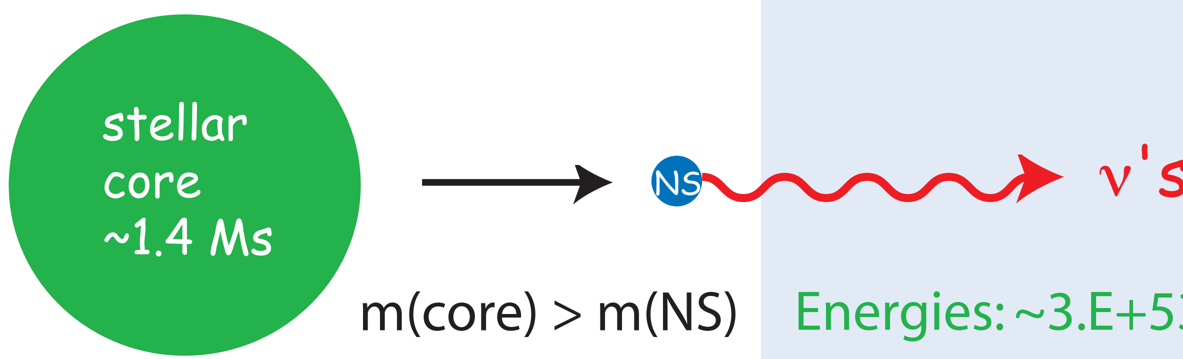
Energies: keV-MeV

... of neutron stars

Gravitation
&
Pauli principle

+



m(core) > m(NS)
Δm ~ 0.1 Ms

Energies: ~3.E+53 erg

Mass defects...

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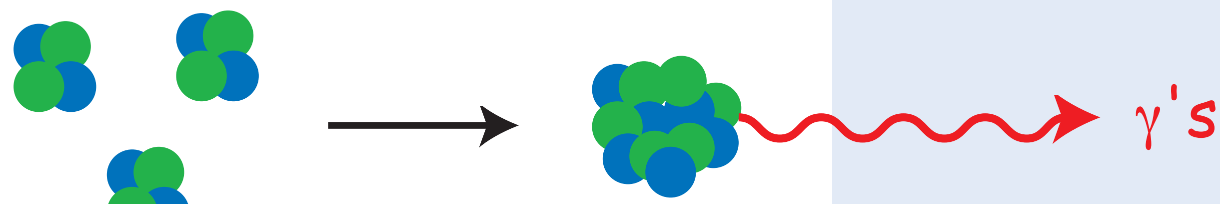

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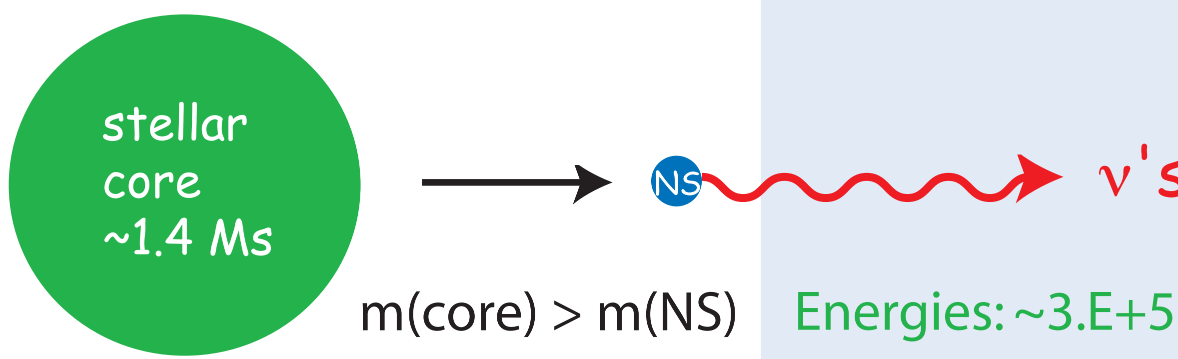

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Energies: ~3.E+53 erg

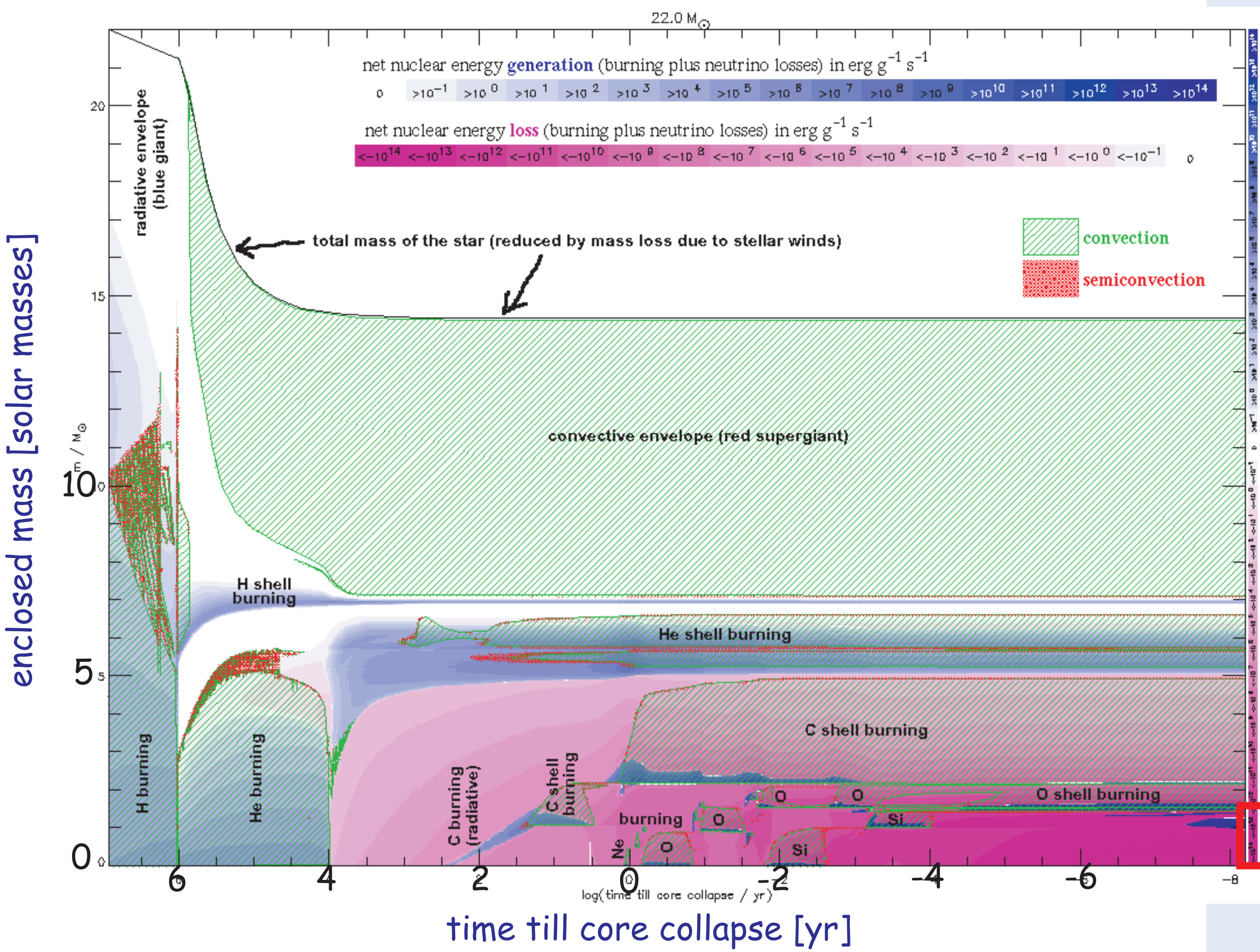
...but

1) This binding energy is achieved at nuclear matter density
2) Energy of neutrinos >~10MeV

Nuclear physics
involved?

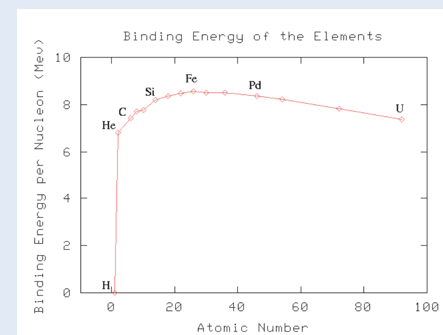
Stellar Evolution

Overview of burning phases in stellar evolution



stellar core collapse
<-- happens here!

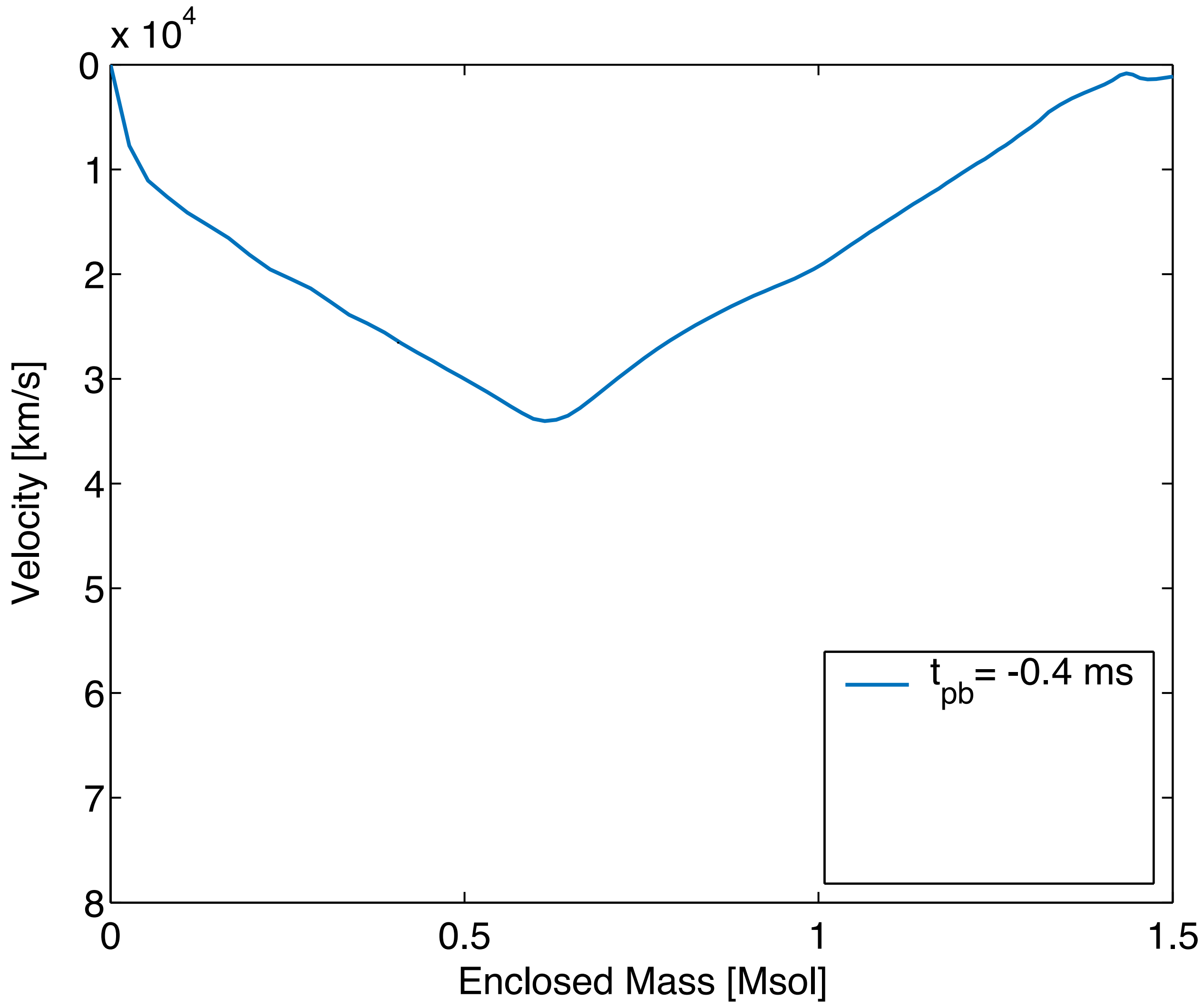
- Fusion in core reaches maximum binding energy per baryon

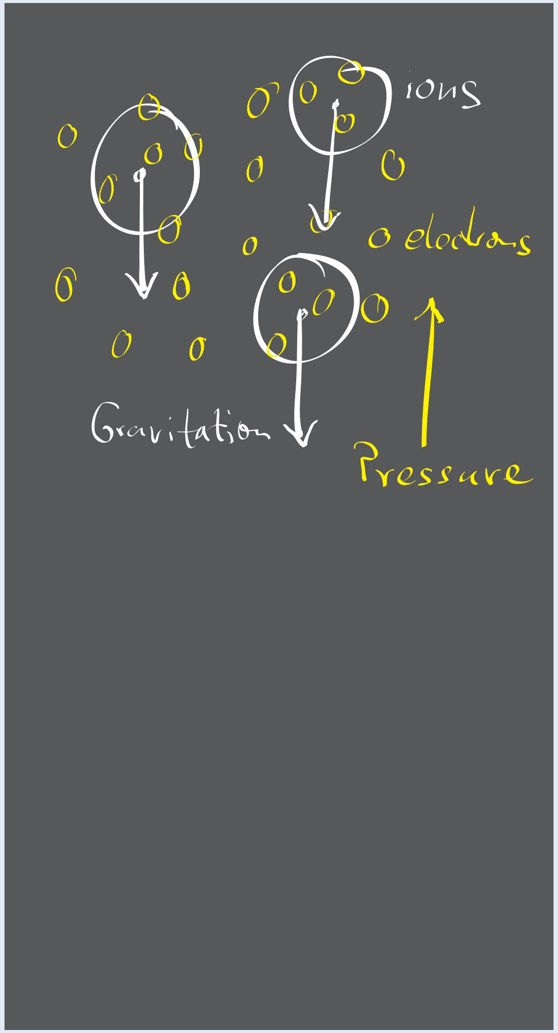


- There is a maximum stable mass: Chandrasekhar mass

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

The collapse phase





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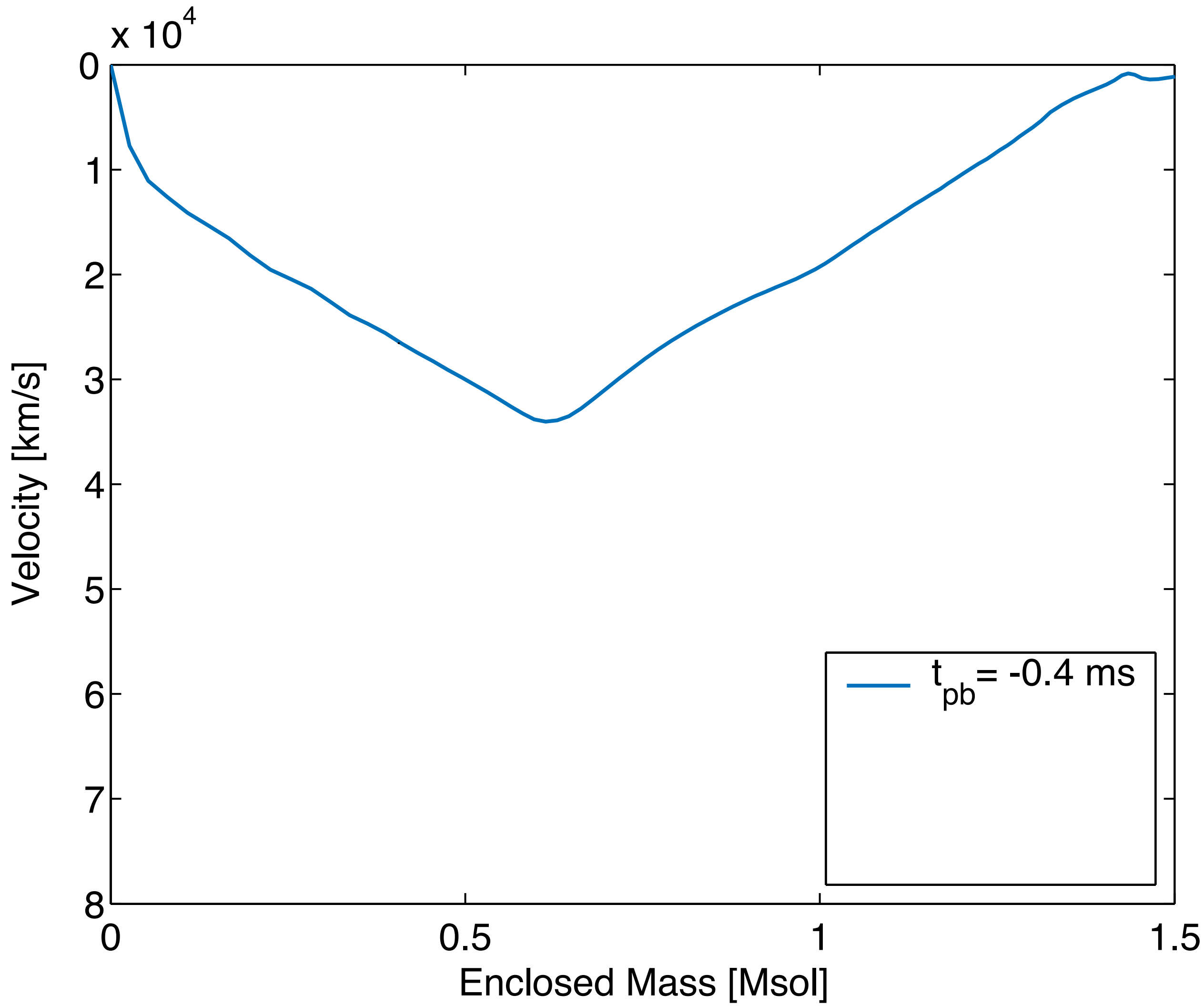
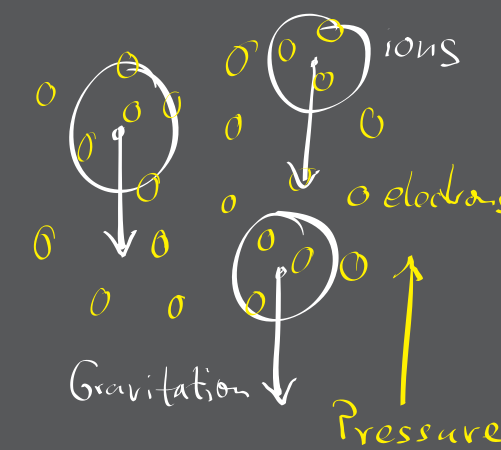
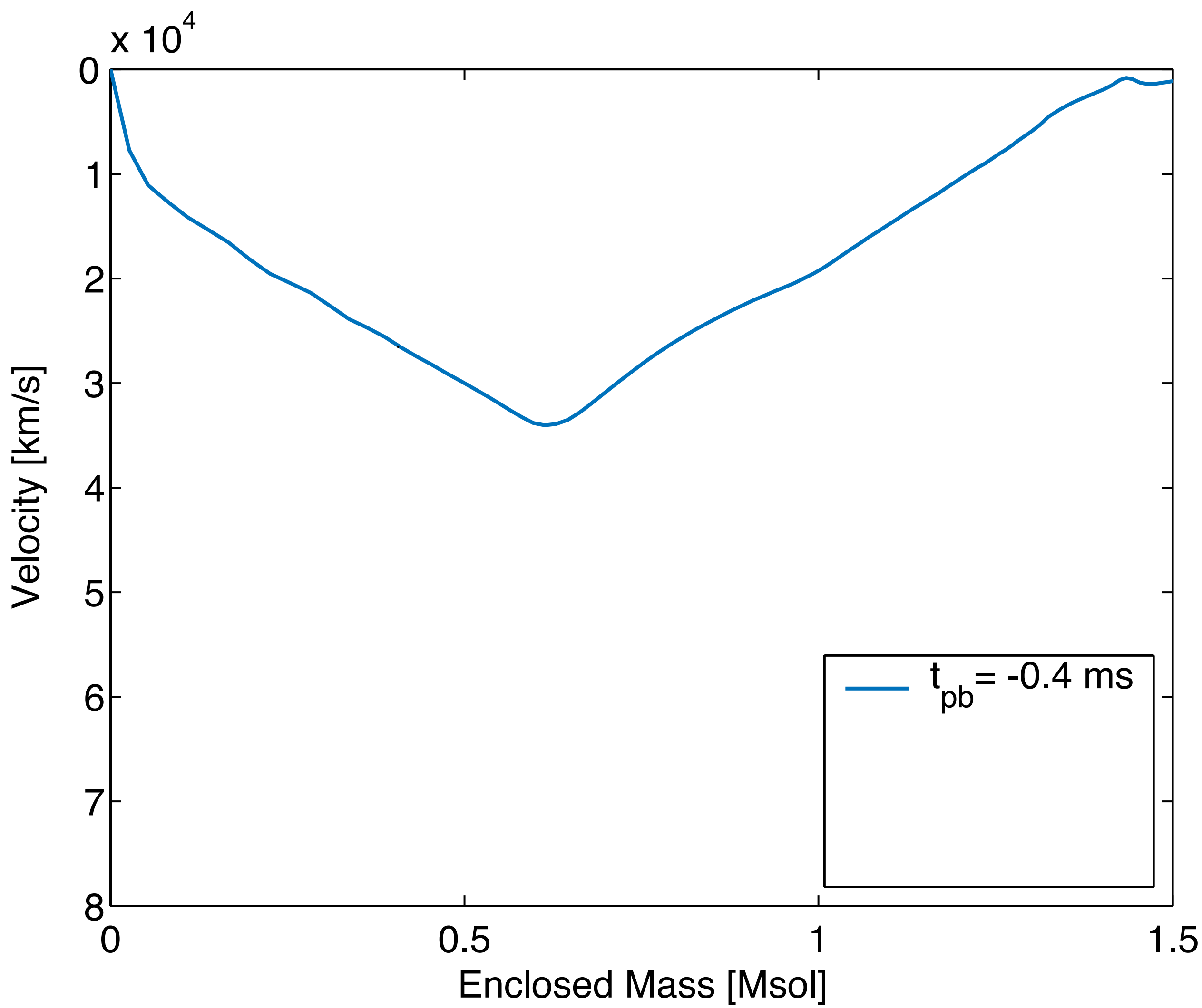


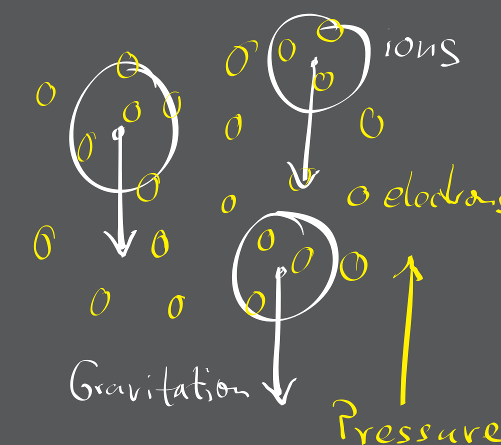


electron fraction

$Y_e = n_e / n_{baryon}$

The collapse phase





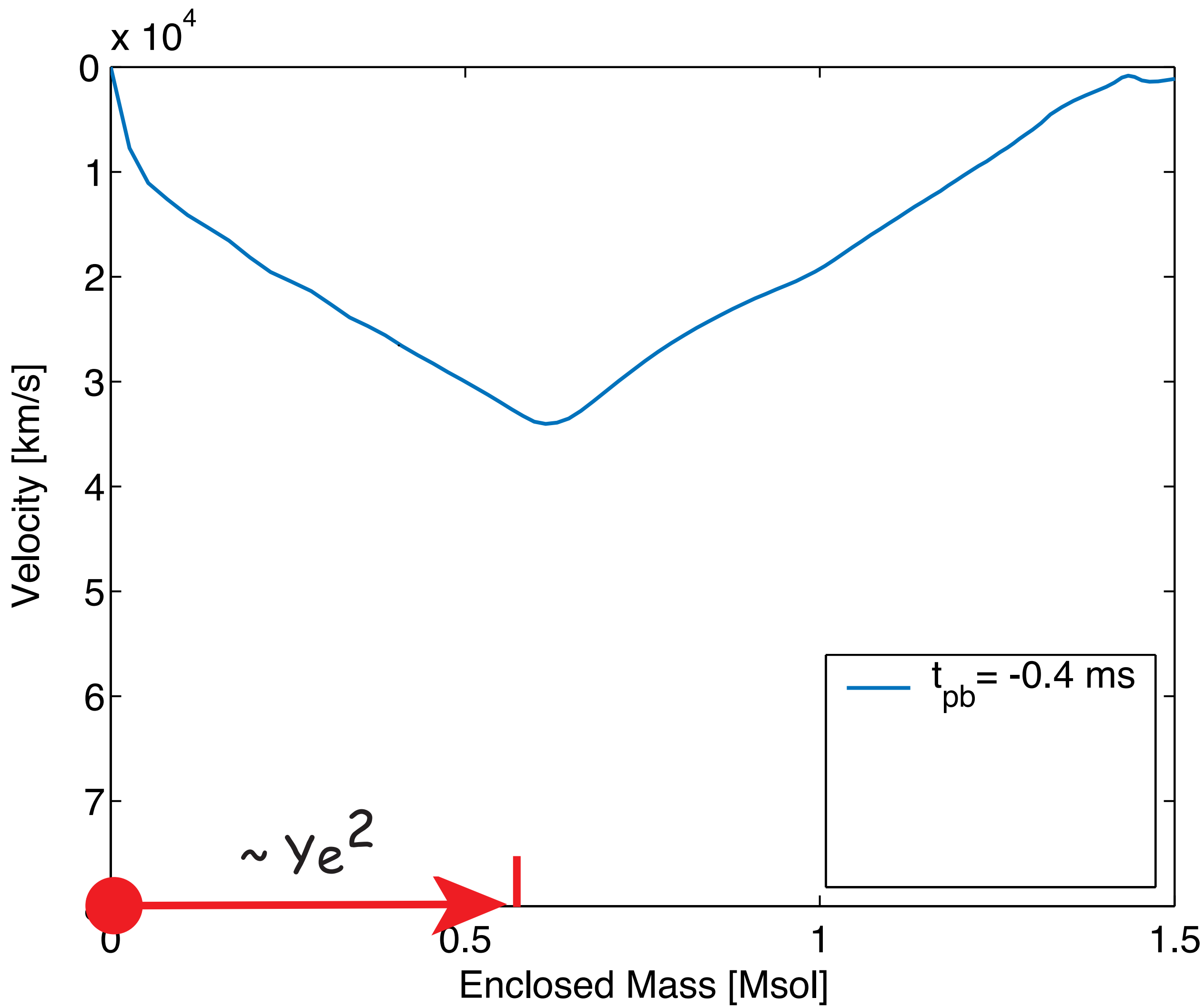
electron fraction

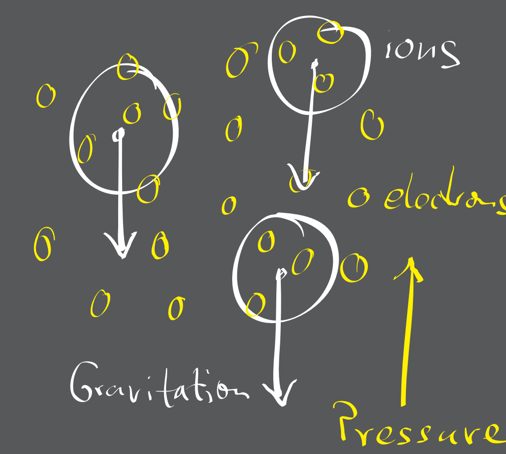
Ye = ne/nbaryon

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

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

The collapse phase





electron fraction
Ye = ne/nbaryon

Fermi gas $P = \kappa \rho^\gamma$

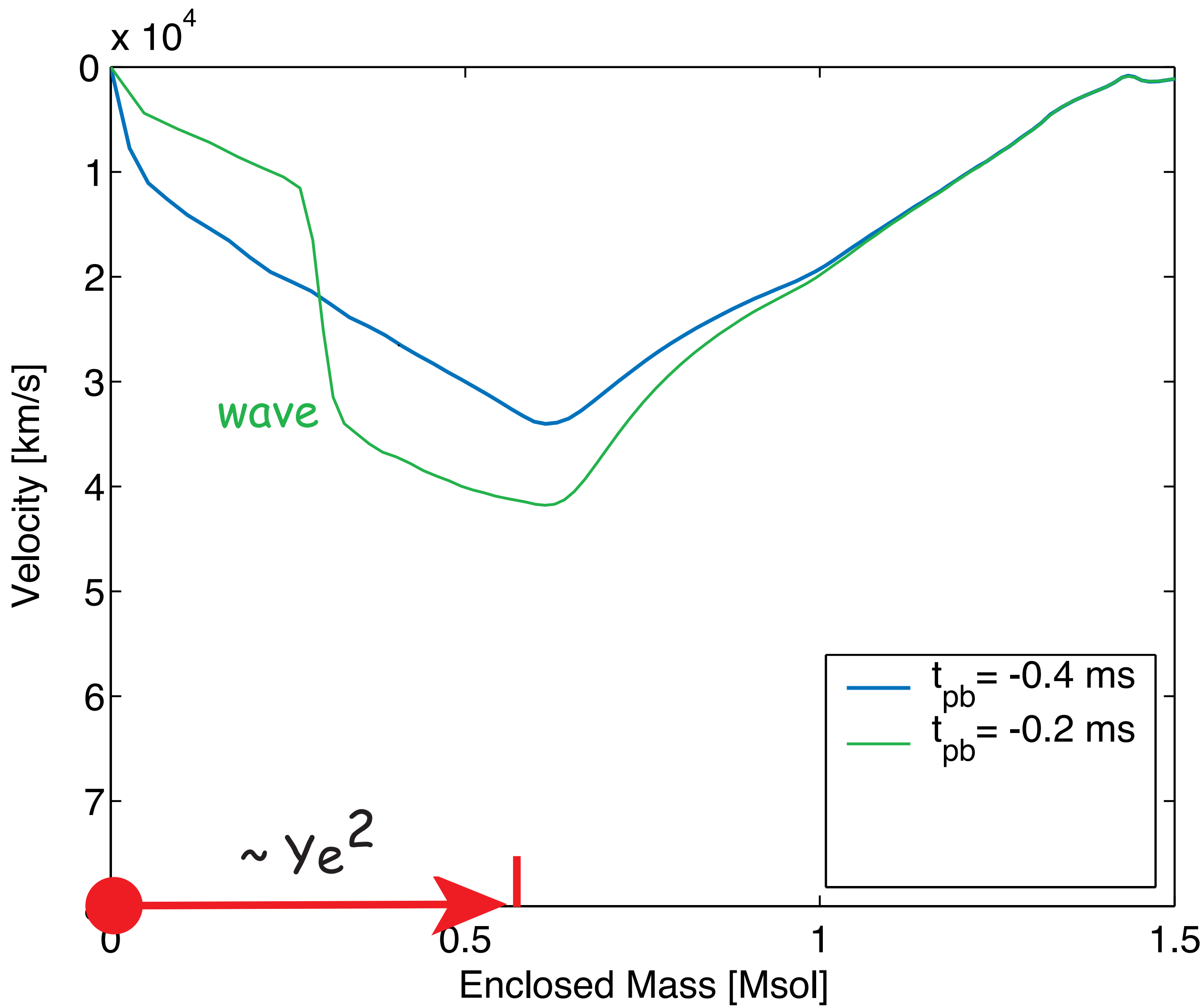
$$\kappa \approx \frac{\hbar c}{4} \left(3\pi^2\right)^{\frac{1}{3}} \left(\frac{Y_e}{m_B}\right)^{\frac{4}{3}}$$

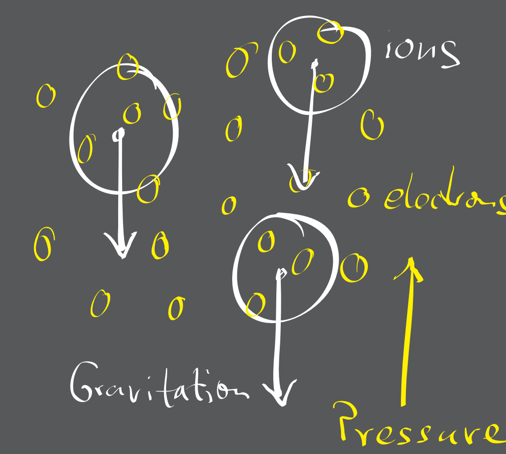
homologous collapse:

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

(Goldreich & Weber 1980)

The collapse phase





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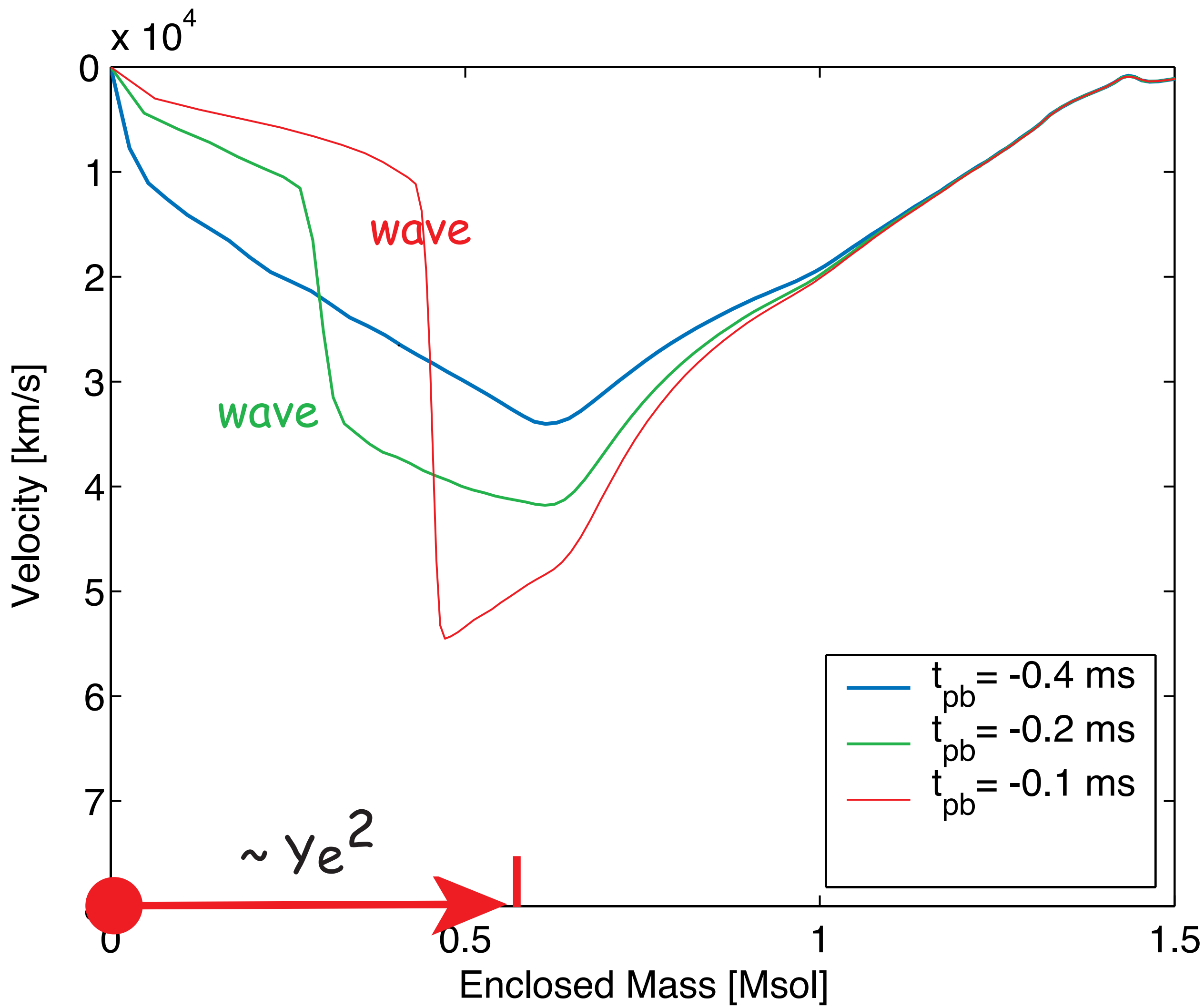

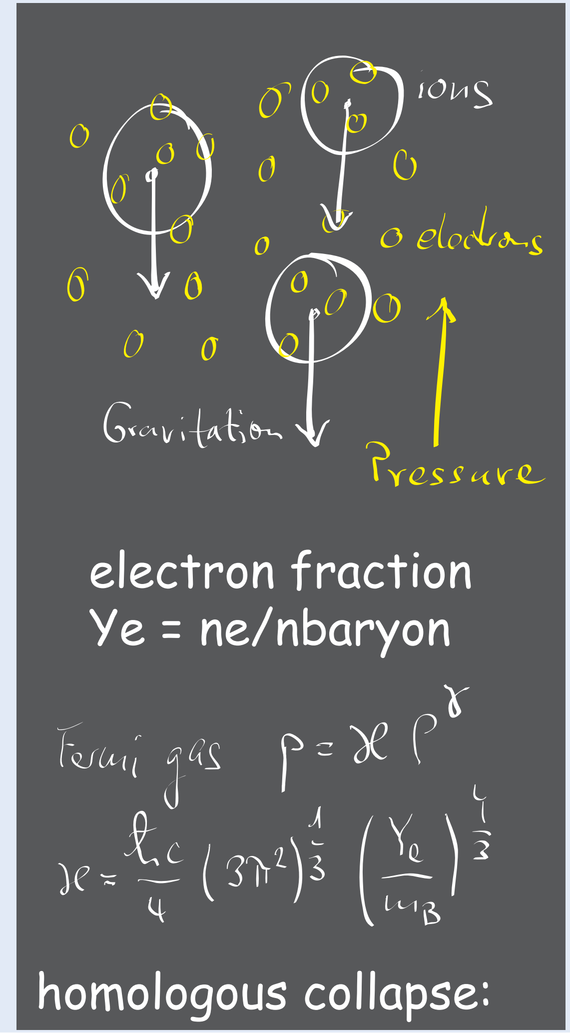

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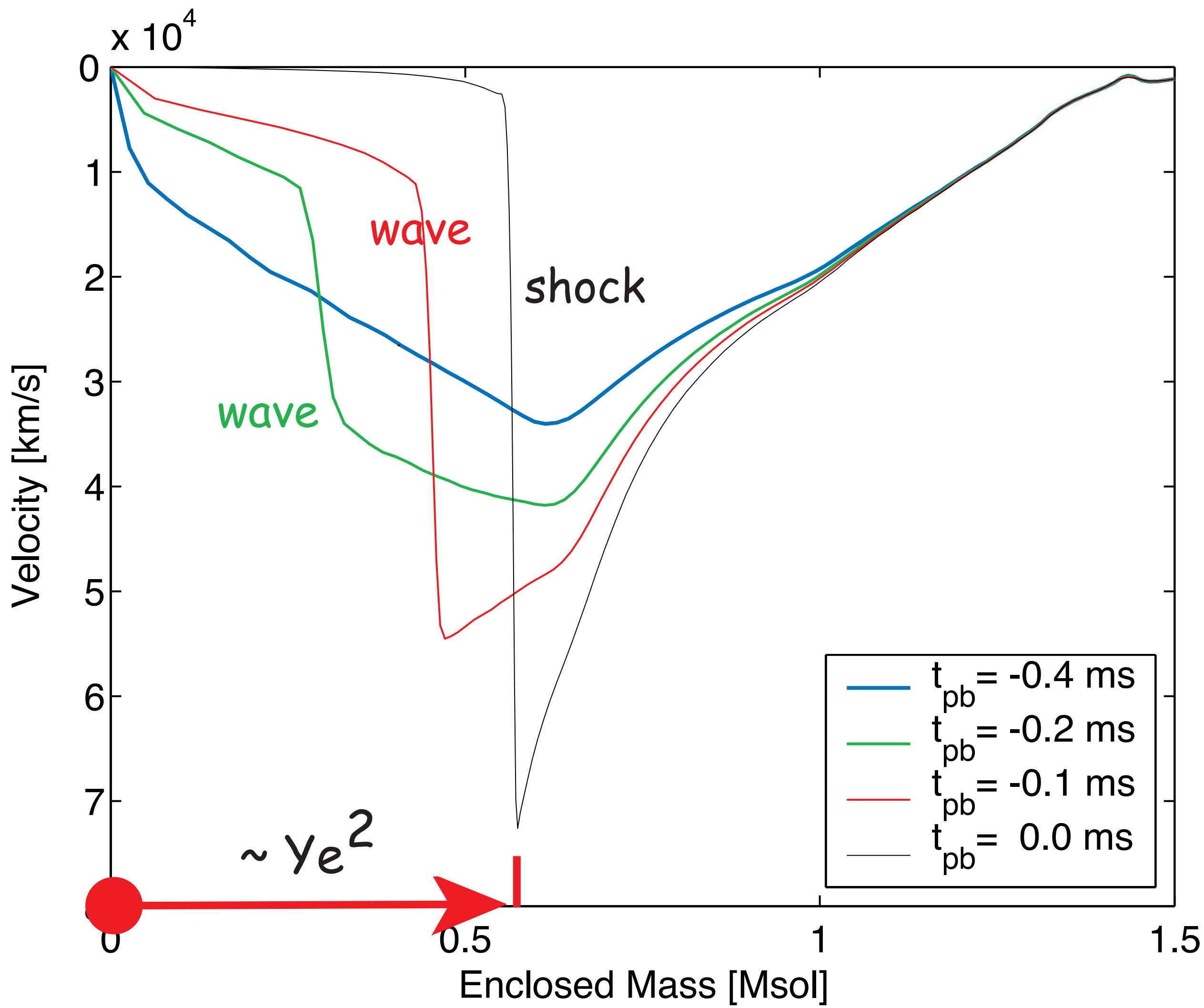

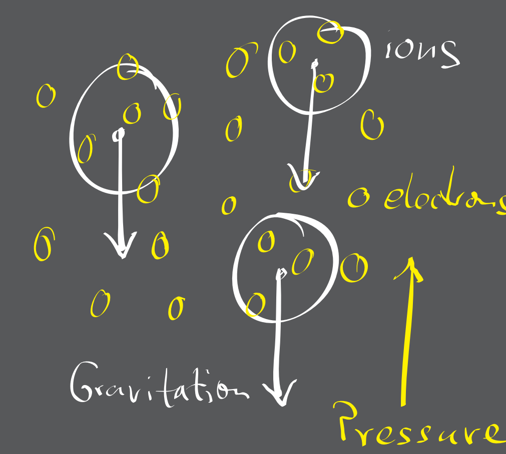

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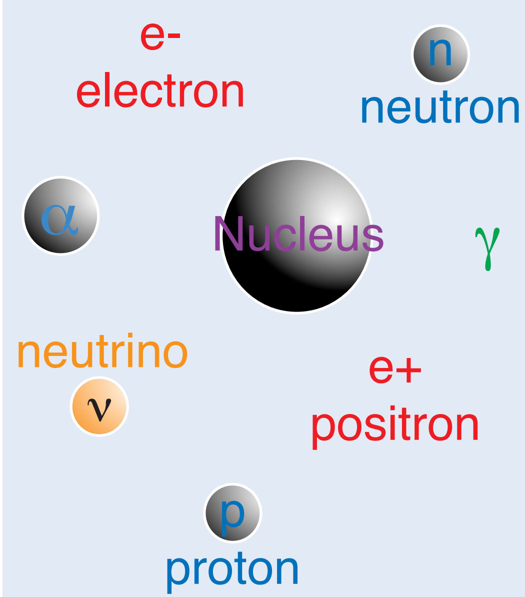
Description of supernova matter...

- Main composition:



- Weak interactions:

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

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

Description of supernova matter...

Conservation laws:

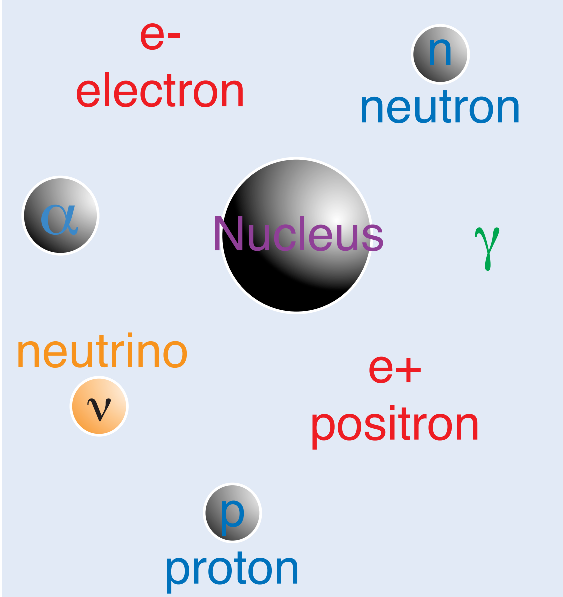
- Baryon number
- Lepton number
- Energy
- Momentum
- Magnetic flux

Conditions:

- Nuclear statistical equilibrium (NSE)
- Charge neutrality
- Detailed balance
- div(B) = 0

Conservation laws are for computational physicists what ropes are for the rock climber: First you think you can survive by just being careful,...

- Main composition:



- Weak interactions:

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

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

Description of supernova matter...

... but in astrophysics you always meet the situation where they are indispensable!

- Main composition:

e- electron

n neutron

α

Nucleus

γ

neutrino ν

e+ positron

p proton

- Weak interactions:

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

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

Microscopic input physics

Weak interactions between neutrinos and matter
(Bruenn, ApJS 58, 1985 and Refs. therein)

Coherent scattering of neutrinos on nuclei

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

Ion-ion correlations (Itoh 1975)

Neutrino-electron scattering

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

Electron/neutrino capture on nuclei

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

Electron/neutrino capture on nucleons

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

Neutrino-nucleon scattering

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

Pair creation/annihilation

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

Nucleon-Nucleon bremsstrahlung (Thompson et al. 2002)

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

Cool collapse

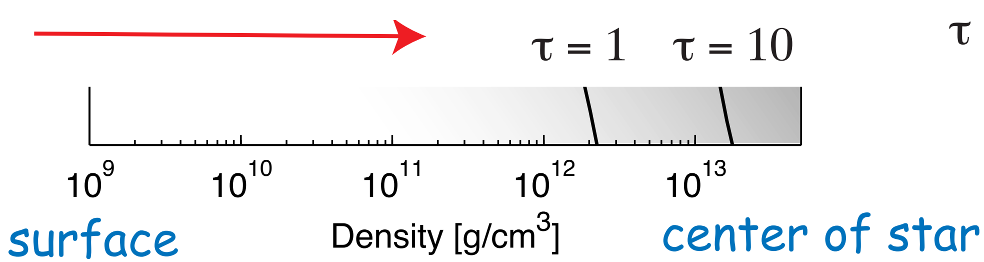
Equation of state:

- charge neutrality
- nuclear statistical equilibrium (NSE)
- finite temperature

- Liquid drop (Lattimer-Swesty 1991)
- Rel. Mean Field (Shen et al. 1998)

Hot postbounce

Deleptonization



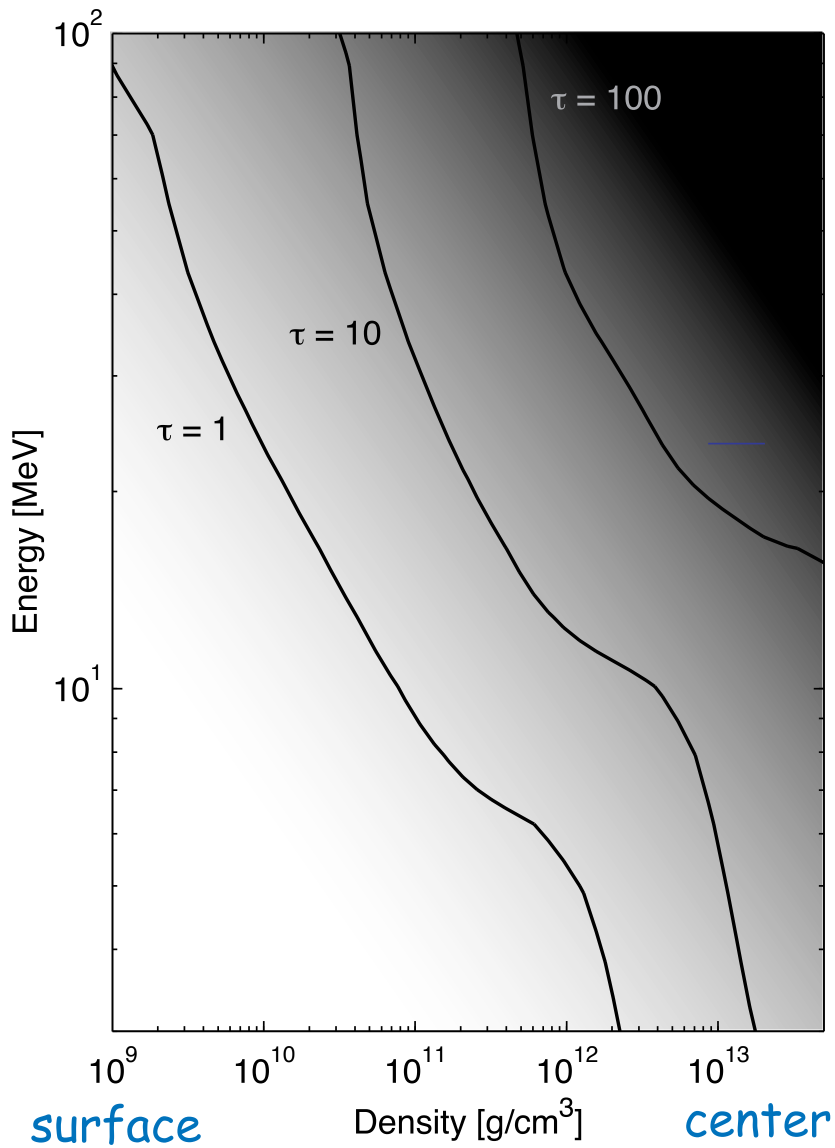
Bethe (1990)
mean free path:

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

Optical depth:

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

Deleptonization



surface

center of star

Bethe (1990)
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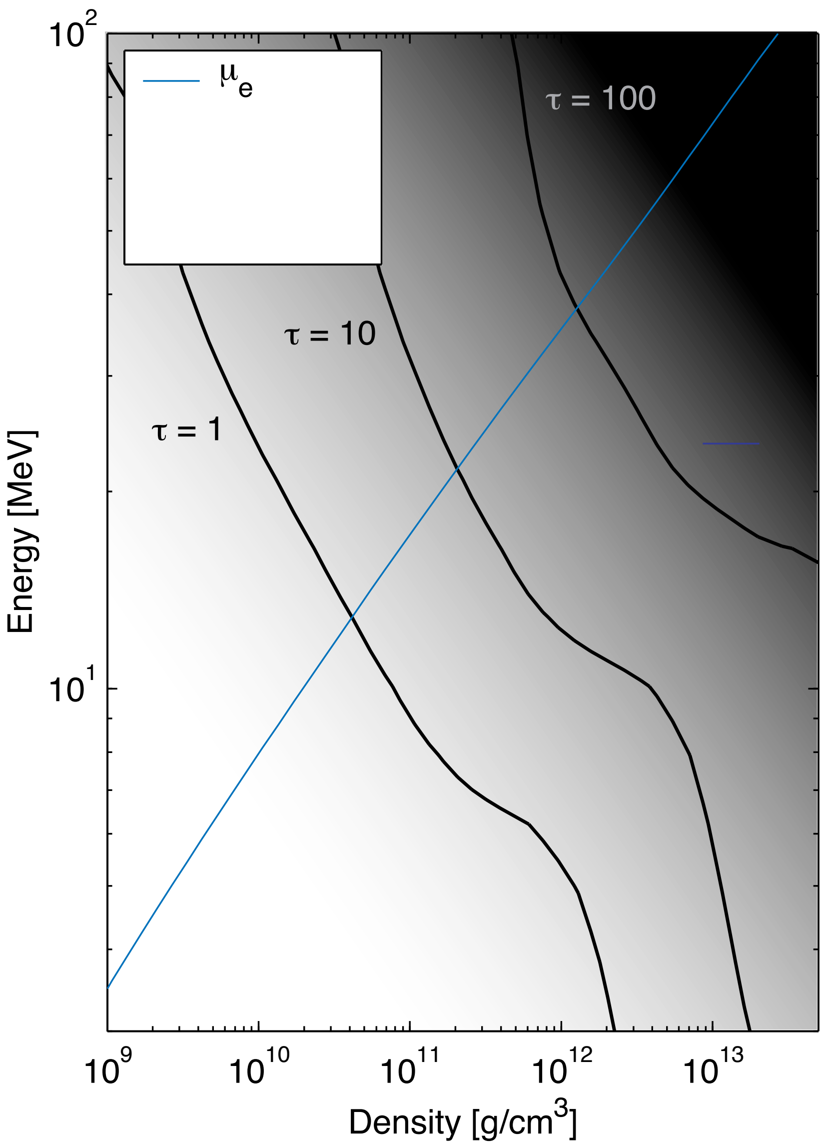
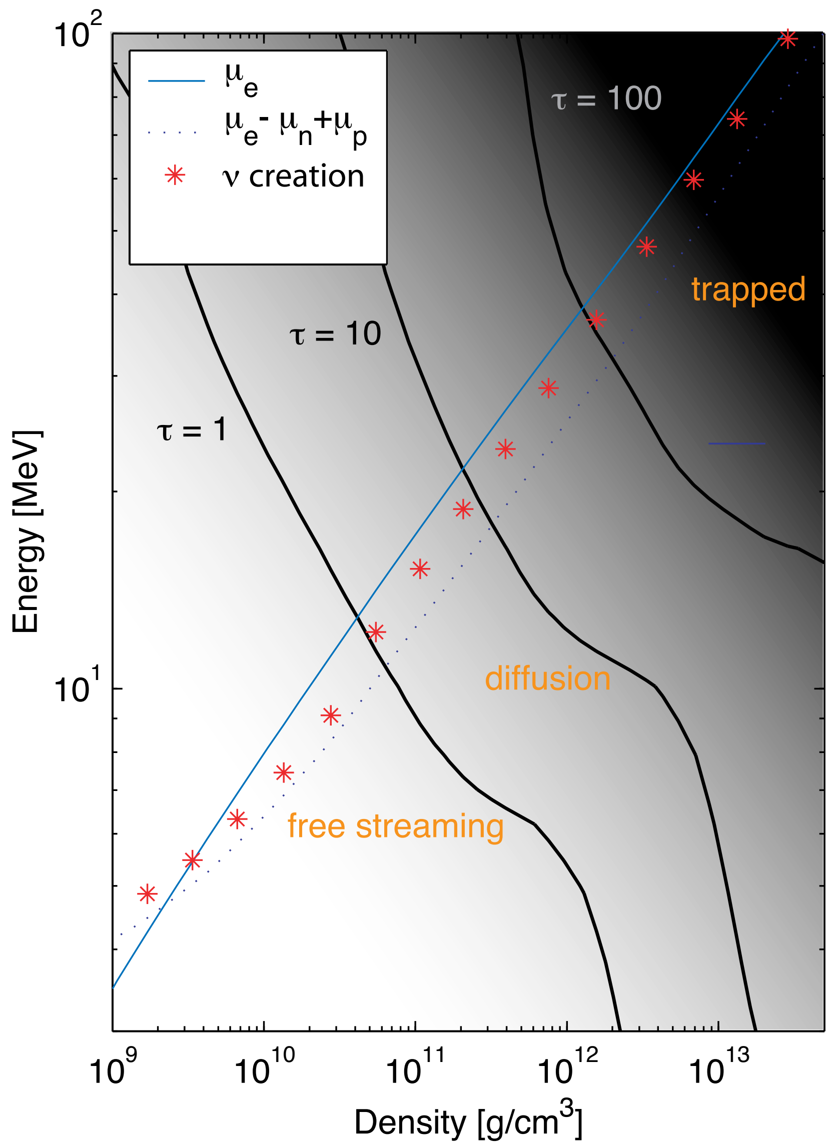


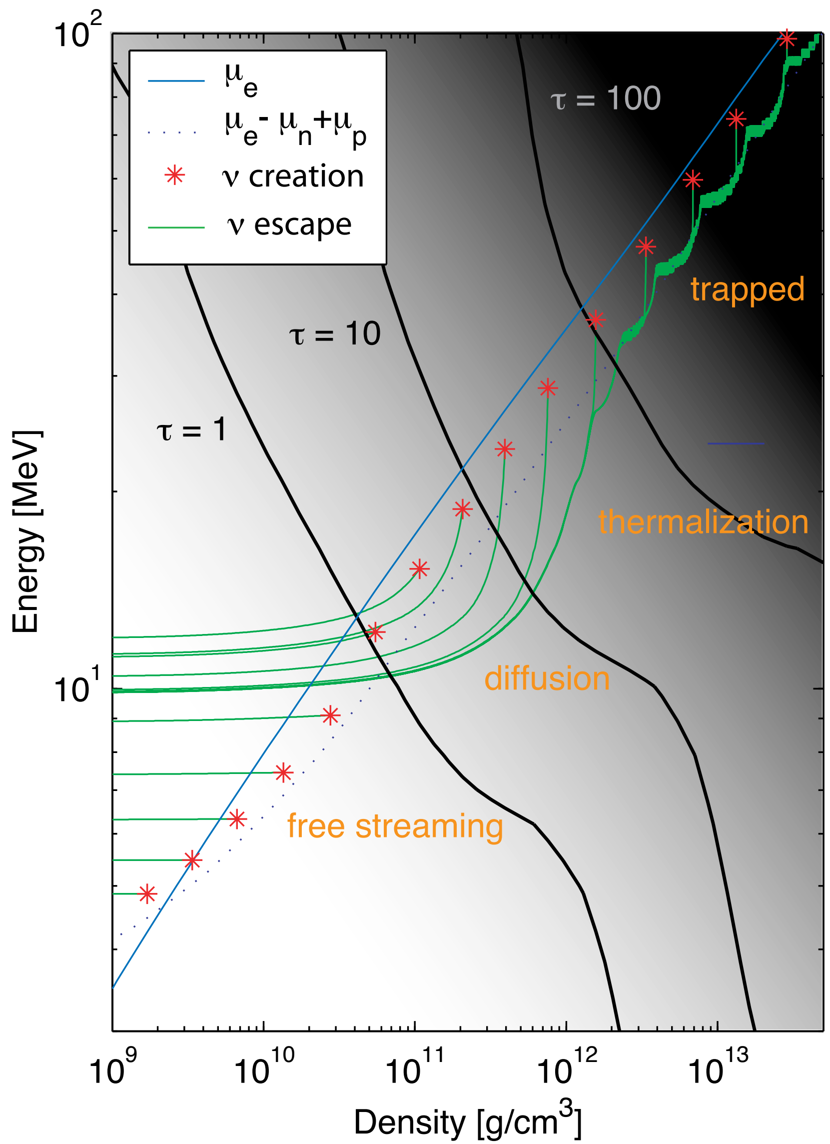
(Martinez-Pinedo, Liebendoerfer, Frekers, 2006)

Deleptonization



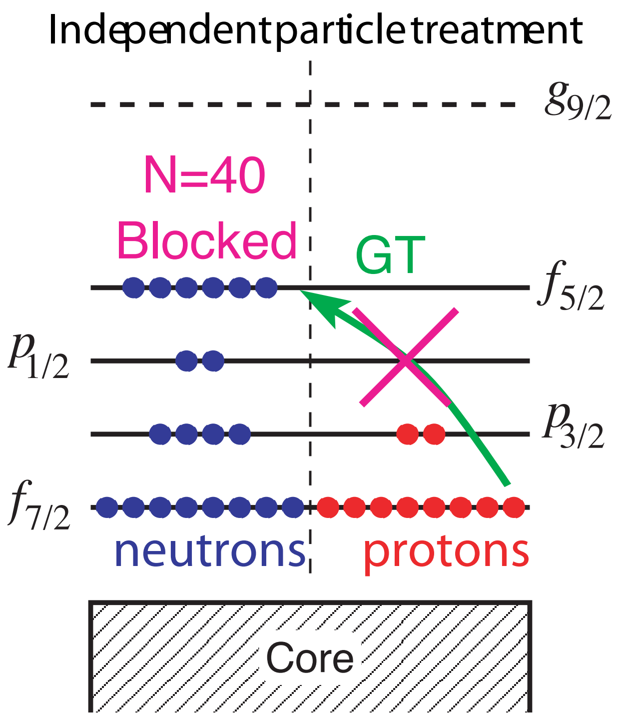
(Martinez-Pinedo, Liebendoerfer, Frekers, 2006)

Deleptonization



(Martinez-Pinedo, Liebendoerfer, Frekers, 2006)

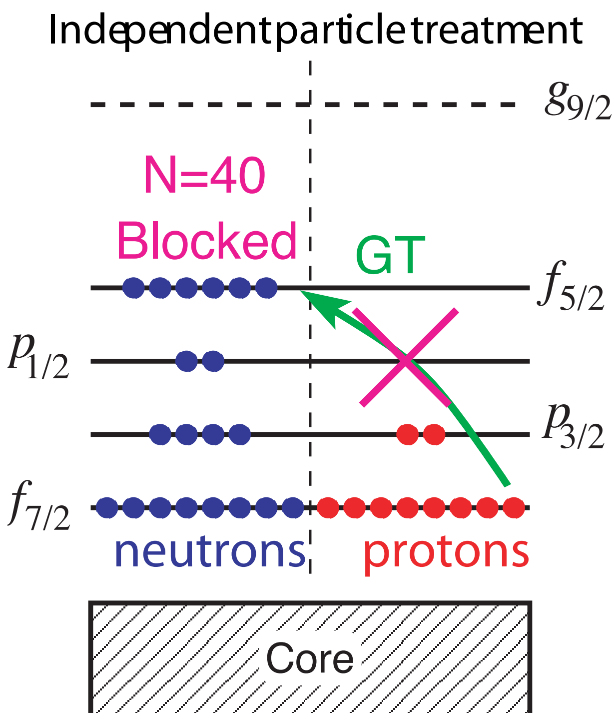
More neutrinos from electron capture

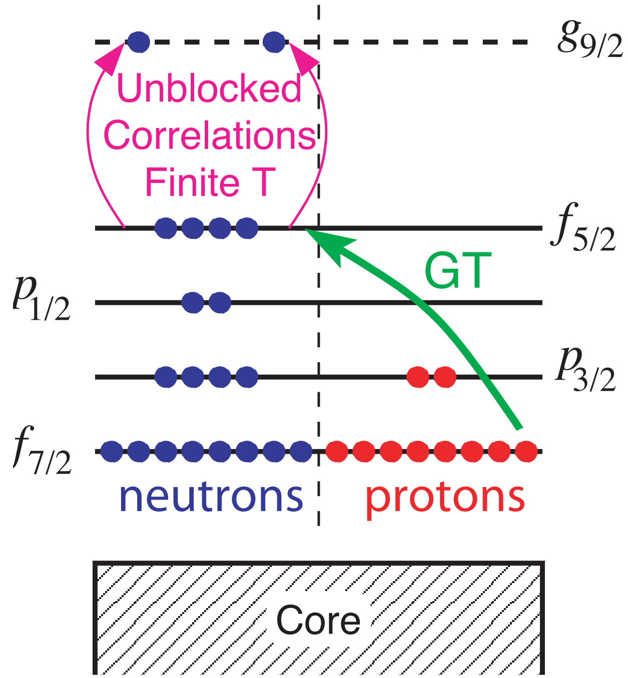


- Traditional input physics:

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

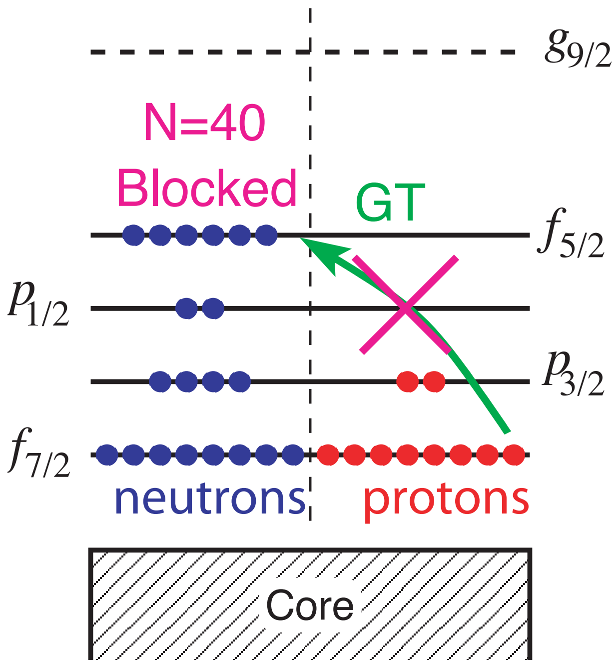
- Most recent input physics:

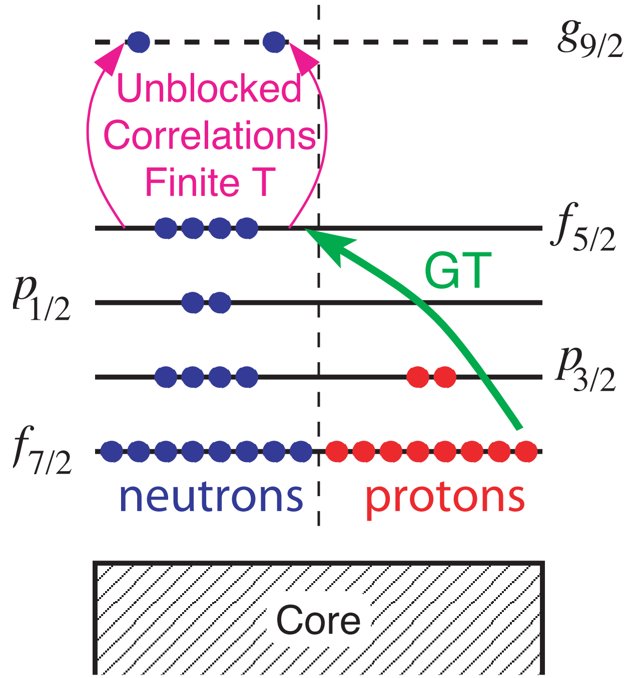
Electron captures on heavy nuclei proceed and dominate!

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

More neutrinos from electron capture

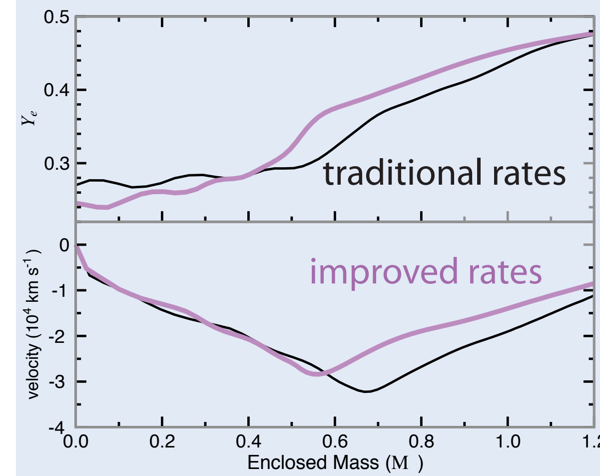
Independent particle treatment





(Martinez-Pinedo & Langanke 2002)

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



(Langanke et al. 2003)

- Traditional input physics:

Electron capture reactions blocked for neutrino-rich heavy nuclei

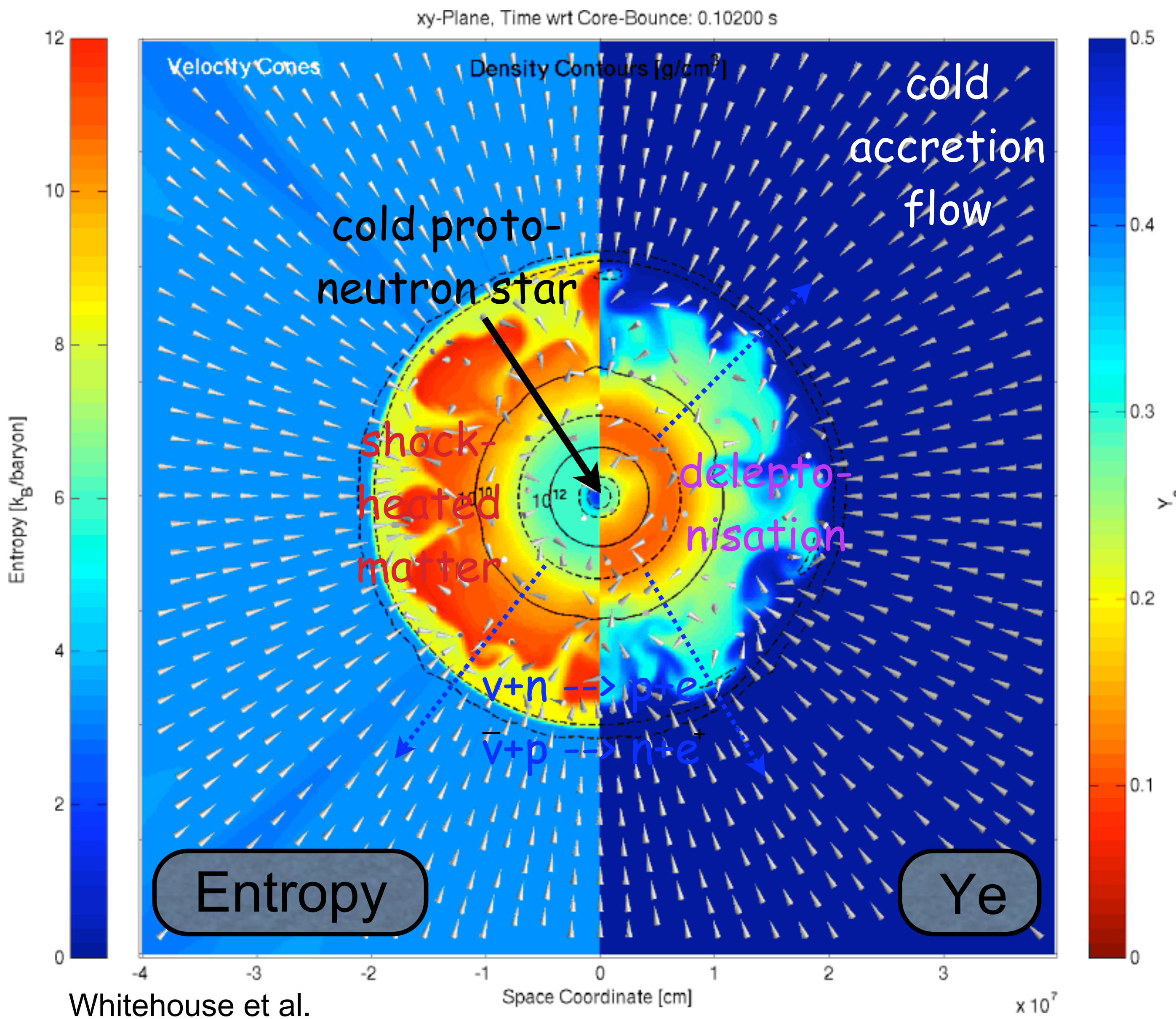
- Most recent input physics:

Electron captures on heavy nuclei proceed and dominate!

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

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

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?