
VLT (ESO)


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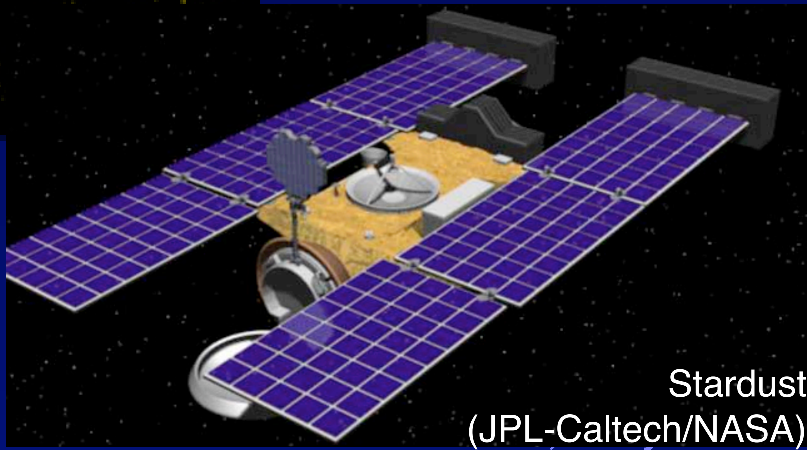
(SST/HST/CXO/NASA)

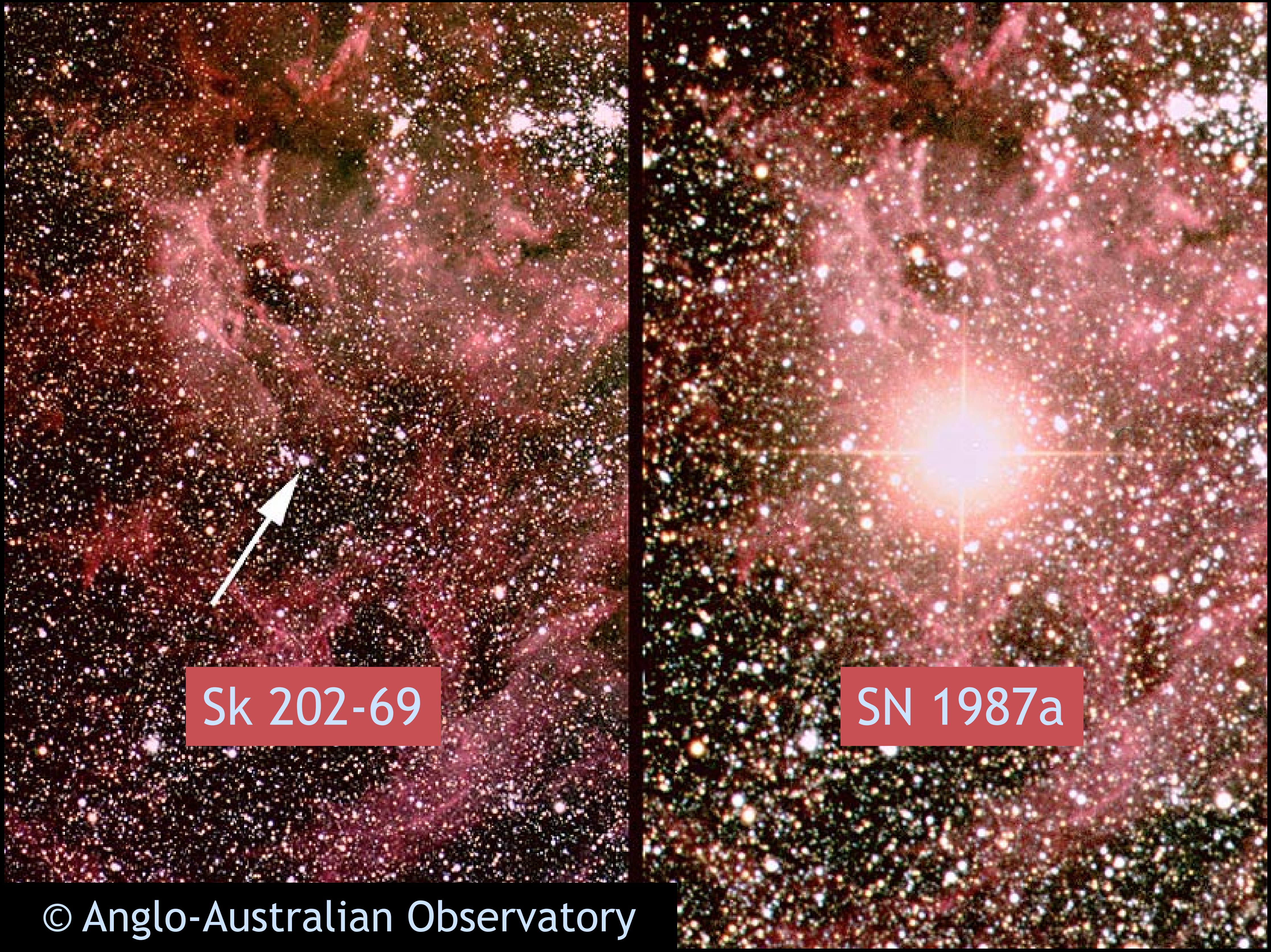
Supernova Science with Radioactive Ion Beams


SNO

W.R. Hix (ORNL/UTK)


Stardust (JPL-Caltech/NASA)

Supernova!



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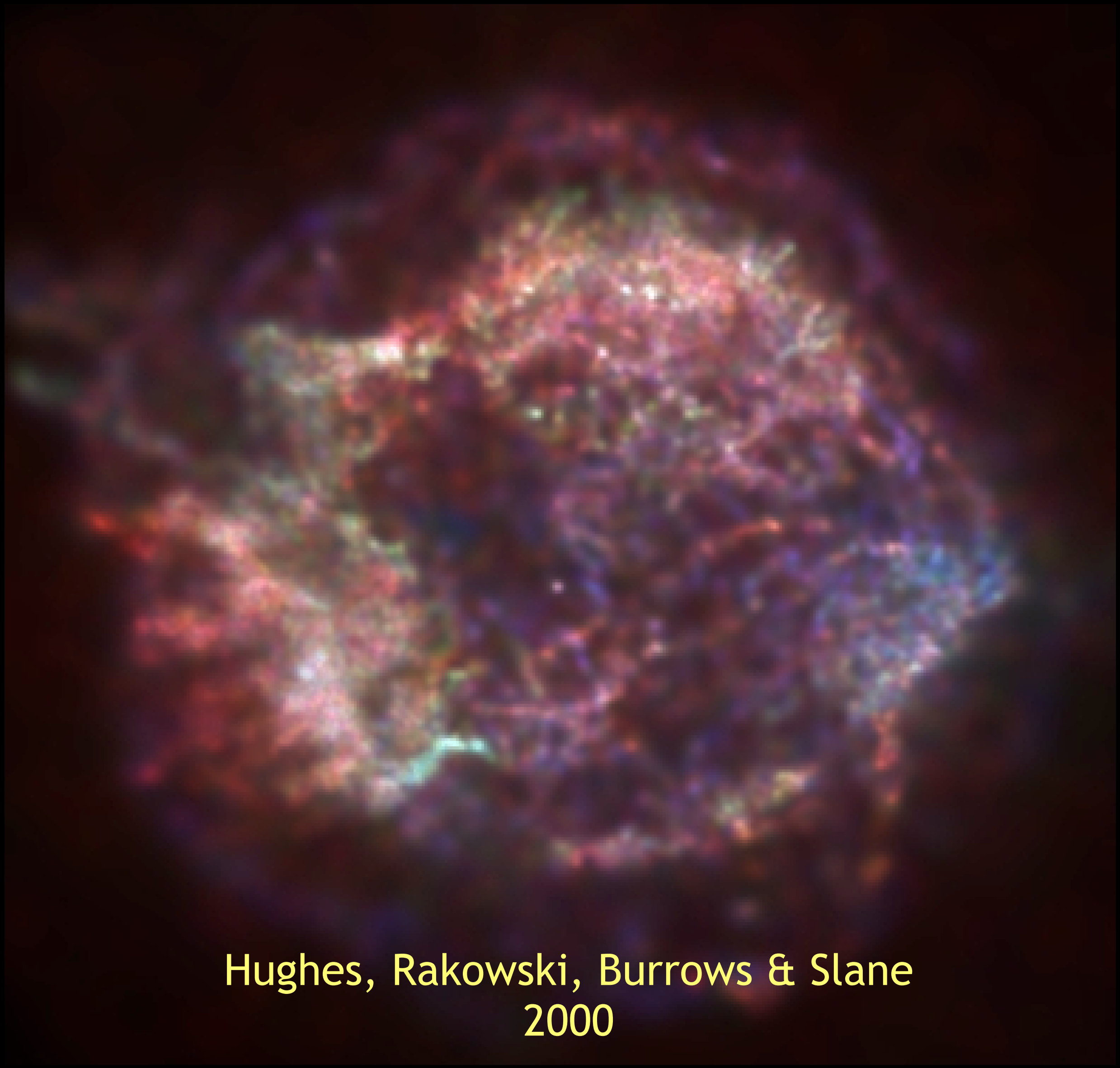
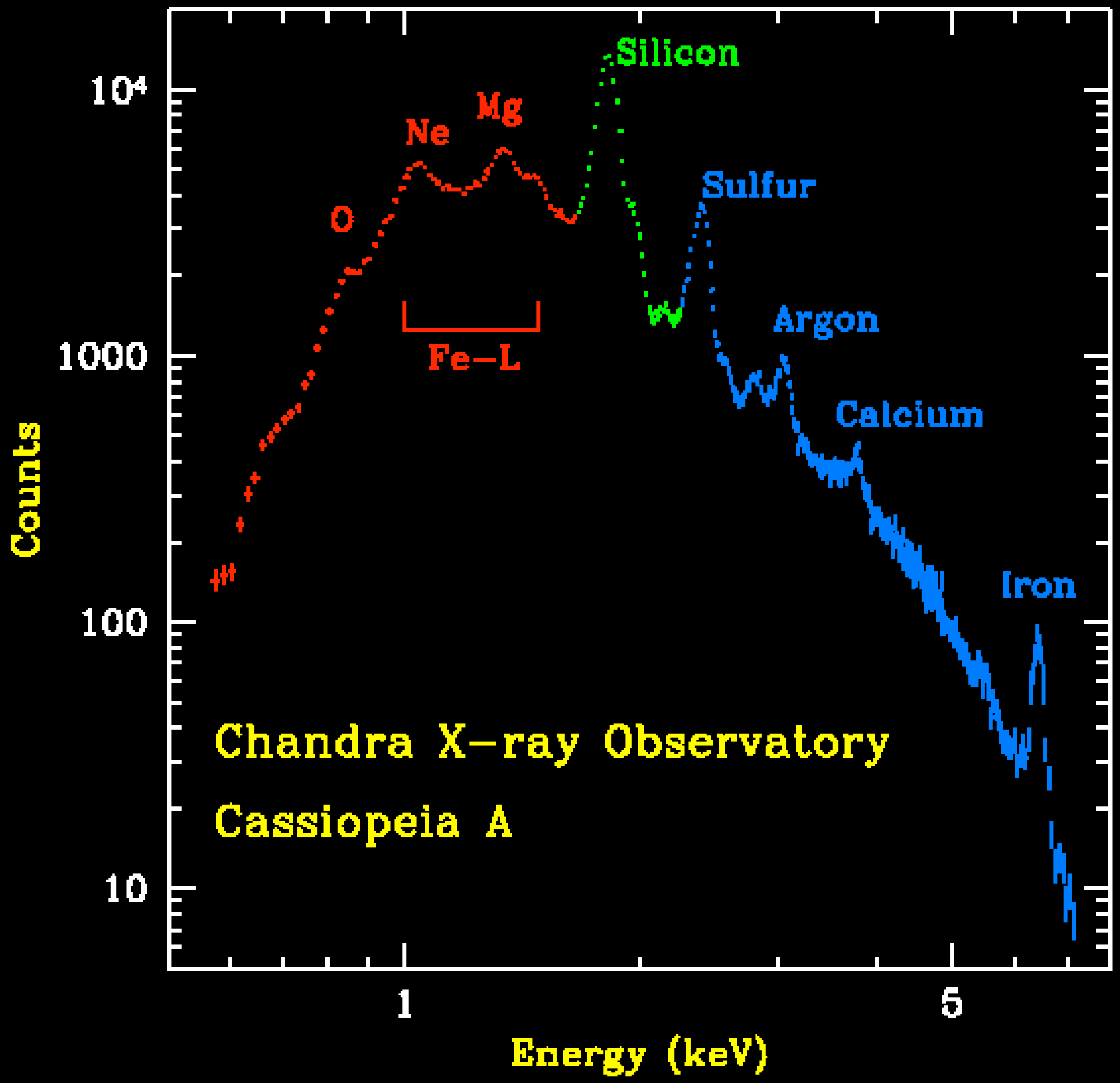
Ejecta Rich in Heavy Elements

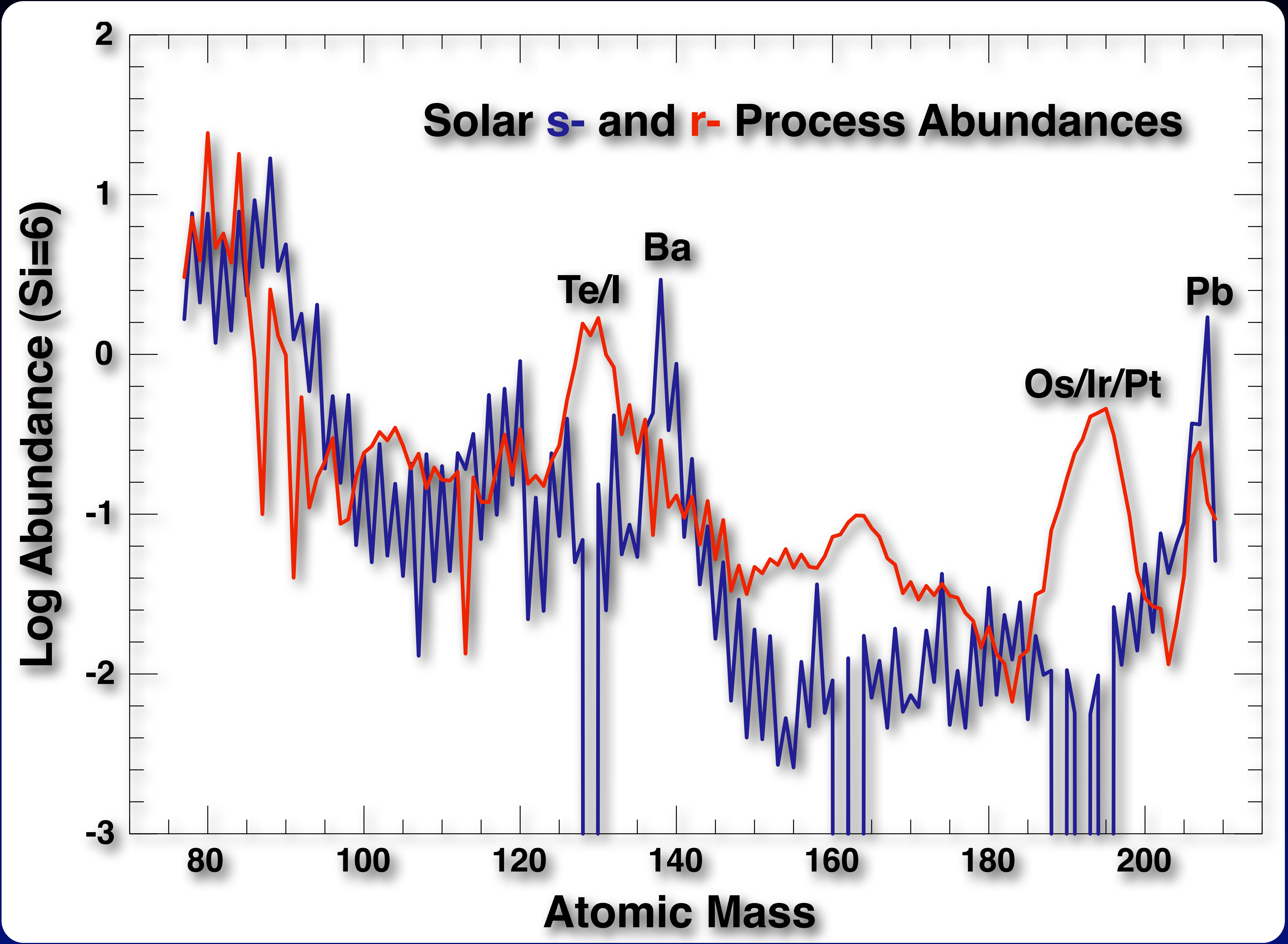


Hughes, Rakowski, Burrows & Slane
2000

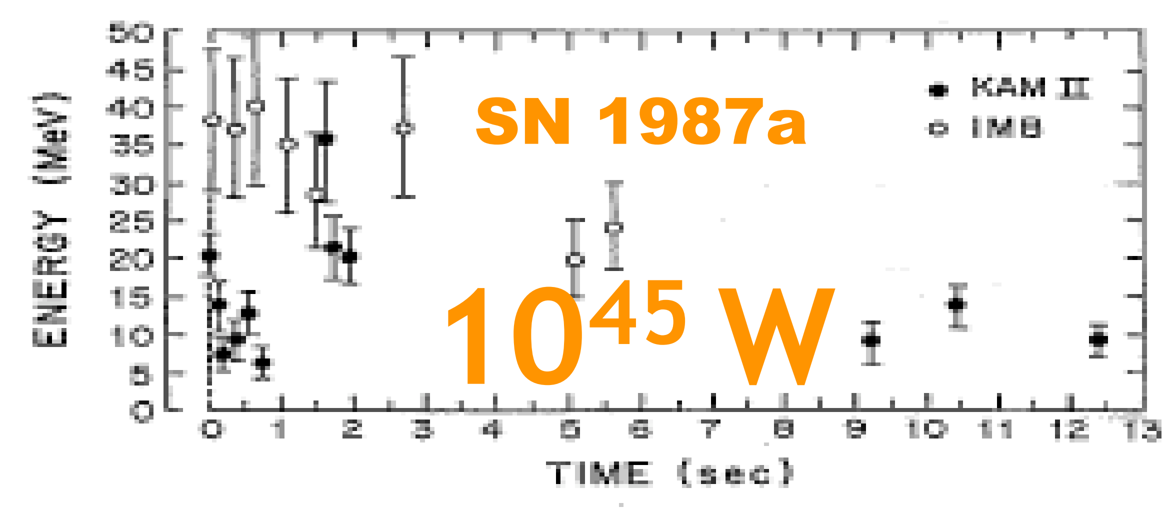


Supernovae from Massive Stars produce most of the elements from Oxygen to Calcium and half of the Iron/Cobalt/Nickel.
They may also be responsible for the r-process.

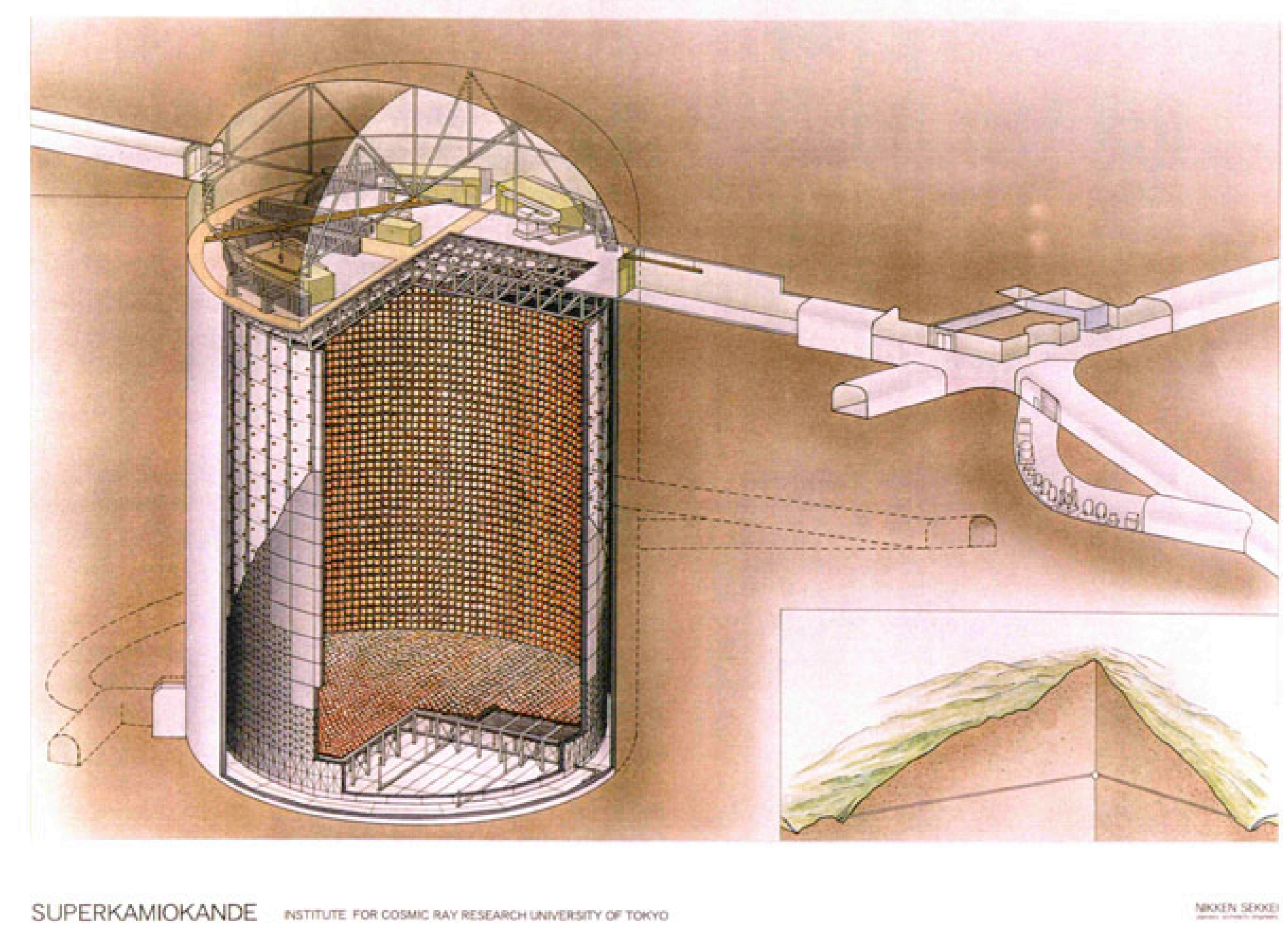
From where did our atoms come?

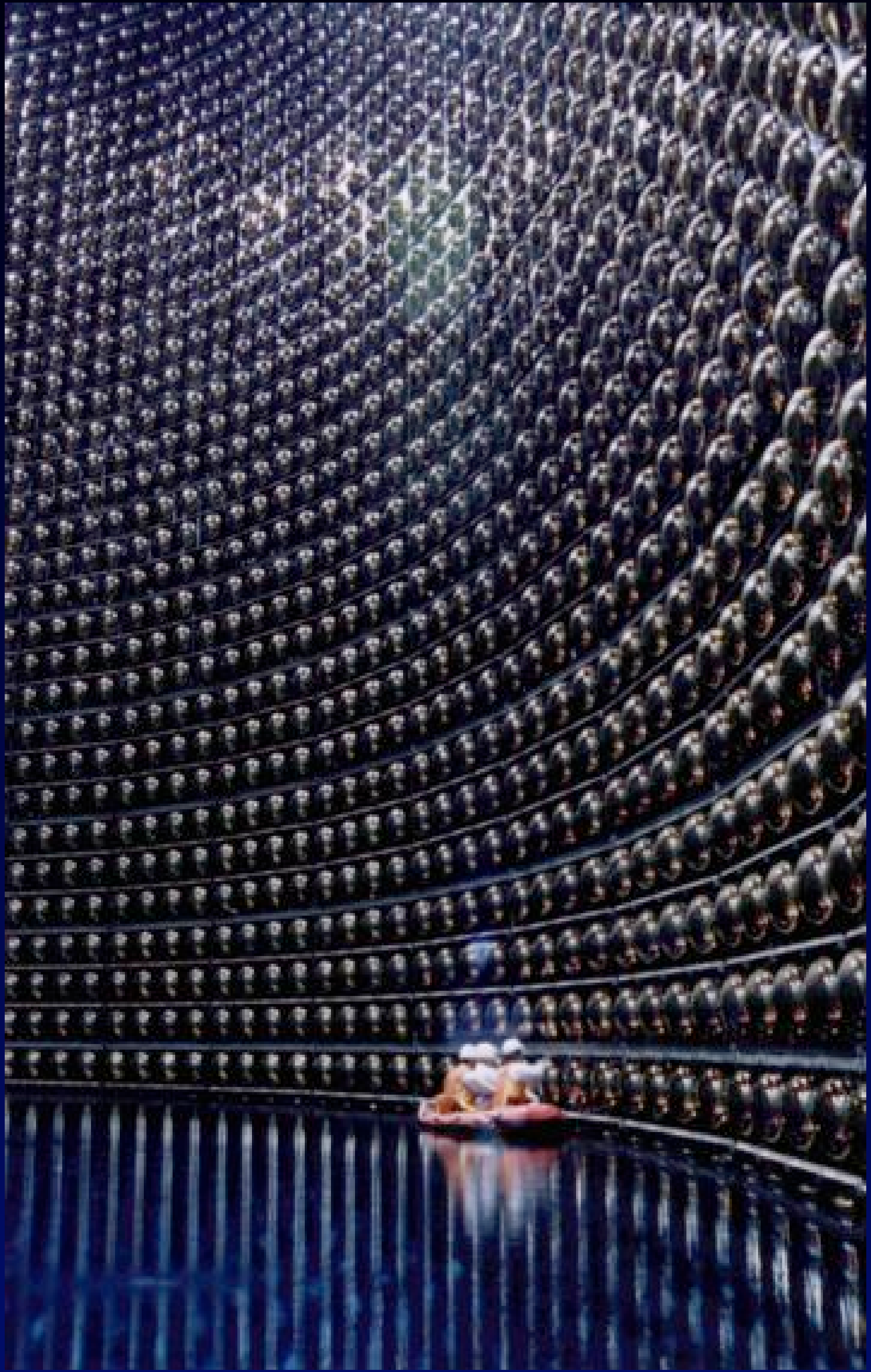


Observing Supernova Neutrinos

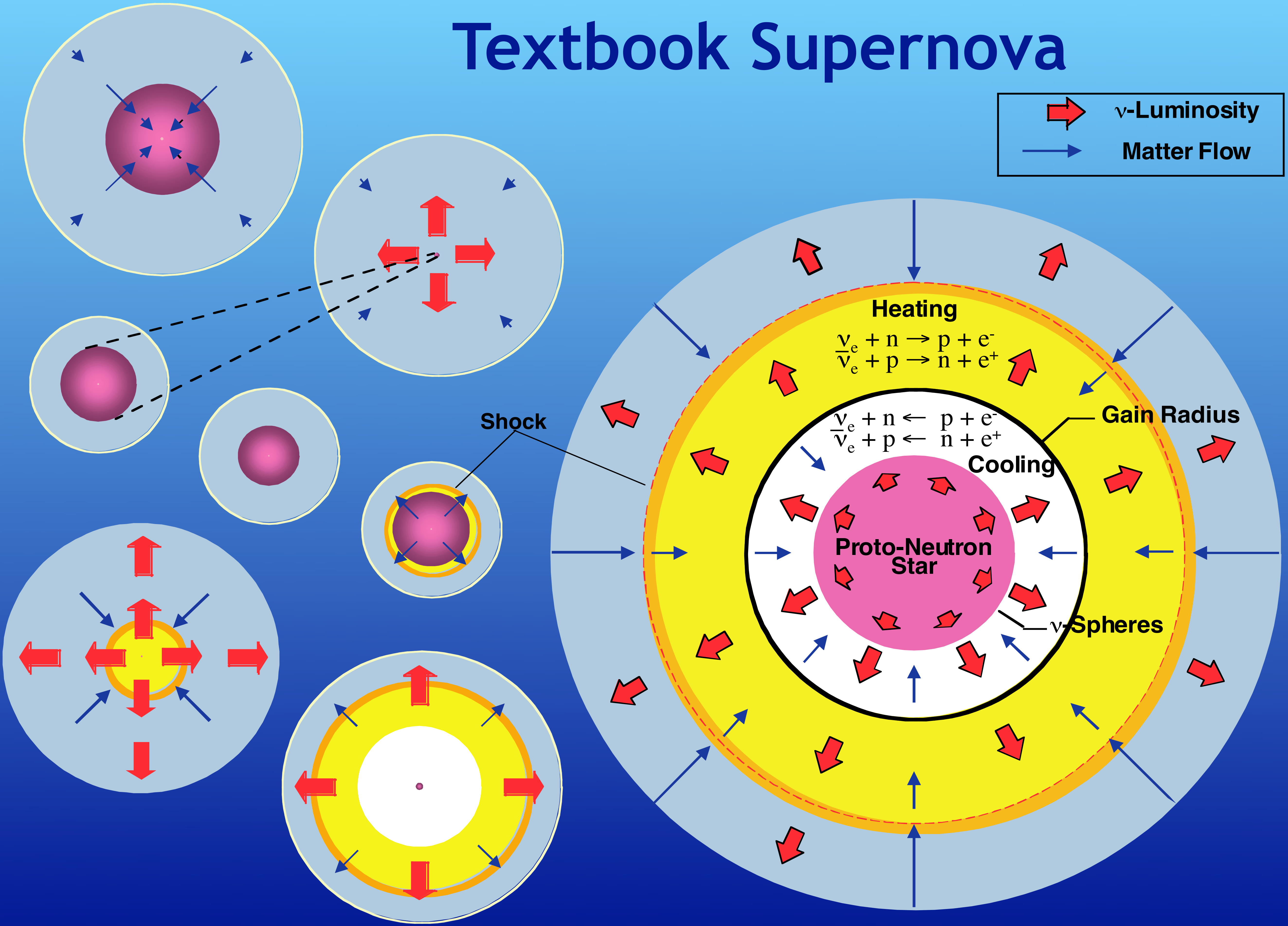

SN 1987a

10^{45} W

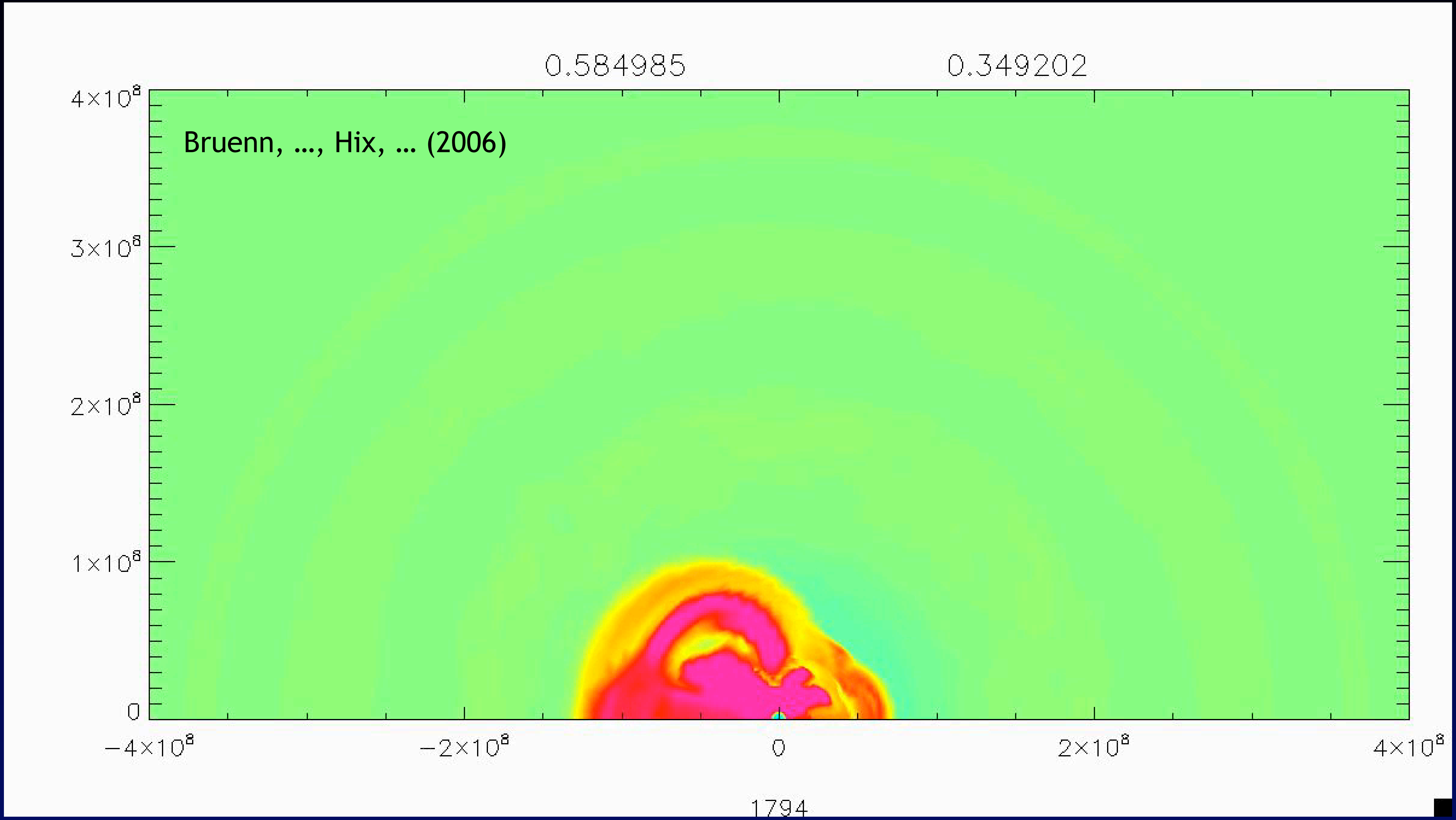




Textbook Supernova



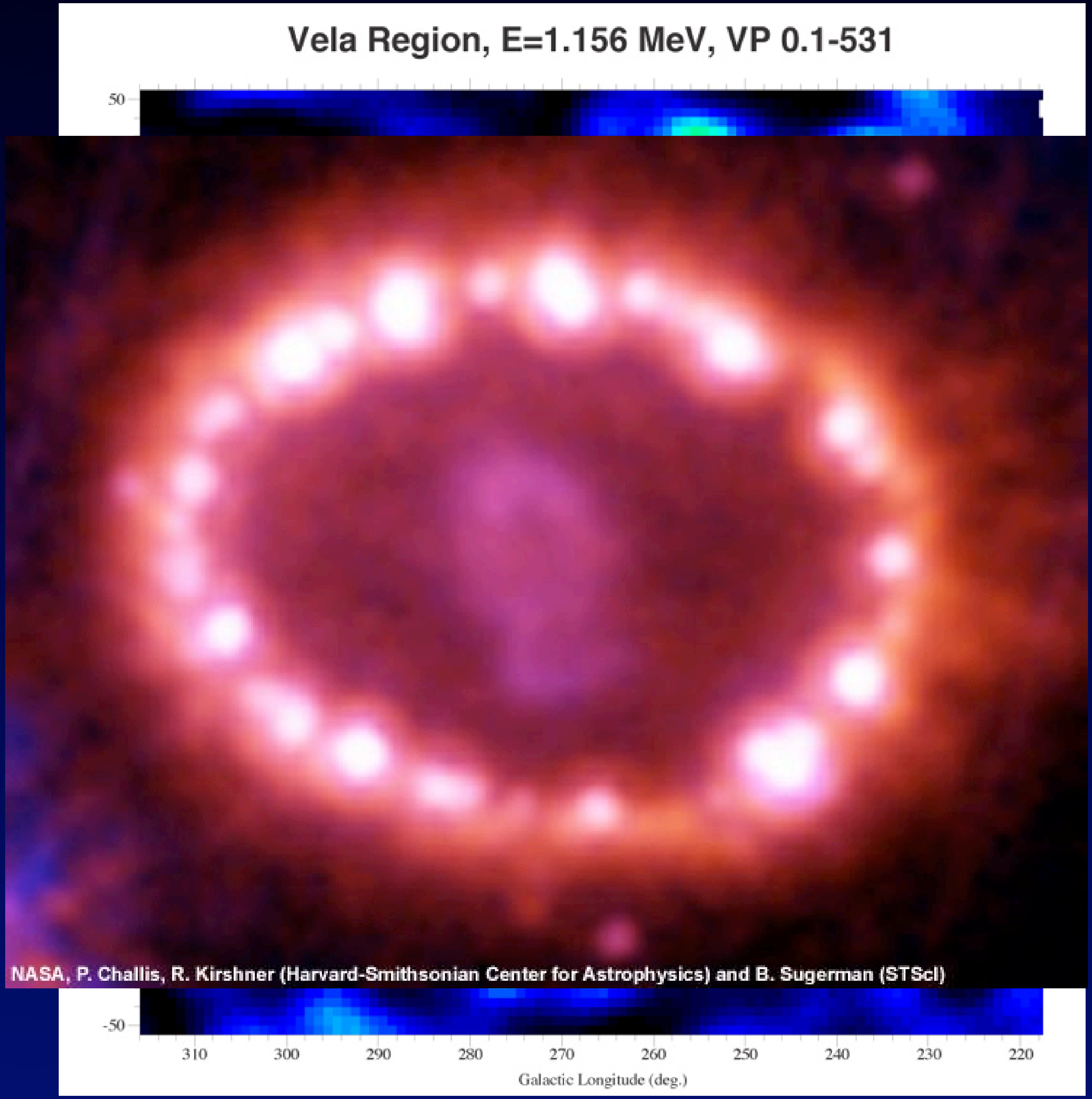
Supernovae Modeling is Ongoing



Much Work Remains to do; 3D, General Relativity, Magnetic Fields, Nuclear Reactions, Equation of State, Neutrino Oscillations, …

Radioactive Nuclei in Supernovae

- **Core Collapse Mechanism**
  - Nuclei present during collapse/above shock
  - Nuclear EOS
- **Nucleosynthesis**
  - Iron-peak
    - ^{56}Ni, ^{57}Ni, ^{44}Ti, etc.
  - p-process
  - r-process



NASA, P. Challis, R. Kirshner (Harvard-Smithsonian Center for Astrophysics) and B. Sugerman (STScI)

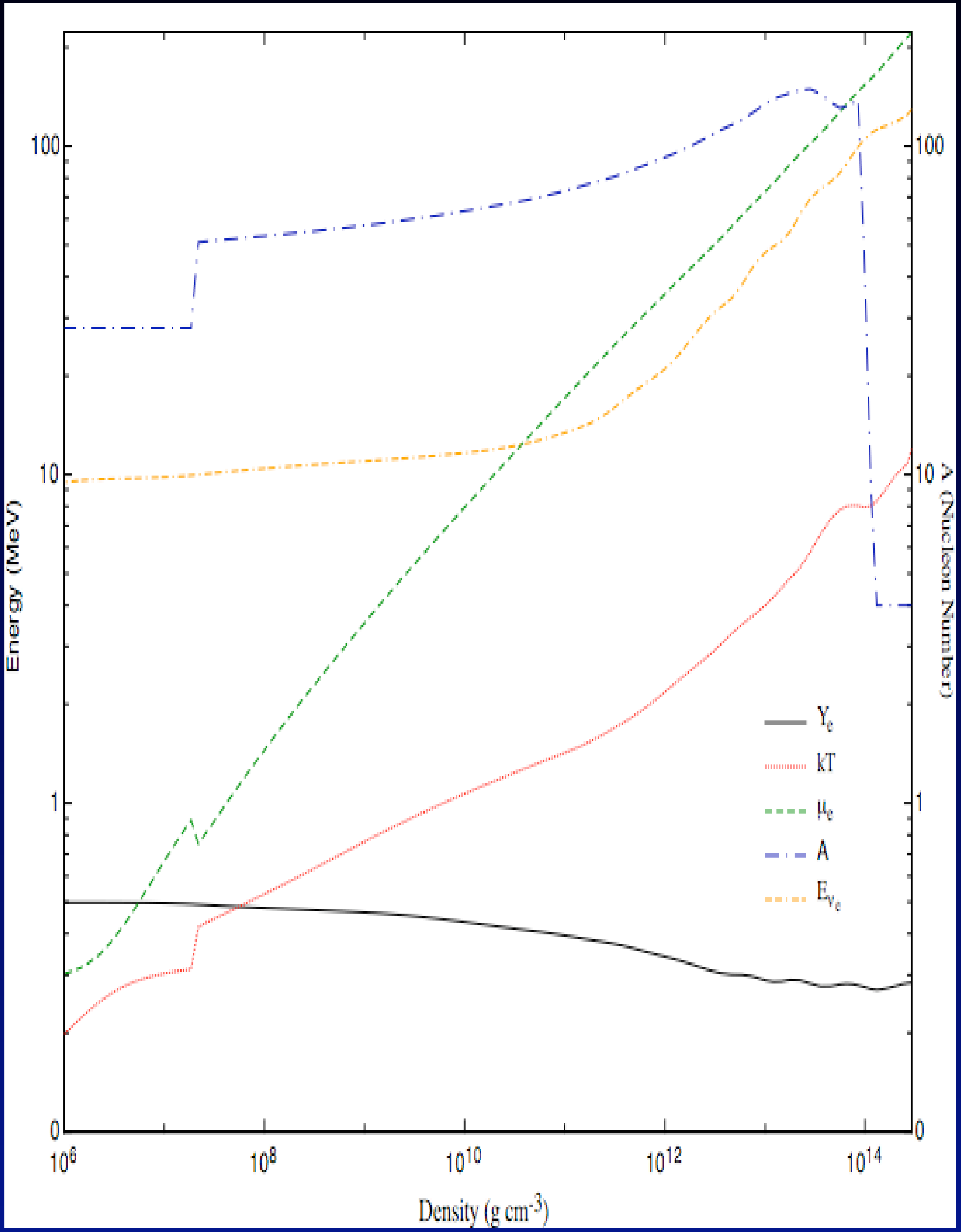
History of Captures on Nuclei

Entropy of iron core is low (S/k ~1) so few free nucleons are present. Thus e^- and ν capture on heavy nuclei via ${}^1f_{7/2} \Leftrightarrow {}^1f_{5/2}$ GT transition dominates. (Bethe, Brown, Applegate & Lattimer 1979)

During collapse, average mass of nuclei increases, quenching e^- capture (at N=40).

Thermal unblocking and first forbidden were considered but rates too small. (Fuller 1982, Cooperstein & Wambach 1984)

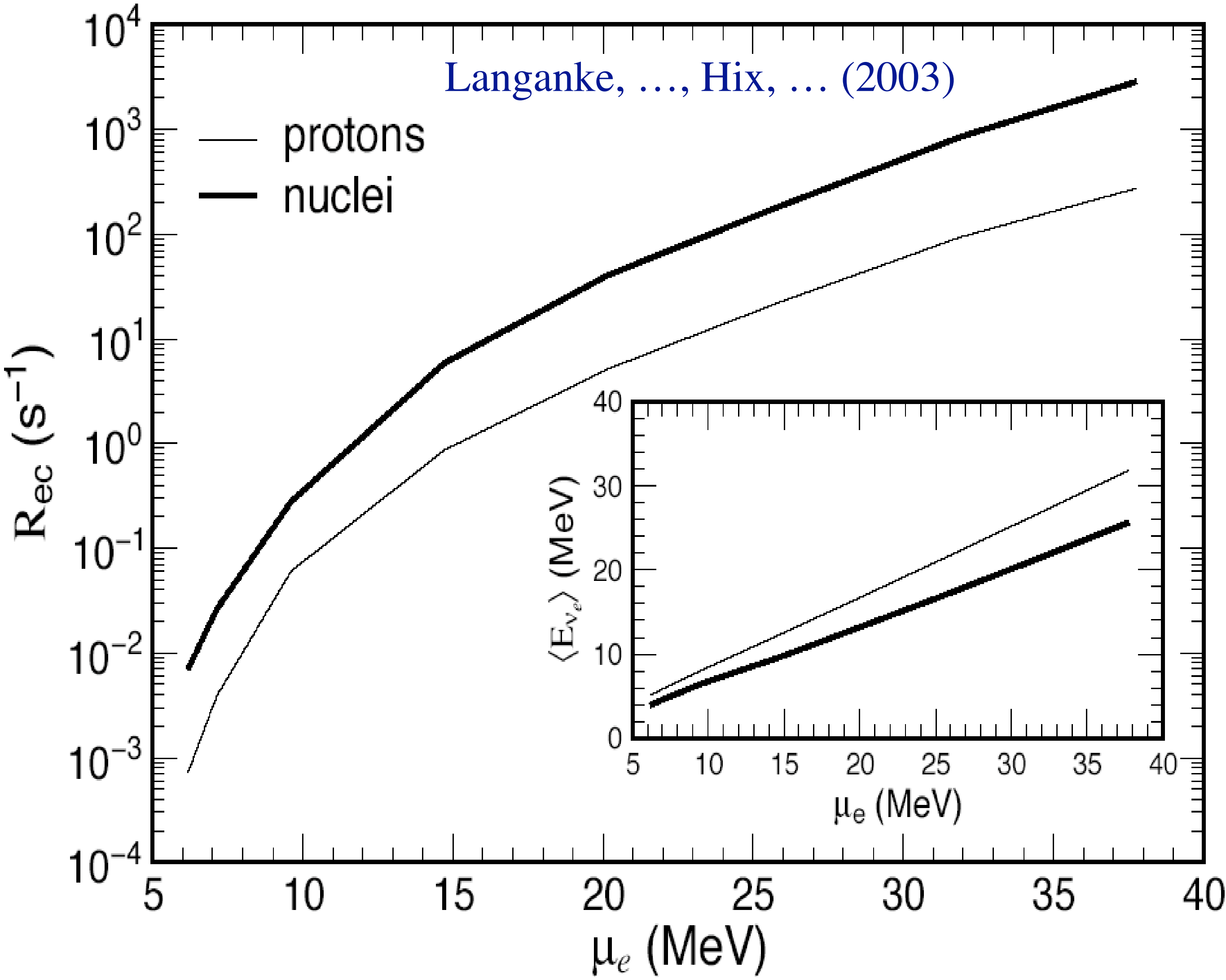
Implemented using average nucleus. Bruenn (1985)



New e^-/ν Capture Rates

Shell Model calculations are currently limited to A~65.

Langanke et al (2003) have employed a hybrid of shell model (SMMC) and RPA to calculate a scattering of rates for A<110.



Electron/neutrino capture on heavy nuclei remains important throughout collapse.

Effects of Nuclear Electron/Neutrino Capture during Core Collapse

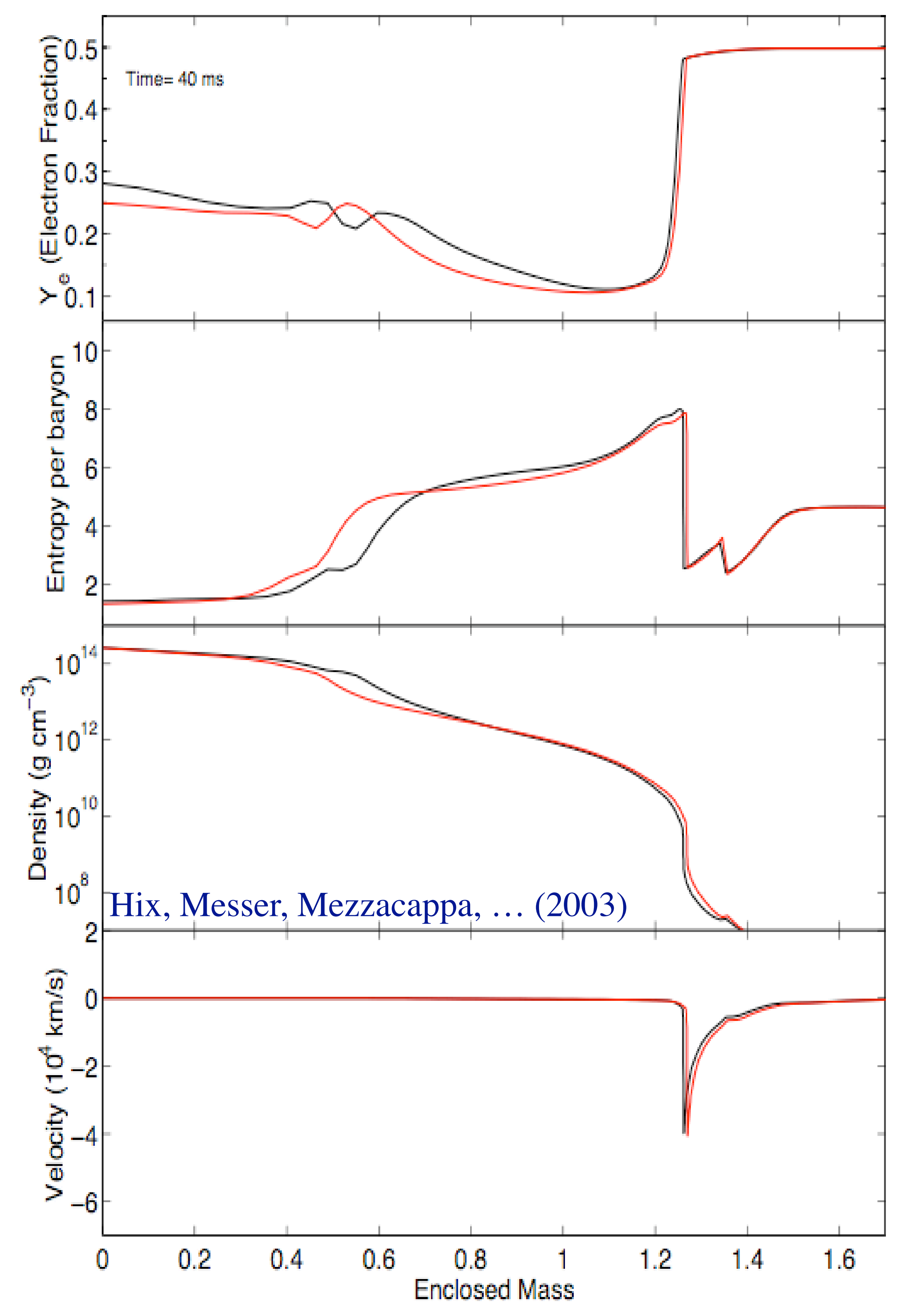
There are 2 separate effects.

1) Continuation of nuclear electron capture at high densities results in lower interior Y_e.

2) SMD rates result in less electron capture at low densities.

Initial mass interior to the shock reduced by ~20%.

Shock is ~15% weaker.



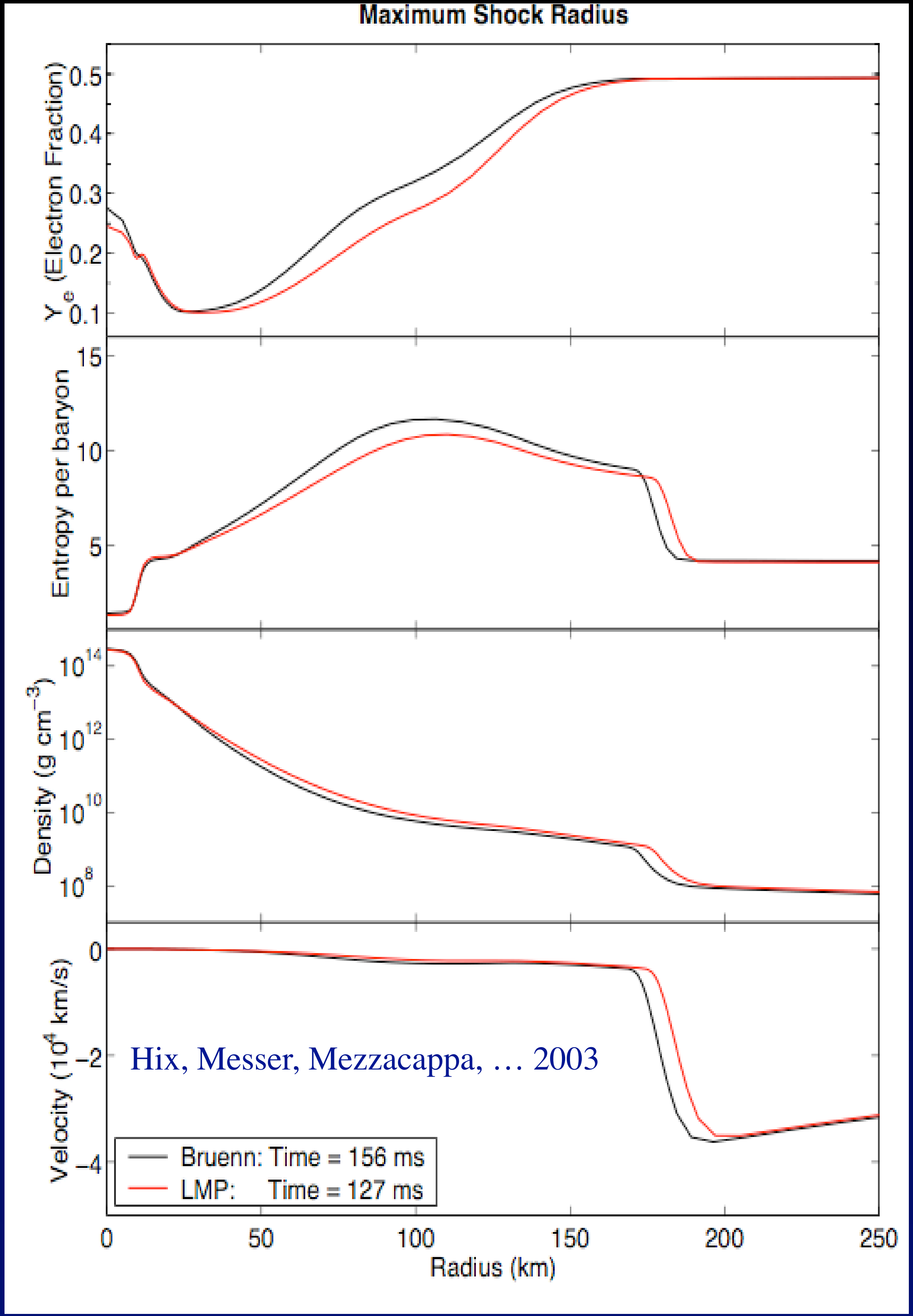
Hix, Messer, Mezzacappa, … (2003)

Effects on Shock propagation

Gradients which drive convection are altered.

“Weaker” shock is faster.

Maximum excursion of the shock is 10 km further and 30 ms earlier.

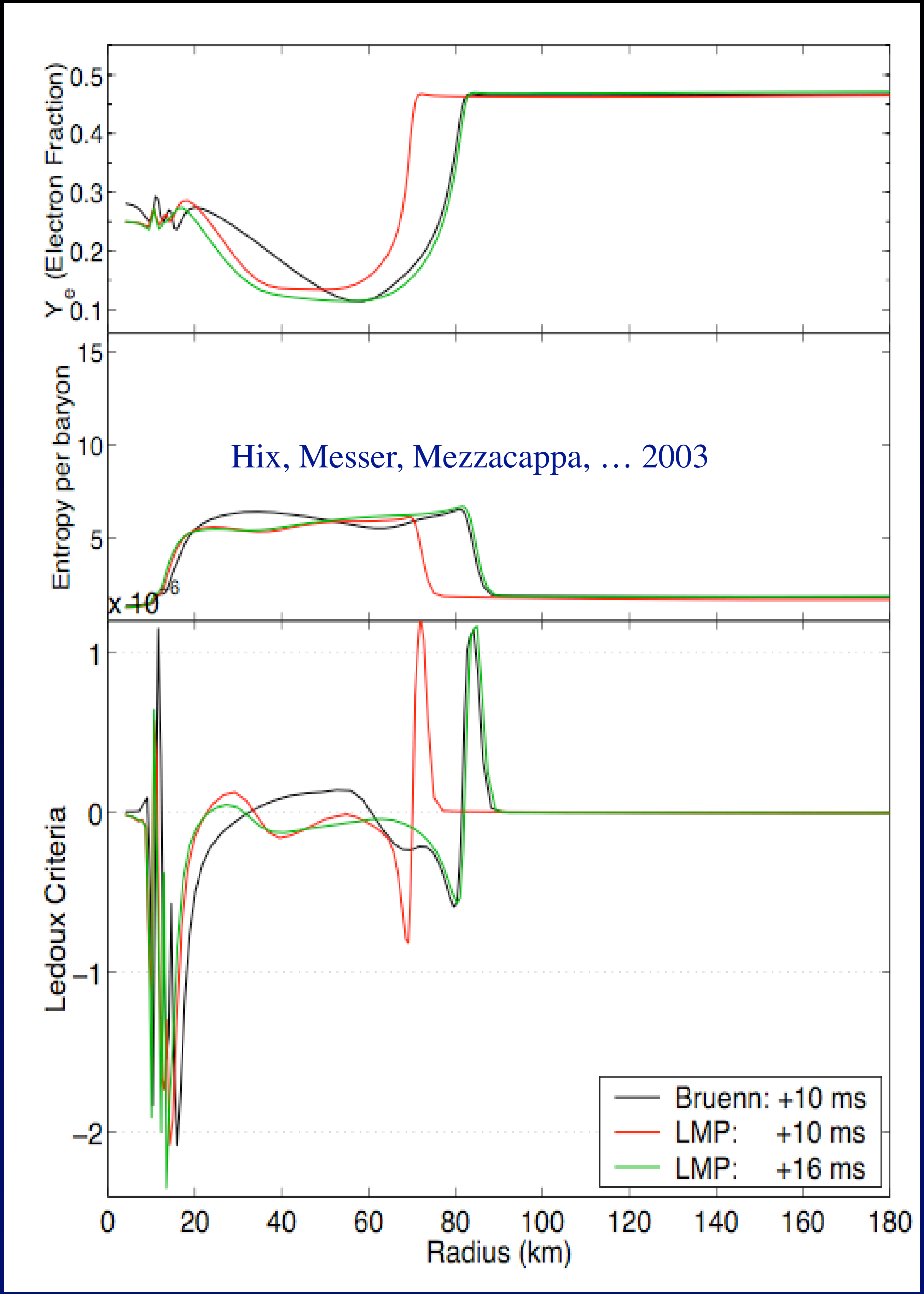


Hix, Messer, Mezzacappa, … 2003

PNS Convection

Fluid instabilities which drive convection result from complete neutrino radiation-hydrodynamic problem including nuclear interactions.

Updated nuclear e^-/ν capture restricts PNS convection to smaller, deeper region.



Hix, Messer, Mezzacappa, … 2003

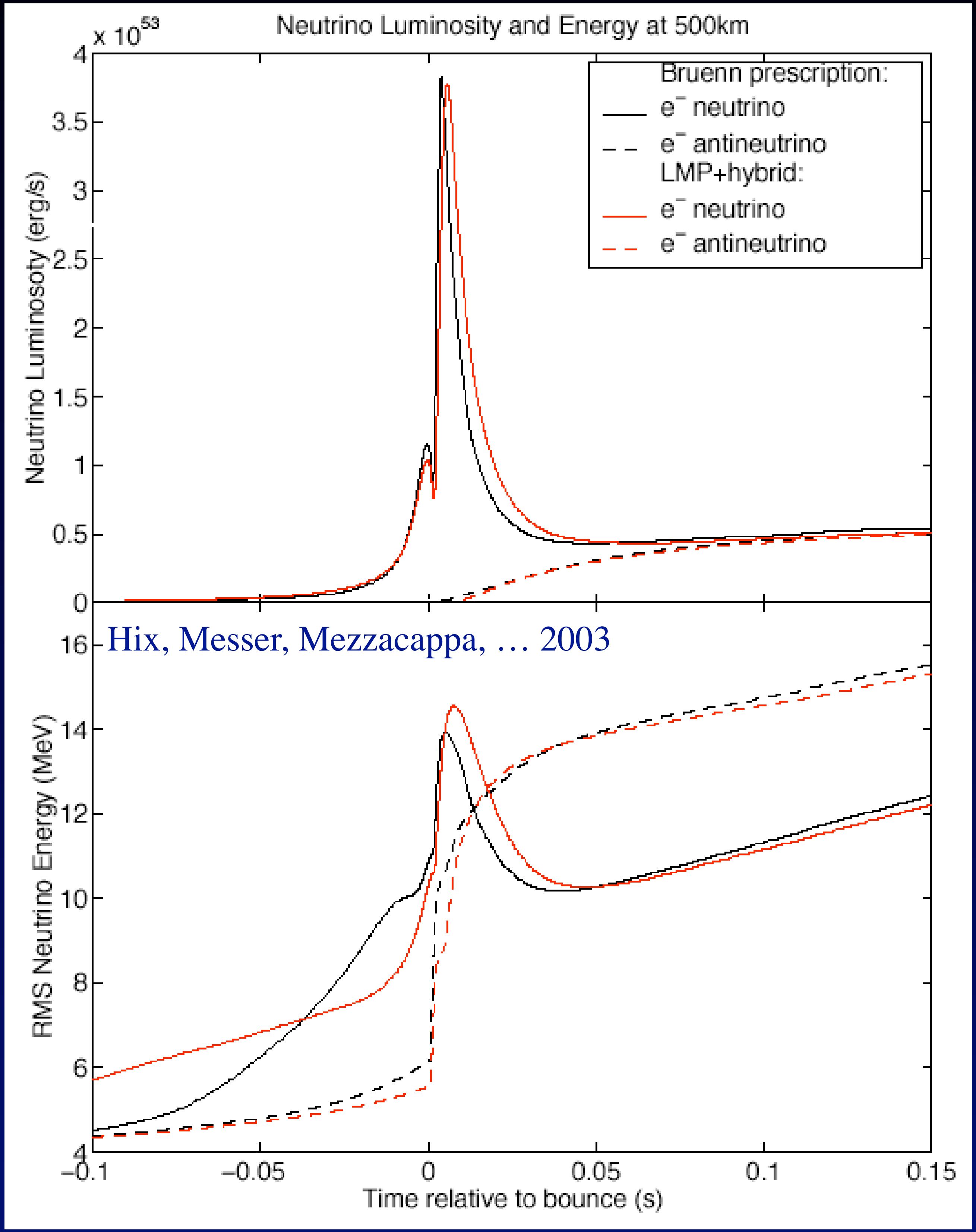
Changes in Neutrino Emission

ν_e burst slightly delayed and prolonged.

Other luminosities minimally affected (~1%).

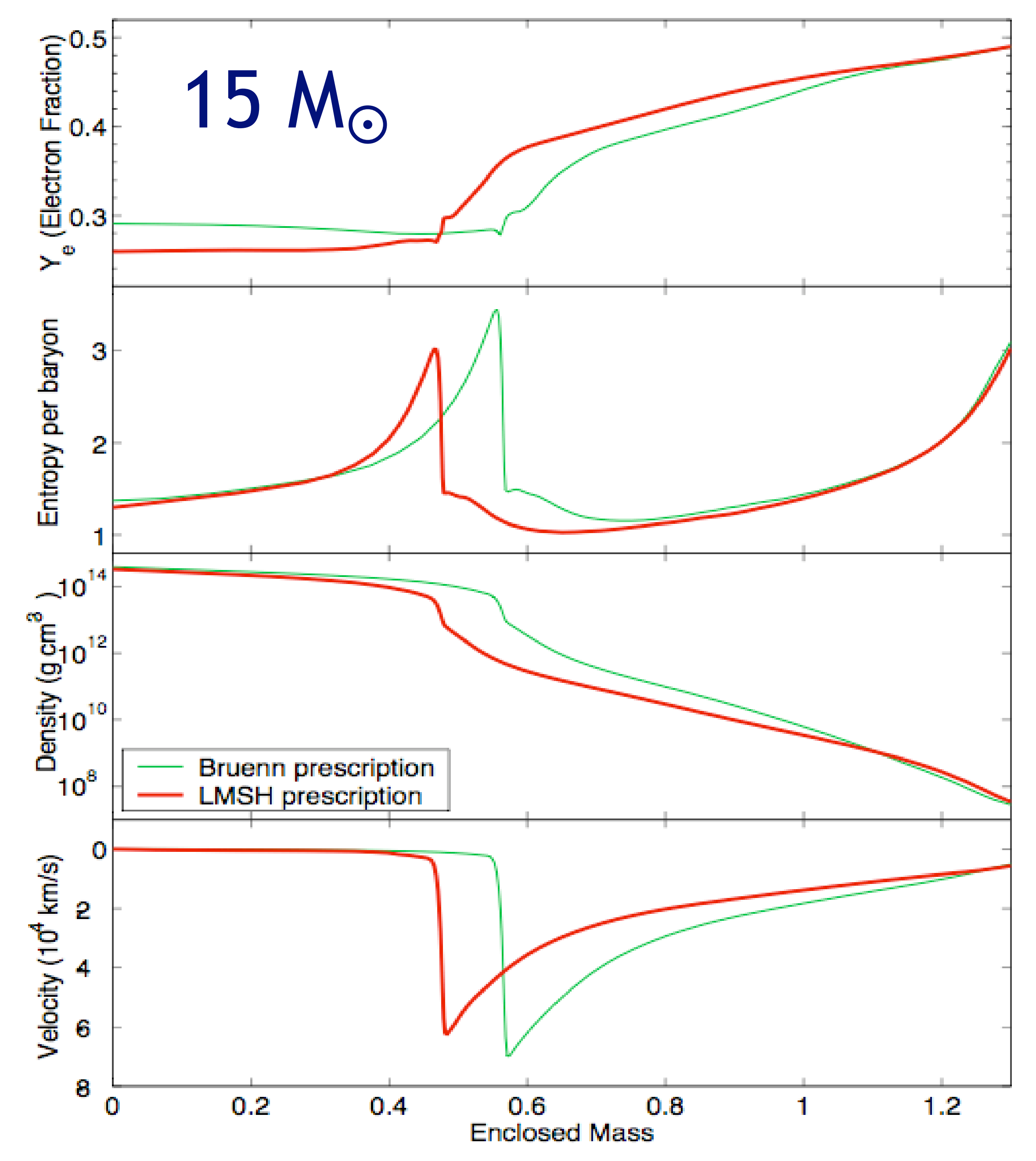
Mean ν Energy altered:

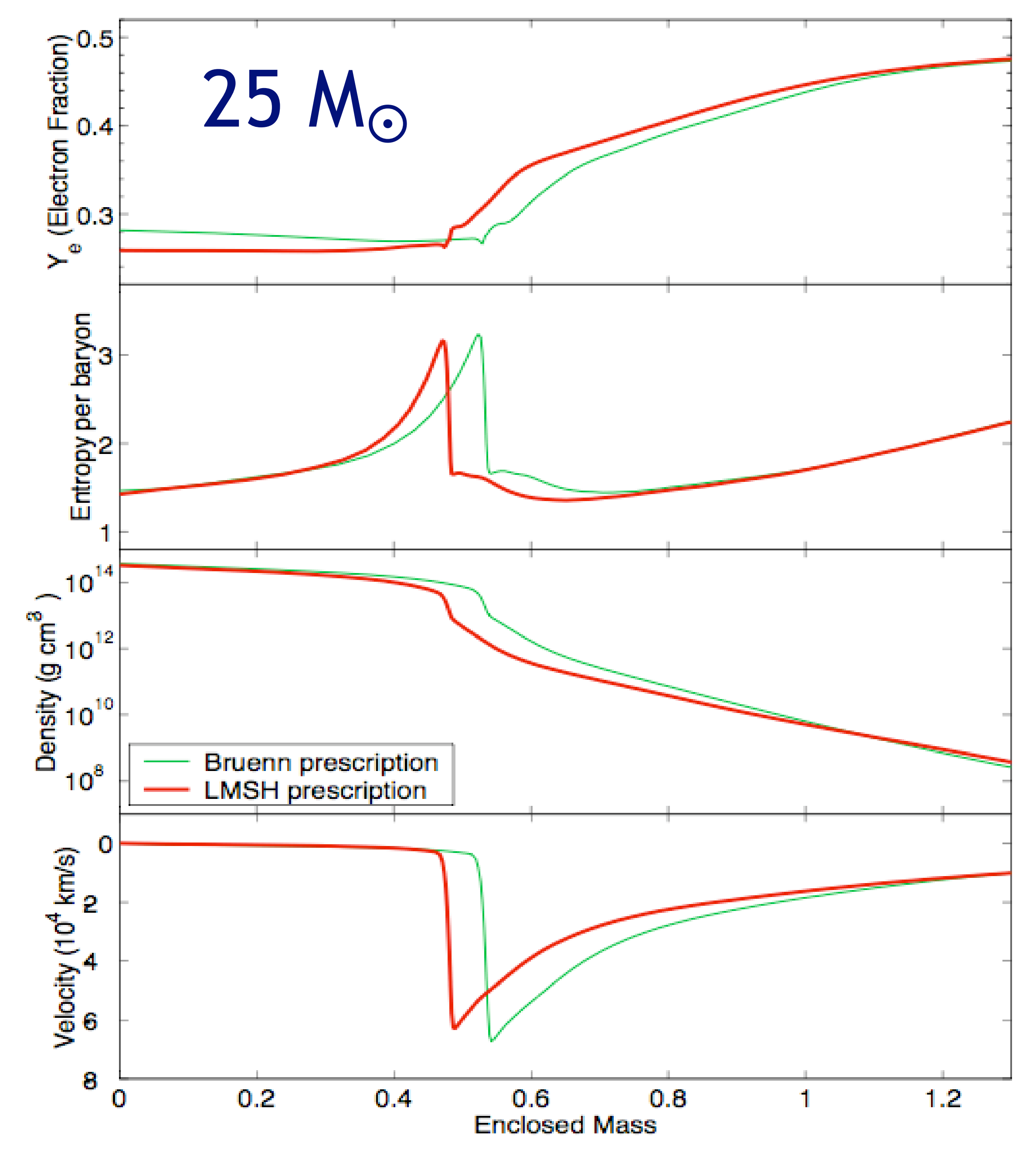
- 1-2 MeV during collapse
- ~1 MeV up to 50ms after bounce
- ~.3 MeV at late time



Hix, Messer, Mezzacappa, … 2003

The impact of stellar mass





Higher mass cores have higher initial entropy.

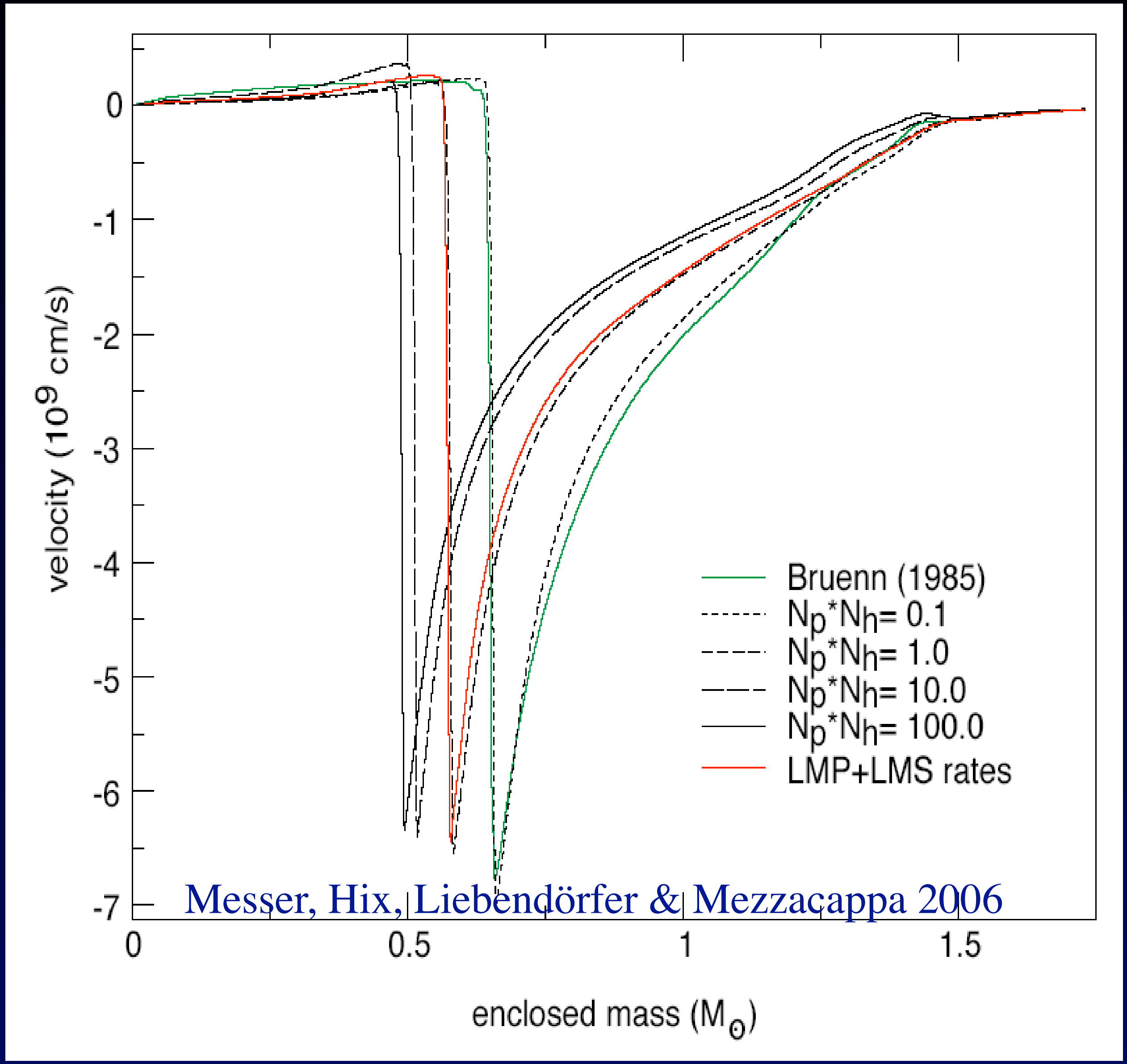
Effects of nuclear electron capture are reduced but comparable (1/2 to 2/3).

Testing the Sensitivity

Used Bruenn (1985) as a reproducible starting point.

Replaced quenching term with parameter $(N_p N_h)$ = 0.1-100

Changes from current electron capture rate of a factor of 10 move shock formation by ~0.1 solar mass.



Messer, Hix, Liebendörfer & Mezzacappa 2006

$$j_{nuclear} = \frac{2}{7}\frac{(2\pi)^4 G_F^2}{\pi h^4 c^4} g_A^2 \frac{\rho X_H}{m_B A} N_p(Z) N_h(N) (E+Q')^2 \left[1 - \left(\frac{M_e}{E+Q'}\right)^2\right]^{1/2} F_e(E+Q'), \quad (1)$$

where

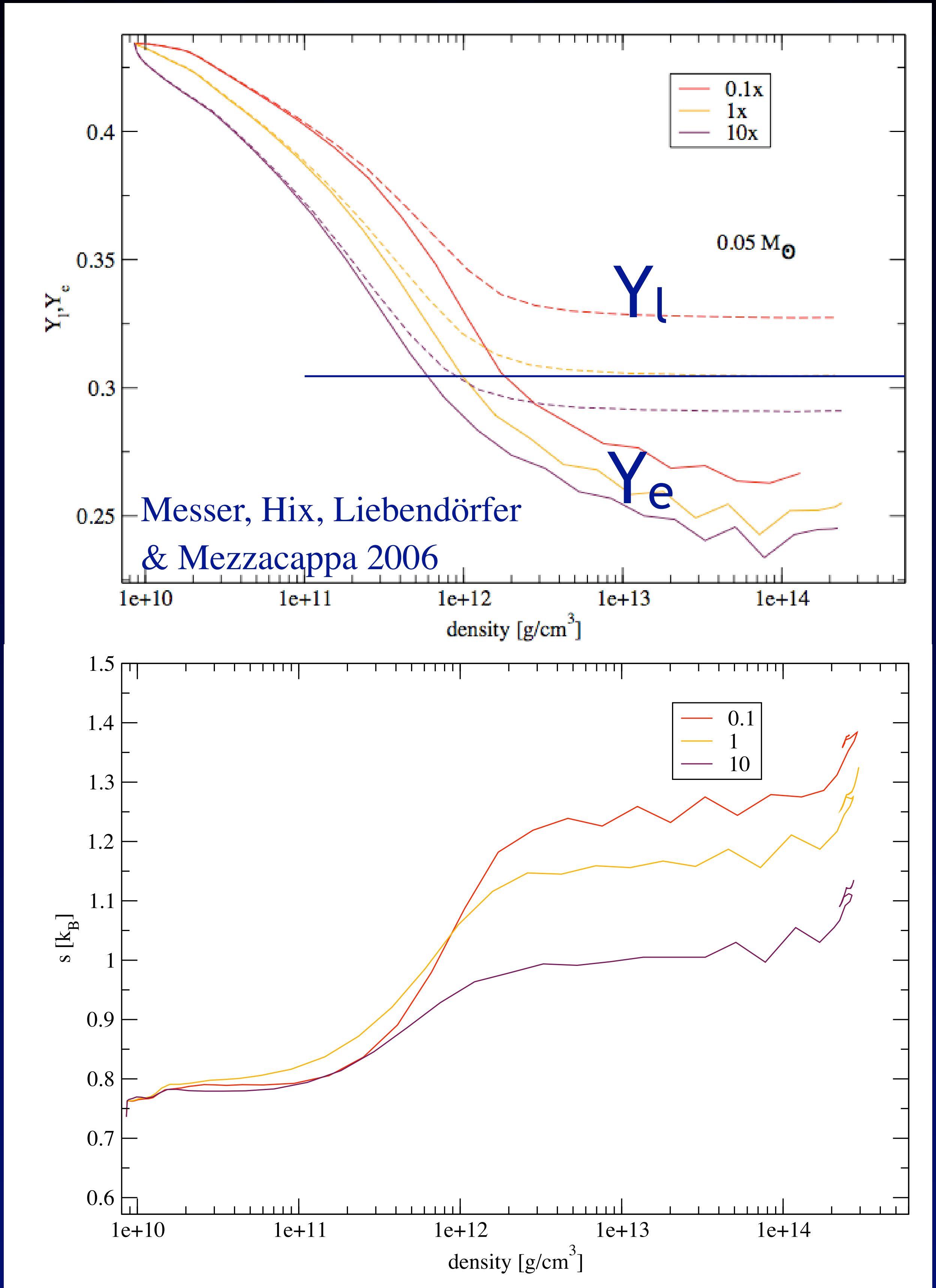
$$N_p(Z) = \begin{cases} 0 & Z < 20 \\ Z-20 & 20 < Z < 28 \\ 8 & Z > 28 \end{cases} \quad \text{and} \quad N_h(N) = \begin{cases} 6 & N < 34 \\ 40-N & 34 < N < 40 \\ 0 & N > 40\,. \end{cases} \quad (2)$$

Determining Y_e and Entropy

Change in lepton abundance ($Y_l=Y_e+Y_\nu$) occurs gradually over 2+ decades of density up to ~3×10^{12} g/cm^3.

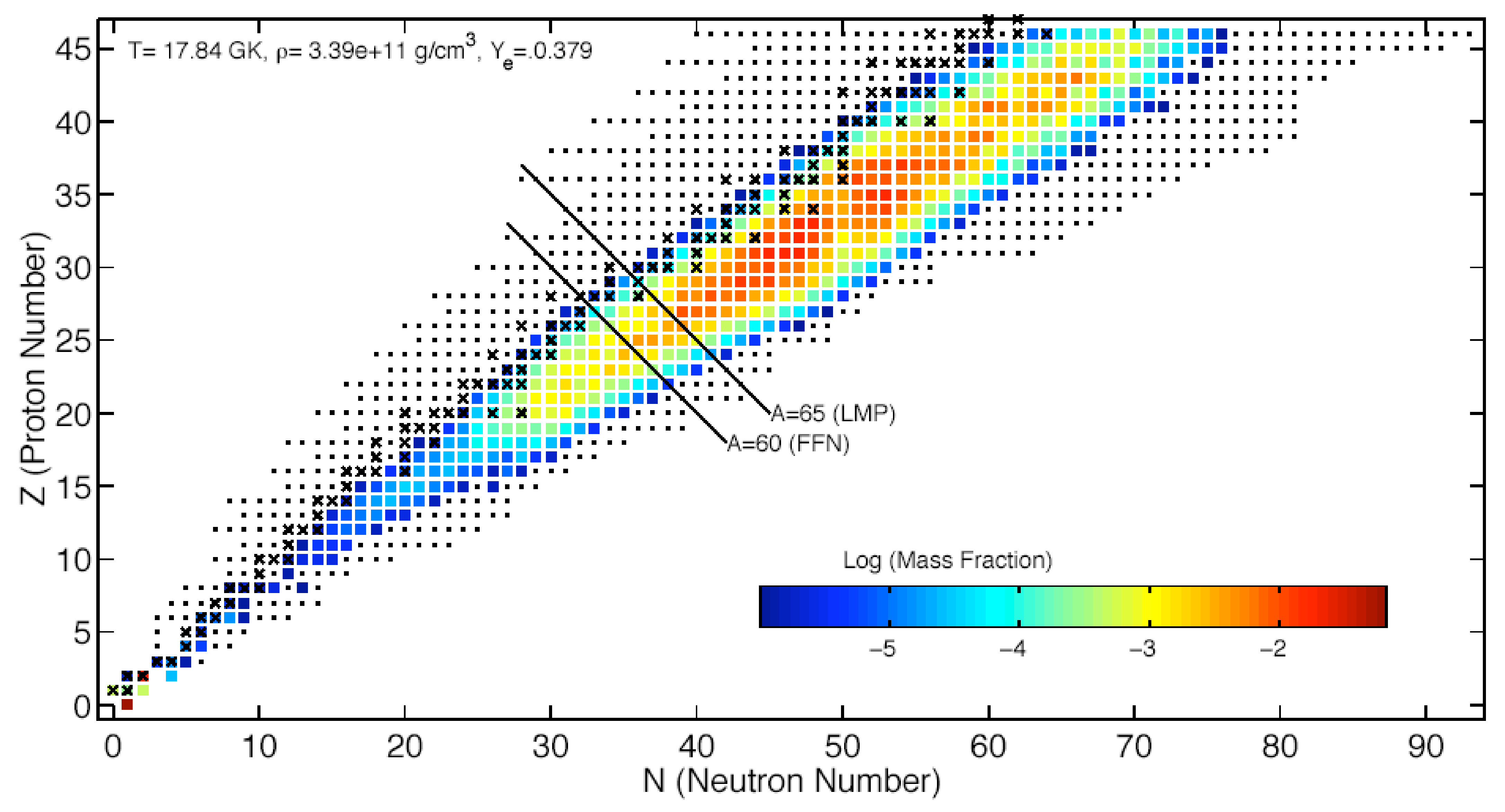
Beyond equilibration, variations in Y_e reflect thermodynamic changes.

Entropy is flat until appreciable Y_ν is achieved allowing significant neutrino capture and heating then flattens after equilibration.



Messer, Hix, Liebendörfer & Mezzacappa 2006

Needed Electron Capture Rates



Nuclei with A ~ 120 contribute to e^{-}/ν capture.

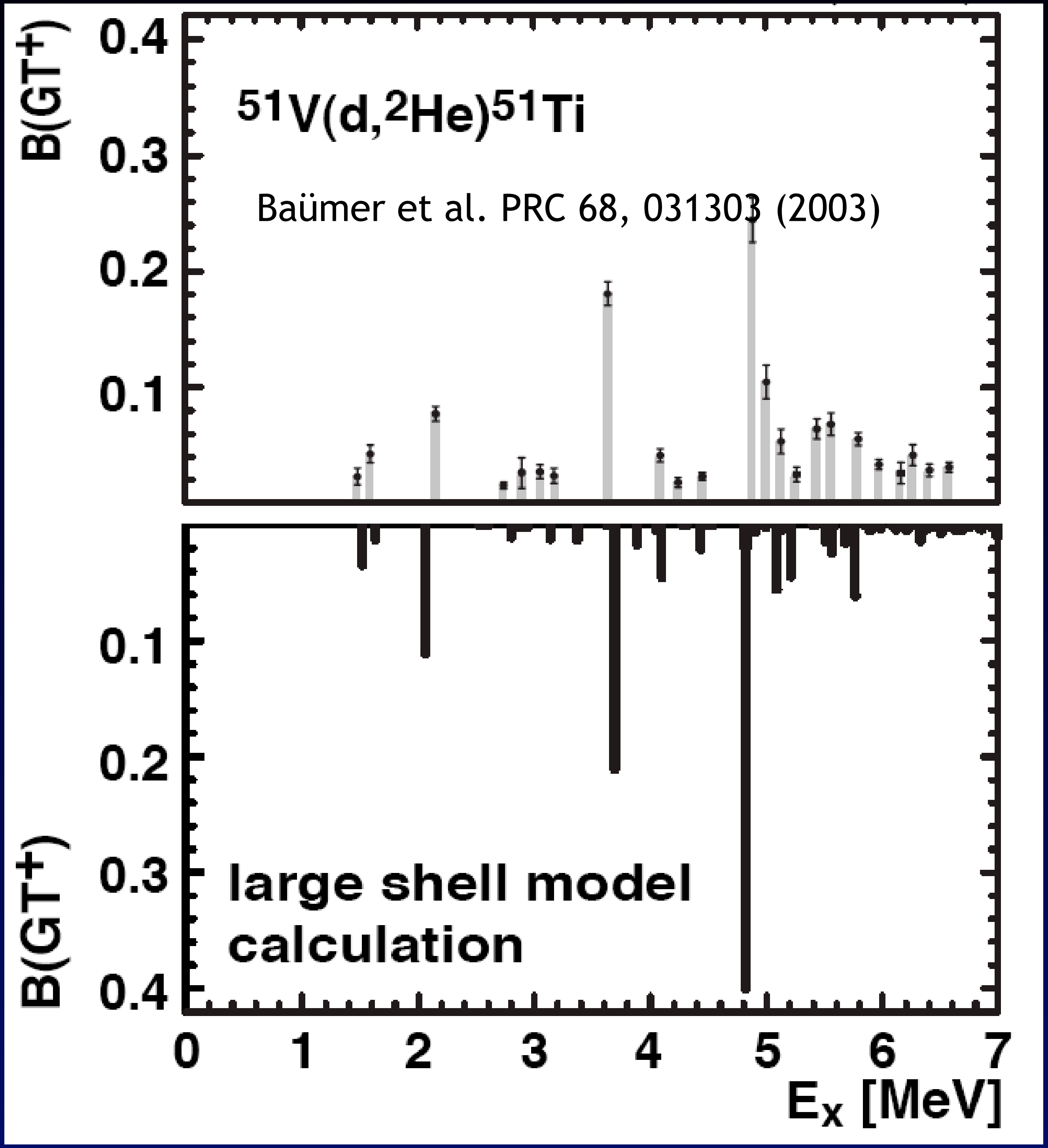
Many rates are needed, with declining quality needed with increasing mass.

What can RIBs say about e^-/ν Capture?

Charge Exchange Reactions, e.g. (n,p),(d,^{2}He),(t,^{3}He), also sample GT+ strength distribution, providing strong constraints on structure models.

Current Experiments, on stable nuclei, agree well with shell model calculations for A<60.

For A=80-100 nuclei of interest are 2-6 neutrons richer than stability.



Should be achievable with NextGen RIBs.

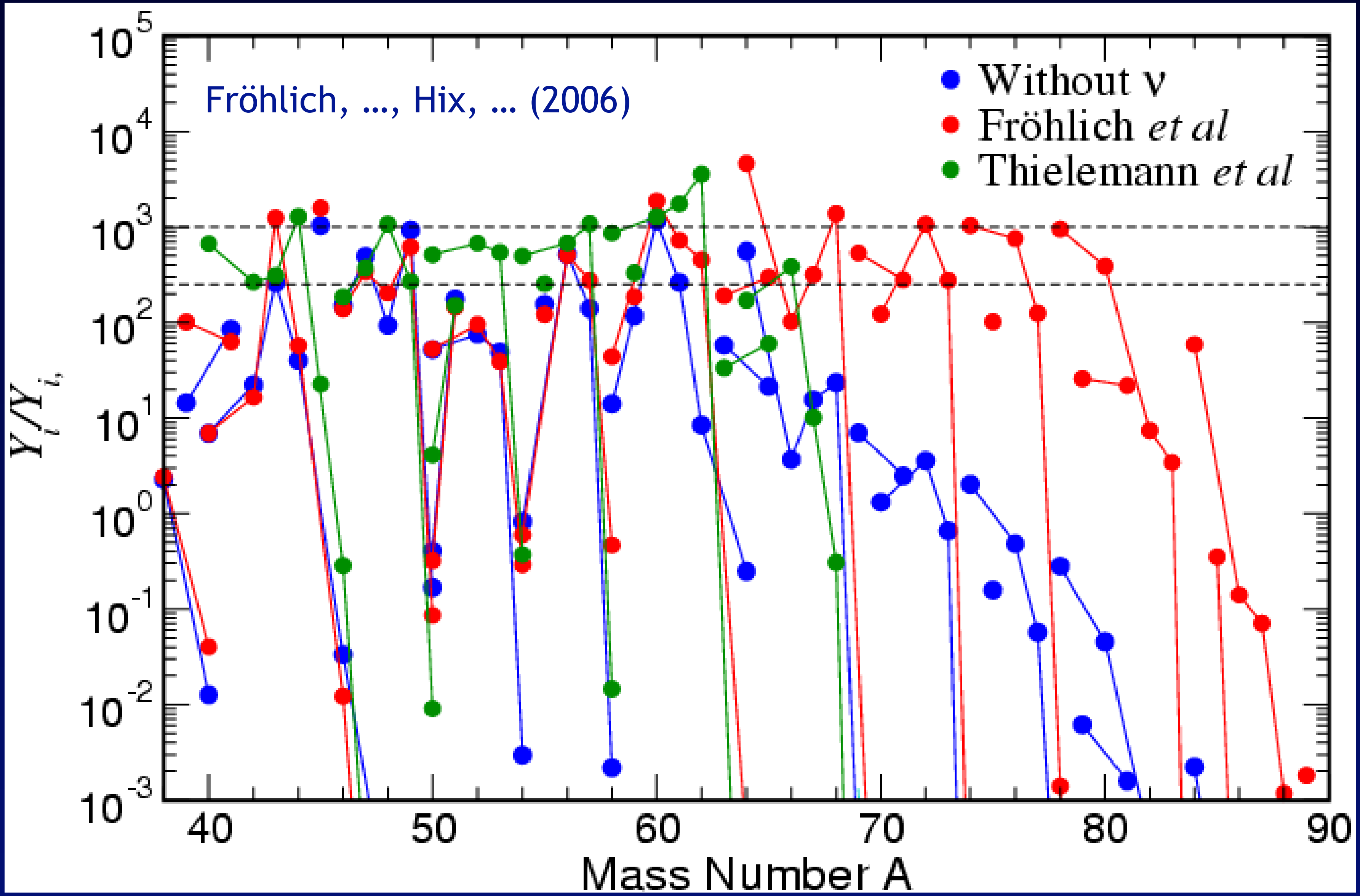
ν-Effects on Supernova Nucleosynthesis

1. Improved agreement with abundances of Sc, Cu & Zn observed in metal-poor stars.
2. Reduction in over-production of neutron-rich Fe, Ni.
3. rp-process pattern of elements from A=64 to 80+.

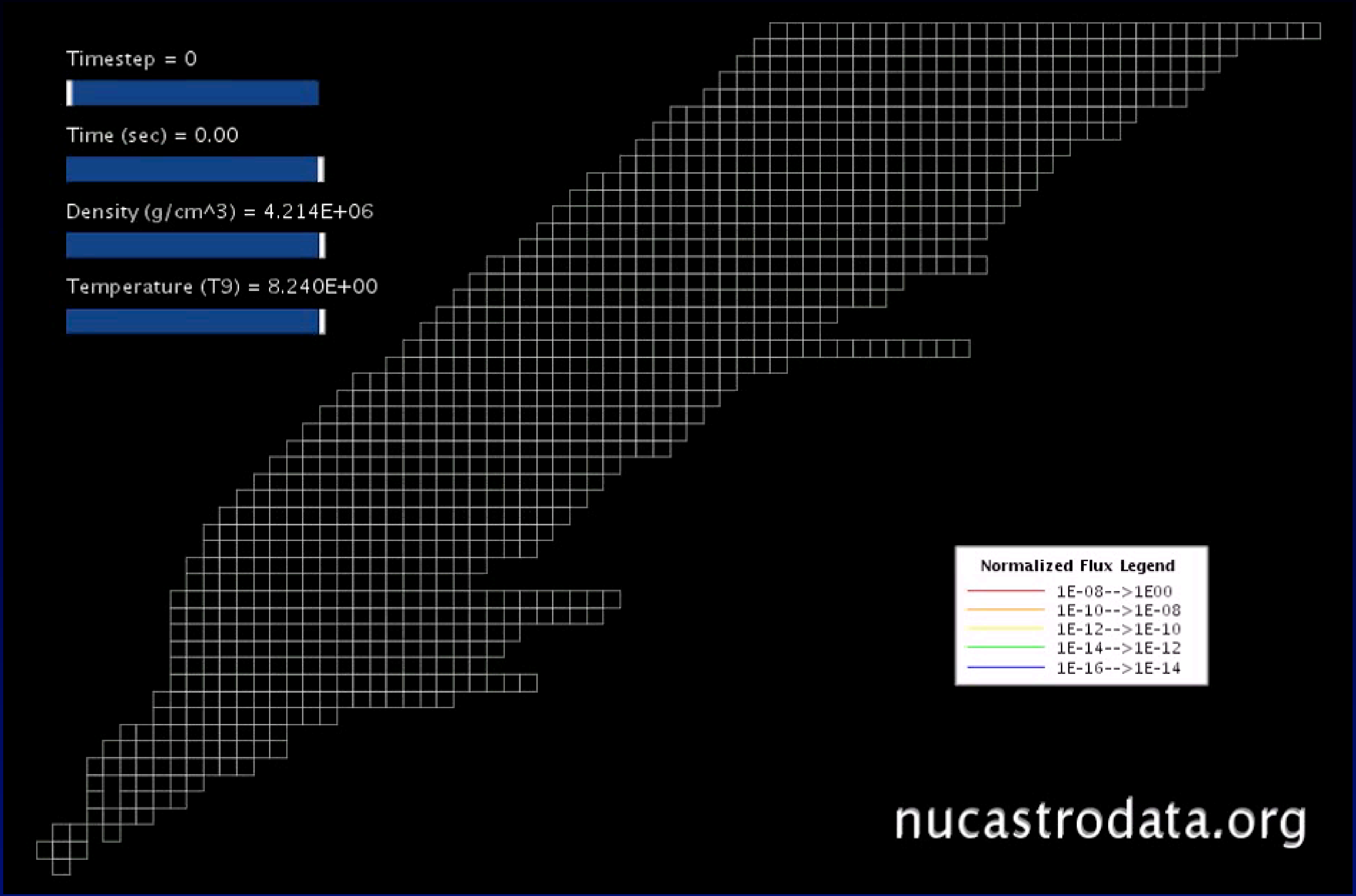
Enhancement of waiting-point nuclei:

$^{64}\mathrm{Ge} \rightarrow {}^{64}\mathrm{Zn}$
$^{68}\mathrm{Se} \rightarrow {}^{68}\mathrm{Zn}$
$^{72}\mathrm{Kr} \rightarrow {}^{72}\mathrm{Ge}$
$^{76}\mathrm{Sr} \rightarrow {}^{76}\mathrm{Se}$
$^{80}\mathrm{Zr} \rightarrow {}^{80}\mathrm{Kr}$
$^{84}\mathrm{Mo} \rightarrow {}^{84}\mathrm{Sr}$

Similar Effects seen in GRB disks with low accretion rate. (Surman, McLaughlin & Hix 2006)

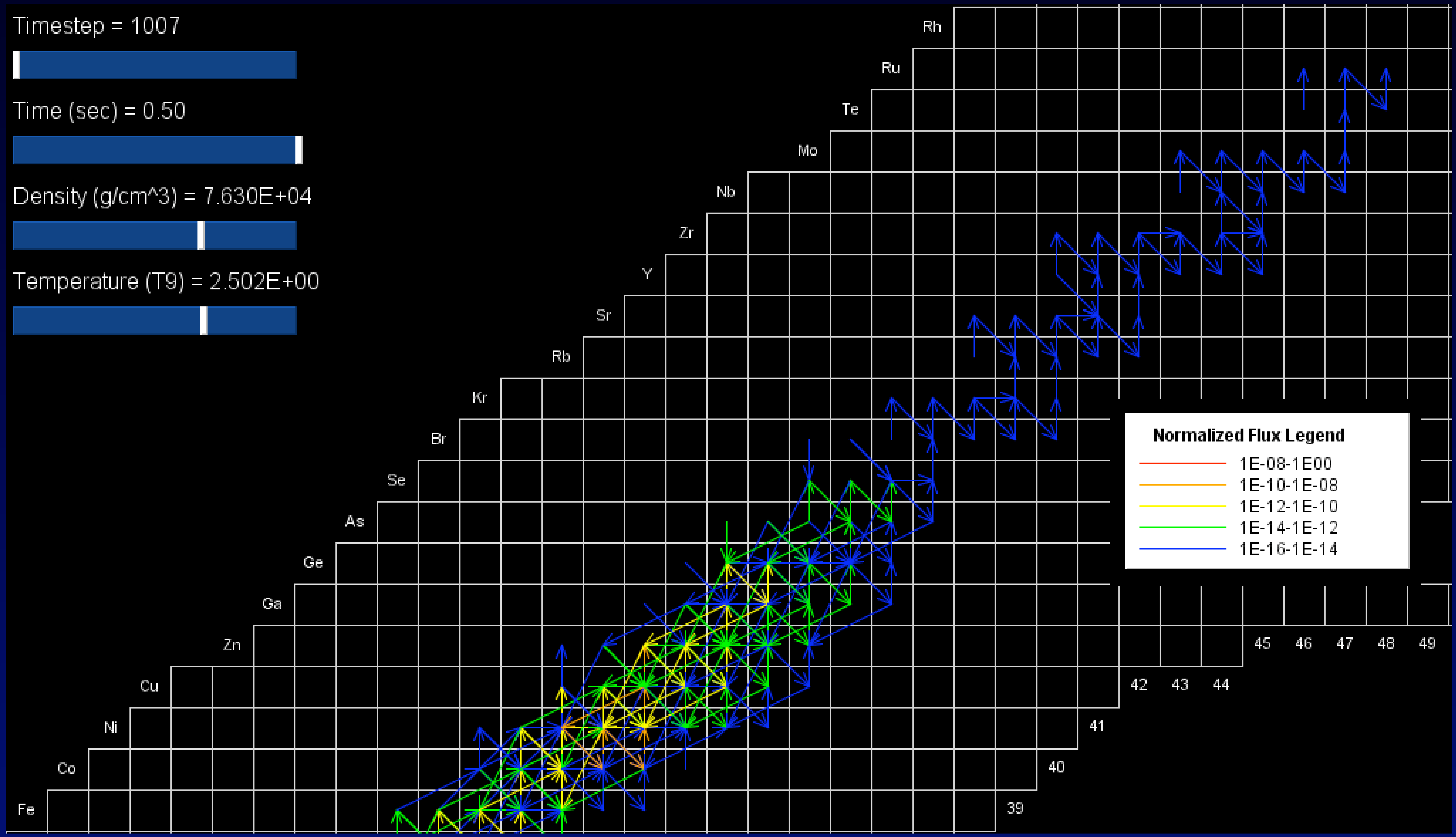


νp-process


Timestep = 0
Time (sec) = 0.00
Density (g/cm^3) = 4.214E+06
Temperature (T9) = 8.240E+00
Normalized Flux Legend
1E-08-->1E00
1E-10-->1E-08
1E-12-->1E-10
1E-14-->1E-12
1E-16-->1E-14
nucastrodata.org

How to get beyond A=64?

As Pruett et al. (2005) point out, true rp-process is limited by slow β decays, e.g. $\tau(^{64}\mathrm{Ge}) = 64$ s



Timestep = 1007

Time (sec) = 0.50

Density (g/cm^3) = 7.630E+04

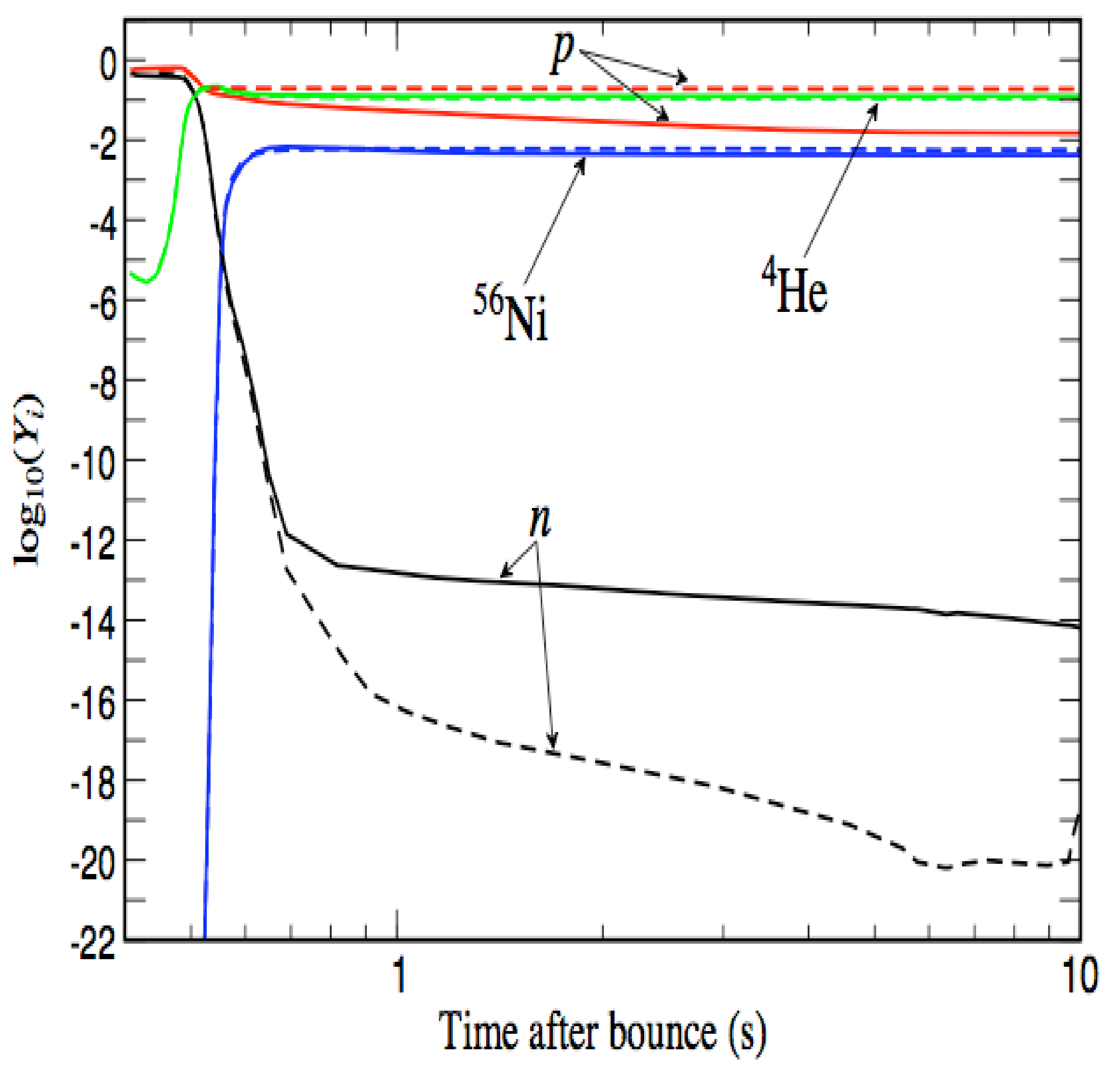
Temperature (T9) = 2.502E+00

Neutrons in a proton-rich environment?

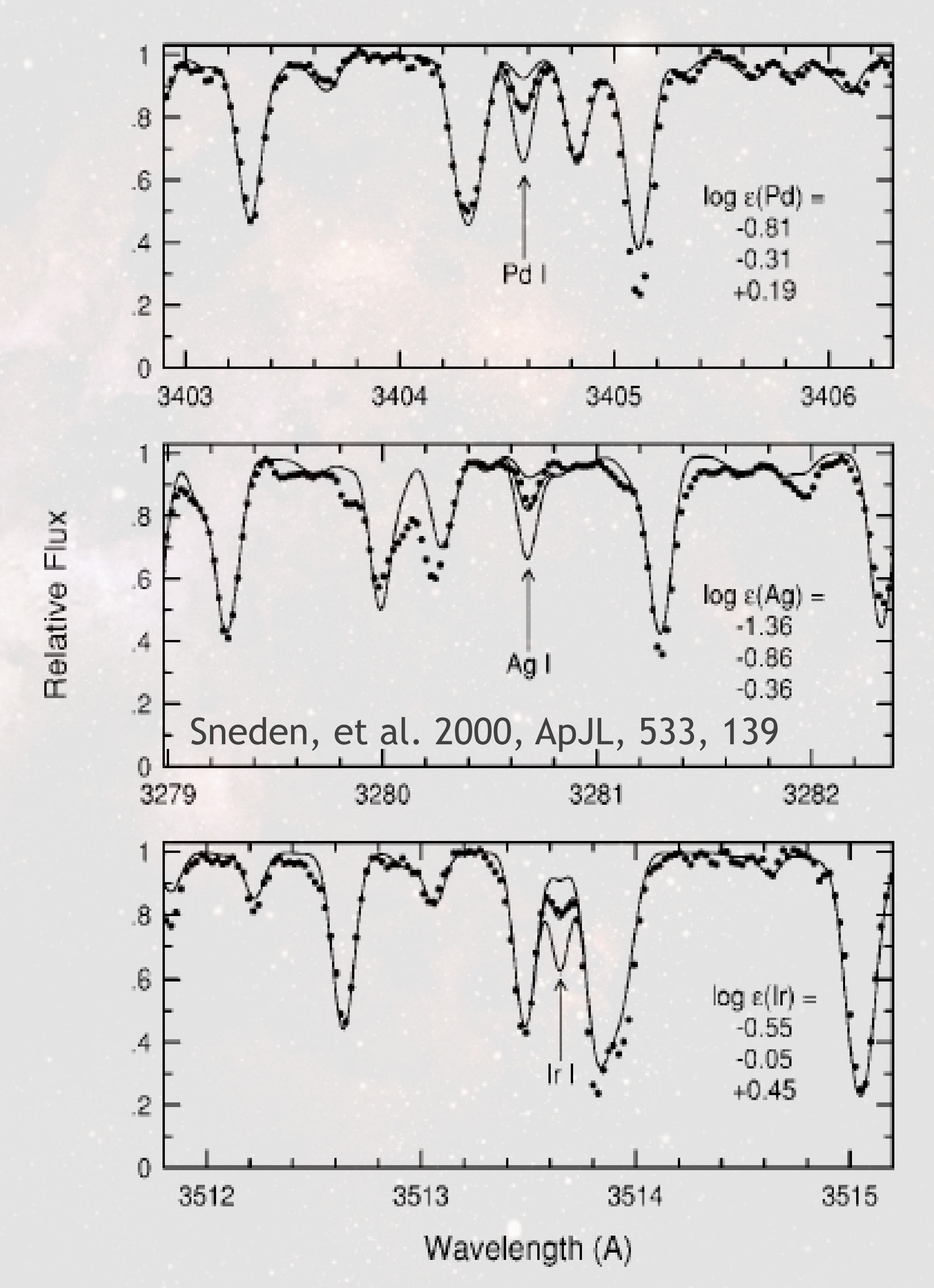
Main abundances: ^{1}H, ^{4}He, ^{56}Ni from p-rich and α-rich freeze-out.

Protons converted to neutrons via anti-neutrino capture.

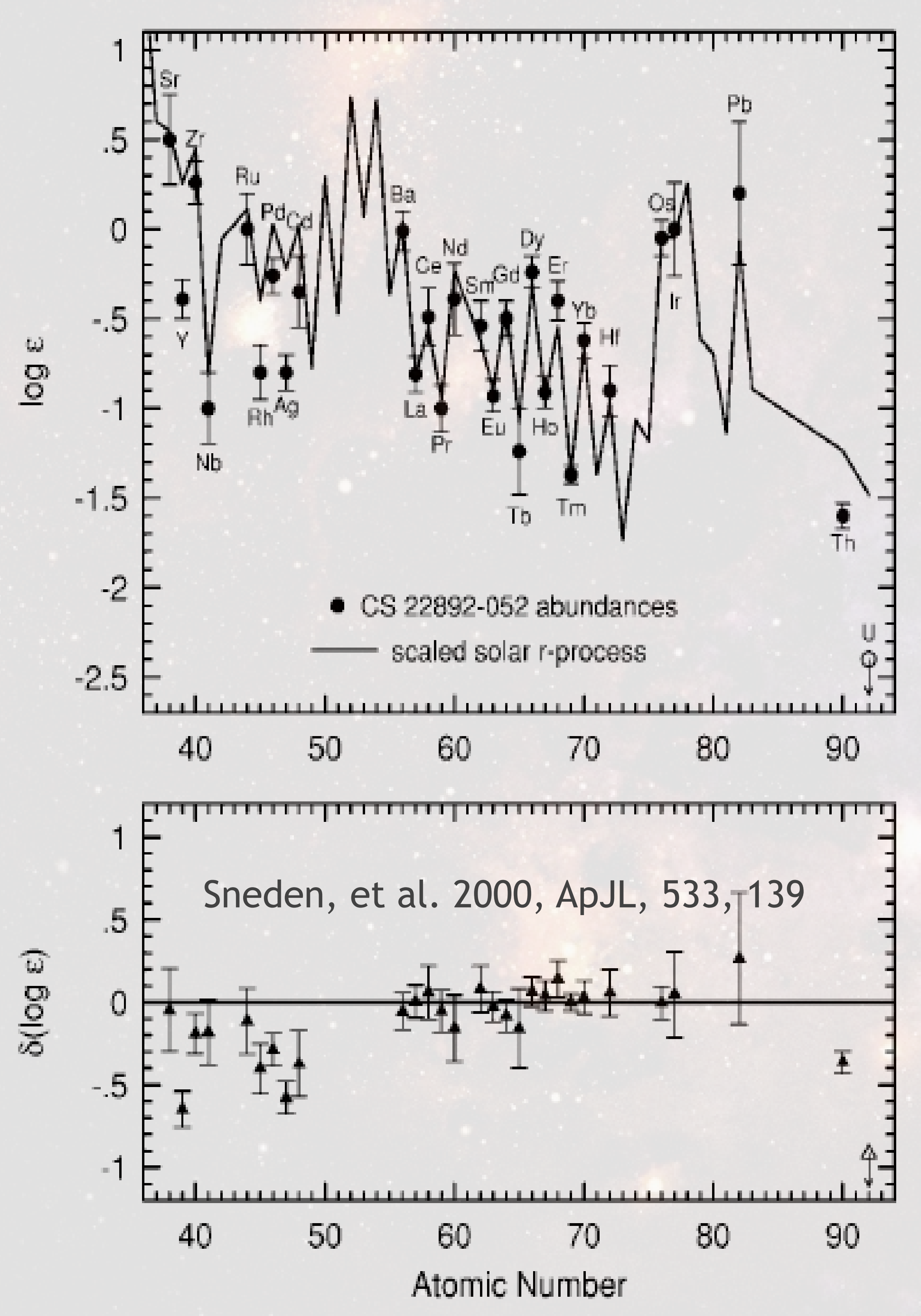
(n,p) and (n,γ) “accelerates” β decays.



Detecting the r-process in old stars



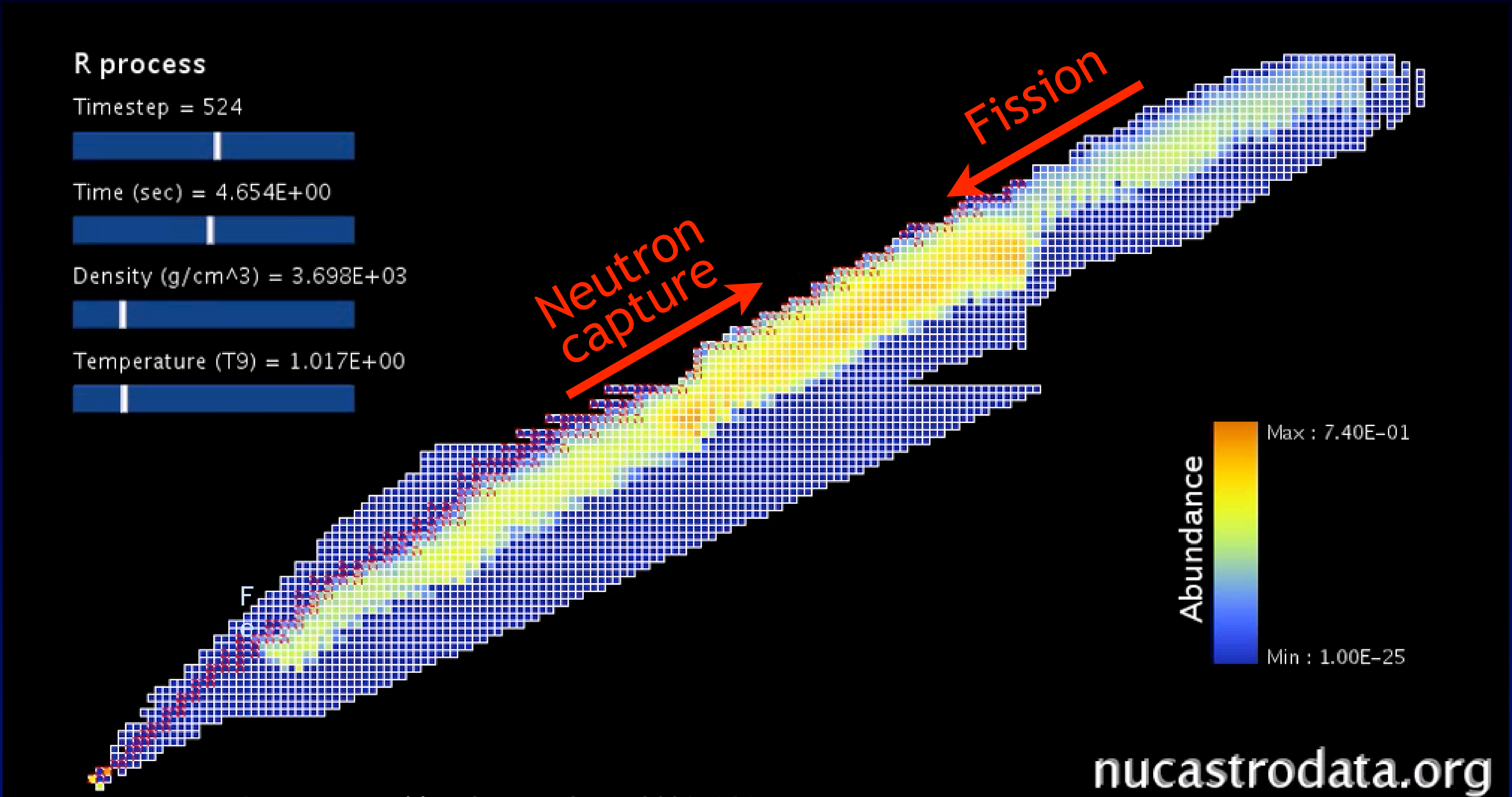
Sneden, et al. 2000, ApJL, 533, 139



Sneden, et al. 2000, ApJL, 533, 139

Simulating the r-process

Uncertainties about the site of the r-process provide considerable latitude for modeling.



R process

Timestep = 524

Time (sec) = 4.654E+00

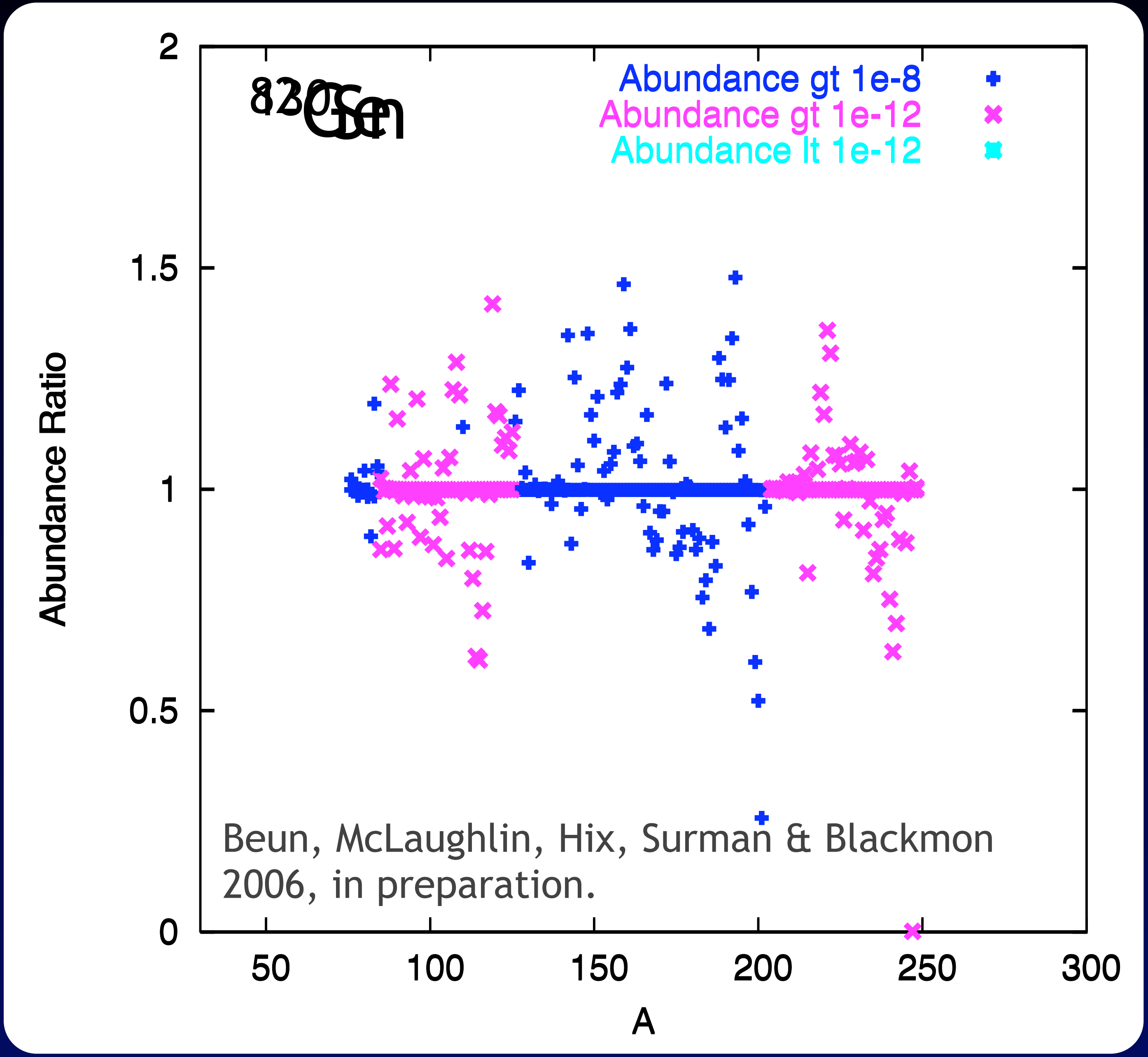
Density (g/cm^3) = 3.698E+03

Temperature (T9) = 1.017E+00

Beun, McLaughlin, Surman & Hix 2006, PRD in press.

R-process Data

- For most of the r-process, (n,γ)(γ,n) equilibrium holds.
- Much of what’s needed are masses and β−decay rates.
- (n,γ) rates matter as equilibrium breaks down.



Beun, McLaughlin, Hix, Surman & Blackmon 2006, in preparation.

To achieve desired accuracy of r-process predictions will require neutron capture rates, at least near stability.

Next Generation Radioactive Ion Beams will:

1) provide better constraints on nuclear structure relevant for electron and neutrino captures.

2) provide important constraints on the properties of neutron-rich nuclear matter.

3) allow measurement of most of the rates of interest to rp-processes, including the νp–process, and iron peak nucleosynthesis.

4) provide many masses and β-decay rates needed for the r-process, as well as selected measurements of (n,γ) and fission rates.

All of these are needed to better understand core collapse supernovae and their nucleosynthesis.