
VLT (ESO)

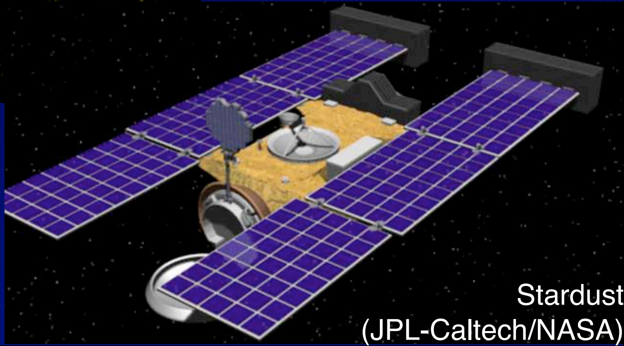

Integral (ESA)


(SST/HST/CXO/NASA)

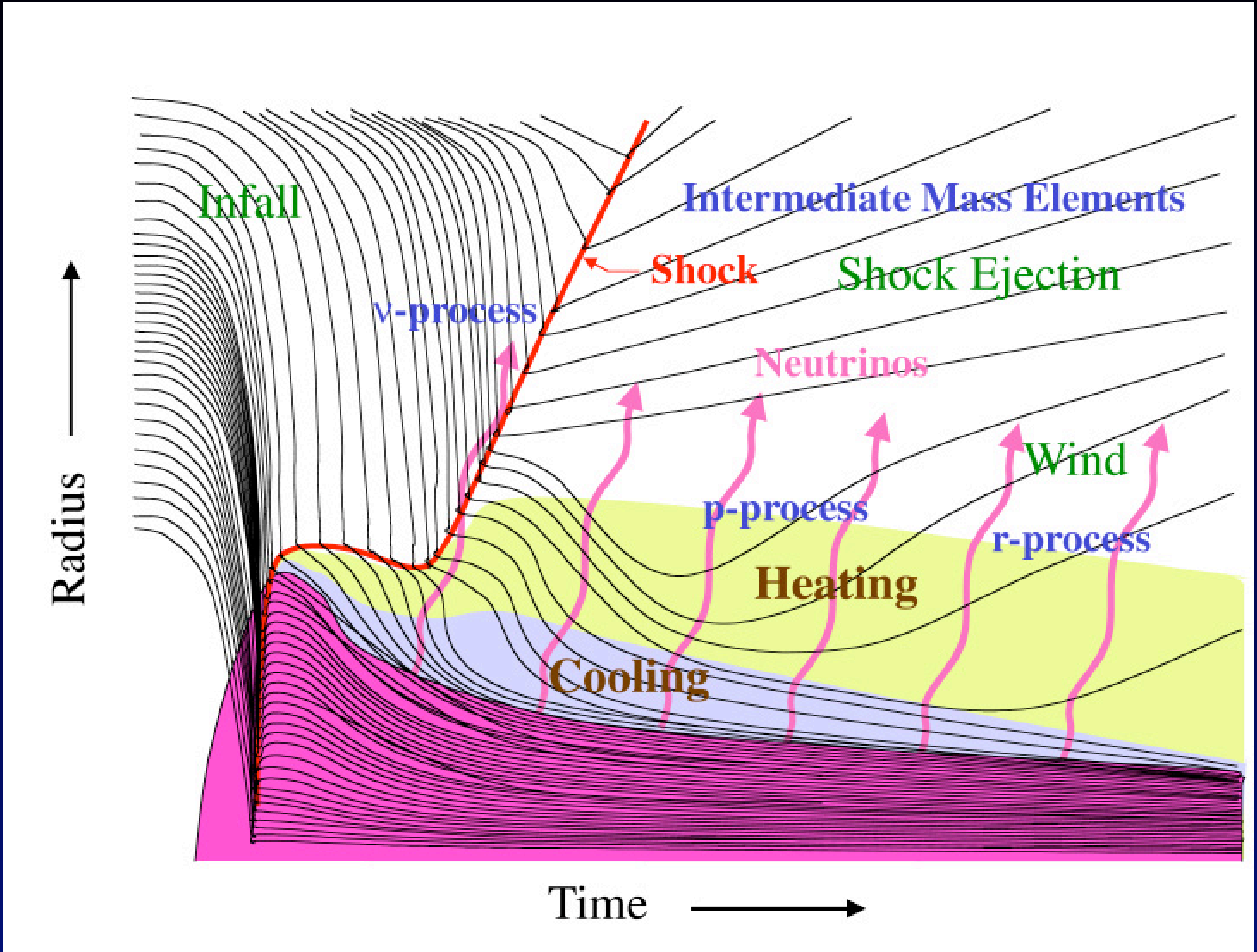
Supernova Science with Radioactive Ion Beams

W.R. Hix (ORNL/UTK)

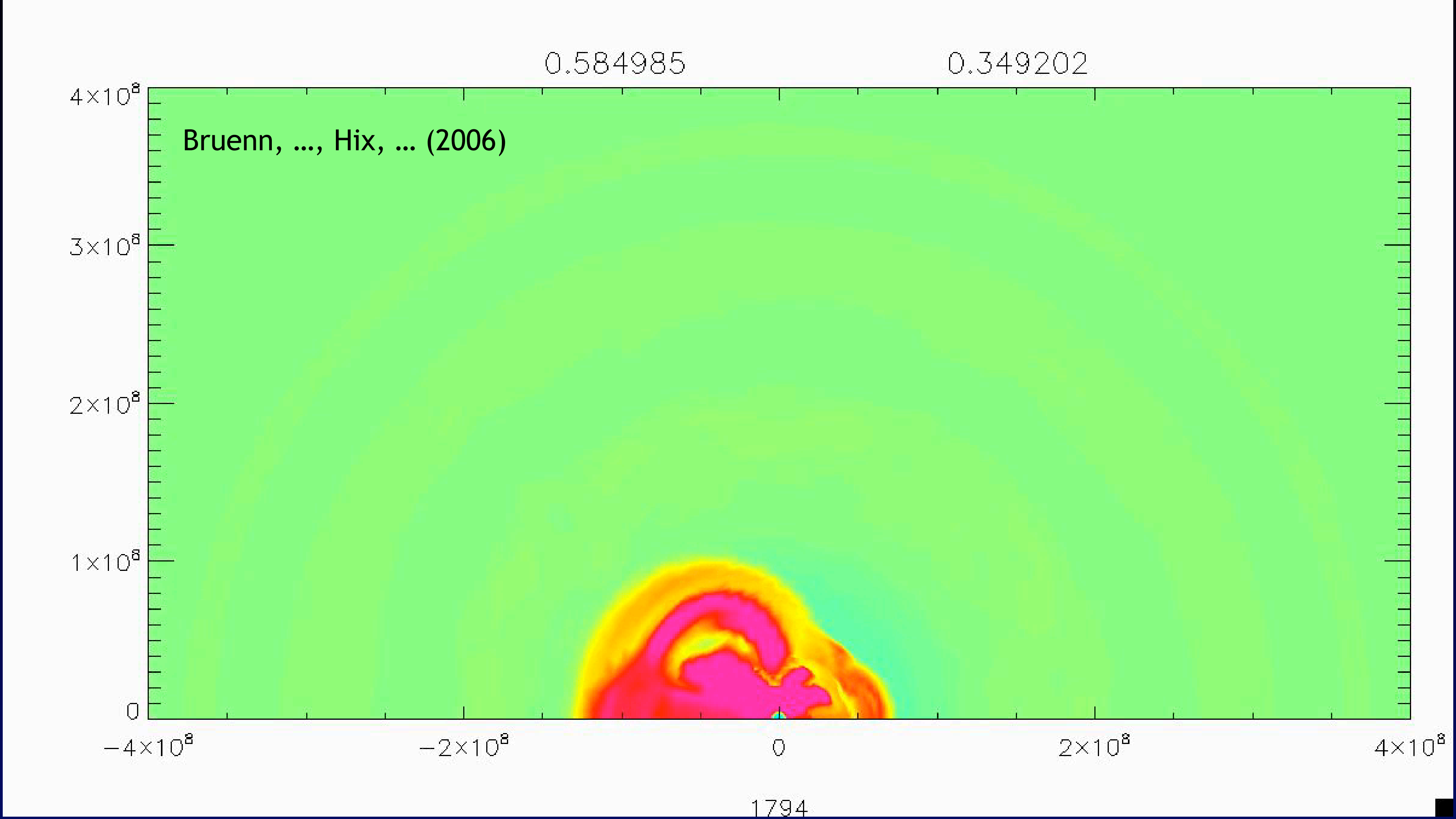

SNO


Stardust
(JPL-Caltech/NASA)

Supernova and their Nucleosynthesis



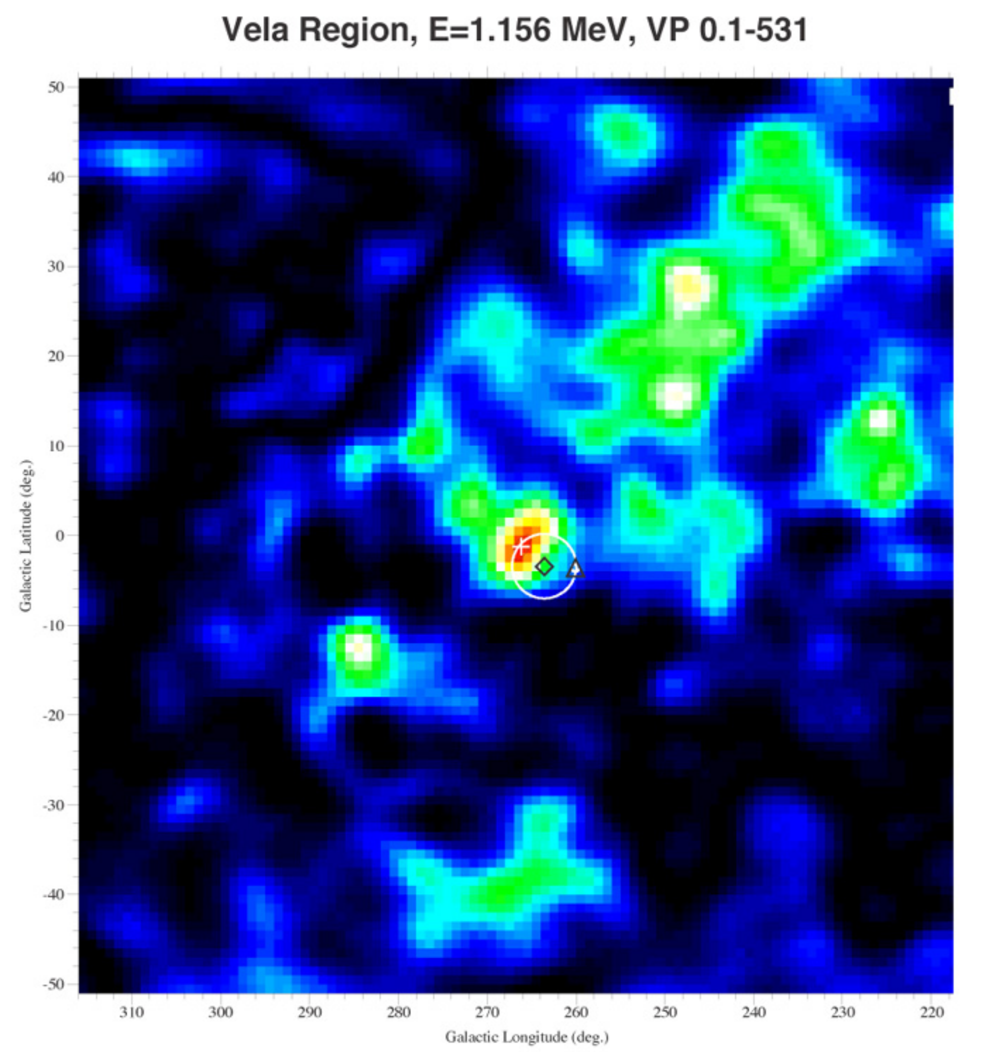
Supernova Modeling is Ongoing



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
  - Shed light on Nuclear EOS
- **Nucleosynthesis**
  - Iron-peak
    - ^{56}Ni, ^{57}Ni, ^{44}Ti, etc.
  - p-process
  - r-process



Effects of Nuclear Electron/Neutrino Capture during Core Collapse

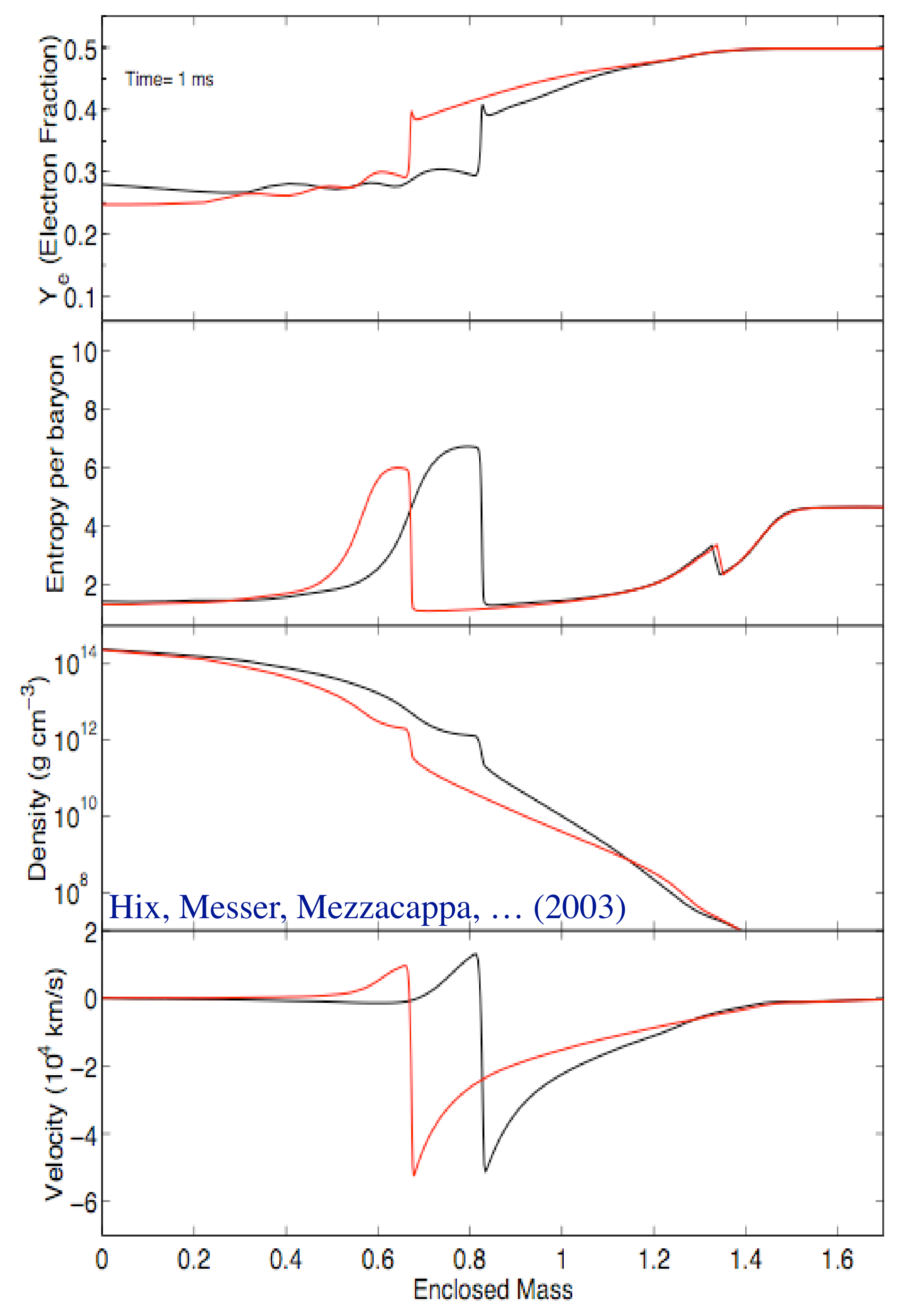
There are 2 separate effects.

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)

Changes in Neutrino Emission

ν_e burst slightly delayed and prolonged.

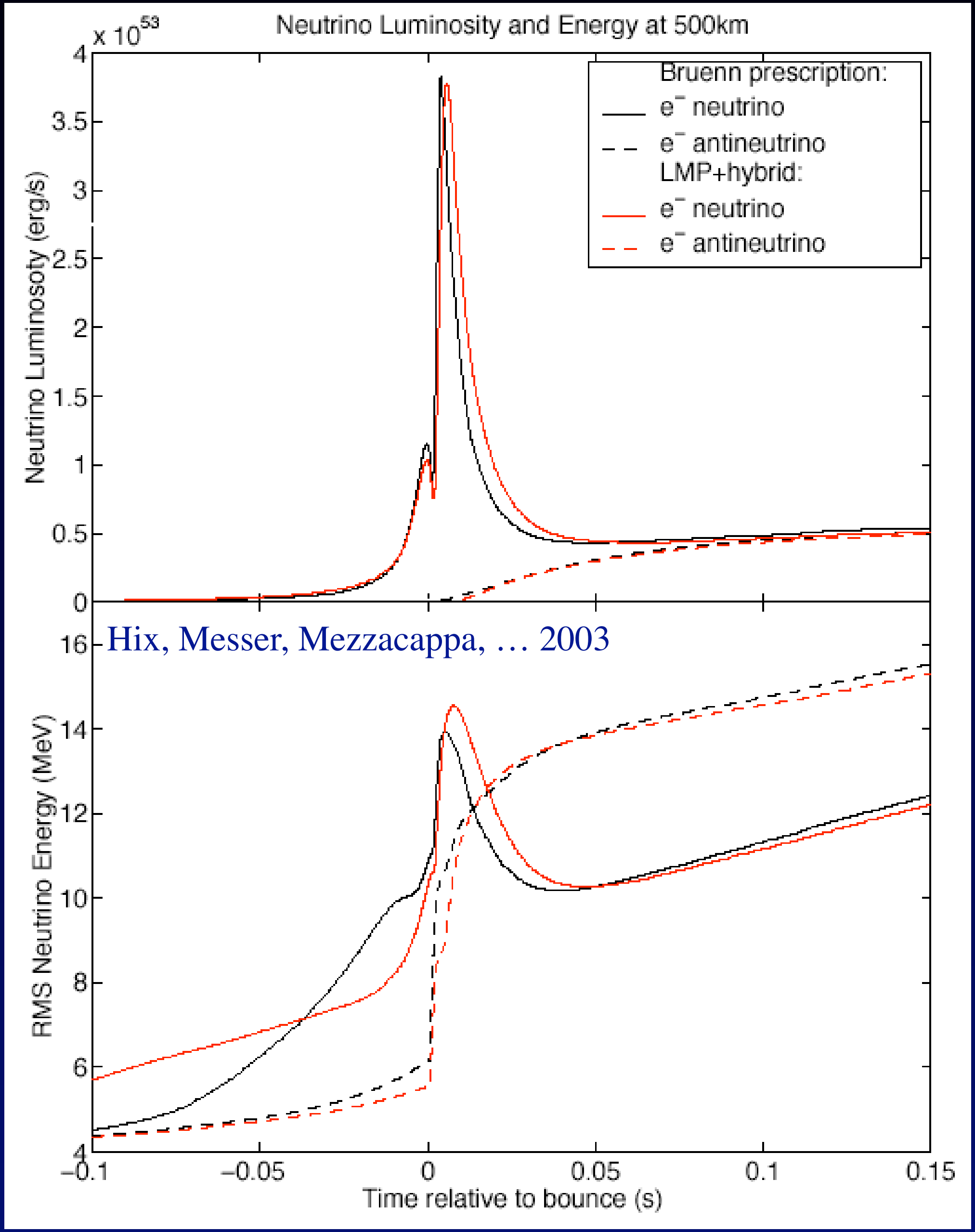
Other luminosities minimally affected (~1%).

Mean ν Energy altered:

1-2 MeV during collapse

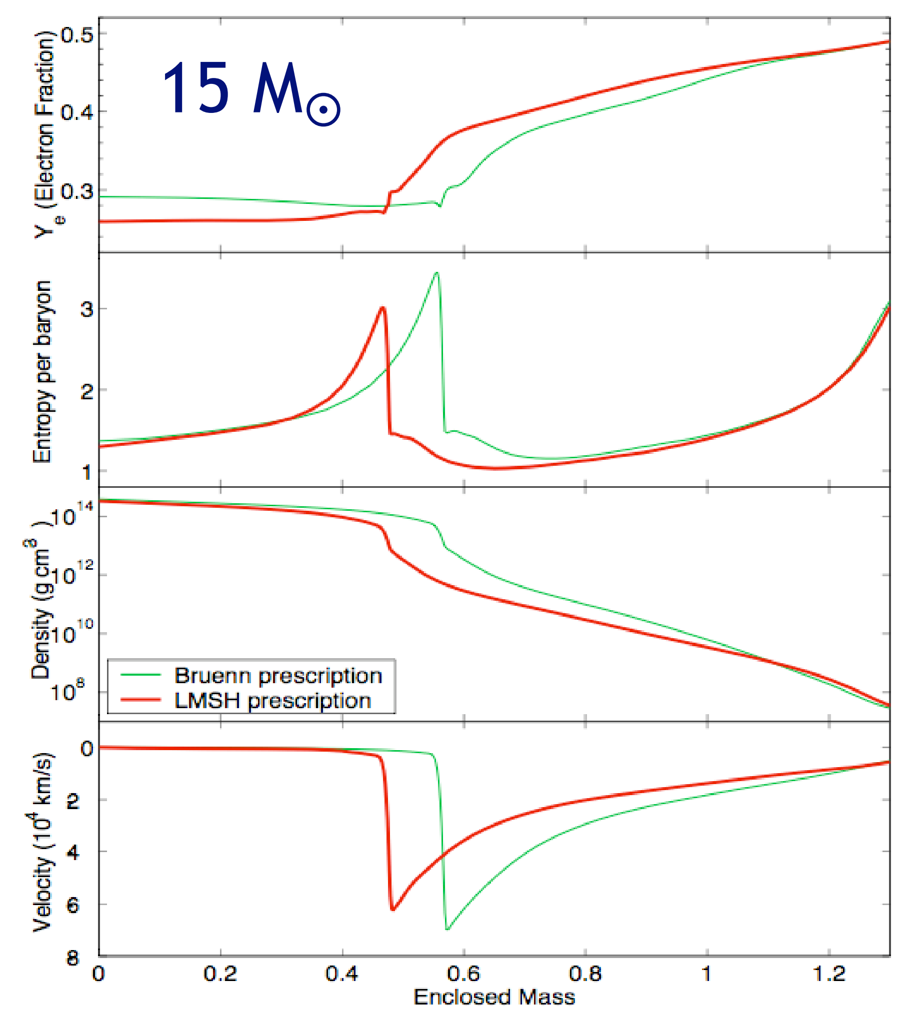
~1 MeV up to 50ms after bounce

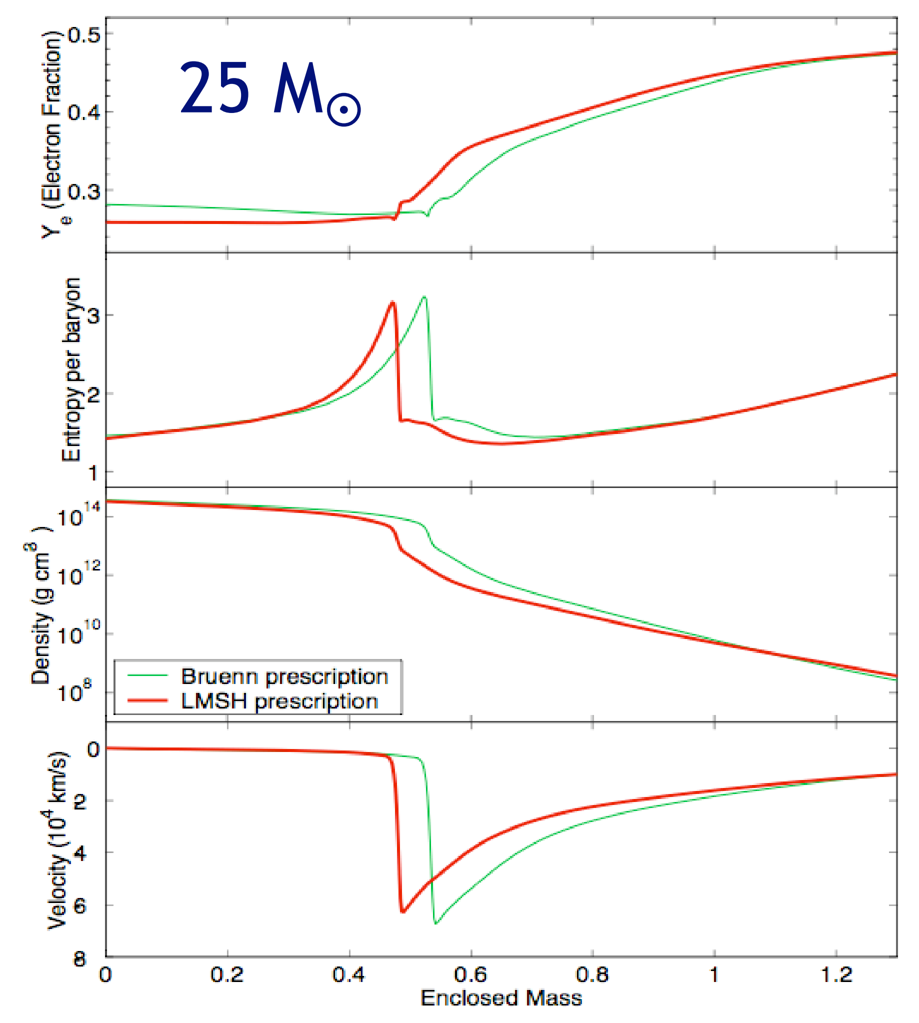
~.3 MeV at late time



Hix, Messer, Mezzacappa, … 2003

The impact of stellar mass





Higher mass cores have higher initial entropy.

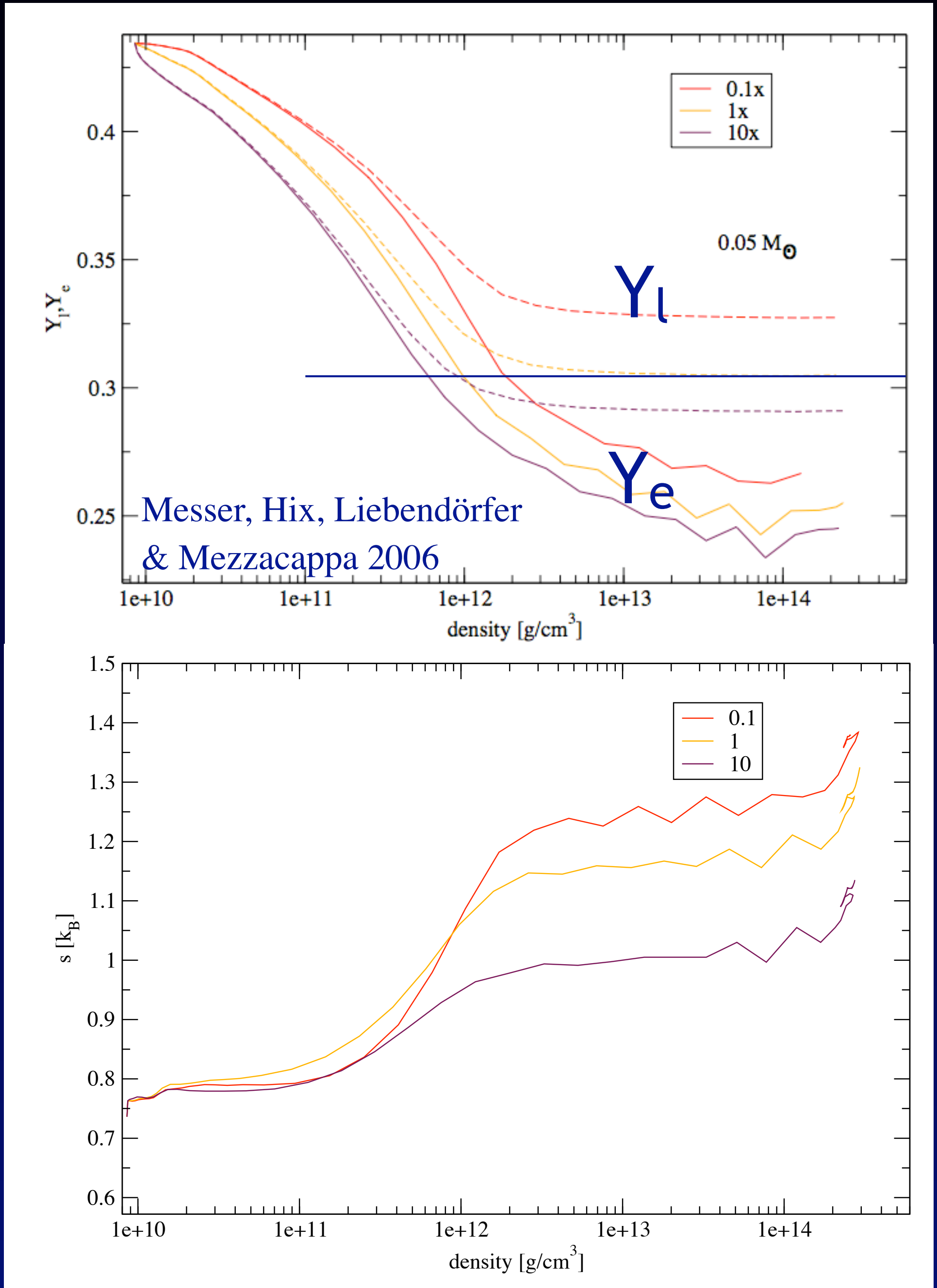
Effects of nuclear electron capture are reduced but comparable (1/2 to 2/3).

Determining Y_e and Entropy

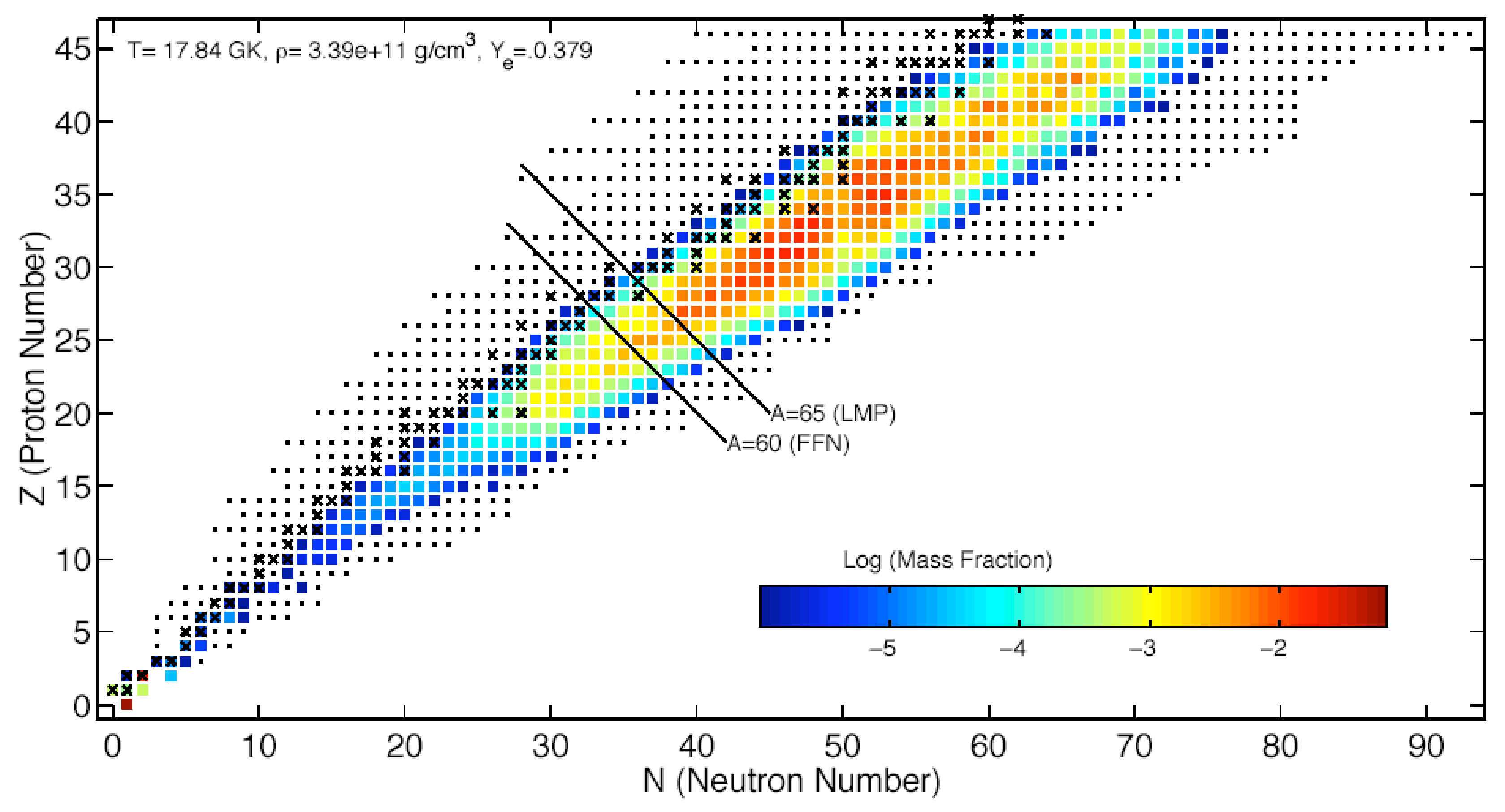
Change in lepton abundance ($Y_l=Y_e+Y_\nu$) occurs gradually over 2+ decades of density up to ~3×10^{12} g/cm^3.

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

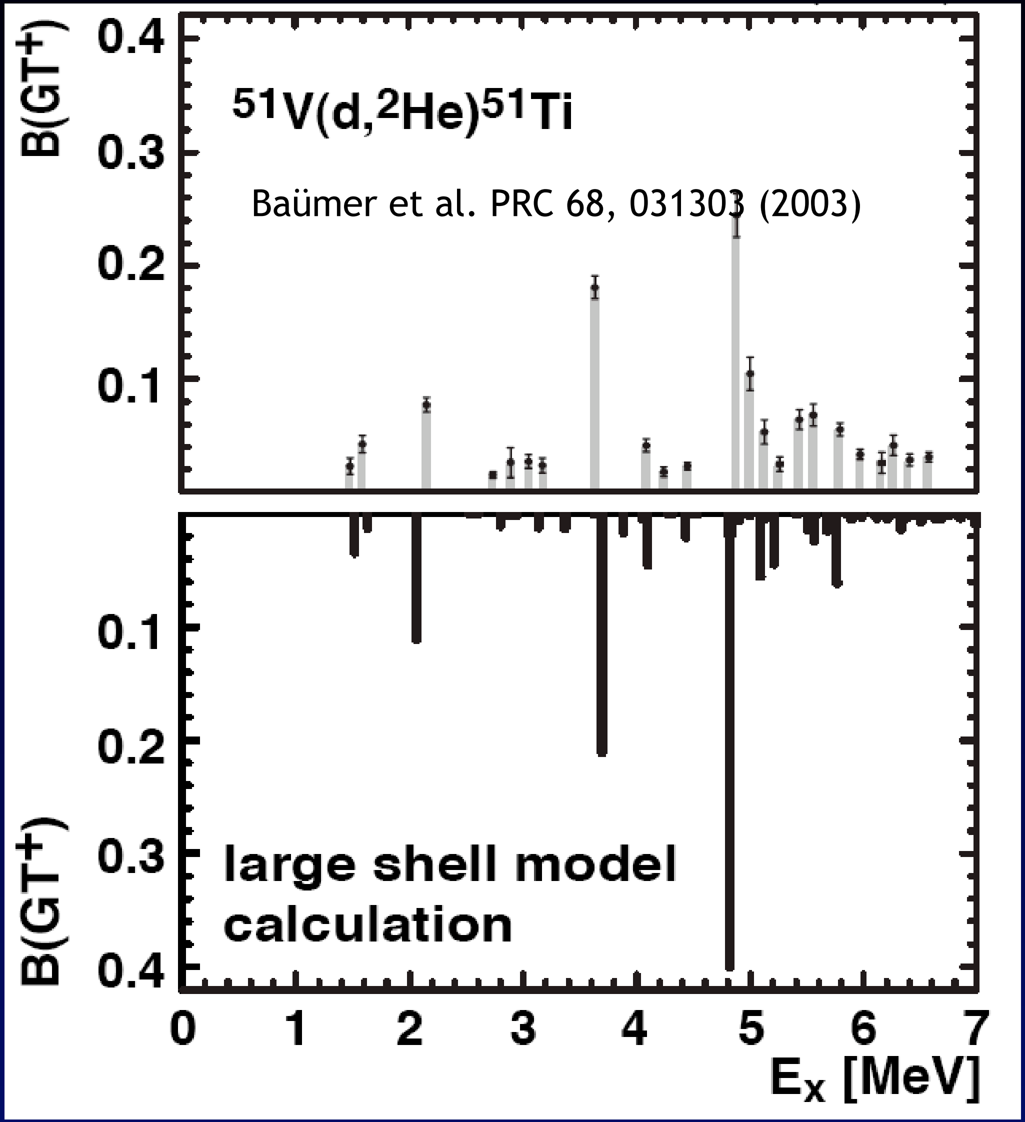


Nuclei with A ~ 100+ contribute to e^-/ν capture.

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.

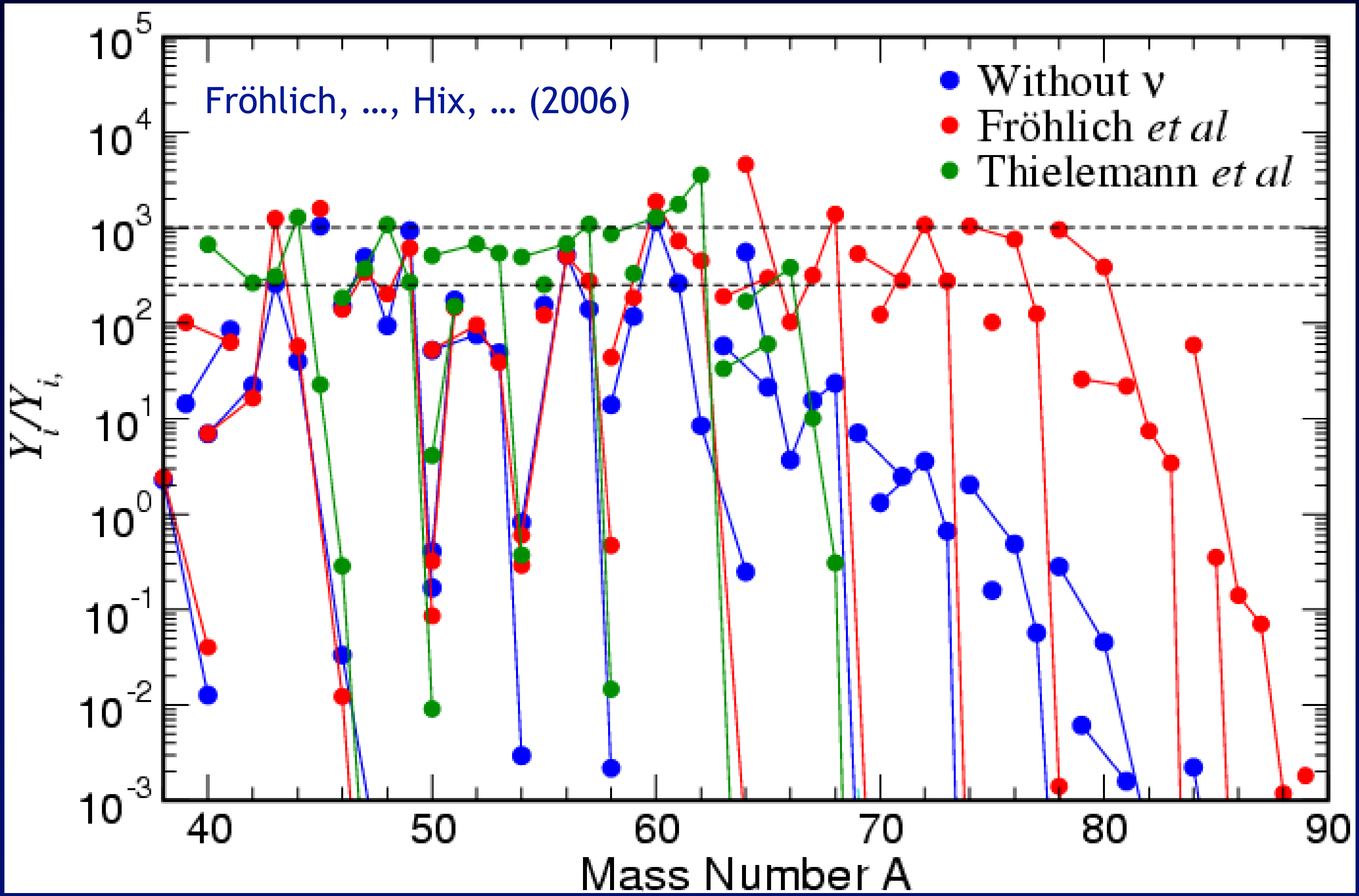
ν-Effects on Supernova Nucleosynthesis

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:

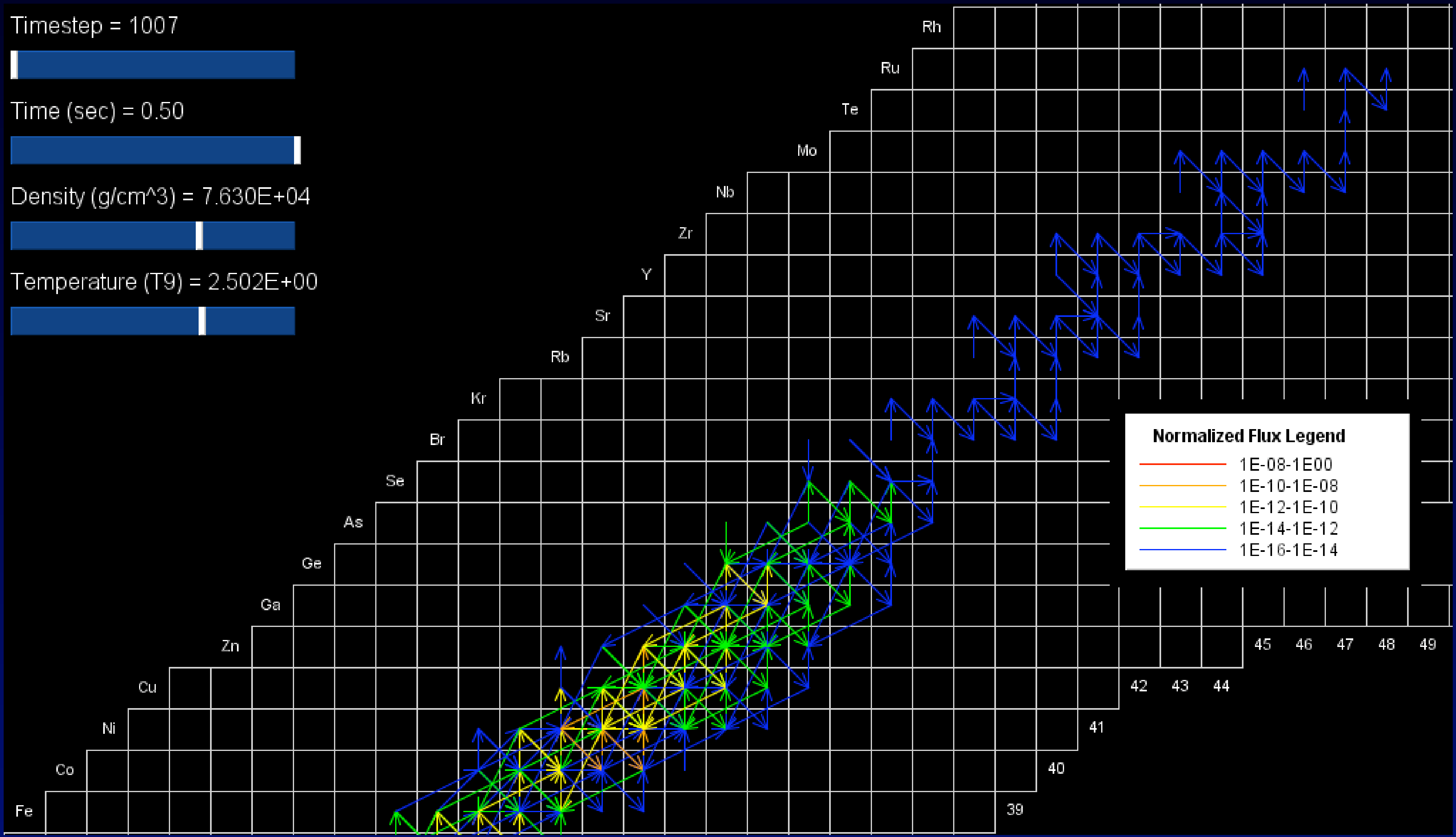
^{64}Ge → ^{64}Zn
^{68}Se → ^{68}Zn
^{72}Kr → ^{72}Ge
^{76}Sr → ^{76}Se
^{80}Zr → ^{80}Kr
^{84}Mo → ^{84}Sr

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



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

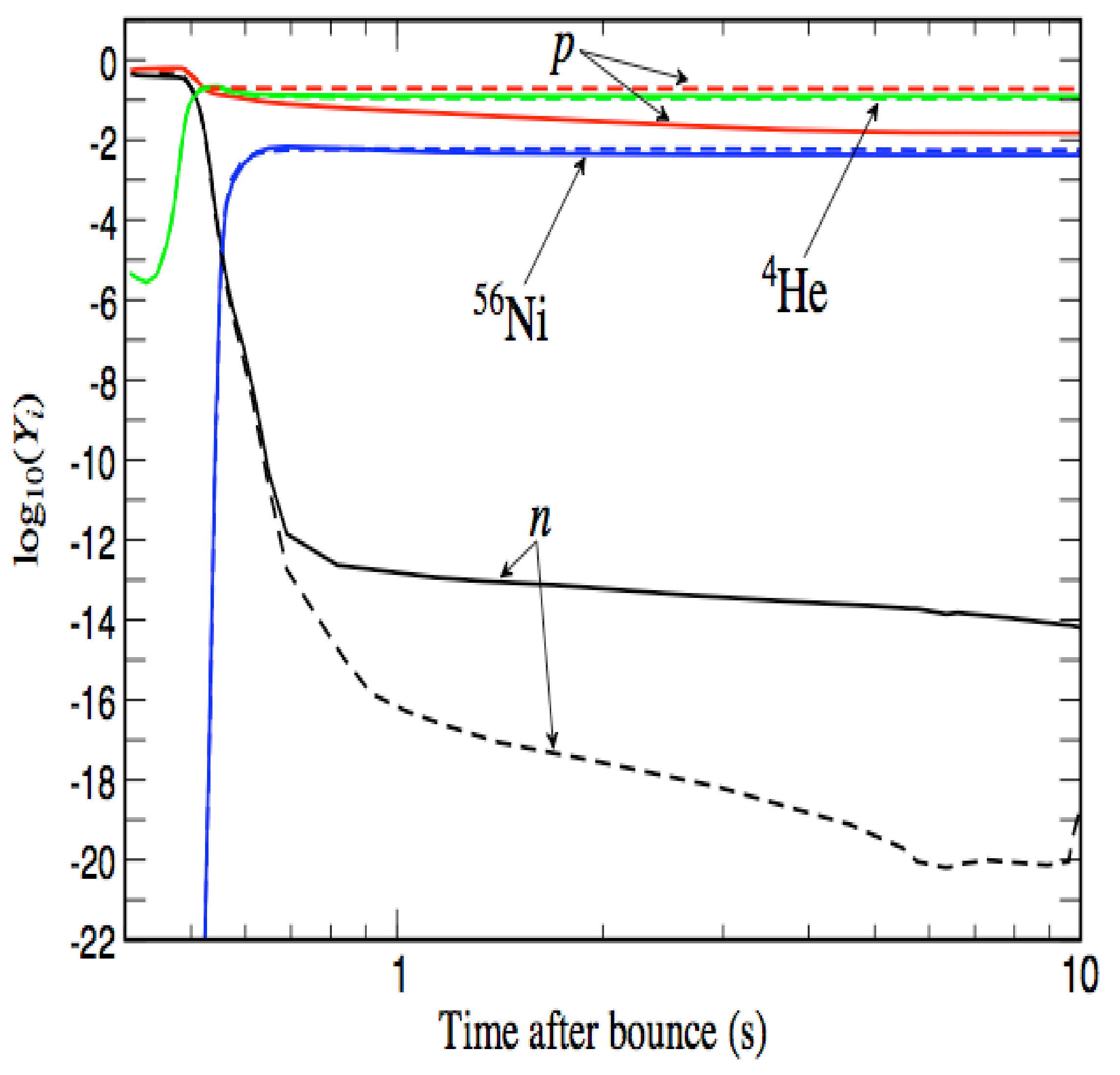
Temperature (T9) = 2.502E+00

Neutrons in a proton-rich environment?

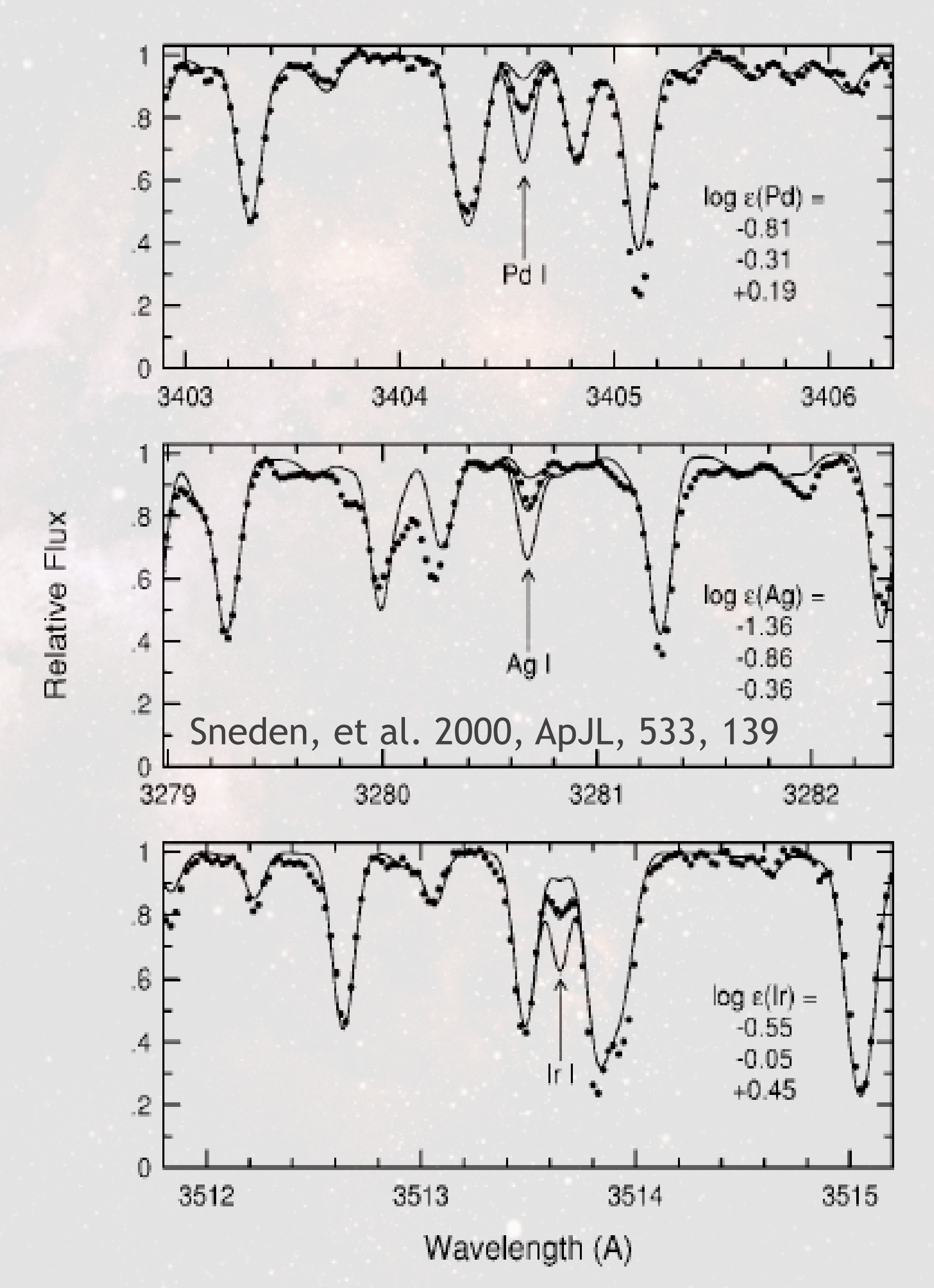
Main abundances: ^{1}H, ^{4}He, ^{56}Ni from p-rich and α-rich freeze-out.

Protons converted to neutrons via anti-neutrino capture.

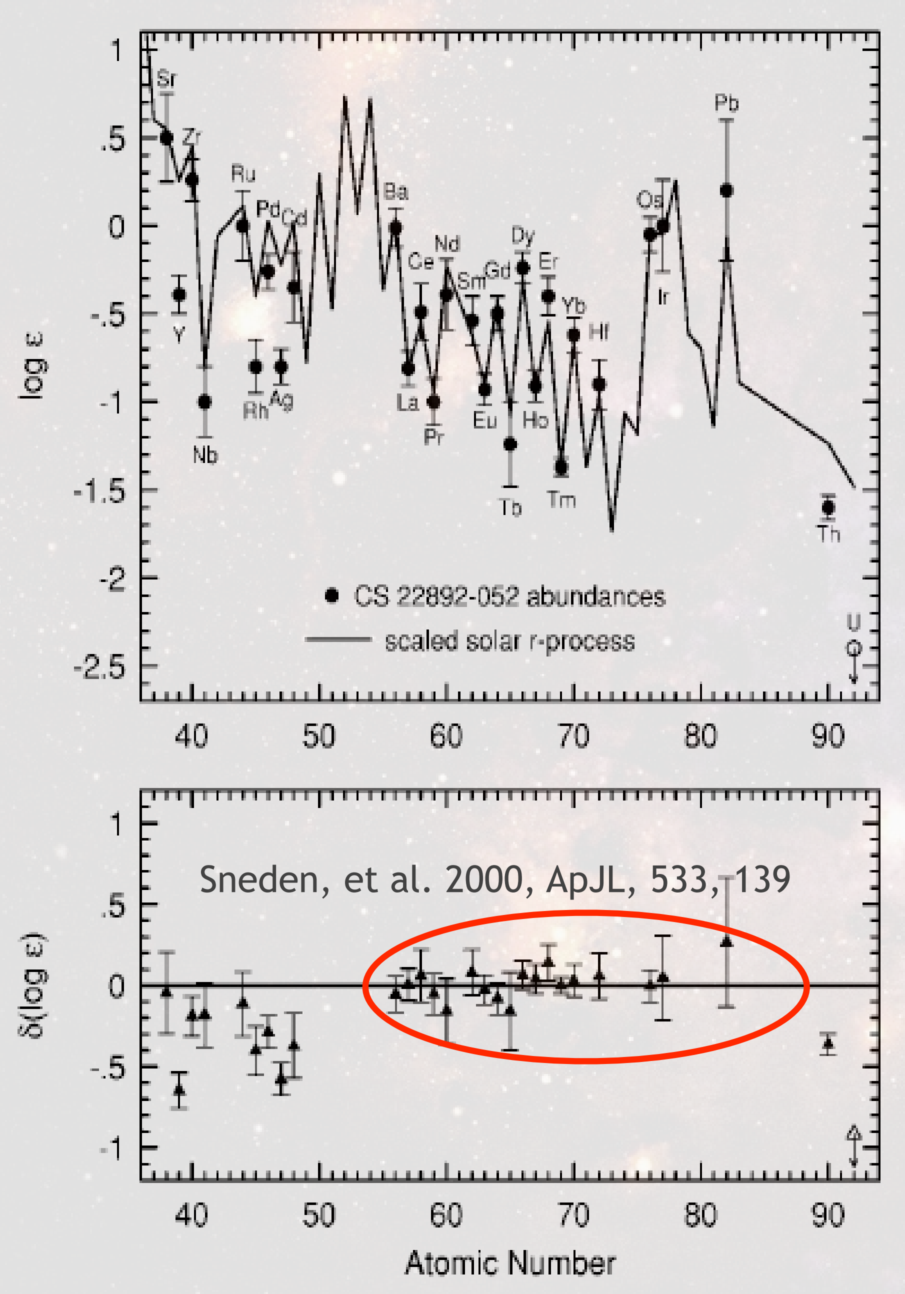
(n,p) and (n,γ) "accelerates" β decays.



Detecting the r-process in old stars



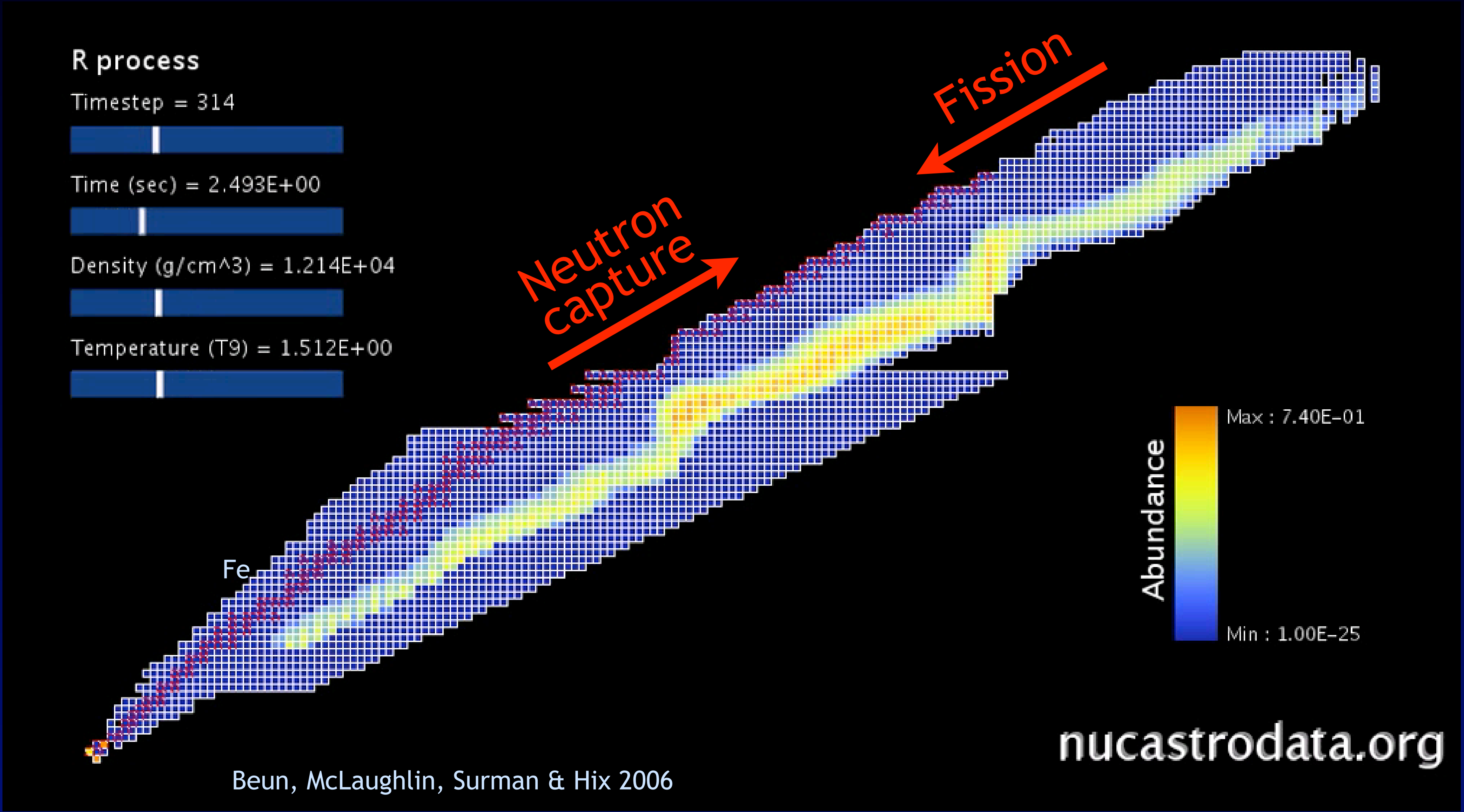
Sneden, et al. 2000, ApJL, 533, 139



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

Simulating the r-process

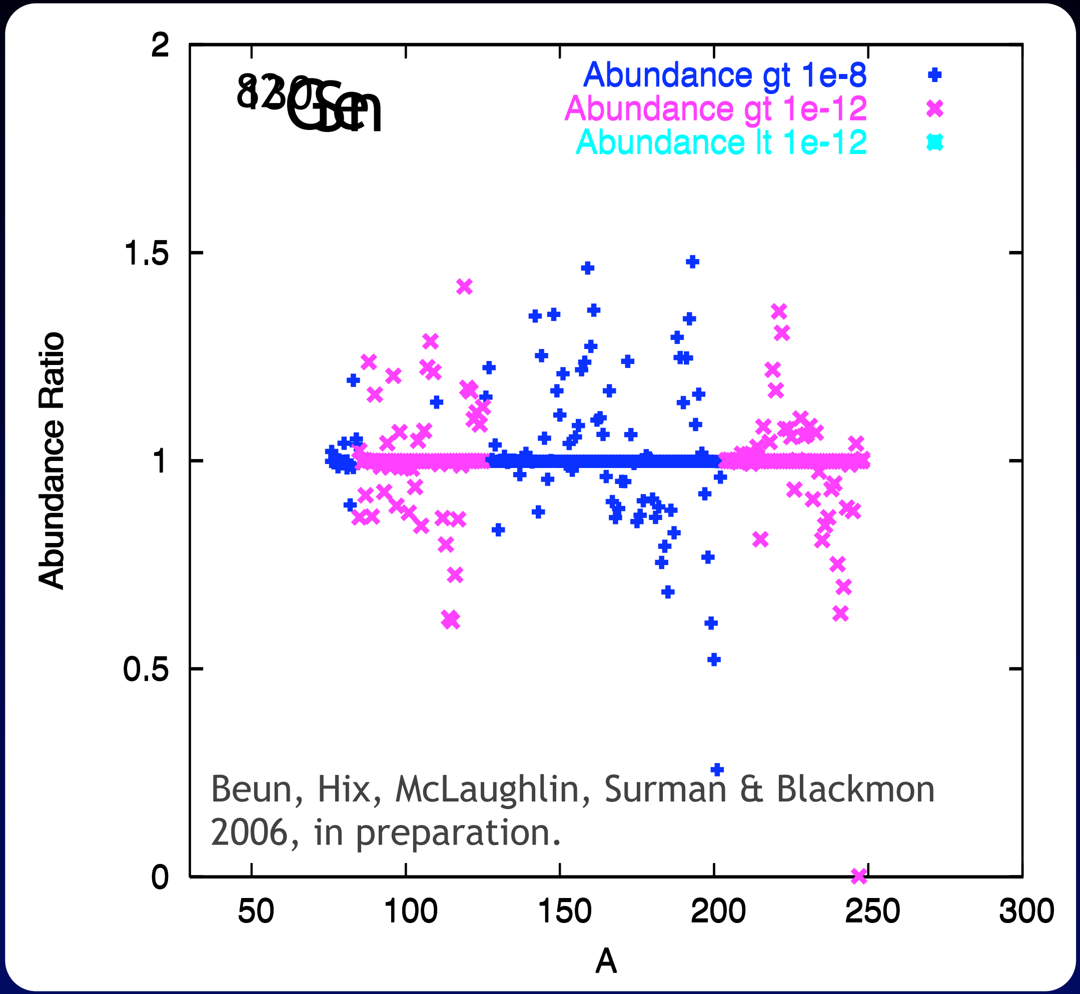
Uncertainties about the site of the r-process provide considerable latitude for modeling.



Beun, McLaughlin, Surman & Hix 2006

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

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

Radioactive Ion Beams can:

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 rates of interest to rp-processes, including the $\nu p-$process, and iron peak nucleosynthesis.

4) provide 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.