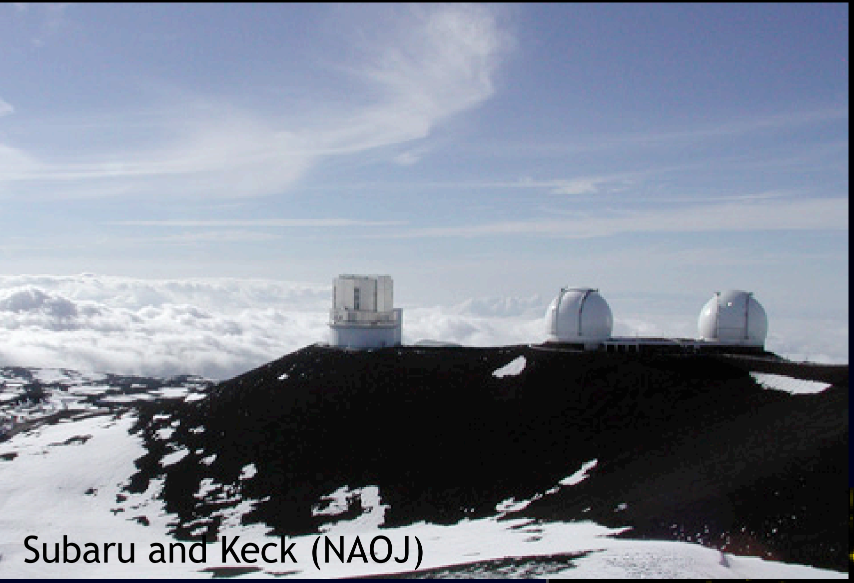
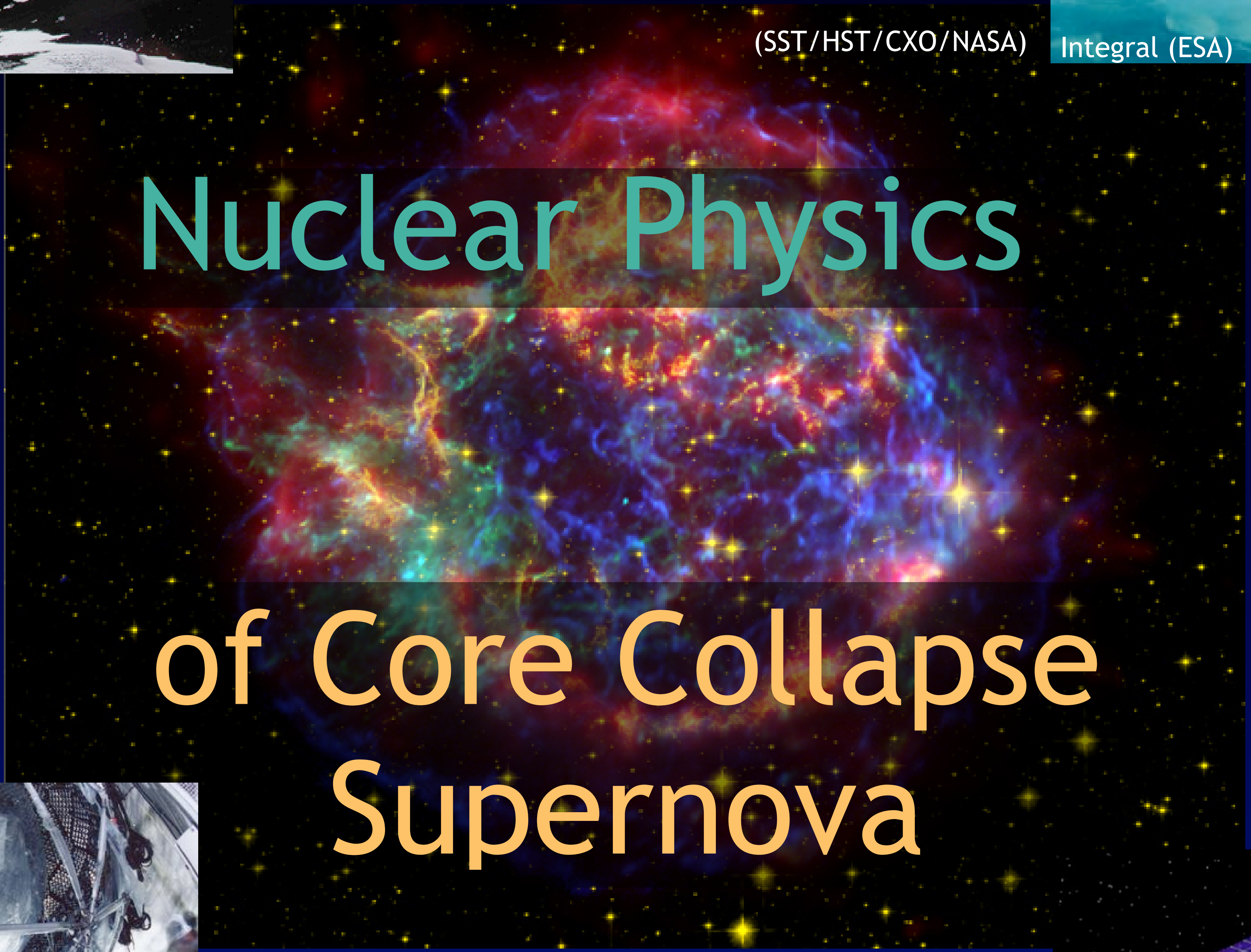

Subaru and Keck (NAOJ)

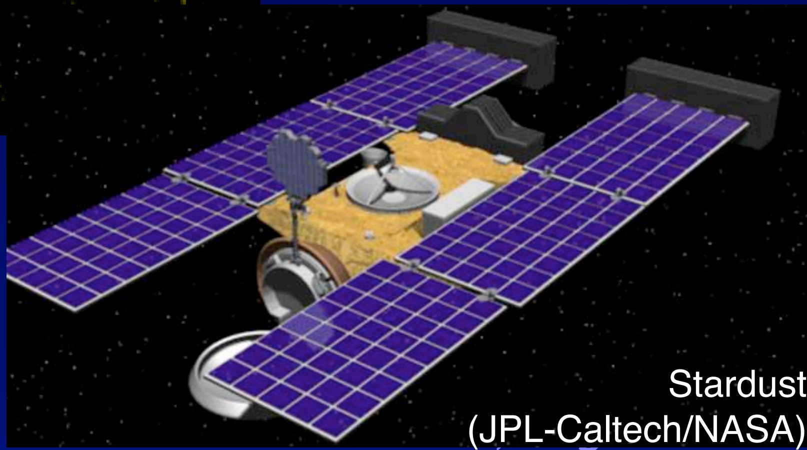

Integral (ESA)


(SST/HST/CXO/NASA)

Nuclear Physics of Core Collapse Supernova

W.R. Hix (ORNL/UTK)

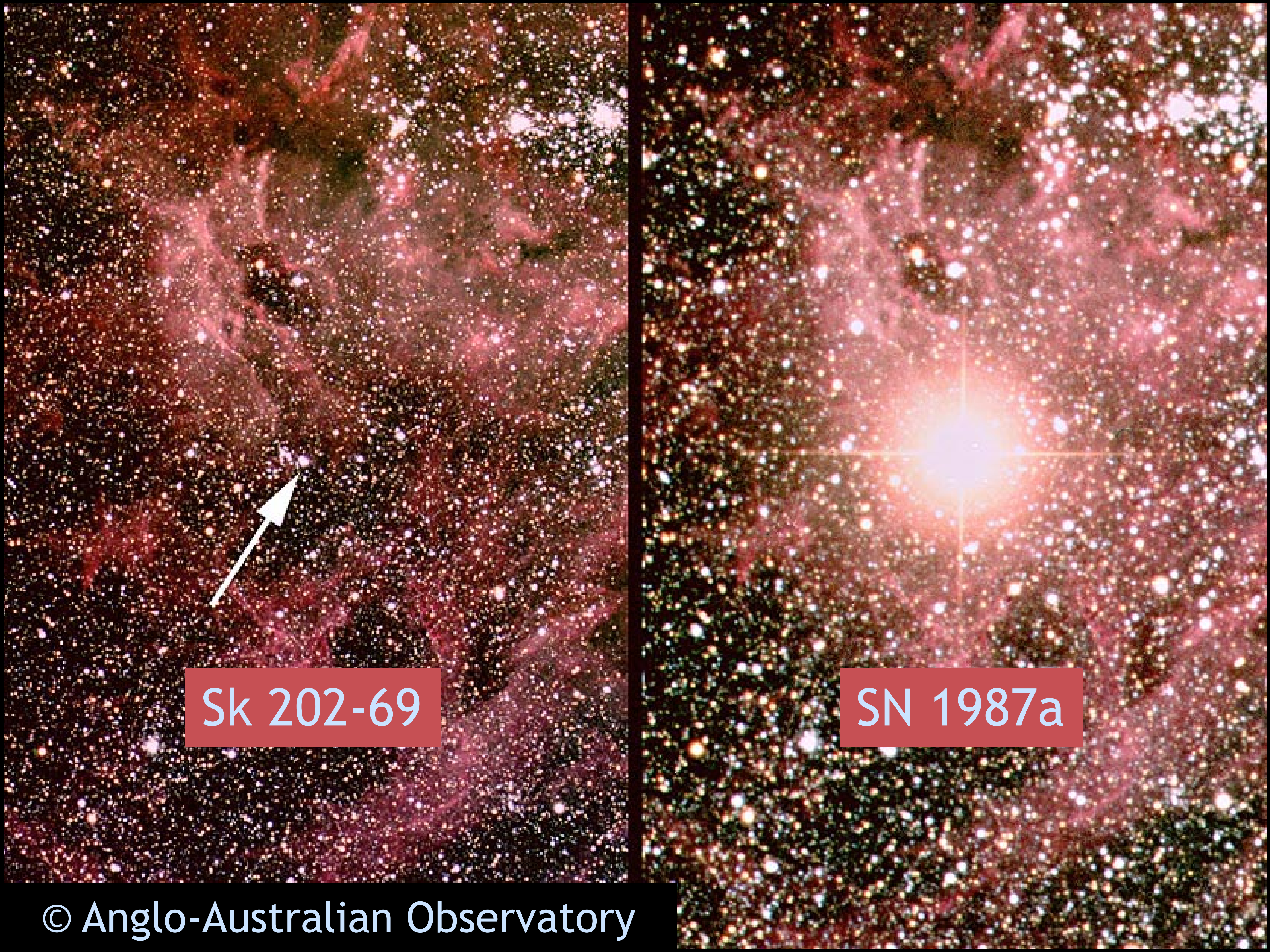

SNO


Stardust (JPL-Caltech/NASA)

Lecture Schedule

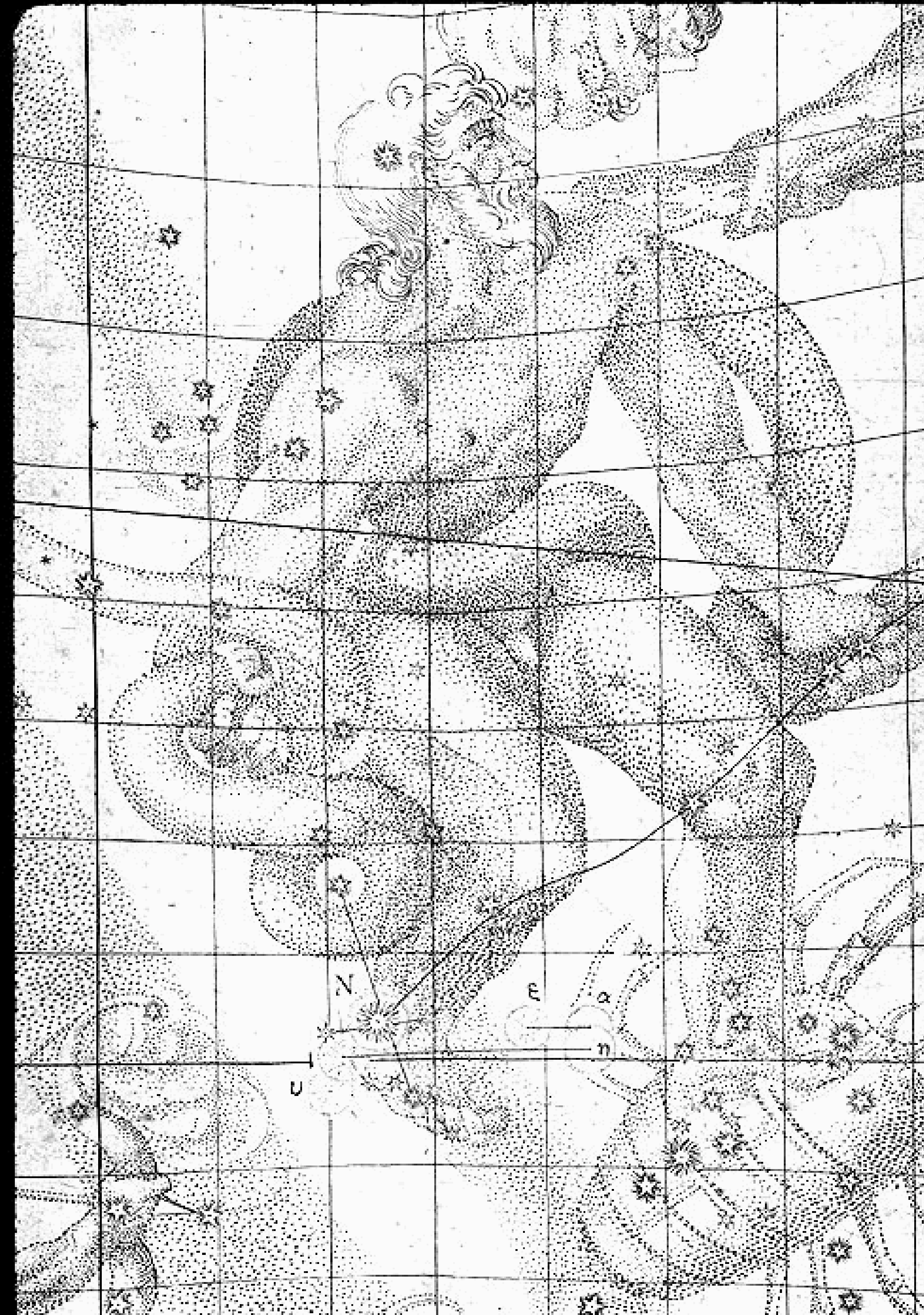
1. Nuclear Physics for Astrophysics
2. Lives of Stars
3. Core Collapse Supernovae
   a) What role to CC SN play in cosmic nuclear evolution?
   b) How does nuclear physics affect the supernova explosion and the resulting nucleosynthesis?
4. Stellar Afterlife

Supernova!



Historical Supernovae

Name	Year
RX J1713.7-3946	393
G327.6+14.6	1006
Crab Nebula	1054
3C 58	1181
Tycho	1572
Kepler	1604
Cassiopeia A	1668
S Andromedae	1885
Shelton	1987



Kepler, *De Stella Nova in Pede Serpentarii,* (1606)

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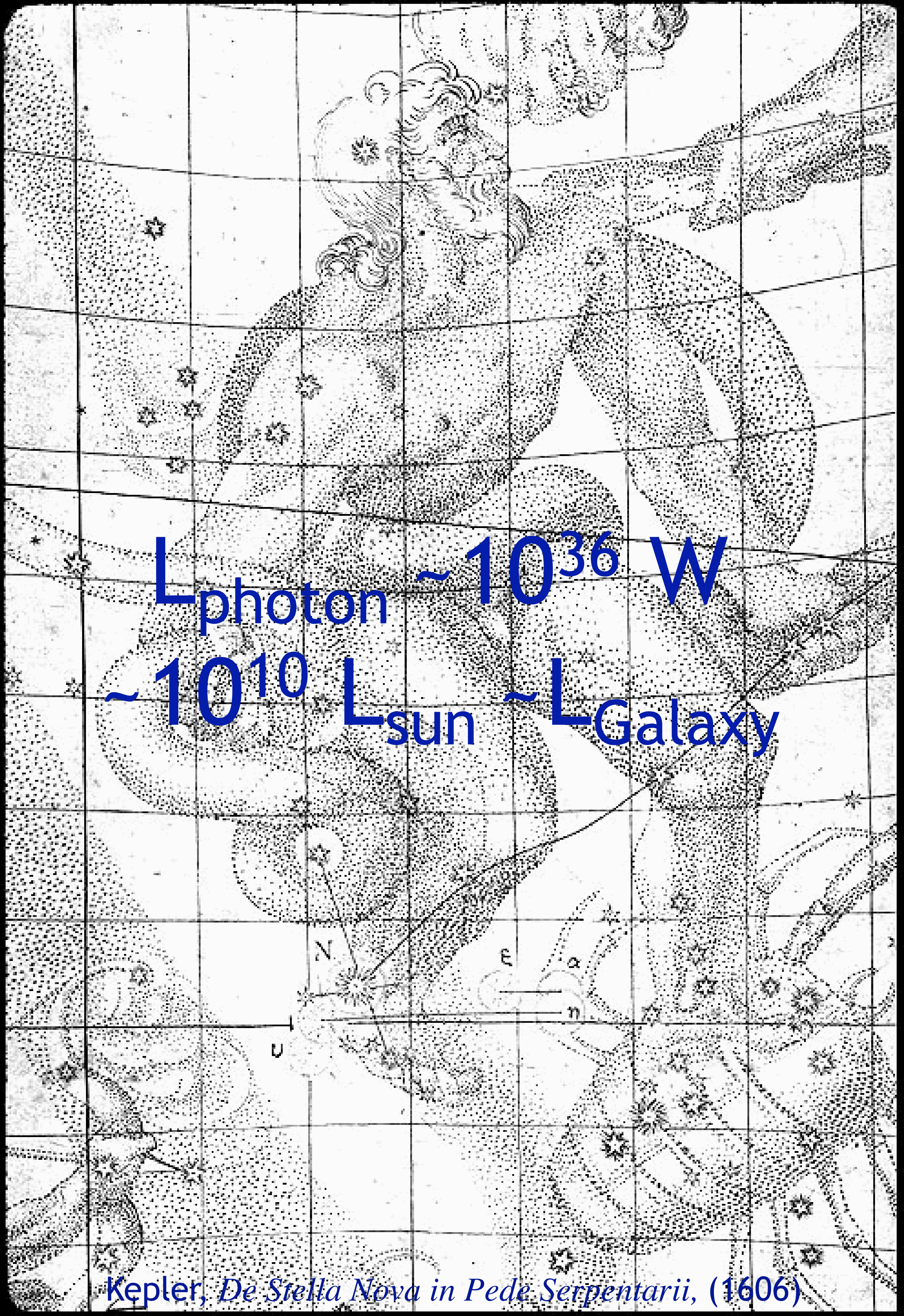

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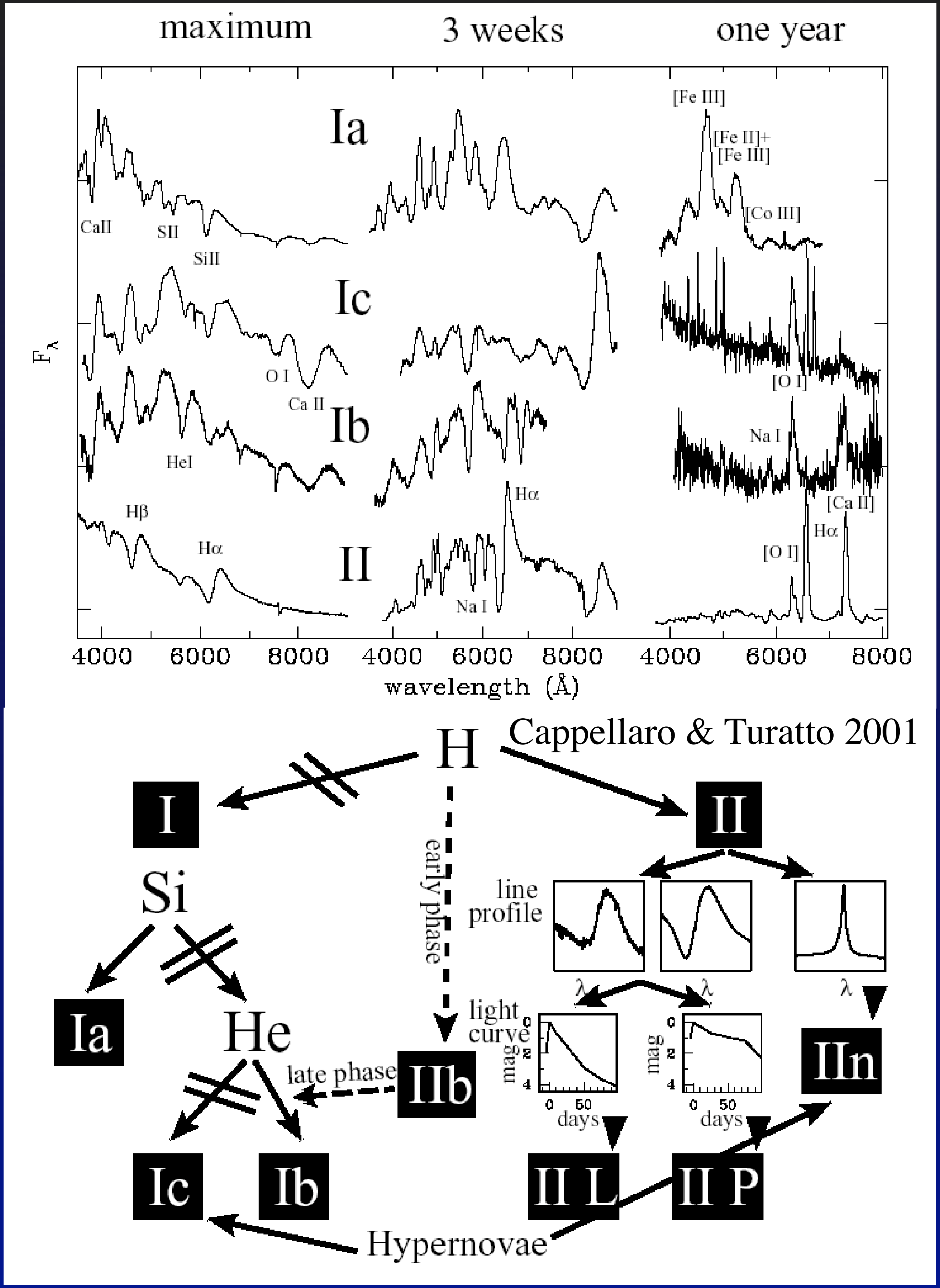
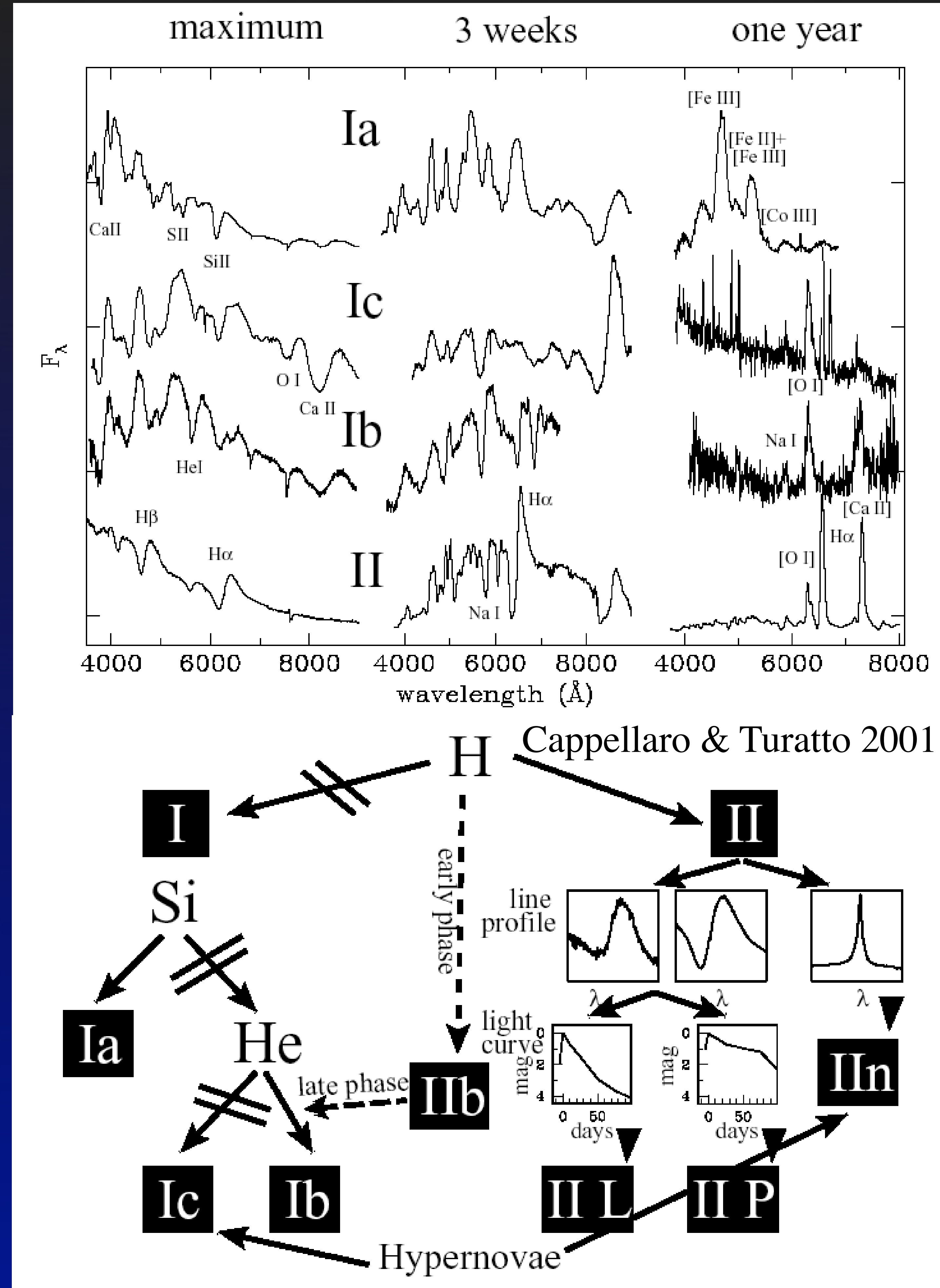
Supernova Taxonomy



Supernova Taxonomy

Observationally, there are 2 types (and 7 subtypes) based on their spectra and light curves.

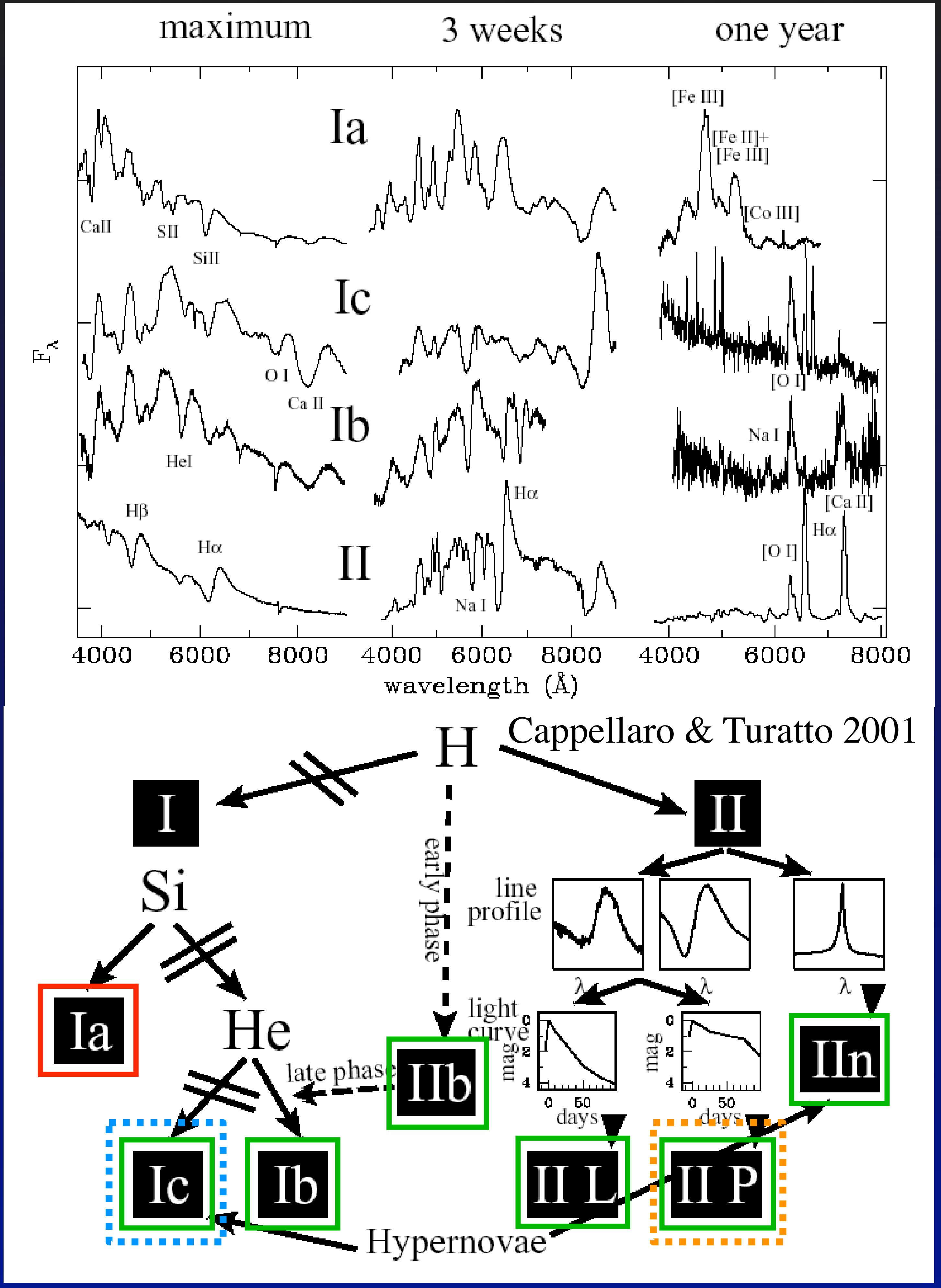


Cappellaro & Turatto 2001

Supernova Taxonomy

Observationally, there are 2 types (and 7 subtypes) based on their spectra and light curves.

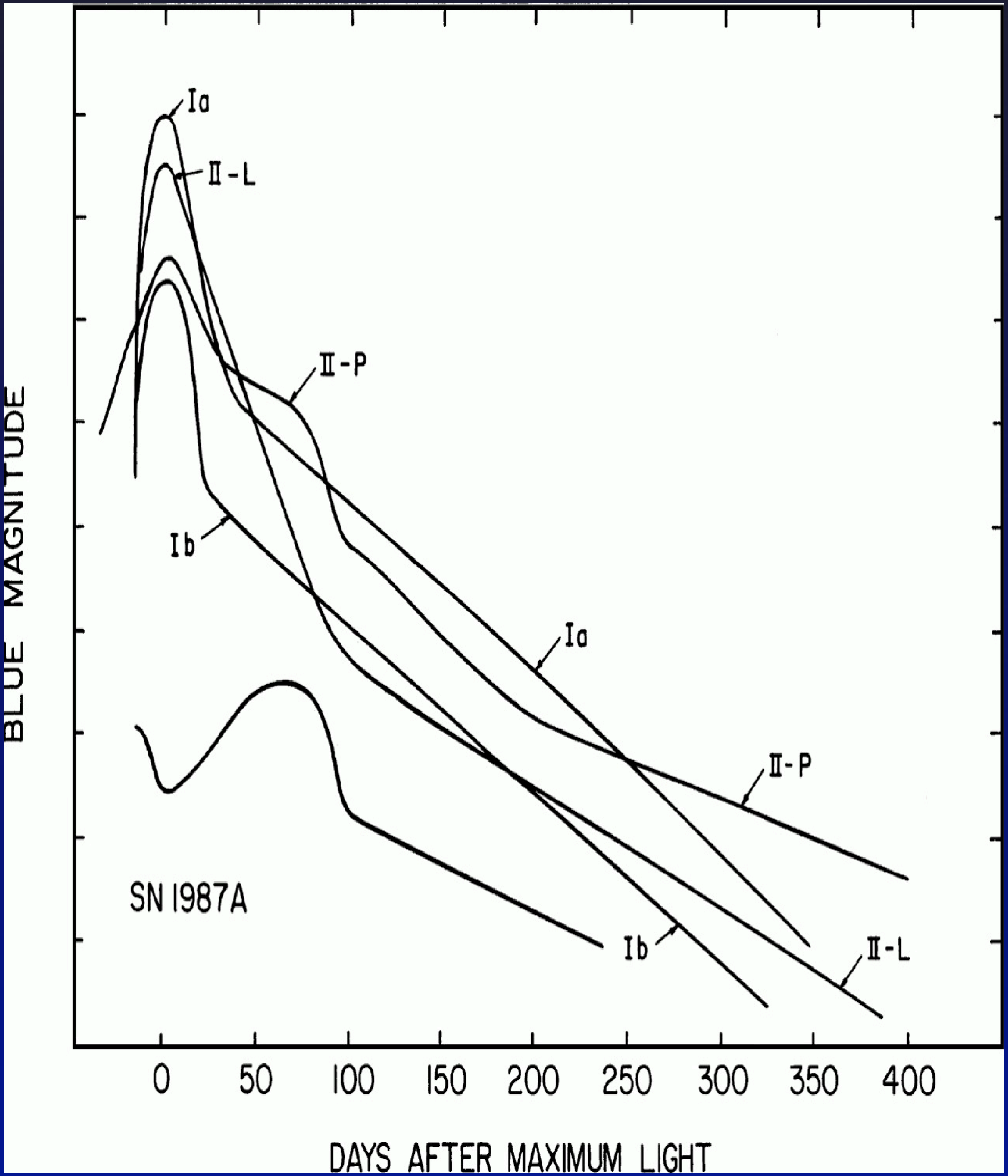
Physically, there are ~~2~~ ~~3~~ 4 mechanisms, thermonuclear (white dwarf), core collapse (massive star), collapsar (very massive star), pair (very very massive star)



6 from 1, 1 from another

The core collapse mechanism results in supernovae with quite varied spectra and light curves because of the variations in the stellar envelope which surrounds the central engine.

In contrast, the Type Ia SN are remarkable similar, suggesting a mechanism with little variation.



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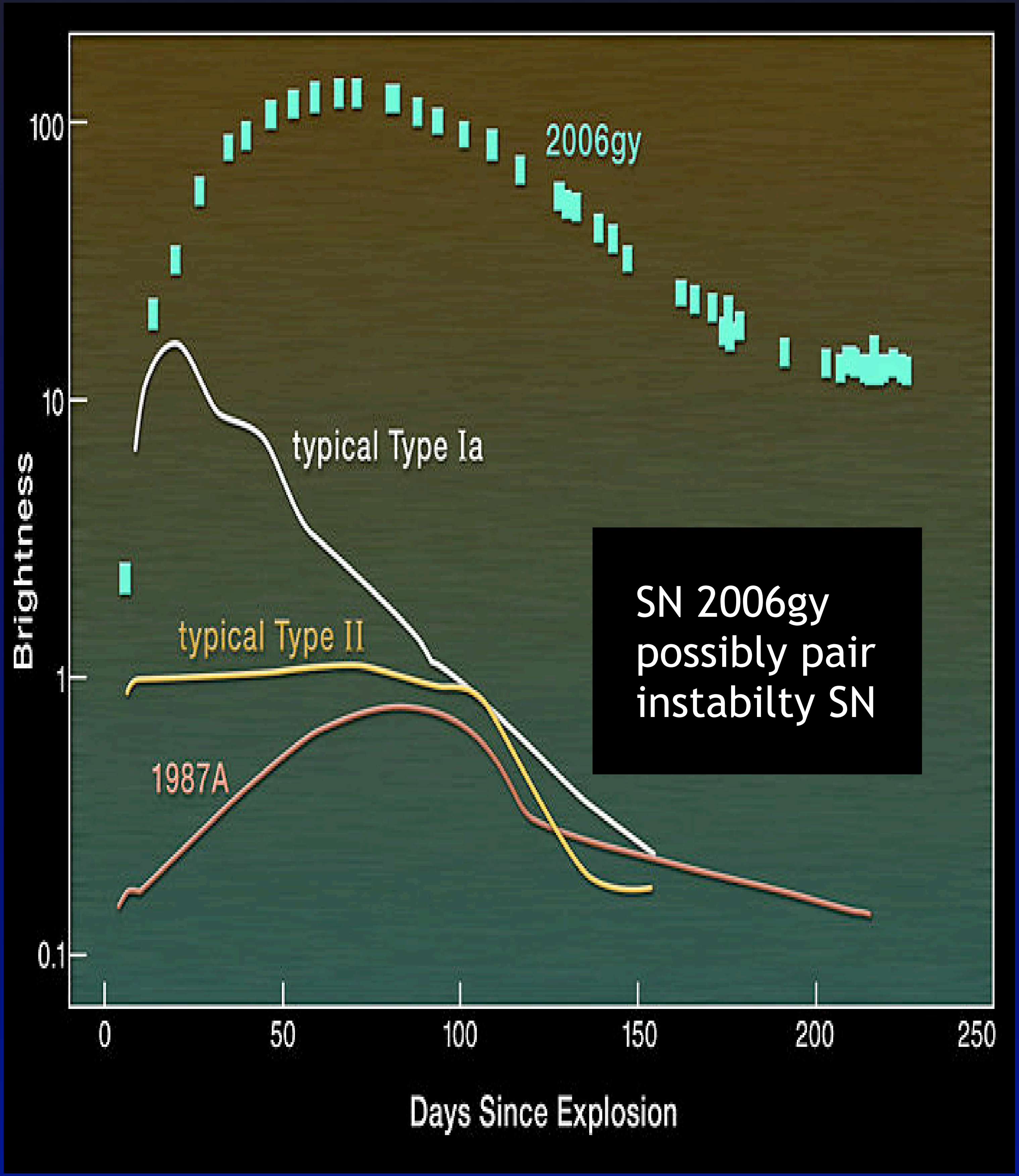
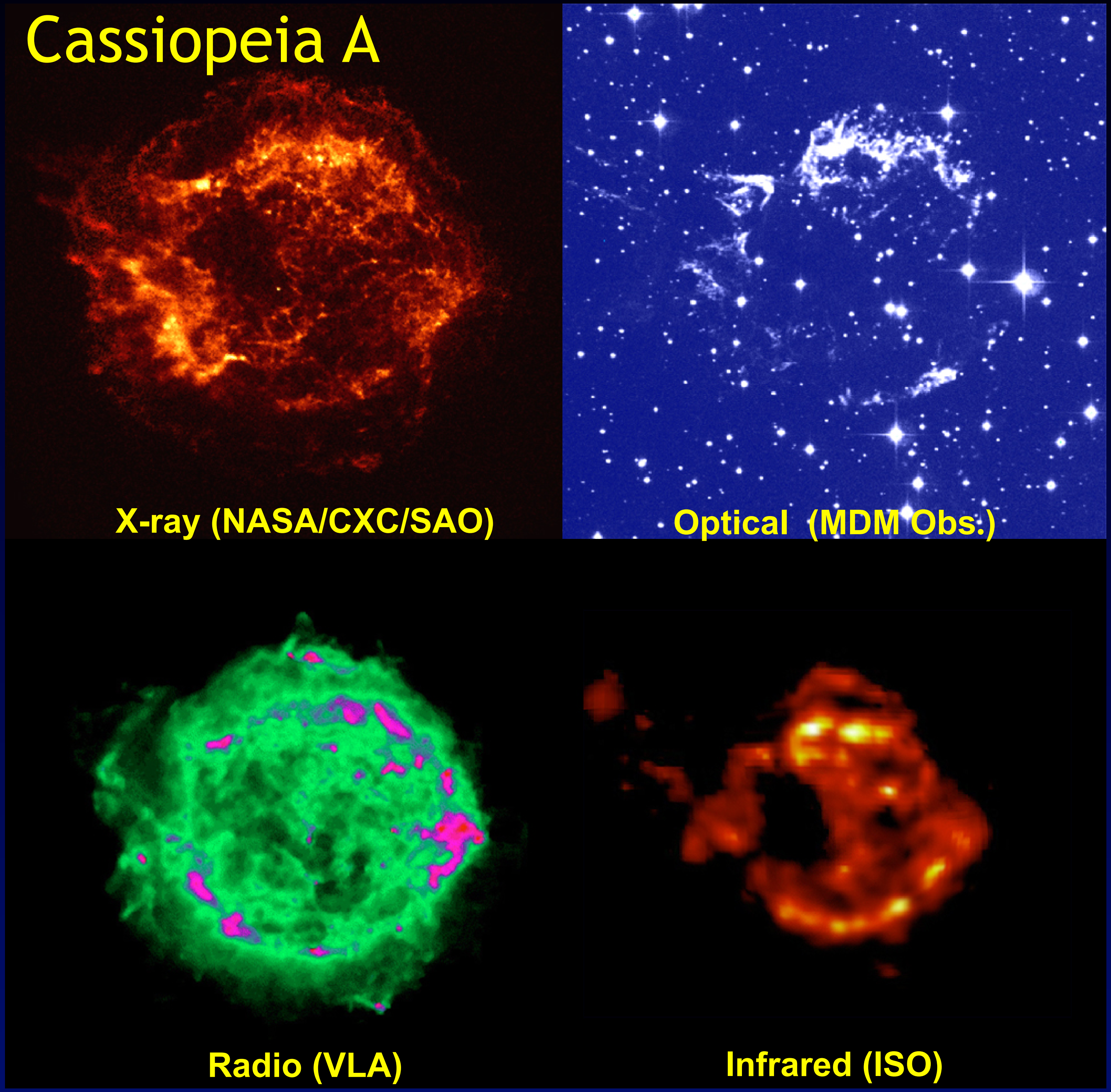
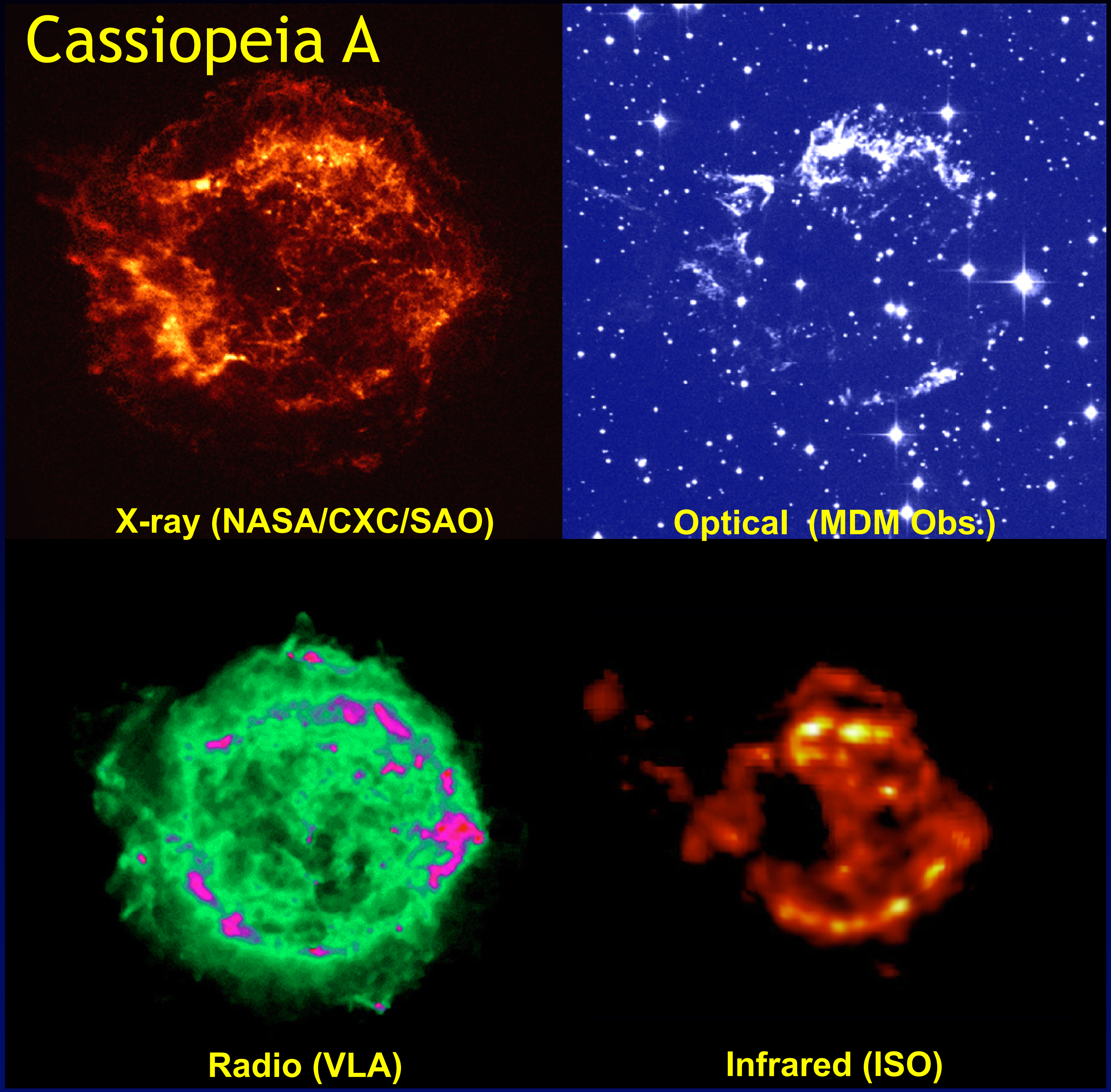


Supernova at 320 Years Old

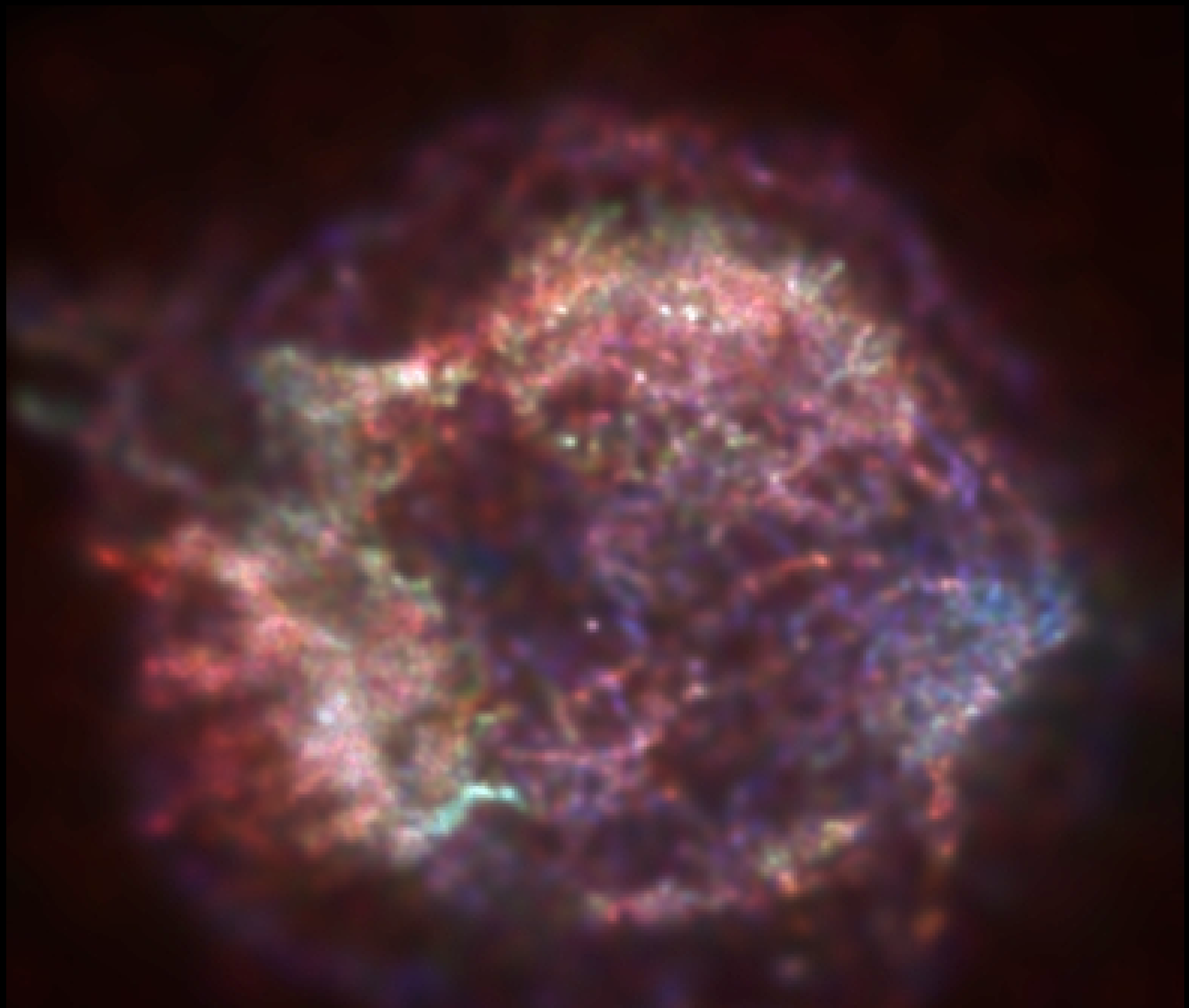


Supernova at 320 Years Old

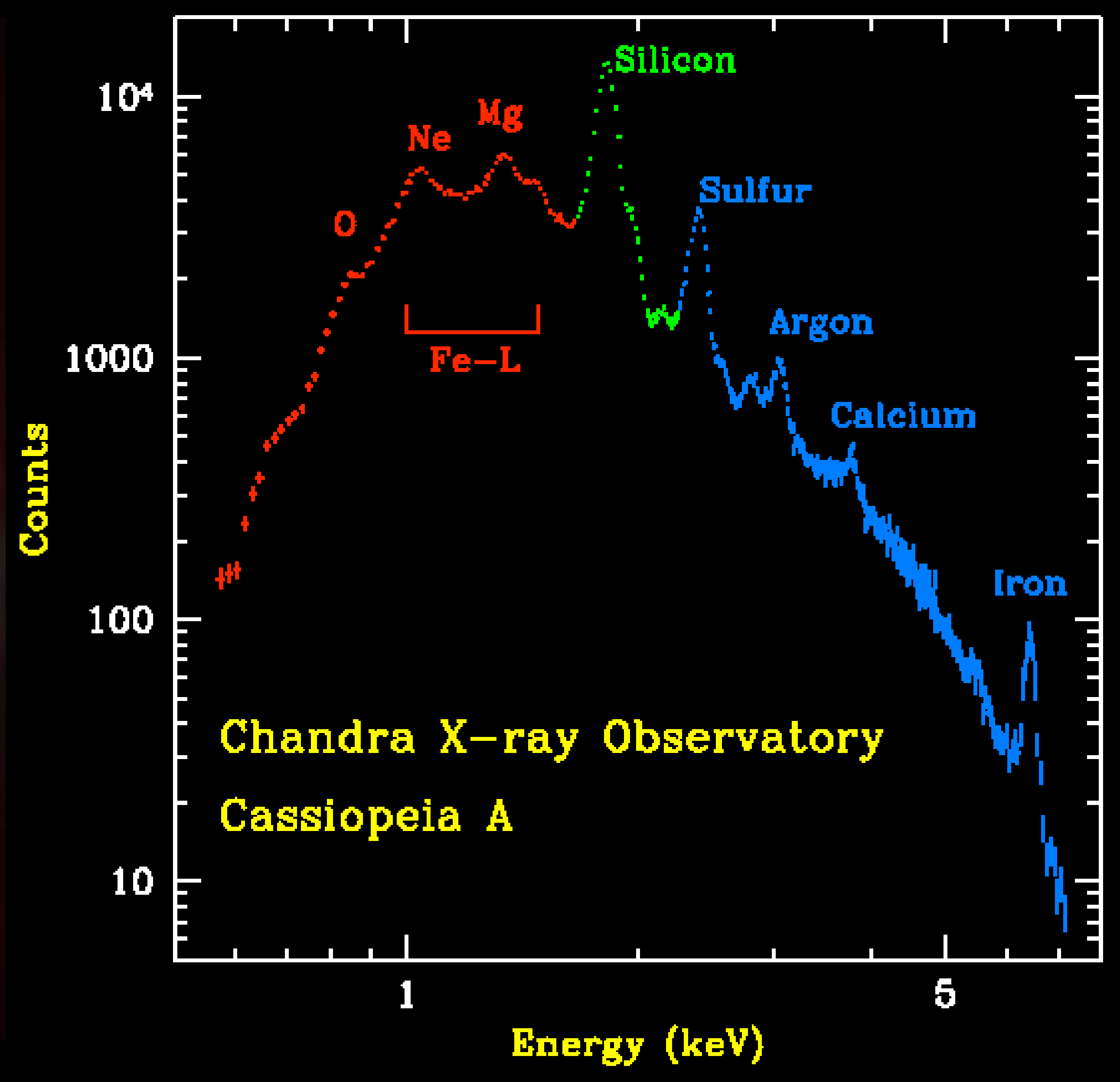


10^{44} J (10^{28} MegaTons TNT) of Kinetic Energy into the ISM

Ejecta Rich in Heavy Elements

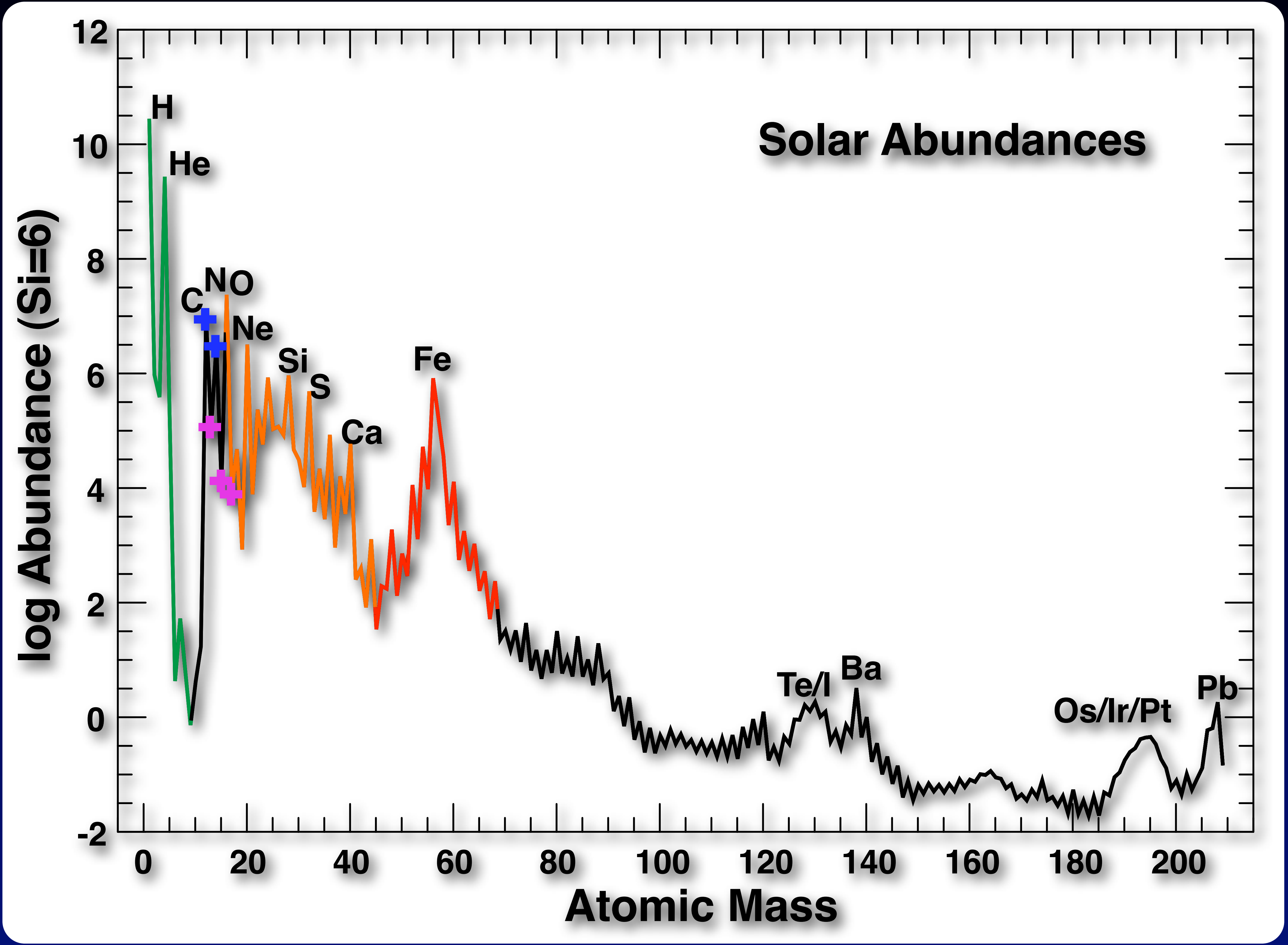


Hughes, Rakowski, Burrows & Slane
2000



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?



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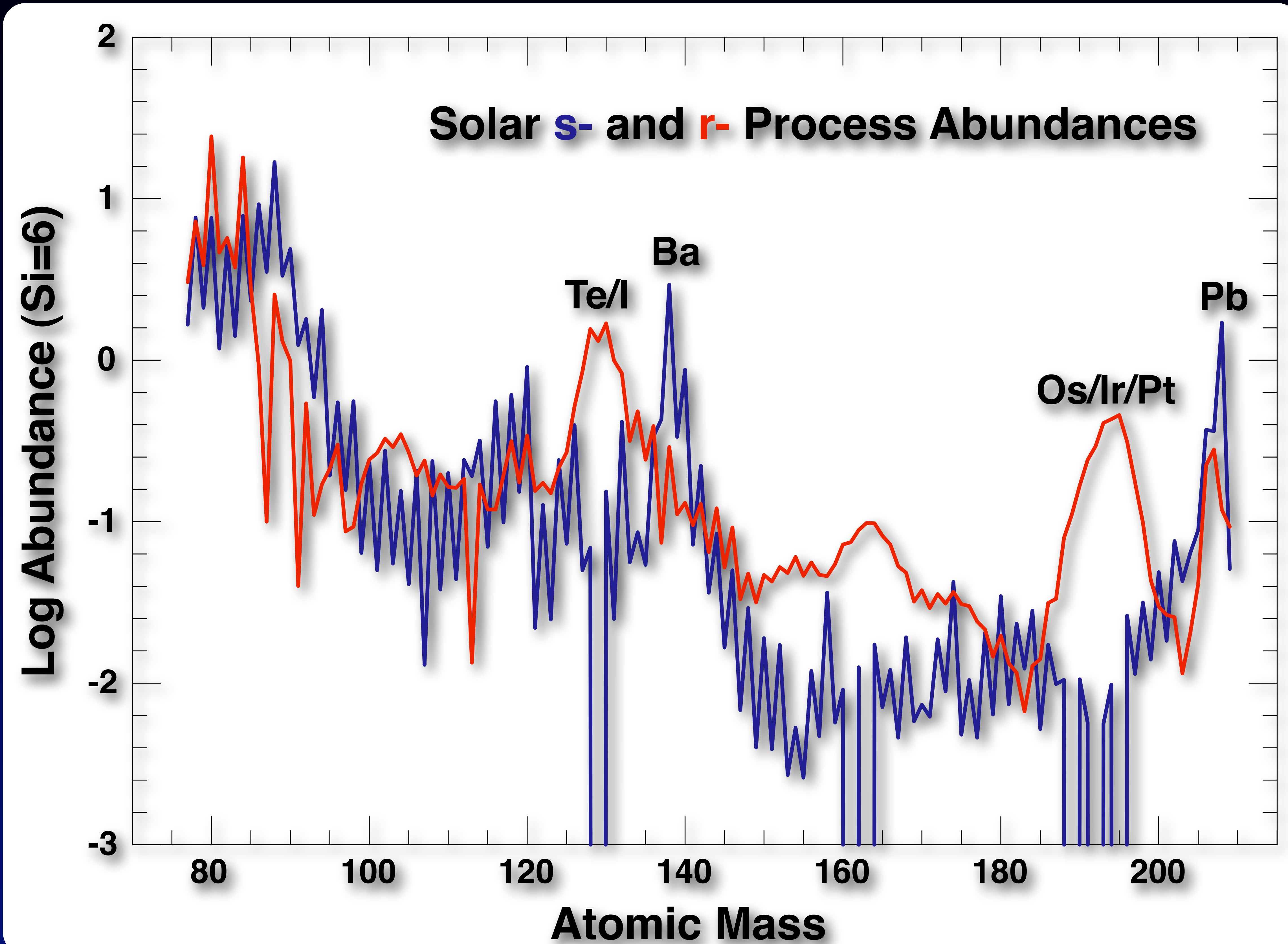

Neutron Star Remnants

Core Collapse SN explosion also leaves behind a Neutron Star or Black Hole.

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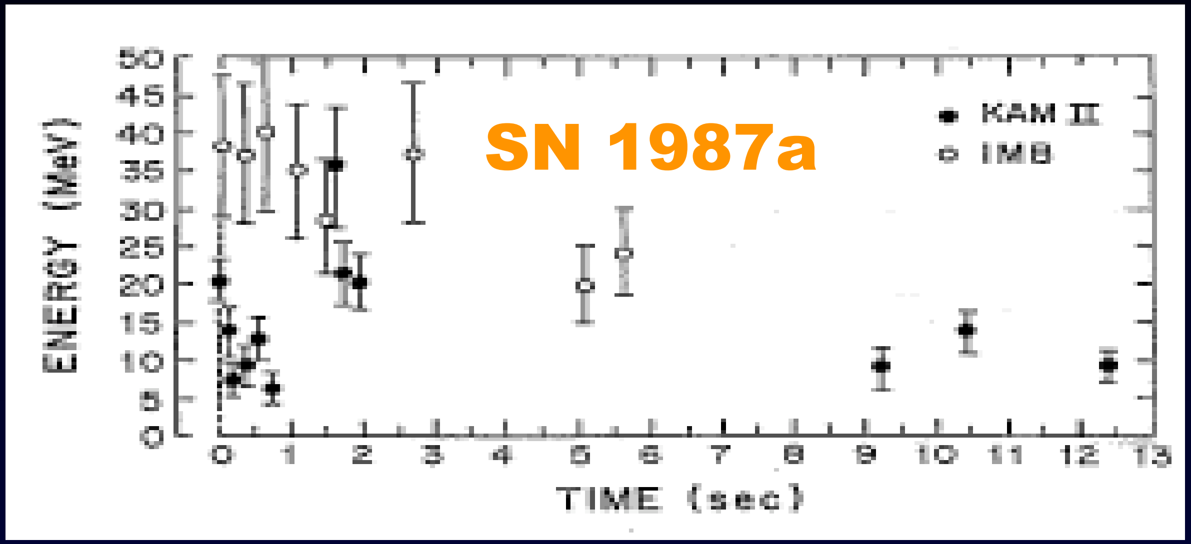
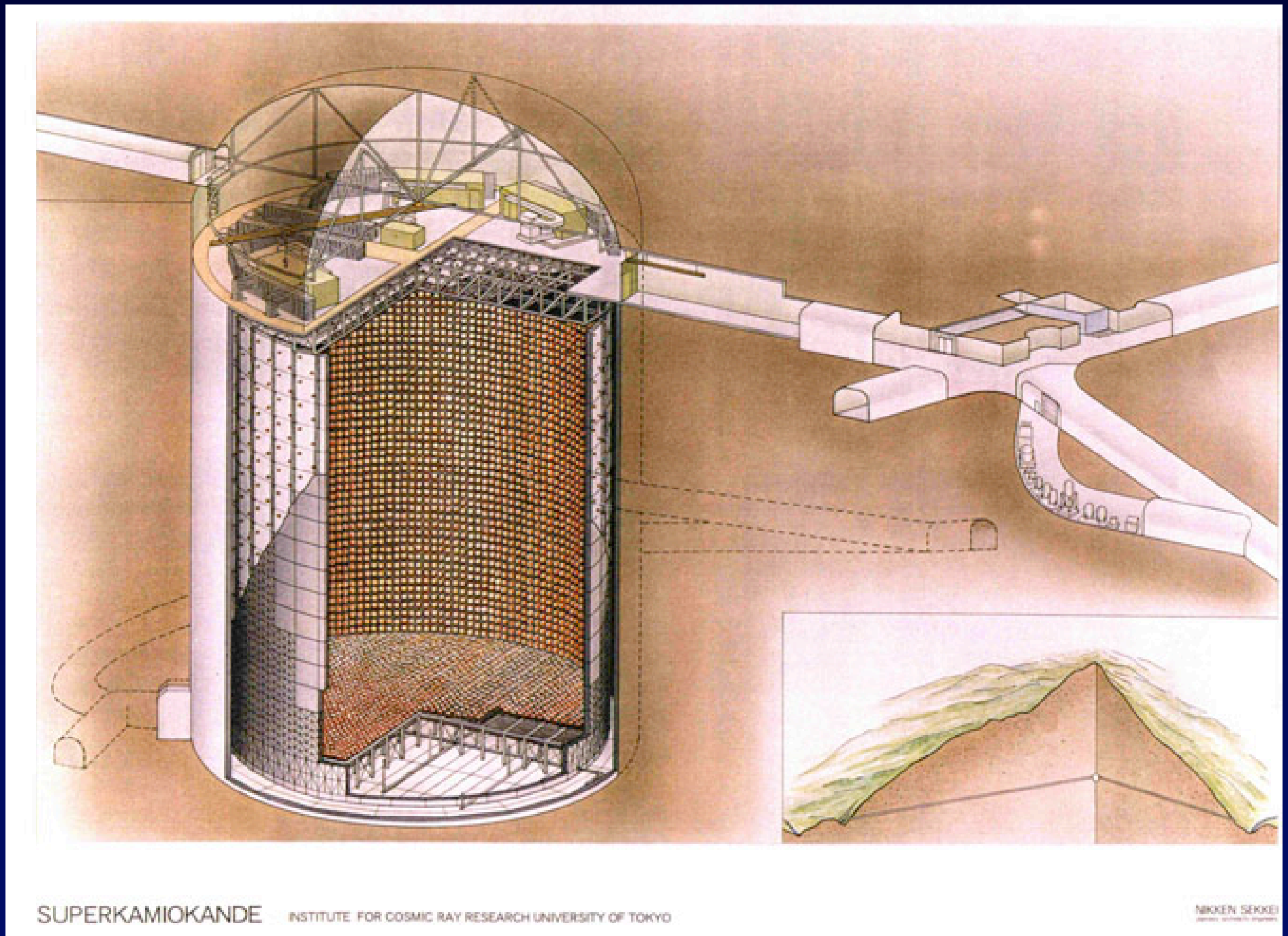
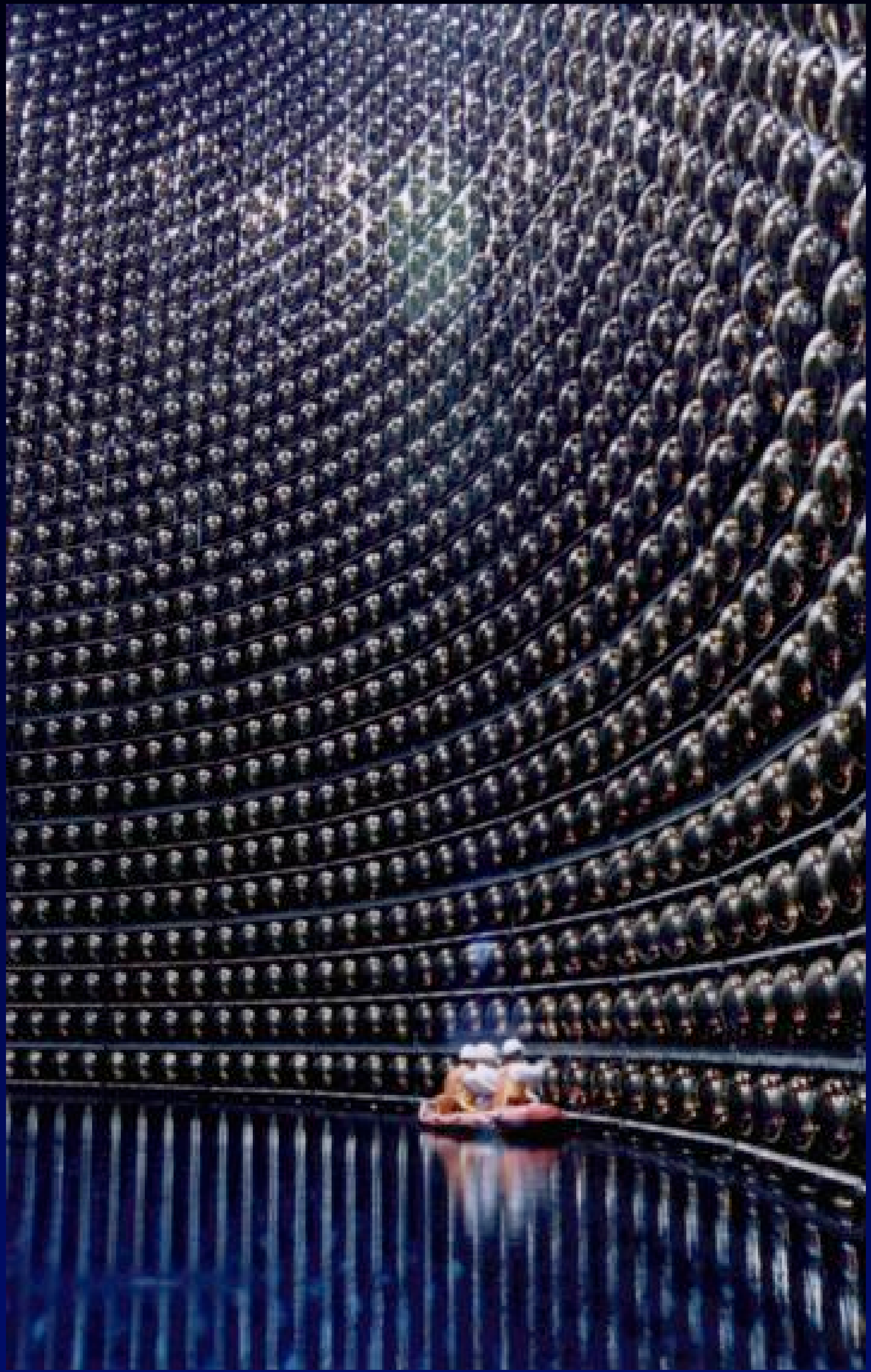
Observing Supernova Neutrinos







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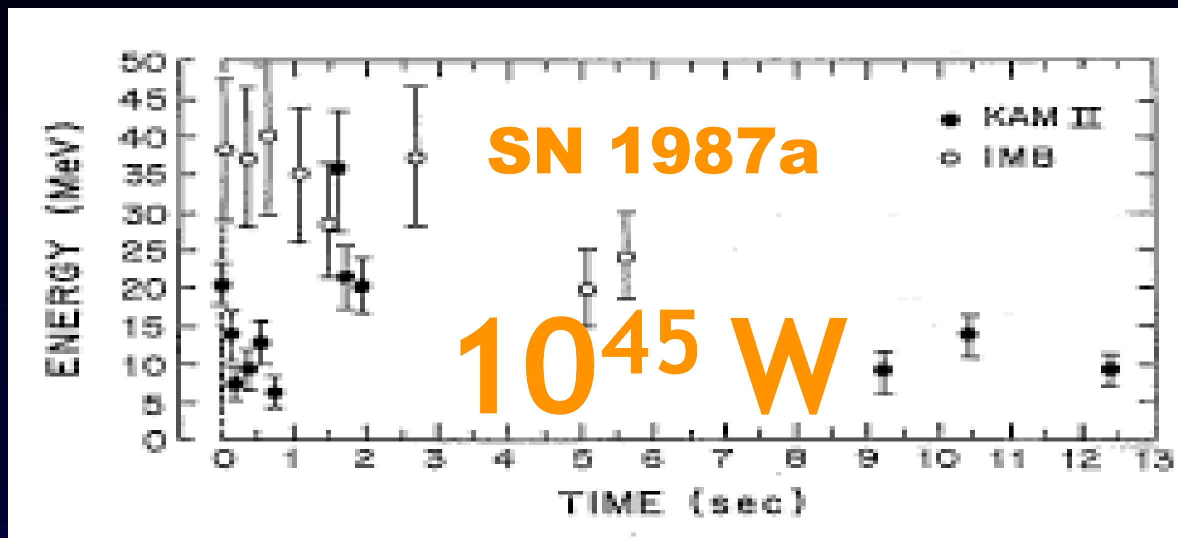
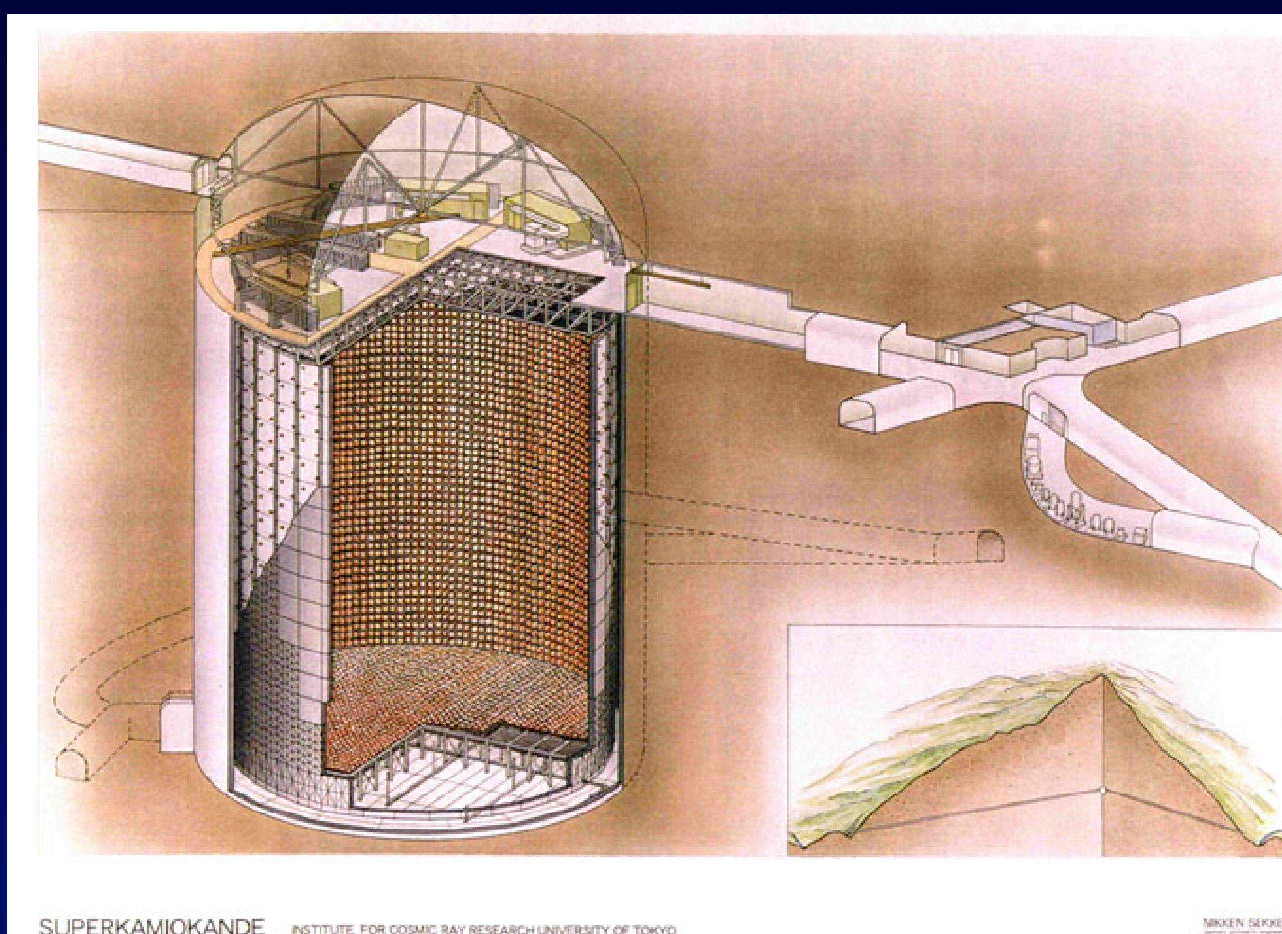
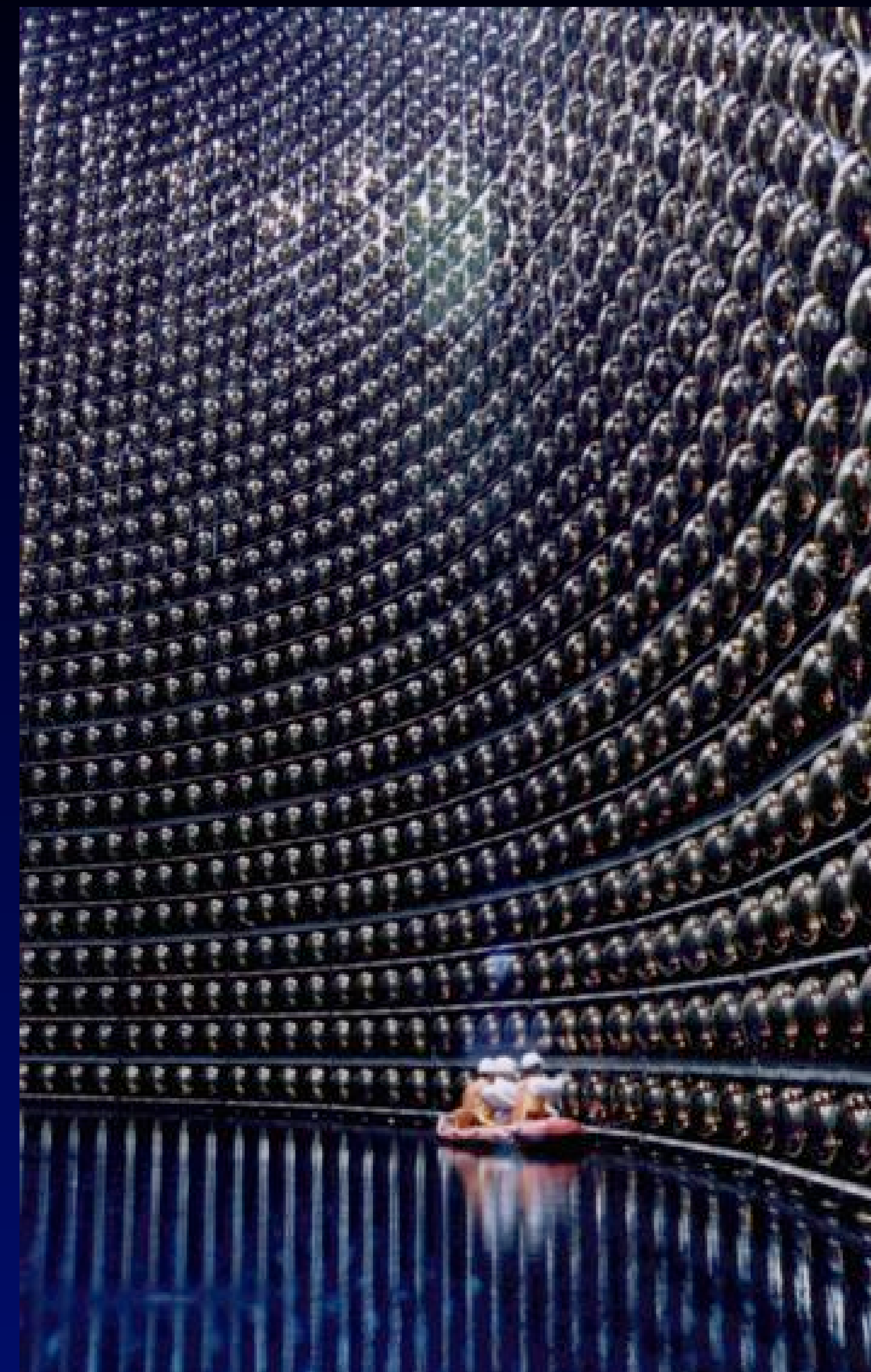
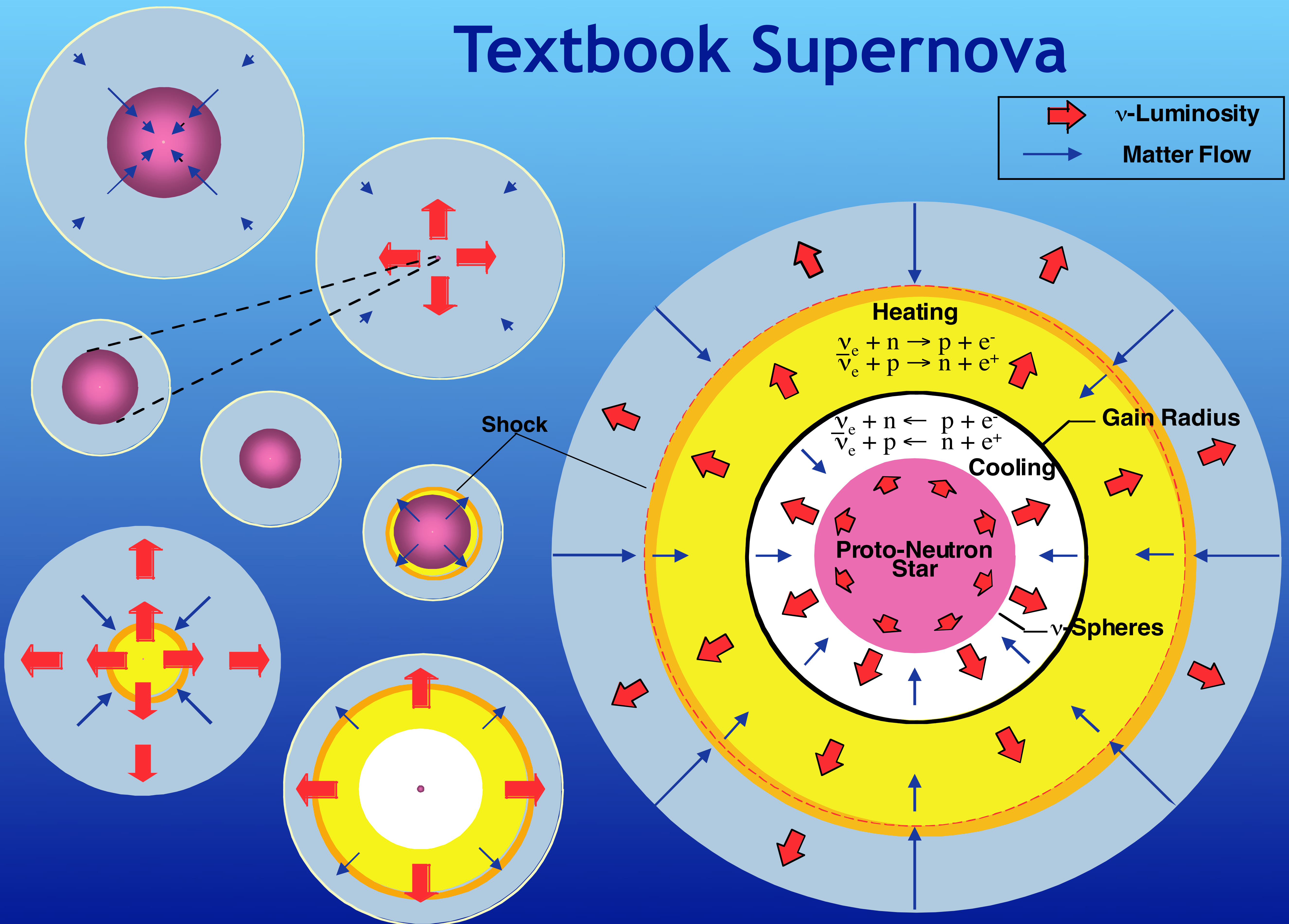


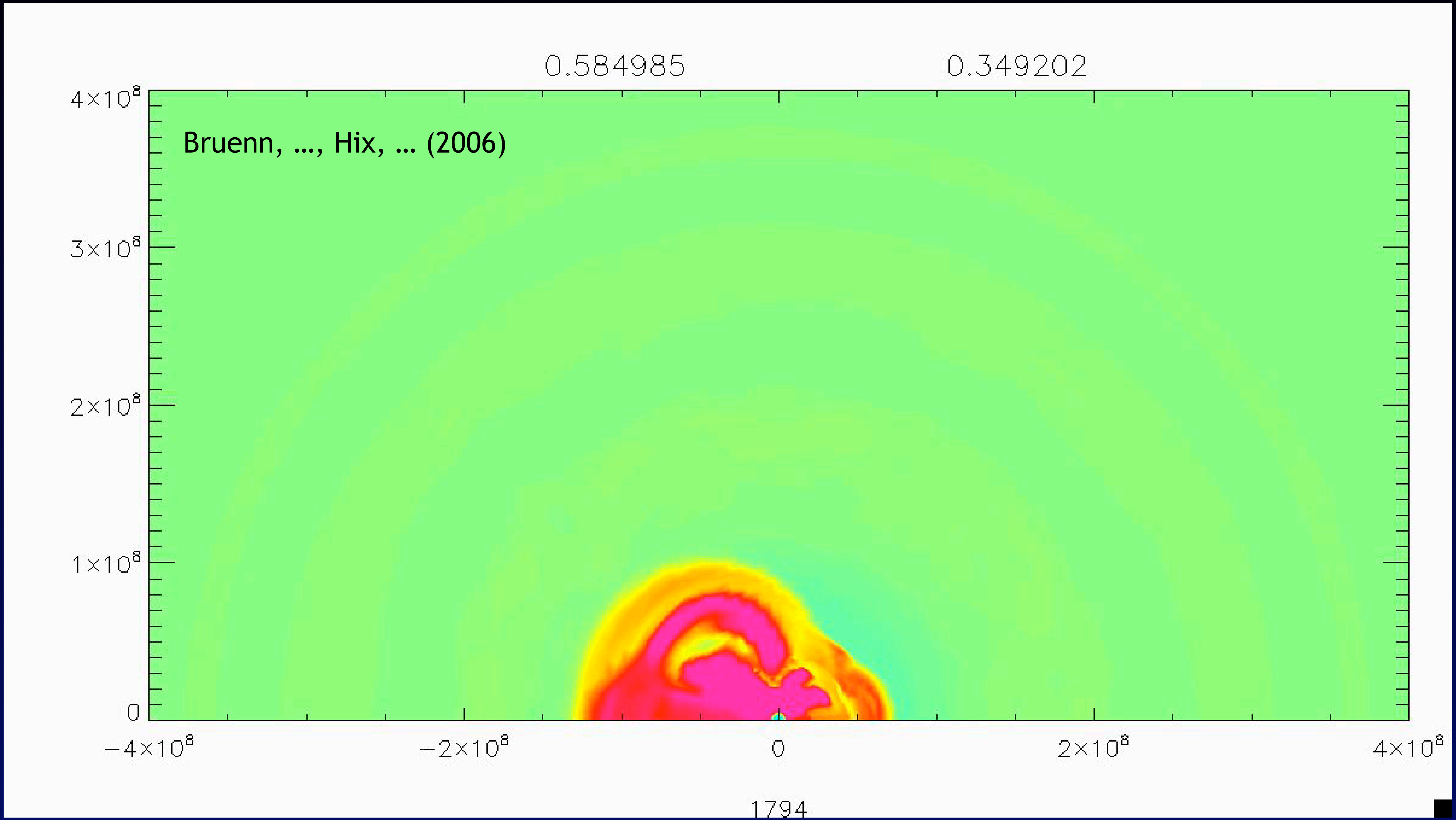




Textbook Supernova



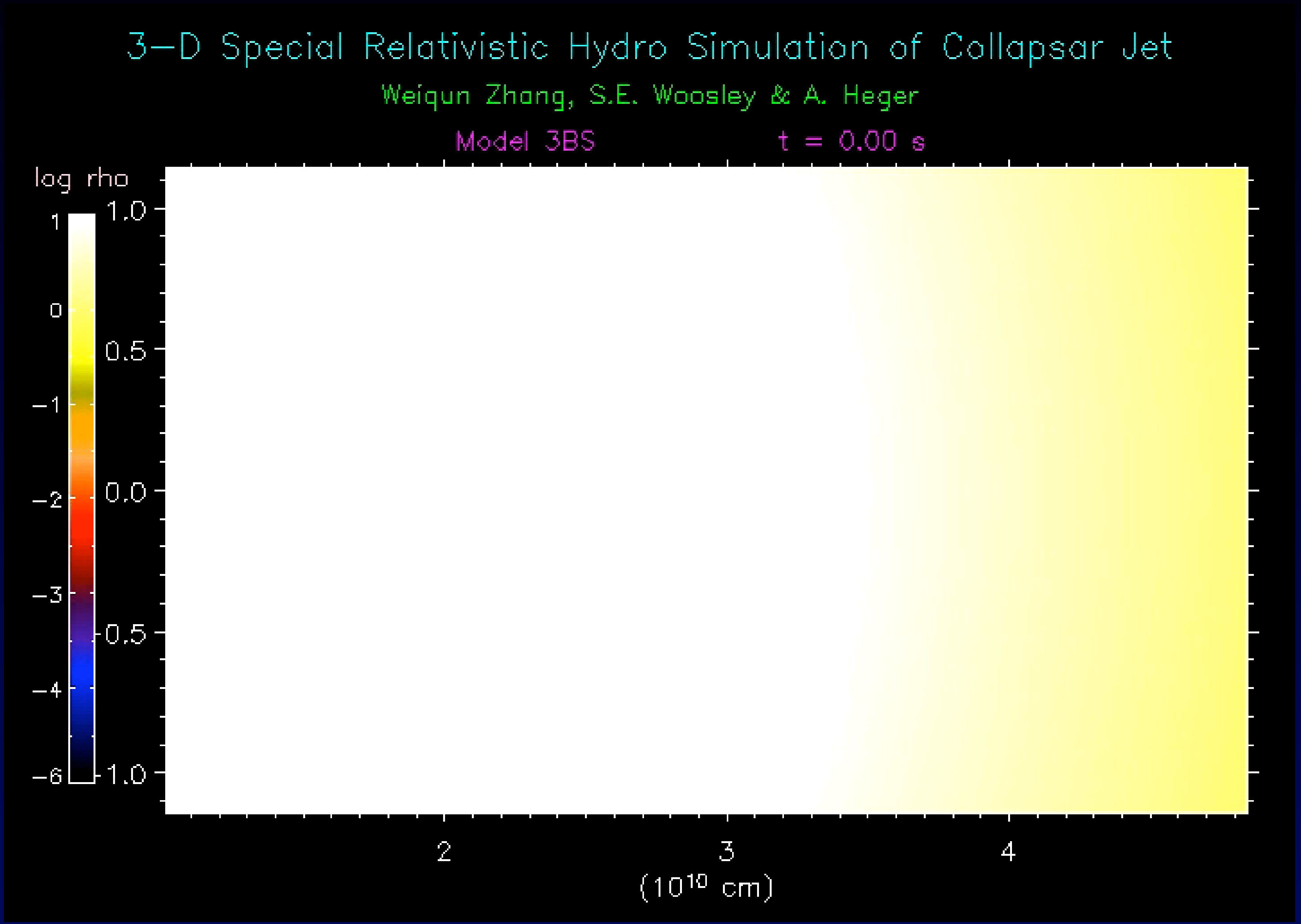
Supernovae Modeling is Ongoing



New idea! Explosions occur when Oxygen layer reaches shock, driven by interplay of neutrino heating, hydrodynamic instabilities and nuclear burning.

Supernova and γ-ray Bursts

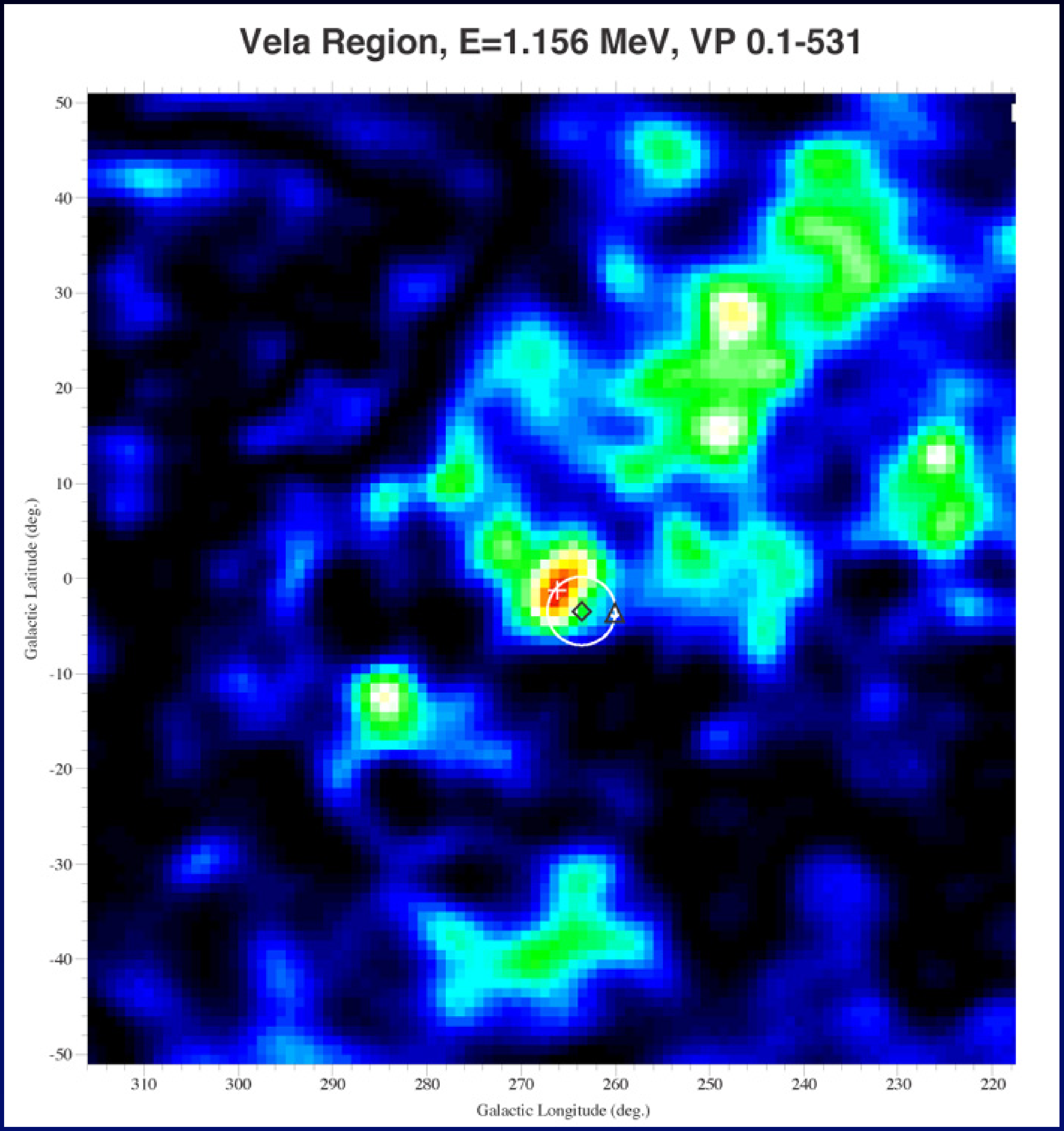
Recent observations have tied some peculiar, hyper-energetic Type Ic supernovae (called hypernovae by some) to GRBs.



One proposed model is a collaspar, where an accretion disk forms around a newly formed black hole in a failed supernova (M>?30 solar masses), producing a jet which we see as the GRB.

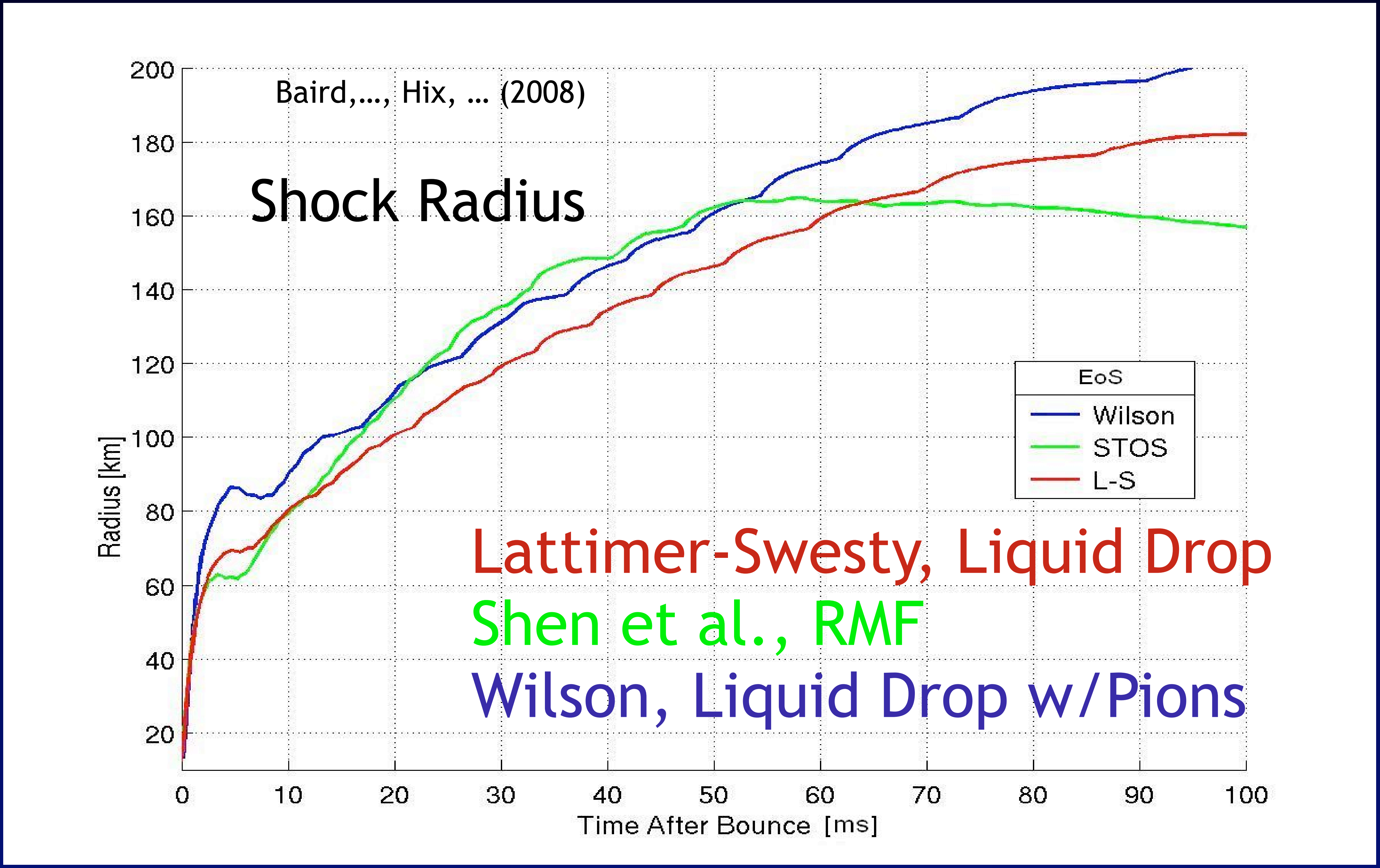
Nuclear Physics in Supernovae

- ✳ 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
- ✳ Nuclear Matter



Supernovae and Nuclear Matter

Bounce shock results from stiffening of the Equation of State in Nuclear Matter. Different approaches affect SN models.



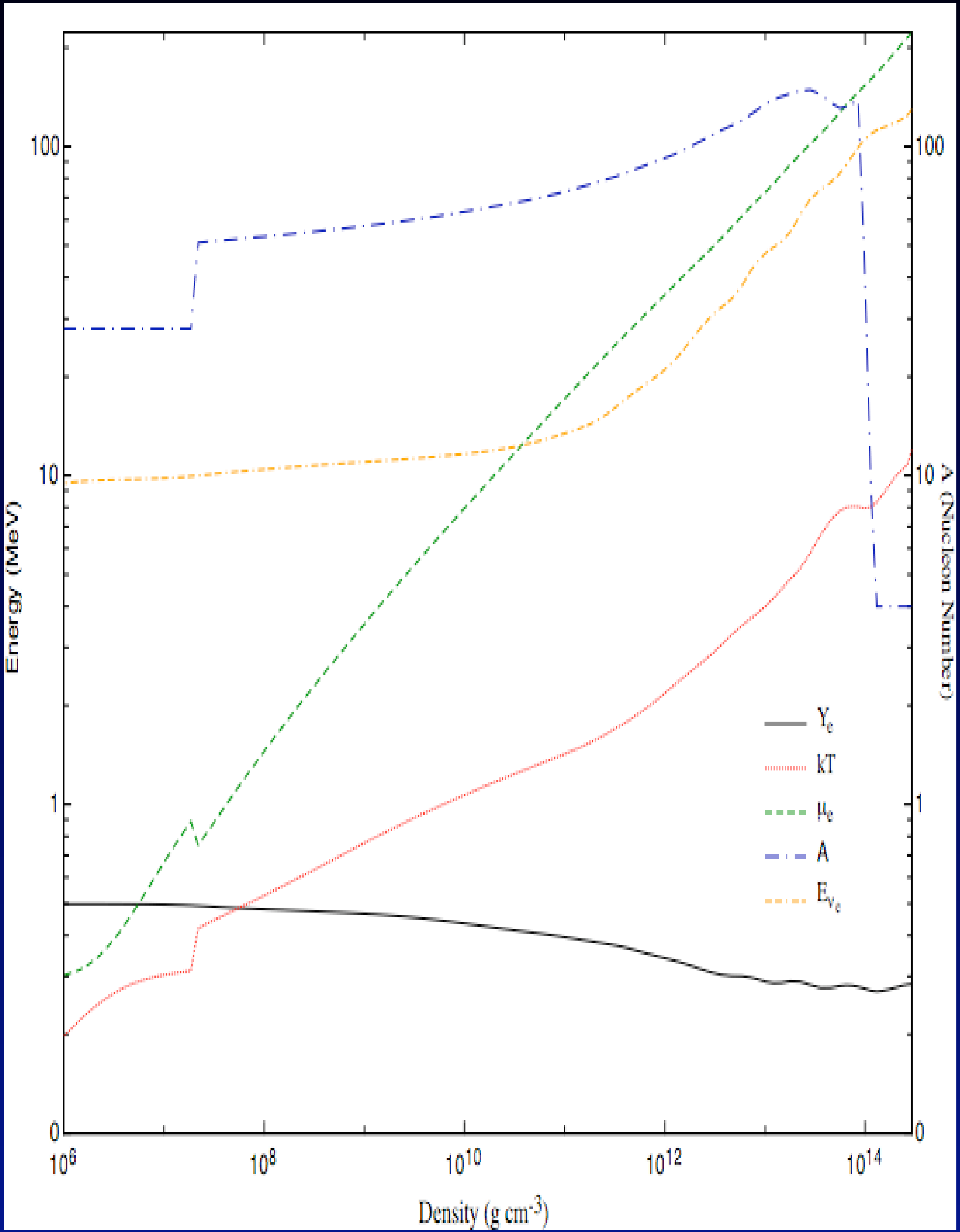
Electron Captures on Nuclei

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)

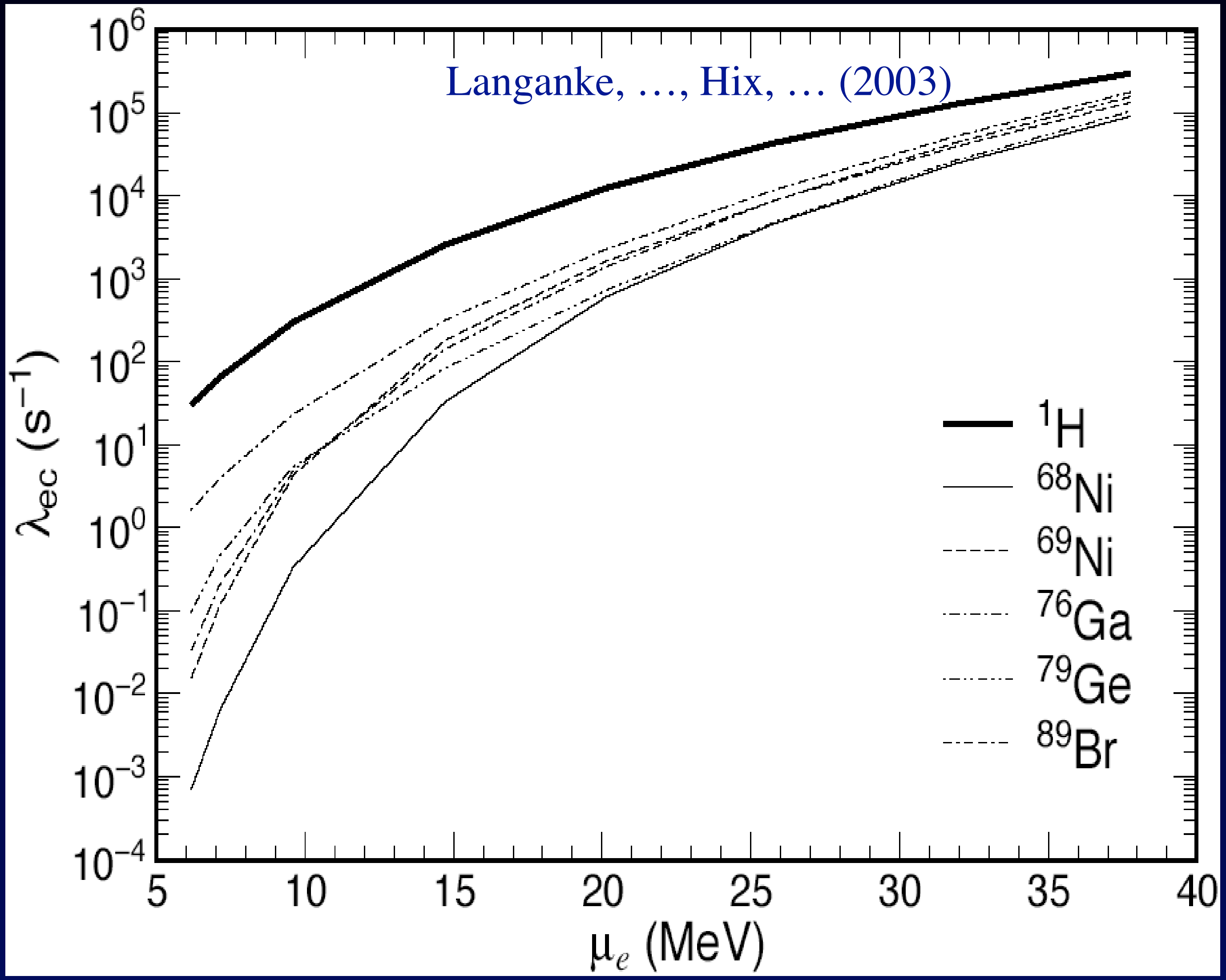
Implemented using average nucleus. Bruenn (1985)



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.



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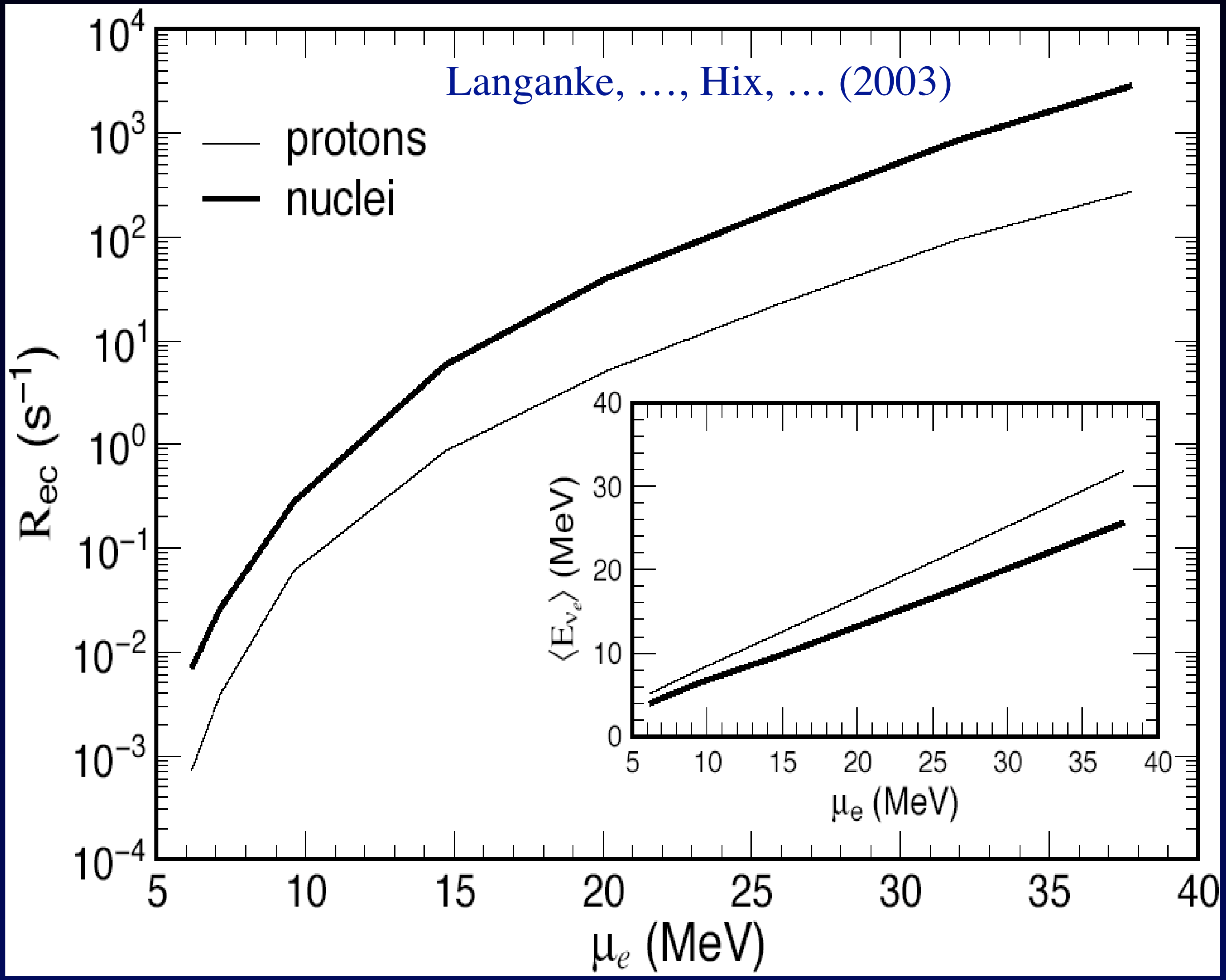

Electron/neutrino capture on heavy nuclei remains important throughout collapse.

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.

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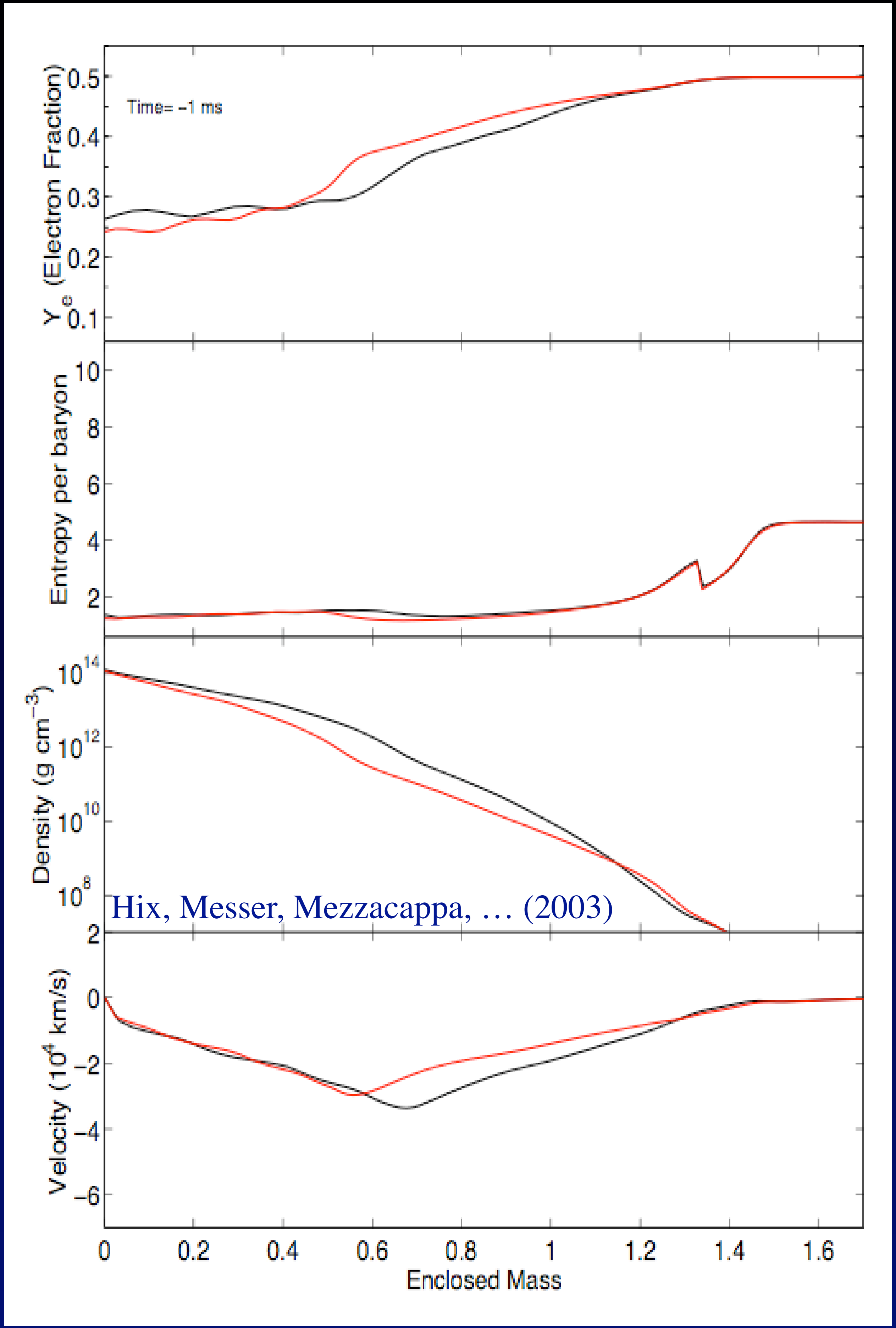

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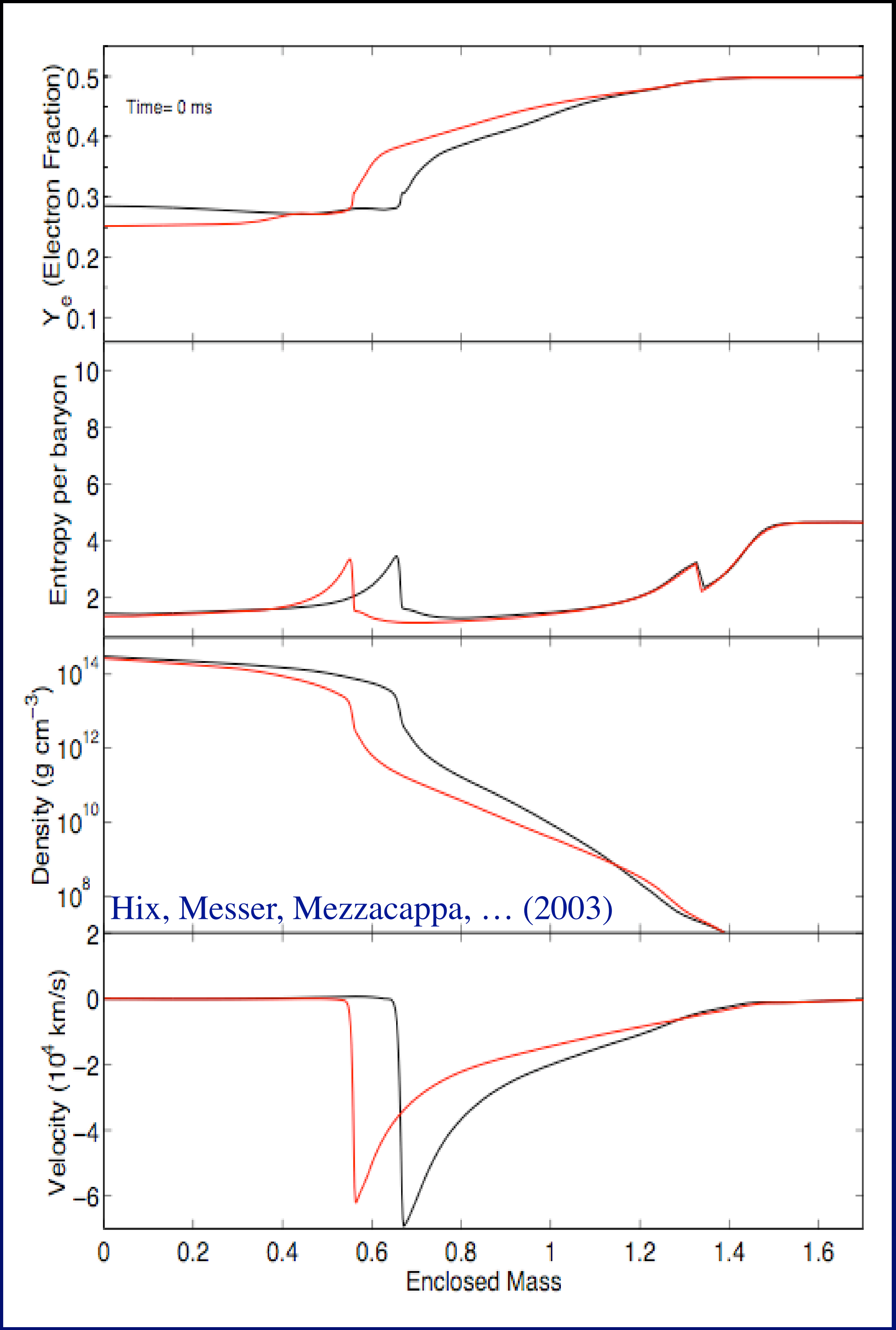

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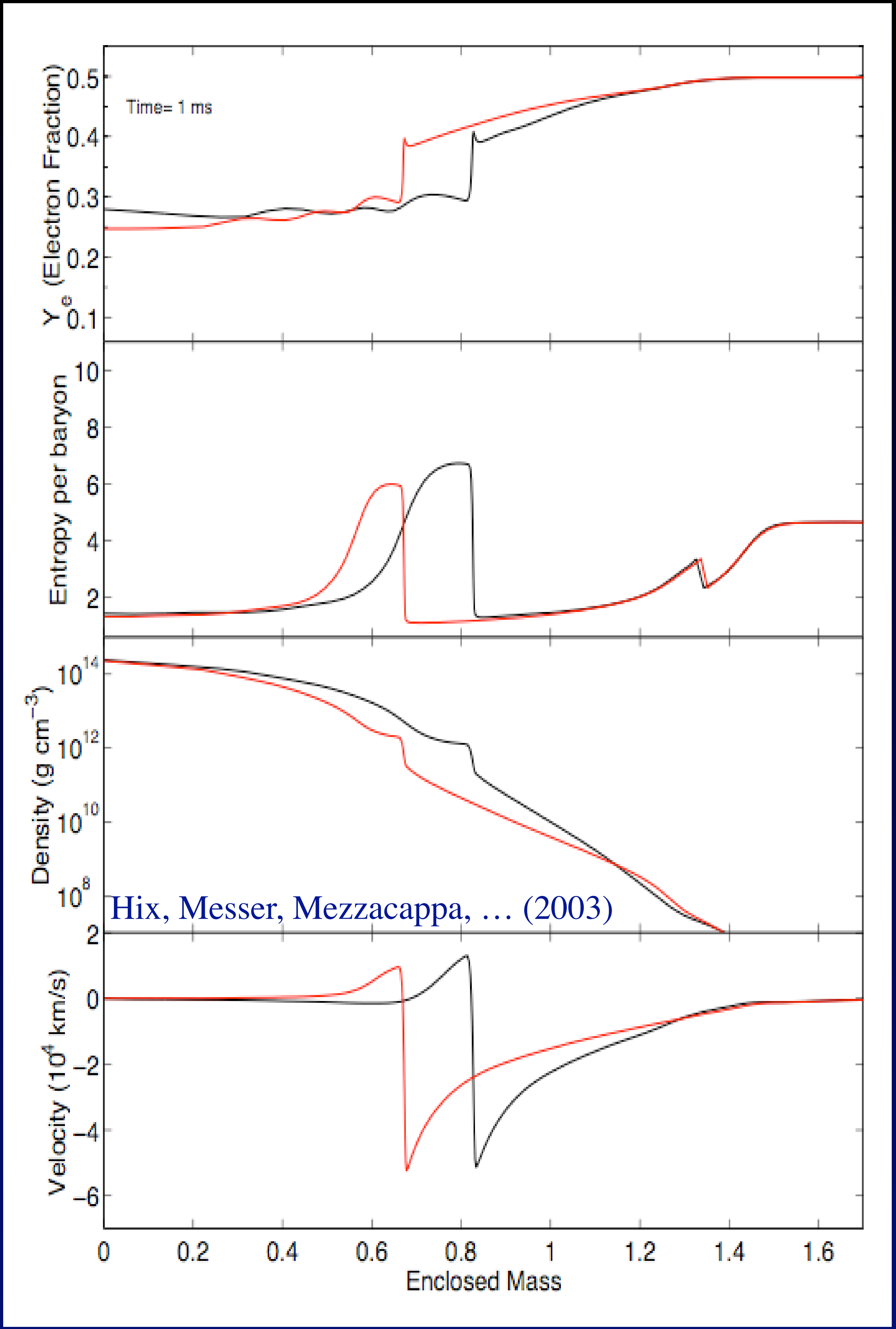

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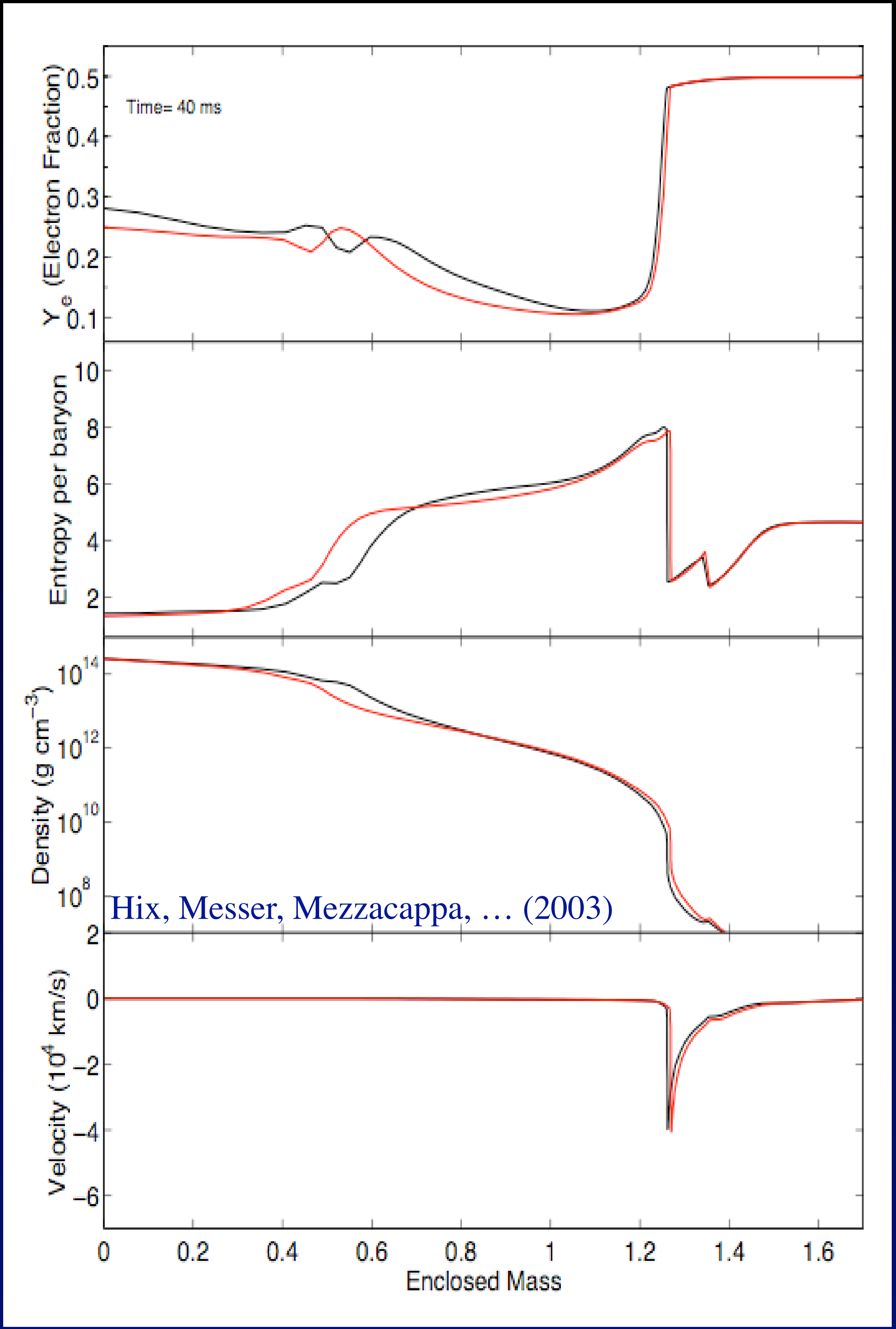
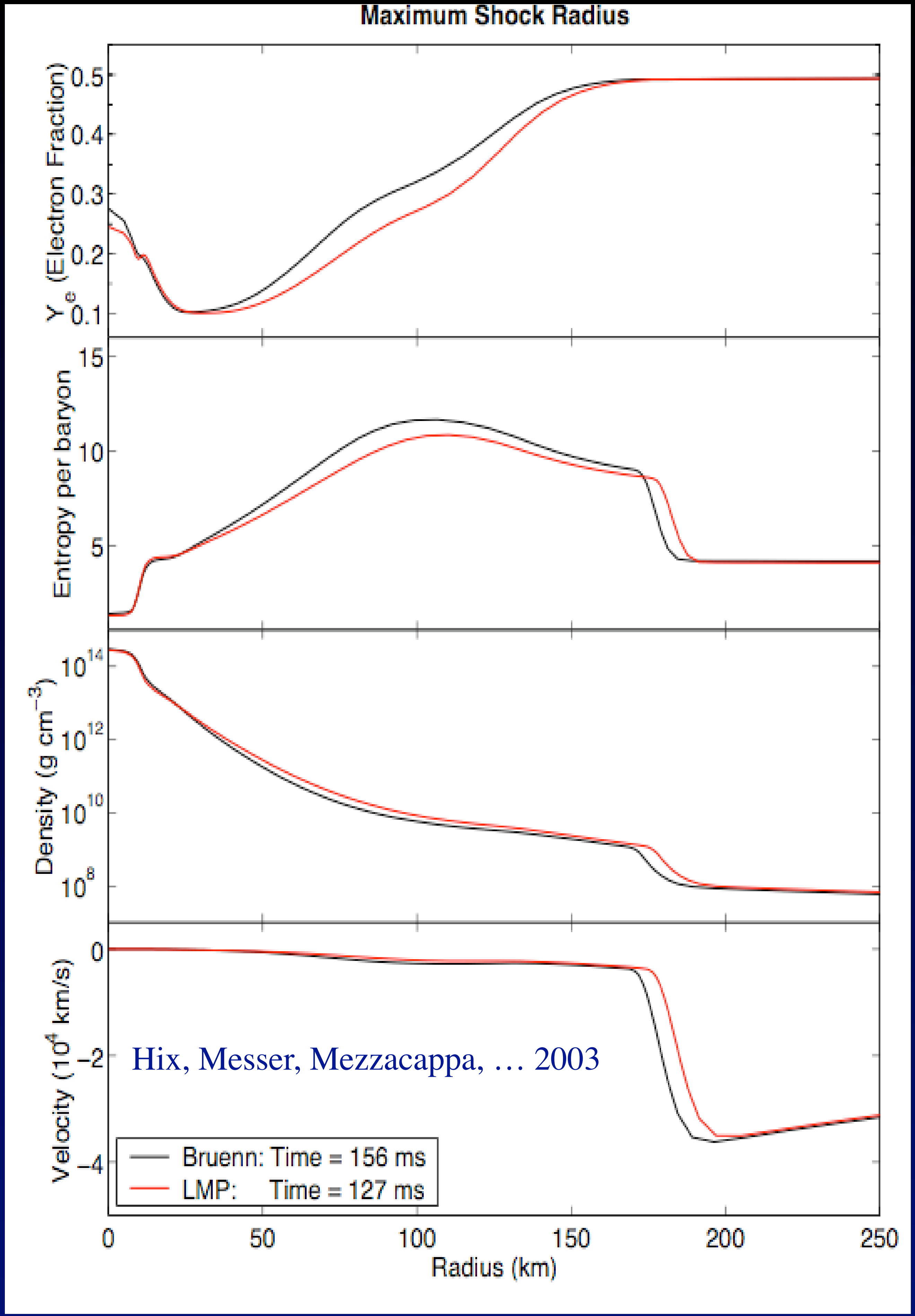


Effects on Shock propagation

Gradients which drive convection are altered.

"Weaker" shock is faster.

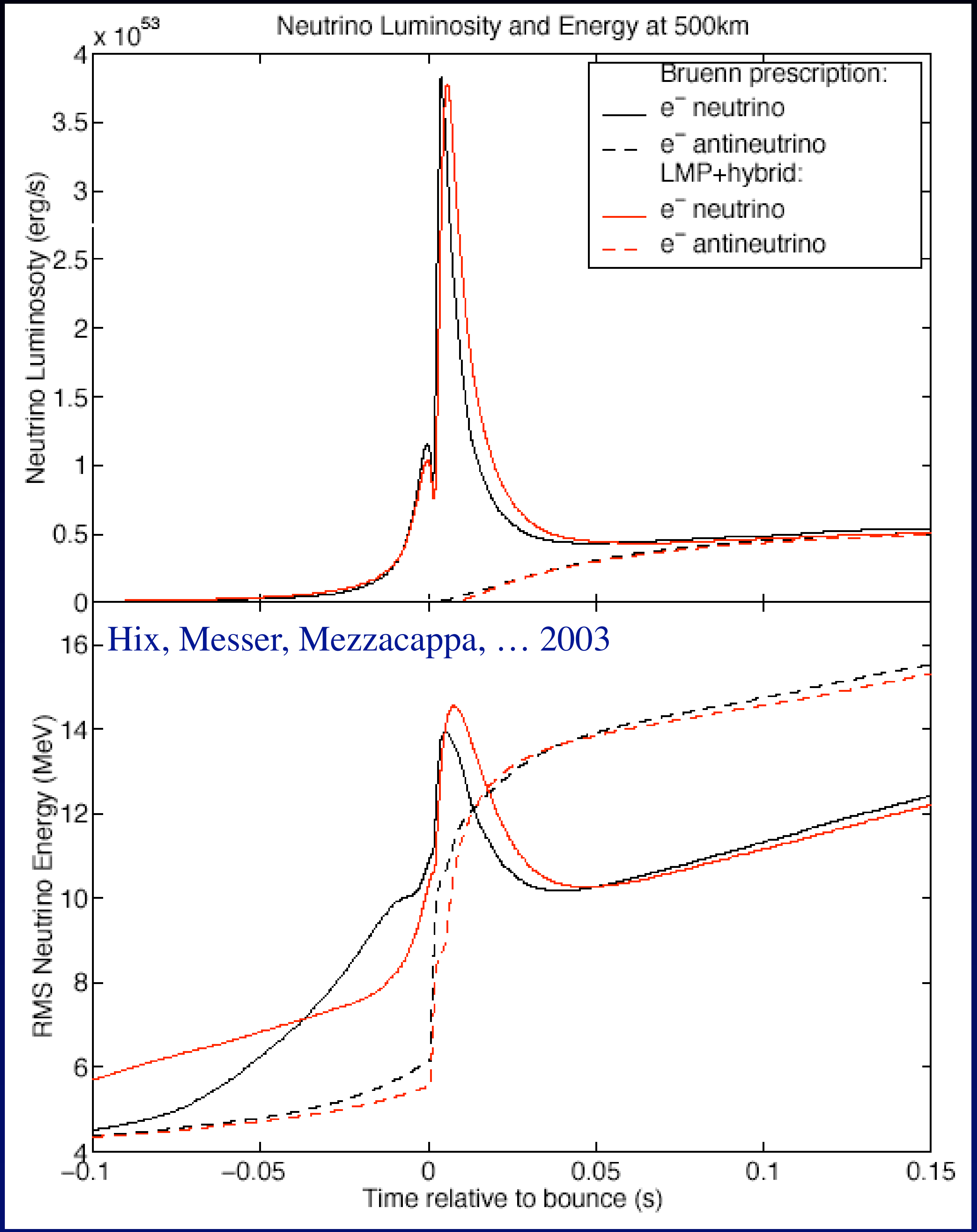
Maximum excursion of the shock is 10 km further and 30 ms earlier.



Changes in Neutrino Emission

ν_e burst slightly delayed and prolonged.

Other luminosities minimally affected (~1%).



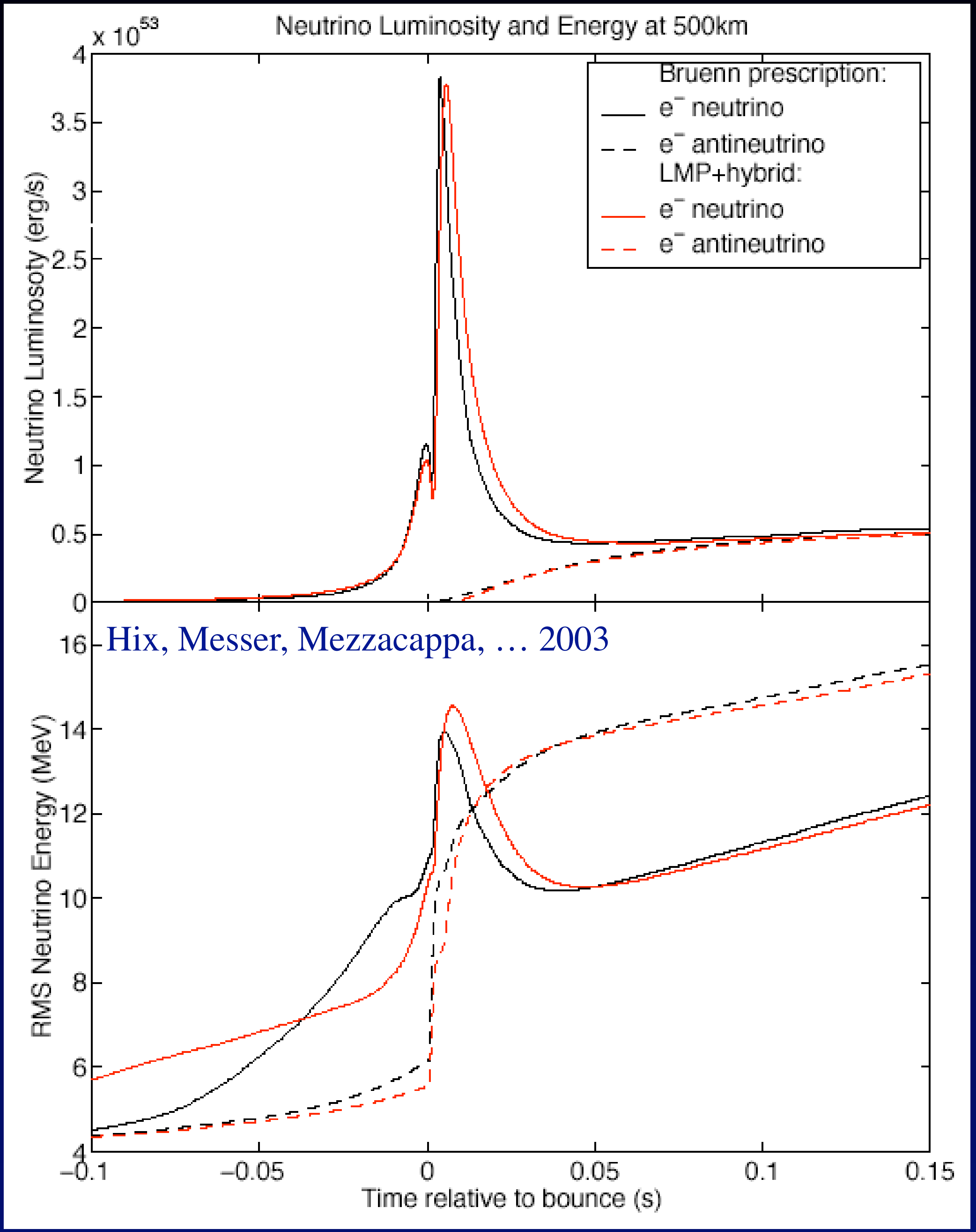
Changes in Neutrino Emission

ν_e burst slightly delayed and prolonged.

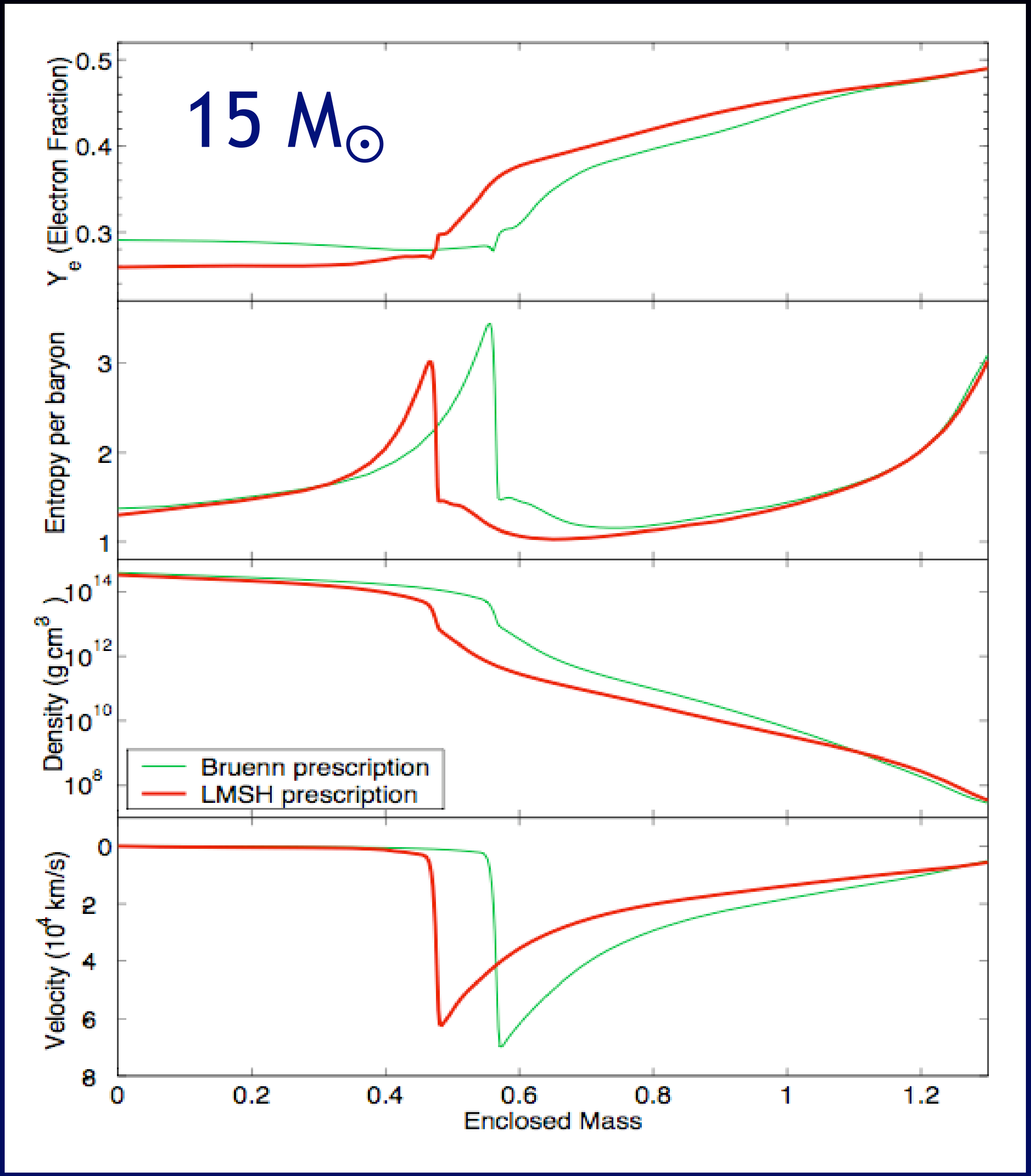
Other luminosities minimally affected (~1%).

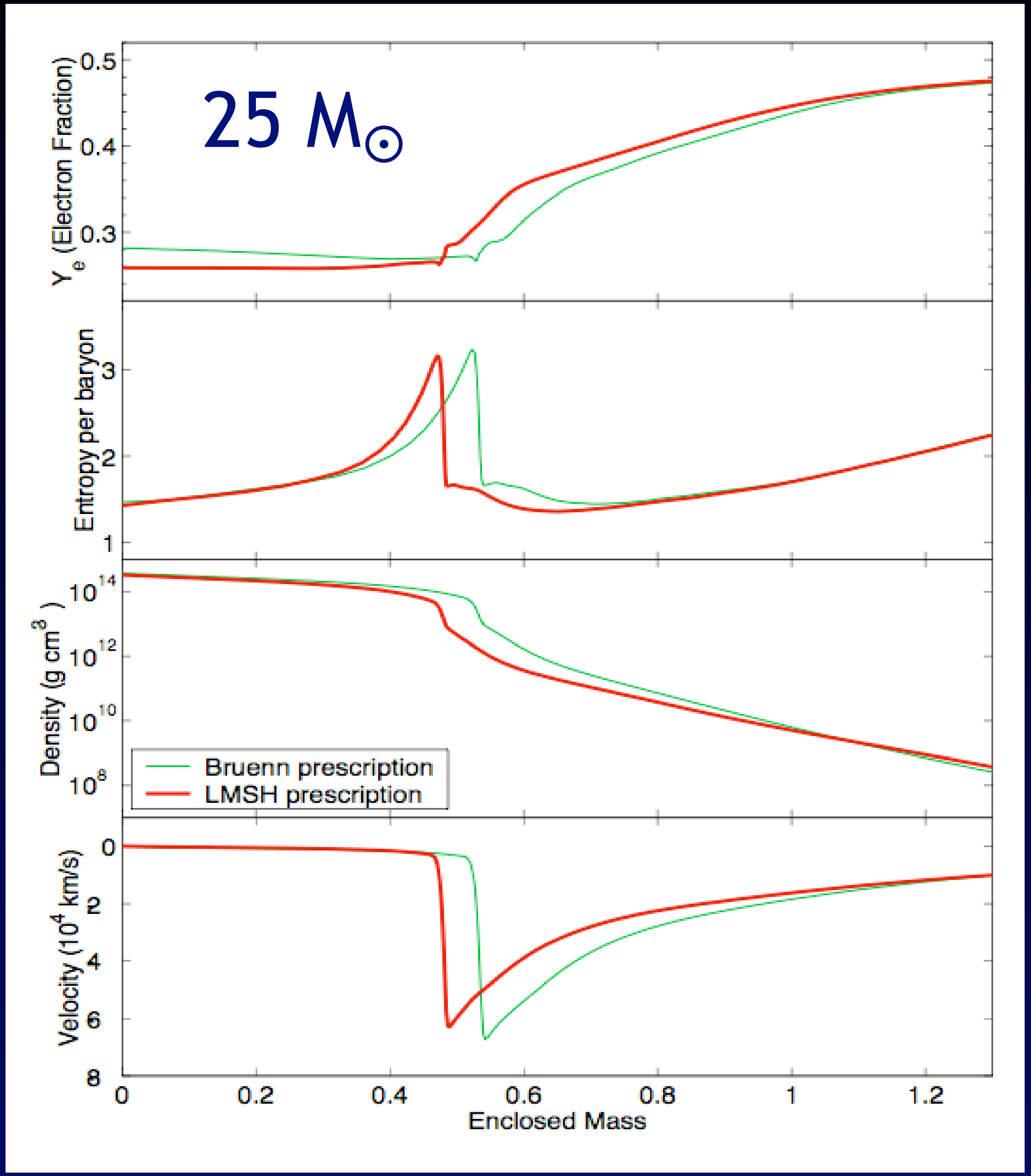
Mean ν Energy altered:

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



The impact of stellar mass

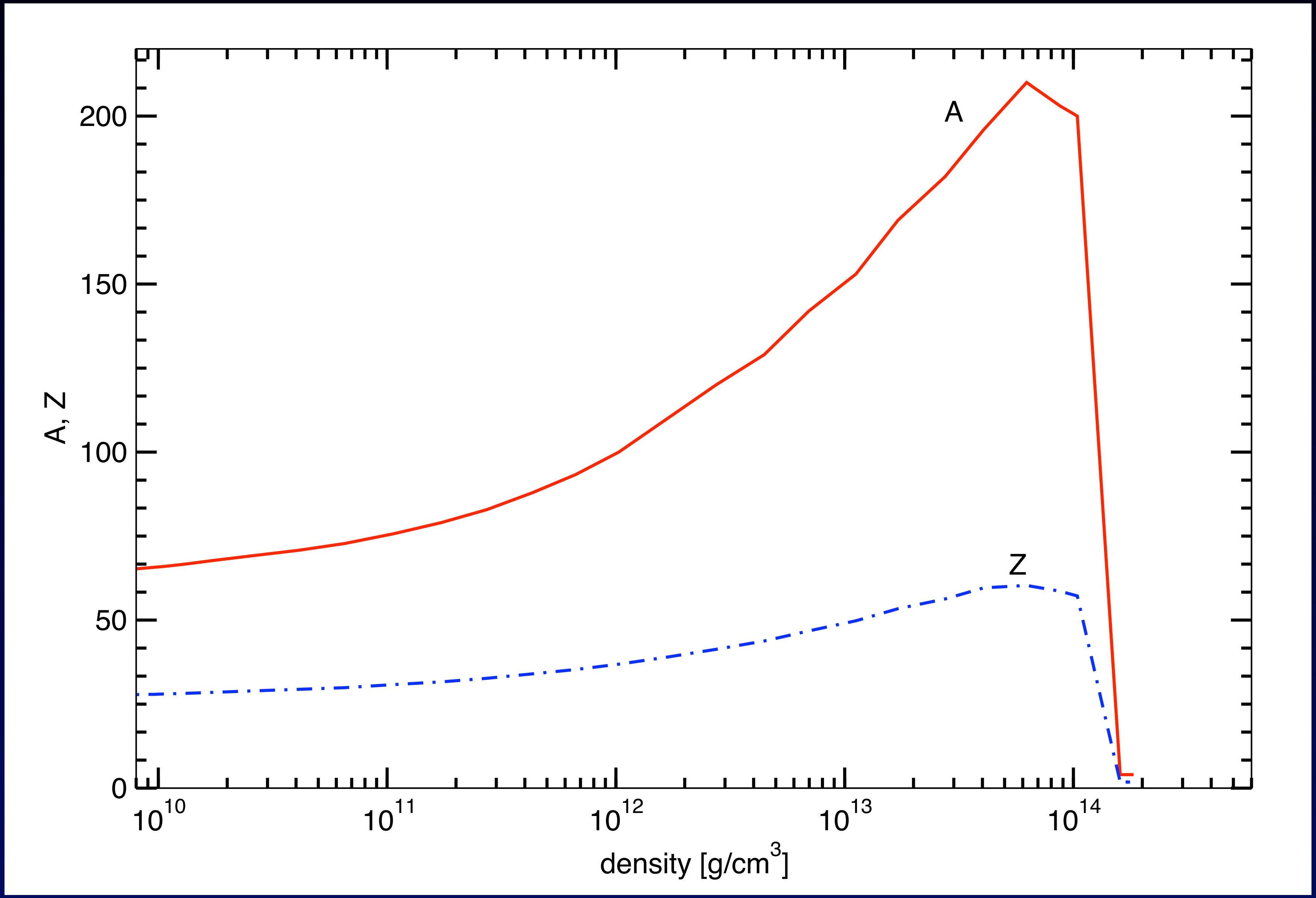




Higher mass cores have higher initial entropy.

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

Needed Electron Capture Rates



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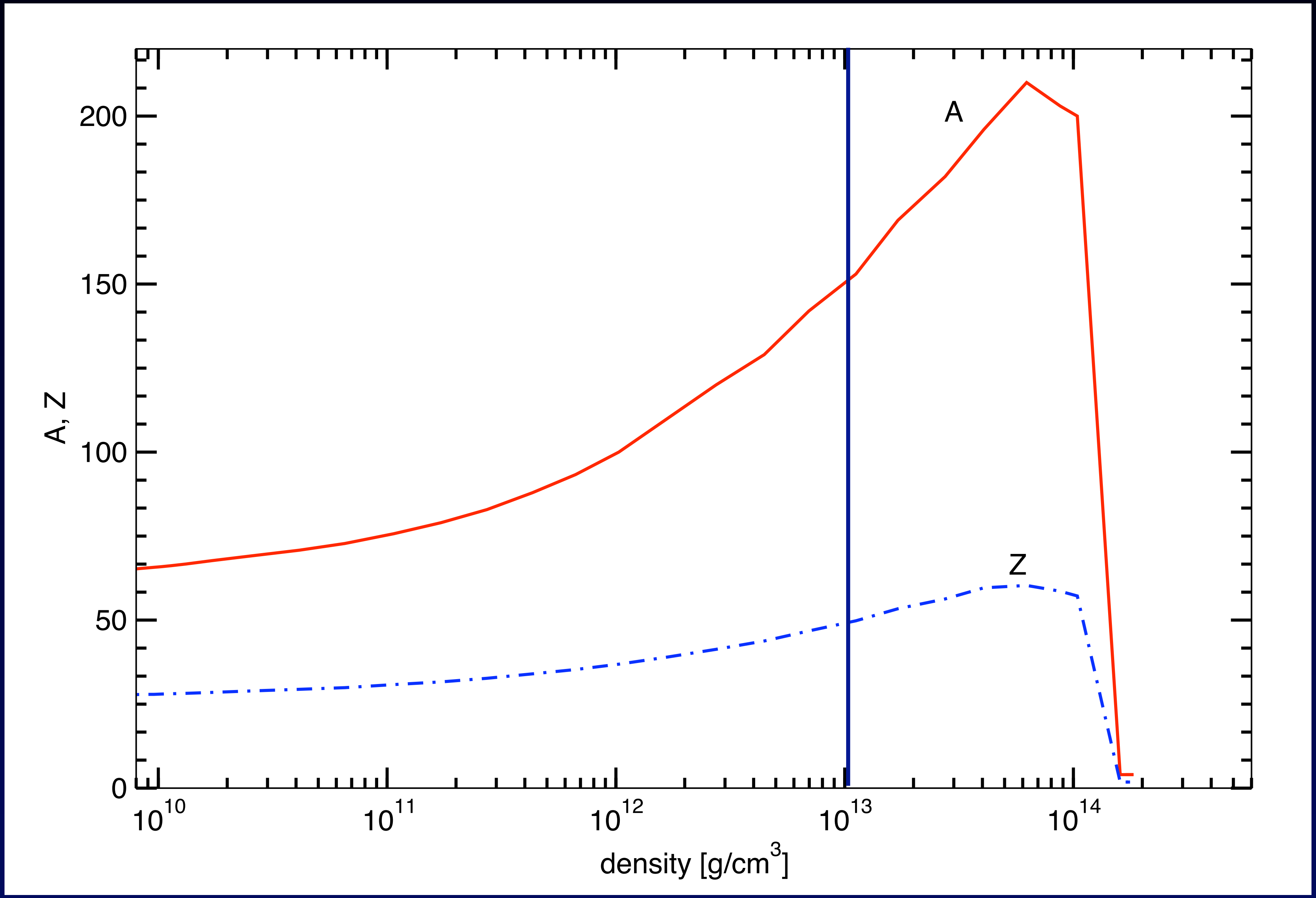

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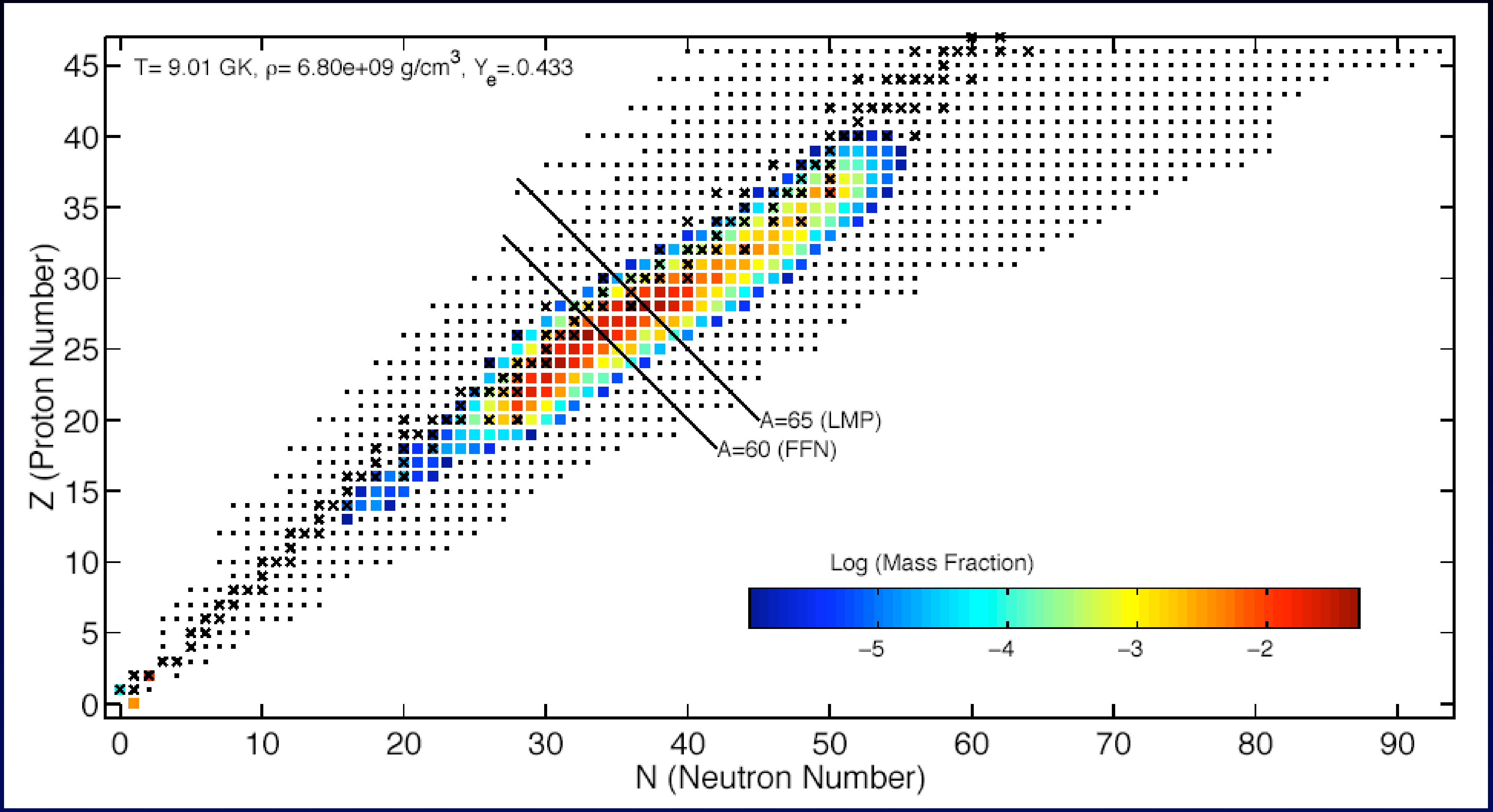

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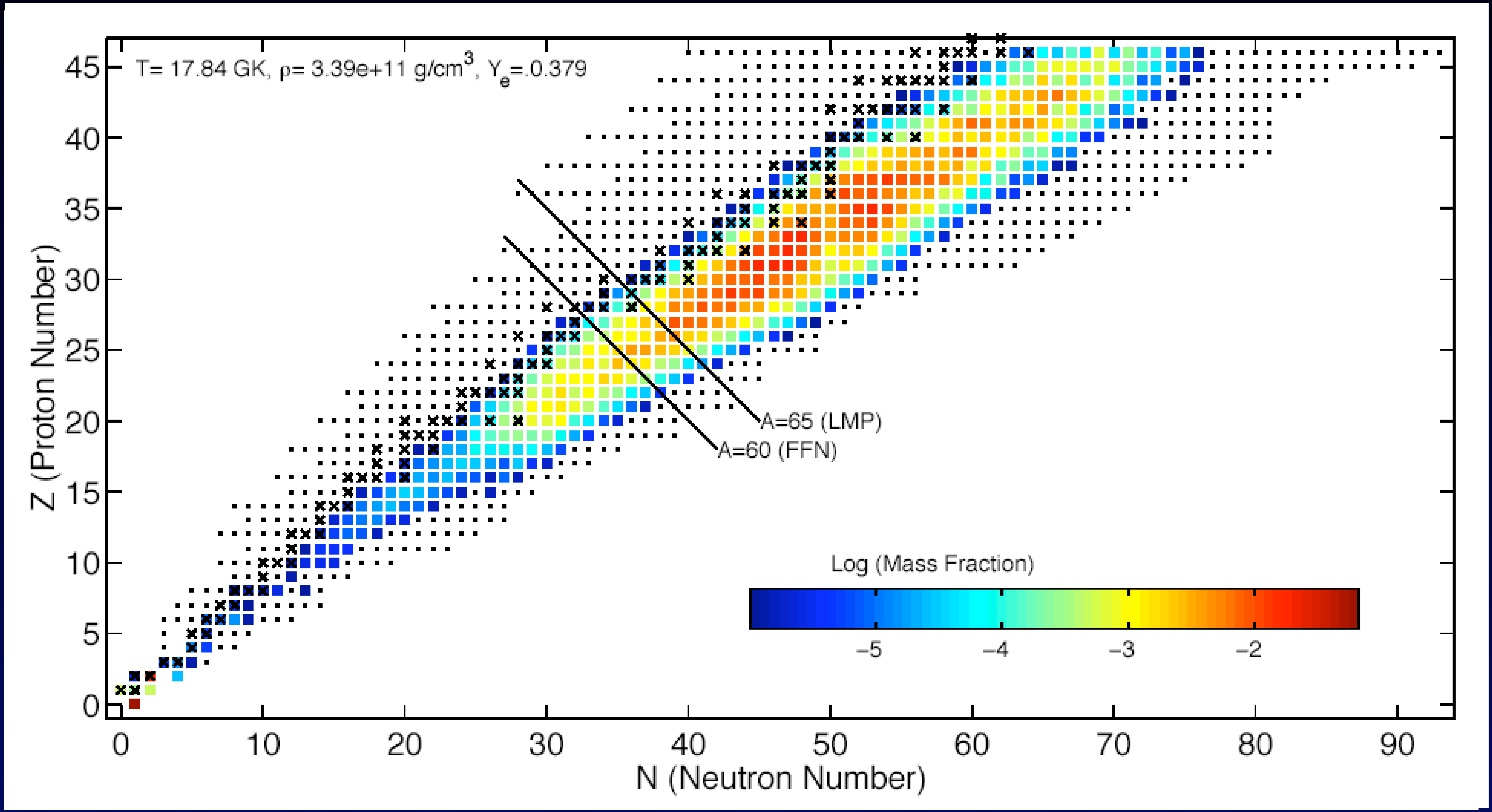
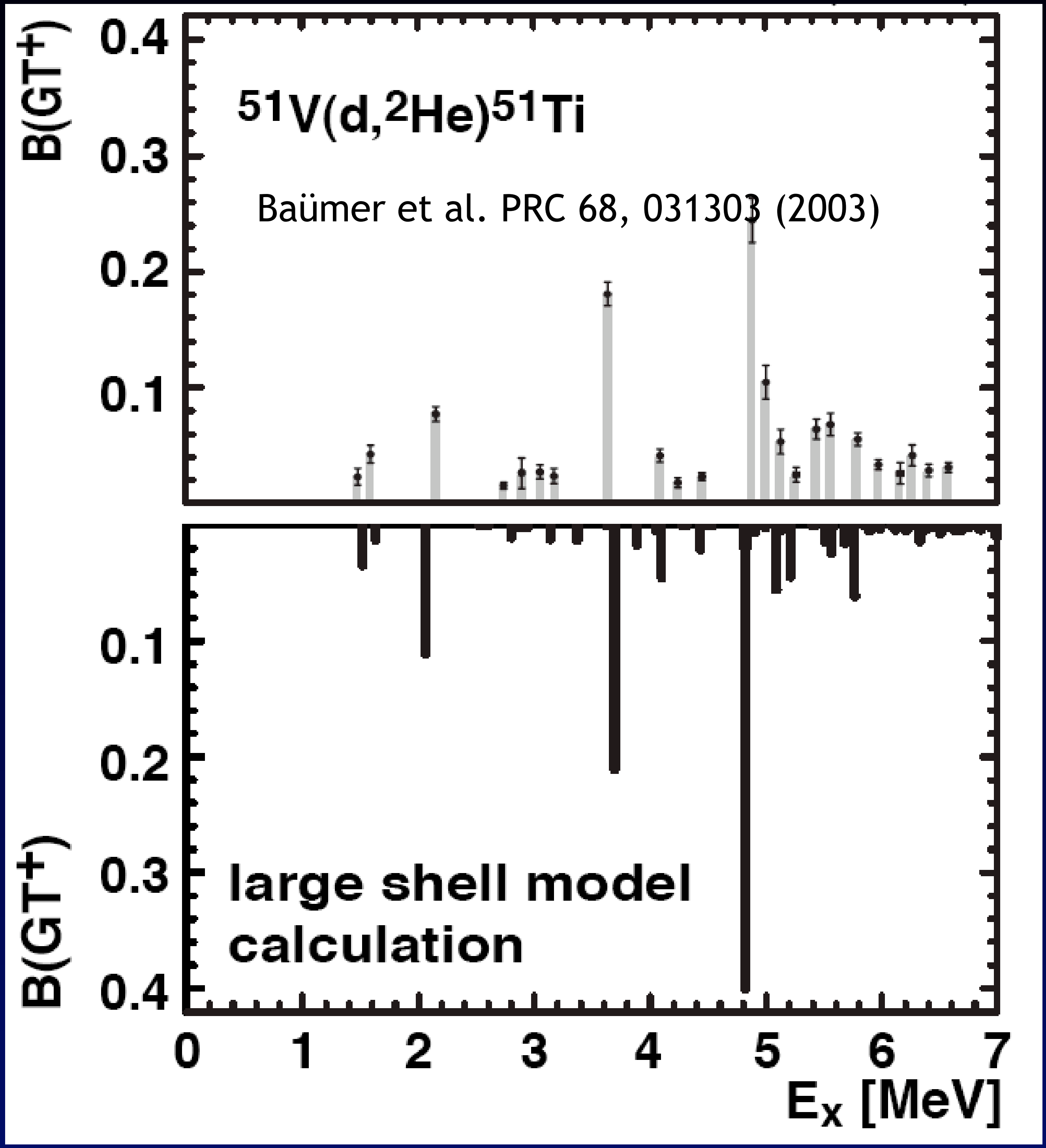


Nuclei with A ~ 120 contribute to e^-/ν capture.

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

How can we learn 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.

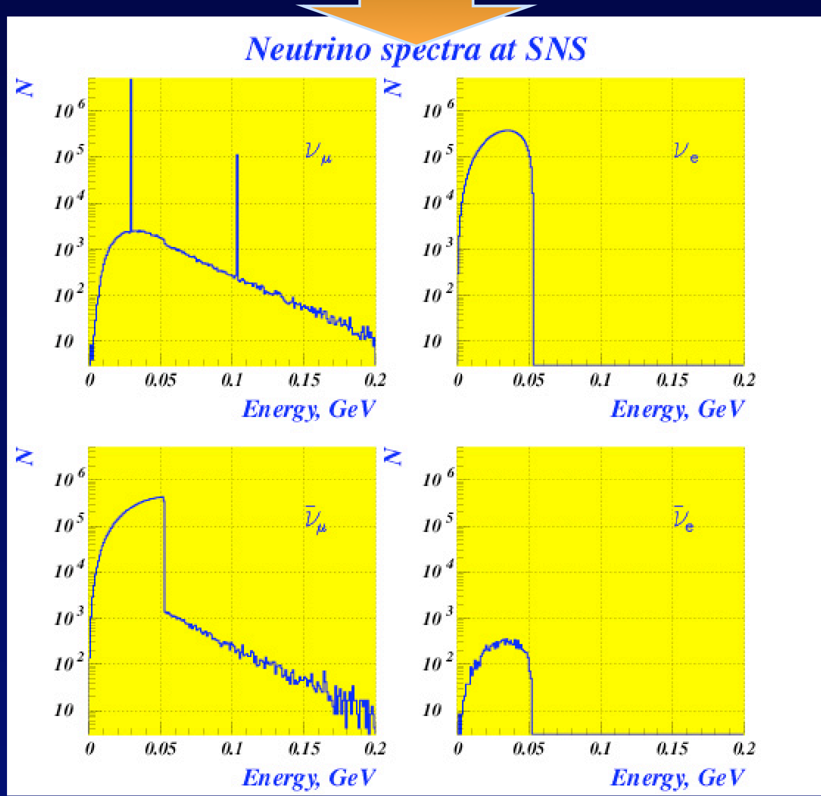
For A=80-100 nuclei of interest are 2-6 neutrons richer than stability.

Should be achievable with NextGen RIBs.

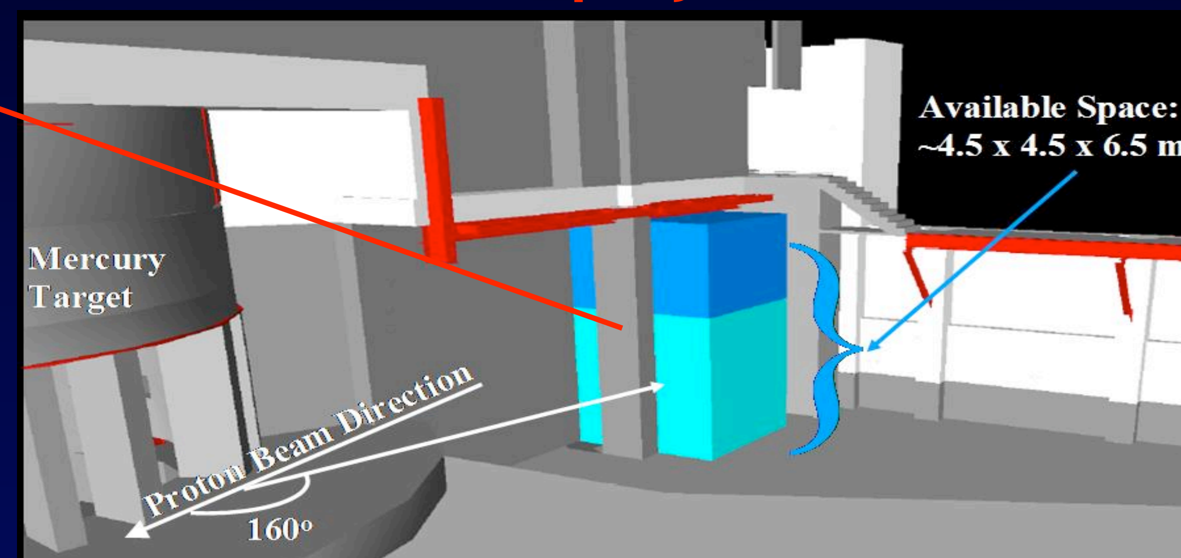
One can also measure ν captures

Spallation Neutron Source

sec^{-1}



ν-SNS an experimental program to study neutrino cross sections in the region of interest for astrophysics



2 universal ~ 20 tones detectors located 20 meters from the SNS target

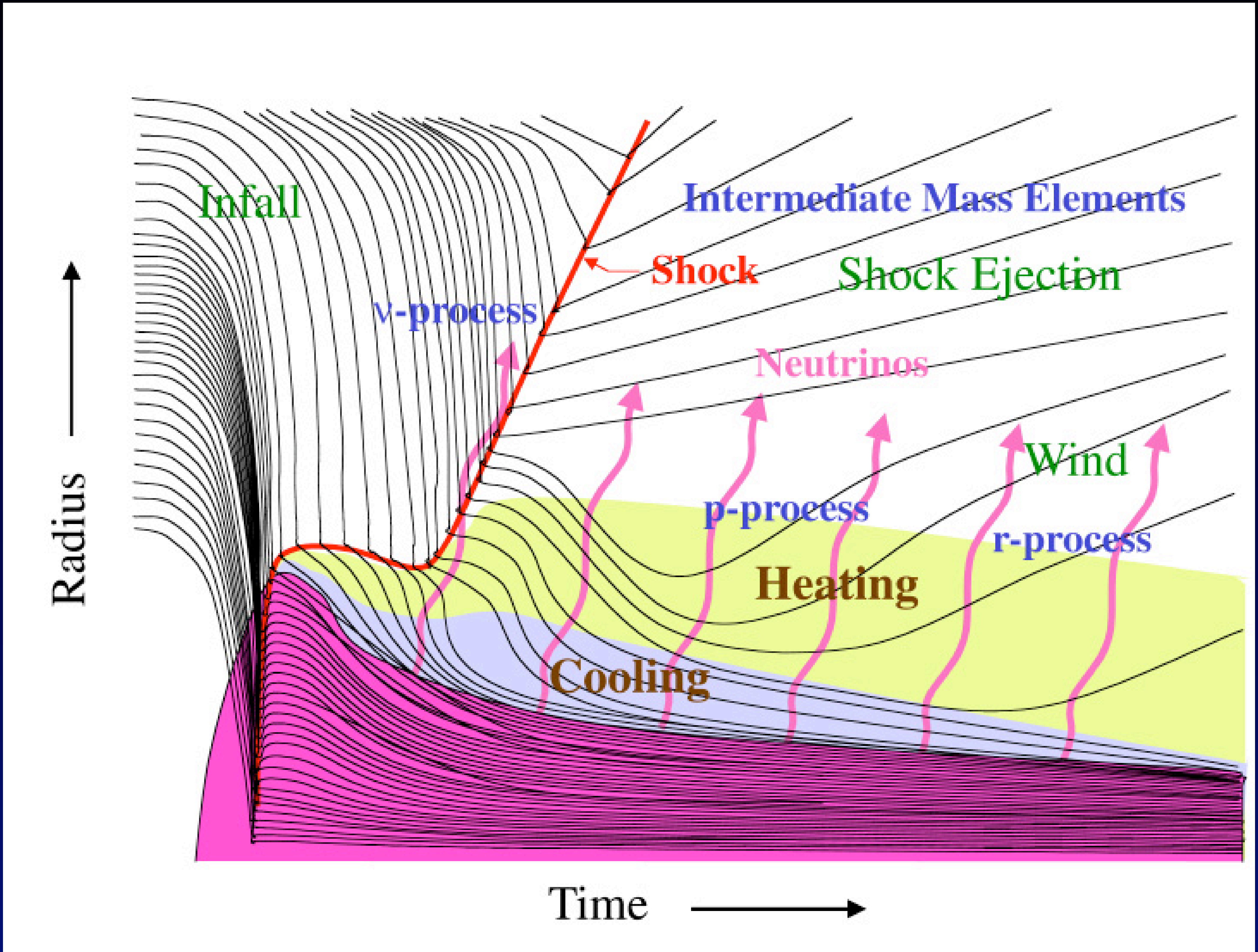
Segmented detector for solid targets

^{51}V, ^{27}Al, ^{9}Be, ^{11}B, ^{52}Cr, ^{56}Fe, ^{59}Co, ^{209}Bi, ^{181}Ta

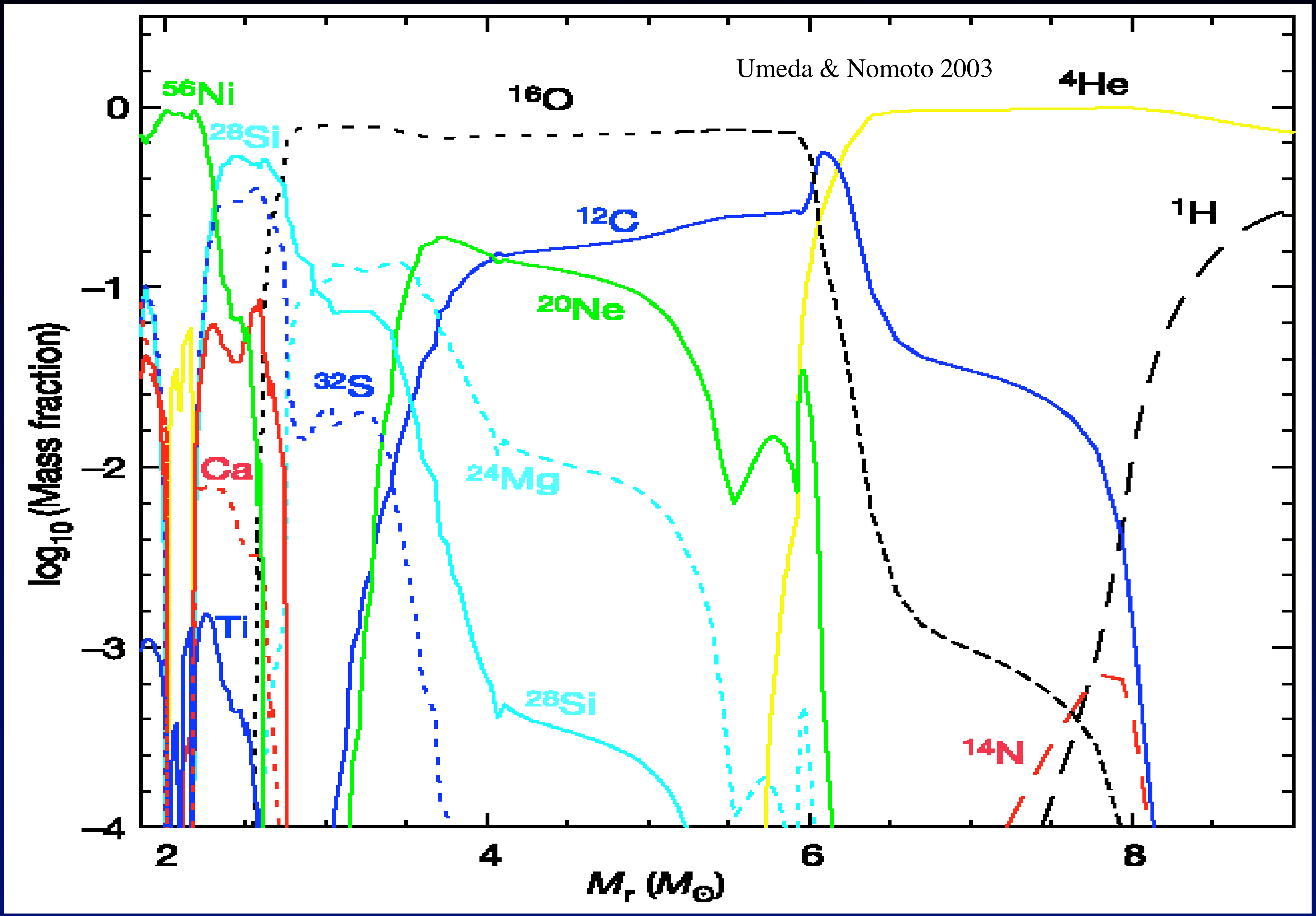
Homogeneous detector for **Liquid targets**

^{2}d, ^{12}C, ^{16}O, ^{127}I

Supernova Nucleosynthesis



Models are rich in heavy elements



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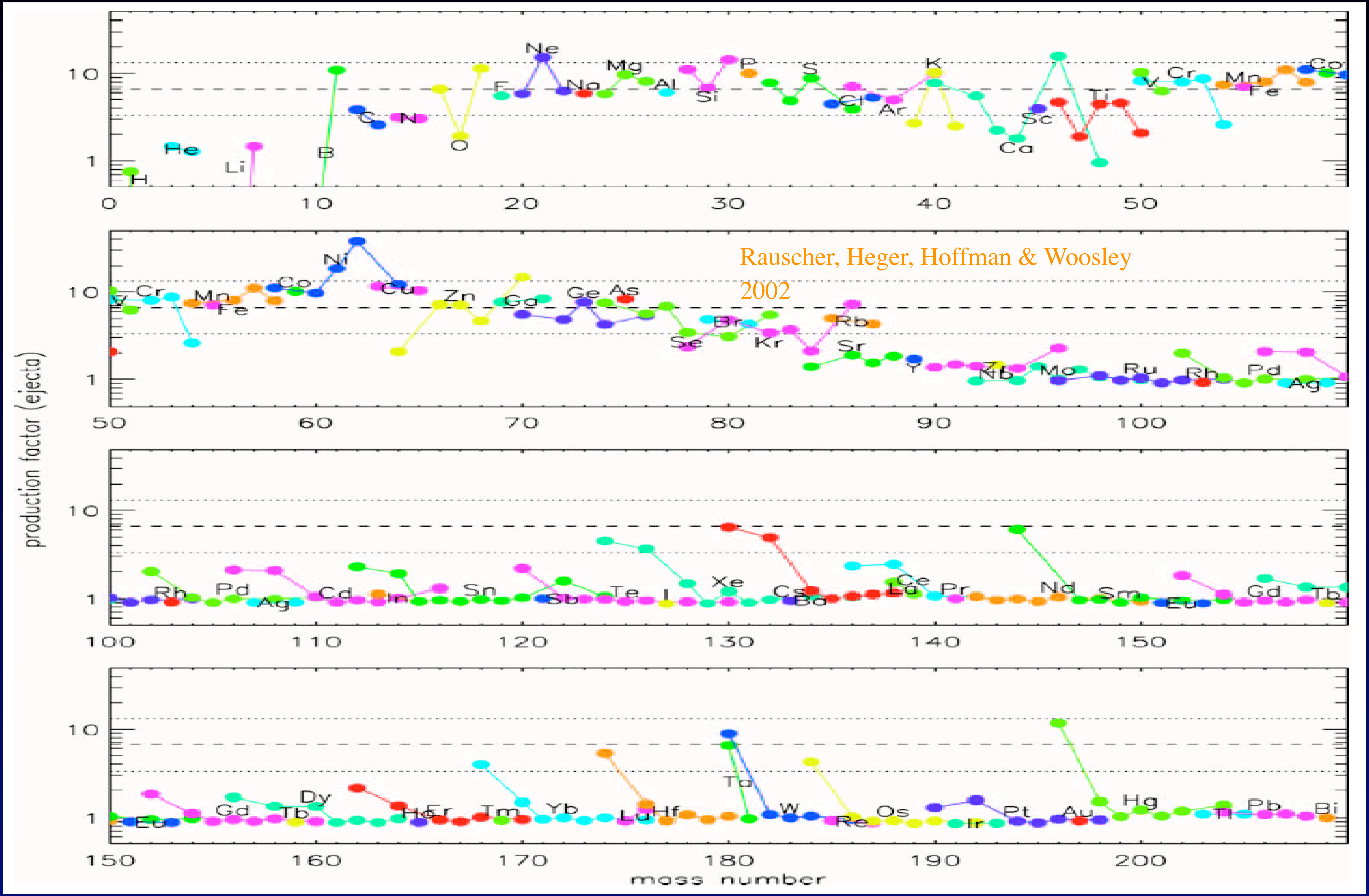
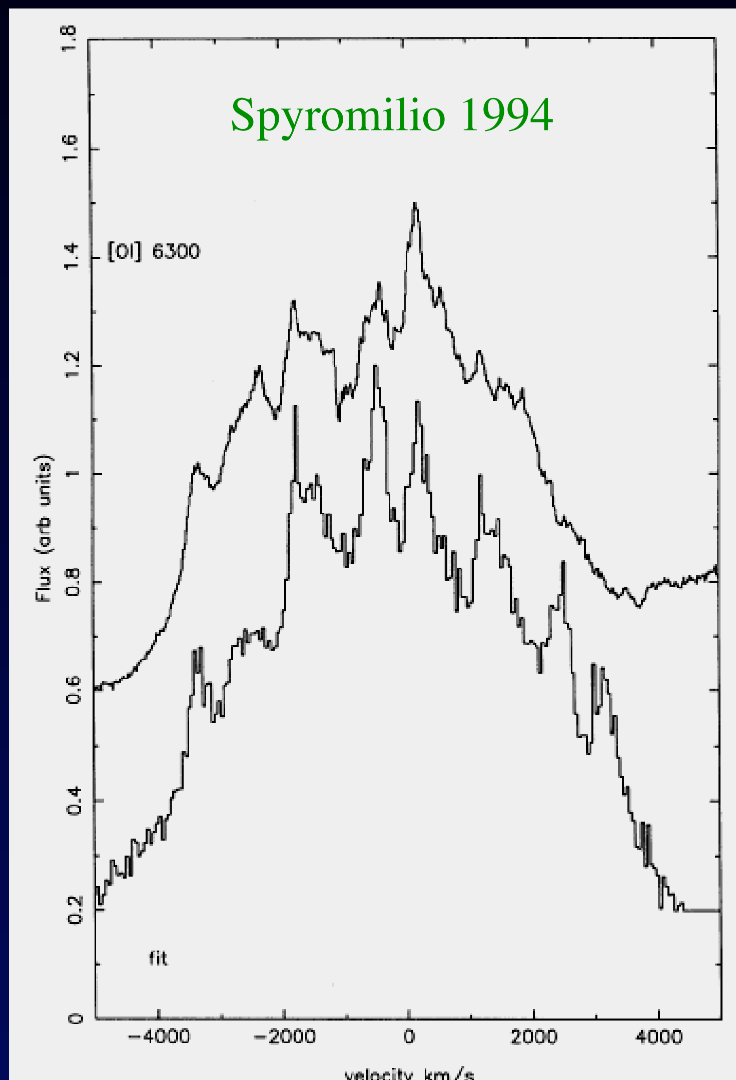
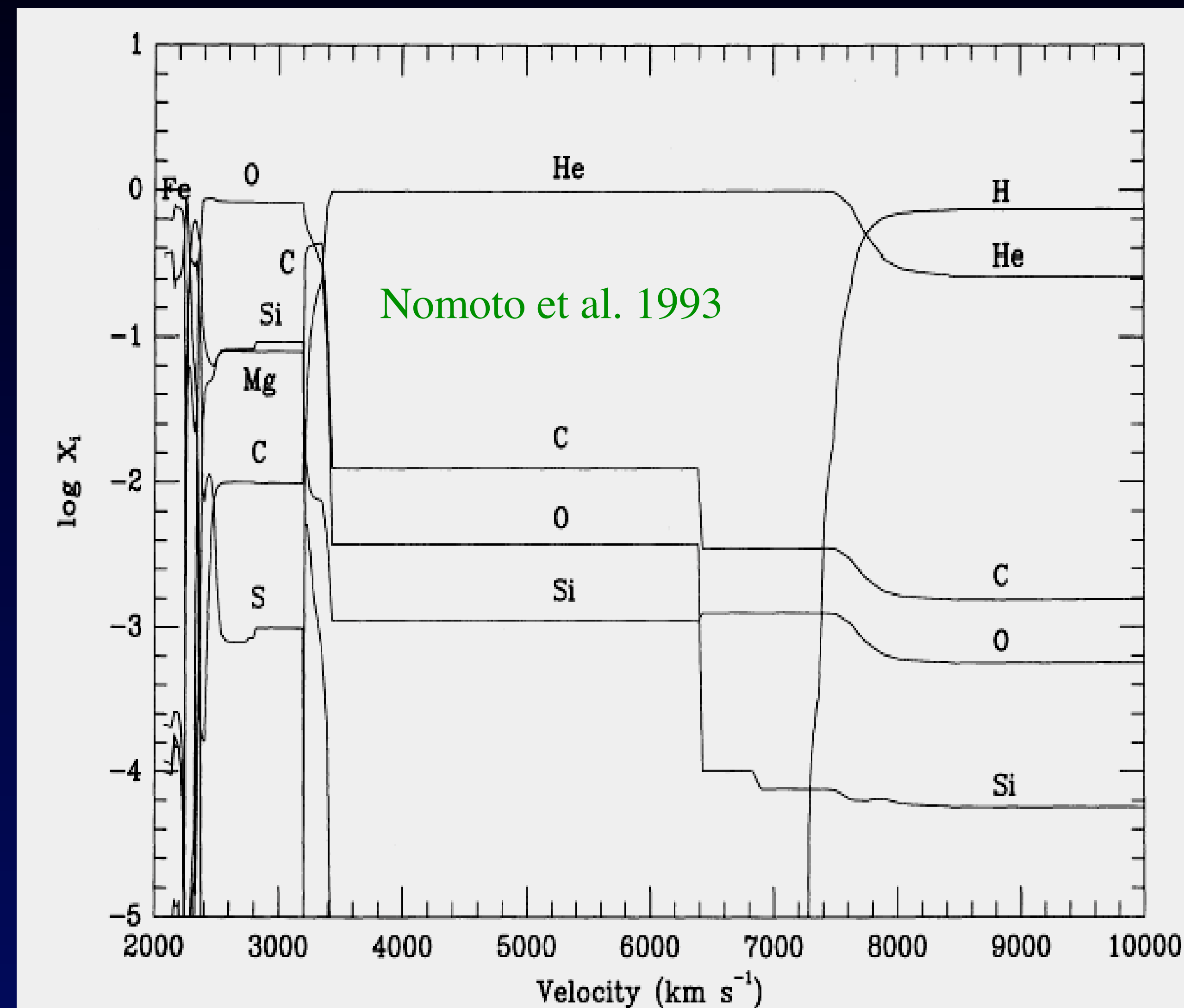


Parameterized Nucleosynthesis





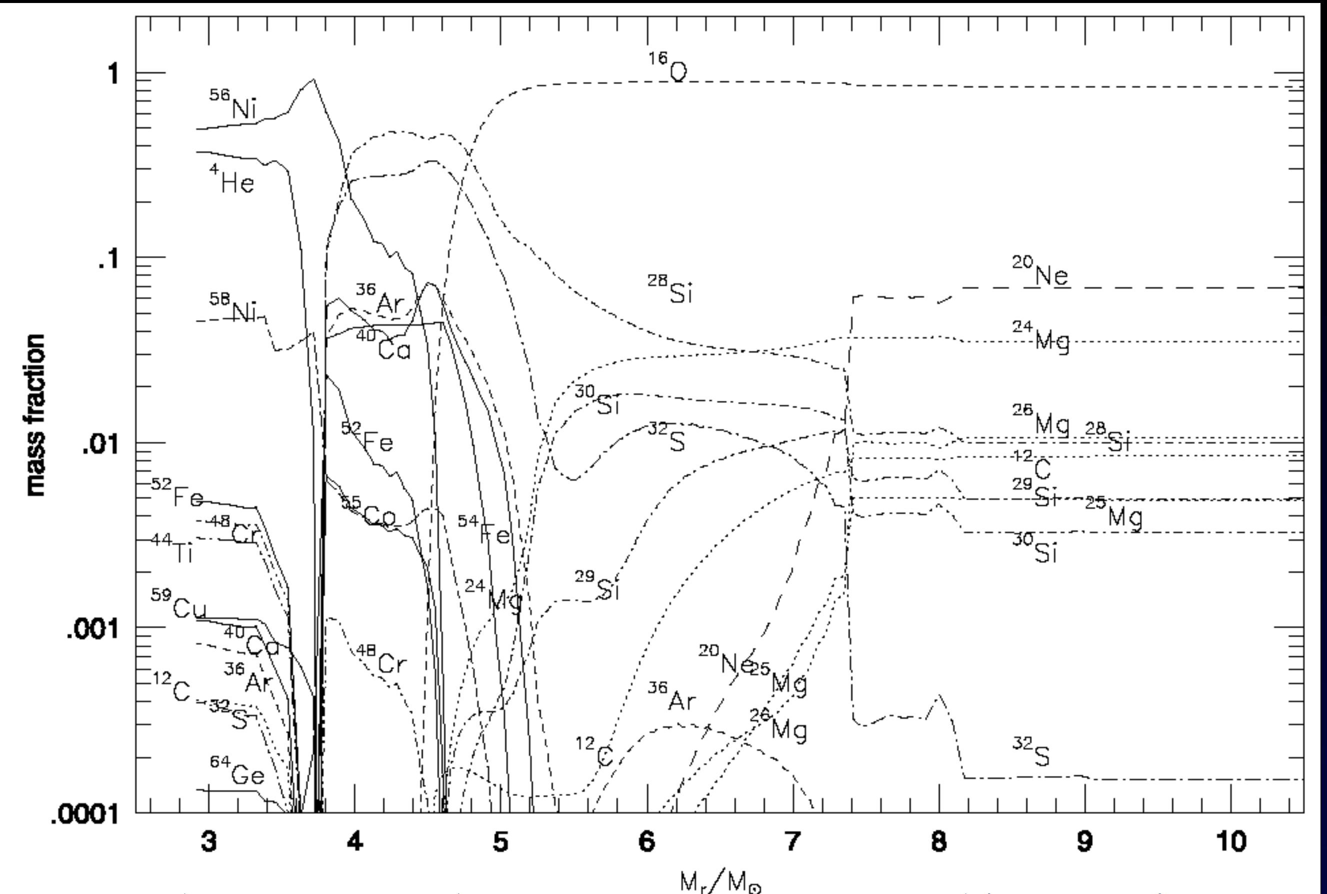
In current models, 2 parameters, the Bomb/Piston energy and the mass cut, are constrained by observations of explosion energy and mass of ^{56}Ni ejected.

Hypernovae

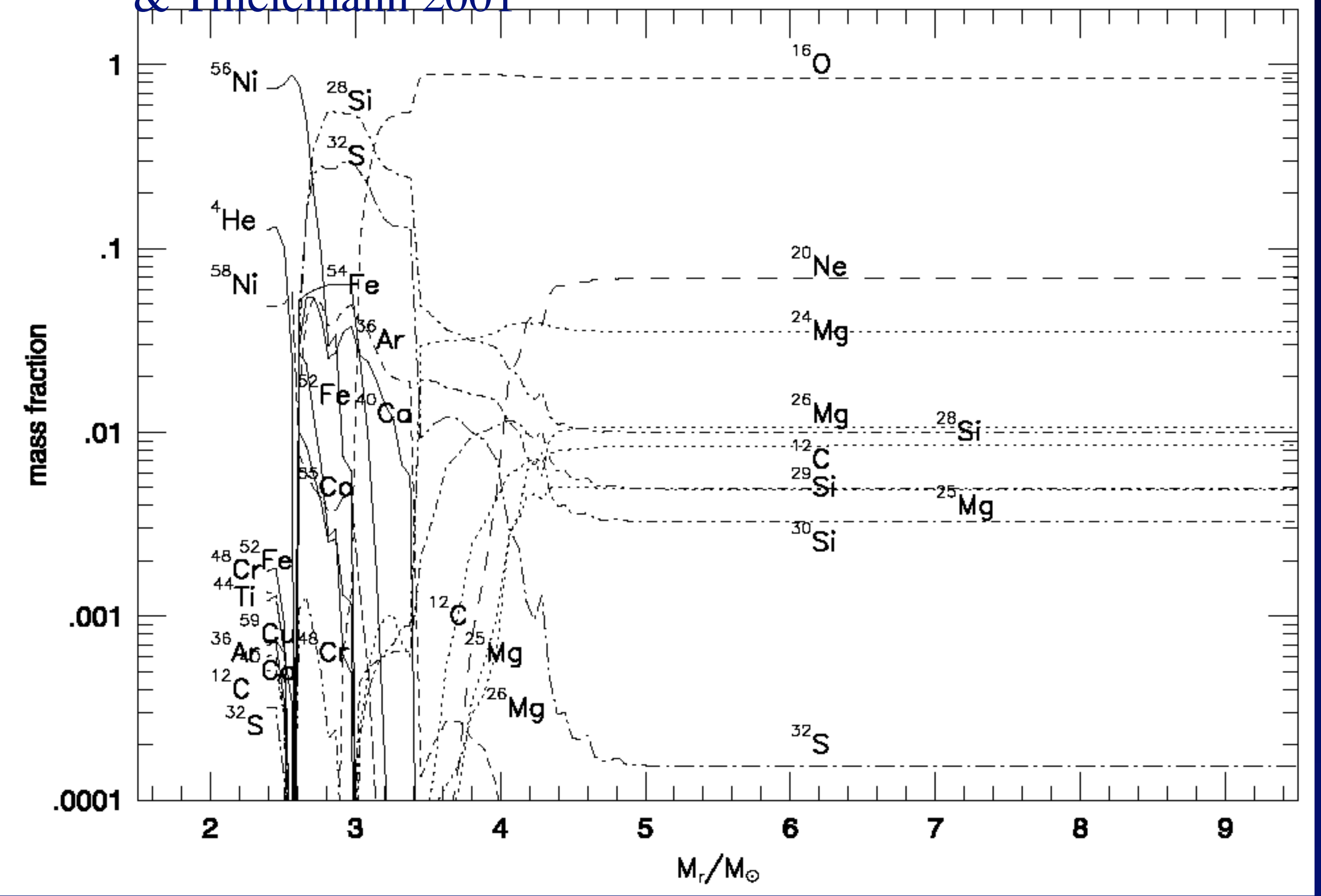
Observation GRB with SN raises question of changes in nucleosynthesis from a “Hyper”-energetic blast wave.

- Si/O, Fe/O increase because more O is destroyed.
- Ti/Fe, Zn/Fe increase because of more α-rich freezeout.
- Cr/Fe, Mn/Fe decrease while Co/Fe increases due to more complete Si burning

Match to puzzles in metal-poor stars and BH companions



Nakamura, Umeda, Iwamoto, Nomoto, Hashimoto, Hix & Thielemann 2001

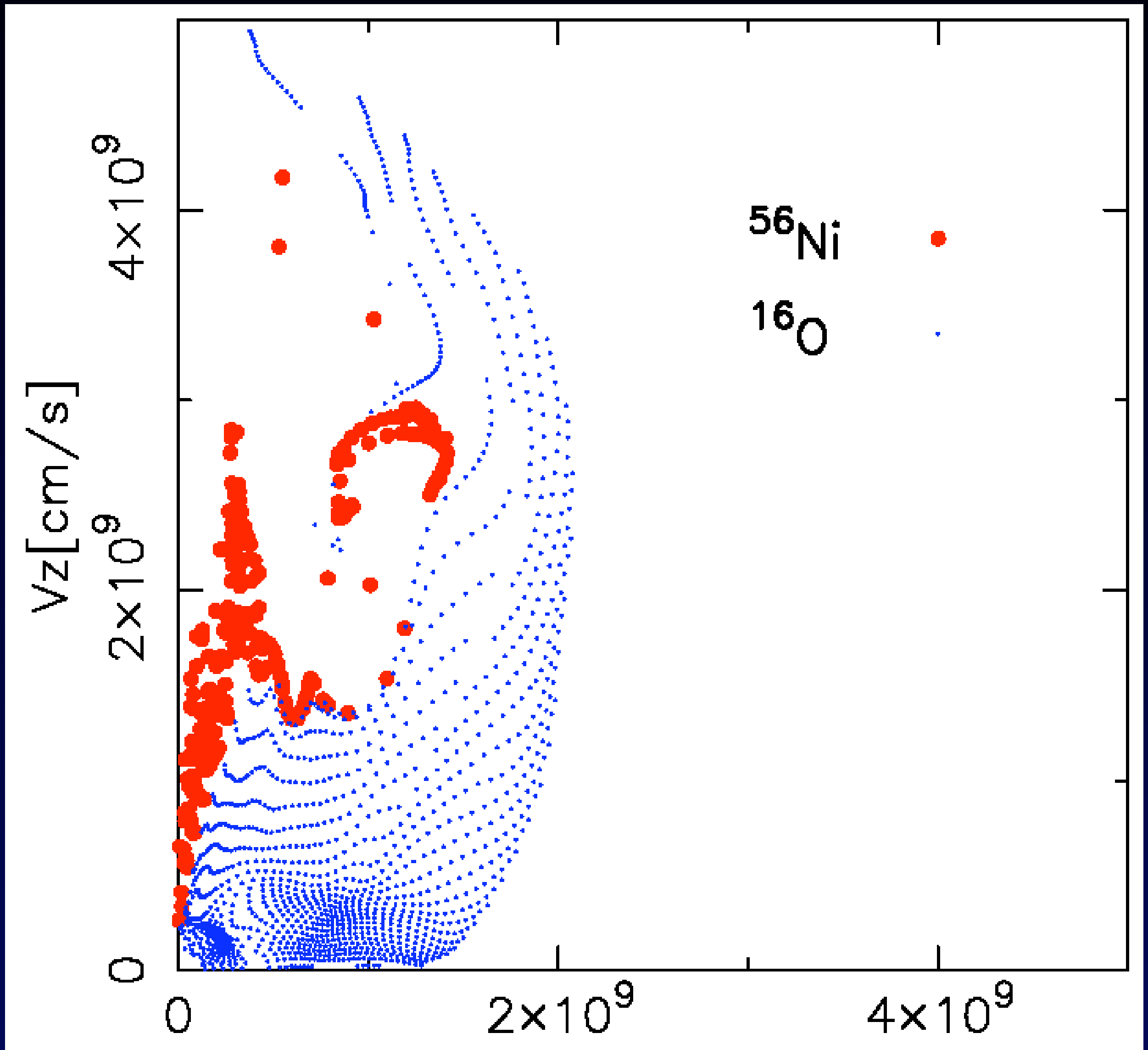


Multi-D Explosions

SN associated with GRB can not be spherical. Jet like models require Multi-D simulations. (Umeda, Nakamura, Nomoto, Mazzali, Patat, Hachisu 2002)

Ni production and α-rich freezeout enhanced along jet.

Ordinary SN also evidence nonspherical features. (Nagataki, Hashimoto, Sato & Yamada 1997, 1998)



Multi-D Explosions

SN associated with GRB can not be spherical. Jet like models require Multi-D simulations. (Umeda, Nakamura, Nomoto, Mazzali, Patat, Hachisu 2002)

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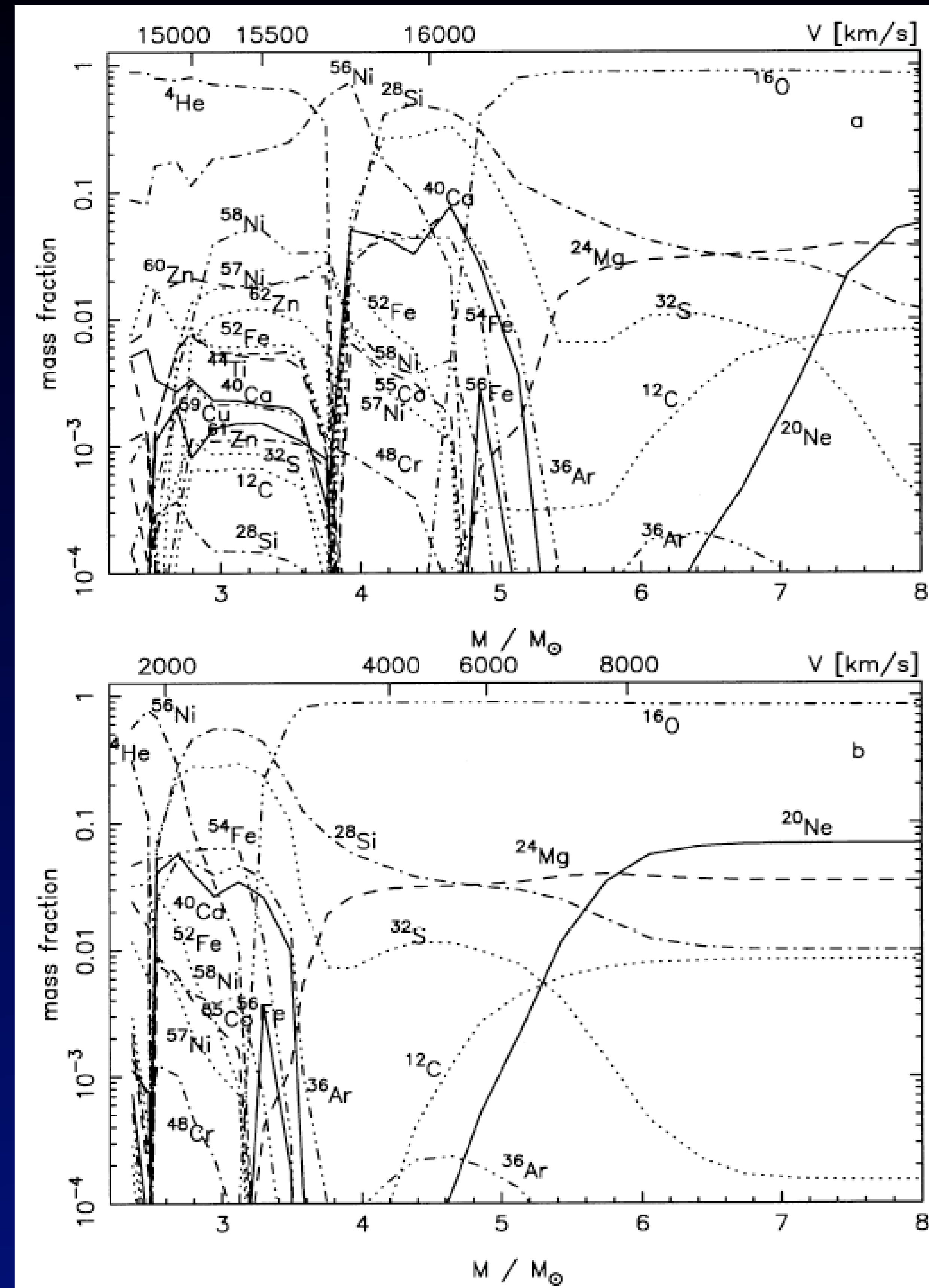

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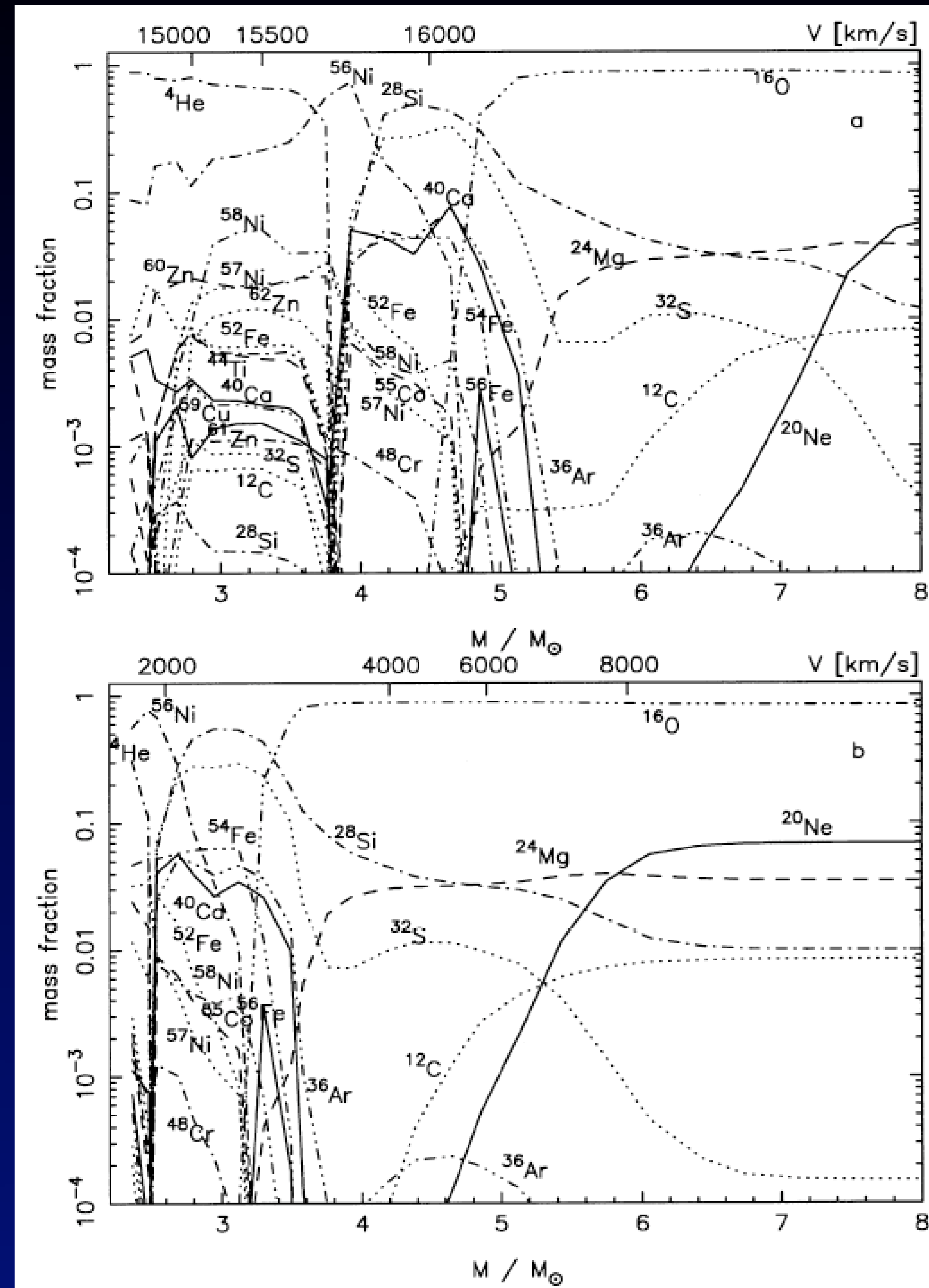
These models lack “in situ” nucleosynthesis and neutrino effects.



First of the Next Generation

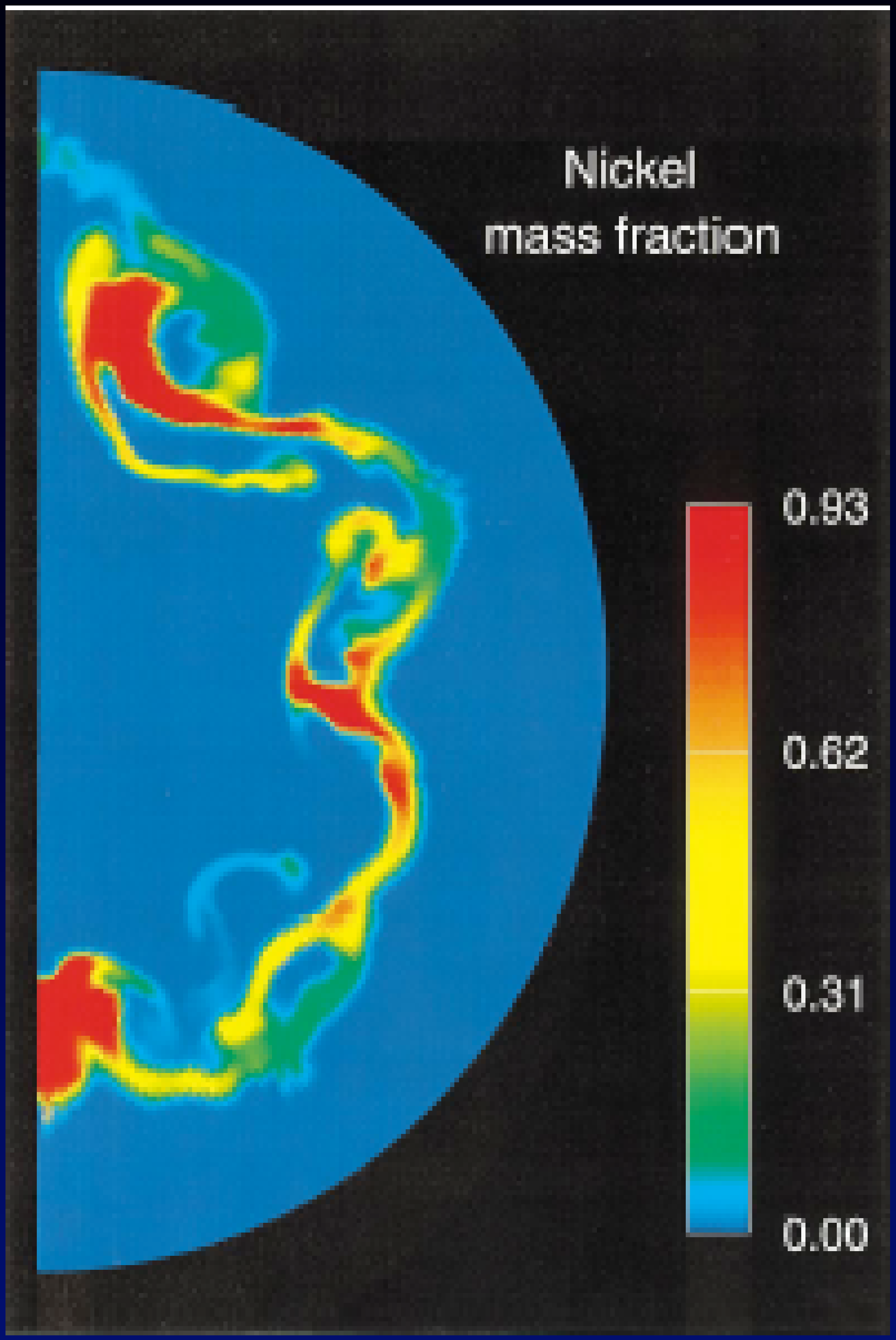
Kifonidis, Plewa, Janka & Müller (2003) first model to include a network in a multi-D neutrino transport code.

Added an α network to Janka & Müller (1996). After ~1 second, mapped result to a non-transport code.

Limitations:

α network is a poor approximation for Si-burning and α-rich freezeout

Mapping prevents study of mass cut.

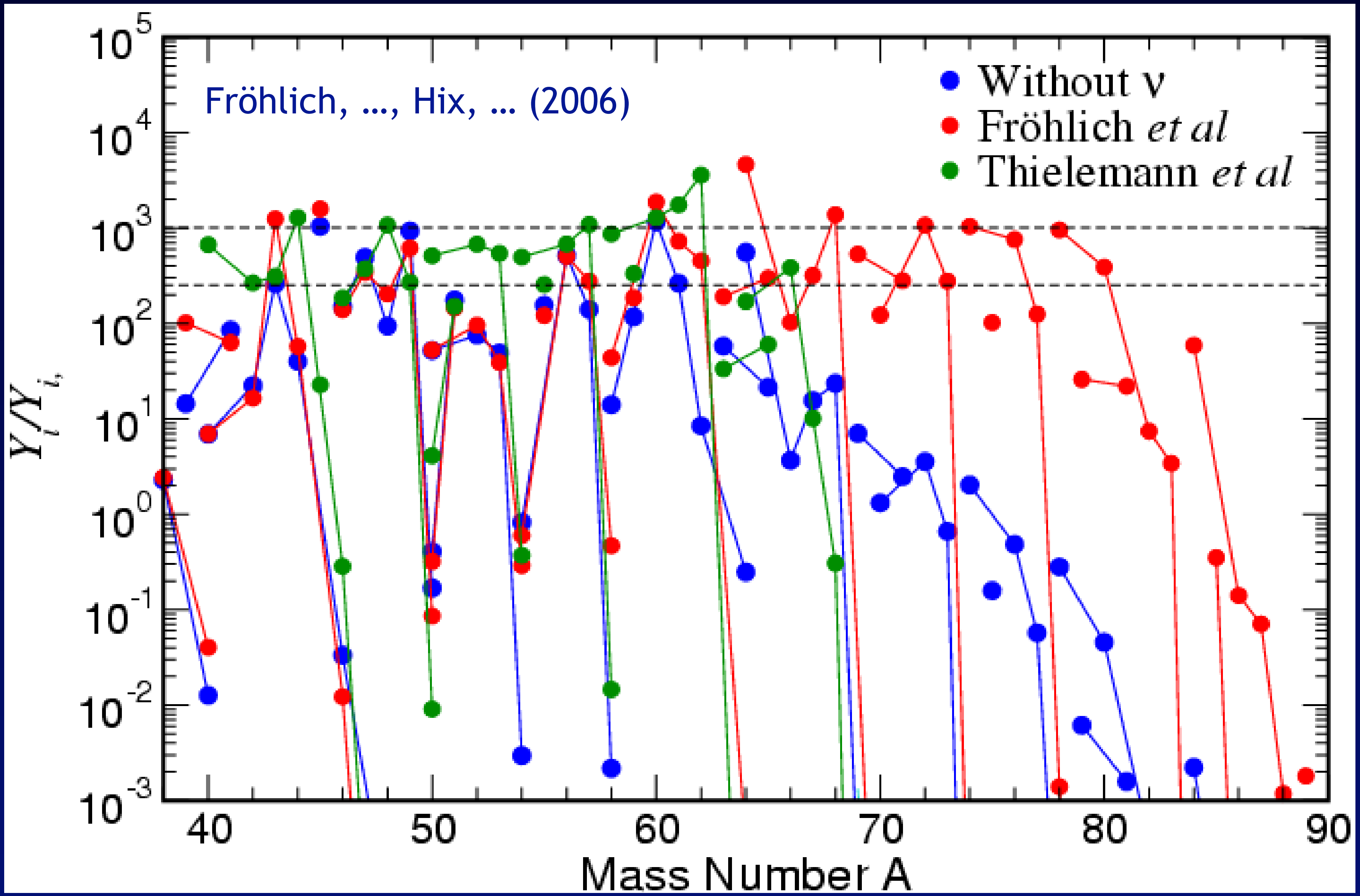


ν-Effects on Supernova Nucleosynthesis

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:

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



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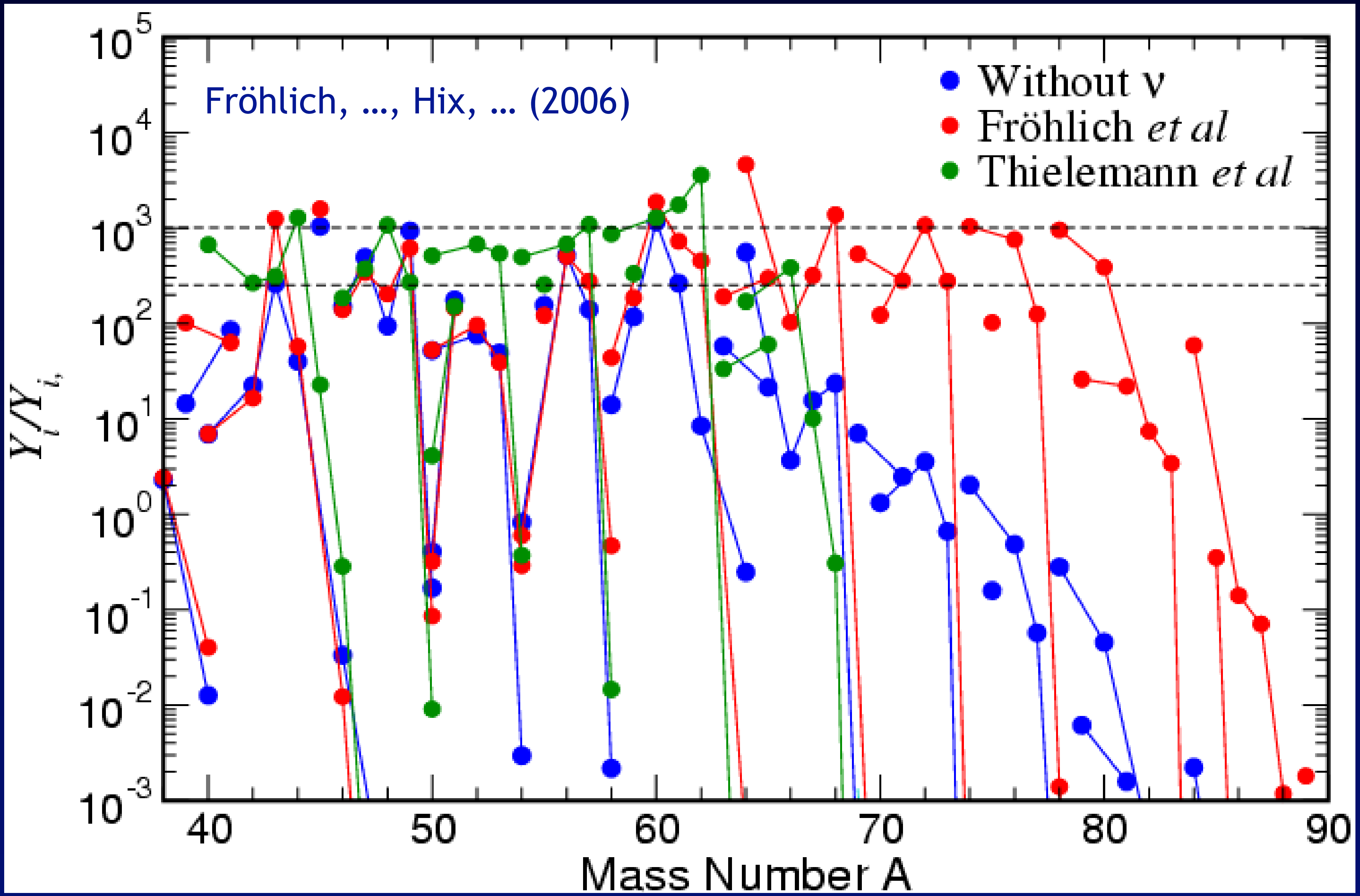
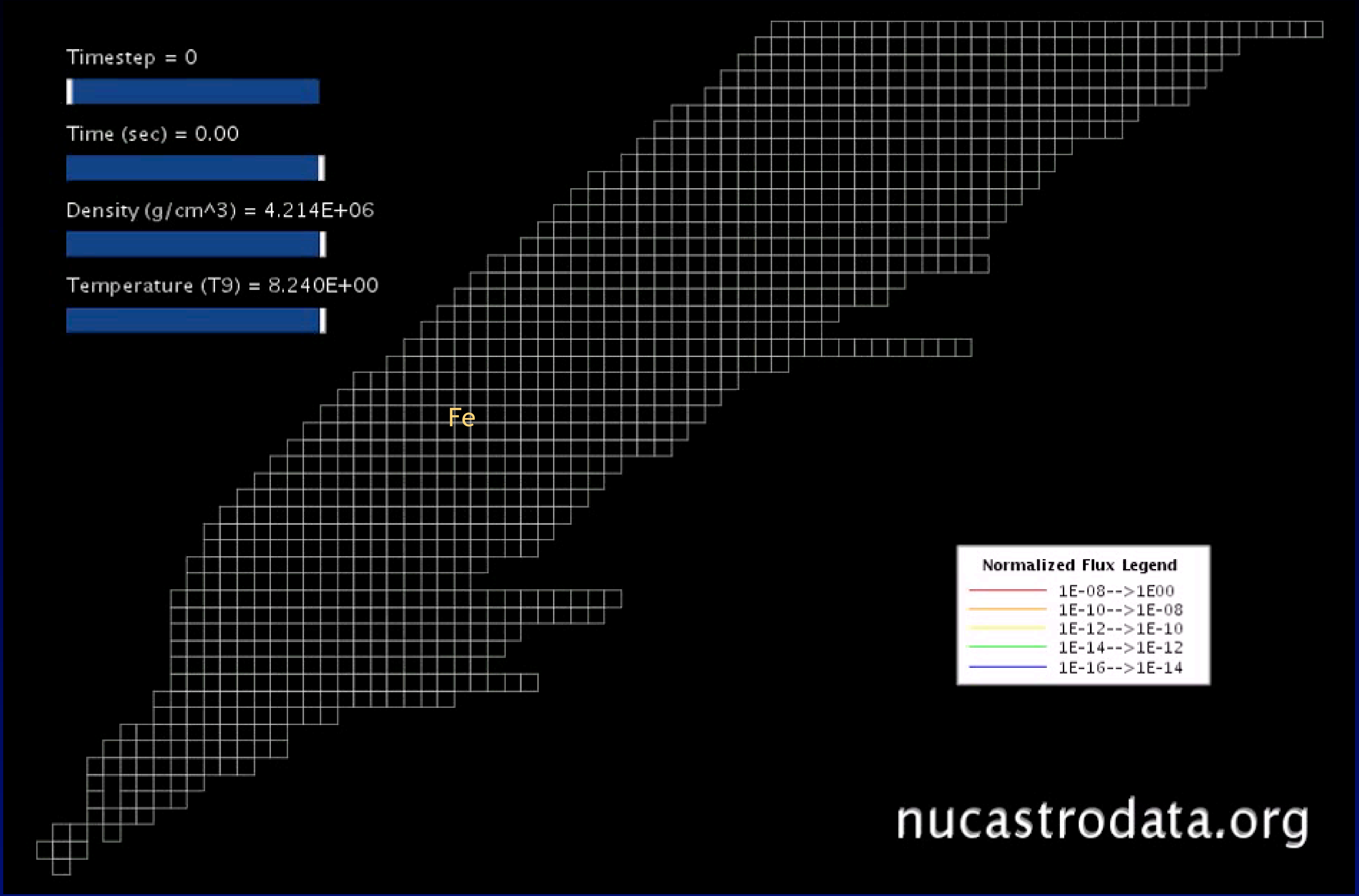


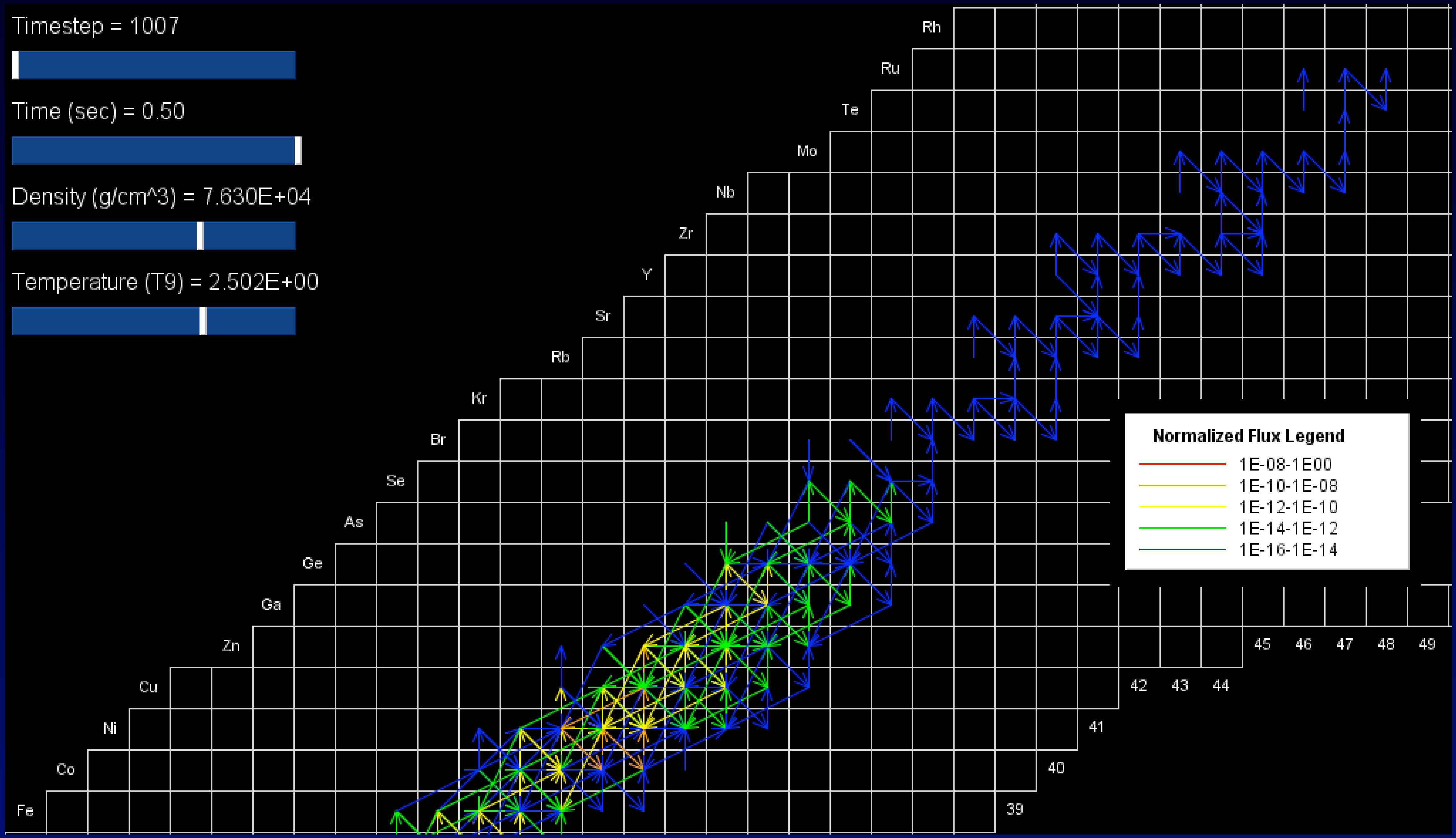
Similar Effects seen in GRB disks with low accretion rate. (Surman, McLaughlin & Hix 2006)

νp-process


Timestep = 0
Time (sec) = 0.00
Density (g/cm^3) = 4.214E+06
Temperature (T9) = 8.240E+00
Fe
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. $\tau(^{64}Ge) = 64$ s

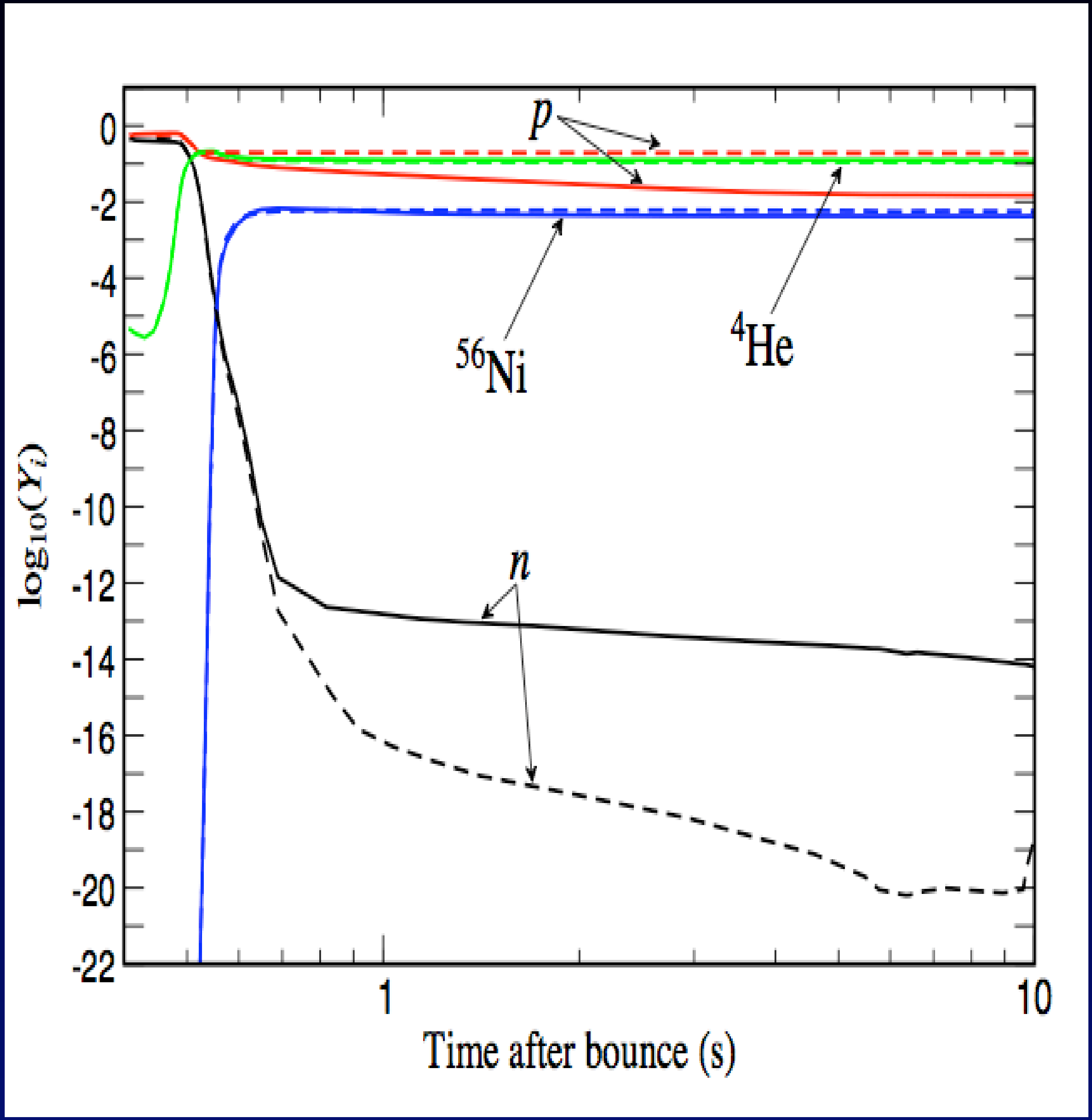


Neutrons in a proton-rich environment?

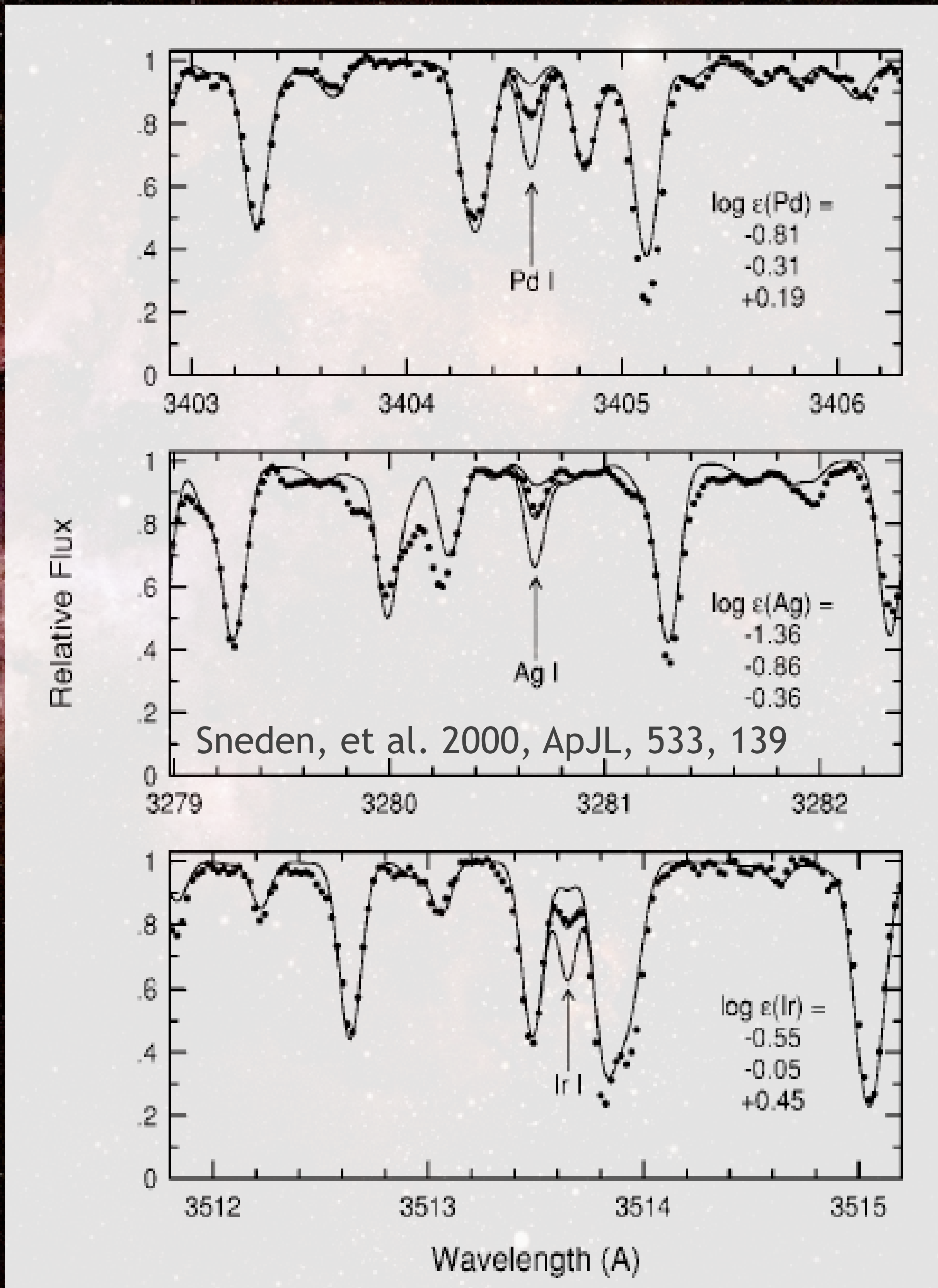
Main abundances: ^{1}H, ^{4}He, ^{56}Ni from p-rich and α-rich freeze-out.

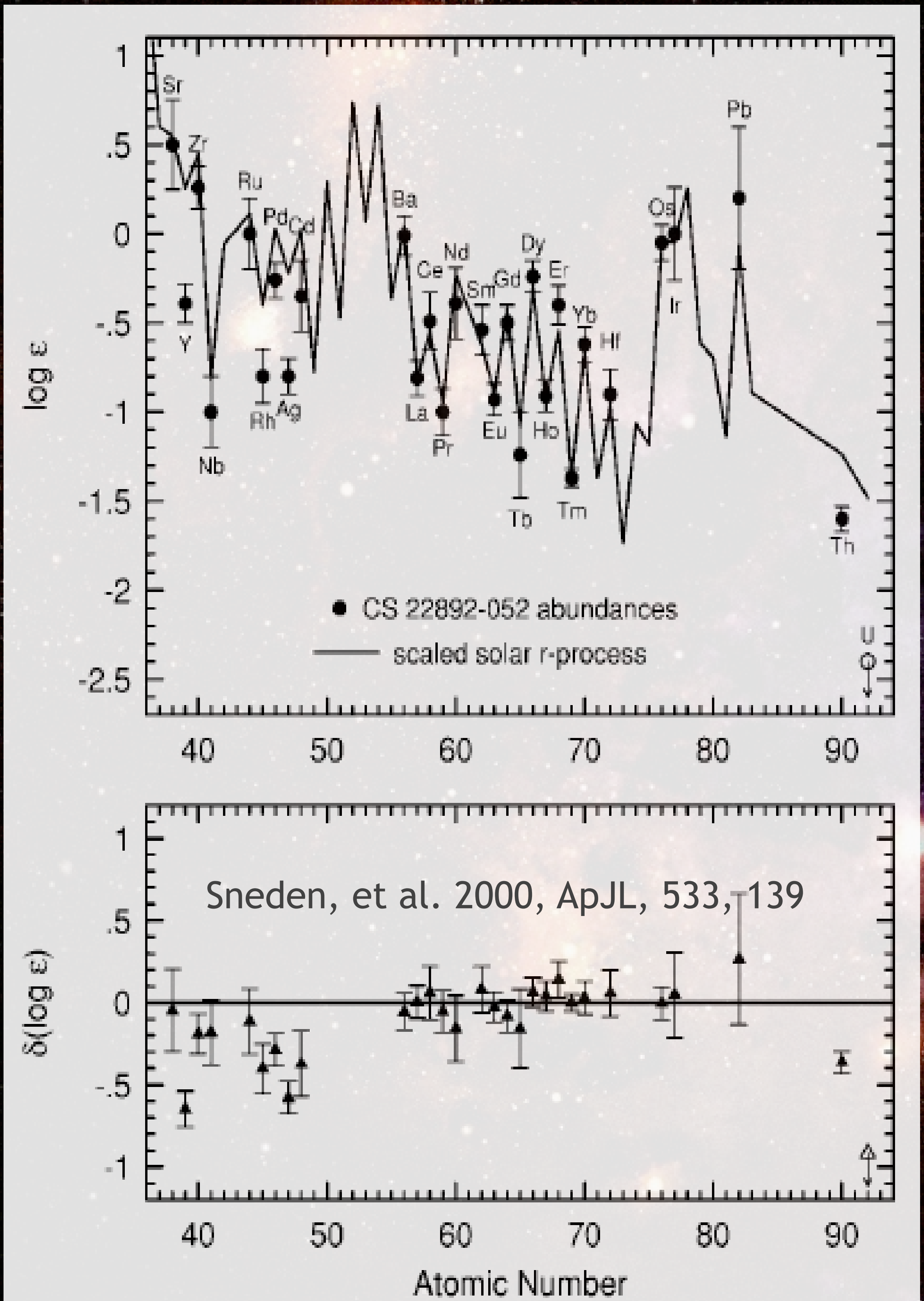
Protons converted to neutrons via anti-neutrino capture.

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



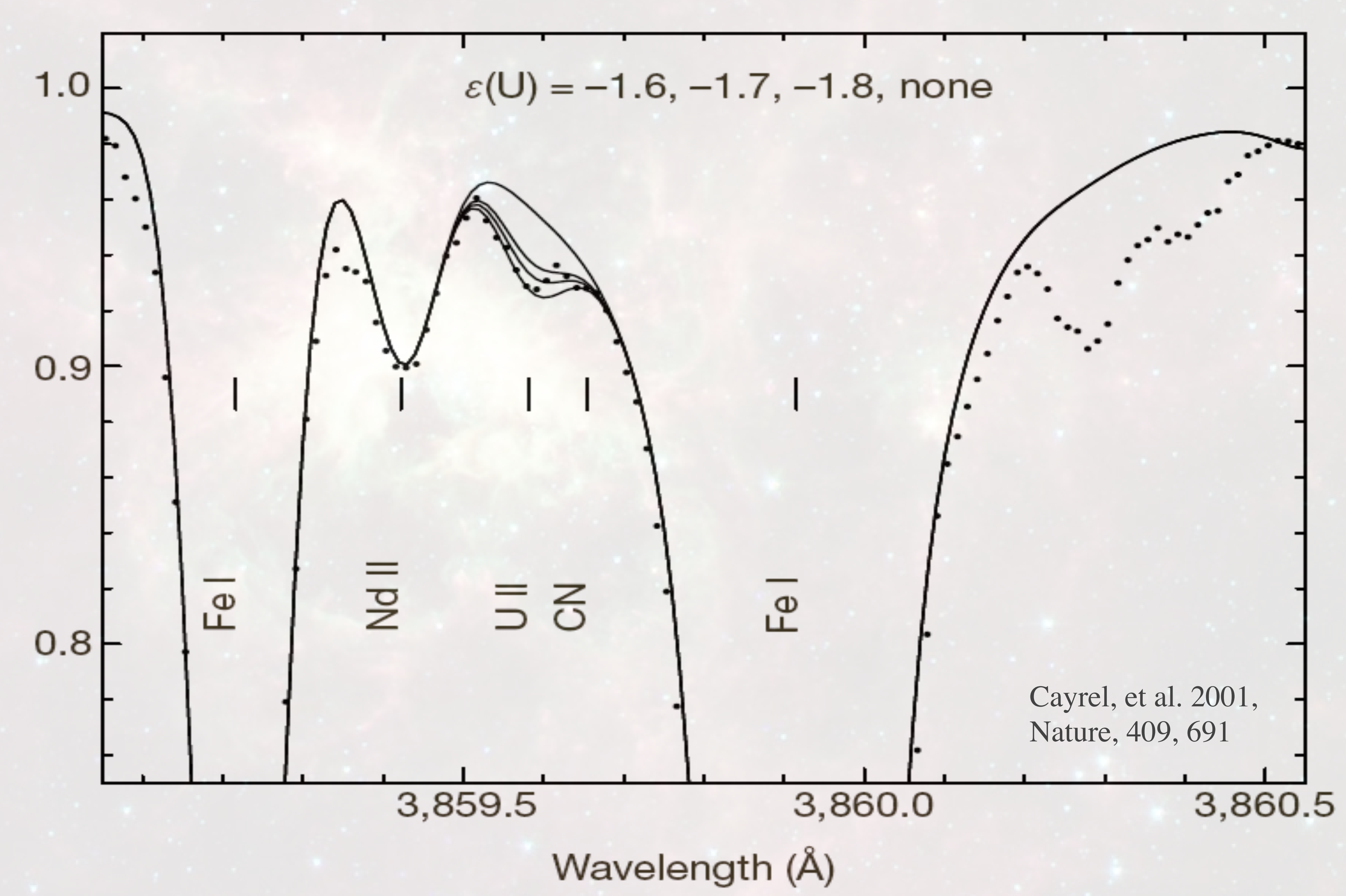
Detecting the r-process in old stars





Uranium?

CS31082-001 has 1/800 Solar Fe but 1/9 Solar Os/Ir

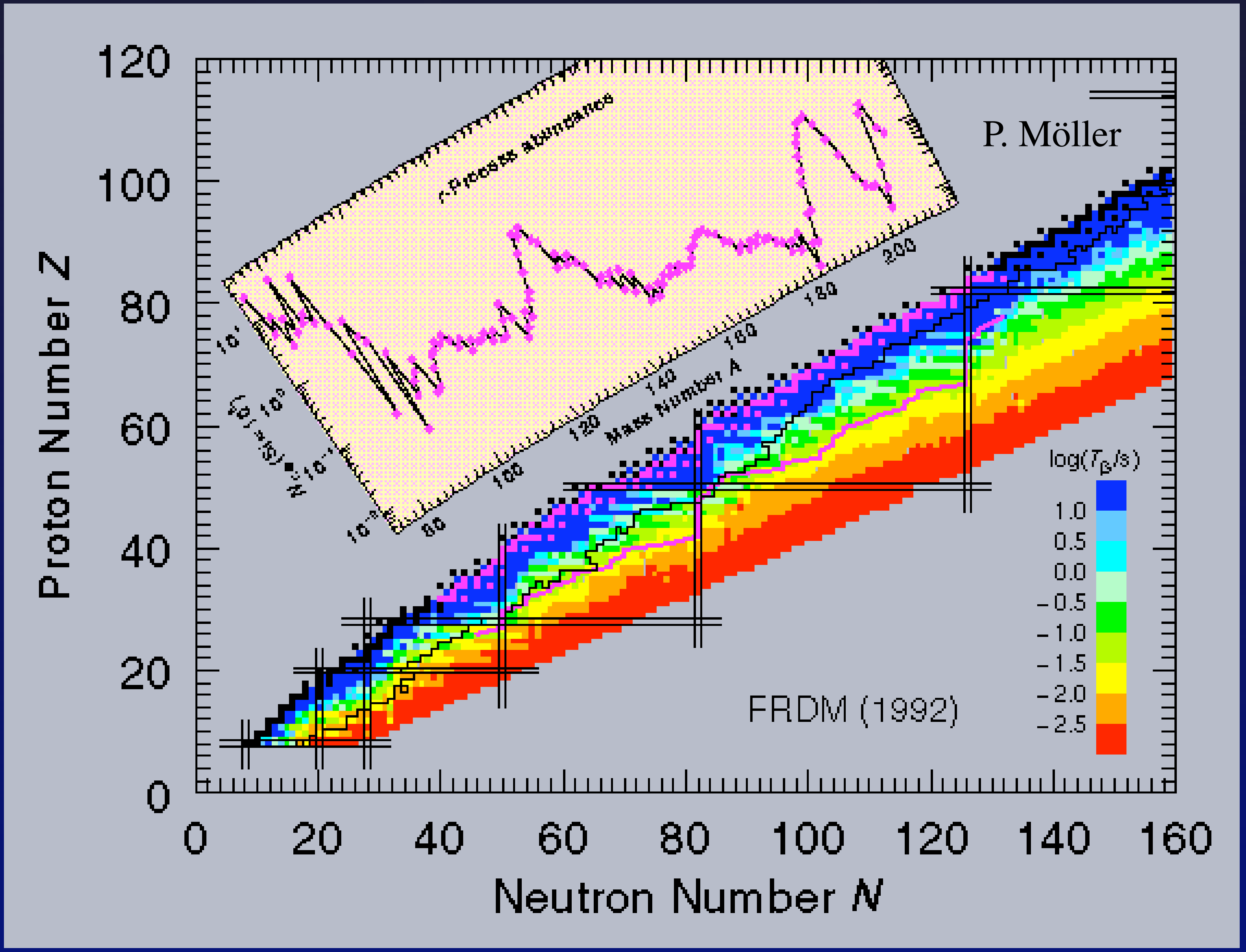


Decay of ^{238}U ($\tau_{1/2}$=4.5 Gyr) implies 12.5±3 Gyr

Shell Effects and the r-process path

In the r-process neuton capture are faster than beta decays. Nuclear flow proceeds far from stability.

Abundances accumulate near closed shells where the rates are slowest.



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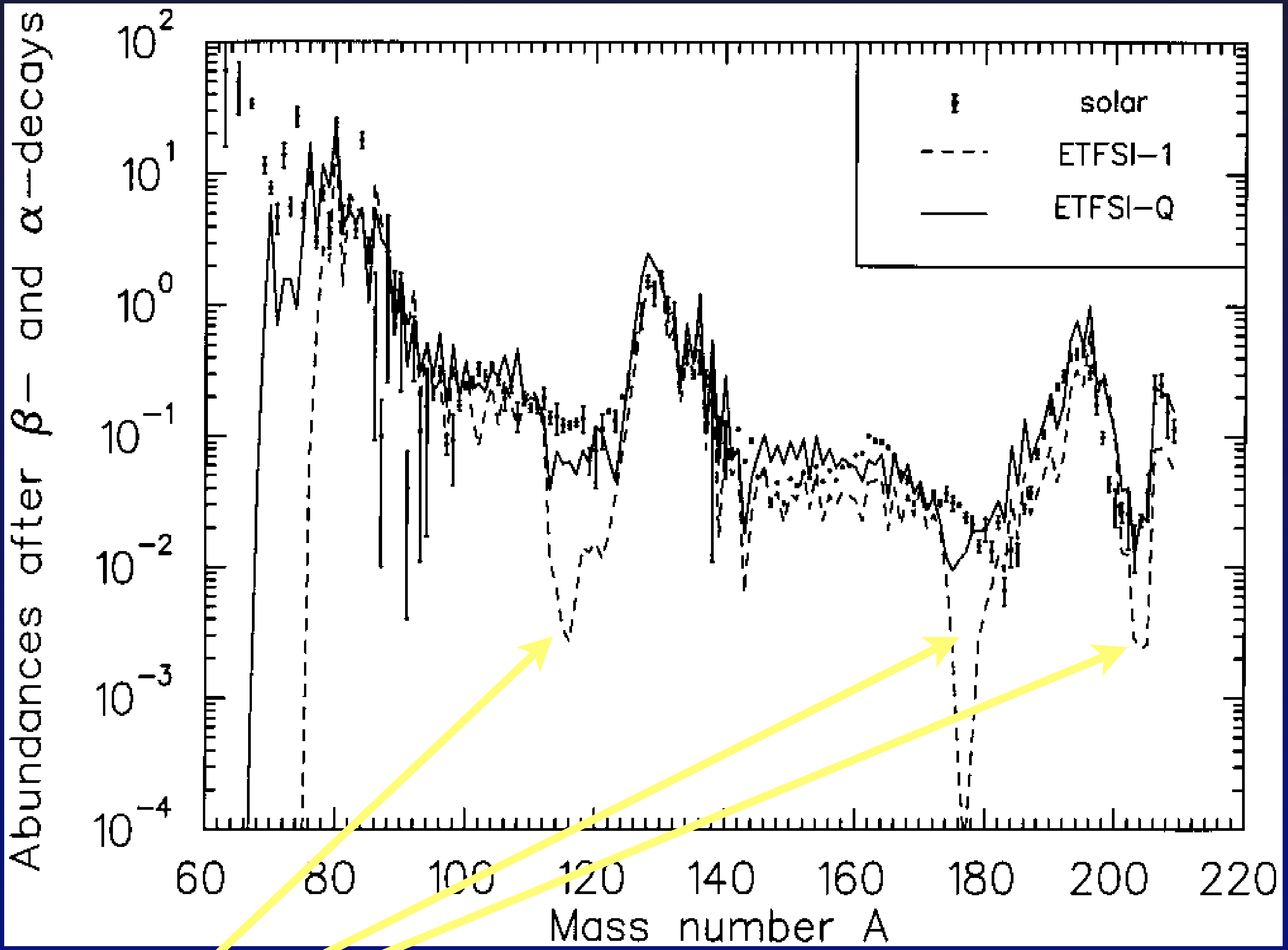
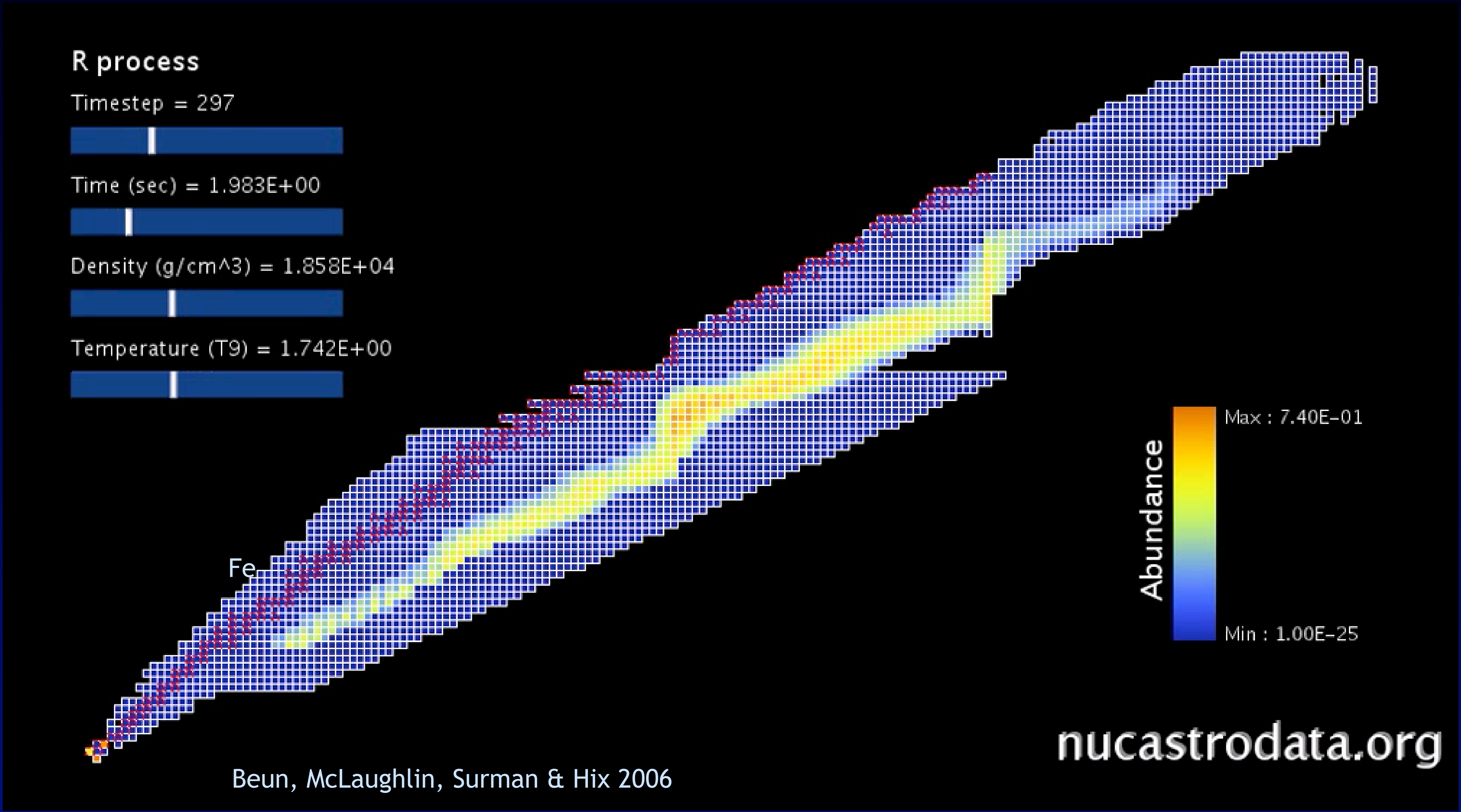


Mass Model has been shown to strongly effect the predicted abundances.

Simulating the r-process

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



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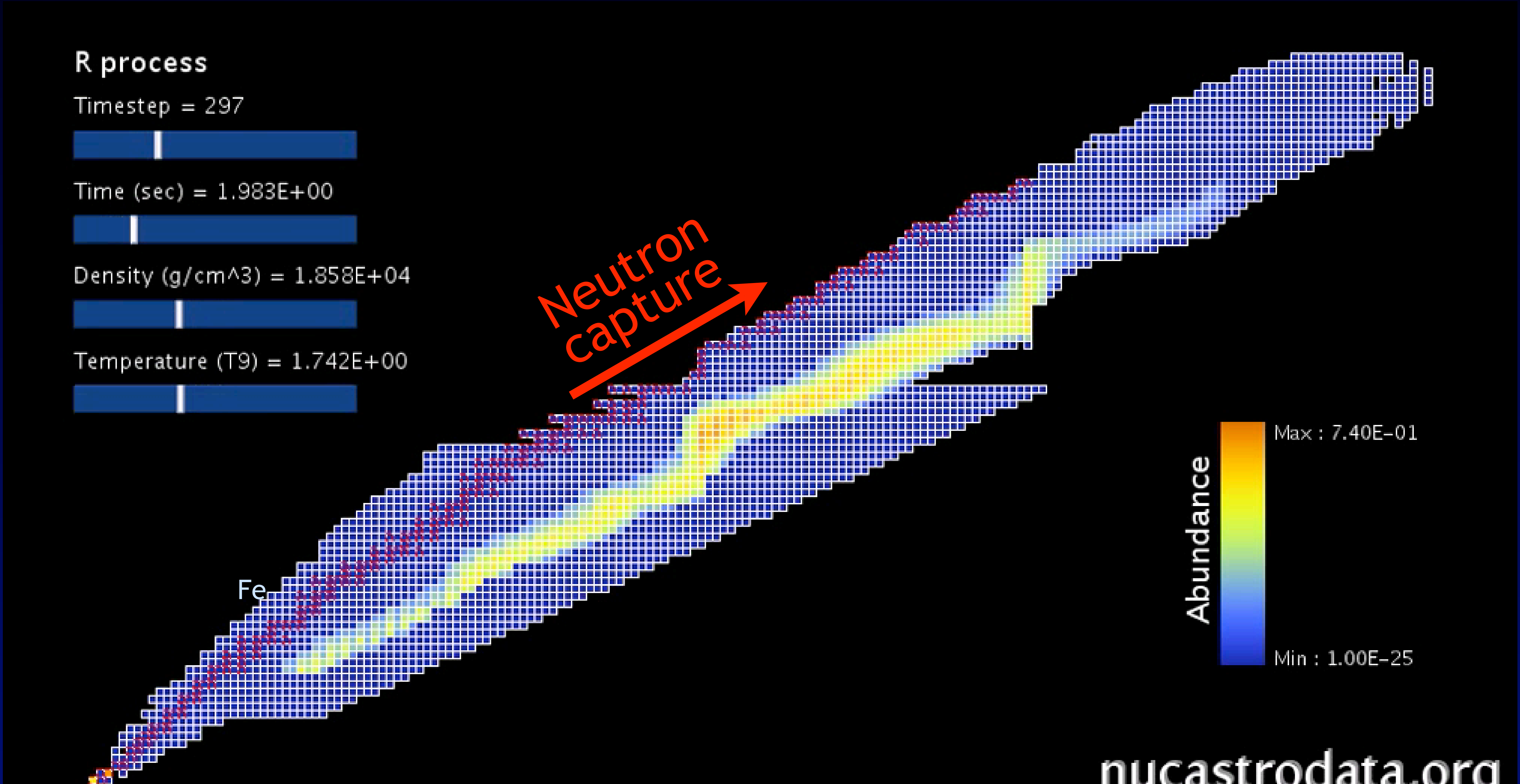

Beun, McLaughlin, Surman & Hix 2006

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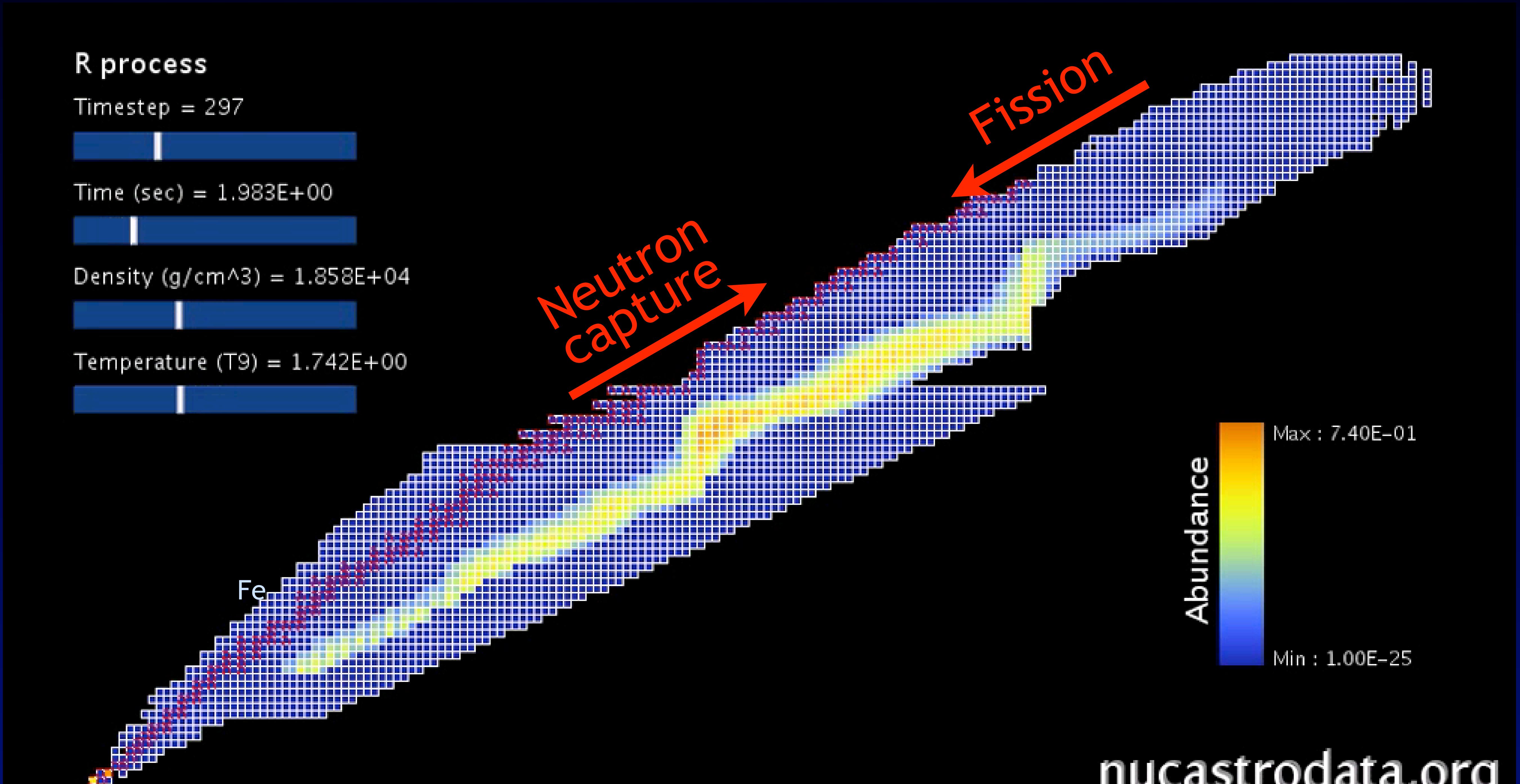
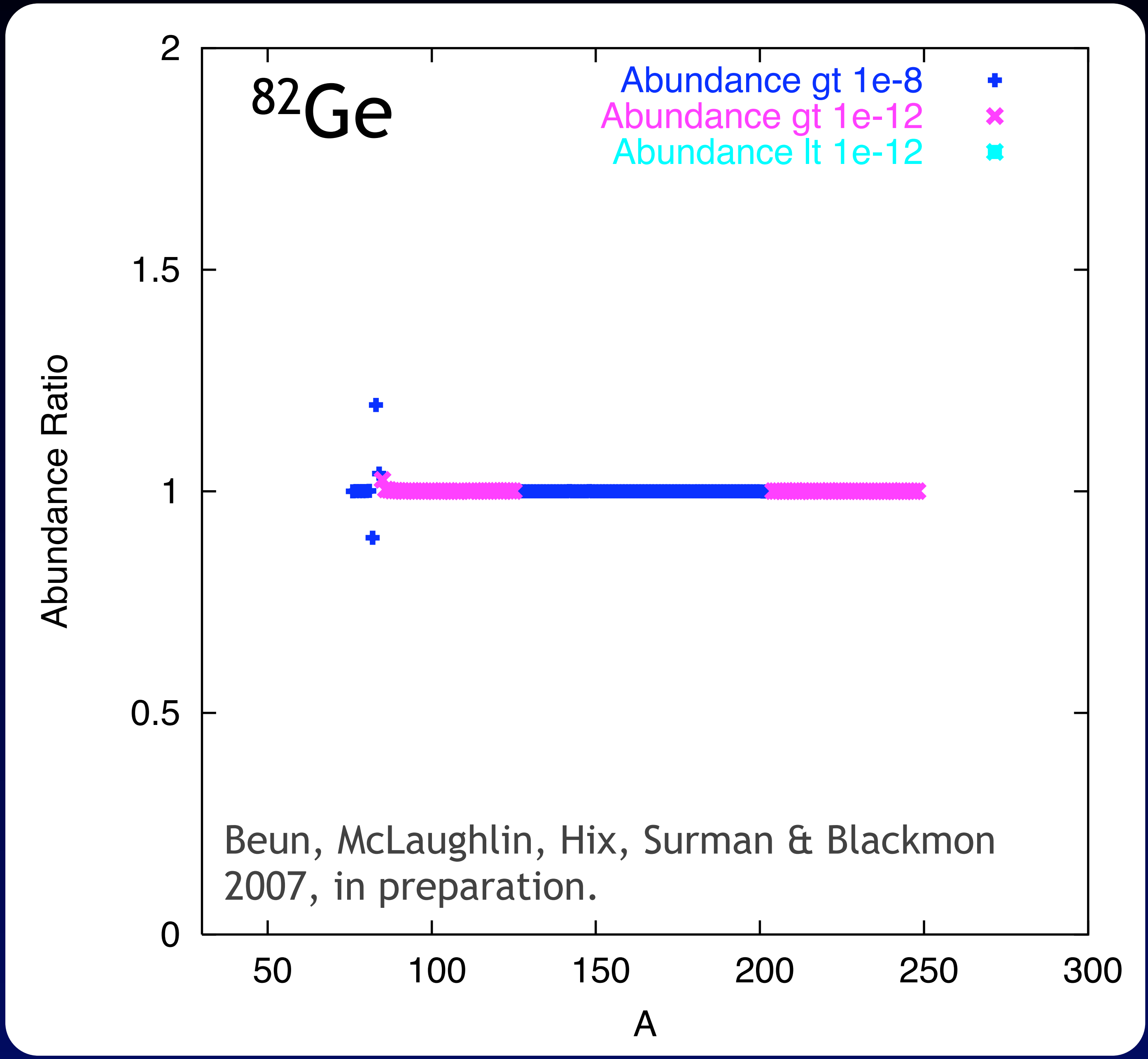


Beun, McLaughlin, Surman & Hix 2006

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.



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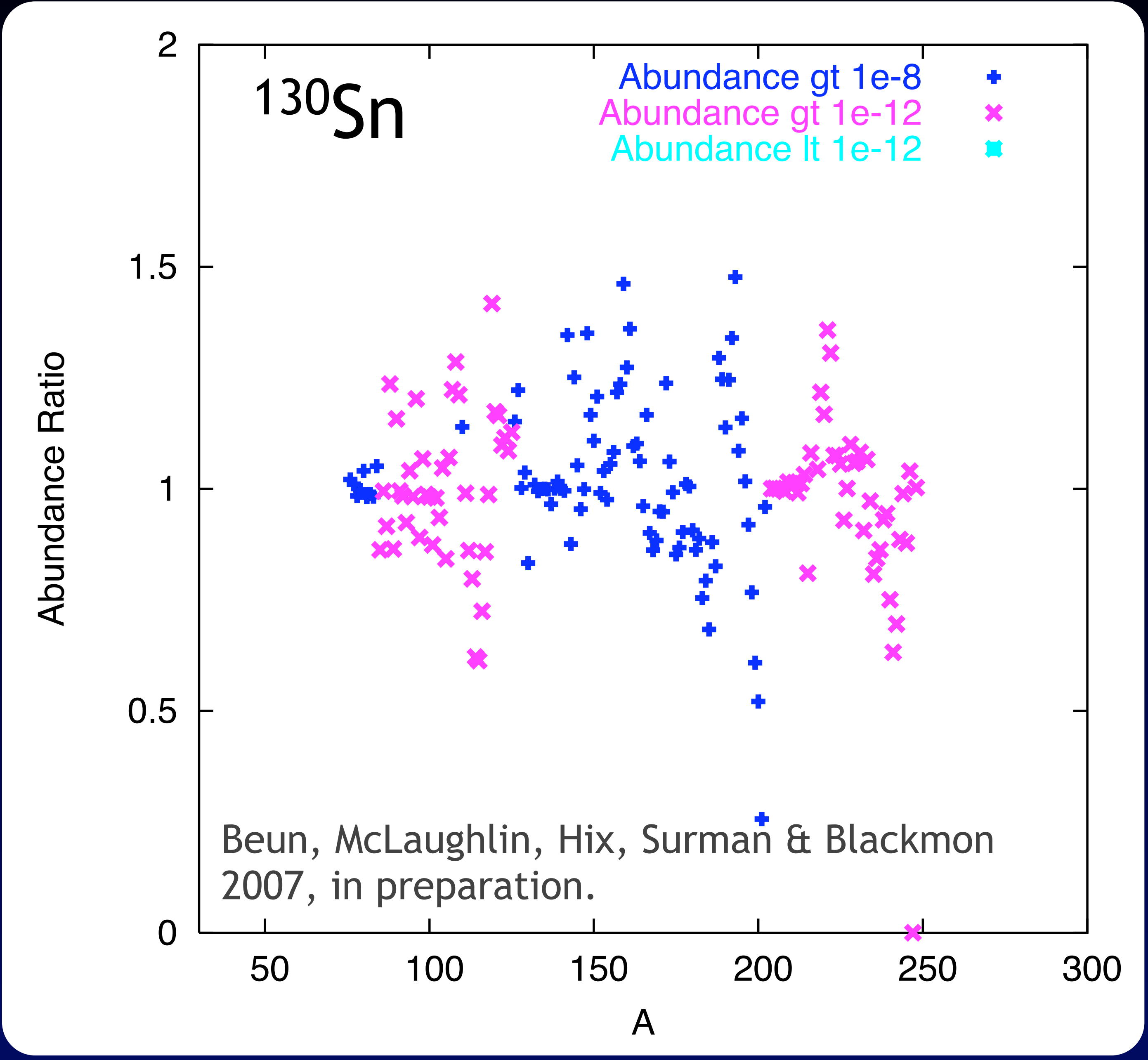

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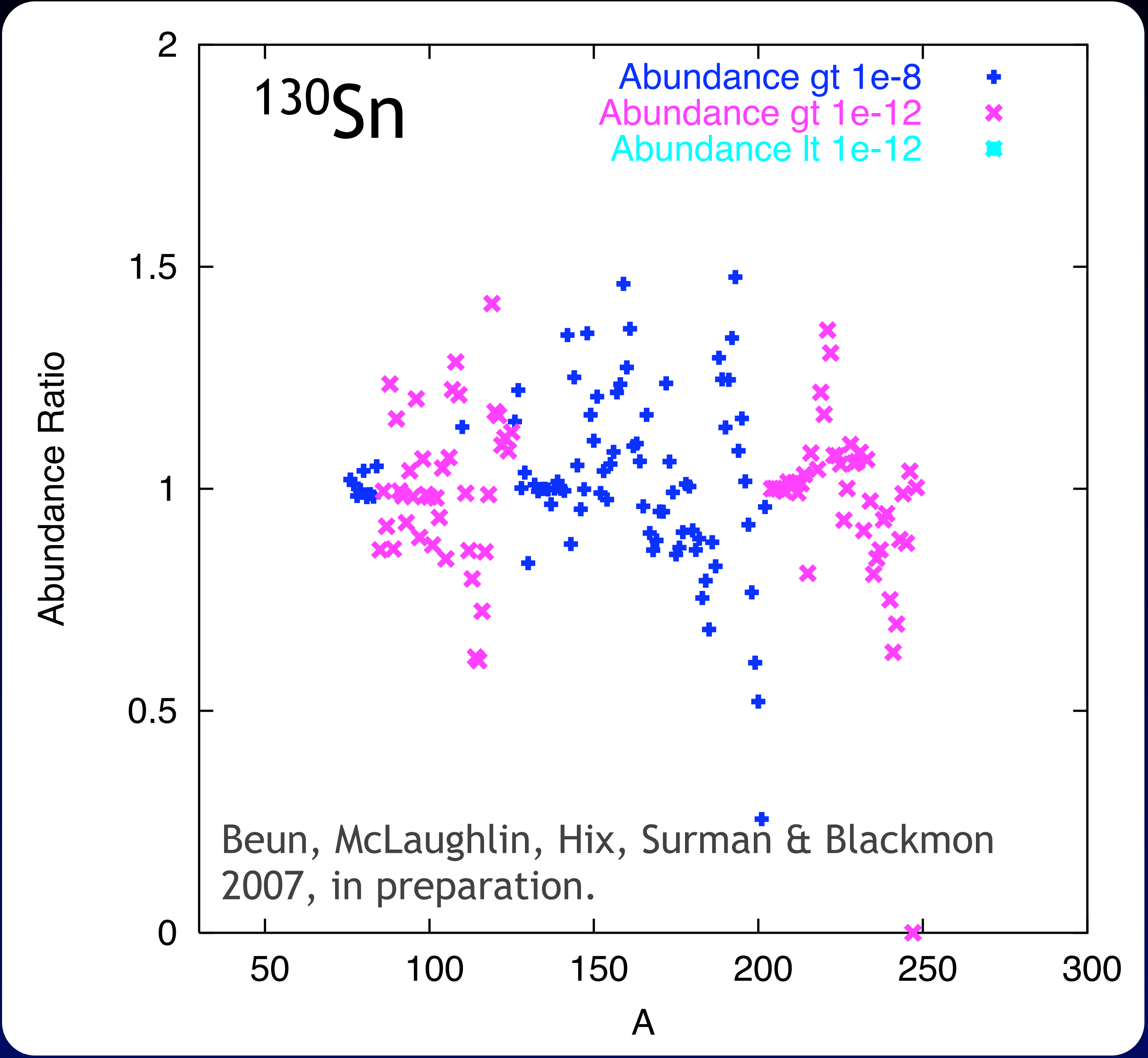
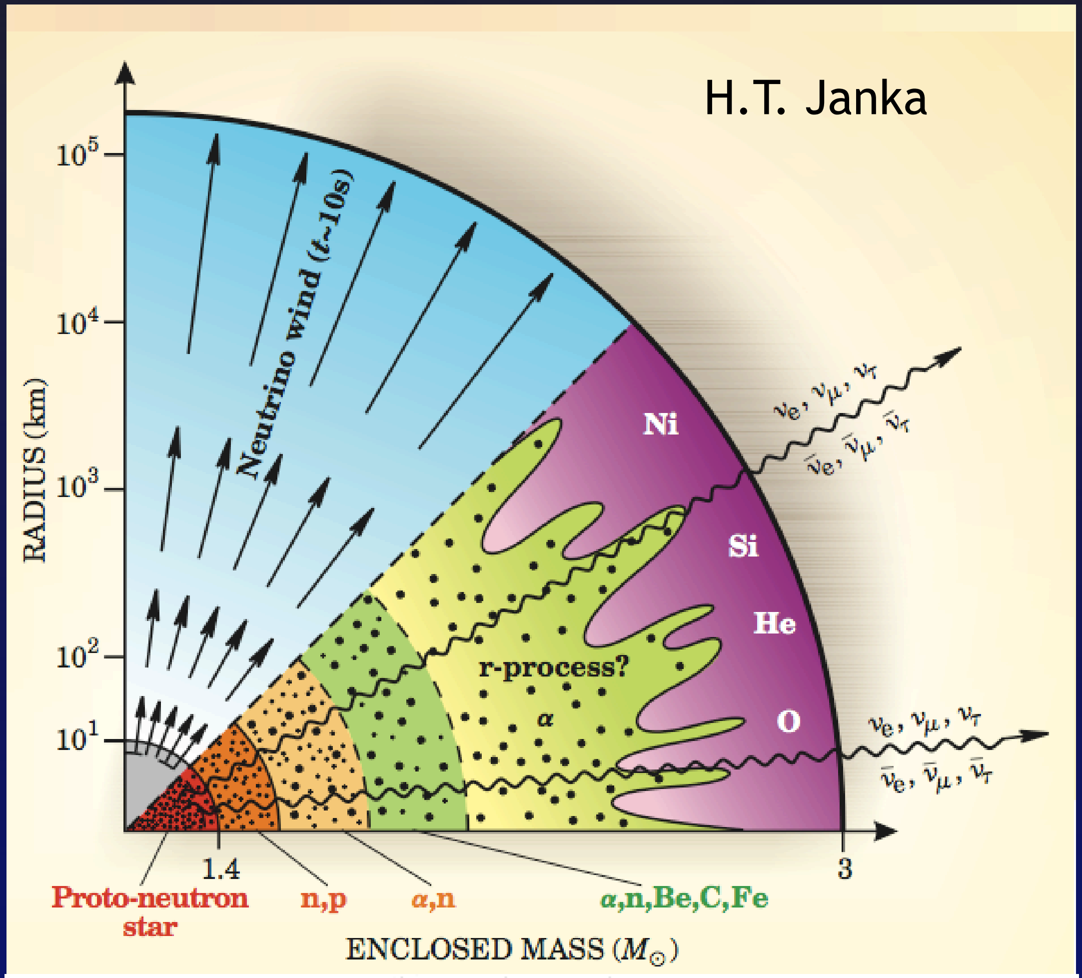
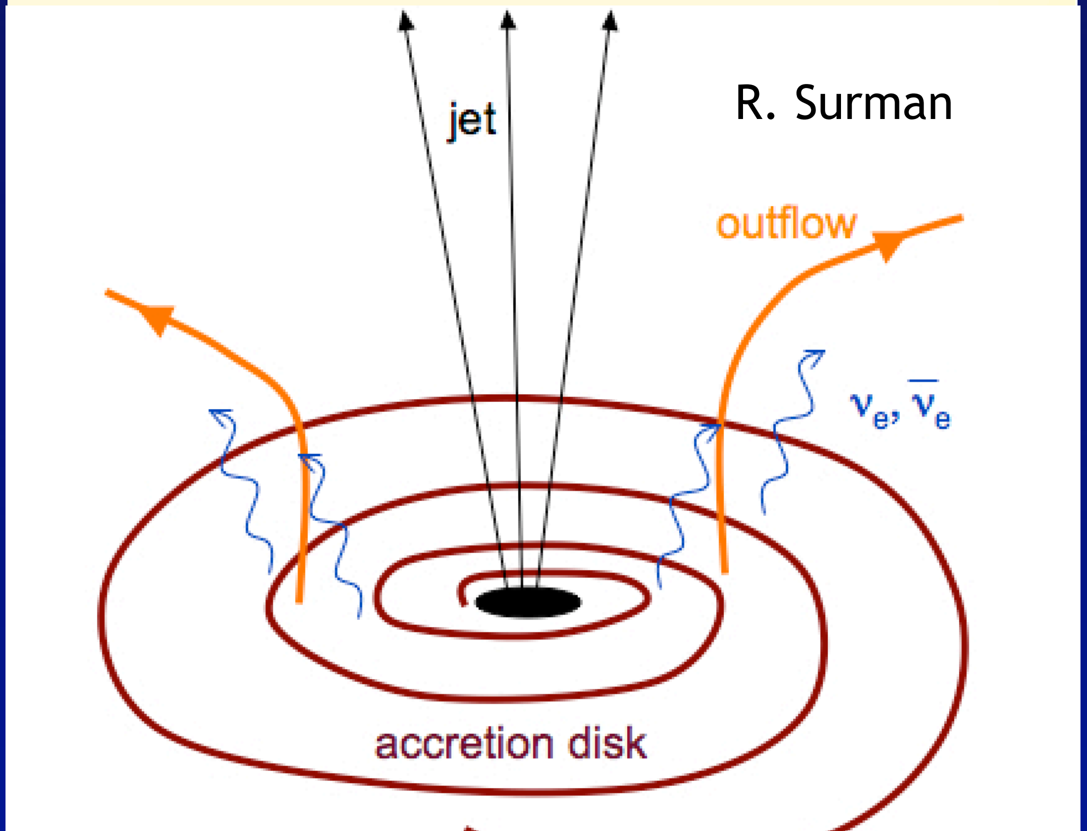


To achieve desired accuracy of r-process predictions will require neutron capture rates, at least near stability.

Site of the r-process

Formation of r-process requires neutron-rich, high entropy matter. May occur in the 1) wind from a new neutron star in an SN, 2) in a wind from a collapsar disk, or 3) in a neutron star merger.





Nuclear Physics in Core Collapse Supernovae

1) What role to CC SN play in cosmic nuclear evolution?
   a) Preeminent factory for heavy elements, producing O-Fe and probably the r-process as well.
2) How does nuclear physics affect the supernova explosion and the resulting nucleosynthesis?
   a) Nuclear Matter equation of state and electron capture on heavy nuclei strongly affect the explosion mechanism.
   b) Nuclear reaction rates, masses and partition functions needed for the many isotopes produced in SN.