MRC-2: Supernovae, Nucleosynthesis and Chemical Evolution

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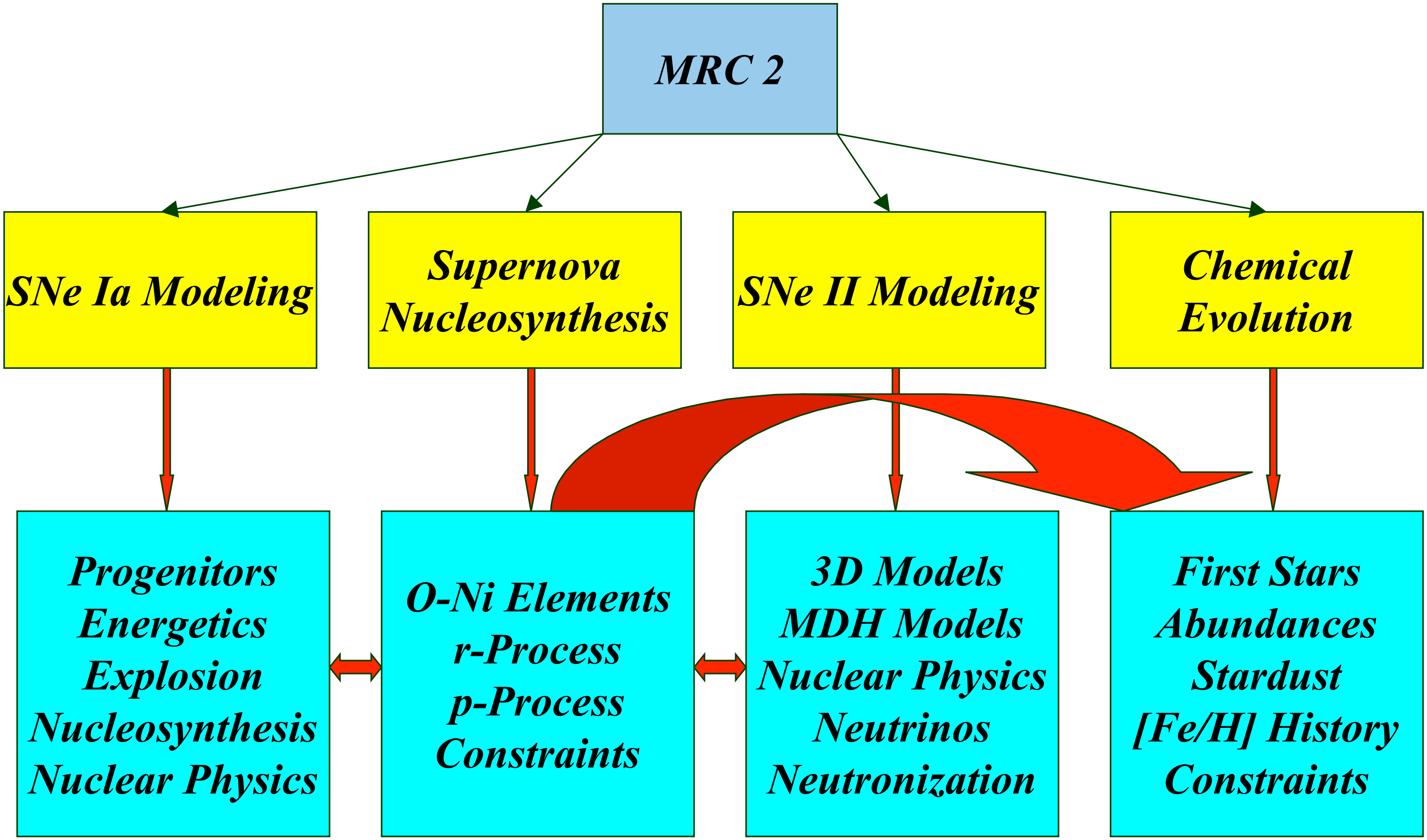


MRC 2

SNe Ia Modeling

Supernova Nucleosynthesis

SNe II Modeling

Chemical Evolution

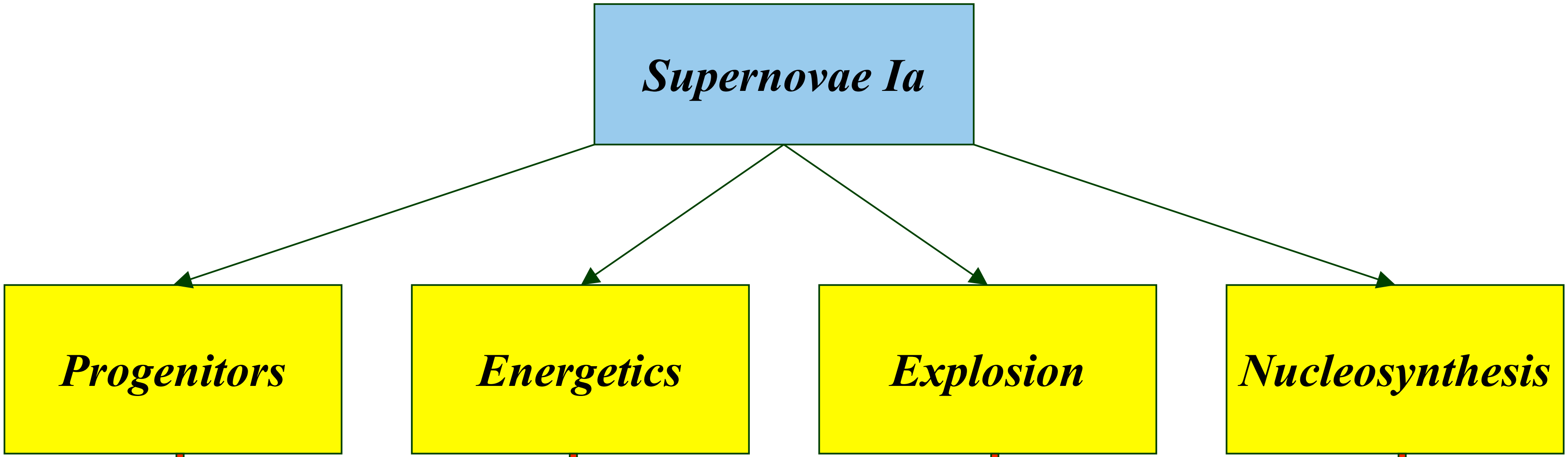
Progenitors
Energetics
Explosion
Nucleosynthesis
Nuclear Physics

O-Ni Elements
r-Process
p-Process
Constraints

3D Models
MDH Models
Nuclear Physics
Neutrinos
Neutronization

First Stars
Abundances
Stardust
[Fe/H] History
Constraints

MRC-2: Supernova Modeling



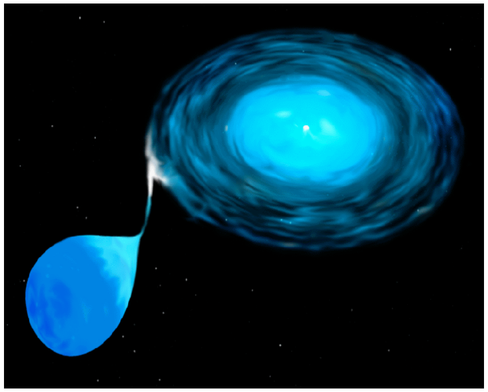
Supernovae Ia

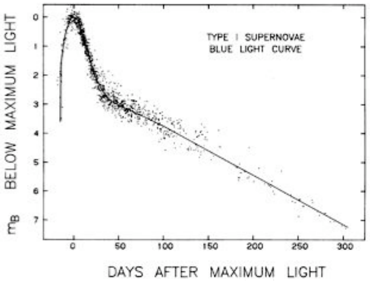
Progenitors

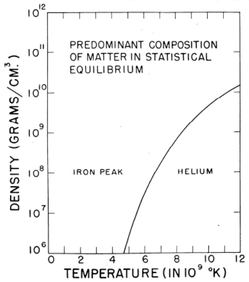
Energetics

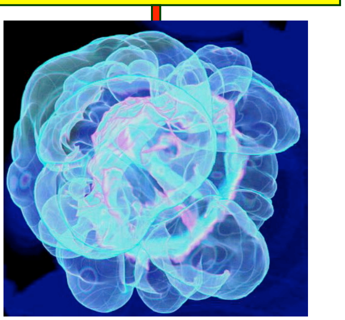
Explosion

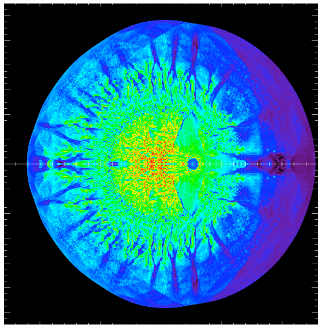
Nucleosynthesis

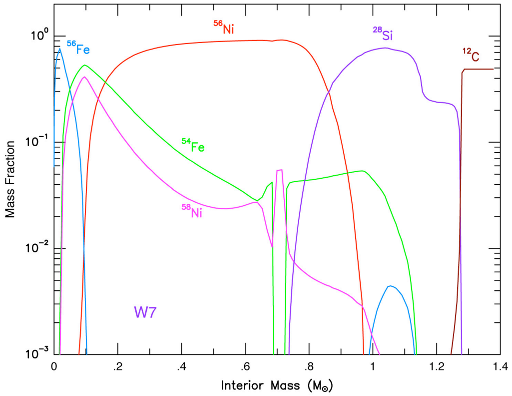






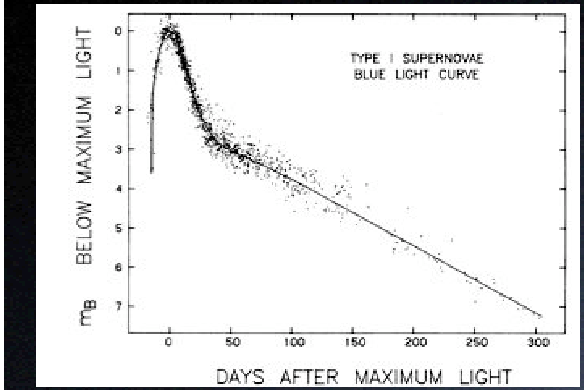




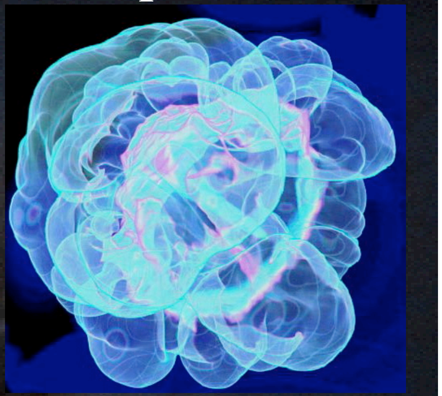


Type Ia Supernovae

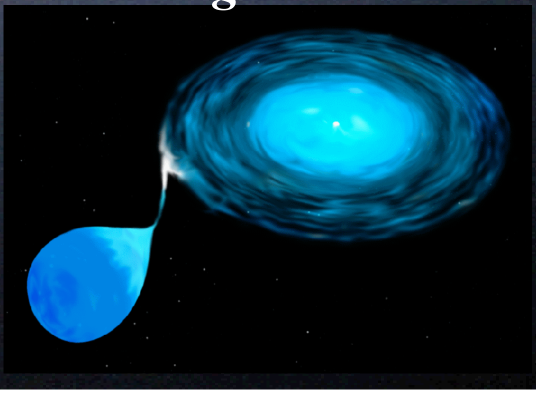
Energetics



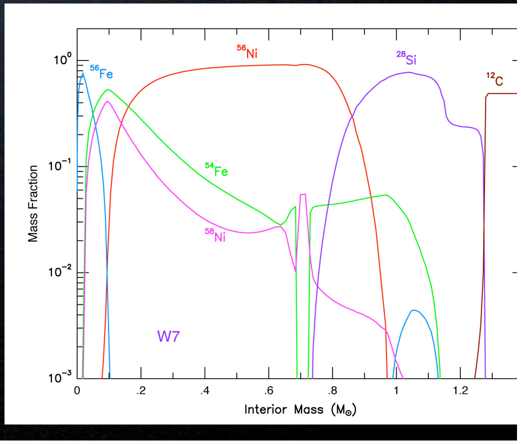
Explosion



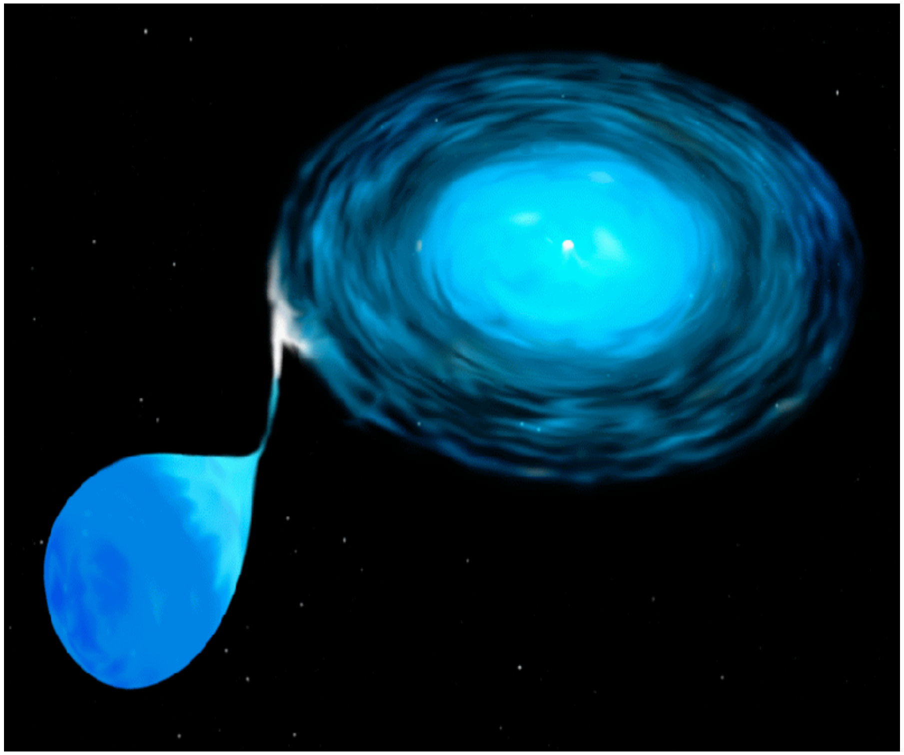
Progenitors



Nucleosynthesis

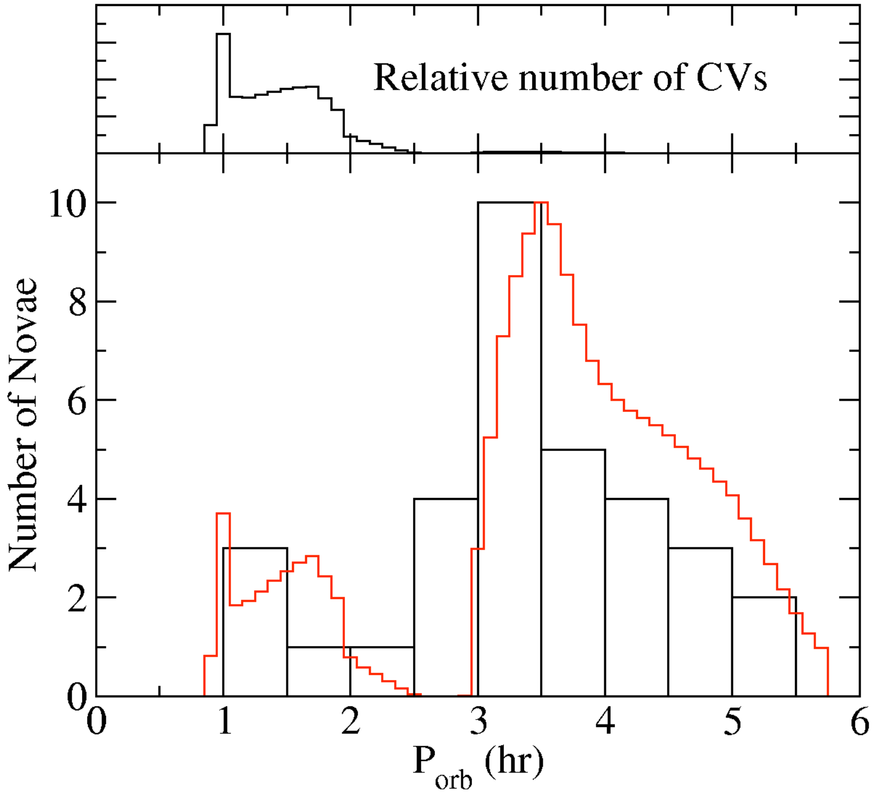


Type Ia Supernovae: Theory



- "Standard model" **(Hoyle & Fowler 1960):**
  - SNe Ia are thermonuclear explosions of C+O white dwarf stars.
- Evolution to criticality:
  - Accretion from a binary companion (Whelan and Iben 1973) leads to growth of the WD to the critical (Chandrasekhar) mass (1.4 solar masses).
- After ~1000 years of thermonuclear "cooking", a violent explosion is triggered at or near the center.
- Complete incineration occurs within two seconds, leaving no compact remnant.
- **Light curve powered by radioactive decay of ^{56}Ni. (Nickel mass ≈ 0.6 $M_{\odot}$.) Peak luminosity ∝ M(^{56}Ni).**

Constraining the Accreting WD population with Classical Novae



Townsley & Bildsten 2005, ApJ, 628, 395
CV population (top) from Howell et al. 2001
Data (*black*) from Kolb & Ritter CV catalog

Theory uses interrupted stellar wind braking to calculate CV population and accretion rate from orbital period (Howell, Nelson & Rappaport 2001, ApJ, 550, 897)

Nova ignition mass relates population and accretion rate to Nova rate

The first consistent ignition masses considering the WD thermal state (Townsley & Bildsten 2004, ApJ, 600, 390) reproduce the observed distribution

Can infer with some confidence overall CV population from Nova rate (CN rate from Williams & Shafter 2004, ApJ, 612, 867)

- 60-180 CVs per $10^6 L_{\odot,K}$
- CV birthrate 2-4 × 10^{-4} yr^{-1} per $10^{10} L_{\odot,K}$, similar to Type Ia supernova rate in ellipticals

CV Birthrate similar to Type Ia supernova rate in old stellar populations

CV = Low mass WD   Type Ia = High mass WD

Inconsistent with our current understanding of WD mass distribution

Critical Physics of Type Ia Supernovae

- Critical features of the nuclear evolution of the matter ejected in Type Ia events include: (1) the degree of neutronization achieved in the dense inner regions; and (2) the fraction of the outer regions of the star that fail to reach NSE but rather produce intermediate mass elements. These factors constrain/dictate the mass ejected as ^{56}Ni - upon which the brightness of a SNe Ia at maximum is directly dependent.

  - Critical nuclear input involves:

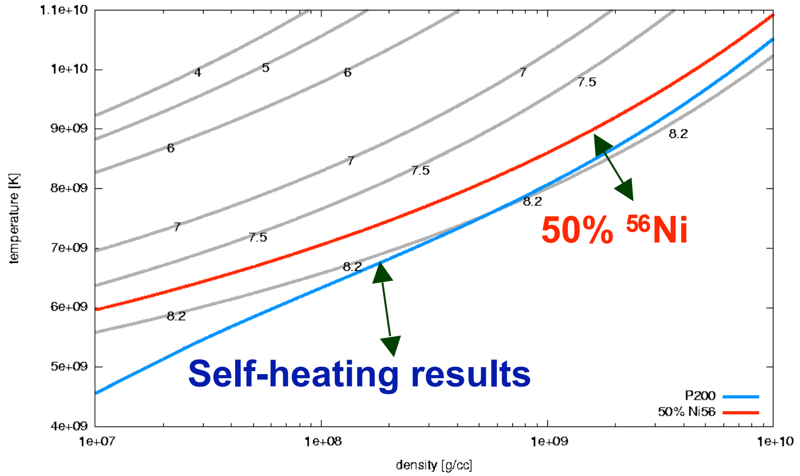
  - thermonuclear reaction rates (including a proper treatment of Coulomb effects and screening) and

  - rates of electron capture and associated neutrino losses.

Burning and Energetics in SNE Ia

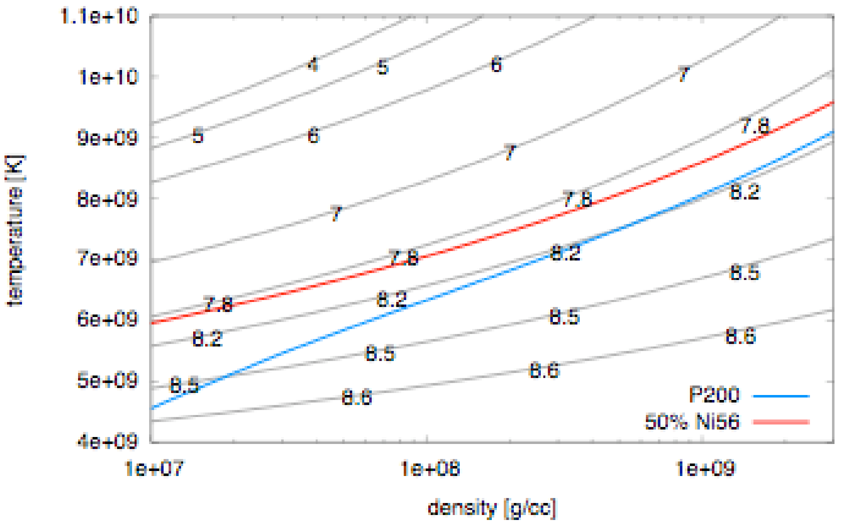
- Deflagration models for SNeIa.
  - “Self-heating” simulations define peak temperatures achieved in NSE as a function of density.
  - Post-flame treatment uses evolving NSE state of ash.
  - Initially hot ash expands and cools.
  - BE increases as initial helium is converted to iron-peak nuclei. At values $Y_e \approx 0.5$, ^{56}Ni dominates NSE.
  - At the highest densities, electron captures significantly lower Y_e.
  - BE increases further as more tightly bound ^{56}Fe replaces ^{56}Ni, but the net energetics are strongly influenced by neutrino losses.

(Calder et al. 2006)

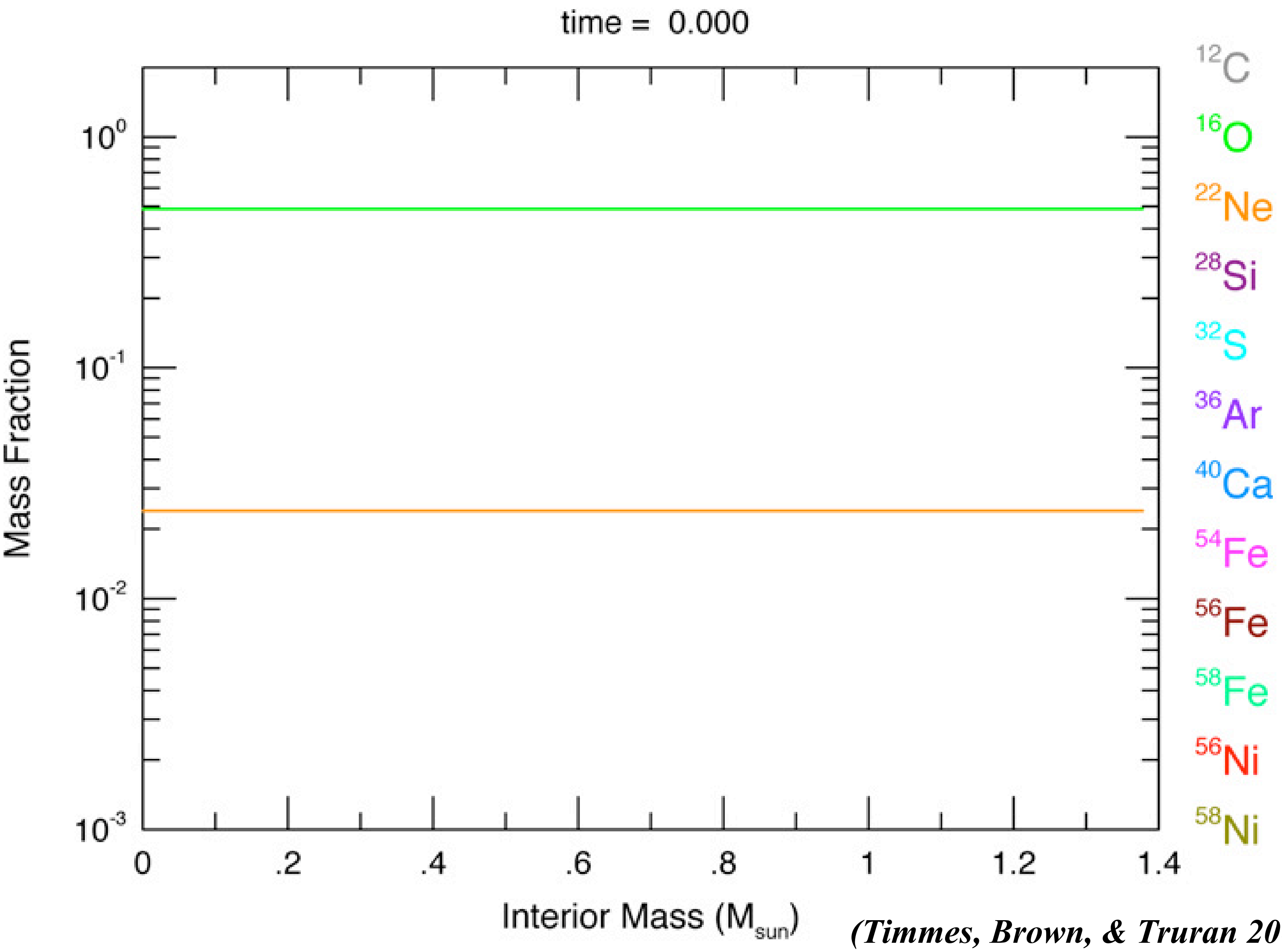


50% ^{56}Ni

Self-heating results



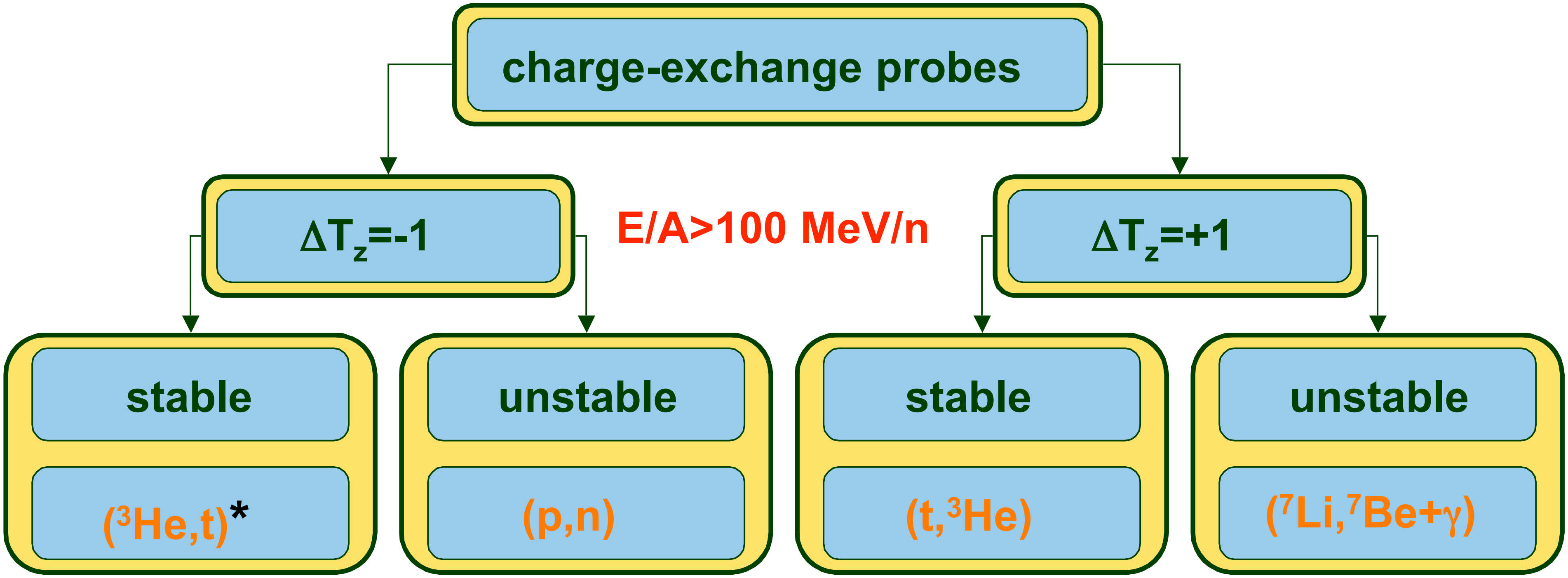
Nickel Production in SNe Ia



(Timmes, Brown, & Truran 2003)

The charge-exchange program at the NSCL

CE group @ NSCL: K. Geerlings (U), C. Guess (S), G.W. Hitt (S), M. Howard (S,OSU), B. Martinez (U), B. Sherrill, Y. Shimbara (PD), **R.G.T. Zegers**
Astrophysics: E. Brown, S. Gupta, H. Schatz
Theory: A. Brown, V. Zelevinsky



charge-exchange probes

ΔT_z=-1

E/A>100 MeV/n

ΔT_z=+1

stable

(^{3}He,t)*

unstable

(p,n)

stable

(t,^{3}He)

unstable

(^{7}Li,^{7}Be+γ)

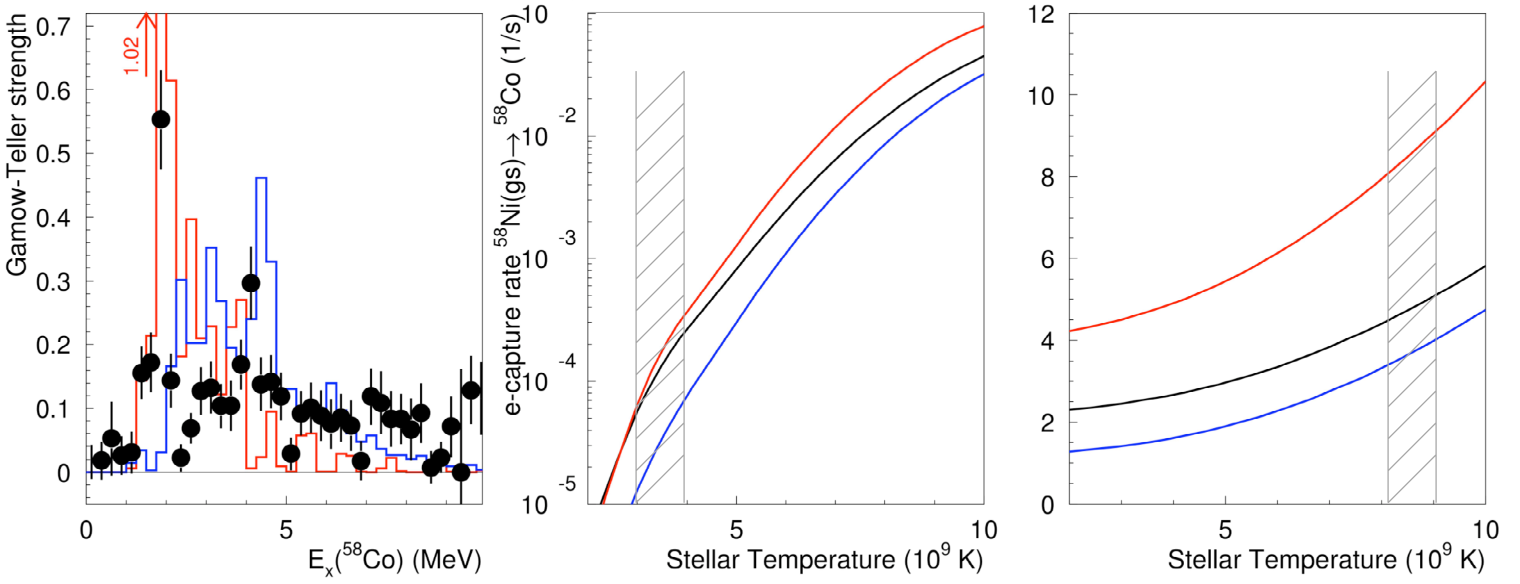
Charge-exchange with unstable beam (inverse kinematics) at intermediate energies are unexplored so far

*** Experiments carried out at RCNP, Osaka**

Gamow-Teller Strength in ^{58}Co via ^{58}Ni(t,^{3}He)

early in pre-collapse
$\rho Y_e = 10^7$ g/cm^3

just before pre-collapse
$\rho Y_e = 10^9$ g/cm^3



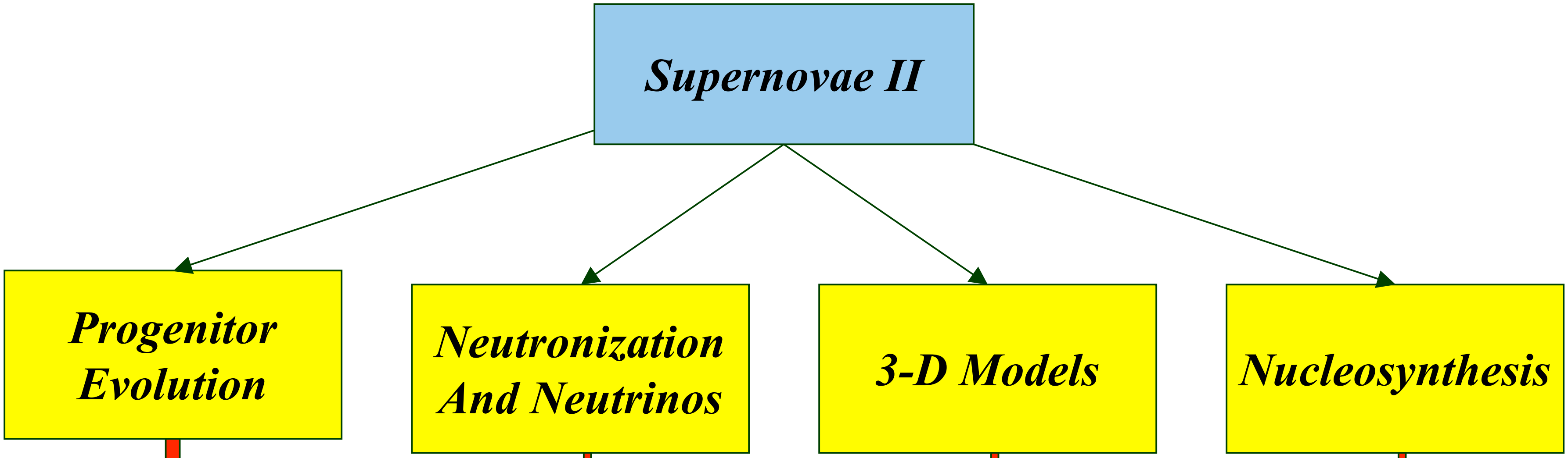
— ● (t,^{3}He) data (syst. error in overall scale 25%)

— large-scale shell model KB3G interaction

— large-scale shell model GXPF1 interaction

▨ relevant temperature range at specific ρY_e

MRC-2: Supernova Modeling



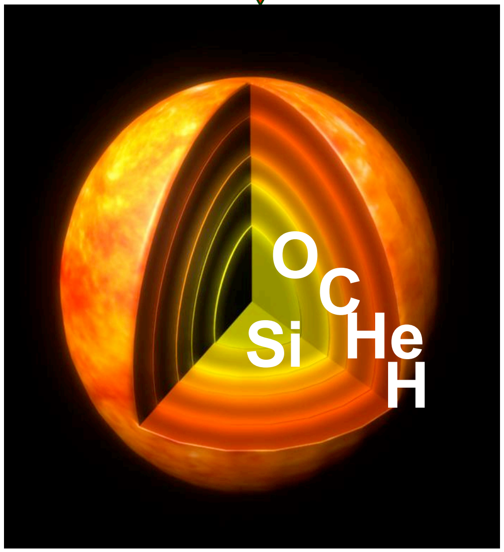
Supernovae II

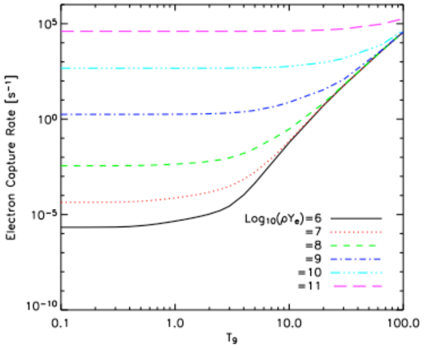
Progenitor Evolution

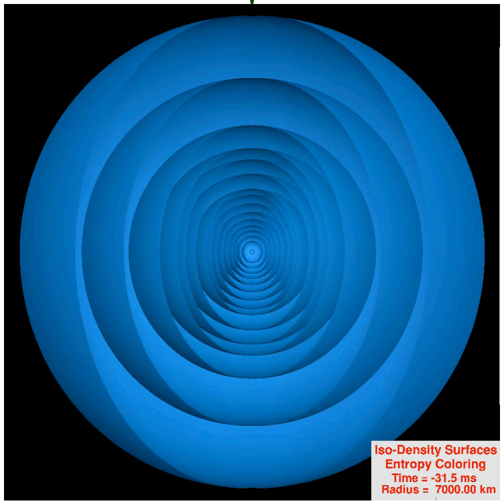
Neutronization And Neutrinos

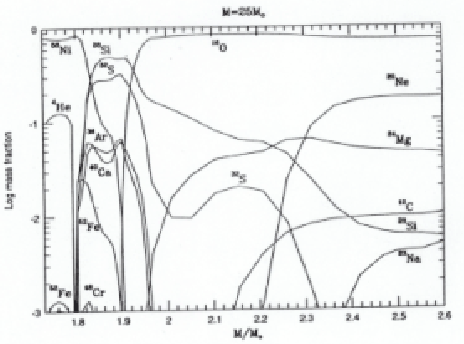
3-D Models

Nucleosynthesis



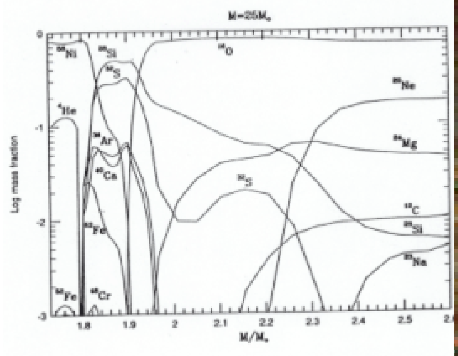




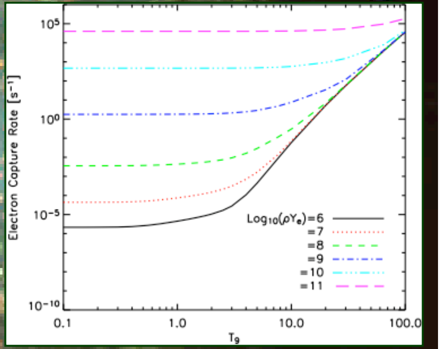


Research on Type II Supernovae

Nucleosynthesis

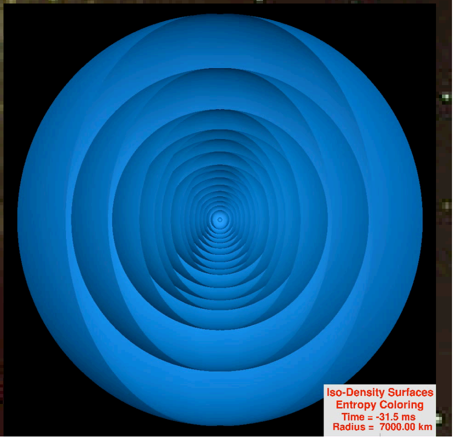


Neutronization

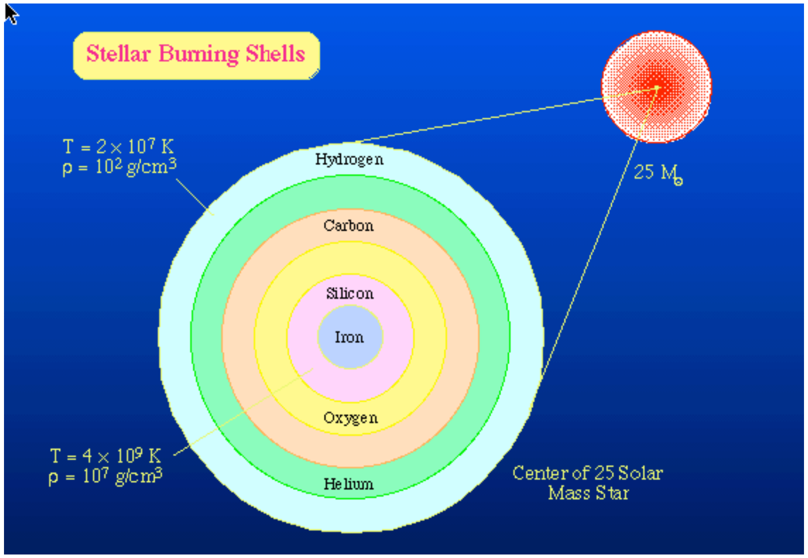


Progenitor Evolution

Explosion

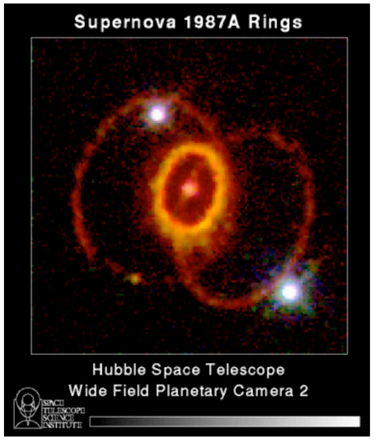


Type II Supernovae: Theory



Courtesy Mike Guidry: guidry@utk.edu

SNe1054: Crab Nebula



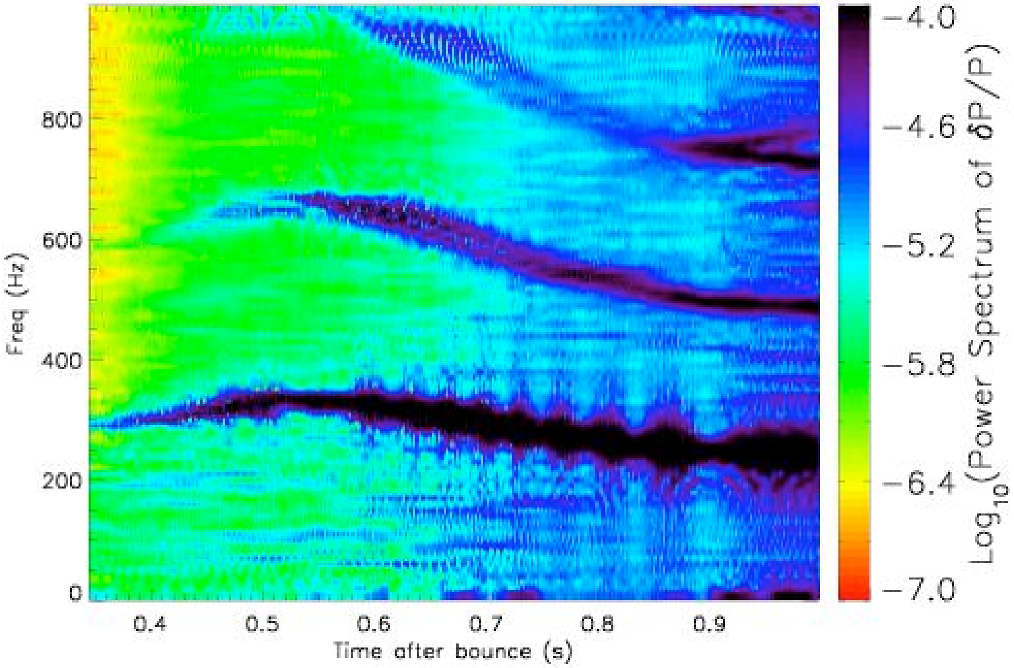
SNe1987A Hubble Image

- ☐ **"Standard model" (Hoyle & Fowler 1960):**
  - ☐ **SNe II are the product of the evolution of massive stars $10 < M < 100\ M_\odot$.**
- ☐ **Evolution to criticality:**
  - ☐ **A succession of nuclear burning stages yield a layered compositional structure and a core dominated by ^{56}Fe.**
  - ☐ **Collapse of the ^{56}Fe core yields a neutron star or black hole.**
  - ☐ **The gravitational energy is released in the form of neutrinos, which interact with the overlying matter and drive explosion.**
- ☐ **Remnants: Neutron stars and black holes are both possible SNe II remnants.**
- ☐ **Nucleosynthesis contributions: elements from oxygen to iron (formed as ^{56}Ni) and neutron capture products from krypton through uranium and thorium. ($\tau_{\text{nucleosynthesis}} < 10^8$ yrs)**
  Production of $\approx 0.1\ M_\odot$ of ^{56}Fe as ^{56}Ni.

JINA Projects at the University of Arizona: Adam Burrows

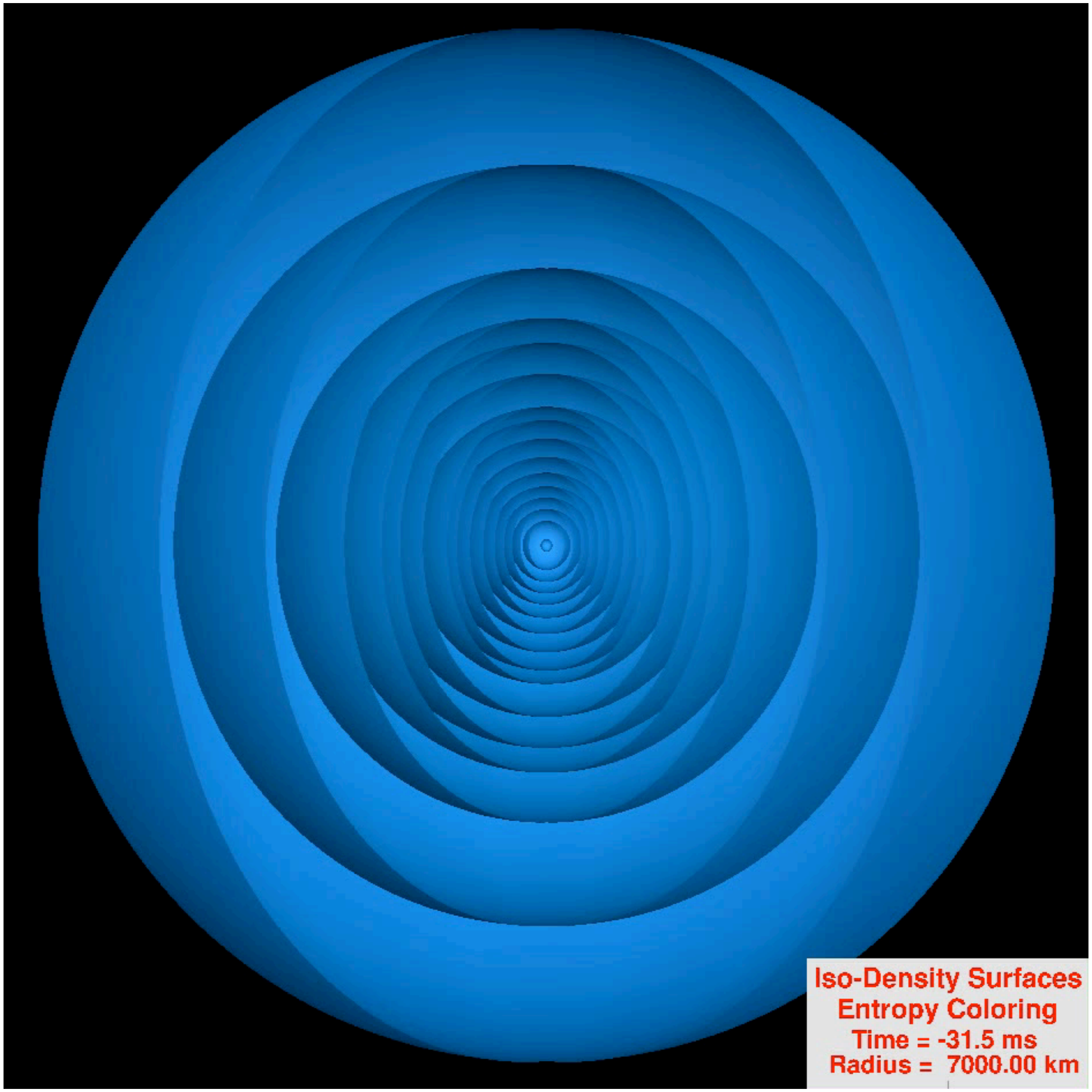
❑ Accretion induced collapse of an ONeMg white dwarf:

- ❑ VULCAN 2D MGFLD code development
- ❑ Multi-D Collapse supernova simulations
- ❑ Neutrino and Gravitational Radiation signatures
- ❑ Potential new SN mechanism: Acoustic power and core oscillations?
- ❑ High entropies for r-process naturally obtained?
- ❑ Stability analyses of massive and protoneutron star cores (J. Murphy: JINA Fellow)
- ❑ Plans: Supernova Nucleosynthesis



Frequency-Time Evolution of Pulsating Core at 30 km

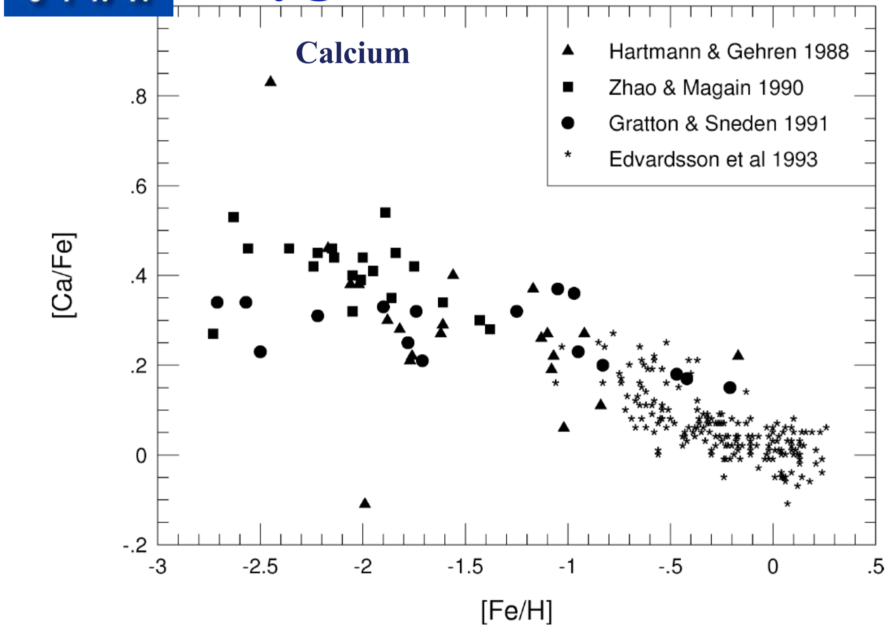
Accretion Induced Collapse of ONeMg White Dwarfs

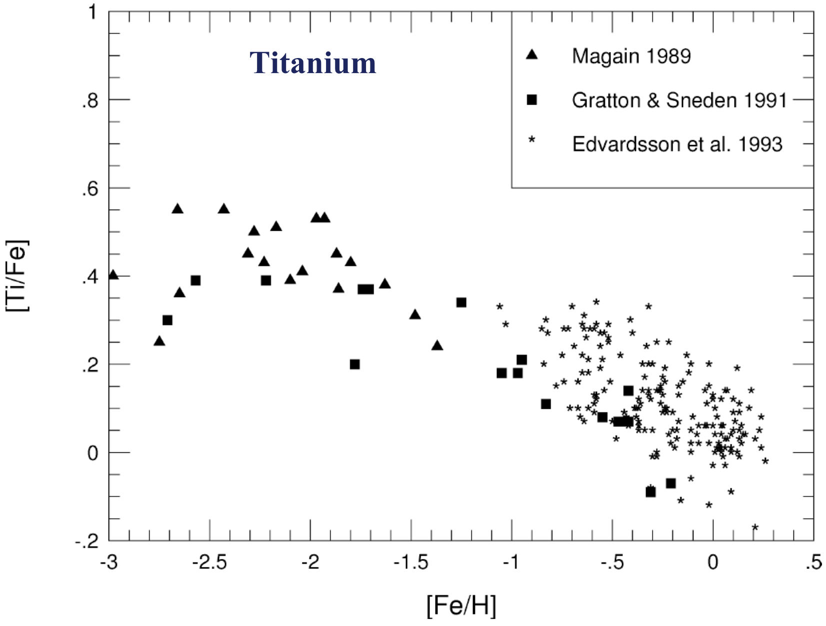


*Dessart,
Burrows,
Ott, Livne,
Yoon, &
Langer
(2006)*

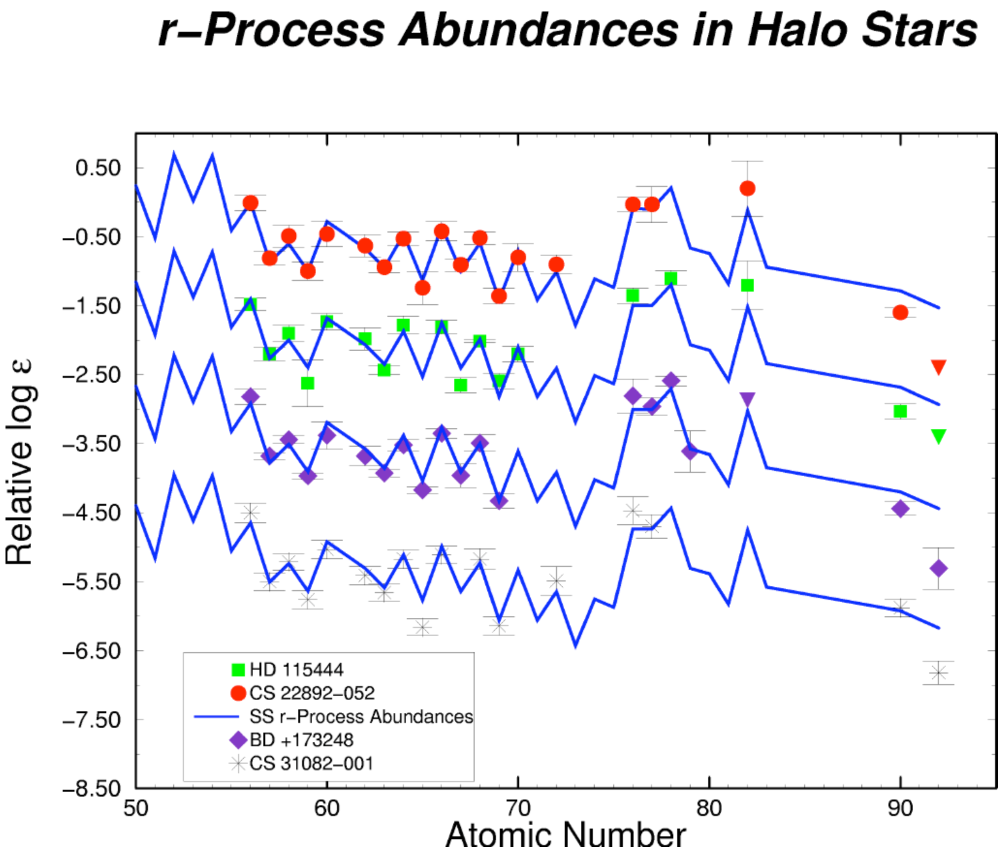
Nucleosynthesis Trends in Halo Star Abundances

Oxygen and α-Elements





R-Process Elements



(Truran et al. 2002)

❑ **These behaviors are compatible with nucleosynthesis predictions for SNe II.**

The helium-driven r-process in supernovae

Possible neutron sources:

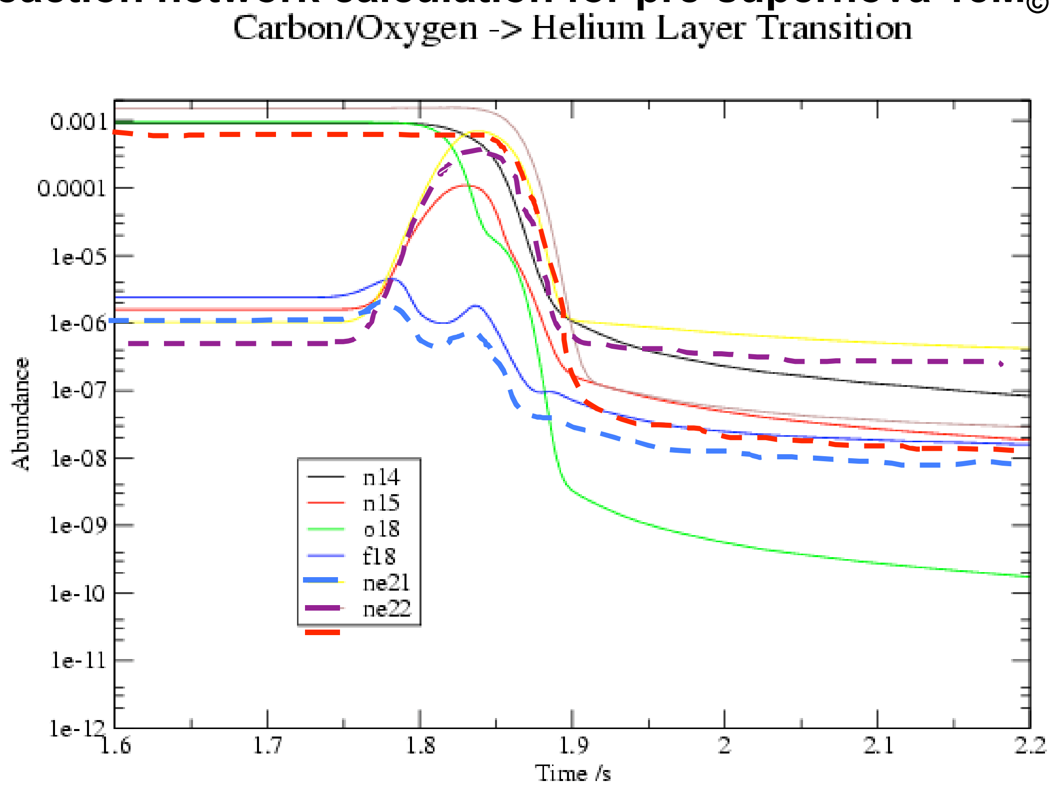
a. $^{14}N(\alpha,\gamma)^{18}F(\beta^{+}\nu)^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)^{25}Mg$

b. $^{14}N(\alpha,\gamma)^{18}F(\beta^{+}\nu)^{18}O(\alpha,n)\ ^{21}Ne(\alpha,n)^{24}Mg$

At low temperature, β+ is dominant.

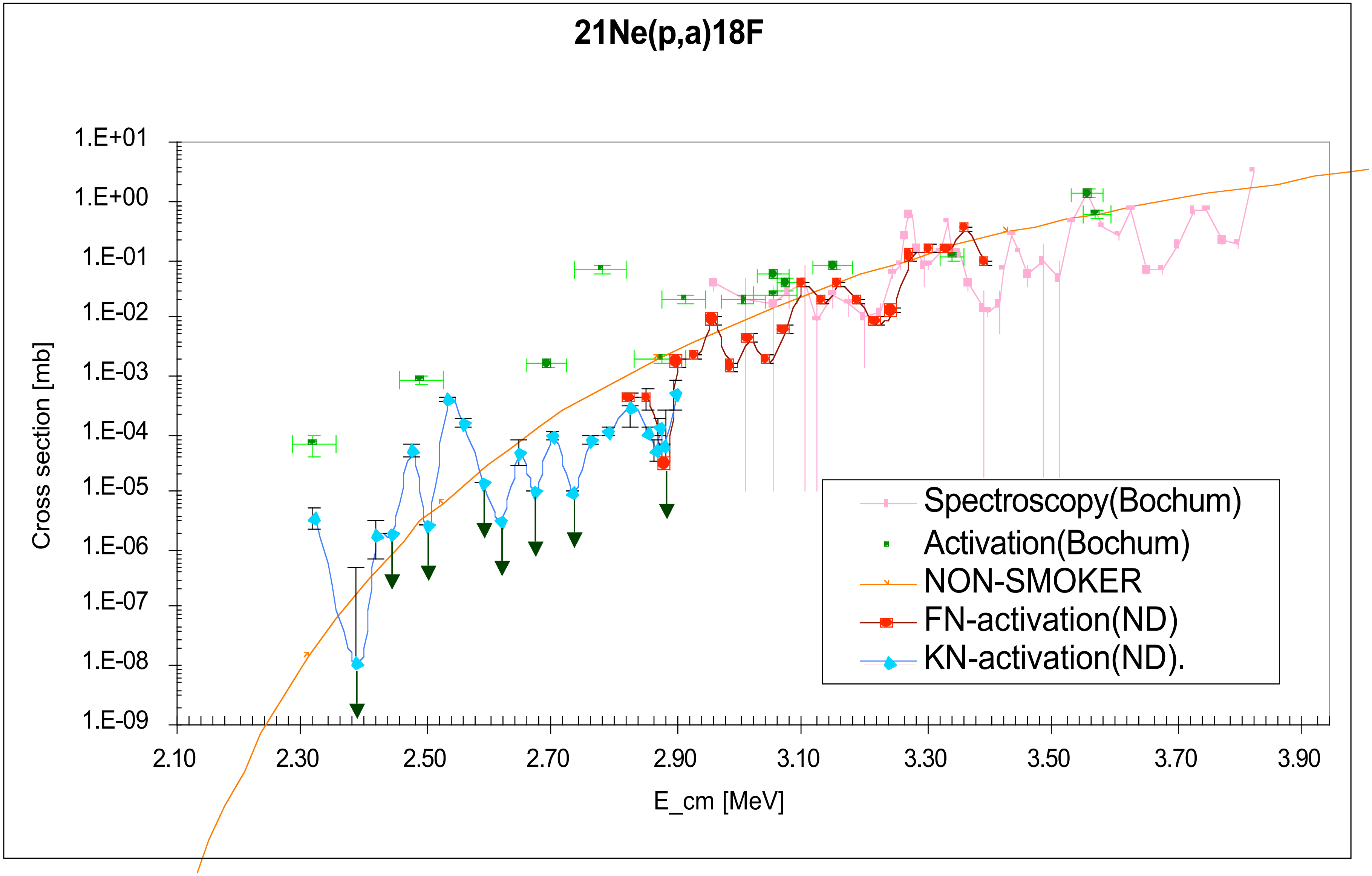
c. $^{18}F(\alpha,p)^{21}Ne(\alpha,n)^{24}Mg$ ← At high temperature(T_9>0.4), (α,p) is more favored.

Reaction network calculation for pre-supernova 15M$_\odot$ star



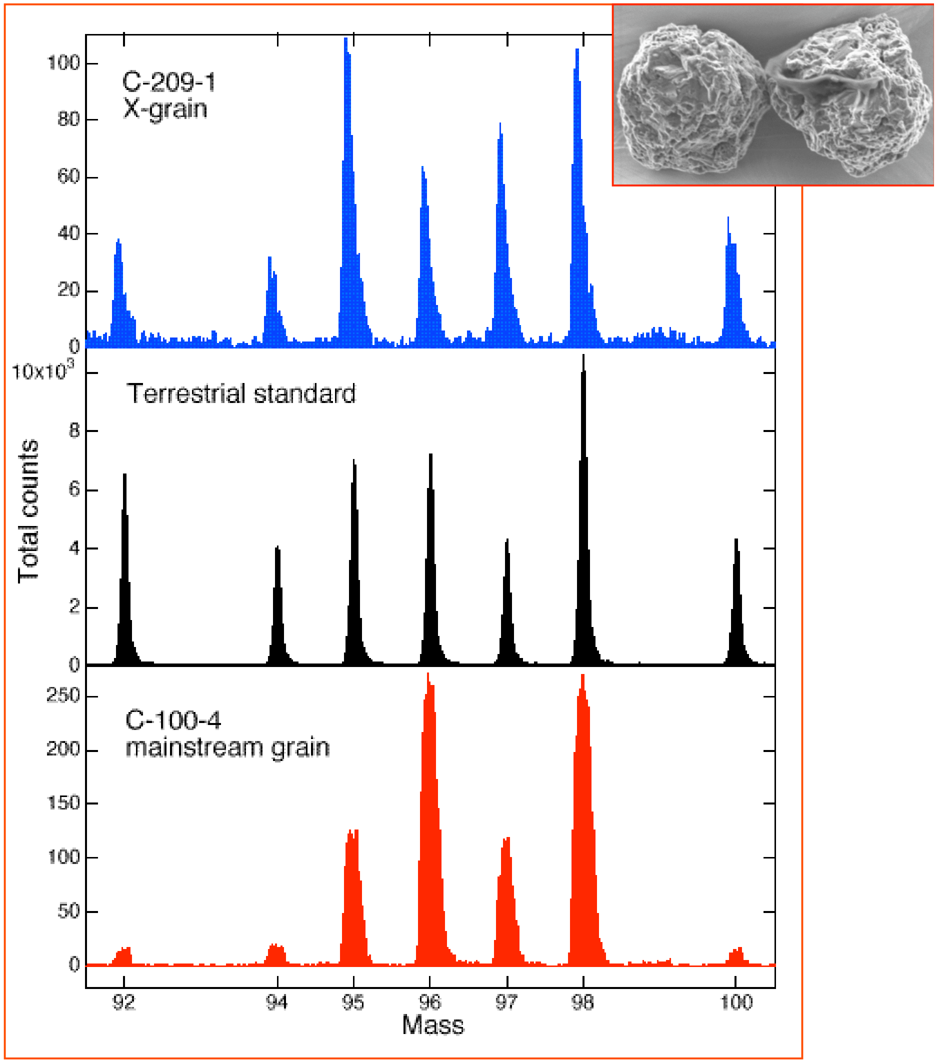
As the stage of r-process, the explosive helium burning is valid during the supernova explosion(T_9~1). But the reaction rate is not yet determined experimentally.

Measurement of $^{21}Ne(p,\alpha)^{18}F$



SiC Grain Mo Isotopic Patterns

- X-grain heavy elements are isotopically distinct from either terrestrial or mainstream.
- Enahnacement of ^{96}Mo indicates significant s-process material present.
- All r-process isotopes show significant enhancements.
- $[\mathrm{Mo}]_{\text{X-grain}} \ll [\mathrm{Mo}]_{\text{Mainstream}}$
- ^{95}Mo and ^{97}Mo enhancements predicted by Clayton et. al.
- p-process isotopes, ^{92}Mo and ^{94}Mo, present but relative abundance's are different from terrestrial.



Slide Courtesy of Mike Pellin (ANL)

MRC-2: Supernova Nucleosynthesis

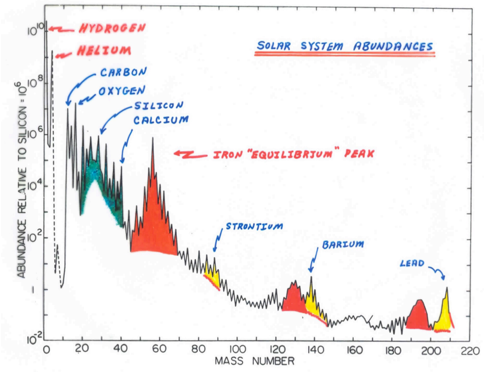
Supernova Nucleosynthesis

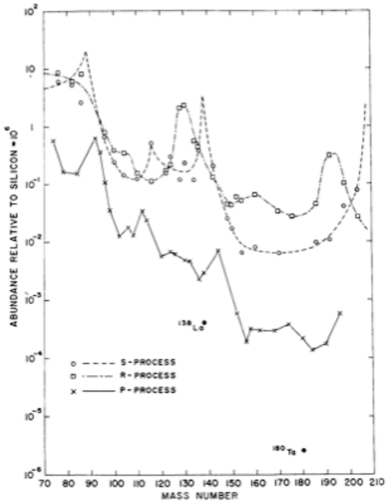
Oxygen to Iron Elements

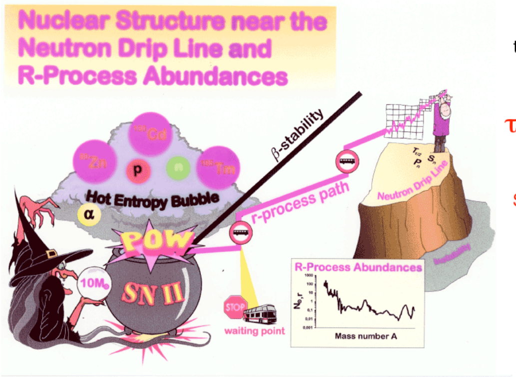
P-Process

R-Process

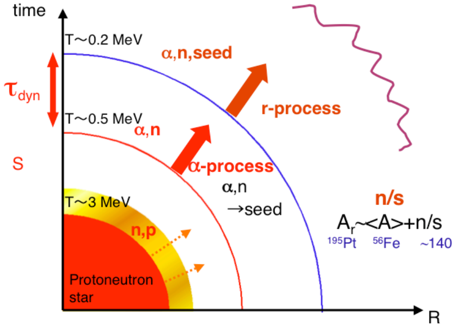
ν - Process



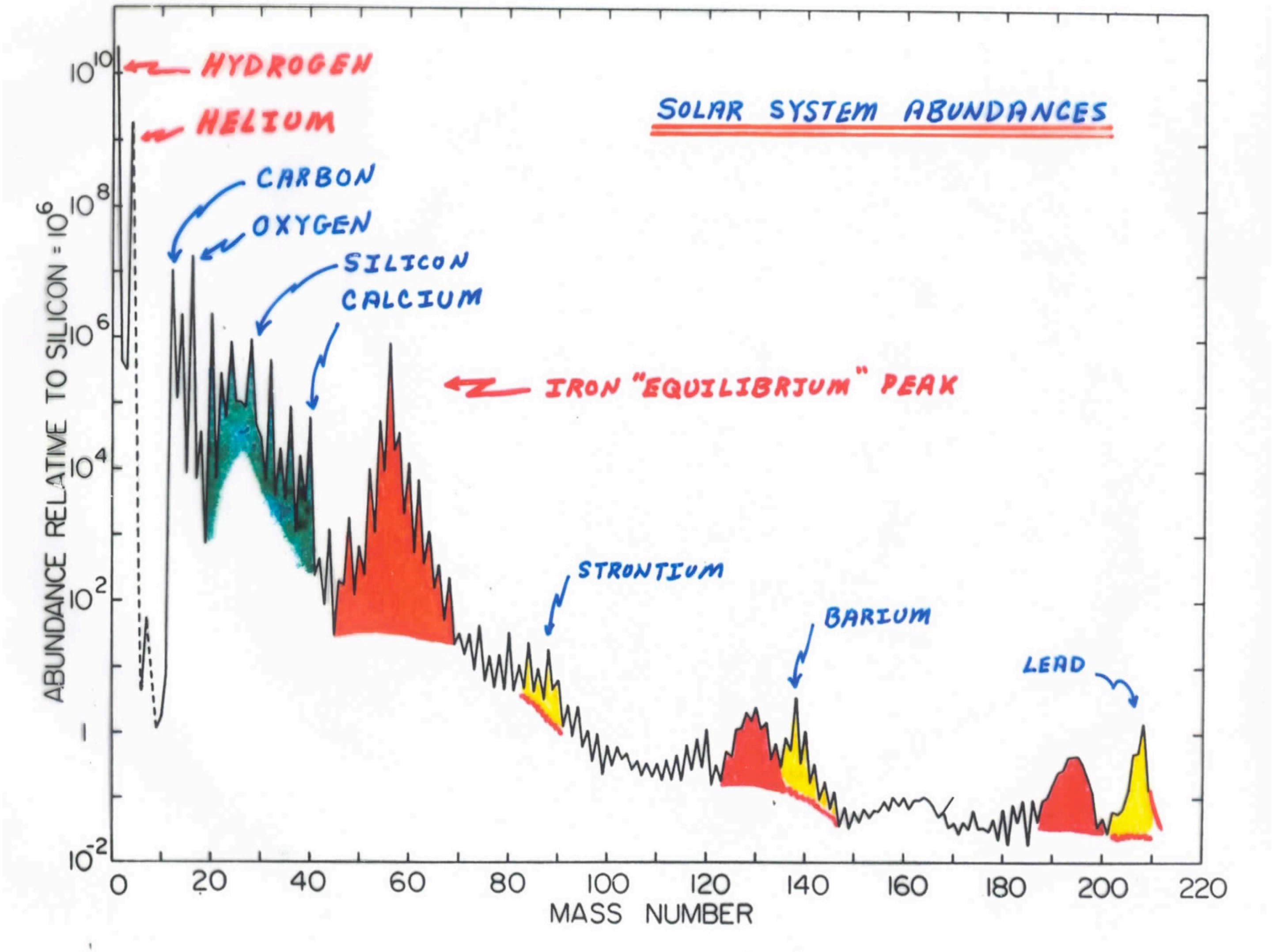



Nuclear Structure near the Neutron Drip Line and R-Process Abundances

r-process in Neutrino Winds



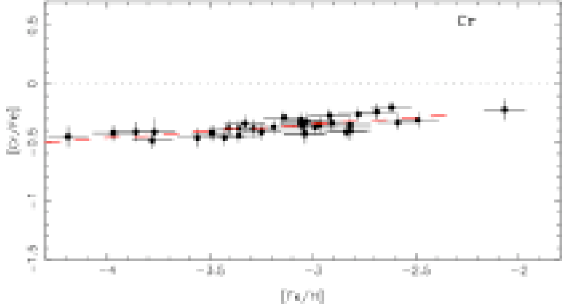
"Cosmic" Abundances of the Elements



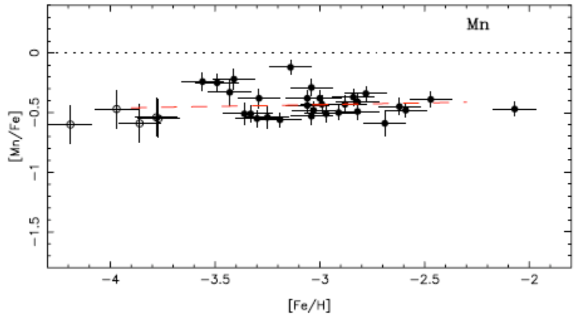
Explosive Nucleosynthesis of Fe-Peak Nuclei

Cayrel et al. (2005)

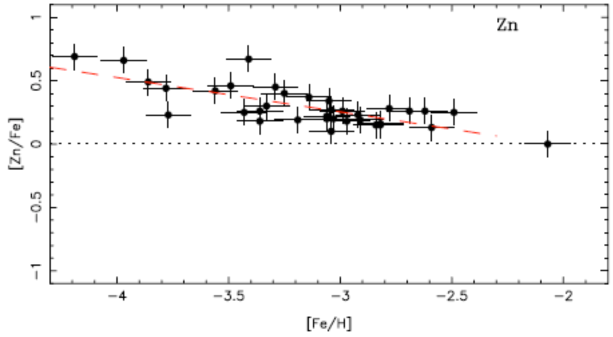
[Cr/Fe]



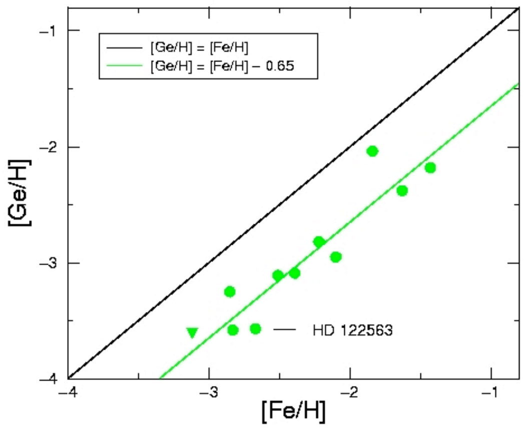
[Mn/Fe]

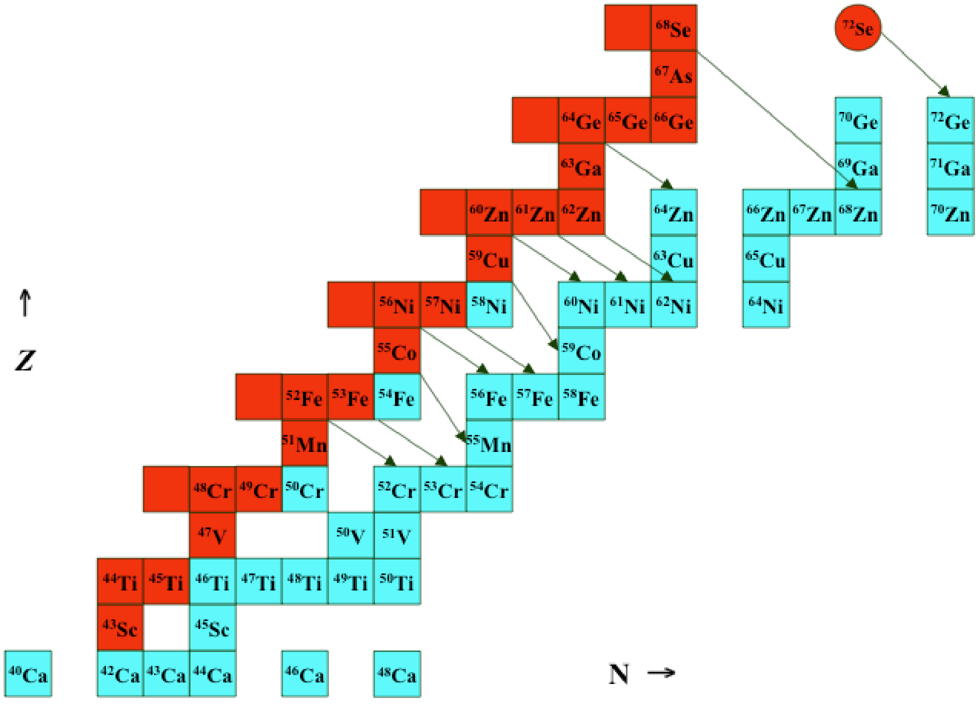


[Zn/Fe]



Ge Trends with Metallicity





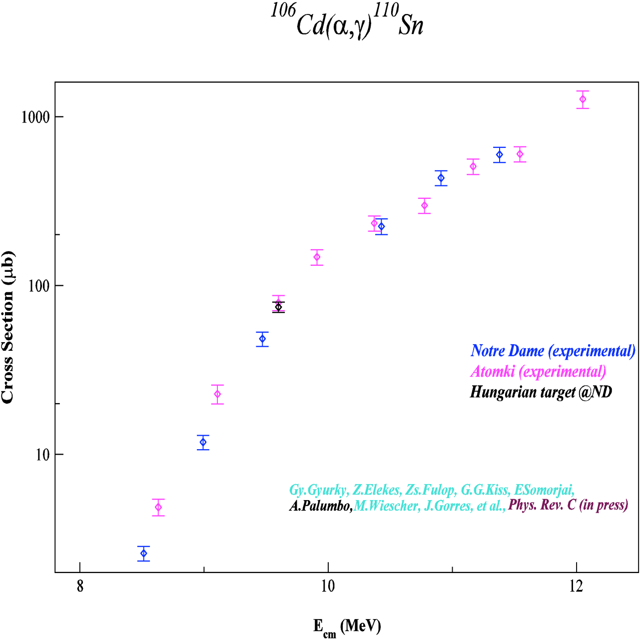
P-process

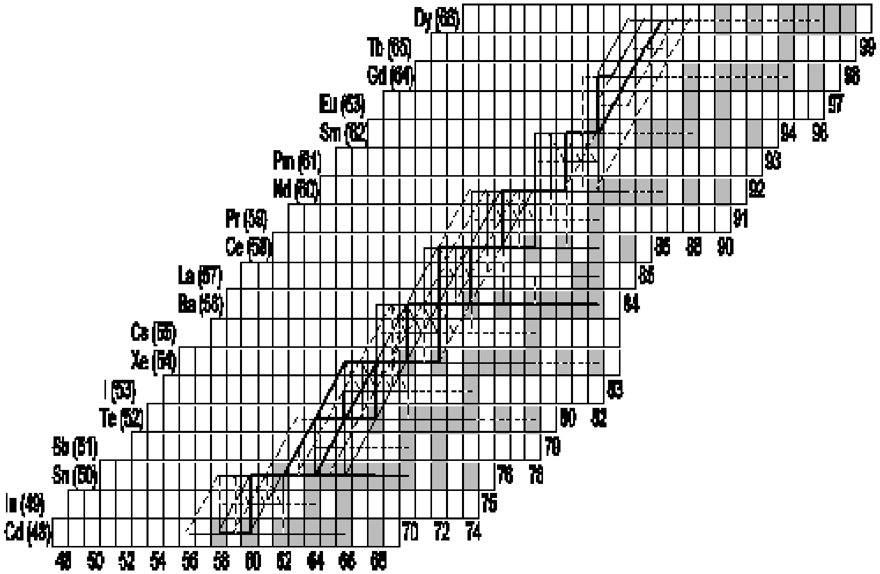
Requirements for proton rich nuclei to form:

- a. Sufficiently abundant seed nuclei
- b. Suficiently high temperatures (T_9 = 2-3)
- c. Short time scales (for freeze out)

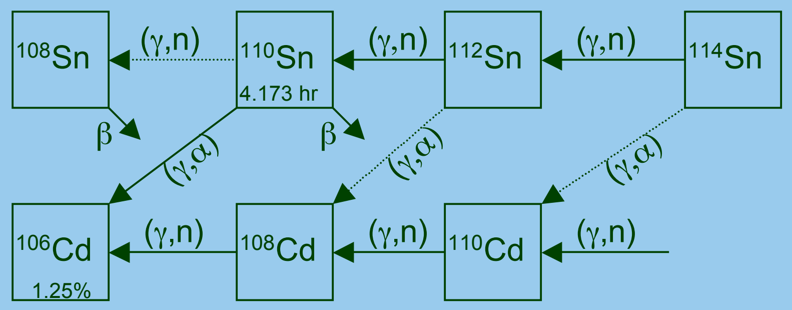
These conditions are best met in the Ne/O layer of Type II Supernova

New Experimental Results





p-process synthesis path



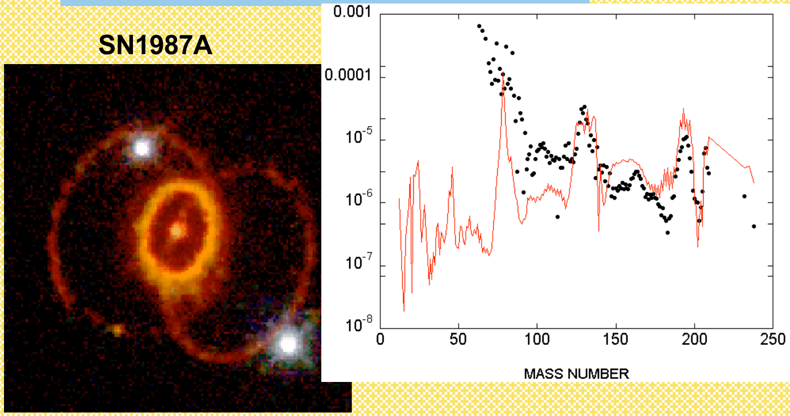
P-process reaction flow at the Cd-Sn region. For simplicity, only even-even isotopes are shown, hence the (γ,n) arrow indicates two subsequent neutron emissions. The solid arrows show the main reaction flow path while dashed arrows indicate weaker branchings.

T.Rausher, Nucl.Phys. A, in press

Astrophysical Site for the ‘Main’ r-Process

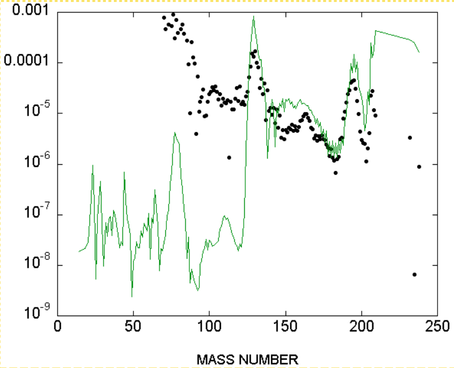
Dominant Candidate

Neutrino-driven wind in Type II supernovae

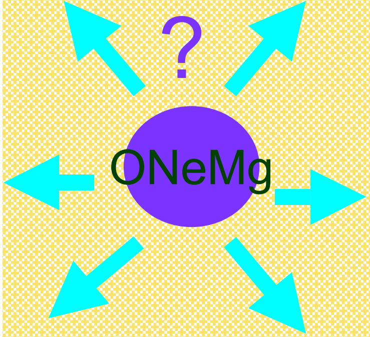

SN1987A

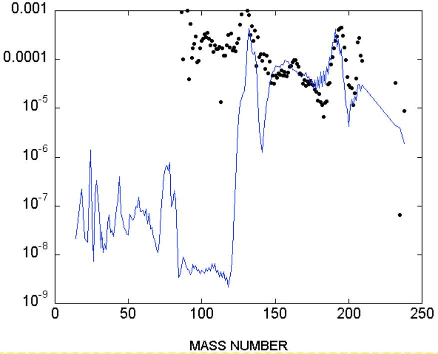
Neutron star mergers

Simulation of NS mergers (from Hayden planetarium)



Prompt explosion of low mass supernovae





New Candidate?
Quark Novae (Jaikumar et al. 2006)

nuclear–quark phase transition at the center of a cold neutron star yields a nova-like explosion.

- ✓Conditions similar to Neutron star mergers
- ✓Highest neutron-to-seed ratio

r-process abundance patterns arising from different environment are distinguishable.
If nuclear physics uncertainties were reduced, we could identify astrophysical site via observations.

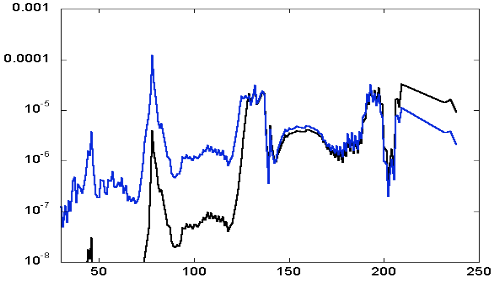
Impact of light elements reactions on r-process

r-process is primary process → light element reactions are important.

neutron-capture of light elements
Z<10 (Terasawa et al. 2001)

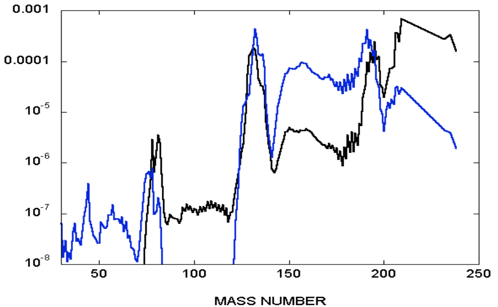
Neutrino wind

Fewer actinide elements and more 2nd peak elements.



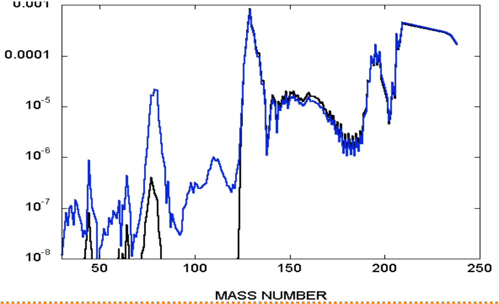
Low mass supernovae

Fewer actinide elements and more 2nd peak &3rd peak elements.



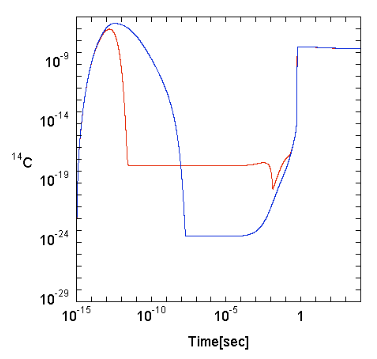
Neutron star mergers

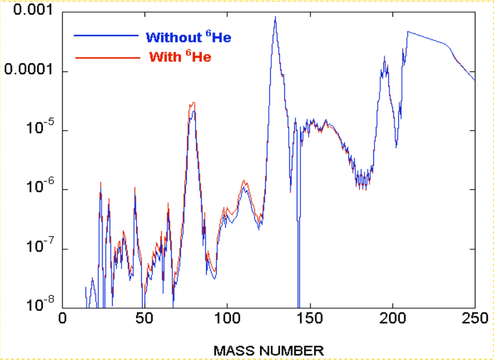
Due to fission recycling, we find no significant difference for A>130.



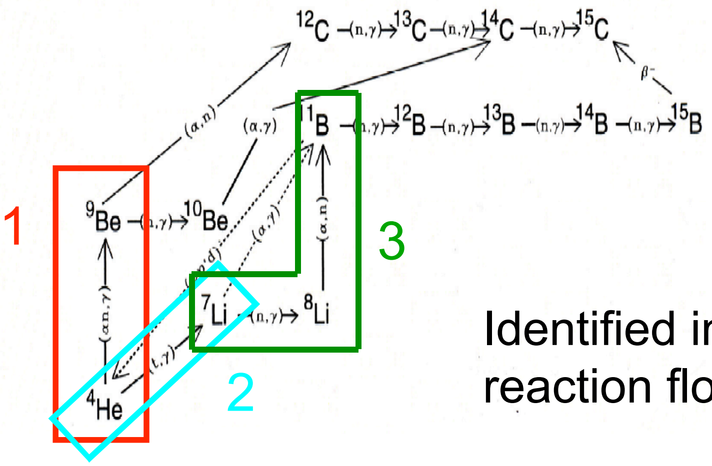
Important for all candidates.
More reliable rates are needed!

Di-neutron capture of ^{4}He





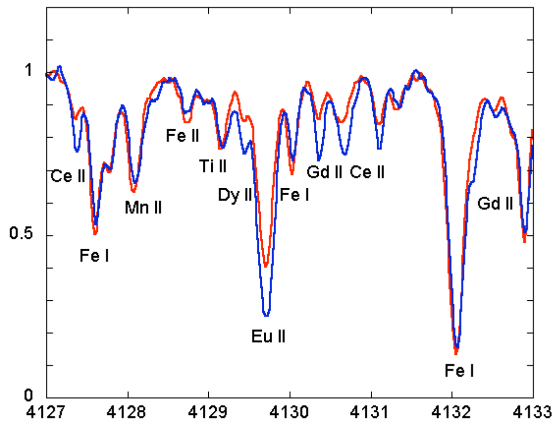
New reaction flow $^{4}\text{He}(^{2}n,\gamma)^{6}\text{He}(\alpha,n)^{9}\text{Be}$ could be important for r-process in low S, low T environments.

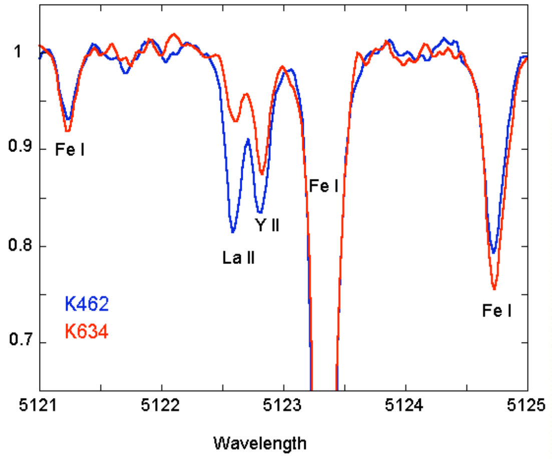


Identified important reaction flow

Neutron capture elements in M15

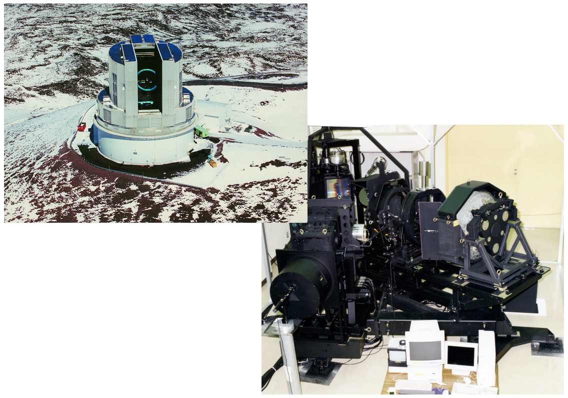
We identified an anti-correlation between Eu and the [Y, Zr/Eu] ratio in M15. Our results indicated that the heavy r-process elements were less dispersed than light r-process elements when M15 stars were formed.



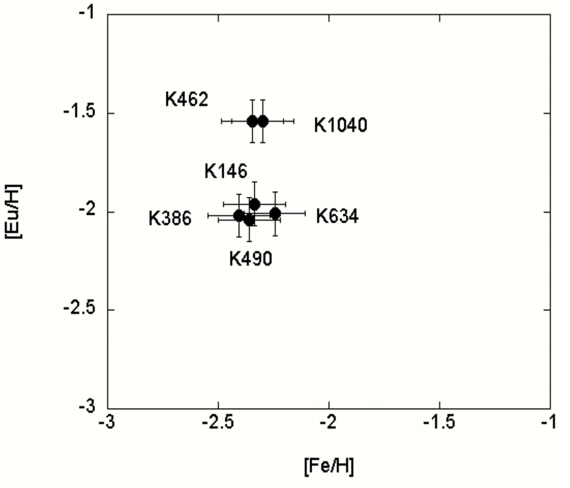


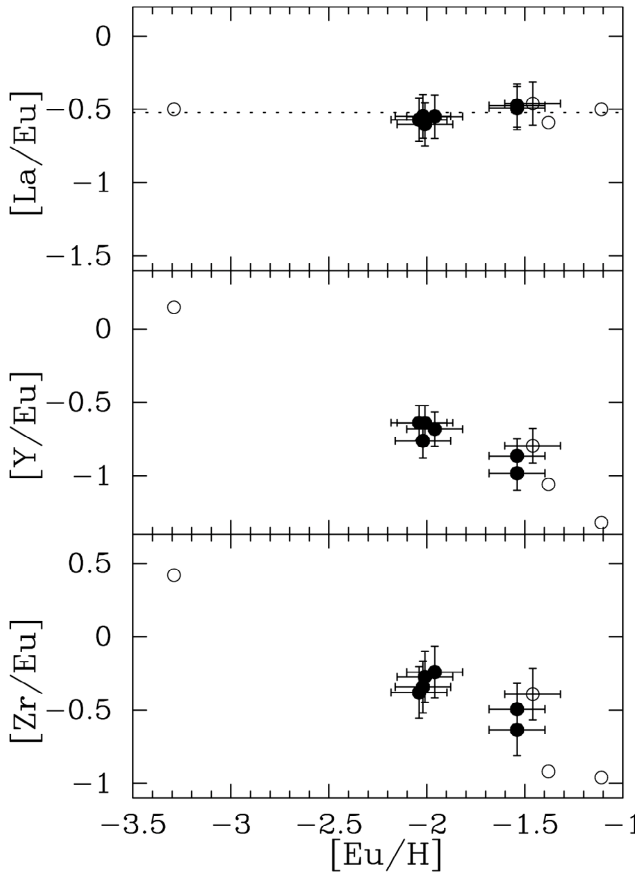
Examples of spectra of M15 stars obtained by Subaru/HDS

Subaru Telescope and HDS (High Dispersion Spectrograph)



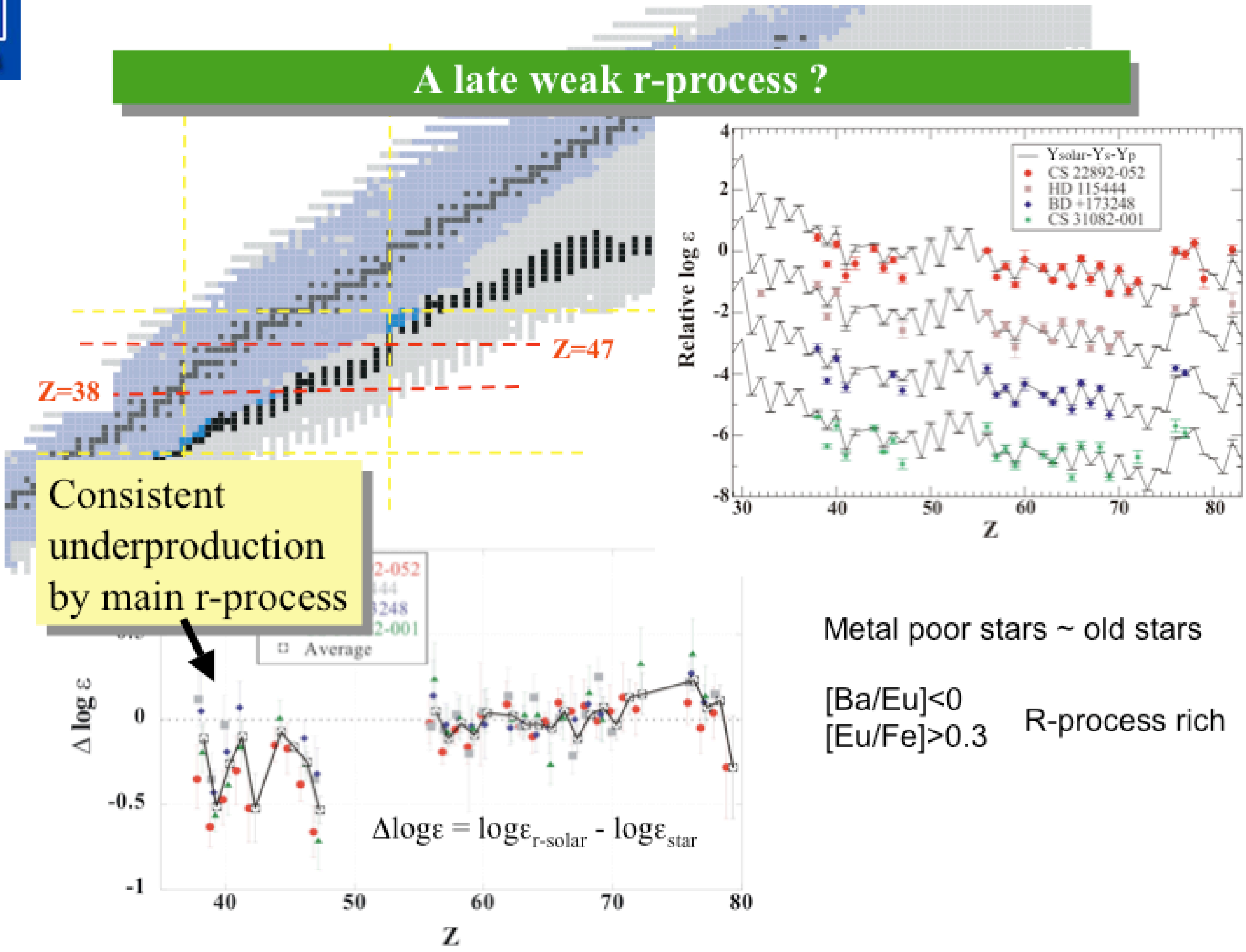
Observed [Fe/H] vs. [Eu/H]. [Fe/H] is almost uniform.





(Top) No significant s-process contribution.
(Middle &Bottom) Anti-correlations between [Eu/H] and [Zr, Y/Eu]

A late weak r-process ?



Consistent underproduction by main r-process

$\Delta\log\varepsilon = \log\varepsilon_{r\text{-solar}} - \log\varepsilon_{star}$

Metal poor stars ~ old stars

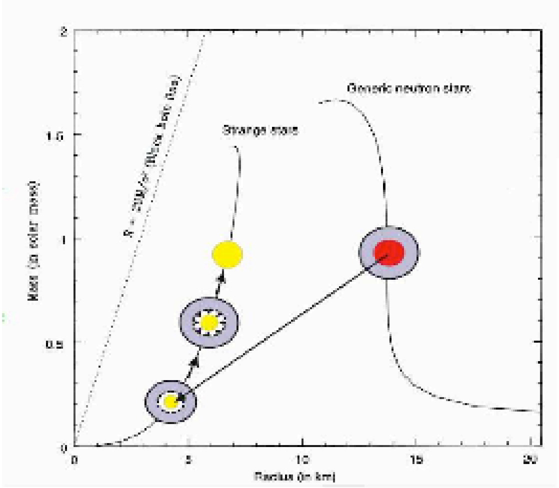
[Ba/Eu]<0
[Eu/Fe]>0.3

R-process rich

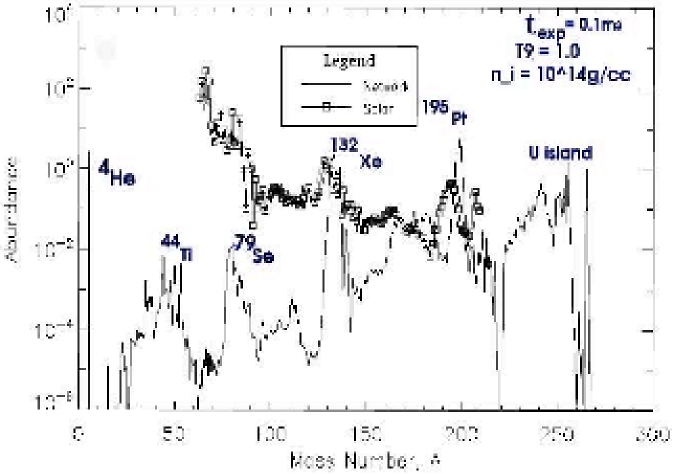
Courtesy Fernando Monte (MSU)

r-PROCESS FROM DECOMPRESSING NEUTRON MATTER

P. Jaikumar (Argonne), K. Otsuki (U. Chicago) and B. S. Meyer (Clemson U.)



- Envelope of neutron star is ejected from the surface by a nuclear-quark phase transition in the core.
- estimate of frequency of conversion : 1/1000 neutron stars in current epoch.



- r-process material ejected/event $\approx 10^{-2} M_\odot$
- efficient production of neutron-rich elements (2^{nd}, 3^{rd} peak)
- Quark-Nova leaves behind a hot Quark star shining in γ-rays

JINA Interactions Drive Research

Fission and the r-Process

- Jorge Pereira is a JINA postdoc at MSU; Kaori Otsuki is a JINA postdoc at UC; Ivo Seitenzahl is a JINA graduate student at UC.
- First encounter at JINA workshop in ND
- JINA provided friendly and collegial environment. Discussions led to collaboration on problem of common interest: the impact of nuclear fission on the r-process
- JINA support enables travel for interactions: Ivo has twice stayed with Jorge at MSU; Jorge has visited Kaori and Ivo at UC
- Progress on incorporation of fission into the r-process code utilized by Kaori Otsuki
- Closely collaboration has continued at scientific meetings and workshops: Santa Barbara and Russbach

JINA Interactions Drive Research

- Further JINA generated and enabled interactions include:
  - Interactions of Fang Peng (student at Chicago) and Ed Brown (MSU) with Alex Heger (LLNL) on issues concerning the effects of diffusion on successive outbursts of X-ray burst systems.
  - Interactions of Kaori Otsuki (postdoc at Chicago) with Prashanth Jaikumar (postdoc at Argonne), arising from Argonne/Chicago joint meetings, on the problem of r-process synthesis associated with the decompression of neutron star matter triggered by a nuclear-quark phase transition.
  - Interactions of Laurent Piau (postdoc at Chicago) with Tim Beers (MSU) on the interpretation of lithium abundances in halo stars.
  - Strong interactions involving JINA researchers (Dean Townsley, postdoc, Ivo Seitenzahl and Fang Peng, graduate students), ASC Flash Center researchers (Alan Calder, postdoc), and Ed Brown (Faculty at MSU) on thermonuclear burning associated with Type Ia supernova outbursts.

MRC-2: Chemical Evolution

Chemical Evolution

- **First Stars**
- **Abundances: Halo Stars, Stardust, DLα’s**
- **Cosmic Evolution**
- **Abundance Constraints**