MRC-2: Supernovae, Nucleosynthesis and Chemical Evolution

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University of Chicago
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QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

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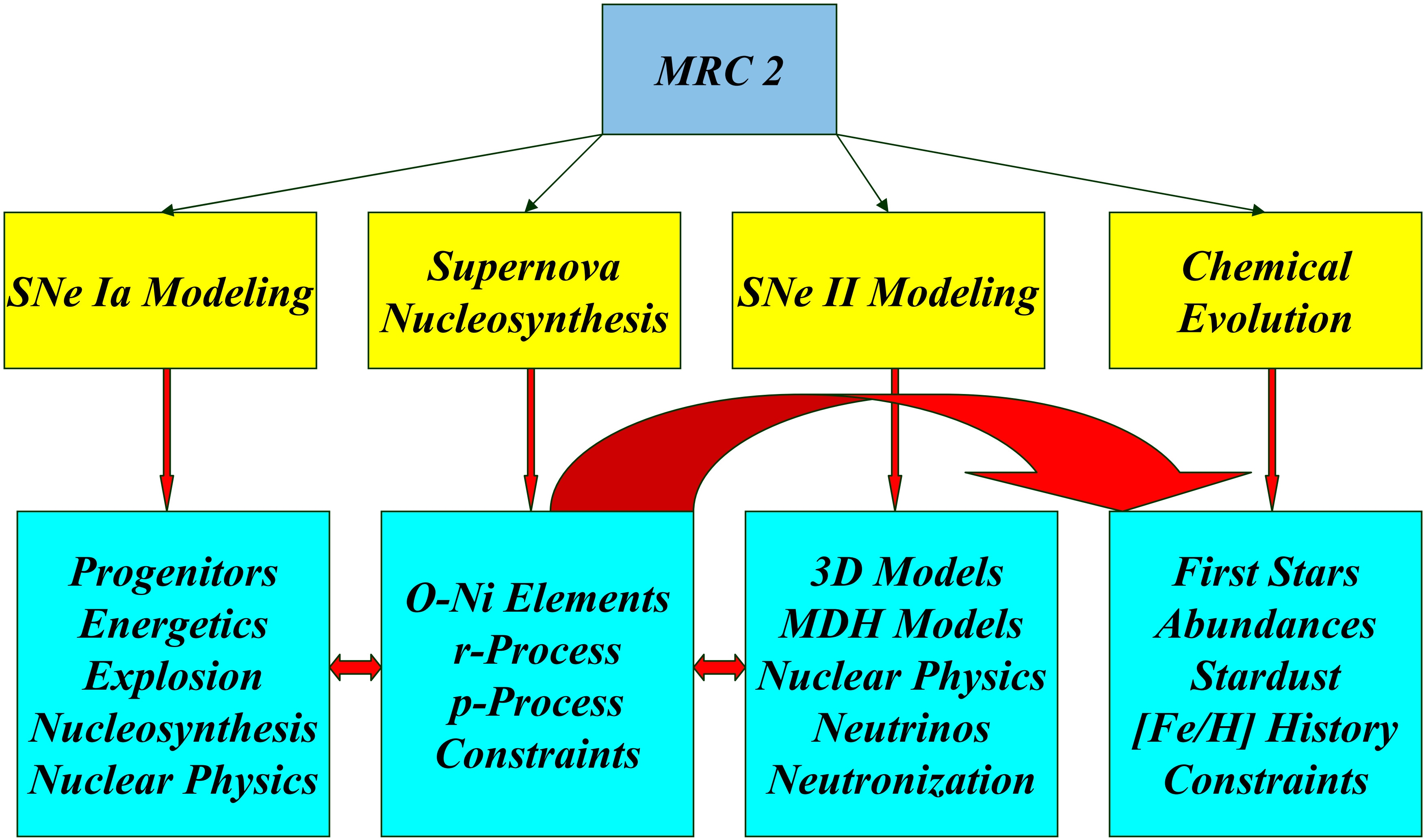

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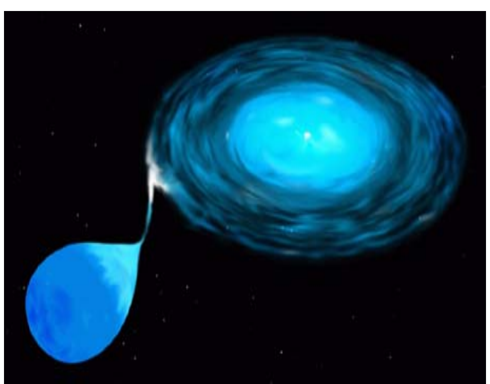
MRC-2: Supernova Modeling

Supernovae Ia

- **Progenitors**
- **Energetics**
- **Explosion**
- **Nucleosynthesis**



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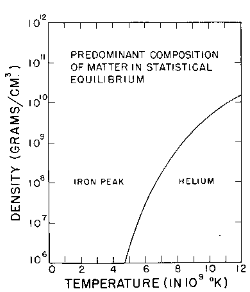

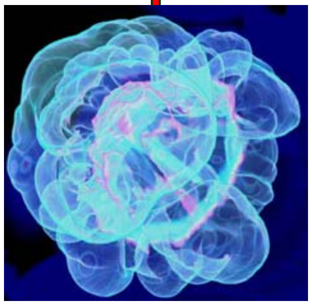

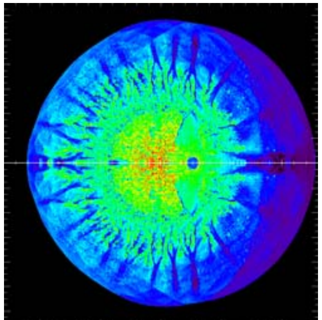

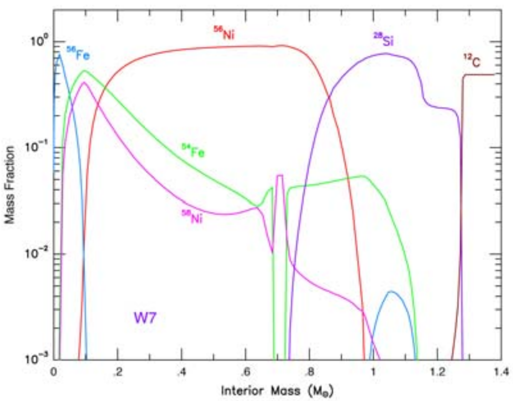

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Supernova Ia Simulations

A Possible Supernova Ia Explosion Mechanism

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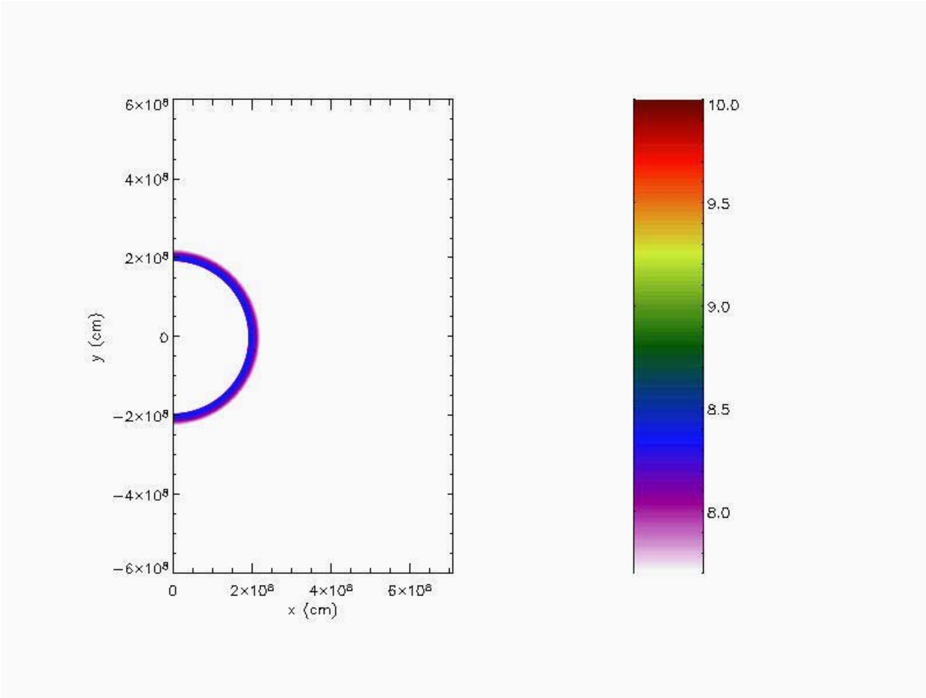

Off-center Deflagration Simulation

(Calder et al. 2003)

Possible Consequences of Breakout

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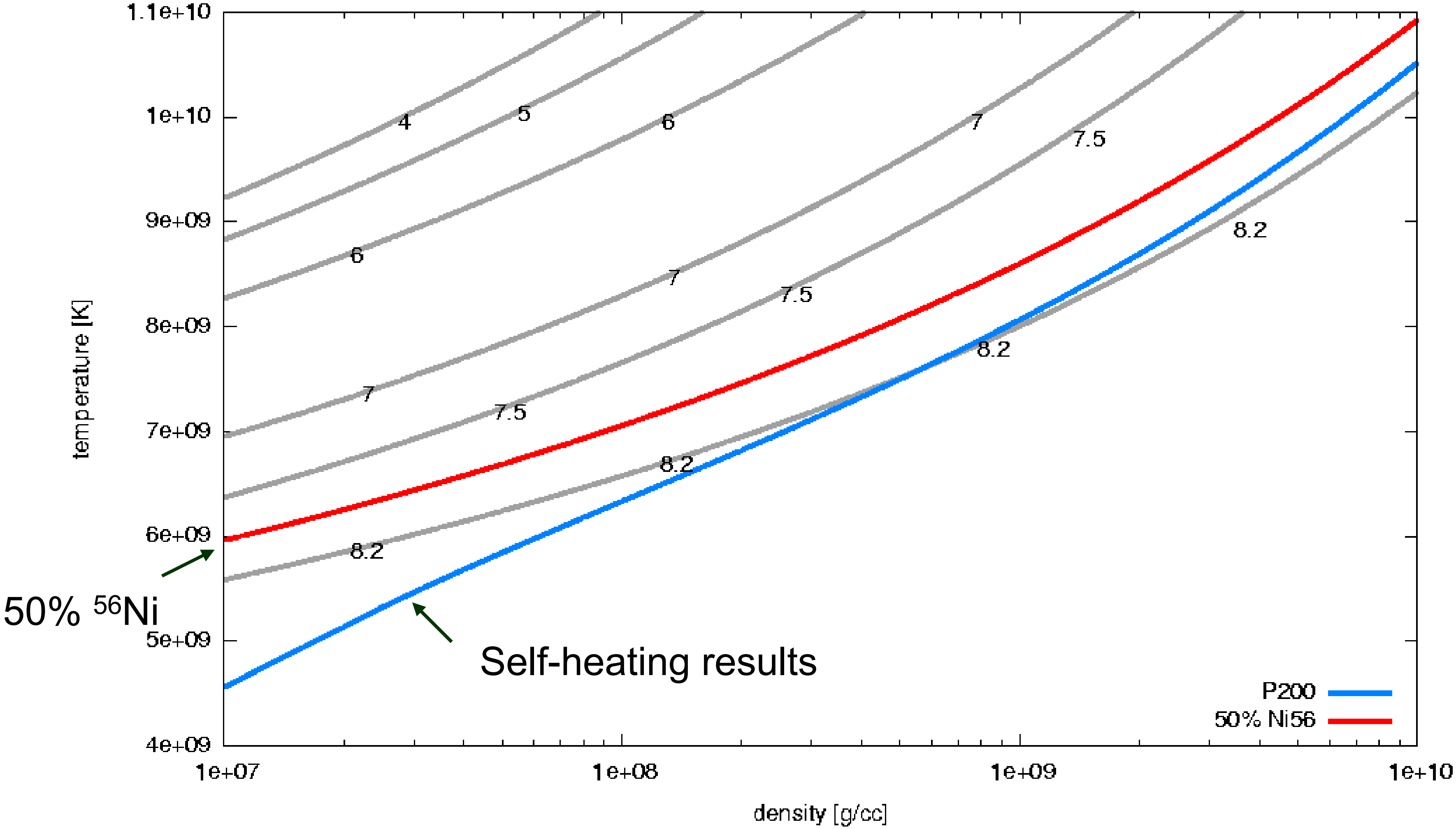
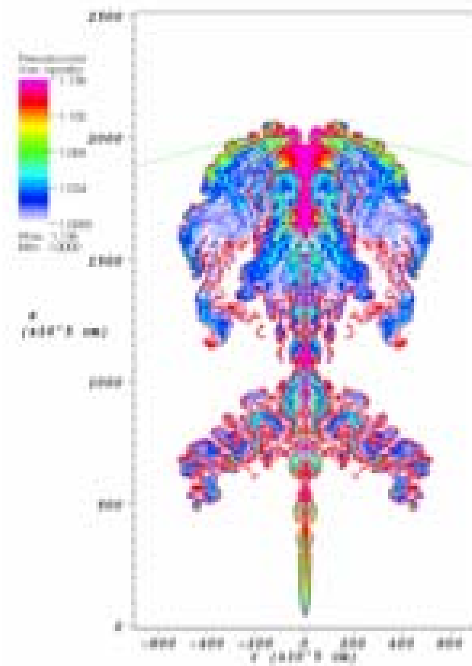
Average Binding Energy per Nucleon



Average Binding Energy per Nucleon

- Post-flame model uses evolving NSE state of ash
- Initially hot ash expands and cools
- BE increases as initial Helium converts to Nickel
- Electron captures lower Y_e
- BE increases further as more tightly bound Fe replaces Ni



Ratio of neutrons to protons in rising, burning material during a Type Ia supernova. The green line indicates the original surface of the star, and the red outline is the interface between burned material (interior) and unburned carbon and oxygen. This plume has grown for 0.98 seconds from an ignition 40 km from the center of the star.

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Nickel Production in SNe Ia (W7)

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

(Timmes, Brown, & Truran 2003)

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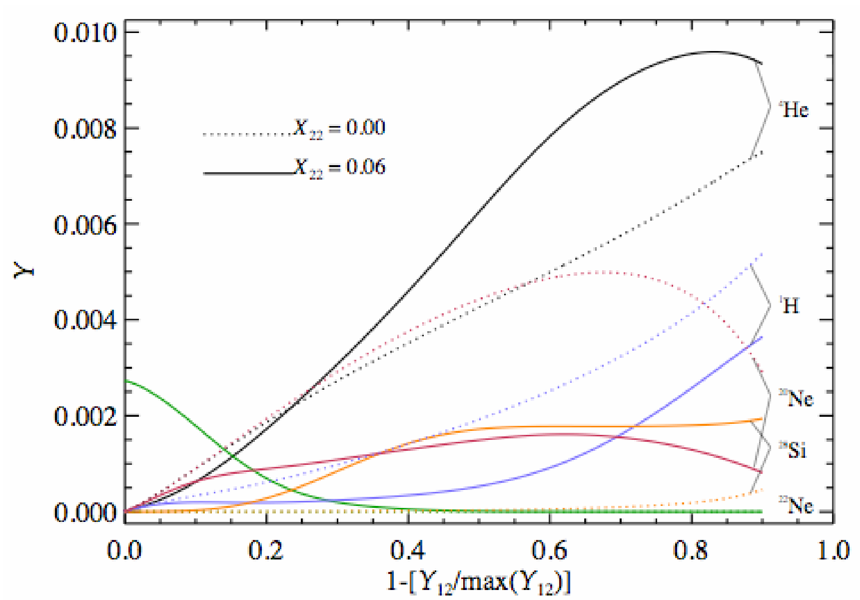
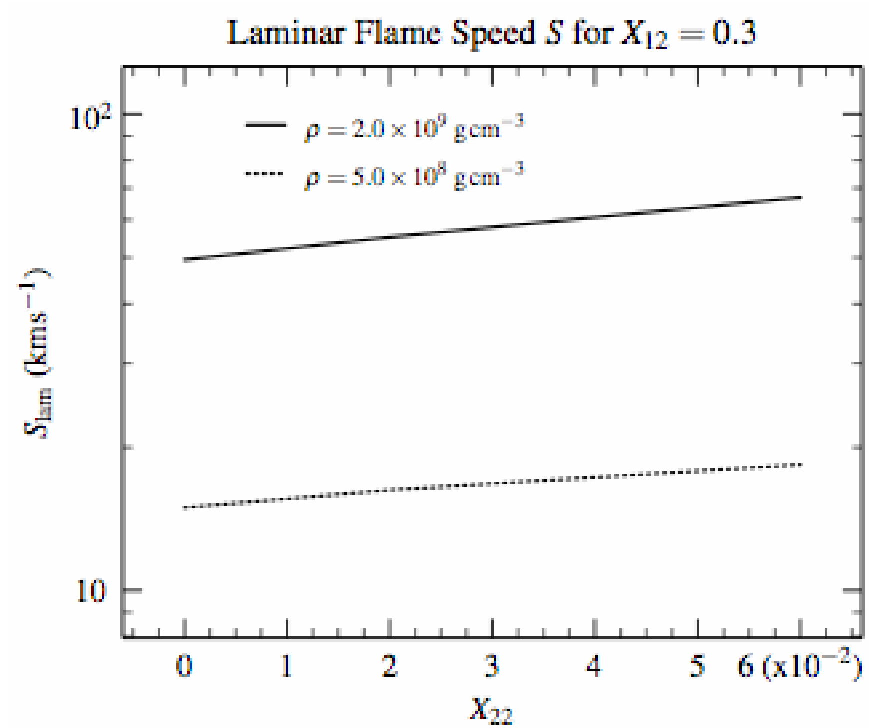
Laminar flame speedup by ^{22}Ne enrichment in SNe Ia

Chamulak, Brown, & Timmes (2007), ApJ, 655, L93





During ^{12}C burning in the flame front, *n* liberated by ^{22}Ne(α,*n*) capture onto other burning produce. This facilitates converting available *p* into α, and enhances the heating.

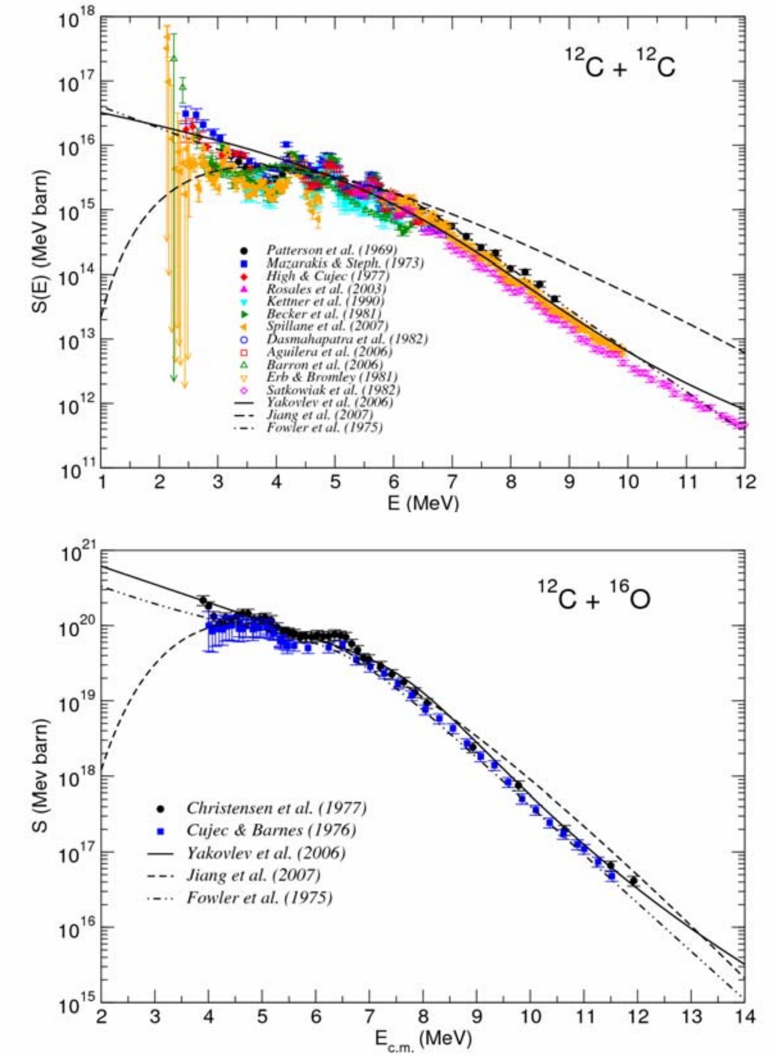
The flame speed is roughly linear with ^{22}Ne abundance, with a speedup of ≈ 30% for *X*(^{22}Ne)=0.06.

This speedup is relevant to the initial burning front near the center, and at lower densities where the flame may make a transition to distributed burning.

Ignition Conditions in Type Ia Supernovae

Recent heavy ion fusion cross section measurements indicate a decrease in S-factor with low energies. This was explained by a hindrance factor associated with the stiffness of nuclear matter. Adopting this explanation to stellar ^{12}C+^{12}C, ^{16}O+^{16}O fusion date a phenomenological fit suggests a significant reduction in S-factor as well. This has dramatic consequences for the ignition conditions type I supernovae and superburst in accreting neutron stars.

Collaborators:
Notre Dame, MSU
ANL, ANU, Joffe,



Standard potential model extrapolation of existing fusion data in comparison with fit extrapolation by Jiang et al. 2007.

SNe Ia and Stellar Population

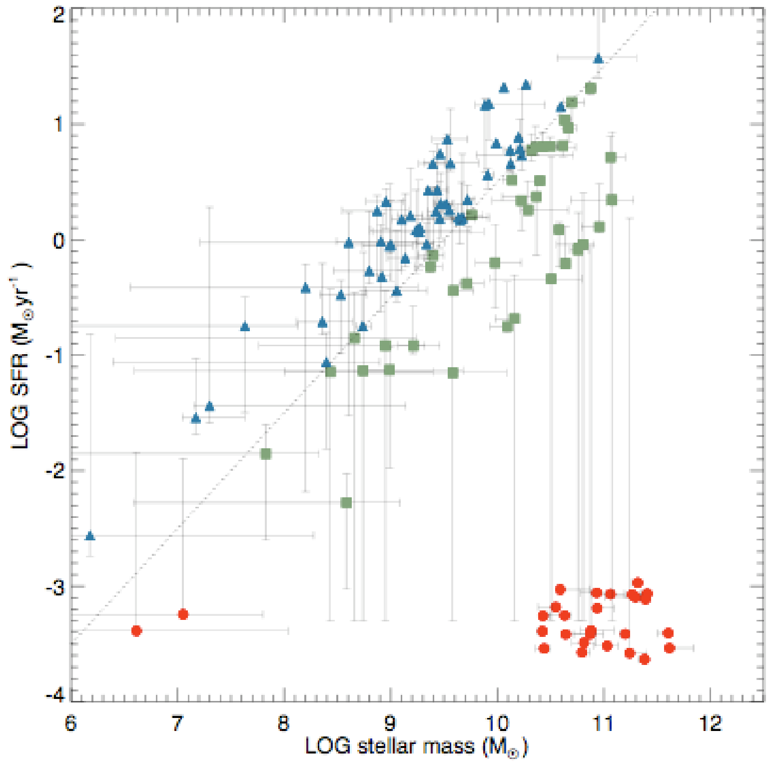


Fig. 5.— The distribution of the SN Ia host galaxies in the SFR-mass plane. Each galaxy is coded according to its assigned type. Passive galaxies are shown as circles (red), normal star-forming galaxies as squares (green), and vigorous star-formers as triangles (blue). The black diagonal dotted line shows the division in specific star-formation rate used to sub-divide those hosts that are star-forming. The passive galaxies (which have a zero SFR in our models) are assigned a random SFR centered on $0.005 M_\odot yr^{-1}$ for illustration purposes.

Deflagration Phase of Type Ia Flame Evolution

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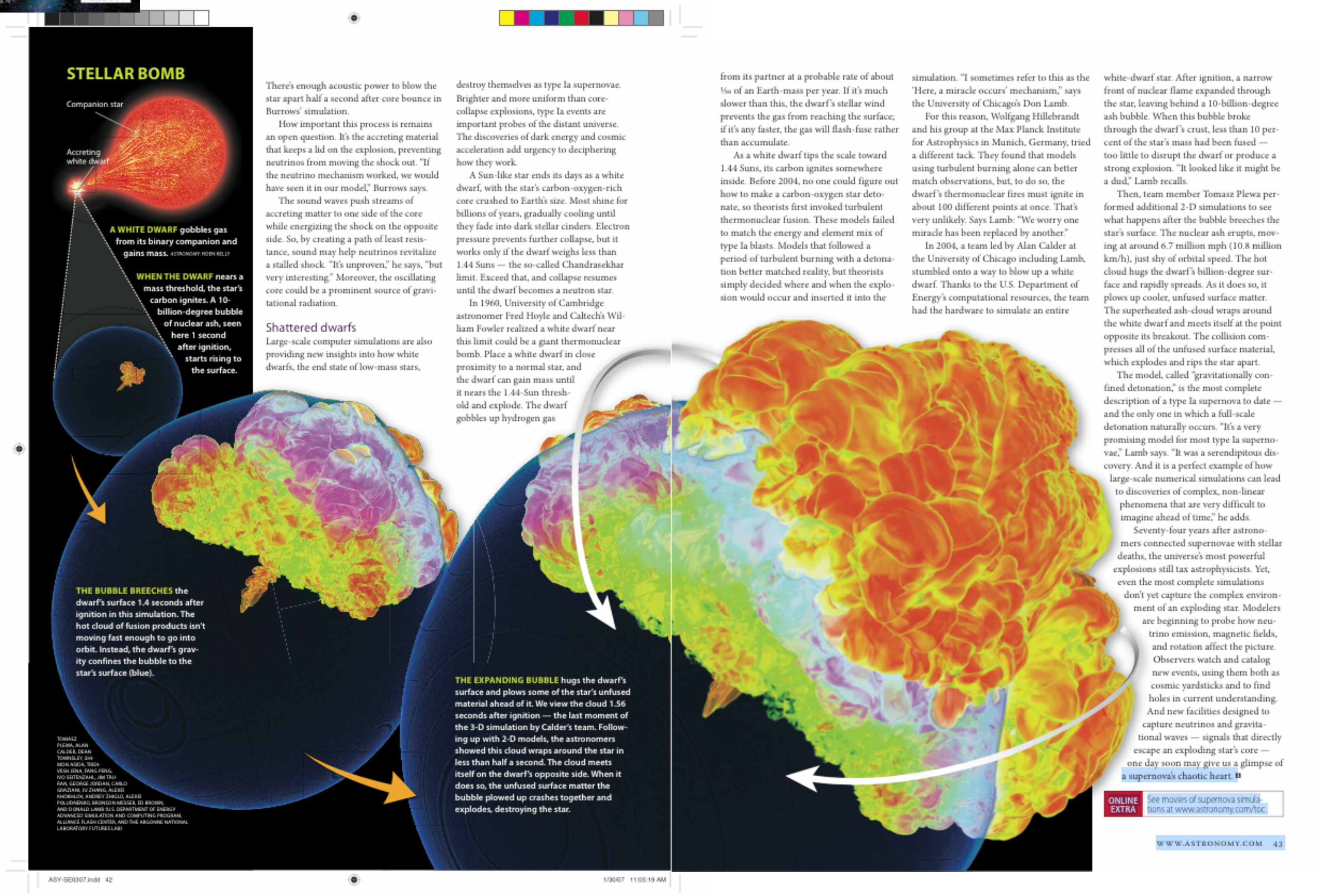

STELLAR BOMB

Companion star

Accreting white dwarf

A WHITE DWARF gobbles gas from its binary companion and gains mass. ASTRONOMY: ROEN KELLY

WHEN THE DWARF nears a mass threshold, the star's carbon ignites. A 10-billion-degree bubble of nuclear ash, seen here 1 second after ignition, starts rising to the surface.

THE BUBBLE BREECHES the dwarf's surface 1.4 seconds after ignition in this simulation. The hot cloud of fusion products isn't moving fast enough to go into orbit. Instead, the dwarf's gravity confines the bubble to the star's surface (blue).

TOMASZ PLEWA, ALAN CALDER, DEAN TOWNSLEY, SHIMON ASIDA, TRIDIVESH JENA, FANG PENG, IVO SEITENZAHL, JIM TRURAN, GEORGE JORDAN, CARLO GRAZIANI, YU ZHANG, ALEXEI KHOKHLOV, ANDREY ZHIGLO, ALEXEI POLUDNENKO, BRONSON MESSER, ED BROWN, AND DONALD LAMB (U.S. DEPARTMENT OF ENERGY ADVANCED SIMULATION AND COMPUTING PROGRAM, ALLIANCE FLASH CENTER, AND THE ARGONNE NATIONAL LABORATORY FUTURES LAB)

There's enough acoustic power to blow the star apart half a second after core bounce in Burrows' simulation.

How important this process is remains an open question. It's the accreting material that keeps a lid on the explosion, preventing neutrinos from moving the shock out. "If the neutrino mechanism worked, we would have seen it in our model," Burrows says.

The sound waves push streams of accreting matter to one side of the core while energizing the shock on the opposite side. So, by creating a path of least resistance, sound may help neutrinos revitalize a stalled shock. "It's unproven," he says, "but very interesting." Moreover, the oscillating core could be a prominent source of gravitational radiation.

Shattered dwarfs

Large-scale computer simulations are also providing new insights into how white dwarfs, the end state of low-mass stars, destroy themselves as type Ia supernovae. Brighter and more uniform than core-collapse explosions, type Ia events are important probes of the distant universe. The discoveries of dark energy and cosmic acceleration add urgency to deciphering how they work.

A Sun-like star ends its days as a white dwarf, with the star's carbon-oxygen-rich core crushed to Earth's size. Most shine for billions of years, gradually cooling until they fade into dark stellar cinders. Electron pressure prevents further collapse, but it works only if the dwarf weighs less than 1.44 Suns — the so-called Chandrasekhar limit. Exceed that, and collapse resumes until the dwarf becomes a neutron star.

In 1960, University of Cambridge astronomer Fred Hoyle and Caltech's William Fowler realized a white dwarf near this limit could be a giant thermonuclear bomb. Place a white dwarf in close proximity to a normal star, and the dwarf can gain mass until it nears the 1.44-Sun threshold and explode. The dwarf gobbles up hydrogen gas from its partner at a probable rate of about 1/10 of an Earth-mass per year. If it's much slower than this, the dwarf's stellar wind prevents the gas from reaching the surface; if it's any faster, the gas will flash-fuse rather than accumulate.

As a white dwarf tips the scale toward 1.44 Suns, its carbon ignites somewhere inside. Before 2004, no one could figure out how to make a carbon-oxygen star detonate, so theorists first invoked turbulent thermonuclear fusion. These models failed to match the energy and element mix of type Ia blasts. Models that followed a period of turbulent burning with a detonation better matched reality, but theorists simply decided where and when the explosion would occur and inserted it into the simulation. "I sometimes refer to this as the 'Here, a miracle occurs' mechanism," says the University of Chicago's Don Lamb.

For this reason, Wolfgang Hillebrandt and his group at the Max Planck Institute for Astrophysics in Munich, Germany, tried a different tack. They found that models using turbulent burning alone can better match observations, but, to do so, the dwarf's thermonuclear fires must ignite in about 100 different points at once. That's very unlikely. Says Lamb: "We worry one miracle has been replaced by another."

In 2004, a team led by Alan Calder at the University of Chicago including Lamb, stumbled onto a way to blow up a white dwarf. Thanks to the U.S. Department of Energy's computational resources, the team had the hardware to simulate an entire white-dwarf star. After ignition, a narrow front of nuclear flame expanded through the star, leaving behind a 10-billion-degree ash bubble. When this bubble broke through the dwarf's crust, less than 10 percent of the star's mass had been fused — too little to disrupt the dwarf or produce a strong explosion. "It looked like it might be a dud," Lamb recalls.

Then, team member Tomasz Plewa performed additional 2-D simulations to see what happens after the bubble breeches the star's surface. The nuclear ash erupts, moving at around 6.7 million mph (10.8 million km/h), just shy of orbital speed. The hot cloud hugs the dwarf's billion-degree surface and rapidly spreads. As it does so, it plows up cooler, unfused surface matter. The superheated ash-cloud wraps around the white dwarf and meets itself at the point opposite its breakout. The collision compresses all of the unfused surface material, which explodes and rips the star apart.

The model, called "gravitationally confined detonation," is the most complete description of a type Ia supernova to date — and the only one in which a full-scale detonation naturally occurs. "It's a very promising model for most type Ia supernovae," Lamb says. "It was a serendipitous discovery. And it is a perfect example of how large-scale numerical simulations can lead to discoveries of complex, non-linear phenomena that are very difficult to imagine ahead of time," he adds.

Seventy-four years after astronomers connected supernovae with stellar deaths, the universe's most powerful explosions still tax astrophysicists. Yet, even the most complete simulations don't yet capture the complex environment of an exploding star. Modelers are beginning to probe how neutrino emission, magnetic fields, and rotation affect the picture. Observers watch and catalog new events, using them both as cosmic yardsticks and to find holes in current understanding. And new facilities designed to capture neutrinos and gravitational waves — signals that directly escape an exploding star's core — one day soon may give us a glimpse of a supernova's chaotic heart.

THE EXPANDING BUBBLE hugs the dwarf's surface and plows some of the star's unfused material ahead of it. We view the cloud 1.56 seconds after ignition — the last moment of the 3-D simulation by Calder's team. Following up with 2-D models, the astronomers showed this cloud wraps around the star in less than half a second. The cloud meets itself on the dwarf's opposite side. When it does so, the unfused surface matter the bubble plowed up crashes together and explodes, destroying the star.

ONLINE EXTRA See movies of supernova simulations at www.astronomy.com/toc.

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TIFF (Uncompressed) decompressor
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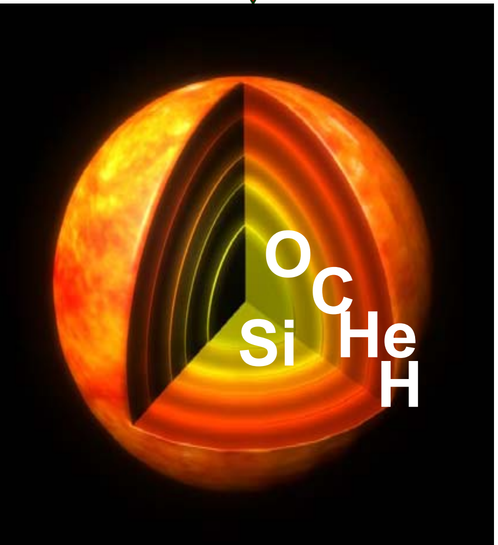
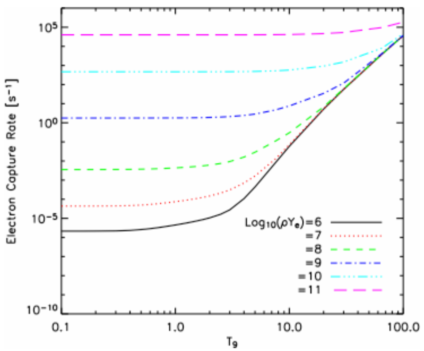
MRC-2: Supernova Modeling

Supernovae II

- ***Progenitor Evolution***
- ***Neutronization And Neutrinos***
- ***3-D Models***
- ***Nucleosynthesis***





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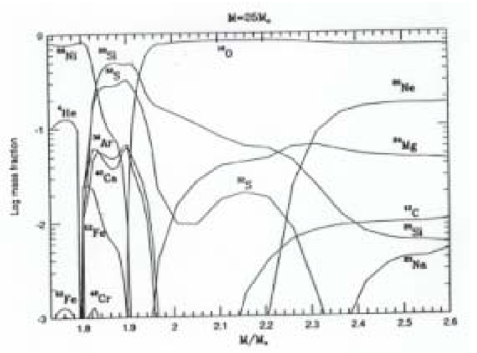
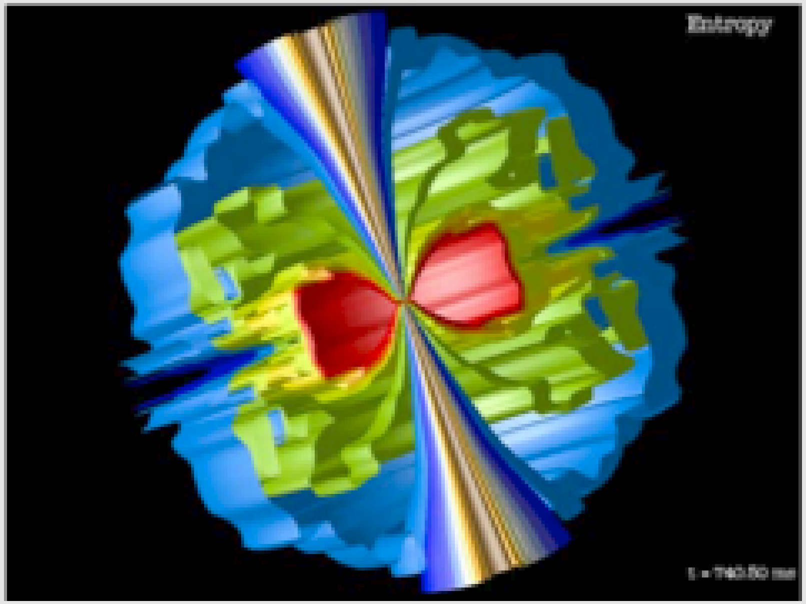


Accretion Induced Collapse of a Rotating ONeMg WD



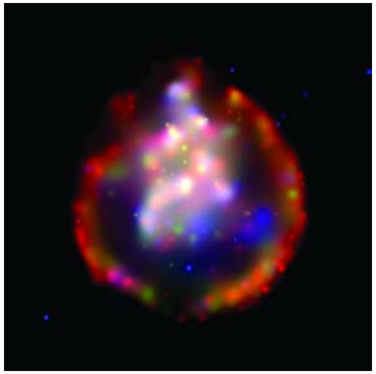
The figure shows the supernova-like explosion after the collapse of a rapidly rotating white dwarf due to accretion from a companion star above the critical Chandrasekhar mass. The explosion is bipolar, driven by anisotropic neutrino heating. The inner red region is the newly-born accretion disk. The yellow cones render the cores of the neutrino-driven jets. The sheets are iso-density contours and this snapshot was taken ~750 milliseconds after the onset of collapse (from a publication by the Arizona JINA group, Dessart et al. 2006).

The Arizona group also shows that the accretion-induced collapse (AIC) of a rotating white dwarf explodes easily, and is driven by a polar neutrino-powered wind (Dessart et al. 2006). This is the most thorough published study of rapidly rotating core-collapse performed to date, and, with a uniquely capable code VULCAN/2D, revealed for the first time the degree of anisotropic neutrino emissions that rapid rotation imposes. These AIC models also suggest one class of gamma-ray burst (GRB).

Researchers: A. Burrows, J. Murphy, C. Ott

Weak Reaction Rates in Astrophysics

SNR 0103-72.6 Chandra
observatory NASA/CXC/SAO



Core-collapse supernovae

- key nuclear physics input: weak rates on medium-heavy (A~40-120) mostly unstable nuclei
- electron density/collapse trajectory/core properties

Sn Ia 1994D in NGC 4526
NASA/ESA/Hubble

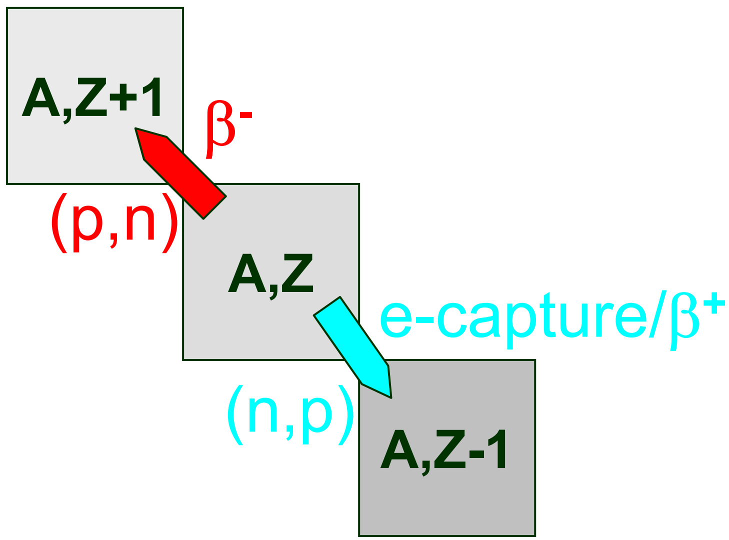
Thermonuclear (Type Ia) supernovae

- exact nature of explosion not well understood
- accurate weak rates constrain scenario
- unstable pf-shell nuclei including ^{56}Ni

- neutron-star crust processes (A~20-104)
- ν-process (forbidden weak transitions)
- s-process
- neutrino-physics

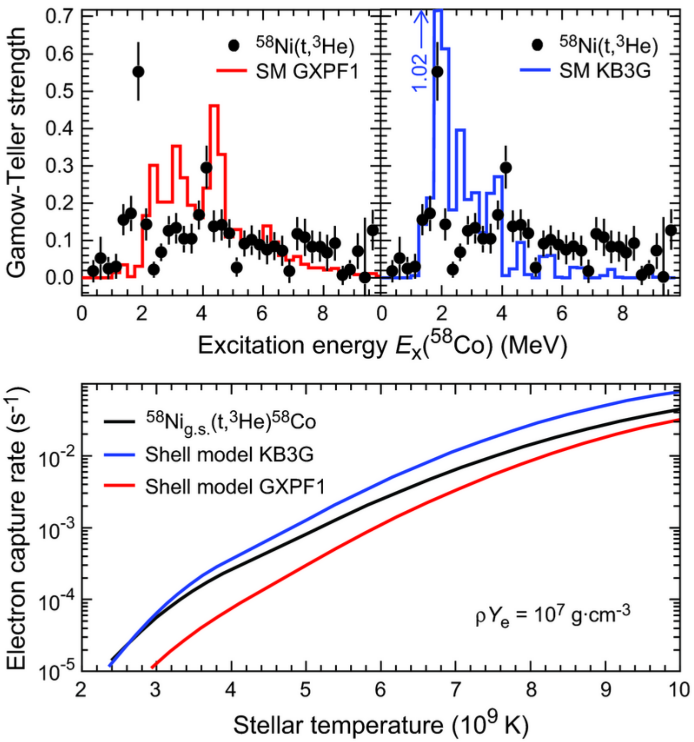
Charge-exchange reactions & Astrophysics

- spin-isospin response of light asymmetric systems
- isovector giant resonances in, and macroscopic properties of unstable nuclei
- weak rates in astrophysics
  - type II and Ia supernovae
  - neutron crust
  - ν-process
  - s-process



- stable nuclei: (t,^{3}He) (NSCL) and (^{3}He,t) (RCNP)
- unstable nuclei:
  - ^{34}P(^{7}Li,^{7}Be) experiment in inverse kinematics: Feb. 2007
  - Neutron detector for (p,n) in inverse kinematics: under construction

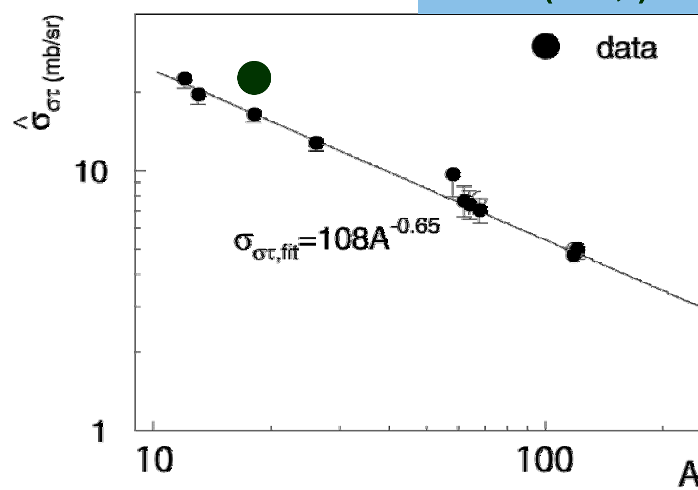
Weak Rates via Charge-Exchange Reactions: Stable Targets



Comparison between data and theory on the Gamow-Teller distribution in ^{58}Co and the deduced e-capture rates in a star just prior to its collapse

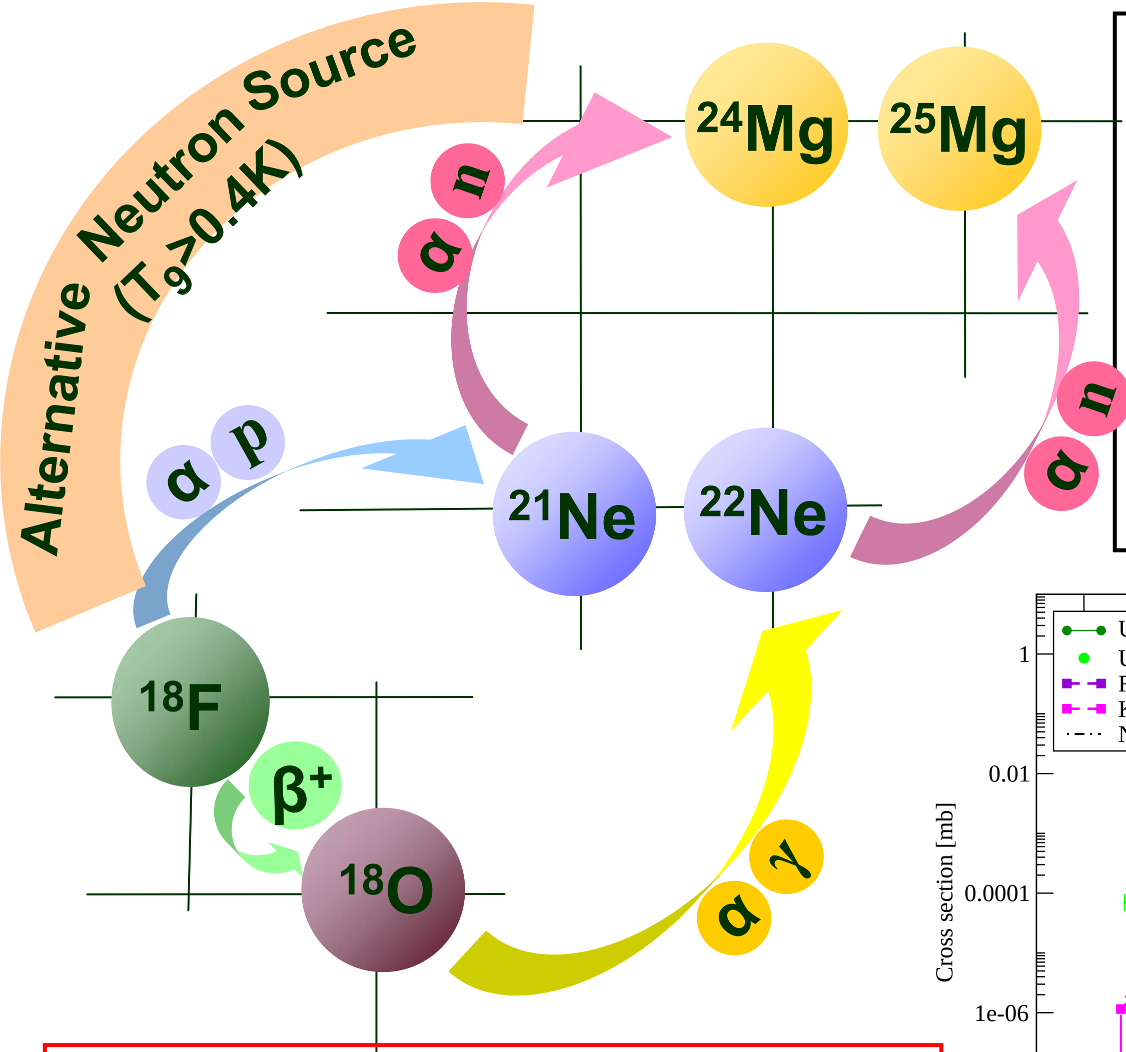
- (t,^{3}He) program at the NSCL
- Analysis of ^{63}Cu,^{64}Zn,^{94}Mo(t,^{3}He) in progress
- Calibration of unit cross sections $\hat{\sigma}$ with (^{3}He,t) data taken at RCNP, Osaka: completed - **$\sigma = \hat{\sigma}$ B(GT)**

From (^{3}He,t) 420 MeV

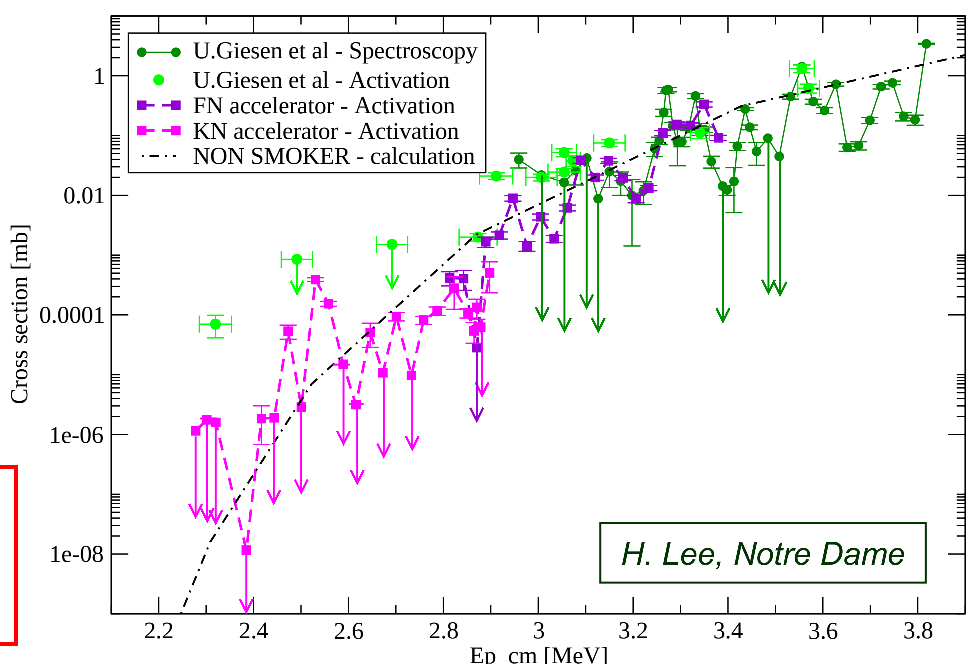


- Combination of (t,^{3}He) and (^{3}He,t) experiments: used for validating theory used in describing neutrinoless double beta decay
  - NSCL focus ^{150}Sm(t,^{3}He) & ^{150}Nd(^{3}He,t)

Search for an alternative r-process site : $^{18}F(\alpha,p)^{21}Ne$ (I)



Once ^{18}F is produced by $^{14}N(\alpha,\gamma)$, it usually decays to ^{18}O, then α-captures to make neutrons for r-process by $^{22}Ne(\alpha,n)$. At He-rich environment with high temperature, such as a shock front passing through He-layer in pre-supernova, ^{18}F can have (α,p) reaction to provide an alternative neutron source as $^{21}Ne(\alpha,n)$.



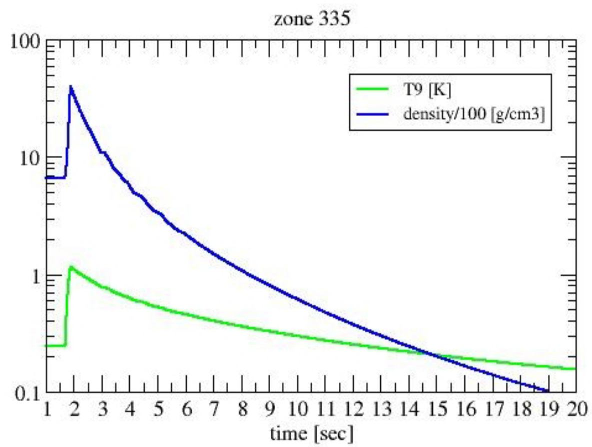
For the first time, the reaction rate of 18F(a,p) was determined experimentally from the measured cross section.

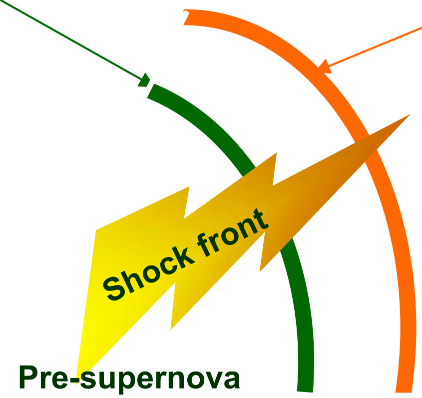
Search for an alternative r-process site : $^{18}F(\alpha,p)^{21}Ne$ (II)

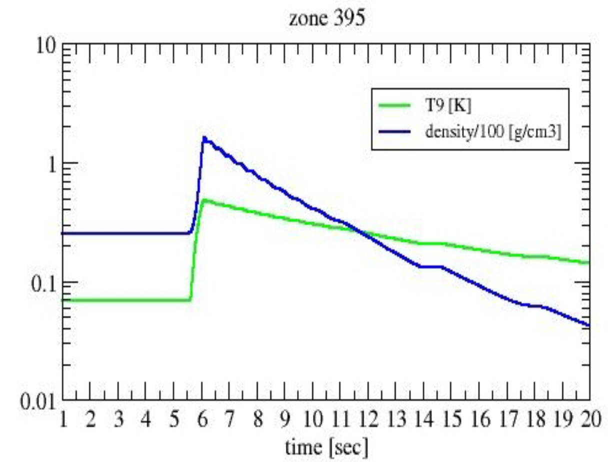
Multi-zone Supernova Explosion calculation and Full Network Code as a post process :

Beginning of He layer -> zone 335

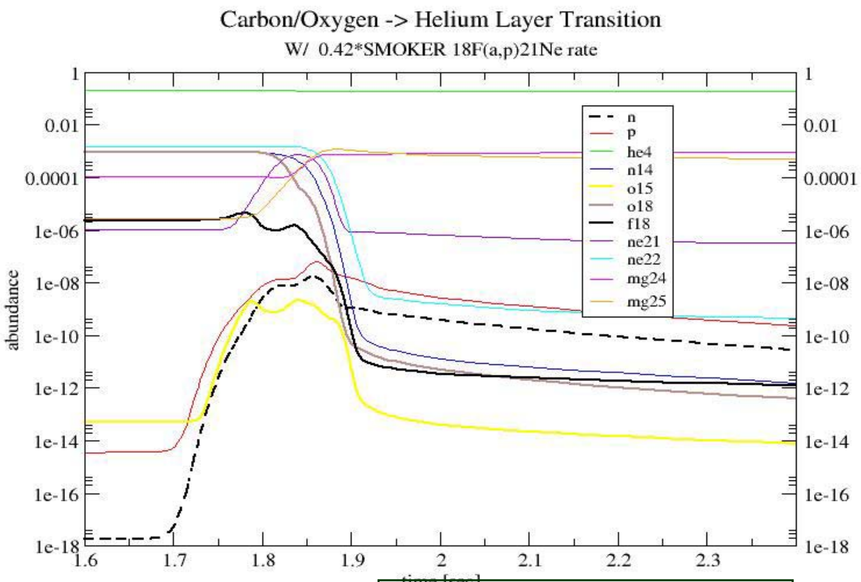
End of He layer -> zone 395







A. Heger, LANL



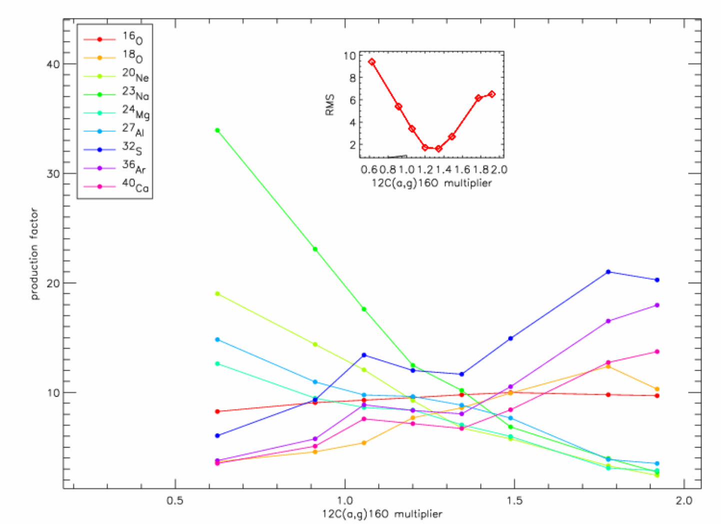
T. Elliot & H. Schatz, MSU

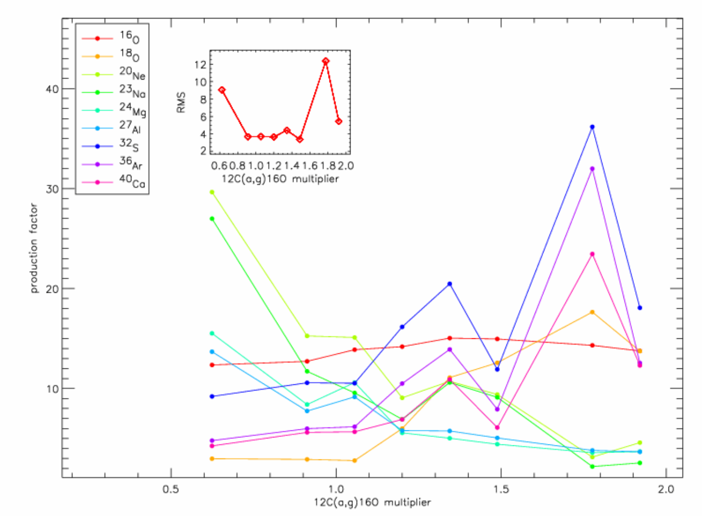
For 15M$_{\Theta}$ stars, inclusion of the reaction rate of $^{18}F(\alpha,p)$, which was experimentally normalized Hauser-Feshbach calculation, did not make contribution for enhancement of ^{21}Ne production. This is still under study for different mass stars and applying directly the measured reaction rate to codes.

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

HOW DO DIFFERENCES IN SOLAR ABUNDANCE SETS AND VARIATIONS IN THE RATES OF THE HELIUM BURNING REACTIONS INFLUENCE NUCLEOSYNTHESIS BY SNII PROGENITORS? (C. Tur, A. Heger, S.M. Austin)

Production factors for some medium-weight elements as a function of the 12C(a,g)16O rate multiplier (multiplier of 1 = Buchmann 1996 value). This is the study where the triple alpha rate is constant and only the 12C(a,g)16O rate is varied.

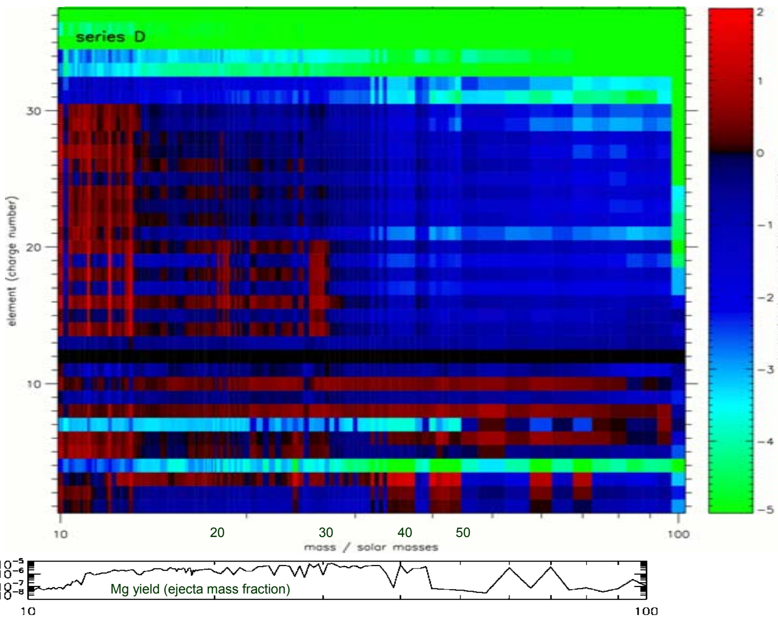




ANDERS & GREVESS 1989 abundances. 8 star average (13, 15, 17, 19, 21, 23, 25, 27 Msun).
1.2 x Buchmann appears as a tight minimum (RMS) order to co-produce those elements (as in A. Weaver & S.E Woosley (1993) ApJ,129:377 and subsequent work).

LODDERS 2003 abundances. 2 star average (15 and 25 Msun).
1.2 x Buchmann appears as a much broader minimum (RMS) now…

Pop III Nucleosynthesis



Elemental Yields
as a function of initial mass

(Heger & Woosley 2007)

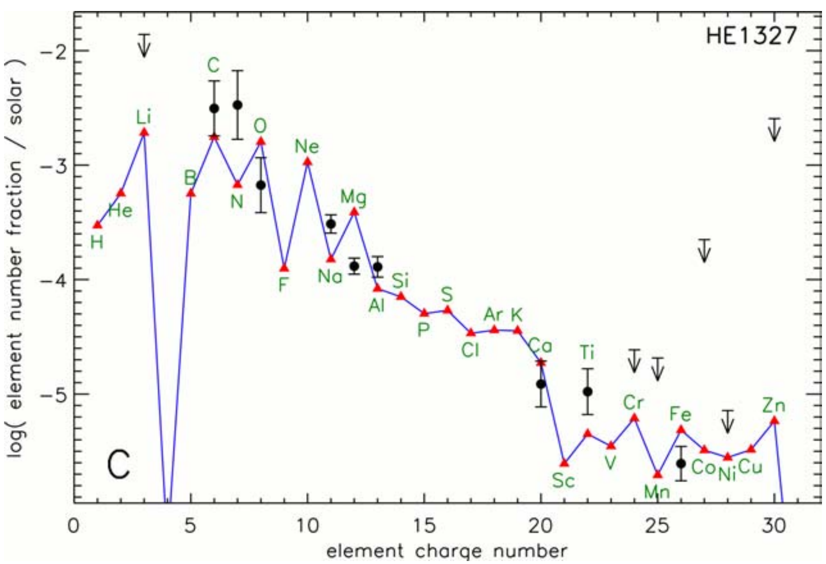
non-rotating stars

120 stellar masses

"complete" reaction network

normalized to Mg

RESULTS:
e.g.,
Production of ^{7}Li by neutrino interaction in very compact stellar envelope!



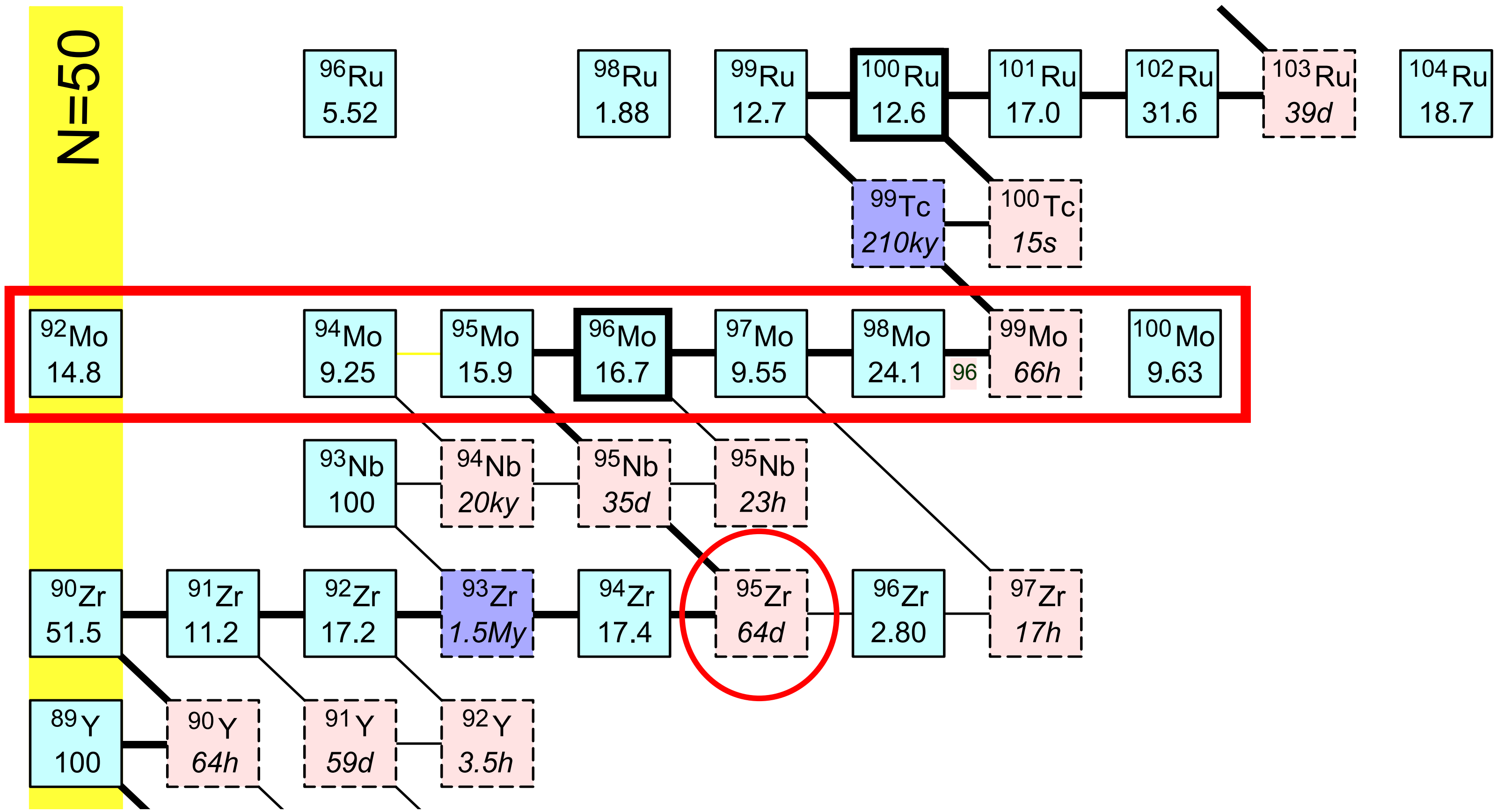
Library of 10 different explosion energies and different amount of mixing in the explosion

Developed tool to mach observed abundance patterns to single stars or different assumed IMFs.

Will make available tool to community after completion of paper.

Developed, in part, as part of SciDAC CAC-3 and LANL LDRD 20050031DR

Mo s-process nucleosynthesis

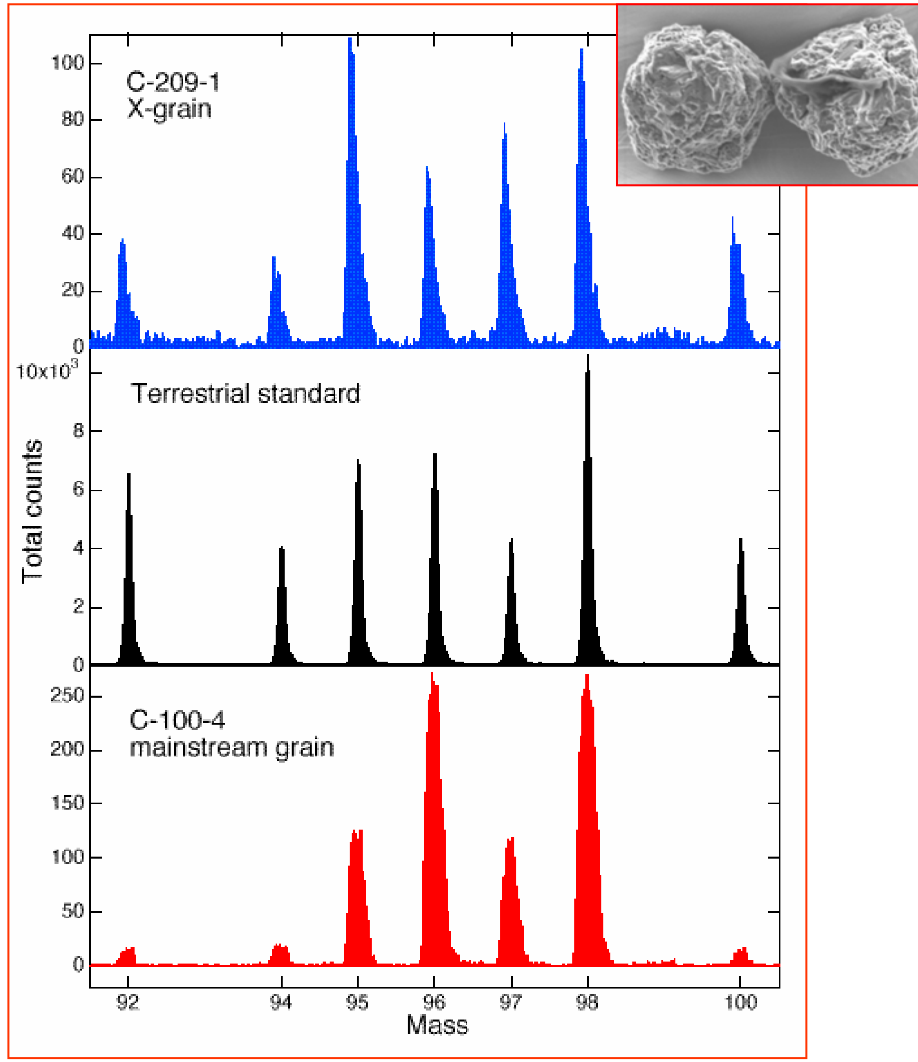


Branch point at ^{95}Zr ($t_{1/2}$ = 64 days) controls ^{97}Mo/^{96}Mo ratio

Slide Courtesy of Mike Pellin (ANL)

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.
- $[Mo]_{X\text{-grain}} \ll [Mo]_{Mainstream}$
- ^{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.



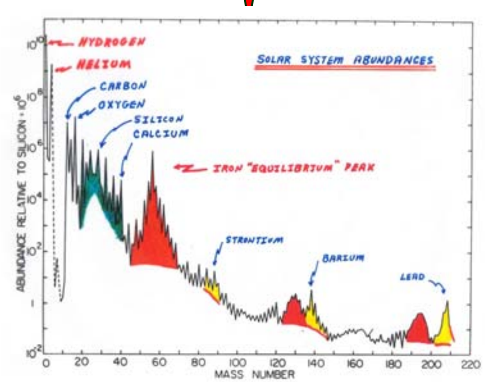
Slide Courtesy of Mike Pellin (ANL)

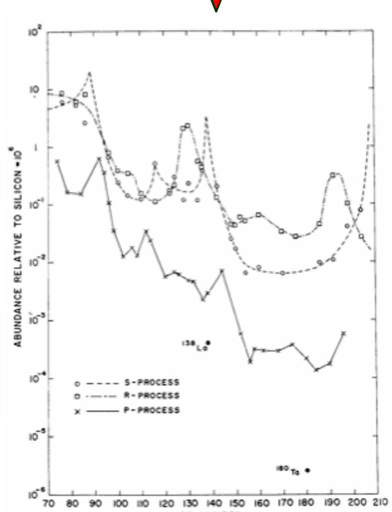
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

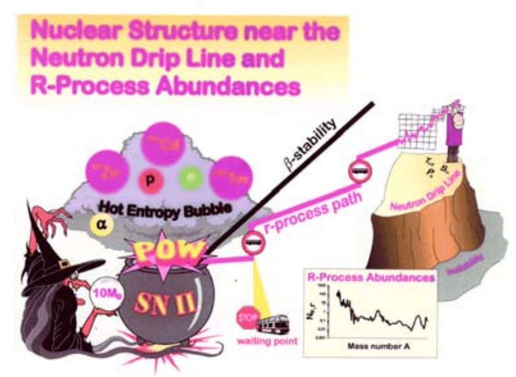
MRC-2: Supernova Nucleosynthesis

Supernova Nucleosynthesis

- **Oxygen to Iron Elements**
- **P-Process**
- **R-Process**
- **ν - Process**

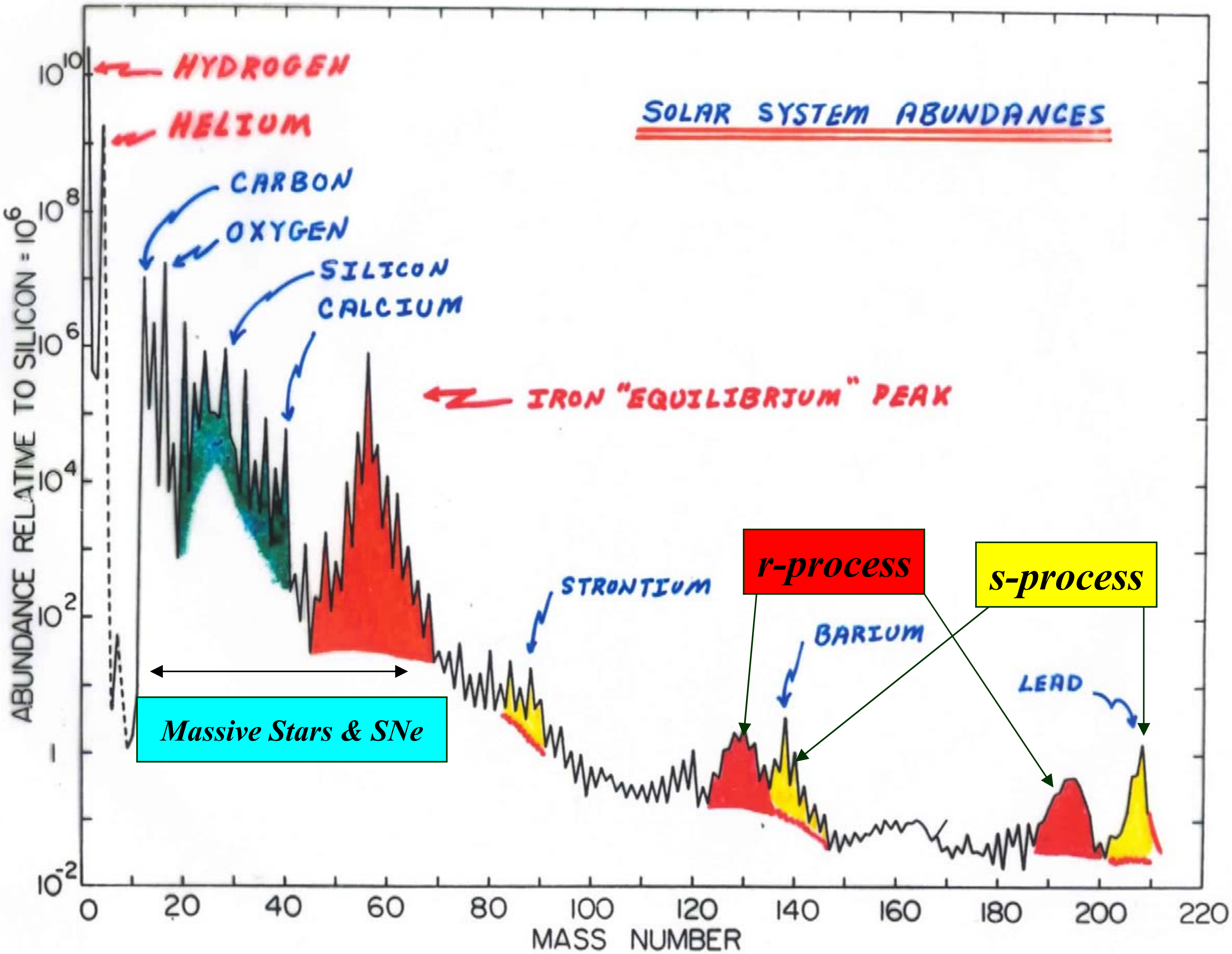






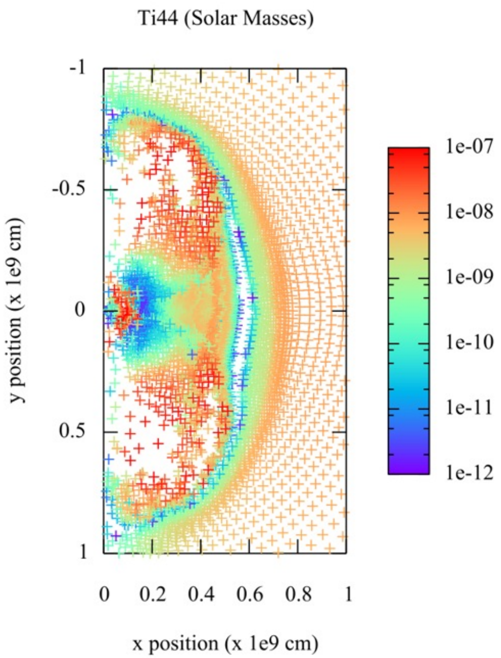
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

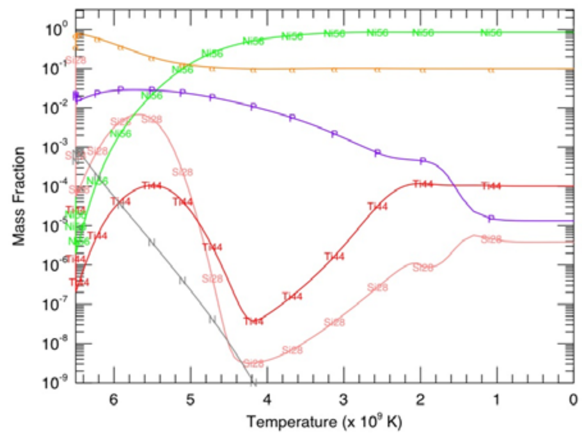
"Cosmic" Abundances of the Elements

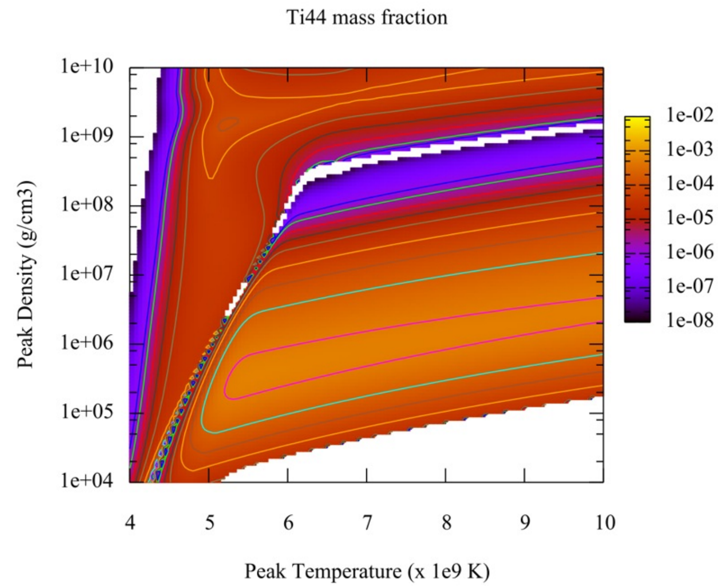


New Examination of ^{44}Ti and ^{56}Ni from Core-collapse Supernovae

Hungerford, Fryer, & Timmes 2007







A. Hungerford, C. Fryer, and F. Timmes (LANL) have recently investigated the production of radioactive ^{44}Ti and ^{56}Ni from core-collapse supernovae models. Radioactive ^{44}Ti, an observable diagnostic of core-collapse supernovae, is an isotope of extraordinary astrophysical significance. Its primary observable effects are:

(1) The relatively large abundance of ^{44}Ca is overwhelmingly due to its synthesis as ^{44}Ti parent.

(2) Gamma rays from radioactive decay from young core collapse supernovae are visible in several Galactic remnants. The ^{44}Ti yield probes the dynamics of core collapse supernova nucleosynthesis, and in particular, the location of the proverbial "mass cut", the pre-supernova composition inside ~ 2 $M_{\odot}$, and the maximum temperature and density reached during the passage of the shock wave in the ejecta. The ^{44}Ti detection in Cas A has generated great enthusiasm.

(3) ^{44}Ca-enriched silicon-carbide particles extracted from meteorites have been identified as pre-solar particles that condensed within supernova ejecta during their first few years of expansion, while ^{44}Ti was still at its initial value. These grains may be of enormous value in probing the dynamics and make up of supernova ejecta.

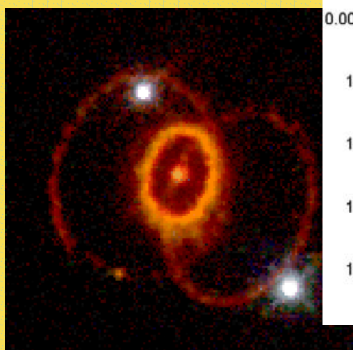
The presence of explosion asymmetries in supernovae alters both the extent of the hydrodynamically mixed regions and the conditions for burning within the supernova shock. This serves to change both the distribution and abundance of the ejected elements. In these preliminary efforts, the trends in burning processes for a range of physical conditions which exist in core-collapse supernova simulations are examined with a detail parameterized nuclear reaction network.

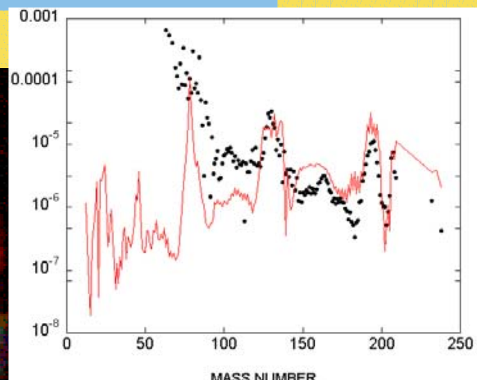
Astrophysical site for the 'main' r-process

Dominant Candidate

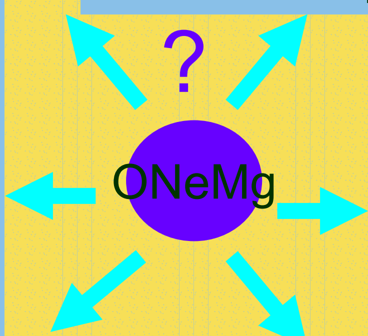
Neutrino-driven wind in Type II supernovae

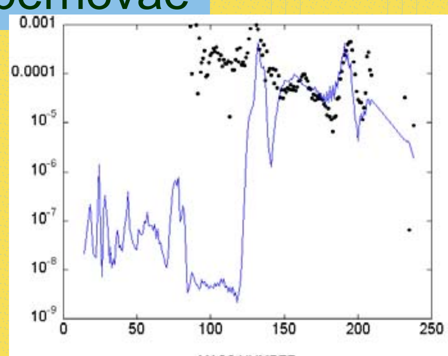
SN1987A





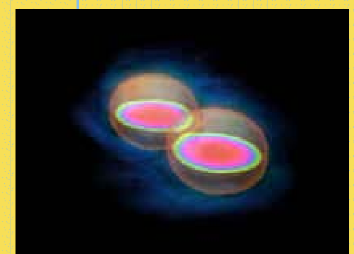
Prompt explosion of low mass supernovae

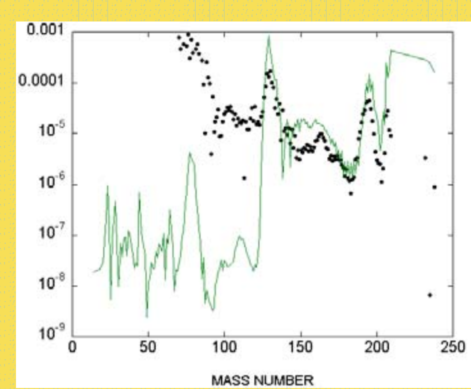




Neutron star mergers

Simulation of NS mergers (from Hayden planetarium)





New Candidate?

Quark Novae (Jaikumar et al. 2006)

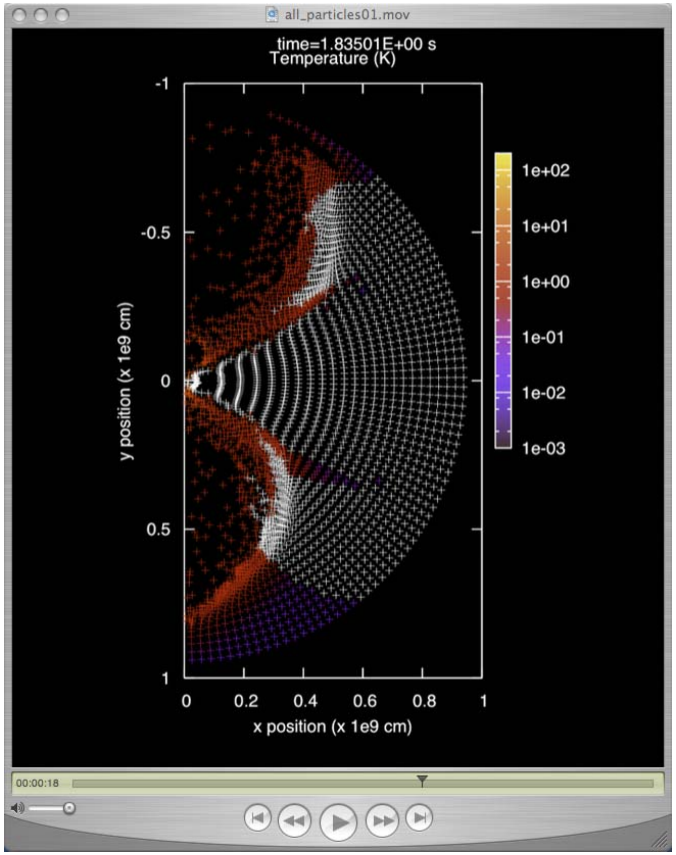
nuclear –quark phase transition at the center of cold neutron star caused nova-like explosion.

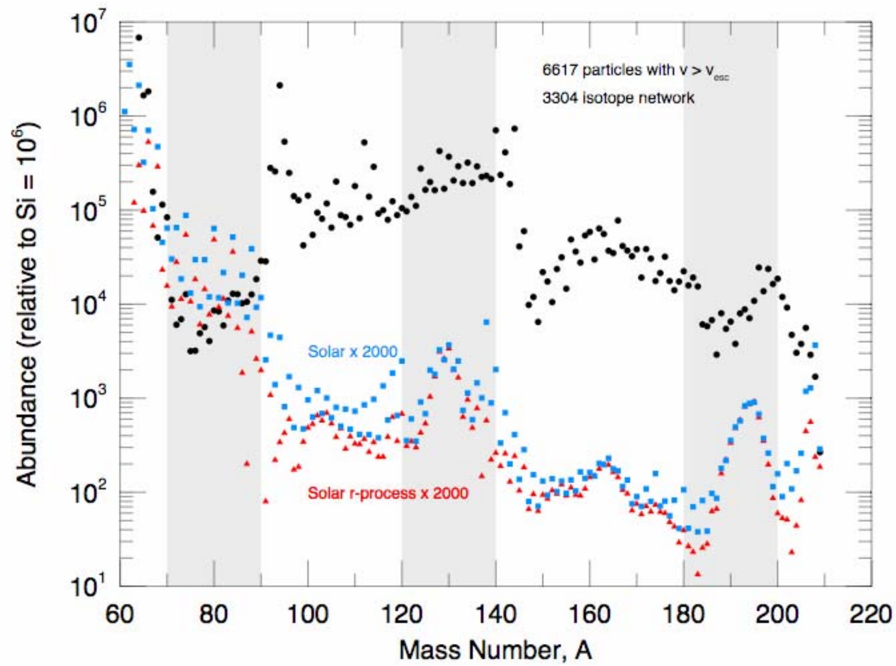
✓Conditions similar to Neutron star mergers
✓Highest neutron-to-seed ratio

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

New Models for the r-process Mechanism and Site of Origin

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.





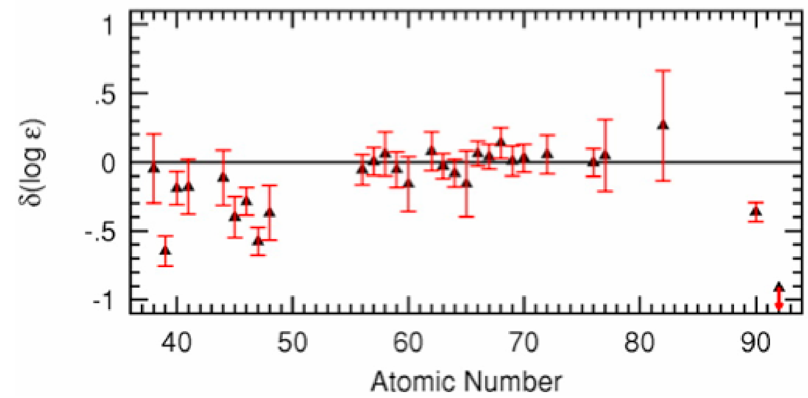
C. Fryer (LANL), A. Hungerford (LANL), F. Herwig (Keele) and F. Timmes (LANL) have recently investigated a pathbreaking model for the rapid neutron capture process involving the mass ejected by fallback in a supernova explosion. The nucleosynthetic products of this ejected material produces r-process elements, including those in the vicinity of the elusive 3rd peak at mass number 195. Trans-iron element production beyond the second peak is made possible by a rapid (< 1 ms) non-equilibrium freeze-out of alpha particles which leaves behind a large nucleon (including protons!) to r-process seed ratio. This rapid phase is followed by a relatively long (> 15 ms) simmering phase at approximately 2 billion K, which is the thermodynamic consequence of the hydrodynamic trajectory of the turbulent flows in the fallback outburst. During the slow phase high mass elements beyond the second peak are first made through rapid capture of both protons and neutrons. The flow stays close to the valley of beta stability during this phase. After freeze-out of protons the remaining neutrons cause a shift out to short-lived isotopes as is typical for the r-process. A low electron fraction isn't required in this model, however, the detailed final distribution is sensitive to the electron fraction. Theser simulations suggest that supernova fallback is a viable alternative scenario for the r-process.

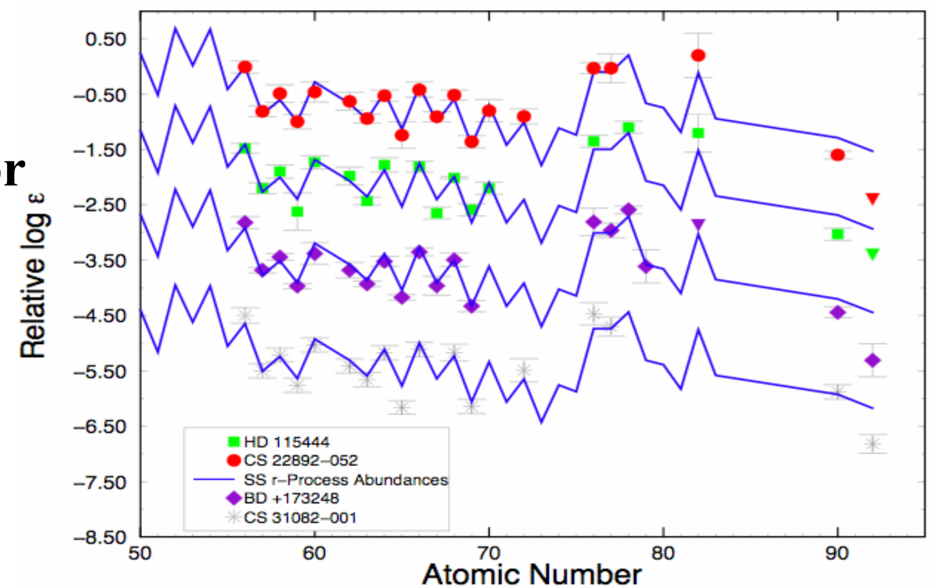
Fryer, Hungerford, Herwig, & Timmes (2006)

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Fission and R-process Synthesis

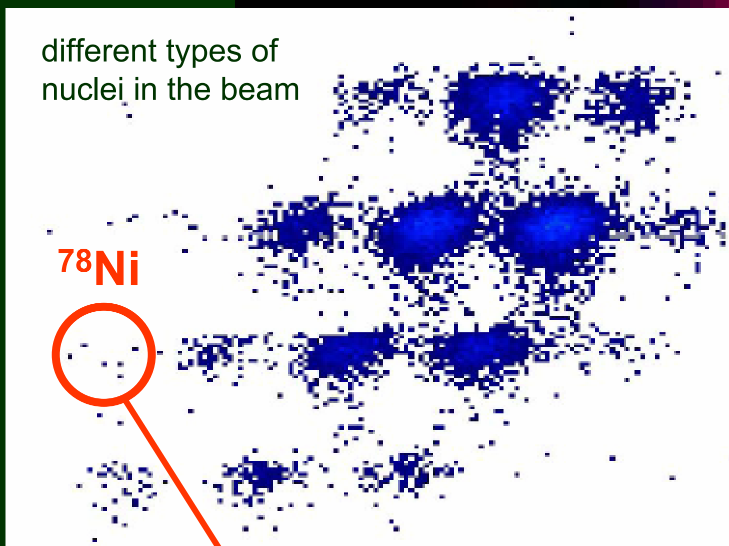
- Main component of r-processs exhibits distinct robustness
- Fission cycling suggested to explain robustness
- Fission can significantly effect production ratios of actinide chronometers
- Good fission model should allow for asymmetric fission
- Neutron and ν induced, β delayed, spontaneous compete
- Interactions of yields with ν field after freezeout possibly important



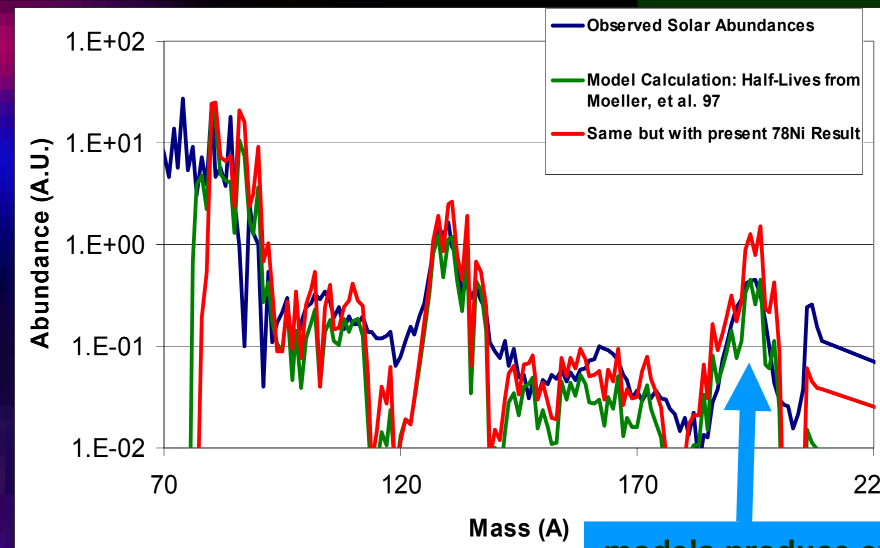


Doubly magic nucleus accelerates synthesis of heavy elements

Particle identification in rare isotope beam from NSCL at Michigan State University



Model calculation for synthesis of heavy elements during the r-process in supernova explosions



models produce excess of heavy elements with new shorter 78Ni half-life

Measured half-life of ^{78}Ni with 11 events
This is the most neutron rich of the 10 possible classical doubly-magic nuclei in nature.

→ the synthesis of heavy elements in the r-process proceeds faster than previously assumed

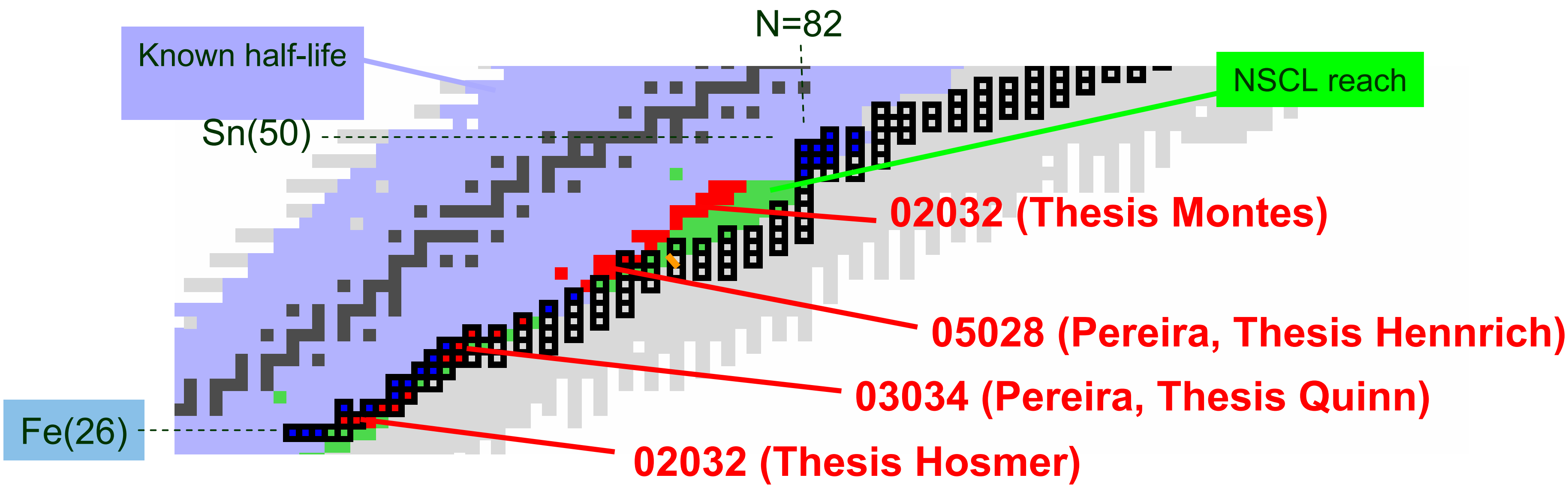
→ a step towards the answer of the open question of the origin of the heavy elements in the cosmos

Result: 110 $^{+100}_{-60}$ ms

P. Hosmer et al. accepted in PRL

JINA-NSCL r-process experimental campaign

JINA collaboration: MSU – Mainz – Notre Dame



Reach critical r-process region on broad front:

→ This is where more than one r-process could contribute
→ Testbed for shell effects (probably fast freezeout – sensitivity !)
→ Site specific signatures: α-rich freezeout contribution, ν-effects, …)

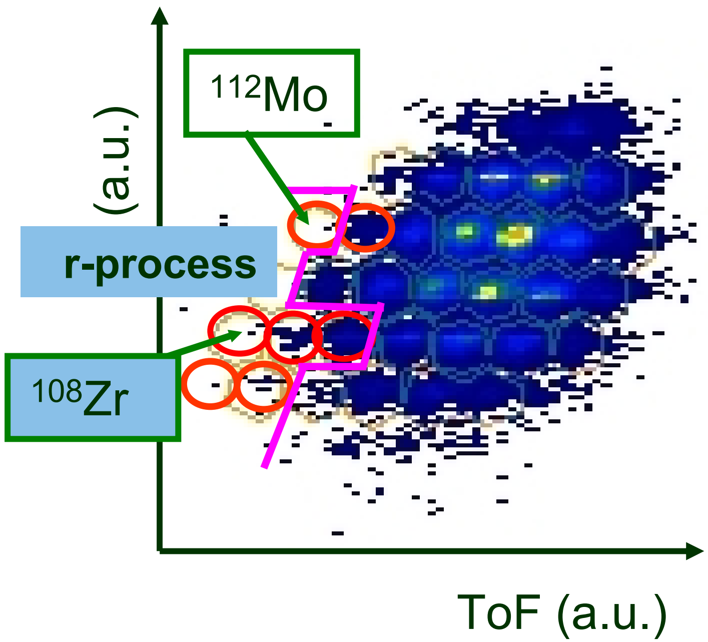
Reliable modeling of (short) stretch of r-process is within reach

Example: recent r-process experiment around A=110

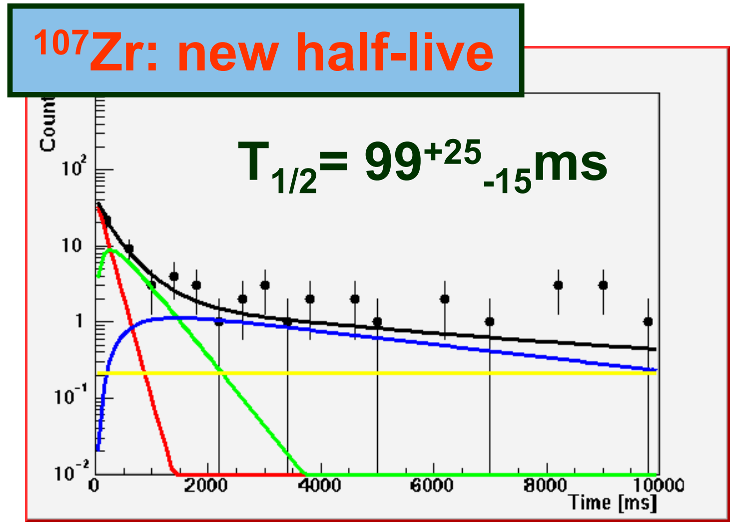
J. Pereira, JINA postdoc

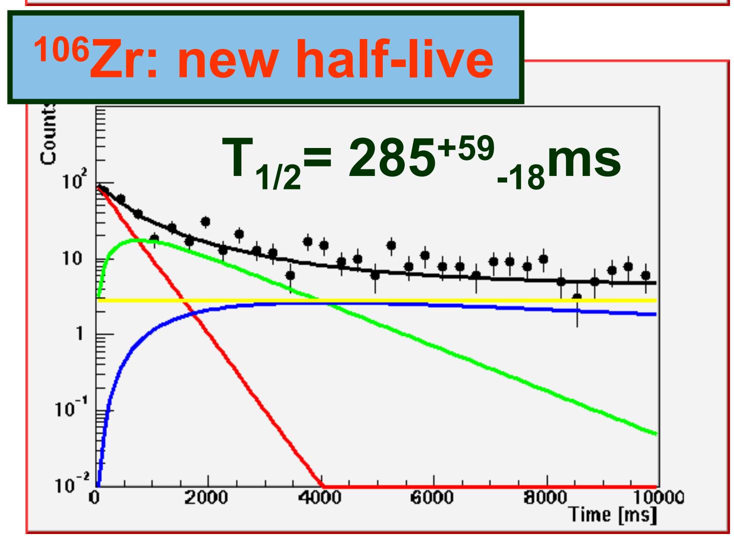
Particle Identification in mixed beam
→ Can measure all simultaneously

○ New half-life



Measure half-life and neutron emission probability





JINA r-process collaboration meeting Jan 17, 07

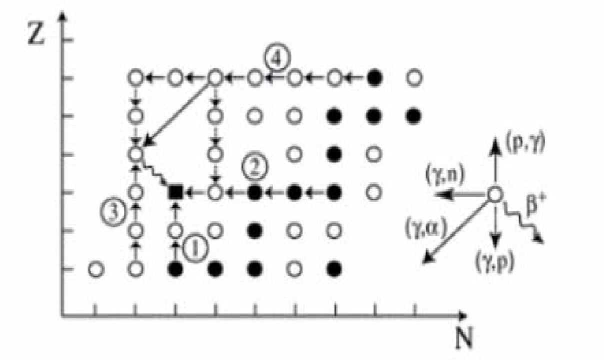
15 participants from Arizona, Chicago, LANL, MSU, Notre Dame, Ohio

Identified new collaborative projects
and new ways to connect observations, experiment, theory

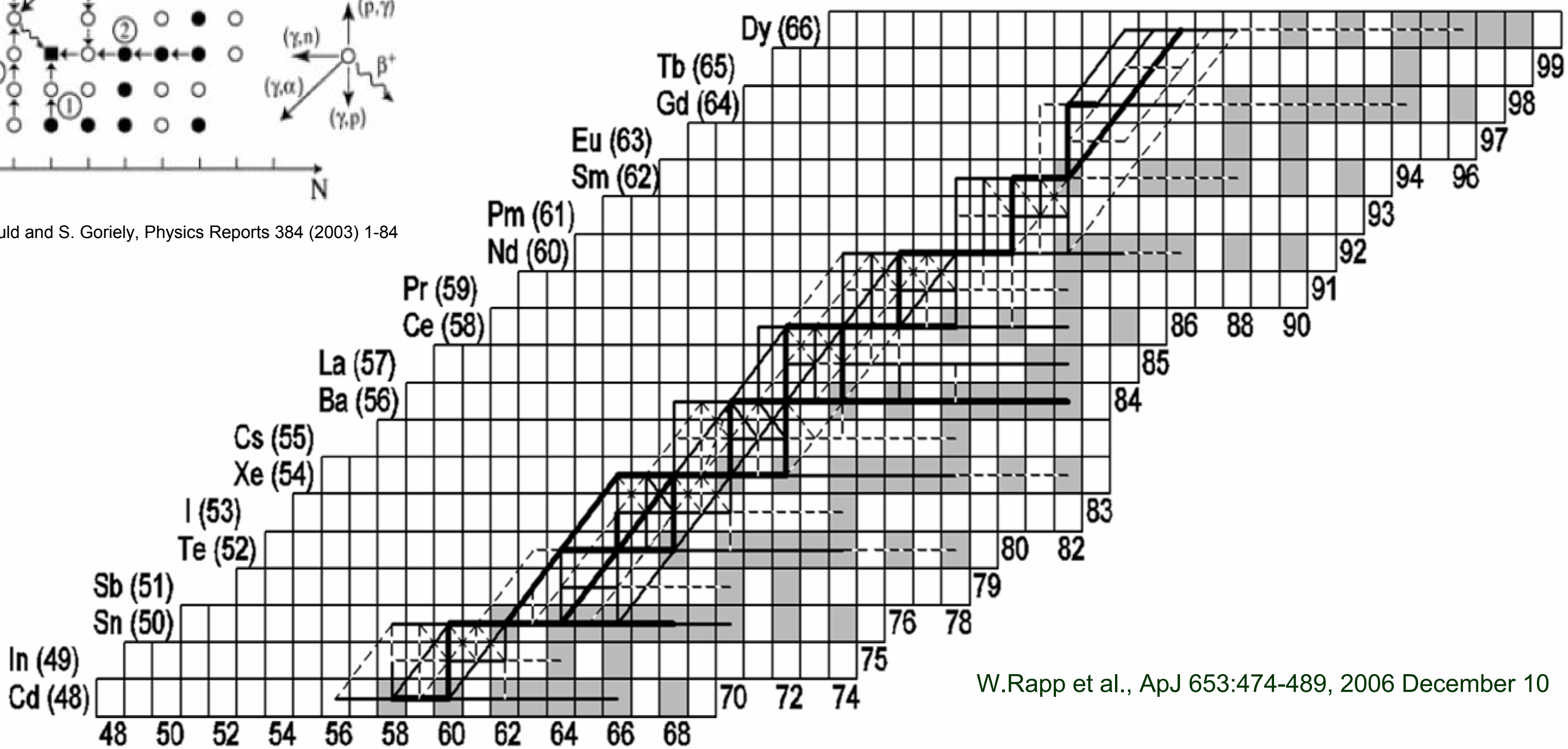
Examples of results:

- **Create new r-process nuclear data library and new public JINA network code**
- **Use existing codes at LANL and Chicago to postprocess Arizona supernova trajectories**
- **Tim Beers will have available ~8 new stellar abundance patterns**
  → use MSU, LANL, Chicago codes to investigate robustness of r-process
- **Use r-process codes with new experimental data to disentangle LEPP/r-process isotopic compositions from observed elemental abundances**
- **Continue these meetings frequently**
- **Create collaboration website to exchange ideas and data more efficiently**

p-Process Nucleosynthesis



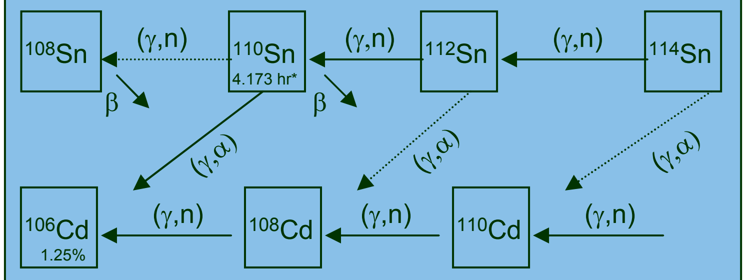
M. Arnould and S. Goriely, Physics Reports 384 (2003) 1-84



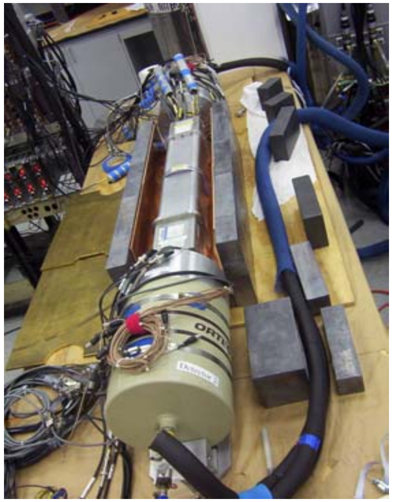
W.Rapp et al., ApJ 653:474-489, 2006 December 10

Activation technique: $^{106}Cd(\alpha,\gamma)^{110}Sn$ and $^{112}Sn(\alpha,\gamma)^{116}Te$

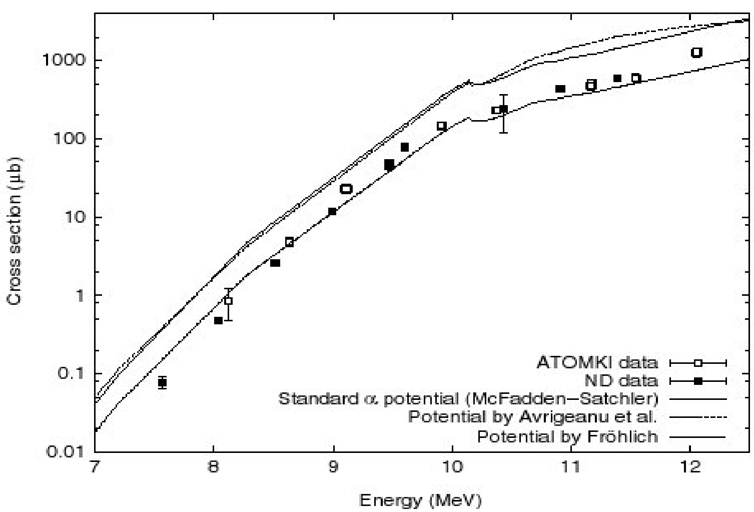
Notre Dame Van de Graaff tandem accelerator



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.

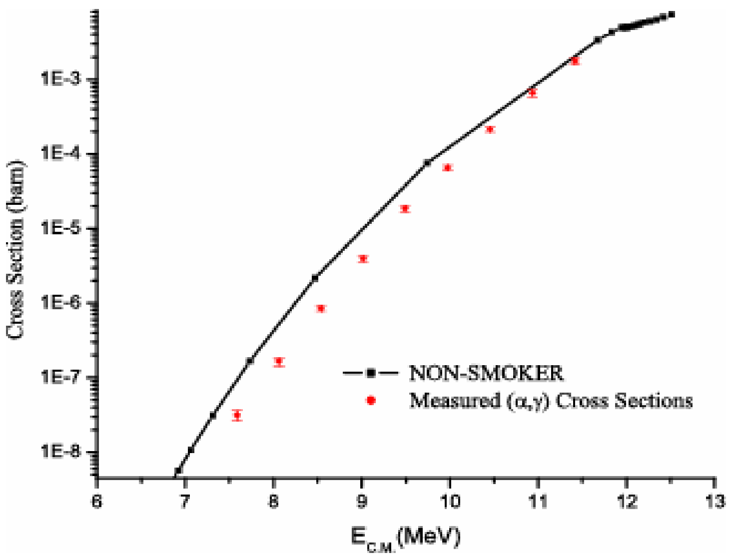


Two ND clovers in close geometry



Gy. Gyürky et al., Phys. Rev. C 74, 025805 (2006)

Experimental cross sections of the $^{106}Cd(\alpha,\gamma)^{110}Sn$ and $^{112}Sn(\alpha,\gamma)^{116}Te$ reactions compared to theoretical predictions



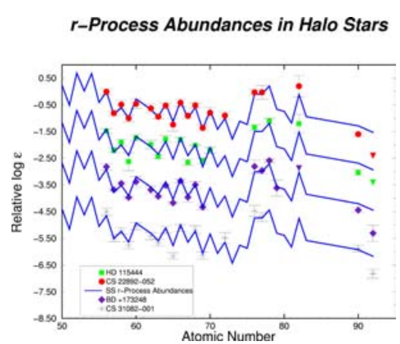
N. Özkan et al., Phys. Rev. C 75, 025801 (2007)

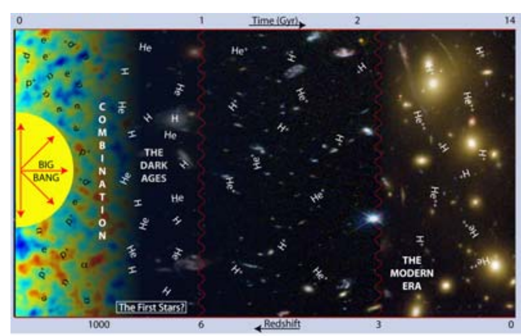
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

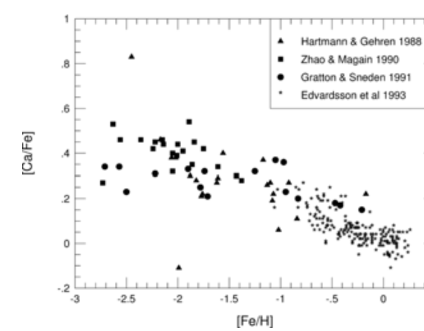
MRC-2: Chemical Evolution

Chemical Evolution

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

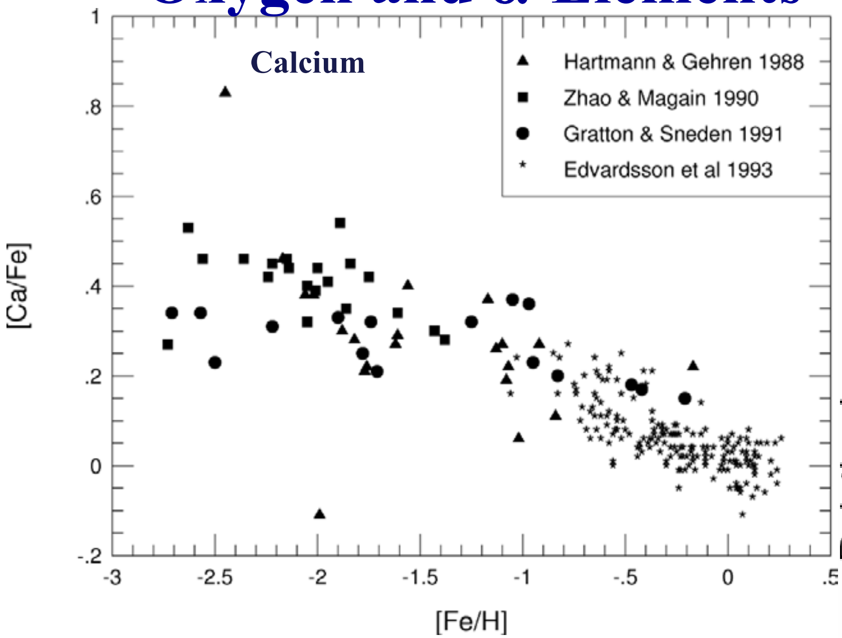


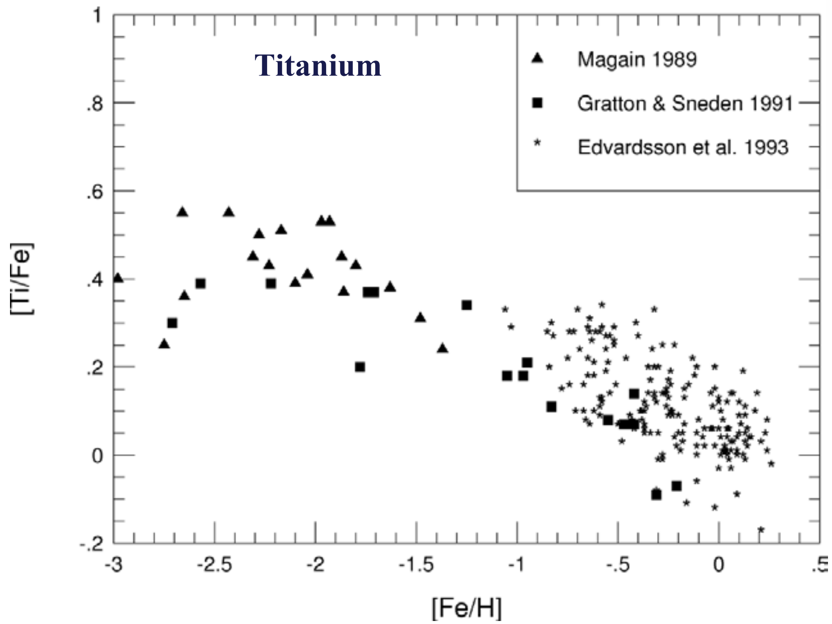




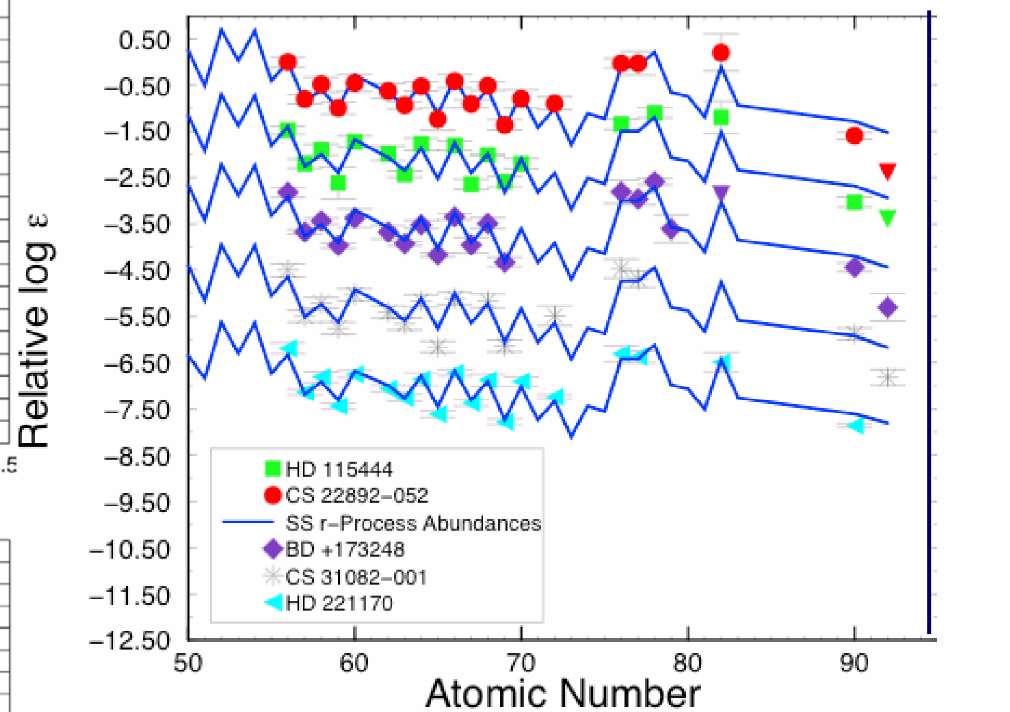
Halo Abundance Trends for -3 ≤ [Fe/H] ≤ -1

Oxygen and α-Elements





R-Process Elements



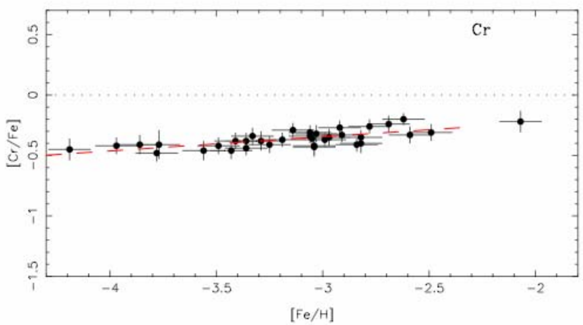
(Truran et al. 2002)

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

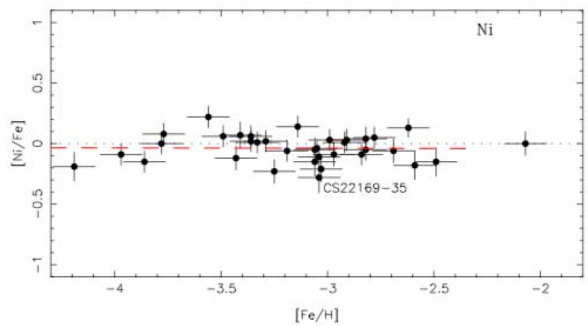
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Explosive Nucleosynthesis Processes

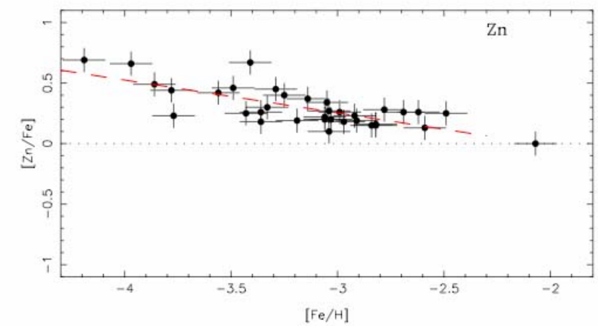
[Cr/Fe]



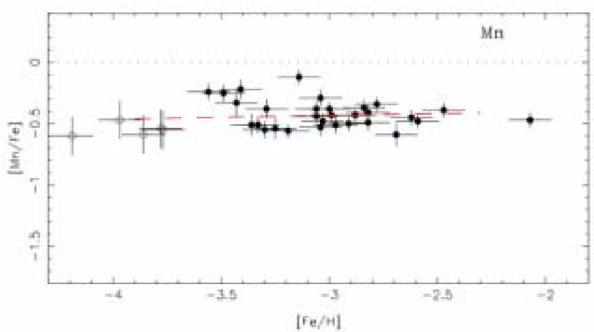
[Ni/Fe]



[Zn/Fe]

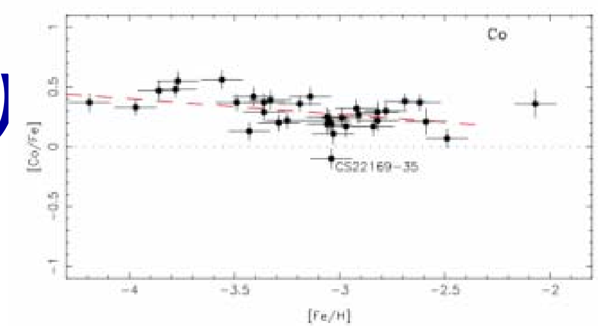


[Mn/Fe]



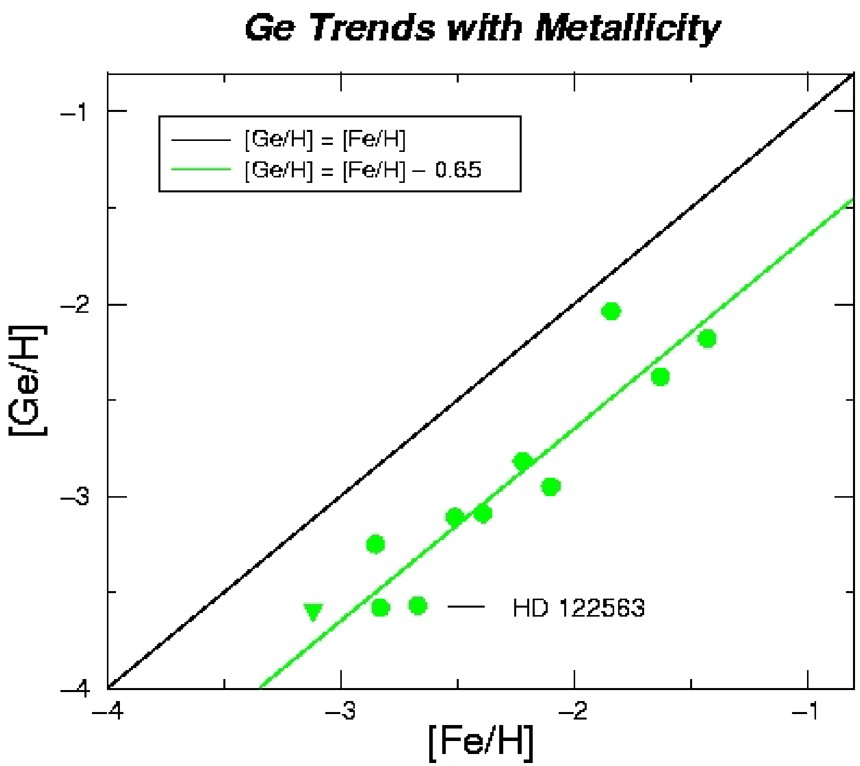
Cayrel et al. (2004)

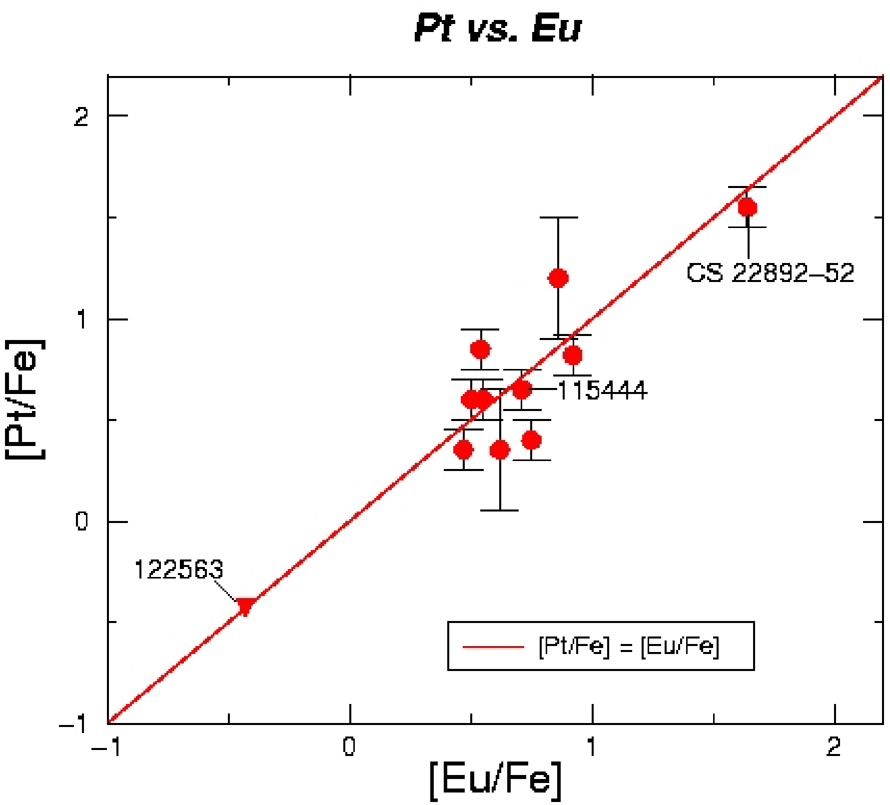
[Co/Fe]



Metallicity Trends in Ge and Pt

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

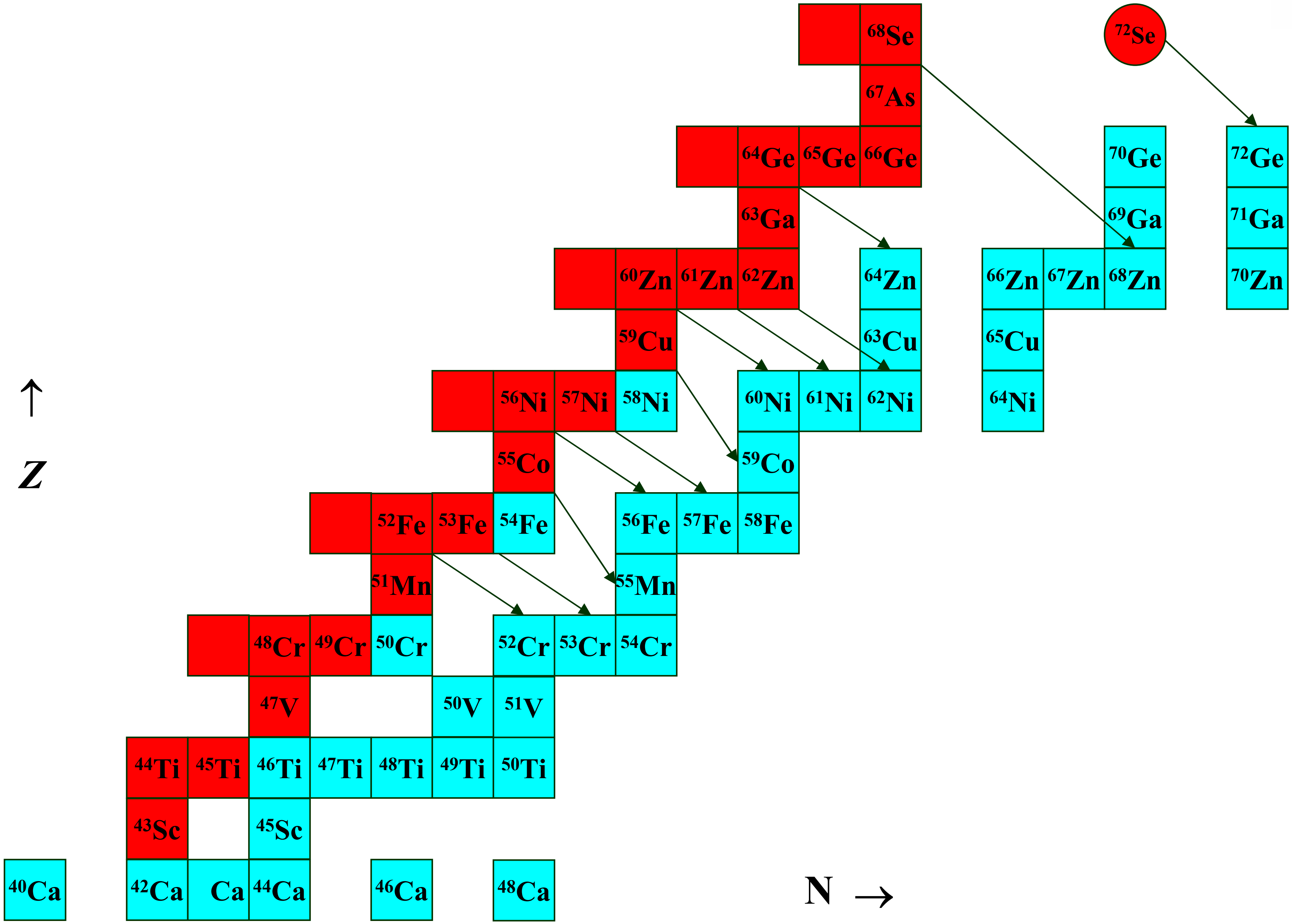




Truran et al. (2002); Cowan et al. (2005)

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Explosive Nucleosynthesis of Fe-Peak Nuclei



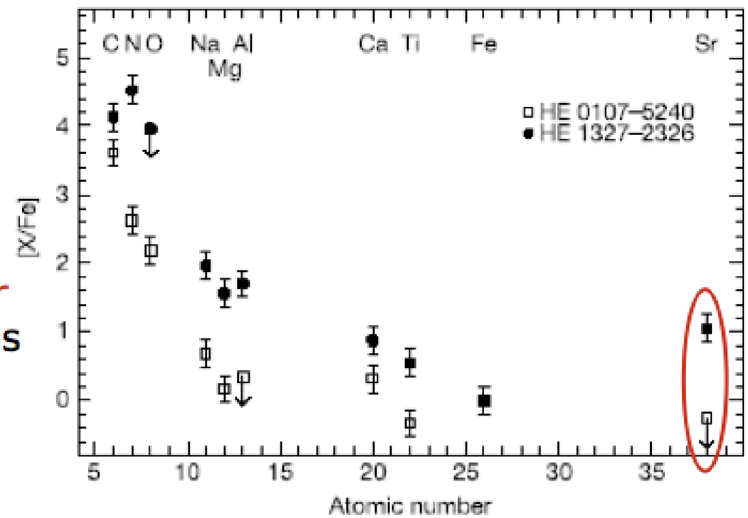
Abundance Pattern in HE 1327-2326

[Fe/H]=-5.4 ± 0.2   (HE 1327-2326)

Surprisingly Sr/Fe ratio enhanced by factor of ~10

Unexpectedly high Sr abundance challenges existing theoretical models

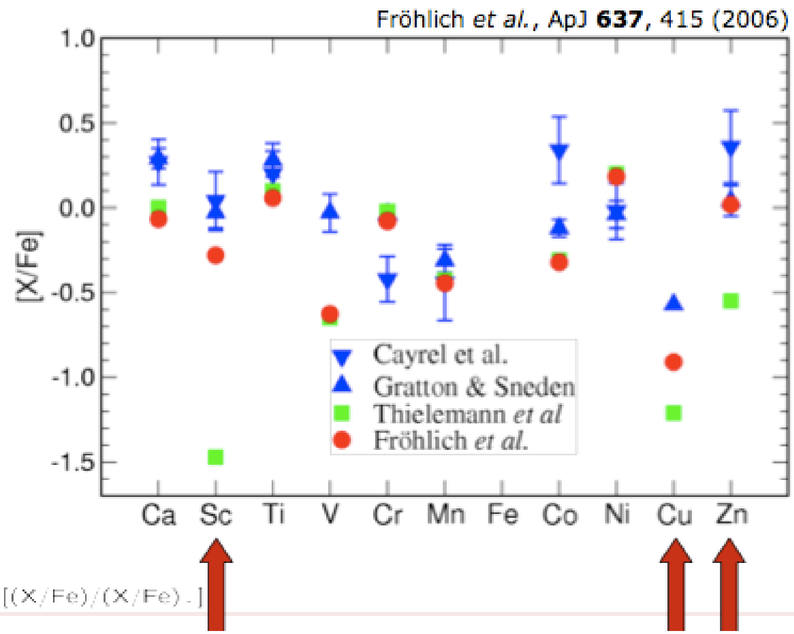
Frebel *et al.*, Nature **434**, 871 (2005)



$$[X/Fe] = \log_{10}[(X/Fe)/(X/Fe)_{\odot}]$$

Predictions of νp-Process

- Metal-poor stars (-4.1 < [Fe/H] < -0.2)



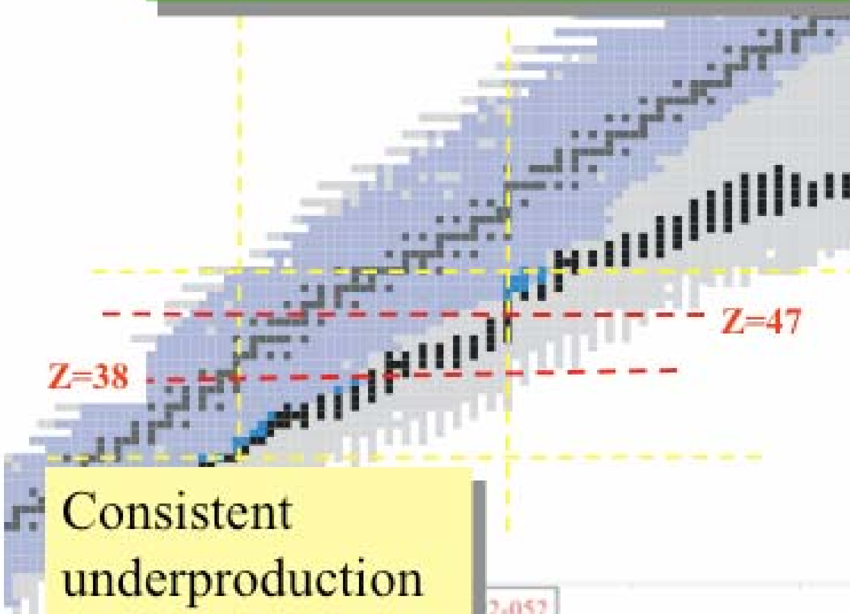
$[X/Fe] = \log_{10}[(X/Fe)/(X/Fe)_\odot]$

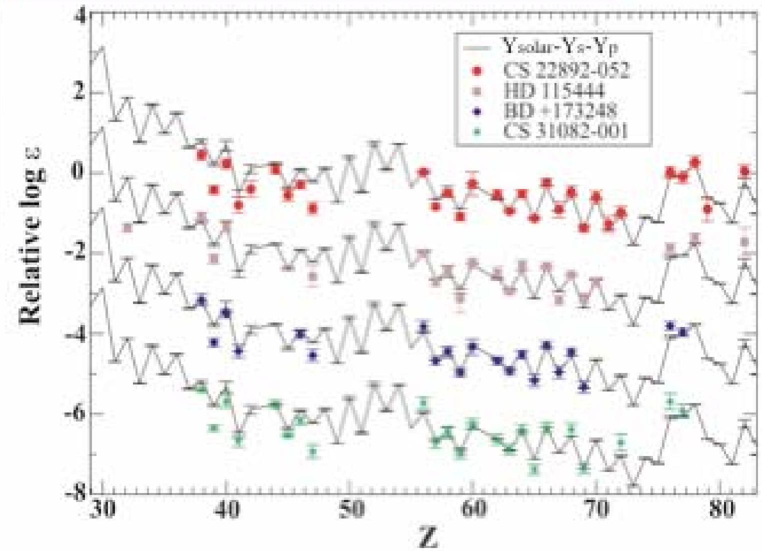
νp-Process

Summary νp-process

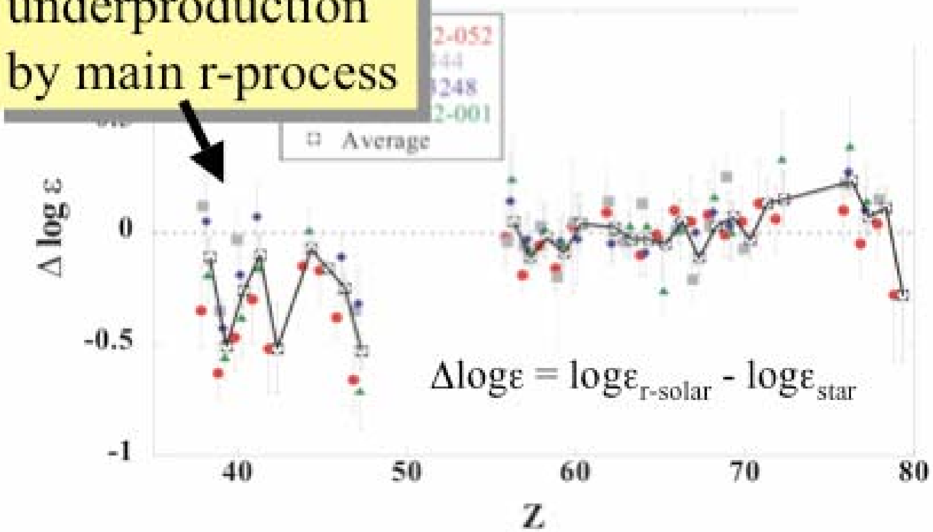
- proton-rich matter is ejected under the influence of neutrino interactions
- Antineutrinos help bridging long waiting points via (n,p) reactions
- Primary process, associated with explosive scenarios
- Contributes to nucleosynthesis of light p-nuclei
- Possible explanation of Sr and other elements beyond Fe in early stage of galactic evolution
- Possible candidate for LEPP

A late weak r-process ?





Consistent underproduction by main r-process



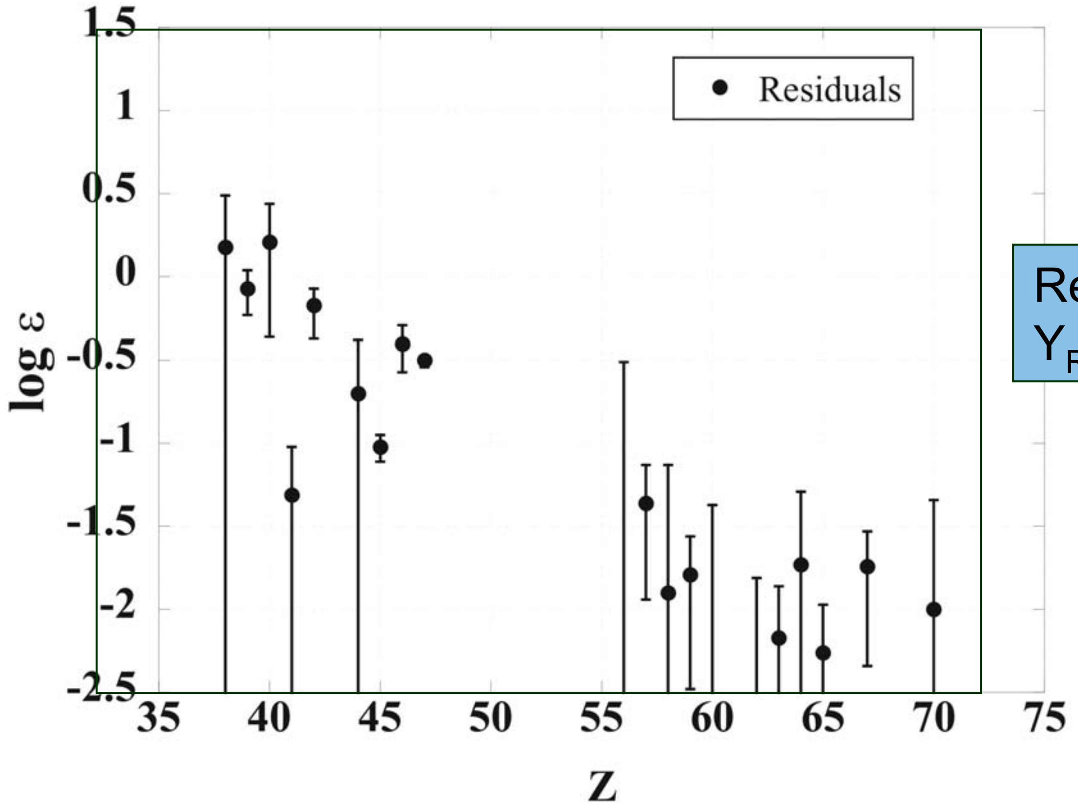
Metal poor stars ~ old stars

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

R-process rich

Courtesy Hendrik Schatz (MSU)

Conditions needed to produce residual ?



Residuals

$Y_{RES}=Y_{solar}-Y_s-Y_p-Y_{star}$

Astrophysical conditions:

T temperature ?

n_n neutron density ?

τ neutron flux duration ?

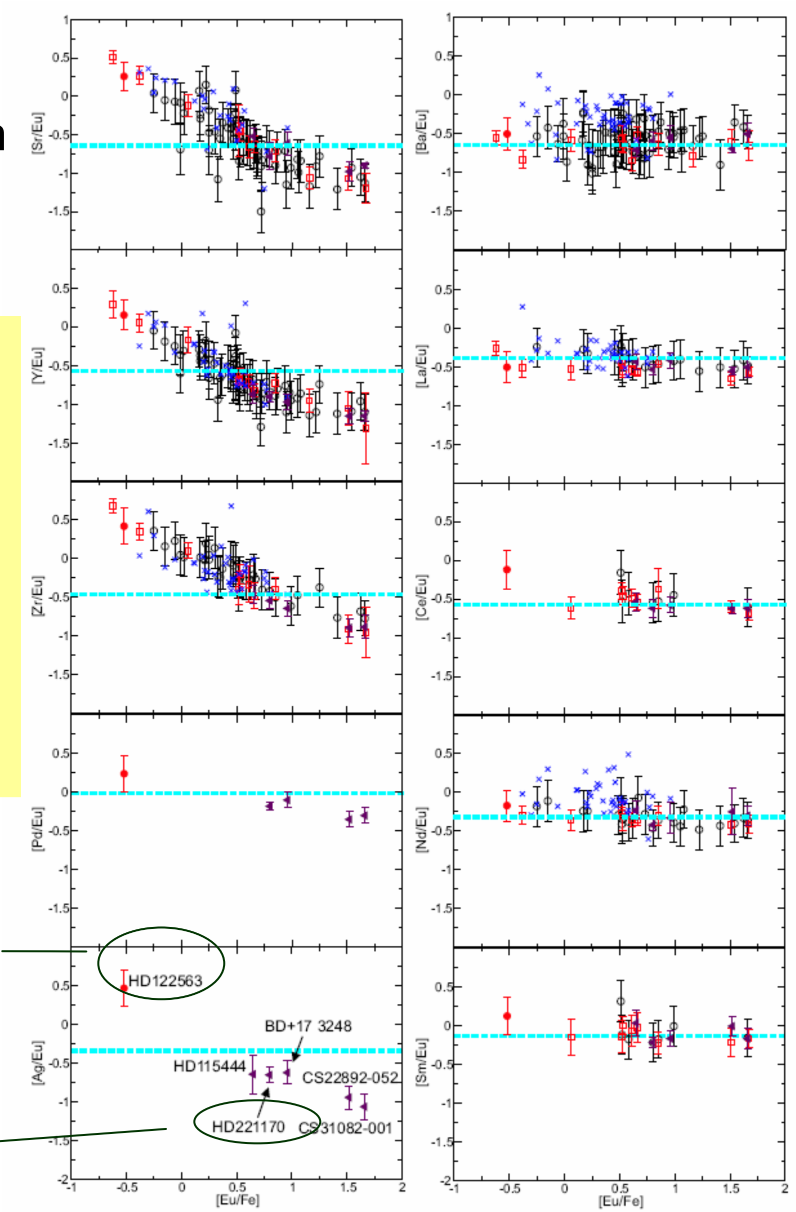
Courtesy Hendrik Schatz (MSU)

New nucleosynthesis process identified

F. Montes et al.

Light r-process elements as a function of Eu enrichment

→ Varying ratio to Eu
→ for high enrichment below solar (well known under-production)
→ need new process that is mixed in in various proportions



Honda et al. 2006

Ivans et al. 2006

Heavy r-process elements as a function of Eu enrichment

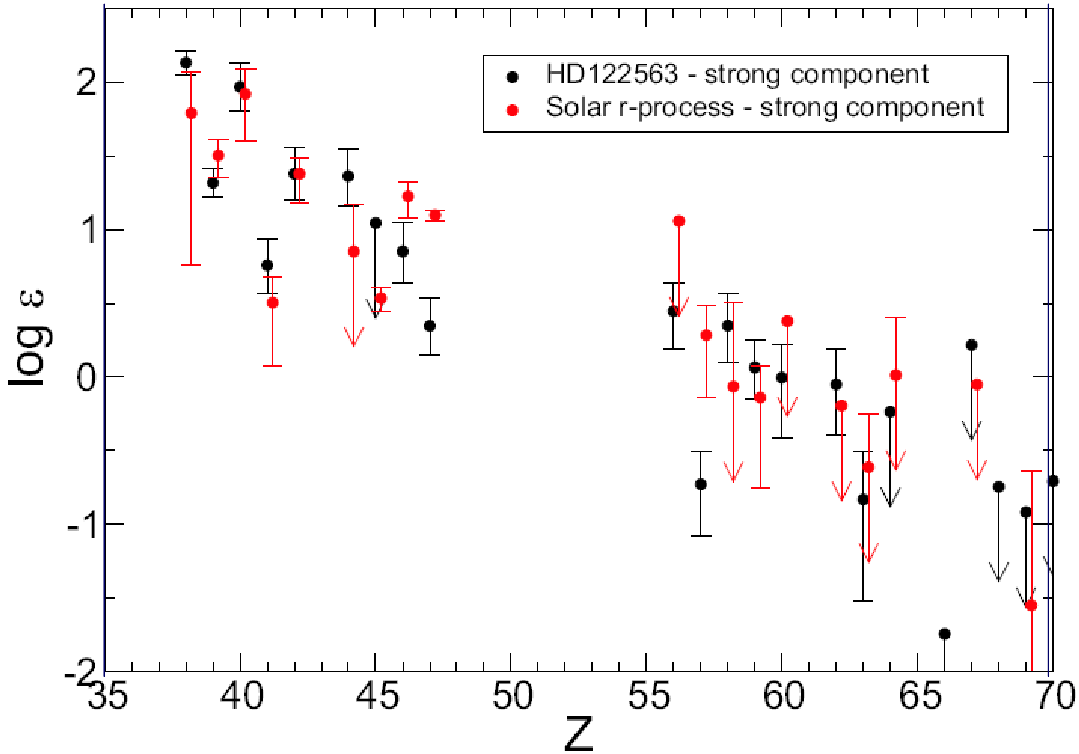
→ Consistent pattern
→ agrees with solar

→ Clear evidence for LEPP

New nucleosynthesis process identified

F. Montes et al.

The new LEPP abundance pattern – can now search for a site



2 independent ways to extract pattern from observations

Conclusions:

→ LEPP produces consistent abundance pattern

→ identified LEPP abundance pattern

→ first model calculations indicate $n_n < 10^{14}$

(so new process is more s-process than weak r-process)

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

The Standard Model for SNe Ia

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

- **Progenitor: White dwarf in a binary system**
- **Growth to the Chandrasekhar limit by mass transfer**