Nuclear Equation of State Constraints From r-Process Abundance Ratios

Can We Learn Something About the Nuclear EOS From r-Process Abundances?

M.A. Famiano [1], T. Kajino [2,3], W. Aoki [2], T. Suda [3], R. N. Boyd [2], I.U. Roederer [4], B. Meyer [5], Y. Motizuki [6]

[1]Western Michigan University, [2]National Astronomical Observatory of Japan, [3]University of Tokyo, [4]University of Michigan, [5]Clemson University, [6]RIKEN

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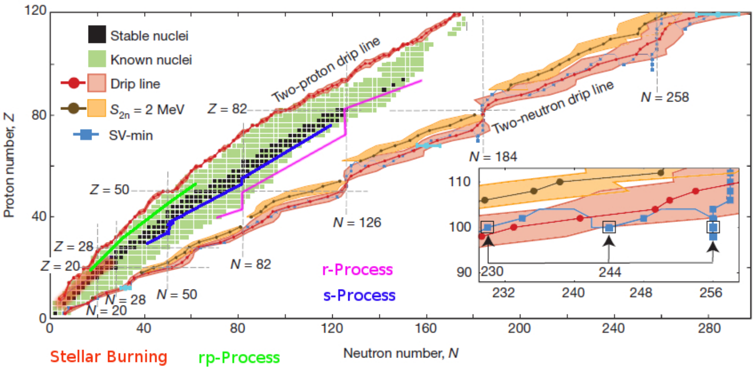
Outline

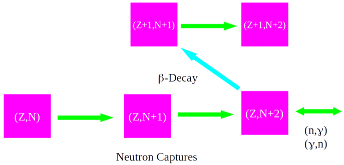
The r-Process

Nuclear Physics



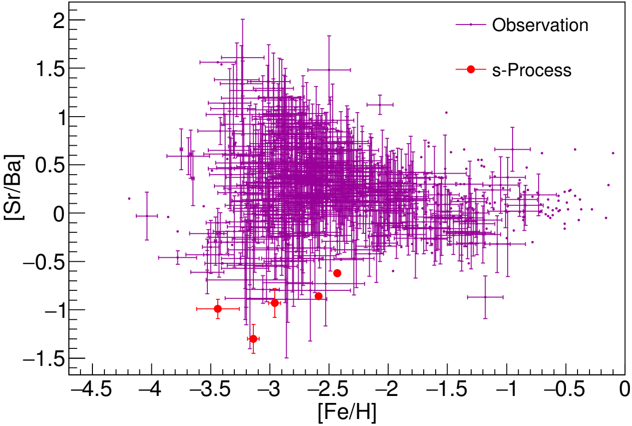
r-Process responsible for >50% of all elements heavier than iron and nearly all actinides.

r-Process site: Neutrino-driven winds? NS mergers? MHD jets?



Metal-Poor and Extremely Metal-Poor Stars

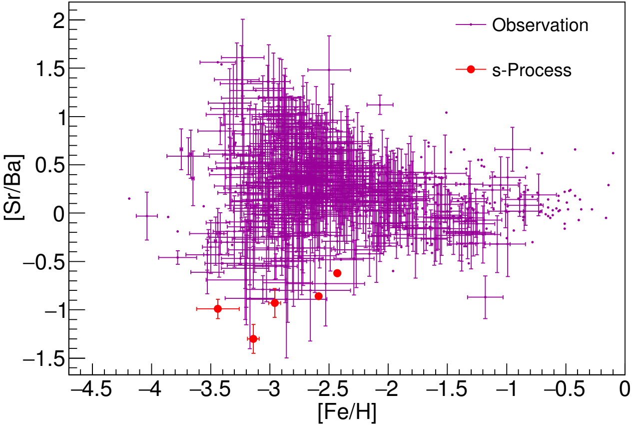
Scatter in r-Process Elemental Abundances



SAGA Database (Suda et al.) EMP Stars. Sr-Ba in the same observation.

Metal-Poor and Extremely Metal-Poor Stars

Scatter in r-Process Elemental Abundances

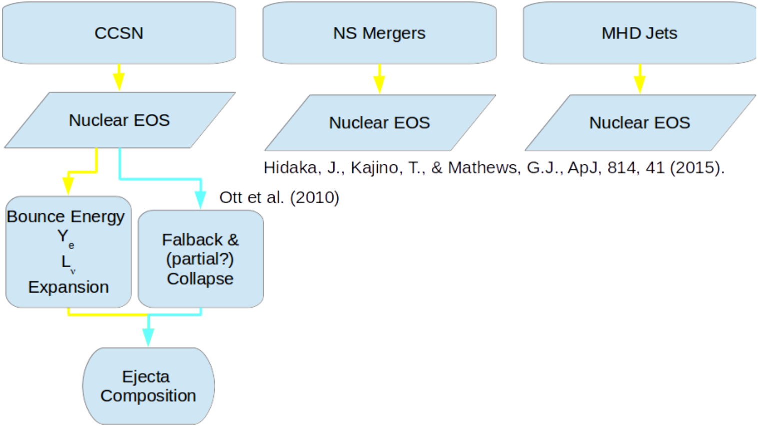


What is the sensitivity of isotopic ratios to the EOS?

Can we use isotopic ratios to constrain the nuclear EOS?

Nuclear EOS and the r-Process

How does the Nuclear EOS Affect the r-Process?

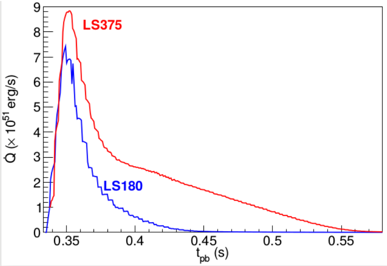


Couch (2013), Hempel et al. (2012), Lattimer et al. (2000)

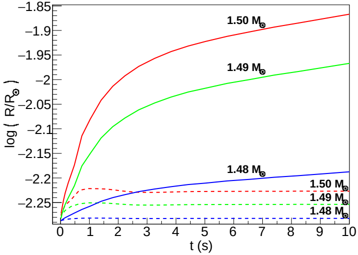
EOS Effects in Post-Bounce Evolution

Computations of Stellar Bounce

- 1D Core Bounce
- EOS coupled to deleptonization
- Heating in gain region
- Cherubini Talk



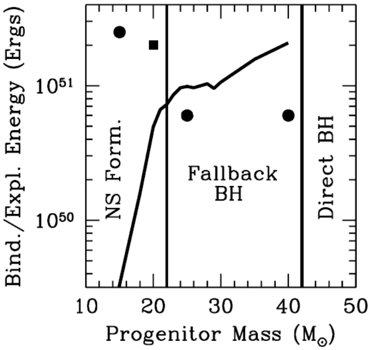
Post-bounce heating coupled to 1D explosion code



PRELIMINARY FIGURES

Fallback & Accretion-Induced Collapse in CCSNe

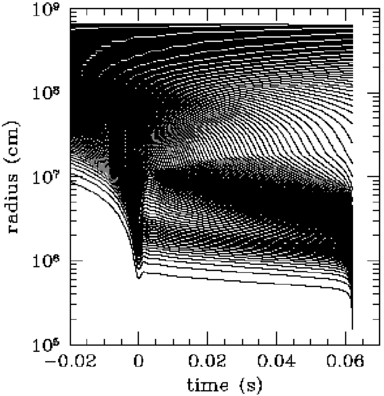
Prior Work and Background



Fryer et al. (1999)

Fallback BH forms for intermediate mass SNII

Collapse time and radius depends on progenitor mass

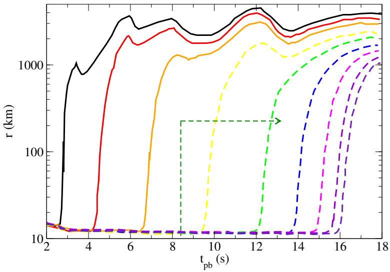


Nakazato et al. (2007)

For fallback, mass shells with escape velocity may undergo r-processing.

(Turatto et al.(1998))

GCE Model of the tr-Process

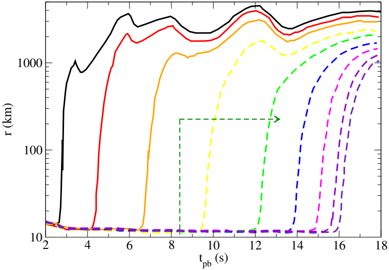


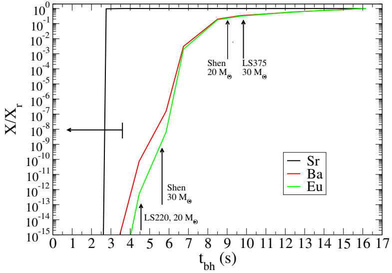
Assume enrichment hindered by fallback.
High S, slow explosion model (Woosley, 1994).
Fallback in CCSN (to a BH?). (Fryer, 1999, 2014).
EOS-dependent collapse in 1D GR code.
Concentrating on GCE and not hydrodynamics.

Possible GCE Cases:

- Prompt collapse→No ejecta→no r-processing (BH?)
- Fallback/Delayed collapse→partial ejecta→some r-processing→GRB Jets?
- Late collapse→post r-processing collapse (fallback below/after hot bubble?)

GCE Model of the tr-Process





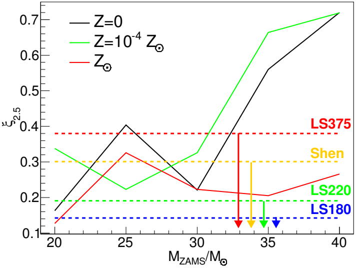
$$\frac{X\left(t_{pb}, M_*\right)}{X_\circ\left(M_*\right)} = \frac{X\left(t_{pb}, 20M_\odot\right)}{X_\circ\left(20M_\odot\right)}$$

- Yields for progenitor mass and metallicity based on Cescutti et al. (2006) and Ishimaru et al. (2004)
- Assume ejecta **normalized** yield as a function of post-bounce time independent of progenitor
- Assume a primary r-process source
- Multi-zone GCE (Timmes (1995))

Collapse Time in the tr-Process

How Do We Determine the Cutoff Time?

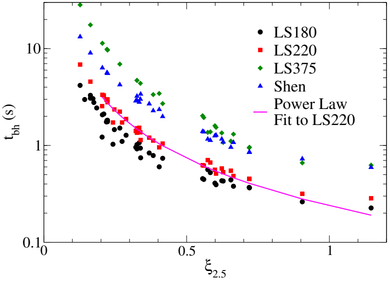
Progenitor mass is related to bounce compactness.



Horizontal lines indicate compactness below which collapse time is greater than 3.5 s.

Collapse time is related to bounce compactness.

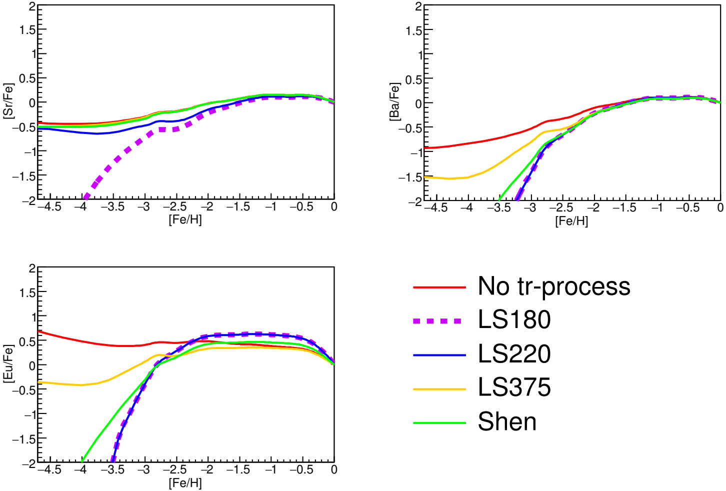
$$\xi_{M/M_\odot} = \frac{M/M_\odot}{R(M)/1000km}$$



Oconnor & Ott (2011)

EOS Comparisons

Variations in GCE Results With EOS

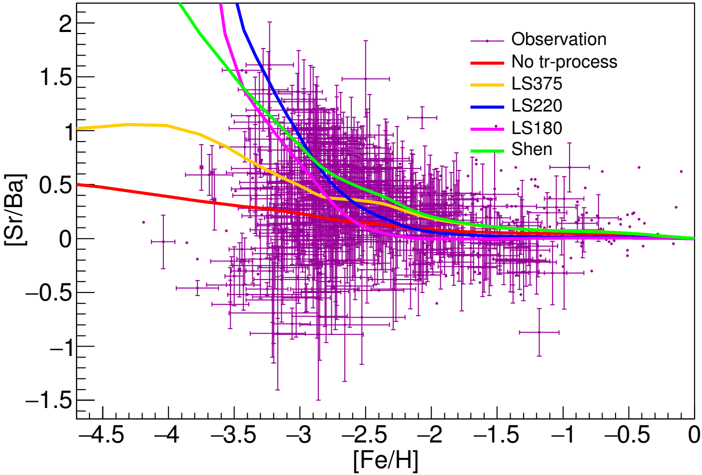


Famiano, Kajino, Aoki, Suda (2016).

Lightest nuclei → Ejected earlier → Only affected by the softest EOS.

[Sr/Ba] Dependence on EOS

Comparison to Data



Famiano, Kajino, Aoki, Suda (2016).

[Sr/Eu] Dependence on EOS

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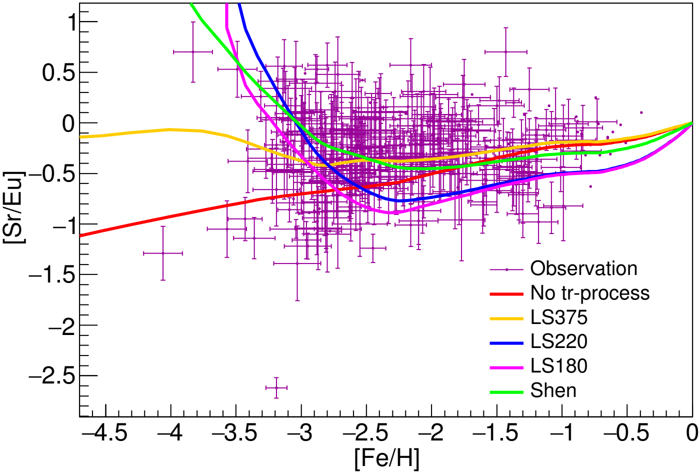


Famiano, Kajino, Aoki, Suda (2016).

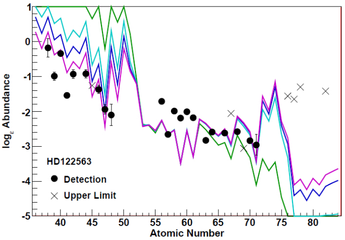
Conclusions

- Can we constrain the softness of the nuclear EOS using astronomical observations of EMP stars?
  - Neutron star masses provide a minimum stiffness.
  - Isotopic ratios are sensitive to the EOS and constrain the softness.
- The scatter in heavy element yields can be explained with a turbulent mixing and ejection model.
  - **Extreme** values determined by EOS.
  - **Scatter** determined by mixing, rotation, etc.
  - Larger collapse times will reduce the extreme values: e.g. rotation, neutrino effects, etc
- Future work:
  - Full explosion model: EOS-dependent composition
  - Hydrodynamics cases for fallback
  - Collapse not necessary in full explosion model
  - NS mergers

Work supported by NSF PHY-1204486 and PHY-1064280 and NAOJ Visiting Professorship

Nucleosynthesis in Fallback SNe

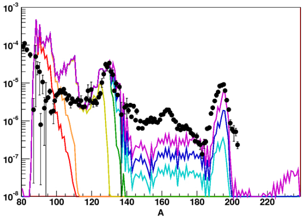
The tr-Process: Cutting Off the r-Process



Comparison To HD 122568 elemental Abundance distributions.

Production sensitive to collapse time and radius!

Boyd, Famiano, et al. (2012)



$$Y = \frac{1}{M_{ej}} \sum m_i Y_i$$

We should be a little careful, as the r-process progresses very rapidly through the rare earths. Where we cut it off at can be quite fine.

Nucleosynthesis in Fallback SNe

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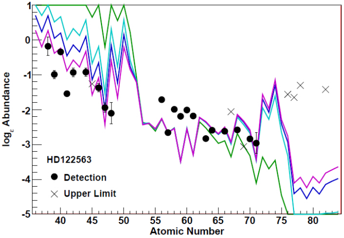

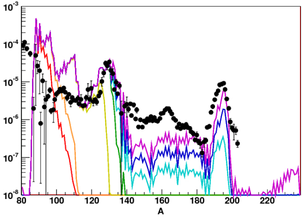

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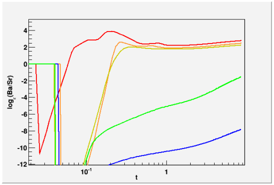
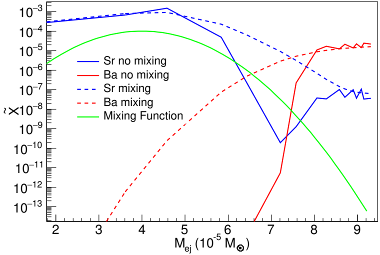


GCE Contributions From Mixing in SNII: Turbulent Mixing

In simple model, mixing not in supernova ejecta. Worth noting here. This mixing changes ejected yields.

←Outer shells: Inner Shells →



- Mixing between adjacent layers in SNII ejecta.
- Material near the core is moved closer to the surface.
- Material near the surface moved deeper into the star.
- Net effect is to smear out the yields of individual mass layers.

$$\tilde{X}(m) = \frac{1}{M_+ - M_-}\int_{M_-}^{M_+} X(m')\omega(m-m')dm'$$

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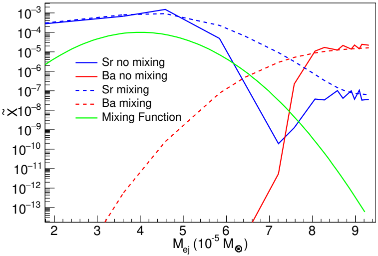

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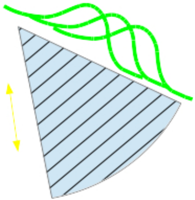
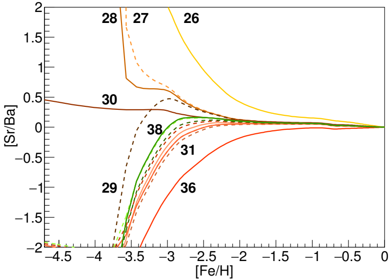


$$\tilde{X}(m) = \frac{1}{M_+ - M_-}\int_{M_-}^{M_+} X(m')\omega(m-m')dm'$$

GCE Contributions From Mixing in SNII: Turbulent Ejection

Here, we parametrize turbulence by assuming turnover in ejected shells by exchanging some mass between one shell and others.



- Mixing between all shells with a single shell.
- Preferential ejection of one particular shell over another.
- Used to simulate turnover in ejecta.
- GCE effect is to completely alter [Sr/Ba].
- Extreme turbulence case.

$$\tilde{X}(m) = \frac{1}{M_+ - M_-}\int_{M_-}^{M_+} X(m')\omega(m - m_\circ)dm'$$

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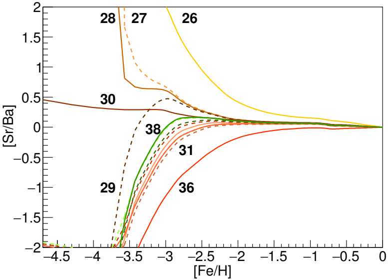

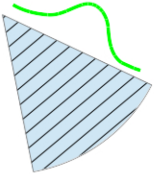

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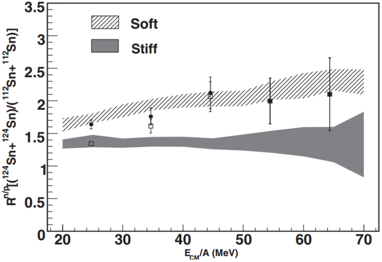
Experimental & Observational Constraints

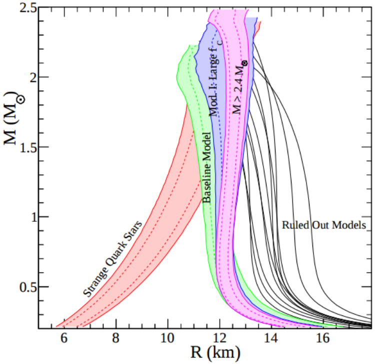
How do we constrain the nuclear EOS?

- Experimental Constraints
- Heavy Ion Collisions
- Isotopic and Meson Observables
- Goal: Higher Density



Famiano et al. (2006)

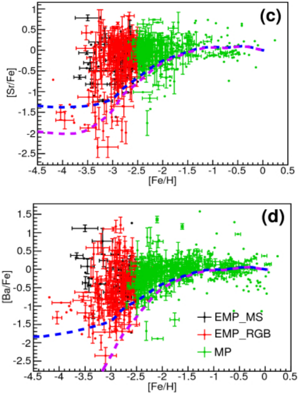
- NS Masses
- Mass-radius relationship
- Lower Limit



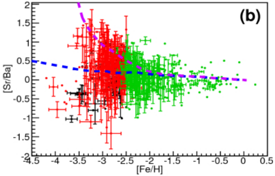
Steiner et al. (2012)

GCE Results

r-Process Abundance Distributions



- EMP stars only
- Primary r-process contribution
- Points from SAGA database
- Soft and stiffer EOS shown



Aoki et al. (2013), Suda et al. (2009)