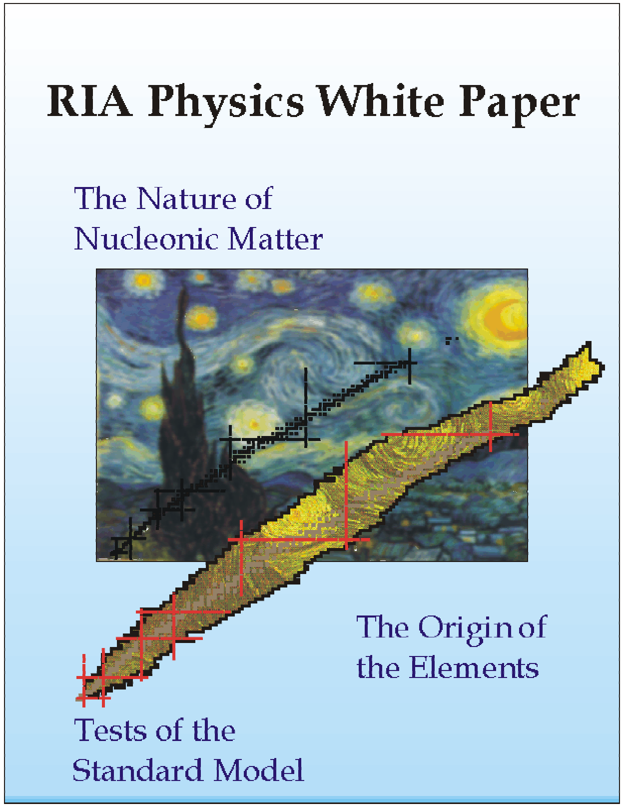
The Science of RIA (part II)

Brad Sherrill, Michigan State University

- The Origin of the Elements and Energy Generation in Stars
- Tests of the Standard Model and of Fundamental Conservation Laws
- Isotopes to Meet Societal Needs



http://www.orau.org/ria/

Connecting Quarks to the Cosmos

Eleven Science Questions for the New Century (2003) – National Academy Study, Chair M. Turner

—What is dark matter?

—What is the nature of the dark energy?

—How did the Universe begin?

—Did Einstein have the last word on gravity?

—What are the masses of the neutrinos and how have they shaped the evolution of the universe?

—How do cosmic accelerators work and what are they accelerating?

—Are protons unstable?

—Are there new states of matter at exceedingly high density and temperature?

—Are there additional space-time dimensions?

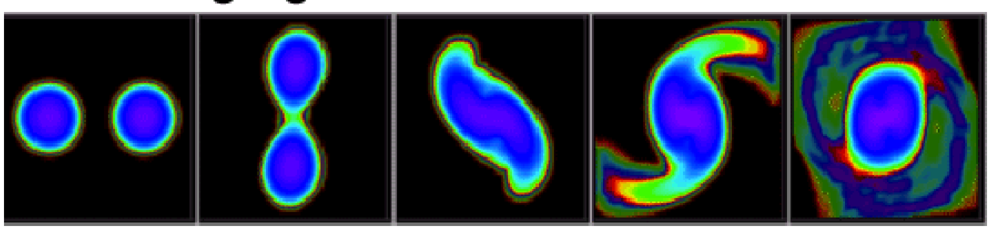
✓ How were the heavy elements from iron to uranium made?

—Is a new theory of matter and light needed at the highest energies?

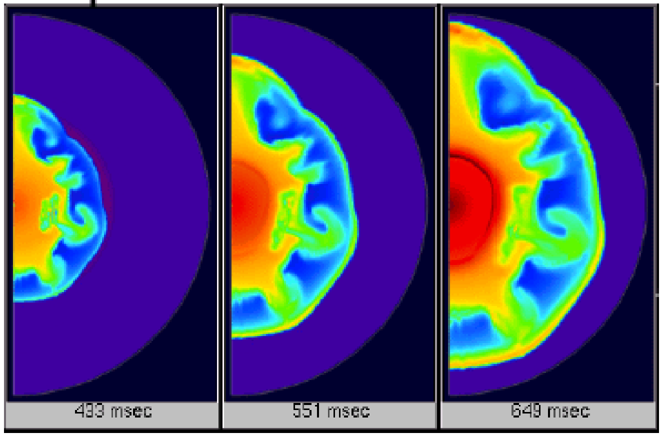
Rapid Neutron Capture Process (r-process)

How were the heavy elements from iron to uranium made? We can infer most are made in a very neutron rich environment and on a short time scale. This is called the rapid-neutron capture process or r-process. However, at the moment we do not know where that occurs. Two possibilities…

Merging Neutron Stars



Supernova shock



To answer this question we need:

Hydrodynamics – Computation – Astronomy – Radiation Transport – Nuclear Physics

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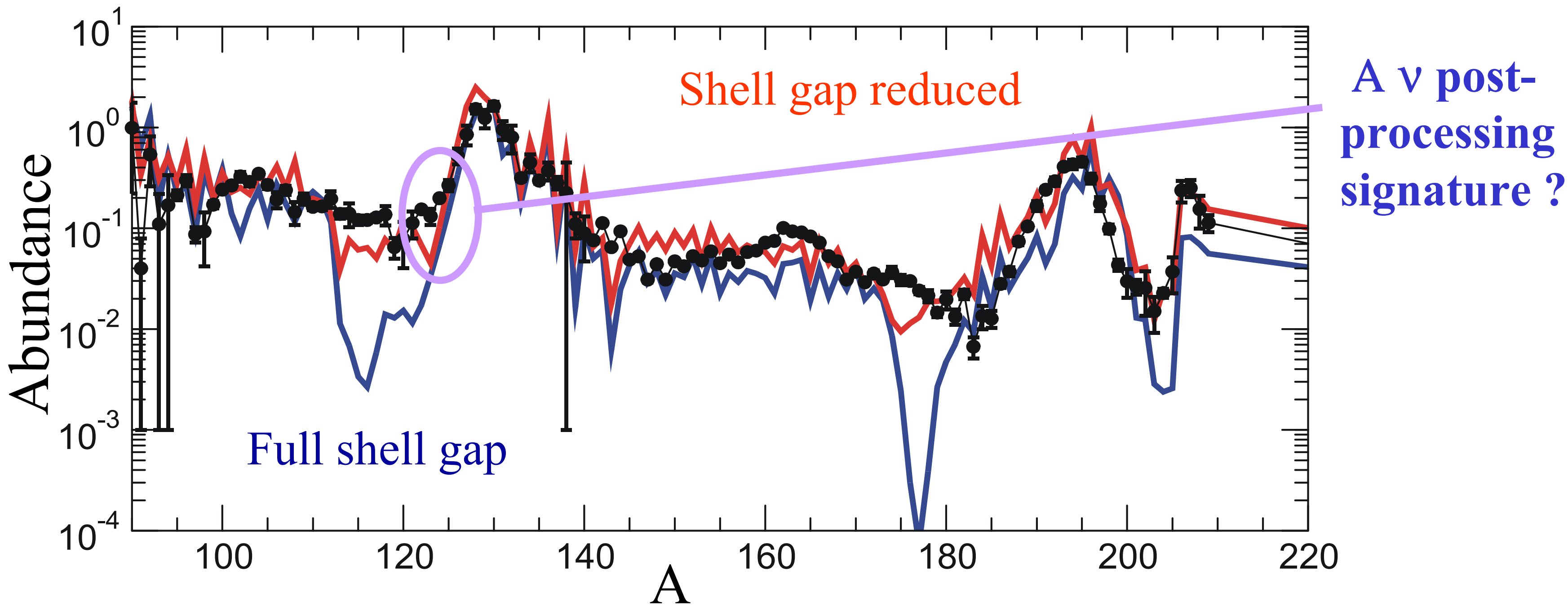
Importance of Nuclear Physics in the r-process

In r-process model calculations shell structure affects the results.

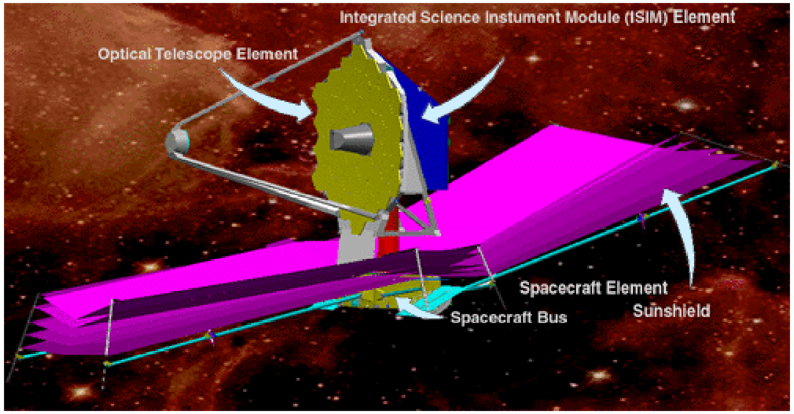


Need to determine experimentally the properties of nuclei that participate in the r-process.

- Are our astrophysical models wrong?
- What does the abundance distribution tell us about the site?

Astronomy and Astrophysics in the New Millennium

The most recent Astronomy Decadal Survey recommended more than $1,800,000,000 for space based telescopes.



• *NGST (Webb Space Telescope):* "… it will be possible to address a number of fundamental questions: …What is the history of star formation and element production in galaxies?"

• *CONSTELLATION- X:* "The premier instrument to: … contribute to nuclear physics by measuring the radii of neutron stars, and trace the formation of the chemical elements."

Recommendations from the Scientific Community

Astronomy Decadal Survey…

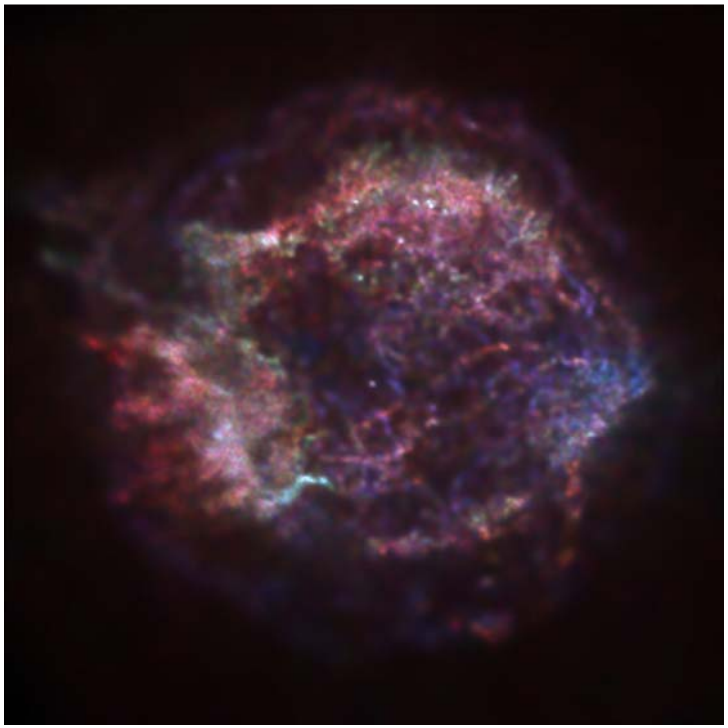
"The committee emphasizes that telescopes alone do not lead to a greater understanding of the universe. So that maximum benefit can be obtained from the current and proposed new facilities, the committee recommends a vigorous and balanced program of astrophysics theory, …, and laboratory astrophysics."

Connecting Quarks to the Cosmos…

"The masses and lifetimes of many nuclei that cannot be reached with existing technology are also important input parameters; however, a complete theoretical description of such nuclei remains out of reach. Almost all the relevant r-process nuclei could be accessible for study in a suitably designed two-stage acceleration facility (such as RIA) that produces isotopes and reaccelerates them."

Supernovae

CHANDRA X-Ray Obs.



NASA/CXC/SAO/Rutgers/J.Hughes
ApJL January 2000

- **Explosion Mechanism (core collapse)**

  Measure weak interaction rates on unstable nuclei

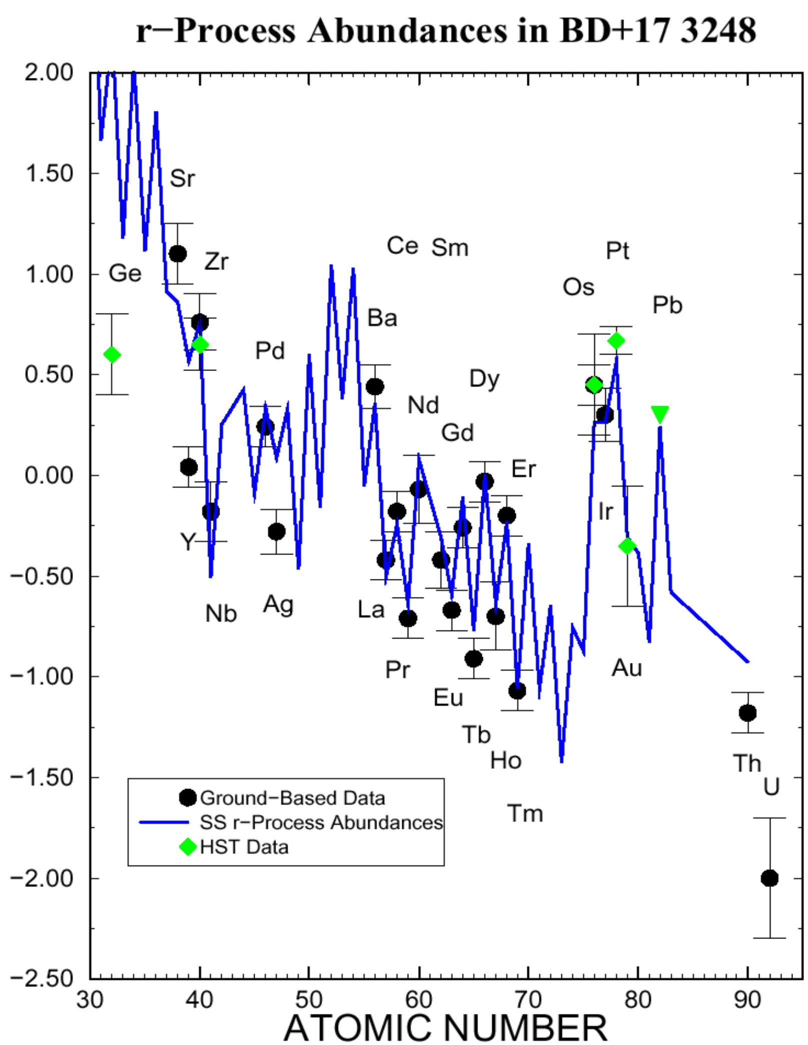
- **Nucleosynthesis (as constraint on explosion, neutrino properties)**

  Measure nuclear properties and reaction rates

- **Role of neutrinos in post processing of material (Is there a neutrino signature?)**

  Measure weak interaction rates on unstable nuclei and binding energies

Study of the oldest Stars – r-process abundances



J. Cowen *et al.*

Stars born in early universe (measured by HST and KECK telescopes) match solar element distributions.

The identical pattern implies a unique source, fixed by nuclear structure and forces.

The Uranium and Thorium abundance will provide another test on the age of the Universe.

Th/Eu and Th/U yield
Age = 13.8(40) Gy

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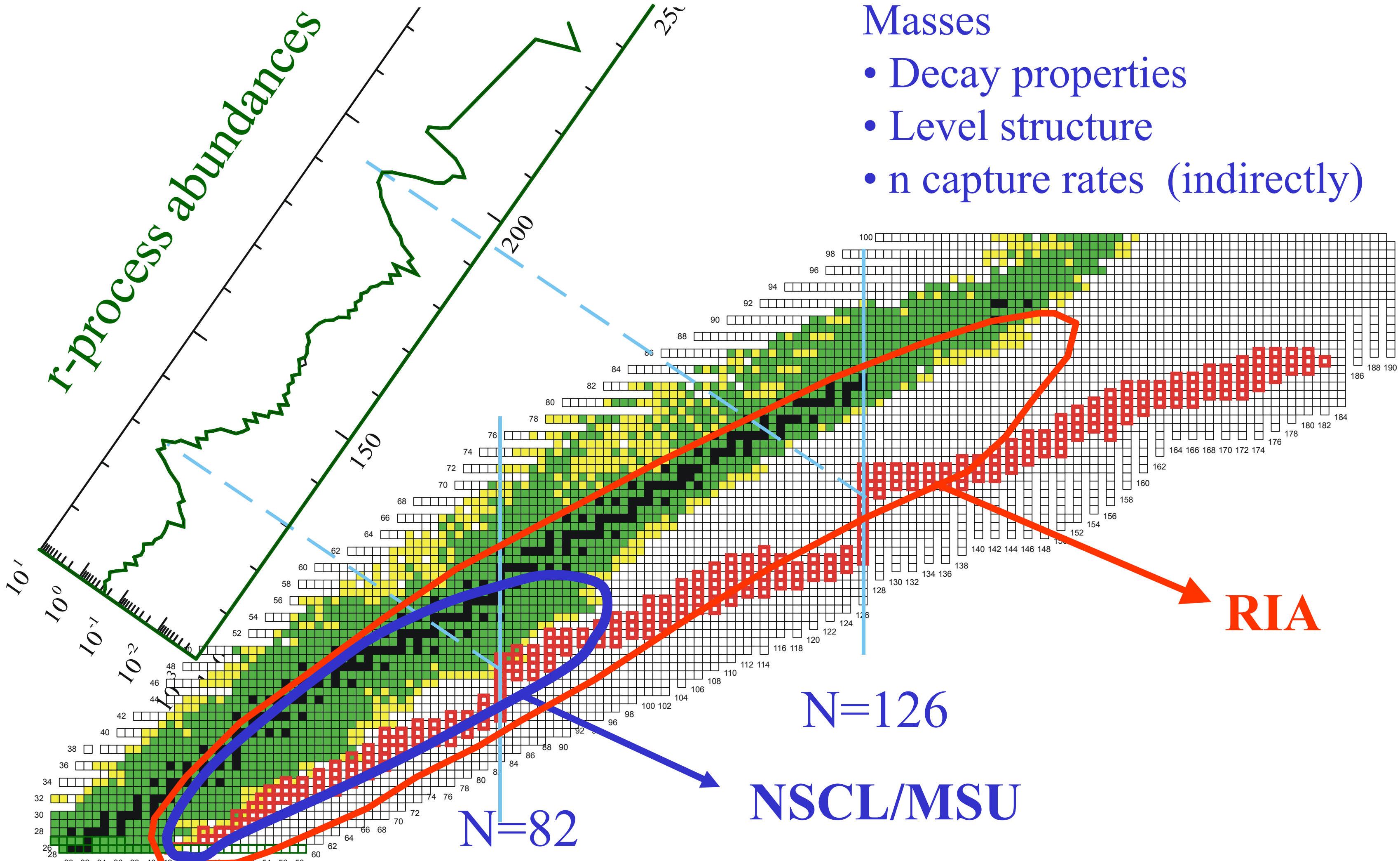
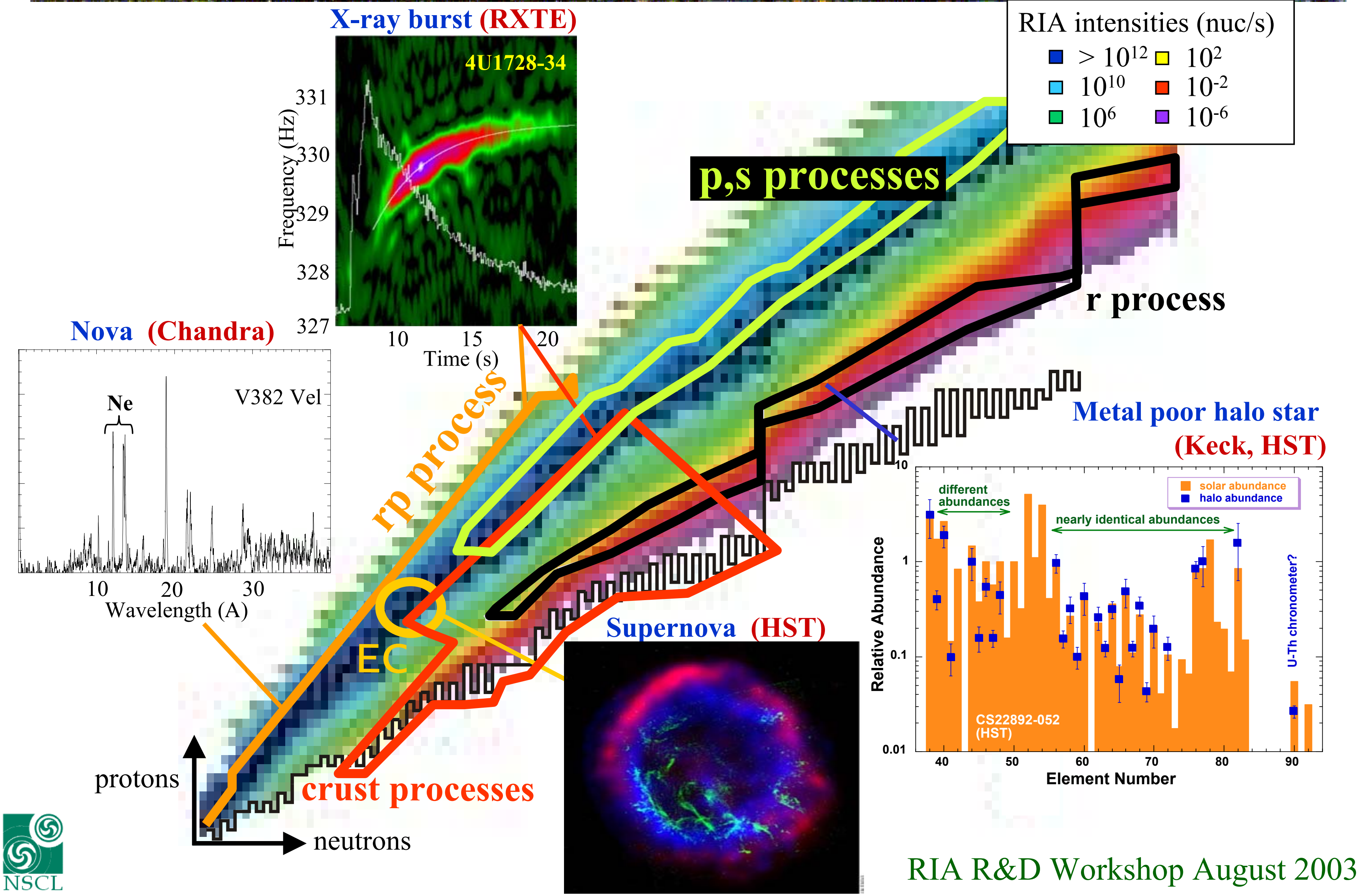
Neutron rich nuclei are key to the r-process

Masses
- Decay properties
- Level structure
- n capture rates (indirectly)



H. Schatz *et al.*

Origin of the Elements, Overall Picture



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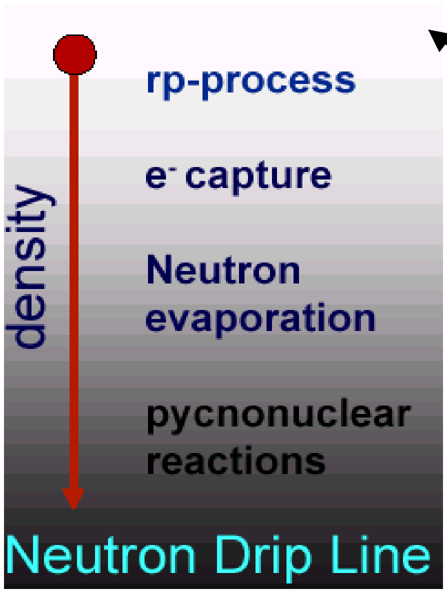
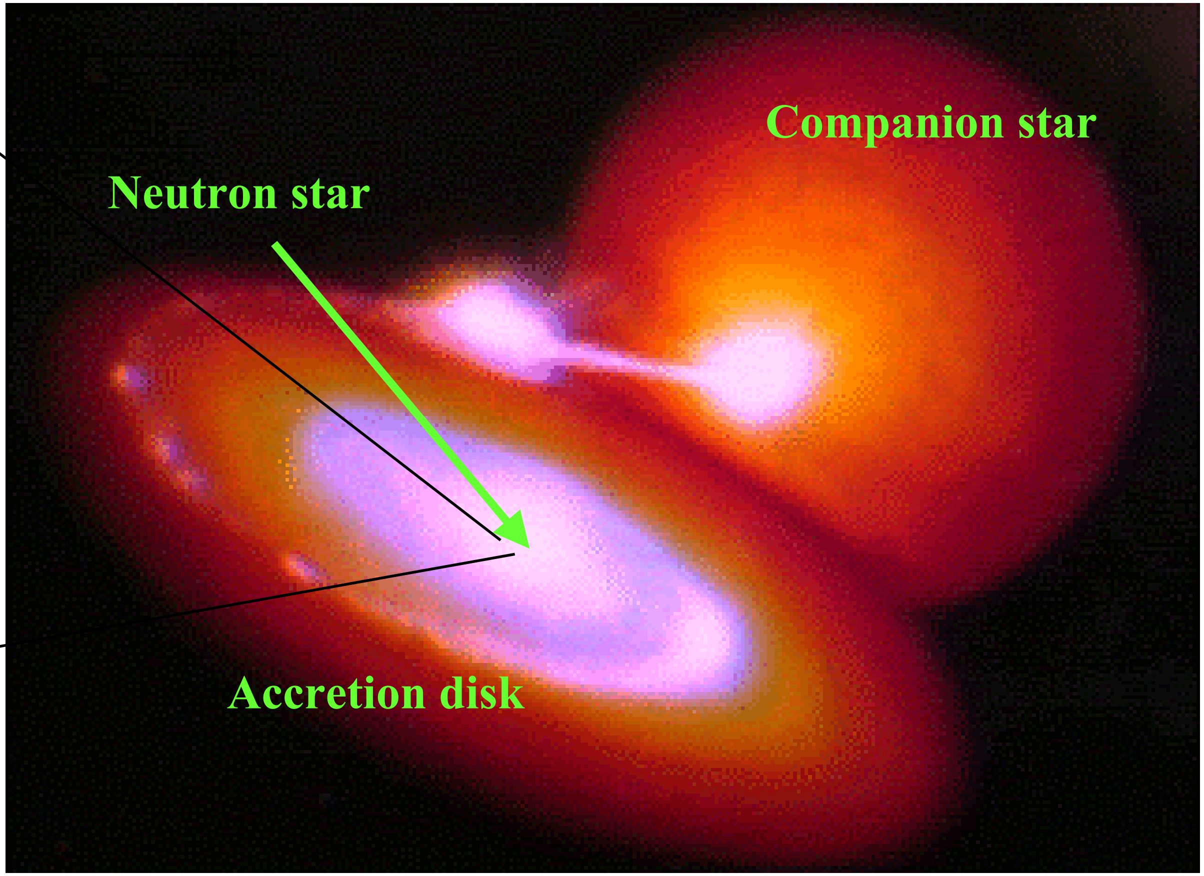
Neutron Star Binary Systems – X-ray emission

X-ray bursts, super-bursts, and the fate of matter rp- process at extreme gravitational conditions



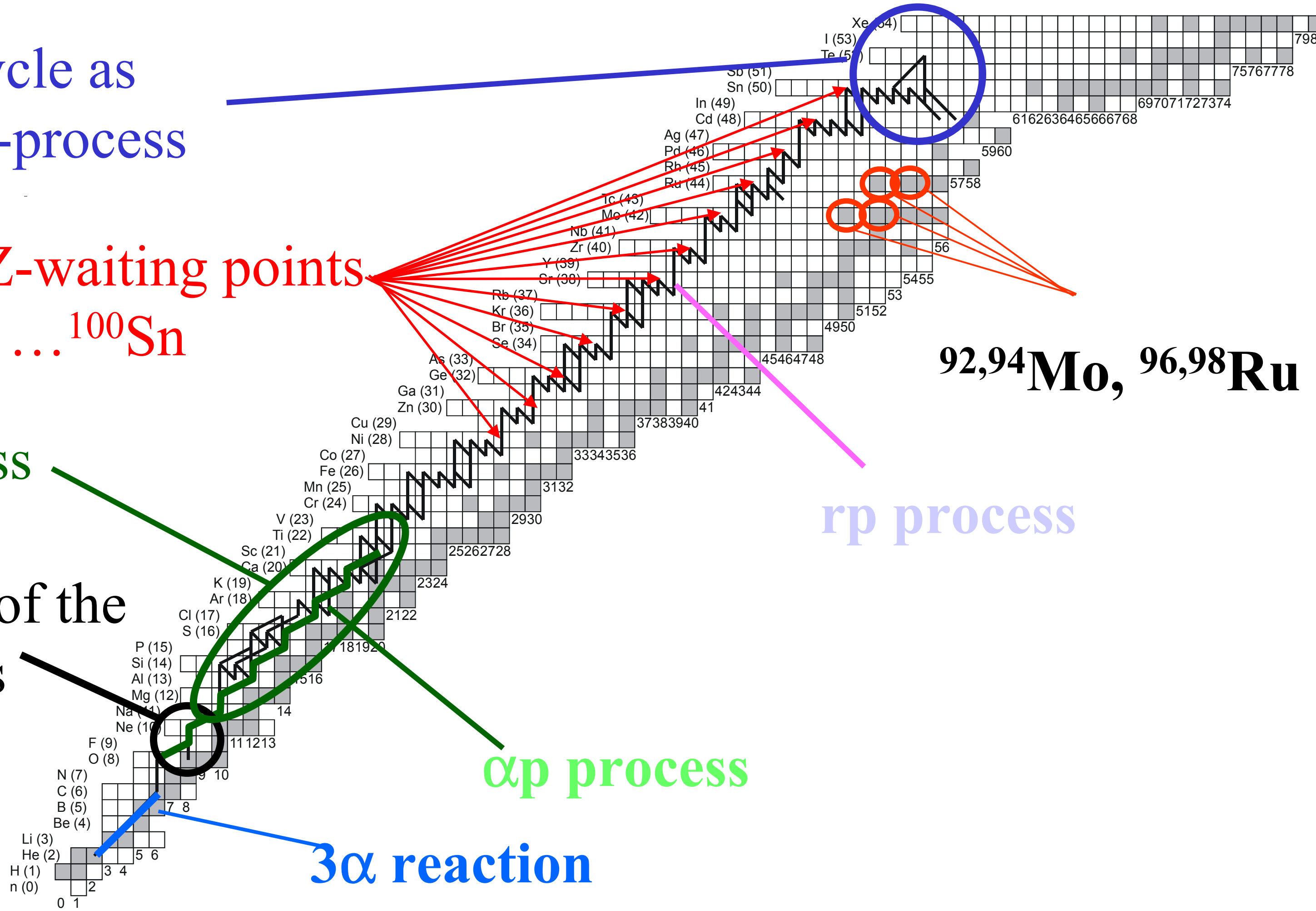


RIA will allow the production and detailed study of most of the key nuclei.

Nuclear Reactions during the X-ray Burst

<u>Key unknown nuclear physics data:</u>

- In the Sn-Te- cycle as End-point of rp-process
- Around the N=Z-waiting points ^{56}Ni, ^{64}Ge, ^{68}Se, …^{100}Sn
- In the αp process
- In the breakout of the hot CNO cycles



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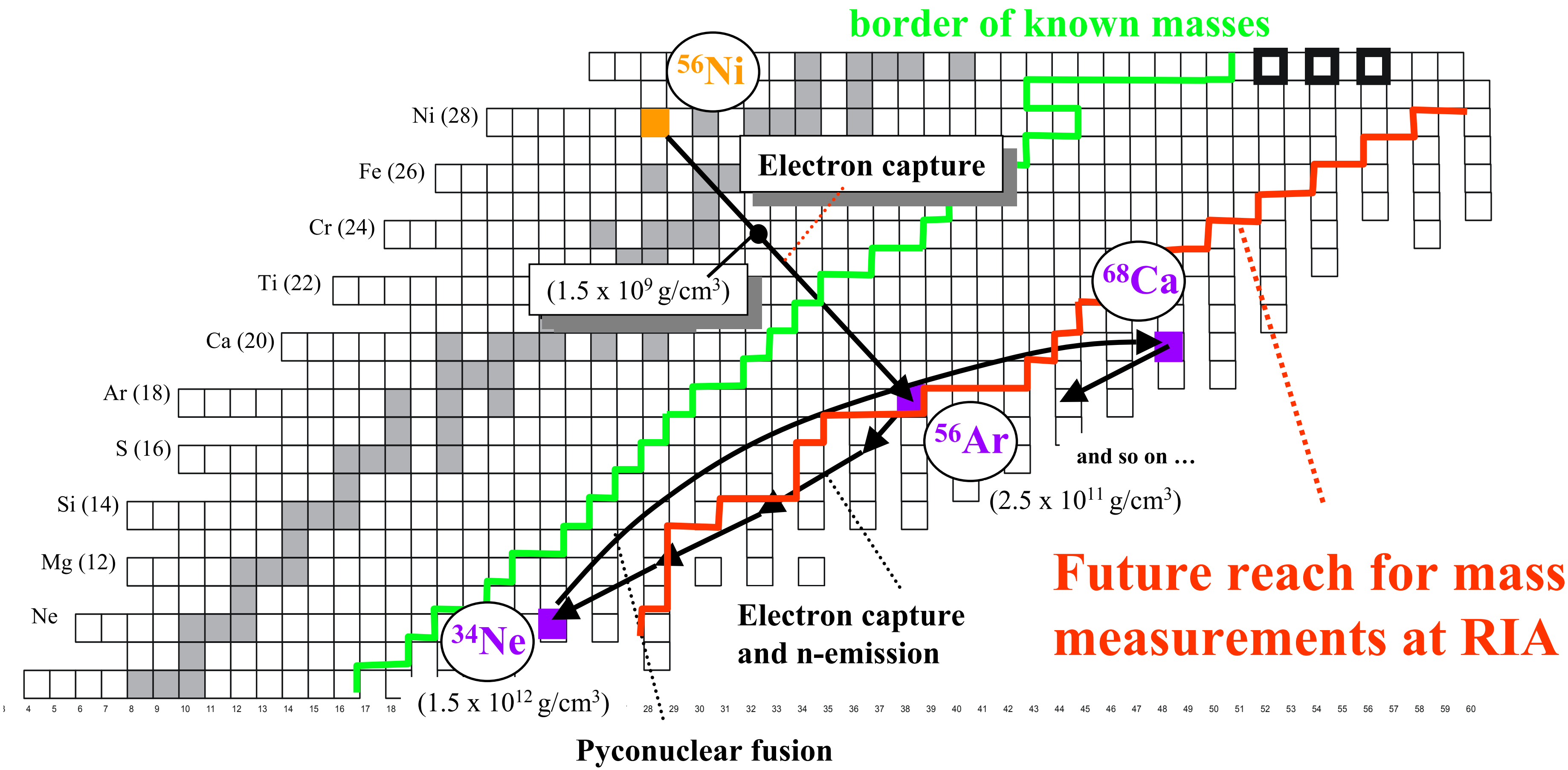
Nuclei in Neutron Star Crusts



- crust deformation ⟶ gravitational wave emission
- crust heating ⟶ thermal radiation and burst behavior

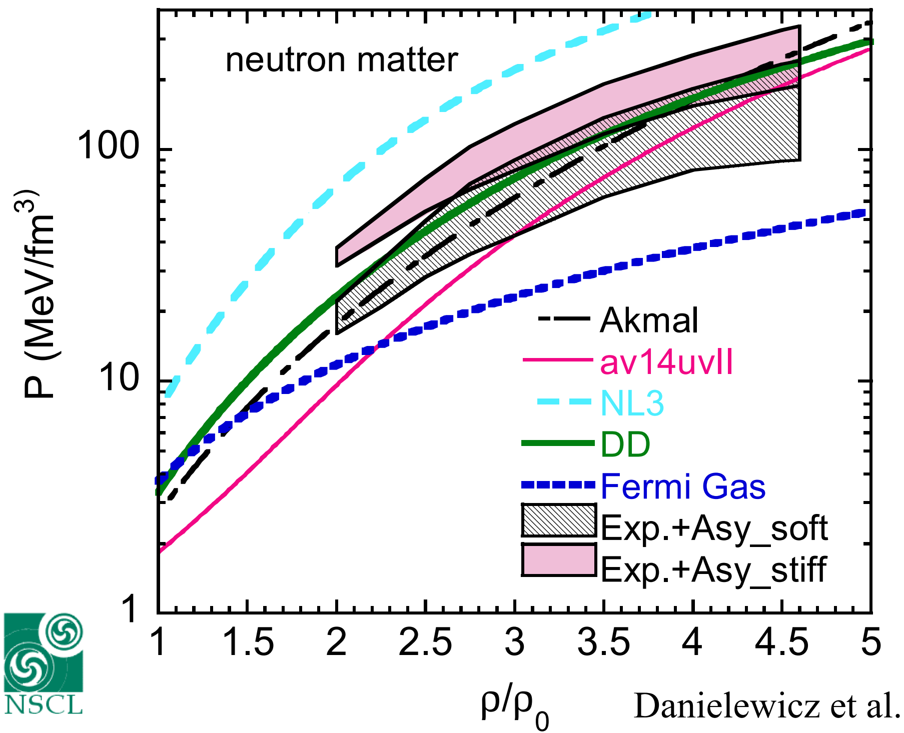
NSCL H. Schatz *et al.*

Equation of State of Neutron Matter

The neutron-matter EOS is critical to models of neutron stars and supernovae, however it is presently poorly known. RIA gives an opportunity to explore the neutron matter EOS.

•At 200-400 MeV/u collisions compress nuclear matter to up to 3x normal density. Current experiments study the EOS of symmetric matter. RIA will allow the extension to neutron matter.

• The size of neutron skins will provide data on the volume asymmetry term.

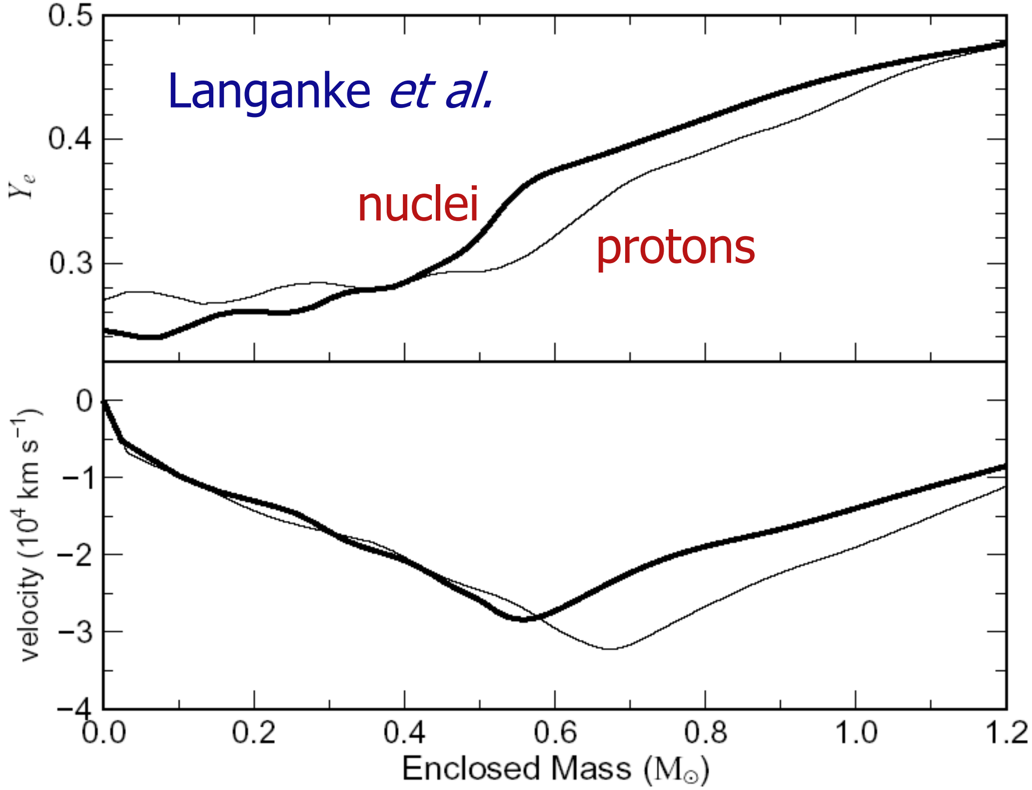


Danielewicz et al., Science (2002)

These items can be measured and compared to models with different EOS assumptions.

- **Sideward Flow**
- **Balance energy**
- **Elliptic Flow**

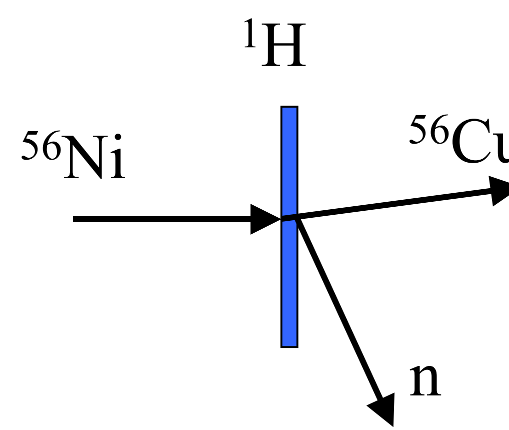
Charge Exchange Studies for Supernova Models



Presupernova core evolution depends on the rates of electron captures and β-decays in A~ 60 to 120 nuclei.

Langanke *et al.* and A. Heger et al., Phys. Rev. Lett. 86

- Inverse kinematics (E_B> 100 MeV/u)
  - ^{1}H(^{56}Ni, n)^{56}Cu or t(^{56}Ni,^{56}Co)^{3}He
- γ-ray detection
  - t(^{57}Co, ^{57}Fe)^{3}He



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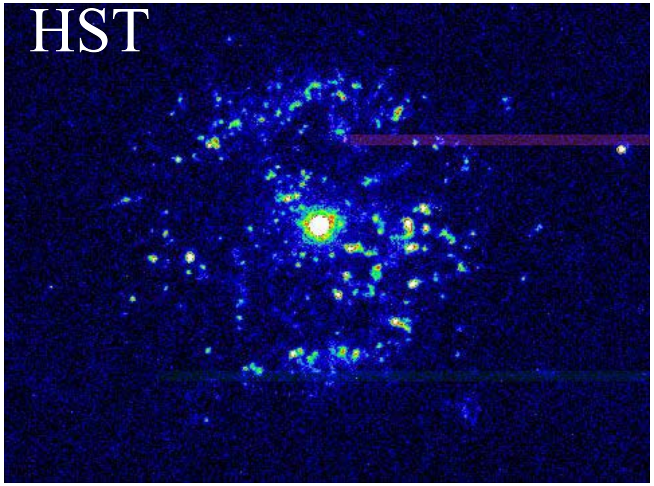
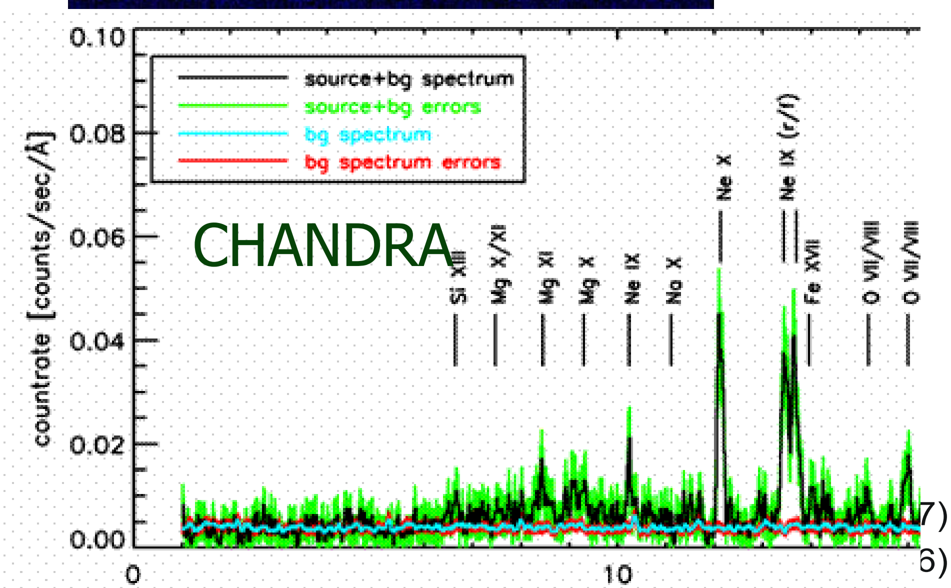
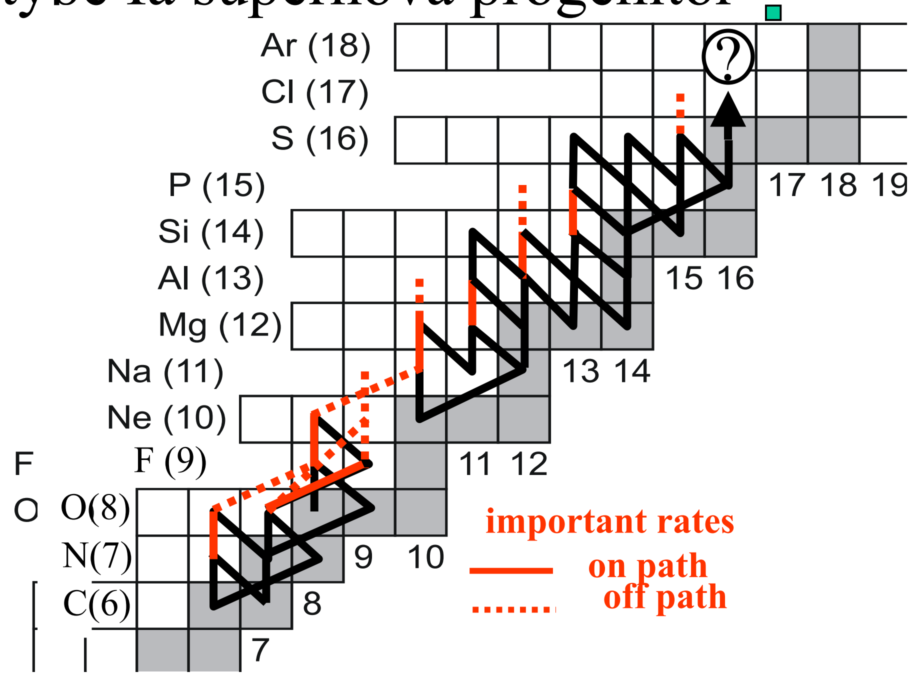
Nuclei in Nova



- Contribution to galactic γ-ray activity ?
- Why is ejected mass so large ?
- How is white dwarf matter mixed in ?
- Evolution of accreting white dwarfs

→ type Ia supernova progenitor



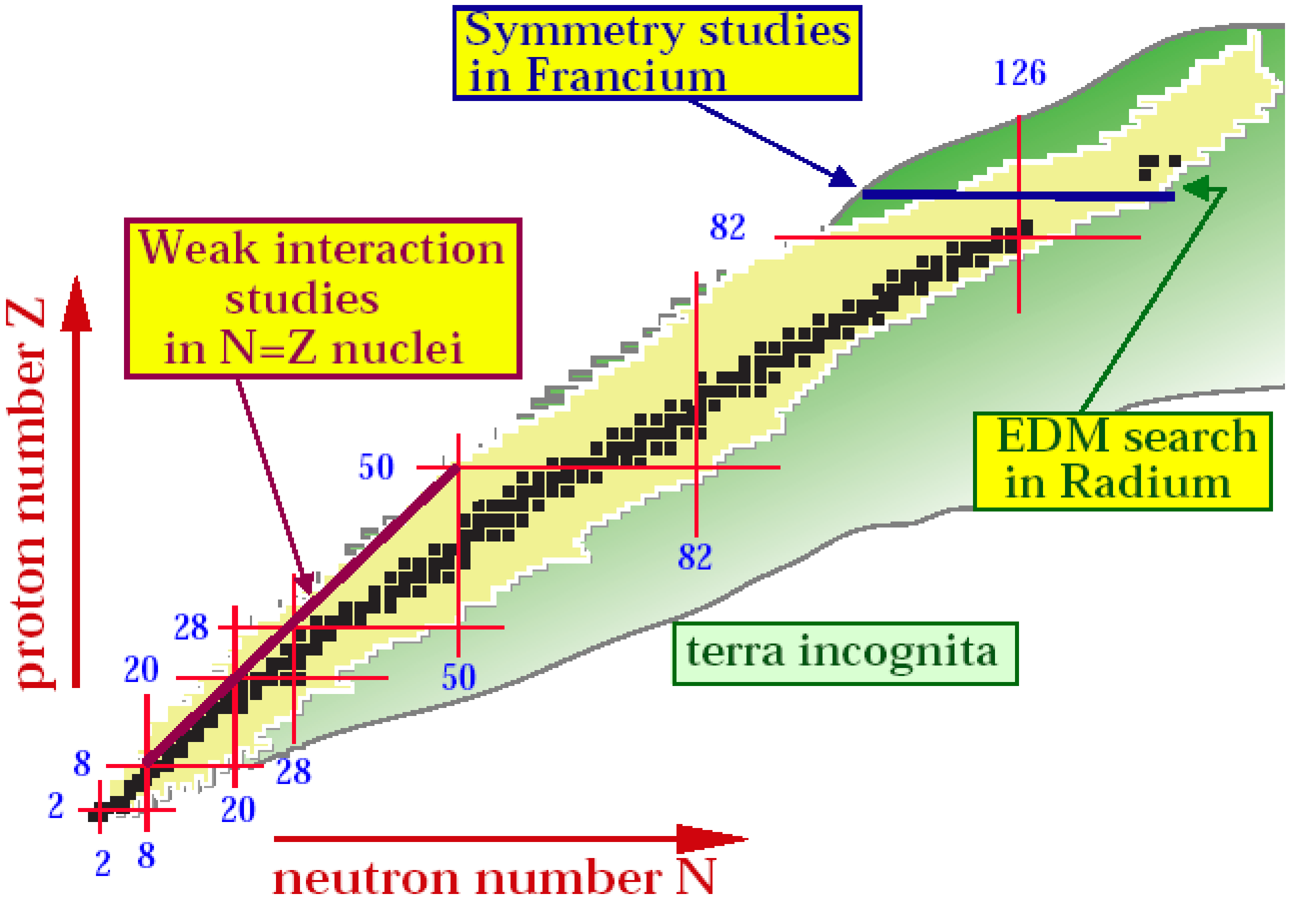


Burwitz et al. 2002 AIP 637,377

Requirements for the RIA facility (Obvious Ones)

- RIA should be able to provide a majority of the r-process nuclei for study. It should allow the study of all for the N=82 waiting point nuclei and many of the N=126 waiting point nuclei.
- RIA should allow the production of N=Z nuclei up to ^{100}Sn at rates of 1000/s for studies of X-ray bursts and novae.
- RIA should provide $>10^9$ ions/s at <1 MeV/u for direct measurements of key reaction rates. In some cases 10^{12} ion/s will be necessary.
- RIA should provide nuclei (at all energies) with sufficient neutron excess to allow the determination of the neutron matter propertiesand the neutron matter EOS.
- RIA should provide beams of 200 MeV/u in the mass 56 and 120 regions to allow the determination of weak interaction strengths in stellar environments.

Tests of the Fundamental Symmetries in Nature



Specific nuclei offer new opportunities for precision tests of:

- CP and P violation – baryon asymmetry on the Universe

Standard Model Tests:

- Unitarity of CKM matrix
- Physics beyond V-A
- $\sin^2\Theta_W$ at low q

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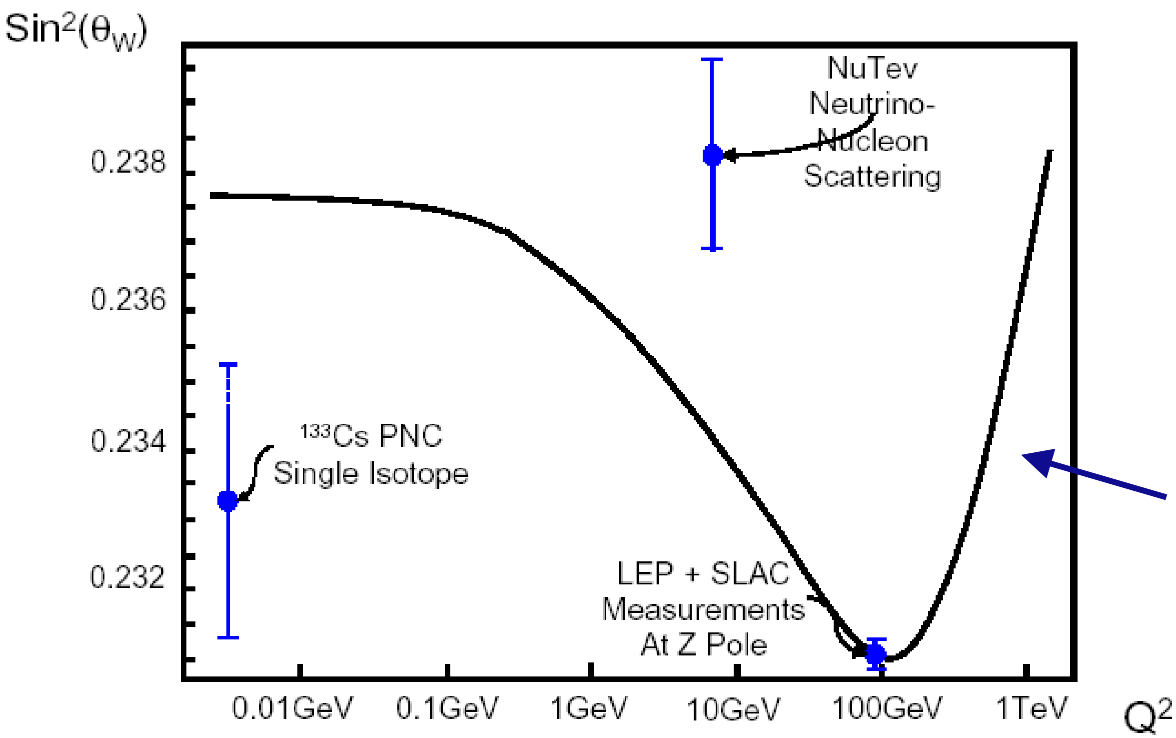
Test of the Q^2 Dependence of $Sin^2(\theta_w)$



This is an example of the so called running of the fundamental constants.

Prediction of the Standard Electro-Weak Theory

G. Sprouse

Rare-isotope facilities provide a credible path to necessary improvements on parity non-conservation in atoms.

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Search for EDM in Nuclei

Baryon asymmetry in the Universe may be related to CP violation beyond the SM. Extensions predict EDM in nuclei that can be tested at RIA.

Current status of searches:

$|d_n| < 6.3 \times 10^{-26}$ e cm

$|d_e| < 1.6 \times 10^{-27}$ e cm

$|d(Hg)| < 2.1 \times 10^{-28}$ e cm

	^{223}Rn	^{223}Ra	^{225}Ra	^{223}Fr	^{129}Xe	^{199}Hg
$T_{1/2}$	23.2 m	11.4 d	14.9 d	22 m	-	-
I	7/2	3/2	1/2	3/2	1/2	1/2
ΔE_{th}	37	170	47	75	-	-
ΔE_{exp}	-	50.2	55.2	160.5	-	-
$10^5 S$ (e fm^3)	1000	400	300	500	1.75	1.4
$10^{28} d_A$ (e cm)	3300	3300	2500	2800	0.8	5.6

V.A. Dzuba et al., Phys. Rev. A 66, 012111 (2002)

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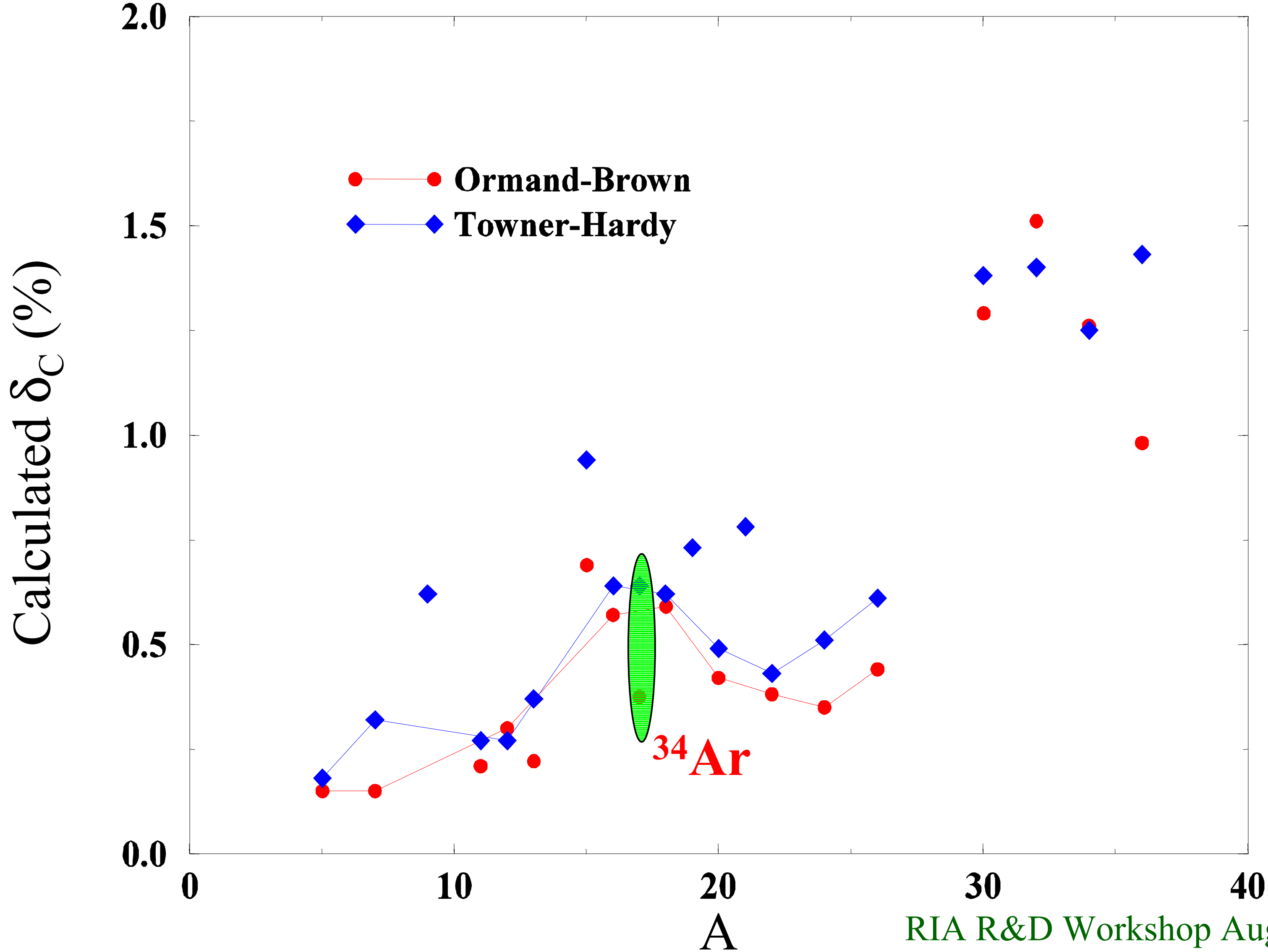
Test of the Unitarity of the CKM Matrix



Summary of the key science requirements

- Francium isotopes at 10^9/s over a wide range of isotopes
- Hg, Xe, Ra, Rn isotopes at 10^9/s to10^{11}/s for a search for electric dipole moments. The effects are enhanced for isotopes with specific features.
- N=Z nuclei up to ^{100}Sn at rates of 1000/s for test of the unitarity of the CKM matrix.
- Availability of nuclei with special features, e.g. ^{35}K, at greater than 10^6/s for precision tests of V-A.

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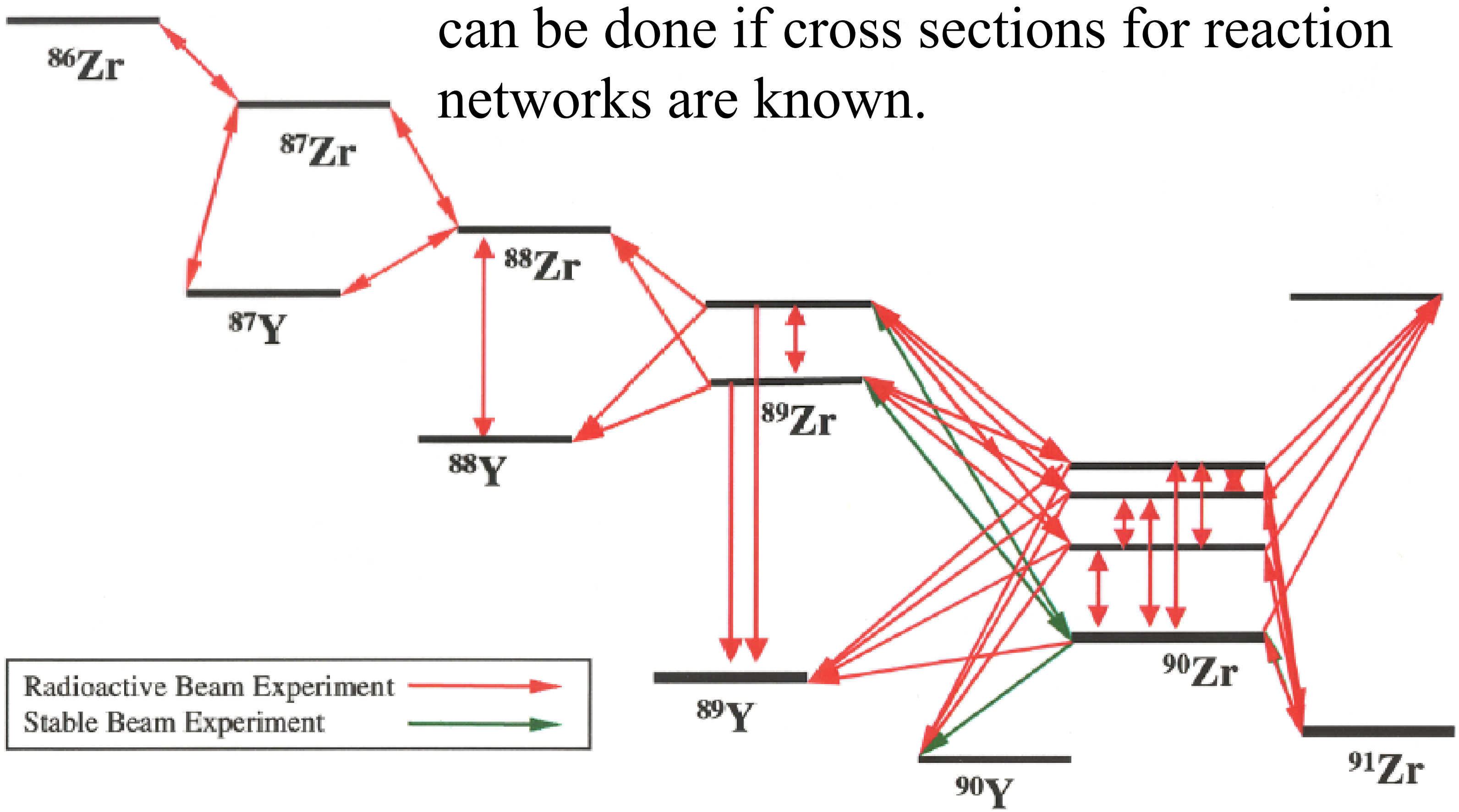
Applications of nuclides from RIA

- Development of techniques and manpower for dealing with radioisotopes.
- Stockpile stewardship – allow measurements of necessary cross sections to interpret weapons data.
- Allow testing of new radioisotopes for medicine.
- Isotopes, e.g. ^{7}Be, for wear studies.
- Tracers for various studies.
- Soft doping, etc.

Workshops at Los Alamos and Lawrence Livermore Labs

RIA will provide important measurements for SBSS

Need to determine neutron fluxes in extreme environments (NIF, weapons data, stars) . This can be done if cross sections for reaction networks are known.



Talk by Ed Hartouni, LLNL, today

Requirements for RIA

- There is a large potential for RIA to supply isotopes for research is the physical and biological sciences.
- For stewardship, RIA must provide up to 10^{13} ions/s (near stability) and allow them to be collected for target production.
- RIA should allow the collection and chemical extraction of isotopes. Radiochemical facilities and capabilities will be needed to provide the full benefit from RIA. Modest quantities of short lived nuclides (µCi) are useful.
- RIA should provide research quantities and availability. Industrial or wide-scale medical production of isotopes is currently not discussed for RIA.

Conclusions

- One of the goals of RIA is to answer the question of the origin of the elements heavier than iron and develop a quantitative understanding of the chemical evolution of the Universe.
- RIA will also improve our understanding of supernovae, novae, X-ray sources, etc.
- Data from RIA and improved nuclear models will be essential to interpret the wealth of data from the current and next generation of Earth and space-based telescopes.
- Nuclei play a key role in the processes of the Universe. Data from RIA will help provide the necessary laboratory component to our observational capabilities.
- RIA has the potential to contribute to our understanding of the fundamental symmetries in nature.
- RIA should be constructed to provide key isotopes for research and defense.