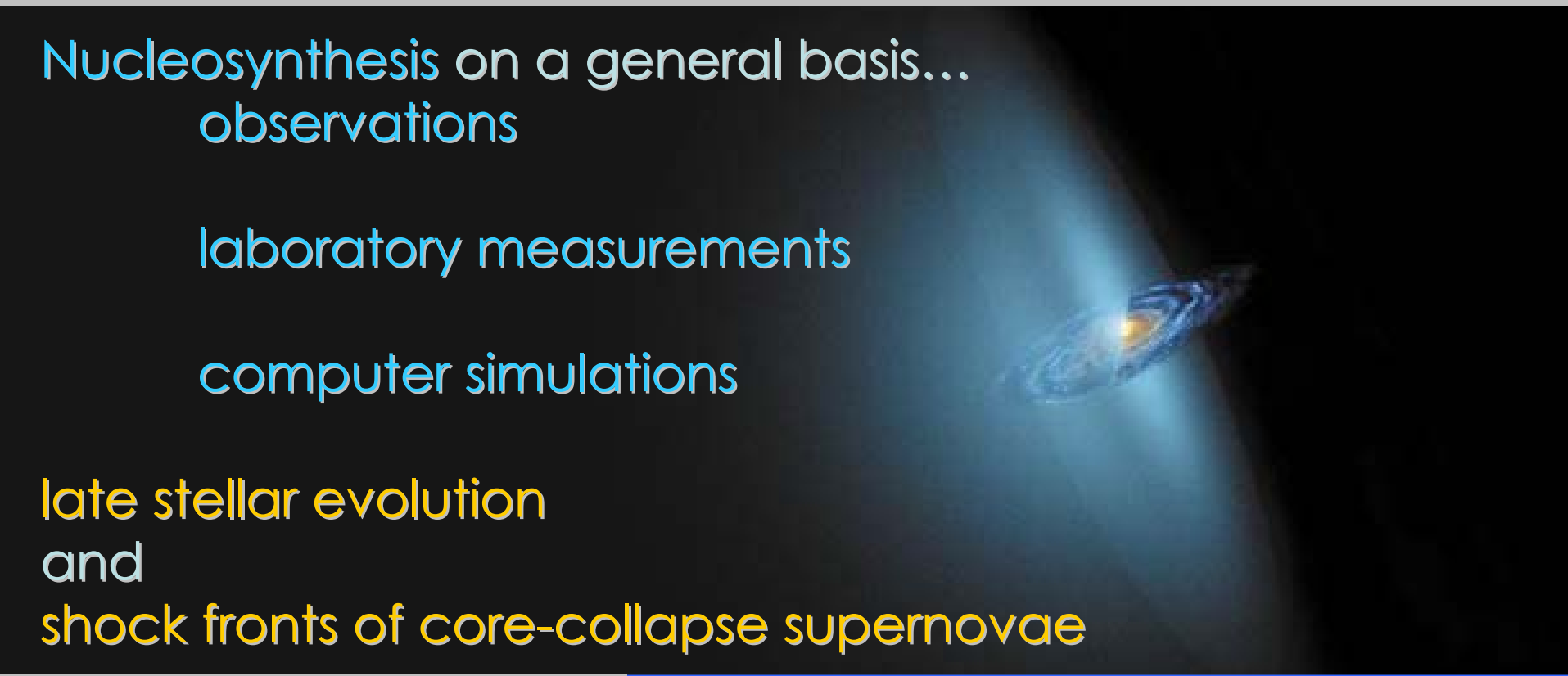
MRC1: The Origin of the Elements
stellar evolution & type-II SN nucleosynthesis

A. Aprahamian



Nucleosynthesis on a general basis…

observations

laboratory measurements

computer simulations

late stellar evolution
and
shock fronts of core-collapse supernovae

Nuclear experiment

Nuclear Theory

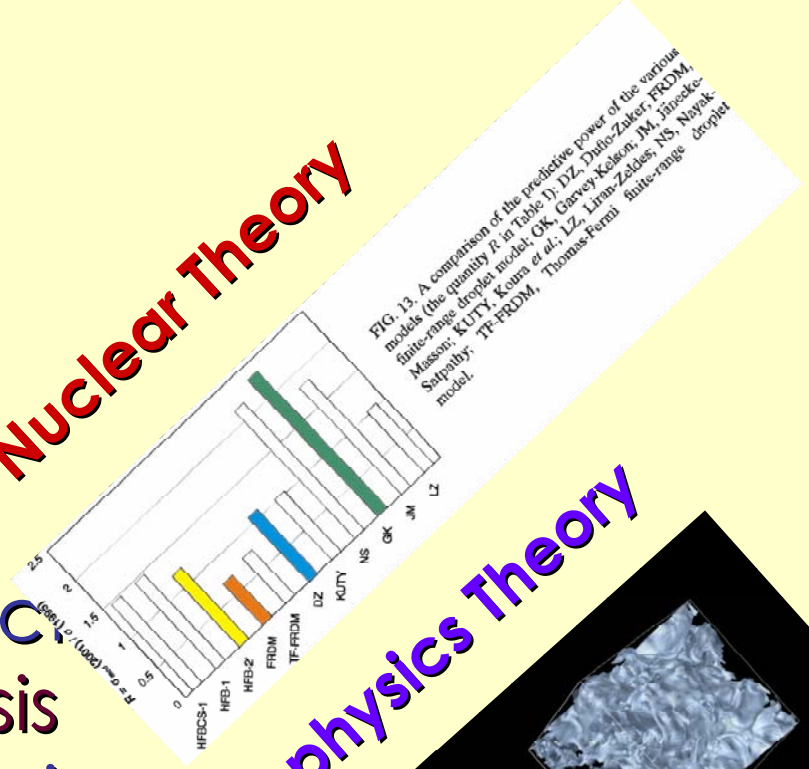


FIG. 13. A comparison of the predictive power of the various models (the quantity R in Table I): DZ, Duflo-Zuker; FRDM, finite-range droplet model; GK, Garvey-Kelson; JM, Jänecke-Masson; KUTY, Koura *et al.*; LZ, Liran-Zeldes; NS, Nayak-Satpathy; TF-FRDM, Thomas-Fermi finite-range droplet model.

low energy nuclear reac

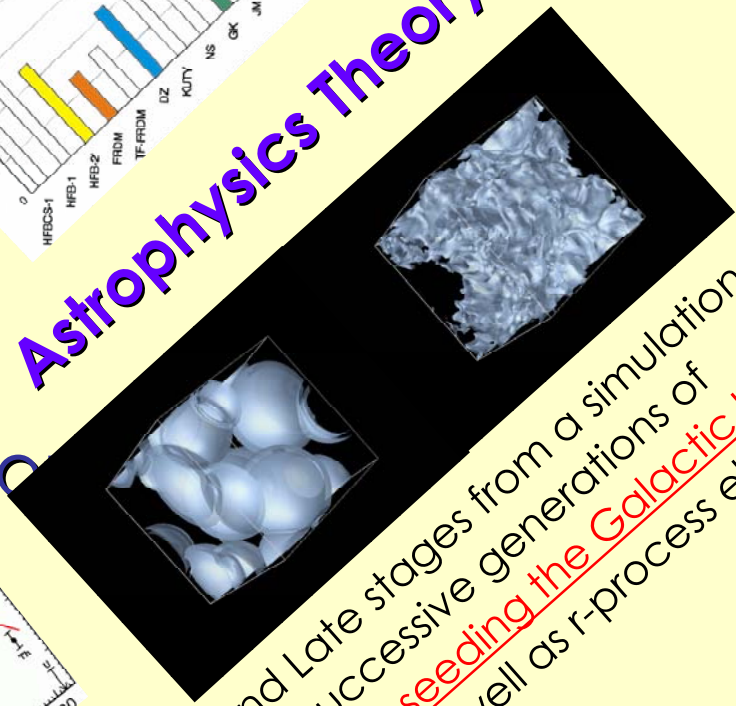
r-process nucleosynthesis

p-process nucleosynthesis

Shockfront analysis (simulatio

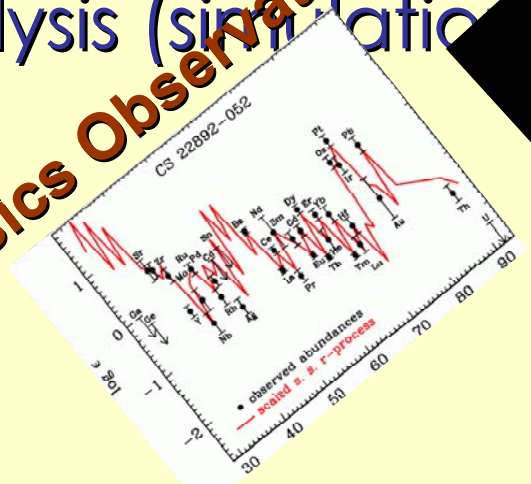
Observations

Astrophysics Theory



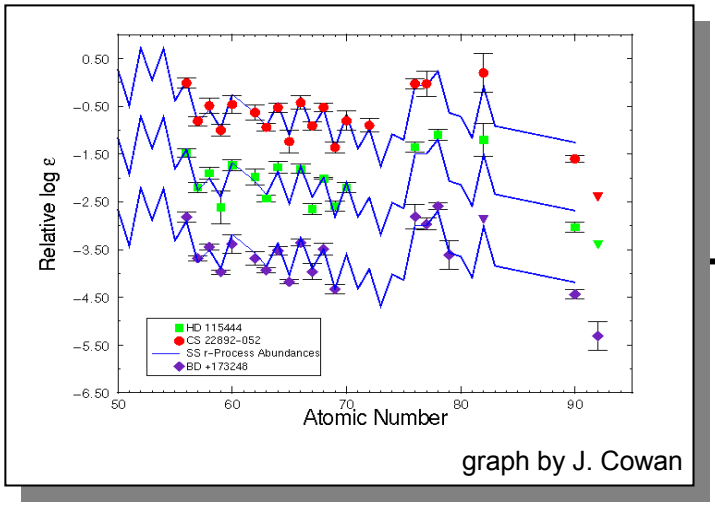
Early and Late stages from a simulation showing successive generations of Supernovae seeding the Galactic ISM w turbulence as well as r-process eleme

Astrophysics Observation

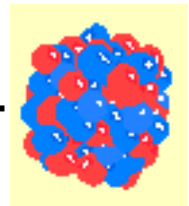


The origin of the heavy elements – the site of the r-process

New precision observations of r-process elements



Nuclear Physics



Missing link

r-process models

Supernova ?

- Neutrino wind ?
- Jets ?
- Explosive burning ?
- Prompt Explosions ?

Image: Burrows et al. 1995

Neutron star merger ?

- Need nuclear physics to find the correct model from element observations (the only available direct experimental constraint on the r-process)
- Need nuclear physics to use element observations as precision probes for physics in some of the most extreme cosmic environments

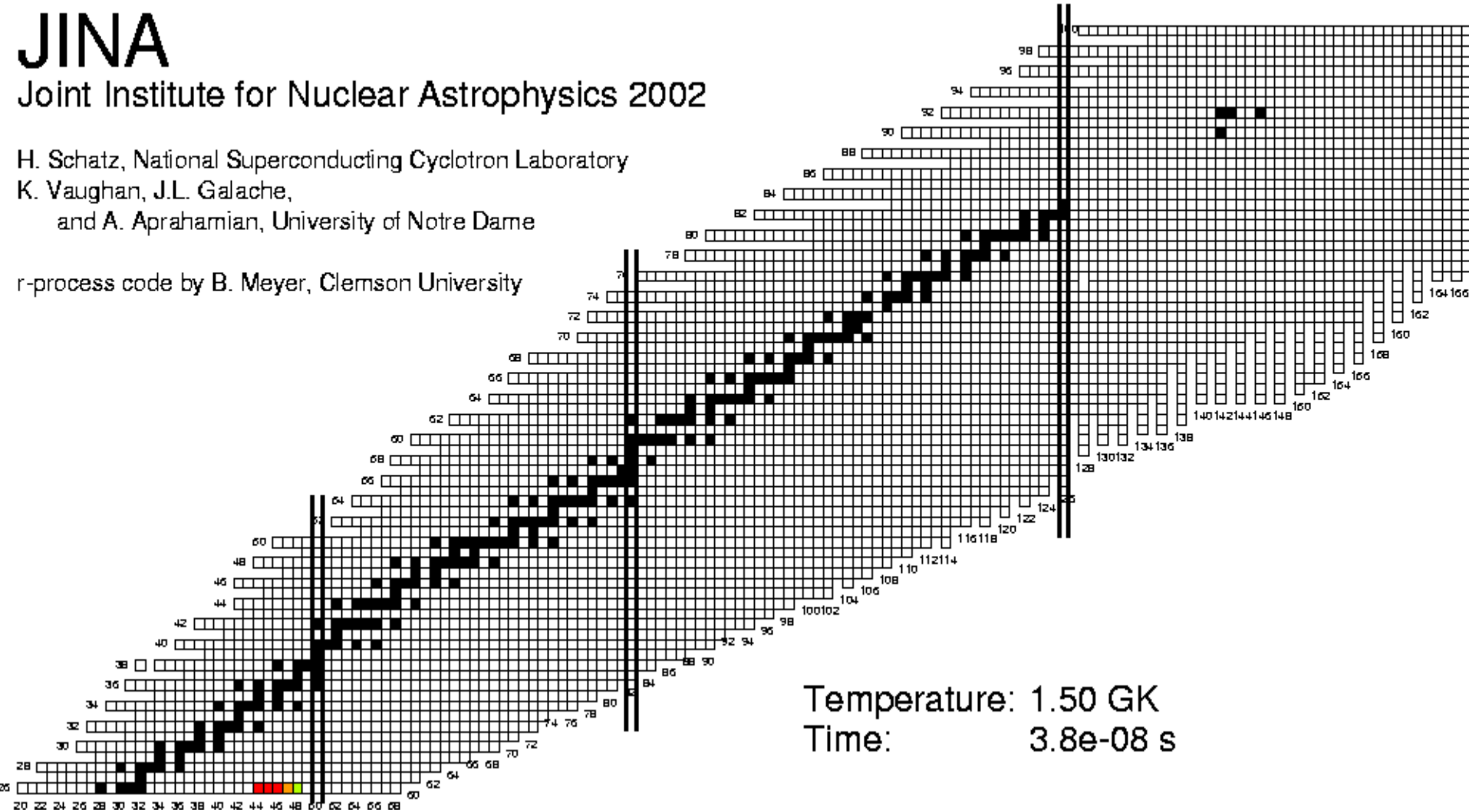
Nucleosynthesis in the r-process

JINA

Joint Institute for Nuclear Astrophysics 2002

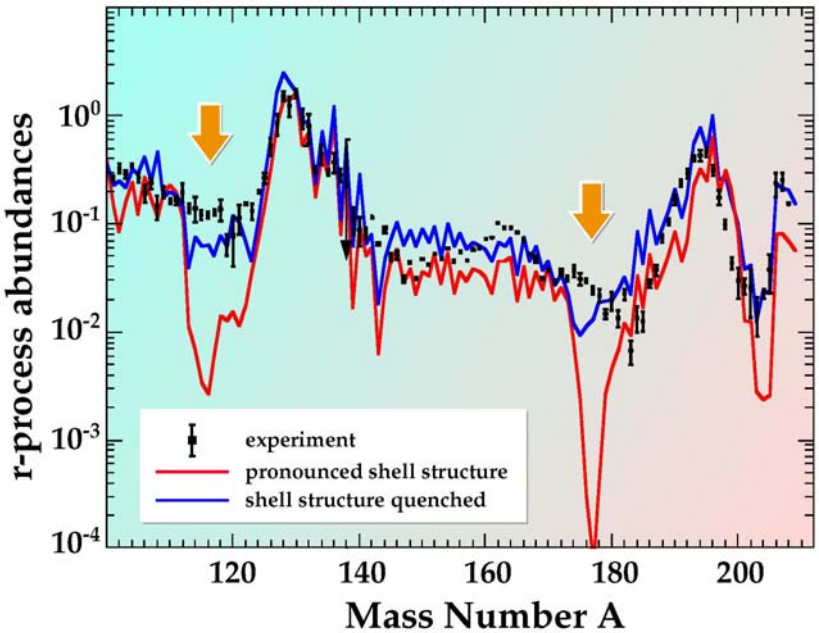
H. Schatz, National Superconducting Cyclotron Laboratory
K. Vaughan, J.L. Galache,
and A. Aprahamian, University of Notre Dame

r-process code by B. Meyer, Clemson University



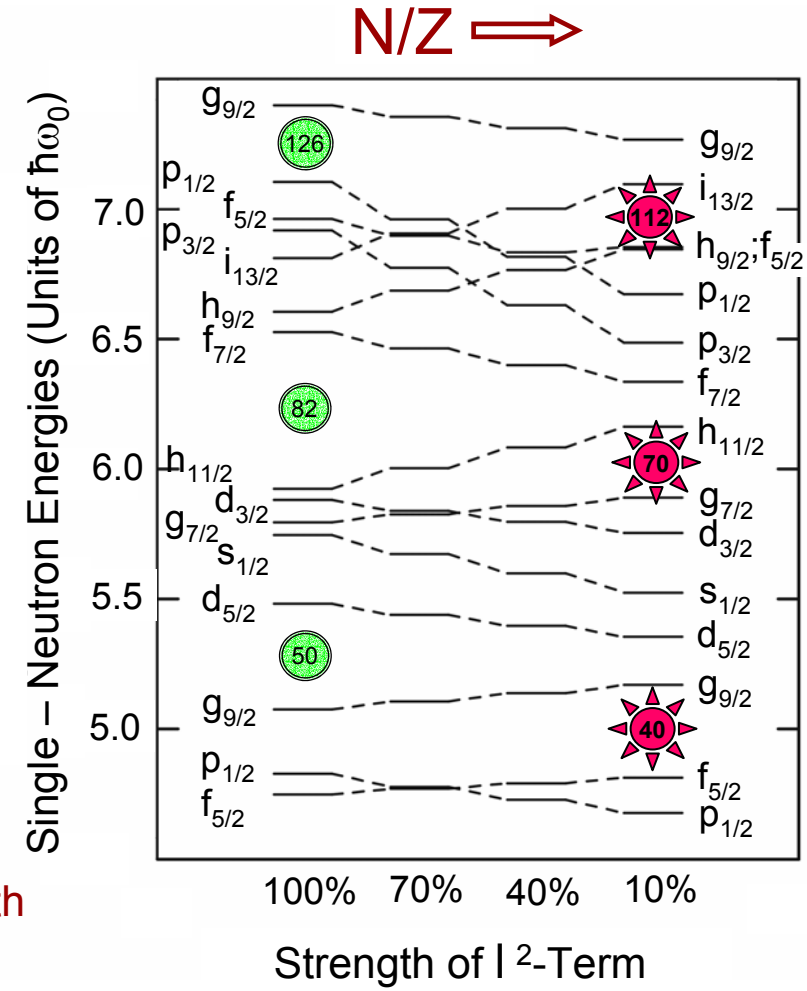
Closed shell nuclei have small S_n, enrichment around N=50, 82,126

R - abundances ⟷ **Nuclear structure**

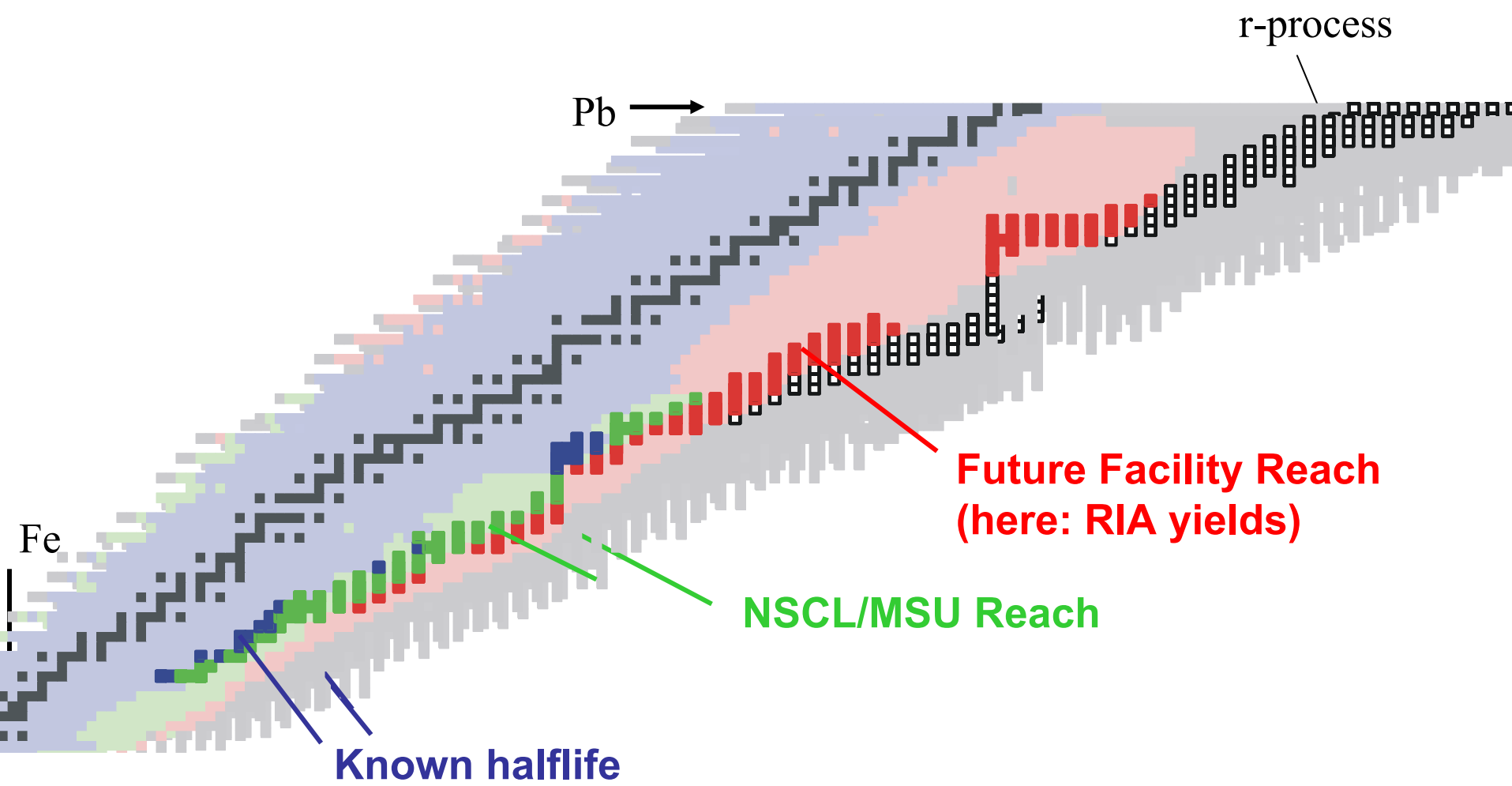


FK²L (Ap.J. 403 ; 1993)

"..the calculated r-abundance 'hole' in the A ≅ 120 region reflects the weakening of the shell strength ... below ^{132}Sn 50 " 82



From K.-L. Kratz 2004

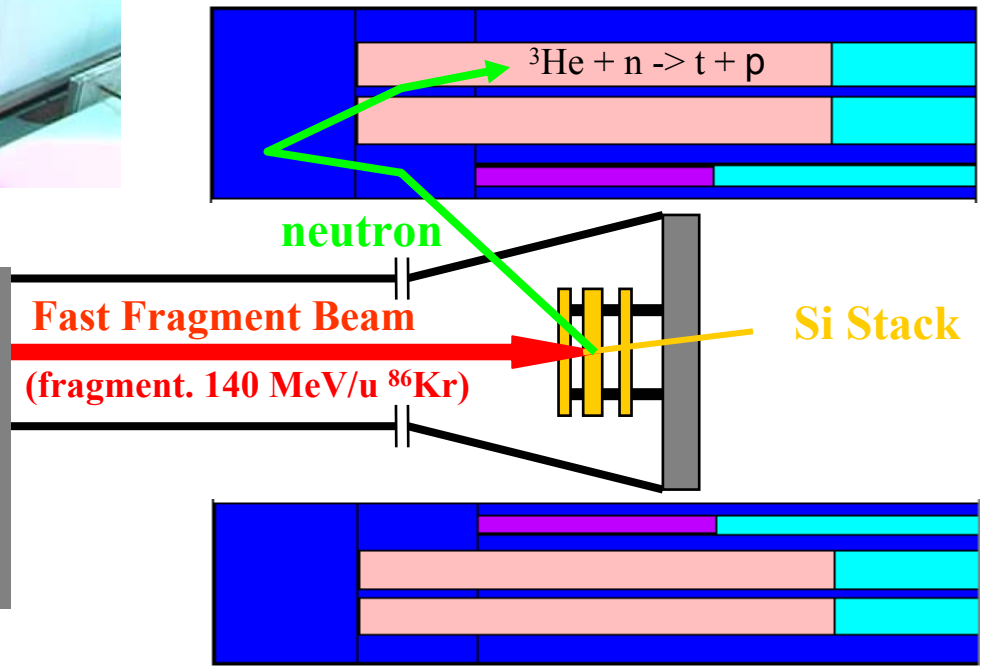

r-process
Pb
Fe
Future Facility Reach
(here: RIA yields)
NSCL/MSU Reach
Known halflife

r-process experiments at new NSCL CCF facility

Measure:

- β-decay half-lives
- Branchings for β-delayed n-emission

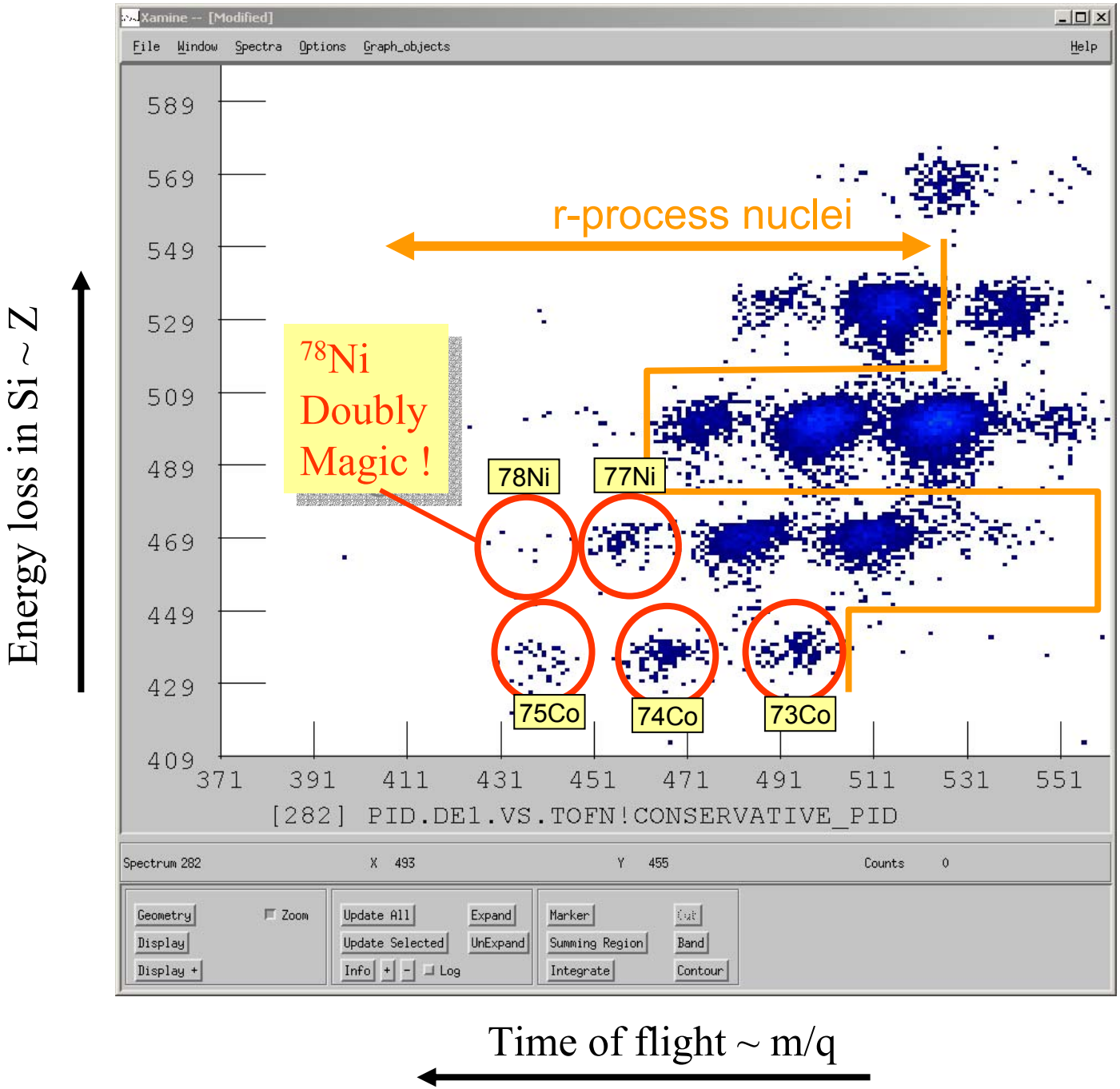
New NSCL Neutron detector NERO

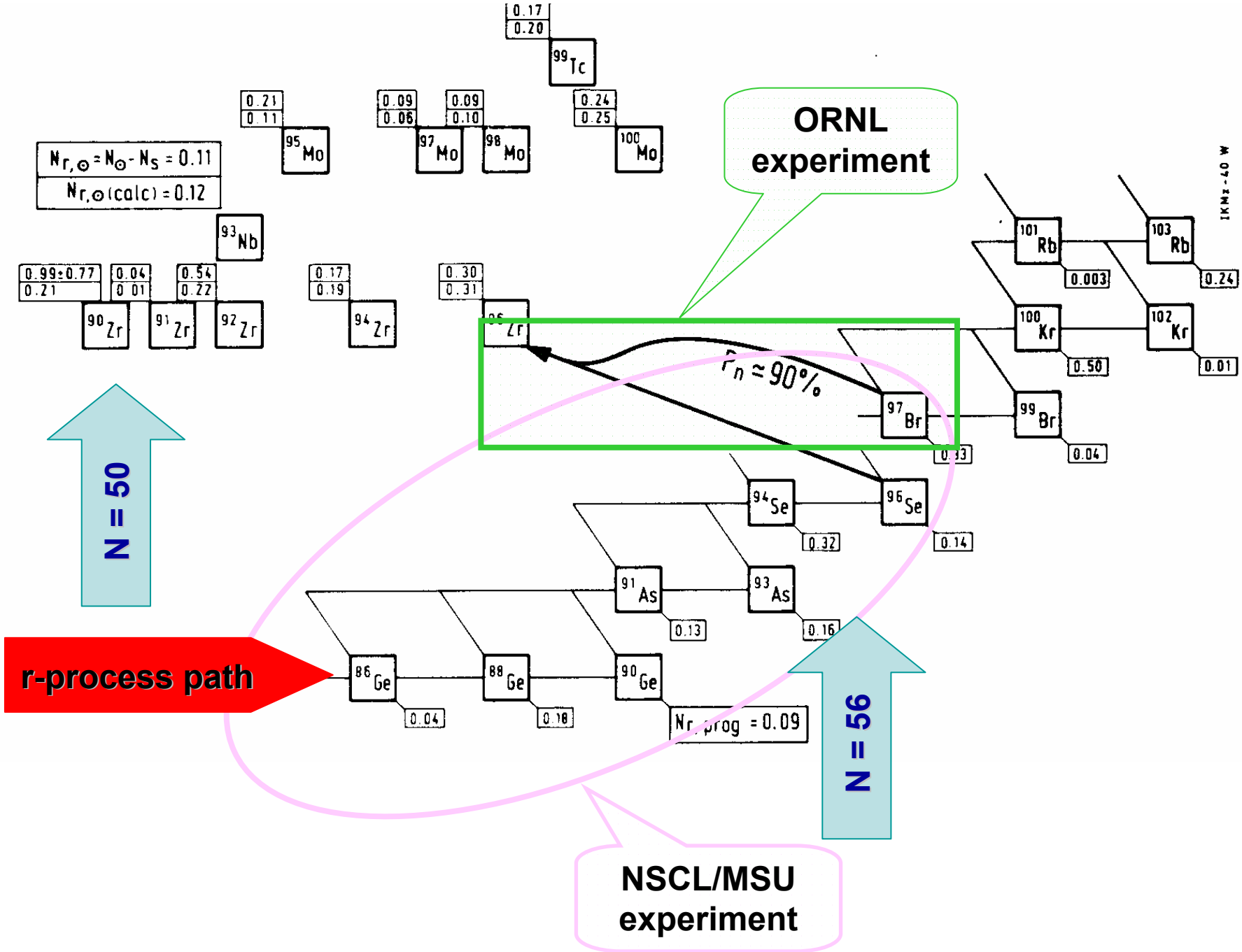


Detect:

- Particle type (TOF, dE, p)
- Implantation time and location
- β-emission time and location
- neutron-β coincidences

Particle Identification:




ORNL experiment
$N_{r,\odot} = N_\odot - N_s = 0.11$
$N_{r,\odot}(calc) = 0.12$
$P_n \simeq 90\%$
N = 50
N = 56
r-process path
NSCL/MSU experiment
$N_{r,prog} = 0.09$

r-Process Nuclei

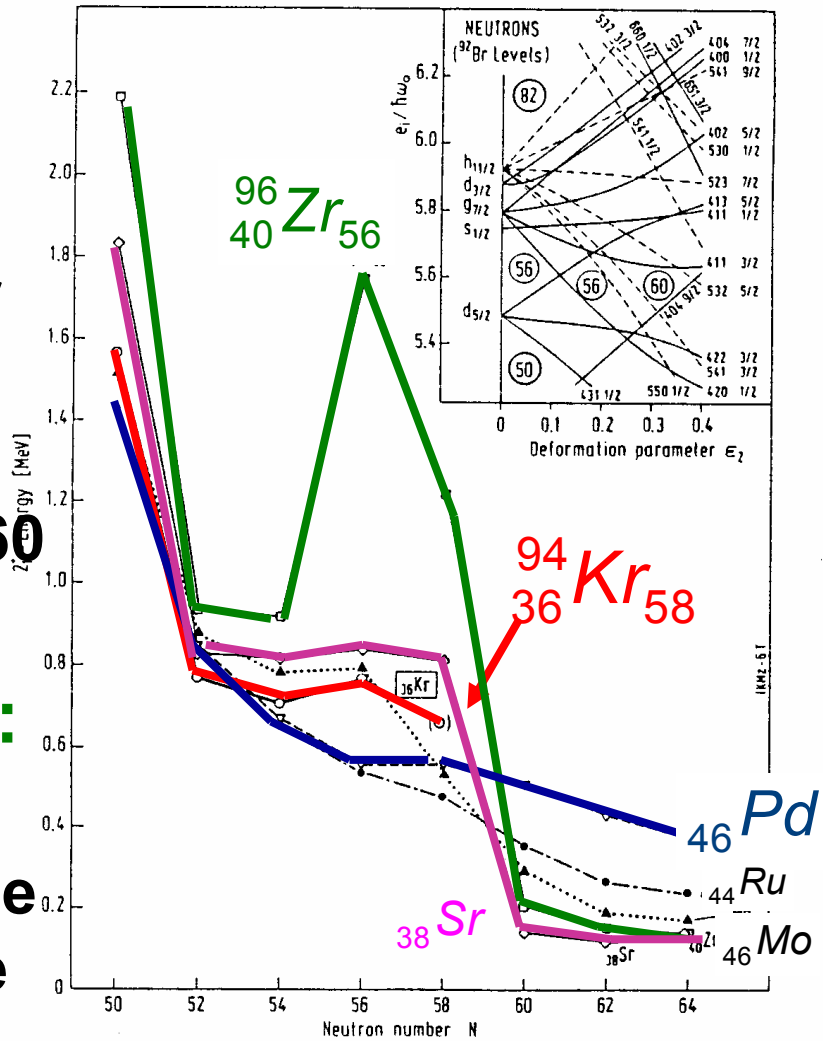
- Nuclear Structure Properties of Neutron-Rich Ge-Br Isotopes in the Astrophysical r-Process (3034)
  - (ND, NSCL-MSU, KCh-Mainz Collaboration)

- Beta-Decay Studies of Neutron-Rich Bromine Isotopes: Towards N = 60
  - (ND, ORNL, UT, LSU Collaboration)

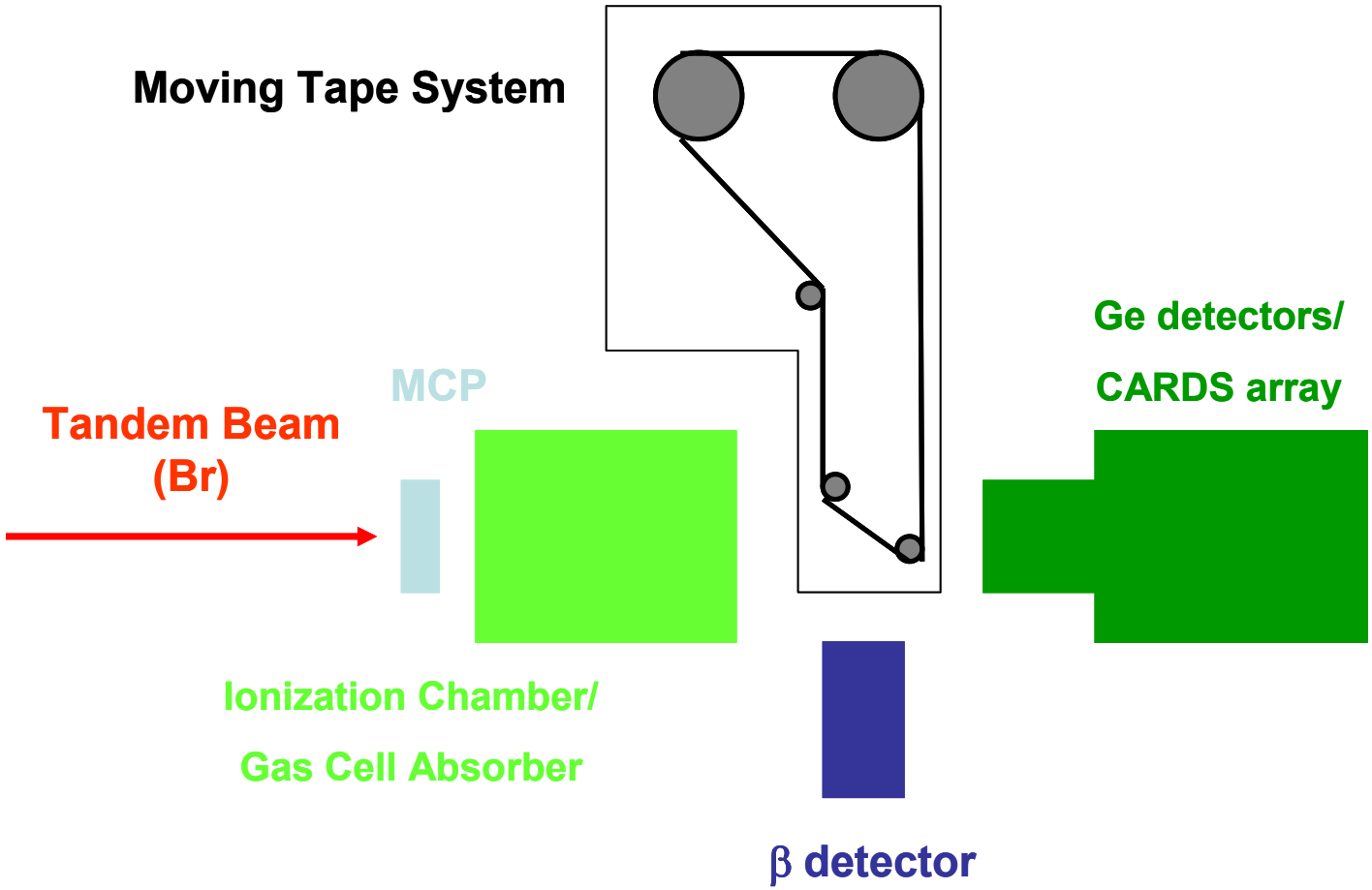
- Beta-Decay Study of Very Neutron-Rich Cd Isotopes with a Chemically Selective Laser Ion Source
  - submitted (KCh-Mainz, Maryland, ND, NSCL-MSU, Chemistry Oslo, ISOLDE Collaboration)

2^+ level energies

- **nuclear structure signatures:**
  - **pronounced N = 56 subshell closure for ^{96}Zr**
  - **sudden onset of deformation at N = 60 for ^{98}Sr and ^{100}Zr**
- **Experimental goals:**
  - **extension of 2^+ measurements to the neutron-rich Kr – Se isotopes**



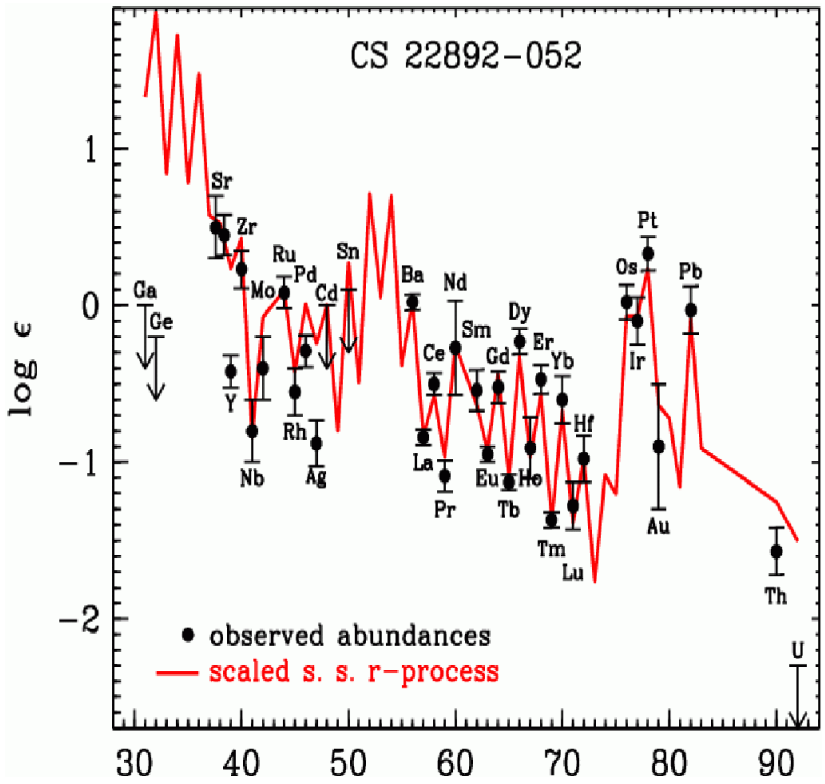
Experimental setup for ORNL-experiment



Astronomical Searches for Neutron-Capture Signatures

8m-10m telescope high-resolution spectroscopy of old, metal-poor halo stars are constraining the nature of :

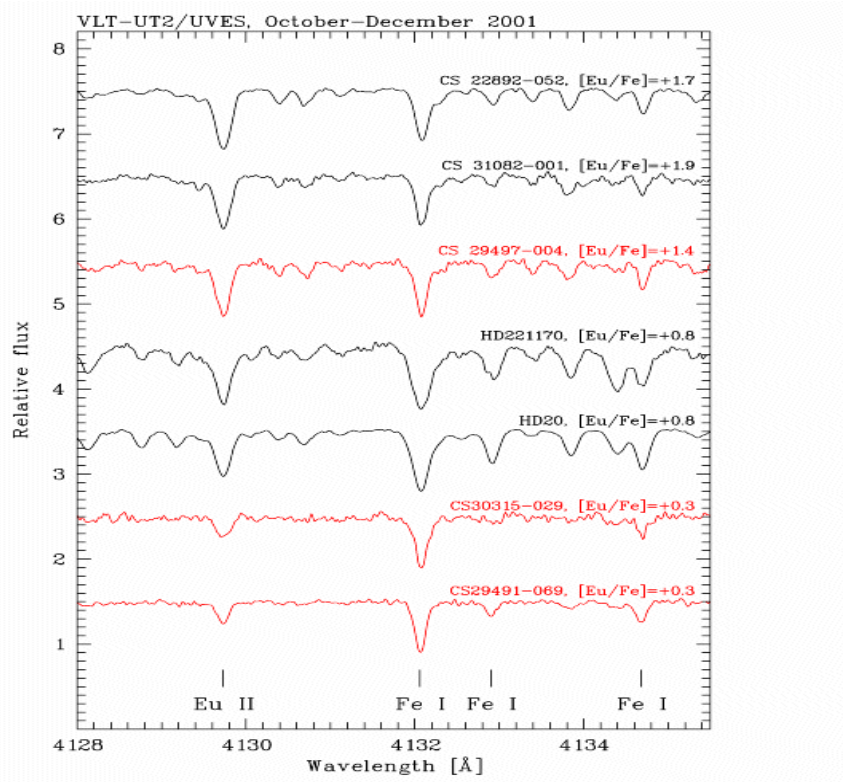
- the r-process
- the s-process
- elemental production of first-generation stars



Additional Searches for r-process Enhanced Stars

Dedicated searches of halo giants with [Fe/H] < -2.5 (VLT / Subaru) are identifying large numbers rare r- and s-process enhanced stars

Require improved masses and models for formation of neutron-capture elements



Space Observatories

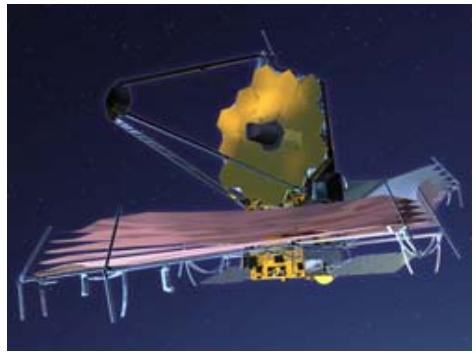
Present, near-term and long-term space-based observatories that rely on improved measurements of nuclear data:

INTEGRAL: Gamma rays as probes of composition

SWIFT: Gamma ray bursts

JWST: Direct imaging of primordial stars

Constellation X: Compact object accretion, SN remnant abundances



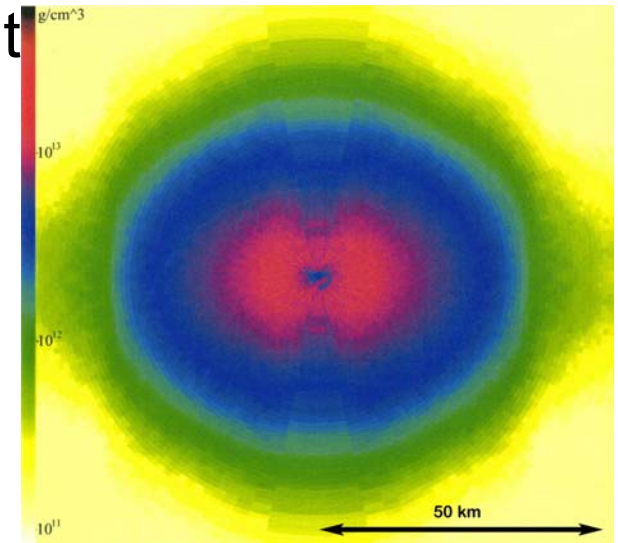
Kinetic Theory for Supernova Explosions

(*T. Strother, T. Bollenbach, W. Bauer, MSU*)

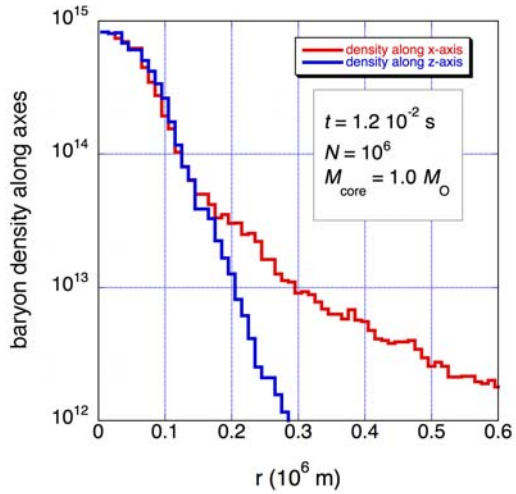
- Time evolution for one-body phase space density, $f(\vec{r},\vec{p},t)$
- Solve problem including one-body potentials (nuclear, electron, gravity) and two-body scattering
- Hydro limit: infinite scattering cross section
- Coupled equations for baryons, neutrinos, photons with realistic scattering cross sections => radiation pressure & neutrino transport
- Technology developed for description of relativistic heavy ion collisions (BUU)
- Test particle method wit

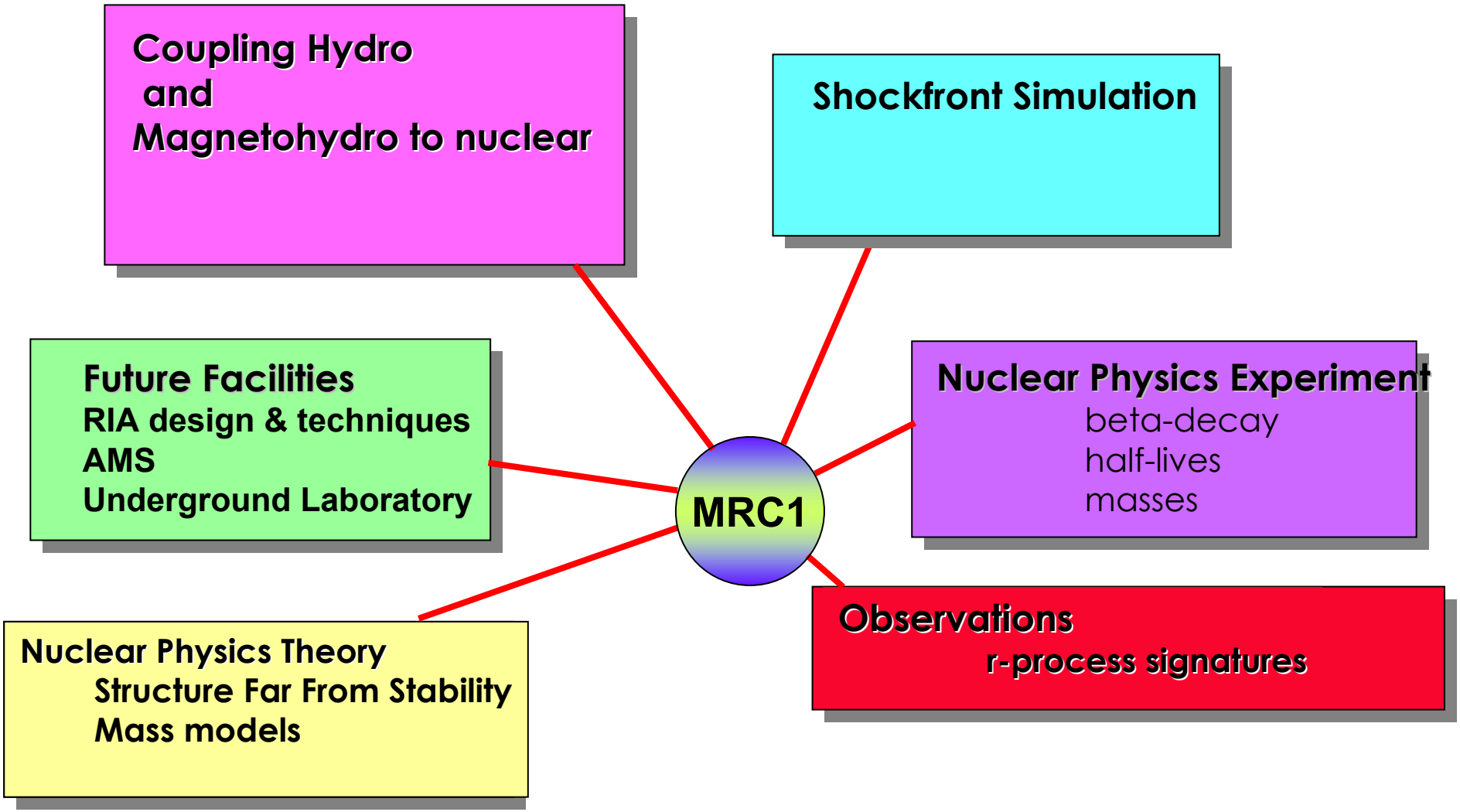
Output:

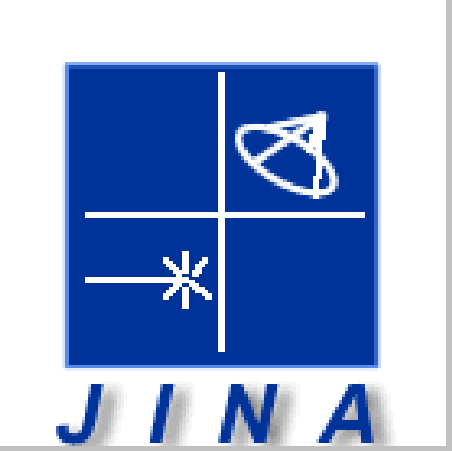
- Fully 3-dimensional code
- Effects of rotation
- Self-consistent
- Fast
- Future: magnetic fields



Rotation: Vortex formation




Coupling Hydro
and
Magnetohydro to nuclear
Shockfront Simulation
Future Facilities
RIA design & techniques
AMS
Underground Laboratory
MRC1
Nuclear Physics Experiment
beta-decay
half-lives
masses
Observations
r-process signatures
Nuclear Physics Theory
Structure Far From Stability
Mass models



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stellar evolution & type-II SN nucleosynthesis

Conclusions:

r-process studies going forward full-force

p-process collaborations in place
supplemental funding from International programs

low energy nuclear reactions