Rare Isotopes in Cosmic Explosions and Accelerators on Earth

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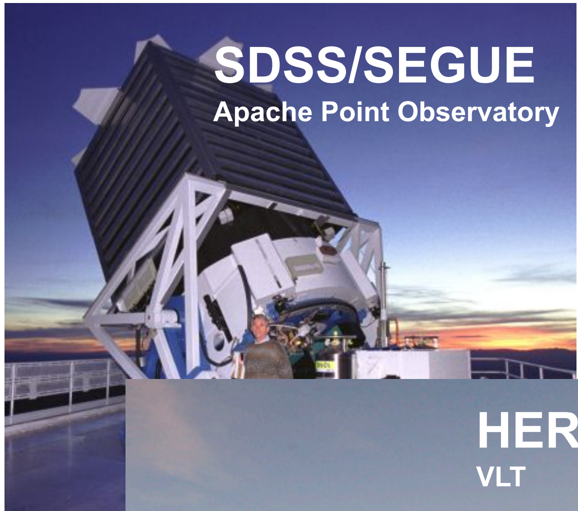
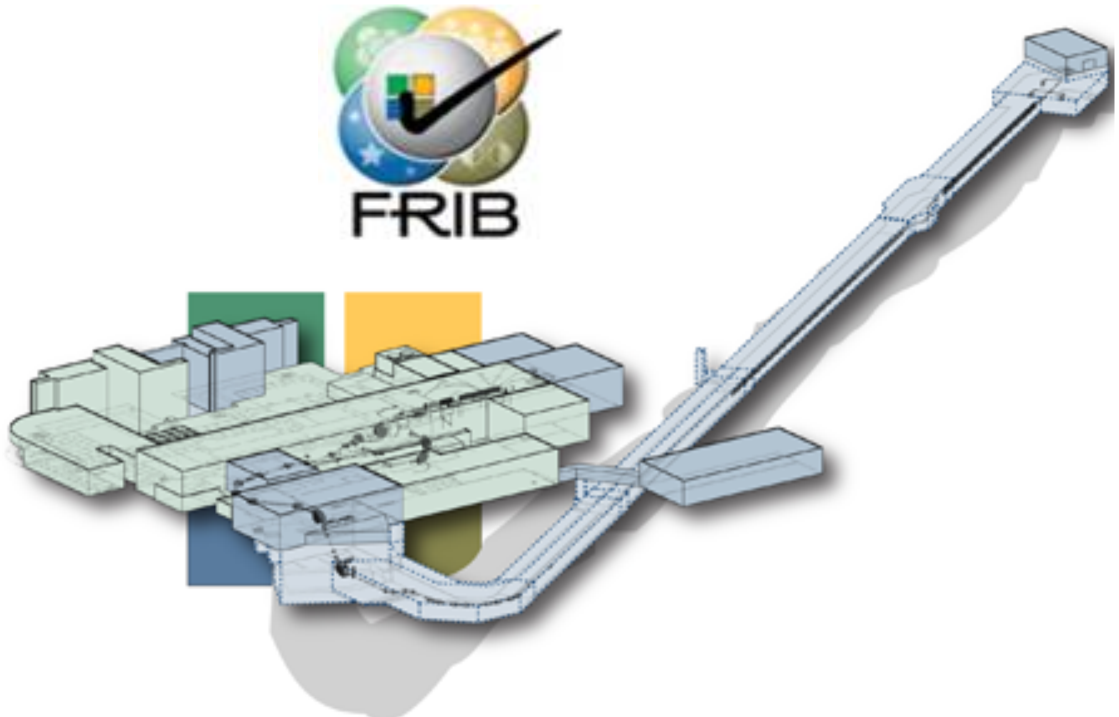
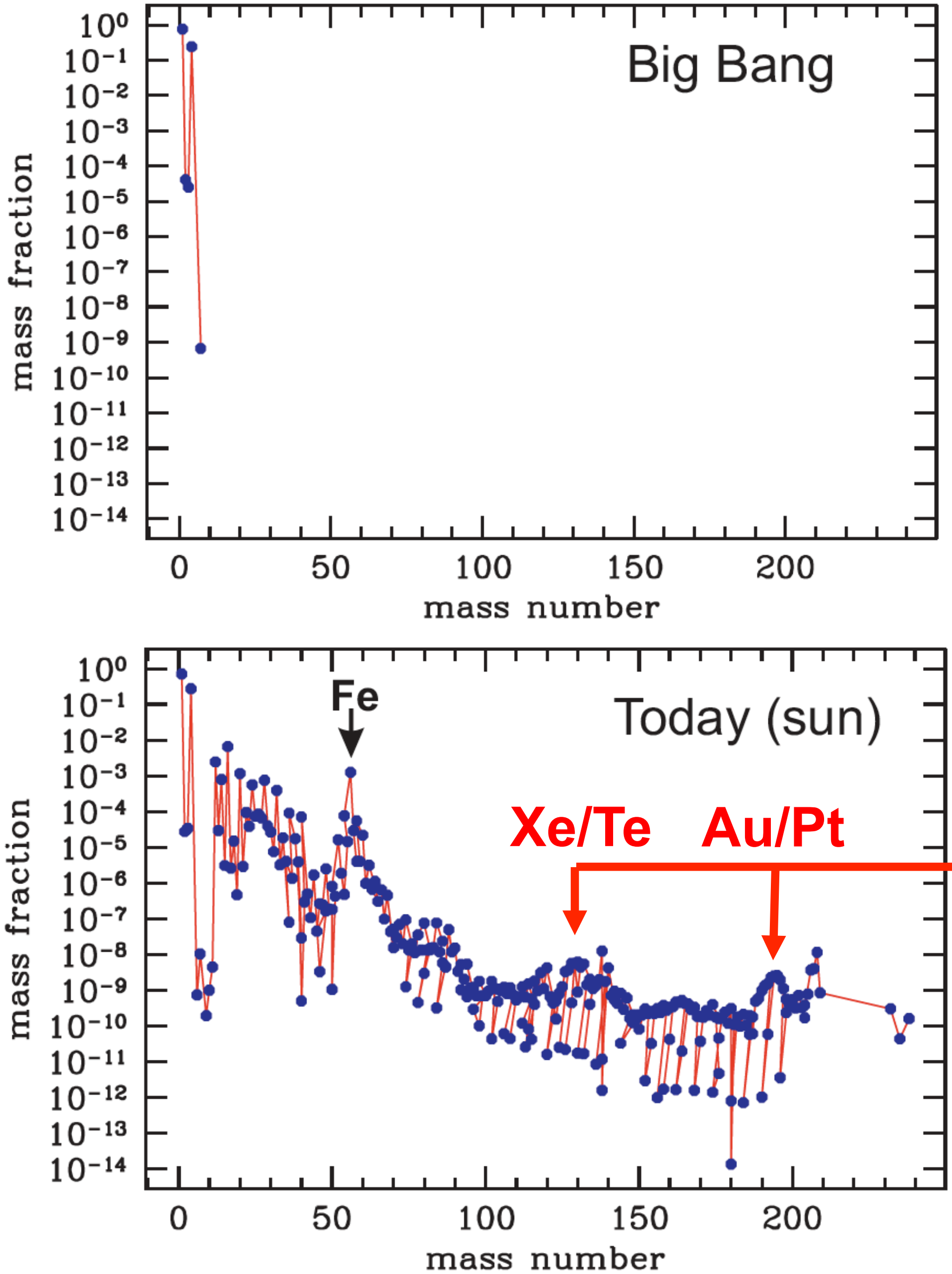


and more …



The Origin of the Elements



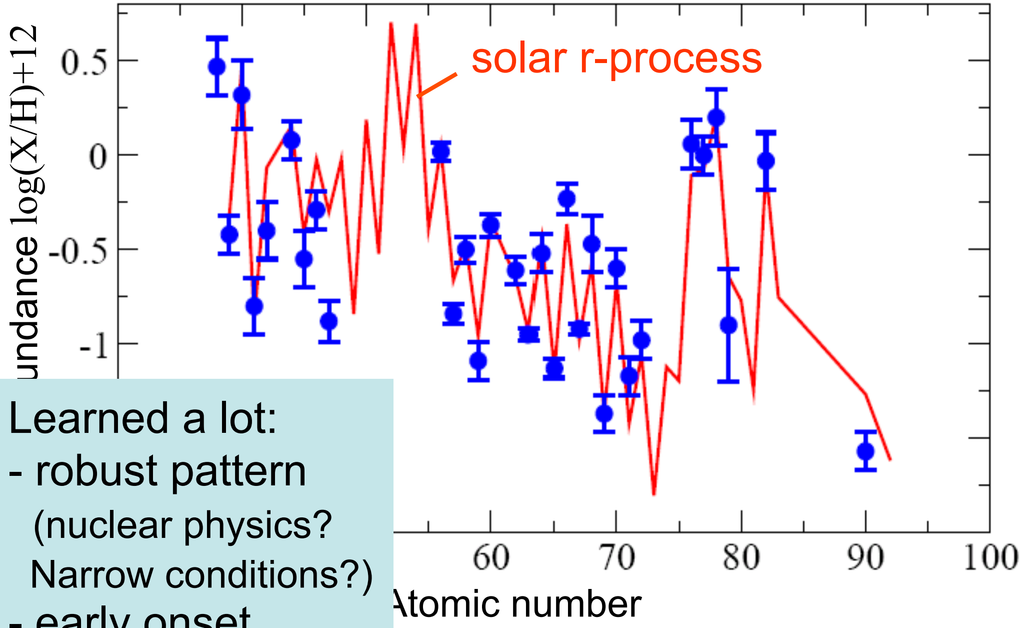
?

Signatures of rare isotope properties in r-process contribution (makes about 40% of heavy elements)

+ s-process and p-process

Major progress in astronomy – new processes found!

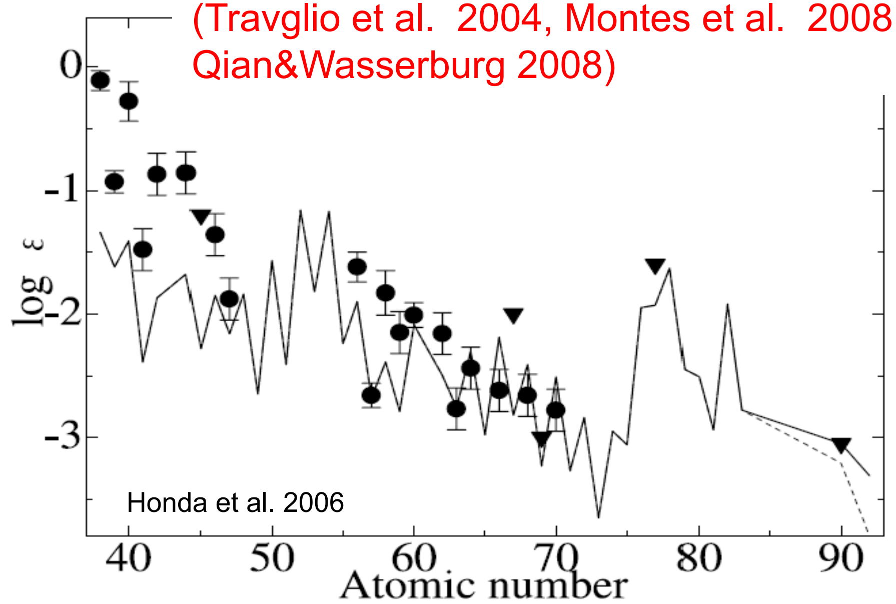
r-rich (Eu) rich, s-poor star: Main r-process

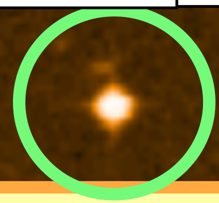


Learned a lot:
- robust pattern
  (nuclear physics? Narrow conditions?)
- early onset

r- poor, s - poor star: ?? LEPP

(Travglio et al. 2004, Montes et al. 2008 Qian&Wasserburg 2008)





CS 22892-052

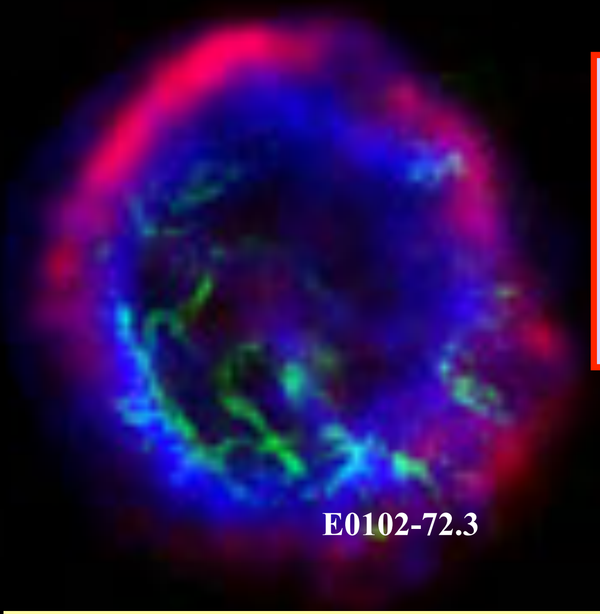
Find more such stars ?

• Ongoing Surveys (and analysis of past) sample millions of stars and will drastically increase number

→ Will obtain a fossil record of chemical evolution

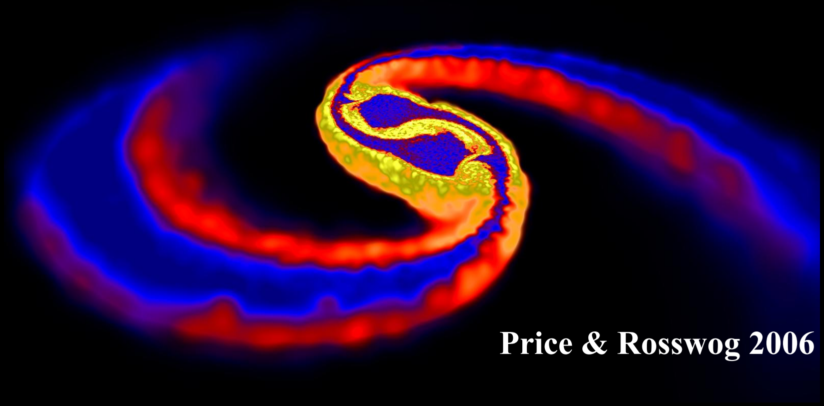
But what is the r-process site?

Supernovae: ν-driven wind?
(not enough neutrons, p-rich environment?)
Fall back? Jets? Shocked O-Ne cores?



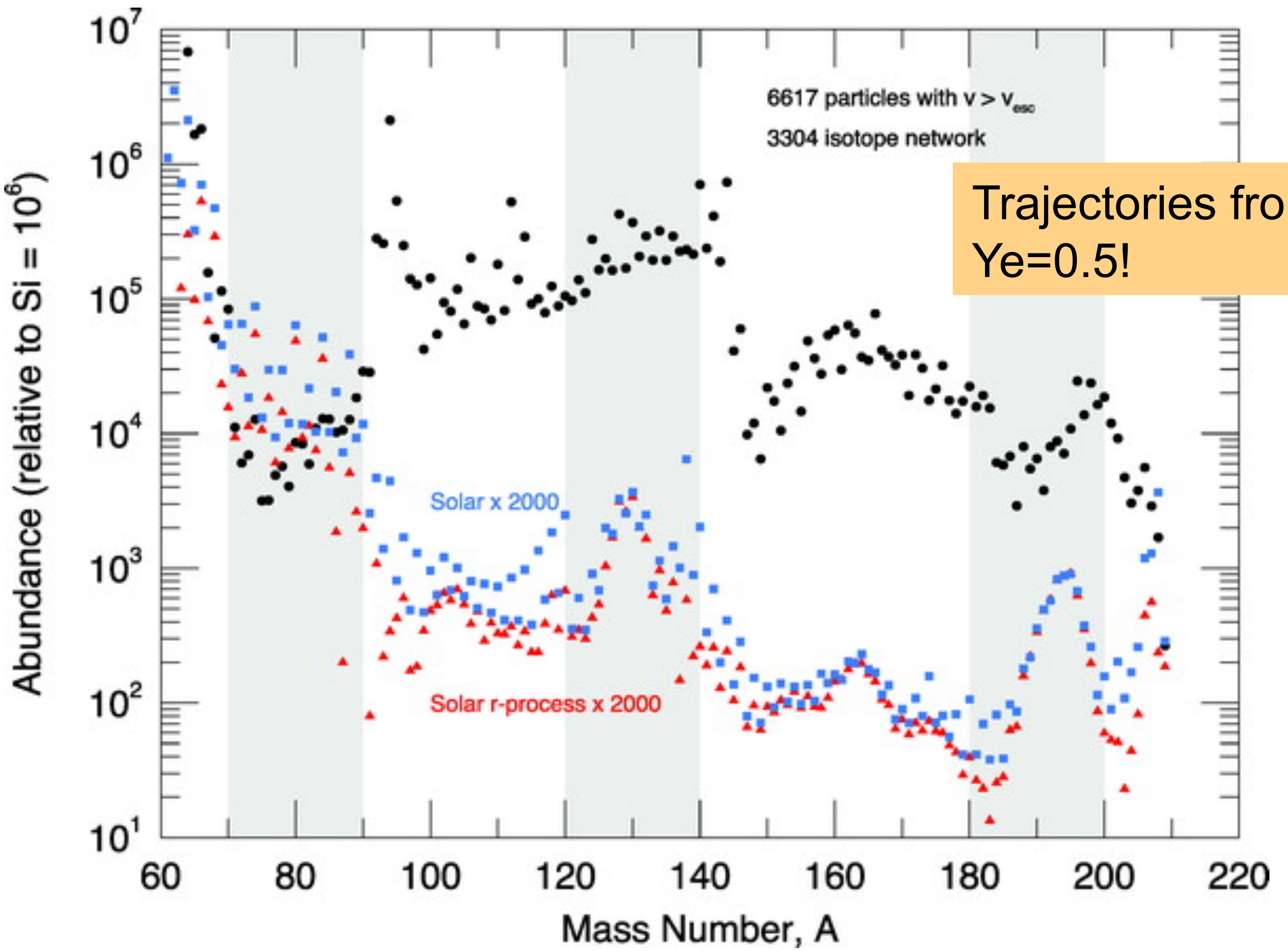
Needed: **Data**
- precision observations of abundance patterns produced by the r-process in nature
- nuclear experimental data (plus theory) for all models

Neutron star mergers ?
(to slow to fit GCE? Ejected material?)



Gamma ray burst accretion disks ?
(too rare)

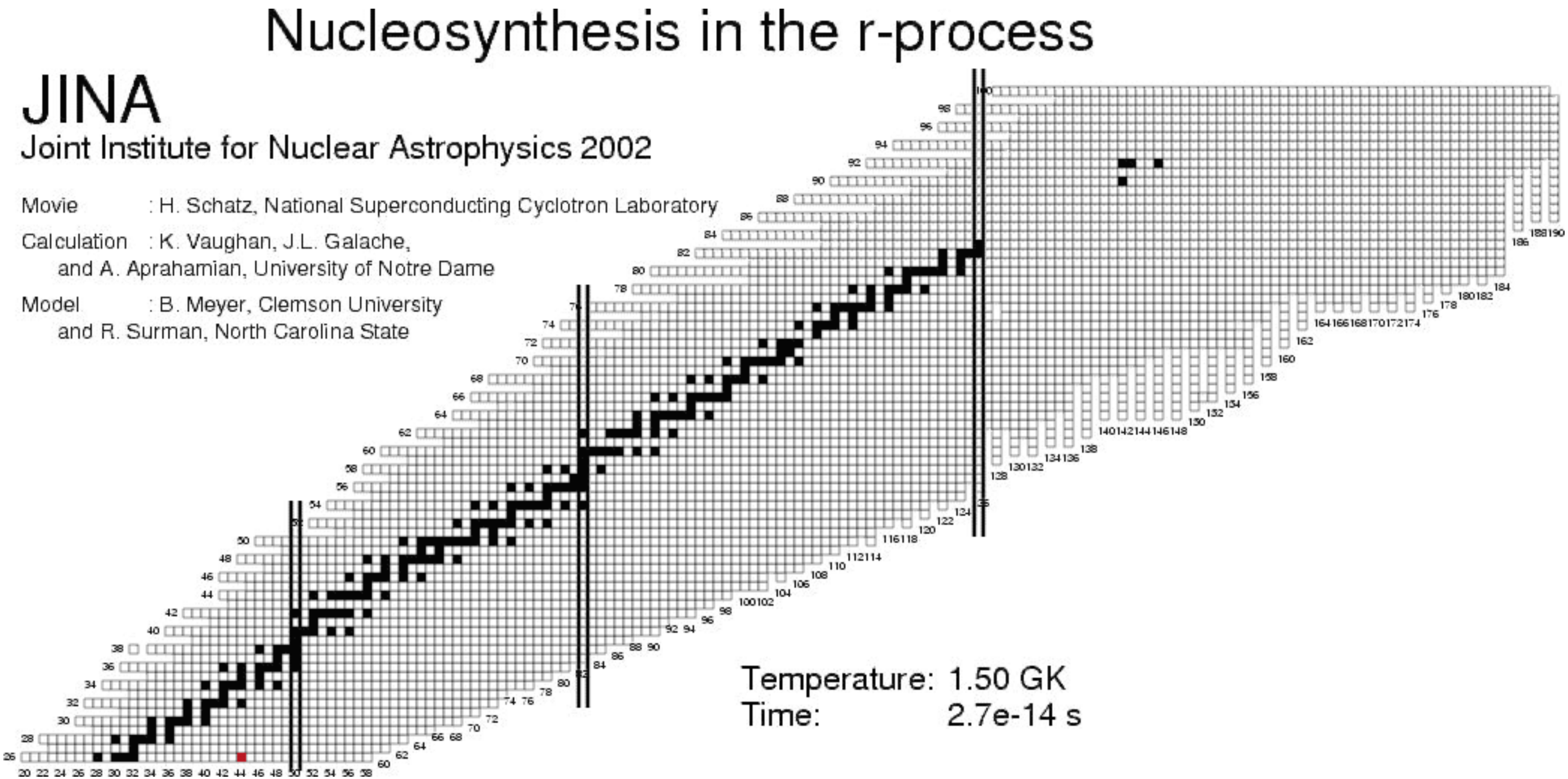
Example: Supernova fallback (Fryer et al. 2006)



Trajectories from 2D SN model
Ye=0.5!

"… our current simulation is far from reproducing the solar *r*-process signature. […] One reason for this could well be the uncertainties in the β-decay rates."
(Fryer et al. 2006)

A possible pathway of the r-process

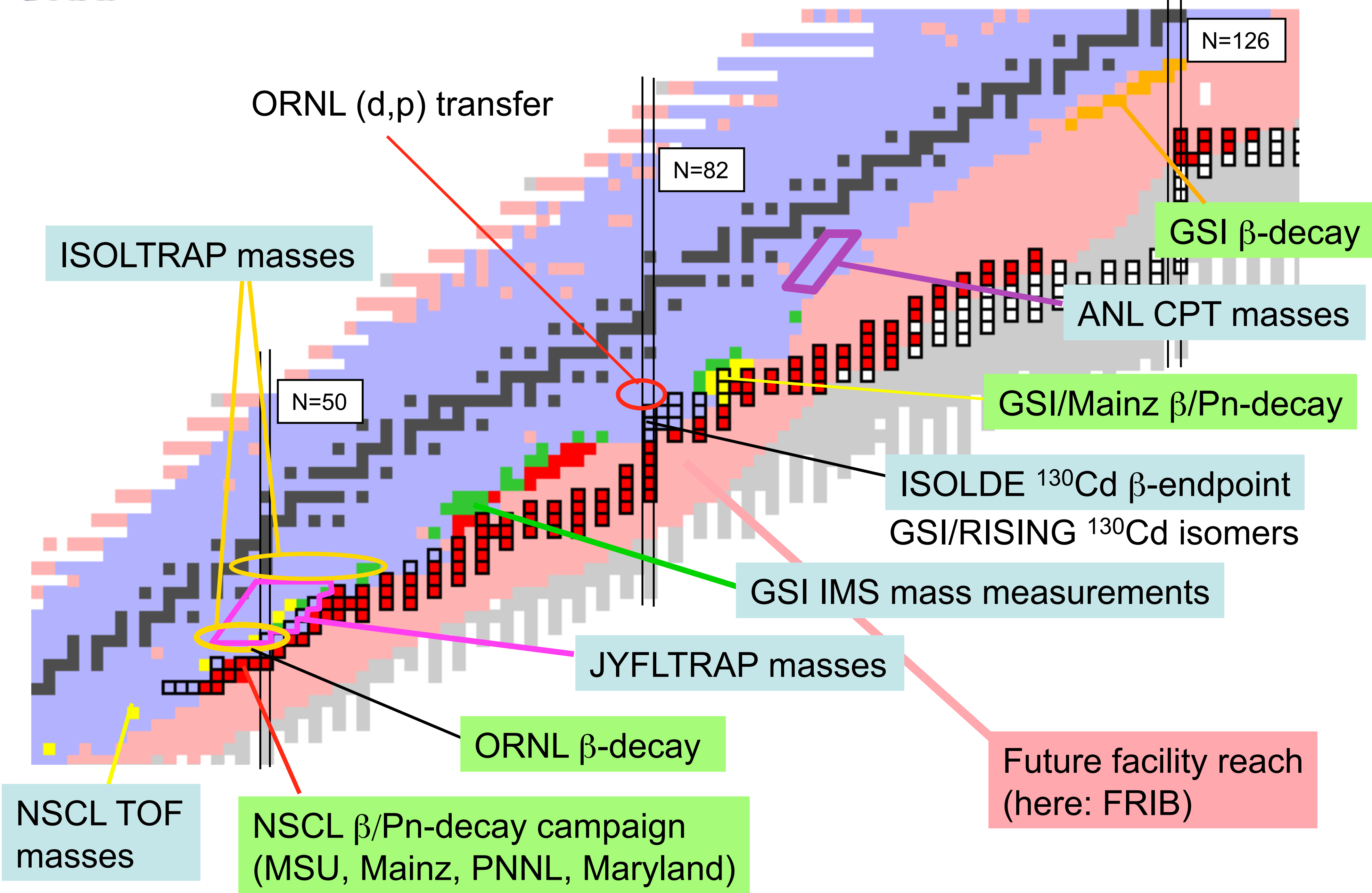


Compare calculated results with many precision abundance observations ?

→ Masses, half-lives, and n-emission of very unstable, exotic nuclei need to be known

→ Need experimental data and nuclear theory (for addtl. data and astro corr.)

Recent r-process related experiments



National Superconducting Cyclotron Laboratory

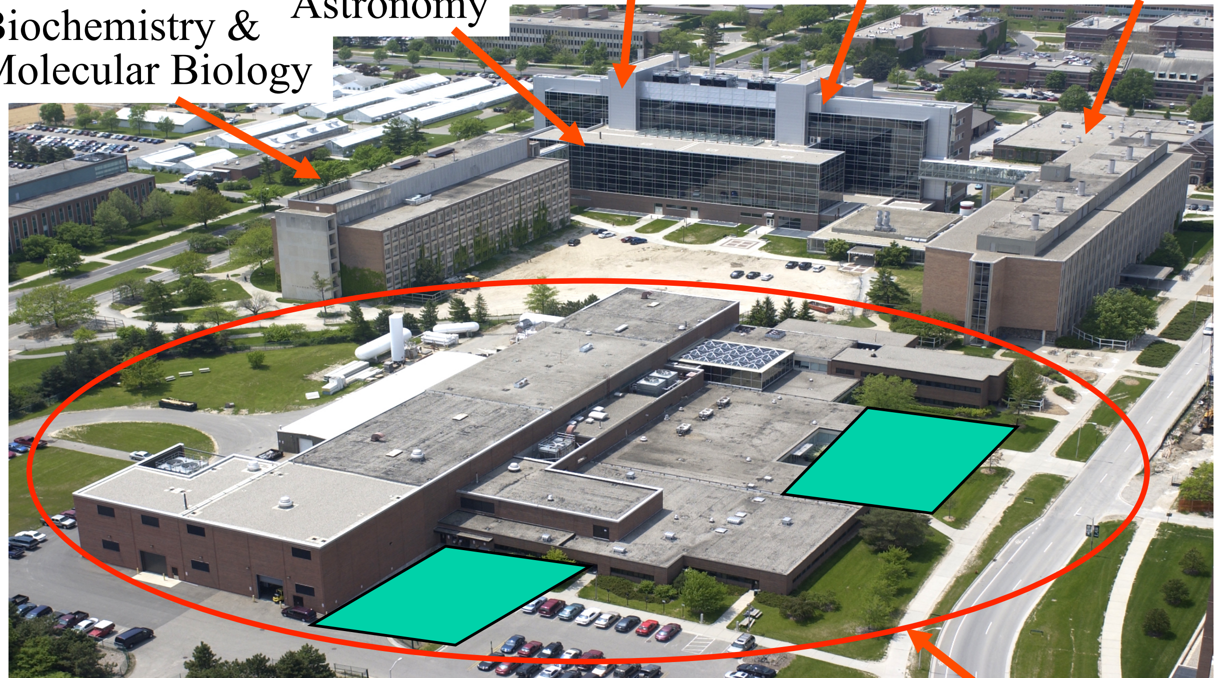
MICHIGAN STATE UNIVERSITY

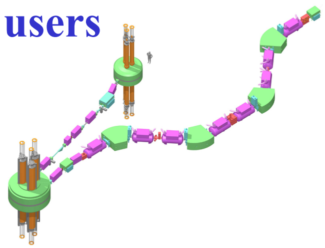
A national user facility for research and education in:

- **Nuclear science**
- **Astro-nuclear physics**
- **Accelerator physics**
- **Societal applications**

~50 Undergraduate students
~71 Graduate students
~19 Postdocs
~33 Faculty
~170 Staff

The Coupled Cyclotron Facility user group has 700 registered users



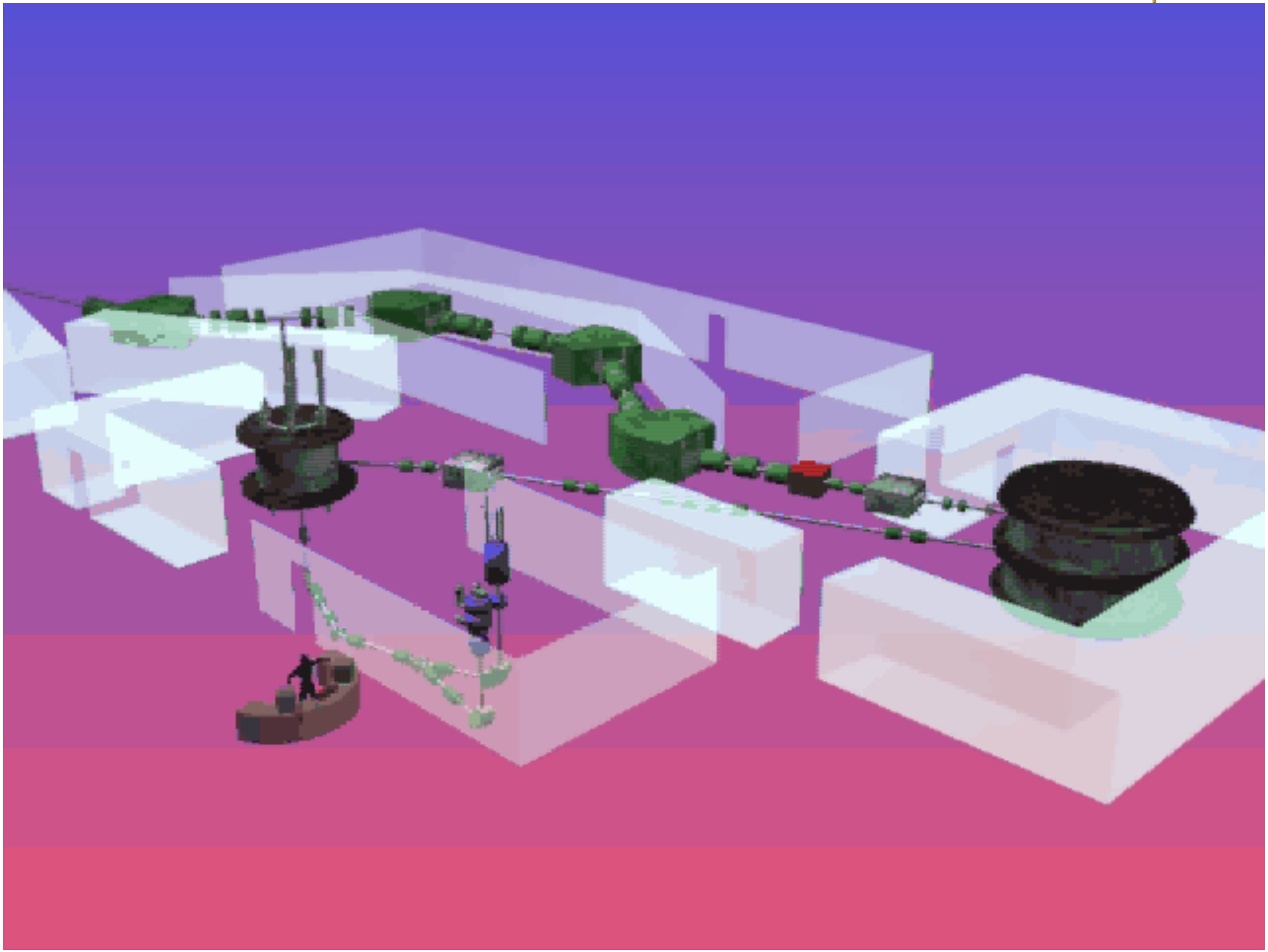


The NSCL is located on the campus of Michigan State University

NSCL

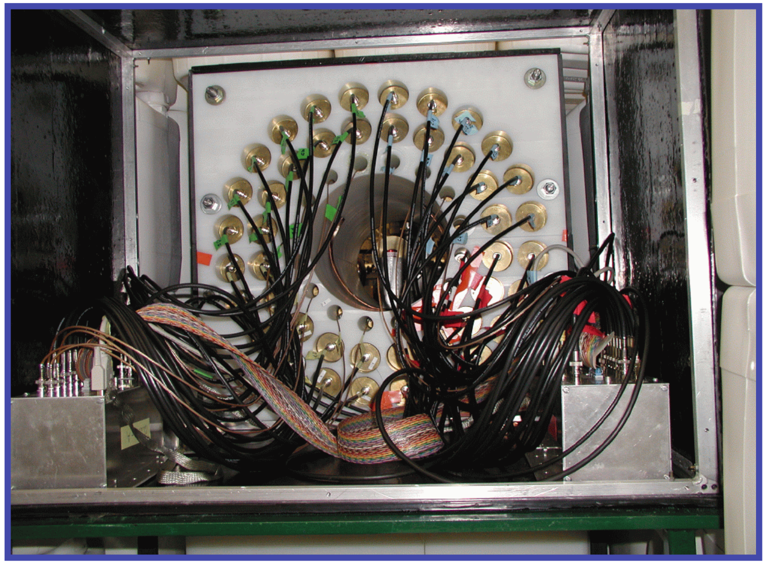
Funded by the National Science Foundation (NSF)

NSCL Coupled Cyclotron Facility since 2001



The Joint Institute for Nuclear Astrophysics

Mainz - Notre Dame - NSCL collaboration

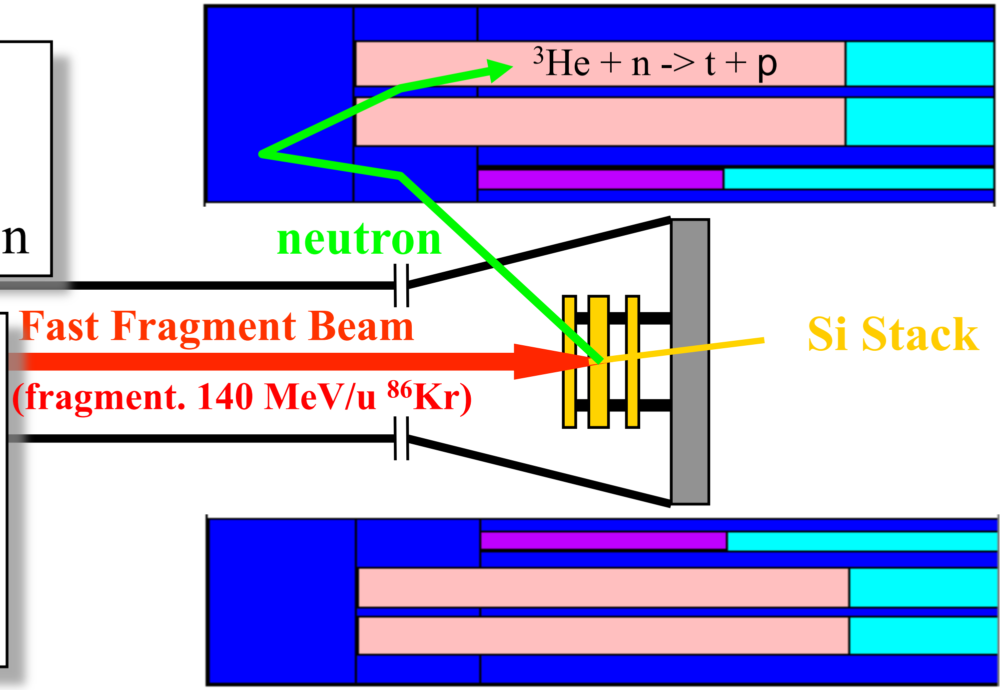


NERO efficiency: 30-38% for <2 MeV

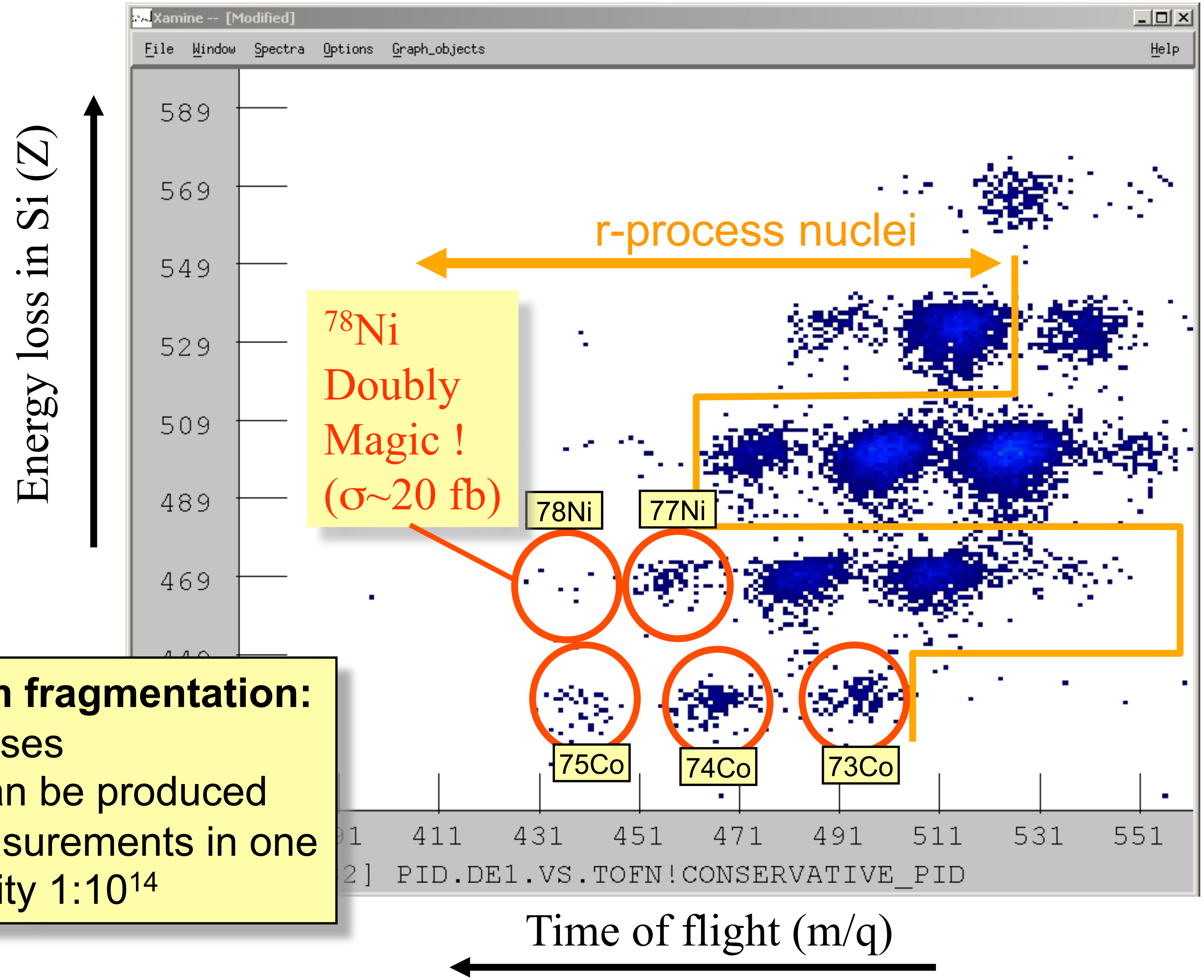
Measure:
- β-decay half-lives
- Branchings for β-delayed n-emission

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

New NSCL Neutron detector NERO



Particle Identification

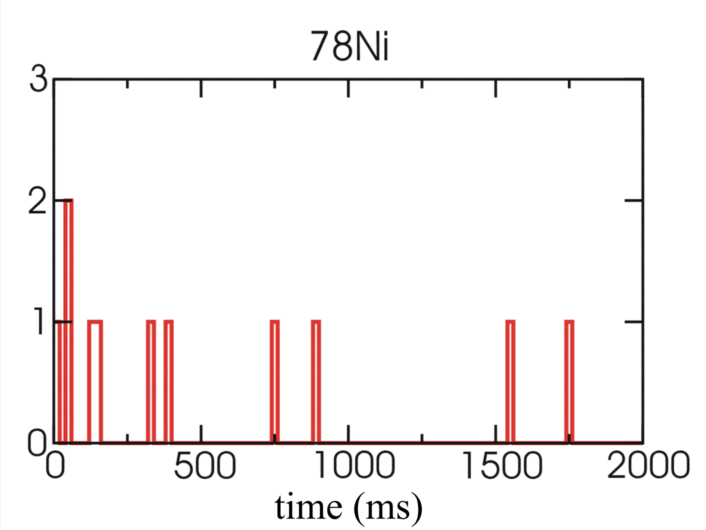


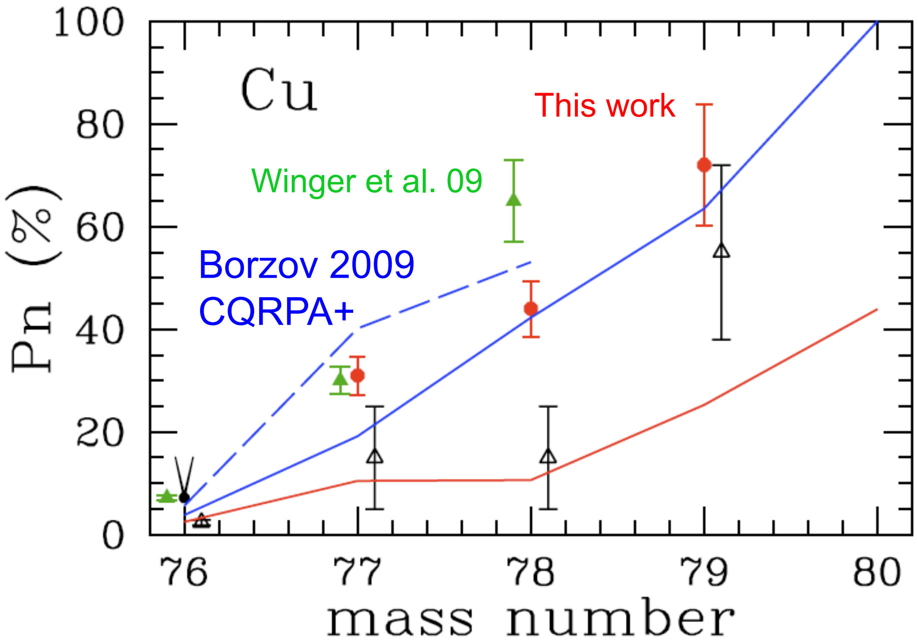
Fast RIB from fragmentation:

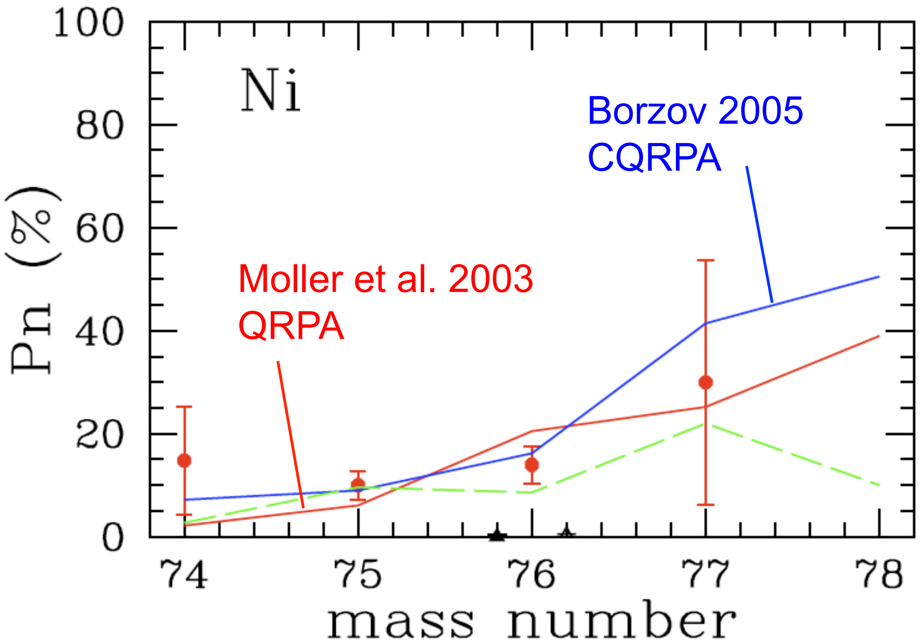
- no decay losses
- any beam can be produced
- multiple measurements in one
- high sensitivity 1:10^{14}

Some results from the Mainz/MSU/Notre Dame campaign

Time between arrival and decays:





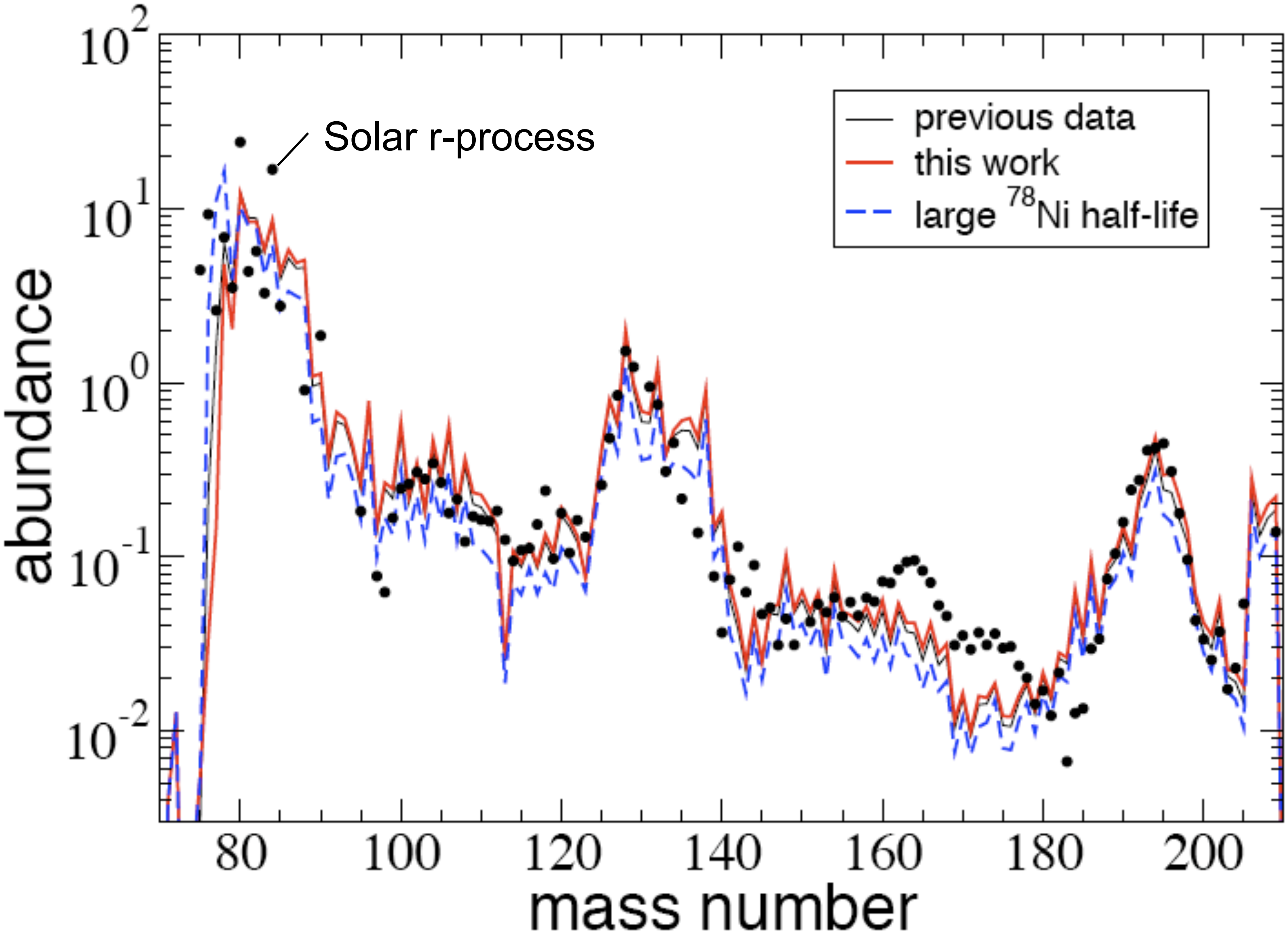


Result for half-life:

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

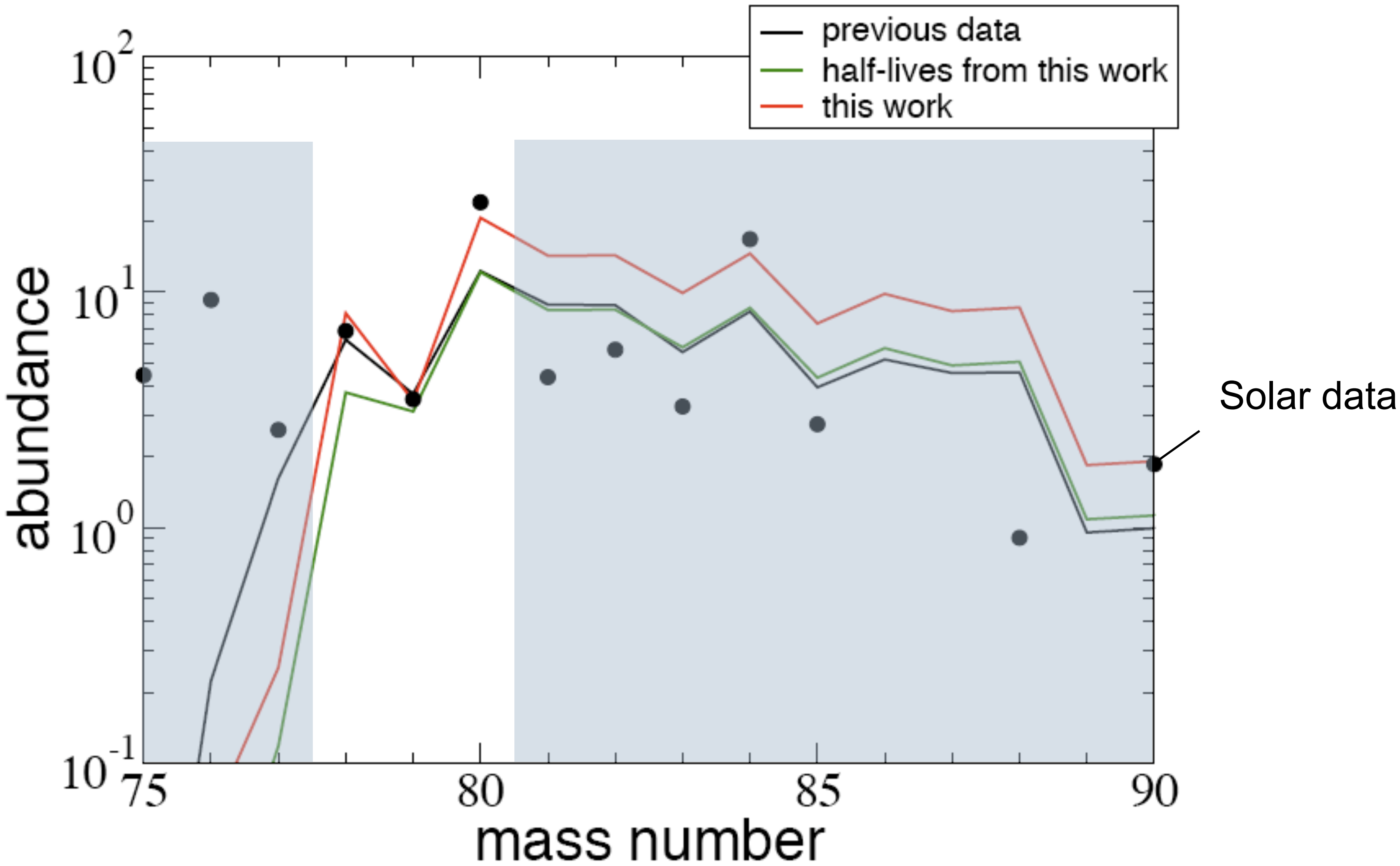
Compare to theoretical estimate used:470 ms

Classical model fit (3 parameters describing $n_n(t)$ and T)



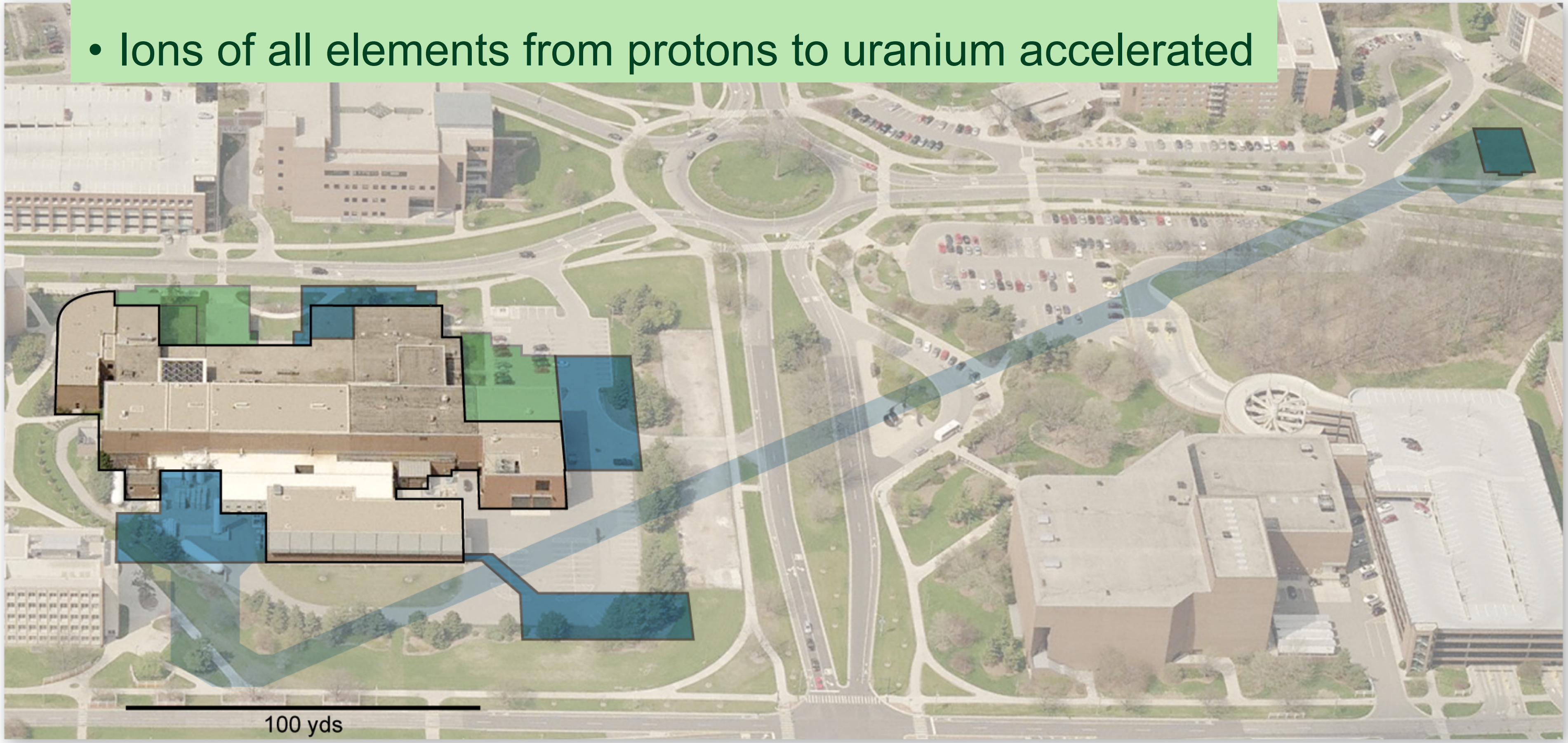
Can we perform a first test for classical model?

Together with precision mass measurements of ^{80}Zn, ^{81}Zn (Baruah et al. 2009)



FRIB project on MSU Campus

- Driver linac with 400 kW and greater than 200 MeV/u for all ions
- Ions of all elements from protons to uranium accelerated



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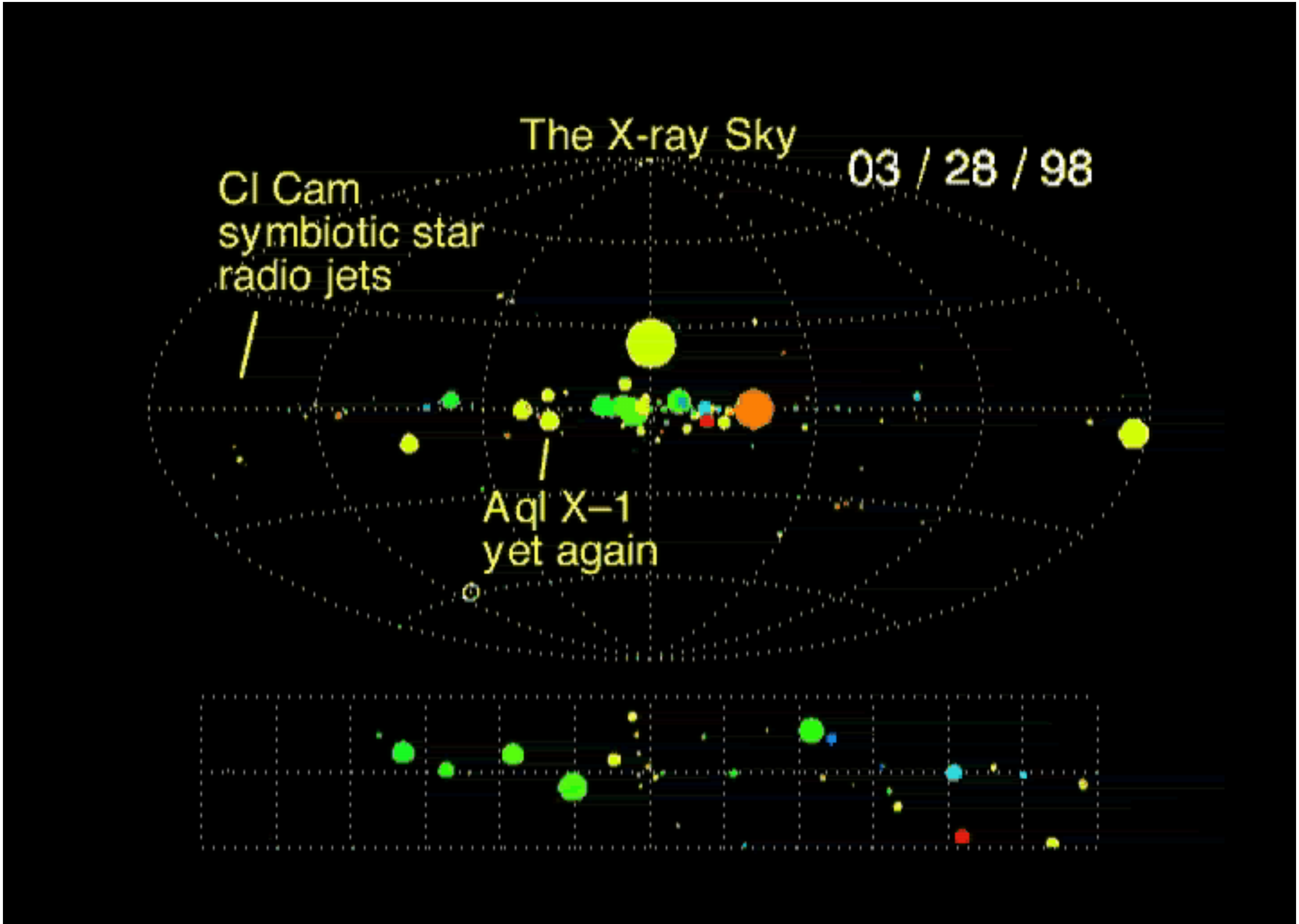
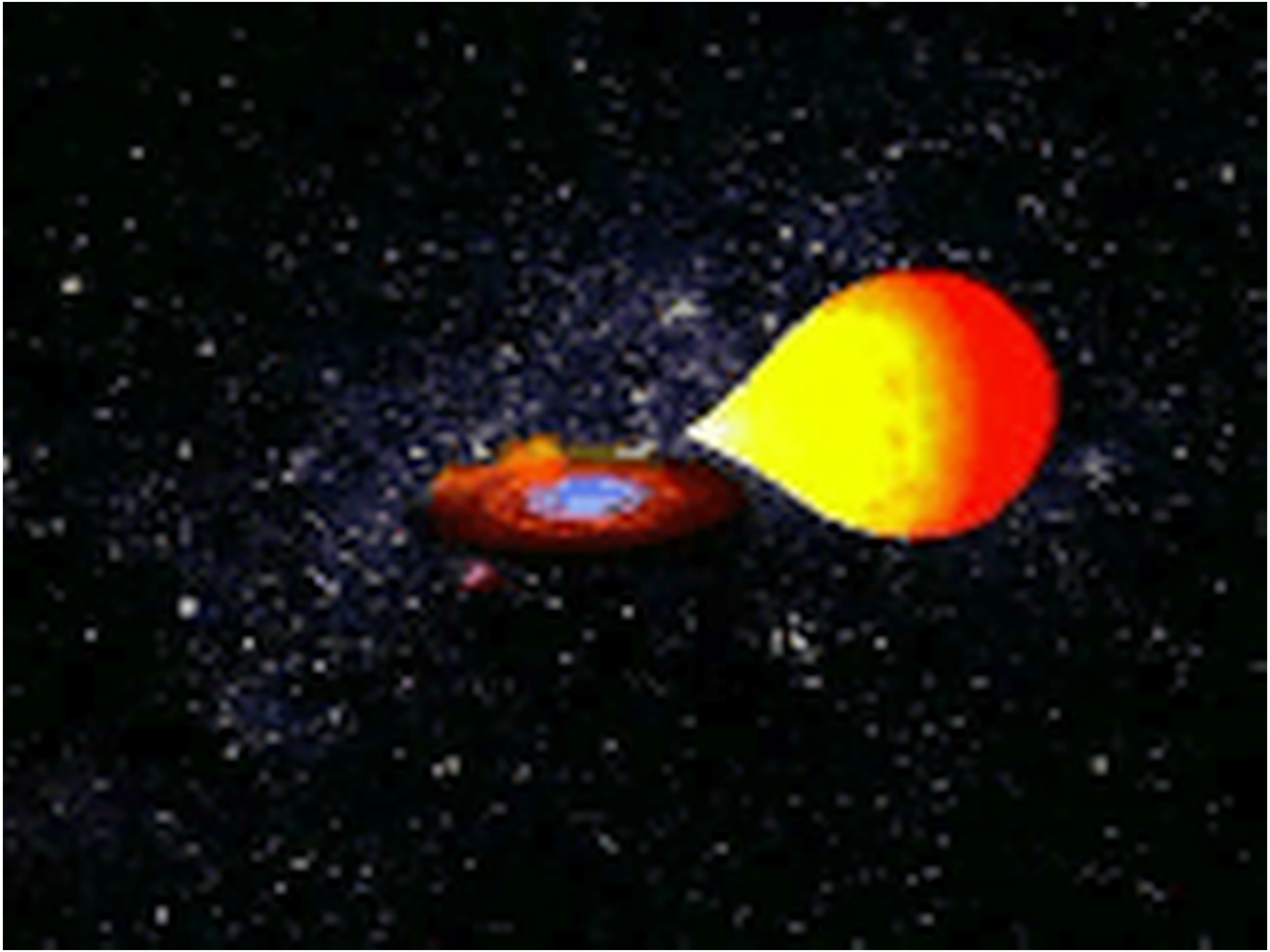
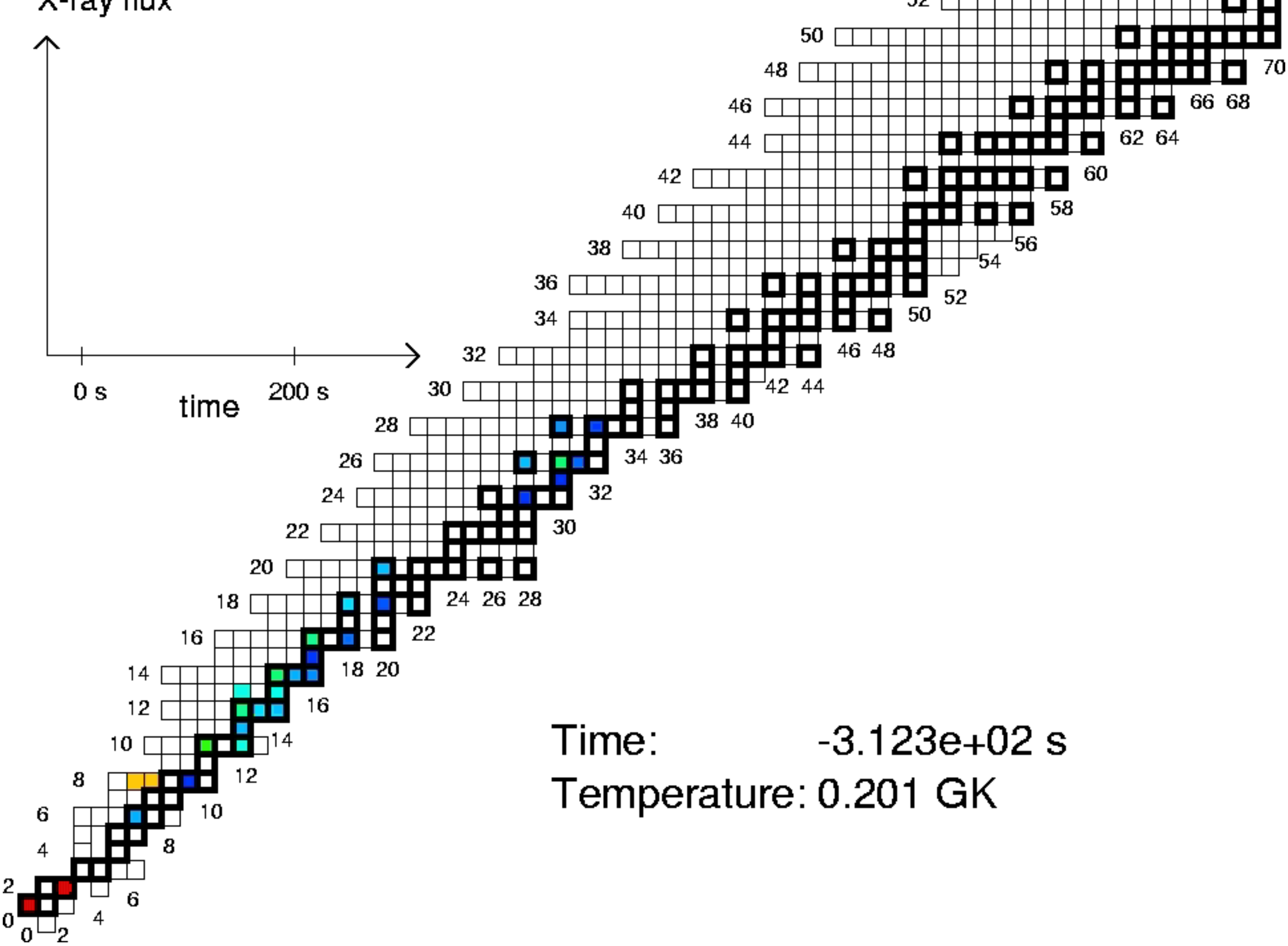
Office of Science



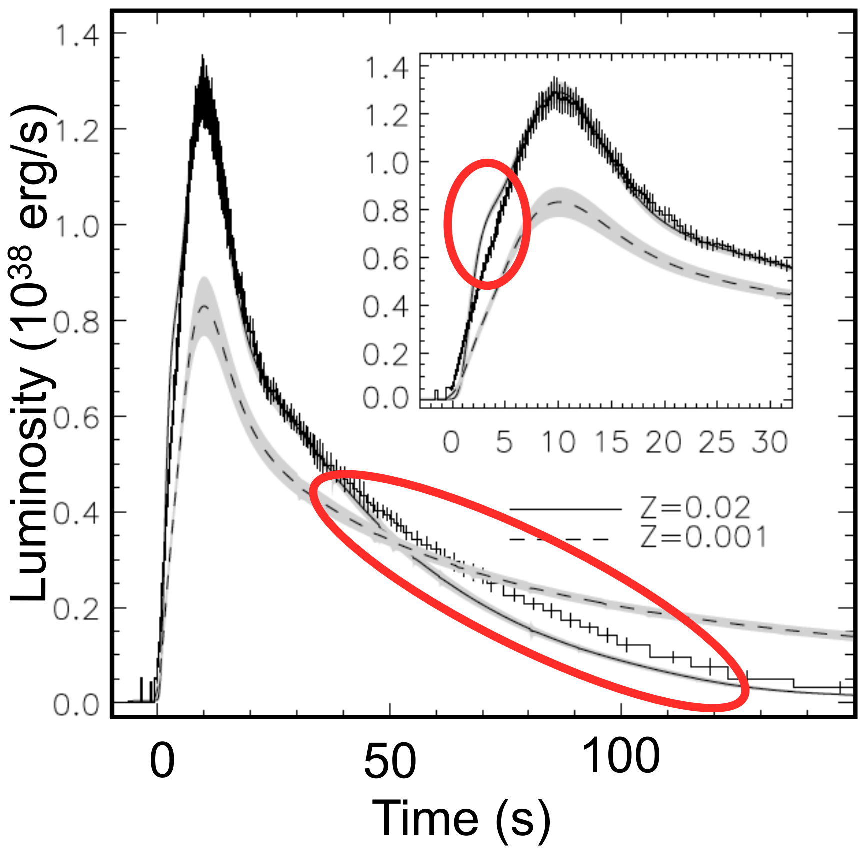
D.A. Smith, M. Muno, A.M. Levine, R. Remillard, H. Bradt 2002 (RXTE All Sky Monitor)




X-ray flux
time
0 s
200 s
Time: -3.123e+02 s
Temperature: 0.201 GK

Open questions

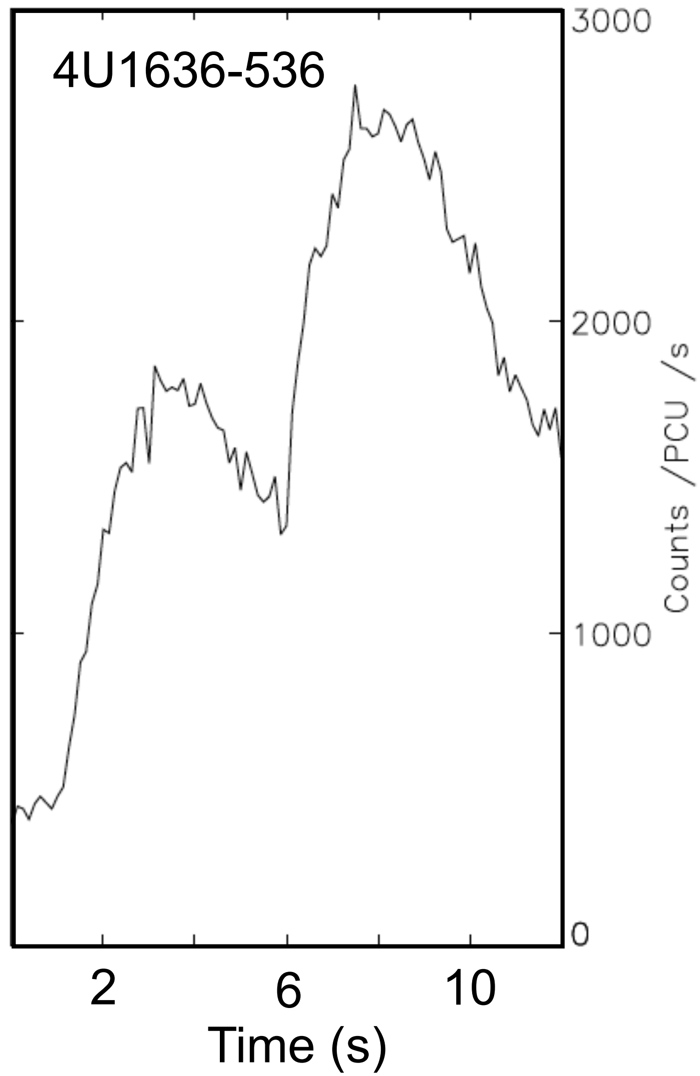
Textbook burster GS1826-24



Heger et al. 2008

- extract quantitative system characteristics (accretion rate and composition, NS properties)
- search for signatures beyond simple 1D model

Multi-peaked burst rises?



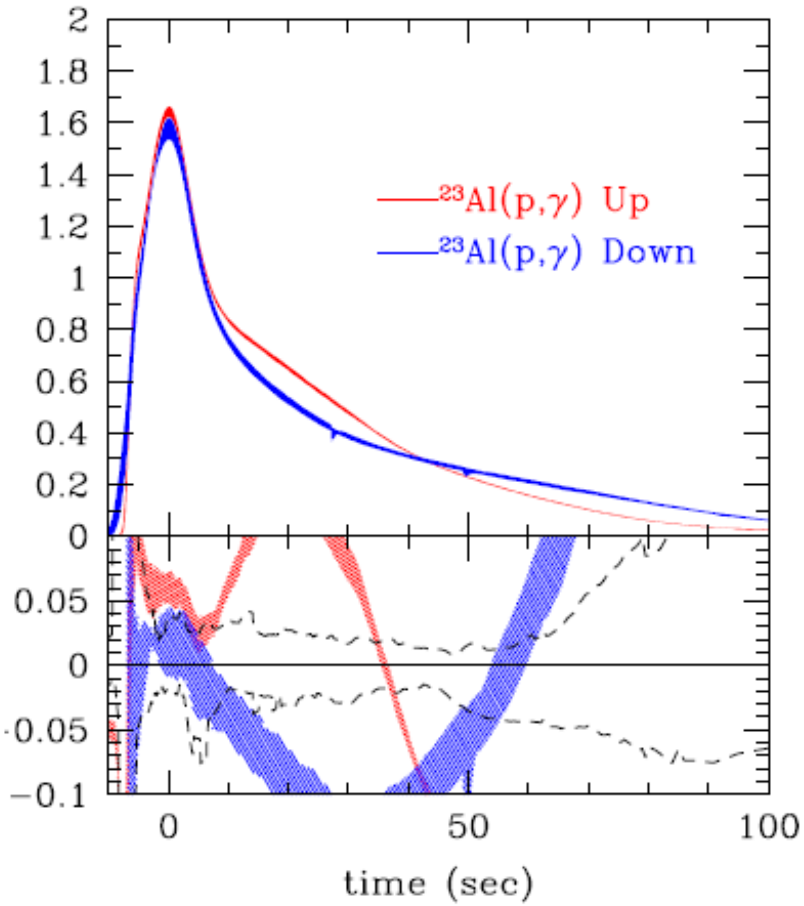
Maurer&Watts 2008

Nuclear reaction rates matter !

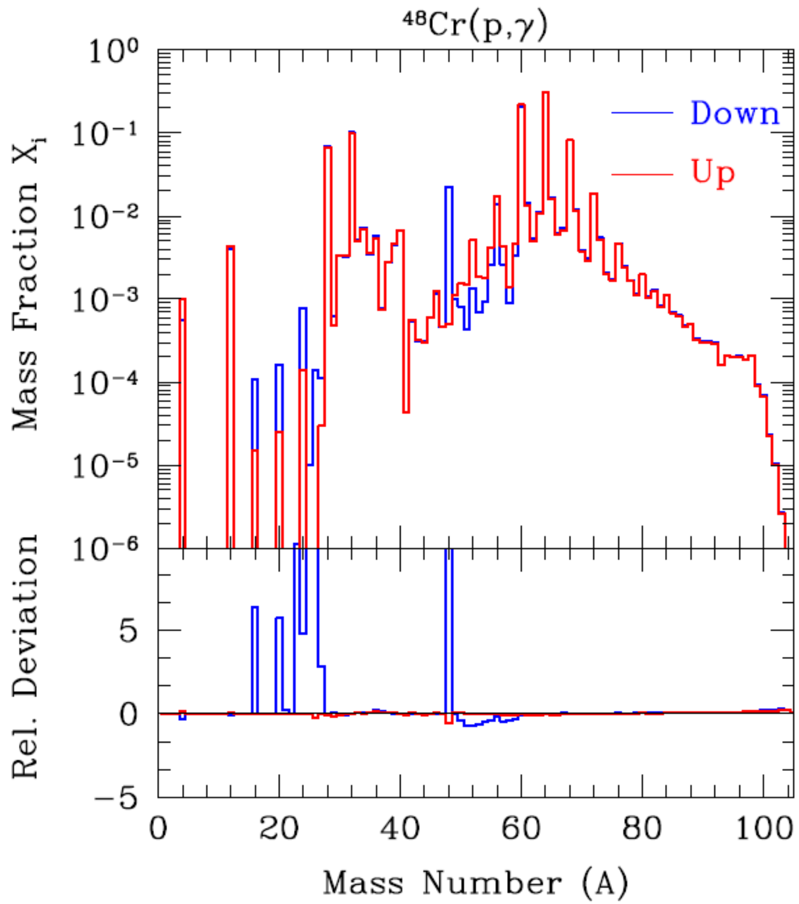
The Joint Institute for Nuclear Astrophysics

First sensitivity study for full 1D burst model from Heger (Cyburt, Amthor, et al.)

Burst X-ray light curve



Final composition of ashes



(see also post-processing study by Parikh et al. 2008)

Nuclear input:

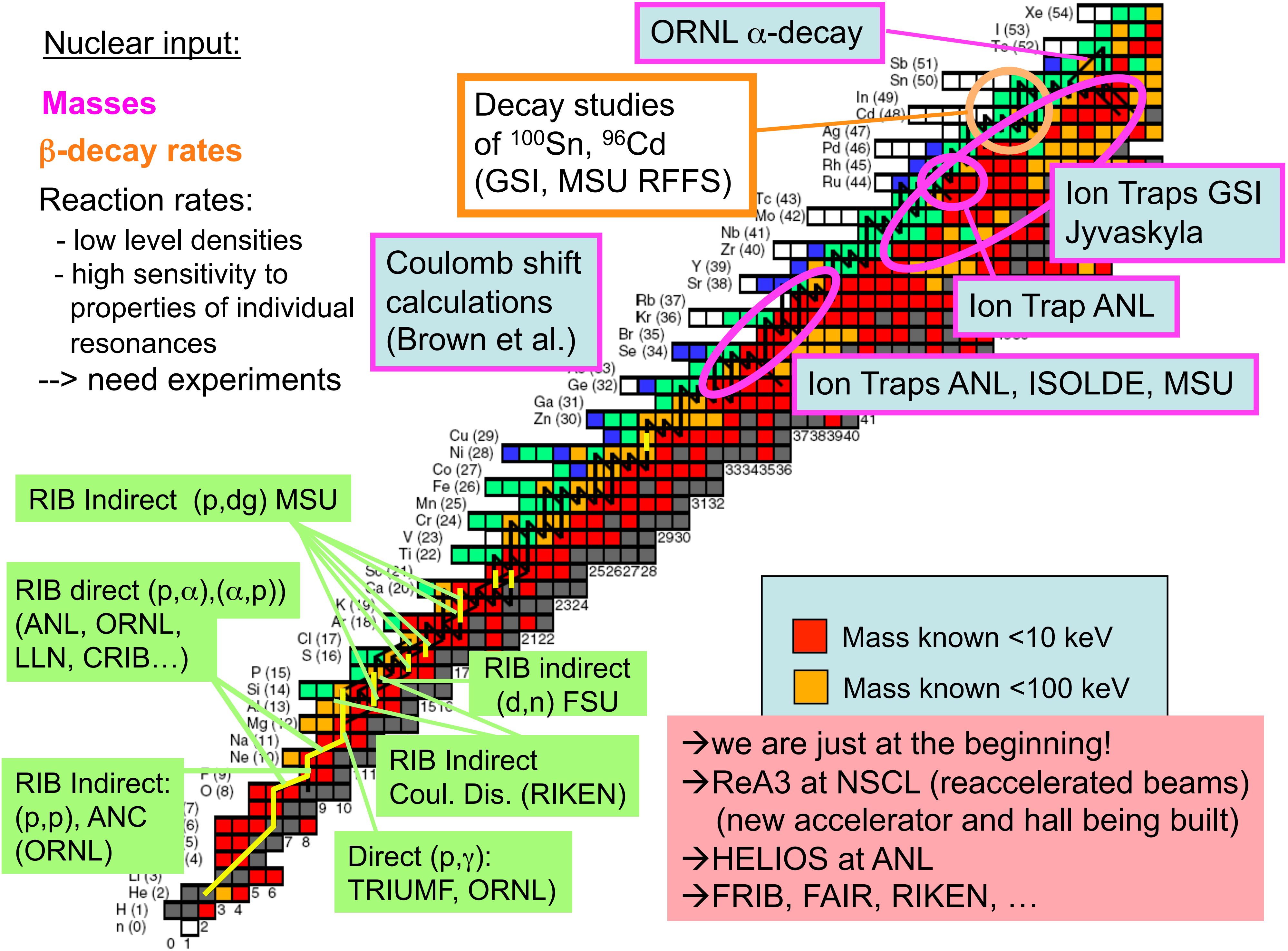
Masses

β-decay rates

Reaction rates:

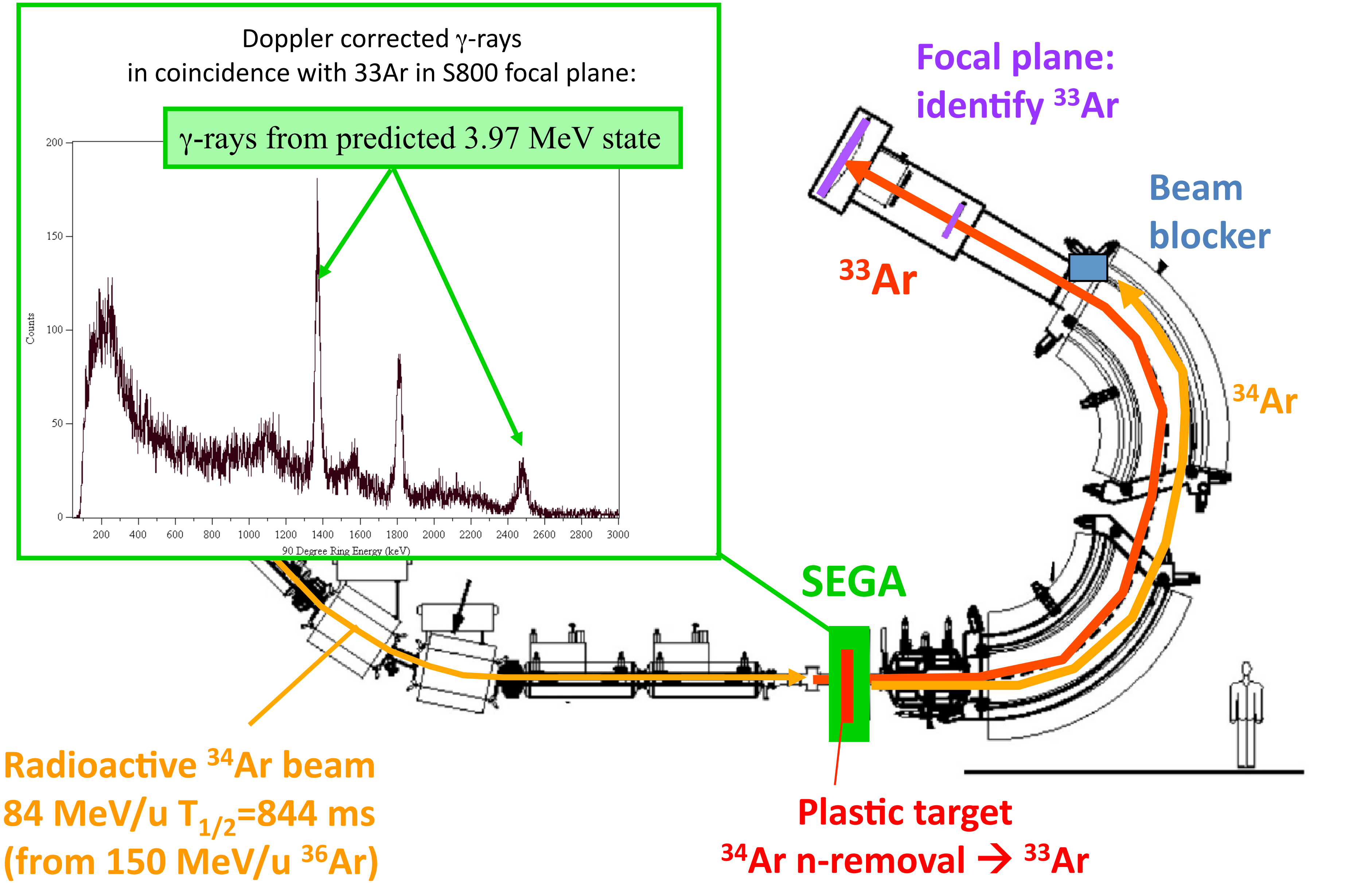
- low level densities
- high sensitivity to properties of individual resonances

--> need experiments



→we are just at the beginning!
→ReA3 at NSCL (reaccelerated beams) (new accelerator and hall being built)
→HELIOS at ANL
→FRIB, FAIR, RIKEN, …

n-removal related to astrophysical $^{32}Cl + p \rightarrow ^{33}Ar + \gamma$ rate at NSCL



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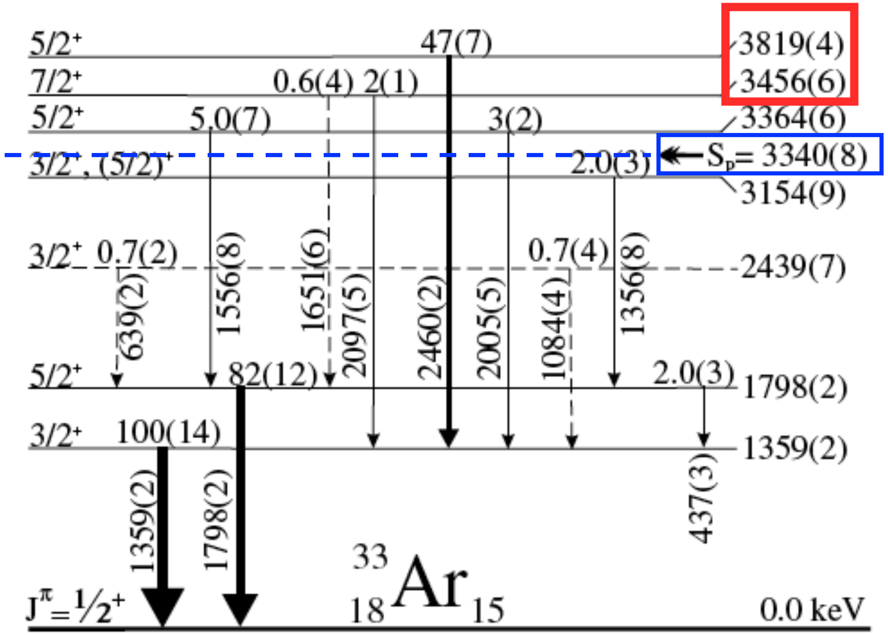
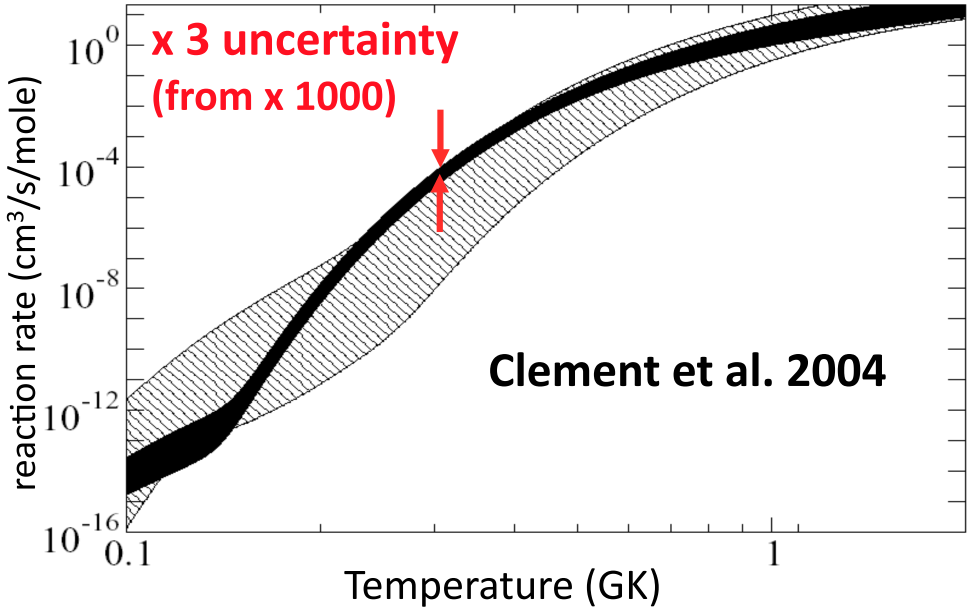
n-removal at NSCL



$^{32}Cl(p,\gamma)^{33}Ar$ astrophysical reaction rate



Other examples: Yoneda et al. 2006: ^{24}Si; **Amthor** et al.: ^{37}Ca; **Galaviz** et al. : ^{30}S; Chen et al.: ^{26}Si

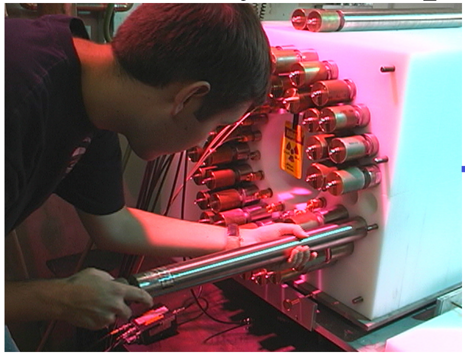
- first and dominant step in improving rate uncertainties
- further improvements IF NEEDED
  - better shell model
  - transfer reactions for p-widths, mirror lifetime for g-widths
  - direct measurement of rate with ^{32}Cl beam on p target

Joint Institute for Nuclear Astrophysics (JINA)

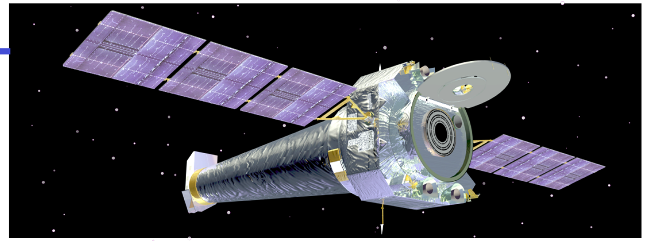
a NSF Physics Frontiers Center – **www.jinaweb.org**

- Interdiciplinary approach to nuclear astrophysics research
- JINA schools, workshops, and conferences
- Virtual Journal for Nuclear Astrophysics
- Continuously updated public data base for reaction rates (reaclib)

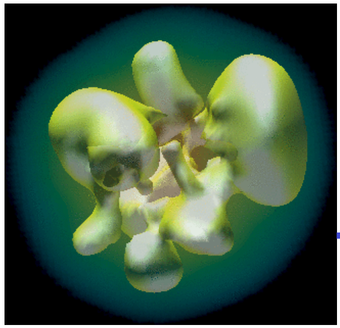
Nuclear Physics Experiments



Astronomical Observations



Astrophysical Models



JINA

Core institutions:
- **Notre Dame**
- **MSU**
- **U. of Chicago**

Associated:
- **Arizona State University**
- **Argonne Natl. Lab**
- **Princeton**
- **University of Minnesota**
- **University of Victoria**
- **EMMI (GSI)**
- **LANL**
- **UC Berkeley**
- **Universe Cluster Munich**
- **Western Michigan**

Nuclear Theory

Summary

- Rare isotopes play a critical role in the cosmos
  - as the progenitors of many of the stable isotopes found in nature
  - as energy source in thermonuclear explosions (X-ray bursts)
  - in the crusts of neutron stars

- We are now entering an era where, enabled by new machines such as FRIB there is hope to study most of the relevant rare isotopes
  (others: ISAC-TRIUMF, FAIR, RIKEN-RIBF, SPIRAL-II, …)

- In nuclear astrophysics, interdisciplinary approaches are necessary
  Field is getting into shape with Joint Institute for Nuclear Astrophysics, EMMI, Munich Universe Cluster, …

- In nuclear astrophysics: strong interplay with reactions on stable isotopes
  also need stable beam accelerators, DUSEL, e-beams, γ-beams, ν-beams …

Collaboration for NSCL r-process experiments

P. Hosmer,[1,2] A. Aprahamian,[3,4] O. Arndt,[5] R. R. C. Clement,[1,6] A. Estrade,[1,2] K.-L. Kratz,[5,7] S. N. Liddick,[1,8] A. F. Lisetskiy,[9] P. F. Mantica,[1,8] P. Möller,[10] W. F. Mueller,[1] F. Montes,[1,4] A.C. Morton,[1,11] M. Ouellette,[1,2] E. Pellegrini,[1,2] J. Pereira,[1,4] B. Pfeiffer,[5] M. Quinn,[3,4] P. Reeder,[12] P. Santi,[1,13] H. Schatz,[1,2,4] M. Steiner,[1] A. Stolz,[1] B. E. Tomlin,[1,8] W. B. Walters,[14] and A. Wöhr[3]

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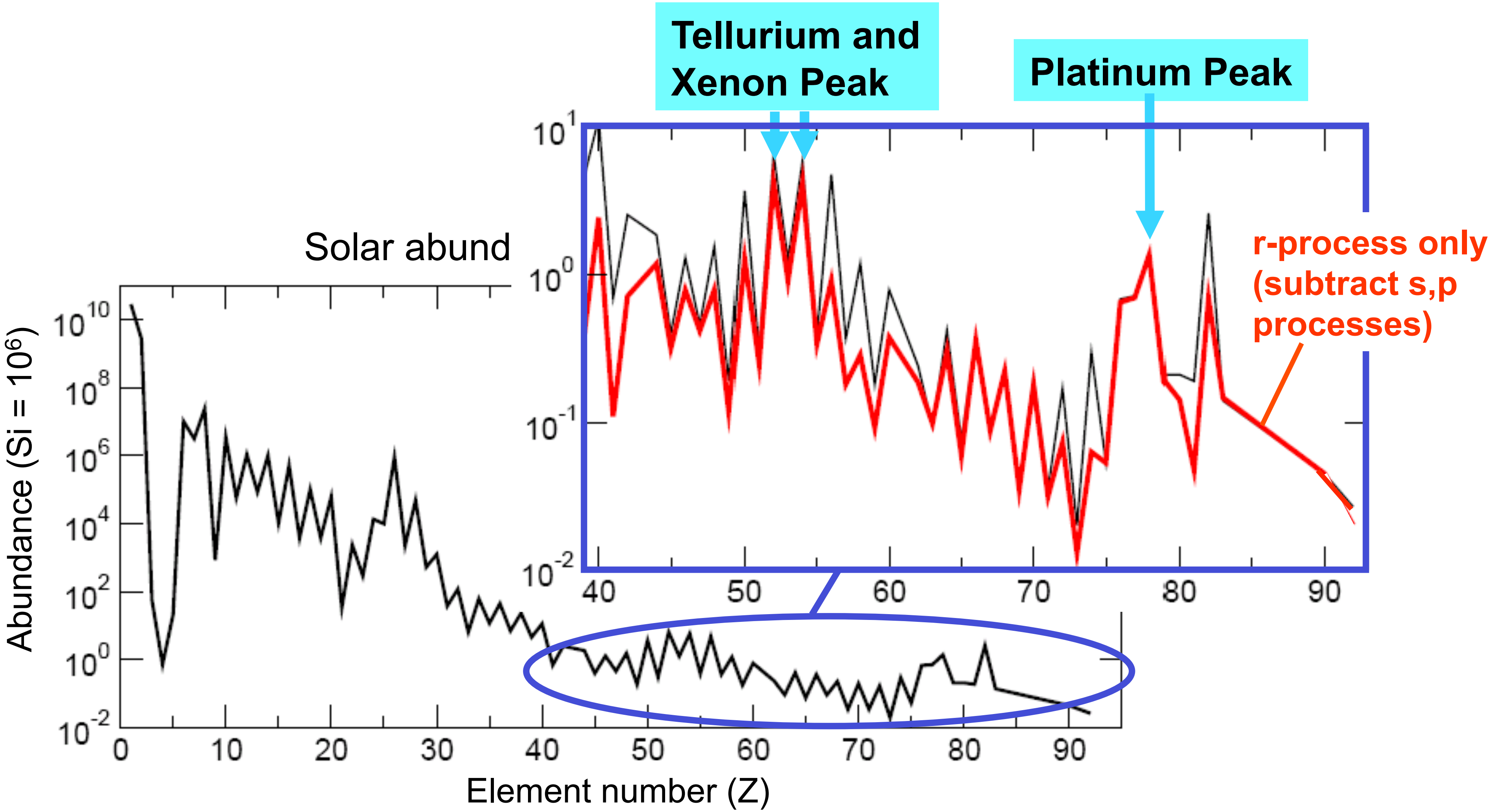
Abundance pattern of the r-process ?



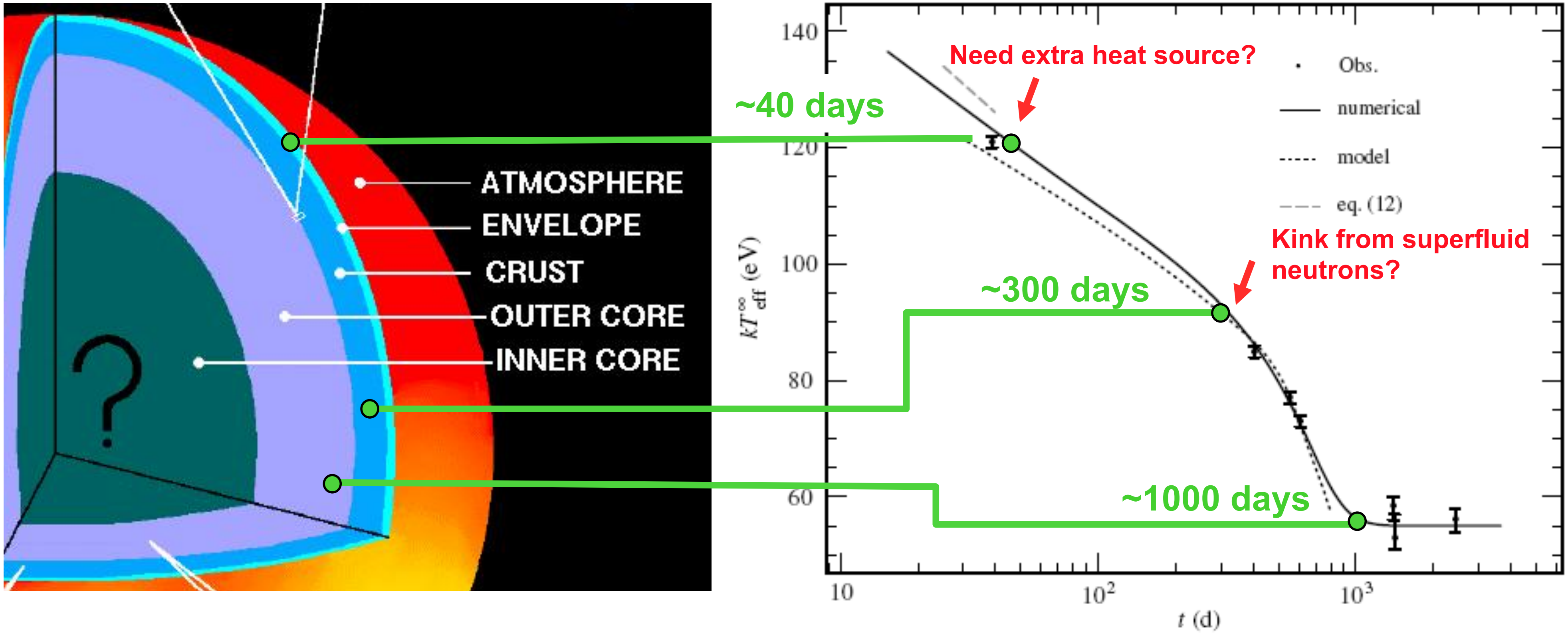
But: sun formed ~10 billion years after big bang: many stars contributed to elements

→ This is an endpoint of a chemical evolution process

→ This could be an accidental combination of many different patterns

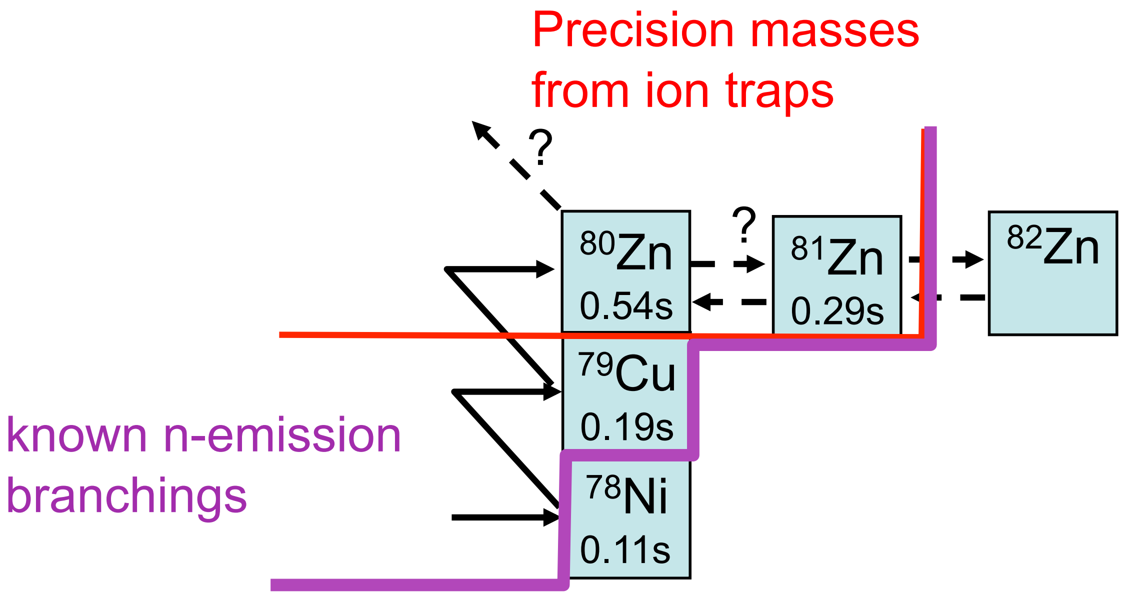
Neutron star heat tomography

Cooling crust probes increasing depth
(Brown and Cumming 2009)



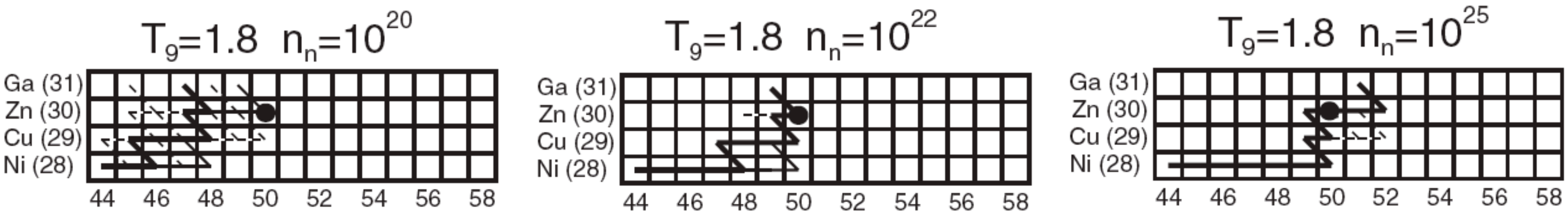
Characteristic heat distribution in crust depends sensitively on compositon of burst ashes (Gupta 2007)

The r-process at A=80



> Unique region where main nuclear physics for the r-process is now experimentally constrained

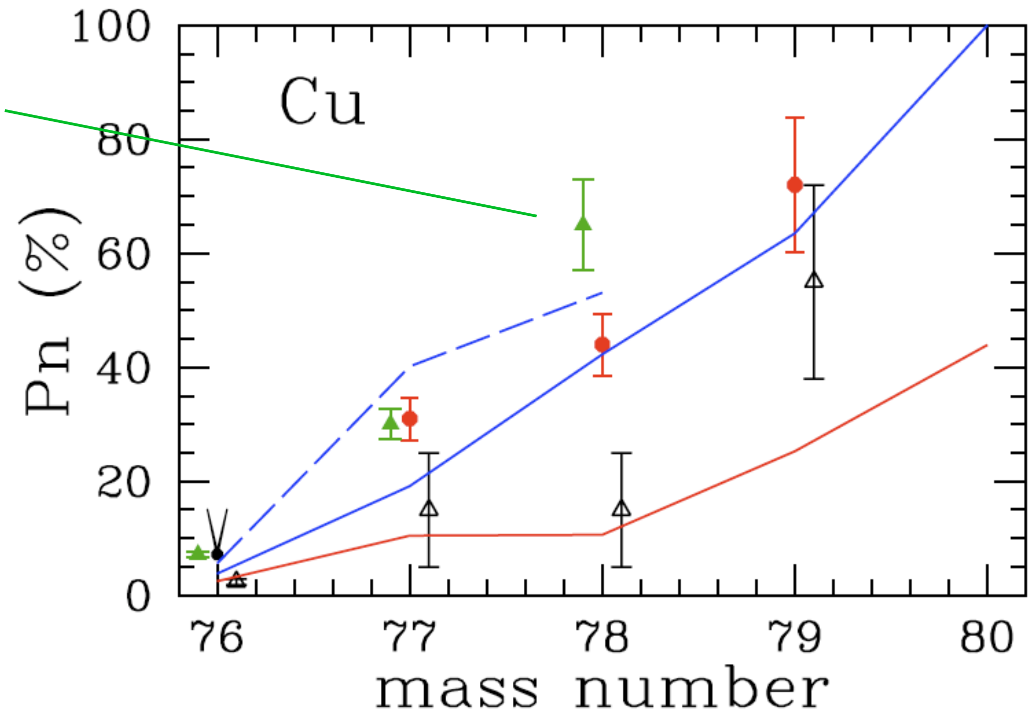
Network calculation: when is ^{80}Zn a waiting point?



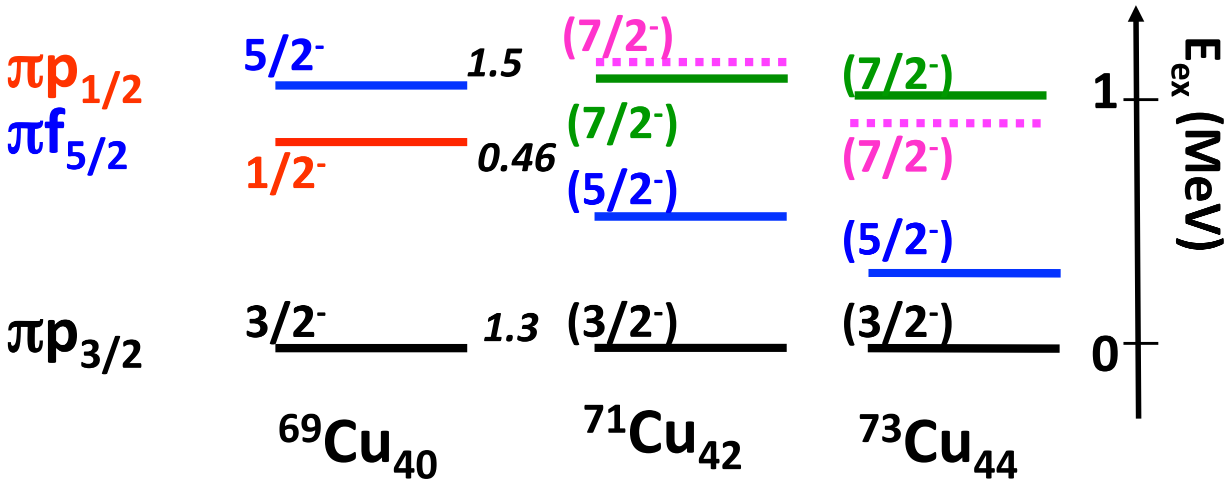
Baruah et al. 2008

Results (Hosmer et al. 2005, Hosmer et al. to be published)

New data by Winger et al.
PRL 102, 142502 (2009)



From talk by Georgiev 2009:



Evidence for 5/2⁻ gs for ^{75}Cu, ^{77}Cu (Walters, Flanagan private communication)

^{67,69}Cu: B. Zeidman et al. (1978). ^{71}Cu: R. Grzywacz et al. (1998) ^{69,71,73}Cu: S. Franchoo et al., (1998, 2001). .