Nuclear Astrophysics with Radioactive Beams

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Michigan State University

National Science Foundation
U.S. DEPARTMENT OF ENERGY | Office of Science

Credit: Bob King

National Science Foundation

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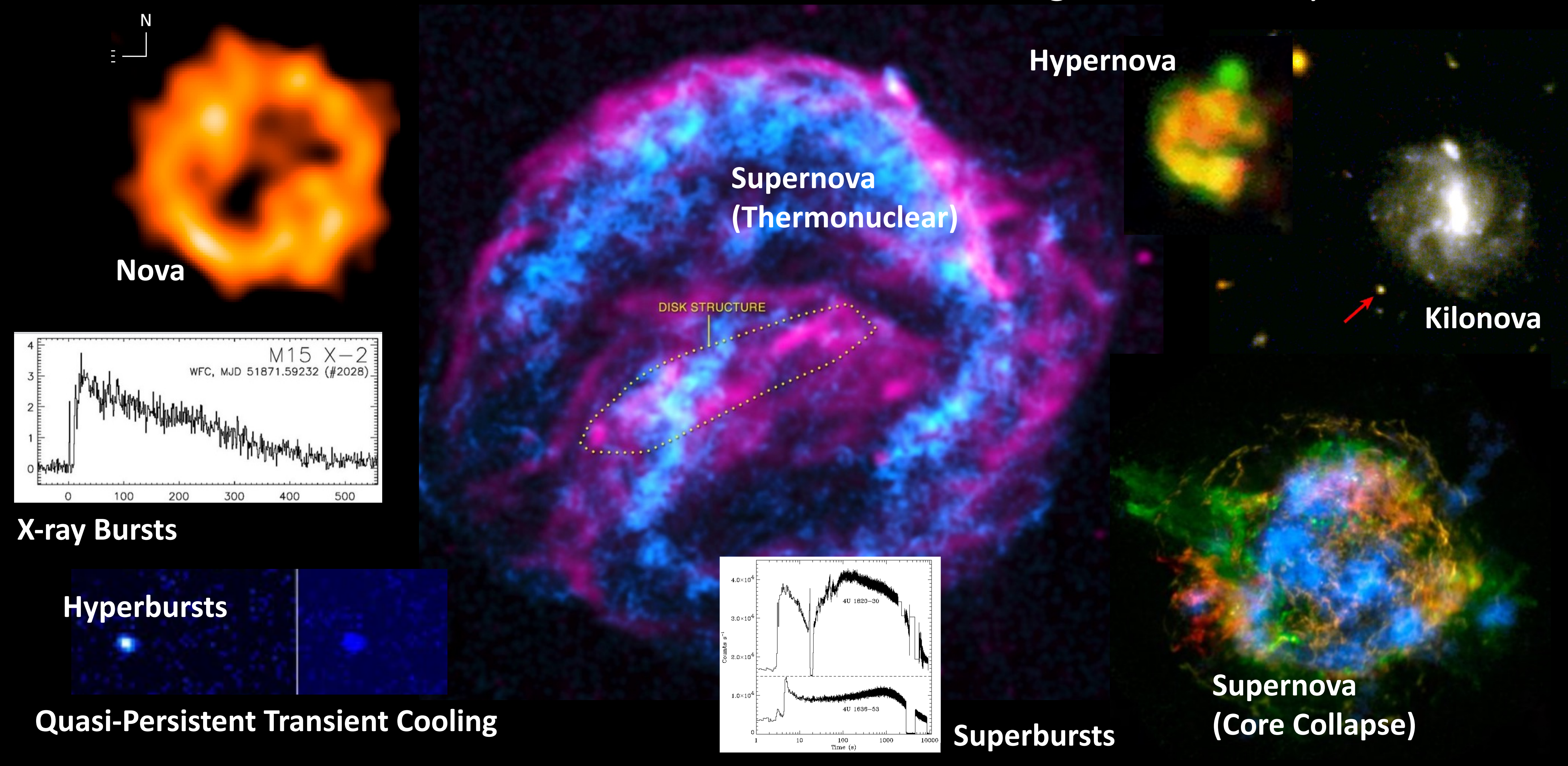
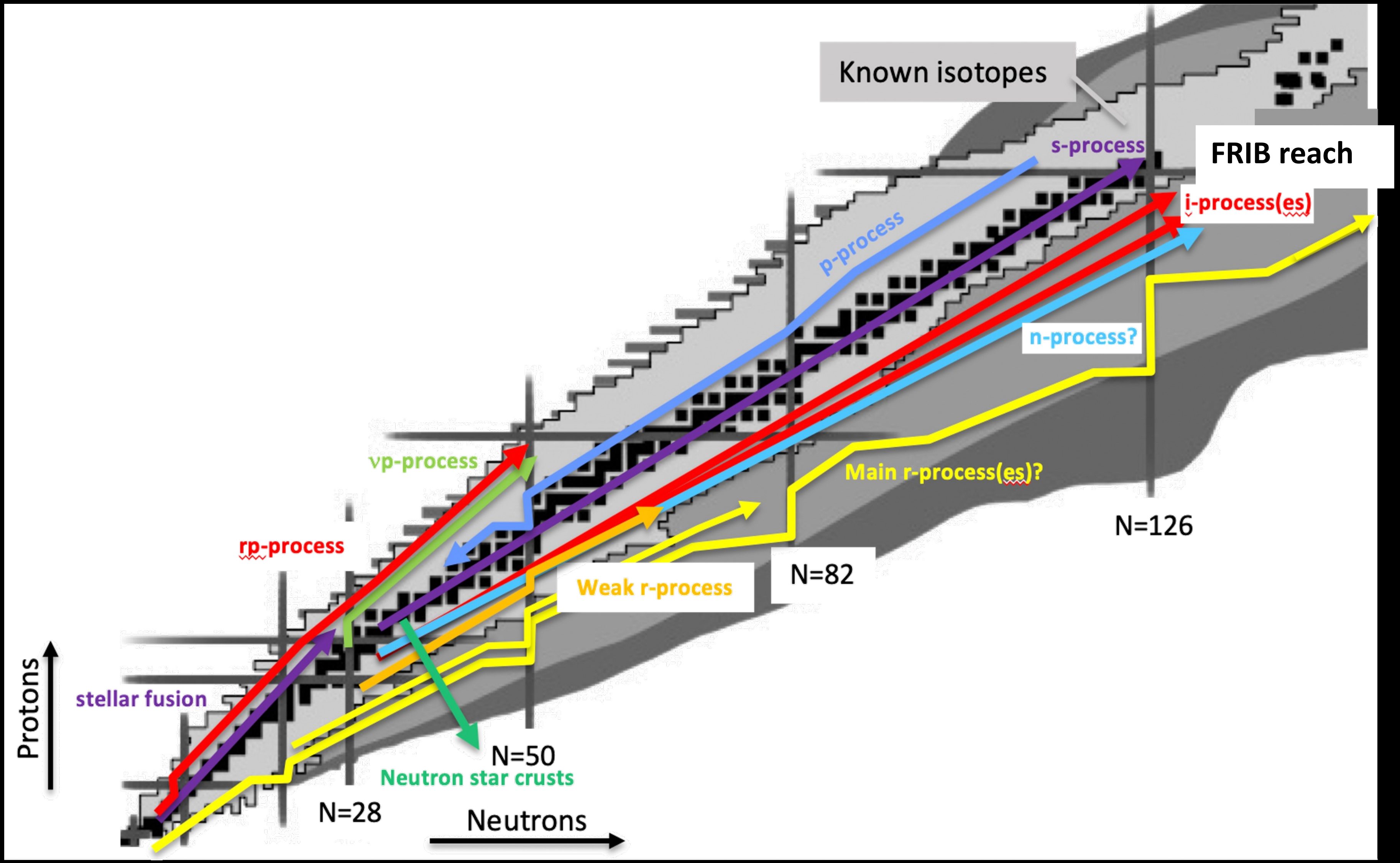
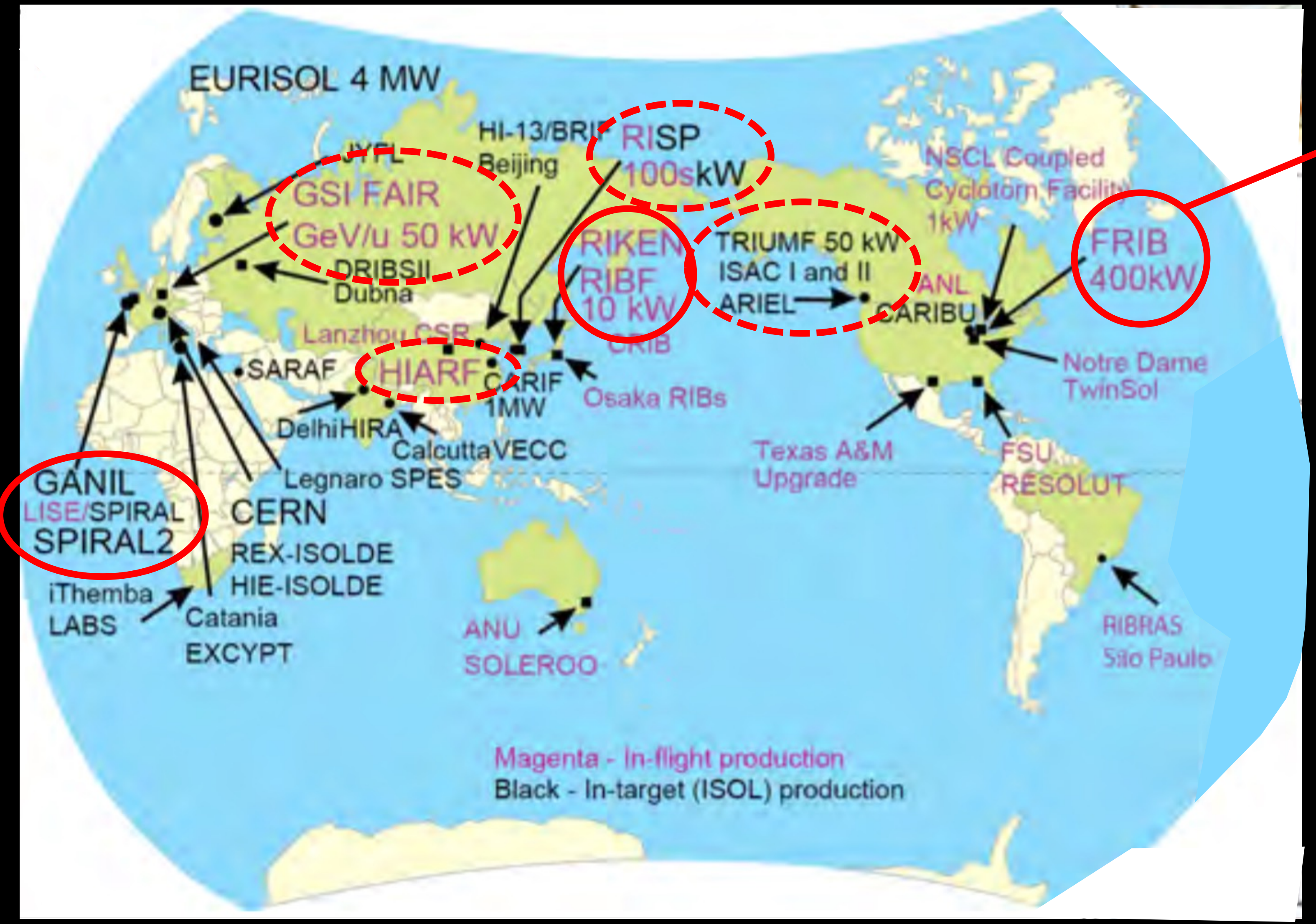
Explosive Cosmic Events are Powered by Radioactive Isotope Reactions and at the Heart of the Multi-Messenger Astronomy



A Multitude Of Astrophysical Processes Involve 1000s of Radioactive Isotopes Across the Chart of Nuclides



New Era: New Generation of RIB Facilities



FRIB at Michigan State University

FRIB Status:

- First experiment May 2022 at 1 kW
- Since then two PACs, routine operation
- Power ramp up to 10 kW now
- 400 kW over next few years (~2028)
- 400 MeV upgrade planned

Nuclear Astrophysics Opportunities from Emerging Radioactive Beam Capabilities Were Realized Early on

"It is in my view that continued development and application of radioactive beam techniques could bring the most exciting results in laboratory astrophysics in the next decade"

Nobel Laureate Willy Fowler, 1984

Michael Was Faster …

8th paper, 1983

IEEE Transactions on Nuclear Science, Vol. NS-30, No. 2, April 1983 1387

RISOAR: A FACILITY FOR PRODUCTION OF BEAMS OF RADIOACTIVE IONS

R.N. Boyd, L. Rybarcyk, M. Wiescher and H.J. Hausman
Department of Physics
The Ohio State University, Columbus, Ohio 43210

Summary

A facility to produce beams of low energy radioactive ions such as ^{7}Be, ^{11}C, ^{13}N, ^{15}O and ^{19}Ne is presently under construction at The Ohio State University. The beams, having expected intensities of order

fraction of the life of any star, it is thought to be responsible for a large fraction of the nucleosynthesis performed by the star.

The nuclear reactions which govern this mode of nucleosynthesis have, for the most part, never been

Nuclear astrophysics and explosive nucleosynthesis is the main motivation

Science Motivation for TRIUMF ISOL Facility

TRIUMF proposal for ISOL facility 1985

Private Communication from M. Wiescher 1984
^{19}Ne(p,γ) and ^{15}O(α,γ)

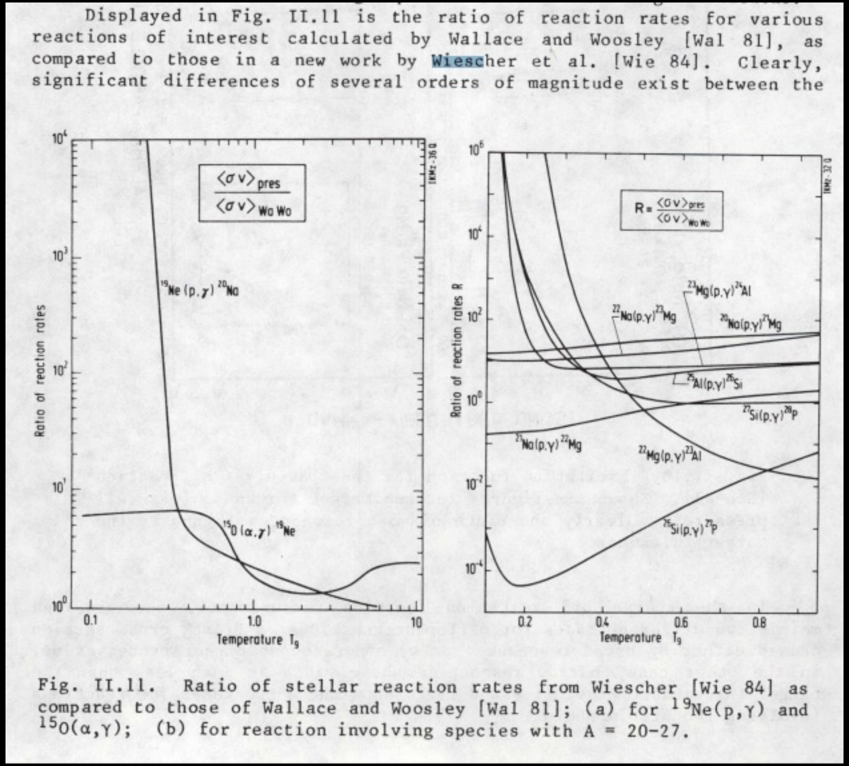
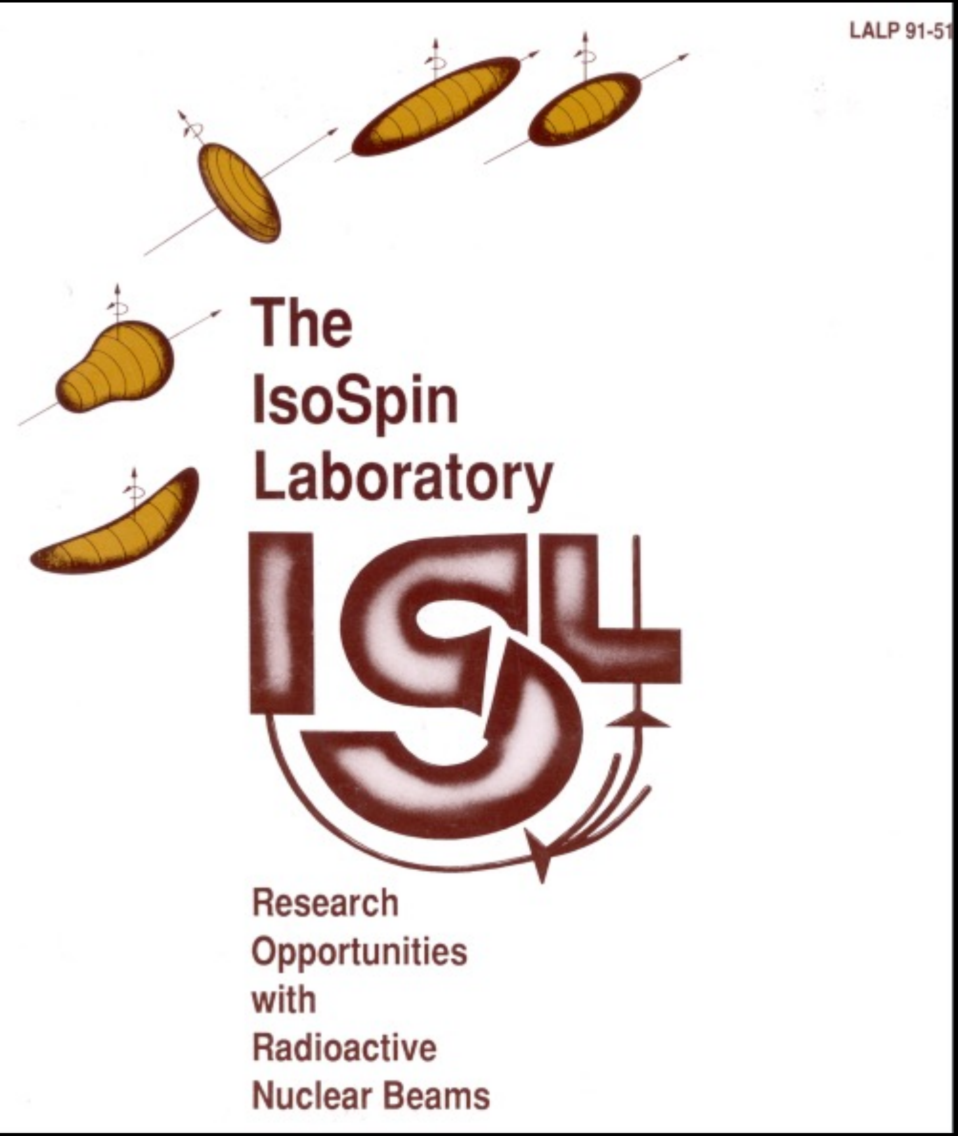

Displayed in Fig. II.11 is the ratio of reaction rates for various reactions of interest calculated by Wallace and Woosley [Wal 81], as compared to those in a new work by Wiescher et al. [Wie 84]. Clearly, significant differences of several orders of magnitude exist between the

Fig. II.11. Ratio of stellar reaction rates from Wiescher [Wie 84] as compared to those of Wallace and Woosley [Wal 81]; (a) for ^{19}Ne(p,γ) and ^{15}O(α,γ); (b) for reaction involving species with A = 20-27.

The Beginnings of FRIB: ISL White Paper 1991



North American Steering Committee for the IsoSpin Laboratory (ISL)

Richard F. Casten, Chairman
Brookhaven National Laboratory

John M. D'Auria
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Argonne National Laboratory

Jerry D. Garrett
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Bradley M. Sherrill
Michigan State University

David J. Vieira
Los Alamos National Laboratory

Michael Wiescher
University of Notre Dame

Edward F. Zganjar
Louisiana State University

Astrophysics-nucleosynthesis: In explosive stellar events, nuclear processes occur far from stability. Only with RNBs can these reaction processes be studied in the laboratory. […] The study of these processes with RNBs will give tremendous leverage in constraining our understanding of their nature and the time evolution of these dramatic events.

ISL Steering Committee 1995 Report

Experiments with radioactive nuclear beams are essential to test the multitude of nuclear parameters used for modeling the explosive nucleosynthesis processes. The first measurements of nuclear reaction rates with radioactive beams, like $^{13}N(p,\gamma)^{14}O$, $^{8}Li(\alpha,n)^{11}B$ and $^{19}Ne(p,\gamma)^{20}Na$, have been successfully completed on small scale, university based radioactive beam facilities.[1-3] New detector systems have been developed in the course of these experiments to handle low event rates under high background conditions. This signals a promising future for such experiments. Higher intensity beams are required to push the measurements further away from the line of stability and to investigate, in particular, slow reactions which are expected to set the time scale in explosive stellar nucleosynthesis.

Review Papers Played an Important Role

Radioactive ion beams and explosive nucleosynthesis

Show affiliations

Görres, J. ; Wiescher, M.

Explosive hydrogen burning involves (p, γ) reactions on proton-rich, unstable nuclei. The knowledge of the reaction rates for these reactions is important to calculate the energy production and reaction paths in different astrophysical scenarios, e.g. nova, supernova and supermassive stars. A direct measurement of these reaction rates requires the use of radioactive ion beams. Two examples, $^{13}N(p, \gamma)^{14}O$ and $^{19}Ne(p, \gamma)^{20}Na$, are used to define demands, which such a facility should meet to enable the direct measurements of these reaction rates.

Publication: Nuclear Instruments and Methods in Physics Research Section B, Volume 56, p. 536-539.

Pub Date: May 1991

Laid out requirements for a RIB facility for astrophysics experiments:

A radioactive ion beam facility should cover the energy range of 0.2–10 MeV/amu. This would not only allow the direct measurements of reaction rates, but would also offer the opportunity to study weaker reactions indirectly using transfer reactions. A high beam intensity, $\geq 10^{10}$/s, is essential in order to limit experiments not only to few, very strong reactions. Of equal importance is the development of a detector system capable to detect reaction products with a low counting rate in the presence of a large γ background.

Nuclear Astrophysics and Nuclei Far from Stability

2004

Karlheinz Langanke[1], Friedrich-Karl Thielemann[2], and Michael Wiescher[3]

[1] Institute for Physics and Astronomy, University of Aarhus, 8000 Aarhus, Denmark,
[2] Department of Physics and Astronomy, University of Basel, 4056 Basel, Switzerland,
[3] Department of Physics, University of Notre Dame, IN 46556, USA

Michael Played A Key Role In Subsequent Committees

2004 NSAC Subcommittee on "Comparison of the Rare Isotope Accelerator (RIA) and the Gesellschaft für Schwerionenforschung (GSI) Future Facility"
→ Complementary Facilities

RIA Steering Committee
2002 White Paper The Intellectual Challenges of RIA:
"It is clear that data on nuclei in the r-process path, accessible only with RIA, and the improved understanding of the nuclear quantum many-body problem that will follow, thus directly influences our knowledge of element production in the Universe"

2006 Rare-Isotope Science Assessment Committee (RISAC)
National Research Council of the National Academies
Opportunities with a Rare-Isotope Facility in the United States

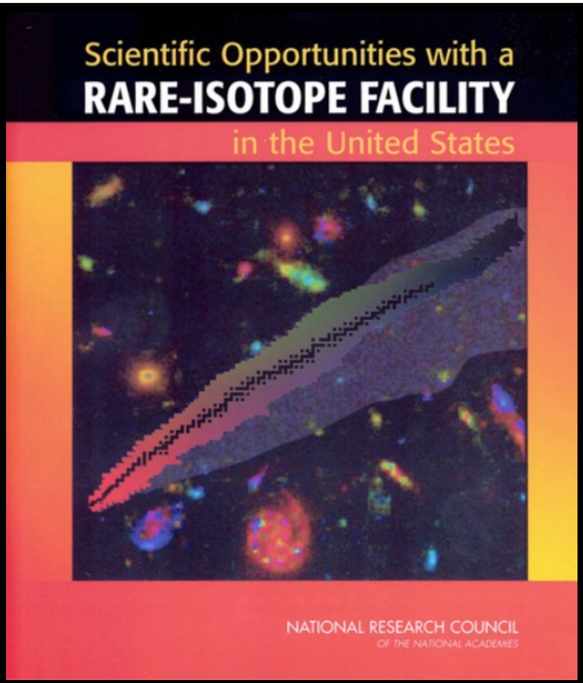
2015 Long Range Plan writing committee

Report of the NSAC Subcommittee on

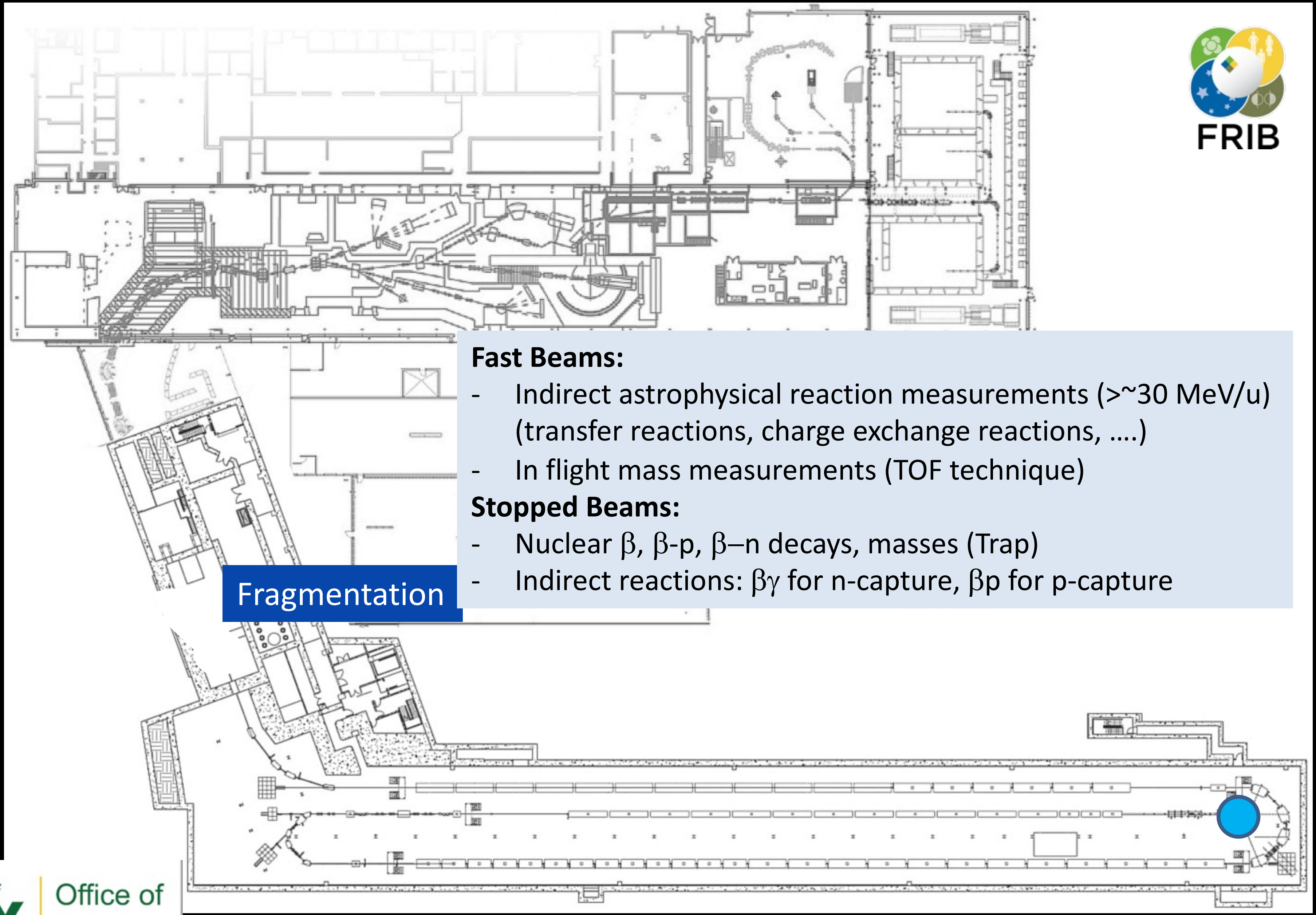
Comparison of the Rare Isotope Accelerator (RIA) and the Gesellschaft für Schwerionenforschung (GSI) Future Facility

Sub Committee Members:

James Beene	Oak Ridge National Laboratory
Peter Bond	Brookhaven National Laboratory (Chair)
Steven Koonin	California Institute of Technology
Curtis Meyer	Carnegie Mellon University
Jack Sandweiss	Yale University
James Symons	Lawrence Berkeley National Laboratory
Michael Wiescher	University of Notre Dame
Stan Woosley	University of California at Santa Cruz



FRIB Provides Fast, Stopped, and Reaccelerated Beams



Fast Beams:

- Indirect astrophysical reaction measurements (>~30 MeV/u) (transfer reactions, charge exchange reactions, ….)
- In flight mass measurements (TOF technique)

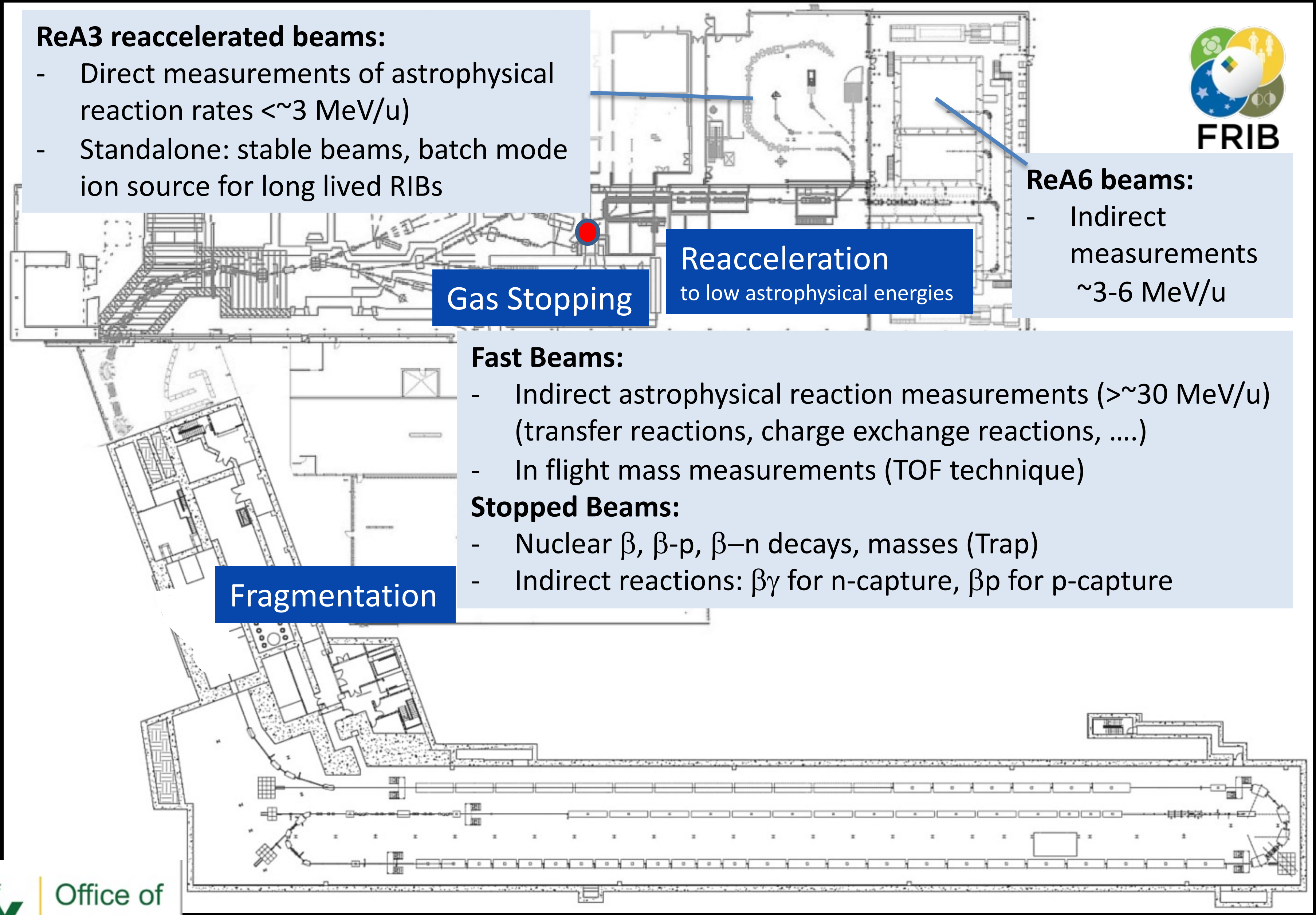
Stopped Beams:

- Nuclear β, β-p, β–n decays, masses (Trap)
- Indirect reactions: βγ for n-capture, βp for p-capture

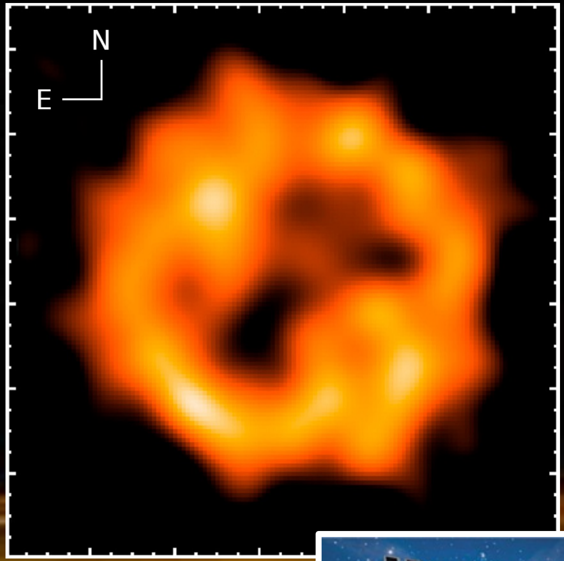
FRIB

U.S. DEPARTMENT OF ENERGY | Office of Science

FRIB Provides Fast, Stopped, and Reaccelerated Beams



Radioactive Isotopes in Nova Explosions



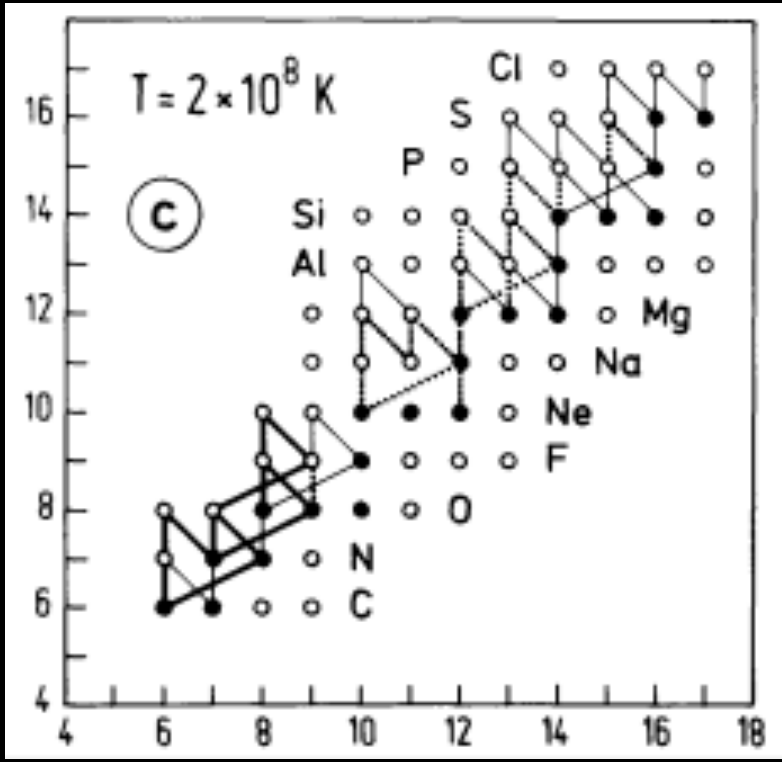
Open Questions:

- What are the (heaviest) elements produced?
- Source of radioactive ^{26}Al found spread out in Galaxy?
- Are other observable long lived radioactive isotopes produced?
- Are presolar grains with unusual isotopic compositions from Novae?
- Does the white dwarf increase or decrease in mass over time?

Strategy:

- Compare observed element signatures with nuclear physics networks
- Pin down the critical nuclear physics with experiments
- Make predictions

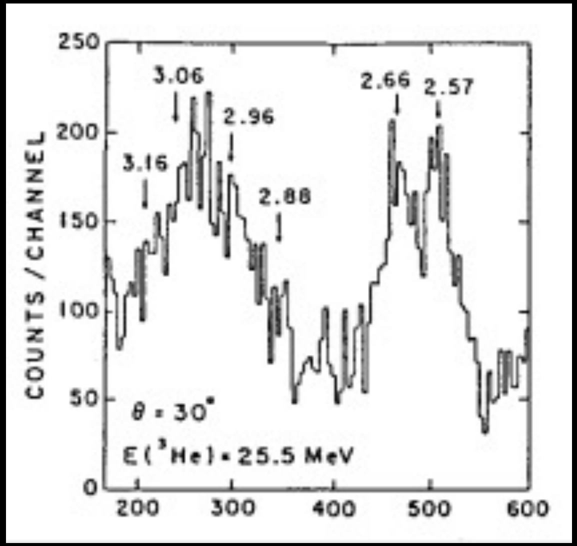
Key Nuclear Physics Identified



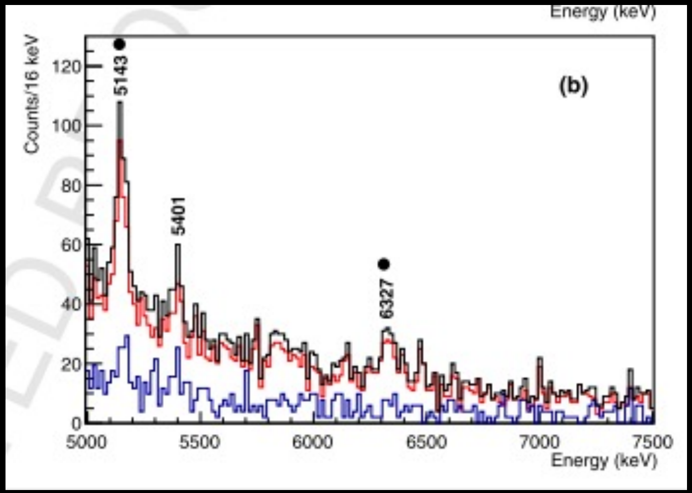
Wiescher, Görres,
Thielemann,
Ritter 1986

Long history of experimental activities

Wiescher et al. 1987
”NEW EXPERIMENTAL RESULTS FOR NUCLEAR REACTIONS IN EXPLOSIVE HYDROGEN BURNING”
^{20}Ne(^{3}He,t)^{20}Na at Notre Dame spectrograph for ^{19}Ne(p,γ);
later also pioneering **direct** RIB measurements at Louvain-la-Neuve (e.g. Page et al. 1994)

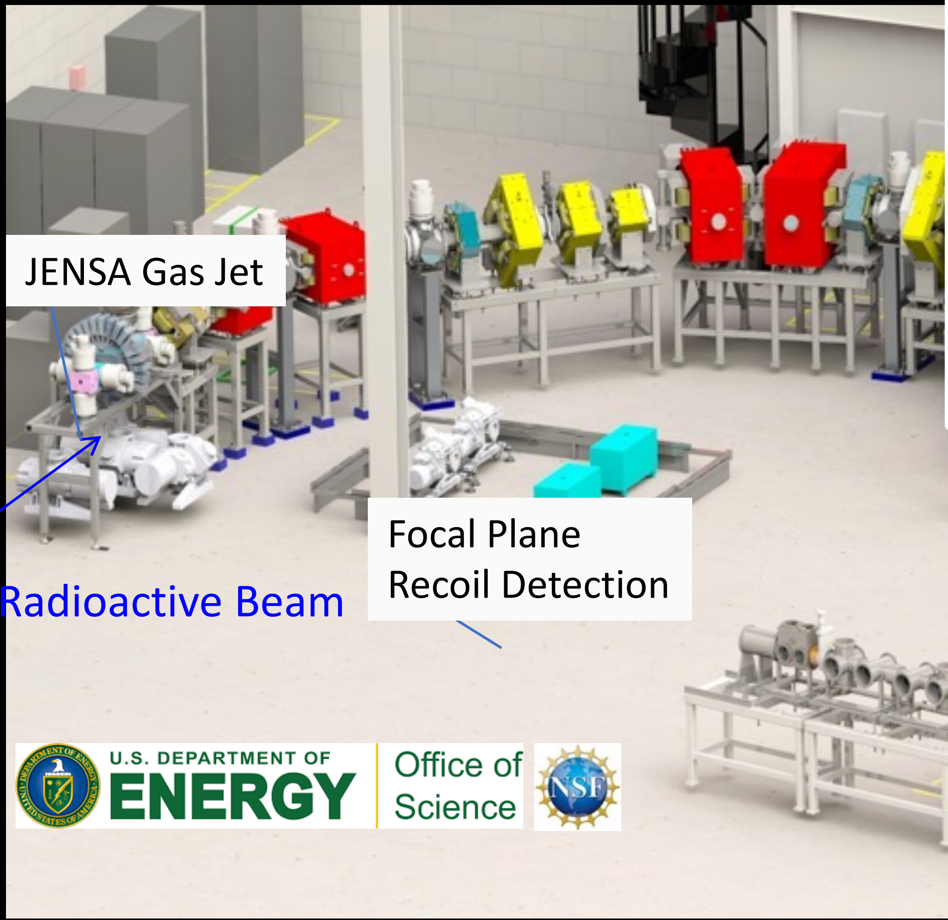


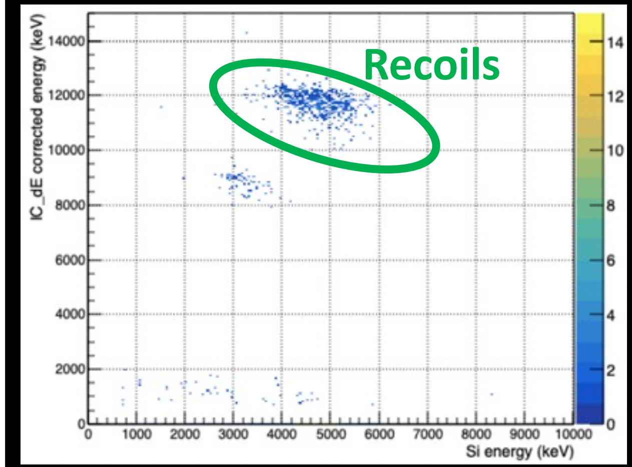
Kankainen et al. 2017
^{30}P(d,n)^{31}S at NSCL S800 spectrograph
and GRETINA gamma-ray array
For ^{30}P(p,γ)

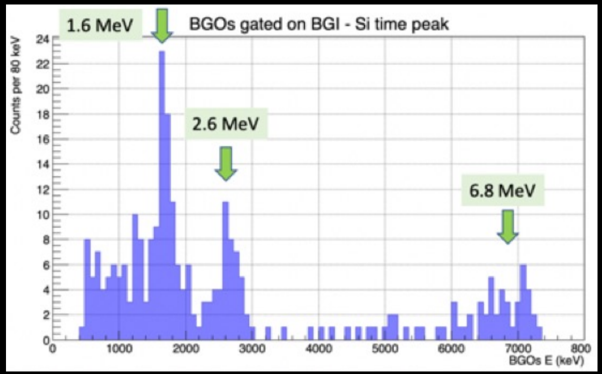


Direct Reaction Measurements at FRIB enabled by SECAR

Lead
G. Berg, M. Couder, Notre Dame
F. Montes, H. Schatz, MSU
J. Blackmon, LSU
K. Chipps, M. Smith, ORNL
U. Greife, CSM







- First recoil detection from
- $^{16}O(\alpha,\gamma)^{20}Ne$ concludes construction
- 2 NSCL experiments carried out
- Test experiments for first hydrogen induced experiments ongoing

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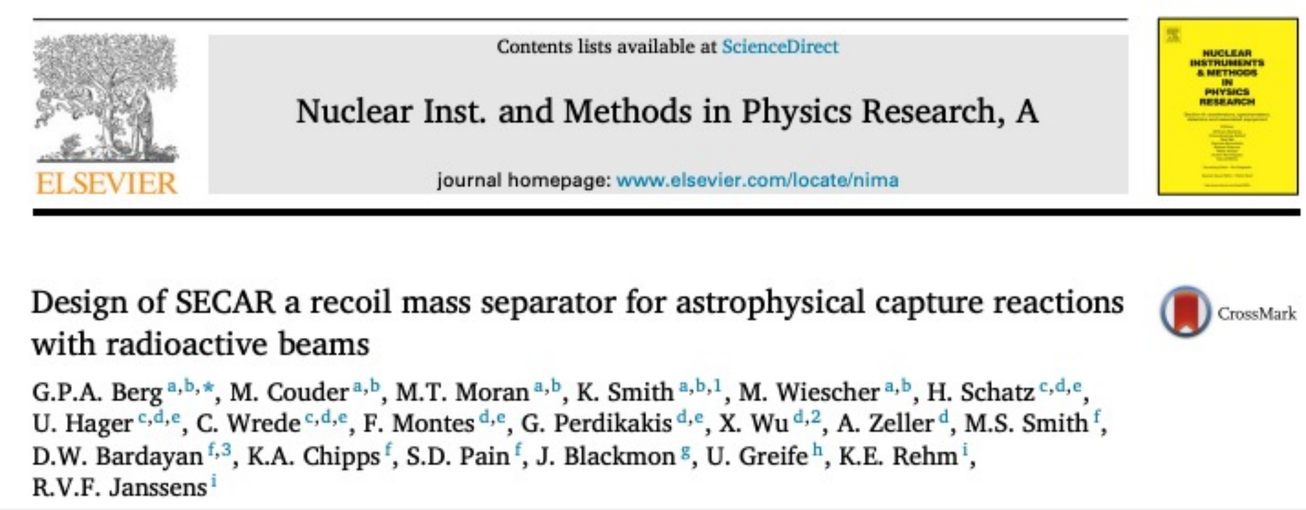
SecAR Lineage from St. George Separator at Notre Dame


Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

ELSEVIER

Design of SECAR a recoil mass separator for astrophysical capture reactions with radioactive beams

G.P.A. Berg[a,b,*], M. Couder[a,b], M.T. Moran[a,b], K. Smith[a,b,1], M. Wiescher[a,b], H. Schatz[c,d,e], U. Hager[c,d,e], C. Wrede[c,d,e], F. Montes[d,e], G. Perdikakis[d,e], X. Wu[d,2], A. Zeller[d], M.S. Smith[f], D.W. Bardayan[f,3], K.A. Chipps[f], S.D. Pain[f], J. Blackmon[g], U. Greife[h], K.E. Rehm[i], R.V.F. Janssens[i]

SECAR based on St. George Ideas

- Adds second Wien Filter separation stage
- Higher mass resolution for p,γ

Neutron Stars as Unique Probes of Dense Matter

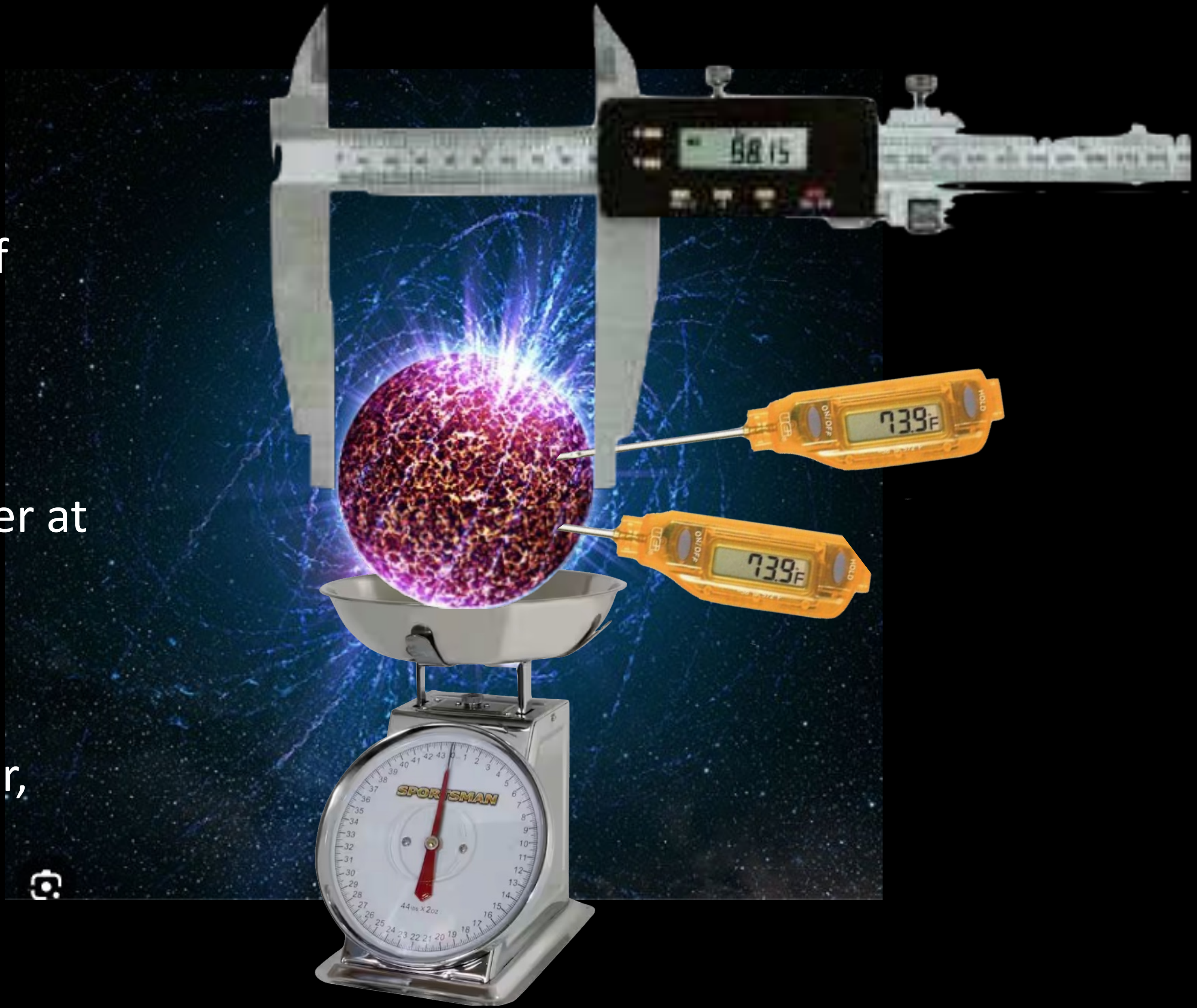
~10 km radius

~1.4 solar masses

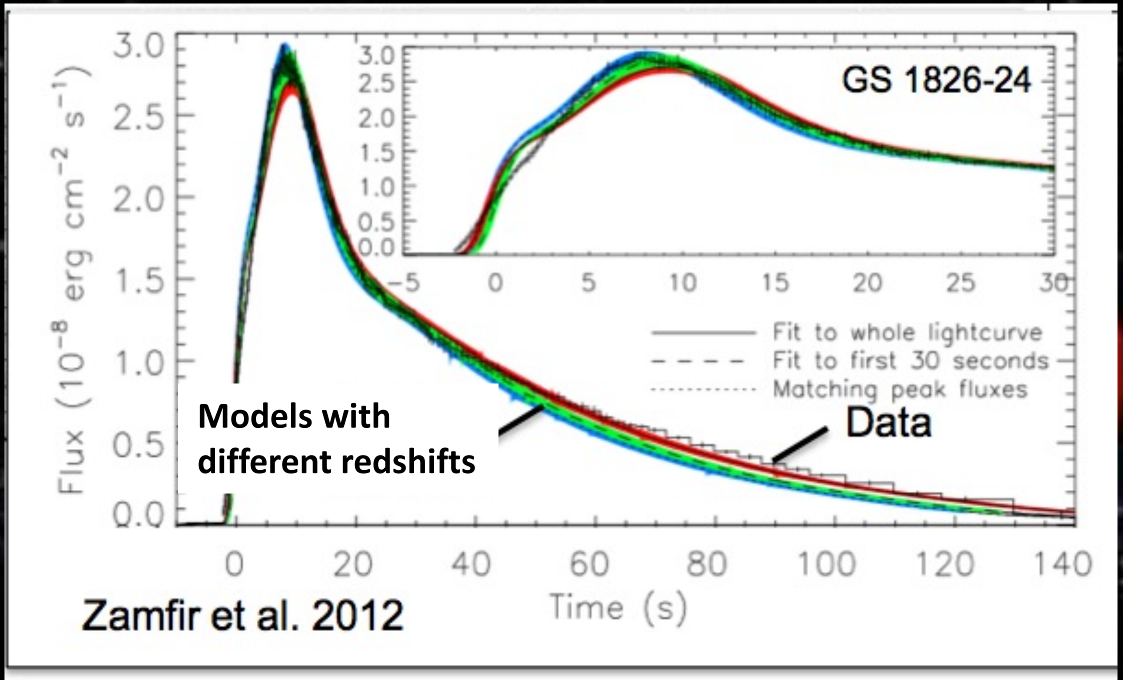
→Some of the densest samples of matter in the universe

Questions:

- What are the properties of matter at extreme densities?
- What does that tell us about the nuclear force?
- Are there exotic phases of matter, especially in the center?

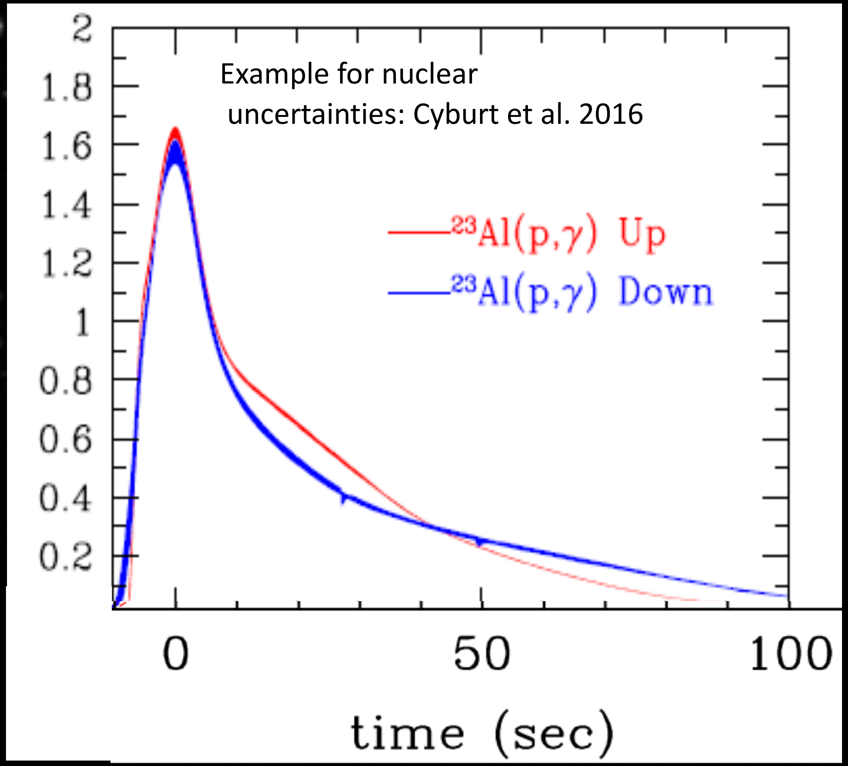


Accreting Neutron Stars and X-ray Bursts

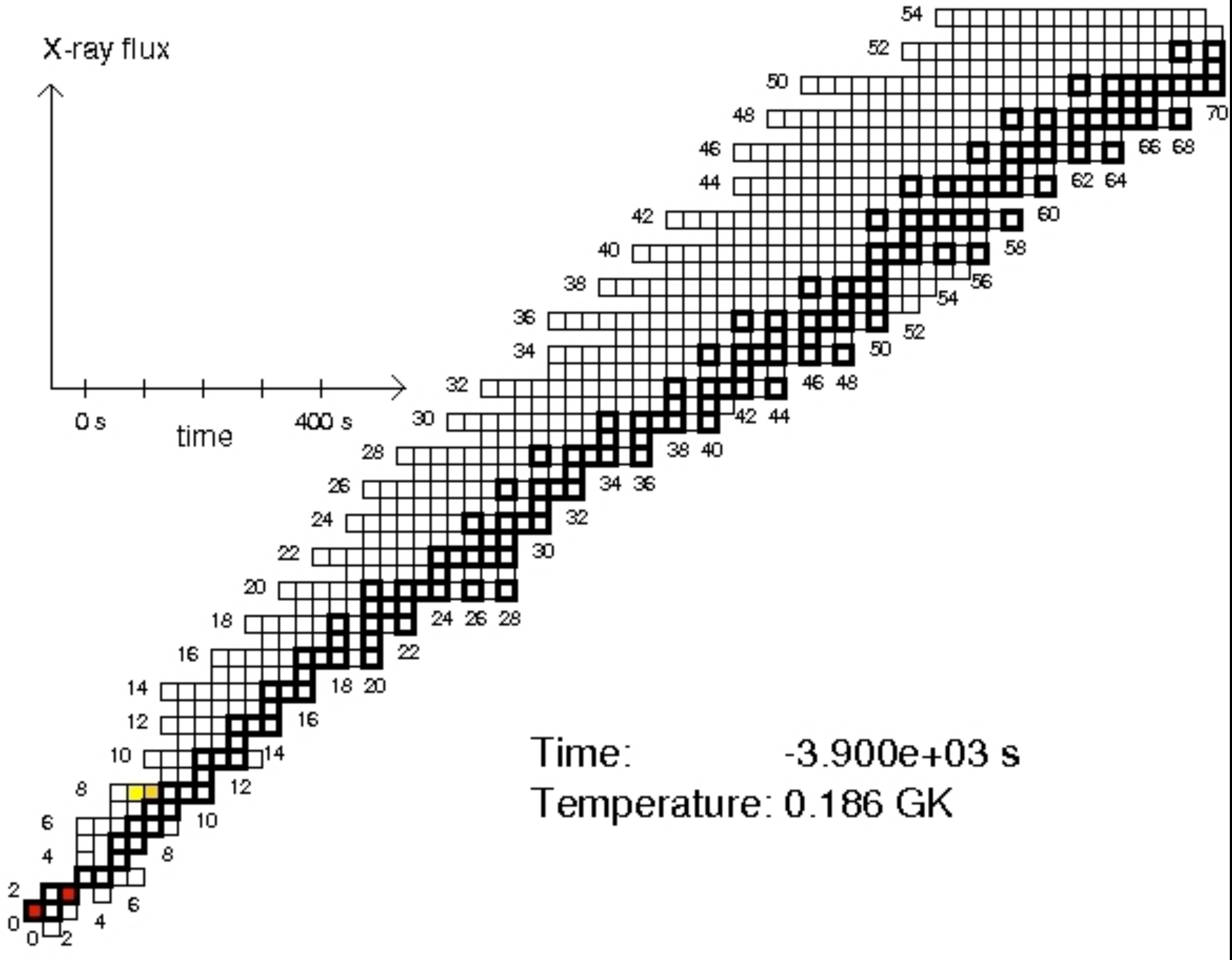


→ Surface red-shift related to mass and radius !!

Nuclear Physics Uncertainties



→ A more gentle probe compared neutron star mergers
→ 100s in the Galaxy and extremely bright and easy to observe
→ Many open questions



A. Heger

X-ray Burst Radioactive Beam Measurements with Michael

Also indirect studies with stable beams at Notre Dame, e.g. $^{15}O(\alpha,\gamma)$ Tan et al. 2007

^{80}Y decay @ ANL
Döring, …,Wiescher, … et al. 1999

βp-decay of ^{69}Kr @ TRIUMF
to get mass of unbound ^{69}Br

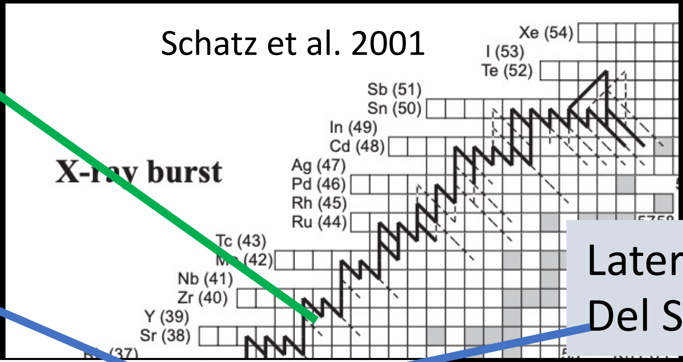
Later@NSCL
Del Santo et al., … Wiescher … 2014

$^{56}Ni(p,\gamma)$ @ ANL
Indirect via $^{56}Ni(d,p)$
Rehm, …,Wiescher, … et al. 1998

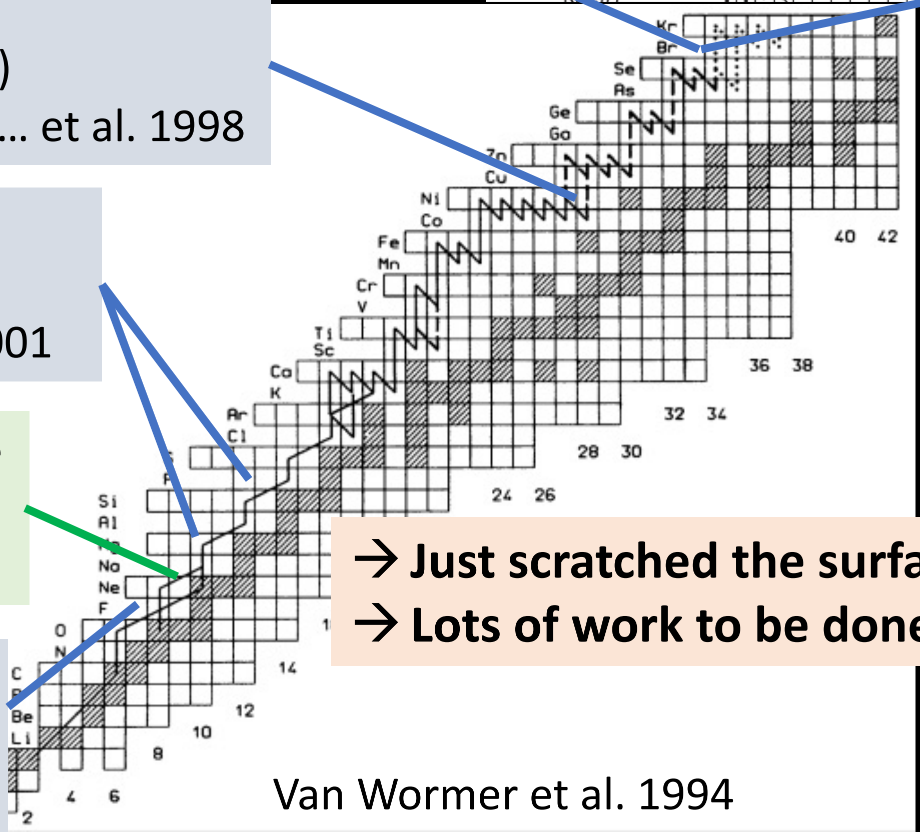
$^{22}Mg(p,g)$ and $^{26}Si(p,g)$ @ NSCL
Indirect via (7Li,8He)^{23}Al, ^{27}P
Caggiano, …,Wiescher, … et al. 2001

$^{18}Ne(\alpha,p)$ Direct @Louvain la Neuve
Bradfield-Smith, …,Wiescher, …et al. 1999

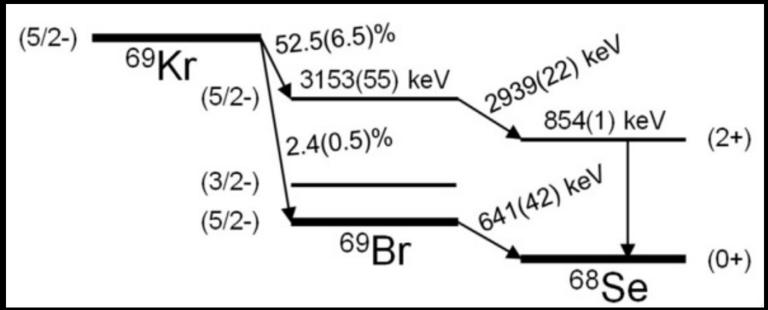
$^{17}Ne(\gamma,2p)^{15}O$ @ GSI
Indirect via Coulomb Breakup
Marganiec, …Wiescher … et al. 2016

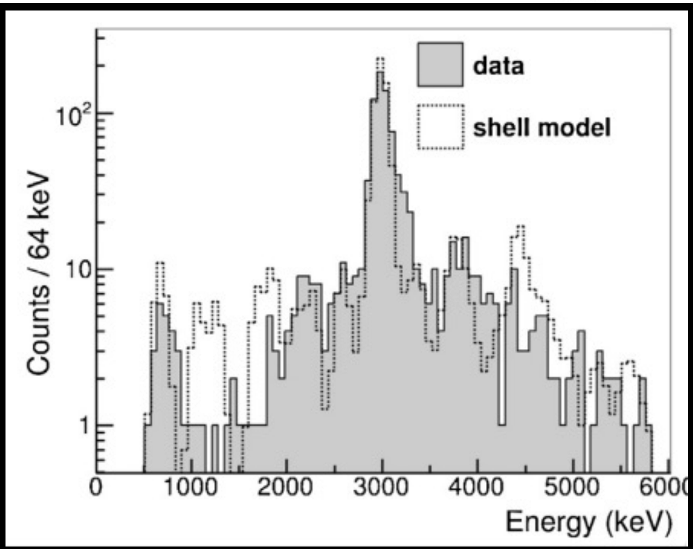


Schatz et al. 2001

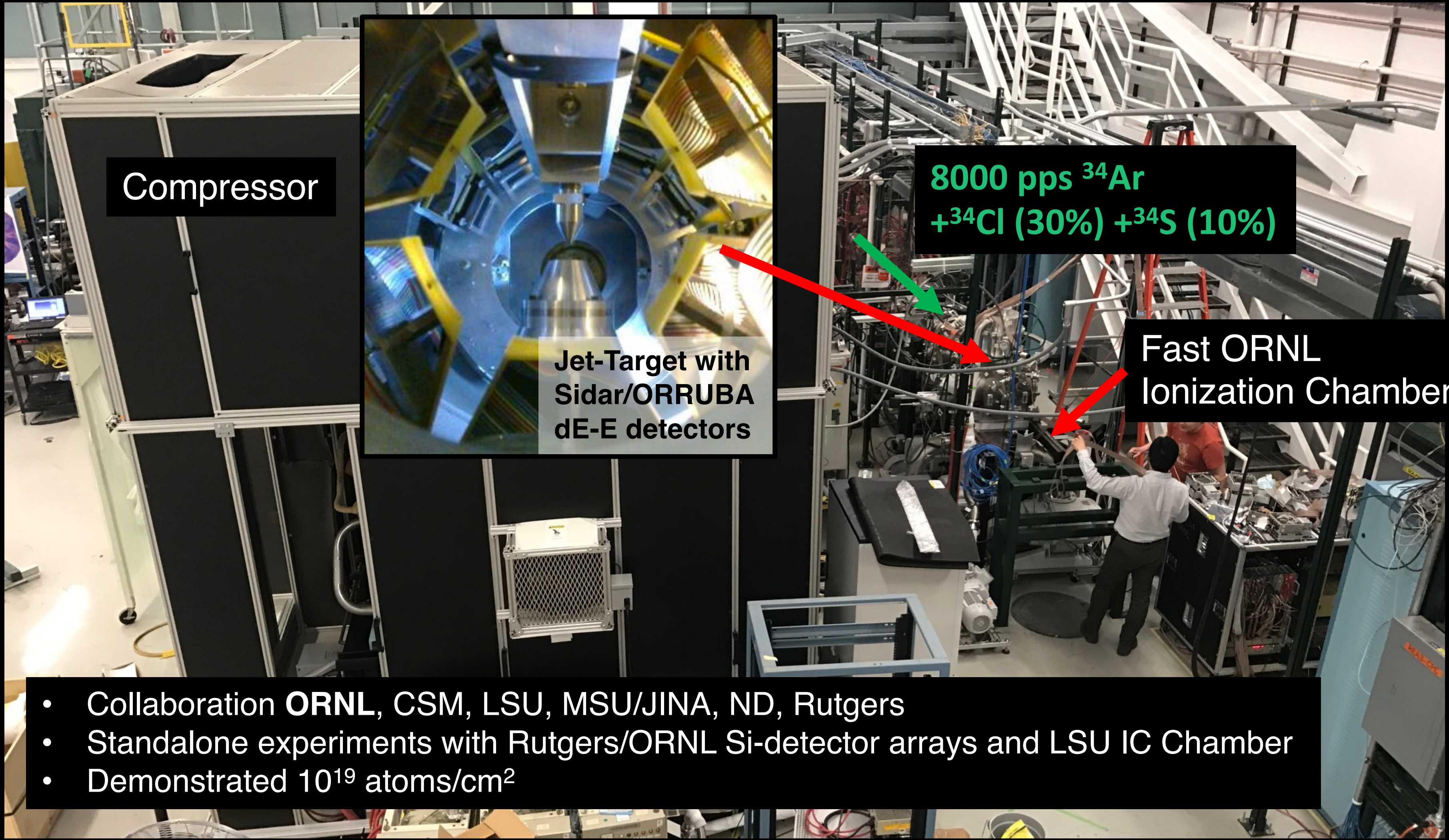

Van Wormer et al. 1994

→ Just scratched the surface
→ Lots of work to be done





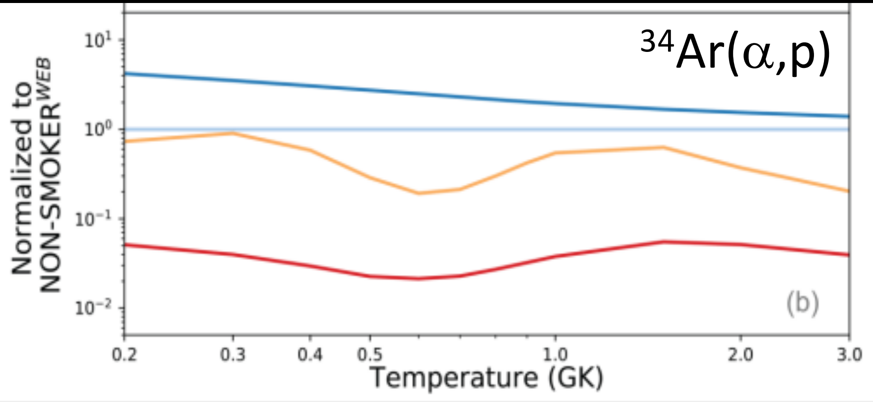
JENSA Gas Jet Target for direct (α,p) Measurements with Reaccelerated Beams at NSCL and now FRIB



- Collaboration **ORNL**, CSM, LSU, MSU/JINA, ND, Rutgers
- Standalone experiments with Rutgers/ORNL Si-detector arrays and LSU IC Chamber
- Demonstrated 10^{19} atoms/cm^2

Many Open Questions Related to (α,p) Reaction Rates

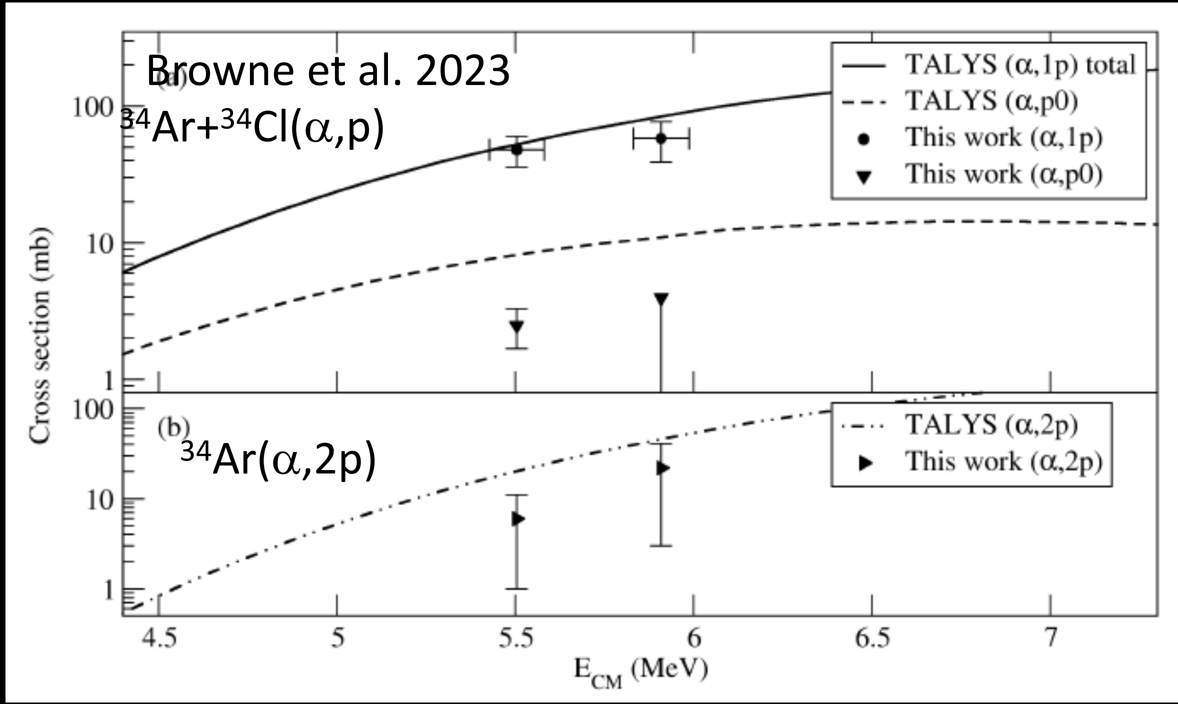
Pioneering work led by Michael using (p,t) @iThemba LABS with stable beams (Long et al. 2017)



Theory

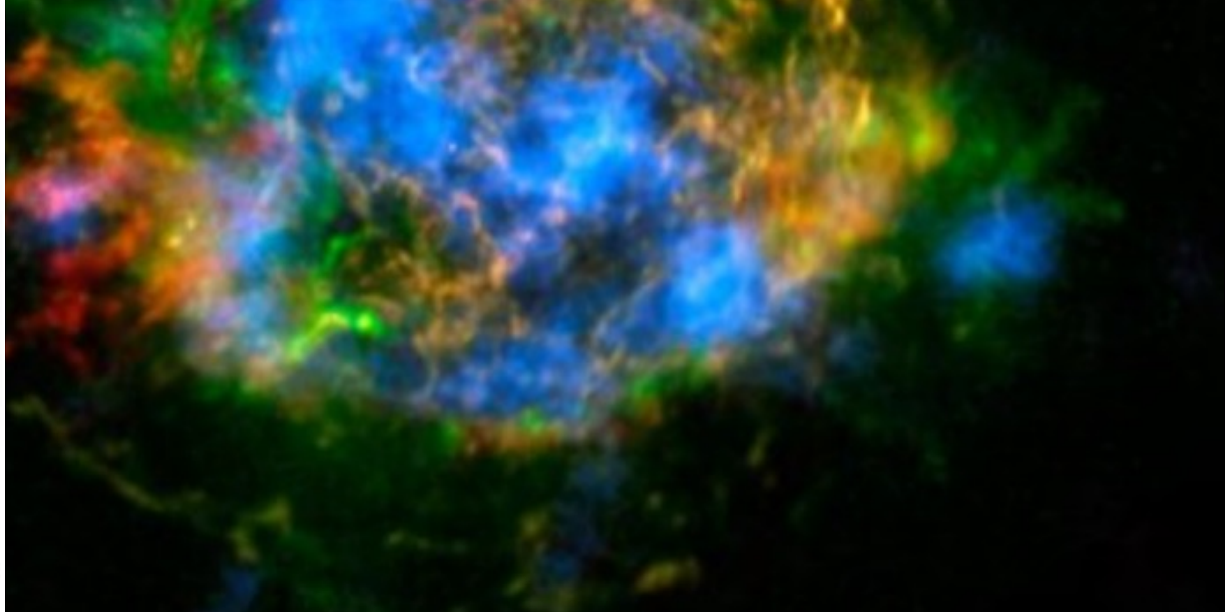
Clustering enhancement

Estimate from ^{40}Ca(p,t) levels



→ Current theory surprisingly good
→ Issues compensated with cluster effects?
→ Need to push to lower energies
(probe upper end of Gamow Window at 3 GK)

What Radioactive Isotopes Are Produced in Supernovae and What do they Tell us about Explosion Mechanism and Nucleosynthesis?

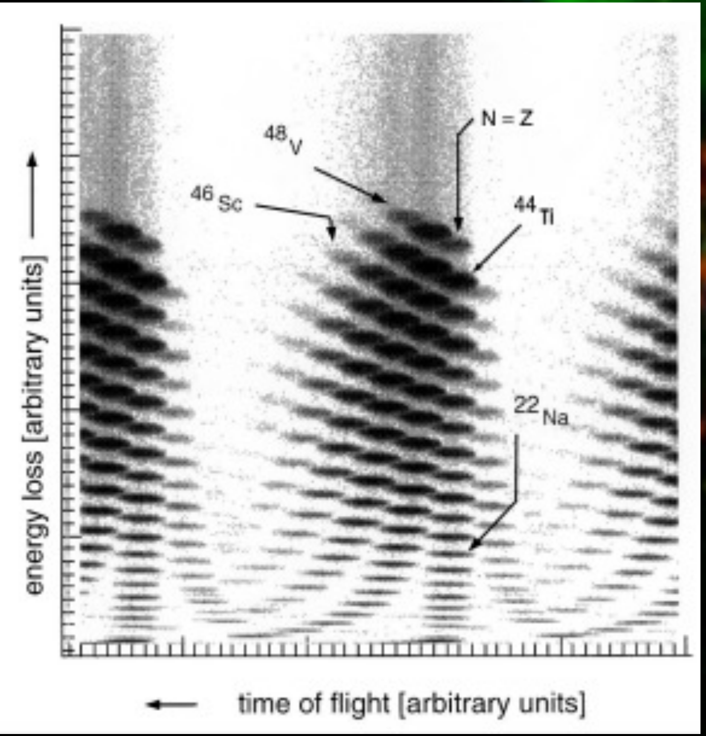


^{44}Ti with NuSTAR

VOLUME 80, NUMBER 12 PHYSICAL REVIEW LETTERS 23 MARCH 1998

Half-Life of ^{44}Ti as a Probe for Supernova Models

J. Görres,[1] J. Meißner,[1,*] H. Schatz,[1] E. Stech,[1] P. Tischhauser,[1] M. Wiescher,[1] D. Bazin,[2] R. Harkewicz,[2] M. Hellström,[2,†] B. Sherrill,[2] M. Steiner,[2] R. N. Boyd,[3] L. Buchmann,[4] D. H. Hartmann,[5] and J. D. Hinnefeld[6]



Half-life: 60+-1 yrs @NSCL

Hermansen et al. 2020

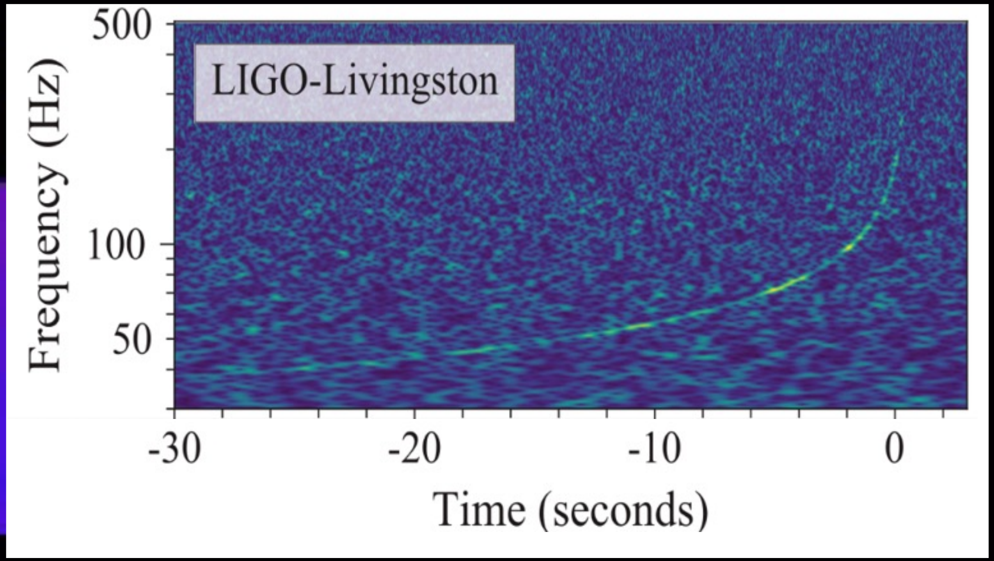
Reaction	Impact	Isotope Affected
^{42}K(n,γ)^{43}K	4.18	^{43}K
^{44}Ti(α,p)^{47}V	2.61, 1.31, 1.12^{a}	^{44}Ti, ^{48}V, ^{49}V
^{43}K(p,n)^{43}Ca	2.51	^{43}K
^{59}Cu(p,γ)^{60}Zn	2.16	^{59}Ni
^{42}K(p,n)^{42}Ca	2.13	^{43}K
^{23}Na(α,p)^{26}Mg	2.12, 1.14, 1.13, 1.12^{a}	^{43}K, ^{47}Sc ^{49}V, ^{55}Fe
^{27}Al(α,p)^{30}Si	1.91, 1.58^{a}	^{43}K, ^{47}Sc
^{28}Al(p,α)^{25}Mg	1.89, 1.37^{a}	^{43}K, ^{47}Sc
^{47}Sc(n,γ)^{48}Sc	1.88	^{47}Sc
^{47}Ti(n,p)^{47}Sc	1.85	^{47}Sc
^{48}Cr(α,p)^{51}Mn	1.84, 1.16^{a}	^{48}V, ^{51}Cr
^{51}Mn(p,γ)^{52}Fe	1.76	^{51}Cr
^{41}K(p,α)^{38}Ar	1.72	^{43}K
^{43}K(n,γ)^{44}K	1.65	^{43}K
^{46}Sc(n,γ)^{47}Sc	1.55	^{47}Sc
^{46}Sc(p,n)^{46}Ti	1.45	^{47}Sc
^{53}Fe(n,p)^{53}Mn	1.41	^{53}Mn
^{49}Mn(p,γ)^{50}Fe	1.34	^{49}V
^{55}Co(p,γ)^{56}Ni	1.32	^{55}Fe
^{45}Ca(n,γ)^{46}Ca	1.31	^{47}Sc
^{32}S(n,α)^{29}Si	1.31, 1.29^{a}	^{43}K, ^{47}Sc
^{40}Ar(p,γ)^{41}K	1.30	^{43}K
^{44}Ca(p,γ)^{45}Sc	1.29	^{47}Sc
^{40}K(n,γ)^{41}K	1.29	^{43}K
^{45}Sc(p,γ)^{46}Ti	1.27	^{47}Sc
^{59}Cu(p,α)^{56}Ni	1.25	^{59}Ni
^{49}Cr(n,p)^{49}V	1.25	^{49}V
^{57}Ni(n,p)^{57}Co	1.24, 1.21^{a}	^{57}Co, ^{59}Ni
^{41}Ca(n,α)^{38}Ar	1.23	^{43}K
^{41}K(p,n)^{41}Ca	1.21	^{43}K
^{59}Fe(n,γ)^{60}Fe	1.19	^{59}Fe
^{49}V(p,γ)^{50}Cr	1.19	^{49}V
^{25}Mg(α,n)^{28}Si	1.19, 1.11^{a}	^{47}Sc, ^{43}K
^{43}Sc(p,γ)^{44}Ti	1.18	^{44}Ti
^{57}Cu(p,γ)^{58}Zn	1.17	^{59}Ni
^{46}Ca(p,γ)^{47}Sc	1.16	^{47}Sc
^{52}Fe(α,p)^{55}Co	1.15	^{52}Mn
^{48}Cr(p,γ)^{49}Mn	1.15	^{49}V
^{43}Sc(p,α)^{40}Ca	1.15	^{44}Ti
^{41}Ca(n,γ)^{42}Ca	1.15	^{47}Sc
^{39}Ar(n,γ)^{40}Ar	1.15	^{43}K
^{28}Al(p,n)^{28}Si	1.15	^{43}K
^{13}N(α,p)^{16}O	1.15, 1.15, 1.14, 1.14, 1.11^{a}	^{52}Mn, ^{55}Fe, ^{49}V, ^{53}Mn, ^{48}V
^{49}Cr(p,γ)^{50}Mn	1.14	^{49}V
^{40}Ca(α,γ)^{44}Ti	1.14	^{44}Ti
^{41}K(p,γ)^{42}Ca	1.13	^{43}K
^{47}Ca(p,n)^{47}Sc	1.11	^{47}Sc
^{45}V(p,γ)^{46}Cr	1.10	^{44}Ti

What did we miss?

Open Question: Are Neutron Star Mergers Producing the Heavy Elements Attributed to the r-Process?

$t = .02\ ms$

Breakthrough gravitational wave observation GW170817 by LIGO
(together with gamma-ray burst detection by Fermi Gamma-ray Space Telescope)



→ Short Gamma Ray Bursts are Neutron Star Mergers
→ Neutron star mergers happen frequently

Daniel Price
Stephan Rosswog

GW170817 Associated Kilonova

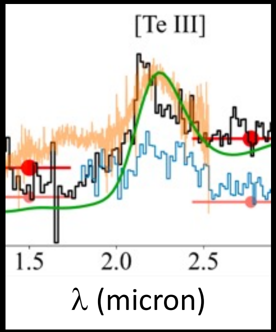
ESO/N.R. Tanvir, A.J. Levan
and the VIN-ROUGE collaboration

Region in the sky where gravitational waves from a neutron star merger were received from (GW170817)

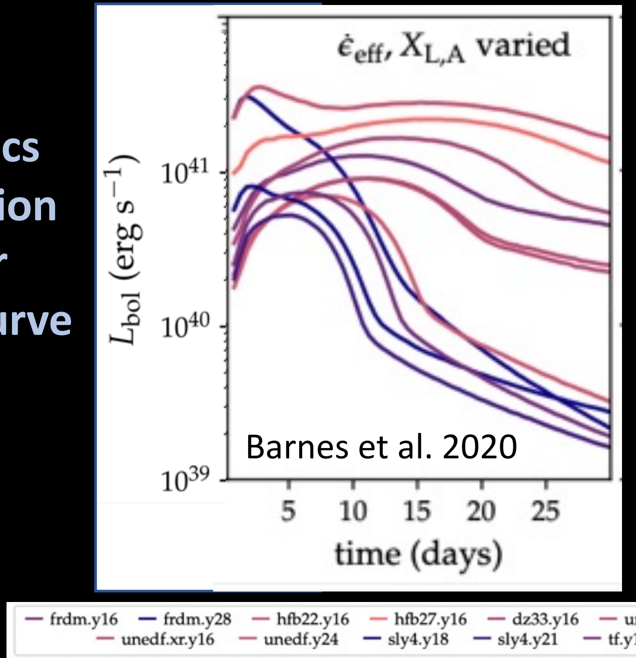
A Kilonova!
And its getting red!
→ Indicates large amounts of heavy elements ejected
→ NSM make enough heavy elements to be a significant Galactic source

Limited spectral information on actual elements (e.g. hints for Sr, but could also be He)
→ **Need nuclear physics to determine elements made**

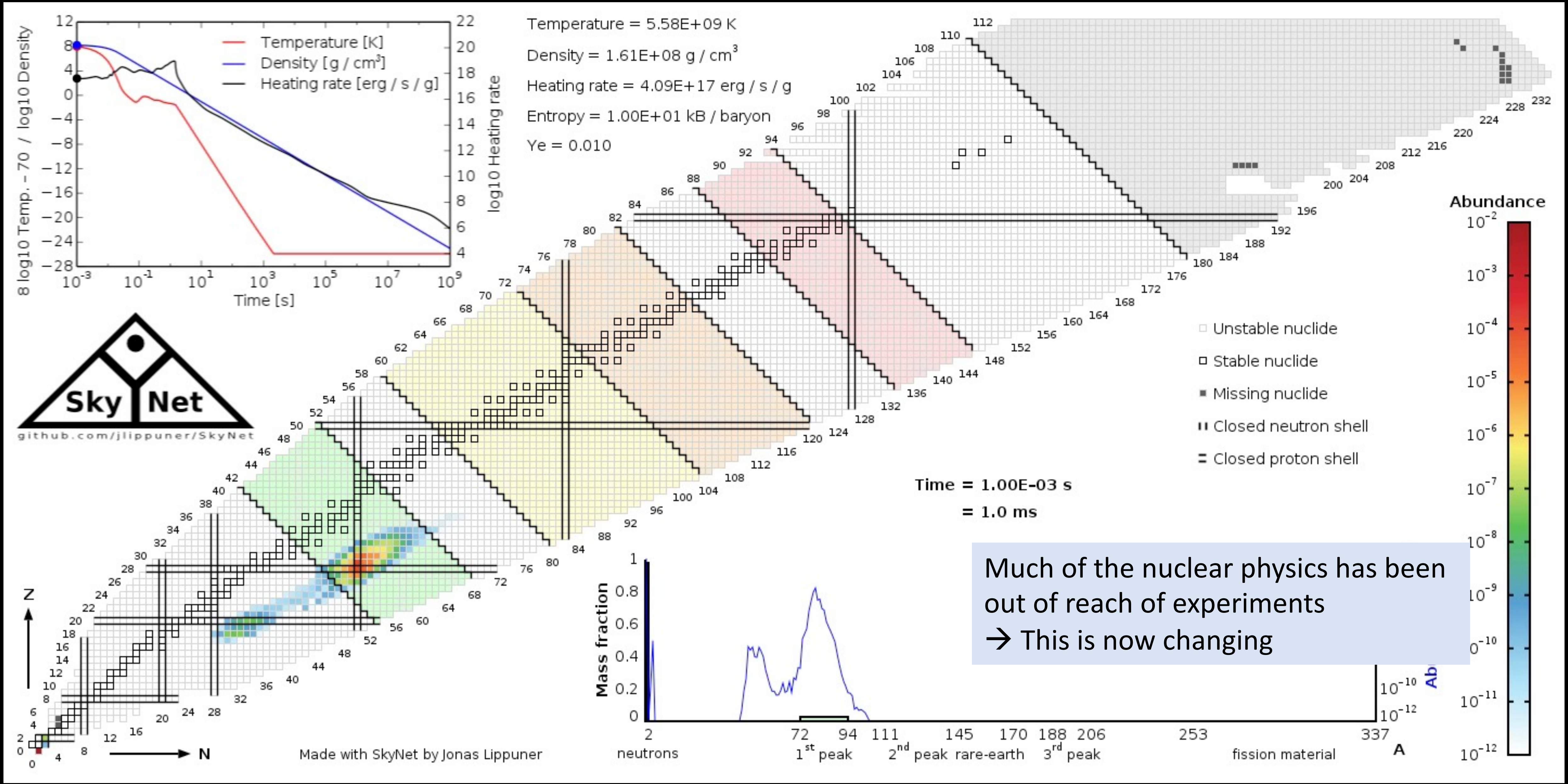
Levan et. al.
JWST detection of Te
in GRB230307 afterglow



Light curve depends on composition
→ **Need nuclear physics**
to predict composition
to probe NS merger models with light curve observations



r-Process Involves Neutron Capture on Extremely Unstable Nuclei

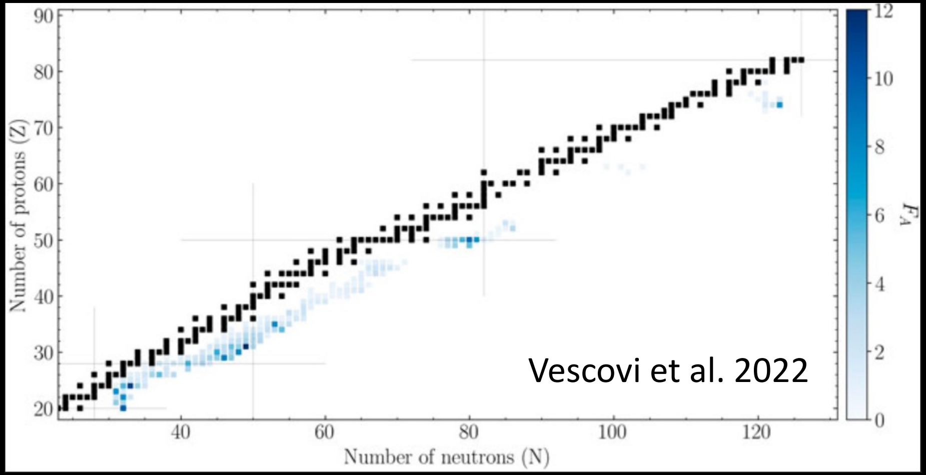


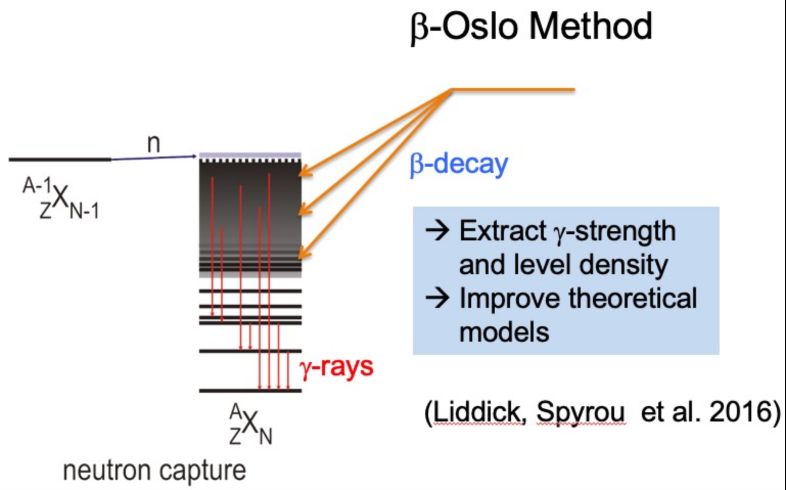
Much of the nuclear physics has been out of reach of experiments

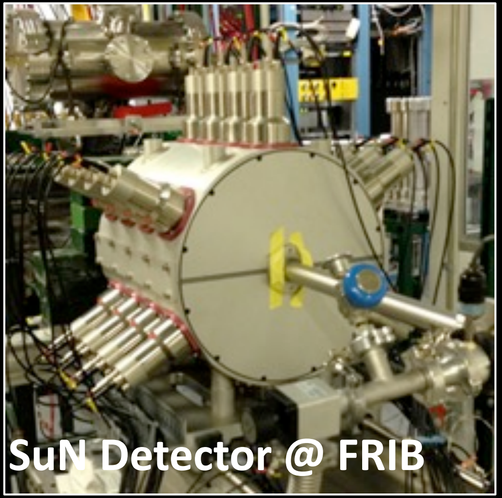
→ This is now changing

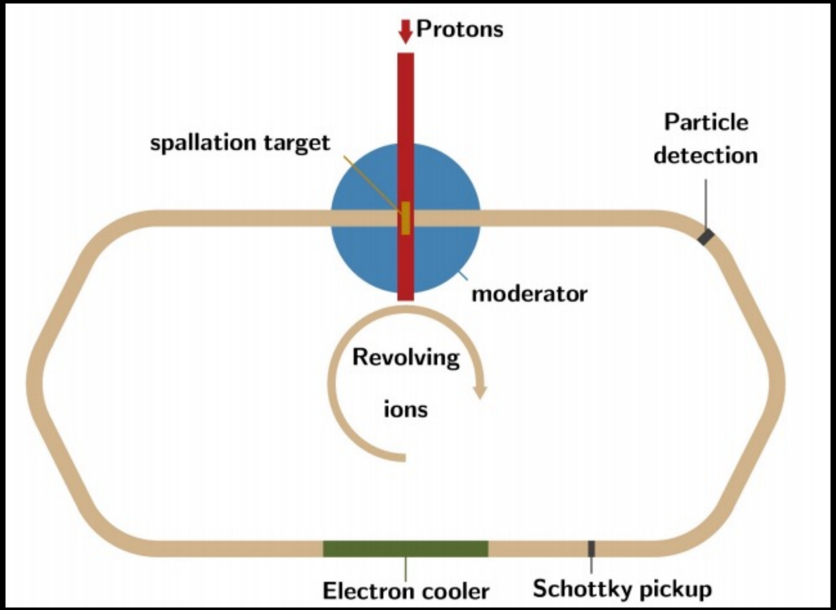
How can we Measure Neutron Captures on Unstable Nuclei?

Important reactions identified

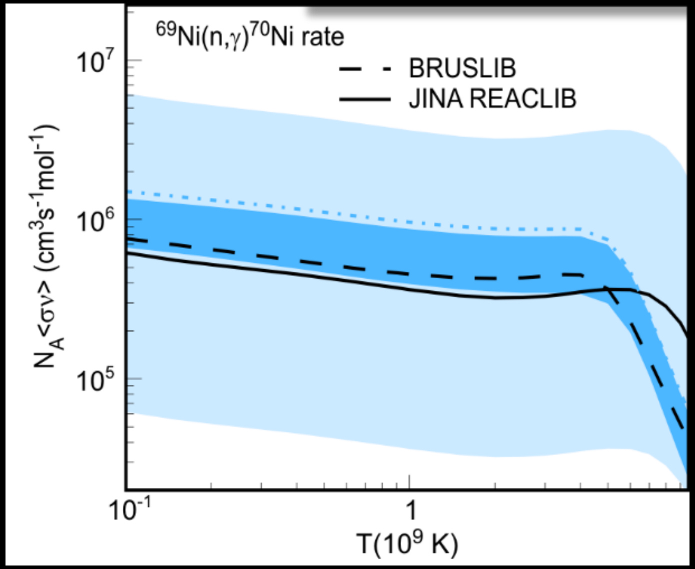








Reifarth, Litvinov et al. 2015, 2018



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INVESTIGATION OF CAPTURE REACTIONS FAR OFF STABILITY BY ß-DELAYED NEUTRON EMMISSION

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Abstract

Beta-delayed neutron spectroscopy is applied to determine reaction rates of neutron capture on several neutron rich nuclei. The results of these experiments are presented and discussed in the light of their astrophysical implications. Furthermore, the experimental possibilities and limits of planned measurements are advertised.

1985

Summary

- Incredible scientific opportunities in nuclear astrophysics ahead with a new generation of radioactive beam facilities
  - Coinciding with advent of multi-messenger astronomy
  - Coinciding with advances on computational capability to take advantage of data
- Close collaborative connections between nuclear experiment, nuclear theory, astrophysics modeling, observations, cosmo-chemistry are essential
  - Founding of JINA under Michael's leadership was a game changer and model for how this can be accomplished
  - Legacy continues with CeNAM (Center for Nuclear Astrophysics Across Messengers) and IReNA (International Research Network for Nuclear Astrophysics) Network of Networks (EMMI Partner)
- Thank you Michael for your pioneering work and advocacy that set nuclear astrophysics on this exciting path
- Happy Birthday