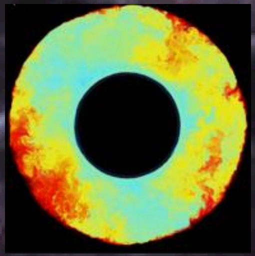
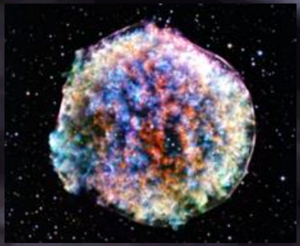
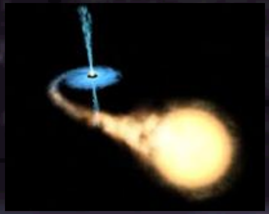
Cosmic Formation of the (Heavy) Elements And Rare Isotope Experiments at FRIB

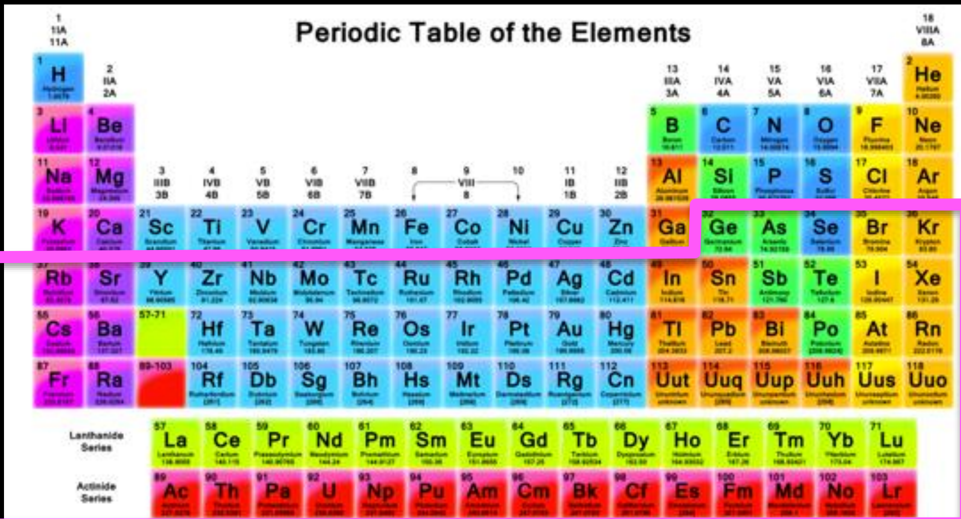
Hendrik Schatz
Facility for Rare Isotope Beams and Dept. of Physics and Astronomy
Michigan State University





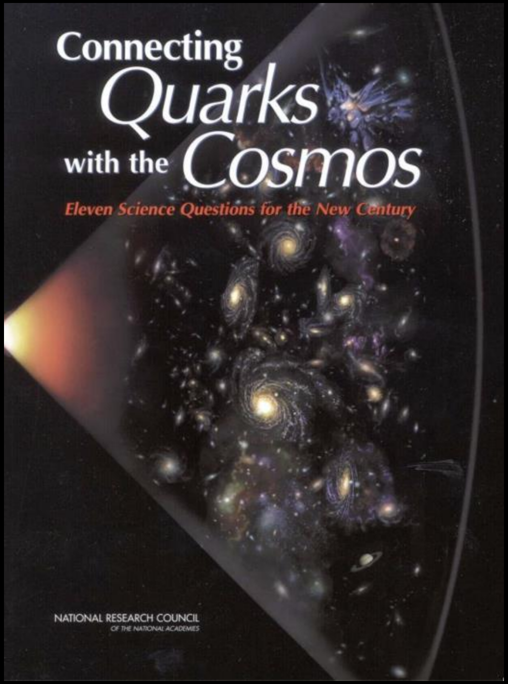


Cosmic Formation of the Elements: Open Question at the Beginning of the Century



Elements from "Iron" to Uranium:

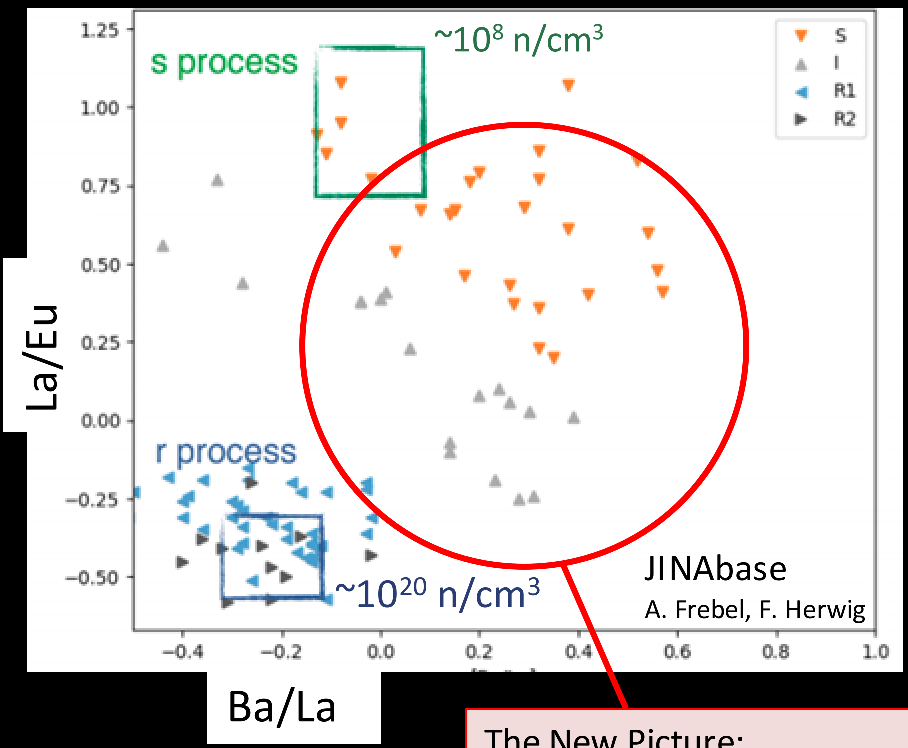
- Half by slow neutron capture (s-process)
  - In red giant stars
- Half by rapid neutron capture (r-process)
  - Site?

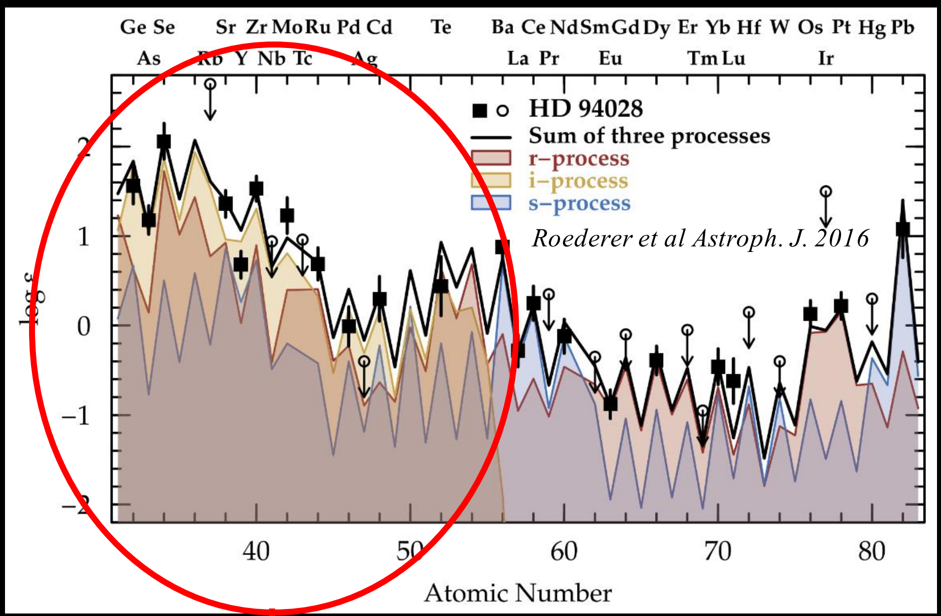


2003 "Committee on the Physics of the Universe":
11 Science Questions for the New Century:
- How were the elements from iron to uranium made

A New Picture of Nucleosynthesis – A Continuum (Zoo?) of Processes

Evidence from metal poor stars – fossils of chemical evolution
+ current understanding of nuclear physics





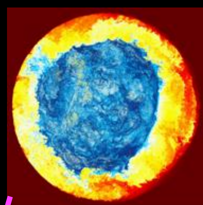
The New Picture:

- Continuum of neutron capture processes
  - slow (s), intermediate, rapid n-capture processes
- Independent weak r-process?
- νp-process?

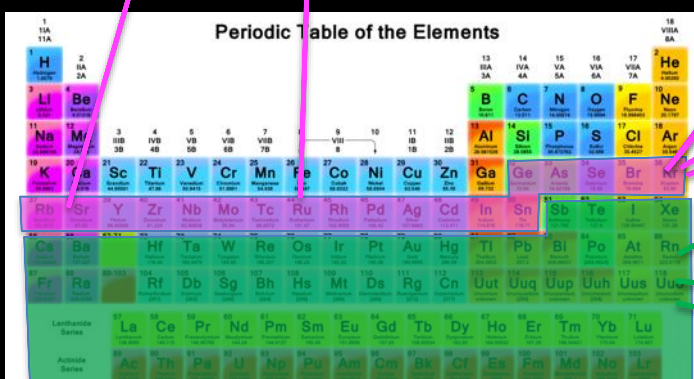
→ **Need nuclear physics to disentangle**

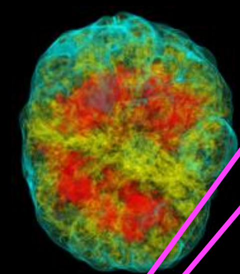
A More Complex (complete?) Picture of the Origin of the "r-process" Elements is Emerging

Hydrogen ingestion in stars:
i-process



Rapidly Accreting White Dwarfs:
i-process

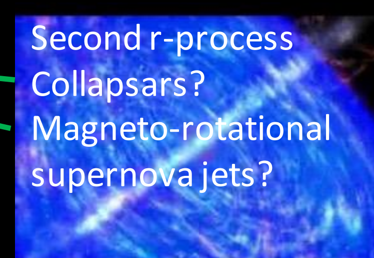




Supernovae
- νp-process
- Weak r-process

NS Mergers – r-rpocess

Dynamical ejecta
Wind ejecta
Disk ejecta



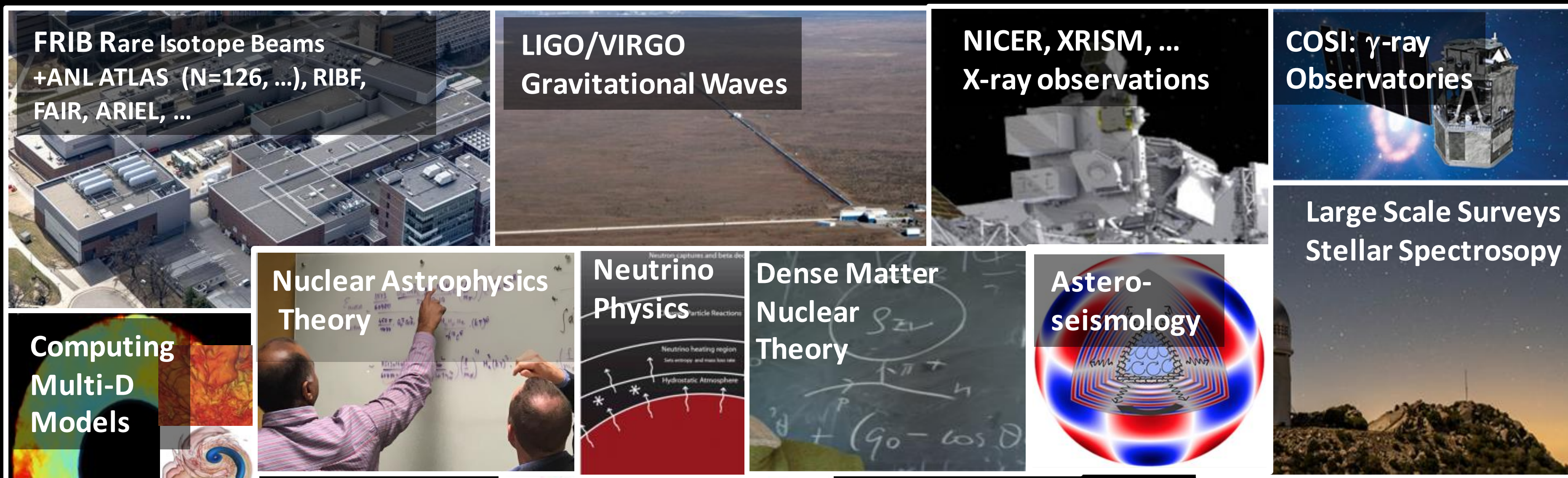
Strong dependence of nucleosynthesis on properties of dense matter

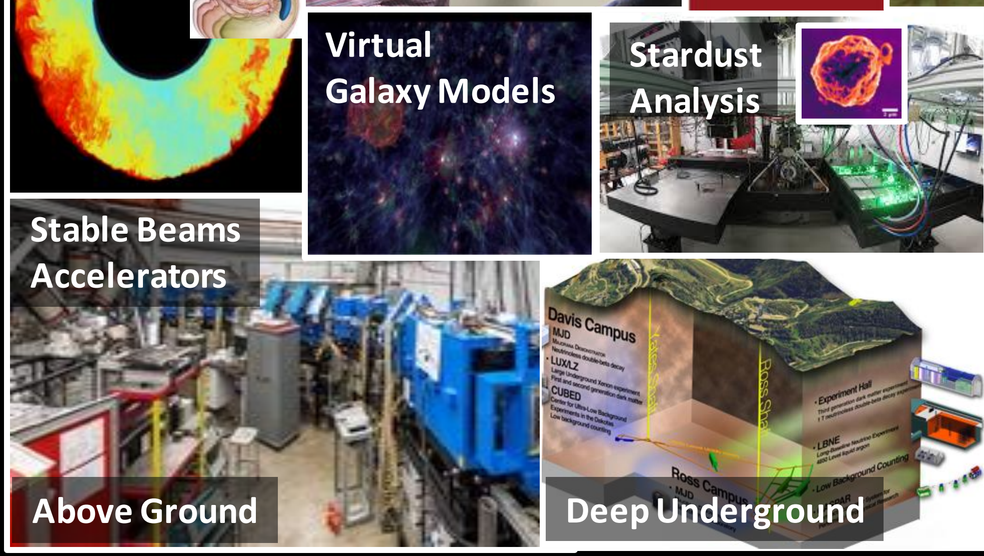
Accreting neutron stars

+ NS Mergers
  Kilonovae
  Gravitational waves
+ X-ray pulsars
+ Heavy ion collision experiments

→ Rare Isotopes are Key in All These Possible Sites

Major Advances in Broad Range of Areas Across Fields Coincide – Unique Opportunity for Nuclear Astrophysics





- → Close international collaboration across field boundaries
- → Need to build a new expanded interdisciplinary nuclear astrophysics community

The new CeNAM Collaboration builds on the Joint Institute for Nuclear Astrophysics to form such a community

Center for Nuclear Astrophysics Across Messengers CeNAM

- Joint Institute for Nuclear Astrophysics has brought together nuclear scientists and astronomers since 2003 (**jinaweb.org**)
- The new Center for Nuclear Astrophysics Across Messengers Links
    - 57 institutions in 11 countries
    - 12 Core Institutions in US and Canada (with budget)
    - Diverse range of institutions: 30 US Research universities of various sizes, 9 Minority Serving Institutions, 4 US National Laboratories + NASA, Carnegie Observatories

International Research Network for Nuclear Astrophysics (IReNA)

- CeNAM will take advantage of the International Research Network for Nuclear Astrophysics (IReNA), a NSF AccelNet network of networks
- IReNA will links 8 international networks in nuclear astrophysics spanning 41 countries

www.irenaweb.org

A New White Paper for Nuclear Astrophysics

arXiv:2205.07996v1 [nucl-ex] 16 May 2022

Horizons: Nuclear Astrophysics in the 2020s and Beyond

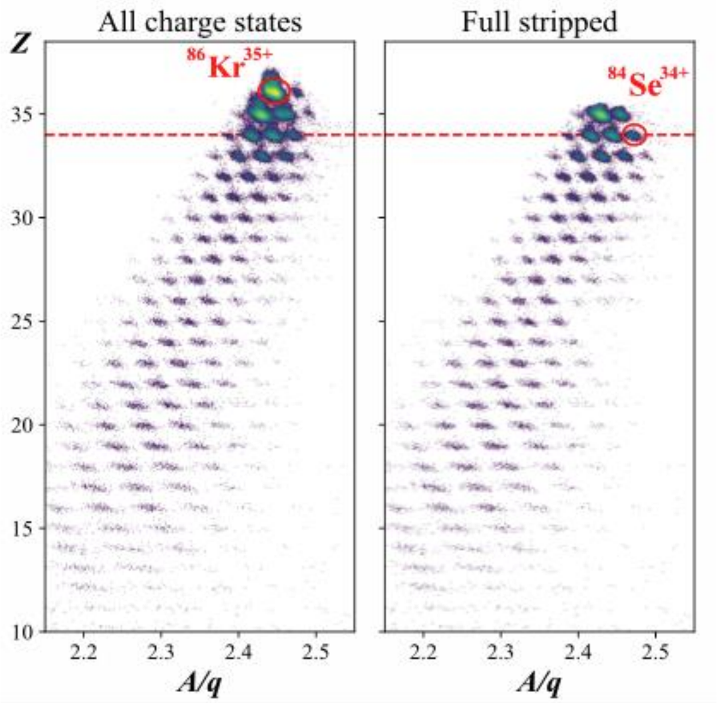
H Schatz[1,2,3], A D Becerril Reyes[2,3], A Best[4,5], E F Brown[1,2,6,3], K Chatziioannou[7,8], K A Chipps[9,10], C M Deibel[11], R Ezzeddine[12,3], D K Galloway[13,14,15], C J Hansen[16,17,18], F Herwig[19,3], A P Ji[20,21], M Lugaro[22,23,13], Z Meisel[24,3], D Norman[25], J S Read[26], L F Roberts[27], A Spyrou[1,2,3], I Tews[28], F X Timmes[29,3], C Travaglio[30], N Vassh[31], C Abia[32], P Adsley[33], S Agarwal[34,3], M Aliotta[35], W Aoki[36,37], A Arcones[38,39], A Aryan[40], A Bandyopadhyay[40], A Banu[41], D W Bardayan[42,3], J Barnes[43], A Bauswein[39], T C Beers[42,3], J Bishop[44], T Boztepe[45], B Côté[19,22,3], M E Caplan[46], A E Champagne[47,48], J A Clark[49,3], M Couder[42,3], A Couture[50], S E de Mink[51,52], S Debnath[53], R J deBoer[54], J den Hartogh[22], P Denissenkov[19,3], V Dexheimer[55], I Dillmann[56,19,3], J E Escher[57], M A Famiano[34,3,58], R Farmer[51], R Fisher[59], C Fröhlich[60,3], A Frebel[61], C Fryer[62], G Fuller[63], A K Ganguly[64], S Ghosh[60], B K Gibson[65], T Gorda[66,67], K N Gourgouliatos[68], V Graber[69,70], M Gupta[71], W Haxton[72,73], A Heger[13,14,74,3], W R Hix[9,10], W C G Ho[75], E M Holmbeck[76,3], A A Hood[44], S Huth[66,77], G Imbriani[4], R G Izzard[78], R Jain[1,2,3], H Jayatissa[79], Z Johnston[1,3], T Kajino[36,37,80], A Kankainen[81], G G Kiss[82], A Kwiatkowski[56,19], M La Cognata[83], A M Laird[84], L Lamia[85,83,86], P Landry[87], E Laplace[88,52], K D Launey[11], D Leahy[89], G Leckenby[31,90], A Lennarz[31,91], B Longfellow[57], A E Lovell[28], W G Lynch[1,2], S M Lyons[92,3], K Maeda[93], E Masha[94], C Matei[95], J Merc[96,97], B Messer[98,10], F Montes[2,3], A Mukherjee[99,100], M Mumpower[28,62,3], D Neto[101], B Nevins[1,2,3], W G Newton[102], L Q Nguyen[54], K Nishikawa[103], N Nishimura[104,105], F M Nunes[2,1], E O'Connor[106], B W O'Shea[6,1,2,3], W-J Ong[57,3], S D Pain[9,10], M A Pajkos[1,6,3], M Pignatari[22,107,108], R G Pizzone[83], V M Placco[25], T Plewa[109], B Pritychenko[110], A Psaltis[38,108], D Puentes[1,2], Y-Z Qian[111], D Radice[112,113,114], D Rapagnani[4,5], B M Rebeiro[115,116], R Reifarth[16], A L Richard[57,2], N Rijal[2], I U Roederer[117,3], J S Rojo[118], J S K[119], Y Saito[90,56], A Schwenk[66,77,120], M L Sergi[85,83], R S Sidhu[39,120,35], A Simon[54], T Sivarani[121], Á Skúladóttir[122,123], M S Smith[9], A Spiridon[124], T M Sprouse[28,62], S Starrfield[29], A W Steiner[125,9], F Strieder[126], I

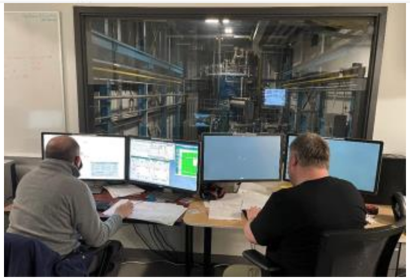
Sultana[127,3], R Surman[54,3], T Szücs[82], A Tawfik[128], F Thielemann[129,39], L Trache[124], R Trappitsch[130,108], M B Tsang[2], A Tumino[131,83], S Upadhyayula[31], J O Valle Martínez[132], M Van der Swaelmen[123], C Viscasillas Vázquez[133], A Watts[52], B Wehmeyer[22,134], M Wiescher[42,35,3], C Wrede[1,2], J Yoon[135,3], R G T Zegers[1,2,3], M A Zermane[136], M Zingale[137]

Organized by JINA, IReNA Partner Networks

- 579 participants JINA Horizon Horizon Meeting December 2020
- White Paper: 165 co-authors from 20 countries
- Includes:
  - Scientific vision for the field
  - DEIA vision for the field
  - Needs of early career scientists
  - Role of interdisciplinary centers and networks and the importance of collaboration
- Currently being refereed – available for scientists on arXiv

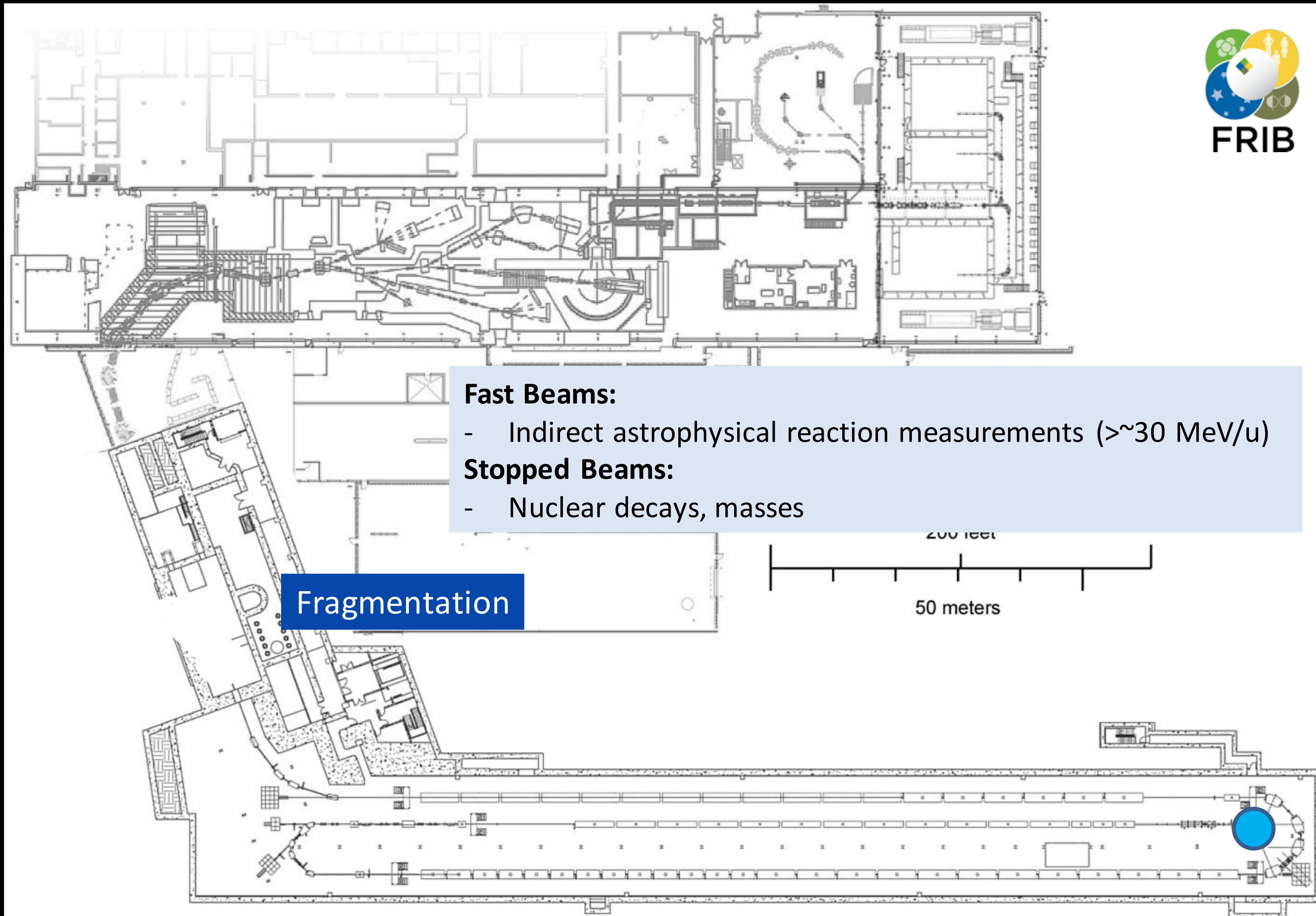
Facility for Rare Isotope Beams (FRIB) Provides New Opportunities for Nuclear Astrophysics





- FRIB is a $730 million scientific user facility funded by the Department of Energy Office of Science (DOE-SC), Michigan State University, and the State of Michigan and located at Michigan State University in the US
- First FRIB experiments have begun in May 2022
- Unique opportunities for Nuclear Astrophysics

FRIB Provides Fast, Stopped, and Reaccelerated Beams



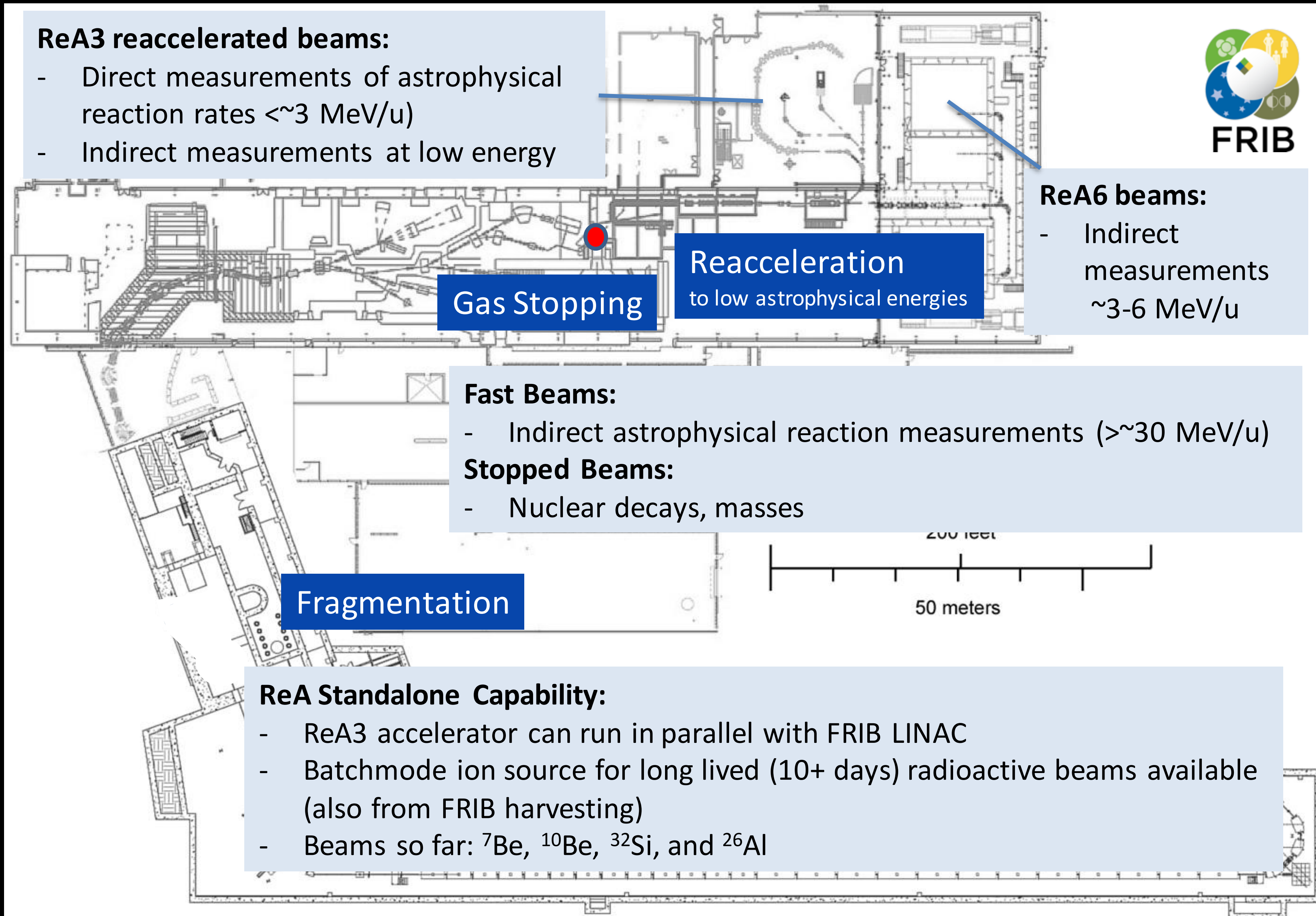
Fast Beams:

- Indirect astrophysical reaction measurements (>~30 MeV/u)

Stopped Beams:

- Nuclear decays, masses

FRIB Provides Fast, Stopped, and Reaccelerated Beams



ReA3 reaccelerated beams:

- Direct measurements of astrophysical reaction rates <~3 MeV/u)
- Indirect measurements at low energy

ReA6 beams:

- Indirect measurements ~3-6 MeV/u

Fast Beams:

- Indirect astrophysical reaction measurements (>~30 MeV/u)

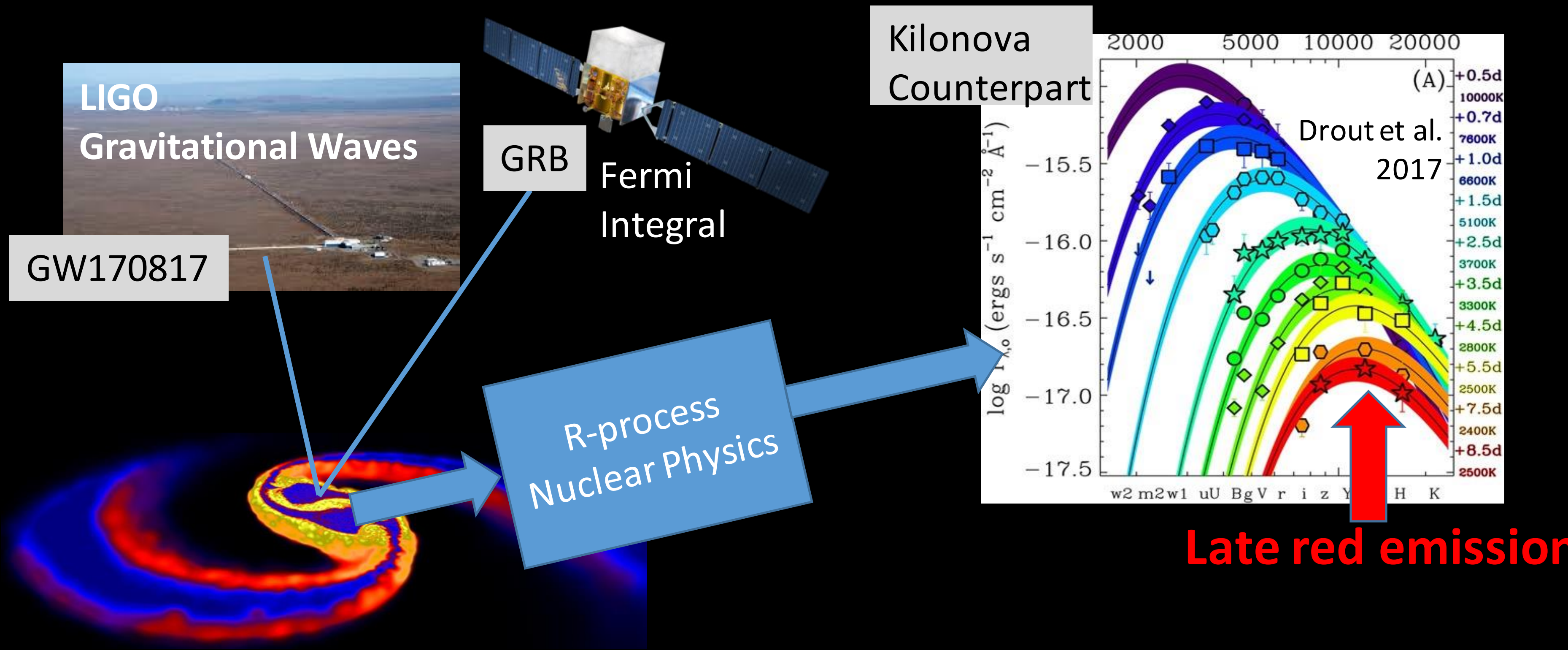
Stopped Beams:

- Nuclear decays, masses

ReA Standalone Capability:

- ReA3 accelerator can run in parallel with FRIB LINAC
- Batchmode ion source for long lived (10+ days) radioactive beams available (also from FRIB harvesting)
- Beams so far: ^{7}Be, ^{10}Be, ^{32}Si, and ^{26}Al

Are Neutron Star Mergers the Site of the Main R-process?



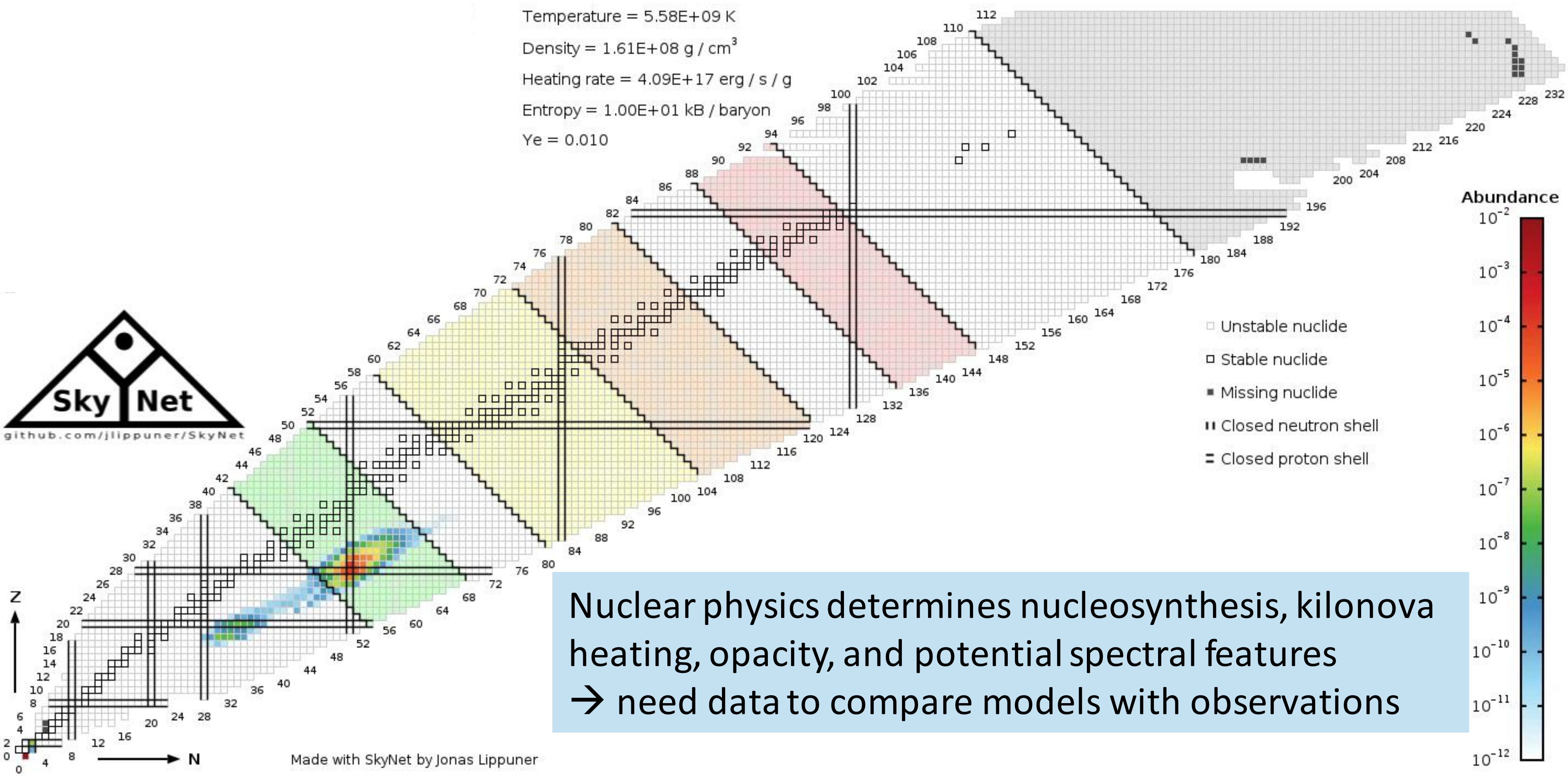
Direct Evidence for synthesis and ejection of large amounts of heavy elements

Open nucleosynthesis questions:

- What elements do NS mergers make?
- Are NS mergers the only source of r-process elements? (Probably not)
- What do observed heavy element features tell us about the engine and dense matter?

→ All these require nuclear physics

Models Identify r-process Nuclear Physics



Nuclear physics determines nucleosynthesis, kilonova heating, opacity, and potential spectral features
→ need data to compare models with observations

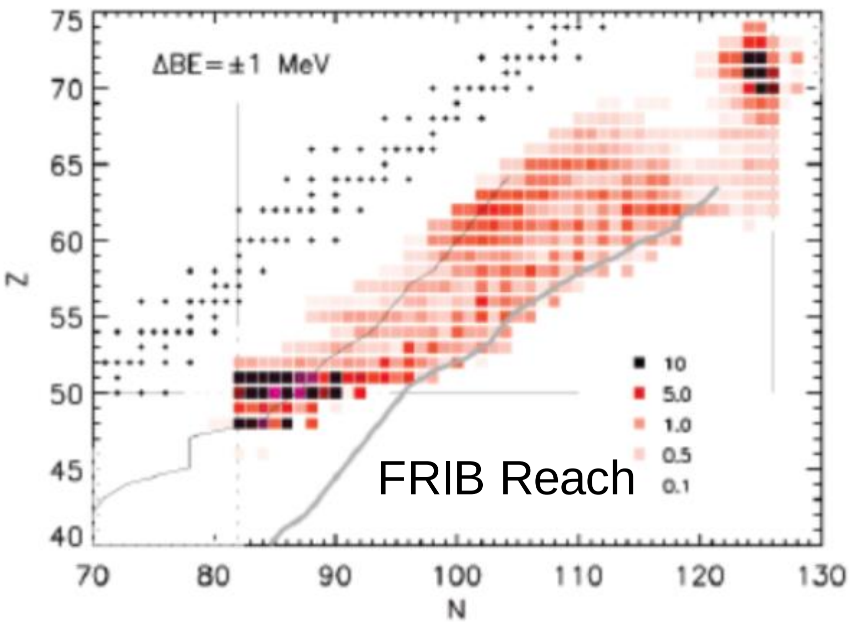
Thanks to Jonas Lippuner and Luke Roberts

Radice et al. 2016

Nuclear Uncertainties Prevent Meaningful Prediction of Elements Created in NS Mergers

Rare isotope physics identified:

Example: nuclear masses for the r-process



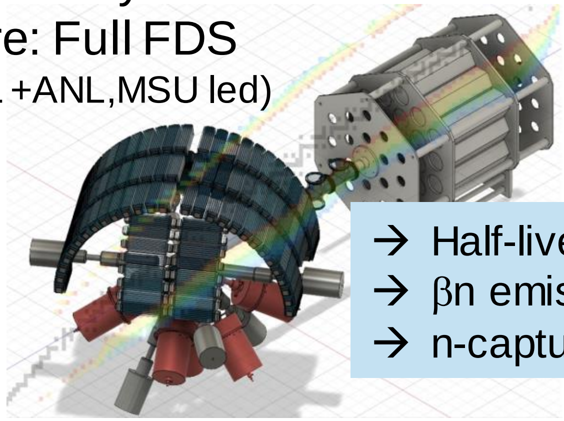
Mumpower, Surman, Aprahamian

FRIB Experiments:

FRIB Decay Station Initiator

Future: Full FDS

(ORNL +ANL,MSU led)



- → Half-lives
- → βn emission
- → n-capture

LEBIT Penning Trap

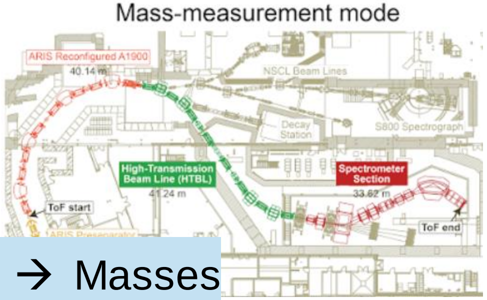
(MSU led)

→ Masses

S800 Spectrometer – Future: HRS

(CMU +WMU,MSU led)

Mass-measurement mode



→ Masses

FRIB Laboratory, Michigan State University
U.S. Department of Energy Office of Science
National Science Foundation

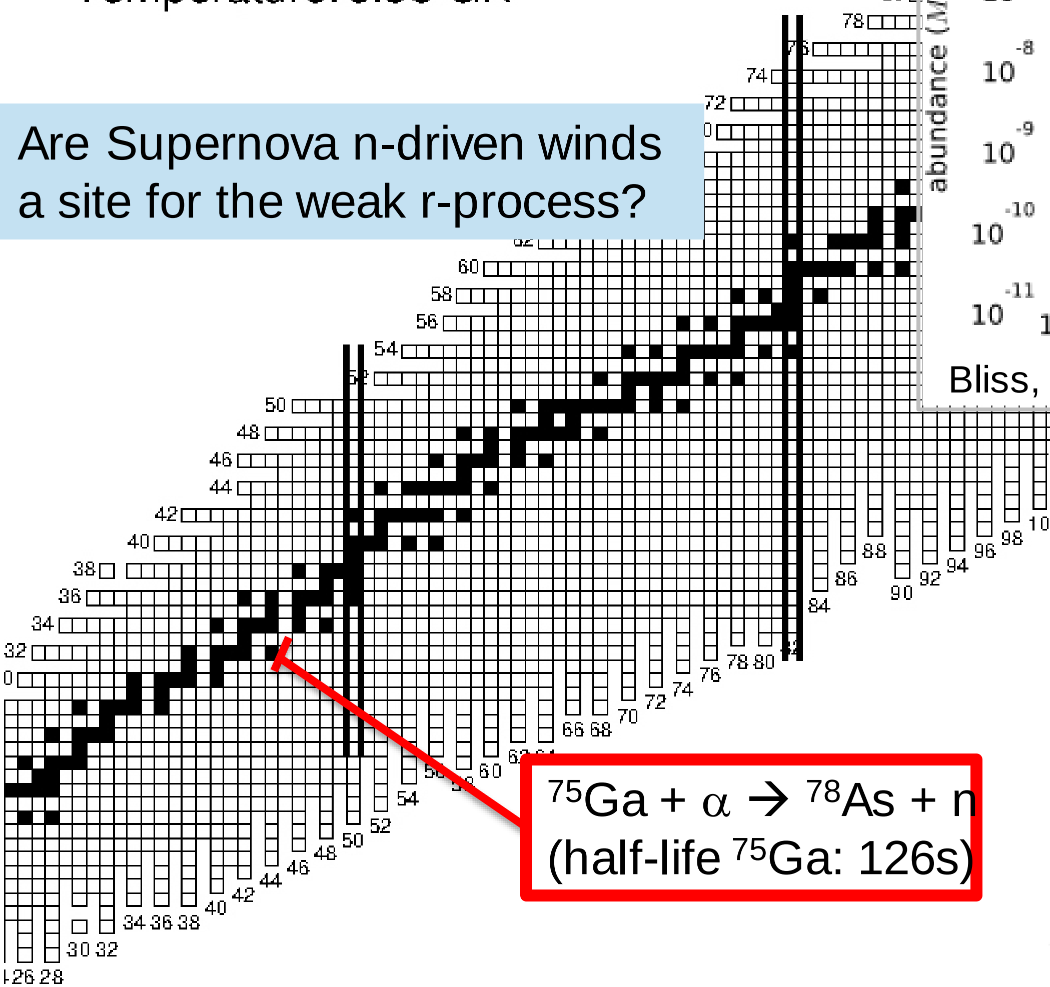
Nucleosynthesis in the failed r-process

Joint Institute for Nuclear Astrophysics 201

Time: 6.5e-03 s

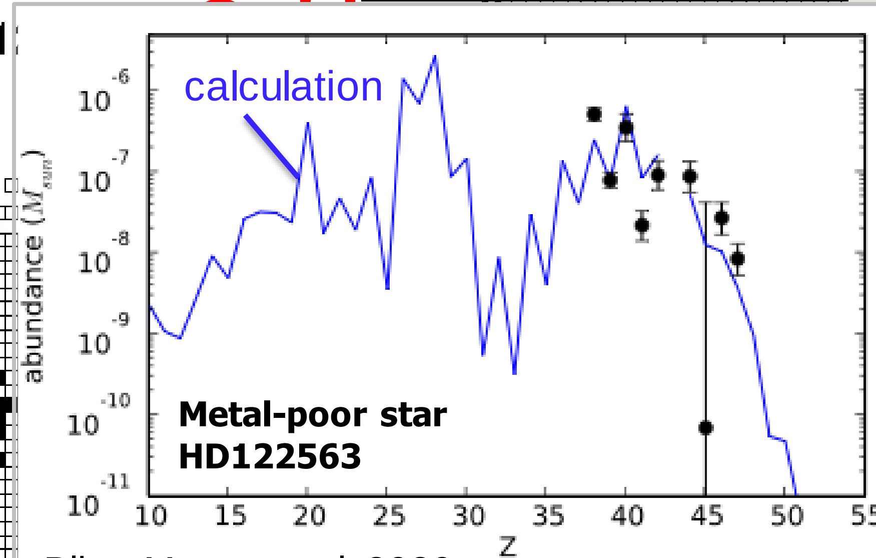
Temperature: 6.58 GK

Are Supernova n-driven winds a site for the weak r-process?

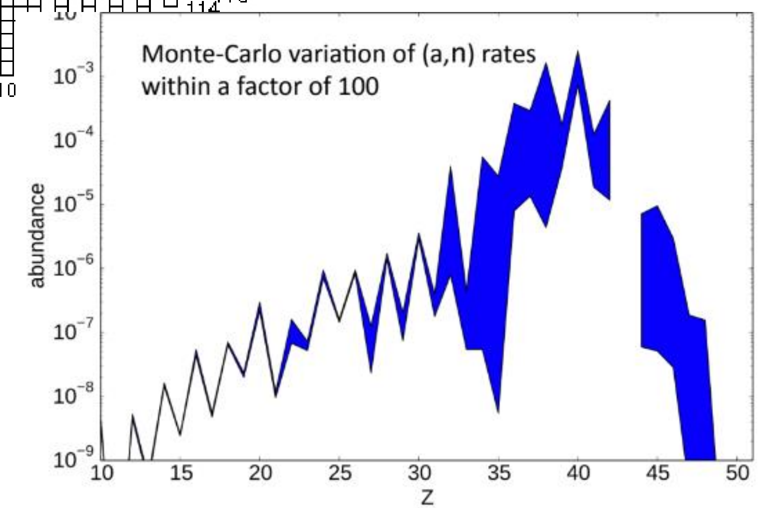


$^{75}Ga + \alpha \rightarrow {}^{78}As + n$

(half-life ^{75}Ga: 126s)

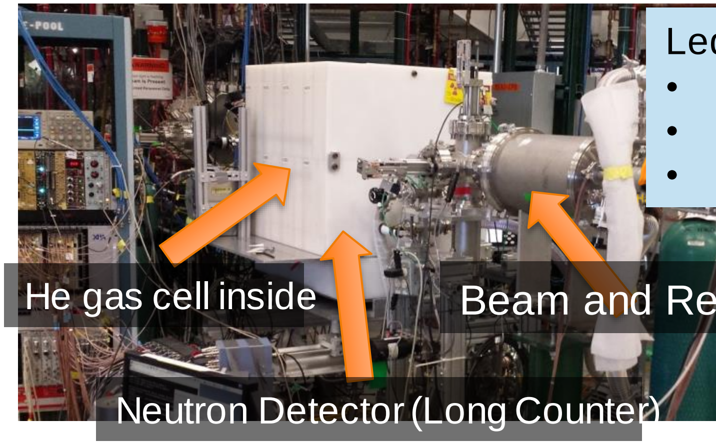


Bliss, Montes et al. 2020



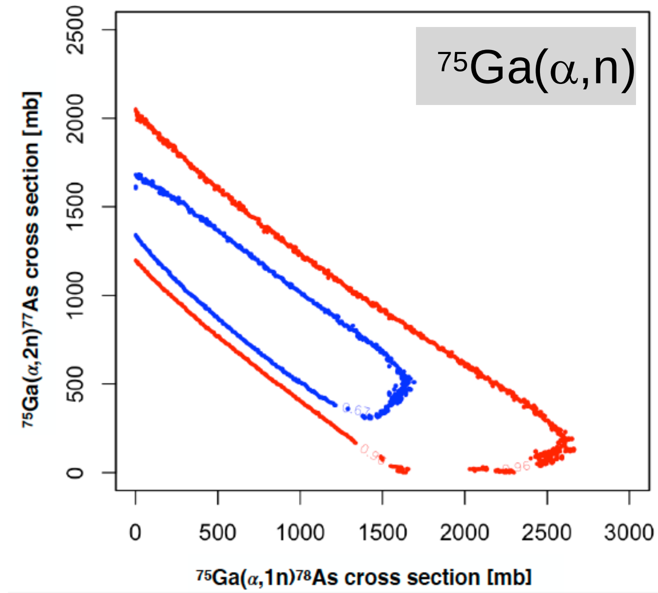
Complementary Techniques used at FRIB to directly measure (α,n) reactions with reaccelerated beams

HABANERO Neutron Detector



Led by:

- Zach Meisel (Ohio)
- F. Montes (MSU)
- T. Ahn (IBS, Korea)



MUSIC Active Target Detector

Led by:

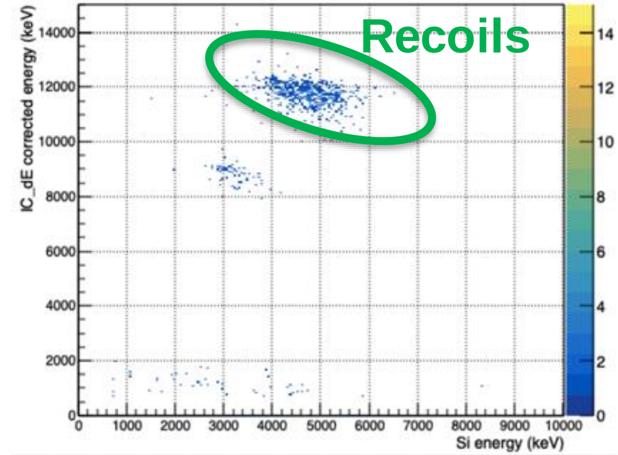
- M. Avila (ANL)
- J. Pereira (MSU)
- F. Montes (MSU)

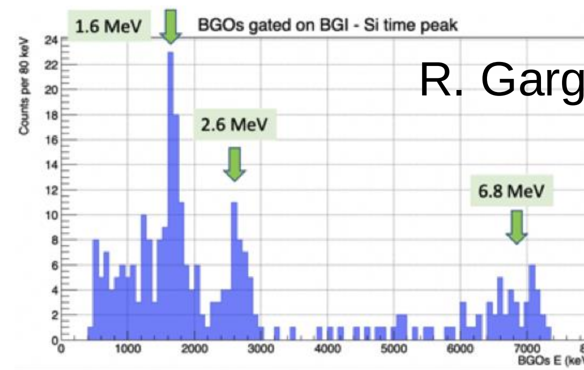
SECAR Recoil Separator Enables Direct Measurements of p,γ and α,γ-Astrophysical Reactions at FRIB

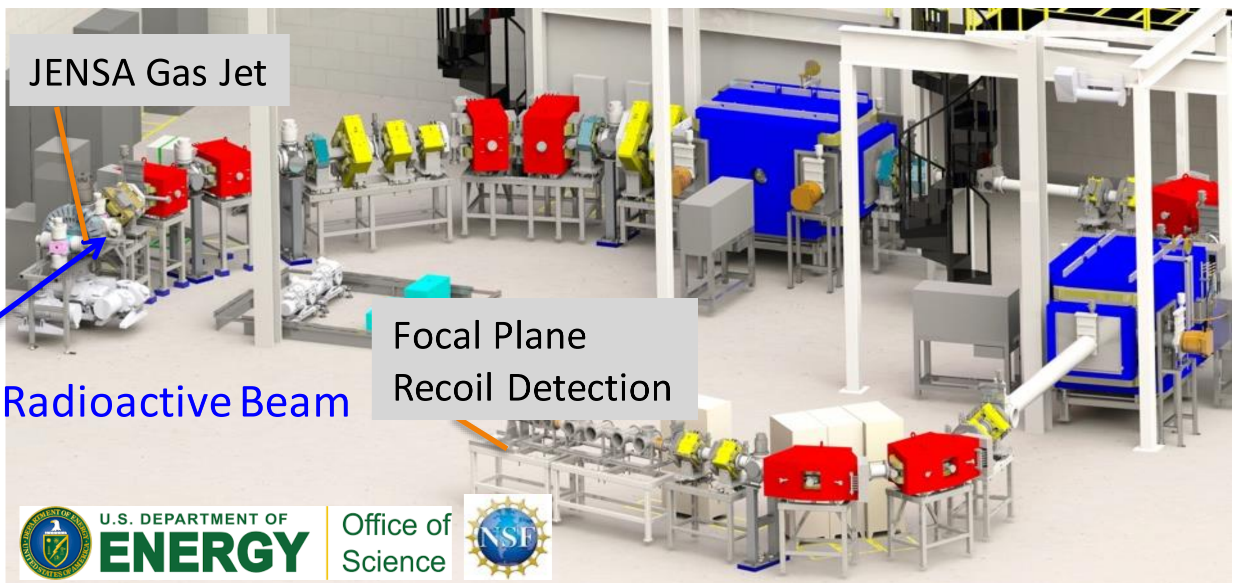
Notre Dame – MSU – LSU – Colorado School of Mines – ORNL – CMU- Ohio U collaboration

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

New device scientist
Kiana Seetodehnia



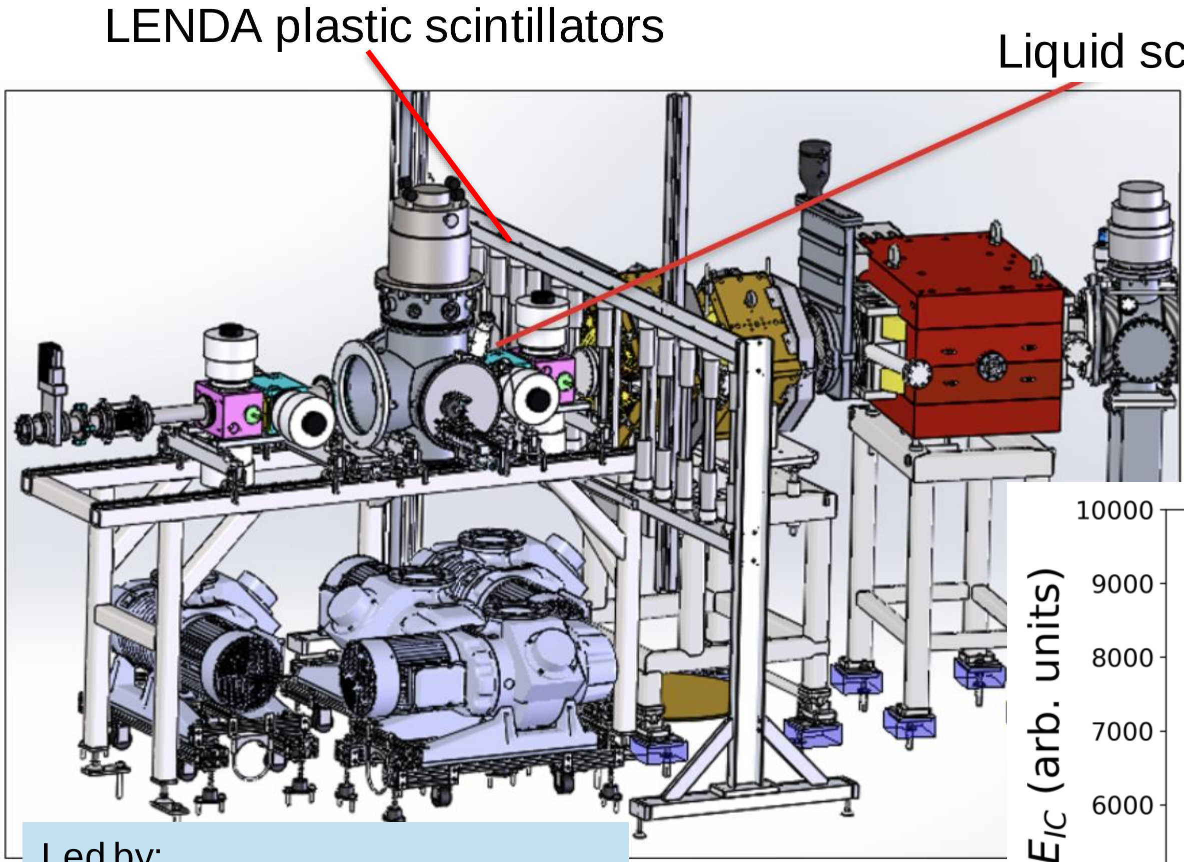




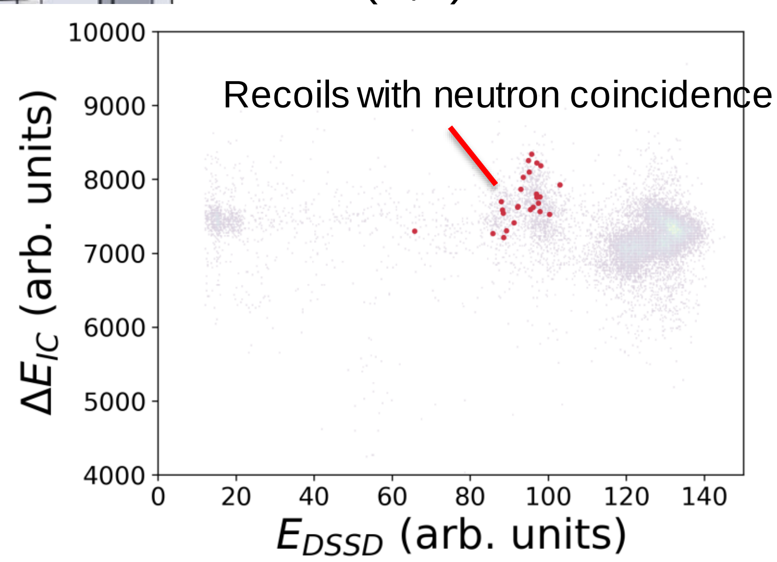
U.S. DEPARTMENT OF ENERGY | Office of Science | NSF

First recoil detection from $^{16}O(\alpha,\gamma)^{20}Ne$ concludes construction

SECAR with Neutron Detection for (α,n) and (p,n) Reaction Measurements



^{86}Kr(α,n) reaction

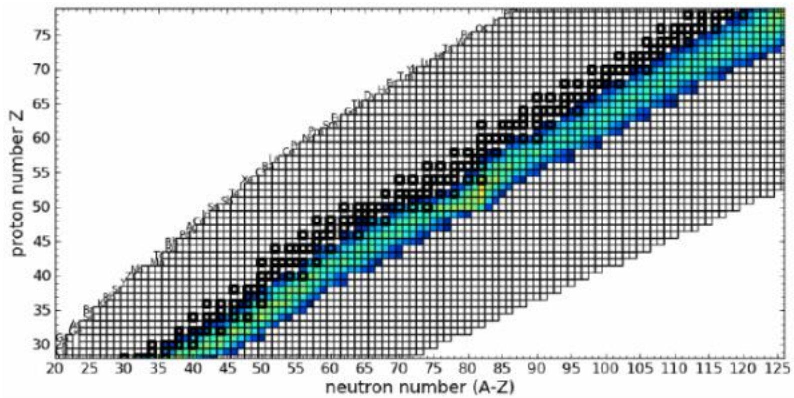


Led by:

- Z. Meisel/C. Marshall (Ohio)
- J. Pereira (MSU)
- F. Montes (MSU)

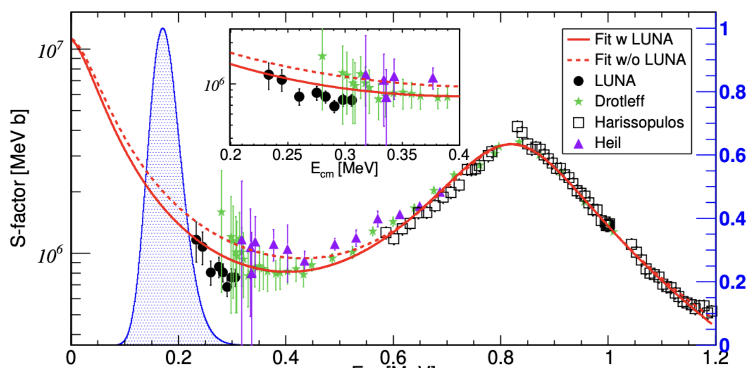
i-Process: Need n-Capture and n-Source Rates

i-process path



Challenge: rate of n-source reaction

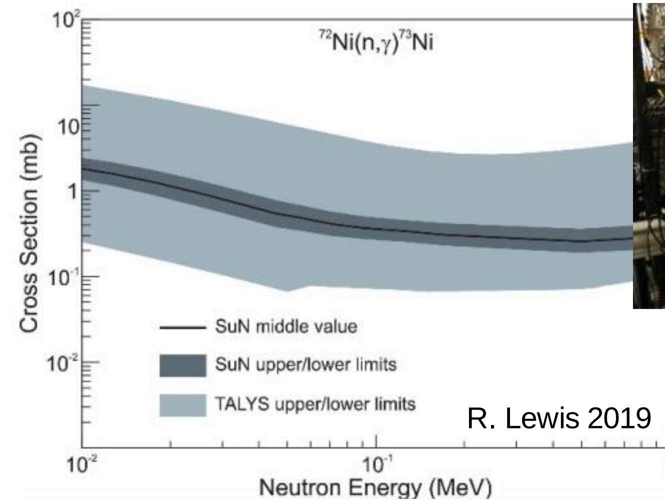
Ciani et al. 2021 (LUNA)

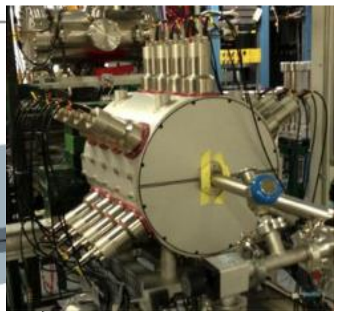


See also Febbraro et al. 2020 (Notre Dame)

Challenge: n-capture rates on unstable nuclei

β-Oslo Method: Level density and γ-strength from β-delayed γ–spectroscopy (S. Liddick, A. Spyrou NSCL)





SuN Total Absorption Spectrometer

Other possibilities:

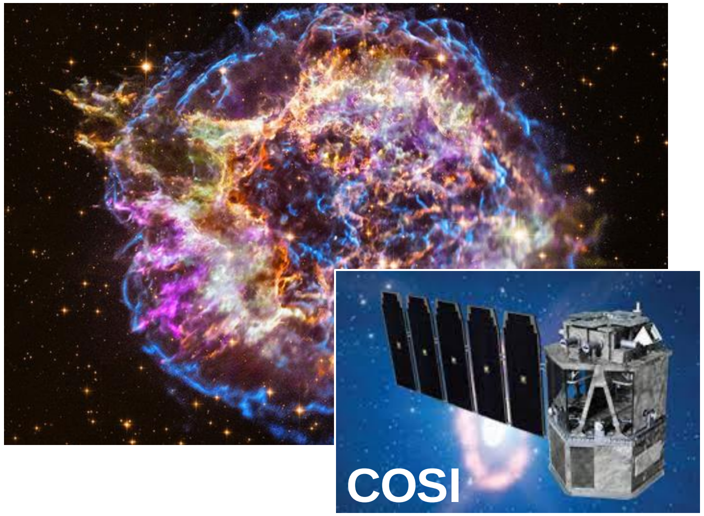
- For long-lived targets: isotope harvesting
- Storage ring with neutron beam?

→ Close collaboration between RIB and stable beam facilities needed

FRIB Will Address Reactions in Explosive Stellar Burning

Open Questions:

- What are the abundances of long-lived γ-ray emitters in supernova ejecta?
- What would observations with γ-ray observatories (e.g. future COSI) tell us about supernova physics?



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

Reaction	Impact	Isotope Affected
^{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

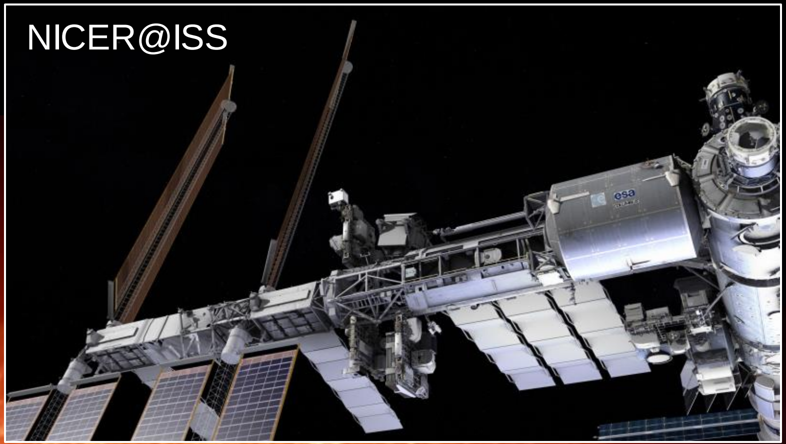
Key reactions for broad range of γ-ray emitters identified (Hermansen et al. 2020)

Broad range of reactions needed:

- Rare isotope beam experiments
  - Some beams sufficiently long-lived for batch mode production
- Stable beam experiments

→ Close collaboration between RIB and stable beam facilities needed

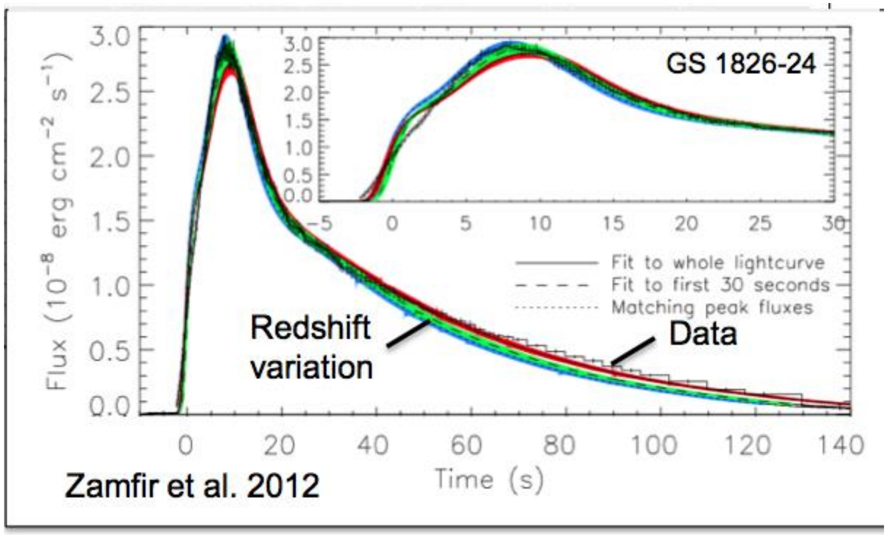
Accreting Neutron Stars are Unique Laboratories for Dense Matter



- X-rays from accreting neutron stars probe response of neutron star to accretion
- Complementary dense matter messenger to GW/EM signatures from NS mergers
- Opportunity with FRIB to pin down much of the nuclear physics
- New observations e.g. NICER, XRISM (launch date 2022) – key as not all data suitable for precision comparisons

Transition to Quantitative Analysis of Observations – Need Rare Isotope Nuclear Physics

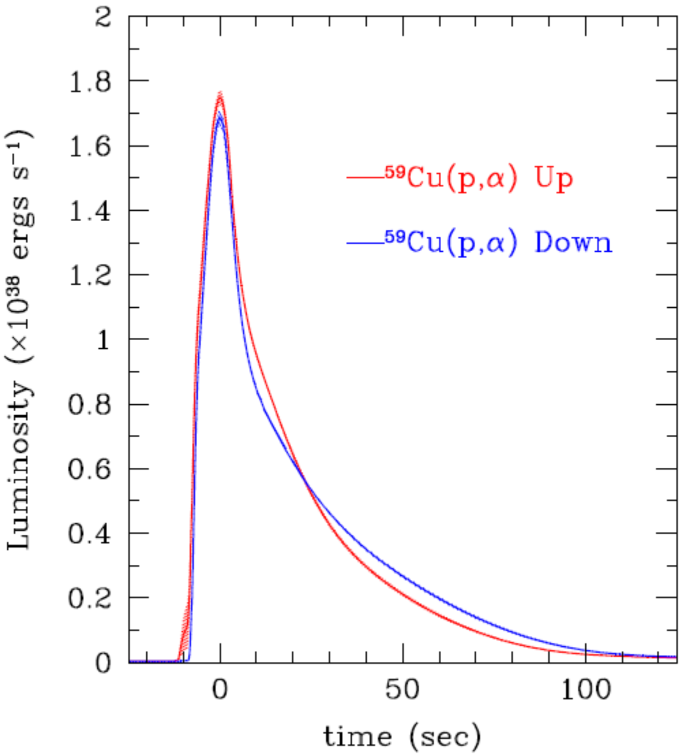
Precision X-ray Burst Observations



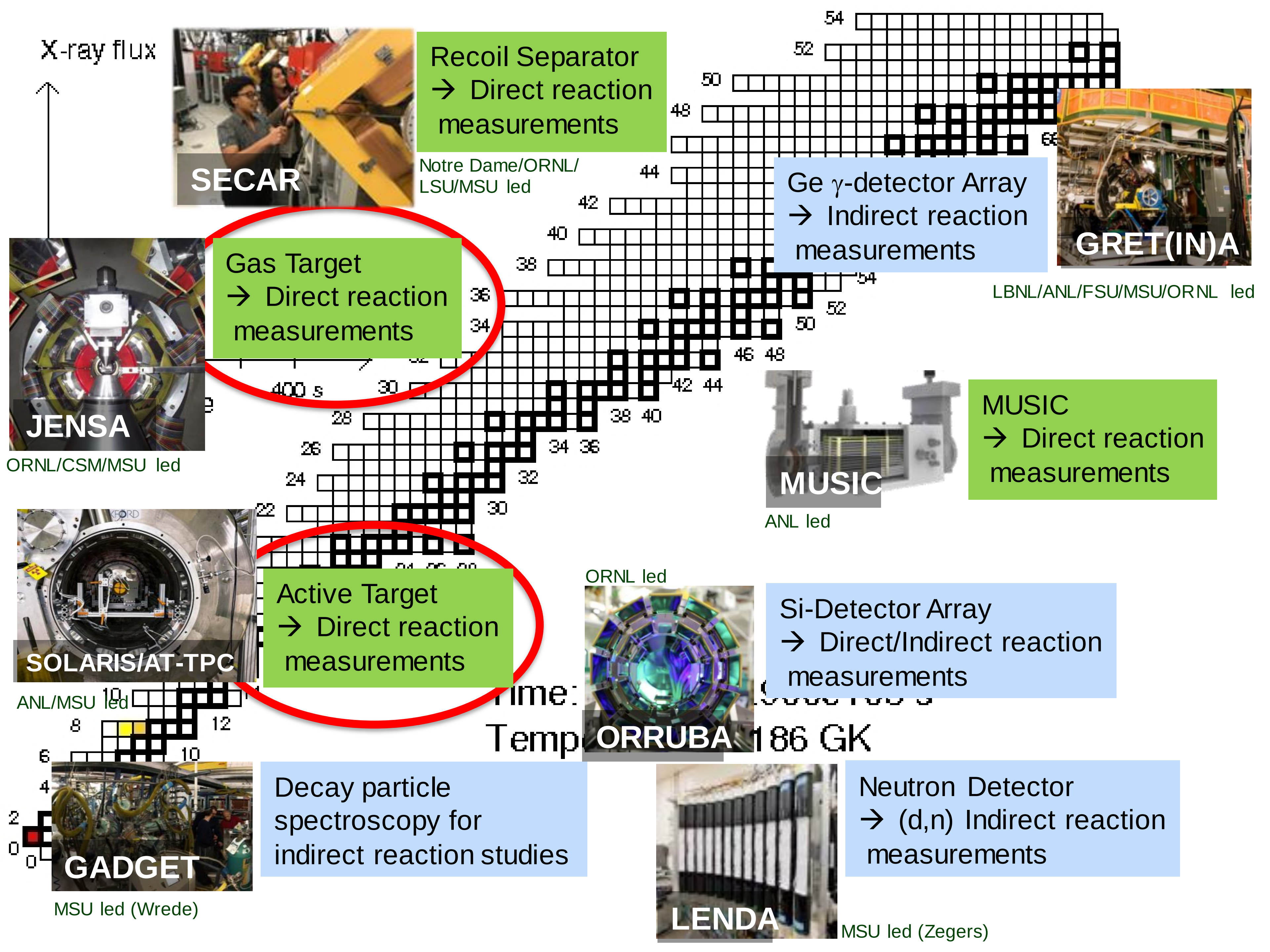
→ Model template comparison to extract surface red shift

→ Constrains compactness of neutron star and equation of state

Models highly sensitive to Nuclear Physics



Cyburt et al. 2016

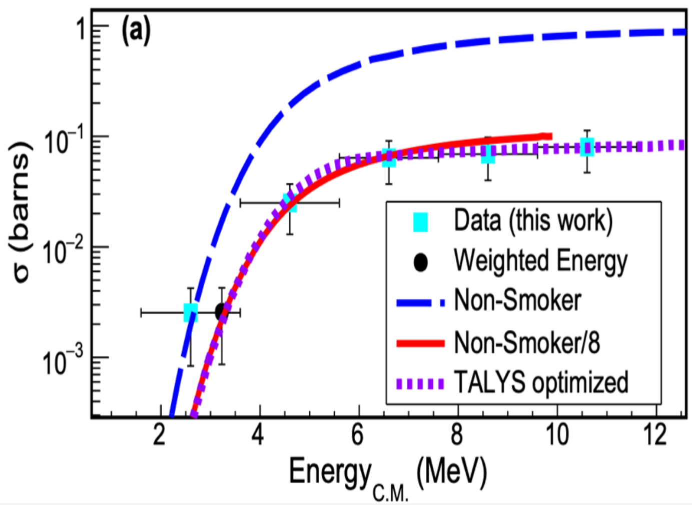

X-ray flux
SECAR
Recoil Separator
→ Direct reaction measurements
Notre Dame/ORNL/LSU/MSU led
Ge γ-detector Array
→ Indirect reaction measurements
GRET(IN)A
LBNL/ANL/FSU/MSU/ORNL led
Gas Target
→ Direct reaction measurements
JENSA
ORNL/CSM/MSU led
400 s
MUSIC
→ Direct reaction measurements
MUSIC
ANL led
SOLARIS/AT-TPC
ANL/MSU led
Active Target
→ Direct reaction measurements
ORNL led
ORRUBA
Si-Detector Array
→ Direct/Indirect reaction measurements
Temp 186 GK
GADGET
MSU led (Wrede)
Decay particle spectroscopy for indirect reaction studies
LENDA
Neutron Detector
→ (d,n) Indirect reaction measurements
MSU led (Zegers)

Recent progress on (α,p) reaction rates at NSCL

- Indications from indirect experimental data on nuclear excitation levels that (α,p) rates are currently overpredicted by theory factors of 100 or more (e.g. Matic et al. 2011)

AT-TPC: ^{22}Mg(α,p)

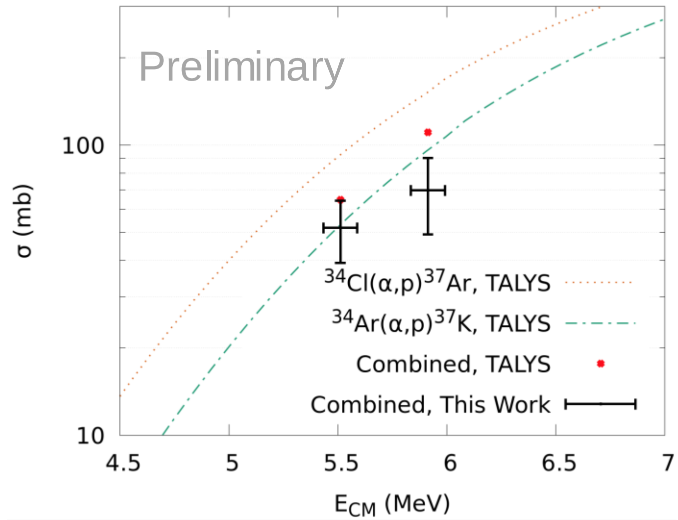
Randhawa 2020 @ NSCL AT-TPC



→ x8 lower than HF predictions

JENSA + ORRUBA ^{34}Ar(α,p)

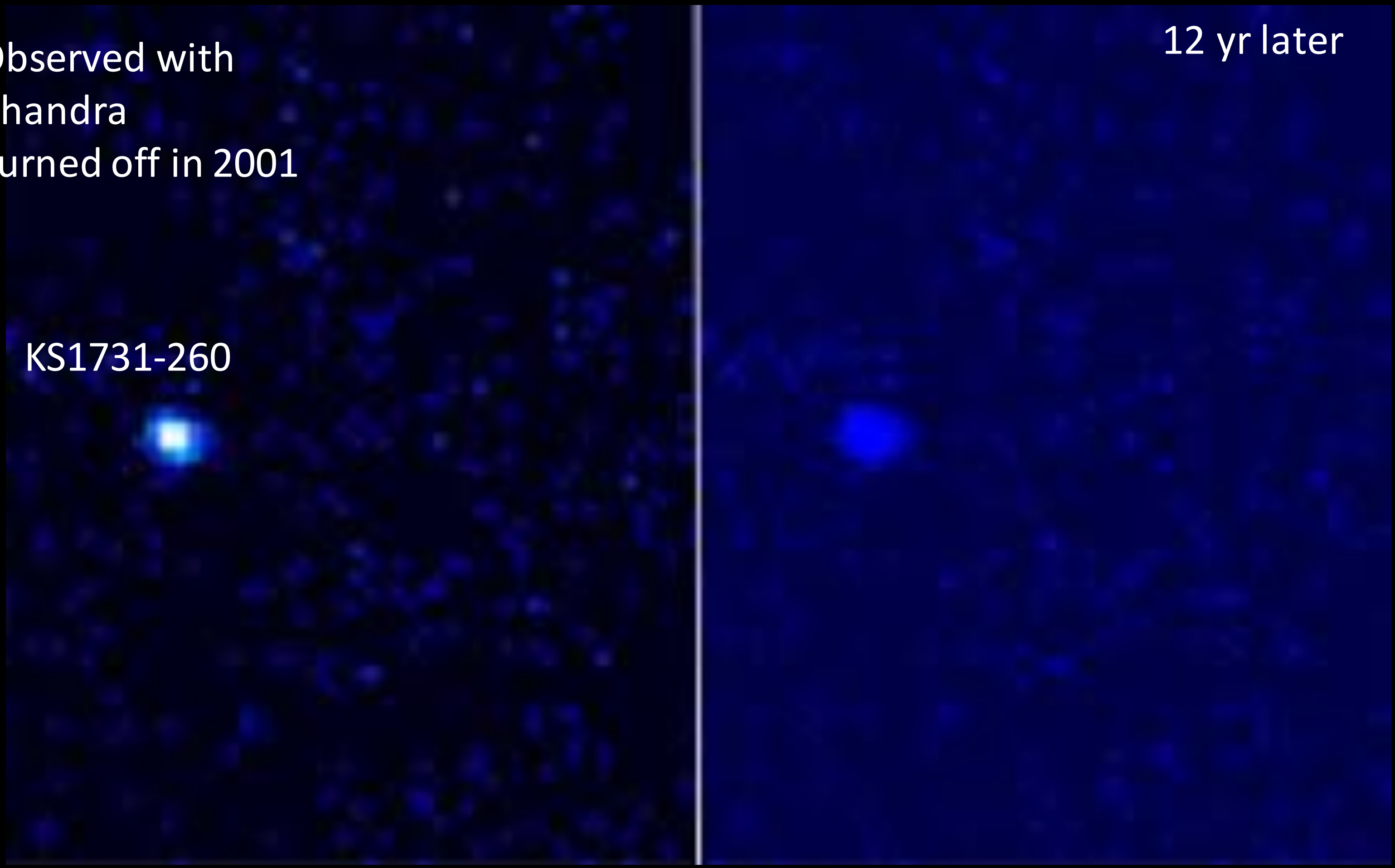
Browne, Schmidt, Chipps et al. @ NSCL JENSA



→ Agreement with HF predictions within x2

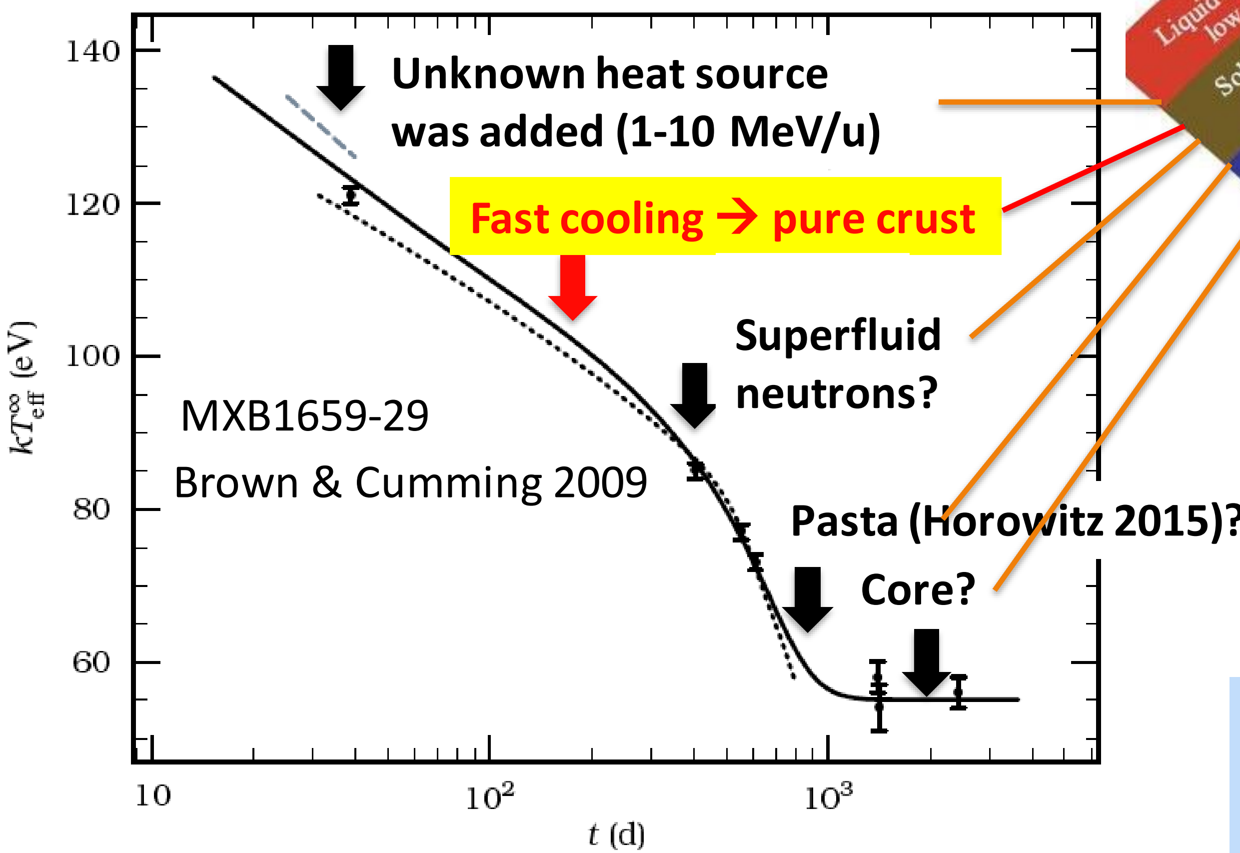
- Factor of 100 overprediction by theory not confirmed
- Significant discrepancy with Hauser-Feshbach predictions in some cases
- More data needed, especially at lower energies, Gamow window for <1 GK not reached

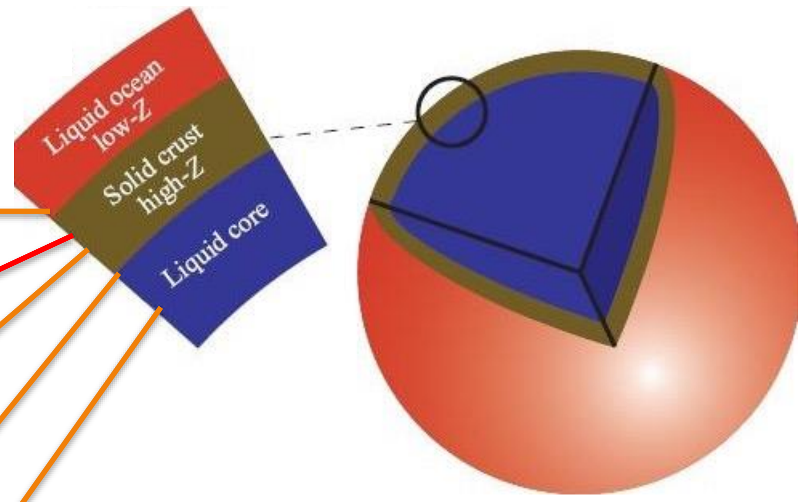
Transiently Accreting Neutron Stars Provide Additional Observables that Depend on Rare Isotope Physics



During Quiescence: Cooling Observations Reveal Neutron Star Interior

Observing the cooling crust





Drawing: E. Brown

BUT: Isn't the crust made of burst ashes?
→ Definitely NOT pure

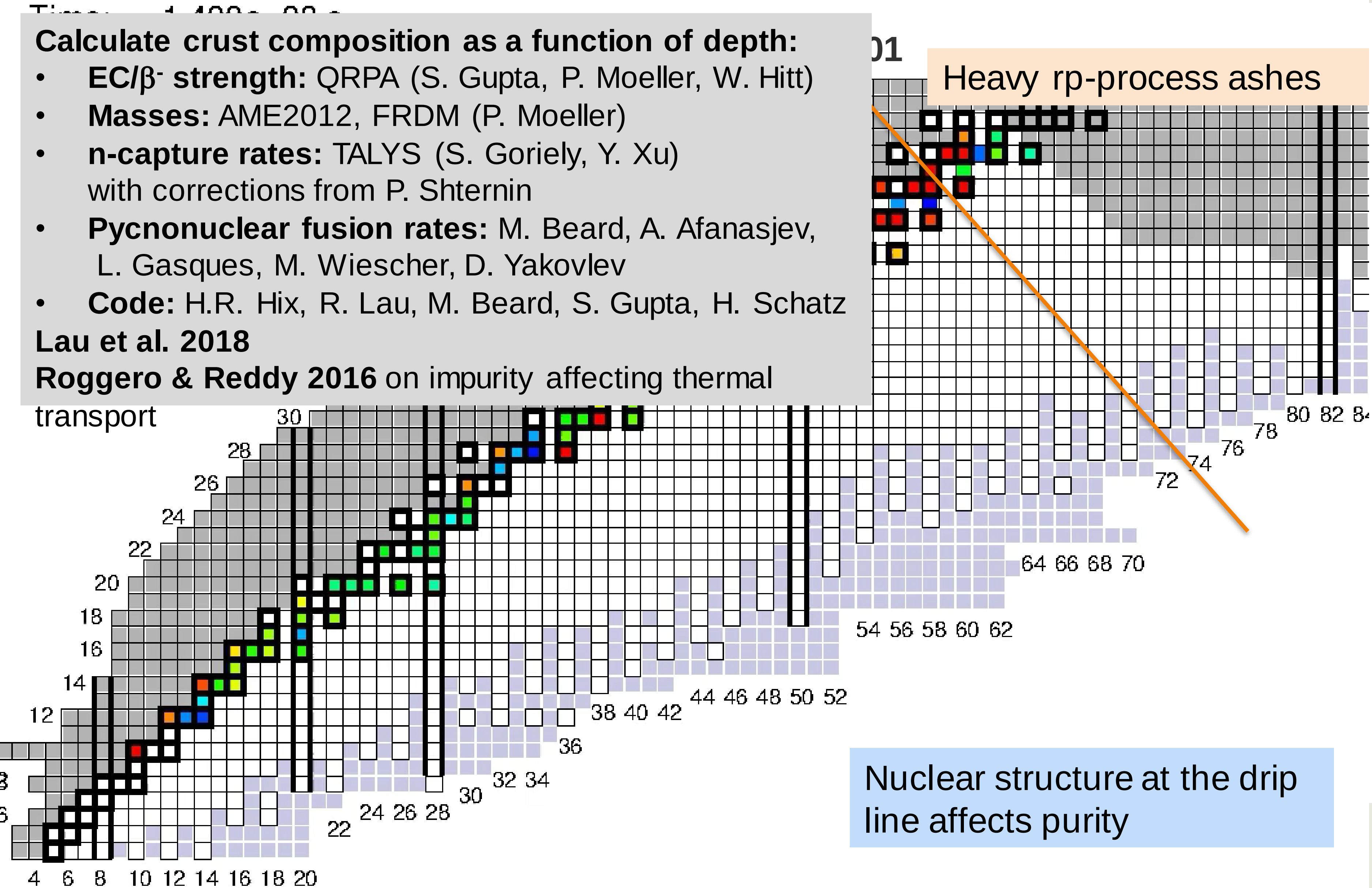
Crust Becomes Pure Beyond Neutron Drip Depth Solves one Observational Puzzle

Calculate crust composition as a function of depth:

- **EC/β$^-$ strength:** QRPA (S. Gupta, P. Moeller, W. Hitt)
- **Masses:** AME2012, FRDM (P. Moeller)
- **n-capture rates:** TALYS (S. Goriely, Y. Xu) with corrections from P. Shternin
- **Pycnonuclear fusion rates:** M. Beard, A. Afanasjev, L. Gasques, M. Wiescher, D. Yakovlev
- **Code:** H.R. Hix, R. Lau, M. Beard, S. Gupta, H. Schatz

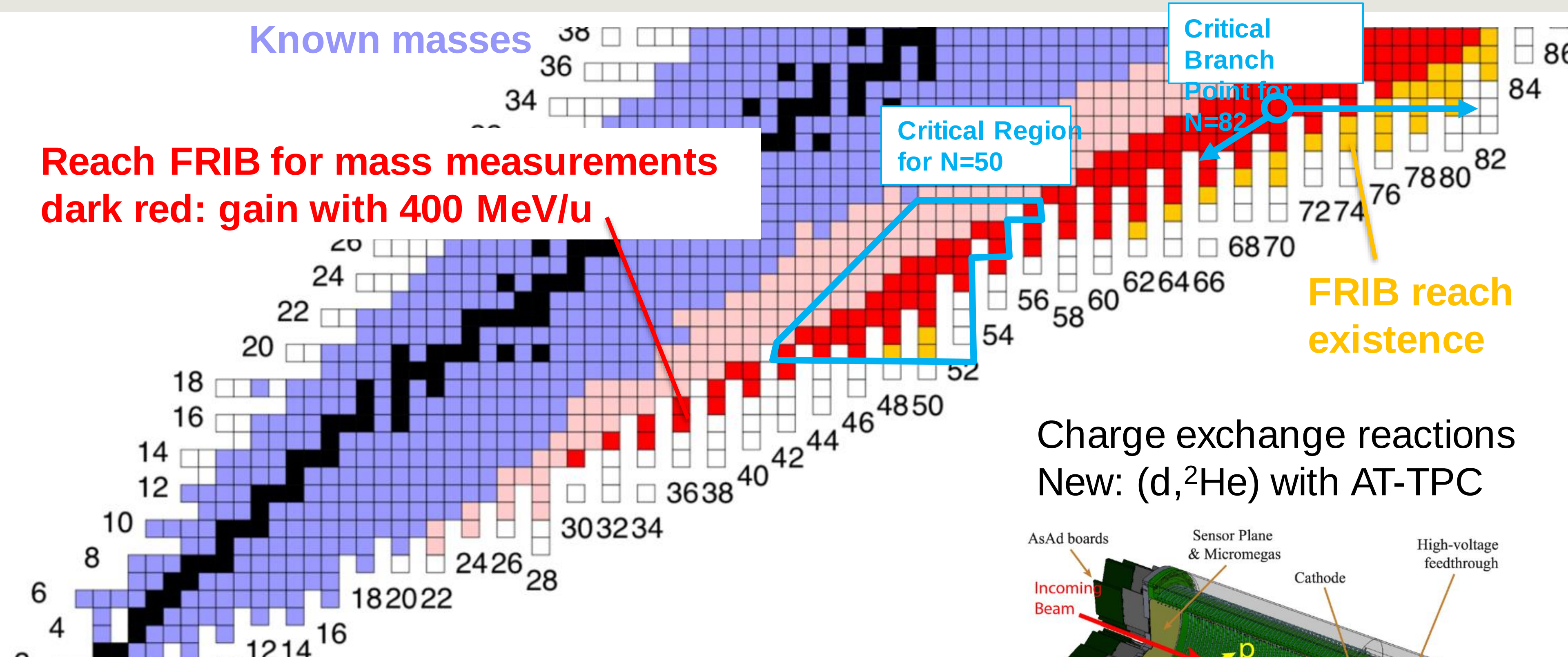
Lau et al. 2018

Roggero & Reddy 2016 on impurity affecting thermal transport

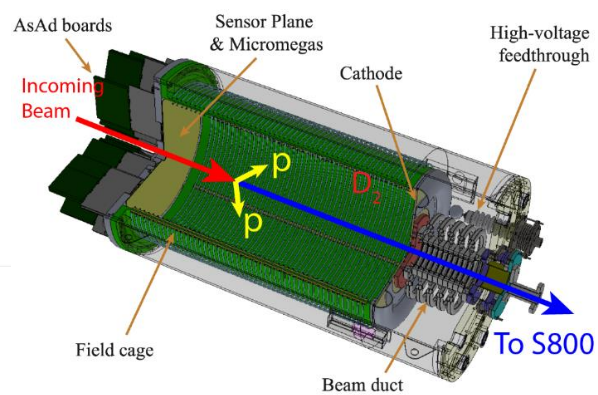


Nuclear structure at the drip line affects purity

Critical Nuclei in Accreted Neutron Star Crusts Within FRIB Reach



Charge exchange reactions
New: (d,^{2}He) with AT-TPC



→ EC transition strengths

- Mass Measurements (LEBIT, S800, HRS)
- Decay measurements (FDSi/FDS)

Led by R. Zegers

Summary

- Confluence of advances in nuclear science, astronomy, computational science that creates unique opportunities for progress in nuclear astrophysics towards a theory of nucleosynthesis
- In Nuclear Science a new generation of rare isotope facilities and capabilities will be critical for nuclear astrophysics
- The breadth of the nuclear science facility landscape with complementary facilities for rare isotope beams, stable beams, neutron beams, gamma-beams is essential for nuclear astrophysics
  - Coordination and collaboration across all facilities is important
- Interdisciplinary coordination and collaboration with facilities and groups across nuclear science (experiment and theory), theoretical astrophysics, observational astronomy in its full breadth, gravitational wave physics, cosmo-chemistry …. is important
  - This requires special efforts to build the necessary scientific communities that do not necessarily interact with each other
  - The CeNAM collaboration and the IReNA network will be important to take full advantage of the extraordinary scientific opportunities in this area