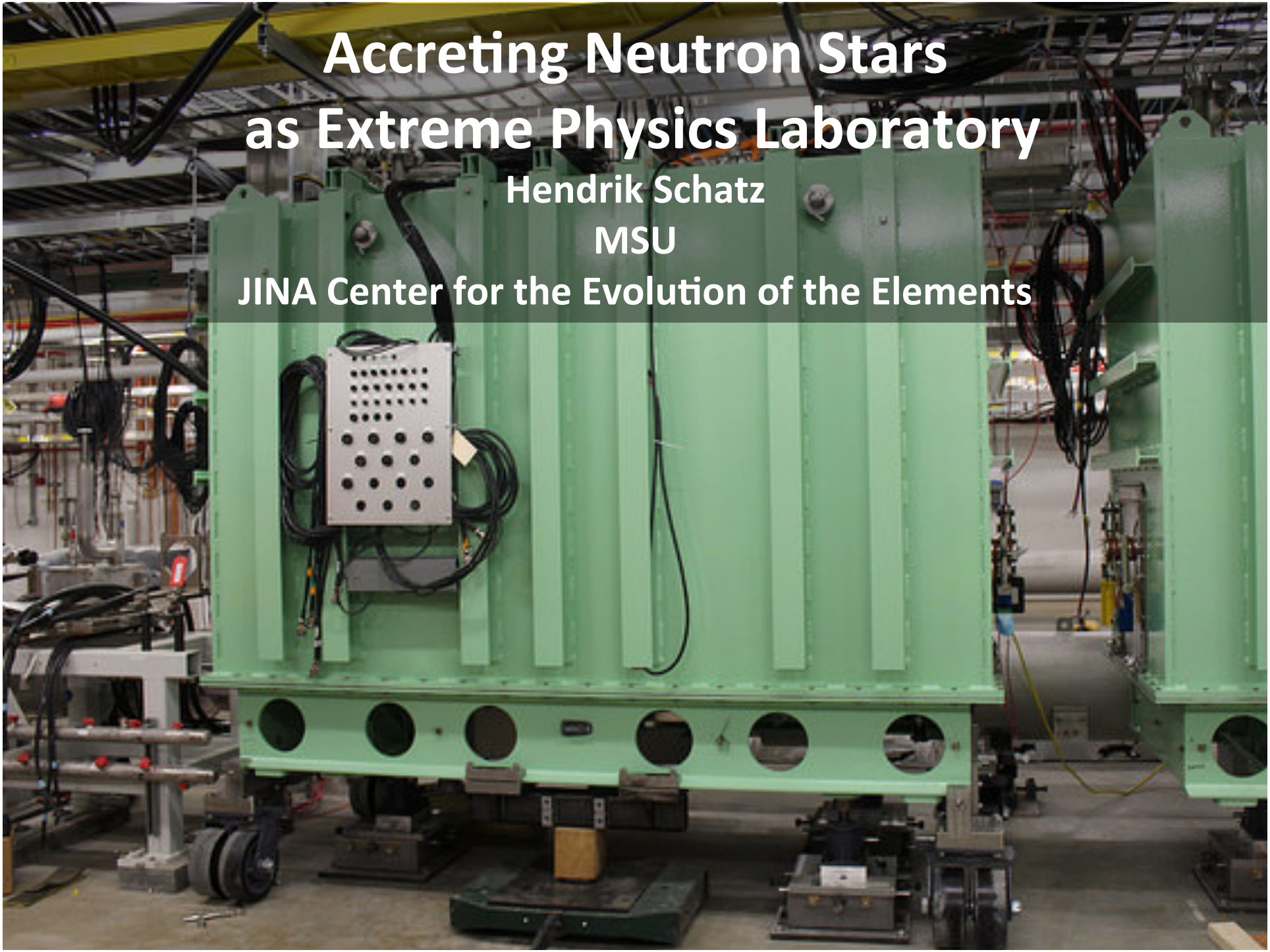
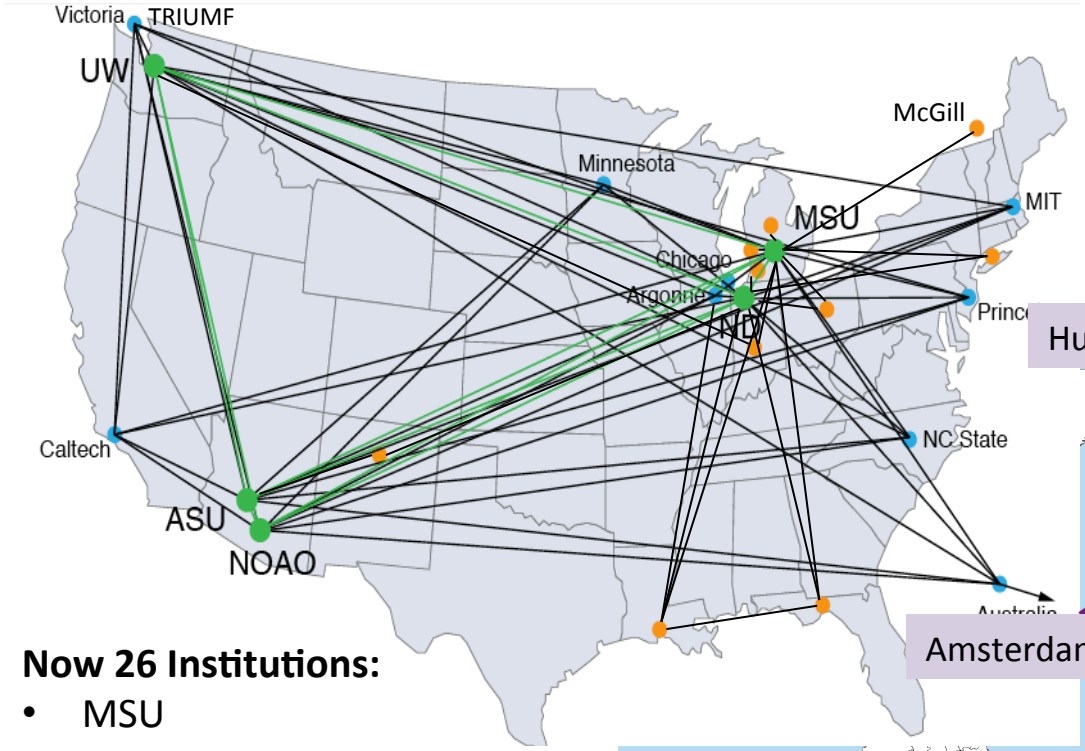


Accreting Neutron Stars as Extreme Physics Laboratory

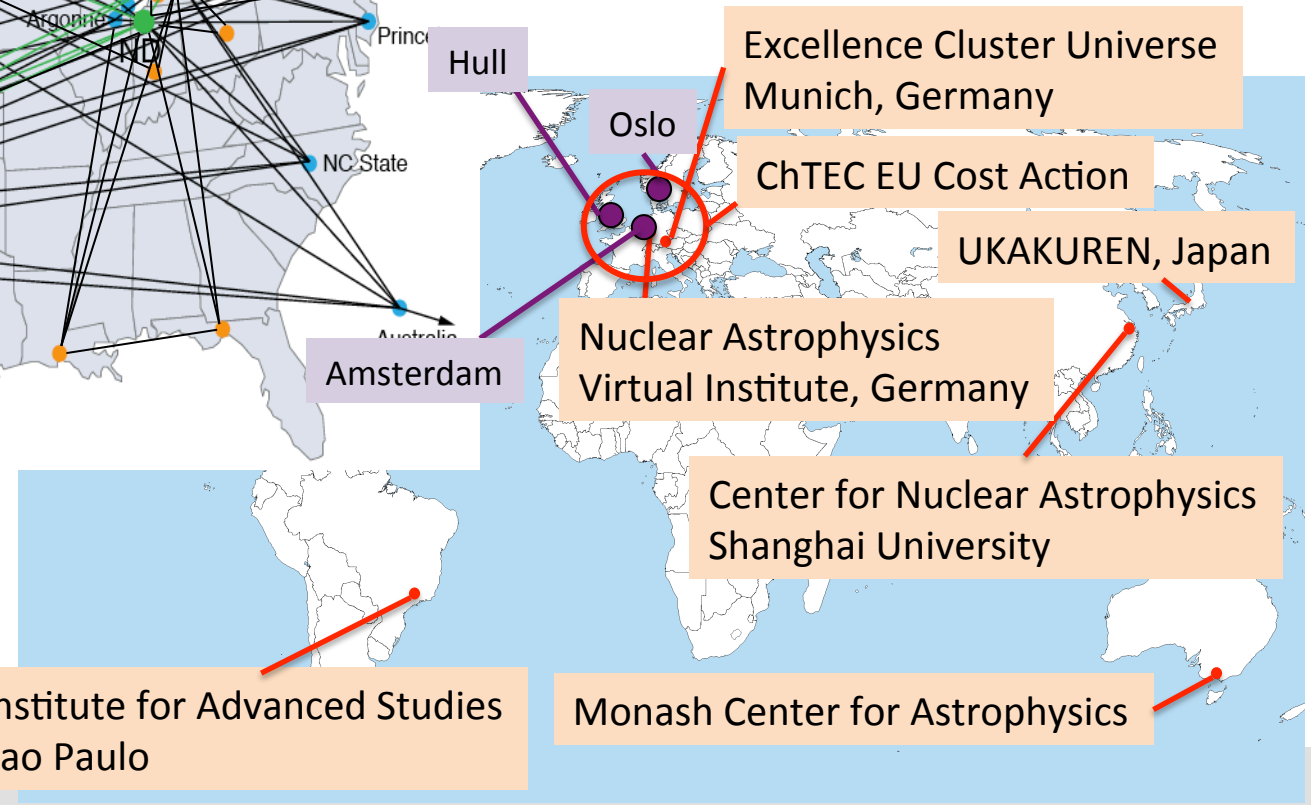
Hendrik Schatz
MSU
JINA Center for the Evolution of the Elements

JINA-CEE NSF Physics Frontiers Center
Resources: jinaweb.org

Joint Institute for Nuclear Astrophysics – Center for the Evolution of the Elements



- Nuclear Experimenters
- Nuclear Theorists
- Astrophysics Theorists
- Astronomers
- Computational Physicists

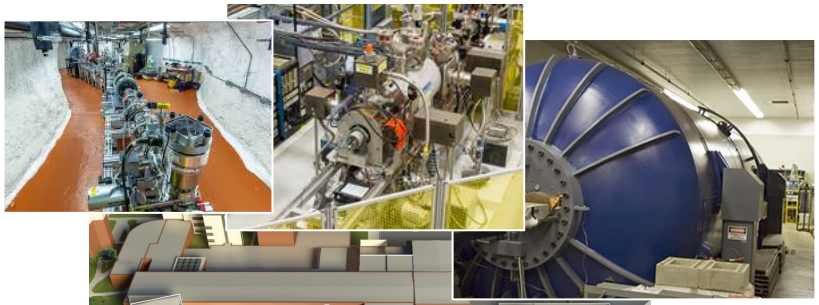


Now 26 Institutions:

- MSU
- Notre Dame
- ASU
- University of Washington/INT

+ 22 associated institutions

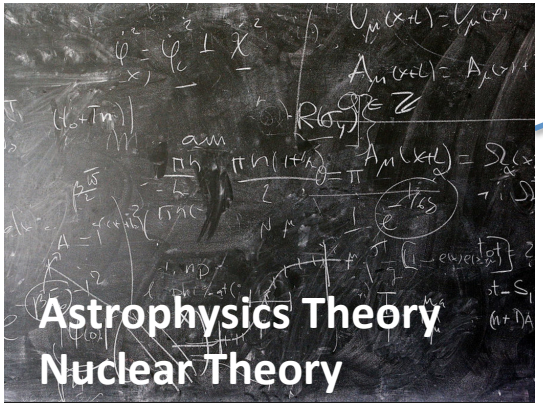
Nuclear Astrophysics is Enabled by Close Connections across Various Subfields



Accelerator Facilities:
Stable beam, Radioactive Beam
Underground

High Performance Computing

JINA-CEE



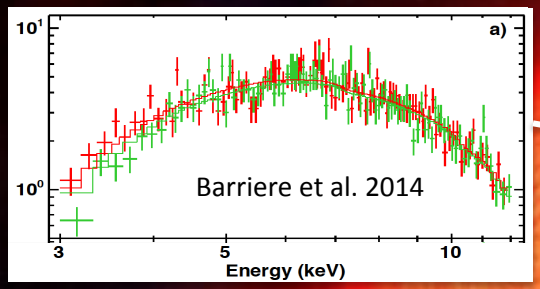
Astrophysics Theory
Nuclear Theory

What is the origin of the elements?
What is the nature of dense matter?

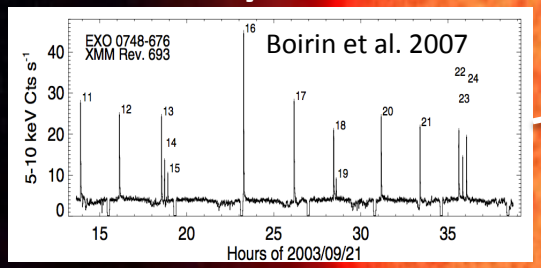
Telescopes
(optical, UV, X-ray, GW)

Accreting Neutron Stars: Nature's Dense Matter Laboratory

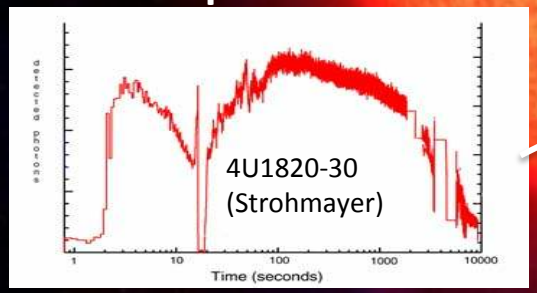
Lines



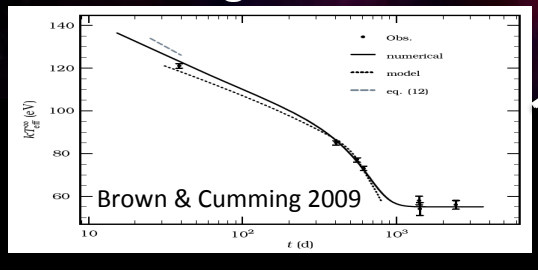
X-ray bursts

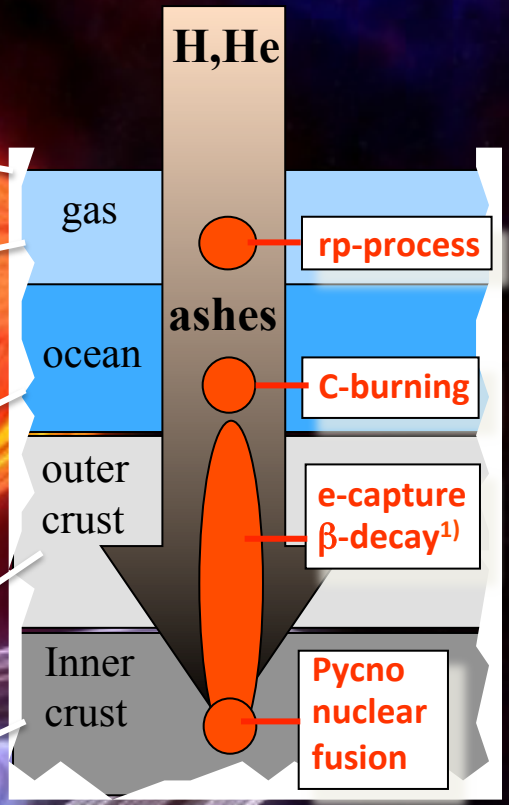


Superbursts

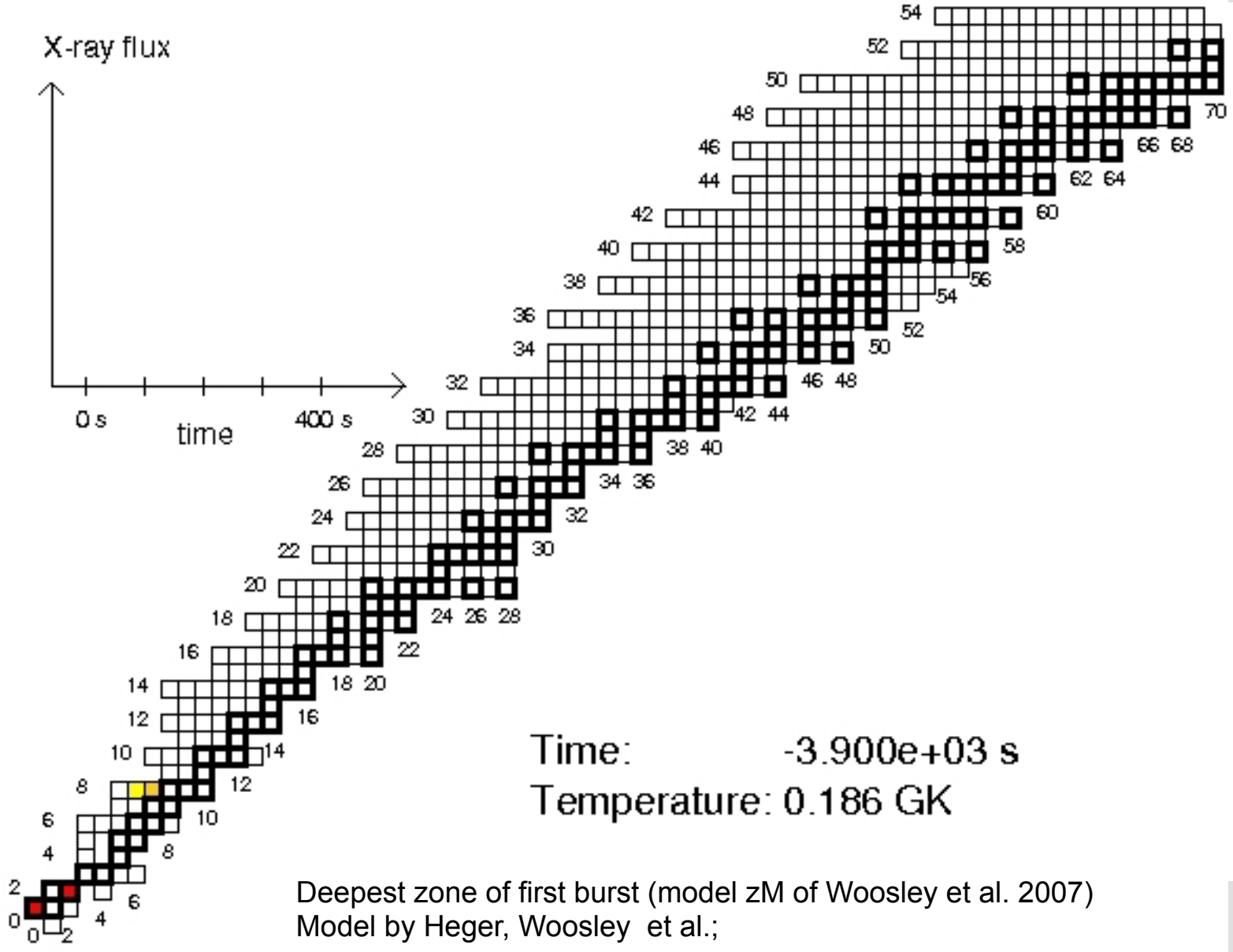


Cooling Transients





Nuclear Reactions Connect Neutron Star Physics with Burst Observations

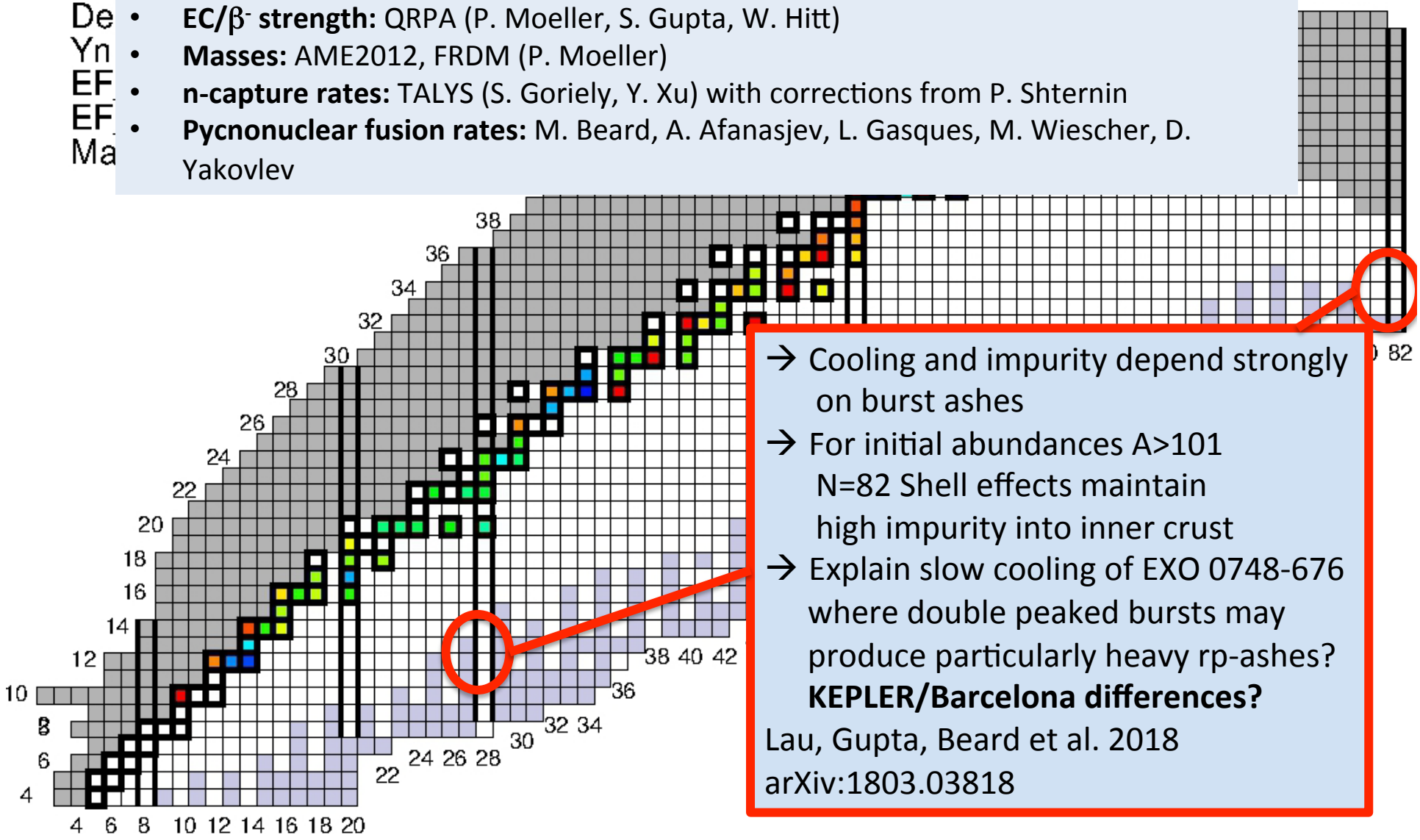


Deepest zone of first burst (model zM of Woosley et al. 2007)
Model by Heger, Woosley et al.;

Burst Physics Impacts Crust Physics

Multi-Institutional JINA/JINA-CEE effort:

- **EC/β^- strength:** QRPA (P. Moeller, S. Gupta, 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



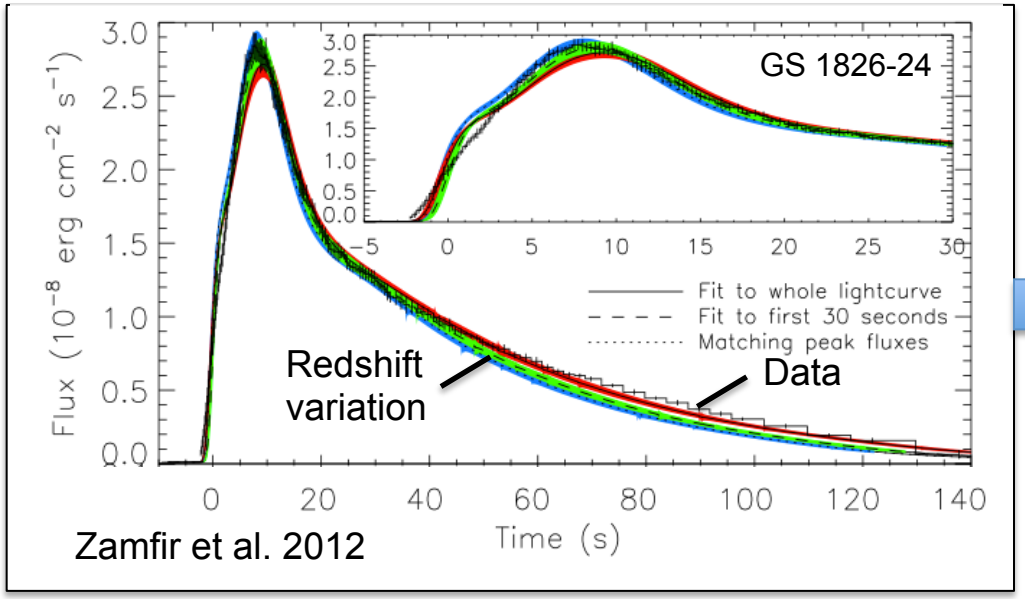
→ Cooling and impurity depend strongly on burst ashes

→ For initial abundances A>101 N=82 Shell effects maintain high impurity into inner crust

→ Explain slow cooling of EXO 0748-676 where double peaked bursts may produce particularly heavy rp-ashes? **KEPLER/Barcelona differences?**

Lau, Gupta, Beard et al. 2018
arXiv:1803.03818

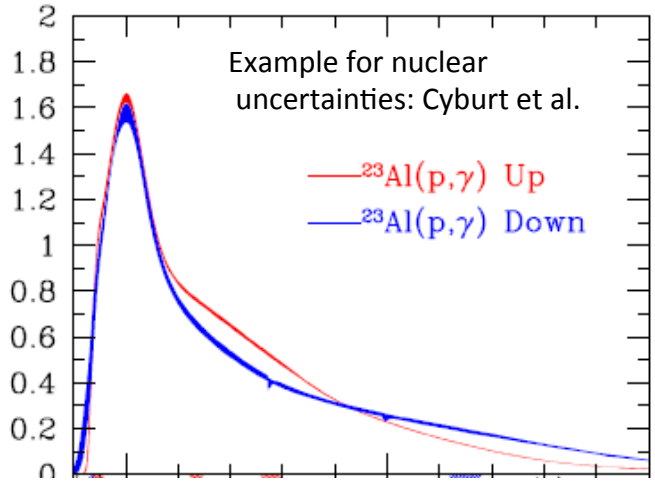
Observable Probes can Constrain a Wide Range of System Physics if Nuclear Physics is in Placce



Zamfir et al. 2012

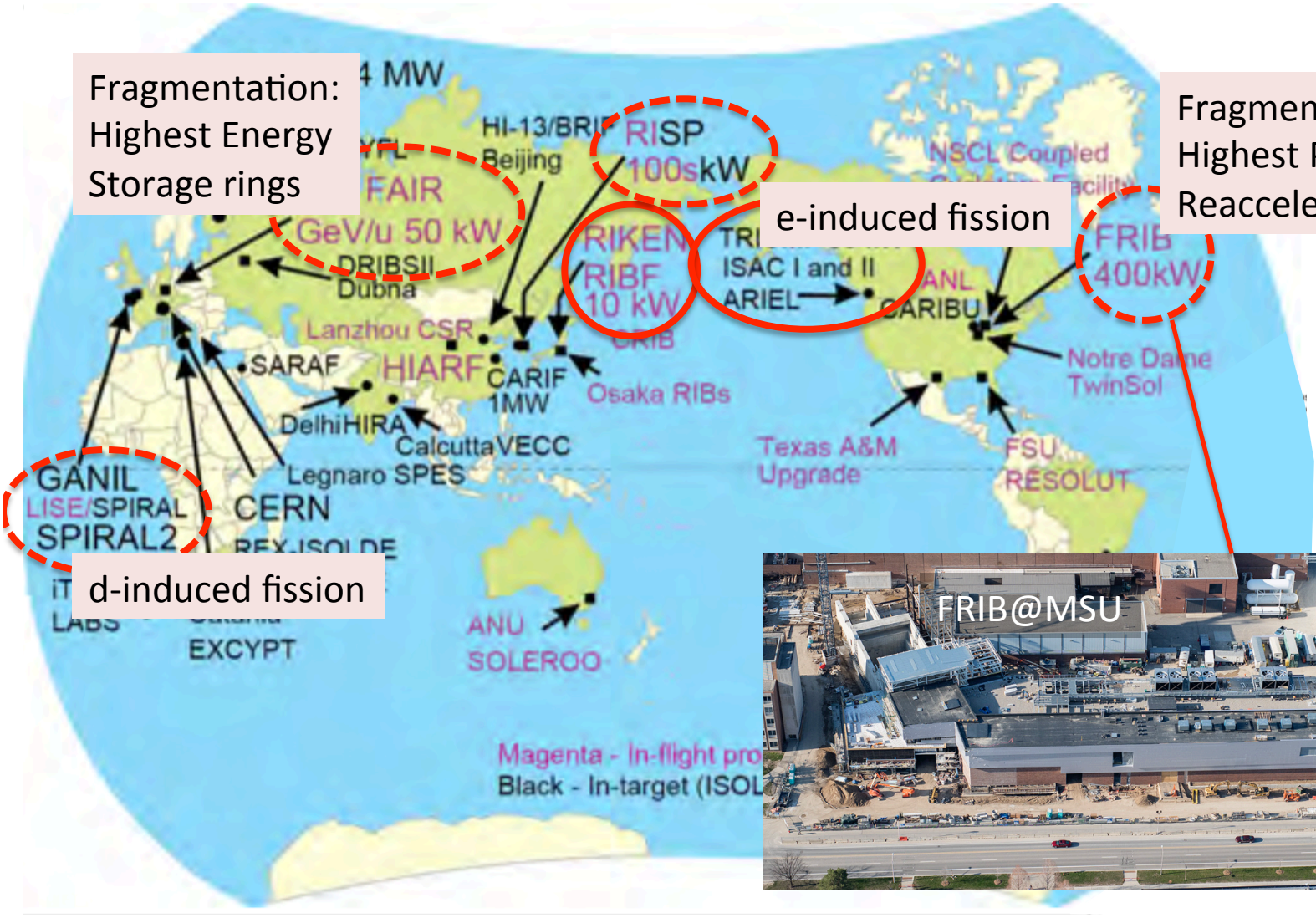
Can extract from observations:

- Accretion Rate
- Hydrogen mass fraction
- Metallicity
- Heating from Crust
- Surface gravity
- Surface redshift
- Distance
- Inclination
- Elements?



→ Need better observational data AND better nuclear physics

A New Generation of Rare Isotope Facilities
Can Astronomy Help?



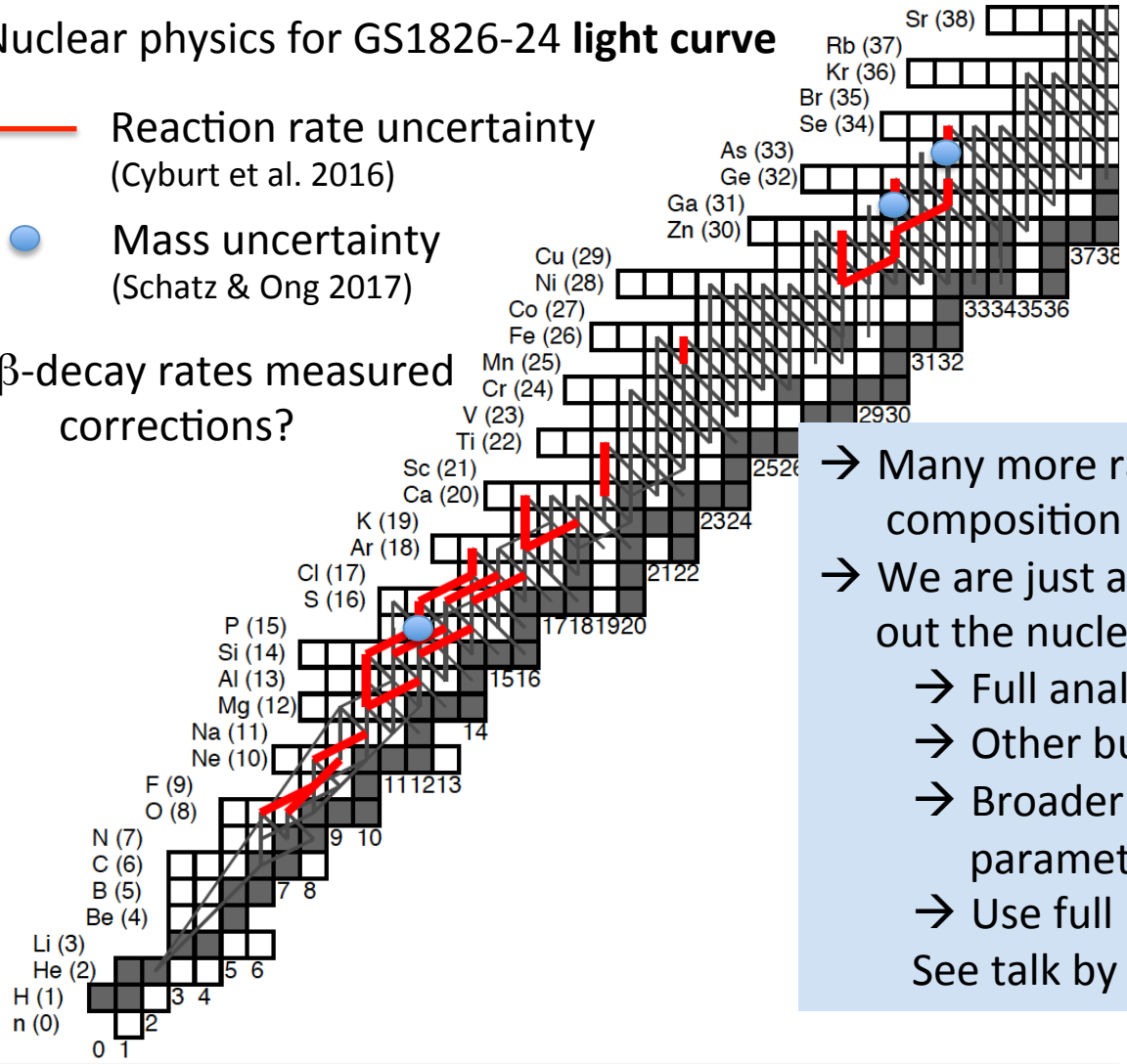
Nuclear Physics Road Map Emerging

Nuclear physics for GS1826-24 **light curve**

Reaction rate uncertainty
(Cyburt et al. 2016)

Mass uncertainty
(Schatz & Ong 2017)

β-decay rates measured
corrections?



→ Many more rates and masses affect composition (not fully identified)

→ We are just at the beginning of figuring out the nuclear physics connection

- → Full analysis of composition impacts
- → Other burst types
- → Broader range of parameters to enable parameter fitting to observations
- → Use full 1D models

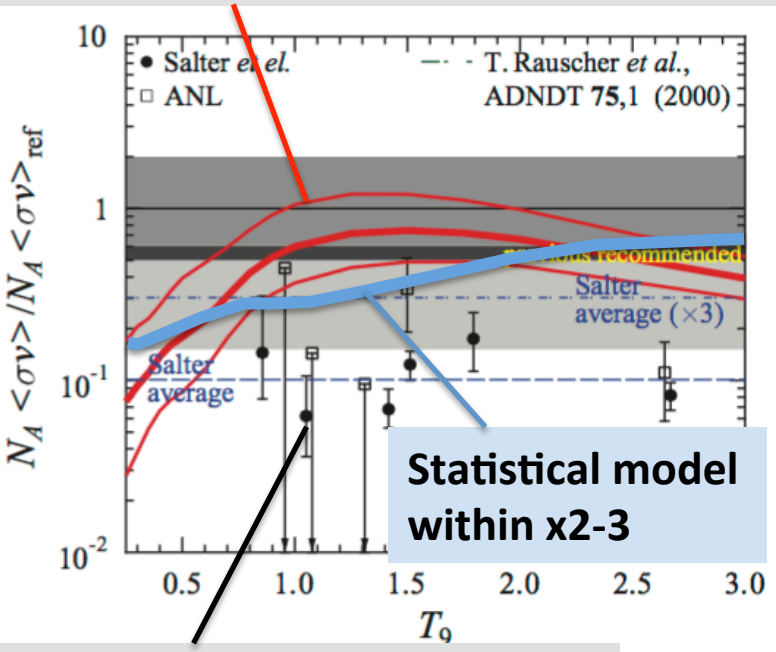
See talk by Adam Jacobs

(α,p) reactions – major surprises

new data question commonly used statistical model rates

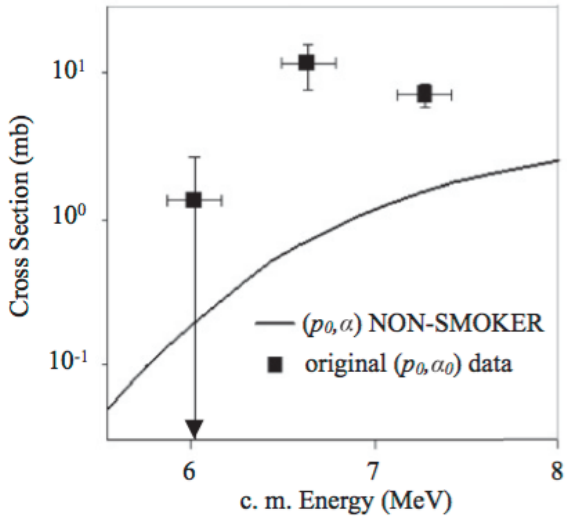
^{18}Ne(α,p)^{21}Na Mohr et al. 2014

^{24}Mg(p,t)^{22}Mg RCNP (Matic 2012)
^{21}Na(p,p)^{21}Na CRIB (Hu 2013, Zhang 2014)



Statistical model within x2-3

Inverse ^{21}Na(p,α)^{18}Ne TRIUMF
Salter 2012 (lower limit)

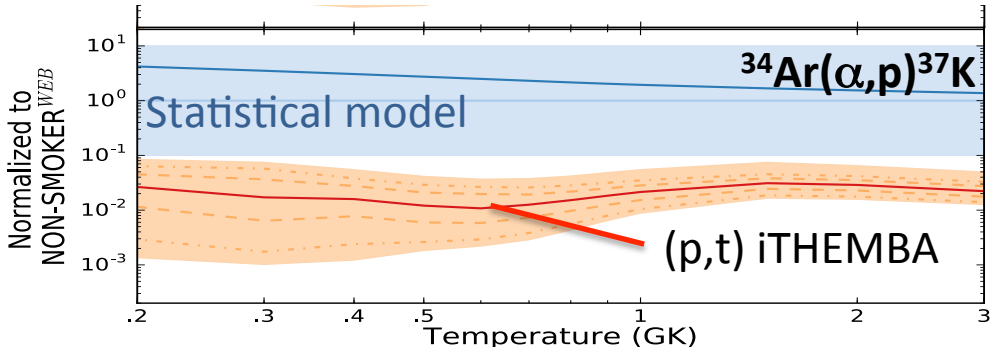


Inverse ^{33}Cl(p,α)^{34}Ar at ANL

Deibel et al. 2011

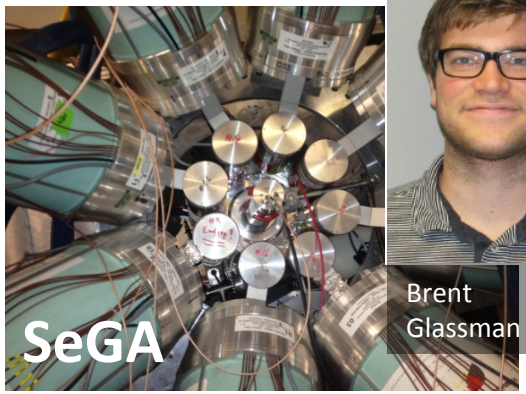
Statistical model x10 too low

Long et al. TBP



Statistical model x100 too high

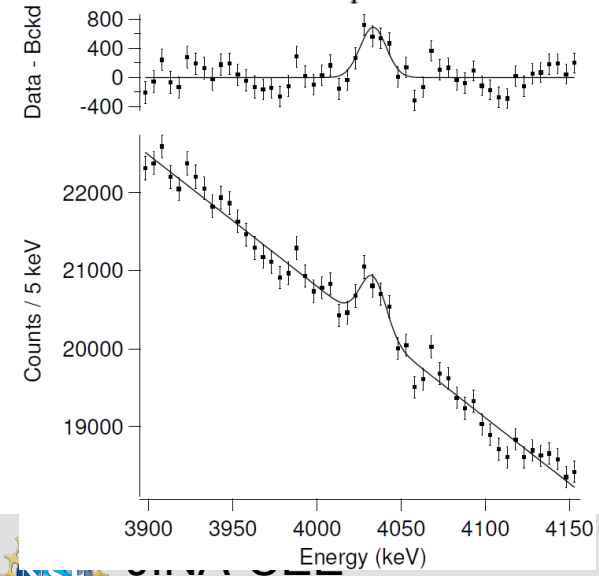
A New Portal to Determine $^{15}O(\alpha,\gamma)$

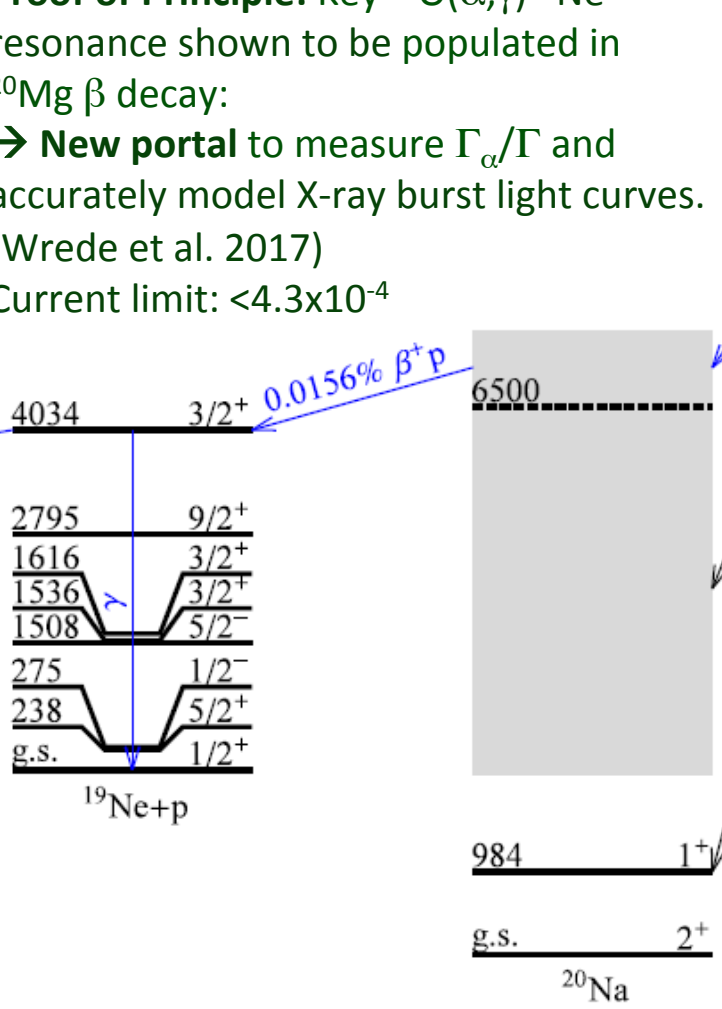


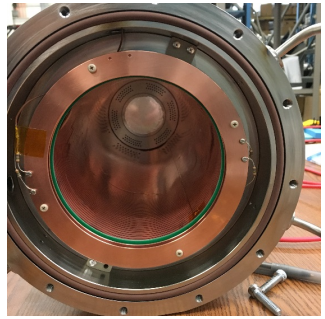
Proof of Principle: Key $^{15}O(\alpha,\gamma)^{19}Ne$ resonance shown to be populated in ^{20}Mg β decay:

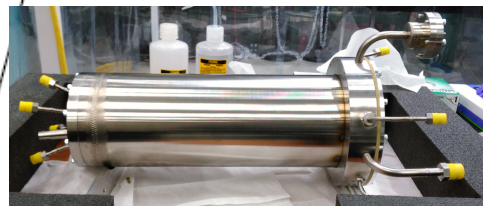
→ **New portal** to measure Γ_α/Γ and accurately model X-ray burst light curves. (Wrede et al. 2017)

Current limit: $<4.3\times10^{-4}$









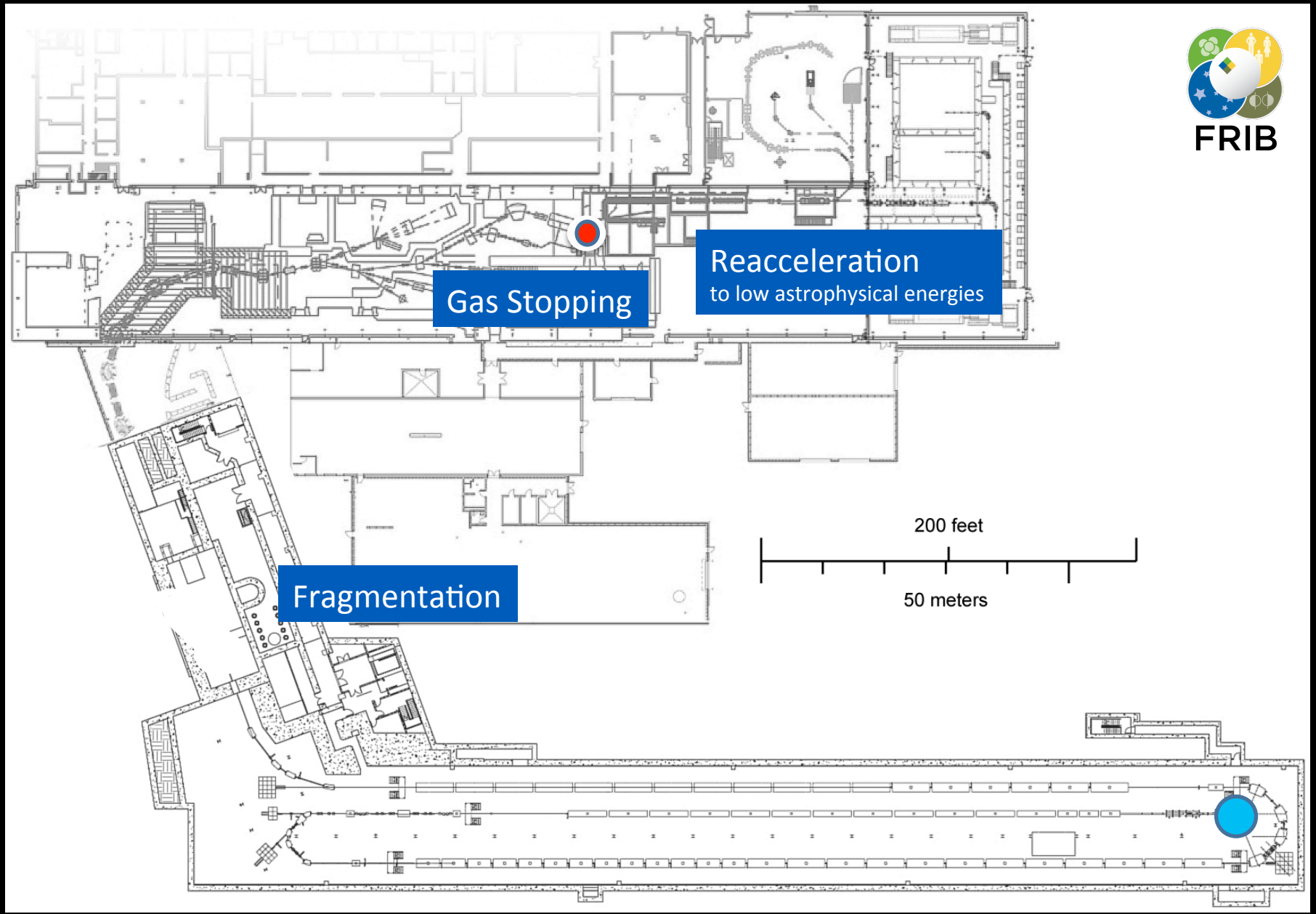
Proton Detector upgrade to TPC in 2018/19 to measure Γ_α/Γ via $^{20}Mg(\beta p\alpha)^{15}O$

C. Wrede *et al.*, Phys. Rev. C 96, 032801 (R) (2017)

FRIB Project Summary

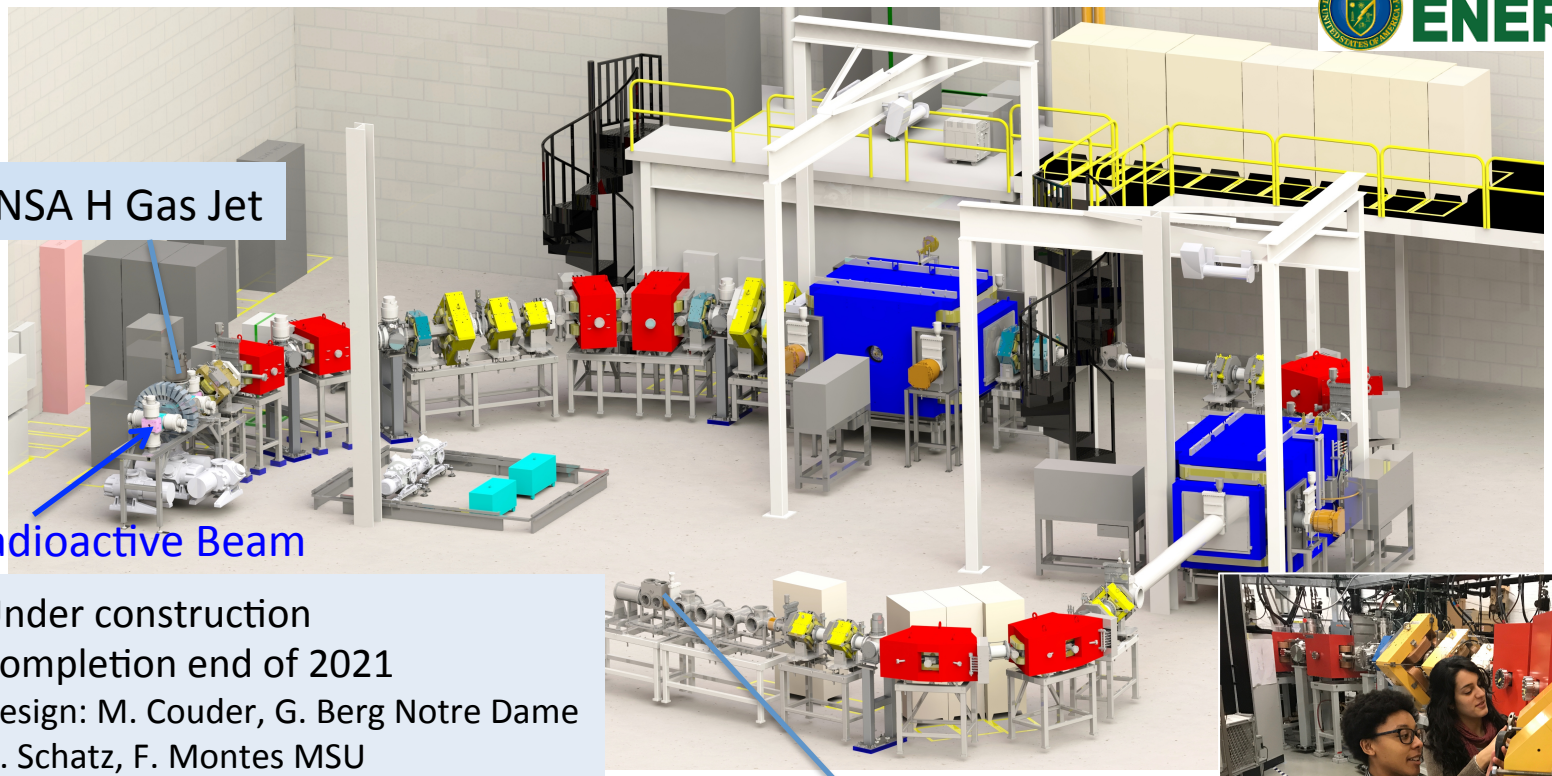
- FRIB will be a $730 million national user facility funded by the Department of Energy Office of Science (DOE-SC), Michigan State University, and the State of Michigan
- FRIB Project completion date is June 2022, managing to an early completion in fiscal year 2021
- FRIB will serve as a national user facility for world-class rare isotope research, (~1400 scientists currently engaged) and builds on more than 50 years of nuclear science expertise developed at MSU

FRIB Provides Fast, Stopped, and Reaccelerated Beams

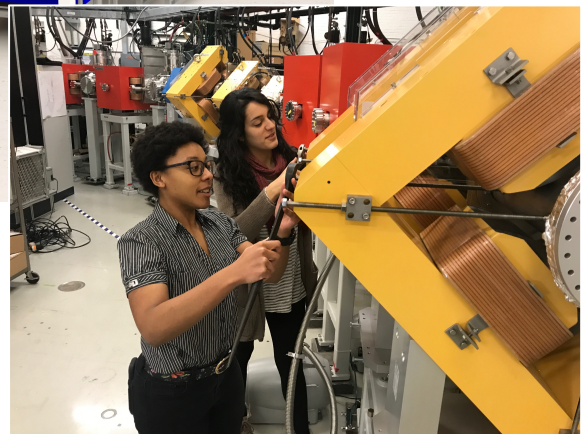


FRIB Progress

SECAR Recoil Separator Enables Direct Astrophysical Reaction Rate Measurements at FRIB



Under construction
Completion end of 2021
Design: M. Couder, G. Berg Notre Dame
H. Schatz, F. Montes MSU
J. Blackmon LSU
K. Chipps, M. Smith ORNL
U. Greife CSM
+ many other institutions



U.S. DEPARTMENT OF ENERGY | Office of Science

NSF

Summary

There is now an opportunity to extract quantitative information about accreting neutron star systems – discovery potential!

- **High quality observational data** (new missions)
  → NICER, new mission concepts advancing
- **Consistently analyzed, curated observational data archives**
  → MinBAR
- **Nuclear facilities and experimental equipment**
  → FRIB, FAIR, … is all happening
- **Consistently evaluated, curated nuclear data archives**
  → JINA Reaclib, STARLIB, planned efforts in USNDP
- **Strategies for complete multi-parameter analysis**
  → Monash Group (Zac Johnston, …) others?
- **Strategies for exploiting complete accretion sequences** (burst sequences and cooling in transients consistently)
  → ?
- **Bring it all together**
  → JINA-CEE, this workshop