# FRIB status and current experimental nuclear reaction research at MSU

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U.S. DEPARTMENT OF ENERGY | Office of Science

This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

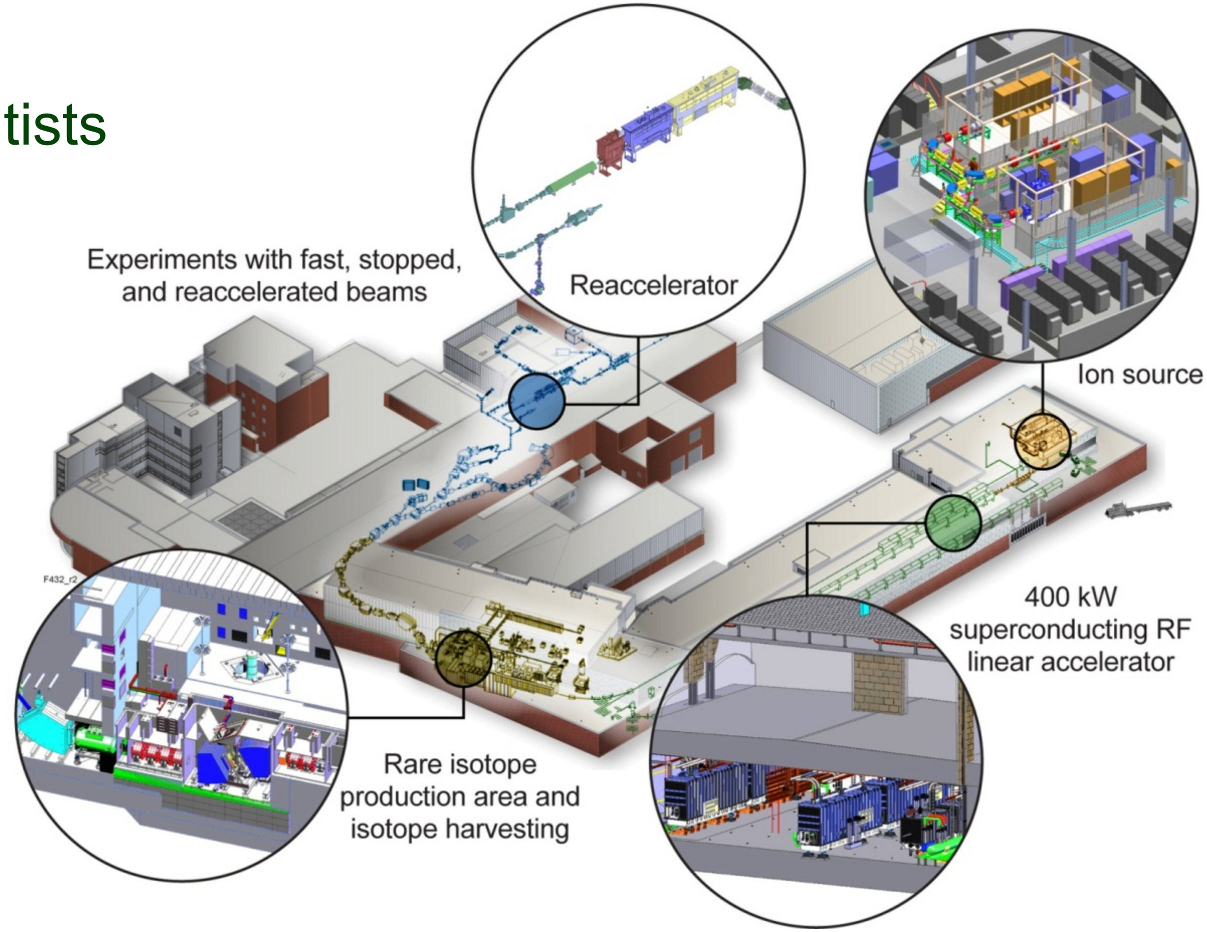
# Facility for Rare Isotope Beams

- 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 DOE-SC national user facility for world-class rare isotope research supporting the mission of the Office of Nuclear Physics in DOE-SC

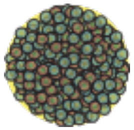
*FRIB will enable scientists to make discoveries about the properties of these rare isotopes in order to better understand the physics of nuclei, nuclear astrophysics, fundamental interactions, and applications for society*

# Facility for Rare Isotope Beams
## A Future DOE-SC Scientific User Facility for Nuclear Physics

- Funded by U.S. Department of Energy Office of Science with contributions and cost share from Michigan State University and State of Michigan
- Serving over 1,300 scientists
- Key feature is 400 kW beam power
- Separation of isotopes in-flight
  - Fast development time for any isotope
  - Suited for all elements and short half-lives

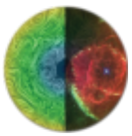


# FRIB Enables Scientists to Make Discoveries



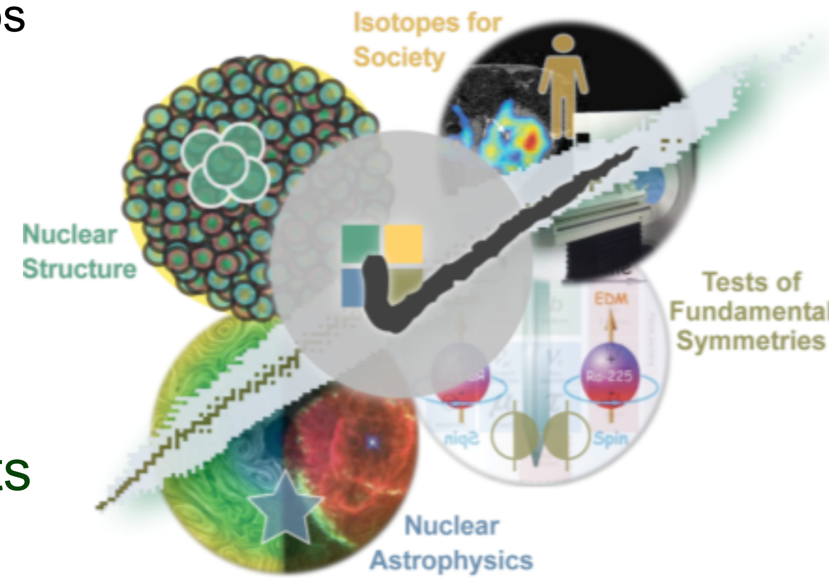
## Properties of atomic nuclei

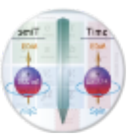
- Develop a predictive model of nuclei and their interactions
- Many-body quantum problem: intellectual overlap to mesoscopic science, quantum dots, atomic clusters, etc.



## Astrophysics: What happens inside stars?

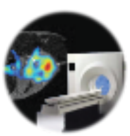
- Origin of the elements in the cosmos
- Explosive environments: novae, supernovae, X-ray bursts …
- Properties of neutron stars



## Tests of laws of nature

- Effects of symmetry violations are amplified in certain nuclei

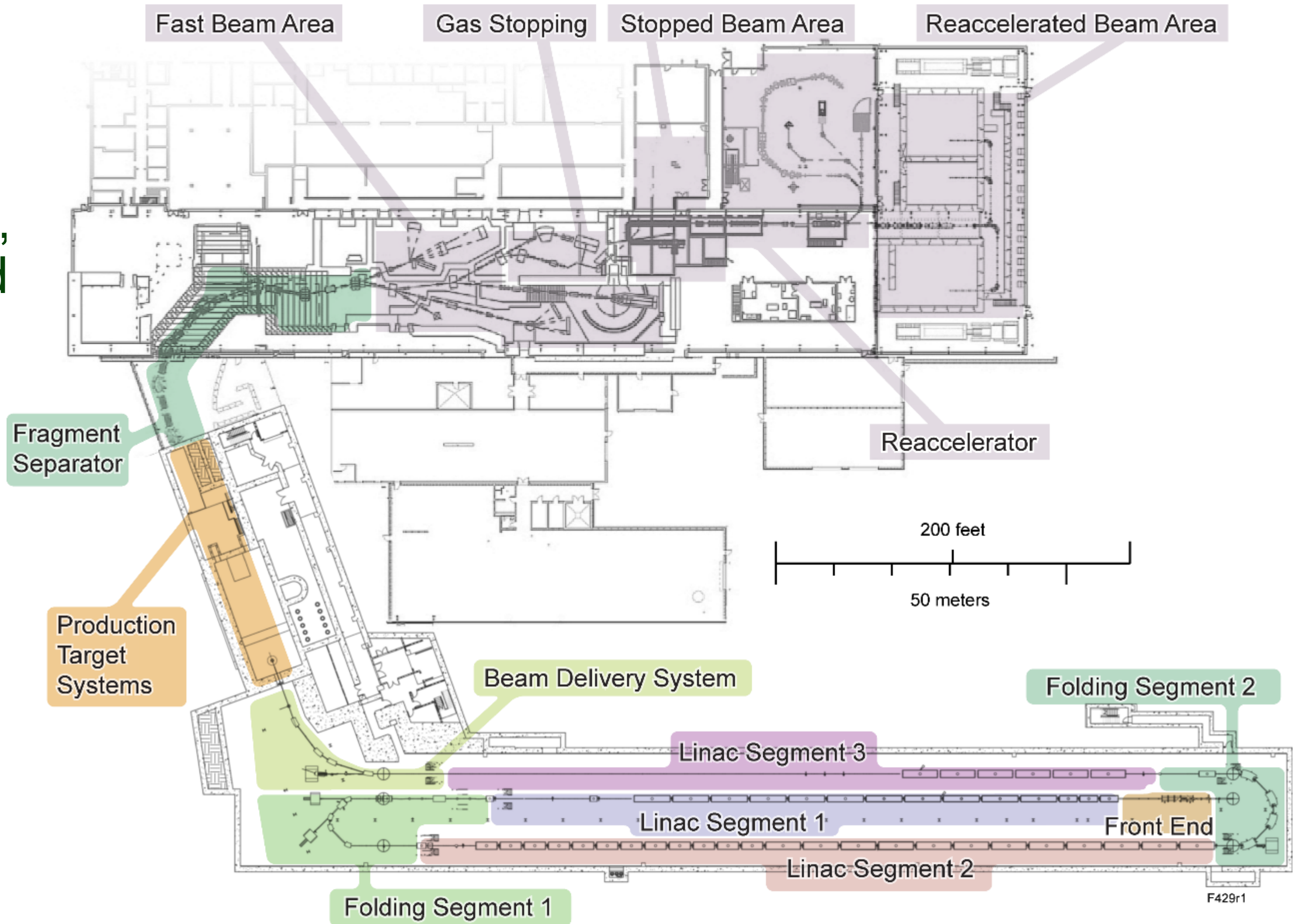


## Societal applications and benefits

- Medicine, energy, material sciences, national security

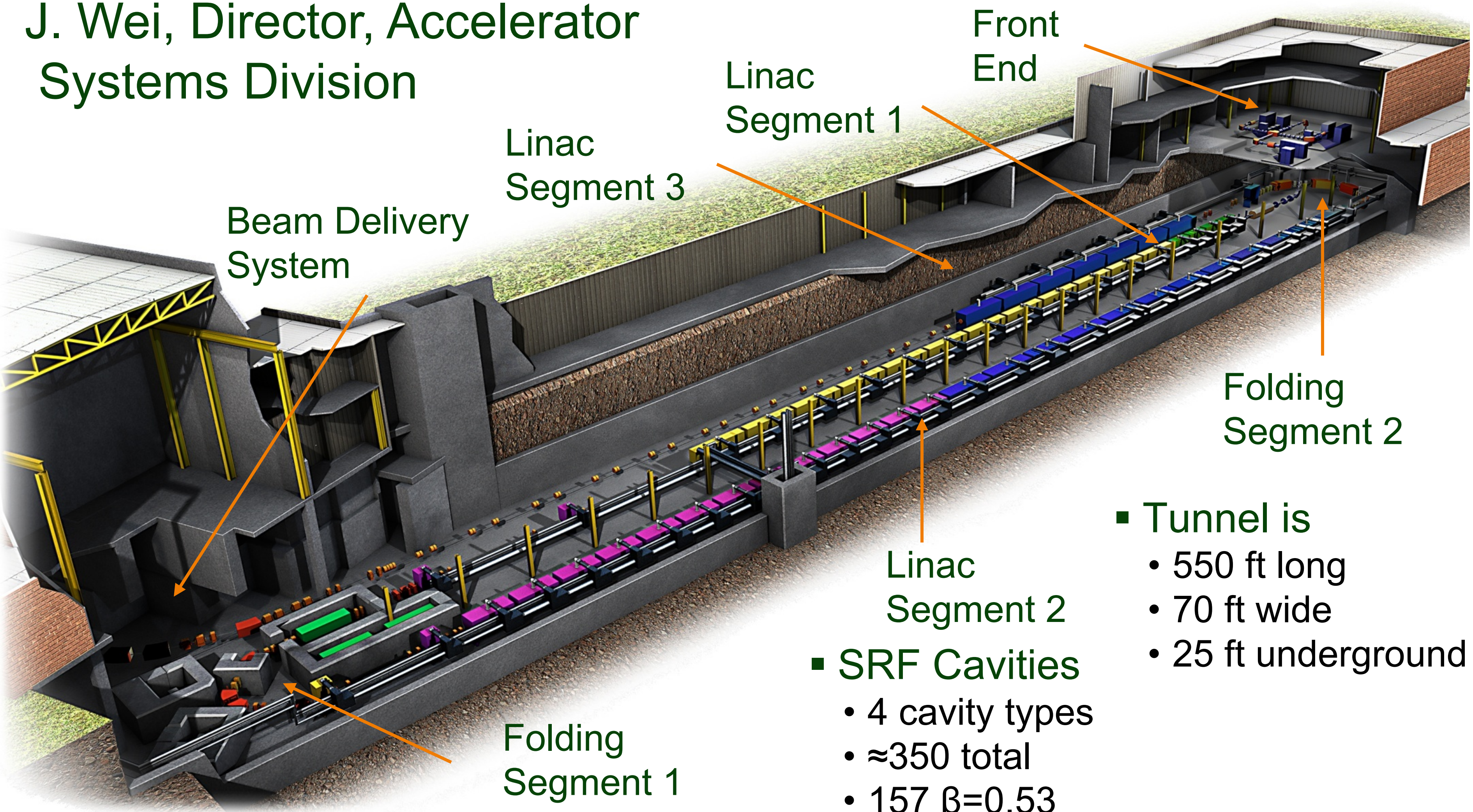
# FRIB Scientific Capabilities

- Key Capabilities: Fast, Stopped, Reaccelerated Beams



# FRIB Driver Linear Accelerator

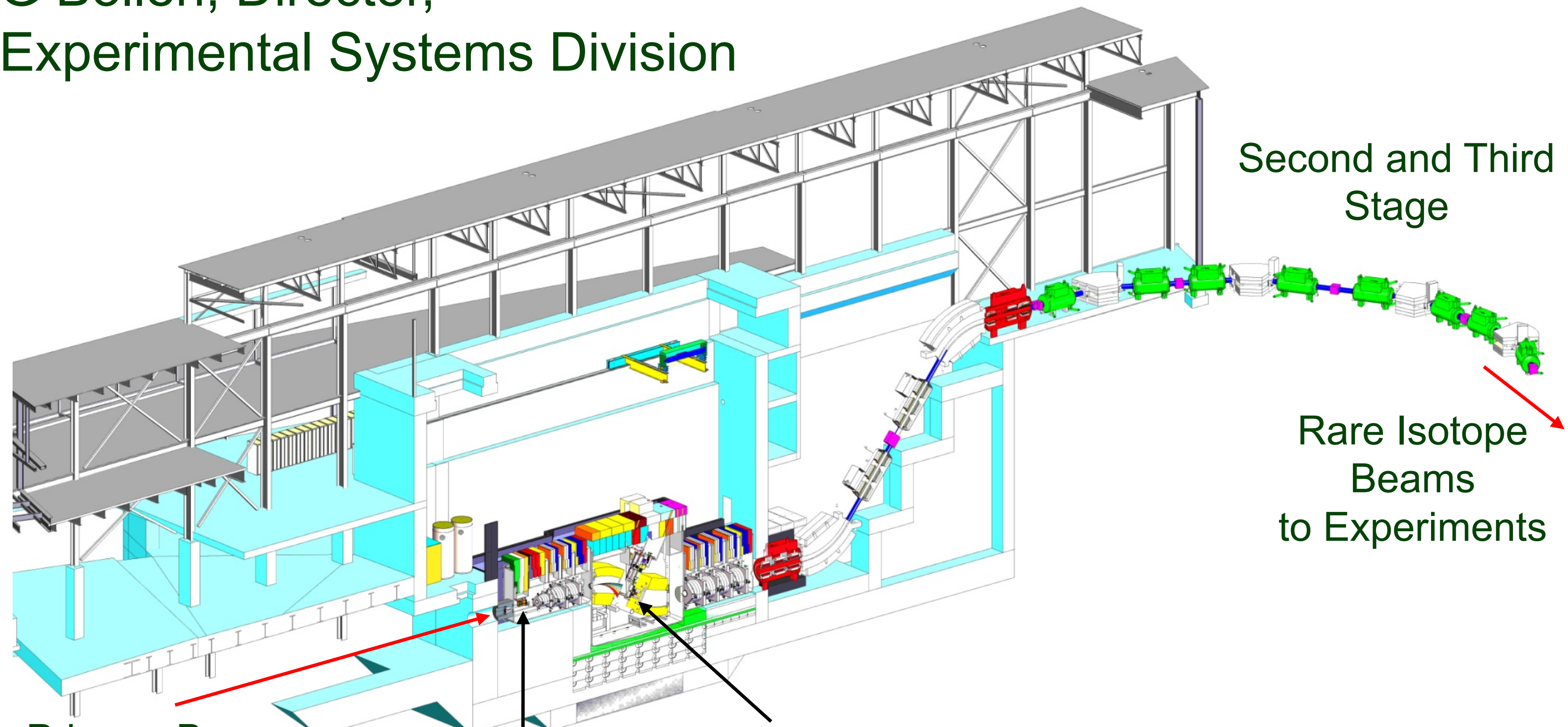
J. Wei, Director, Accelerator Systems Division




- SRF Cavities
  - 4 cavity types
  - ≈350 total
  - 157 β=0.53
- Tunnel is
  - 550 ft long
  - 70 ft wide
  - 25 ft underground

# Isotope Production Area
# Target and Fragment Separator

G Bollen, Director,
Experimental Systems Division



# Reaction Mechanisms at FRIB

- Fragmentation, Fission, Multi-nucleon transfer production mechanisms
- Fast beams (> 30 MeV/u)
  - Total reaction cross section – size and shape
  - Nucleon knockout – single particle nature, single particle states
  - Nucleon pickup – high-l orbits
  - Coulomb excitation – B(E2), low-lying structure
  - Charge exchange – B(GT)
- Reaccelerated beams (ReA facility)
  - Stripping and pickup reactions – constrain capture reactions, shell model studies
  - ANCs – constrain capture reactions
  - Surrogate Reactions
  - Fusion
  - Multi-nucleon transfer
  - Deep inelastic

# FRIB Project Managed Like All Office of Science Projects

- Project started in June 2009: Cooperative Agreement between DOE-SC and MSU
  - Project delivery per DOE Order 413.3B: Acquisition Executive SC-2 Dr. Patricia Dehmer, DOE-SC Office of Project Assessment reviews, Federal Project Director from SC-Chicago; MSU shares $94.5M in cost and contributions; decommissioning is MSU's responsibility
- CD-1 approved in September 2010: Conceptual design complete
- CD-2 (Performance Baseline) and CD-3a (Start of Civil Construction) approved in August 2013, pending notice to proceed for civil construction upon FY14 appropriation
- Civil construction began March 3, 2014
- CD-3b DOE-SC Office of Project Assessment review in June 2014 to assess readiness for technical construction
- Technical construction started in October 2014

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- Managing to early completion in fiscal year 2021
- CD-4 (project completion) is June 2022
- Funding from DOE-SC - $635.5M
  - Total project cost of $730M includes $94.5M MSU cost share (reimbursed from State of Michigan)
  - Additional MSU contributions exceed $300M

# FRIB Construction is Underway: Ground Breaking March 17, 2014

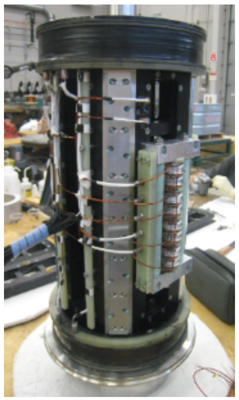
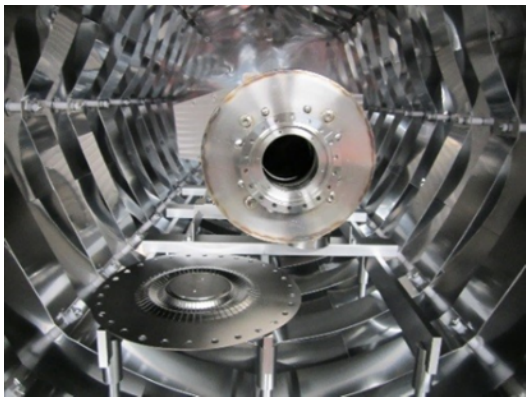
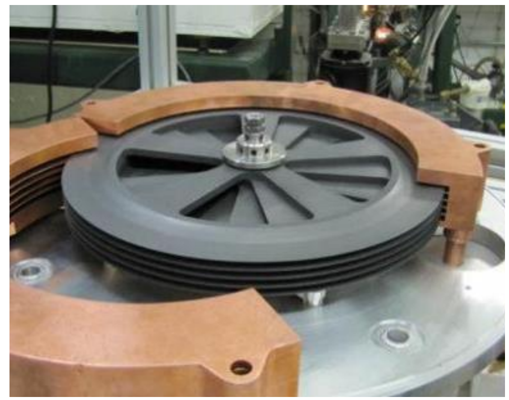
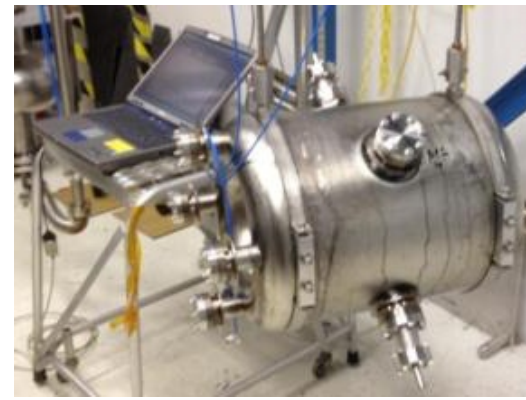
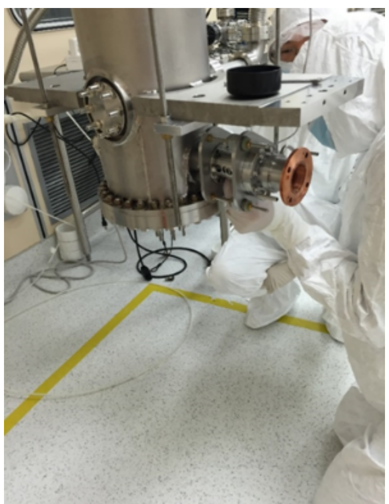
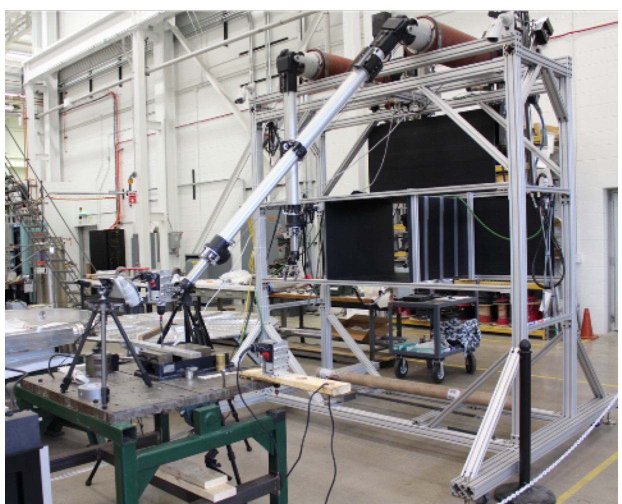
FRIB construction site 17 March 2014 – www.frib.msu.edu

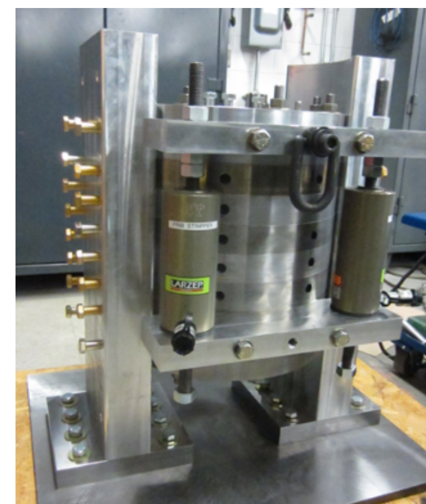
# Civil Construction Eight Weeks Ahead of Baseline Schedule- Completion March 2017

FRIB construction site – March 2016
Web cameras at www.frib.msu.edu

# Technical Construction Underway

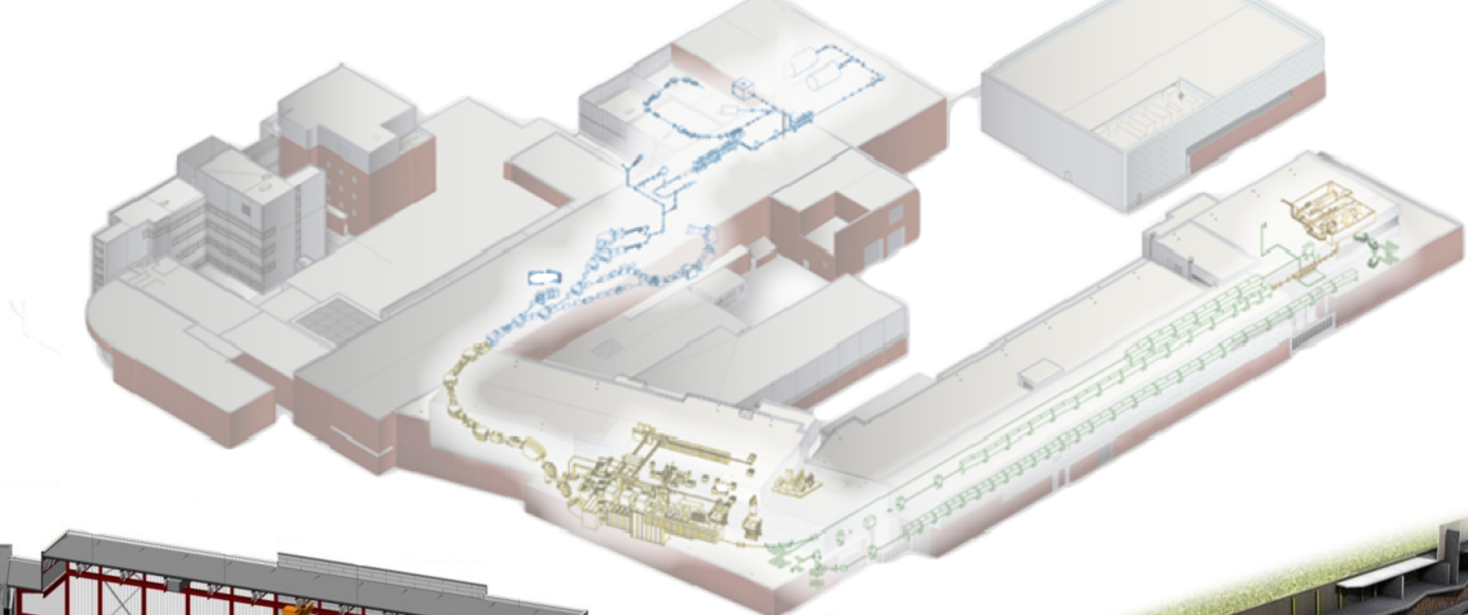
- Technical construction started in October 2014

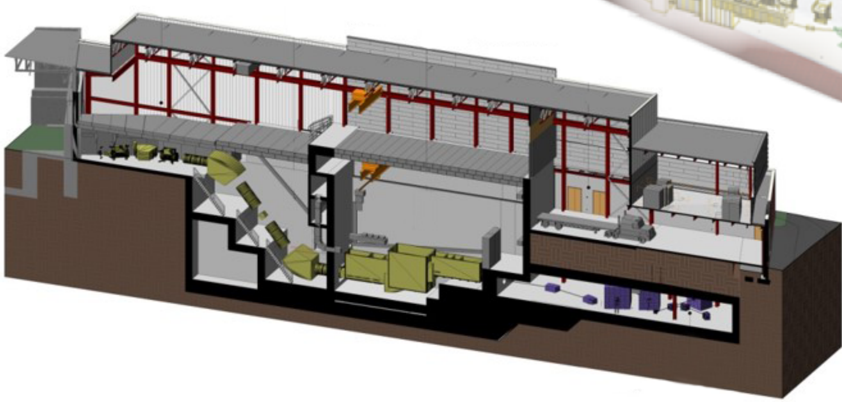







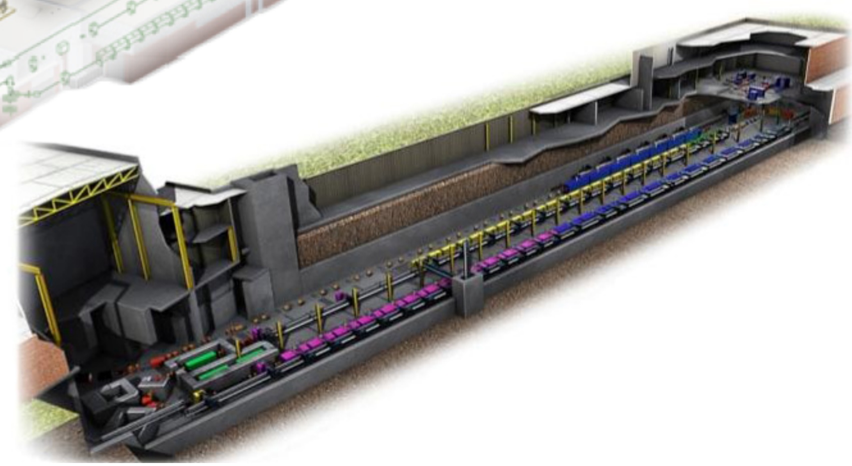


# Integrated Design Includes Options for Science-Driven Upgrades

Possibilities include higher beam energy, isotope harvesting, multi-user operation, ISOL, higher-energy reacceleration, storage rings, …

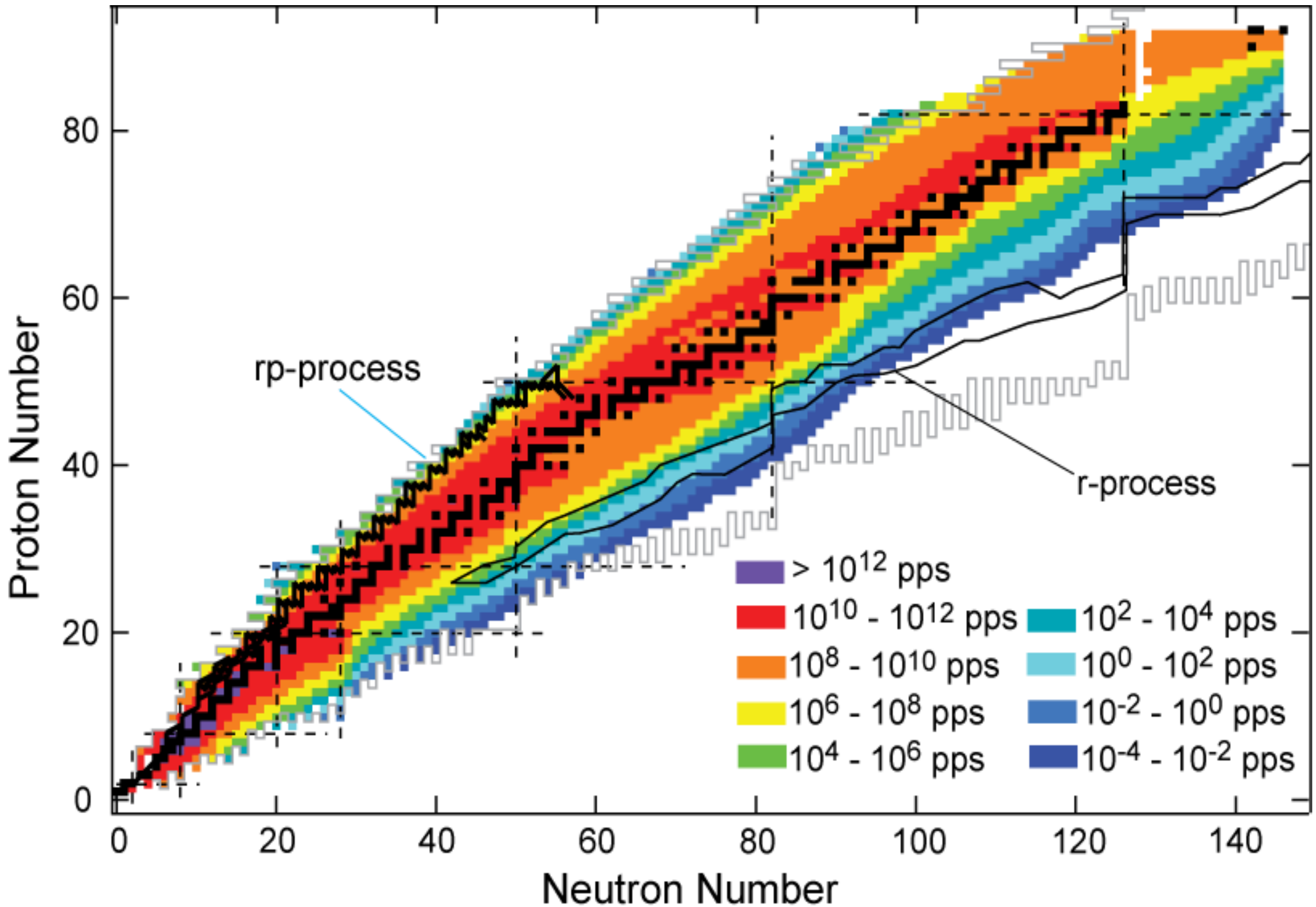




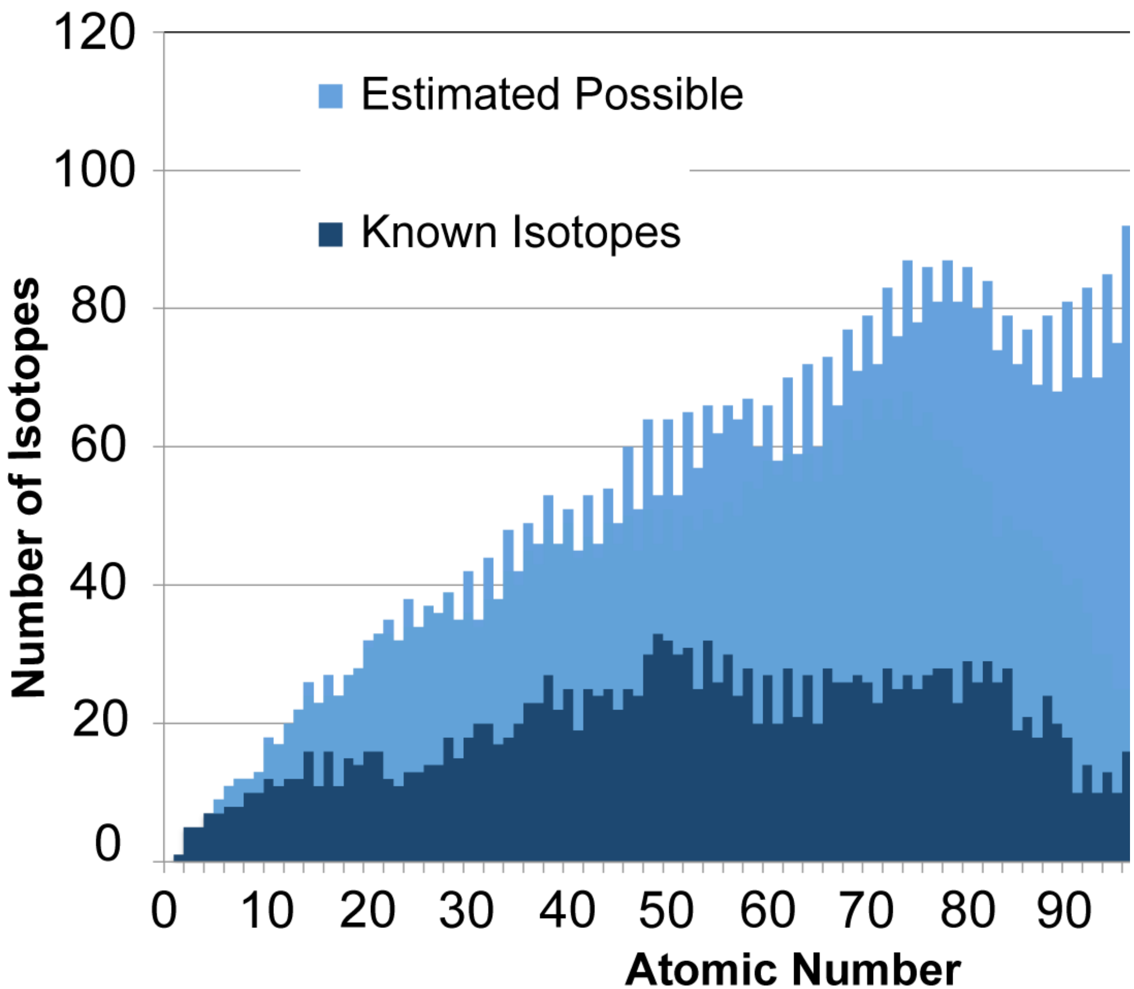


# Scientific Reach of FRIB – Rare Isotope Beam Rates

O. Tarasov - groups.nscl.msu.edu/frib/rates/

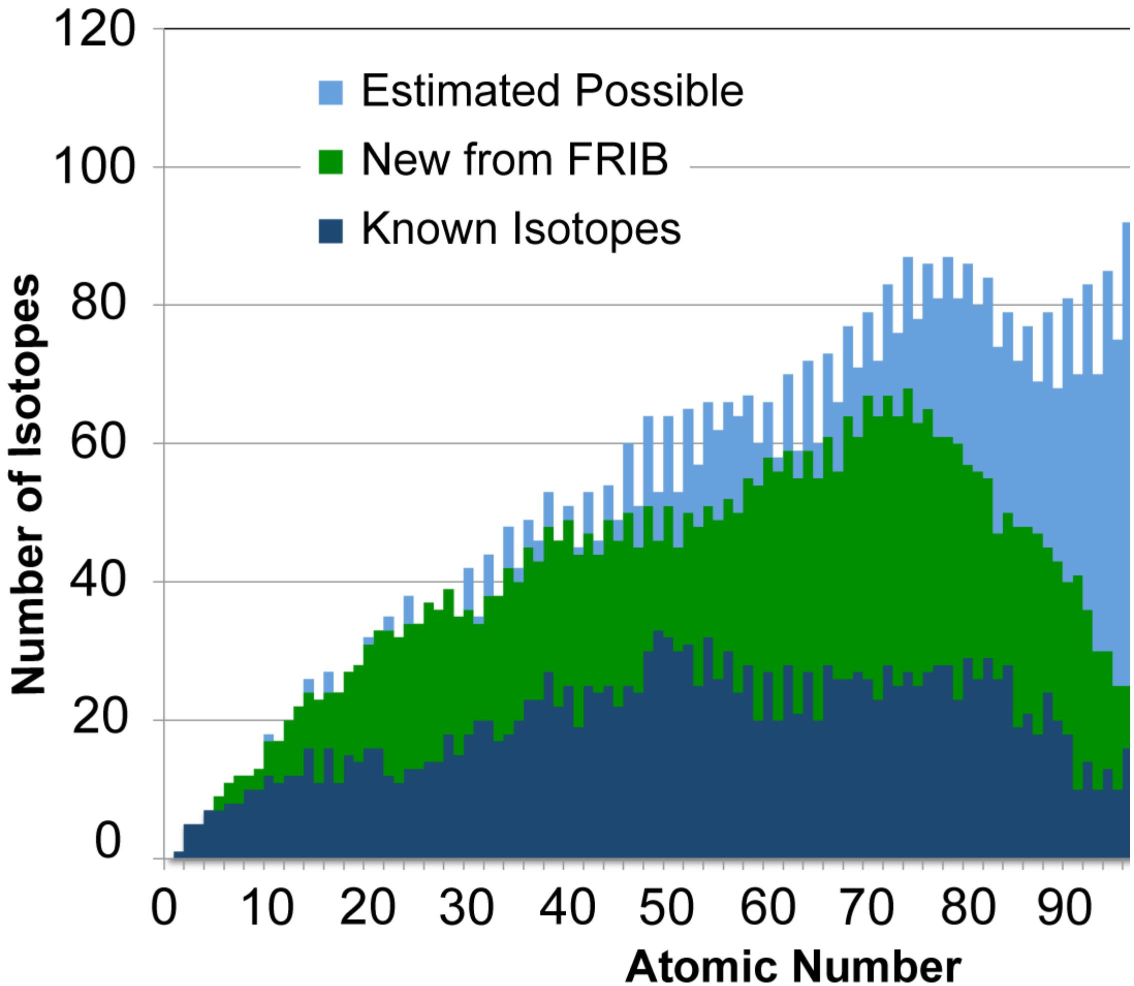


# How many isotopes might exist?



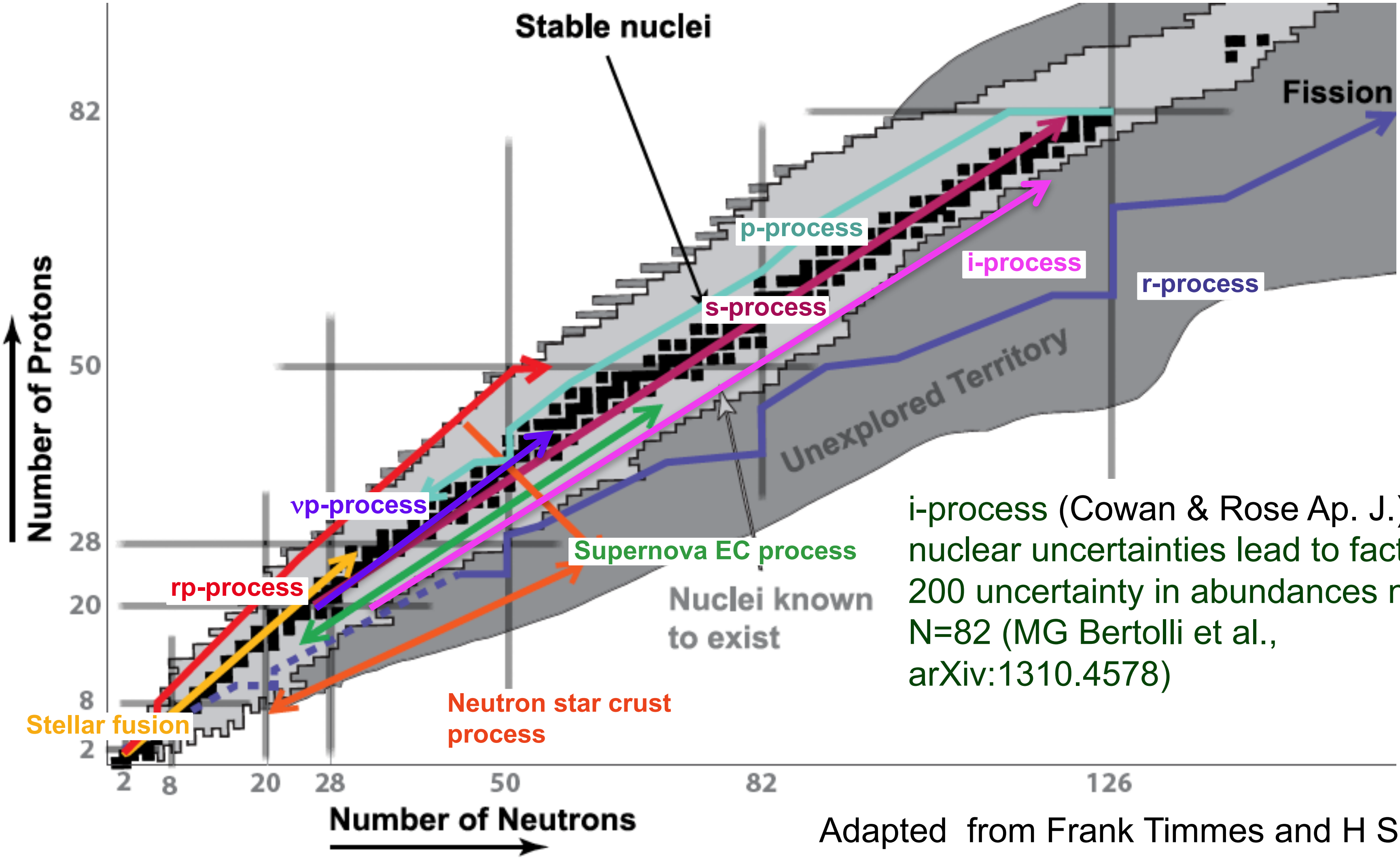

- Estimated Possible: Erler, Birge, Kortelainen, Nazarewicz, Olsen, Stoitsov, Nature 486, 509–512 (28 June 2012) , based on a study of EDF models
- “Known” defined as isotopes with at least one excited state known (1900 isotopes from NNDC database)
- Represents what is possible now

# The Number of Isotopes Available for Study at FRIB (next generation facilities)




- Estimated Possible: Erler, Birge, Kortelainen, Nazarewicz, Olsen, Stoitsov, Nature 486, 509–512 (28 June 2012) , based on a study of EDF models
- "Known" defined as isotopes with at least one excited state known (1900 isotopes from NNDC database)
- For Z<90 FRIB is predicted to make > 80% of all possible isotopes

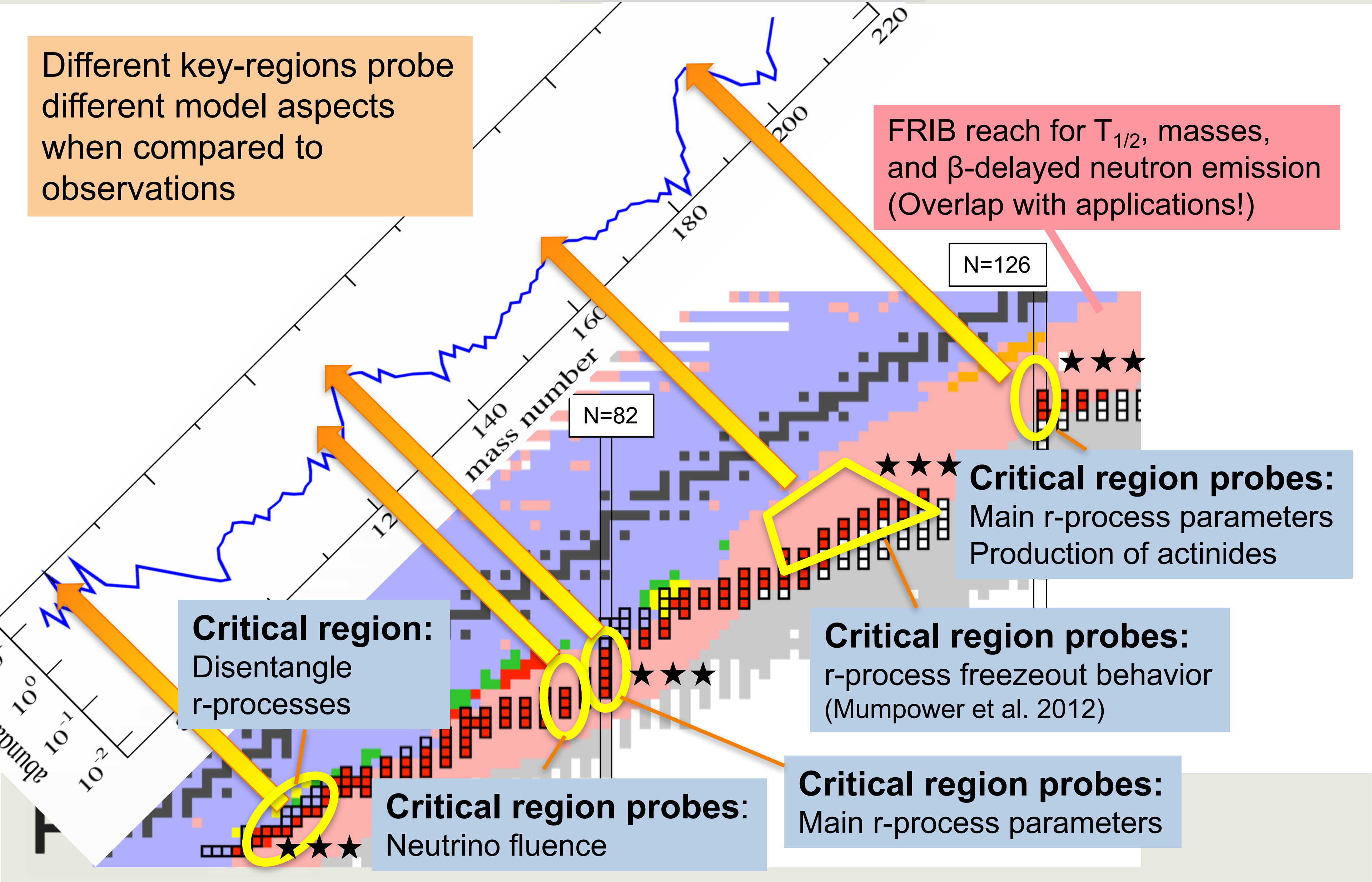
# Nuclear Physics Discoveries with FRIB



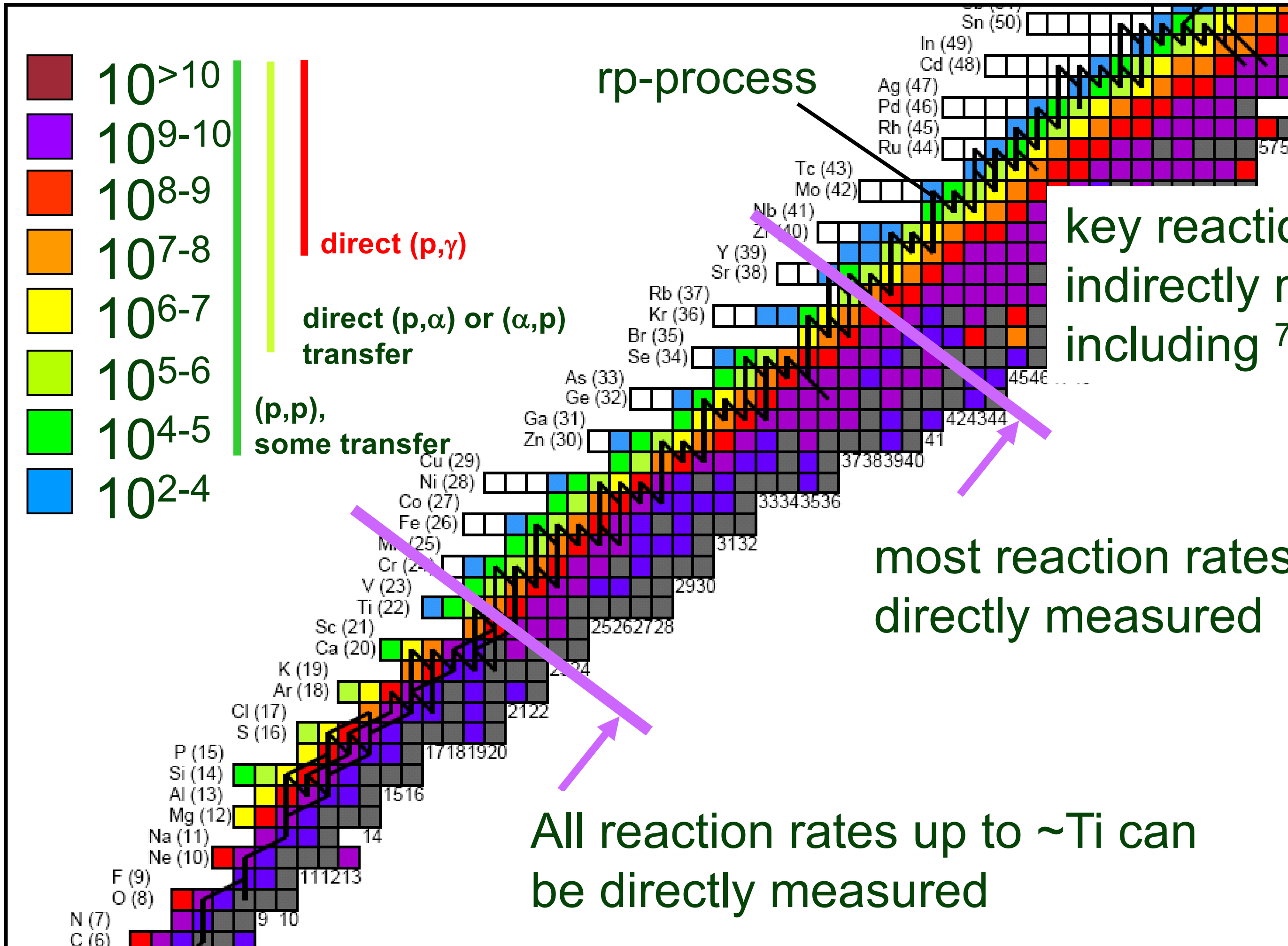

i-process (Cowan & Rose Ap. J.) nuclear uncertainties lead to factor of 200 uncertainty in abundances near N=82 (MG Bertolli et al., arXiv:1310.4578)

Adapted from Frank Timmes and H Schatz

# New Facilities will Enable the Needed Breakthrough in Nuclear Physics

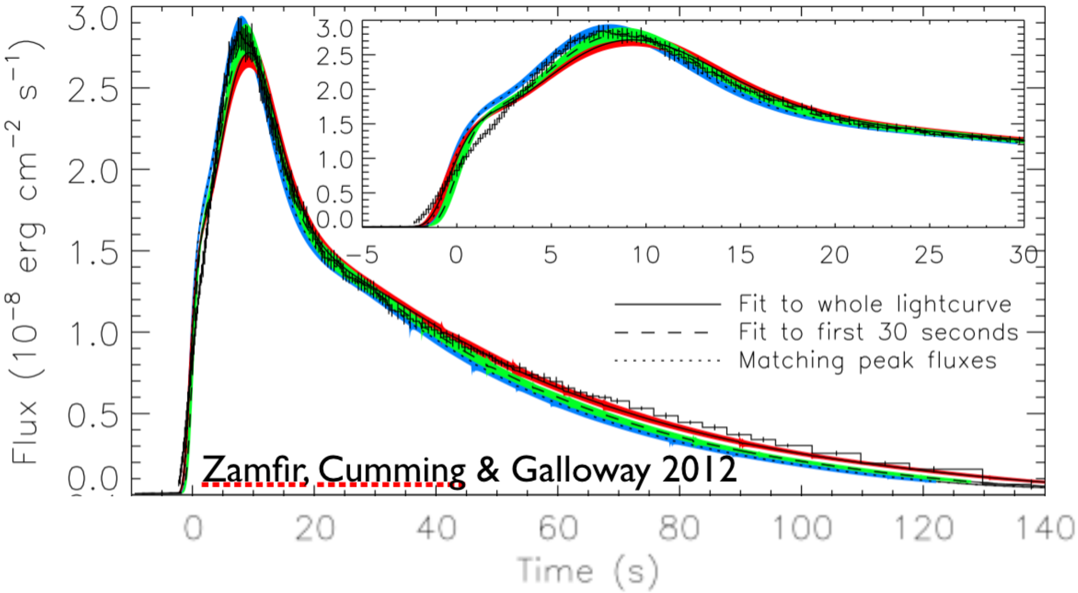


# FRIB Reach for Novae and X-ray burst reaction rate studies

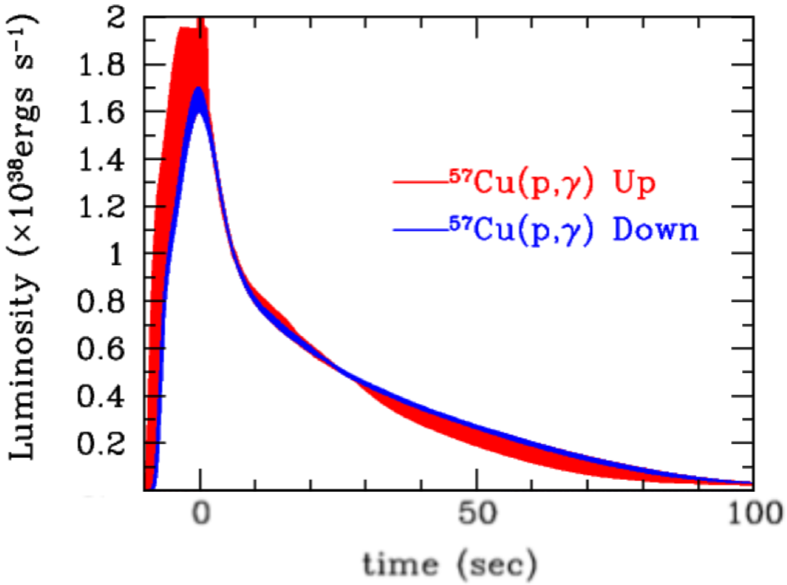


# Reaction rates directly determine X-ray burst behavior

GS1826-24
X-ray burster




1D multi-zone high accretion model




Mass and radius of neutron star determined based on set of astrophysical parameters that best fit observations

- Variations of burst profiles?
- Initial composition?
- Superbursts, Oscillations..?
- Neutron star physics?
- Ashes? Magnetic fields? Rotation?

# Direct or indirect measurement?

$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi\mu}} (kT)^{3/2} \int_0^\infty \sigma E e^{-E/(kT)} dE$$

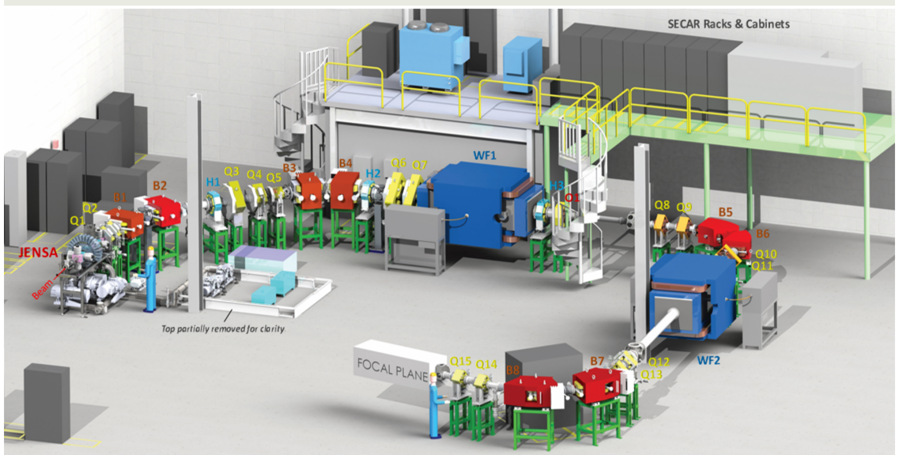
$$\sigma(E) = \pi\lambda\!\!\!^{-2} \frac{2J+1}{(2J_x+1)(2J_y+1)} \frac{\Gamma_x \Gamma_y}{(E-E_r)^2 + (\Gamma/2)^2}$$

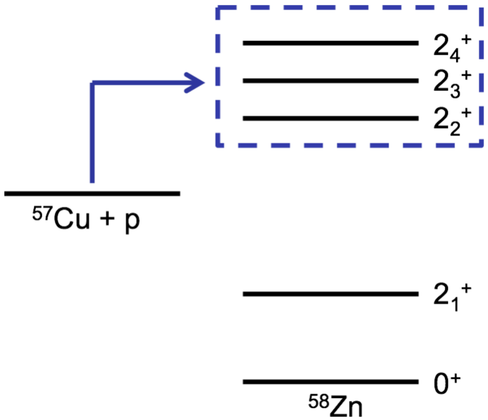
Measure cross section directly
BUT
very low cross sections

OR

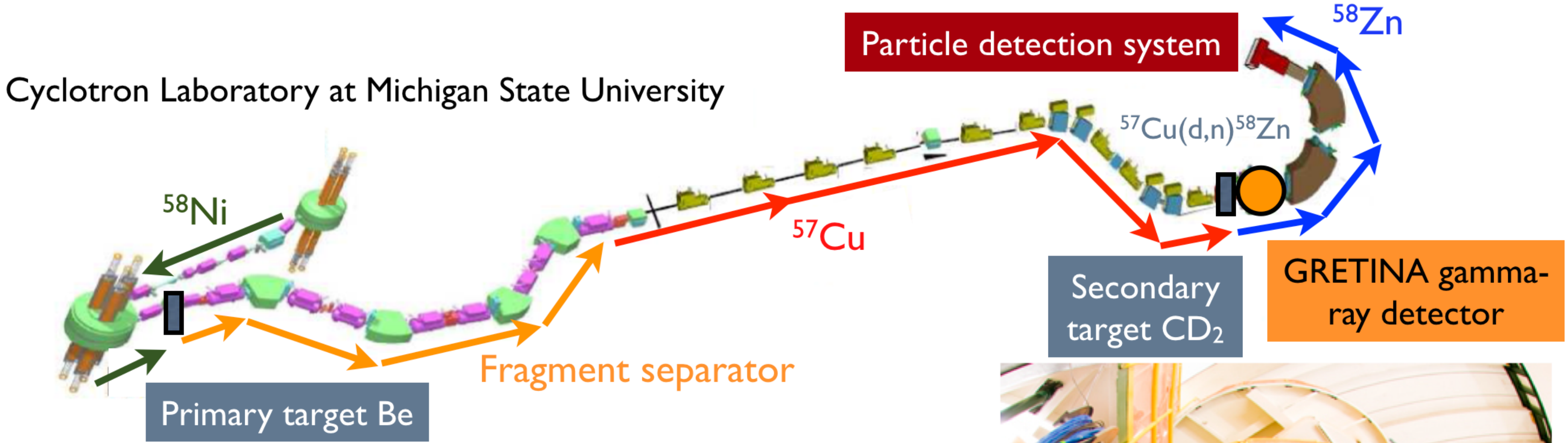
Measure cross section indirectly:
Measure spins, resonance energies, masses, single particle strengths, g-widths and spectroscopic factors

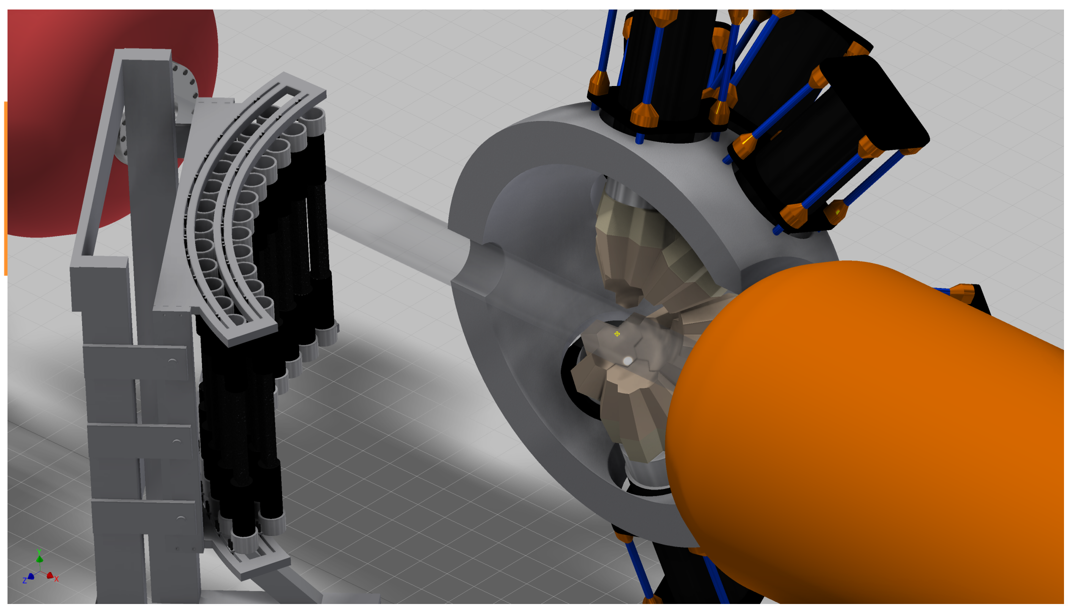
**SECAR Recoil Separator for Capture Reactions in Astrophysics**

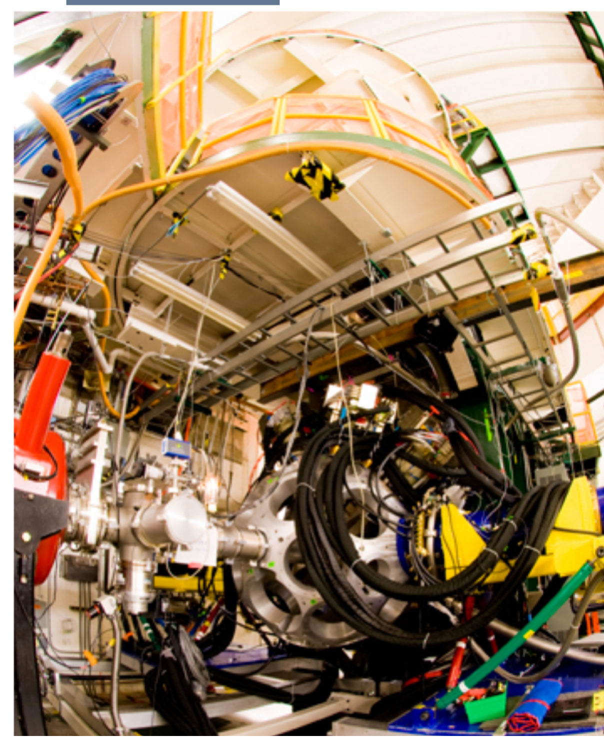


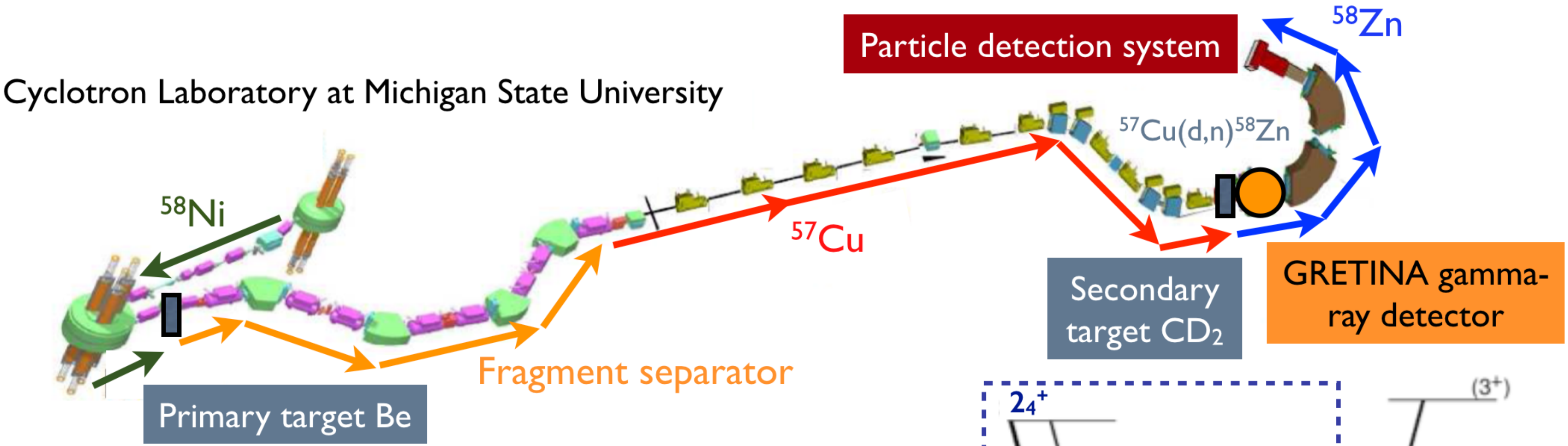
# Indirect reaction rate (d,n)

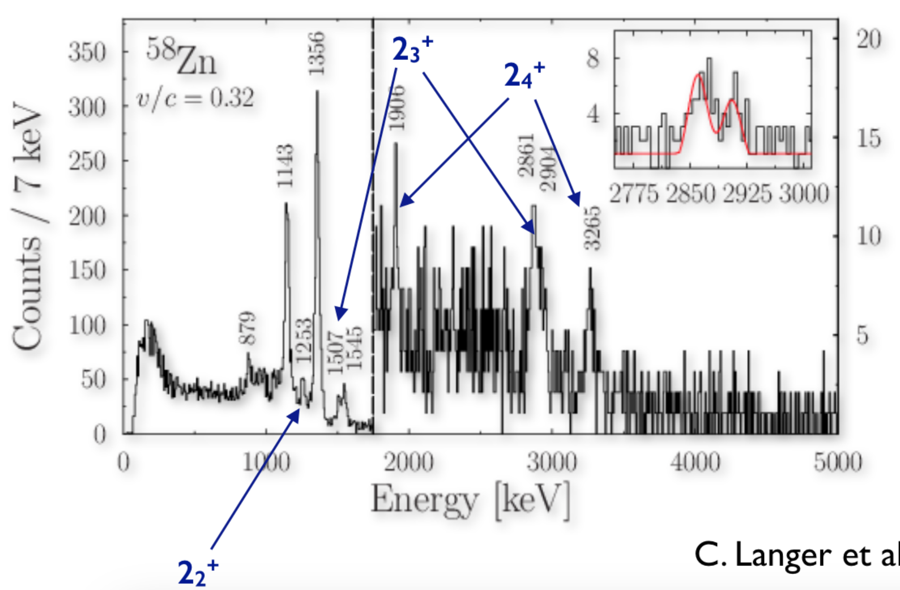


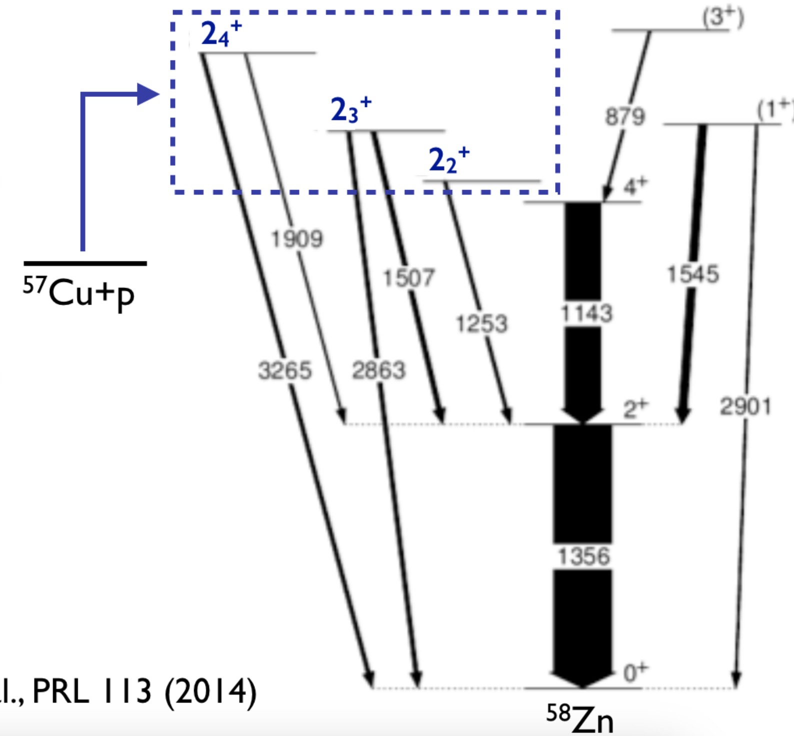





# Indirect measurement: $^{57}Cu(d,n)^{58}Zn$



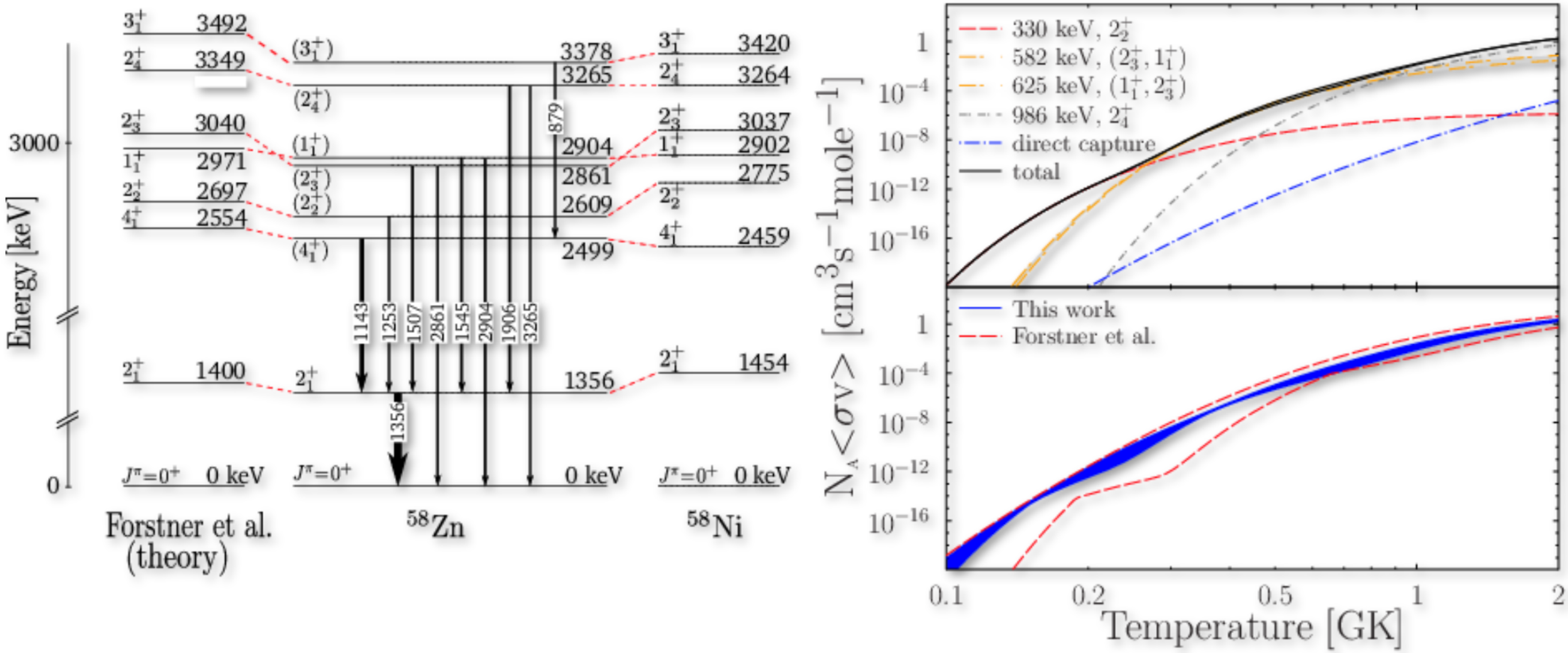




C. Langer et al., PRL 113 (2014)

# Thermonuclear rate: $^{57}Cu(p,\gamma)^{58}Zn$

C. Langer et al., PRL 113 (2014)

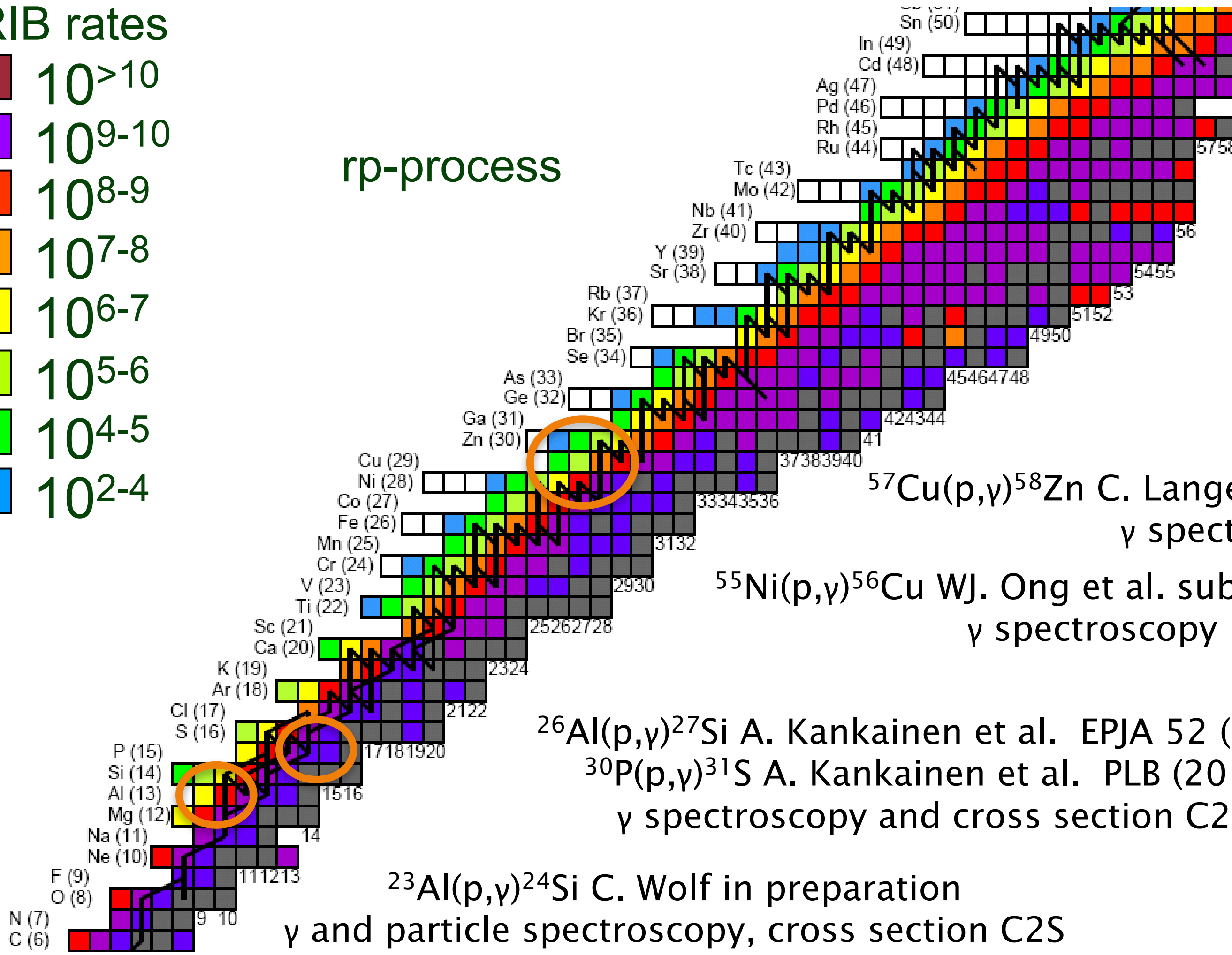



Obtained rate used in typical rp-process conditions effectively reduced the $^{56}Ni$ lifetime to ~200 ms

# Current status indirect studies

FRIB rates
- $10^{>10}$
- $10^{9-10}$
- $10^{8-9}$
- $10^{7-8}$
- $10^{6-7}$
- $10^{5-6}$
- $10^{4-5}$
- $10^{2-4}$

rp-process



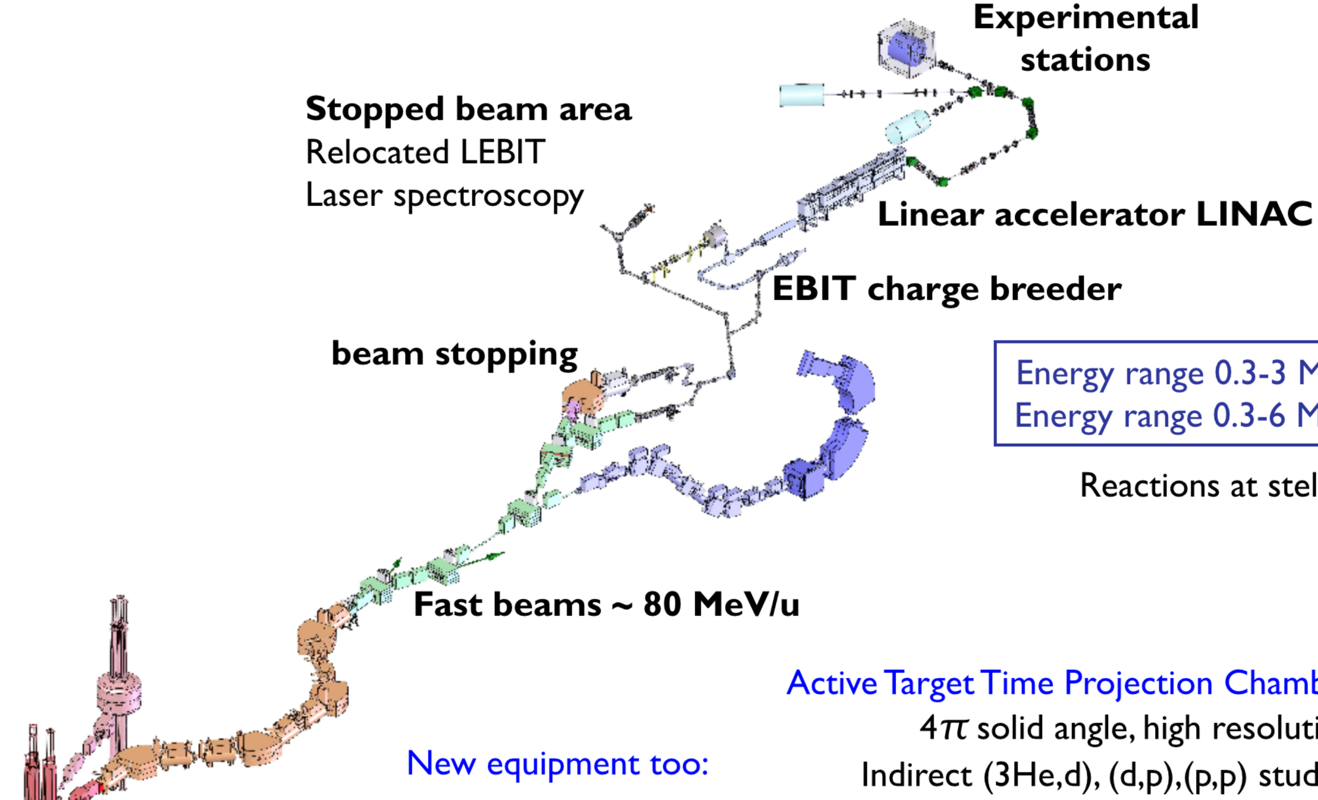

$^{57}$Cu(p,γ)$^{58}$Zn C. Langer et al. PRL 113 (2014)
γ spectroscopy

$^{55}$Ni(p,γ)$^{56}$Cu WJ. Ong et al. submitted to PRC
γ spectroscopy

$^{26}$Al(p,γ)$^{27}$Si A. Kankainen et al. EPJA 52 (2016)
$^{30}$P(p,γ)$^{31}$S A. Kankainen et al. PLB (2017)
γ spectroscopy and cross section C2S

$^{23}$Al(p,γ)$^{24}$Si C. Wolf in preparation
γ and particle spectroscopy, cross section C2S

# Reaccelerated beams (ReA)

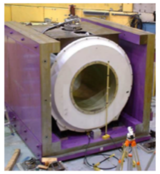


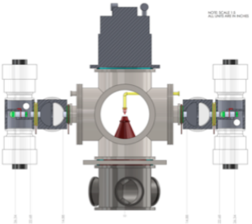

Energy range 0.3-3 MeV/u for $^{238}U$
Energy range 0.3-6 MeV/u for $^{48}Ca$

Reactions at stellar energies!

New equipment too:

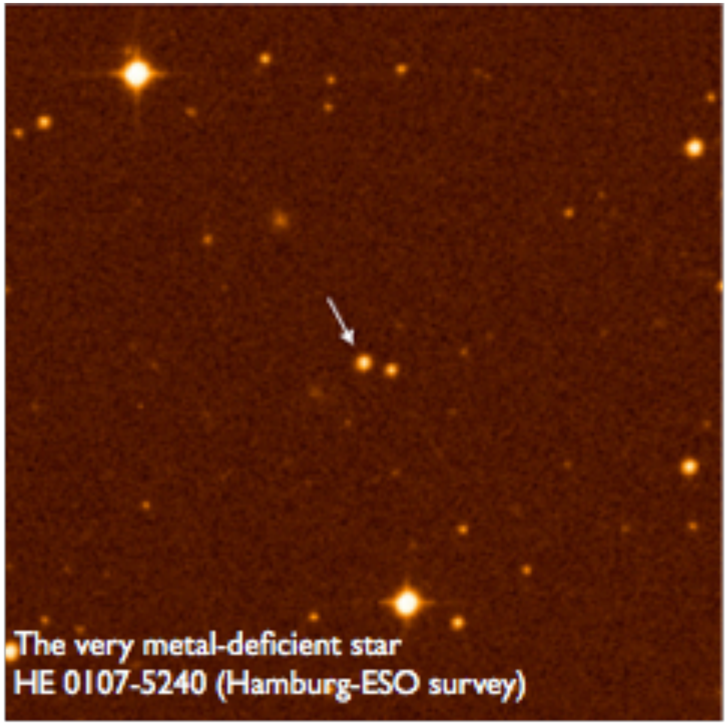
Active Target Time Projection Chamber
$4\pi$ solid angle, high resolution
Indirect (3He,d), (d,p),(p,p) studies

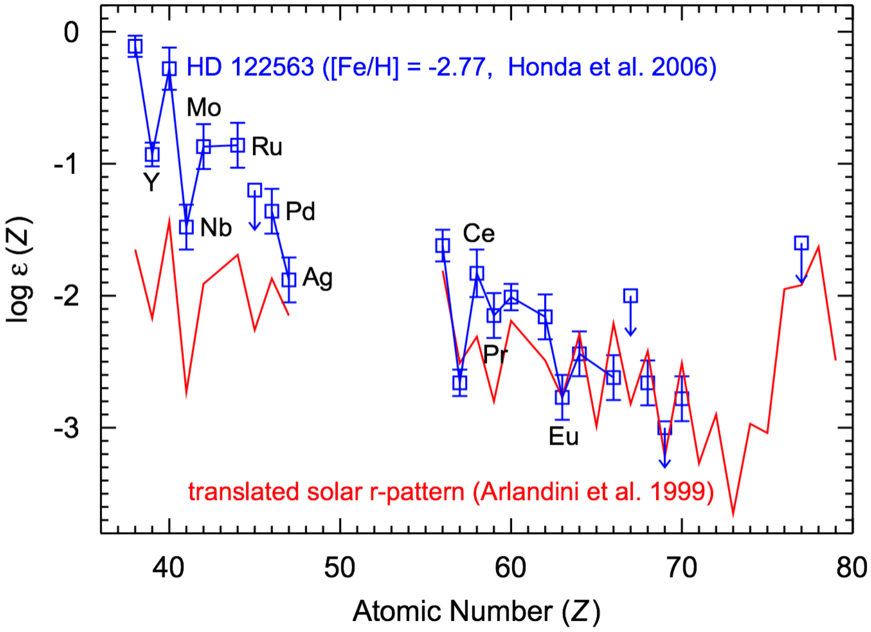




Gas target (JENSA)
($\alpha$,p) study of direct reaction. Important in x-ray bursts ($^{14}O$, $^{18}Ne$, $^{22}Mg$, $^{26}Si$, $^{30}S$)

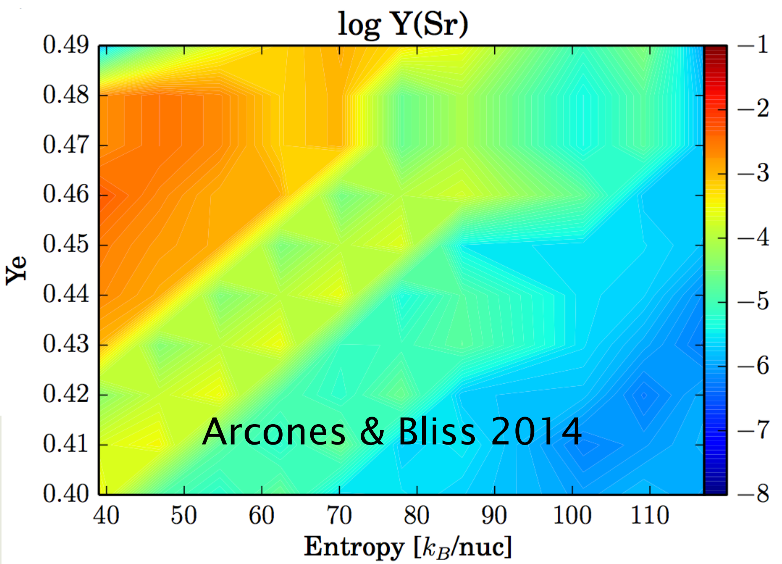
# Nucleosynthesis in the early universe



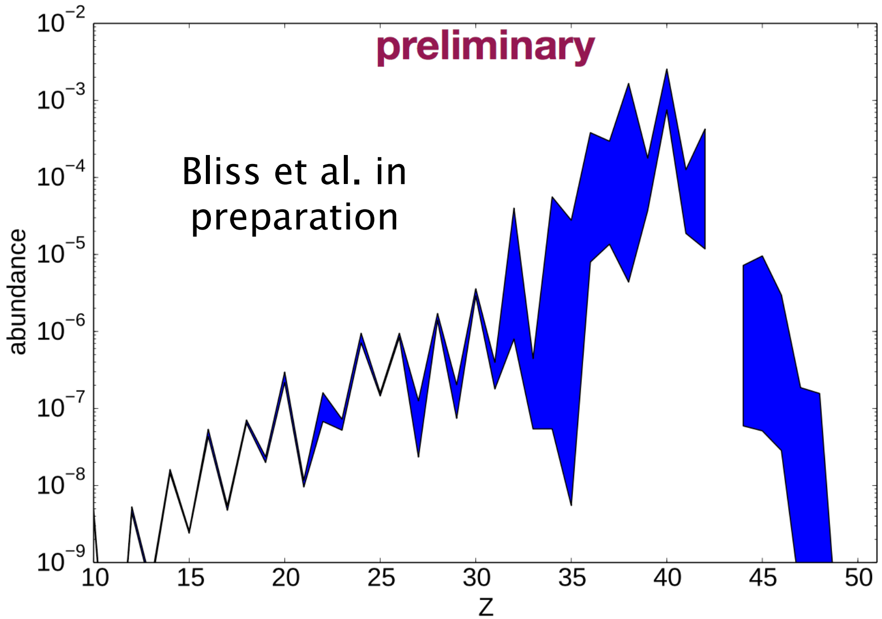



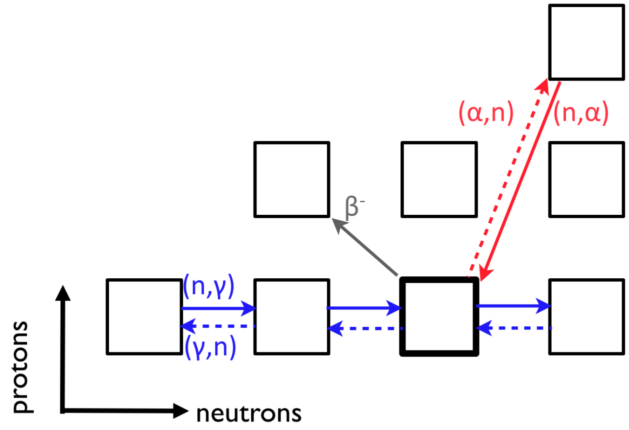

**Possible site:** Neutrino driven winds in core-collapse Supernovae

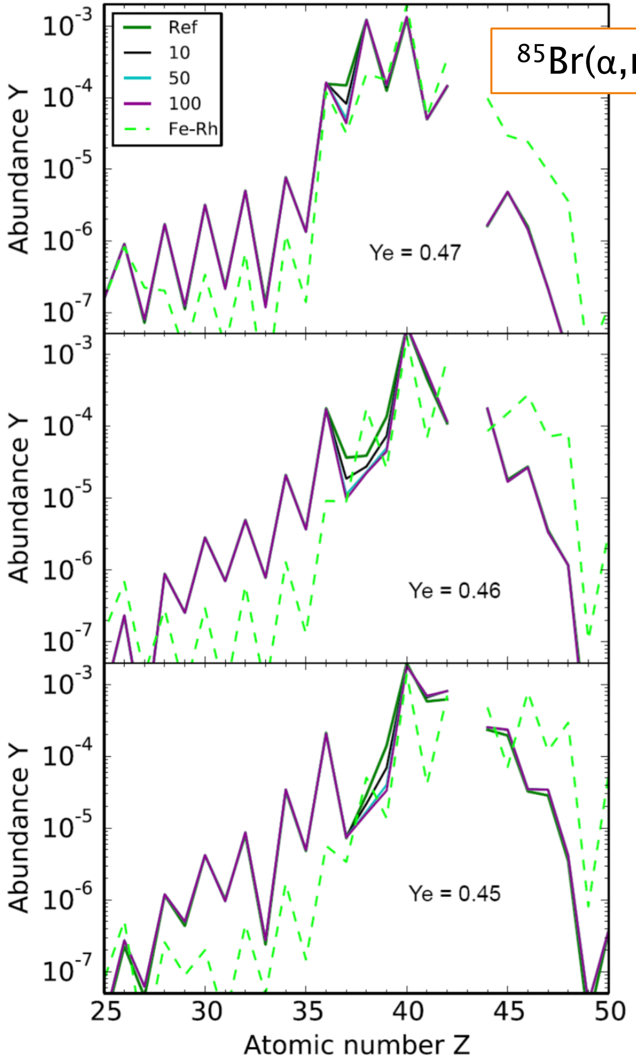
- Models affected by both astro and nuclear uncertainties



# Reaction rate uncertainties

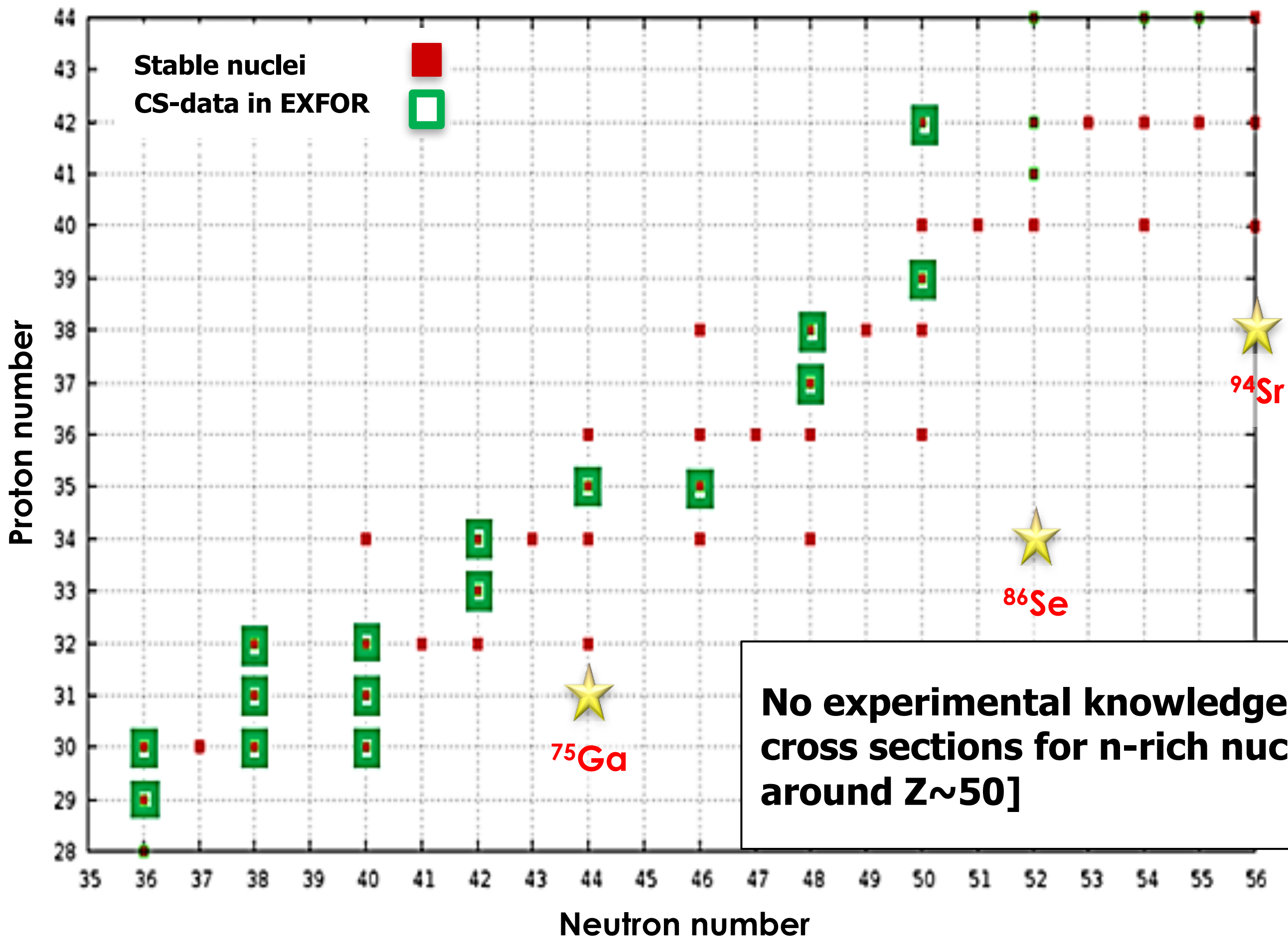


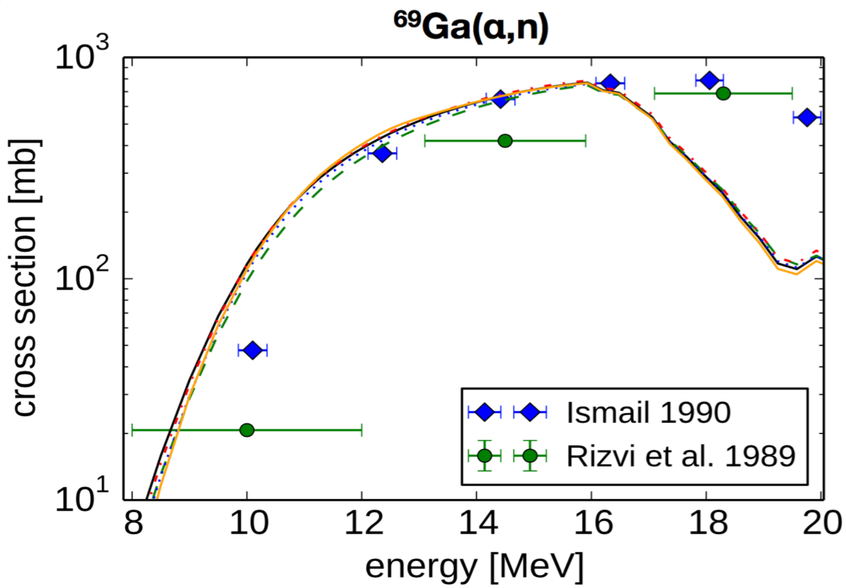

$^{85}Br(\alpha,n)^{88}Rb$

# Measured (α,n) cross sections



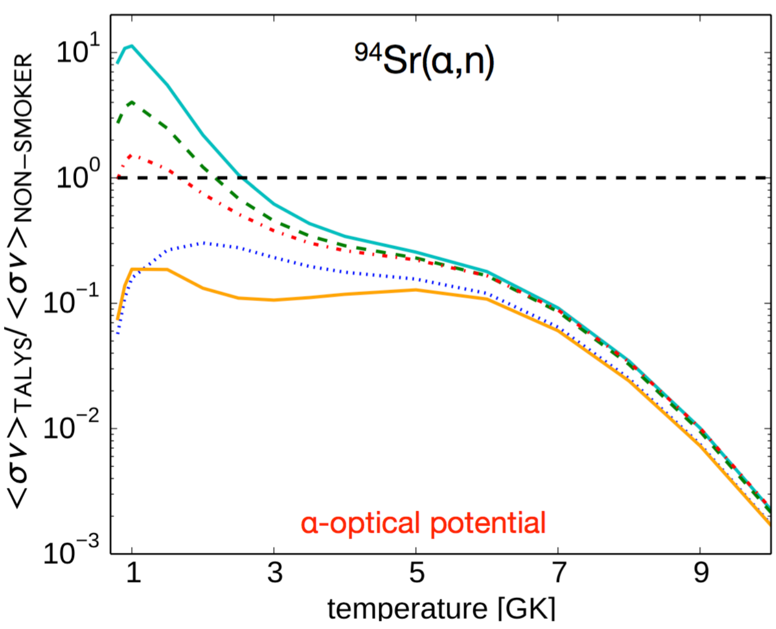

**No experimental knowledge of (α,x*n*) cross sections for n-rich nuclei [except around Z~50]**

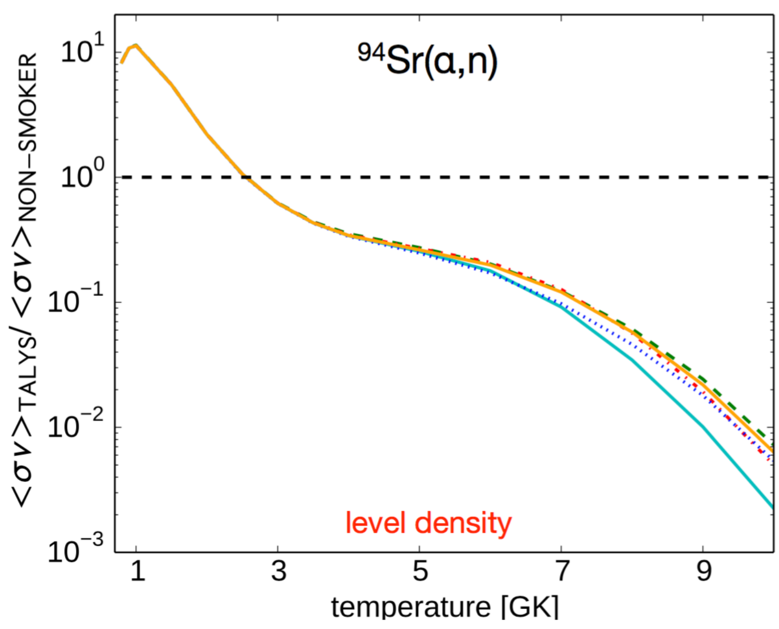
# (α,n) uncertainties



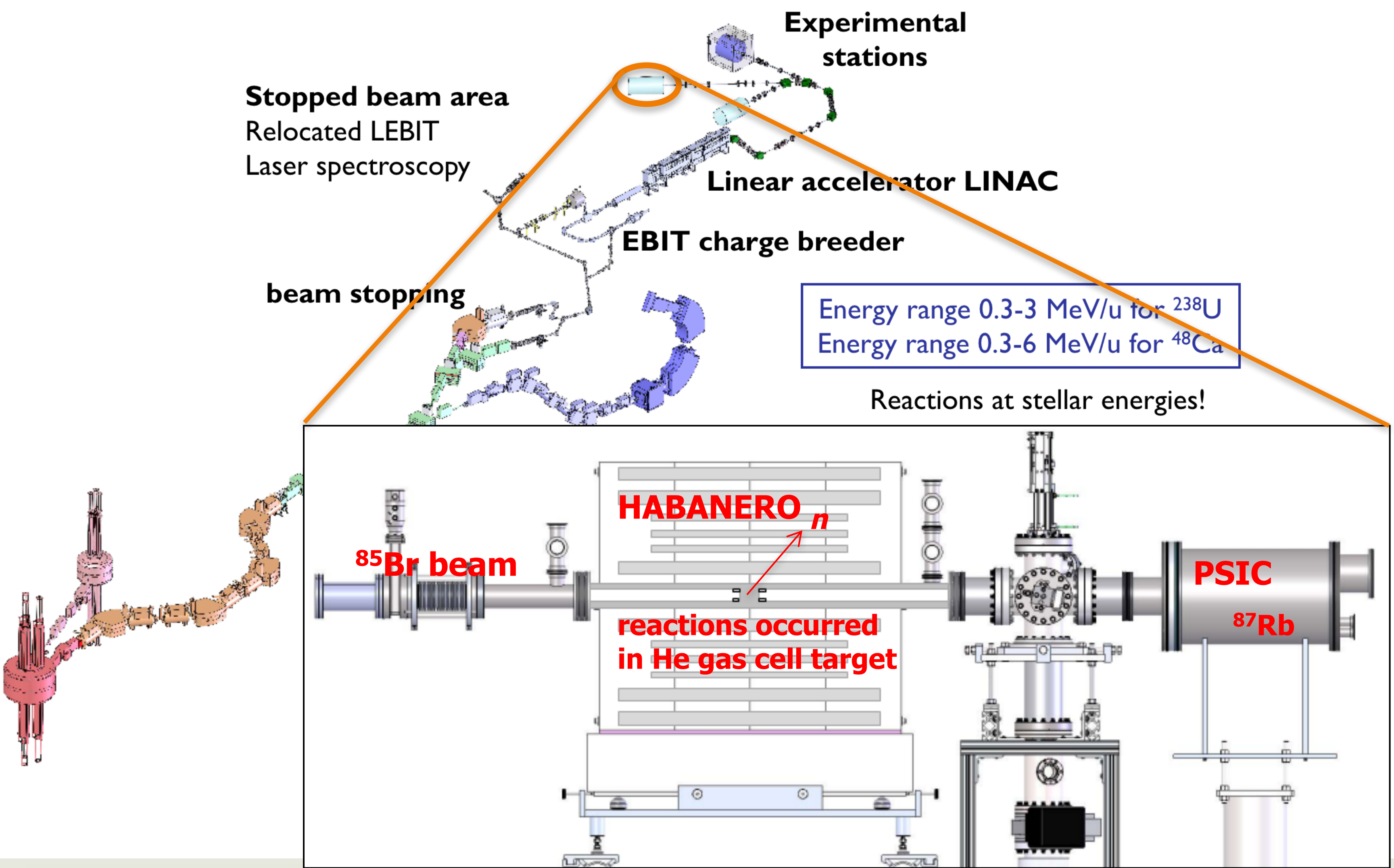

- Gamow window between 3-11 MeV. Few measurements in this range
- HF calculation within a factor 1-10 of measurements
- Experimental measurements disagree up to a factor of 3

Pereira & Montes PRC 93 (2016)
Mohr PRC 94 (2016)

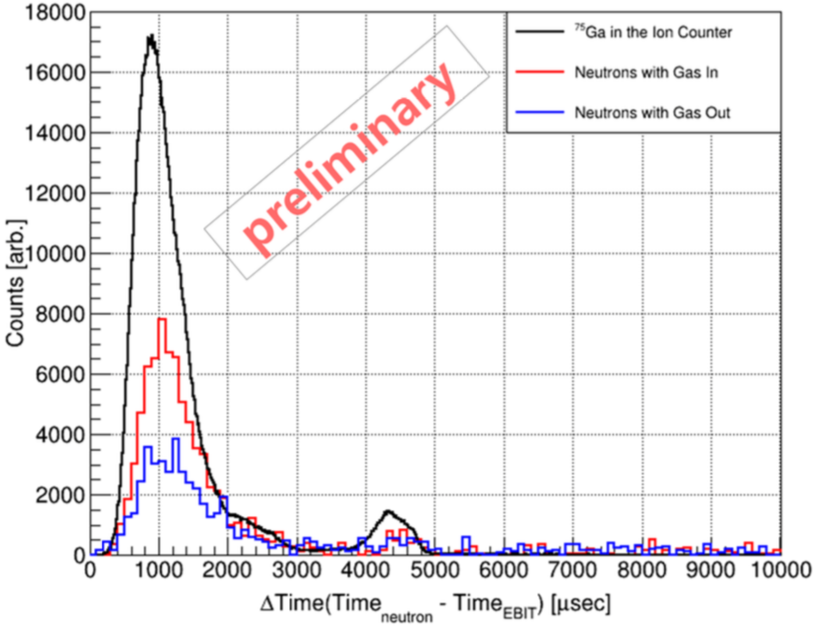


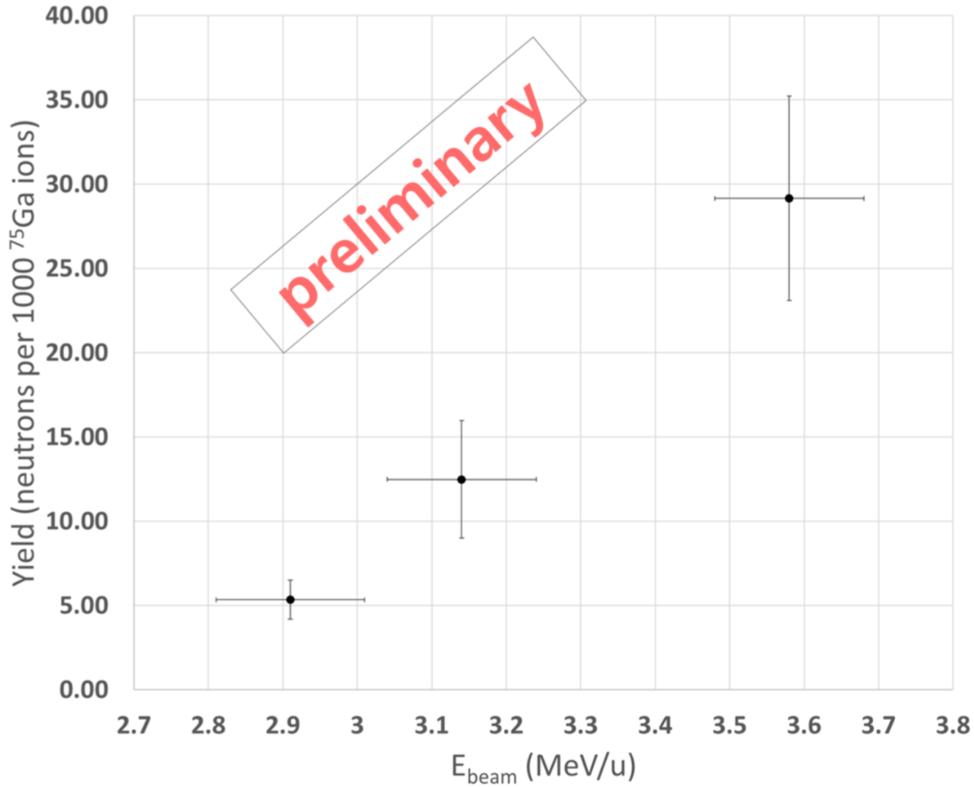
# Constraining (α,n) reaction rates



# Constraining $^{75}Ga(\alpha,n)^{77}As$ reaction rate




T. Ahn et al. in preparation



# Future experiments

Relevant (α,n) reactions