Nuclear Structure and Reactions at NSCL and FRIB through the Lens of Astrophysics: Lecture 2

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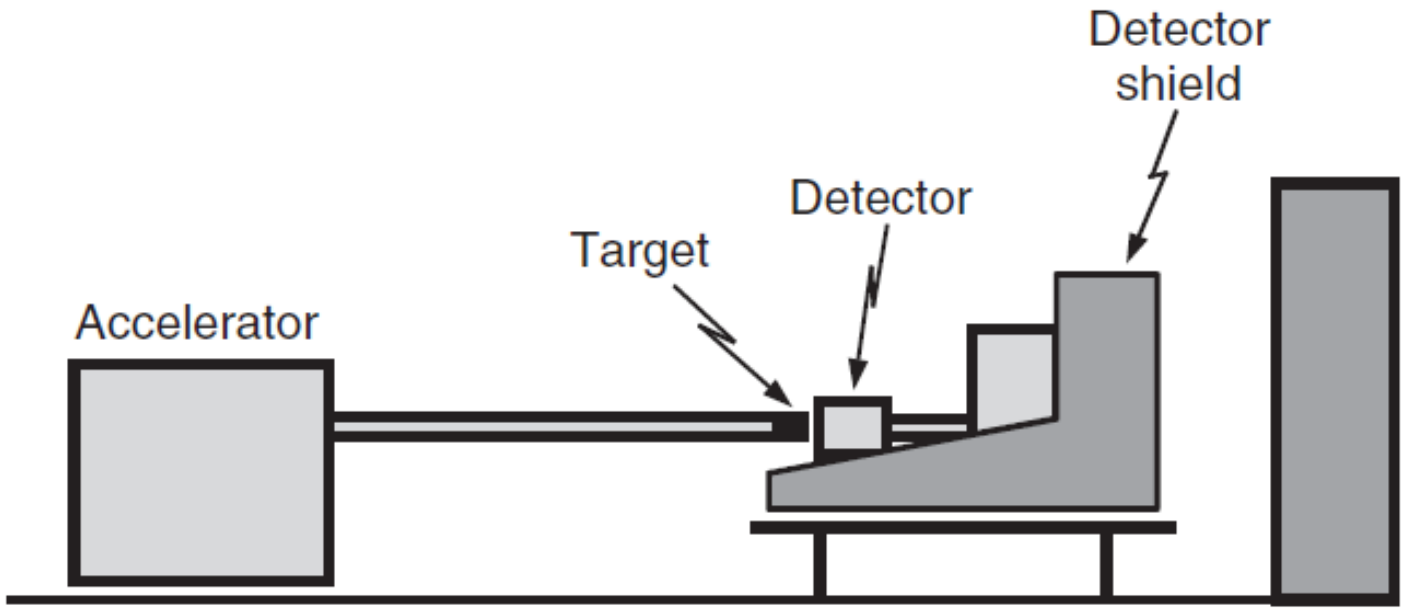
HUGS @ JLab

May 29th, 2019

Outline

- Lecture 1: History, stellar evolution & thermonuclear rates
- **Lecture 2: Charged-particle reactions: direct measurements**
- Lecture 3: Charged-particle reactions: indirect measurements
- Lecture 4: Slow neutron capture process: direct measurements
- Lecture 5: Rapid neutron capture process: indirect measurements

Direct measurements (stable reactants)



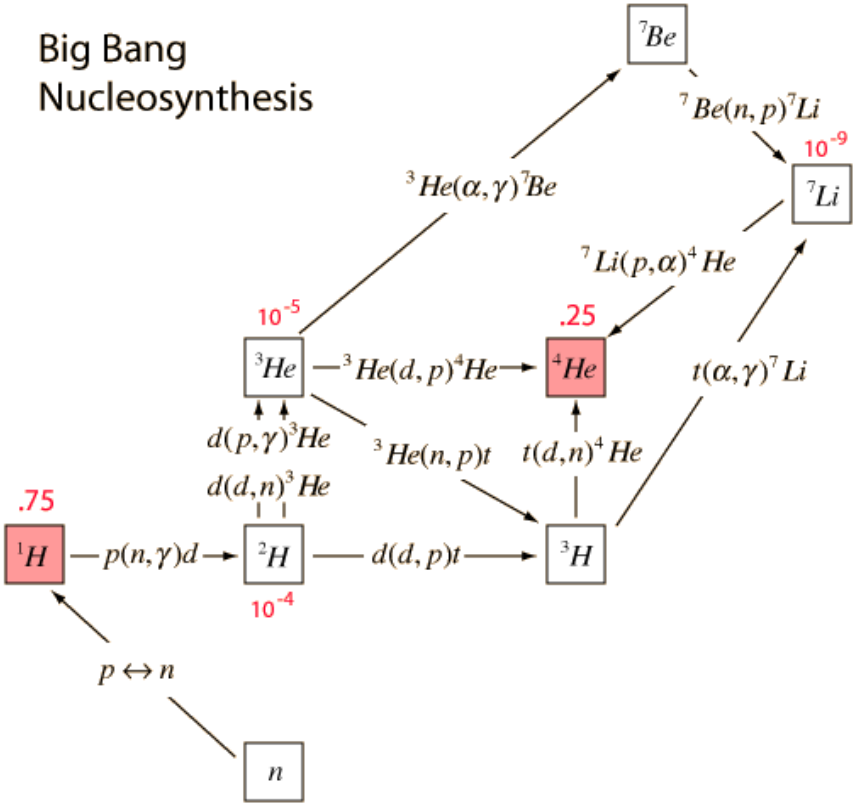
- Accelerator produces ion beam of one reactant at appropriate energy
- Beam directed on a chemically stable target composed of other reactant
- Reaction like $A(a,\gamma)B$ or $A(a,b)B$ takes place in target
- Reaction products (usually γ rays or light particles) measured in detector
- Reduce background as much as possible (pure beam, clean target, shielding, …)

Nuclear Physics of Stars, Iliadis, 2nd Ed.

Example: $^3He(\alpha,\gamma)^7Be$ reaction

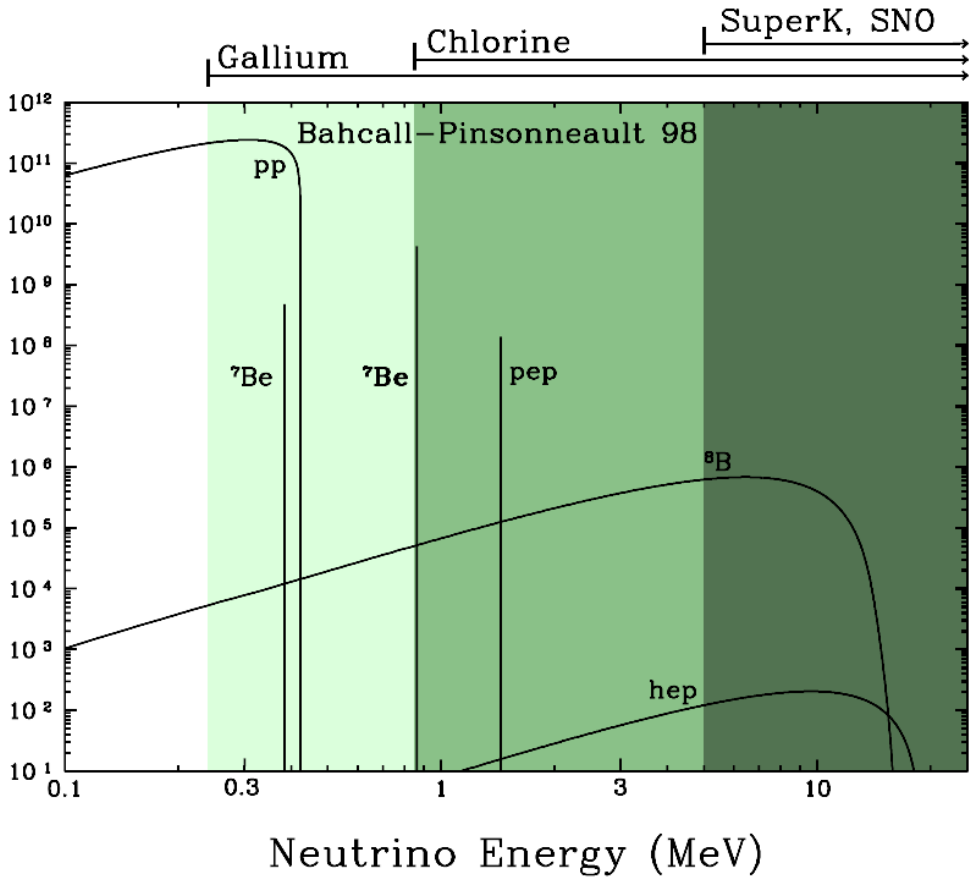
Motivation 1: Big Bang Nucleosynthesis (BBN) & cosmological Li problem:

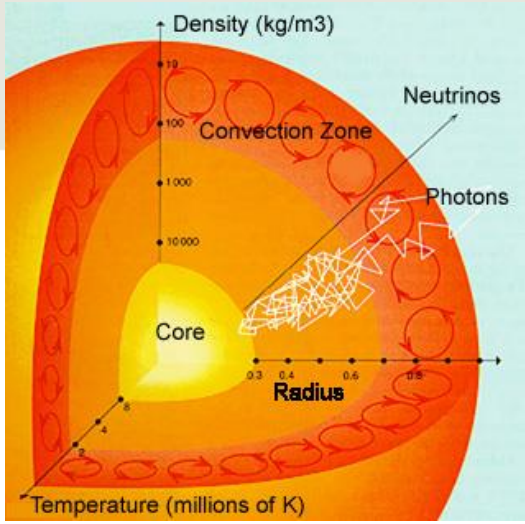
Why do we observe 3-4 times less ^7Li than BBN predicts?

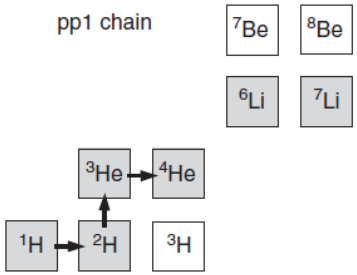


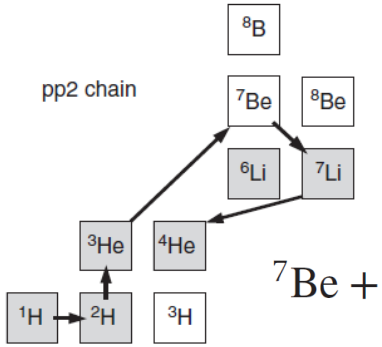
$^3He(\alpha,\gamma)^7Be$ reaction

Motivation 2: Solar hydrogen burning and neutrinos

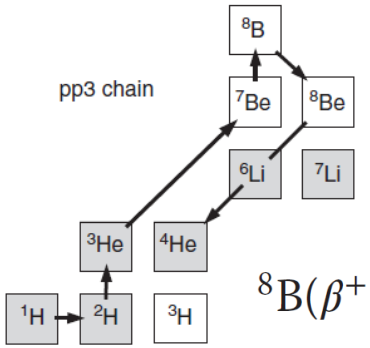








$$^7Be + e^- \rightarrow {}^7Li + \nu$$

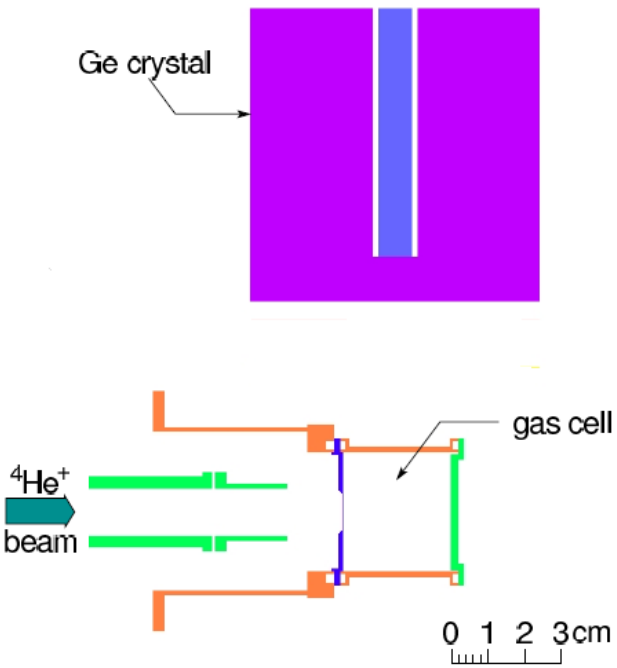


$$^8B(\beta^+\nu)^8Be$$

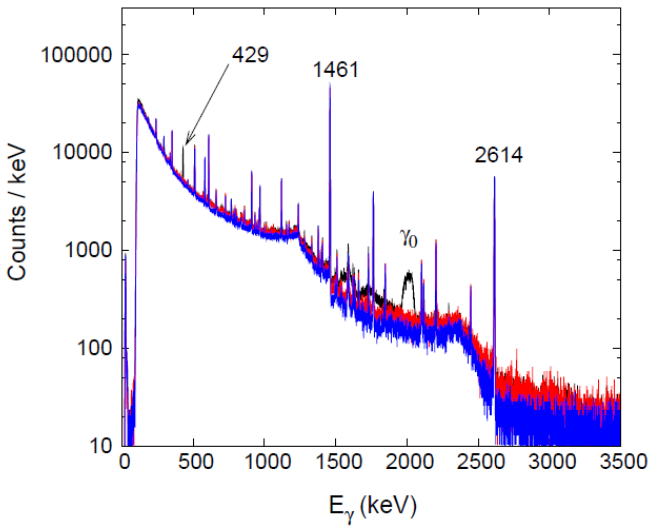
Nuclear Physics of Stars, Iliadis, 2nd Ed.

$^3He(\alpha,\gamma)^7Be$ reaction experiment

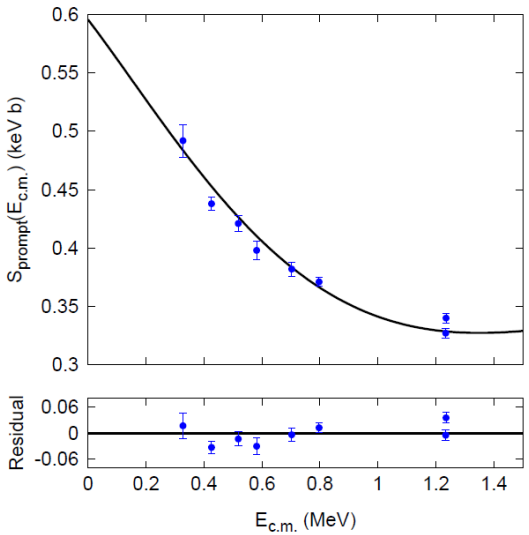
Setup



Spectrum at E_{cm} = 0.43 MeV



S factor



$$Y(E_0) = n\sigma$$

Y = yield (# reactions per ion)

n = # target nuclei per unit area

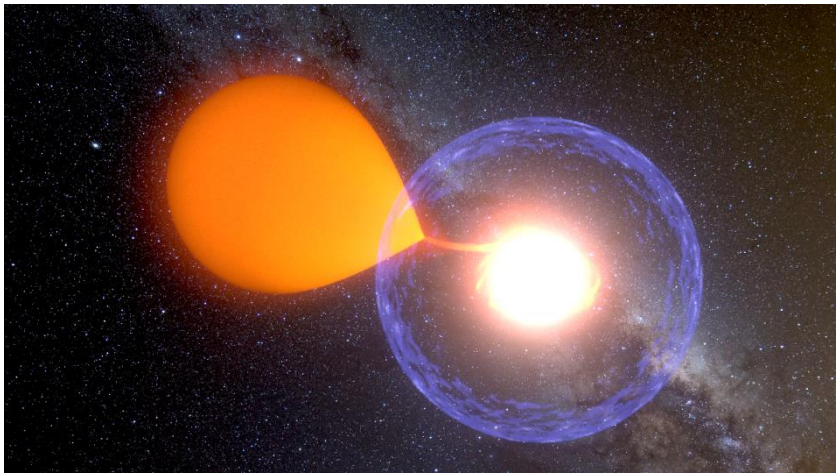
σ = nuclear cross section

Measured at University of Washington's Center for Experimental Nuclear Physics and Astrophysics.

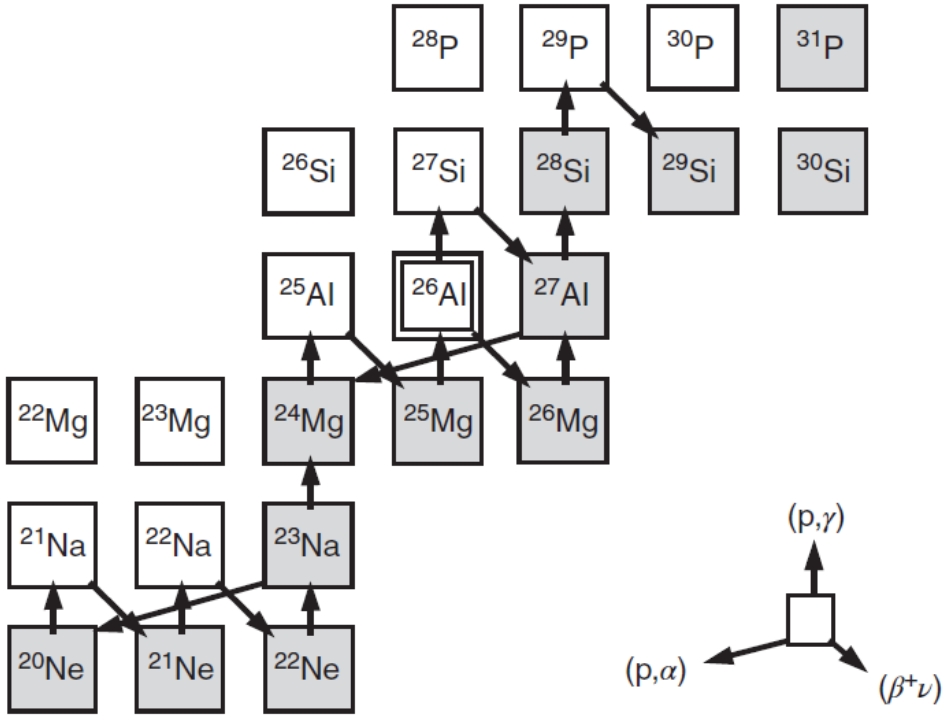
T. A. D. Brown *et al.*, Phys. Rev. C 76, 055801 (2007)

Example: $^{31}P(p,\alpha)^{28}Si$ reaction

Artist's impression of a thermonuclear explosion on an accreting white dwarf star (classical nova)



Hydrogen burning before explosive temperatures are reached



Resonances in the $^{31}P(p,\alpha)^{28}Si$ reaction determine if there is a Si-P cycle during (explosive) hydrogen burning on accreting compact stars: rapid proton-capture (rp) process.

phys.org
Nuclear Physics of Stars, Iliadis, 2nd Ed.

Narrow resonance reaction rates

For narrow, isolated resonances, thermonuclear rate is:

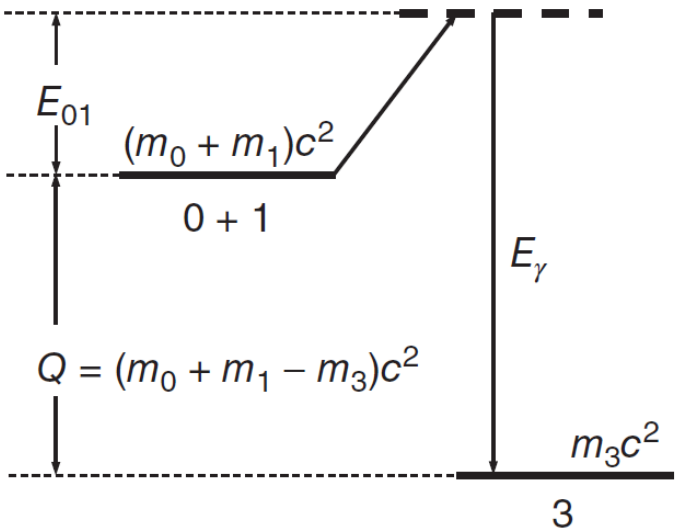
$$N_A\langle\sigma v\rangle = N_A\left(\frac{2\pi}{m_{01}kT}\right)^{3/2}\hbar^2 e^{-E_r/kT}\omega\gamma$$

Depends on nuclear physics:

1. Resonance energy $E_r = E_{01} = E_\gamma - Q$
2. Resonance strength $\omega\gamma$, which is like integral of $\sigma(E)$ over resonance

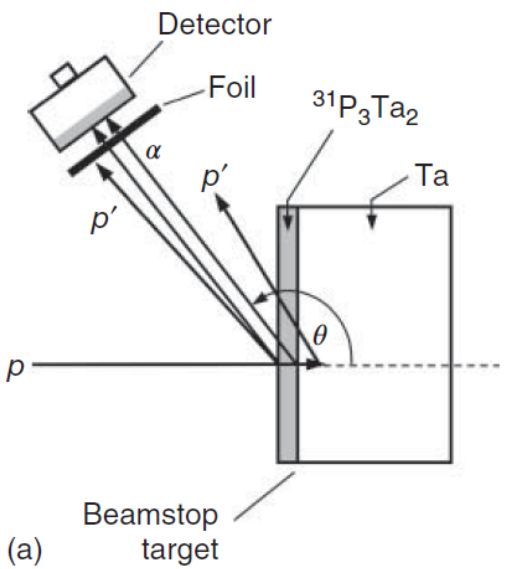
Depends on astrophysical environment:

1. Temperature T

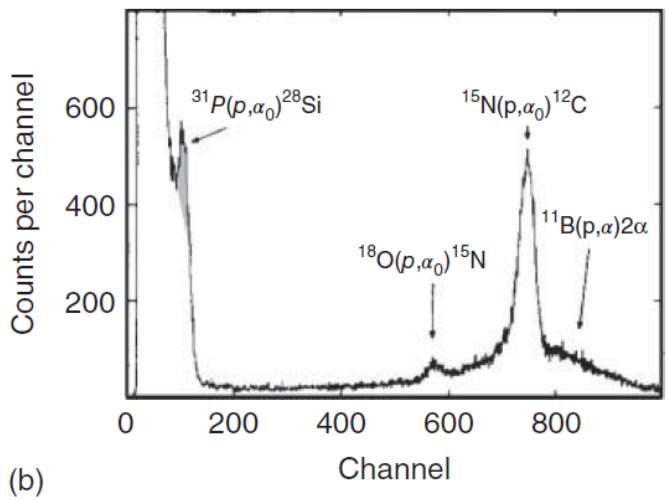


$^{31}P(p,\alpha)^{28}Si$ reaction experiment

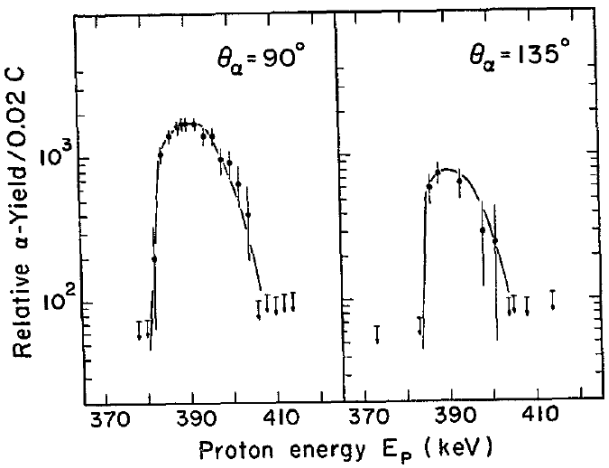
Setup



Spectrum at E_p = 390 keV



Excitation function



$$Y = \frac{\lambda_r^2}{2\pi}\frac{\omega\gamma}{\varepsilon_r}$$

Y = yield (# reactions per ion)

λ = proton deBroglie wavelength

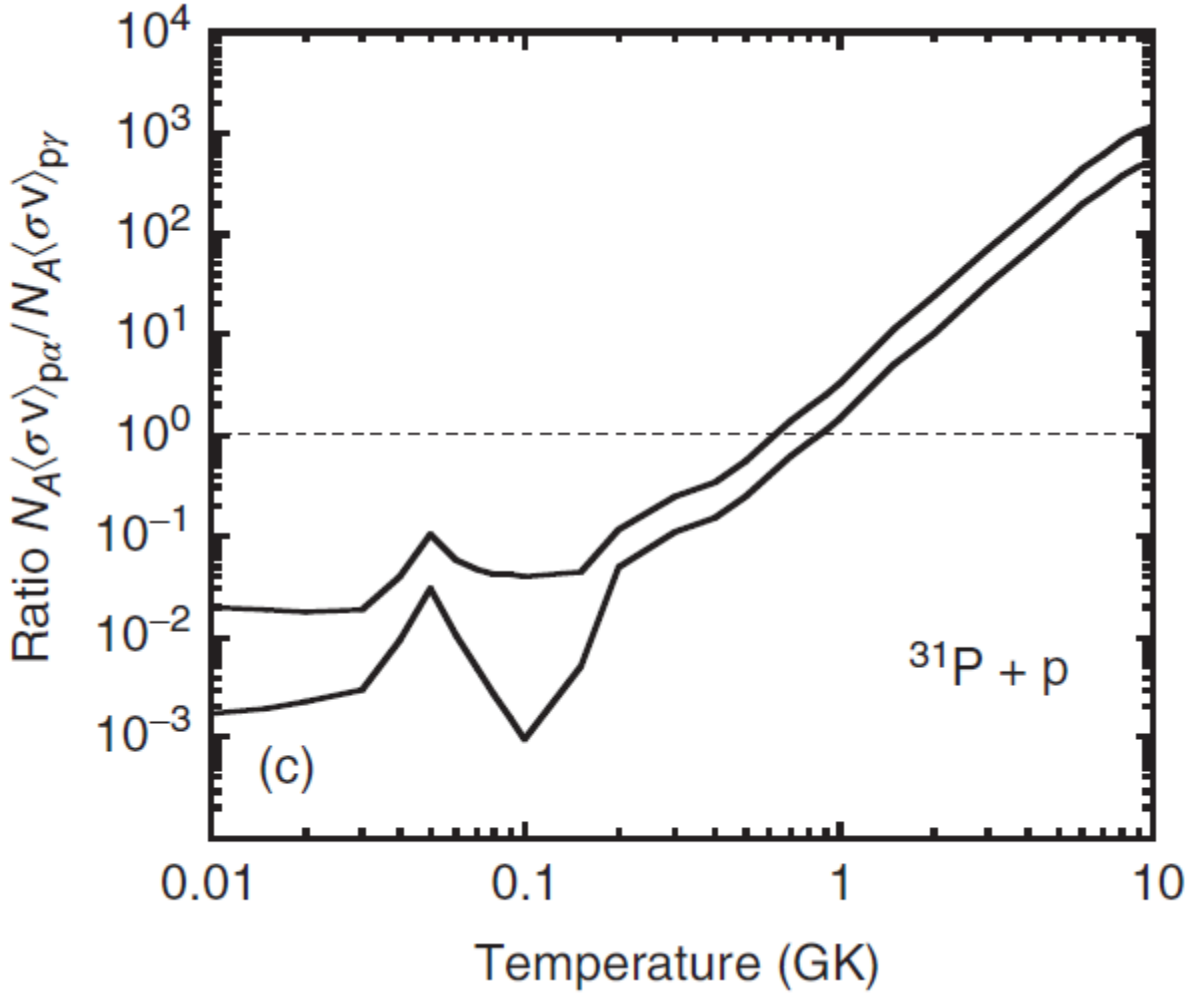
ε = stopping power

$\omega\gamma$ = resonance strength

Measured at the Kellogg facility at Caltech.

Nuclear Physics of Stars, Iliadis, 2nd Ed.
Iliadis *et al.*, Nucl. Phys. A533, 153 (1991)

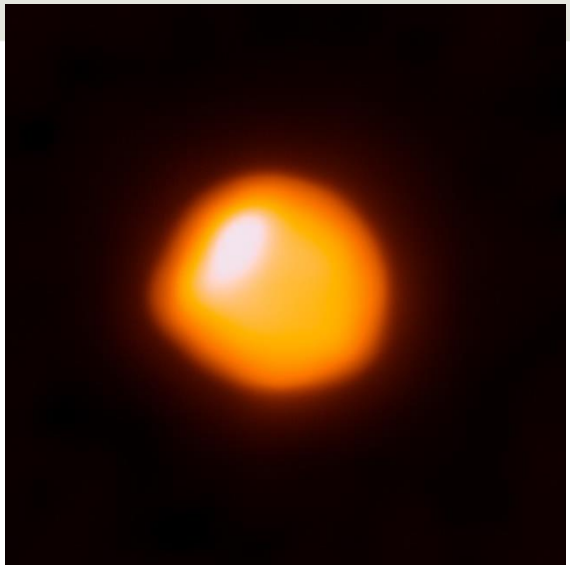
Result: no strong SiP cycle



No strong SiP cycling below about 1 GK

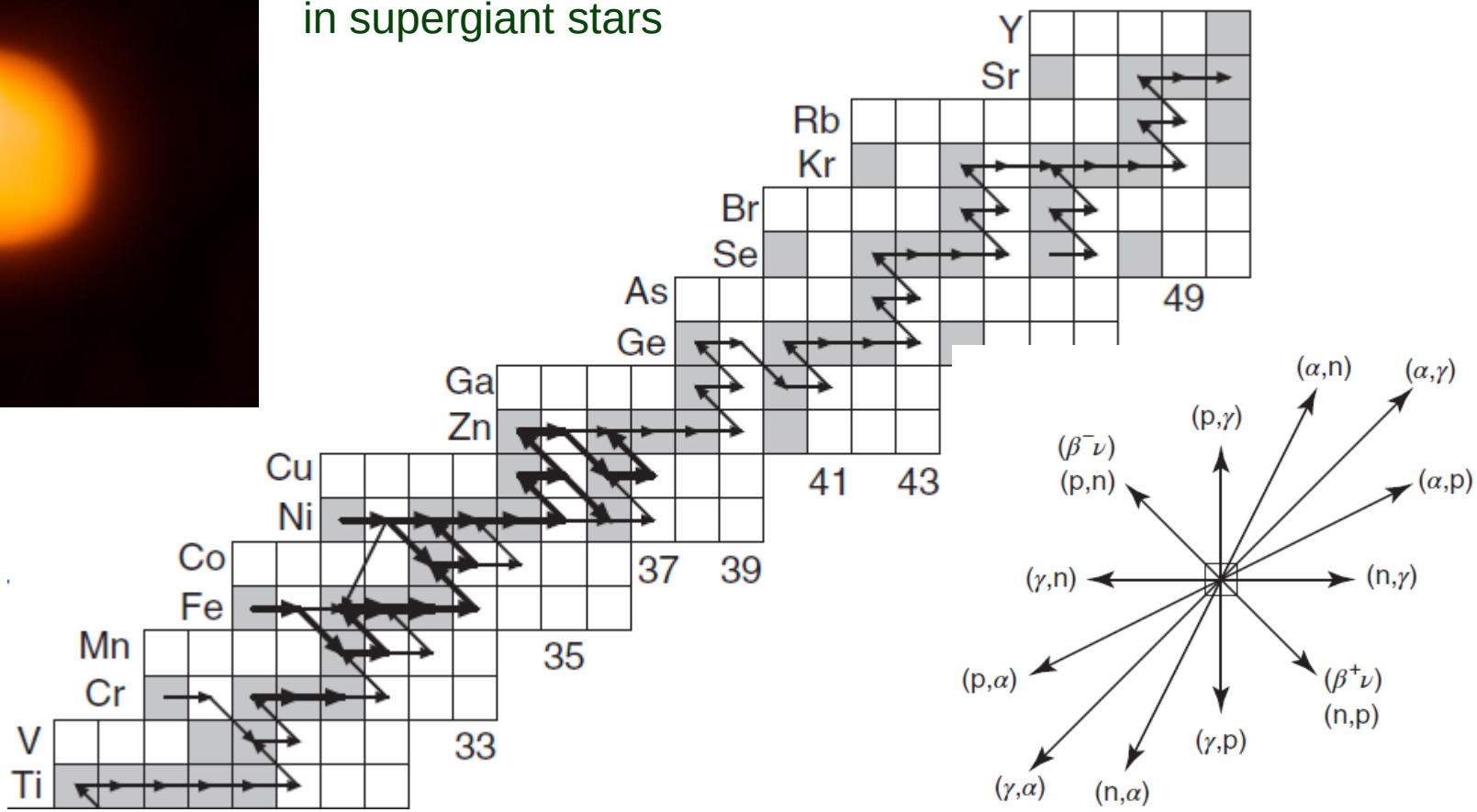
Nuclear Physics of Stars, Iliadis, 2nd Ed.
Iliadis *et al.*, Nucl. Phys. A533, 153 (1991)

Example: $^{22}Ne(\alpha,n)^{25}Mg$ reaction



Betelgeuse

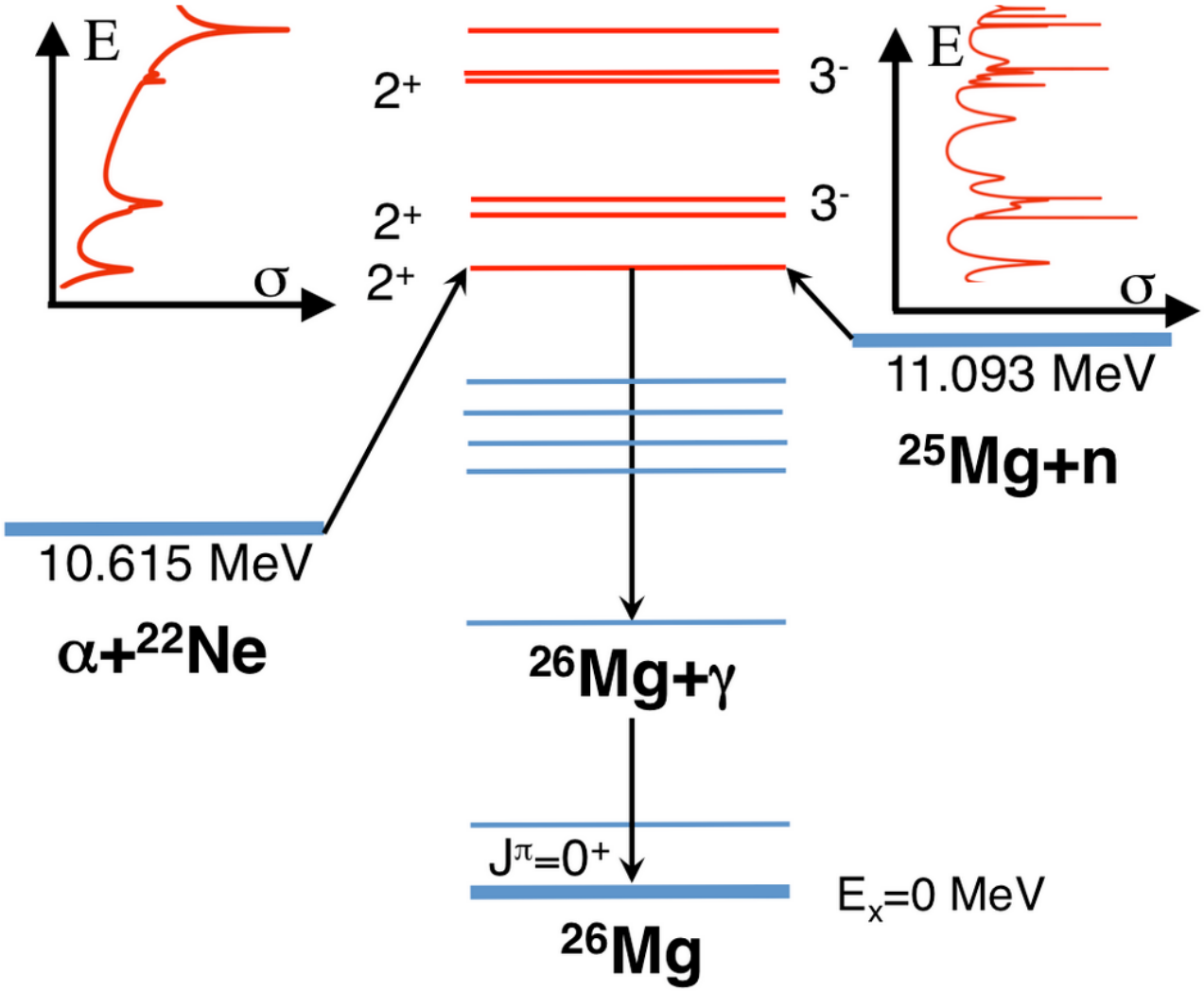
Weak s-process occurs in supergiant stars



The $^{22}Ne(\alpha,n)^{25}Mg$ reaction is one of two major sources of neutrons for the slow neutron capture (s) process that produces half of the heavy elements

Nuclear Physics of Stars, Iliadis, 2nd Ed.
astronomynow.com

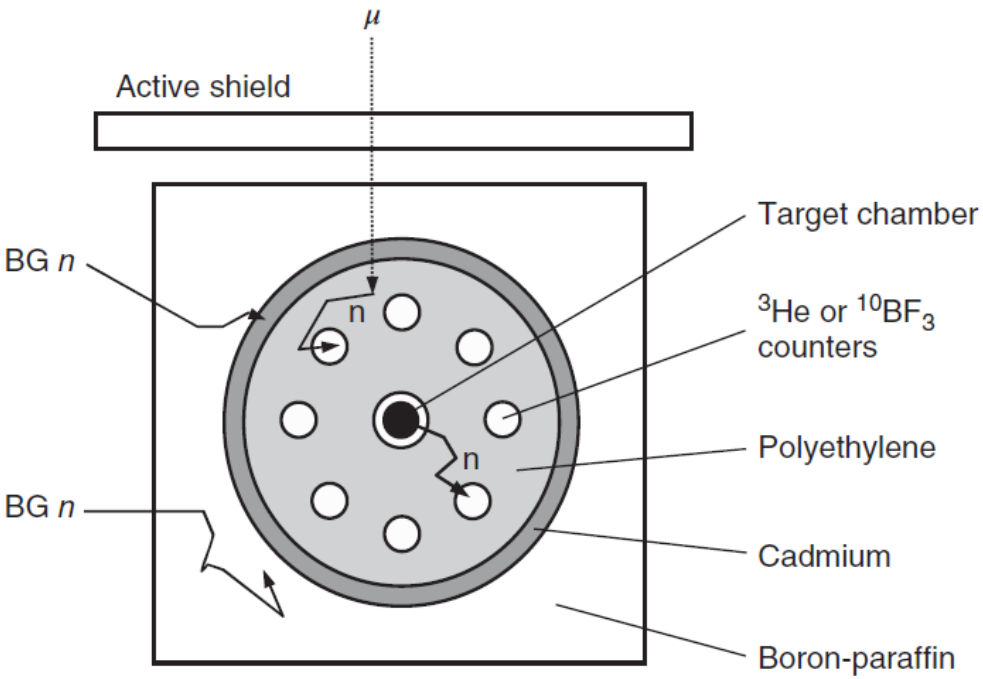
^{22}Ne + α competition



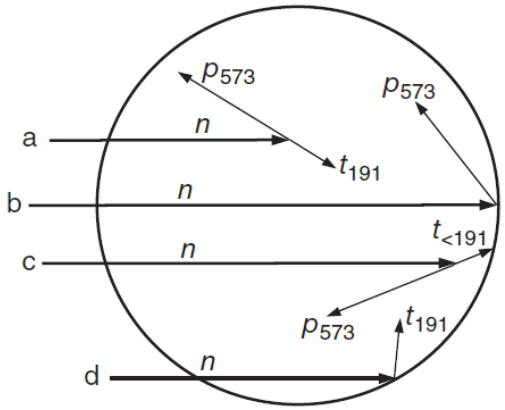
Massimi *et al.*, Phys.Lett. B768 (2017)

$^{22}Ne(\alpha,n)^{25}Mg$ reaction experiment

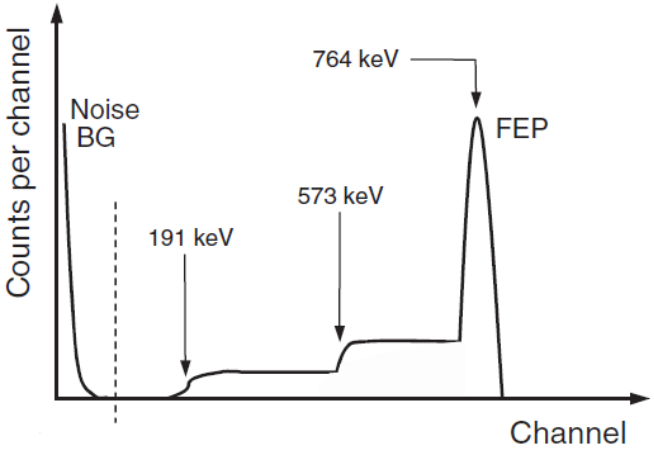
Generic setup



Inside ^{3}He counter: mechanism



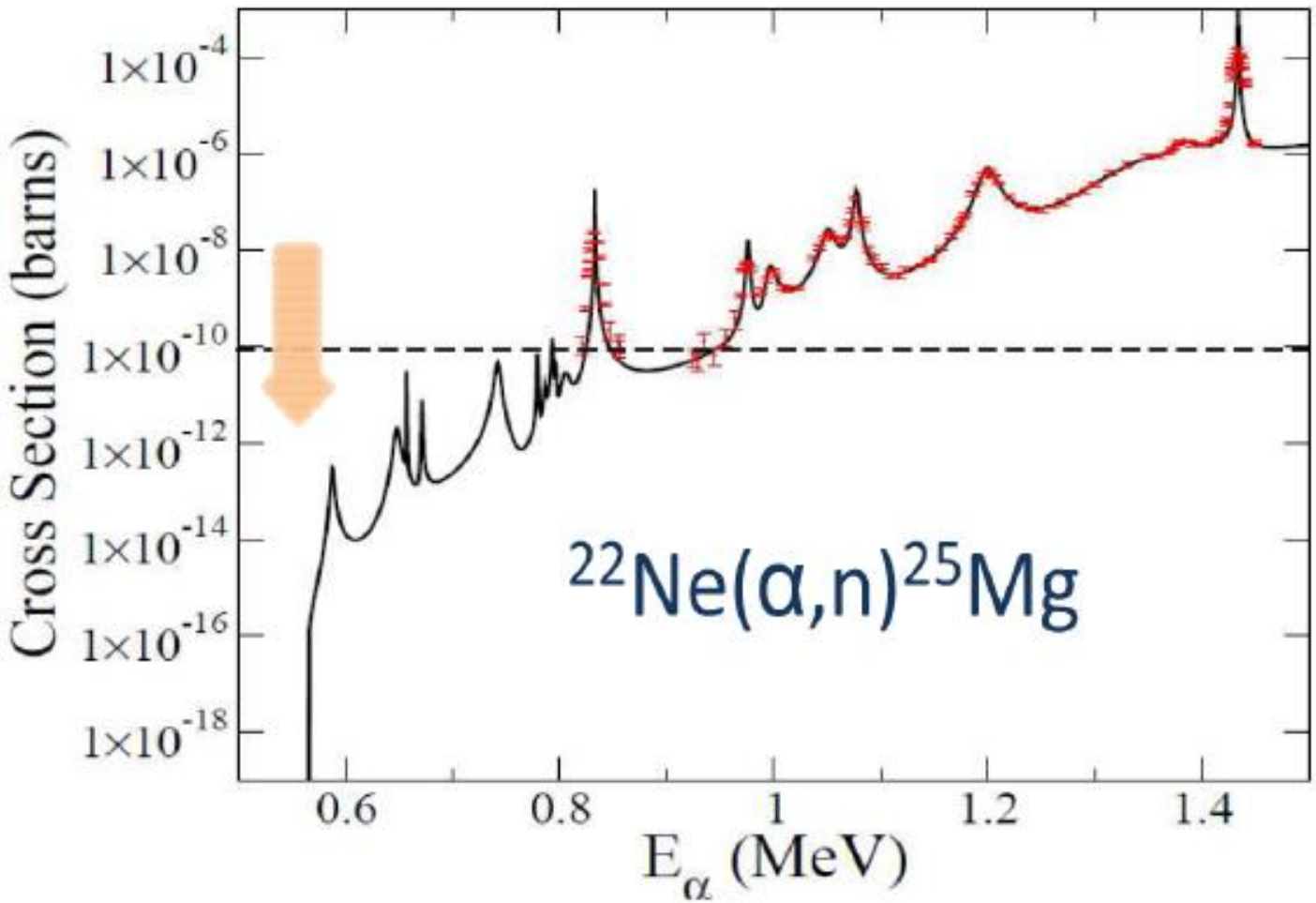
^{3}He counter: spectrum



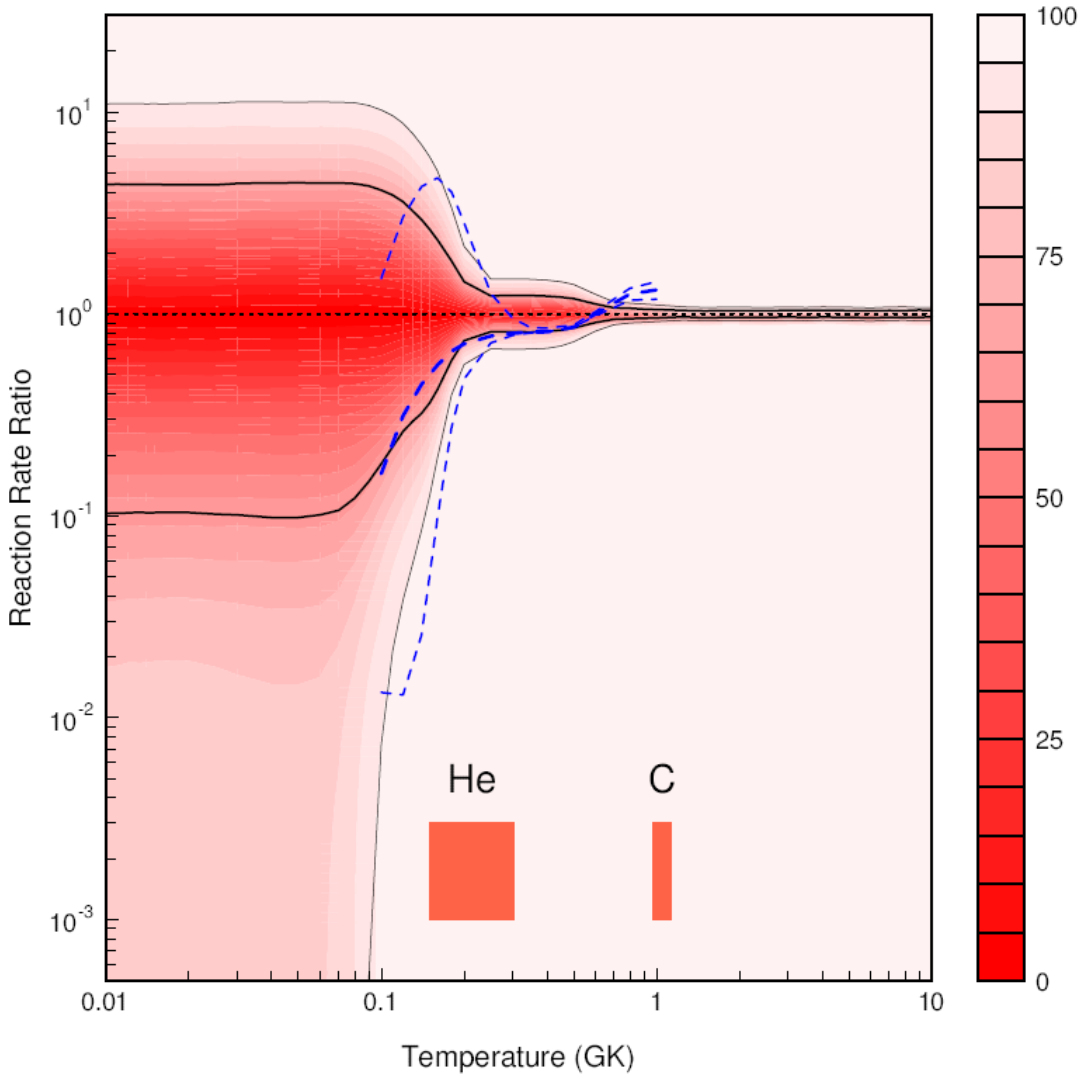
Measured using similar techniques at many facilities.

Nuclear Physics of Stars, Iliadis, 2nd Ed.
Eg. M. Jaeger et al., PRL 87, 202501 (2001)

Result: $^{22}Ne(\alpha,n)^{25}Mg$ cross section



$^{22}Ne(\alpha,n)^{25}Mg$ reaction rate uncertainties



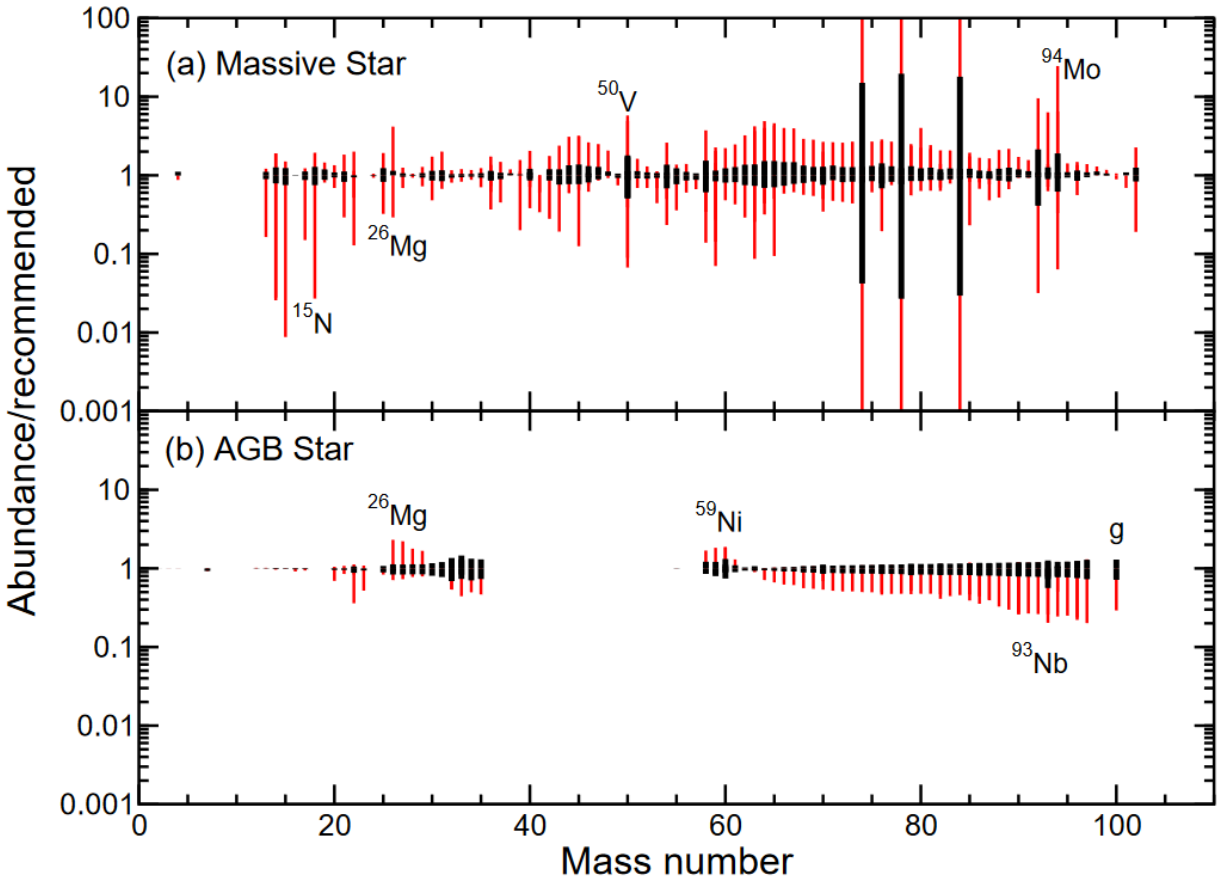
Monte Carlo method employed to sample probability densities of all input parameters

He: helium burning

C: carbon shell burning

Longland *et al*. (2012)

s process yield uncertainties



Red: previous

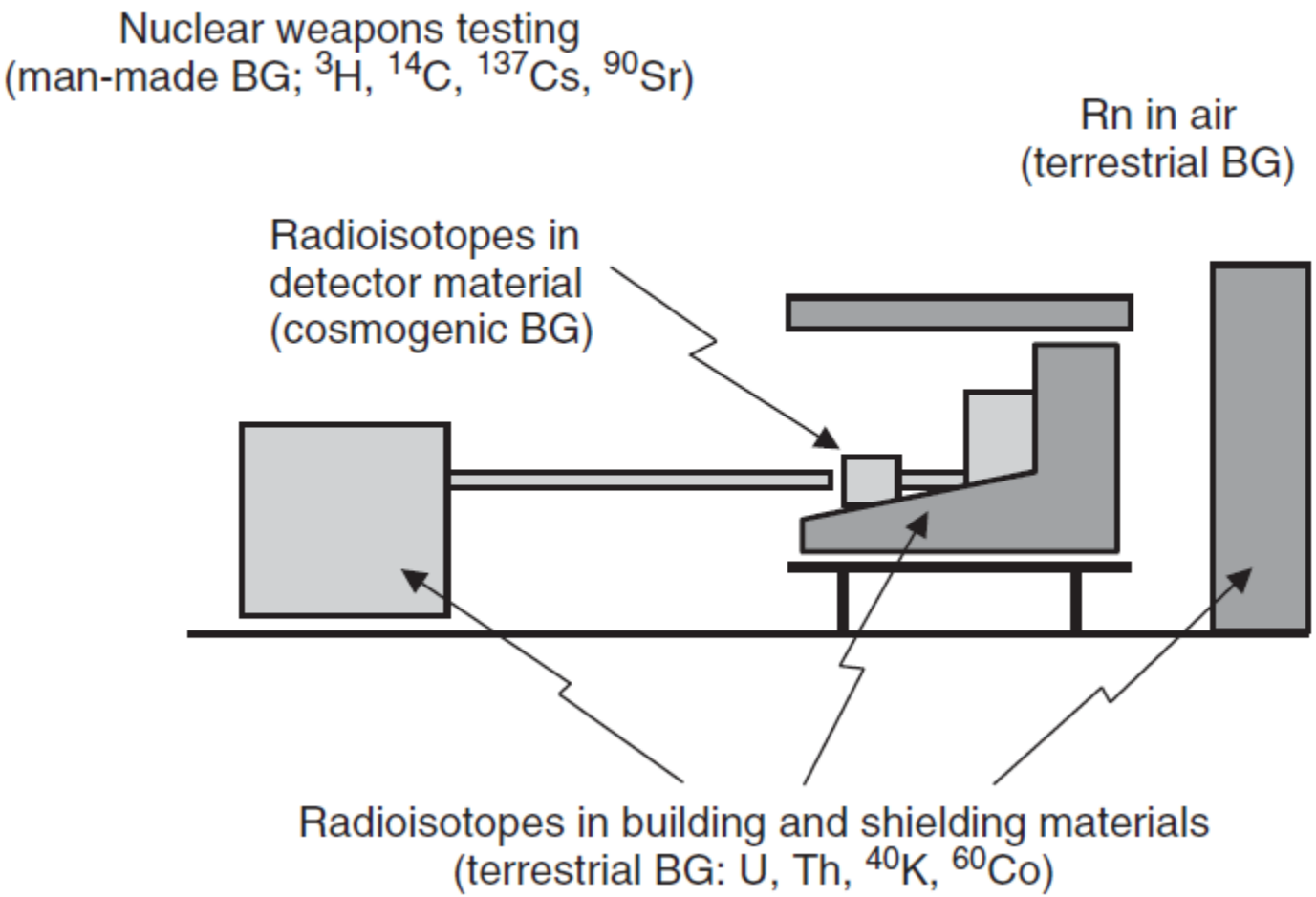
Black: present

Conclusion: still need to improve ^{22}Ne + α reaction rates

Note: calculated *s*-process yields subtracted from solar abundances to determine r-process abundances

Longland *et al*. (2012)

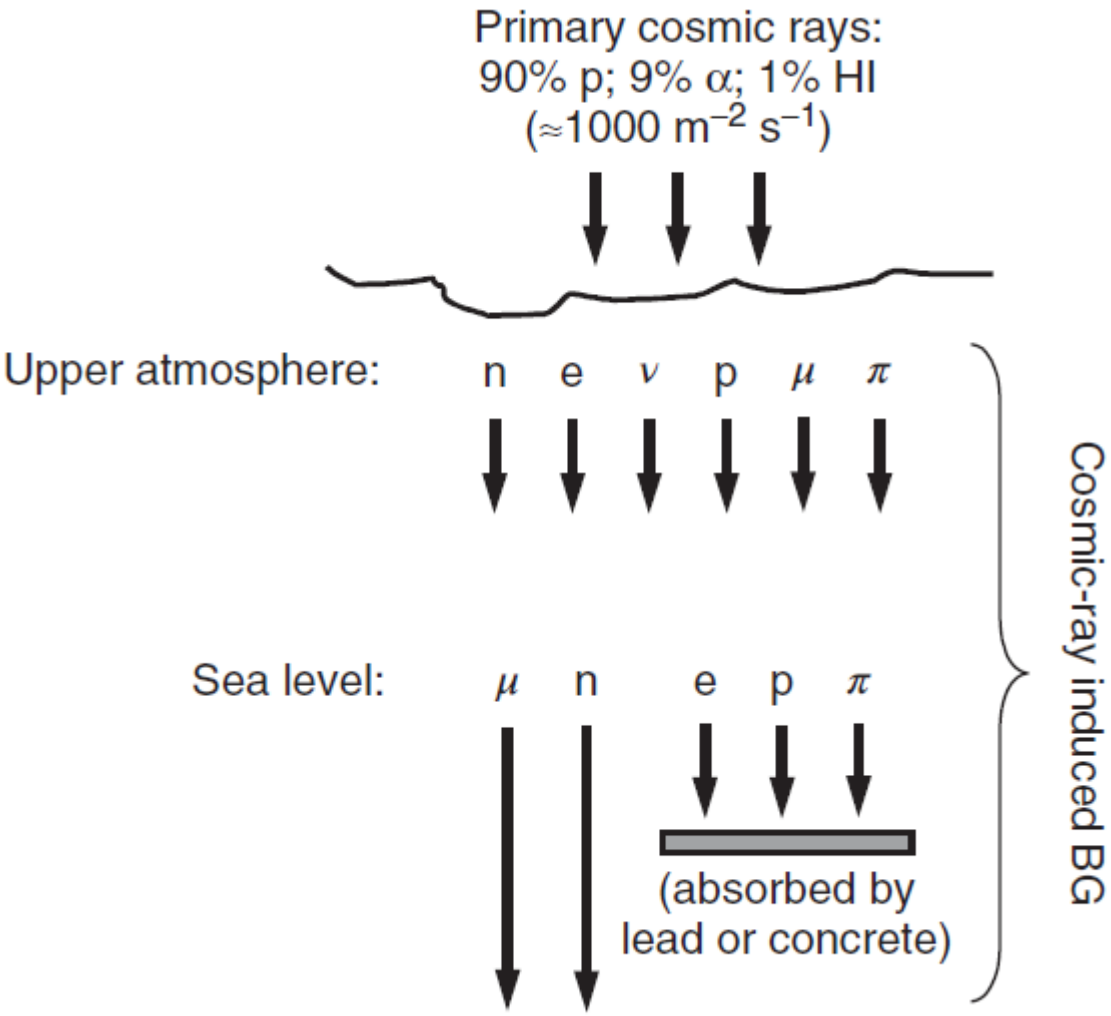
Room-background radioactivity



Charged-particle nuclear cross sections are low at astrophysical energies, so background levels can determine the sensitivity of an experiment: need to mitigate them!

Nuclear Physics of Stars, Iliadis, 2nd Ed.

Cosmic-ray backgrounds

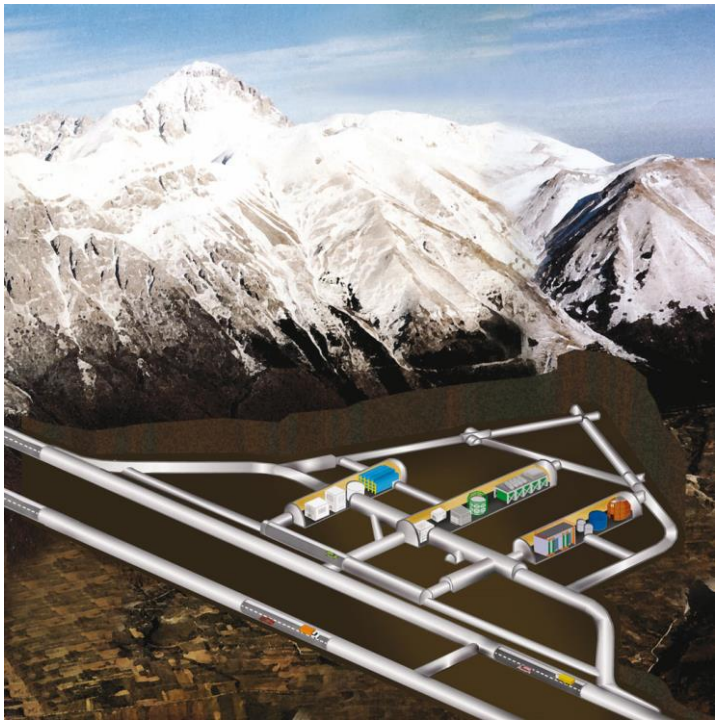


Nuclear Physics of Stars, Iliadis, 2nd Ed.

Passive background shielding

- Use material to block radiation from interacting with the detectors

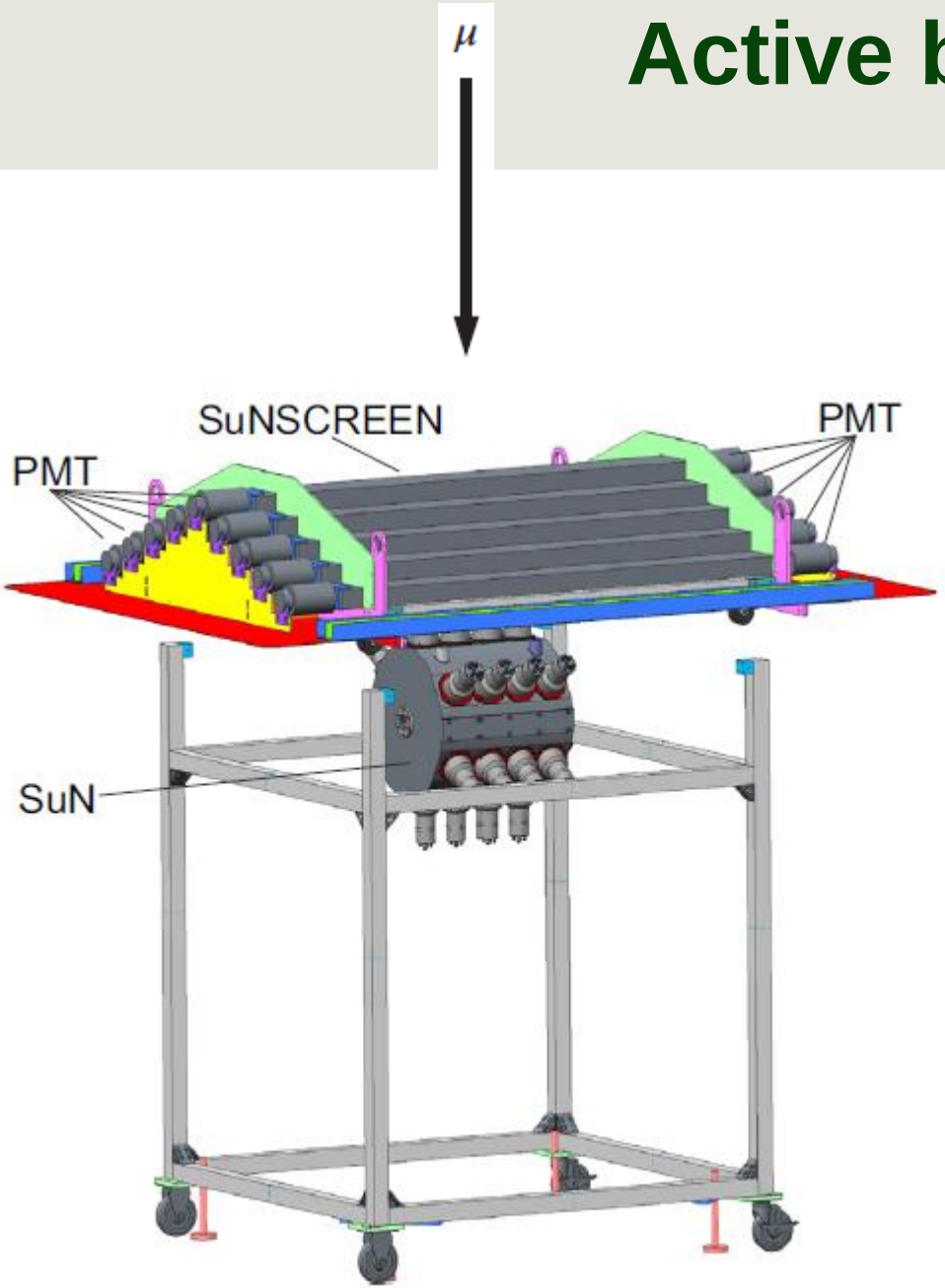
High-*Z* material (eg. Pb) to block gamma rays



Large overburden of Earth to block cosmic-ray muons

+Moderator for neutrons (eg. polyethylene) with component to capture thermal neutrons (^{10}B, ^{6}Li, Cd)

Active background shielding

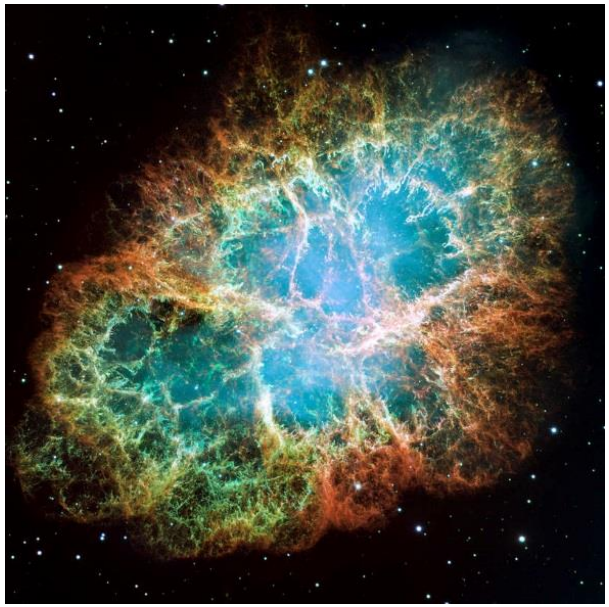


- Surround detector with a material like plastic scintillator
- Use anti-coincidence condition to veto events that were likely from cosmic rays
- Eg. SuNSCREEN at NSCL (left) to veto cosmic-ray muons

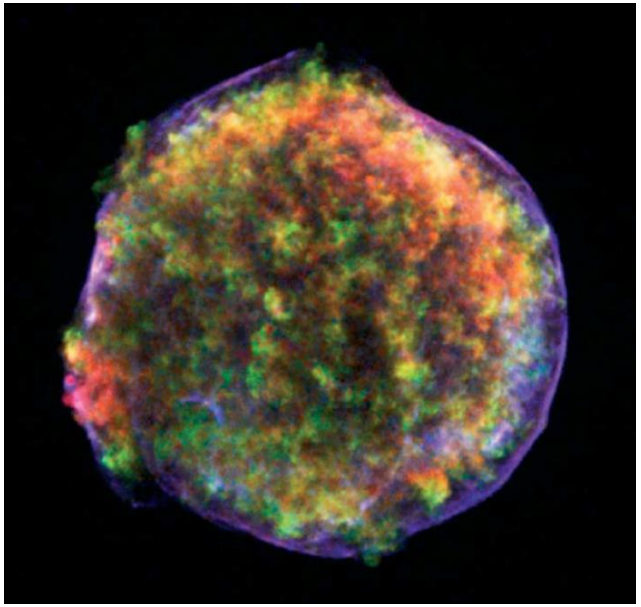
E. Klopfer et al., NIMA 788, 5 (2015)

Rare Isotope Beams (RIBs)

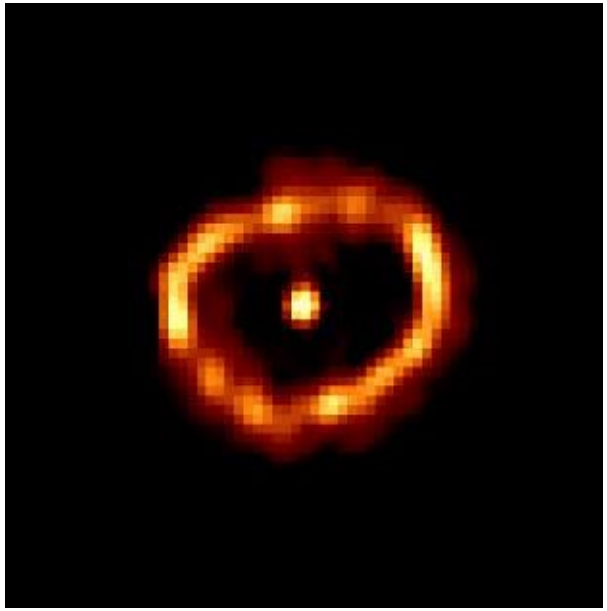
Core-collapse supernovae



Thermonuclear supernovae



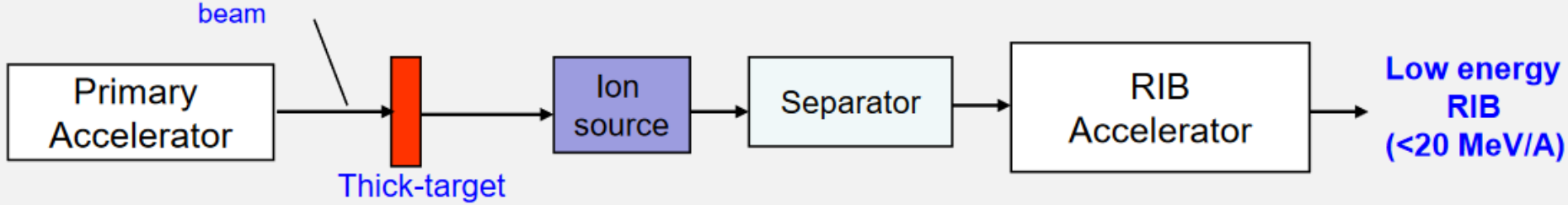
Classical novae



- Stars (especially exploding stars) produce radioactive nuclides that undergo reactions
- Can't make a target for p and α induced reactions out of short-lived radioactive nuclides
- Instead, use *inverse kinematics*: bombard H or He target with RIB
- Need high-quality, high-intensity, low-energy RIB

Methods for RIB production

Isotope Separator On Line (ISOL) method

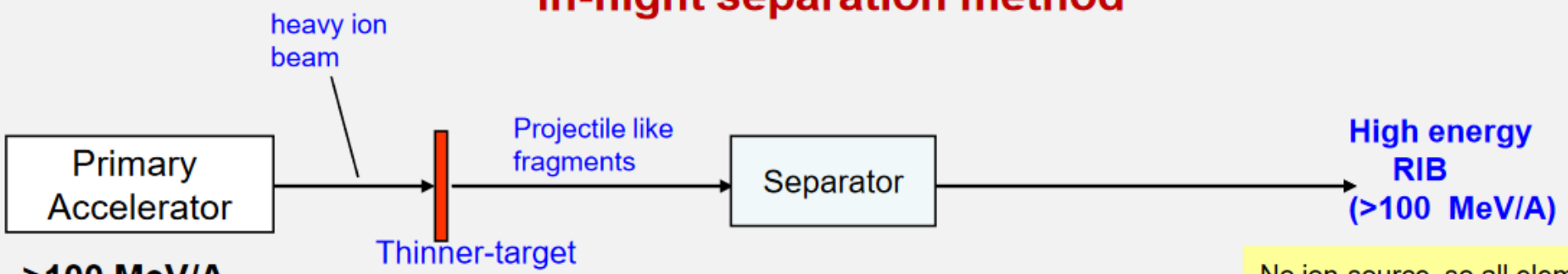


CN/Spallation/fission/ fragmentation of target nuclei

Online : primary accelerator & RIB accelerator operate simultaneously

High beam purity, quality , But element dependent intensity, $T_{1/2}$ limit ≥ 1sec

In-flight separation method

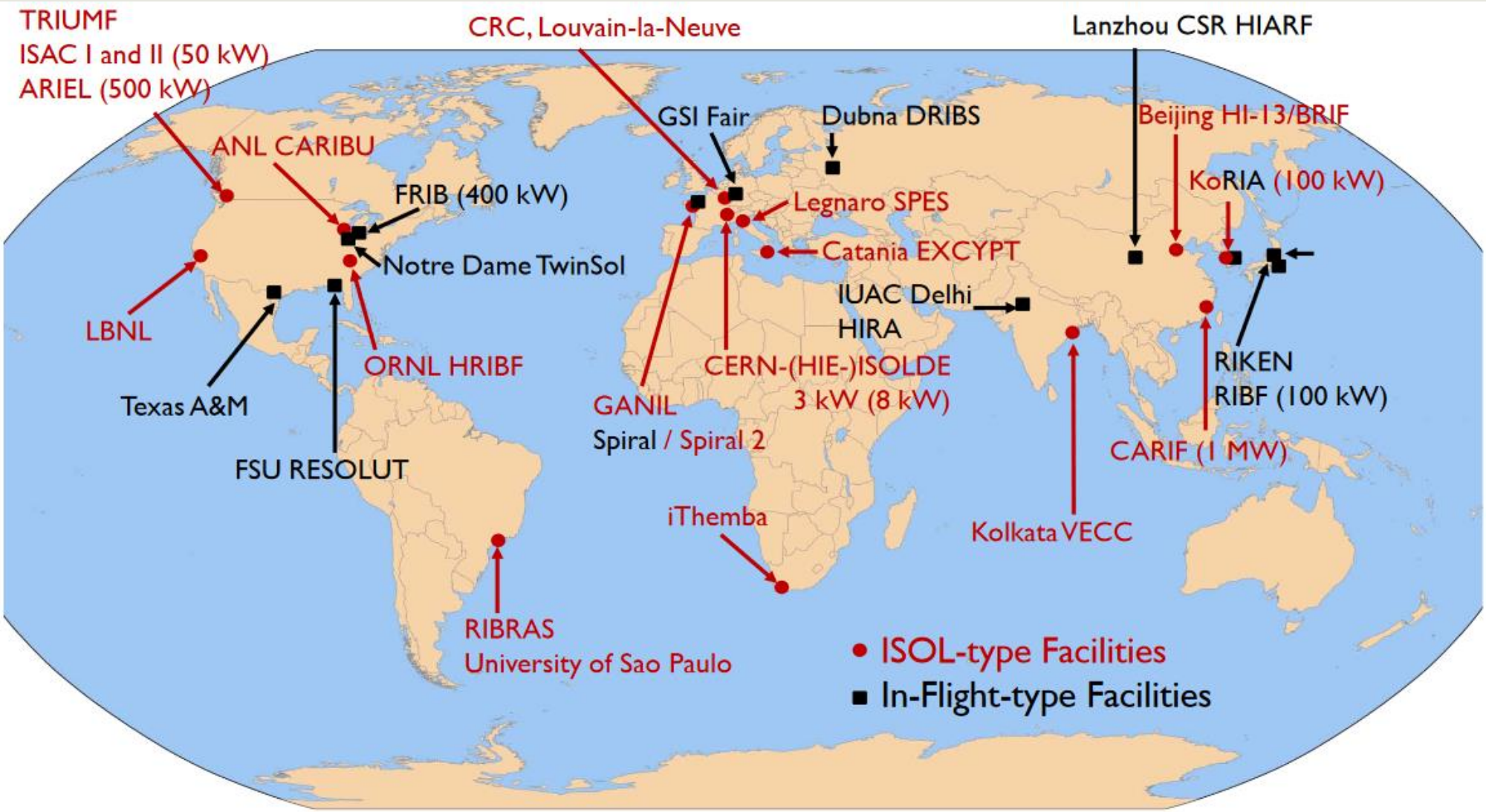


Fragmentation of beam nuclei

Isotones cannot be separated; rejection of primary beam a challenge

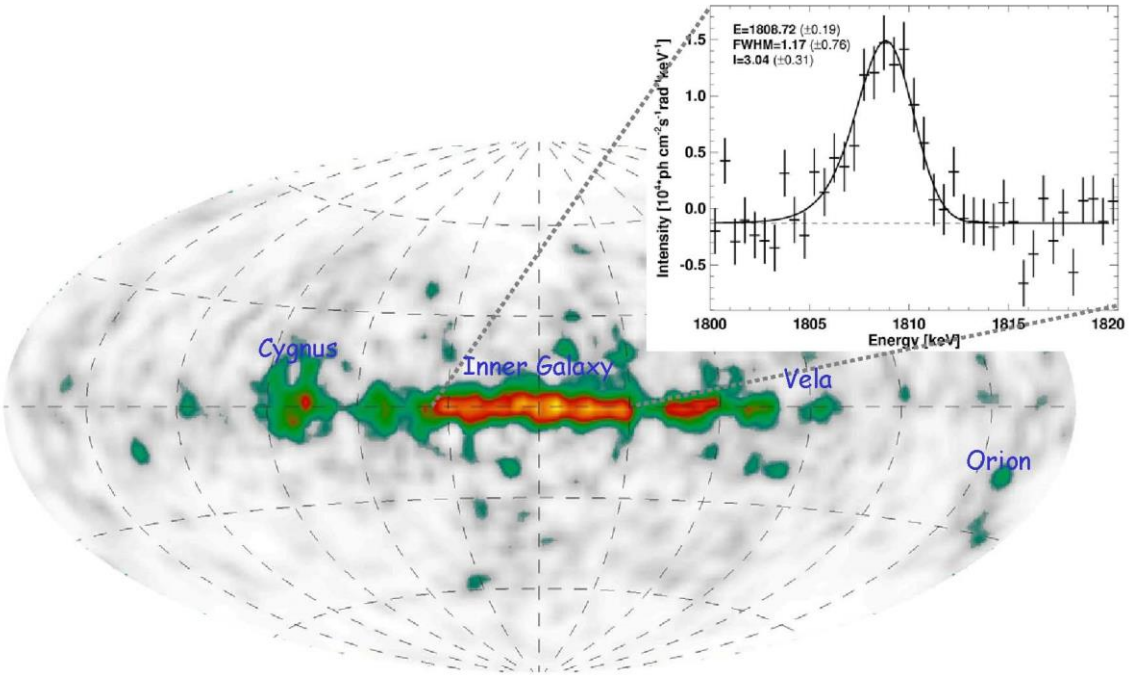
No ion-source, so all elements transported, no half-life limit But lower beam purity, quality

RIB facilities worldwide

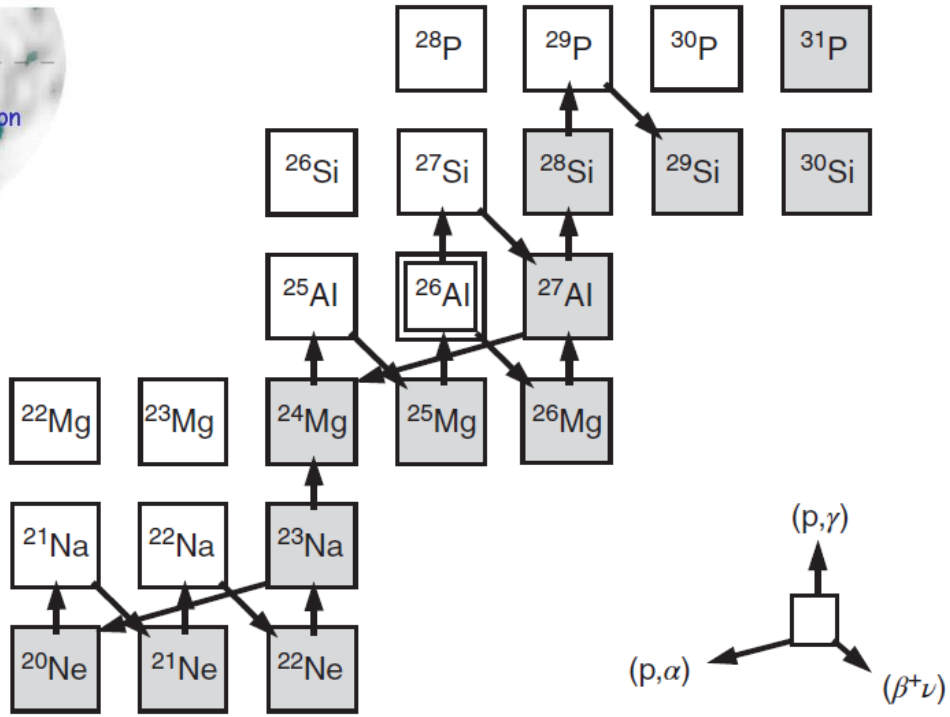


Source: Introduction to ISOL Target Stations, Alexander Gottberg, Bill Paley, June 22, 2015

Example: $^{26}Al(p,\gamma)^{27}Si$ reaction



Hydrogen-burning

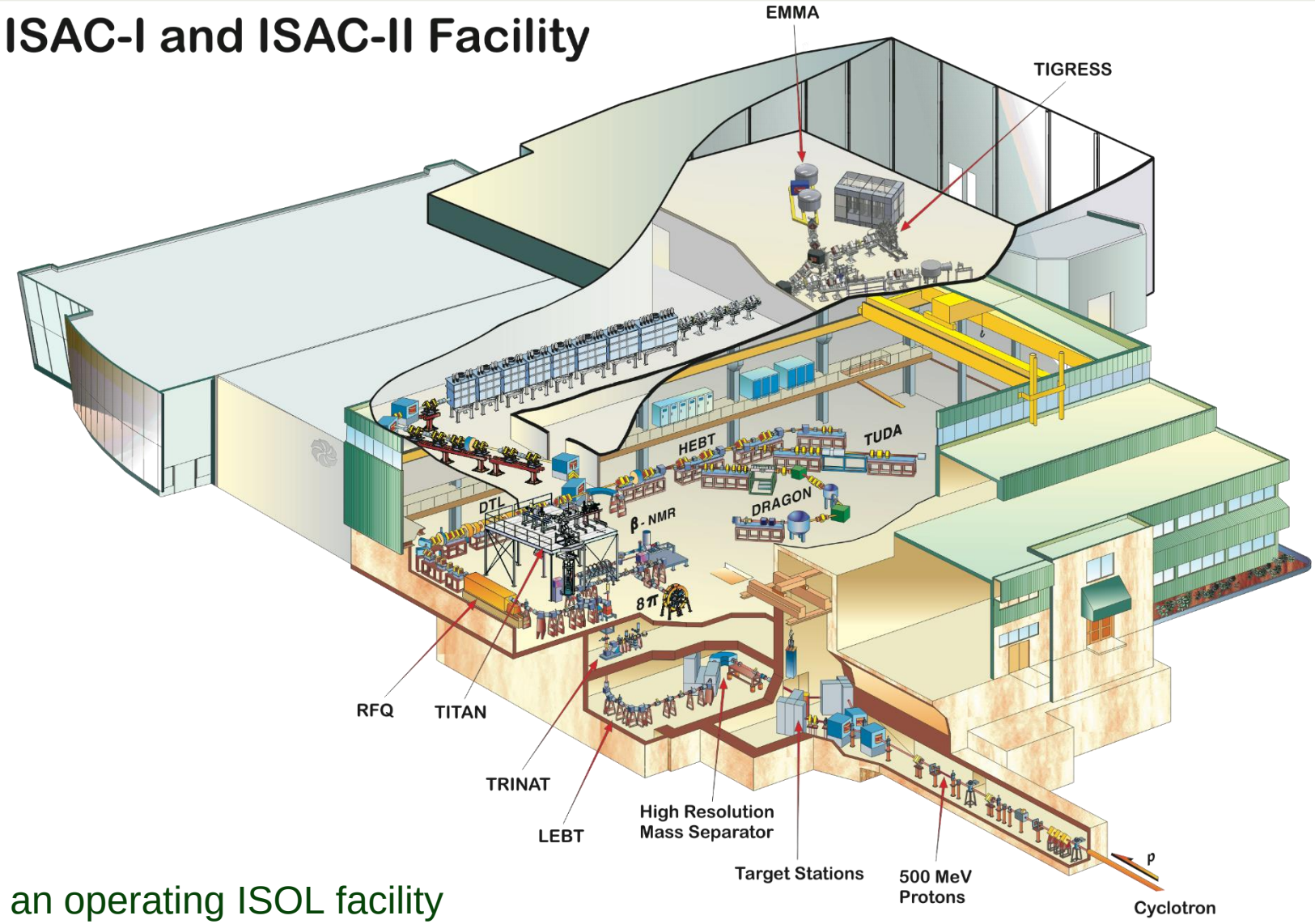


How are the 2 solar masses of ^{26}Al ($\tau \sim 1$ Myr) radioactivity observed across the Milky Way produced?

The reaction $^{26}Al(p,\gamma)^{27}Si$ destroys ^{26}Al in stars: need to know the rate.

Nuclear Physics of Stars, Iliadis, 2nd Ed.

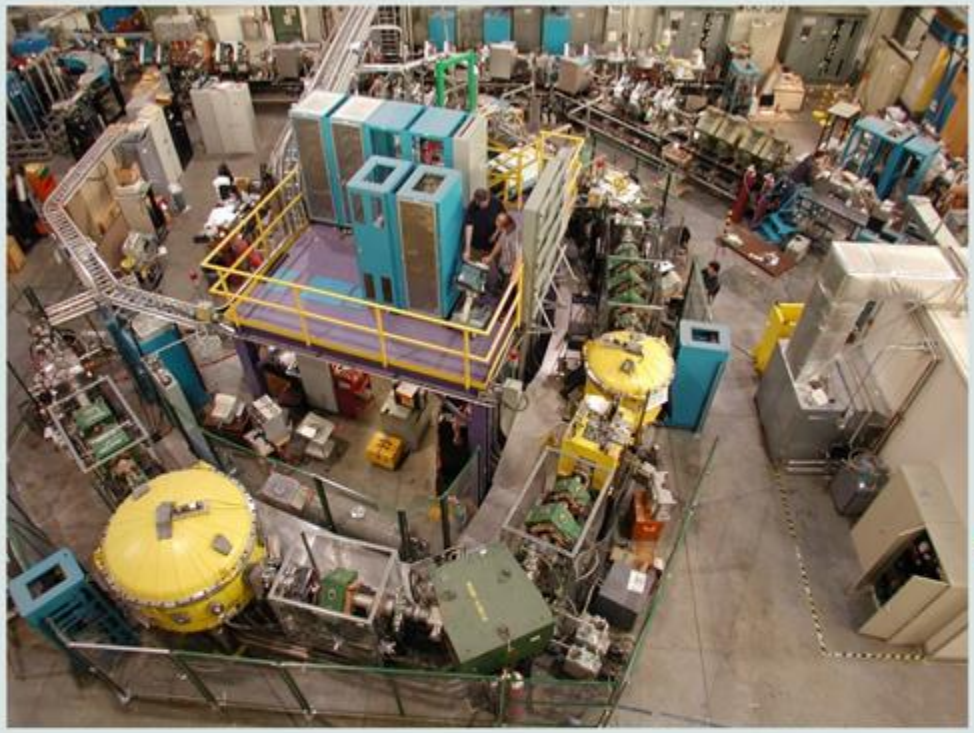
TRIUMF-ISAC in Vancouver, Canada

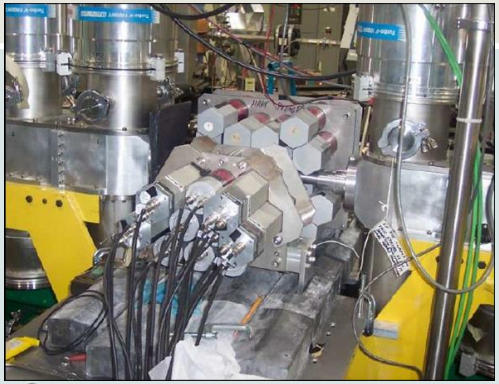


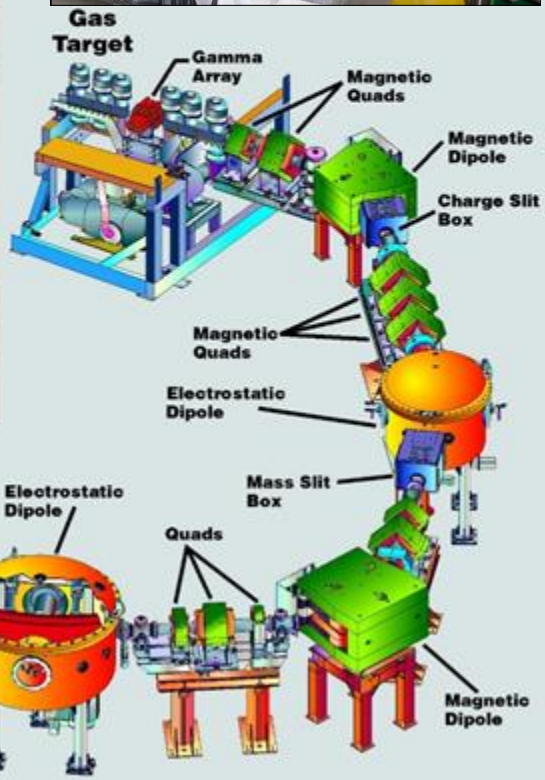
ISAC is an operating ISOL facility

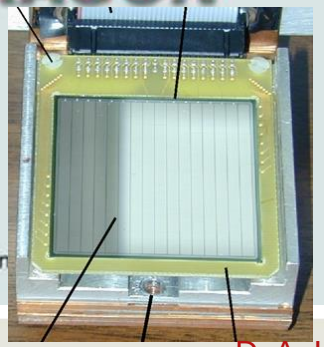
DRAGON at TRIUMF-ISAC

DRAGON: Detector of Recoils and Gammas of Nuclear Reactions









DRAGON

TRIUMF
Vancouver, Can

D. A. Hutcheon *et al.*, NIM A498, 190 (2003)

RIB from ISAC facility hits H gas target inducing (p,γ) reaction.

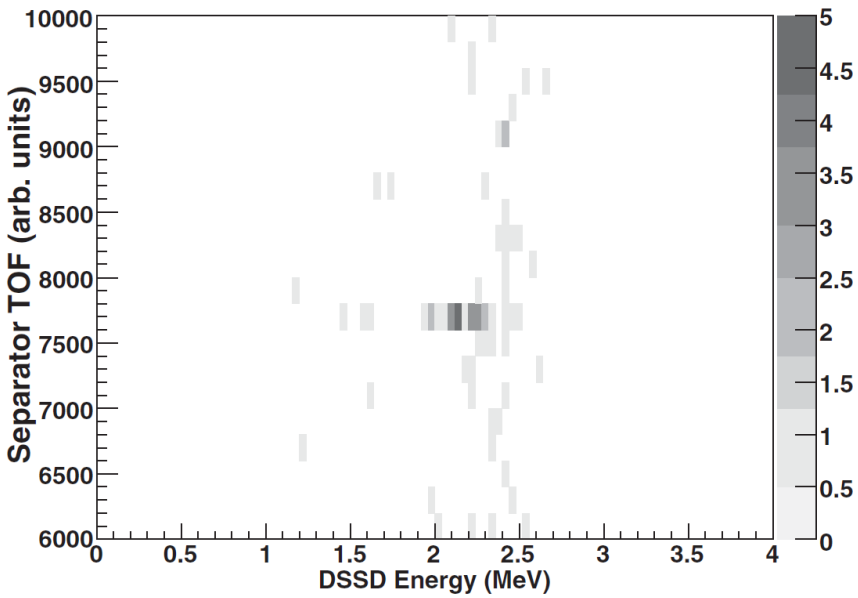
Detect γ-rays at target position.

Separate reaction products from beam with electromagnetic separator.

Detect reaction products at the end of the separator.

Example: $^{26}Al(p,\gamma)^{27}Si$ with DRAGON

Energy of recoils combined with time-of-flight through separator used to distinguish reaction products from "leaky" beam at E_{cm} = 0.184 MeV resonance.



$$Y(\infty) = \frac{\lambda^2}{2}\frac{M+m}{m}\epsilon^{-1}\omega\gamma$$

Y = yield (# reactions per ion)

λ = proton deBroglie wavelength

M, m = masses of reactants

ε = stopping power

$\omega\gamma$ = resonance strength

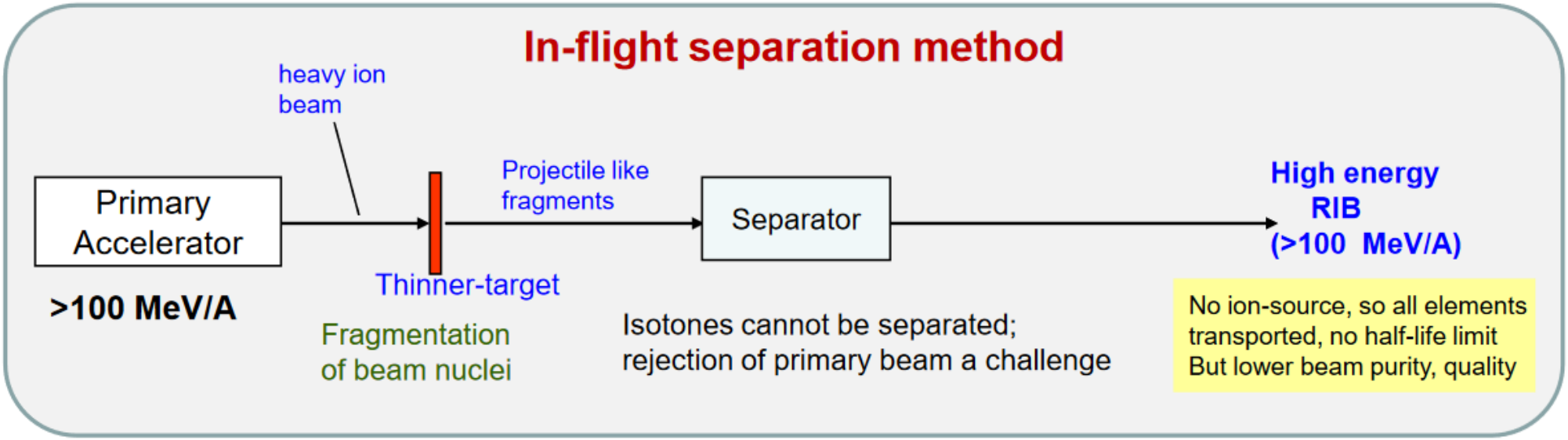
C. Ruiz *et al*., Phys Rev. Lett. 96, 252501 (2006)

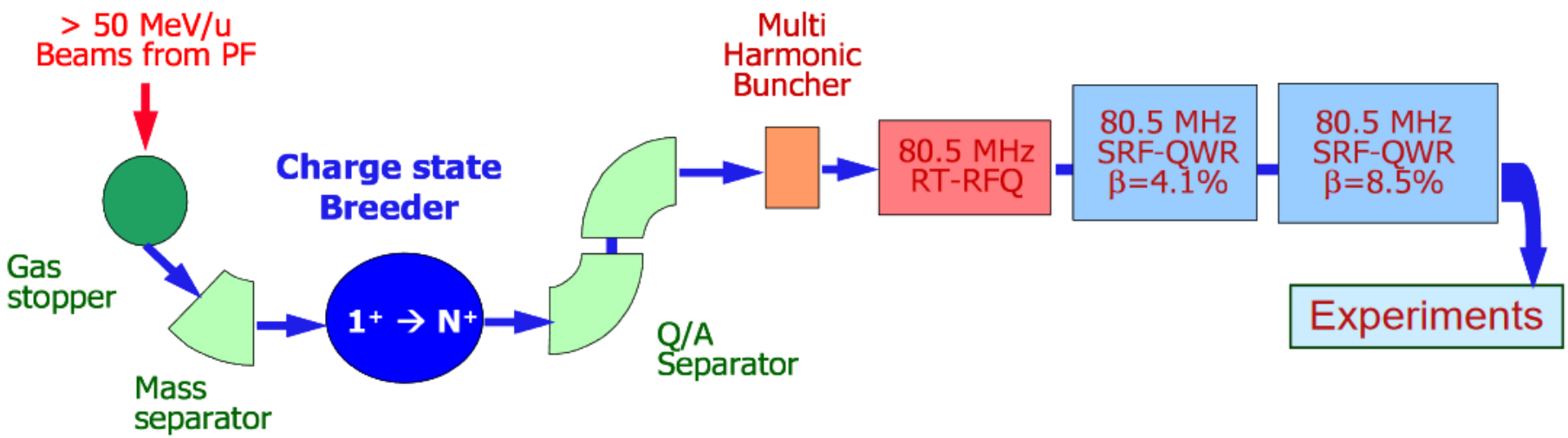
NSCL/FRIB

National user facility for rare isotope science and education:
Nuclear structure, nuclear astrophysics, fundamental symmetries, societal applications

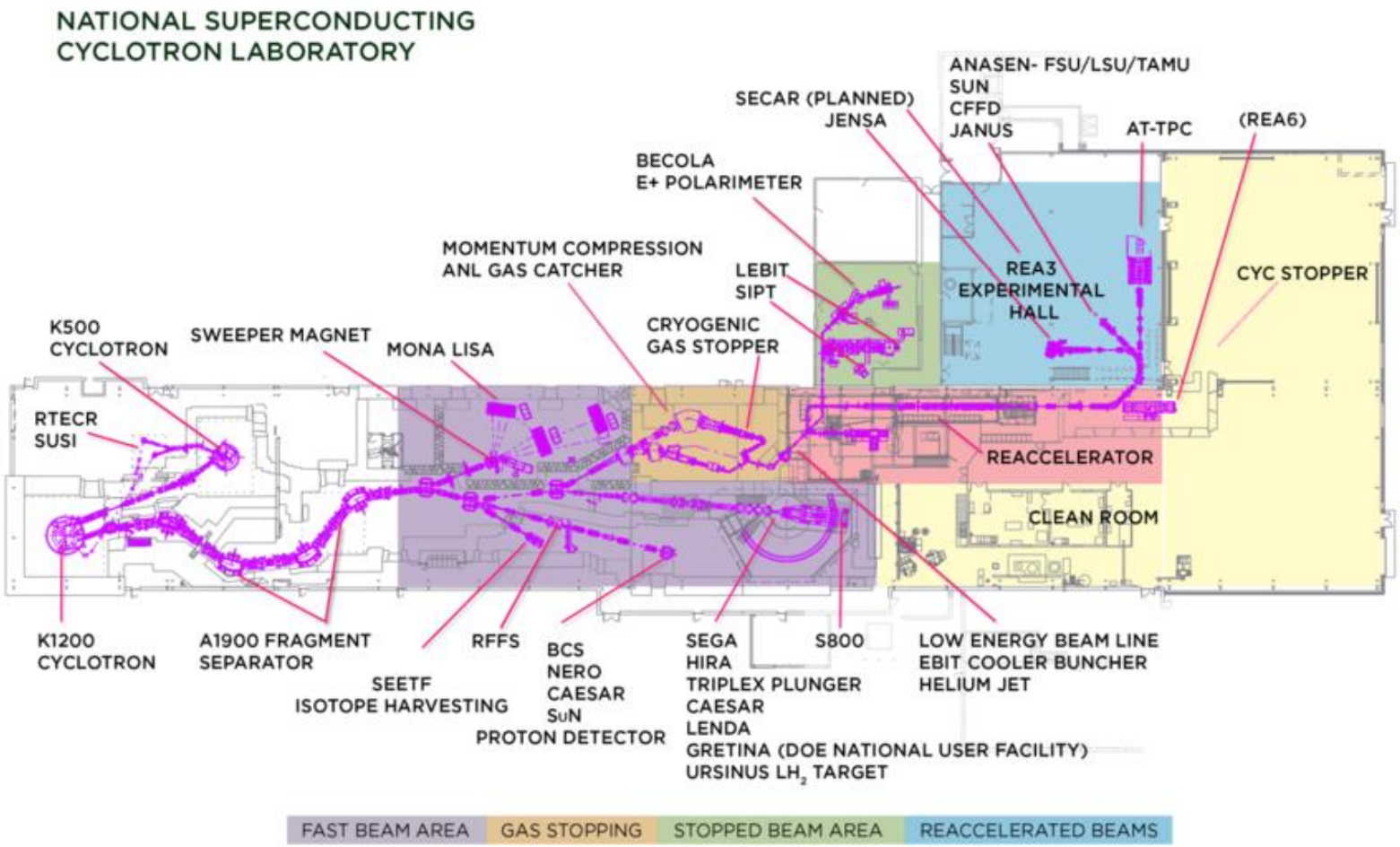
On Michigan State University campus

NSCL/FRIB Re-accelerator (ReA3)





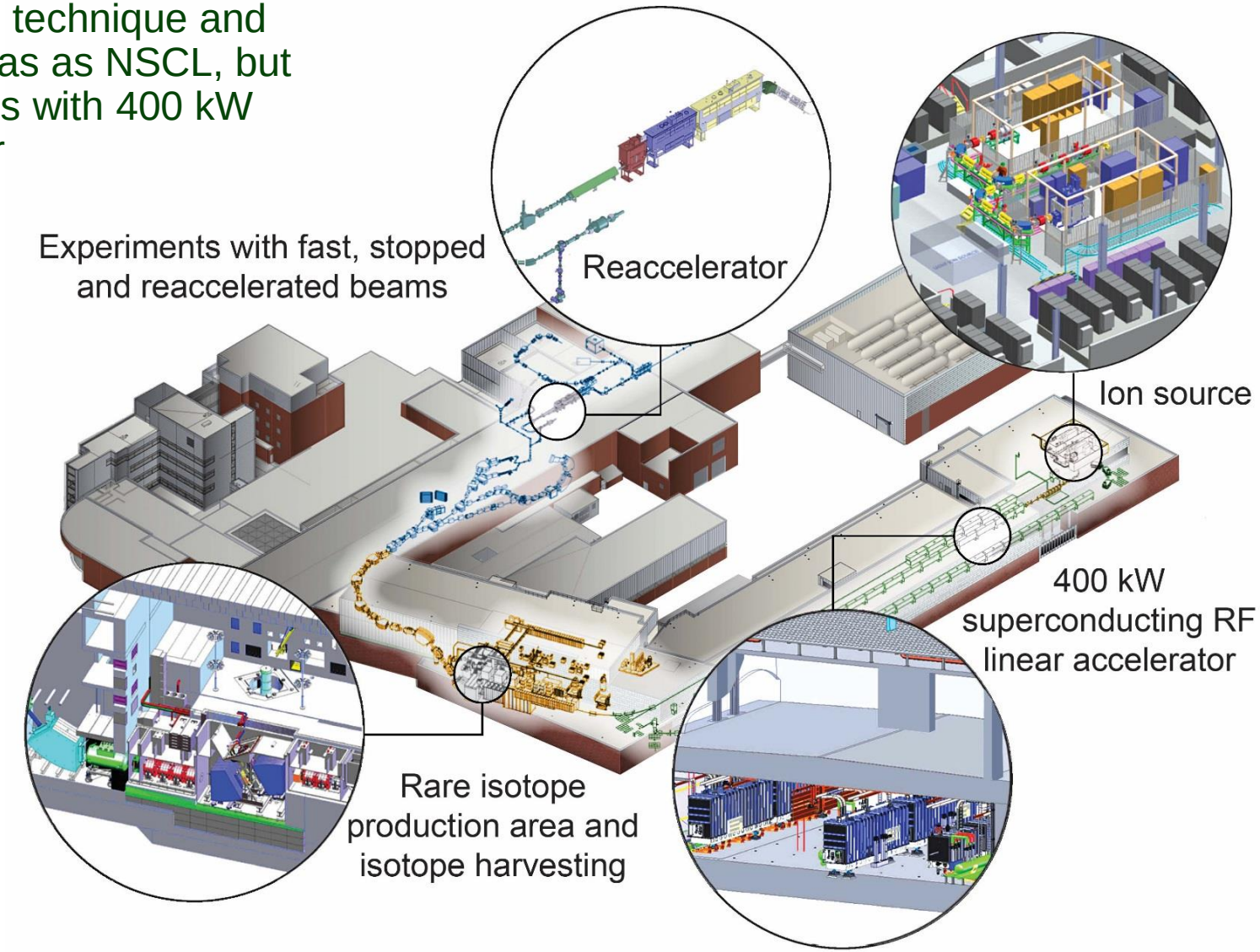
RIBs from nuclear fragmentation at NSCL



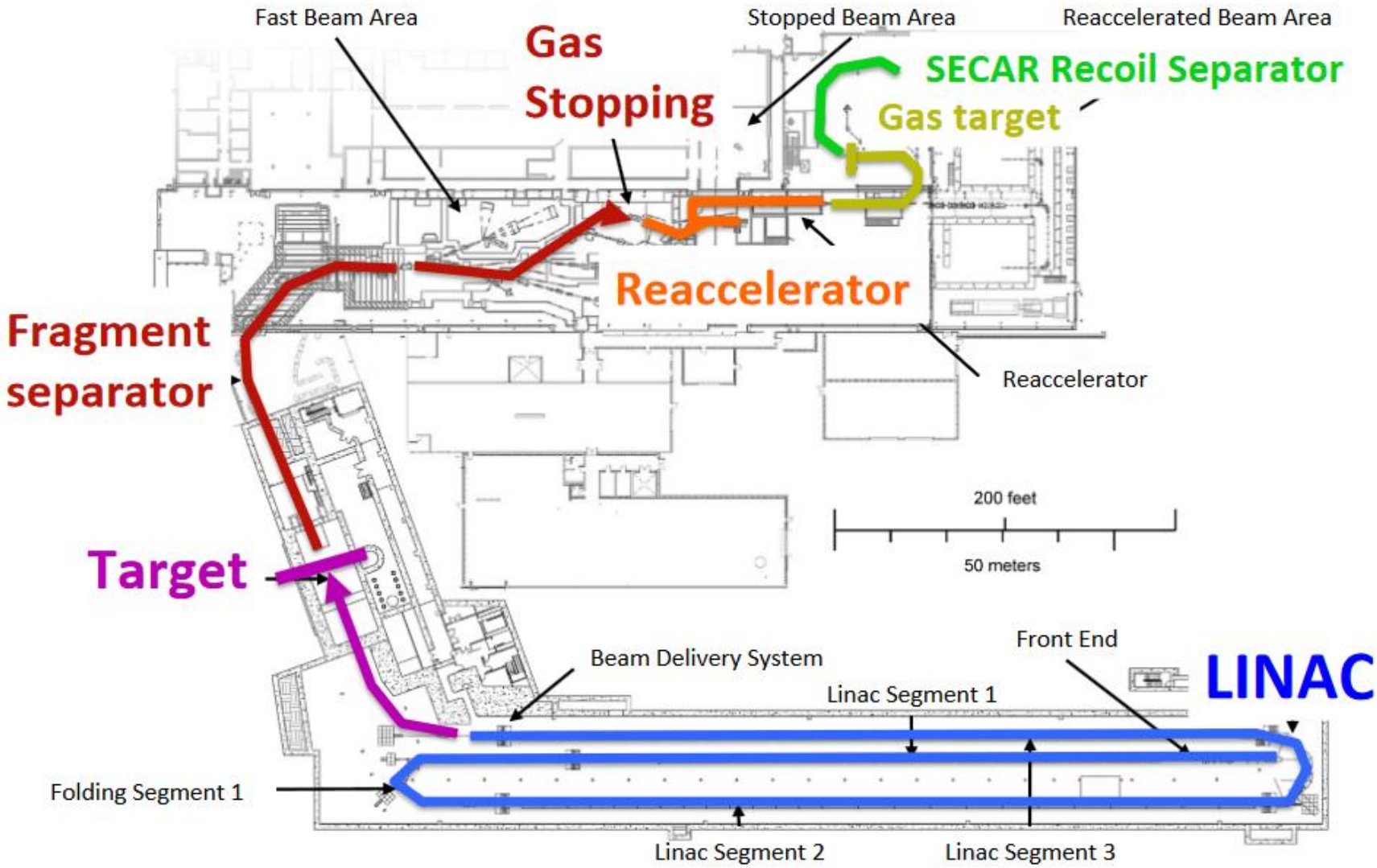
Accelerate heavy ion beam with cyclotrons and bombard thin, light, target. Reaction products fly forward, are separated in flight, and delivered to experiments directly (fast beam), thermalized (stopped beam), or reaccelerated (ISOL-like beam)

RIBs from FRIB

Same production technique and experimental areas as NSCL, but replace cyclotrons with 400 kW linear accelerator

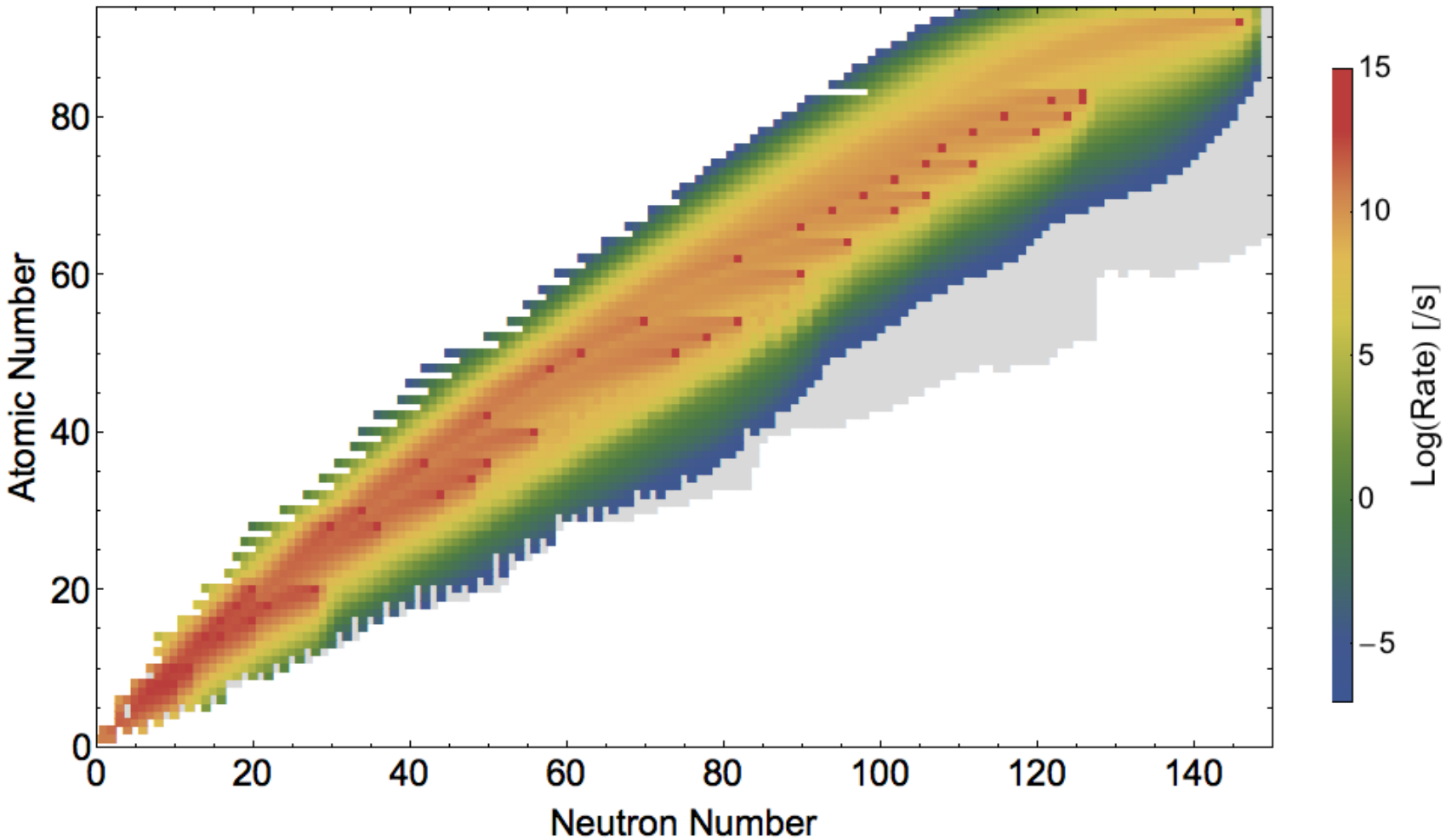


RIB production: fragmentation (FRIB)



Scientific Reach of FRIB – Rare Isotope Beam Rates

FRIB at full power will deliver 1000x the rare isotope quantities as NSCL by ~2025



FRIB

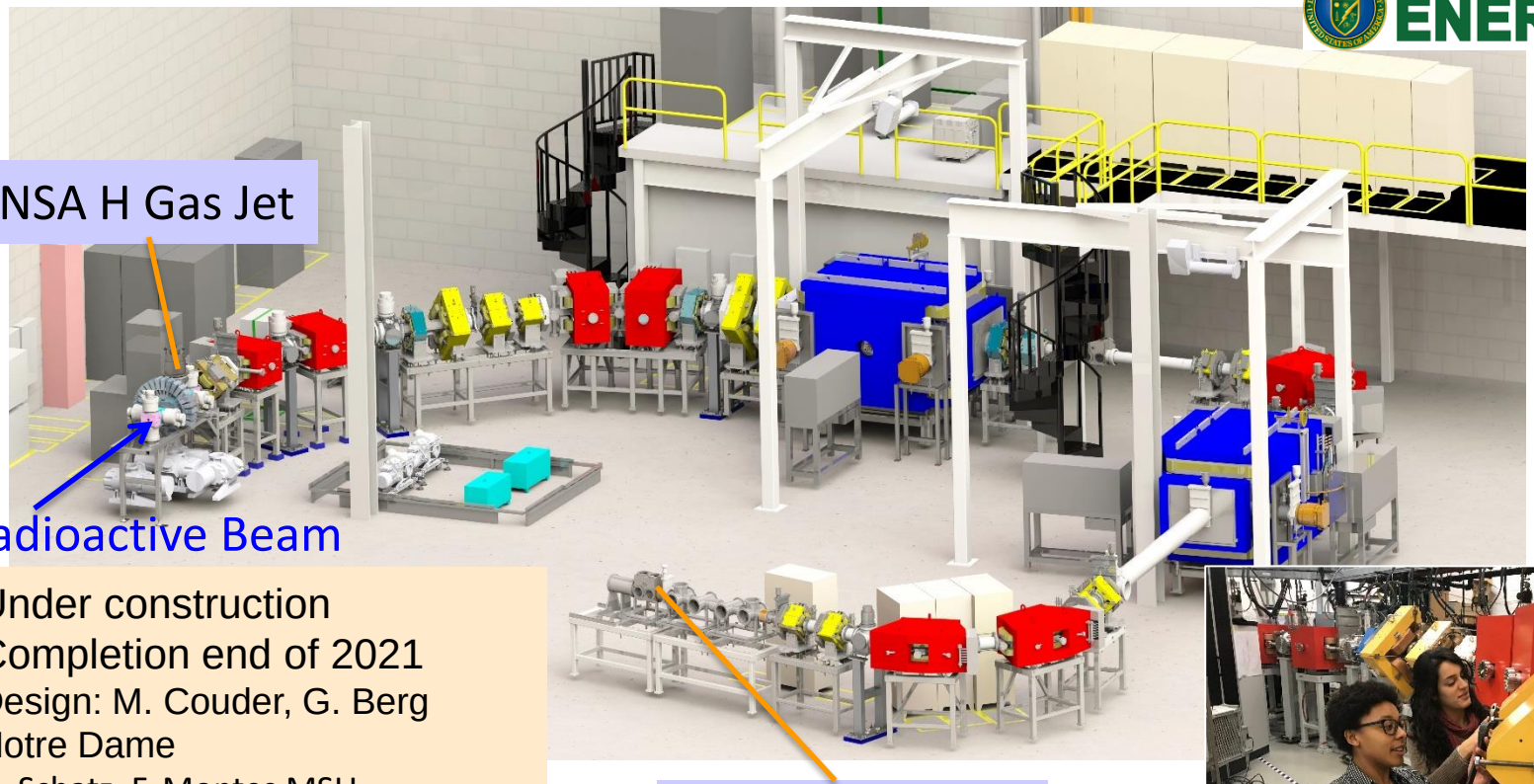
Civil construction complete

Technical construction and concurrent commissioning underway

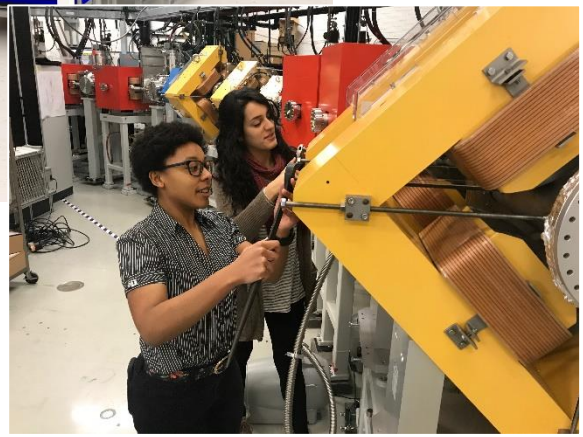
First RIB delivery to users in 2022 (possibly as early as 2021)

SECAR at NSCL/FRIB ReA3

SECAR: Separator for Capture Reactions



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



SECAR performs the same role as DRAGON, but several differences and improvements

Summary

- Charged-particle reactions are strongly suppressed by the Coulomb barrier at astrophysical energies
- Cross sections and resonance strengths for stable species typically measured using light beams and heavy targets, being mindful of backgrounds and often extrapolating to astrophysical energies
- Cross sections and resonance strengths for unstable species typically measured in the laboratory using heavy RIBs, gas targets, and recoil separators
- Next: indirect measurements of charged-particle reactions

Thank you for your attention!