NSCL

Experimental Nuclear Astrophysics: Lecture 1

Chris Wrede

National Nuclear Physics Summer School

June 19th, 2018

MICHIGAN STATE UNIVERSITY

Outline

- **Lecture 1: Introduction & charged-particle reactions**
- Lecture 2: Neutron-capture reactions
- Lecture 3: What I do (indirect methods)

Today

- Stellar evolution
- Thermonuclear reaction rate formalism
- Measurements of charged-particle reaction rates

Foundations of nuclear astrophysics

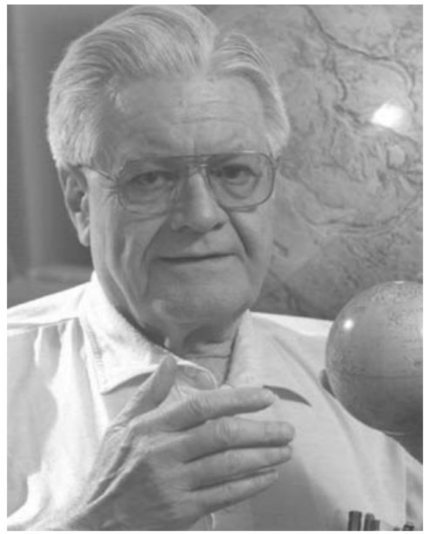
REVIEWS OF

MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

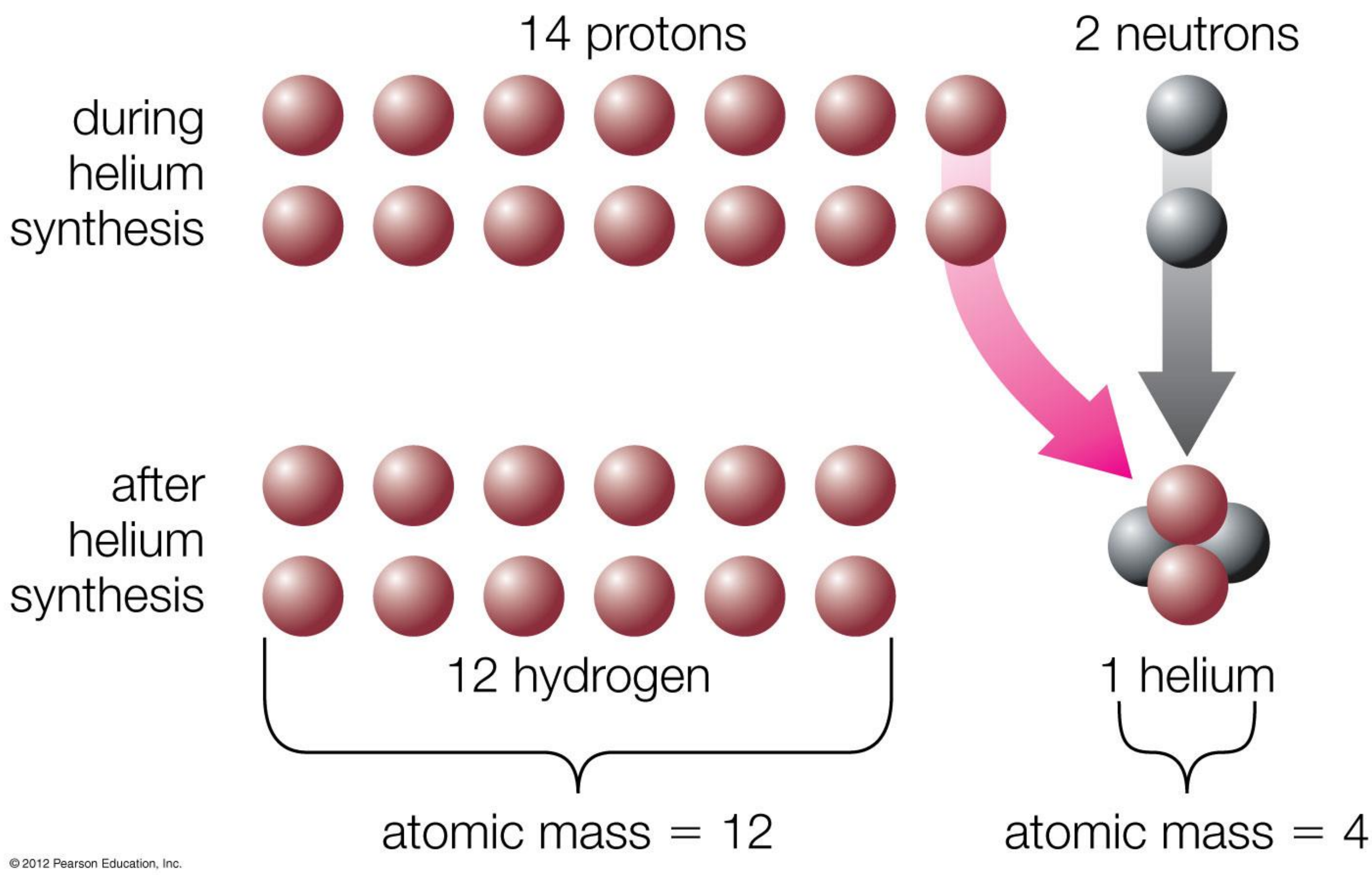


+ Al Cameron

independently in Chalk River internal report

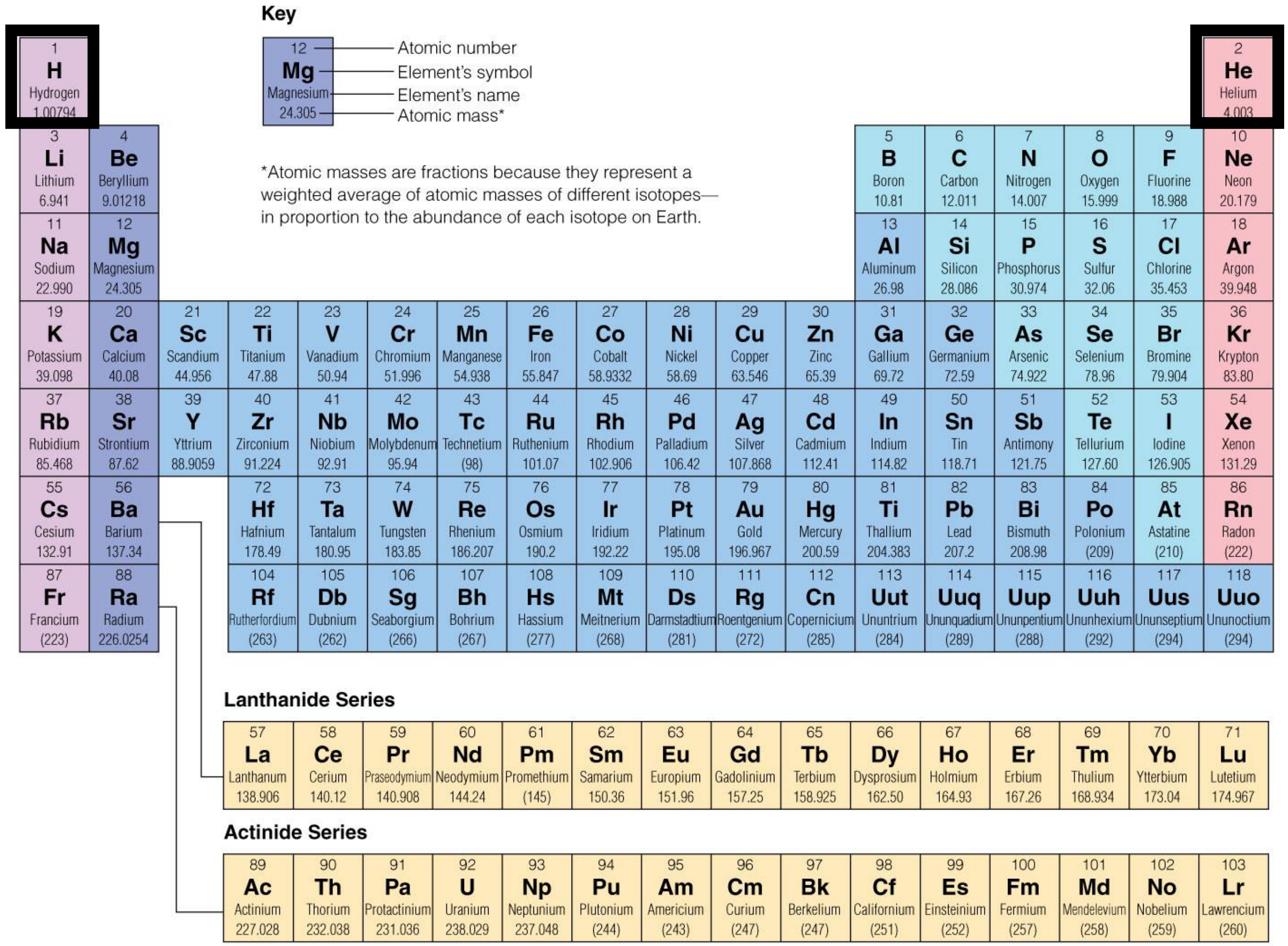
Nuclear reactions in stars are responsible for energy generation and creation of elements

Big Bang nucleosynthesis



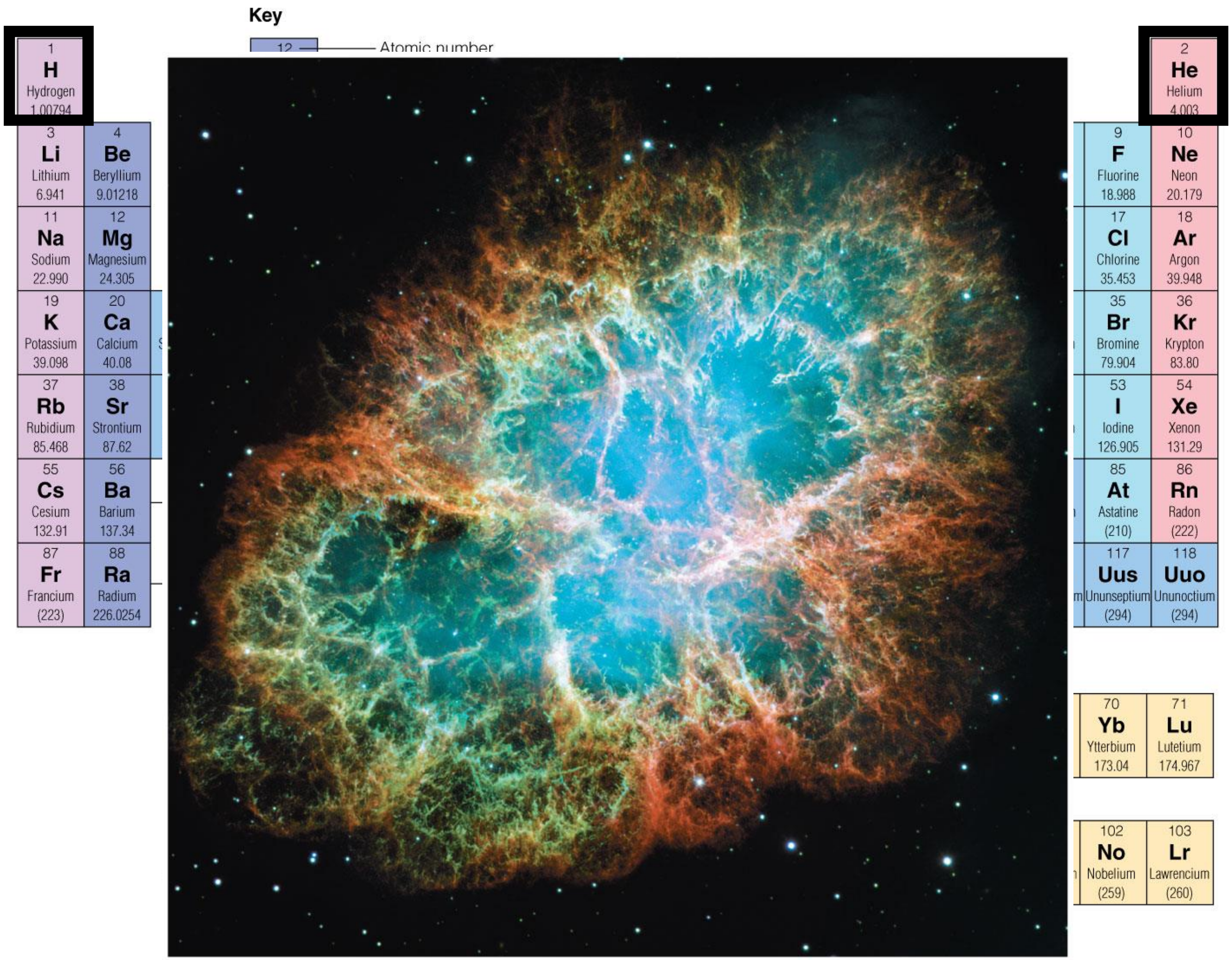
Big Bang made 75% H and 25% He, by mass in about 1000s

How were other elements made?



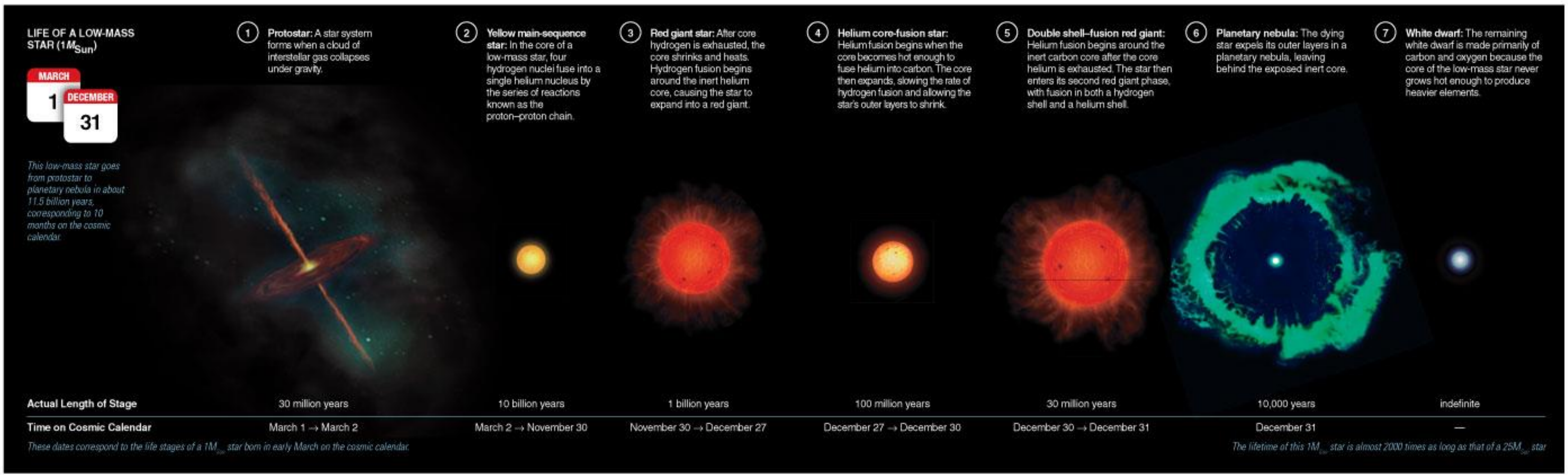
The Essential Cosmic Perspective, Bennett, Donahue, Schneider, Voit, 7th Ed.

In stars and stellar events!



Life of a low-mass star
(less than about 8 solar masses)

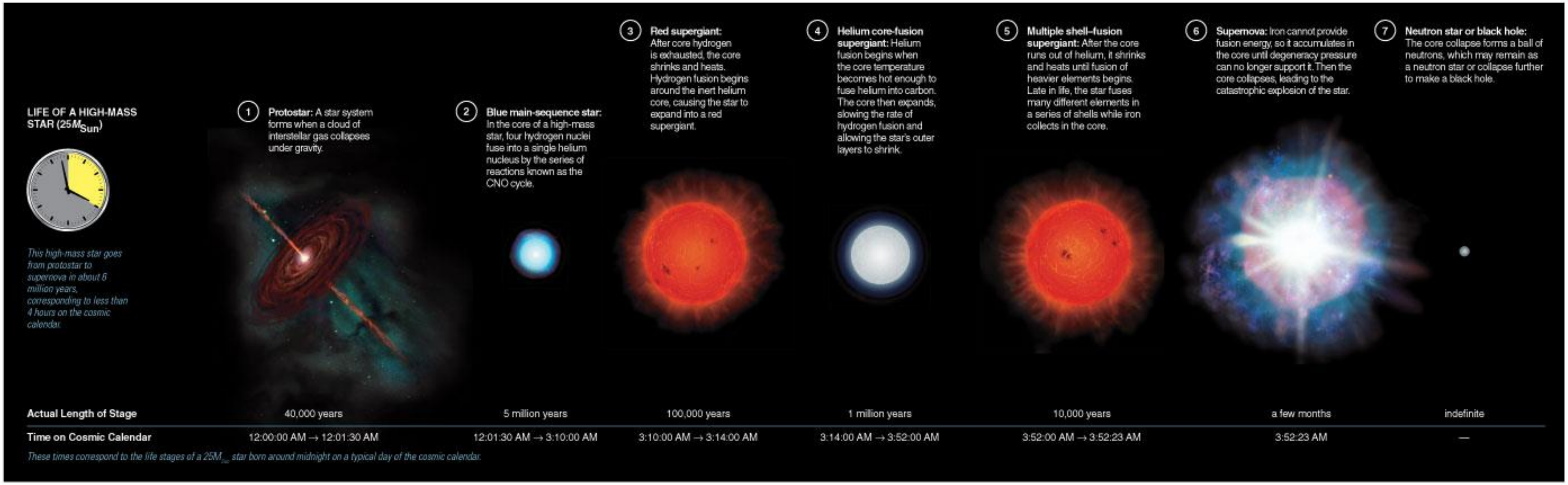
1. Protostar: cloud of cold gas collapses under gravity
2. Main Sequence: H fuses to He in core
3. Red Giant: H fuses to He in shell around He core until He flash
4. Helium Core Fusion: He fuses to C in core while H fuses to He in shell
5. Double Shell Fusion: H and He both fuse in shells
6. Planetary Nebula: outer layers expelled
7. White dwarf star left behind



The Essential Cosmic Perspective, Bennett, Donahue, Schneider, Voit, 7th Ed.

Life of a massive star
(more than about 8 solar masses)

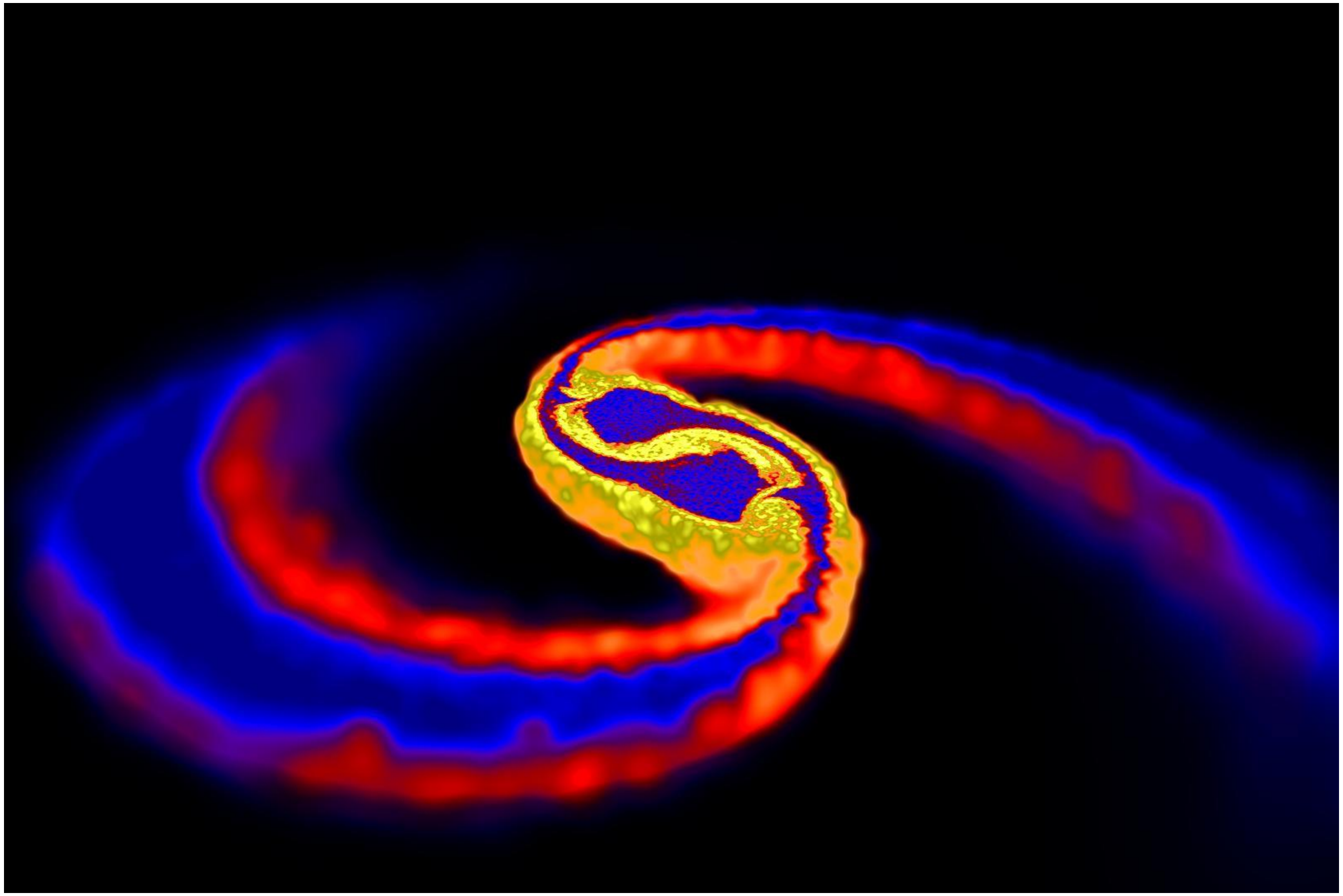
1. Protostar: cloud of cold gas collapses under gravity
2. Main Sequence: H fuses to He in core
3. Red Supergiant: H fuses to He in shell around He core
4. Helium Core Fusion: He fuses to C in core while H fuses to He in shell
5. Multiple Shell Fusion: many elements fuse in shells
6. Supernova (type II) explosion after iron core collapses
7. Neutron star or black hole left behind



The Essential Cosmic Perspective, Bennett, Donahue, Schneider, Voit, 7th Ed.

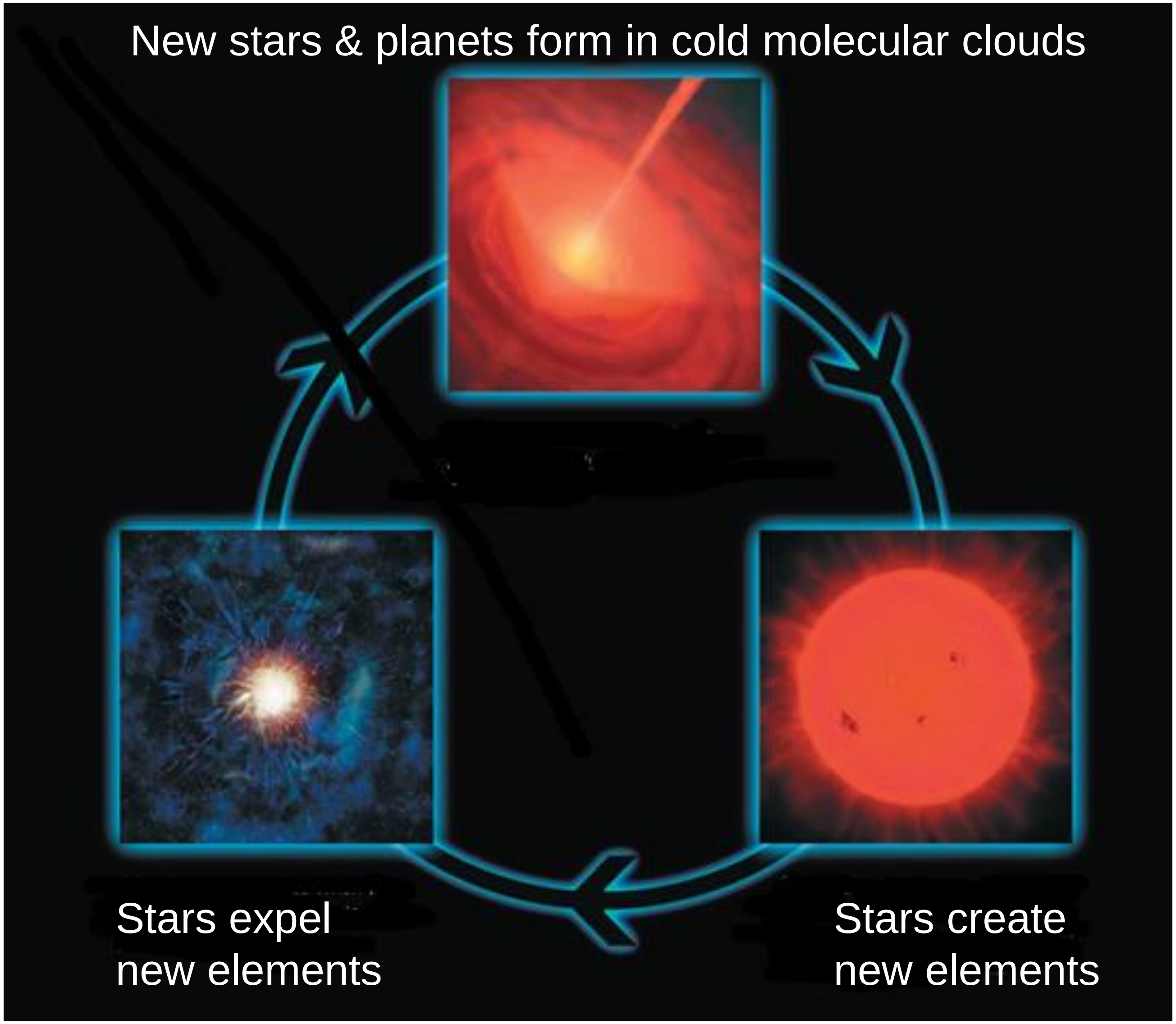
Binary star systems

Half of all stars are in binary systems



Can lead to neutron-star mergers, thermonuclear (Ia) supernovae, classical novae, ...

The Milky Way: a cosmic recycling plant

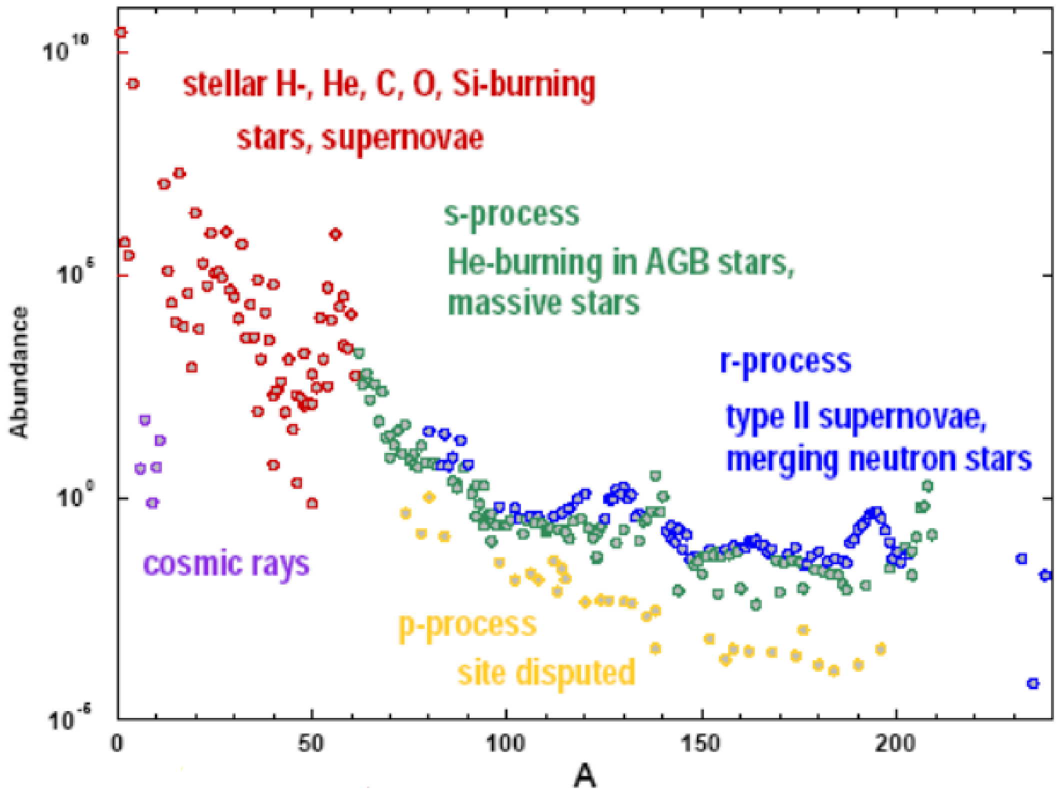


The Essential Cosmic Perspective, Bennett, Donahue, Schneider, Voit, 7th Ed.

Synthesis of elements in stars

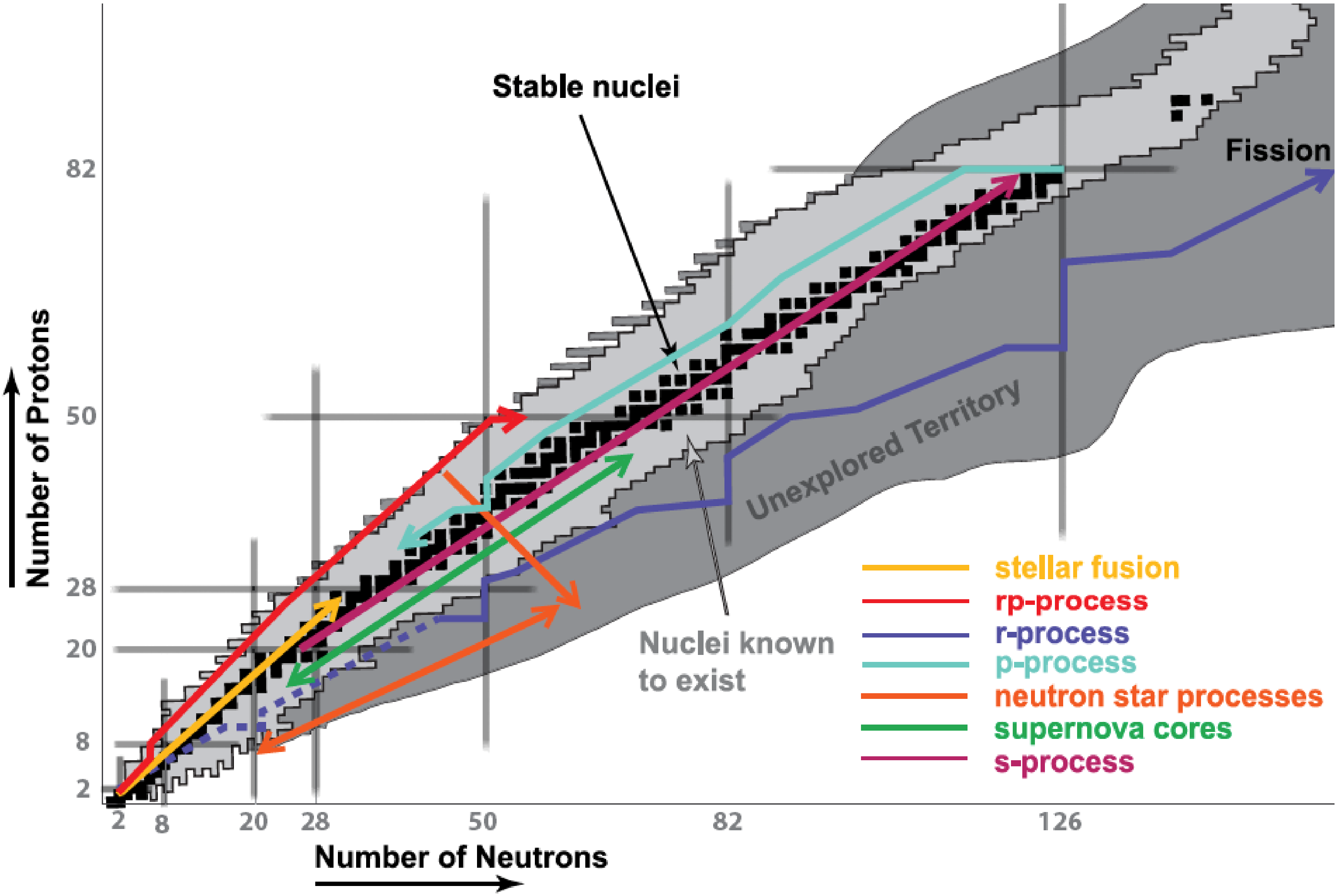
1. H burning → conversion of H to He
2. He burning → conversion of He to C, O …
3. C, O and Ne burning → production of A: 16 to 28
4. Si burning → production of A: 28 to 60
5. s-, r- and p-processes → production of A>60
6. Li,Be, and B from cosmic rays

Solar abundances



M. Wiescher / A. Tumino

Nuclear astrophysics processes



Need stellar nuclear reaction rates to understand nucleosynthesis processes

Stellar reaction rates: *thermo*nuclear

stellar reaction rate $\langle \sigma v \rangle = \int \sigma(v)\phi(v) v dv$

need: a) velocity distribution $\phi(v)$

b) cross section $\sigma(v)$

a) velocity distribution

interacting nuclei in plasma are in thermal equilibrium at temperature T

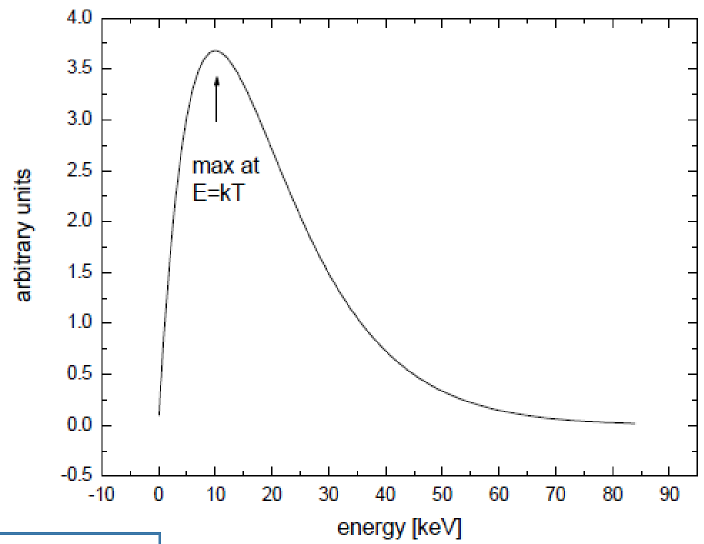
also assume non-degenerate and non-relativistic plasma

⇒ Maxwell-Boltzmann velocity distribution

$$\phi(v) = 4\pi \left(\frac{\mu}{2\pi kT} \right)^{3/2} v^2 \exp\left(-\frac{\mu v^2}{2kT} \right)$$

with $\mu = \frac{m_p m_T}{m_p + m_T}$ reduced mass

v = relative velocity



$kT \sim 8.6 \times 10^{-8}$ T[K] keV

example: Sun $T \sim 15 \times 10^6$ K ⇒ kT ~ 1 keV

Stellar reaction rates: thermo*nuclear*

b) cross section

no nuclear theory available to determine reaction cross section a priori

cross section depends sensitively on:

- the properties of the nuclei involved
- the reaction mechanism

and can vary by orders of magnitude, depending on the interaction

examples:

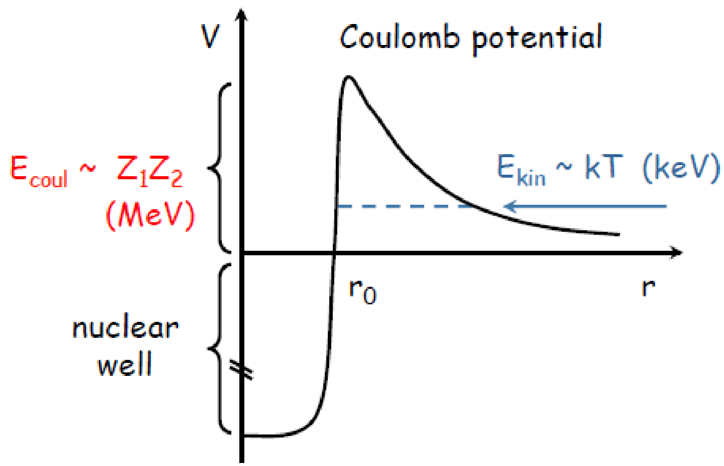
Reaction	Force	σ (barn)	E_{proj} (MeV)
$^{15}N(p,\alpha)^{12}C$	strong	0.5	2.0
$^{3}He(\alpha,\gamma)^{7}Be$	electromagnetic	10^{-6}	2.0
$p(p,e^{+}\nu)d$	weak	10^{-20}	2.0

1 barn = 10^{-24} cm^2 = 100 fm^2

M. Aliotta

Stellar reaction rates: *thermonuclear*

charged particles ➡ Coulomb barrier



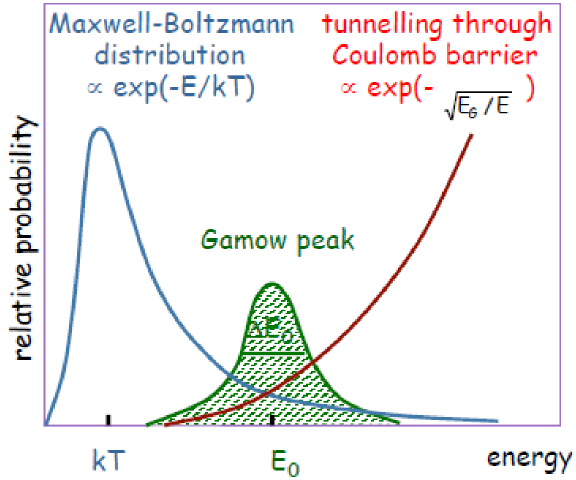
energy available: from thermal motion

during static burning: $kT \ll E_{coul}$

$T \sim 15 \times 10^6$ K (e.g. our Sun) $\Rightarrow$ $kT \sim 1$ keV

reactions occur through TUNNEL EFFECT

➡ tunneling probability $P \propto \exp(-2\pi\eta)$



Gamow peak: energy of astrophysical interest where measurements should be carried out

$kT \ll E_0 \ll E_{coul}$

10^{-18} barn < σ < 10^{-9} barn

⬇

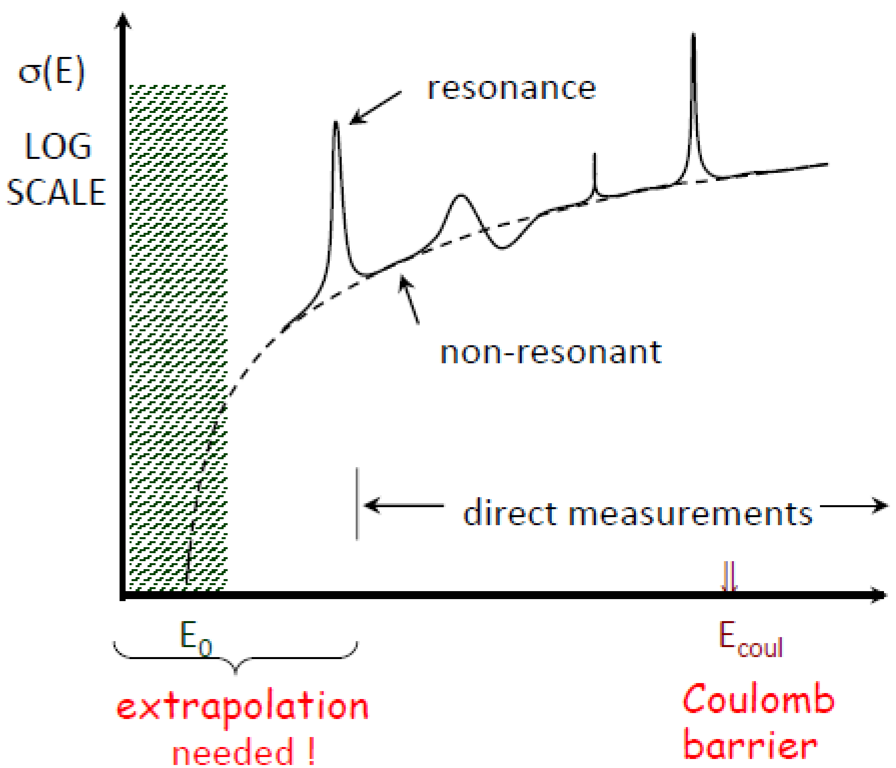
major experimental challenges

Experimental approach

Measure $\sigma(E)$ as low as possible in energy and extrapolate if necessary

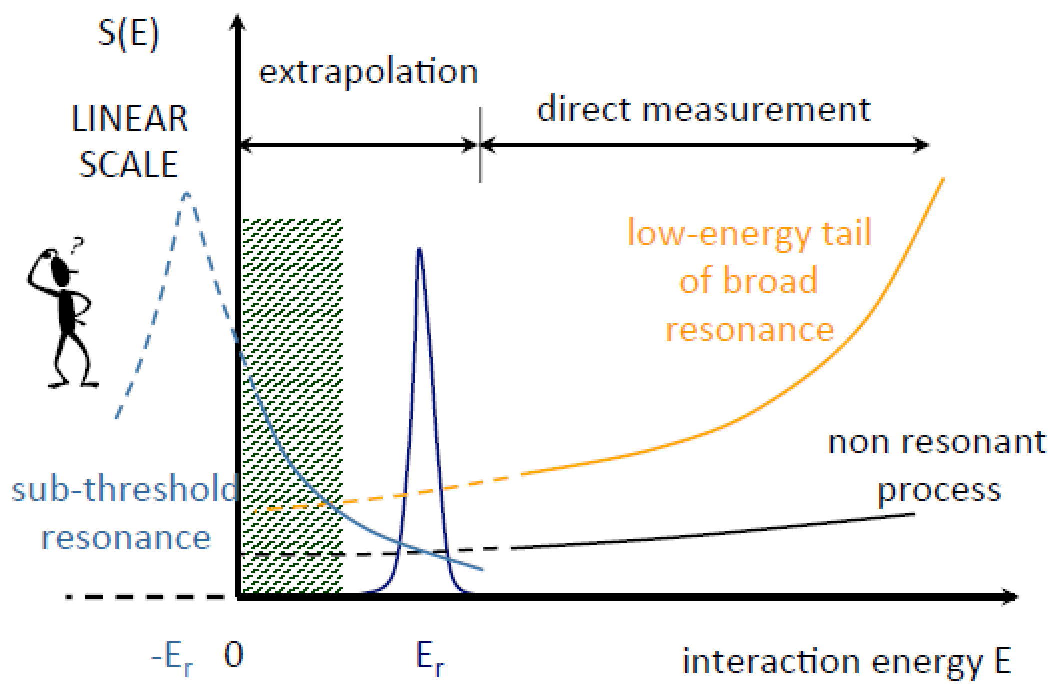
CROSS SECTION

$$\sigma(E) = \frac{1}{E} \exp(-2\pi\eta)\, S(E)$$



S-FACTOR

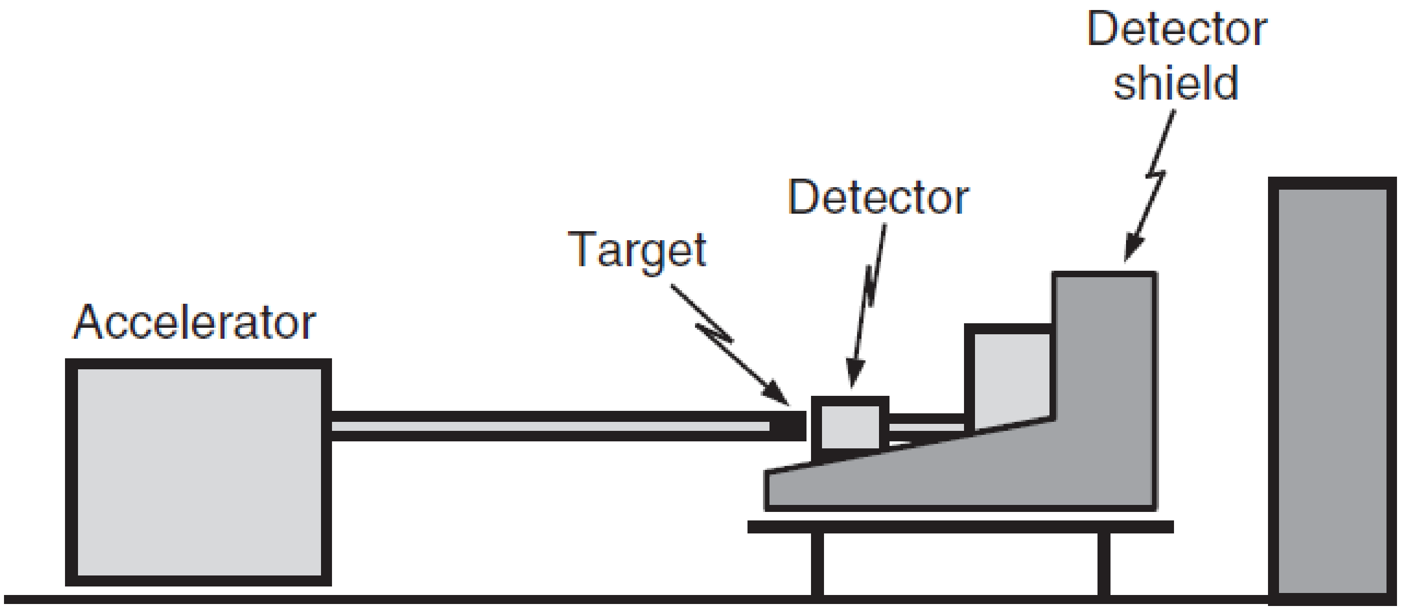
$$S(E) = E\sigma(E) \exp(2\pi\eta)$$



DANGER OF EXTRAPOLATION !

A. Tumino

Direct measurements (stable reactants)

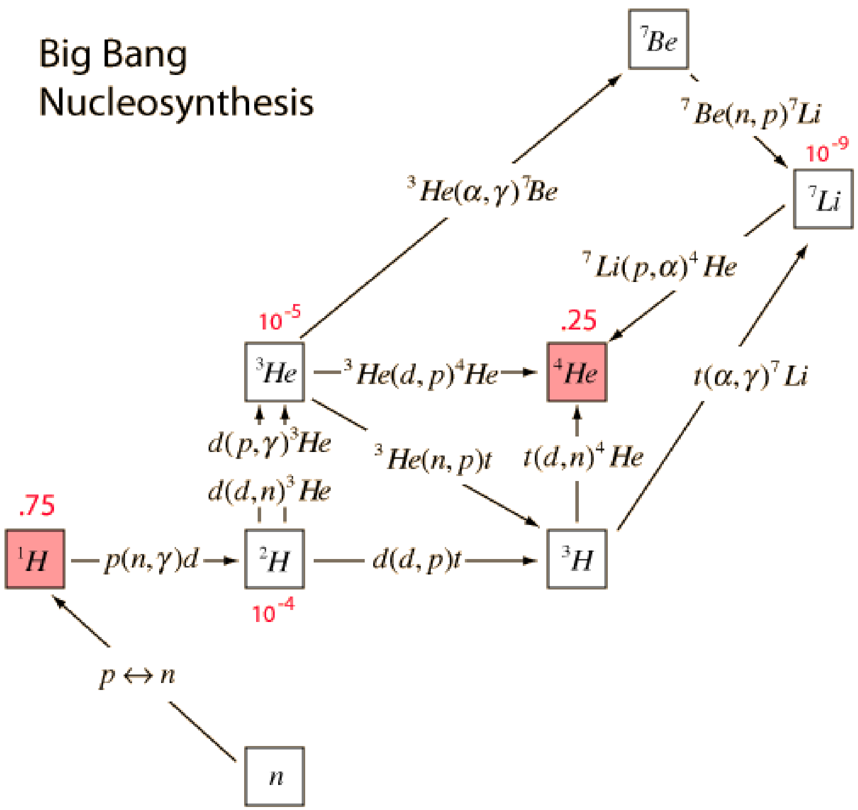


- Accelerator produces ion beam of one reactant at an appropriate energy
- Beam directed on a chemically stable target composed of other reactant
- Reaction like $A(a,\gamma)B$ or $A(a,b)B$ takes place in target
- Reaction products (usually γ rays or light particles) measured in detector
- Reduce background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

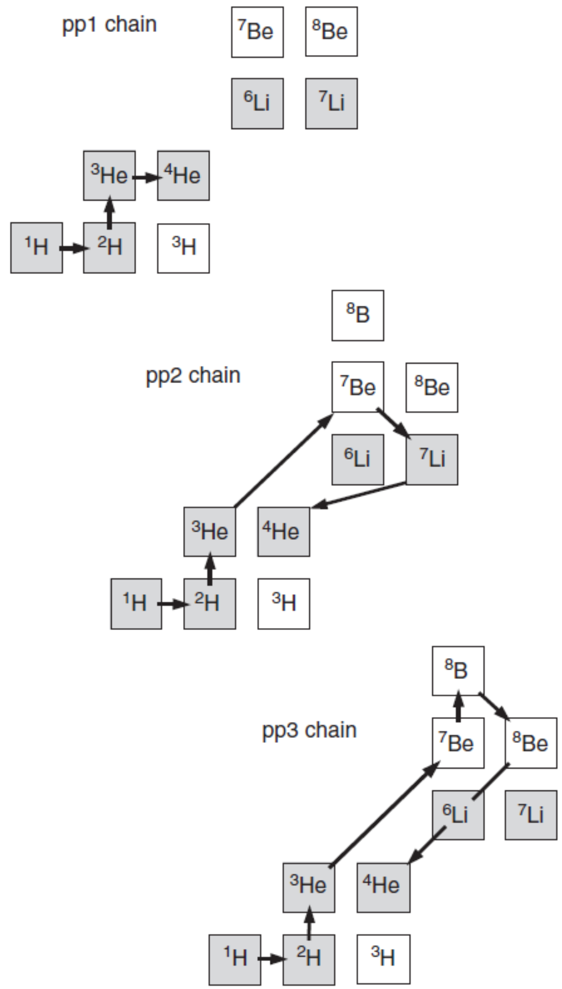
Nuclear Physics of Stars, Iliadis, 2nd Ed.

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

Big Bang Nucleosynthesis & Li problem

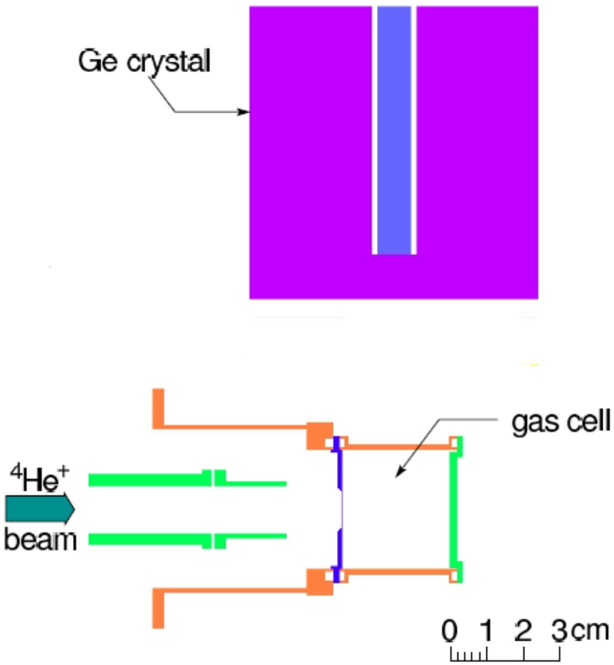


Solar hydrogen burning and neutrinos

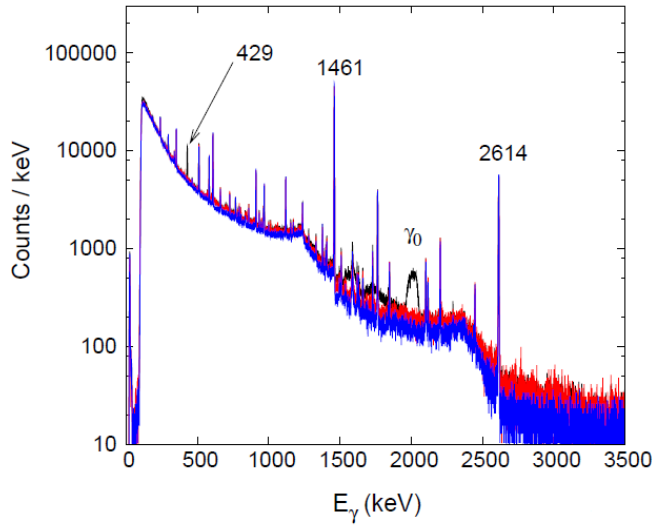


Example: $^{3}He(\alpha,\gamma)^{7}Be$ reaction

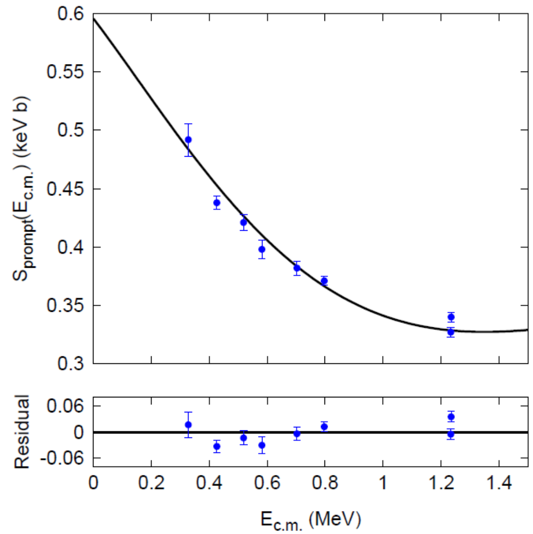
Setup



Spectrum at E_{cm} = 0.43 MeV



S factor

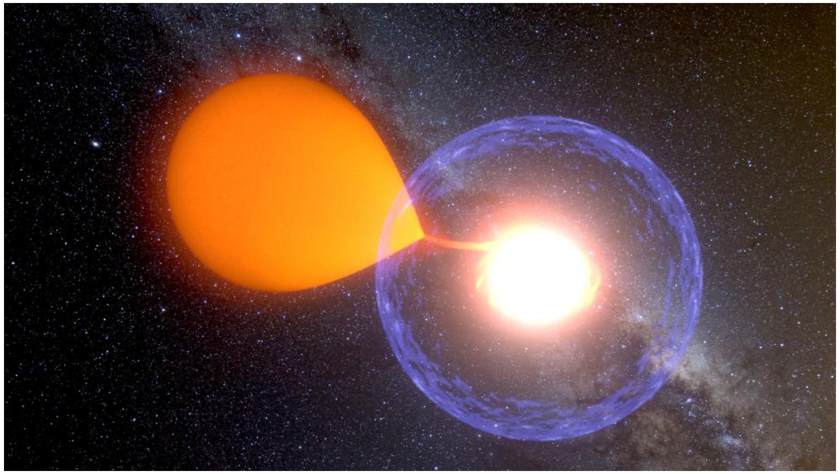


Measured at University of Washington's Center for Experimental Nuclear Physics and Astrophysics.

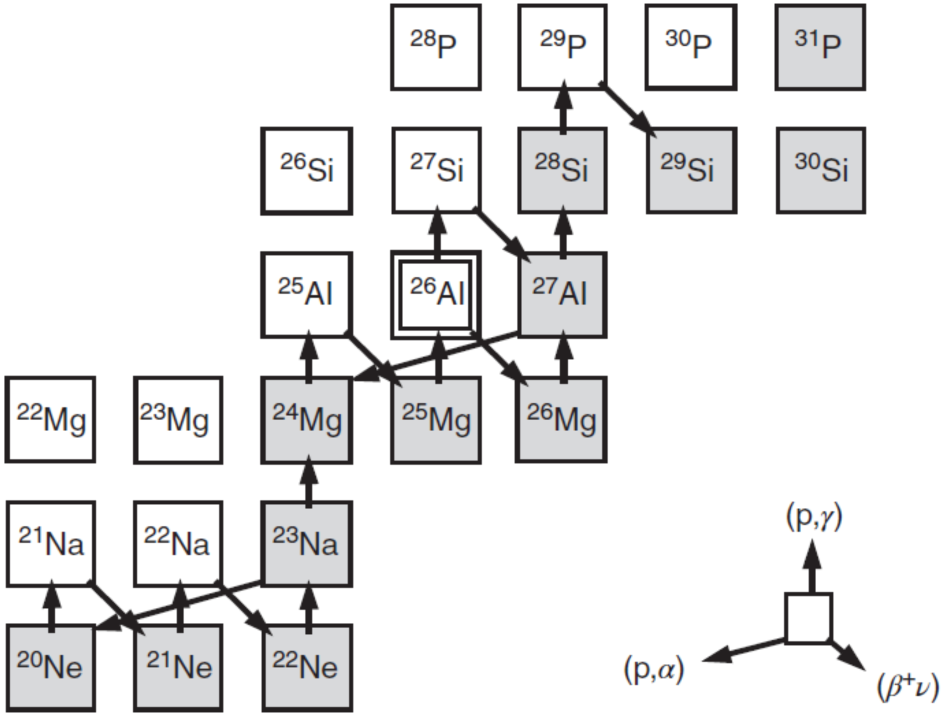
T. A. D. Brown *et al.*, Phys. Rev. C 76, 055801 (2007)

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

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



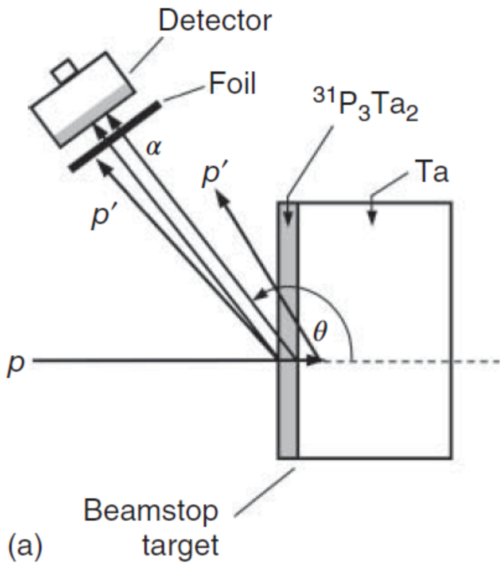
Hydrogen burning before explosive temperatures are reached



The $^{31}P(p,\alpha)^{28}Si$ reaction determines if there is a Si-P cycle during (explosive) hydrogen burning on accreting compact stars (rp-process).

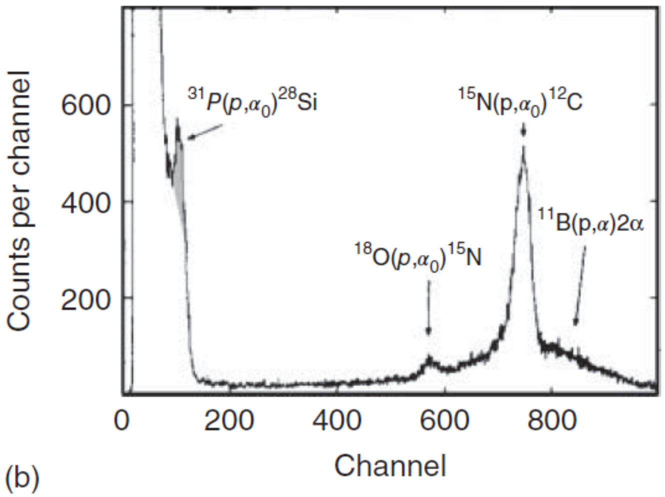
Example: $^{31}P(p,\alpha)^{28}Si$ reaction

Setup



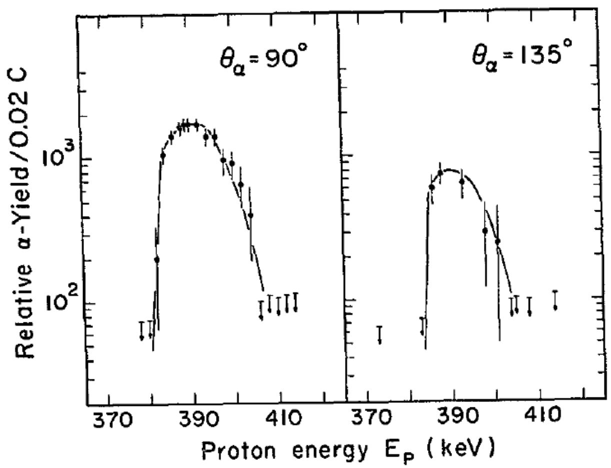
(a)

Spectrum at E_p = 390 keV



(b)

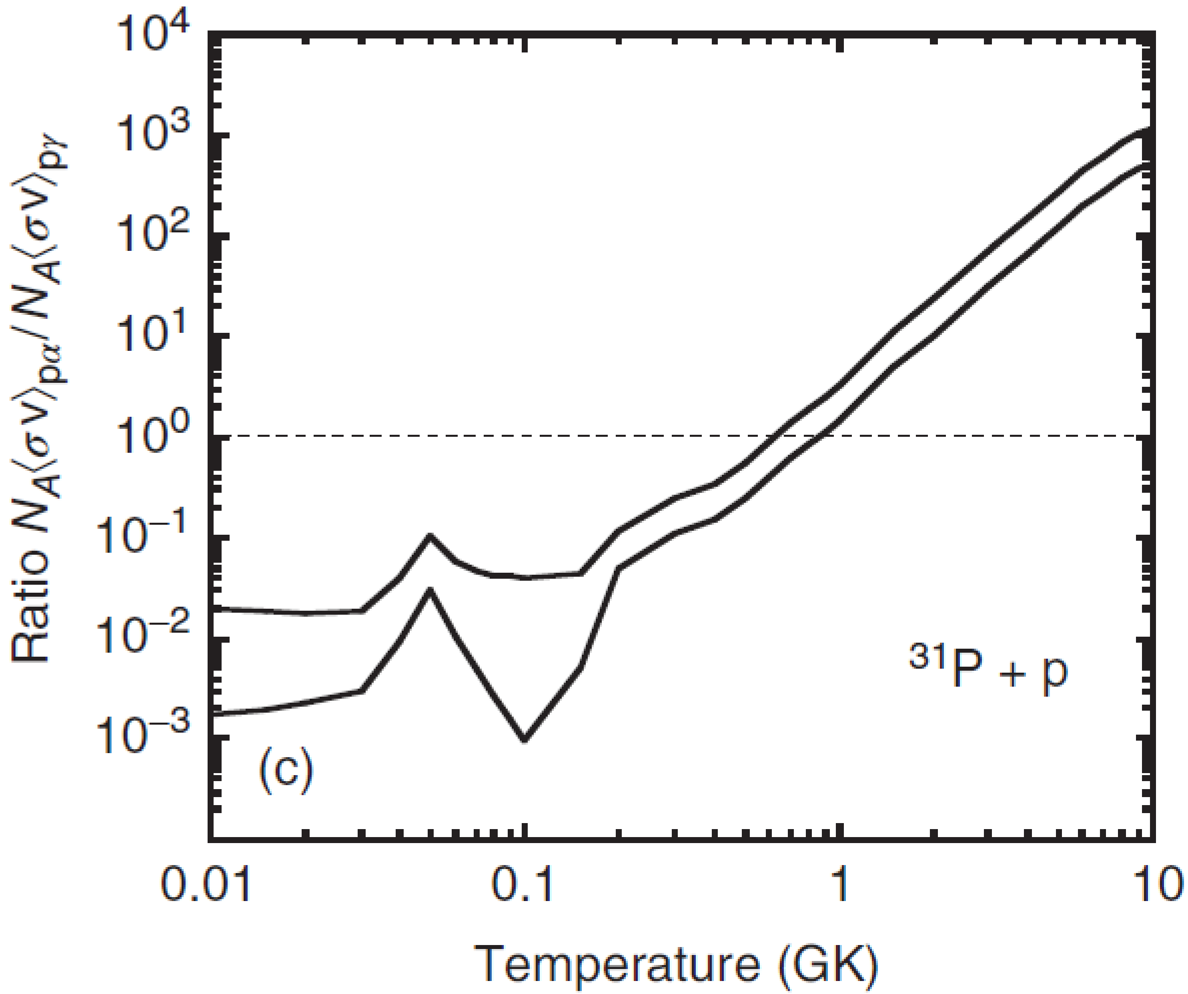
Excitation function



Measured at the Kellogg facility at Caltech. No strong SiP cycling.

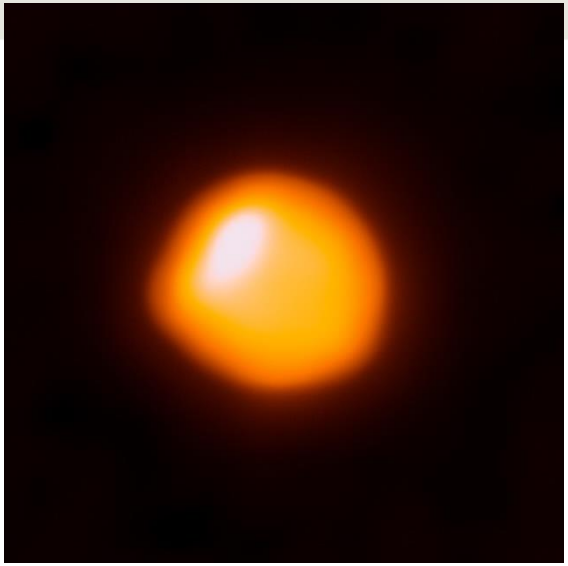
Nuclear Physics of Stars, Iliadis, 2nd Ed.
Iliadis *et al.*, Nucl. Phys. A533, 153 (1991)

SiP cycle?



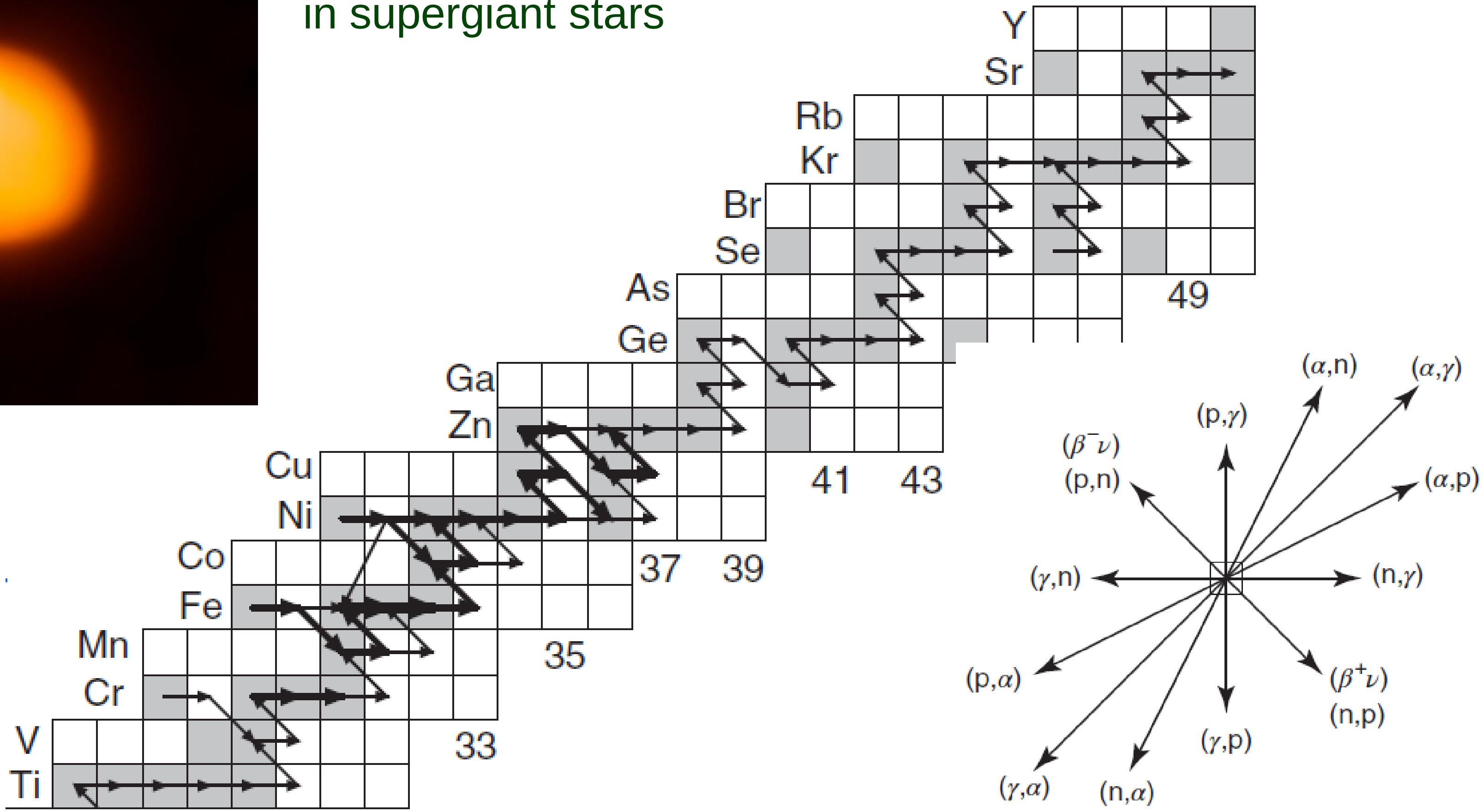
No strong SiP cycling below about 1 GK

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



Betelgeuse

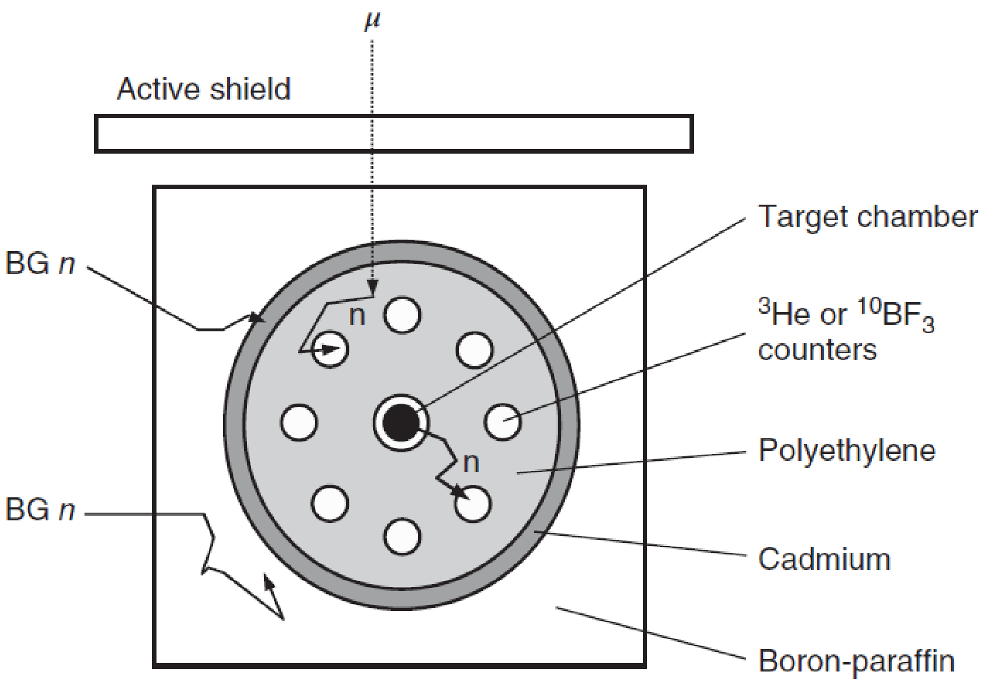
Weak s-process occurs in supergiant stars



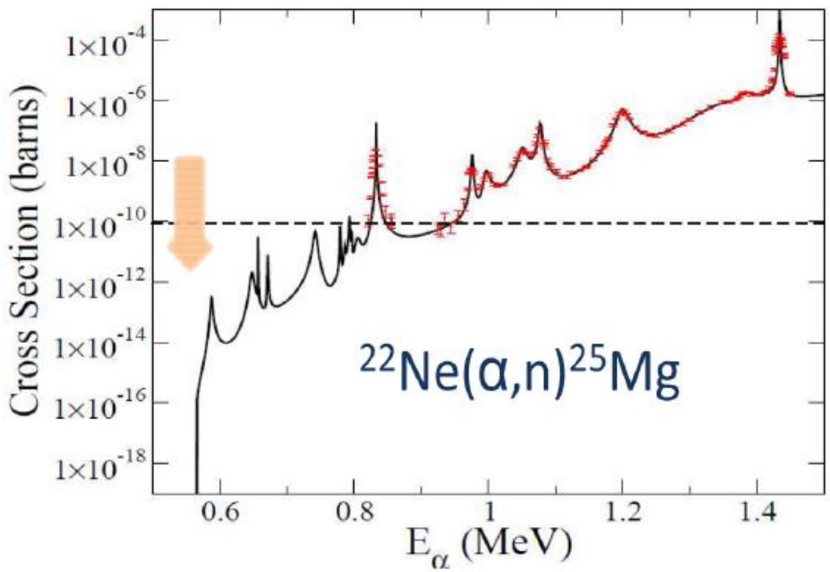
The $^{22}Ne(\alpha,n)^{25}Mg$ reaction is one of two major sources of neutrons for the slow neutron capture (s) process that produces half of the heavy elements

Example: ^{22}Ne(α,n)^{25}Mg reaction

Generic setup



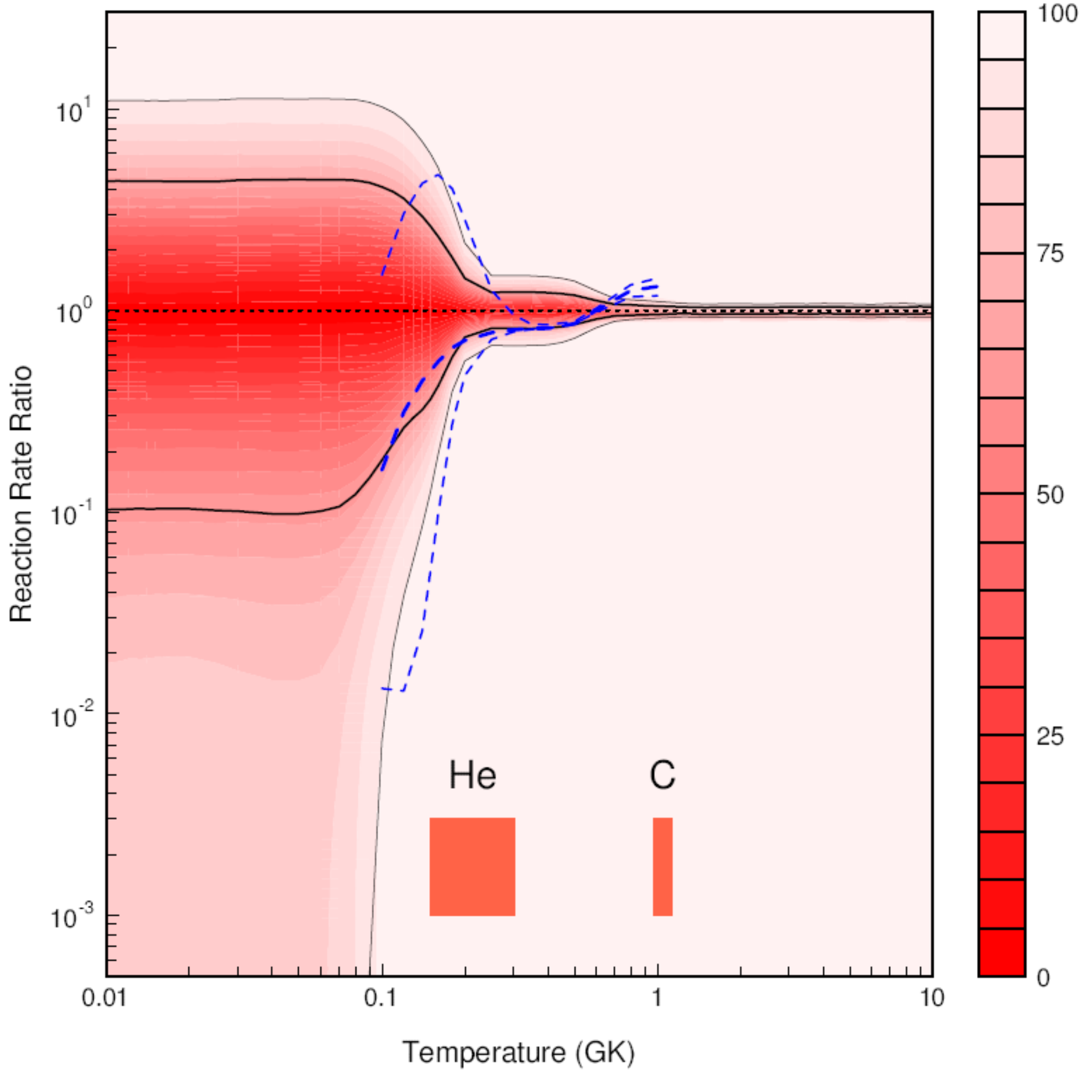
Cross section



Measured using similar techniques at many facilities.

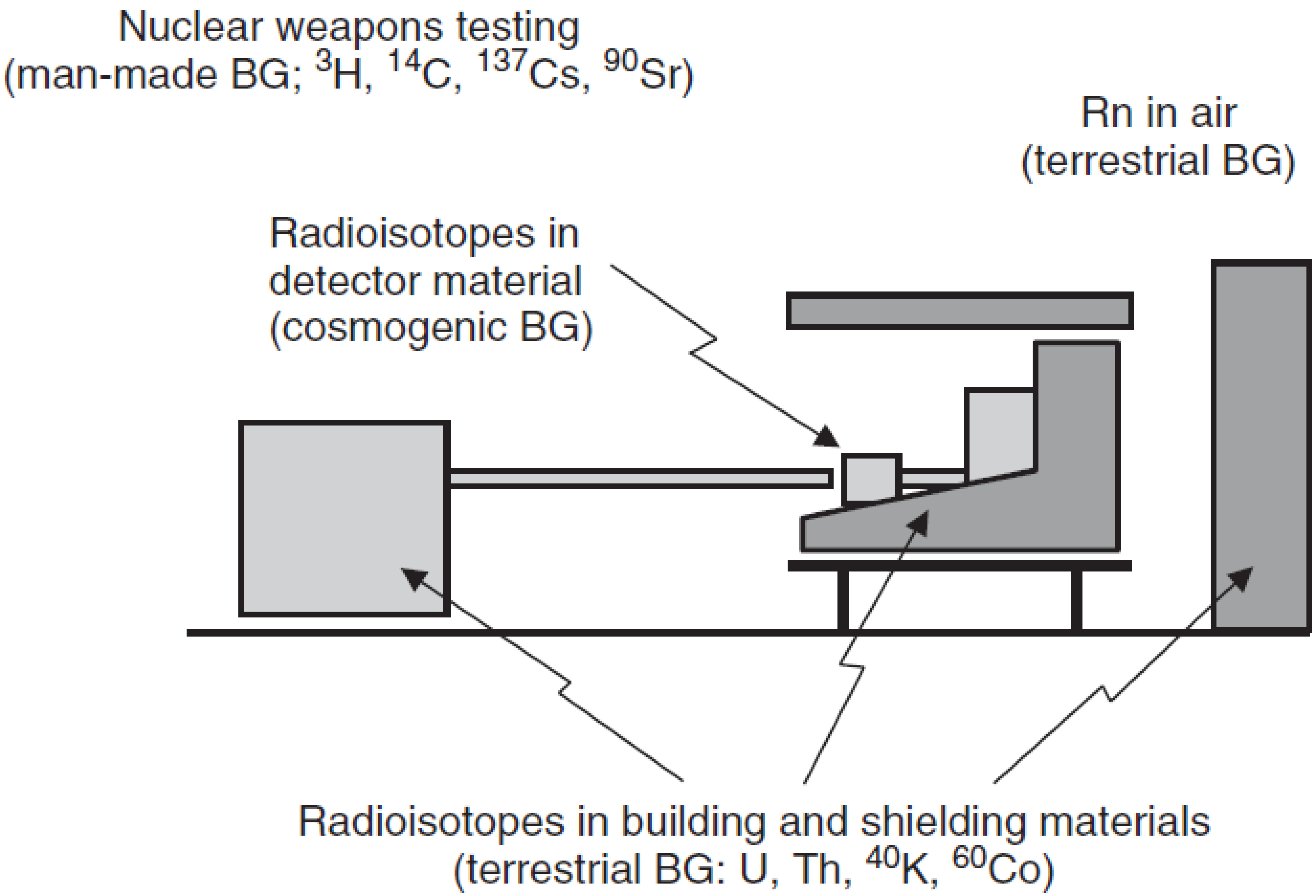
Nuclear Physics of Stars, Iliadis, 2nd Ed.

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



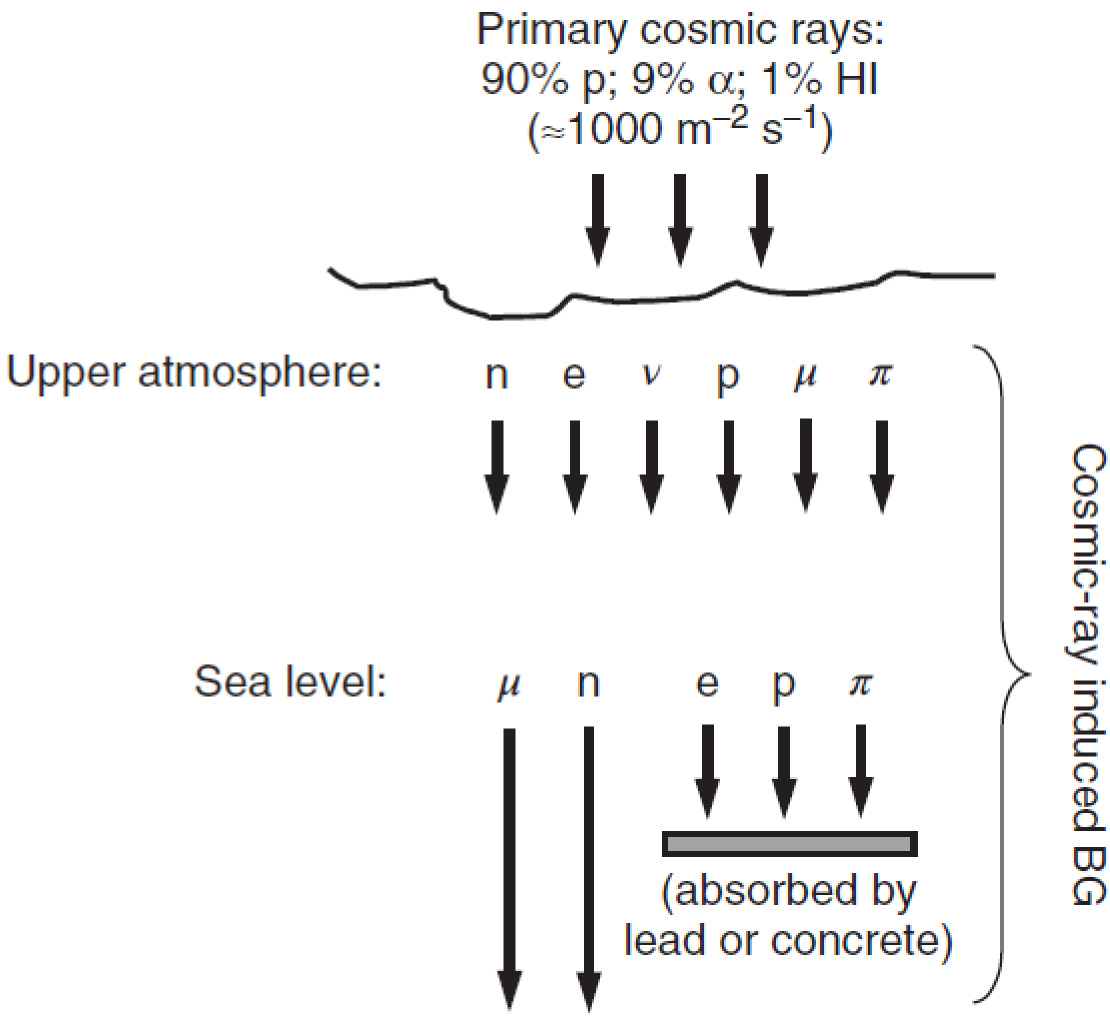
Longland *et al*. (2012)

Background radioactivity



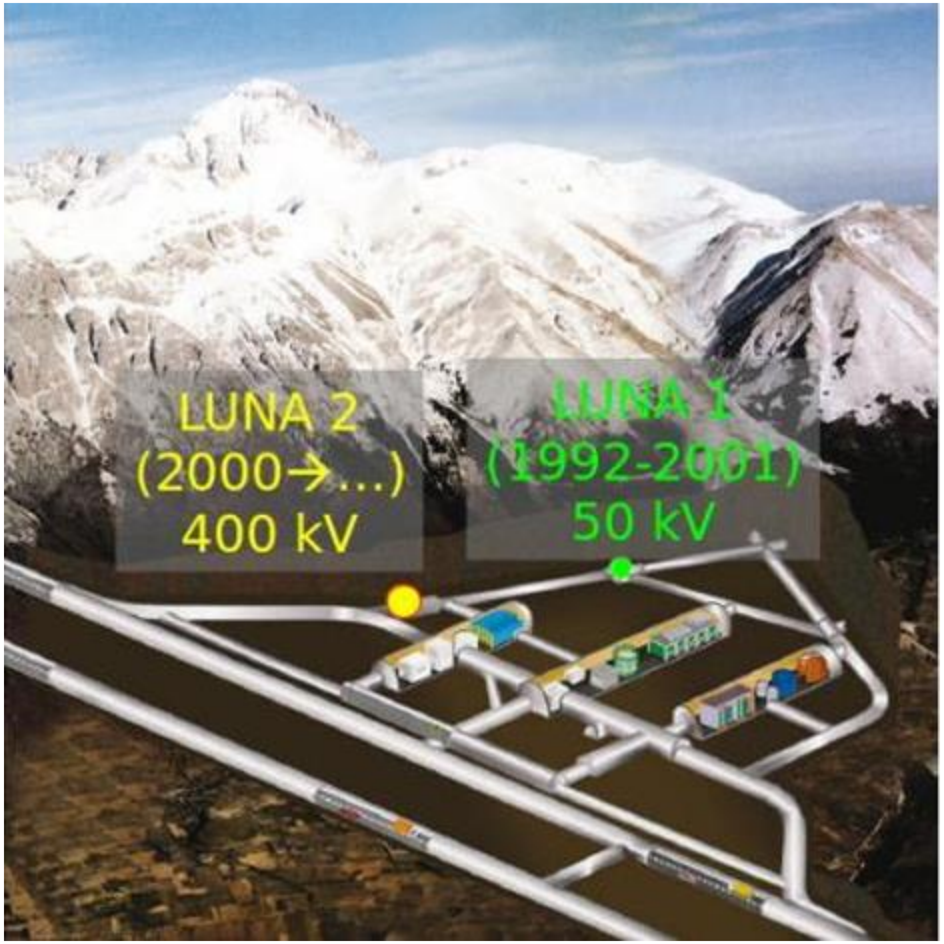
Nuclear Physics of Stars, Iliadis, 2nd Ed.

Cosmic-ray backgrounds



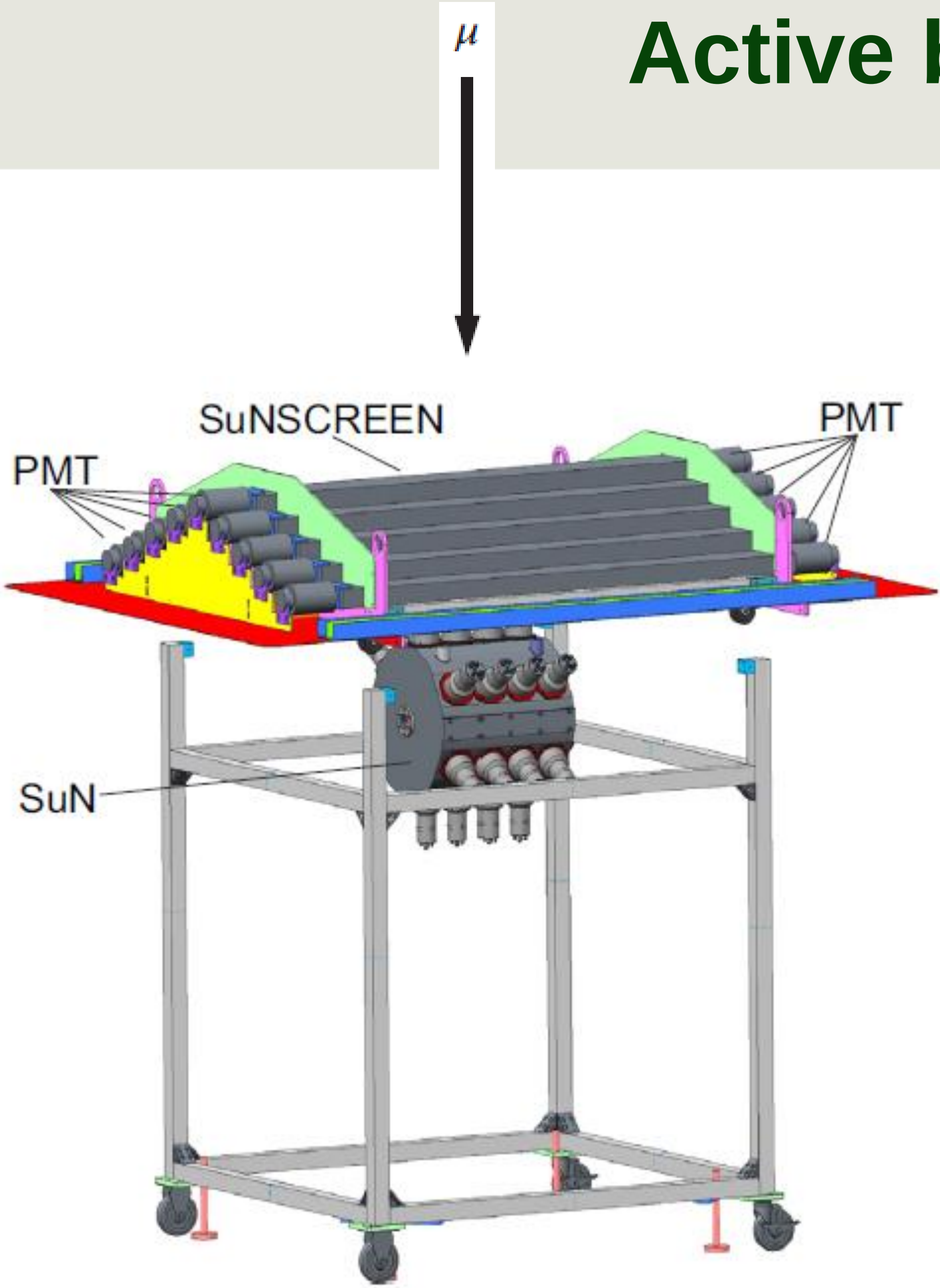
Nuclear Physics of Stars, Iliadis, 2nd Ed.

Passive background shielding



- Use material to block radiation from interacting with the detectors
- High-*Z* material (eg. Pb) to block gamma rays
- Moderator for neutrons (eg. polyethylene) with component to capture thermal neutrons (^{10}B, ^{6}Li, Cd)
- Large overburden of Earth to block cosmic-ray muons

Active background shielding

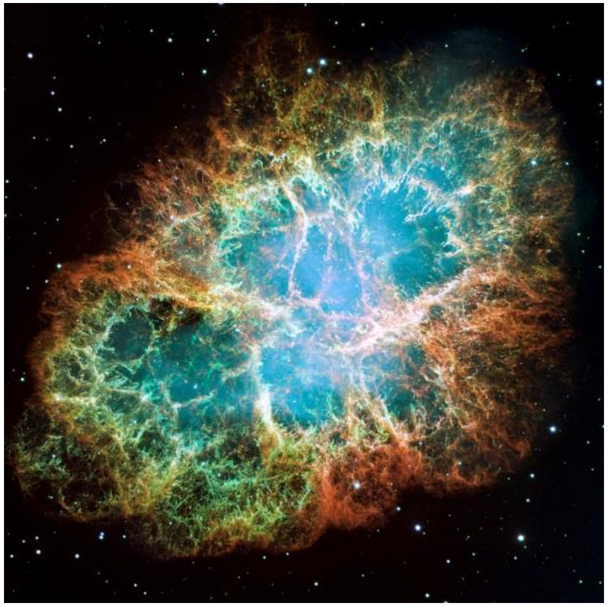


- Surround detector with a material (eg. plastic scintillator) that can detect the background radiation
- Use anti-coincidence condition to veto events that were likely from cosmic rays
- Eg. SuNSCREEN at NSCL (left) to veto cosmic-ray muons

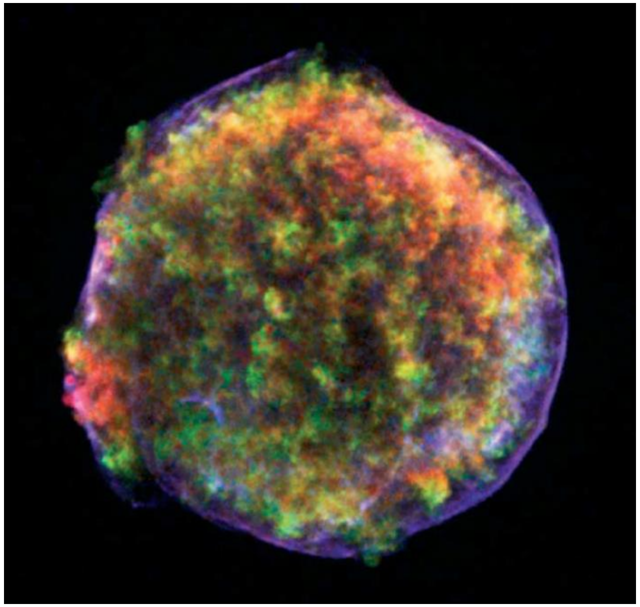
A. Spyrou

Rare Isotope beams (RIBs)

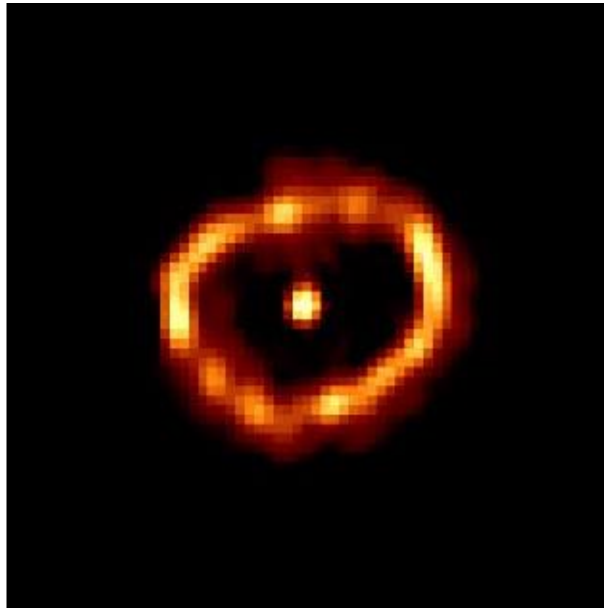
Core-collapse supernovae



Thermonuclear supernovae

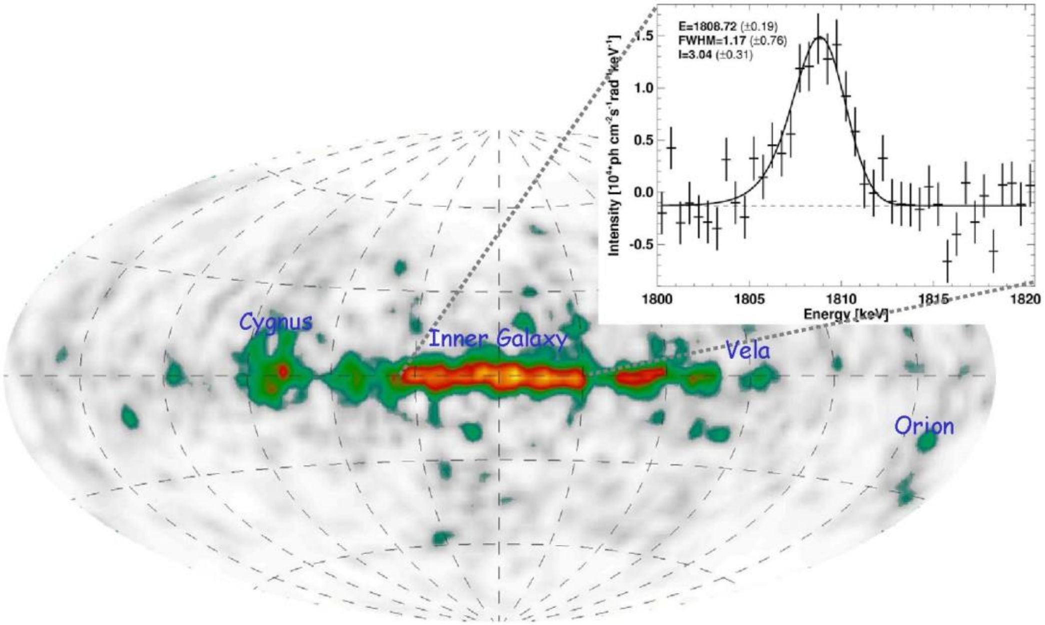


Classical novae



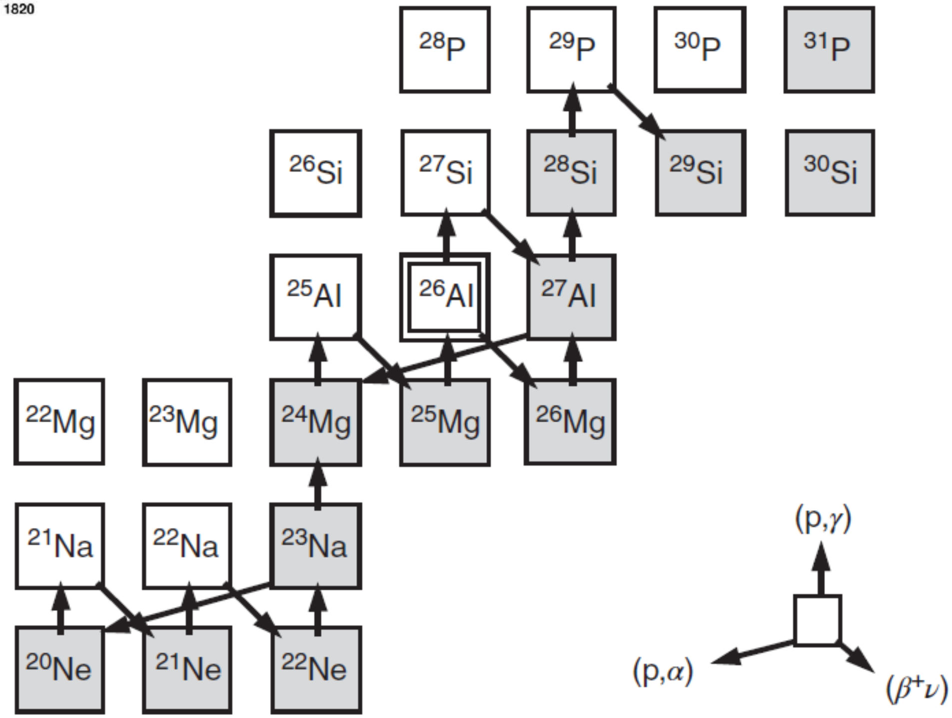
- Stars (especially exploding stars) produce radioactive nuclides that undergo reactions
- Can't make a target for p and α induced reactions out of short-lived radioactive nuclides
- Instead, use *inverse kinematics*: bombard H or He target with RIB
- Need high-quality, high-intensity, low-energy RIB

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

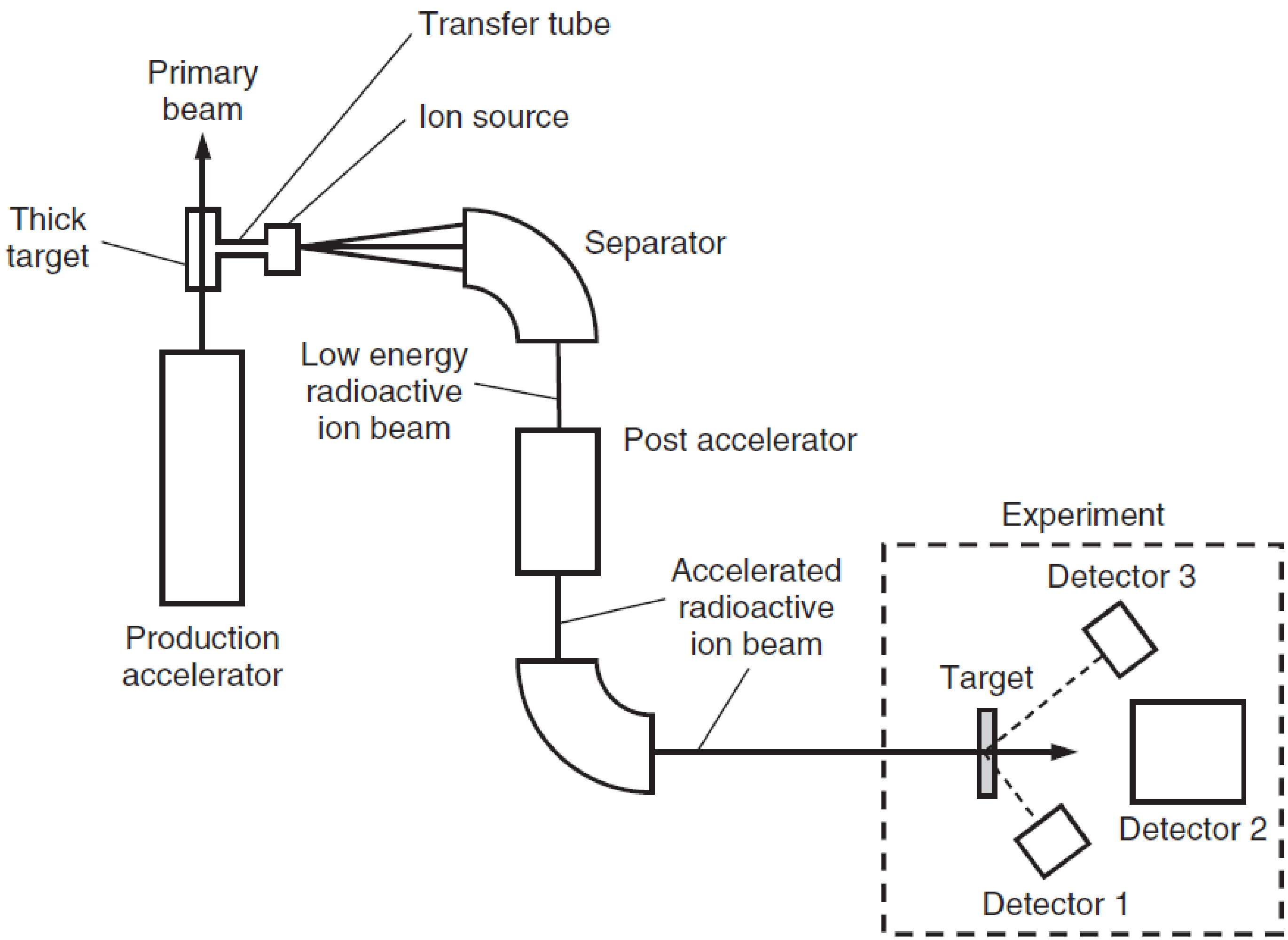


How is ^{26}Al radioactivity observed across the Milky Way is produced?

Hydrogen-burning

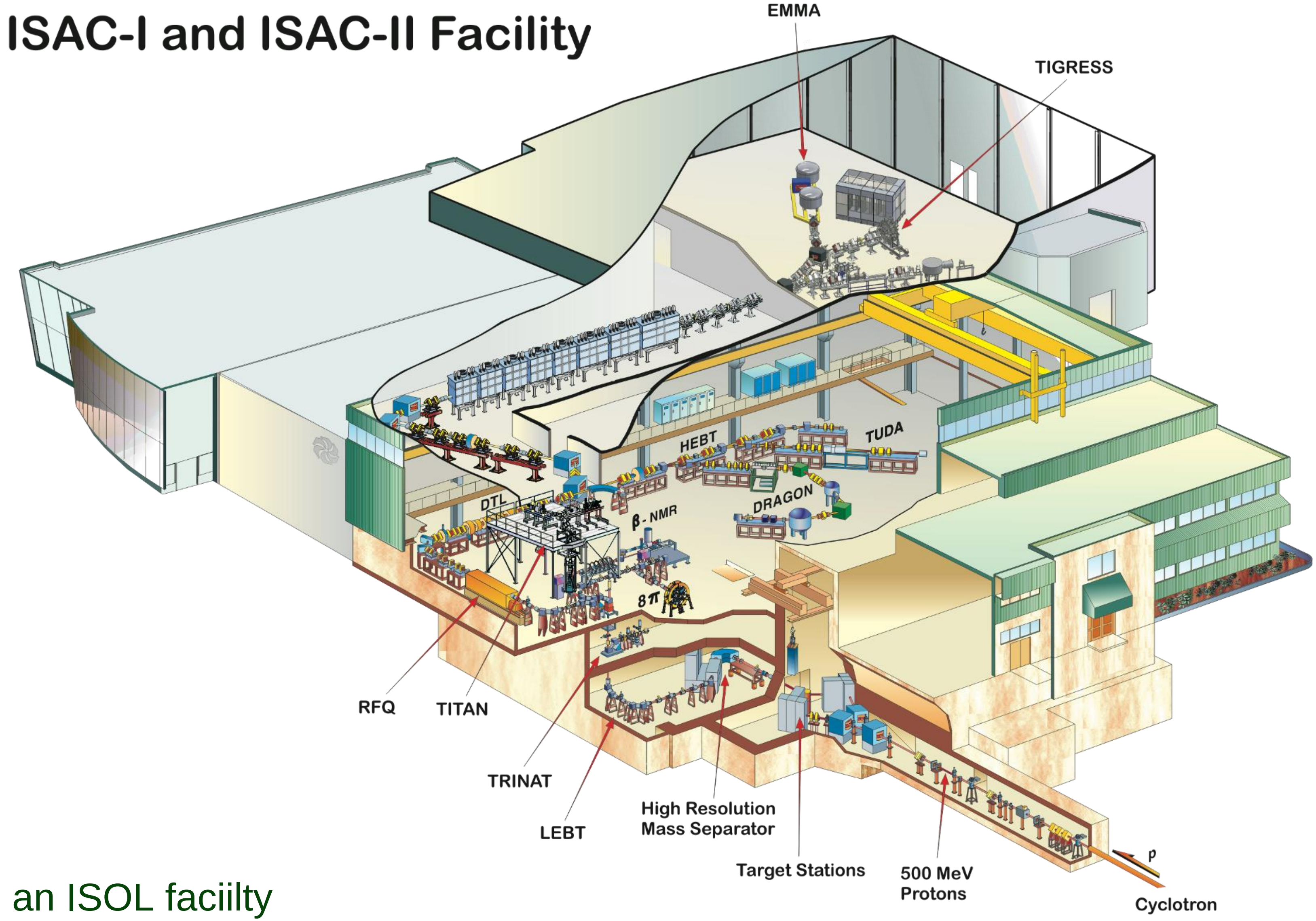


RIB production: ISOL technique



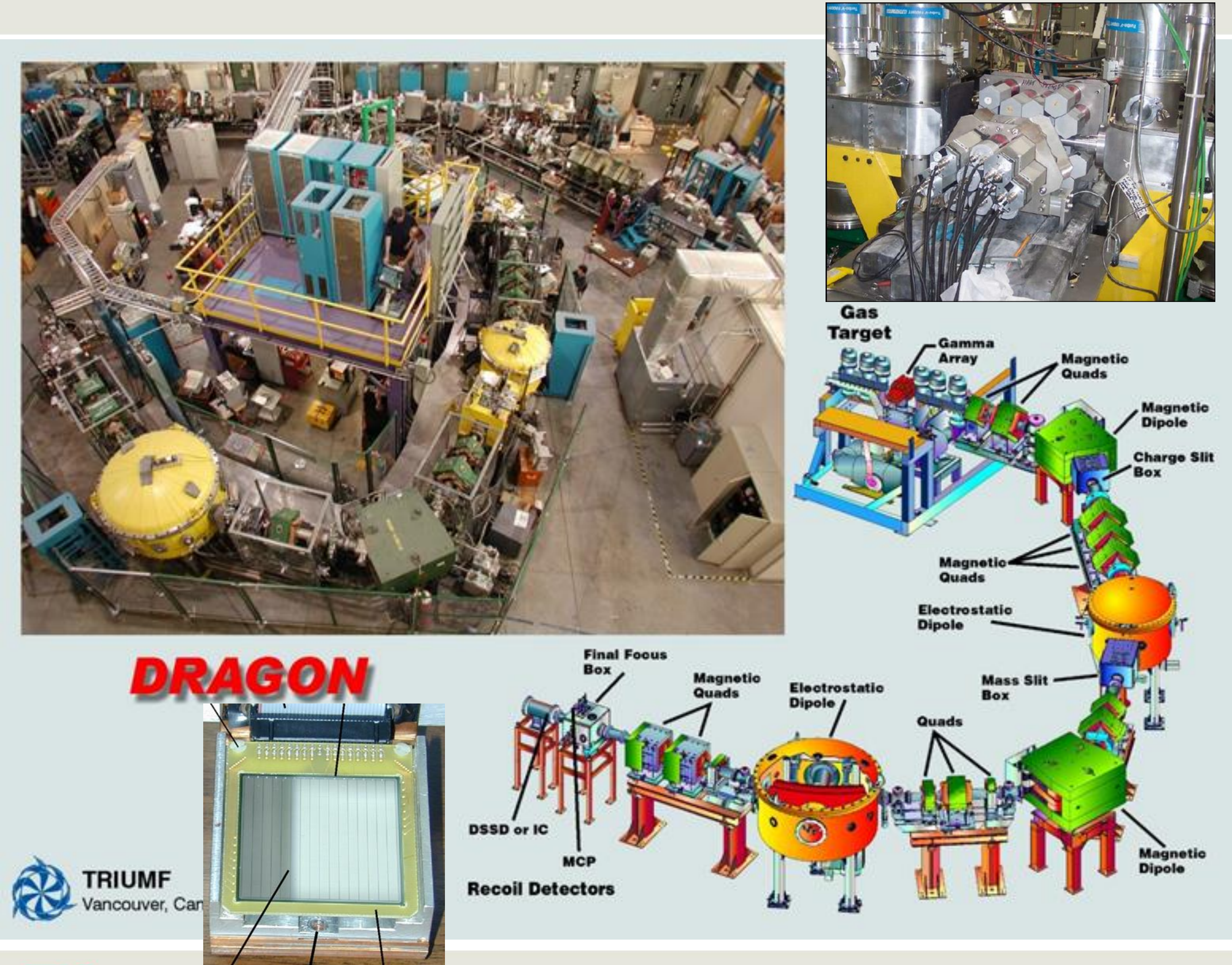
ISOL: Isotope Separation On-Line

TRIUMF-ISAC in Vancouver, Canada



ISAC is an ISOL faciilty

DRAGON at TRIUMF-ISAC



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

Detect γ-rays at target position.

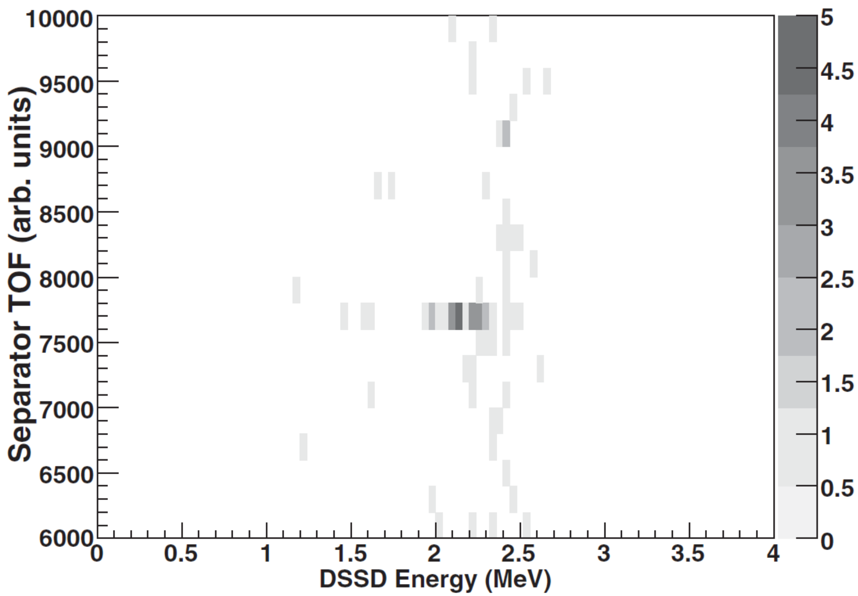
Separate reaction products from beam with electromagnetic separator.

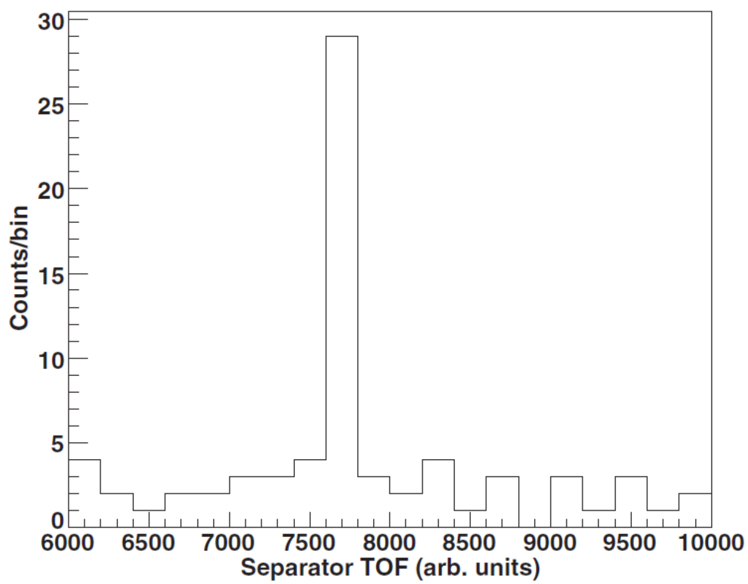
Detect reaction products at the end of the separator.

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

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

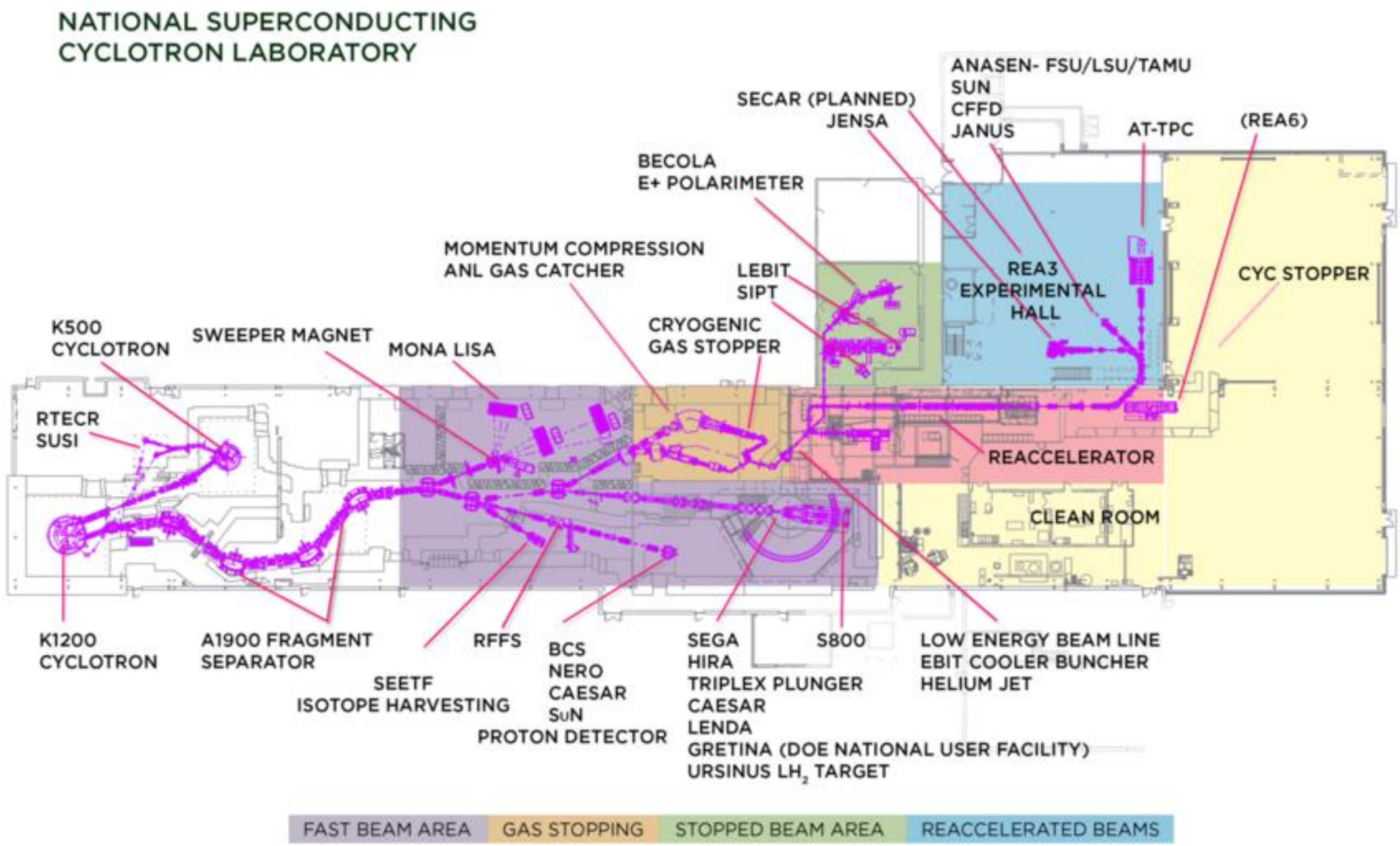
Energy of recoils combined with time-of-flight through separator used to distinguish reaction products from "leaky" beam at E_{cm} = 0.184 MeV





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

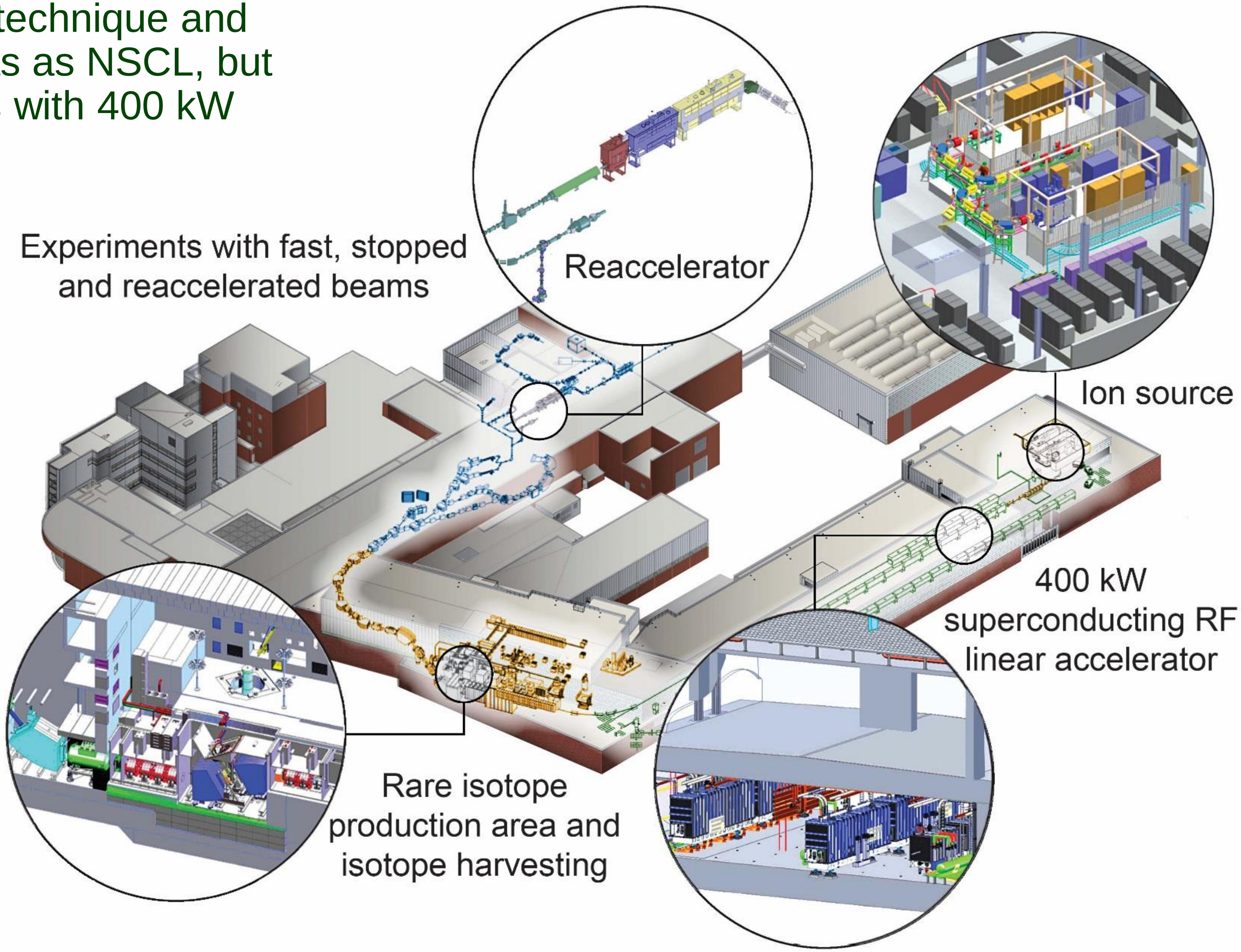
RIBs from nuclear fragmentation at NSCL



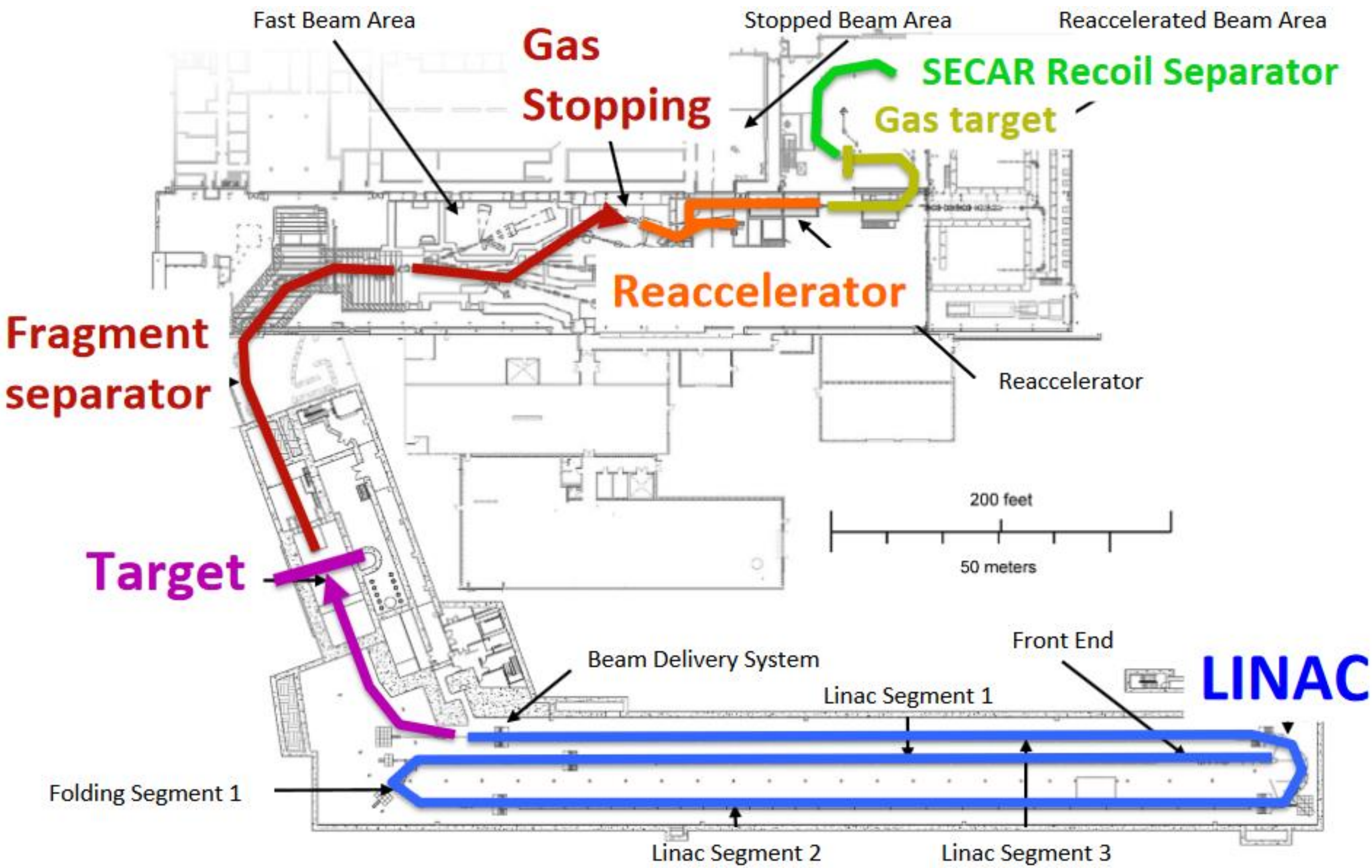
Accelerate heavy ion beam with cyclotrons and bombard thin, light, target. Reaction products fly forward, are separated in flight, and delivered to experiments directly (fast beam), thermalized (stopped beam), or reaccelerated (ISOL-like beam)

RIBs from FRIB

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

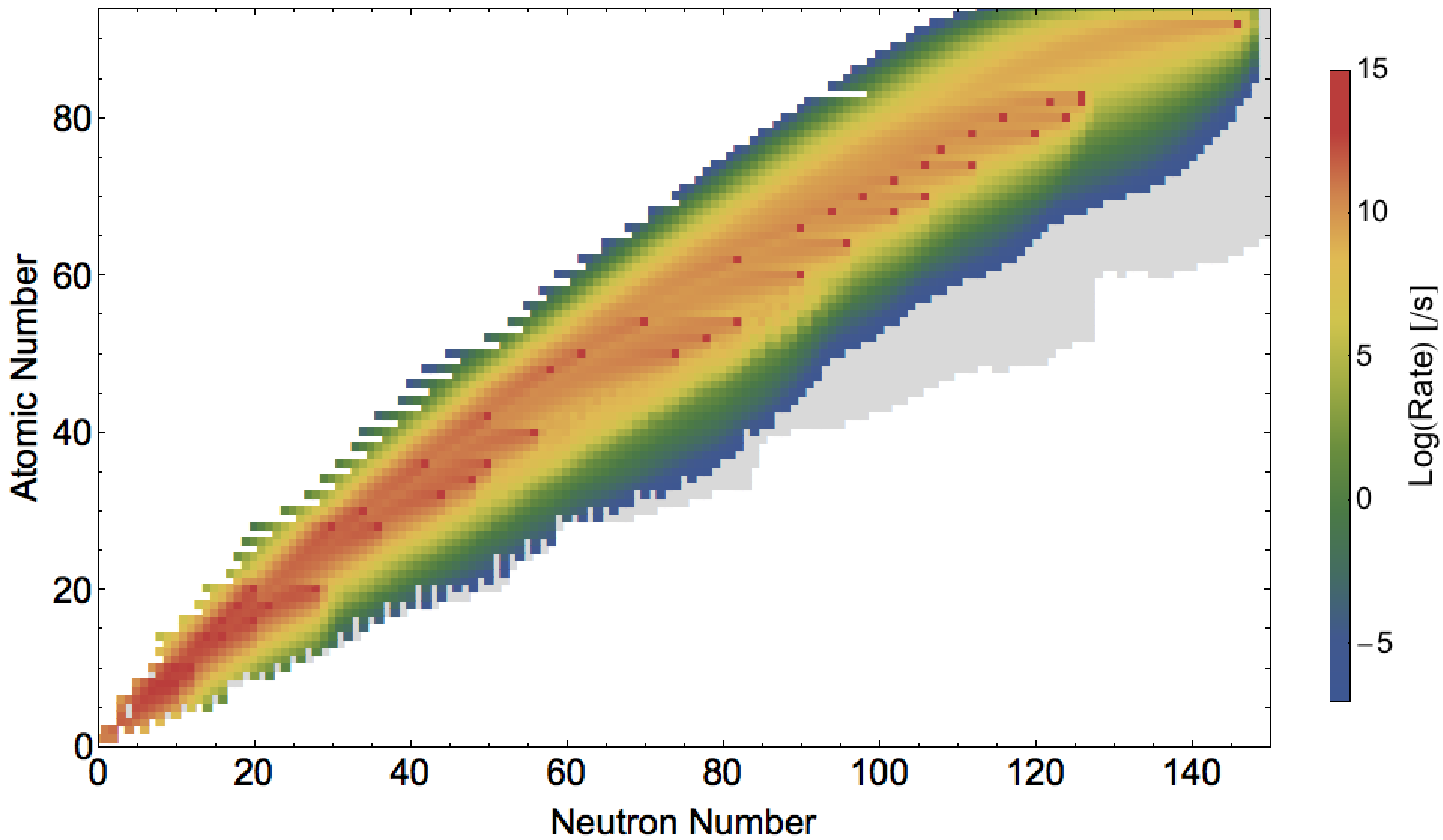


RIB production: fragmentation (FRIB)



Scientific Reach of FRIB – Rare Isotope Beam Rates

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

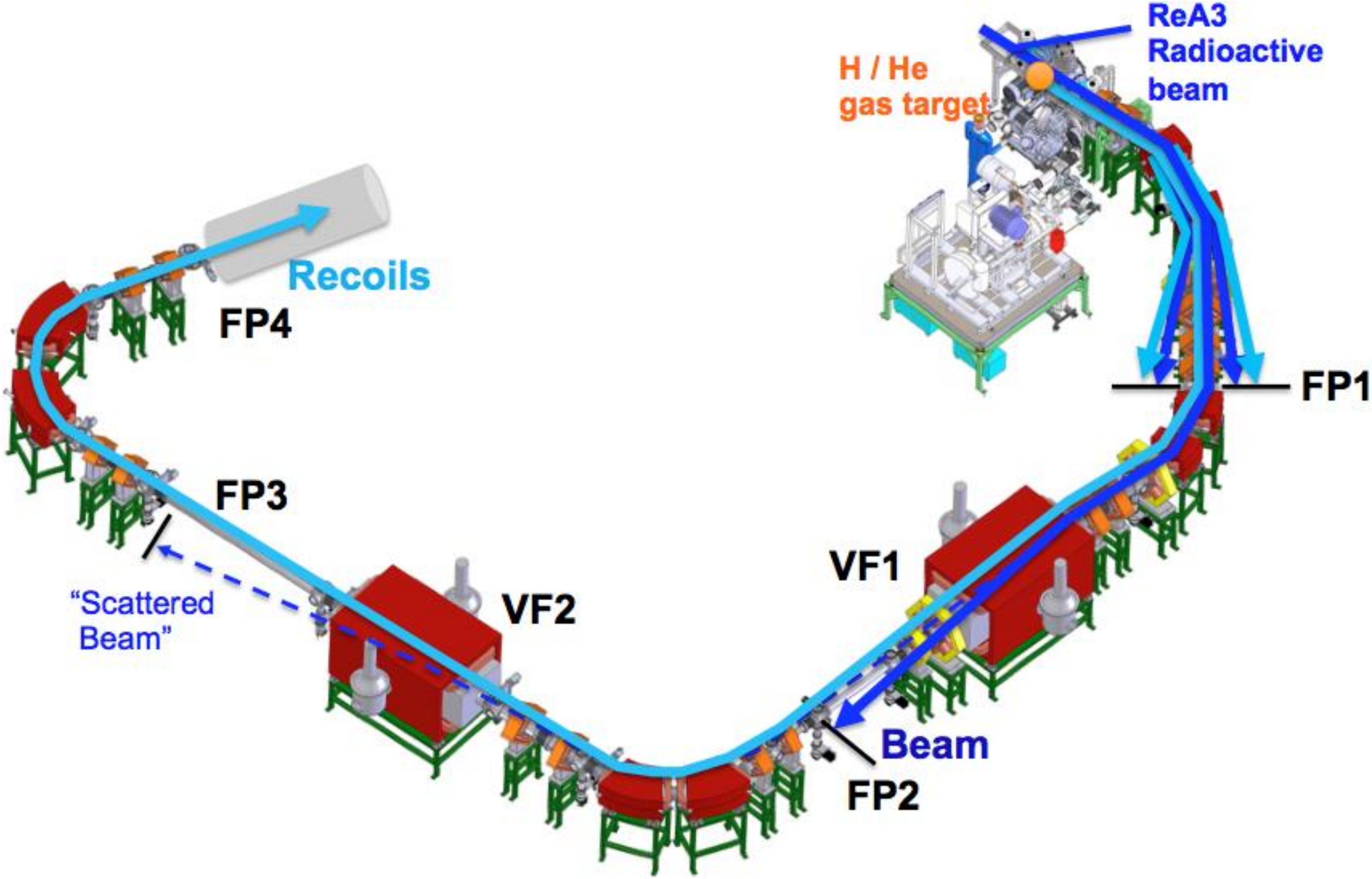


FRIB

Civil construction complete

Technical construction well underway for completion in 2022 (possibly 2021)

SECAR at NSCL/FRIB



SECAR at NSCL/FRIB

Thank you for your attention!