September 24-25, 2009
HIM @ APCTP

# Prospects for Nuclear Astrophysics Experiments at KoRIA

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Ewha Womans University

# Outline

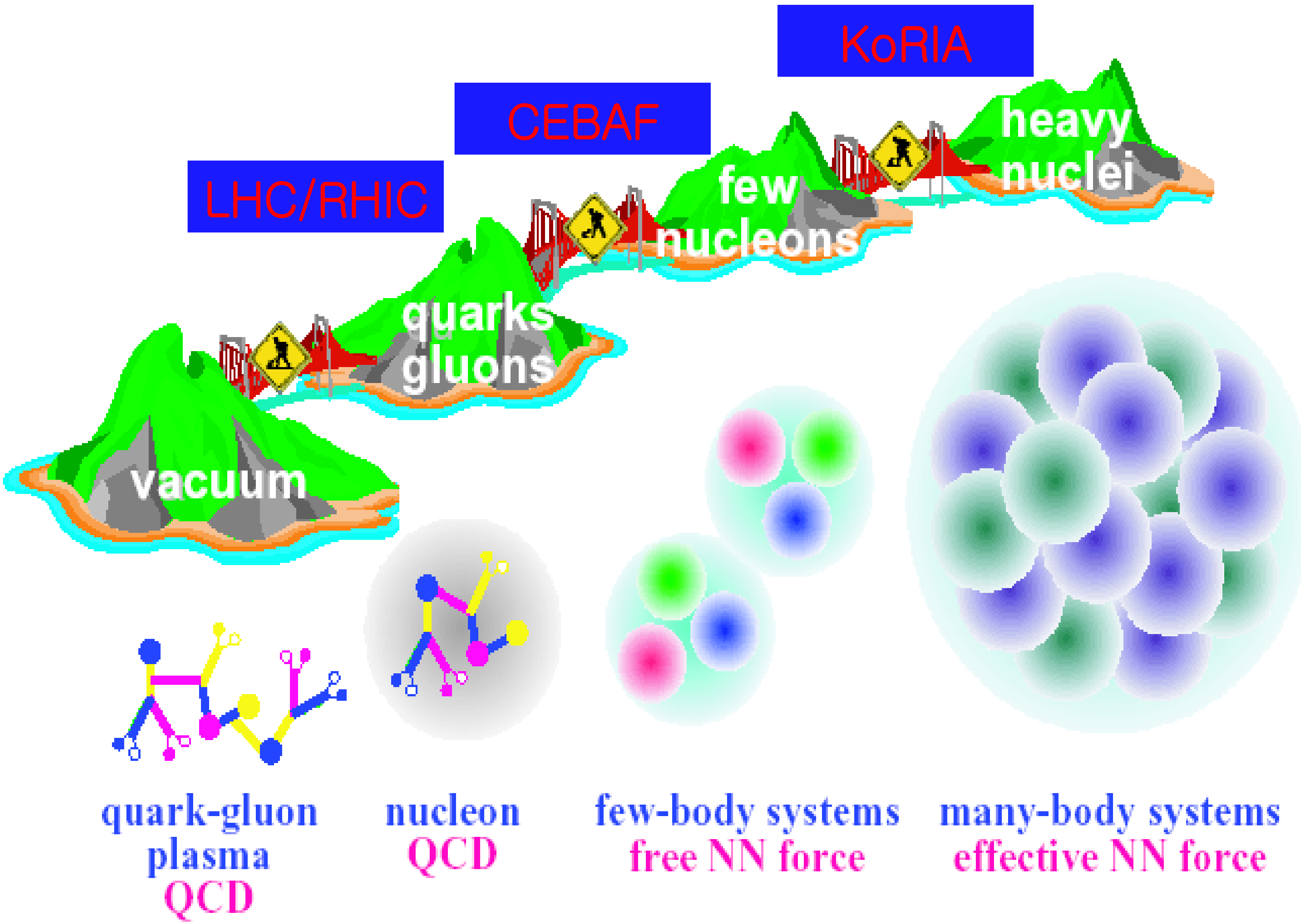
- Introduction
  - KoRIA
  - Nuclear Astrophysics
- Experimental Considerations
  - Why radioactive ion beams?
  - Direct Measurements with RIB
- Experiments with RIB
  - Experiments @ RIKEN, TRIUMF, ORNL
- Summary

# What is KoRIA(가칭)?

- KoRIA stands for Korea Rare Isotope (Radioactive Ion) Accelerator.
- Accelerator facility for producing RI beams.
- Under the Basic Science Institute (기과연)

# Physics Objectives

- Nuclear Physics
  - New Radioactive Isotopes
  - New, comprehensive understanding of nuclei
- Nuclear Astrophysics
  - Properties of radioactive isotopes
  - Cross section measurements with RIB
- Origin of elements in the Universe


LHC/RHIC
CEBAF
KoRIA
vacuum
quarks
gluons
few
nucleons
heavy
nuclei
quark-gluon
plasma
QCD
nucleon
QCD
few-body systems
free NN force
many-body systems
effective NN force

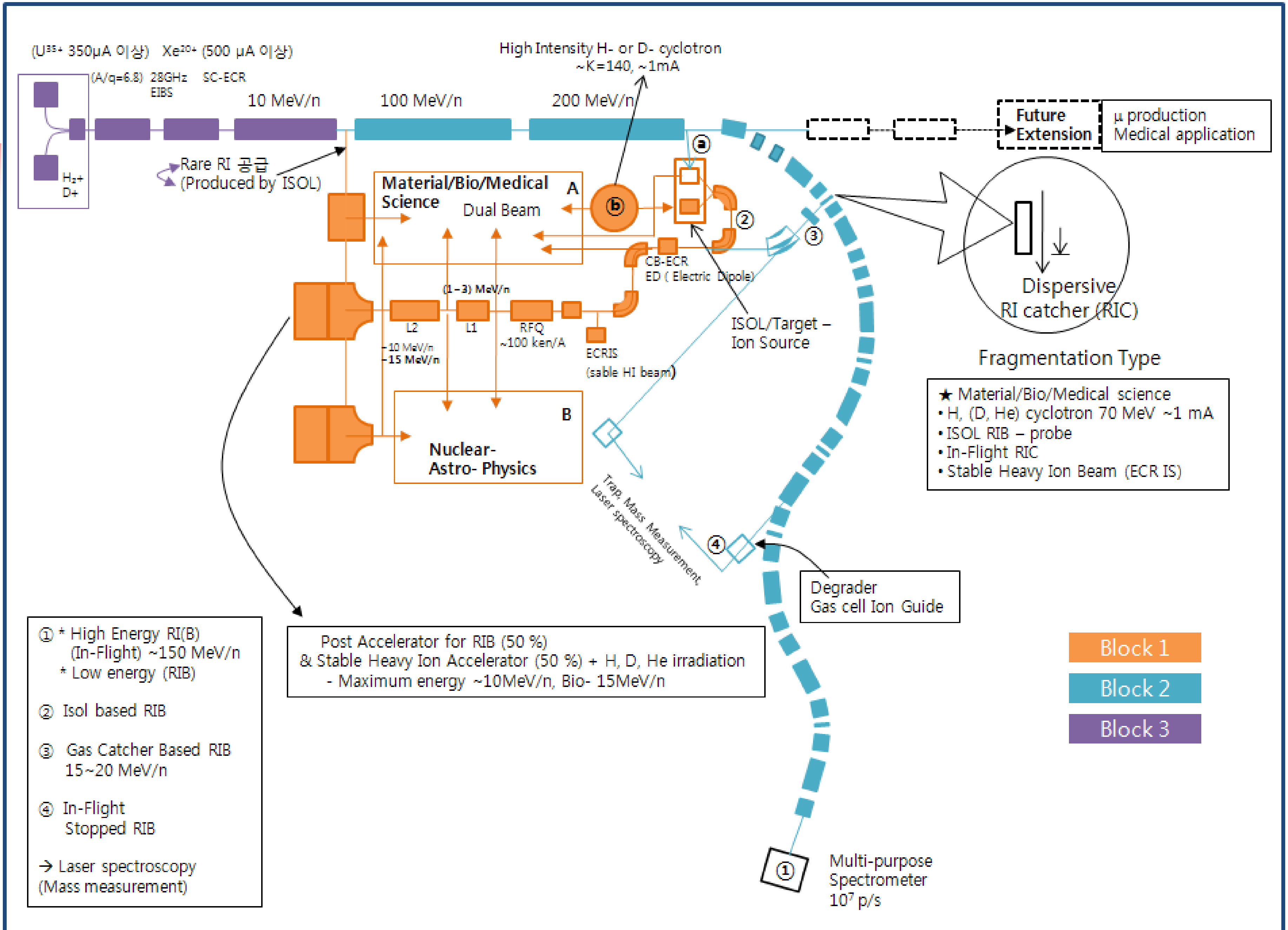
# Proposed Specs.

- Superconducting Linear Accelerator
  - U : 200 MeV/u
  - U : 2 microA
  - In-flight fragmentation / fission
- Cyclotron
  - Proton : 50 MeV
  - ISOL
- Re-acceleration of RIB from ISOL

# Budget & Time Line

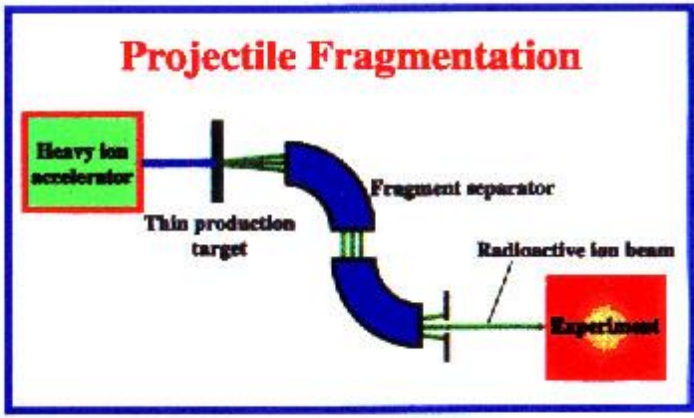
- Budget
  - 460 Billion Wons ( ~$460M)
  - In-flight fragmentation / fission
- Time line
  - 2009 – 2011 : CDR, TDR
  - 2012 – 2016 : Construction
  - ~2015 : First Experiments with KoRIA

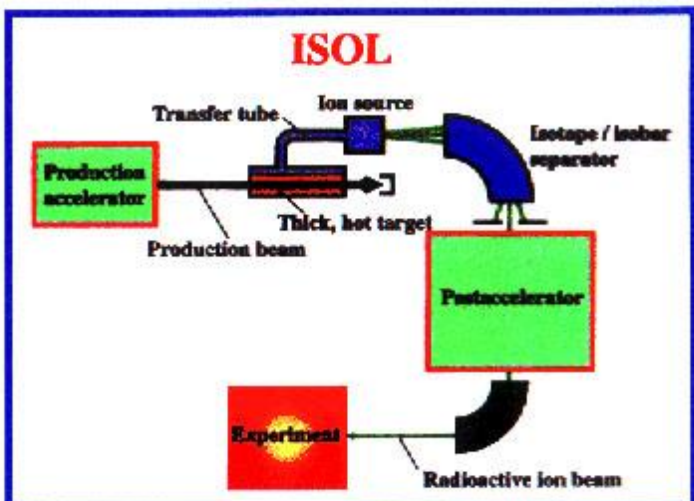
# Tentative Facility Schematic Diagram



John M. D'Auria

# Production of Radioactive Ion Beams




Projectile Fragmentation Based

**In-Flight Fragmentation**
**(heavy ion energetic beams)**

- NSCL (MSU)
- GSI (Germany)
- RIKEN (Japan)
- GANIL (France)

**ISOL Method**
**(2 accelerators)**

- ISOLDE (Cern)
- Louvain (Belgium)
- ISAC (Canada)
- HRIBF (ORNL)
- SPIRAL (France)
- Jyvaskala (Finland)
- (EXCYT) (Italy)

**TAMU,UND**

**Future : FRIB, KoRIA, EURISOL**

# Nuclear Astrophysics

- Some of the most compelling questions in nature
  - How were the elements from iron to uranium made?
  - How does the sun shine for so many years?
  - What is the total density of matter in the universe?
  - How do the stars, galaxies evolve?
- Require a considerable amount of nuclear physics information as input

# 80 Years of Nuclear Astrophysics

## A Story of Success

1928 Gamow-Factor
George Gamow

1931 Stellar Structure & Theory of White Dwarfs
Subramanyan Chandrasekhar

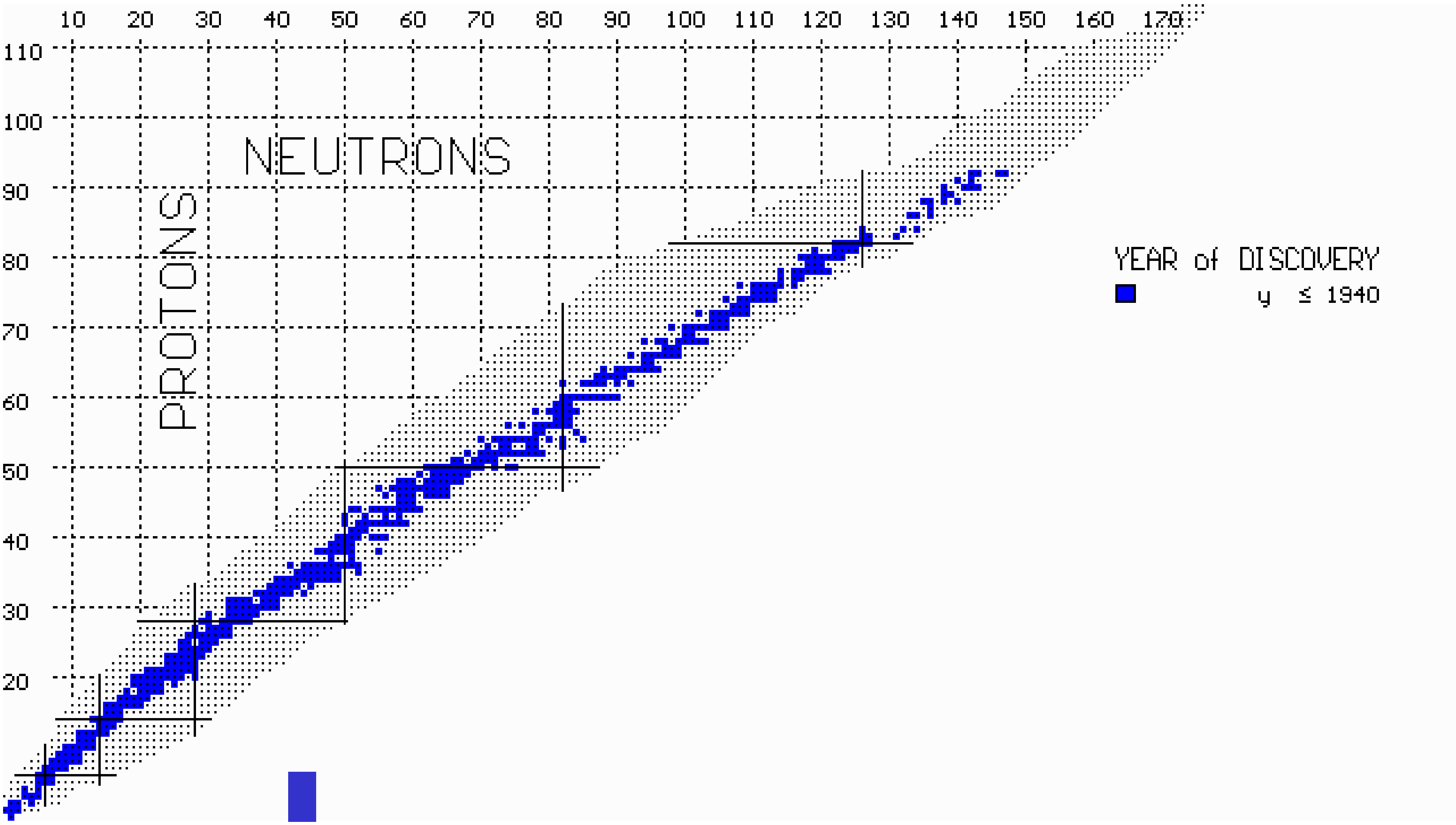
1938 CNO Cycle - C. F. von Weizsacker
CNO Cycle, pp Chain - Hans Bethe

1957 Nucleosynthesis of Elements in Stars
Margaret &Geoffrey Burbridge, William Fowler and Fred Hoyle = $B^2FH$

1983 Nobel Prize: William Fowler
Subramanyan Chandrasekhar

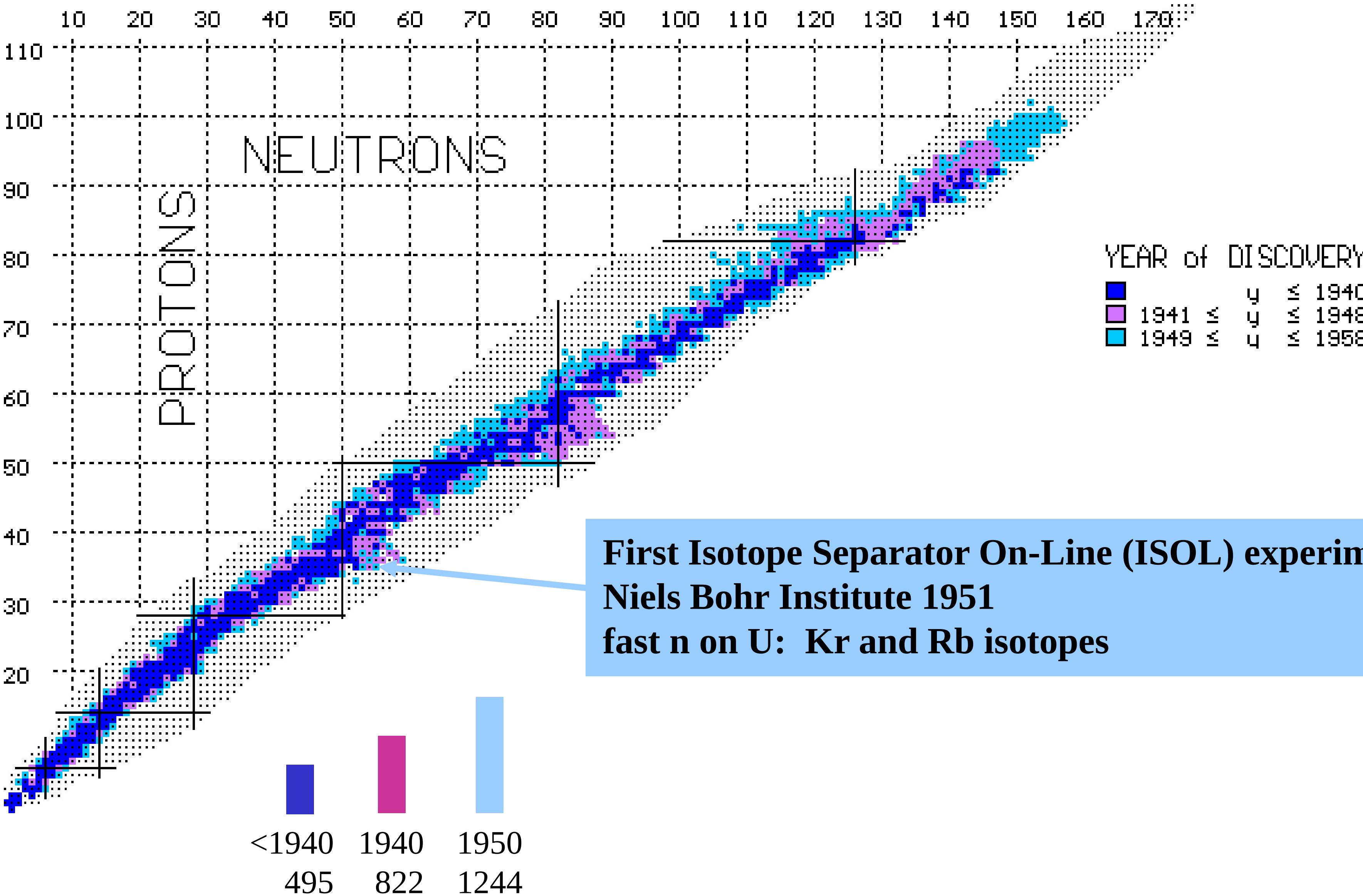
2002 Nobel Prize for Neutrino Detection
Raymond Davis & Masatoshi Koshiba
X-ray Astronomy - Riccardo Giacconi

# The exploration of the chart of nuclei



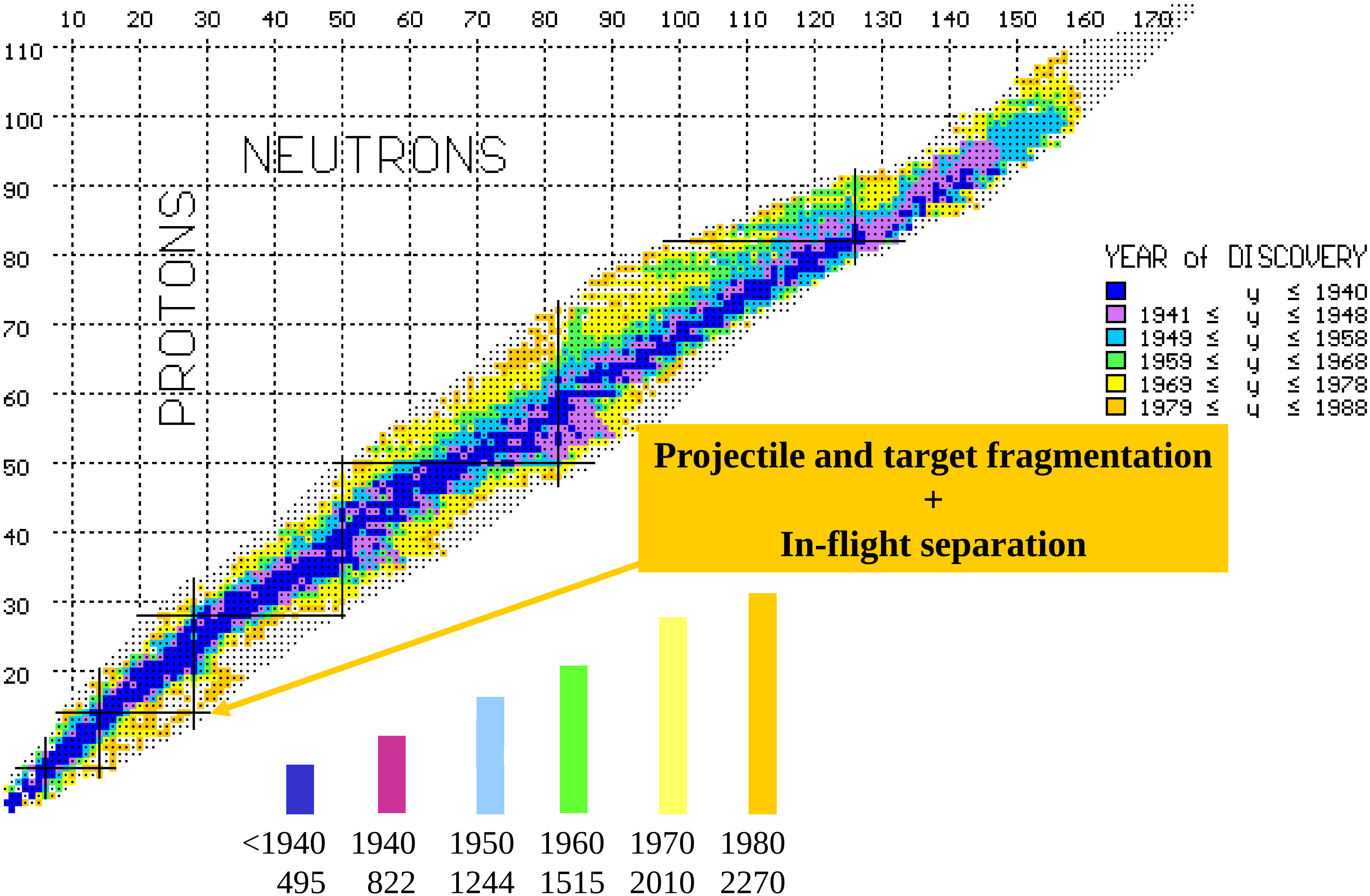

<1940
495

# The exploration of the chart of nuclei

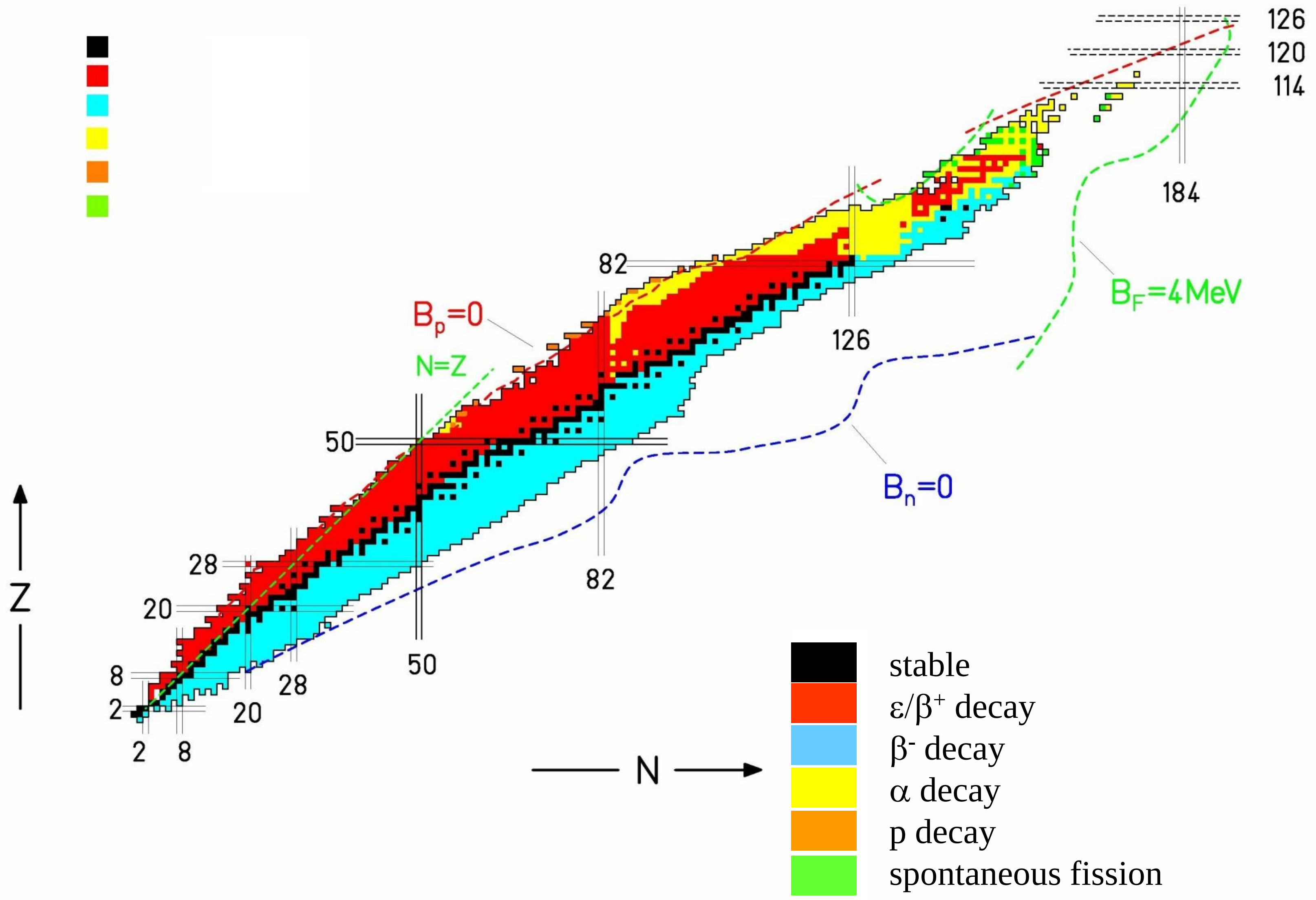



**First Isotope Separator On-Line (ISOL) experiment**
**Niels Bohr Institute 1951**
**fast n on U: Kr and Rb isotopes**

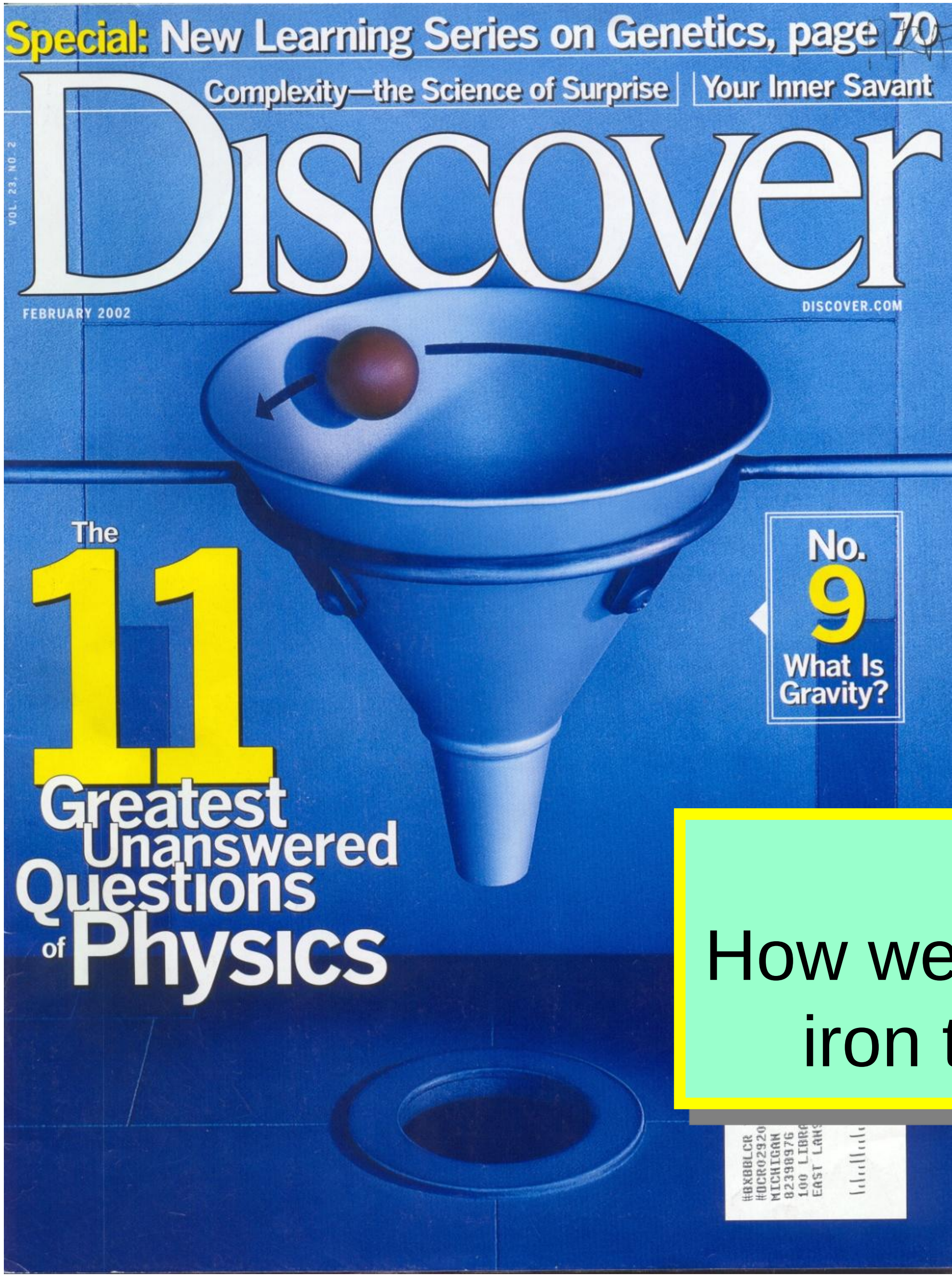
# The exploration of the chart of nuclei



# The present chart of nuclei




| 293 | 2,771 | 3,064 | NNDC (BNL, 2000) |
|---|---|---|---|



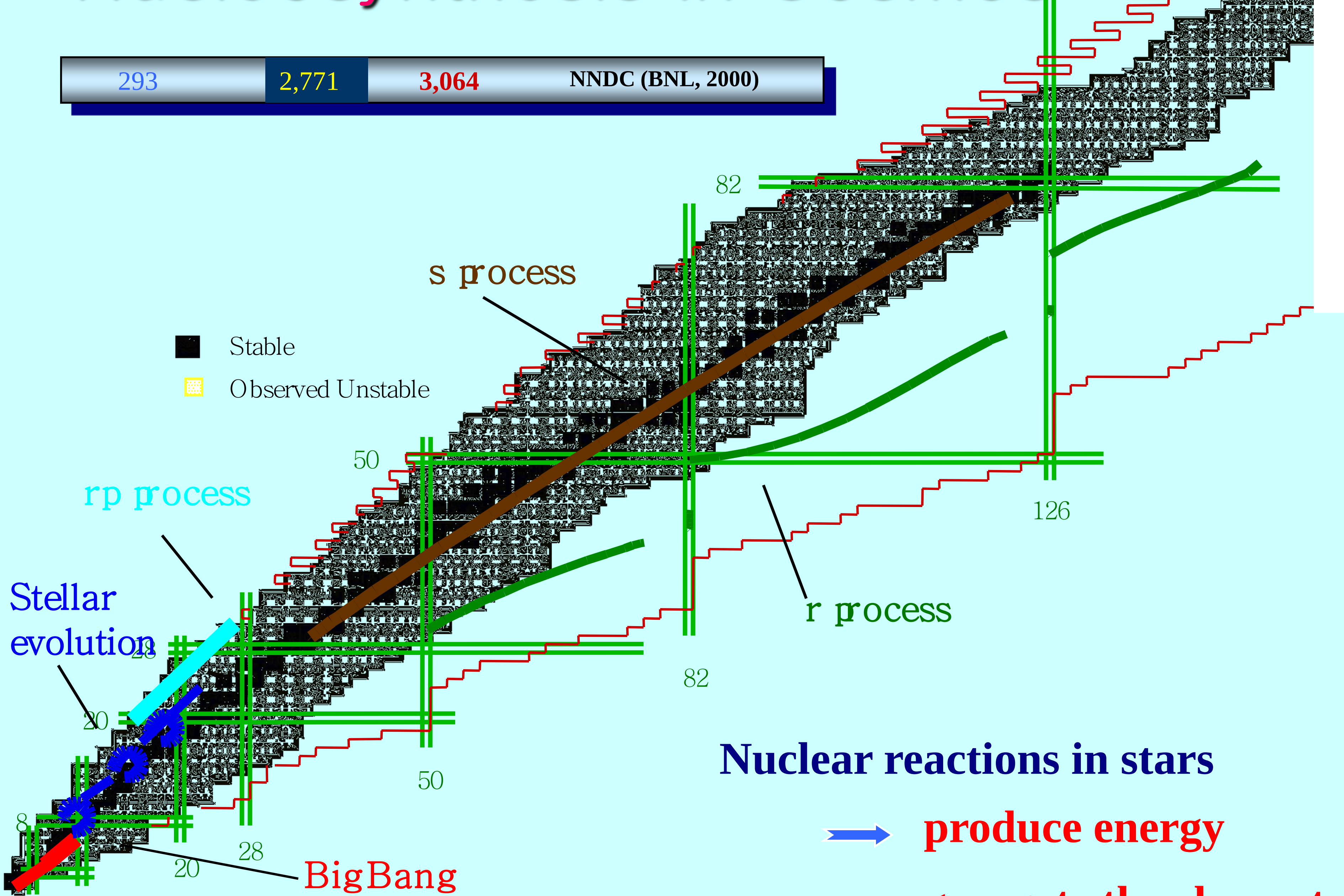

Based on National Academy of Science Report

[Committee for the Physics of the Universe (CPU)]

**Question 3**

How were the elements from iron to uranium made ?

# Nucleosynthesis in Cosmos

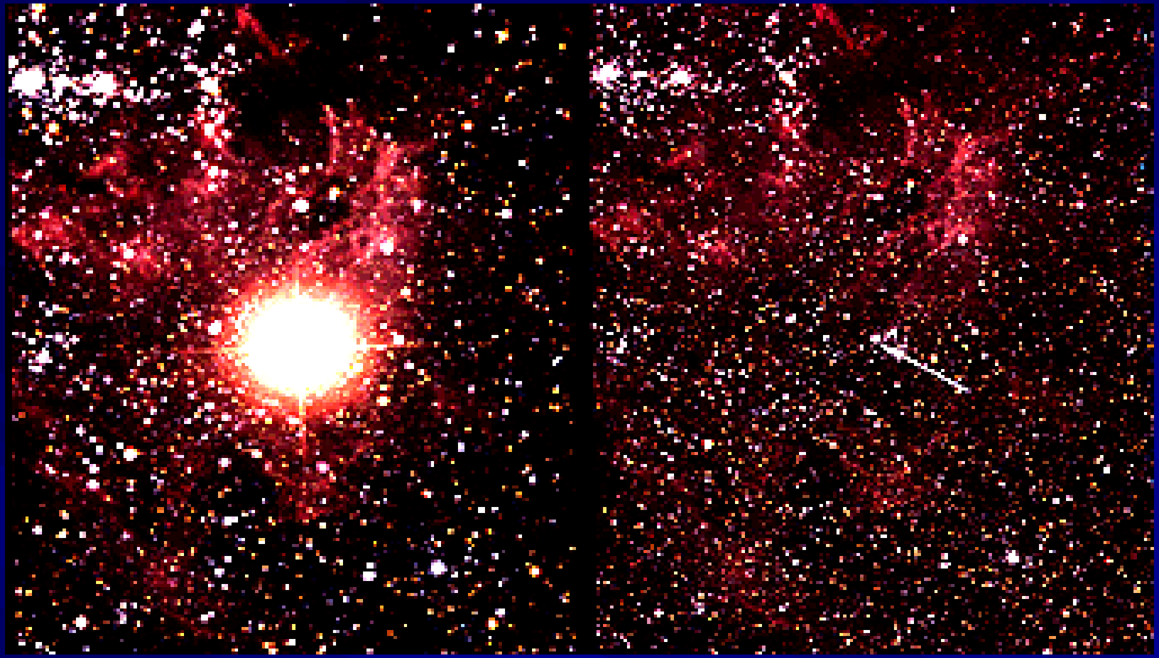



**Nuclear reactions in stars**

→ **produce energy**

→ **generate the elements**

# Experimental Nuclear Astrophysics



Nuclear reactions in stars

→ produce energy

→ generate the elements

Lab studies of reaction cross-sections

# Astrophysically Important Nuclear Reactions

$^{7}Be(p,\gamma)^{8}B$

$^{8}Li(\alpha,n)^{11}B$

$^{12}C(\alpha,\gamma)^{16}O$

$^{14}O(\alpha,p)^{17}F$

$^{15}O(\alpha,\gamma)^{19}Ne$

$^{17,18}F(p,\alpha)^{14,15}O$

$^{25}Al(p,\gamma)^{26}Si$

$^{44}Ti(\alpha,p)^{47}V$

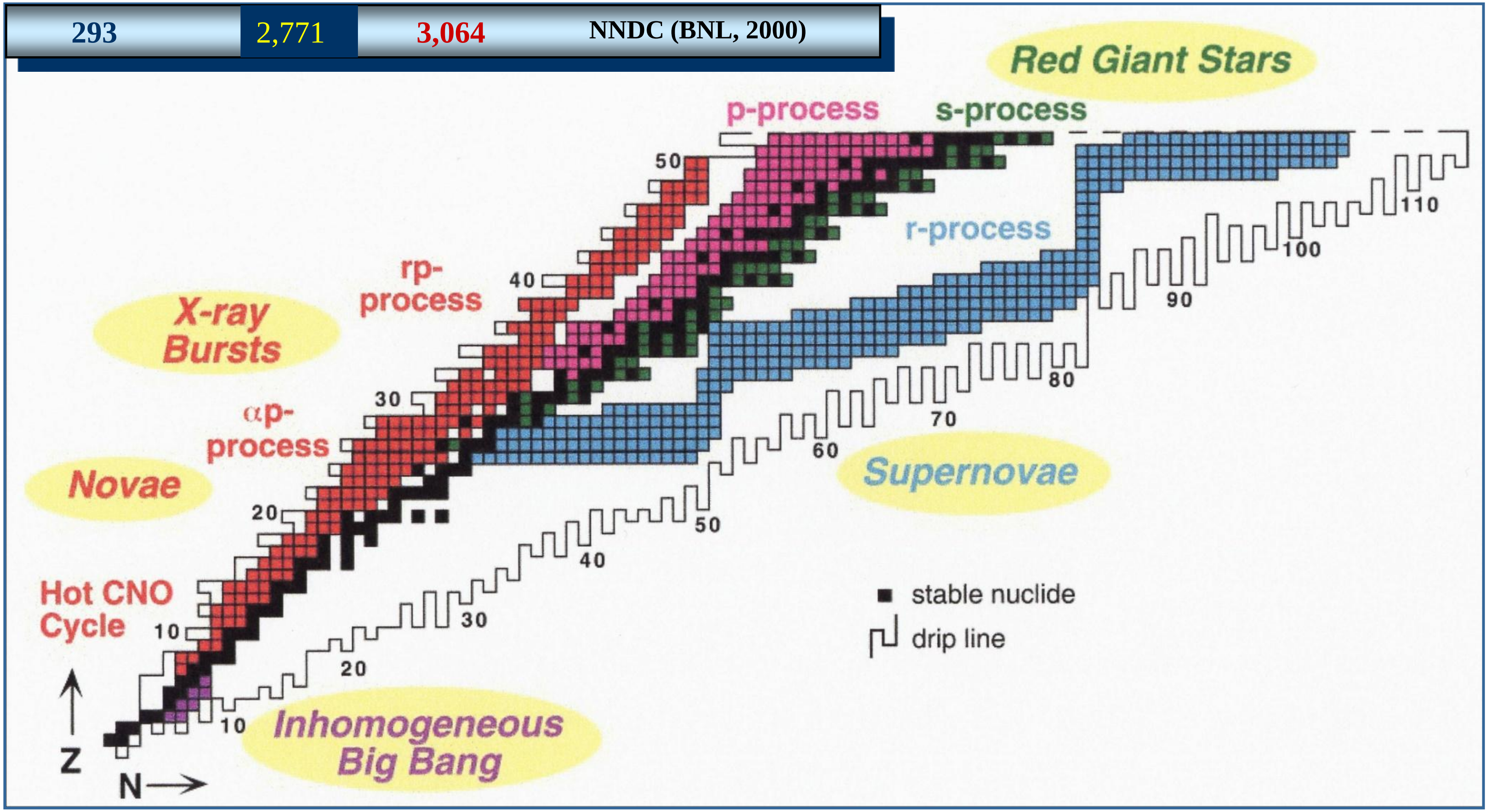
$^{56}Ni(p,\gamma)^{57}Cu$

$^{85}Kr(n,\gamma)^{86}Kr$

$^{134}Cs(n,\gamma)^{135}Cs$

and many others

M.S. Smith and K.E. Rehm,
Ann. Rev. Nucl. Part. Sci, 51 (2001)

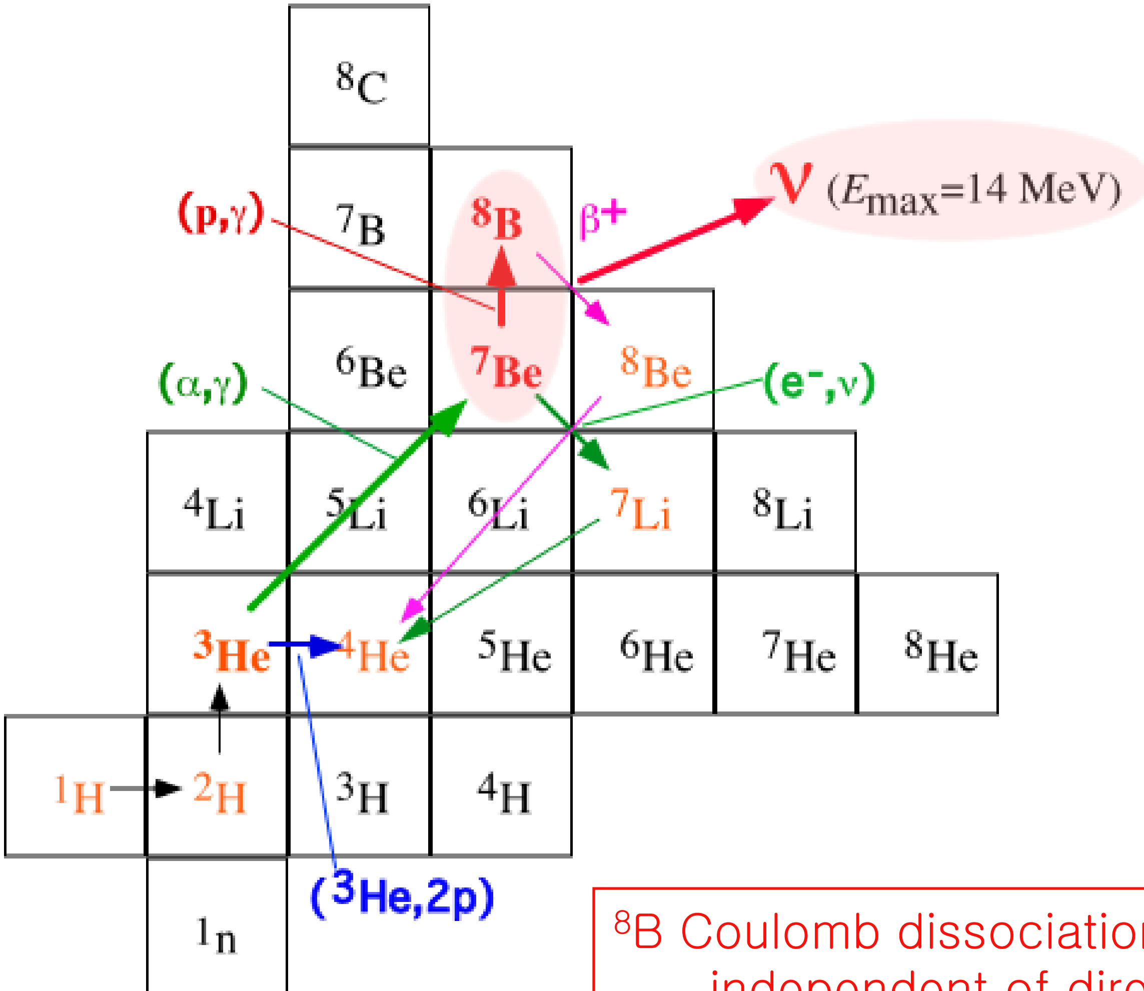



In many cosmic phenomena, radioactive nuclei play an influential role, hence the need for Radioactive Ion Beams

- 1985 by Fowler
  - "We stand on the verge of one of those exciting periods which occur in science from time to time. ...there is an urgent need for data on the properties and interactions of radioactive nuclei ... for use in nuclear astrophysics."

$^{7}Be(p,\gamma)^{8}B$

# p-p chain in the sun

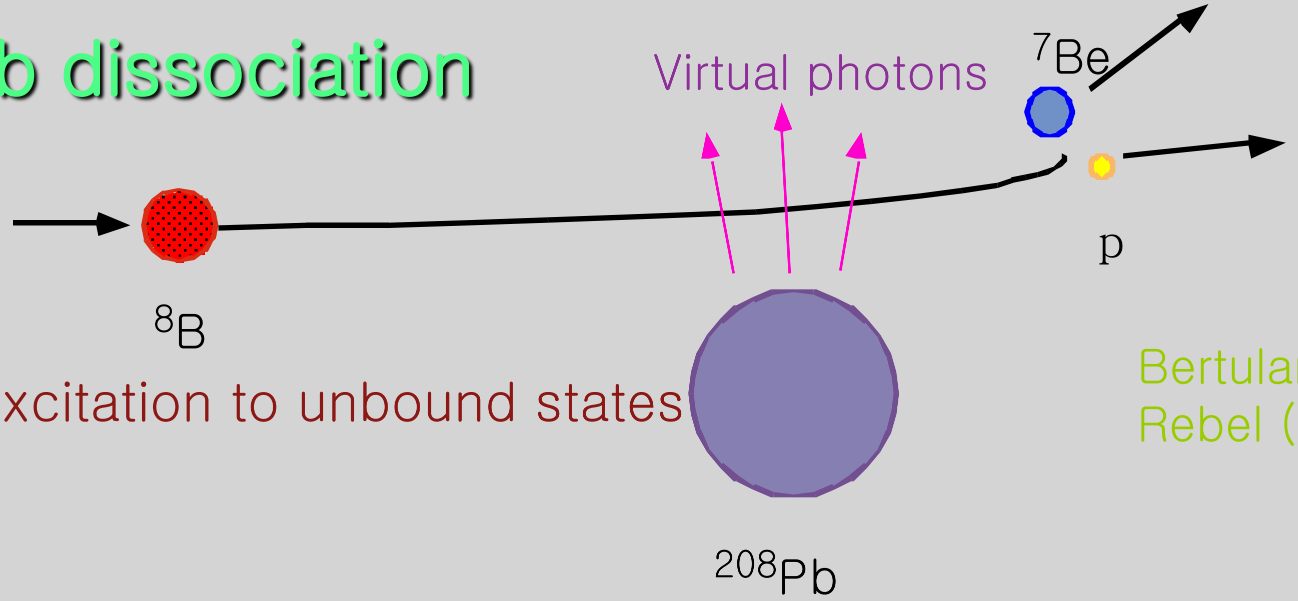



$^{8}B$ Coulomb dissociation:
independent of direct measurements

From Motobayashi

Santa Tecla

# Coulomb dissociation




= Coulomb excitation to unbound states

Bertulani, Baur, Rebel (1986)

$^8$B+$^{208}$Pb –> $^7$Be+p+$^{208}$Pb (C.D.)

virtual photon theory or DWBA

$^8$B($\gamma$,p)$^7$Be (abs.)

detailed balance

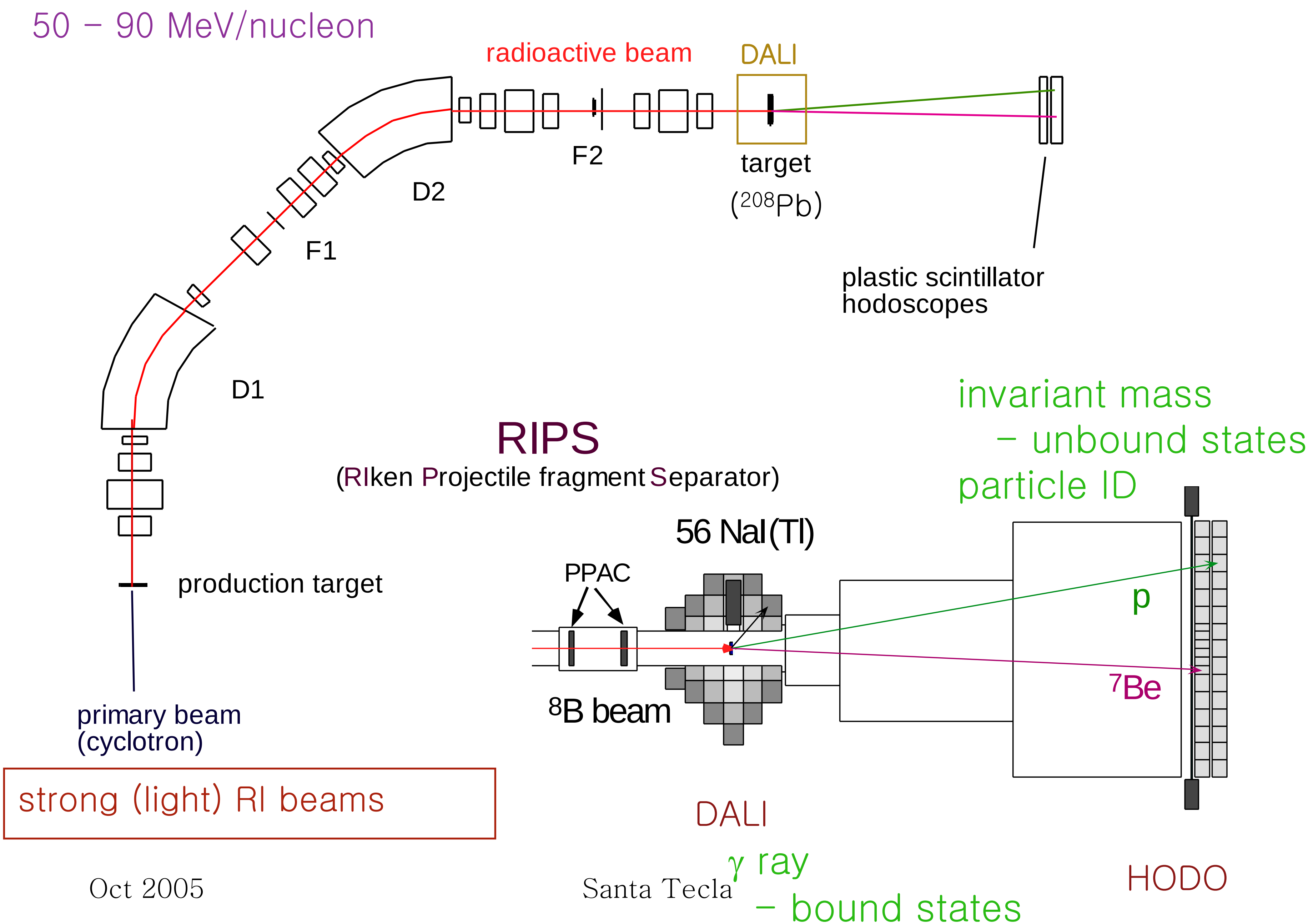
$^7$Be(p,$\gamma$)$^8$B (capt.)

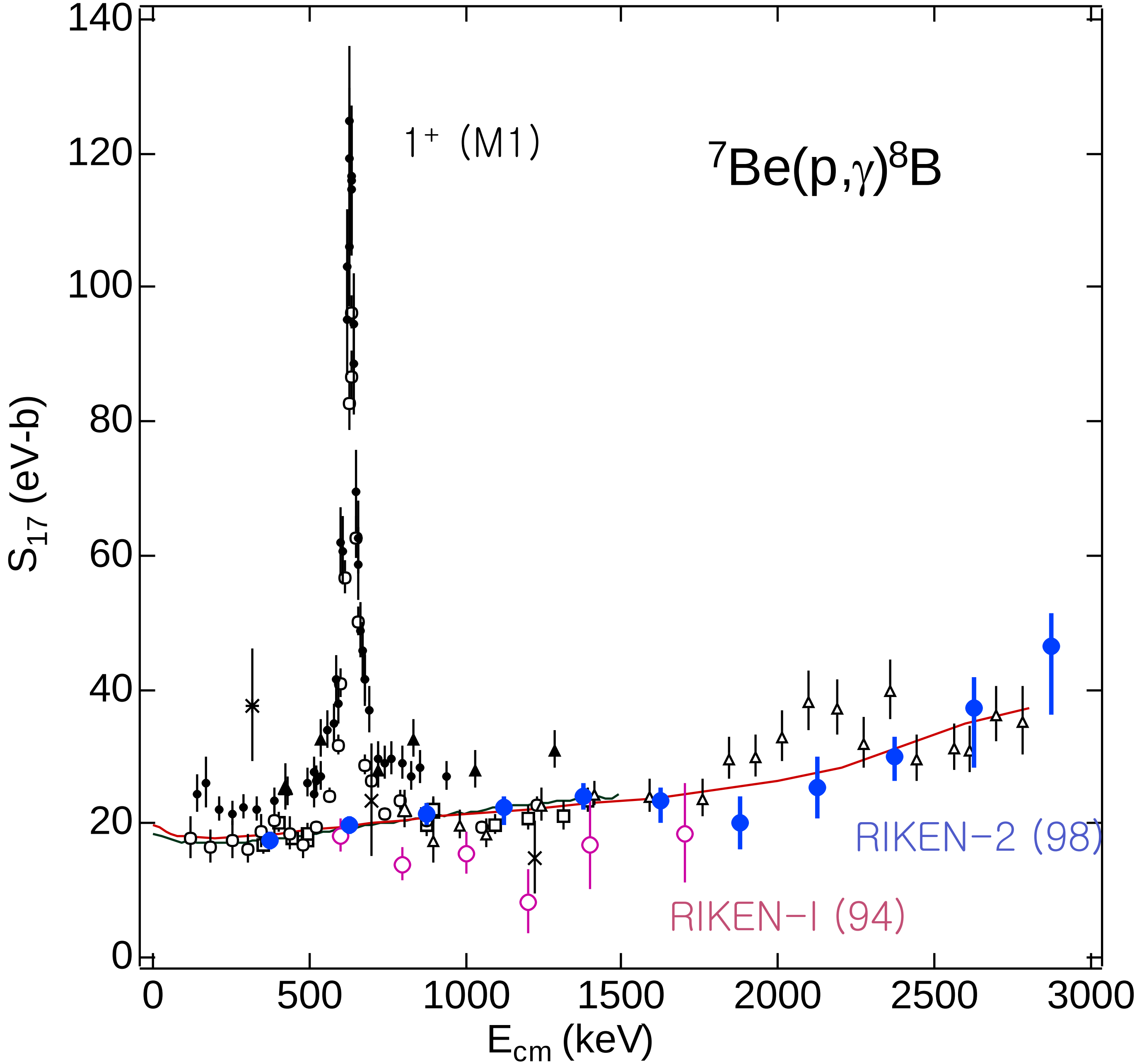
large $\sigma$

thick target (intermediate energy)

experiments with R.I. beams

# spectroscopy of unstable nuclei



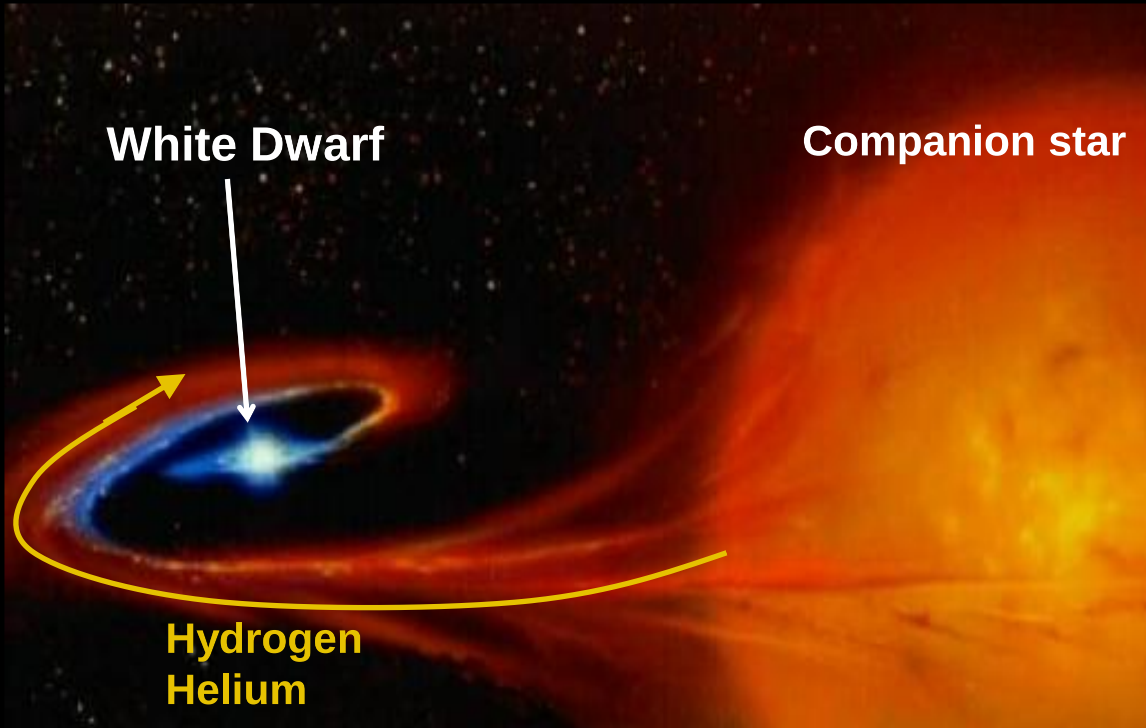




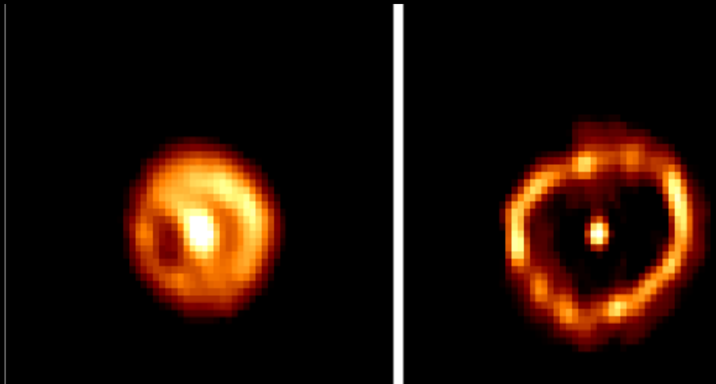

RIKEN-1: PRL 73, 2680 (1994)

# Nova models

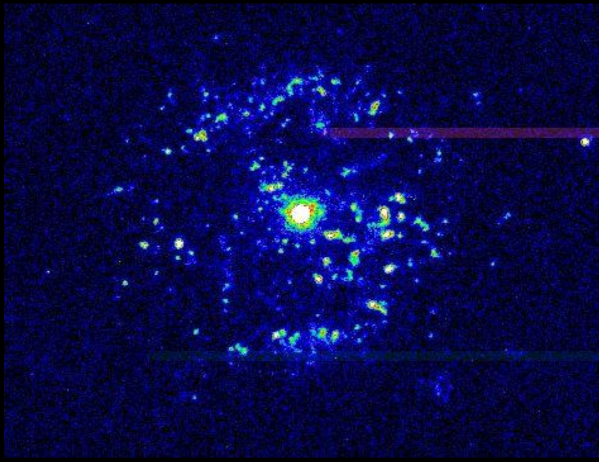
Explosion: thermonuclear runaway on surface of
accreting white dwarf



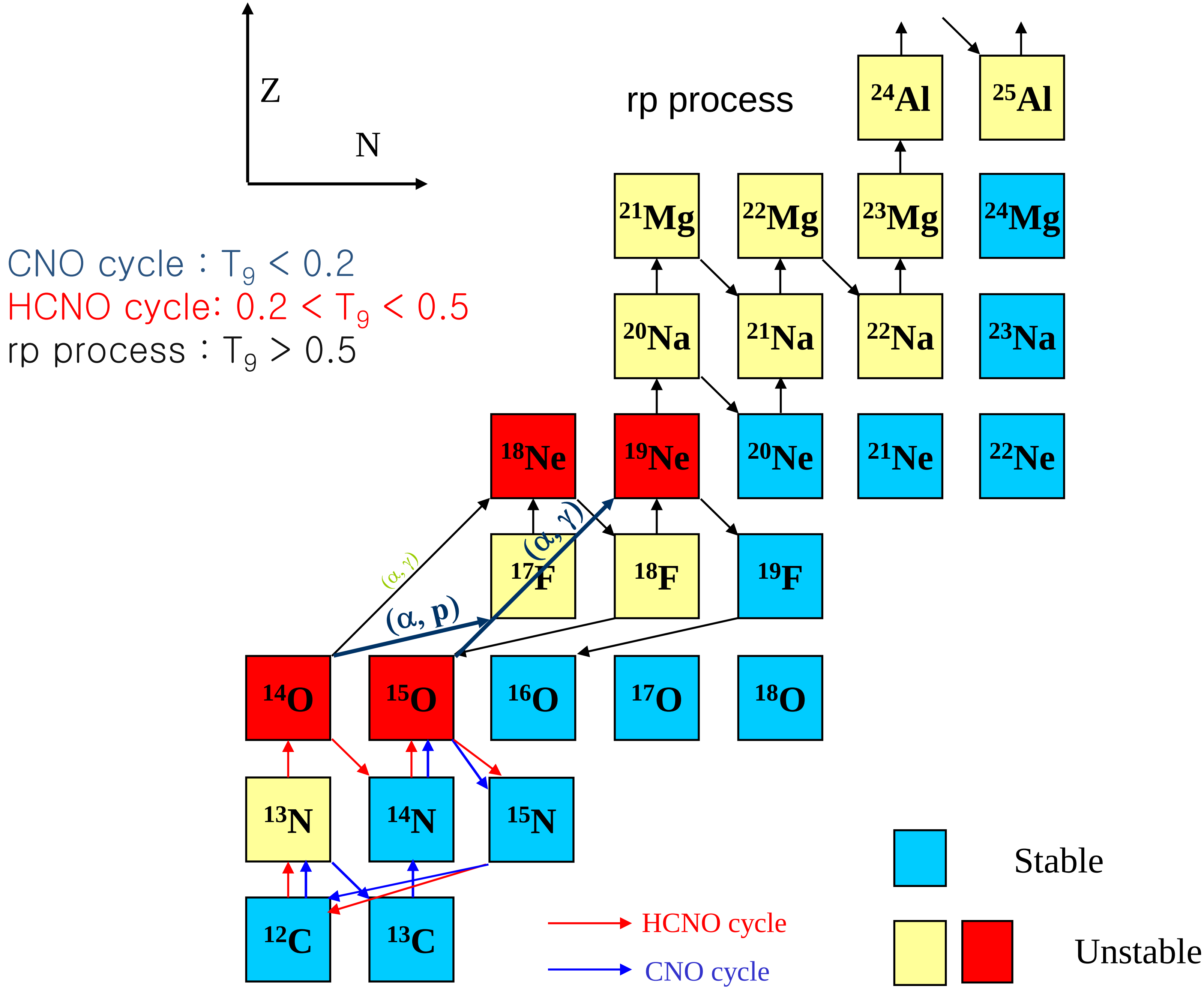
# Nova observations

Nova Cygni



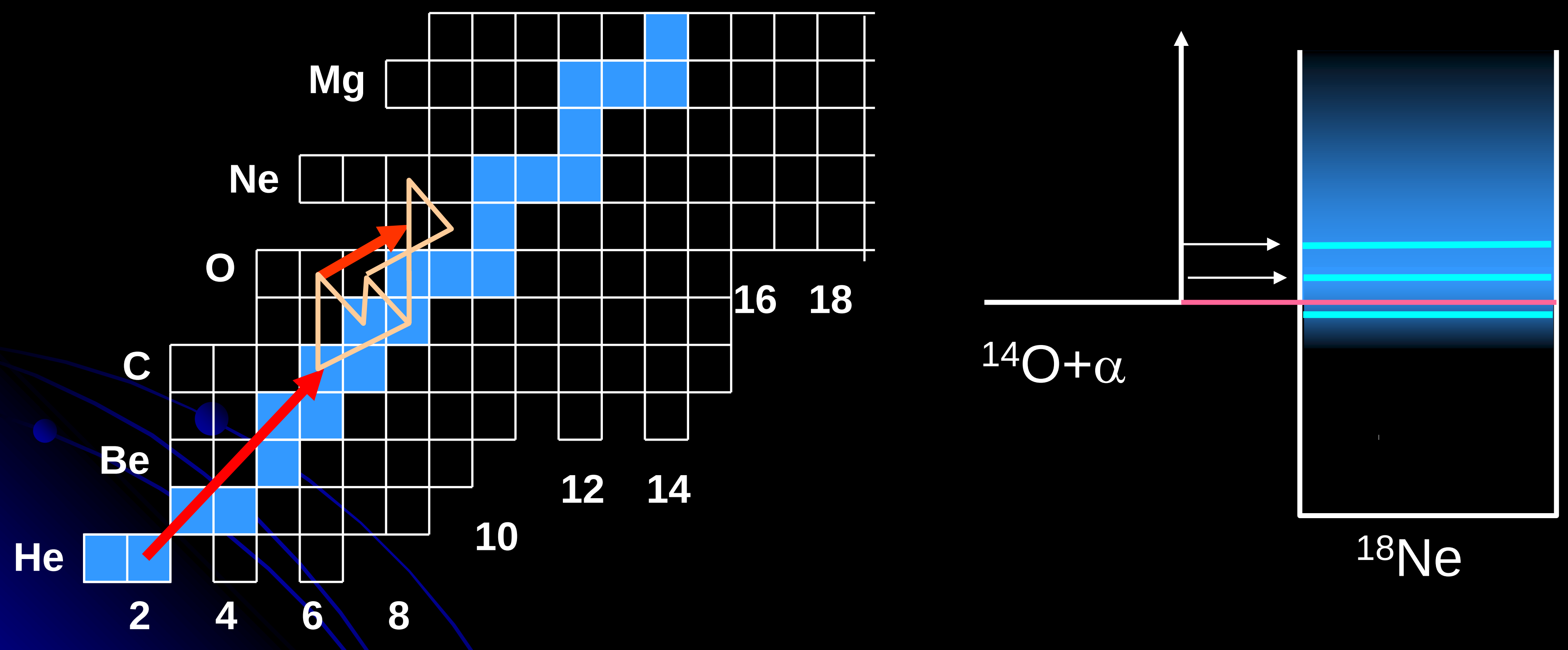
Nova Persei



Z
N
CNO cycle : $T_9 < 0.2$
HCNO cycle: $0.2 < T_9 < 0.5$
rp process : $T_9 > 0.5$
rp process
$^{24}$Al
$^{25}$Al
$^{21}$Mg
$^{22}$Mg
$^{23}$Mg
$^{24}$Mg
$^{20}$Na
$^{21}$Na
$^{22}$Na
$^{23}$Na
$^{18}$Ne
$^{19}$Ne
$^{20}$Ne
$^{21}$Ne
$^{22}$Ne
$(\alpha, \gamma)$
$(\alpha, \gamma)$
$^{17}$F
$^{18}$F
$^{19}$F
$(\alpha, p)$
$^{14}$O
$^{15}$O
$^{16}$O
$^{17}$O
$^{18}$O
$^{13}$N
$^{14}$N
$^{15}$N
$^{12}$C
$^{13}$C
HCNO cycle
CNO cycle
Stable
Unstable

# Break-Out: $^{14}O(\alpha,p)$

$^{14}O(\alpha,p)^{17}F$

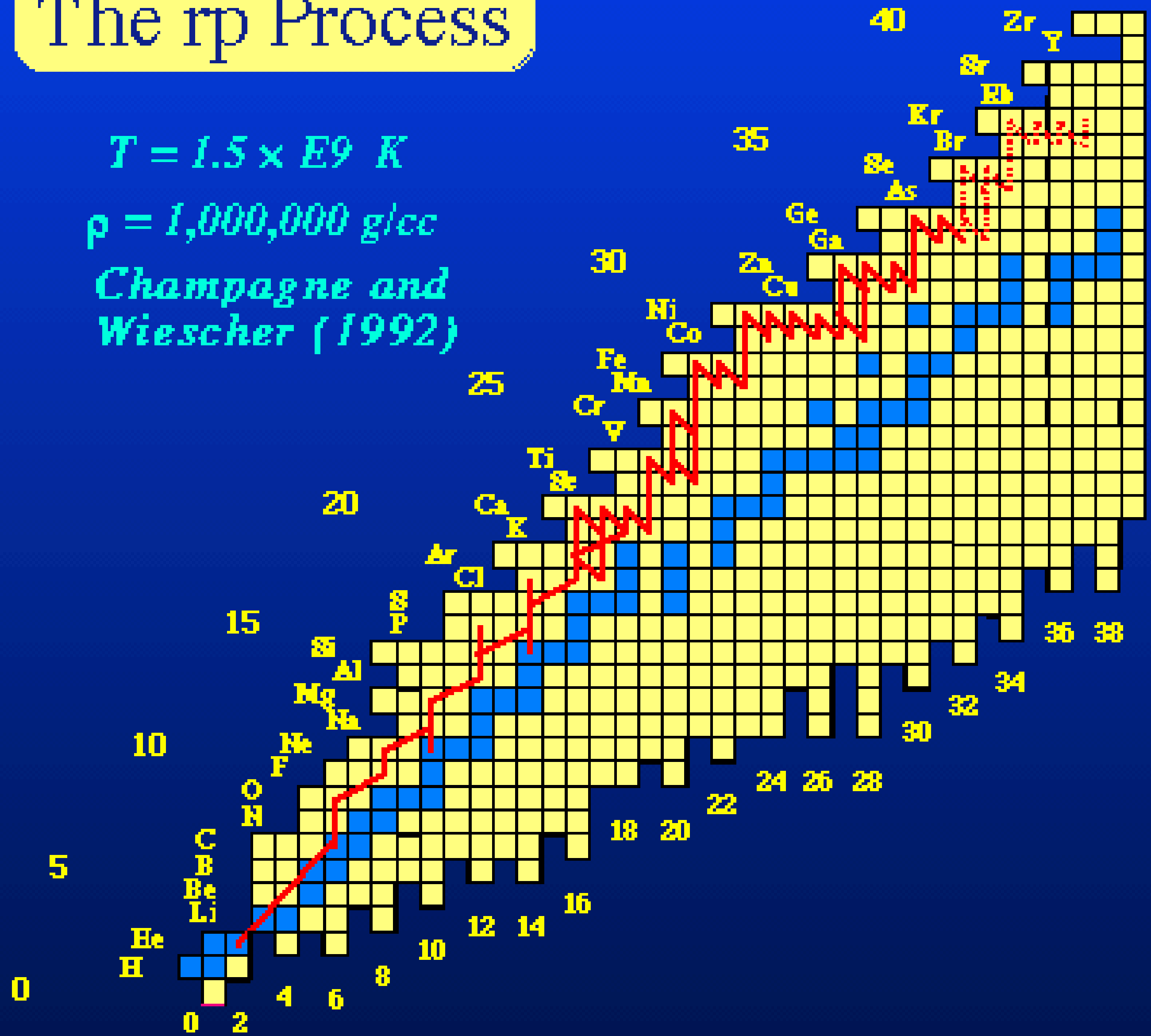


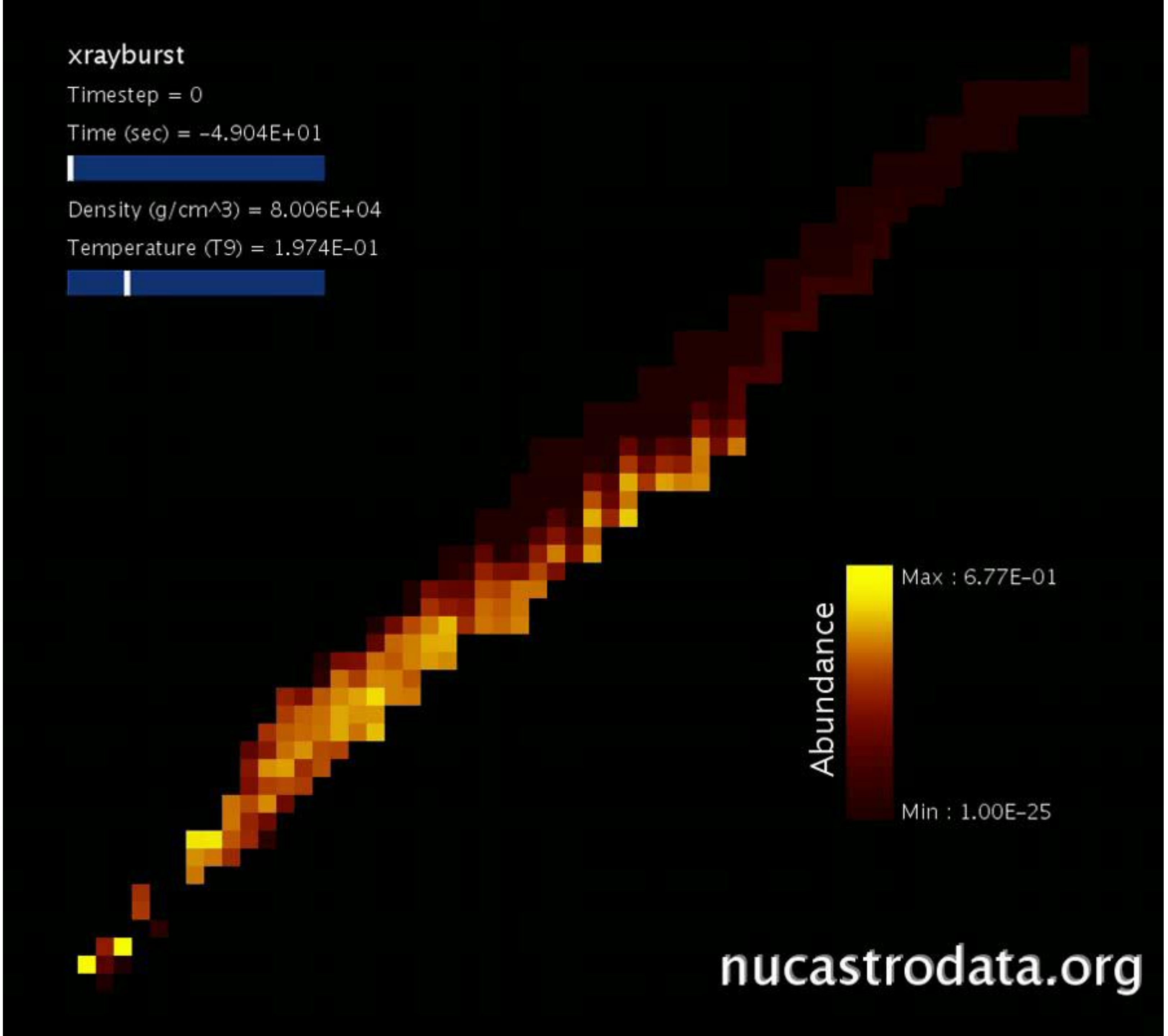
# The rp Process

*T = 1.5 x E9 K*

*ρ = 1,000,000 g/cc*

*Champagne and Wiescher (1992)*




xrayburst
Timestep = 0
Time (sec) = -4.904E+01
Density (g/cm^3) = 8.006E+04
Temperature (T9) = 1.974E-01
Abundance
Max : 6.77E-01
Min : 1.00E-25
nucastrodata.org

# Experimental considerations

Nucleosynthetic reactions are typically dominated by Coulomb barriers

$$E_B = \frac{Z_1 Z_2 e^2}{R} = \frac{1.44 Z_1 Z_2}{R(fm)} \; MeV$$

$$E_T \approx kT = 8.62 \times 10^{-8} T \; keV$$

| | |
|---|---|
| $T \approx 10^8 \; K$ | $\mathrm{E_T} \approx 10$ keV |
| $\mathrm{d} + \mathrm{p} \rightarrow {}^{3}\mathrm{He} + \gamma$ | $\mathrm{E_B} \approx 400$ keV |
| ${}^{17}\mathrm{F} + \mathrm{p} \rightarrow {}^{18}\mathrm{Ne} + \gamma$ | $\mathrm{E_B} \approx 2.52$ MeV |
| ${}^{14}\mathrm{O} + \alpha \rightarrow {}^{18}\mathrm{Ne} + \gamma$ | $\mathrm{E_B} \approx 4.00$ MeV |

Large Coulomb barrier makes direct measurement of the reaction rates almost impossible

Stellar reaction rate

$$S(E) \equiv \sigma(E)E \exp\left(\frac{2\pi Z_1 Z_2 e^2}{\hbar v}\right)$$

$$\lambda = \langle \sigma v \rangle = \int_0^\infty \sigma(E) v(E) \Psi(E) dE$$

$$= \int_0^\infty \frac{S(E)}{E} \exp(-bE^{-1/2}) \sqrt{\frac{2E}{\mu}} \frac{2}{\sqrt{\pi}} \frac{E}{kT} \exp\left(-\frac{E}{kT}\right) \frac{dE}{(kTE)^{1/2}}$$

$$= \left(\frac{8}{\mu\pi}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \frac{S(E)}{E} \exp\left(-\frac{E}{kT} - bE^{-1/2}\right) dE$$

# Hahn et al. PRC (1996)

TABLE V. Summary of $^{18}$Ne states with $E_x \geq 4$ MeV.

| $^{16}O(^3He,n)\ ^{18}Ne$ | | $^{12}C(^{12}C,^6He)\ ^{18}Ne$ [a] | $^{20}Ne(p,t)\ ^{18}Ne$ [b] | | |
|---|---|---|---|---|---|
| $E_x$ (MeV ± keV) | Γ (keV) | $E_x$ (MeV ± keV) | $E_x$ (MeV ± keV) | Γ (keV) | $J^\pi$ |
| 4.520 ± 7 | 9 ± 6 | | 4.520[c] | | $1^-$ [d] |
| 4.561 ± 9 | 25[e] | | | | $3^+$ |
| 4.589 ± 7 | 4 ± 4 | | 4.589[c] | | $0^+$ [d] |
| 5.106 ± 8 | 50 ± 10 | | 5.106[c] | 49 ± 6; 45 ± 5[f] | $2^+$ |
| 5.153 ± 8 | ≤20 | | 5.153[c] | ≤20; ≤15[f] | $3^-$ |
| 5.454 ± 8 | ≤20 | 5.45[g] | | | $2^-$ |
| 6.15 ± 10 | ≤40 | 6.15 ± 20 | | | $(1^-)$ |
| 6.30 ± 10 | | | 6.286 ± 10 | ≤20 | $(3^-)$ |
| 6.35 ± 10 | | | 6.345 ± 10 | 45 ± 10 | $(2^-)$ |
| 7.07 ± 10 | 200 ± 40 | | | | |
| (7.05 ± 30) | (≤120) | | | | $(4^+)$ |
| (7.12 ± 30) | (≤120) | 7.12 ± 20 | | | |
| 7.35 ± 18 | ≤50 | 7.35 ± 20 | | | $(1^-)$ |
| | | 7.62 ± 20 | | | |
| 7.72 ± 10 | ≤30 | 7.73 ± 20 | | | |
| 7.94 ± 10 | 40 ± 10 | 7.94 ± 20 | 7.92 ± 20 | 70 ± 20 | |
| 8.11 ± 10 | ≤30 | 8.11[g] | | | |
| | | 8.30 ± 20 | | | |
| | | (8.45 ± 30) | | | |
| | | 8.55 ± 30 | | | |
| | | 8.94 ± 20 | | | |
| | | 9.18 ± 20 | | | |
| | | 9.58 ± 20 | | | |

[a] The multiplets at $E_x$ = 4.5, 5.1, and 6.3 MeV are not resolved in the $^{12}C(^{12}C,^6He)\ ^{18}Ne$ data.
[b] From the Indiana experiment unless specified otherwise.
[c] From our $^{16}O(^3He,n)\ ^{18}Ne$ experiment.
[d] From Ref. [6].
[e] Estimated from a Woods-Saxon calculation.
[f] From the Princeton experiment.
[g] Used for the energy calibrations.

# $^{18}$Ne Low Energy Excited State

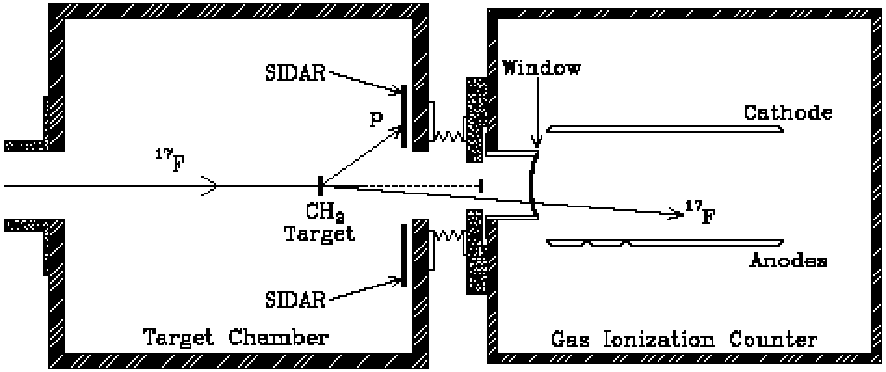



FIG. 1. Our experimental configuration is shown with the $^{17}$F ions impinging on a polypropylene target. The scattered protons were detected in the SIDAR, while recoil $^{17}$F ions were detected in coincidence in a gas-filled ionization counter.

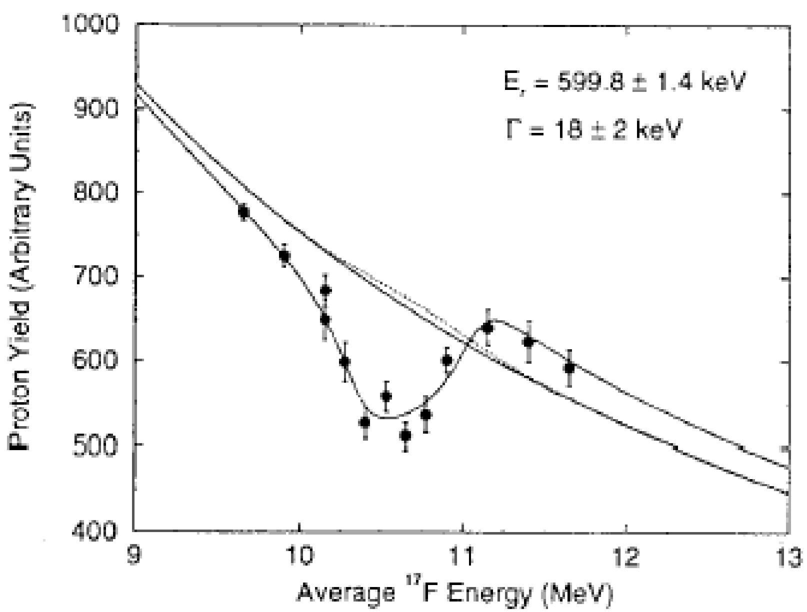



**Figure 27. The figure shows the excitation function [55] in the $^{17}$F (p,p)$^{17}$F reaction. The resonance observed defines the width and energy of the 3$^+$ state in $^{18}$Ne populated in the $^{17}$F (p, γ)$^{18}$Ne reaction (see text).**

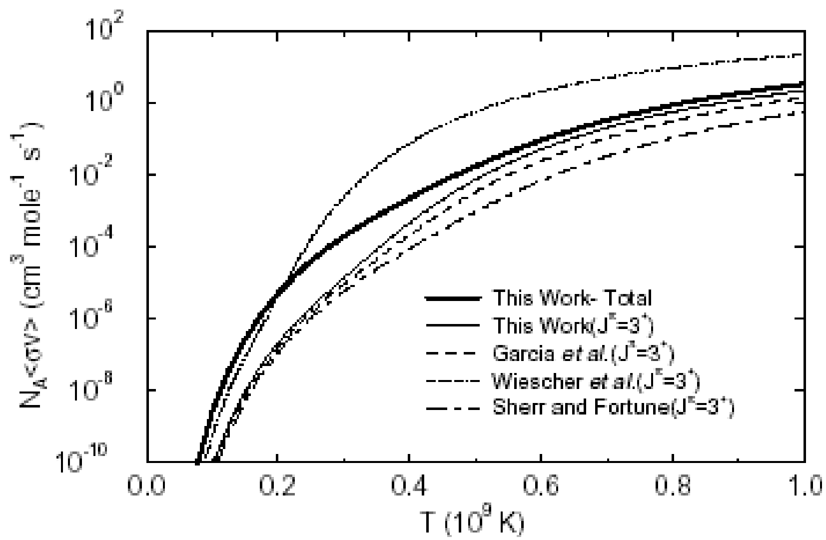



FIG. 4. The contribution to the $^{17}$F$(p,\gamma)^{18}$Ne reaction rate from the 3$^+$ state is plotted as a function of stellar temperature. This is compared to estimates of the rate from previously published predictions of the resonance parameters from García *et al.* [8], Wiescher *et al.* [7], and Sherr and Fortune [9]. The total reaction rate, which includes contributions from nearby resonances as well as direct capture, is also shown.

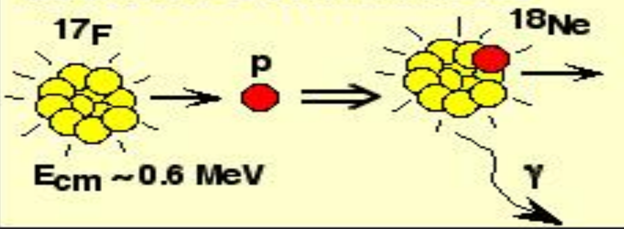
# Direct Measurements

- Desirable way to measure astrophysically important reactions over indirect methods.
- Only became possible after new generation of accelerators that can make the $^{17}F$ and $^{14}O$ radioactive ion beams in the late 90's.
- Very low cross sections
- Have to identify the experimental conditions very carefully – rely on properties obtained from indirect methods

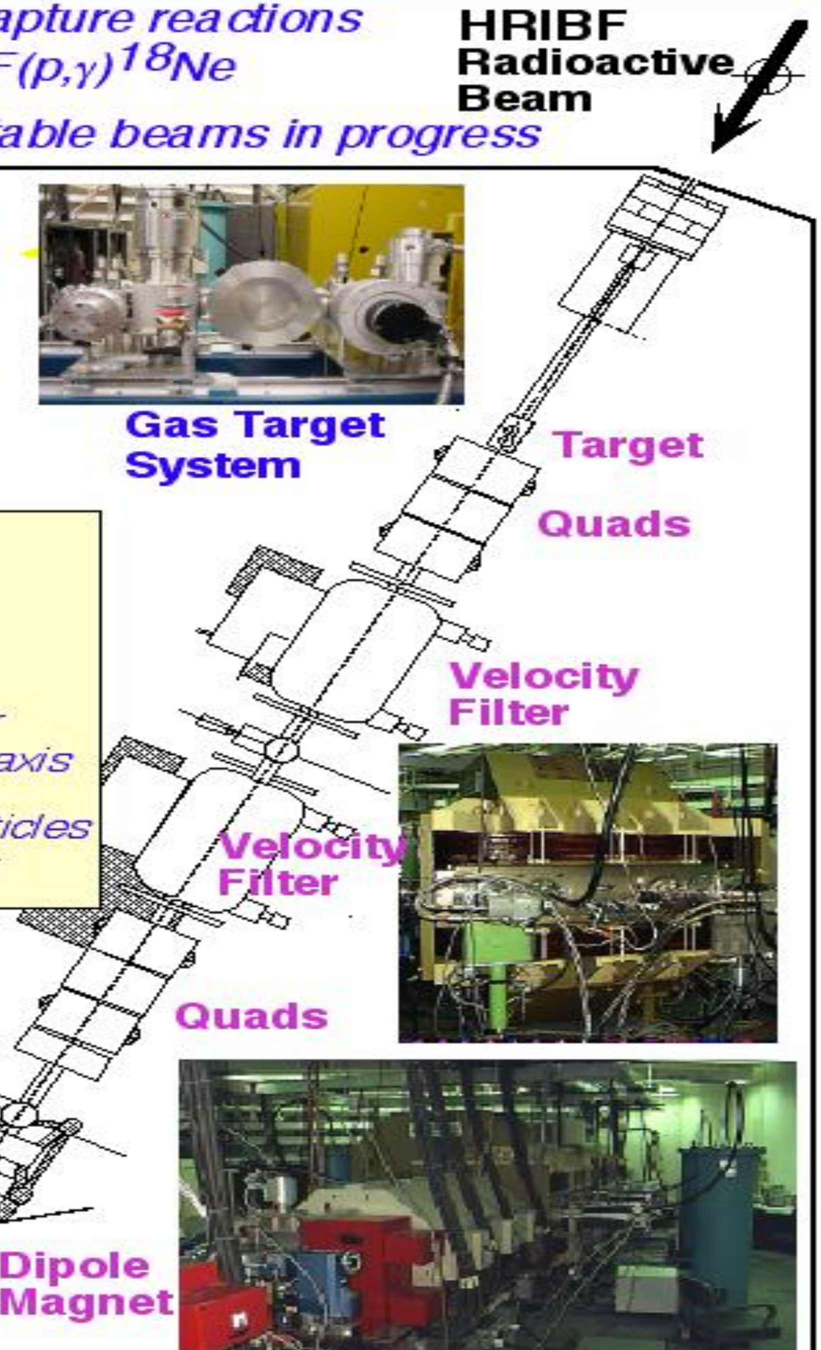
# HRIBF Daresbury Recoil Separator

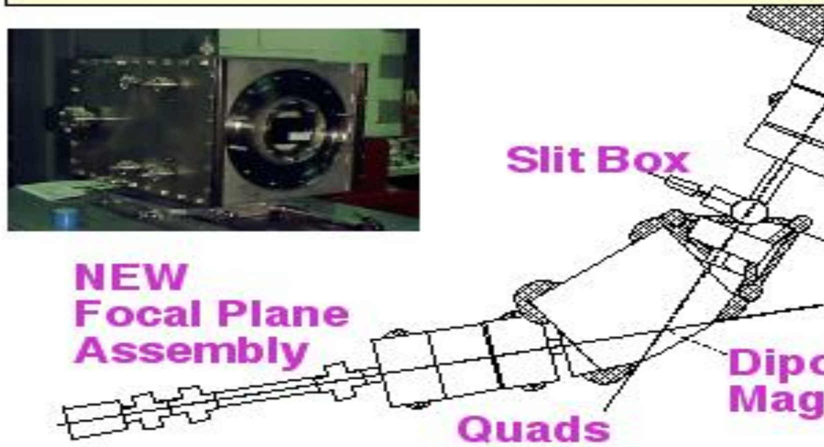
- *Utilization: measurement of capture reactions such as $^{7}Be(p,\gamma)^{8}B$ and $^{17}F(p,\gamma)^{18}Ne$*
- *Status: commissioning with stable beams in progress*

**Resonant Proton Capture in Inverse Kinematics**




- *only 1 in $10^{12}$ fuse with protons; all other beam particles pass through target*
- *all fusion reaction products and unreacted beam particles enter separator located along beam axis*
- *recoil separator deflects beam particles away, steers recoils to detector*



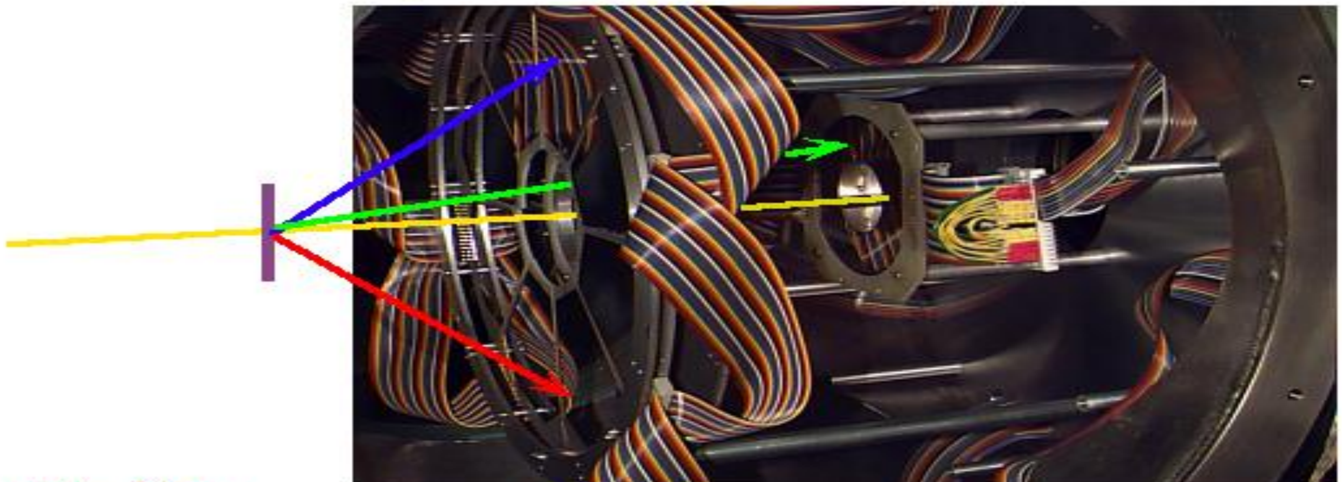
# HRIBF Silicon Detector Array (SIDAR)

## Utilization

- *measure crucial resonance parameters $^{17}F(p,p)$ ...*
- *directly measure astrophysical reactions $^{18}F(p,\alpha)$ ...*

## Specifications

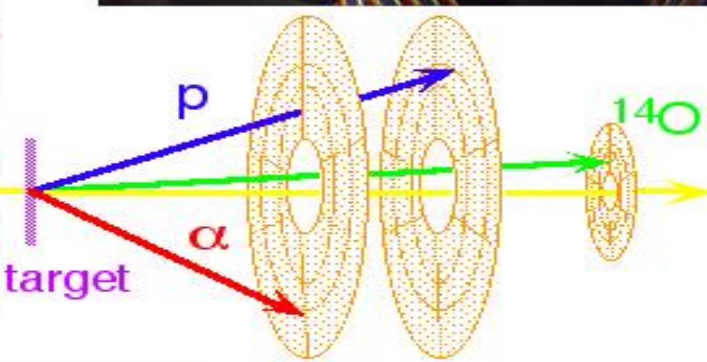
- *3 arrays of 128, 128, and 64 Si strip detectors*
- *stacked detectors ⇒ particle ID*

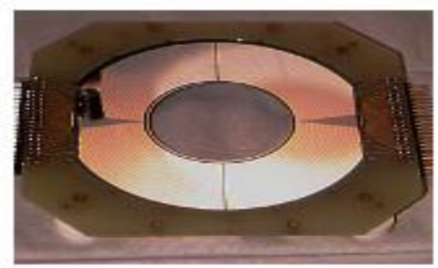


$p(^{17}F,^{14}O)\alpha$
$p(^{17}F,^{17}F)p$

$^{17}F$ rad beam

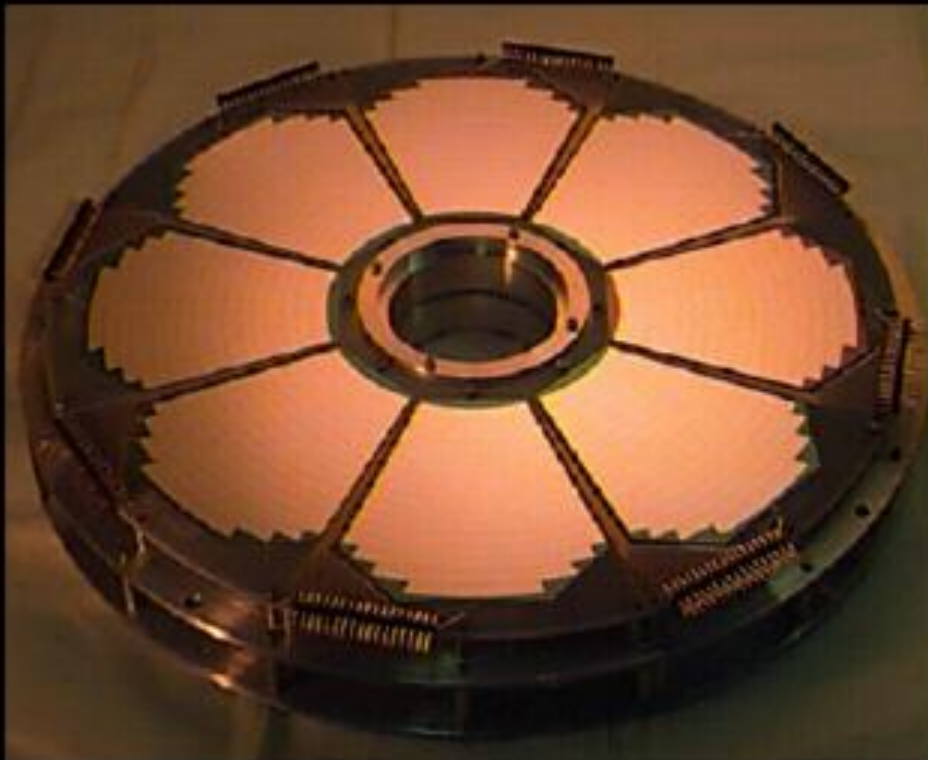
thin foil
$(CH_2)_n$ target

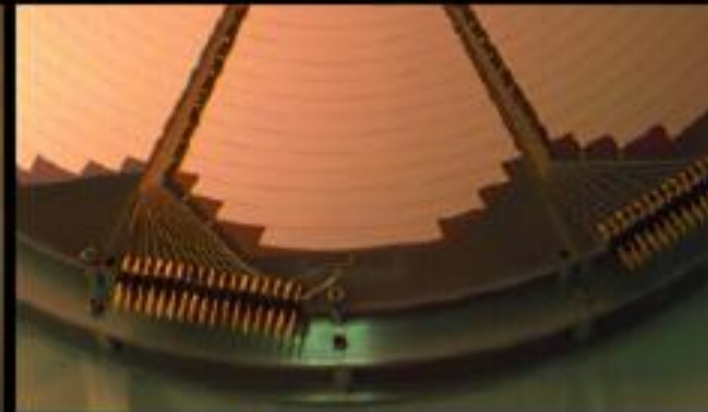


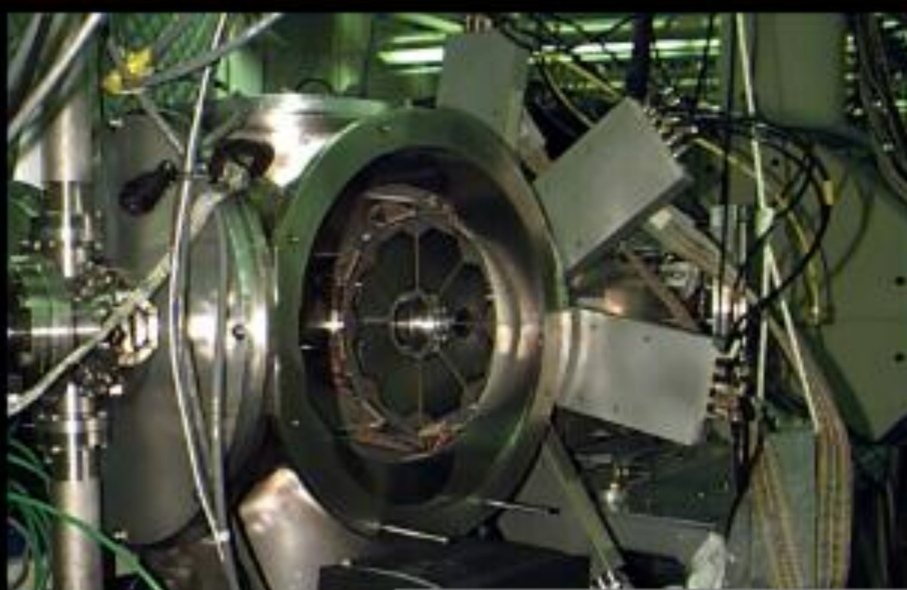



## Performance

- ***Completed RIB experiments:** $^{17,18}F(p,p)$, $^{17,18}F(p,\alpha)$, $^{17}F(p,p')$*
- ***High Energy Resolution, Low Backgrounds***







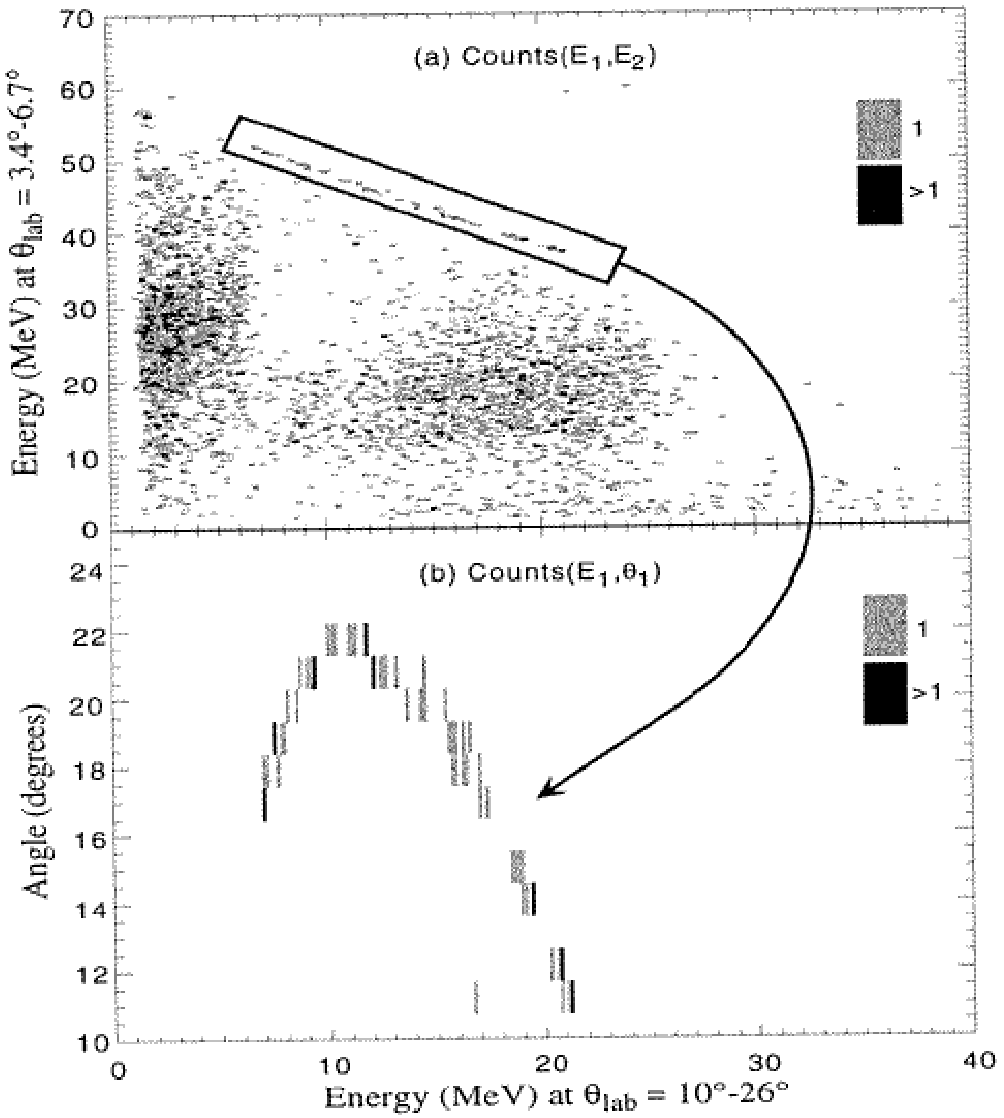
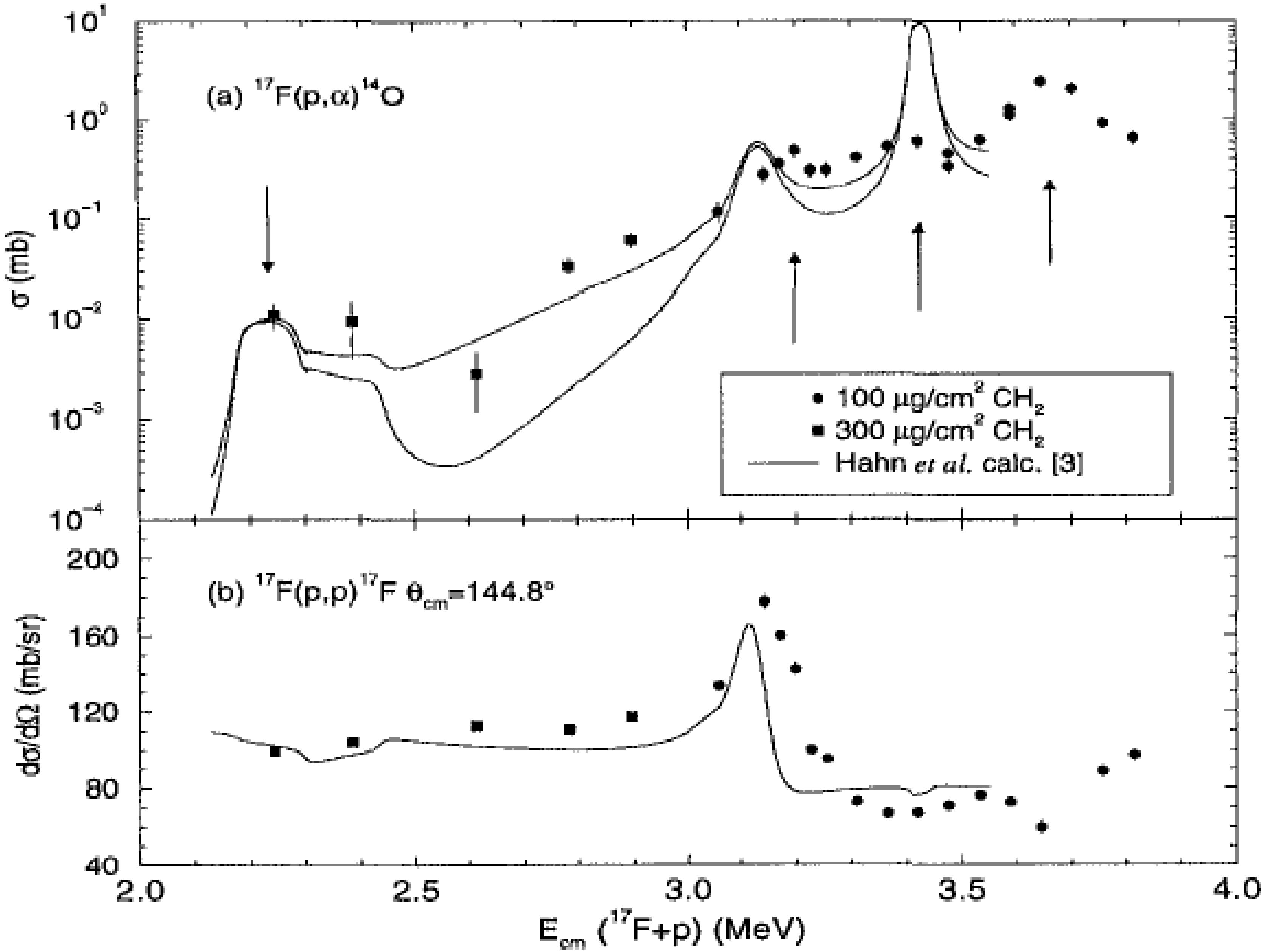



Figure 1. Data collected at a beam energy of 60.5 MeV with a 96 $\mu g/cm^2$ $CH_2$ target and a beam current of $1.1 \times 10^6$ $s^{-1}$ for 5.8 hours. (a) Counts as a function of the energies of 2 particles detected in time coincidence. (b) Counts as a function of the lab angle and energy for events which fall into the energy-energy gate shown in (a).




Blackmon et al. @Oak Ridge

# Stellar Reactions with Short-Lived Nuclei: $^{17}$F$(p,\alpha)^{14}$O

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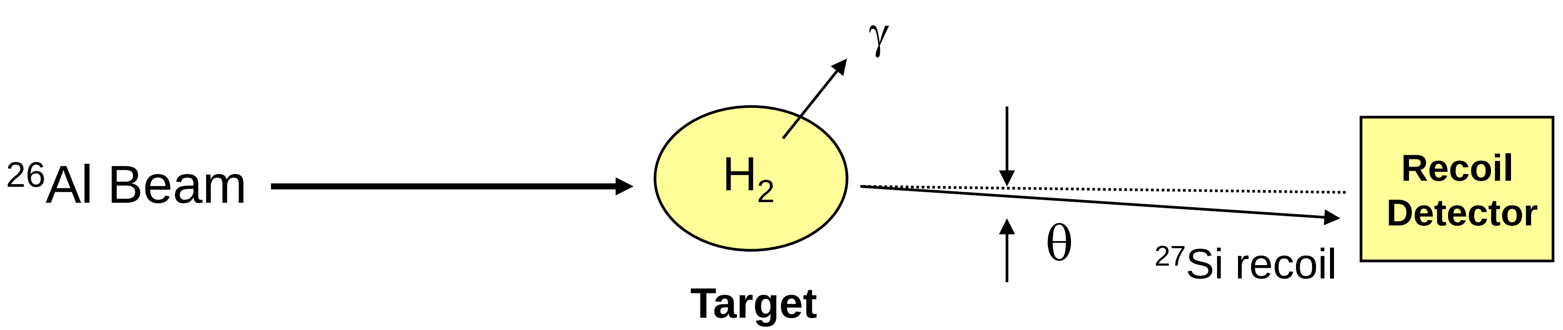
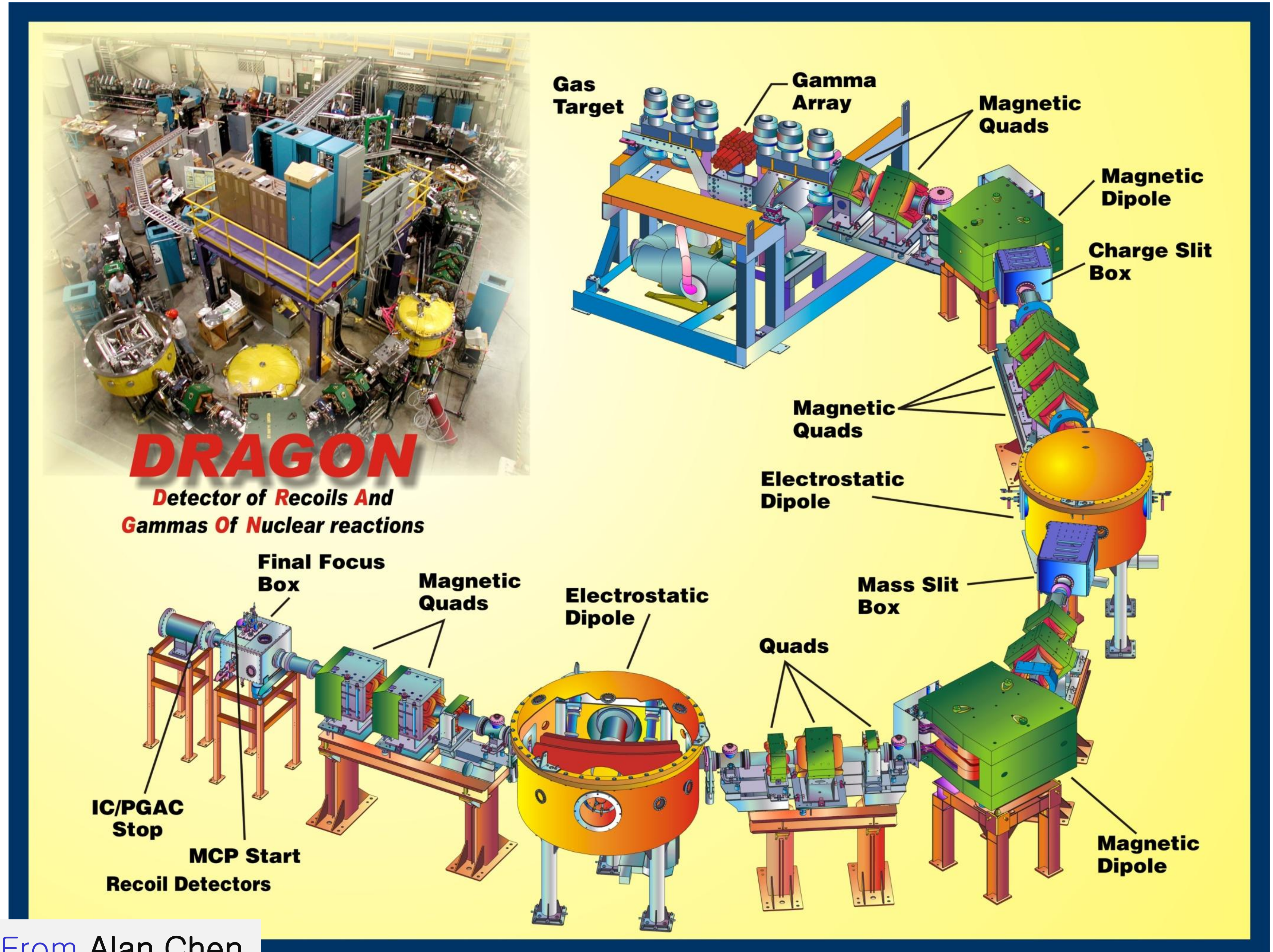
A method has been developed that can provide beams of many short-lived nuclei of interest in nucleosynthesis along the *rp* process path. With a $^{17}$F beam ($T_{1/2} = 64$ s) the excitation function of the $^{17}$F$(p,\alpha)^{14}$O reaction was measured to determine properties of excited states in $^{18}$Ne. These states influence the rate of the $^{14}$O$(\alpha,p)^{17}$F reaction which is important for understanding energy generation and nucleosynthesis in x-ray bursts. The present direct measurements yield a pattern of resonances and cross sections which differ substantially from previous estimates. [S0031-9007(99)09166-8]

# Measurement of $^{26}Al(p,\gamma)^{27}Si$ at TRIUMF-ISAC

- Goal of experiment: determine the strength of the $E_{cm}$ = 188 keV resonance at TRIUMF-ISAC:
  - $E_{beam}(^{26}Al)$ ~ 200 keV/u
  - required beam intensity > $10^9$ ions per second
  - Measure the yield of $^{27}Si$ recoils with DRAGON recoil separator (coincidence with prompt gamma rays)




From Alan Chen



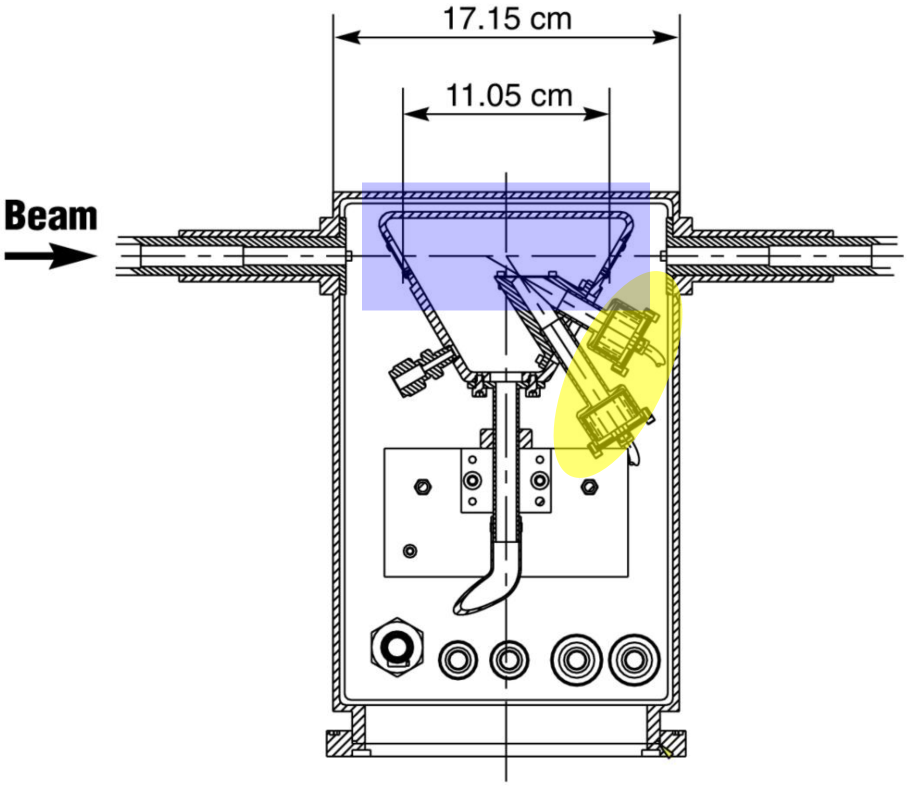

From Alan Chen

# DRAGON Gas Target

•Windowless gas target

• Silicon detectors:
  detect elastically scattered par
  ticles for beam normalization

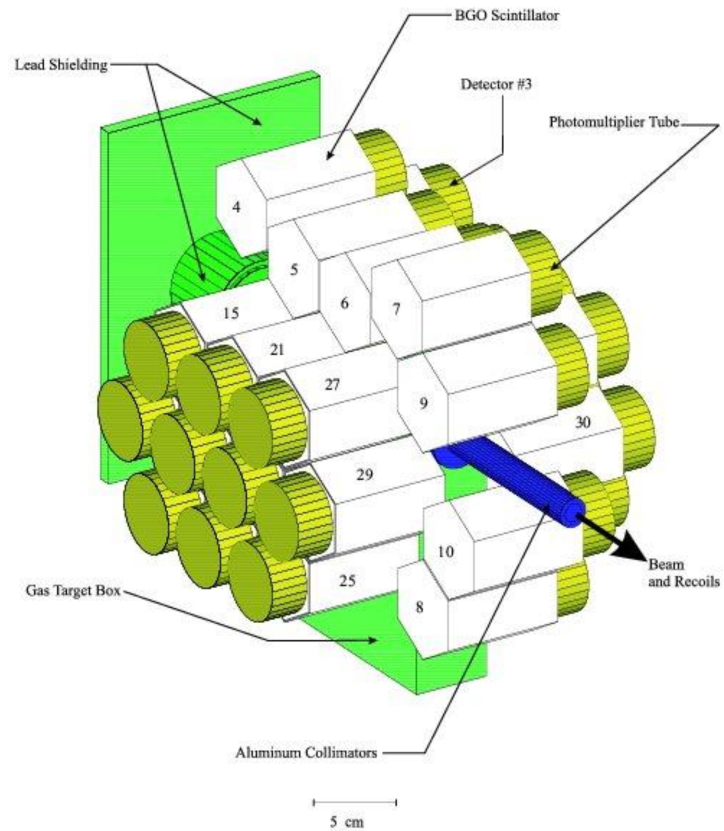
• Pressure = 4 – 8 Torr $H_2$
  (or He)




From Alan Chen

# DRAGON Gamma Array

- 30 bismuth germanate (BGO) detectors surrounding gas target
- Efficiency = (76 ± 10)%  from GEANT and data



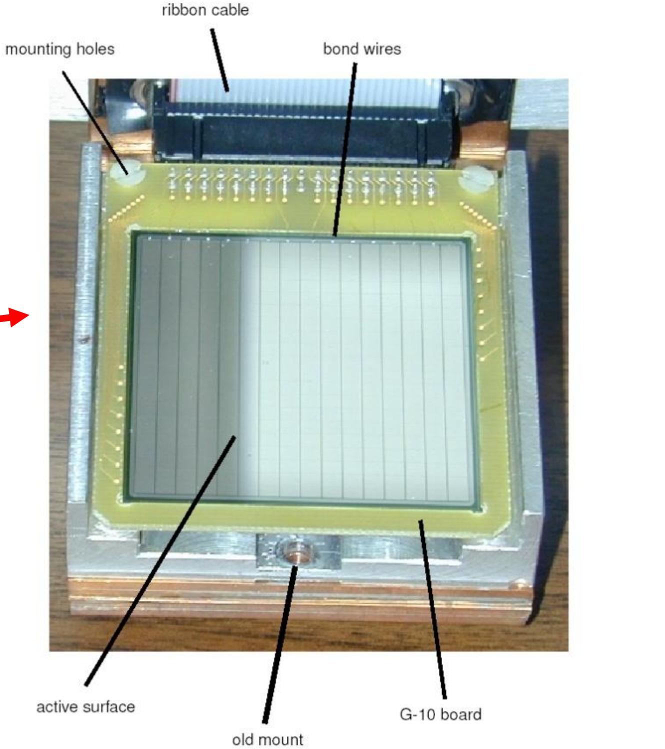

Location of resonance in gas target can be determined from detector positions → $E_R$

From Alan Chen

# DRAGON focal plane detectors

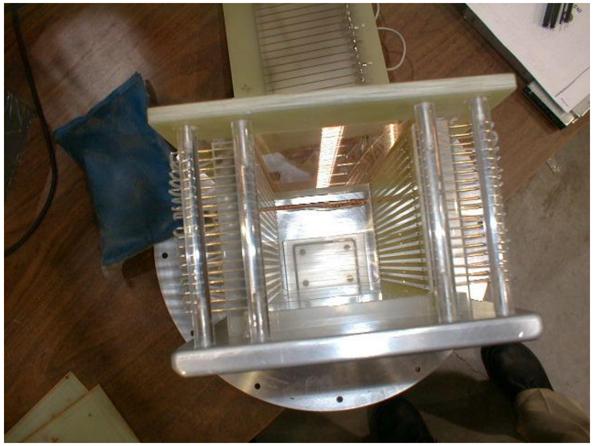
Silicon strip detector (DSSSD)

- $^{26}Al(p,\gamma)^{27}Si$
- timing, position, energy




Ionization chamber (IC)

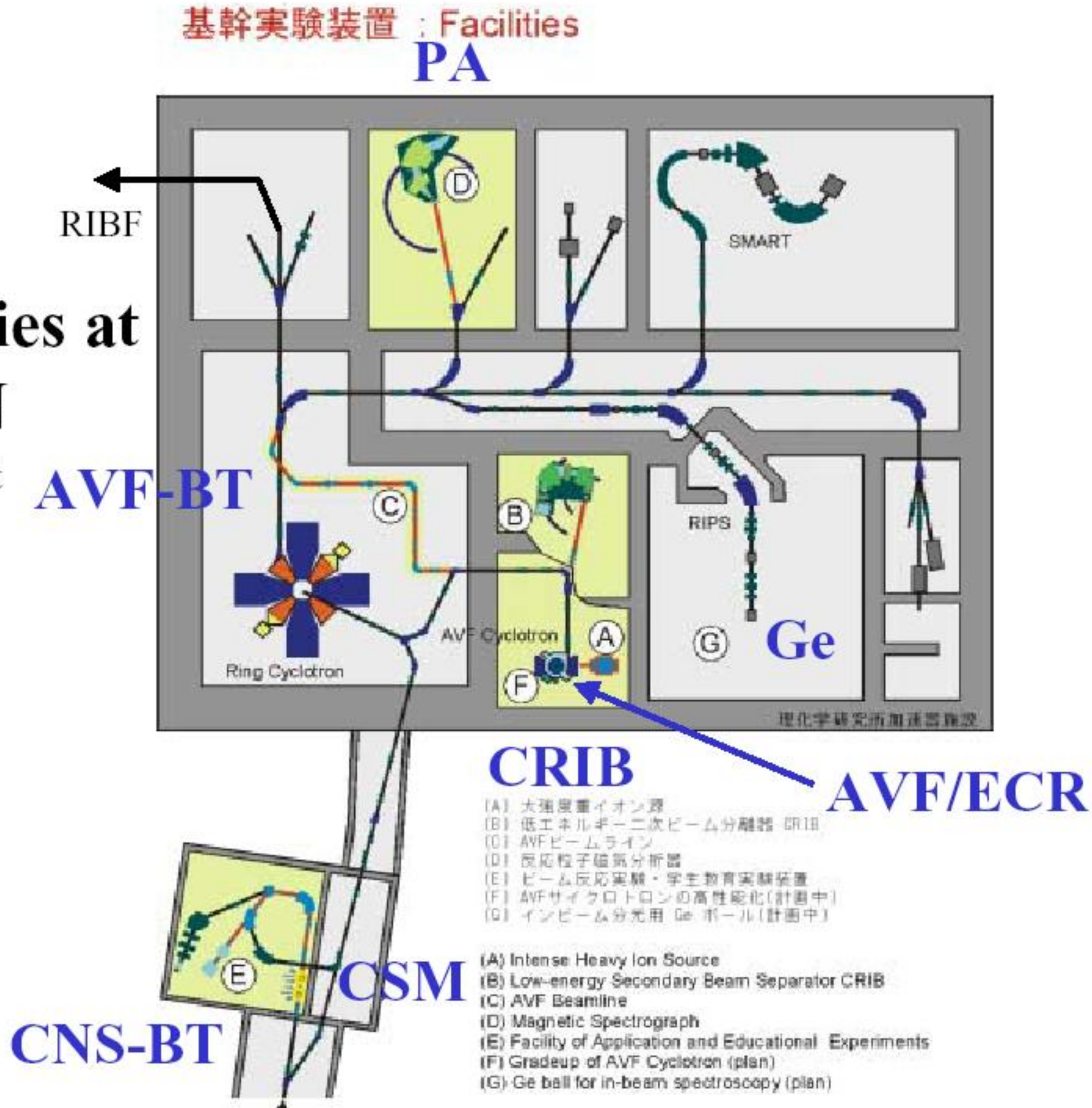
- $^{40}Ca(\alpha,\gamma)^{44}Ti$
- particle ID, energy



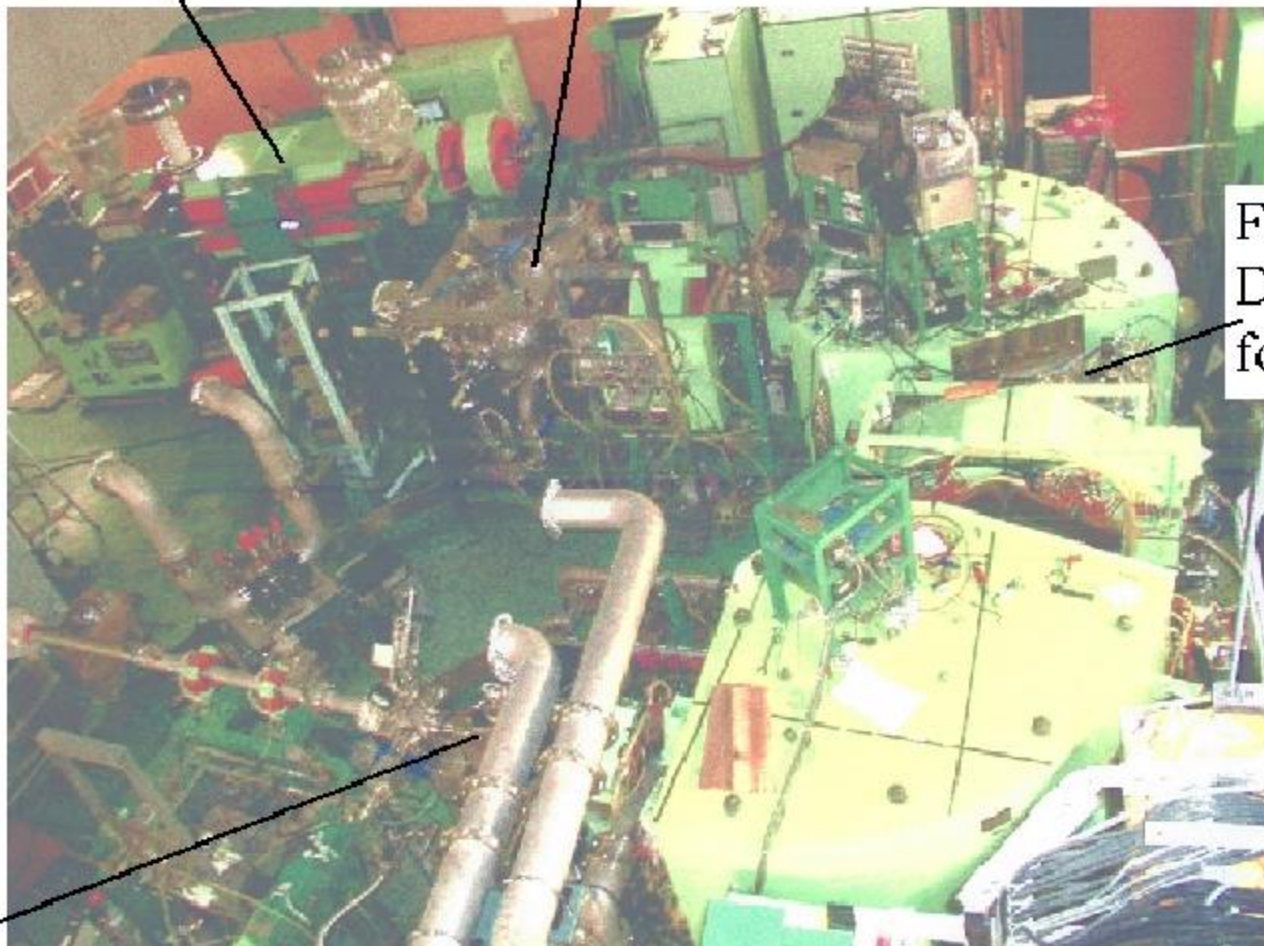
From Alan Chen

# CNS Facilities at RIKEN

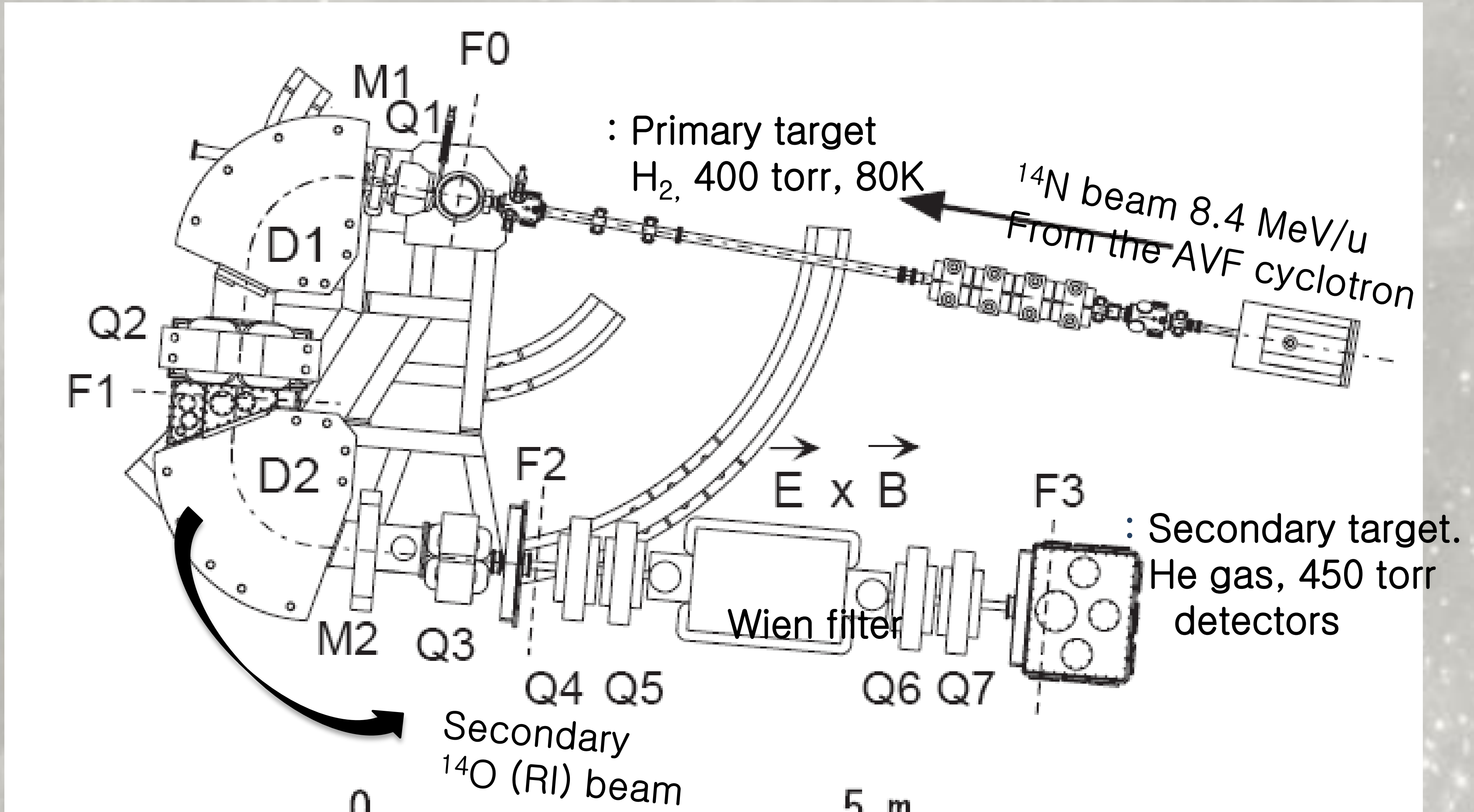
(Under CNS-RIKEN joint venture)



# CNS RIB Separator (CRIB)

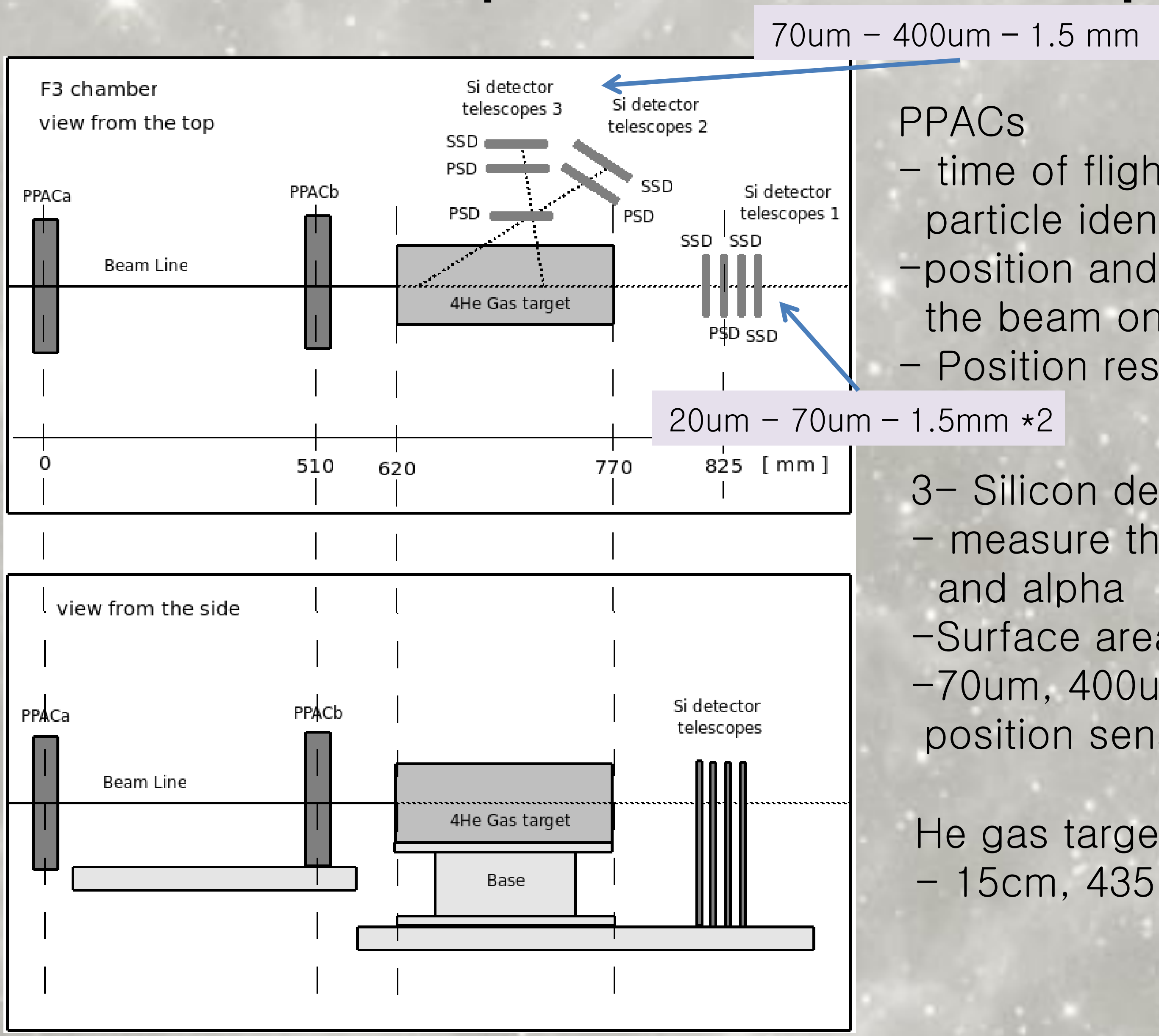


We measured the cross section in June, 2008




$^{14}$O secondary beam was produced through reaction $^{14}$N (p,n) $^{14}$O

# Experimental setup

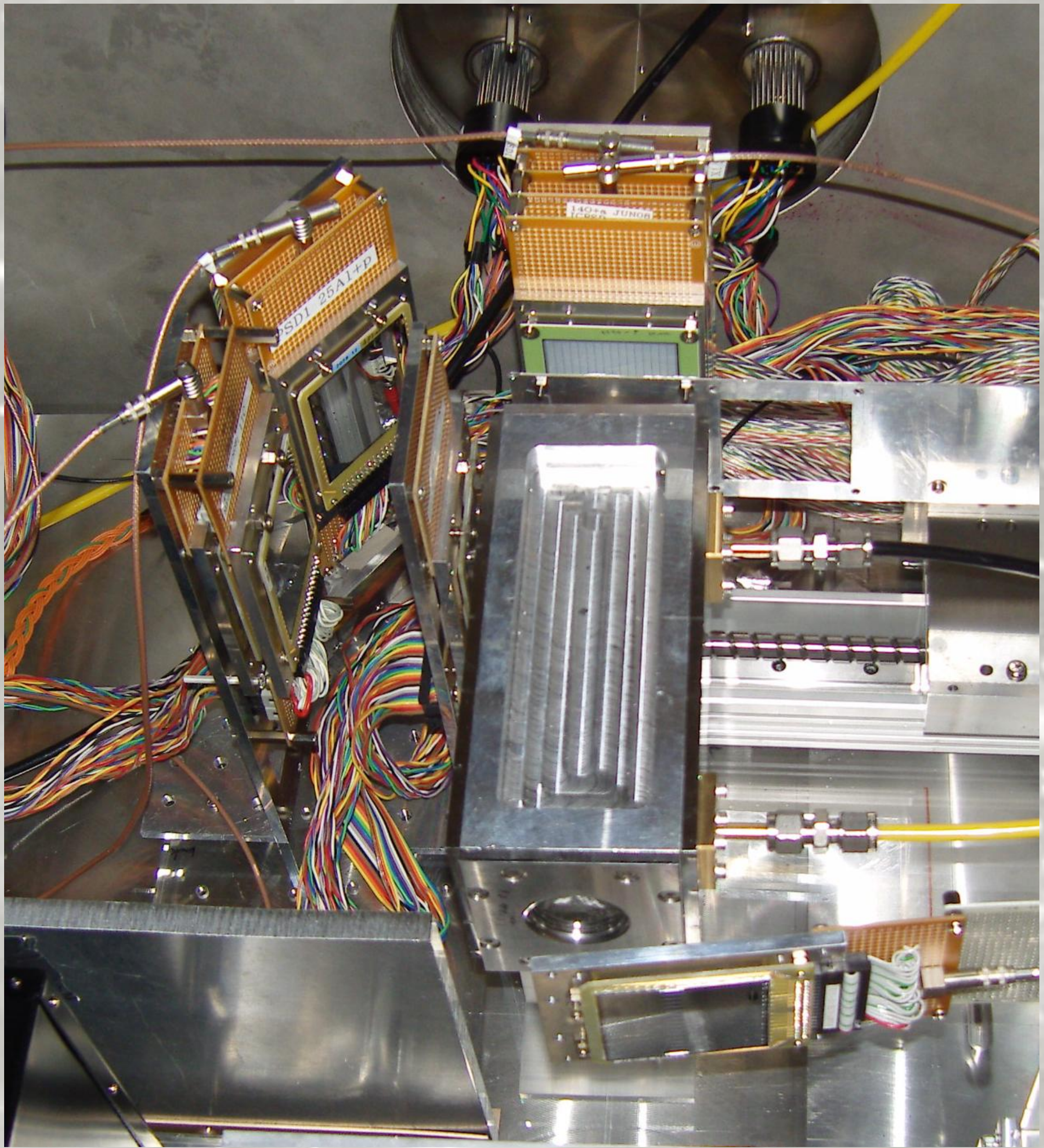


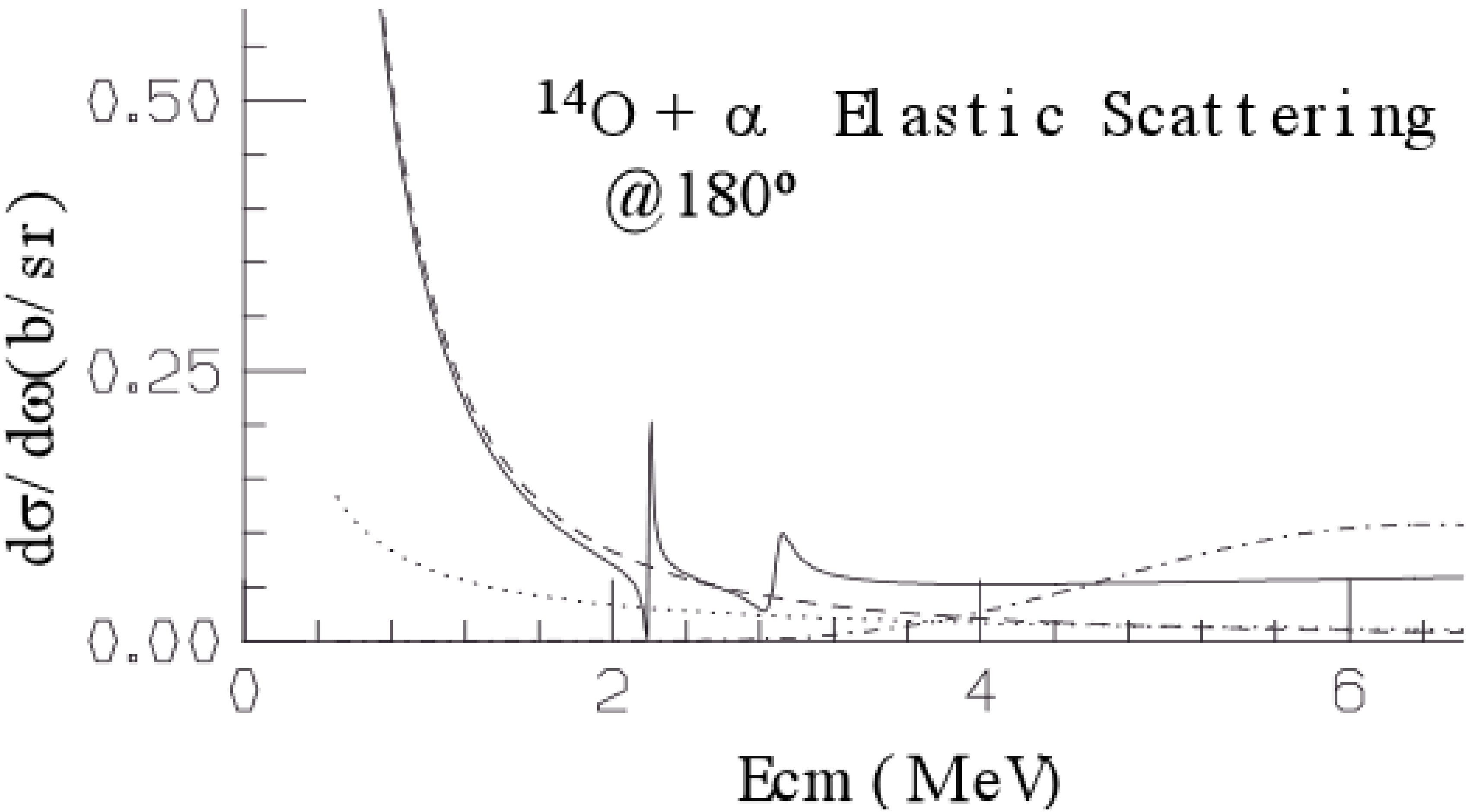

PPACs
- time of flight spectrum for particle identification of the beam
- position and incident angle of the beam on the secondary target
- Position resolution: 1mm

3- Silicon detector telescopes
- measure the recoiled proton and alpha
- Surface area: 5cm x 5cm
- 70um, 400um: 16 x 16 strip position sensitive detector

He gas target
- 15cm, 435 torr, 300K

# Experimental setup



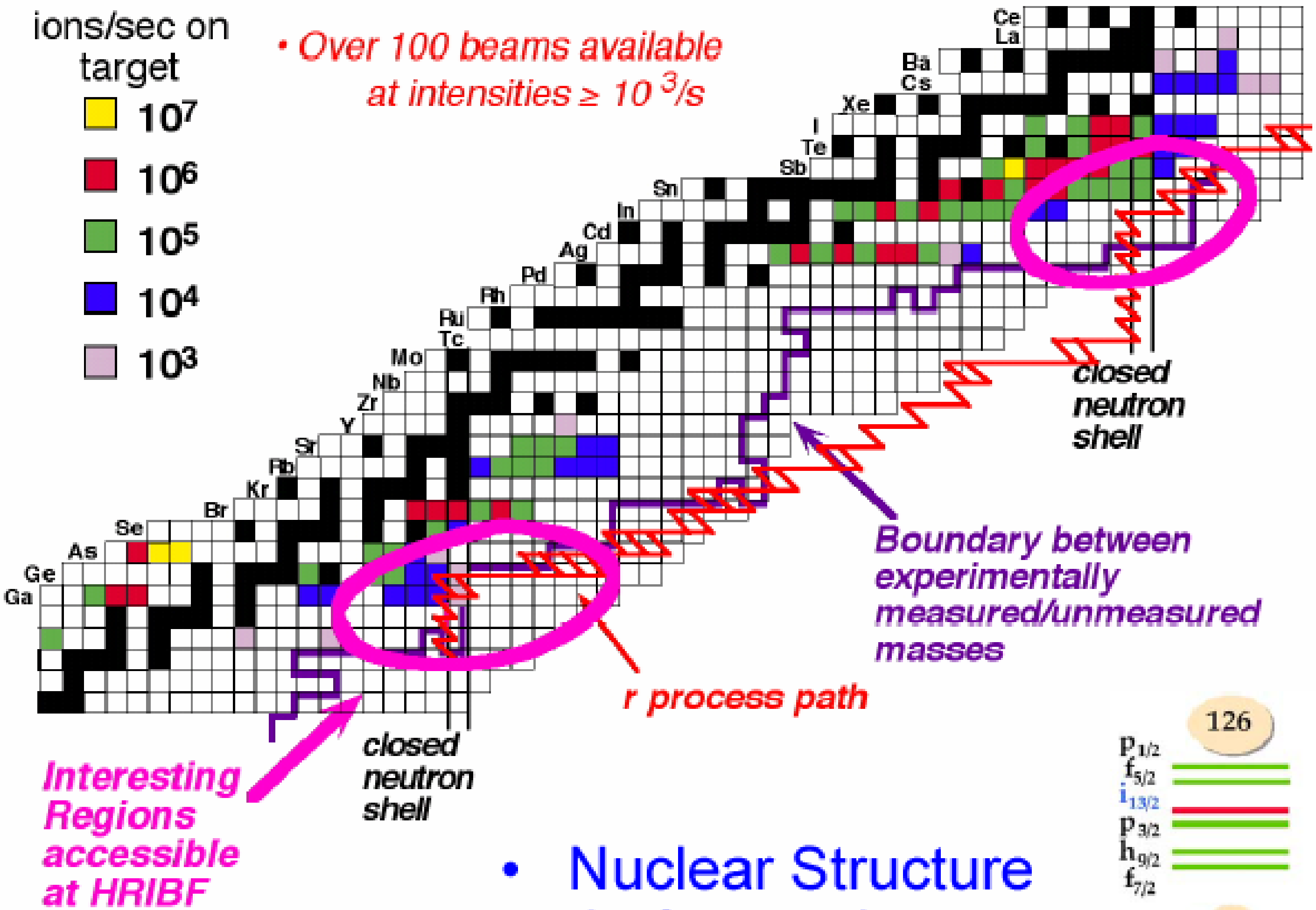


$^{14}O + \alpha$ Elastic Scattering
@180°
0.50
0.25
0.00
dσ/dω(b/sr)
0
2
4
6
Ecm ( MeV)

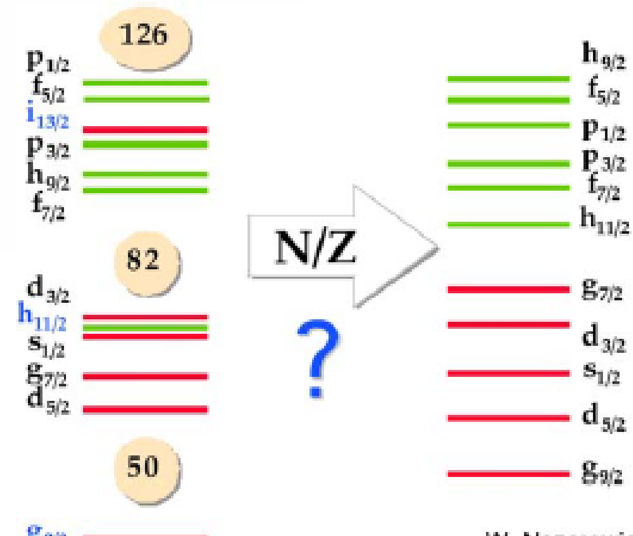
# Measurements

- Direct measurements have a serious problem due to their very low cross sections
- Indirect measurements
  - Transfer reactions (selectivity, resolution)
  - Resonant elastic scattering
  - $^{4}He(^{14}O,\alpha)^{14}O$ and $^{4}He(^{15}O,\alpha)^{15}O$

# Nuclear Structure Studies at Large Neutron Excess




- Nuclear Structure in & near the r-process path

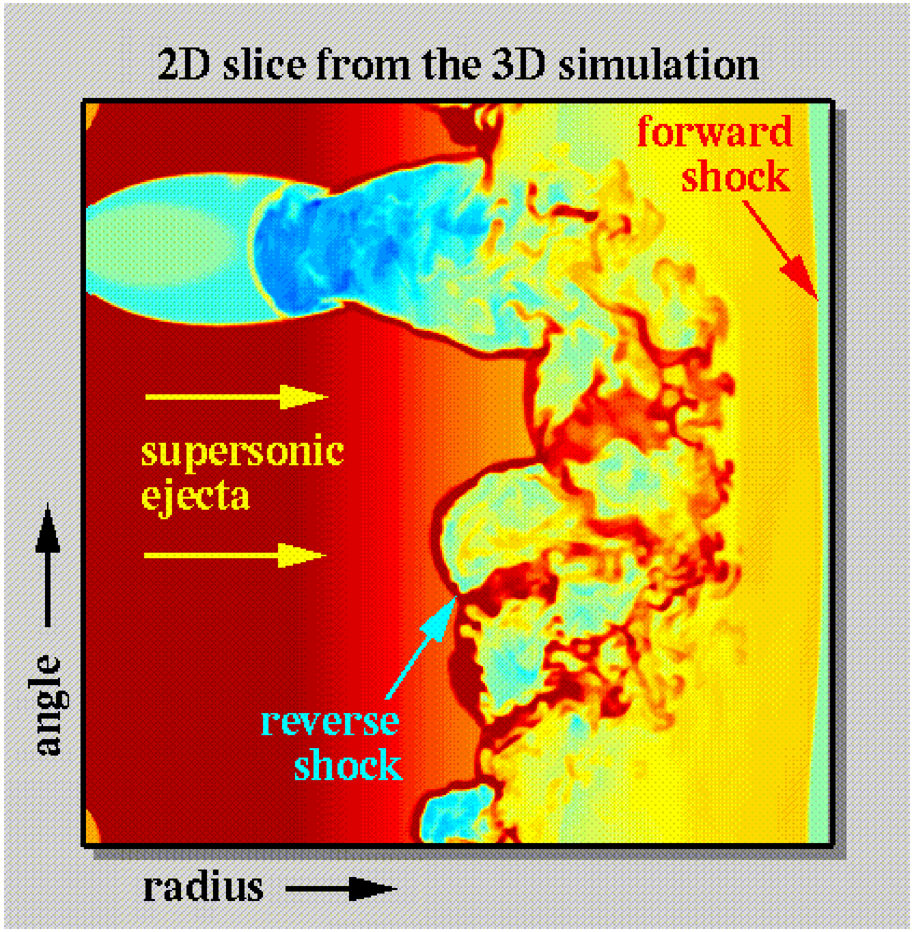



W. Nazarewicz

# A Better Set of Models for Explosive Events

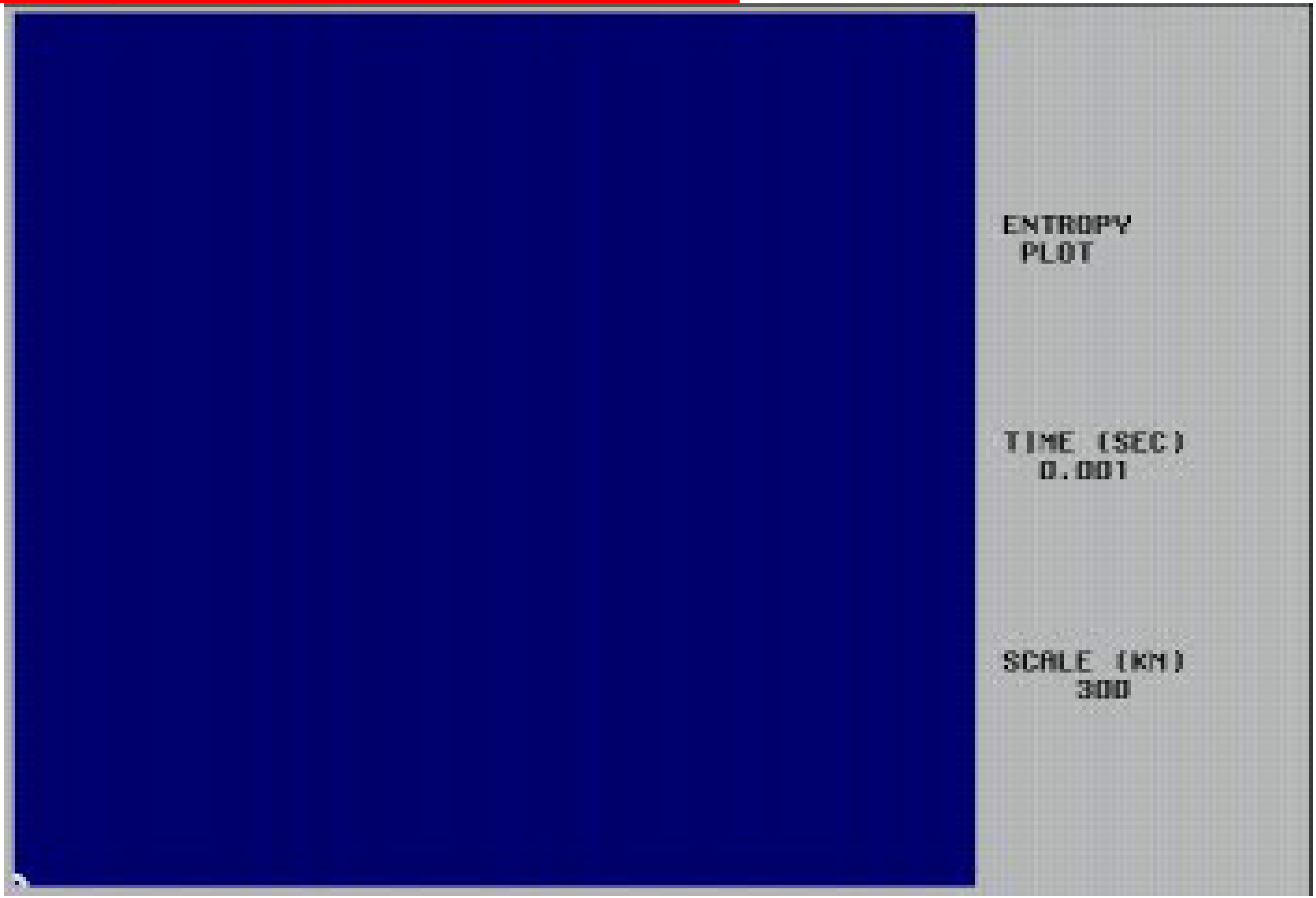
Hydrodynamic Properties

- Temperature
- Density
- Flow
- Etc.



# Supernova Simulations

First 300 ms: A. Burr




→ 10 km

300 km

# SUPERNOVA R-PROCESS

Otsuki, Tagoshi, Kajino & Wanajo
2000, ApJ 533, 424
Wanajo, Kajino, Mathews & Otsuki
2001, ApJ 554, 578

**t = 0**

**Neutrino-driven wind forms right after SN core collapse.**

n + p ⟶ n + α

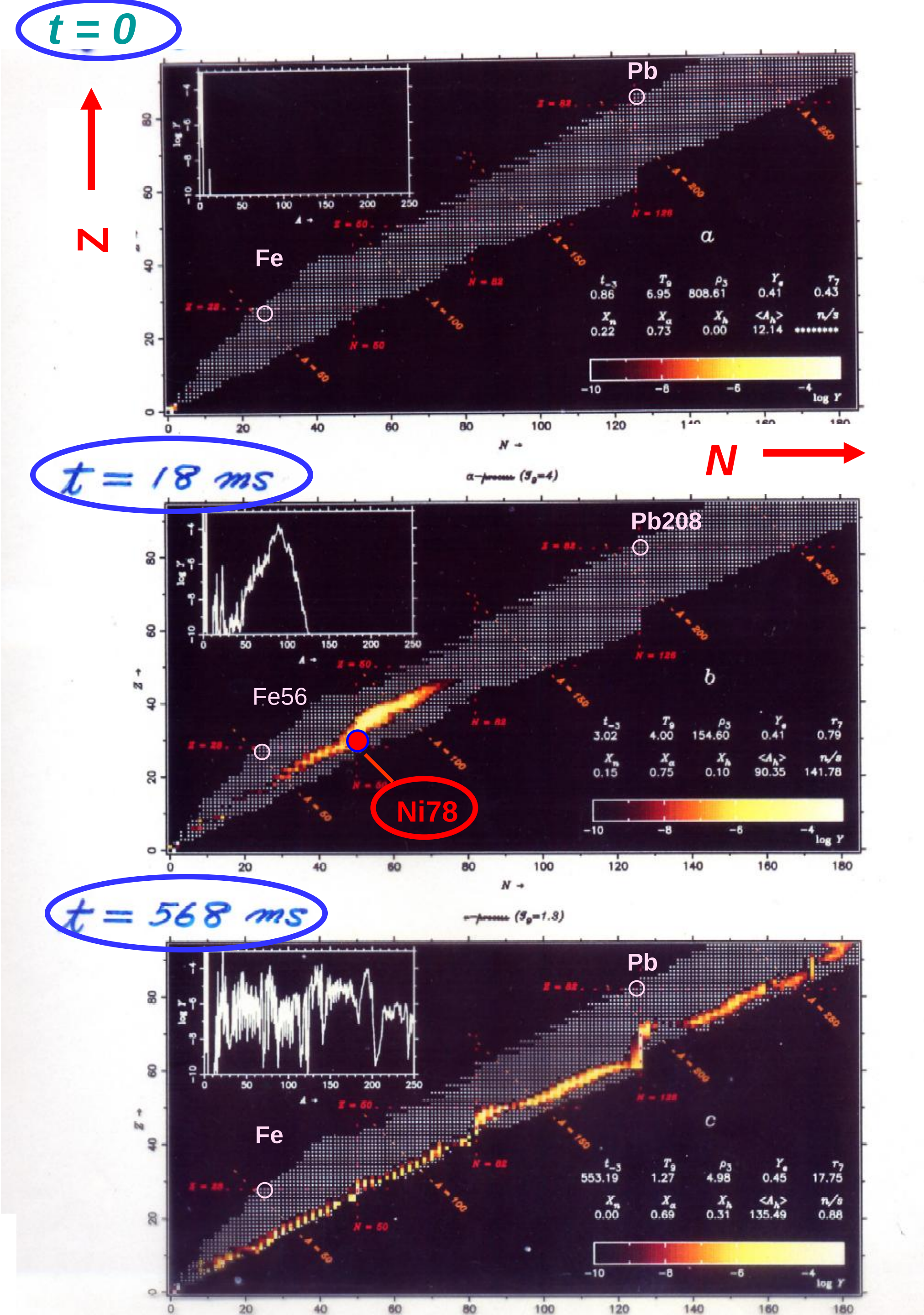
**t = 18 ms**

**Seeds form.**

**Exotic neutron-rich $^{78}$Ni**

**t = 568 ms – 1 s**

**Heavy r-elements synthesize.**



# Summary

- Indirect measurement with RIB
  - Coulomb dissociation
- Direct measurements with RIB
  - More intense radioactive beams @ RIKEN, KoRIA & FRIB(future)
- Measurements using RI beams will give us a deeper understanding
  - Big bang, the sun, novae, supernovae, etc
  - the origin of elements (r-process)

Thank you !