Nuclear Astrophysics Programs with Low-Energy RI Beams at CRIB

(CRIBからの低エネルギーRIBを用いた宇宙核物理研究)

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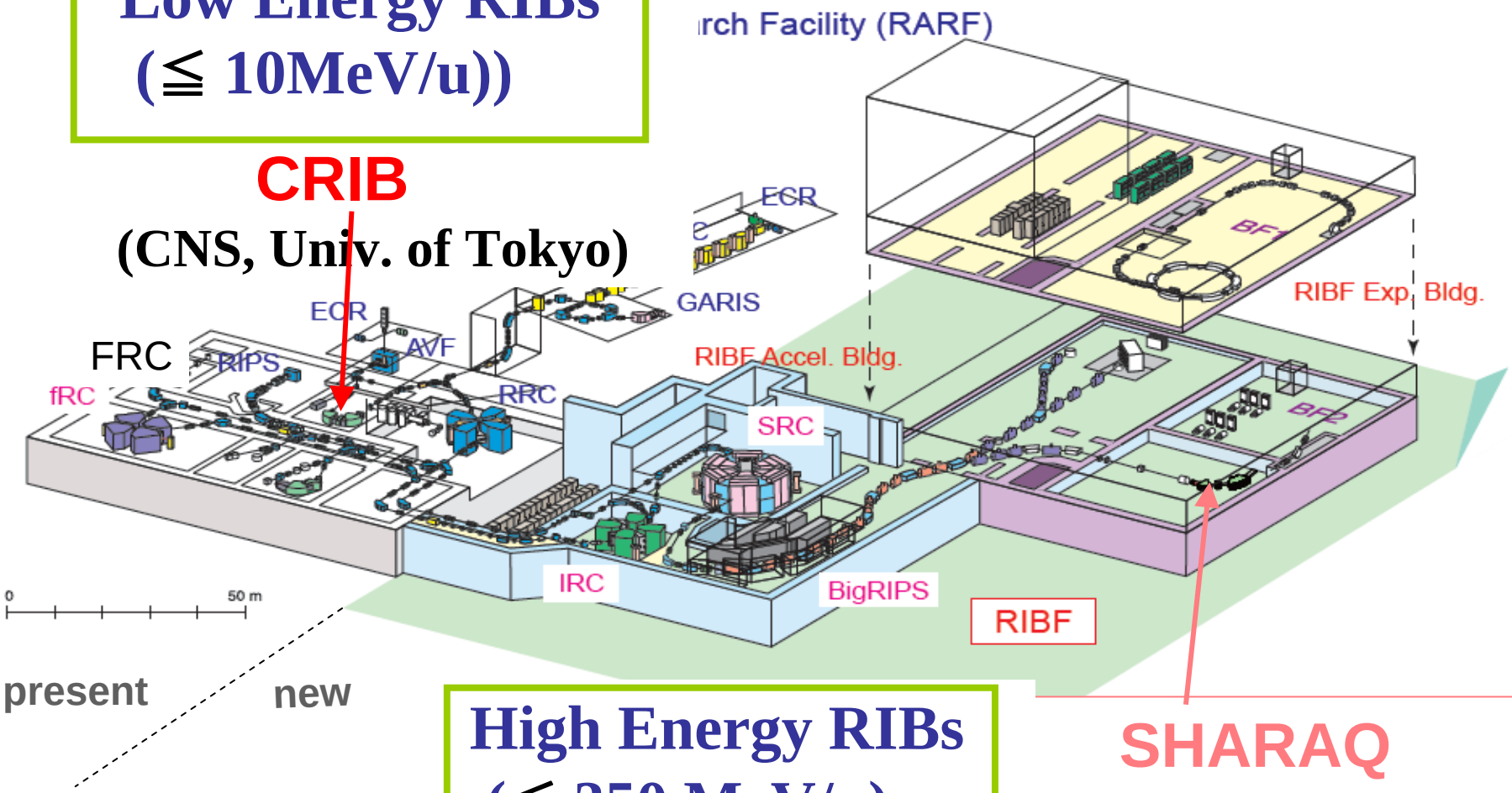
1. Introduction
2. The CRIB Project and the RI beams
3. Some experimental results
4. Possibility and Scope

RIKEN RIBF Facility

Low Energy RIBs
(≦ 10MeV/u))

CRIB
(CNS, Univ. of Tokyo)



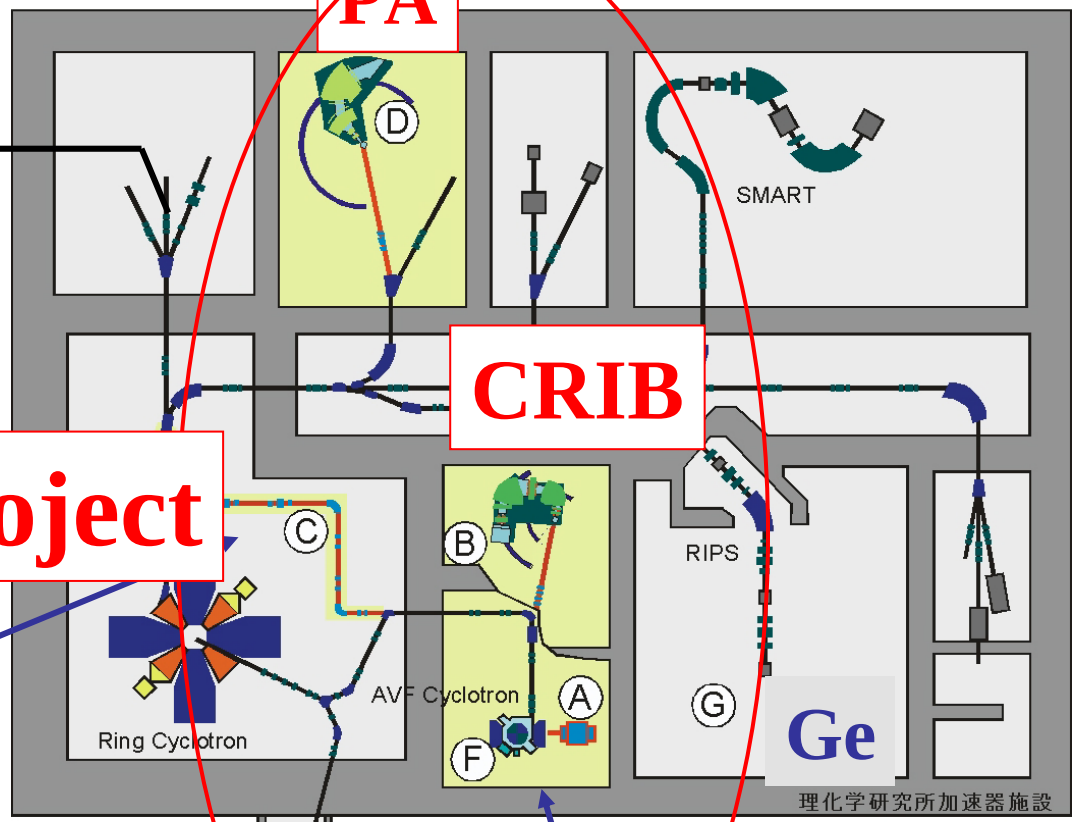
High Energy RIBs
(≦ 350 MeV/u)

SHARAQ
(High-resolution Spectrograph)
(CNS, Univ. of Tokyo)

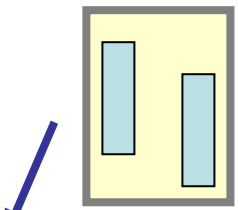
CNS Facilities at RIKEN

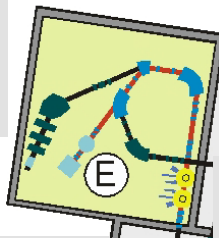
(Under CNS-RIKEN joint venture, 2000~)

RIBF



Parallel processor system (Theory/Otsuka)





CSM

CNS-BT

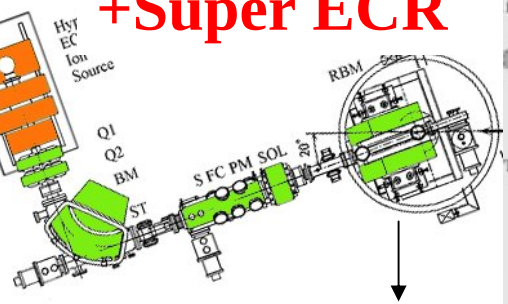
AVF /HyperECR

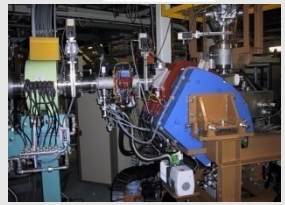
(A) 大強度重イオン源
(B) 低エネルギー二次ビーム分離器 CRIB
(A) Intense Heavy Ion Source
(B) Low-energy Secondary Beam Separator CRIB
(C) AVF Beamline
(D) Magnetic Spectrograph
(E) Facility of Application and Educational Experiments
(F) Gradeup of AVF Cyclotron (plan)
(G) Ge ball for in-beam spectroscopy (plan)

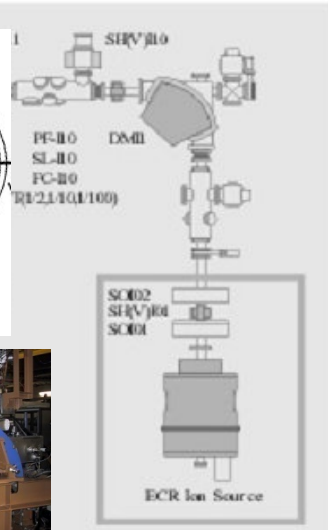
AVF Upgrade Project

HyperECR

+Super ECR







PA

AVF

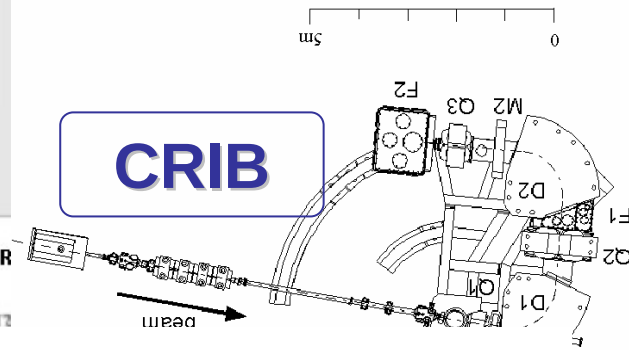
+flat-top

+K=45 => K=79

+New central inflector

+ H=1, 3

CRIB



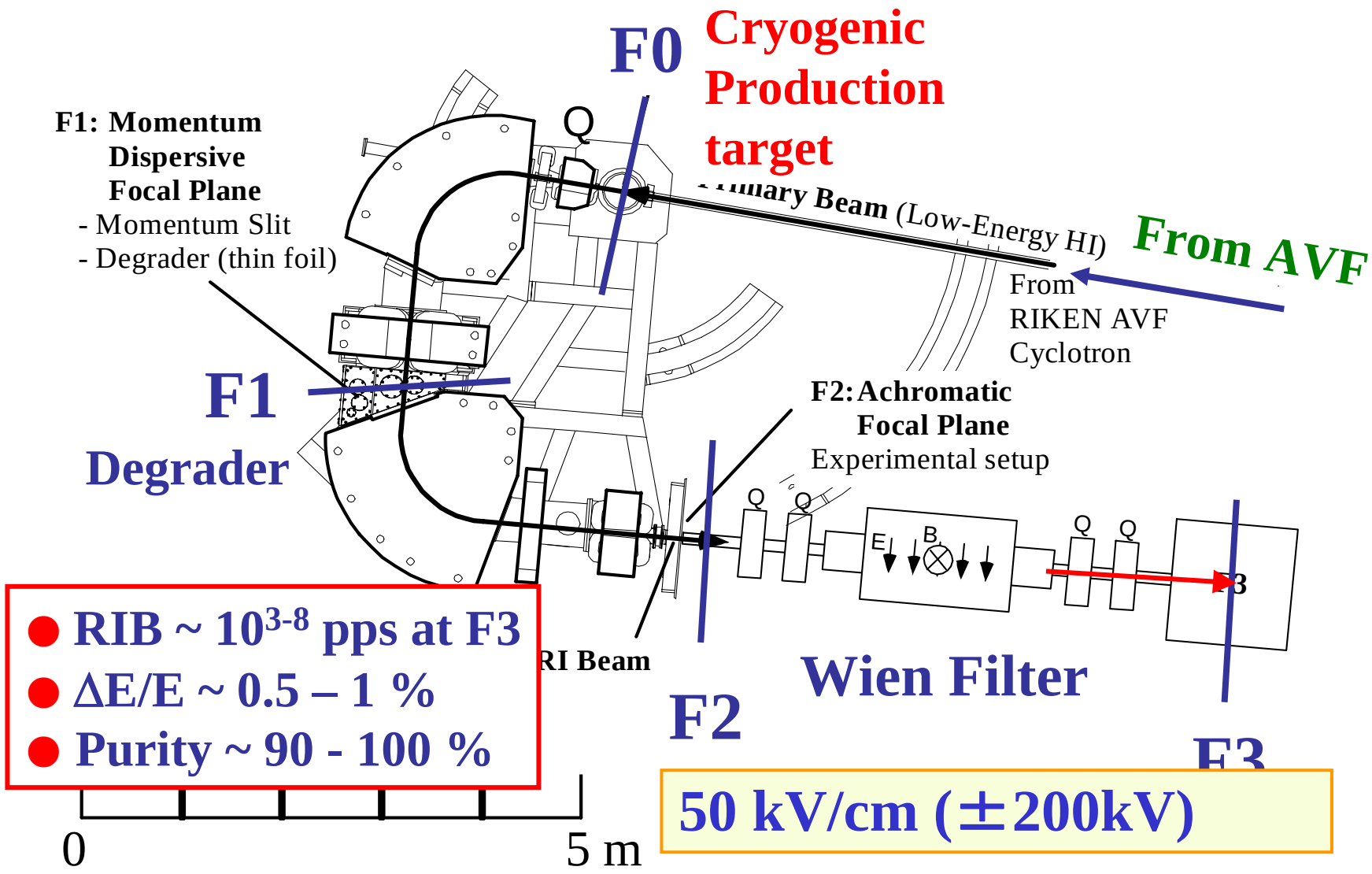
+LiqN-cooling target

+ Multipole-mag.

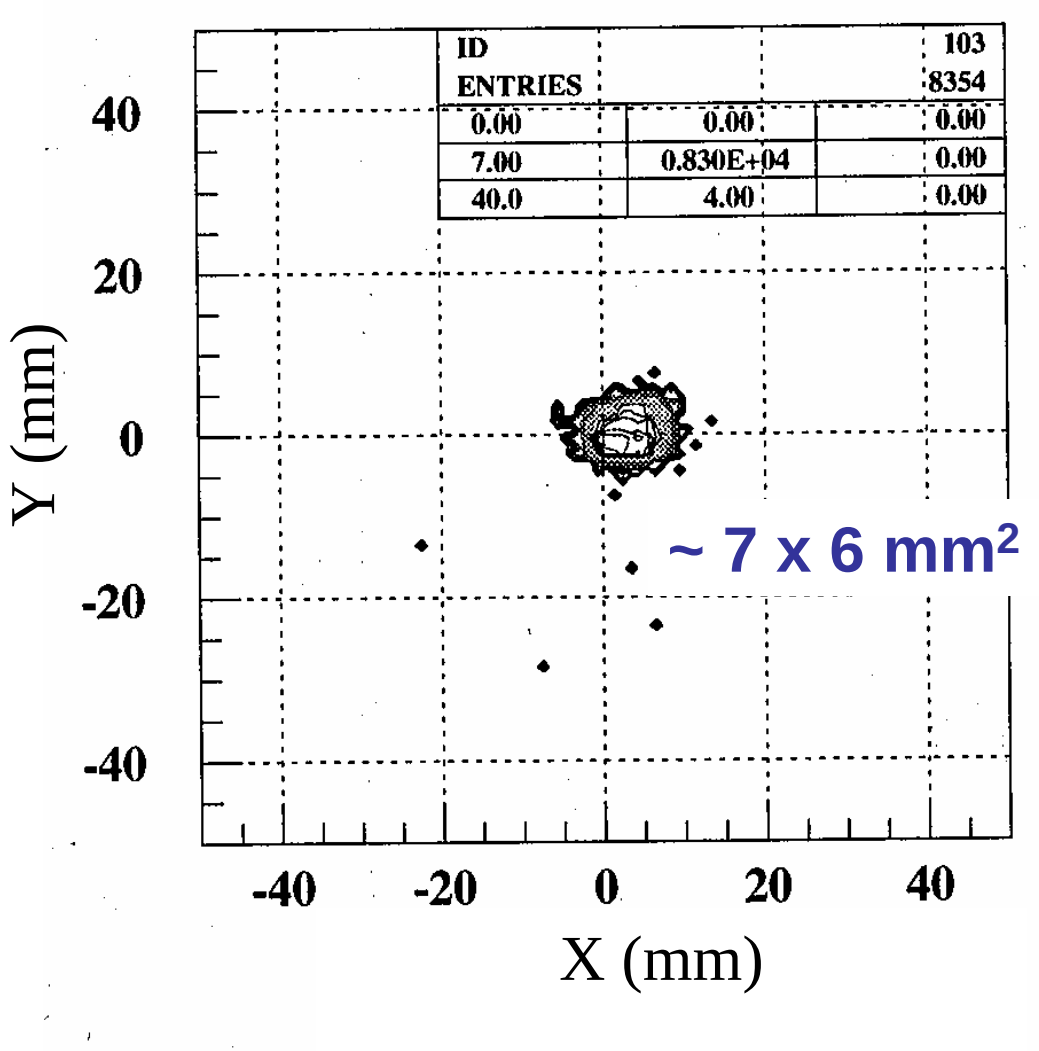
+ Gas production target

+ Low room background

CRIB; Low-Energy In-Flight RI Beam Separator at CNS



Beam size of ^{14}O at F3



- Without a degrader
- Small spot size

Higher order correction

↓

Smaller RI beam spot size !

Radioactiv Beams produced by CRIB (A<20) - with room temperature target -

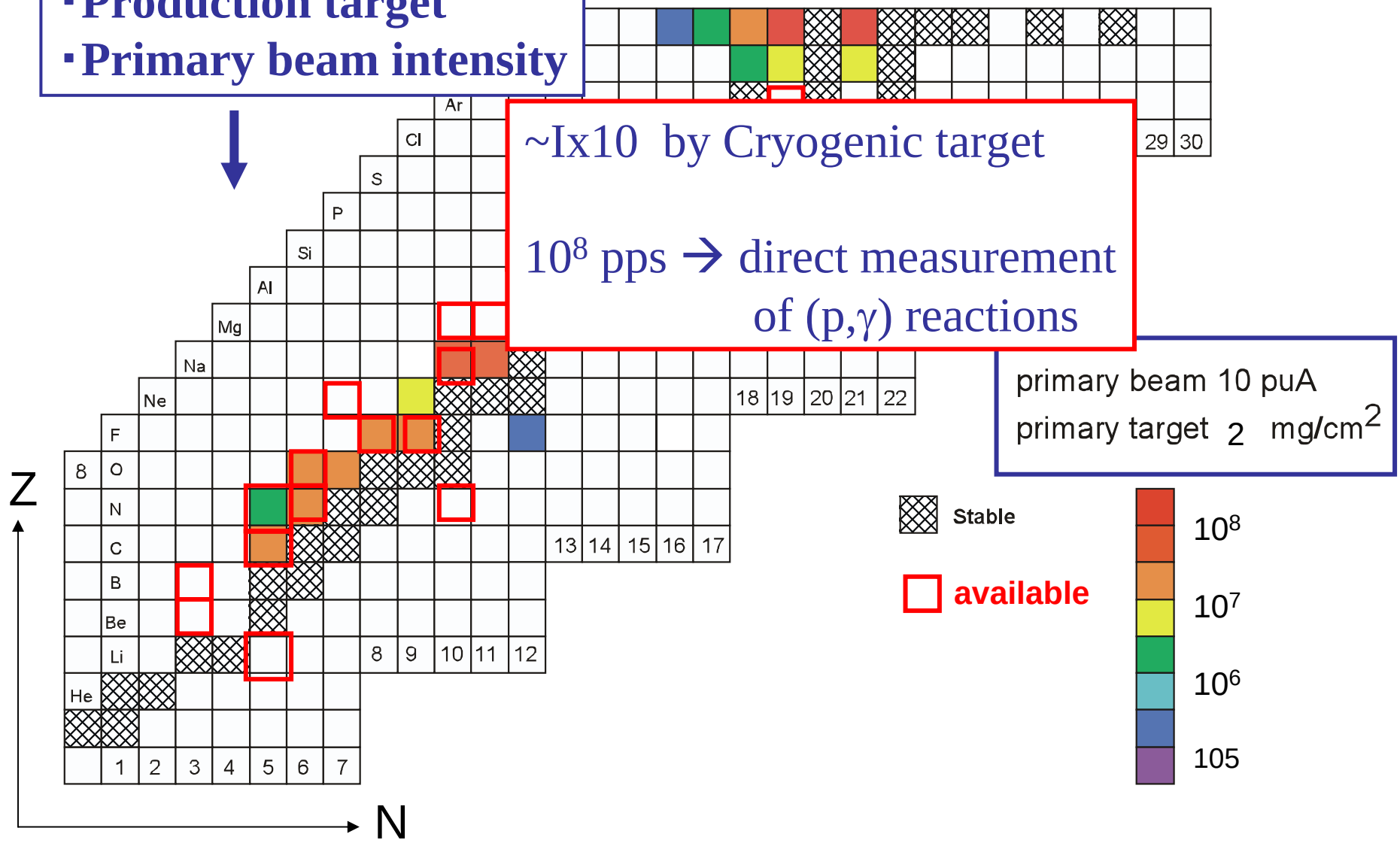
Secondary Beam	Primary Beam	Reaction	Target (mg/cm2)	Intensity (1/sec)	Purity
$^{7}Be^{4+}$ 8.1 *A* MeV	$^{7}Li^{3+}$ 150 pnA	(p,n)	H_2 gas (0.67)	3×10^{5}	100%
$^{10}C^{6+}$ 6.1 *A* MeV	$^{10}B^{4+}$ 200 pnA	(p,n)	CH_4 gas (1.33)	1.6×10^{5}	90 %
$^{13}N^{7+}$ 6.5 *A* MeV	$^{13}C^{5+}$ 500 pnA	(p,n)	H_2 gas (0.33)	2×10^{5}	95 %
$^{14}O^{8+}$ 6.7 *A* MeV	$^{14}N^{6+}$ 500 pnA	(p,n)	CH_4 gas (1.33)	1.7×10^{6}	80 %
$^{18}F^{9+}$ 2.7 *A* MeV	$^{18}O^{4+}$ 500 pnA	(p,n)	H_2 gas (0.67)	1.5×10^{5}	98%
^{11}C 3.4 *A* MeV	$^{10}B^{4+}$ 200 pnA	(^{3}He,np)	^{3}He gas (0.25)	1.7×10^{4}	17 %
^{12}N 3.9 *A* MeV	$^{10}B^{4+}$ 200 pnA	(^{3}He,n)	^{3}He gas (0.25)	2.5×10^{3}	3 %
^{8}Li 6.5 *A* MeV	$^{7}Li^{3+}$ 330 pnA	(d,p)	D_2 gas (1.33)	2×10^{5}	98 %
^{17}N 2.0 *A* MeV	$^{18}O^{6+}$ 750 pnA	(^{9}Be,^{10}B)	Be foil (2.5)	1×10^{5}	25 %

Radioactiv Beams produced by CRIB (A>20) - with room temperature target -

Secondary Beam	Primary Beam	Reaction	Target (mg/cm^2)	Intensity	Purity
^{21}**Na** 4.2 *A* MeV	$^{20}Ne^{8+}$ 200 pnA	**(^{3}He,np)**	^{3}He gas (0.25)	**2.3×10^4**	**12 %** **no WF**
^{22}**Mg** 4.6 *A* MeV	$^{20}Ne^{8+}$ 200 pnA	**(^{3}He,n)**	^{3}He gas (0.25)	**6.6×10^3**	**3 %** **no WF**
^{25}**Al** 4.0 *A* MeV	$^{24}Mg^{8+}$ 125 pnA	**(^{3}He,np)**	^{3}He gas (0.25)	**1.2×10^4**	**6 %** **no WF**
^{26}**Si** 4.0 *A* MeV	$^{24}Mg^{8+}$ 125 pnA	**(^{3}He,n)**	^{3}He gas (0.25)	**3×10^3**	**1.5 %** **no WF**
^{23}**Mg** 4.0 *A* MeV	$^{24}Mg^{8+}$ 125 pnA	**(d,t)**	D_2 gas (0.33)	**3.2 ×10^4**	**12 %** **no WF**
^{39}**Ar^{15+}** 4.0 *A* MeV	$^{40}Ar^{11+}$ 120 pnA	**(3He,α)**	^{3}He gas (1.0)	**3.2 ×10^4**	**20 %**

RIB intensity to be obtained at CRIB

- Production target
- Primary beam intensity



Recent Development

- **System development;**

  New Ions – P, Fe, Rb,

  Super ECR source installation to AVF

  (CNS Iss' supply all the beams for AVF cyclotron)

- **AVF upgrade – Acceleration > 10 MeV/u**

  – Better transmission

- **RIB production with fusion reactions**

  e.g. ^{46}Cr

- **Trojan Horse Method applied for stellar reaction study.**

What is First generation star ?

Very massive ?

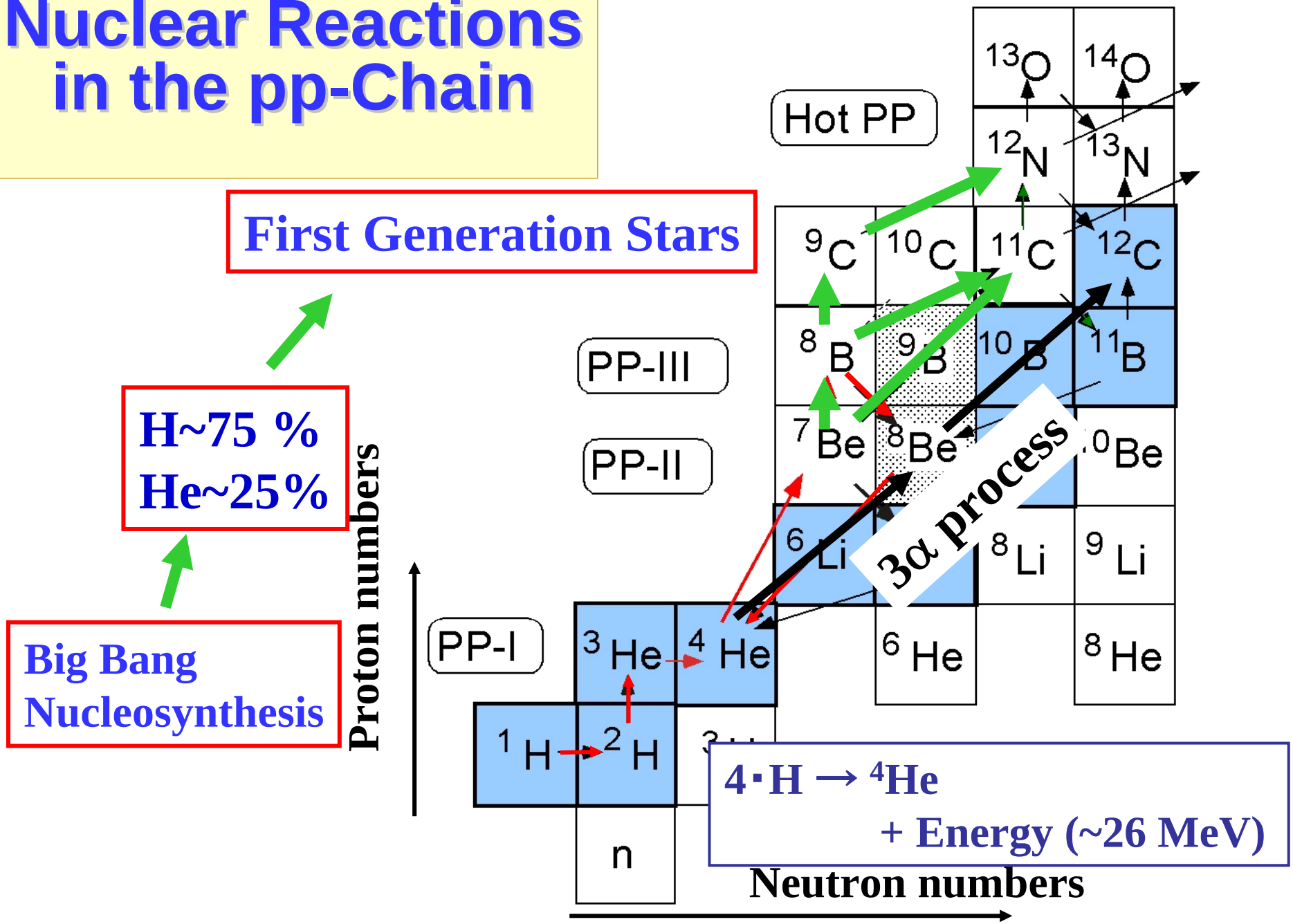
Ends with a Supernova ?

How to make CNO ?

Big Bang

Galaxies

Nuclear Reactions in the pp-Chain



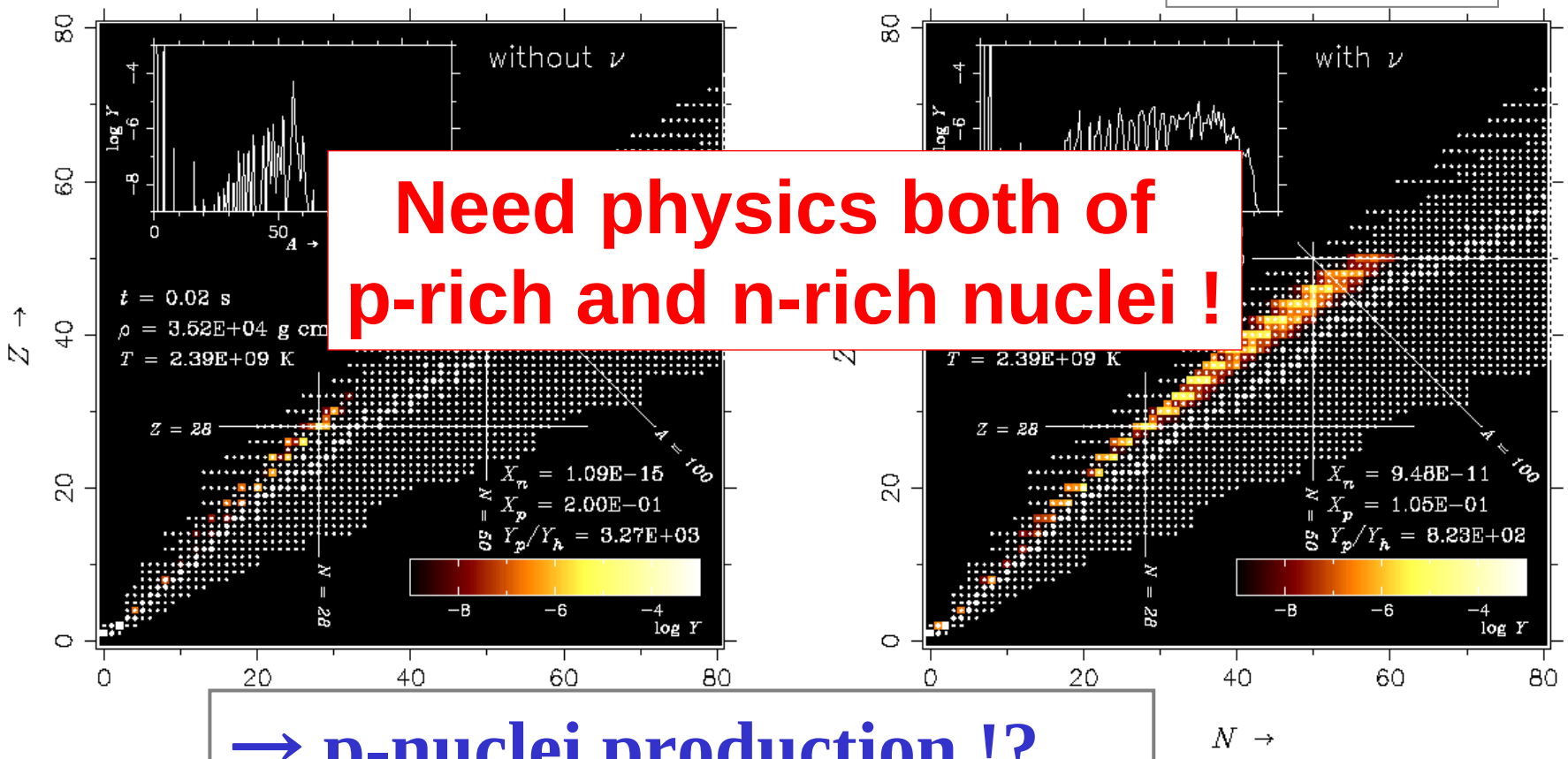
νp-process in SNeII

Extremely high flux of ν induces proton-rich environment in the very early stage of SNeII

νe+n⇔p+e-
ν̄e+p⇔n+e+

without ν

with ν

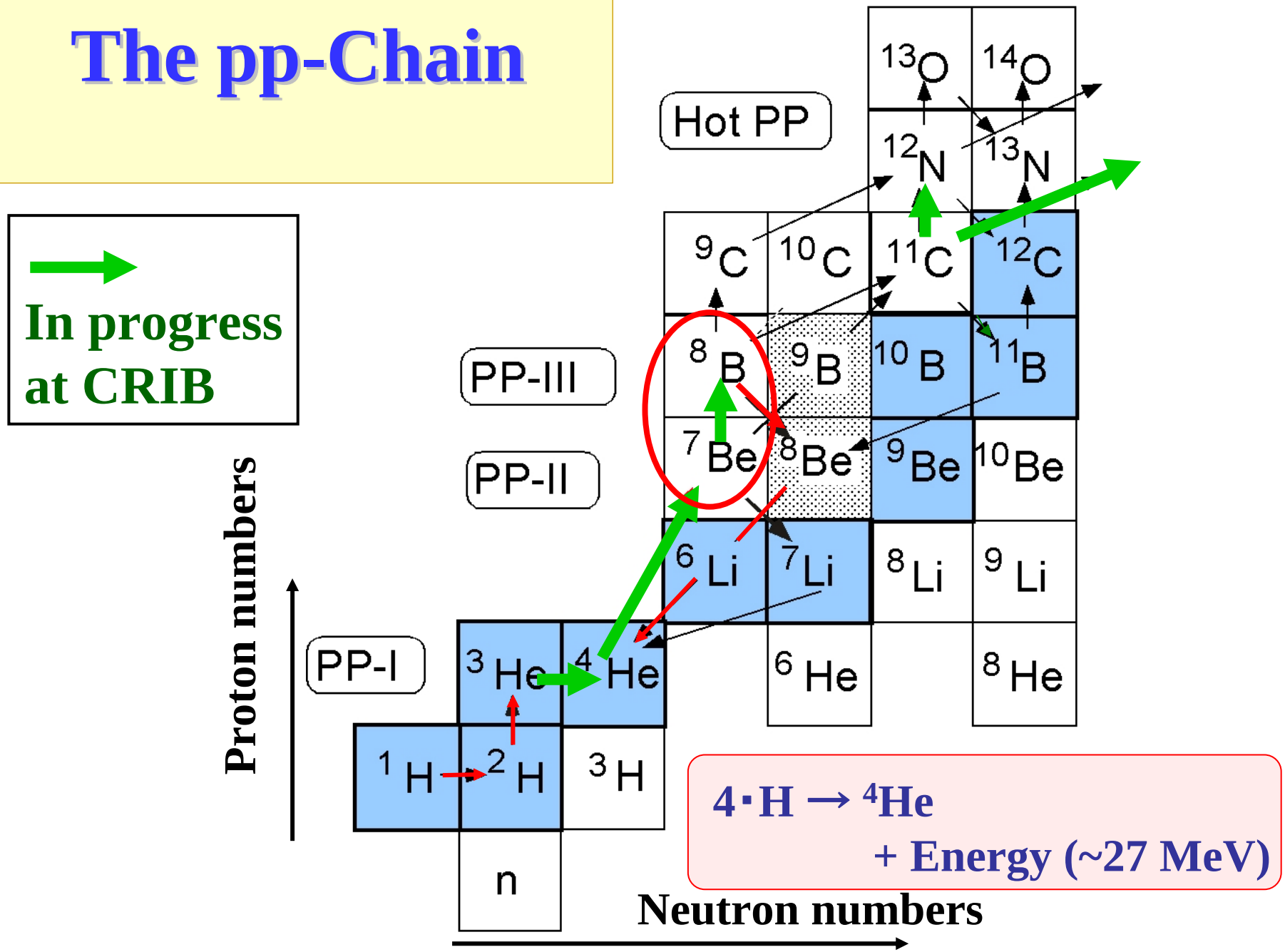


Need physics both of p-rich and n-rich nuclei !

→ p-nuclei production !?

(Wanajo, OMEG05)

The pp-Chain

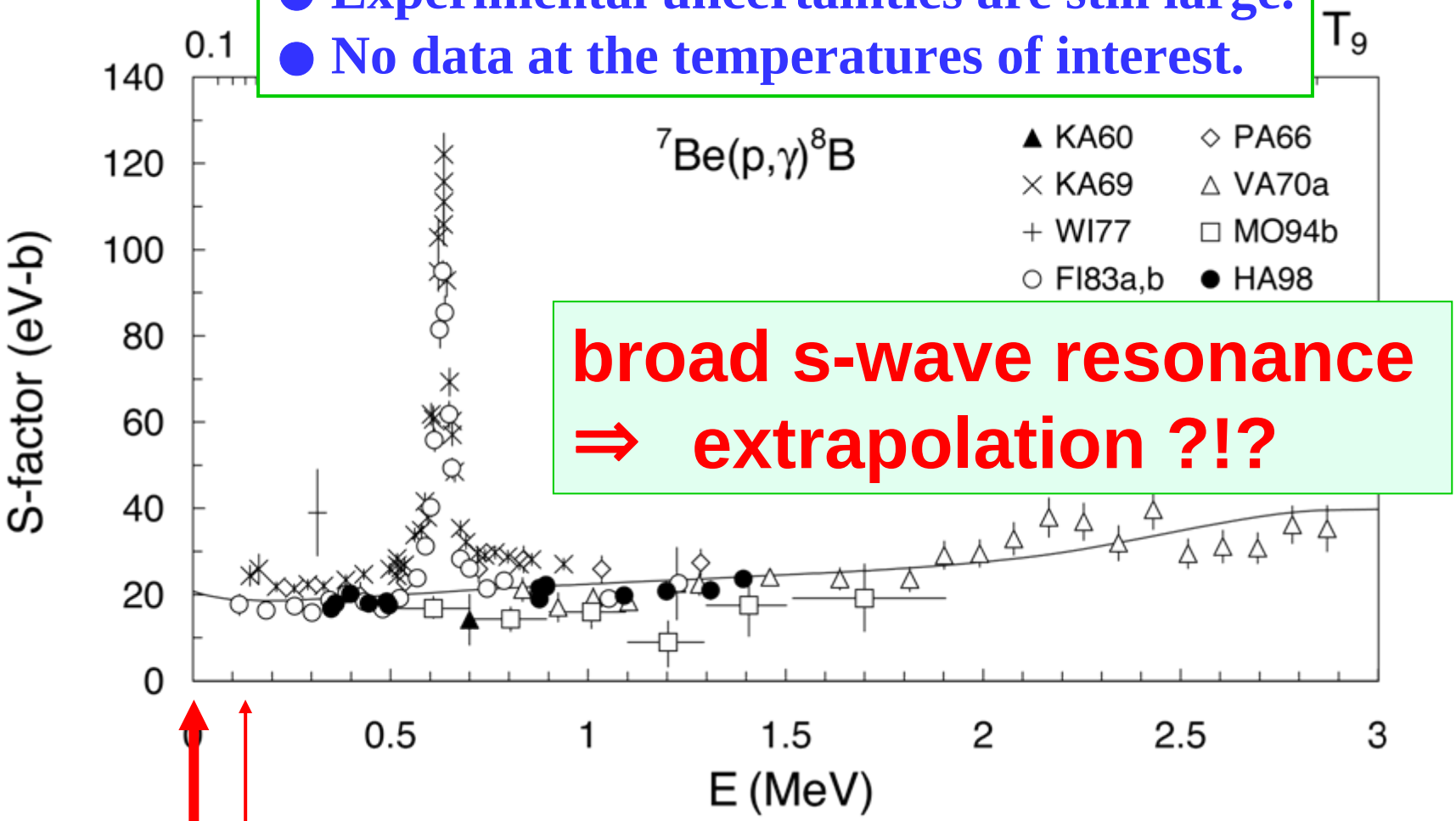

In progress at CRIB
Hot PP
PP-III
PP-II
PP-I
Proton numbers
Neutron numbers
^{13}O
^{14}O
^{12}N
^{13}N
^{9}C
^{10}C
^{11}C
^{12}C
^{8}B
^{9}B
^{10}B
^{11}B
^{7}Be
^{8}Be
^{9}Be
^{10}Be
^{6}Li
^{7}Li
^{8}Li
^{9}Li
^{3}He
^{4}He
^{6}He
^{8}He
^{1}H
^{2}H
^{3}H
n
4·H → ^{4}He
+ Energy (~27 MeV)

^{7}Be(p,γ)^{8}B study

H. Yamaguchi (CNS) , et al.

Astrophysical S-factor of $^{7}Be(p,\gamma)^{8}B$

- Experimental uncertainties are still large.
- No data at the temperatures of interest.



broad s-wave resonance
⇒ extrapolation ?!?

Gamow energy ($T_\odot$)

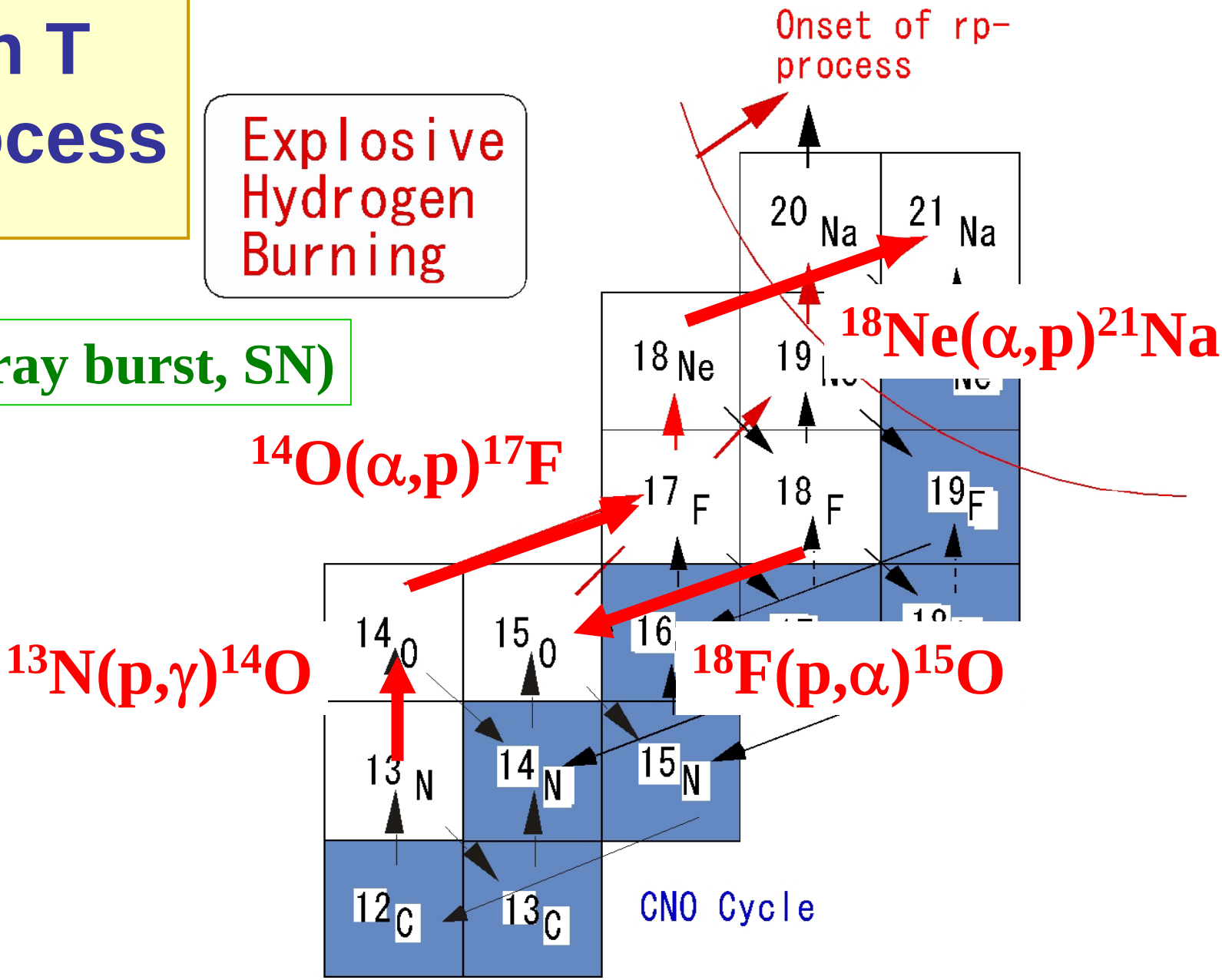
Gamow energy (3GK)

$S_{17}(0)$=0.019+0.004 -0.002 (keV b)
(Adelberger *et al.*, 1997)

High T rp-Process

Explosive Hydrogen Burning

(e.g. X-ray burst, SN)

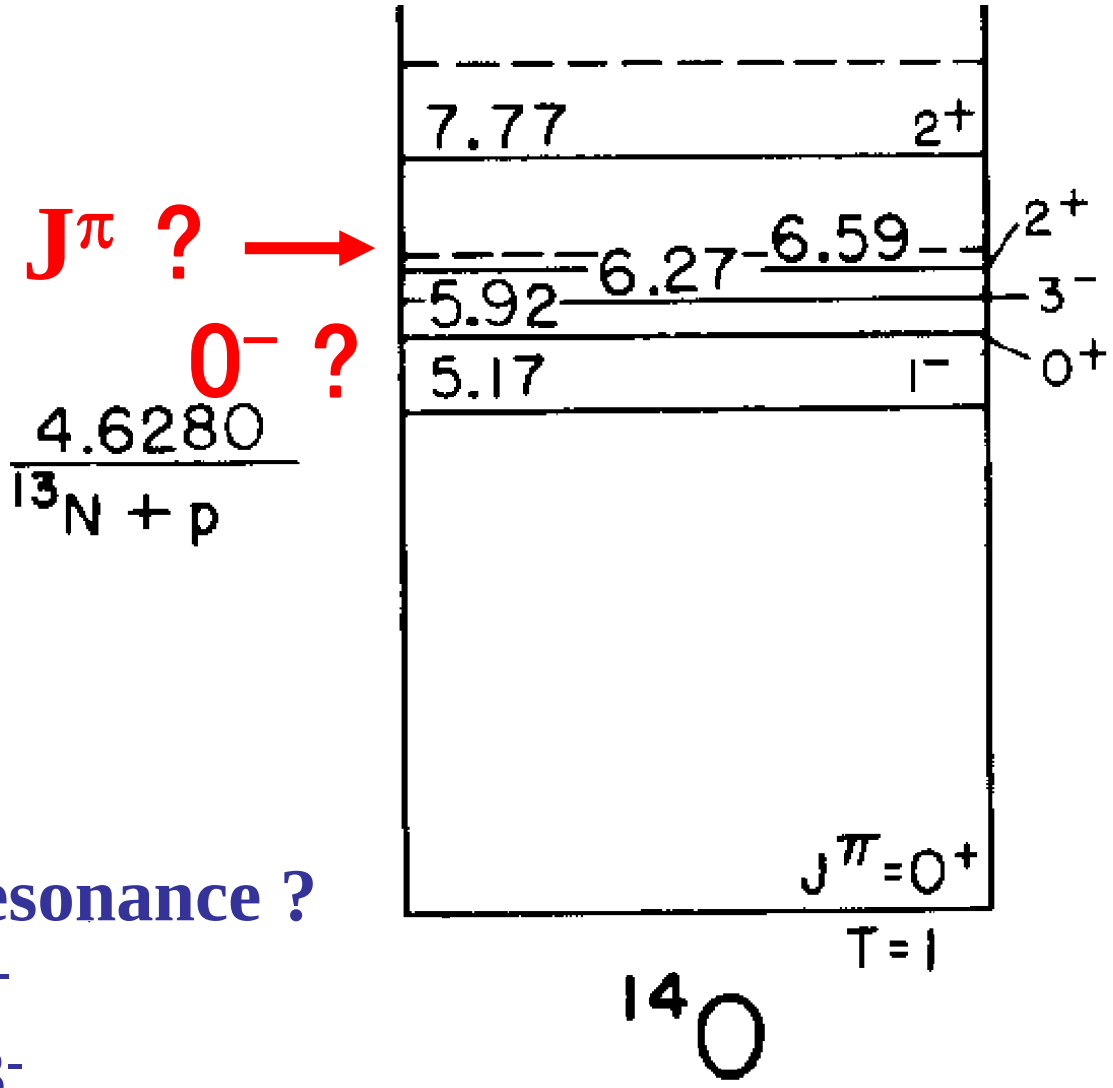


Recent Result;
Resonance Search of ^{13}N+p

by T. Teranishi (Kyushu U.)

^{13}N+p experiment (^{14}O resonances)

- Search for unknown resonances
  Astrophysical ^{13}N(p,γ)^{14}O reaction rates
- Spectroscopic factors for single-particle proton orbitals

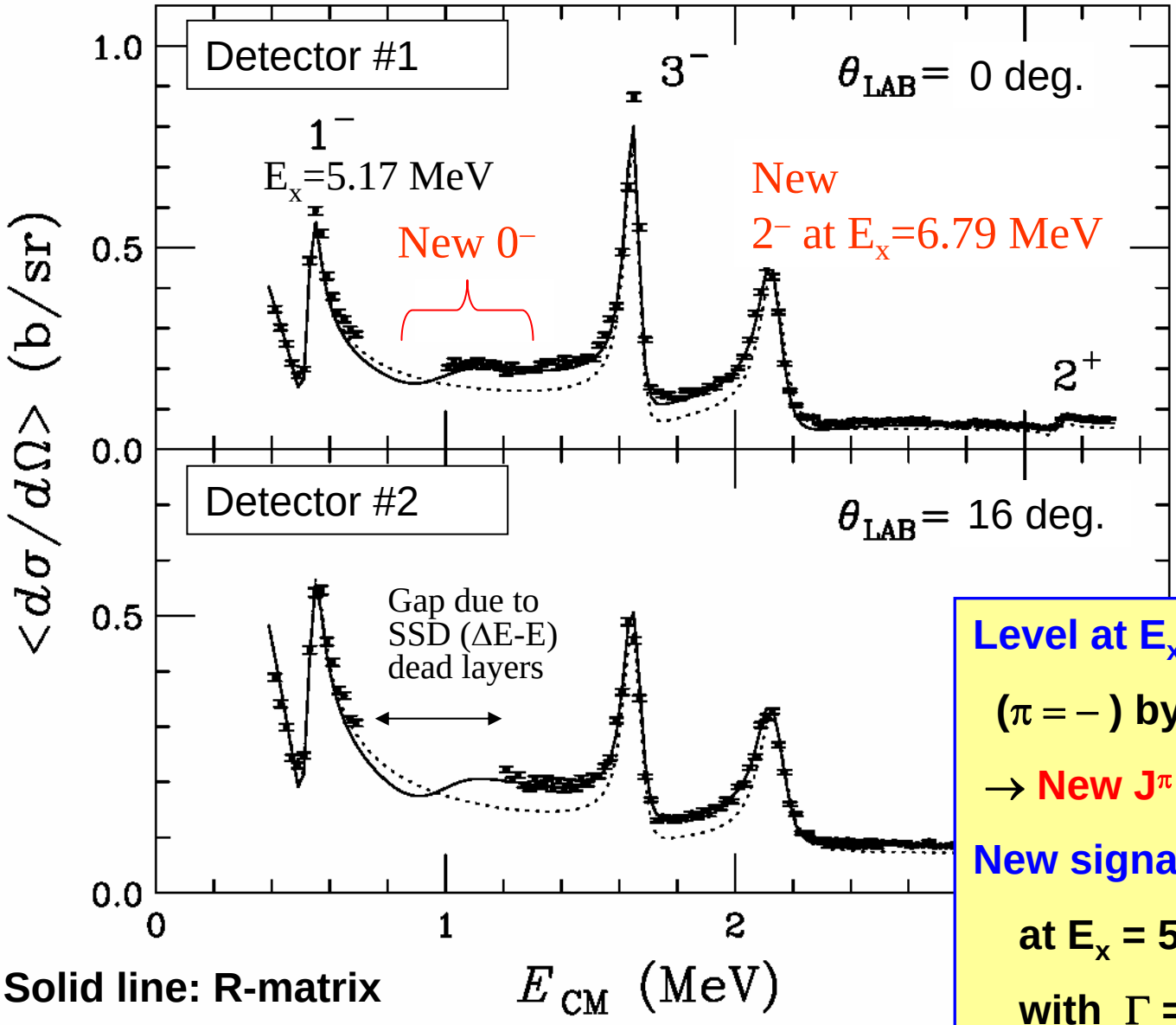


single particle resonance ?

$(p_{1/2} \cdot s_{1/2})$ $J=0^-, 1^-$

$(p_{1/2} \cdot d_{5/2})$ $J=2^-, 3^-$

^{13}N+p result (^{14}O resonances)



Solid line: R-matrix

Energy resolution ~20 keV (FWHM)

Level at E_x = 6.79 MeV

($\pi = -$) by ^{14}N(^{3}He,t) reaction

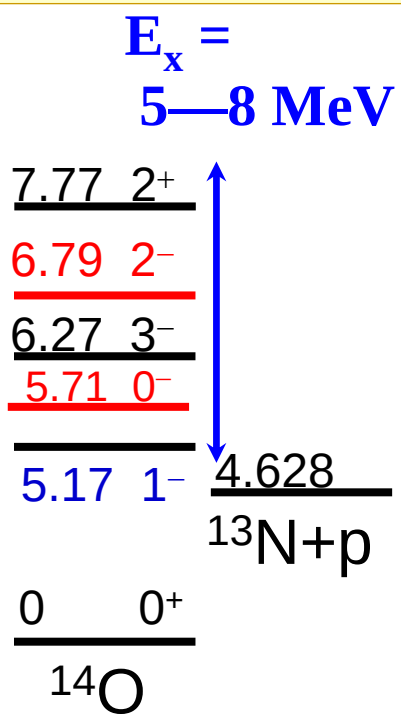
→ New J^π assignment $J^\pi = 2^-$

New signature of 0^- level

at E_x = 5.71(2) MeV

with Γ = 400(100) keV

Summary of ^{13}N+p



J^π	l_j	Γ_{exp} (keV)	$\Gamma_{s.p.}$ (keV)
1^-	$s_{1/2}$	42(3)	45
0^-	$s_{1/2}$	400(100)	550
3^-	$d_{5/2}$	42(3)	53
2^-	$d_{5/2}$	96(4)	130

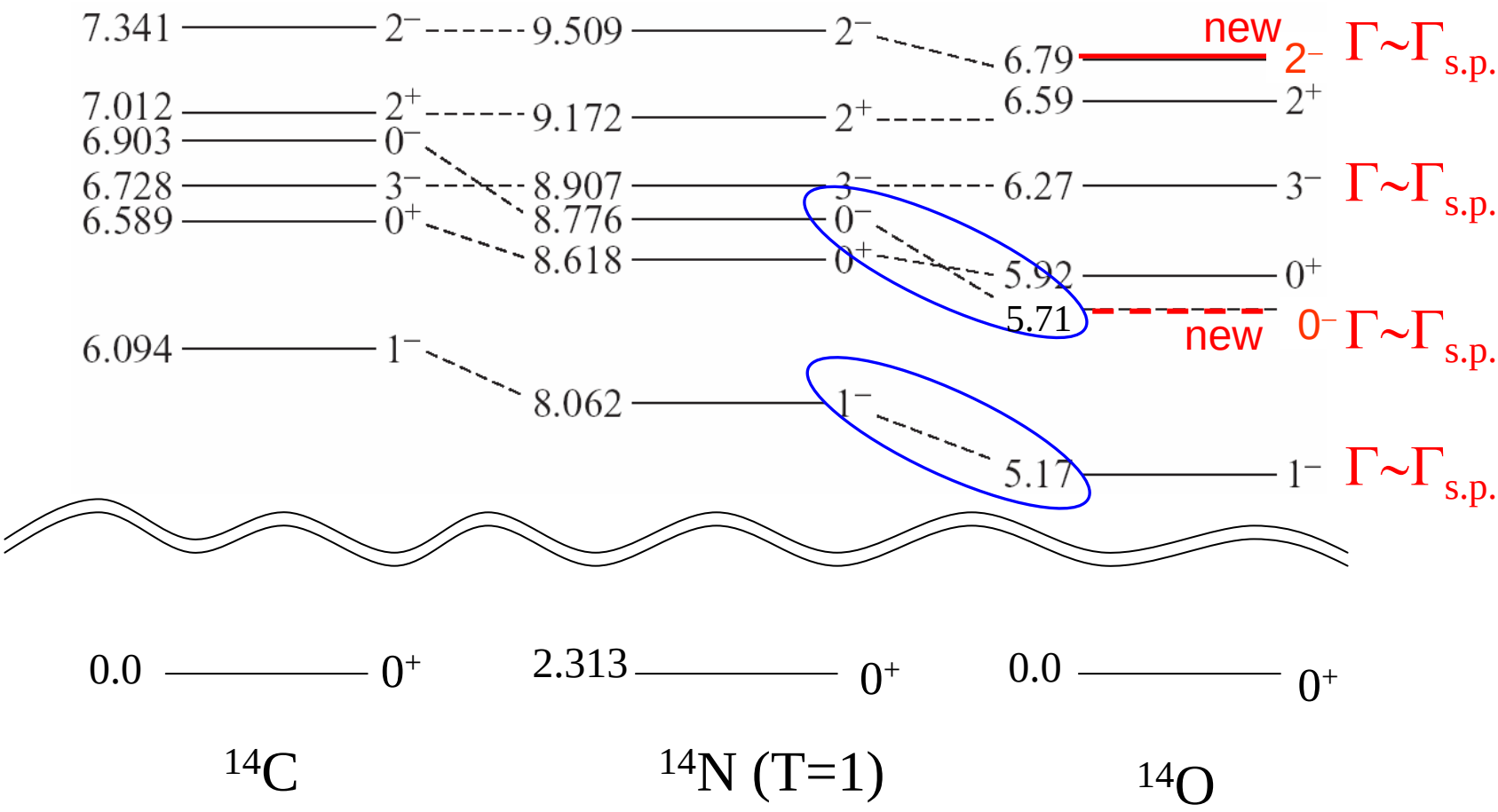
- The first experimental signature of the 0^- levels in ^{14}O.
- $J^\pi = 2^-$ has been clearly established for the 6.8 MeV level.
- The Γ of 1^-, 0^-, 3^- & 2^- levels are comparable to the single-particle values (Γs.p.).

$\Gamma_{s.p.}$ values were estimated using phase shifts in a Woods-Saxon potential model.

1^- & 0^- levels: ^{13}N+p ($2s_{1/2}$) resonance

3^- & 2^- levels: ^{13}N+p ($1d_{5/2}$) resonance

T=1 triplets in A=14 nuclei



Very large Thomas-Ehrman shifts for s-wave resonances !

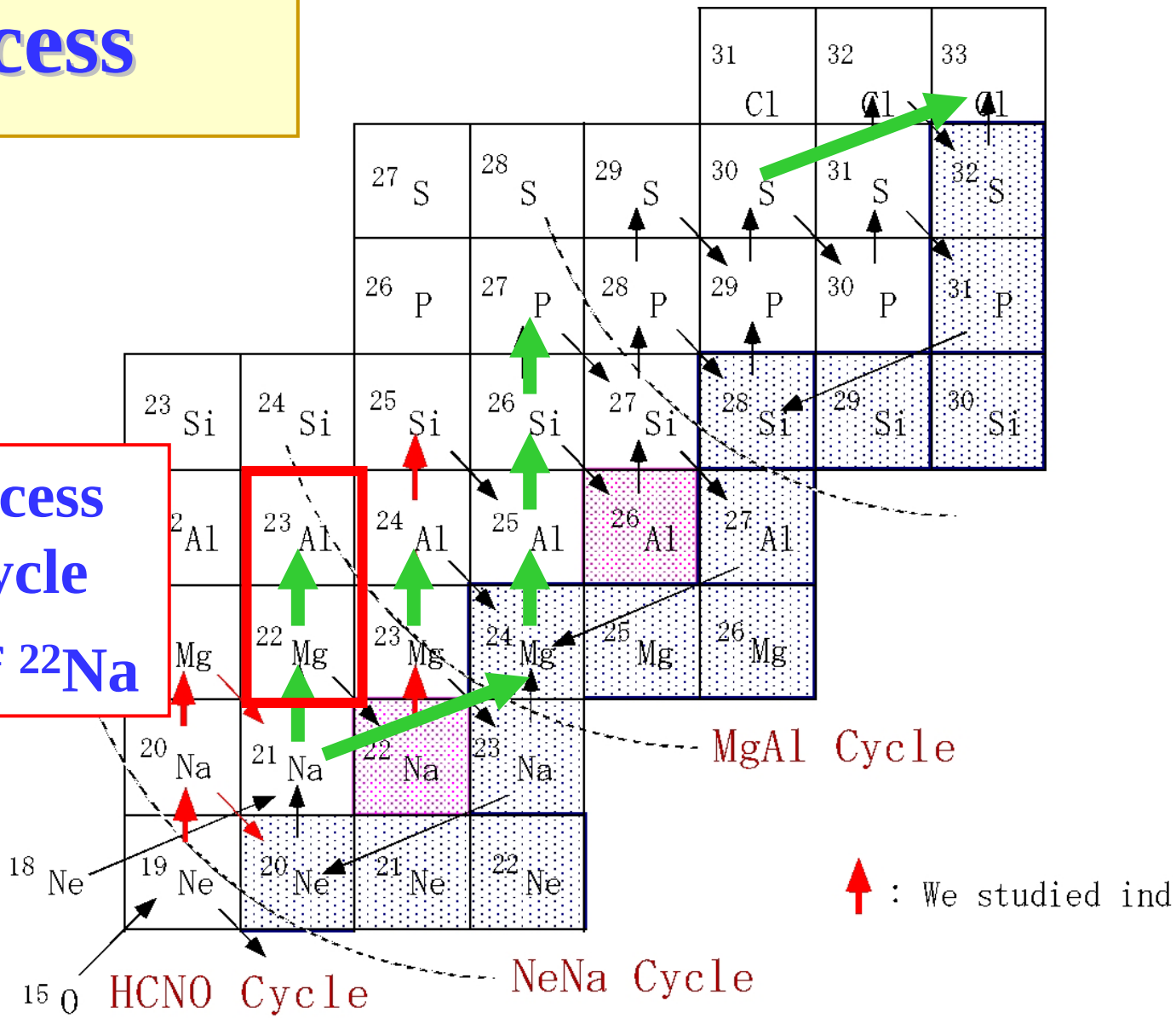
^{22}Mg+p Resonant Scattering

J.J. He, Lanzhou/CNS

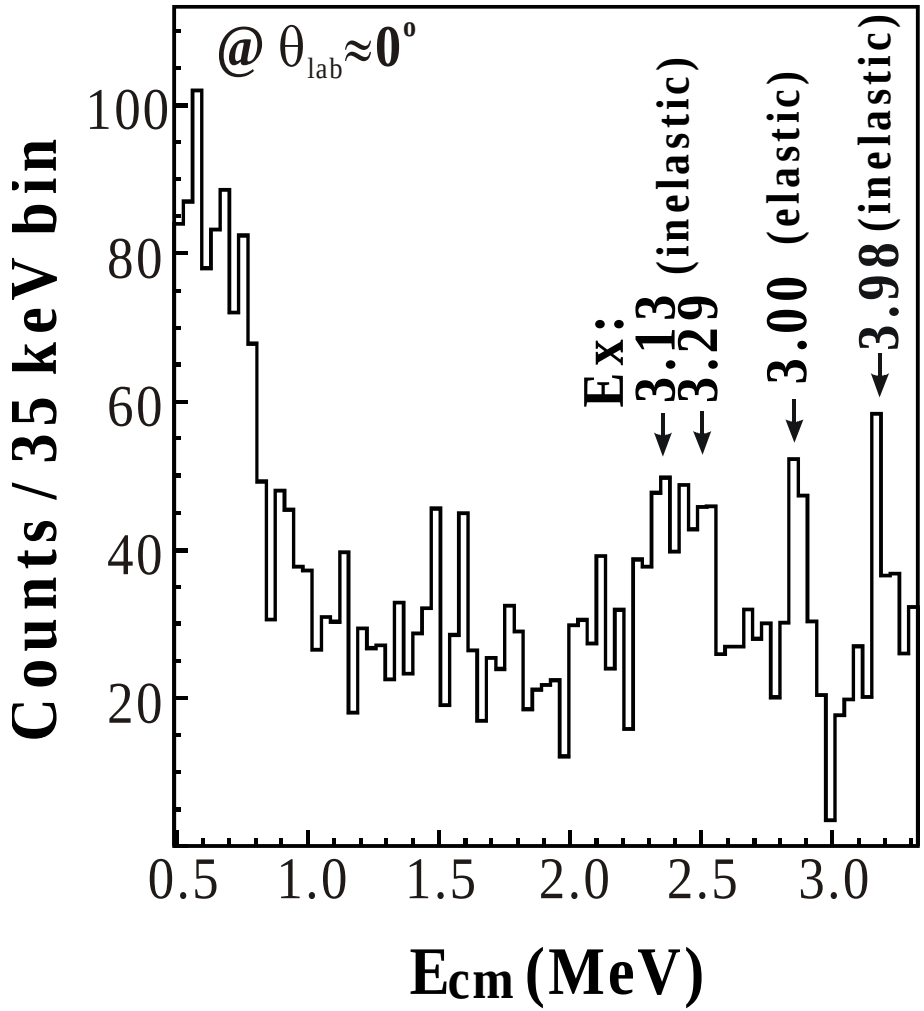
Early Stage of rp-Process

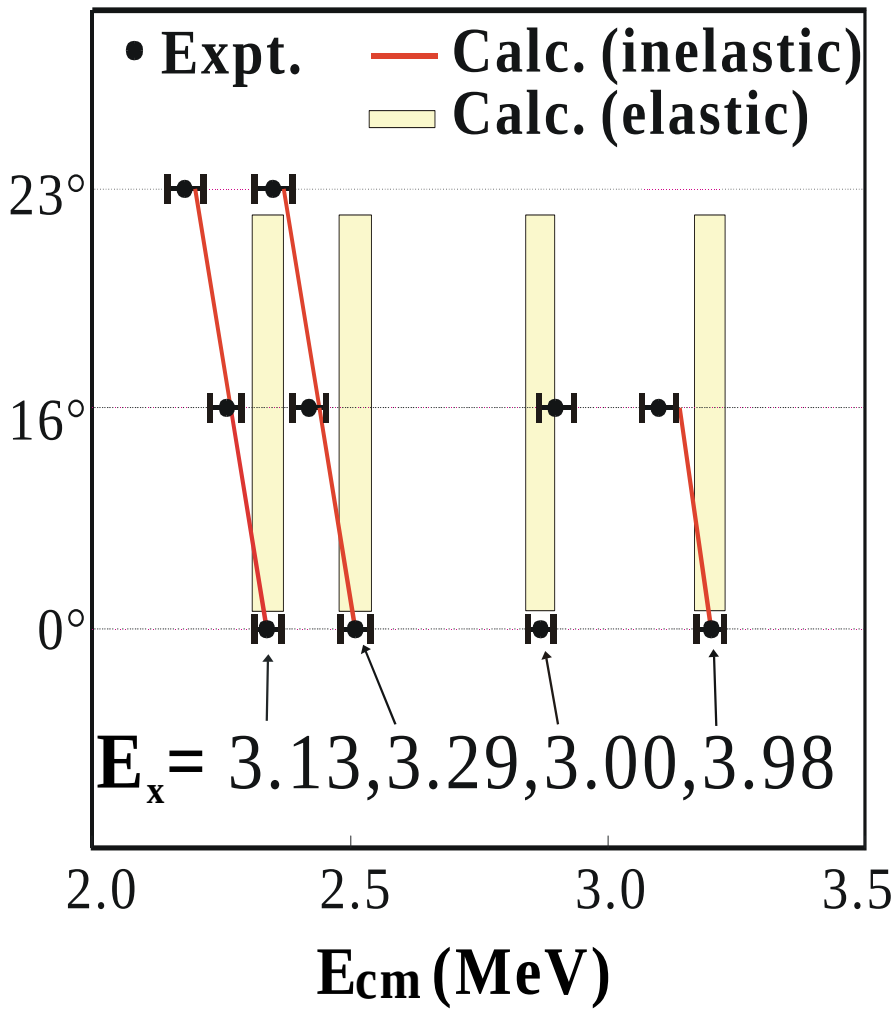
In progress at CRIB

- Breakout process from NeNa Cycle
- Production of ^{22}Na

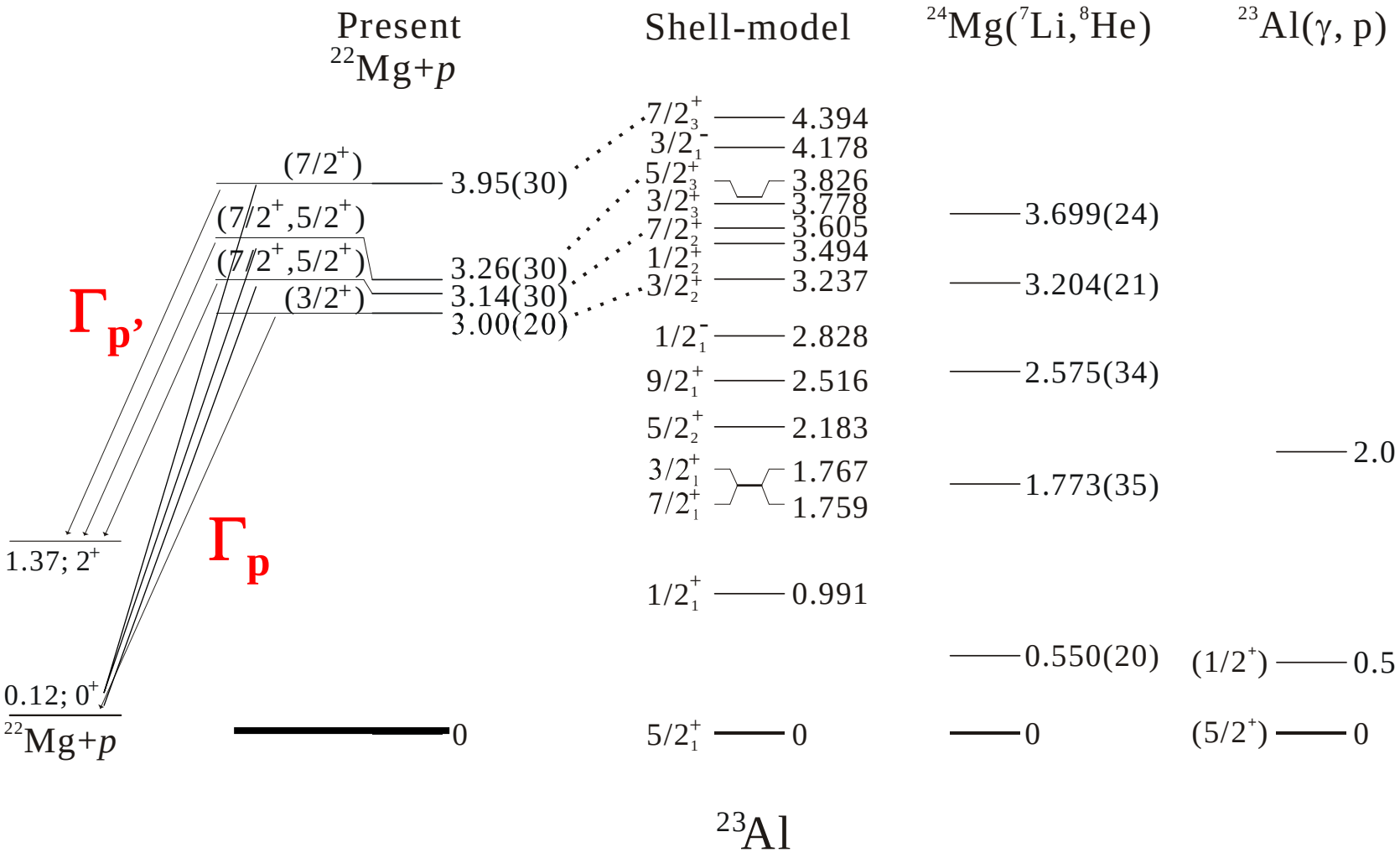


Spectrum of ^{22}Mg+p Scattering





Level Scheme in ^{23}Al



Comparisons

E_x	J^{π}_{expt}	J^{π}_{calc}	ℓ	$\Gamma_{p,(p')}^{exp}$	$\Gamma_{p,(p')}^{cal}$
0.55	$(1/2^+)$	$1/2_1^+$	0		0.074
1.77	$(3/2^+)$	$3/2^+$	2		1.0
3.00					
3.14*					
3.26*	$(7/2^+, 5/2^+)$	$5/2_3^+$	0	30(20)	10
3.95*	$(7/2^+)$	$7/2_3^+$	2	30(20)	18

Good tool to study
single particle state ⓧ the excited core component !

* Their widths are for the decay branches to the 1st states in ^{22}Mg.
(Energy in MeV and width in keV)

(p,γ) Reaction under High Temperature Equilibrium

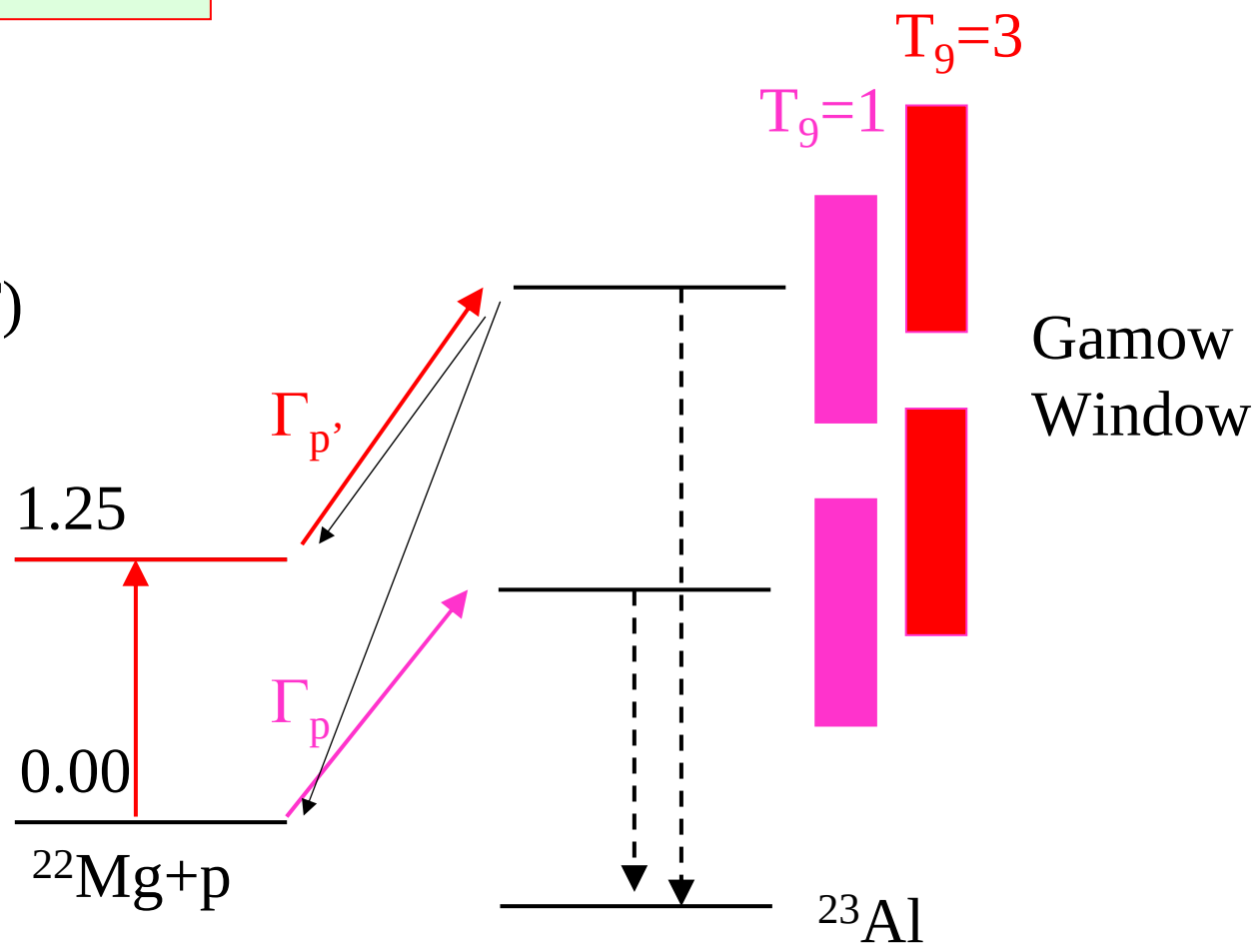
Direct information (p,γ) on excited state

The core-coupled single-particle structure

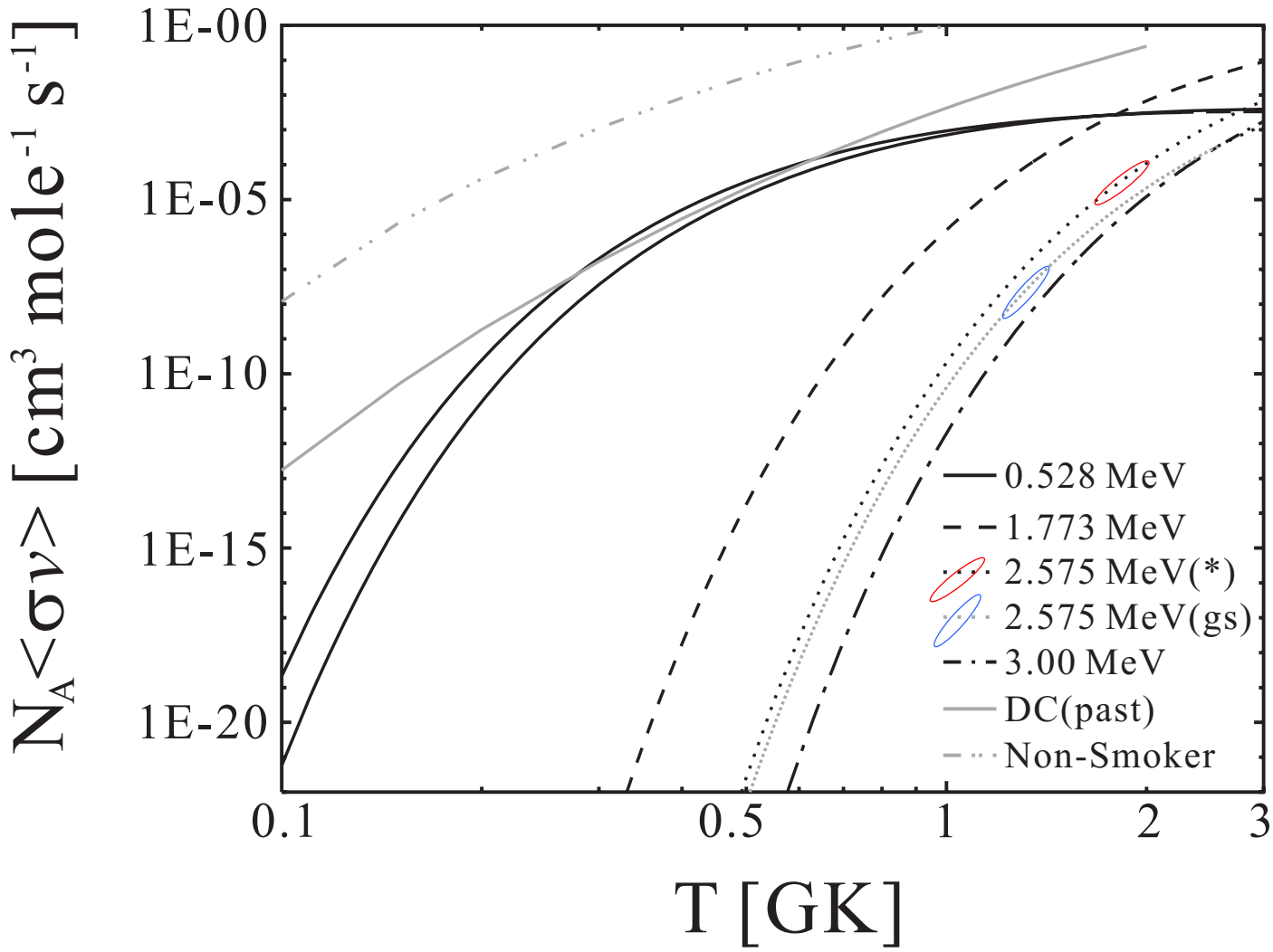
Partition:

$=(2J_i+1)\exp(-Ex/kT)$

T_9=1	3
3×10^{-6}	**0.04**
1.0	0.96



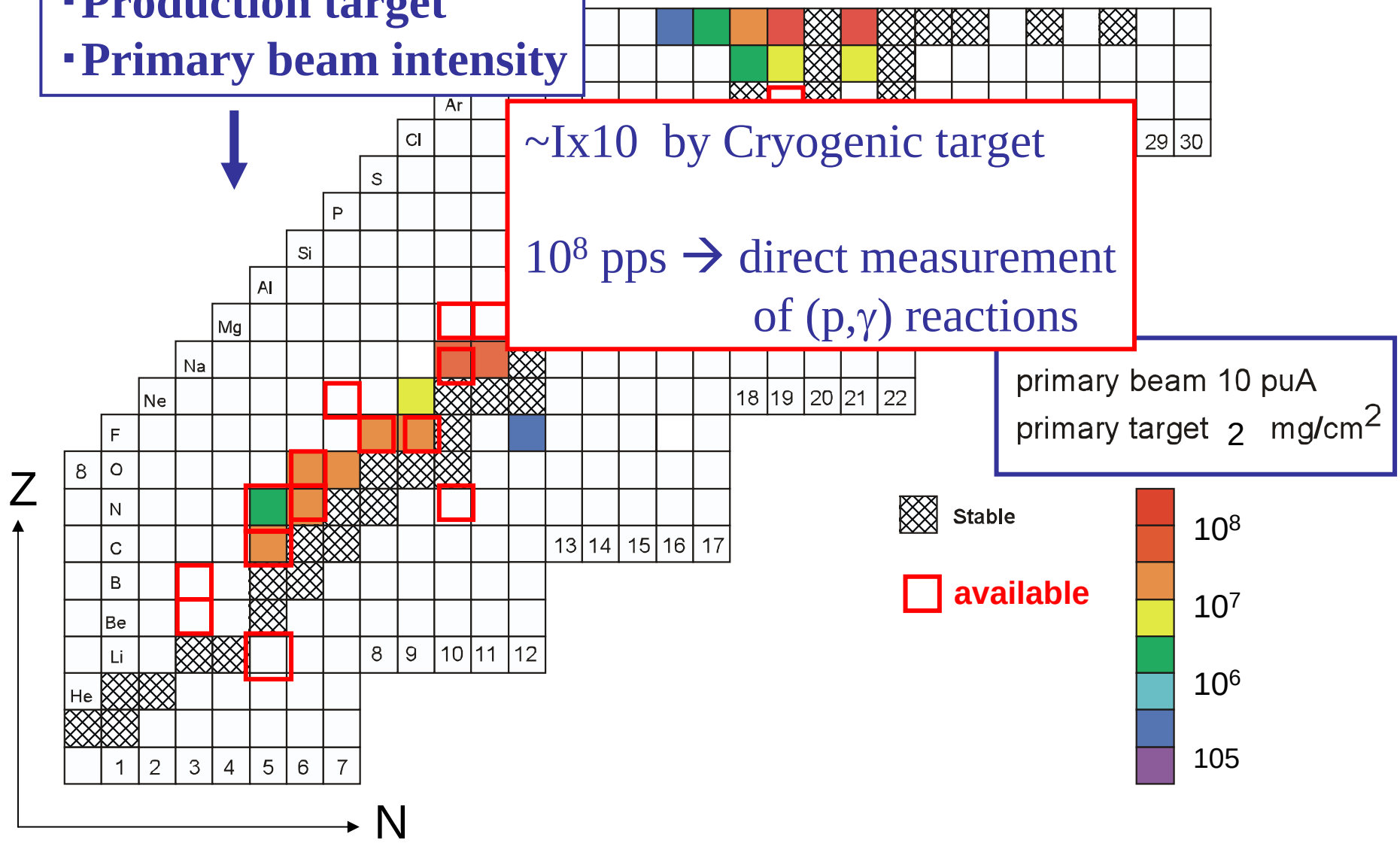
$^{22}Mg(p,\gamma)^{23}Al$ Stellar Reaction Rate



Higher RI beam Production

RIB intensity to be obtained at CRIB

- Production target
- Primary beam intensity



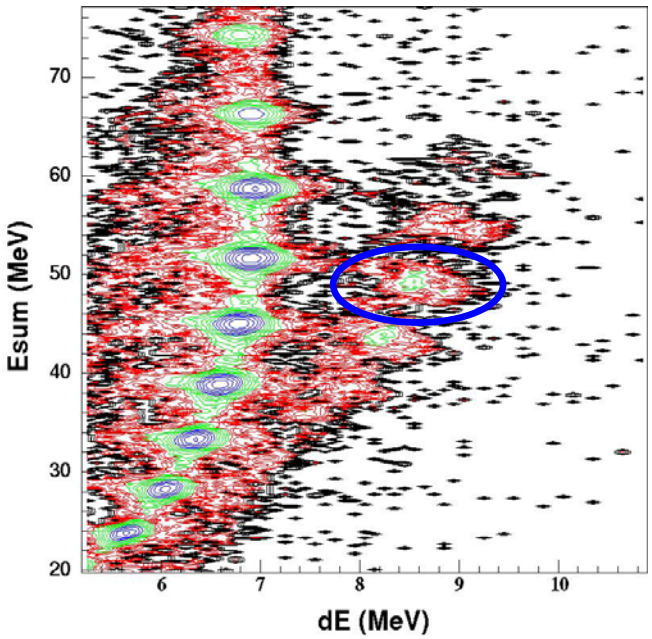
- **Many heavy ion beams are available with higher beam intensities.**
- **Target foil durability limits the use.**

- **Window-less target**
- **With better primary beams**

Production of fp-shell RI beams

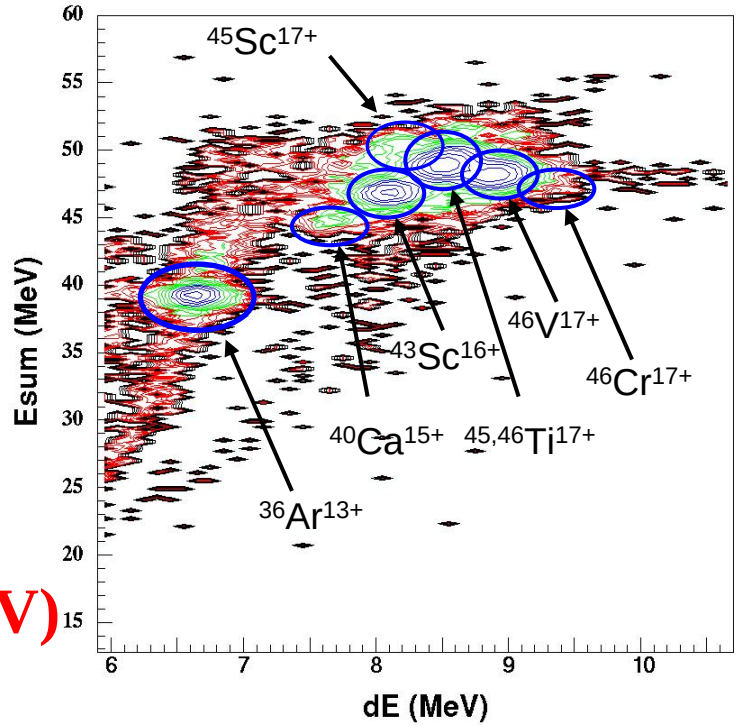
$^{12}C+^{36}Ar \rightarrow ^{46}Cr$ Fusion Reaction

PI of Monolithic Si@F3



W.F. 80kV

(PI will be improved with ±200 kV)

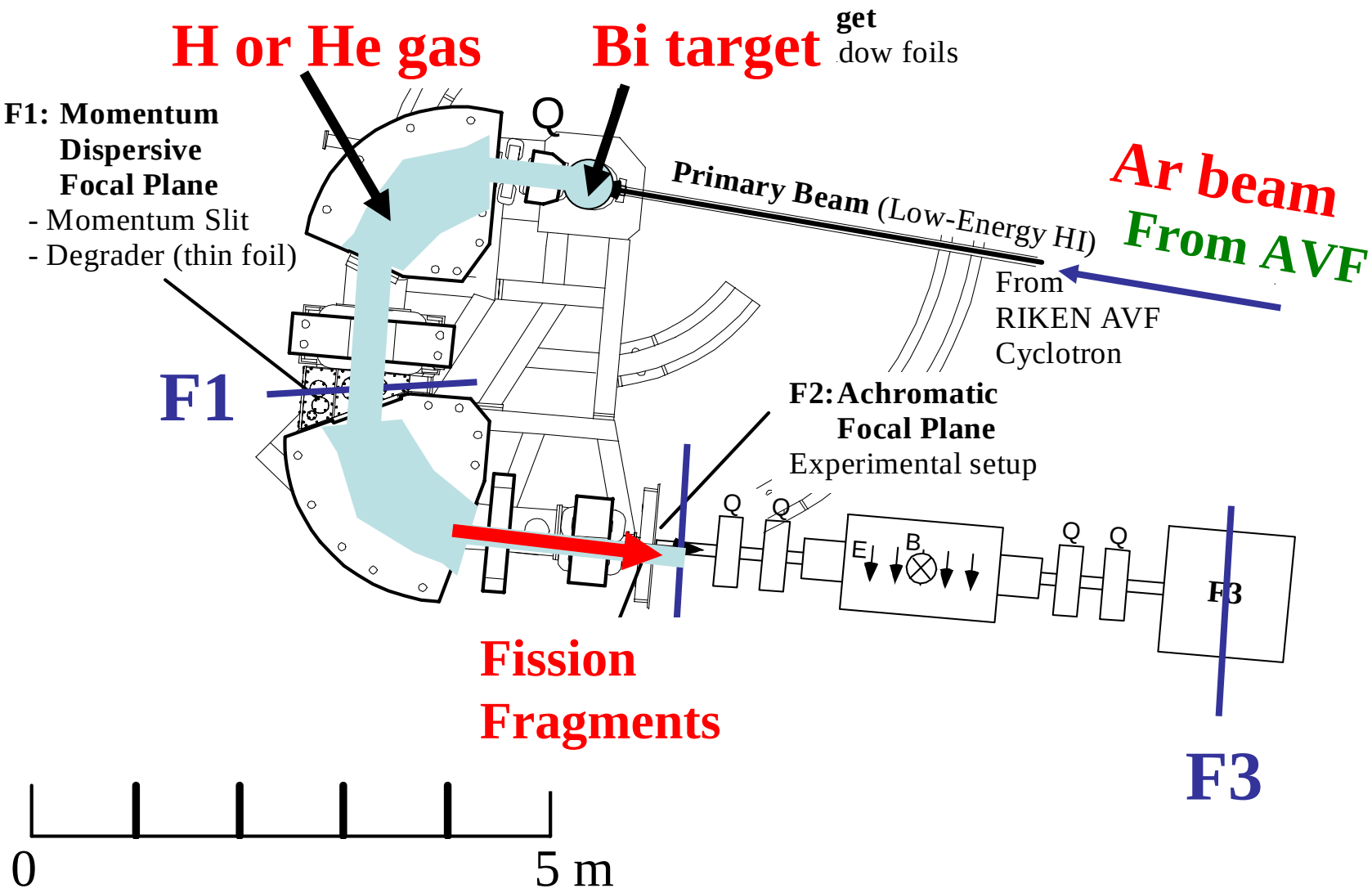


Nuclide	^{46}Cr	^{46}V	^{45}Ti	^{46}Ti	^{43}Sc	^{45}Sc	^{40}Ca	^{36}Ar	Total
Purity (%)	**1.2**	28.6	3.0	38.2	13.1	0.9	0.7	15.4	
Intensity (pps)	**2.4**	57.3	6.2	76.6	26.4	1.8	1.4	33.2	213

Purities and intensities of secondary beams with primary beam of 20 pnA

RI beams of fission products

CRIB→Gas-filled Recoil Isotope Separator



Mass resolution and yields

Preliminary tests have been made;

A large production of the fragments
(σ > 1b)
ΔM/M ~ 10-15 % for A~100
(2-3 % -- best value in a literature)

→ Need good ID method.
mass measurements, ..,

END