Nuclear Astrophysics with Low-Energy, High-Intensity RI Beams at CRIB

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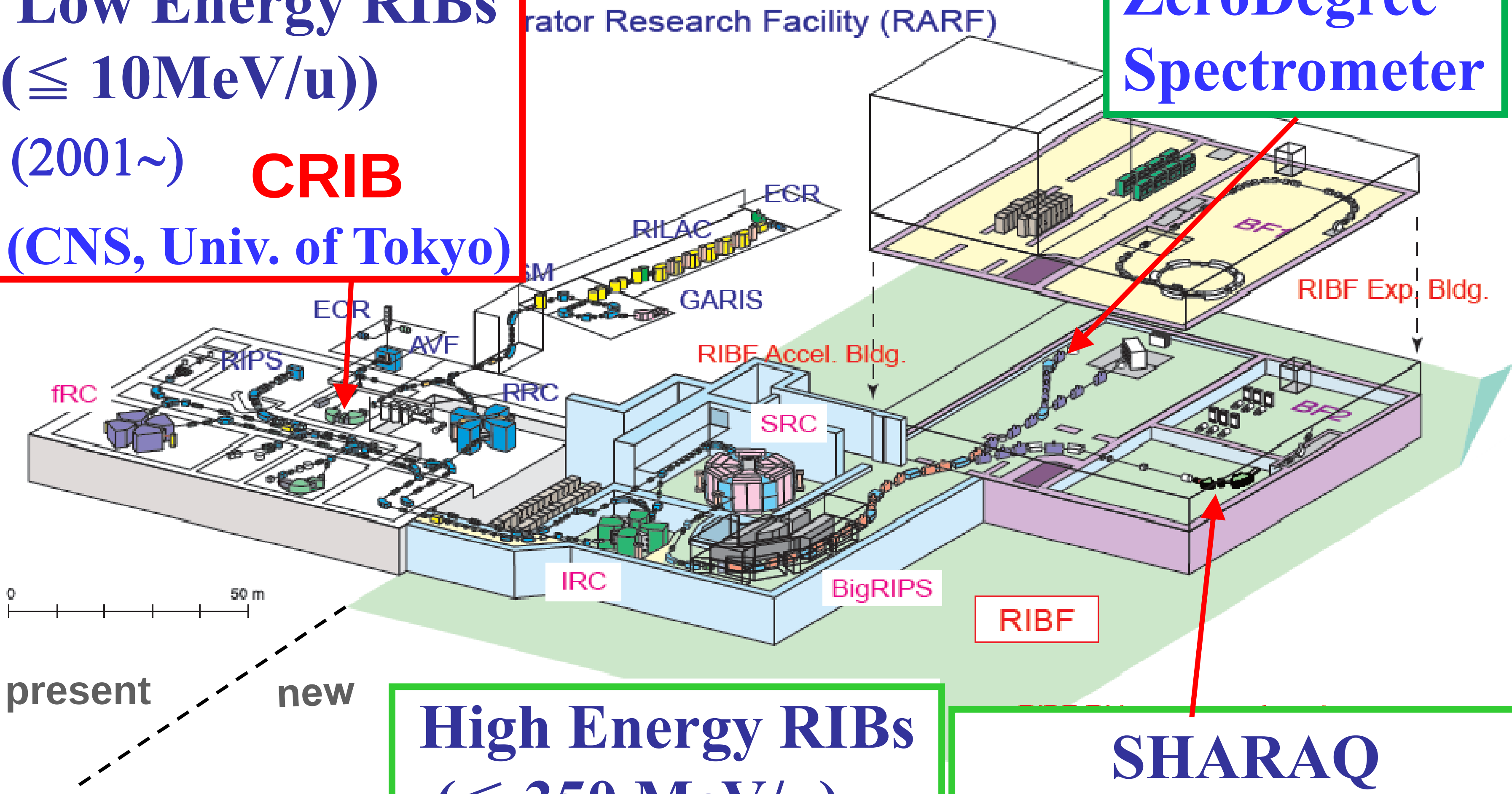
1. Low-energy RI beam facility; CRIB
2. Ignition and early stage of explosive nucleosynthesis
   - First generation stars, X-ray bursts , Core-collapse supernovae
3. Summary

Low-Energy RI Beam Facility; CRIB

RIKEN RIBF Facility

Low Energy RIBs (≦ 10MeV/u))
(2001~) **CRIB**
(CNS, Univ. of Tokyo)

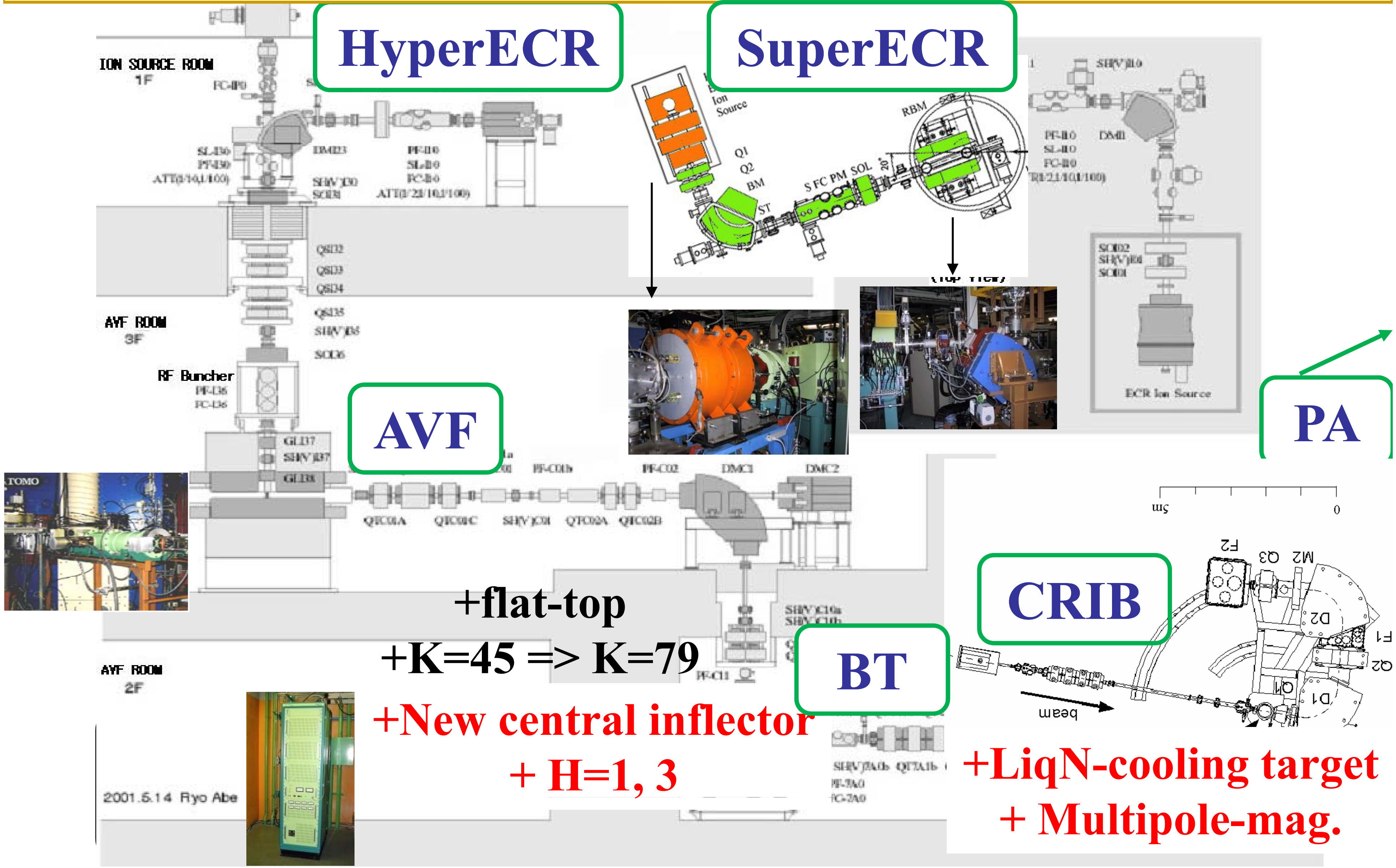
ZeroDegree Spectrometer



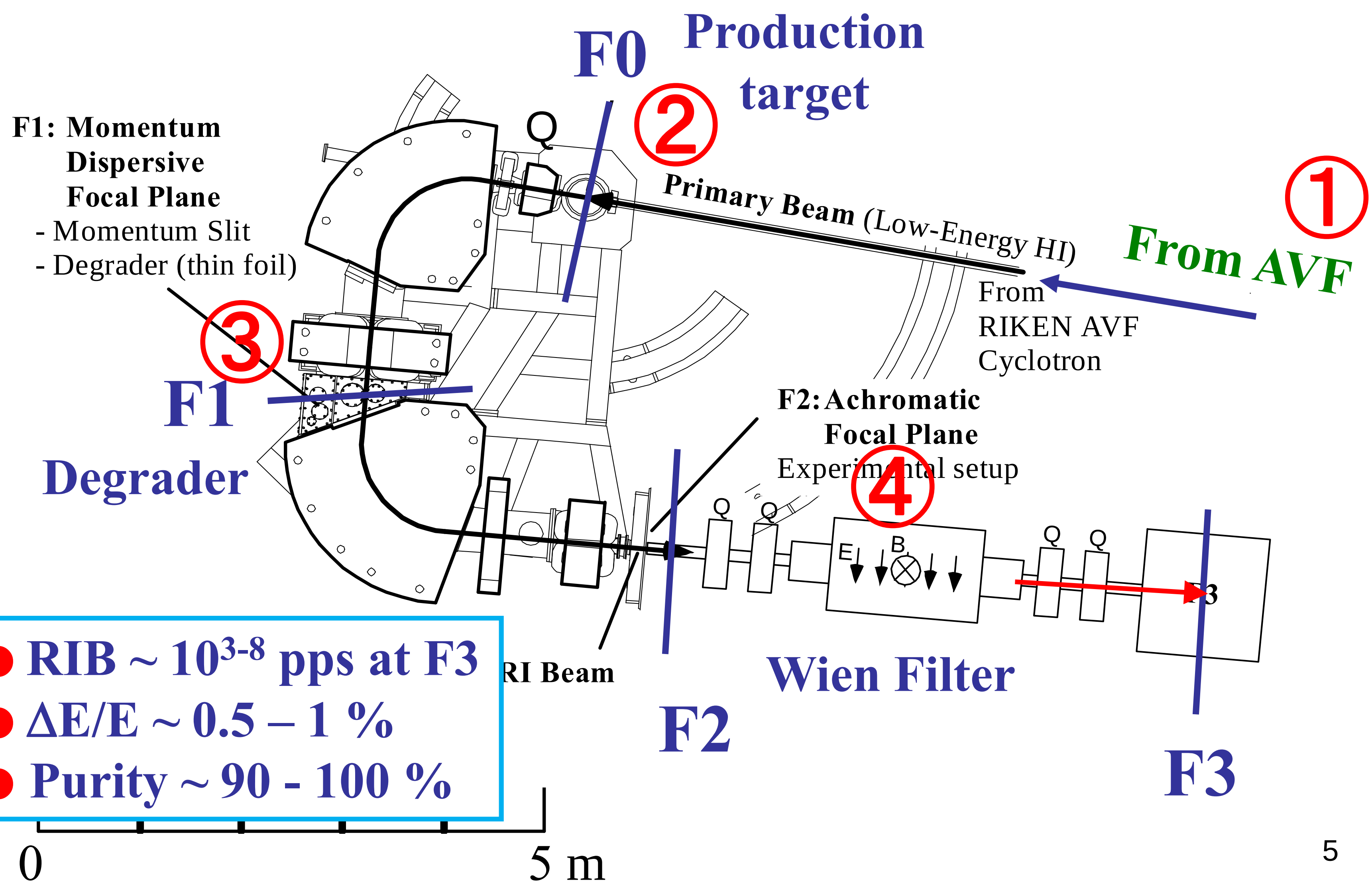
High Energy RIBs (≦ 350 MeV/u)

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

AVF Upgrade Project

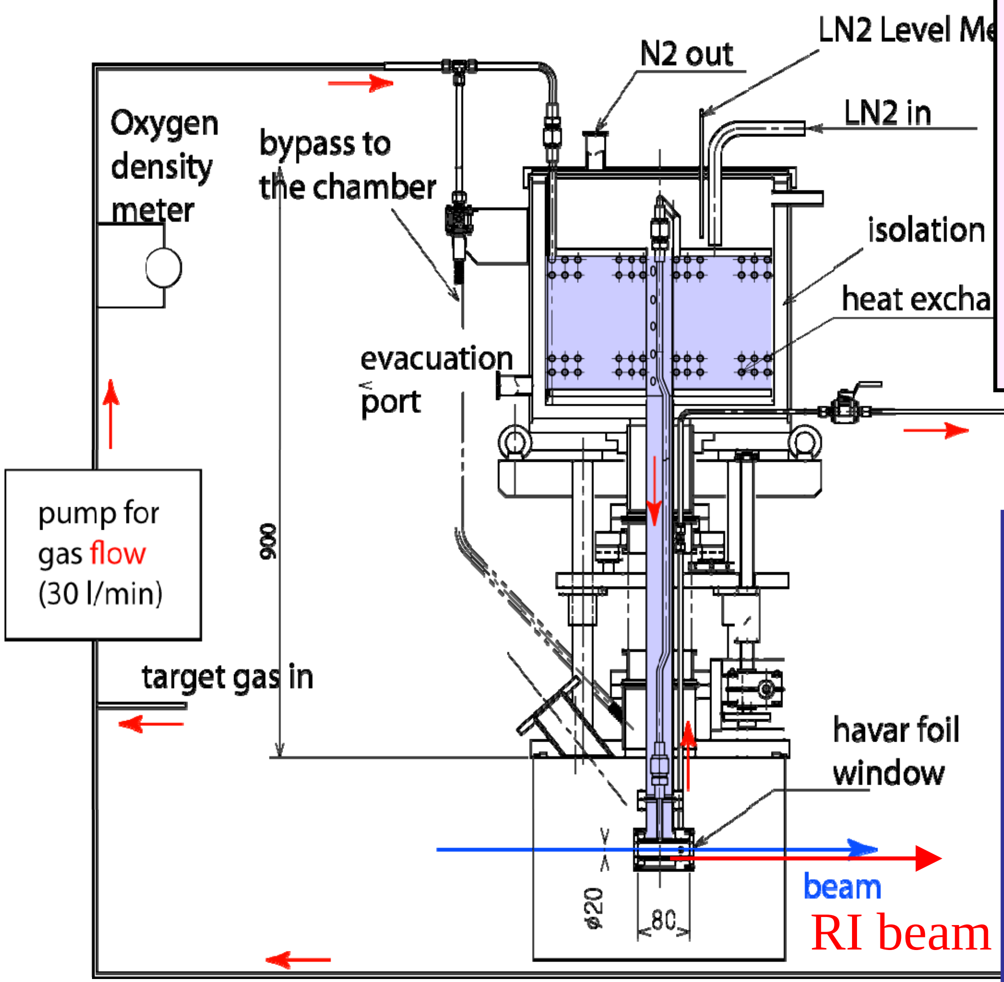


CRIB; Low-Energy In-Flight RI Beam Separator at CNS



- RIB ~ 10^{3-8} pps at F3
- ΔE/E ~ 0.5 – 1 %
- Purity ~ 90 - 100 %

Low-Temperature Production Target



Flow ≦100 lit/min.

Target durability ~ x 3-4
Gas target density ~x 3

↓

~ x 10 intensity increase

- Forced target gas flow (100 l/min) to

d

sensor.

H_2 target cooled by liquid Nitrigen

↓

^{7}Be ~ 2x10^{8} achieved !
@ 1-2 MeV/u
with 1.8 pμA

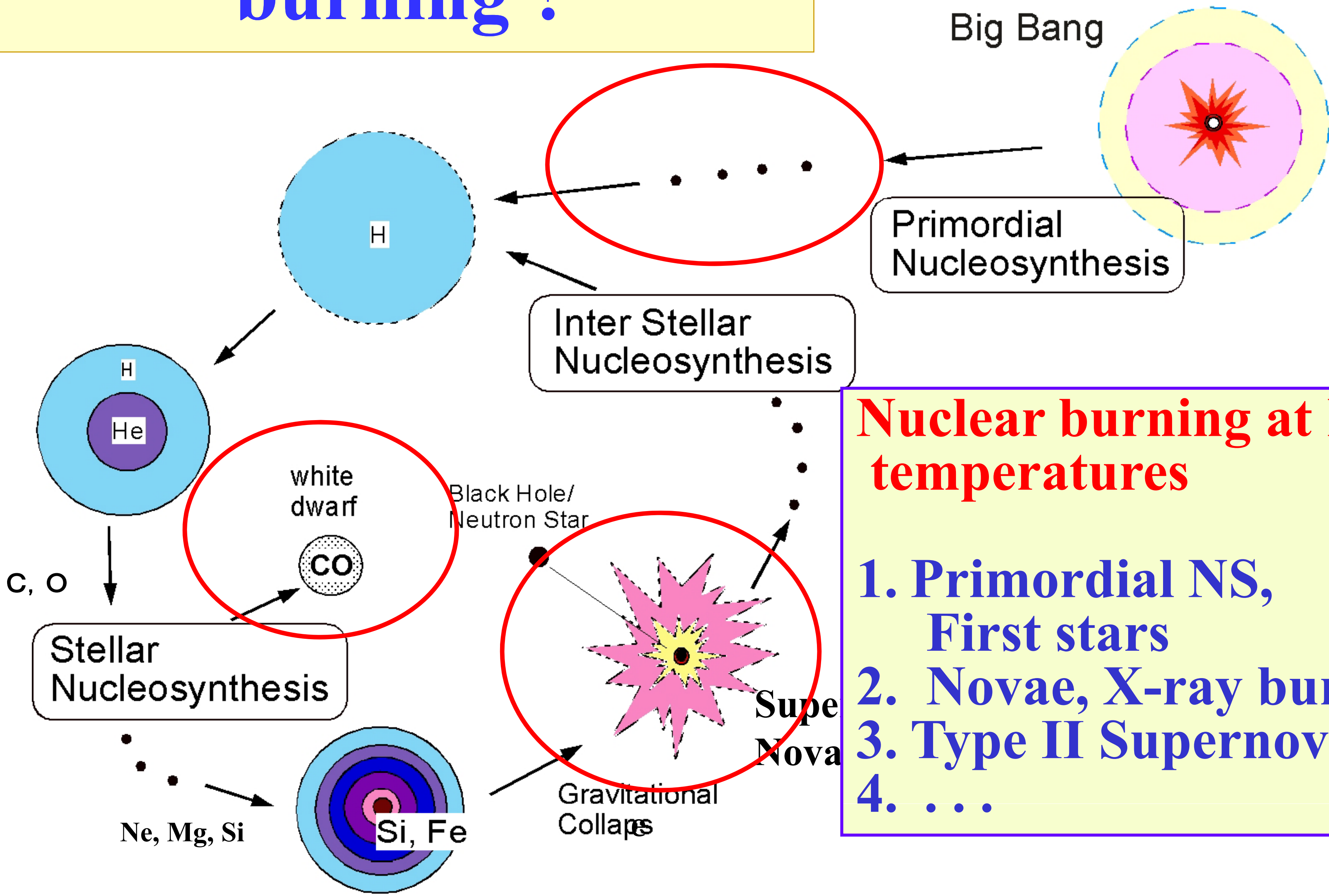
Direct Method with RI Beams

RIB intensities		reaction type
10^4 pps	→	Resonant scattering w/thick target method eg. ^{22}Mg+p
10^6 pps	→	Rearrangement reactions eg. (α,p), (α,n), (d,p), . . .
10^8 pps	→	(p,γ), (α,γ), . . .

Total system development=AVF Upgrade project

1. Ion source
   - SuperECR
2. Accelerator
   - FT mode, Modify central region
3. Beam transport
4. Production target
5. Separator - Multipole element

Where high-T burning ?



Nuclear burning at high temperatures

1. Primordial NS, First stars
2. Novae, X-ray burst
3. Type II Supernovae
4. . . .

Ignition and early stage of explosive nucleosynthesis

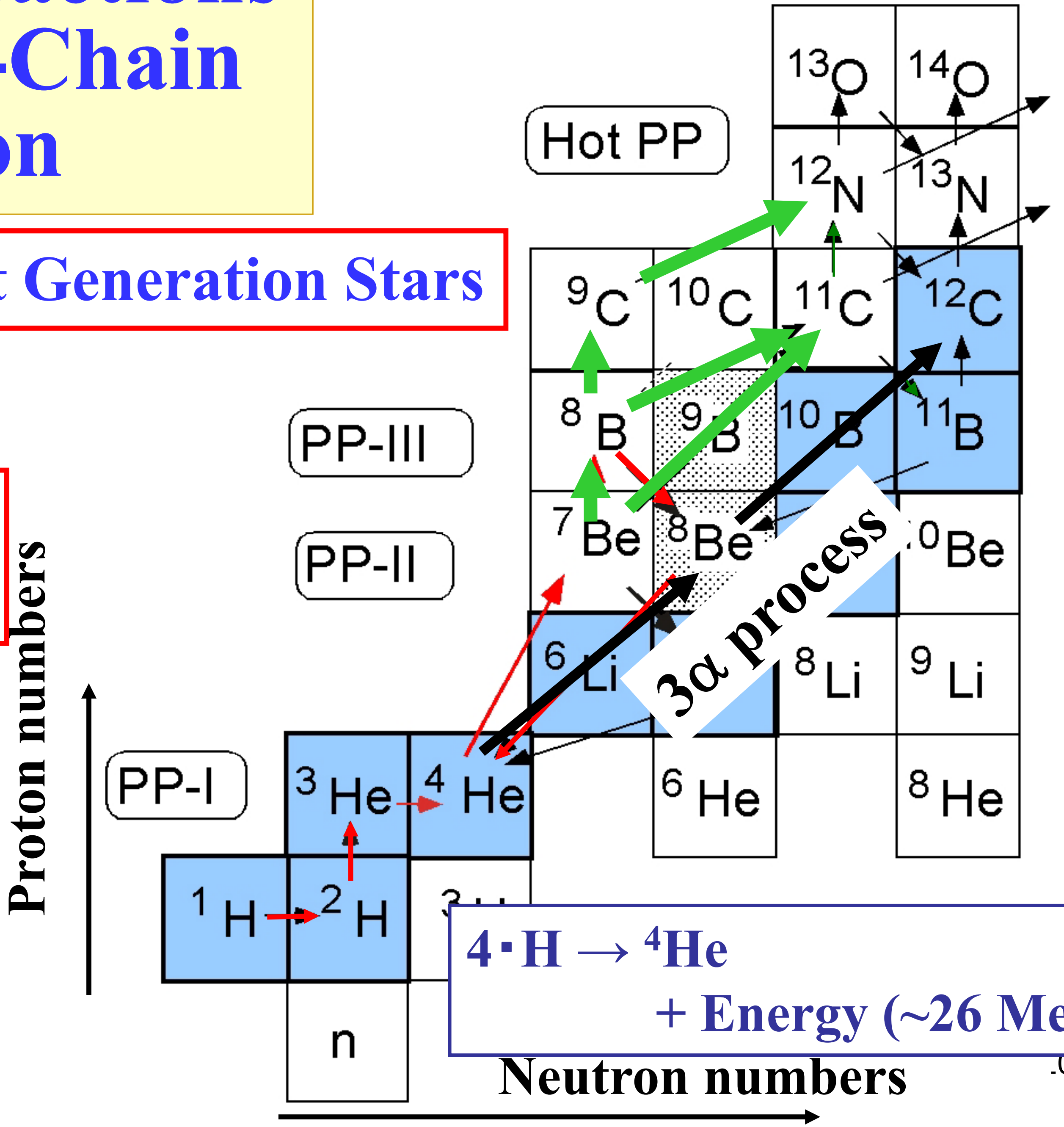
- **First-generation stars**
- **Novae, X-ray bursts**
- **Type-II Supernovae**

Nuclear reactions in the pp-Chain region

First Generation Stars

H~75 %
He~25%

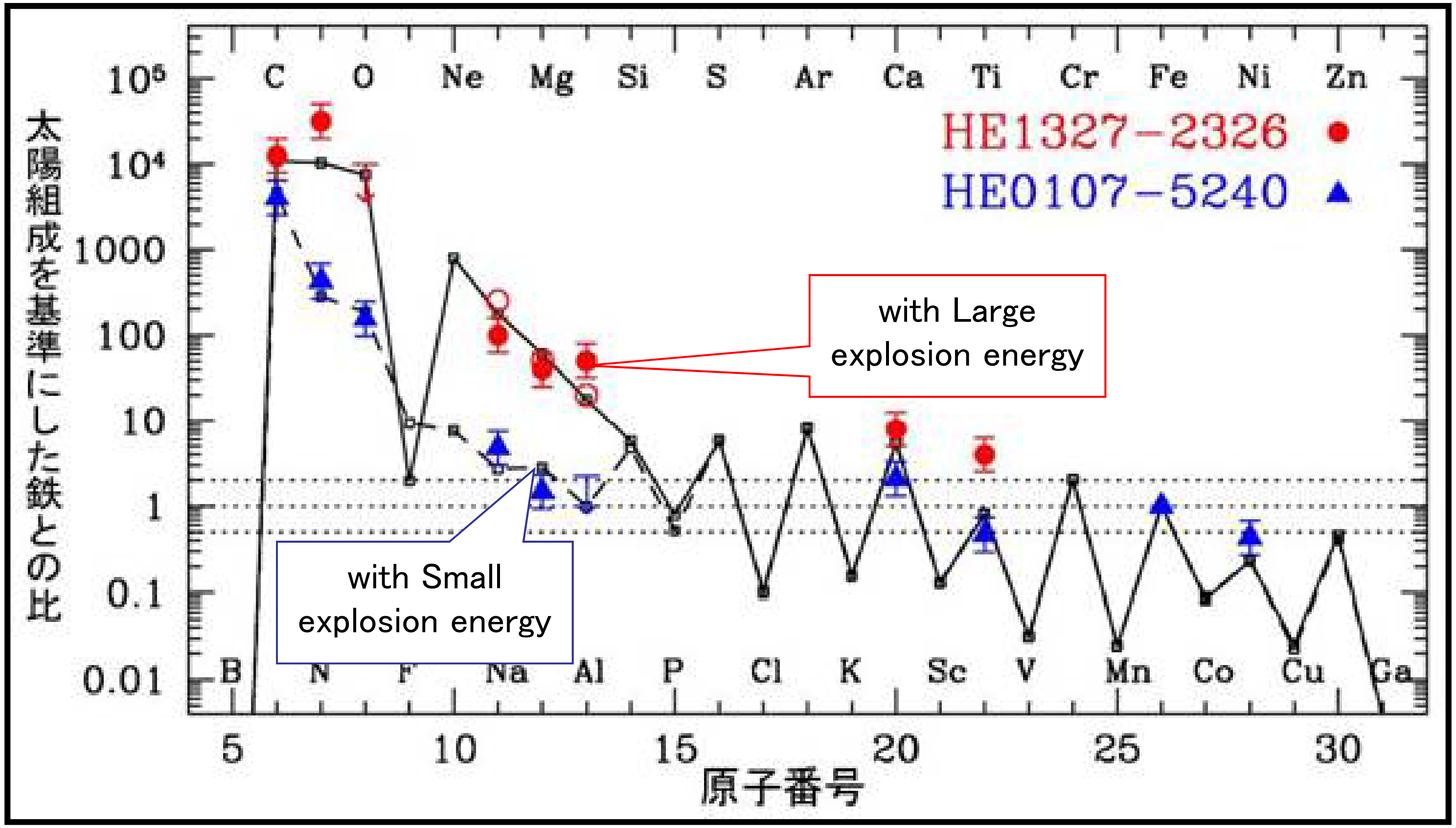
Big Bang Nucleosynthesis



$4 \cdot H \rightarrow {}^4He$
$+$ Energy (~26 MeV)

Observation of Early Stars

= Ultra metal poor stars =



(Nomoto, 06)

Primordial Nucleosynthesis = H, He, (Li) → How ? @T, ρ ? → Abundant C, O + Sr, ..

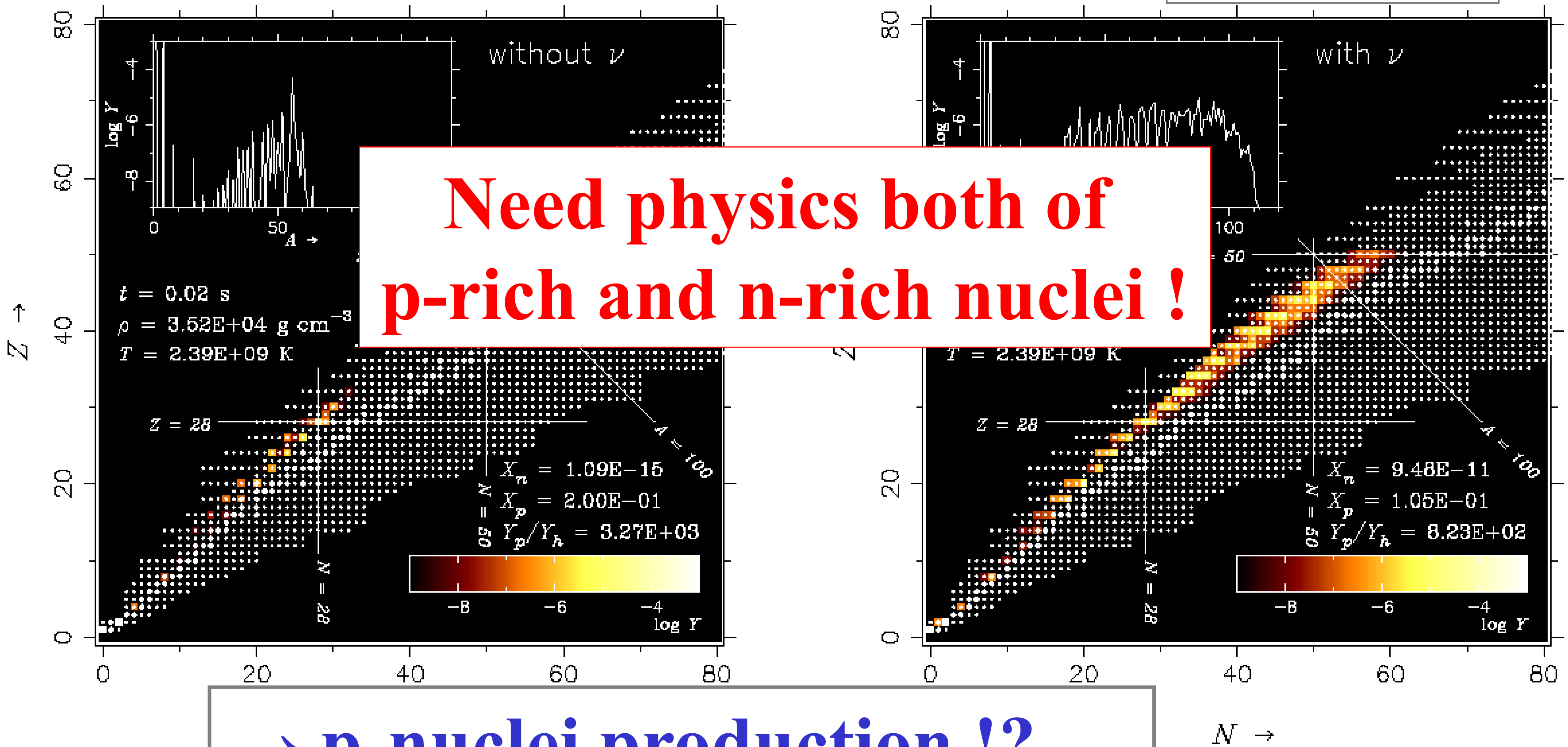
νp-process in SNeII

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

νe+n⇔p+e-
$\bar{\nu}$e+p⇔n+e+

without ν

with ν

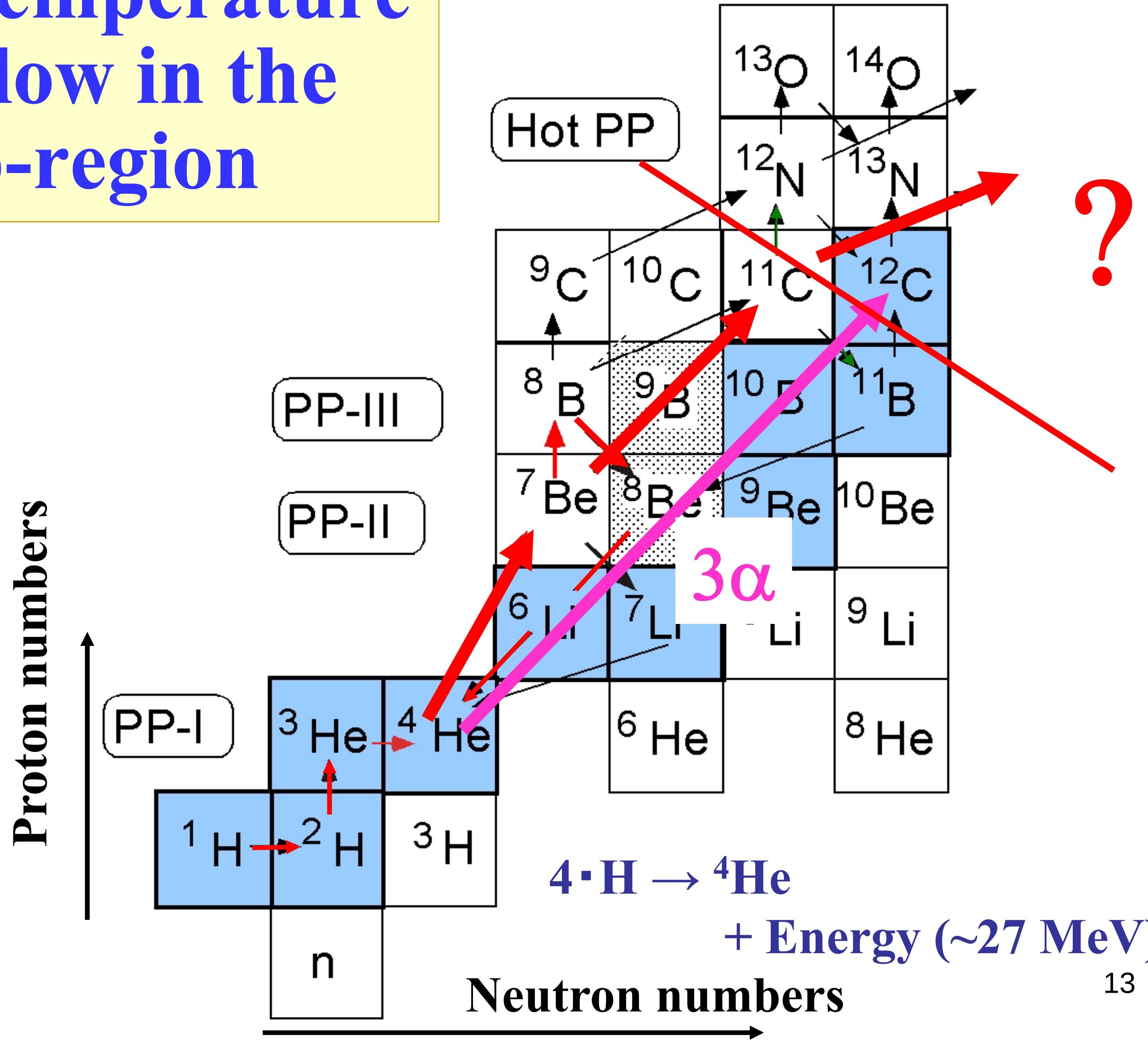


Need physics both of p-rich and n-rich nuclei !

→ p-nuclei production !?

(Wanajo, OMEG05)

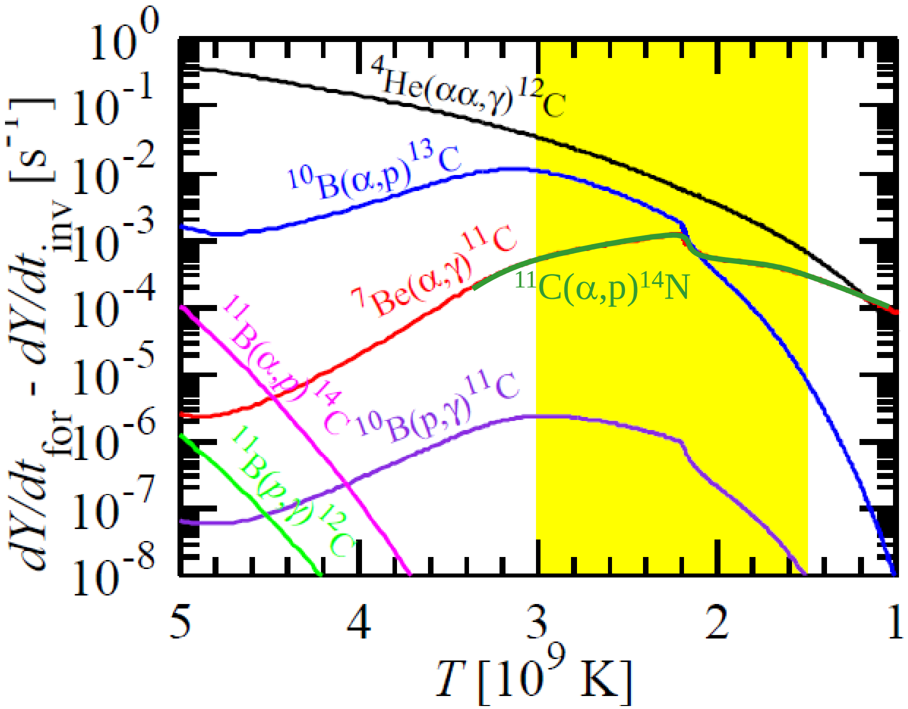
High-temperature NS flow in the pp-region

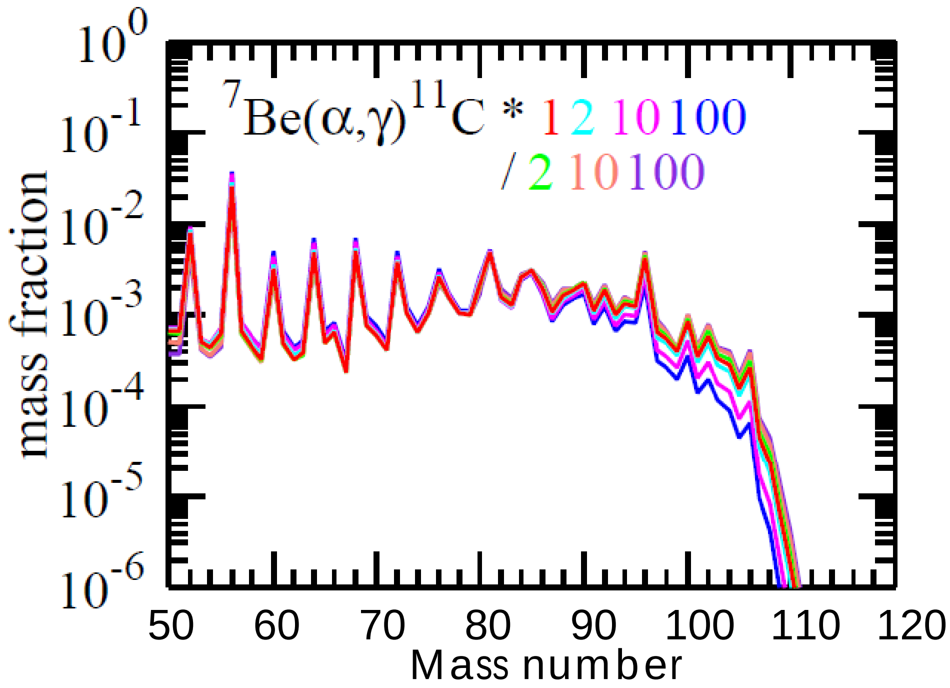


$4 \cdot H \rightarrow {}^4He$
$+$ Energy (~27 MeV)

$^{7}Be(\alpha,\gamma)^{11}C(\alpha,p)^{14}N$ in the νp-process

- Wanajo, Janka, Kubono, arXiv:1004.4487v1, 2010

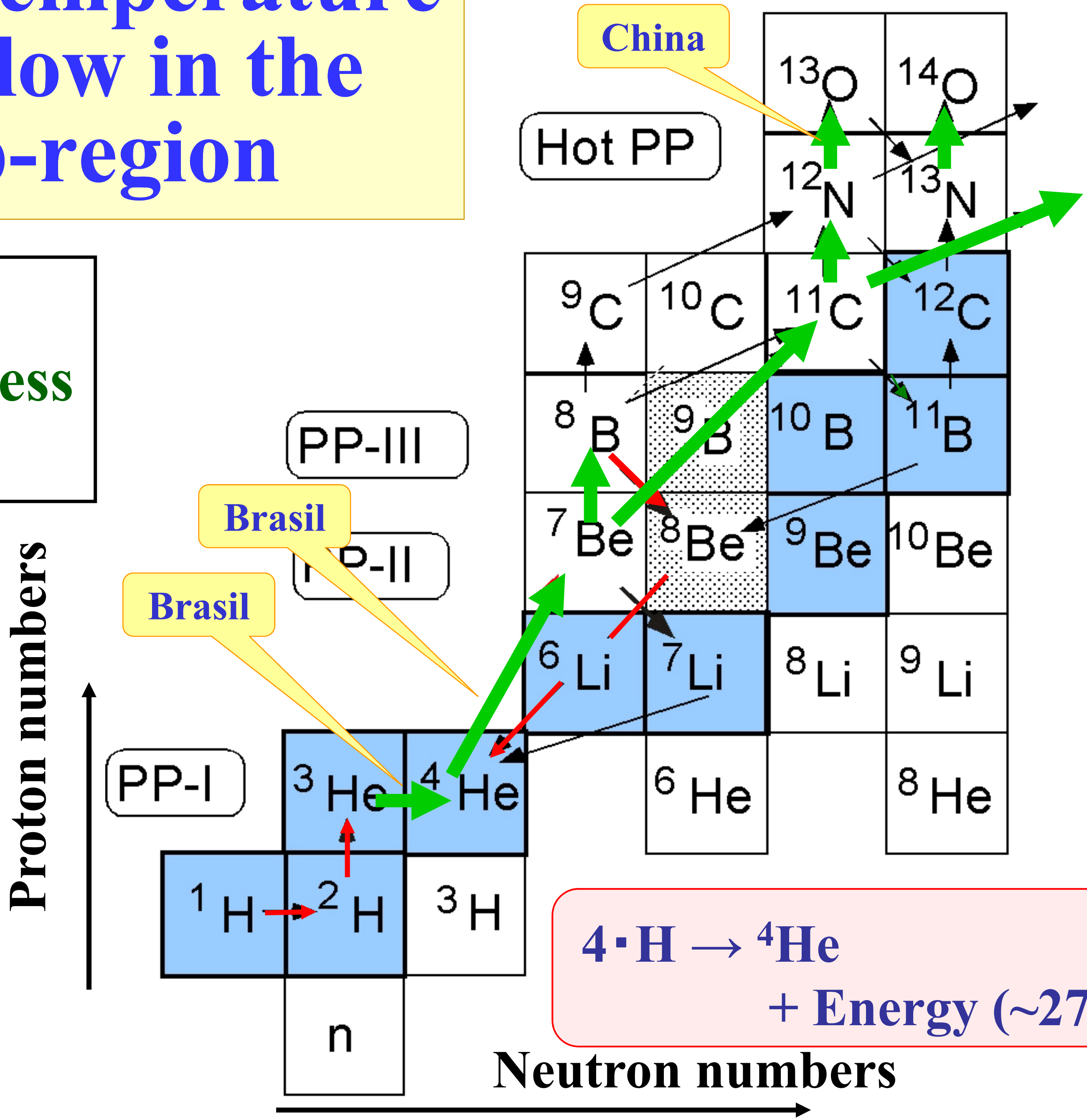




- $^{11}C(\alpha,p)$ overlaps $^{7}Be(\alpha,\gamma)$
  - ⇒ ^{11}C is mostly produced from $^{7}Be(\alpha,\gamma)$, and then $(\alpha,p)^{14}N$ follows.
  - ⇒ $^{11}C(\alpha,p)$ rate > $^{7}Be(\alpha,\gamma)$ rate
- $^{7}Be(\alpha,\gamma)$ rate tends to less mass fraction around A = 100.
  - Limited resonance information only for $T_9 < 2$. (New measurement!! Yamaguchi, NIC_XI_124)
- $^{11}C(\alpha,p)$ rate would become more important if $^{7}Be(\alpha,\gamma)$ has a higher rate.
  - Time-reversal reaction studies by activation method. ⇒ Gives only $(\alpha,p_0)^{14}N_{g.s.}$

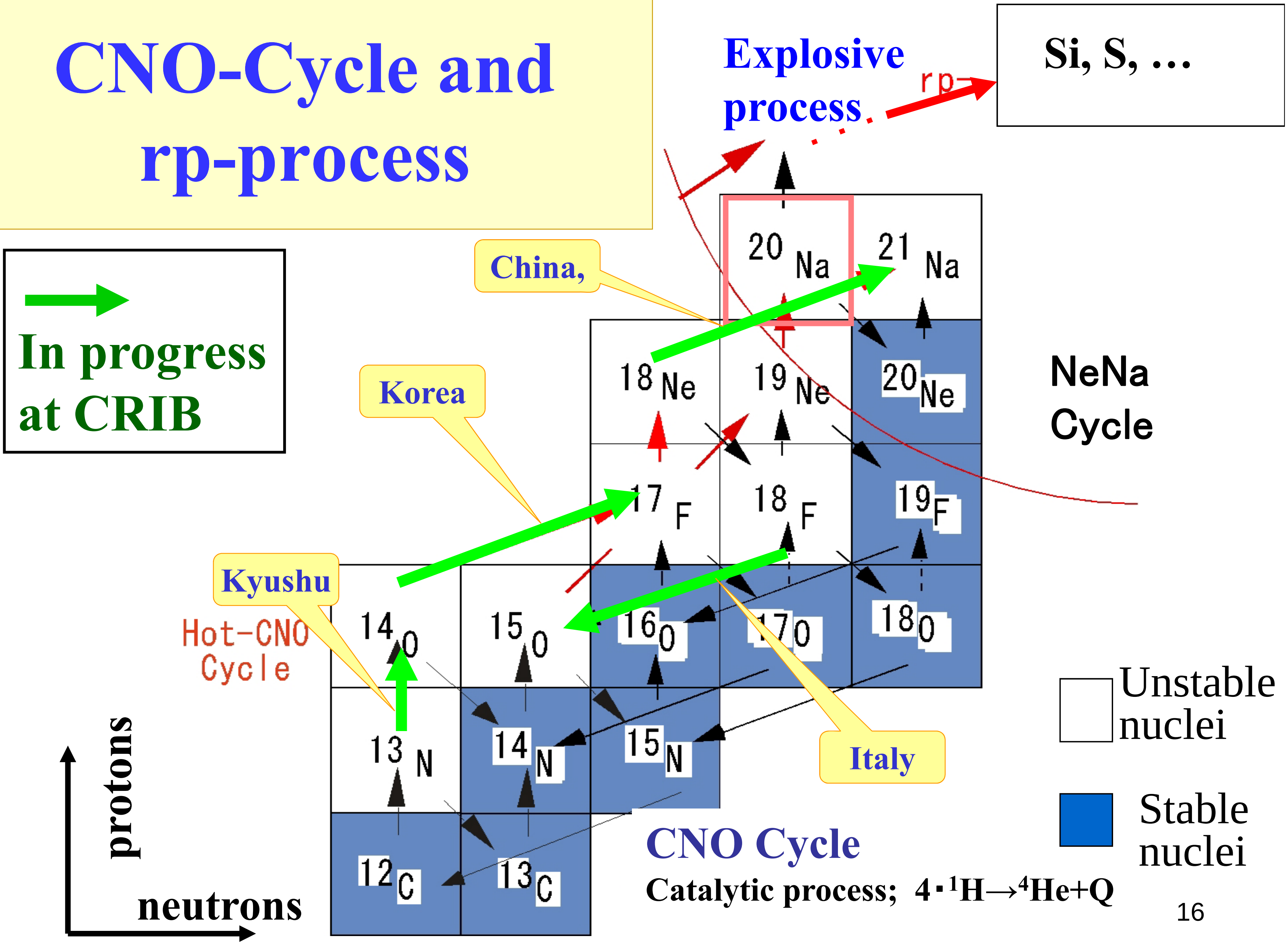
High-temperature NS flow in the pp-region

In progress at CRIB



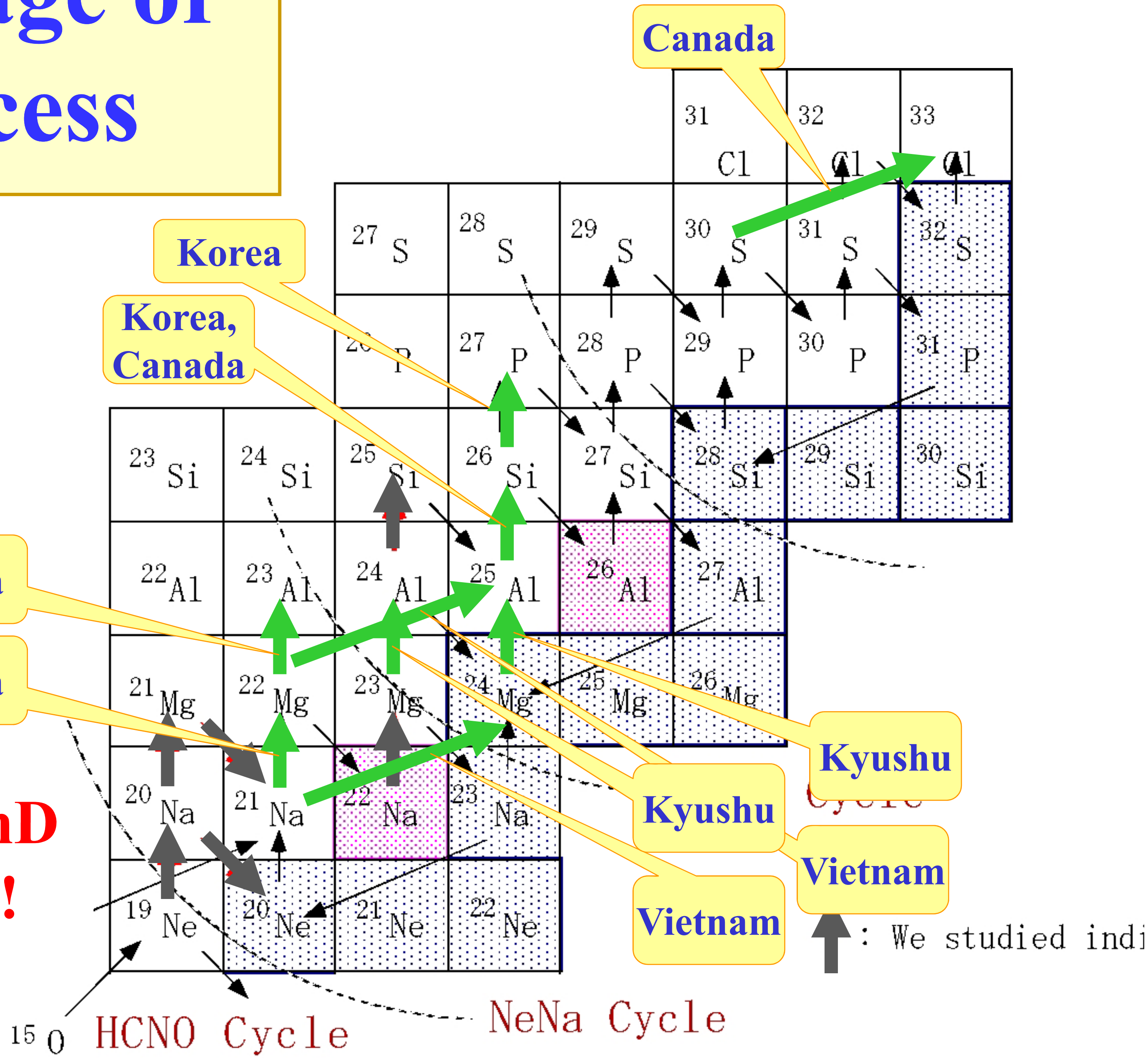
$4 \cdot H \rightarrow {}^4He$
$+ \text{Energy } (\sim 27 \text{ MeV})$

CNO-Cycle and rp-process



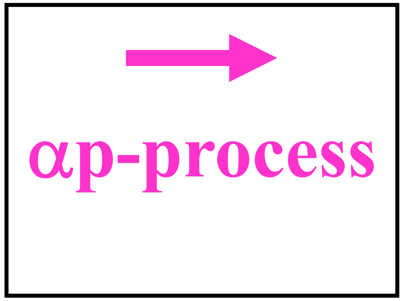
Early Stage of rp-Process

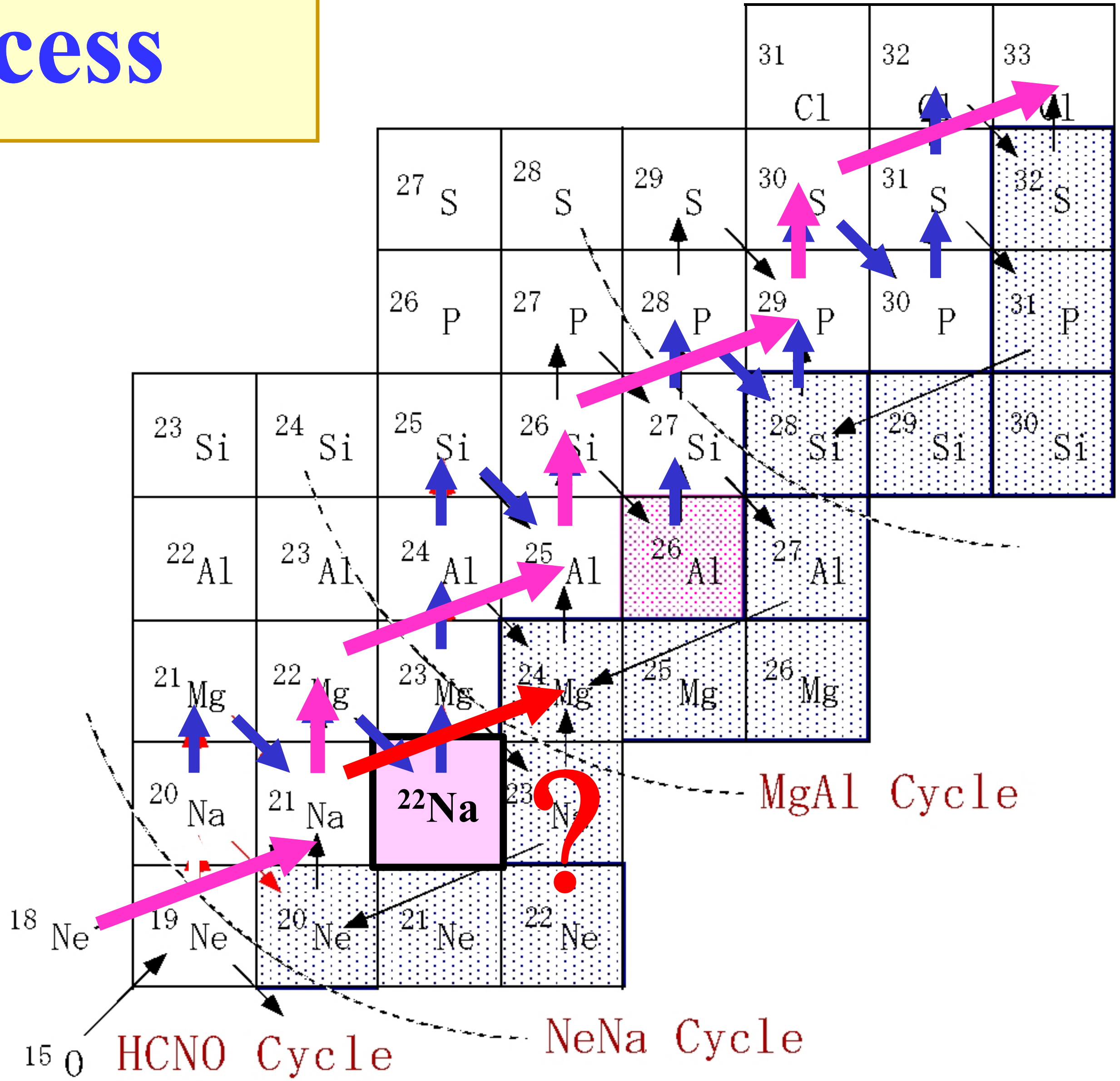
In progress at CRIB



Several MS, PhD works made !

Early Stage of rp-Process





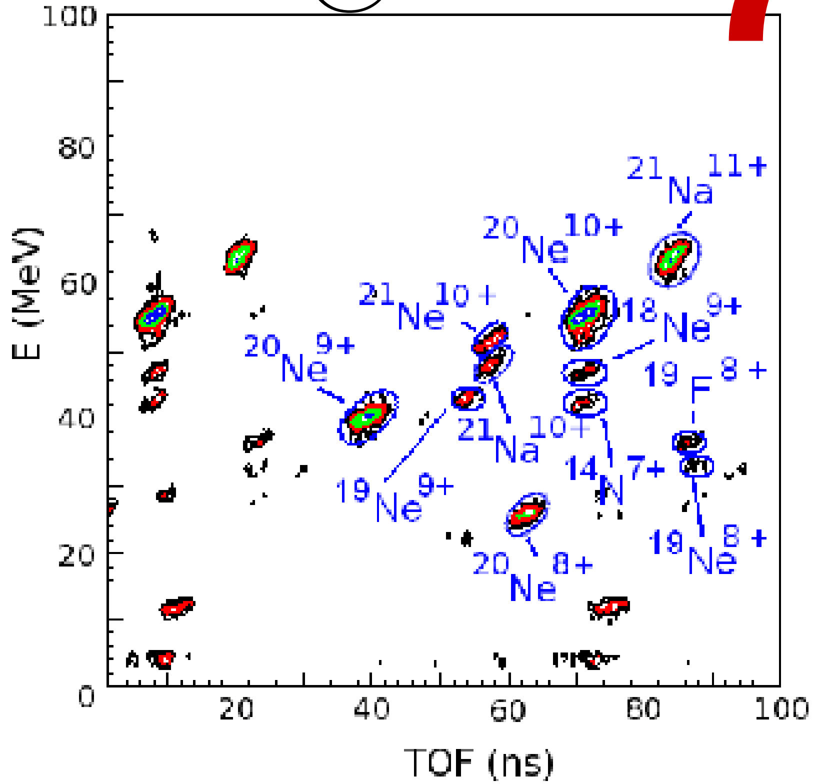
^{21}Na(α, p) stellar reaction

(coll. with IOP)

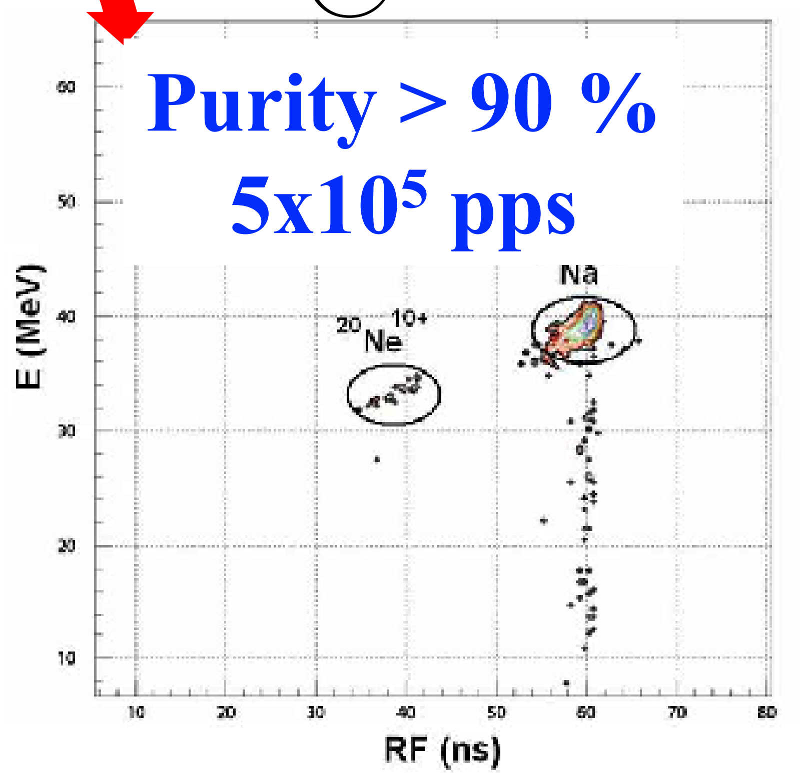
^{21}Na beam production at CRIB

Wien Filter

@ F2



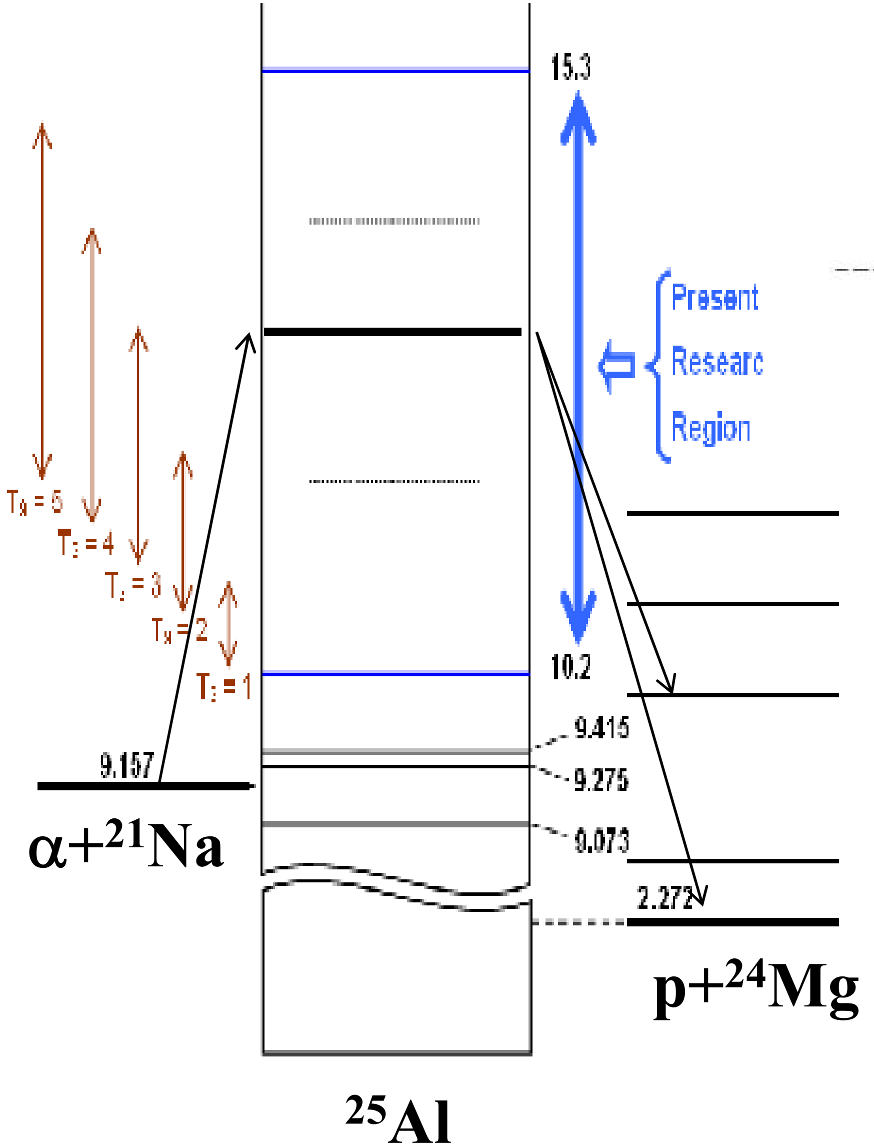
@ F3

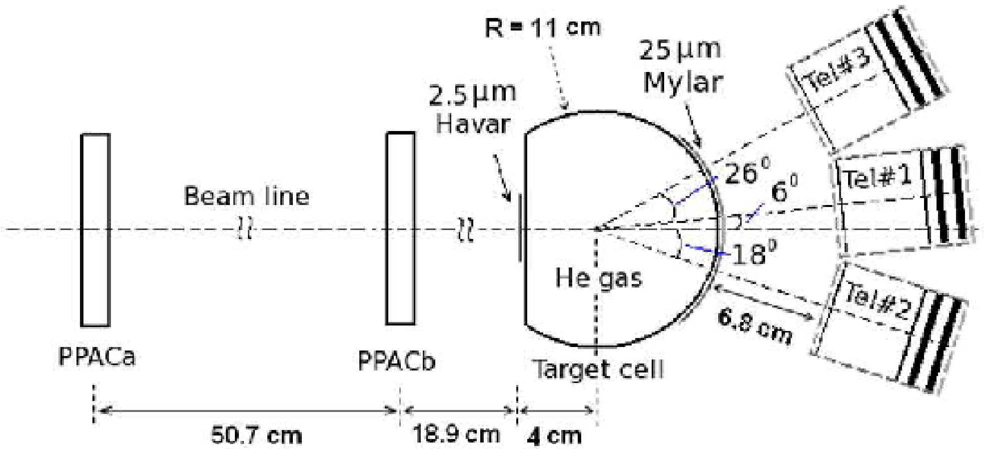


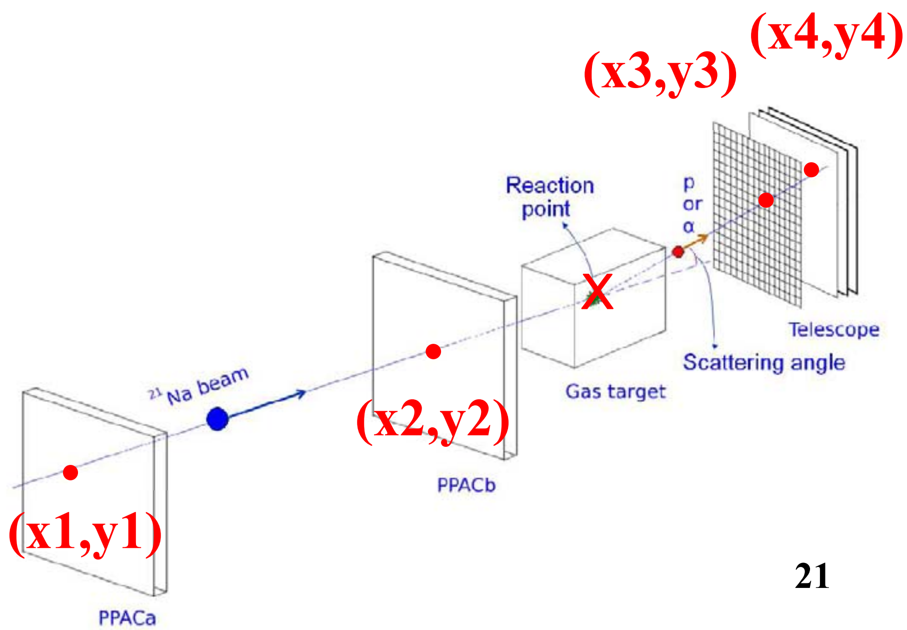
E=2.5 MeV/u

ΔE=±2%

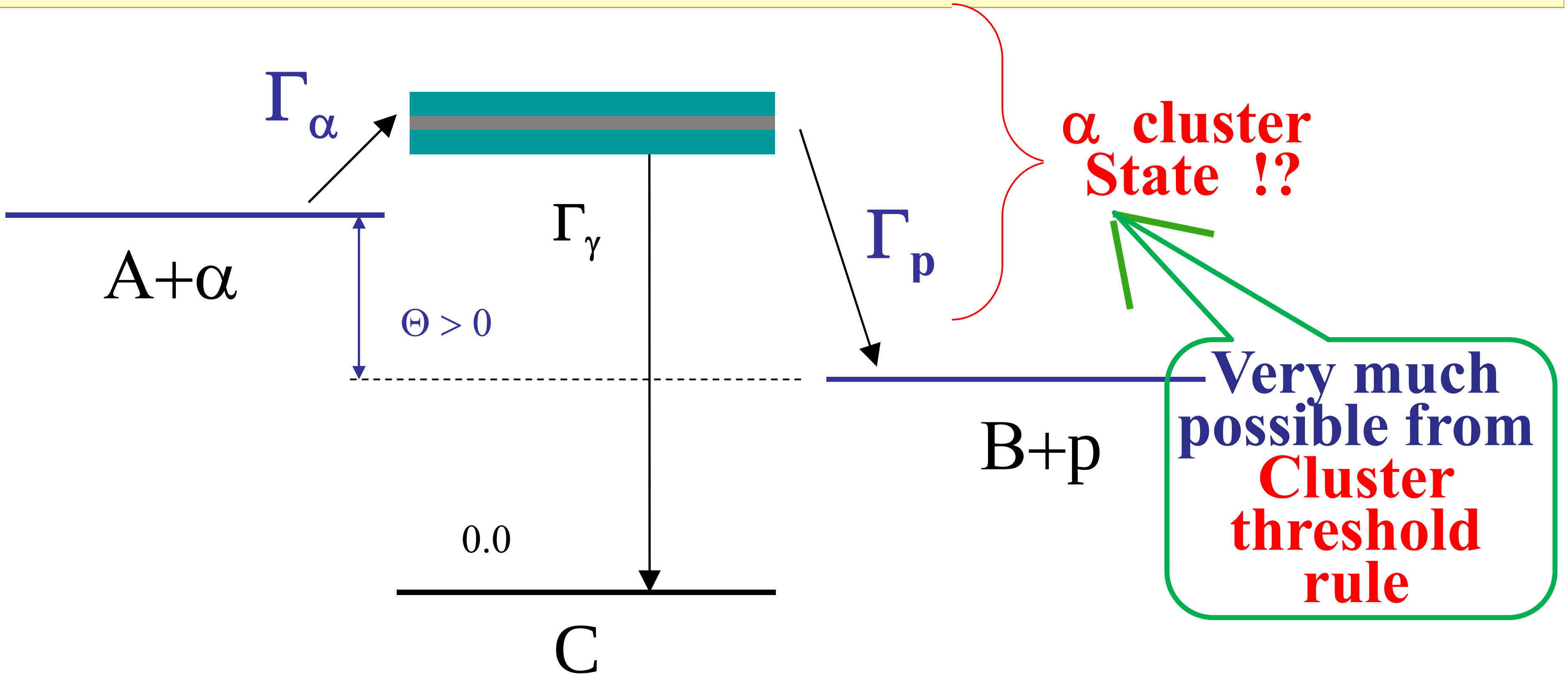
Physics problem and experimental setup







Basic flow of A(α, p) reactions



Reacti

$$\omega\gamma = \frac{(2J_r+1)}{(2J_\alpha+1)(2J_A+1)}\frac{\Gamma_\alpha\Gamma_p}{\Gamma_{tot}}$$

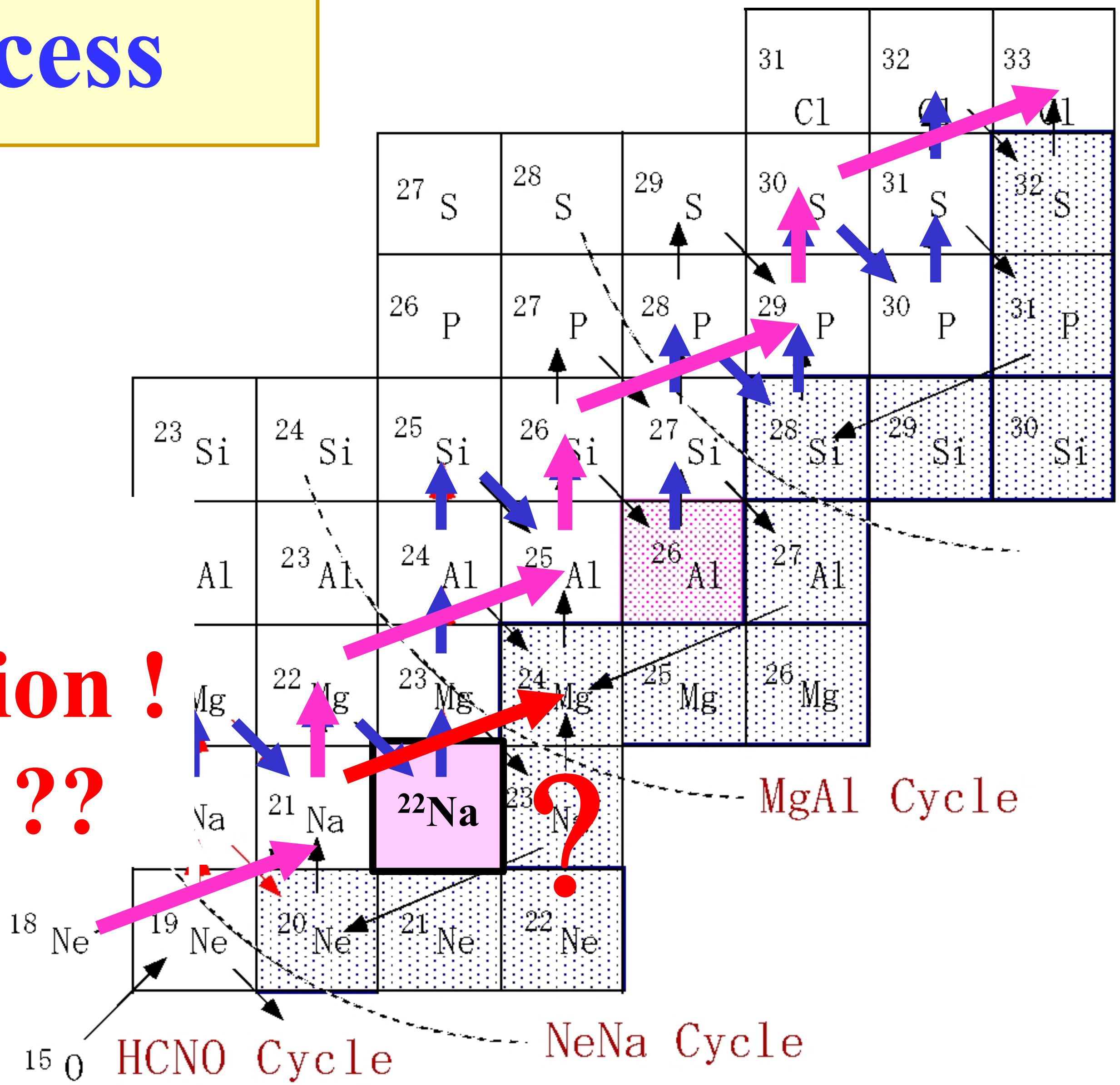
$\propto$ Γ_α **(if G_p>>G_a)**

Γ_α determines the rate !

Early Stage of rp-Process

αp-process

- No ^{22}Na production !
- Scinario ??

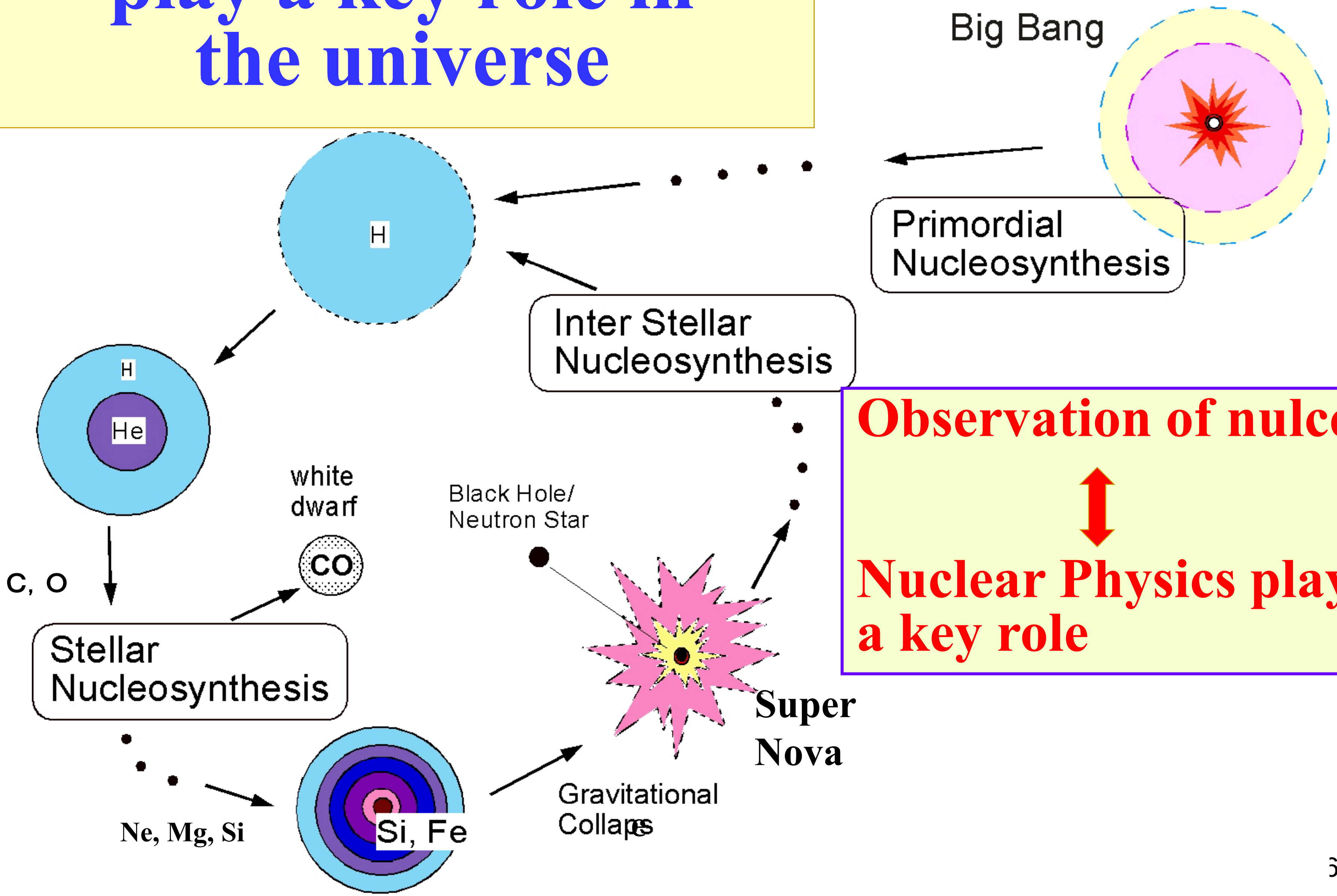


Summary; $^{21}Na(\alpha,p)^{24}Mg$ Stellar Reaction

1. α-cluster resonance plays a crucial role for the (α,p) cross sections, which can not be included in the statistical model prediction.
2. Hauser-Feshbach model fails seriously not only the cross sections, but also the energy dependence.
3. (α,p) transitions to high-lying states in ^{24}Mg are important.

Scope

Nuclear Phyiscs play a key role in the universe



Observation of nulcei

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Nuclear Physics play a key role

Possibilities for the CRIB facility

1. Primary beam quality
2. Production target
3. Secondary beam quality
4. Wien filter transmission
5. Beams of fission fragments
6. Background for gamma spectroscopy
7. Active target

Workshop on Physics with Low-Energy RI Beams

(CNS-RIKEN)

Time; May or June, 2011
Place; RIKEN Campus

1. Nuclear physics
2. Nuclear astrophysics
3. Material science
4. Detector development
5. Scope at CRIB

END