2003.9 @CNS

Nuclear Astrophysics

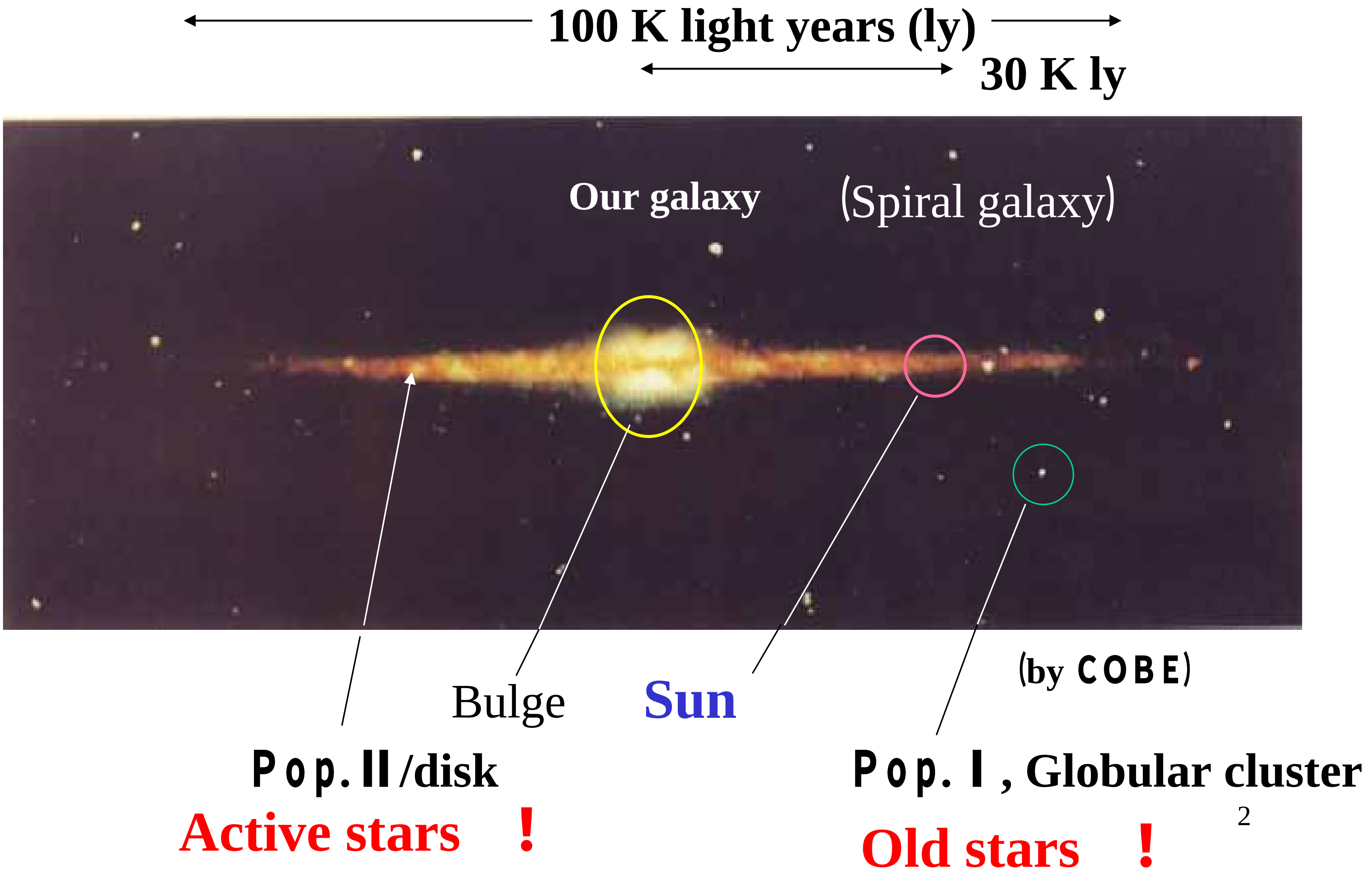
Study of Stellar Reactions with Low-Energy RI Beams in Nuclear Astrophysics

Shigeru KUBONO

Center for Nuclear Study, University of Tokyo

1. New observations and the current problems
2. Unstable Nuclei in Explosive Burning
3. Topics
   - Hot pp-Chain
   - Novae, X-Ray Burst
   - Solar Model
4. Scope; Supernovae and Heavy Element Synthesis

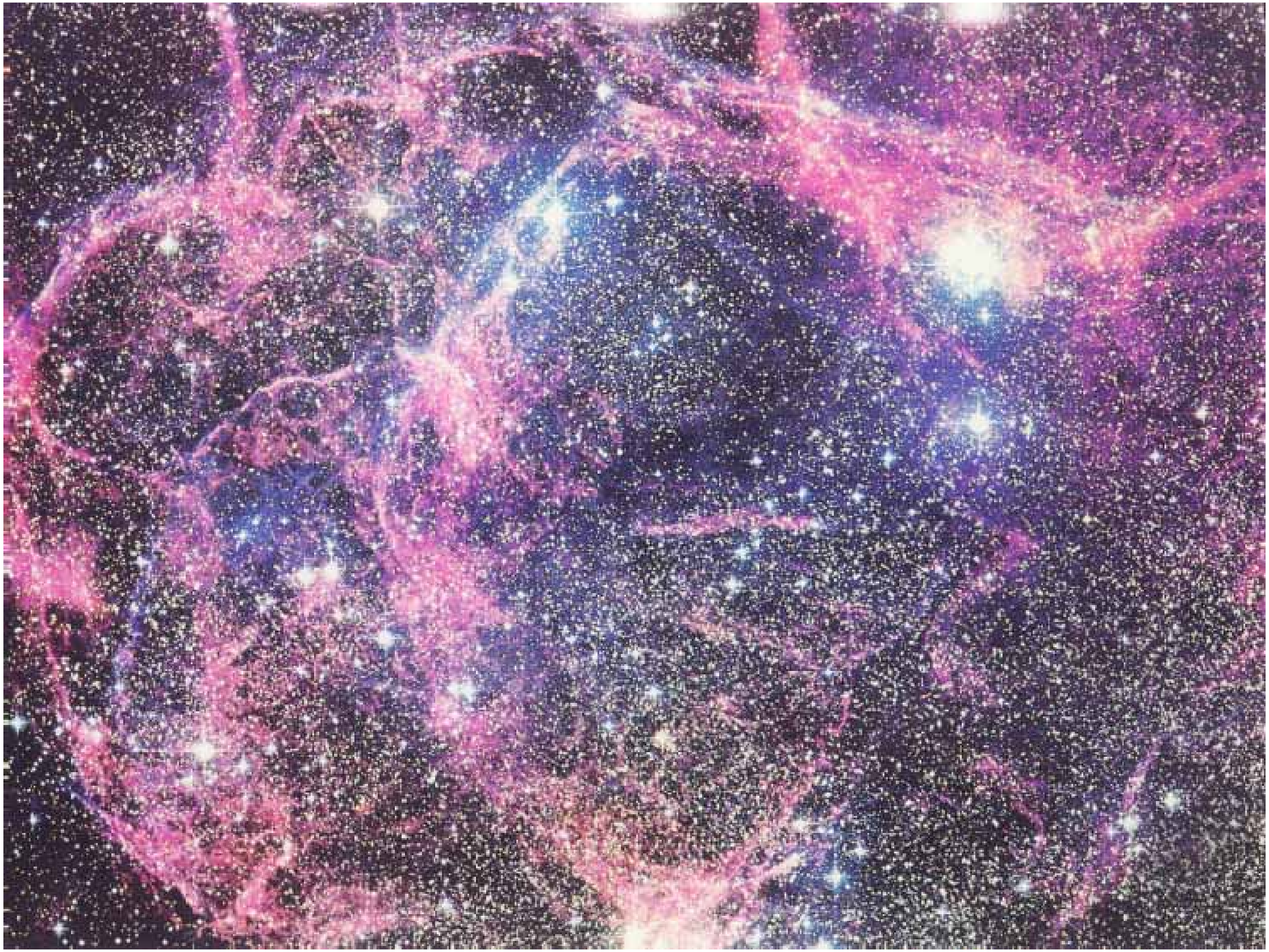
Our Galaxy (～10^{11} stars)



Supernova Remnant in Vela

@1400 ly

30000 years old supernova remnant



Pleiades

@408 ly

SUBARU
(PleiadesM45)

New Stars !

We are in the middle of very active galactic area

Cassio peia-A

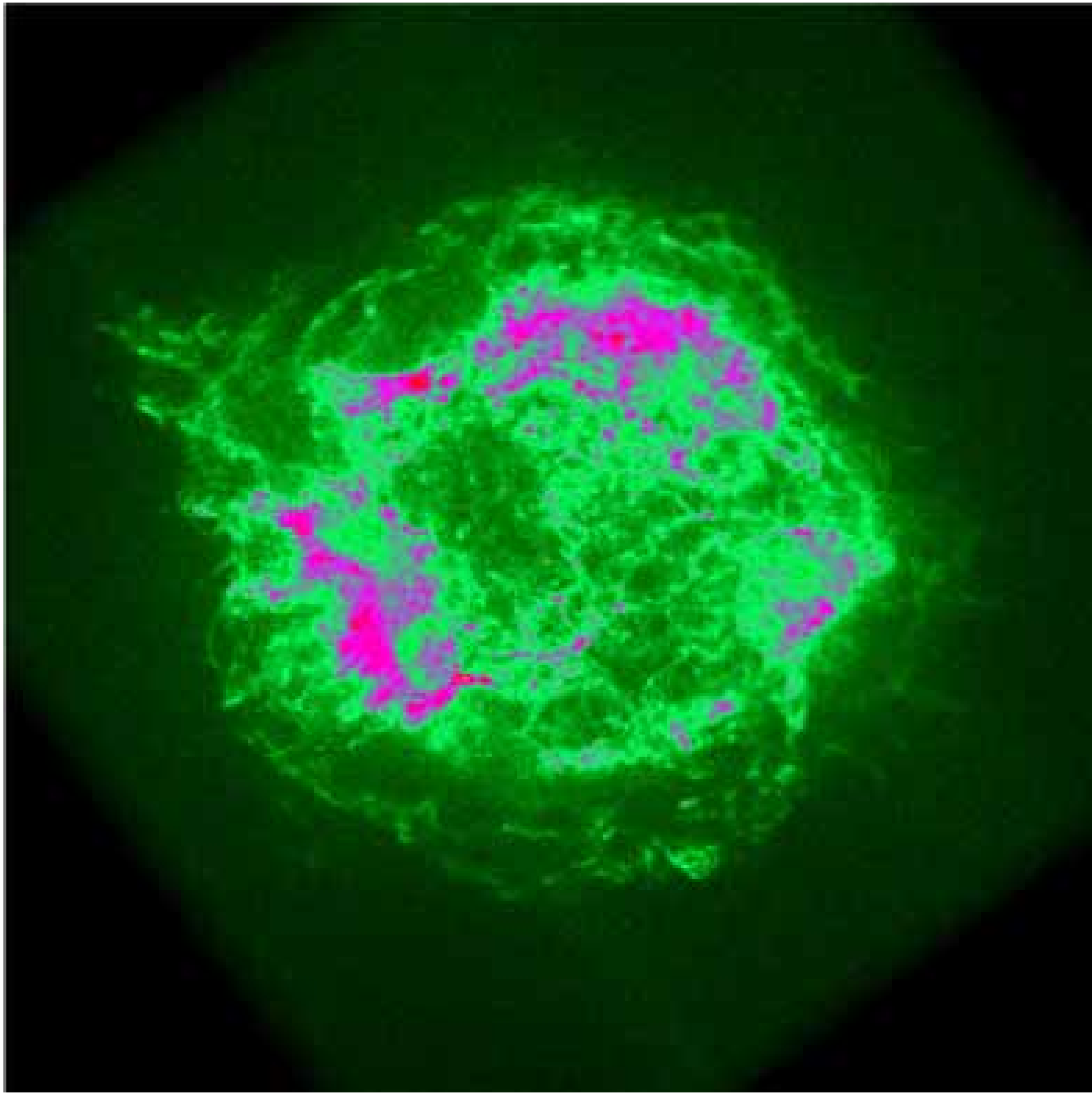
(@ 10 K ly
first obs. in 1680)

Nuclear gamma rays from the decay of ^{44}Ti observed.

($T_{1/2}(^{44}Ti)$~ 60 a)

1. Quantity of ^{44}Ti
2. Identify the reactions

NewAstronomy; Observation of Nuclei

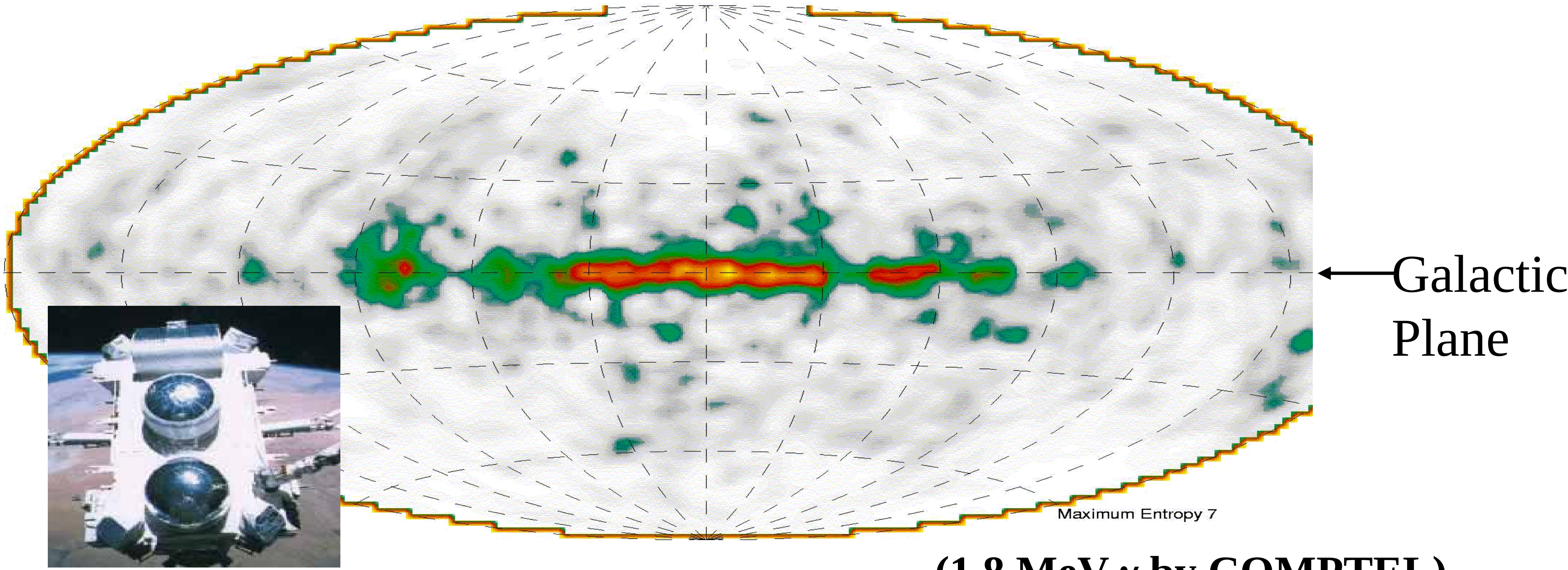


(NASA／CXC／SAO)

Nuclear Gamma-Rays of ^{26}Al

Our galaxy

($T_{1/2}$(^{26}Al)~0.72 M y.)

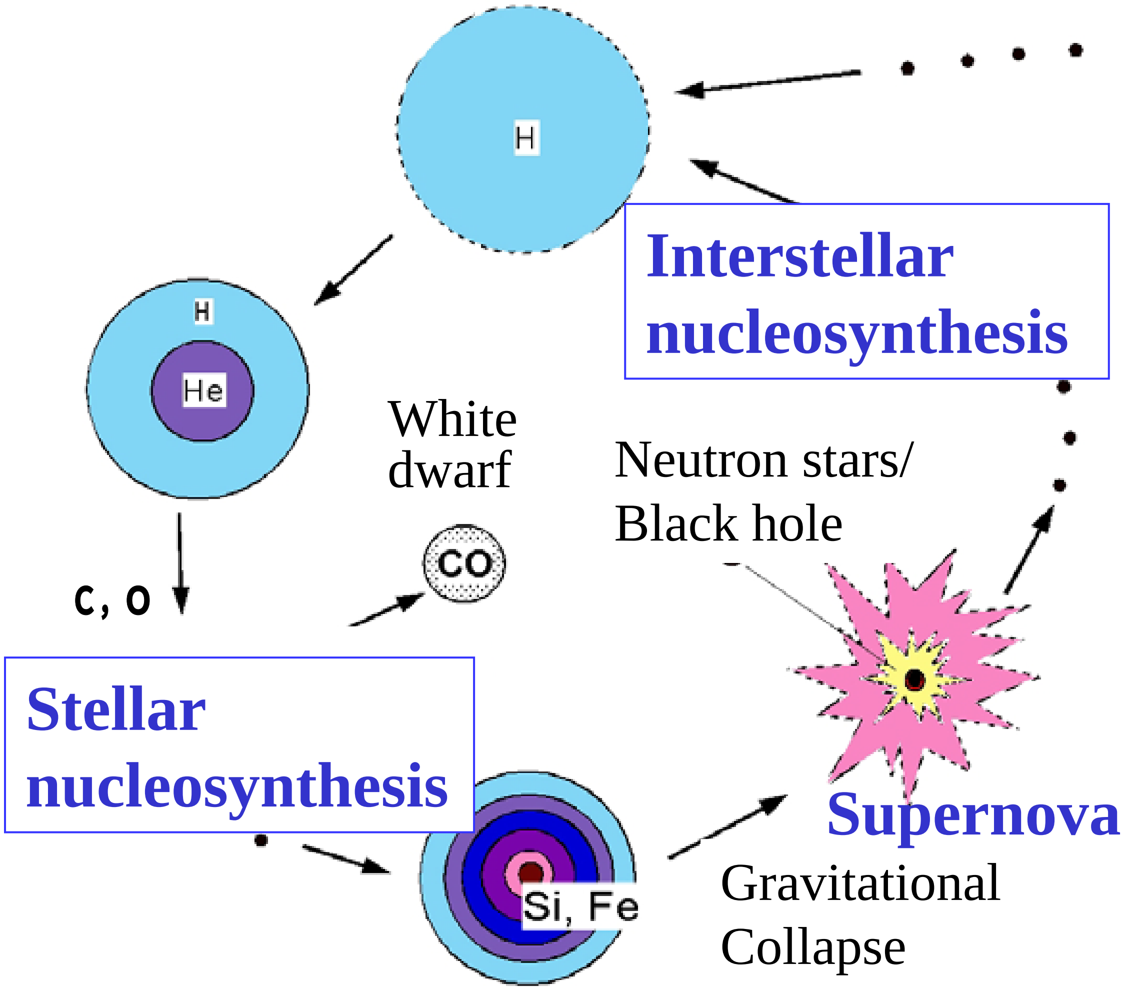


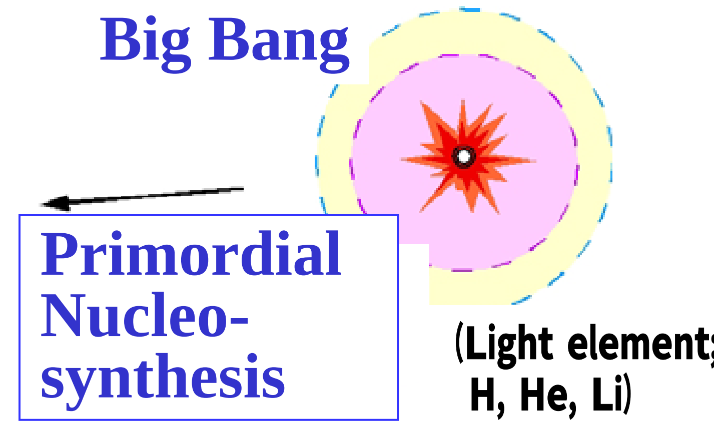
(1.8 MeV γ by COMPTEL)

- **New Observation by Satellites and SUBARU**

＝Observation of isotopic nuclei (^{26}Al)

Evolution of the Universe





1. Synthesis of elements,
2. Production of energy

⇒ Mechanism of stellar evolution

- Variety of nuclear reactions going on.
  - High temperature
  - Unstable nuclei
  - High density, . . .
- We should be able to learn from the Universe for Nuclear Physics.

History of Nuclear Astrophysics

2010

RIBF

RHIC

2000

Neutrino Astrophysics;Koshiba/1987

RI beams (ISOL)

1990

NAP with RIB

Exotic nuclei

Exp. Nuclear A.P.;Fowler/1984

RI beams (fragmentation

1980

1970

Heavy ion physics

1960

Nucleosyhthesis; B^{2}FH/1957

Shell model, collective model

RIKEN Cyclotron /1937

1950

Big Bang Model;Gamow/1947

Nuclear reaction In laboratories

1940

Strong interaction;Yukawa/1934

CN cycle/1932

Fission, neutron

Cyclotron; Lawrence/1930

1930

Quantum Mechanics; Bohr, Heisenberg

Energy of stars; Edington/1920

1920

Nuclear atoms; Rutherford, Nagaoka

1910

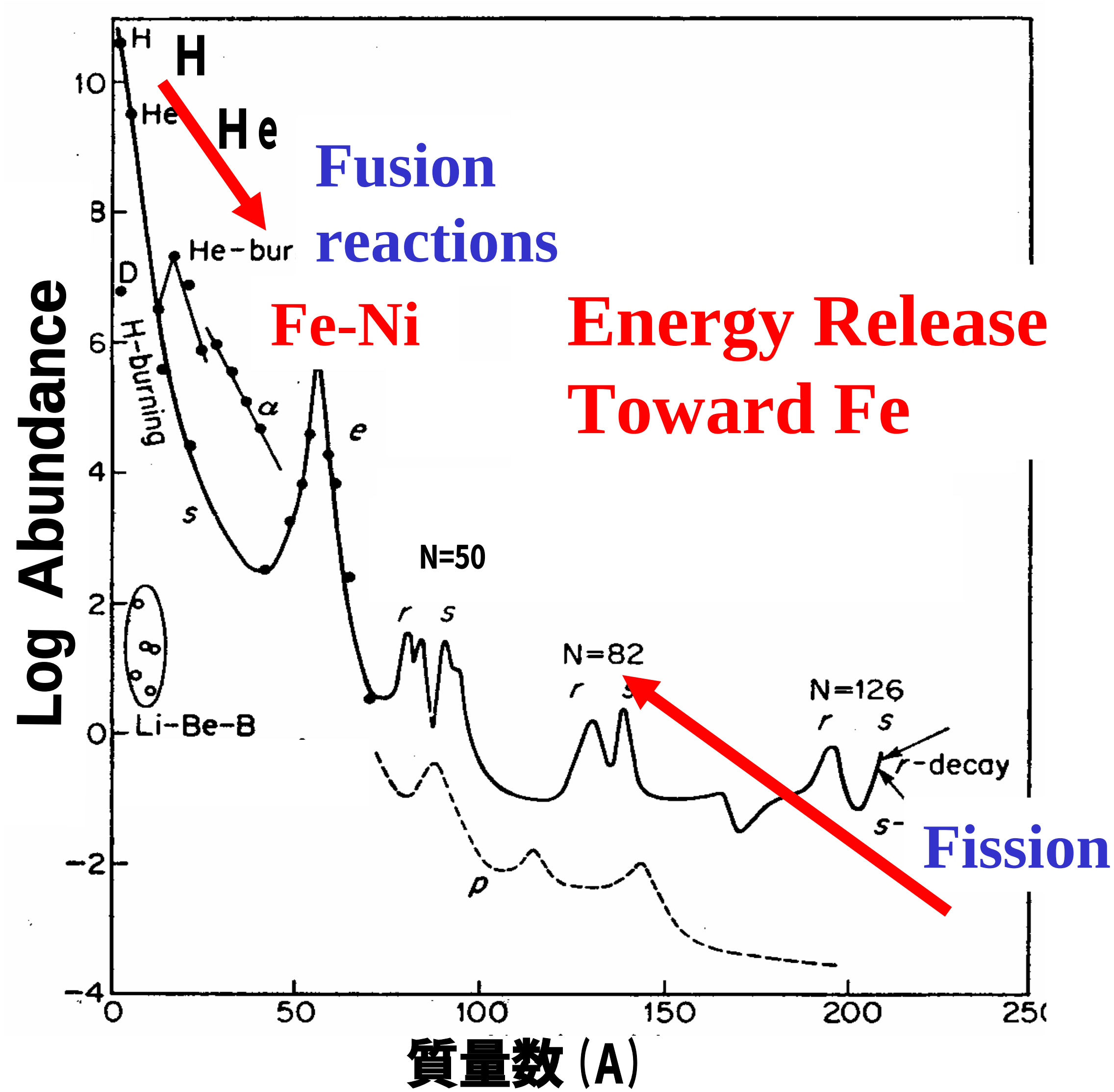
1900

Discovery of nuclear radiation;Becquerel/1896

Solar Abundance

(From S. Austin)

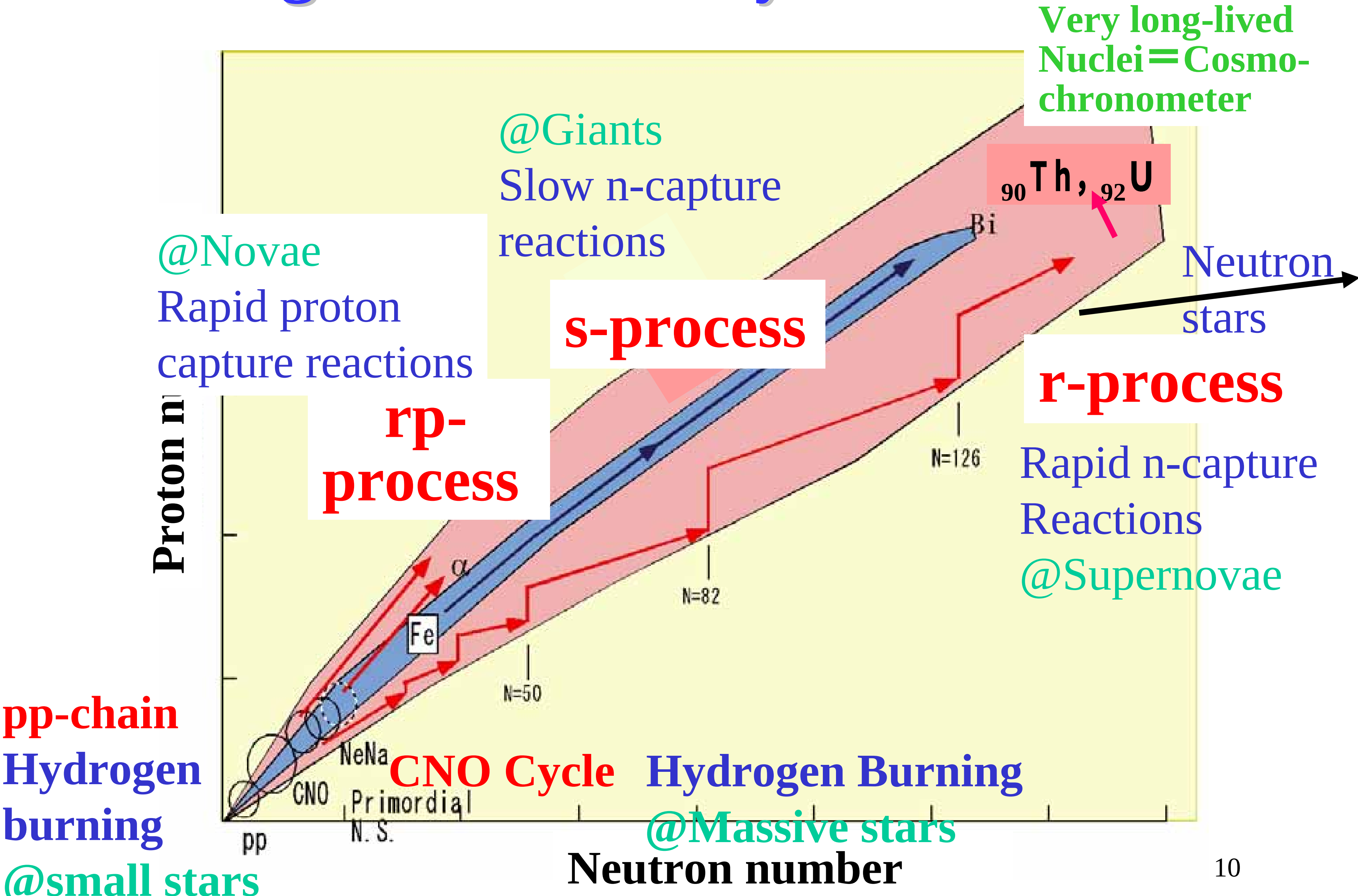
A qualitative view-Suess-Urey Plot



Group		Mass Fraction
$^{1,2}H$		0.71
$^{3,4}He$		0.27
Li, Be, B	10-8	
CNO Ne	$2x10^{-2}$	
Na-Sc		$2x10^{-3}$
A=50-62	$2x10^{-4}$	
A=63-100	10^{-6}	
A>100		10^{-7}

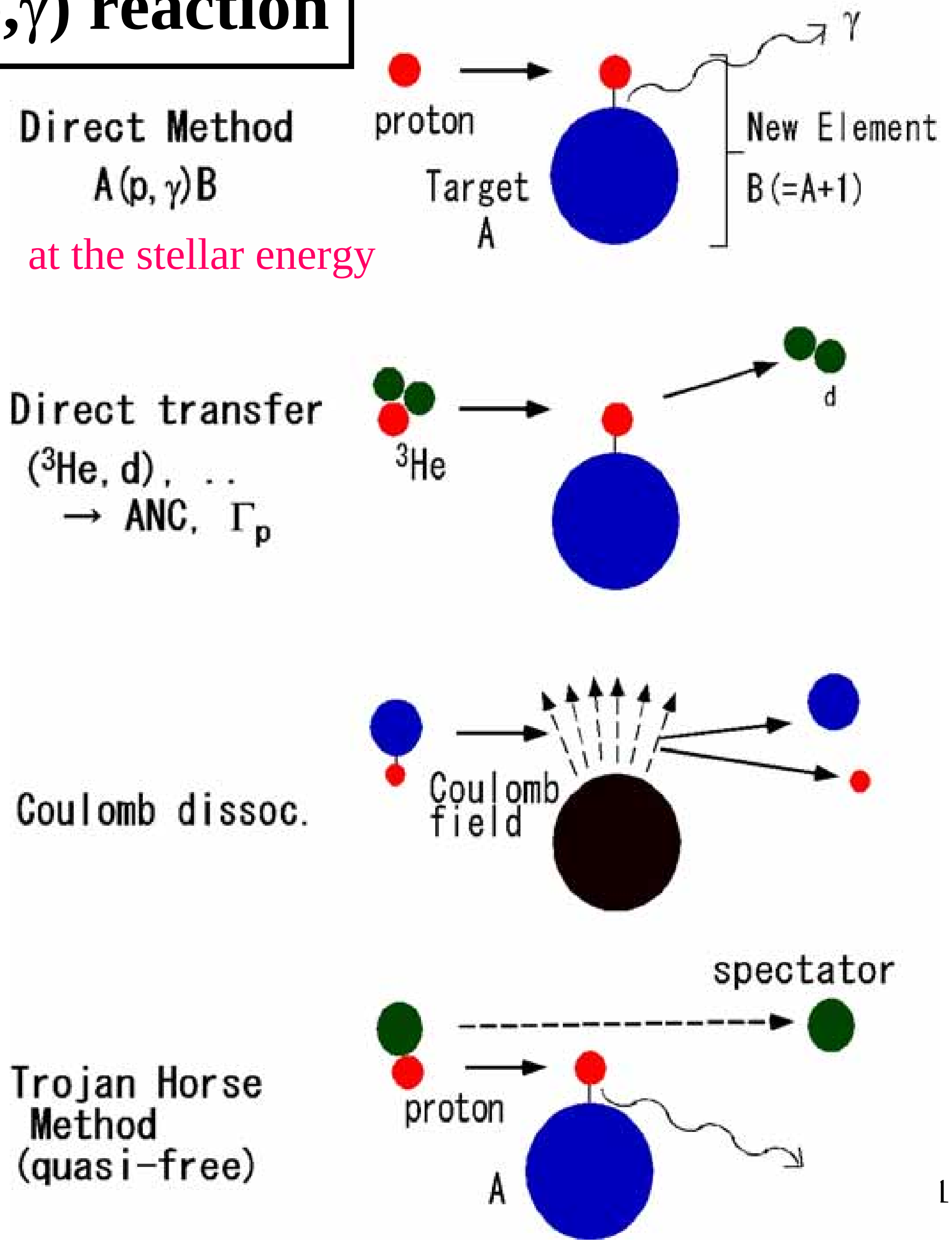
Fe-Ni：Max. binding energy per nucleon.

Flow-diagram of nucleosynthesis

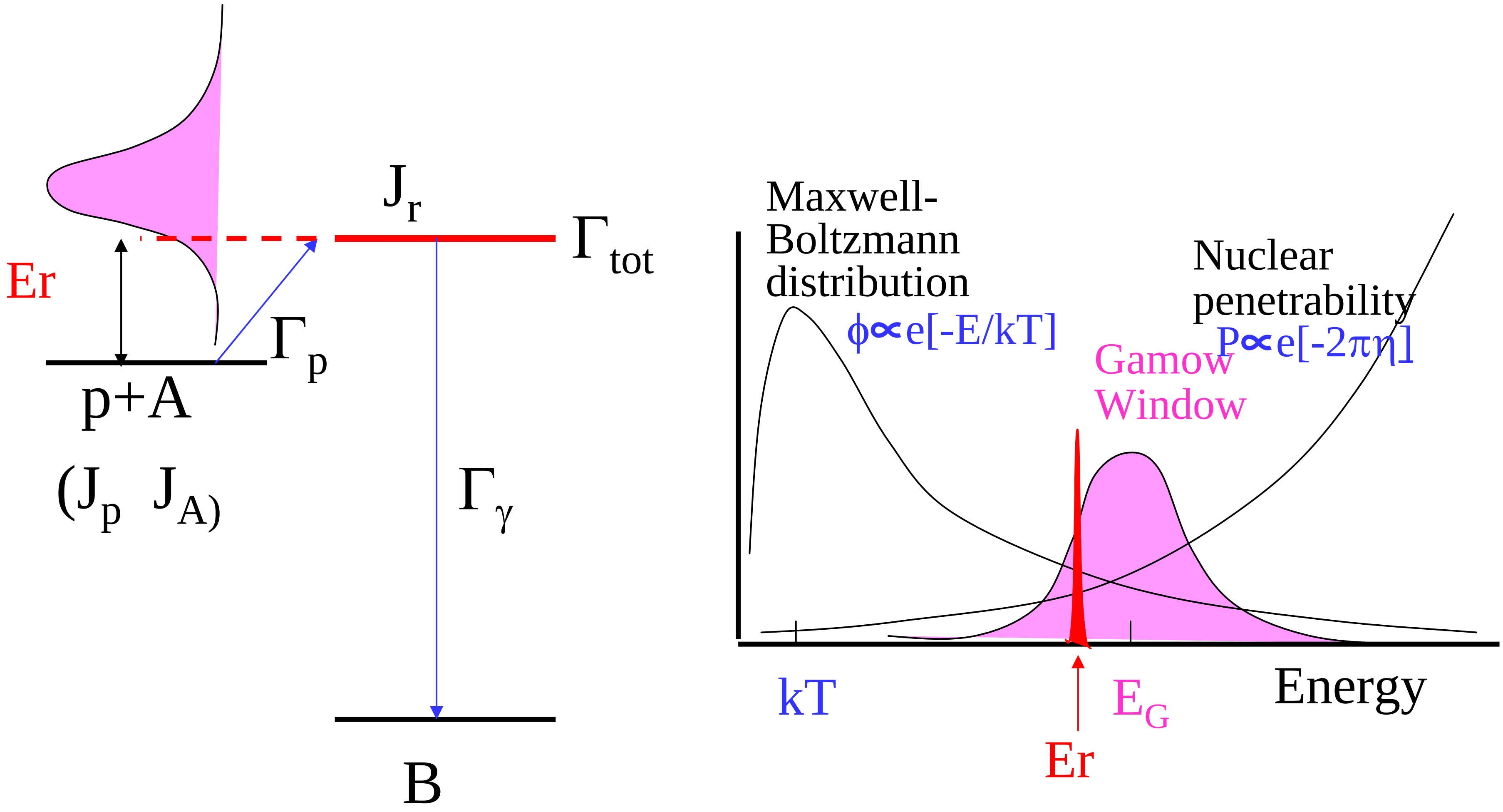


Direct and Indirect (/Simulating) Methods

(p,γ) reaction



Nucleosynthesis by A(p,γ)B



Reaction rate and Rate equation

The reaction cross sections can be written using the astrophysical S- factor S,

$$\sigma(E) = \frac{S(E)}{E} e^{-2\pi\eta}.$$

The Gamow energy defined by the two factors (MB distr. and penetrability) is

$$E_G = \left(\frac{bkT}{2}\right)^{2/3}, \qquad b = 2\pi\mu E^{1/3} = 31.3 Z_1 Z_2 \mu^{1/2} (keV^{1/2}).$$

The reaction rate is the cross sections averaged over the MB dist.,

$$<\sigma\upsilon> = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty S(E) e^{\left(-\frac{E}{kT} - 2\pi\eta\right)} dE.$$

If there is a sharp resonance in the region, the cross section can be expressed by the Breit-Wigner one-level formula,

$$\sigma(E) = \pi \lambda\!\!\!^{-2} \omega \frac{\Gamma_p \Gamma_\gamma}{(E - E_r)^2 + \left(\frac{\Gamma_{tot}}{2}\right)^2}.$$

Thus, the reaction rate can be written as follows;

$$<\sigma\upsilon>=\left(\frac{2\pi}{\mu kT}\right)^{3/2}\hbar^2\omega\gamma\ e^{-\frac{E_r}{kT}}\ .$$

Here, the resonance strength $\omega\gamma$ is defined by

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

The total reaction rate can be

$$<\sigma\upsilon>=<\sigma\upsilon>_{res}+<\sigma\upsilon>_{direct}+<\mathbf{res-dir}>_{int}+<\sigma\upsilon>_{tail}\ .$$

Using these reaction rates for all the possible flow processes, one can obtain the rate equation to solve time-dependently,

$$\frac{dn_i}{dt}=\sum_{n_jn_k}n_jn_k<\sigma\upsilon>_{jk->i}-\sum_{n_m}n_in_m<\sigma\upsilon>_{i+m->n}+\frac{n_h}{\tau_h}-\frac{n_i}{\tau_i}.$$

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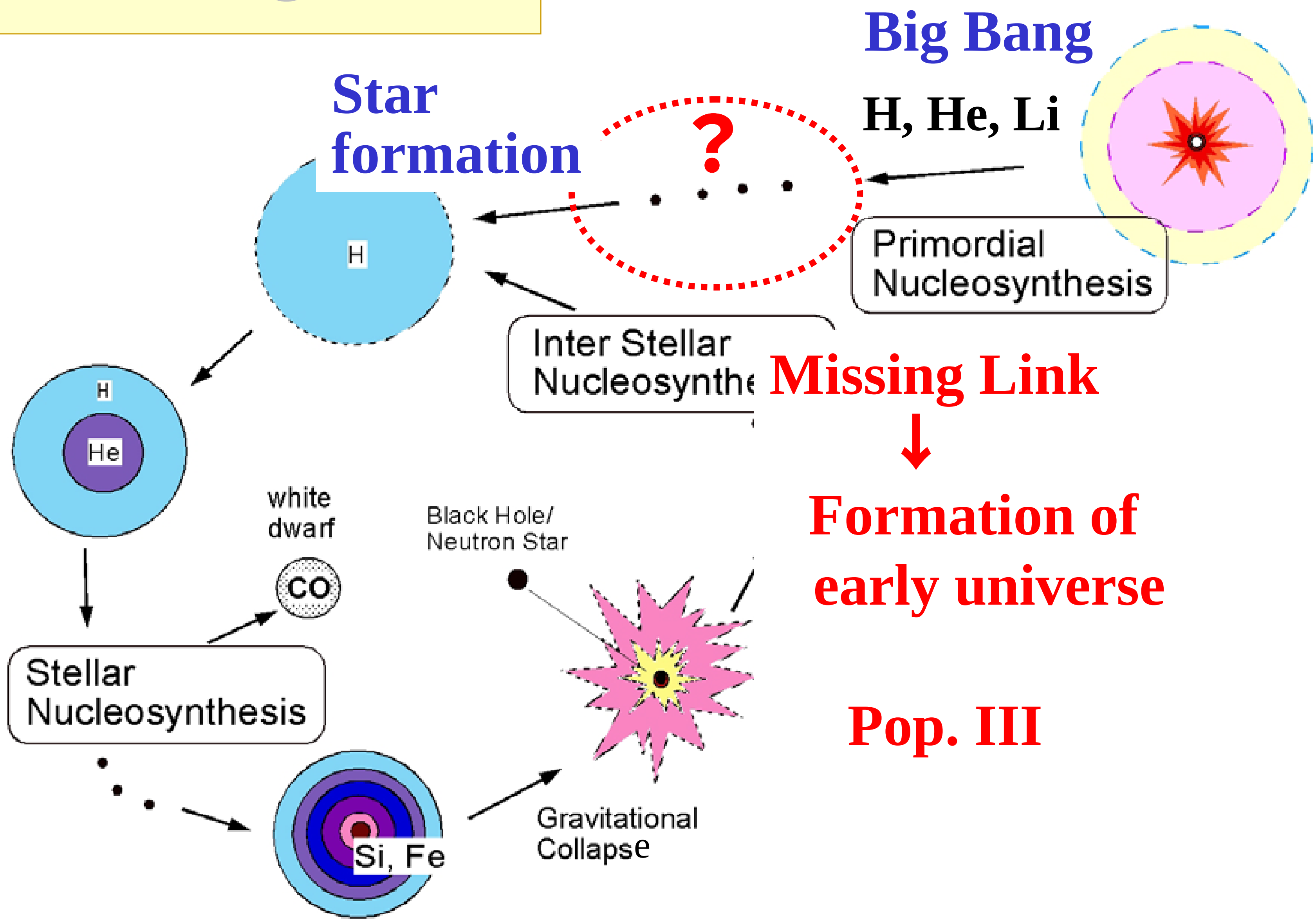
Missing Link



Missing Link

↓

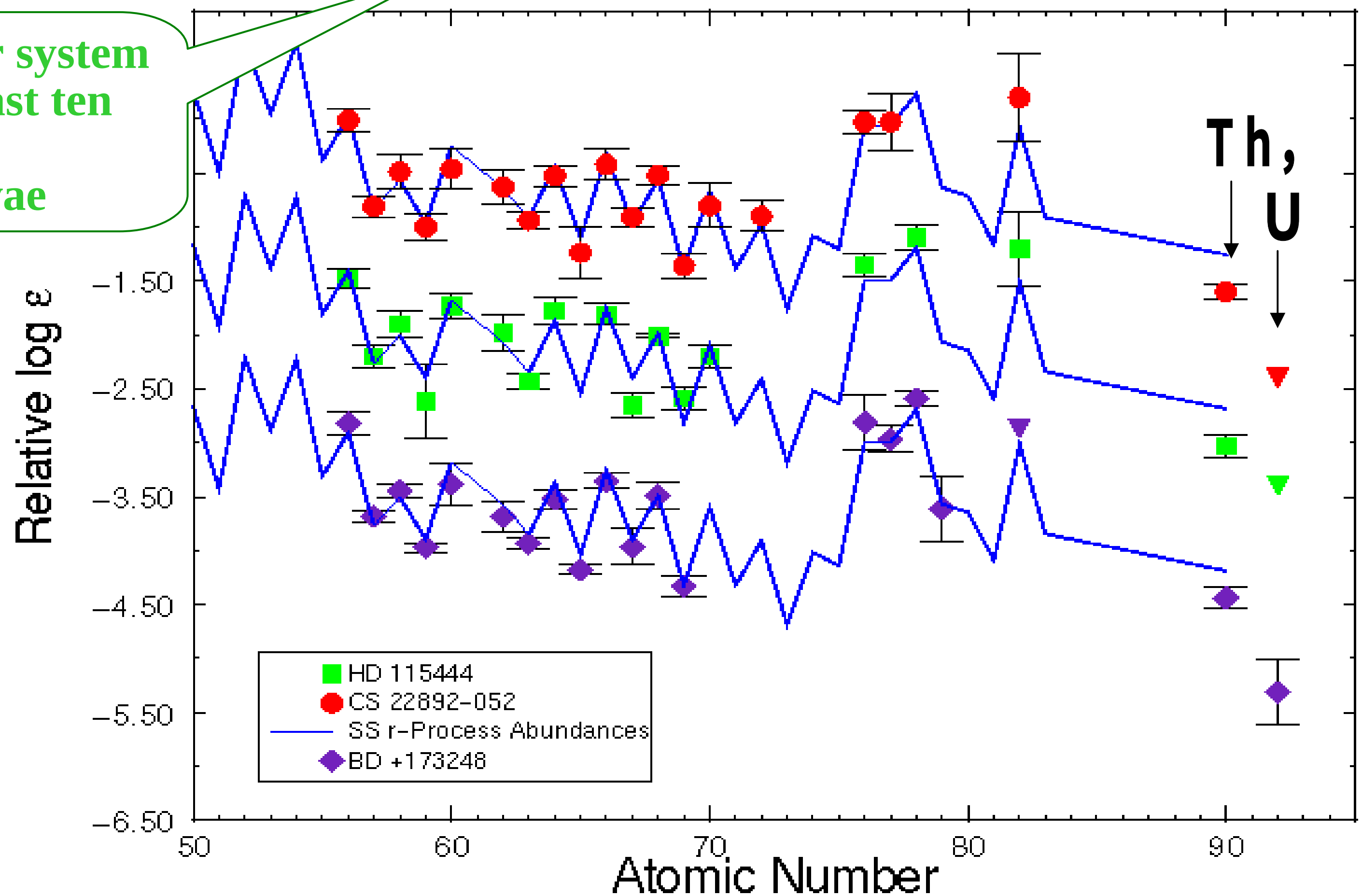
Formation of early universe

Pop. III

Old r-process star of very metal poor

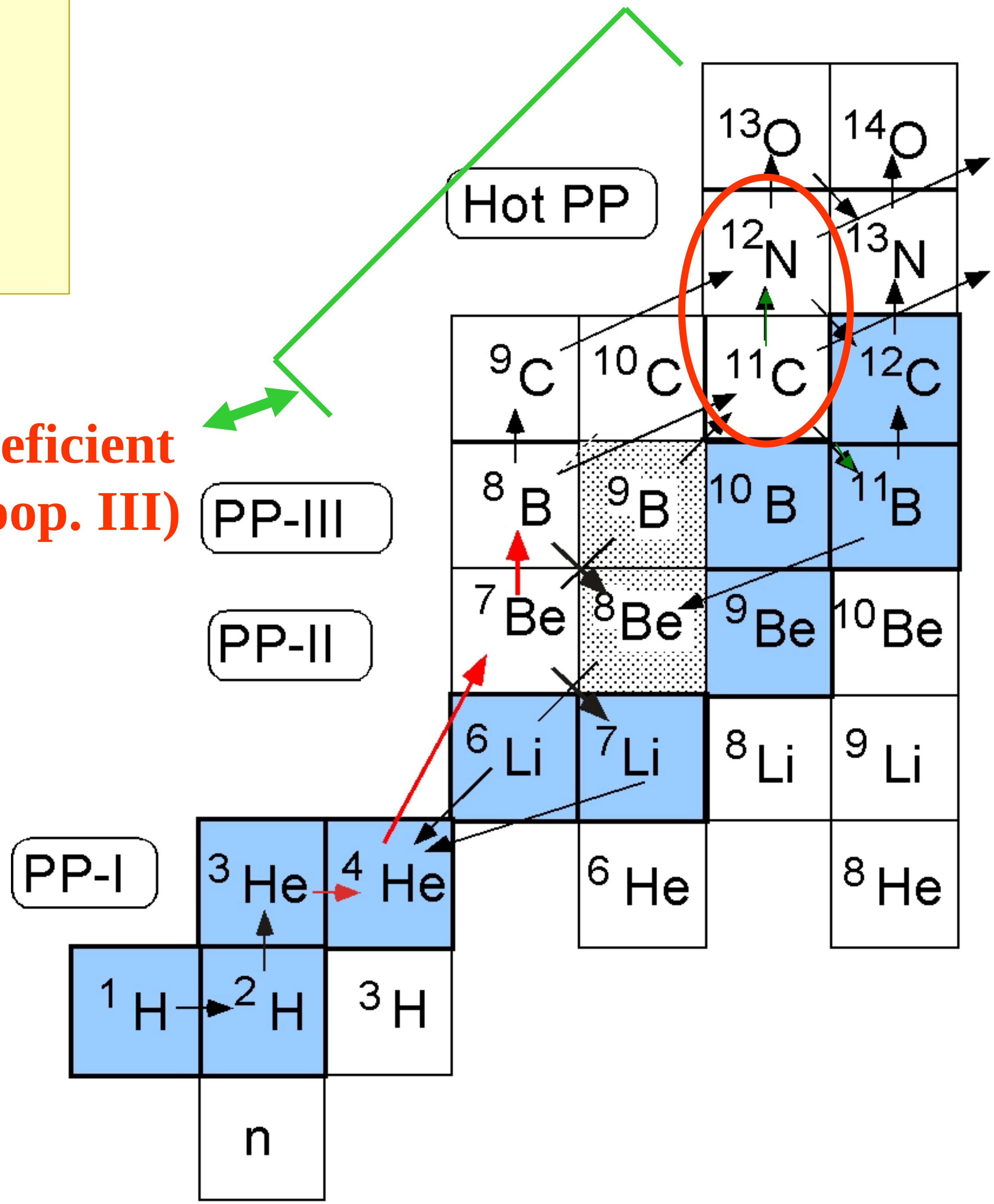
Seem to have only one-time r-process → First generation star ?

Our solar system had at least ten times of Supernovae

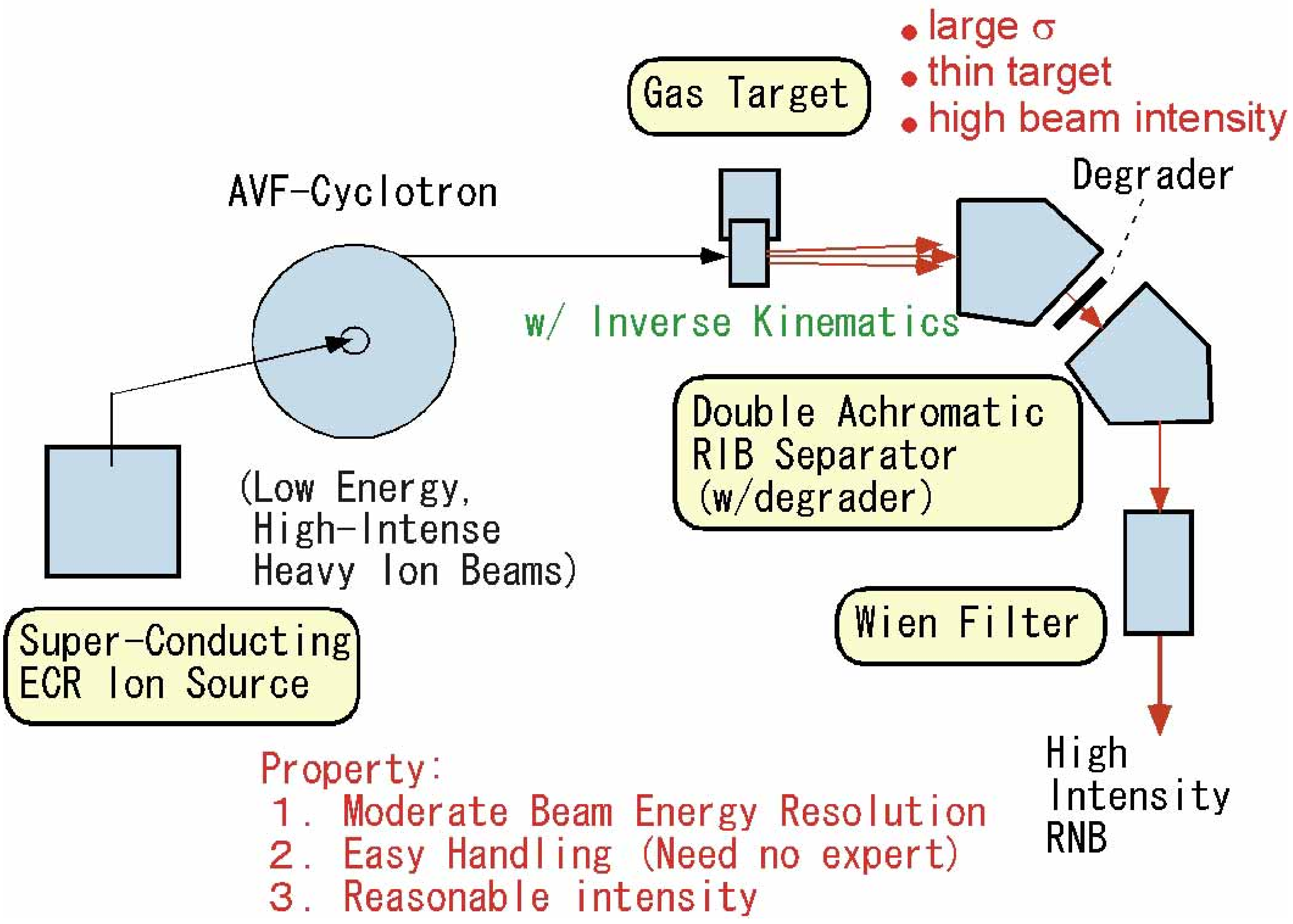


Hot pp-Chain

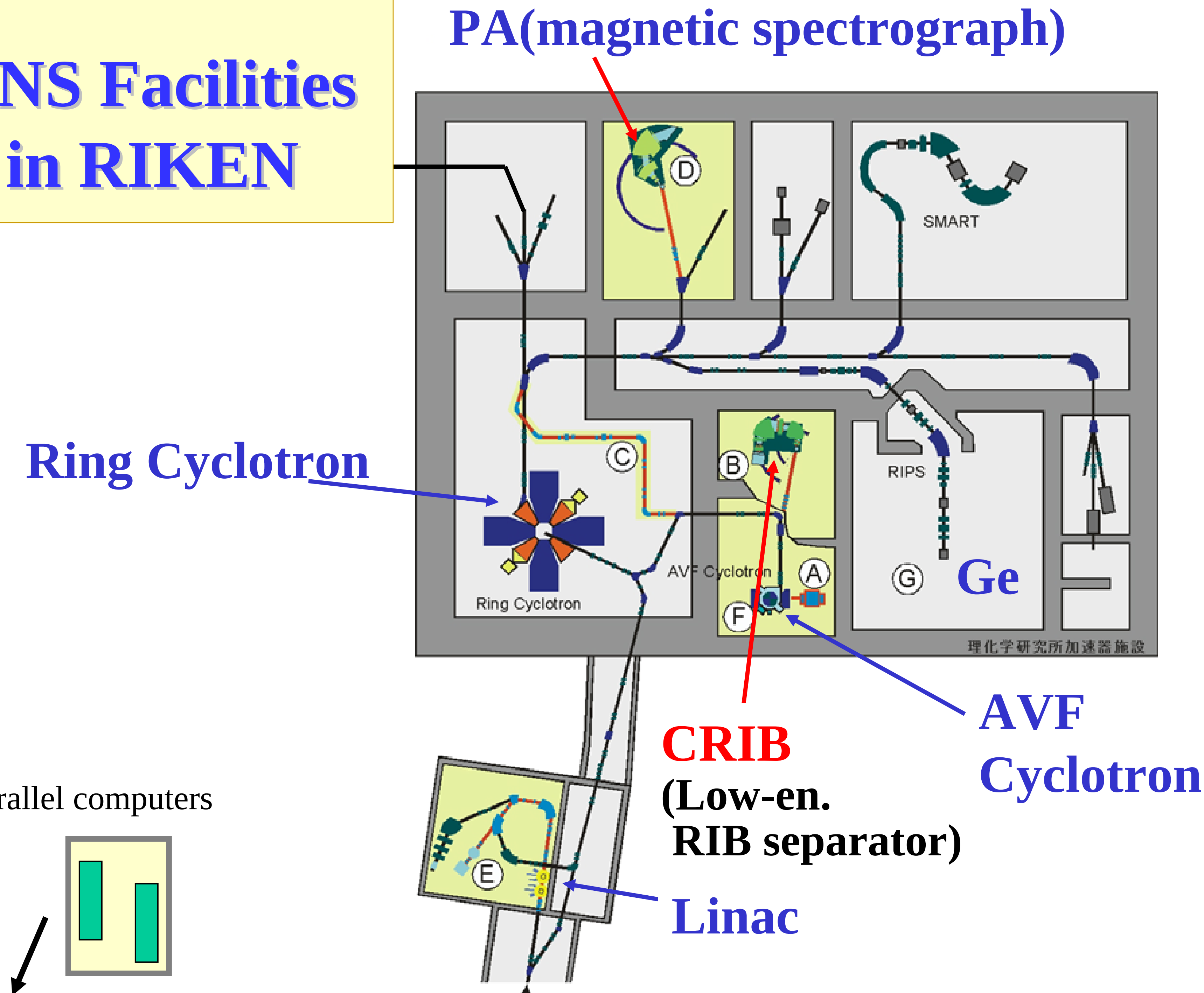
Fate of metal-deficient Massive stars (pop. III)



Low-Energy In-Flight RIB Separator

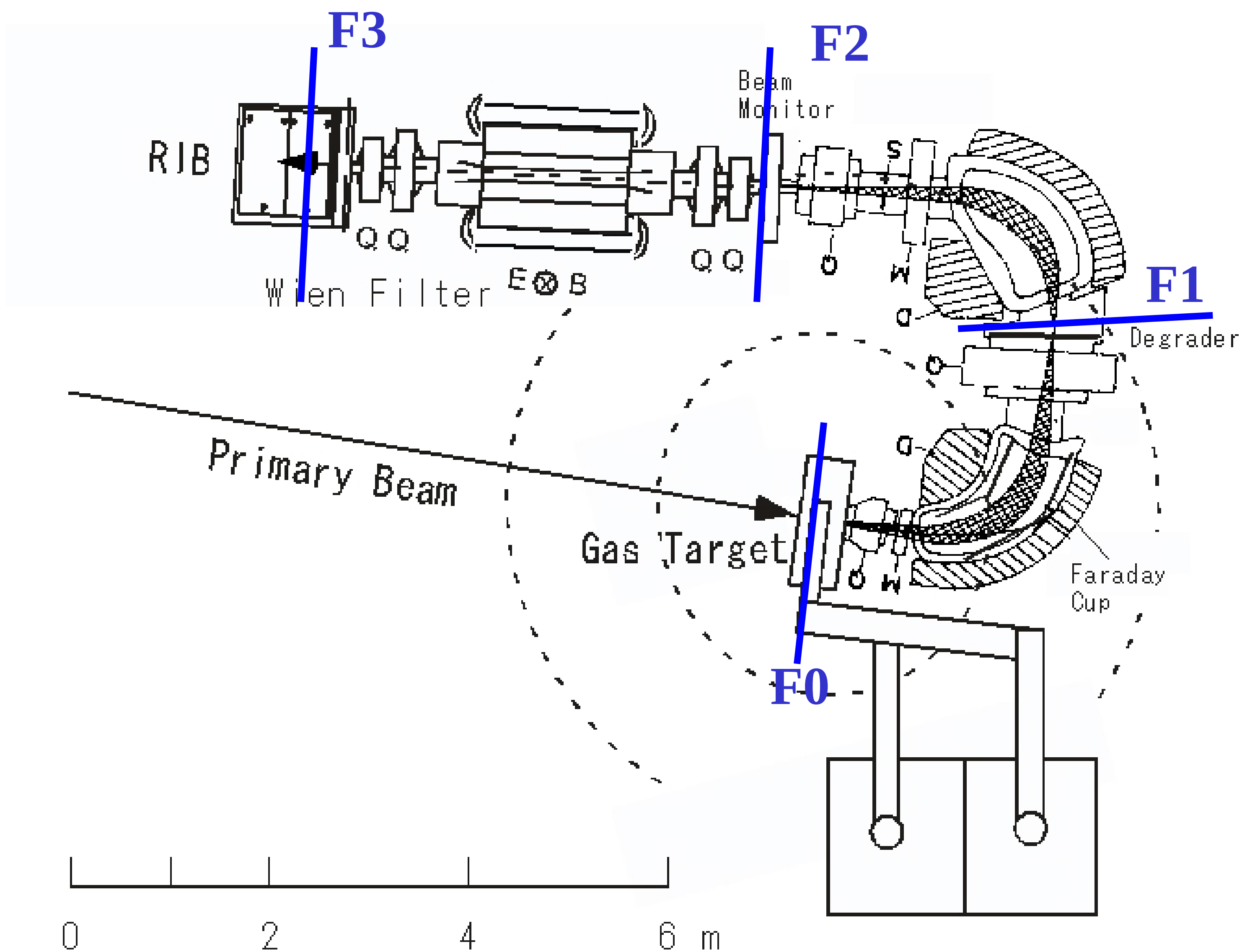


CNS Facilities in RIKEN

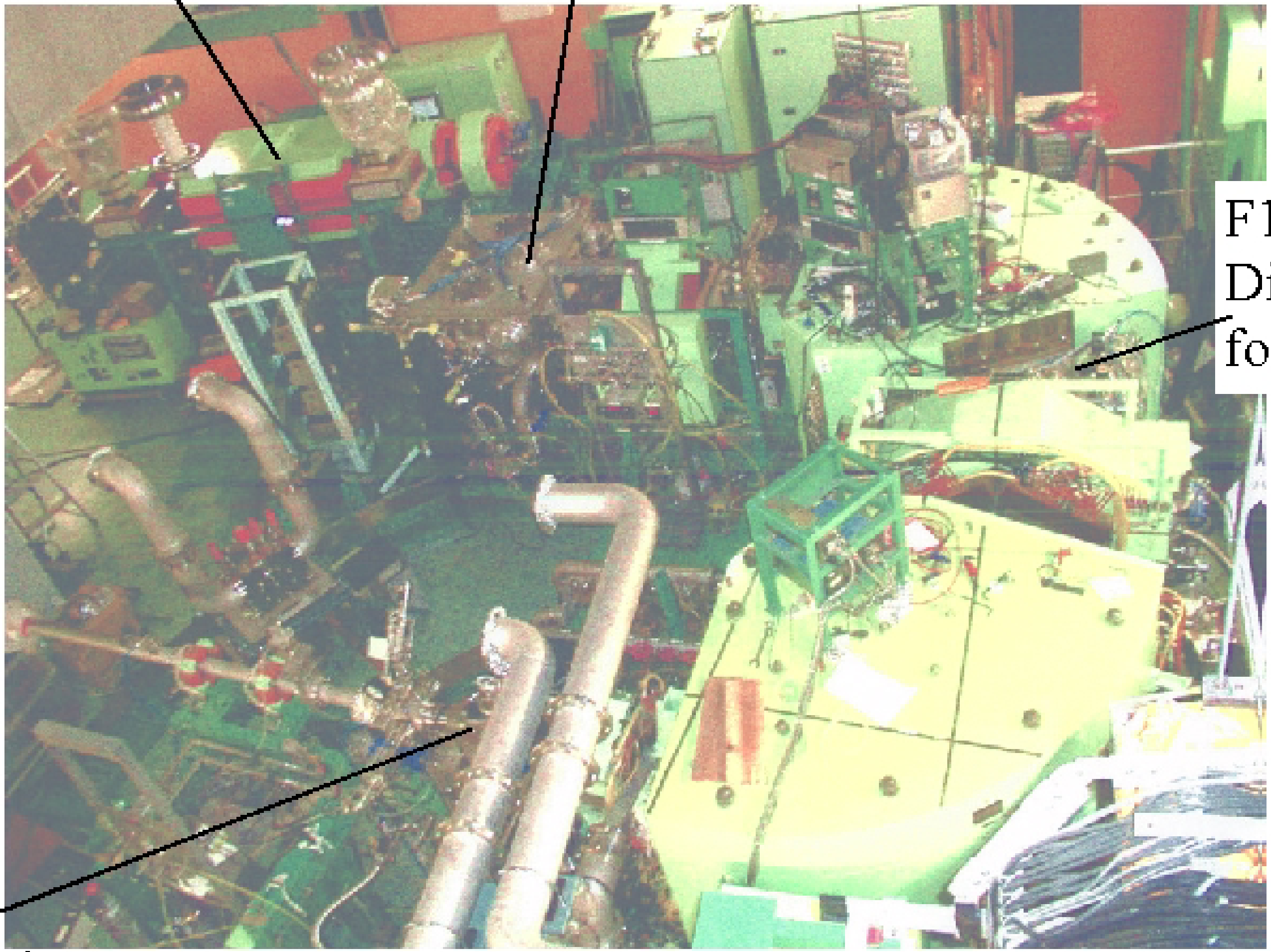


Parallel computers

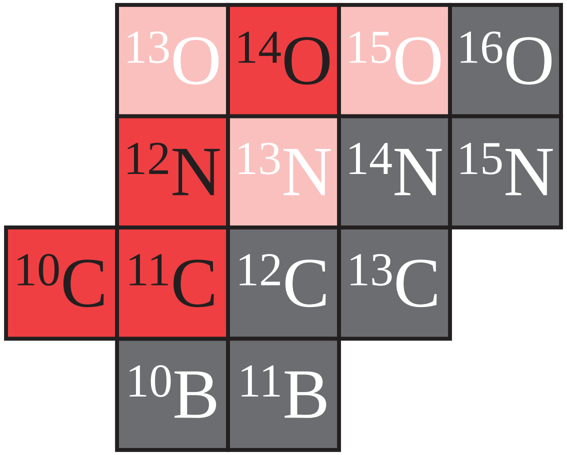
CNS RIB Separator (CRIB)



C R I B


Wien filter
F2: Achromatic focal plane
F1:
Dispersive
focal plane
Primary
beam
Production
target (F0)

Test result of Low-Energy RIB Productions



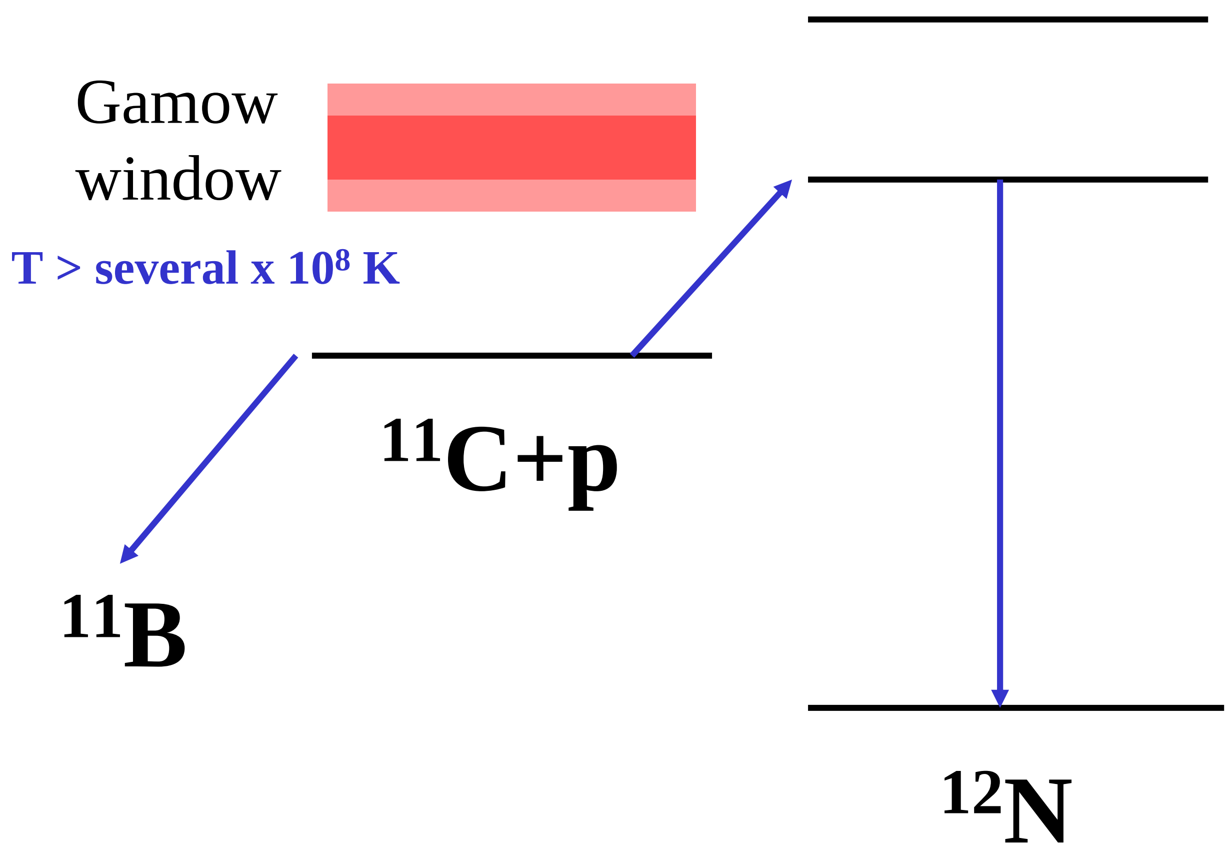
Used the (p,n) & (^{3}He,n) reactions in inverse kinematics.
Measured at F2.

RI beam	Primary beam	Reaction	Cross section	Target	Collection efficiency	Intensity	Purity with degrader
^{10}C 6.1 *A* MeV	^{10}B(4+) 7.8 *A* MeV (200 pnA)	**p(^{10}B,^{10}C)n**	2 mb	CH_4 gas 1.3 mg/cm^2	30 %	**(1.6×10^5 aps)**	90 %
^{14}O 6.7 *A* MeV	^{14}N(6+) 8.4 *A* MeV (500 pnA)	**p(^{14}N,^{14}O)n**	8 mb	CH_4 gas 1.3 mg/cm^2	50 %	**(1.7×10^6 aps)**	80 %
^{12}N 3.9 *A* MeV	^{10}B(4+) 7.8 *A* MeV 200 pnA	**^{3}He(^{10}B,^{12}N)n**	5 mb	^{3}He gas 0.25 mg/cm^2	1 %	**2.5×10^3 aps**	3 %
^{11}C 3.4 *A* MeV	^{10}B(4+) 7.8 *A* MeV 200 pnA	**^{3}He(^{10}B,^{12}N*)n** ^{12}N* → **^{11}C**+p	≈20 mb	^{3}He gas 0.25 mg/cm^2	≈ 2 %	**1.6×10^4 aps**	15 %

^{17}N, ^{22}Mg > 10^4 aps, ~ 10%. ^{23}Mg, ^{25}Al, ^{26}Si.

* ( ); Actual production tests of ^{10}C & ^{14}O were performed at lower intensities.
* Cross-section values are taken from other exp. results.

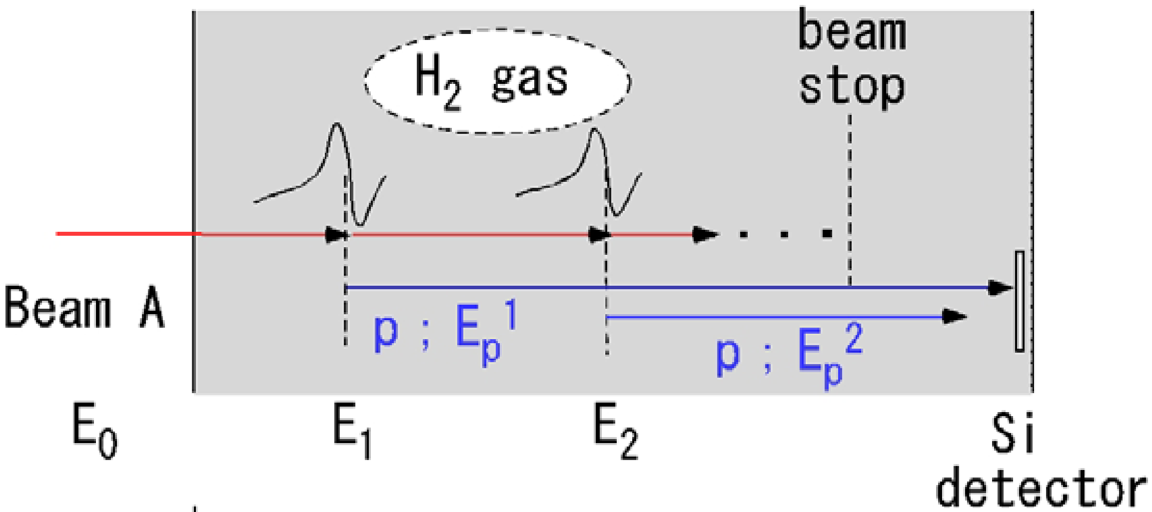
Stellar reaction of $^{11}C(p,\gamma)^{12}N$

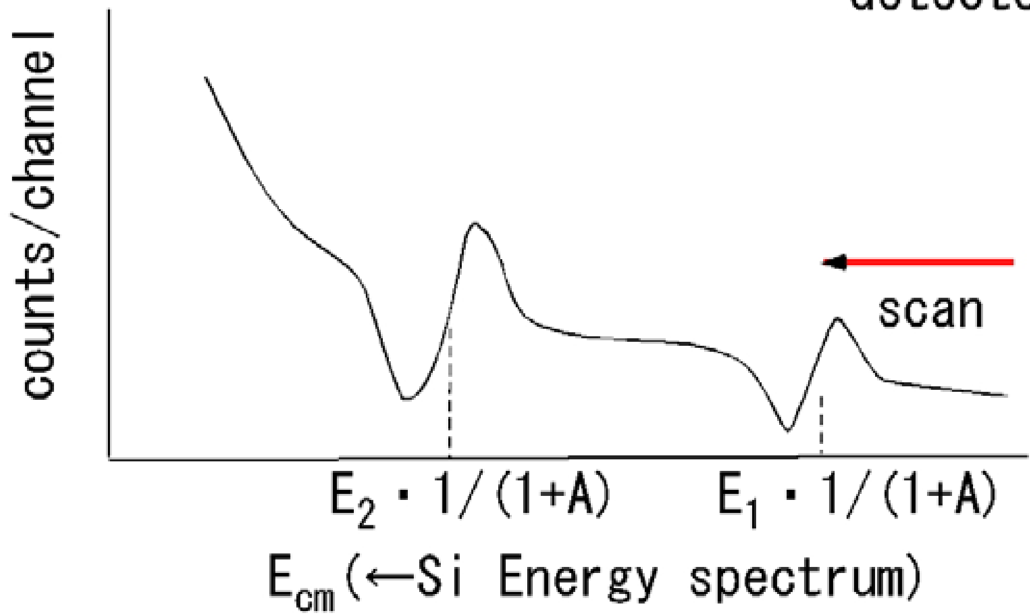


Elastic Resonant Scattering of p + A(RIB)

(Thick target method)

$$* \; E_p^{\,1} = 4 \cdot A/(1+A)^2$$



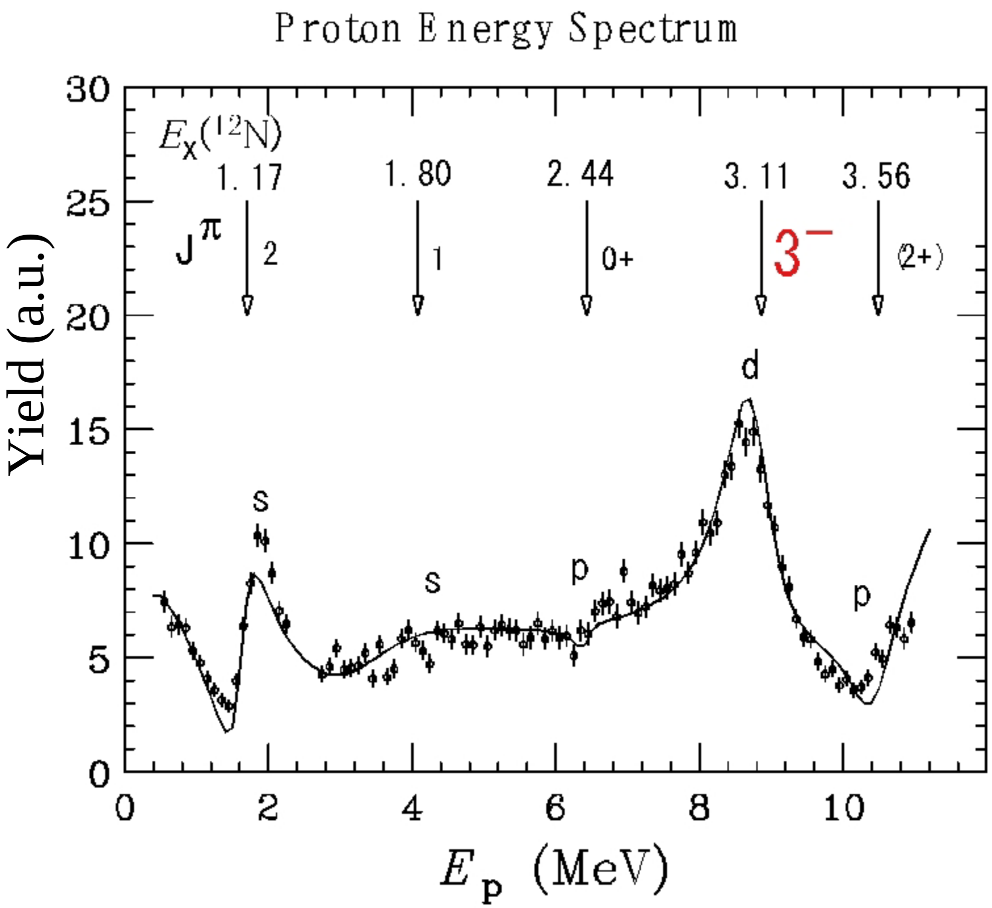


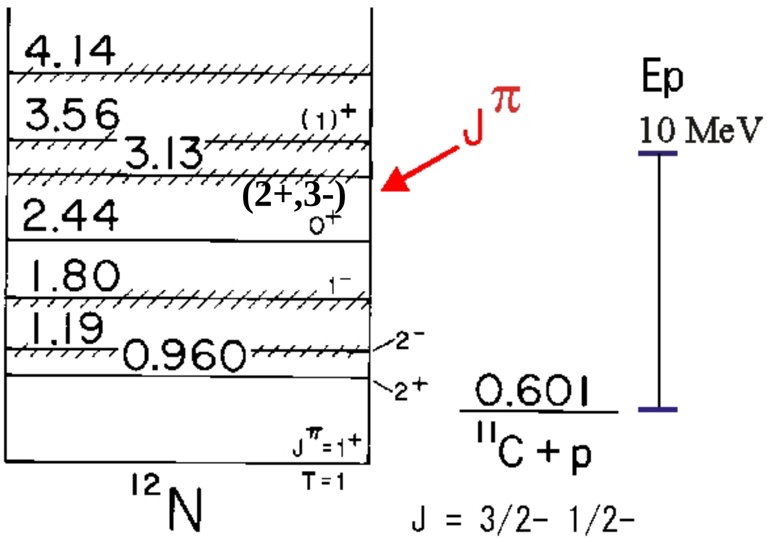
$$Y(E) = I(E)\int_{E-\Delta E/2}^{E+\Delta E/2} \frac{\sigma(E_i)}{\varepsilon(E_i)}\, dE_i$$

I(E) : Number of beam particles

ε(E) : Stopping cross sections

Low-Energy Resonant Elastic Scattering of ^{11}C + p





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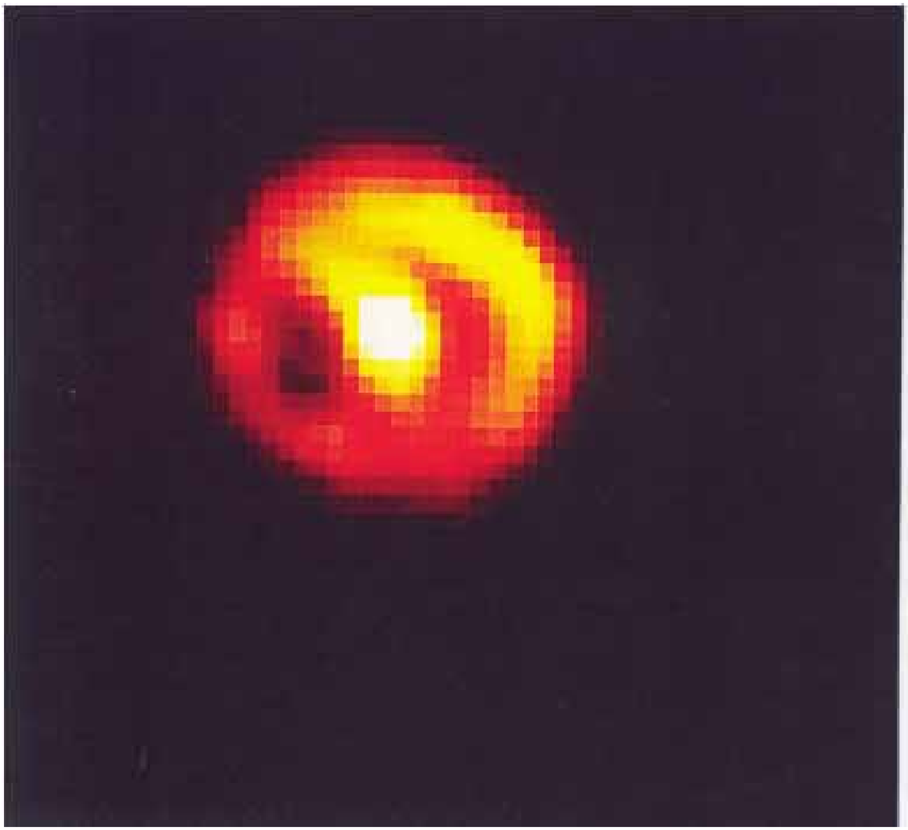
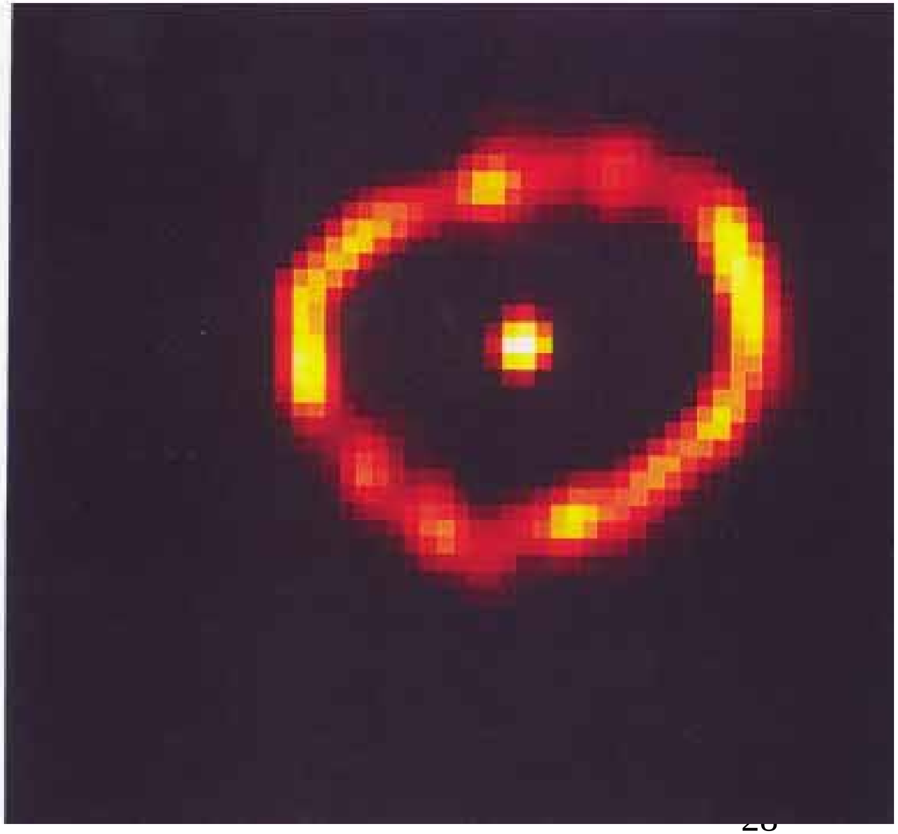
Novae

Cygnus 1992 (**@10 K ly**)

May 1993

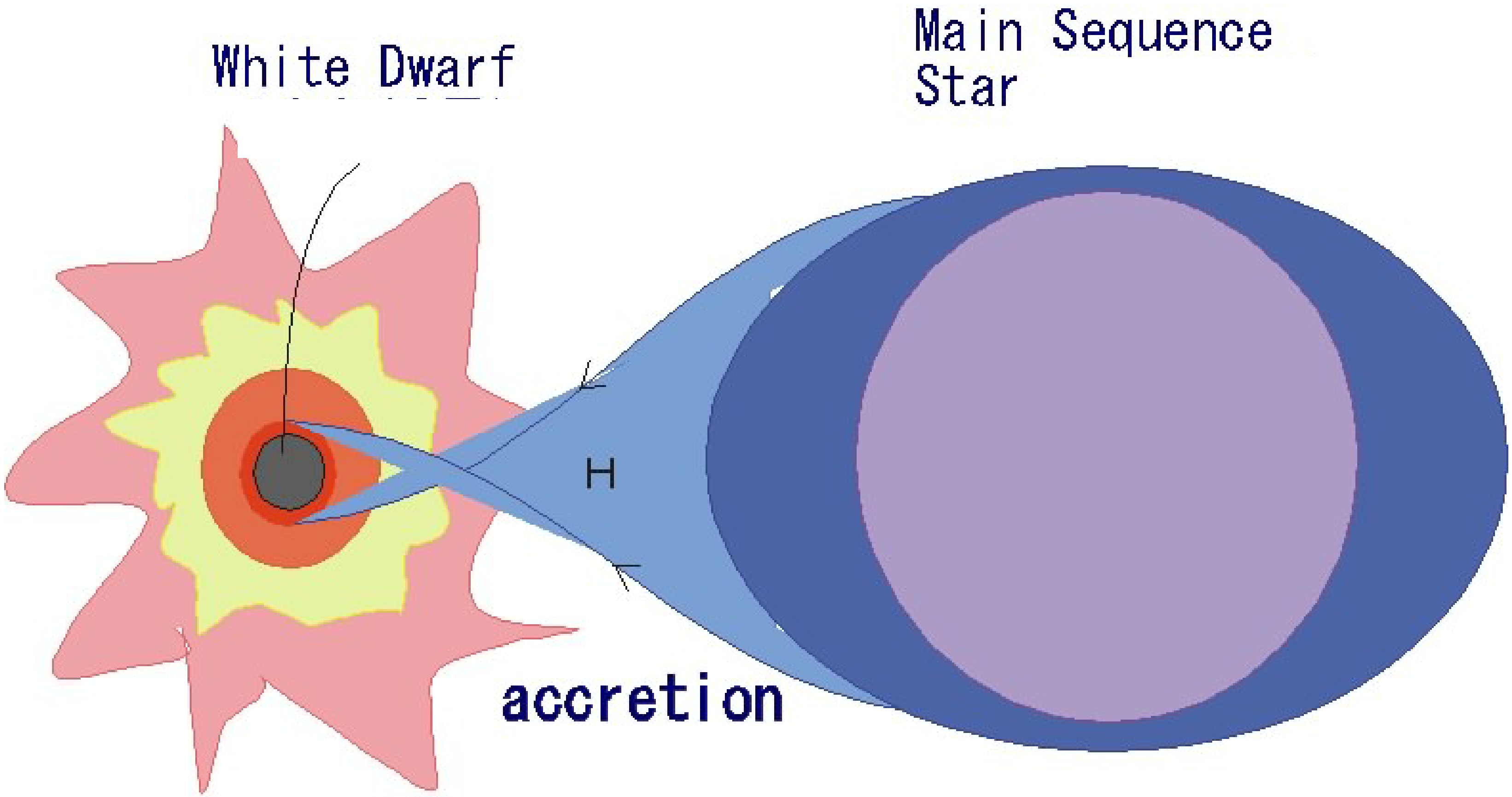


January 1994



(Hubble)

Novae, the problems



Reaction processes in the explosion ?

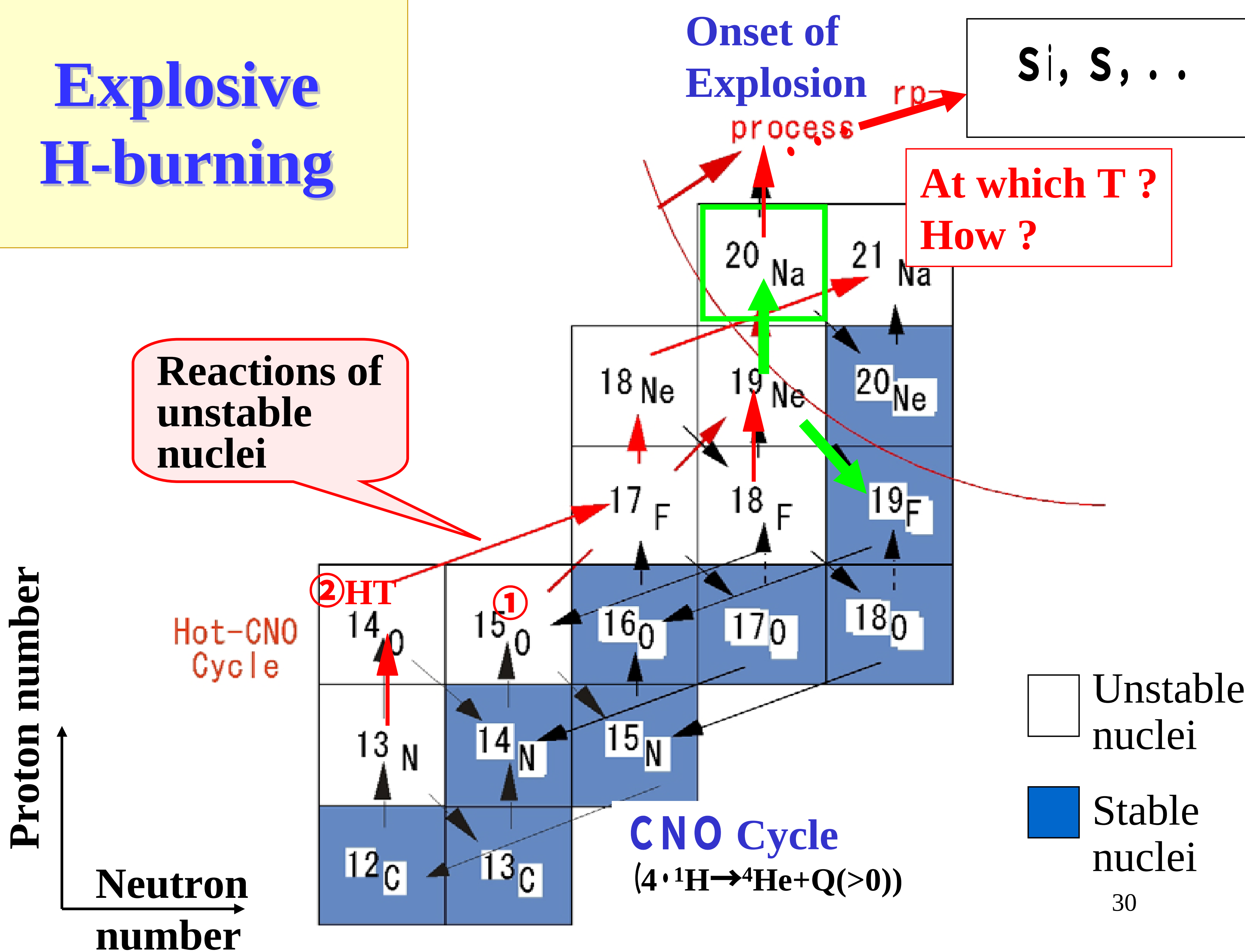
→ Ignition temperature, density, energy ?

[C, O, (Ne, Mg)] ⟶ Si, S, (Ar), . . .

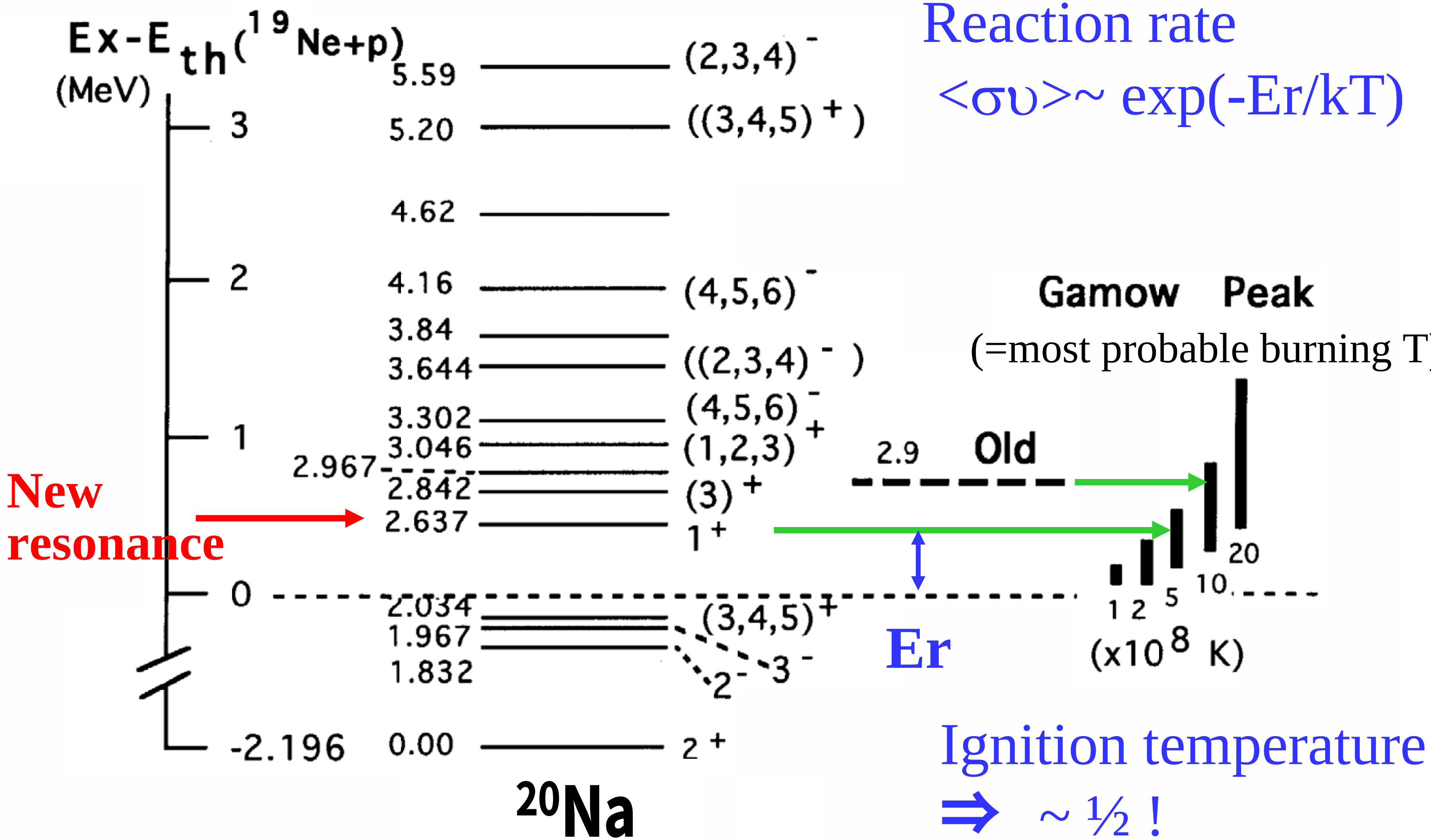
$(p,\gamma)^n\beta^m$

New elements are observed !

Explosive H-burning



$^{19}Ne(p,\gamma)^{20}Na$ stellar reaction



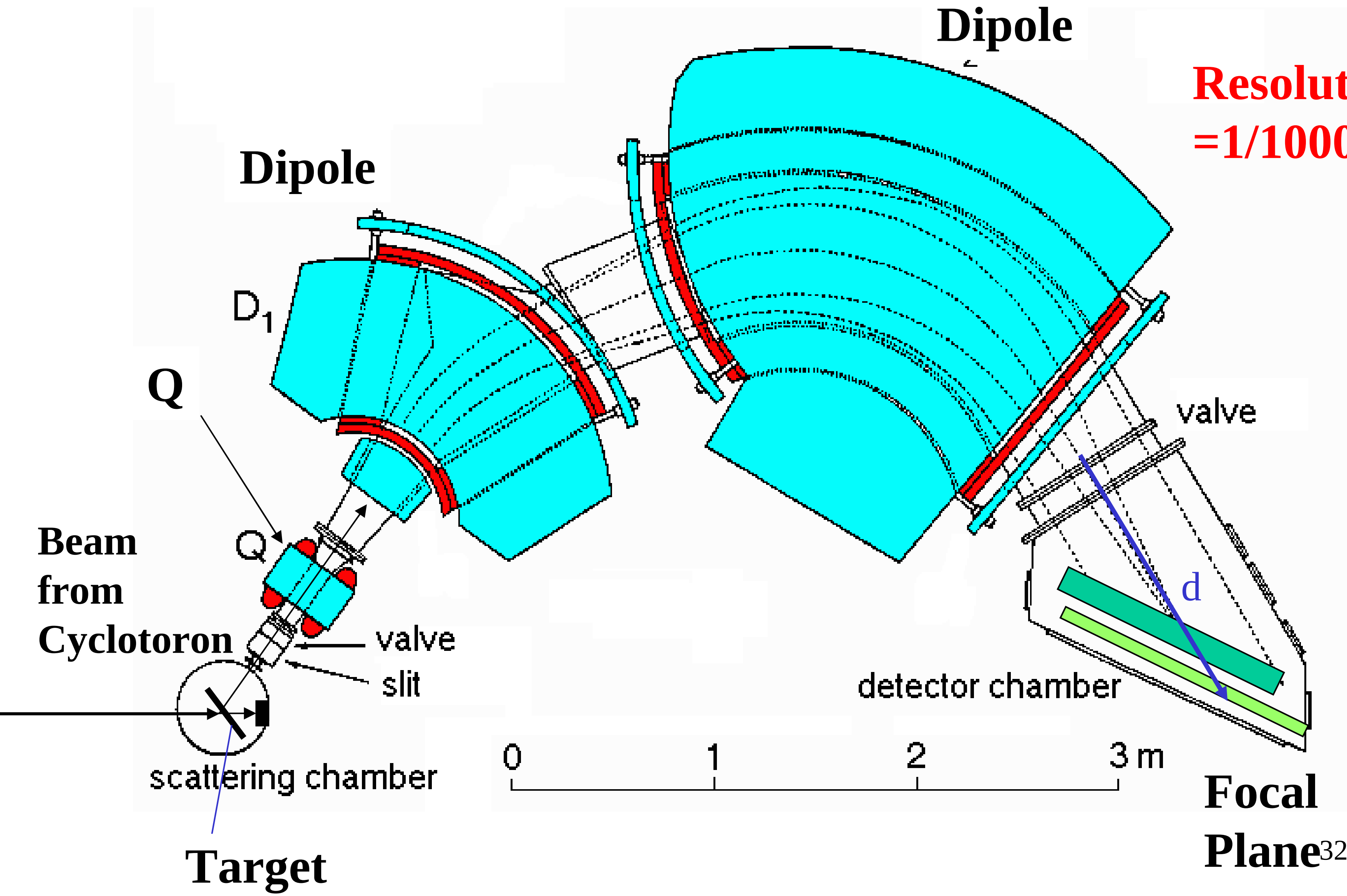
Reaction rate

$<\sigma\upsilon> \sim \exp(-E_r/kT)$

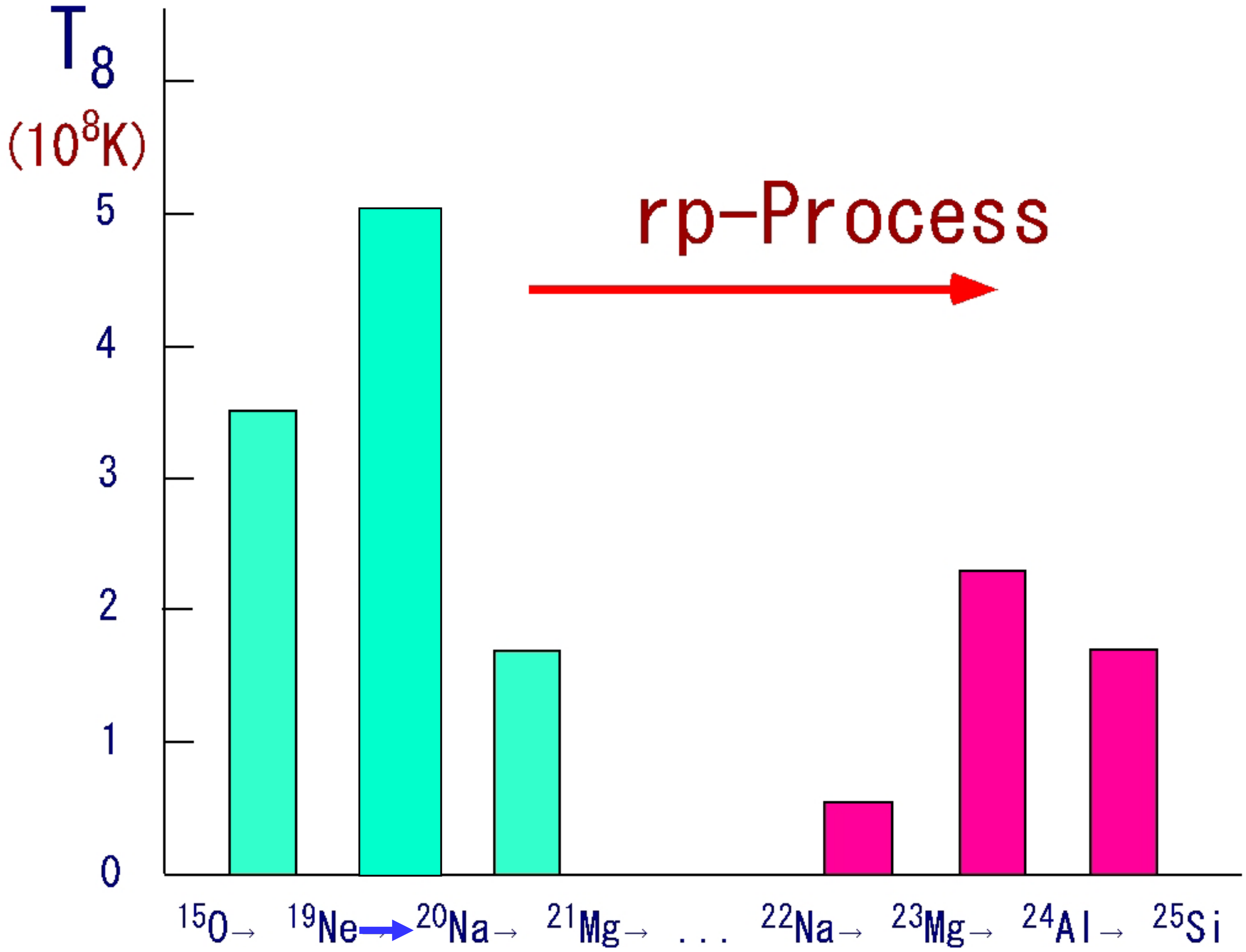
Ignition temperature

$\Rightarrow$ ~ ½ !

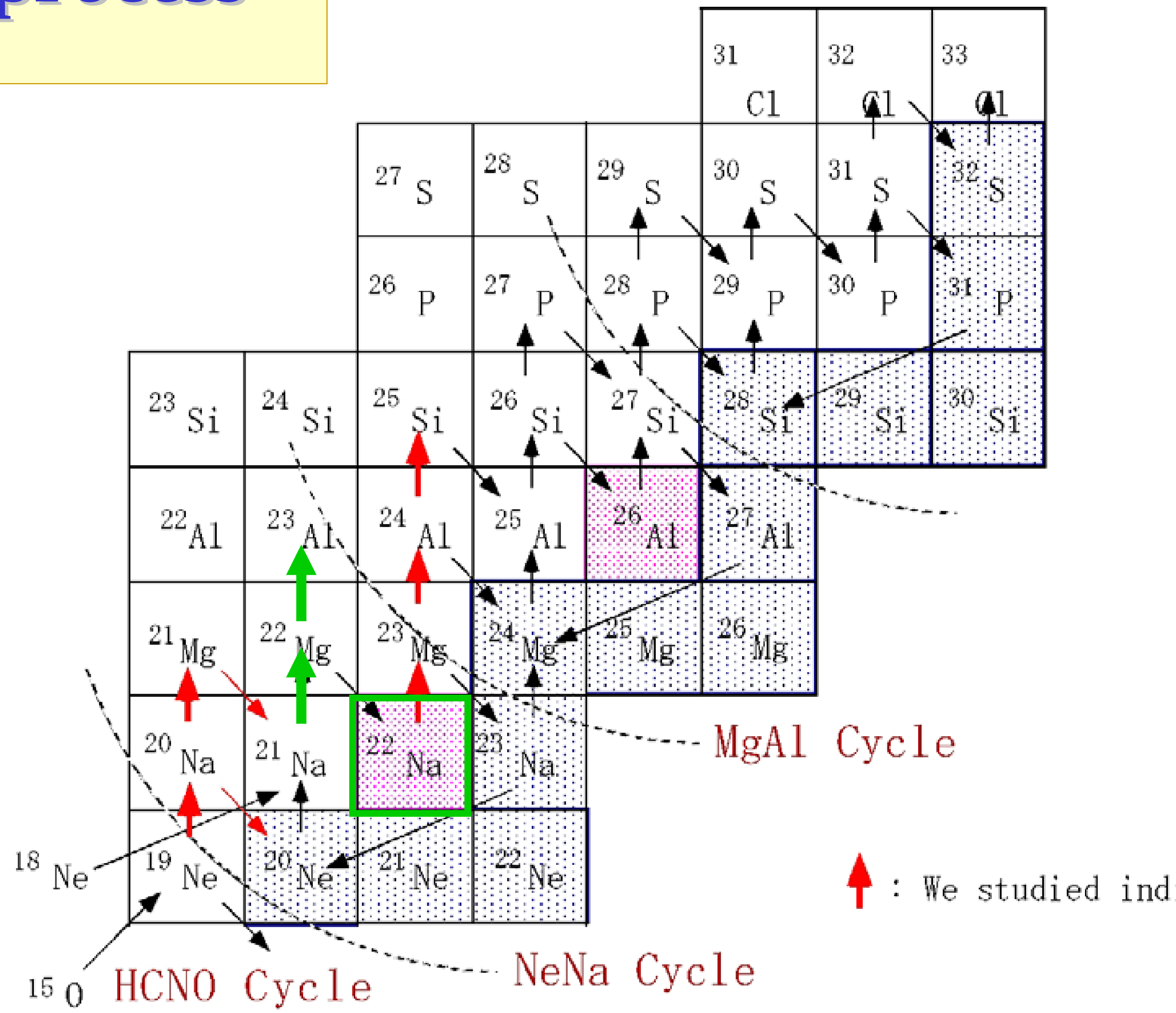
High-resolution magnetic spectrograph (PA)



Ignition temperature



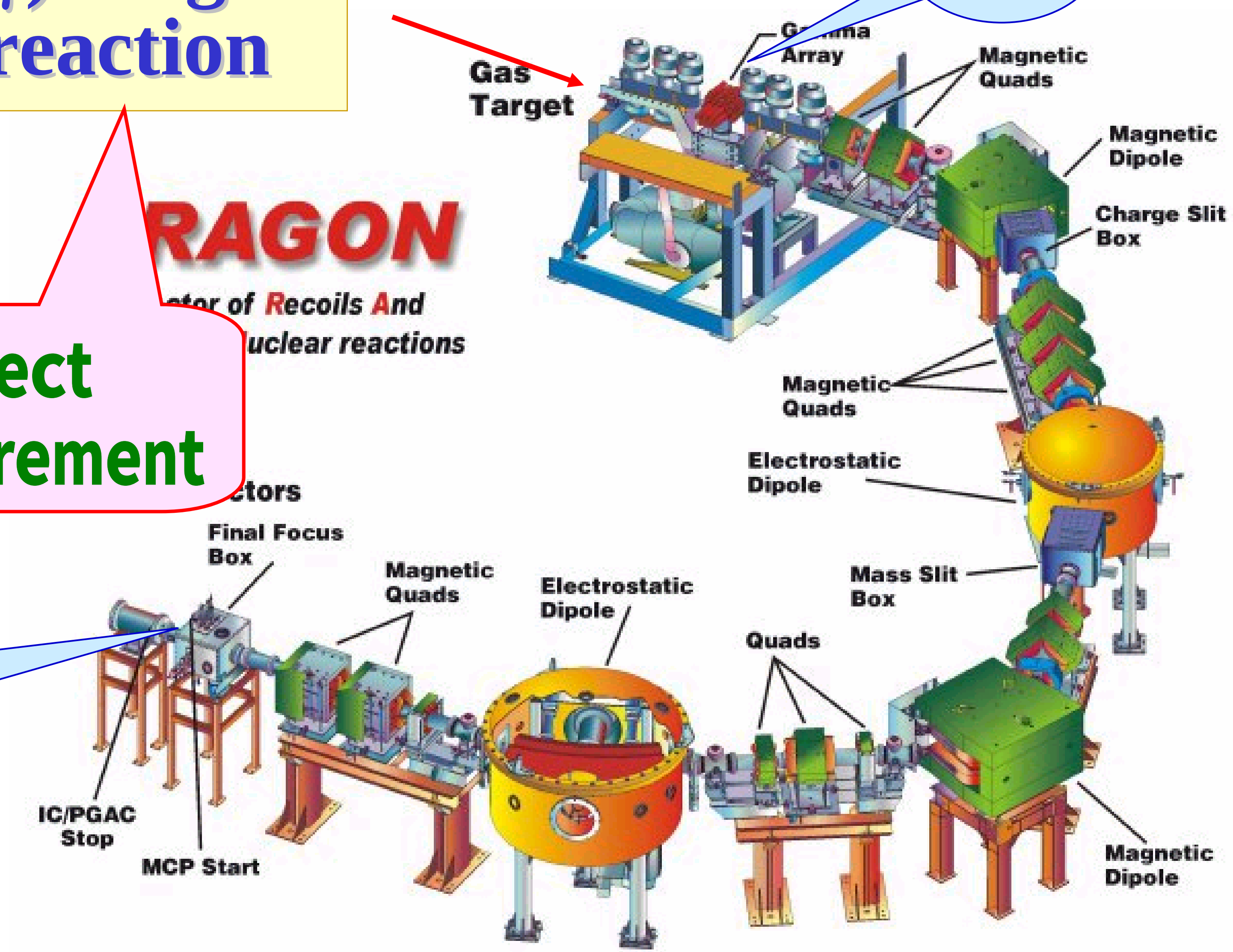
Early rp-process



Measurement of $^{21}Na(p,\gamma)^{22}Mg$ stellar reaction

^{21}Na RIB

γ



Direct Measurement

^{22}Mg

$^{1}H(^{21}Na,\gamma^{22}Mg)$ Measurement at TRIUMF

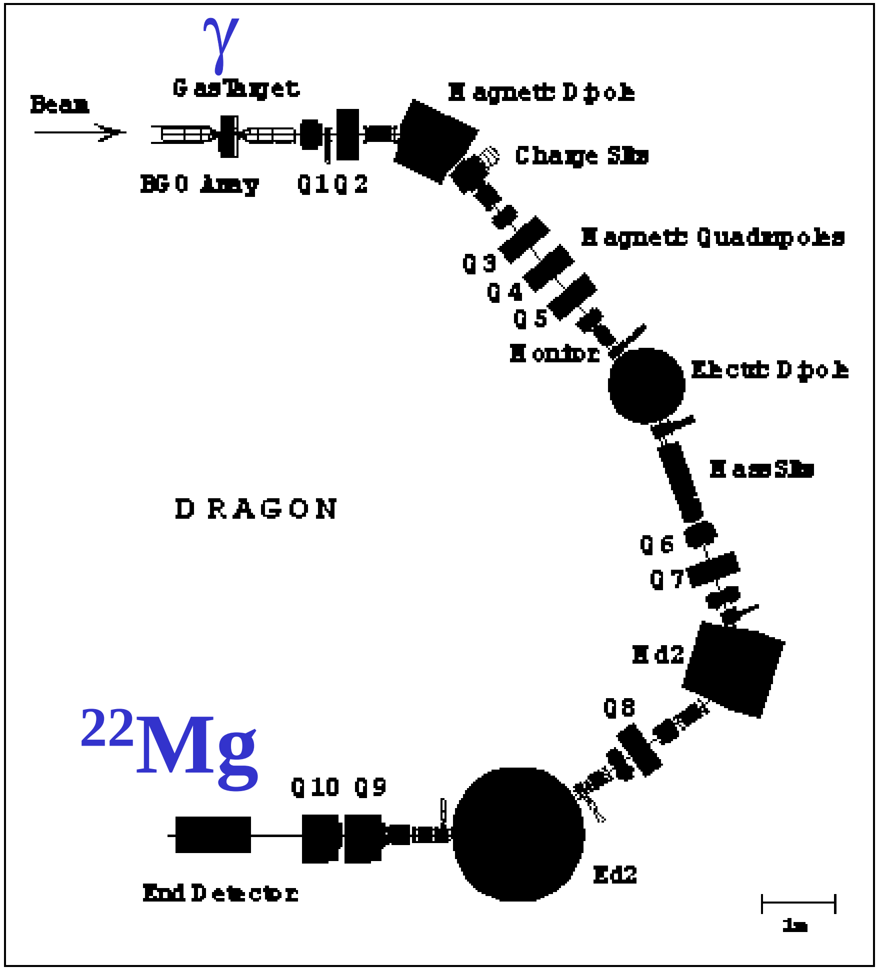


FIGURE 1. The Dragon Recoil Separator

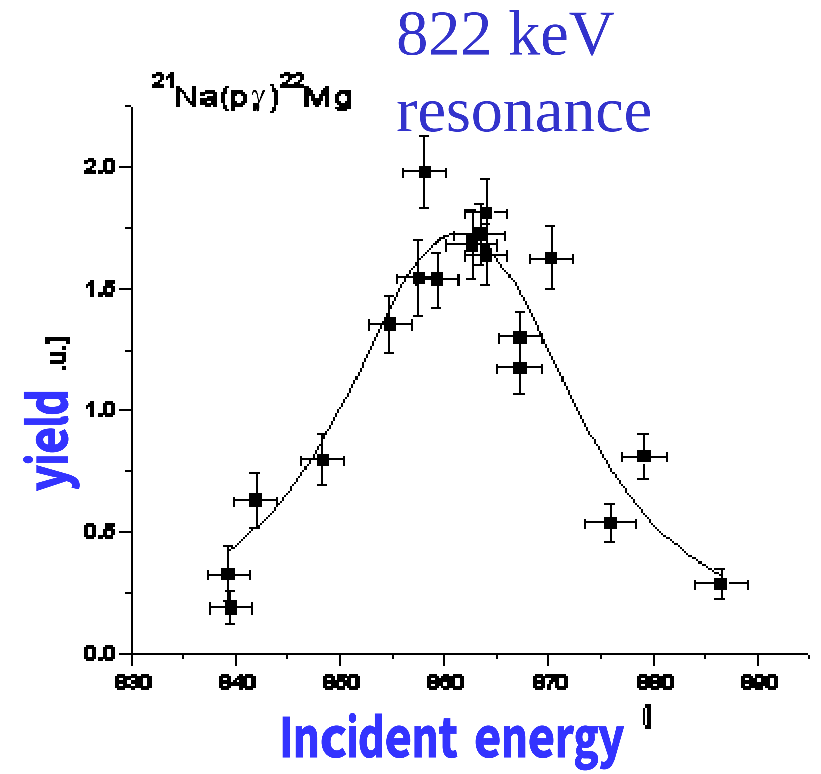
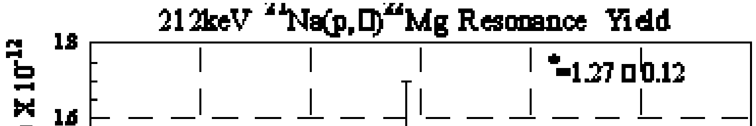


FIGURE 3. Excitation function for the 822 keV/u resonance (preliminary). The curve shows the expected shape for a broad resonance.



Typical temperature and density for nucleosynthesis

	Temperature	Density
Sun	1.5×10^{7} K	10^{2} g/cm^{3}
Novae	$2 \sim 4 \times 10^{8}$	$10^{3\sim4}$
Supernovae	$1 \sim 2 \times 10^{9}$	$10^{5\sim6}$

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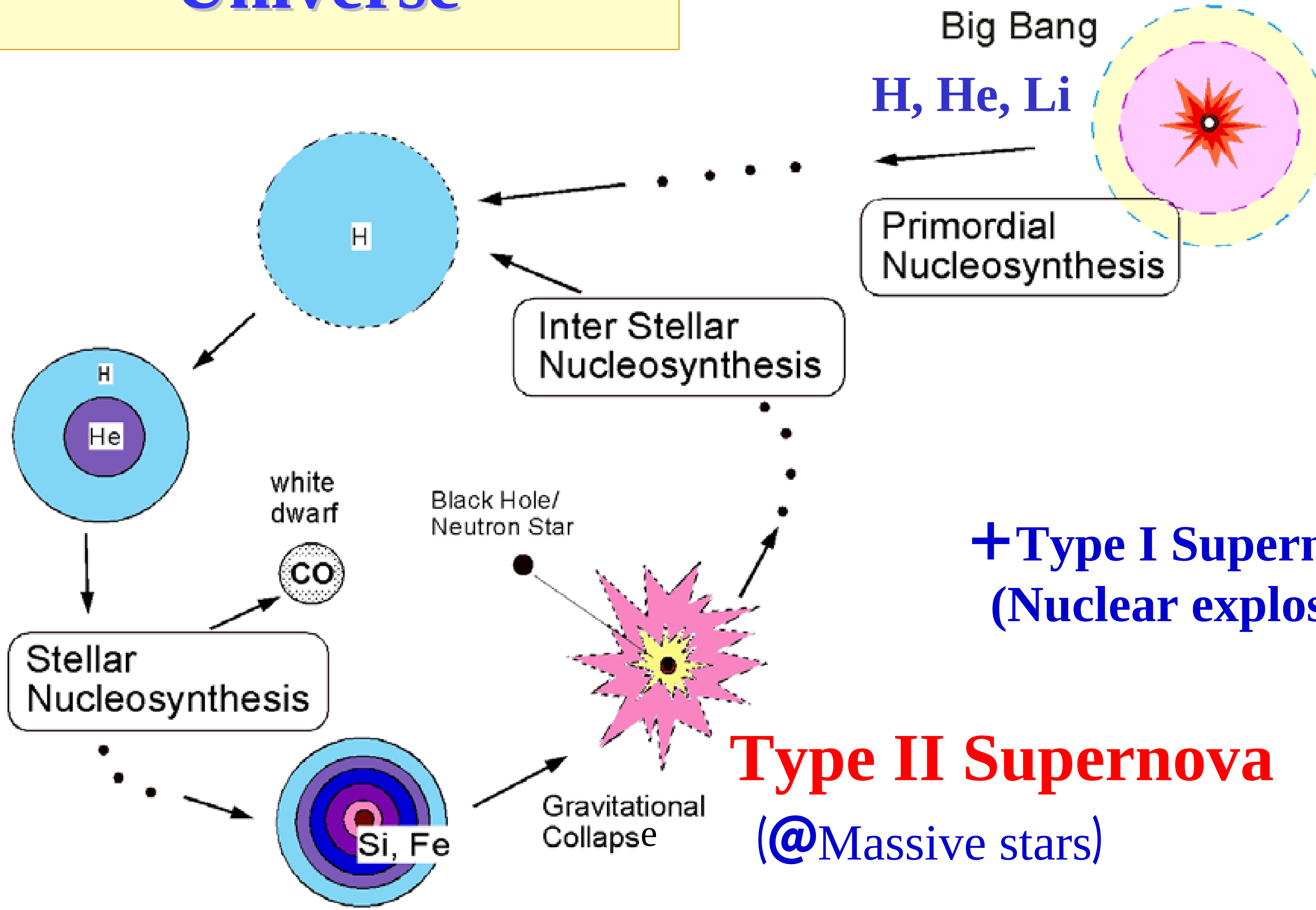
Evolution of the Universe



+Type I Supernova (Nuclear explosion)

Type II Supernova

(@Massive stars)

Supernova 1987A

February 1987; @ Large Magallanic Cloud

Before **After**

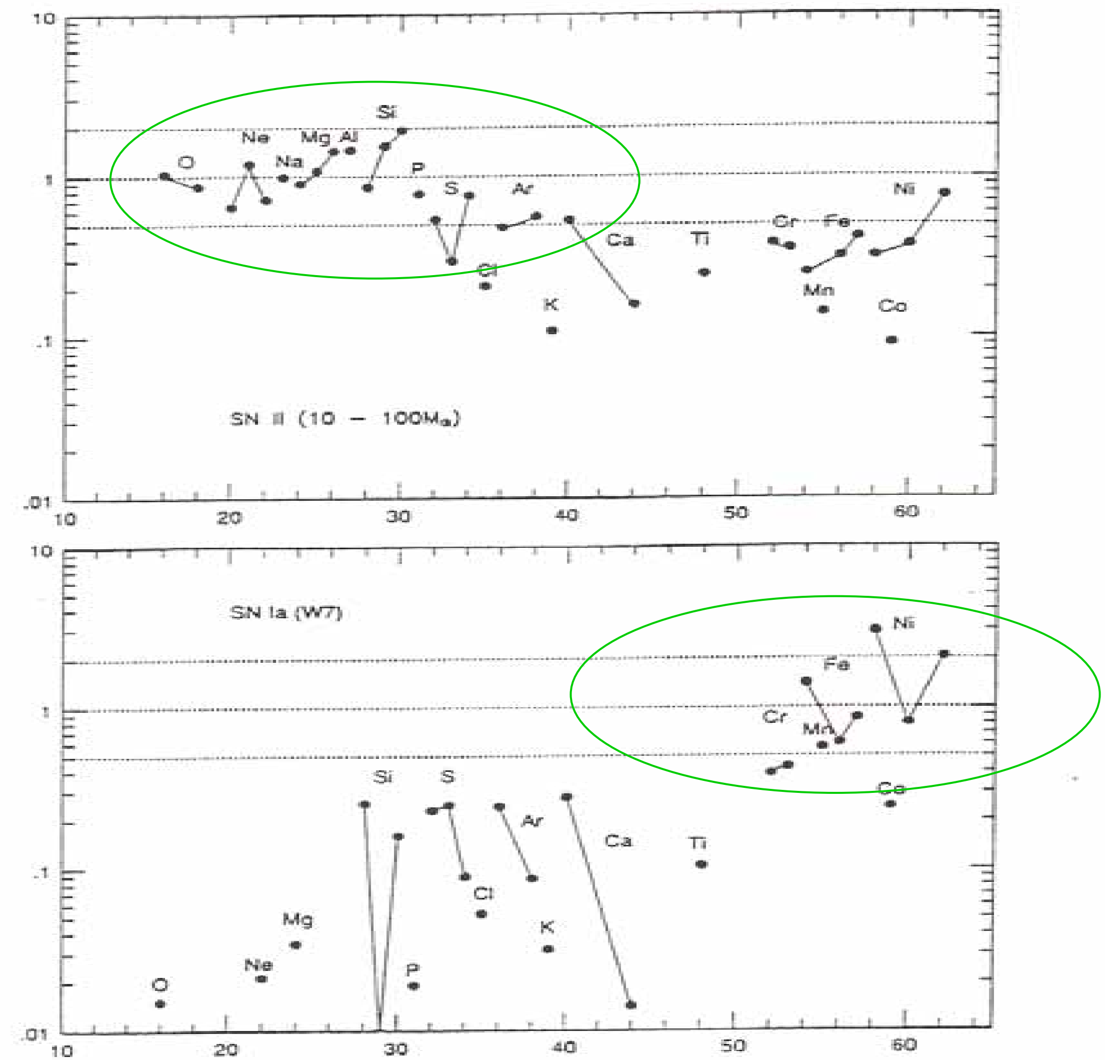
Nucleosynthesis in Supernova
- prediction -

Gravitational collapse (Massive stars)

Type II S.N. Solar abund.

Nuclear Explosion (Small stars)

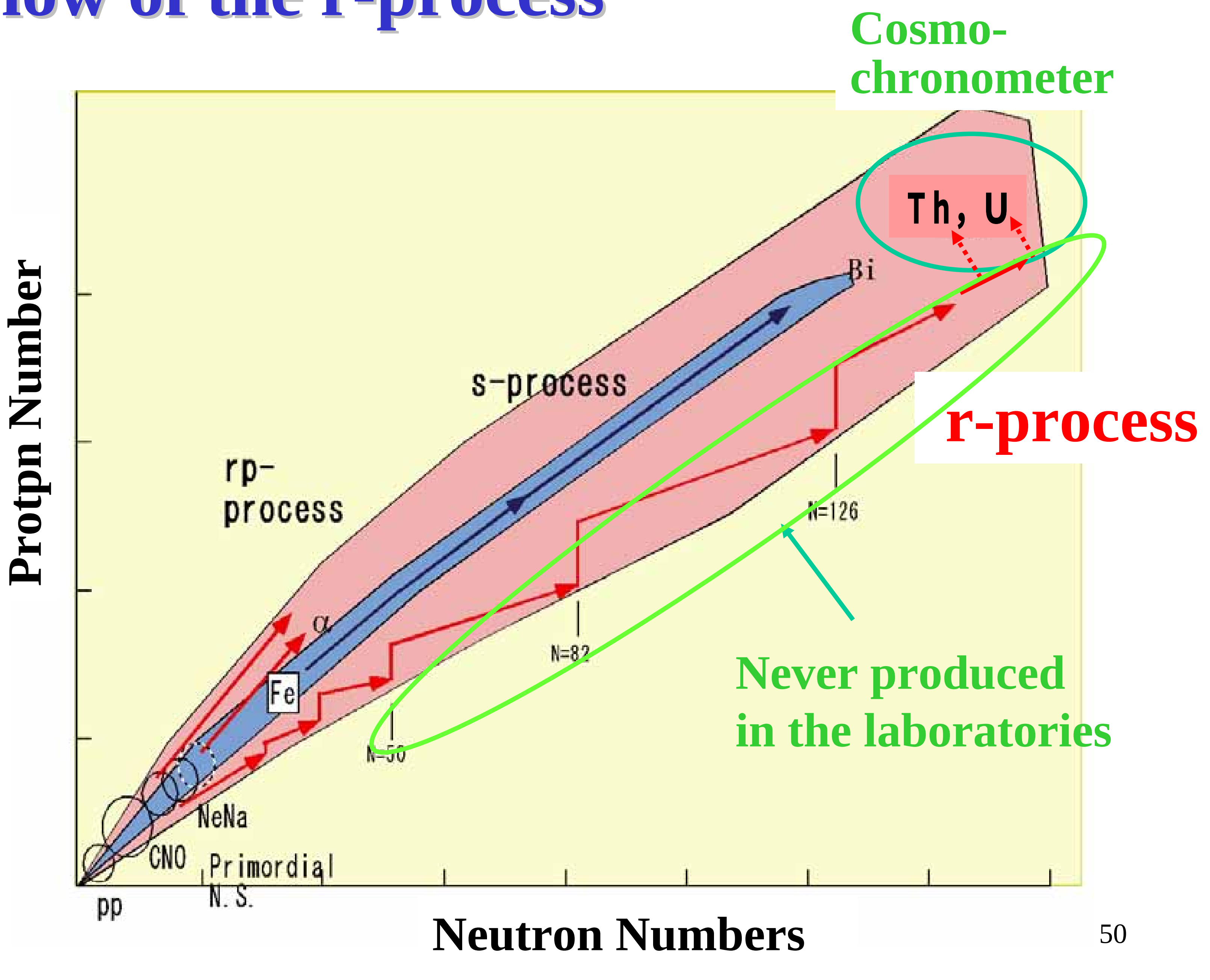
Type I S.N. Solar abund.



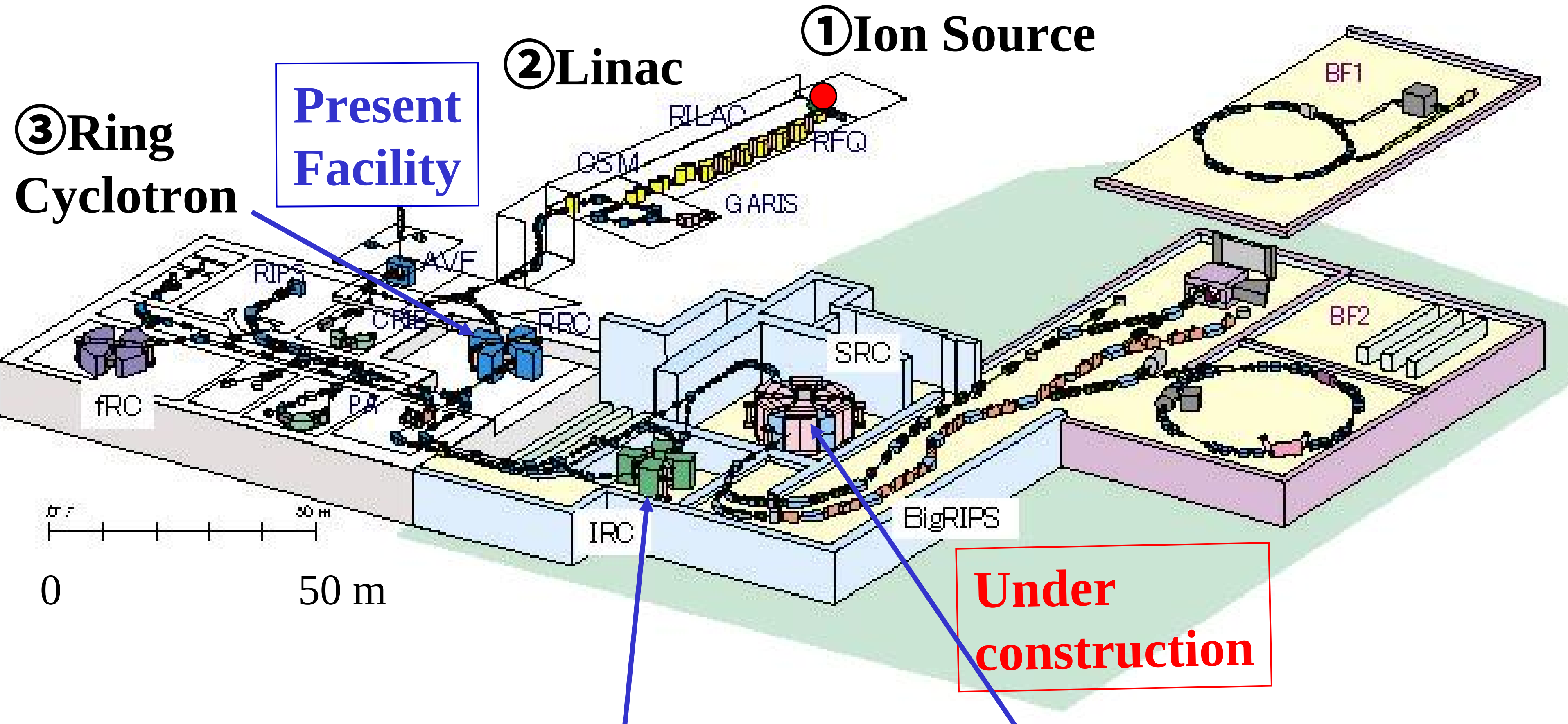
Atomic Mass (A=N+N)

(Nomoto)

Flow of the r-process



RIKEN Accelerator Research Facility

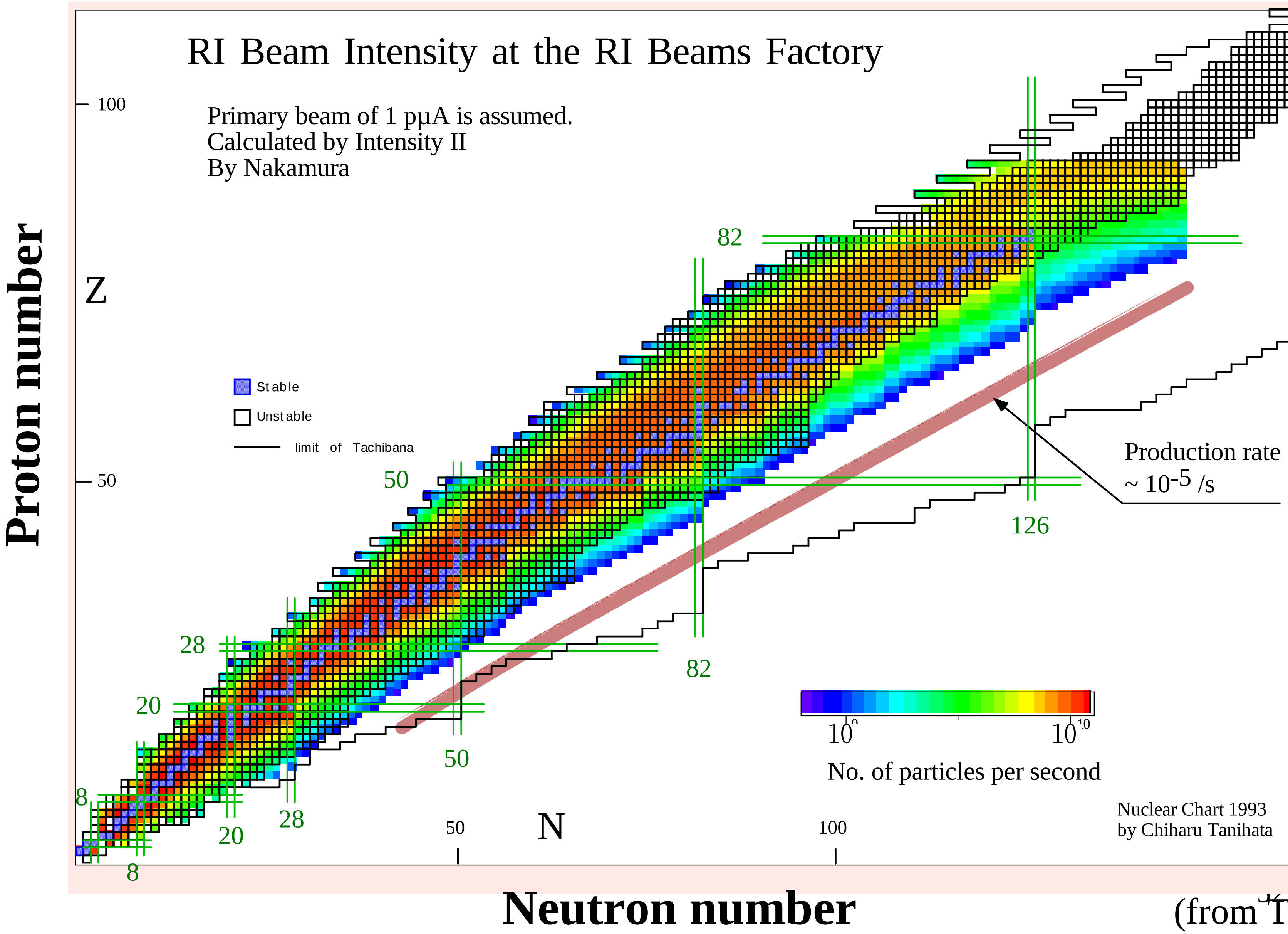


④Intermediate Ring Cyclotron

⑤Super-Cond. Cyclotron

- Highest-energy Cycl.
- Highest intensities
- RI Beams

RI beam intensities predicted at RIBF



(from Tanihata)

Age of the Universe

- Method with Cosmo-chronometers (with very long $T_{1/2}$ nuclei)

  $^{232}_{90}Th$ $T_{1/2}$ = 14.5 billion years

  $^{238}_{92}U$ $T_{1/2}$ = 4.47 billion years

  $^{235}_{92}U$ $T_{1/2}$ = 0.704 billion years

  Produced→Current quantity

  Need to understrand the production mechanism

  c.f. The solar system → 4.7 billion years

- Hubble's Law $v = H \cdot r$ H ; Hubble constant

  Then, $t = r / v = 1 / H$

  If H～70Km/sec/Mpc、 **t～14** billion years

- Age of Halo stars

  Age of the universe > Age of the Halo stars

Nuclear Astrophysics is a fun !