Nuclear astrophysics experiment
or Experimental nuclear astrophysics

Tohru Motobayashi

+ Some (practical) information
on the $^{12}C(p,\gamma)^{13}N$ (and $^{10}Be(p,\alpha)^{7}Be$) experiment

天体核物理実験

本林　透

RIKEN NiSHiNA CENTER

(My) surprises:

element synthesis: in stars (early universe)

"burning" is in gas

When and where?

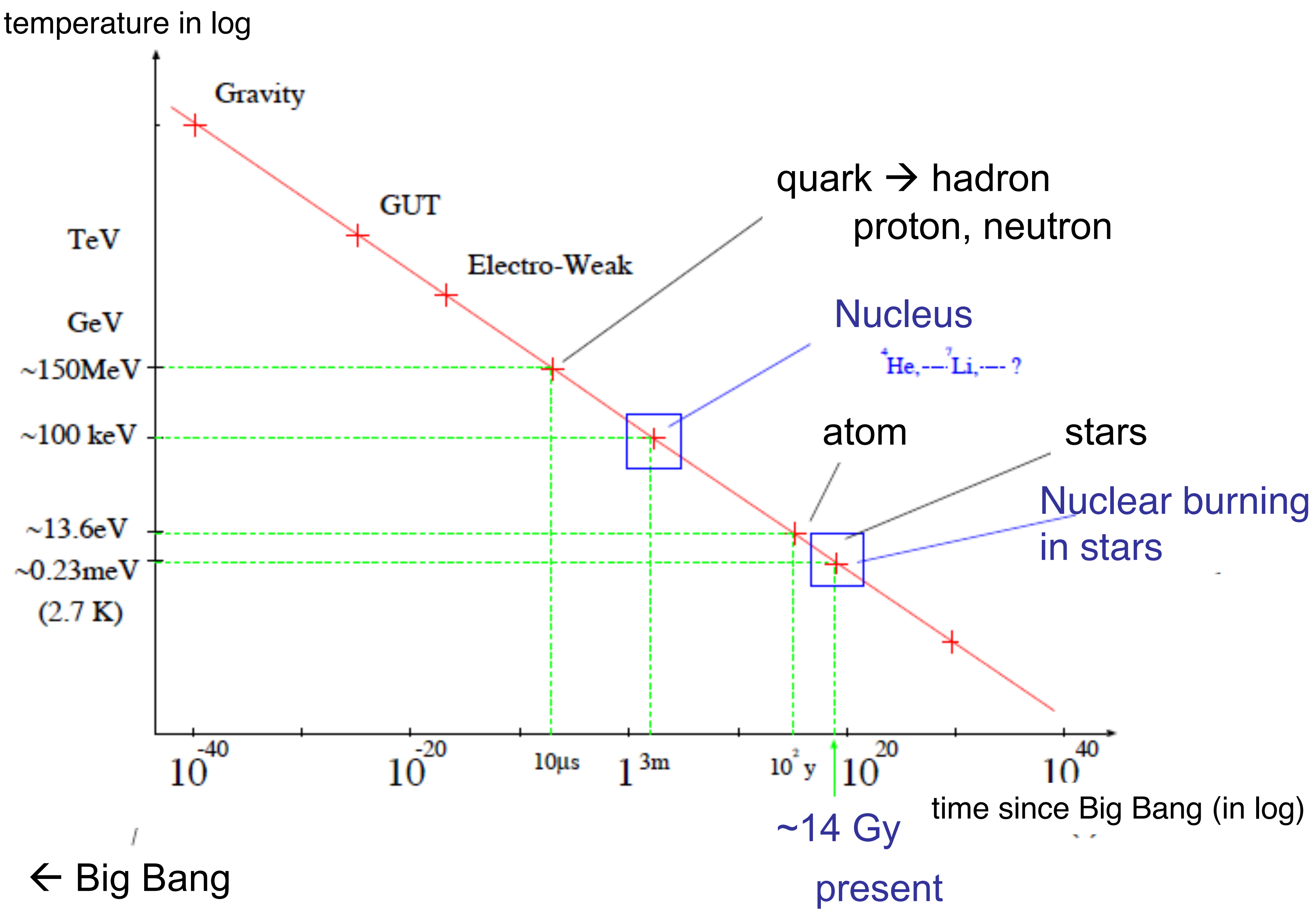
How?

Experiment next week

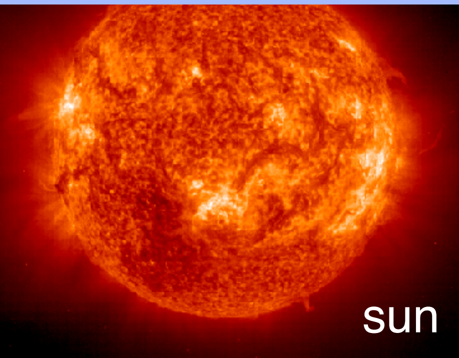
$^{12}C(p,\gamma)^{13}N$

When and where?

(Thermal) history of the Universe

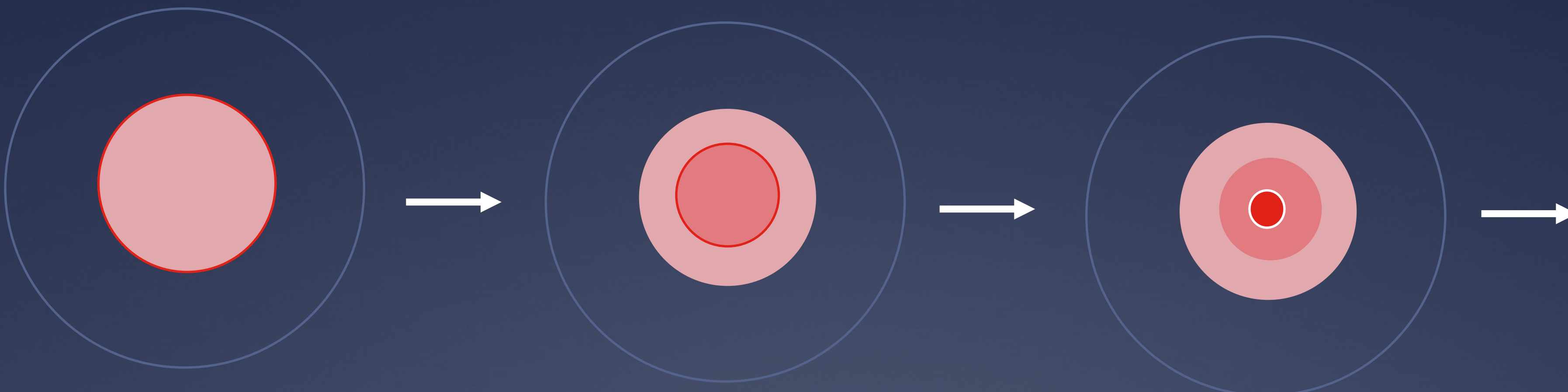


Evolution of (main sequence) stars and element production – Stars shine by (exothermic) nuclear reactions.



Temperature rise by gravity-driven adiabatic compression

ignites nuclear burning (reactions) in hot and dense gas.



Hydrogen “burns”. Helium “burns”. Carbon “burns”. …..

sun → $\sim 5\text{x}10^9$ y

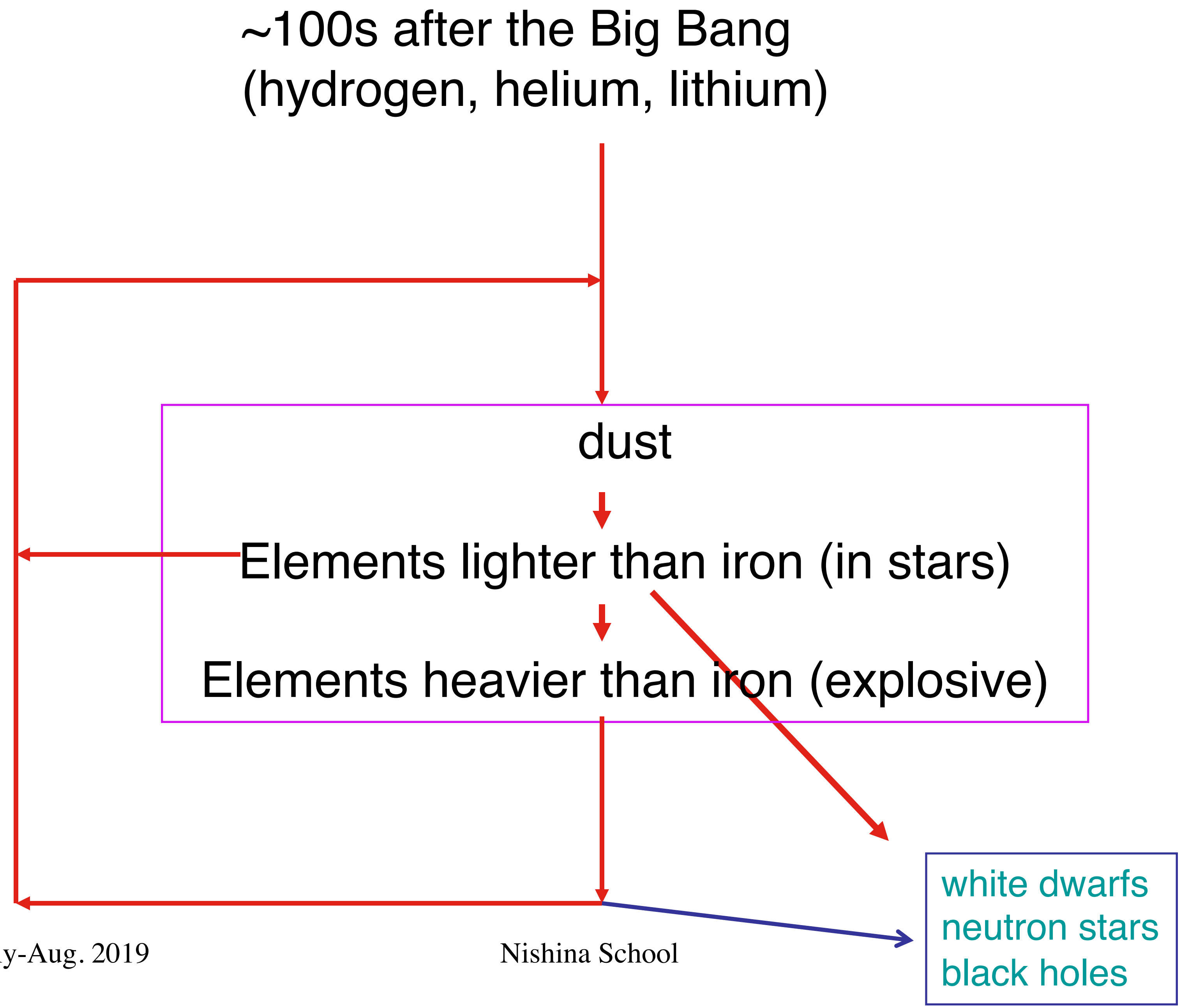
$kT \sim 1$ keV

Up to iron (Fe)

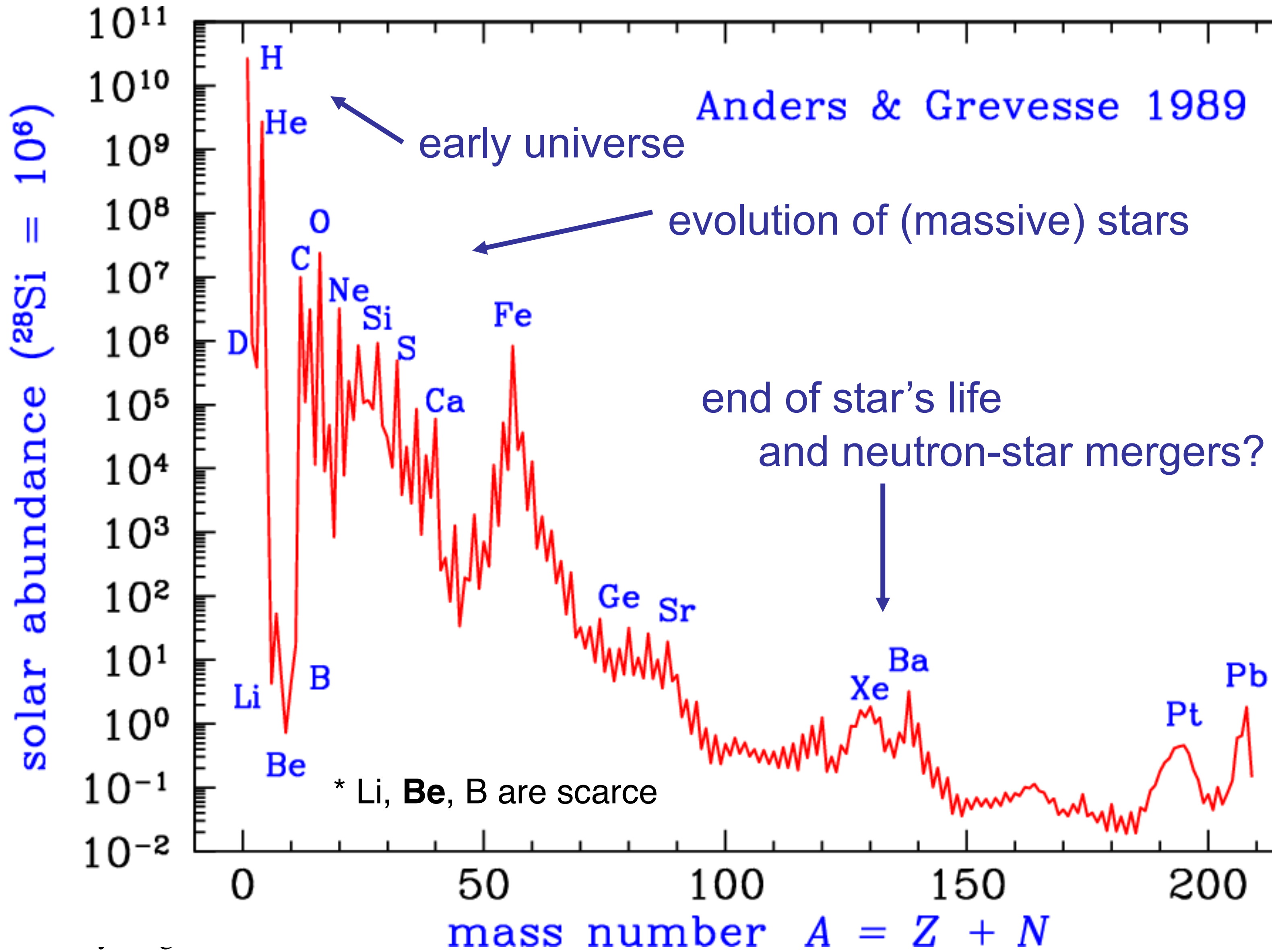
Balance between light radiation and gravity

Nuclei (instead of atoms or molecules) burn.

cycling of matter in the Universe



“solar (~universal) abundance"

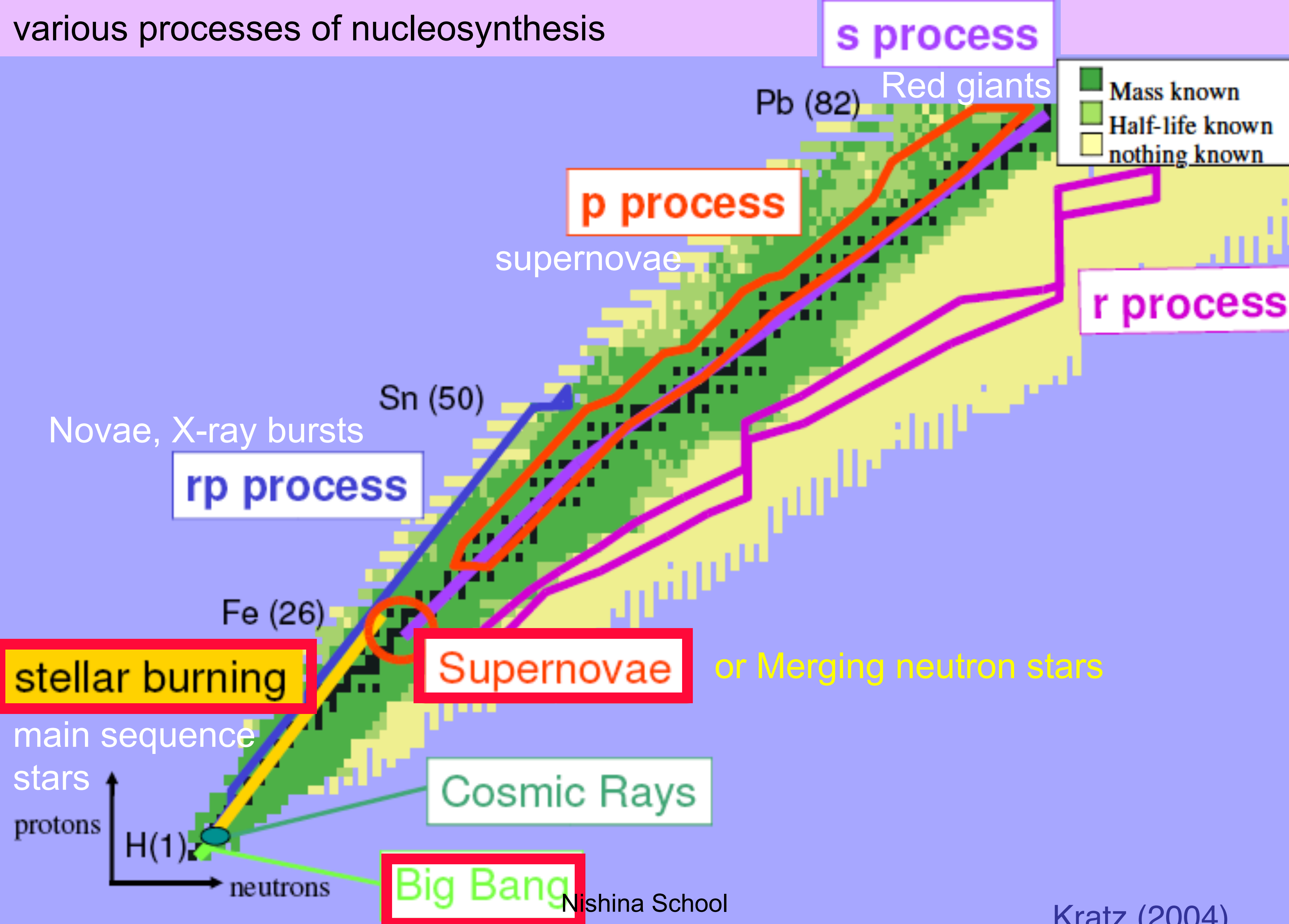


How?

How?

series of nuclear reactions and decays

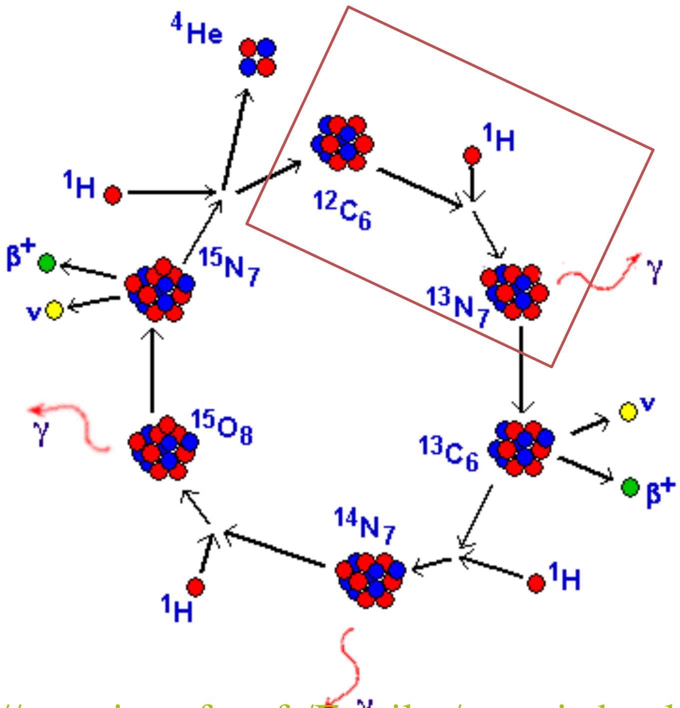
various processes of nucleosynthesis



Nishina School

Kratz (2004)

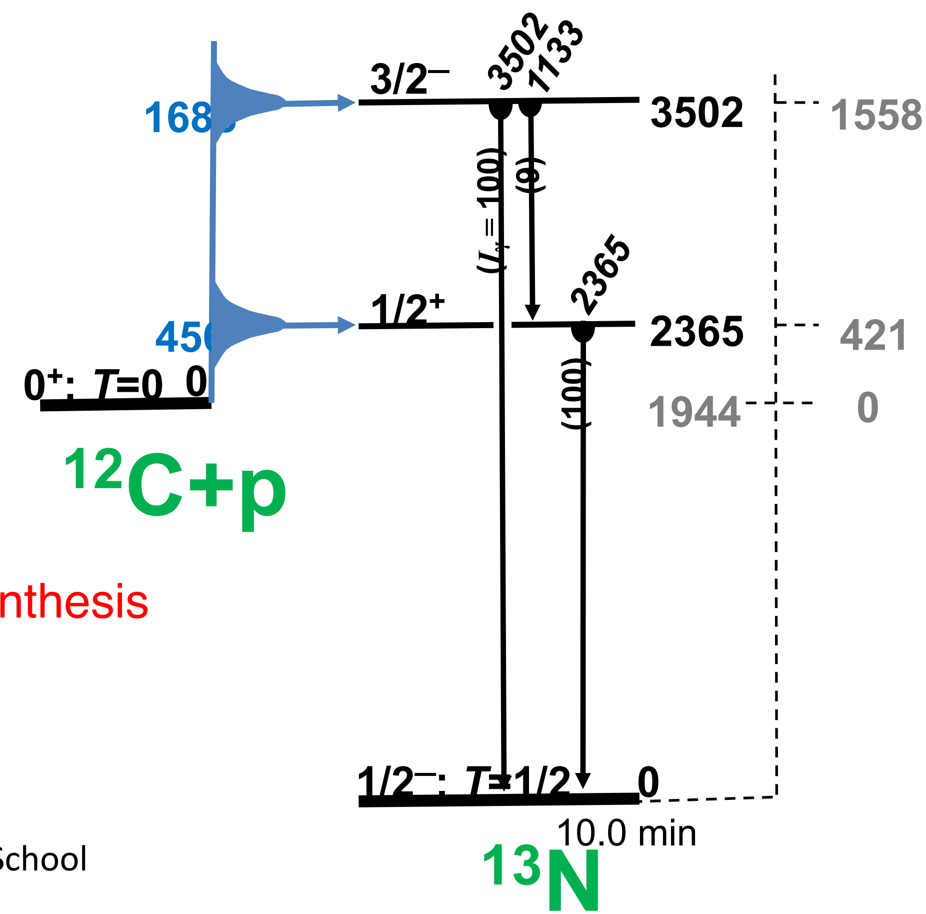
CNO cycle



http://nrumiano.free.fr/Fetoiles/energie.html

$^{12}C(p,\gamma)^{13}N$

$E(^{12}C+p) > E(^{13}N)$ -- exothermic

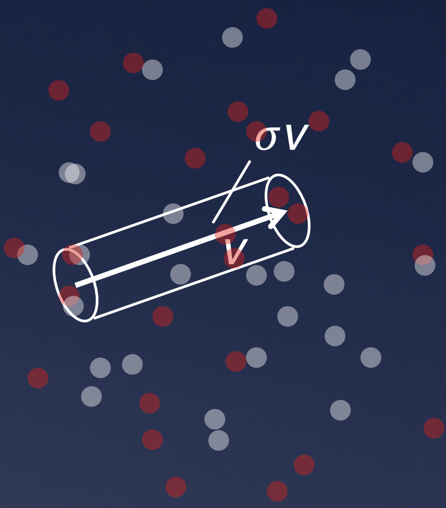


4 protons → 1 ^{4}He (+ γ, β^{+}, ν) - element synthesis
by 3(p,γ)s and 1(p,α)

Energy generation ~26 MeV

Number of reaction per unit time and unit volume

$$P_{12} = \rho_1 \rho_2 \langle \sigma v \rangle$$



in stars

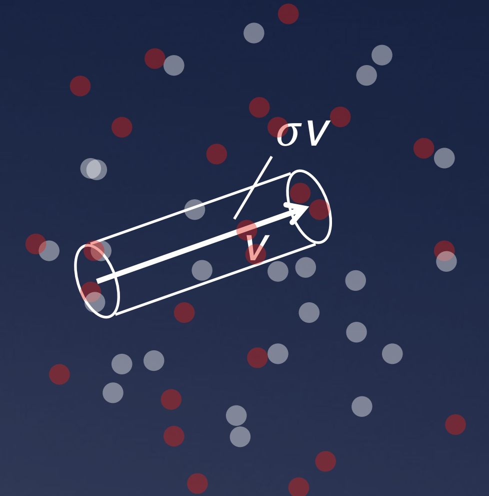
Hot and dense gas

σ: cross section (area of the imaginary circle in the figure)

Number of reaction per unit time and unit volume

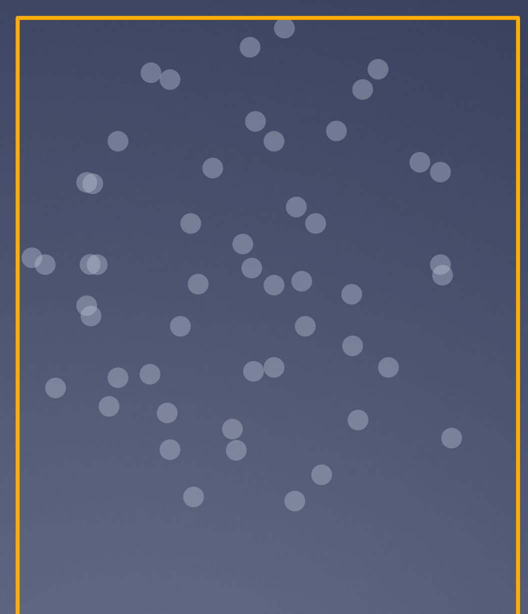
$$P_{12} = \rho_1 \rho_2 \langle \sigma v \rangle$$

in stars



Hot and dense gas

σ: cross section (area of the imaginary circle in the figure)



at laboratories

Reaction rate ← Maxwellian average of σ.

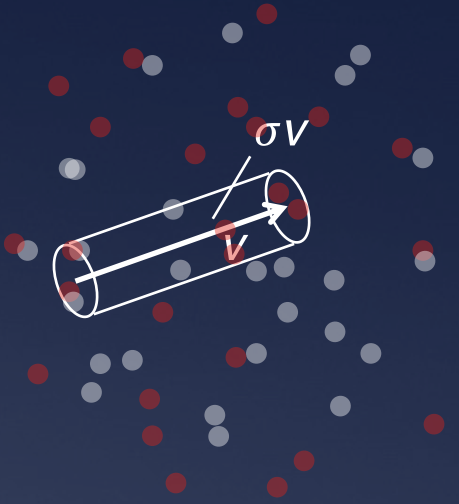
Number of reaction per unit time and unit volume

$$P_{12} = \rho_1 \rho_2 \langle \sigma v \rangle$$

Reaction rate

in stars

$$\langle \sigma v \rangle = \left(\frac{8}{\pi \mu_{12} (kT)^3} \right)^{1/2} \int dE \sigma(E) E \exp\left[-\frac{E}{kT} \right]$$



Hot and dense gas

Reaction rate ← Maxwellian average of σ.

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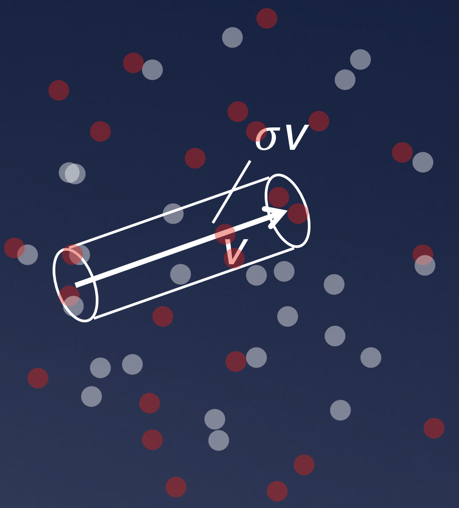


Hot and dense gas

Reaction rate

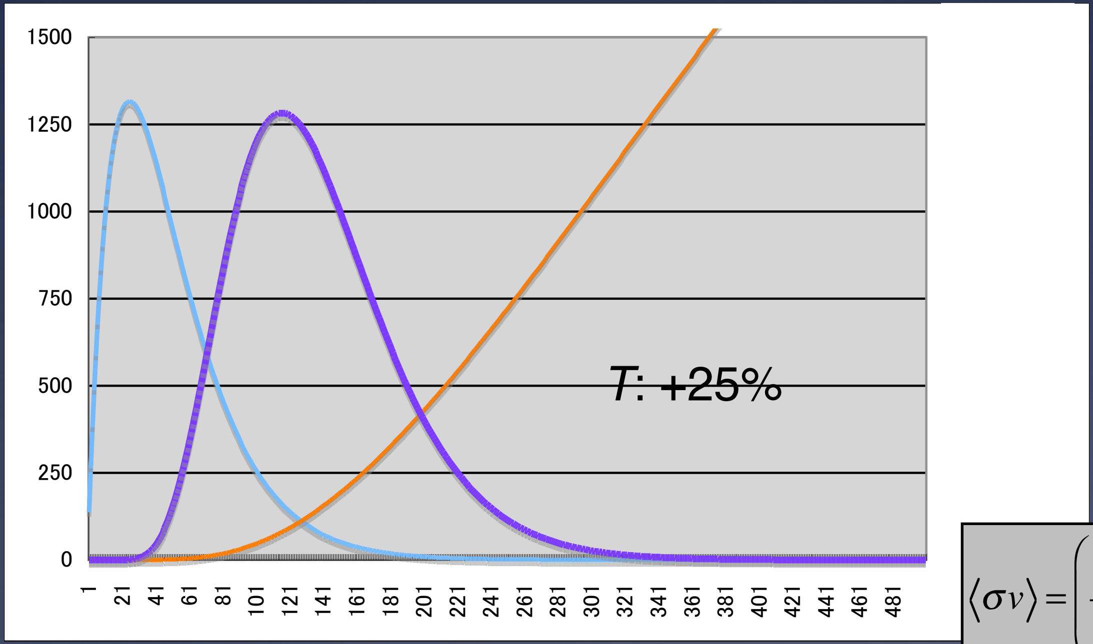
$$\langle \sigma v \rangle = \left(\frac{8}{\pi \mu_{12} (kT)^3} \right)^{1/2} \int dE \sigma(E) E \exp\left[-\frac{E}{kT} \right]$$

If you measure σ(*E*), you can calculate the reaction rate as a function of temperature.
Then ….

The most probable energy is higher than kT.

"Gamow peak"

Reaction rate <σv> depends strongly on *T*.



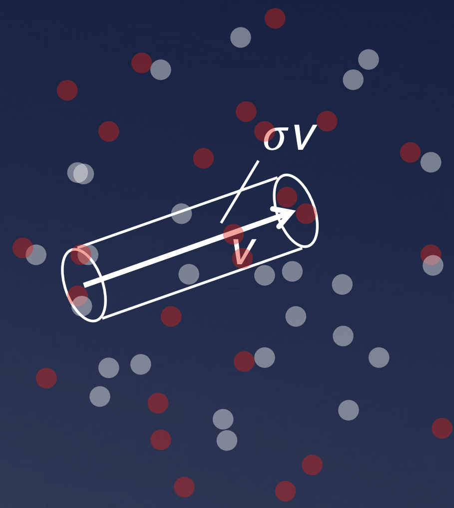
$$\langle \sigma v \rangle = \left(\frac{8}{\pi \mu_{12} (kT)^3} \right)^{1/2} \int dE \sigma(E) E \exp\left[-\frac{E}{kT} \right]$$

light blue: Maxwell-Boltzmann distribution
orange: cross section (direct or non-resonant)
purple: their product

Reaction rate ← Maxwellian average of σ.

Number of reaction per unit time and unit volume

$$P_{12} = \rho_1 \rho_2 \langle \sigma v \rangle$$



Hot and dense gas

Reaction rate

$$\langle \sigma v \rangle = \left(\frac{8}{\pi \mu_{12} (kT)^3} \right)^{1/2} \int dE \sigma(E) E \exp\left[-\frac{E}{kT} \right]$$

For charged particles: σ ← Coulomb penetration (tunnel effect)

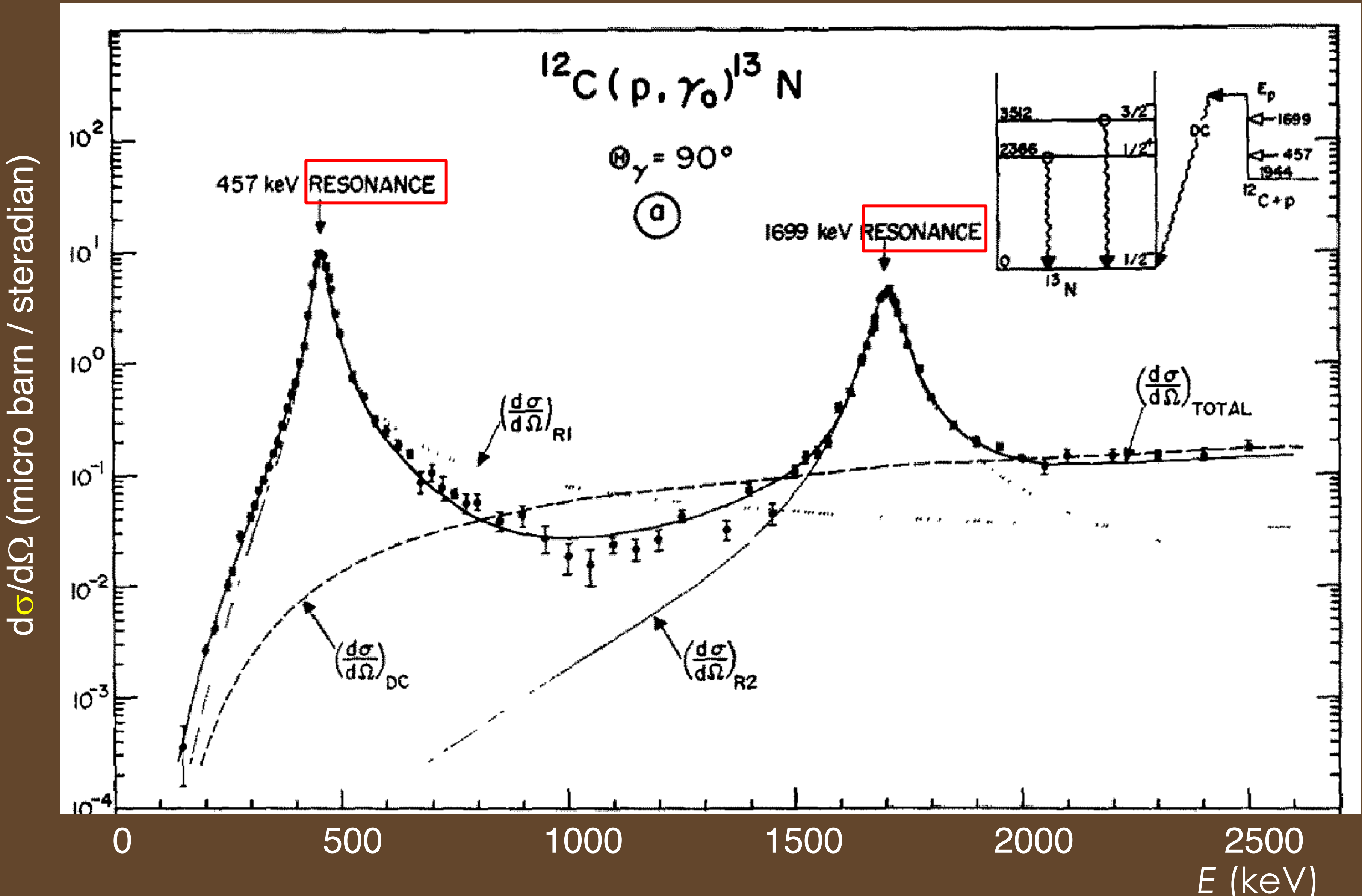
e.g.
$T = 1.5 \times 10^7$ K (sun) → kT = 1.3 keV (E_G = 20 keV)
much lower than the Coulomb barrier

astrophysical *S*-factor ~ constant *v.s.* *E*

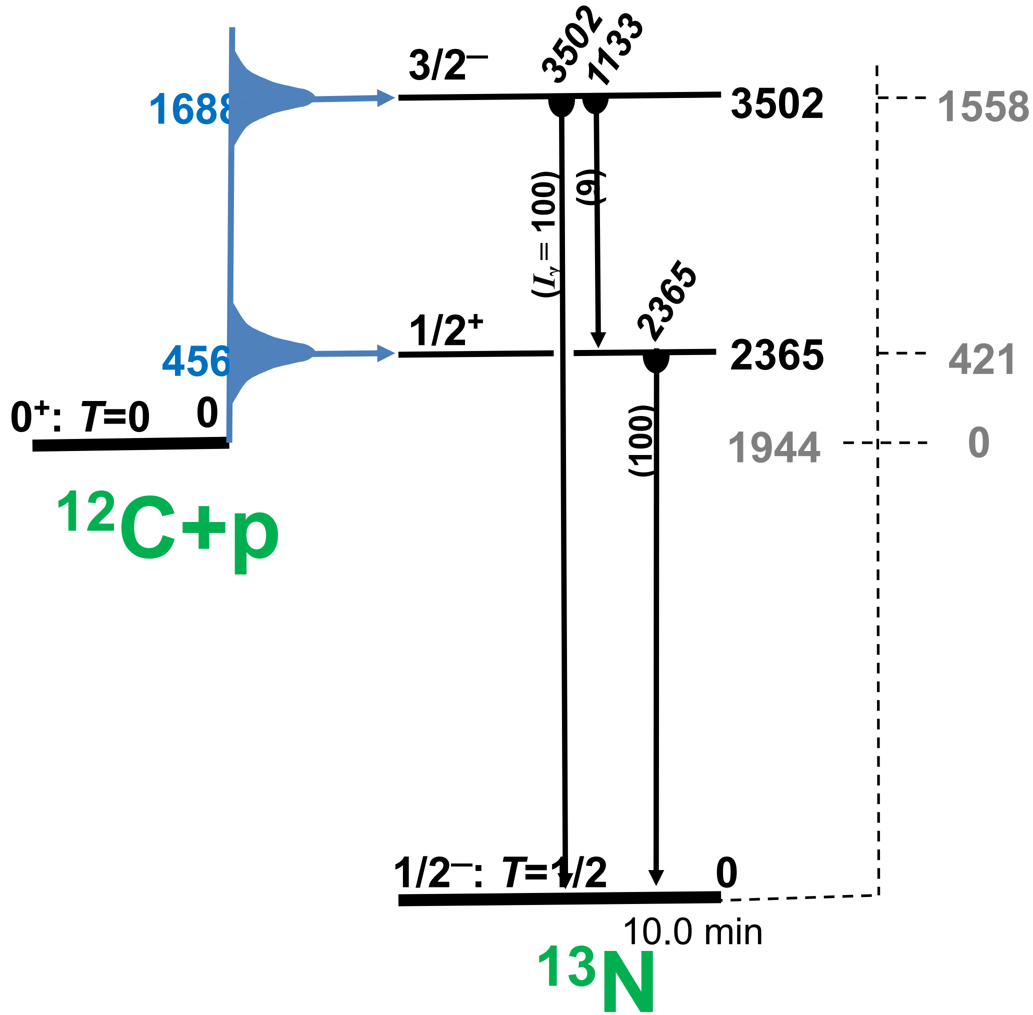
$$S = \sigma E \exp[2\pi\eta]$$

$$\eta = e^2 Z_1 Z_2 / \hbar v$$

Our experiment next week -- $^{12}C+p \rightarrow {}^{13}N+\gamma$



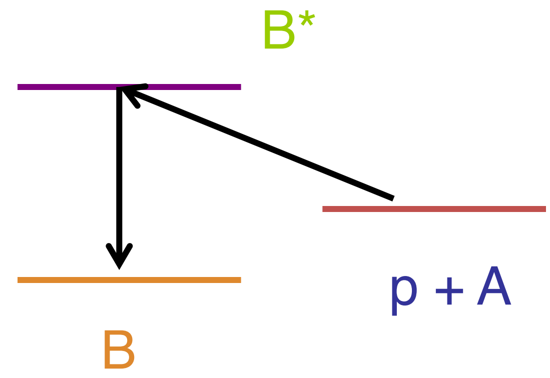
Rolfs and Azuma (1974)



1688
456
0⁺: T=0
0
12C+p
3/2⁻
3502
1133
3502
1558
(Iγ = 100)
(9)
1/2⁺
2365
2365
421
(100)
1944
0
1/2⁻: T=1/2
0
10.0 min
13N

Some basics for resonance

Breit-Wigner formula for an isolated resonance



p + A => B* => γ + B

$$\sigma_{(\mathrm{p},\gamma)} = \pi \lambda\!\!\!^{-}{}^2 \omega \frac{\Gamma_\mathrm{p} \Gamma_\gamma}{(E - E_0)^2 + \frac{1}{4}\Gamma^2}$$

$$=> \ 4\pi \lambda\!\!\!^{-}{}^2 \omega \frac{\Gamma_\mathrm{p} \Gamma_\gamma}{\Gamma^2} \qquad \text{at } E = E_0$$

$$\approx 4\pi \lambda\!\!\!^{-}{}^2 \omega \frac{\Gamma_\gamma}{\Gamma} \qquad \text{if } \Gamma_\mathrm{p} \approx \Gamma >> \Gamma_\gamma$$

ω : spin factor

$$\omega = \frac{2I_{B*} + 1}{(2I_\mathrm{p} + 1)(2I_\mathrm{A} + 1)} = \frac{2I_{B*} + 1}{2(2I_\mathrm{A} + 1)}$$

reaction rate ~ $\sigma_{max}\Gamma <= \Gamma_\gamma$

reaction rate for a process through a resonance

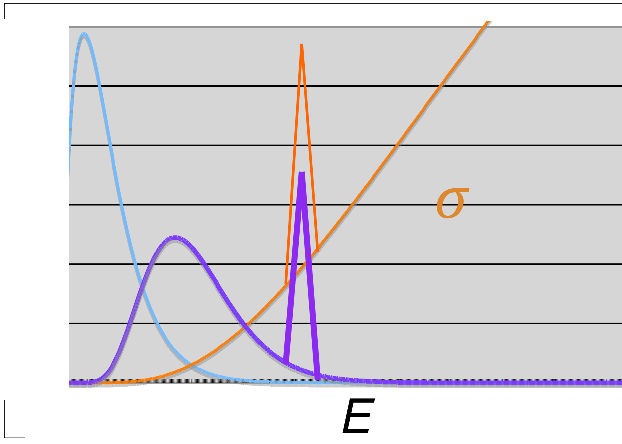
$$\sigma_{(\mathrm{p},\gamma)} \approx 4\pi\lambda\!\!\!^{-2}\omega\frac{\Gamma_\gamma}{\Gamma} \quad \text{at } E = E_0 \quad \text{if } \Gamma_\mathrm{p} \approx \Gamma >> \Gamma_\gamma$$

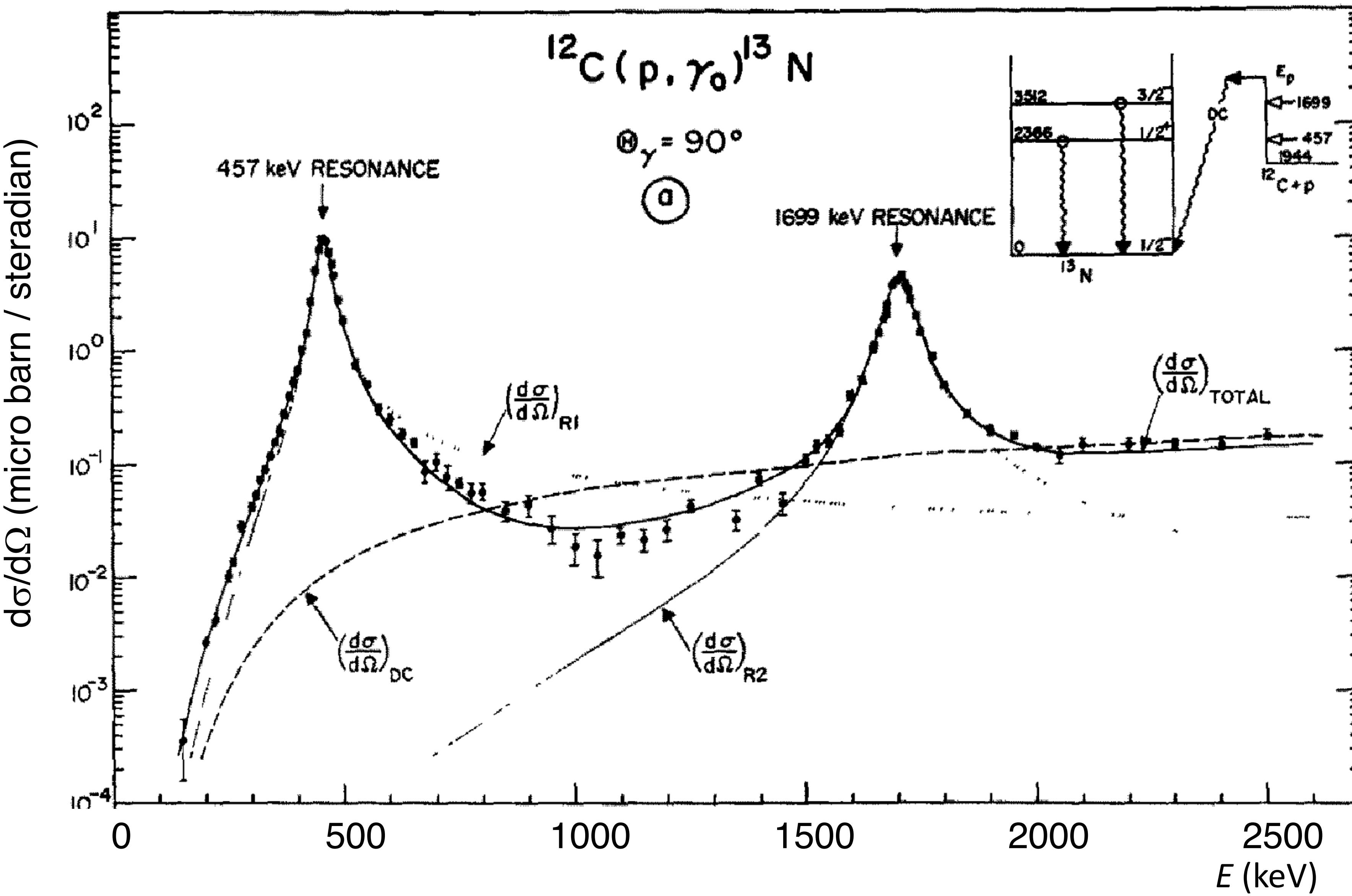
$$\langle\sigma v\rangle = \left(\frac{8}{\pi\mu_{12}(kT)^3}\right)^{1/2}\int dE\sigma(E)E\exp\left[-\frac{E}{kT}\right]$$

If the width Γ is narrow,

$$\langle\sigma v\rangle \propto E_0(kT)^{-3/2}\exp\left[-\frac{E_0}{kT}\right]\pi\lambda\!\!\!^{-2}\omega\int dE\frac{\Gamma_\mathrm{p}\Gamma_\gamma}{(E-E_0)^2+\frac{1}{4}\Gamma^2}$$

$$\propto \omega\Gamma_\gamma(kT)^{-3/2}\exp\left[-\frac{E_0}{kT}\right]$$





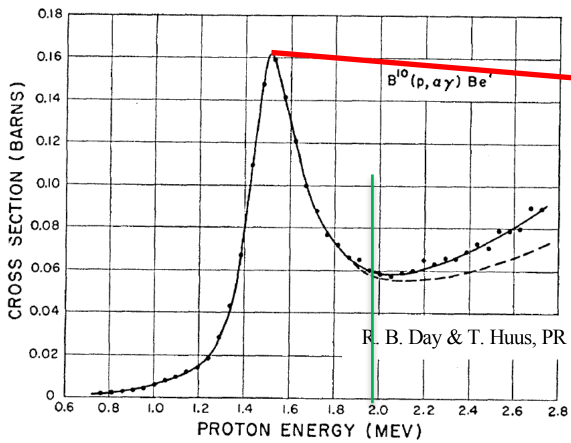
Rolfs and Azuma (1974)

$^{10}B(p,\alpha)^{7}Be$ reaction

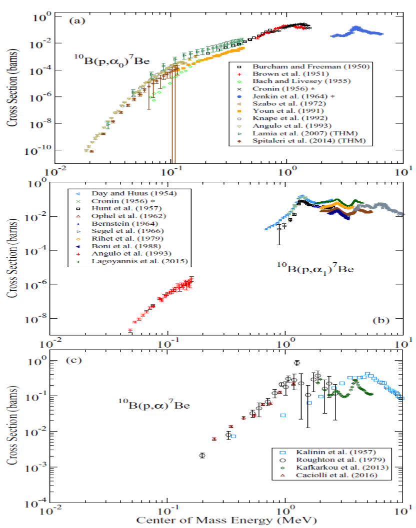
It "destroys" scarce boron. (nucleosynthesis)

It possibly contributes to
$^{11}B+p$ ($\rightarrow 3\alpha$) fusion (energy production)

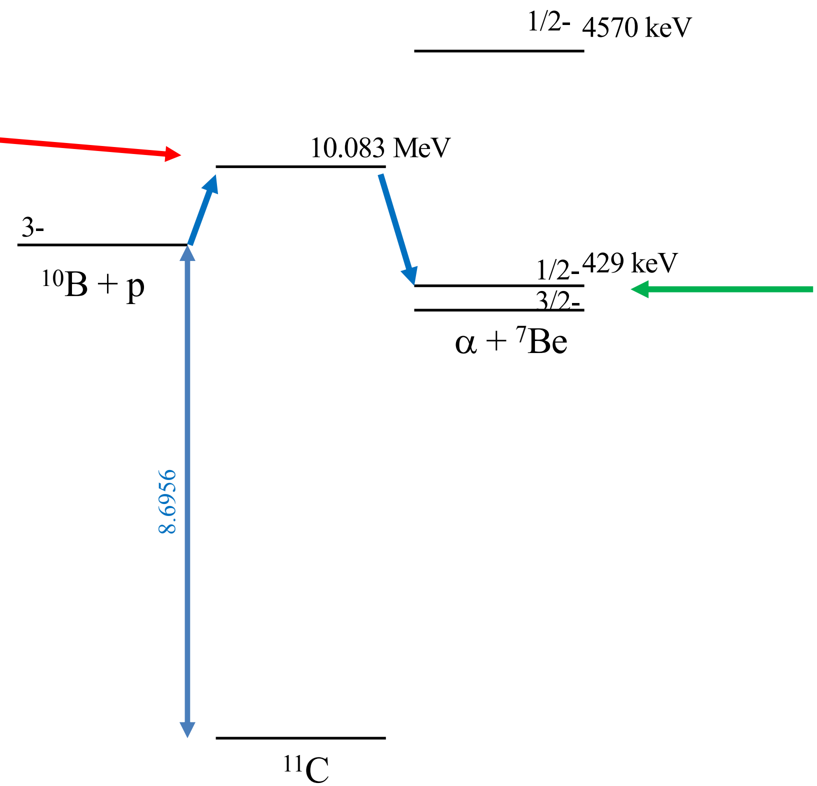
$^{10}B(p, \alpha)^{7}Be$



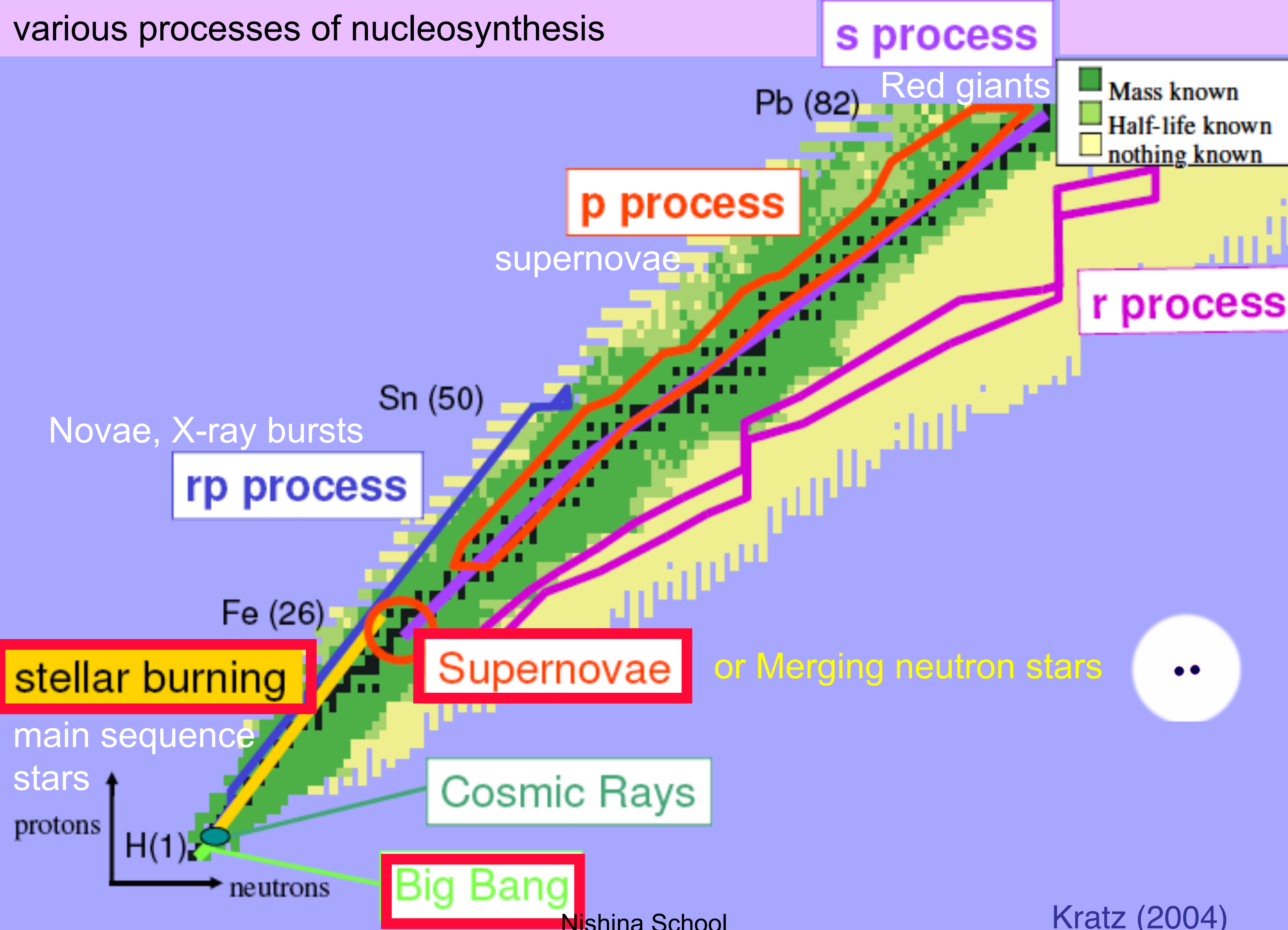
R. B. Day & T. Huus, PR 95(1954)1003



M. Wiescher, et al.,
PRC 95 (2017)044617.



various processes of nucleosynthesis



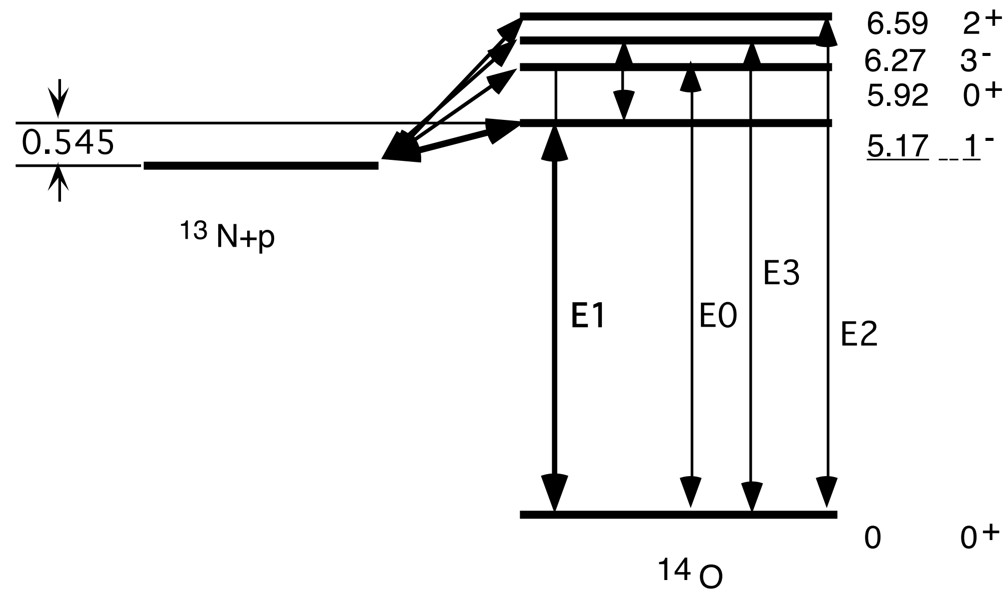
Kratz (2004)

In addition …

$^{13}N(p,\gamma)^{14}O$ – CNO *v.s.* hot CNO   first data ~1991   (RIKEN / Louvain la Neuve)

In hot CNO cycle,
^{13}C is bypassed.
faster cycle.

^{14}O: $t_{1/2}$ = 1min.

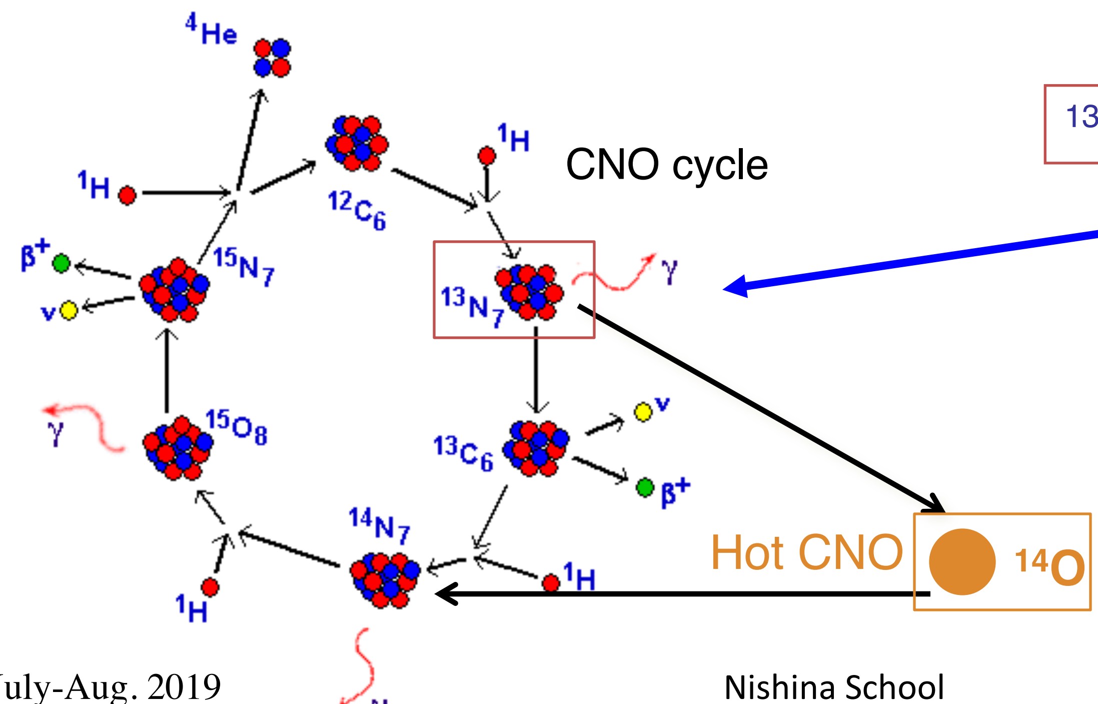


^{13}N: $t_{1/2}$ = 10min.

$^{13}N+p \rightarrow {}^{14}O+\gamma$

$\downarrow \beta^+$

^{13}C



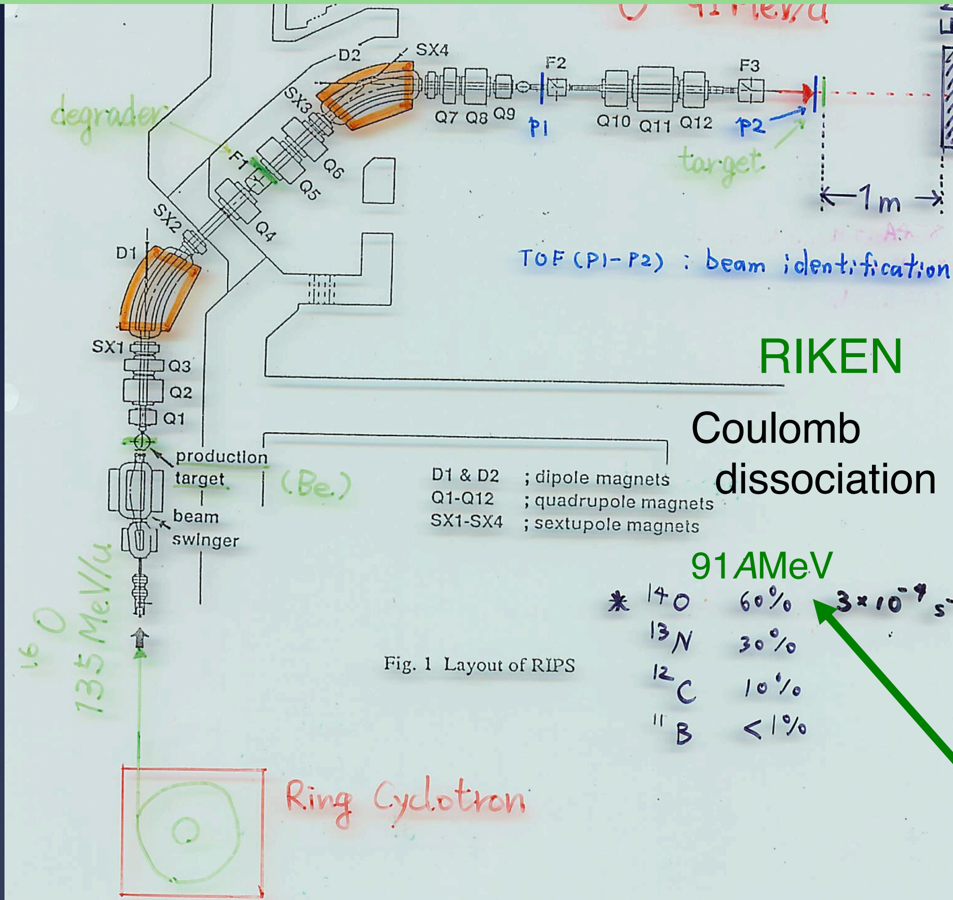
http://nrumiano.free.fr/Fetoiles/energie.html

Two early experiments with RI beams are for the astrophysical reaction $^{13}N(p,\gamma)^{14}O$

Direct measurement

$^{13}N + ^{1}H \rightarrow ^{14}O + \gamma$

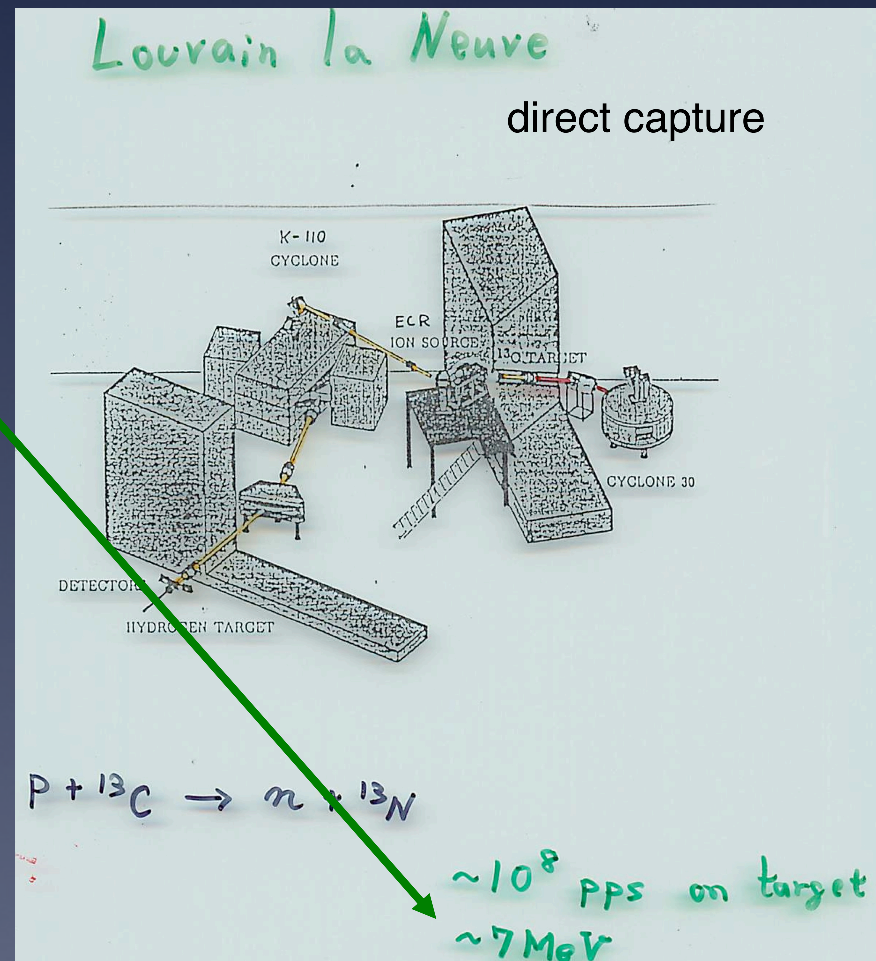
Louvain la Neuve



RIKEN

Coulomb dissociation

91 *A*MeV



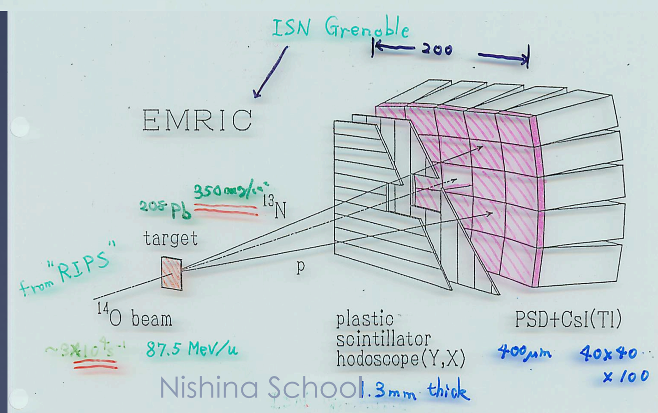
direct capture

Coulmob dissociation

^{14}O+Pb

$\rightarrow ^{13}N$+p+Pb

RIKEN



Results by direct capture / Coulomb dissociation agree. ➔CNO-hot CNO boundary

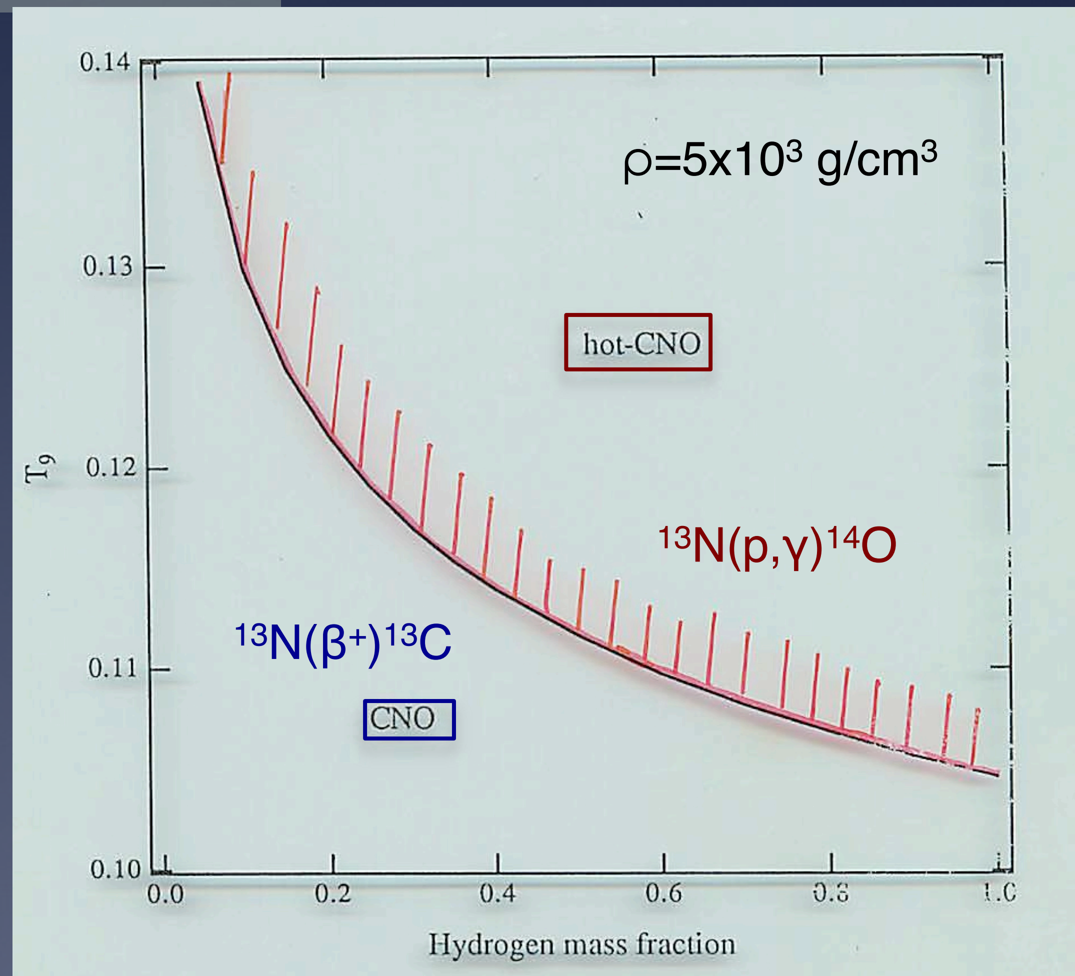
Γ_γ	present	(p,γ)
$^{14}O\ (1^-)$	3.1 ± 0.6 eV	$(3.8 \pm 1.2)^*$ (3.2) 3.4 ± 0.9
$^{13}N\ (1/2^+)$	0.59 ± 0.18 eV	$0.50 \pm 0.04^*$ eV

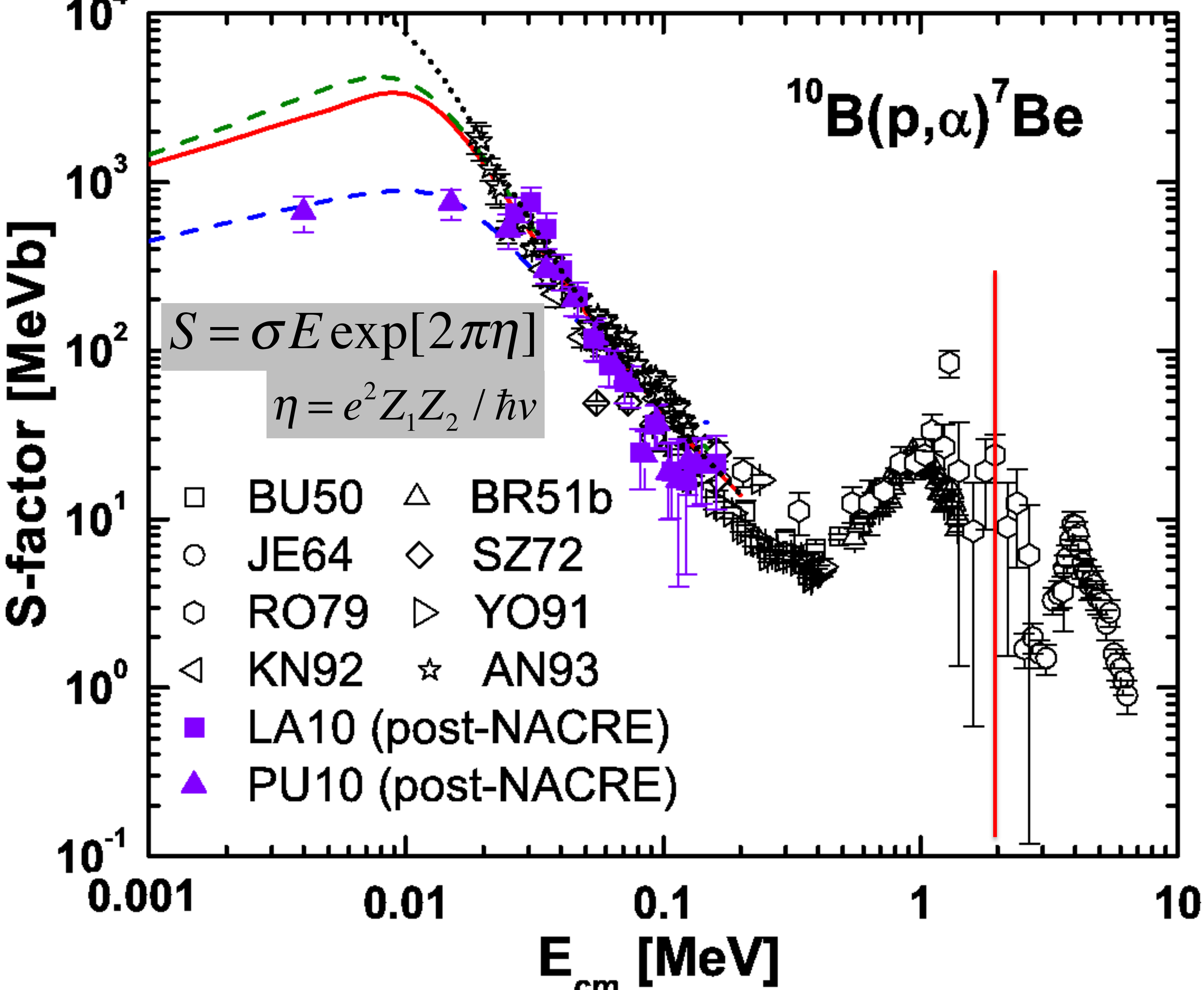
$^{12}C(p,\gamma)^{13}N$

reaction rate ← $\omega\Gamma_\gamma$、E_0

$$\langle \sigma v \rangle \propto \omega\Gamma_\gamma (kT)^{-3/2} \exp\left[-\frac{E_0}{kT}\right]$$

$$P_{12} = \rho_1 \rho_2 \langle \sigma v \rangle$$





$^{10}B(p,\alpha)^7Be$
$S = \sigma E \exp[2\pi\eta]$
$\eta = e^2 Z_1 Z_2 / \hbar v$
BU50
BR51b
JE64
SZ72
RO79
YO91
KN92
AN93
LA10 (post-NACRE)
PU10 (post-NACRE)
S-factor [MeVb]
E_{cm} [MeV]
10^4
10^3
10^2
10^1
10^0
10^{-1}
0.001
0.01
0.1
1
10