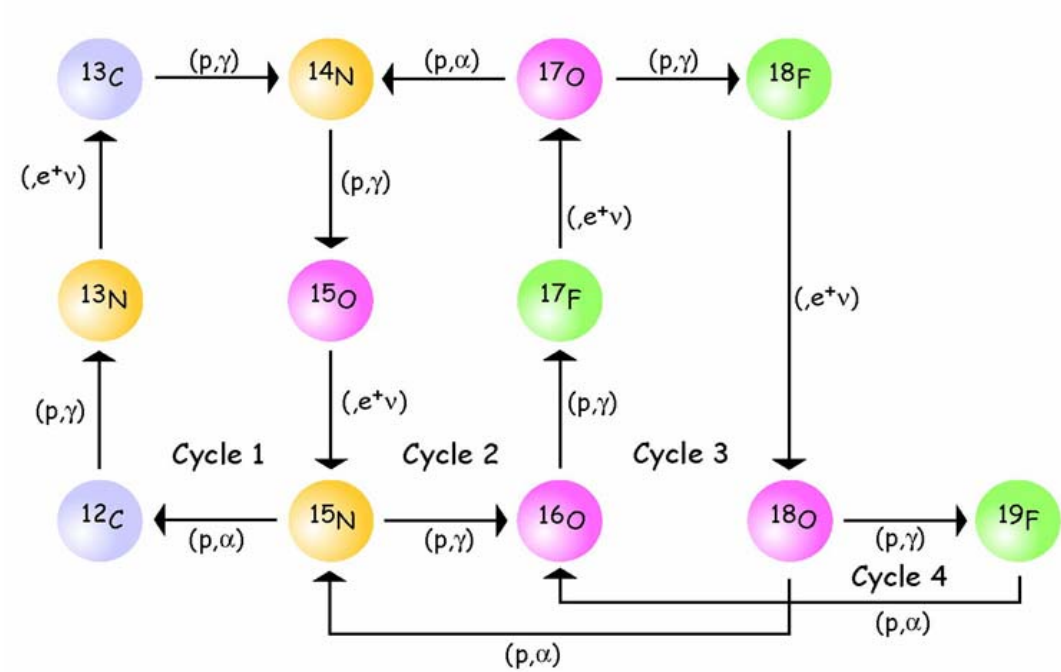
Hydrogen Burning in Stars-II

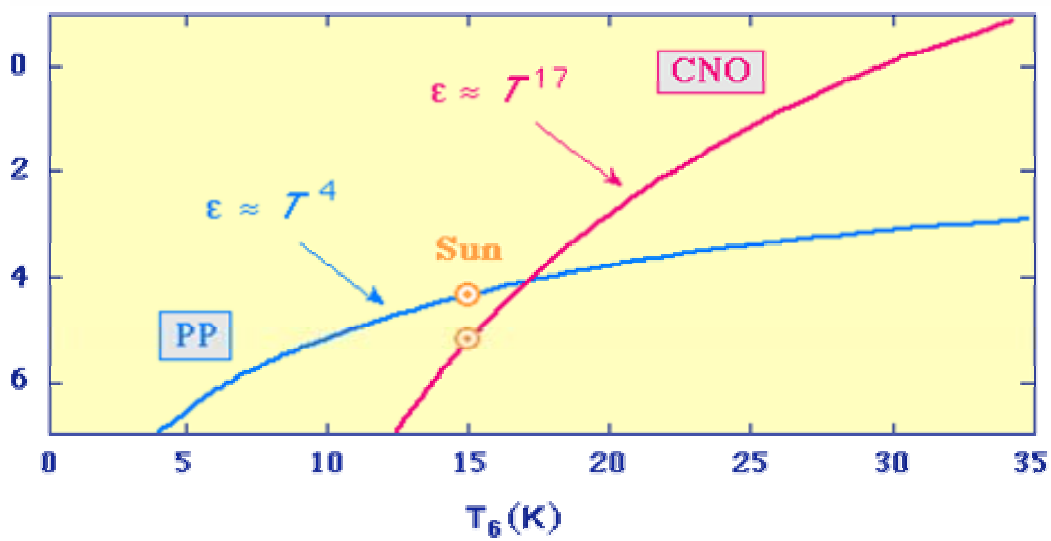
Hydrogen in induced reaction have lowest Coulomb barrier $\Rightarrow$ highest reaction rate

Reaction chain with lowest Z elements are the pp-chains
pp-chains limited by weak interaction based pp-reaction
Take over of hydrogen burning at higher Z C,N,O elements
CNO cycles, governed by electromagnetic and strong interaction based reaction cross sections.

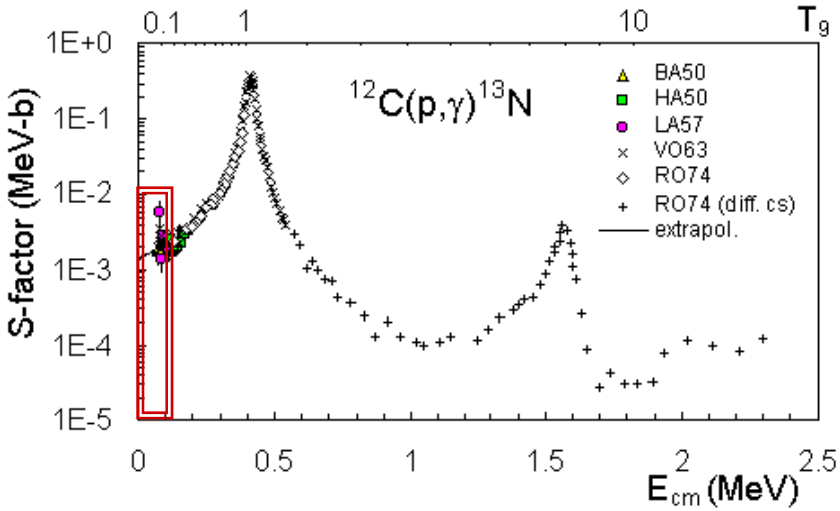
CNO burning stars are the stars on the upper part of the "Main Sequence" in the HR Diagram!

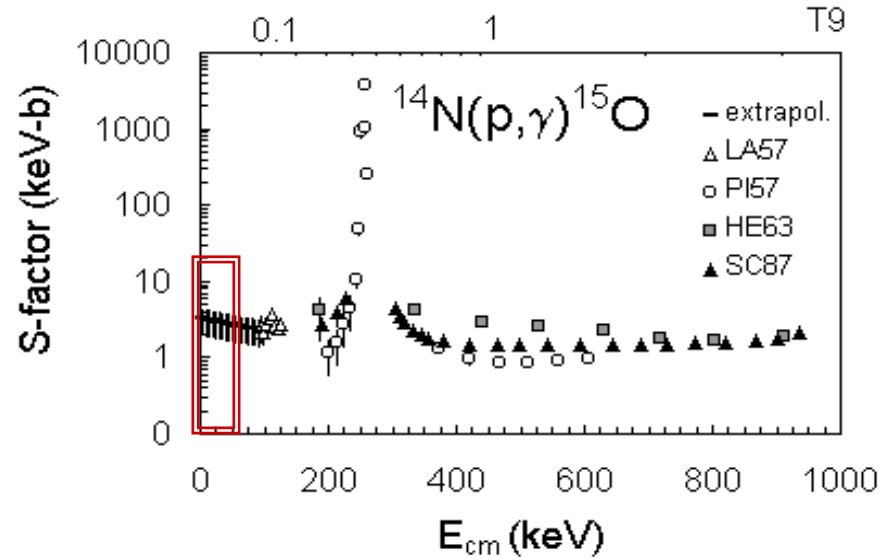
Hydrogen Burning in Massive Stars

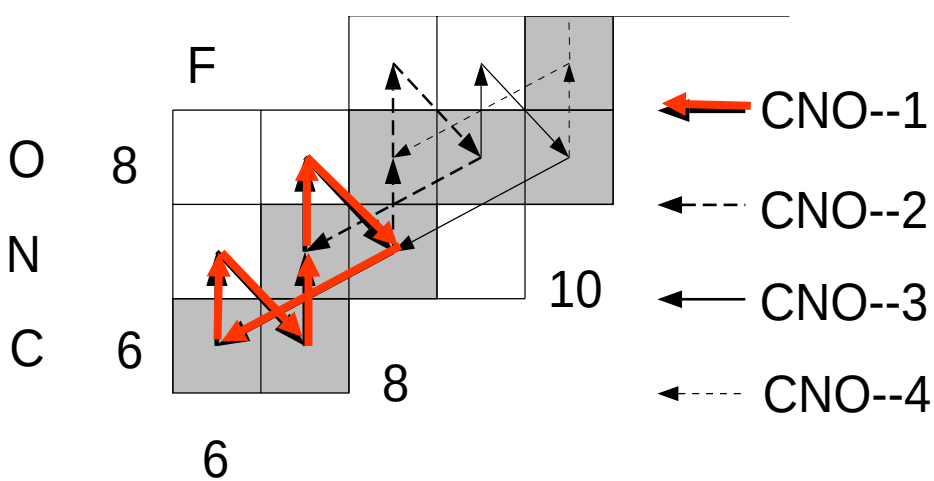


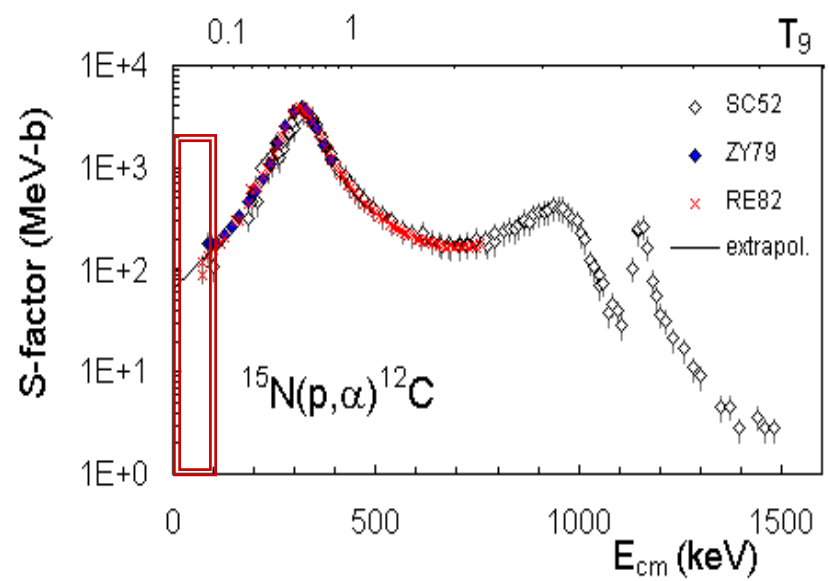


The main CNO cycle









Reactions in the CNO cycles

CNO-1:	$^{12}C(p,\gamma)^{13}N$	$S_{12C(p,\gamma)}=3\ 10^{-3}$ MeV-barn
	$^{13}N(\beta+\nu)^{13}C$	
	$^{13}C(p,\gamma)^{14}N$	
	$^{14}N(p,\gamma)^{15}O$	$S_{14N(p,\gamma)}=2\ 10^{-3}$ MeV-barn
	$^{15}O(\beta+\nu)^{15}N$	
	$^{15}N(p,\alpha)^{12}C$	$S_{15N(p,\alpha)}=1\ 10^{+2}$ MeV-barn
CNO-2:	$^{15}N(p,\gamma)^{16}O$	$S_{15N(p,\gamma)}=5\ 10^{-2}$ MeV-barn
	$^{16}O(p,\gamma)^{17}F$	
	$^{17}F(\beta^{+}\nu)^{17}O$	
	$^{17}O(p,\alpha)^{14}N$	
CNO-3:	$^{17}O(p,\gamma)^{18}F$	
	$^{18}F(\beta^{+}\nu)^{18}O$	
	$^{18}O(p,\alpha)^{15}N$	$\Rightarrow$ CNO-4

Network for CN cycle

$$\frac{dY_{^{12}C}}{dt} = -Y_{^{12}C} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{12}C(p,\gamma)} + Y_{^{15}N} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{15}N(p,\alpha)}$$

$$\frac{dY_{^{13}N}}{dt} = -Y_{^{13}N} \cdot \lambda_{^{13}N(\beta^+)} + Y_{^{12}C} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{12}C(p,\gamma)}$$

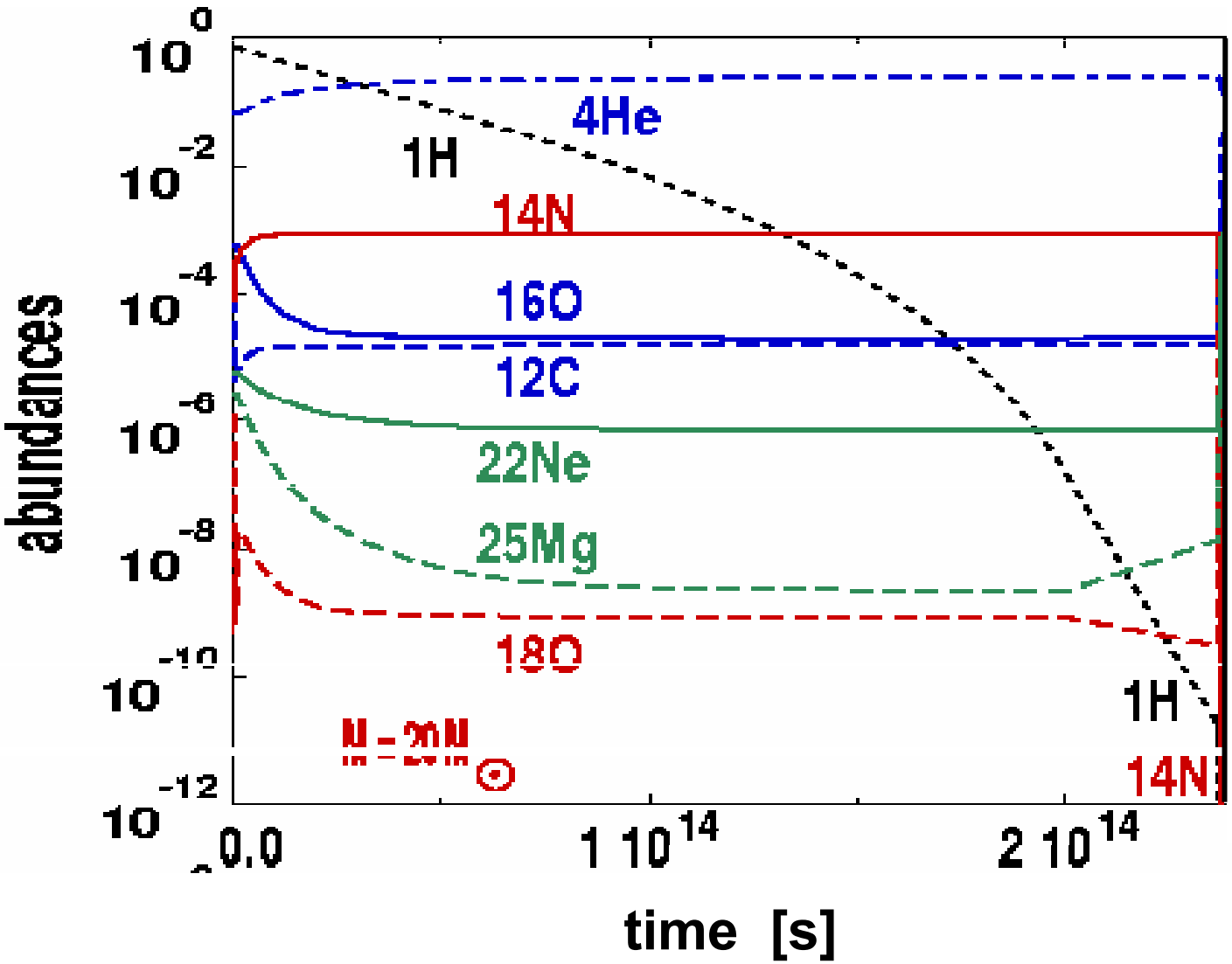
$$\frac{dY_{^{13}C}}{dt} = -Y_{^{13}C} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{13}C(p,\gamma)} + Y_{^{13}N} \cdot \lambda_{^{13}N(\beta^+)}$$

$$\frac{dY_{^{14}N}}{dt} = -Y_{^{14}N} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{14}N(p,\gamma)} + Y_{^{13}C} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{13}C(p,\gamma)}$$

$$\frac{dY_{^{15}O}}{dt} = -Y_{^{15}O} \cdot \lambda_{^{15}O(\beta^+)} + Y_{^{14}N} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{14}N(p,\gamma)}$$

$$\frac{dY_{^{15}N}}{dt} = -Y_{^{15}N} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{15}N(p,\alpha)} + Y_{^{15}O} \cdot \lambda_{^{15}O(\beta^+)}$$

Reaction network of CNO



Conversion of the initial

- ^{1}H to ^{4}He
- ^{12}C, ^{16}O to ^{14}N

Network for higher order CNOs

CNO-II

$$\frac{dY_{^{16}O}}{dt} = -Y_{^{16}O} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{16}O(p,\gamma)} + Y_{^{15}N} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{15}N(p,\gamma)} \left[+ Y_{^{19}F} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{19}F(p,\alpha)} \right]$$

$$\frac{dY_{^{17}F}}{dt} = -Y_{^{17}F} \cdot \lambda_{^{17}F(\beta^+)} + Y_{^{16}O} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{16}O(p,\gamma)}$$

$$\frac{dY_{^{17}O}}{dt} = -Y_{^{17}O} \cdot Y_{^{1}H} \cdot \rho \cdot \left(N_A \langle \sigma \upsilon \rangle_{^{17}O(p,\alpha)} + \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{17}O(p,\gamma)} \right) + Y_{^{17}F} \cdot \lambda_{^{17}F(\beta^+)}$$

mod. CNO-I

$$\frac{dY_{^{14}N}}{dt} = -Y_{^{14}N} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{14}N(p,\gamma)} + Y_{^{13}C} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{13}C(p,\gamma)} + Y_{^{17}O} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{17}O(p,\alpha)}$$

$$\frac{dY_{^{15}O}}{dt} = -Y_{^{15}O} \cdot \lambda_{^{15}O(\beta^+)} + Y_{^{14}N} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{14}N(p,\gamma)}$$

$$\frac{dY_{^{15}N}}{dt} = -Y_{^{15}N} \cdot Y_{^{1}H} \cdot \rho \cdot \left(N_A \langle \sigma \upsilon \rangle_{^{15}N(p,\alpha)} + N_A \langle \sigma \upsilon \rangle_{^{15}N(p,\gamma)} \right) + Y_{^{15}O} \cdot \lambda_{^{15}O(\beta^+)} \left[+ Y_{^{18}O} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{18}O(p,\alpha)} \right]$$

CNO-III

$$\frac{dY_{^{18}F}}{dt} = -Y_{^{18}F} \cdot \lambda_{^{18}F(\beta^+)} + Y_{^{17}O} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{17}O(p,\gamma)}$$

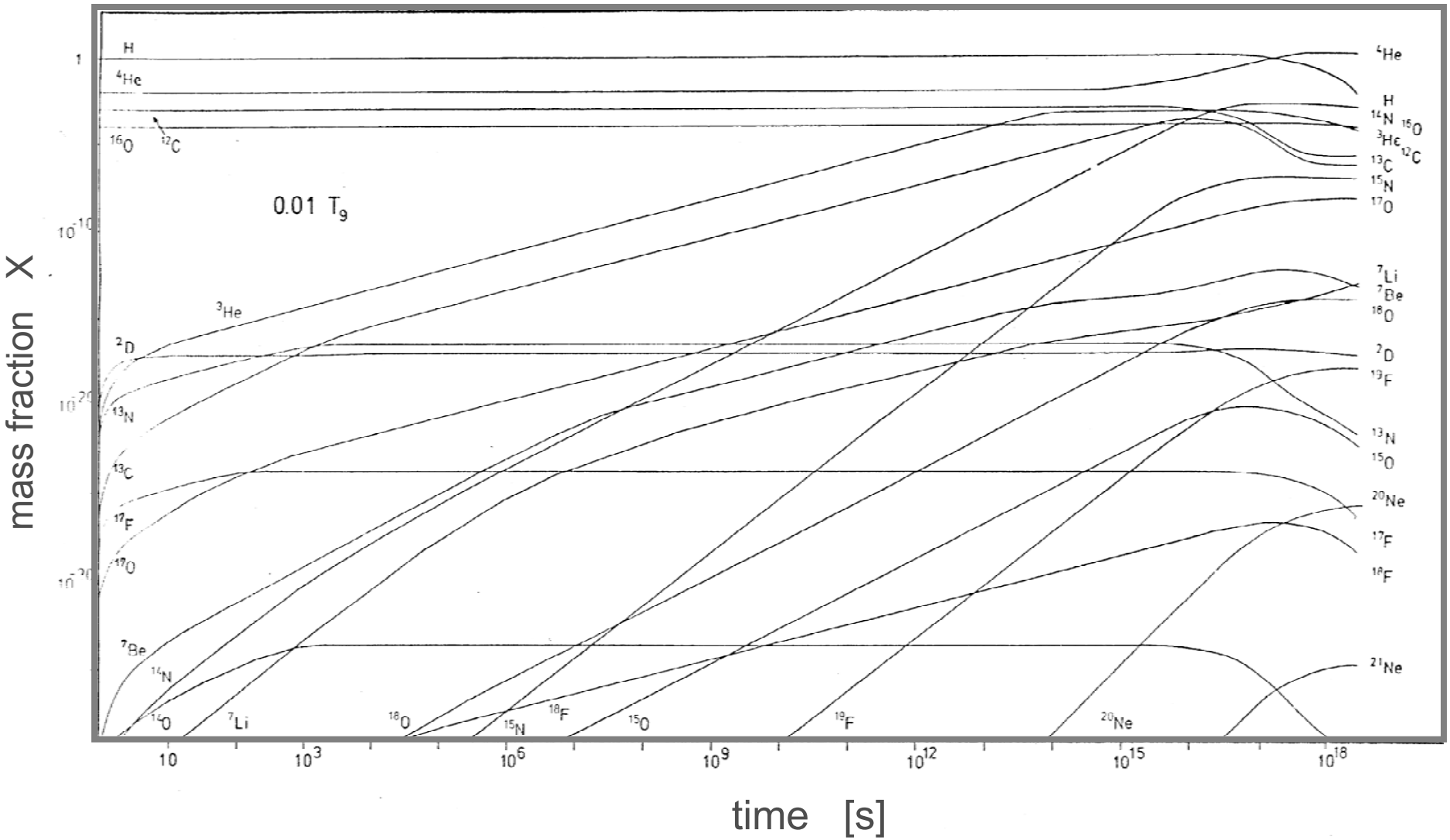
$$\frac{dY_{^{18}O}}{dt} = -Y_{^{18}O} \cdot Y_{^{1}H} \cdot \rho \cdot \left(N_A \langle \sigma \upsilon \rangle_{^{18}O(p,\alpha)} + N_A \langle \sigma \upsilon \rangle_{^{18}O(p,\gamma)} \right) + Y_{^{18}F} \cdot \lambda_{^{18}F(\beta^+)}$$

CNO-IV

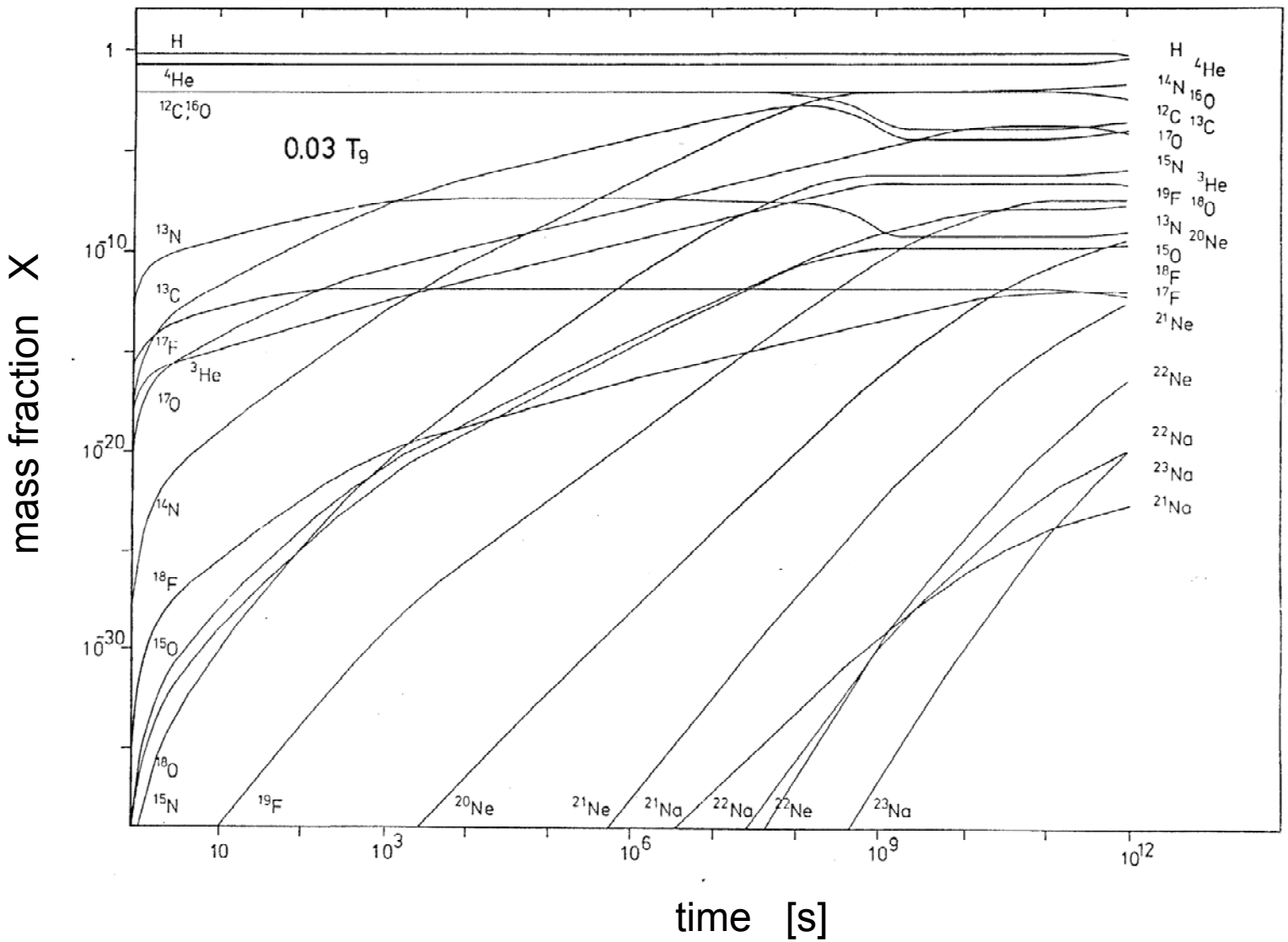
$$\frac{dY_{^{19}F}}{dt} = -Y_{^{19}F} \cdot Y_{^{1}H} \cdot \rho \cdot \left(N_A \langle \sigma \upsilon \rangle_{^{19}F(p,\alpha)} \right) + Y_{^{18}O} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{18}O(p,\gamma)}$$

CNO leakage

Network simulations at low temperature conditions of 10^7 K



Network simulation for Hydrogen burning at $3 \cdot 10^7$ K



Resonance measurements

Reaction rates in CNO cycle reactions have considerable cross section contributions from low energy resonances. Resonance cross section is determined by Breit-Wigner function ⇒ strong energy dependence of cross section!!!

$$\sigma(E) = \pi \lambda\!\!\!^{-2}\, \omega \cdot \frac{\Gamma_{in} \cdot \Gamma_{ex}}{\left((E - E_R)^2 + \left(\frac{\Gamma_{tot}}{2} \right)^2 \right)}$$

if the energy dependence of λ, Δ, ε, $\Gamma_{in/ex}$ is negligible over width Γ of resonance and **if $\Delta \ll \Gamma$** !!!

$$Y(E_0) = \int_{E-\Delta E}^{E} \frac{\sigma(E)}{\varepsilon(E)} dE = \frac{\lambda^2}{2\pi} \omega\gamma \frac{M+m}{M} \frac{1}{\varepsilon(E_0)} \left[\tan^{-1}\left(\frac{E_0 - E_R}{\Gamma/2} \right) - \tan^{-1}\left(\frac{E_0 - E_R - \Delta E}{\Gamma/2} \right) \right]$$

$$Y_{\max}(E_0) = \frac{\lambda^2}{2\pi} \omega\gamma \frac{M+m}{M} \frac{1}{\varepsilon(E_0)}$$

if $\Delta \gg \Gamma$

Yield measurement gives resonance strength!

Resonant Reaction Rate

$$N_A\langle\sigma v\rangle = 1.54\cdot 10^{11}\cdot\omega\gamma\,[MeV]\cdot\left(\frac{1}{\mu\cdot T_9}\right)^{3/2}\cdot e^{-\left(\frac{11.605\cdot E_R[MeV]}{T_9}\right)}$$

$$\omega\gamma = \frac{2\pi}{\lambda^2}\frac{M}{M+m}\varepsilon(E)\cdot Y_{\max}(E)$$

An exact measurement of the resonance energy E_R and the thick-target yield $Y_{max}(E)$ provides the necessary information for calculating the resonant reaction rate $N_A\langle\sigma\nu\rangle$!

Thick target Yield Curve

Yield Y

1/2·Y
⇒ E_R

δE beam
resolution

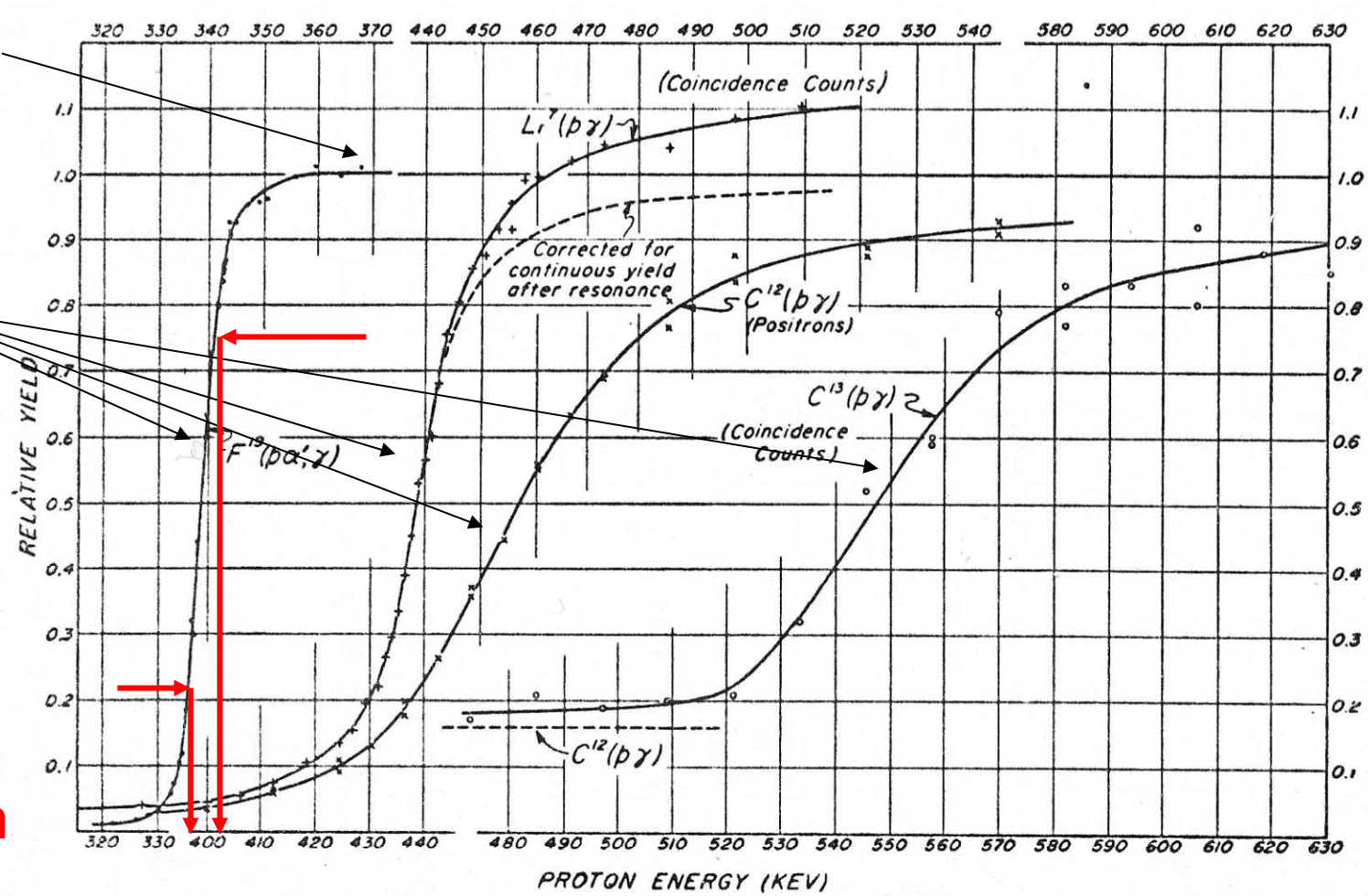
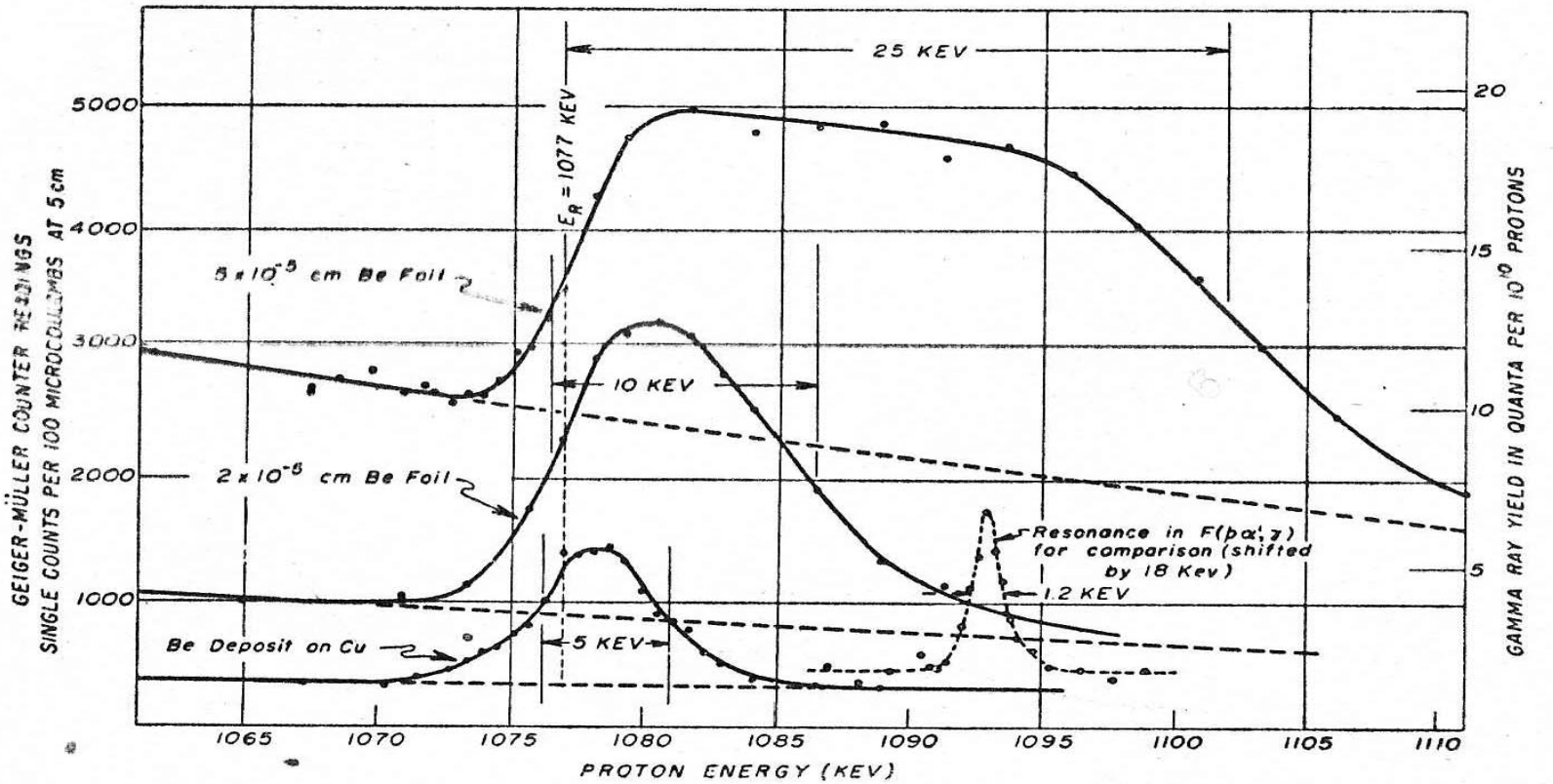


FIG. 1. Thick target excitation curves for the reactions $Li^7(p\gamma)$, $C^{12}(p\gamma)$, $C^{13}(p\gamma)$, and $F^{19}(p\alpha', \gamma)$. In the case of the $C^{12}(p\gamma)$ reaction the positrons from the beta-decay of the residual nucleus, N^{13}, were observed.

Limitation of Thick Target Technique



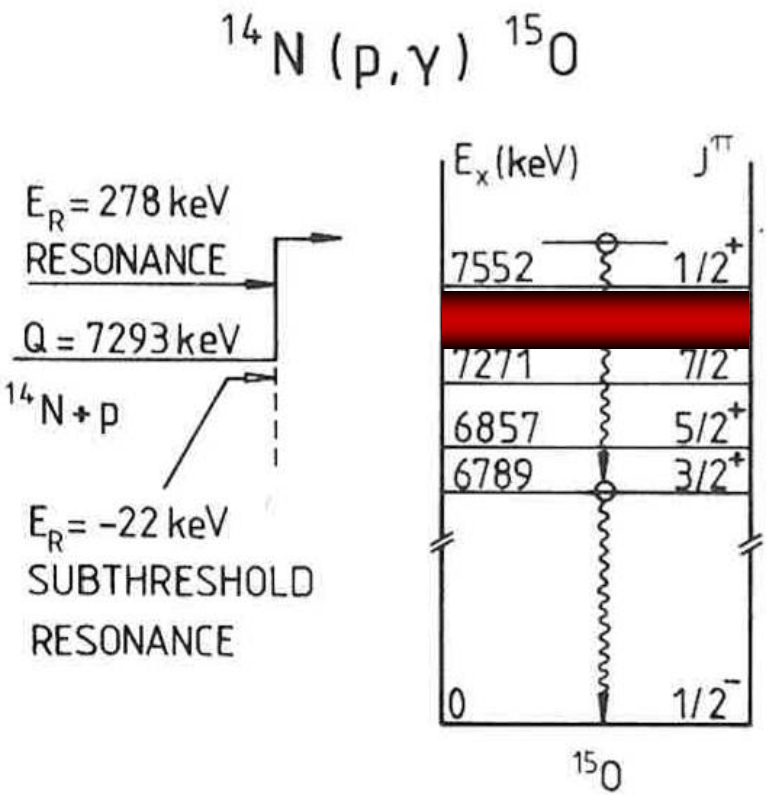
$^{9}Be(p,\gamma)^{10}B$; E_R=1.017 MeV; Γ=4keV

width of yield curve ΔE represents energy loss of particles in target

rule for thick target yield application: $\Delta E \approx 5 \cdot \Gamma$

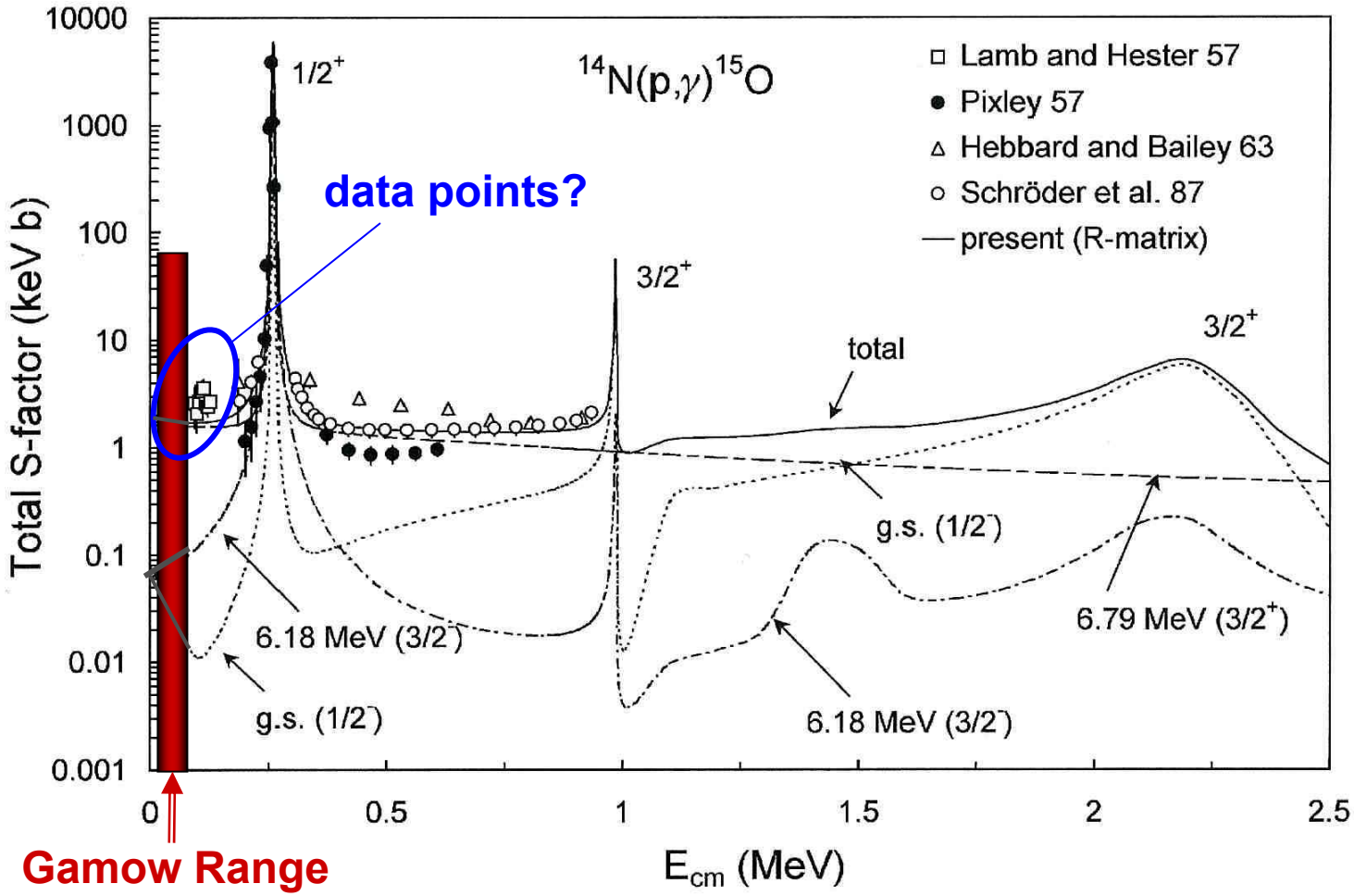
Problems in CNO cycle?

$^{14}N(p,\gamma)^{15}O$ is the slowest reaction in the CNO cycle
$\Rightarrow$ Therefore ^{14}N enrichment during CNO burning!



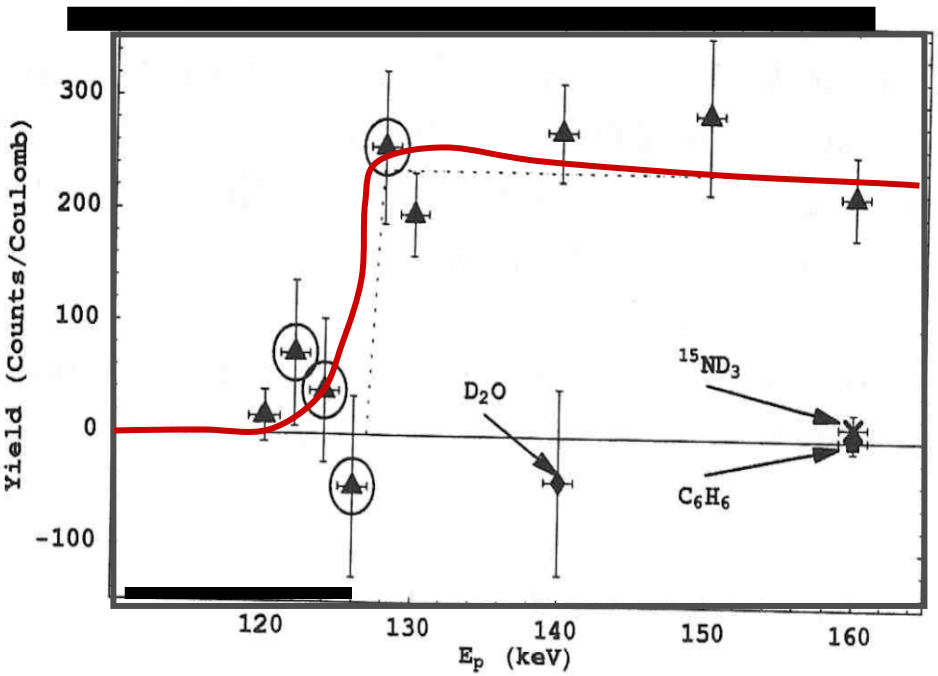
Typical question: are there missing Resonances near the threshold? These could enhance the reaction rate by orders of magnitude and turn $^{14}N(p,\gamma)^{15}O$ into a fast process.

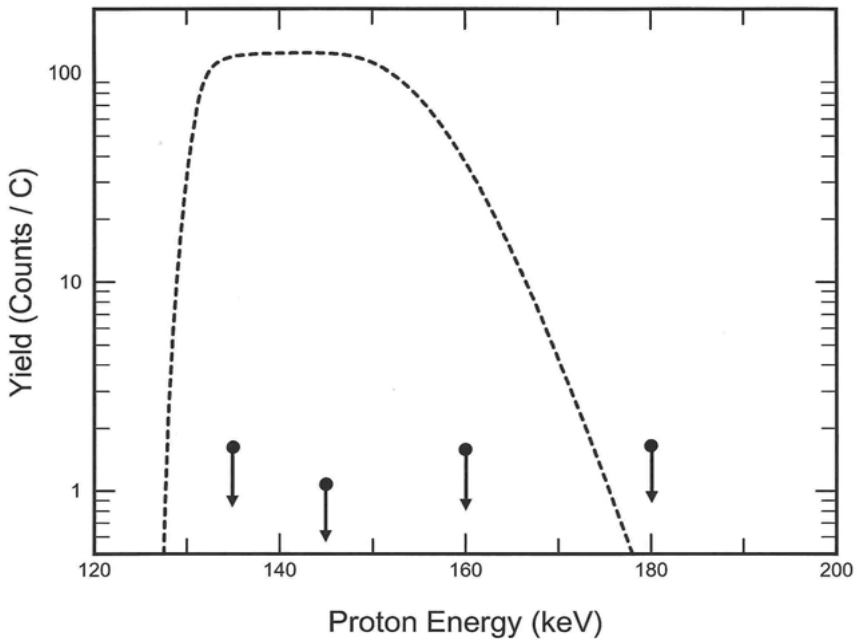
The low energy range of $^{14}N(p,\gamma)^{15}O$



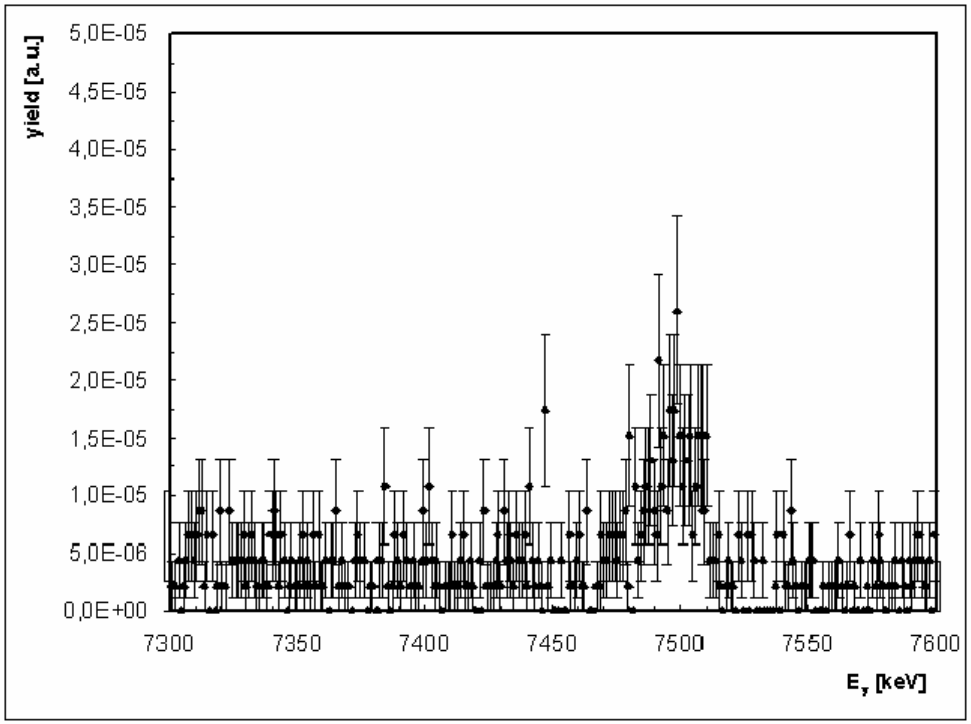
New Resonance?

Infinite thick target measurement TUNL 2001





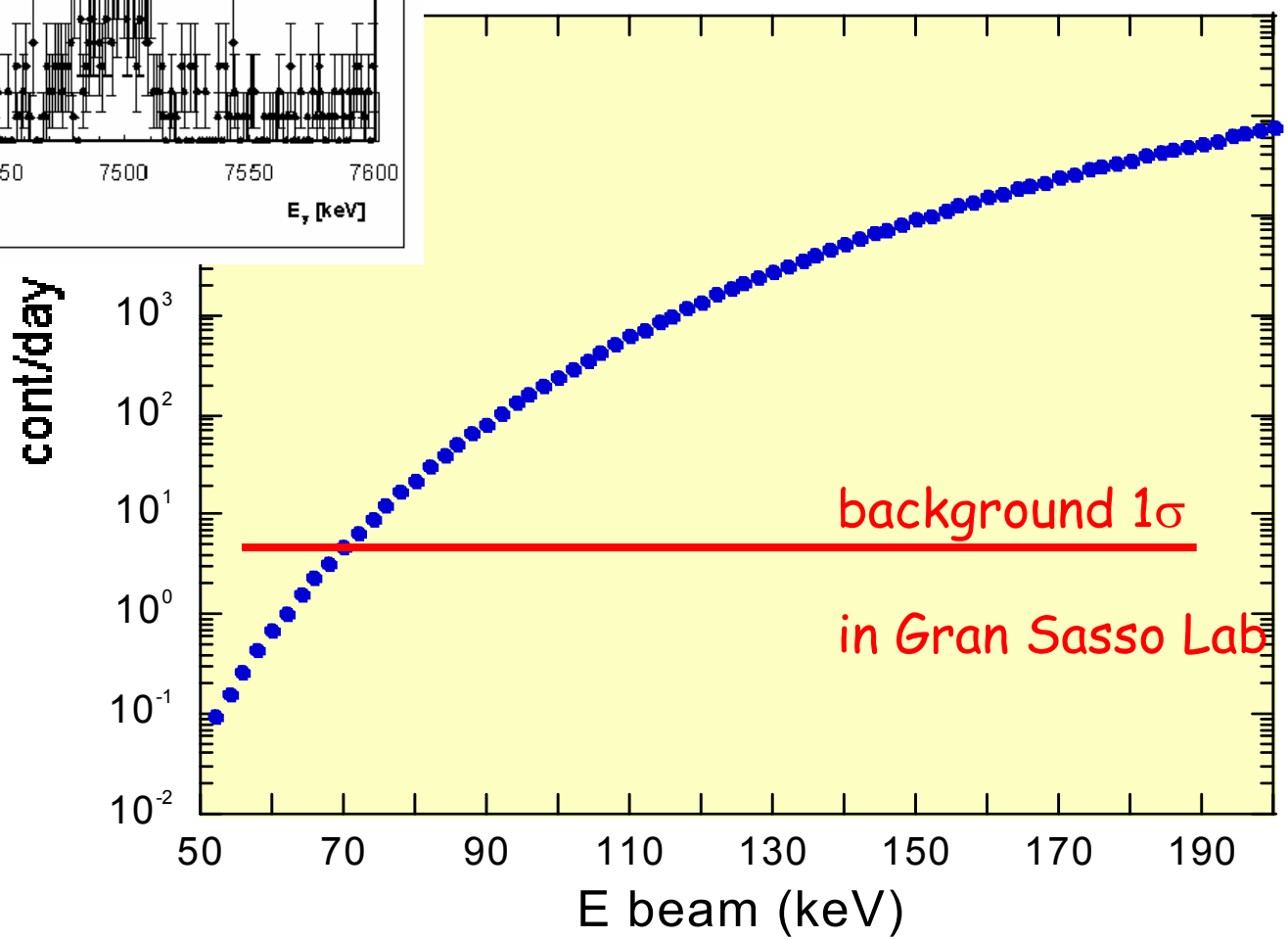
No confirming evidence in UNC data 2002



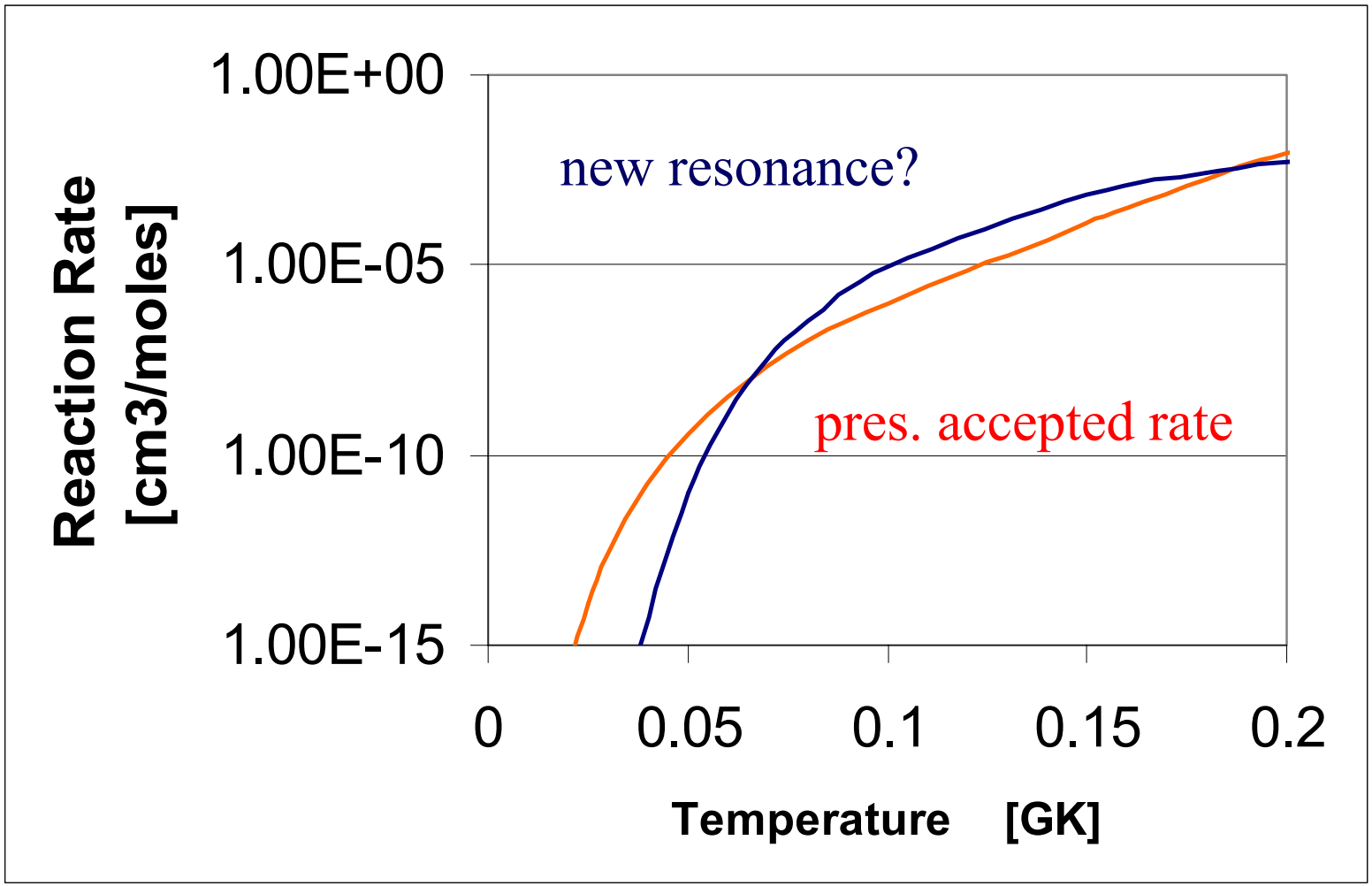
$^{14}N(p,\gamma)^{15}O$

Gamma yield at

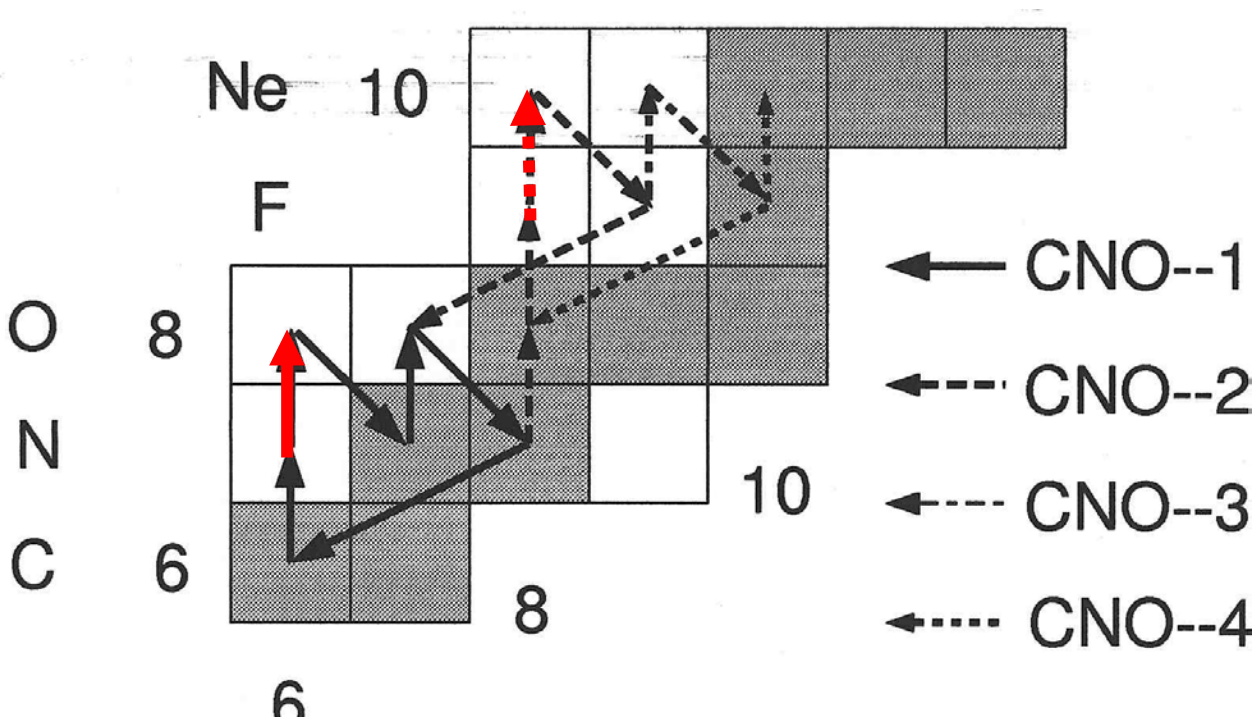
E_{cm}=200 keV
Q = 36 C
I = 400 μA
Δt = 1 day



Impact of speculated resonance!



The hot CNO cycle mode



$$\rho \cdot X_H \cdot N_A \langle \sigma v \rangle (^{13}N(p,\gamma)^{14}O) \geq \lambda(^{13}N(\beta^+)^{13}C)$$

$$\rho \cdot X_H \cdot N_A \langle \sigma v \rangle (^{17}F(p,\gamma)^{18}Ne) \geq \lambda(^{17}F(\beta^+)^{17}O)$$

Hot CNO cycle network

$$\frac{dY_{^{12}C}}{dt} = -Y_{^{12}C} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{12}C(p,\gamma)} + Y_{^{15}N} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{15}N(p,\alpha)}$$

$$\frac{dY_{^{13}N}}{dt} = \left[-Y_{^{13}N} \cdot \lambda_{^{13}N(\beta^+)} \right] - Y_{^{13}N} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{13}N(p,\gamma)} + Y_{^{12}C} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{12}C(p,\gamma)}$$

$$\frac{dY_{^{14}O}}{dt} = -Y_{^{14}O} \cdot \lambda_{^{14}O(\beta^+)} + Y_{^{13}N} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{13}N(p,\gamma)}$$

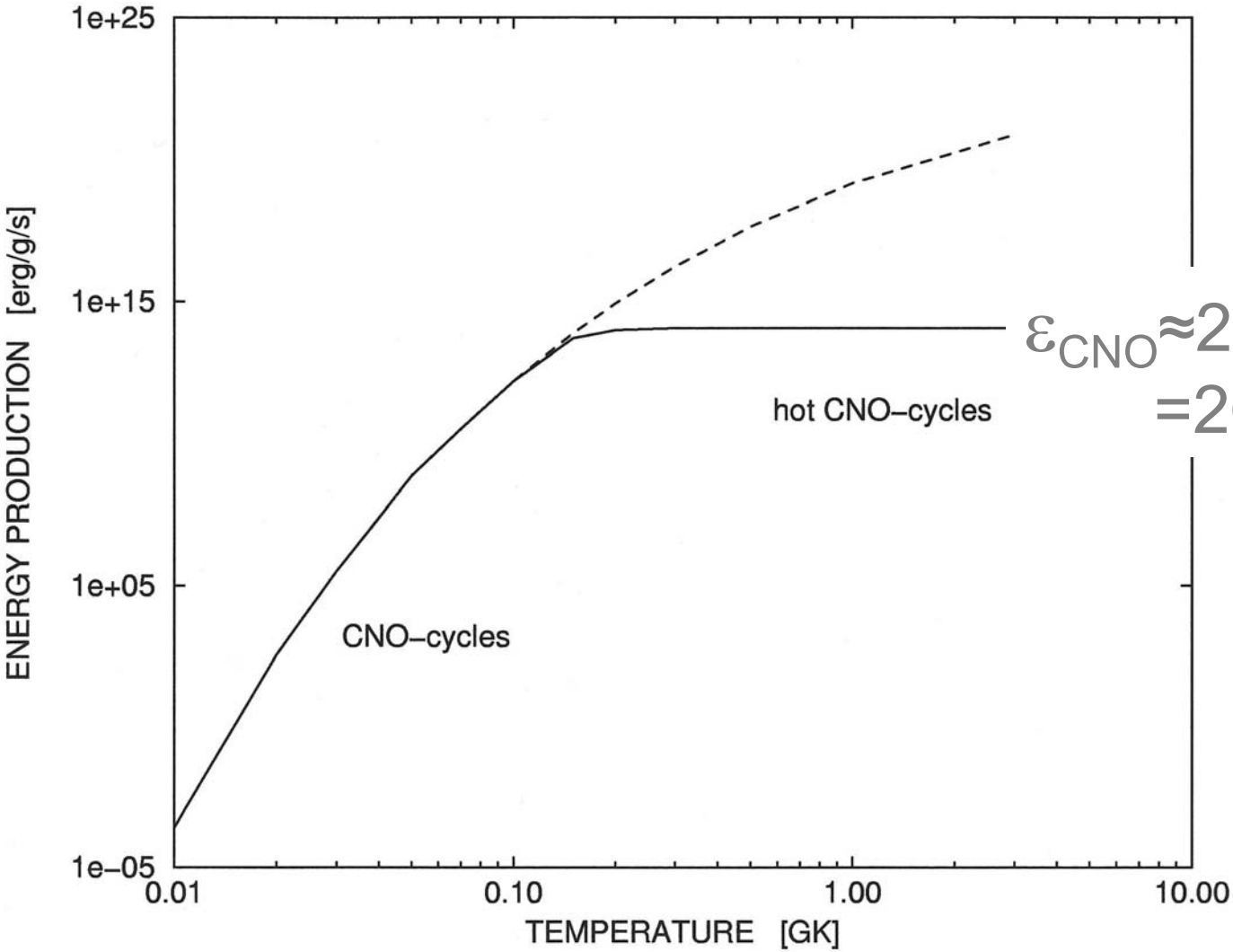
$$\frac{dY_{^{14}N}}{dt} = -Y_{^{14}N} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{14}N(p,\gamma)} + Y_{^{14}O} \cdot \lambda_{^{14}O(\beta^+)}$$

$$\frac{dY_{^{15}O}}{dt} = -Y_{^{15}O} \cdot \lambda_{^{15}O(\beta^+)} + Y_{^{14}N} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{14}N(p,\gamma)}$$

$$\frac{dY_{^{15}N}}{dt} = -Y_{^{15}N} \cdot Y_{^{1}H} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{15}N(p,\alpha)} + Y_{^{15}O} \cdot \lambda_{^{15}O(\beta^+)}$$

slowest reactions become β^+ decays of ^{14}O, ^{15}O

Impact on energy generation



$\varepsilon_{CNO} \approx 26$ MeV/100s
$= 260$ keV/s

Summary hydrogen burning

Hydrogen burning operates mainly through

- the pp-chains for low mass stars
- the CNO cycles for massive stars

hydrogen induced reactions on higher Z nuclei are unlikely due to Coulomb-barrier (high T required)

Nucleosynthesis consequences are of only minor relevance for galactic abundance distribution but creates the basis for the stellar evolution and the subsequent production of massive nuclei!