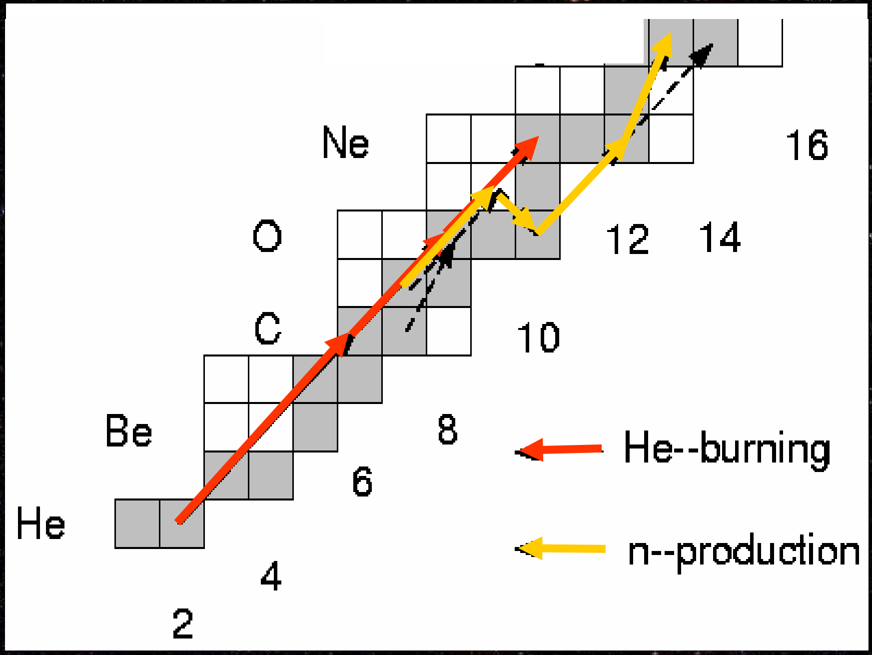
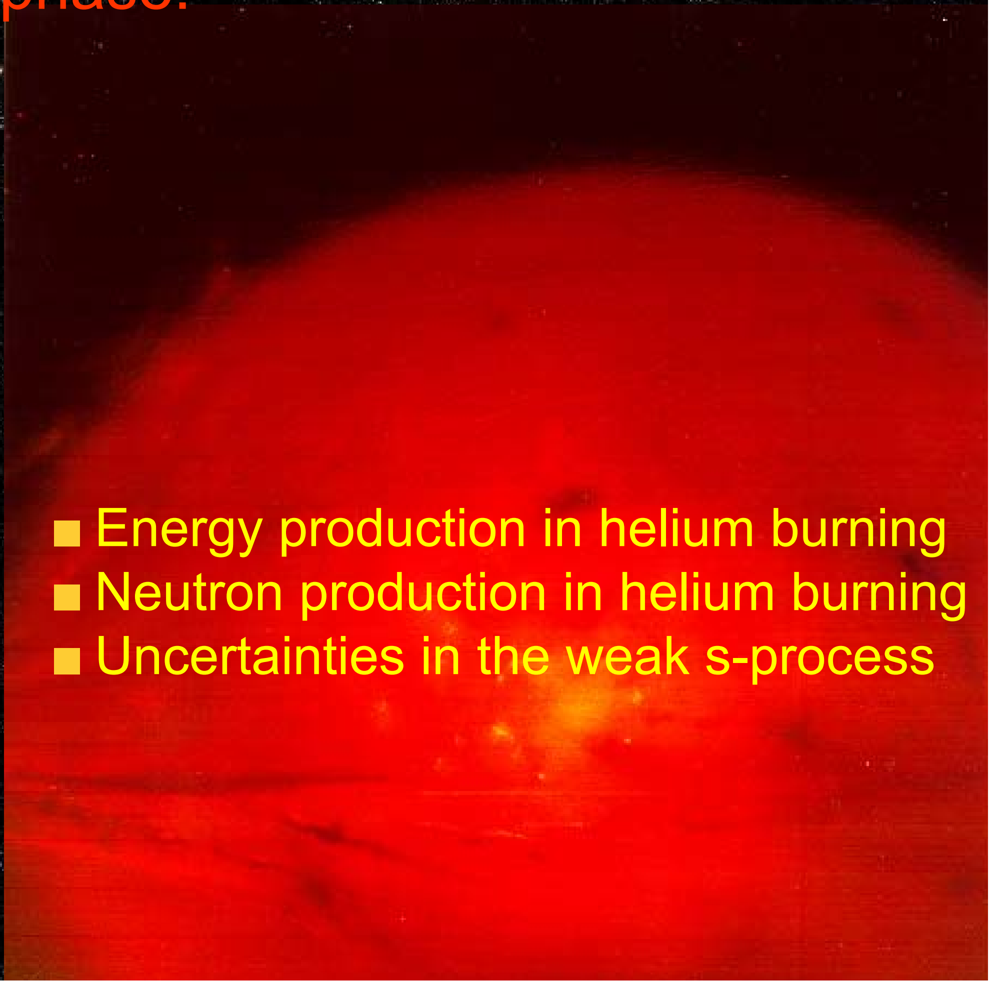
He-Burning in massive Stars

He-burning is ignited on the ^{4}He and ^{14}N ashes of the preceding hydrogen burning phase!

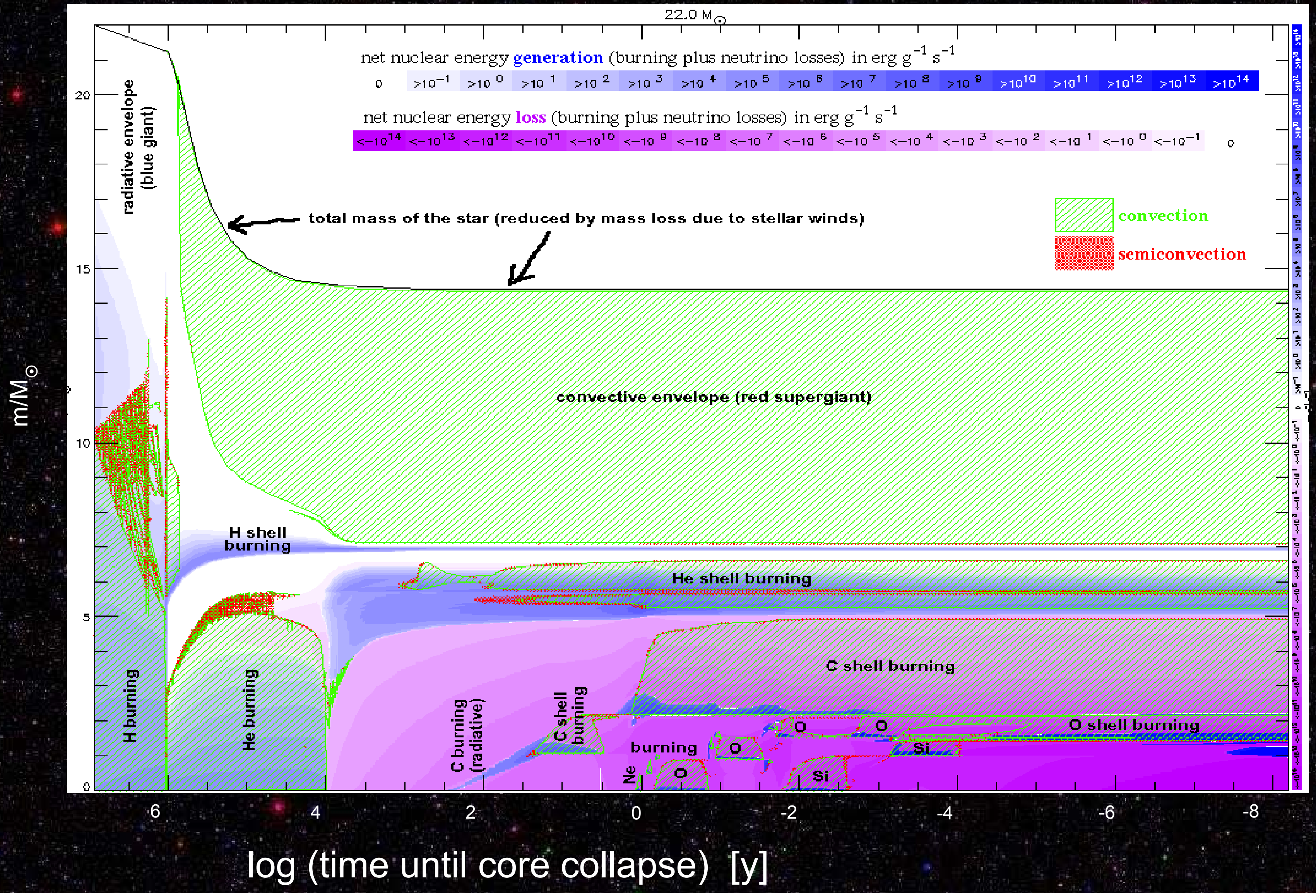


Most important reaction
-triple alpha process –
$3\alpha \Rightarrow {}^{12}C + 7.96$ MeV



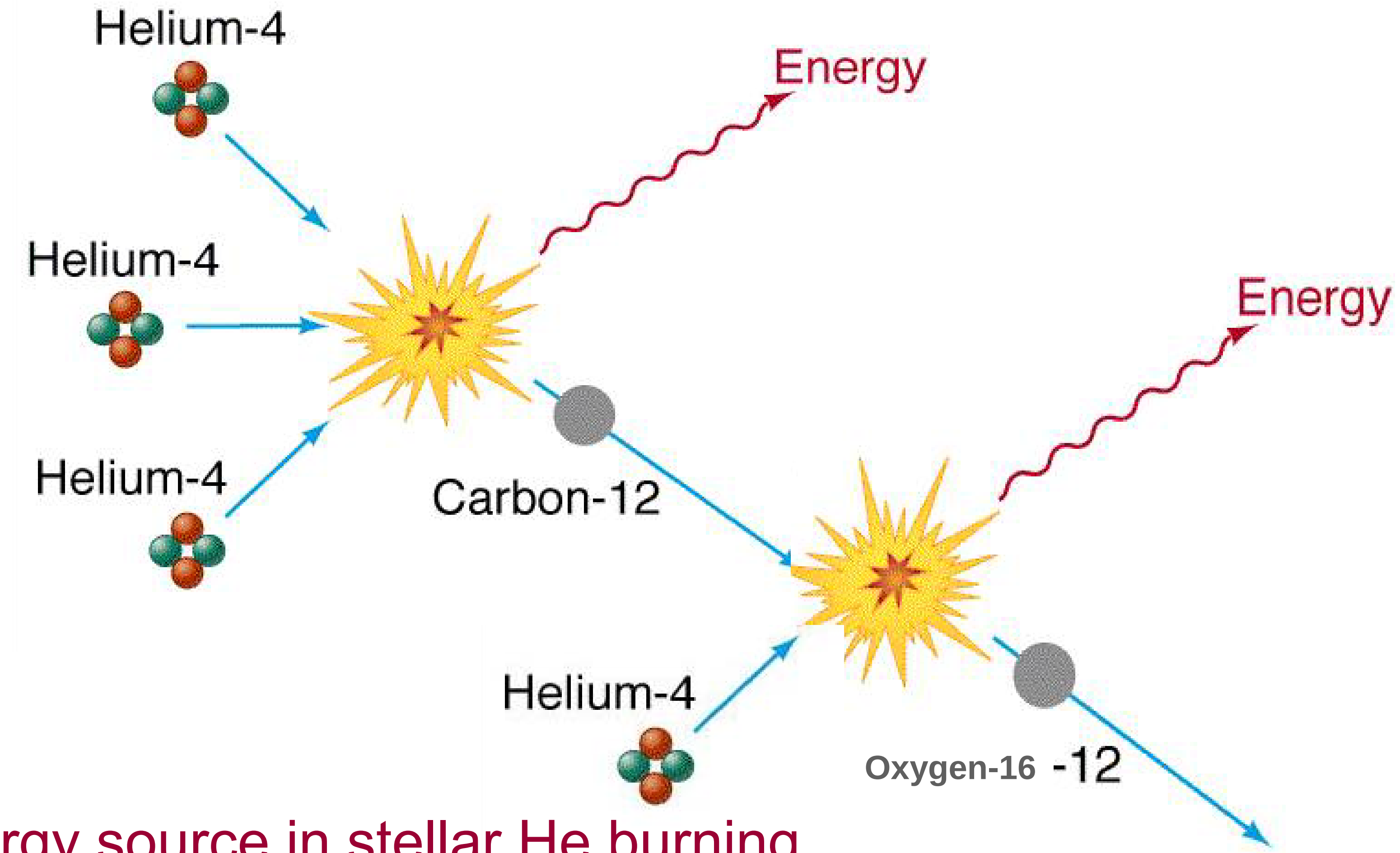
- Energy production in helium burning
- Neutron production in helium burning
- Uncertainties in the weak s-process

Stellar Evolution of Massive Stars



Critical Reactions in He-burning

On helium fuel produced in preceding hydrogen burning



Energy source in stellar He burning
Energy release determined by associated reaction rates

Network for stellar Helium burning

$$\frac{dY_{^{4}He}}{dt} = -3\cdot\frac{1}{6}\cdot Y_{^{4}He}^{3}\cdot\rho^{2}\cdot N_A\left\langle\sigma\upsilon\right\rangle_{3\alpha} - Y_{^{12}C}\cdot Y_{^{4}He}\cdot\rho\cdot N_A\left\langle\sigma\upsilon\right\rangle_{^{12}C(\alpha,\gamma)}$$

$$- Y_{^{16}O}\cdot Y_{^{4}He}\cdot\rho\cdot N_A\left\langle\sigma\upsilon\right\rangle_{^{16}O(\alpha,\gamma)} - Y_{^{14}N}\cdot Y_{^{4}He}\cdot\rho\cdot N_A\left\langle\sigma\upsilon\right\rangle_{^{14}N(\alpha,\gamma)}$$

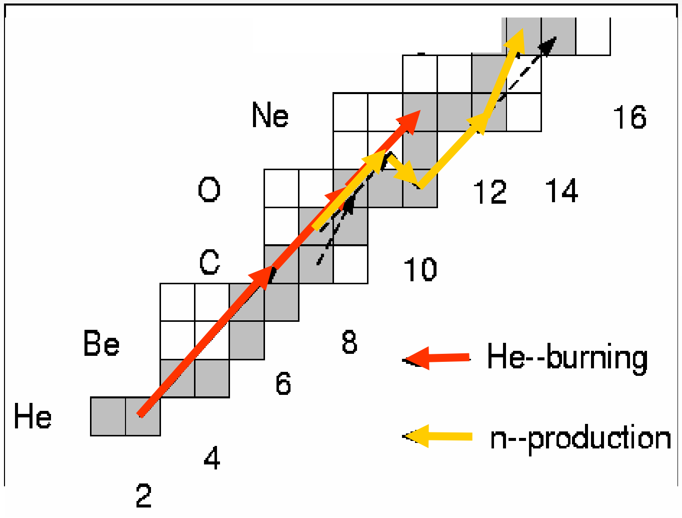
$$\left(- Y_{^{18}O}\cdot Y_{^{4}He}\cdot\rho\cdot N_A\left\langle\sigma\upsilon\right\rangle_{^{18}O(\alpha,\gamma)} - Y_{^{22}Ne}\cdot Y_{^{4}He}\cdot\rho\cdot N_A\left\langle\sigma\upsilon\right\rangle_{^{22}Ne(\alpha,n)}\right)$$

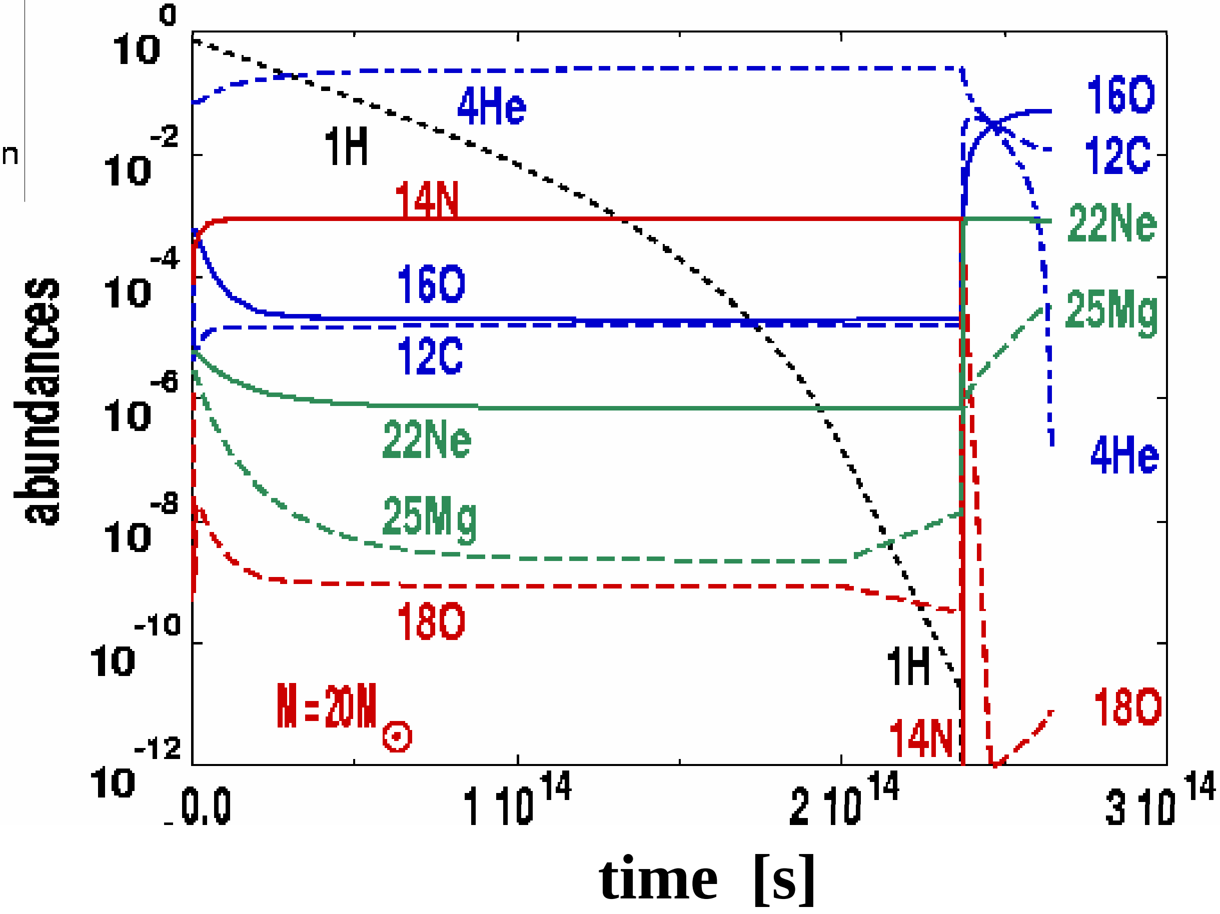
$$\frac{dY_{^{12}C}}{dt} = -Y_{^{12}C}\cdot Y_{^{4}He}\cdot\rho\cdot N_A\left\langle\sigma\upsilon\right\rangle_{^{12}C(\alpha,\gamma)} + \frac{1}{6}\cdot Y_{^{4}He}^{3}\cdot\rho^{2}\cdot N_A\left\langle\sigma\upsilon\right\rangle_{3\alpha}$$

$$\frac{dY_{^{16}O}}{dt} = -Y_{^{16}O}\cdot Y_{^{4}He}\cdot\rho\cdot N_A\left\langle\sigma\upsilon\right\rangle_{^{16}O(\alpha,\gamma)} + Y_{^{12}C}\cdot Y_{^{4}He}\cdot\rho\cdot N_A\left\langle\sigma\upsilon\right\rangle_{^{12}C(\alpha,\gamma)}$$

$$\frac{dY_{^{14}N}}{dt} = -Y_{^{14}N}\cdot Y_{^{4}He}\cdot\rho\cdot N_A\left\langle\sigma\upsilon\right\rangle_{^{14}N(\alpha,\gamma)}$$

Abundance evolution in stellar core

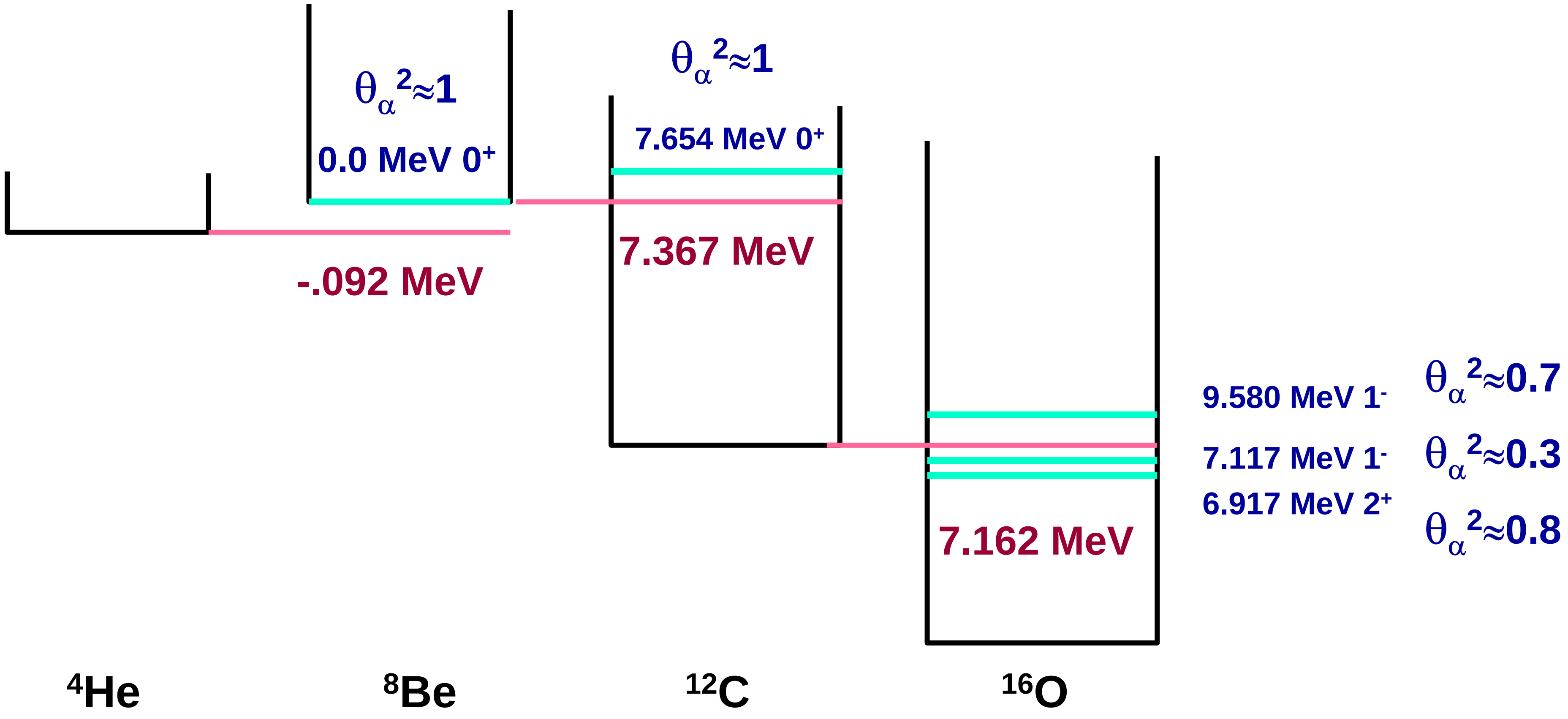




Decline of ^{4}He
(time-scale)
increase in ^{12}C, ^{16}O
⇒equilibrium ^{12}C/^{16}O
Rapid decline in ^{14}N.

The case of: 3-α and $^{12}C(\alpha,\gamma)^{16}O$

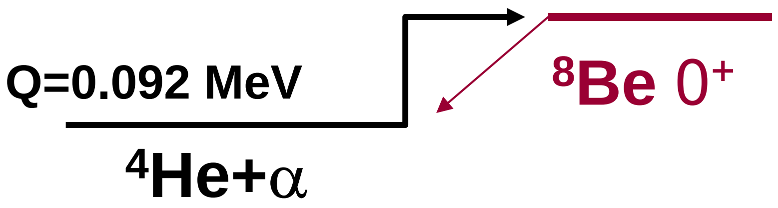
Reaction rates determined by strong resonances and E2 direct capture contributions signifying strong alpha cluster state configurations in the T=0 nuclei along the reaction path!



The (ααα) Reaction as two step process

$$r_{\alpha\alpha\alpha} = N_{^8Be}\cdot\rho\cdot\frac{X_\alpha}{A_\alpha}\cdot N_A\left\langle {}^8Be(\alpha,\gamma)^{12}C\right\rangle$$

first step!



Q=0.092 MeV

^{4}He+α

^{8}Be 0^+

$T_{1/2}(^8\text{Be}) = 9.7\cdot10^{-17}$ s

Γ_α=6.8 eV

pure α cluster configuration

fast capture ⇒ equilibrium between capture and decay

Application of Saha Equation
For calculating ^{8}Be equilibrium:

$$N(^8Be) = N_\alpha^2\cdot\hbar^3\cdot\left(\frac{2\pi}{\mu\cdot kT}\right)^{3/2}\cdot e^{\left(-\frac{Q}{kT}\right)}$$

Example for ^{8}Be equilibrium abundance:

Case of typical He-burning: T=0.1GK ⇒ T_9=0.1; ρ=10^5 g/cm^3

$$N\left({}^8Be\right) = 6\cdot 10^{-35}\cdot N_\alpha^2\cdot T_9^{-3/2}\cdot e^{\left(-\frac{1.068}{T_9}\right)}$$

$$N\left({}^8Be\right) \approx 4.4\cdot 10^{-38}\cdot N_\alpha^2$$

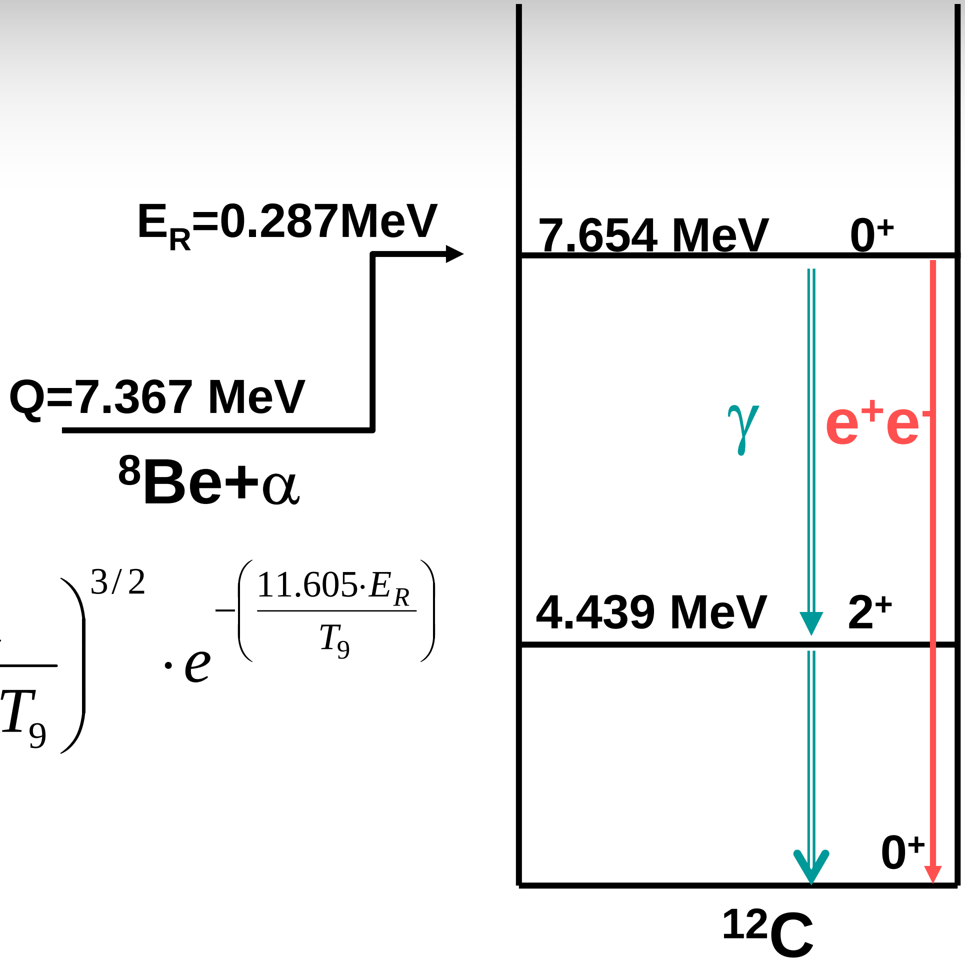
$$N = \rho\cdot N_A\cdot\frac{X_i}{A_i} \quad\Rightarrow\quad \frac{X\left({}^8Be\right)}{X_\alpha^2}\approx 1.3\cdot 10^{-9}$$

~ one ^{8}Be nucleus
for $3\cdot 10^4$ α particles

Resonant capture on ^{8}Be

second step!

The Hoyle resonance!



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

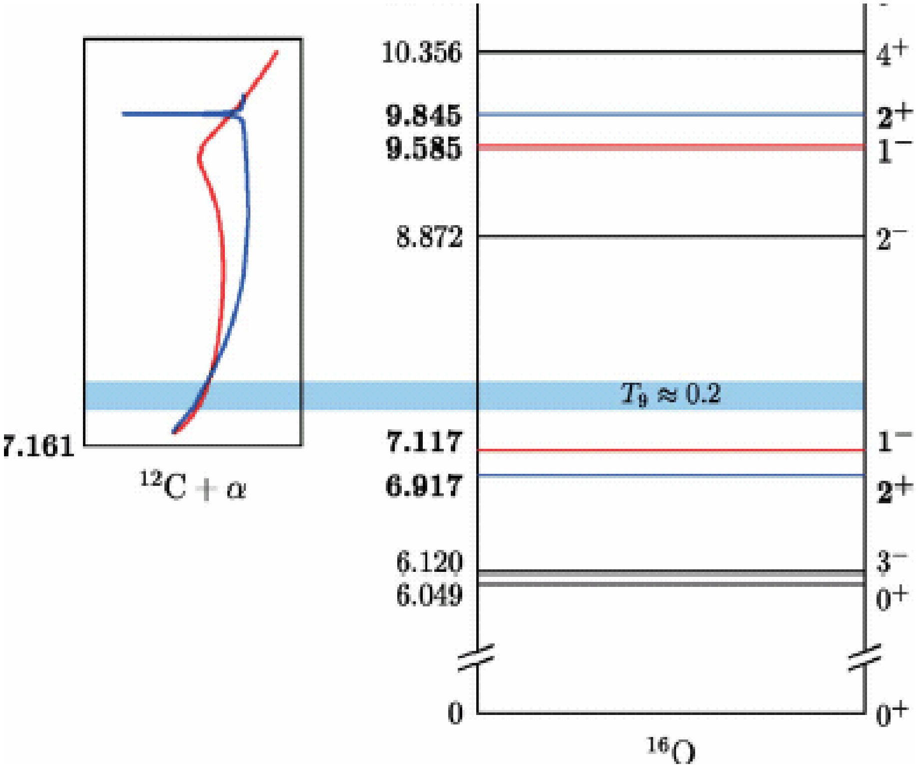
$$\omega\gamma = (2J+1)\cdot\frac{\Gamma_{in}\cdot\Gamma_{out}}{\Gamma_{tot}}$$

$$\boxed{\omega\gamma = 3.58\cdot 10^{-9}\ MeV \quad \pm 12\%}$$

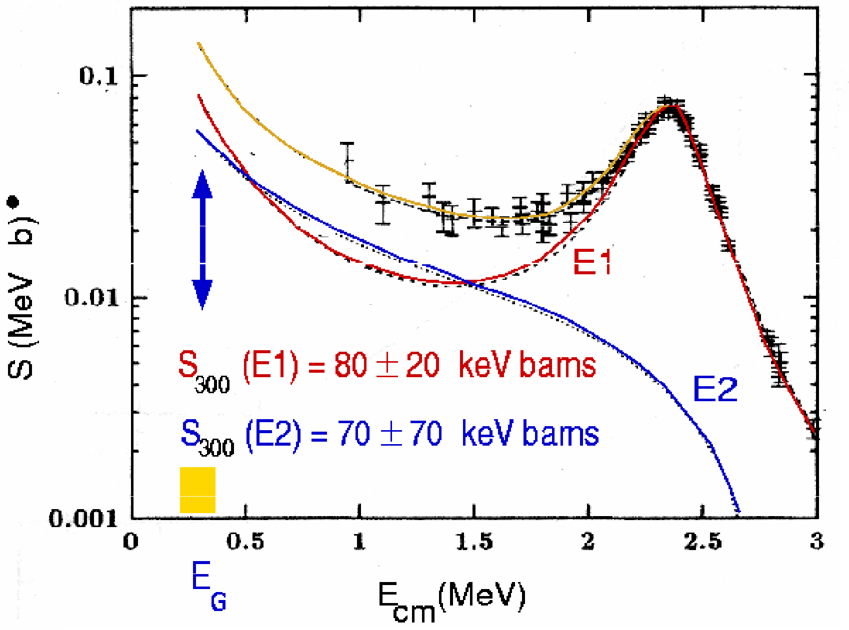
Decay by sequential E2 γ transitions or internal e^+ e^- pair conversion

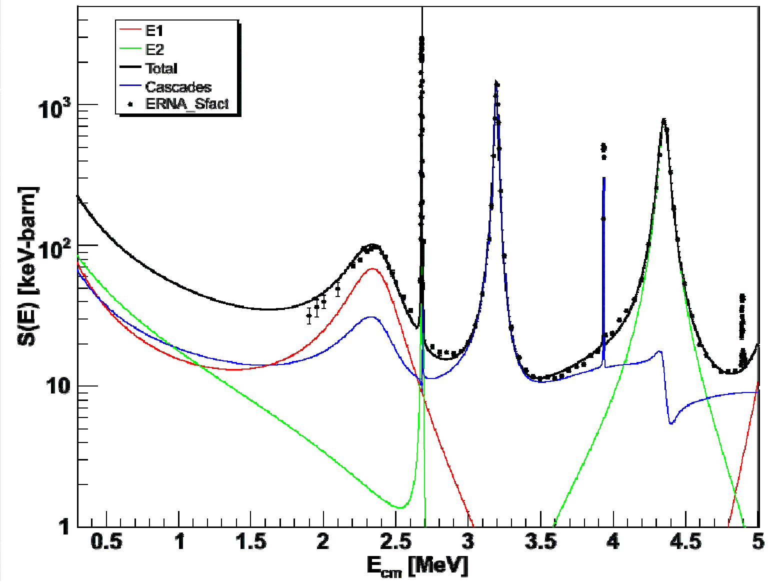
$^{12}C(\alpha,\gamma)^{16}O$, the Holy Grail

Level and Interference Structure between 1^- levels (E1) and 2^+ states and direct capture (E2).



Uncertainty in low energy extrapolation





R-matrix analysis

Complex resonance structure, interfering broad resonances

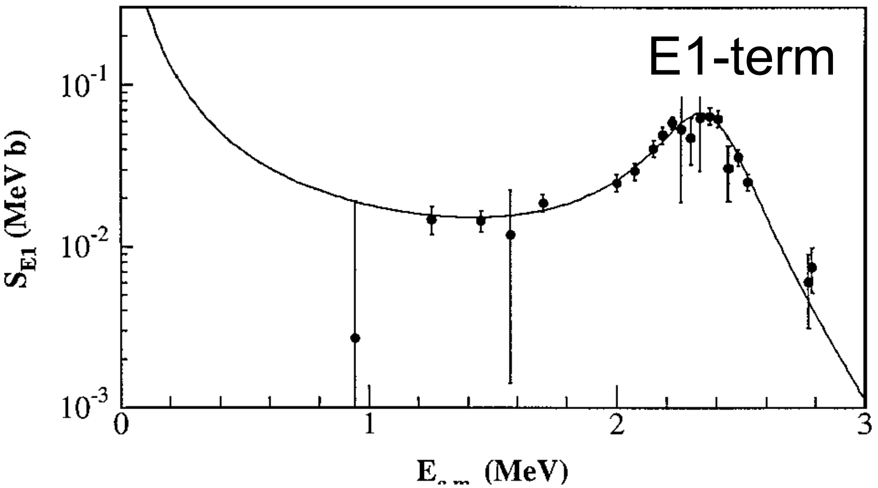
Parameters from probing ^{16}O compound nucleus through

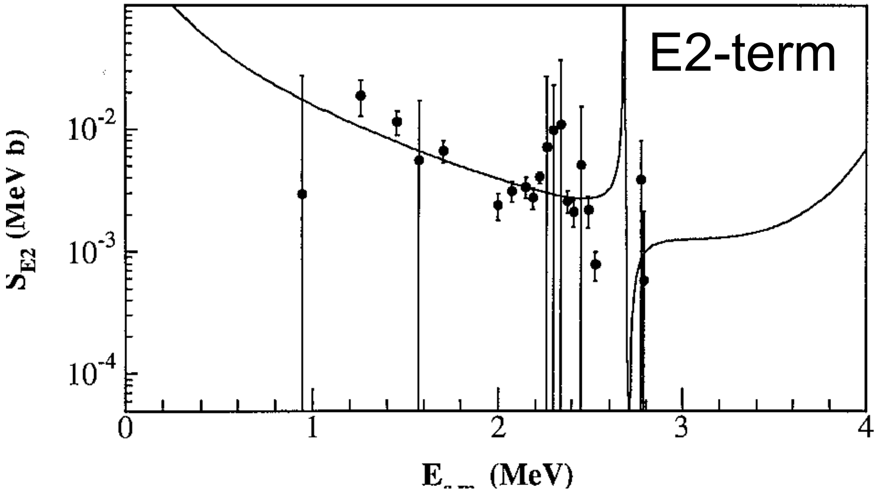
• elastic scattering	$^{12}\mathrm{C}(\alpha,\alpha)^{12}\mathrm{C}$ (Bochum, ND)
• β-delayed α-decay	$^{16}\mathrm{N}(\beta,\alpha)^{12}\mathrm{C}$ (Yale, TRIUMF, ANL)
• resonant α capture	$^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ (Caltech, Münster, Queens, Stuttgart, Bochum)
• α-transfer reaction	$^{12}\mathrm{C}(^{7}\mathrm{Li},t)^{16}\mathrm{O}$ (UM, TUNL)
• photo-dissociation	$^{16}\mathrm{O}(\gamma,\alpha)^{12}\mathrm{C}$ (HIγS)

http://www.jinaweb.org/html/jinaworkshops2.html#event11

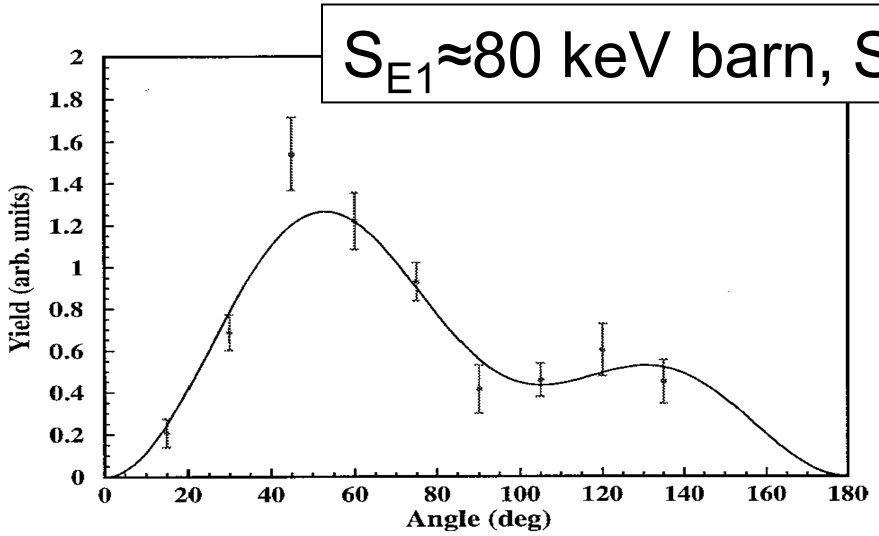
http://www.jinaweb.org/events/caltech06/presentation.html

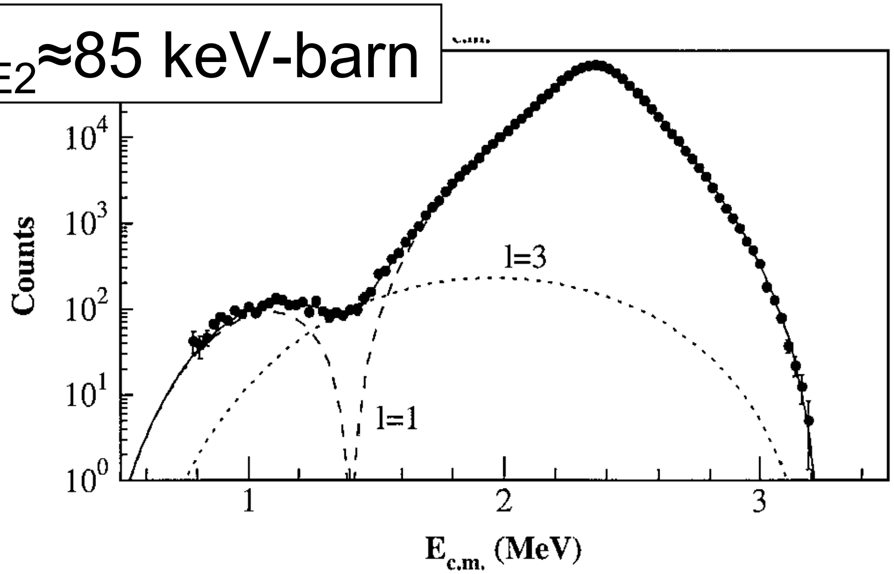
R-matrix fit examples


E1-term


E2-term

S_{E1}≈80 keV barn, S_{E2}≈85 keV-barn





From Kunz et al. PRL 86 (2004)

$^{12}C(\alpha,\gamma)^{16}O$ reaction rate

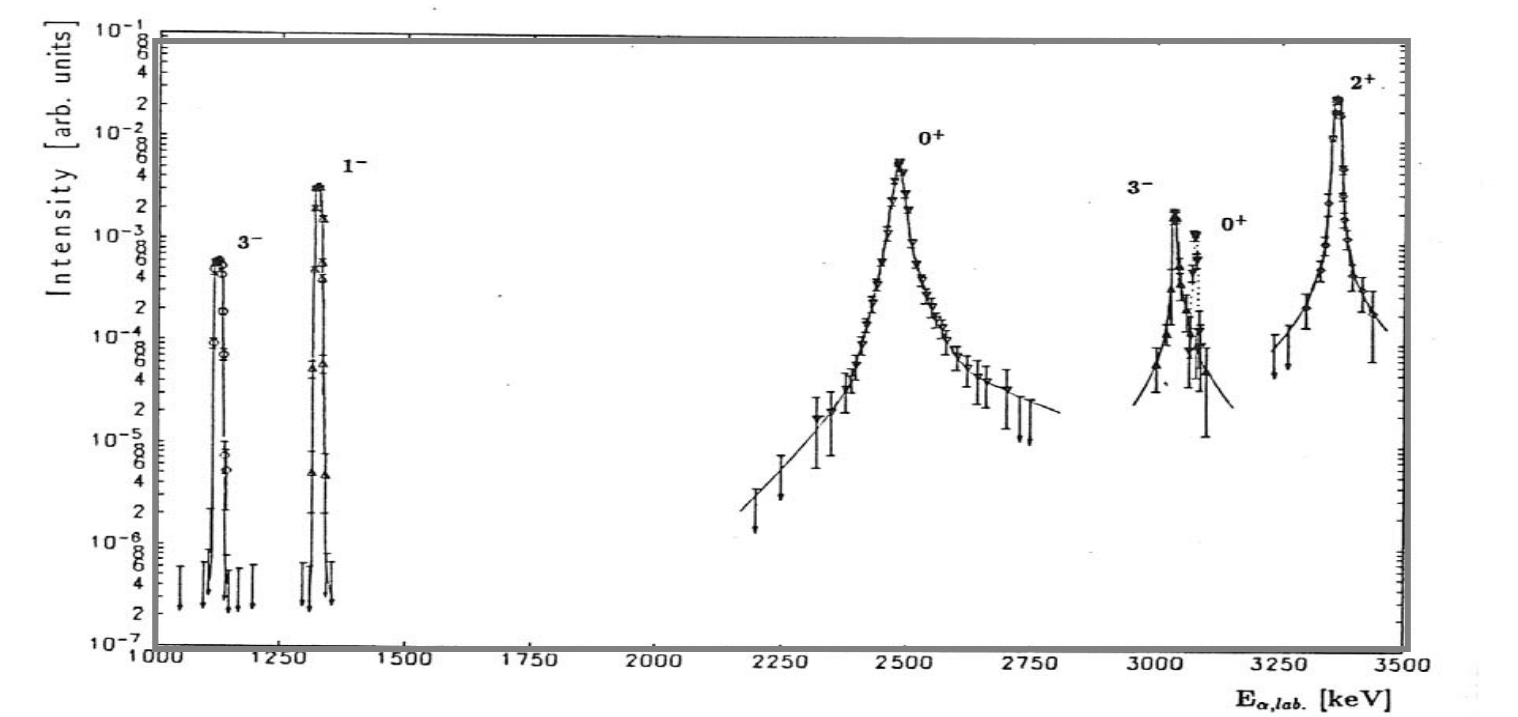
$$N_A\langle\sigma\upsilon\rangle = 6.9\cdot10^8\cdot T_9^{-2/3}\cdot S_{eff}\left[MeV-b\right]\cdot e^{-\frac{32.11}{T_9^{1/3}}}\quad\left[\frac{cm^3}{s}\right]$$

$$S_{eff}\approx 0.17\left[MeV-b\right]$$

$$N_A\langle\sigma\upsilon\rangle \approx 1.2\cdot10^8\cdot T_9^{-2/3}\cdot e^{-\frac{32.11}{T_9^{1/3}}}\quad\left[\frac{cm^3}{s}\right]$$

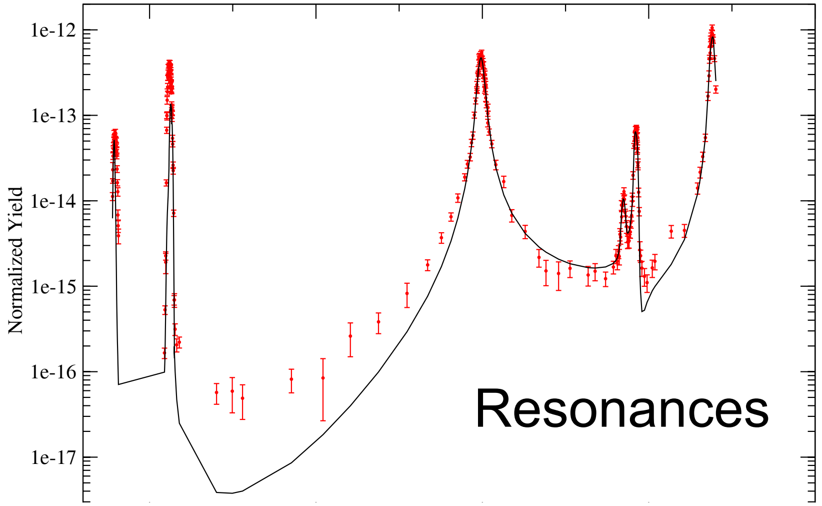
Only very crude estimate!
E-T dependency needs to be considered!

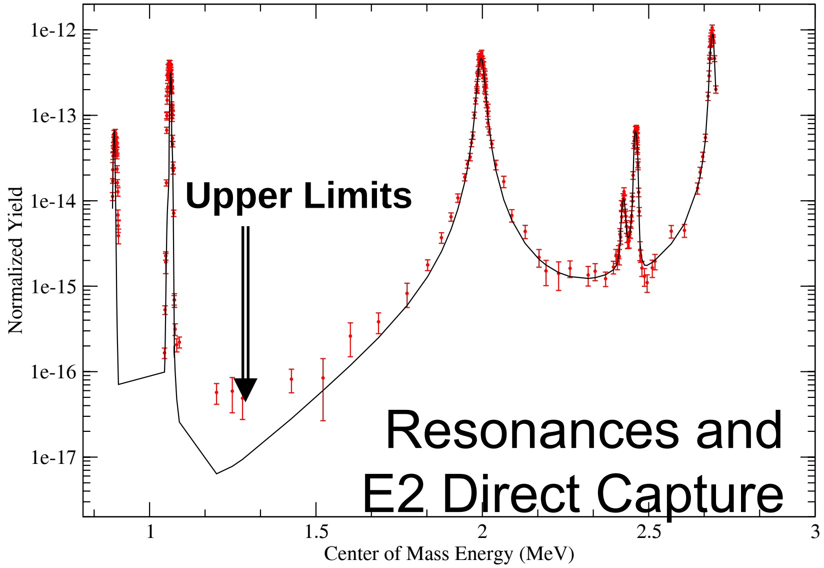
$^{16}O(\alpha,\gamma)^{20}Ne$ rate and …

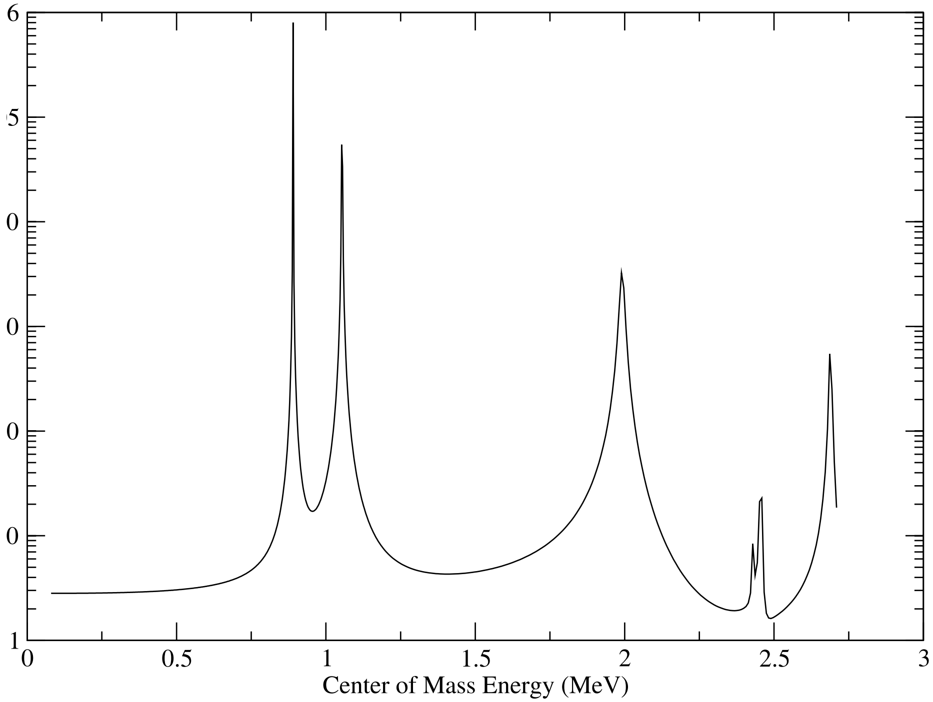


Only a few single resonances, no strong non-resonant term in the excitation curve observed! Non-resonant direct capture E2 component expected. Non-resonant M1 component most likely too weak to be of relevance?

New results, E2 Direct Reaction Component



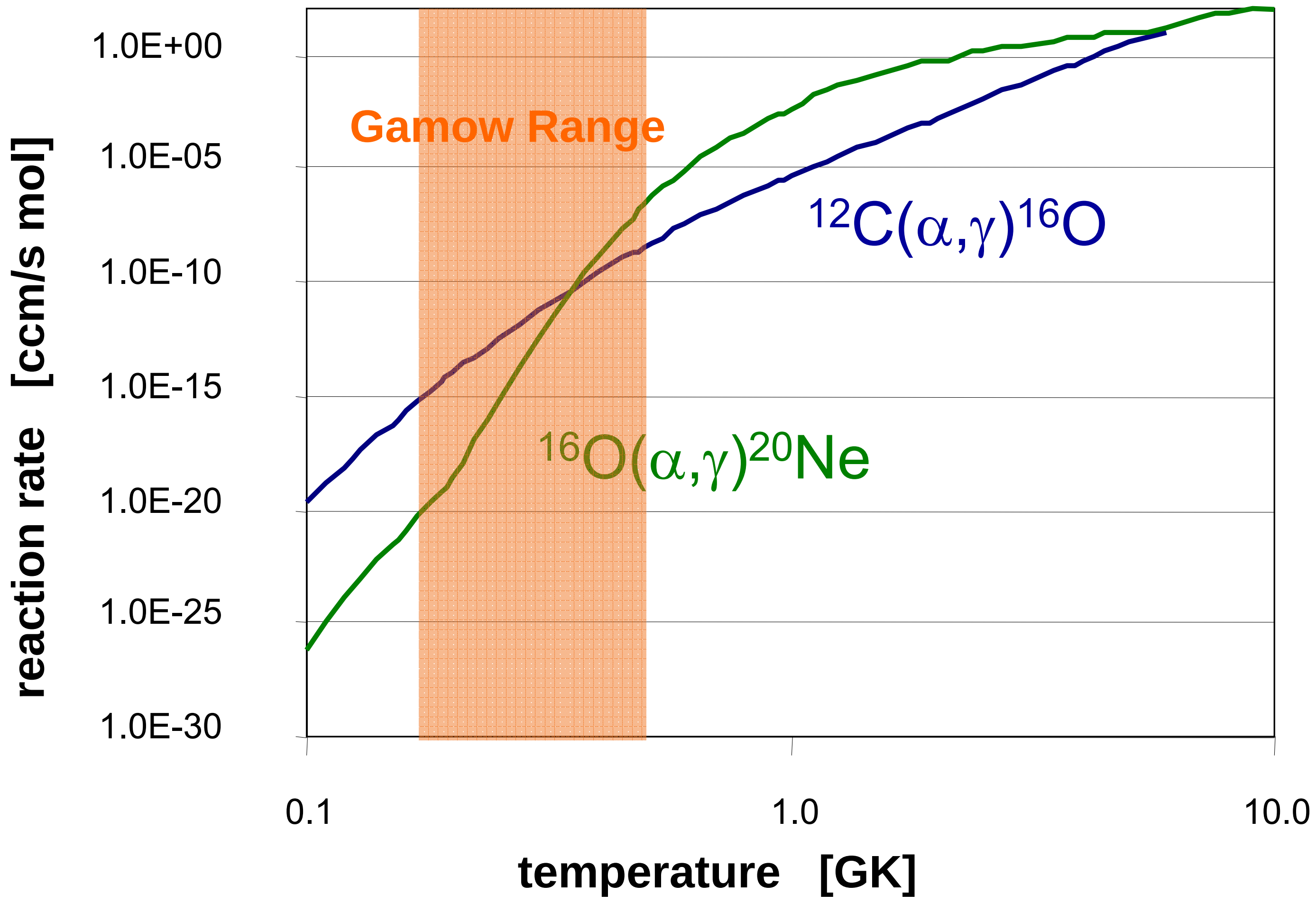




$$S_{eff} \approx 2.8\, MeV - barn$$

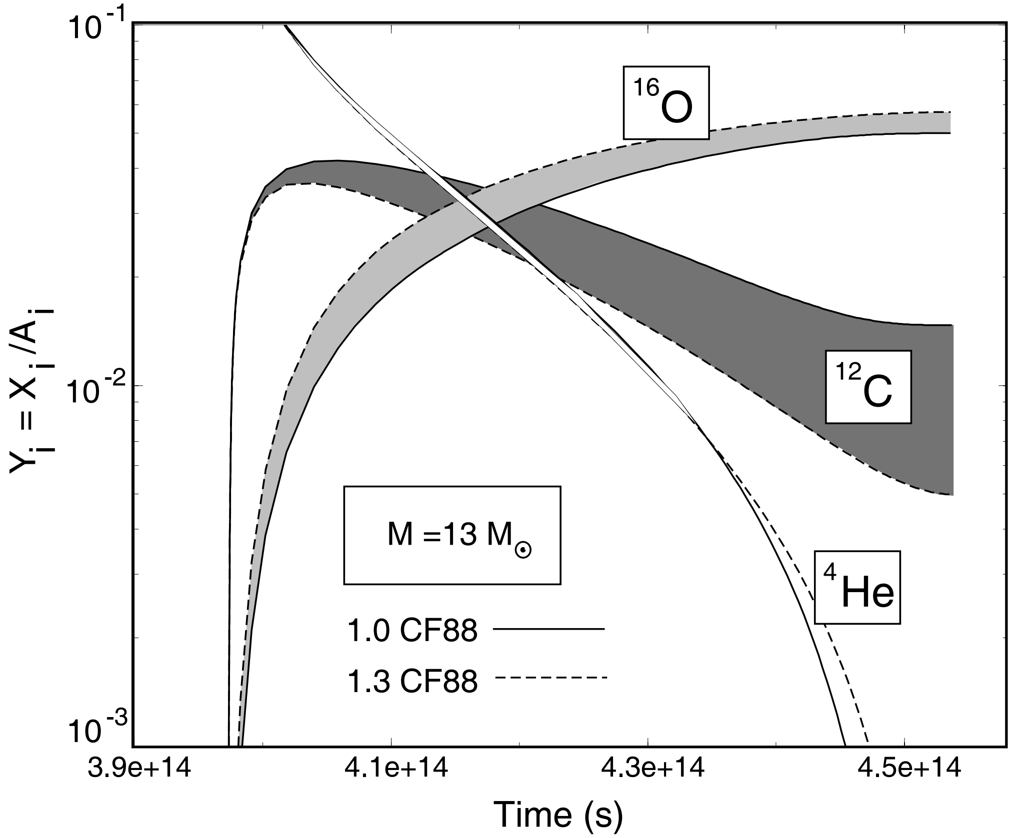
Appreciable non resonant component which needs to be implemented as DC reaction rate contribution.

Reaction Rates for $^{12}C(\alpha,\gamma)^{16}O$ & $^{16}O(\alpha,\gamma)^{20}Ne$



$^{12}C(\alpha,\gamma)^{16}O$ rate dominates over the $^{16}O(\alpha,\gamma)^{20}Ne$ rate at the typical He-burning temperatures T~0.1-0.3 GK.

Consequences of the $^{12}C(\alpha,\gamma)^{16}O$ and $^{16}O(\alpha,\gamma)^{20}Ne$ reaction rates!

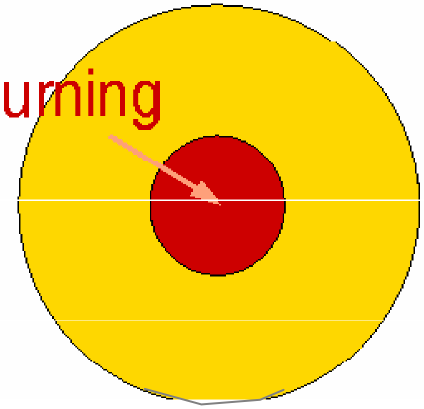


- **Late Stellar Evolution**
  determines Carbon and/or Oxygen phase
- **Type Ia Supernova**
  central carbon burning of C/O white dwarf
- **Type II Supernova**
  shock-front nucleosynthesis in C and He shells of pre-supernova star

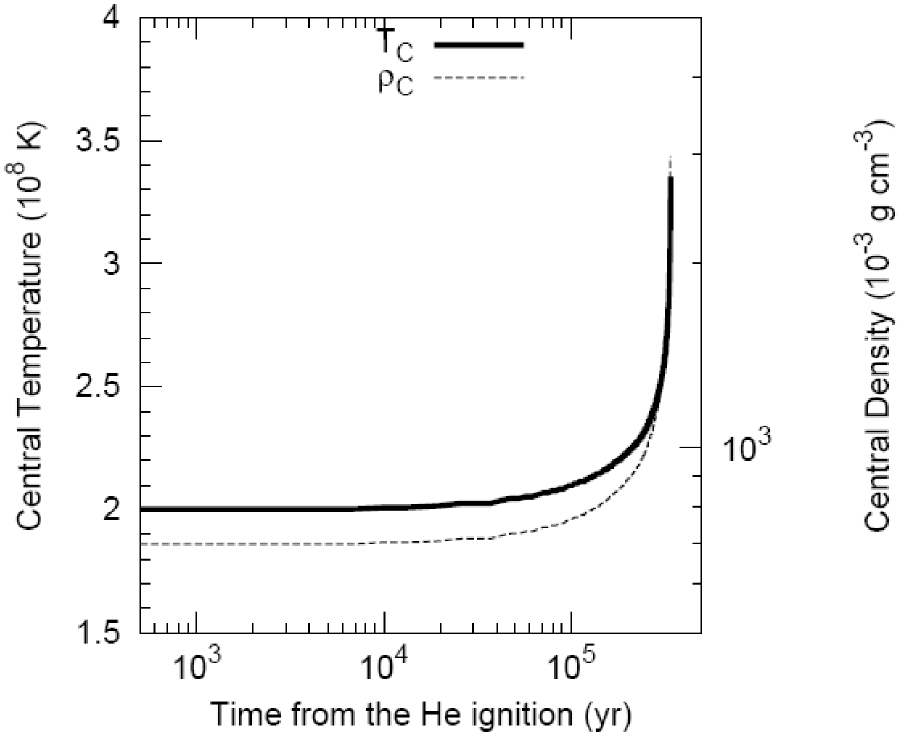
Stellar Neutron Sources in massive Stars

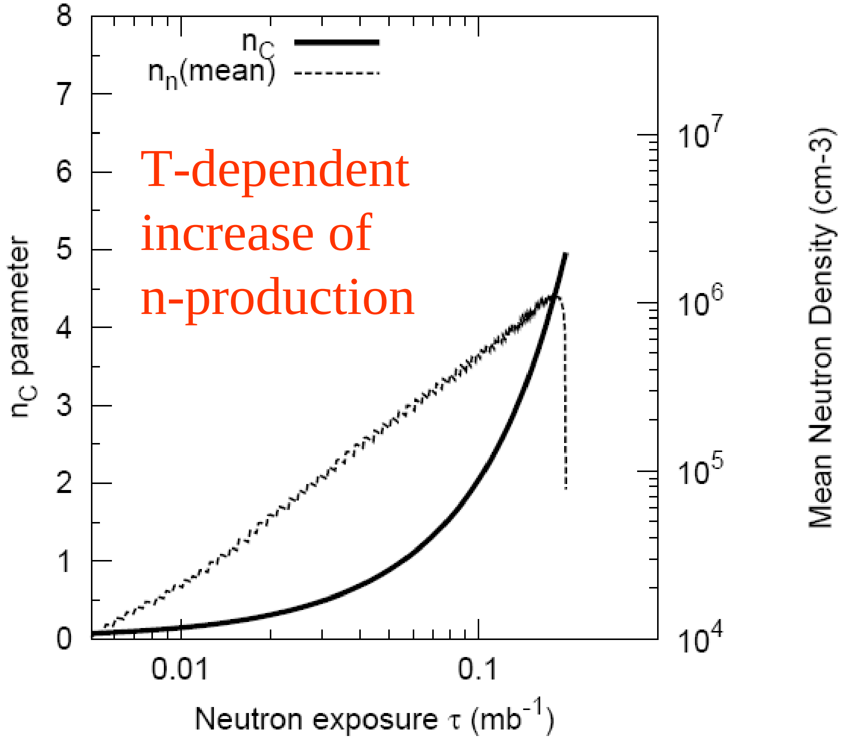
$^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^{+}\nu)^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}(\alpha,n)$

or $^{22}\mathrm{Ne}(\alpha,\gamma)$



core He-Burning





T-dependent increase of n-production

Reaction network for n-sources

$$\frac{dY_{^{14}N}}{dt} = -Y_{^{14}N}\cdot Y_{^{4}He}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^{14}N(\alpha,\gamma)}$$

$$\frac{dY_{^{18}F}}{dt} = -Y_{^{18}F}\cdot\lambda_{^{18}F(\beta^{+})} + Y_{^{14}N}\cdot Y_{^{4}He}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^{14}N(\alpha,\gamma)}$$

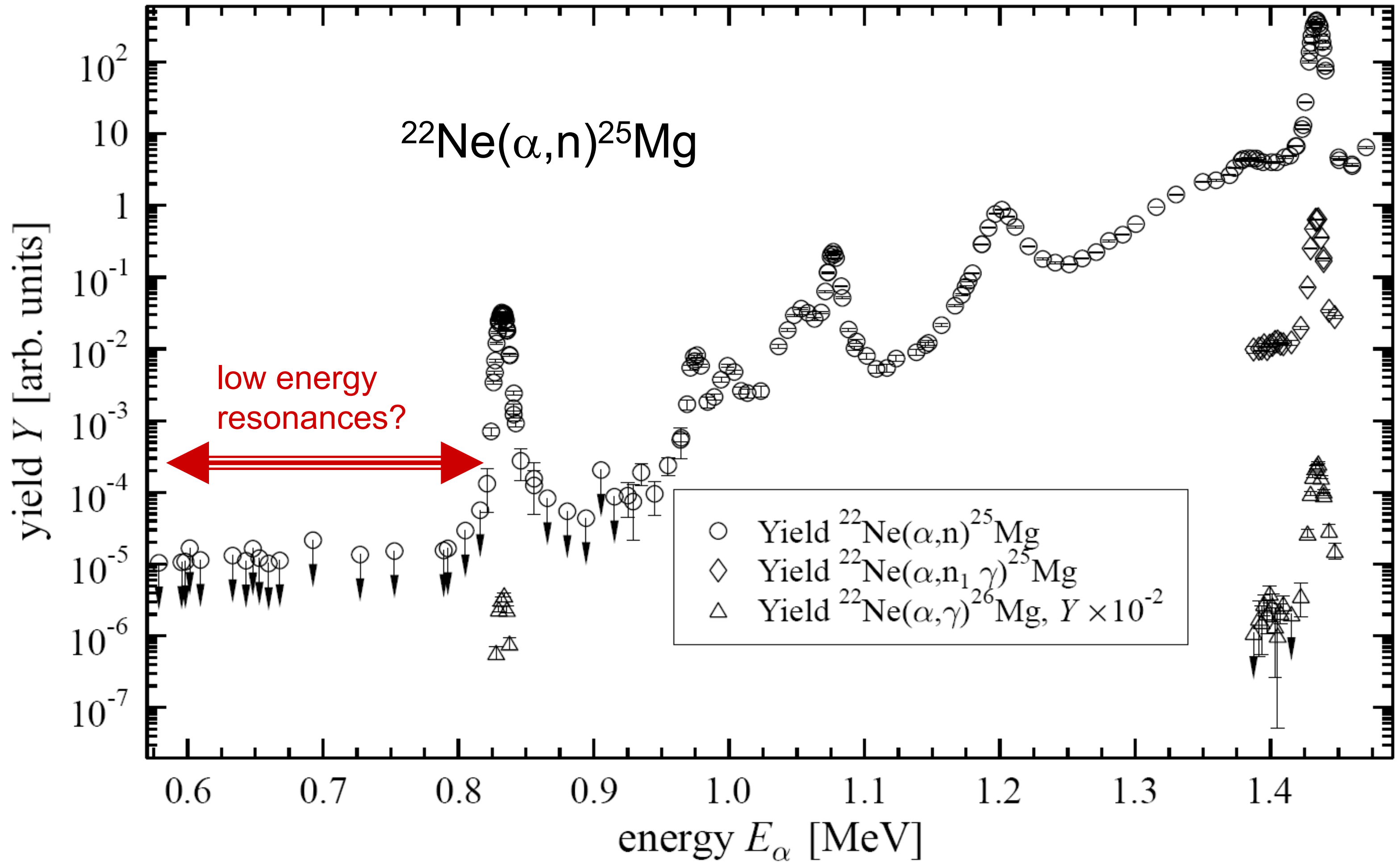
$$\frac{dY_{^{18}O}}{dt} = -Y_{^{18}O}\cdot Y_{^{4}He}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^{18}O(\alpha,\gamma)} + Y_{^{18}F}\cdot\lambda_{^{18}F(\beta^{+})}$$

$$\frac{dY_{^{22}Ne}}{dt} = -Y_{^{22}Ne}\cdot Y_{^{4}He}\cdot\rho\cdot N_A\cdot\left(\langle\sigma\upsilon\rangle_{^{22}Ne(\alpha,n)} + \langle\sigma\upsilon\rangle_{^{22}Ne(\alpha,\gamma)}\right) + Y_{^{18}O}\cdot Y_{^{4}He}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^{18}O(\alpha,\gamma)}$$

$$\frac{dY_{n}}{dt} = -Y_{n}\cdot\lambda_{n(\beta^{-})} - \sum_{x} Y_{X}\cdot Y_{n}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{X(n,\gamma)} + Y_{^{22}Ne}\cdot Y_{^{4}He}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^{22}Ne(\alpha,n)}$$

Neutron production through $^{22}Ne(\alpha,n)^{25}Mg$ depends on reaction rates of this sequence

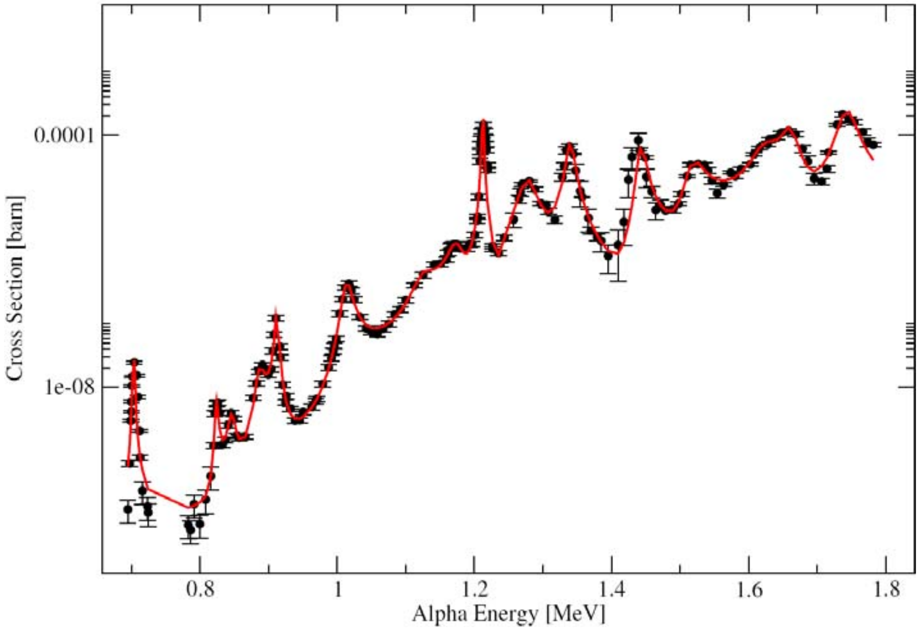
Example: ^{22}Ne(α,n)^{25}Mg

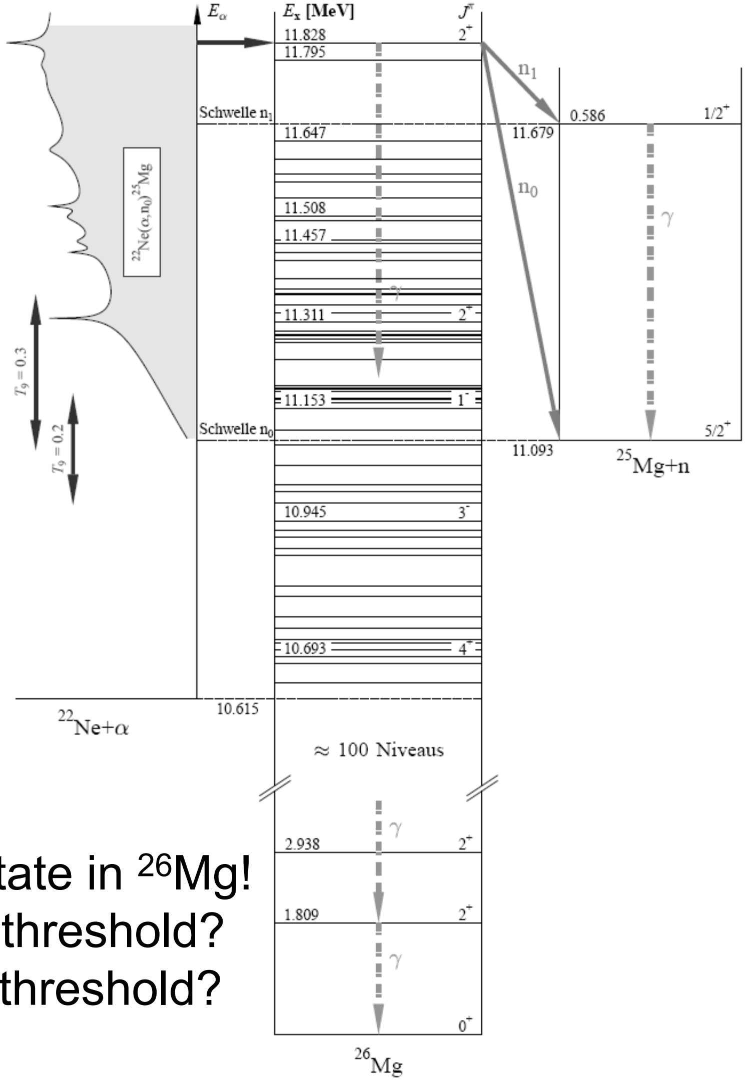


The potential existence of low energy resonances causes considerable uncertainty in reaction rate

Two channel problems!

- Extrapolation to lower energies
- Impact of the ^{22}Ne(α,γ) branch





The 11.311 MeV state is a pronounced α cluster state in ^{26}Mg!

☐ Are there α unbound cluster states above the n threshold?

☐ Are there α unbound cluster states below the n-threshold?

Neutron production

$$\frac{dY_{^{14}N}}{dt} = -Y_{^{14}N}\cdot Y_{^{4}He}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^{14}N(\alpha,\gamma)}$$

$$\frac{dY_{^{18}F}}{dt} = -Y_{^{18}F}\cdot\lambda_{^{18}F(\beta^+)} + Y_{^{14}N}\cdot Y_{^{4}He}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^{14}N(\alpha,\gamma)} = 0$$

$$\frac{dY_{^{18}O}}{dt} = -Y_{^{18}O}\cdot Y_{^{4}He}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^{18}O(\alpha,\gamma)} + Y_{^{18}F}\cdot\lambda_{^{18}F(\beta^+)} = 0$$

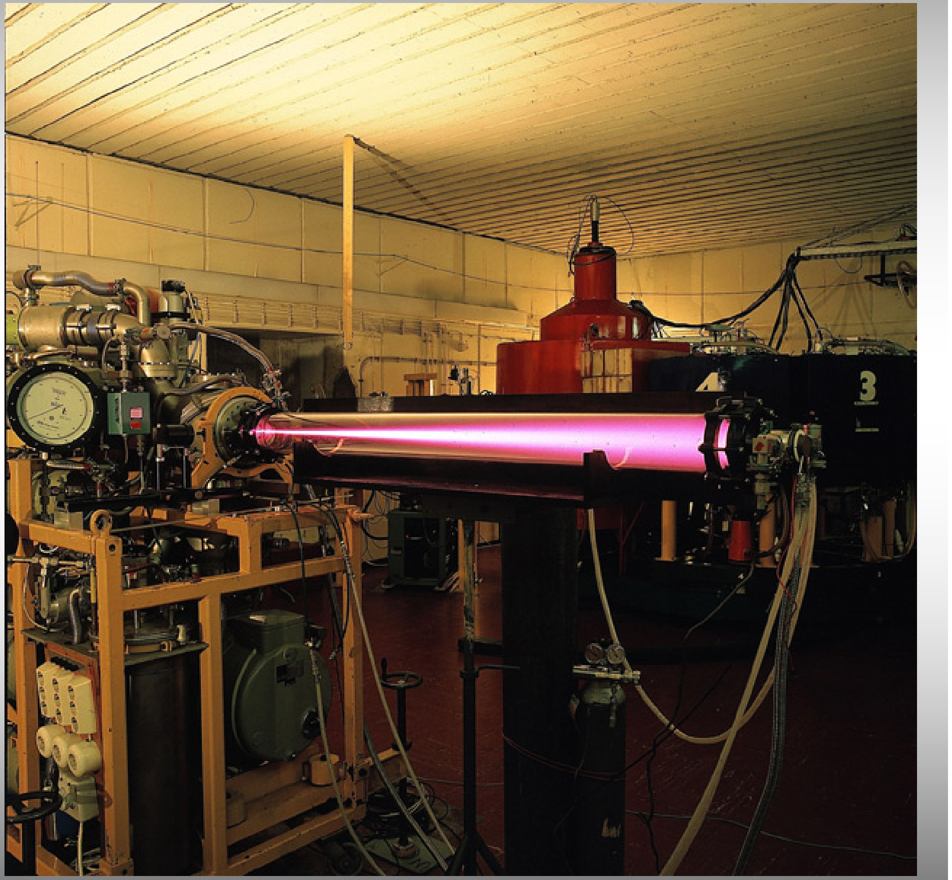
$$\frac{dY_{^{22}Ne}}{dt} = -Y_{^{22}Ne}\cdot Y_{^{4}He}\cdot\rho\cdot N_A\cdot\left(\langle\sigma\upsilon\rangle_{^{22}Ne(\alpha,n)} + \langle\sigma\upsilon\rangle_{^{22}Ne(\alpha,\gamma)}\right) + Y_{^{14}N}\cdot Y_{^{4}He}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^{14}N(\alpha,\gamma)} = 0$$

$$\frac{dY_n}{dt} = -Y_n\cdot\lambda_{n(\beta^-)} - \sum_X Y_X\cdot Y_n\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{X(n,\gamma)} + Y_{^{22}Ne}\cdot Y_{^{4}He}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^{22}Ne(\alpha,n)}$$

$$\frac{dY_n}{dt} = -Y_n\cdot\lambda_{n(\beta^-)} - \sum_X Y_X\cdot Y_n\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{X(n,\gamma)} + Y_{^{14}N} Y_{^{4}He}\cdot\rho\cdot N_A \frac{\langle\sigma\upsilon\rangle_{^{22}Ne(\alpha,n)}\cdot\langle\sigma\upsilon\rangle_{^{14}N(\alpha,\gamma)}}{\left(\langle\sigma\upsilon\rangle_{^{22}Ne(\alpha,n)} + \langle\sigma\upsilon\rangle_{^{22}Ne(\alpha,\gamma)}\right)}$$

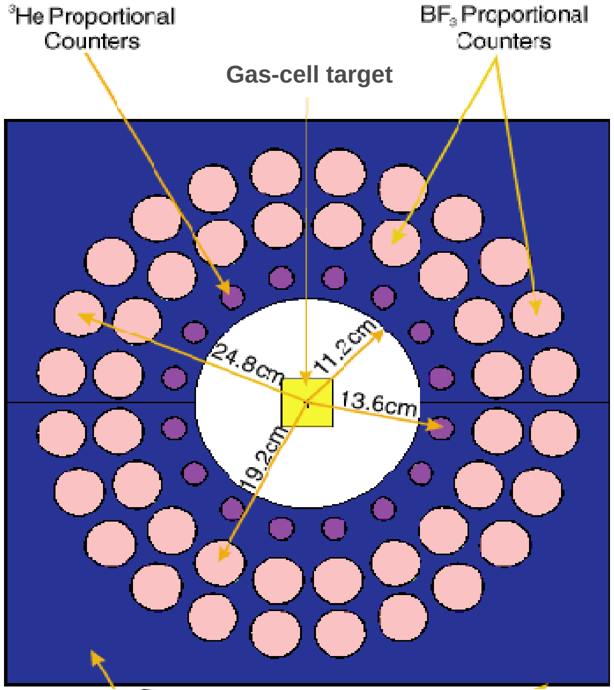
Neutron flux depends on ^{14}N seed abundance from H burning and reaction rate and branching conditions in alpha capture sequence!

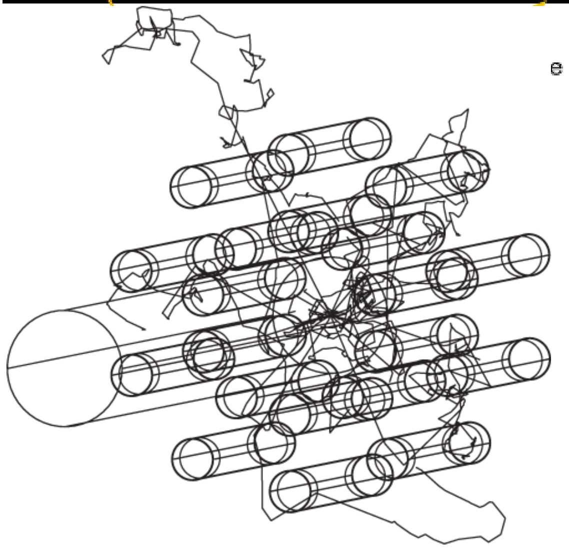
Measurement with gas target

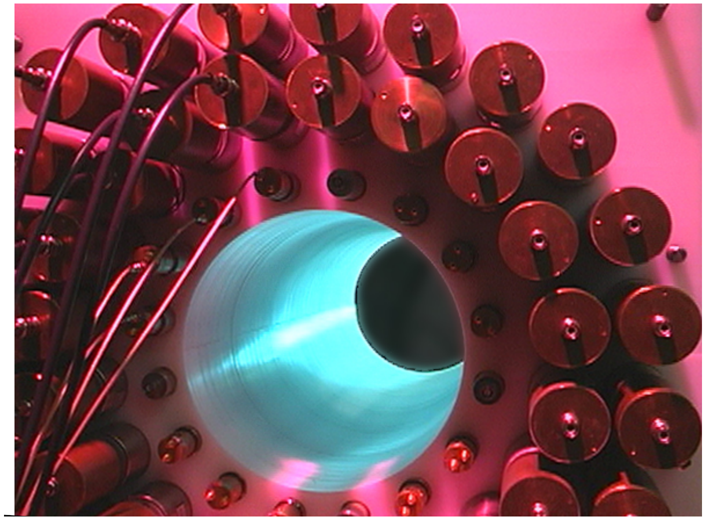


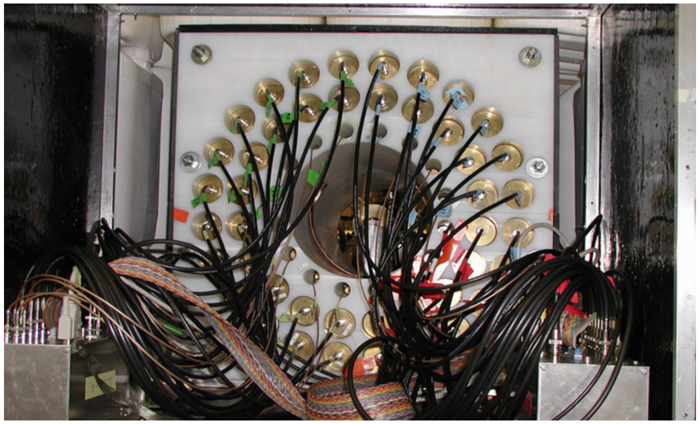
Low energy beam into extended ^{22}Ne gas-target

Neutron Detector Array



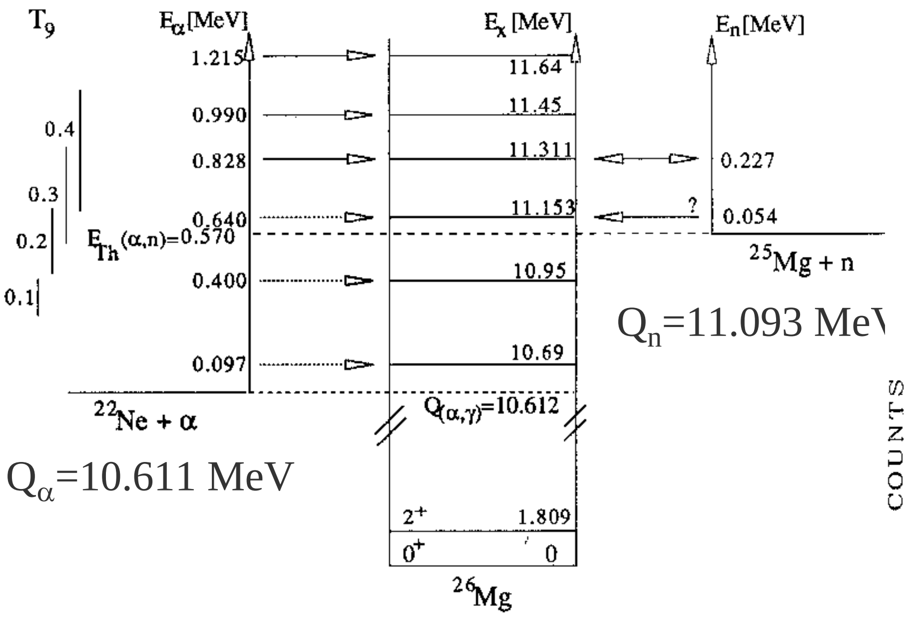






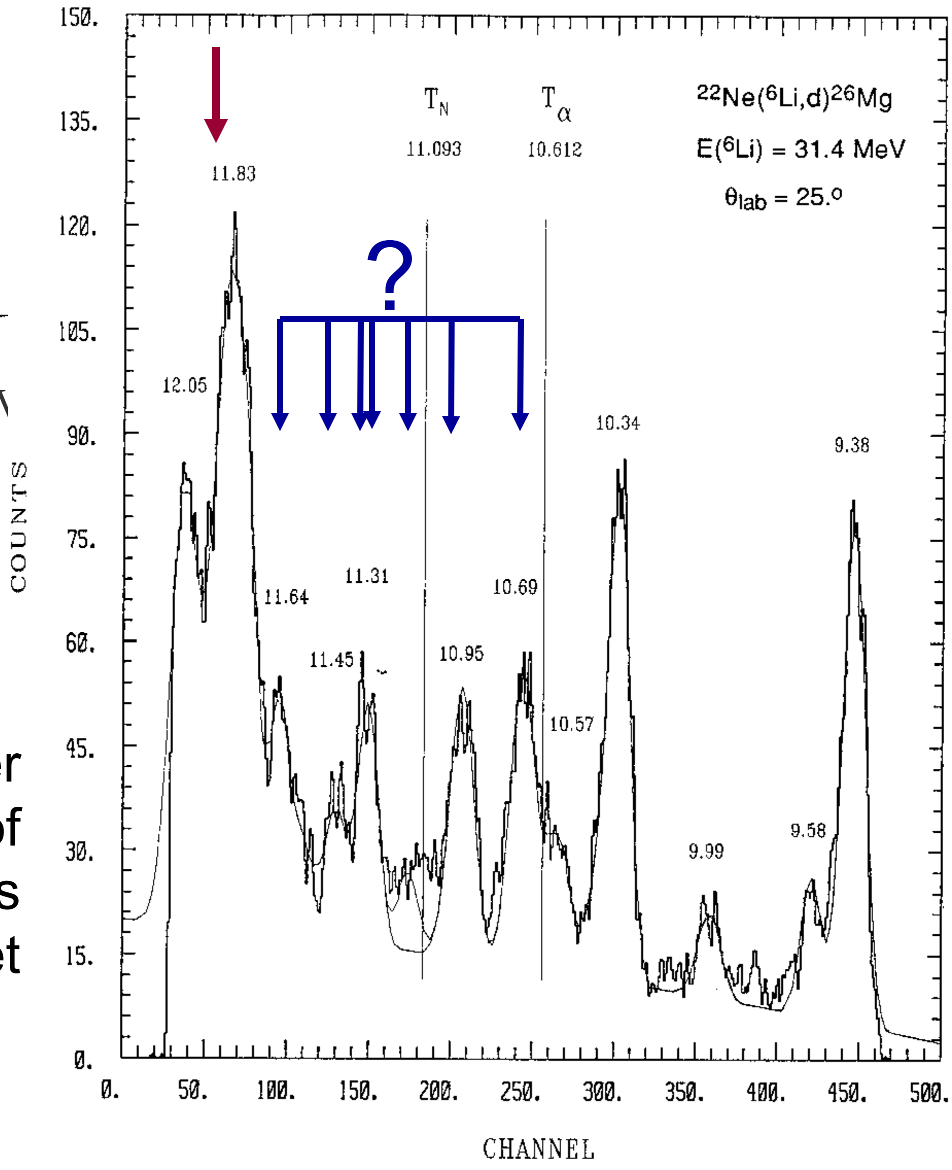
Combination with underground muon shielding necessary for reduction of muon induced neutrons

Complementary α-transfer studies in ^{26}Mg



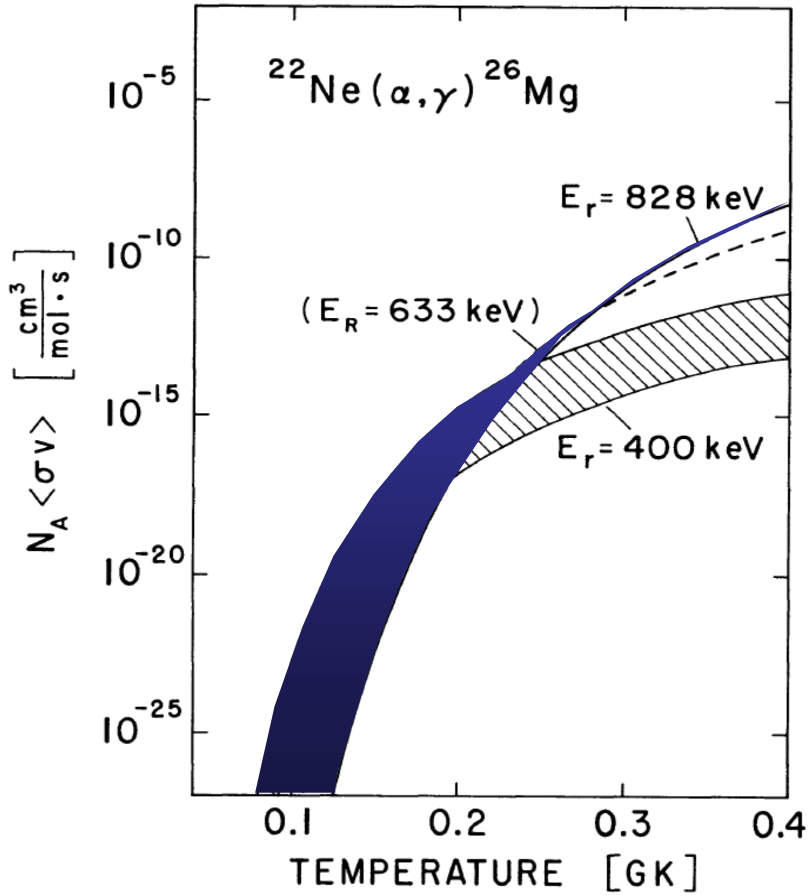
Q_n=11.093 MeV

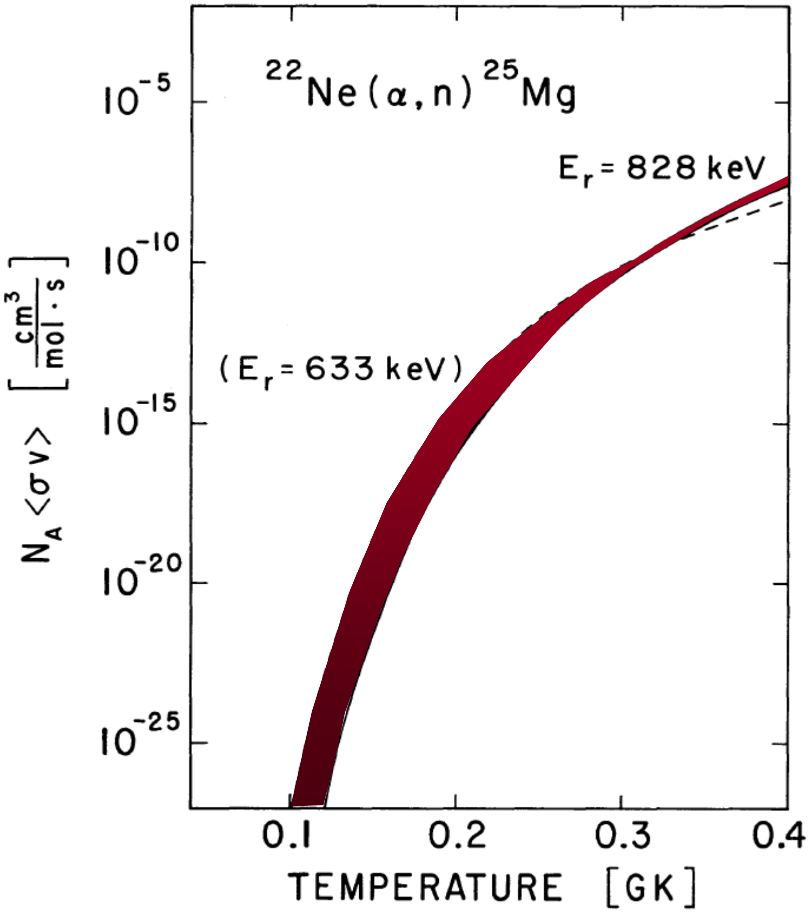
Q_α=10.611 MeV



Observational evidence for α cluster configuration near the α threshold of ^{26}Mg at 10-12 MeV! Recent studies with better resolution by Ugalde et al, confirmed more resonances.

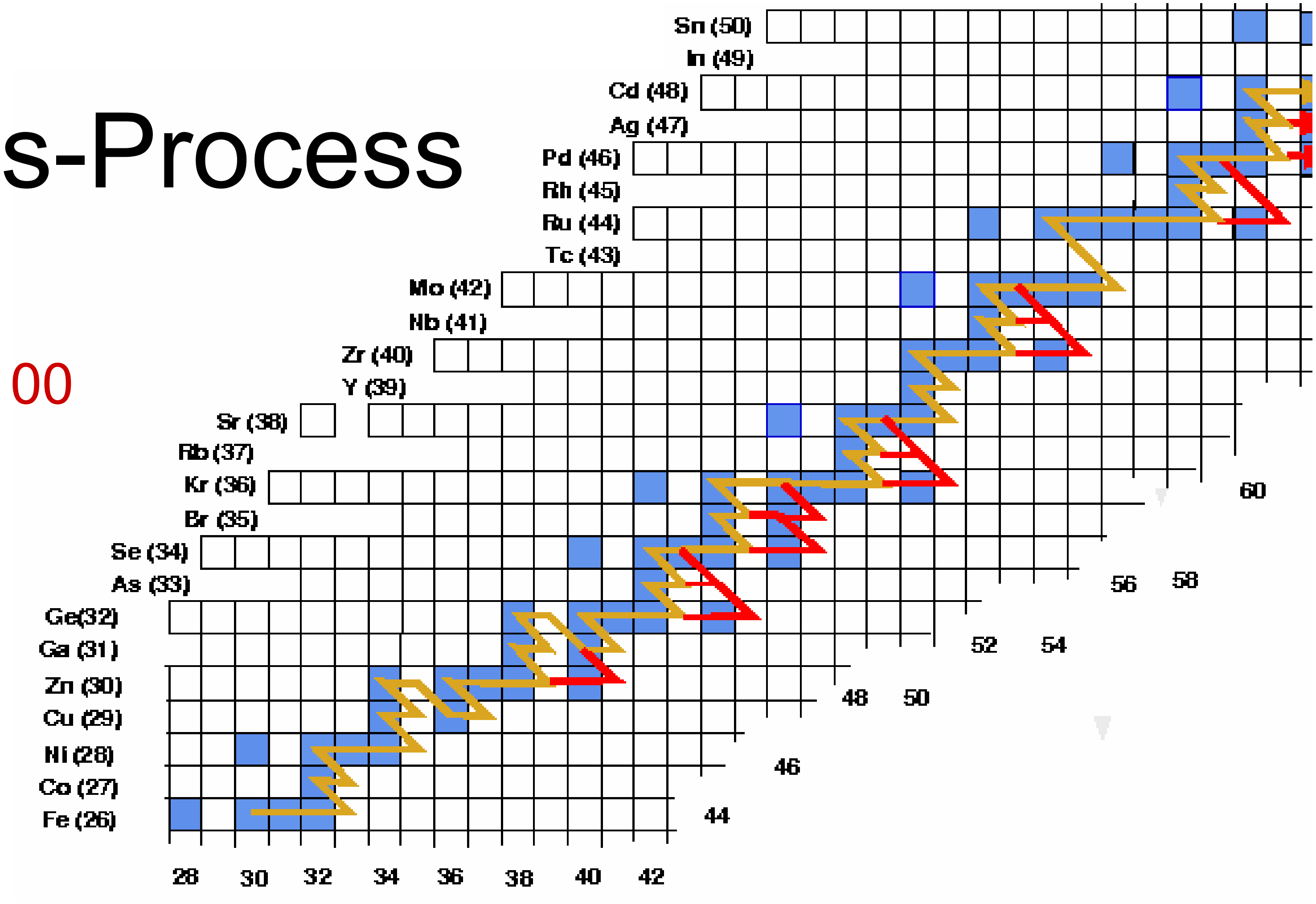
Reaction Rate Limits and Uncertainties





Weak s-Process

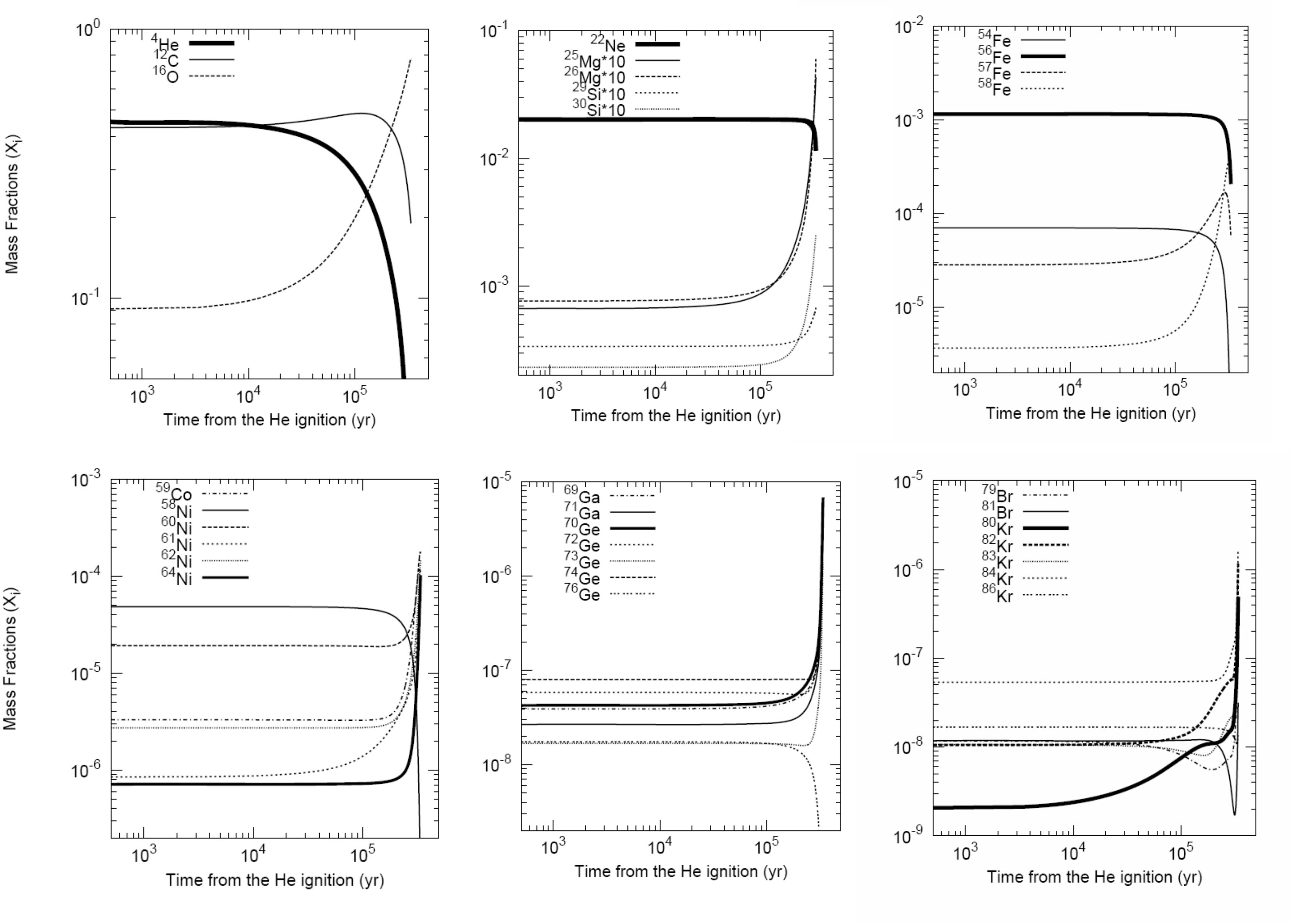
Leads to A~100



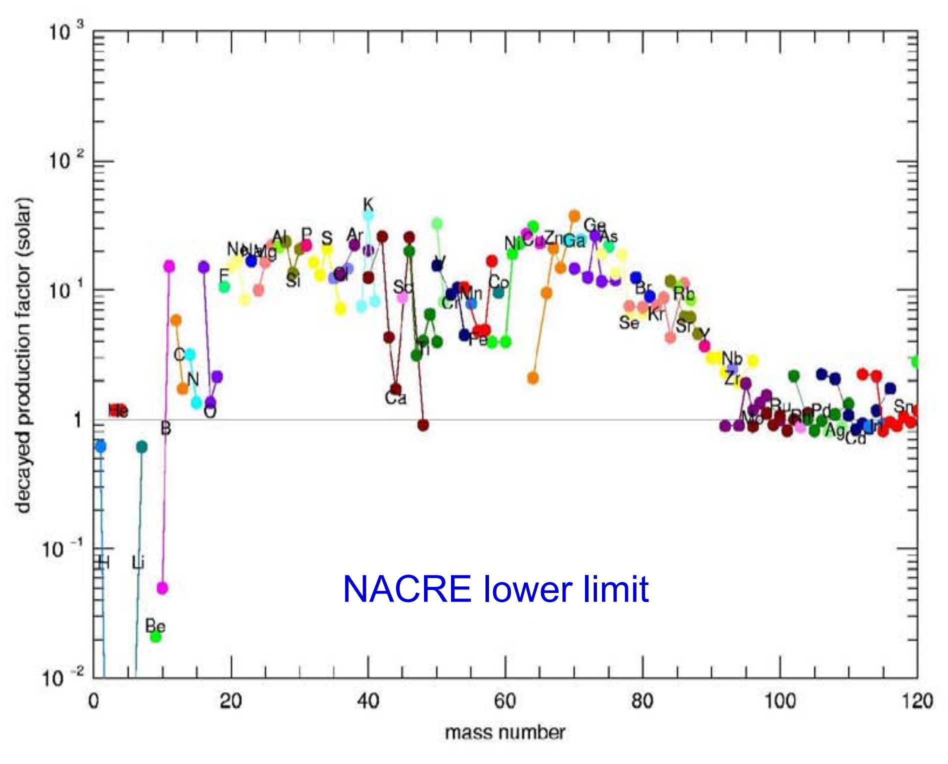
$$\frac{dY_n}{dt} = -\sum_x Y_X \cdot Y_n \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{X(n,\gamma)} + Y_{^{22}Ne} \cdot Y_{^{4}He} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{22}Ne(\alpha,n)}$$

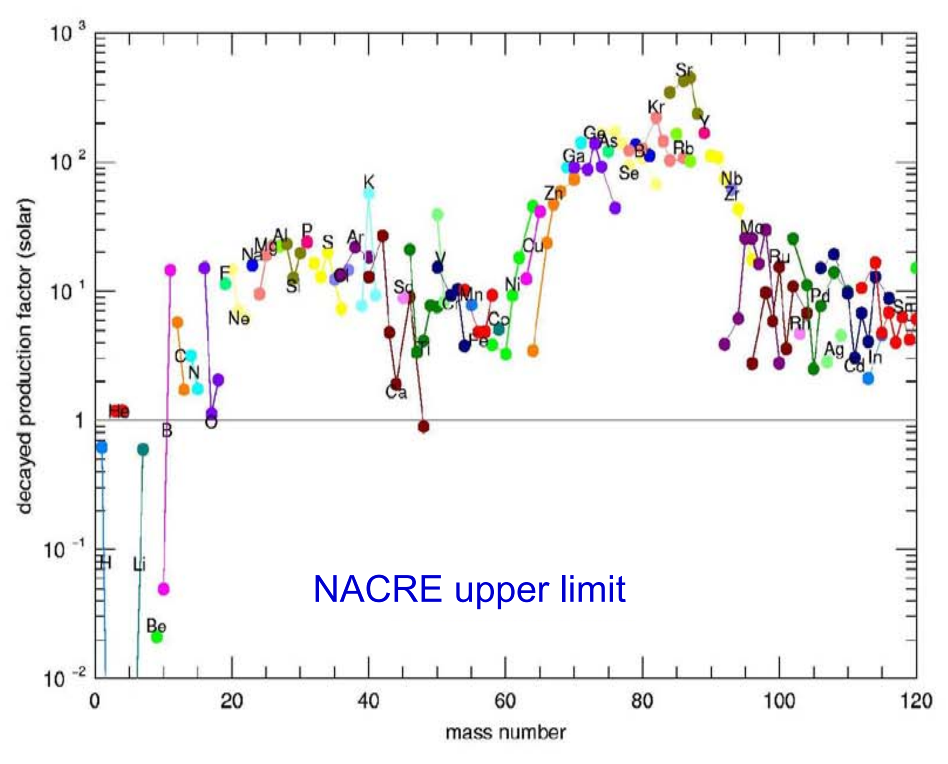
$$\frac{dY_{^{A+1}X}}{dt} = -Y_{^{A+1}X} \cdot Y_n \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{A+1}X(n,\gamma)} - Y_{^{A+1}X} \cdot \lambda_{^{A+1}X(\beta)} + Y_{^{A}X} \cdot Y_n \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{A}X(n,\gamma)} + Y_{^{A}_{Z\pm1}X} \cdot \lambda_{^{A}_{Z\pm1}X(\beta)}$$

Abundance evolution in weak s-process



Weak-s-process abundances

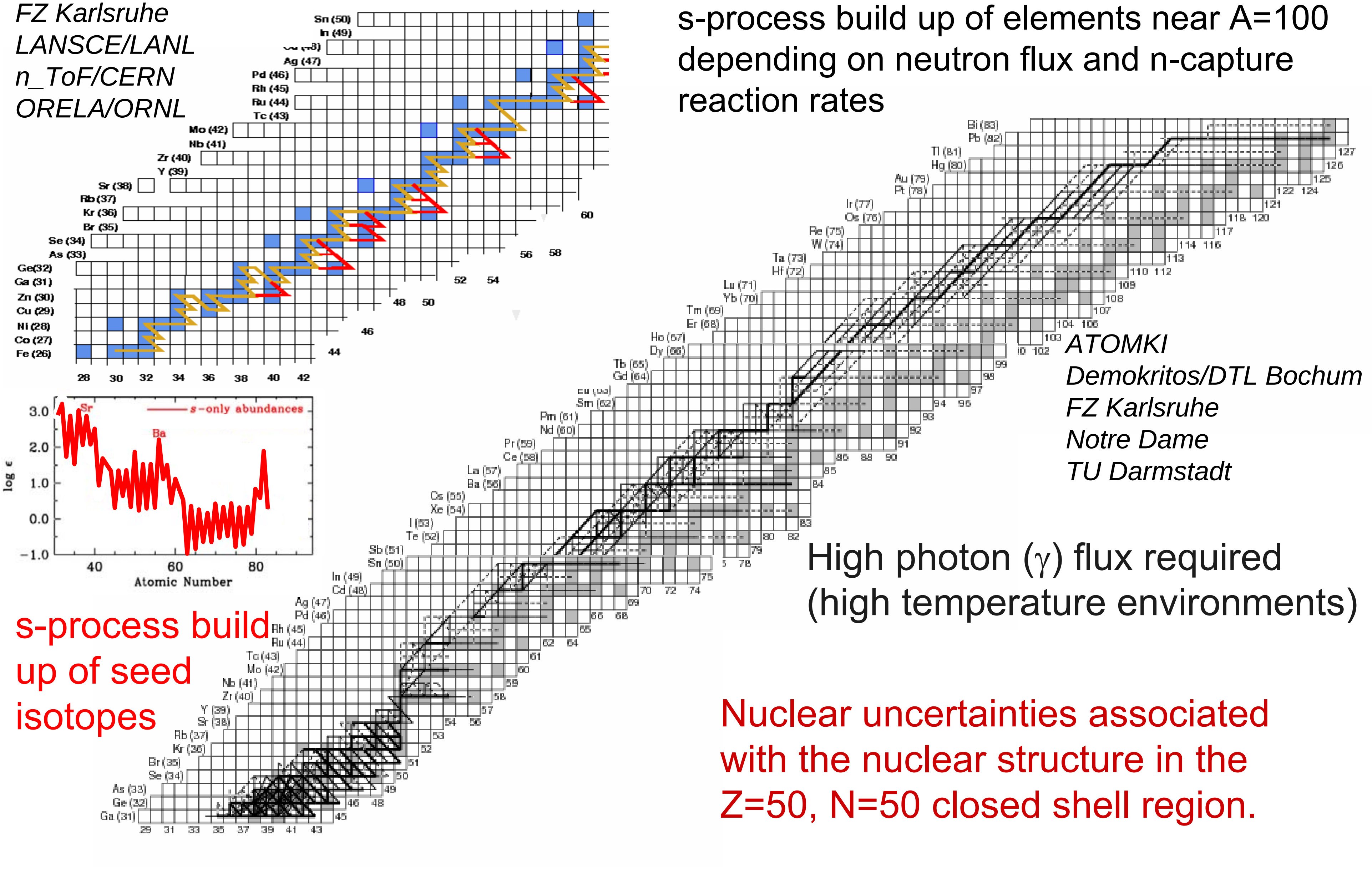




Large uncertainties in the final weak s-process abundance distribution due to the uncertainties in the ^{22}Ne+α rates. This translates into uncertainty for:

- Weak s-process abundances
- Seed material for p-process and p-process abundances
- LEPP or second r-process

From s- to p-Process



FZ Karlsruhe
LANSCE/LANL
n_ToF/CERN
ORELA/ORNL

s-process build up of elements near A=100 depending on neutron flux and n-capture reaction rates

s-process build up of seed isotopes

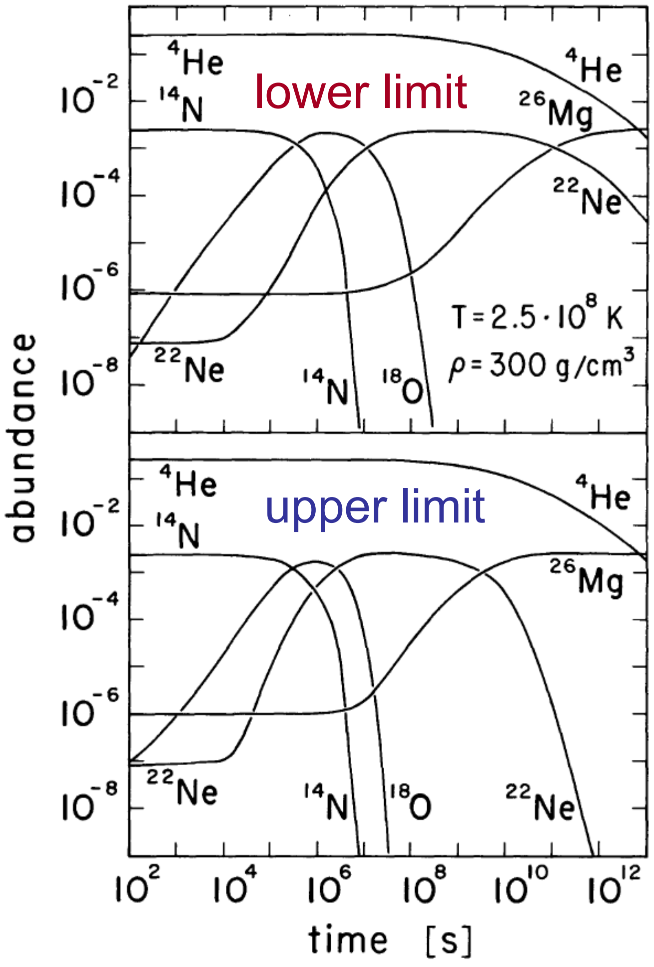
ATOMKI
Demokritos/DTL Bochum
FZ Karlsruhe
Notre Dame
TU Darmstadt

High photon (γ) flux required (high temperature environments)

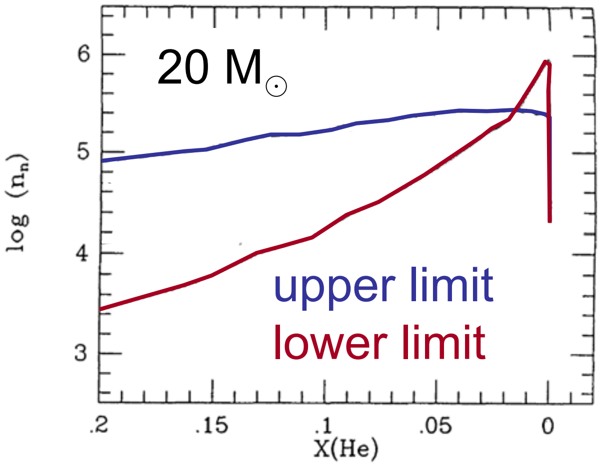
Nuclear uncertainties associated with the nuclear structure in the Z=50, N=50 closed shell region.

Possible impact on seed conditions in next burning sequence

Nucleosynthesis for Z≤12



Neutron production



- ^{22}Ne for Carbon burning as second s-process site
- n-production for s-process

The low energy cross section of $^{13}C(\alpha,n)^{16}O$

Uncertainties:
-3 keV 1/2+ subthreshold state
-490 keV 3/2+ subthreshold state

Direct measurement

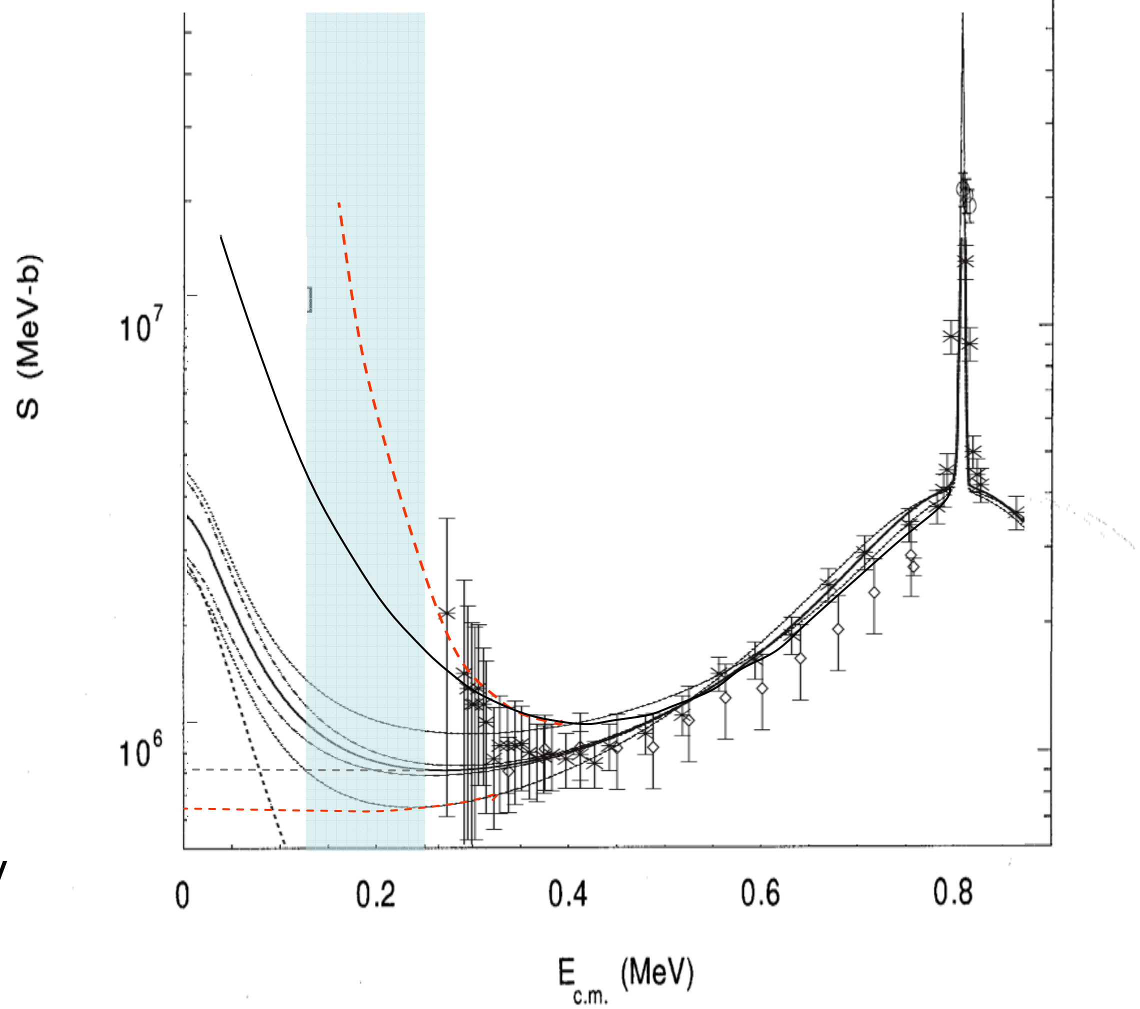
Brune et al. 1993
Drotleff et al. 1993

Strong indication of subthreshold state!

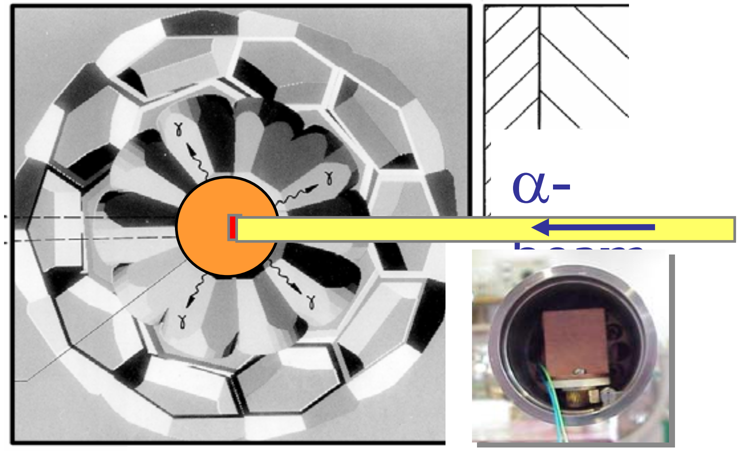
Indirect transfer studies $^{13}C(^{6}Li,d)^{17}O$

Kubono et al. 2003
Keeley et al. 2003
Johnson et al. 2007
Hamache et al 2008

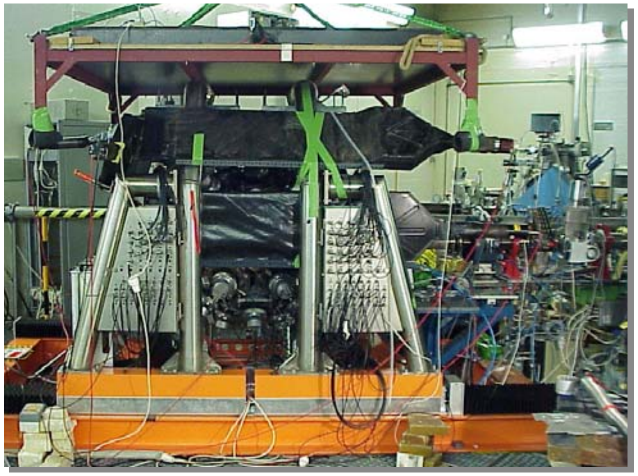
First ANC results indicate a weaker resonance strength as suggested by direct (α,n) S-factor extrapolation, second ANC study increases value!



Low-energy, low-background Experiment with 4π BaF_2 γ-array



Neutron detection through the conversion of neutrons through Cd(n,γ) with γ-detection in surrounding BaF_2 array!

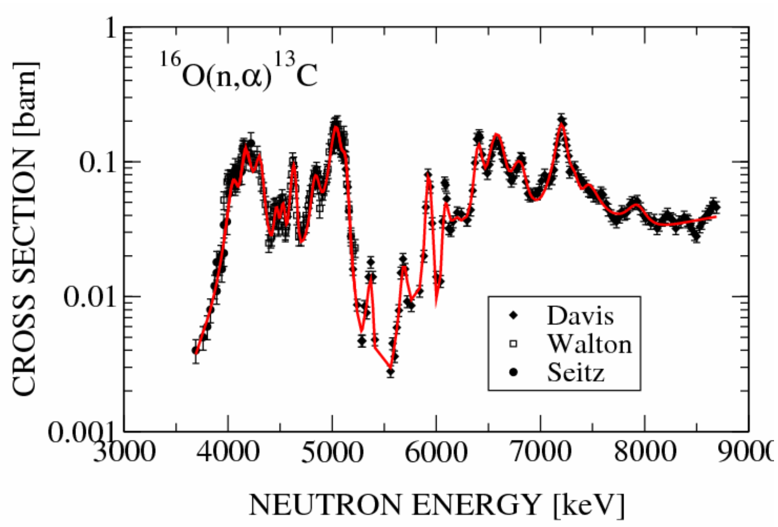


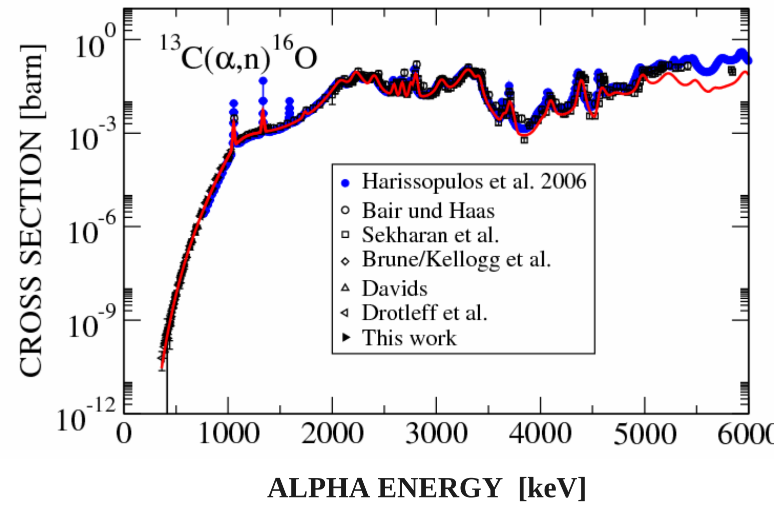
Active shielding techniques;
Pulse shape analysis;

neutron background 0.014 n/s

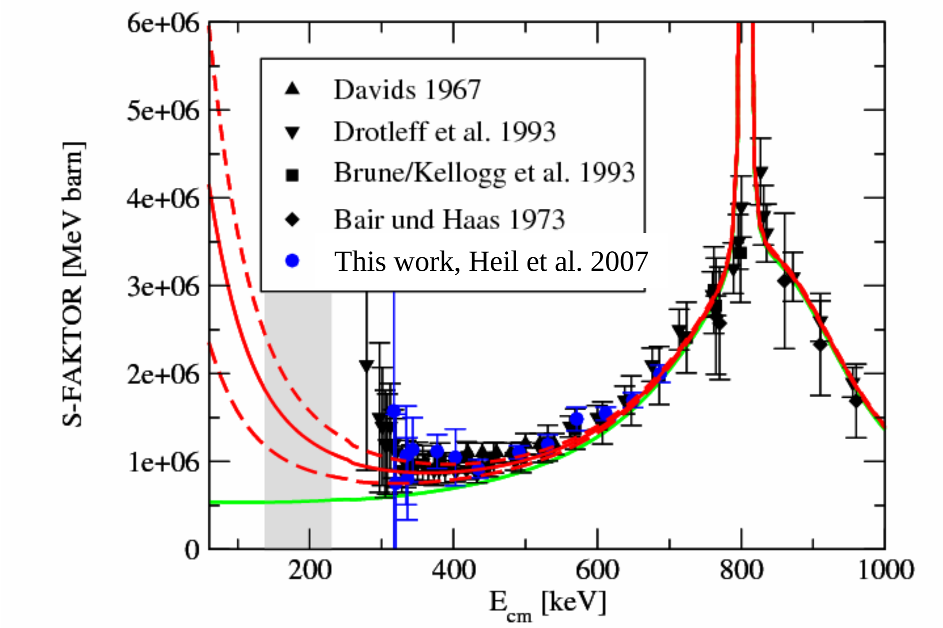
Heil et al. 2008

Fit predictions for $^{13}C(\alpha,n)$ S-factor





Fits of all possible reaction channels
$^{13}C(\alpha,n)^{16}O$, $^{16}O(n,\alpha)^{13}C$,
$^{13}C(\alpha,\alpha)^{13}C$, $^{16}O(n,n)^{16}O$
$^{13}C(\alpha,\alpha'\gamma)^{13}C$, $^{16}O(n,n'\gamma)^{16}O$



Low energy extrapolation in good agreement with the ANC predictions!