The importance of α-clustering in nuclear astrophysics

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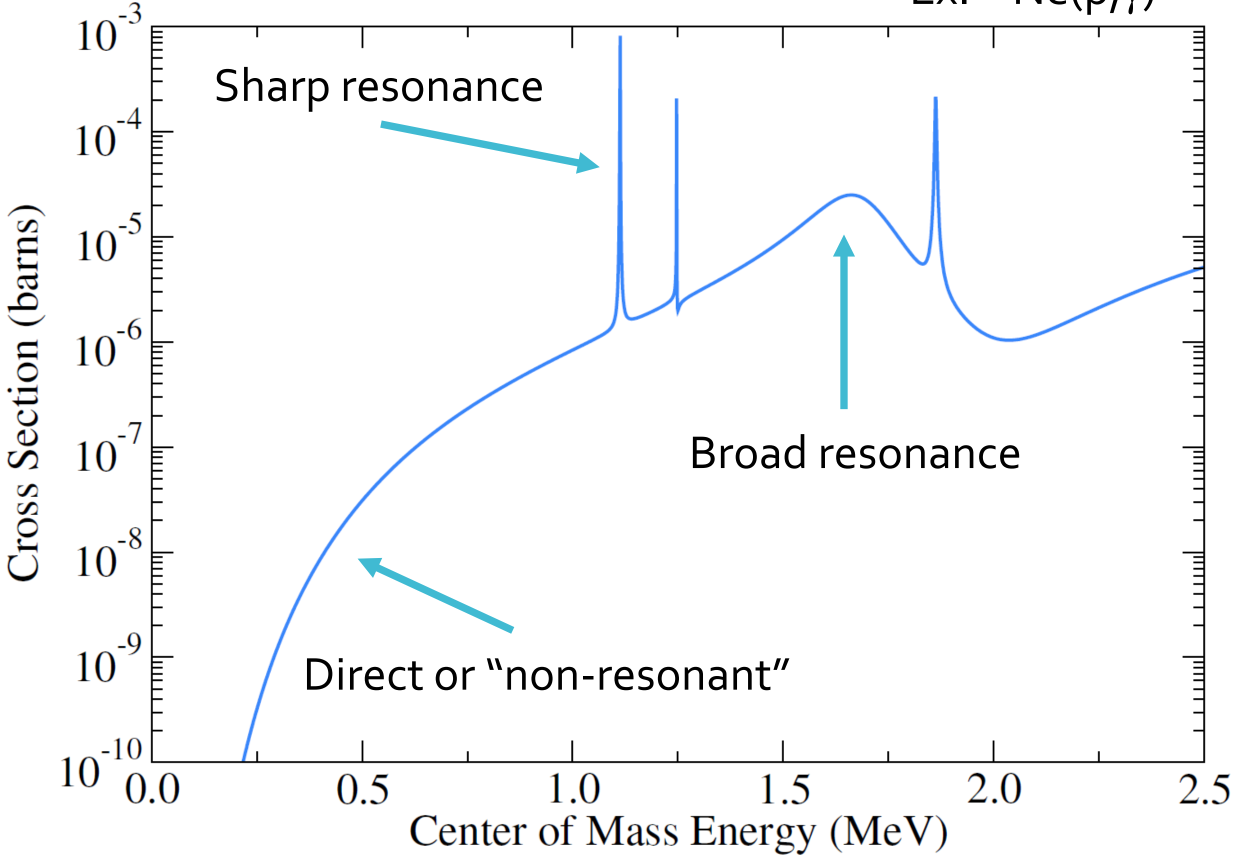
What kind of reactions am I talking about?

- Low mass nuclei (A<30)
  - Capture reactions
    - (α,γ) but also (p,γ)
  - (p,α)
- Low level densities
- Individual state(s) near threshold are critical (Ikeda)

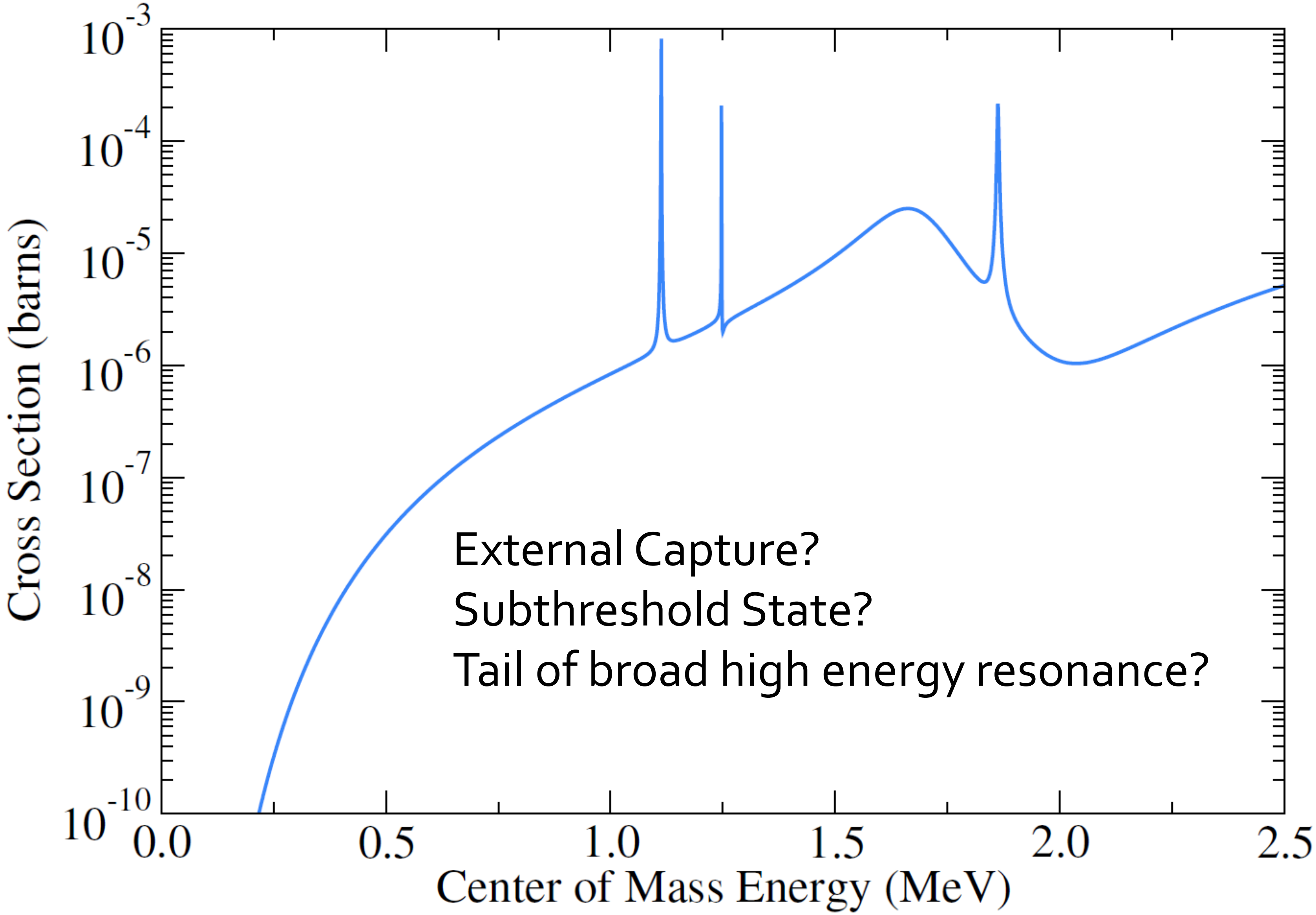
Reaction Rates

$$N_A\langle\sigma v\rangle = N_A \frac{(8/\pi)^{1/2}}{\mu^{1/2}(k_B T)^{3/2}} \int_0^\infty \sigma E \exp(-E/k_B T)\, dE,$$

Ex. $^{20}Ne(p,\gamma)$

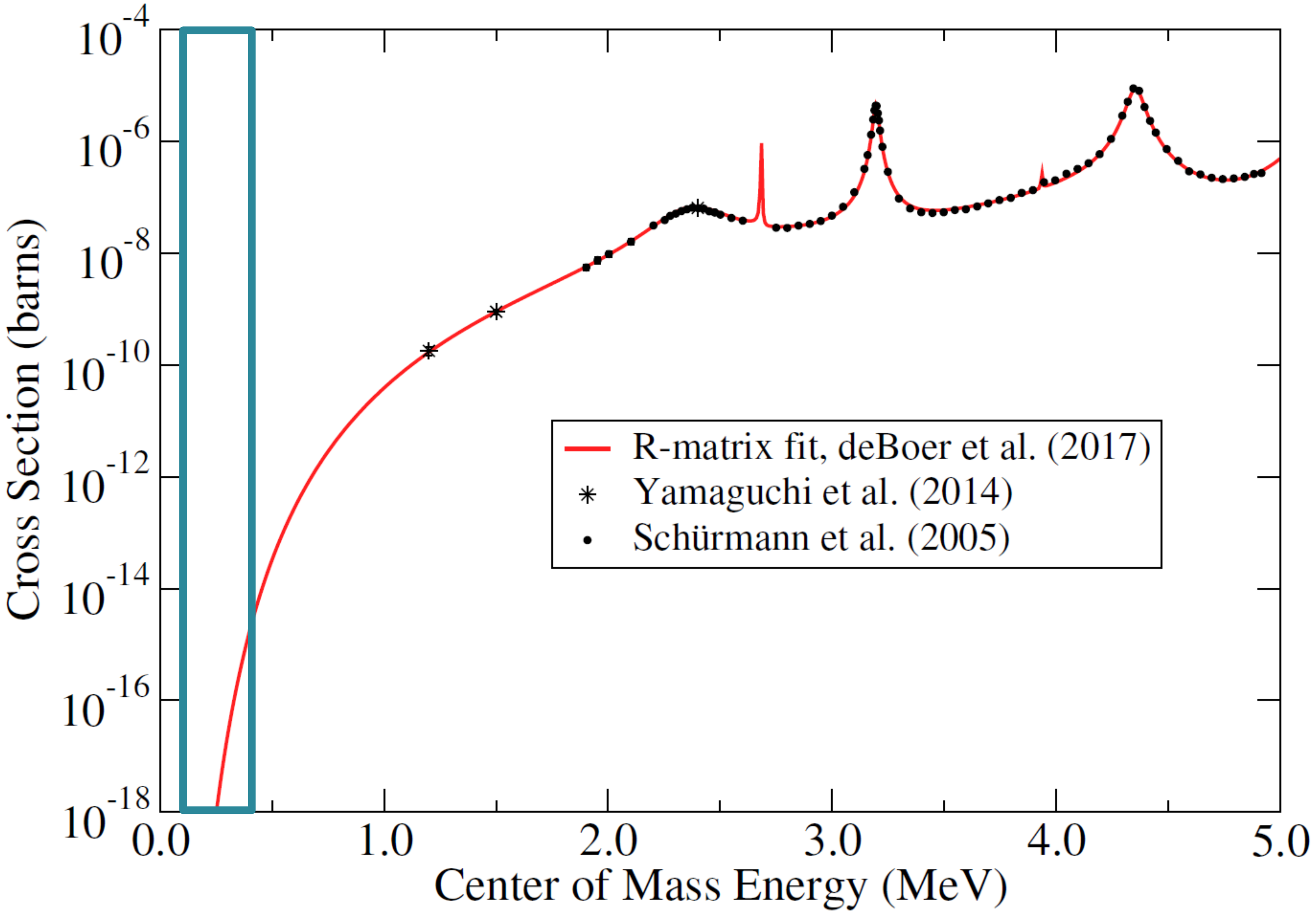


Reaction Components

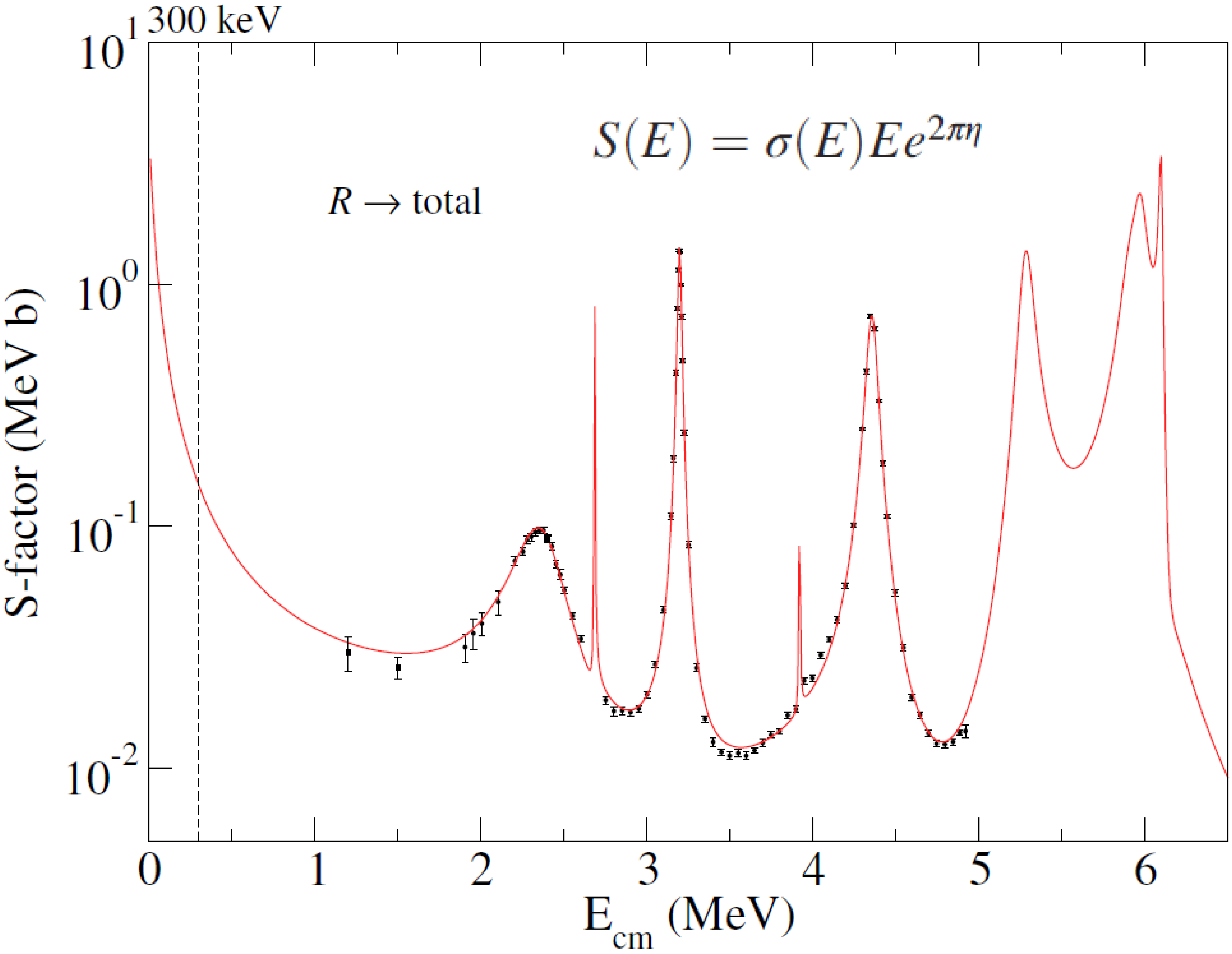


Charged particle cross section extrapolations

T ≈ 0.2 GK



S-factor



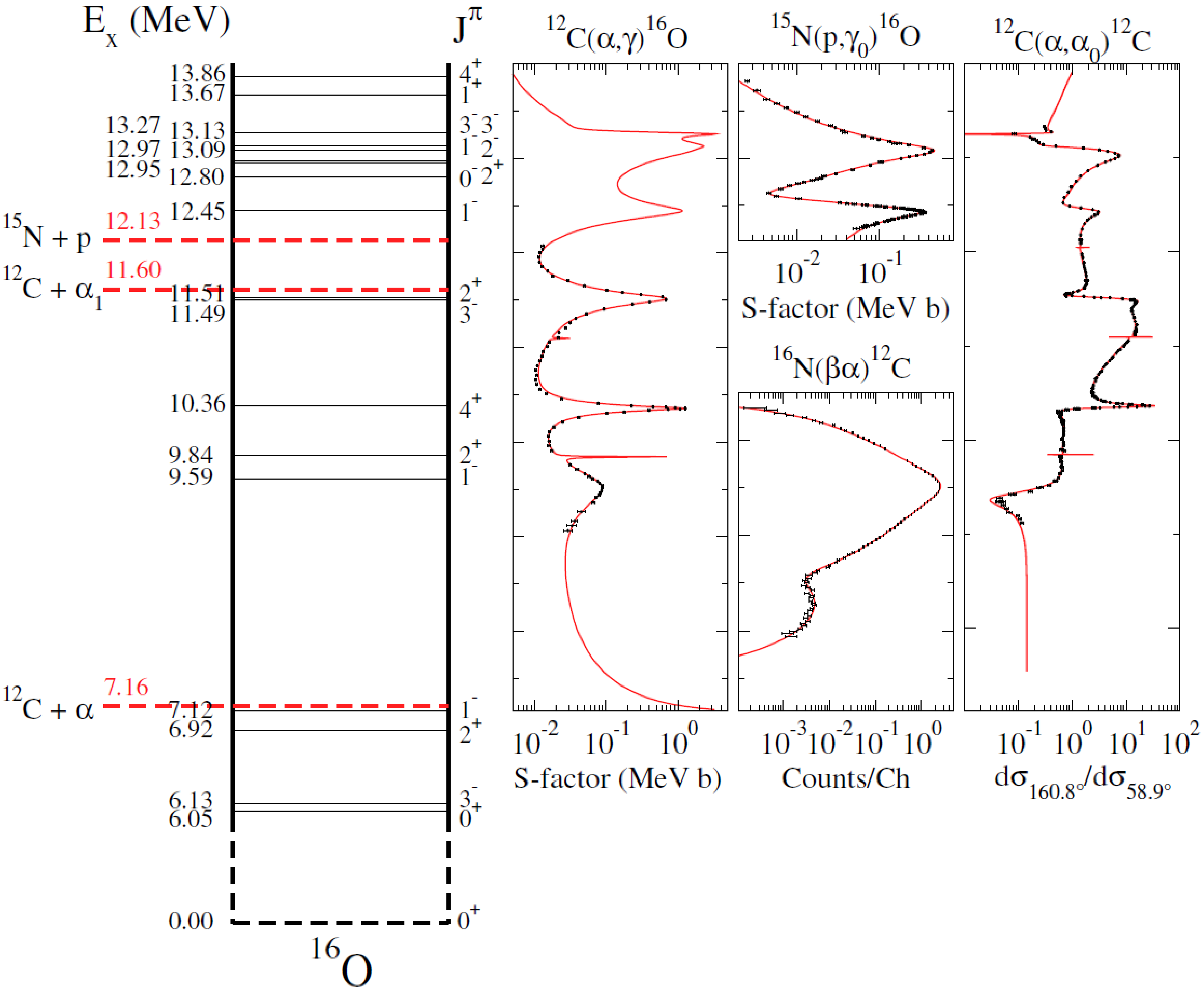
300 keV
$S(E) = \sigma(E)Ee^{2\pi\eta}$
$R \rightarrow$ total
S-factor (MeV b)
10^{1}
10^{0}
10^{-1}
10^{-2}
0
1
2
3
4
5
6
E_{cm} (MeV)

Phenomenological *R*-matrix

- Provides basic framework to calculate cross sections
- Resonances and direct contribution strengths are put in *ad hoc*
- NEED!
  - Good understanding of the nuclear structure
    - Level structure
    - Reaction mechanisms
    - Accurate cross section data

What do you need to do an R-matrix fit?

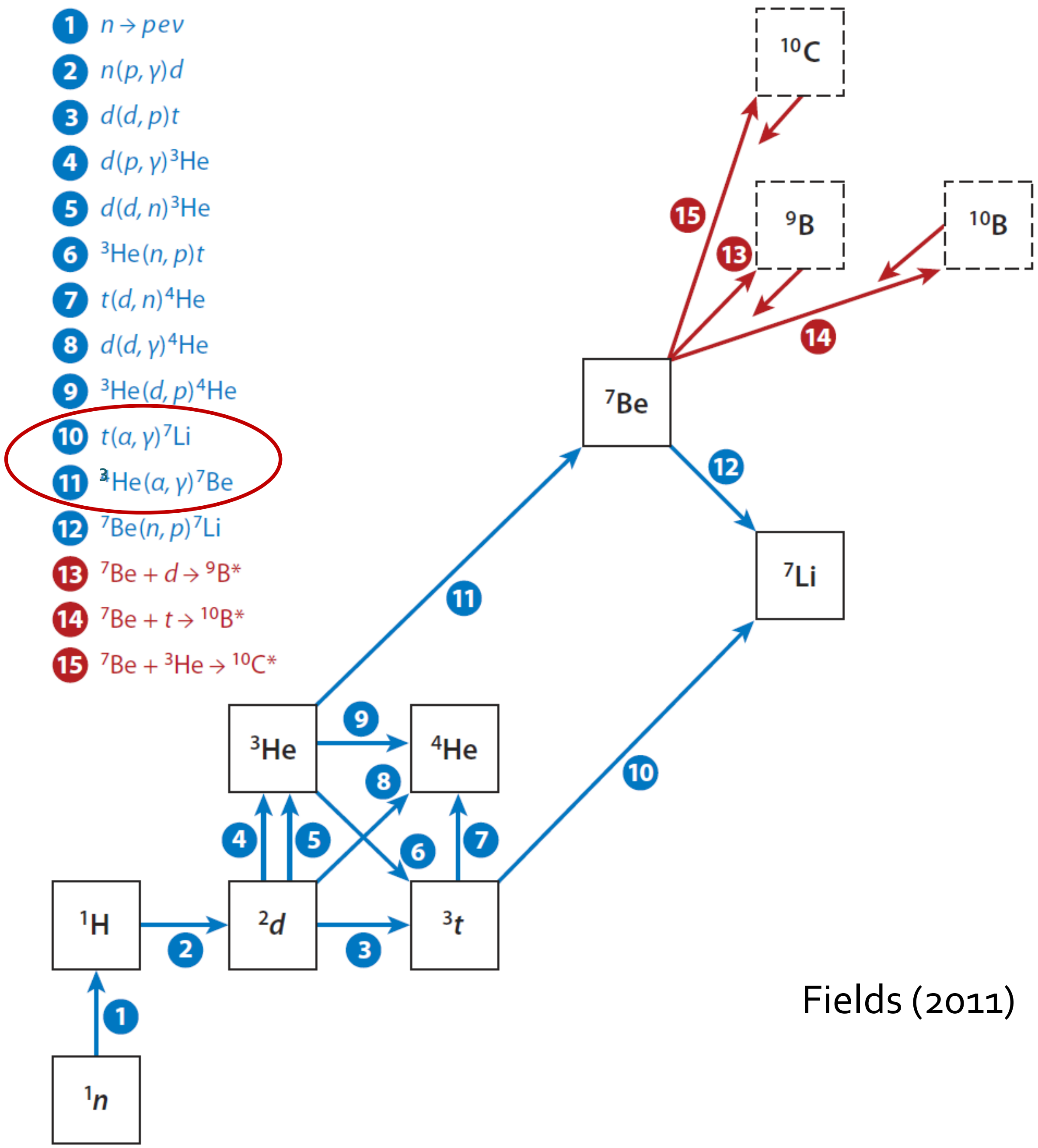
- J^{π}'s
- Energies
- Partial widths
- Asymptotic Normalization Coefficients for subthreshold states
- Data for every decay path



What kinds of nucleosynthesis processes?

- Big Bang (BBN)
- Carbon-Nitrogen-Oxygen (CNO) cycles
- Helium Burning

BBN

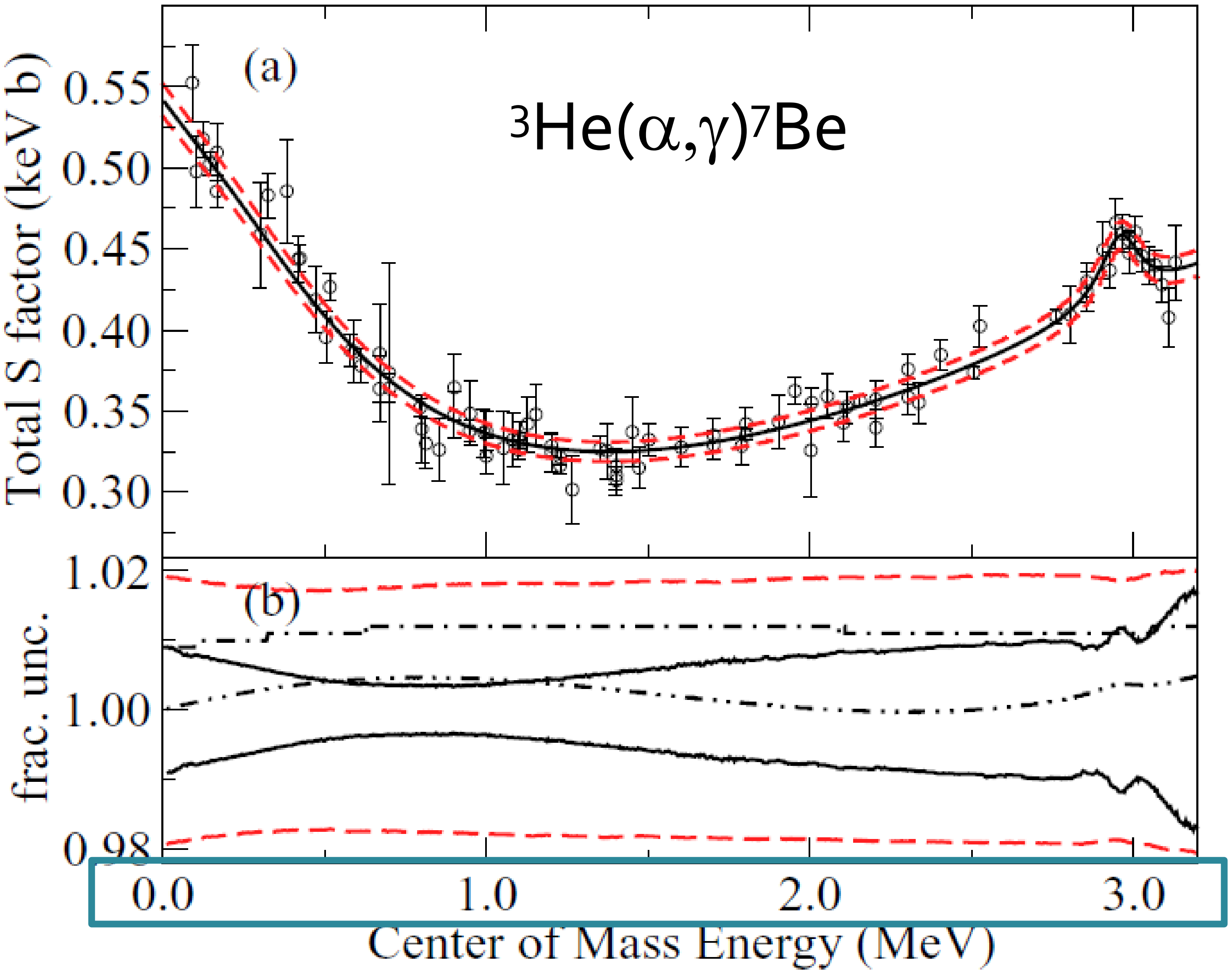


Fields (2011)

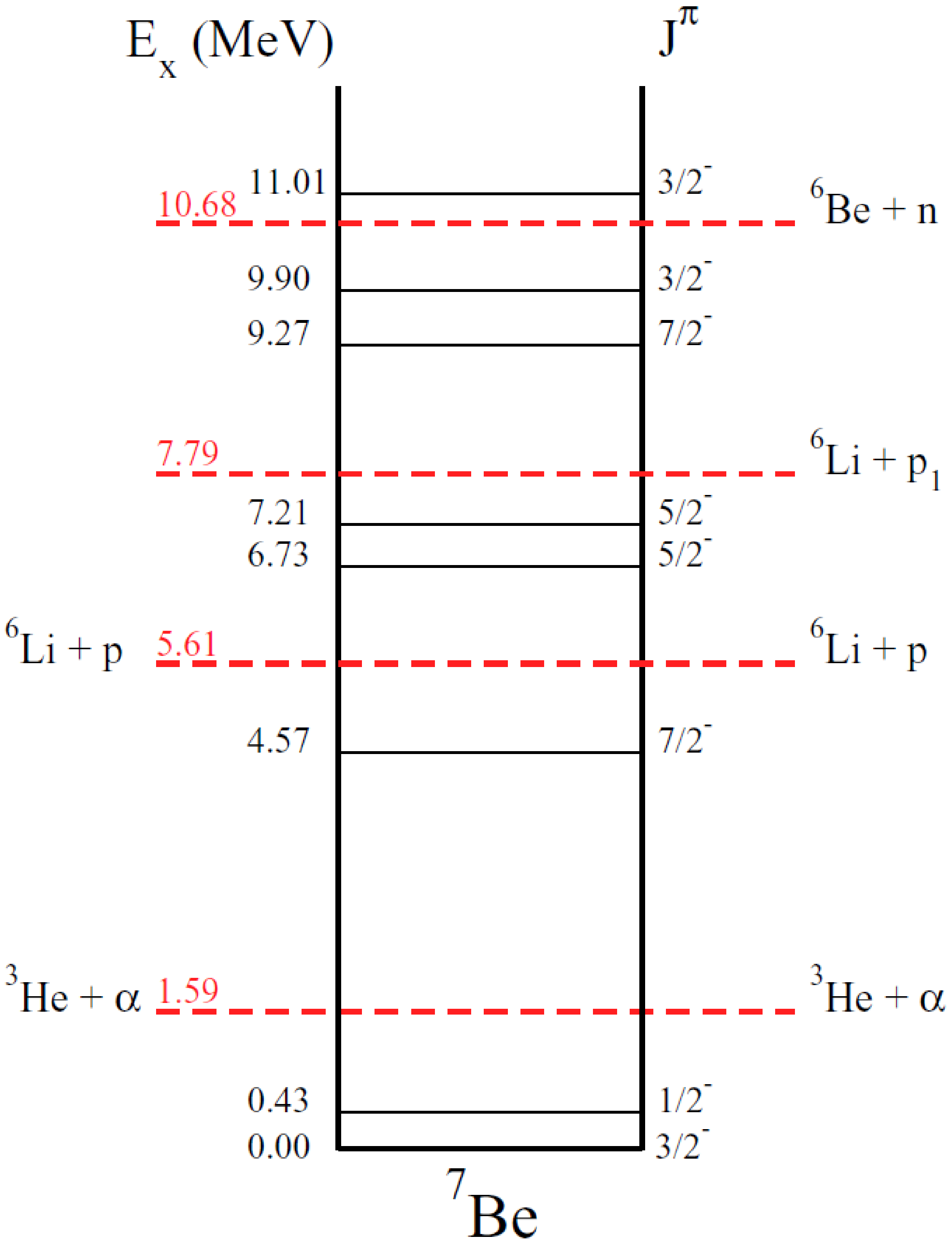
BBN

- $^{3}He(\alpha,\gamma)^{7}Be$

Observed Cross Section:
External Capture?
Subthreshold State?
Tail of broad high energy resonance?

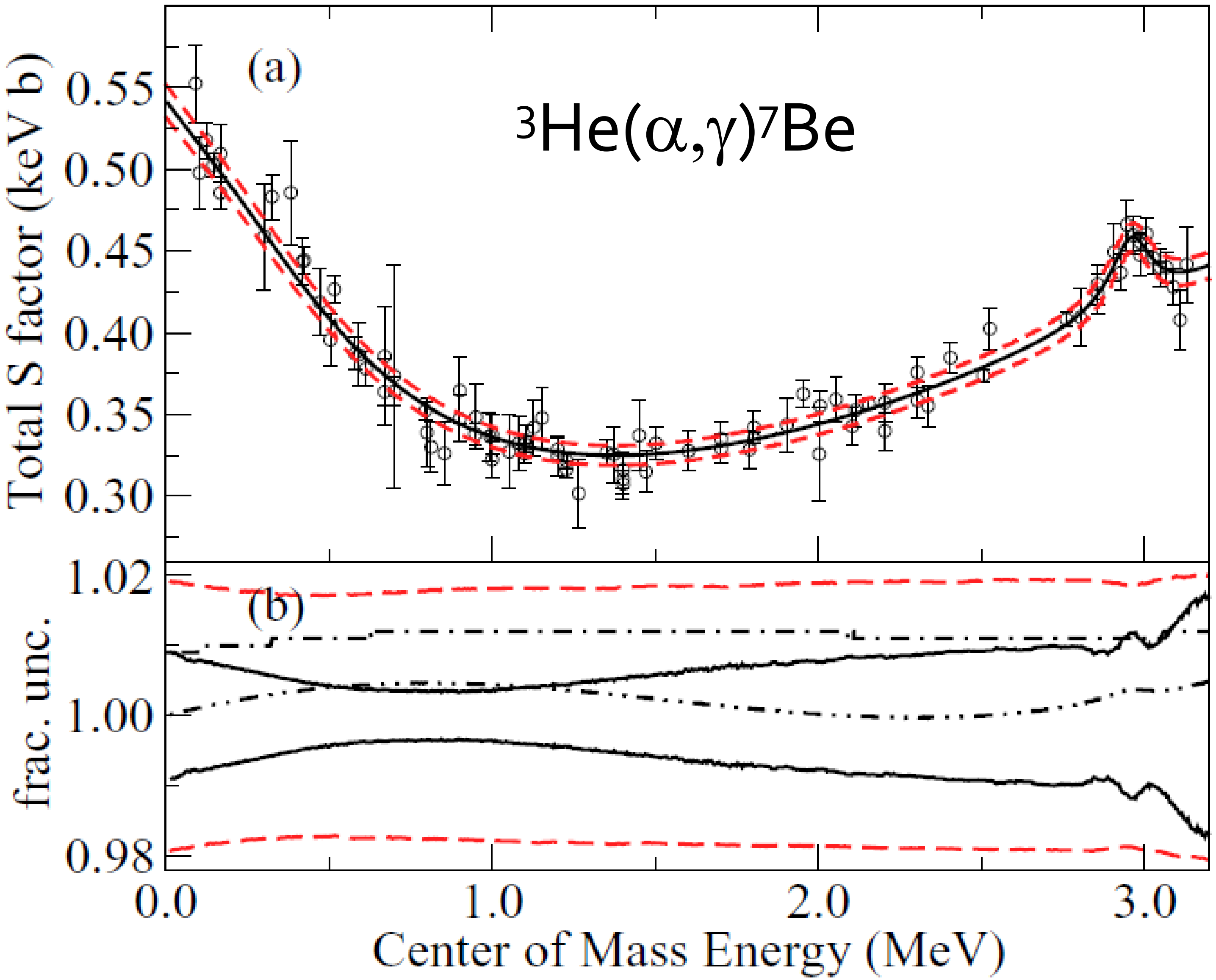


Level structure

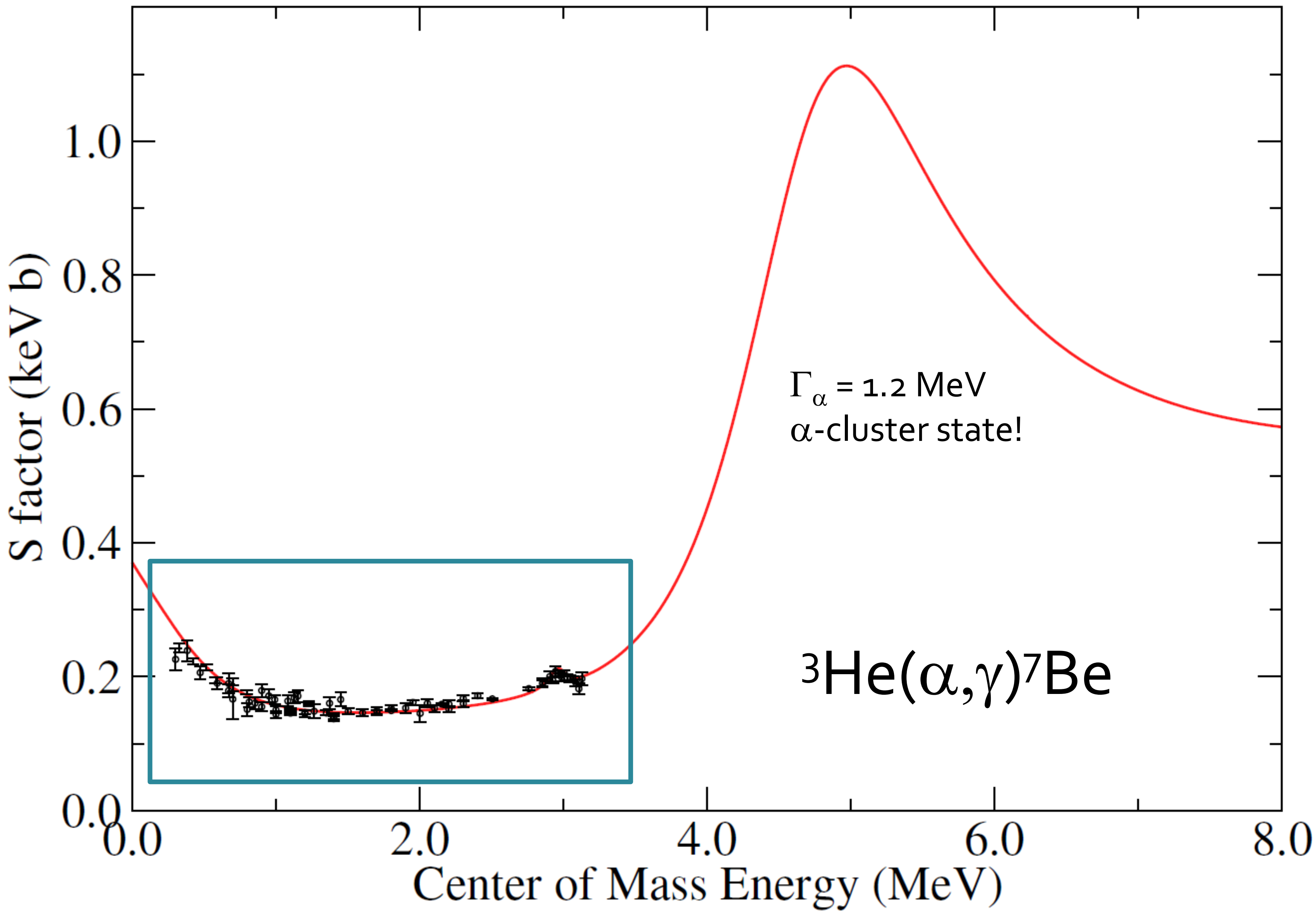


Tails of higher energy states

Observed Cross Section

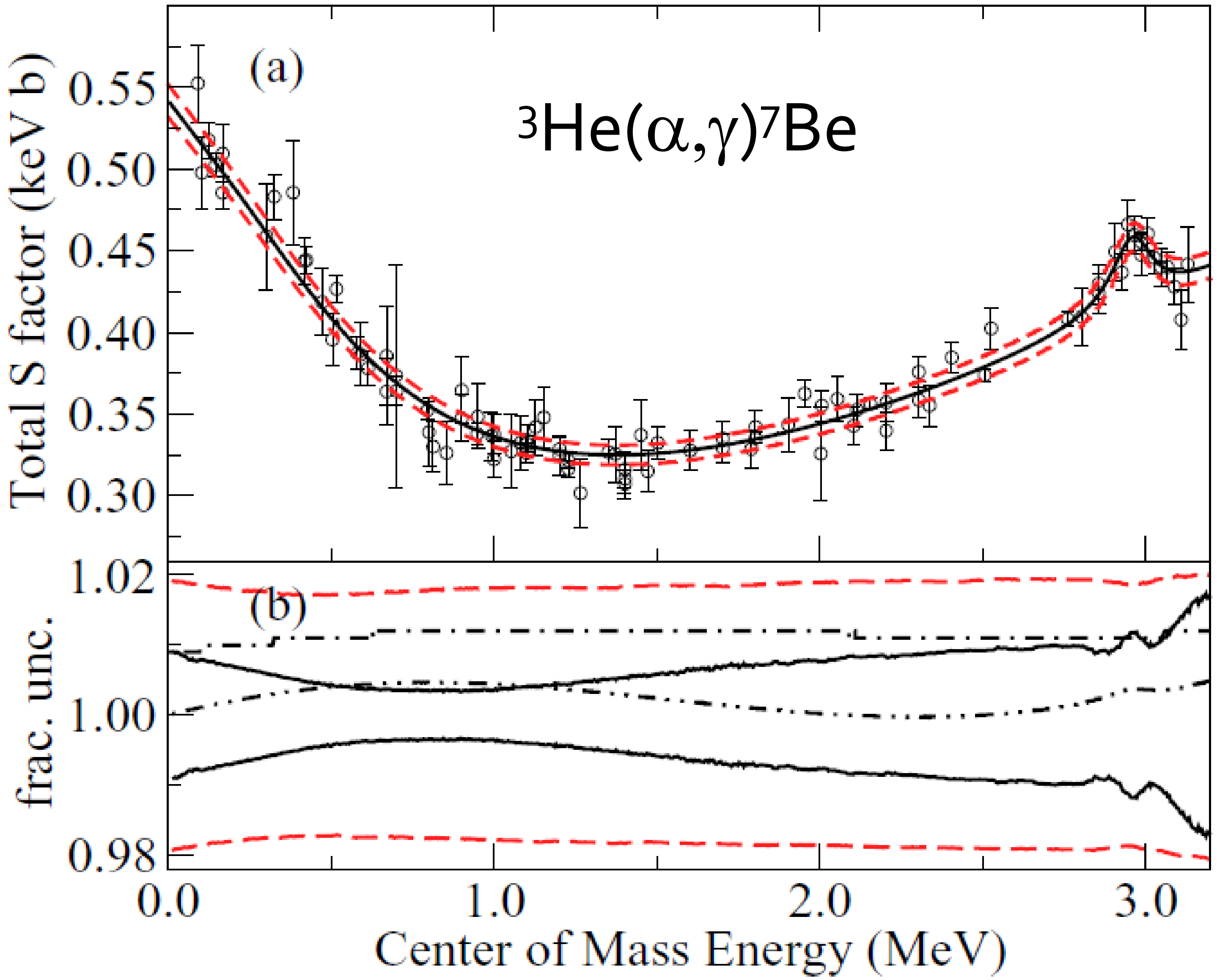


Broad cluster states demand measurements on similar energy scales

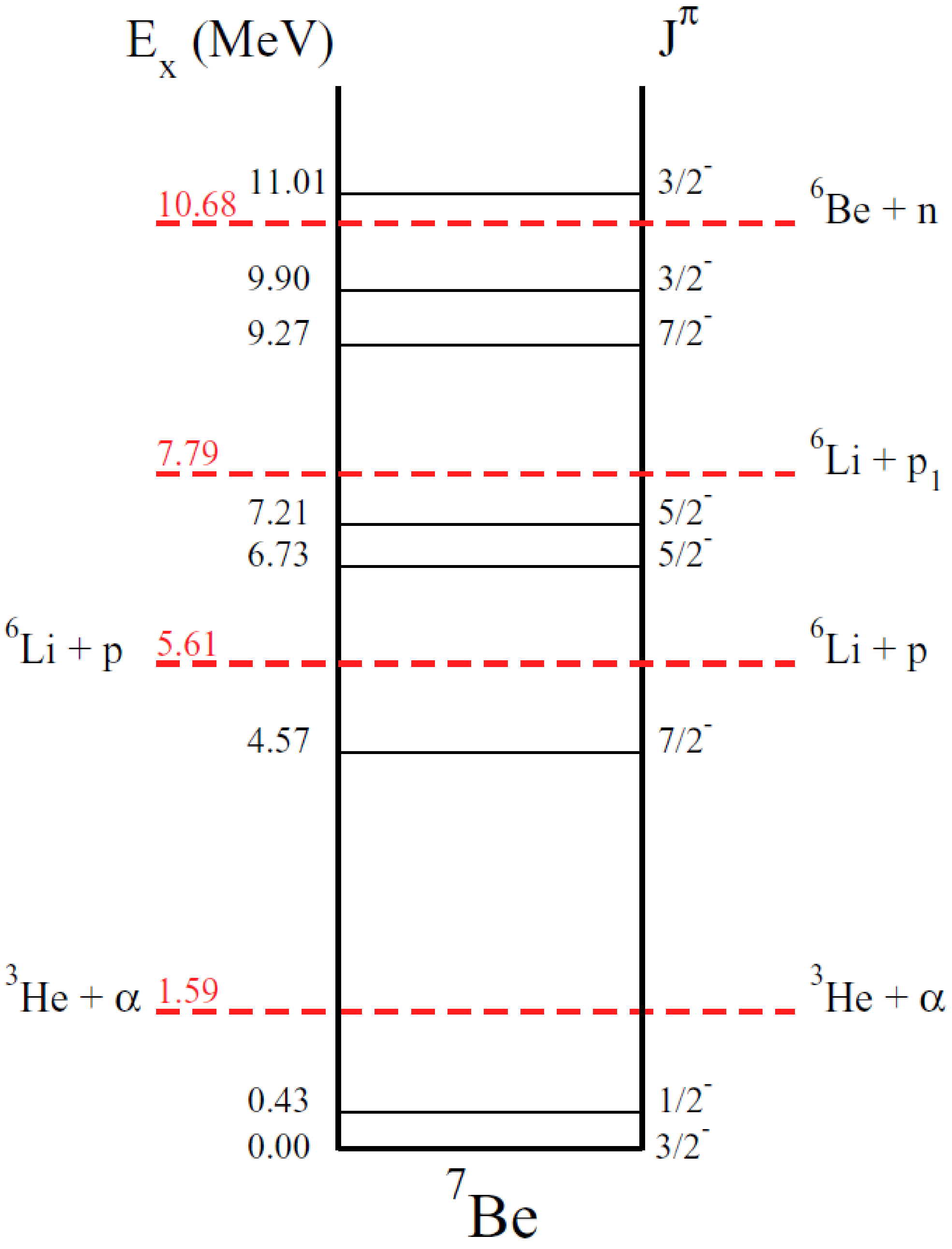


External Capture

Observed Cross Section

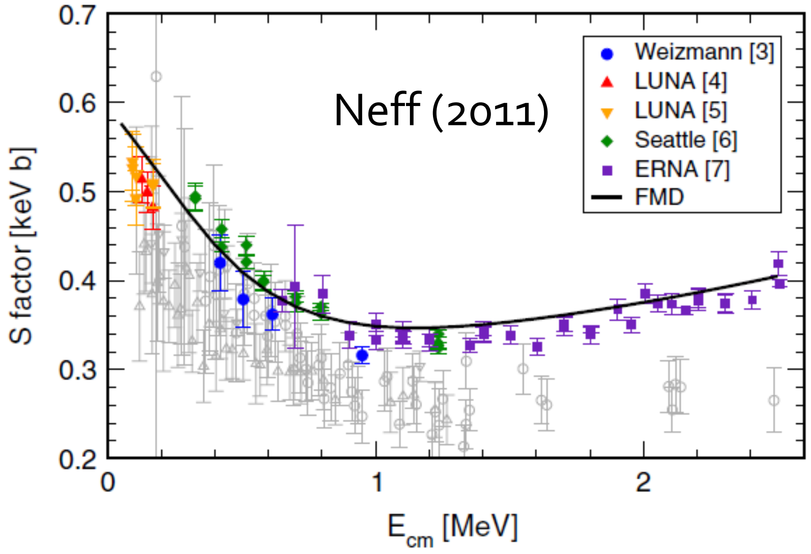


Level structure

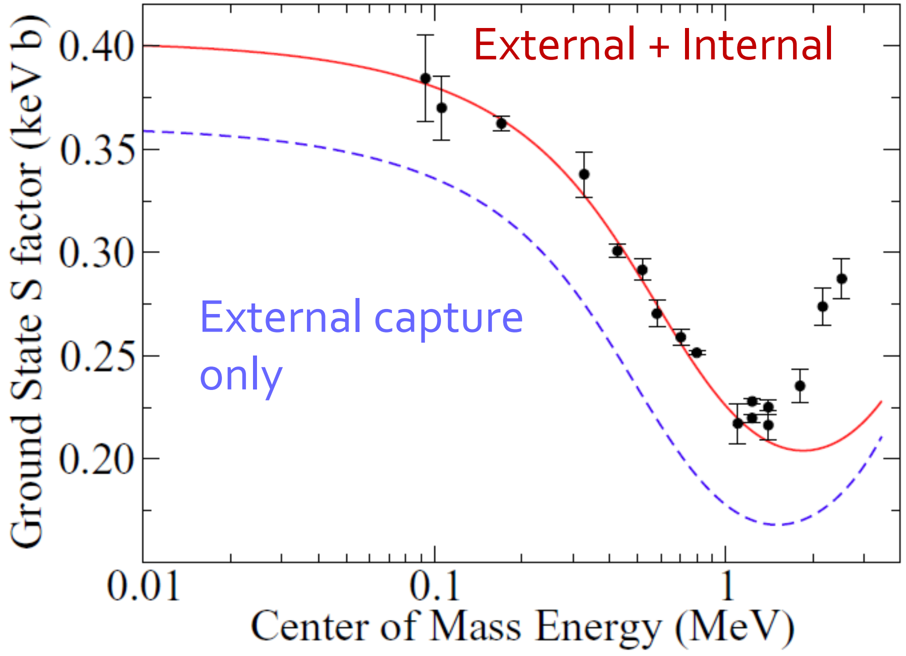


Two bound states in ^{7}Be

- Cross section is external capture dominated (since the 1960's)
- Nollet (2001) and Neff (2011), internal contributions are significant
- α asymptotic normalization coefficients of both of these states have not been measured
- Largest sources of uncertainty



$^{3}He(\alpha,\gamma)^{7}Be$



CNO cycle

Branch point reactions

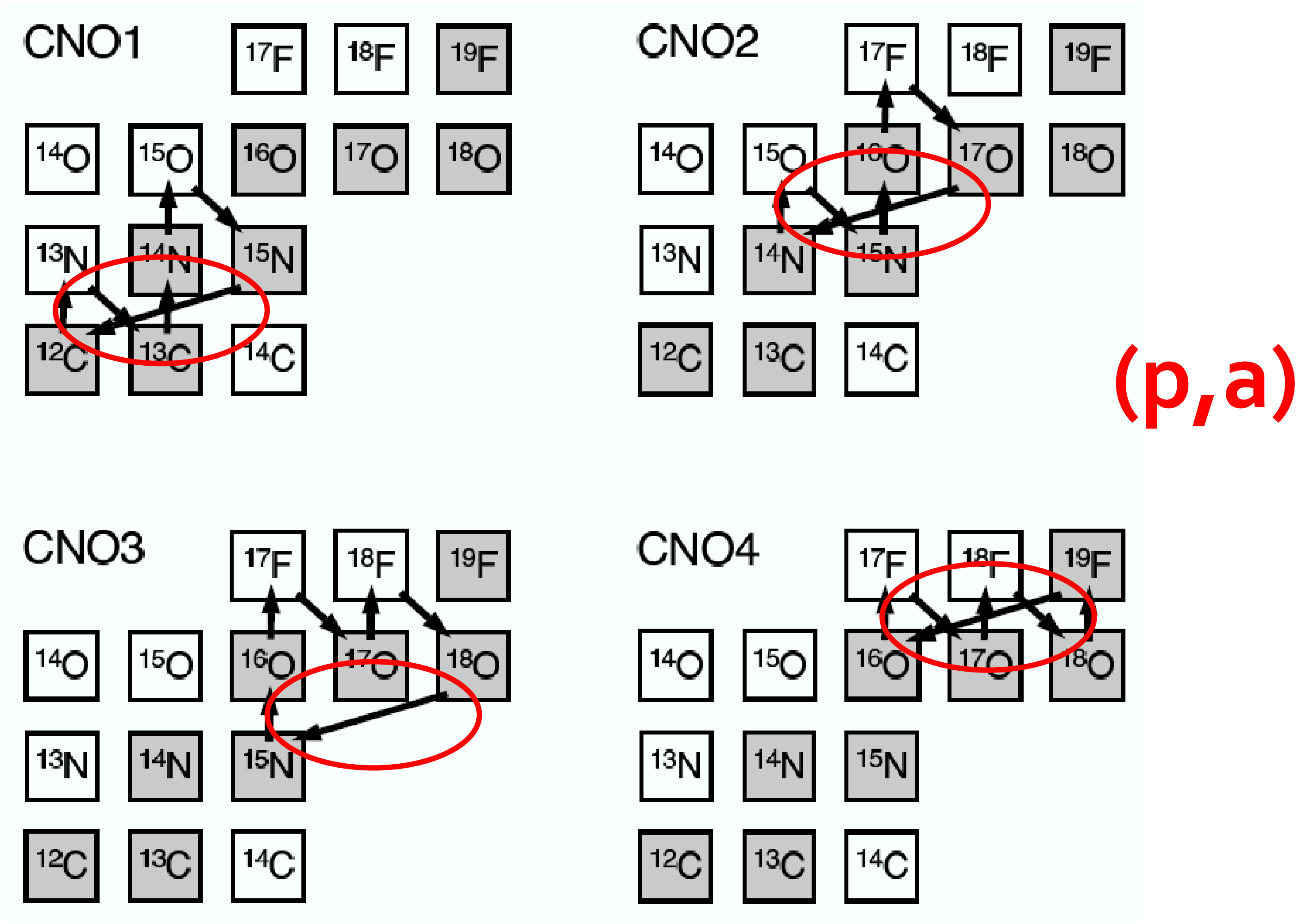


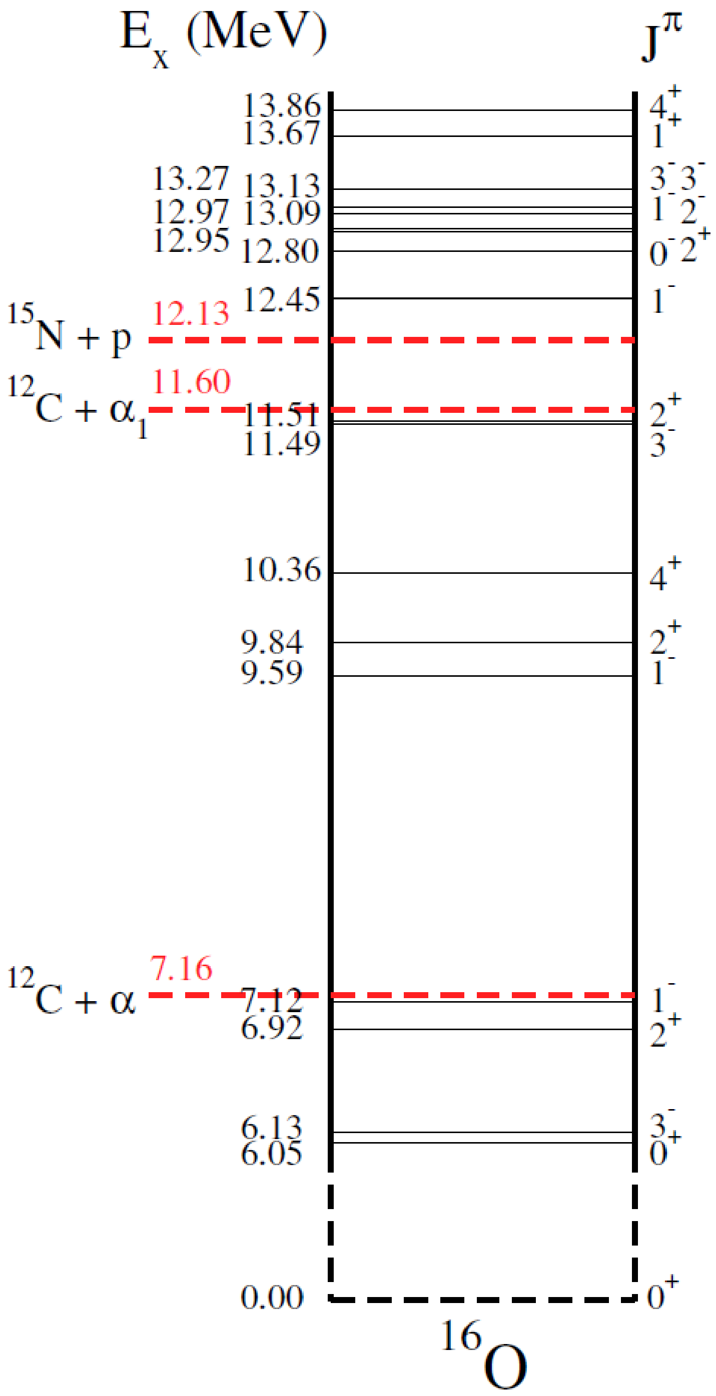
Fig. 5.8 Representation of the four CNO cycles in the chart of the nuclides. Stable nuclides are shown as shaded squares. Each reaction cycle fuses effectively four protons to one ^{4}He nucleus.

Christian Iliadis, *Nuclear Physics of Stars*

CNO cycles

- Direct reaction or broad resonance?
  - $^{15}N(p,\alpha)^{12}C$, ^{16}O CN
  - $^{19}F(p,\alpha)^{16}O$, ^{20}Ne CN

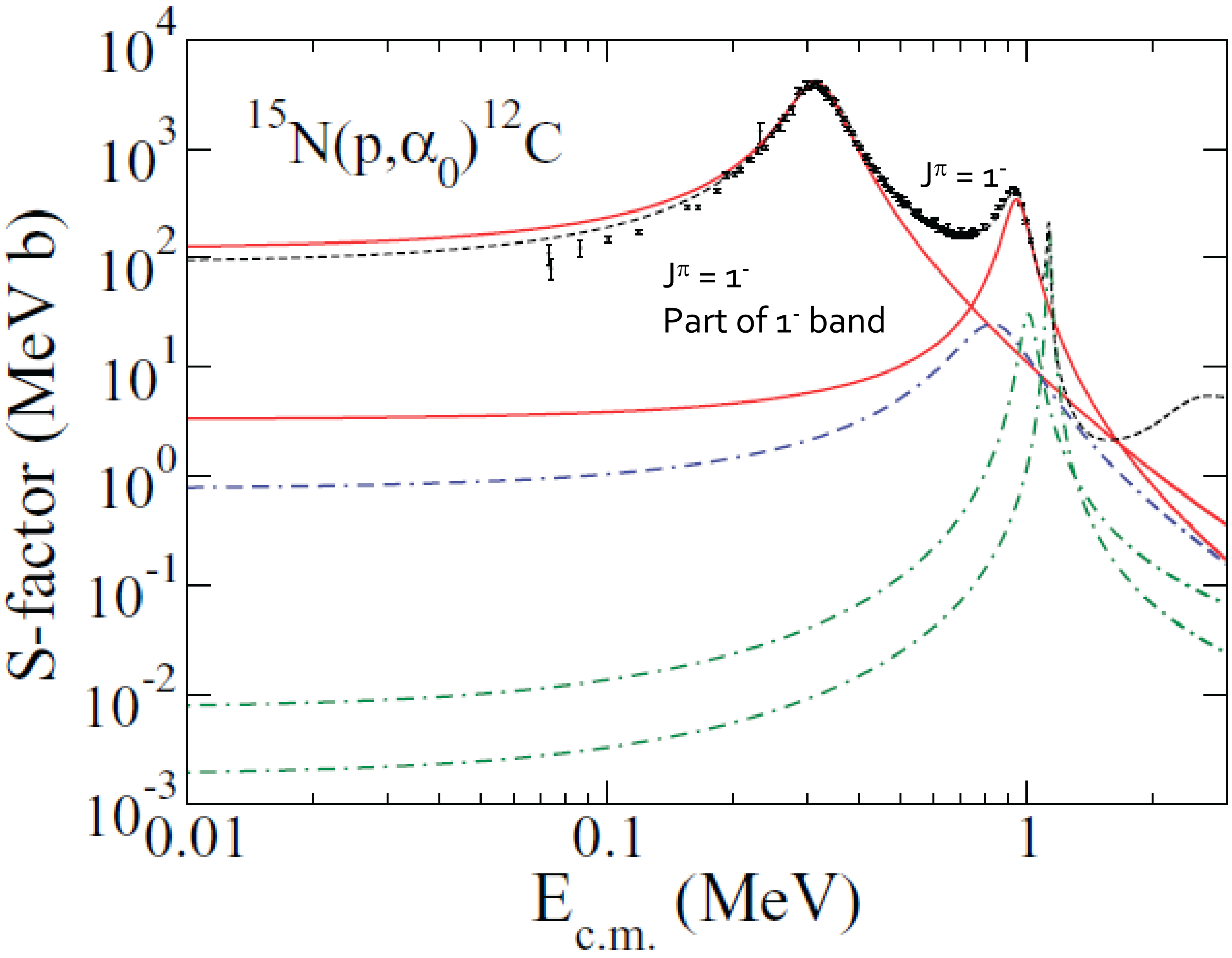
α separation energy
<
proton separation energy



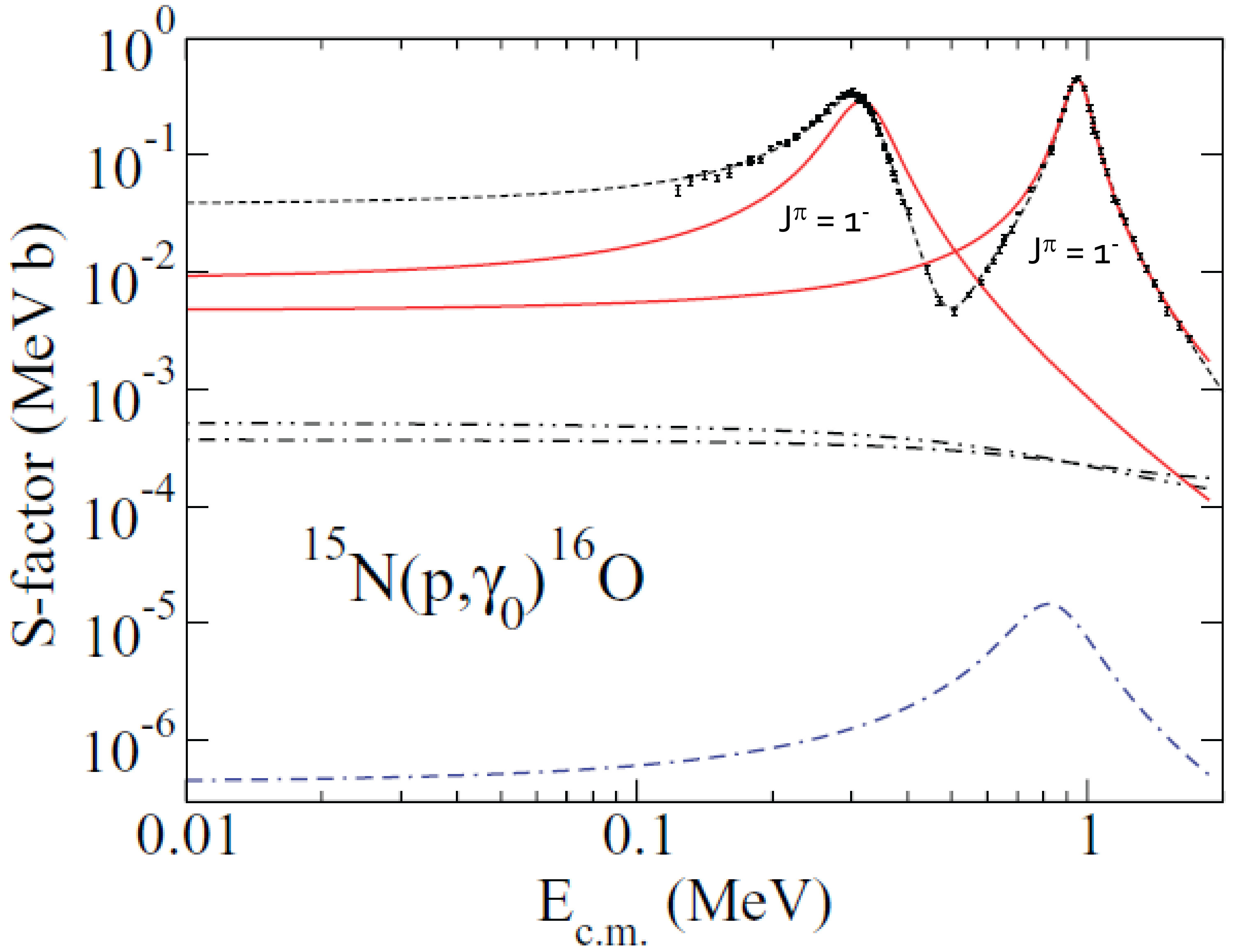
$^{15}N(p,\alpha)^{12}C$

Same for $^{19}F(p,\alpha)^{16}O$ reaction that populates the ^{20}Ne compound nucleus.

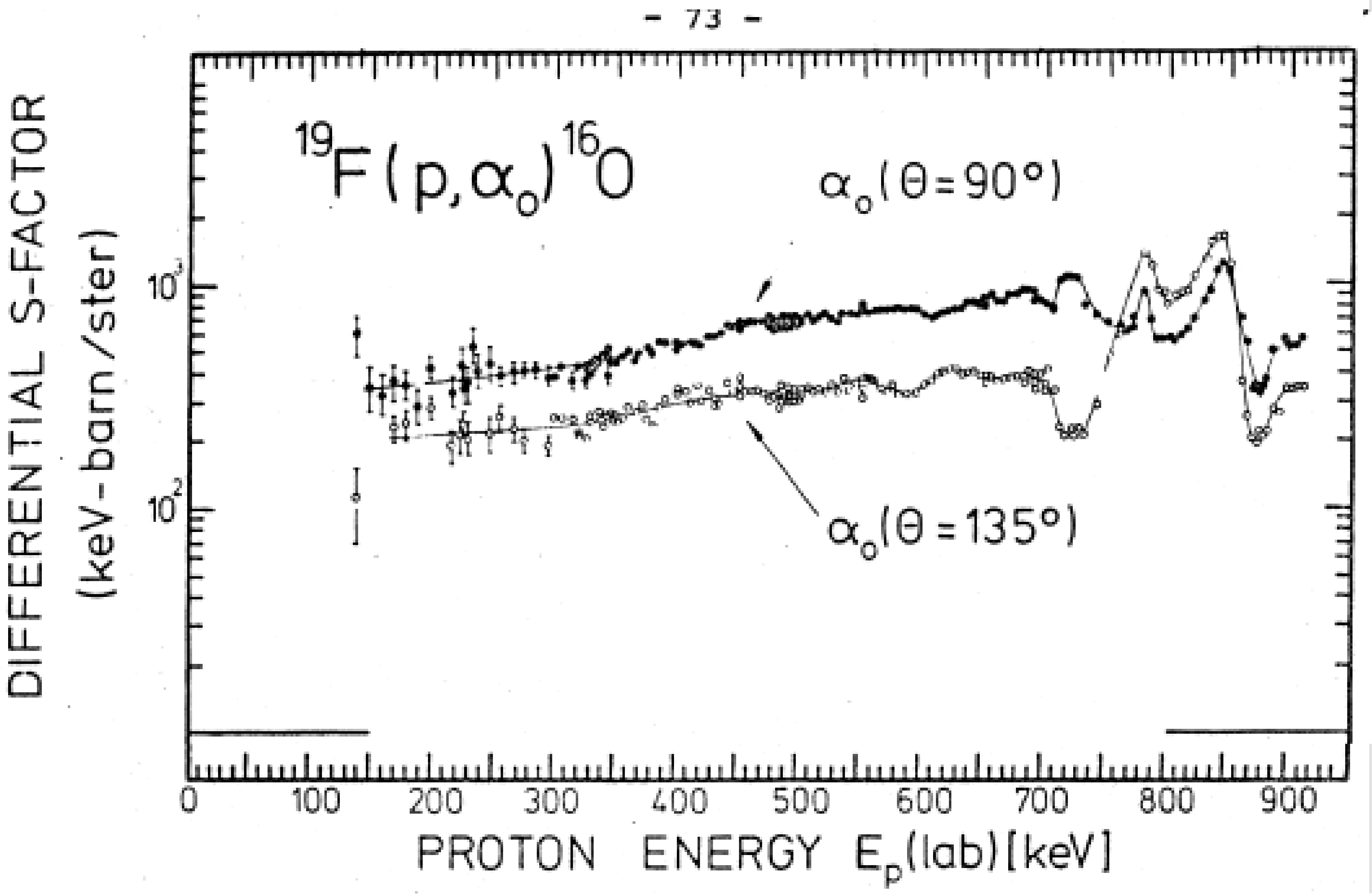
$^{15}N(p,\alpha)^{12}C$



$^{15}N(p,\gamma)^{16}O$

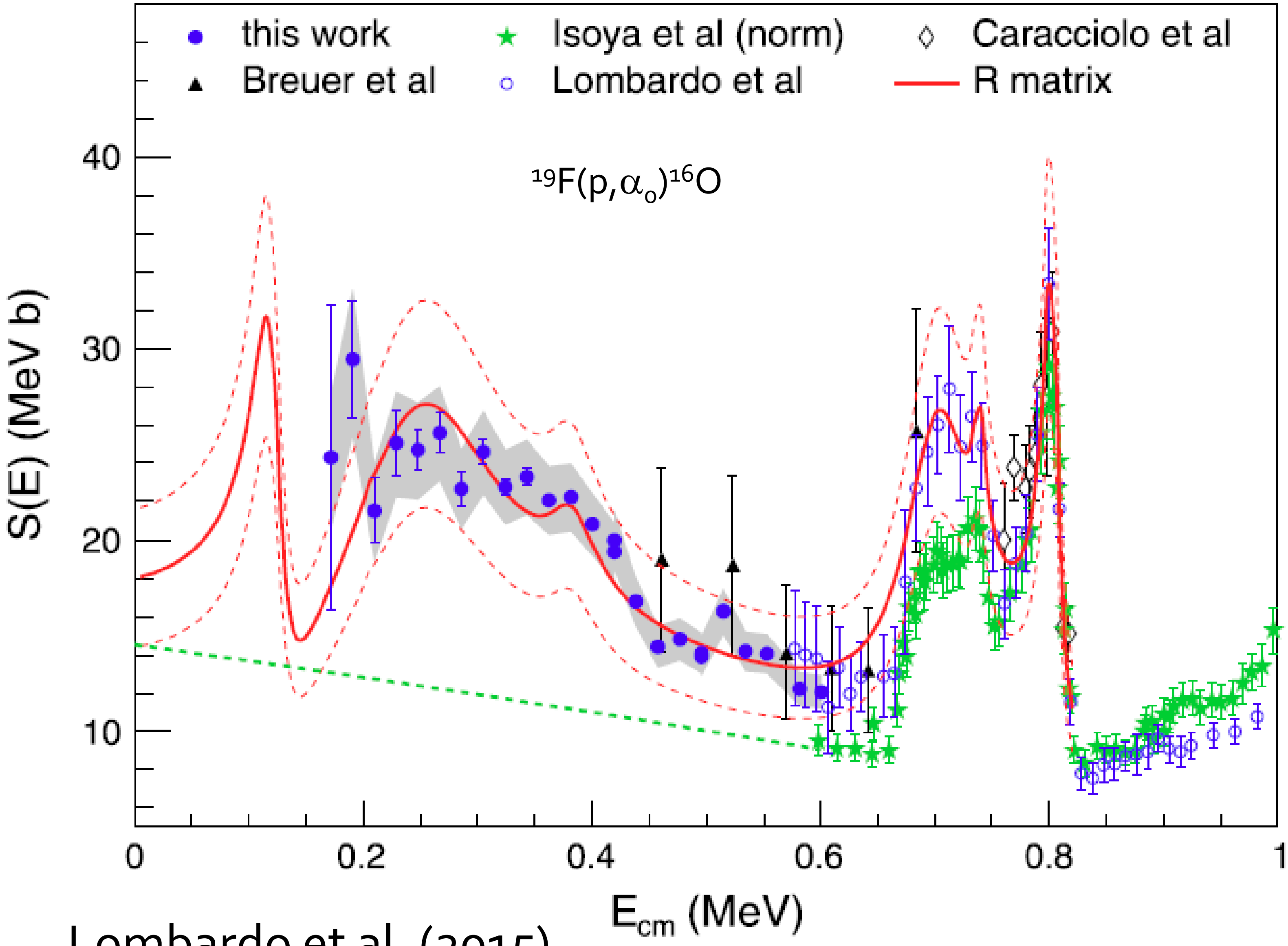


$^{19}F(p,\alpha)^{16}O$



H. Lorentz-Wirzba thesis, Münster (1978)

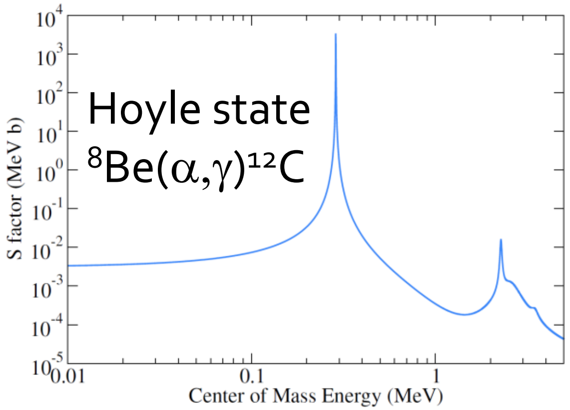
$^{19}F(p,\alpha)^{16}O$



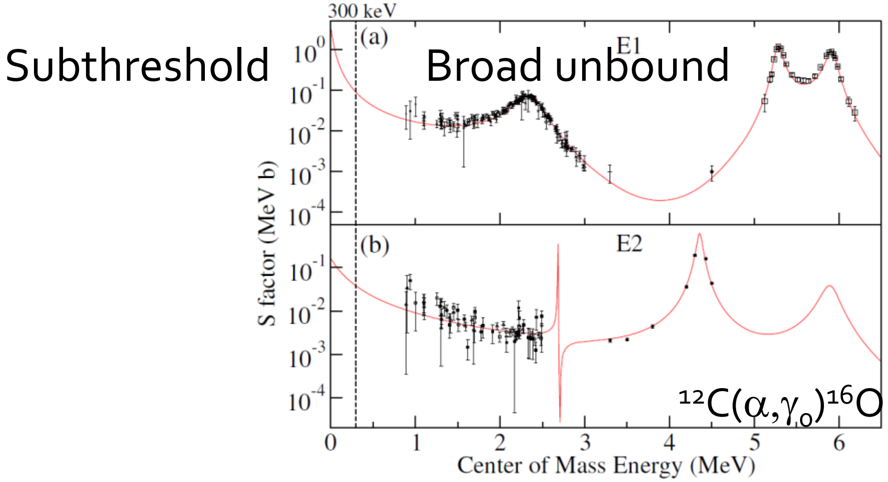
Lombardo et al. (2015)

Helium Burning

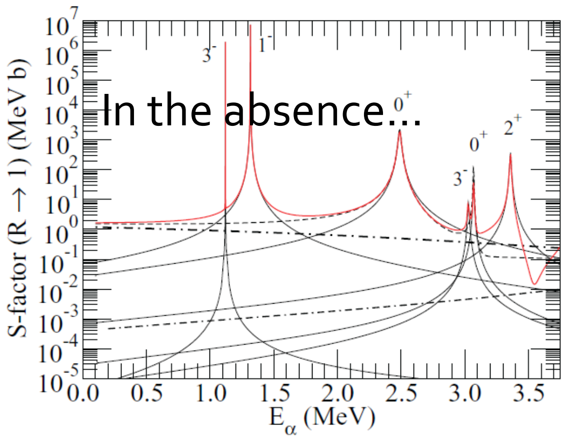
- $3\alpha \rightarrow {}^{12}C$



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



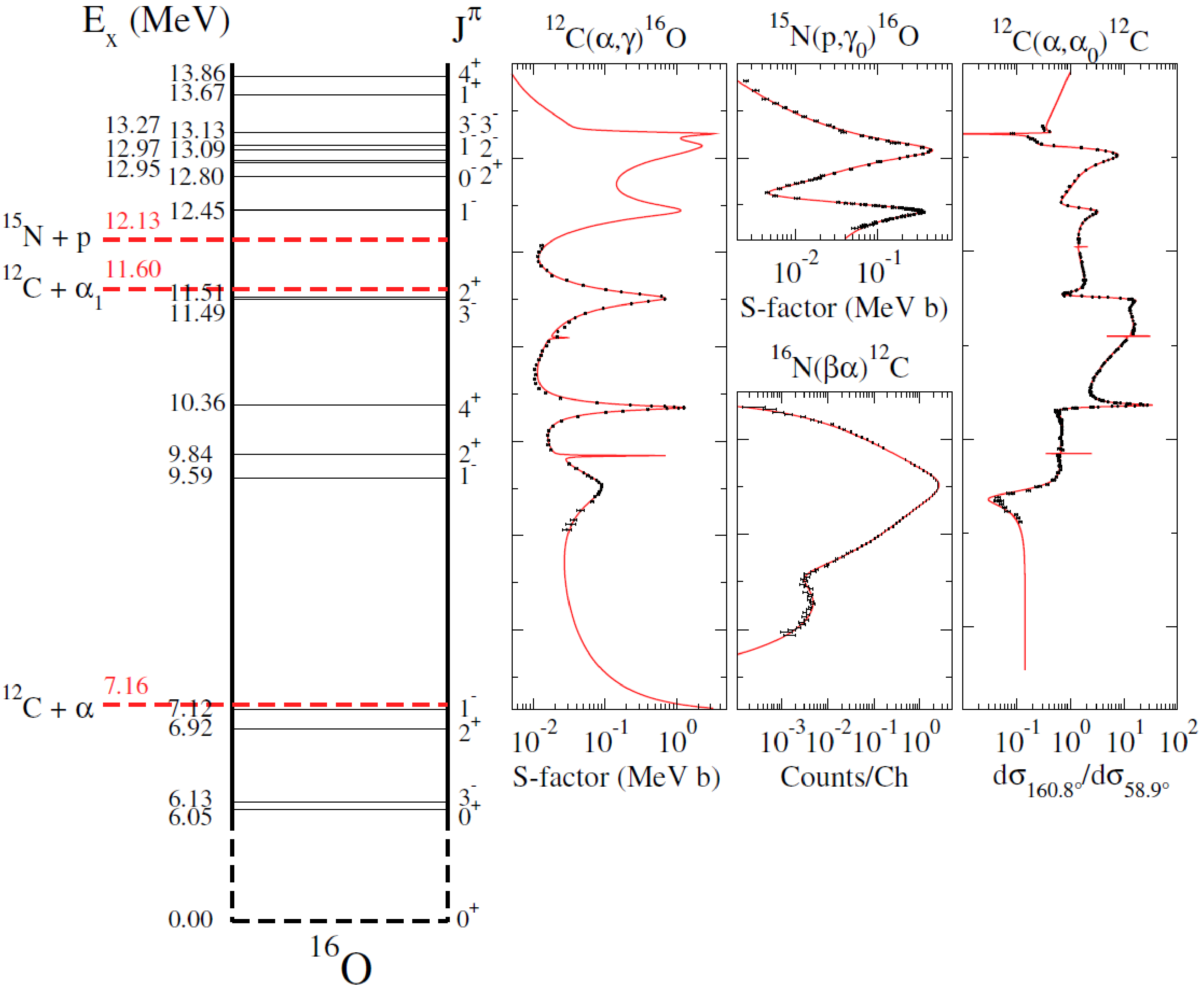
- $^{16}O(\alpha,\gamma)^{20}Ne$



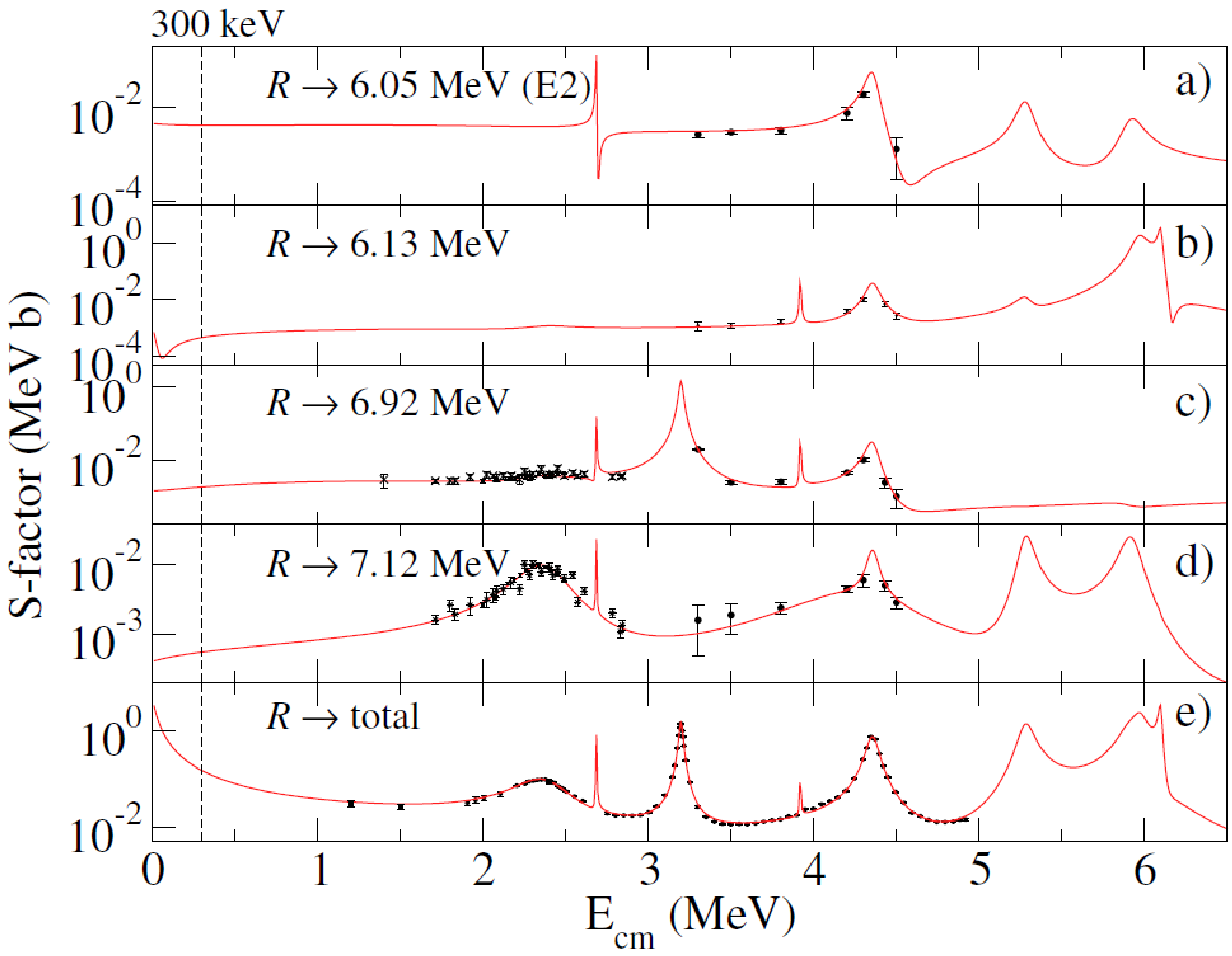
Helium Burning

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

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

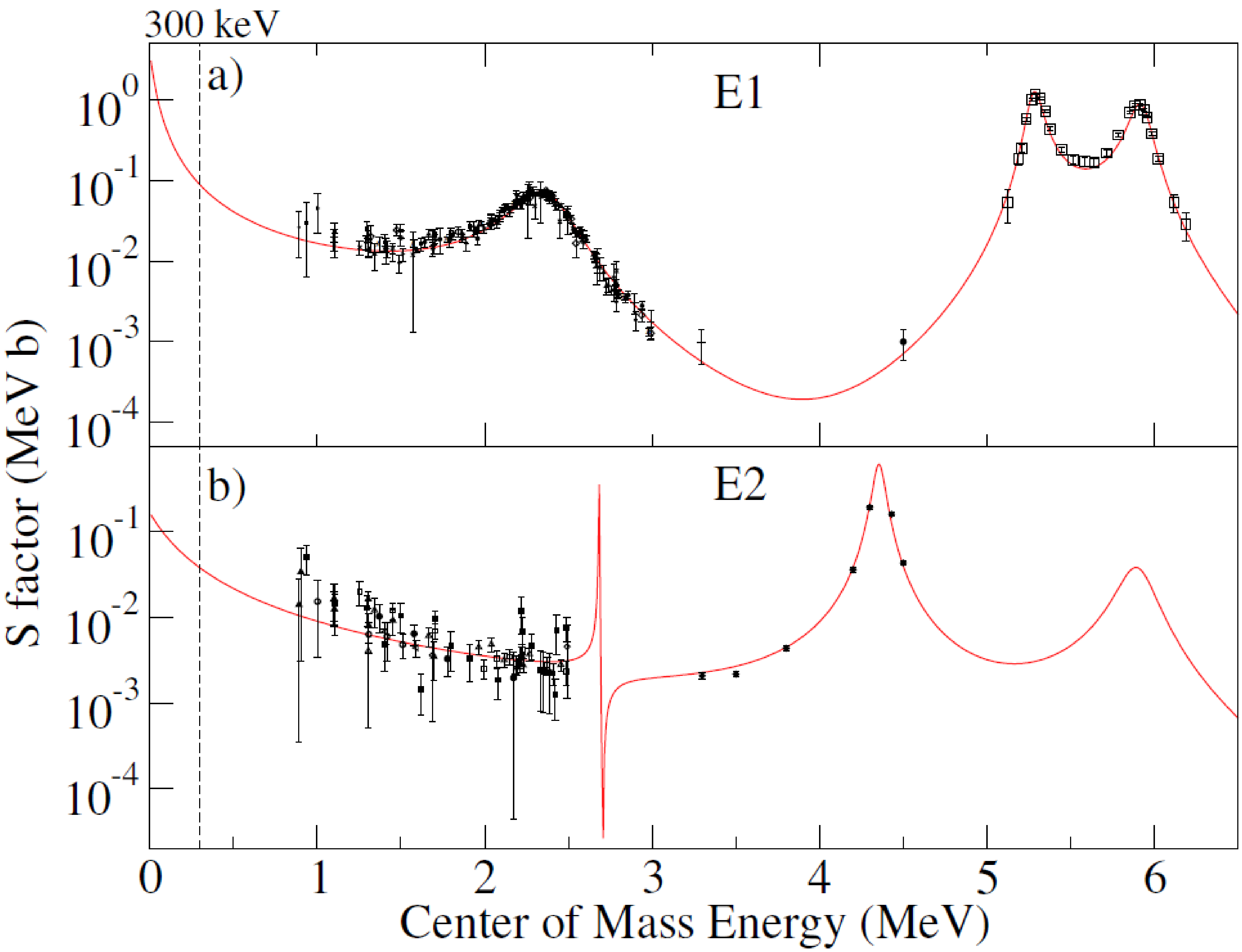


Different Transitions for $^{12}C(\alpha,\gamma)^{16}O$



Schürmann et al. (2012)

$^{12}C(\alpha,\gamma)^{16}O$ Ground State



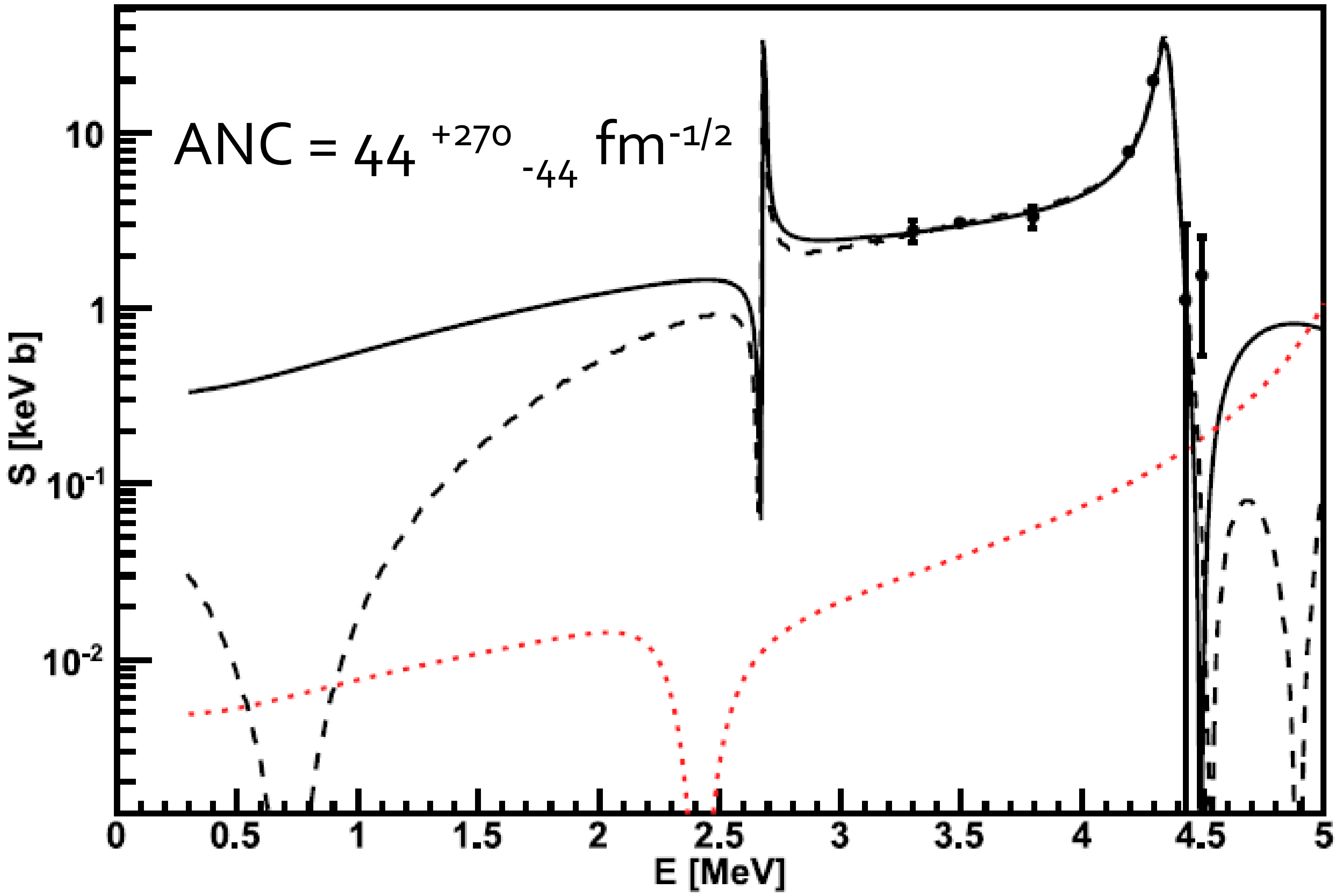
Subthreshold state ANCs

- Determined by
  - $^{12}C(\alpha,\alpha)^{12}C$ Scattering --- large uncertainty
  - $^{12}C(\alpha,\gamma)^{16}O$ Capture --- large uncertainty
  - Beta delayed α emission of ^{16}N --- inconsistent data
  - Sub-Coulomb α transfer $^{12}C(^{6}Li,d)^{16}O$ and $^{12}C(^{7}Li,t)^{16}O$

- Theory calculations of ANCs are highly desired

6.05 MeV transition

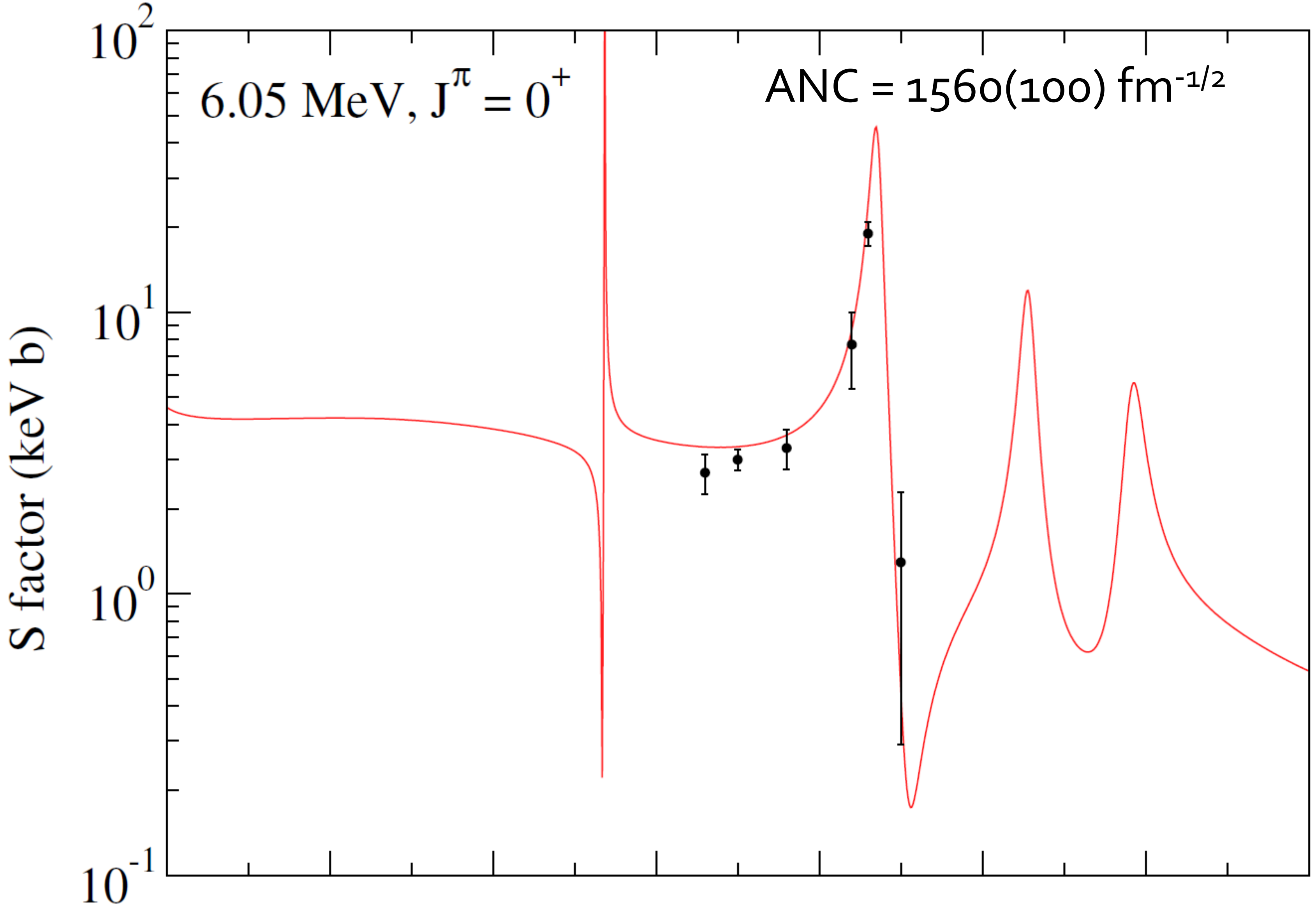
$^{12}C(\alpha,\gamma_{6.05\ MeV})^{16}O$ transition



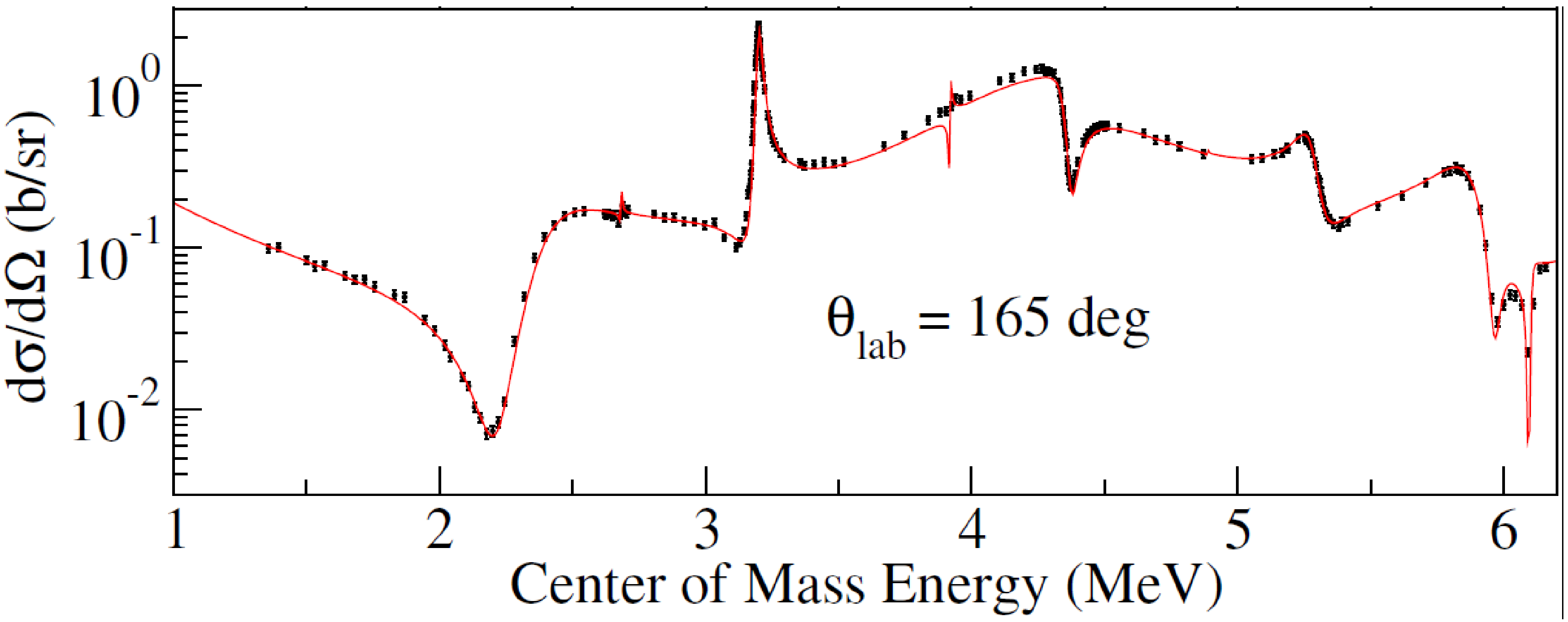
Schürmann et al. (2011)

Avila et al. (2015)

6.05 MeV transition

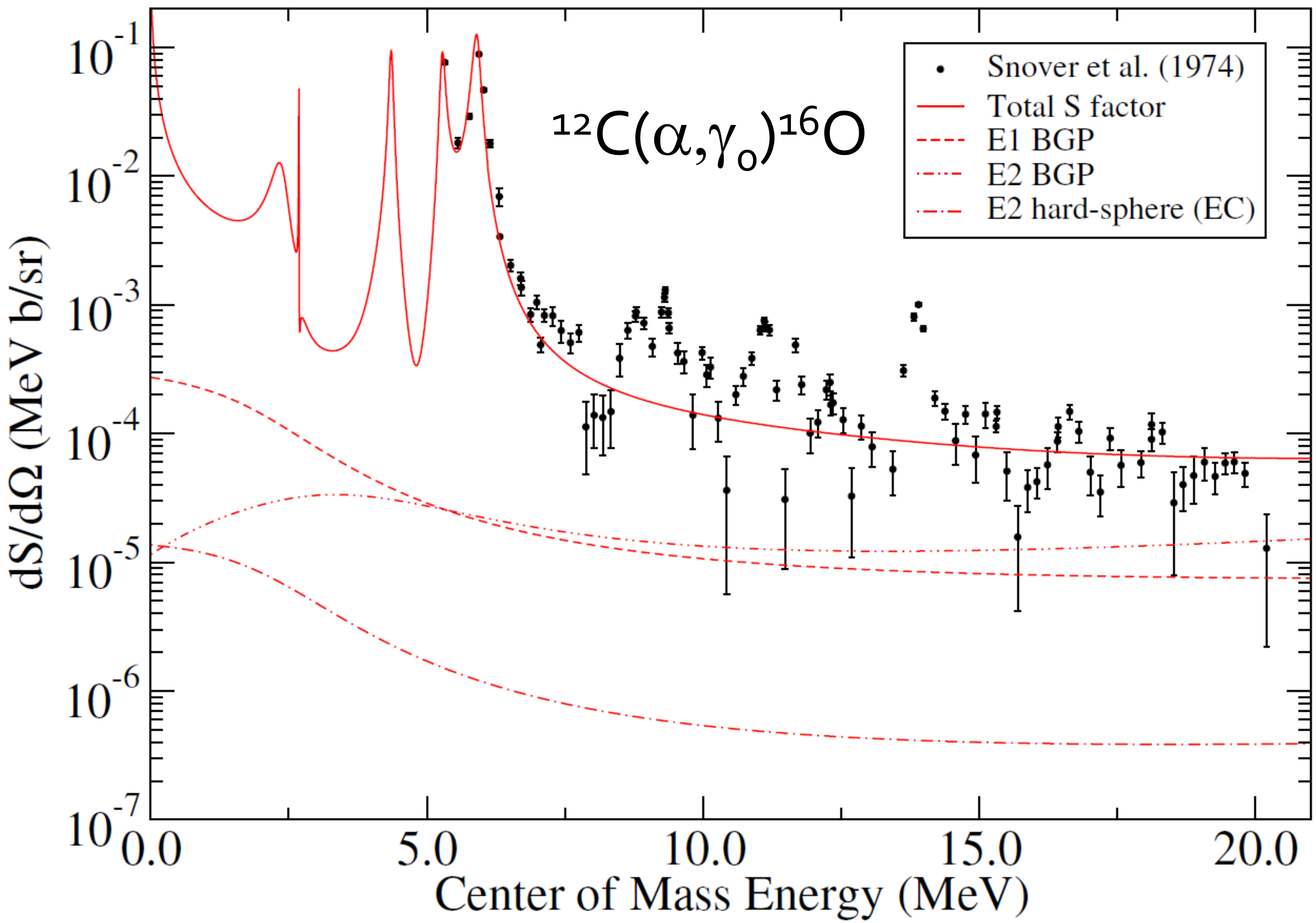


Scattering is important too!



Feng et al. (1996)

Higher energy data is very important too!



Conclusion

- Phenomenological fits + theory calculations yield the very accurate cross section descriptions
  - Theory calculations
    - Level structure
    - Underlying reaction mechanisms
    - Accurate data for all open reaction channels

- NSF Phys-0758100 and Phys-1430152 (JINA)