Nuclear Astrophysics - Underground

- problems and requirements for an underground accelerator -

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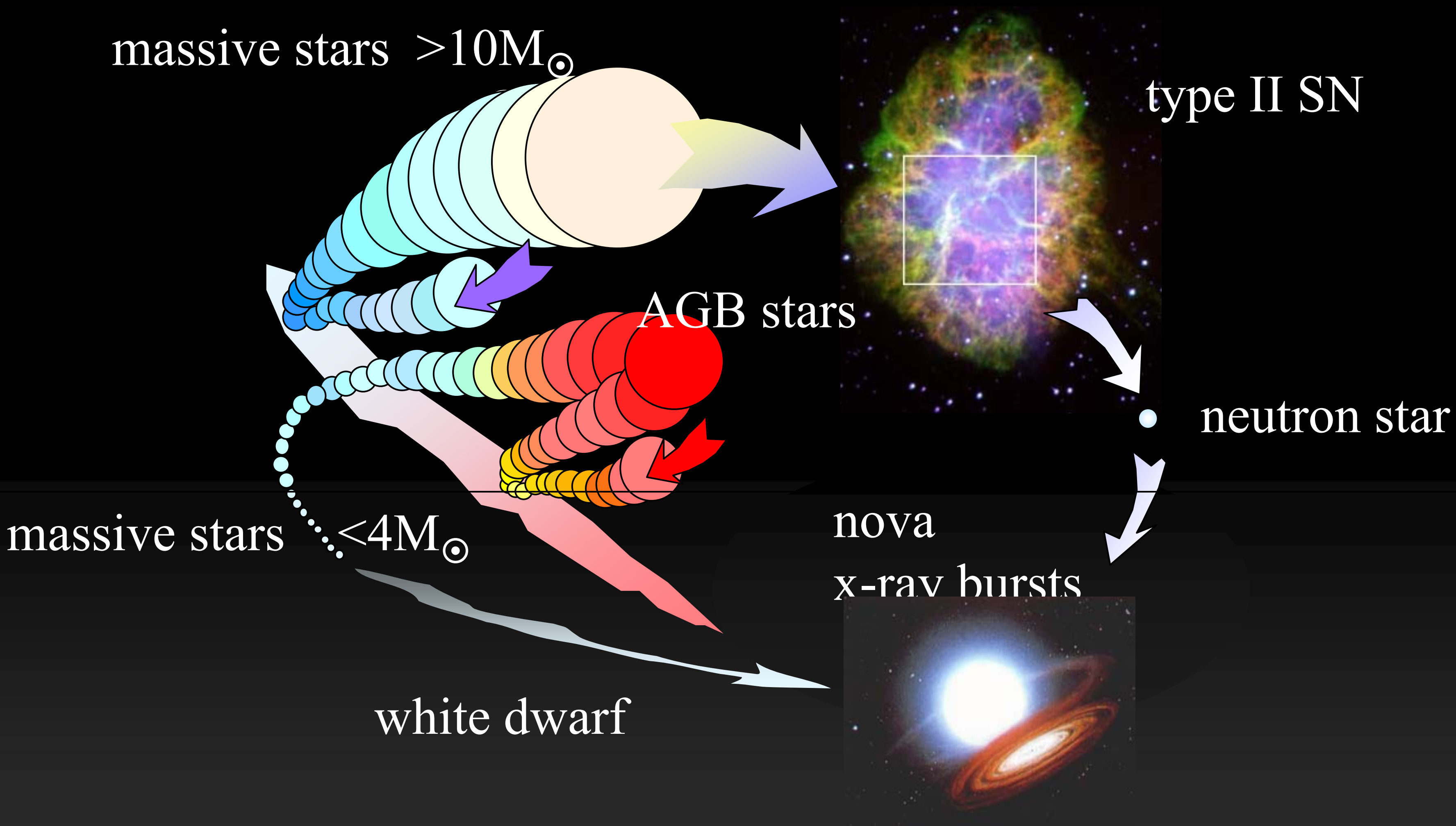
- Conditions in Stellar Burning
- Energy Range for Nuclear Processes
- Experimental Requirements
- Experimental Limitations

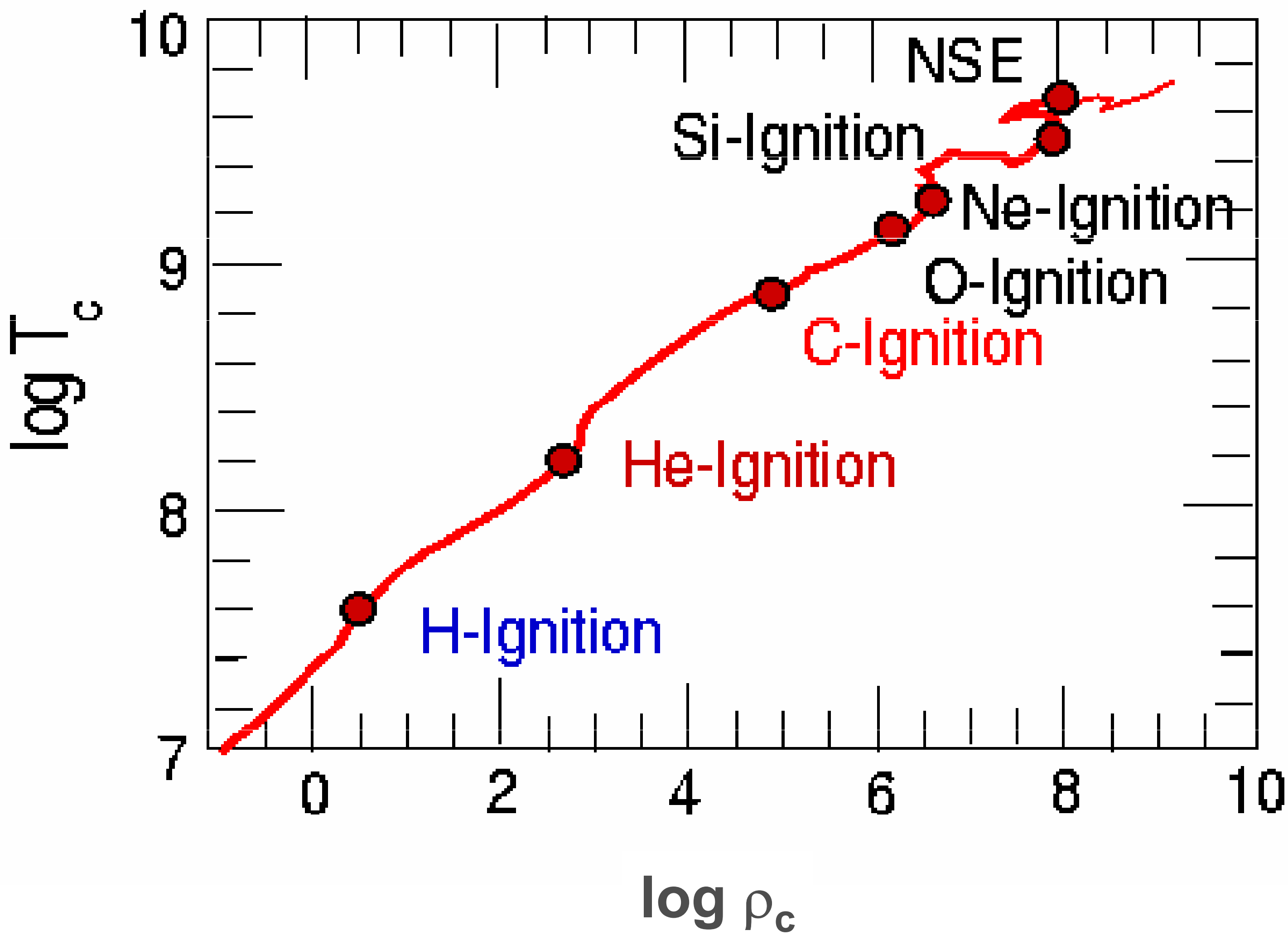
Current Problems in Experimental Nuclear Astrophysics

- nucleosynthesis in stellar explosion
  experiments far of stability ⇒ GSI, RIA
- nucleosynthesis with neutrons
  experiments with high n-flux ⇒ n-ToF, LANSCE, SNS
- nucleosynthesis in stellar evolution
  experiments at low energies ⇒ underground laboratory?

Stellar Temperatures and Energies



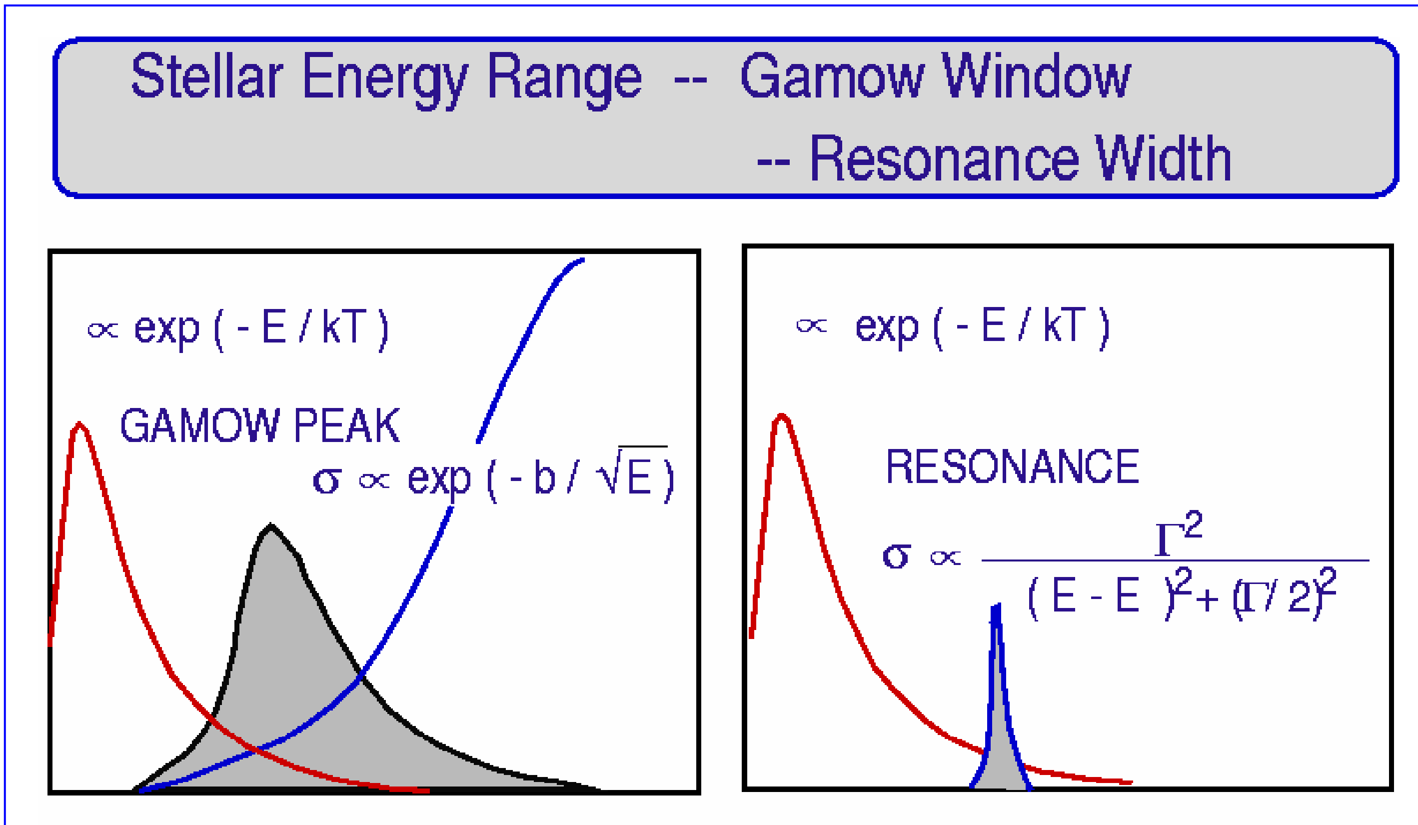
Conditions in Stellar Cores



$25M_\odot$ star

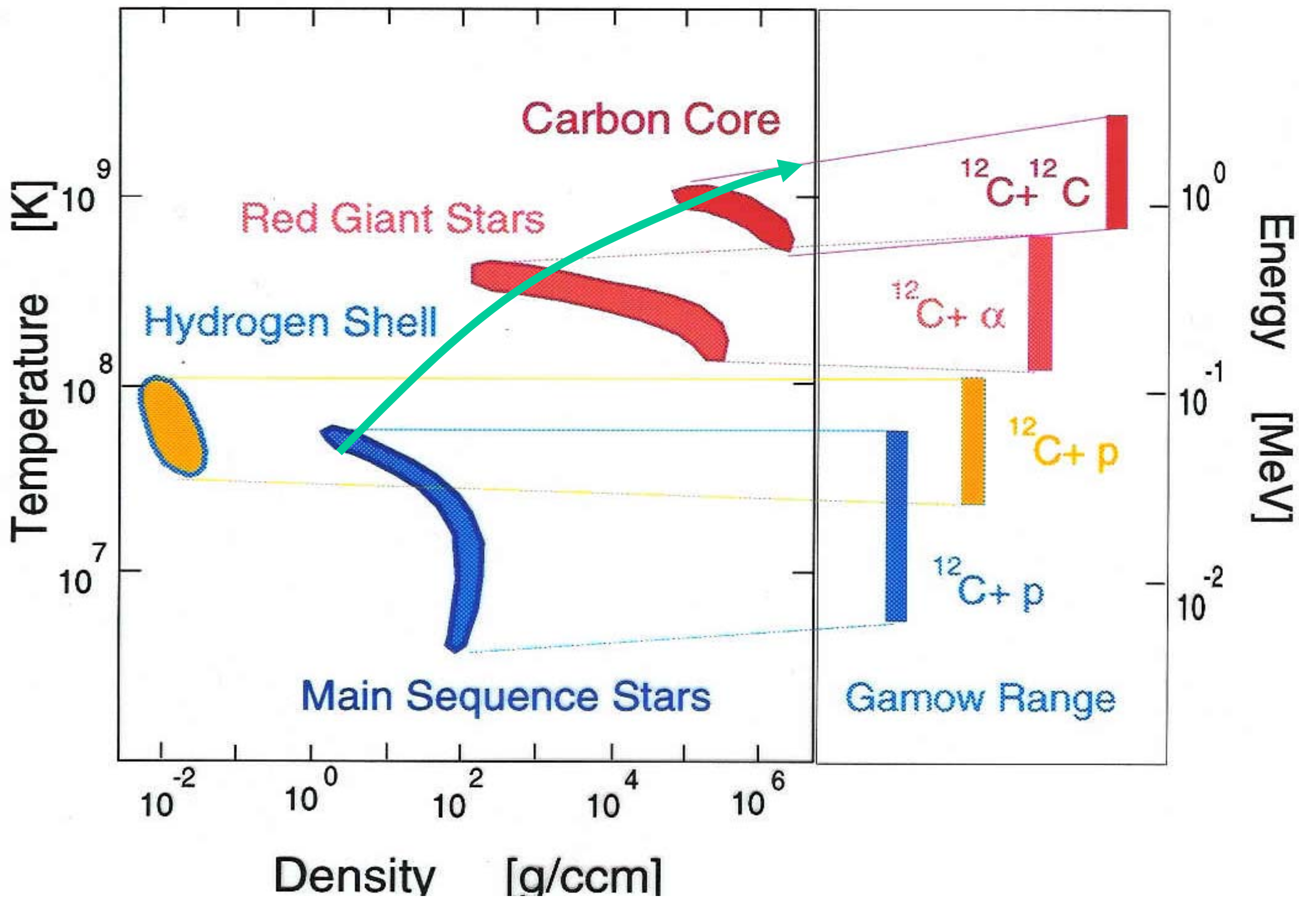
Energies in Stellar Core

$$kT = 0.086 \cdot T_9 \qquad E_G = 0.122 \cdot \left(Z_1^2 Z_2^2 A\right)^{1/3} T_9^{2/3}\ \text{MeV}$$



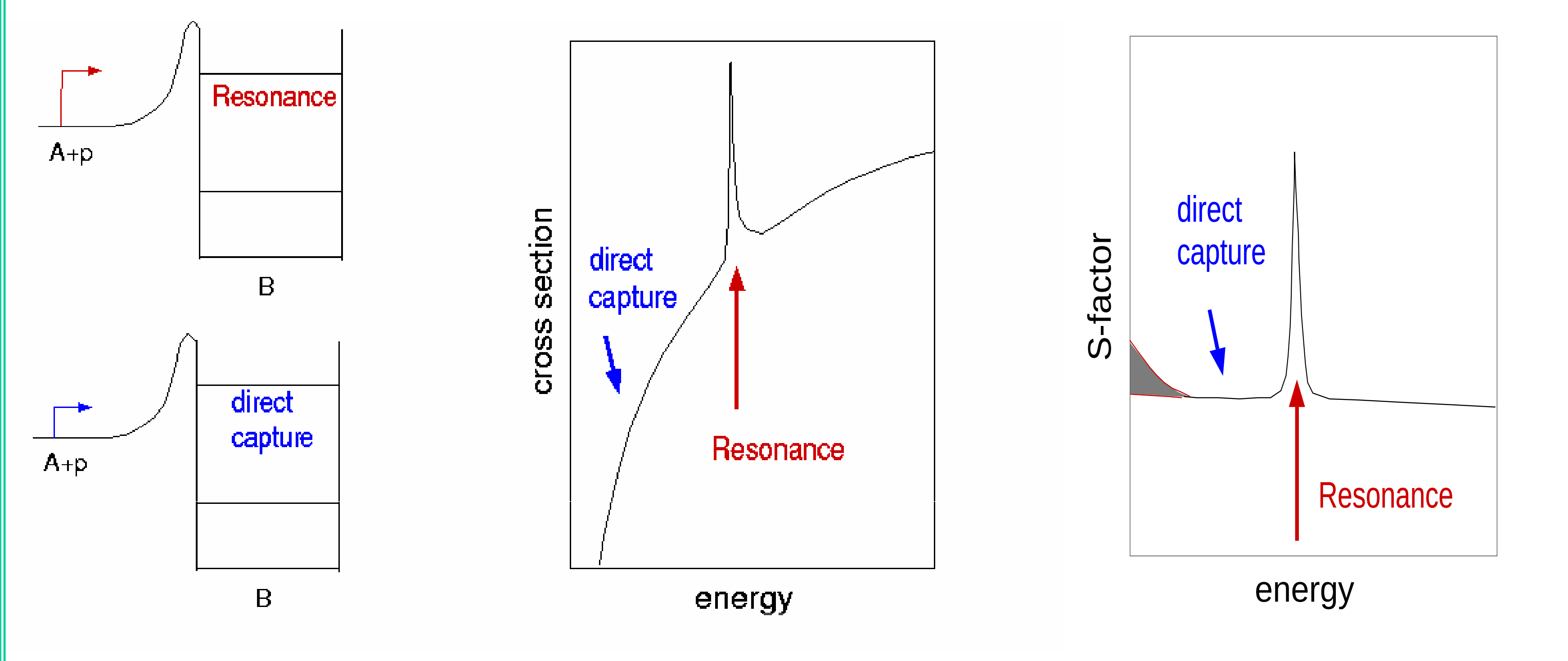
Energies in the Gamow Range

$$E_G = 0.122 \cdot \left(Z_1^2 Z_2^2 A\right)^{1/3} T_9^{2/3} \text{ MeV}$$



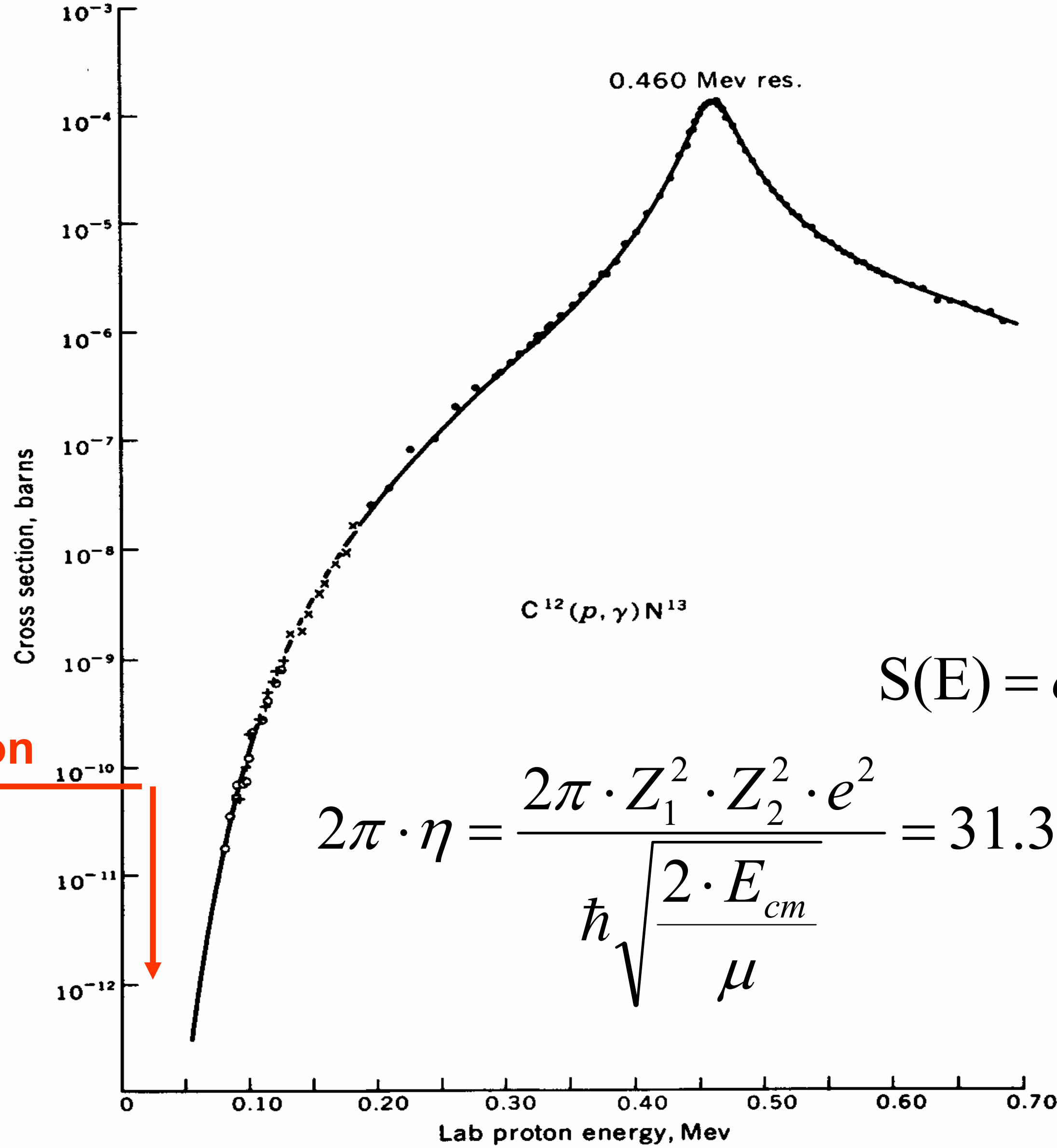
Cross-Section and S-Factor

cross section often expressed as S-factor



S-factor to correct for Coulomb barrier: $S(E) = \sigma(E)\, E\, e^{2\pi\eta}$

Example: $^{12}C(p,\gamma)$ cross section

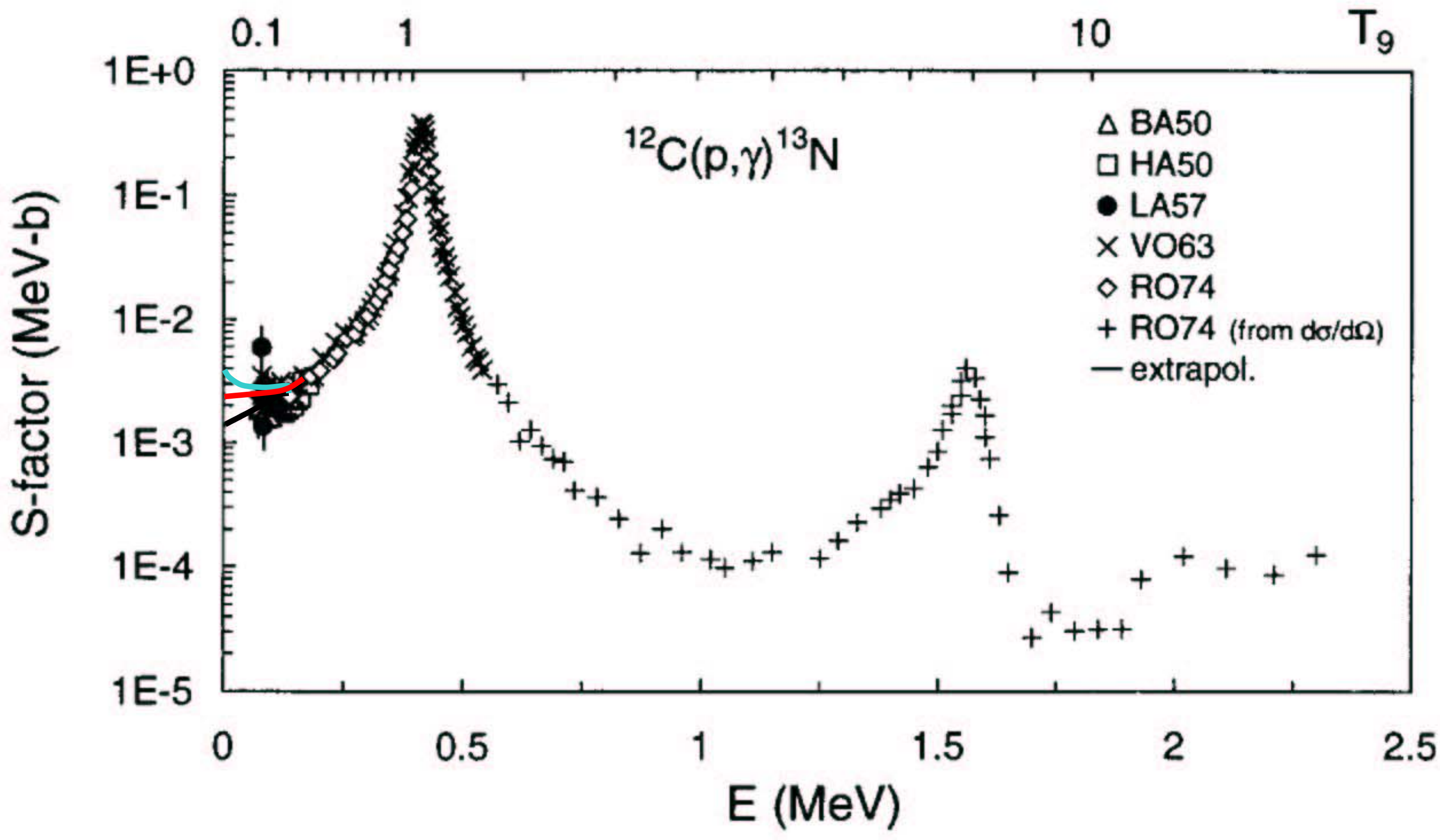


need cross section here !

$$S(E) = \sigma \cdot e^{2\pi\cdot\eta}$$

$$2\pi\cdot\eta = \frac{2\pi\cdot Z_1^2\cdot Z_2^2\cdot e^2}{\hbar\sqrt{\frac{2\cdot E_{cm}}{\mu}}} = 31.38\cdot\frac{Z_1^2\cdot Z_2^2\cdot\sqrt{\mu}}{\sqrt{E_{cm}\,[MeV]}}$$

S-factor Conversion



From the **NACRE compilation** of charged particle induced reaction rates on stable nuclei from H to Si (Angulo et al. Nucl. Phys. A 656 (1999) 3

Stellar Reaction Rate

If S-factor ~ constant over the Gamow range
the rate is calculated in terms of the S-factor
if resonance in terms of resonance strength ωγ

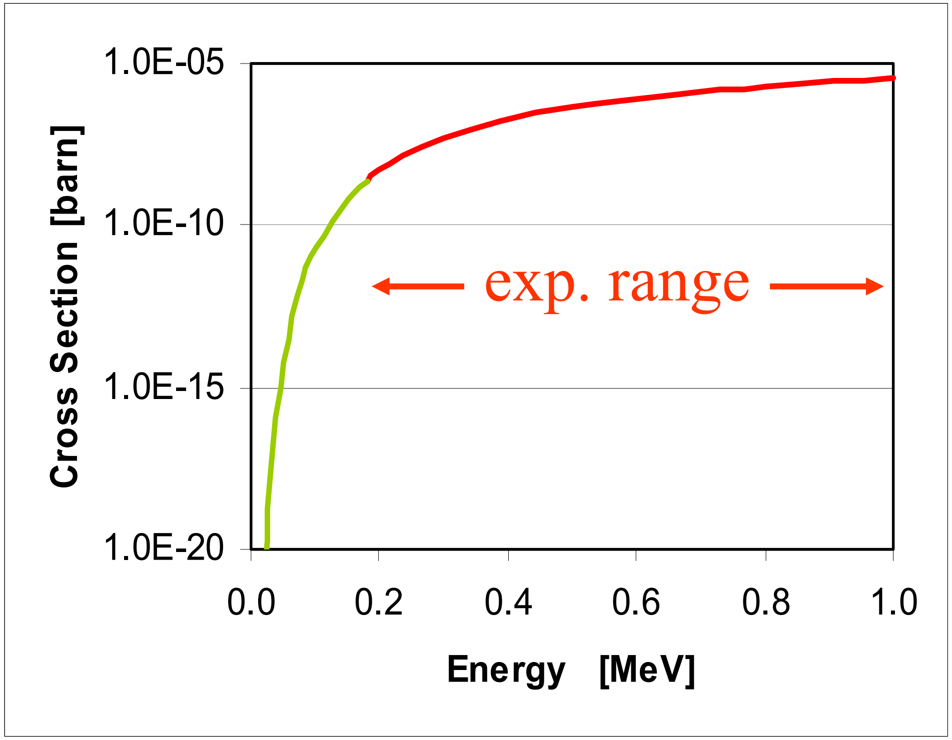
$$N_A < \sigma v >_{DC} = 7.83 \cdot 10^9 \left(\frac{Z_1 Z_2}{\mu T_9^2} \right)^{1/3} S(E_0)[\text{MeV barn}]\ e^{-4.2487\left(\frac{Z_1^2 Z_2^2 \mu}{T_9}\right)^{1/3}}$$

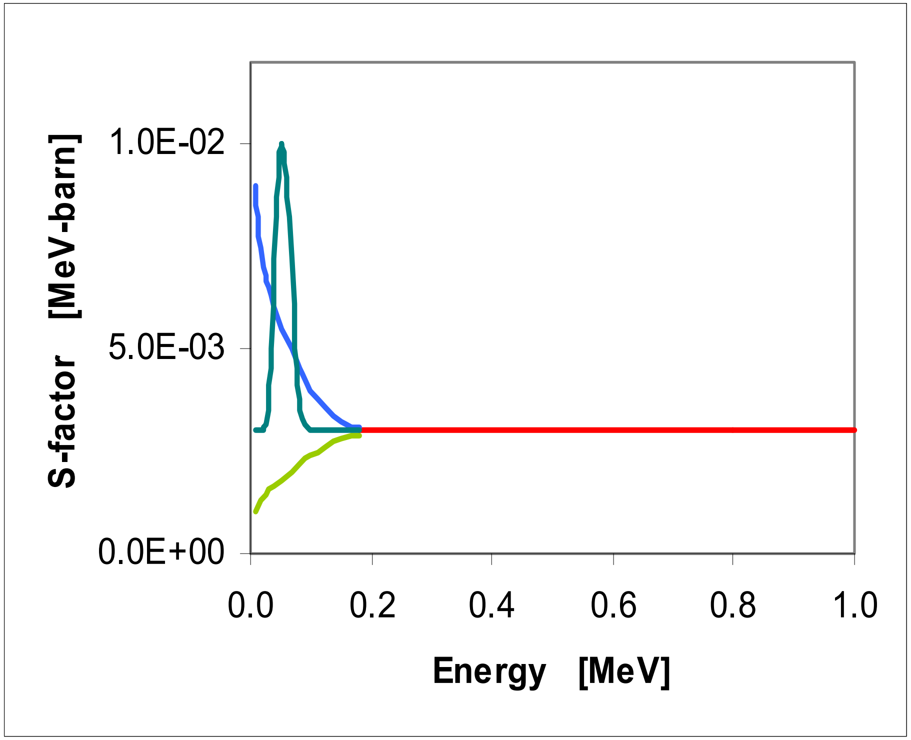
$$N_A \langle \sigma v \rangle = 1.54 \cdot 10^{11} \cdot \omega\gamma\,[MeV] \cdot \left(\frac{1}{\mu \cdot T_9} \right)^{3/2} \cdot e^{-\left(\frac{11.605 \cdot E_R [MeV]}{T_9}\right)}$$

$$\omega\gamma = \frac{2(J+1)}{2(j_p+1) \cdot 2(j_T+1)} \cdot \frac{\Gamma_{in} \cdot \Gamma_{out}}{\Gamma_{tot}} \qquad \Gamma_{tot} = \sum_i \Gamma_i$$

Cross Section Extrapolation to Stellar Energies

experimental uncertainties and extrapolation technique

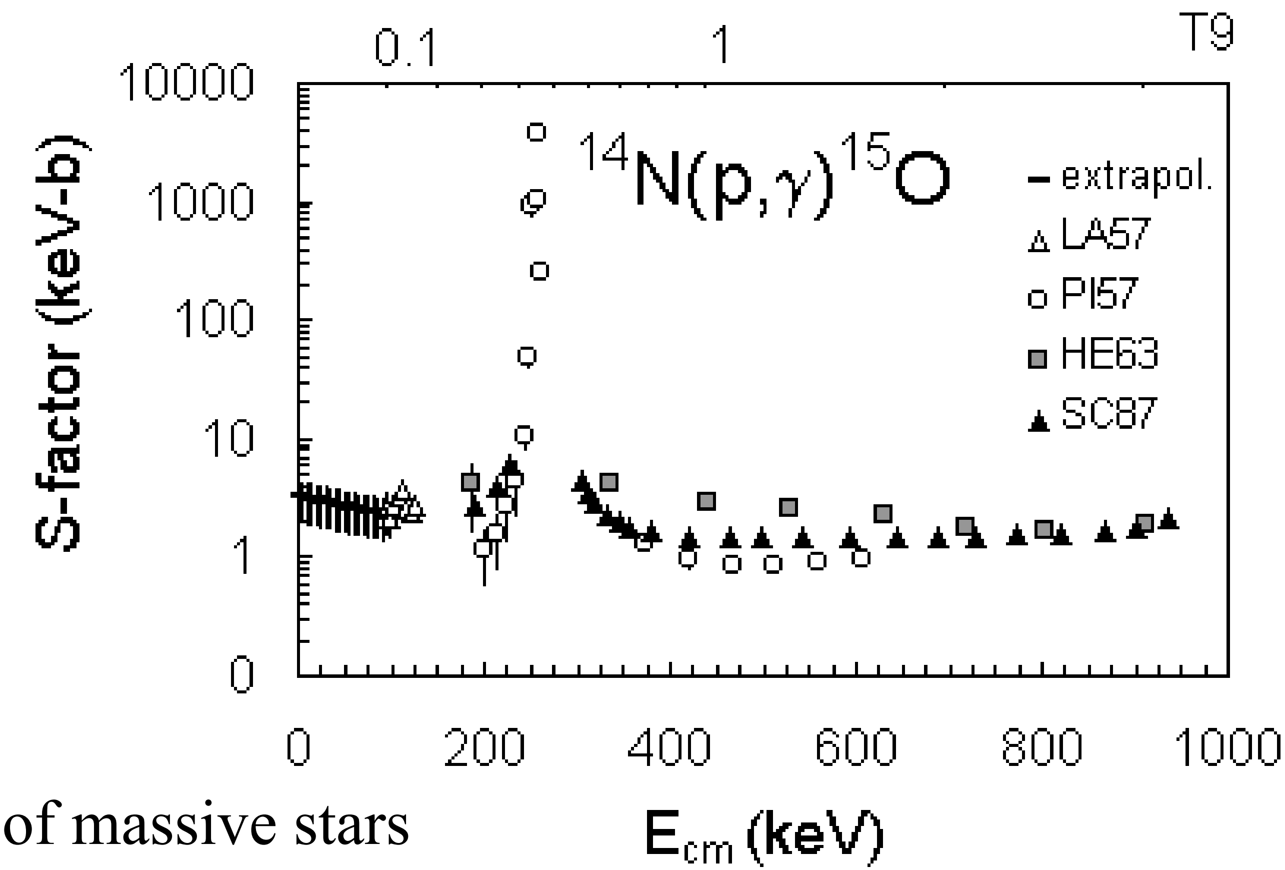




extrapolation is uncertain due to:
ℓ-dependence or resonance dependence of S-factor

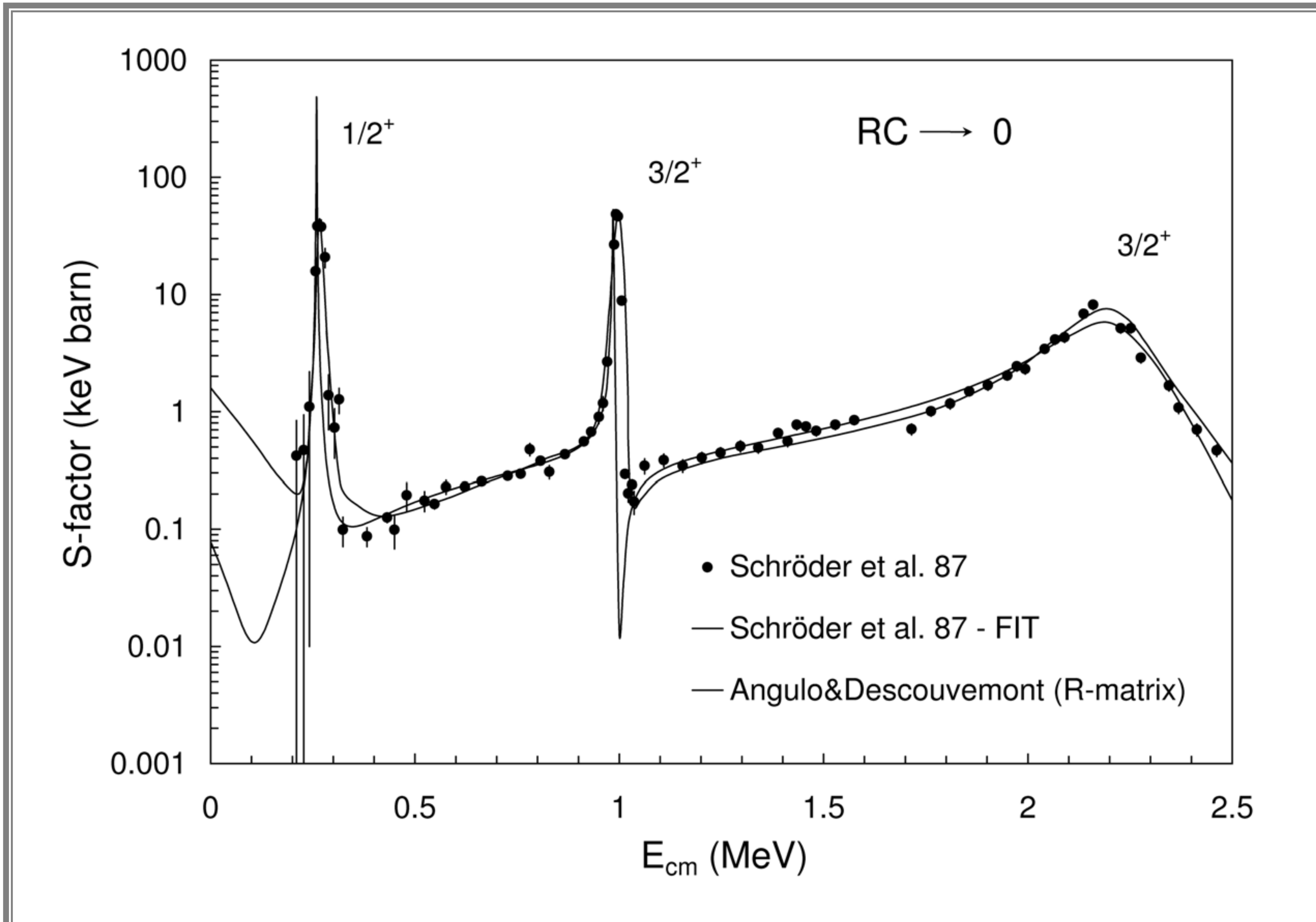
Extrapolation for $^{14}N(p,\gamma)^{15}O$

controls CNO hydrogen burning



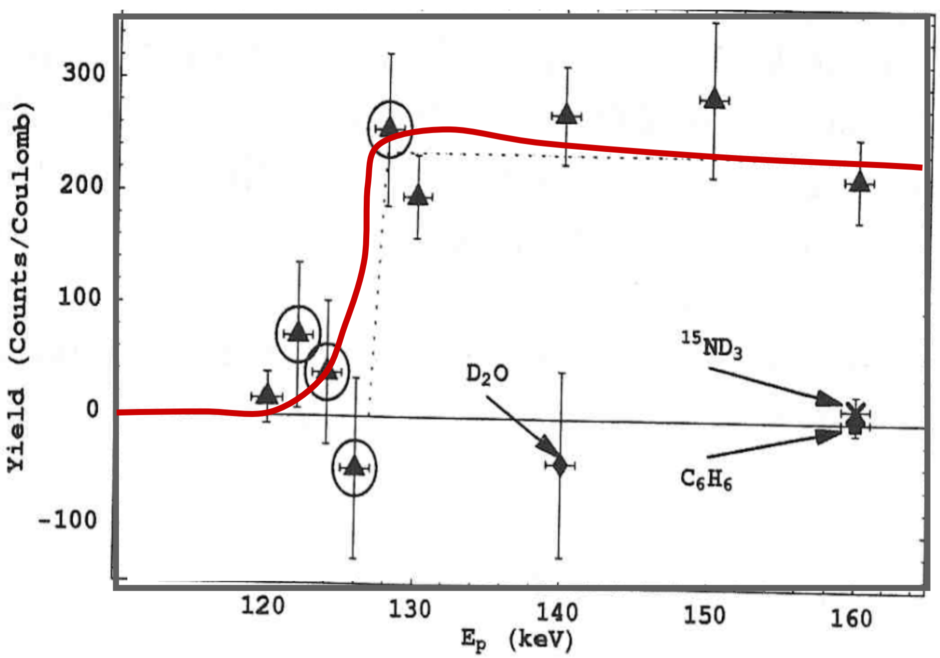
- o lifetime of massive stars
- o n-production in Red Giants
- o weak s-process

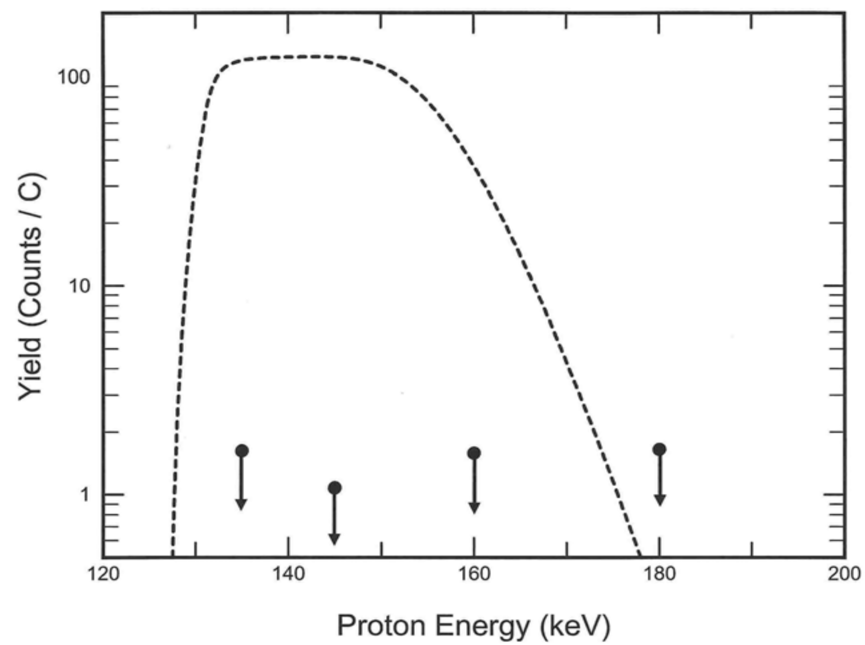
R-Matrix Extrapolation Uncertainties



New Resonance?

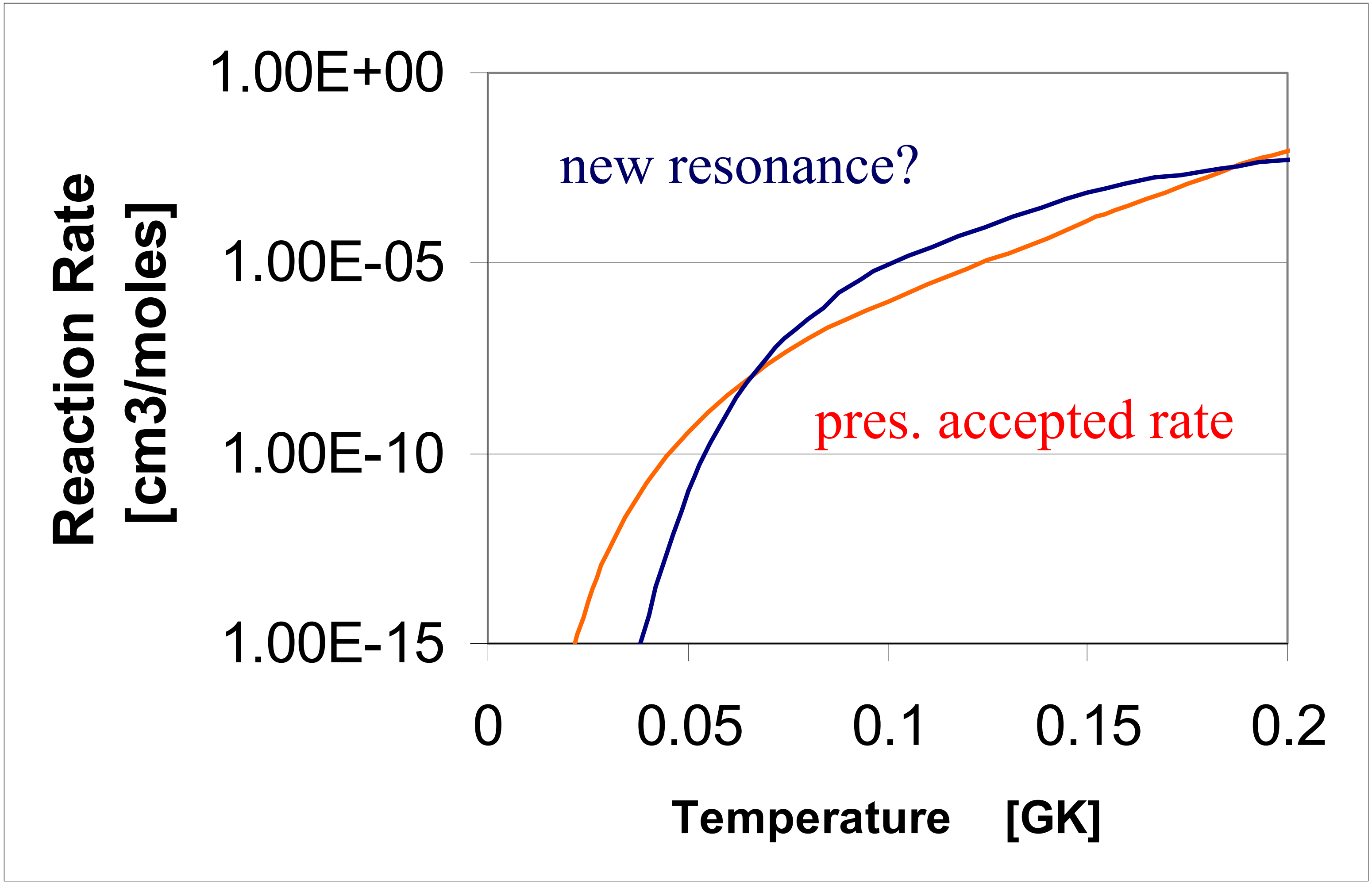
Infinite thick target measurement TUNL 2001



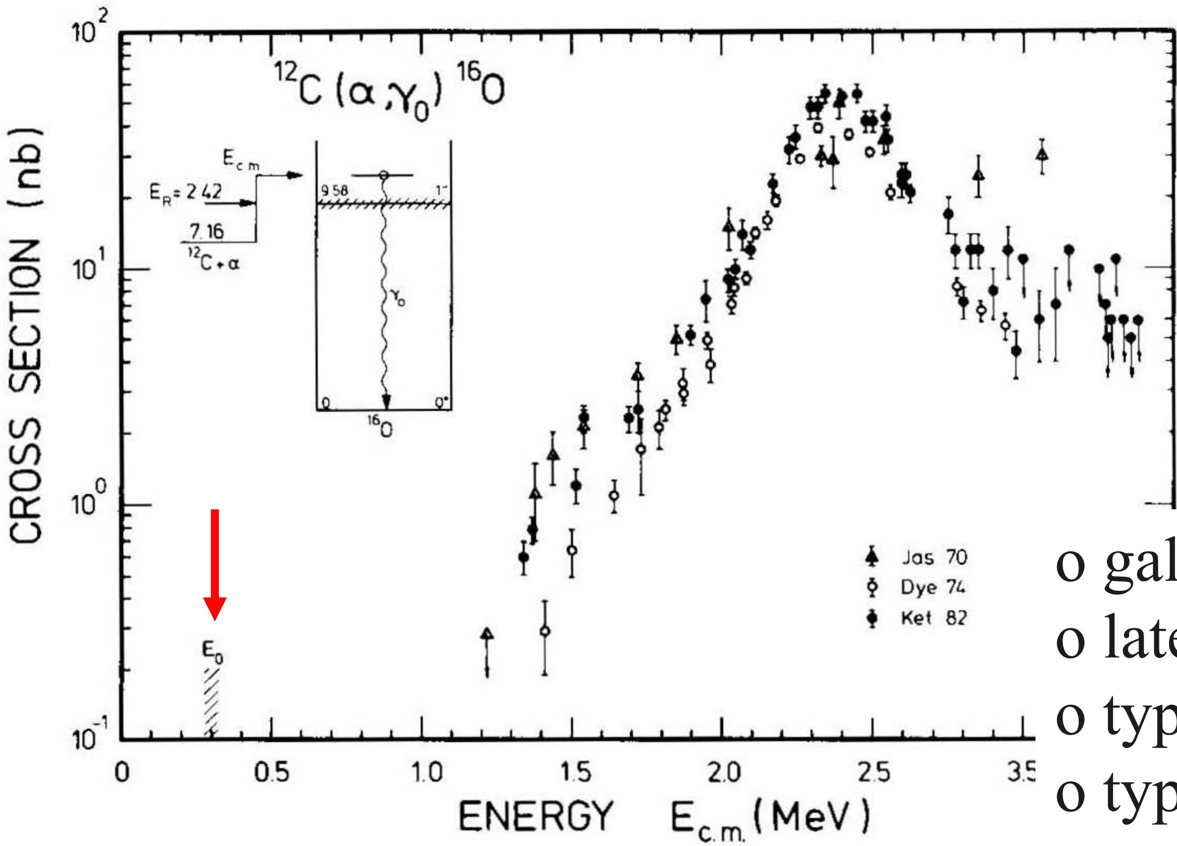


No confirming evidence in UNC data 2002

Impact of speculated resonance!



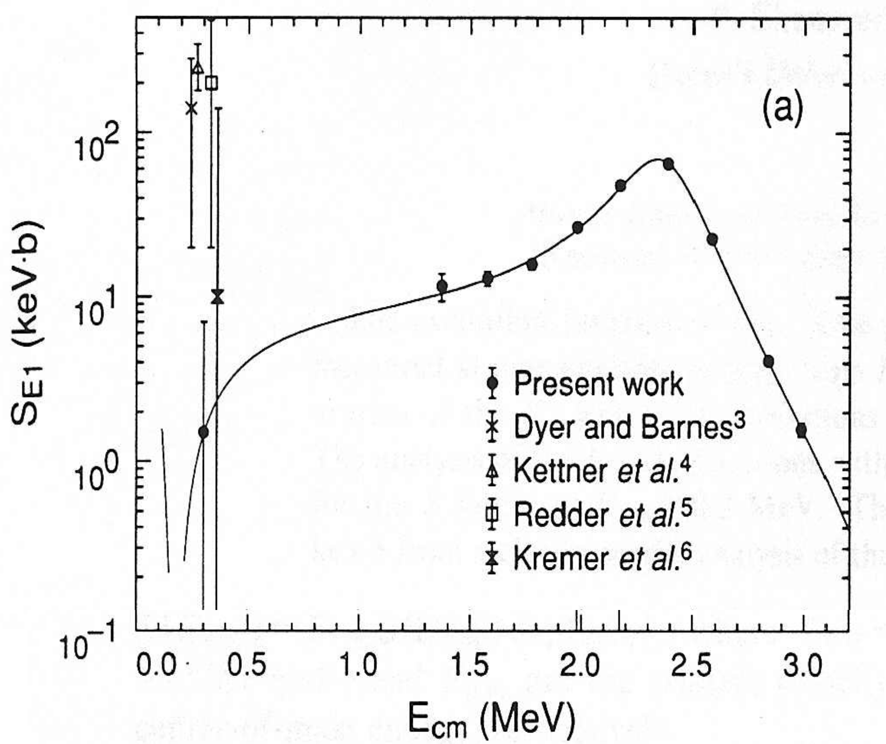
$^{12}C(\alpha,\gamma)^{16}O$ in stellar He-Burning

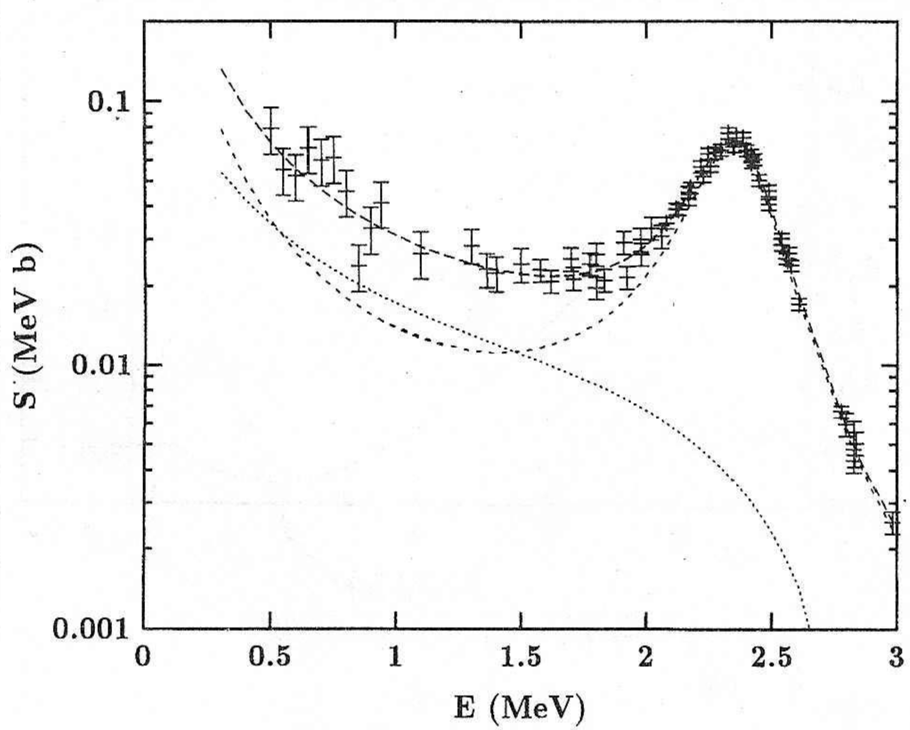


The “holy grail” of nuclear astrophysics

- o galactic $^{12}C/^{16}O$ ratio
- o late stellar evolution
- o type-I SN explosion
- o type-II SN nucleosynthesis

R-Matrix Fit Uncertainties





- ❑ constructive or destructive interference?
- ❑ tail, DC and resonance contributions?

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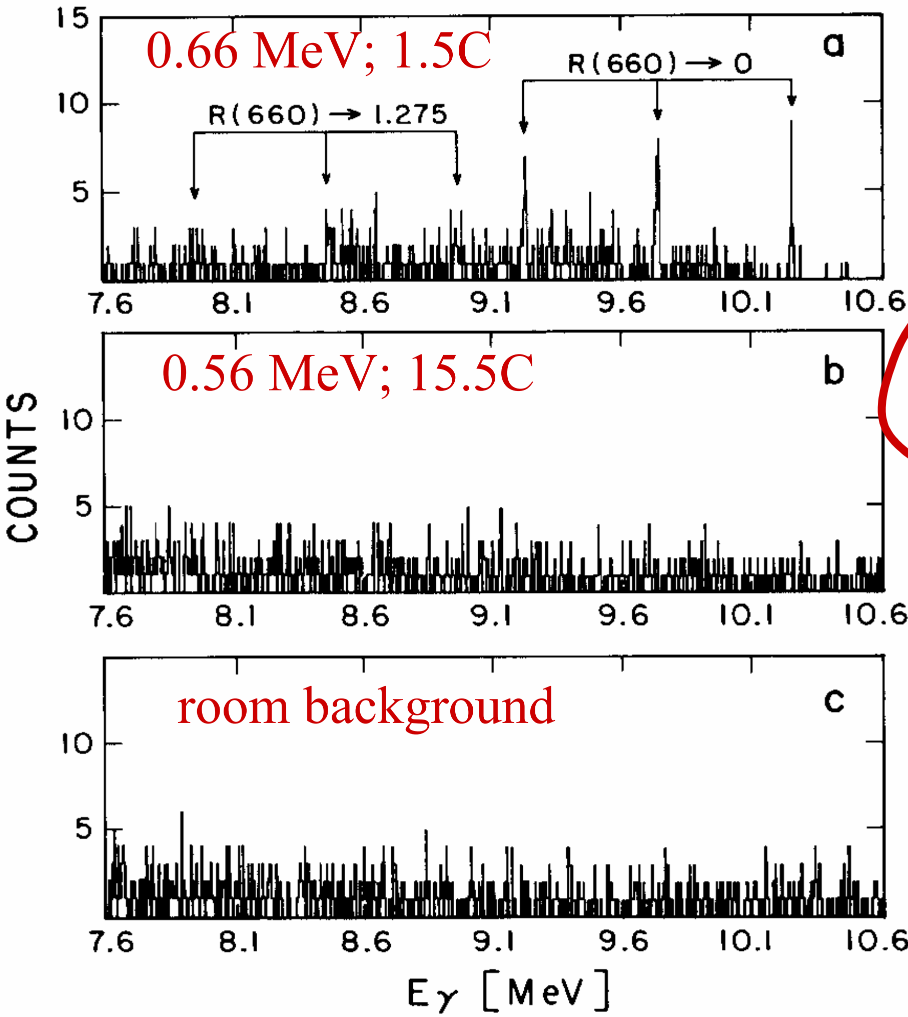
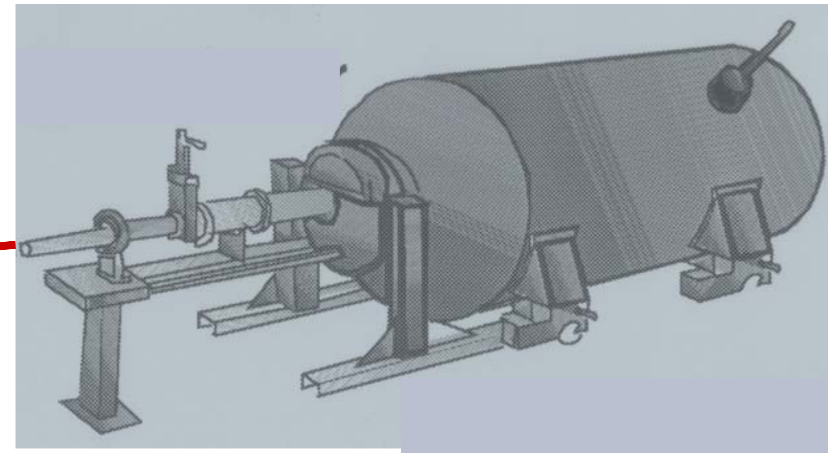
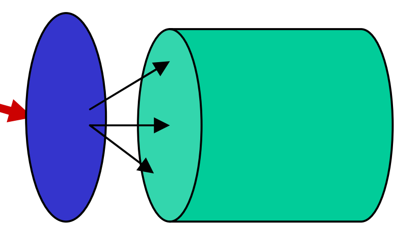
Forward Kinematics Technique
- Yield & Background –

Classical Approach – $^{18}O(\alpha,\gamma)^{22}Ne$



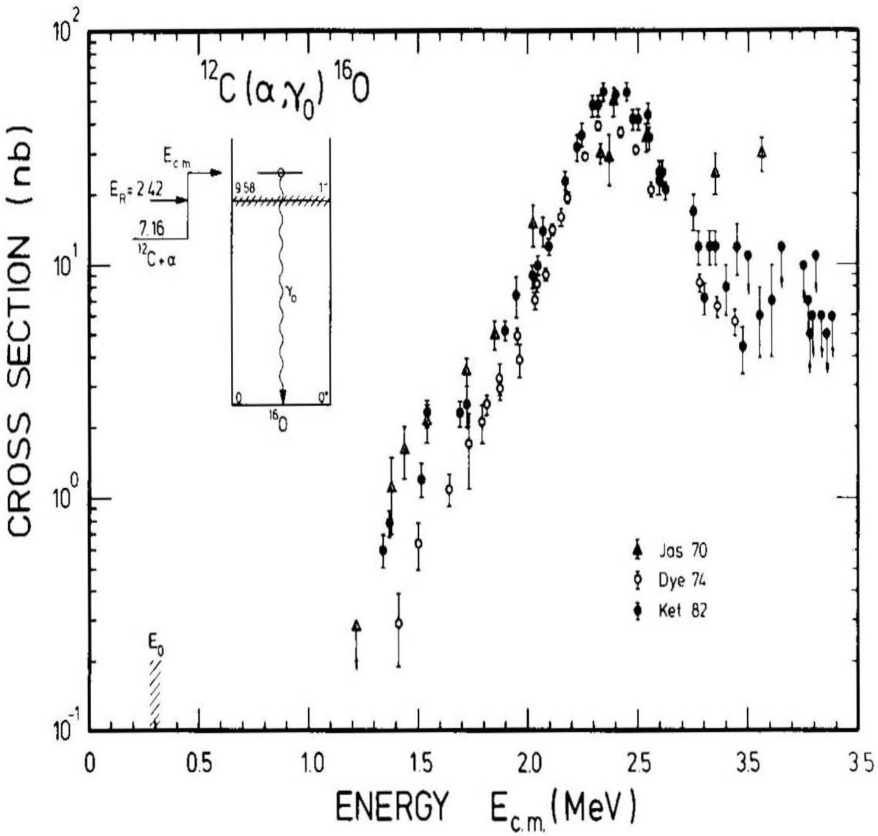


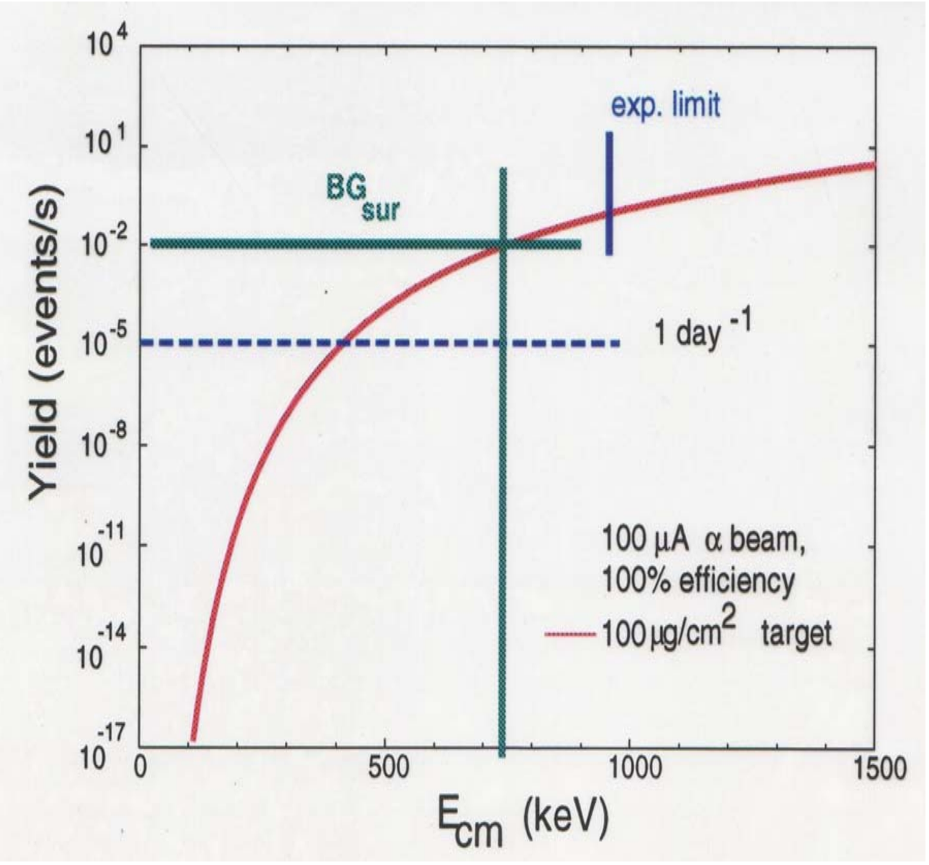
I=50-150 μA



Ge-detector

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



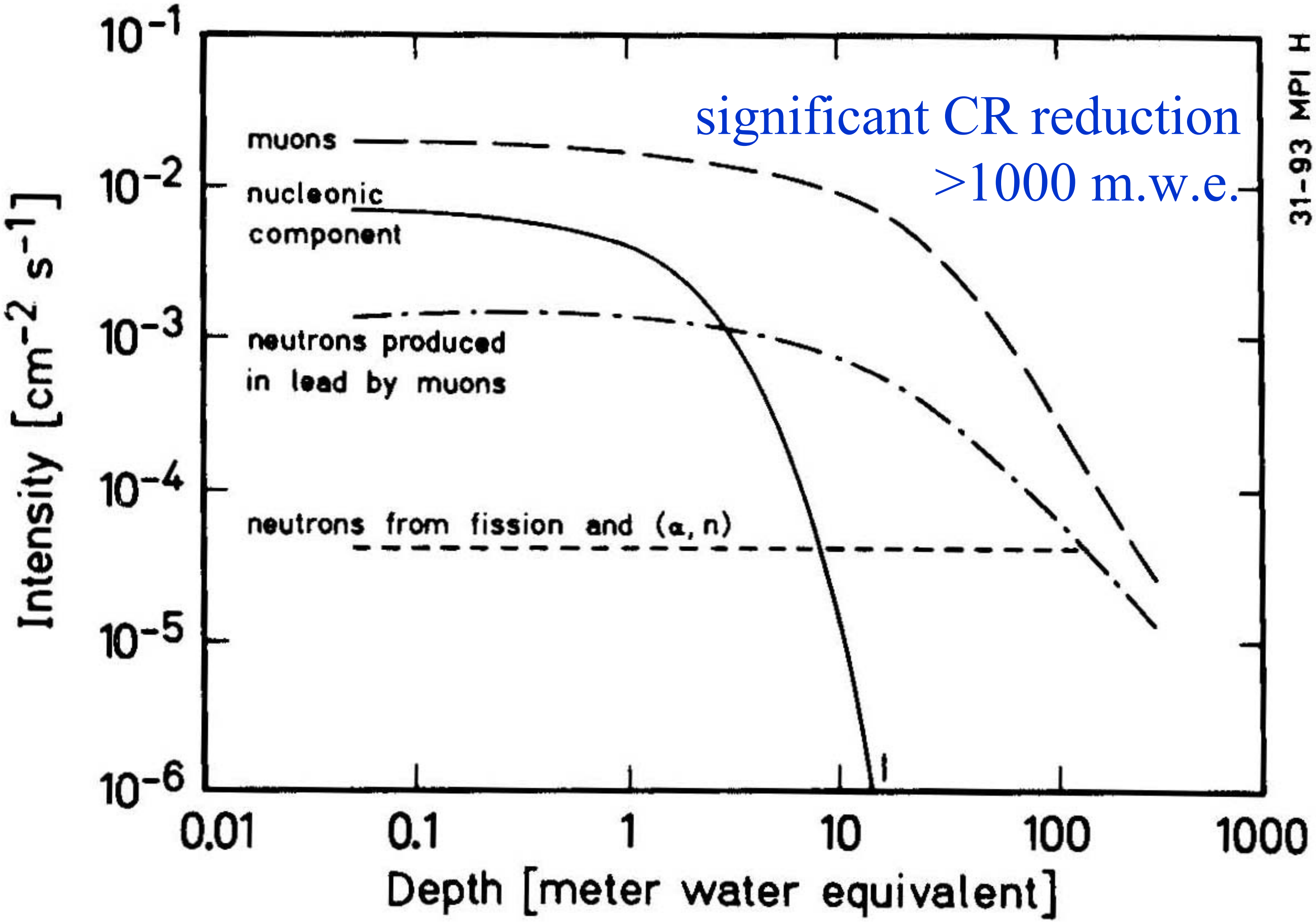


$$Y = \sigma \cdot n_T \cdot d \cdot n_p$$

low energy measurements
limited by background rate

Background Reduction Techniques

Underground Laboratory

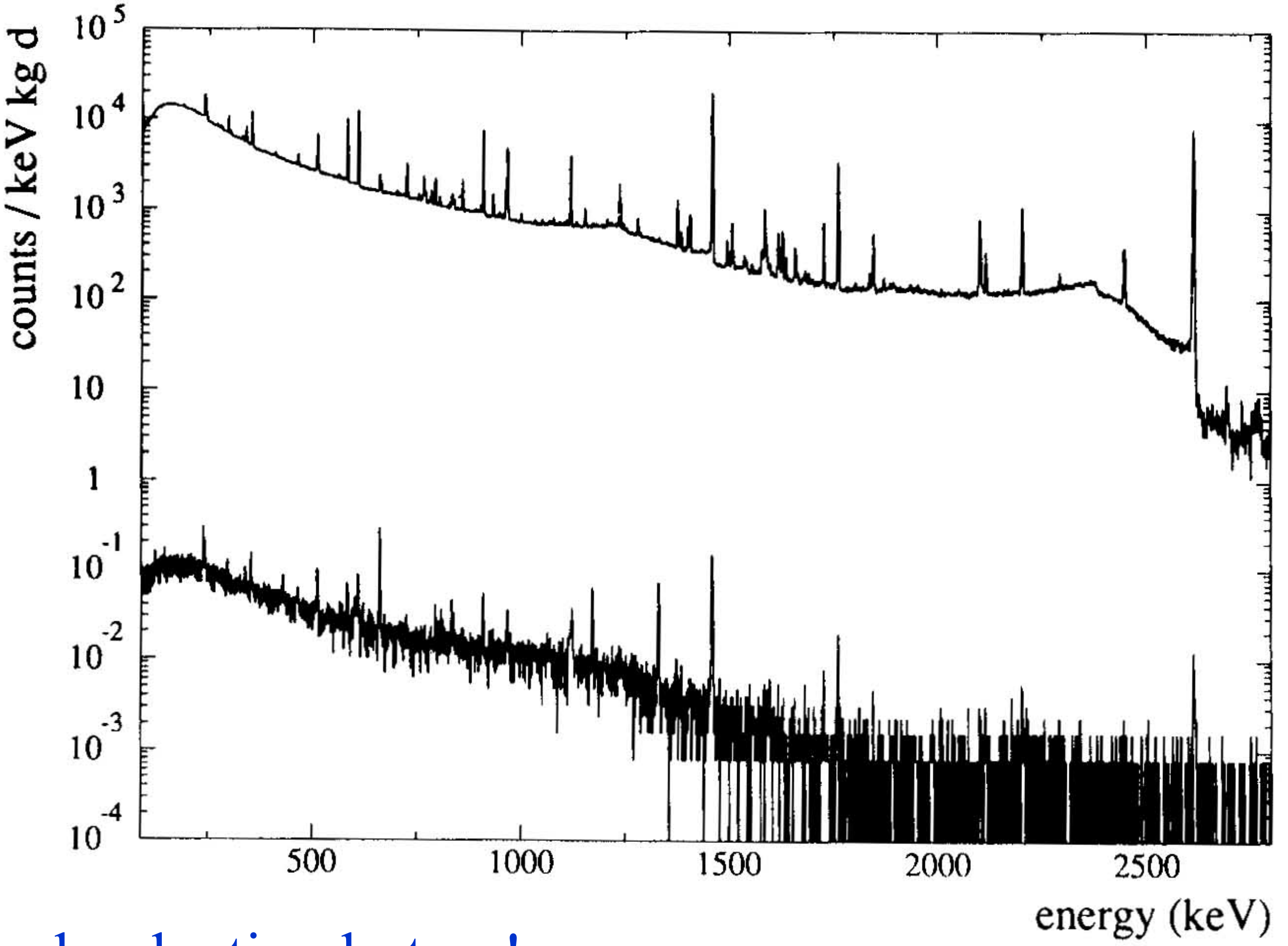


Passive Background Reduction

Ge-detector background spectrum

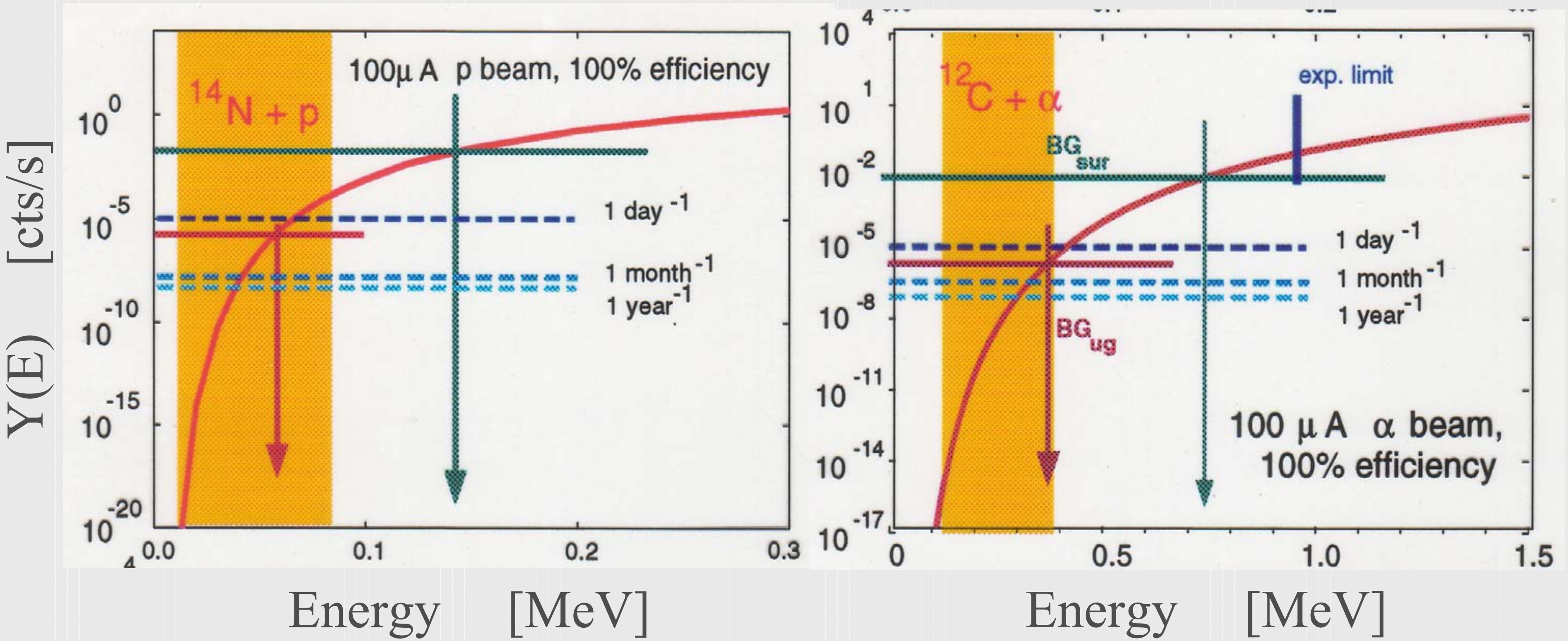
15 m.w.e.
unshielded

3400 m.w.e.
40cm Pb shield



Significant background reduction but …!

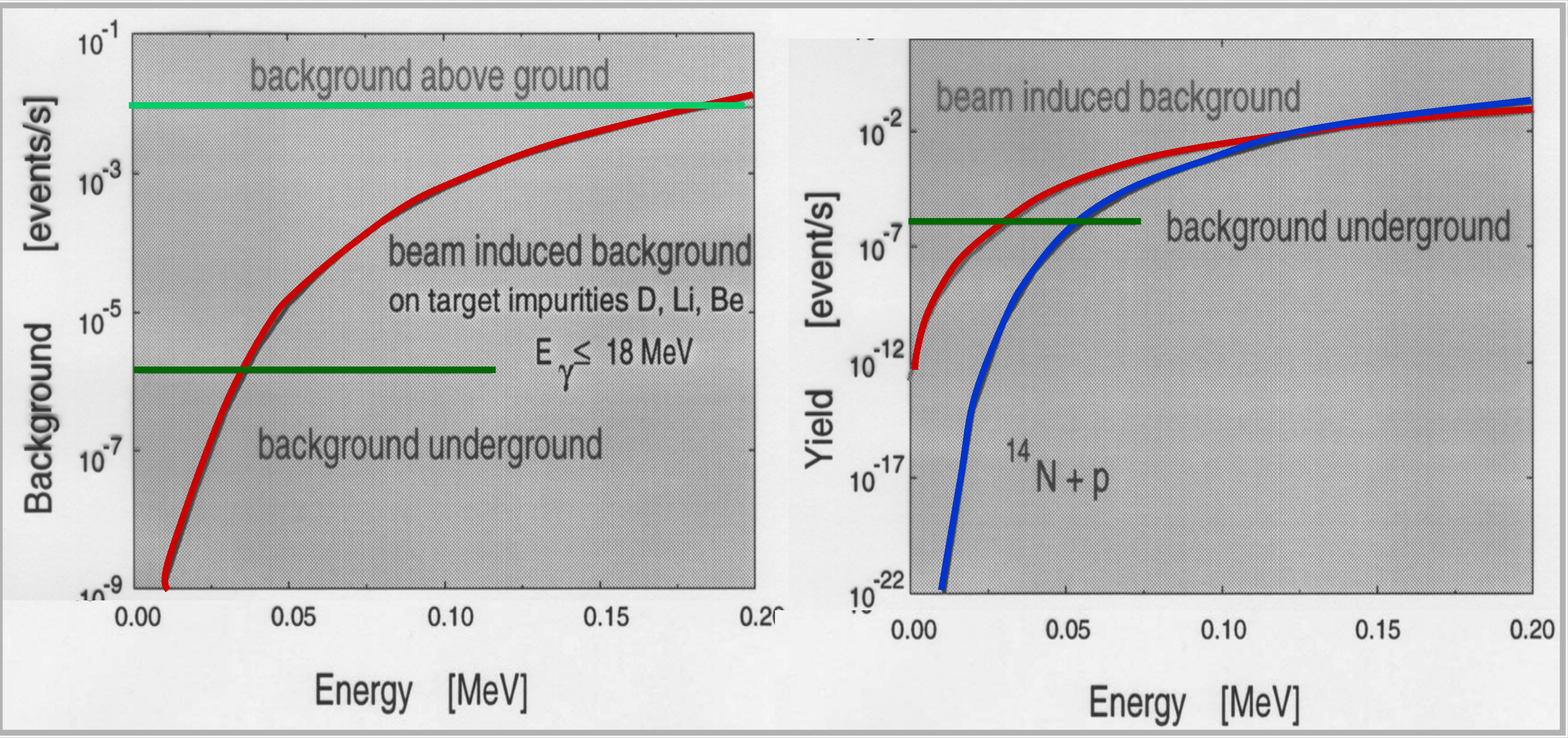
Background conditions



$$Y(E) = N_p \cdot \int_E \frac{\sigma(E)}{\varepsilon(E)} dE$$

gas jet target
10 μg/cm^2

Beam Induced Background?



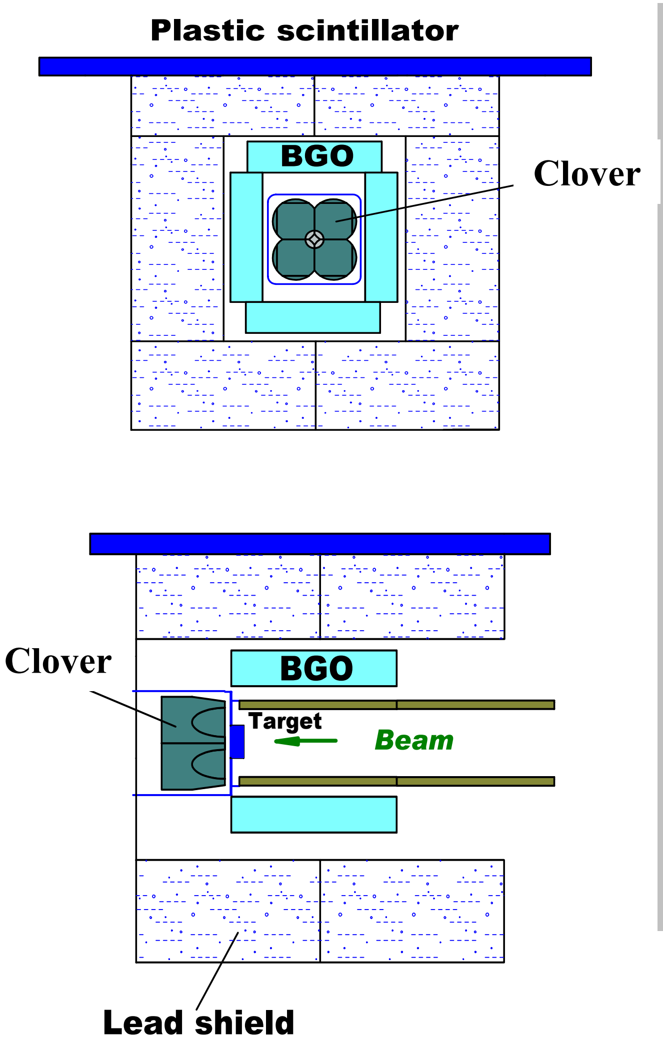
light target impurities can introduce considerable background

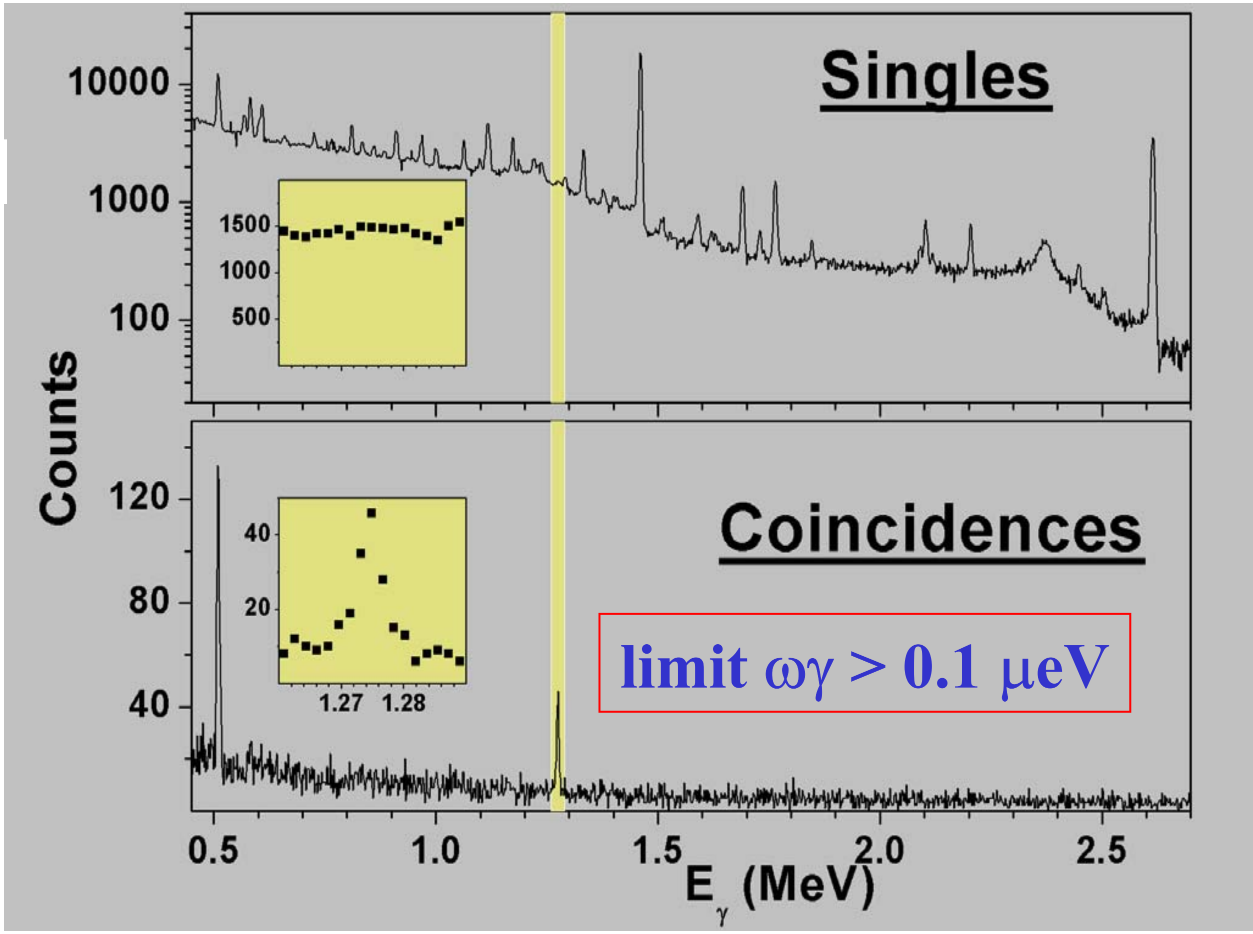
⇒ active background reduction necessary (see ^{3}He(^{3}He,2p)^{4}He)

⇒ or event identification required!

Active Background Reduction

E_r=566 keV; $\omega\gamma$=0.71μeV

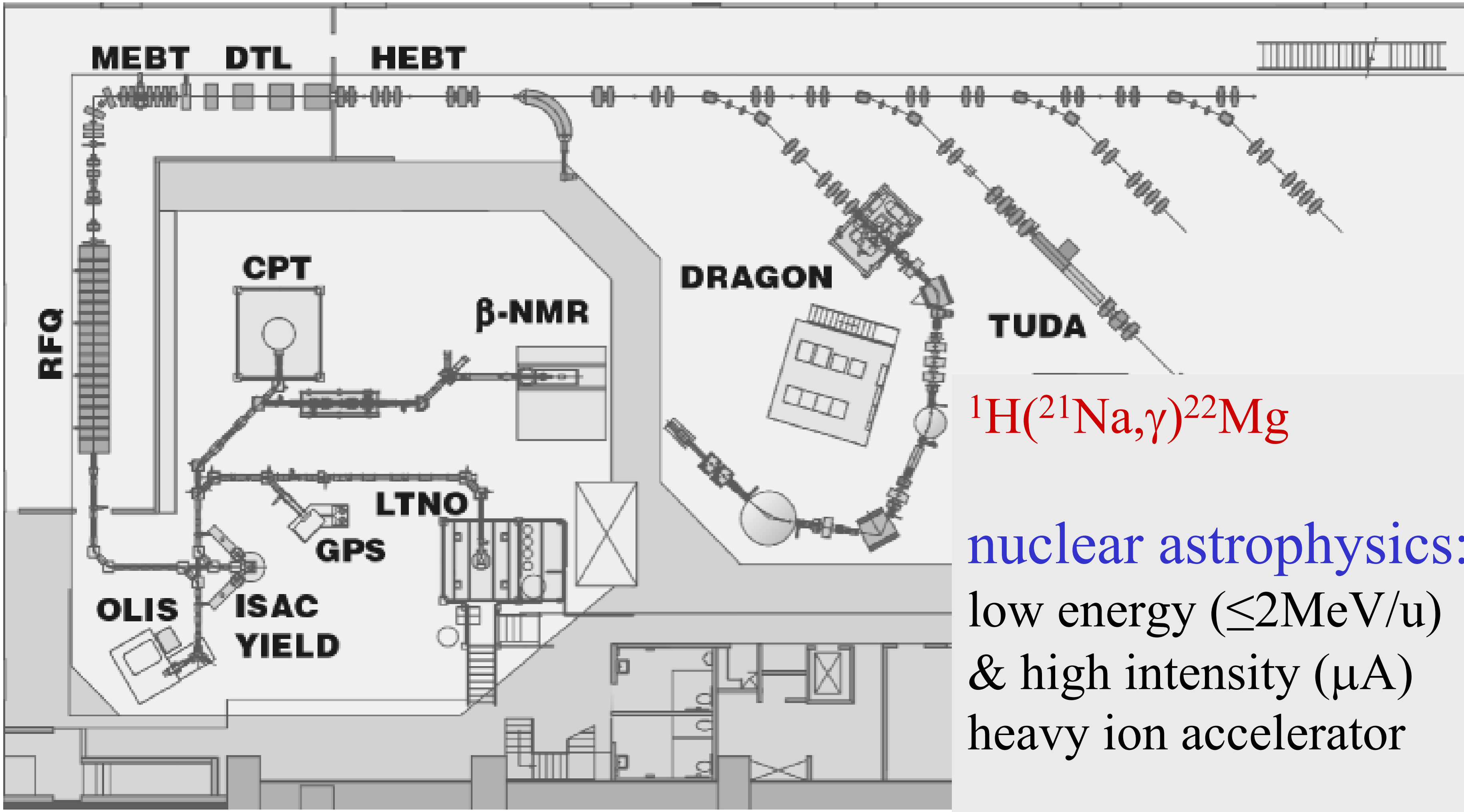




limitation in background reduction!

Inverse Kinematics Technique

Inverse Kinematics Techniques with RIBS @ ISAC-TRIUMF



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

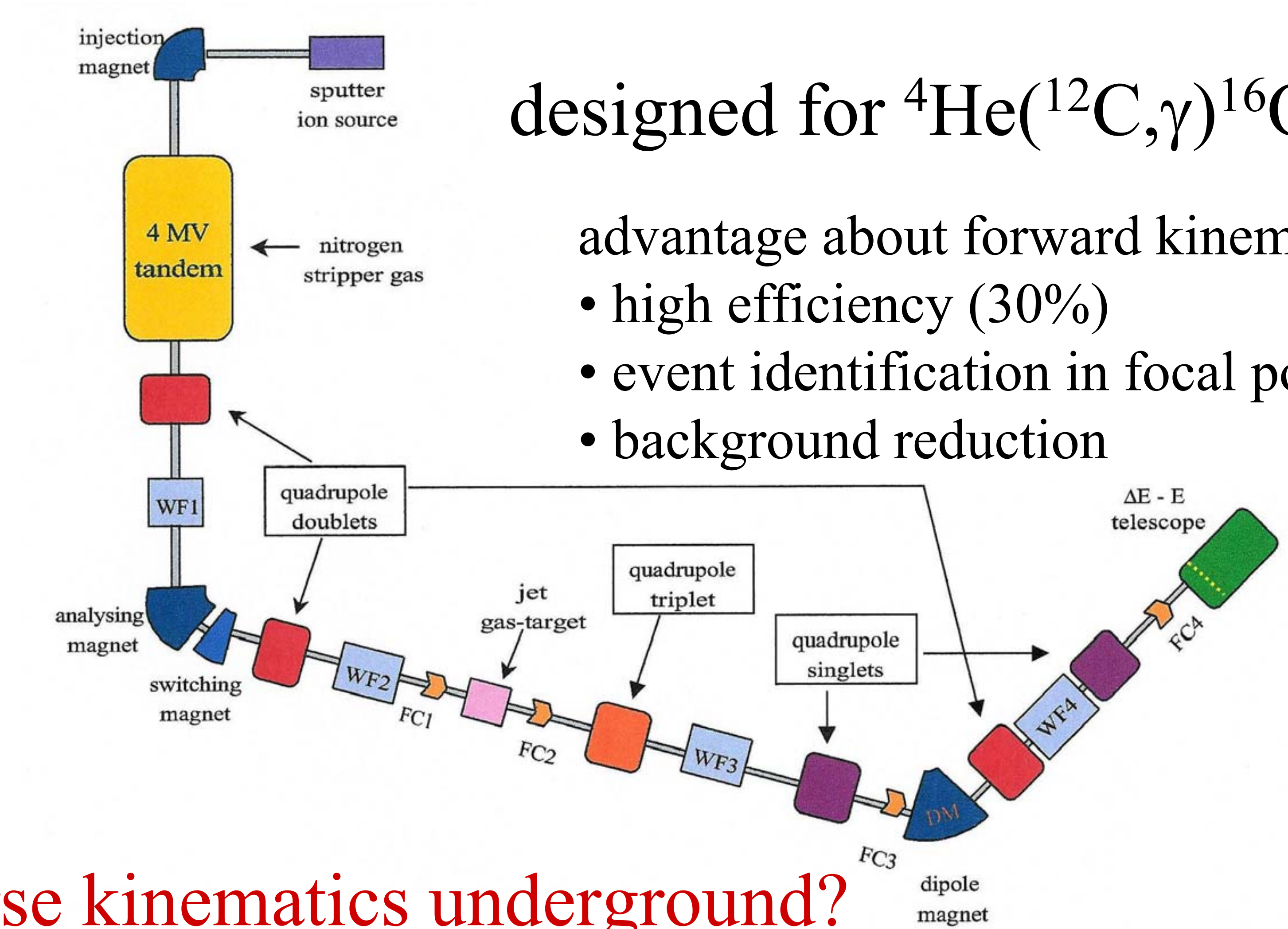
nuclear astrophysics:

low energy (≤2MeV/u)

& high intensity (μA)

heavy ion accelerator

Inverse Kinematics Techniques with SIBs at Dynamitron Bochum



designed for $^{4}He(^{12}C,\gamma)^{16}O$

advantage about forward kinematics:

- high efficiency (30%)
- event identification in focal point
- background reduction

Inverse kinematics underground?

Recoil Separator Requirements for event identification with recoils

anticipated event rate in low energy case 1 event/day

RIBs

incoming beam $<10^{10}$ particles/s$=10^{15}$ particles/day

beam reduction ratio $R=10^{-15}$

SIBs

incoming beam $\approx 100\ \mu A$ ($\approx 5\ 10^{19}$ particles/d)

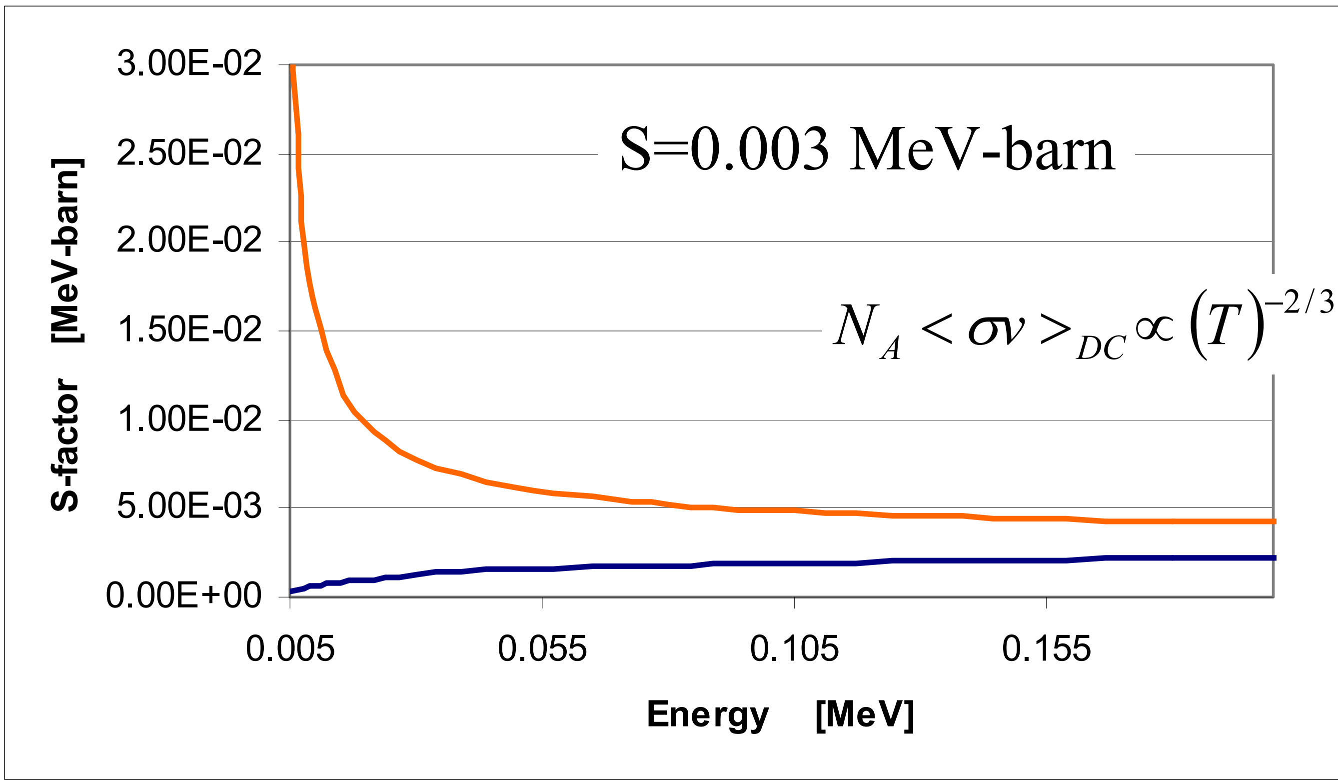
beam reduction ratio $R<10^{-19}$

is that achievable???

Energy Calibration Specifications and Beam Intensity Requirements

energy calibration for S-factor

conversion of cross section to S-factor $S(E) = \sigma(E) \cdot E \cdot e^{2\pi\eta}$



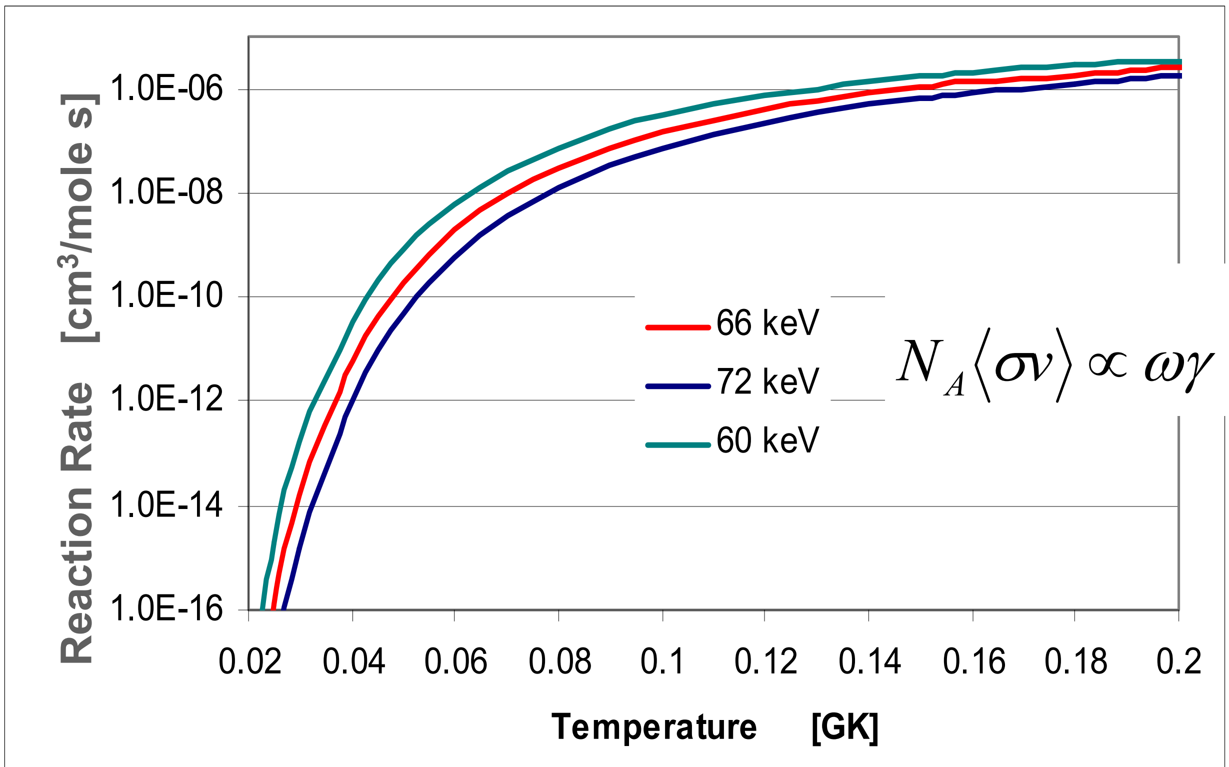
$$N_A < \sigma v >_{DC} \propto (T)^{-2/3} S(E_0) \, e^{-\tau(T)}$$

with energy calibration off by 5% up to a factor of 10

energy calibration of <1% accuracy required

<<1% requirement for energy calibration

$^{17}O(p,\gamma)^{18}F$: resonance at 66±6 keV; $\omega\gamma = 6\cdot 10^{-11}$ eV



$$N_A\langle\sigma v\rangle \propto \omega\gamma \cdot (T)^{-3/2} \cdot e^{-\left(\frac{\cdot E_R}{kT}\right)}$$

10% uncertainty in resonance energy ⇒ 2 orders of magnitude in rate

1% uncertainty in resonance energy ⇒ factor 2 uncertainty in rate

energy and intensity requirements

• energy calibration:	< 0.1%
• energy resolution:	< 0.1%
• long-term stability	> days to months
• beam intensity:	I >100 μA
• count rate limitation	σ > 200 fbarn
of 1 event/day	$\omega\gamma_{(p,\gamma)}$ > 10 peV
30% efficiency	$\omega\gamma_{(\alpha,\gamma)}$ > 0.1 neV

10% statistics with peak/background=1
requires 150 days!

limits cross section measurement to E>50 keV
resonance measurements to E>30 keV

Conclusion

- low energy measurements necessary
  to remove or reduce cross section extrapolation uncertainties!

- Optimization of peak to background crucial!
  High intensity beams, passive or active background reduction!

- standard light ion beam approach
  with underground passive and/or
  coincidence active shielding
  (e.g. summing signal coincidence or event tracking)

- inverse kinematics with heavy ion beam
  with underground passive shielding
  and recoil event identification and/or light signal coincidence