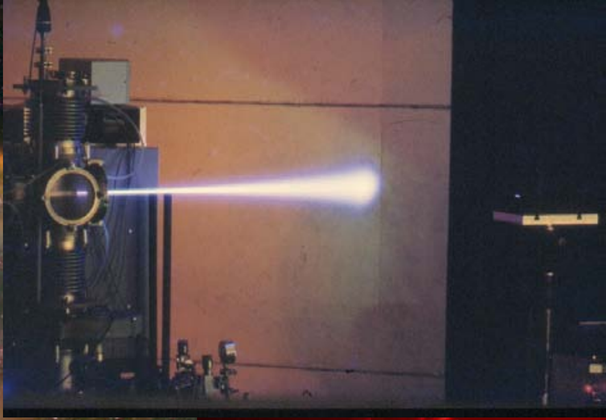
Carbon fusion reactions in stars



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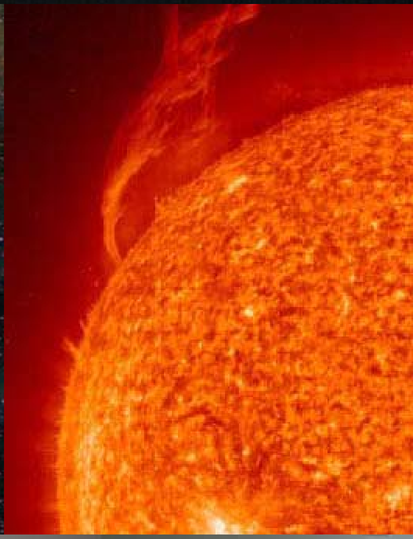


Symposium on Nuclei in the Cosmos XI
Heidelberg, Germany
19.07.2010

Outline of Presentation

Carbon Fusion Reactions in Stars

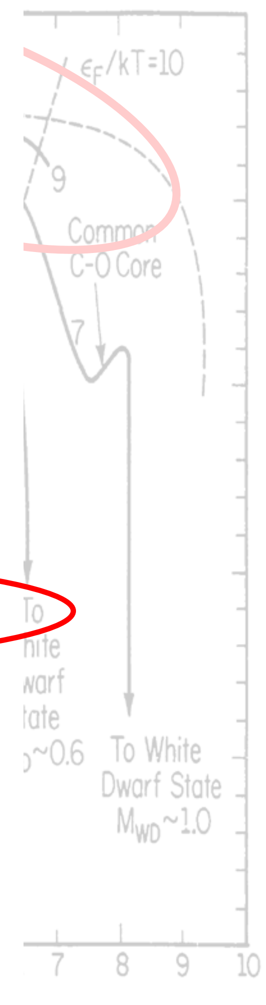
- Astrophysical Motivation – Importance of ^{12}C + ^{12}C
- ^{12}C + ^{12}C via particle spectroscopy (CIRCE Caserta/Napoli)
- Background Considerations
- Results

Motivation – Stellar Evolution

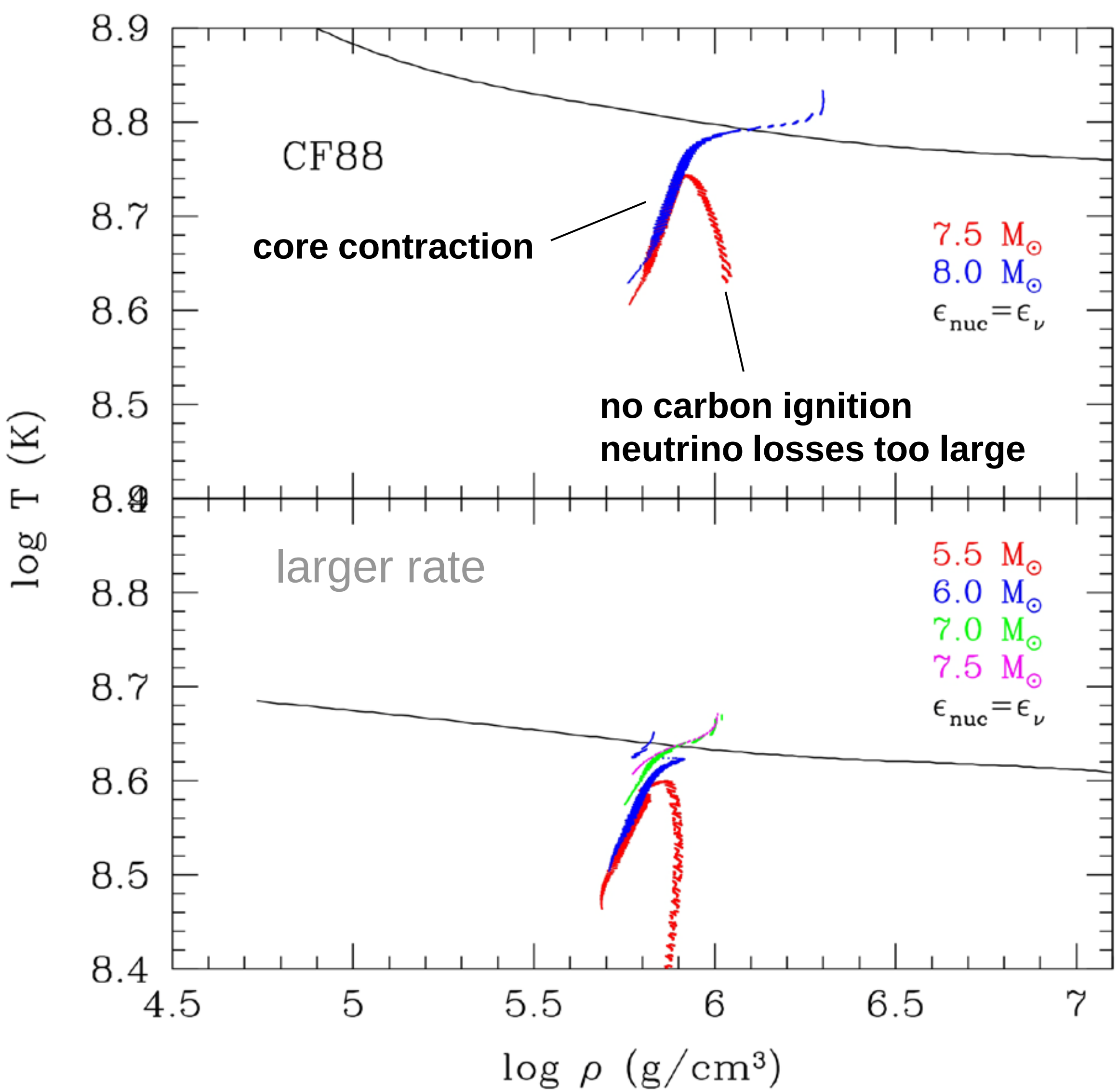
Nuclear burning stages

(e.g., 20 solar mass star)

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\,H \xrightarrow{CNO} {}^4He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	$3\,He^4 \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$
O	Si, S	Cl, Ar, K, Ca	2.0	0.8	$^{16}O + {}^{16}O$
Si	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	$^{28}Si(\gamma,\alpha)\ldots$



Astrophysical consequences and implications



computed with the FRANEC code

stellar model calculation
(private communication Oscar Straniero)

important implications on progenitor stars of Type II Supernovae

larger rate
perhaps in better agreement with recent astronomical observations, which suggest a lower mass limit than presently given by models

Astrophysical Motivation $^{12}C + {}^{12}C$ fusion

Results of current Stellar Models suggest:

$M_{up} \equiv$ minimum mass for carbon ignition

- **Stars with $M < M_{up}$ (presently $8M_{solar}$)**
  These stars shed their H-rich envelopes during He burning (AGB phase) and end as CO White Dwarfs

→ Impact on the Nucleosynthesis and the chemical evolution of the Universe

→ the expected observational rates for Supernovae and Novae depend on the fundamental mass limits M_{up} and M'_{up} and, thus on the $^{12}C+{}^{12}C$ reaction rates

- **Stars with $M > M'_{up}$**
  Ignition of central carbon burning followed by Ne, O, and Si burning. The subsequent evolution proceeds in most cases to a core collapse Supernova.
  → These stars make the bulk of newly processed matter that is returned to the ISM.

Carbon Burning in Stars

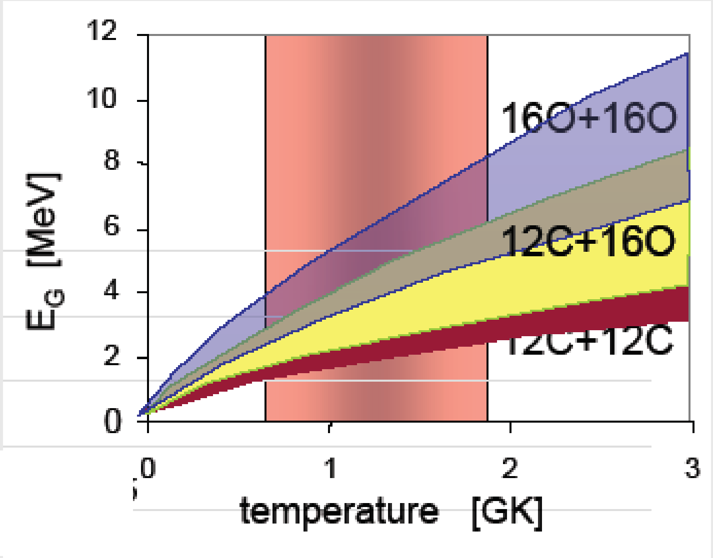
Wide range of possible heavy ion reactions – at low energies most important: $^{12}C + {}^{12}C$ (lowest Coulomb Barrier)

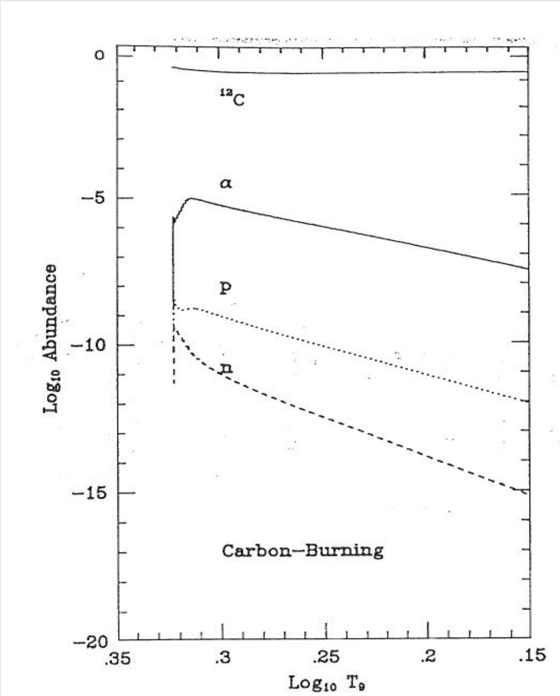
$^{12}C(^{12}C,p)^{23}Na$ Q = 2.240 MeV

$^{12}C(^{12}C,\alpha)^{20}Ne$ Q = 4.617 MeV

$^{12}C(^{12}C,n)^{23}Mg$ Q = -2.598 MeV

$$E_G = 2.42 \times T_9^{2/3} \pm 0.75 \times T_9^{5/6}$$

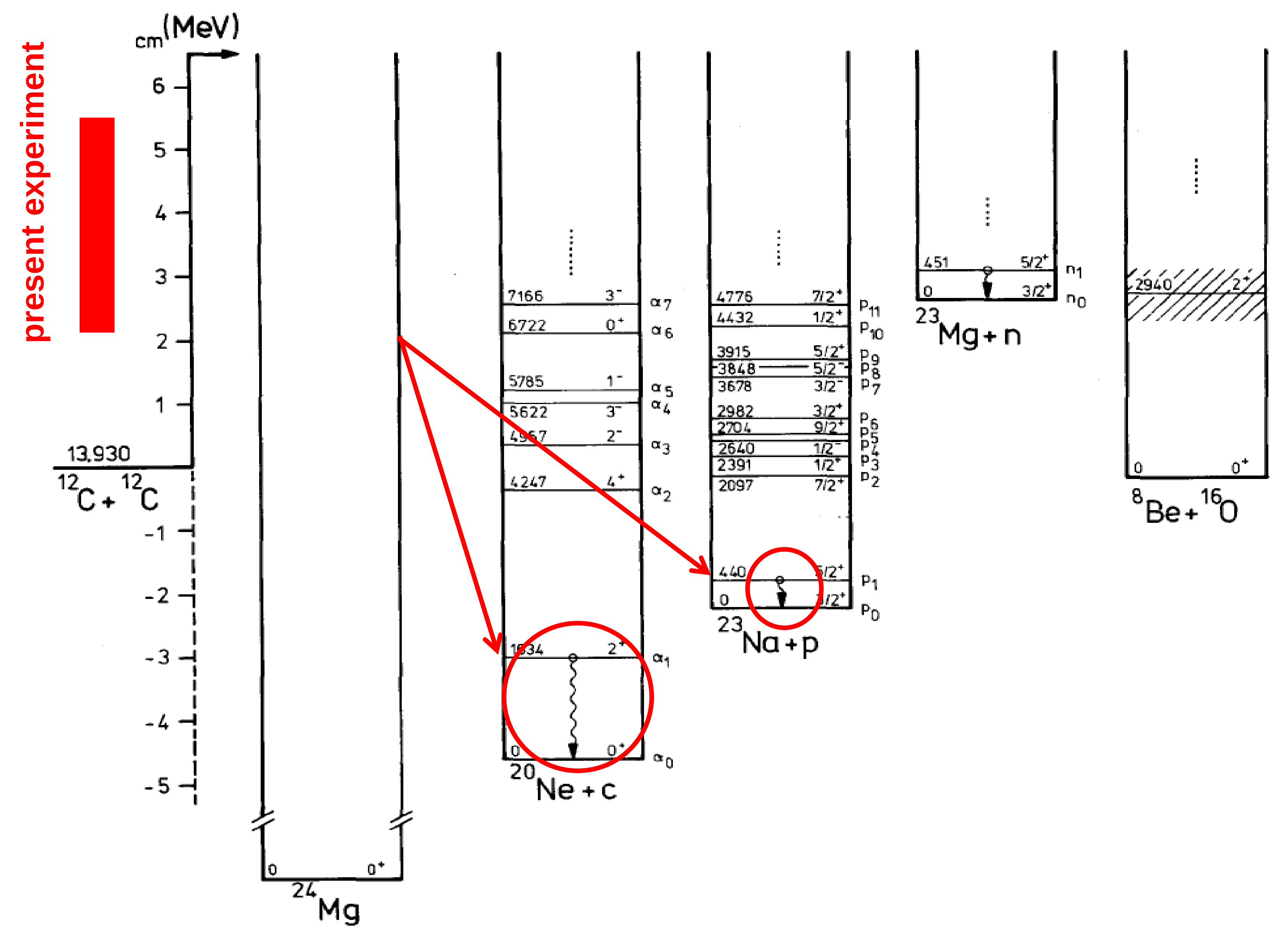




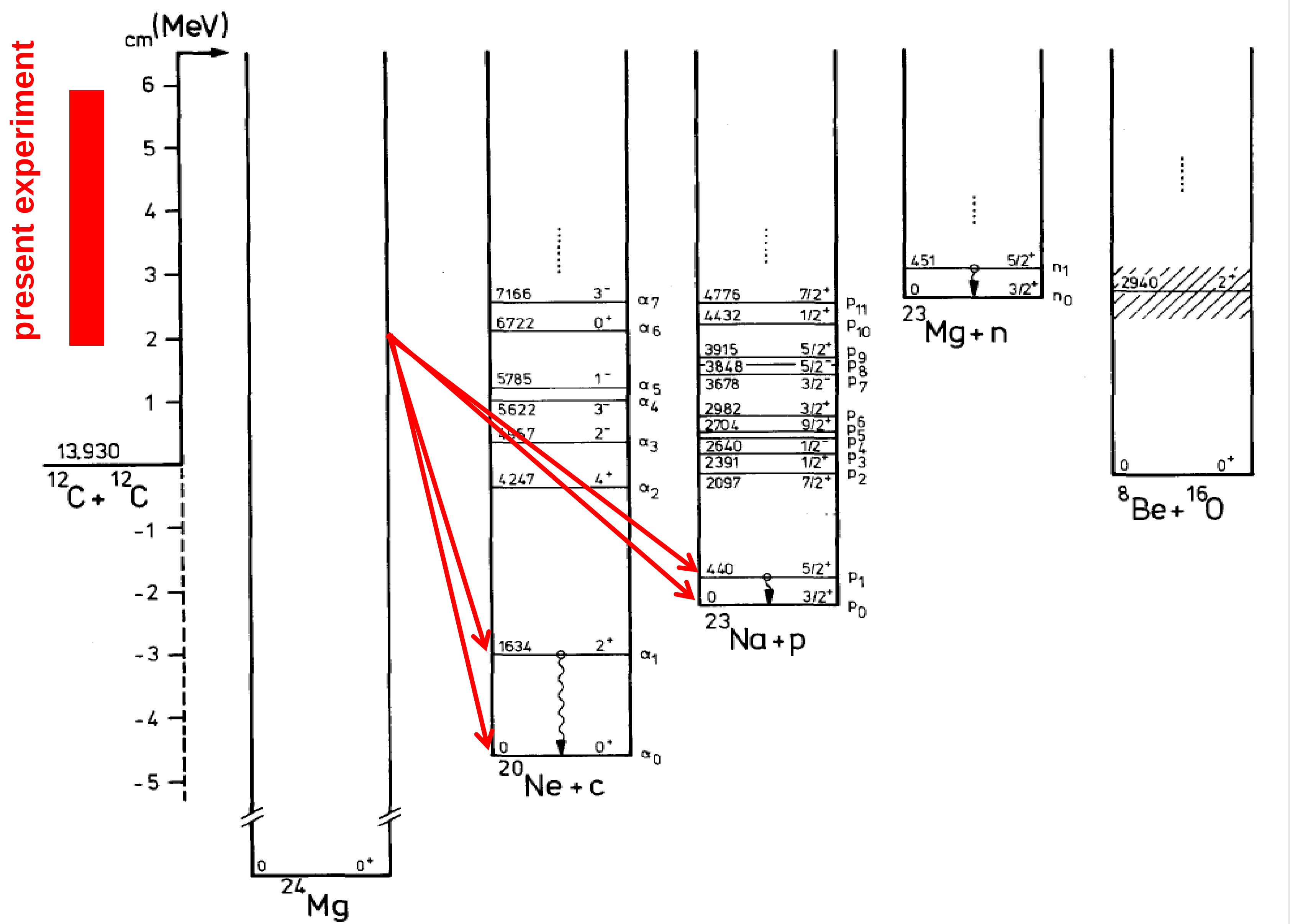
The $^{12}C+{}^{12}C$ fusion reactions produce light elements; their abundances stay relatively low and reflect the rate ratio of the reactions destroying them and of $^{12}C+{}^{12}C$.

Nucleosynthese in surrounding burning shell

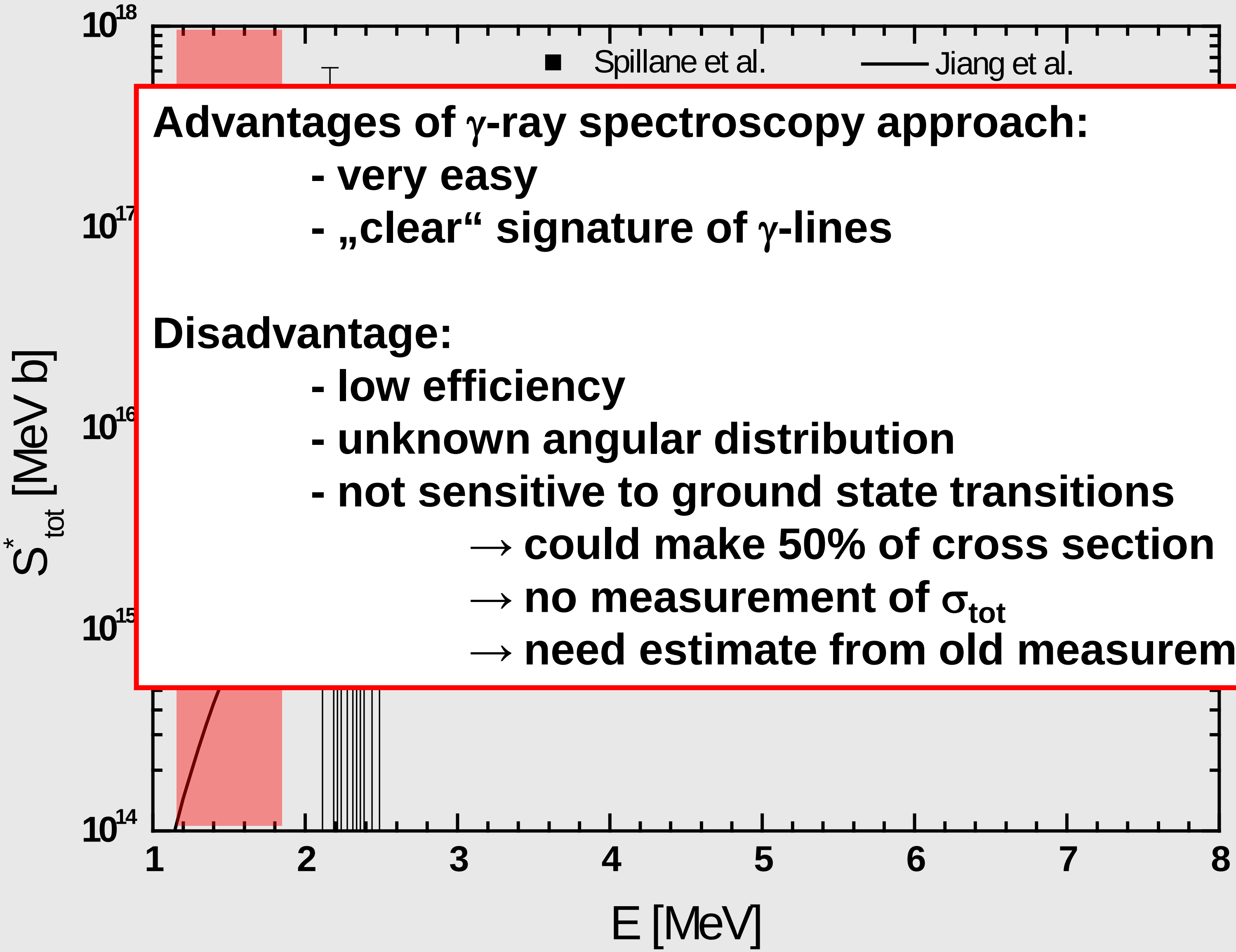
Level Scheme - γ-ray spectroscopy



Level Scheme - particle spectroscopy



Experimental Results – total S-factor



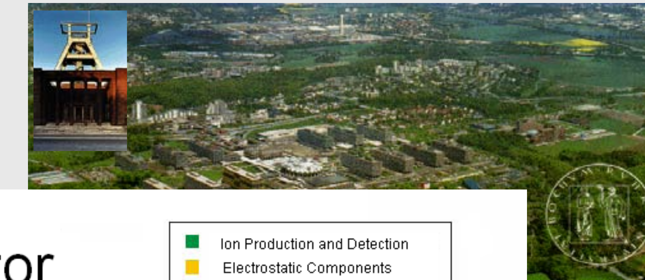
Advantages of γ-ray spectroscopy approach:

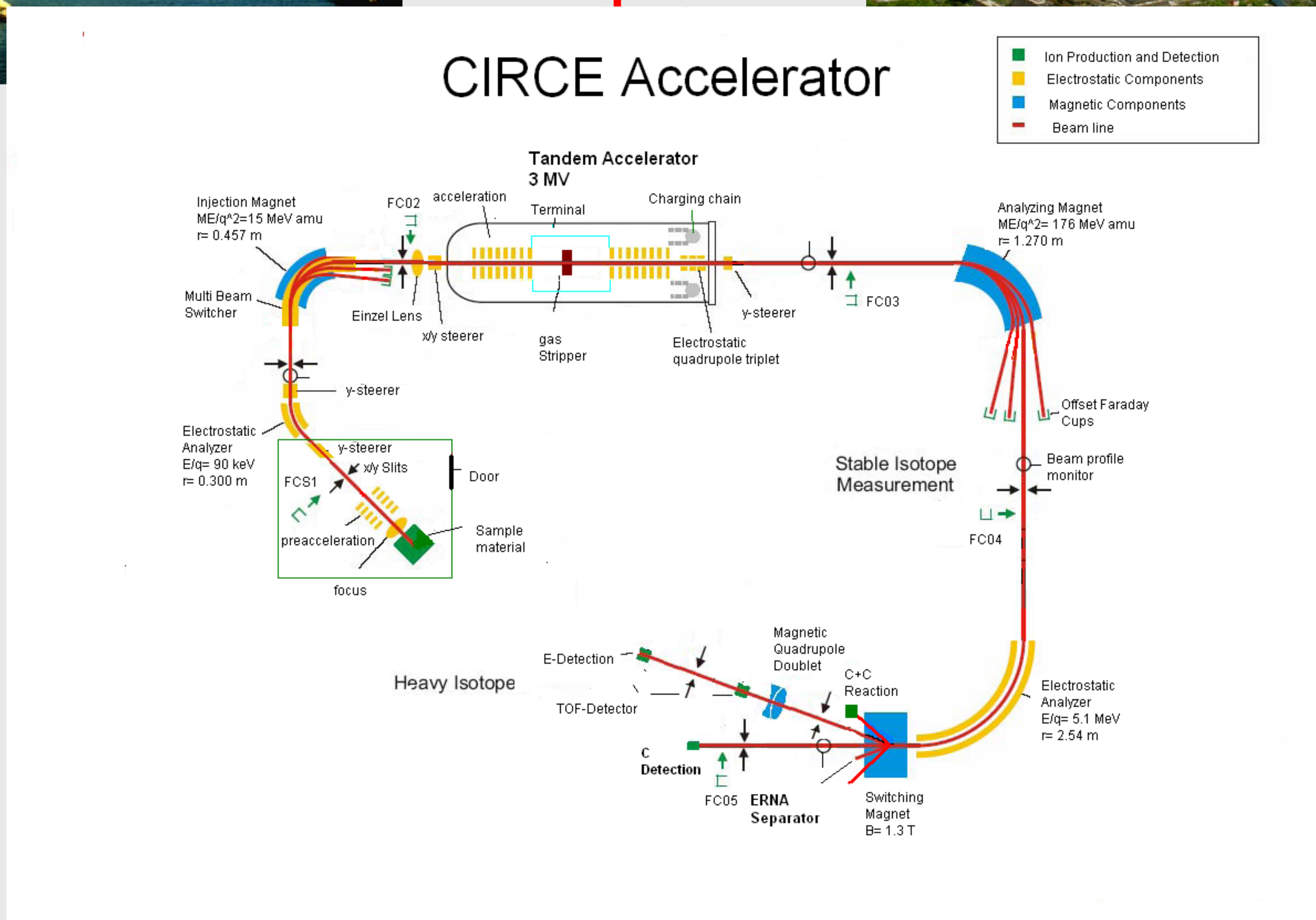
- very easy
- „clear“ signature of γ-lines

Disadvantage:

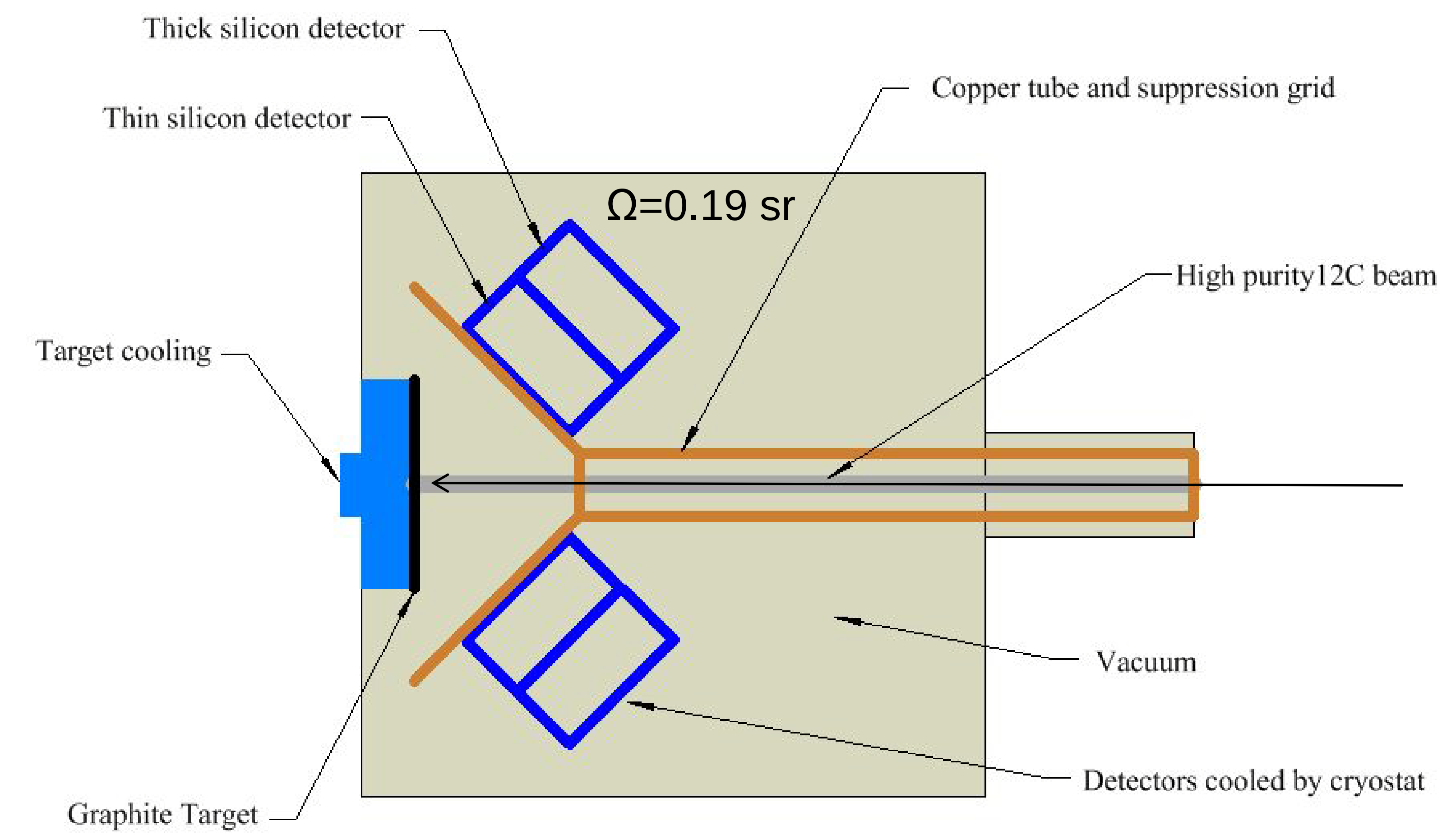
- low efficiency
- unknown angular distribution
- not sensitive to ground state transitions
  - → could make 50% of cross section
  - → no measurement of σ_{tot}
  - → need estimate from old measurement

Setup - Accelerator





Experimental Setup - particle spectroscopy

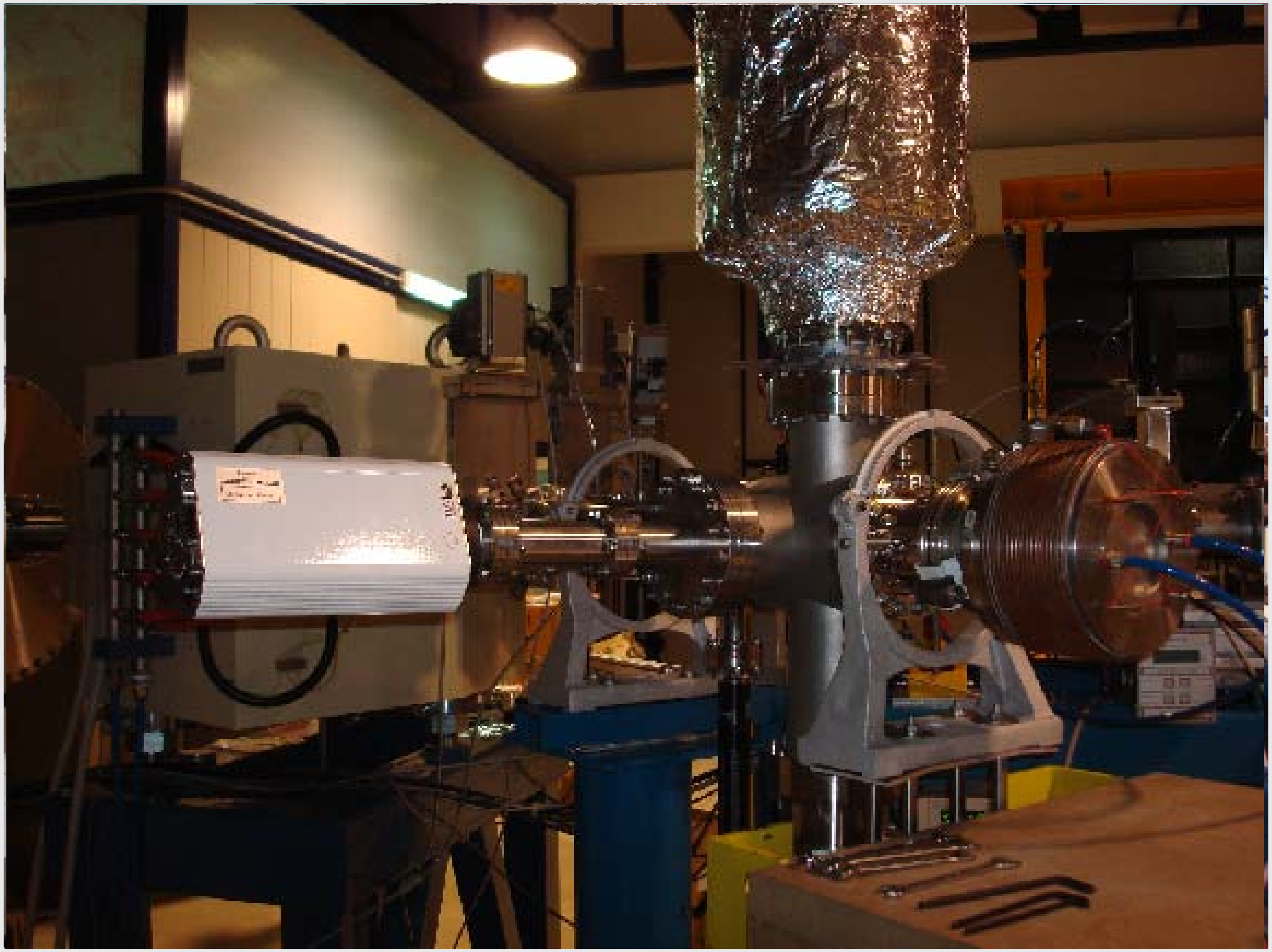


preliminar tests wth single detector:

→ beam induced background too high at lower energies

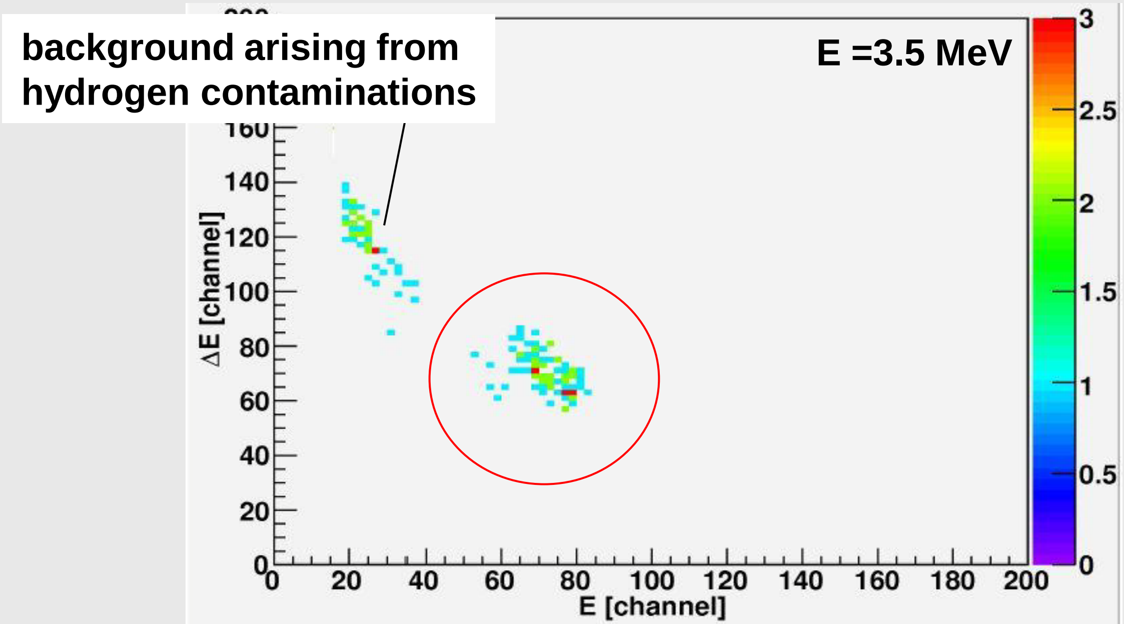
→ ΔE-E particle detector telescope

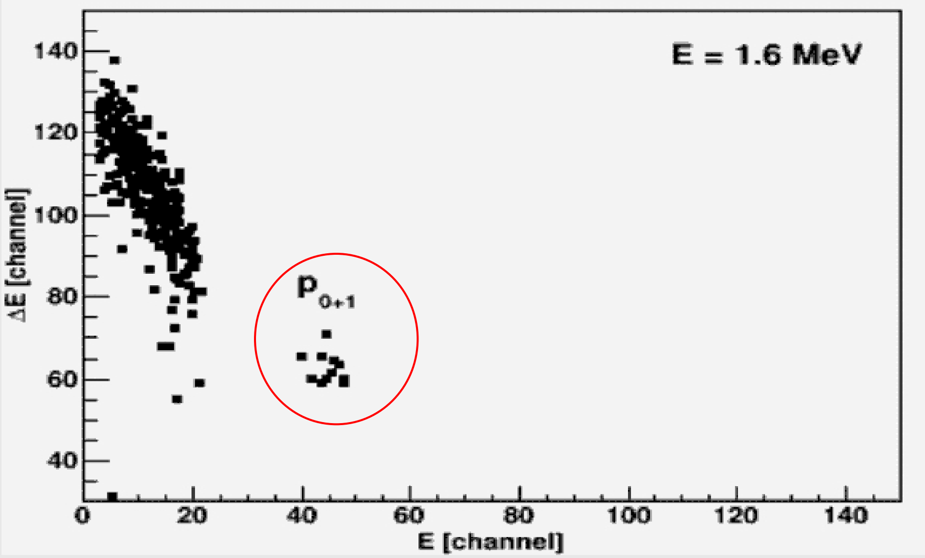
Experimental Setup - particle spectroscopy



Completely separate detector volume from target using foils and sheet metal
→ Target sputtering causing large leak currents on silicon detectors

Experimental Results - particle spectroscopy





first phase:
- only p channel is detected
- $^{12}C(^{12}C,p_{0,1})^{23}Na$
- ΔE detector too thick
- α particles are stopped
- background tests

second phase:
- $^{12}C(^{12}C,\alpha_{0,1})^{20}Ne$ with small size ion chamber telescope or Bragg curve detector
- starts late 2010

Background Considerations

disadvantage of particle spectroscopy:

very poor energy resolution

from kinematics as well as experimental technique

→ background discrimination not as „easy" as for γ-ray spectroscopy

→ test with various beams and targets (^{7}Li, ^{9}Be, ^{10,11}B, ^{13}C)

no impact observed so far

but:

water, i.e. deuterium, remains as a huge problem

Background Considerations

in γ-ray spectroscopy measurements main source of background

$^{12}C(d,\mathbf{p}\gamma)^{13}C$ or $d(^{12}C,\mathbf{p}\gamma)^{13}C$

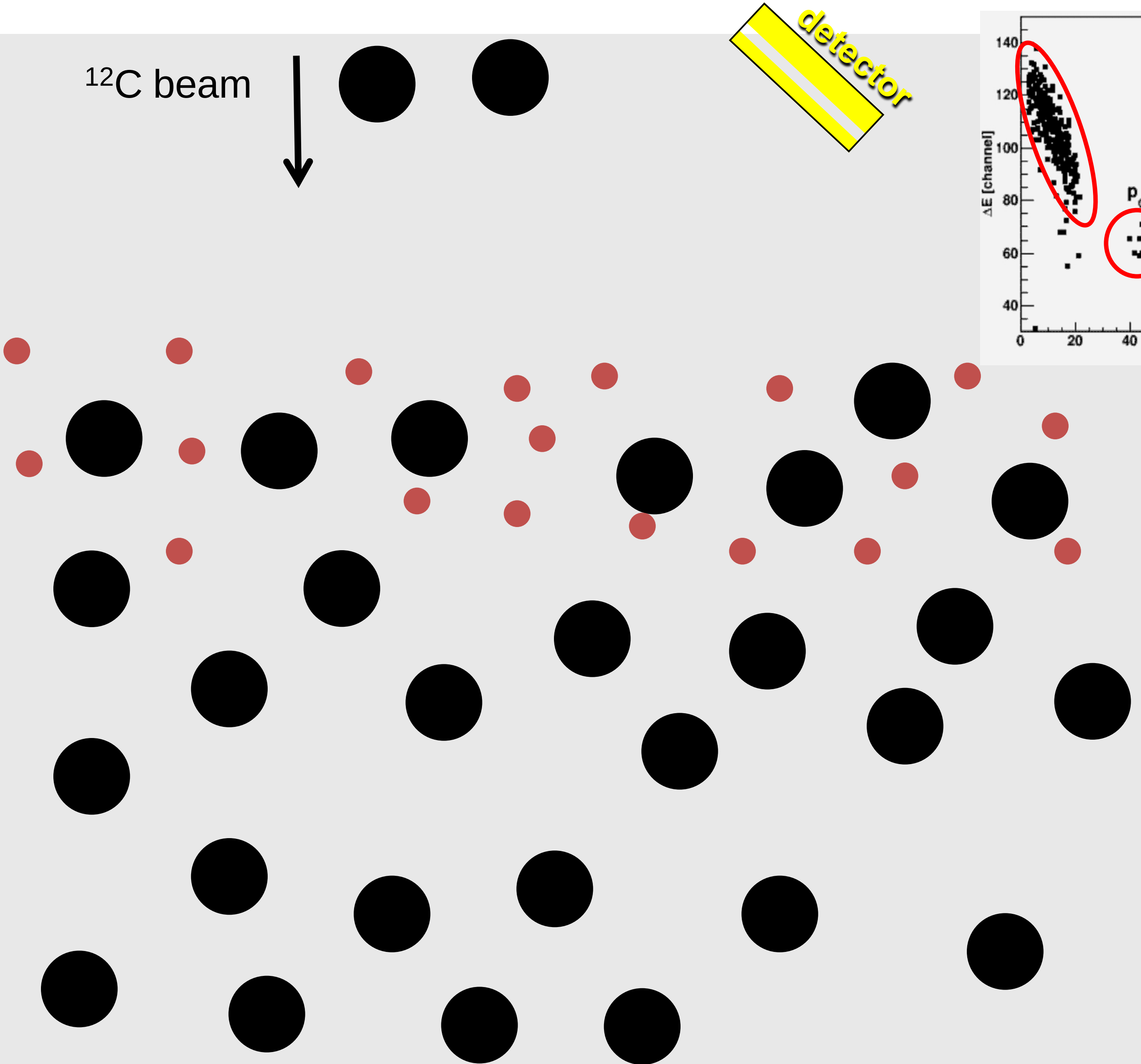
→ Proton from this contaminat reaction too low in energy

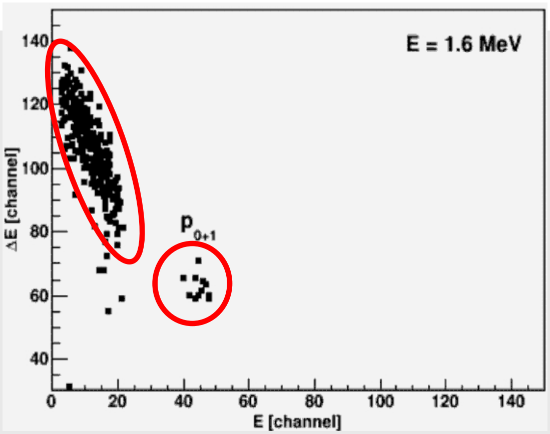
but:

→ Elastic scattering under forward anlges $d(^{12}C,d)^{12}C$

→ followed by $^{12}C(d,\mathbf{p}\gamma)^{13}C$, but then at <u>higher</u> CM energy

Background Considerations





deuterium (water) contamination

graphit target

Background Considerations

in γ-ray spectroscopy measurements main source of background

$^{12}C(d,\mathbf{p}\gamma)^{13}C$ or $d(^{12}C,\mathbf{p}\gamma)^{13}C$

→ Proton from this contaminat reaction too low in energy

but:

→ Elastic scattering under forward anlges $d(^{12}C,d)^{12}C$

→ followed by $^{12}C(d,\mathbf{p}\gamma)^{13}C$, but then at higher CM energy

→ higher proton energy, in the region of $^{12}C(^{12}C,\mathbf{p})^{23}Na$ (!!!!)

→ checked with ^{16}O beam (advantage: contamination can be monitored)

Background Considerations

in γ-ray spectroscopy main source of background $^{12}C(d,p\gamma)^{13}C$ or $d(^{12}C,p\gamma)^{13}C$

Improvements:

→ all vacuum components in CF – on vacuum level of 10^{-7} mbar a build up of water is likely, at 10^{-9} mbar sputtering is fast than the build up

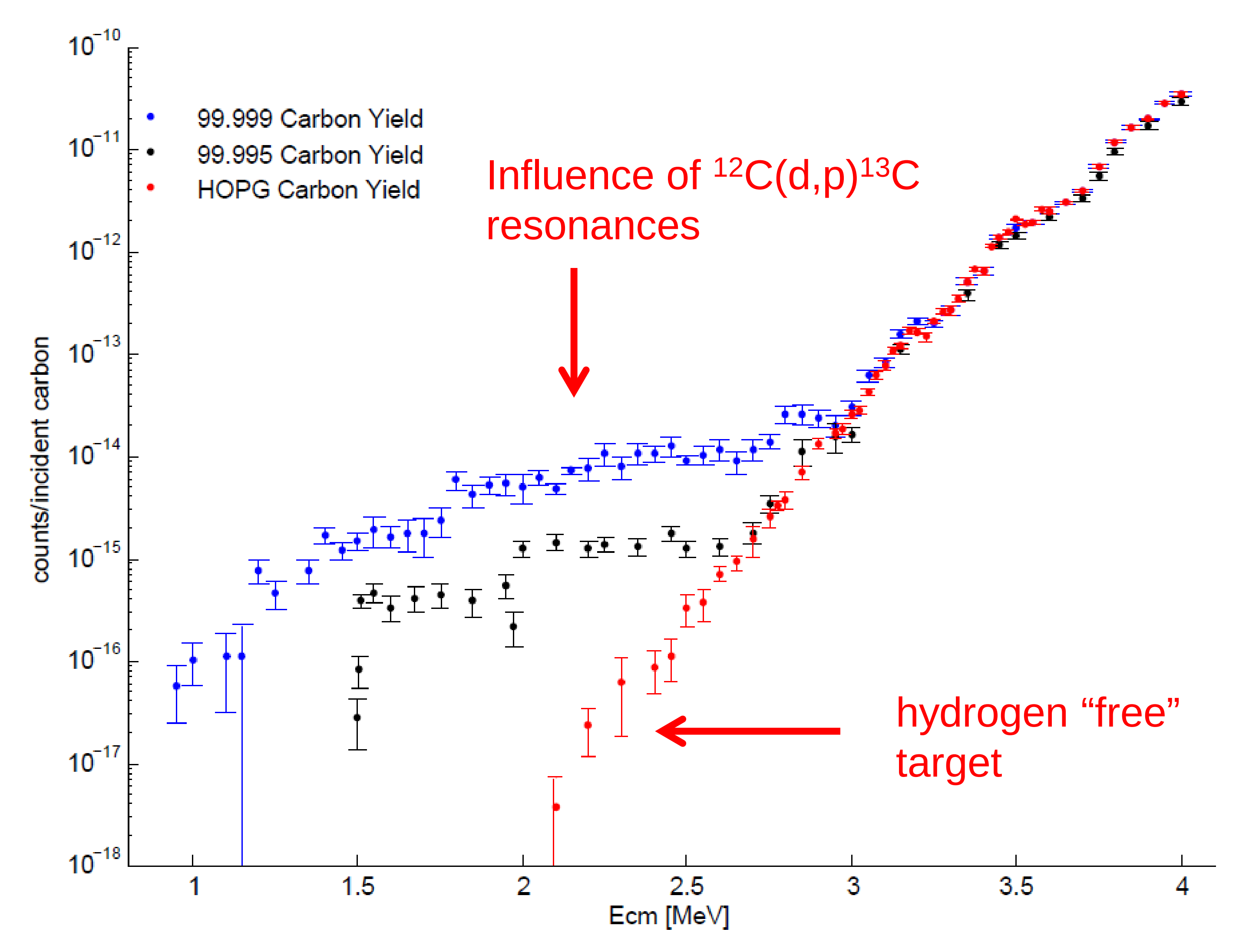
→ „radon“ box: experimental setup closed in a box flushed with argon suppression of hydrogen and nitrogen (water to a lesser extend)

→ HOPG targets: graphite almost free of hydrogen and oxygen

→ cold trap with liquid nitrogen (suppression of water)

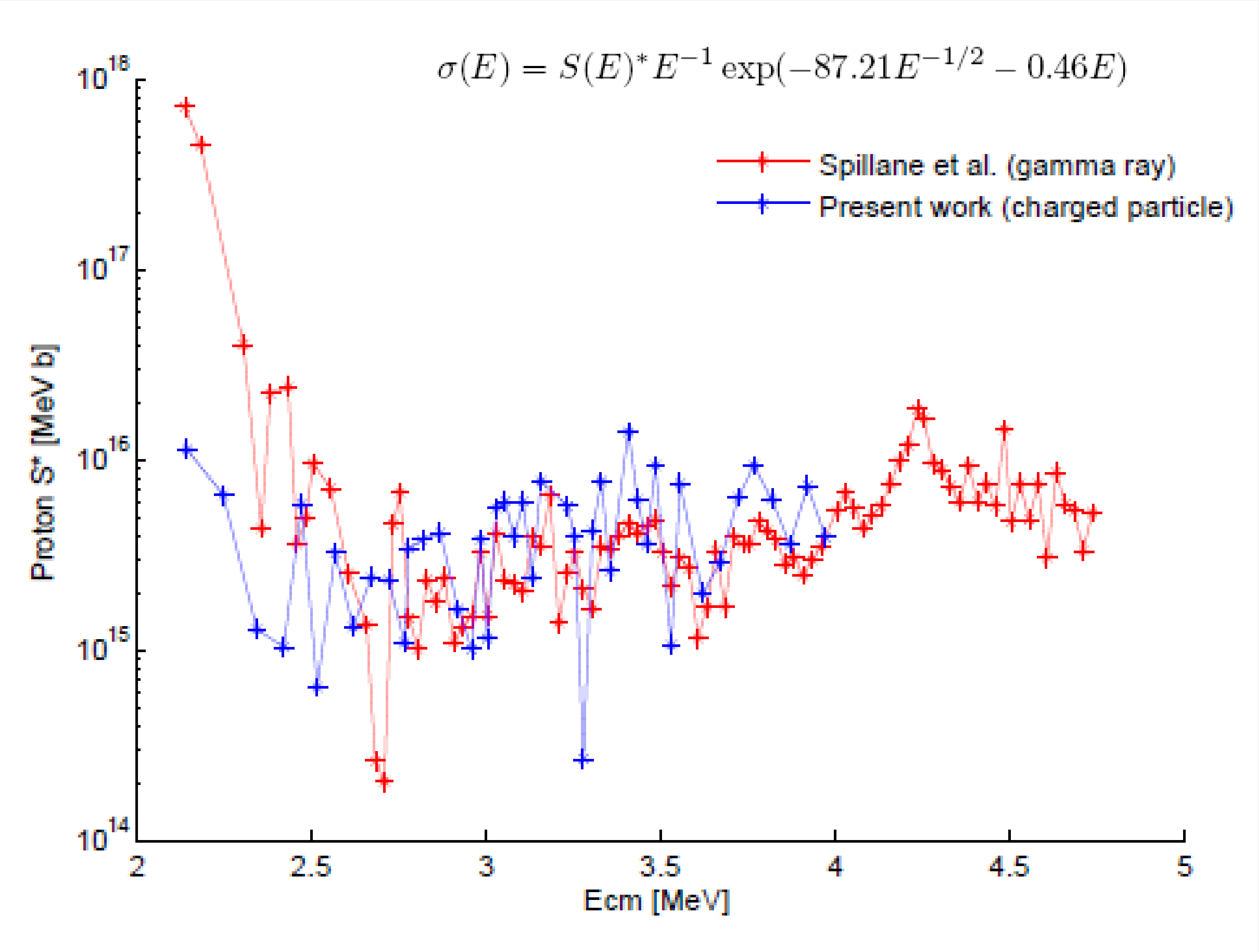
Impact on the α-channel: hydrogen suppression is probably a huge problem due to the gas in Bragg detectors, hydrogen in the rest gas cannot be avoided, but most likely there is no similar contamination in the α-channel.
However, you never know before you did the experiment at such low-level

Preliminary New Results (very recent)



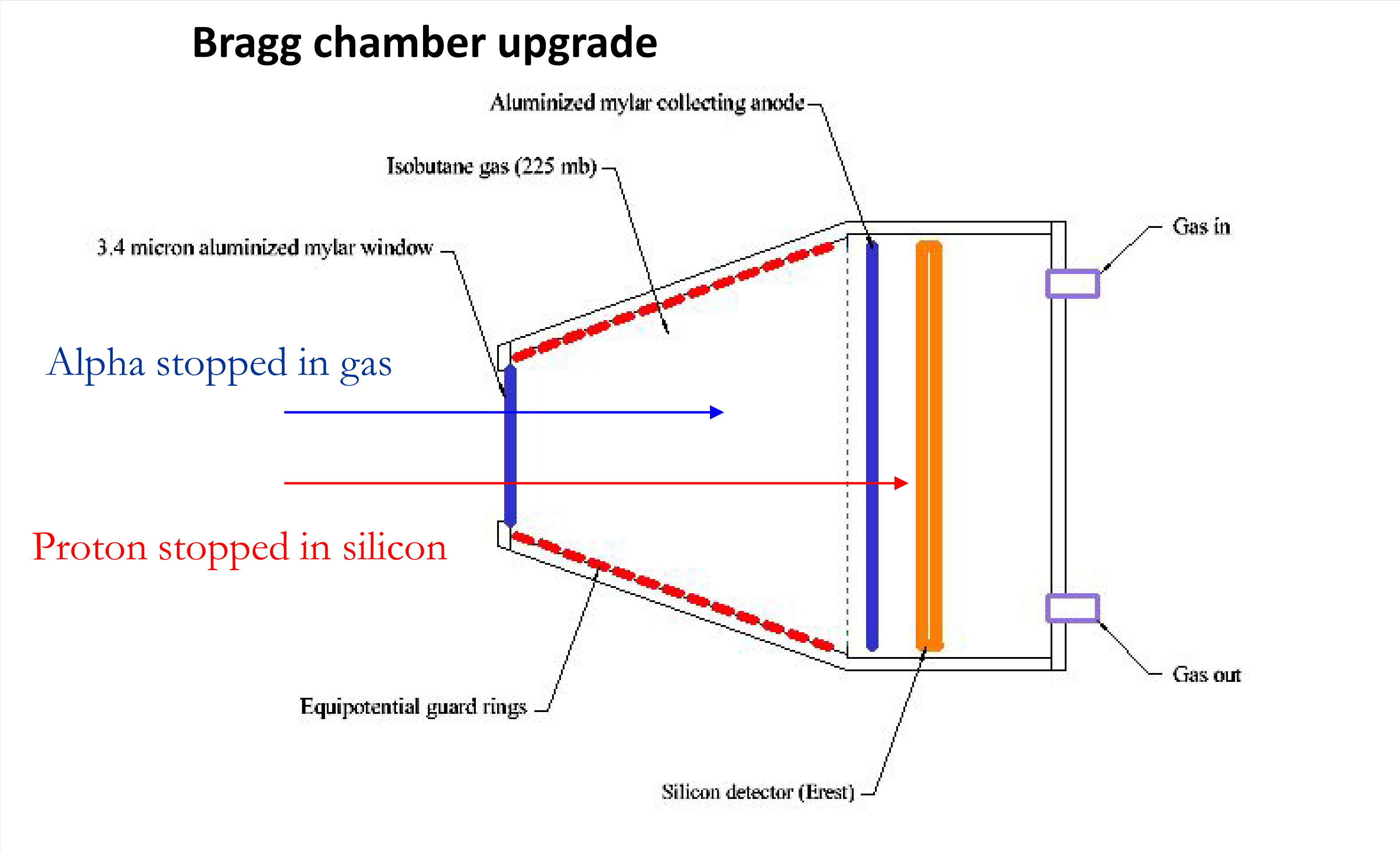
Courtesy Jim Zickefoose

Preliminary New Results (very recent)



Courtesy Jim Zickefoose

Future measurements → α-channel



Larger solid angle than current telescope

Summary of Presentation

The ^{12}C + ^{12}C fusion reactions at astrophysical energies

- ^{12}C + ^{12}C Experiment with γ-ray spectroscopy
  - completed in 2007
- ^{12}C + ^{12}C Experiment with particle spectroscopy
  - partly (proton channel) on the way, we had to learn a lot …
  - α channel to be done next year
- exciting results → discovery of new resonances (?)
- Astrophysical Implications:
  - stellar evolution – impact on nucleosynthesis
  - supernovae rates ??
- room for improvements with new measurements
  - Underground Laboratory
  - high intensity accelerator

Team and Thanks

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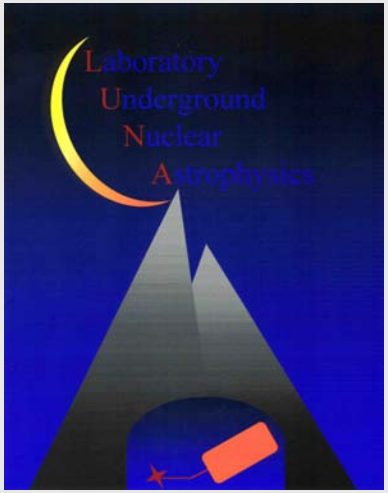
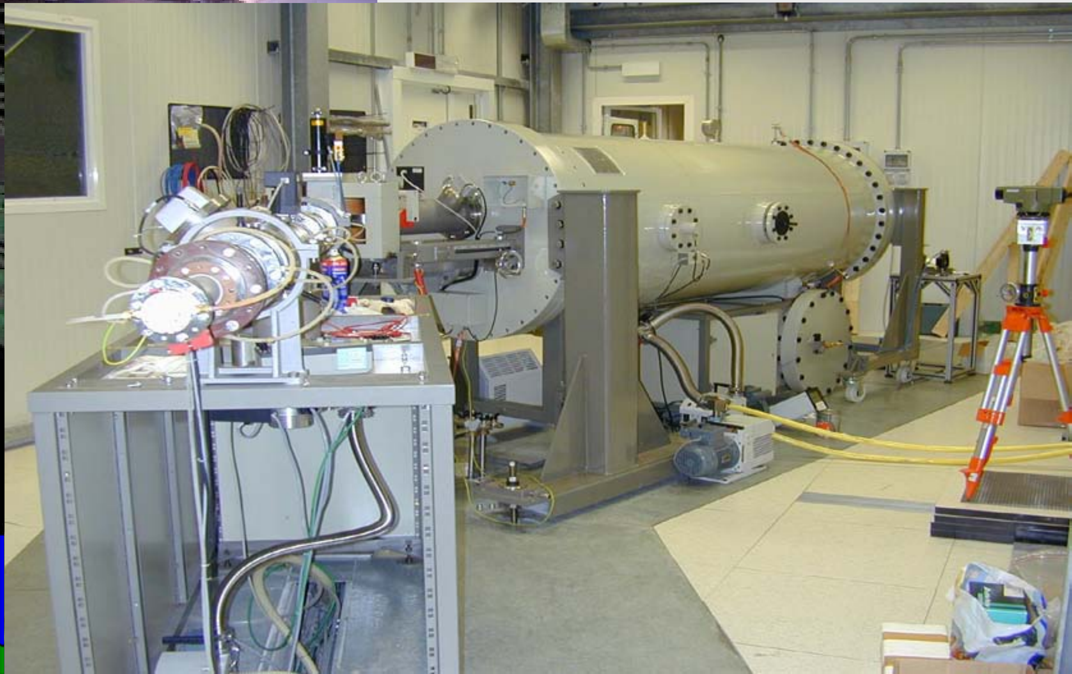
Osservatorio Astronomico Collurania Teramo
Oscar Straniero, Luciano Piersanti

Horia Hulubei -National Institute of Physics and Nuclear Engineering, Bucharest, Romania
Cristina Bordeanu

additional slides

Perspectives for Underground Accelerators



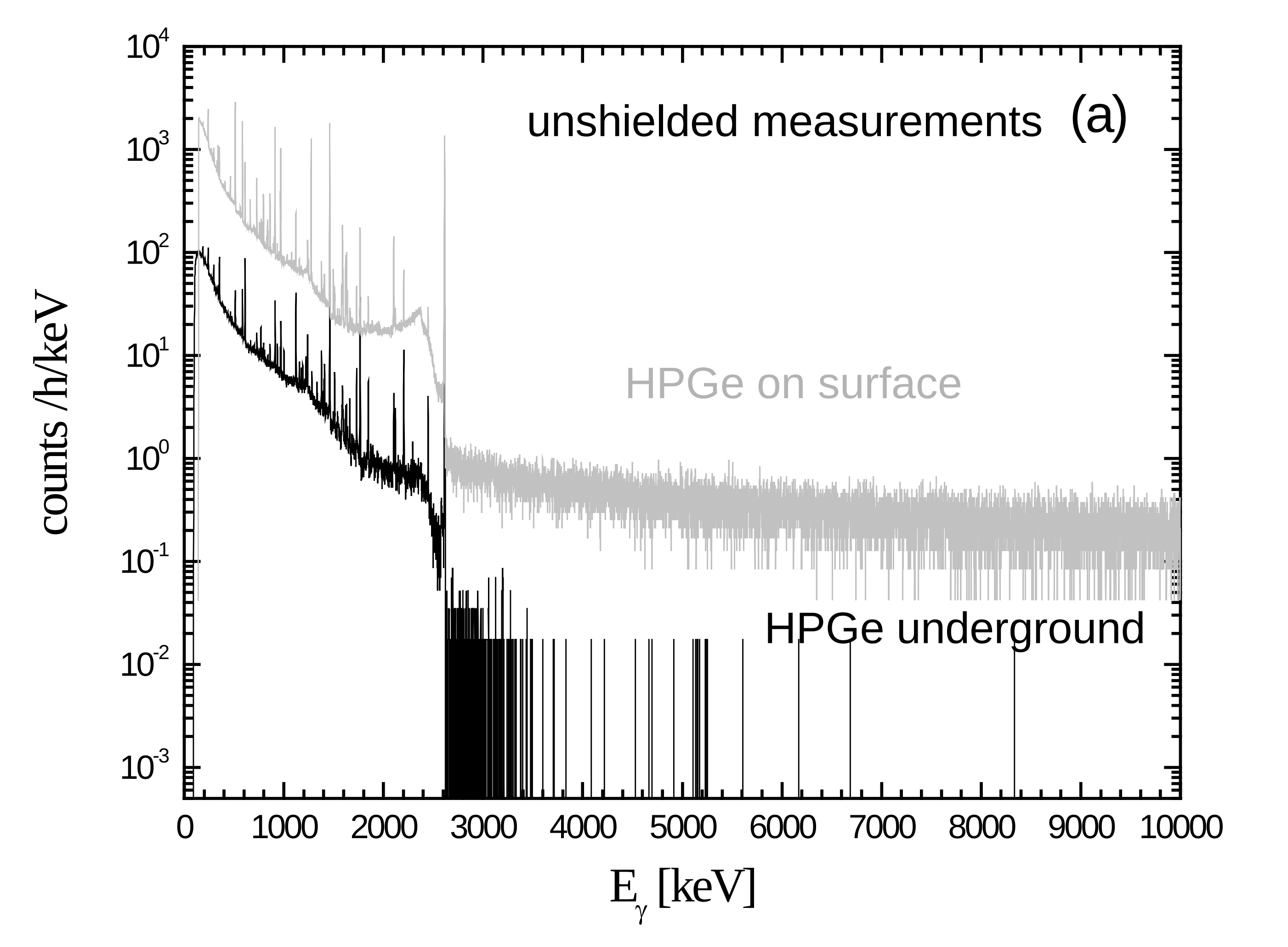


Background reduction in LNGS (shielding ≡ 4000 m w.e.)

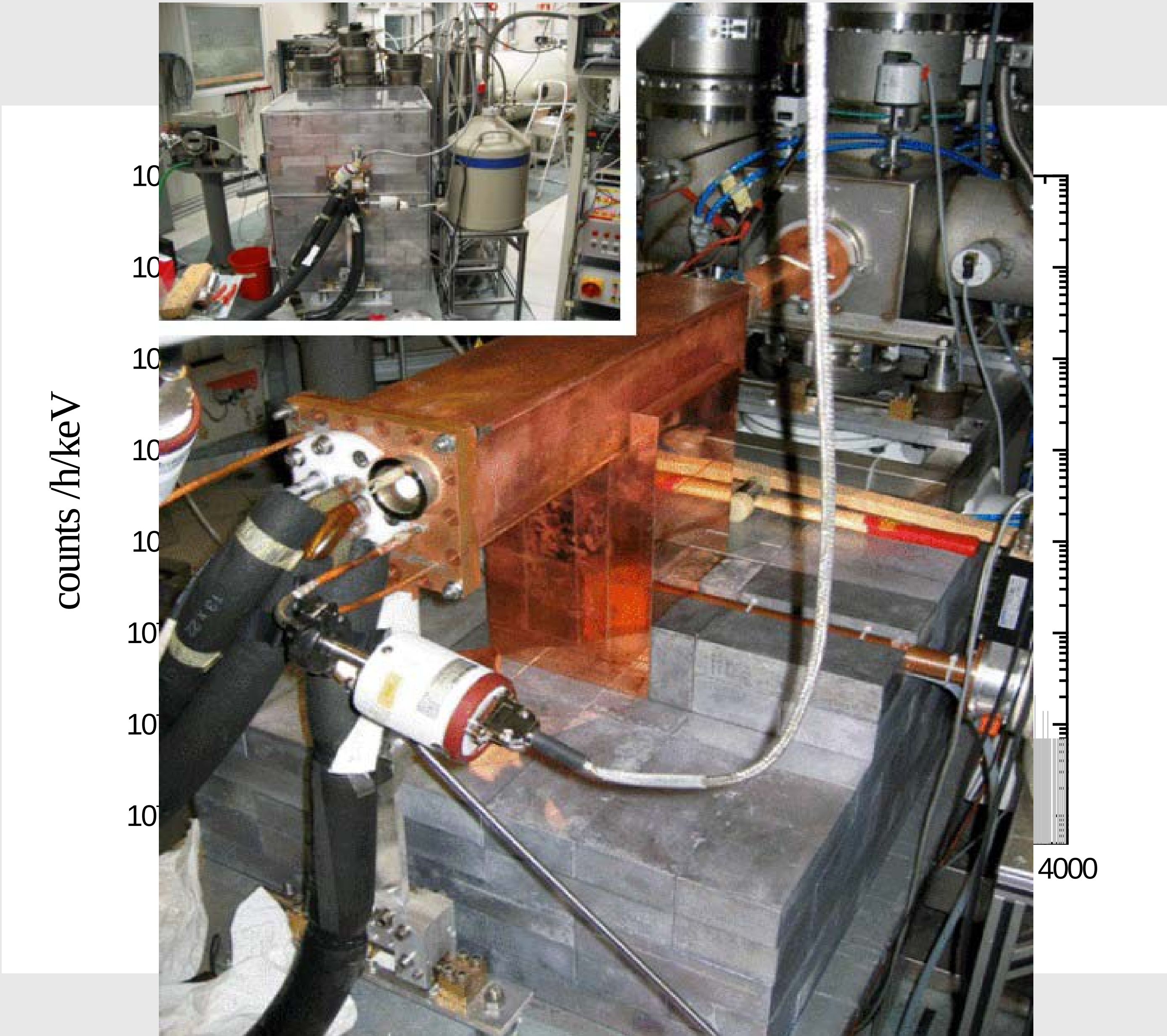
Radiation	LNGS/surface
Muons	10^{-6}
Neutrons	10^{-3}
Photons	10^{-1}

Benefit of an Underground Laboratory

in γ-ray spectroscopy

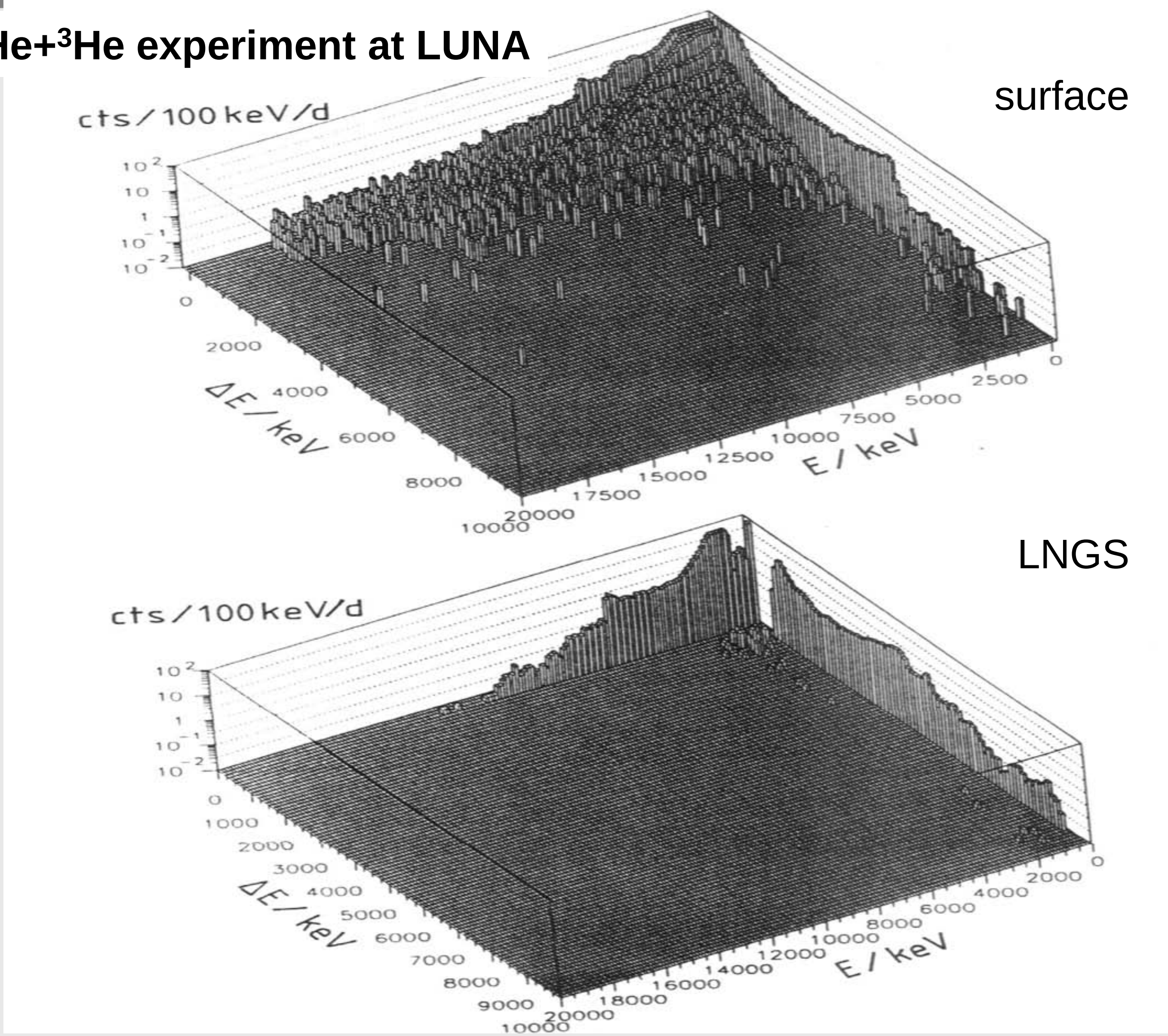


Benefit of an Underground Laboratory

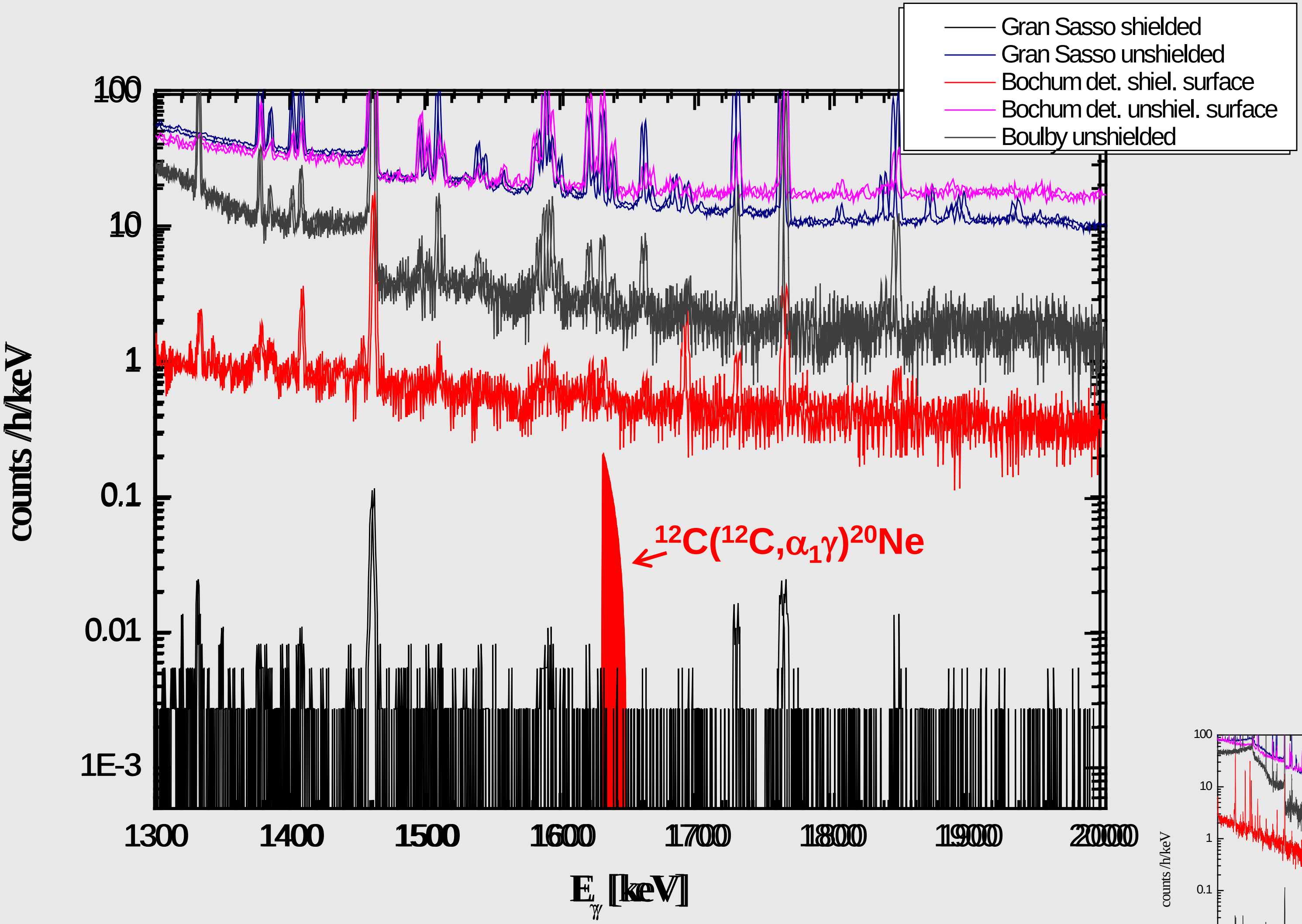


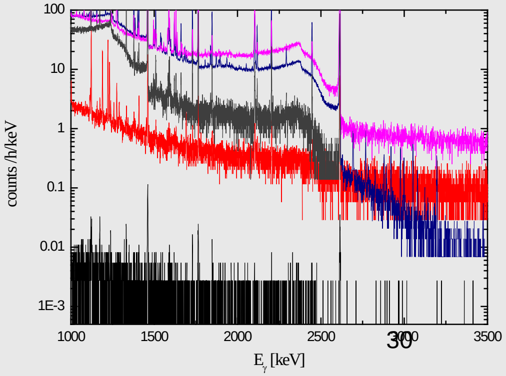
Benefit of an Underground Laboratory

Example: $^{3}He+^{3}He$ experiment at LUNA



Improvements Underground





Extraction of S-factor from thick target

Thick target yield → σ(E) (and $\tilde{S}$(E))

All energies up to the beam energy are represented in the yield:

$$Y^{\infty}(E_0) \sim \int_0^{E_0} \frac{\sigma(E)}{\epsilon(E)} dE \qquad \tilde{S}(E) = \sigma(E)E \times exp\left(2\pi\eta + gE\right)$$

Point-to-point differentiation is one method to extract σ(E):

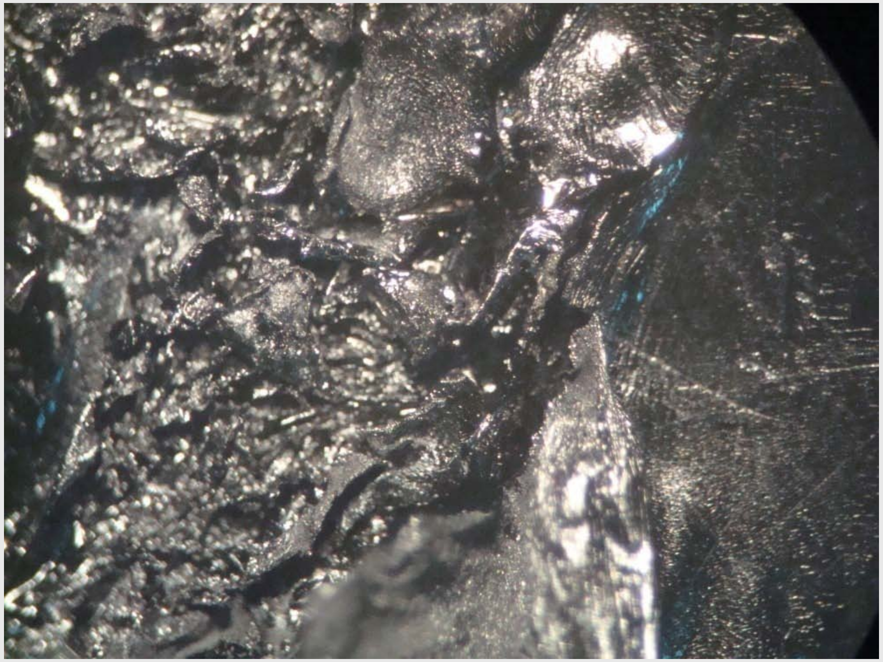
$$Y^{\infty}(E) - Y^{\infty}(E - \Delta) \sim \frac{\Delta}{\epsilon(E)} \sigma(E_{eff})$$

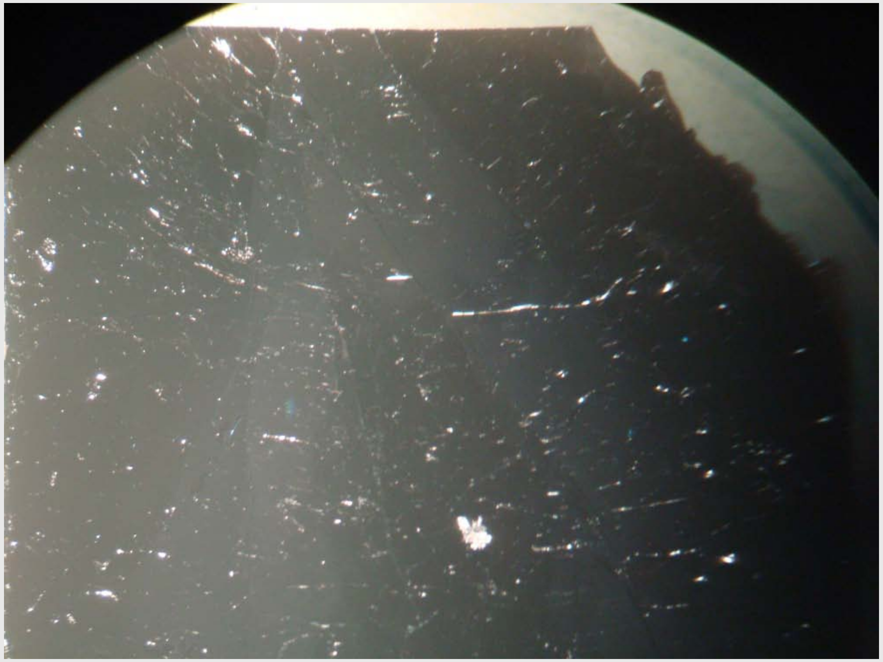
Advantages:

- Allows for thick targets
- Narrow structure resolved

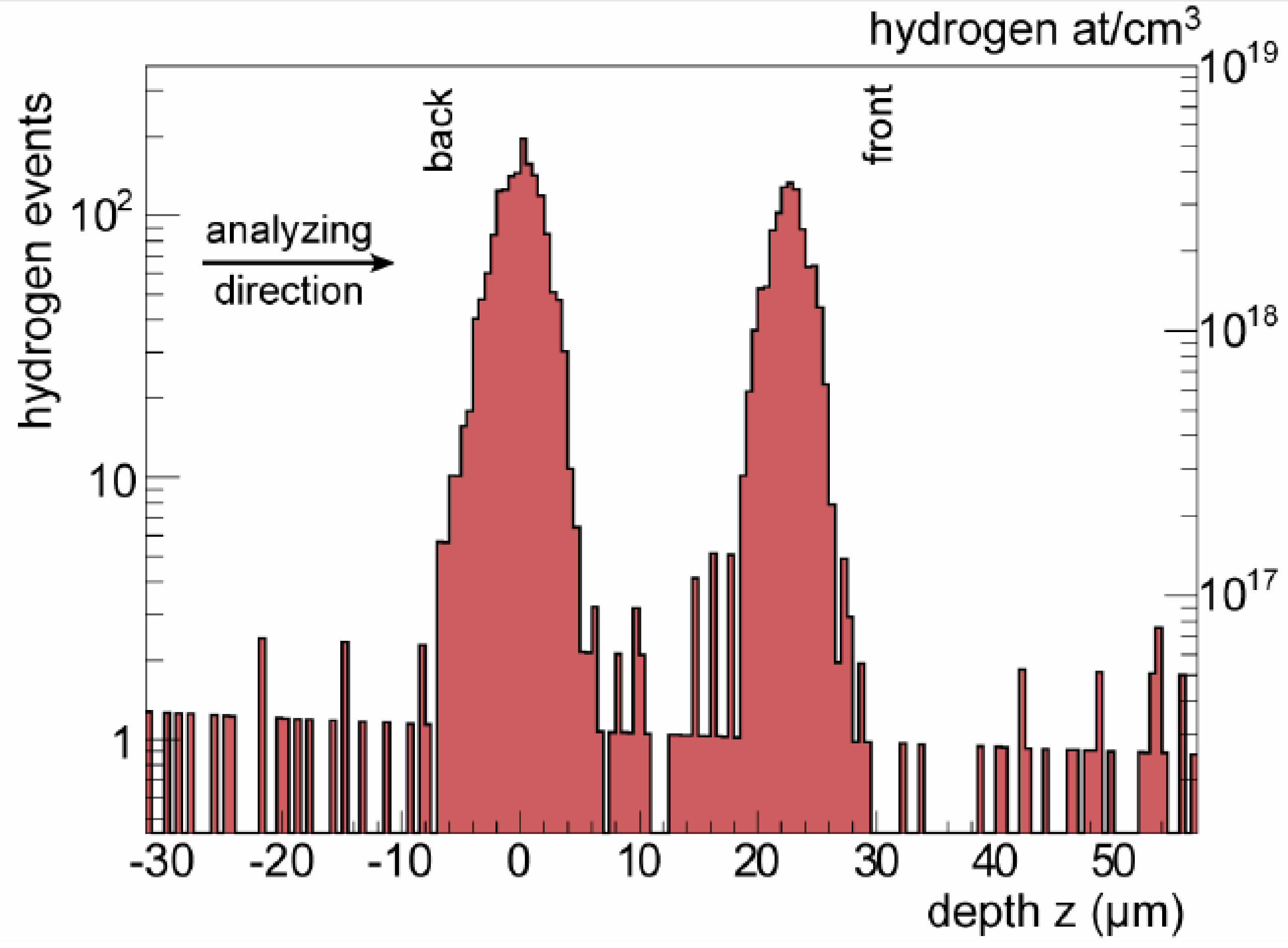
Disadvantages:

- Small Δ required
- Differentiation propagates error

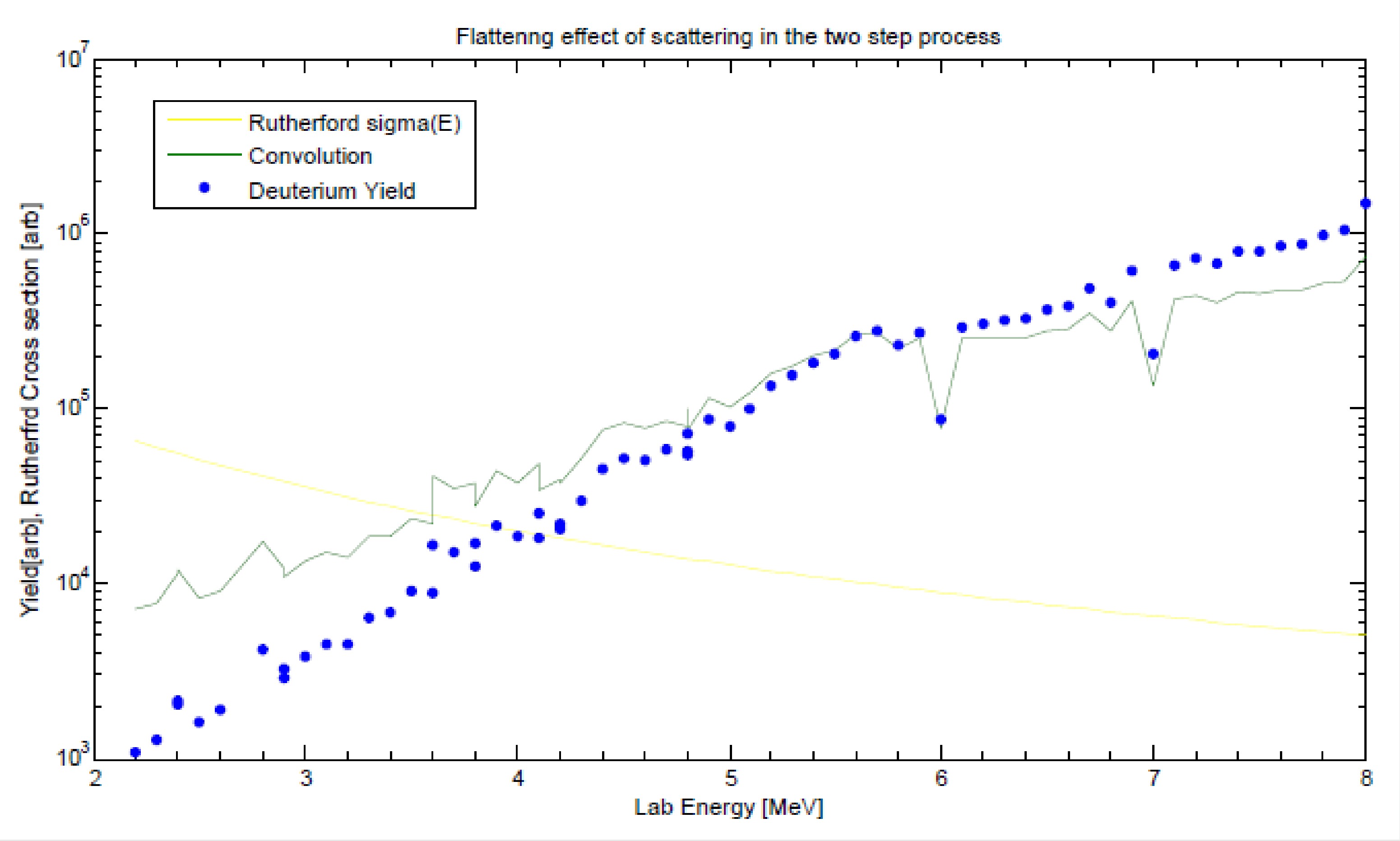

After beam

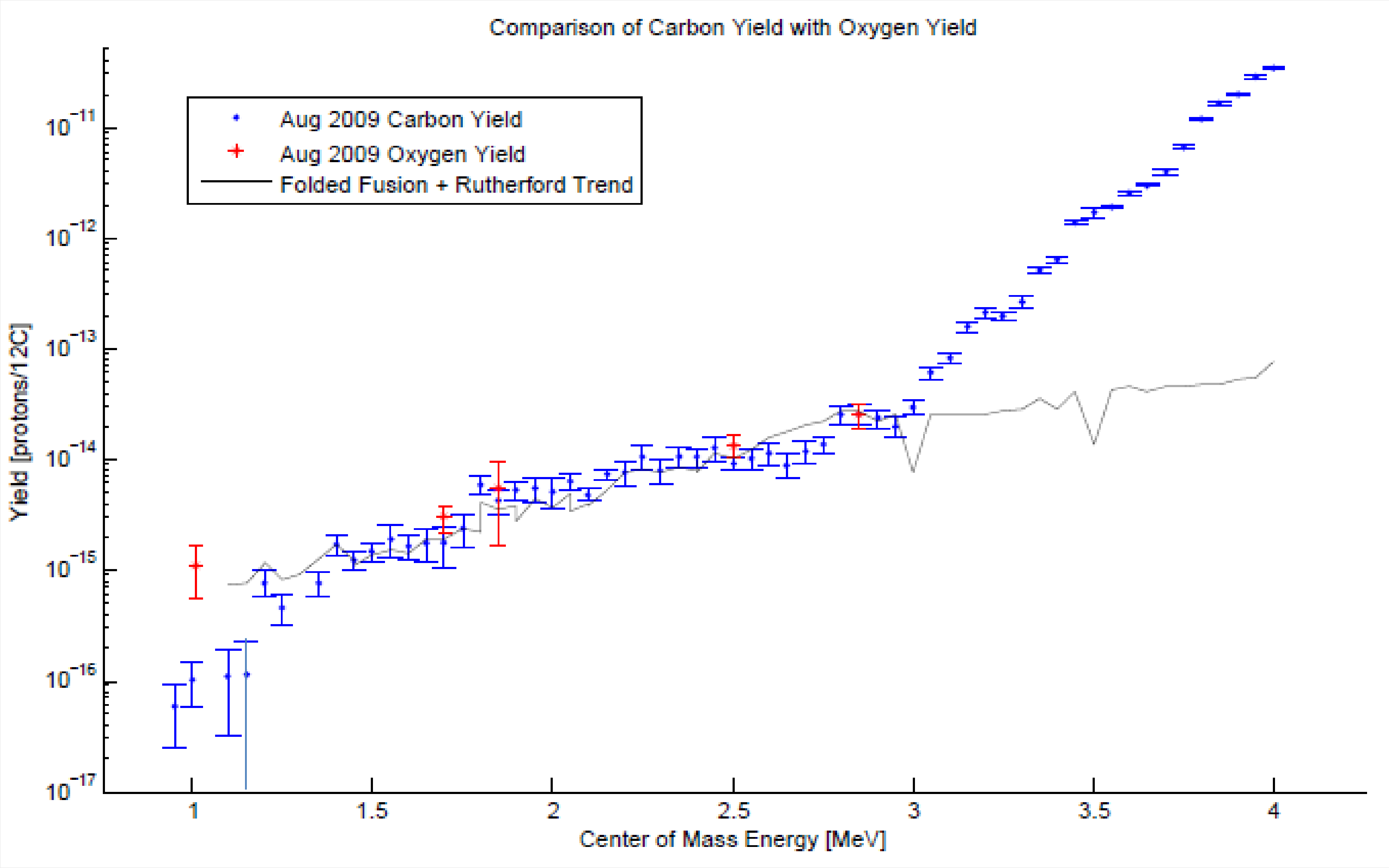

Before beam

Target sputtering causing large leak currents on silicon detectors



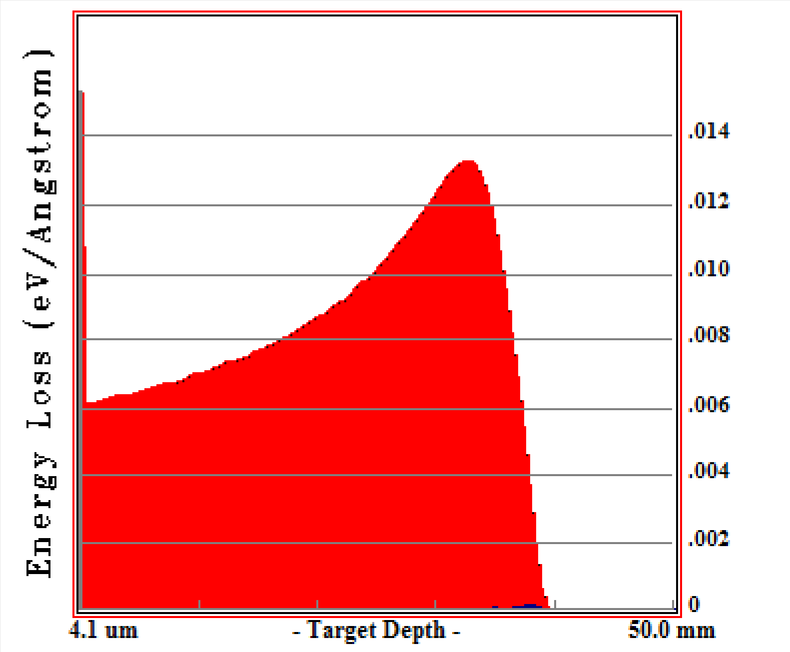
Reichart et al.


Flattenng effect of scattering in the two step process
Rutherford sigma(E)
Convolution
Deuterium Yield
Yield[arb], Rutherfrd Cross section [arb]
Lab Energy [MeV]
10^7
10^6
10^5
10^4
10^3
2
3
4
5
6
7
8

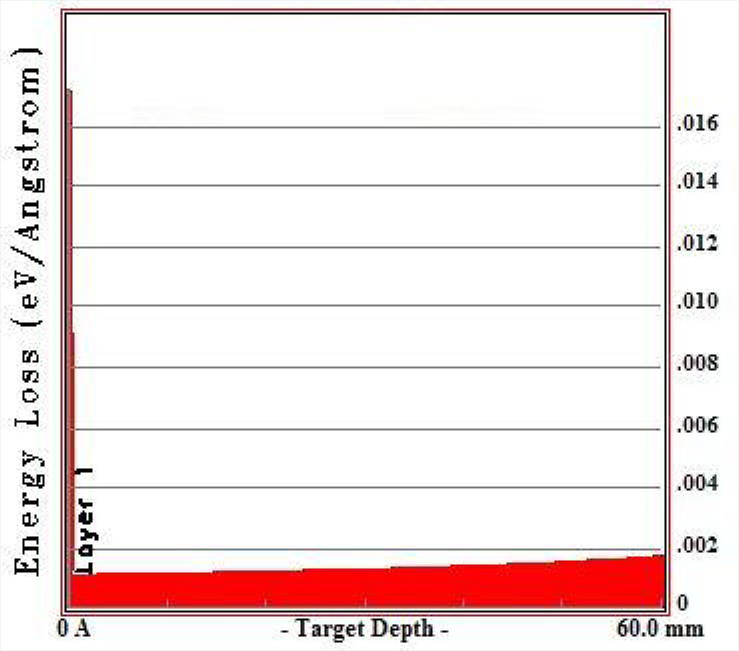

Comparison of Carbon Yield with Oxygen Yield
Aug 2009 Carbon Yield
Aug 2009 Oxygen Yield
Folded Fusion + Rutherford Trend
Yield [protons/12C]
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
1
1.5
2
2.5
3
3.5
4
Center of Mass Energy [MeV]

Future measurements → α-channel

α's

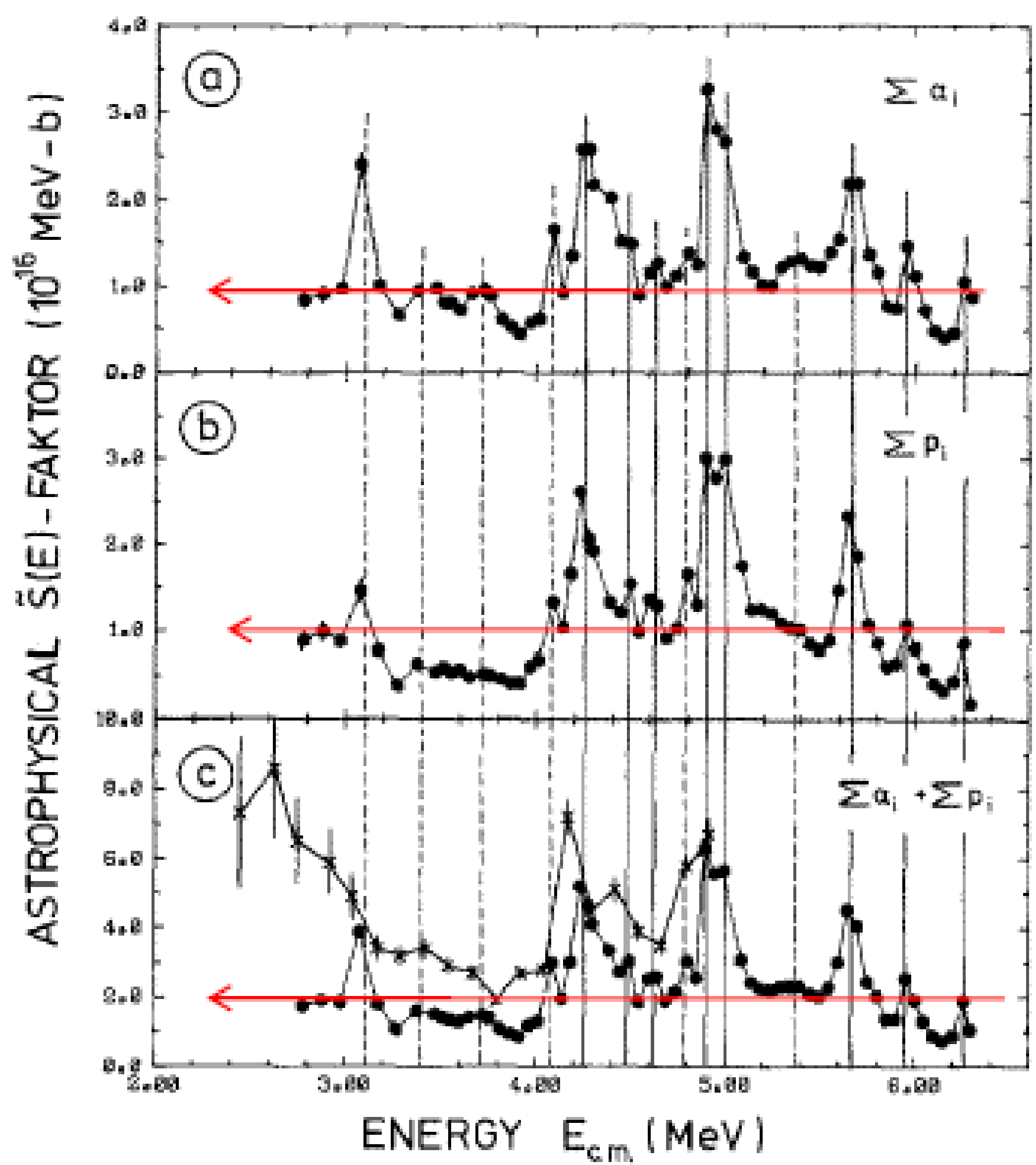


protons



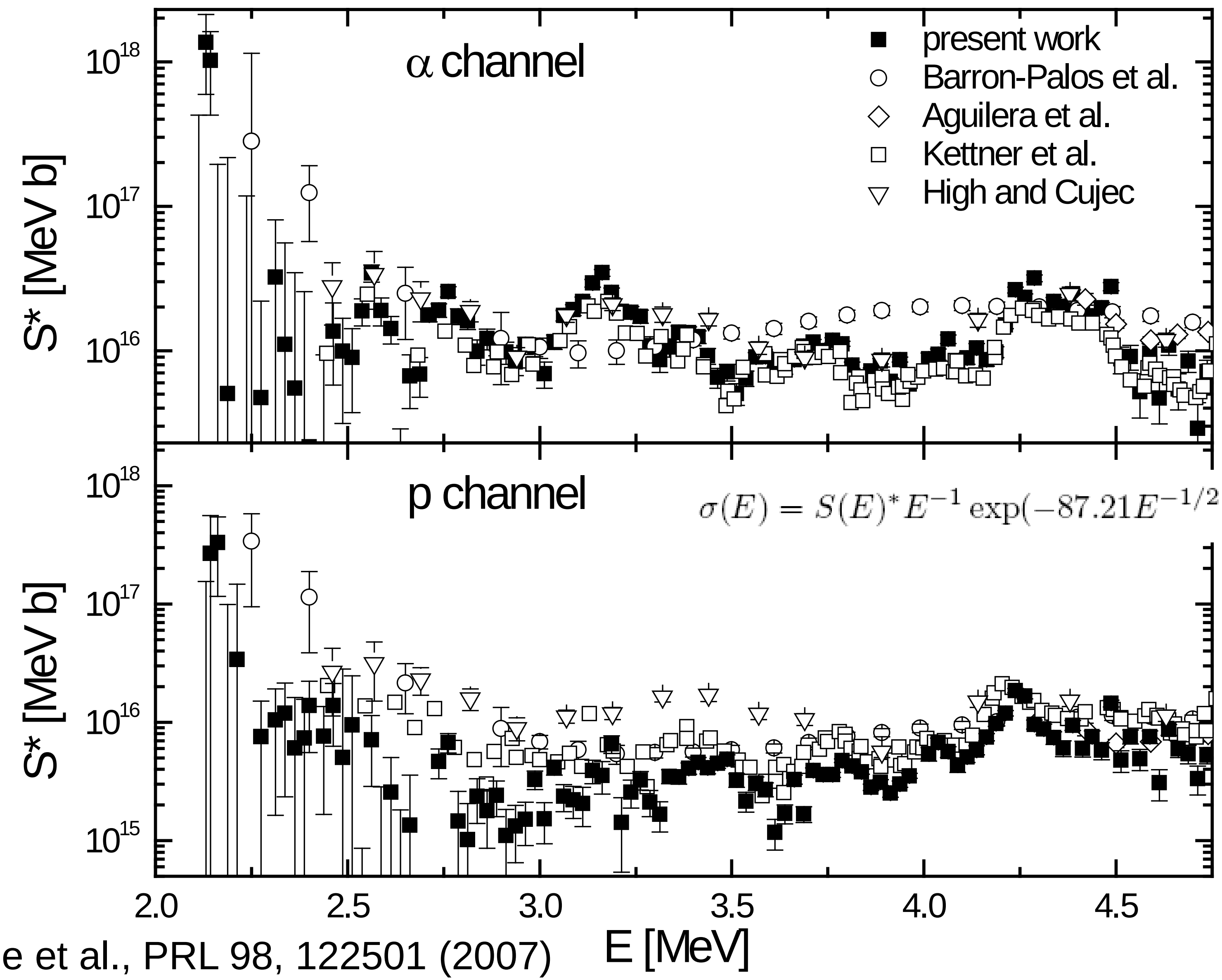
Plot peak ionization Vs total ionization for particle identification

Experimental Results - γ-ray spectroscopy



The 12C+ 12C Reaction at Subcoulomb Energies (II)*
H.W. Becker, K.U. Kettner, C. Rolfs, and H.P. Trautvetter
Z. Phys. A Atoms and Nuclei 303, 305 312 (1981)

Experimental Results - γ-ray spectroscopy



$$\sigma(E) = S(E)^{*} E^{-1} \exp(-87.21 E^{-1/2} - 0.46 E)$$

Spillane et al., PRL 98, 122501 (2007)