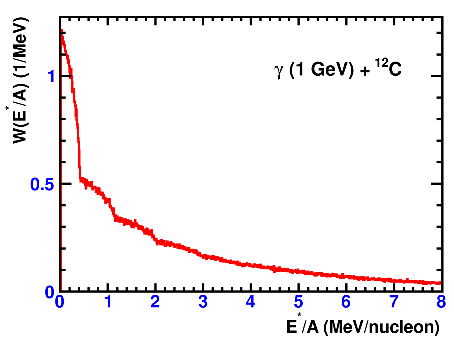
Multifragment break-up of ^{12}C in photonuclear reactions: a theorist's point of view

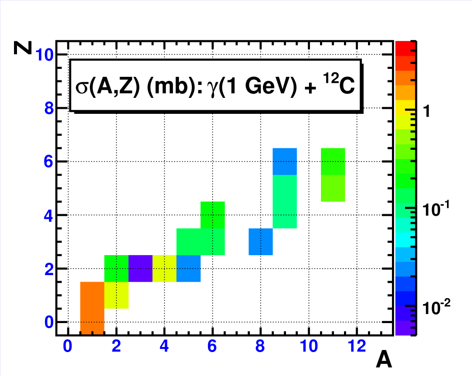
I. Pshenichnov[1], A. Turinge, A. Lapik, A. Mushkarenkov, V. Nedorezov
for the GRAAL Collaboration

Institute for Nuclear Research, Russian Academy of Sciences
117312 Moscow, Russia

[1] e-mail: pshenich@inr.ru



XXII International Baldin Seminar on
High-Energy Physics Problems
Dubna, Russia, September 15-20, 2014



Content

- Absorption of ~1 GeV photons by ^{12}C – an experiment at the GRAAL facility to study multifragment decays of ^{12}C

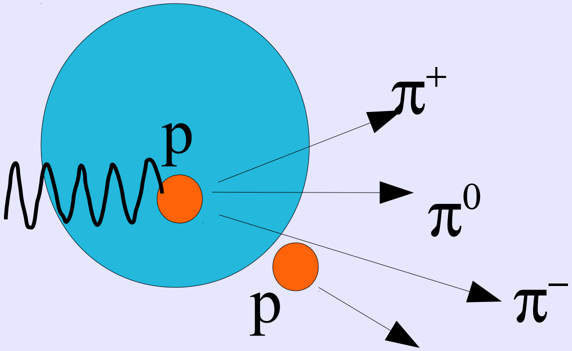
- Details of this experiment in Prof. Nedorezov's talk

- Here a theorist's point of view is presented:
  - a model to describe the break-up of ^{12}C;
  - comparison with photonuclear reactions on heavy nuclei and induced by other projectiles;
  - relations to electromagnetic dissociation of light nuclei

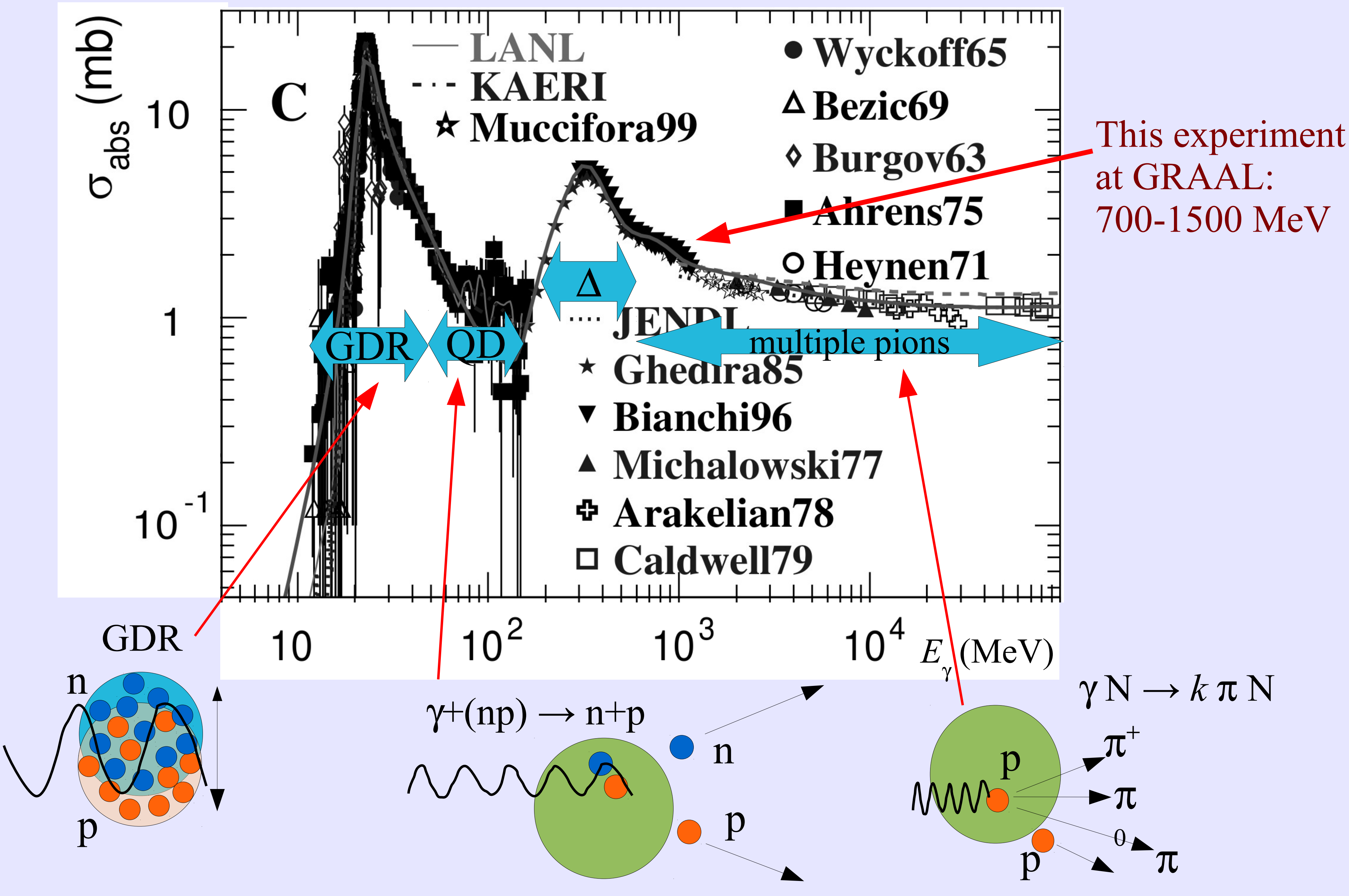
- Comparison with the rates of multifragment decays measured at GRAAL

- Fragmentation reactions in carbon-ion therapy

I. Modelling of photonuclear reactions



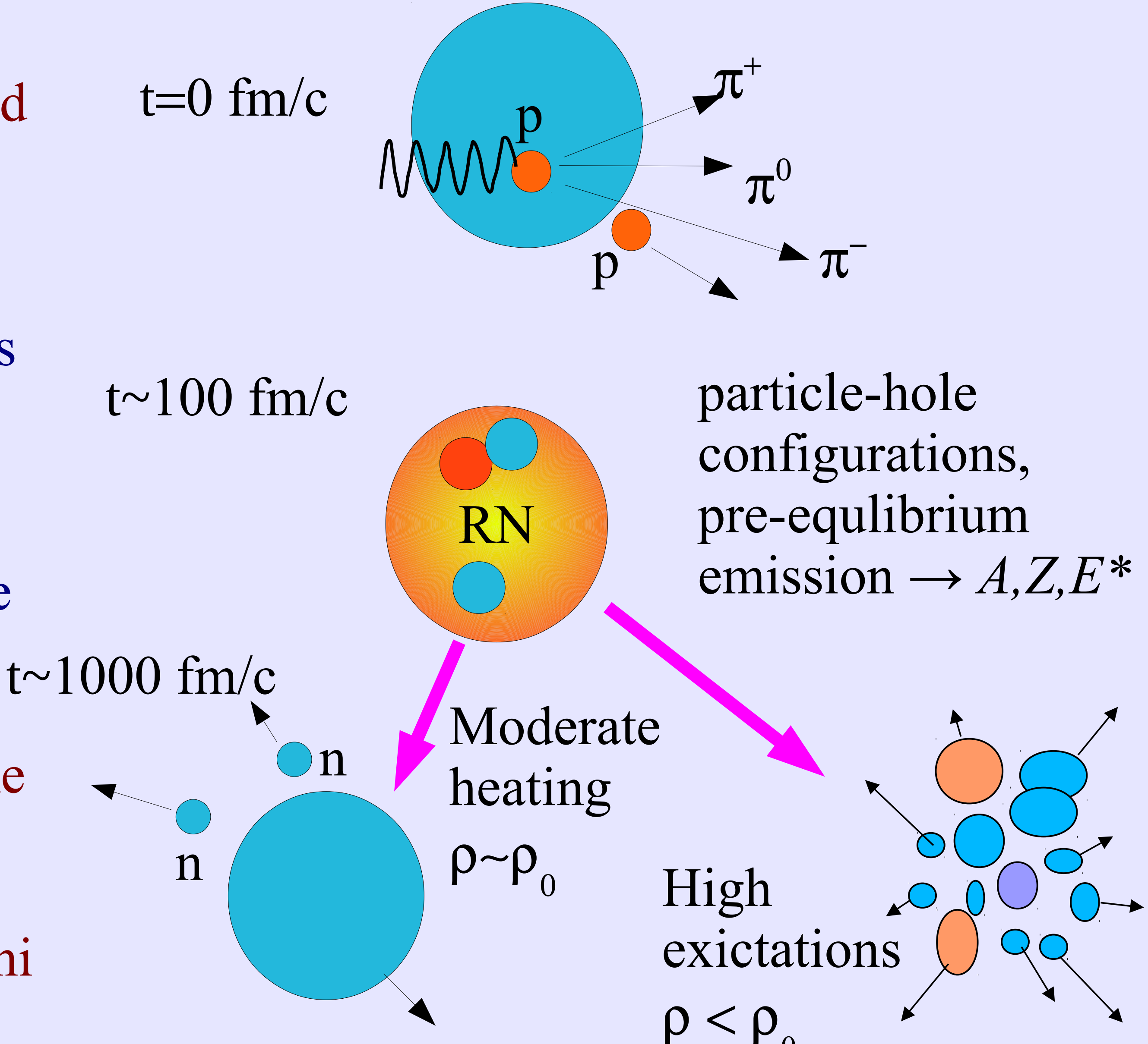
Photoabsorption on carbon: a variety of processes



This experiment at GRAAL: 700-1500 MeV

Basics of the photonuclear reaction model. It is a part of the Relativistic ELectromagnetic DISsociation (RELDIS) model

- Firstly, an Intranuclear cascade process initiated by a projectile is simulated
- Secondly, the properties of a residual nucleus (*A,Z,E**), which is left after the completion of the intranuclear cascade are calculated
- Thirdly, the decay of the thermalized residue is modelled by evaporation/SMM/Fermi break-up models



t=0 fm/c

t~100 fm/c

particle-hole configurations, pre-equlibrium emission → *A,Z,E**

t~1000 fm/c

Moderate heating

$\rho \sim \rho_0$

High excitations

$\rho < \rho_0$

Let's estimate the number of partitions to split a nucleus

Famous Euler's problem: find the number of ways, $P(A_0)$, an integer A_0 can be represented as a sum of integers, $A_0=A_1+A_2+A_3+\ldots$

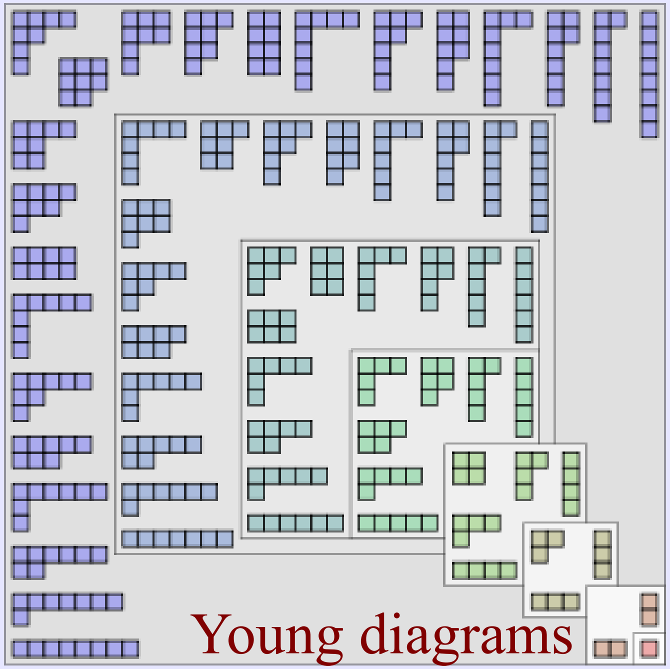
The total number of partitions is rapidly increasing with A_0:

$P(10)=42$, $P(12)=77$, $P(16)=231$,

Large enough already for decays of excited carbon and oxygen nuclei!

$P(50)=2.17*10^5$, $P(100)=2*10^8$

See A.S. Botvina, A.D. Jackson, I.N. Mishustin, Phys. Rev. E62 (2000) R64



Young diagrams for partitions

At large A_0 the result is well approximated by asymptotic Hardy-Ramanujan formula, with the average partition multiplicty:

$$P(A_0)=\frac{1}{4\sqrt{3}A_0}\exp\left(\pi\sqrt{\frac{2A_0}{3}}\right) \qquad \langle M\rangle=\frac{1}{\pi}\sqrt{\frac{3A_0}{2}}\ln\left(\frac{6A_0}{b\pi^2}\right) \qquad b=0.3150$$

Specific to light nuclei (A<17): Fermi break-up model

- Excitation energies of light nuclei can be comparable to their total binding energies - explosive decays.

- Fermi break-up model implemented by A.S. Botvina and co-authors

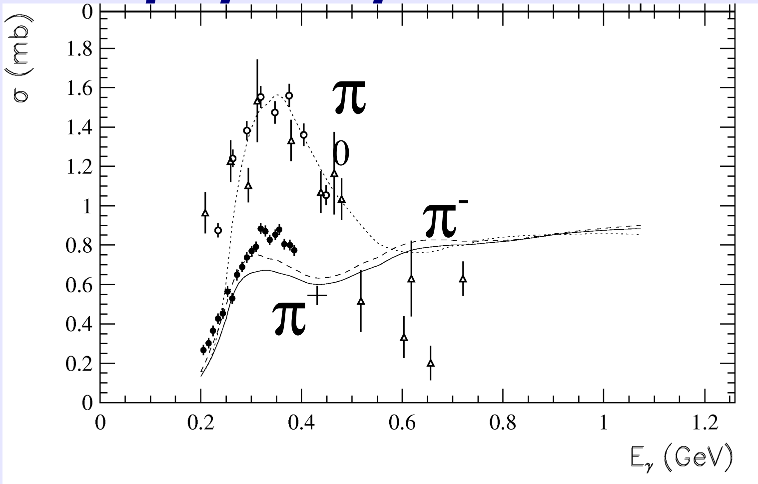
- Fragments are considered in their ground states and also in low-energy excited states stable to nucleon emission.

- The probability of a given decay channel is defined by its statistical weight.

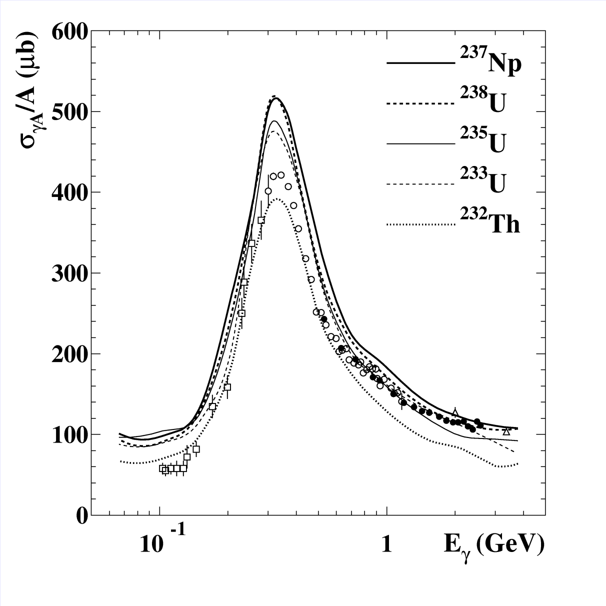
- The list of possible decay channels is quite long, e.g. ~200 channels for ^{12}C, ~1000 for ^{16}O

Wassily Kandinsky
"Several circles", 1926
Guggenheim
Museum, NY

RELDIS model developed at INR, NBI, GSI, FIAS (25+ papers published since 1995)

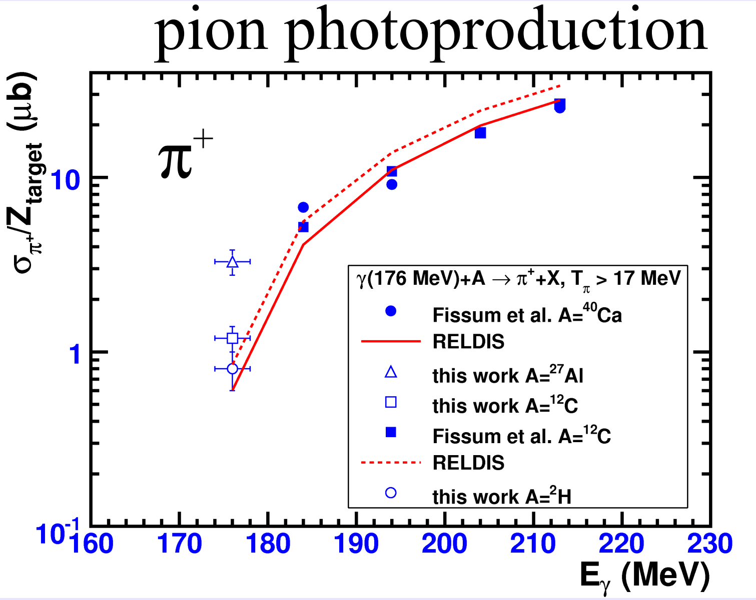


A.S. Iljinov, …, I.P. et al., Nucl. Phys. A 616(1997)575

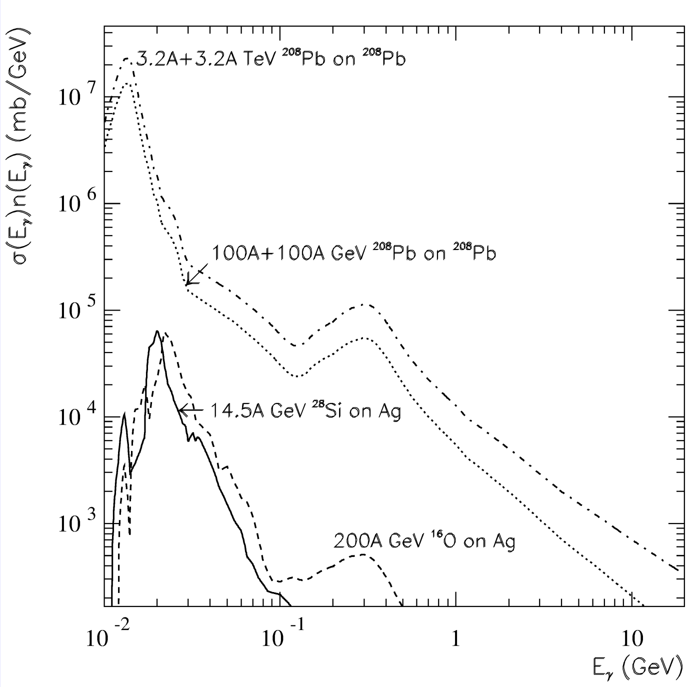


I.P. et al., Eur. J. Phys. A 24(2005)69

fission of heavy nuclei by photons


pion photoproduction

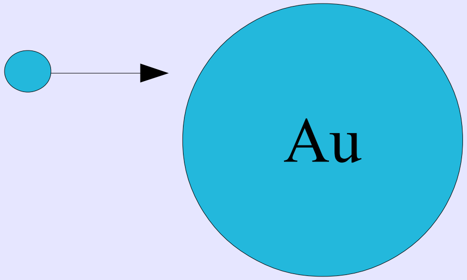
P.Golubev, …, I.P. et al., Nucl. Phys. A 806(2008)216

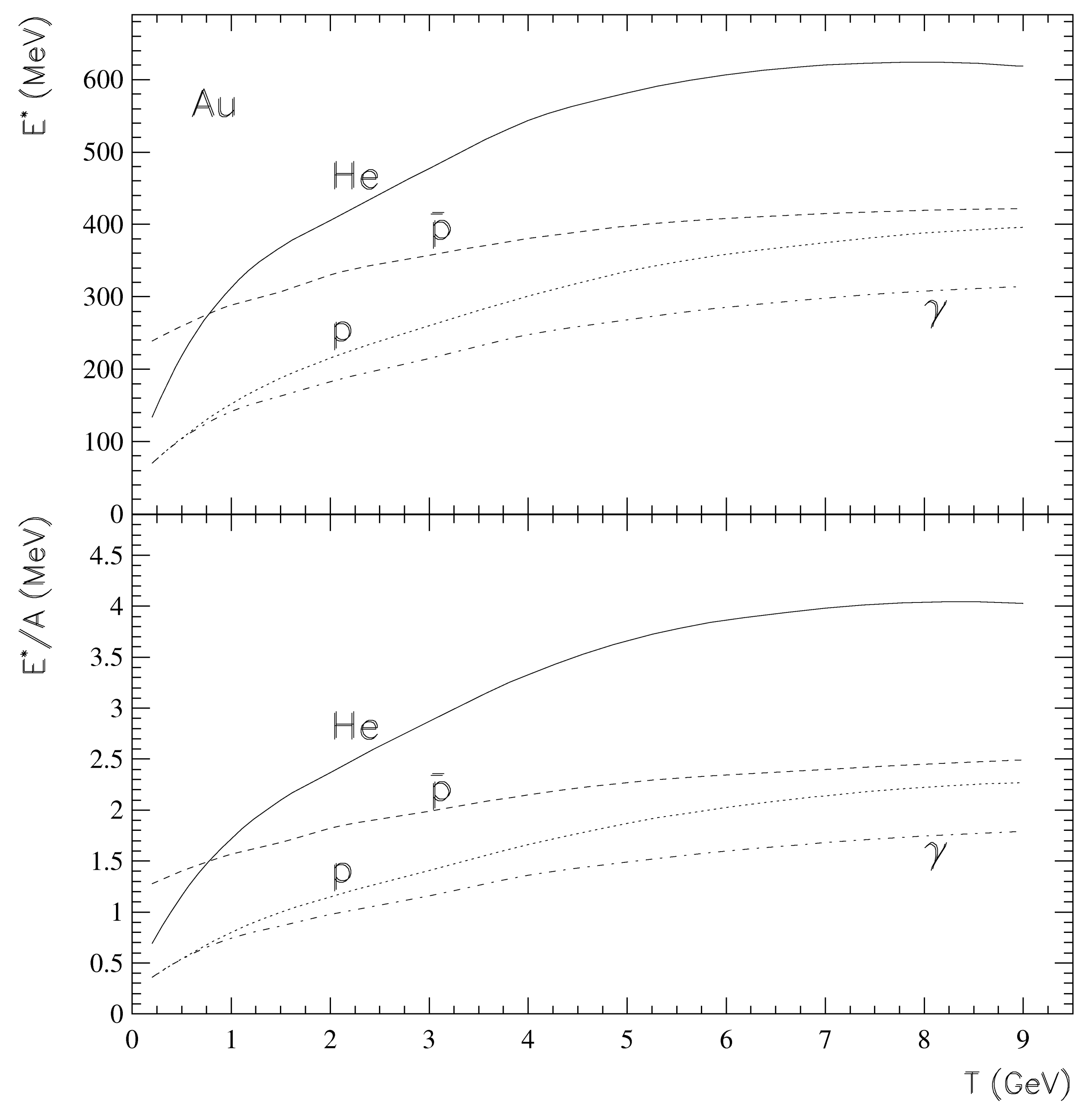


I.P. et al., Phys. Rev. C 57(1998)1920

Electromagnetic dissociation at CERN SPS SIS (GSI), AGS (BNL) (see below)

Average excitation energy of a residual nucleus at the end of the intranuclear cascade.





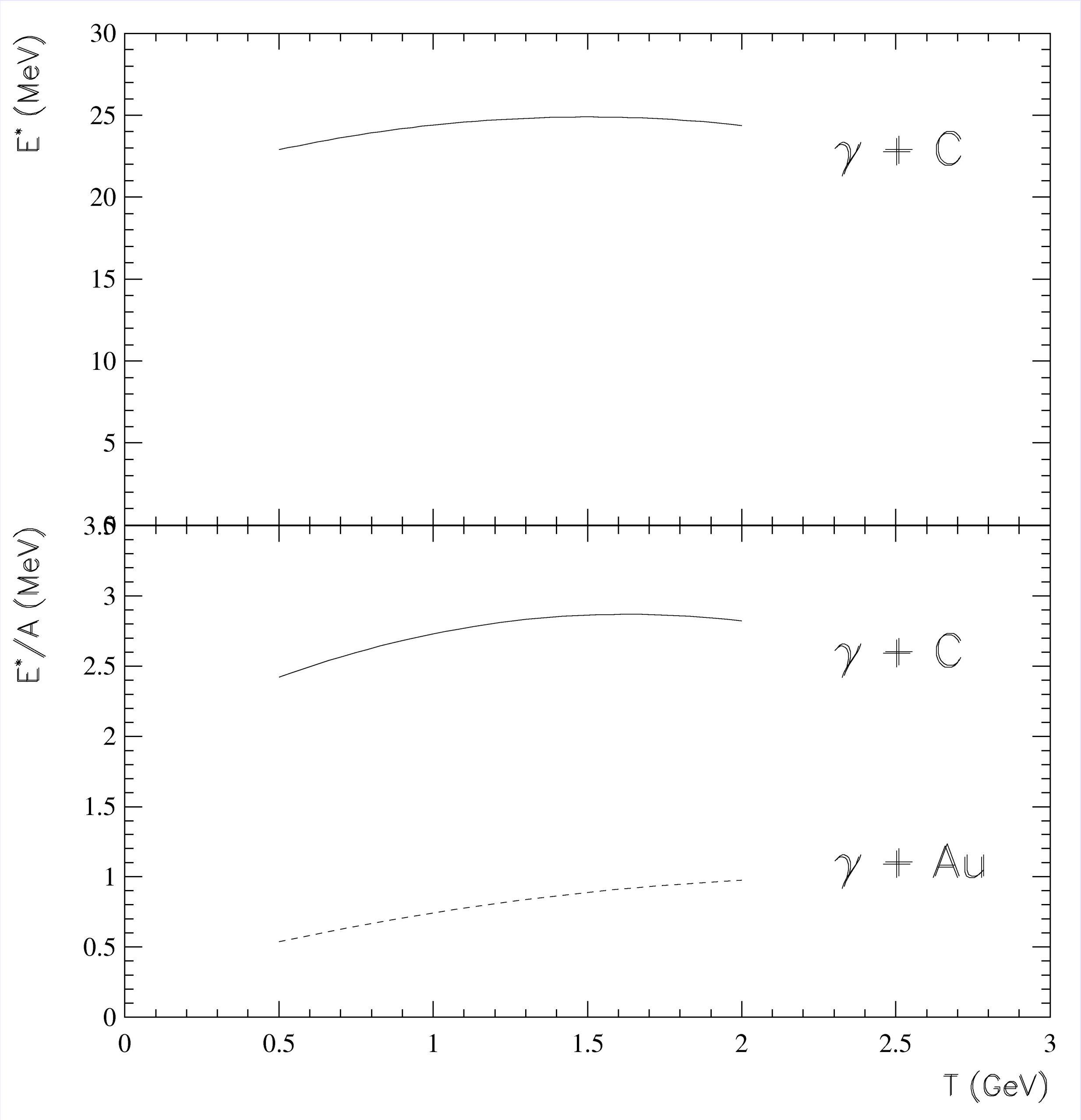
To be compared:
proton,
antiproton,
photon, and ^{4}He projectiles

Photons heat the nucleus less effectively compared to other projectiles

Antiprotons work good at low energy due to their annihilation

Ions (e.g. ^{4}He) is the best option to heat up the nucleus

Comparison of photon absorption by ^{12}C and ^{197}Au

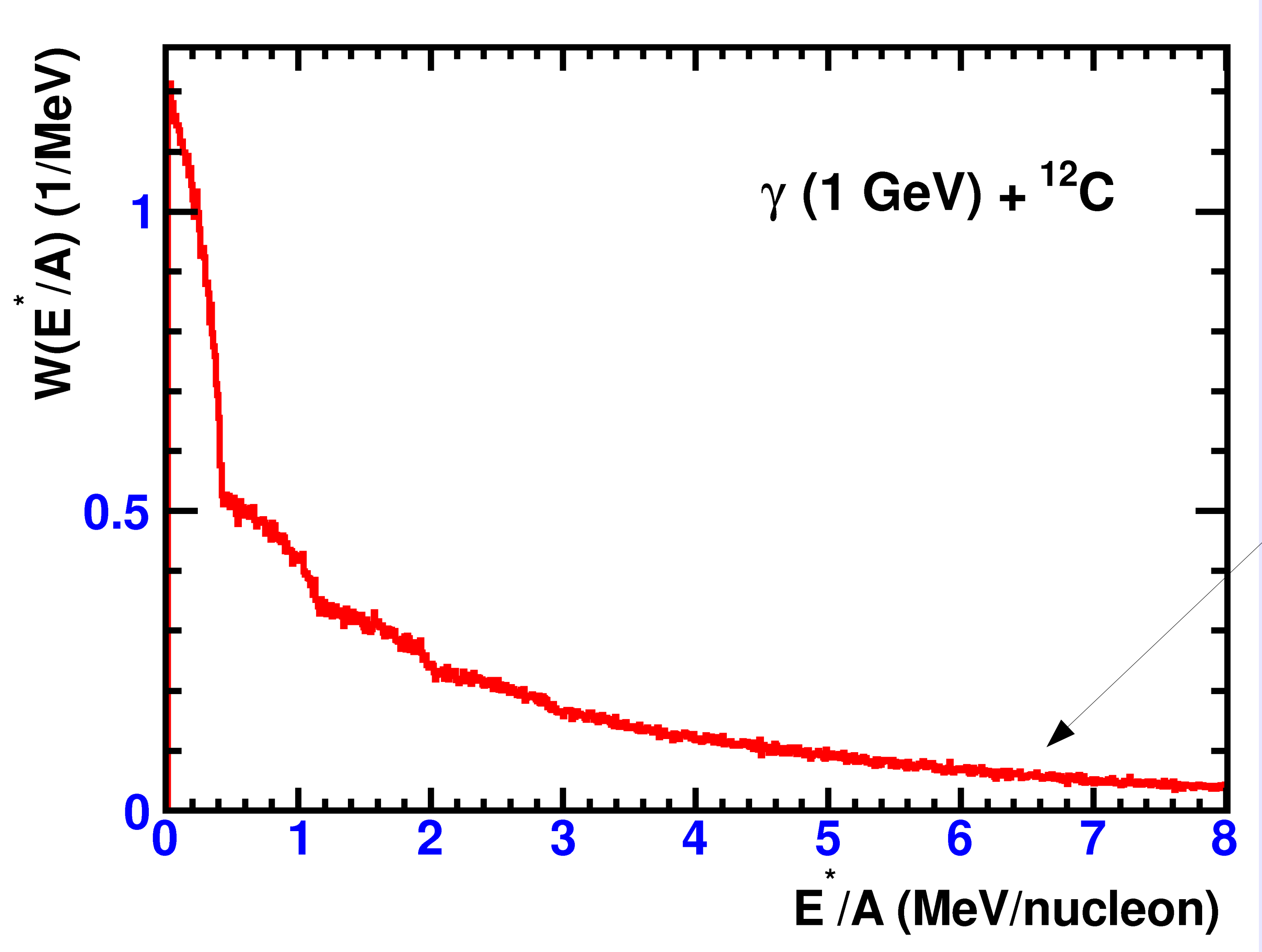


Due to a small number of nucleons in ^{12}C the average excitation energy calculated per nucleon of the residual nucleus is much higher compared to the photoabsorption on ^{197}Au.

The onset of the explosive break-up is expected at ~3 MeV/nucleon

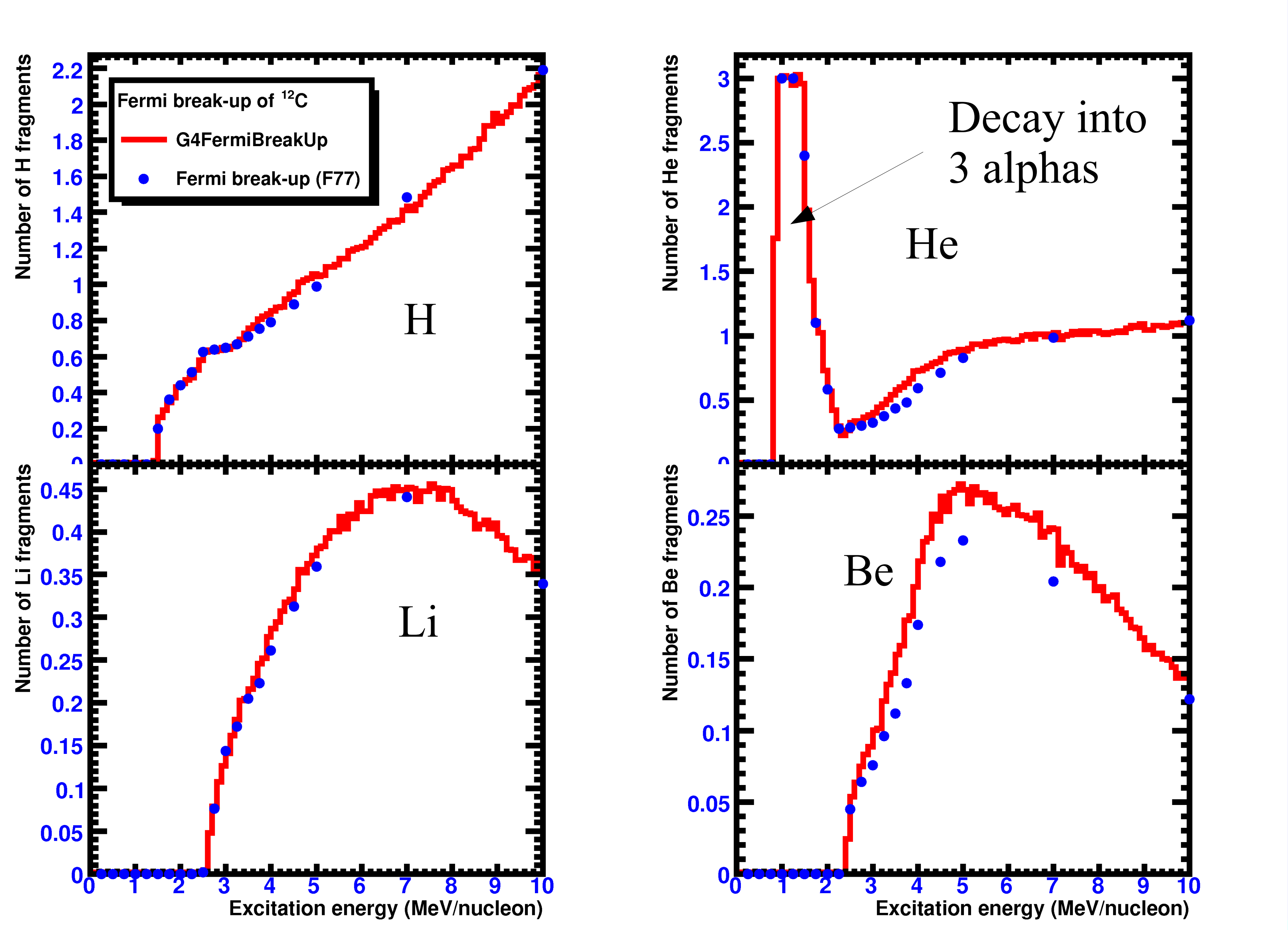
J.P. Bondorf, R. Donangelo, I.N. Mishustin, et al., Nucl. Phys. A443 (1985) 321; A444 (1985) 460;
J.P. Bondorf, A.S. Botvina, A.S. Iljinov, I.N. Mishustin, K. Sneppen, Phys. Rep. 257 (1995) 133

The average values are not very informative: the distribution of excitation energy is very wide

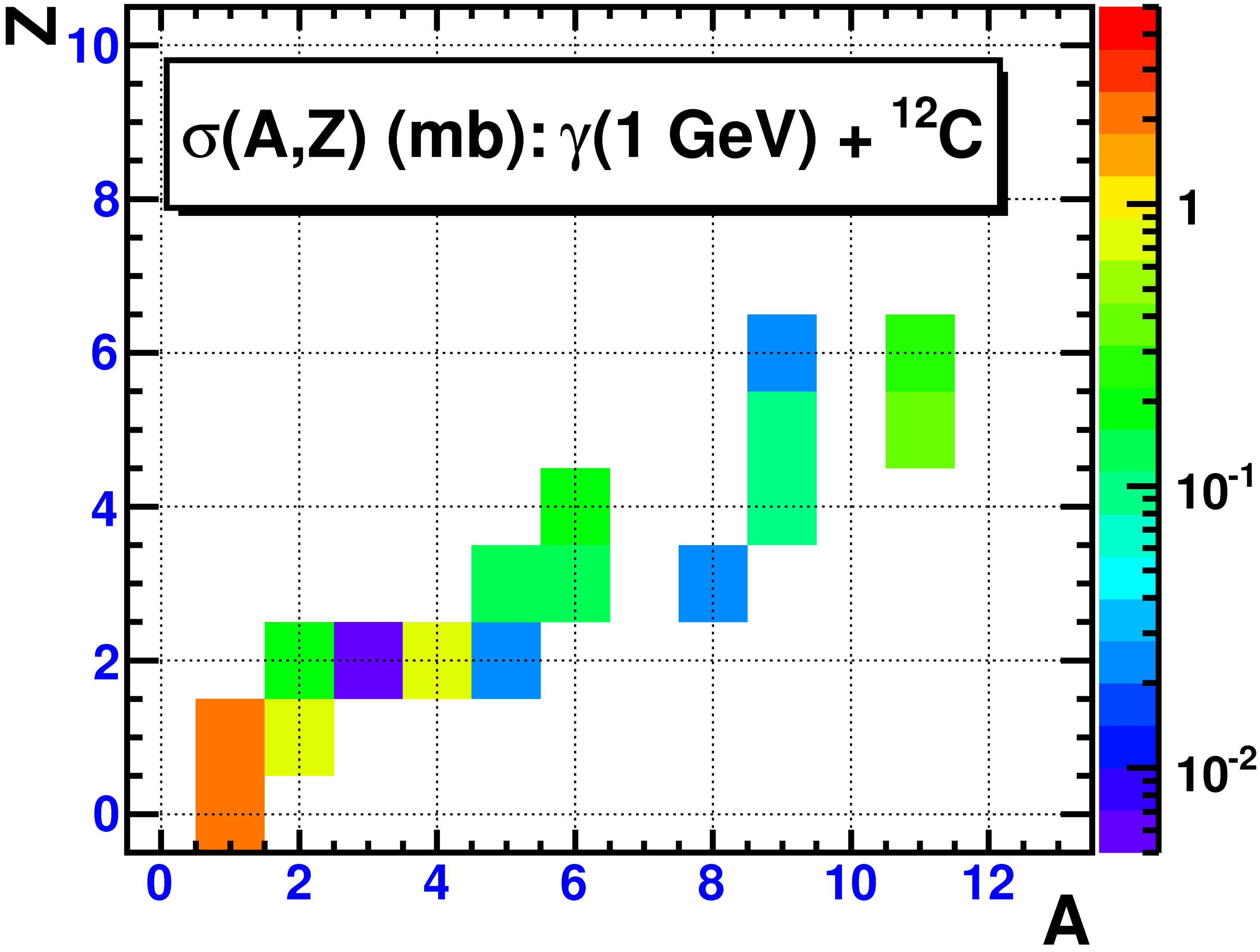


Break-up into individual nucleons

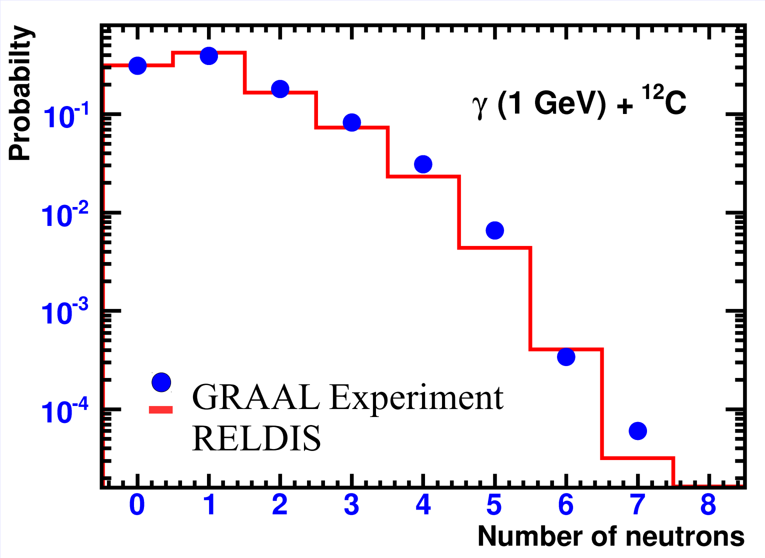
Average number of fragments of ^{12}C of a given element: Fermi Break-up model by A.S. Botvina et al. vs Geant4 implementation



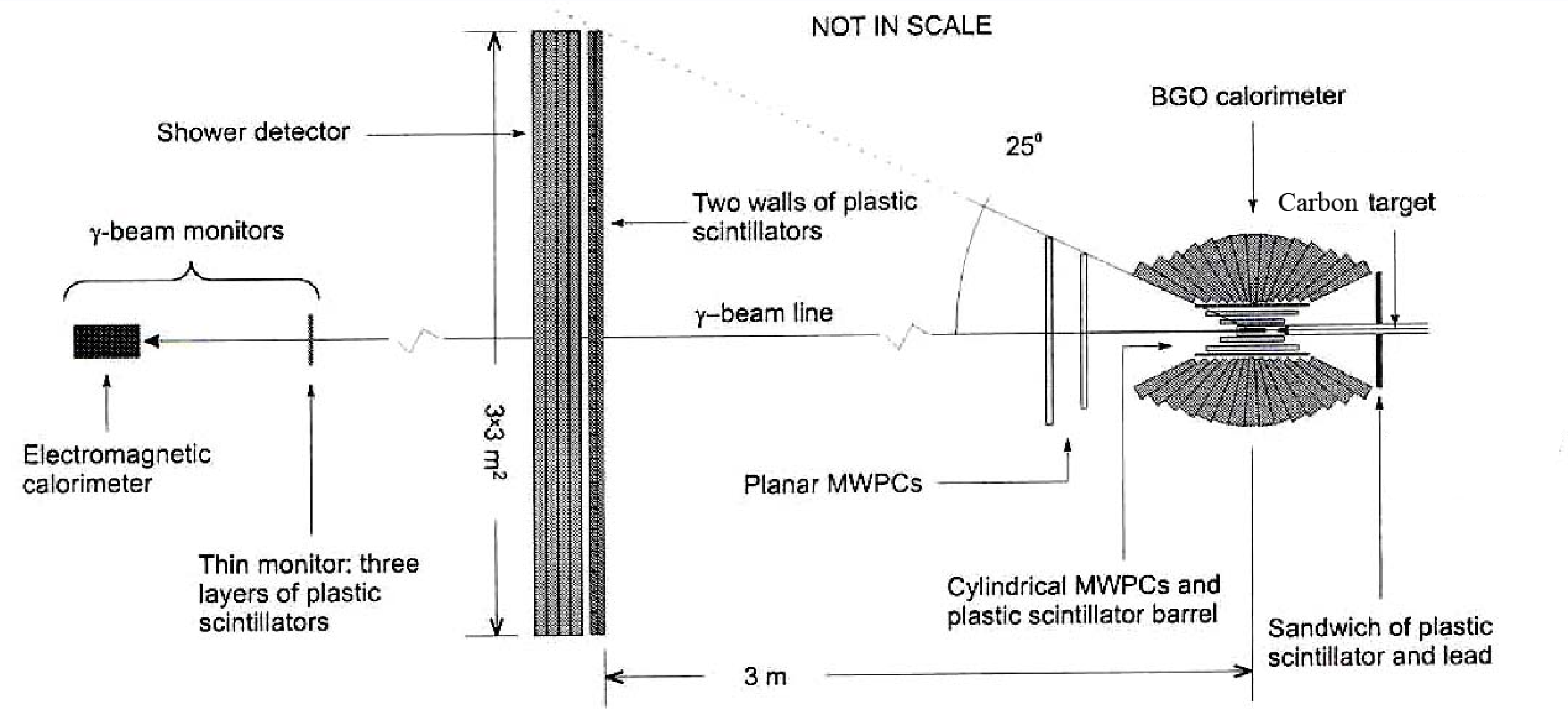
Calculated map of nuclear fragments



II. Comparison with the GRAAL data

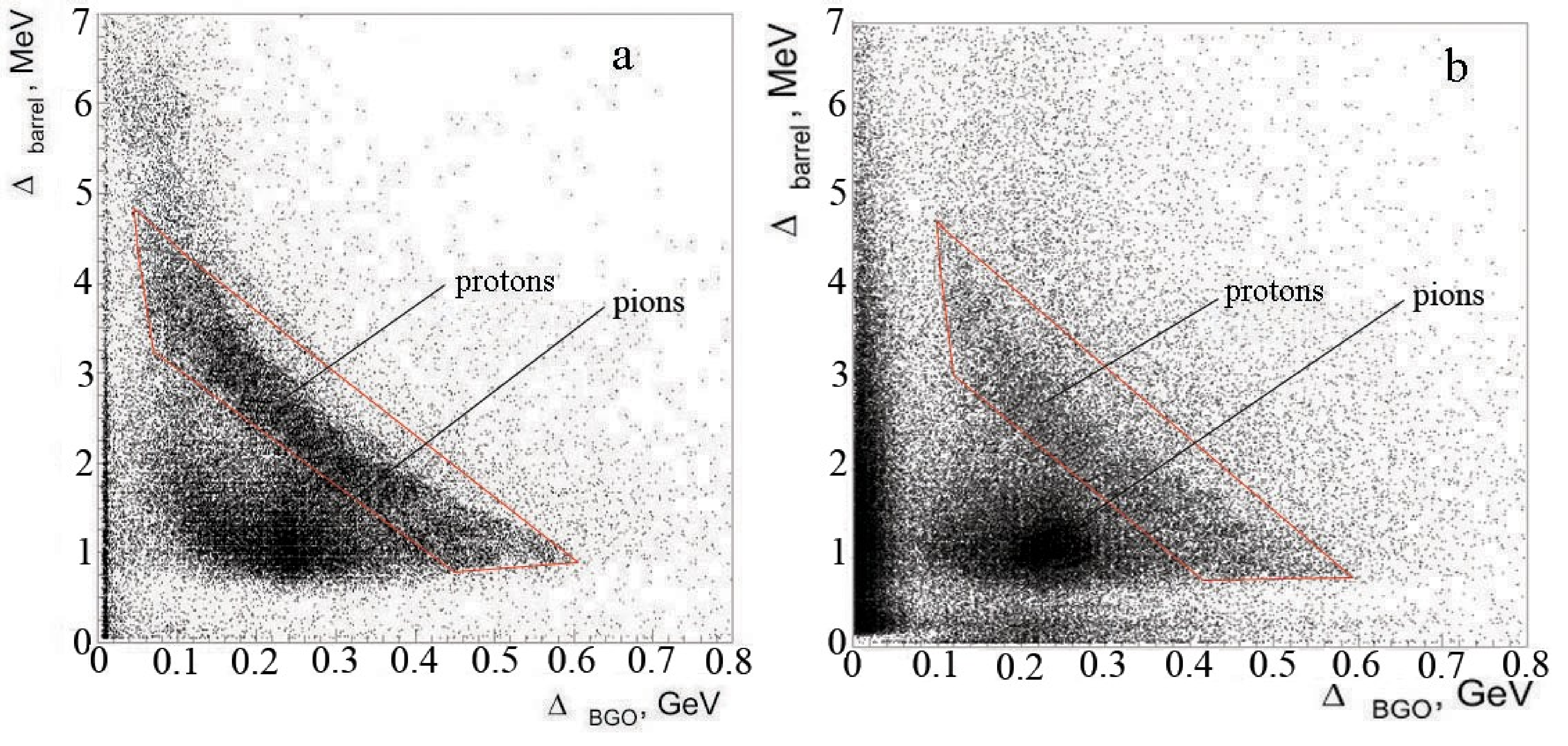


General layout of the GRAAL setup

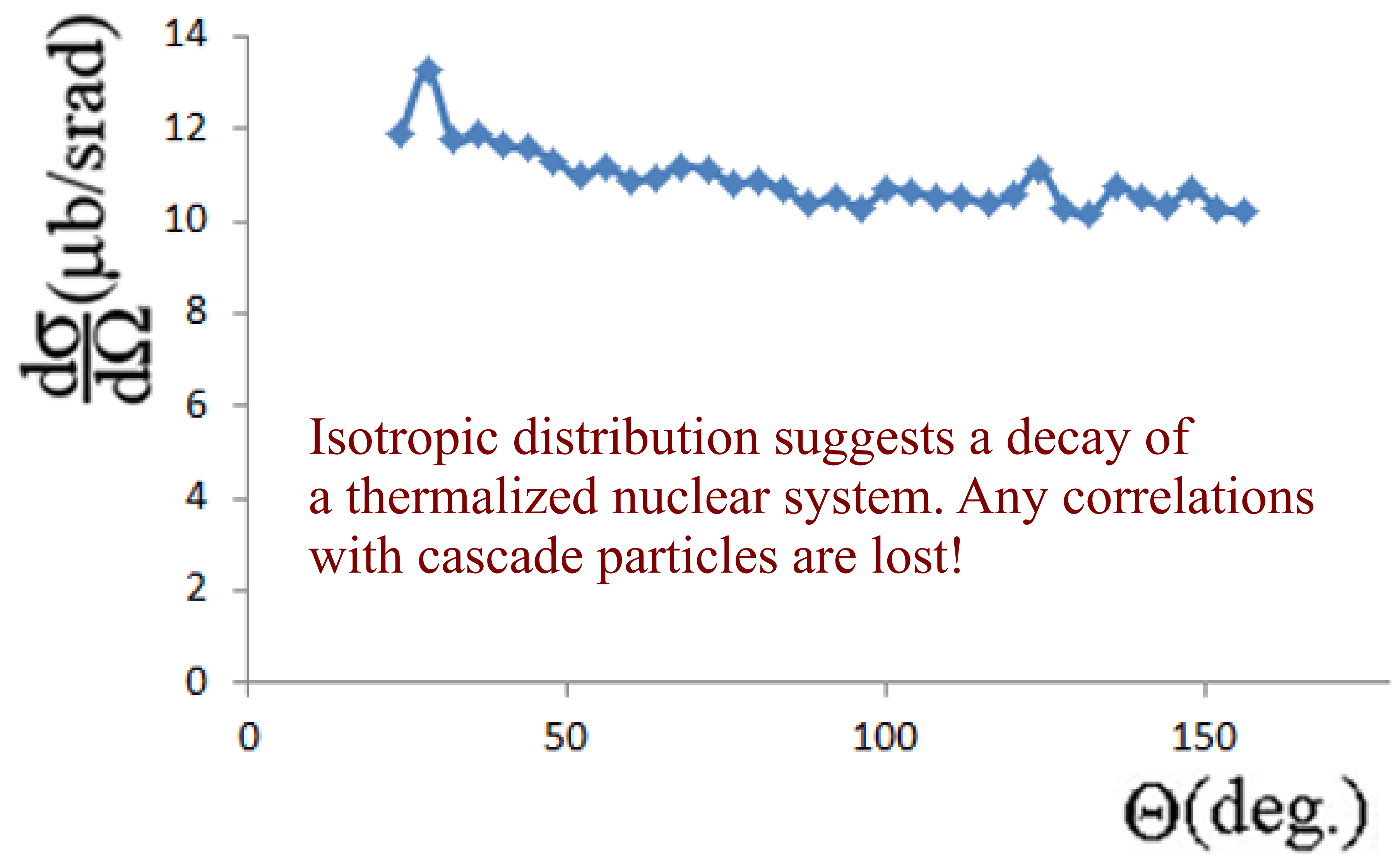


4π detector with a good efficiency of registration of protons and neutrons. This is important for studies of decays of highly excited nuclei.

Distinguishing protons from pions in the BGO calorimeter. Simulated (a) and detected (b) events are shown

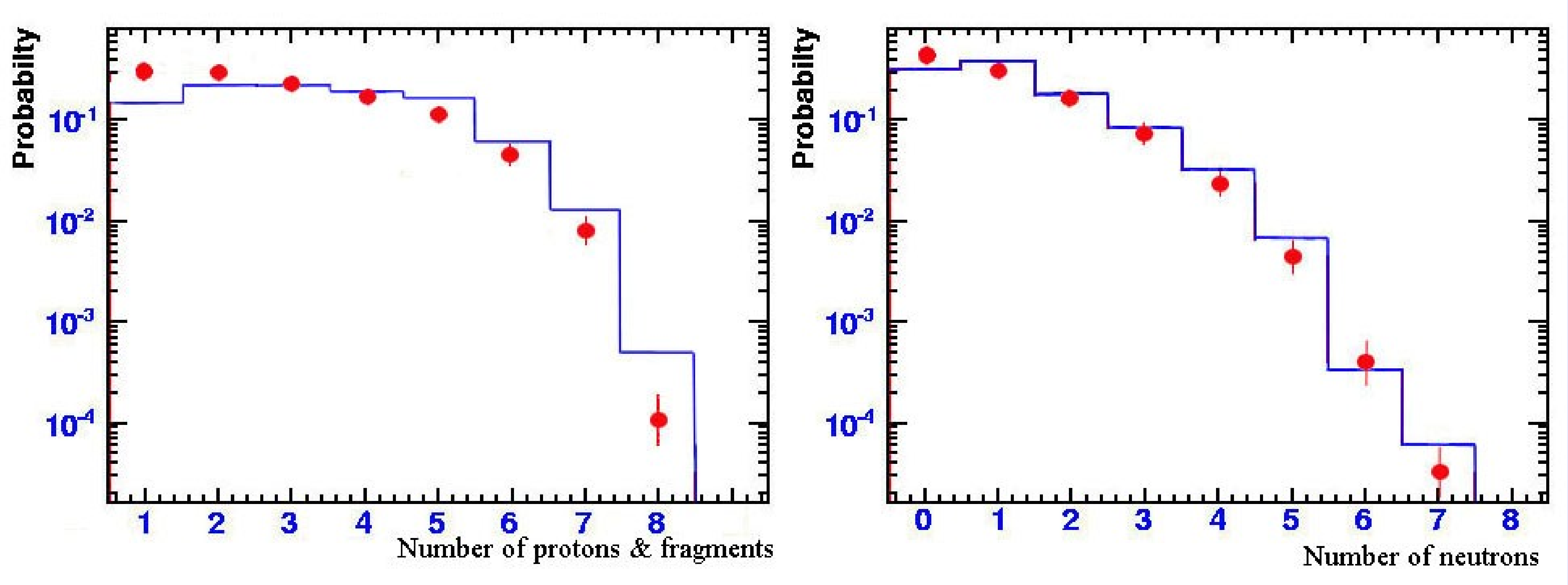


Measured angular distribution of nucleons produced in photodisintegration of ^{12}C in events with more than 7 nucleons.



Isotropic distribution suggests a decay of a thermalized nuclear system. Any correlations with cascade particles are lost!

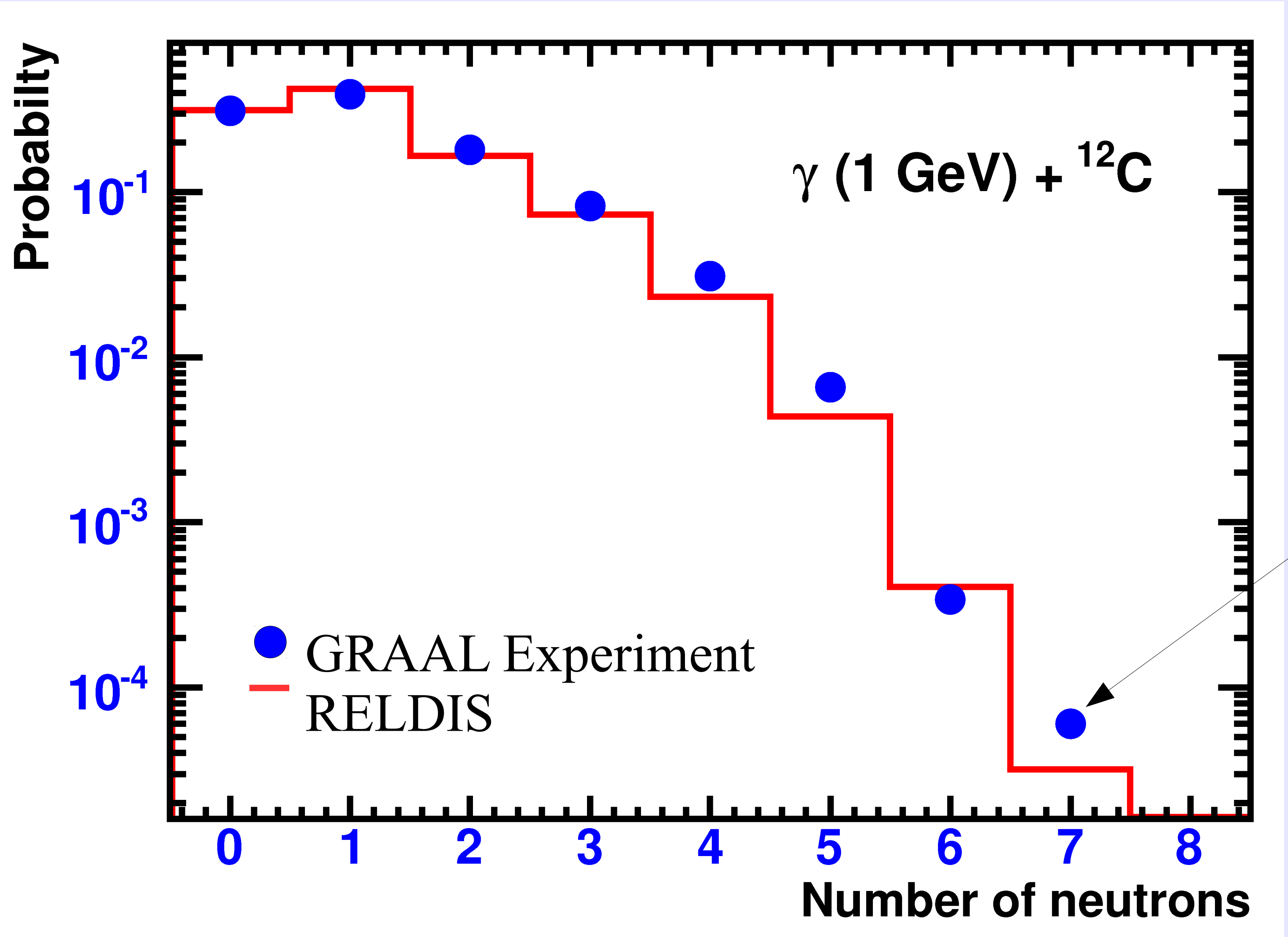
Distributions in the number of protons and neutrons



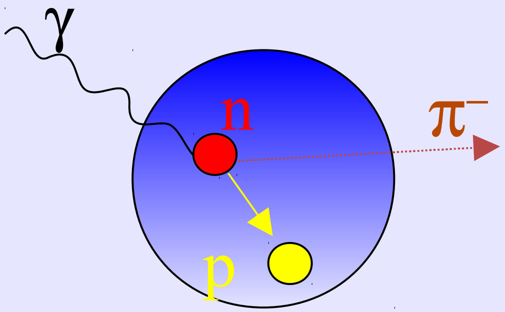
Measured (points) and calculated (histograms) probabilities of photodisintegration of ^{12}C at 0.7-1.5 GeV with given numbers of protons (left) and neutrons (right). Only statistical errors are shown.

Neutron multiplicity distributions

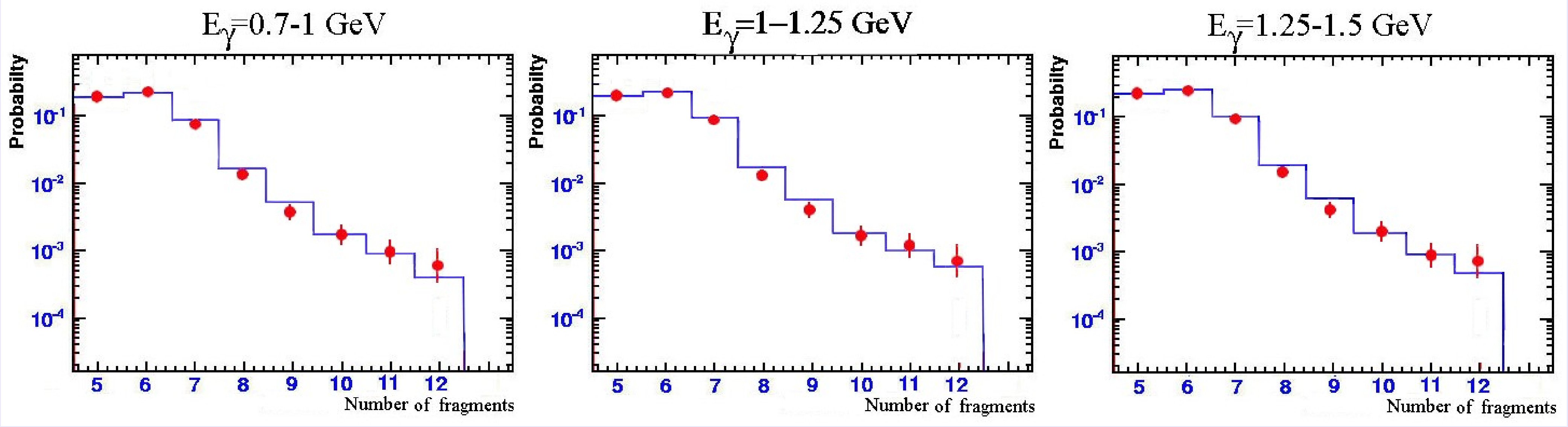
Demonstrate the possibility of a complete disintegration of ^{12}C into individual nucleons



Very rare charge-exchange events



Measured and calculated probabilities of ^{12}C photodisintegration with a given number of fragments.

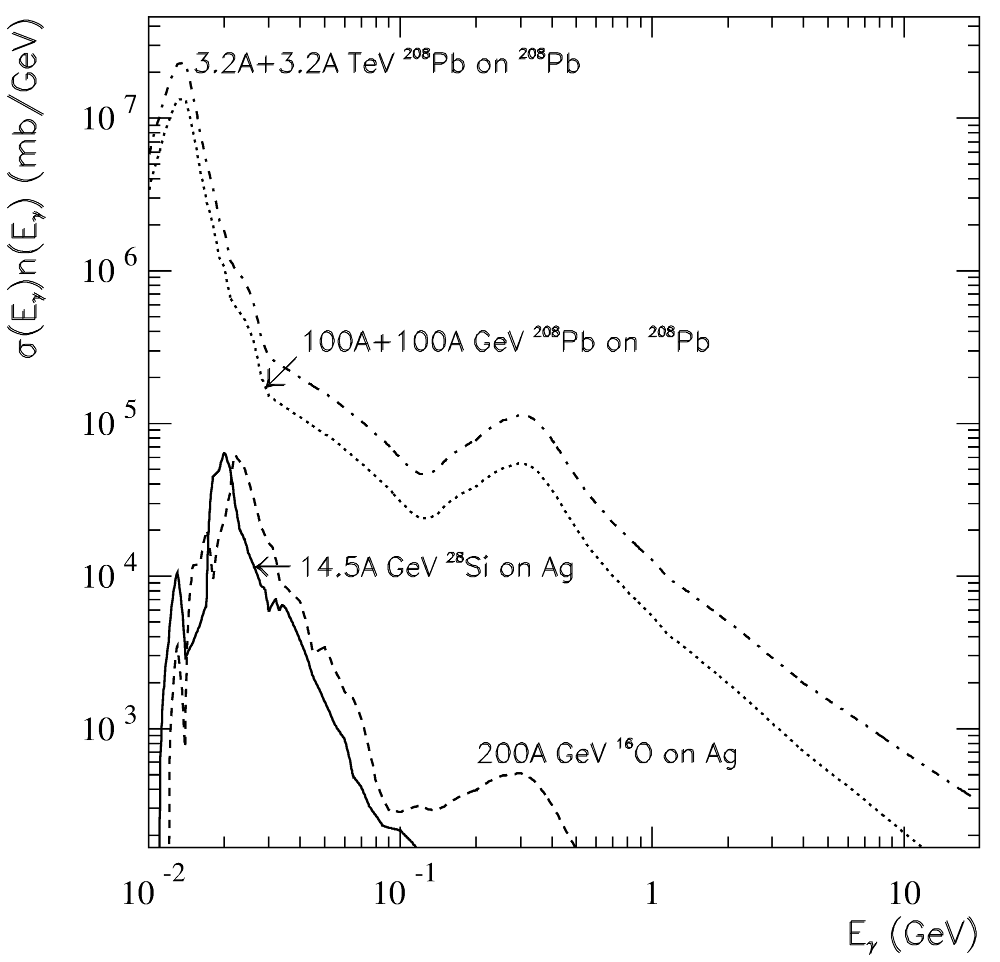


Very good agreement with calculated distributions in all three intervals of photon energy!

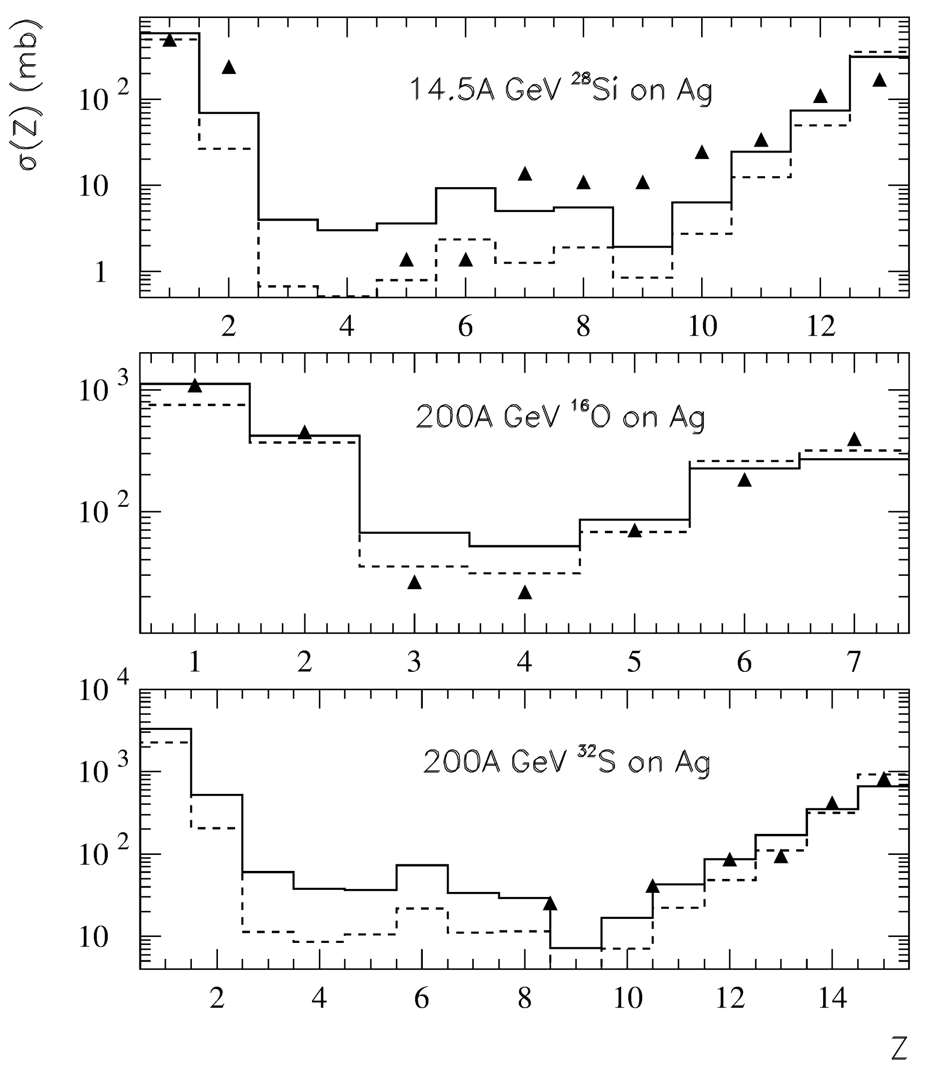
On average, 8 fragments are produced once per ~100 events, while 12 fragments (complete disintegration) once per 2000 events.

Electromagnetic dissociation of light nuclei in nuclear emulsion

Wide distributions of virtual photon energies

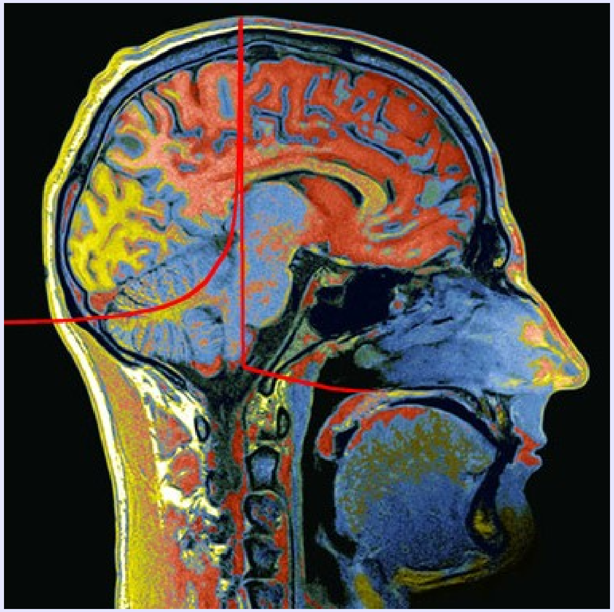


Multifragment decays are also seen

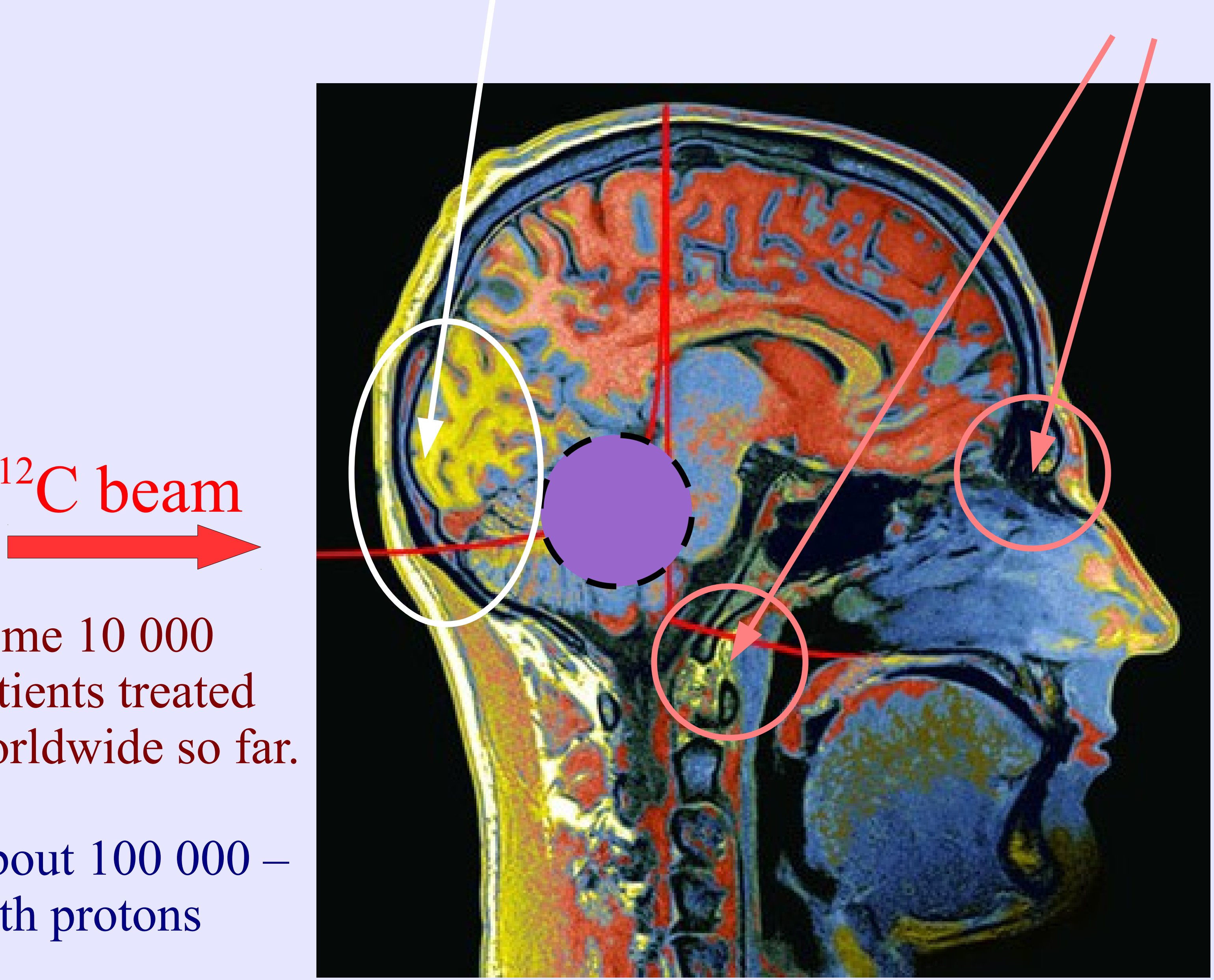


Described w/o multiple photon absorption. I.P. et al. Phys. Rev. C **57** (1998) 1920

III. Why it is important to study the fragmentation of ^{12}C?



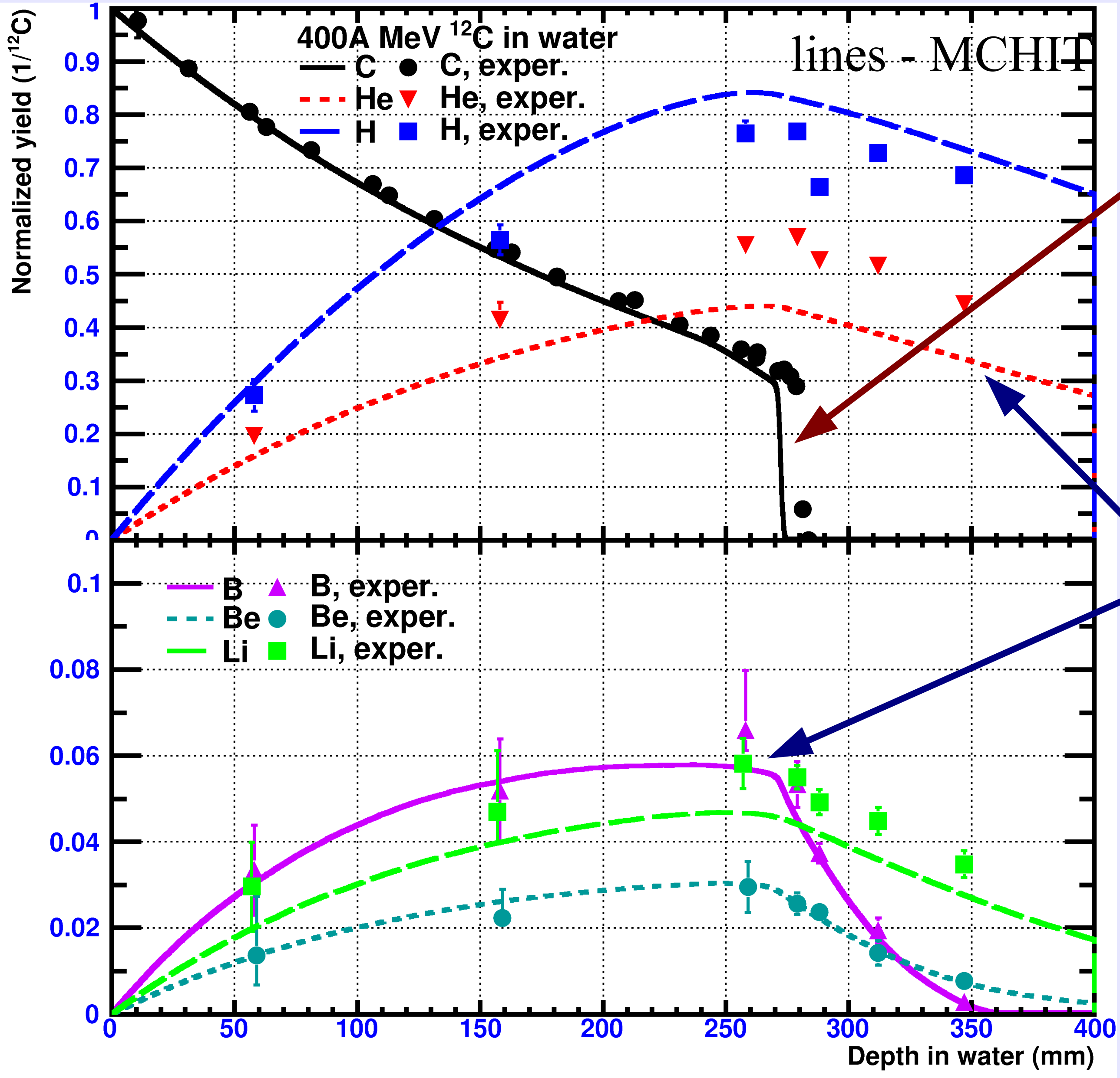
Carbon-ion therapy of cancer: nuclear beams are focused on tumor thus sparing healthy tissues and organs at risk



Some 10 000 patients treated worldwide so far.

About 100 000 – with protons

Fragmentation of 400 A MeV ^{12}C beam

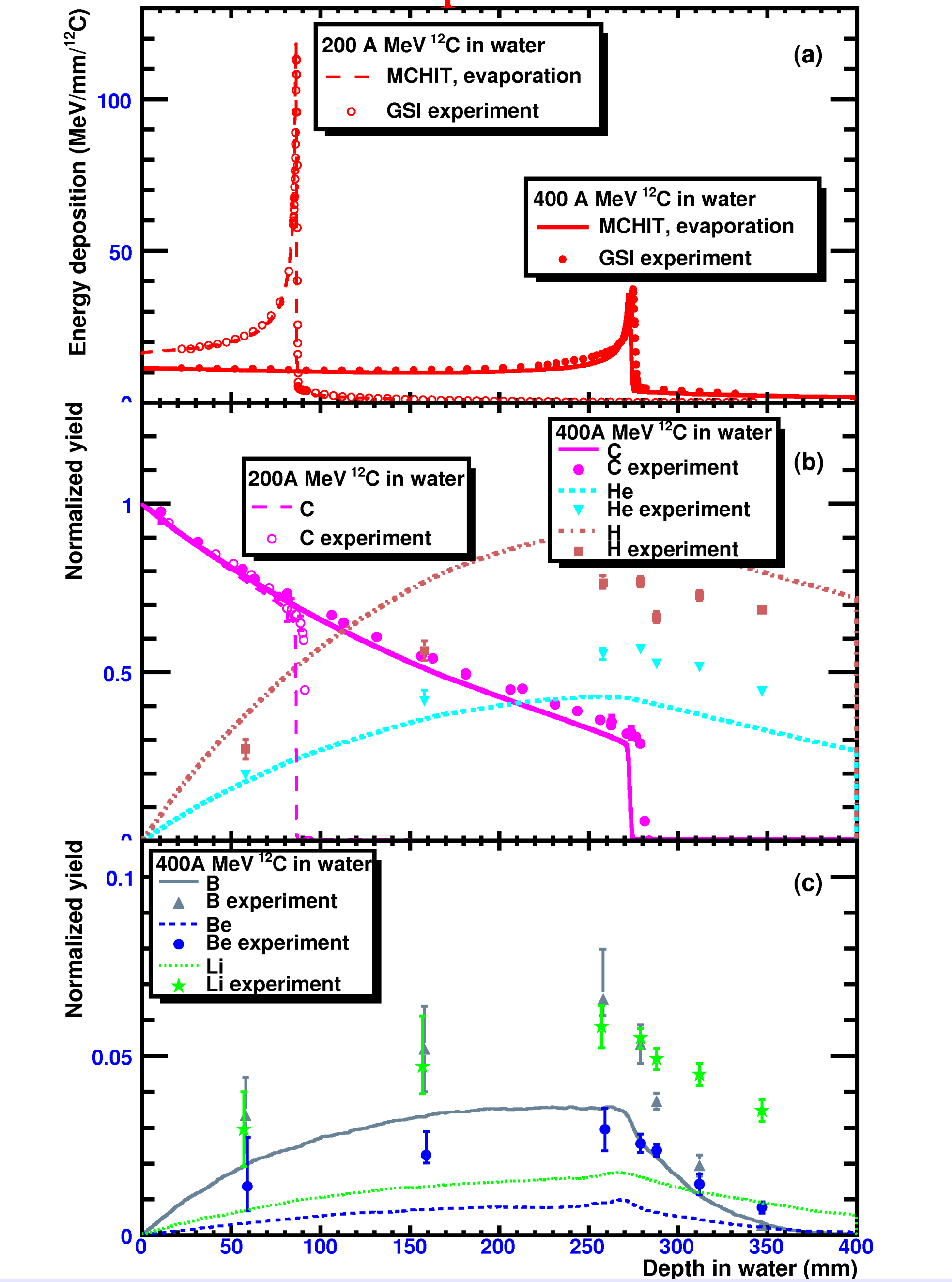


- Up to 70% of beam nuclei are fragmented
- Secondary fragments are created, from protons till Boron with various radiobiological properties
- A lot of work for nuclear fragmentation models!

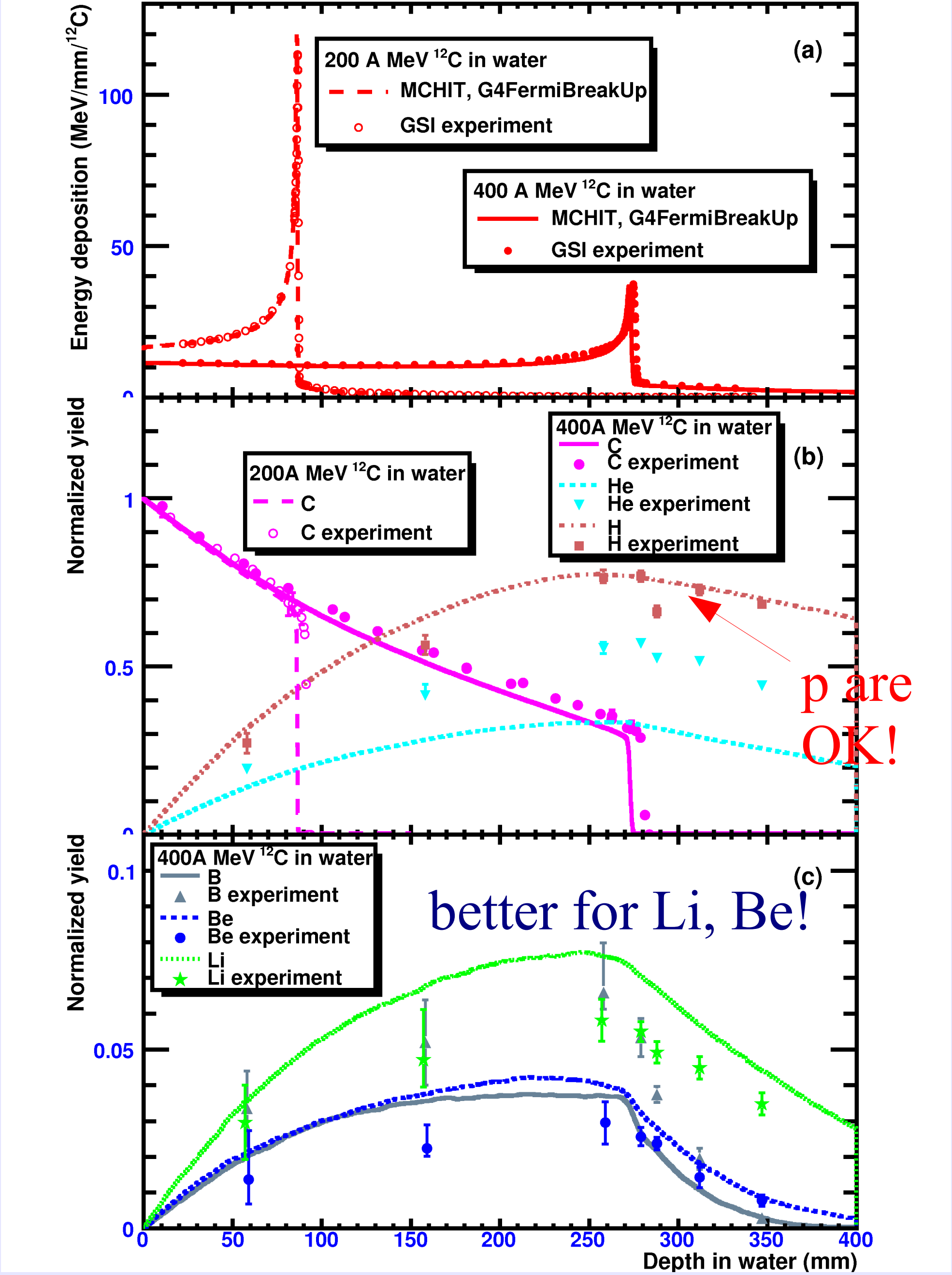
Data: E. Haettner et al., Rad. Prot. Dosim. **122** (2006)48

De-excitations in therapy simulations

Evaporation



Fermi break-up



p are OK!

better for Li, Be!

Data: E. Haettner et al., Rad. Prot. Dosim. **122** (2006)48, within θ<10° acceptance

Conclusions

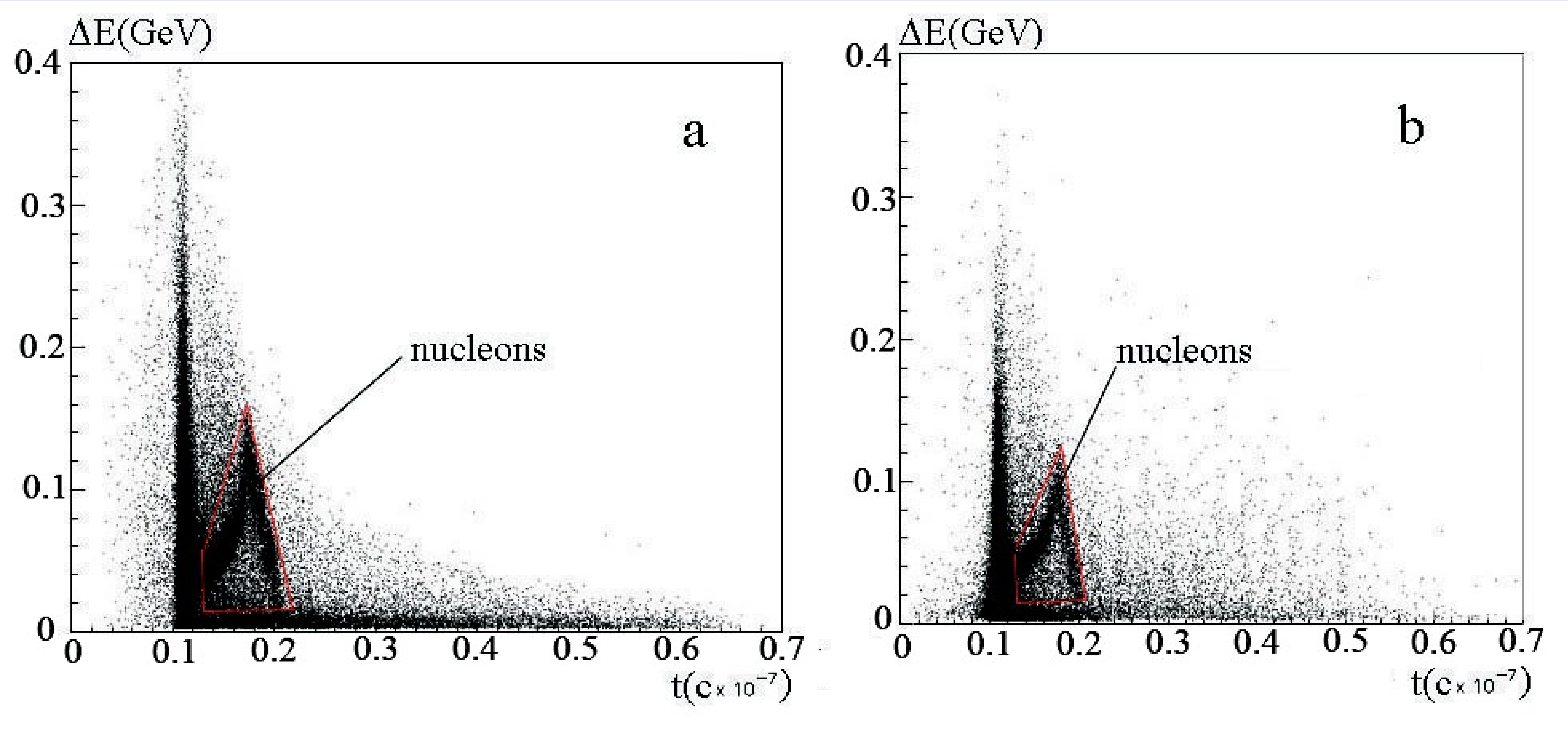
- The RELDIS model predicts a wide distribution of excitation energies of nuclear residues which are created in the photoabsorption of ~1 GeV photons by ^{12}C nuclei.
- The most probable photodisintegration events are characterized by emission of 1 or 2 nucleons.
- However, a complete disintegration of ^{12}C into individual nucleons is also seen in a small (~0.05%) fraction of photoabsorption events.

- Isotropic distribution of nucleon emission in high (>7) multiplicity events suggests that they are emitted by a hot thermalized nuclear residue rather than in a cascade process.
- The model describes the fragment multiplicity distributions very well.

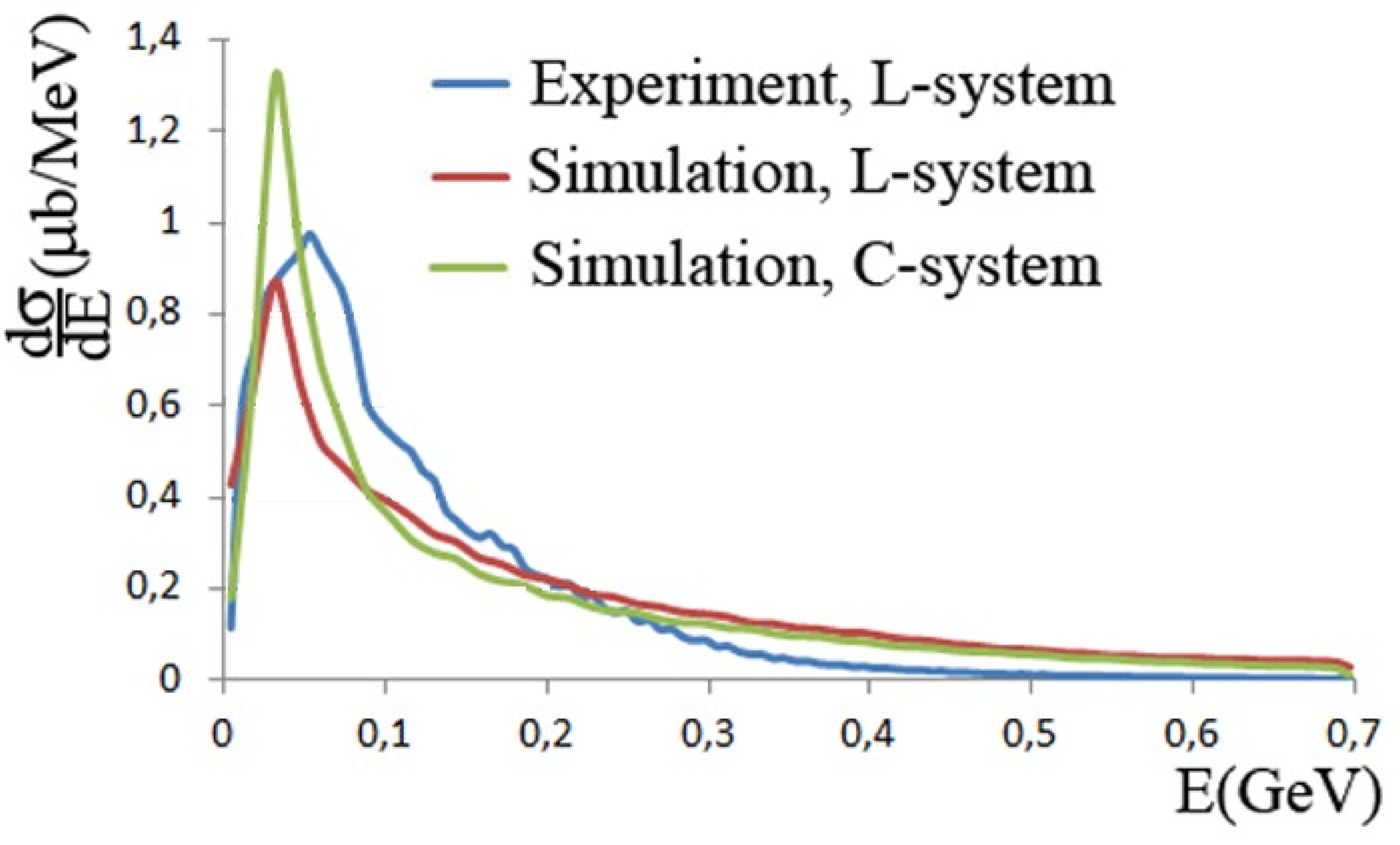
- The present study helps to understand nuclear reactions taking place in human tissues during carbon-ion therapy of cancer.

Back-up slides

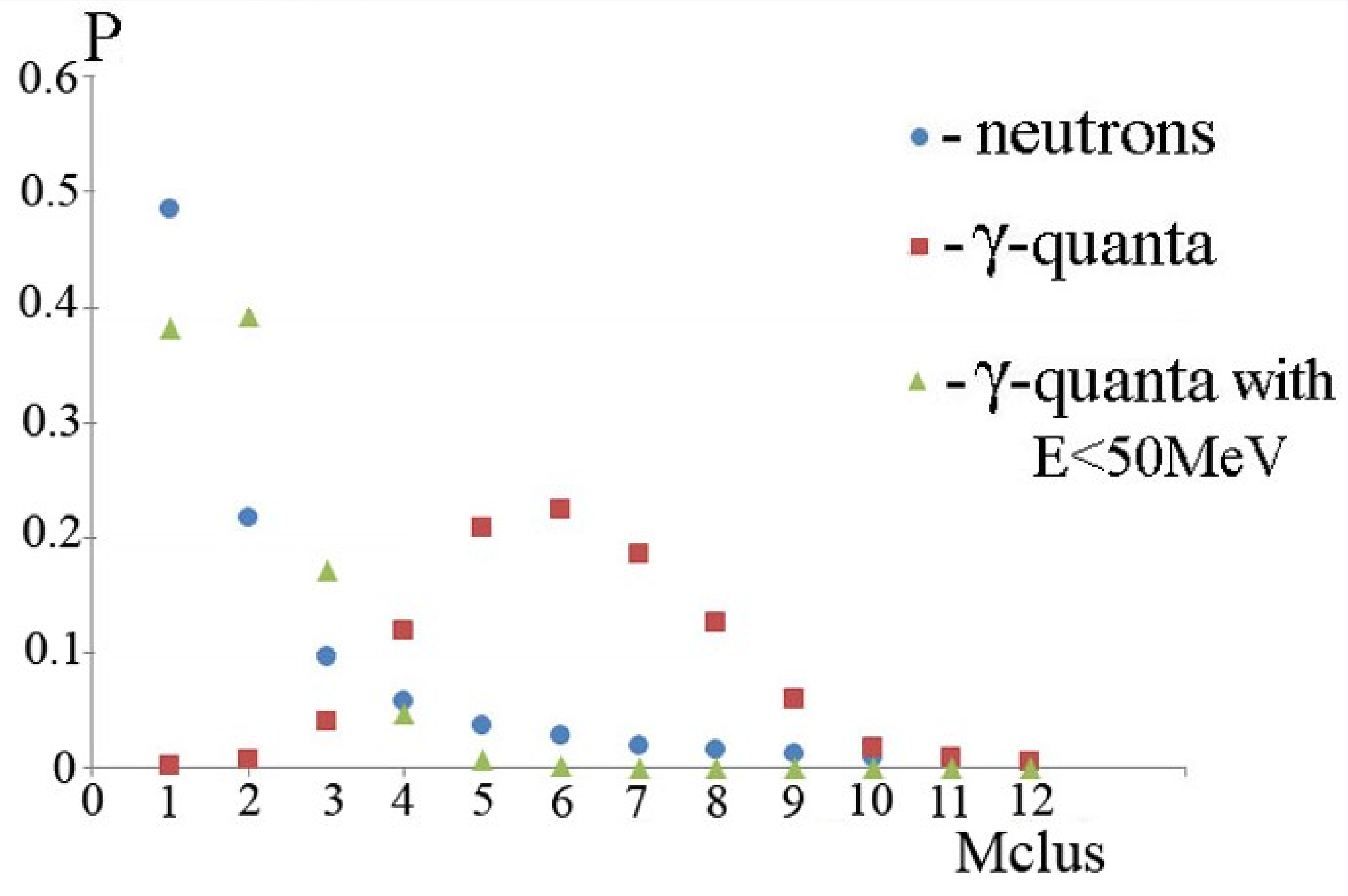
Distinguishing of charged fragments and neutrons from pions and photons in the forward detector. Simulated (a) and detected (b) events are shown.



Energy distributions of nucleons produced in photodisintegration of 12C. Measured (blue line) and calculated (red line) distributions in the laboratory system and calculated distribution (green line) for the center of mass system



Probability to have a given number of fired crystals (cluster size) for neutrons, photons and low energy photons which hit the BGO ball.

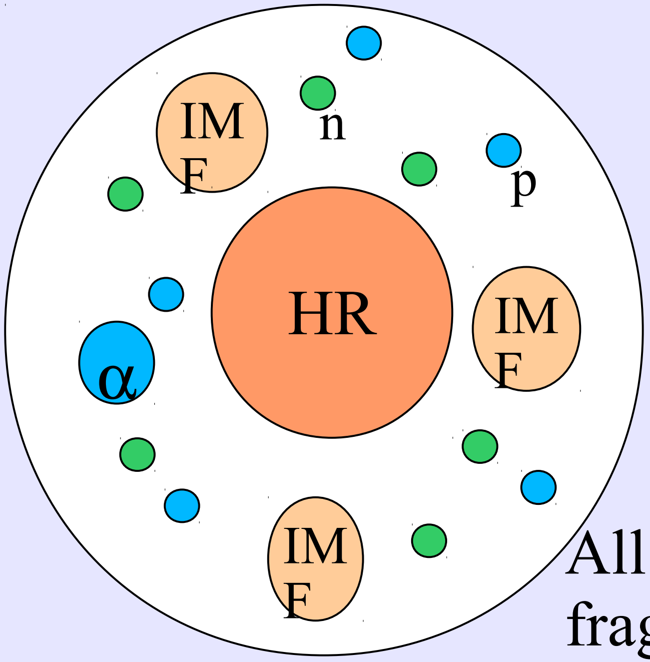


Average numbers of protons and neutrons measured by the BGO ball and forward detectors

	Protons	Neutrons
BGO ball	2,05±0,03	0,57±0,01
Forward direction	0,35±0,01	0,04±0,01

Statistical description of nuclear break-up: SMM

J.P. Bondorf, R. Donangelo, I.N. Mishustin, et al., Nucl. Phys. A443 (1985) 321; A444 (1985) 460;
J.P. Bondorf, A.S. Botvina, A.S. Iljinov, I.N. Mishustin, K. Sneppen, Phys. Rep. 257 (1995) 133



Ensemble of nucleons and fragments
in thermal equilibrium characterized by

neutron number N_0
proton number $Z_0, \; N_0+Z_0=A_0$
excitation energy $E^*=E_0-E_{CN}$
break-up volume $V=(1+\kappa)V_0$

All break-up channels are enumerated by the sets of fragment multiplicities or partitions, $f=\{N_{AZ}\}$, $M_f=\Sigma N_{AZ}$

- Baryon number and charge conservation
- in micro-canonical description: $\Sigma\, AN_{AZ}=A_0\,, \quad \Sigma\, ZN_{AZ}=Z_0$

or in macro canonical: $\Sigma\, A\langle N_{AZ}\rangle=A_0\,, \quad \Sigma\, Z\langle N_{AZ}\rangle=Z_0$

- Statistical distribution of probabilities: $W_f \sim \exp\,\{S_f(A_0, Z_0, E^*, V)\}$

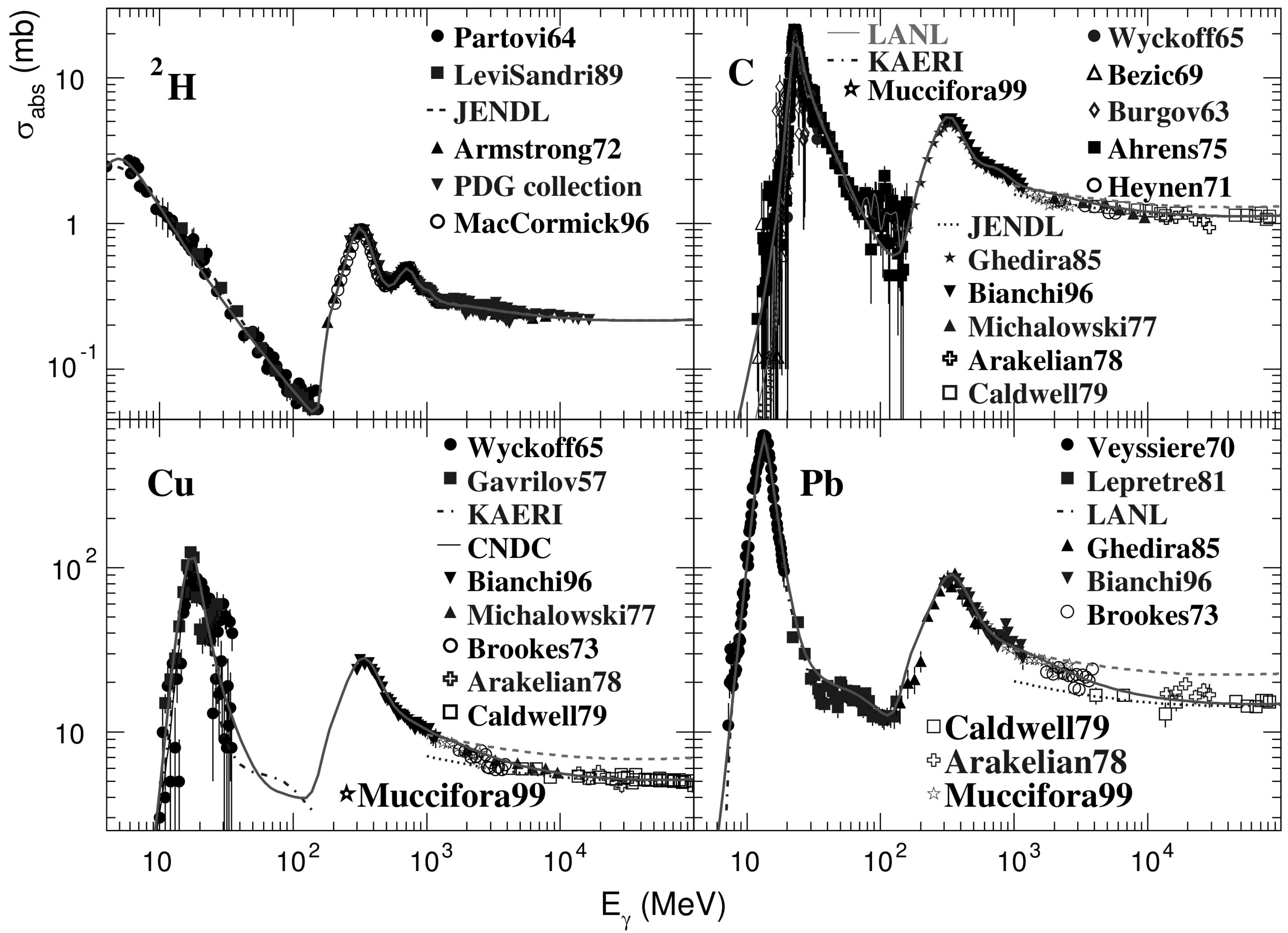
To find more on the RELDIS model:

A.S. Iljinov et al.,
Nucl. Phys. **A616** (1997) 575

I.A.Pshenichnov et al.,
Phys.Rev. **C57** (1998) 1920;
Phys. Rev. **C60** (1999) 044901;
Phys. Rev. **C64** (2001) 024903

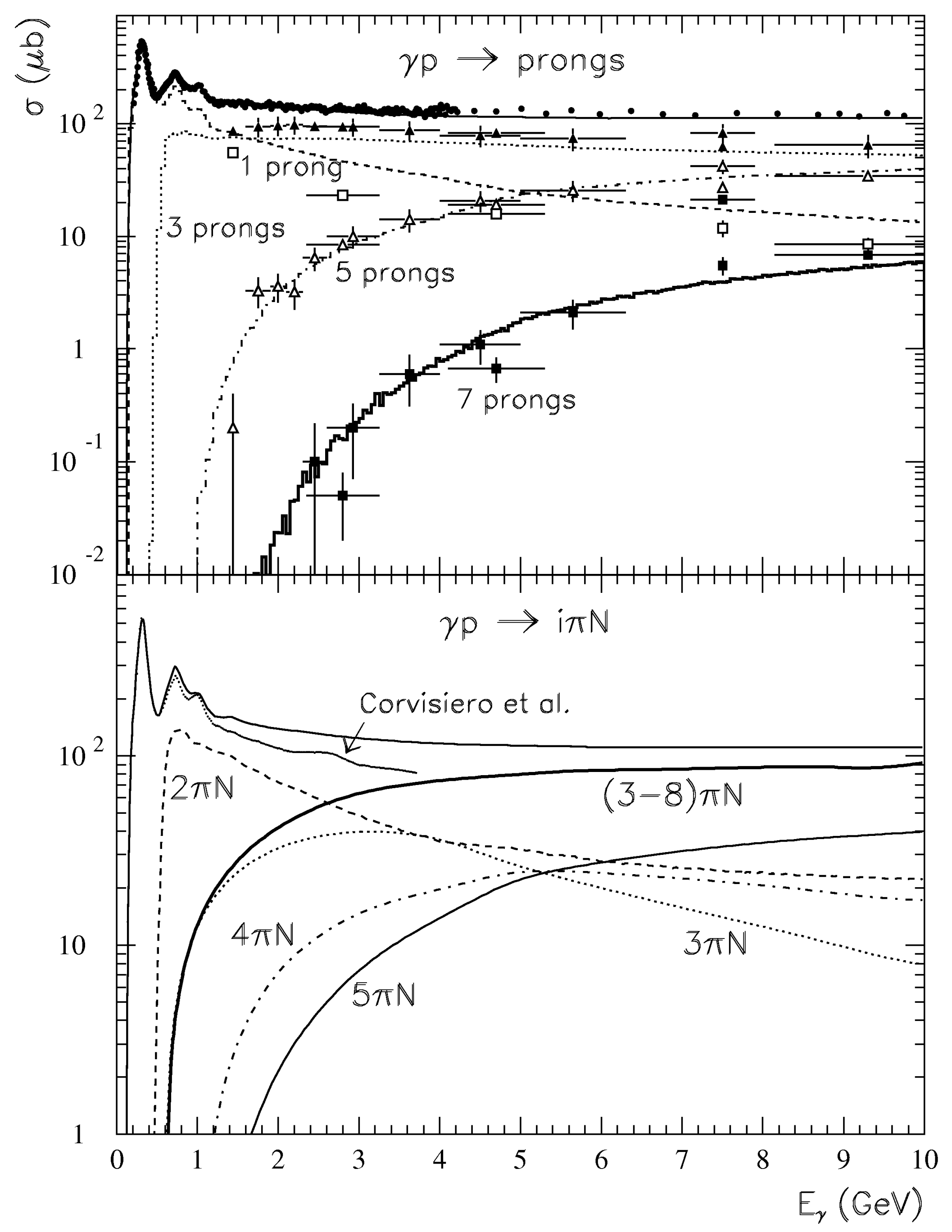
I.A. Pshenichnov,
Phys. Part. Nuclei **42** (2011) 21

Total photoabsorption cross section on nuclei



M.V.Kossov, Eur. Phys. J. A 14, (2002) 377

Meson photoproduction on nucleons



γp	γn
$\gamma p \to \pi^+ n$ $\gamma p \to \pi^0 p$	$\gamma n \to \pi^- p$ $\gamma n \to \pi^0 n$
$\gamma p \to \pi^- \Delta^{++}$ $\gamma p \to \pi^0 \Delta^+$ $\gamma p \to \pi^+ \Delta^0$	$\gamma n \to \pi^- \Delta^+$ $\gamma n \to \pi^0 \Delta^0$ $\gamma n \to \pi^+ \Delta^-$
$\gamma p \to \eta p$ $\gamma p \to \omega p$ $\gamma p \to \rho^0 p$ $\gamma p \to \rho^+ n$	$\gamma n \to \eta n$ $\gamma n \to \omega n$ $\gamma n \to \rho^0 n$ $\gamma n \to \rho^- p$
$\gamma p \to \pi^+ \pi^- p$ $\gamma p \to \pi^0 \pi^+ n$	$\gamma n \to \pi^+ \pi^- n$ $\gamma n \to \pi^0 \pi^- p$
$\gamma p \to \pi^0 \pi^0 \pi^0 p$ $\gamma p \to \pi^+ \pi^- \pi^0 p$ $\gamma p \to \pi^+ \pi^0 \pi^0 n$ $\gamma p \to \pi^+ \pi^+ \pi^- n$	$\gamma n \to \pi^0 \pi^0 \pi^0 n$ $\gamma n \to \pi^+ \pi^- \pi^0 n$ $\gamma n \to \pi^- \pi^0 \pi^0 p$ $\gamma n \to \pi^+ \pi^- \pi^- p$
$\gamma p \to i\pi N (4 \leq i \leq 8)$ (35)	$\gamma n \to i\pi N (4 \leq i \leq 8)$ (35)