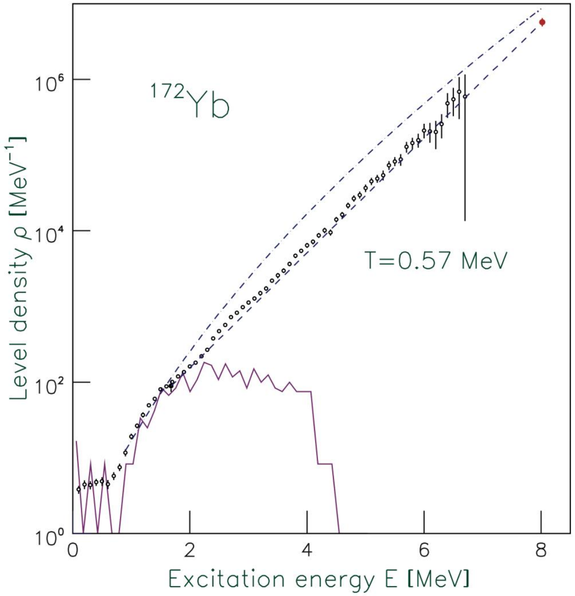
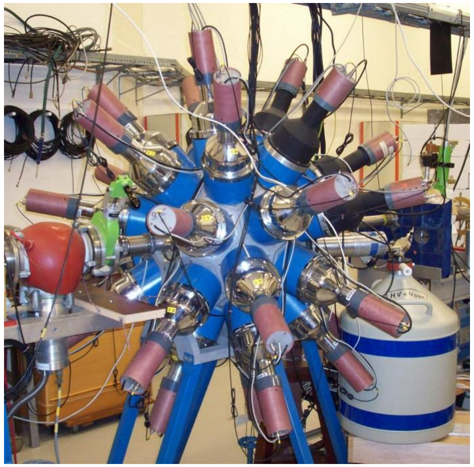
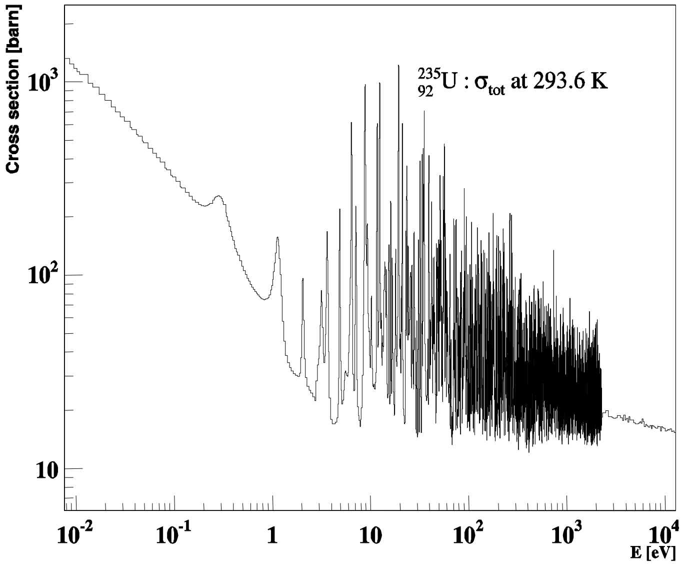
Level Densities, Decay Probabilities and Cross sections in the Actinide Region







J.N. Wilson

Institut de Physique Nucléaire, Orsay

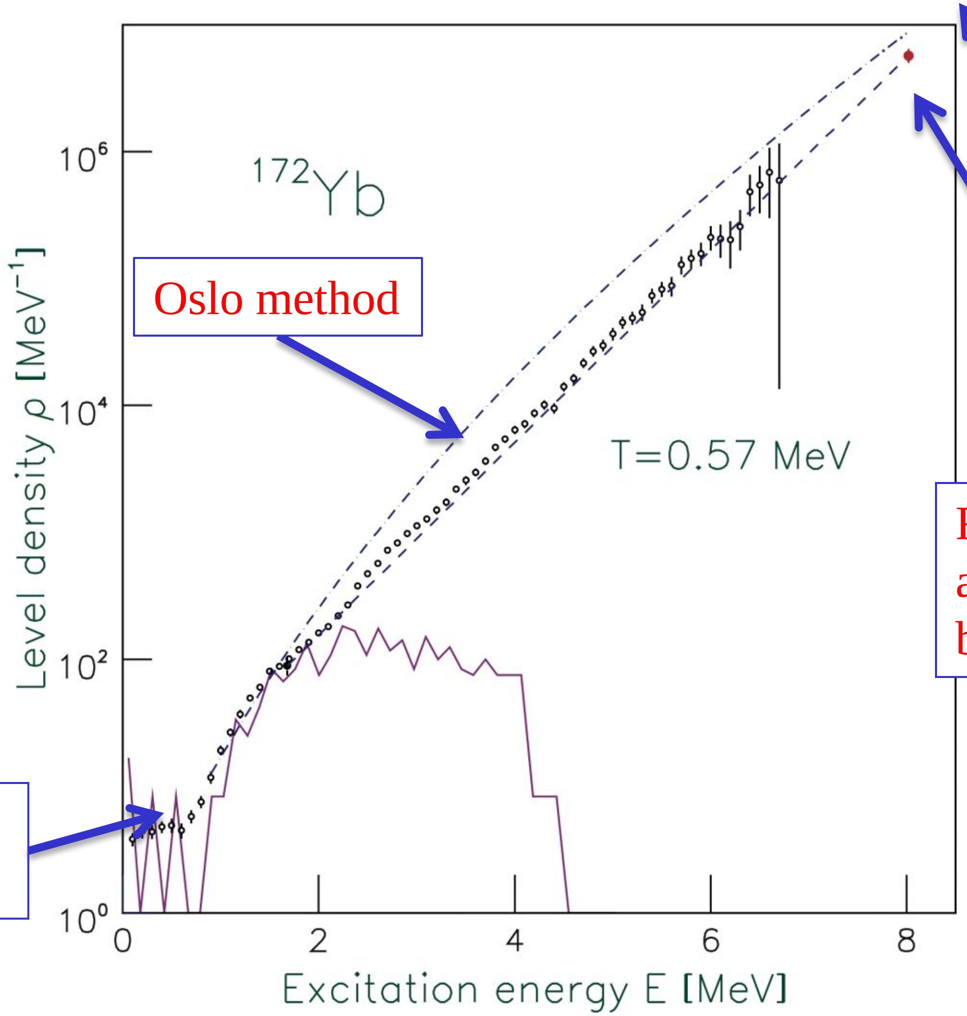
NLD Measurements in the Actinides: Goals & Motivations

1. Fundamental physics – NLD and GSF fine structure, statistical properties of the hot compound nucleus

2. Indirect cross section measurements via surrogate reactions

3. Level density knowledge helps cross section calculations where direct measurements are difficult or impossible

1. Fundamental Physics



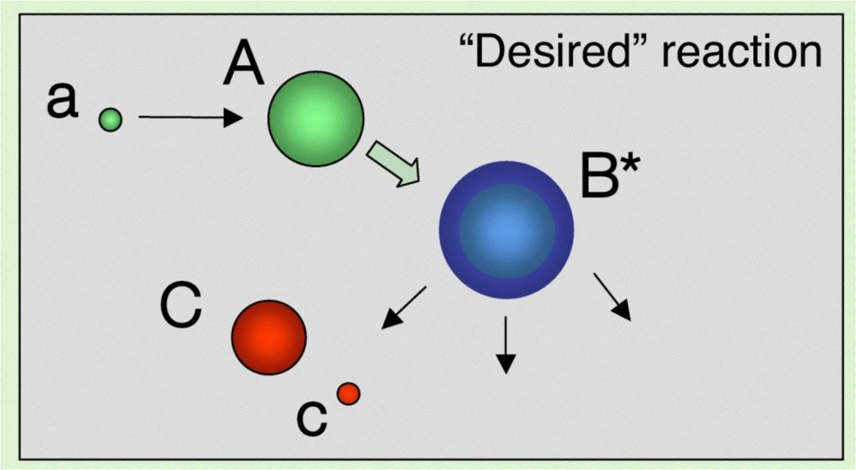
Oslo method

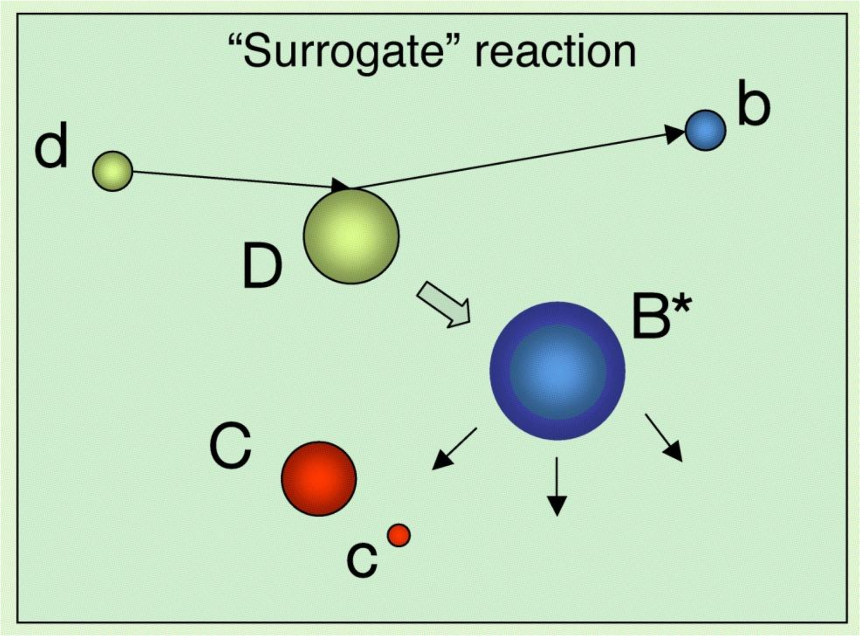
Extrapolation

Resonance spacings at the neutron binding energy

Spectroscopy of low lying states

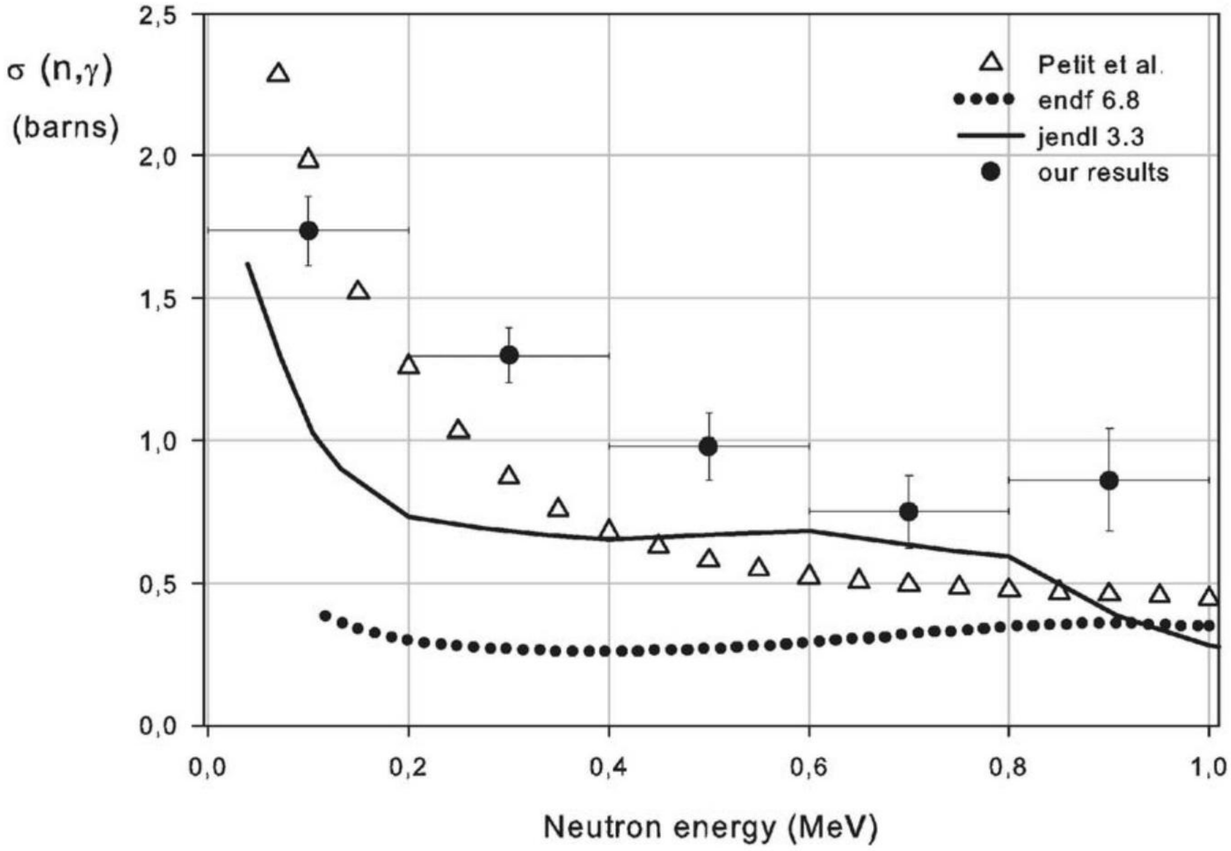
2. Indirect Measurements


“Desired” reaction


“Surrogate” reaction

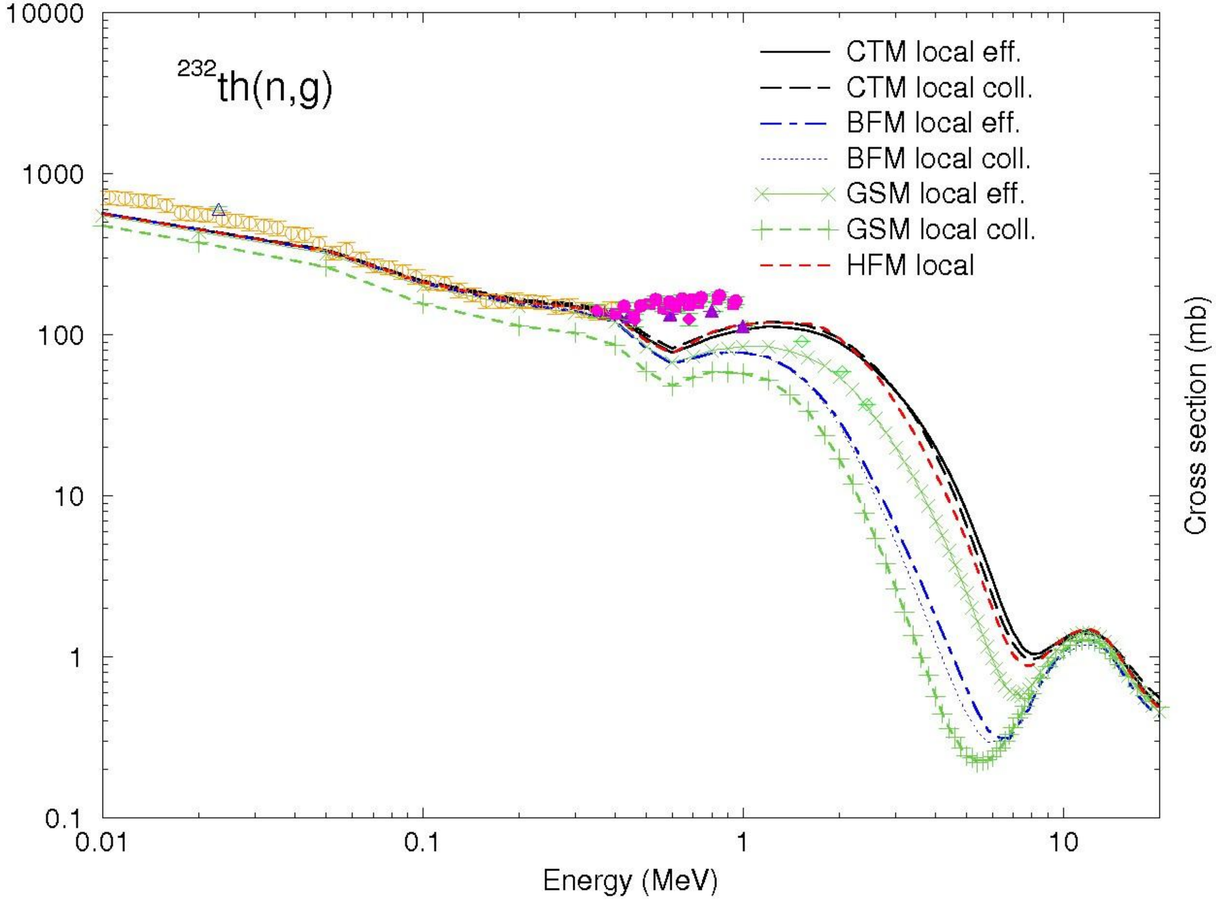
$$\sigma_{n,f}\left(E_n\right) = \underbrace{\sigma_{CN}\left(E_n\right)}_{\text{Optical model calculation}} \cdot \underbrace{P_f\left(E_n\right)}_{\text{Measured}}$$

2. ^{233}Pa Capture Experiment Results



S. Boyer et al. Nucl.Phys. A775, 175 (2006)

3. x-section calculations

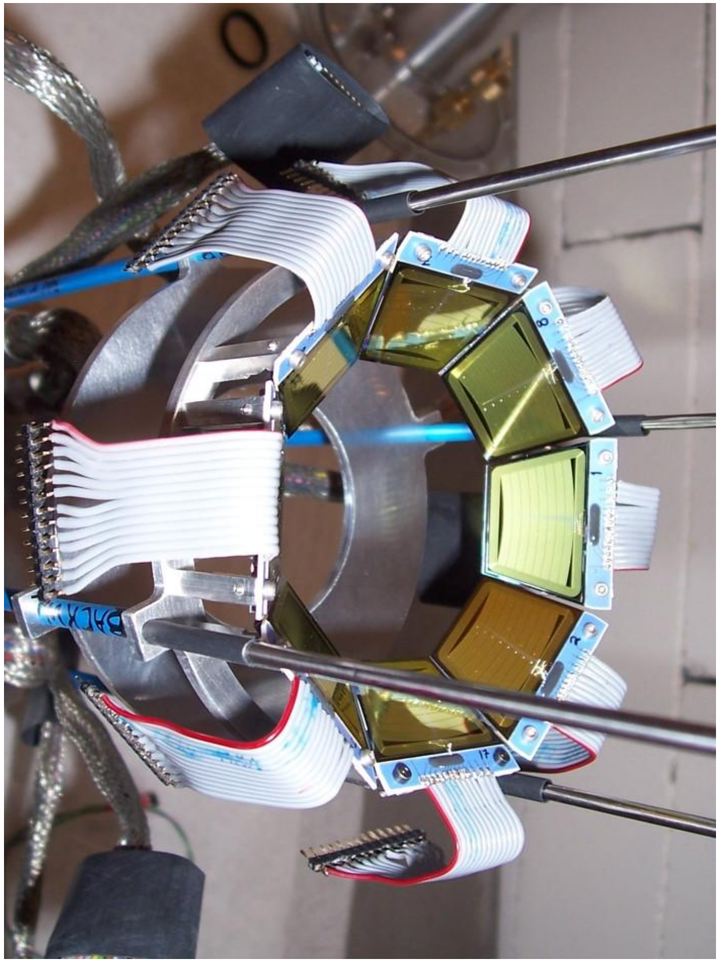


Part I

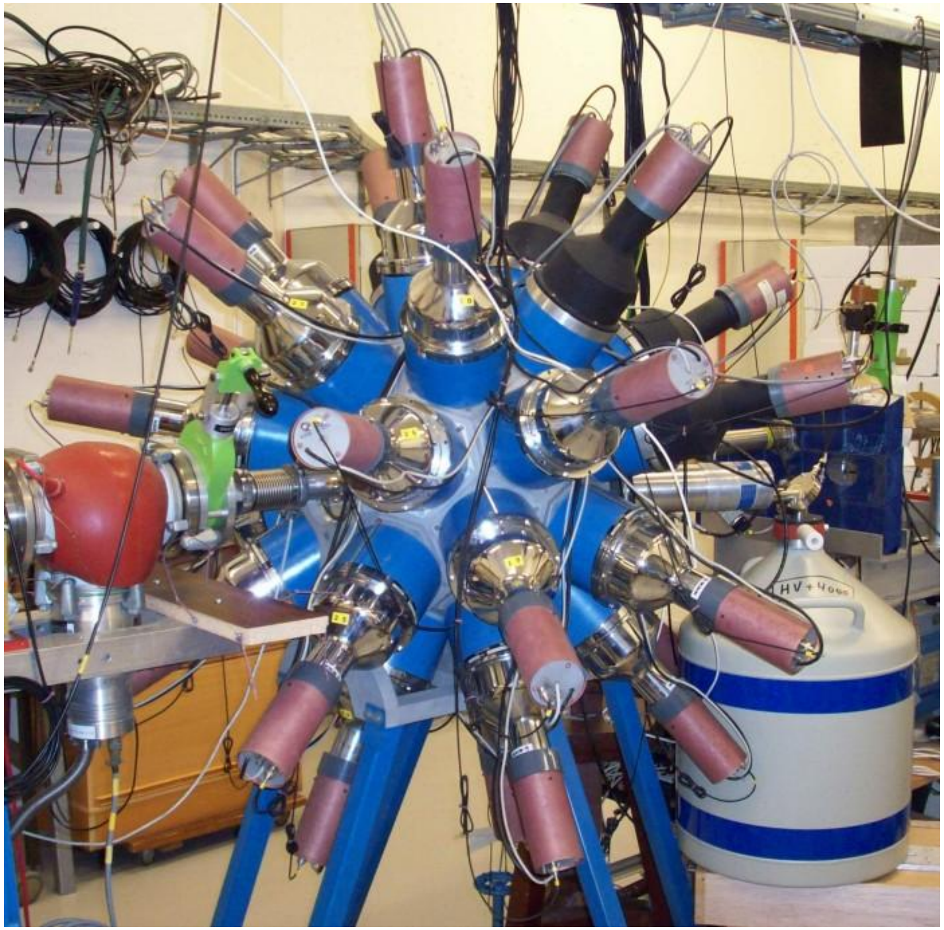
First Experimental Data

Oslo Cyclotron Experiments

Si Ring

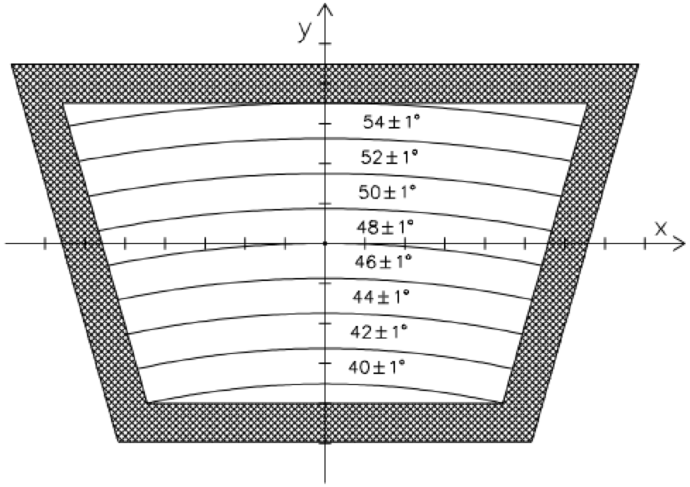


Cactus NaI array



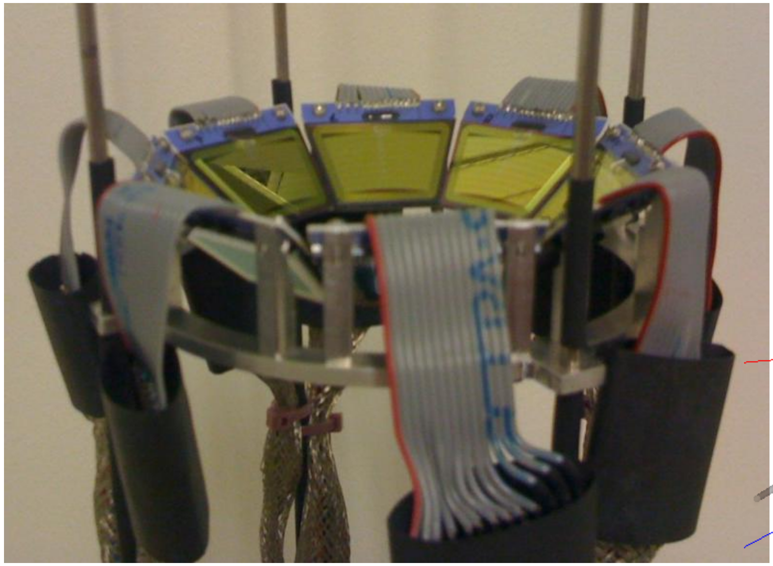
The Silicon Ring

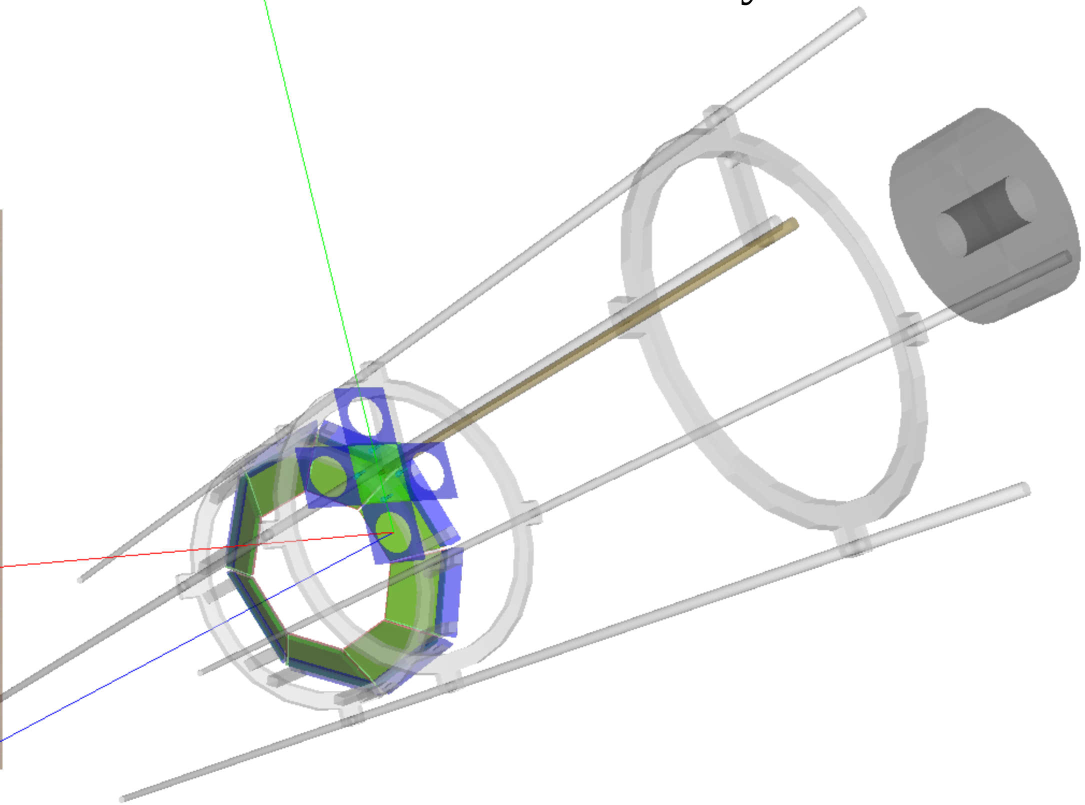
Angle between side rim and vertical=15.77 degrees



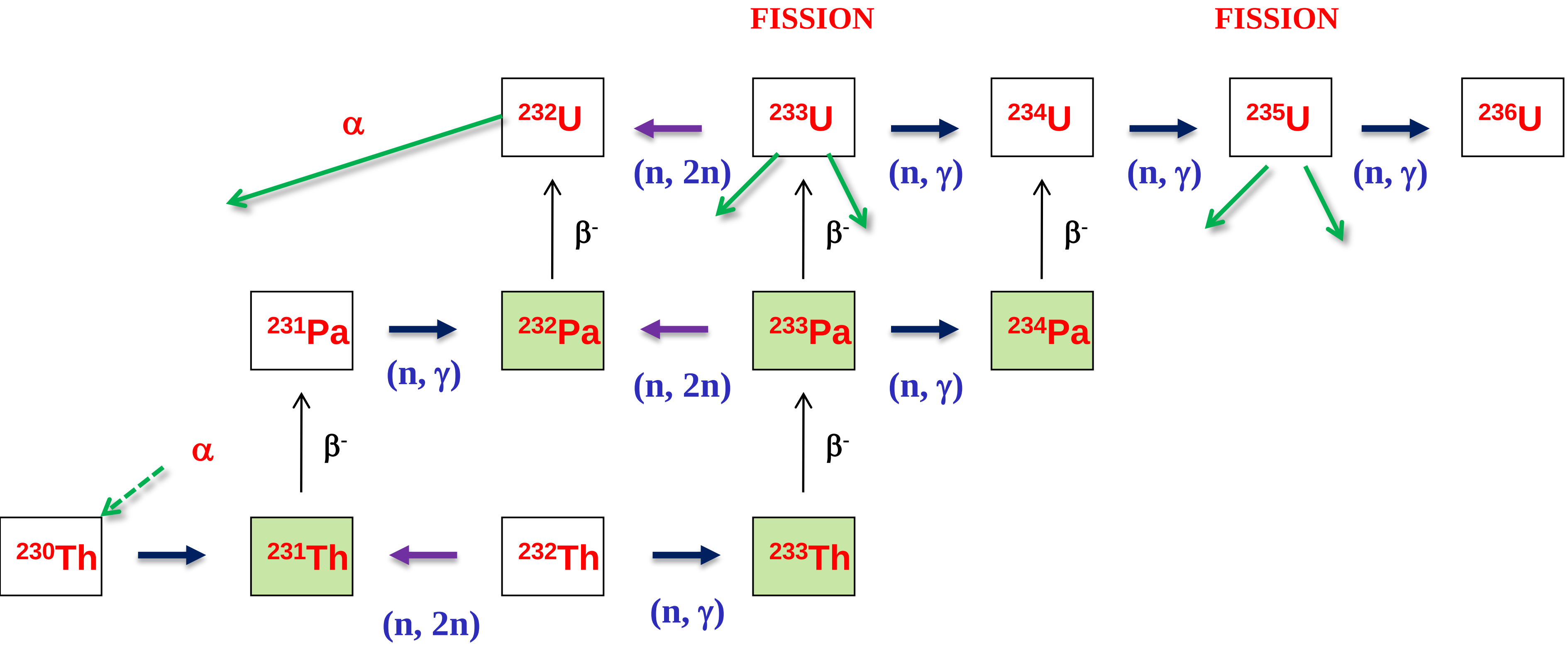
One tick on the axes corresponds to 2 mm in reality

- High efficiency/high angular resolution detection of the outgoing particles (<2°)
- E/ΔE collimators not necessary





2. The Thorium Cycle



Experiment ^{232}Th: 01/12/09 – 13/12/09

^{232}Th(d,x) @ 12 MeV

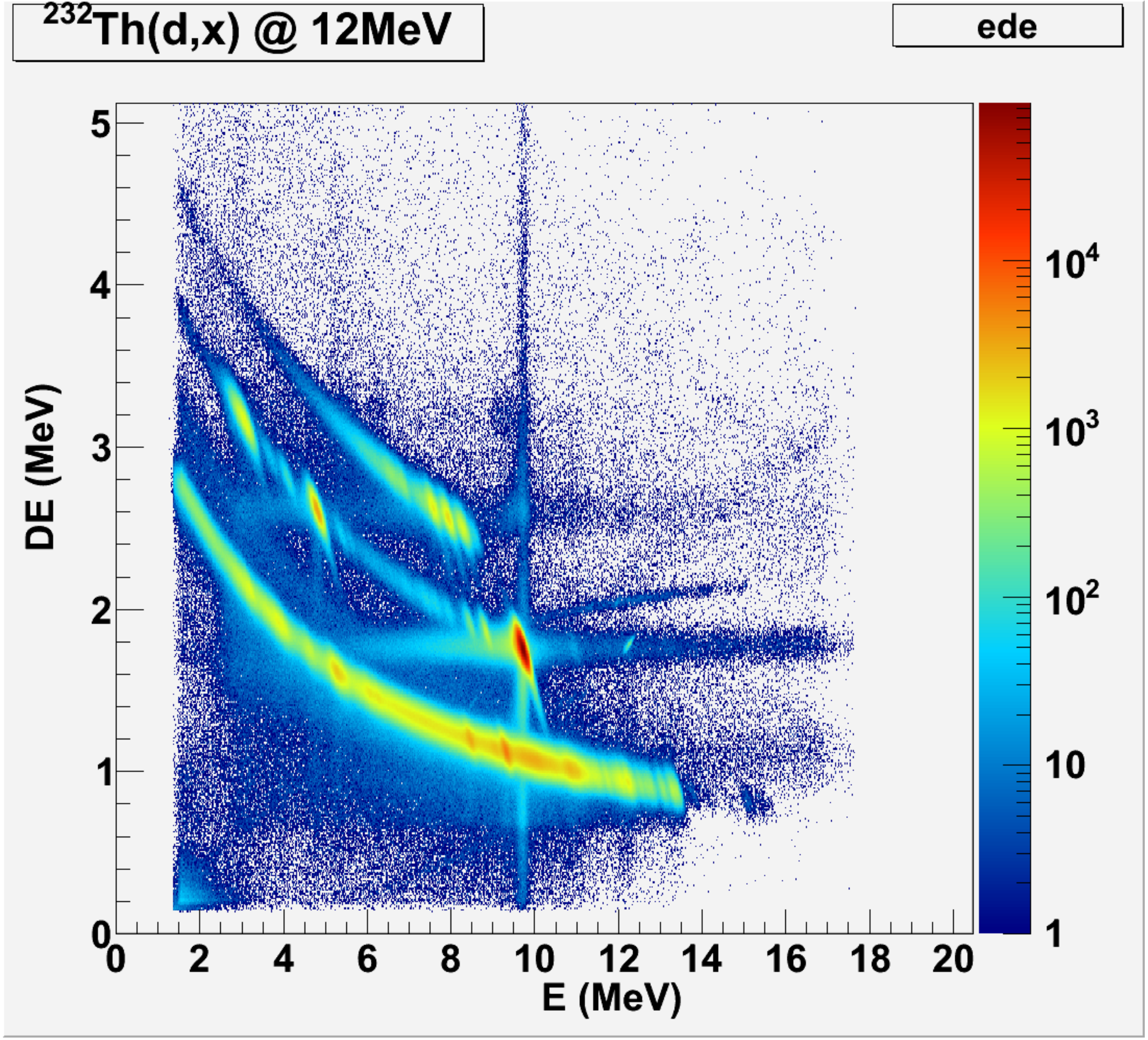
351 M events

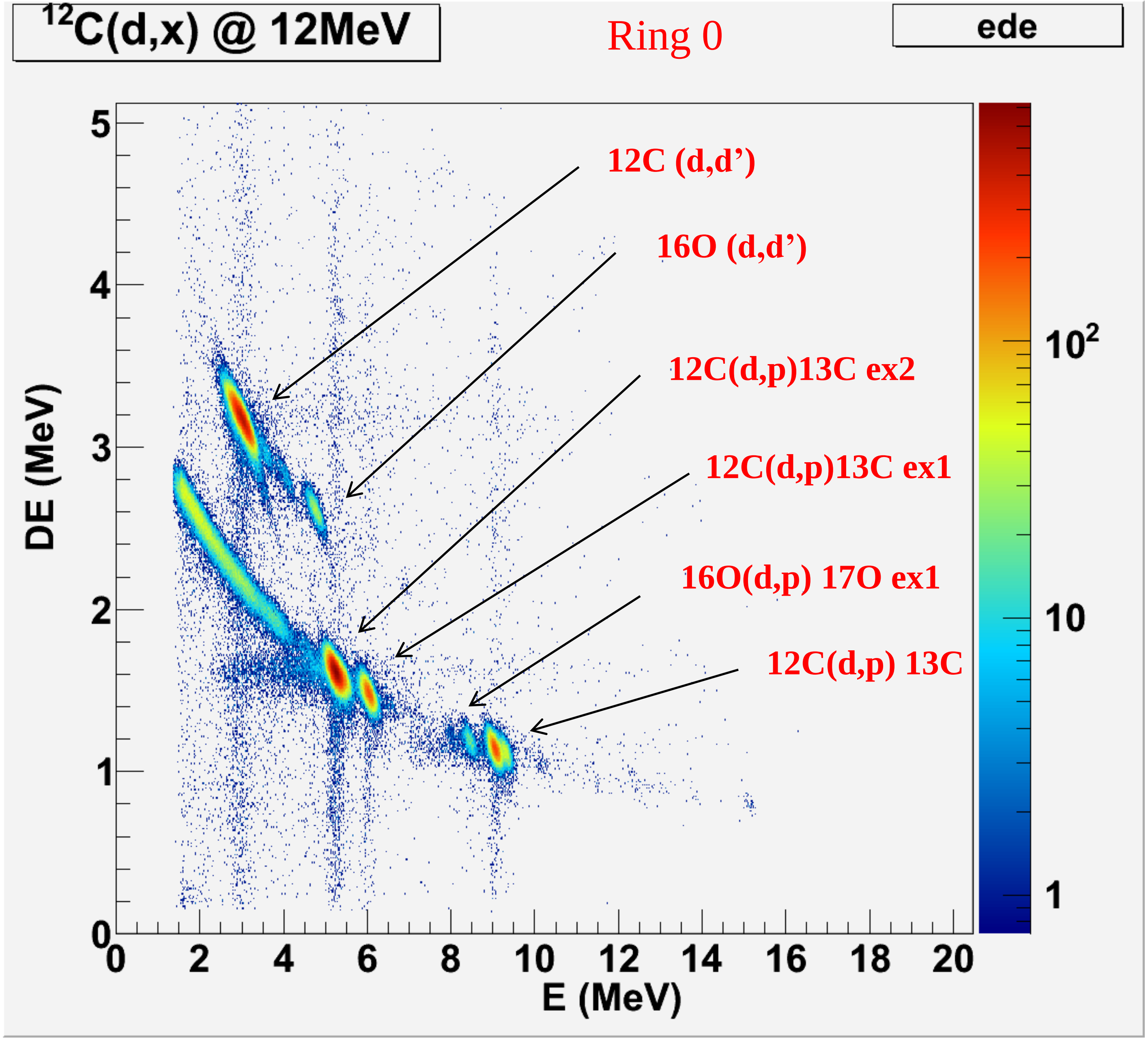
Reaction	Compound Nucleus	Ex-Eg counts
d,p	233Th	23 M
d,d’	232Th	0.24 M
d,t	231Th	1.2 M

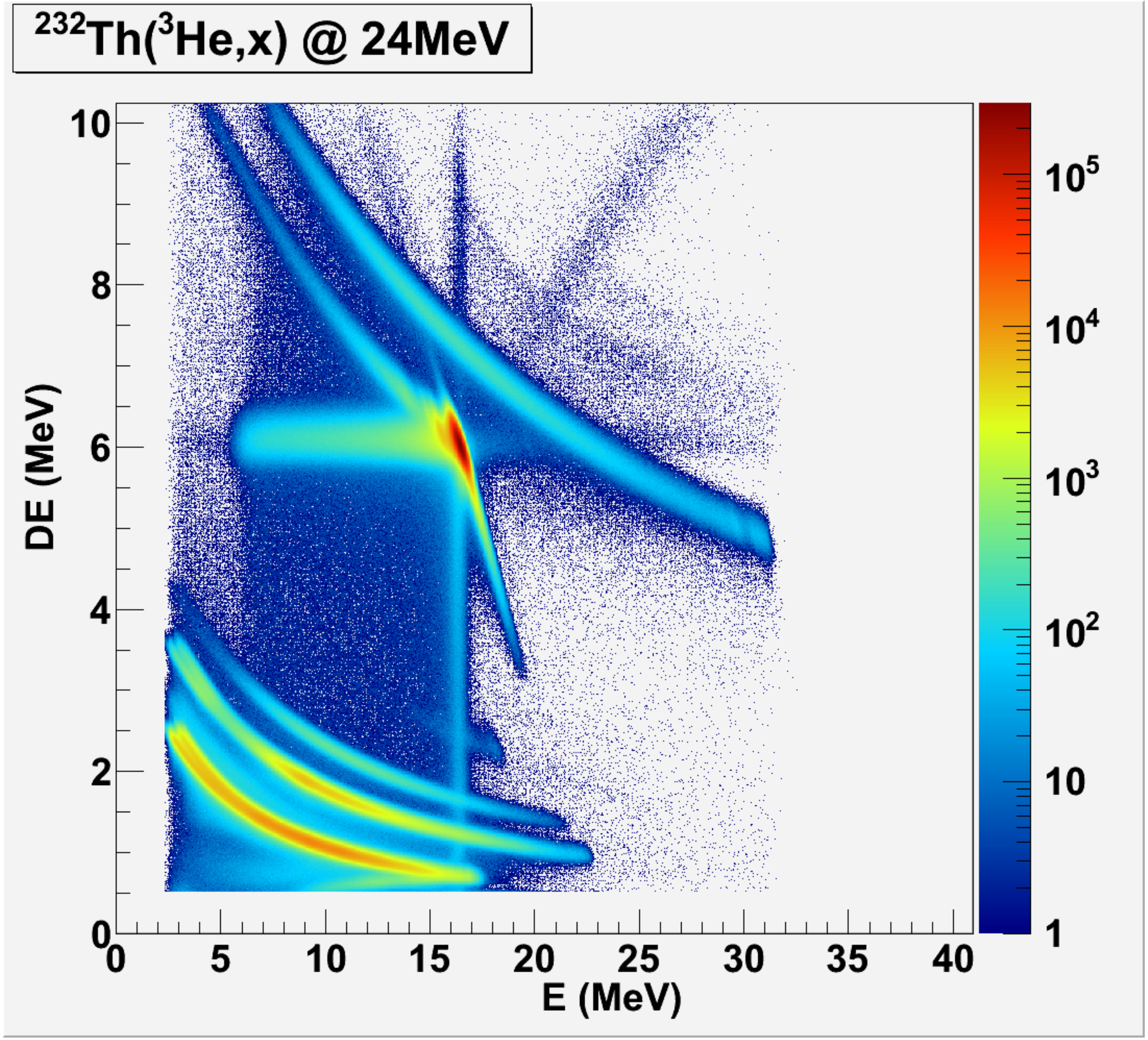
^{232}Th(^{3}He,x) @ 24 MeV

135 M events

Reaction	Compound Nucleus	Ex-Eg counts
3He,p	234Pa	13 M
3He,d	233Pa	6.0 M
3He,t	232Pa	0.57 M
3He,a	231Th	0.79 M


^{232}Th(d,x) @ 12MeV
ede
DE (MeV)
E (MeV)
0
1
2
3
4
5
0
2
4
6
8
10
12
14
16
18
20
1
10
10^2
10^3
10^4

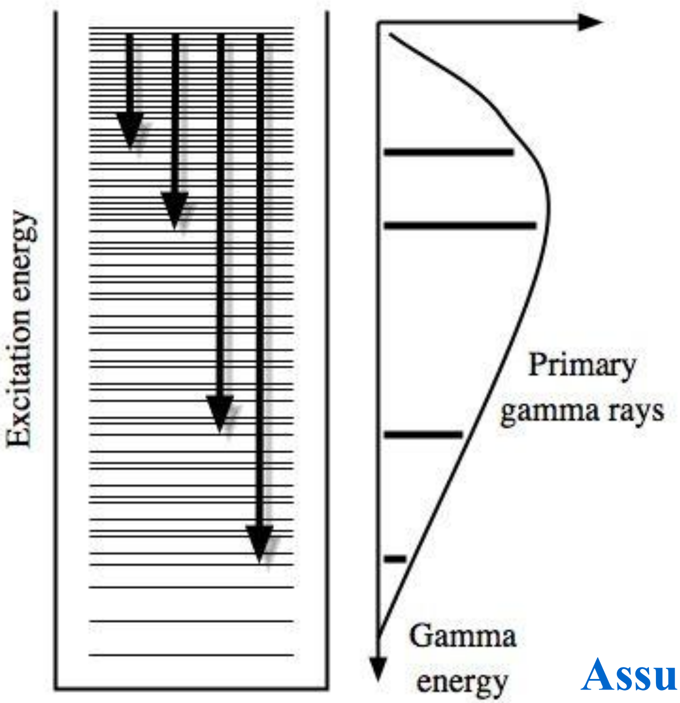

^{12}C(d,x) @ 12MeV
Ring 0
ede
12C (d,d')
16O (d,d')
12C(d,p)13C ex2
12C(d,p)13C ex1
16O(d,p) 17O ex1
12C(d,p) 13C
DE (MeV)
E (MeV)
0
1
2
3
4
5
0
2
4
6
8
10
12
14
16
18
20
1
10
10^2


^{232}Th(^{3}He,x) @ 24MeV
DE (MeV)
0
2
4
6
8
10
E (MeV)
0
5
10
15
20
25
30
35
40
1
10
10^{2}
10^{3}
10^{4}
10^{5}

Part II

Extracting the Level Density

The Brink Axel hypothesis



Level density

Transmission Coefficient

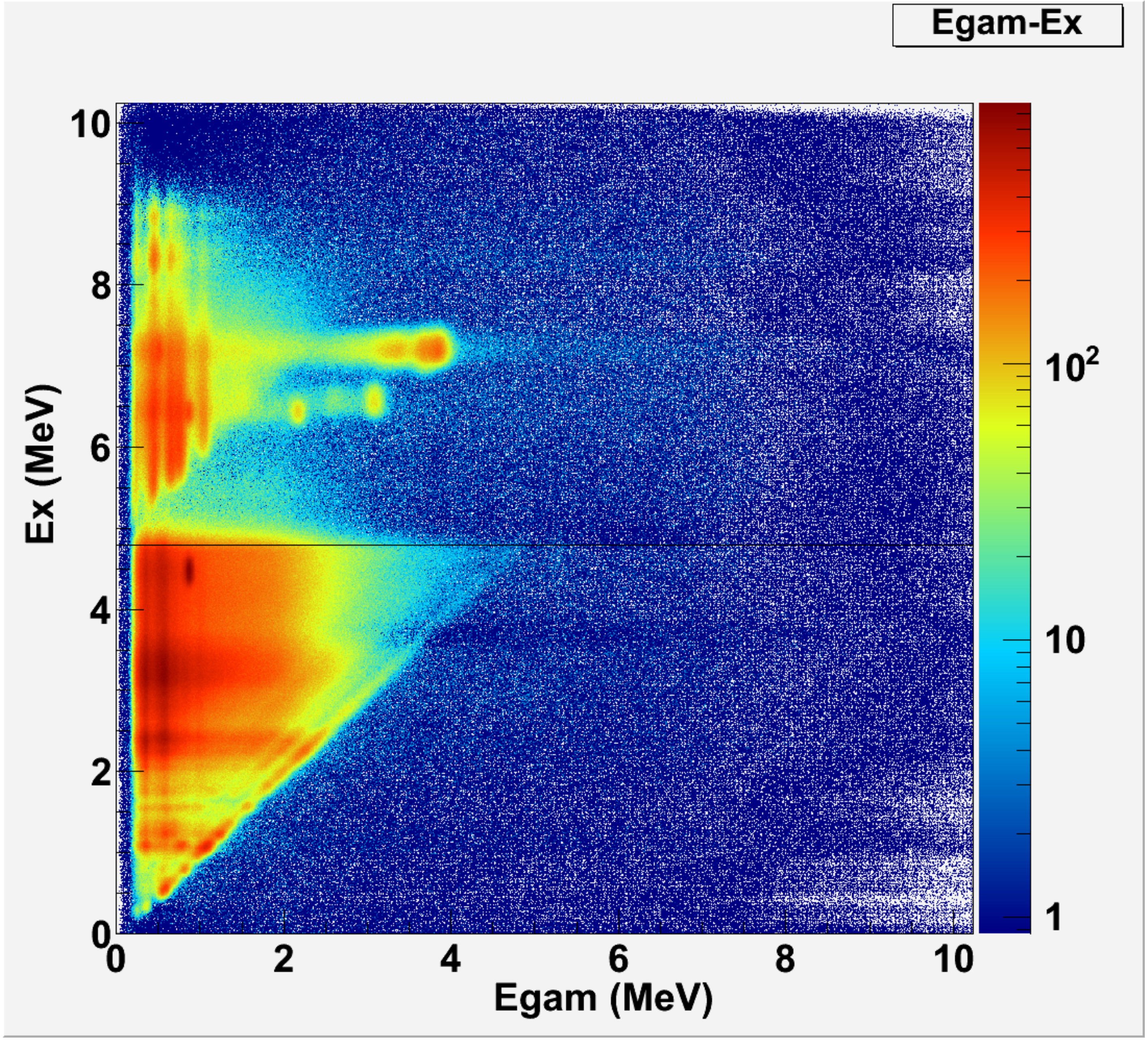
$$\boxed{P(E_i, E_\gamma) \propto \rho(E_f)\cdot T(E_\gamma)}$$

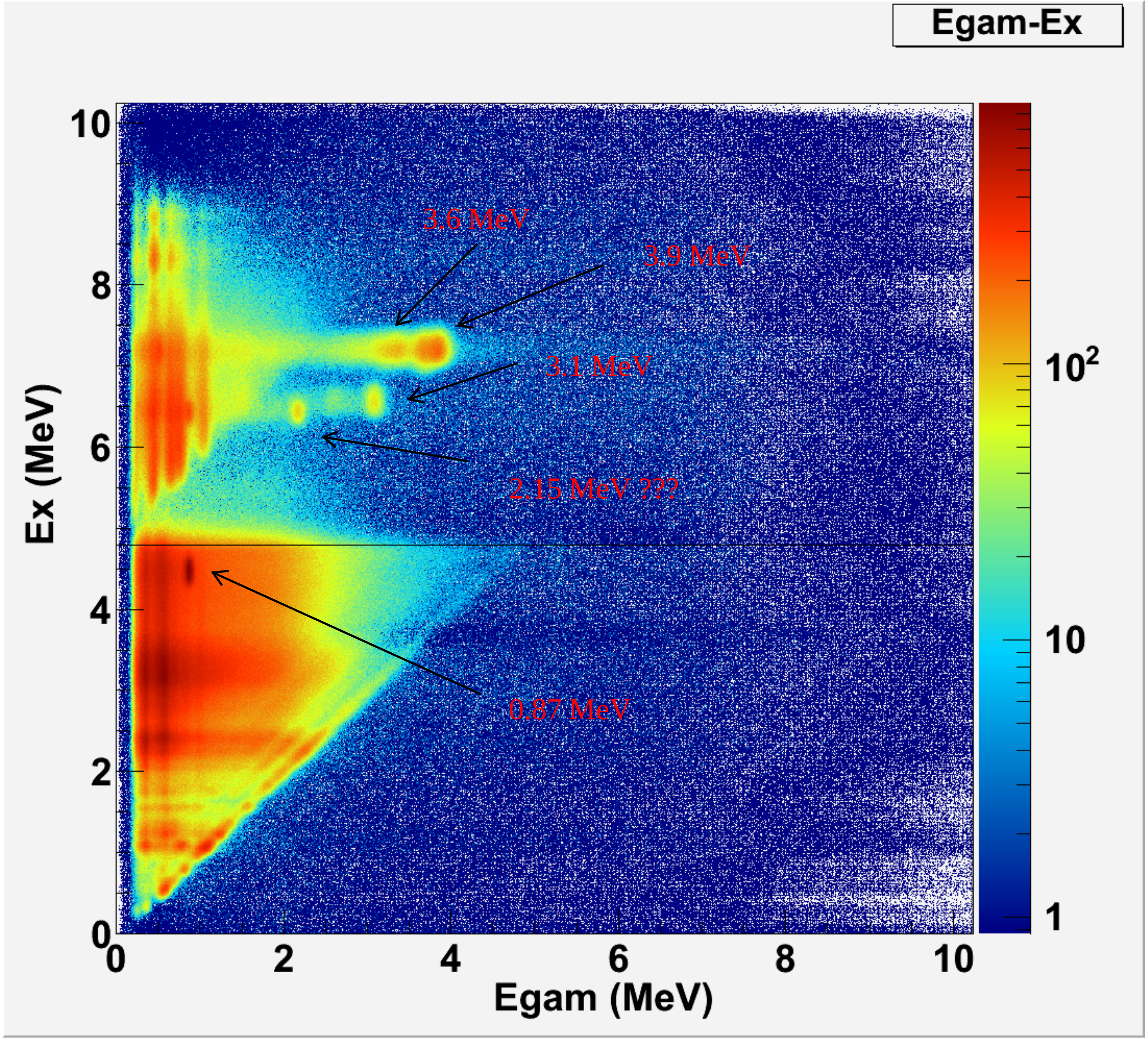
Gamma strength function

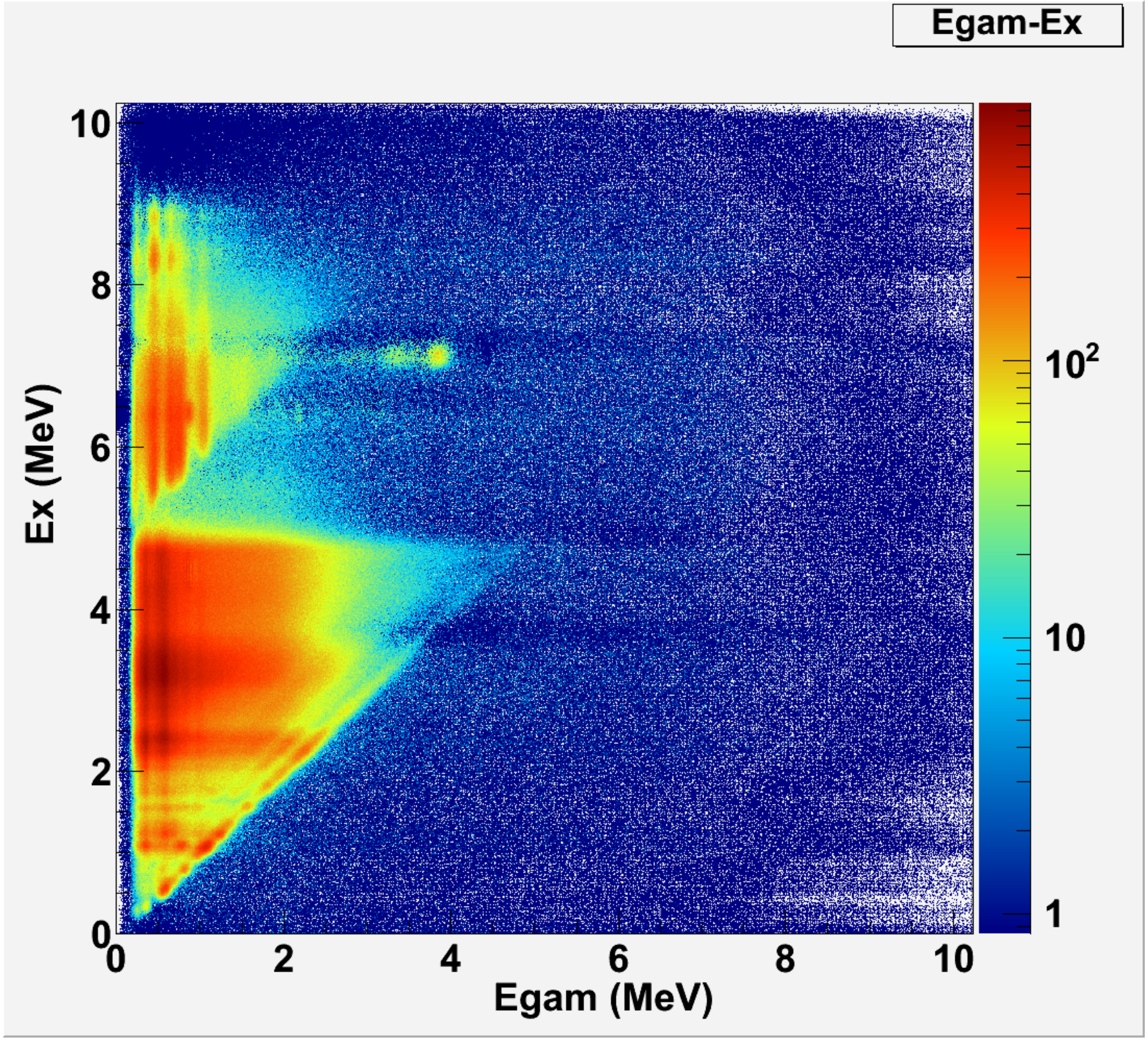
$$\mathcal{T}(E_\gamma) = 2\pi \sum_{XL} E_\gamma^{2L+1} f_{XL}(E_\gamma)$$

Assuming dominance of dipole radiation (*E1 and M1)*

$$f(E_\gamma) \simeq \frac{1}{2\pi}\frac{\mathcal{T}(E_\gamma)}{E_\gamma^3}$$

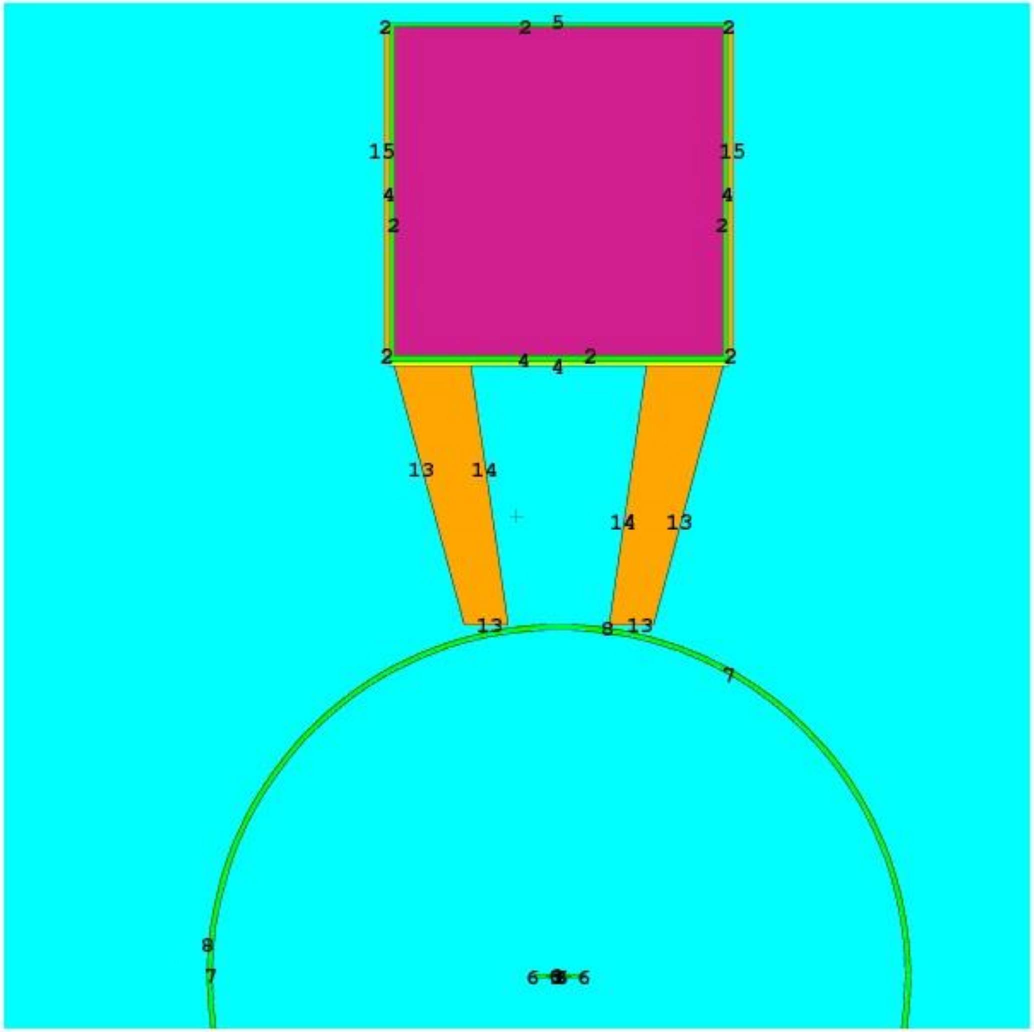

Egam-Ex
Ex (MeV)
10
8
6
4
2
0
0
2
4
6
8
10
Egam (MeV)
10^2
10
1

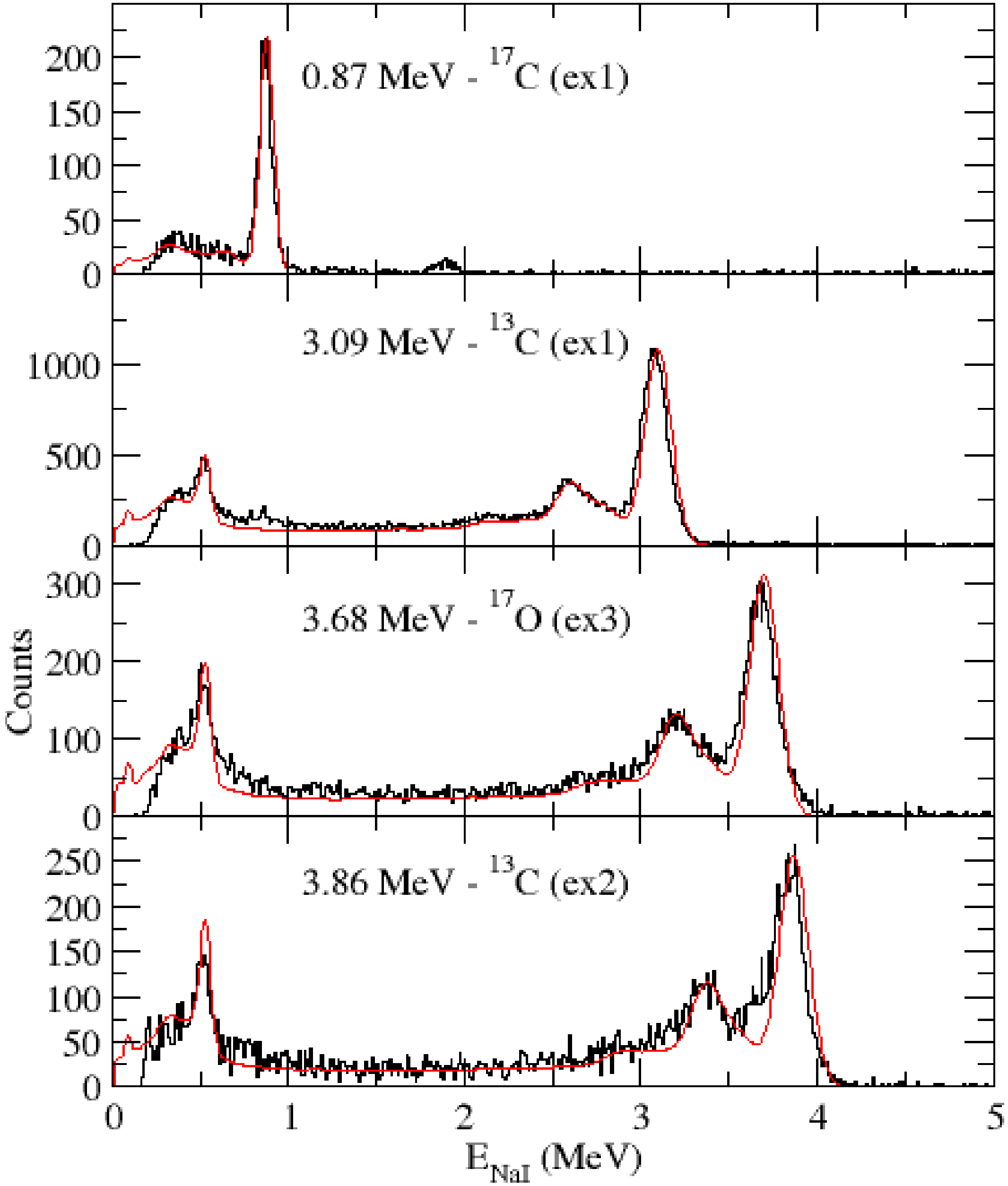

Egam-Ex
10
8
6
4
2
0
Ex (MeV)
0
2
4
6
8
10
Egam (MeV)
10^2
10
1
3.6 MeV
3.9 MeV
3.1 MeV
2.15 MeV ???
0.87 MeV

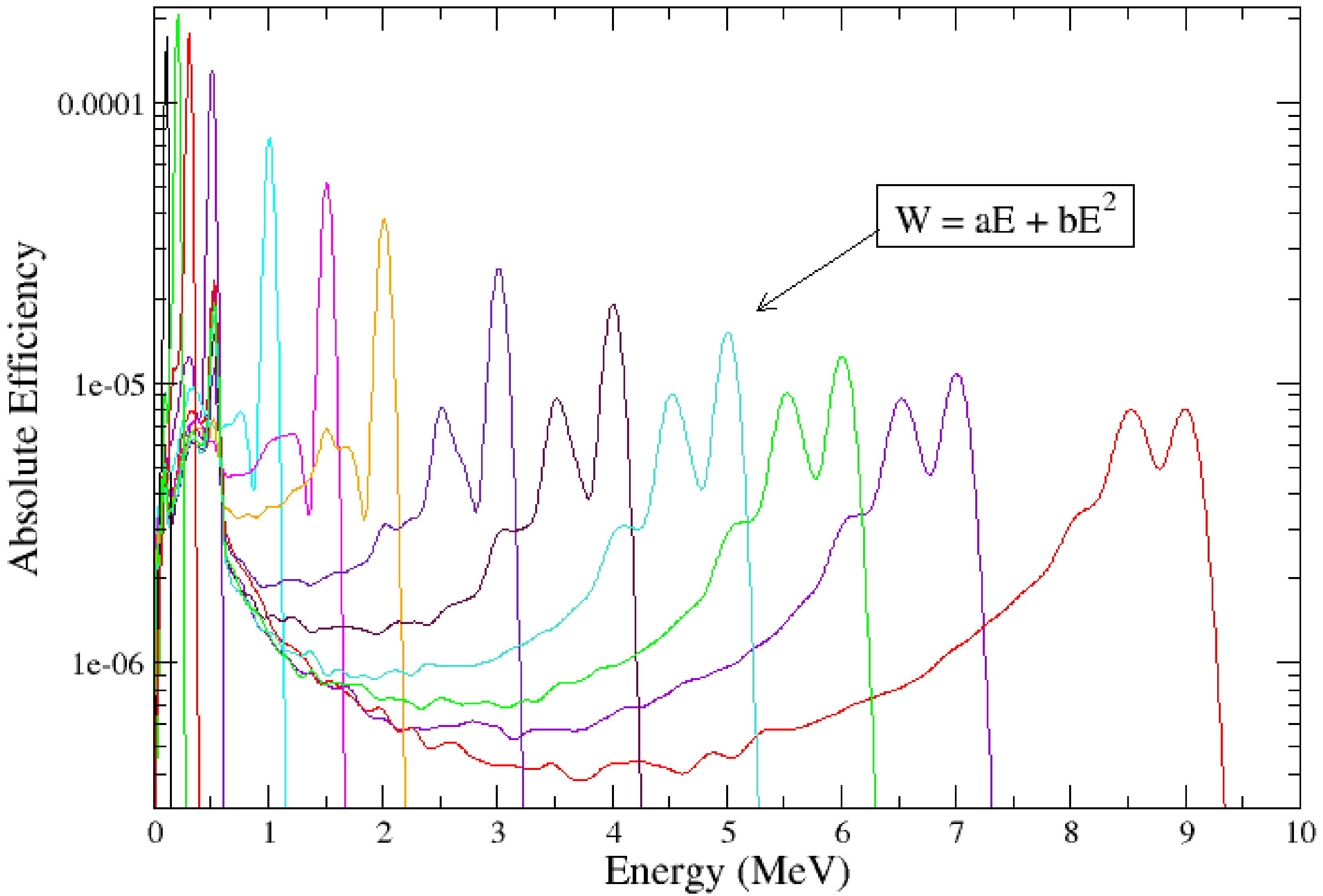

Egam-Ex
Ex (MeV)
10
8
6
4
2
0
0
2
4
6
8
10
Egam (MeV)
10^2
10
1

MCNP simulations of Cactus detector response

```
 06/18/10 17:22:13
gamma-ray efficiency: NaI -
 DETECTOR + THORIUM + COPPER +
 Al CAN
probid =  06/18/10 17:20:58
basis:    YZ
( 0.000000, 1.000000, 0.000000)
( 0.000000, 0.000000, 1.000000)
origin:
(      0.00,     -1.62,     17.80)
extent = (     19.83,     19.83)
```

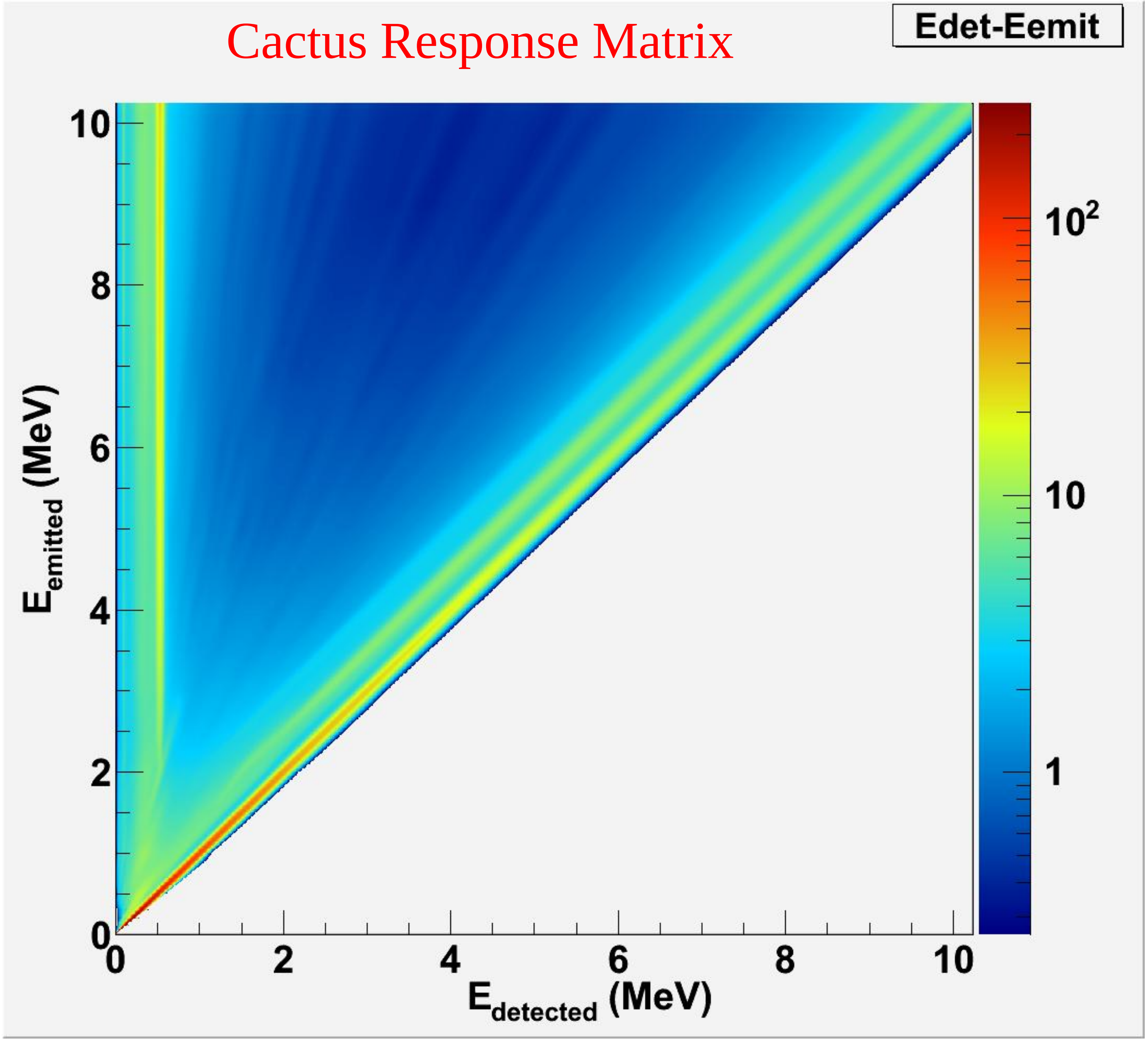


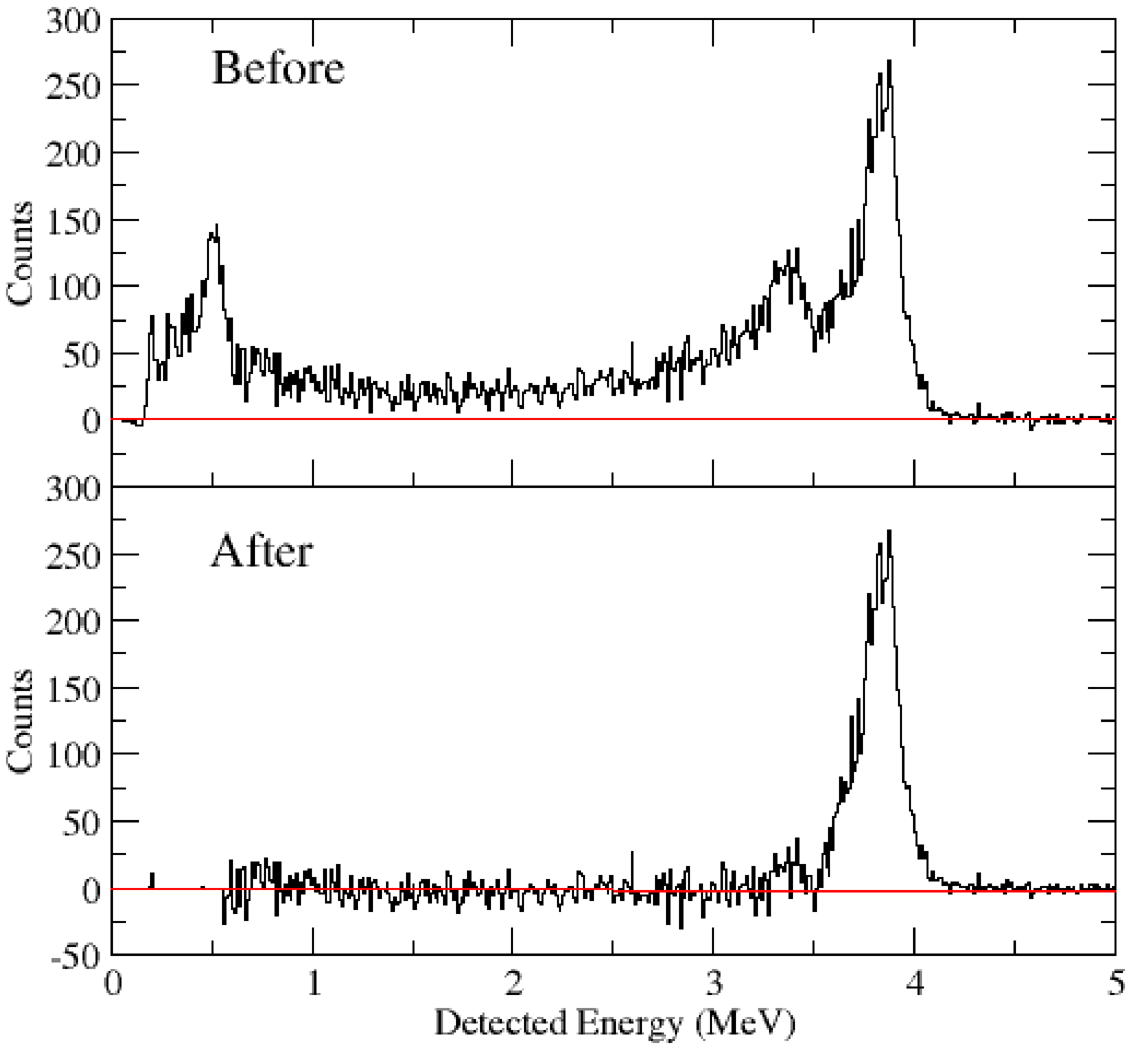

0.87 MeV - ^{17}C (ex1)
3.09 MeV - ^{13}C (ex1)
3.68 MeV - ^{17}O (ex3)
3.86 MeV - ^{13}C (ex2)
Counts
0
50
100
150
200
0
500
1000
0
100
200
300
0
50
100
150
200
250
0
1
2
3
4
5
E_{NaI} (MeV)



0.0001
1e-05
1e-06
Absolute Efficiency
0
1
2
3
4
5
6
7
8
9
10
Energy (MeV)
$W = aE + bE^2$

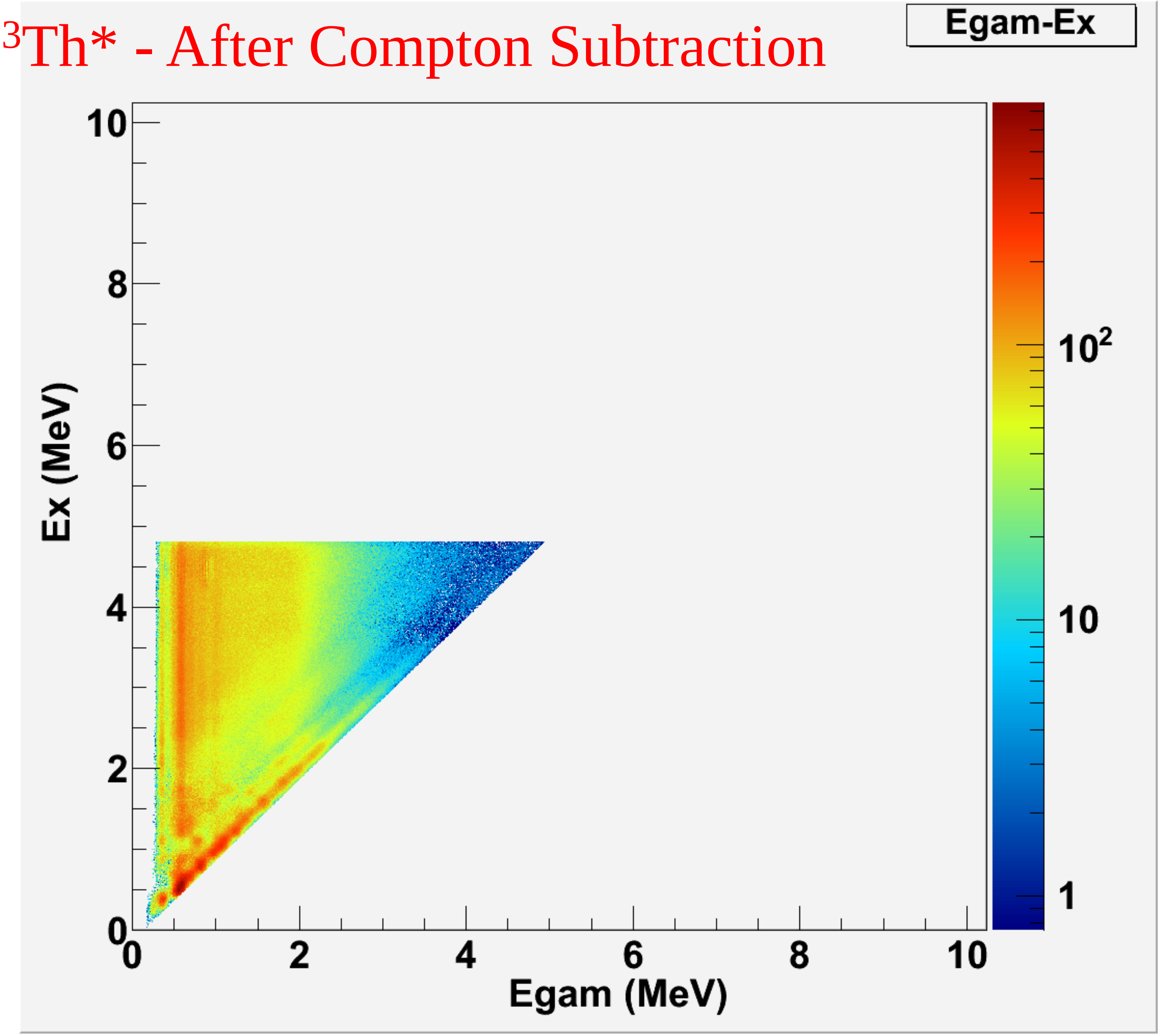
Cactus Response Matrix



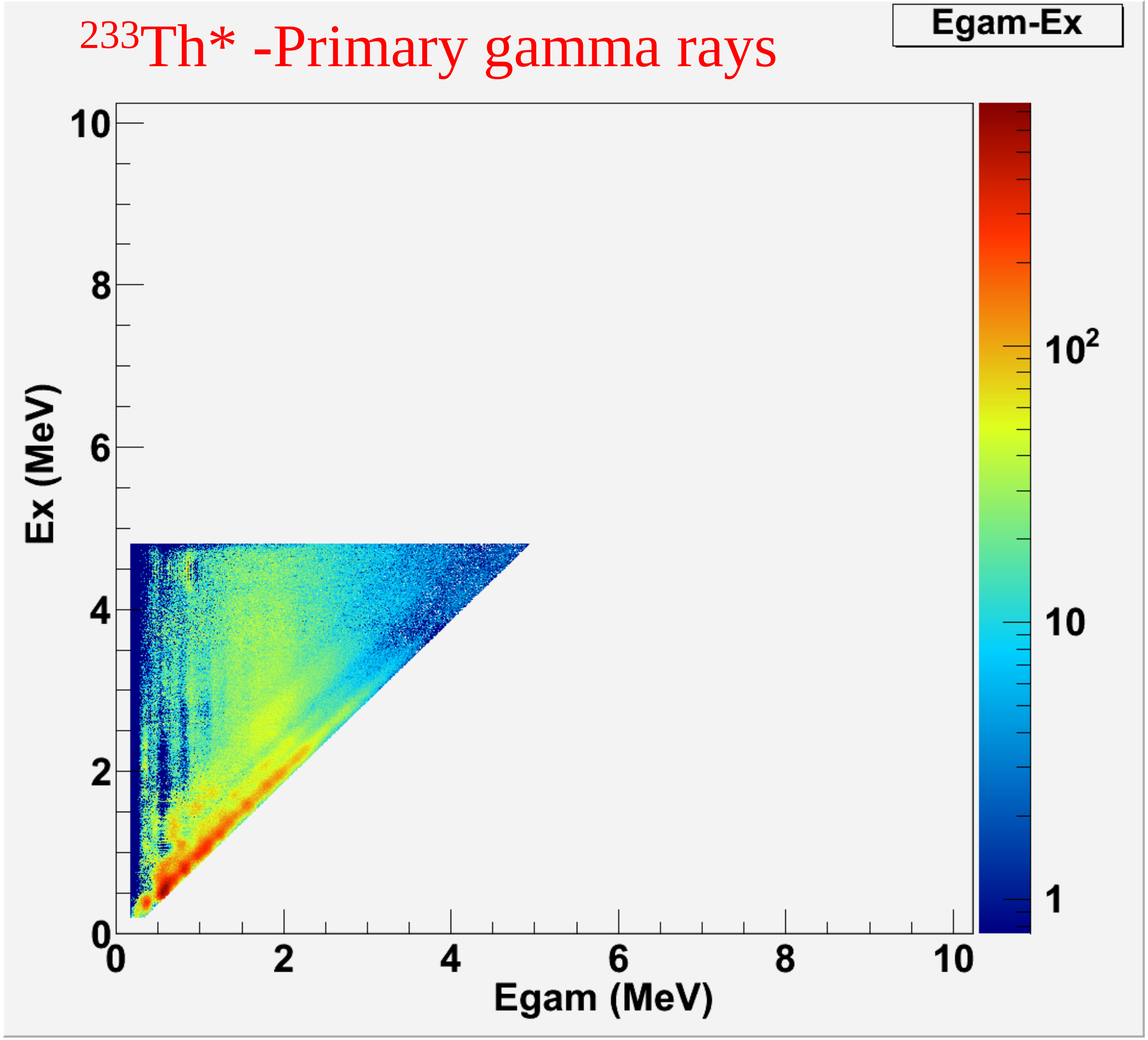


Matrix *response;
Spec *after=before->SubtractComptons(response);

^{233}Th* - After Compton Subtraction



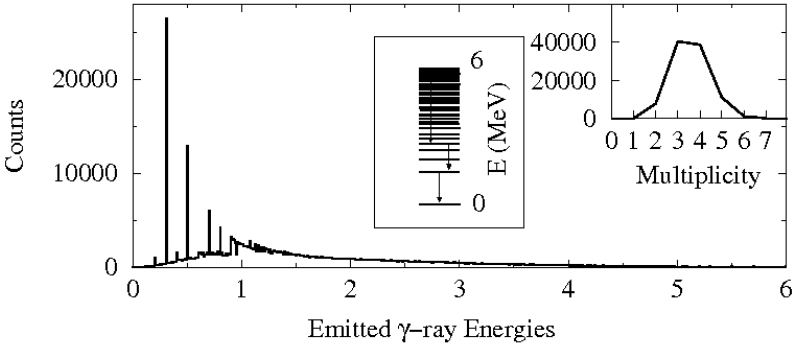
^{233}Th* -Primary gamma rays

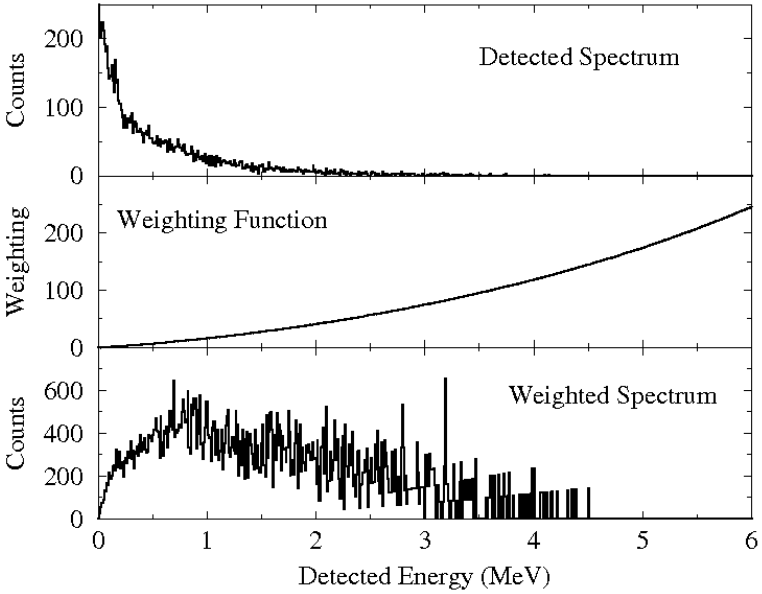


Part III

The surrogate method

Decay probability measurement





Efficiency of detecting a cascade, Ec of m gammas is:

$$\varepsilon_c = 1 - \prod_{j=1..m} (1-\varepsilon_j)$$

If ε is small, then:

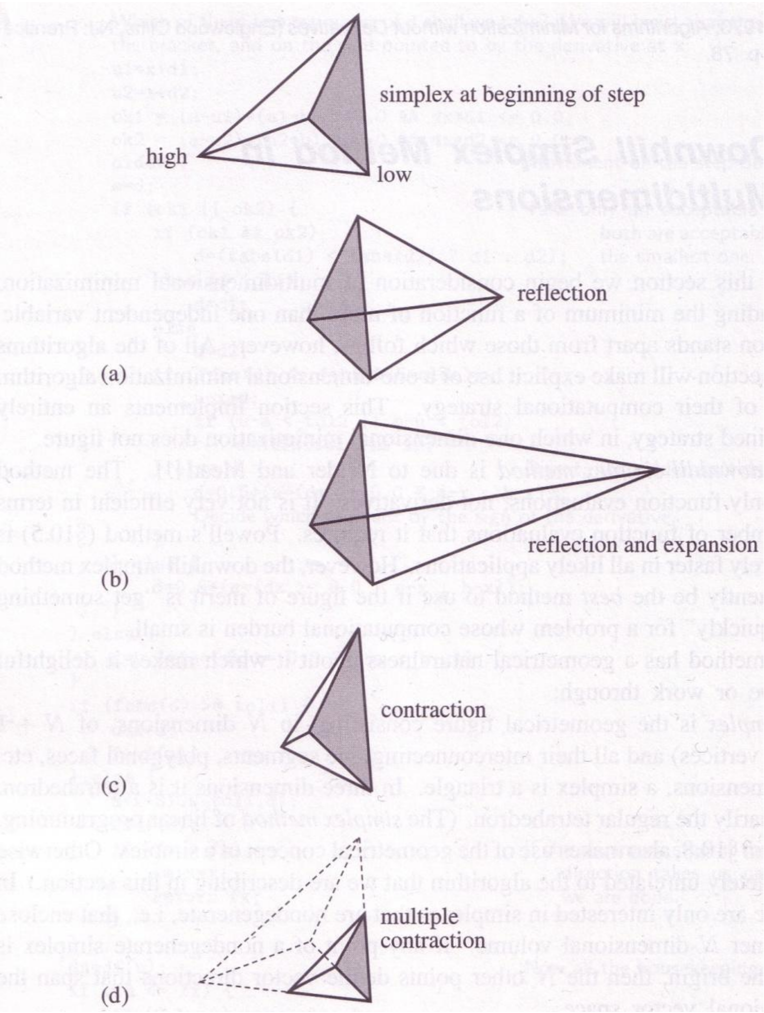
$$\varepsilon_c \approx \sum_{j=1..m} \varepsilon_j$$

Suppose detector has this property: $\boxed{\varepsilon = k\,E_\gamma}$

Then effeciency of detecting a cascade becomes proportional to cascade energy and independent of cascade path!!

$$\sum_d W(E_\gamma) R(E_d, E_\gamma) = kE_\gamma$$

Minimisation with the Downhill simplex method

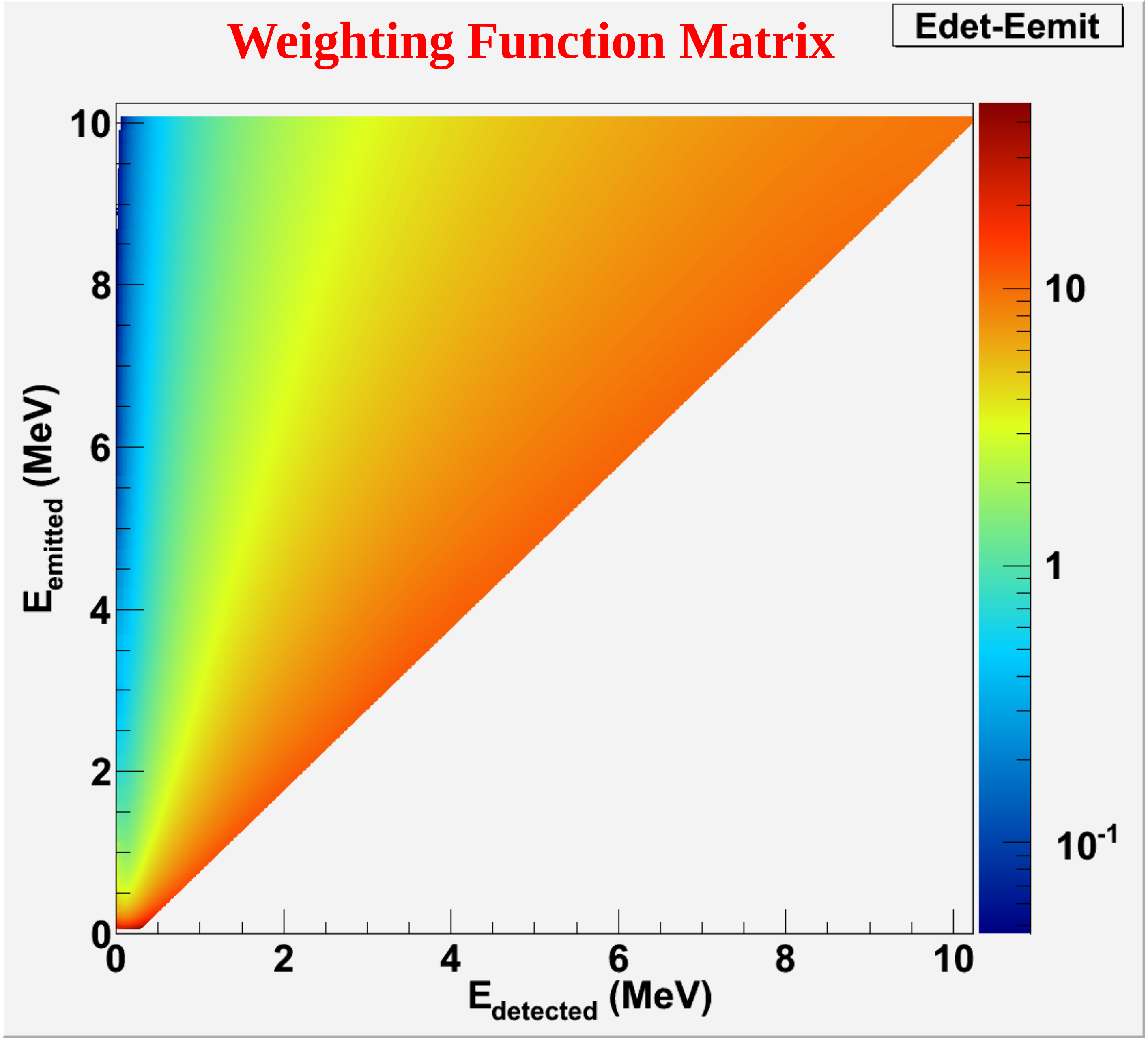


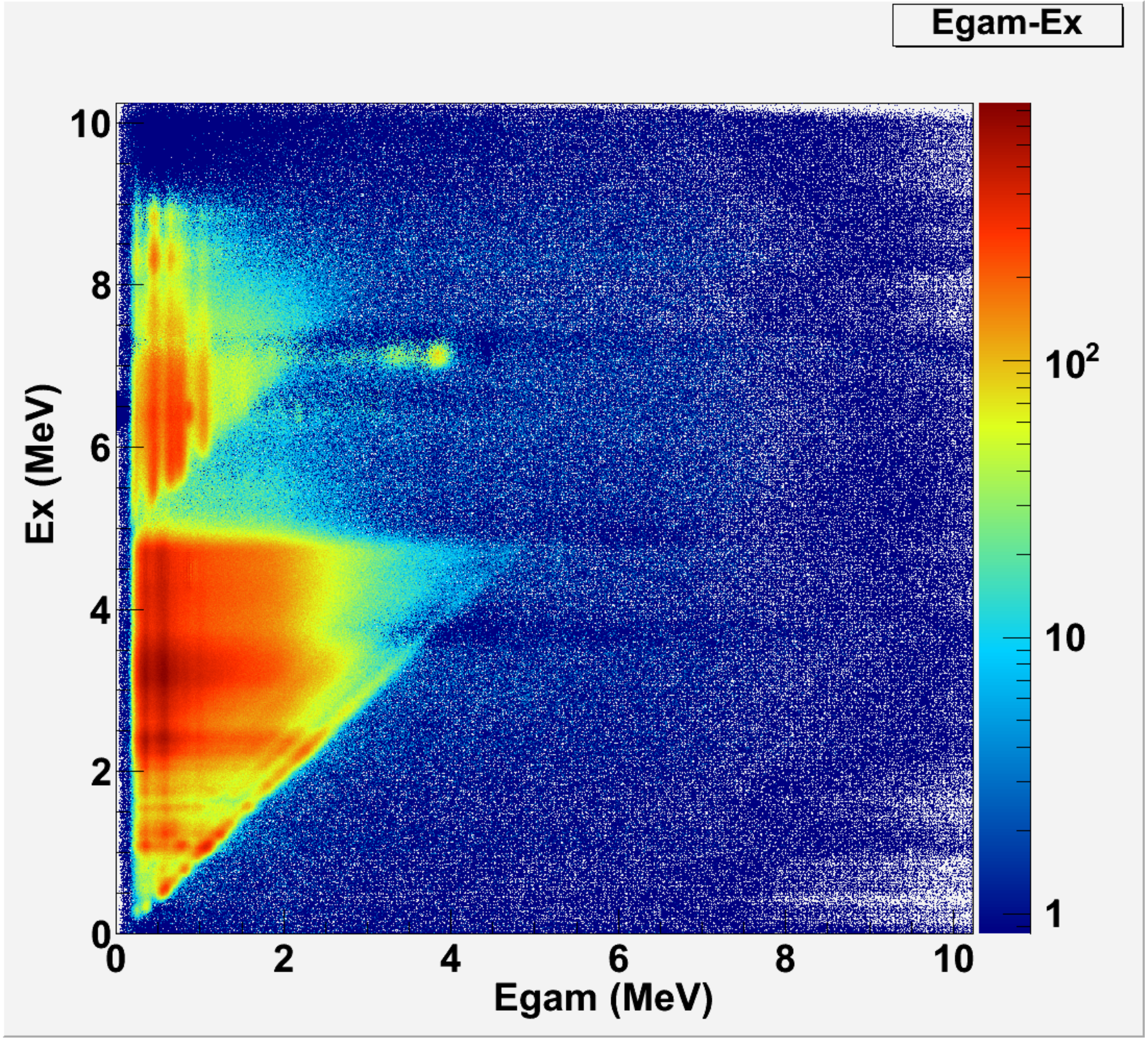
$$\sum_{d} W(E_\gamma) R(E_d, E_\gamma) - kE_\gamma = 0$$

« With four parameters, I could fit an elephant, with five I could make him wiggle his trunk »

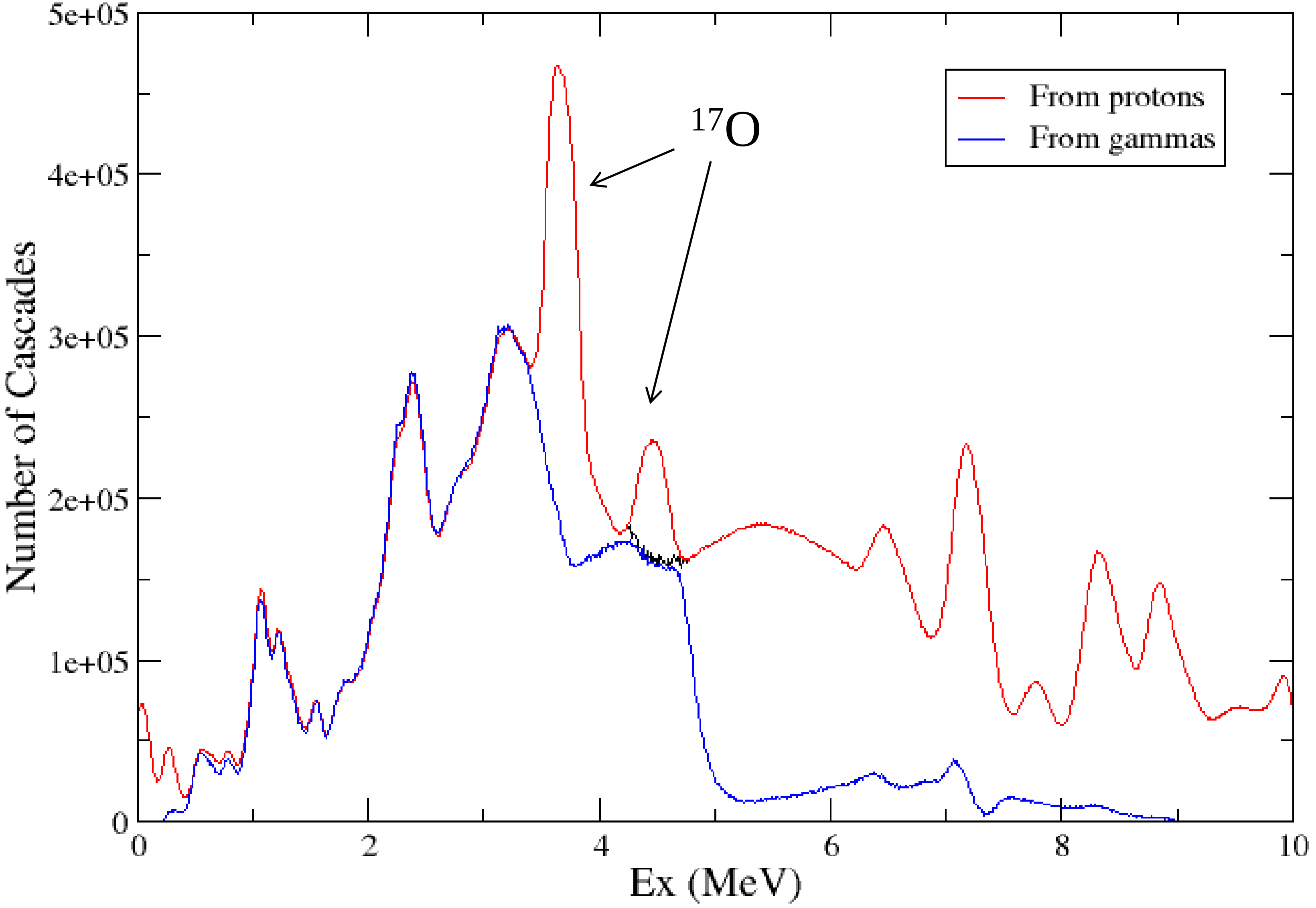
$$W(E) = a + bE + cE^2 + d\,E^3 + eE^4 + f\,E^5$$

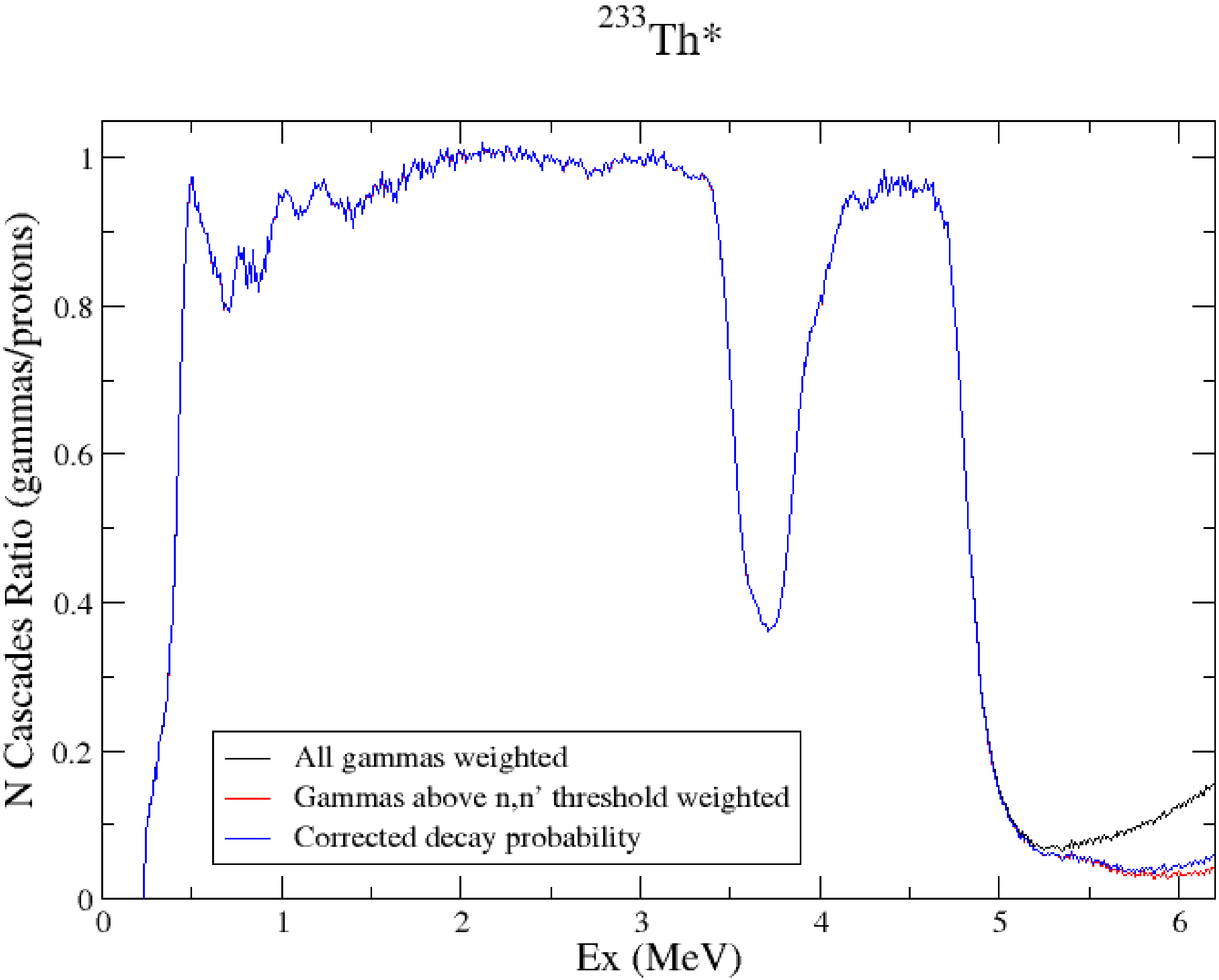
Weighting Function Matrix

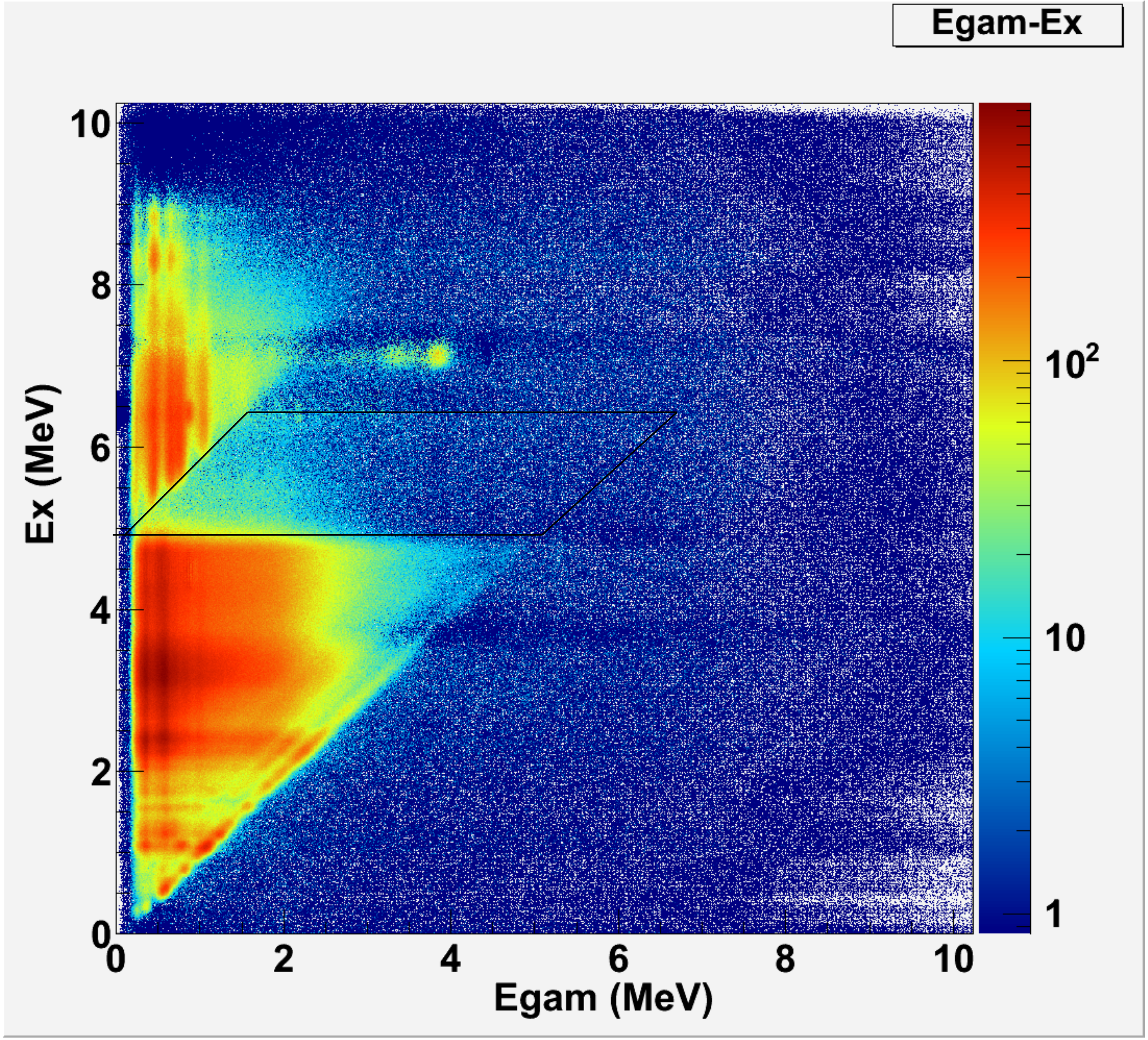



Egam-Ex
Ex (MeV)
0
2
4
6
8
10
Egam (MeV)
0
2
4
6
8
10
1
10
10^2

Cascade counting




^{233}Th*
N Cascades Ratio (gammas/protons)
0
0.2
0.4
0.6
0.8
1
Ex (MeV)
0
1
2
3
4
5
6
All gammas weighted
Gammas above n,n' threshold weighted
Corrected decay probability

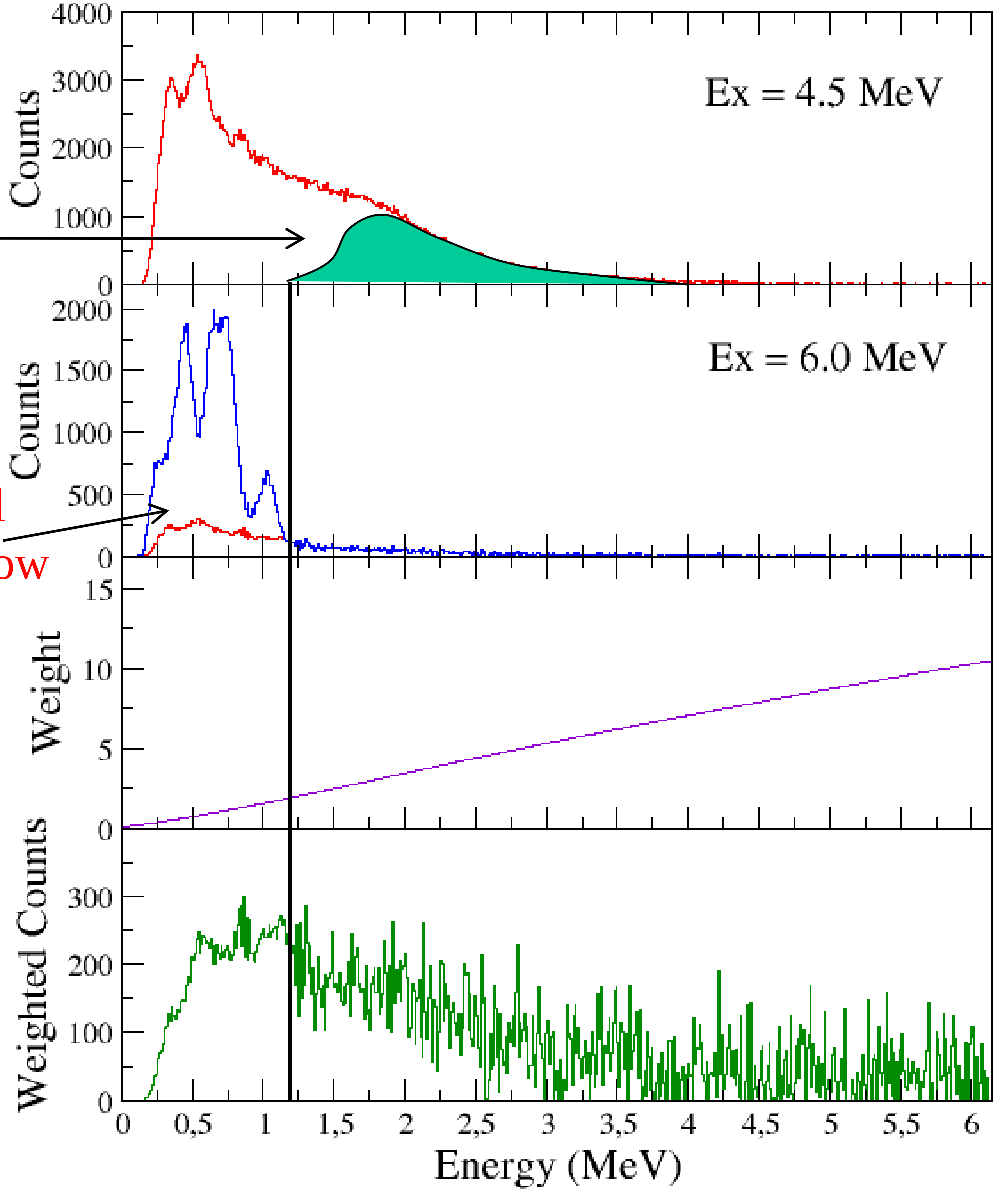

Egam-Ex
Ex (MeV)
0
2
4
6
8
10
Egam (MeV)
0
2
4
6
8
10
1
10
10^2

n,n' correction to measured decay probability

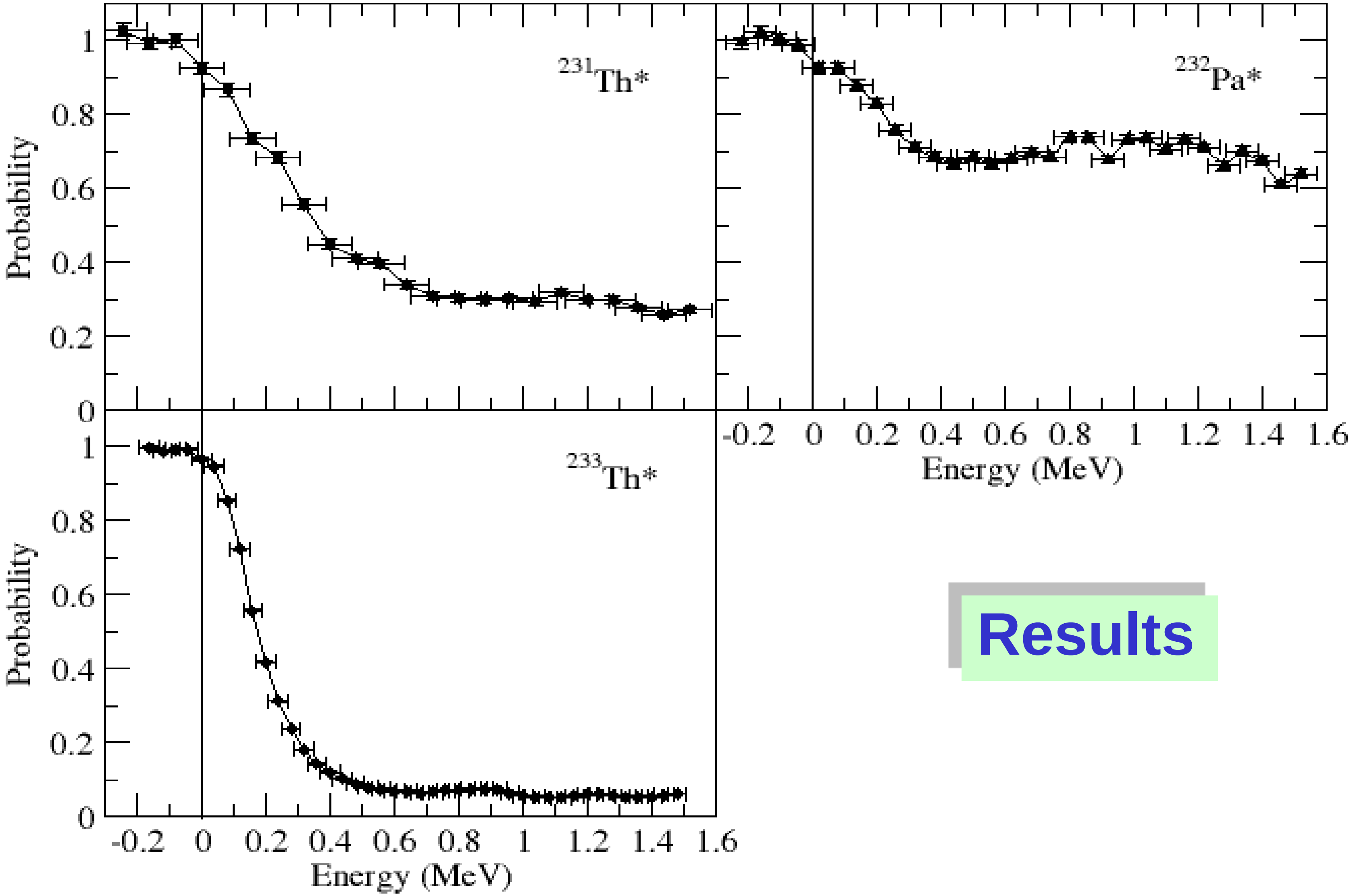
(New Technique)

Primary gamma rays

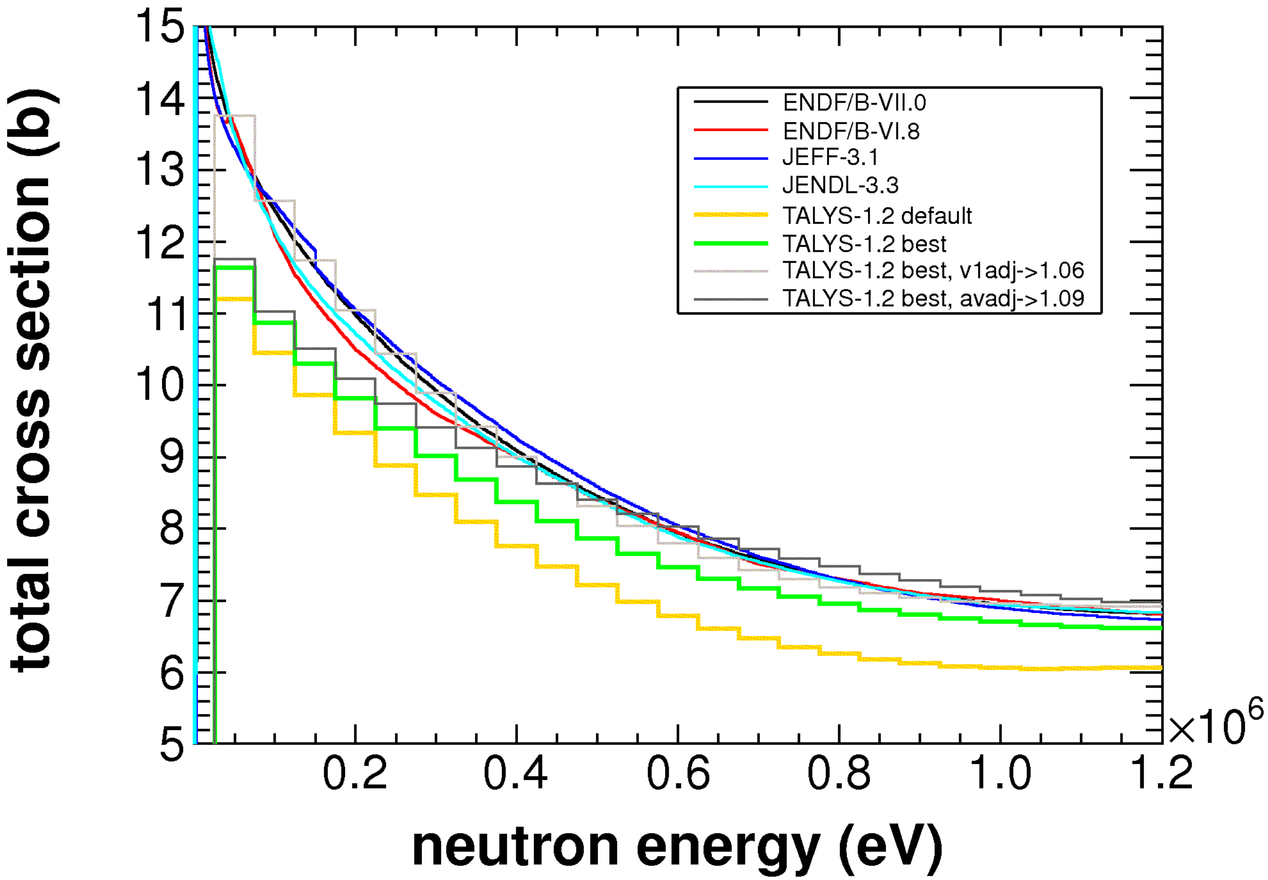
n,gamma spectral extrapolation below n,n'threshold



Results


^{231}Th*
^{232}Pa*
^{233}Th*
Probability
0
0.2
0.4
0.6
0.8
1
Energy (MeV)
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6

TALYS calculations



Compare results with TALYS calculations: **Since 232Th(n,g) has been measured directly at nTOF we can perform a direct test of the optical model and the validity of the surrogate method.**

Conclusions

Level density measurements possible in:

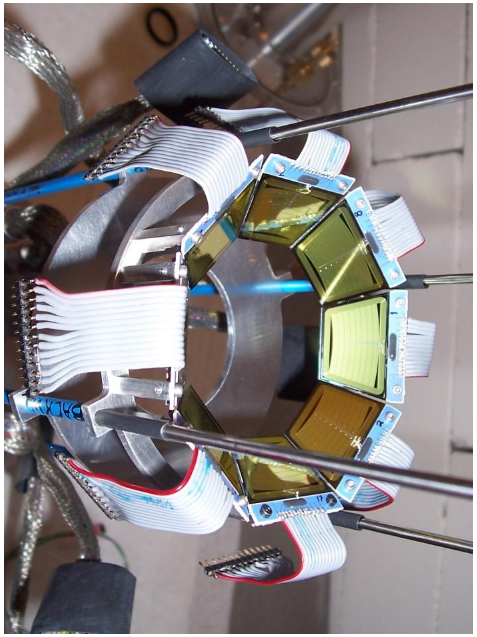
^{233}Th - d,p (0- 5 MeV)
^{232} Th - d,d’ (0- 3.5 MeV)
^{231}Th - d,t (0 – 3 MeV)

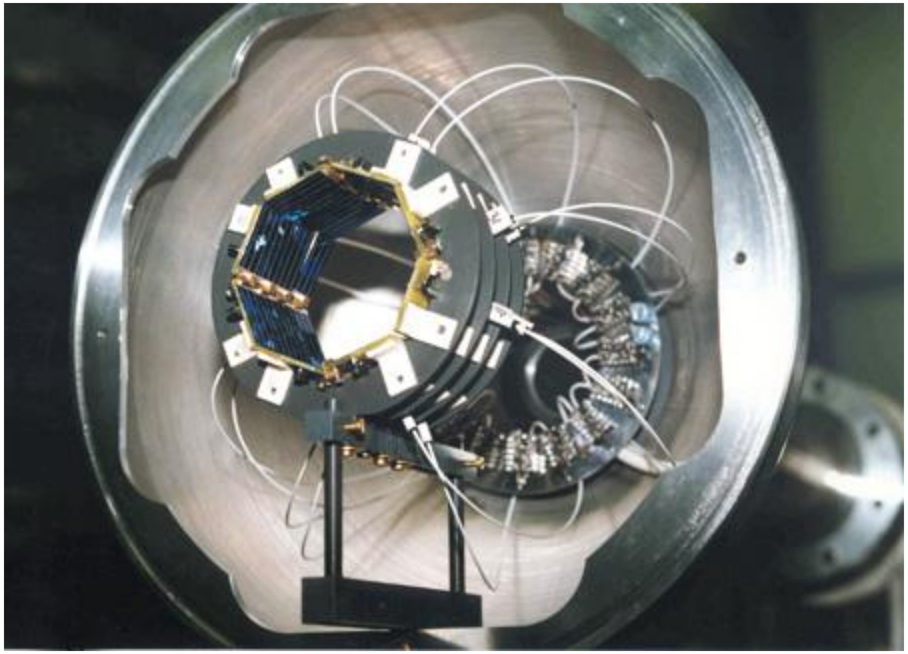
Surrogate reaction & decay probability measurements possible in:

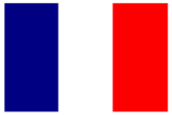
^{233}Th* - d,p
~~^{230}Ac* - d,a~~
~~^{234}Pa* - ^{3}He,p~~
^{232}Pa* - ^{3}He,t
^{231}Th - ^{3}He,^{4}He

The Future

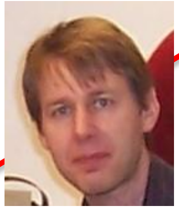
- ^{233}U, ^{231}Pa, ^{234}U targets
- Fission detectors





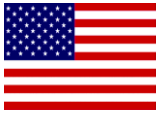


IPN Orsay
J.N. Wilson
B. Leniau



CEA Saclay
F. Gunsing
A. Georgen

Oslo Cyclotron
S. Siem
S. Rose
A. Bürger
M. Guttormsen
A-C. Larsen
T. Wiborg
H. Toft

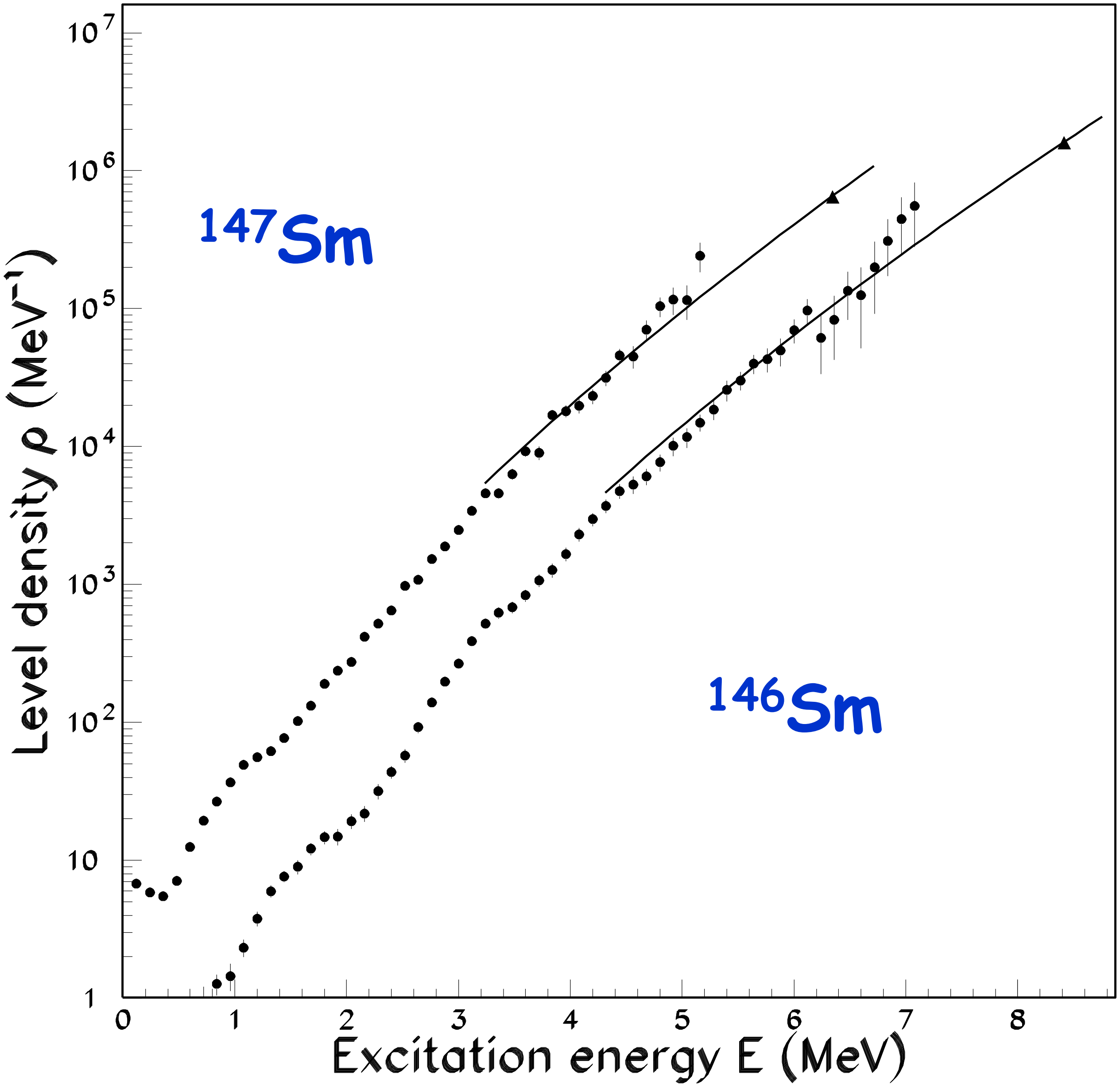


Lawrence Livermoore Lab
M. Weideking
L. Bernstein

Thankyou

Takk

Merci


^{147}Sm
^{146}Sm
Level density ρ (MeV^{-1})
Excitation energy E (MeV)
1
10
10^2
10^3
10^4
10^5
10^6
10^7
0
1
2
3
4
5
6
7
8

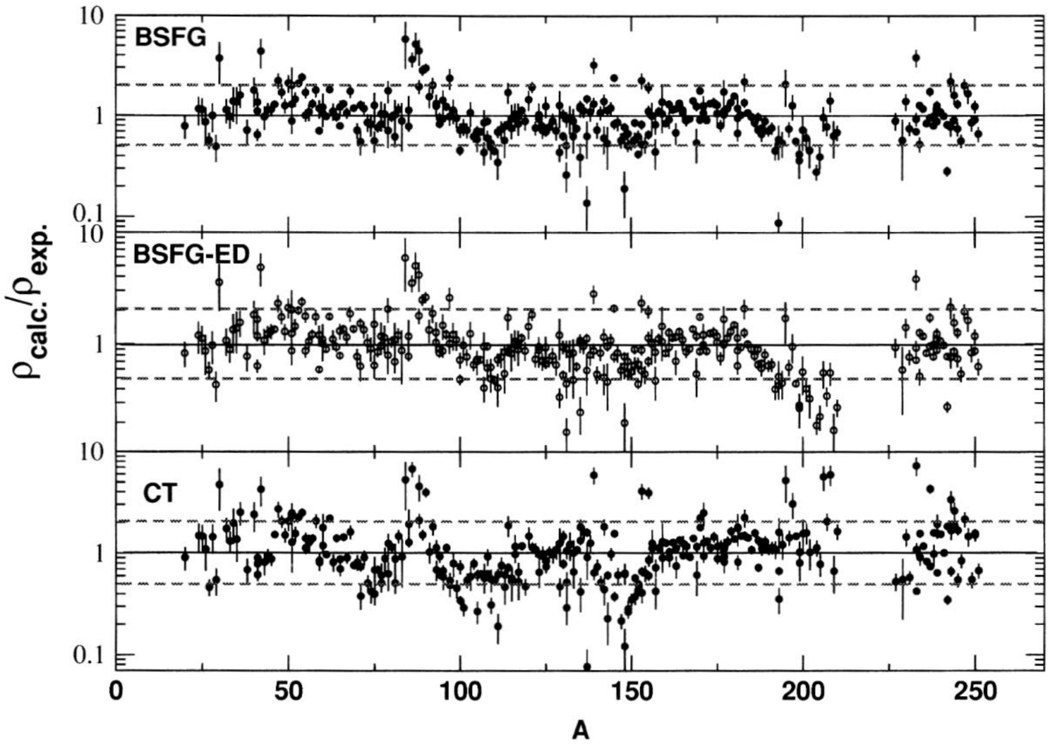
Hauser-Feshbach Formalism

$$\mathbf{a + A \longrightarrow B + b}$$

$$\frac{d\sigma}{d\varepsilon_b}(\varepsilon_a, \varepsilon_b) = \sum_{J\pi} \sigma^{\mathrm{CN}}(\varepsilon_a) \frac{\sum_{I\pi} \Gamma_b(U, J, \pi, E, I, \pi)\rho_b(E, I, \pi)}{\Gamma(U, J, \pi)}$$

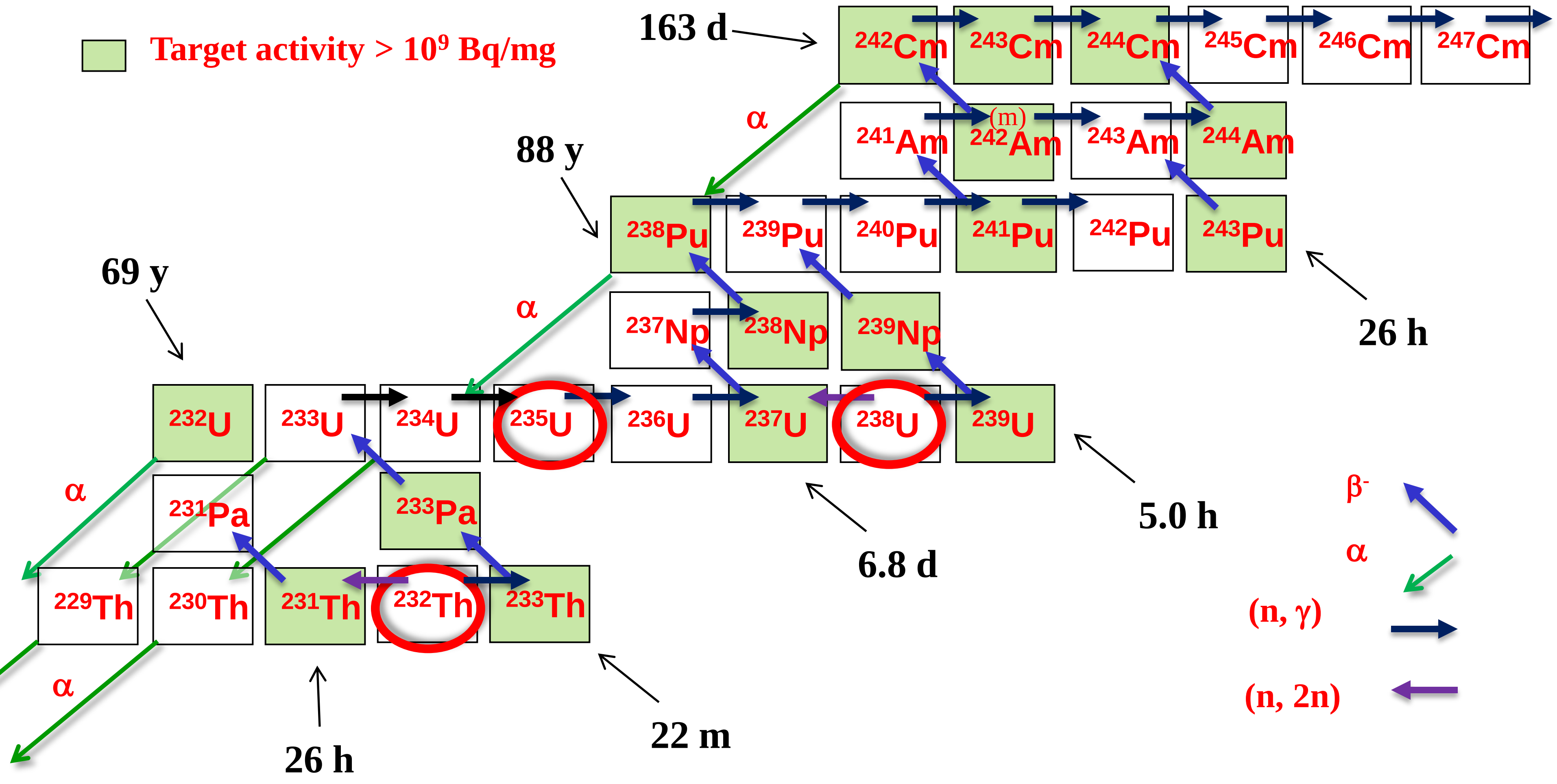
Differential cross section depends on transmission coefficients, **Γ** and level densities of the residual nuclei, ***ρ***

Level Densities Theory and Experiment



- Level density changes due to collectivity, deformation etc.
- Large effects can occur over a small number of nucleons

Nuclei where direct measurements are difficult



$$\text{Decay probability} = \frac{\sigma_\gamma}{\sigma_c}$$

$$\sigma_T = \sigma_\gamma + \sigma_{n,n'} + \sigma_f$$

$$\sigma_T = \sigma_c + \sigma_{pot}$$

$$\sigma_{n,n'} = \sigma_{n,n'}\ compound + \sigma_{n,n'}\ direct$$

$$\sigma_{n,n'} = \sigma_{n,n'}\ compound + \sigma_{pot}$$