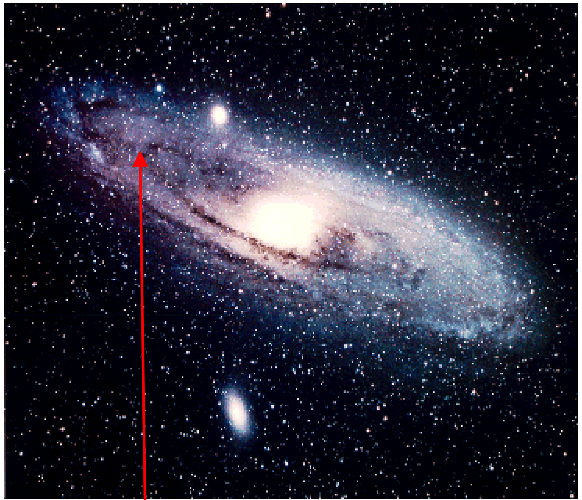
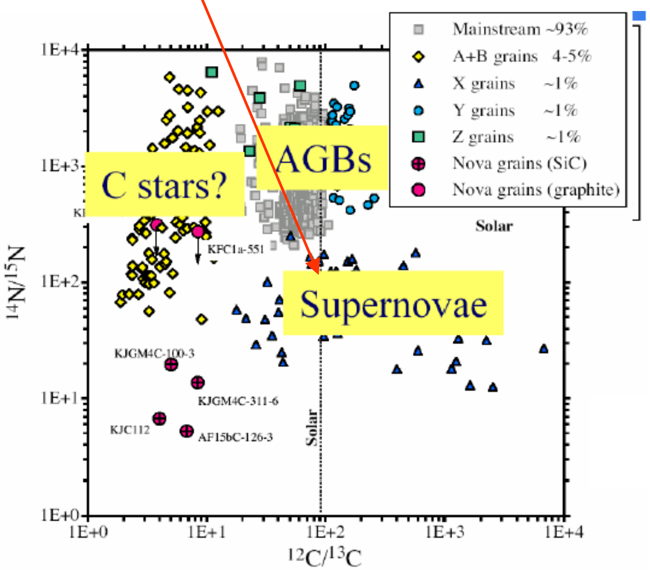


INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS
32nd Course
Particle and Nuclear Astrophysics
Erice-Sicily: 16 - 24 September 2010

You are here

# Underground and above ground nuclear astrophysics





Filippo Terrasi

Dept. Of Environmental Sciences
2nd University of Naples, Caserta

and

Istituto Nazionale di Fisica Nucleare
Naples, Italy

1920: A.S. Eddington; Rep. Brit. Ass. Adv. Sci.; (Cardiff):

"What is possible in the Cavendish Laboratory cannot be too difficult in the Sun."

Date of birth of Nuclear Astrophysics

---

Today: Almost all important events in the Universe have left behind them nuclear clues.

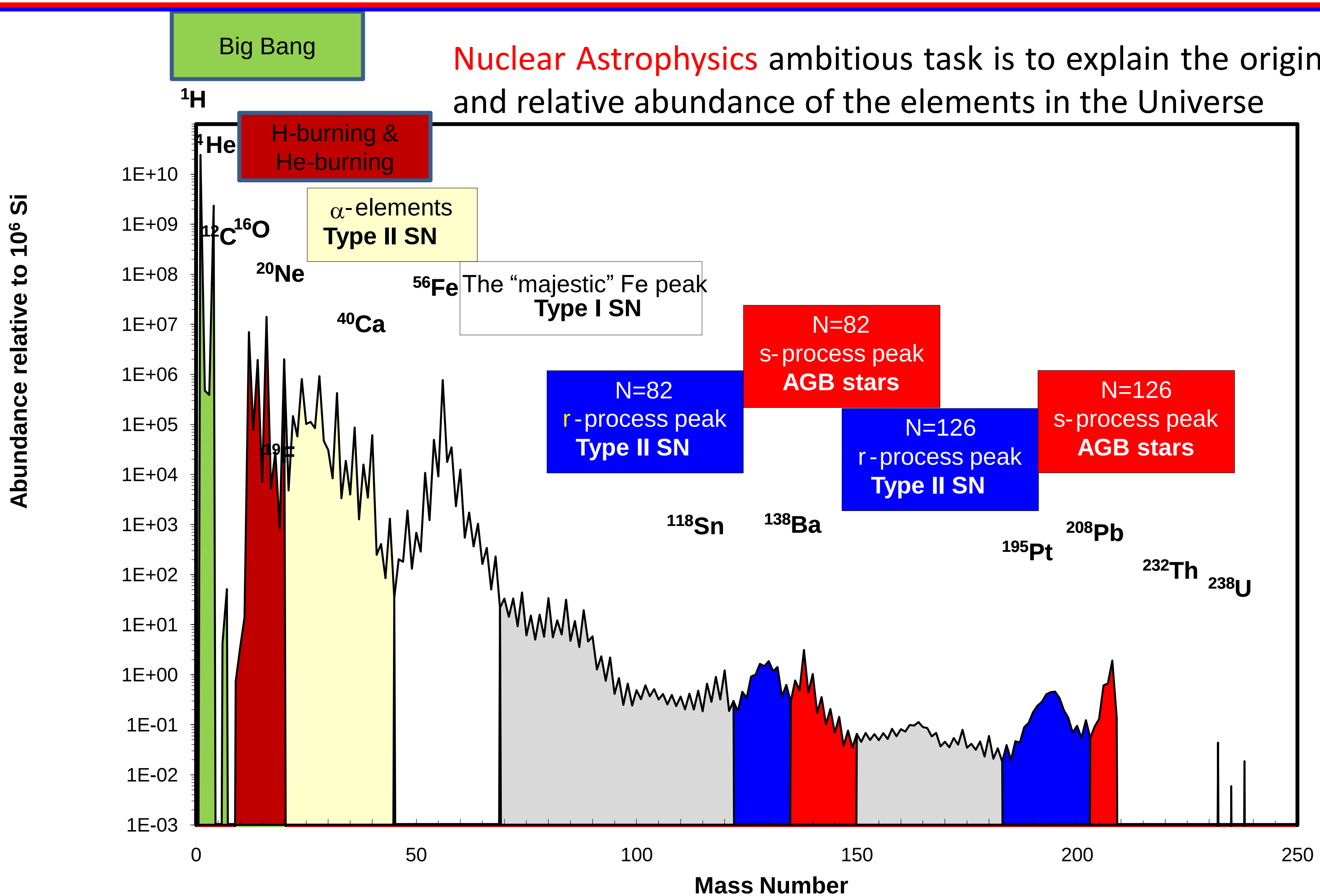
Subject of N.A. is the understanding of nuclear processes taking place in astrophysical environments:

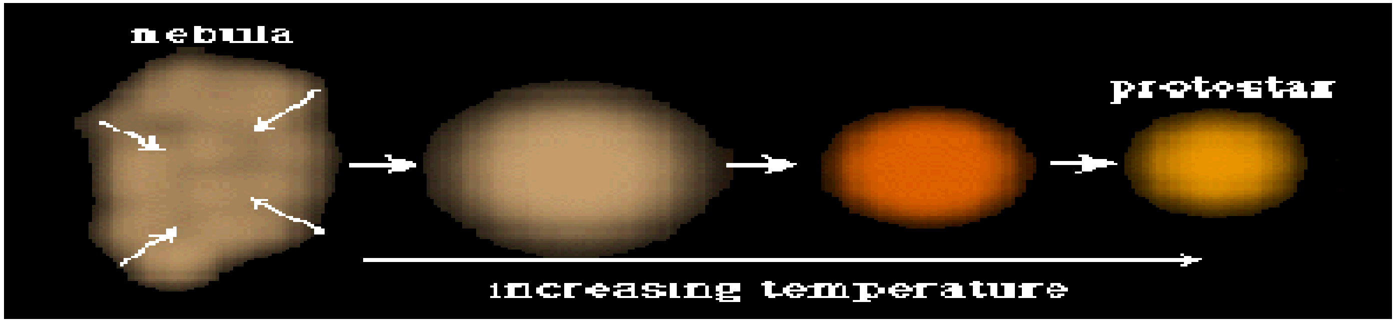
- Primordial nucleosynthesis
- Galactic nucleosynthesis
- Stellar nucleosynthesis and energy generation

**NUCLEAR INPUTS IN ASTROPHYSICAL THEORIES AND MODELS (STRUCTURE AND EVOLUTION) ARE VERY FAR FROM BEING** (WELL) **KNOWN !!!**

# Element abundances in solar system

Nuclear Astrophysics ambitious task is to explain the origin and relative abundance of the elements in the Universe






# Hydrostatic equilibrium

$dP/dr = - G M(r) \rho(r)/r^2$

Equation of state

$P(r) = (k/M) \rho(r) T(r)$

Virial theorem:

$2 E_{int} = - U = -E_G$

$E_{irr} = E_G = G M^2/R = 3.5 \cdot 10^{41}$ J $= \tau L$ ($L=3.8 \cdot 10^{26}$ J/s) Sun: $\tau = 5\ 10^7$ y

Gravitational energy cannot produce the radiated energy during the star lifetime

Nuclear reactions supply the energy released by the star.

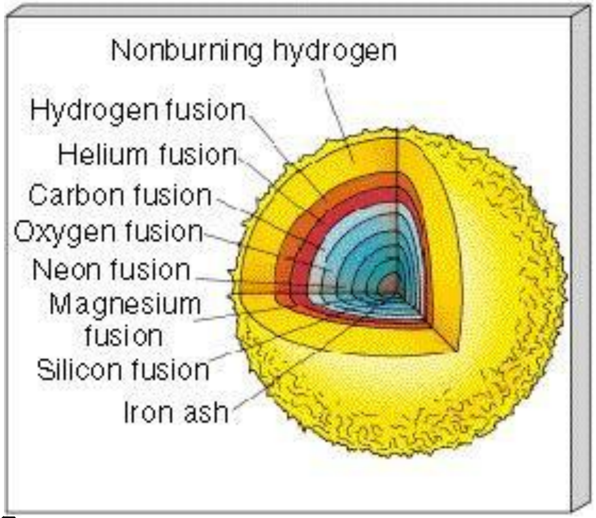
# Stellar evolution during thermal equilibrium

$$\frac{dP}{dM_r} = -\frac{GM_r}{4\pi r^4}$$ hydrostatic equilibrium

$$\frac{dT}{dM_r} = \nabla \frac{GM_r T}{4\pi r^2 P}$$ heat transport

$$\frac{dr}{dM_r} = -\frac{1}{4\pi r^2 \rho}$$ mass continuity

$$\frac{dL_r}{dM_r} = \varepsilon_g + \varepsilon_\upsilon + \varepsilon_n$$ energy conservation




$$\varepsilon_n = \varepsilon_{12} + \varepsilon_{34} = (r_{12} - r_{34})\frac{Q}{\rho}$$

$$r_{12} = N_1 N_2 \langle \sigma v \rangle$$

$$\frac{dY_i}{dt} = \sum_j c_i(j)\lambda_j Y_j + \sum_{j,k} c_i(j,k)\rho N_A \langle \sigma v \rangle_{j,k} Y_j Y_k + \ldots\ldots$$

chemical evolution

# Nuclear inputs to evolutionary models:

## Energetics of reactions

$Q = M_1 + M_2 - M_3 - M_4$

## Reaction rates:

$R_{ij}(T) = (n_i\ n_j / (1+\delta_{ij})) < \sigma_{ij}\ v_{rel} >$

Boltzmann distribution

Exponential behaviour

$<\sigma v> = (8/\pi\mu)^{1/2}\ (1/kT)^{3/2} \int_0^\infty \sigma(E)\ E\ \exp(-E/kT)\ dE$

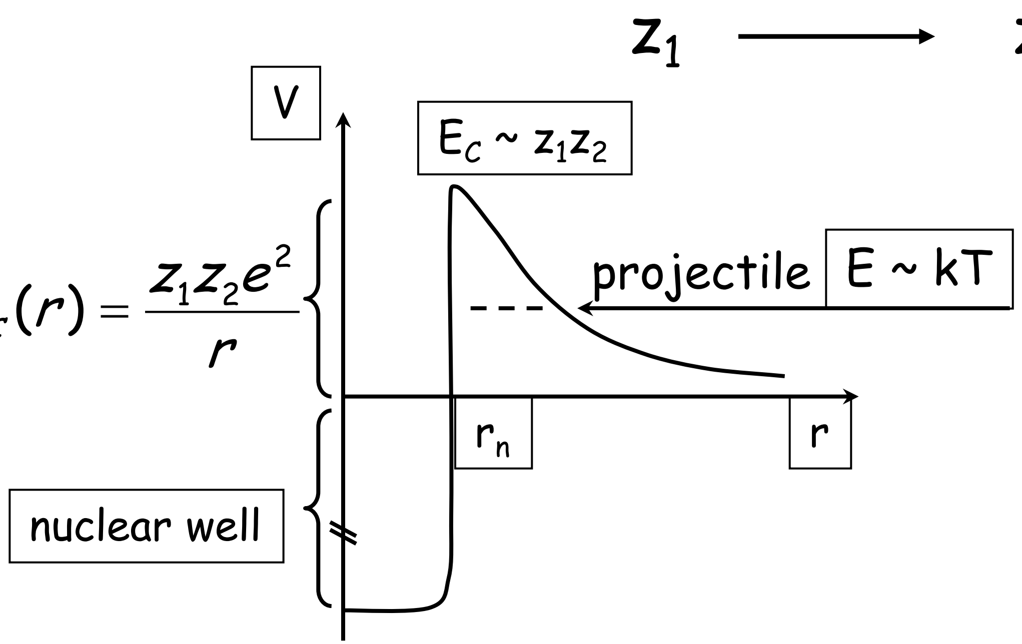
$\tau_{ij}(T) = 1/(n_j\ < \sigma_{ij}\ v_{rel} >)$

Astrophysical S-factor:

$S(E) = \sigma(E)\ E\ \exp(2\pi\eta);\ \eta = Z_1 Z_2 e^2/hv$

# Charged particle reactions in stars

$$V_C(r) = \frac{z_1 z_2 e^2}{r}$$




<u>Example</u>

$z_1$=p and $z_2$=p (e.g. in the Sun)

T ~ 15x10$^6$ K⇒E = kT ~ 1 keV

$E_C$ = 550 keV

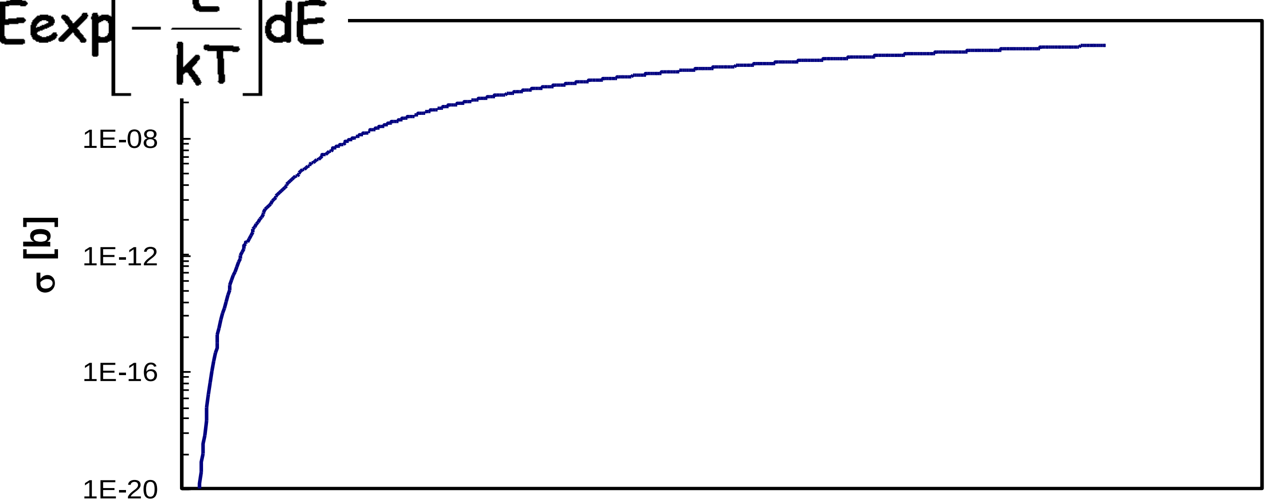
during <u>quiescent burnings</u>:

$kT \ll E_c$

reactions occur through

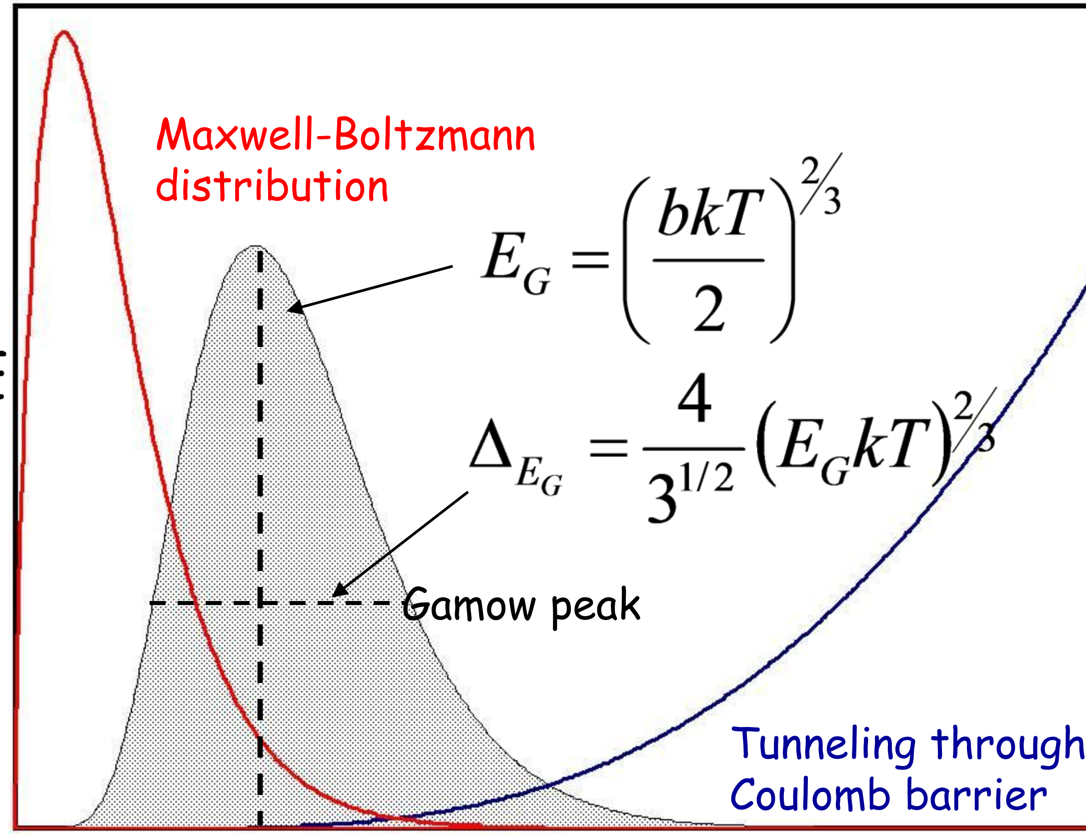
<u>BARRIER PENETRATION</u>

$$<\sigma v> = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma(E) E \exp\left[-\frac{E}{kT}\right] dE$$



# Astrophysical factor and Gamow peak

$$\int_0^\infty \frac{S(E)}{E} \exp\left[-\frac{b}{E^{1/2}}\right] E \exp\left[-\frac{E}{kT}\right] dE$$



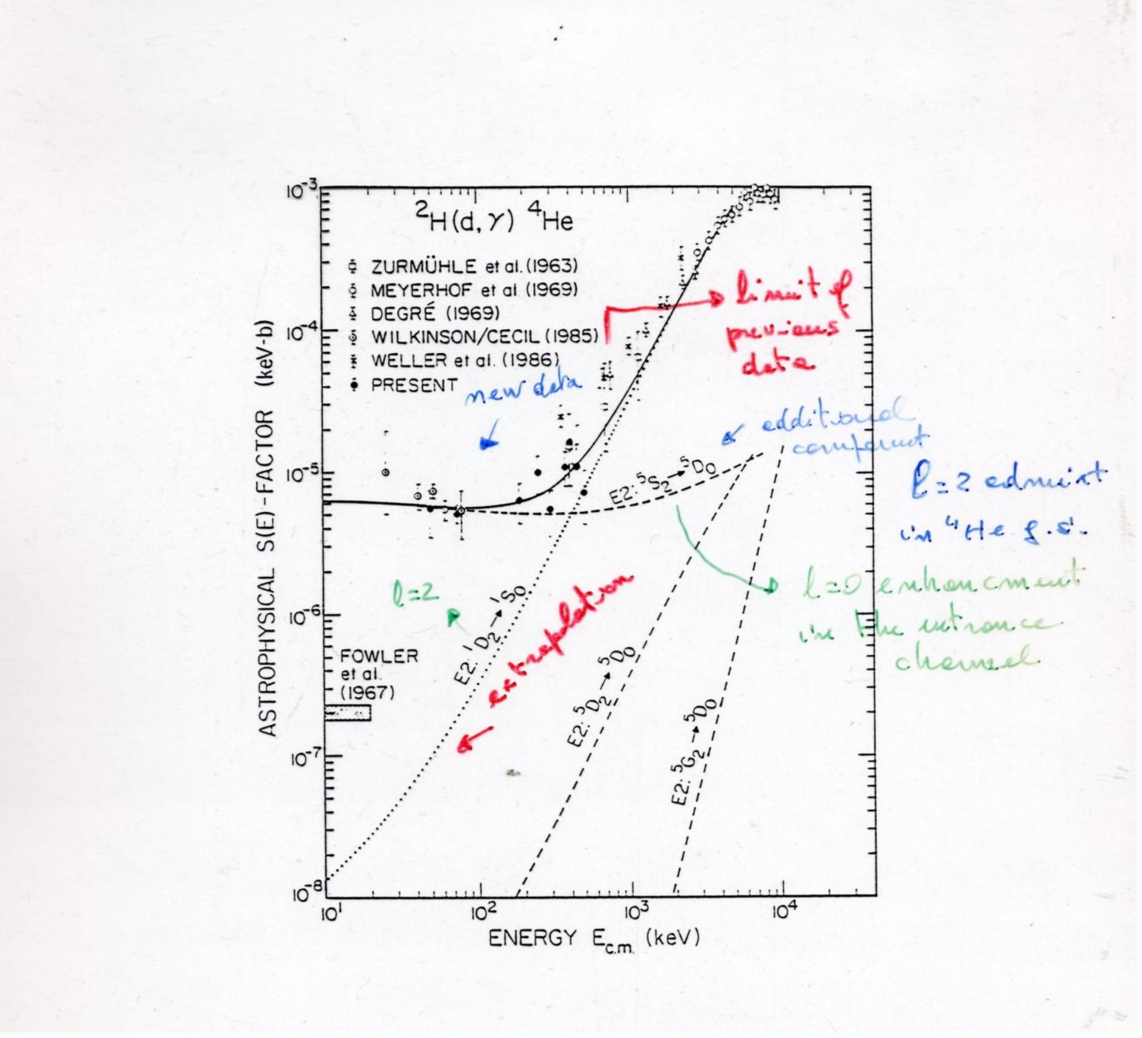

**Sun : $T_6 = 15$**

| reaction | $E_G$(keV) | Integral |
|---|---|---|
| p+p | 5.9 | $7\ 10^{-6}$ |
| p+$^{14}$N | 26.5 | $2.5\ 10^{-26}$ |
| $\alpha$+$^{12}$C | 56 | $5.9\ 10^{-56}$ |
| $^{16}$O+$^{16}$O | 237 | $2.5\ 10^{-237}$ |

**Separate burning phases (Heger)**

**Hydrostatic burning E << CB**

# Do we know S(E) at the relevant energy?




Blind extrapolation may lead to ~ 3 orders of magnitude systematic errors!!

C.Barnes et al.
Phys. Lett. 197(1987)315

## *Importance of **experimental reaction rates** for understanding of nucleosynthesis, energy production in stars, solar neutrino problem, theories of stellar evolution*

- Quiescent burning (essentially p and $\alpha$ radiative capture):
  Eo << CB; $\sigma$ < pb

i) direct measurements at $E = E_0$

ii) extrapolation from higher energy measurements

iii) indirect methods (Coul. break-up, delayed activity transfer reactions, "trojan horses"). (see C. Rolfs talk)

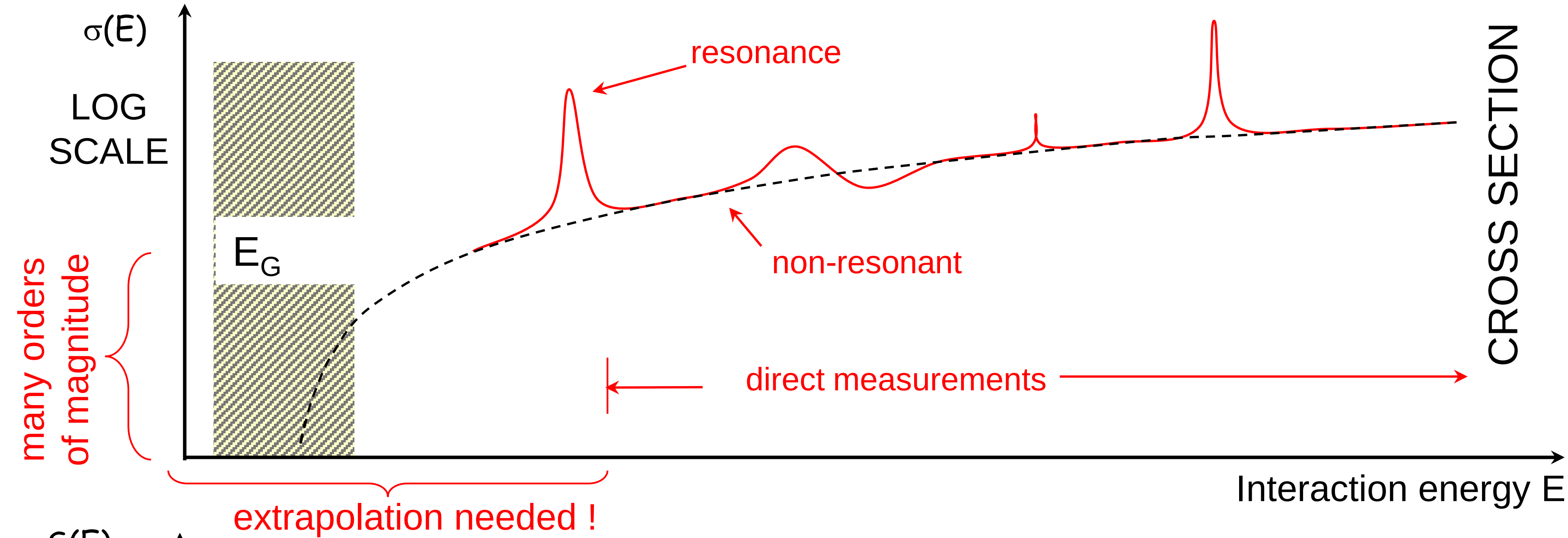
- Explosive/hot burning: Eo ≈ CB but $\tau_{react} \leq 1$ s; RIB (low intensity)

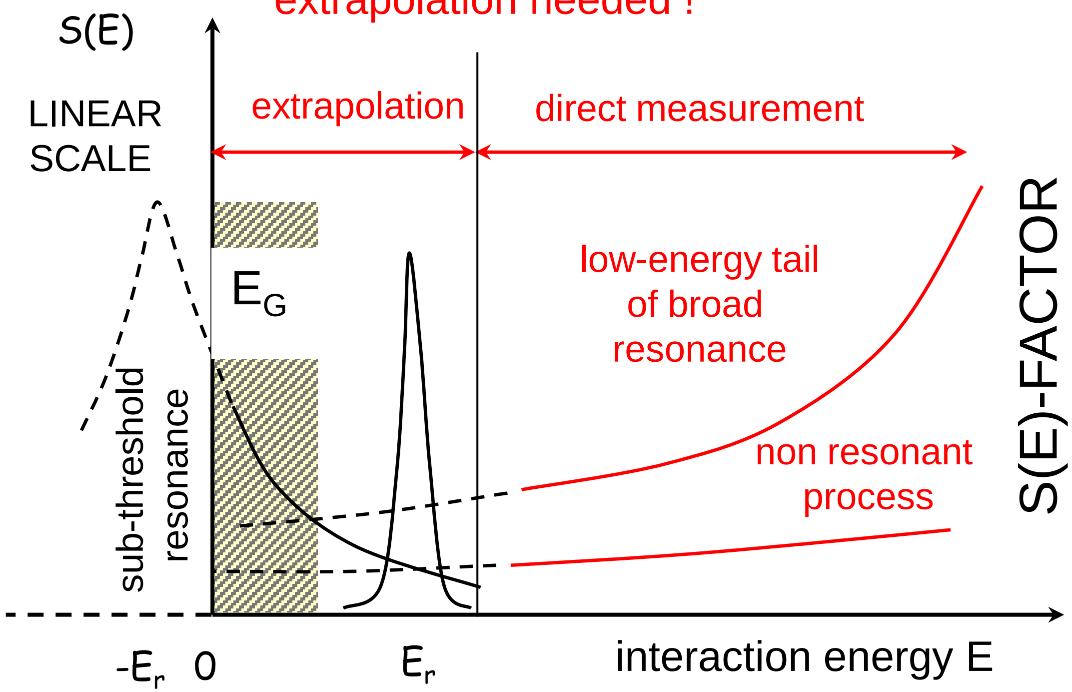
**Imply very low background (underground lab)**

**Imply use of efficient and selective detection apparatuses**

**Imply comparison with direct methods and model tuning**

# Problem of extrapolation

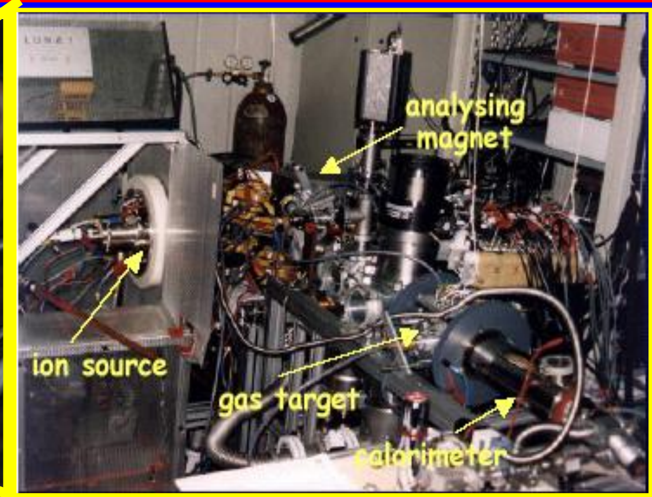


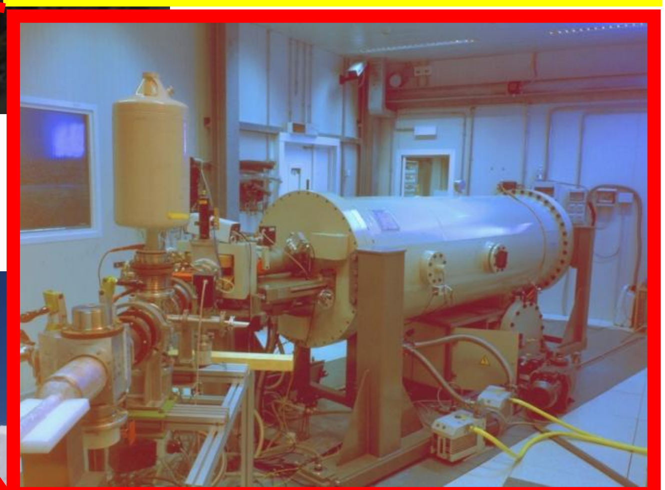

**Most of the reactions of astrophysical interest take place via radiative capture.**

**$^{14}N(p,\gamma)^{15}O$ , $^{12}C(\alpha,\gamma)^{16}C$...**

# LUNA 1997-2010 - experimental set-up


**Voltage Range :**
**1 - 50 kV**
**Output Current:**
**1 mA**
**Beam energy spread:**
**20 eV**



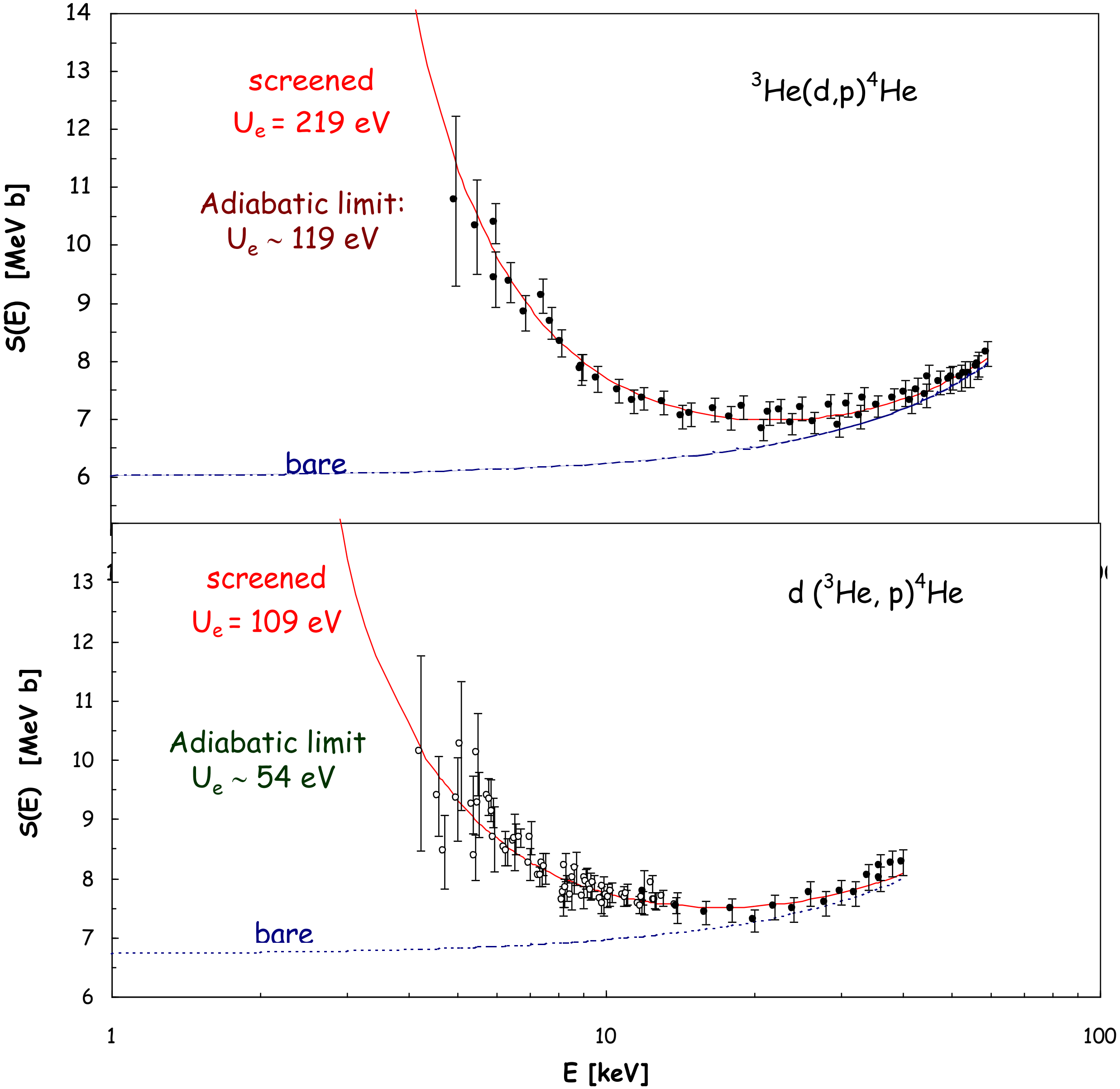
**Voltage Range :**
**50 - 400 kV**
**Output Current:**
**500 μA**
**Beam energy spread:**
**70 eV**

C. Broggini talk

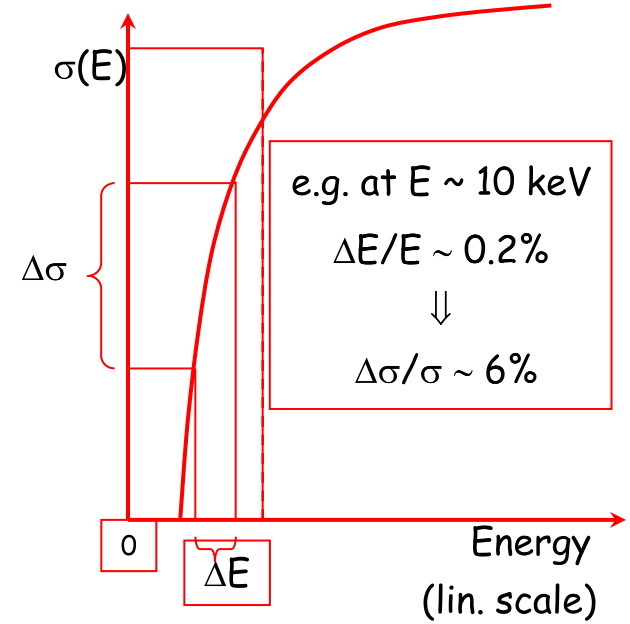
For more details: **H. Costantini, A. Formicola, G. Imbriani, M. Junker, C. Rolfs and F. Strieder**, REPORTS ON PROGRESS IN PHYSICS **72 (2009) 086301**

**LUNA: a laboratory for underground nuclear astrophysics**

# Electron screening: the d+$^3$He reaction:



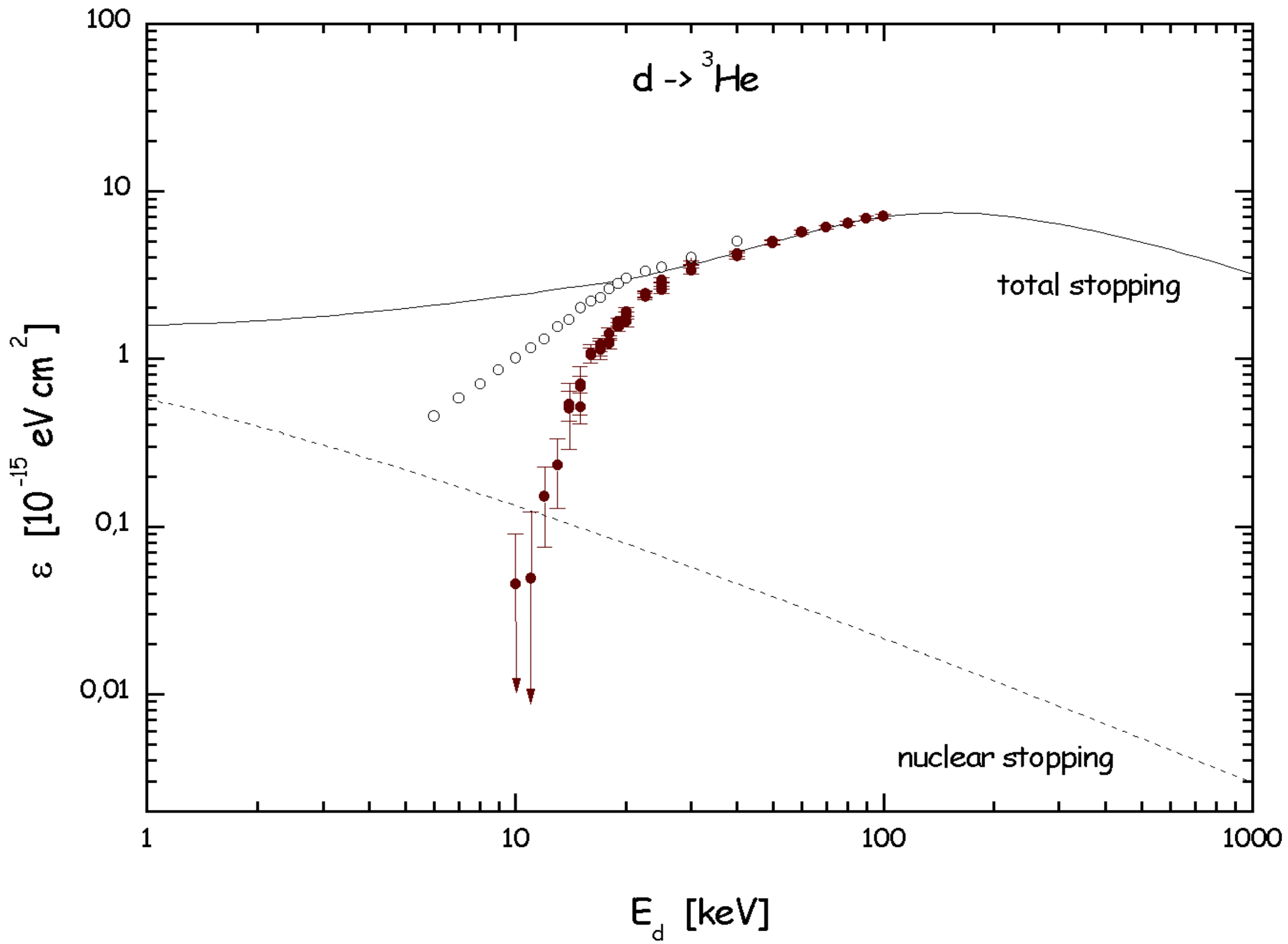

- Stopping Powers ...




Checked in experiment

(see C. Rolfs talk)

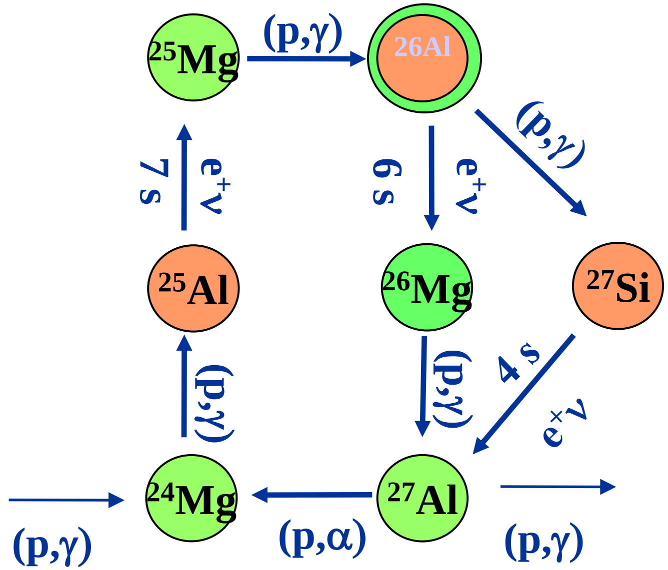
# Stopping powers

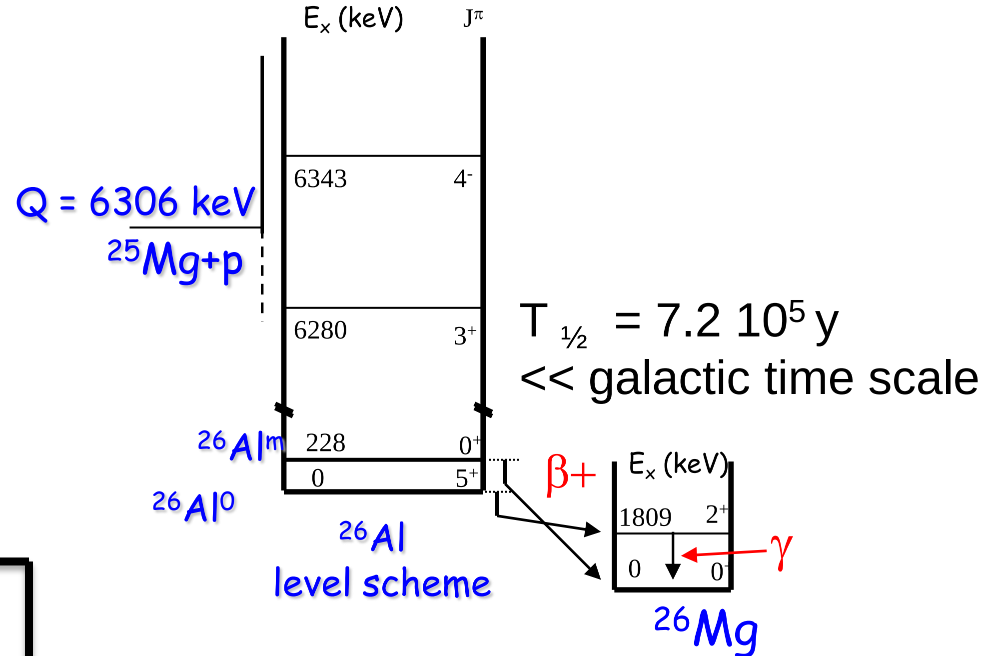



for $E_d$ < 18.2 keV $\Rightarrow$ "electronic stopping power" vanishes

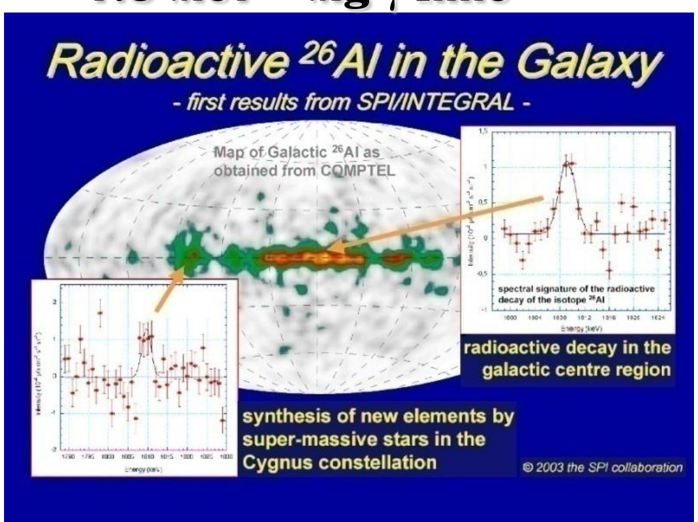
threshold effect

# $^{26}$Al – γ-astronomy and meteorites




**1.8 MeV $^{26}$Mg γ line**

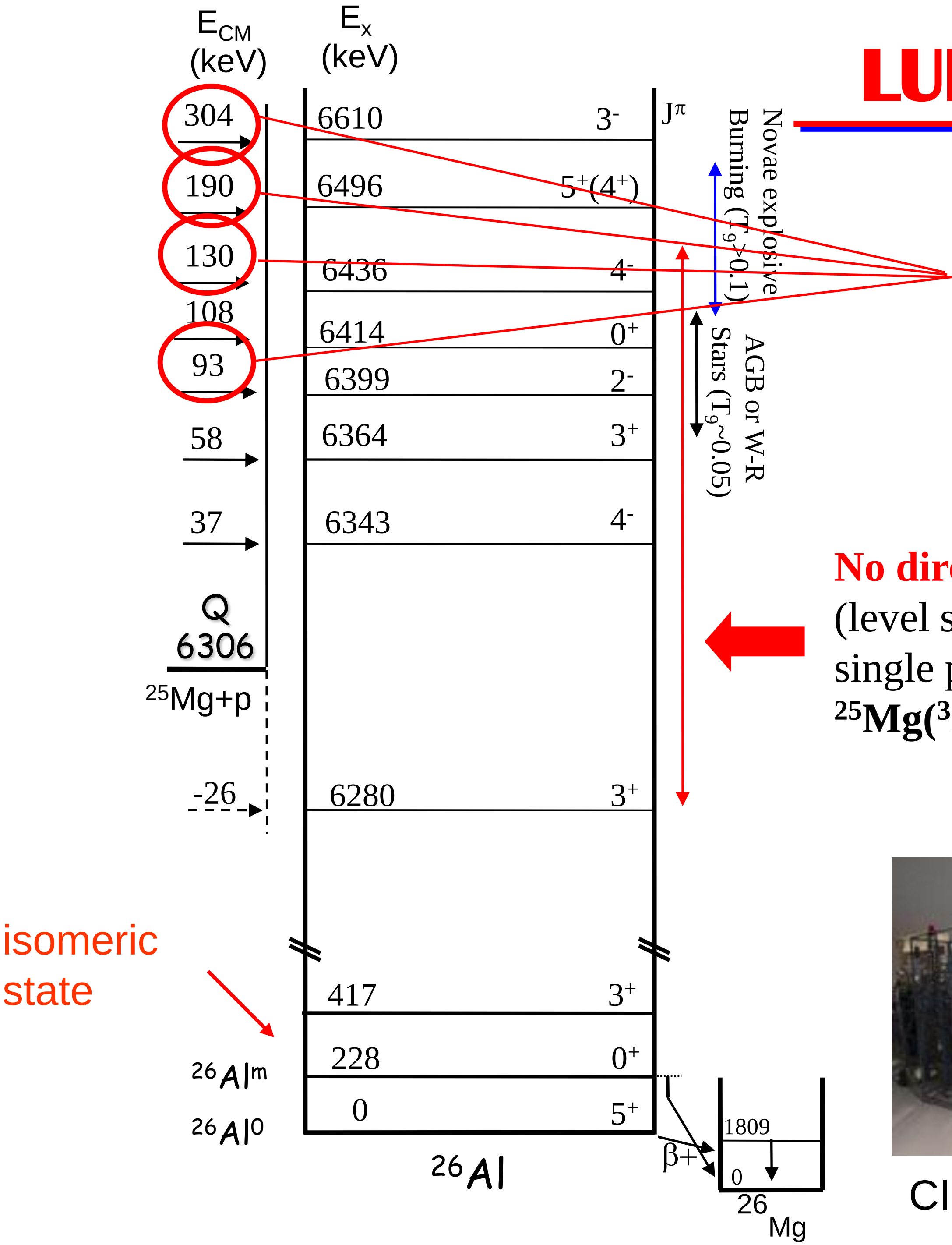



Evidence that $^{26}$Al nucleosynthesis is still active (SN and NOVAE)

**$^{26}$Mg excess in meteorites**

Signature of $^{26}$Mg production during the Hydrogen burning (AGB)

# LUNA Measurements




γ-ray Spectroscopy with HPGe

→ High resolution & Low efficiency (≤1% @ high energy)

solid target @55°

• High efficiency (about 50%)

γ-ray Spectroscopy with 4πBGO

solid target

AMS Irradiation & Measurement

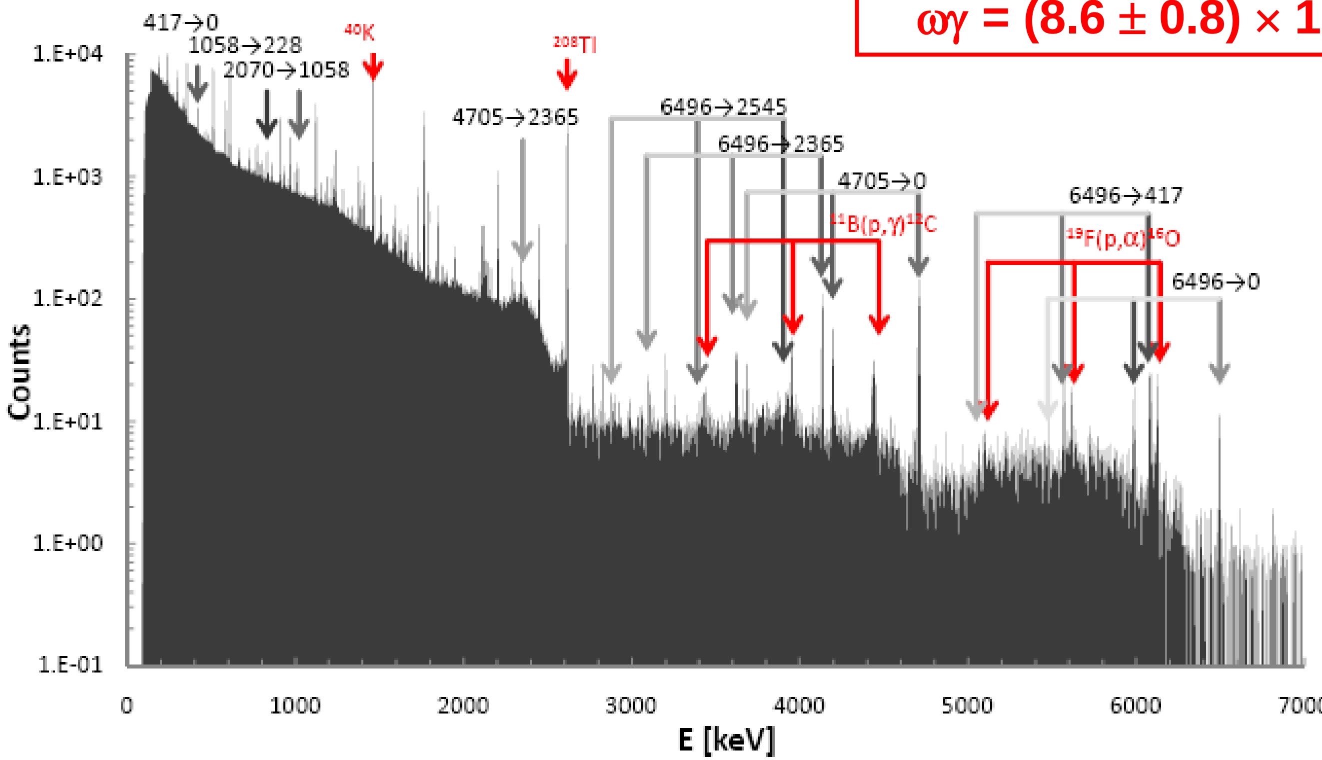
→ resonance strength ωγ

**No direct strength resonance data**

(level structure derived from the single particle transfer reaction: **$^{25}Mg(^{3}He,d)^{26}Al$**)

# $^{25}Mg(p,\gamma)^{26}Al$ – HPGe spectra $E_R = 190$ keV

$\omega\gamma = (8.6 \pm 0.8) \times 10^{-7}$ eV

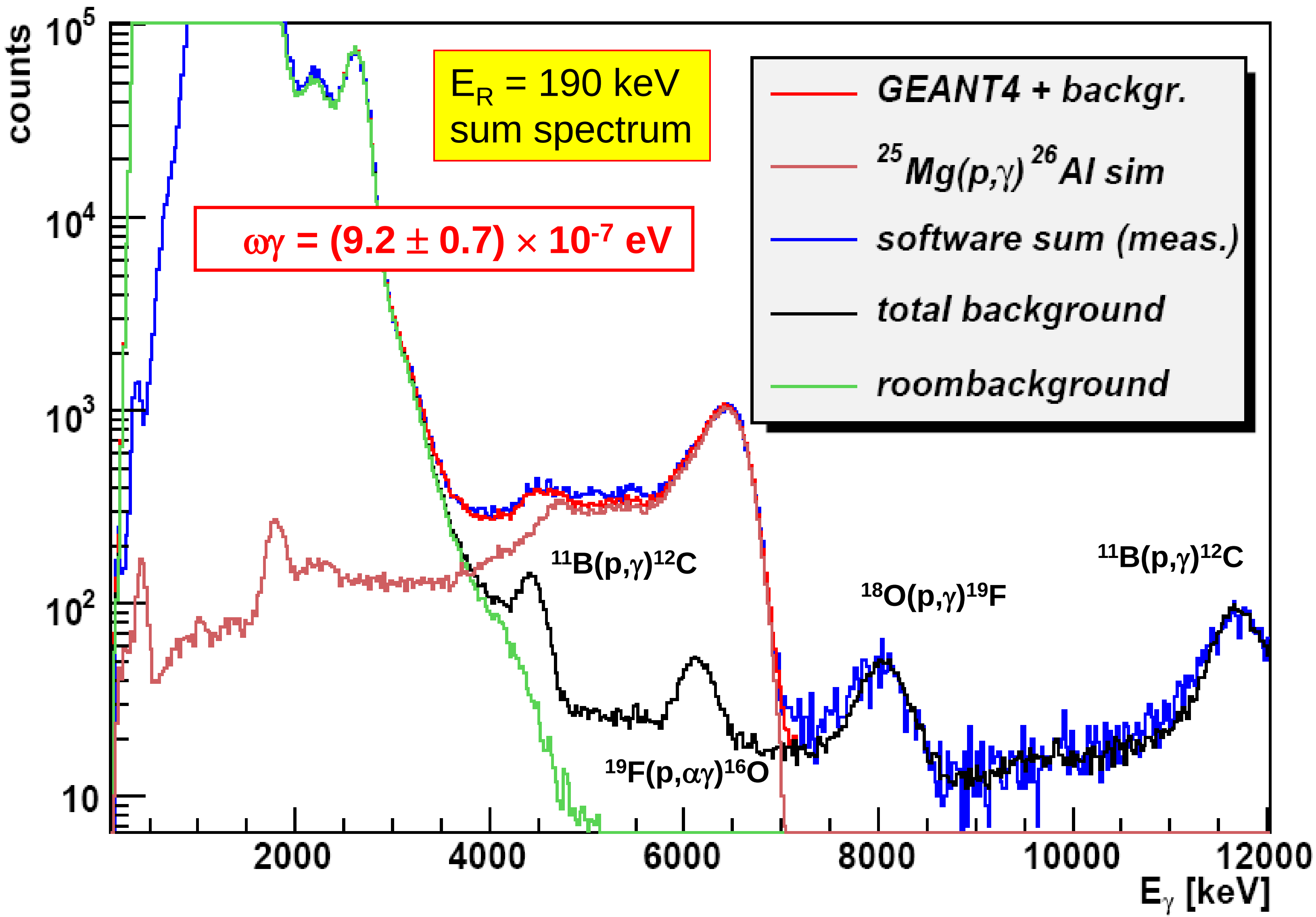



Branchngs

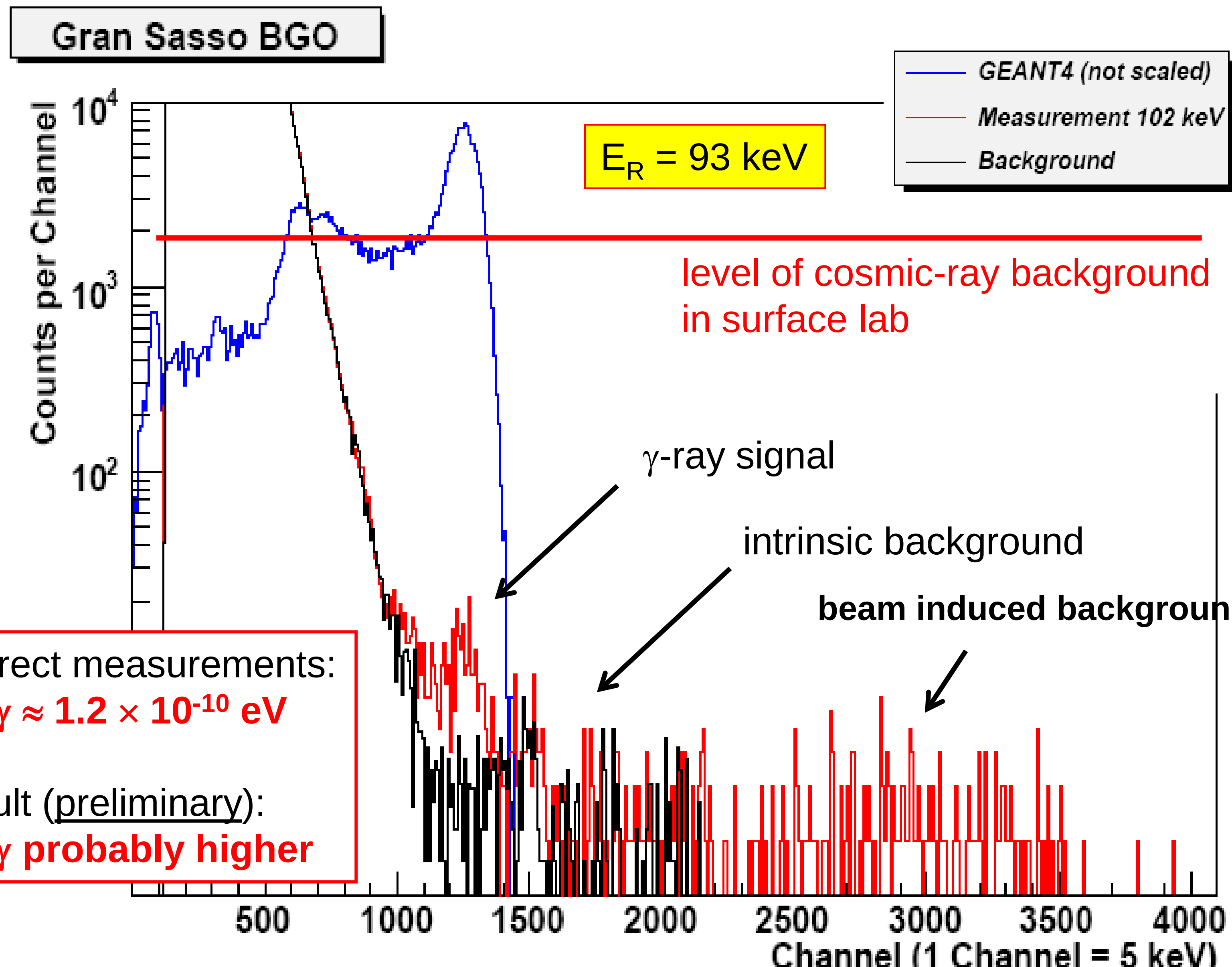
| $E_\gamma$ | **1791** | **3092** | **3951** | **4131** | **6079** | **6496** |
|---|---|---|---|---|---|---|
| $E_X$ | 4705 | 3404 | 2545 | 2365 | 417 | 0 |
| **LUNA [%]** | **51** | **1.6** | **8** | **23** | **11** | **5.8** |
| **err** | **2** | **0.5** | **1** | **2** | **1** | **1.1** |
| Endt [%] | 50 | 4.5 | 5.8 | 19 | 21 | 0 |

**BR→0 = 74.6 %**

# $^{25}Mg(p,\gamma)^{26}Al$ – BGO spectra $E_R = 190$ keV



# $^{25}Mg(p,\gamma)^{26}Al$ – BGO spectra $E_R = 93$ keV

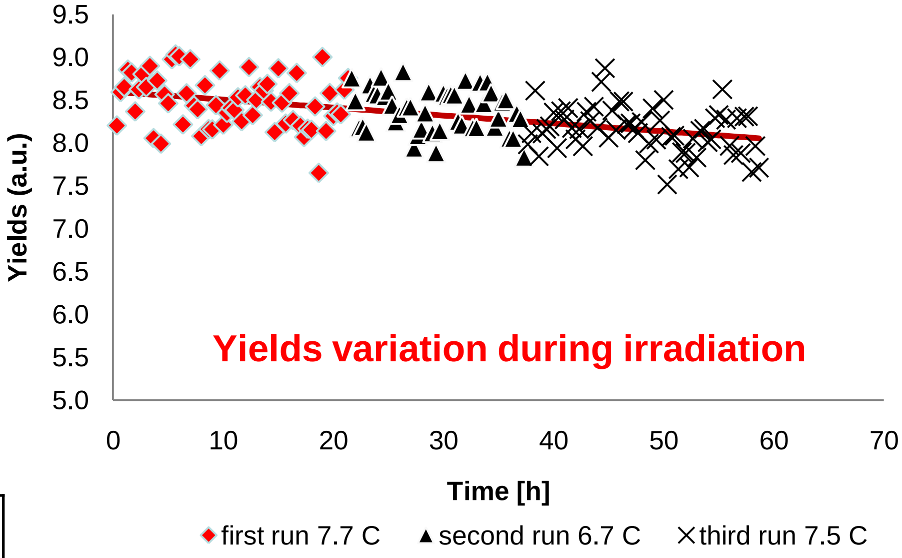



indirect measurements:
**$\omega\gamma \approx 1.2 \times 10^{-10}$ eV**

result (preliminary):
**$\omega\gamma$ probably higher**

# The AMS measurement

CIRCE lab. Caserta, Italy




## Results of the $^{26}Al/^{27}Al$ measurement

| Sample | Total time (s) | Experimental ratio(a.u) | Error (%) |
|---|---|---|---|
| S1 | 11270 | 9.06e-12 | 0.8 |
| S2 | 11270 | 8.90e-12 | 0.9 |
| BLK_1 | 11270 | 3.5e-14 | 37 |
| V1 | 11270 | 1.51e-11 | 0.6 |
| M11 | 11270 | 8.78e-12 | 0.7 |

**$\omega\gamma$ results ($\omega\gamma_{gs}/\omega\gamma$=87.8 %)**

Table 7: Comparison between AMS and BGO prompt-$\gamma$ results

| | AMS | | | | prompt-$\gamma$ | | | |
|---|---|---|---|---|---|---|---|---|
| Target | $\frac{N(^{26}Al)}{N_p}$ | Stat.(%) | Syst.(%) | Err | Yield$^{max} \star f_0$ | Stat.(%) | Syst.(%) | Err |
| 304keV-S | 2.72E-11 | 1 | 3 | 7.69E-13 | 2.54E-11 | 0.2 | 6.7 | 1.70E-12 |
| 304keV-R | 2.38E-11 | 6 | 3 | 6.74E-13 | 2.47E-11 | 0.1 | 6.7 | 1.66E-12 |

# Normalization measurements

→ Natural target with known Oxygen content and stoichiometry

measurement of $^{24,25,26}Mg(p,\gamma)^{25,26,27}Al$ **at $E_{cm}$ = 214, 304, and 326 keV resonances**

with **HPGe (@ 42 cm) and BGO setup**, → normalization for low-energies

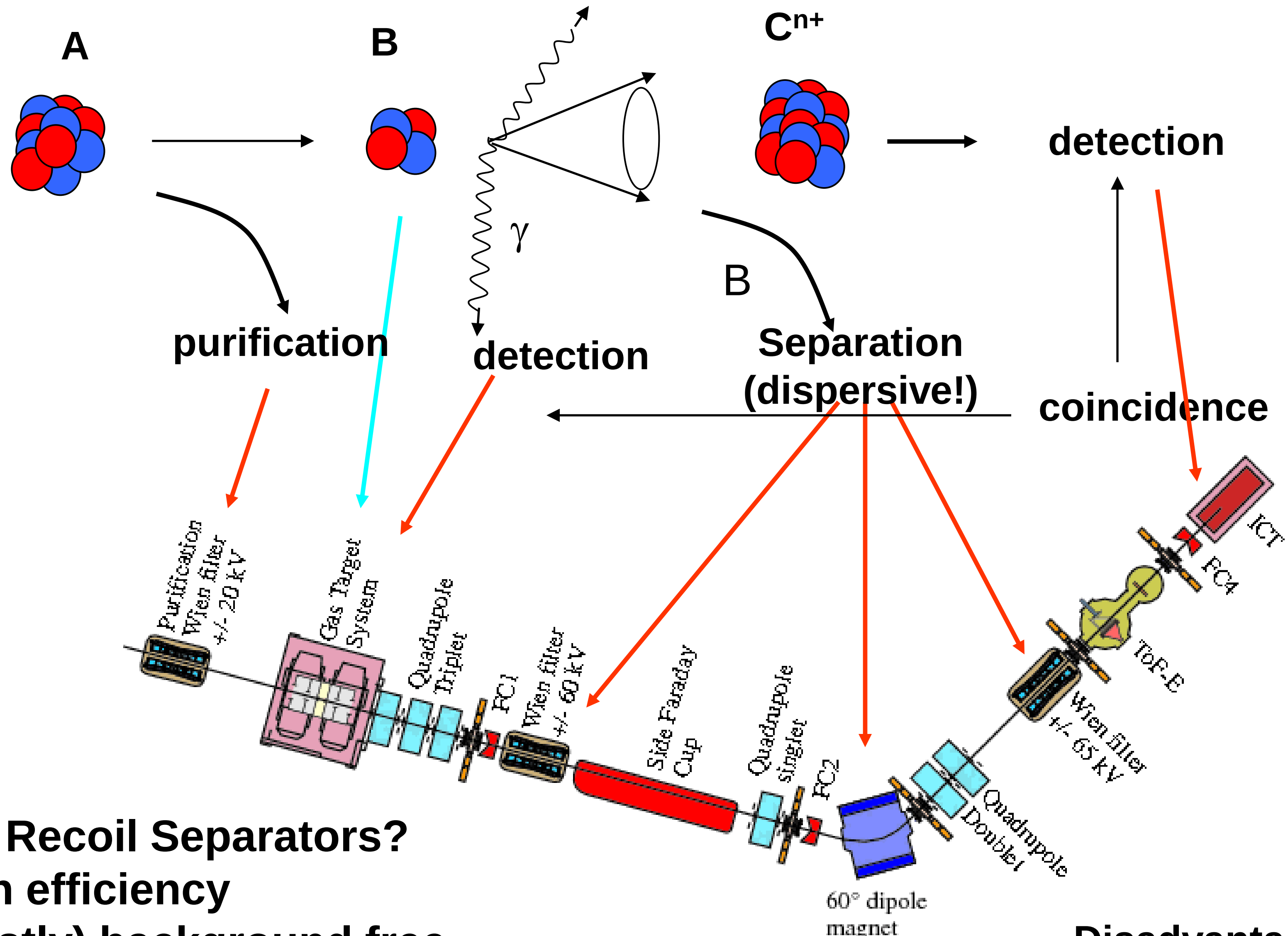
| $^{24}Mg(p,\gamma)\,^{25}Al$ $E_{cm}$ = 214 keV | ωγ [meV] LUNA HPGe | ωγ [meV] LUNA BGO | ωγ [meV] Powell et al. 1999 | ωγ [meV] Trautvetter 1975 |
|---|---|---|---|---|
| | **10.6 ± 0.4** | **10.9 ± 0.5** | 12.7 ± 0.9 | 10.2 ± 0.8 |

| $^{25}Mg(p,\gamma)\,^{26}Al$ $E_{cm}$ = 304 keV | ωγ [meV] LUNA HPGe | ωγ [meV] LUNA BGO | ωγ [meV] Iliadis et al. 1990 | ωγ [meV] NACRE |
|---|---|---|---|---|
| | **31.2 ± 0.9** | **30.6 ± 0.8** | 29 ± 2 | 31 ± 2 |

**BR→0 = 87.8 %**

| $^{26}Mg(p,\gamma)\,^{27}Al$ $E_{cm}$ = 326 keV | ωγ [meV] LUNA HPGe | ωγ [meV] LUNA BGO | ωγ [meV] Iliadis et al. 1990 | ωγ [meV] NACRE |
|---|---|---|---|---|
| | **280 ± 10** | **270 ± 15** | 240 ± 30 | 590 ± 10 |

# An alternative approach: Recoil Mass Separator

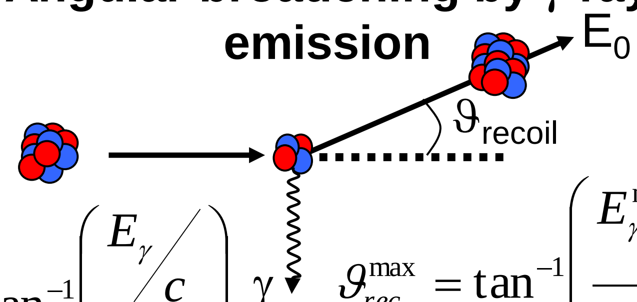



**Why Recoil Separators?**
- **High efficiency**
- **(mostly) background free**
- **Excellent background reduction for γ-spectroscopy**

**Disadvantages**
- **Difficult to do!**

# Recoil collection and identification

**Angular broadening by γ-ray emission**

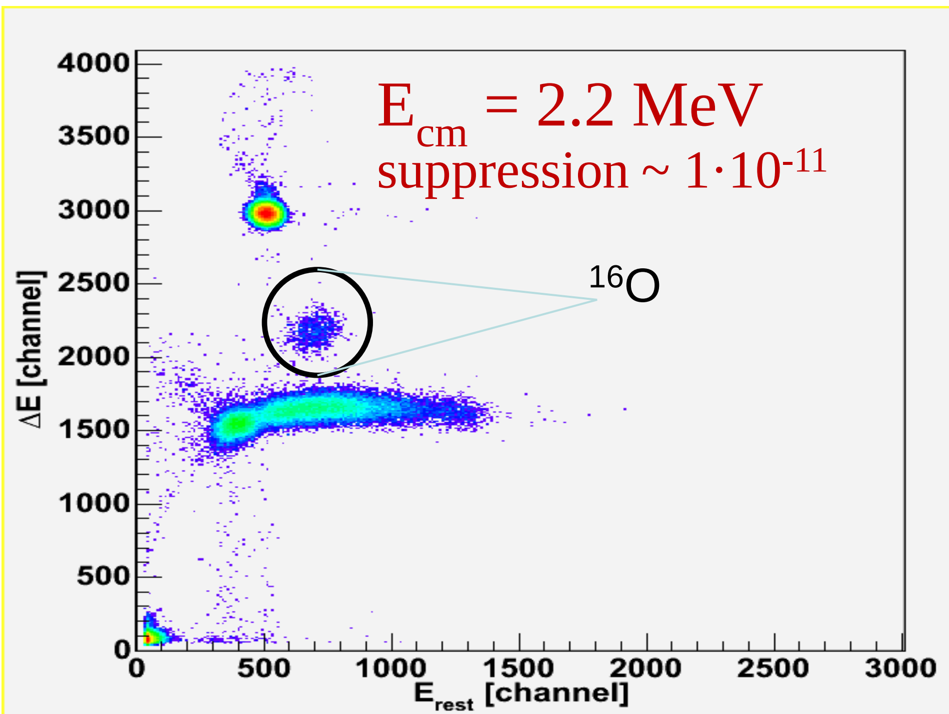


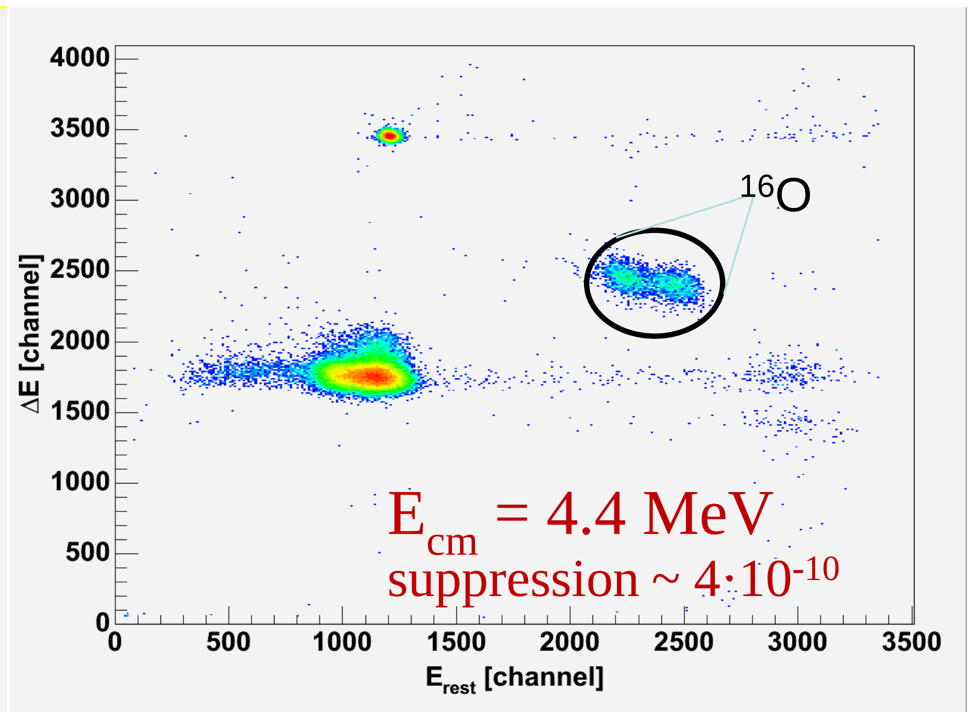

**Example $^{12}C(\alpha,\gamma)^{16}O$**
**$E_{cm}$=1.2 MeV**
**Eγ = 8.4 MeV**

$$\vartheta_{rec} = \tan^{-1}\left(\frac{\Delta p}{p}\right) = \tan^{-1}\left(\frac{E_\gamma / c}{p_{rec}}\right)$$

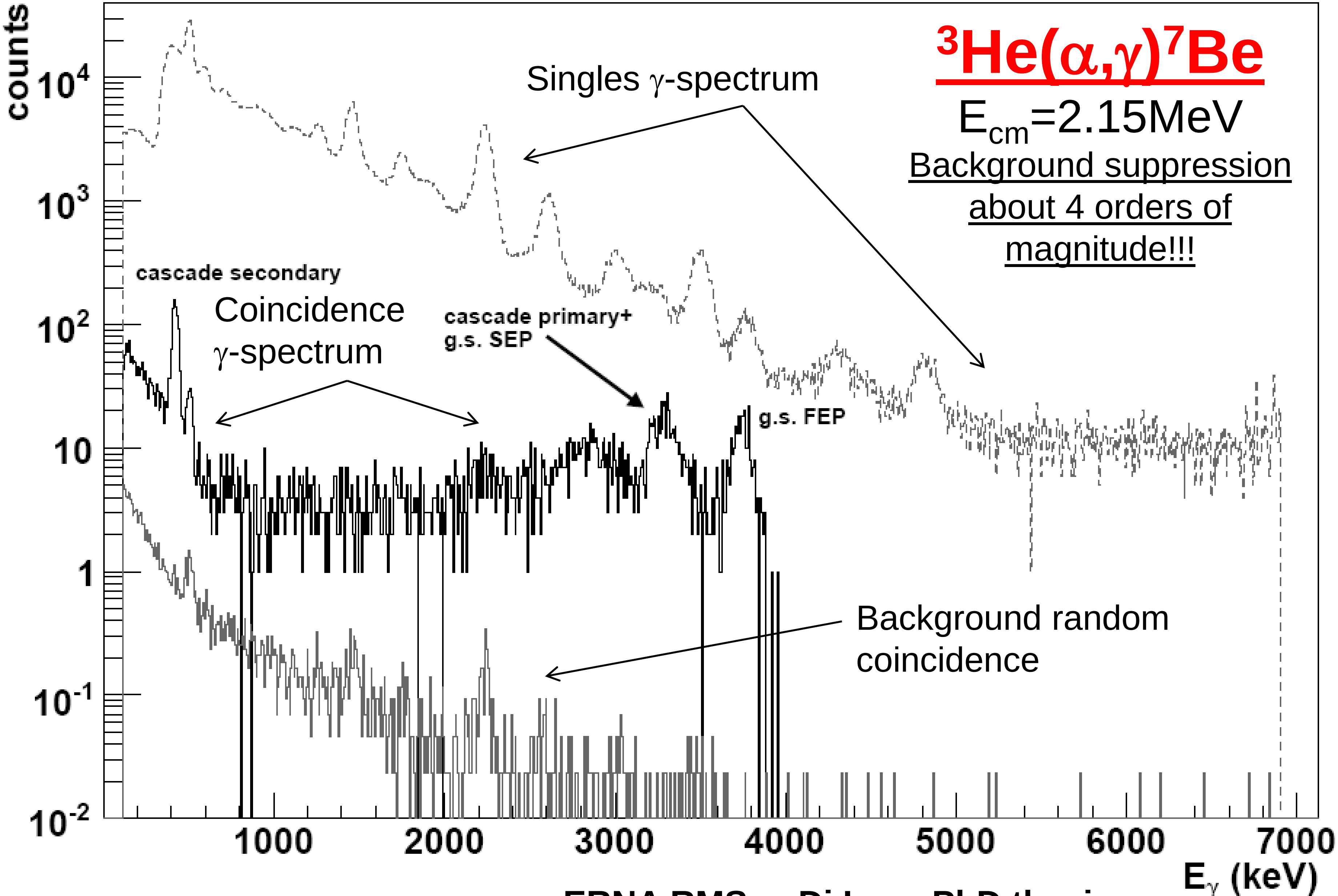
$$\vartheta_{rec}^{max} = \tan^{-1}\left(\frac{E_\gamma^{max} / c}{p_{rec}}\right) = 26 \quad mrad$$

**ø 52 mm after 1 m !**



# Coincidence γ-spectrum



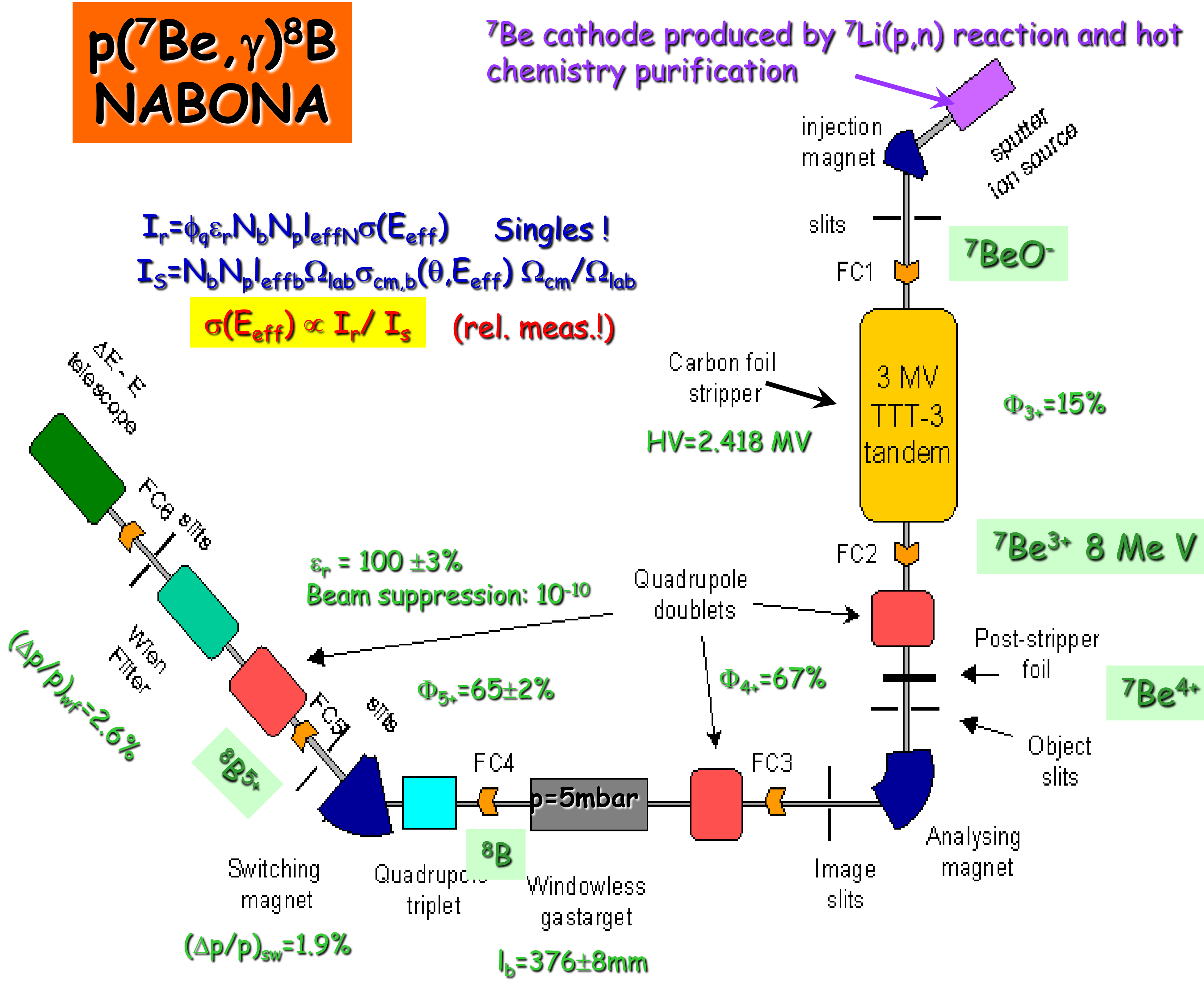

**ERNA RMS - Di Leva PhD thesis**

# $p(^7Be,\gamma)^8B$ NABONA

$I_r = \phi_q \varepsilon_r N_b N_p l_{effN} \sigma(E_{eff})$ **Singles !**

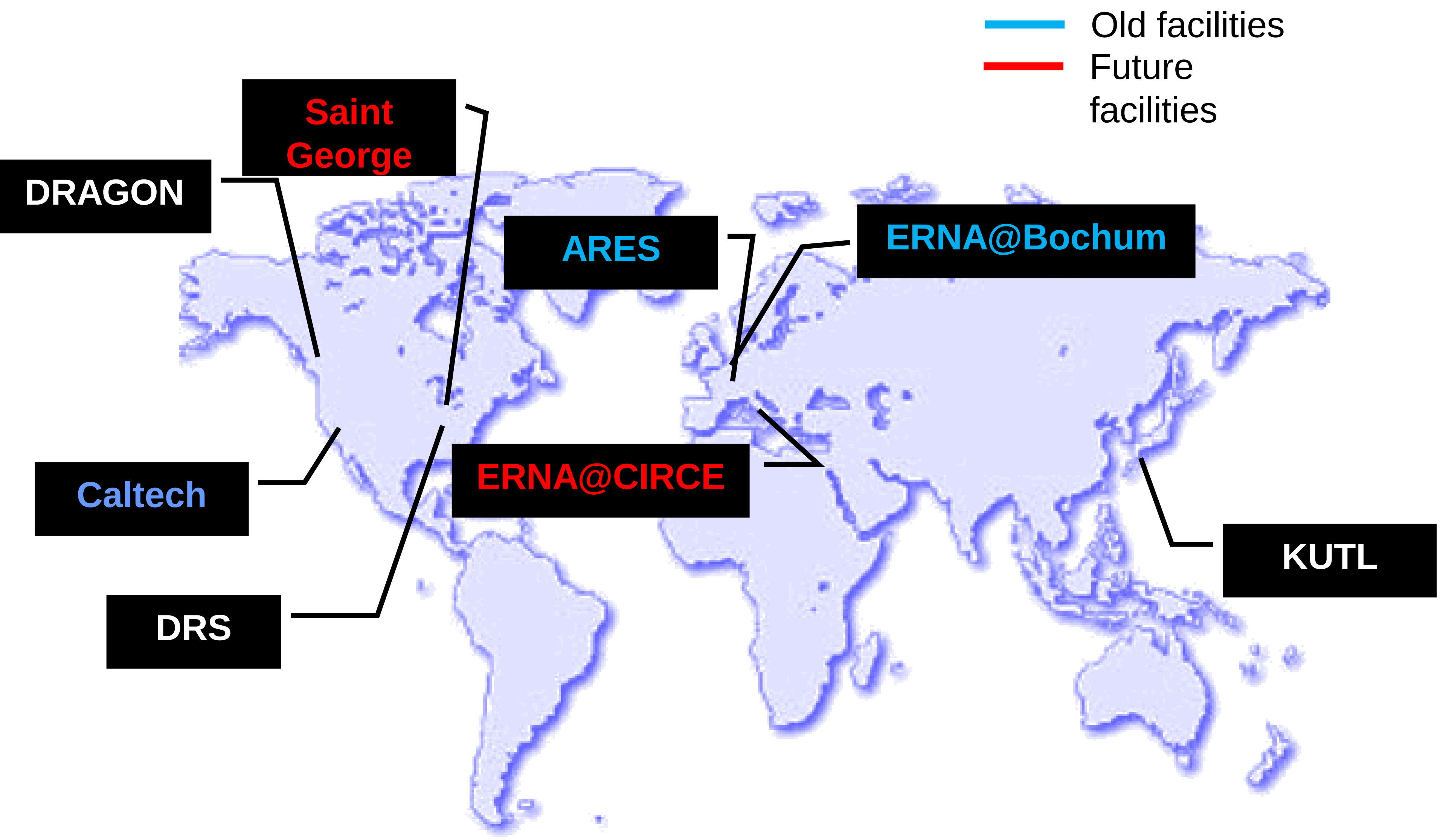
$I_S = N_b N_p l_{effb} \Omega_{lab} \sigma_{cm,b}(\theta, E_{eff})\ \Omega_{cm}/\Omega_{lab}$

$\sigma(E_{eff}) \propto I_r / I_s$ **(rel. meas.!)**

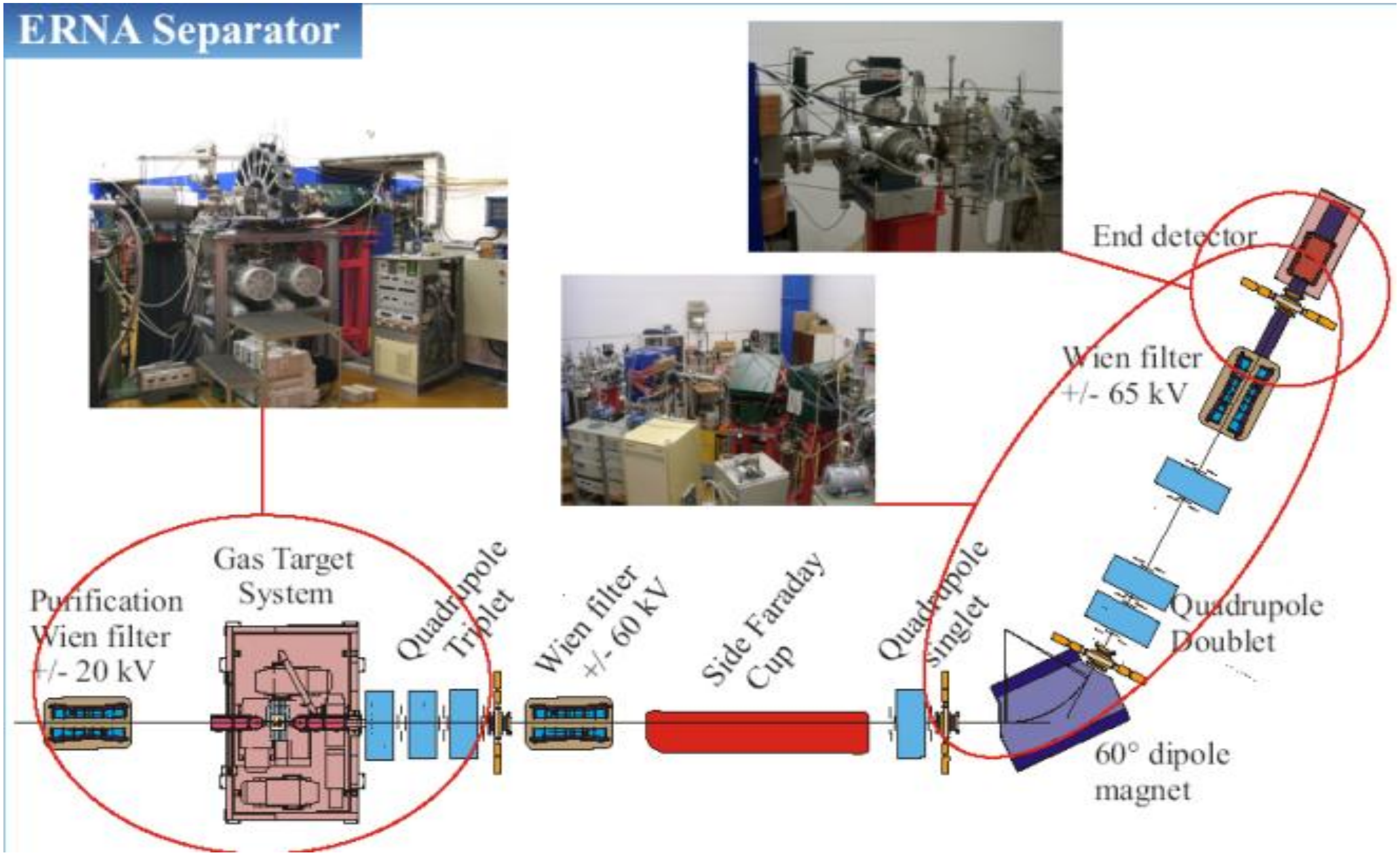


# Recoil Separators

## for Nuclear Astrophysics



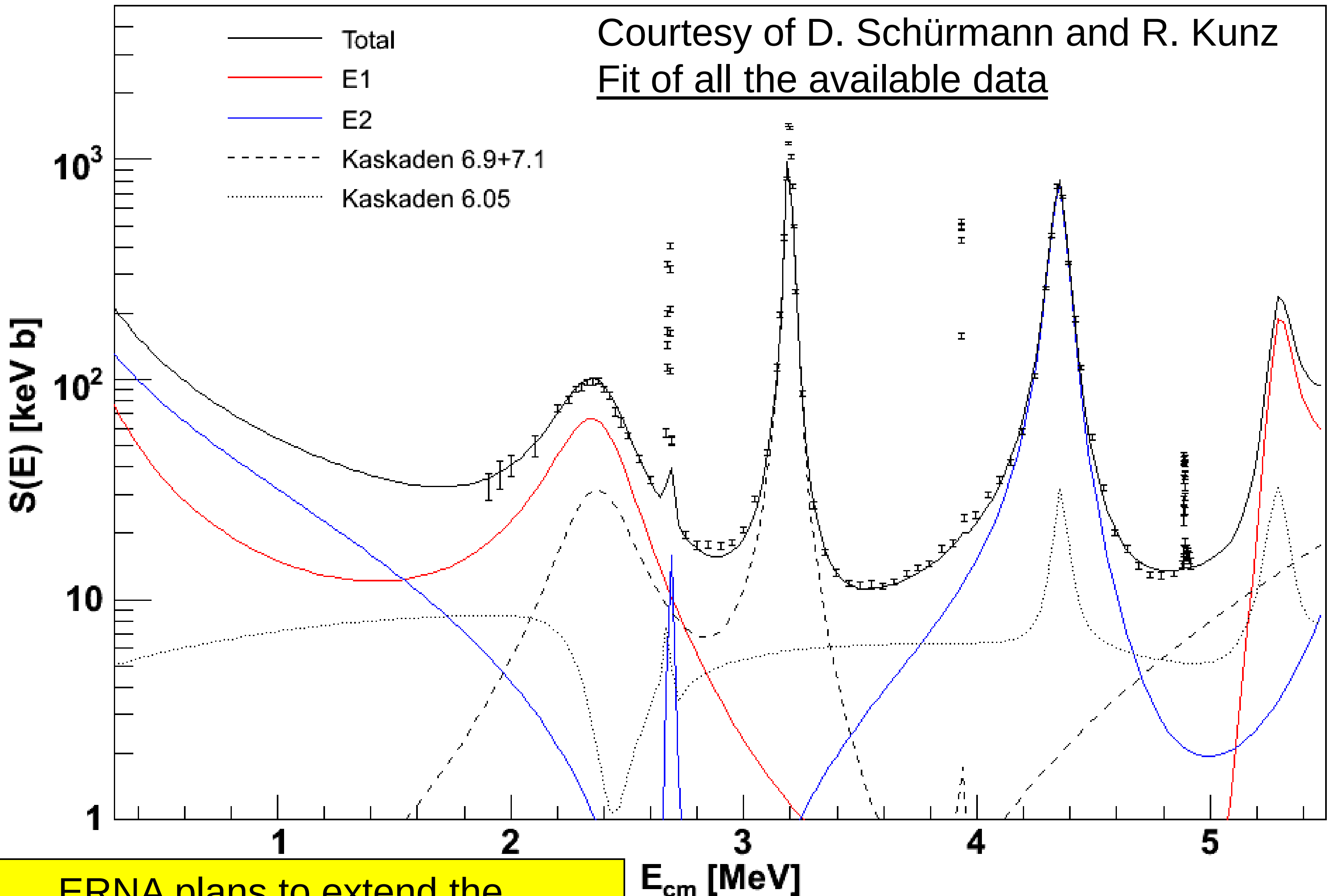
# European Recoil mass separator for Nuclear Astrophysics




Commissioning.

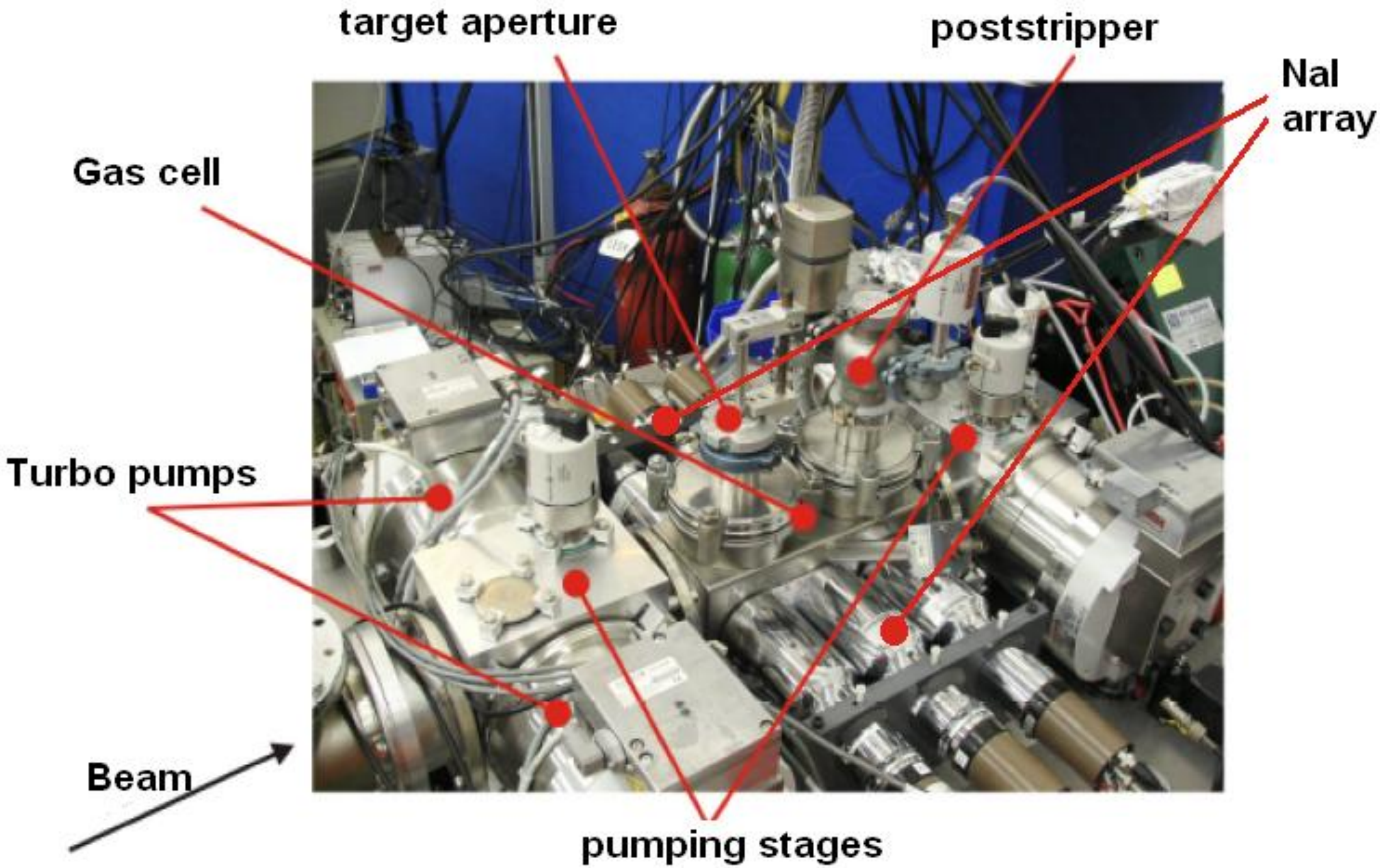
Rogalla et al. EPJ A 6 (1999)471; Rogalla et al NIM A 513(2003) 573; Gialanella et al NIM A 522(2004) 432; Schuermann et al. NIM A 531 (2004) 428; Di Leva at al. NIM A, 595, (2008)381

# $^{12}C(\alpha,\gamma)^{16}O$ total cross section

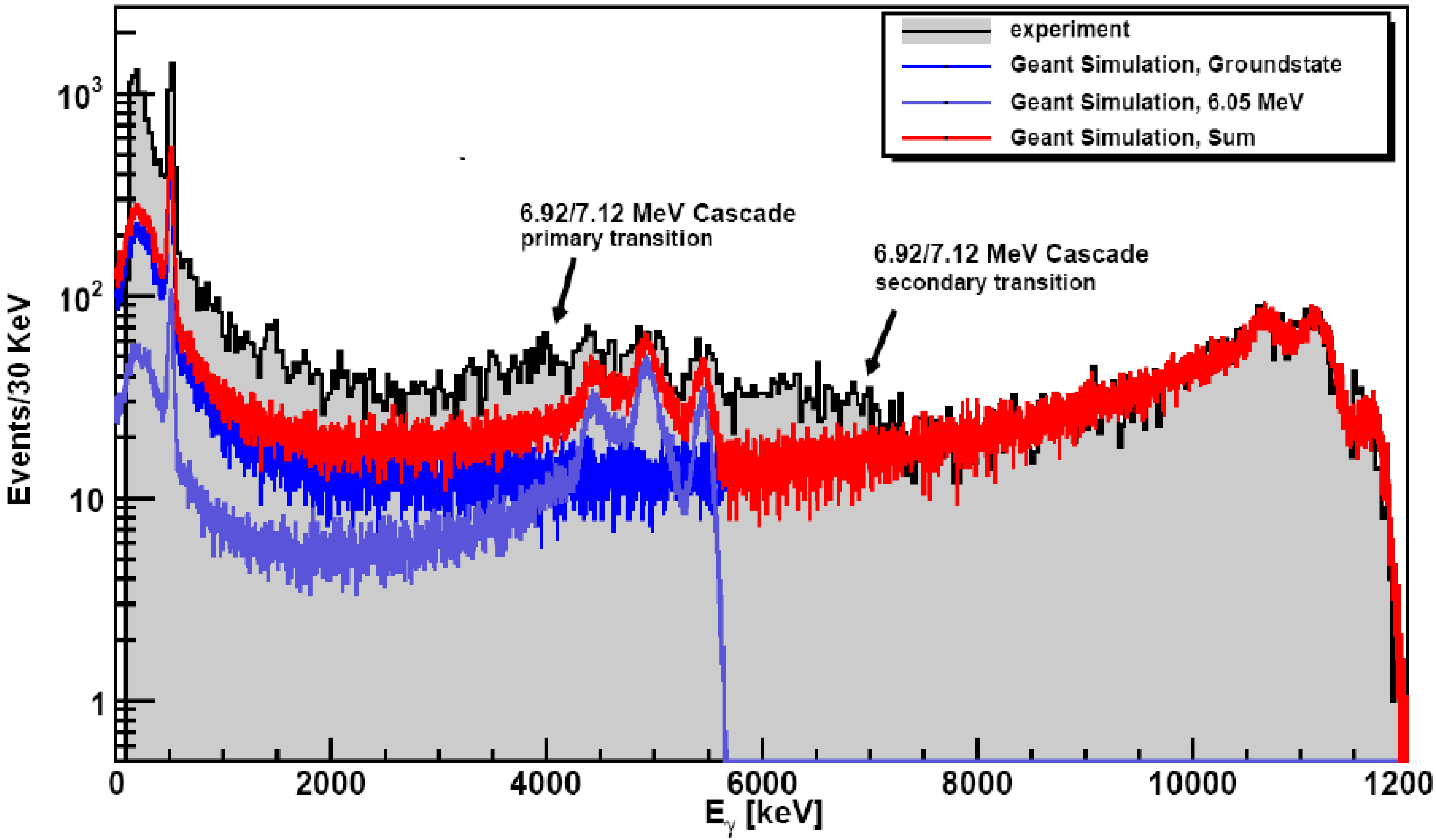



ERNA plans to extend the measurement to low energy with the new configuration @CIRCE

# Gamma-ray detection

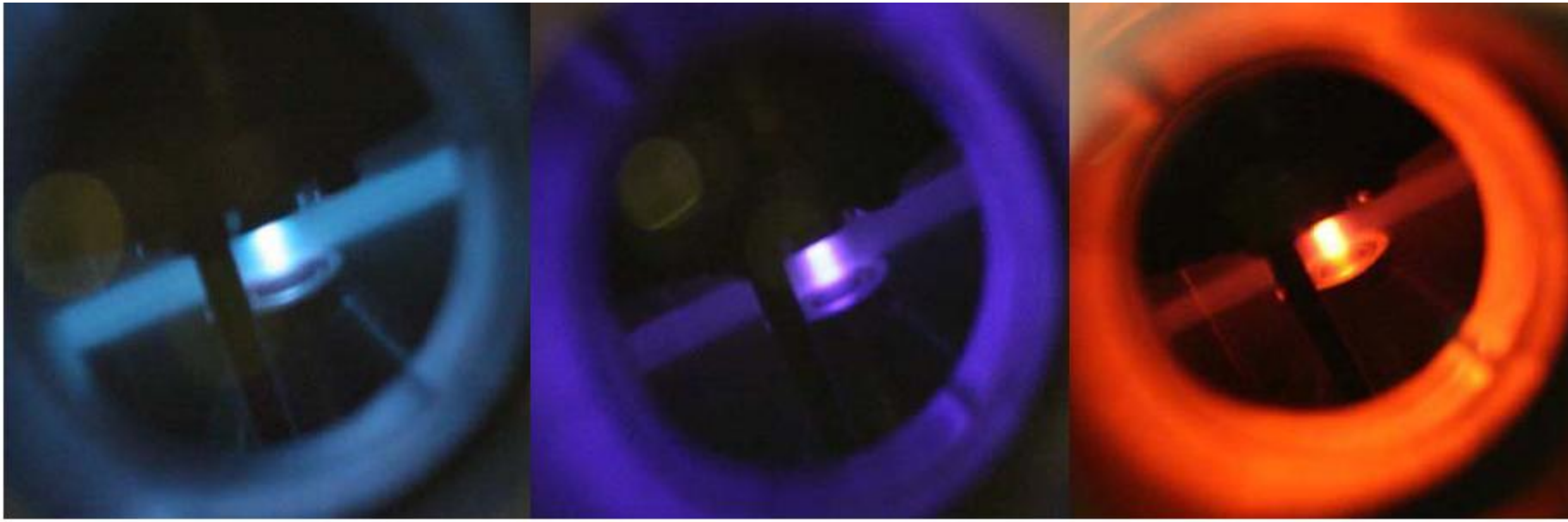


# Gamma-rays gated by recoils to suppress background

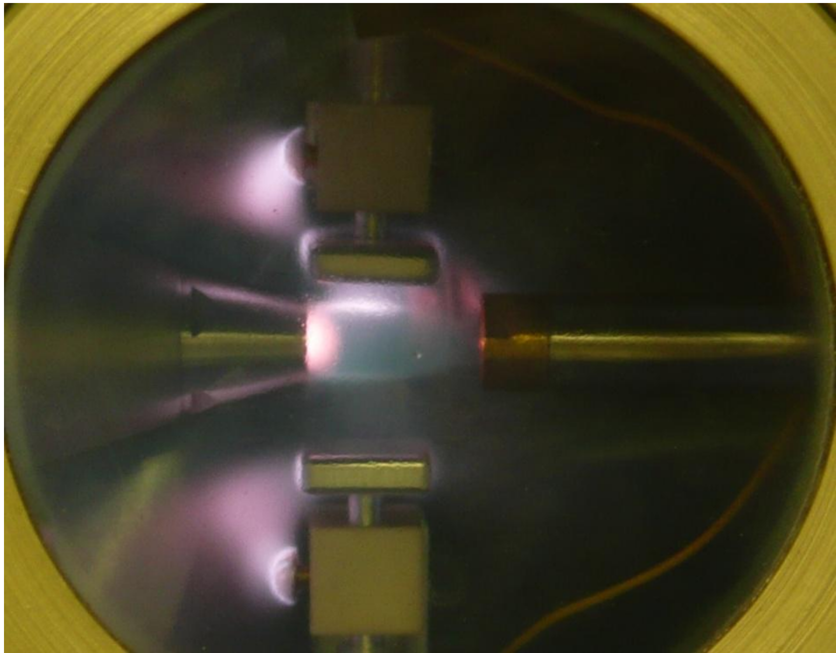



(in preparation)

# ERNA Jet target



Helium-Gas  Argon-Gas  Neon-Gas

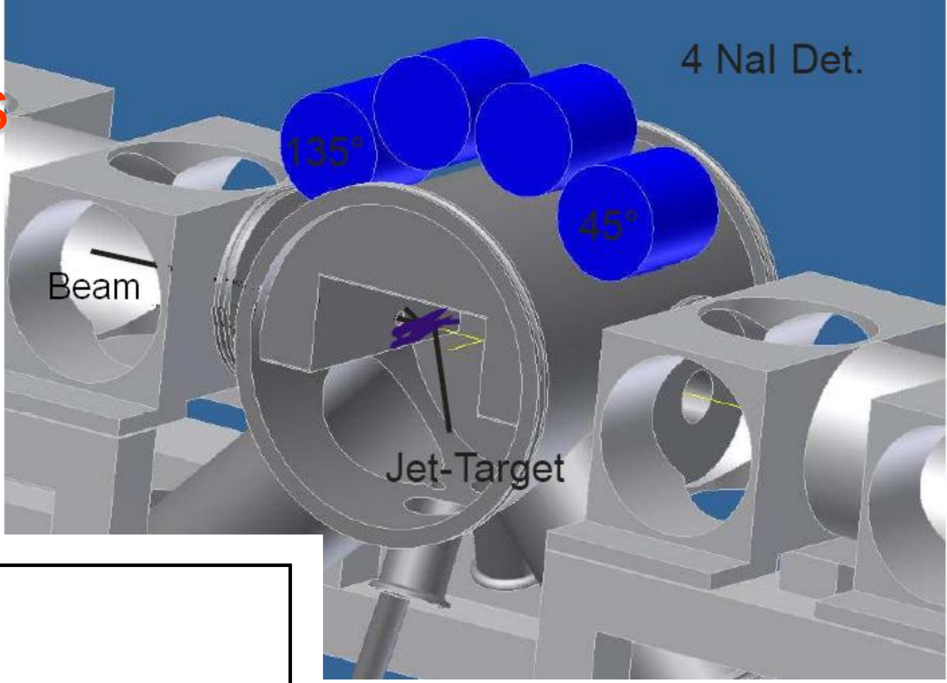


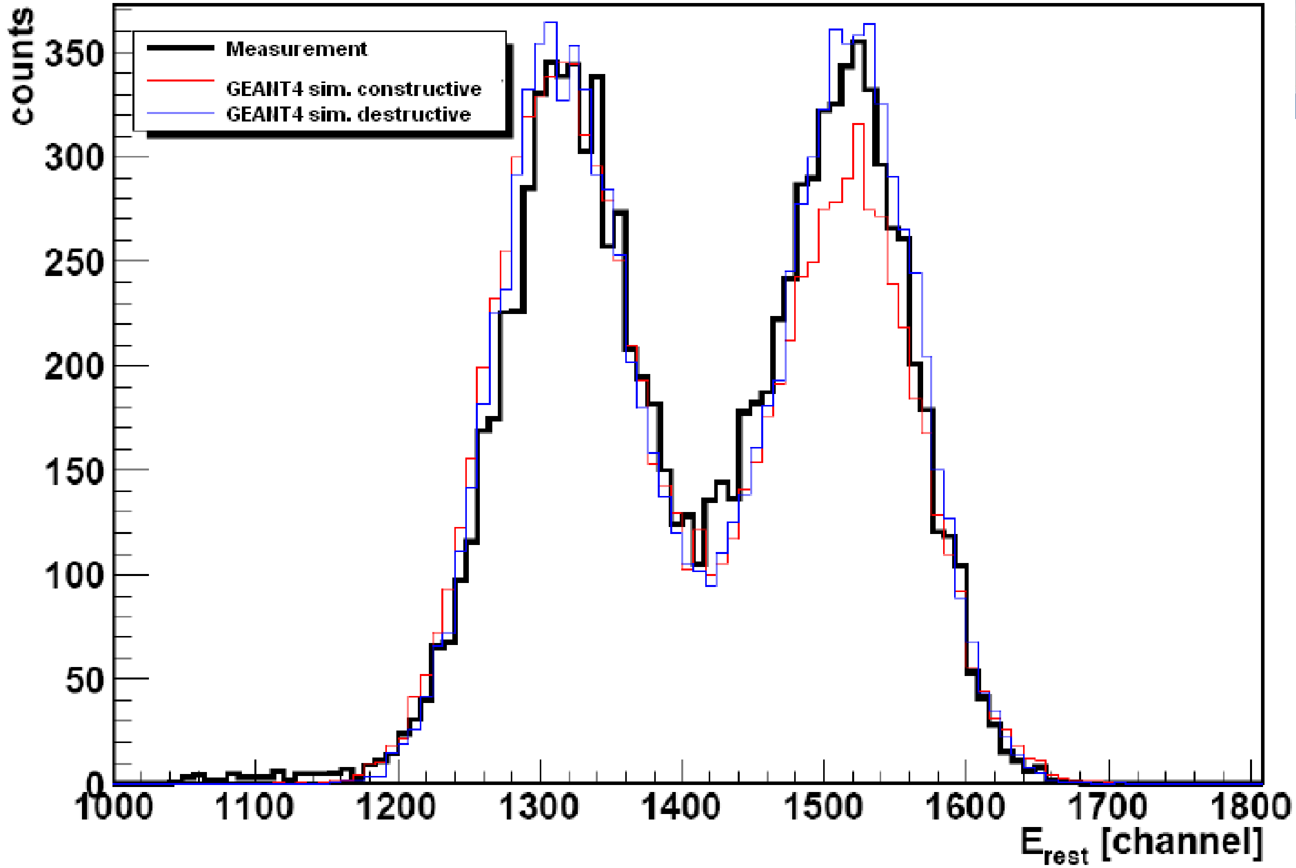
Optimization of nozzle-catcher design.

Collaboration with Notre Dame.

Collaboration with Plasmonx at LNF.

# Recoils gated by gamma-rays to select a transition:

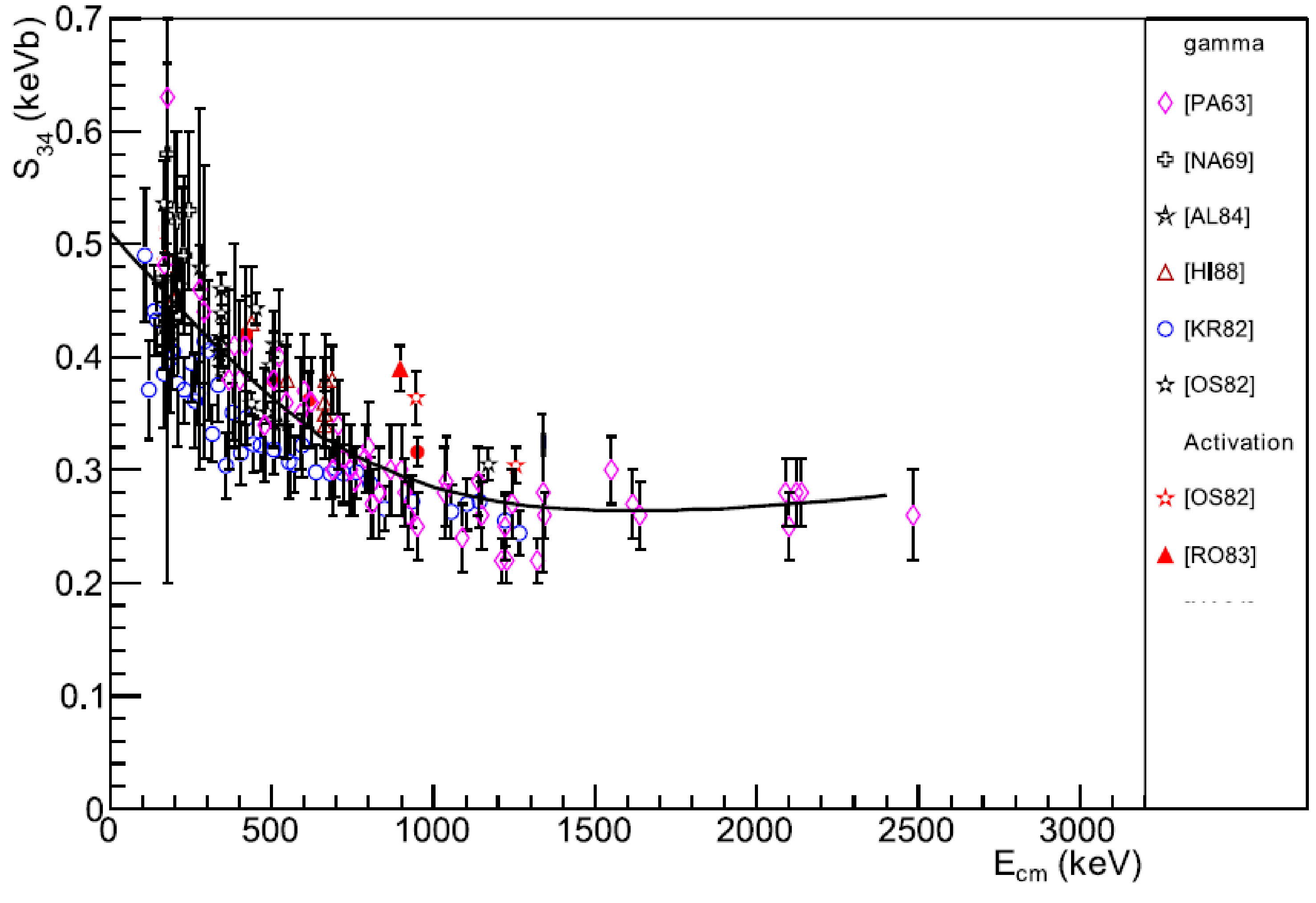


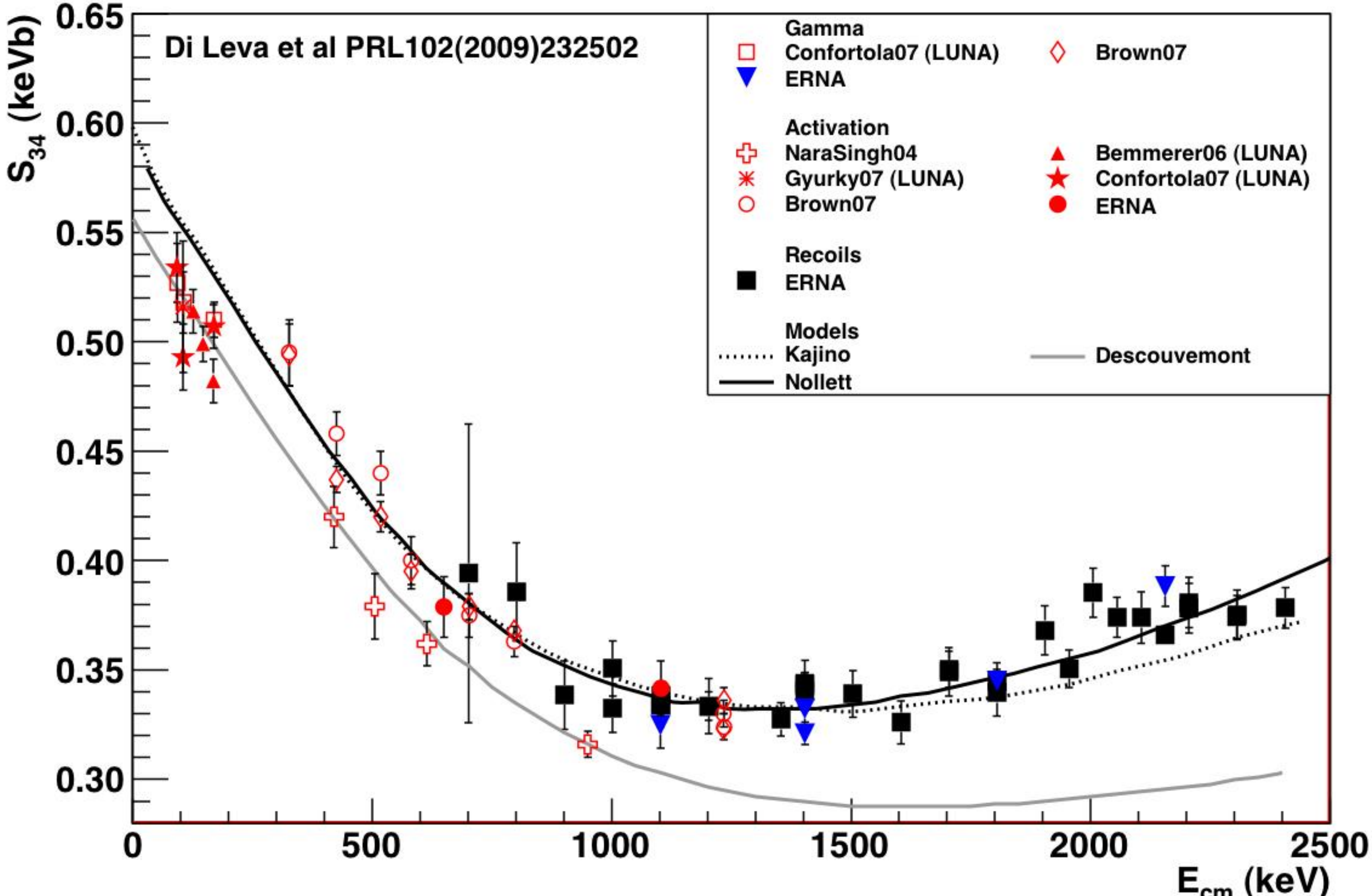

Effect of the gamma-ray angular distribution on the recoil energy spectrum.
Interference study.

# Production of $^7$Be in the Universe: $^3He(\alpha,\gamma)^7Be$

- BBN and stellar nucleosynthesis Palmerini et al PASA, 26-3, (2009)
- Measurement of the total cross section Di Leva et al. PRL102, 232502 (2009) and PRL 103, 159903 (2009)



# $^3He(^4He,\gamma)^7Be$ S-factor



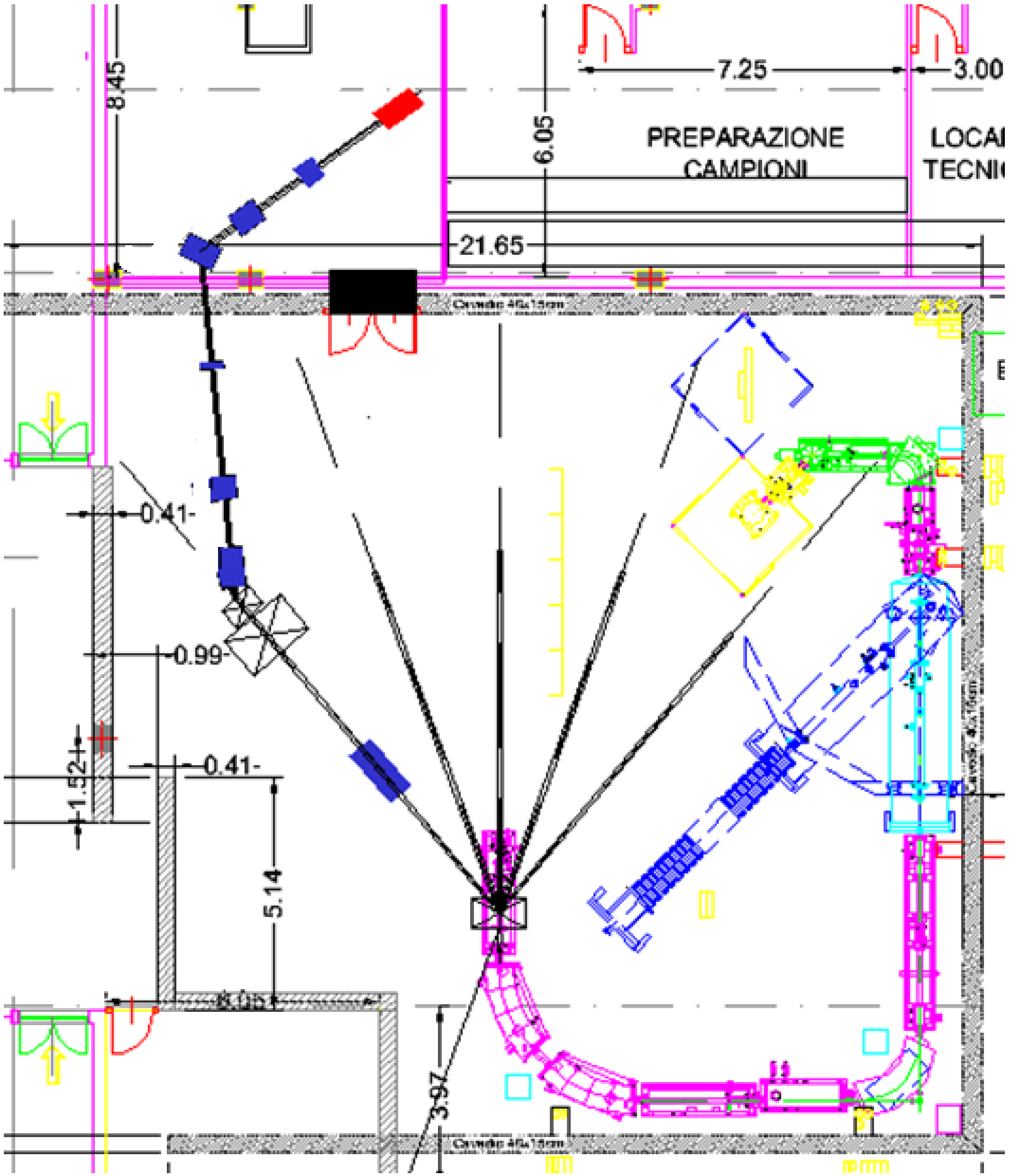

$$S_{34}(0) = 0.57 \pm 0.04\,\mathrm{keV \cdot b}$$

about 7% uncertainty

Di Leva et al., Physical Review Letter 2009

# ERNA @CIRCE

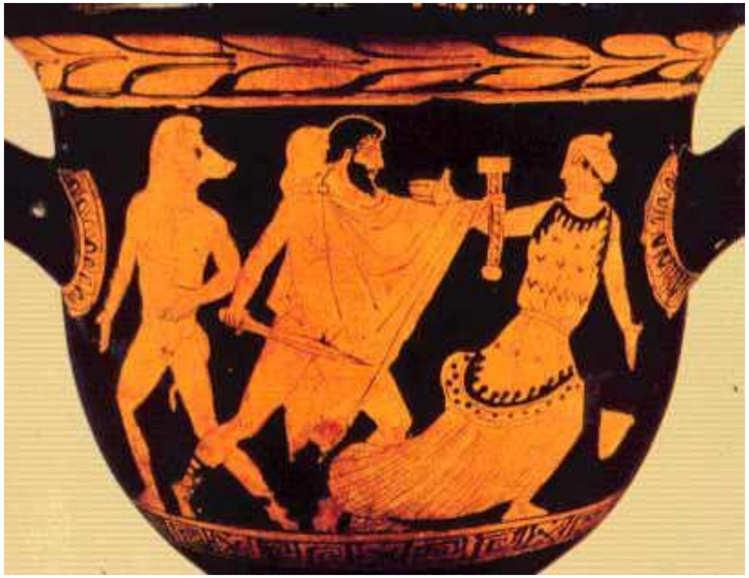
- Improvements in ion optics
-New detection setup



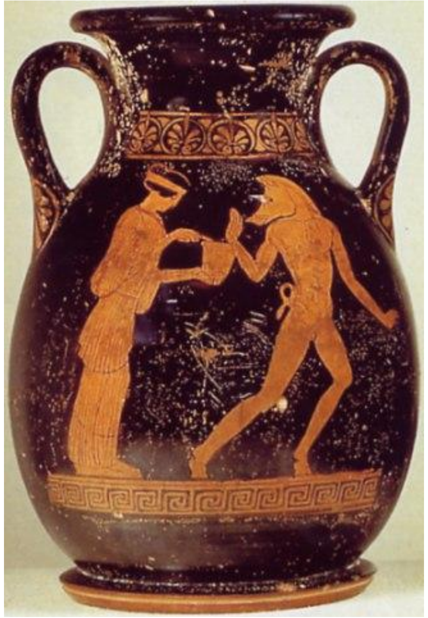
**Κίρκη**

Island of Eea

Dosso Dossi (Giovanni di Niccolo Luteri)
***"Circe"***, c. 1522-1524, canvas, Galleria Borghese, Rome



Circe and Odysseus



28/01/2005: where is it?

29/01/2005: first vacuum

2/02/2005:eppur si muove

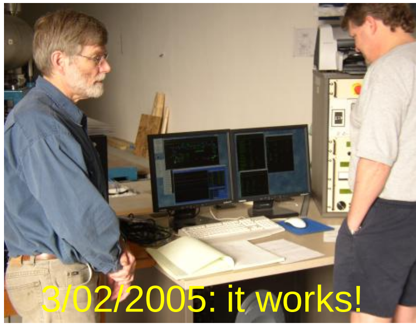
25/01/2005: looks fine

# Center for Isotopic Research on Cultural and Environmental heritage

aserta

INNOVA
CENTRO REGIONALE DI COMPETENZA
PER LO SVILUPPO ED IL TRASFERIMENTO
DELL'INNOVAZIONE APPLICATA AI
BENI CULTURALI E AMBIENTALI

Dipartimento di Scienze Ambientali
DSA-SUN



3/02/2005: it works!

19/01/2005: that's big!

14/02/2005: almost there

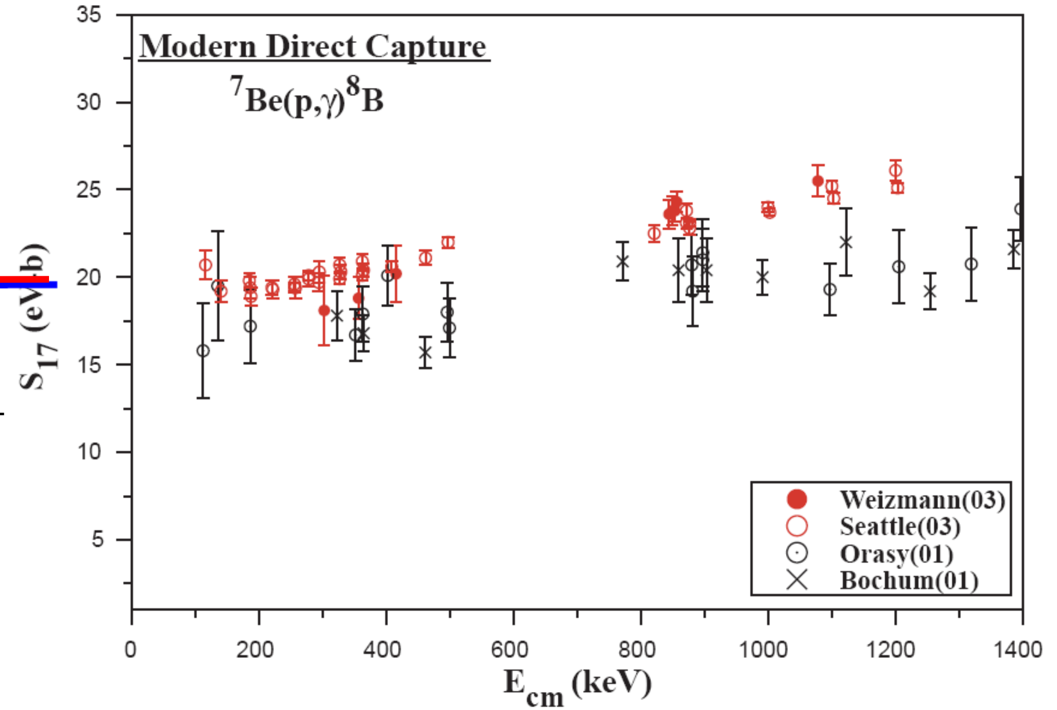
17/1/2005: here it is!

28/02/2005: nice work!

15/01/2005: waiting…

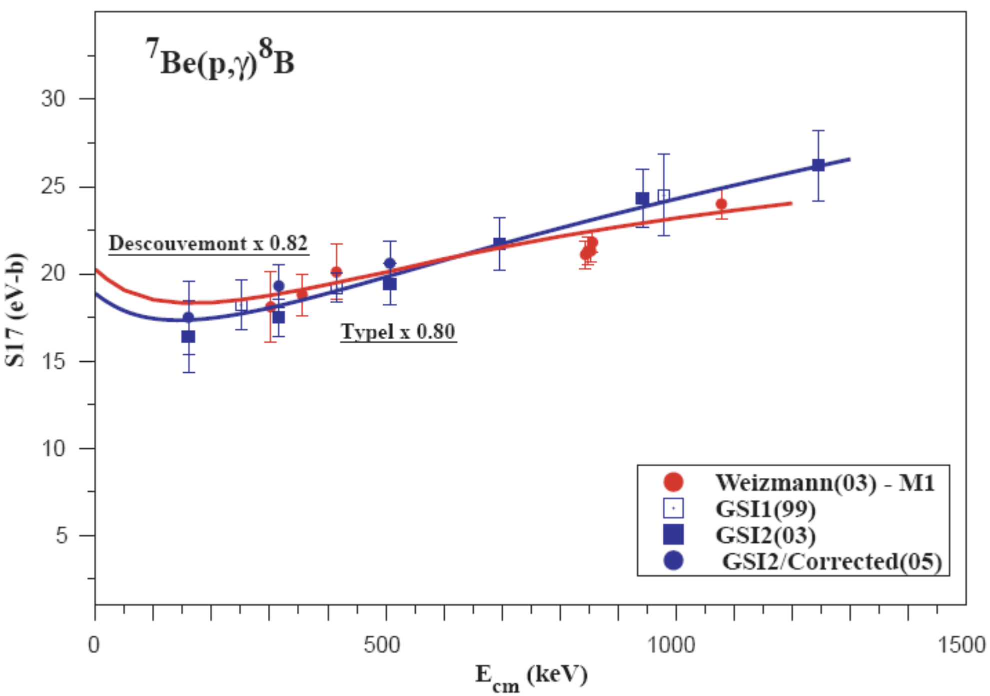
14/02/2005: et voilà

# Destruction of $^7$Be:
# $^7Be(p,\gamma)^8B$




Solar Neutrino
Abundance of light elements in stars

$1^+$



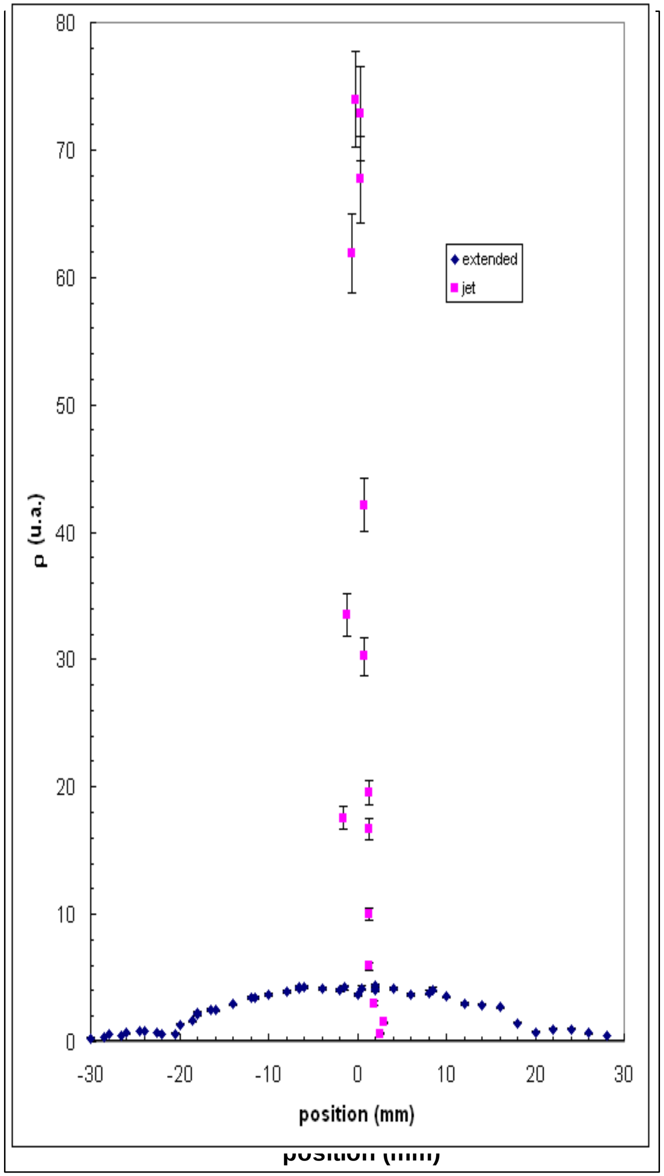

ERNA will measure at
$E_{cm}$=0.4-1.0 MeV

The toughest case:
$E_{cm}$=400 keV $\sigma$ ~160 nb

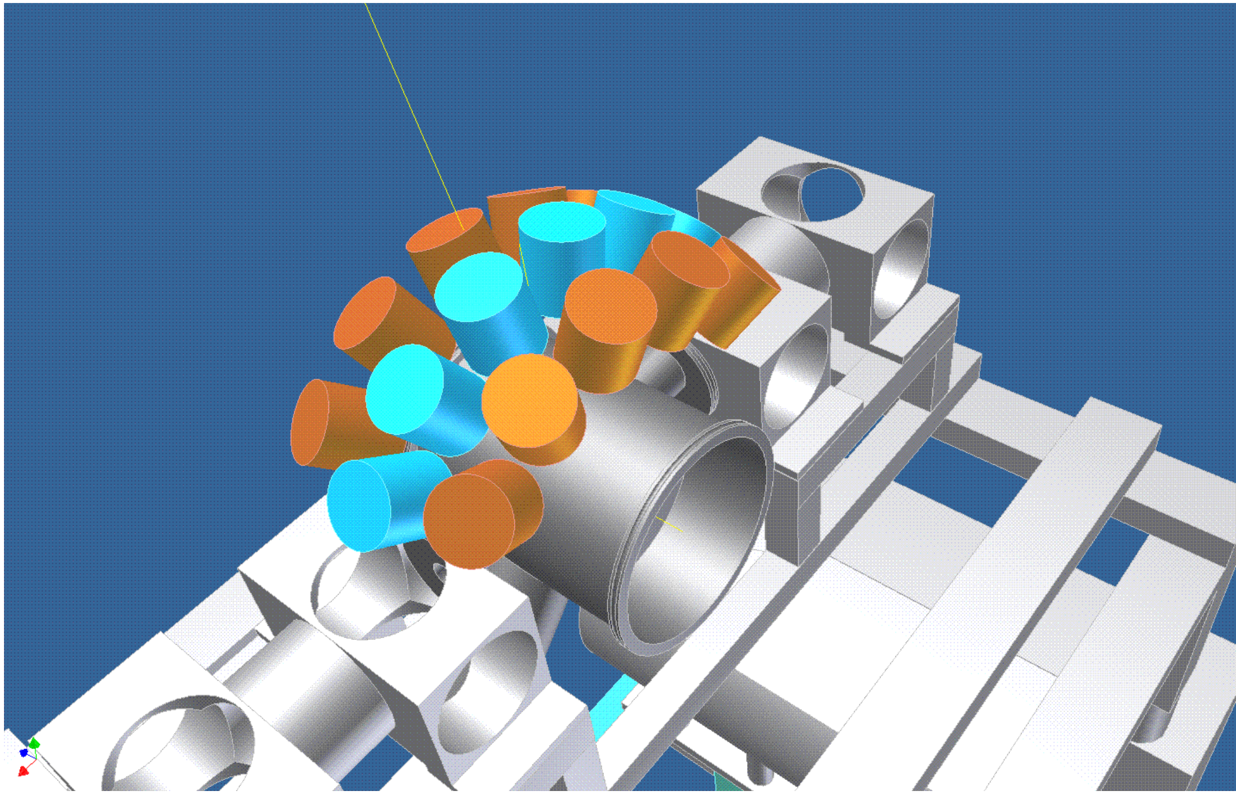
A=10 GBq (multiple cycle)
$\Delta x = 2\ 10^{19}$ at/cm$^2$
$\Delta t$= 1 d

Yield=150

# Gamma-ray detection: angular distribution




La2Br3 array



Determination of E1 and E2 in 12C+4He down to Ecm=1.3 MeV

# Other projects

1) Nucleosynthesis in AGB

2)Blocking of helium burning and carbon burning: $^{16}O(\alpha,\gamma)^{20}Ne$.

$^{16}O(\alpha,\gamma)^{20}Ne$ is a perfect test of the microscopic cluster models used for alpha captures on light nuclei (e.g. PRC 38(1988)2463).

A lot of discussion about a non resonant term.
(PRC36(1987)892 , NPA A612(1997)149c)

Best case for E0 transitions in light nuclei

# Satellite projects

1) $^{12}C+^{12}C$ fusion reactions
Proton channel completed
Alpha channel planned in 2011, possibly in Bochum
(Bragg Spectrometer+Si – Uni Connecticut)