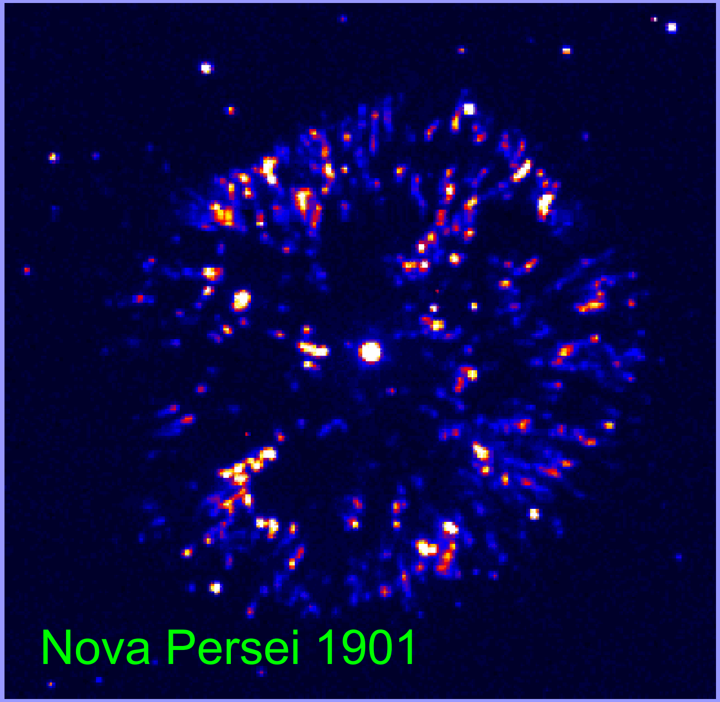
γ-ray emission of classical novae and ^{18}F nucleosynthesis

I. Astrophysical motivations
   i. Classical novae
   ii. γ-ray emission + observation
   iii. ^{18}F: < 511 keV emission

II. ^{18}F(p,α)^{15}O measurement
   i. Experiment
   ii. Results



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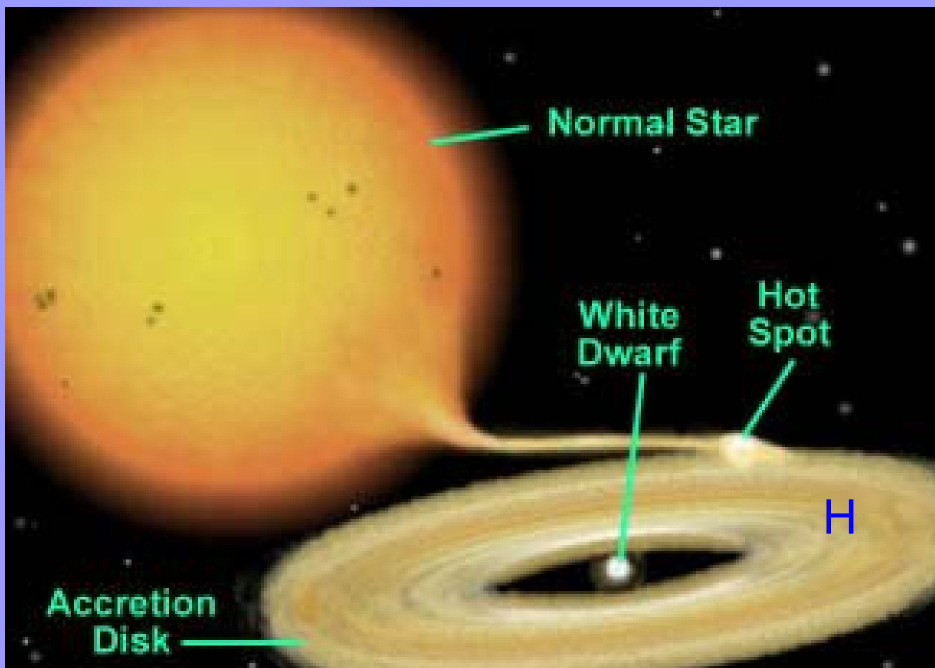
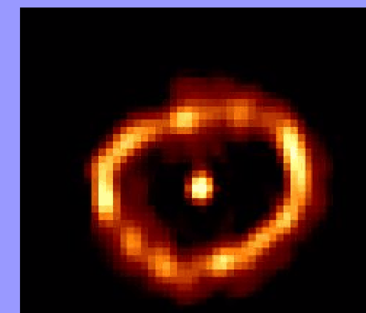
Classical novae

Final evolution of a close binary system



- Accretion (H) from a MS star to the White Dwarf
- Ignition of the combustion at the base of the envelope
- Nucleosyntesis in the convective envelope
- Shell ejection in the interstellar medium



Nova Cygni 1992

- Well-known mechanism BUT:
  - ejected mass < observed mass
  - mixing between accreted and WD material

	Novae	SNII
M_{ej} (M_o)	~ 10^{-5}	~ 10
f (yr^{-1} $galaxy^{-1}$)	~ 30	~ 10^{-2}
L (L_o)	~ 10^{5}	~ 10^{11}
Nucleosynthesis	< S	~ Fe + "r"

→ CO / ONe novae (M_{WD} < 1.4 M_o)

- energetic, expansion velocity
- nucleosynthesis

Production of γ-ray emitters

	Isotope	Decay	τ (lifetime)	E_γ (keV)	Novae type	Seed nuclei
Short lived nuclei	^{13}N	β+	862 s	511 line + continuum	CO + ONe	^{12}C
	^{18}F	β+	158 min			^{16}O
	^{7}Be	e^- capture	77 days	478	CO	^{3}He
Long lived nuclei	^{22}Na	β+	3.75 yr	1275 + 511	ONe	^{20}Ne
	^{26}Al	β+	10^6 yr	1809 + 511	ONe	^{24,25}Mg and ^{23}Na

Why observing γ-ray emission from novae?

- Access to isotopic abundances as a probe of the nucleosynthesis path

- Properties of the expanding shell (511 keV from ^{18}F)
  $\tau(^{18}F)$ = 2h ~ time for the shell to become transparent (a few hours)

- Access to the galactic distribution of novae (cumulative ^{22}Na observations)
  $\rightarrow$ not sensitive to interstellar absorption

γ-ray observations of novae

In the past:

^{7}Be: upper limits derived: GRS (SMM) + TGRS (WIND) (Harris et al.)

^{22}Na: upper limits derived for

- single nova COMPTEL (CGRO) (Iyudin et al. AIP 637)
- cumulative emission

^{26}Al: $\tau = 10^{6}$ yr $\rightarrow$ cumulative emission observed (novae? massive stars)

Next with INTEGRAL:

SPI 3σ detectability

	^{7}Be 478 keV line	^{22}Na 1275 keV line
d (kpc)	0.4	1.1

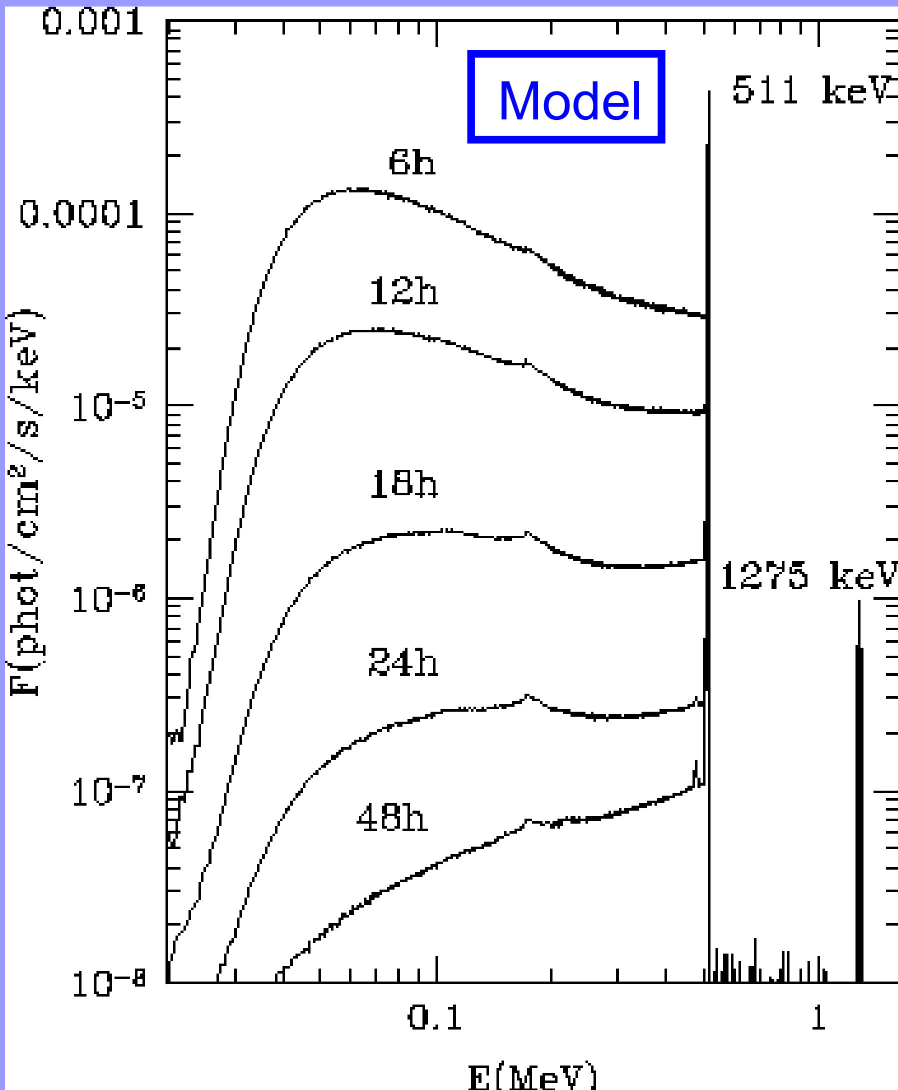
(Hernanz et al. 2001)

$\approx$ a few novae during INTEGRAL lifetime

$\rightarrow$ no positive detection

^{18}F : 511 keV line prediction

ONe nova 1.25 $M_\odot$ @ 1 kpc

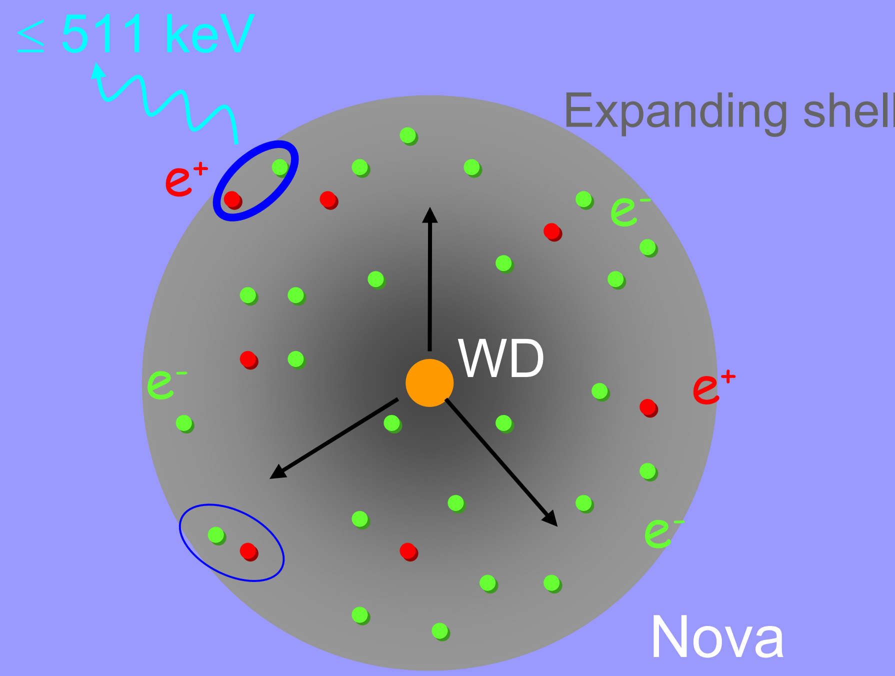


Hernanz, Gomez-Gomar, José (2001)

^{18}F ($T_{1/2}$ = 2h) β+ emitter

→ e+ e- interactions

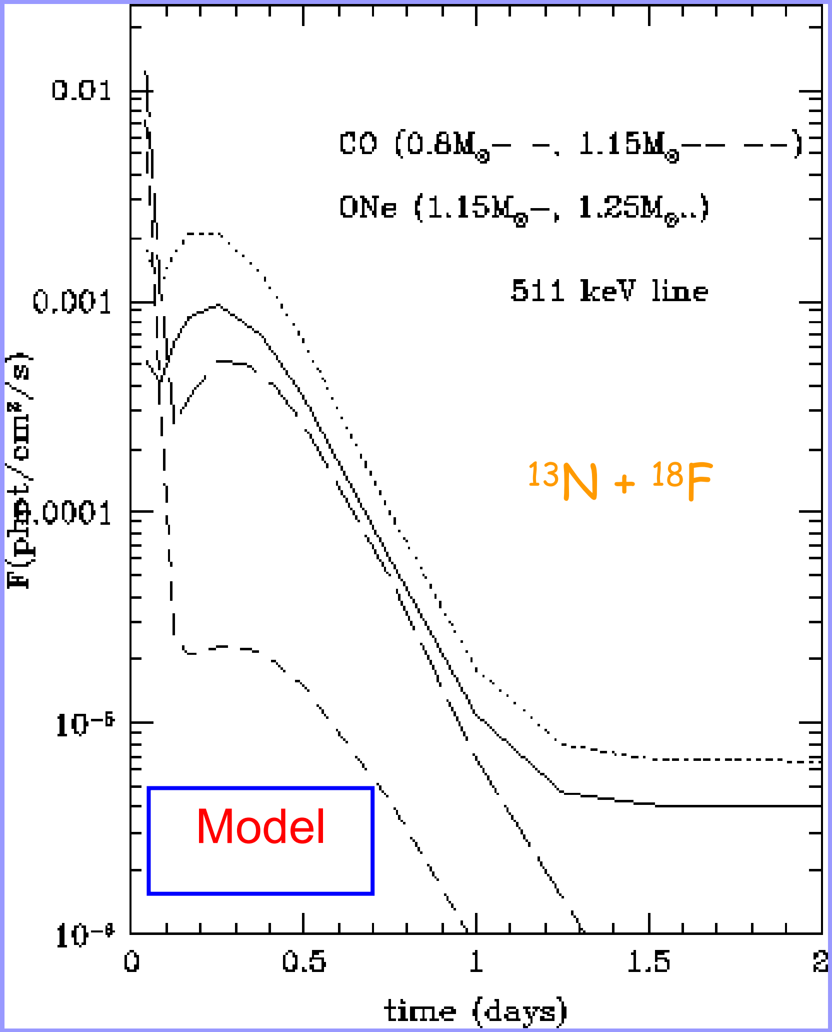
- line @ 511 keV
- continuum< 511 keV
- comptonization
- $e^+ + e^- \rightarrow 3\gamma$ (positronium)



Uncertainty ≈ 300 on the γ-ray flux

^{18}F: 511 keV line observation

511 keV line light-curve



Hernanz, Gomez-Gomar, Jose (2001)

Problem:

→ short-time emission

→ before visual detection

- a posteriori analysis
- wide field of view

In the past:

BATSE (CGRO): NaI (Hernanz et al.)

→ upper limits

TGRS (WIND): Ge (Harris et al. 1999)

→ upper limit for cumulative emission

→ compatible with models

INTEGRAL: SPI 3σ detectability distance (kpc)

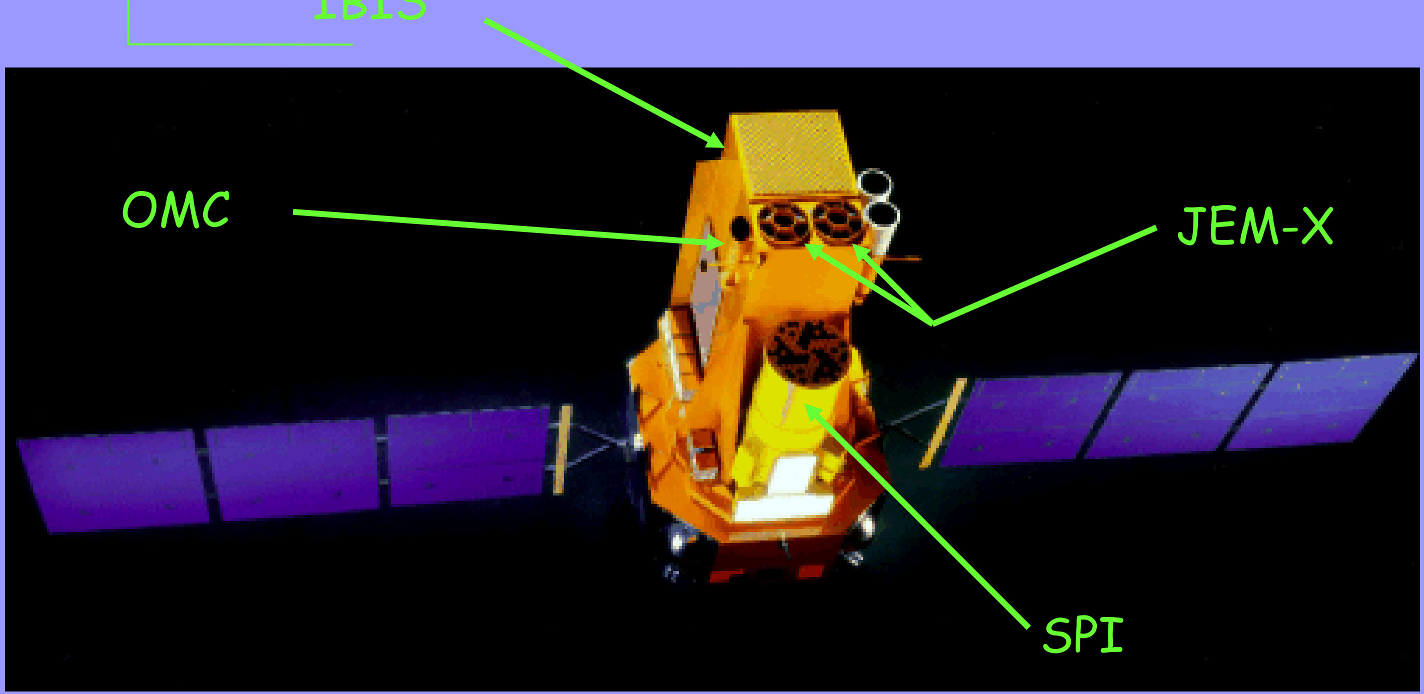
10h integration at the emission maximum

Nova type	511 keV	(170 – 470) keV
CO 0.8 M_o	0.7	0.4
CO 1.15 M_o	2.4	2.0
ONe 1.15 M_o	3.7	3.0
ONe 1.25 M_o	4.3	3.0

INTEGRAL satellite

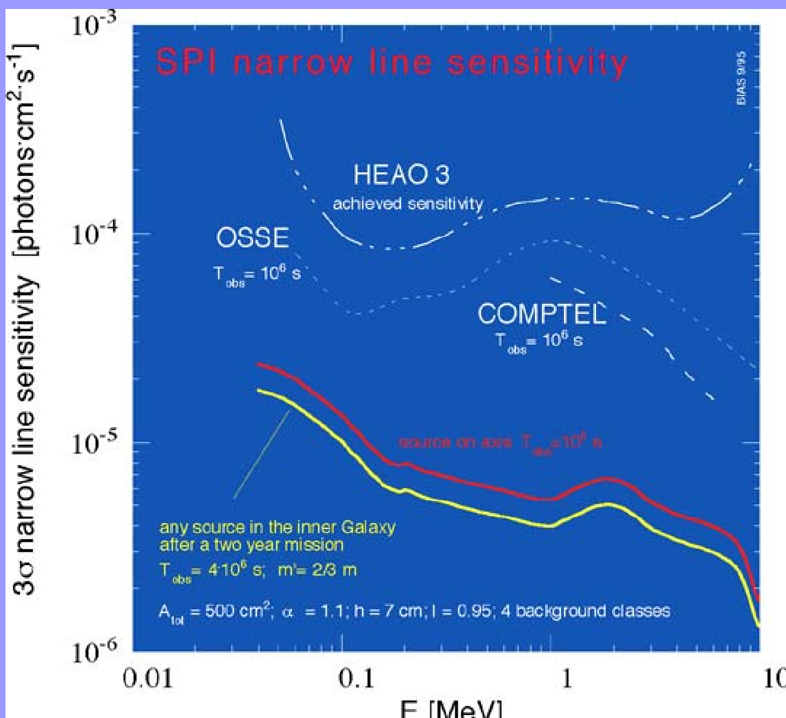
INTEGRAL launched successfully on October 17^{th} 2002 by a Proton rocket (Russia)

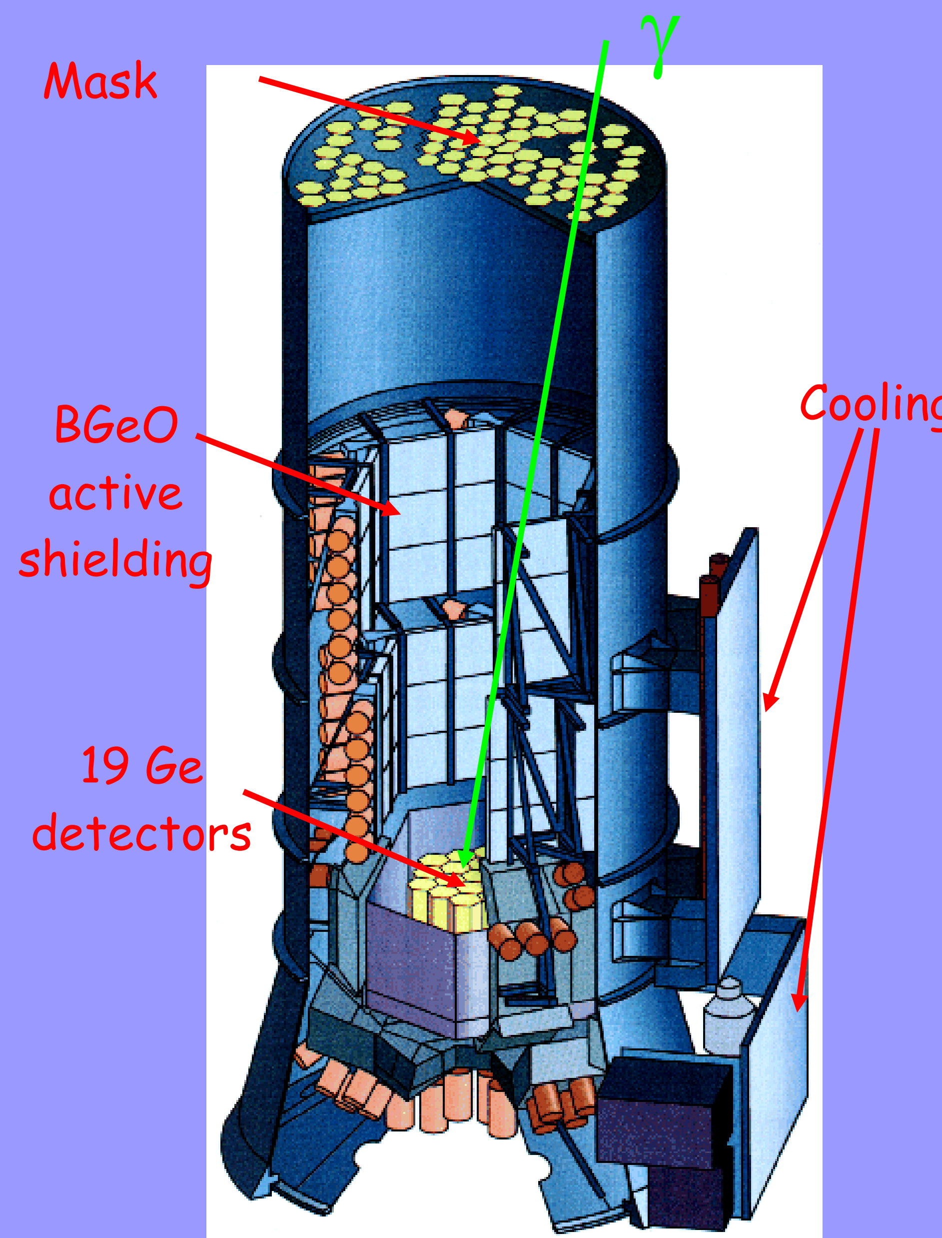
Energy range	15 keV - 10 MeV
Energy resolution	8%
Detectors	16384 CdTe et 4096 CsI
Angular resolution	12’



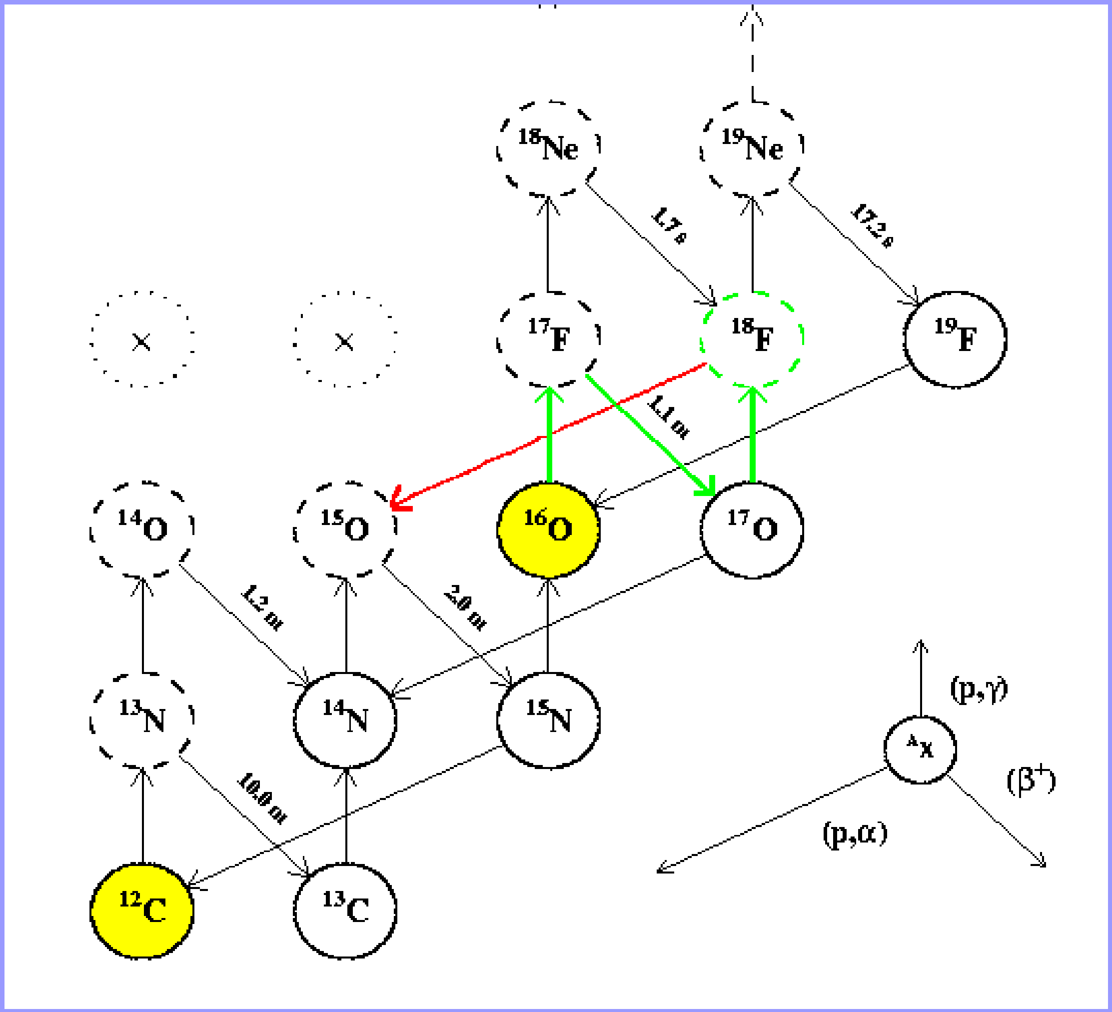
INTEGRAL: SPI spectrometer

Energy range	**20 keV – 8 MeV**
Energy resolution	2 keV @ 1 MeV
Detectors	19 HP Ge @ 85 K
Angular resolution	**2° FWHM**
Field Of View	**16°**
Detector area	500 cm^2





Nucleosynthesis of ^{18}F ($T_{1/2}$ = 110 min)



- Explosive hydrogen burning at the white dwarf surface
- Seed nucleus: ^{16}O
  → CO and ONe novae
- Hydrodynamical calculations
  → SHIVA code
  José & Hernanz (1998)
- Main nuclear uncertainty: ^{18}F(p,α)^{15}O
  → uncertainty ≈ 300 on γ-ray flux
  Coc et al. (2000)

- Other nuclear uncertainties: ^{17}O(p,γ)^{18}F and ^{17}O(p,α)^{14}N
  TUNL + Orsay (CSNSM)

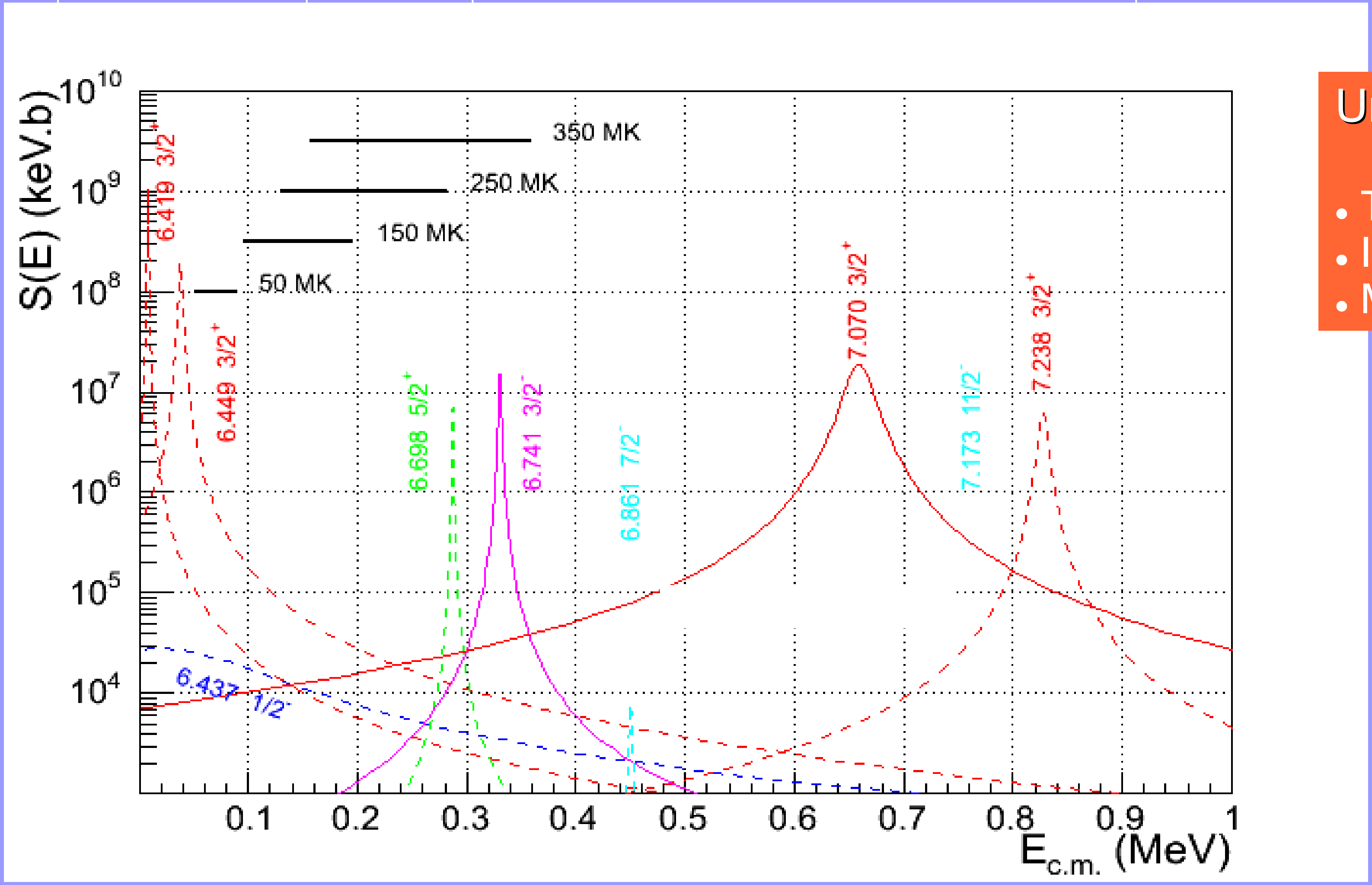
$^{18}F(p,\alpha)^{15}O$ current status

de Séréville et al. 2003
Kozub et al. 2005

Cosach et al. 1995
Rehm et al. 1995
Graulich et al. 2001
Bardayan et al. 2002

(d,p) | (p,p) + (p,α)

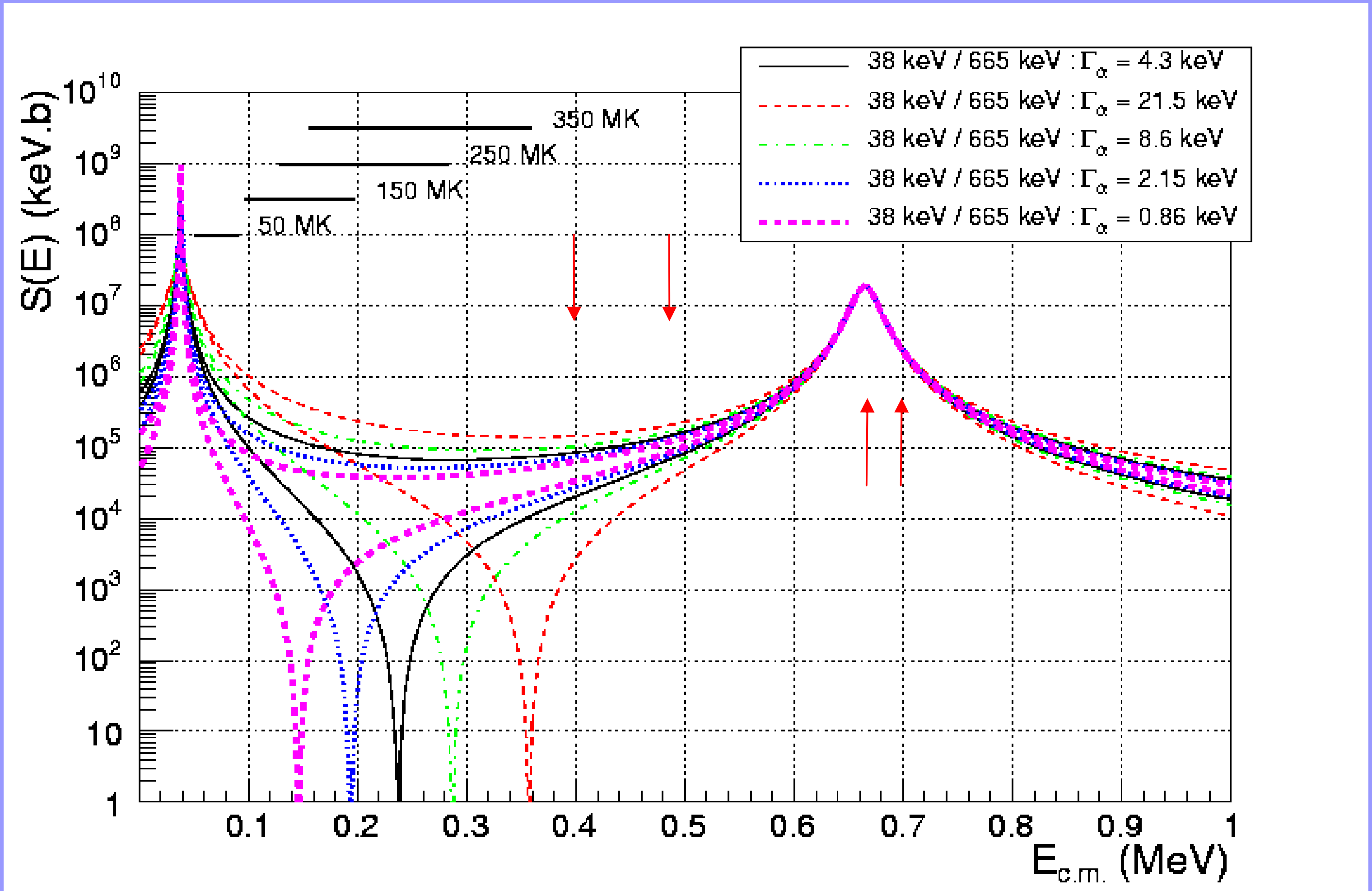
indirect | direct



Uncertainties

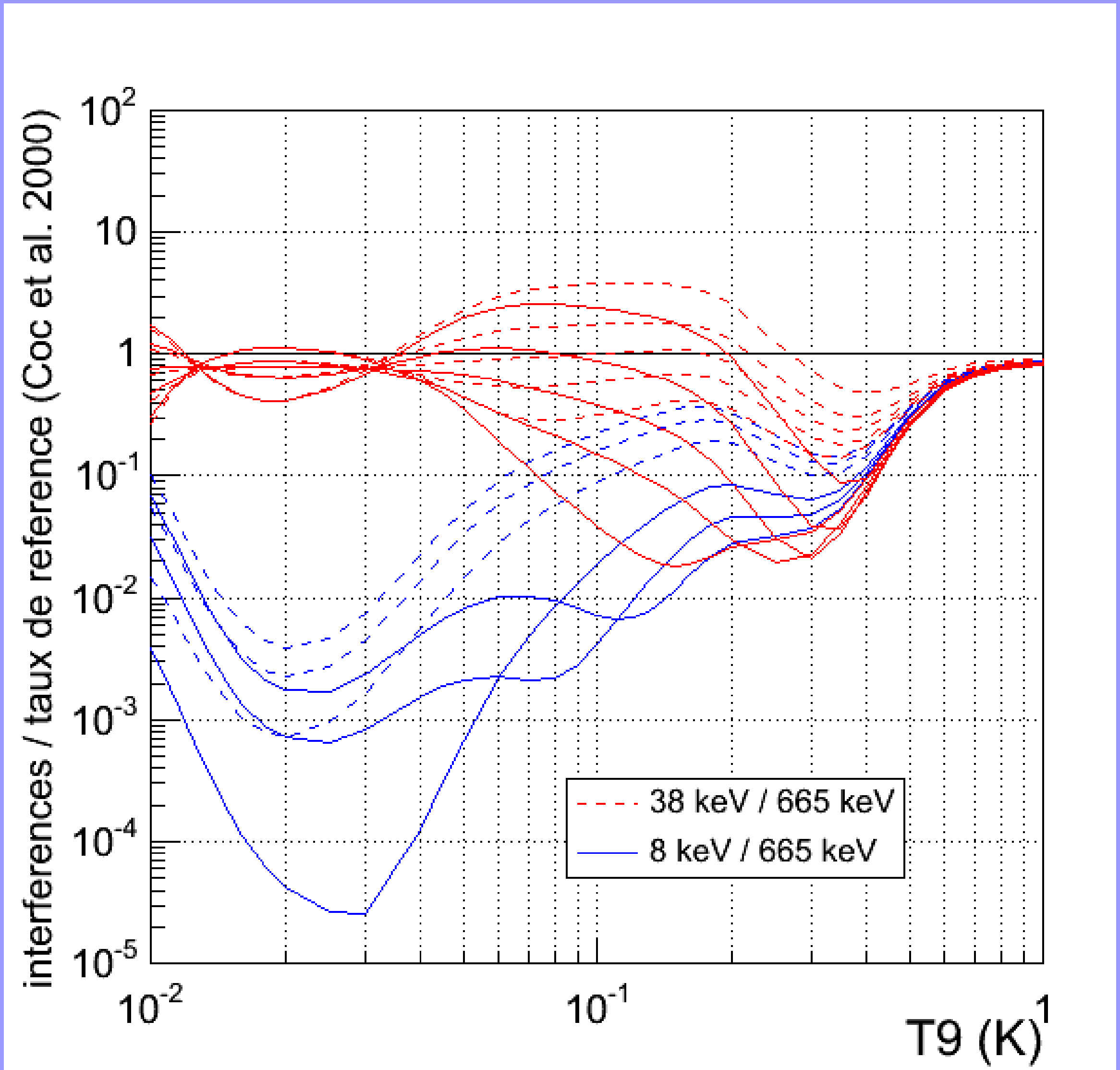
- Total widths
- Interferences
- Missing levels

Interferences effect / experimental method



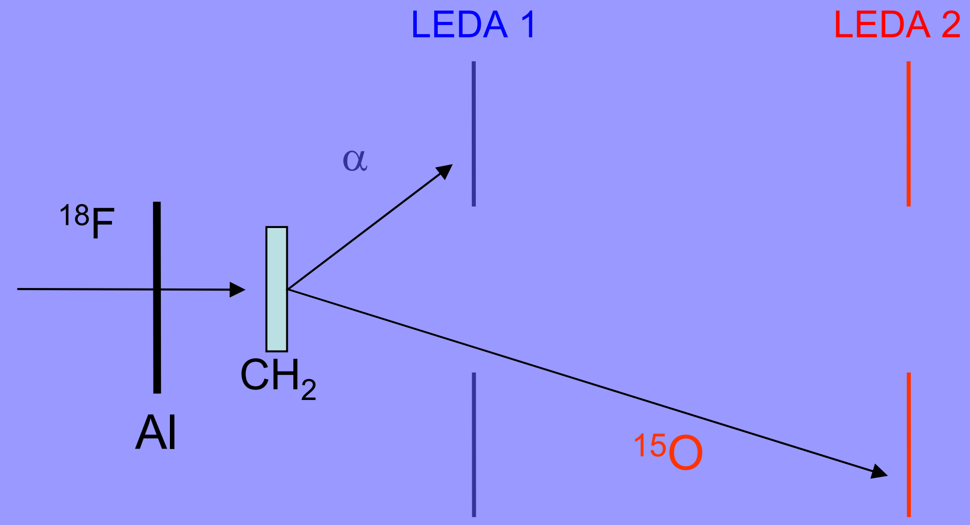
- Interference effect in the Gamow peak
- low intensity ^{18}F beam
  → difficult to measure below 300 keV
- Direct measurement at higher energies
  → 4 energies
- R-matrix analysis

$^{18}F(p,\alpha)^{15}O$ nuclear uncertainties



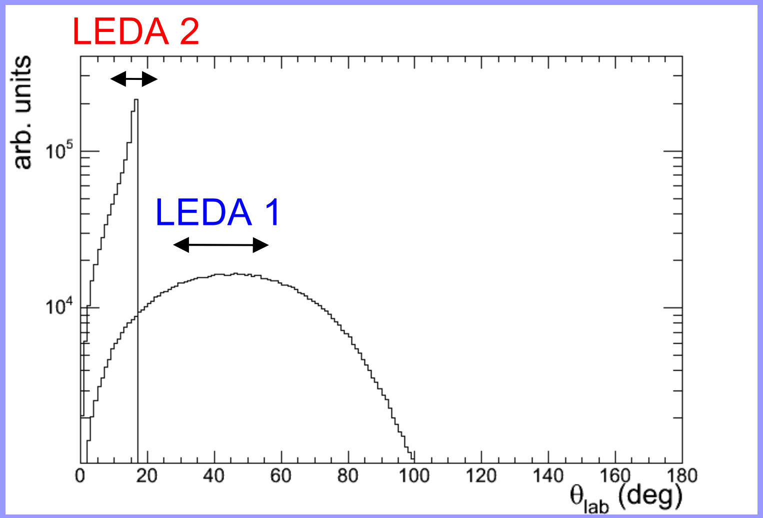
For T > 100 MK, uncertainty of three order of magnitude

Experimental set-up: p(^{18}F,α)^{15}O



Detector positions:

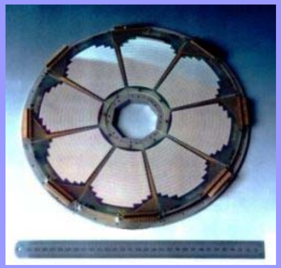
- LEDA1: solid angle
- LEDA2: coincidence efficiency (30%)

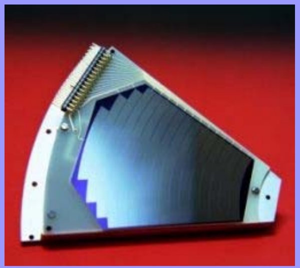


LEDA detectors:

(Louvain LN + Edinburg)

Davinson et al. NIM A 2000





- silicon multistrip detectors (300 μm)
- sector with 16 annular strips
- energy resolution (≈ 30 keV FWHM)

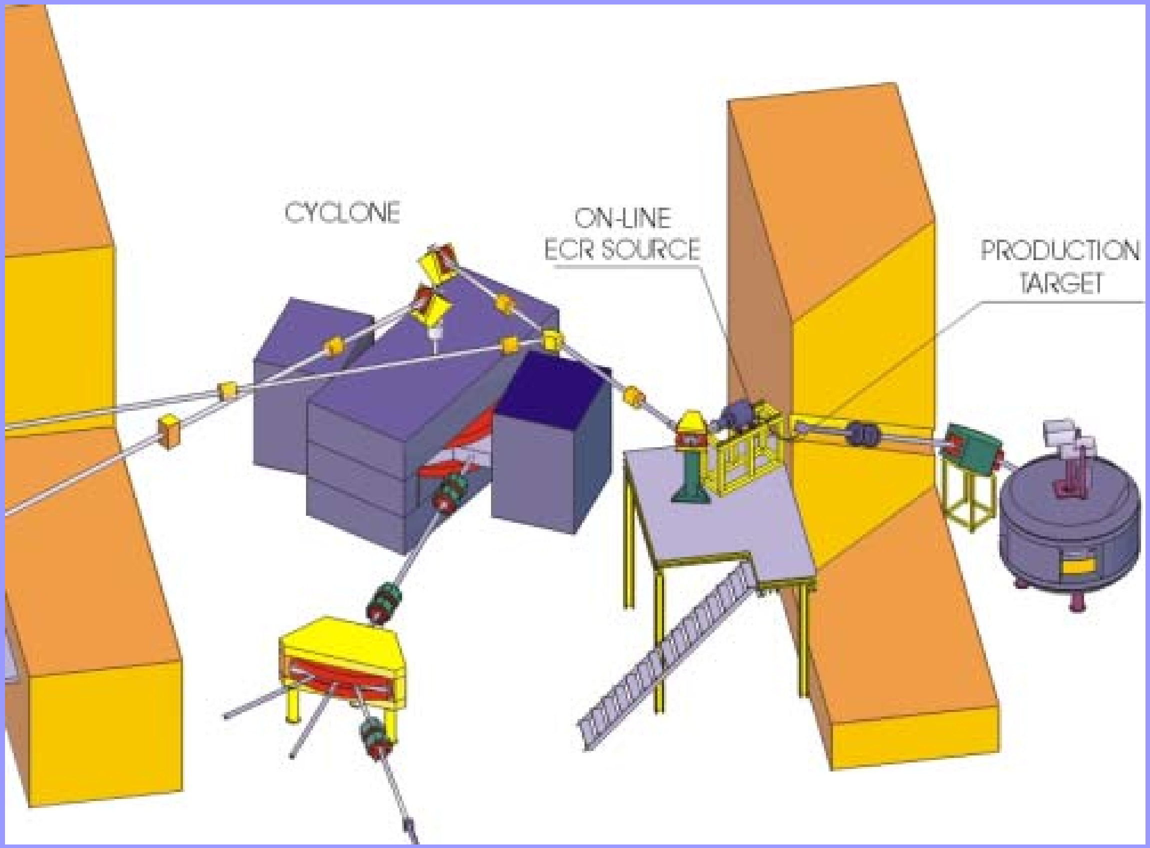
Target: $CH_2 \approx 70\ \mu g/cm^2$

→ covered c.m. energy range / counting rate

Degraders: Al (95, 500, 670 $\mu g/cm^2$)

$E_{c.m.}$ = 665, 485, 400 keV

^{18}F beam production at LLN



Production of ^{18}F ($T_{1/2}$ = 110 min) :

- $^{18}O(p,n)^{18}F$ E_p @ 30 MeV
- chemical extraction (45 min) -> $CH_3{}^{18}F$
- 1 bunch of ^{18}F / 2h (0.5 to 1Ci!)
- 17 bunches of ^{18}F over 1 ½ week

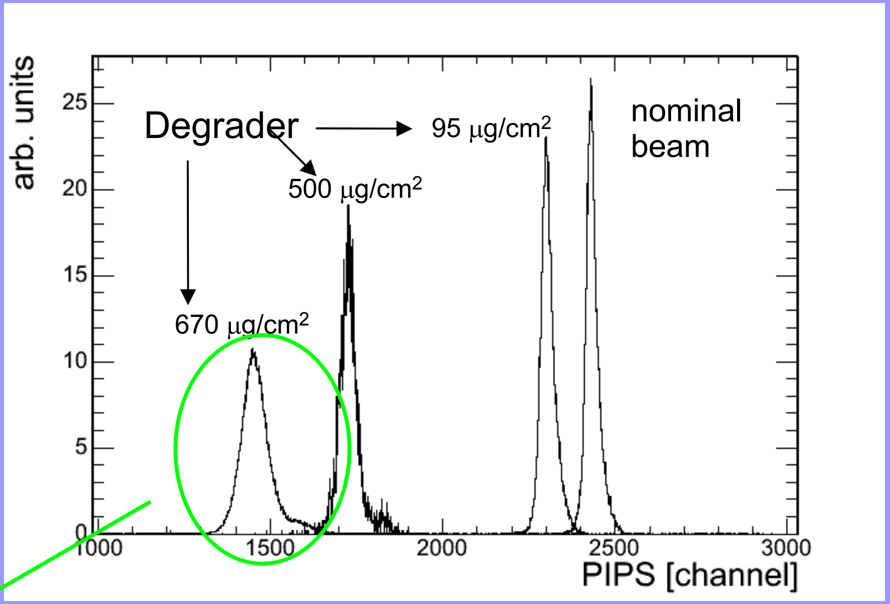
(Cogneau et al. NIM A 1999)

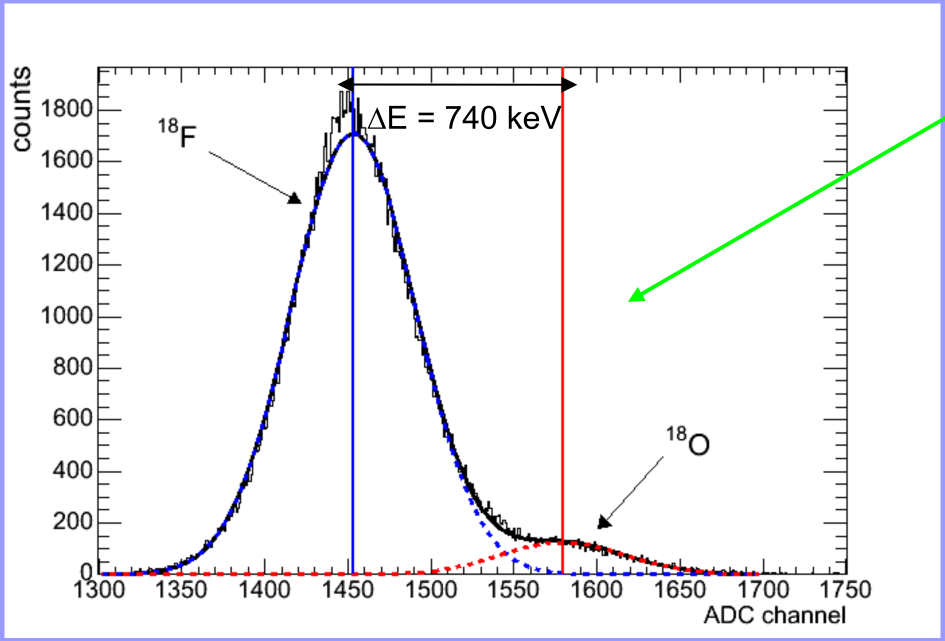
Acceleration :

- E(^{18}F) = 13.8 MeV
- I ≈ 10^6 pps
- rejection of ^{18}O contamination

^{18}F beam characteristics

Measurement at 0 degree (PIPS)
- check degrader thickness
- determine beam energy profile at target entrance

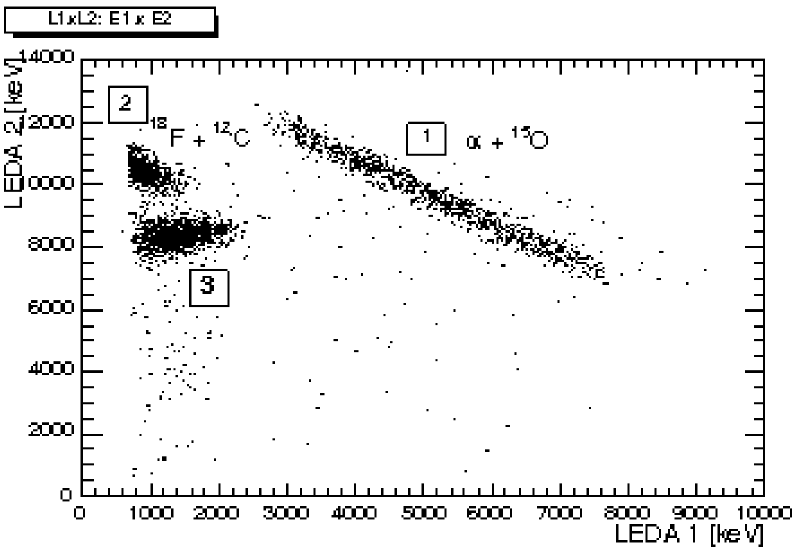




^{18}O contamination:
- ^{18}O / ^{18}F energy loss different for the thicker degrader
- fit with energy of each component as a free parameter

→ ^{18}O / ^{18}F < 1%

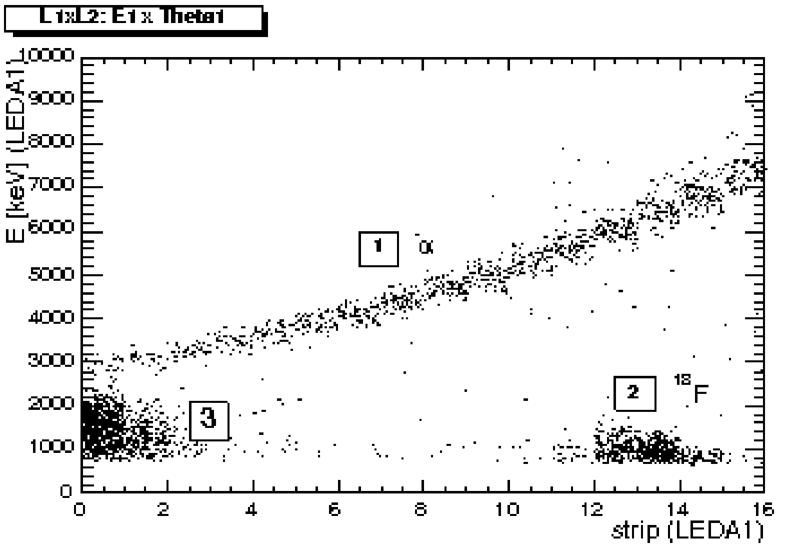
$^{18}F + p$: α – ^{15}O coincidences ON resonance

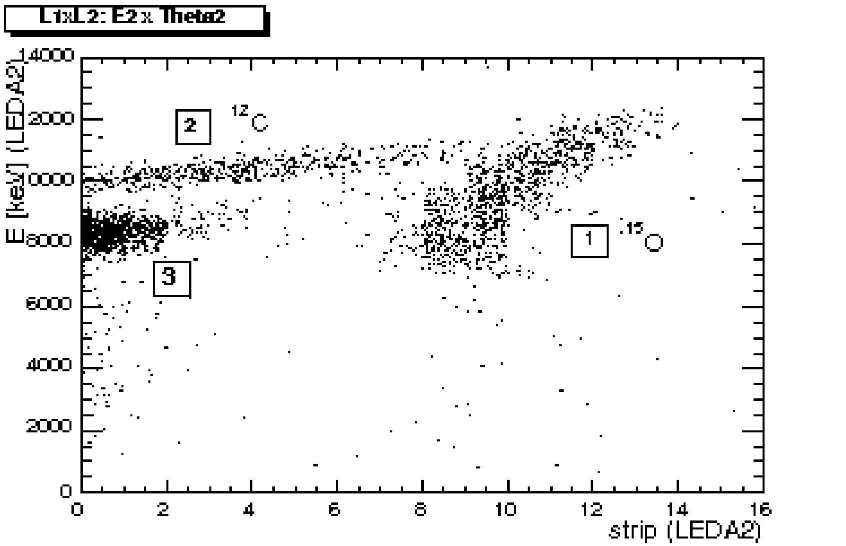


Coincidences LEDA1 x LEDA2

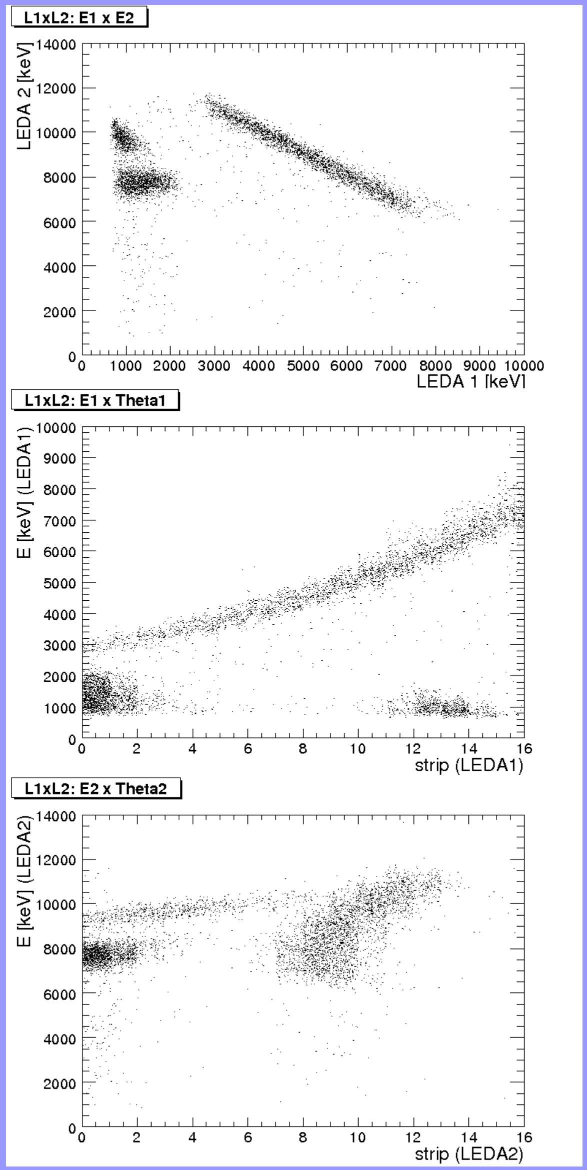
→ clear identification of $^{18}F(p,\alpha)^{15}O$ events

E_{cm} = 665 keV → 4150 events
E_{cm} = 700 keV → 1450 events





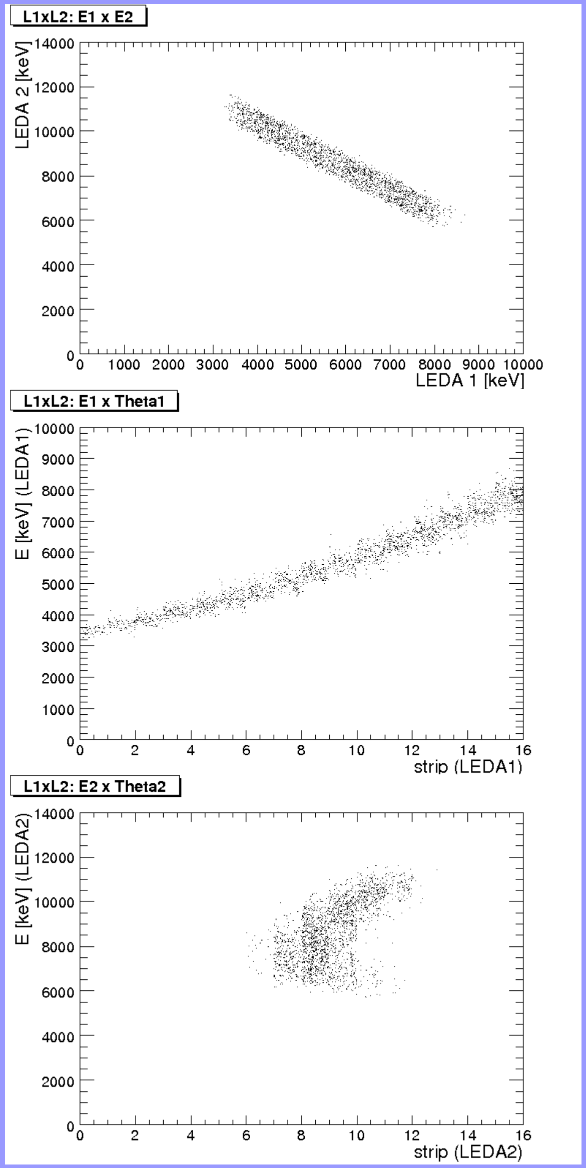
Experiment v.s. Simulations



E_α x E_{15O}

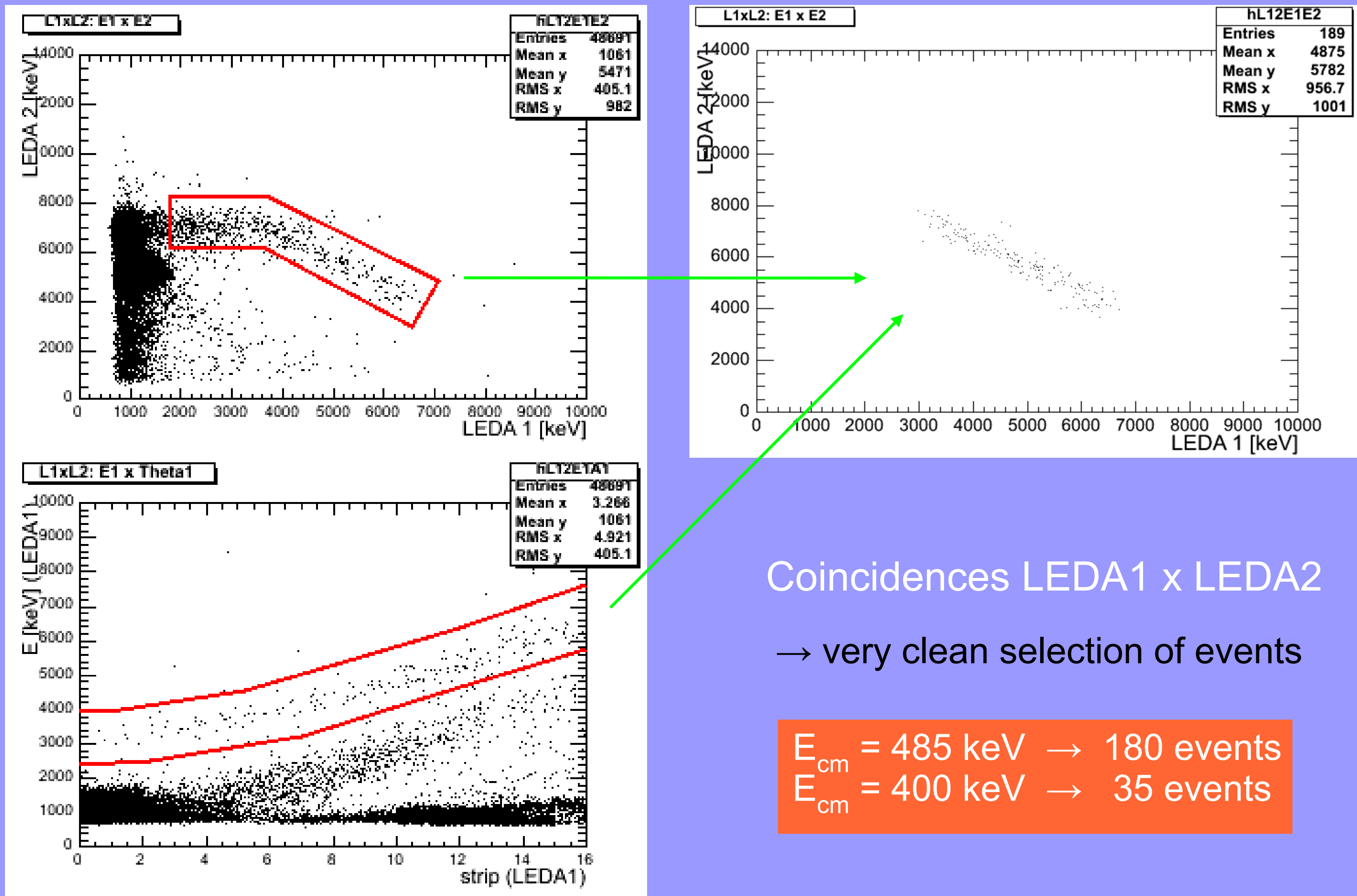
E_α x Θ_α

E_{15O} x Θ_{15O}



Good agreement for $(E_1 x E_2)$, $(E_1 x \Theta_1)$, $(E_1 x \Theta_2)$

$^{18}F + p$: α - ^{15}O coincidences OFF resonance



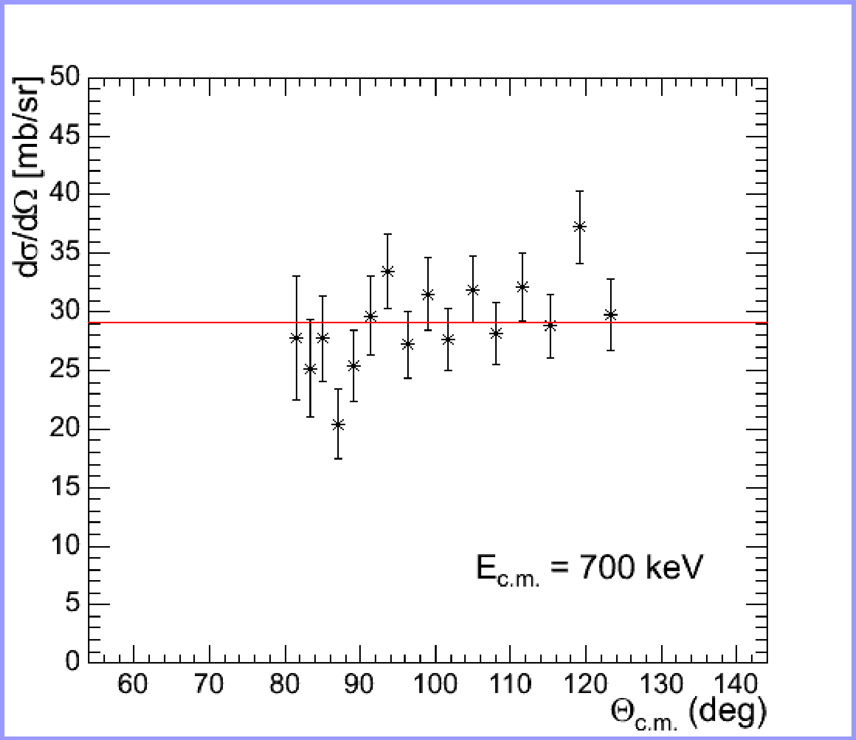
Coincidences LEDA1 x LEDA2

→ very clean selection of events

E_{cm} = 485 keV → 180 events
E_{cm} = 400 keV → 35 events

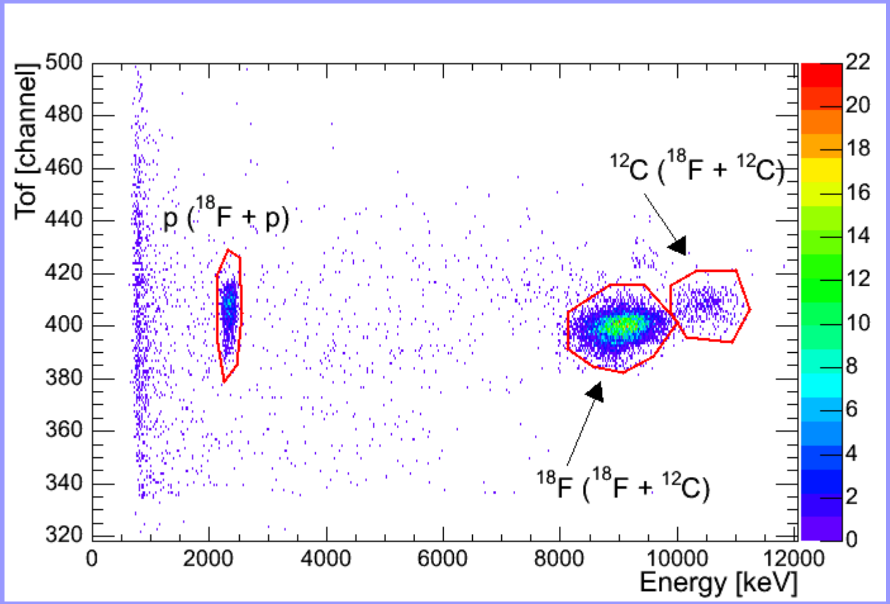
Absolute cross-section (1)

Differential cross-section



→ good agreement with $l = 0$ (resonance 3/2+)

Normalization



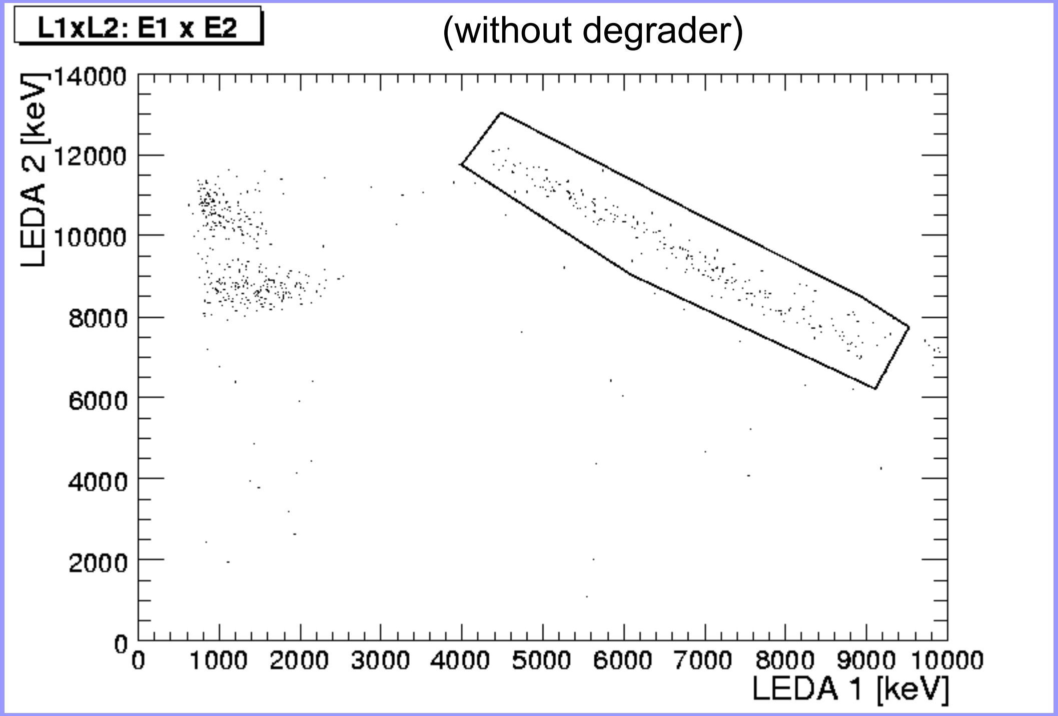
→ Elastic scattering $^{18}F + ^{12}C$ in LEDA2
+ CH_2 stoechiometry

Absolute cross-section

E_{cm} = 700 keV → σ ≈ 100 mb
E_{cm} = 665 keV → σ ≈ 400 mb
E_{cm} = 485 keV → σ ≈ 1 mb
E_{cm} = 400 keV → σ ≈ 0.3 mb

Absolute cross-section (2): $^{18}O(p,\alpha)^{15}N$

$^{18}O(p,\alpha)^{15}N$ data



"Same" kinematics than for $^{18}F(p,\alpha)^{15}O$

- $Q_{gg}[^{18}O(p,\alpha)^{15}N] = 4$ MeV
- $Q_{gg}[^{18}F(p,\alpha)^{15}O] = 3$ MeV

Differential cross-section (l = 0) :

Present experiment

$E(^{18}O) = 13.179$ MeV

$d\sigma/d\Omega = 16.5$ +- 0.5 mb/sr

From literature:

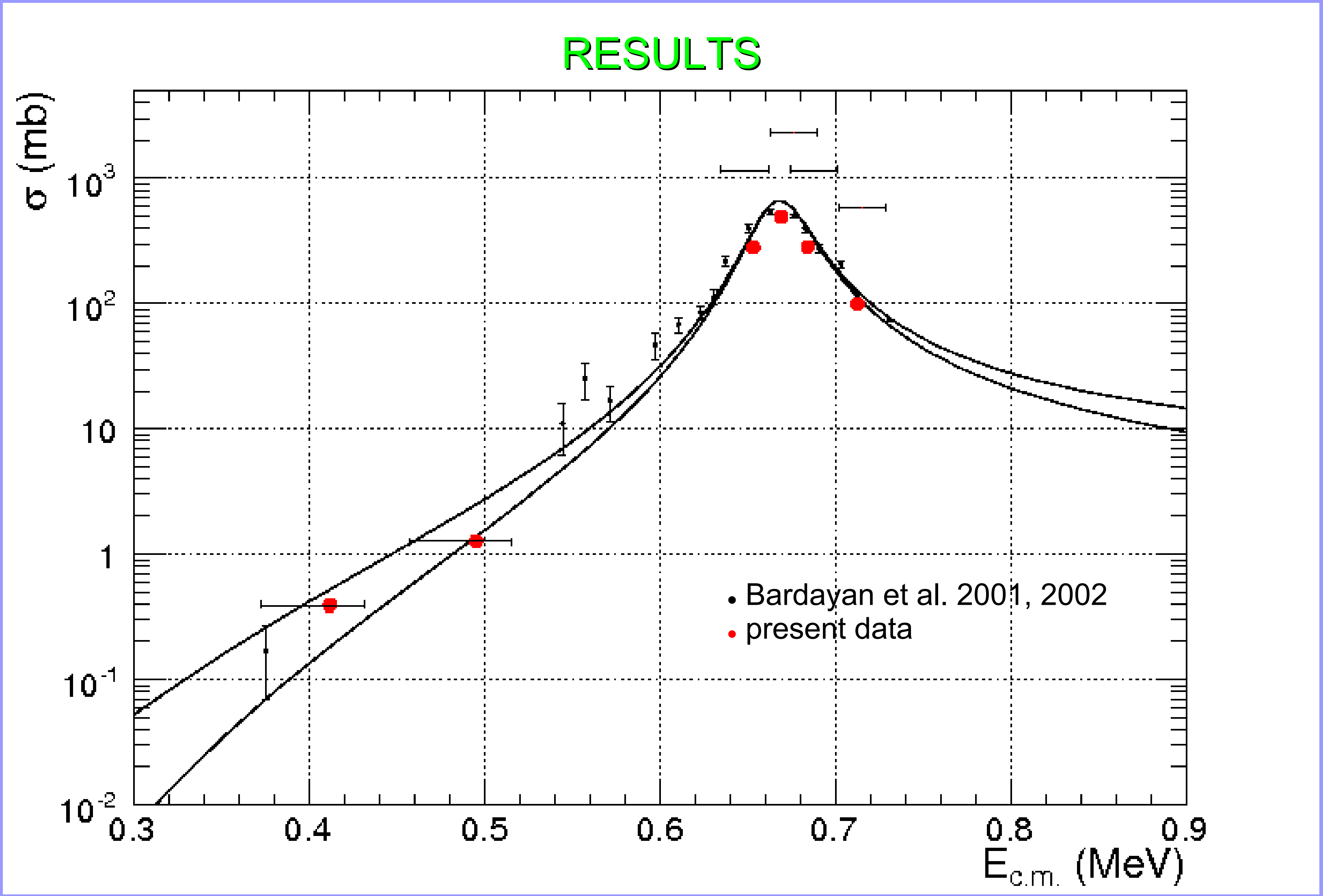
Lorenz-Wirzba et al. NP A313 (1979)
Christensen et al. NIM B51 (1990)

$d\sigma/d\Omega = 19.8$ +- 2.3 mb/sr

(target stoichiometry?)

→ Correction on normalization: 16%
→ Systematic error on normalization: 10%

Comparison with existing data



→ very good agreement with previous experimental data ON resonance
(normalization + energy dependence)

Collaboration

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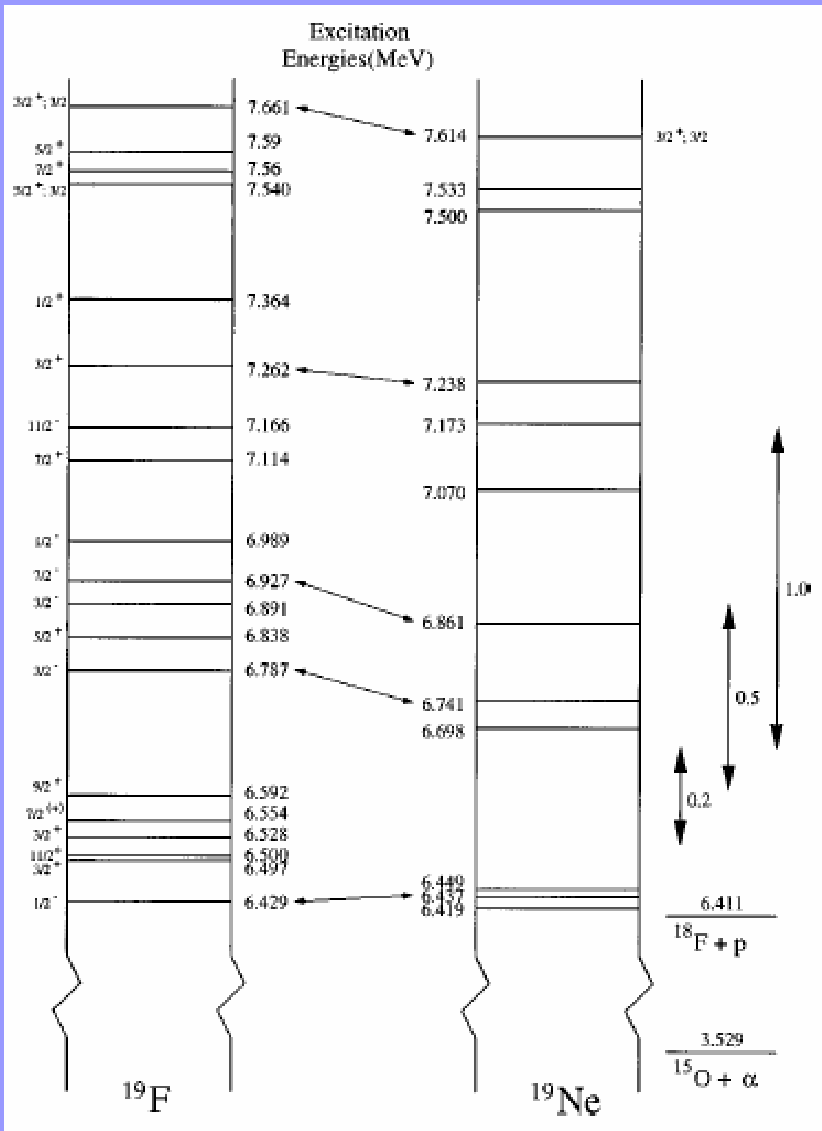
^{19}Ne spectroscopy [de Oliveira et al. accepté]

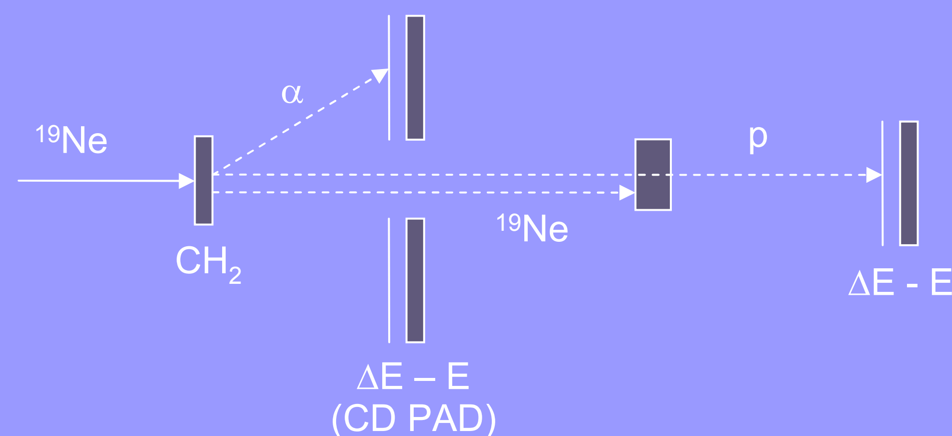
Inelastic scattering : ^{19}Ne(p,p')^{19}Ne* $\rightarrow \alpha$ + ^{15}O



^{19}Ne / ^{19}F: comparison analog states
missing ^{19}Ne levels

Goal:
- new levels
- spin / parity

Characteristics:
- Louvain-la-Neuve
- E(^{19}Ne) = 171 MeV

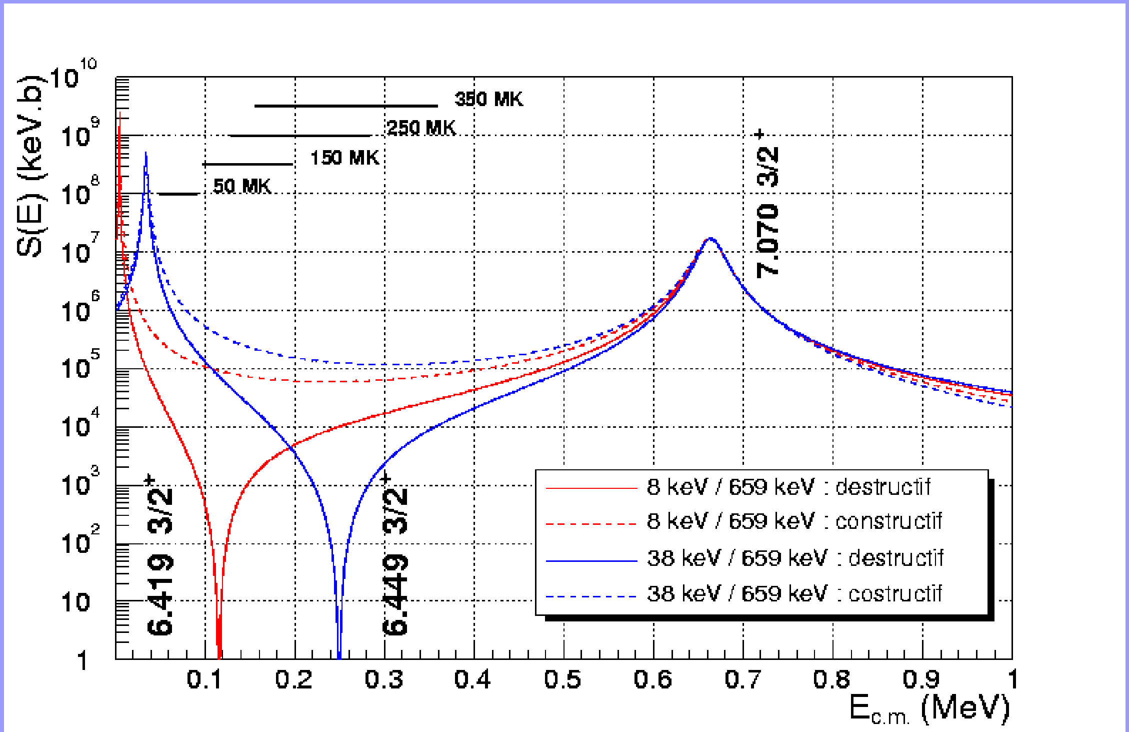


"Direct" measurement of S-factor

➢ Motivation :

Interference between the 3/2+ levels at 8, 38 and 659 keV.

Important effect between 100 and 300 keV (≈ Gamow peak)



➢ Method :

→ Trojan Horse Method for $D(^{18}F,^{15}O\alpha)n$

→ Similar to a (d,n) transfer reaction but α and ^{15}O detected (n spectator) : two LEDA and a ΔE gas detector.

→ Direct measurement of the S-factor.

Summary

Novae are good targets for INTEGRAL and others satellites

→ hope to make the first positive detection

Major uncertainty for the 511 keV γ-ray emission: $^{18}F(p,\alpha)^{15}O$

→ interferences between 3/2+ resonances

Present experiment: direct measurement

→ good agreement of the S-factor on top of the 665 keV resonance