Resonance spectroscopy as an Indirect Method in Nuclear Astrophysics

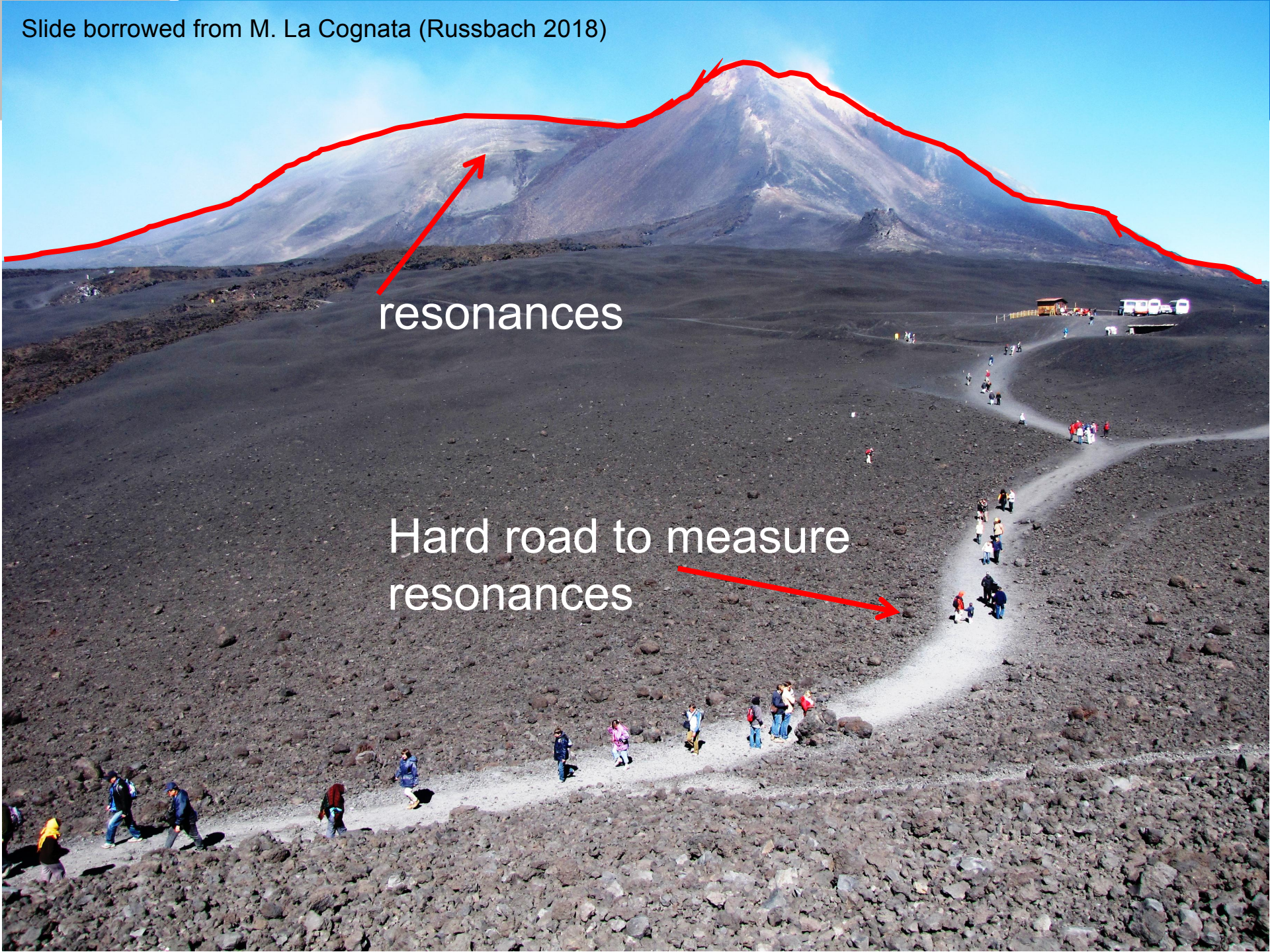
Alexandra Spiridon

IFIN-HH

Indirect Methods in NA

- As LT mentioned on Monday, with IM we can have measurements at lab energies that allow us to estimate cross-sections at stellar energies.
- Most known/used IMs:
  - Coulomb dissociation
  - Breakup
  - Transfer reactions (ANC method)
  - THM
  - Resonance spectroscopy

Resonance spectroscopy...


Slide borrowed from M. La Cognata (Russbach 2018)
resonances
Hard road to measure resonances

Resonance spectroscopy

* **Resonant** reaction is a two-step process.

$$\sigma_\gamma \propto \left|\left\langle E_f \left| H_\gamma \right| E_r \right\rangle\right|^2 \left|\left\langle E_r \left| H_f \right| A + p \right\rangle\right|^2$$

* The cross section (Breit-Wigner):

$$\sigma(E) = \frac{\lambda}{4\pi} \frac{2J+1}{(2J_1+1)(2J_2+1)} \frac{\Gamma_p \Gamma_\gamma}{(E-E_r)^2 + \left(\frac{\Gamma}{2}\right)^2}$$

* The contribution to the reaction rate:

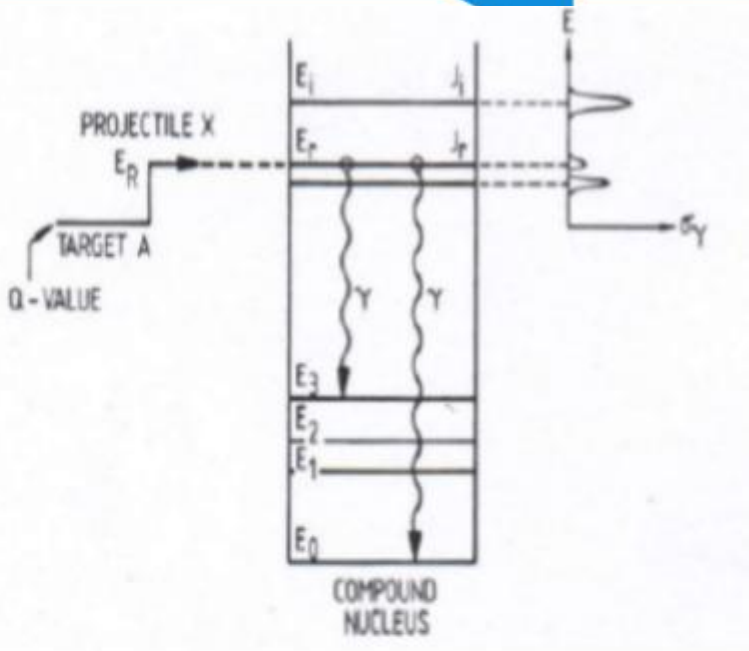
$$\langle \sigma \upsilon \rangle_{res} = \left(\frac{2\pi}{\mu kT}\right)^{3/2} \hbar^2 \omega\gamma \exp\left(-\frac{E_r}{kT}\right)$$

where

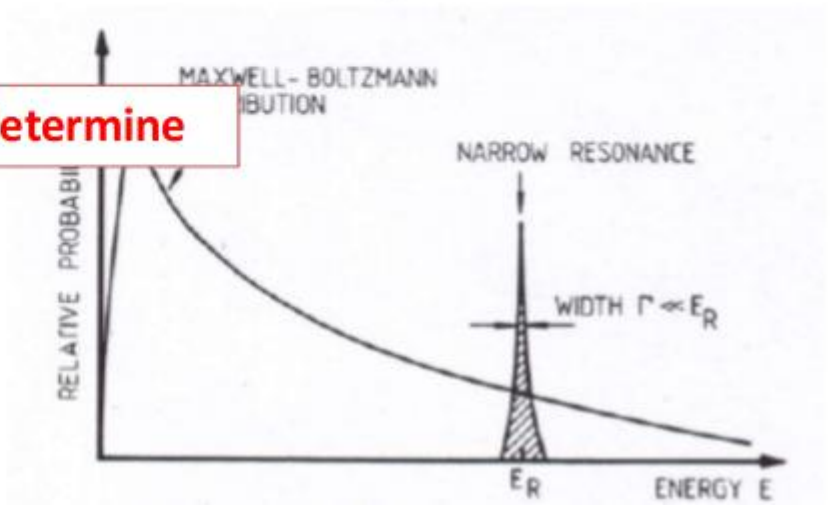
$$\omega\gamma = \frac{2J_r+1}{(2J_p+1)(2J_t+1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma_{tot}}$$

$\omega\gamma$= resonance strength

to determine



* C. Rolfs and W. Rodney, "Cauldrons in the Cosmos".

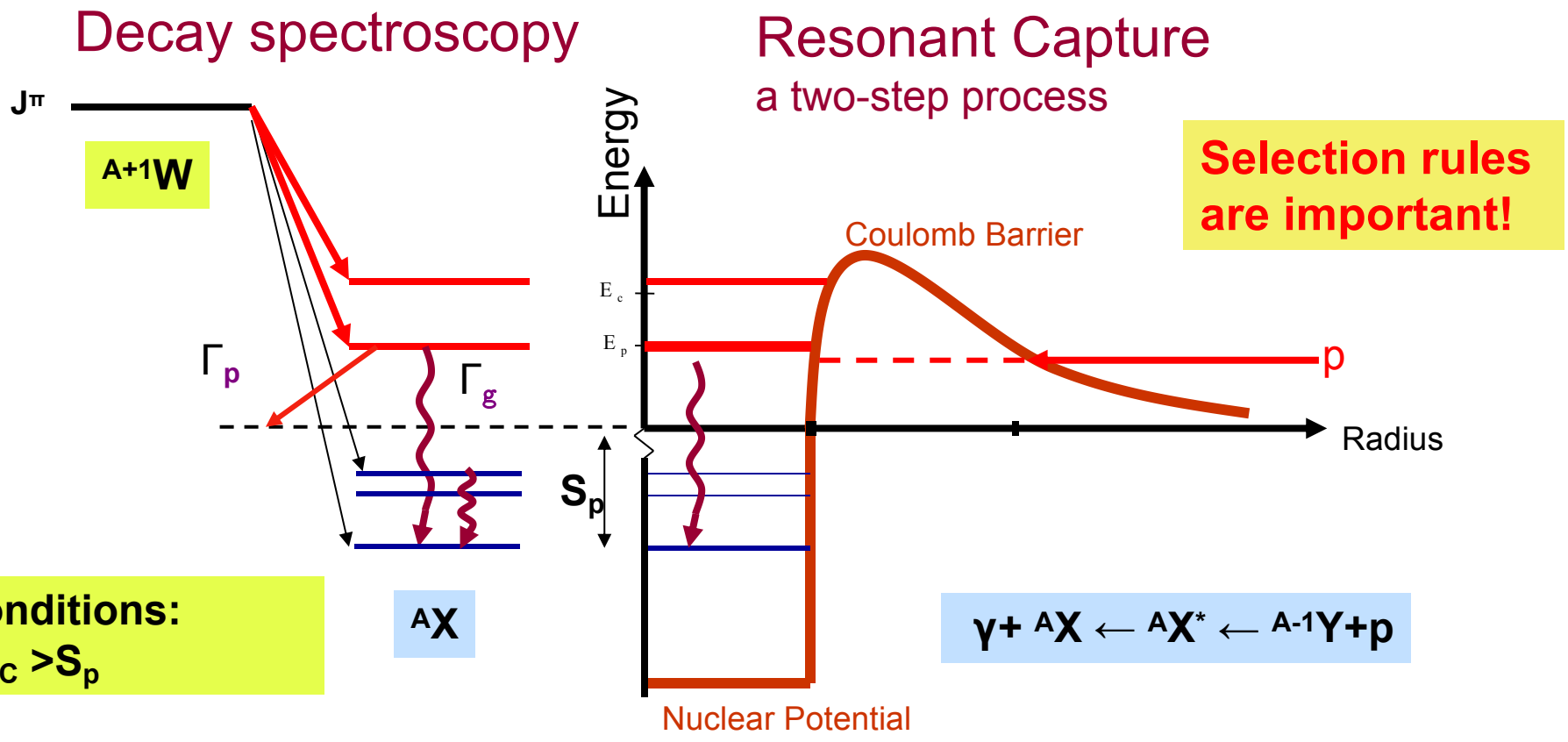


Resonance spectroscopy

- Any spectroscopic method that would populate the states in same CN:
  - Determine location E_r
  - Determine resonance strength $\omega\gamma$
  - b-decay, b-delayed p-decay
  - transfer reactions
  - resonant elastic scattering
  - etc...
- Difficulties:
- Find the appropriate mechanism to populate the resonance(s)
- Most difficult: determine the width ($\omega\gamma$)

β-decay and β-delayed p-decay

- Can be used to study radiative proton capture reactions



β-decay and β-delayed p-decay

- Problems...
  - We are interested in low proton energies!!!!
    - **100 keV - 1000 keV!!!**
  - Beta-background contamination
  - Other experimental difficulties

- Improve exp methods and/or detectors
- Examples: ^{23}Al, ^{31}Cl, ^{35}K (the TAMU experiments)

23Al

Explosive H-burning in novae

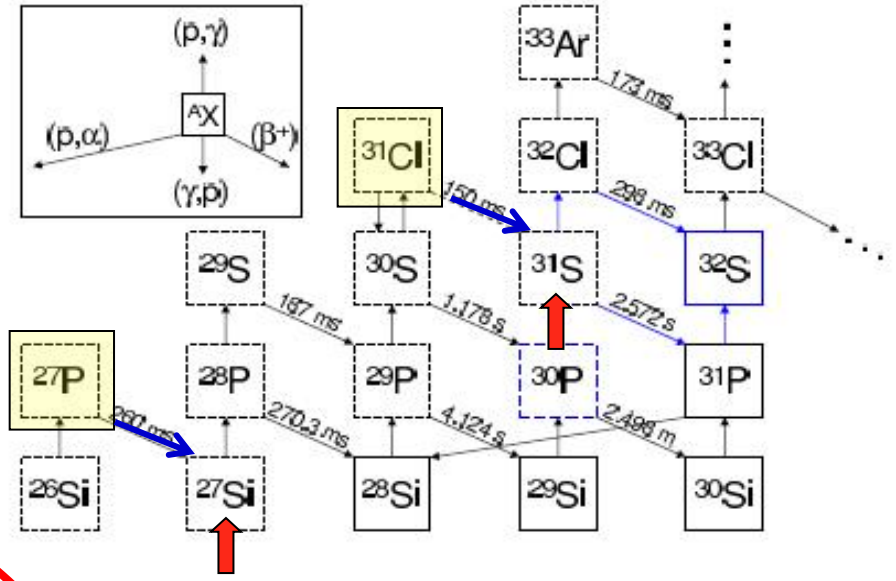
- E=1275 MeV γ ray following the decay of ^{22}Na predicted but **not** observed by gamma telescopes

&

IAS in T_z=-3/2 nuclei

Isospin mixing

GT strength distribution



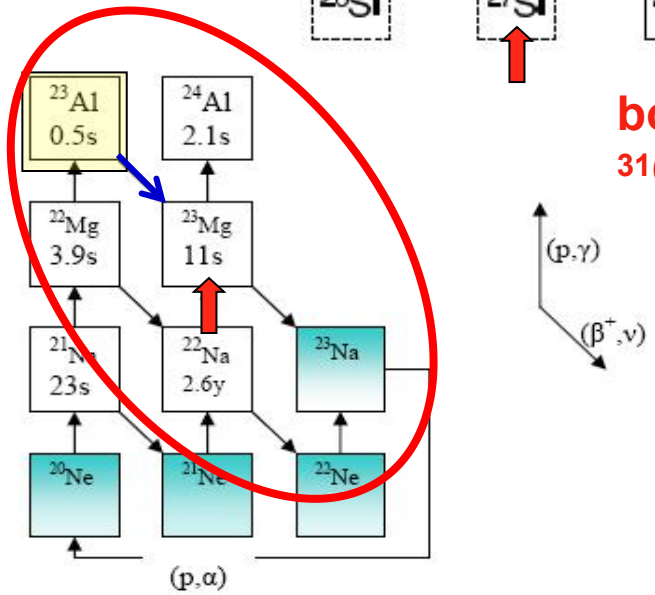
bottleneck r. in novae

^{31}Cl→^{31}S* ⇒ ^{30}P(p,g)^{31}S*

^{22}Na depletion in novae

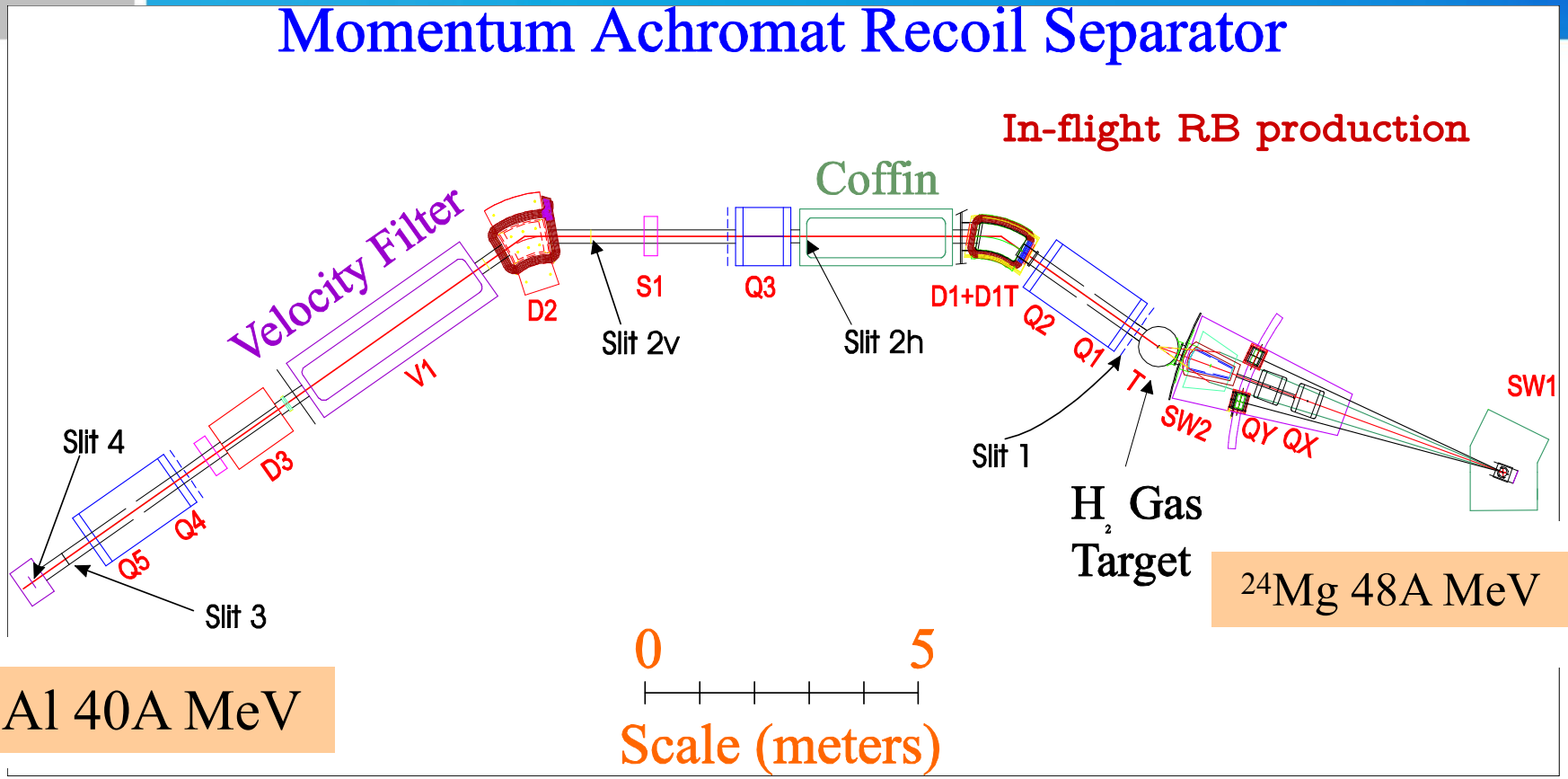
^{23}Al→^{23}Mg* ⇒ ^{22}Na(p,g)^{23}Mg*

& ^{22}Mg(p,g)^{23}Al



MARS

Momentum Achromat Recoil Separator



^{24}Mg 48A MeV

^{23}Al 40A MeV

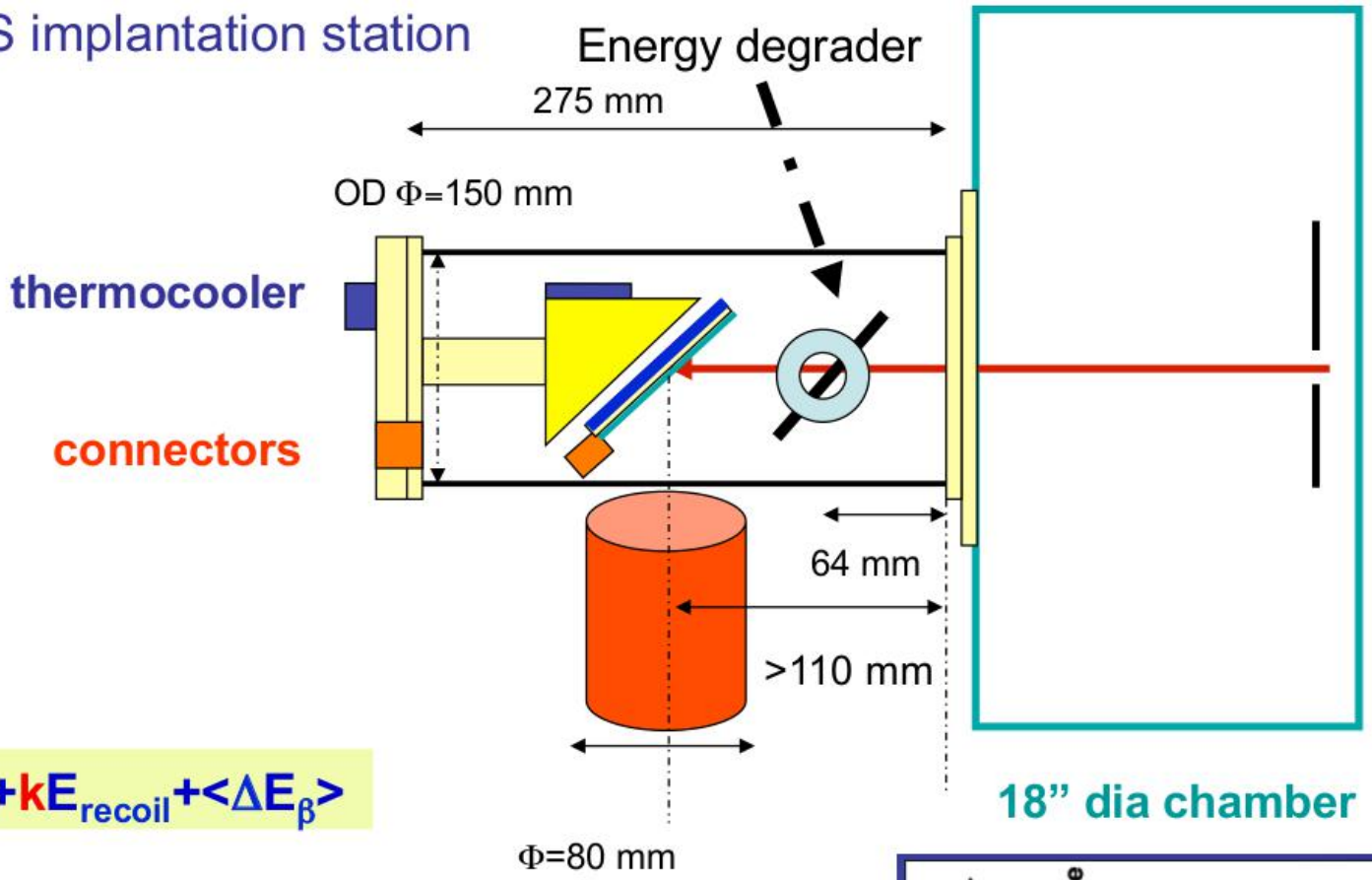
Purity: 90%, or >99% after en degrader
Intensity: ~ 4000 pps
First time - very pure & intense ^{23}Al

Primary beam ^{24}Mg @ 48A MeV – K500 Cycl
Primary target LN_2 cooled H_2 gas p=1.6 atm
Secondary beam ^{23}Al @ 40.2A MeV

(p,2n) reaction

23Al - Si "sandwich" setup

MARS implantation station



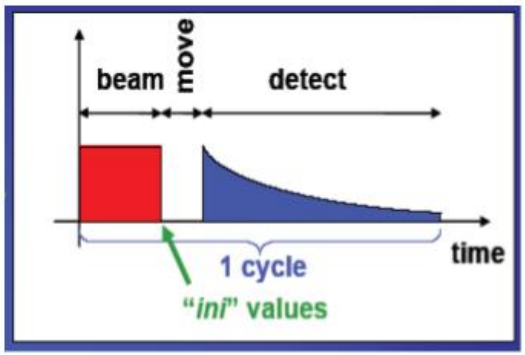
$E=E_p+kE_{recoil}+<\Delta E_\beta>$

p-detector – v. thin DS Si strip 65 or 45 μm
W1-65 BB2-45

β-detector – thick Si det 1 mm

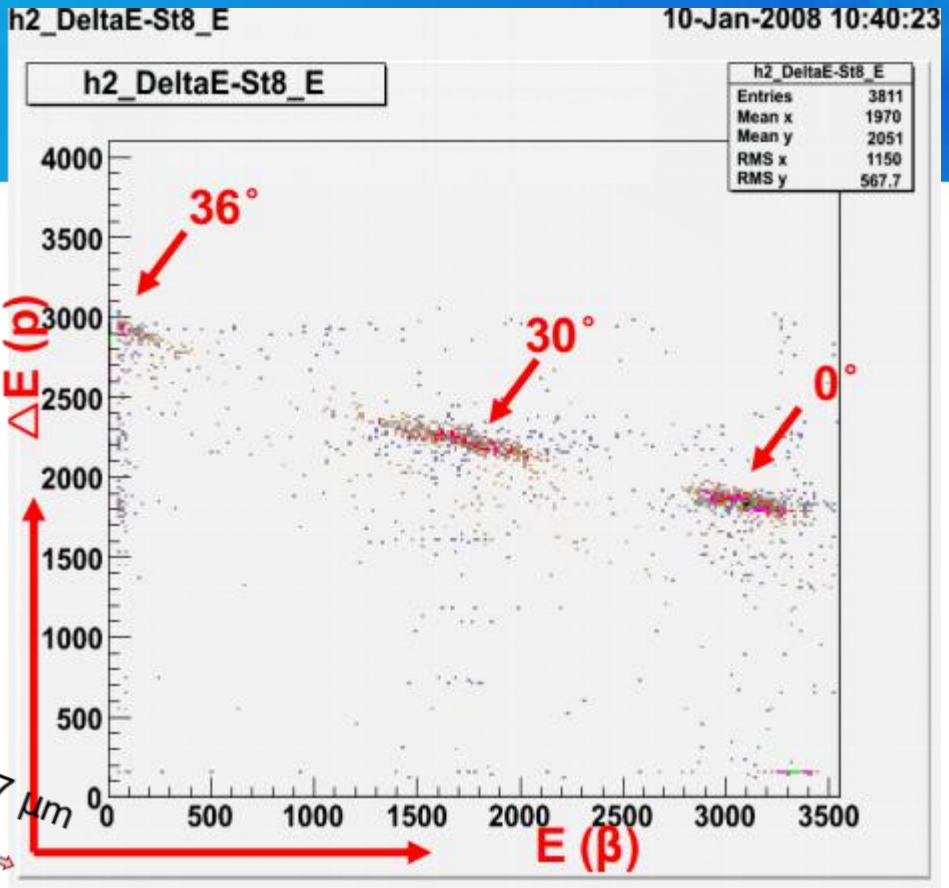
γ-detector – HPGe 70% effic

Pulsed beam



measure simultaneously:

- β-proton and
- β-γ coinc.



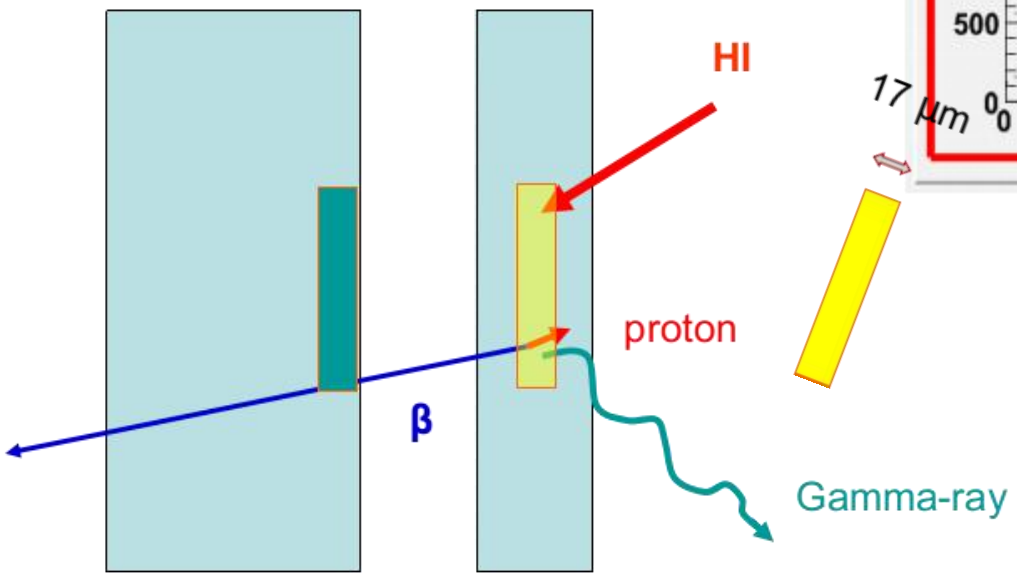
Si 1000 μm

Si strip
61 μm

"HI telescope mode" – control implantation

Signal=E_{HI}

Signal=ΔE_{HI}



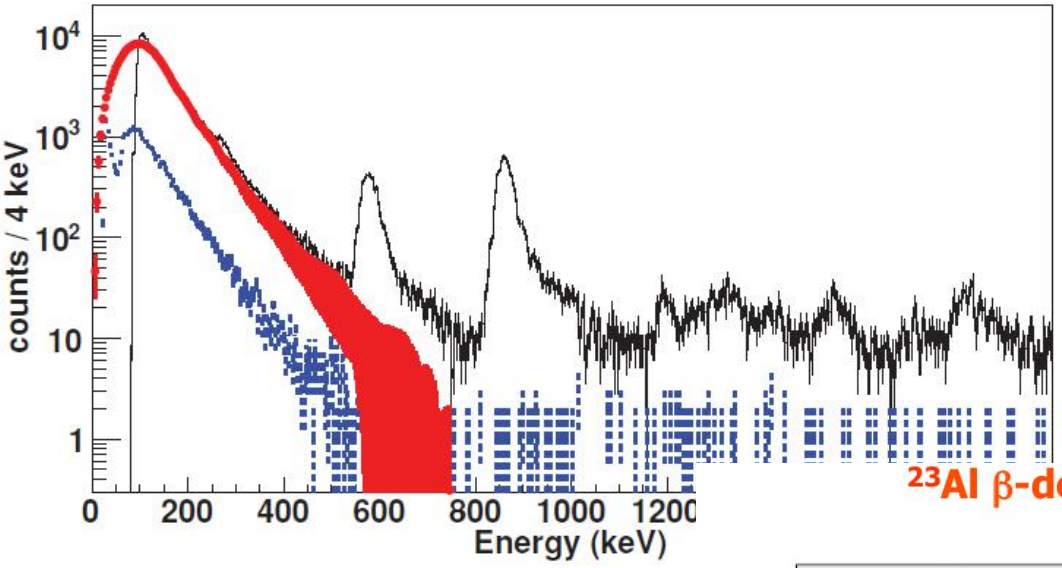
Signal=ΔE_{β}

Signal=$E_p+\Delta E$

"β-proton mode"

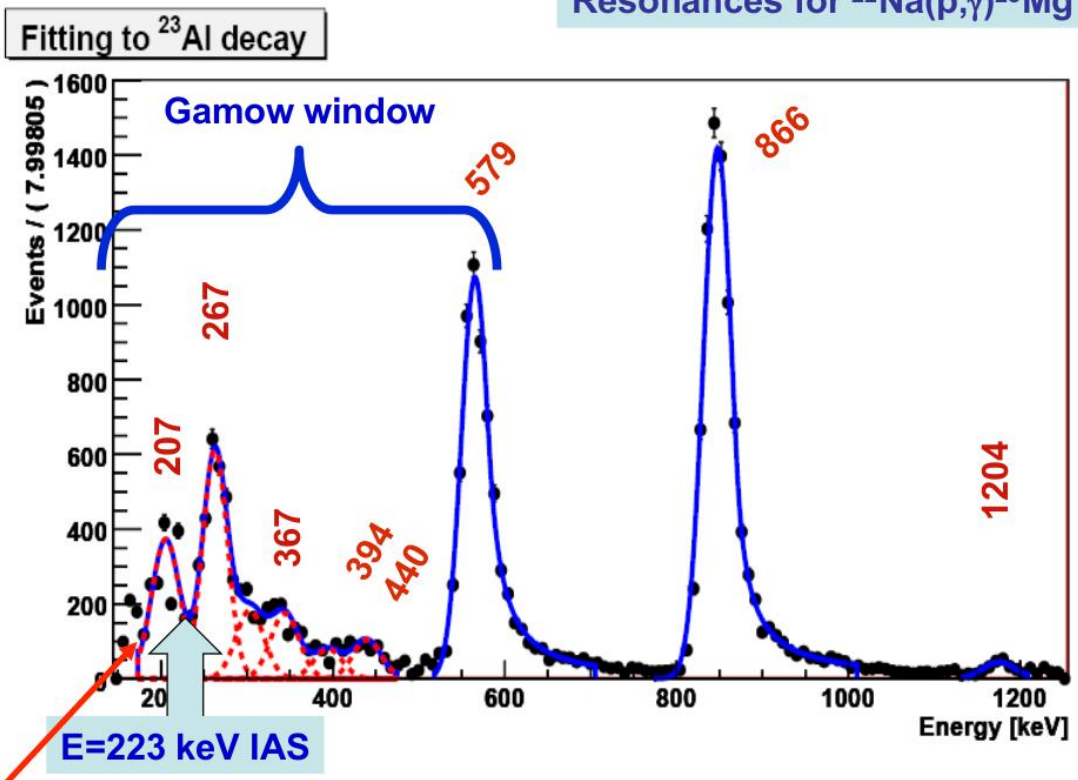
Si stops protons:
½ 65 μm E_p<1.5 MeV

23Al - Si-setup



^{23}Al β-delayed p-decay sp – after bkg subtraction

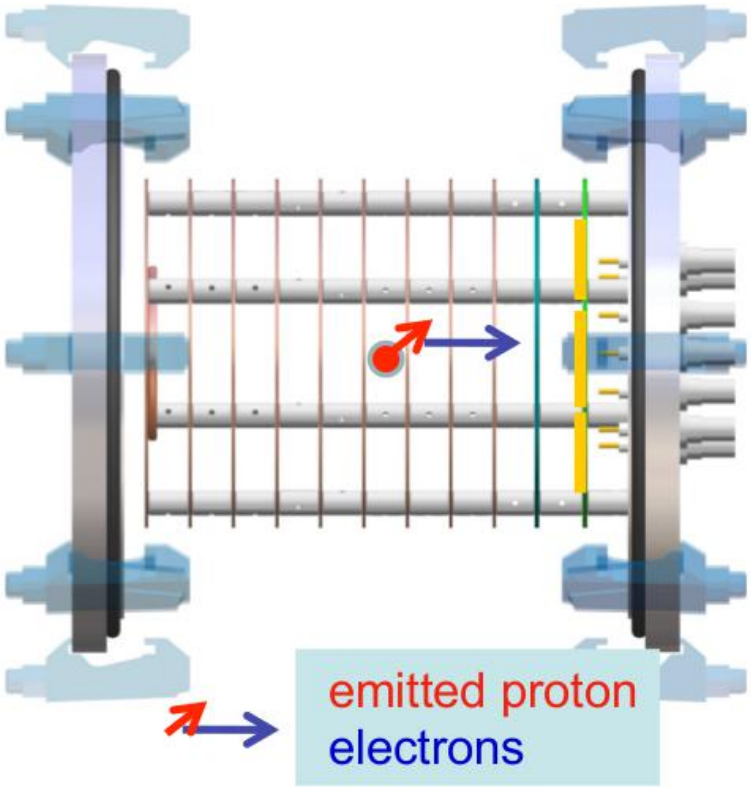
Resonances for ^{22}Na(p,γ)^{23}Mg

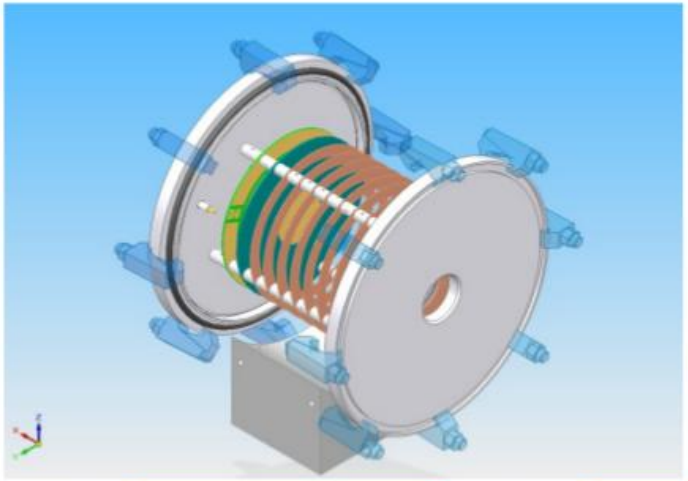


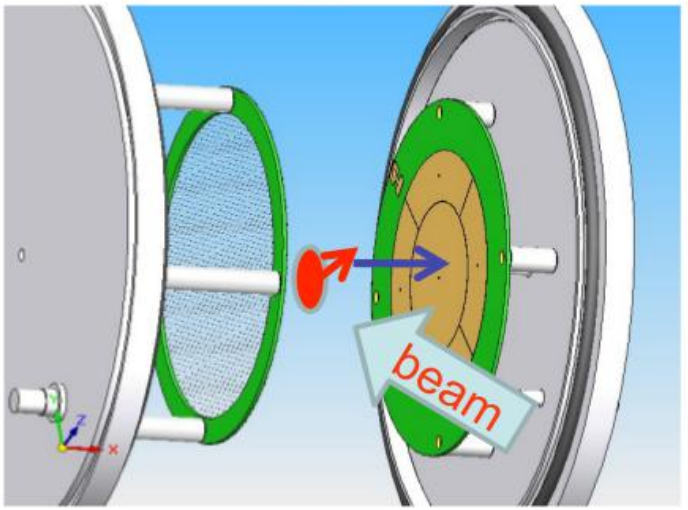
"world record"

Antti Saastamoinen et al., PRC 83, 2011

23Al - AstroBox "1.0" setup

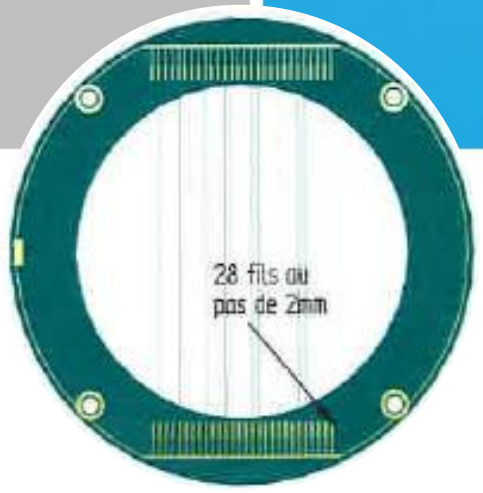


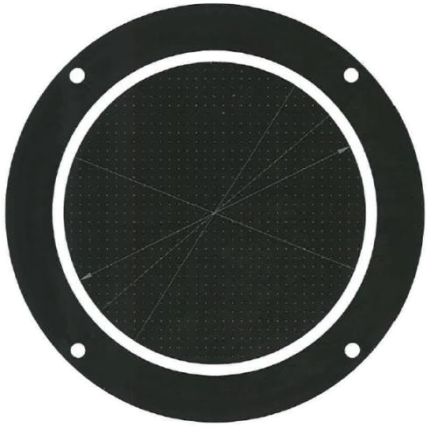


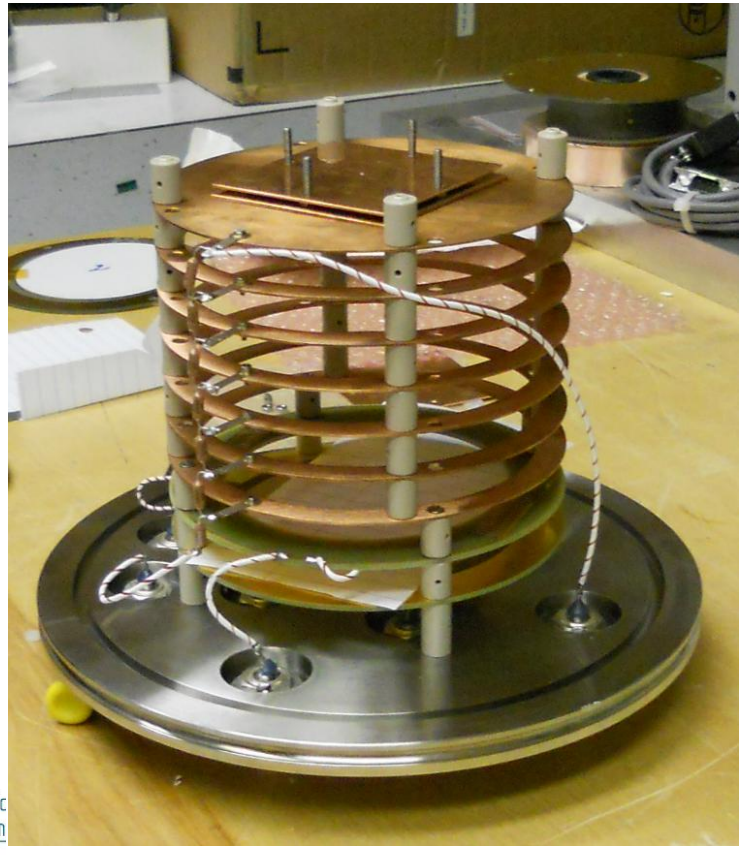


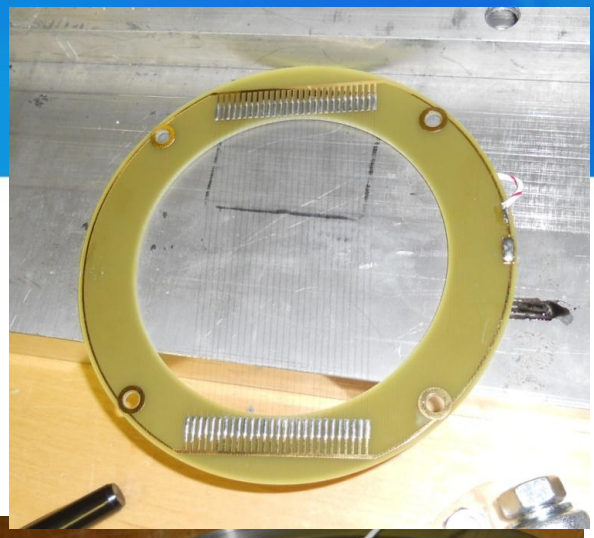
E Pollacco (CEA Saclay) proposed:

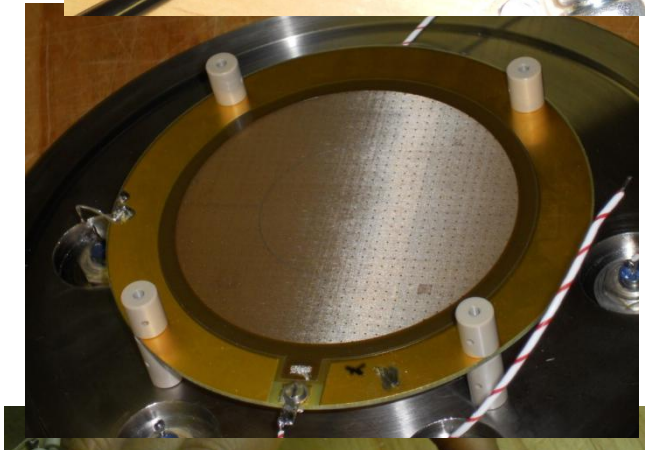
- Gas detector w MICROMEGAS
- Low proton energies (~1-200 keV), good resolution (5-10%)
- Reduced β background

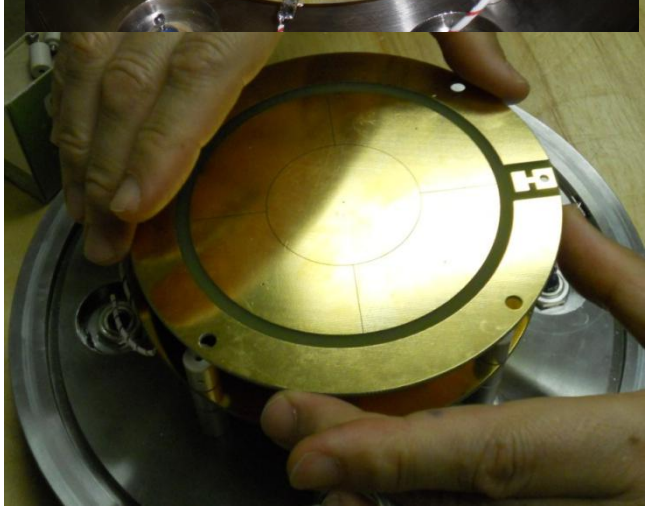

28 fils au
pas de 2mm

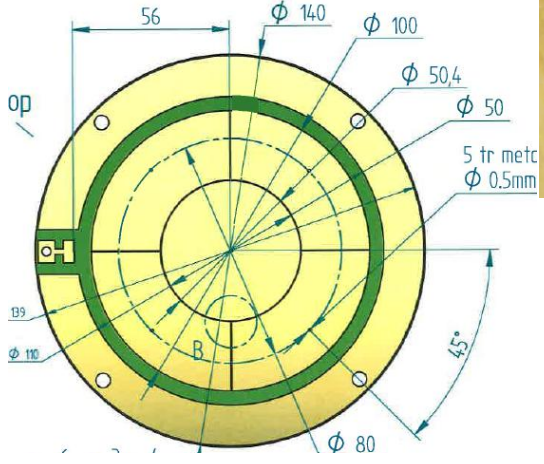











56
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op
139
Φ 110
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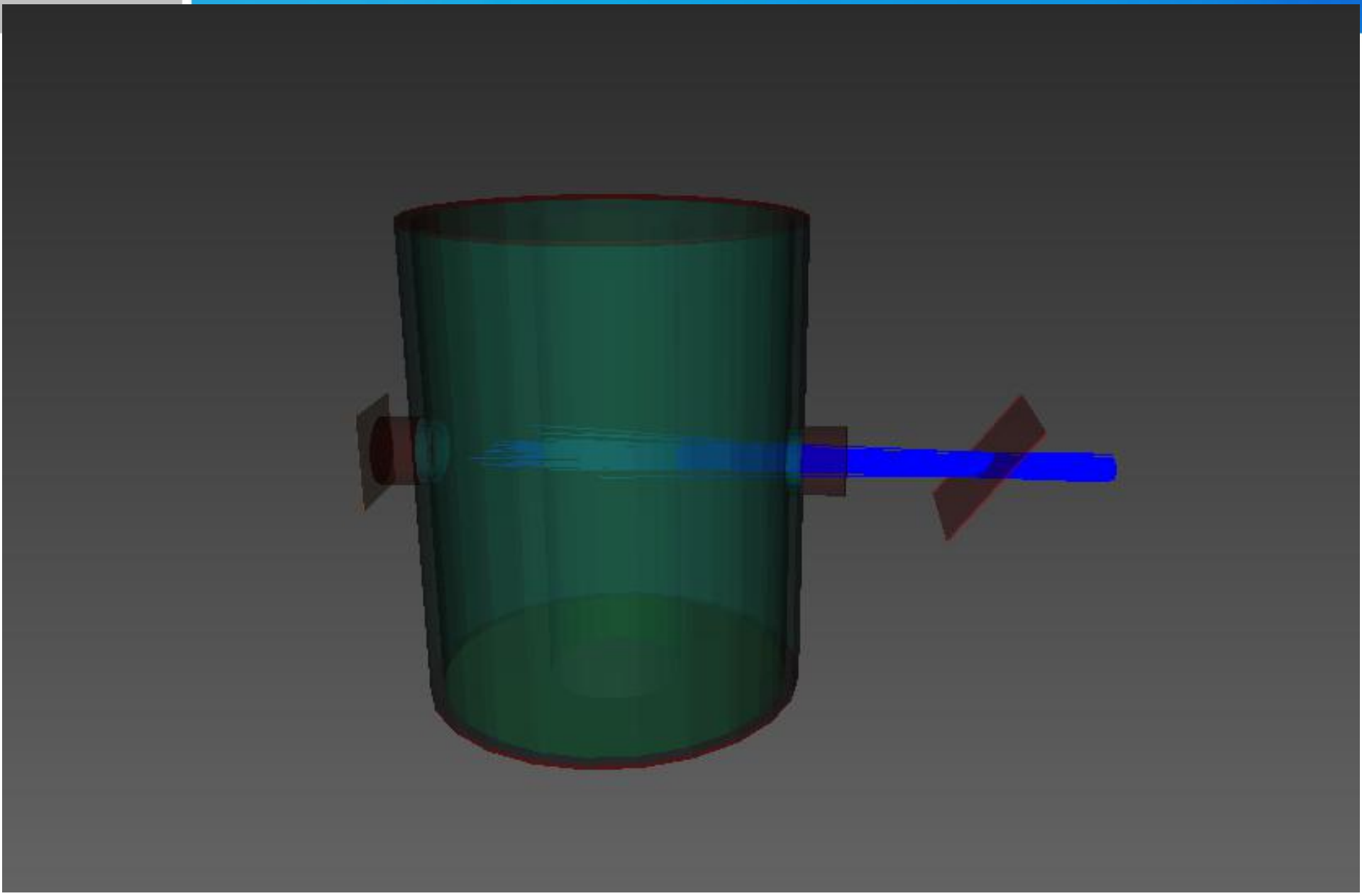
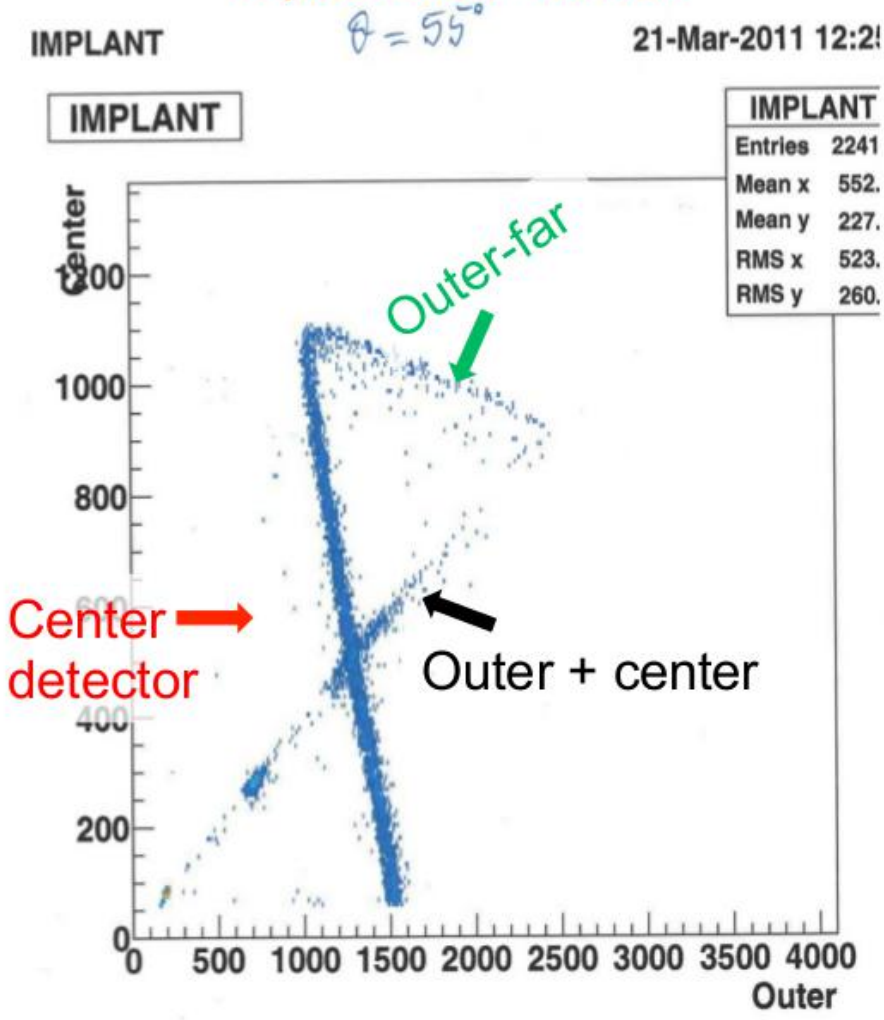
Φ 80

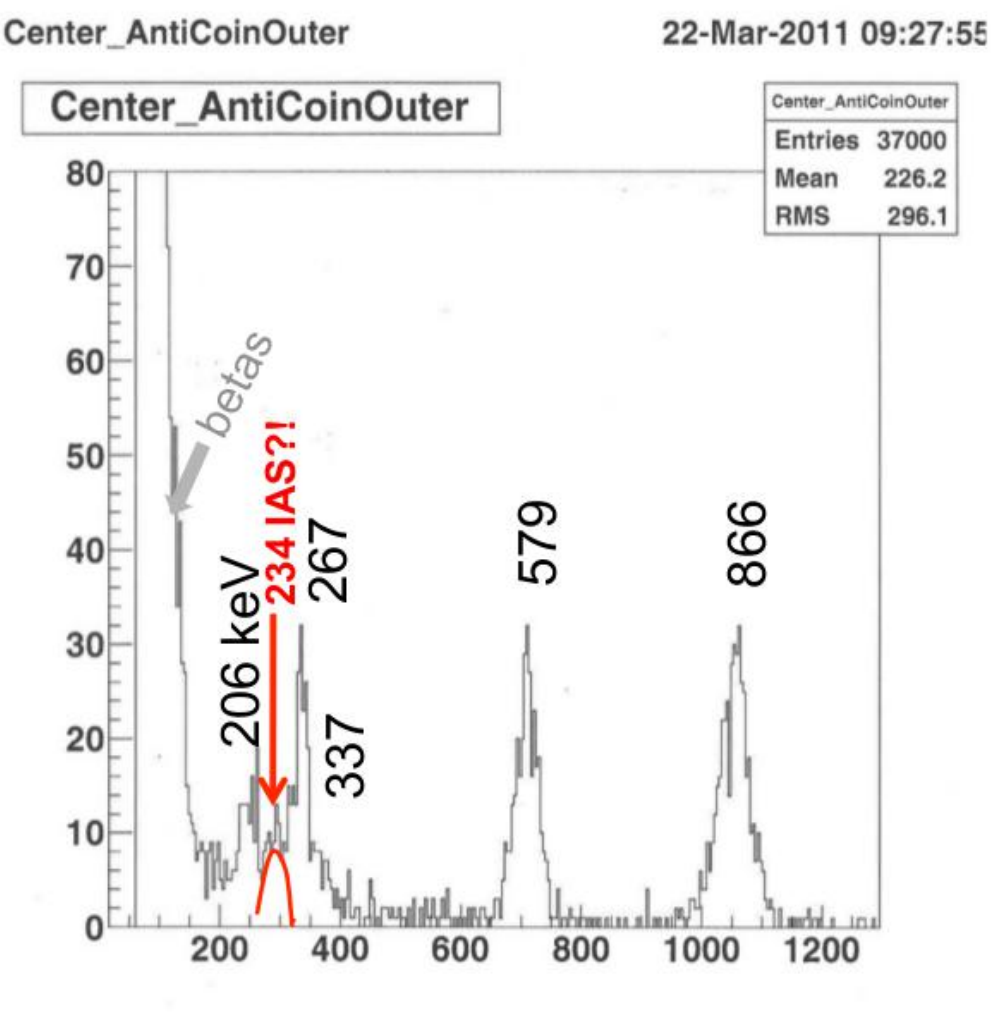


23Al - AstroBox 1 - results

Implantation control

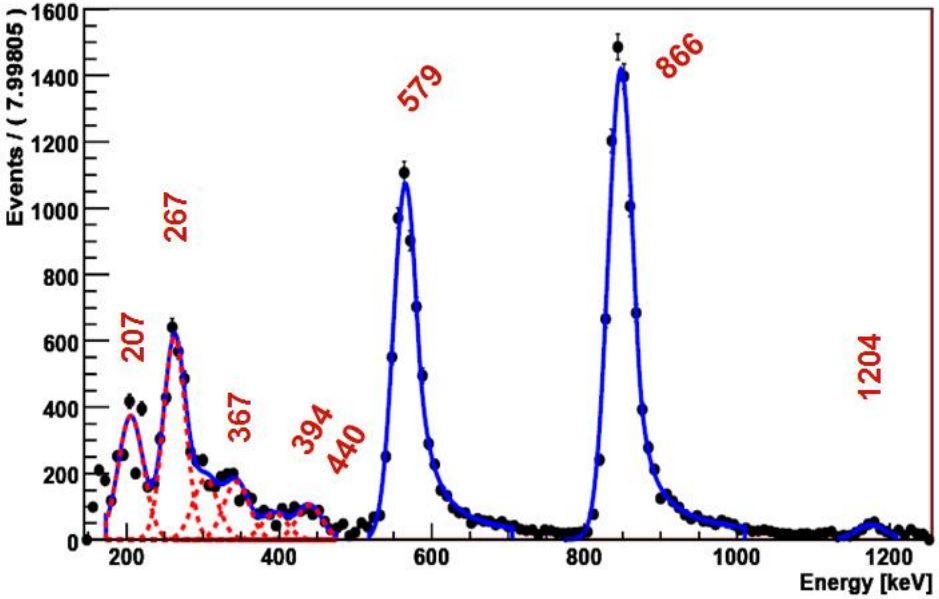


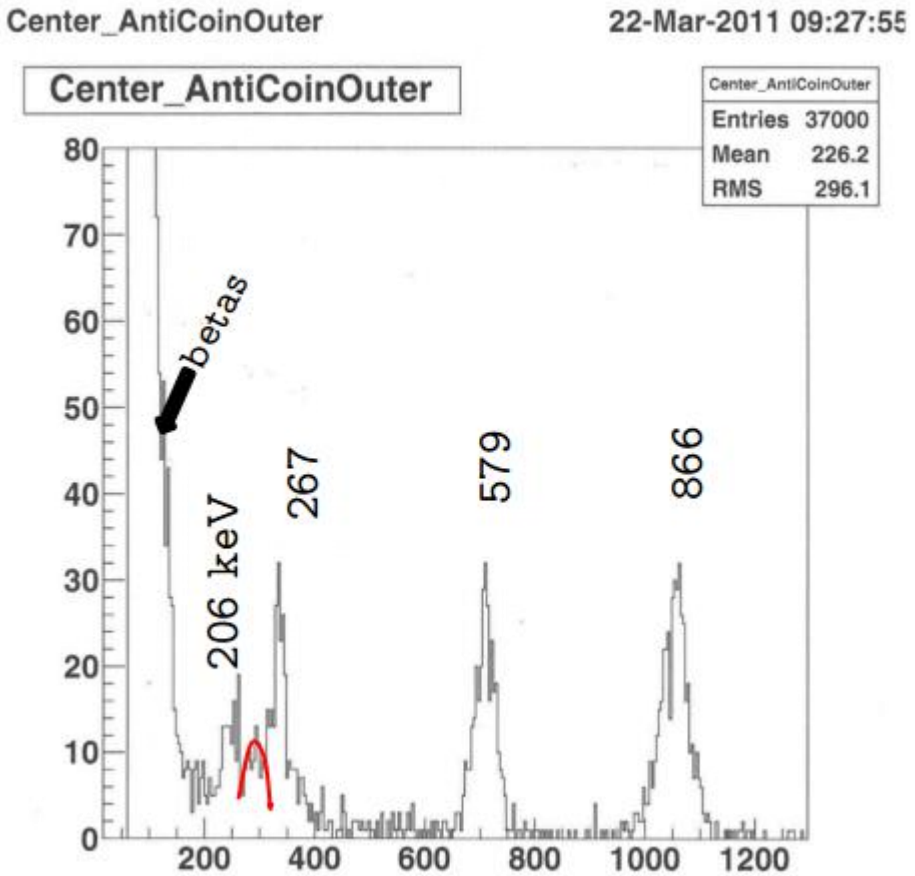
Off-beam spectrum



23Al - comparison between Si and AB 1

- Can go to E_p~80 keV
- Good peak separation
- Very sensitive – clear results within just ~2 hrs of statistics

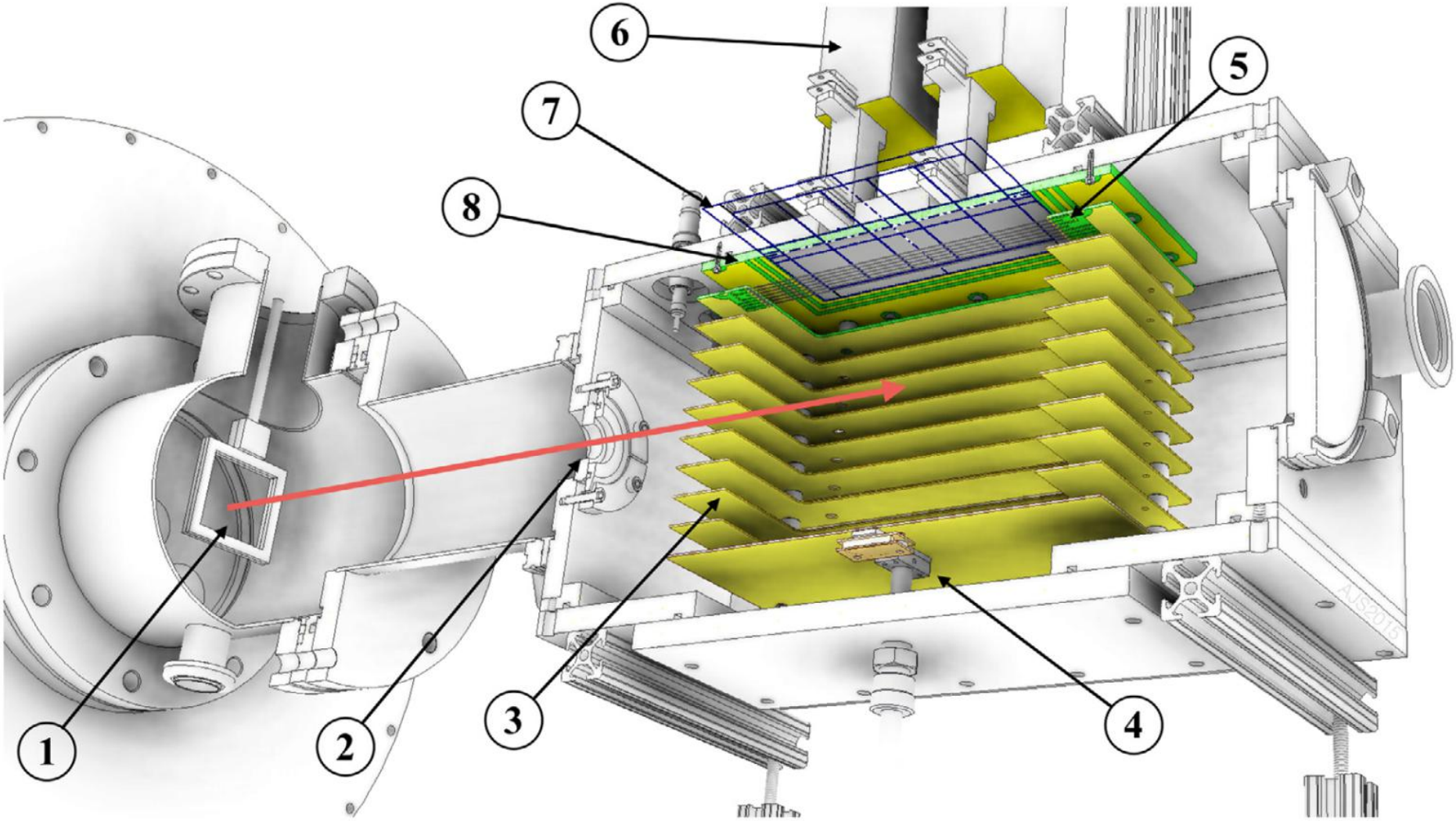


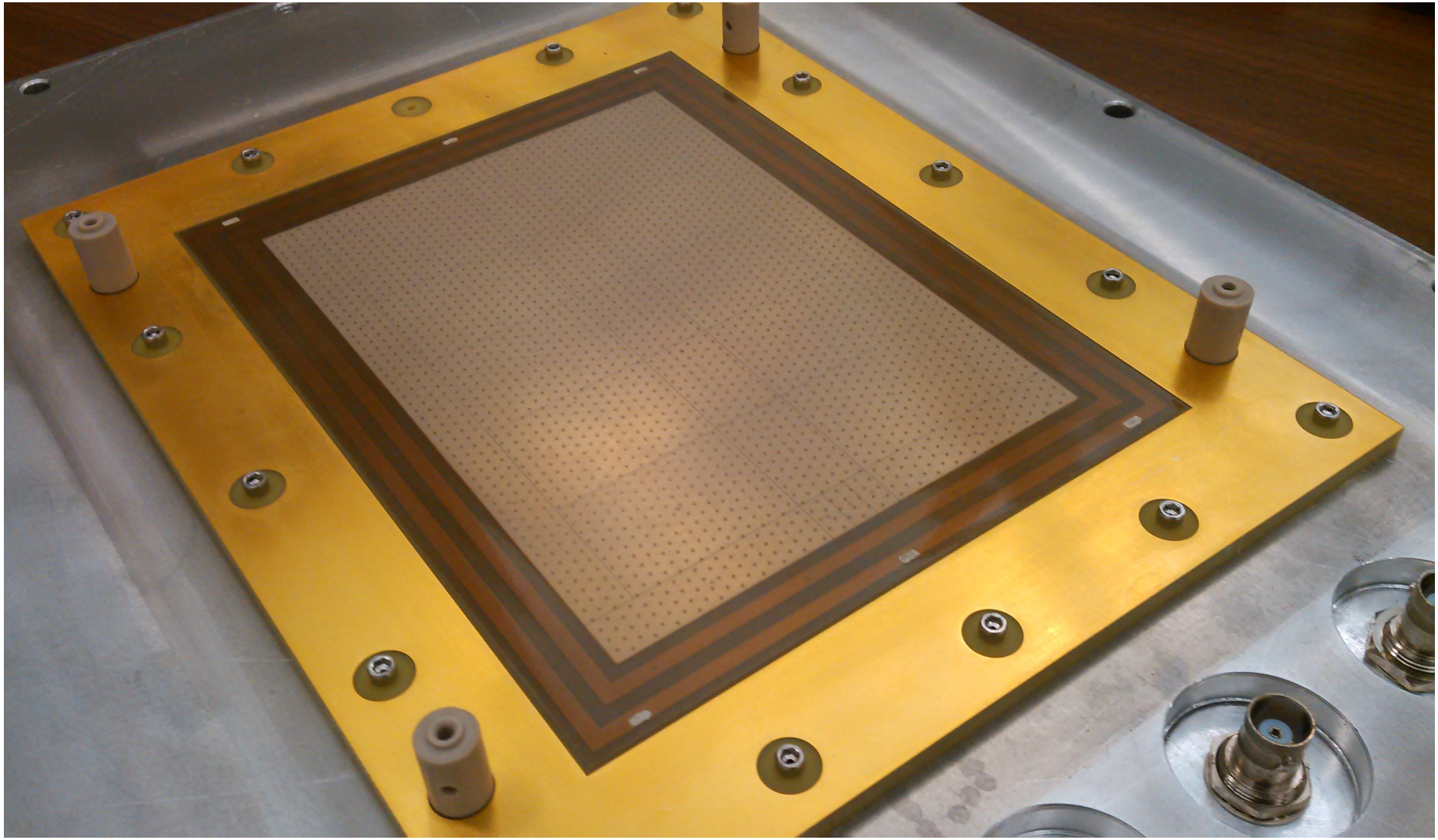


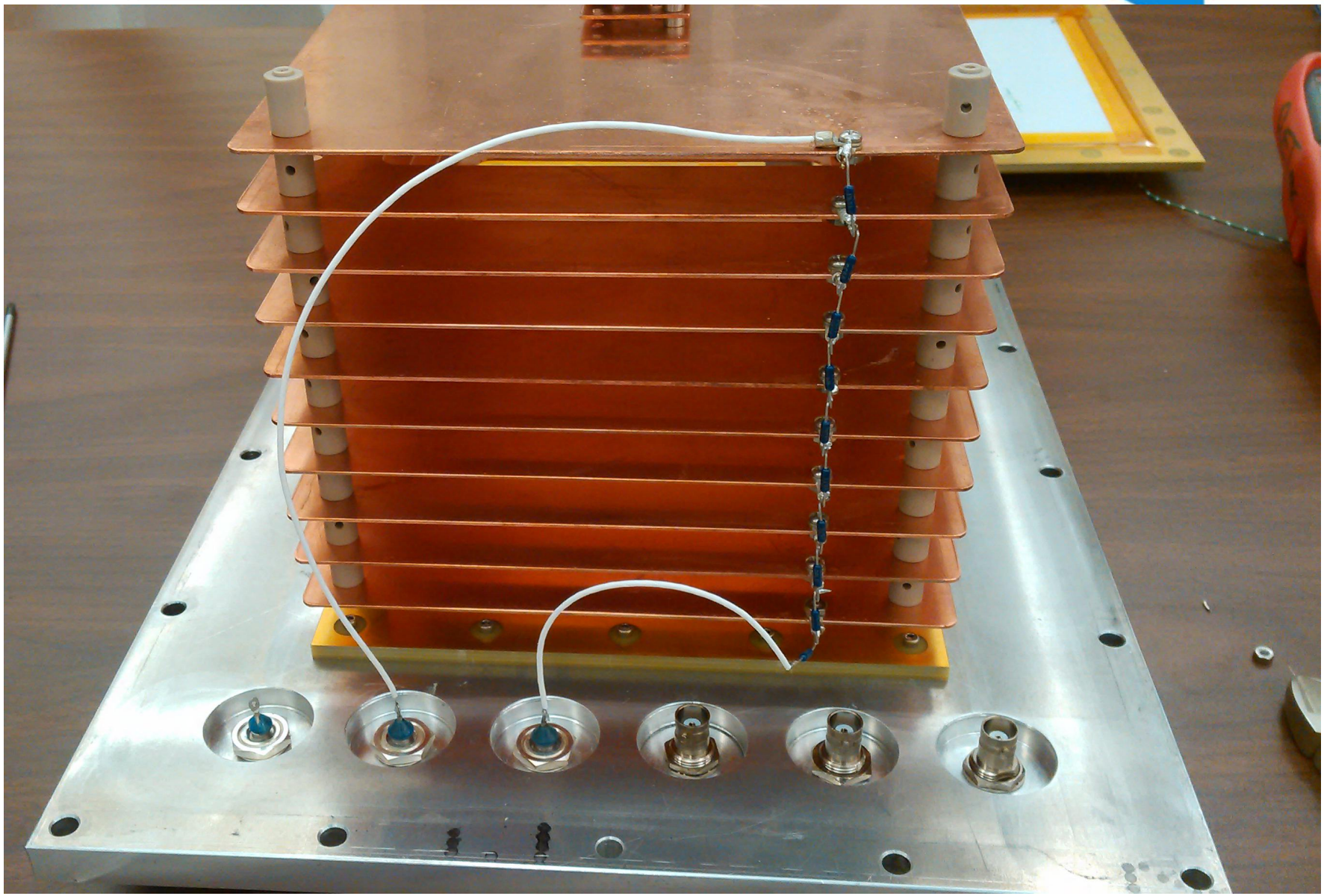
More AstroBox(es)...

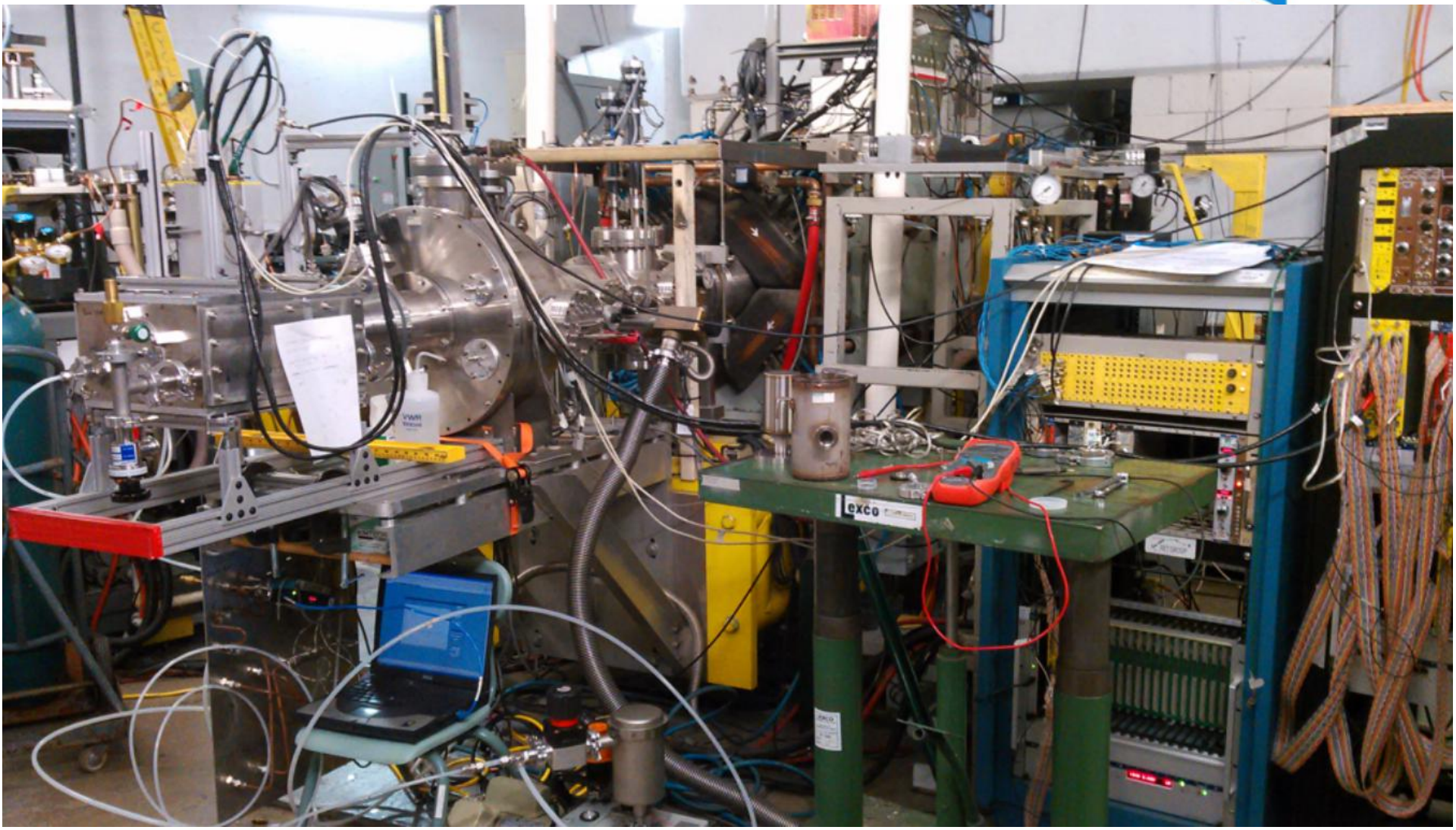
(or go bigger)

23Al - AstroBox "2.0" setup

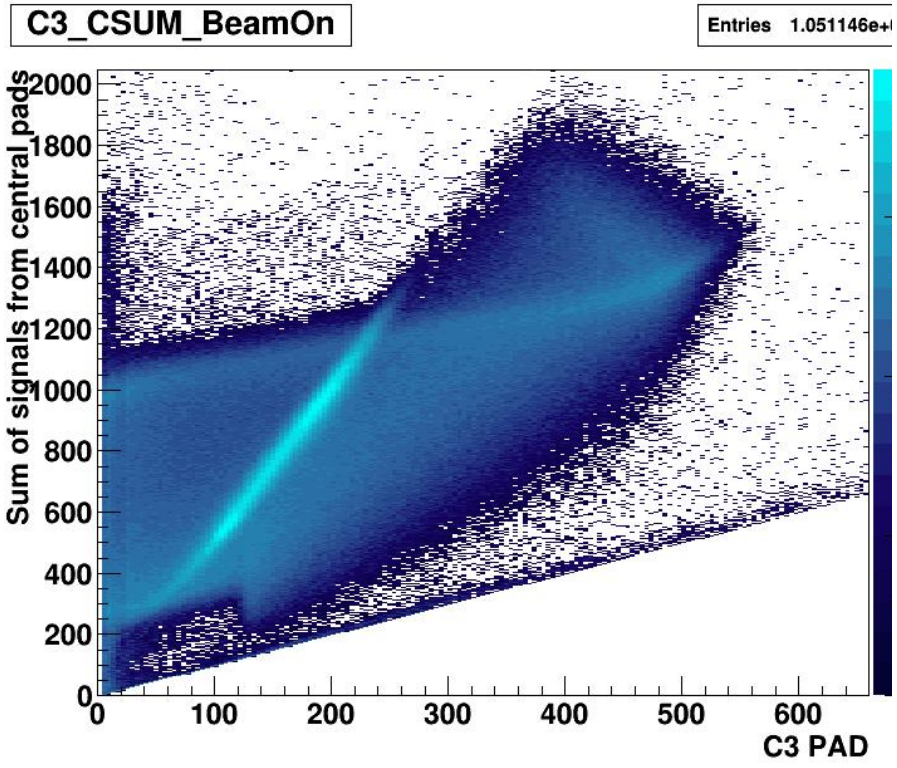


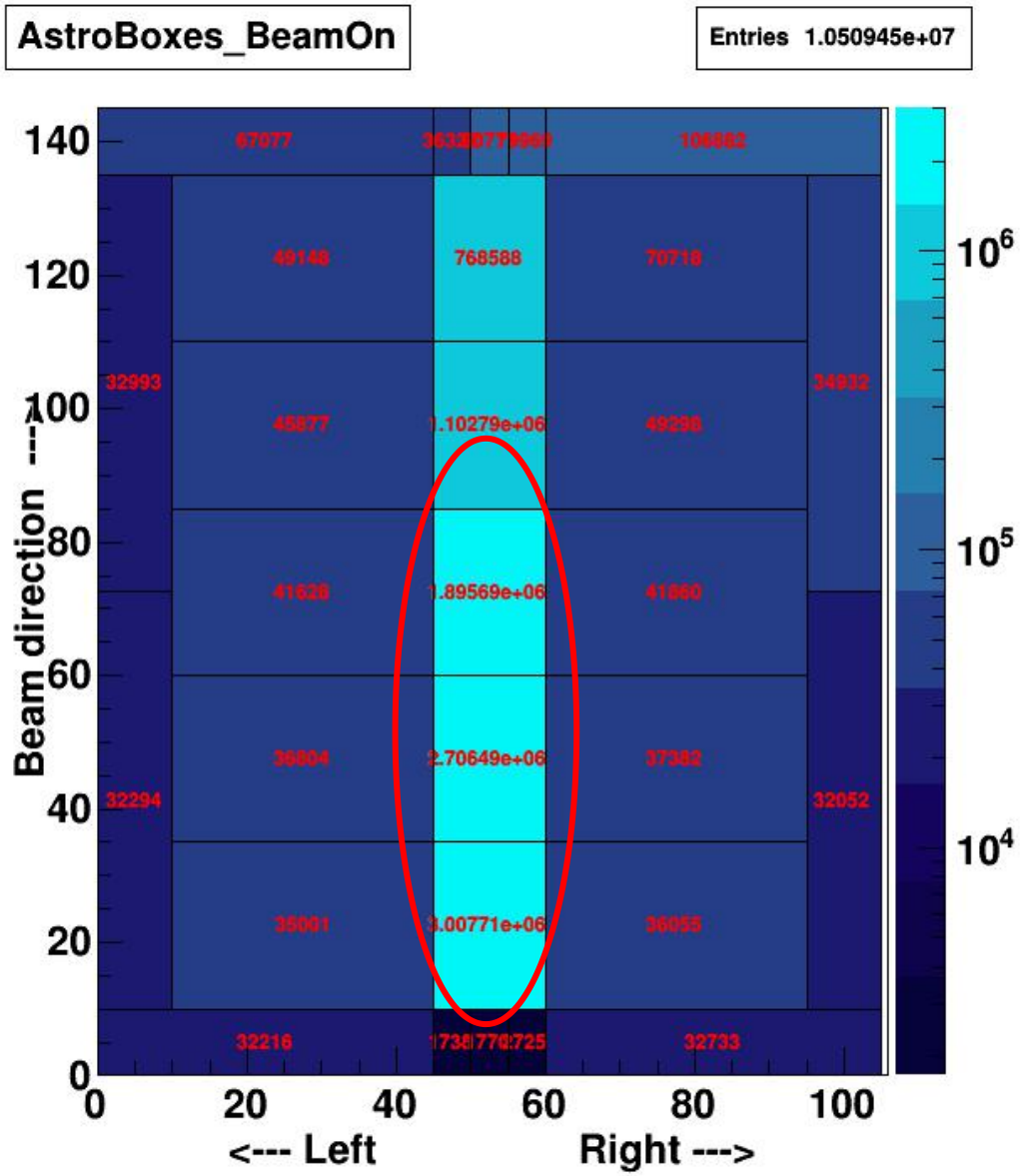




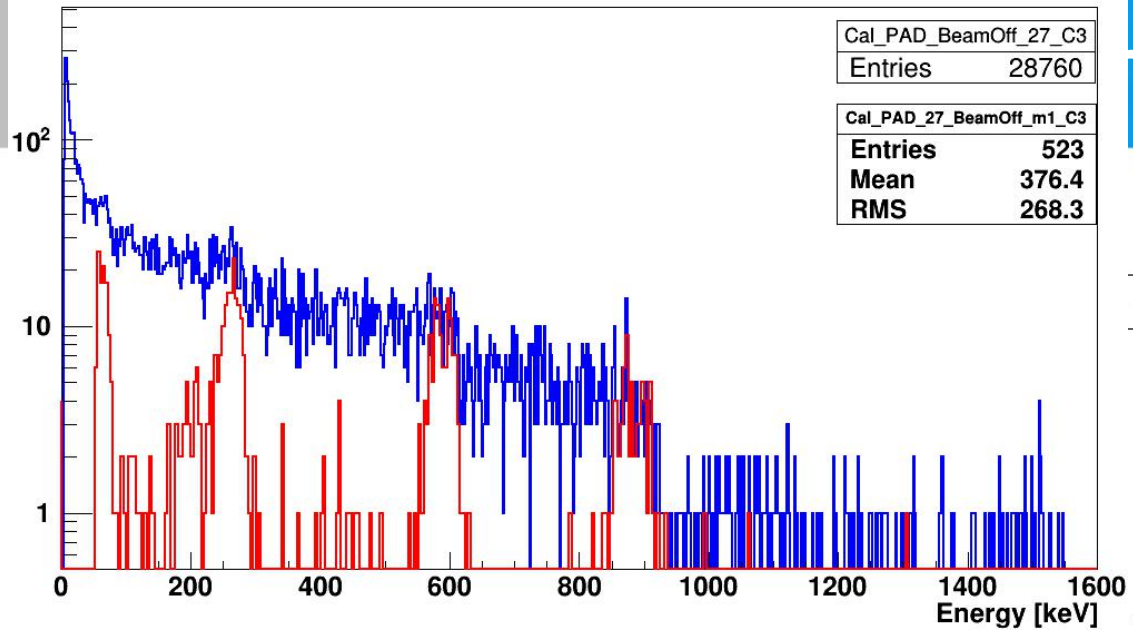

exco

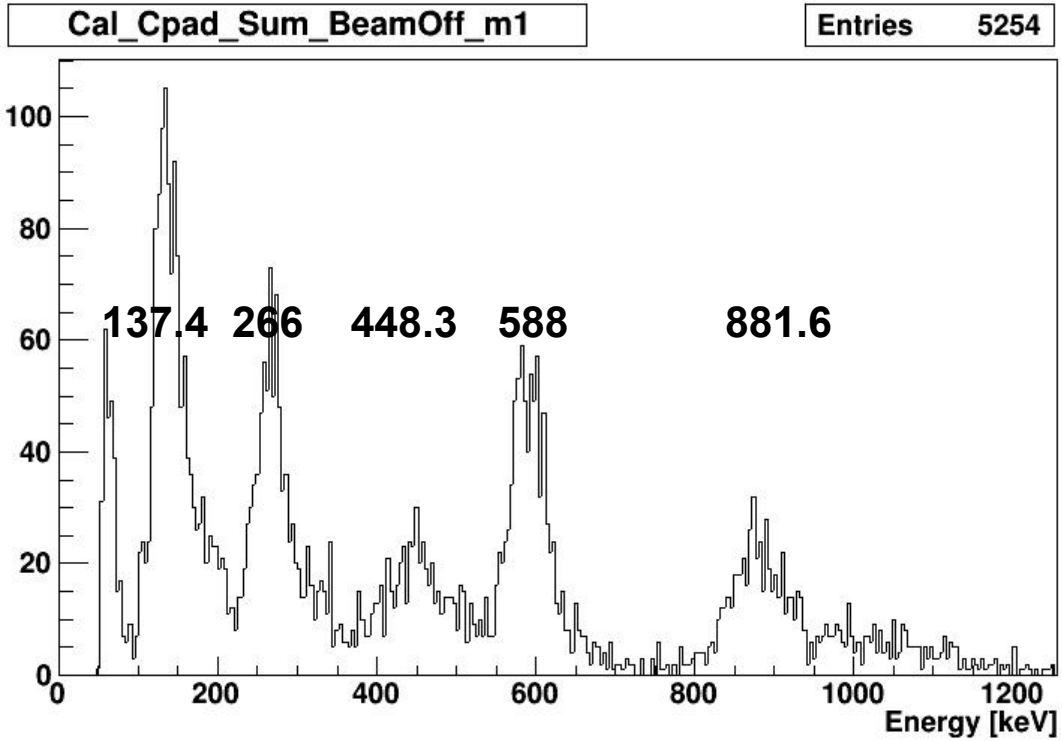
23Al - AstroBox 2 - results

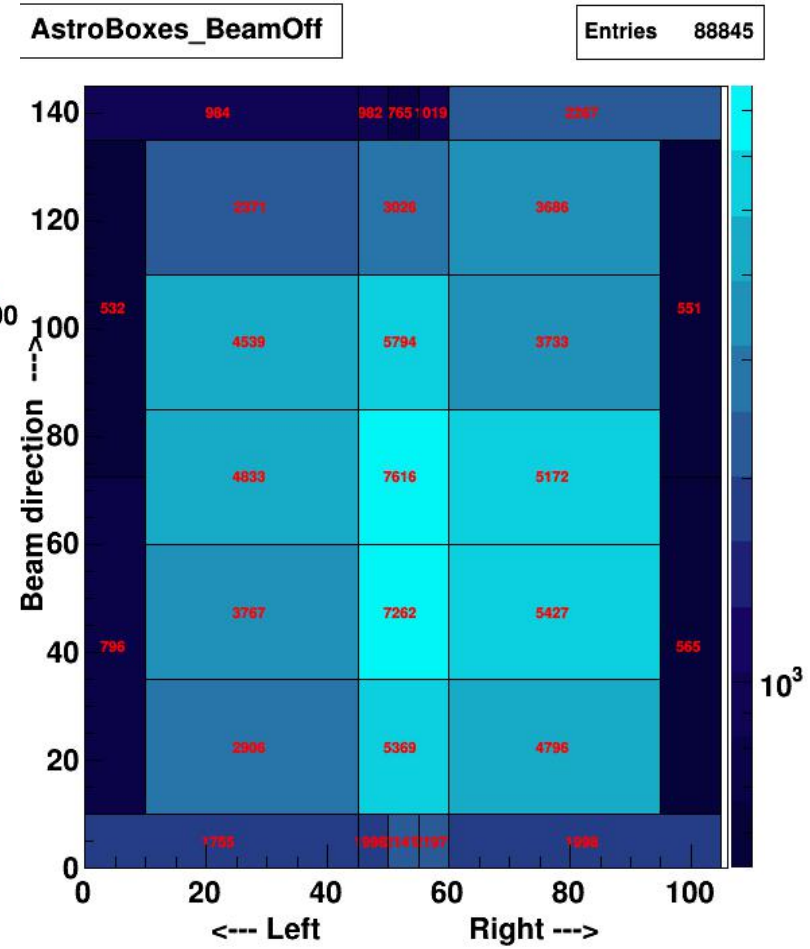




roBox 2 - results







31Cl - motivation

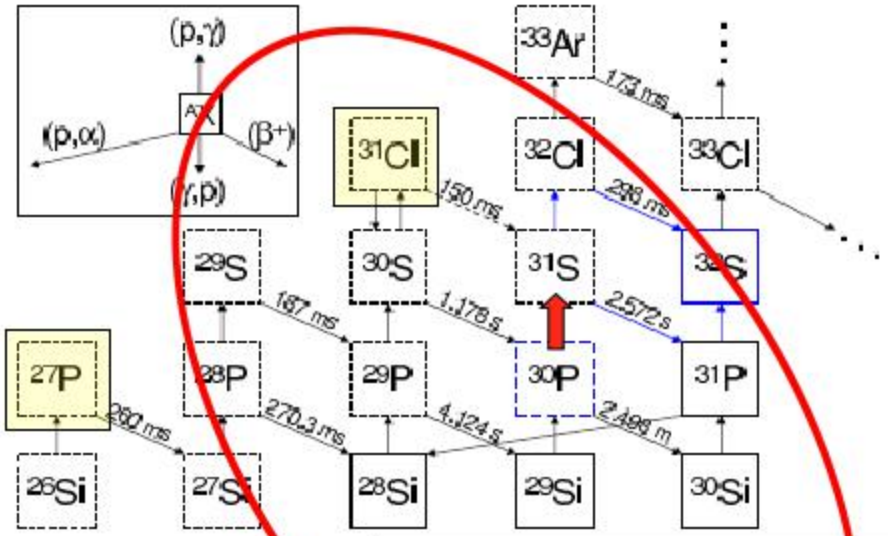
Explosive H-burning in novae

&

IAS in T_z=-3/2 nuclei

Isospin mixing

GT strength distribution

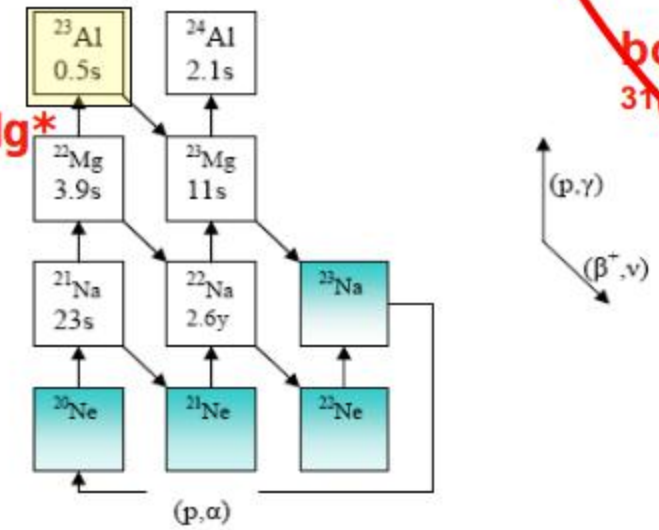


bottleneck r. in novae

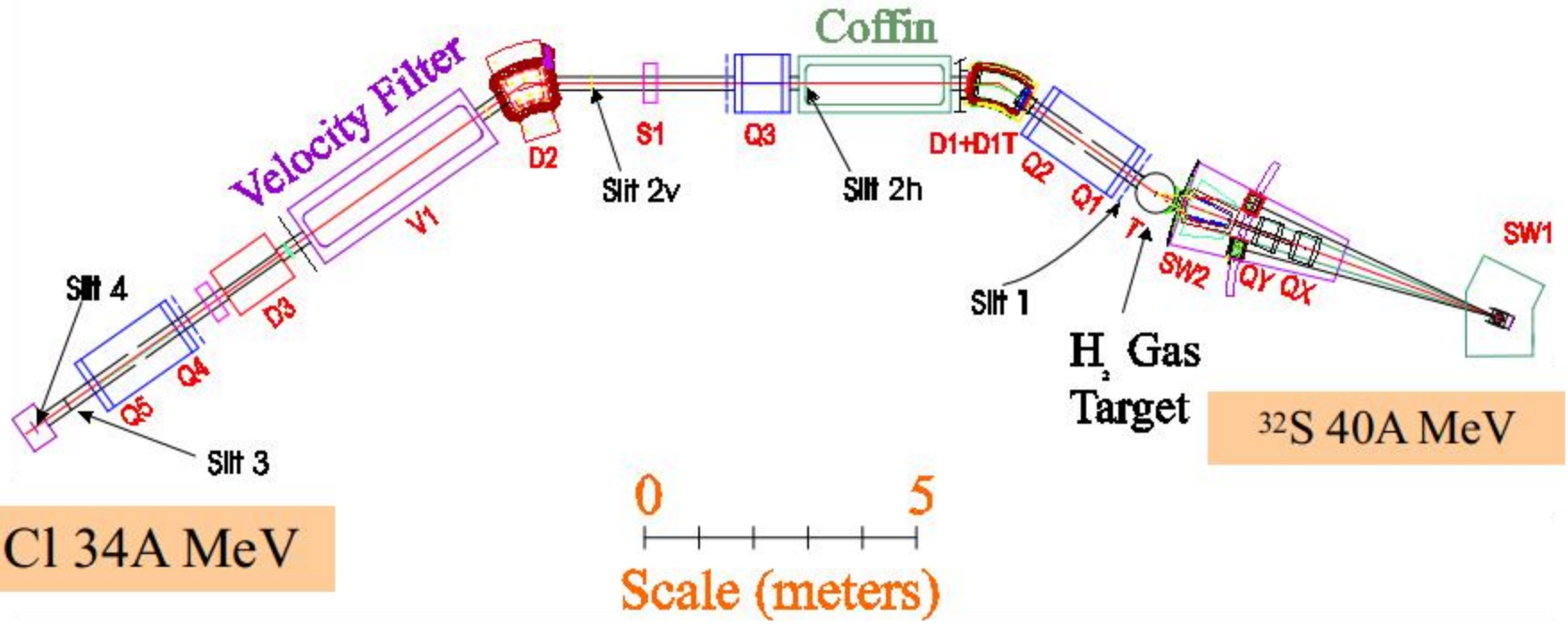
$^{31}Cl \rightarrow ^{31}S^*$ **$^{30}P(p,g)^{31}S^*$**

^{22}Na depletion in novae

$^{23}Al \rightarrow ^{23}Mg^*$ **$^{22}Na(p,g)^{23}Mg^*$**



Momentum Achromat Recoil Separator



^{31}Cl 34A MeV

^{32}S 40A MeV

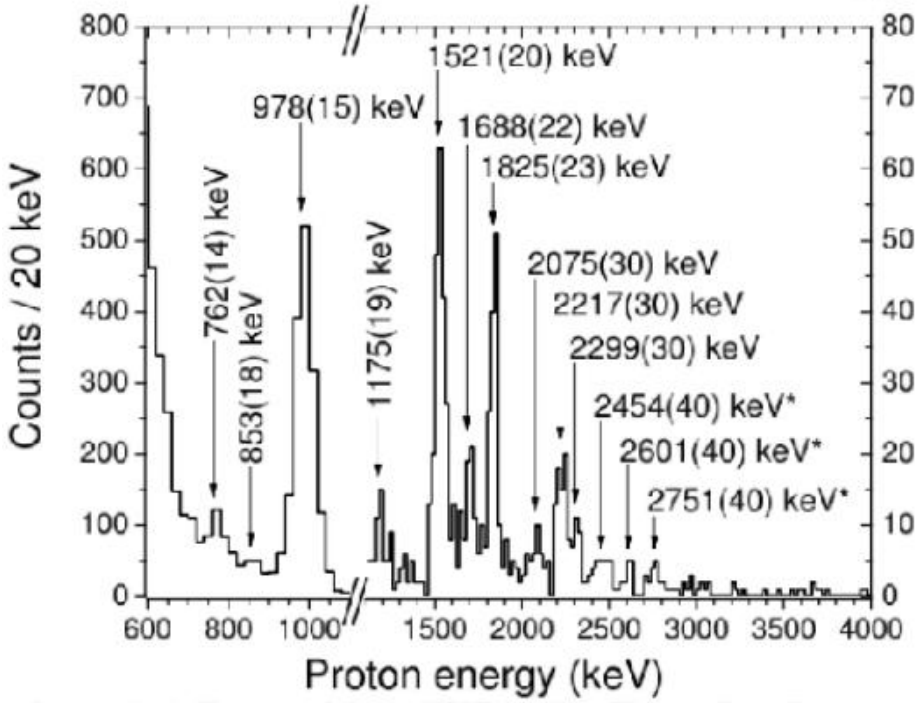
Purity: > 85 % (at target det)
Intensity: ~ 2-3000 pps
difficult - pure & intense ^{31}Cl

Primary beam ^{32}S @ 40A MeV – K500 Cycl
Primary target LN_2 cooled H_2 gas p=2 atm
Secondary beam ^{31}Cl @ 34 A MeV

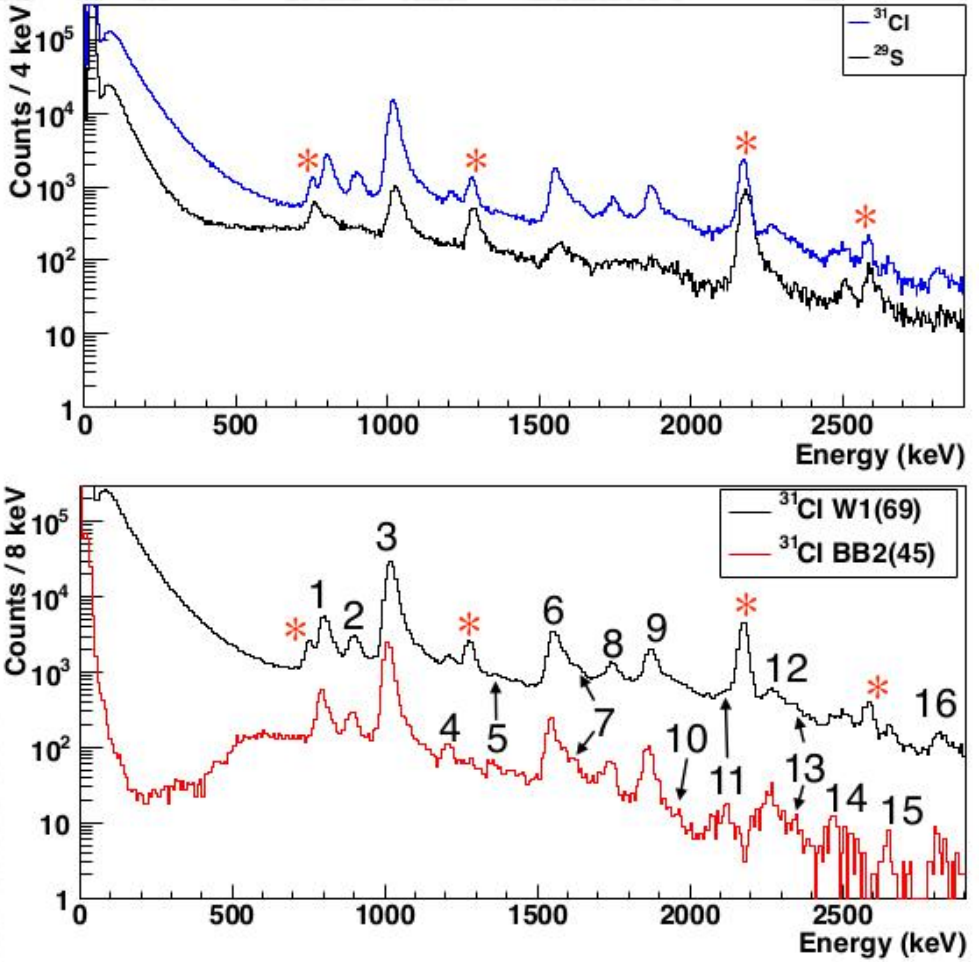
(p,2n) reaction

CYCLOTRON INSTITUTE
Texas A&M University

31Cl - Si - results

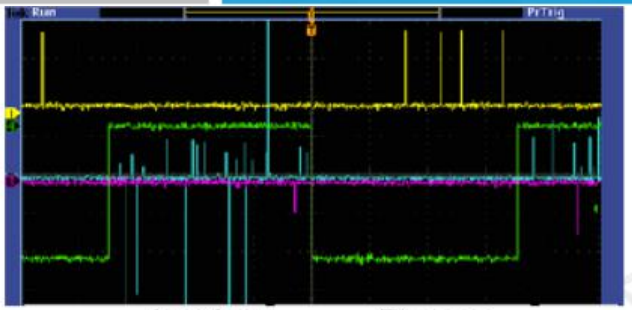


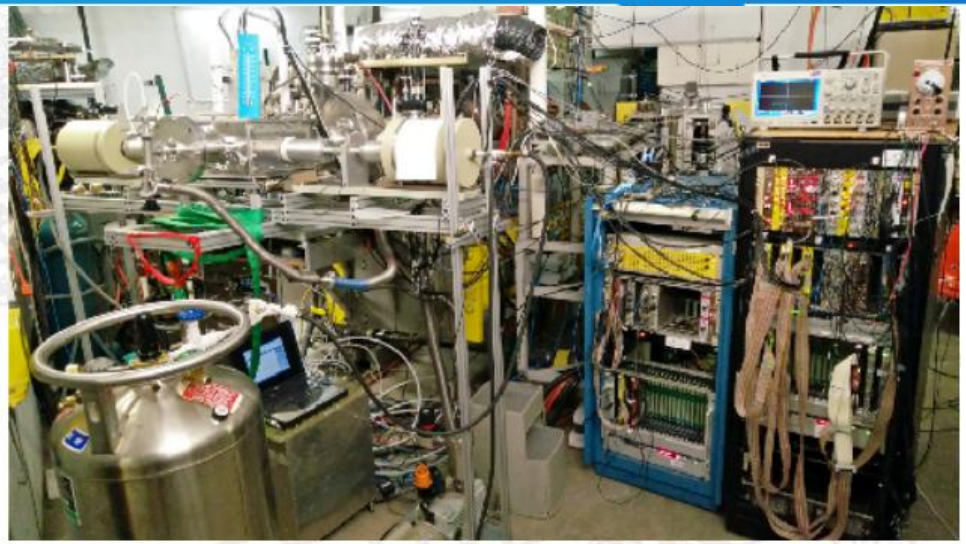
A. Kankainen et al. EPJA 27, 67 (2006)

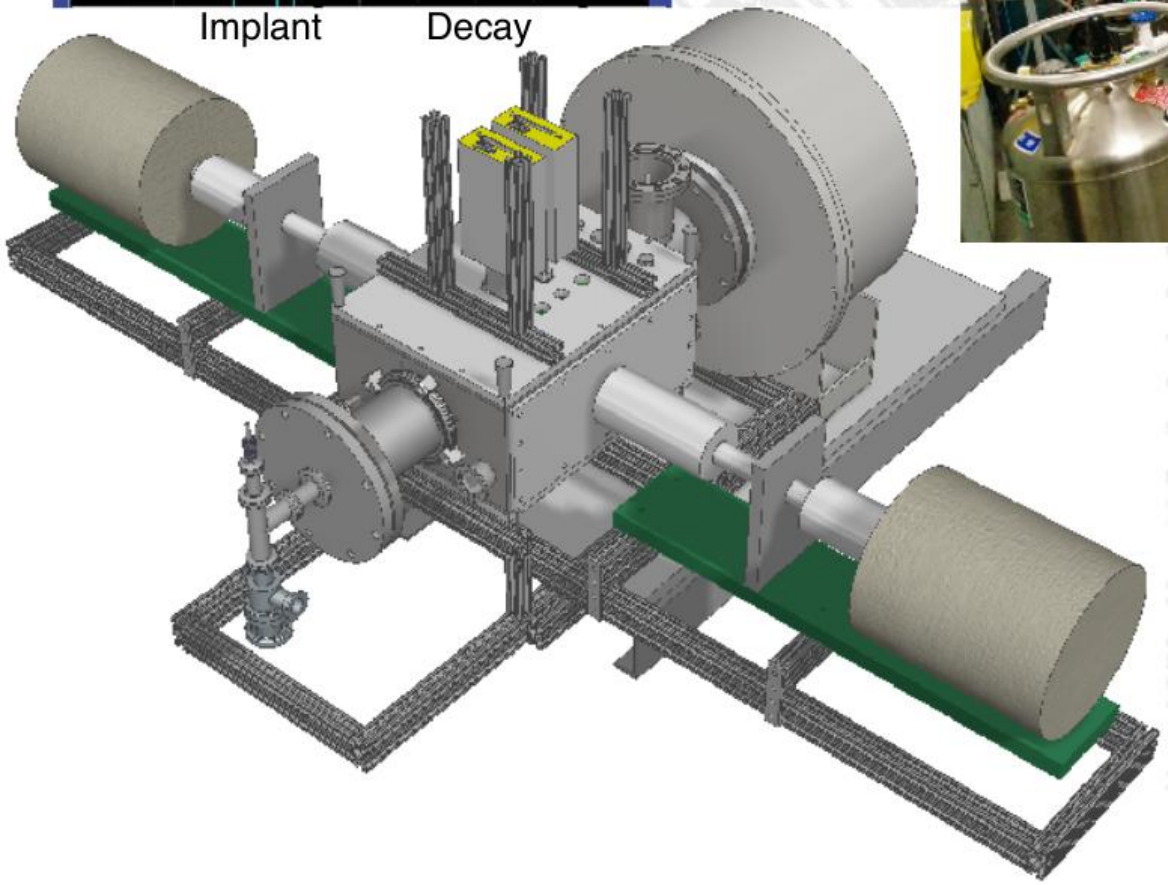


AJS PhD Thesis (2011); AIP Conf. Proc. 1409, 71 (2011)

31Cl - AB 2 - setup



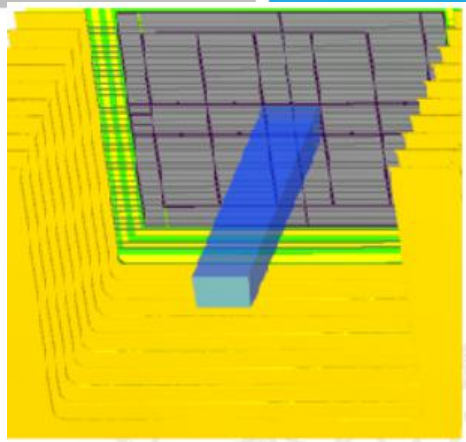


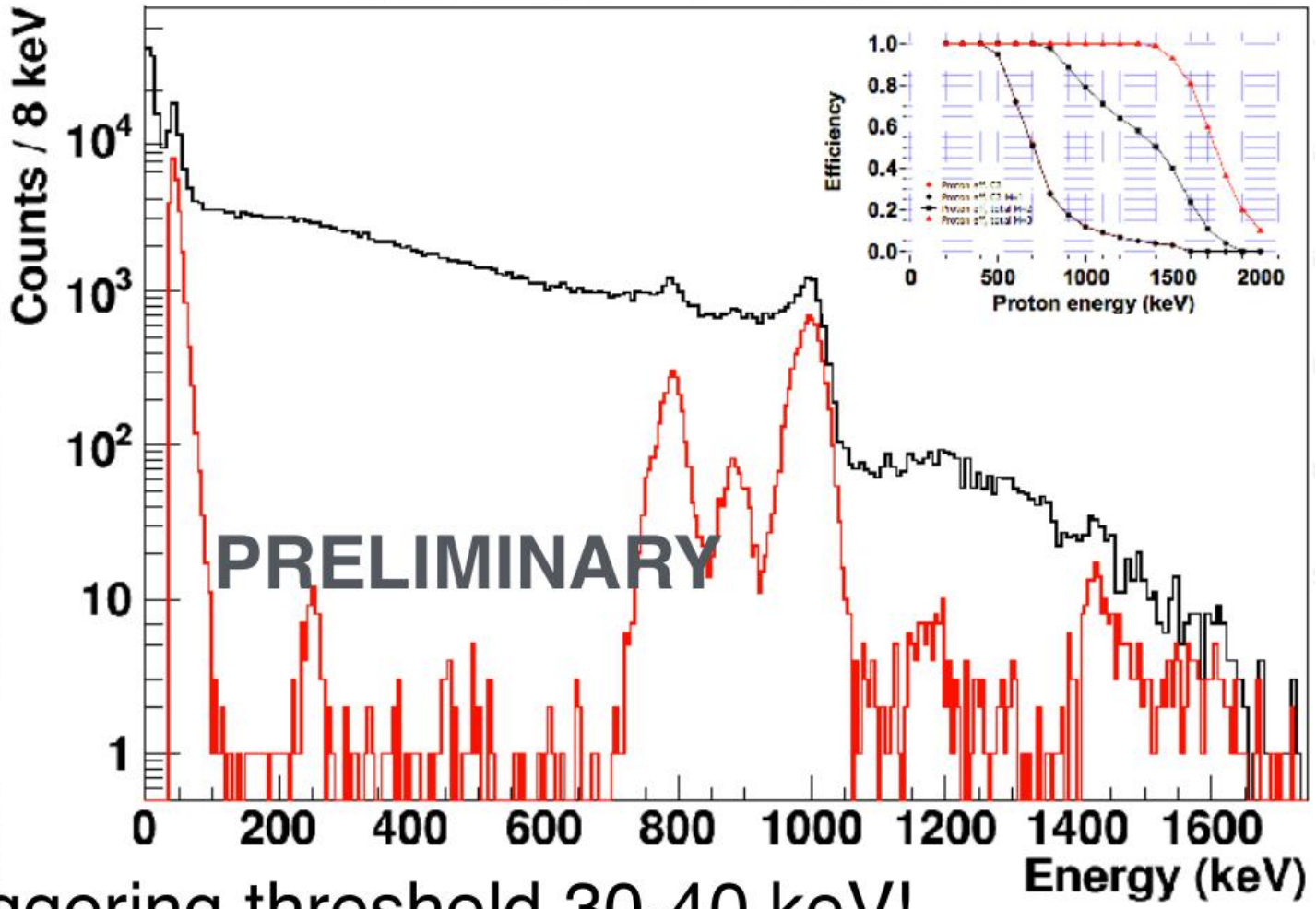


- AstroBox2 (128 µm MPGAD)
- 2 x 70% HPGe
- Independent MicroMEGAS for gain shift monitoring

*Antti Saastamoinen, Nuclear Physics in Astrophysics 8, Catania, Italy. June 22, 2017

31Cl - AB 2 - results



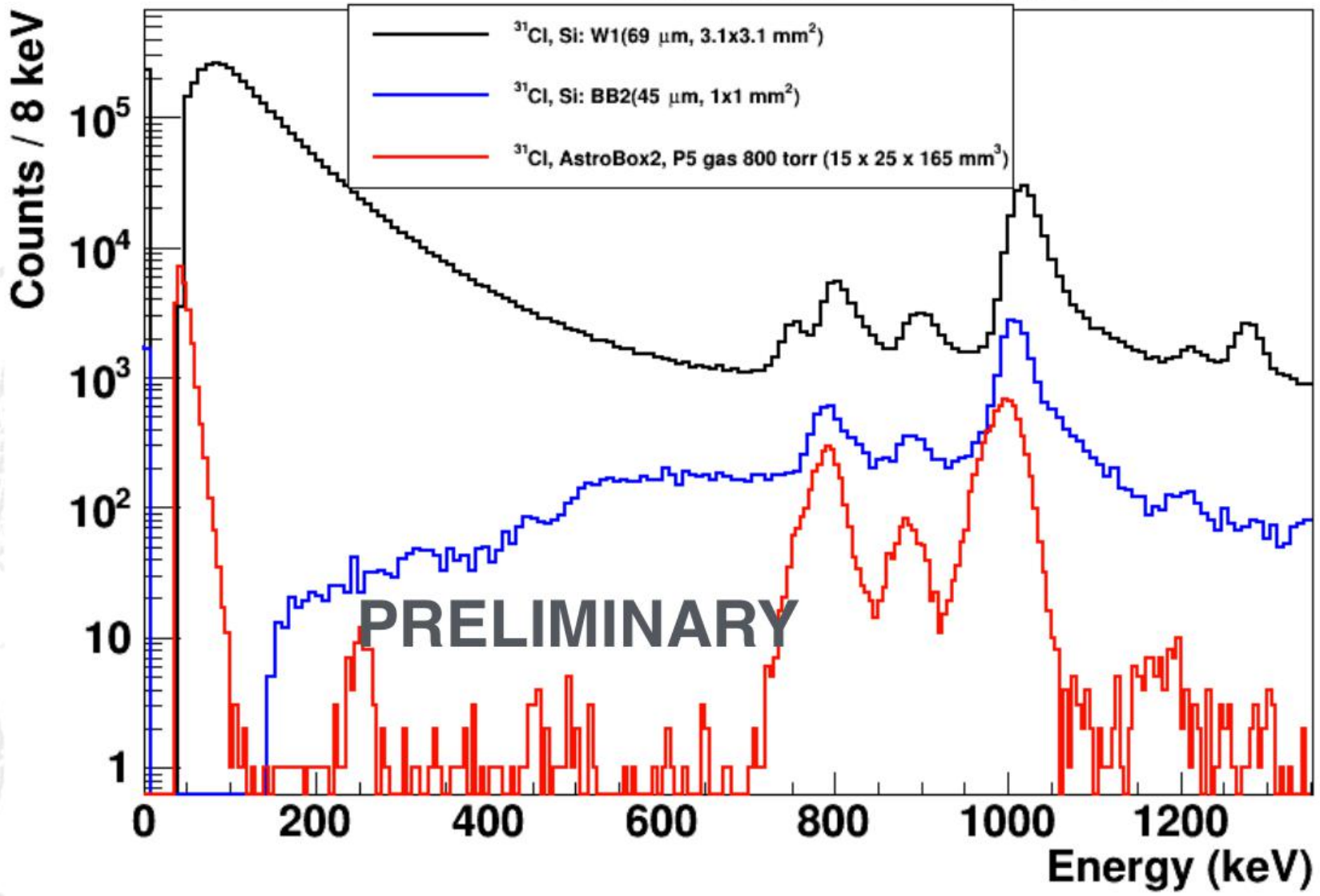


Triggering threshold 30-40 keV!

β-background only up to ~100 keV!

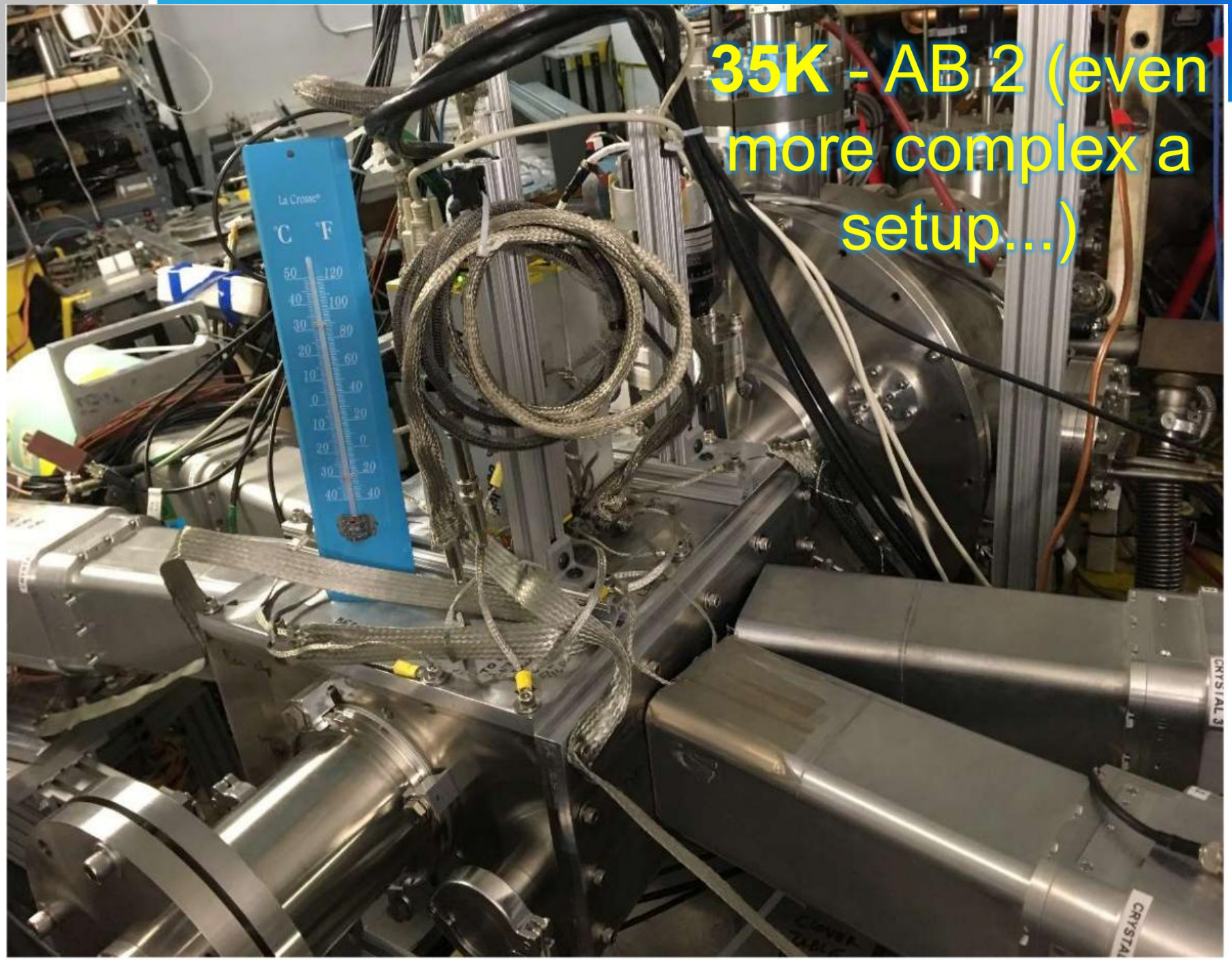
*Antti Saastamoinen, Nuclear Physics in Astrophysics 8, Catania, Italy. June 22, 2017

31Cl - Comparison between Si and AB 2

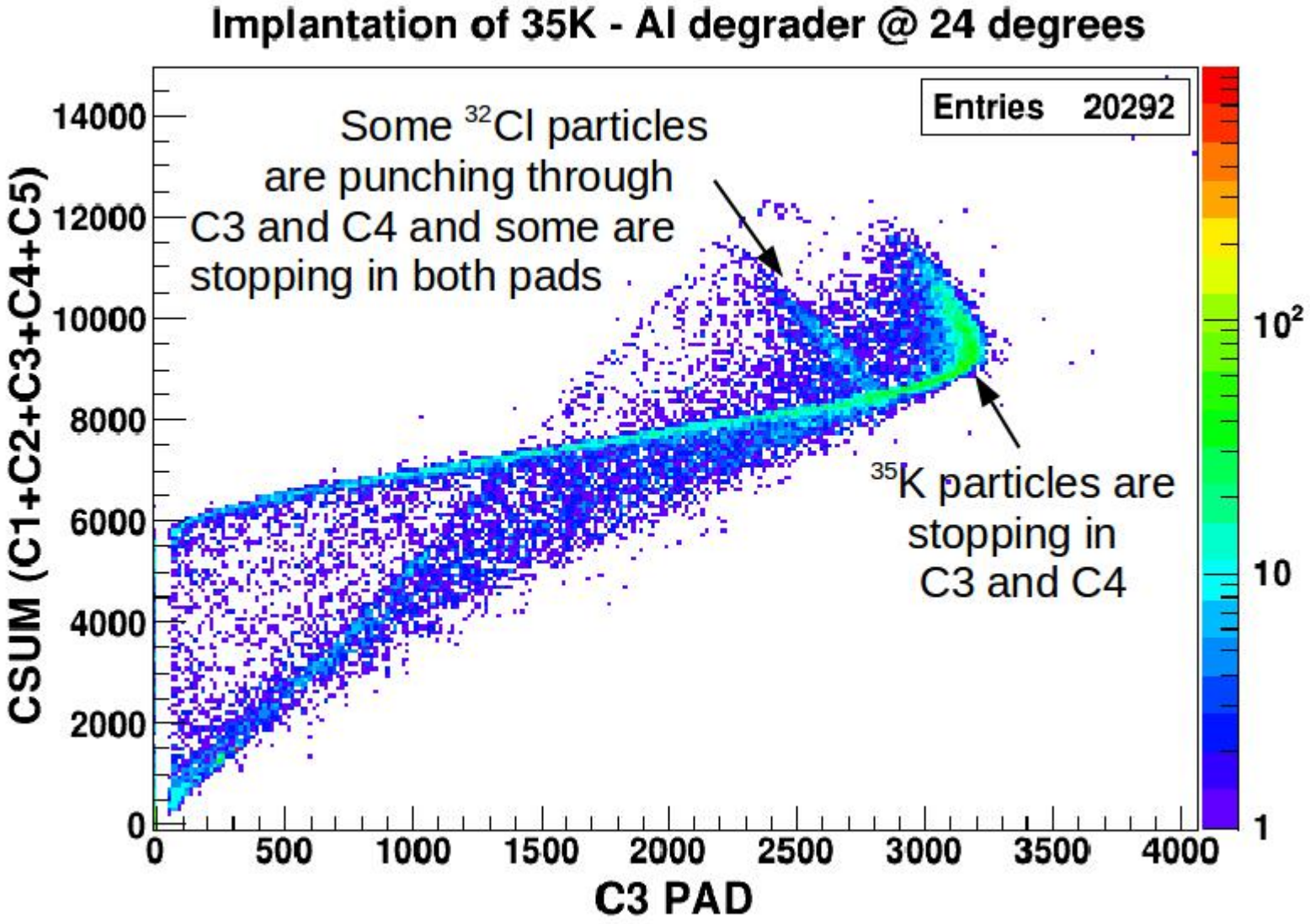


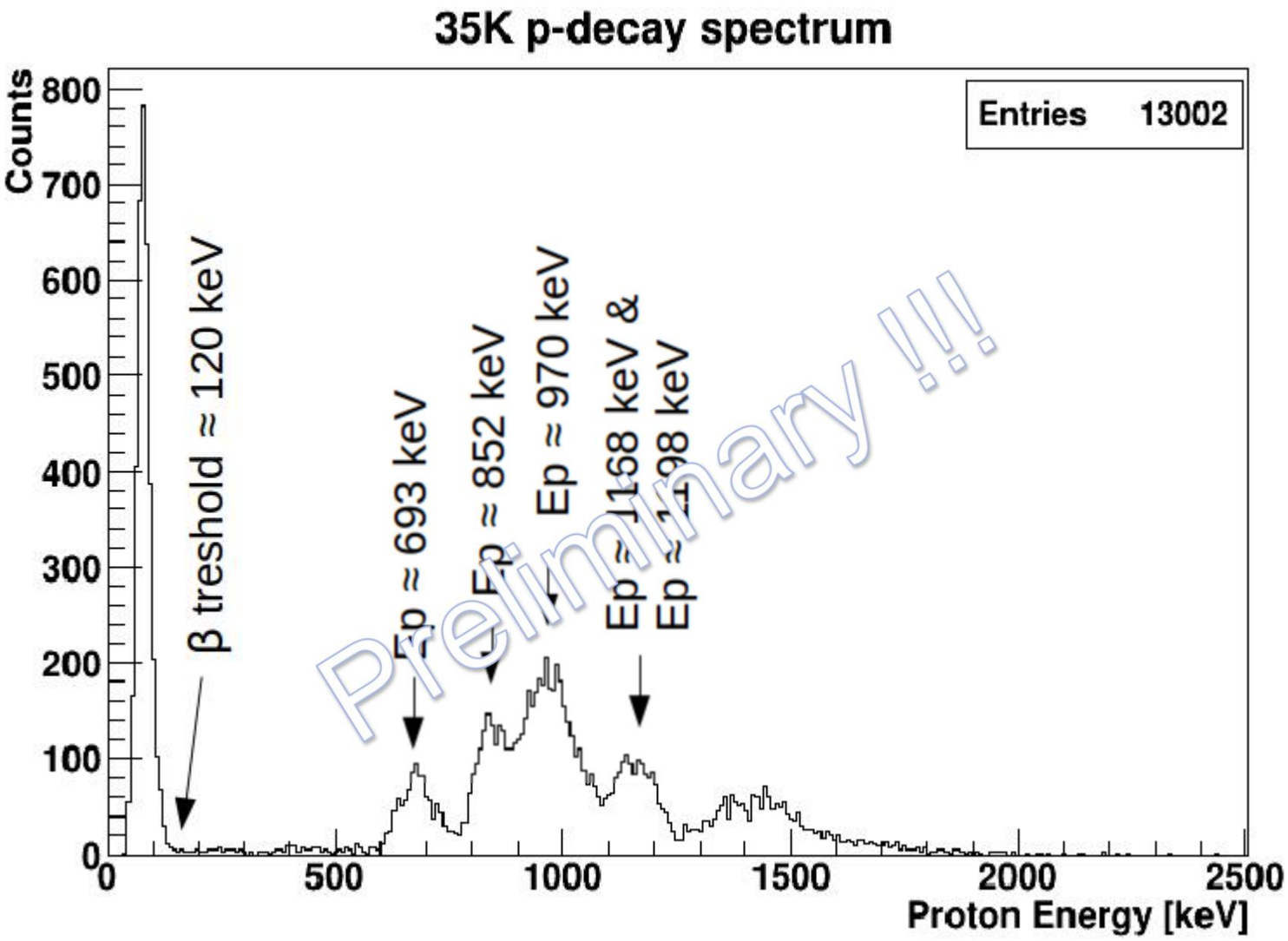
*Antti Saastamoinen, Nuclear Physics in Astrophysics 8, Catania, Italy. June 22, 2017

Went even an alpha higher...


35K - AB 2 (even more complex a setup...)
La Crosse
°C °F
50 120
40 100
30 80
20 60
10 40
0 20
10 0
20
30 20
40 40
CRYSTAL 3

35K

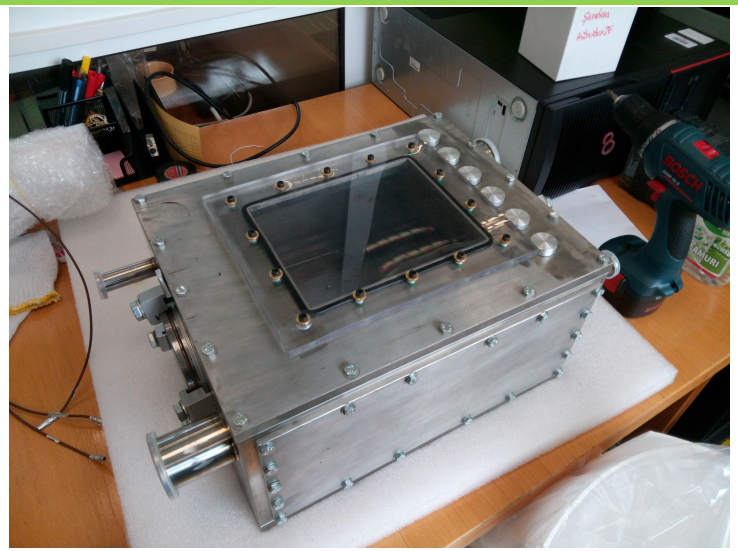

Implantation of 35K - Al degrader @ 24 degrees
Entries 20292
Some ^{32}Cl particles are punching through C3 and C4 and some are stopping in both pads
^{35}K particles are stopping in C3 and C4
CSUM (C1+C2+C3+C4+C5)
C3 PAD
0
2000
4000
6000
8000
10000
12000
14000
0
500
1000
1500
2000
2500
3000
3500
4000
1
10
10^2


35K p-decay spectrum
Entries 13002
Counts
800
700
600
500
400
300
200
100
0
0
500
1000
1500
2000
2500
Proton Energy [keV]
β treshold ≈ 120 keV
Ep ≈ 693 keV
Ep ≈ 852 keV
Ep ≈ 970 keV
Ep ≈ 1168 keV &
Ep ≈ 1198 keV
Preliminary !!!

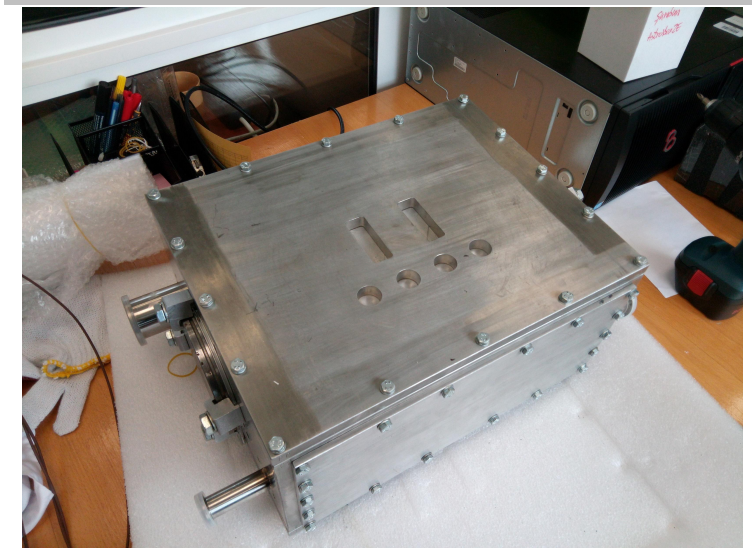
AstroBox2E(uropean vers) - status

- Detector system is being built at IFIN for use at facilities in Europe, specifically GANIL and ISOLDE

The chamber was built&tested to vacuum 10^{-5}mbar
2 MicroMEGAS detectors
Gas control system



Finish the whole gas system
Complete the electronics (few more modules)



Thank you for your attention!