High-precision beta-decay studies to test the weak-interaction standard model

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- Germanium detector calibration
- experimental studies: 0^+ - 0^+ β decay
  mirror β decay
- future work

ISOLDE workshop and users meeting, December 2-4, 2015

What can we learn?

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

weak eigenstates — Cabibbo Kobayashi Maskawa (CKM) matrix — mass eigenstates

Obtain precise value of $G_V^2(1 + \Delta_R)$

Determine V_{ud}^2

$$V_{ud}^2 = G_V^2/G_\mu^2$$

Test CKM unitarity

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1$$

FROM MANY TRANSITIONS

- Test Conservation of the Vector current (CVC)
- Validate the correction terms
- Test for presence of a Scalar current

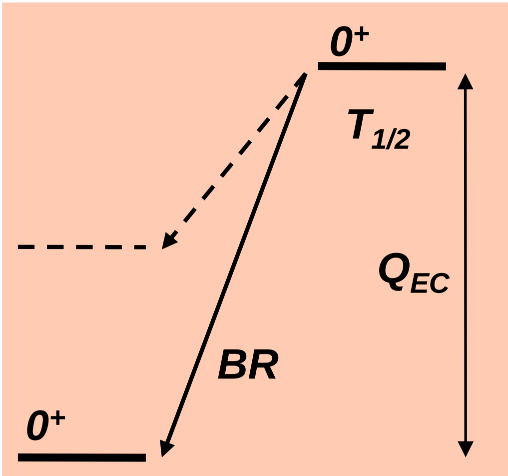
$\mathcal{F}t$ values constant

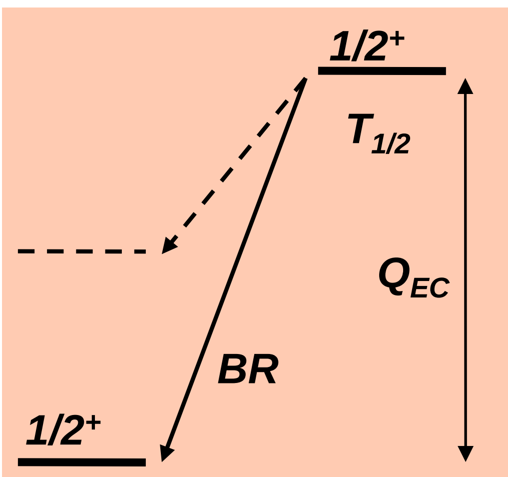
FROM A SINGLE TRANSITION

- Experimentally determine G_V^2

$$\mathcal{F}t = ft\,(1 + \delta_R')[1 - (\delta_C - \delta_{NS})] = \frac{K}{2G_V^2\,(1 + \Delta_R)}$$

Nuclear beta decay





$0^+ \rightarrow 0^+$:

$$Ft = ft\,(1 + \delta_R')\,(1 - \delta_c + \delta_{NS}) = \frac{K}{g_V^2\,(1 + \Delta_R)\,\langle M_F \rangle^2} = cnst$$

- $f(Z, Q_{EC}) \sim 1.5\%$
- f(nucl. structure) ~ 0.3-1.5%
- f(weak interaction) ~ 2.4%
- additional measurement needed

mirror decays:

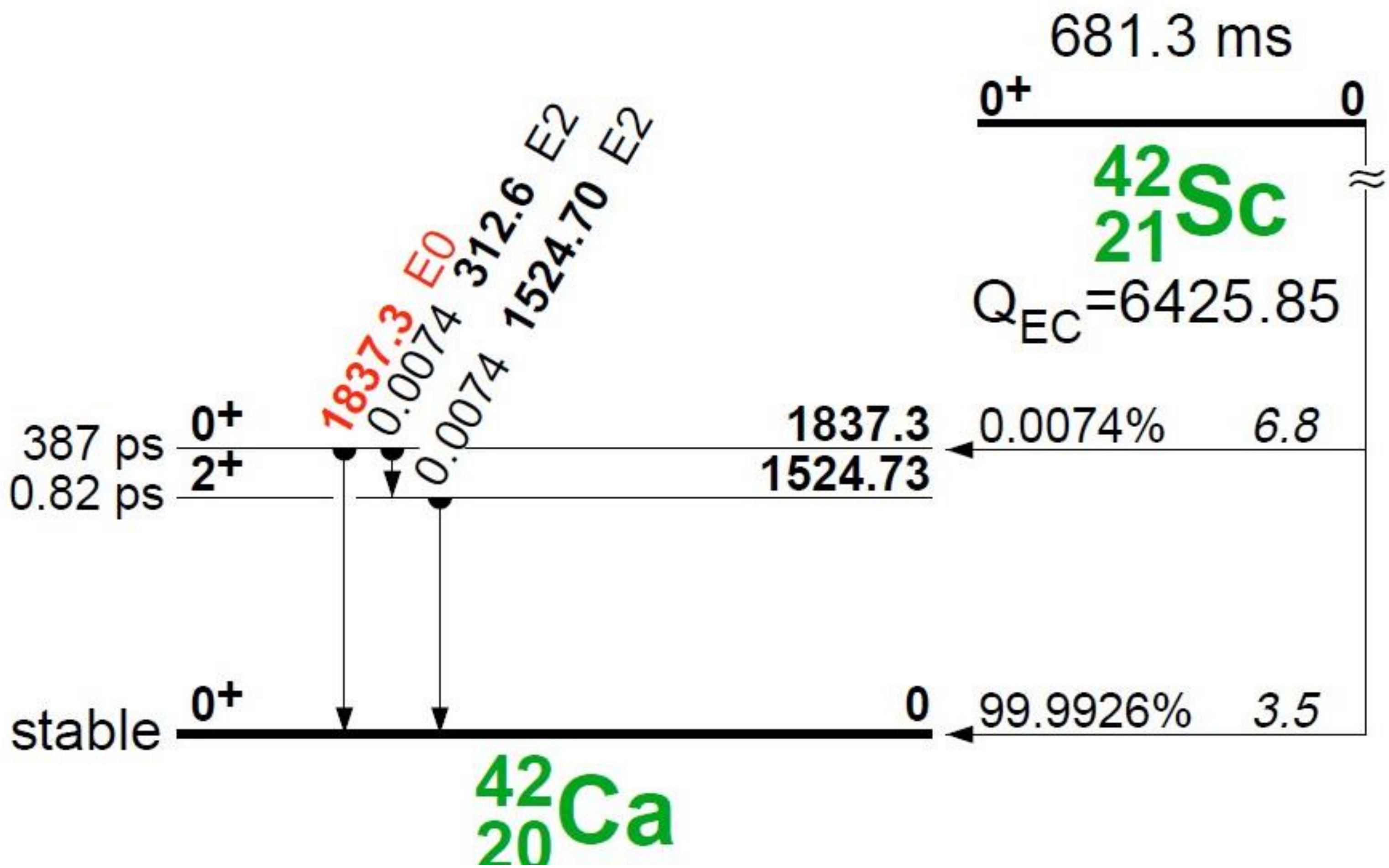
$$Ft = ft\,(1 + \delta_R')\,(1 - \delta_c + \delta_{NS}) = \frac{K}{g_V^2\,(1 + \Delta_R)\,\langle M_F \rangle^2} \times \frac{1}{(1 + f_a/f_v)\,\rho^2} = cnst$$

Precision measurements required: 10^{-3}

- ✓ Q_{EC} → *mass measurements:* $f \sim Q_{EC}^5$
- ✓ $T_{1/2}$, BR → *β-decay studies:* $t = T_{1/2} / BR$
- ✓ ρ^2 → *β-decay angular correlation studies*

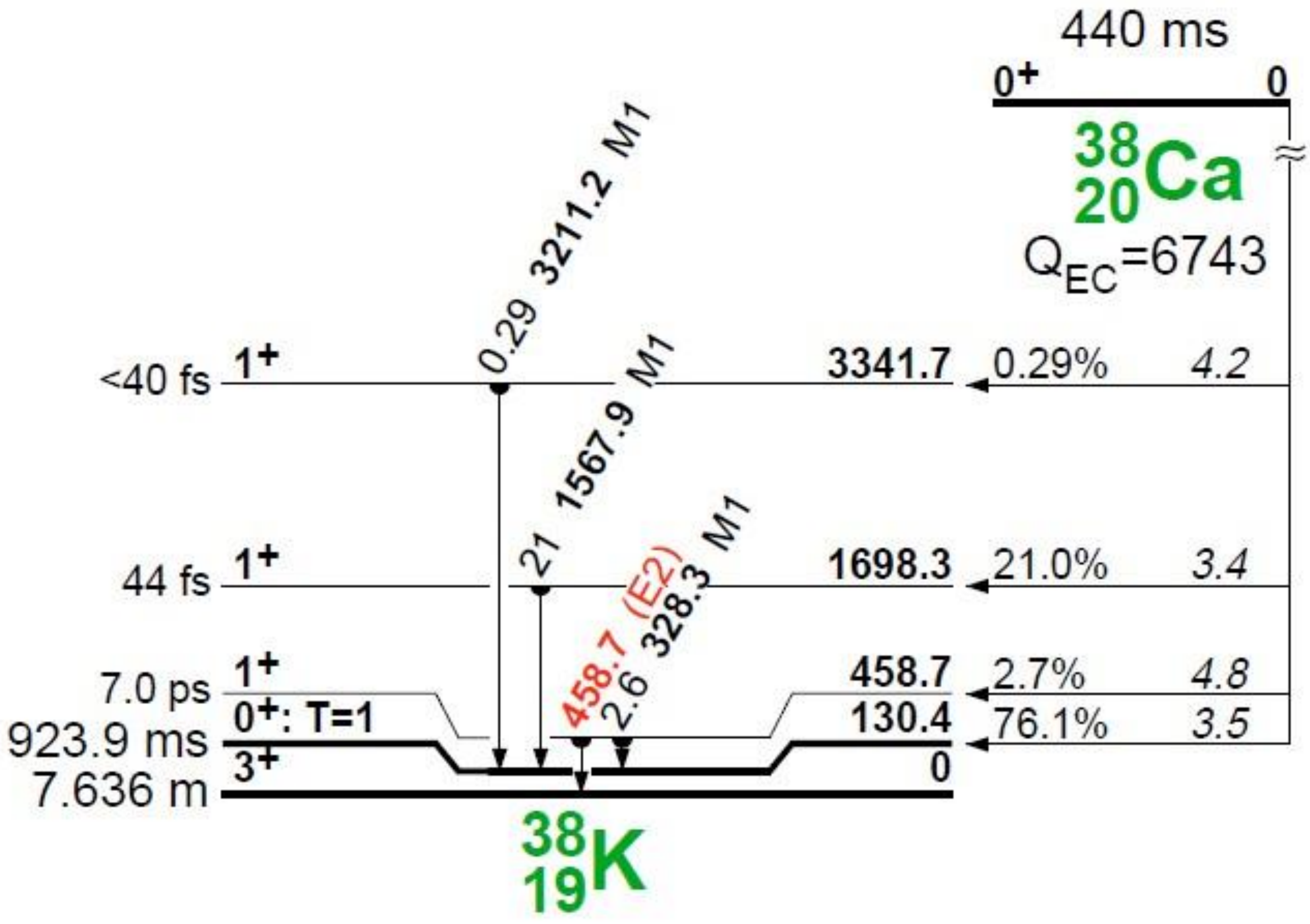
Germanium detector calibration

Super-allowed Fermi transitions for $T_z = 0$



- **close to 100% g.s. to g.s. transition**
- **low precision needed for non-analog transitions**

Super-allowed Fermi transitions for T_z = -1

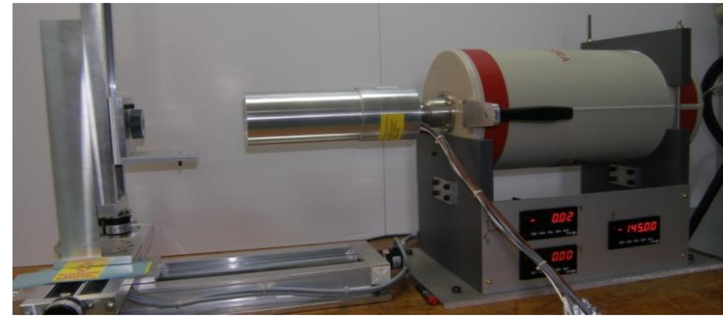


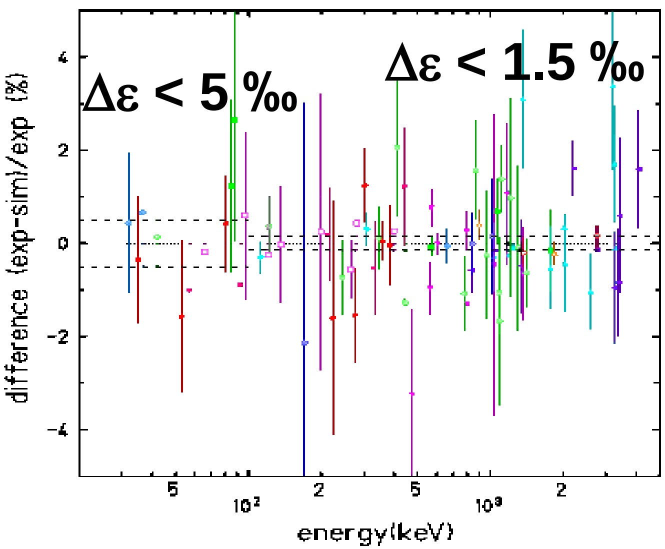
- many decay channels open
- strong non-analog transitions
- high precision of γ efficiency needed ➔ 0.1%

Calibration of germanium detector

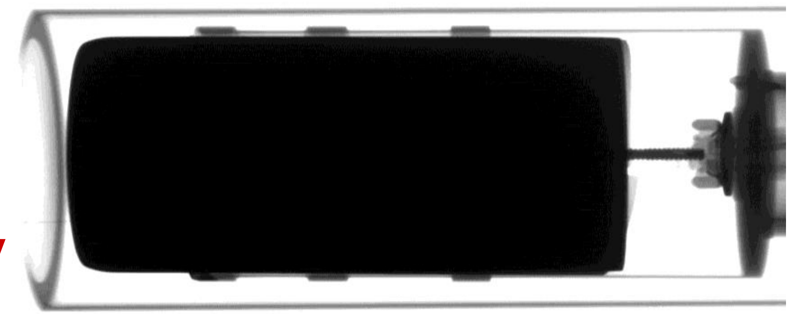
B. Blank et al., NIMA776 (2015) 34

- $\Delta\varepsilon_{rel} = 0.1\%$, $\Delta\varepsilon_{abs} = 0.15\%$
- calibration programme of a HP Ge detector:
  - x-ray photography of detector
  - scan of the crystal at CSNSM
  - source measurements
  - MC simulations: CYLTRAN, GEANT4

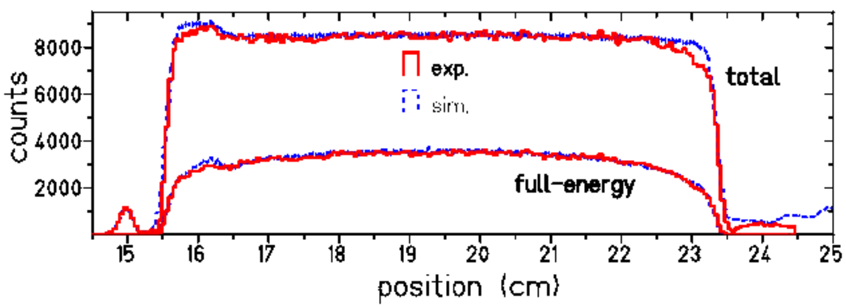


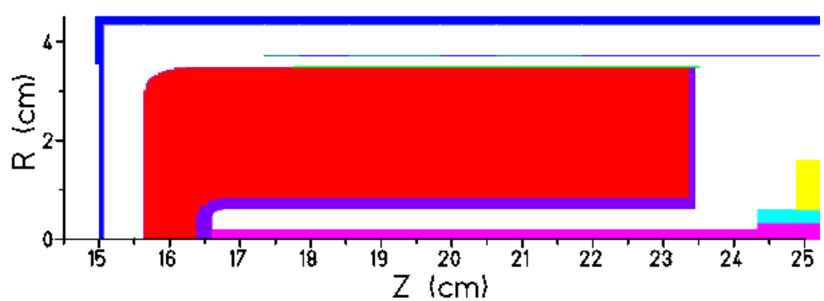


X-ray photography



Scan at CSNSM



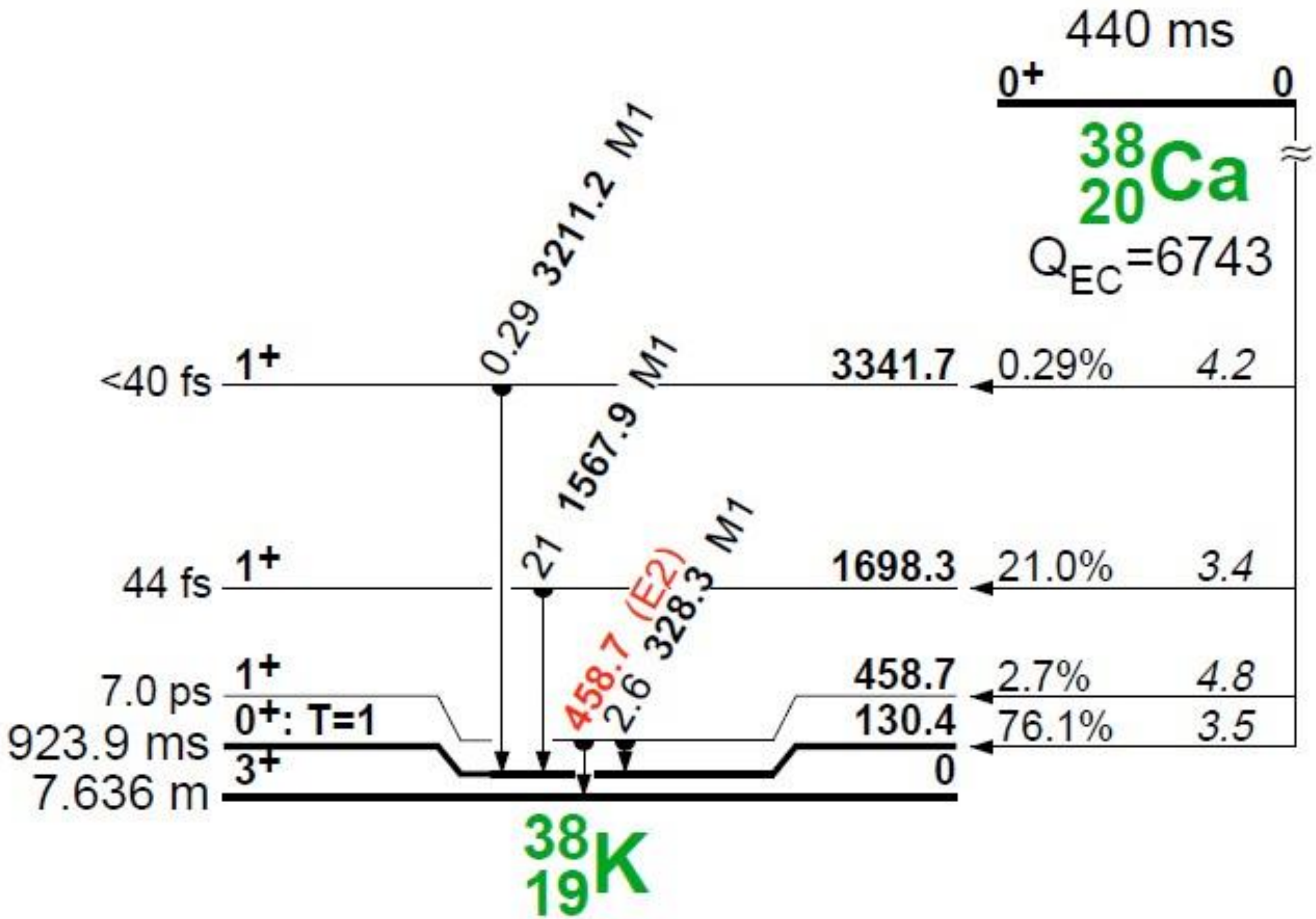


Branching ratios:
^{24}Na, ^{27}Mg, ^{48}Cr, ^{56}Co, ^{60}Co, ^{66}Ga, ^{75}Se, ^{88}Y, ^{133}Ba, ^{134}Cs, ^{137}Ce, ^{152}Eu, ^{180}Hf, ^{207}Bi

Peak/total: ^{22}Na, ^{41}Ar, ^{51}Cr, ^{54}Mn, ^{57}Co, ^{58}Co, ^{65}Zn, ^{85}Sr …ISOLDE sources

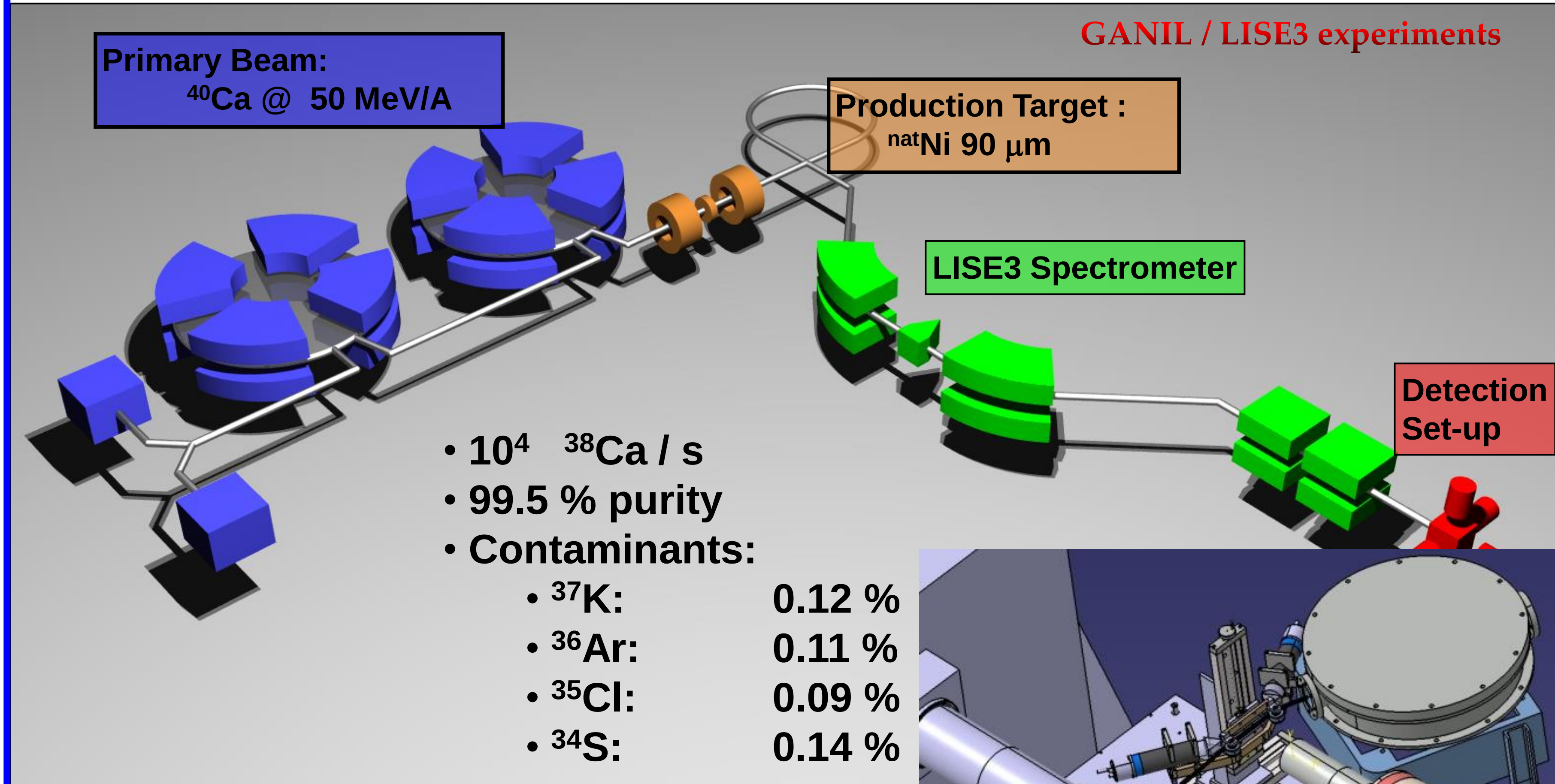
0^+ - 0^+ β decay: ^{38}Ca

Super-allowed Fermi transitions for $T_z = -1$

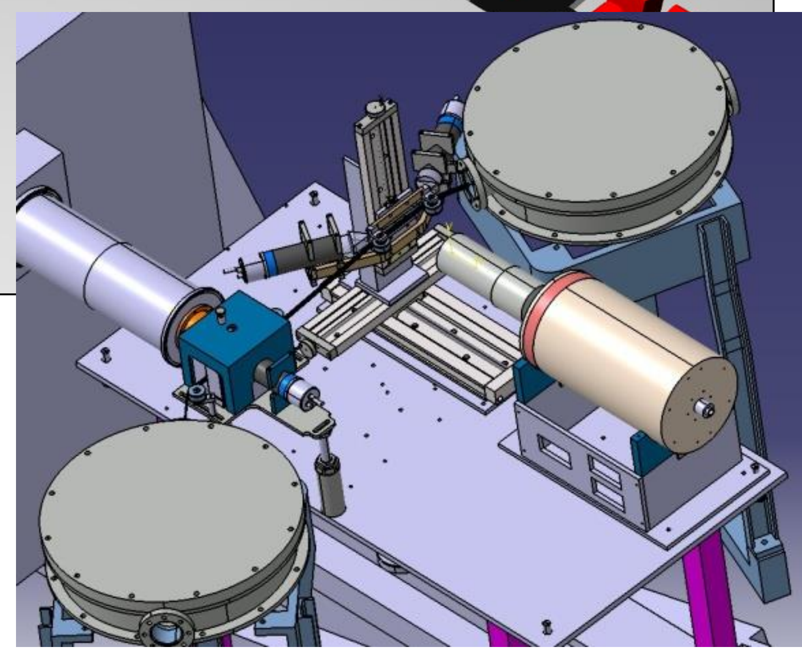


- many decay channels open
- strong non-analog transitions
- high precision of γ efficiency needed ➔ 0.1%

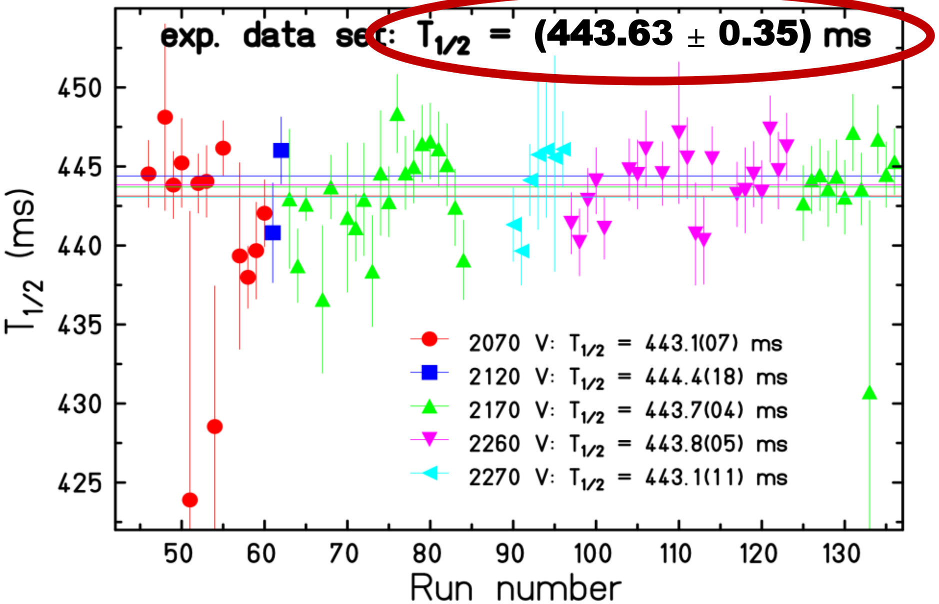
^{38}Ca production at GANIL/LISE3

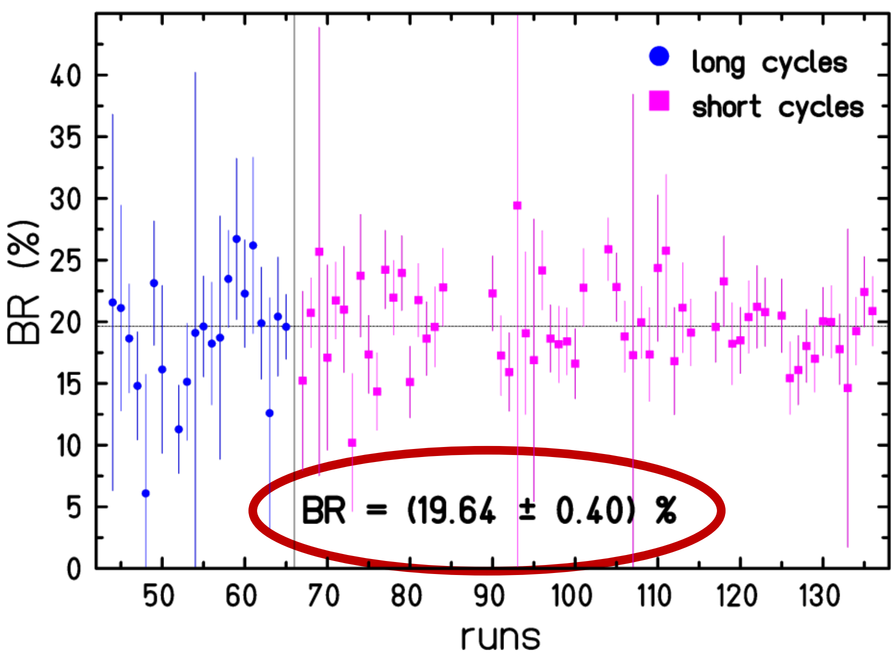


- 10^4 ^{38}Ca / s
- 99.5 % purity
- Contaminants:
  - ^{37}K: 0.12 %
  - ^{36}Ar: 0.11 %
  - ^{35}Cl: 0.09 %
  - ^{34}S: 0.14 %

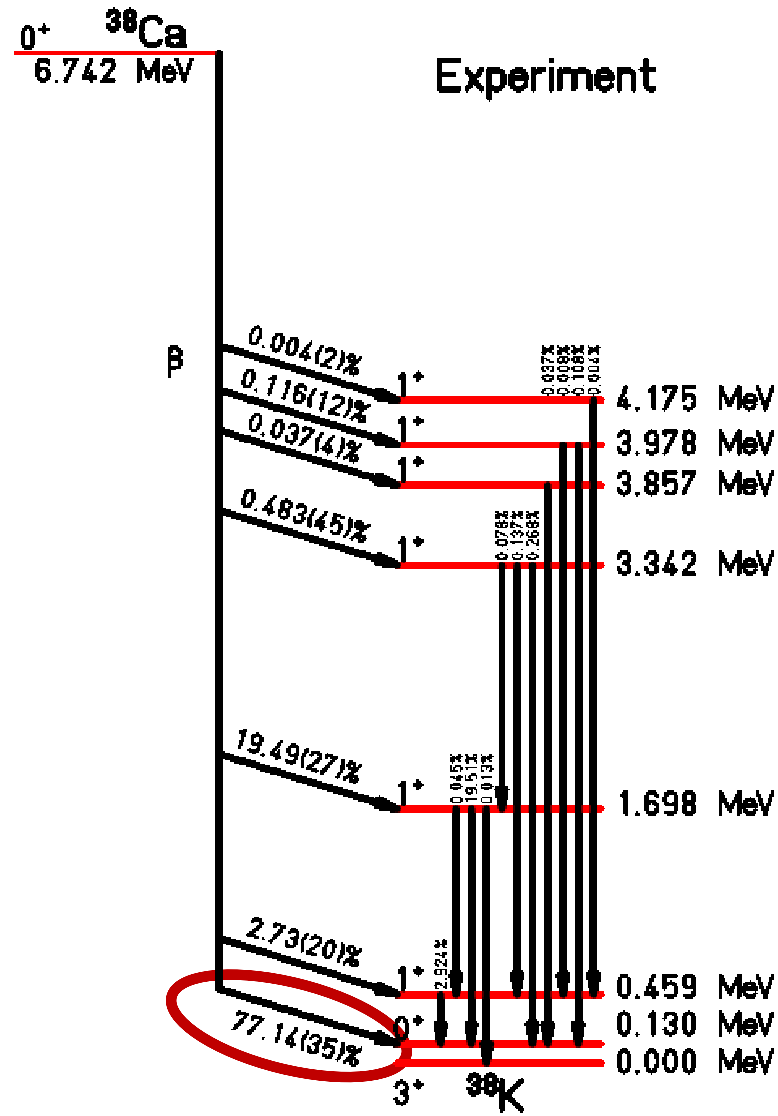


^{38}Ca branching ratios and half-life





Present work and Anderson et al.



B. Blank et al., EPJA 51 (2015) 8

^{38}Ca: result

- **half-life:**

Kavanagh *et al.* [26]	Gallmann *et al.* [27]	Zioni *et al.* [28]	Wilson *et al.* [29]	Blank *et al.* [20]	Park *et al.* [5]	Present	Average
470(20)	439(12)	450(70)	430(12)	443.8(19)	443.77(36)	443.63(35)	443.70(25)

➔➔ **443.70(25) ms**

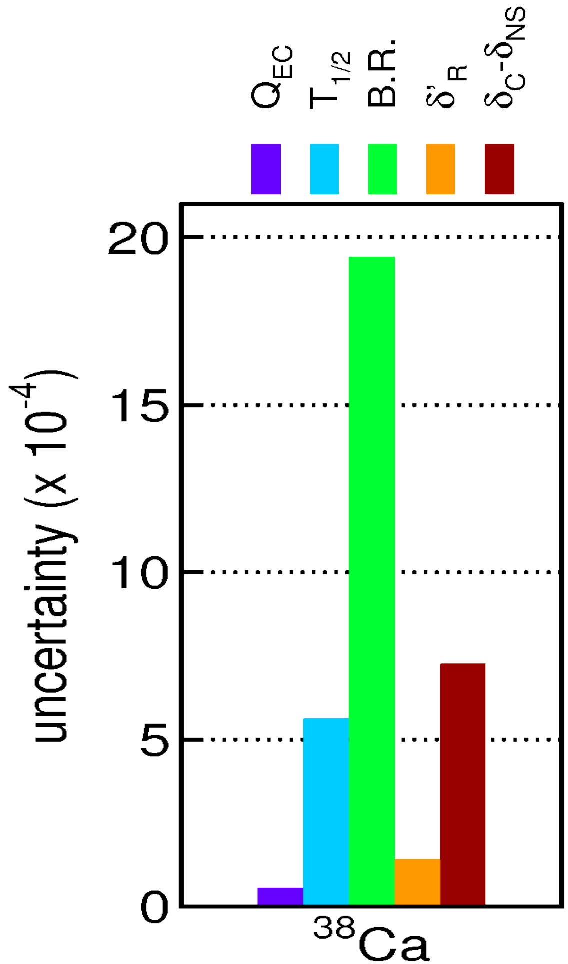
- **BR (0^+ — 0^+):** **present:** **77.09(35) %**
  Park et al.: **77.28(16) %**

➔➔ **77.25(15) %**

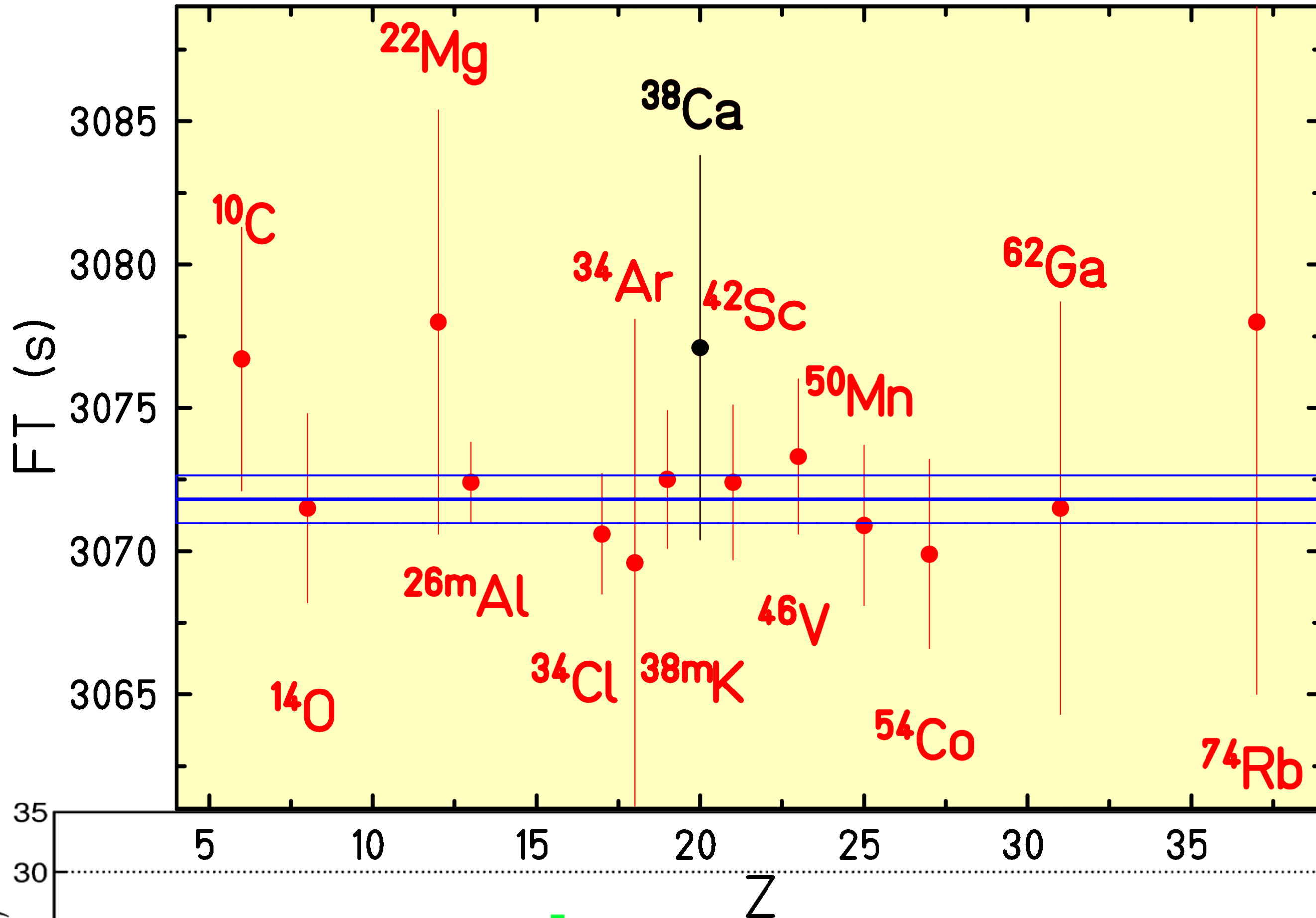
- **Q value:** **Eronen et al.:** **6612.11(7) keV**

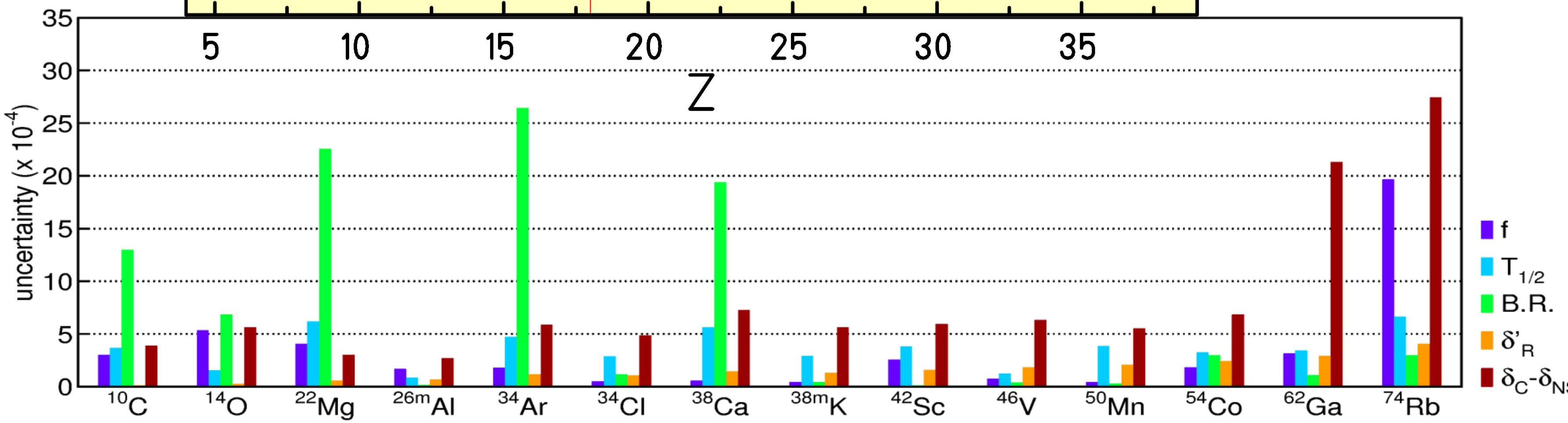
➔ **ft = 3063.3(62) s**

➔ **$\mathcal{F}$t = 3077.5(67) s**



^{38}Ca: result





…. 14 nuclei

BR for all T_z = -1 nuclei largest error

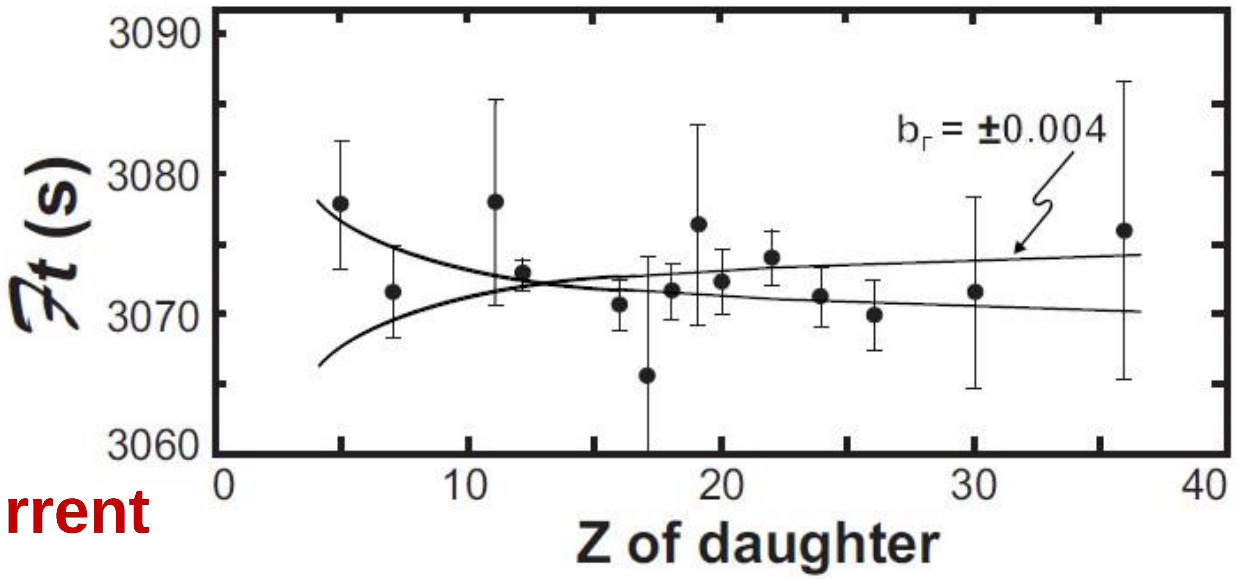
Recent ISOLDE experiment: ^{10}C

$0^+ \rightarrow 0^+$ decays: limits on exotic currents

- assumption: only vector current
- limit on scalar currents:

Severijns et al.

$$b_F = Re((C_s + C'_s) / C_v) = 0.0026(42) \quad (90\%\ CL)$$



- limit on scalar current from β decay:

$|C_s / C_v| \leq 0.065$

Hardy & Towner

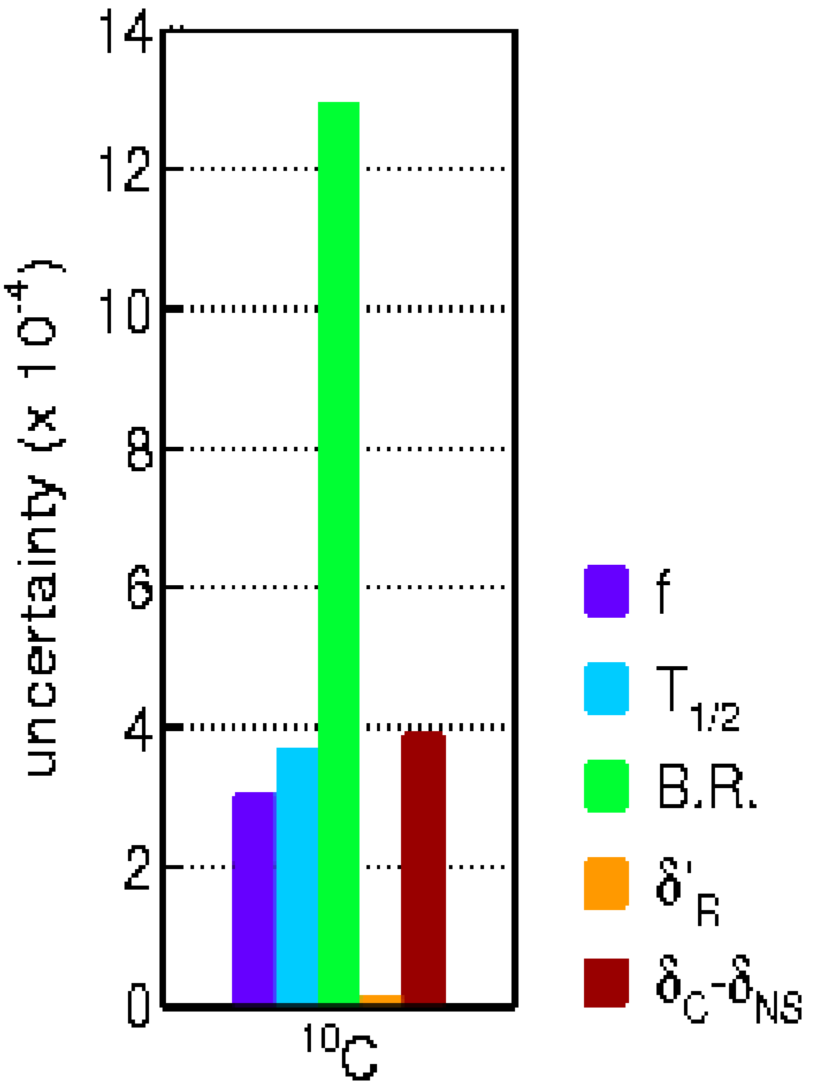
➔➔ improve on low-Z nuclei

- **BR by far largest error**
- **two precise measurements**
  - **Savard et al.: 1.4625(25)%**
    (PRL 74 (1995) 1521)
  - **Fujikawa et al.: 1.4665(38)%**
    (PLB 449 (1999) 6)

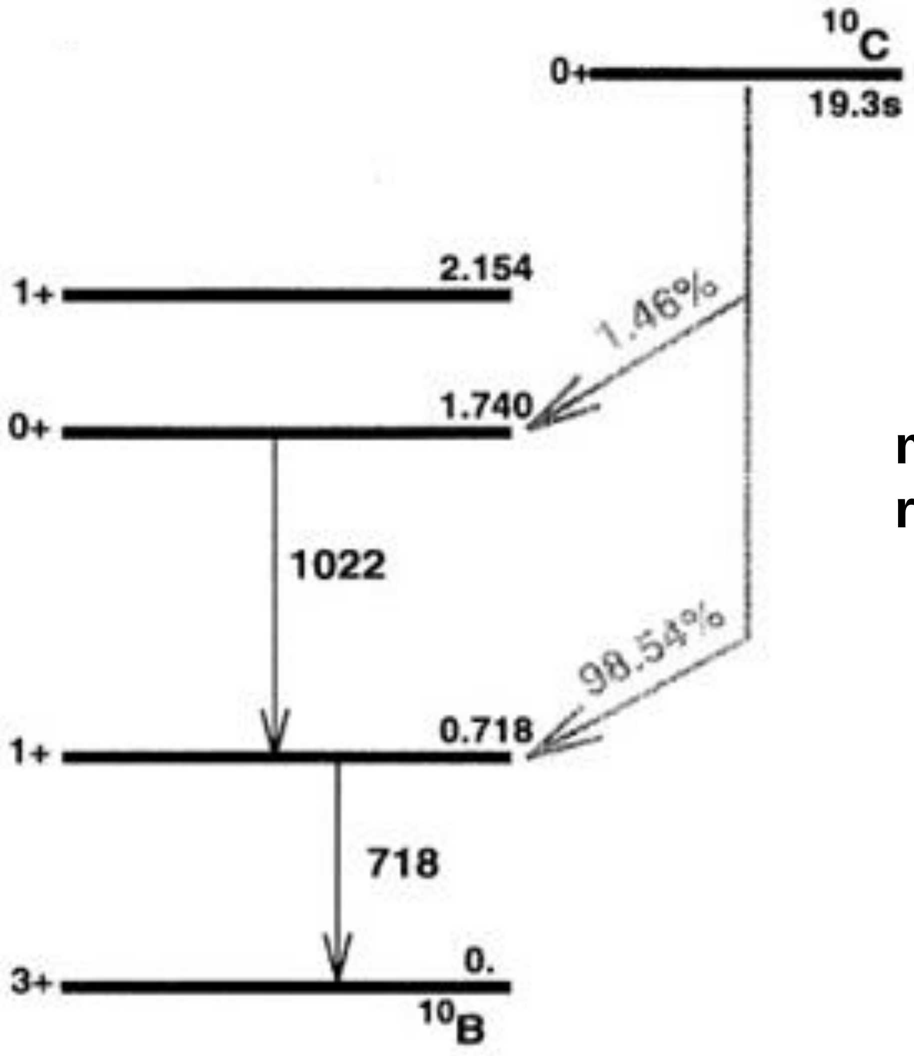
  → measurements with Ge multi-detector array

our approach:

high-precision single-crystal germanium detector



^{10}C decay scheme

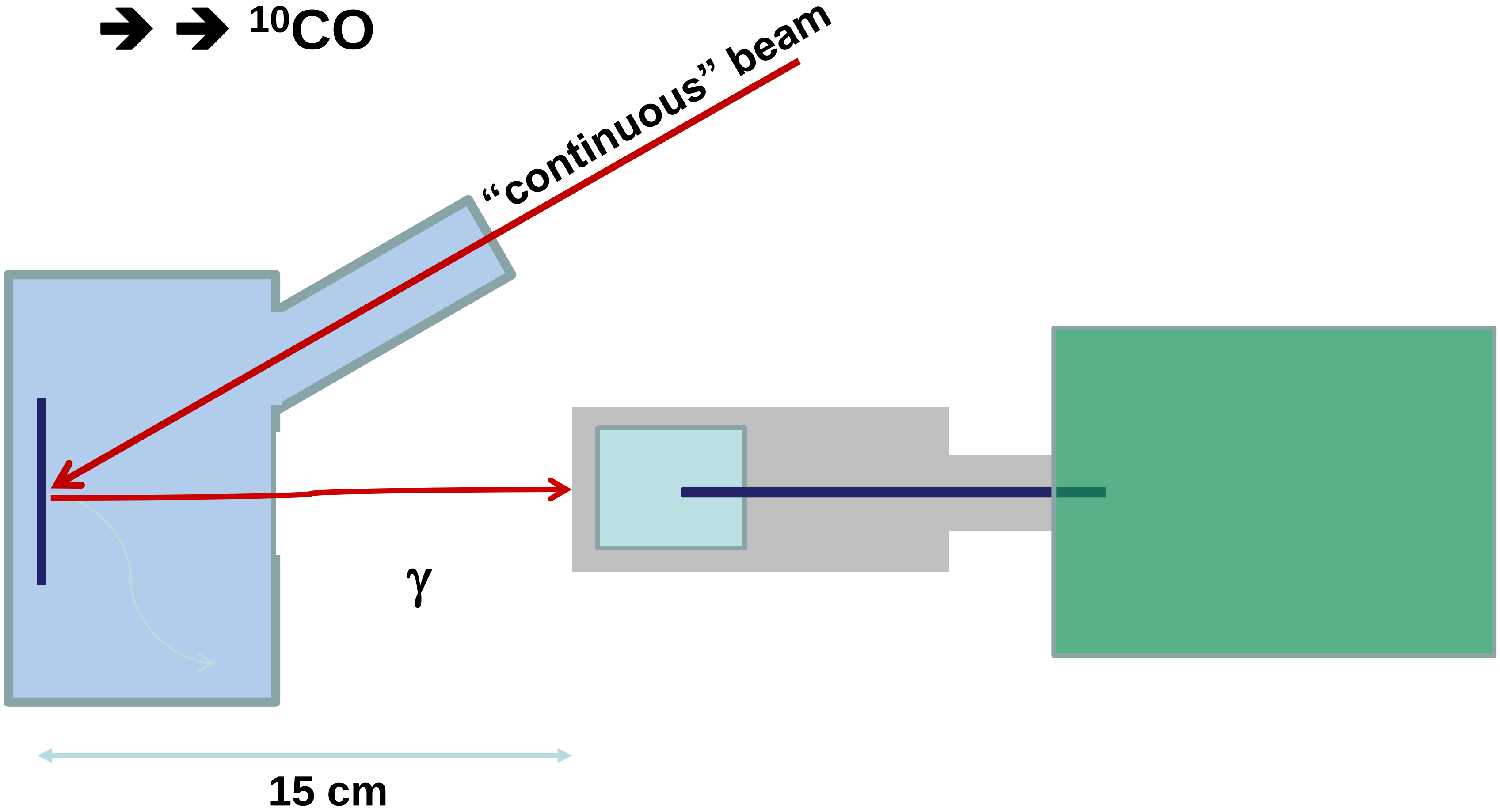


measurement of relative branching ratio

Experimental setup

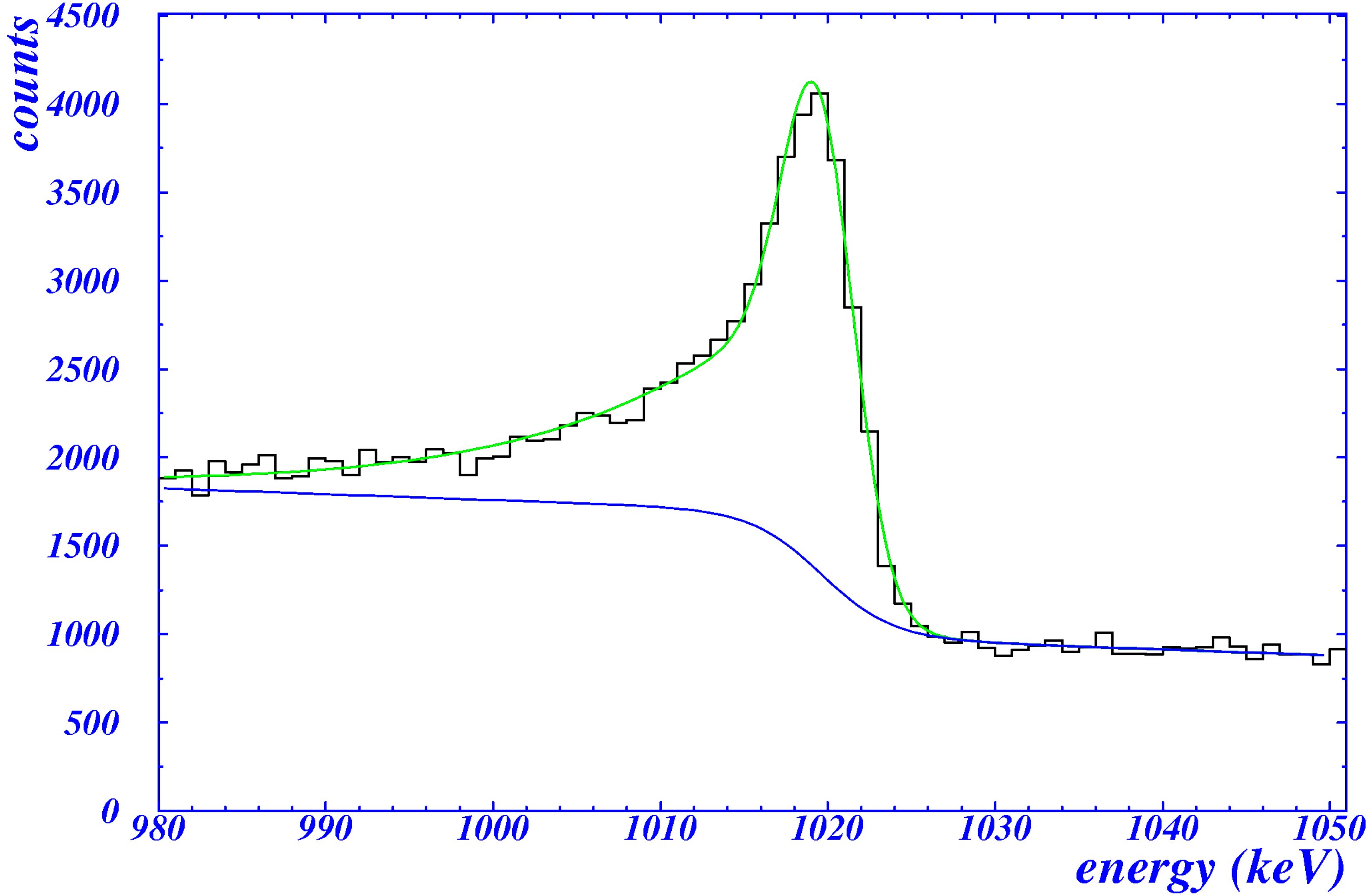
- many proton pulses
- nanoCaO + VD7
- HRS to LA1

➔ ➔ ^{10}CO



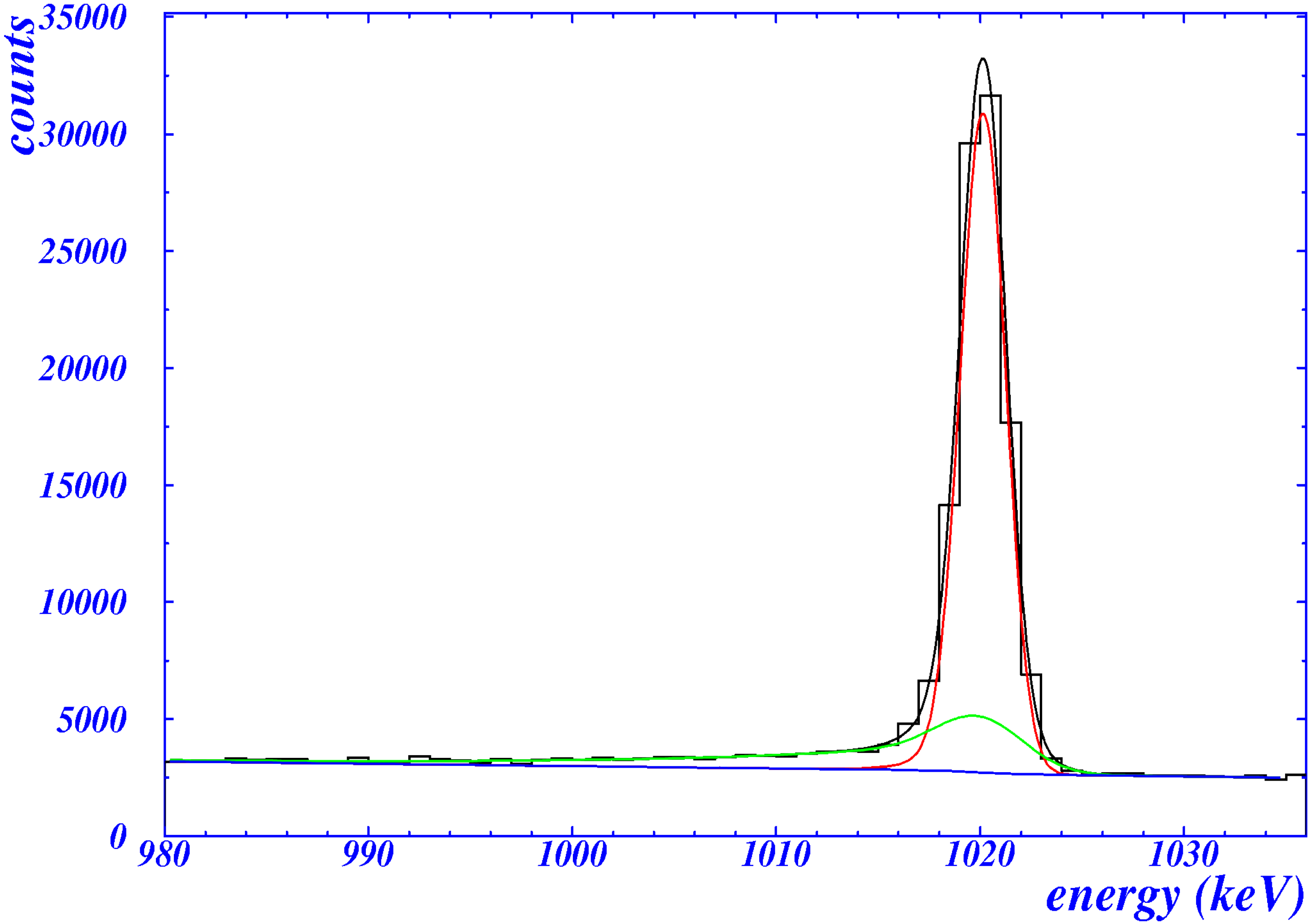
First steps of analysis

- 1022 keV line from ^{19}Ne (same $T_{1/2}$, same Q_{EC}): no 1022 keV peak, only 511-511 pile-up



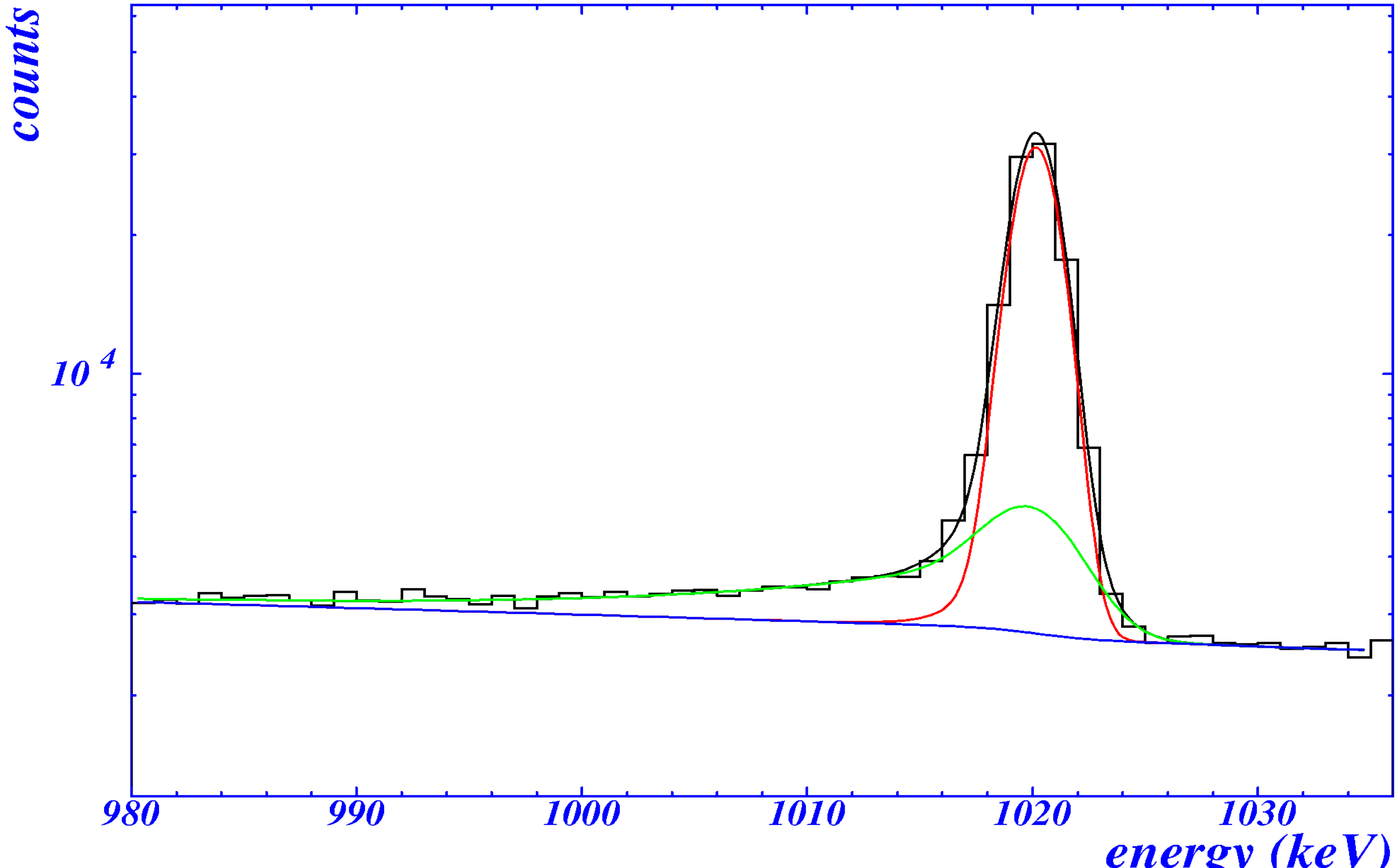
First steps of analysis

- **1022 keV line from ^{10}C:**
  - **1022 keV line + 511+511 pile-up**



First steps of analysis

- 1022 keV line from ^{10}C:
  - 1022 keV line + 511+511 pile-up



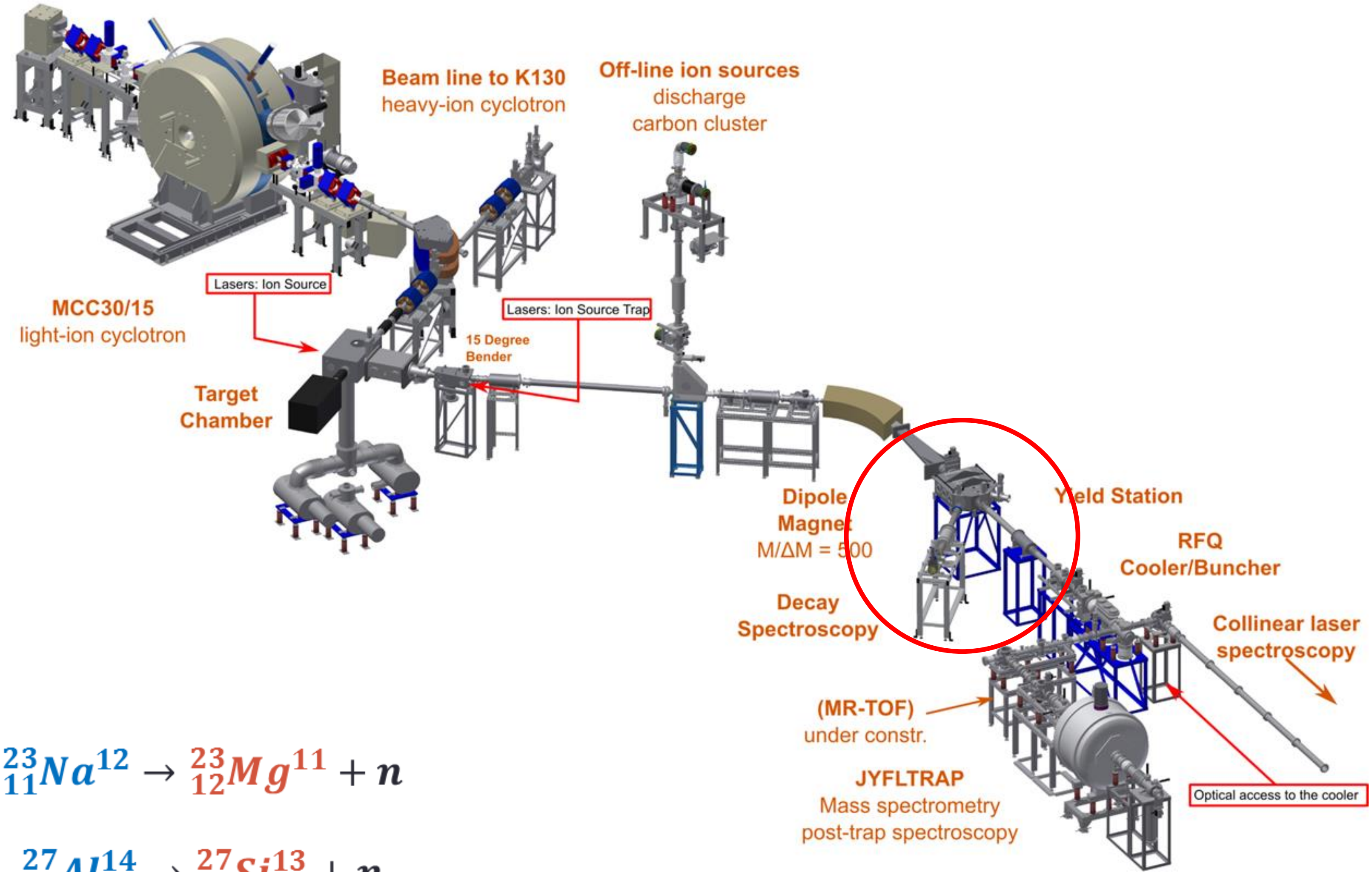
First steps of analysis

1022 keV line from ^{10}C: different ways to analyse

- Fitting with a fixed shape for pile-up peak determined from ^{19}Ne
- Calculate the number of pile-ups from 511 keV singles peak
- Measurements with different shaping times
  ➔ different pile-up probabilities
- Measurements at different distances
  ➔ different pile-up probabilities
- Other problem: at A=26 (CO) a lot of $^{13}N_2$

Mirror β decay: ^{23}Mg and ^{27}Si

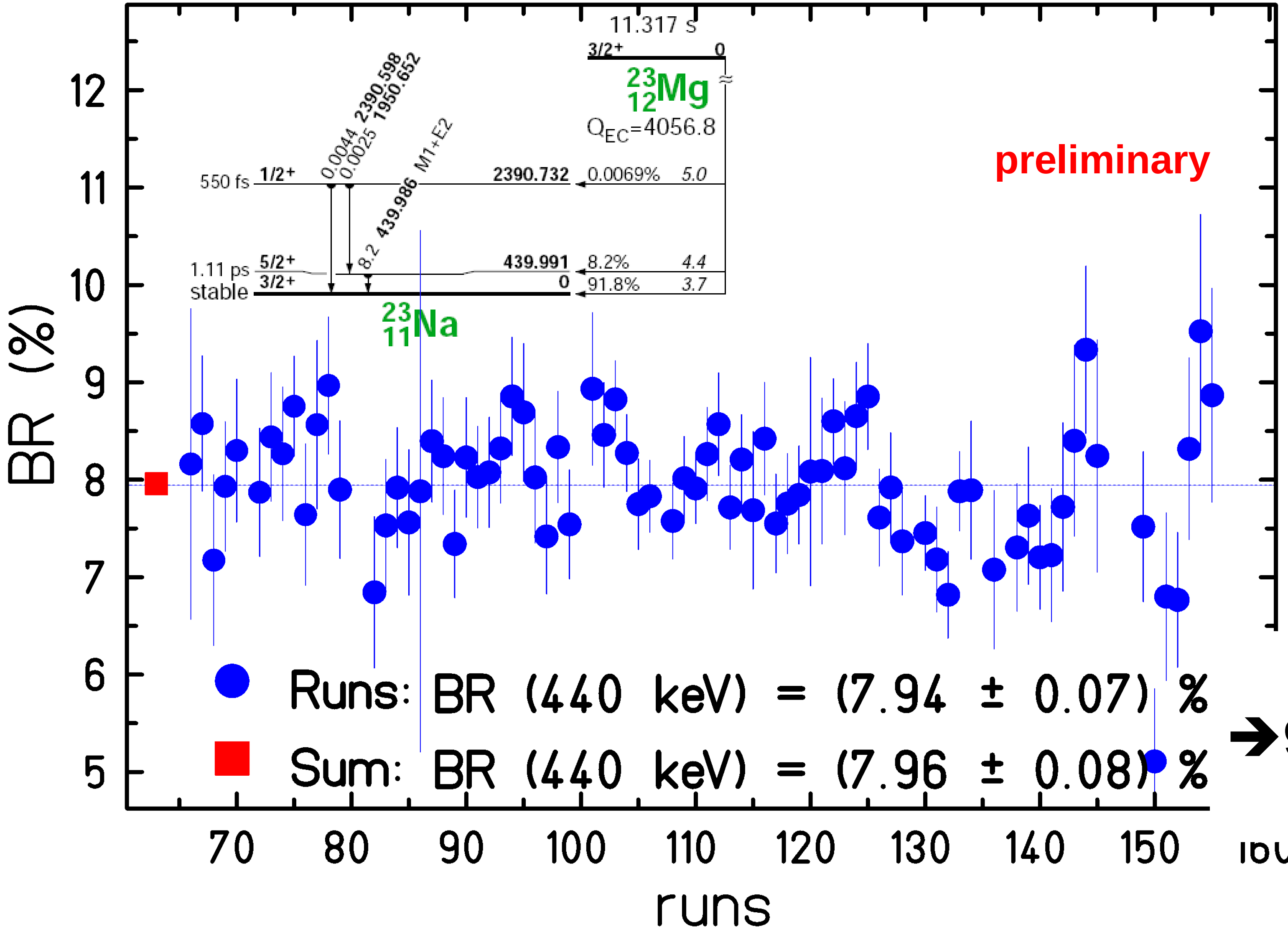
Experiment JYFL2013: ^{23}Mg & ^{27}Si



$$p + {}^{23}_{11}Na^{12} \rightarrow {}^{23}_{12}Mg^{11} + n$$

$$p + {}^{27}_{13}Al^{14} \rightarrow {}^{27}_{14}Si^{13} + n$$

BR of ^{23}Mg

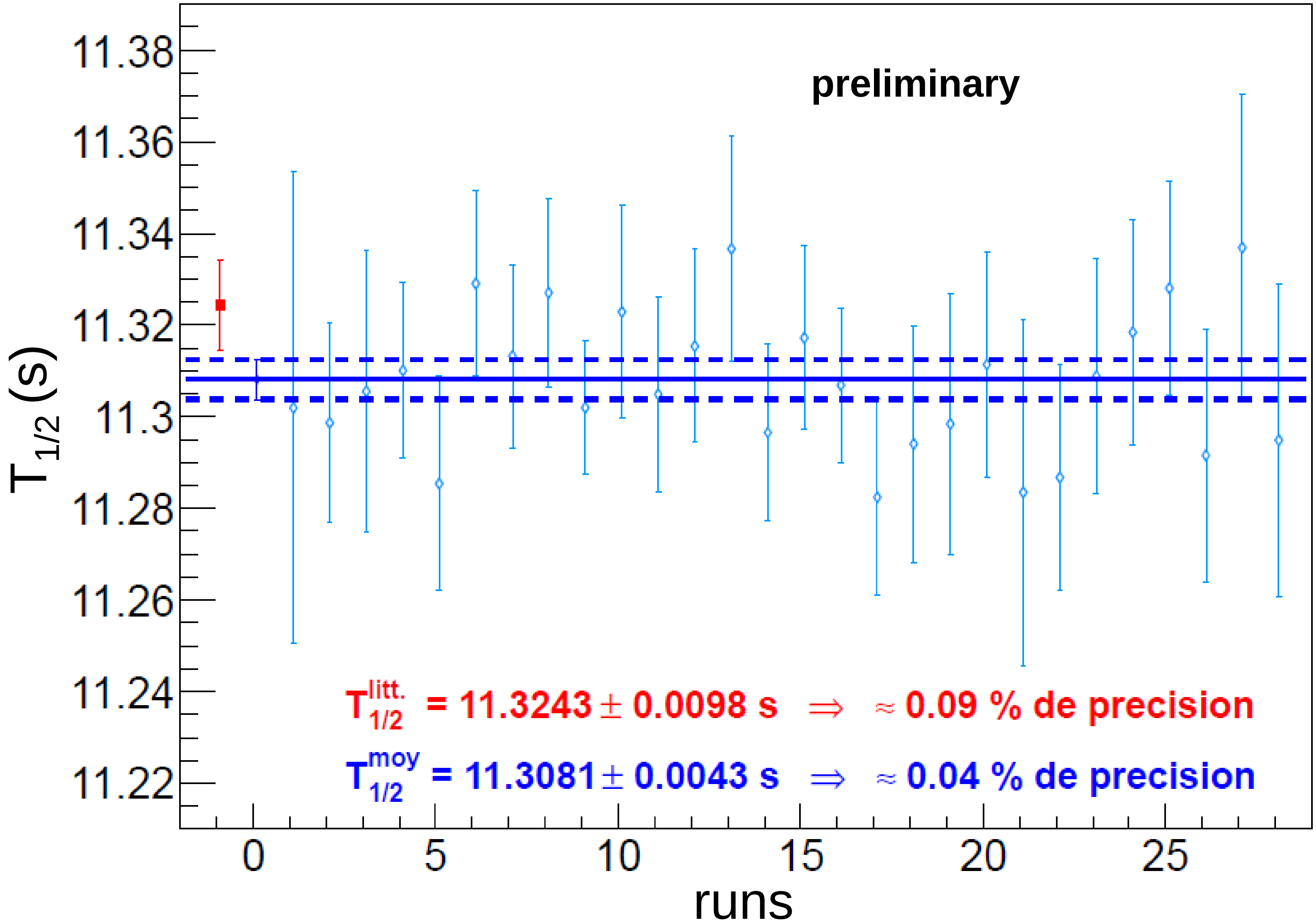


➔92.05(8) %

C. Magron et al.

Literature value: (91.78±0.26)%

Half-life of ^{23}Mg

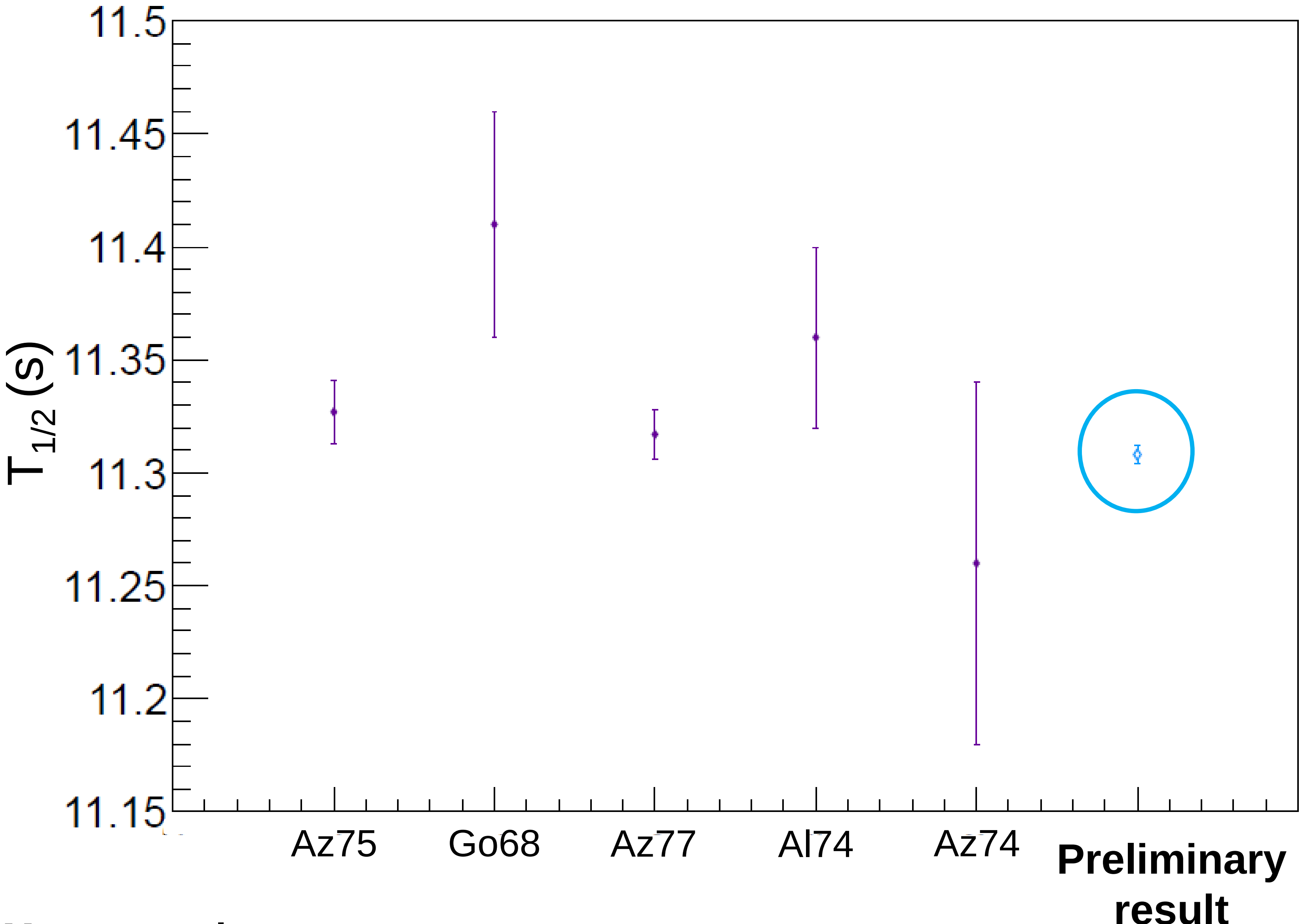


$T_{1/2}^{litt.}$ = 11.3243 ± 0.0098 s ⇒ ≈ 0.09 % de precision

$T_{1/2}^{moy}$ = 11.3081 ± 0.0043 s ⇒ ≈ 0.04 % de precision

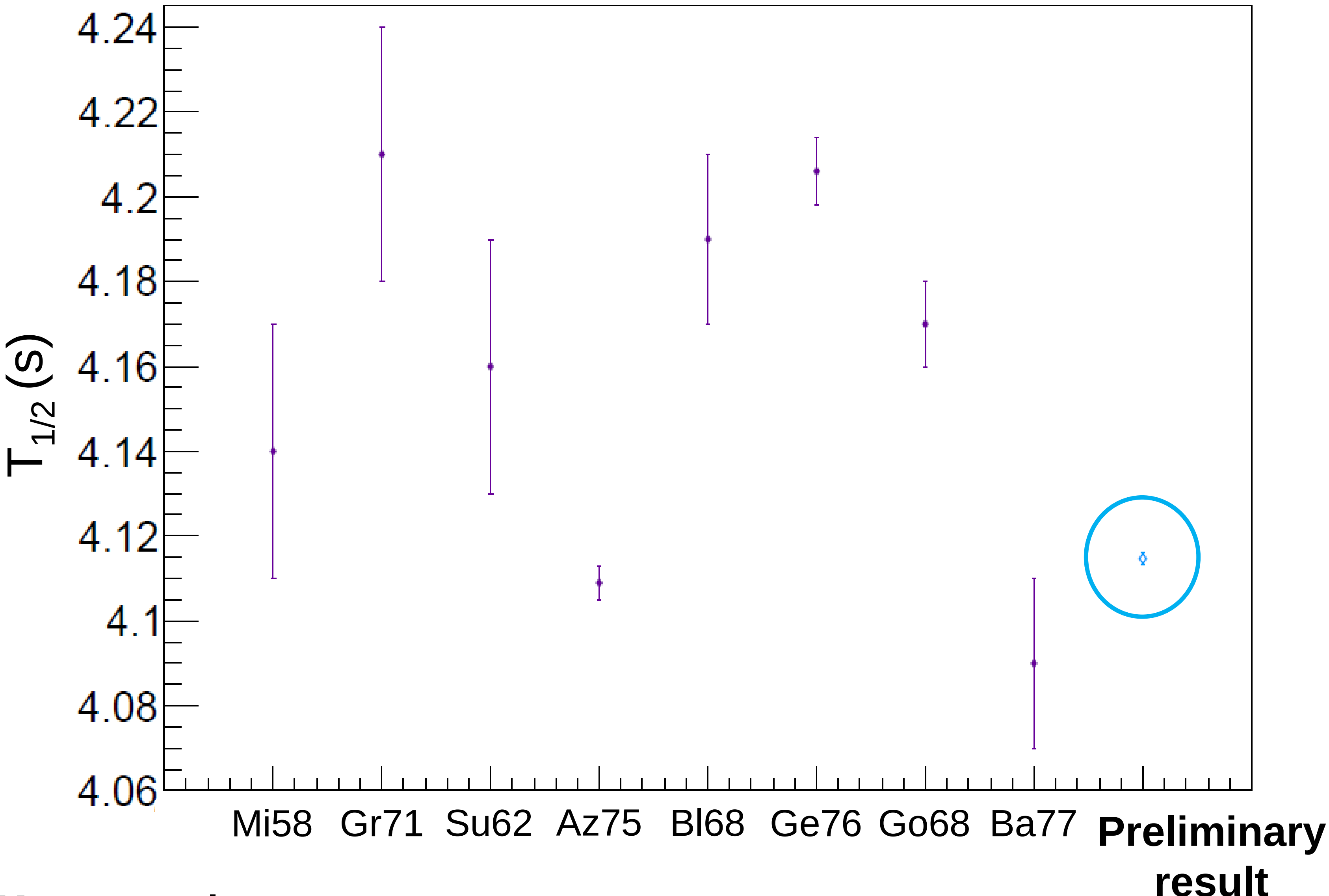
C. Magron et al.

Half-life of ^{23}Mg



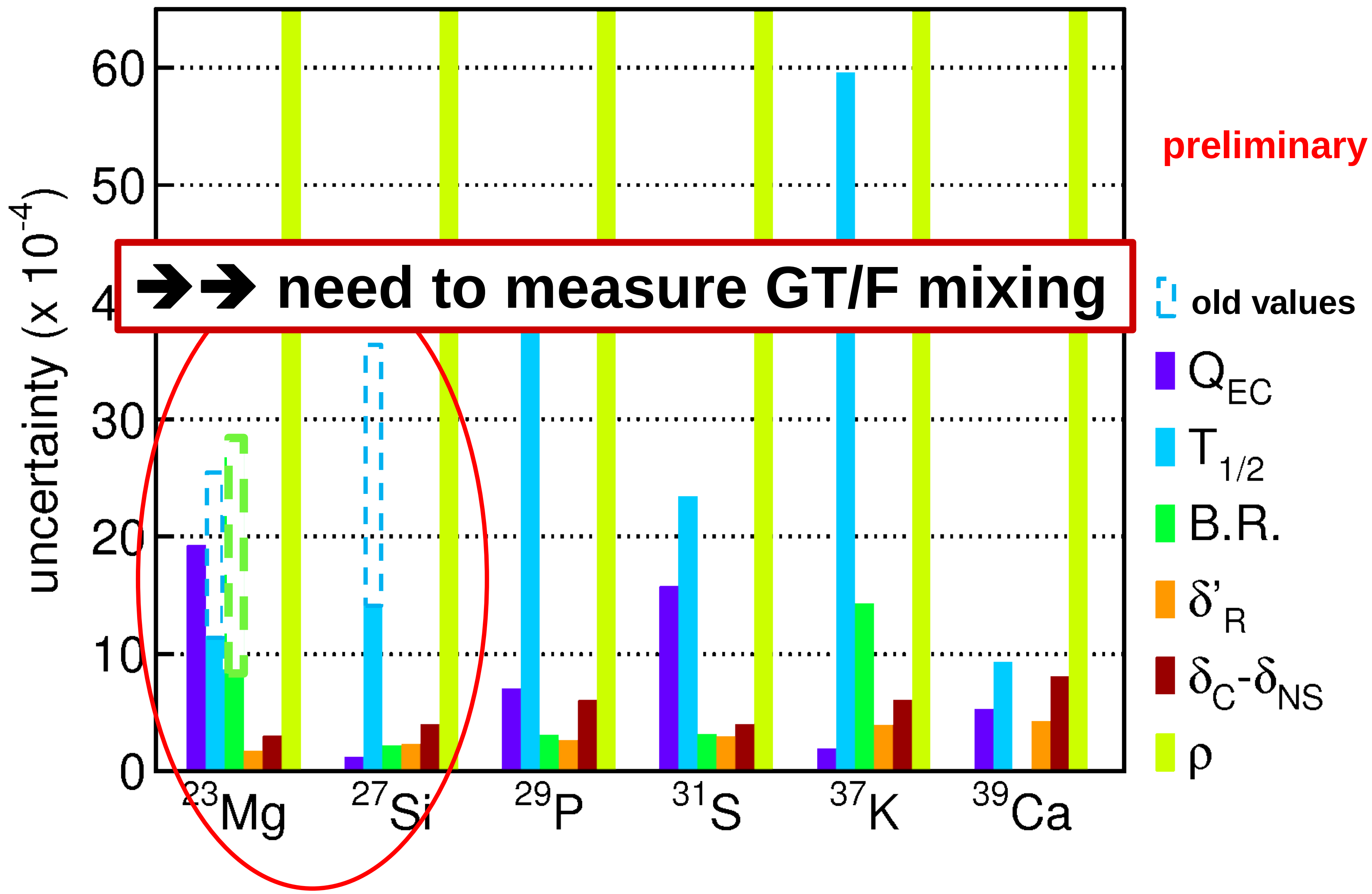
C. Magron et al.

Half-life of ^{27}Si



C. Magron et al.

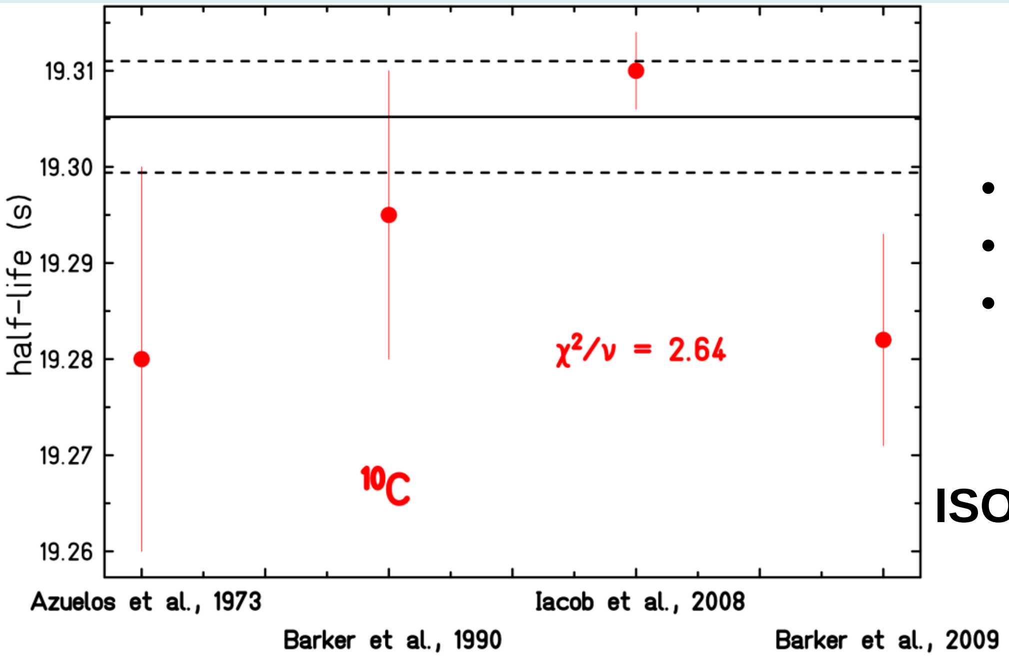
Uncertainties for ^{23}Mg and ^{27}Si



C. Magron et al.

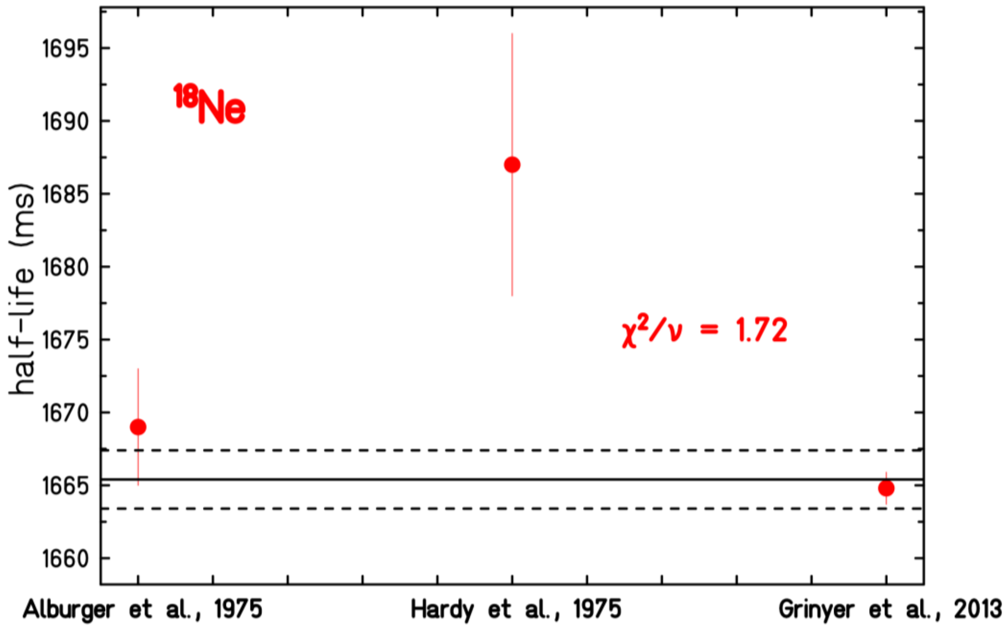
Future plans at ISOLDE

Half-lives of ^{10}C and ^{18}Ne



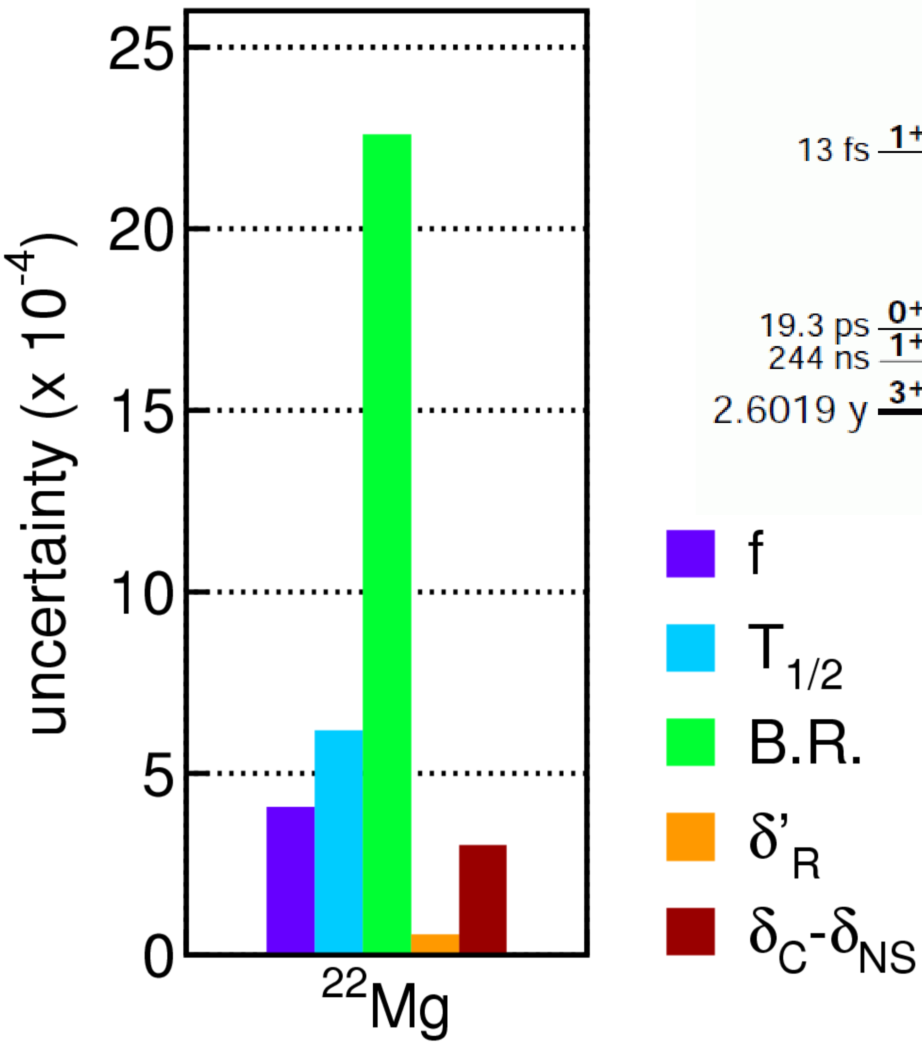
- what is the purity we can achieve?
- trap-assisted decay spectroscopy?
- diffusion out of the catcher?

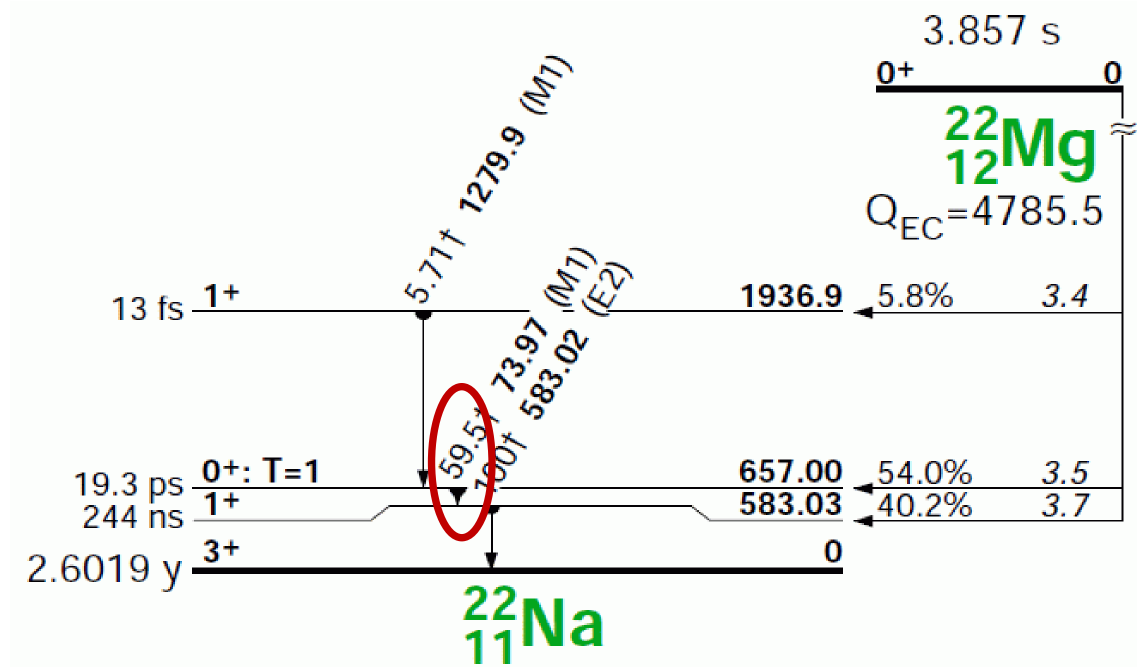
ISOLDE rates: 7.0E+05



ISOLDE rates: 6.9E+05

Branching ratio of ^{22}Mg





➔ **Extent high-precision efficiency calibration below 100 keV**

➔ **ISOLDE rates: 8.0E+06 pps**

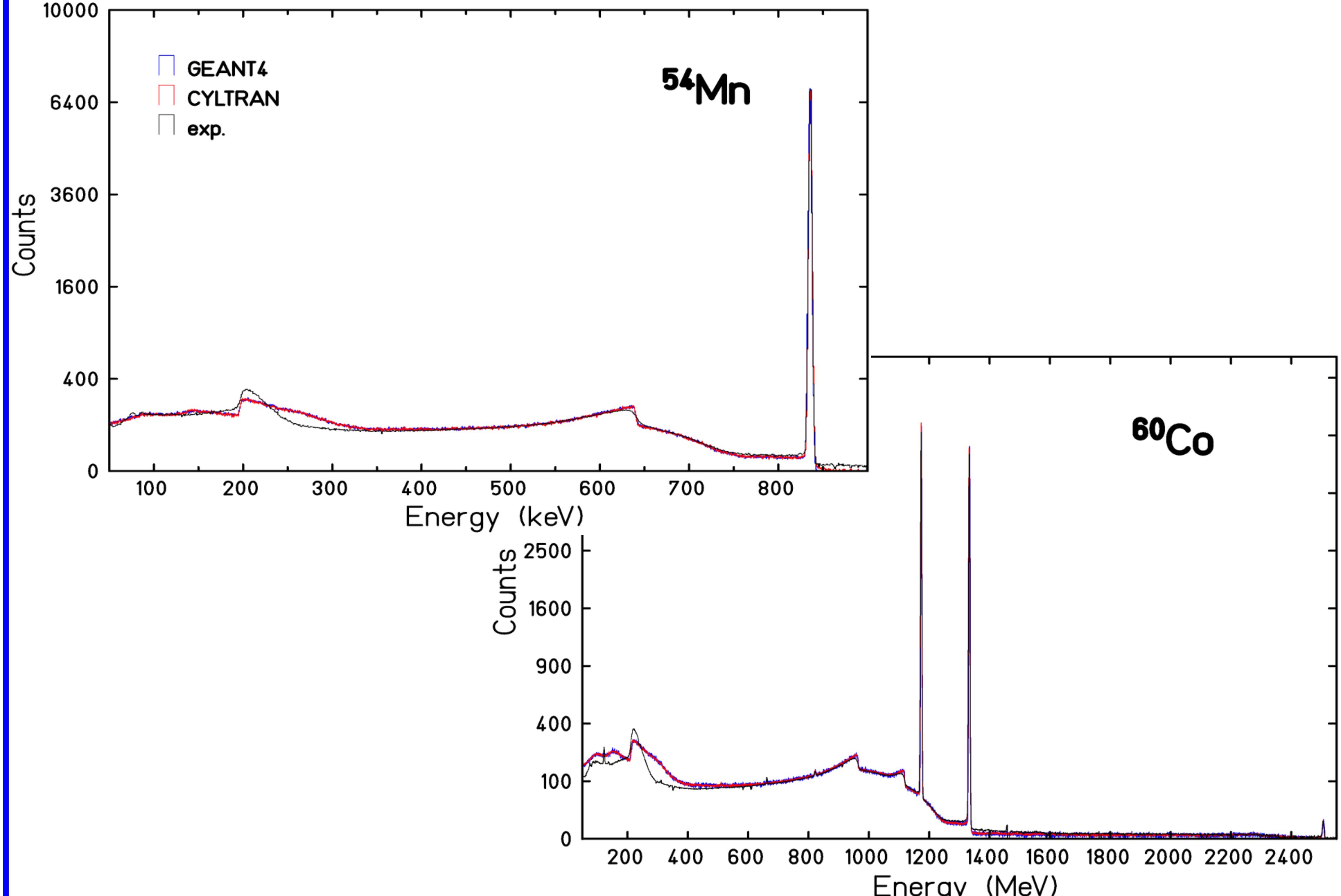
Conclusions

- High-precision Germanium detector is available
  - ➔ Tz = -1 nuclei can be addressed: ^{18}Ne, ^{22}Mg, ^{26}Si, ^{30}S, ^{42}Ti
- Big potential for nuclear mirror decays
  - ➔ need for high-precision GT-F mixing ratio measurements
- What about Tz = -2 nuclei? ^{32}Ar, ^{36}Ca…
- SPIRAL2/S3/DESIR: heaviest N=Z odd-odd nuclei
  - ➔CVC tests over much broader range
- β–ν correlation measurements in a supra-conducting magnet
- Improve theoretical corrections….

Thanks for your attention

Collaborations: CENBG, IGISOL, GANIL, IPNO, IPHC, TRIUMF

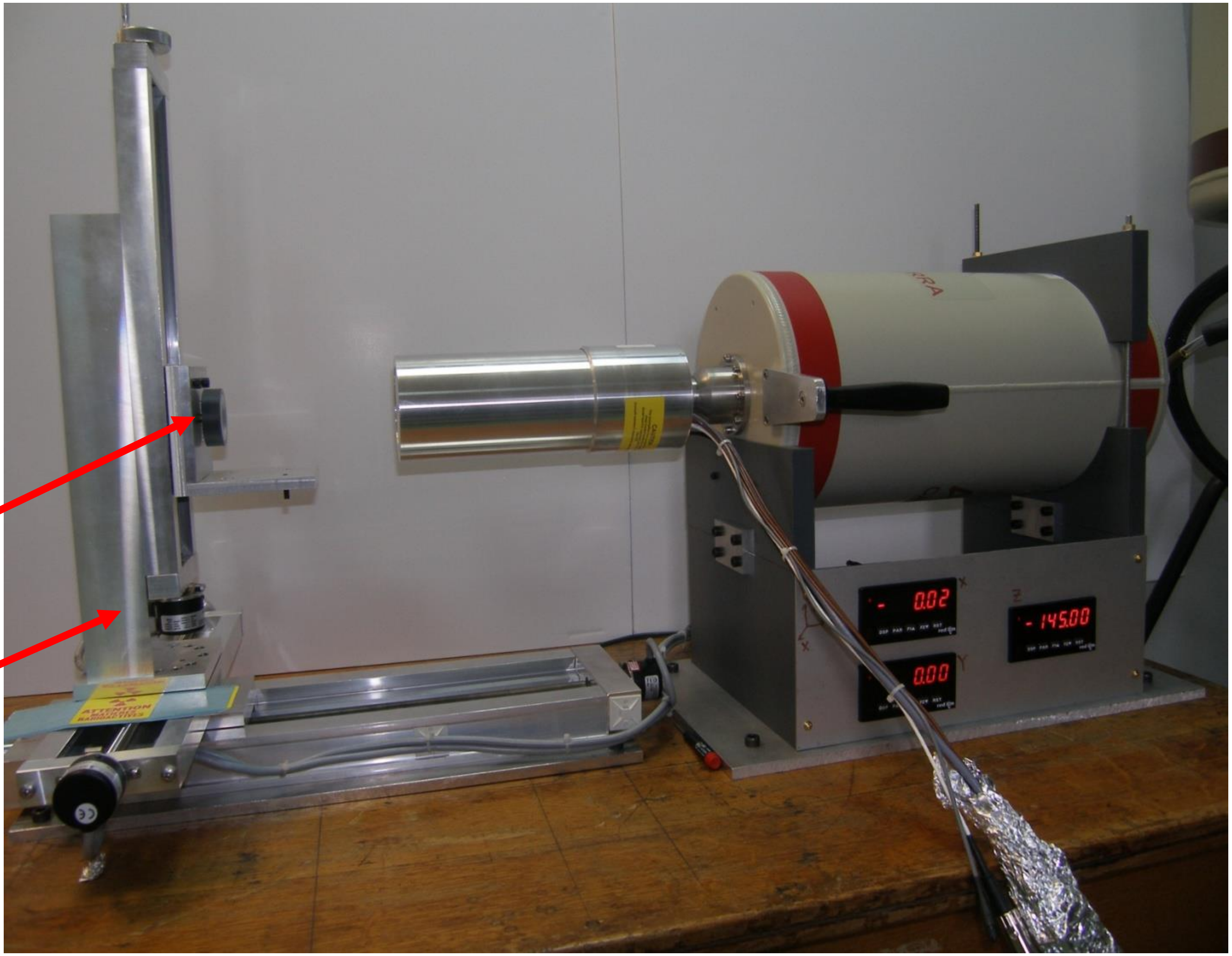
Comparison experiment - simulations



70% HP Germanium on precision test bench

Source position

high-precision X-Y-Z table



• all source measurements at exactly 15 cm from entrance window

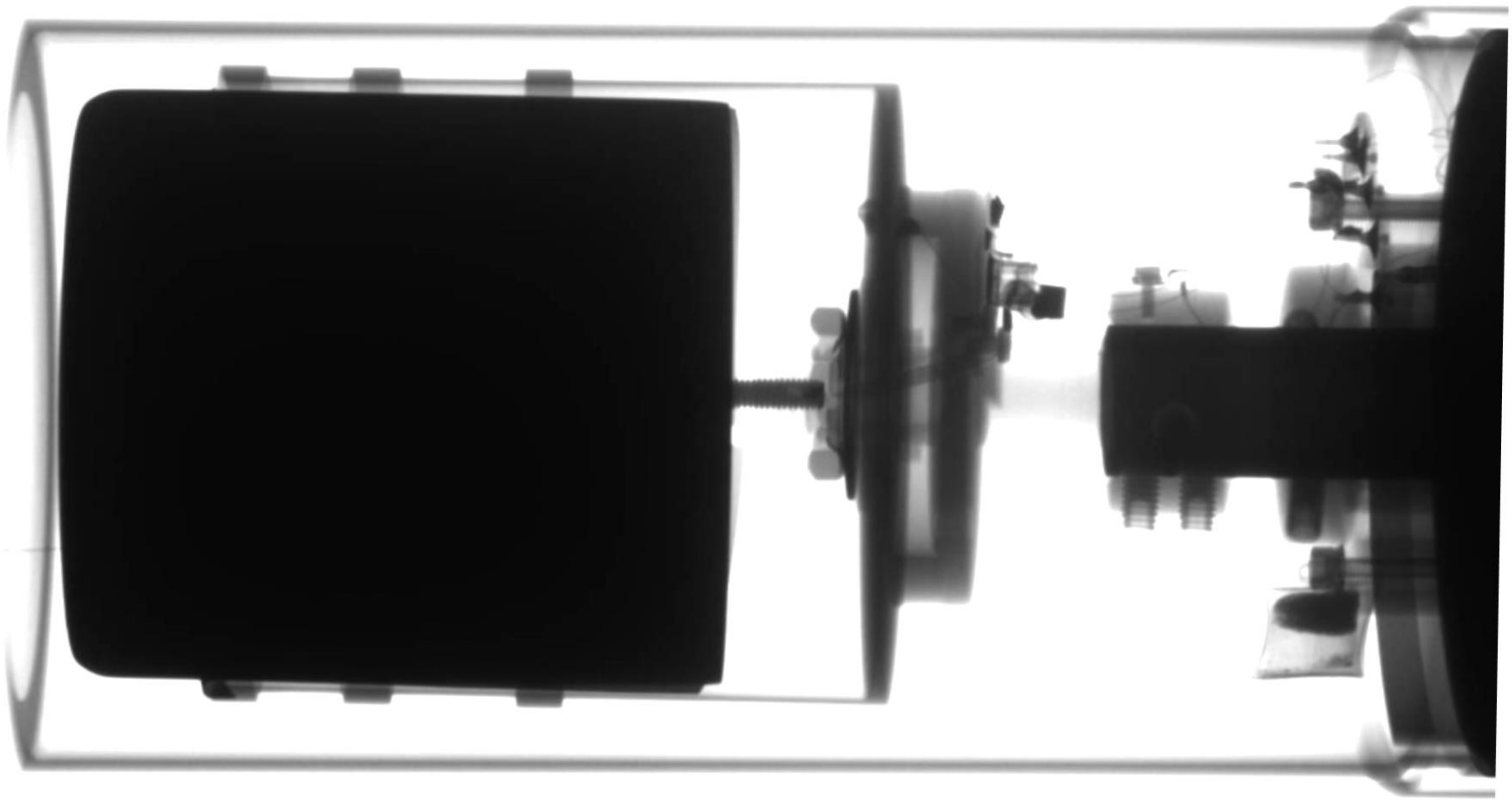
➔ ➔ position precision of better than 10 μm

Calibration Procedure

- X-ray radiography
- γ-ray detector scans
- source measurements
- MC simulations (GEANT4 or CYLTRAN)

➔➔ **develop a model of the detector to calculate efficiencies at any energy at a fixed distance of 15 cm**

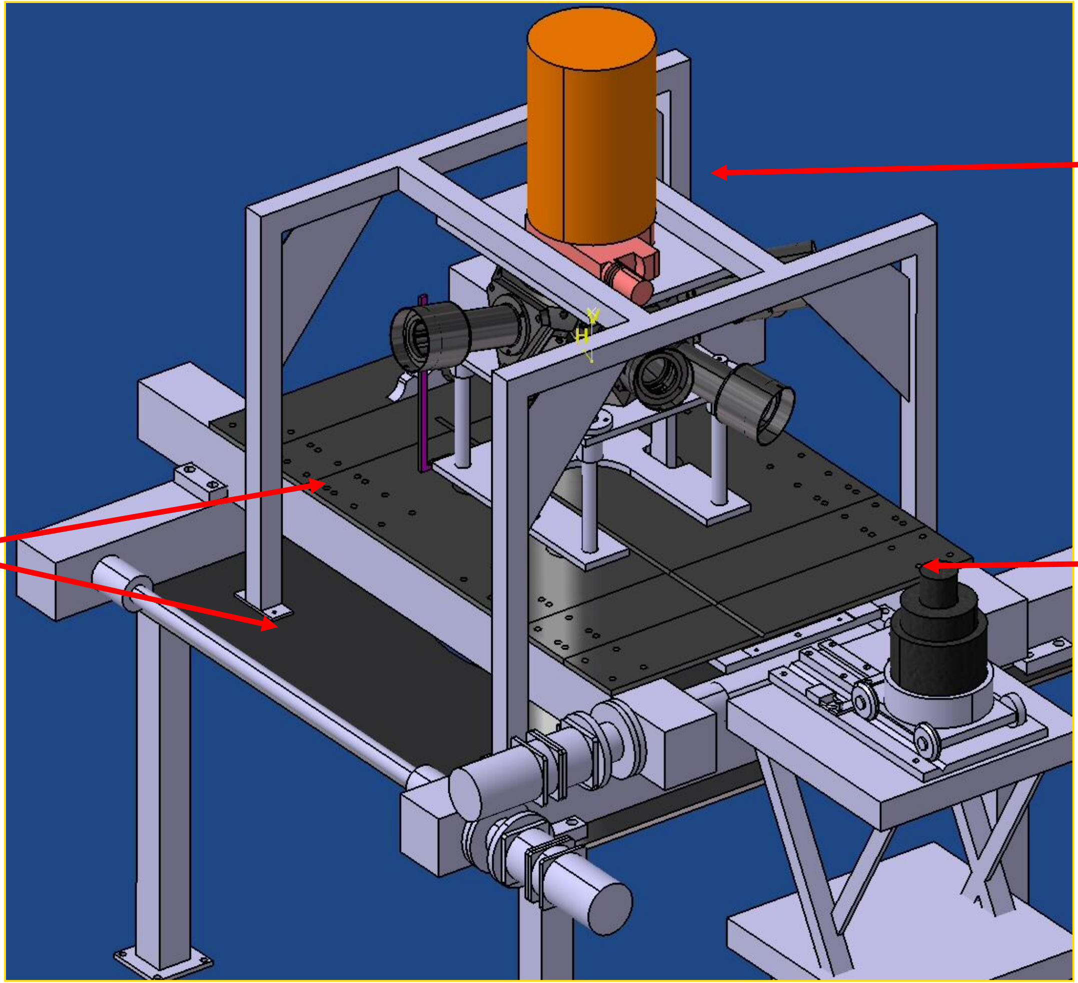
X-ray photography of detector



- ➔ rough size of crystal
- ➔ tilt of crystal with respect to detector housing of 1°
- ➔ according to GEANT4 simulations no influence on results

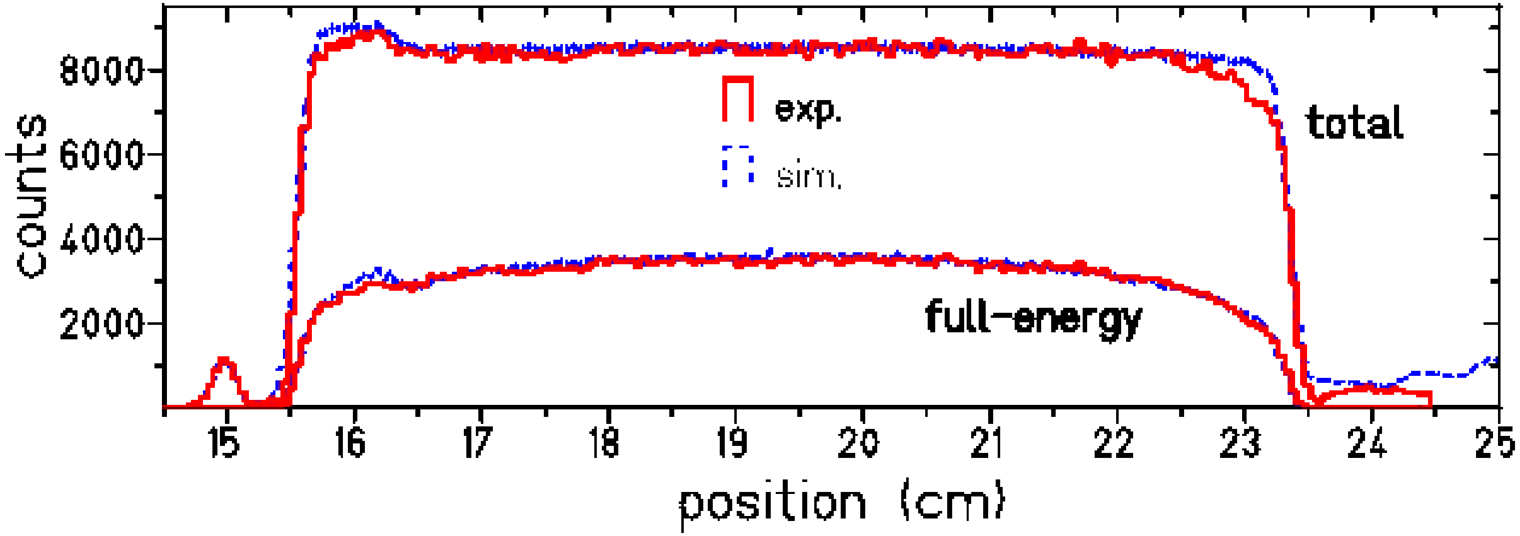
Gamma-ray scan of detector

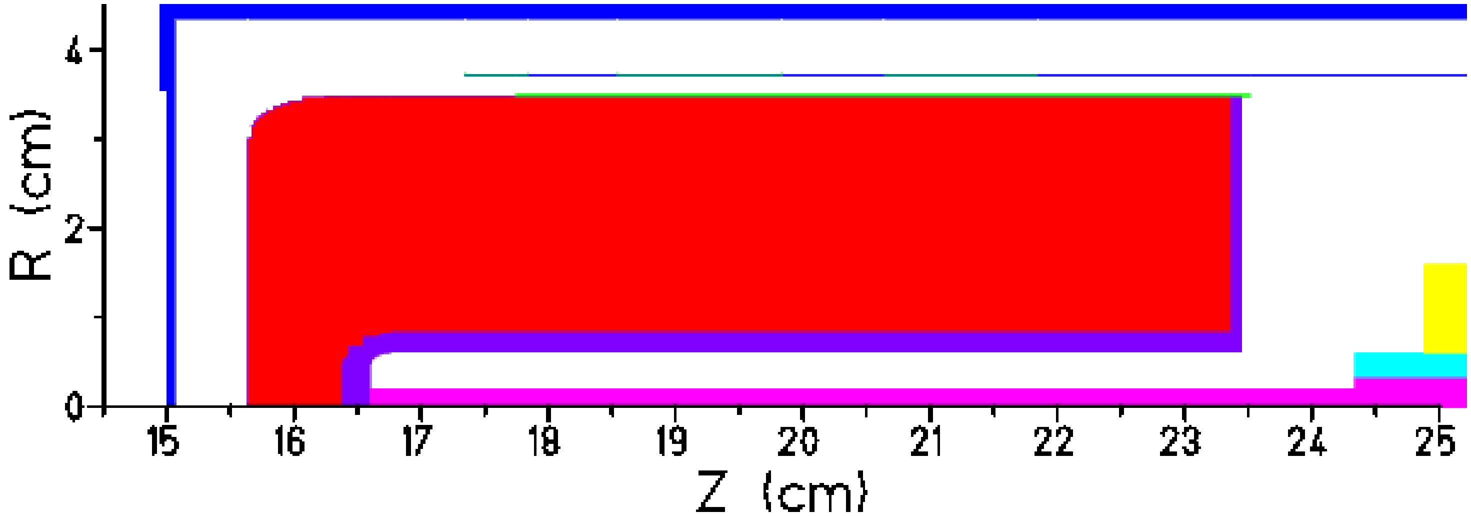
- **AGATA scan table at CSNSM: strongly collaminated ^{137}Cs source**



A. Korichi et al.

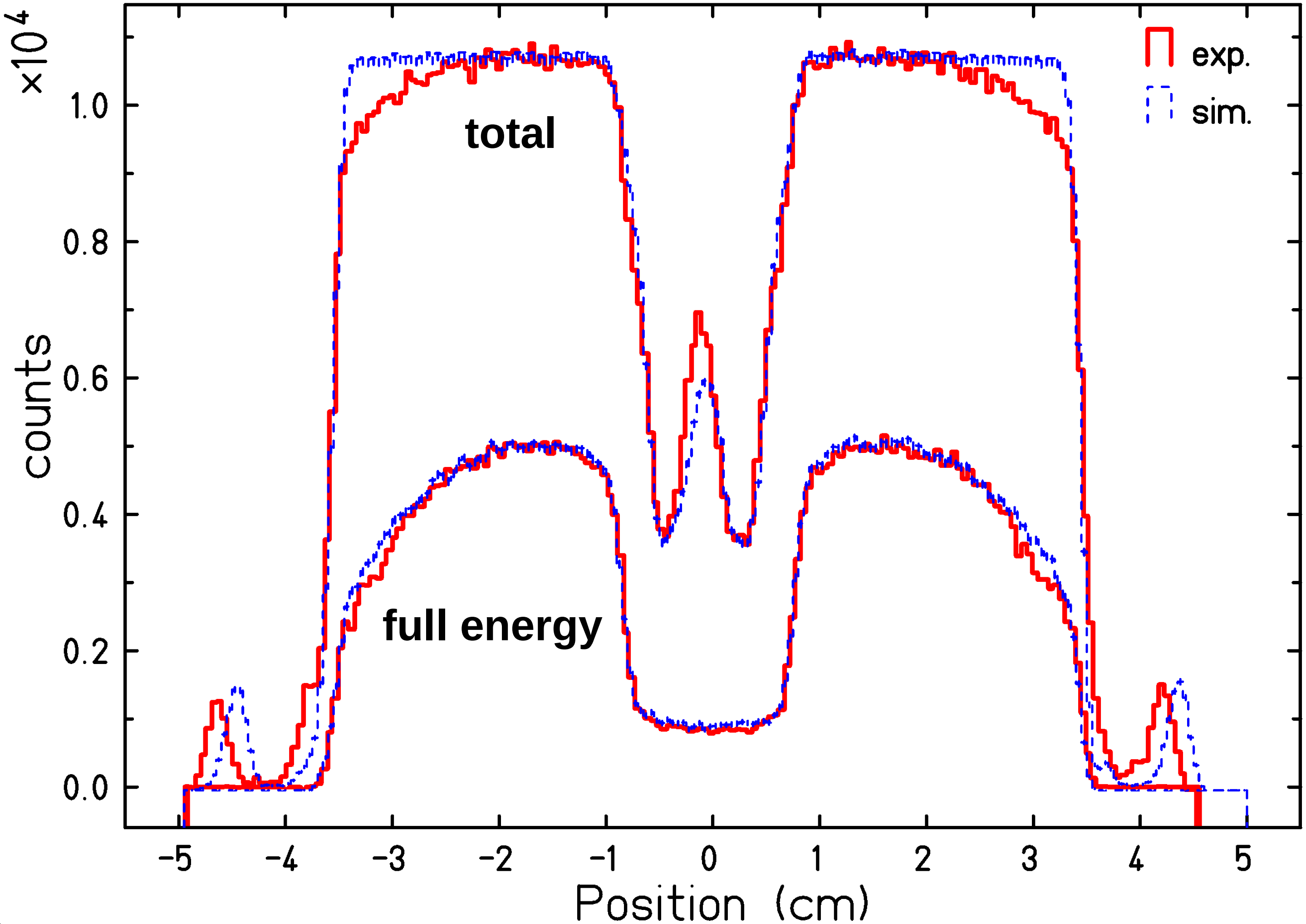
Longitudinal scan: 662 keV





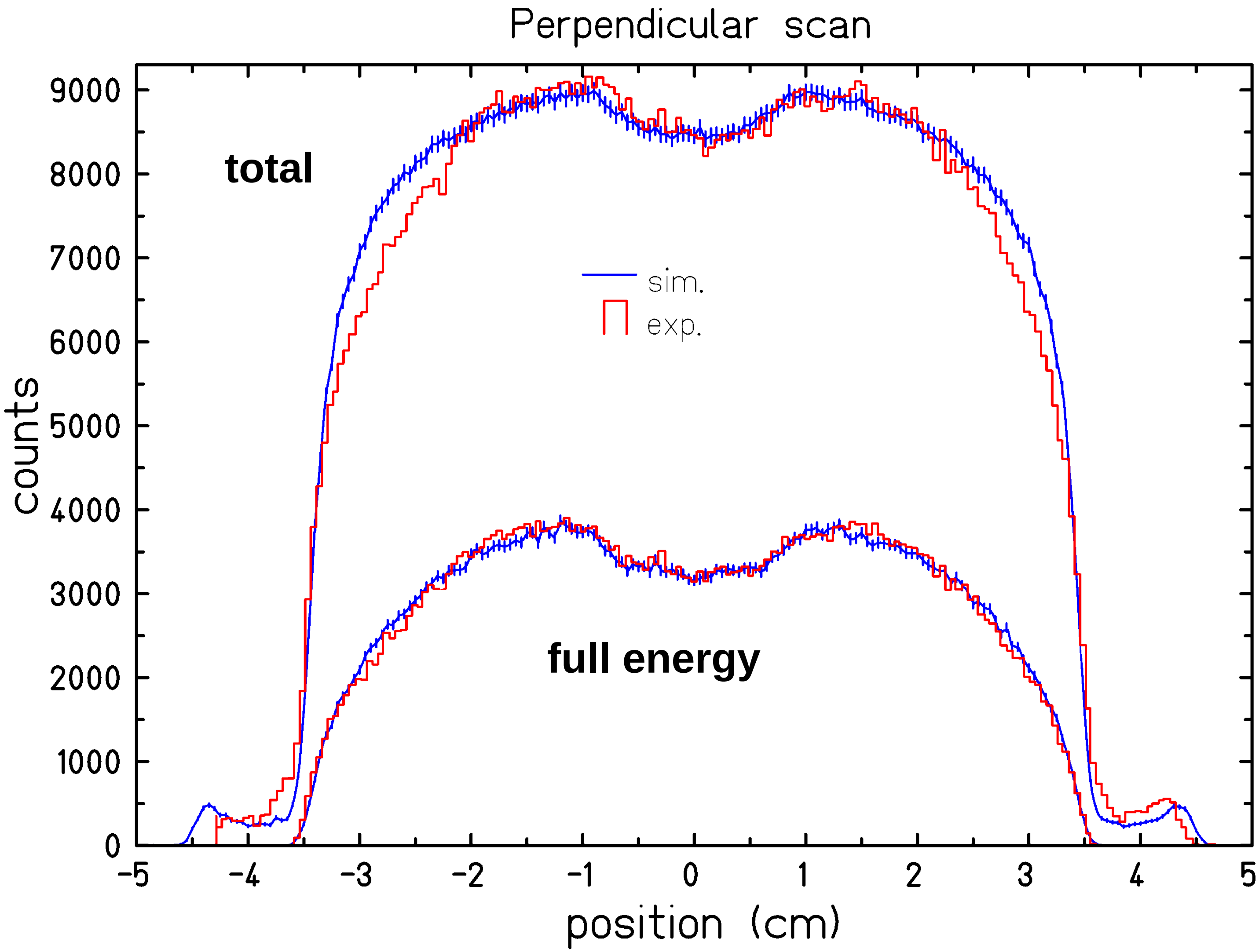
- **excellent full-energy peak spectrum**
- **good total-energy spectrum**

Front scan: 662 keV



- **effect of detector tilt clearly visible**
- **reasonable overall agreement**

Perpendicular scan: 662 keV



- **effect of detector tilt clearly visible**
- **reasonable overall agreement**

Calibration sources

- **peak-to-total sources:**

  ➔ **close to « one single γ ray with 100% branching ratio »**

  - **standard sources:**

    ^{57}Co, ^{51}Cr, ^{85}Sr, ^{137}Cs, ^{54}Mn, ^{60}Co, ^{22}Na

  - **short-lived online sources at ISOLDE:**

    ^{58}Co, ^{65}Zn, ^{41}Ar

- **relative efficiency sources:**

  ➔ **a few well-known branches (BR error <1%) at largely different energies**

  - **standard sources:**

    ^{60}Co, ^{88}Y, ^{133}Ba, ^{134}Cs, ^{137}Cs, ^{152}Eu, ^{207}Bi

  - **short-lived online sources at ISOLDE and IPN Orsay:**

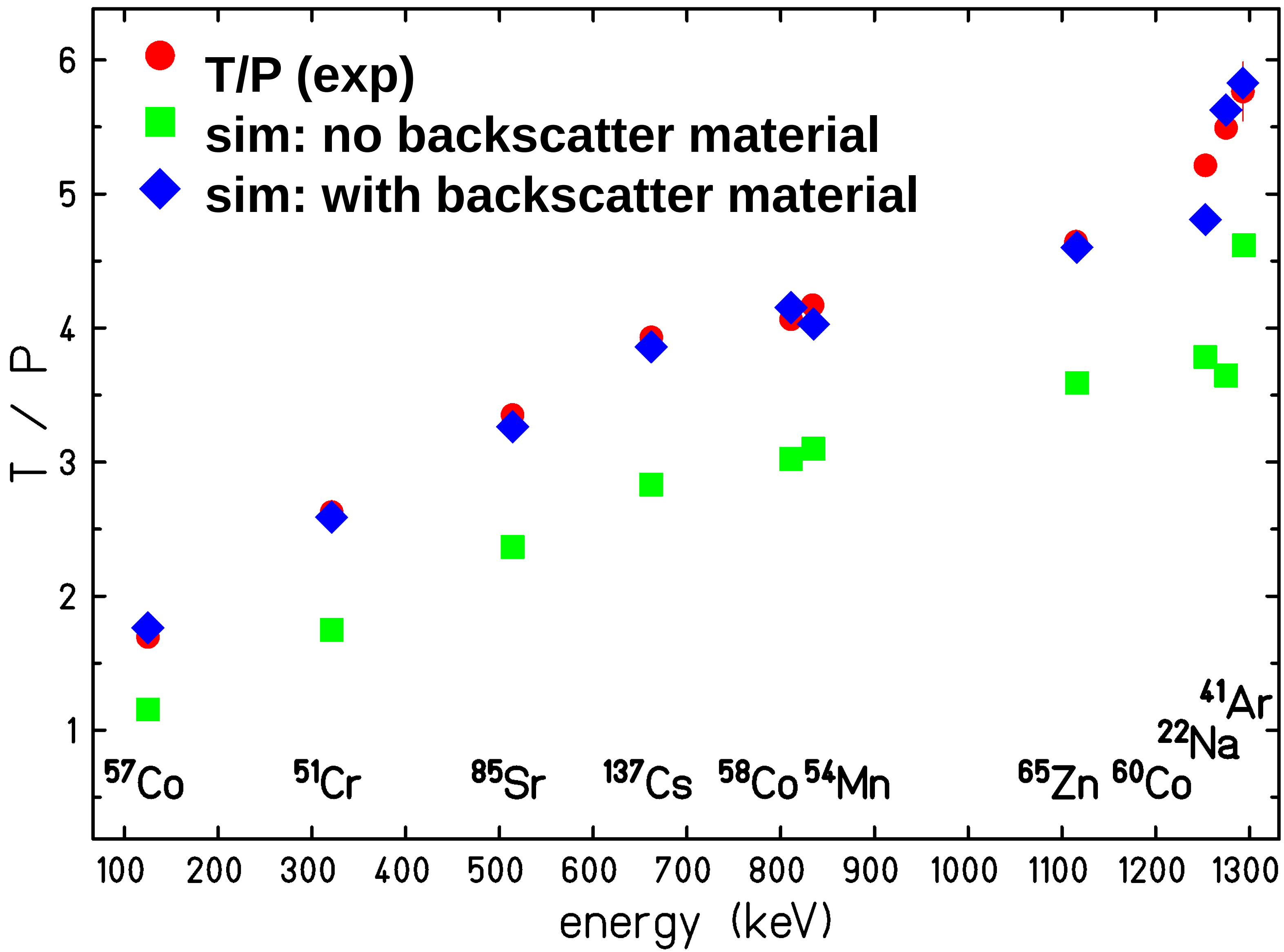
    ^{24}Na, ^{27}Mg, ^{48}Cr, ^{56}Co, ^{66}Ga, ^{75}Se, ^{180m}Hf

- **absolute efficiency:**

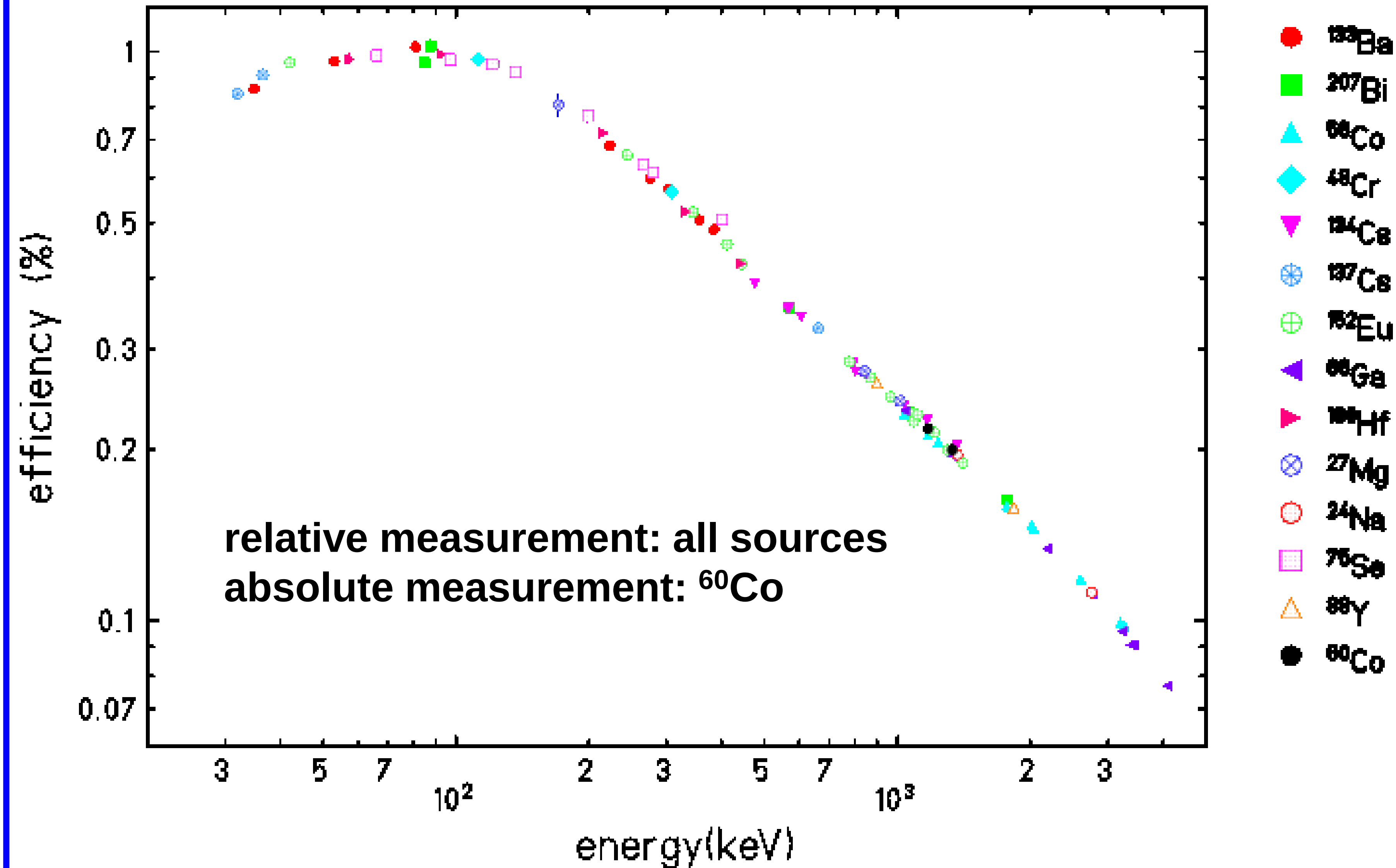
  - **^{60}Co with activity precision of 0.7‰**

  - **γ–γ coincidences**

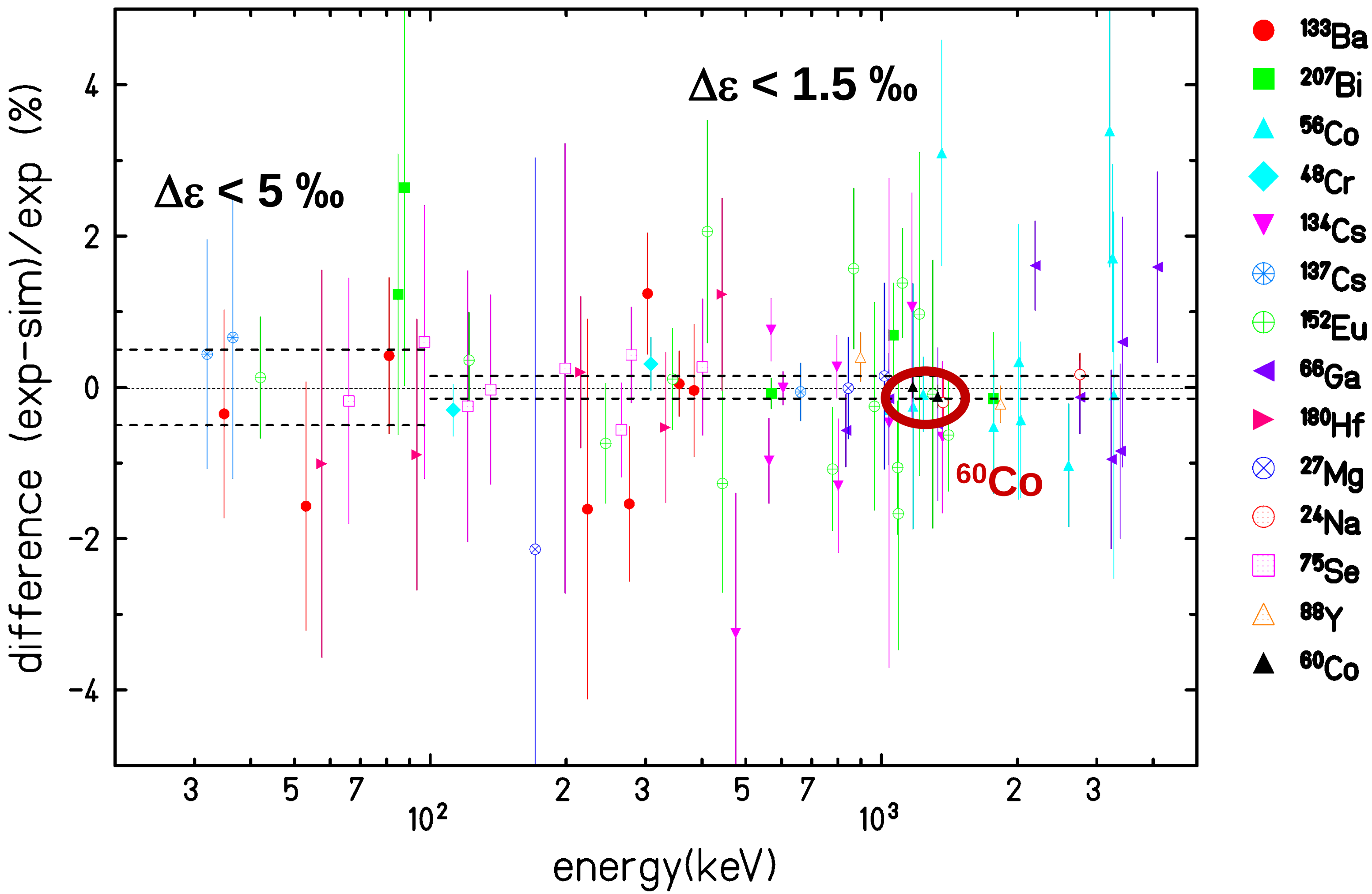
Calibration of germanium detector: peak-to-total



Calibration of germanium detector: absolute efficiency



Calibration of germanium detector: absolute efficiency



Fit 1: $P_0 = -0.016 \pm 0.061$; $\chi^2 = 0.85$ ← < 0.6 ‰ precision

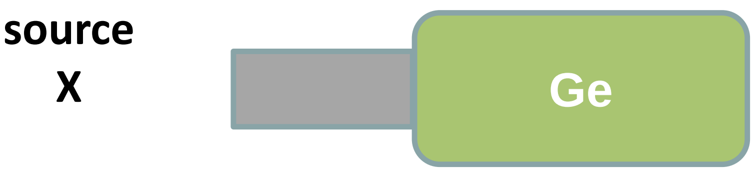
Fit 2: $P_0 = -0.09 \pm 0.48$

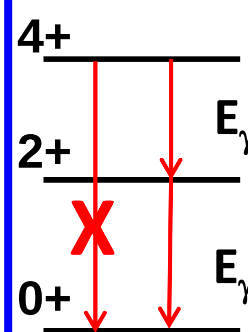
$P_1 = 0.02 \pm 0.16$; $\chi^2 = 0.86$

B. Blank et al., NIMA 776 (2015) 34

Absolute efficiency calibration with γ–γ coincidences

Condition:
- γ–γ cascade with large BR
- no « cross-over » transition
- ➔ ^{60}Co (et ^{24}Na)





$E_{\gamma1}$, Br1 = 99.85 % ➔ I1

$E_{\gamma2}$, BR2 = 99.99826 % ➔ I2

$E_{\gamma1} + E_{\gamma2}$, BR12 ➔ I12

- standard pile-up is same for all peaks
- but: necessity to correct pile-up between two events ($1173_1 + 1332_2$ et vice-versa)

- $I1 = A0 * \varepsilon_1 * BR1 * (1.-\varepsilon_{t2} * w12(\theta))$
- $I2 = A0 * \varepsilon_2 * BR2 * (1.-\varepsilon_{t1} * w12(\theta))$
- $I12 = A0 * \varepsilon_1 * \varepsilon_2 * BR12 * w12(\theta)$

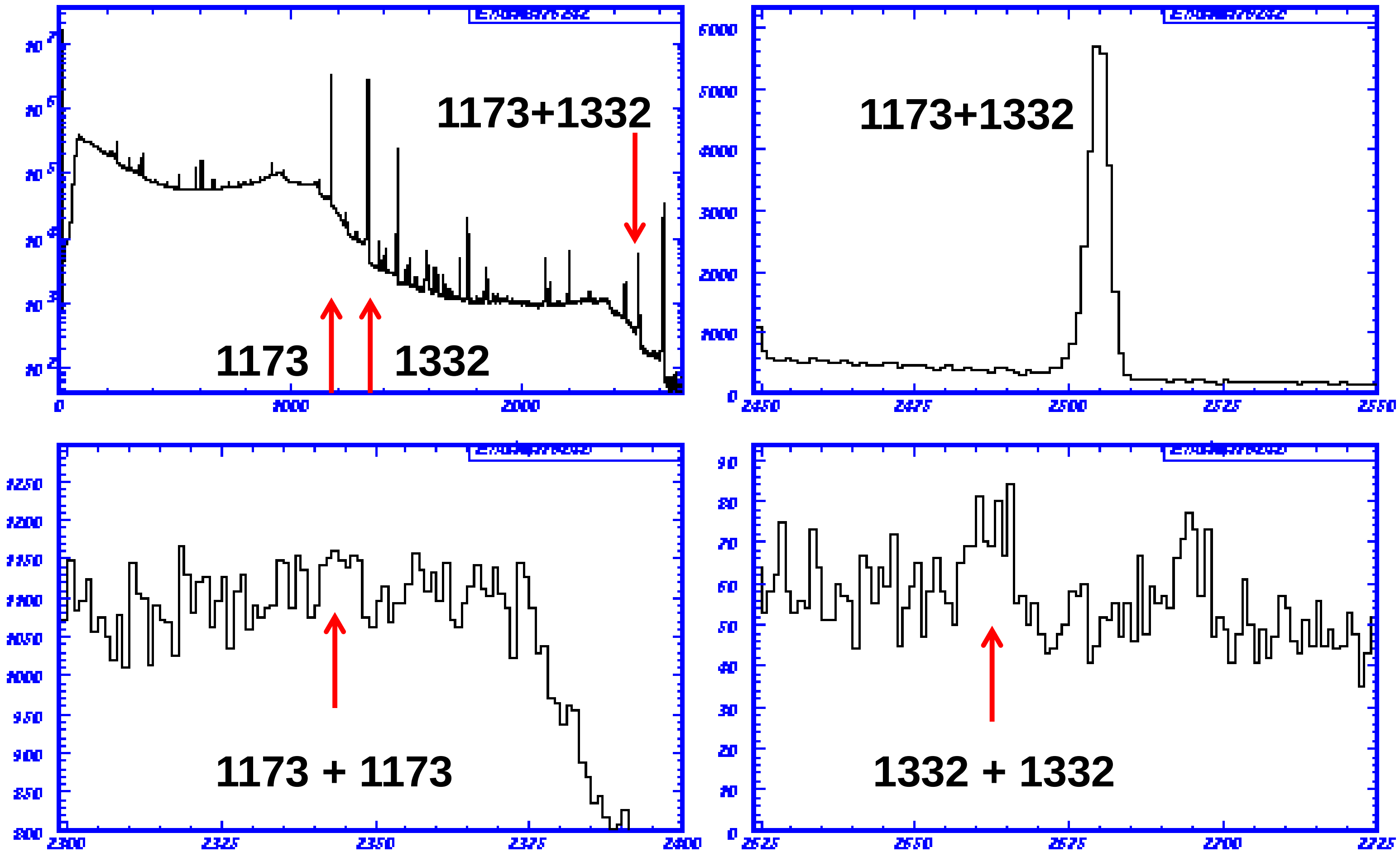
- I12 = I12' – I12_11 – I12_22
- $I12\_11 = I11 * \varepsilon_2 / \varepsilon_1 * BR2 / BR1$
- $I12\_22 = I22 * \varepsilon_1 / \varepsilon_2 * BR1 / BR2$

- ε_{t2} : from other measurements
- $w12(\theta)$: from calculations

- three unknowns: A0, ε_1, ε_2
- three equations

➔ ➔ ε_1, ε_2

Absolute efficiency with γ–γ coincidences: ^{60}Co



➔ ε_1 (γ–γ) = (0.2186 ± 0.0007) %

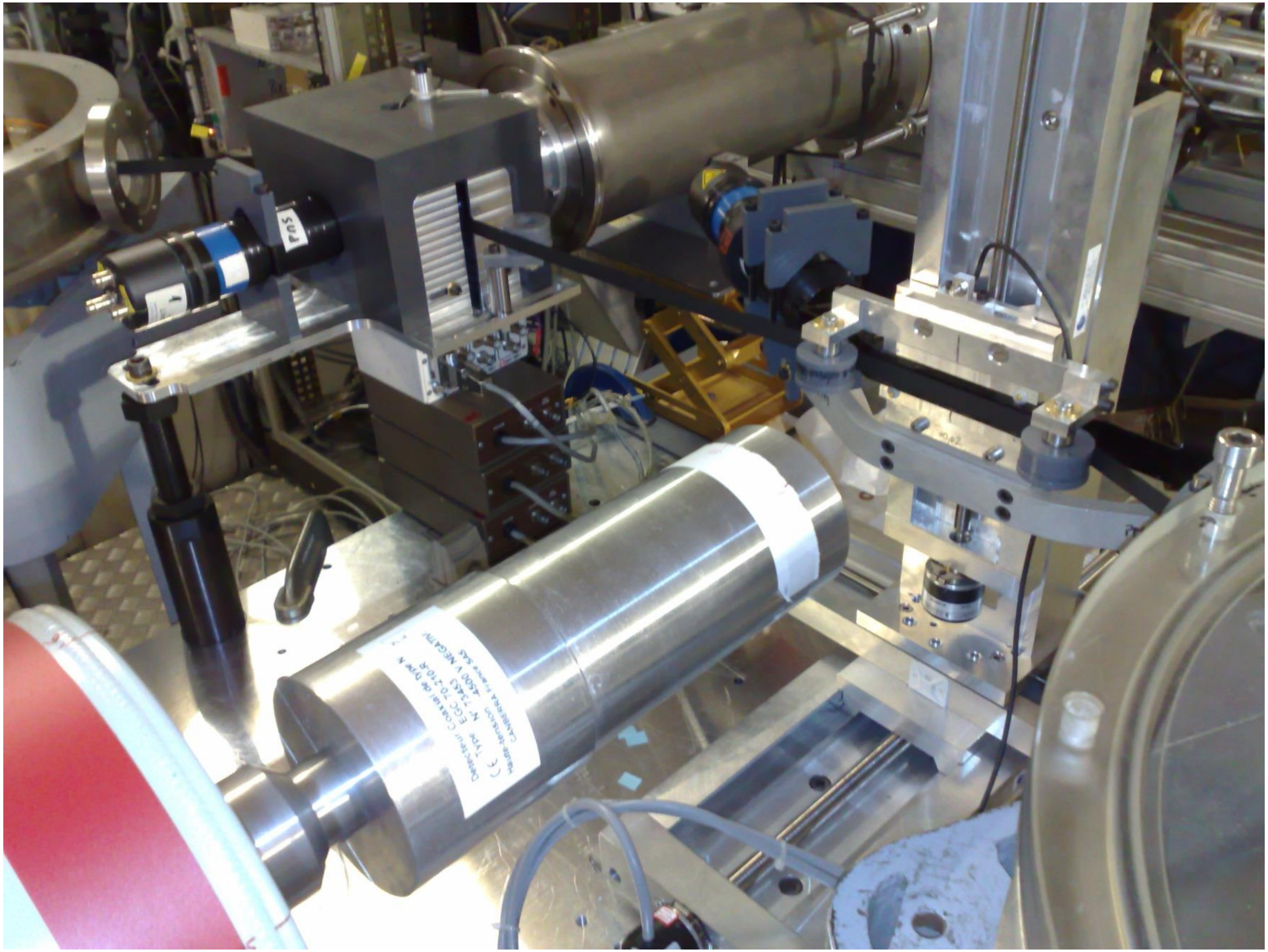
ε_1 (source act.) = (0.2175 ± 0.0003) %

➔ ε_2 (γ–γ) = (0.1996 ± 0.0007) %

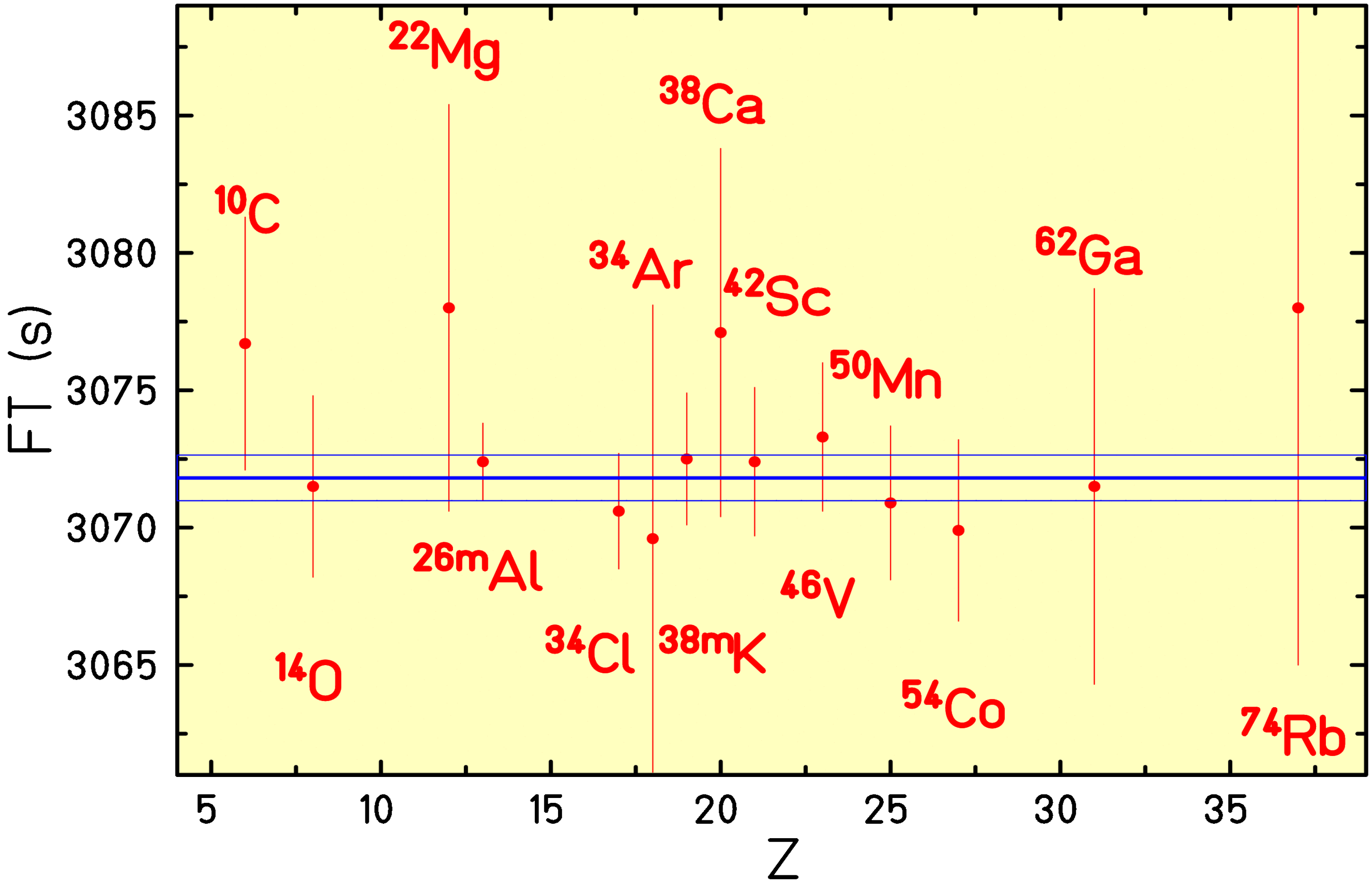
ε_2 (source act.) = (0.1996 ± 0.0003) %

… do ^{24}Na at ISOLDE?

^{38}Ca detection

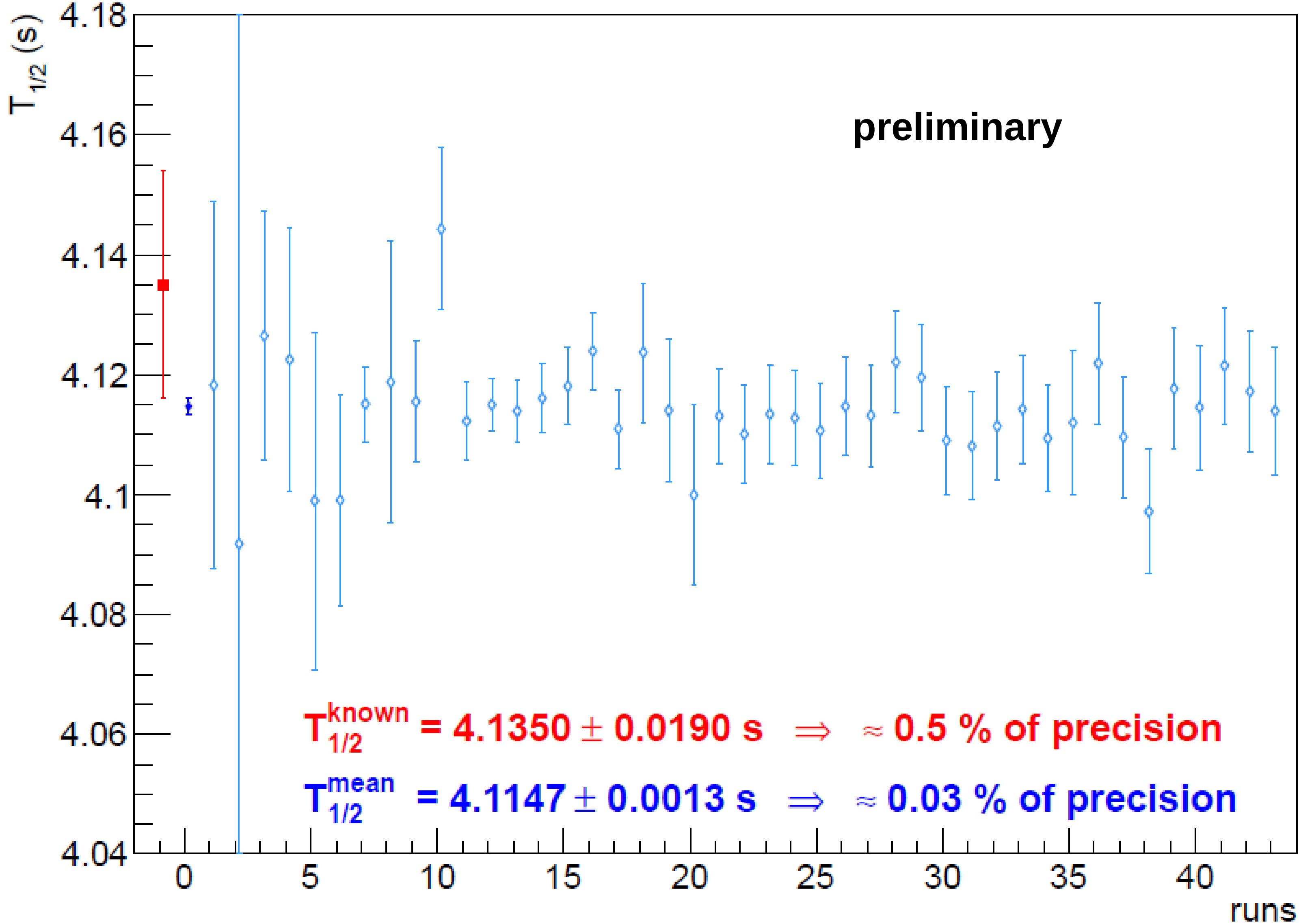


$0^+ \rightarrow 0^+$ decays: status



- 14 nuclei measured with precision of order 10^{-3}
- $V_{ud} = 0.97417 \pm 0.00021$, $\Sigma V_{ux} = 0.99978 \pm 0.00055$

Half-lives of ^{27}Si

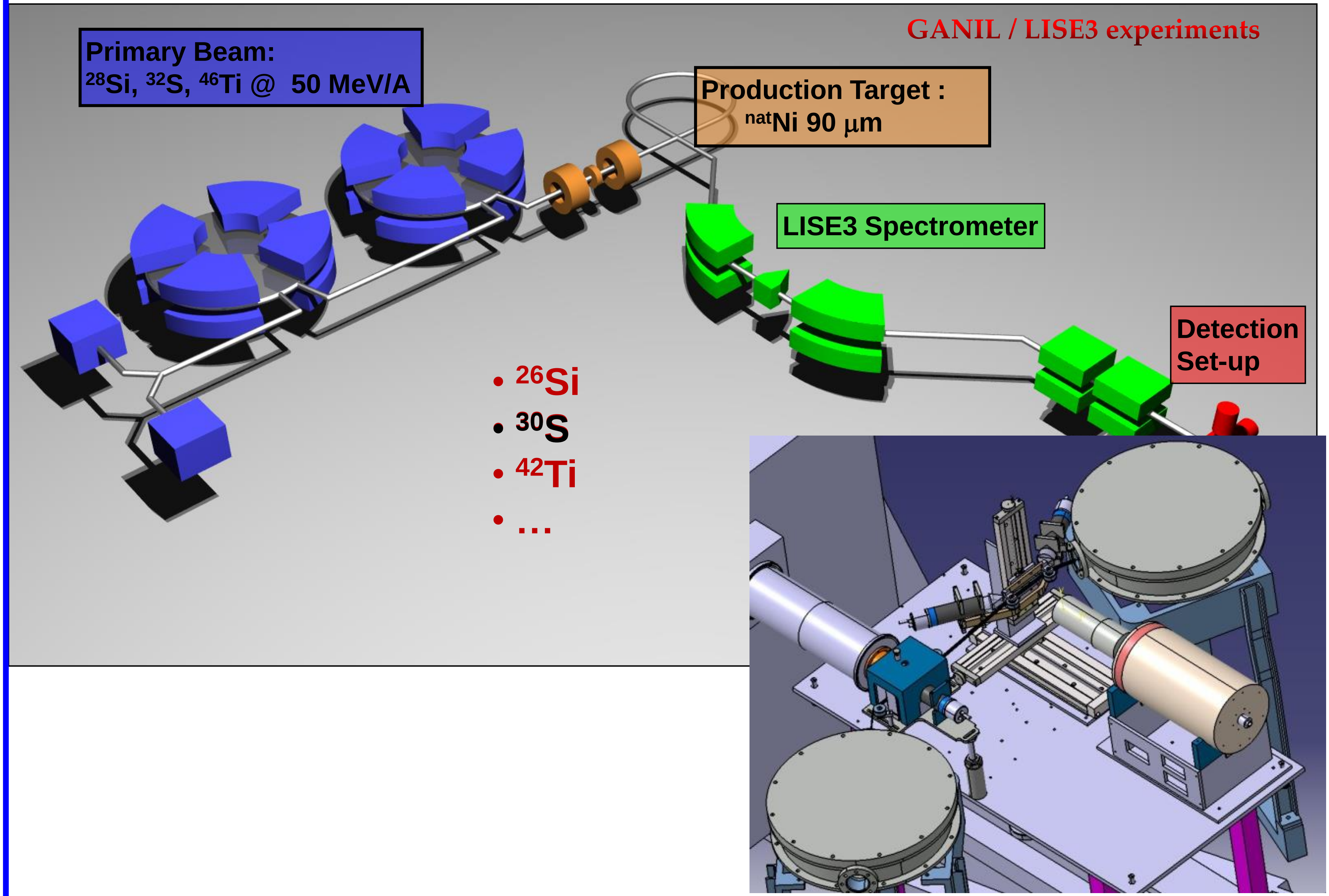


C. Magron et al.

Future plans: GANIL – SPIRAL2 – S3 – DESIR

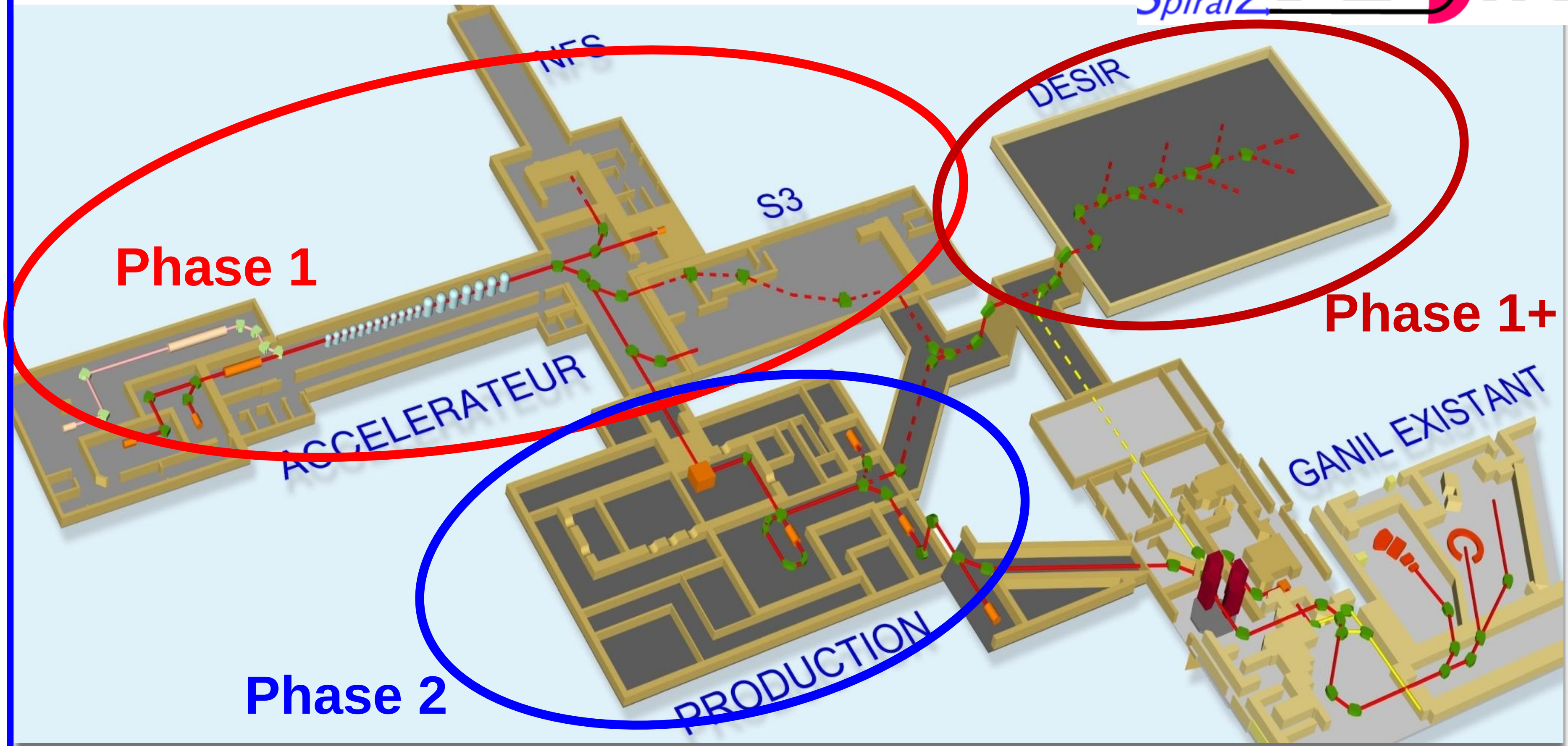
- T_z = -1, 0+ - 0+ decays
- heavy 0+ - 0+ decays

Super-allowed emitter production at GANIL/LISE3



- ^{26}Si
- ^{30}S
- ^{42}Ti
- …

SPIRAL2 facility



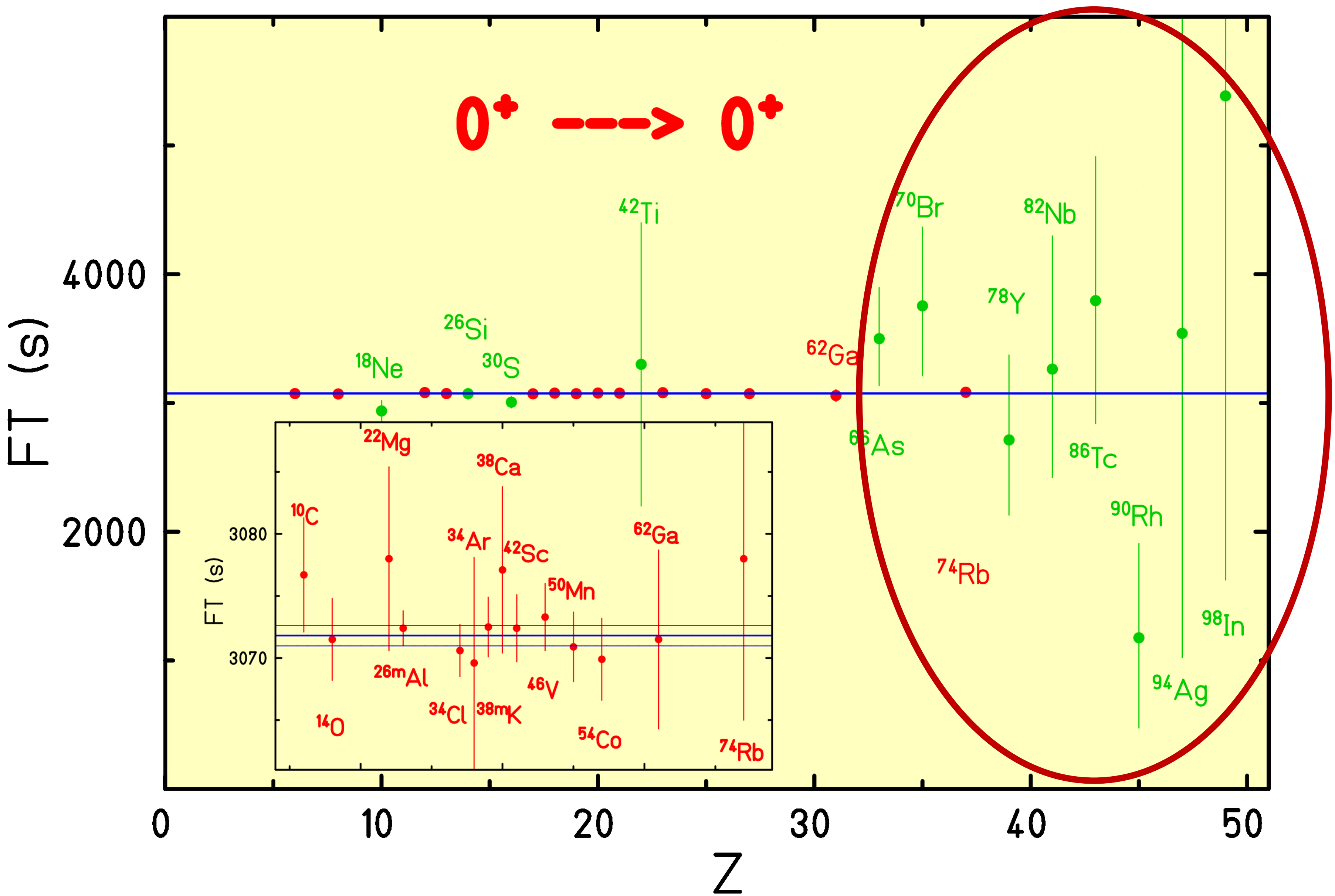
- **NFS and S3 experiments**
- **for DESIR:**
  - **SPIRAL1 (light nuclei from beam/target fragmentation)**
  - ~~**SPIRAL2 (n-rich fission fragments, transfer and fusion-evaporation products)**~~ **at earliest 2020**
  - **S3 (fusion-evaporation, refractory elements)**

Heavy T_z = 0 nuclei

	isotope	half-life (ms)	production rate (pps)
$T_z = 0$	^{66}As	95.77(23)	50000
	^{70}Br	79 .1(8)	35000
	^{74}Rb	64.776(30)	30000
	^{78}Y	54(5)	1500
	^{82}Nb	50(5)	300
	^{86}Tc	55(6)	250
	^{90}Rh	15(7)	200
	^{94}Ag	37(18)	400
	^{98}In	37(5)	0.3

➔ test CVC over a larger range of Z

Heavy T_z = 0 nuclei



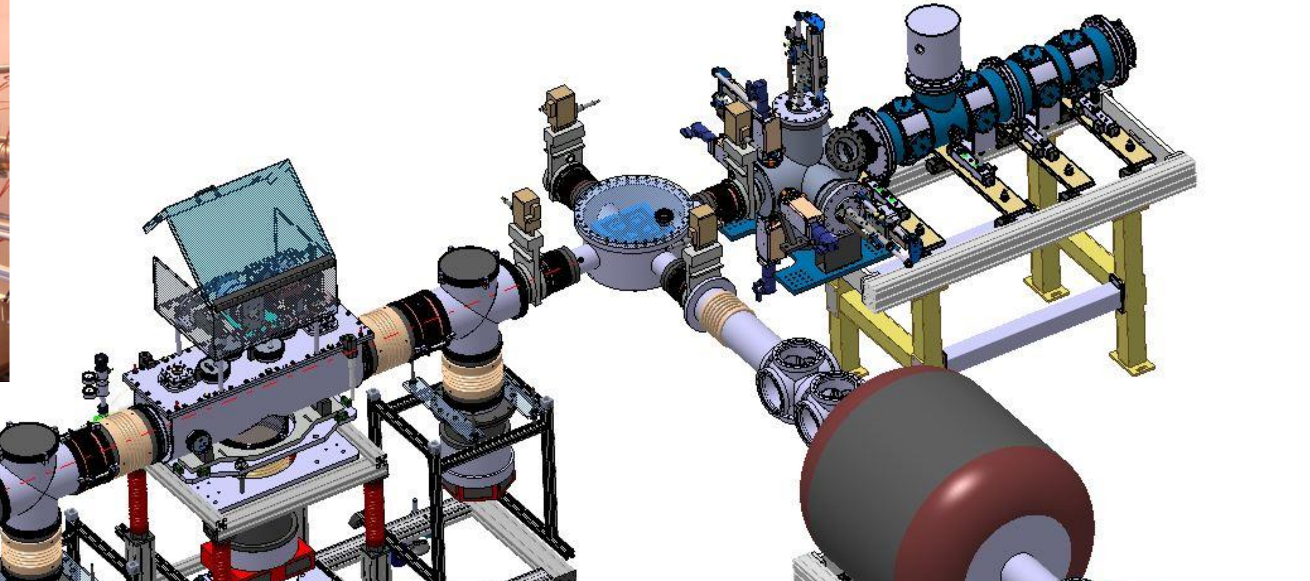
PIPERADE at DESIR

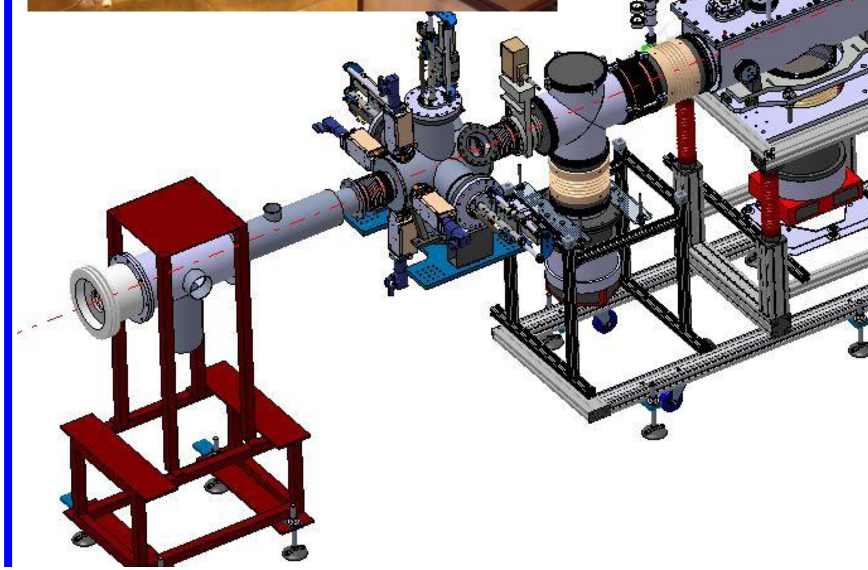
Double Penning trap for high-resolution separation at DESIR facility of SPIRAL2

Requirements

- Purify large samples (>10^4 ions)
- Mass resolution > 10^5
- Fast separation methods

Test set-up at CENBG Bordeaux





Collaboration:
- CEN Bordeaux-Gradignan
- MPIK Heidelberg
- CSNSM Orsay
- GANIL Caen
- LPC Caen

P. Ascher et al., EPJ Web of Conf. 66, 11002 (2014)