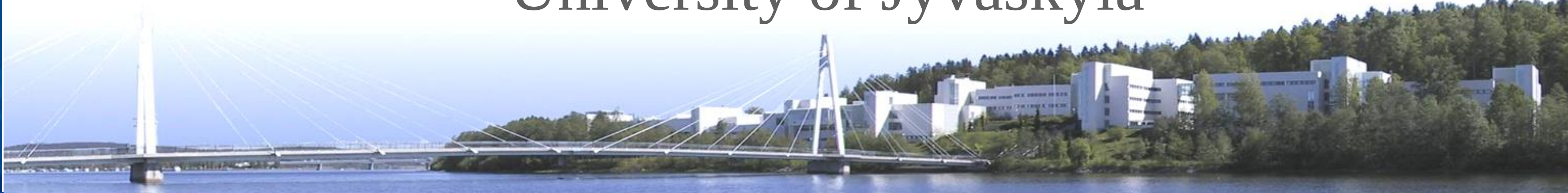
NUSTAR week 2017, Ljubljana, Slovenia

STATUS OF JYFLTRAP AND RECENT MEASUREMENTS

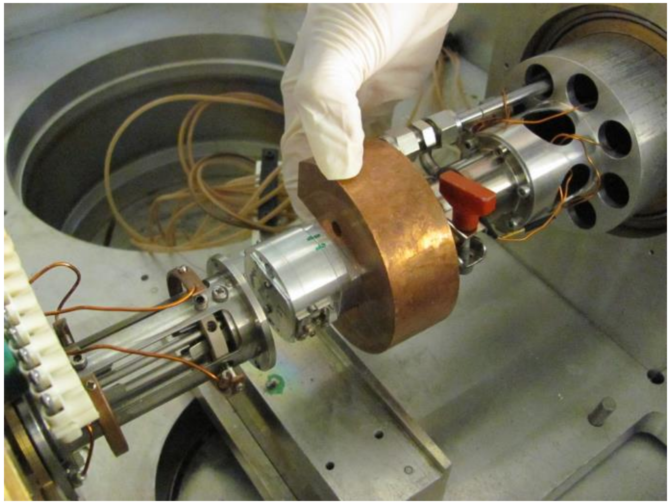
Tommi Eronen

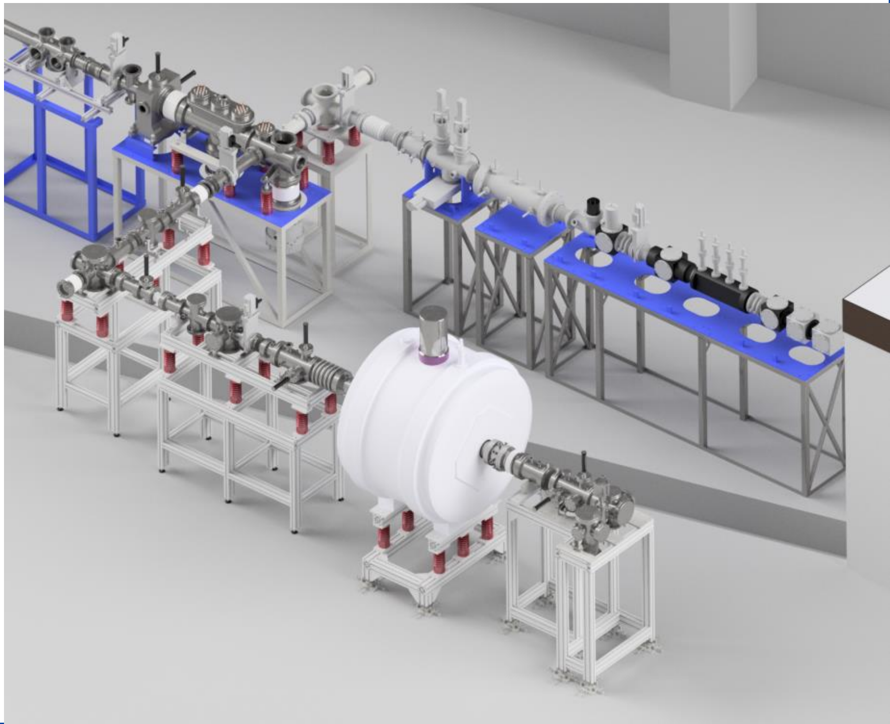
University of Jyväskylä



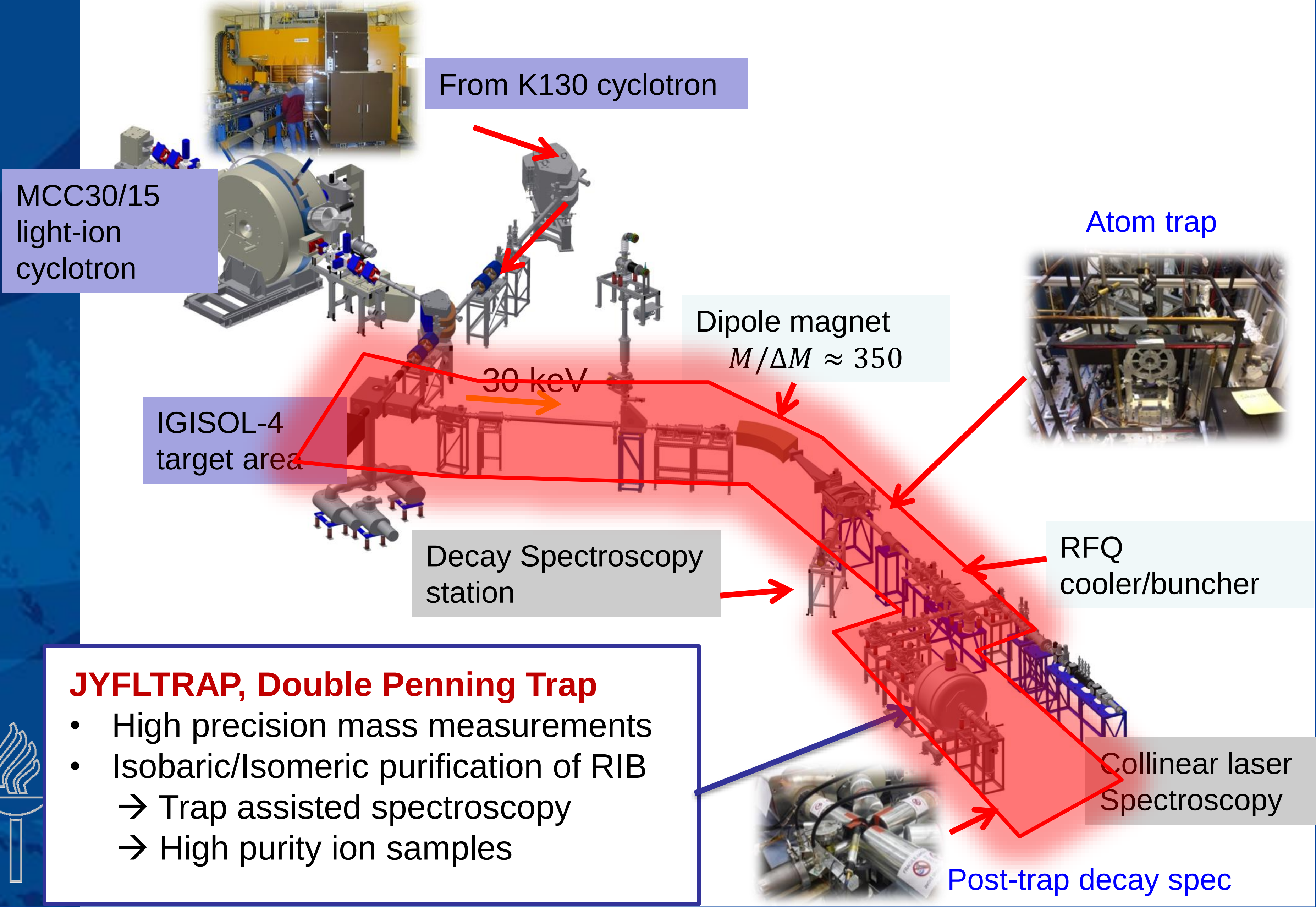
Refresher

- JYFLTRAP is a double Penning trap at IGISOL-4
- IGISOL is Ion Guide ISOL at University Jyväskylä accelerator laboratory
  - Stopping reaction products in gas
  - No chemical selectivity





IGISOL-4 FACILITY LAYOUT

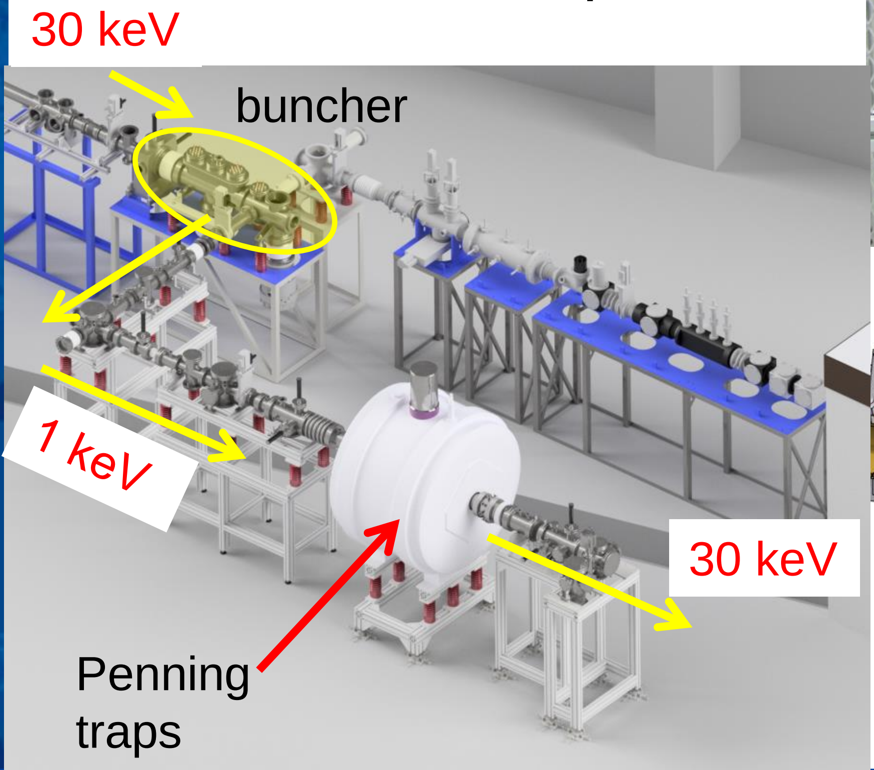


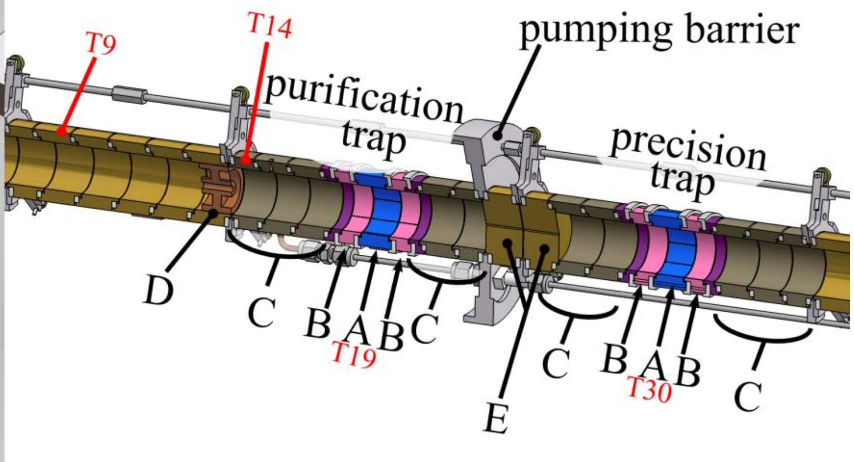
JYFLTRAP, Double Penning Trap

- High precision mass measurements
- Isobaric/Isomeric purification of RIB
  → Trap assisted spectroscopy
  → High purity ion samples

JYFLTRAP

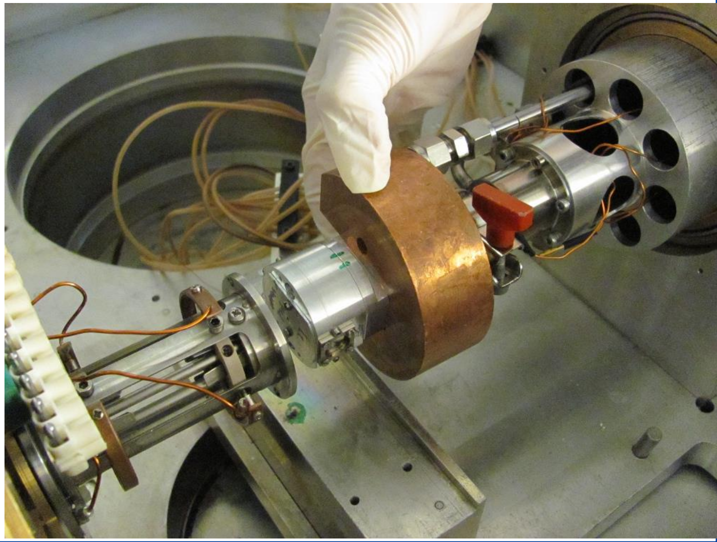
- Buncher
- 2 Penning traps
  - Purification trap
  - Precision trap





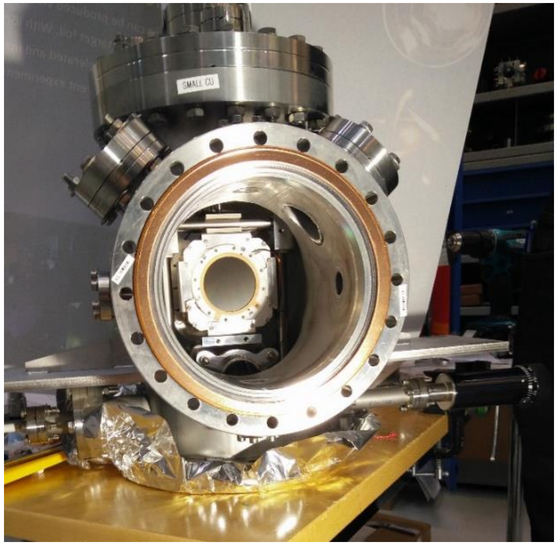
Beams available

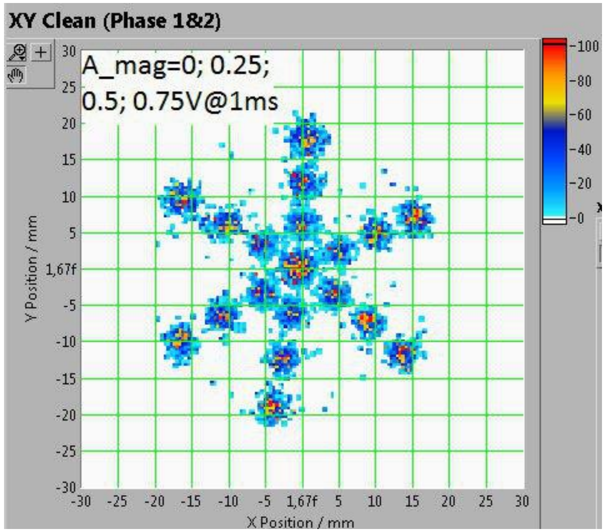
- Before buncher: Stable Rb-Cs-K simultaneously
- Offline ion source upstairs:
  - Stable Rb-Cs-K
  - Electric discharge IS (any metal, powder …) “spark source”
- Online
  - U, Th fission using protons or deuterons
  - Light ion fusion
  - Fusion evaporation



Recent upgrades

- Summer 2016: Finished realignment
  - Added silicon detectors for beta detection
  - Transmission improvements – up to 40% transmission from before the buncher after the trap
- Summer 2017: Installation of 2D MCP detector
  - Enable phase-sensitive detection (PI-ICR method)



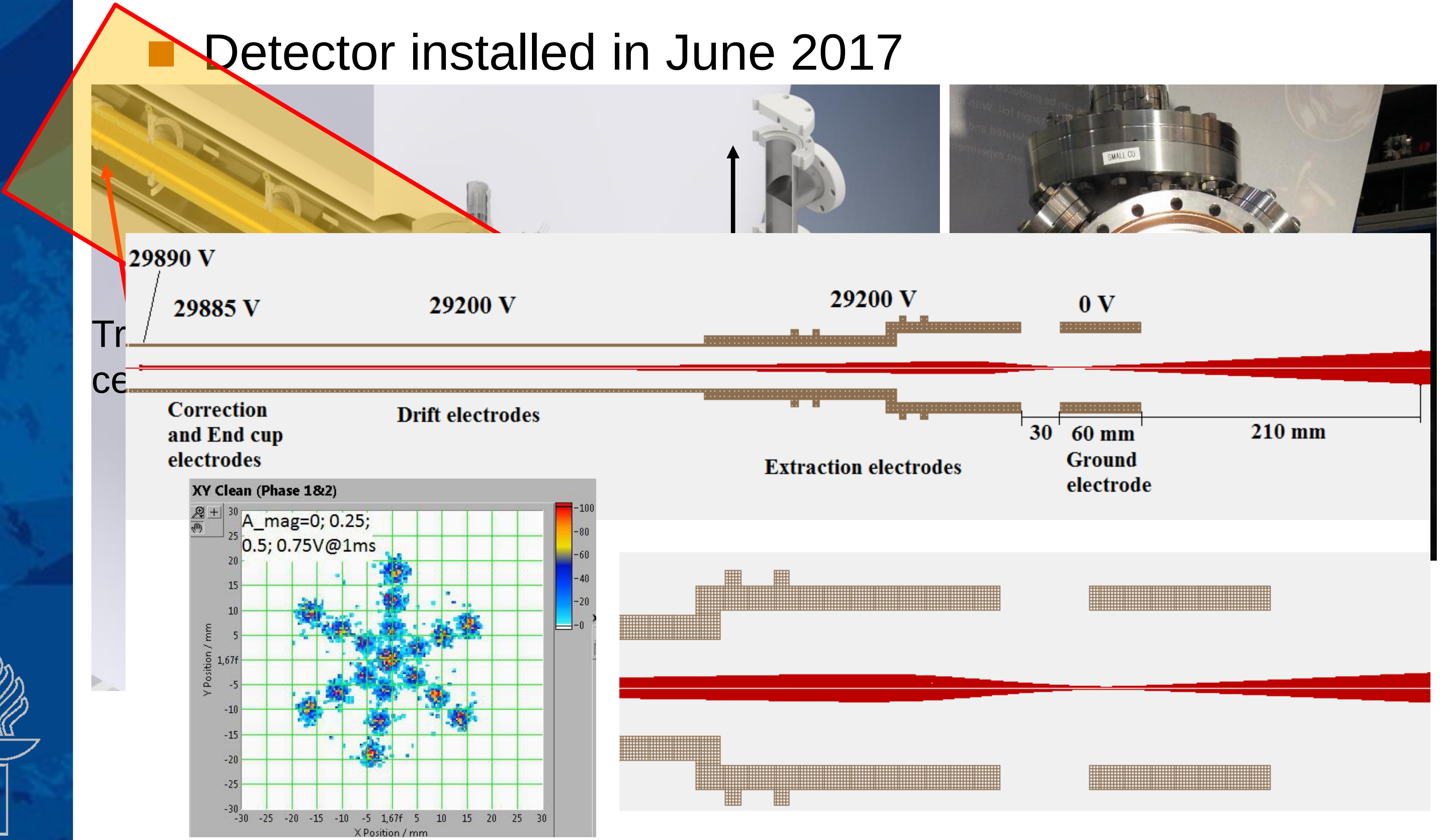


PI-ICR at JYFLTRAP

- Detector installed in June 2017

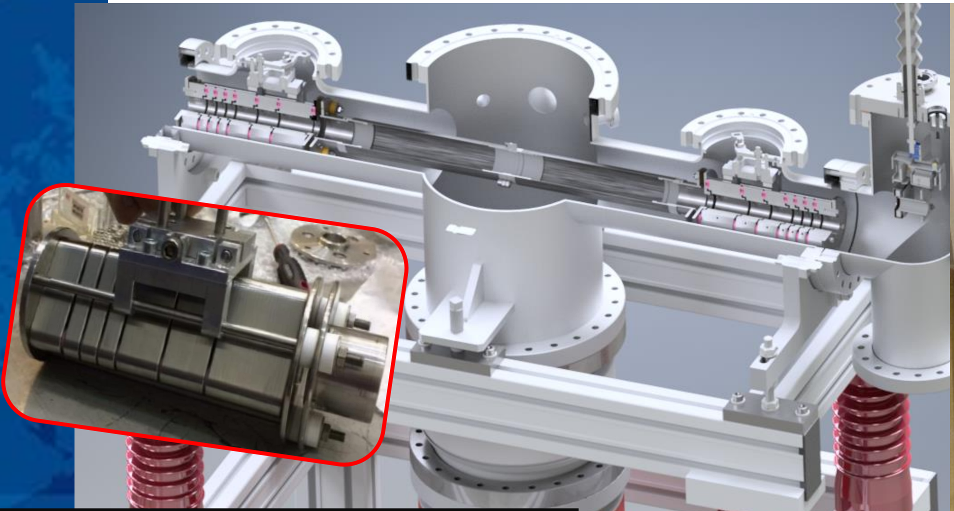
Tr

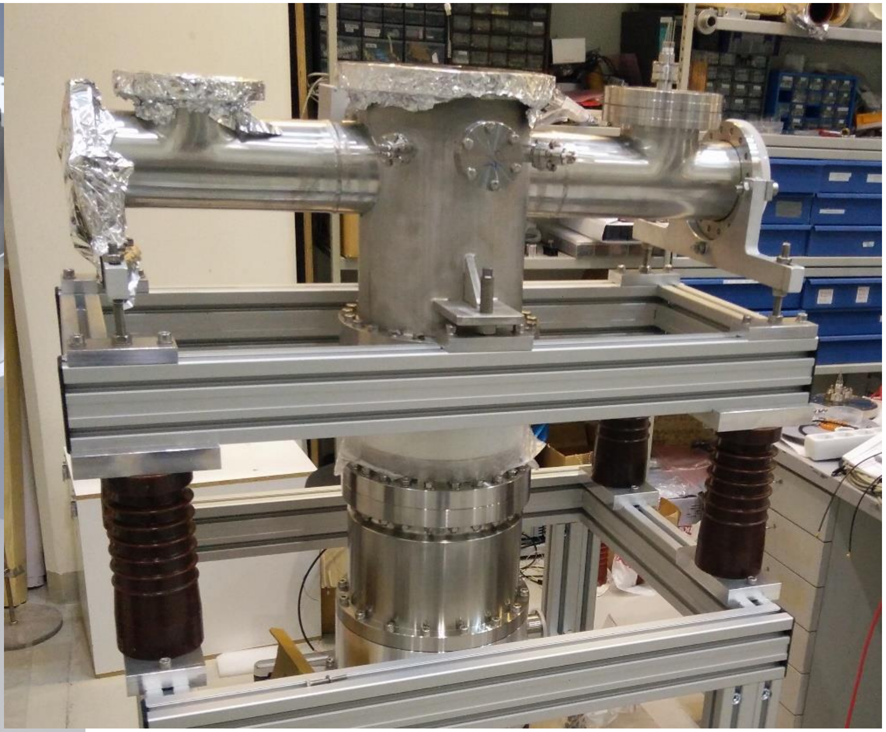
ce

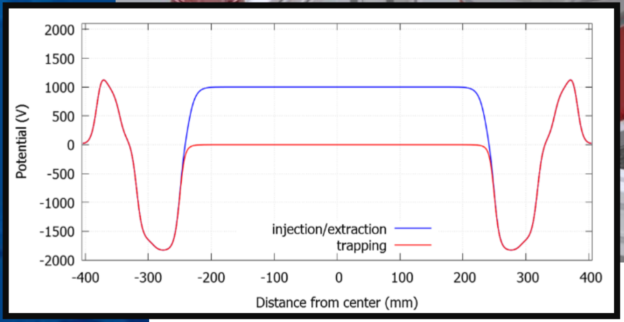


JYFL MR-TOF

- Based and simulated using Uni. Greifswald device
  - R. Wolf et al. **IJMS** 349, 123 (2013)
- In-Trap lift electrode

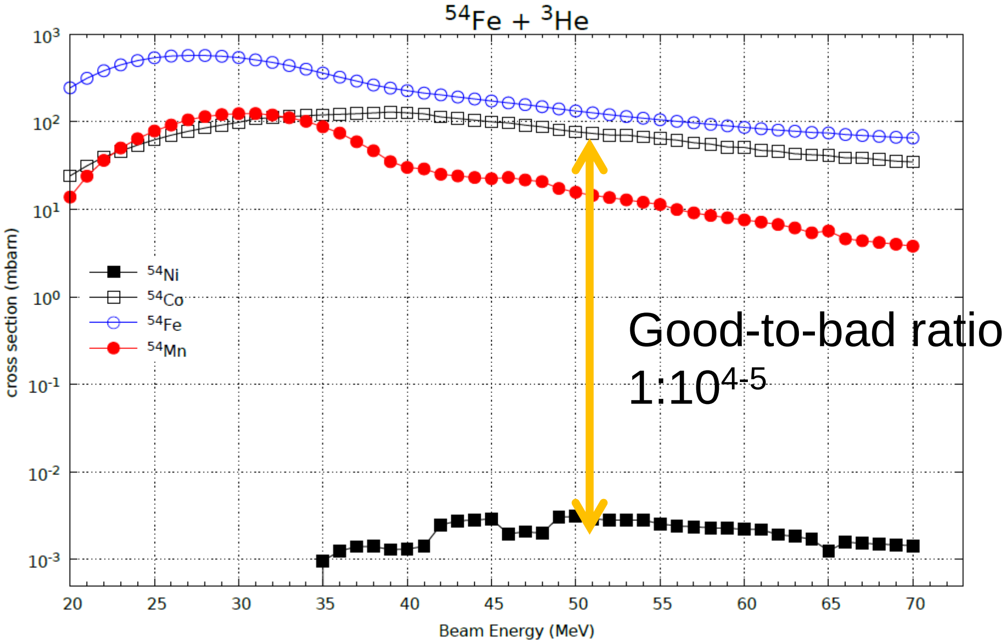






JYFL MR-TOF

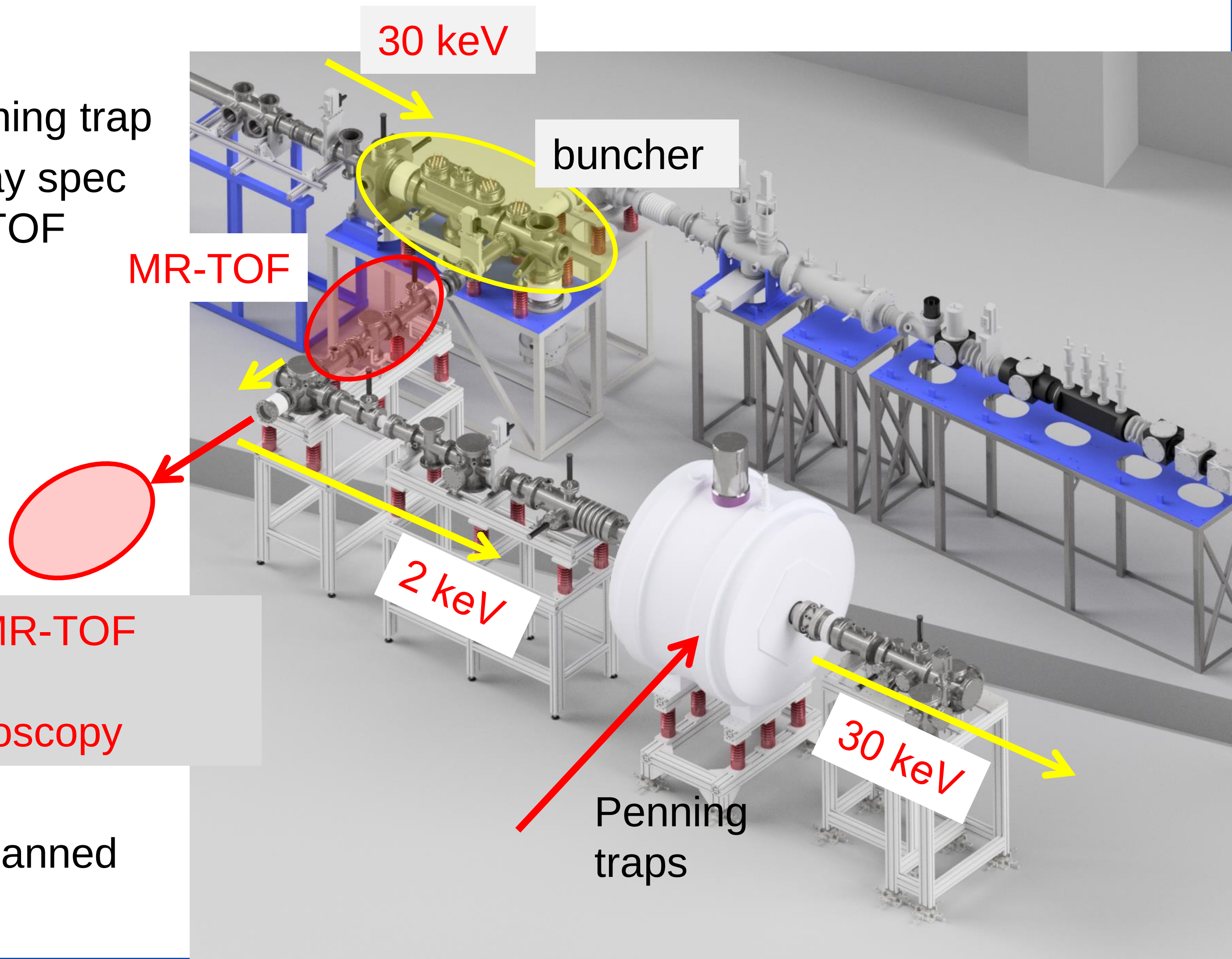
- Mass separator / spectrometer
- Faster cycle time than in Penning trap
  - Smaller needle from the haystack of ions
- Mass measurements with modest precision



Good-to-bad ratio
$1:10^{4\text{-}5}$

JYFL MR-TOF

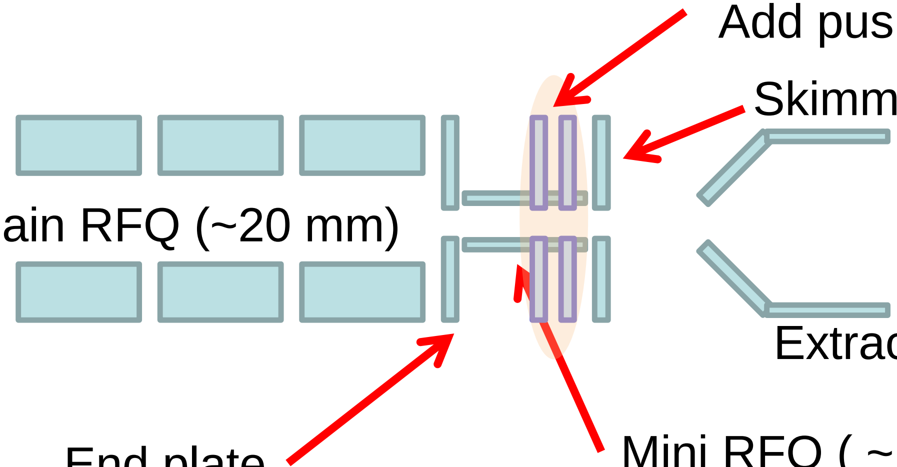
- In HV
- 1. To Penning trap
- 2. To decay spec after MR-TOF



Installation planned 1-6/2018

JYFL Buncher modification

- Collinear laser spectroscopy needs
  - Low energy spread (< 1 eV)
  - (This is also ok for injection to Penning traps)
- MR-TOF needs
  - Good time focus (< 100 ns)
- < 1 eV, < 100 ns can’t be simultaneously satisfied



Add push-pull extraction section

Skimmer plate

Main RFQ (~20 mm)

Extraction electrode

End plate

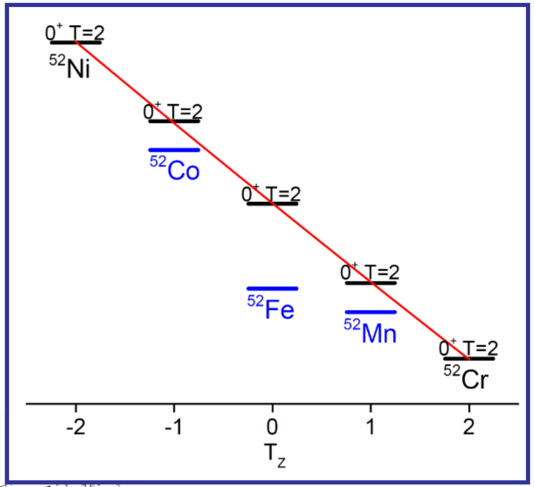
Mini RFQ (~ 2mm)

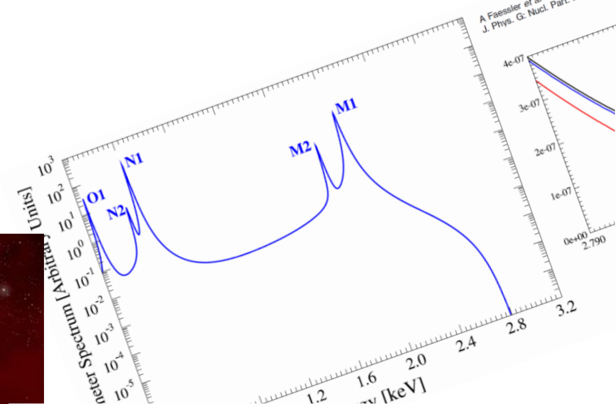
Simulations
M. Schuh
MPIK Heidelberg

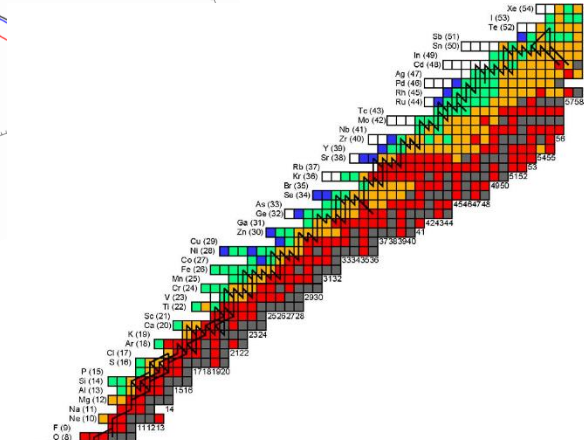
To be installed Q4/2017

Recent JYFLTRAP mass measurements

- Nuclear astrophysics
- Neutrino physics
- Fundamental physics
- Nuclear structure studies







H.Schatz, K.E. Rehm, Nucl. Phys. A 777 (2006) 601

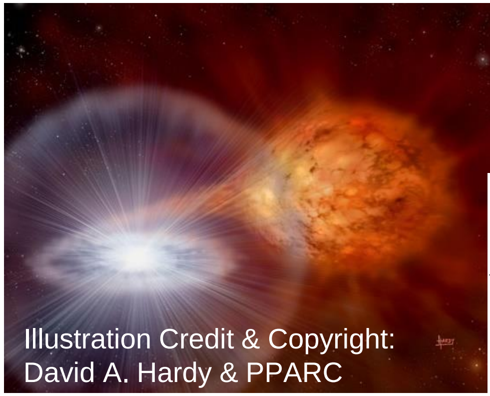
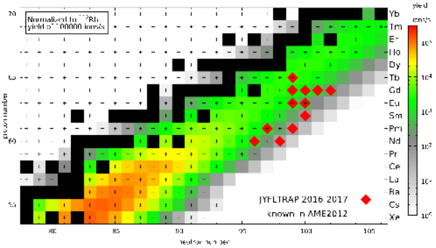


Illustration Credit & Copyright: David A. Hardy & PPARC

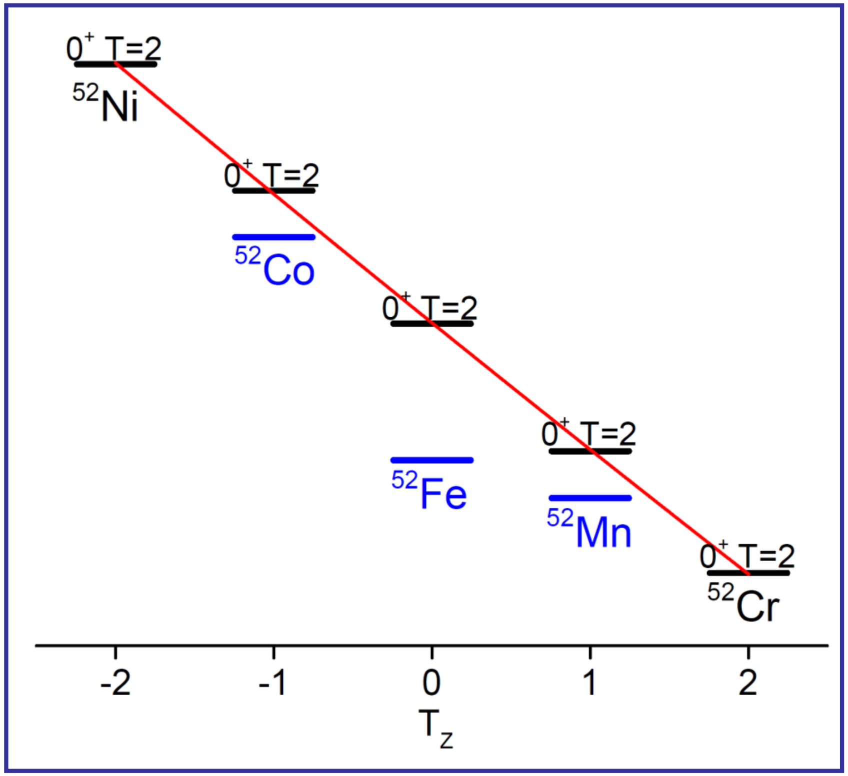


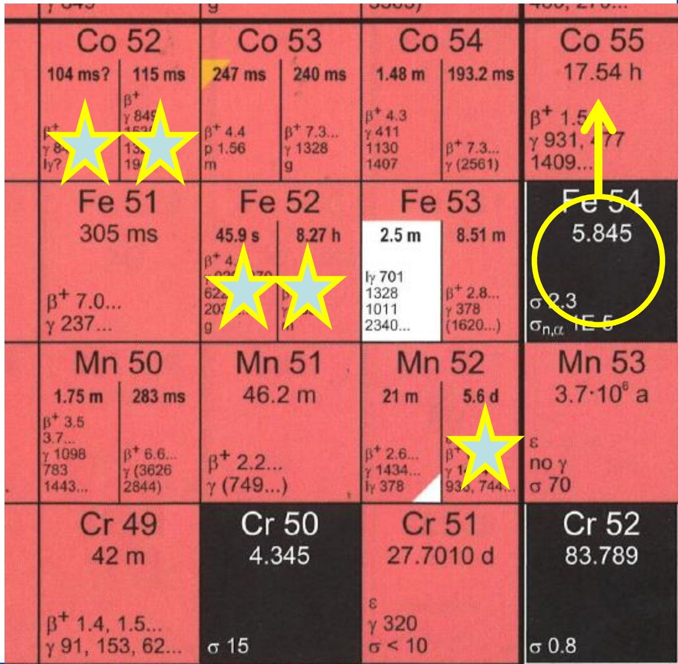
The mass of ^{52}Co for the IMME at A=52 and the rp process

Measured with JYFLTRAP:

- ✓ ^{52}Co, ^{52}Co^{m}
- ✓ ^{52}Fe, ^{52}Fe^{m}
- ✓ ^{52}Mn

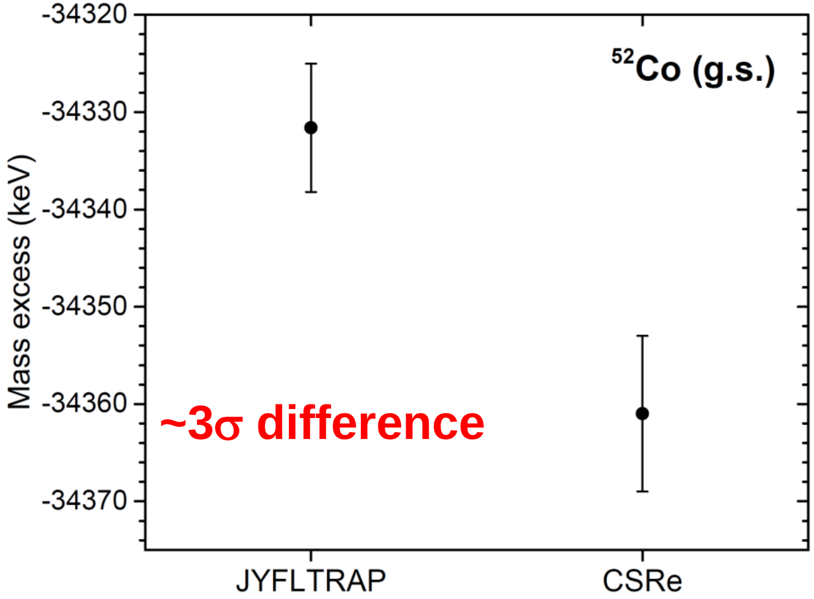
- ➢ The first Penning trap mass measurement of ^{52}Co!
- ➢ Short-lived: $T_{1/2}$=104(7) ms!
- ➢ ^{54}Fe(p,3n)^{52}Co @ 50 MeV: σ≈3 μb (TALYS)





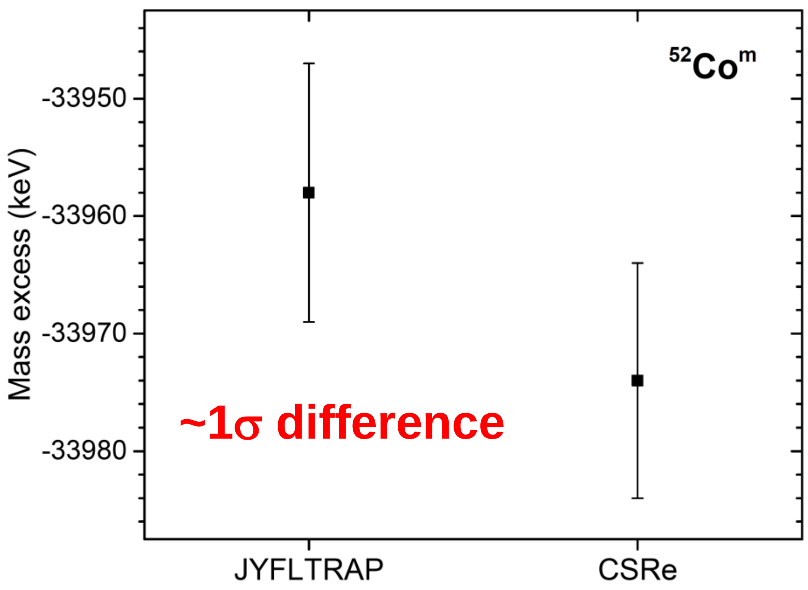
^{52}Co: comparison to other works

JYFL-AME12(#): -342(200) keV



~3σ difference

JYFL-NUBASE12(#): -348(220) keV



~1σ difference

Differs from the CSRe storage-ring IMS results *X. Xu et al., PRL 117, 182503 (2016)*

Spectroscopy:	Ex= 372(3) keV
JYFLTRAP:	Ex= 374(13) keV

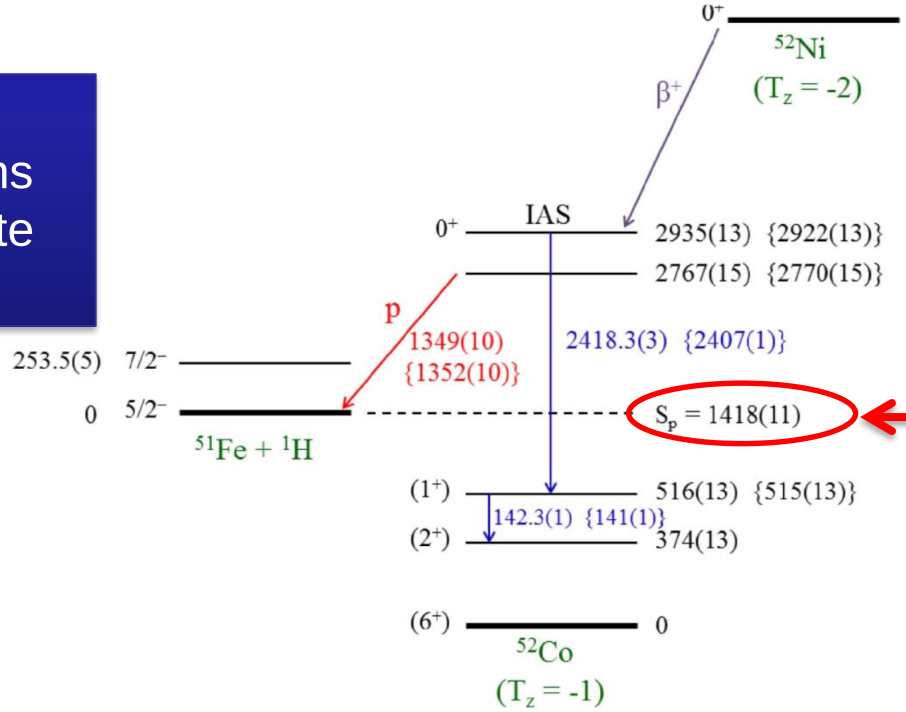
✓

^{52}Co results: decay scheme for ^{52}Ni

Earlier: beta decay studies of ^{52}Ni suggested that the T=2, 0^+ IAS decays both via βp and $\beta\gamma$

C. Dossat et al., Nucl. Phys. A 792 (2007) 18; S. Orrigo et al., PRC 93, 044336 (2016)

This work:
β-delayed protons come from a state below the IAS!



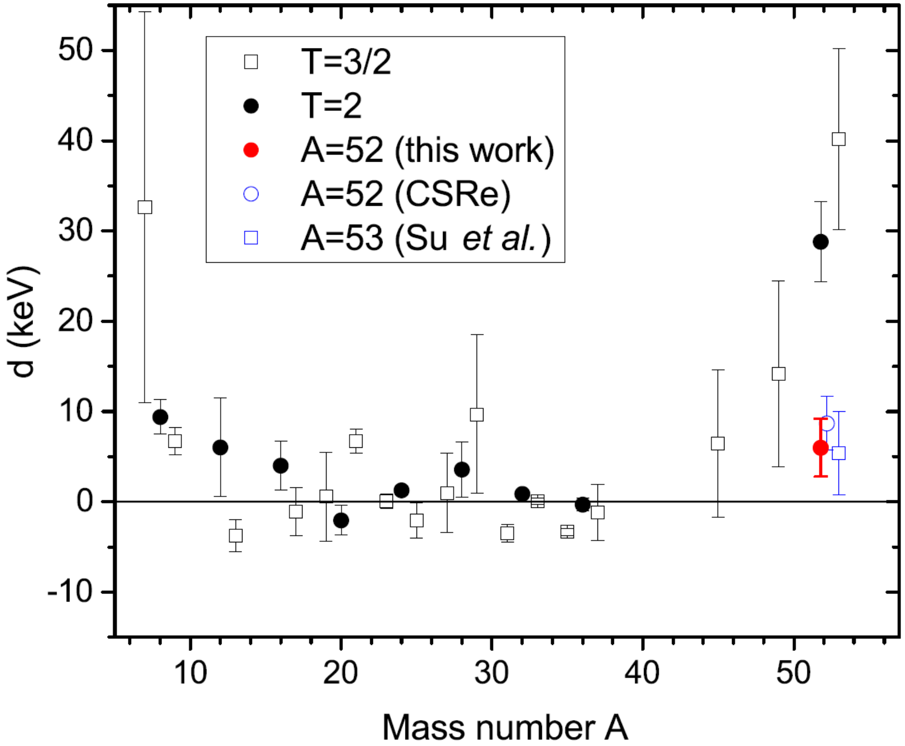
29(16) keV lower than obtained from *X. Xu et al., PRL 117, 182503 (2016)*

D. A. Nesterenko, et al., J. Phys. G: Nucl. Part. Phys. 44 (2017) 065103

^{52}Co results: IMME

Cubic coefficients d:

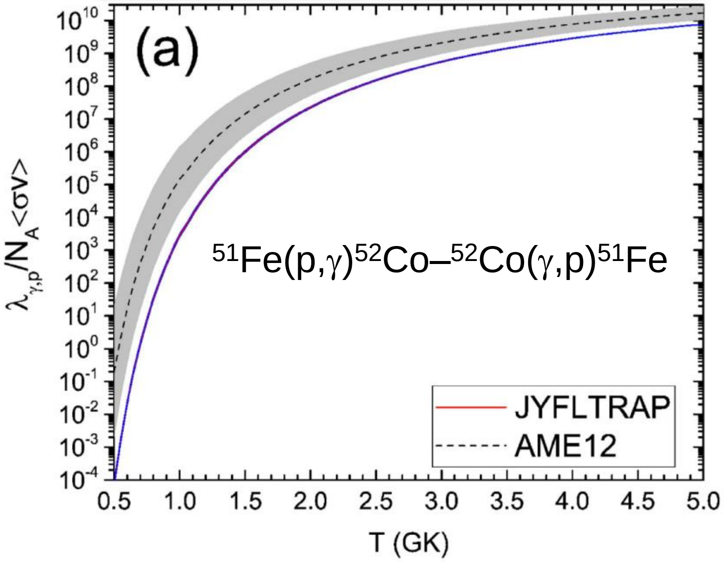
JYFLTRAP: d = 6.0(32) keV
CSRe: d = 5.8(42) keV
CSRe+JYFLTRAP
for ^{52}Fe and ^{52}Mn: d = 8.7(30) keV



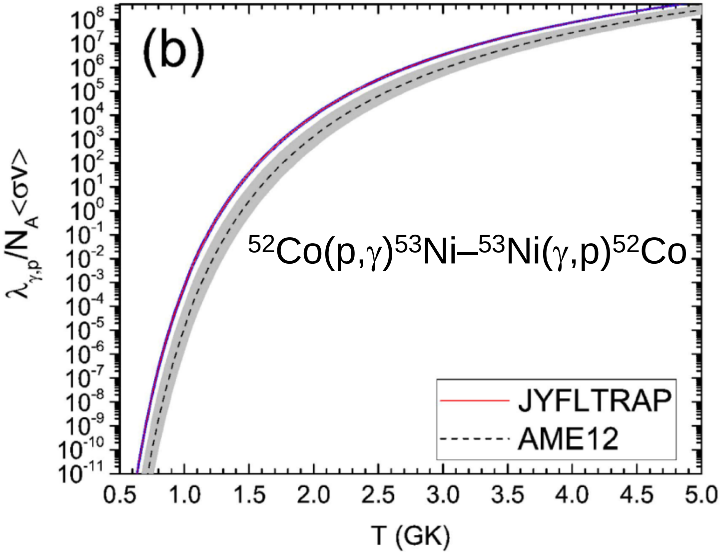
^{52}Co and the rp process

^{52}Co more bound, ^{53}Ni less proton-bound than predicted by the AME12

$S_p(^{52}Co)$ = 1418(11) keV
AME12: 1077(196)# keV



$S_p(^{53}Ni)$ = 2588(26) keV
AME12: 2930(197)# keV

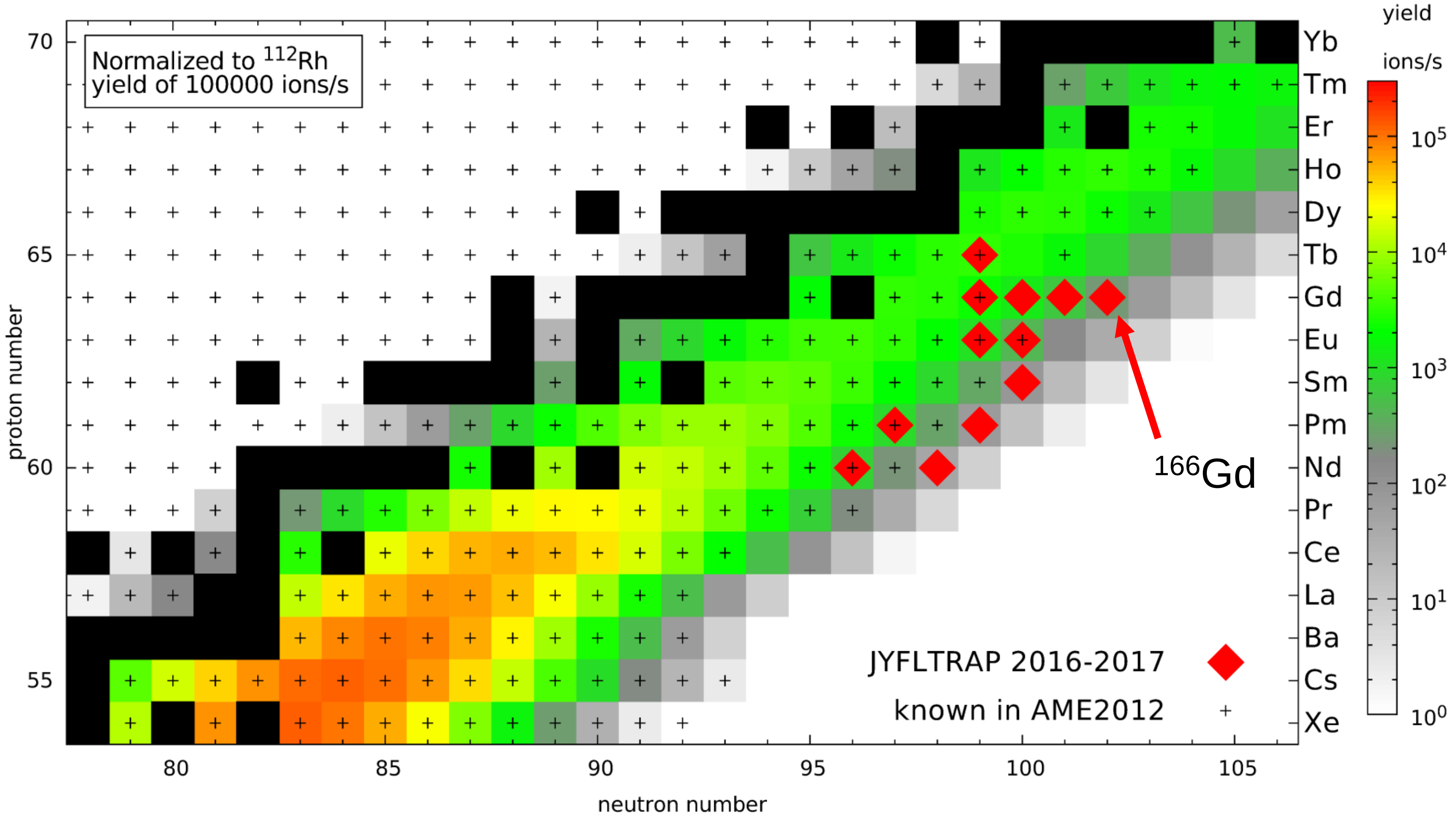


D. A. Nesterenko et al., J. Phys. G: Nucl. Part. Phys. 44 (2017) 065103

Neutron rich rare-earth masses

M. Vilen, J. Kelly, A. Kankainen et al., nuclear astrophysics

University of Jyväskylä
University of Notre Dame



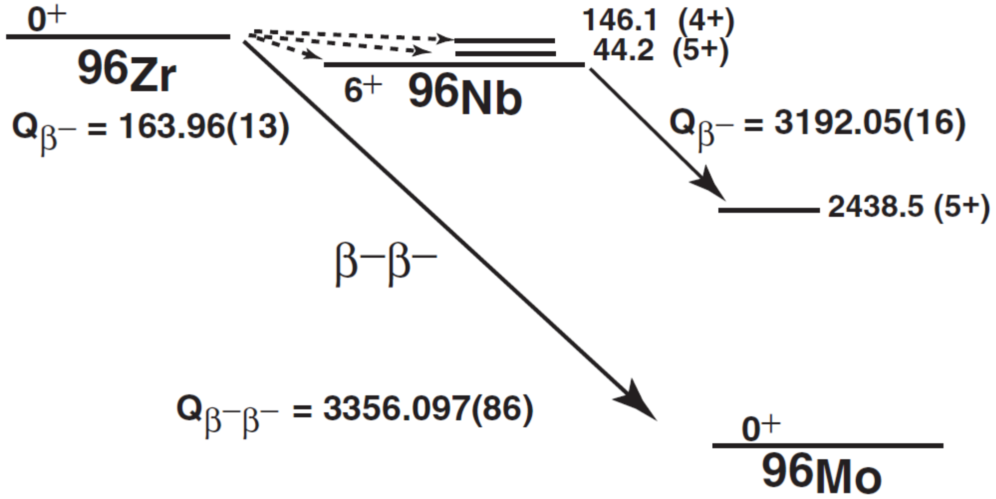


FIG. 1. Decay scheme for the $A = 96$ triplet showing the energy position of ^{96}Zr with respect to its neighbors ^{96}Nb and ^{96}Mo. The Q values are from this work (all energies are in keV).

ZR-96 SINGLE AND DOUBLE BETA DECAY Q-VALUES

D.Frekers, M. Alanssari University of Münster

Slide by Milad Alanssari

Competition between β & ββ decay of ^{96}Zr

two conflicting half-lives:

NEMO-3: $T_{1/2}^{2\nu\beta\beta} = (2.3 \pm 0.2) \times 10^{19}$ y

geo-chem: $T_{1/2} = (0.94 \pm 0.32) \times 10^{19}$ y ①

can this difference be reconciled?
yes, if single β competes with ββ decay

$$\left(T_{1/2}\right)^{-1} = \left(T_{1/2}^{2\nu\beta\beta}\right)^{-1} + \left(T_{1/2}^{\beta}\right)^{-1}$$

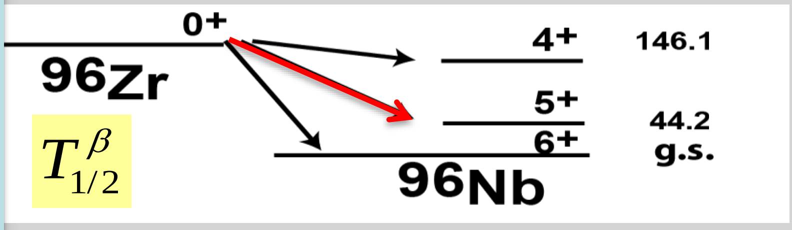
expected $T_{1/2}^{\beta} = (1.6 \pm 0.9) \times 10^{19}$ y

experiment $T_{1/2}^{\beta} > 2.6 \times 10^{19}$ y ②

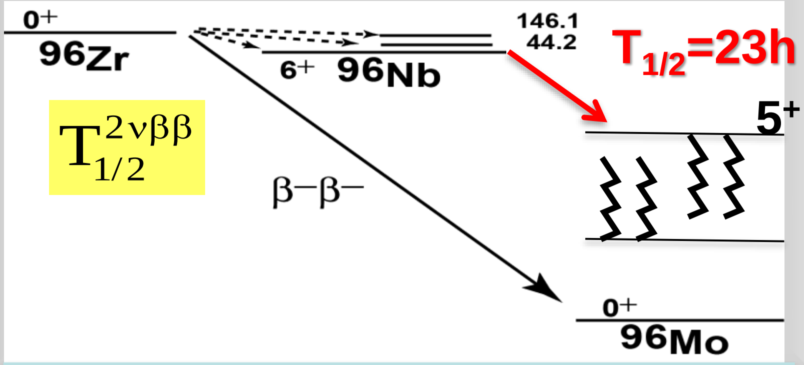
pred. (QRPA) $T_{1/2}^{\beta} = 24 \times 10^{19}$ y ③

BUT

$$(T_{1/2}^{\beta})^{-1} \propto O(Q^{13}) g_A^2 \left\langle M_\beta^{4u} \right\rangle^2$$



0⁺ → 6⁺ 6-fold non-unique (unobservably long)
0⁺ → 5⁺ 4-fold unique (possible)
0⁺ → 4⁺ 4-fold non-unique (no phase space)



Q-value $\longrightarrow M_\beta^{4u} \longrightarrow (T_{1/2}^{0\nu\beta\beta})^{-1} \propto Q^5 \left| M_{\beta\beta}^{0\nu} \right|^2 \left\langle m_{\beta\beta} \right\rangle^2$

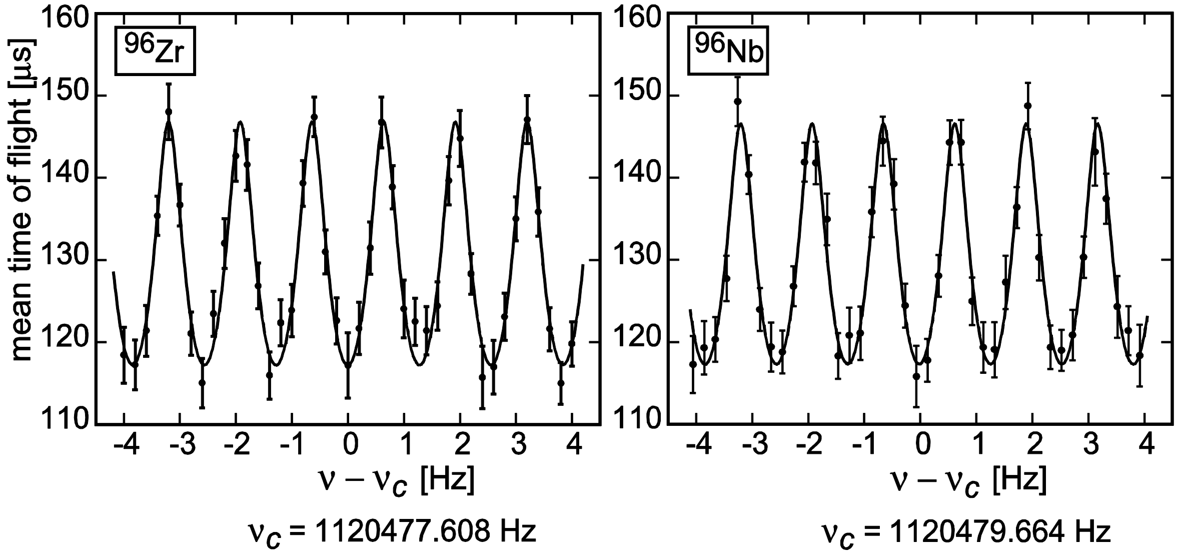
Wieser, PRC64,2001, ① *Barabash, JPG-NPP22, 1996* ② *Heiskanen, JPG3,2007* ③

M. Alanssari et al., Phys. Rev. Lett. **116** 072501 (2016)

Q-values for ^{96}Zr β^- and $\beta^-\beta^-$ decays

- LEBIT@MSU 2015:
  - ββ Q-value higher by 7 keV
- JYFLTRAP 2016:
  - ββ Q-value confirmed
  - β Q-value higher by 5.5 keV

LEBIT 2bb Q-value: K. Gulyuz, Phys. Rev. C 91, 055501 (2015)



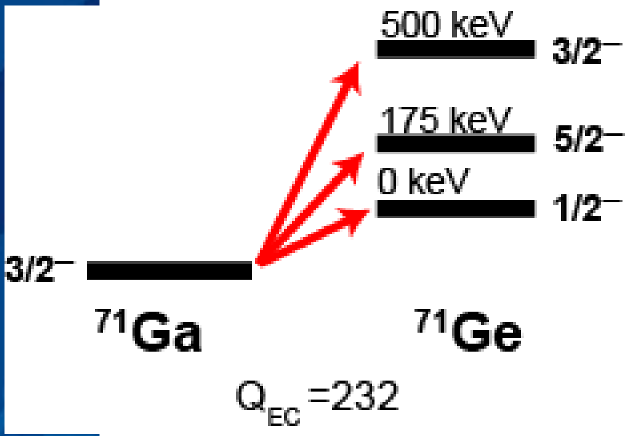
HALF-LIFE DISCREPANCY NOT SOLVED.

- Need new single-β half-life measurement

GALLIUM-71 ANOMALY

GALLEX/ SAGE Calibration results with ^{51}Cr ν source

(ratio= observed/predicted)



experiment	source	ratio
GALLEX	^{51}Cr-1	0.95 ± 0.11
GALLEX	^{51}Cr-2	0.81 ± 0.11
SAGE	^{51}Cr	0.95 ± 0.12
SAGE	^{37}Ar	0.79 ± 0.10
Average	^{37}Ar, ^{51}Cr	0.87 ± 0.05

- **The anomaly could be caused by:**
  - **wrong transition strength from ^{71}Ga → ^{71}Ge**
  - **wrong ^{71}Ga / ^{71}Ge Q-value (from mass meusurements)**
  - **effect of sterile neutrino**
  - **wrong calibration measurement**

Q-value effects on ^{71}Ga

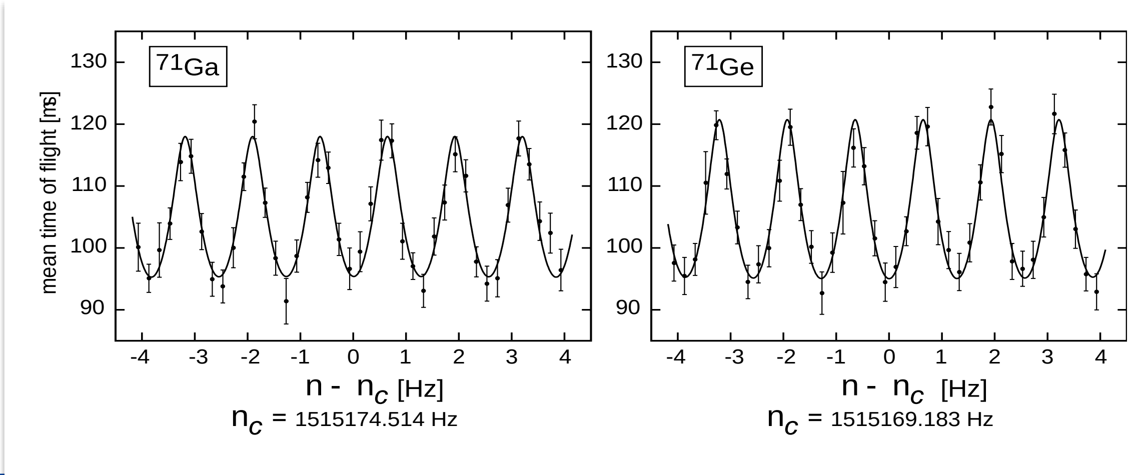
Solves anomaly?

- Q=232.69 keV J. Bahcall, used in calculation
- Q =233.5(12) keV ^{71}Ga-^{71}Ge TITAN-TRIUMF **NO**
  - Frekers et al, Phys. Lett. B 722 (2013) 223
- How about ^{51}Cr Q-value (^{51}Cr used in calibration)?
  - 751.86(55) keV ^{51}Cr-^{51}V TITAN-TRIUMF
    - T. D Macdonald et al, Phys. Rev. C **89** (2014) 044318

NO

- Check ^{71}Ga-^{71}Ge with JYFLTRAP
  - 232.443(93) keV, **x10 more precise** than TITAN-TRIUMF
    - M. Alanssari et al., IJMS **406**, 1 (2016)

NO

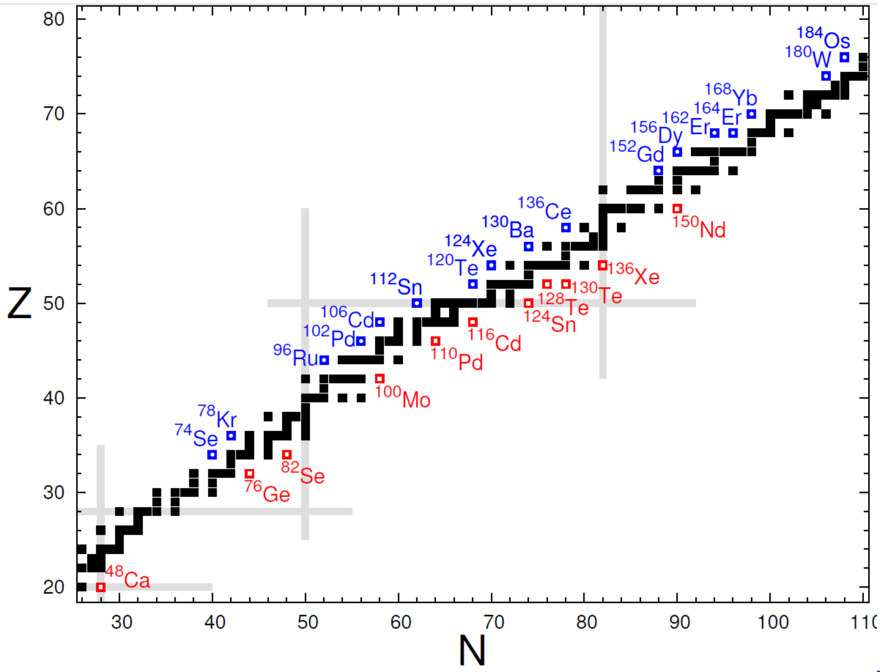


25-750-25 ms Ramsey pattern

ANOMALY REMAINS

2νββ, 0νECEC Q-values

- Almost all cases already studied..
  - 2νββ, 0νββ - endpoints
  - 0νECEC – Search for resonant enhancement
- Mainly measured by SHIPTRAP but most other traps have contributed as well

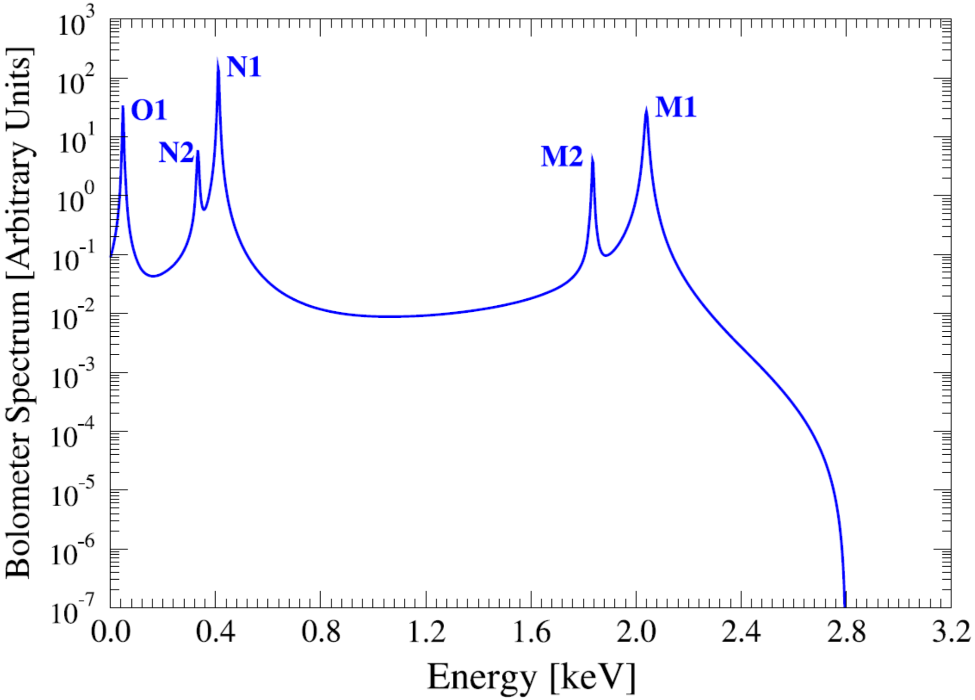


Ordinary (highly forbidden) β and EC Q-values

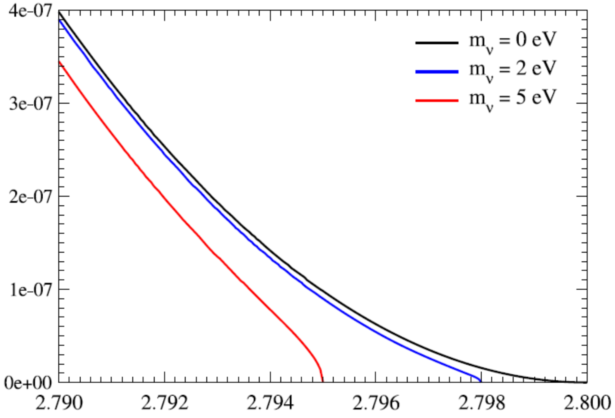
- Ground-state-to-ground state decays:
  - Direct neutrino mass probes, e.g. **tritium**, **^{163}Ho**
- Ground-state-to-excited-state decays
  - Low Q-values of highly forbidden decays

Low Q-value

- For example EC Q-value of ^{163}Ho ($T_{1/2} \approx 4600$ years)
  - Ground state to ground state decay
  - Q-value from Penning trap mass spectroscopy
    - Eliseev et al., PRL 115, 062501 (2015) [PI-ICR technique]
    - $30_{stat} + 15_{syst}$ eV precision

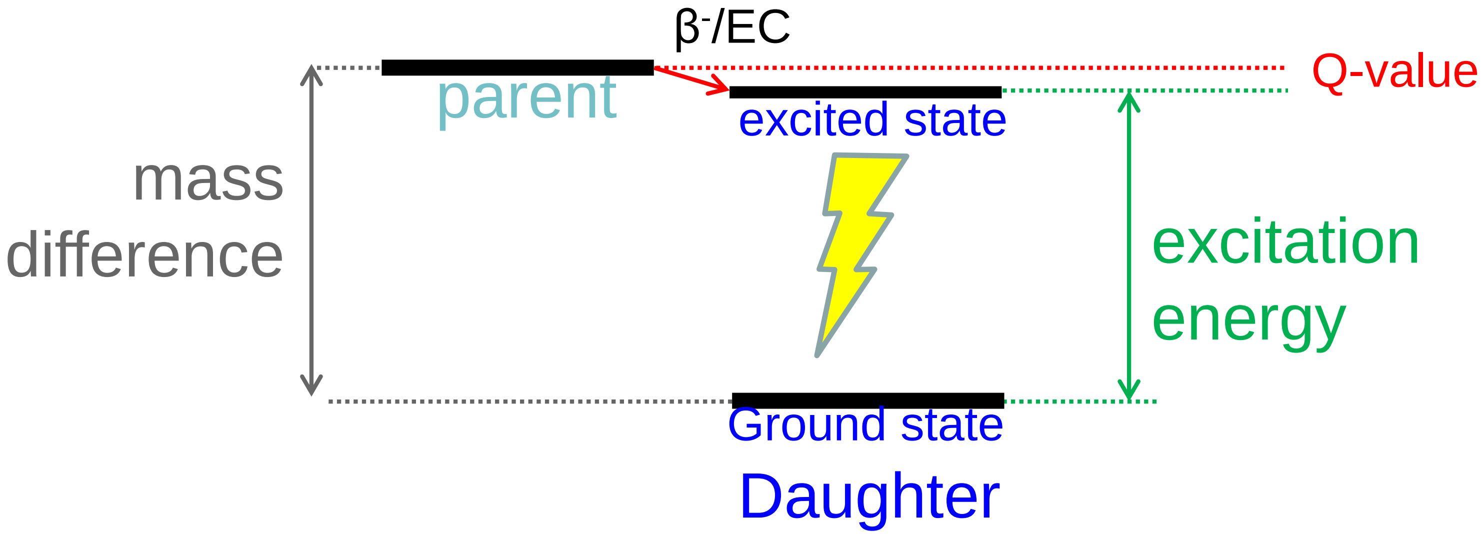


A Faessler *et al*
J. Phys. G: Nucl. Part. Phys. **42** (2015) 015108



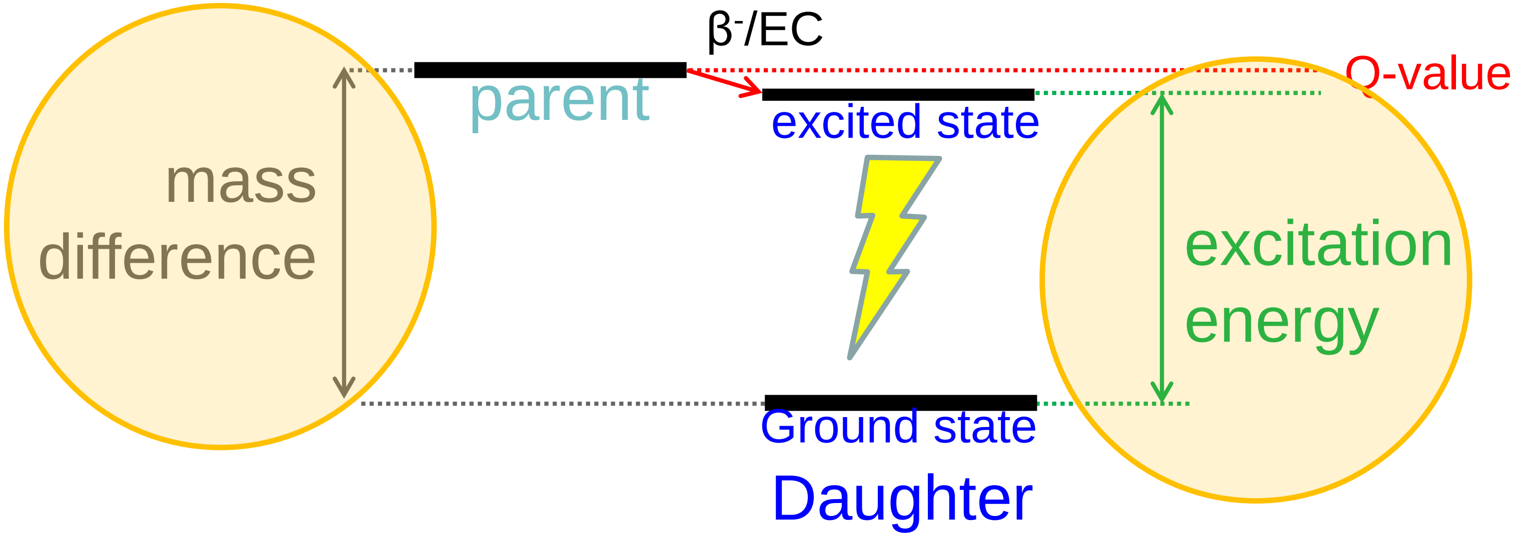
Ultralow Q-value nuclei

- Single β^- and EC capture decays
- Decay with very low Q-value to an excited state
- Bigger fraction of the Q-value in neutrino mass
- Search for ”slightly positive” Q-value



Required experimental quantities

- Parent-daughter decay Q-value – mass difference
  - From mass spectroscopy
- Daughter excited state excitation energy



β^-/EC

Q-value

parent

excited state

mass difference

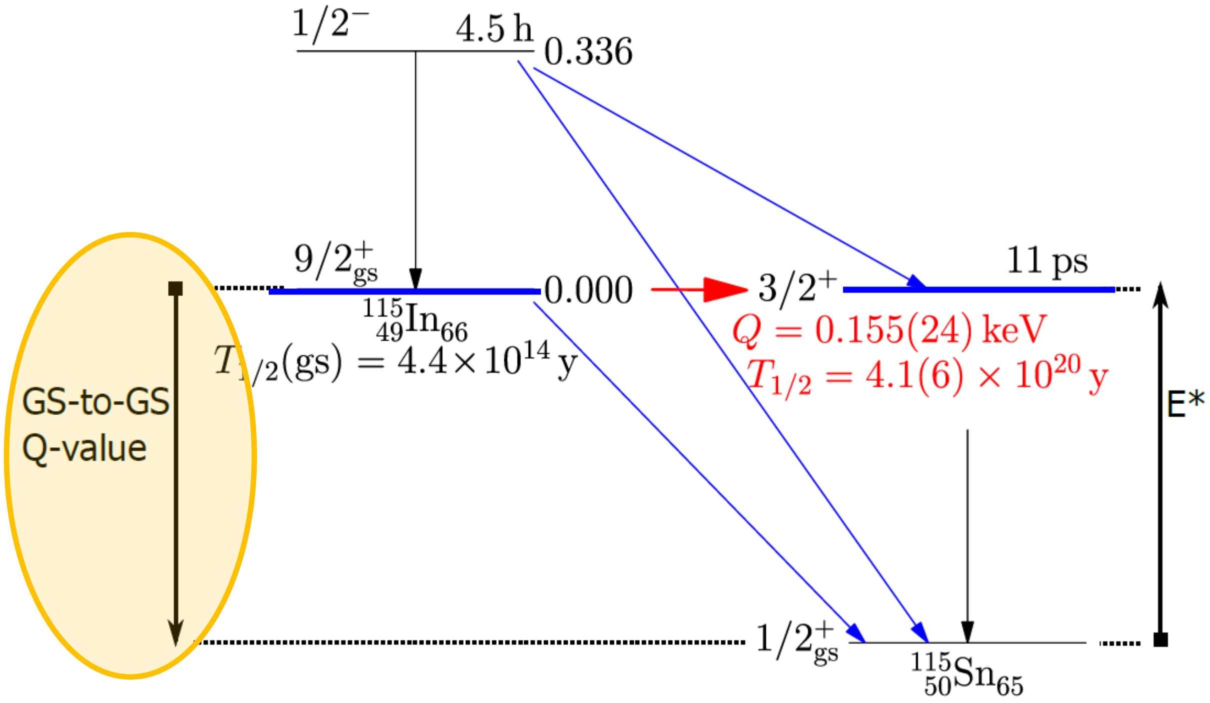
excitation energy

Ground state

Daughter

Example: ^{115}In decay

Cattadori et al. Nucl. Phys A **748,** 333 (2005)



Q-values:

JYFLTRAP 350(170) eV E. Wieslander, J. Suhonen, T. Eronen et al. PRL **103**, 122501 (2009)

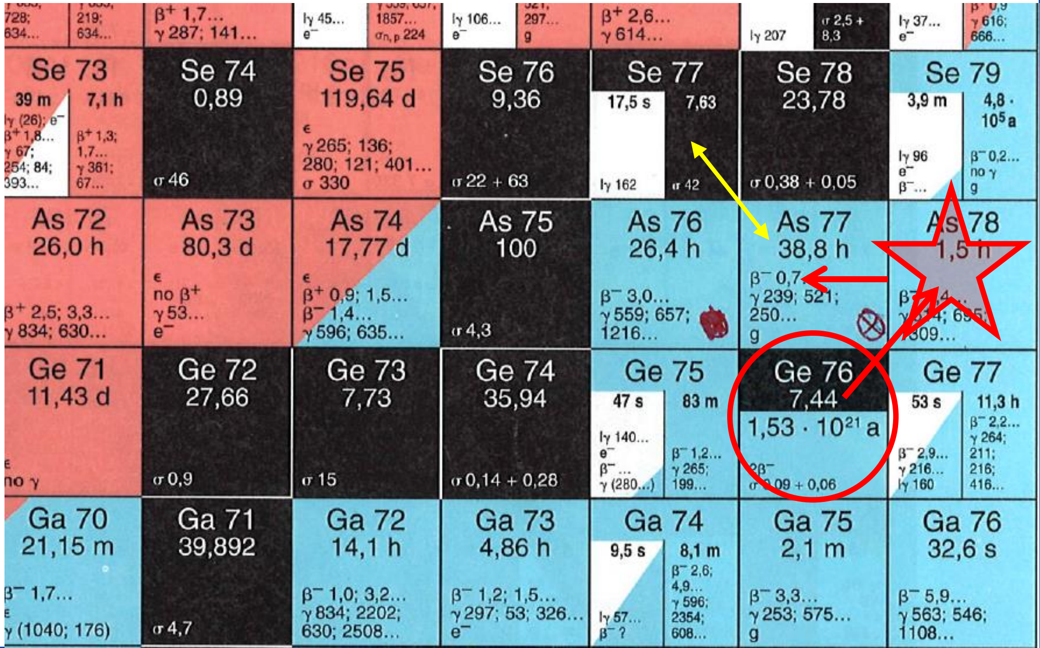
FSU-TRAP 155(24) eV B.J. Mount, M. Redshav, E.G. Myers, PRL **103**, 122502 (2009)

Precisions

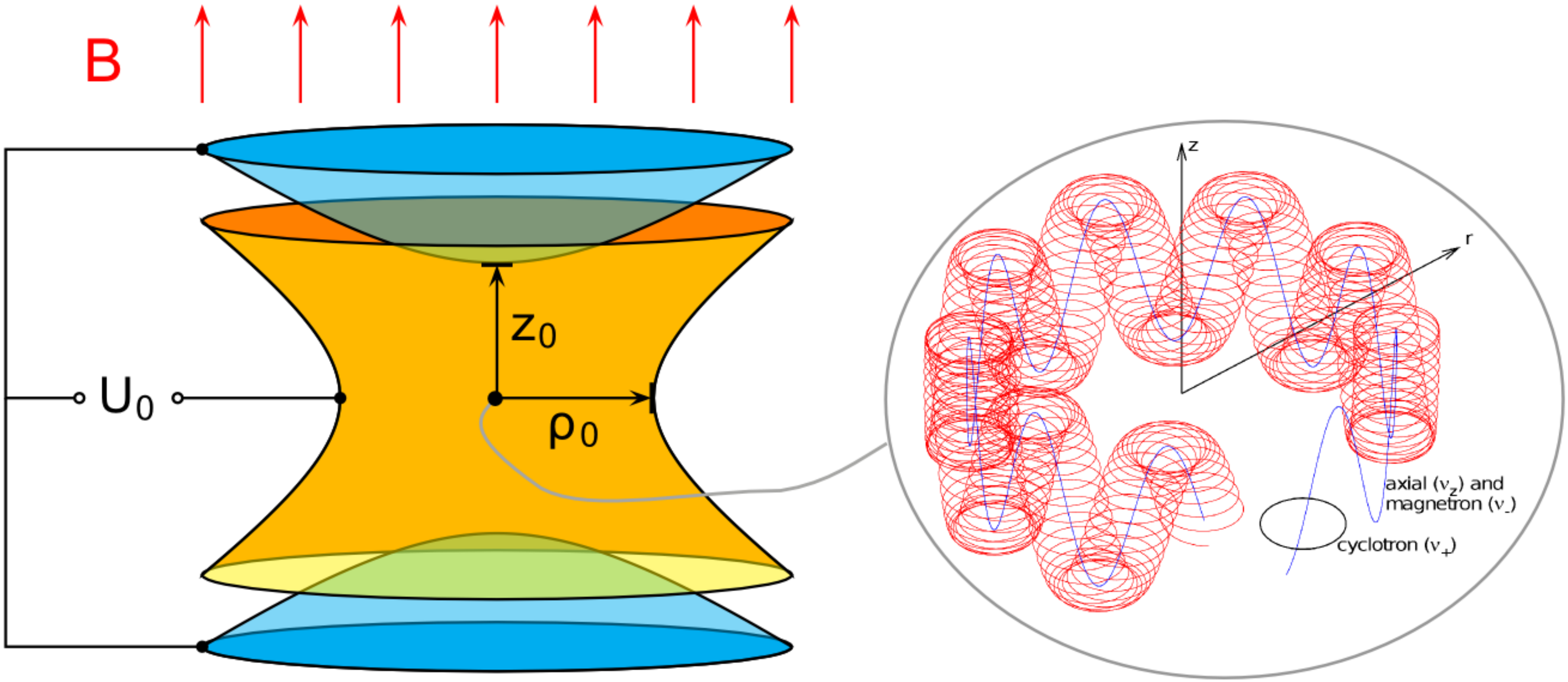
- The goal: Find ”slightly positive Q-value” cases:
- **Phase 1: Coarse selection**
  - Daughter state excitation energies < 100 eV
  - ~100 eV gs-gs precision with Penning traps (***TOF-ICR***)
- **Phase 2: Finer selection**
  - Daughter state excitation energies < 10 eV
  - ~10-50 eV gs-gs precision with Penning traps (***PI-ICR***)
- **Phase 3: Ultimate**
  - Push to eV-level with non-destructive Penning trap mass measurement techniques
  - E.g. with PENTATRAP in MPIK, Heidelberg

Parent and daughter production

- For example ^{77}As -> ^{77}Se Q-value
  - Parent: ^{76}Ge(*d*,*n*)^{77}As @ 7 MeV
  - Daughter: stable selenium exists as a contaminant
- BOTH available simultaneously



Penning trap – confining charged particles



- Three eigenmotions
  - – Axial ν_z
  - – Magnetron ν_-
  - – Modified cyclotron ν_+

$$\nu_z = \frac{1}{2\pi}\sqrt{\frac{U_0}{d^2}\frac{q}{m}}$$

$$\nu_\pm = \frac{1}{2}\left(\nu_c \pm \sqrt{\nu_c^2 - 2\nu_z^2}\right)$$

Free-space cyclotron frequency

- Mass measurements through

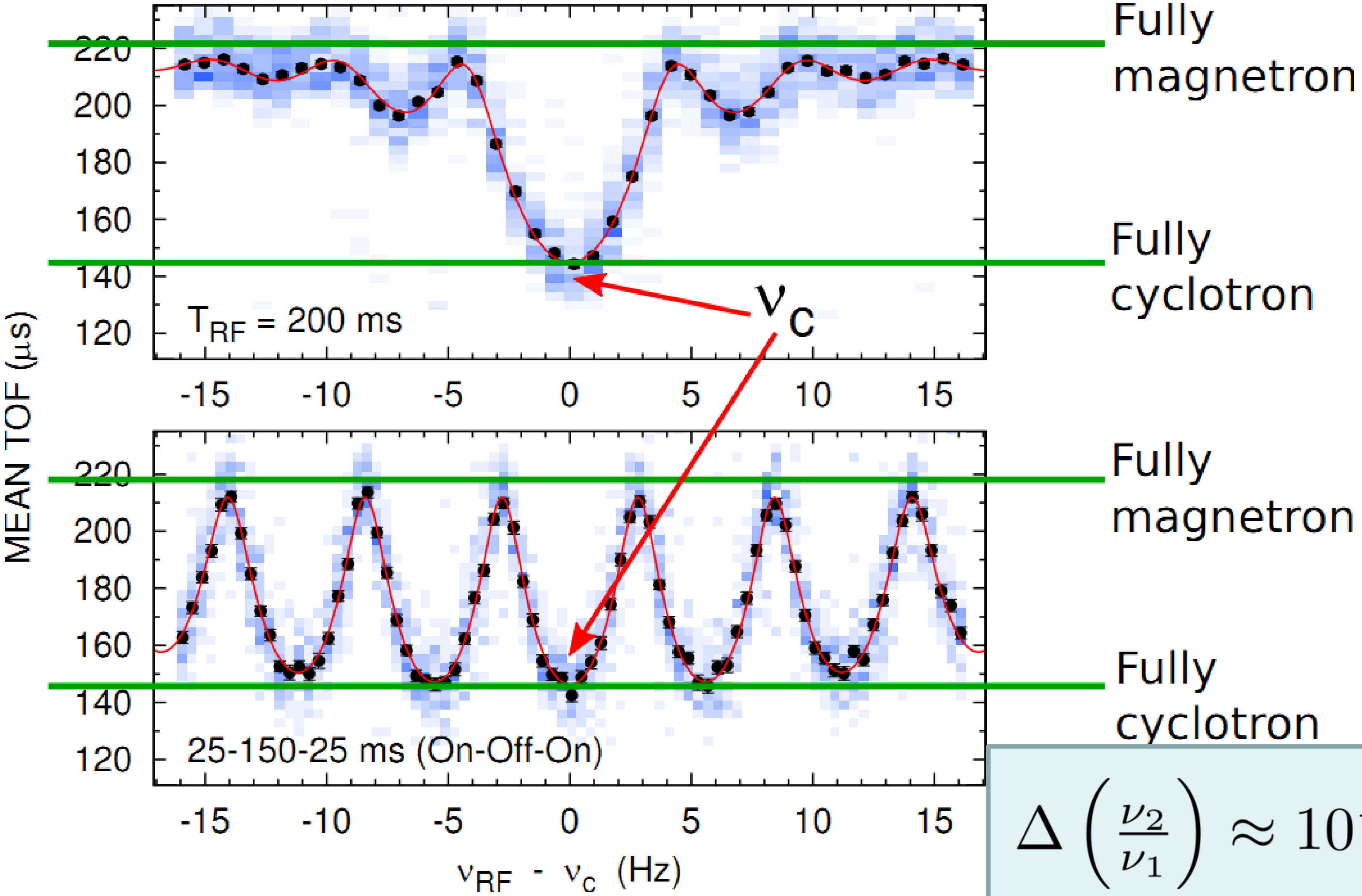
$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

SIDEBAND FREQUENCY: $\nu_c = \nu_- + \nu_+$

G. Gabrielse, Int. J. Mass. Spec. 279 (2009) 107–112

Time-of-flight ion cyclotron resonance (TOF-ICR) method for mass measurements

Example resonances,



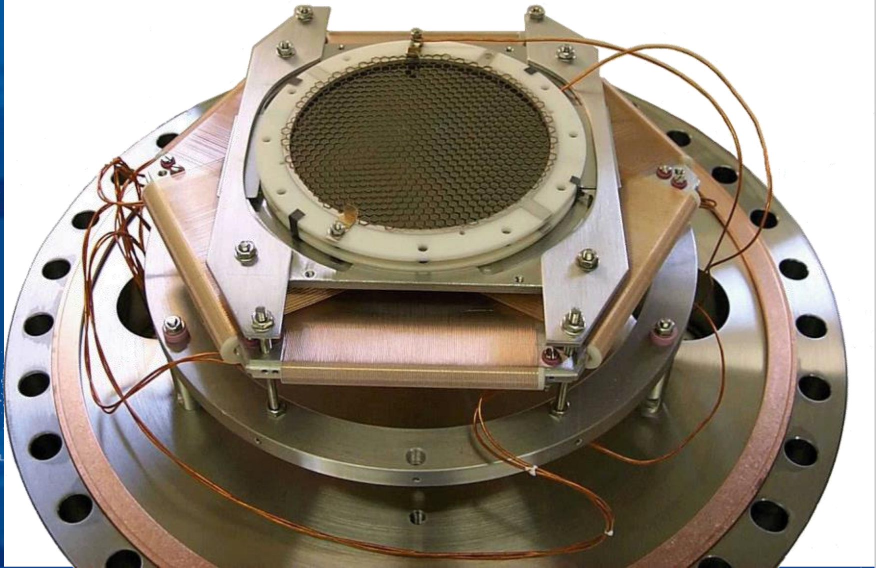
$$\Delta\left(\frac{\nu_2}{\nu_1}\right) \approx 10^{-9}$$

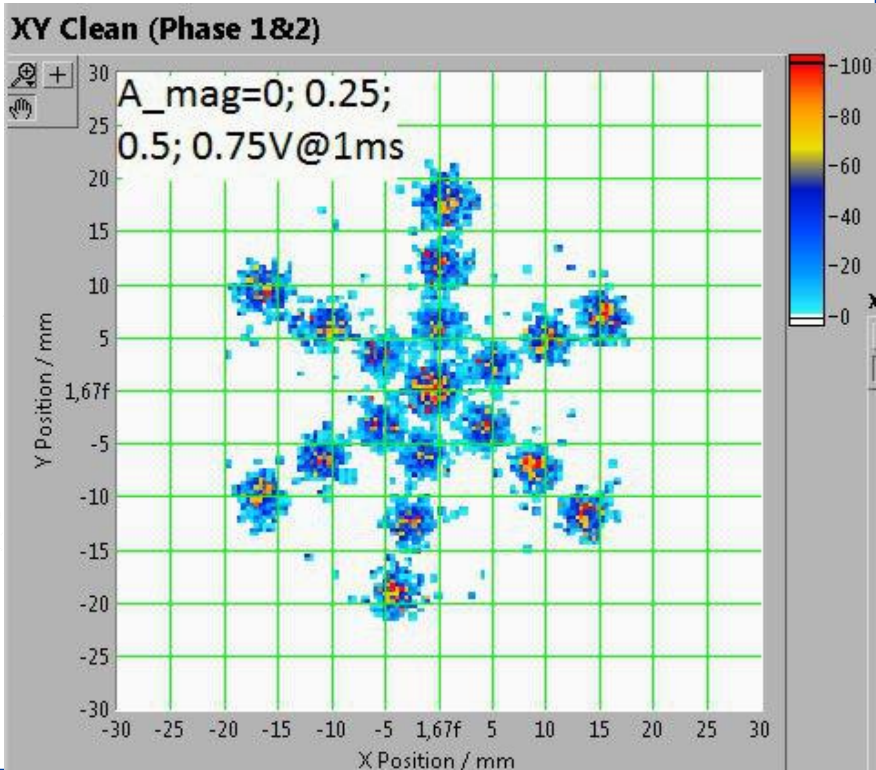
Phase imaging ion cyclotron resonance (PI-ICR) method

for mass measurements

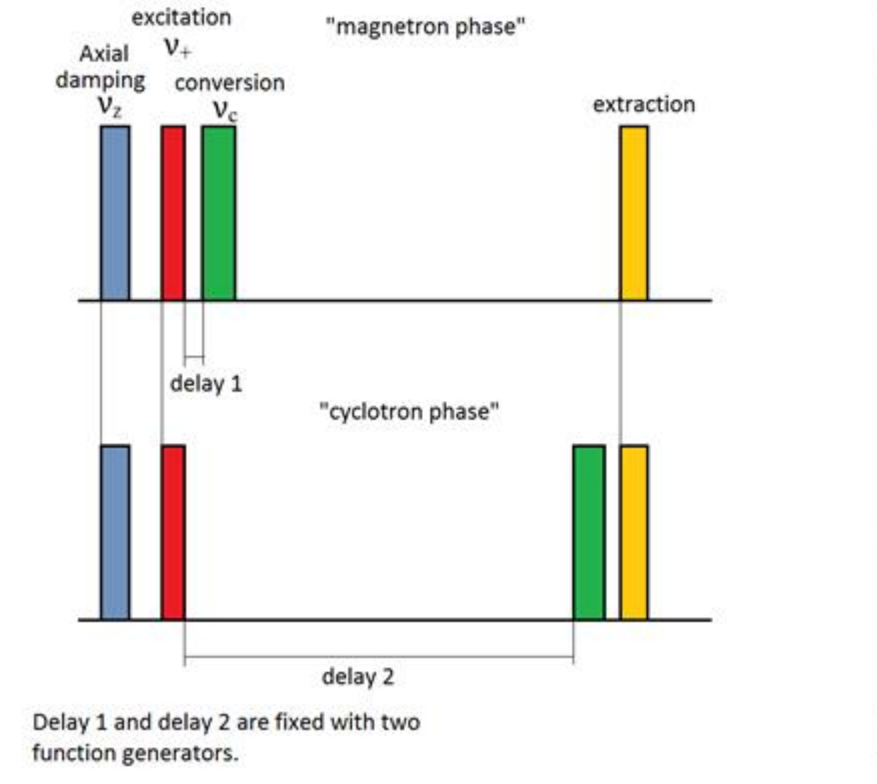
PI-ICR method

- Novel Penning trap mass measurement technique
- Developed by Sergey Eliseev, MPIK Heidelberg at SHIPTRAP GSI
- Faster by 40x

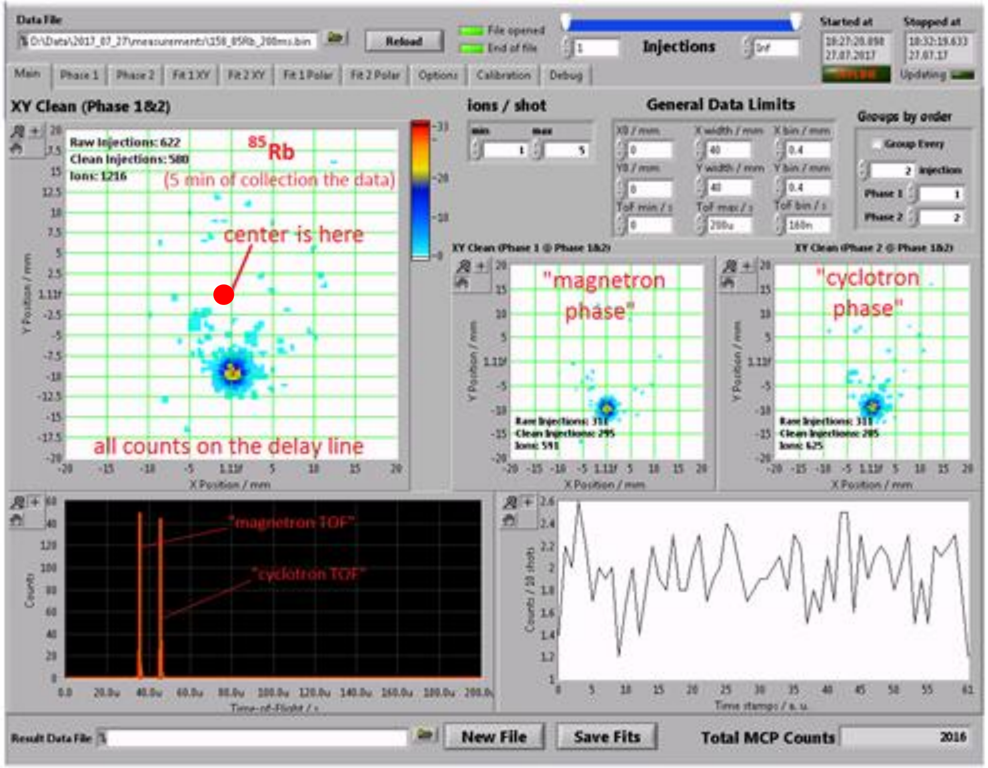




PI-ICR scheme for mass measurements



Delay 1 and delay 2 are fixed with two function generators.



Data File: D:\Data\2017_07_27\measurements\158_85Rb_200ms.bin

Started at: 18:27:20.898 27.07.2017

Stopped at: 18:32:19.633 27.07.17

Raw Injections: 622
Clean Injections: 580
Ions: 1216

ions / shot: min 1, max 5

X0 / mm: 0; X width / mm: 40; X bin / mm: 0.4
Y0 / mm: 0; Y width / mm: 40; Y bin / mm: 0.4
ToF min / s: 0; ToF max / s: 200u; ToF bin / s: 160n

Group Every 2 injection
Phase 1: 1
Phase 2: 2

Total MCP Counts: 2016

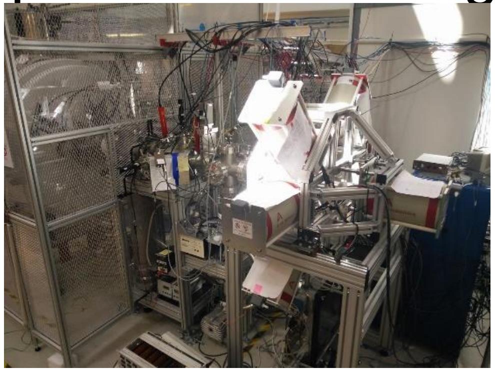
PI-ICR results

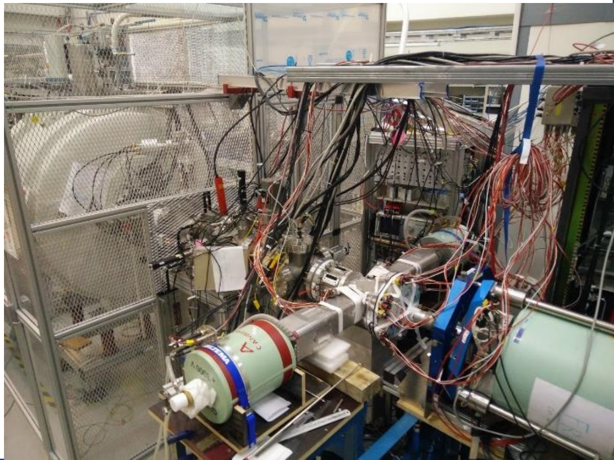
- SHIPTRAP at GSI: **^{163}Ho-^{163}Dy** Q-value with uncertainty $30_{stat} + 15_{syst}$ eV
  - Eliseev et al., PRL 115, 062501 (2015)
- JYFLTRAP test measurement **^{85}Rb-^{87}Rb**
  - 52 eV precision (preliminary, to be tightened)
  - This is better than 10^{-9} !

In general: few ten eV precision available (few x 10^{-10} frequency ratio precision)

Post-trap decay spectroscopy

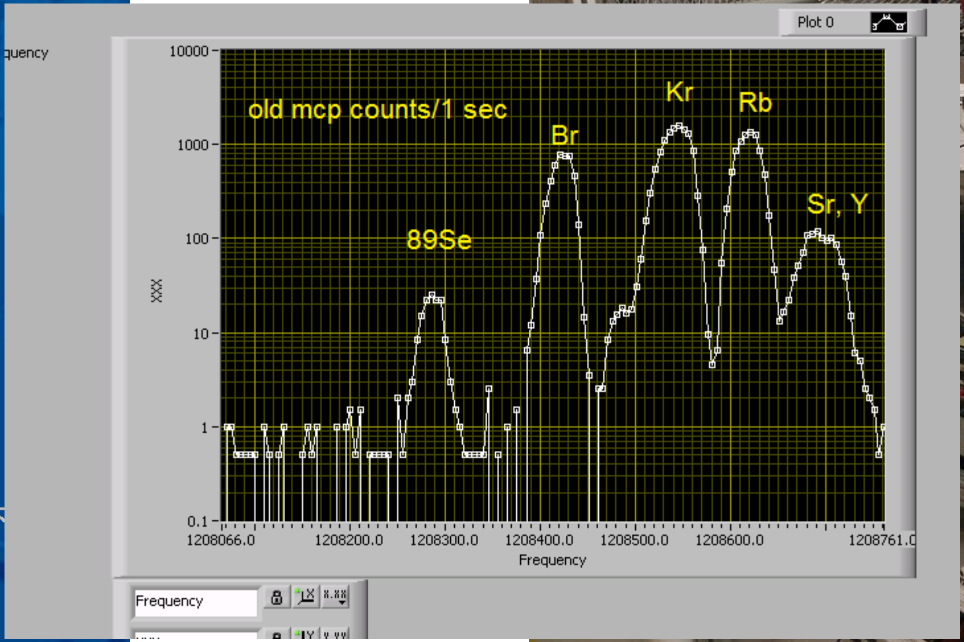
- JYFLTRAP used for several decay spec experiments to provide monoisotopic/-meric beam
- Using purification trap (*R* up to 10^5)
- Ramsey cleaning (*R* > 10^6)
  - Not always so suitable for decay spec
    - If too small wanted/unwanted ratio
    - Recooling in trap1 wastes time
- ***New:*** Phase-dependent cleaning

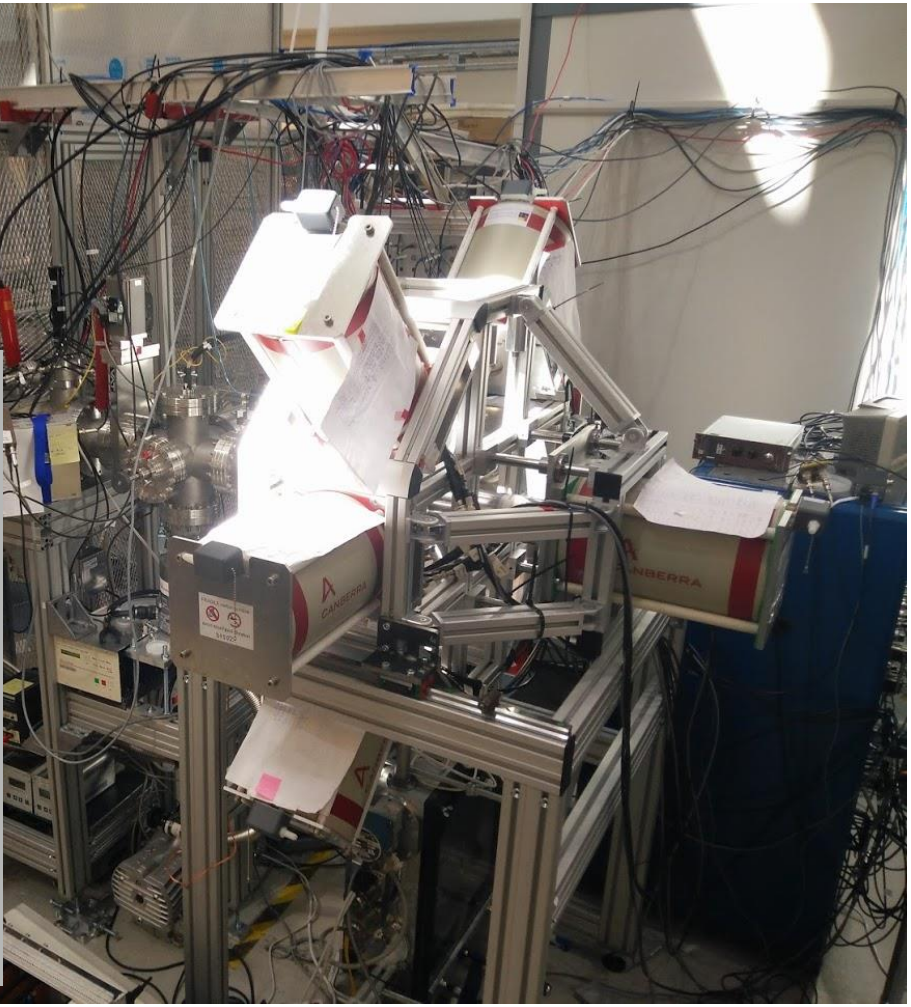




University of Warsaw Ge array

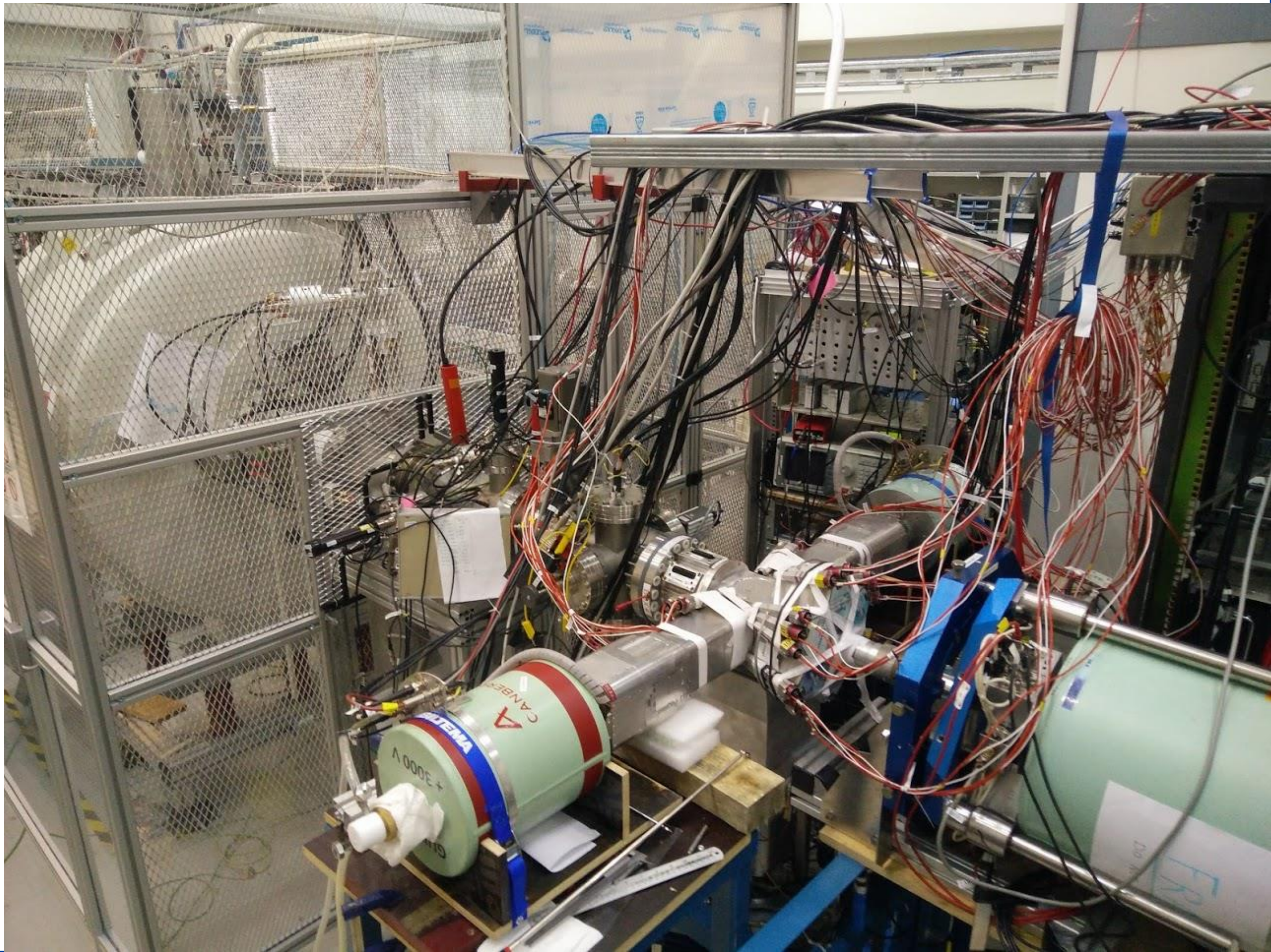
- ^{89}Se
- July-17





TASISPEC at JYFL 2017

- ^{127}Cd
- Aug-17



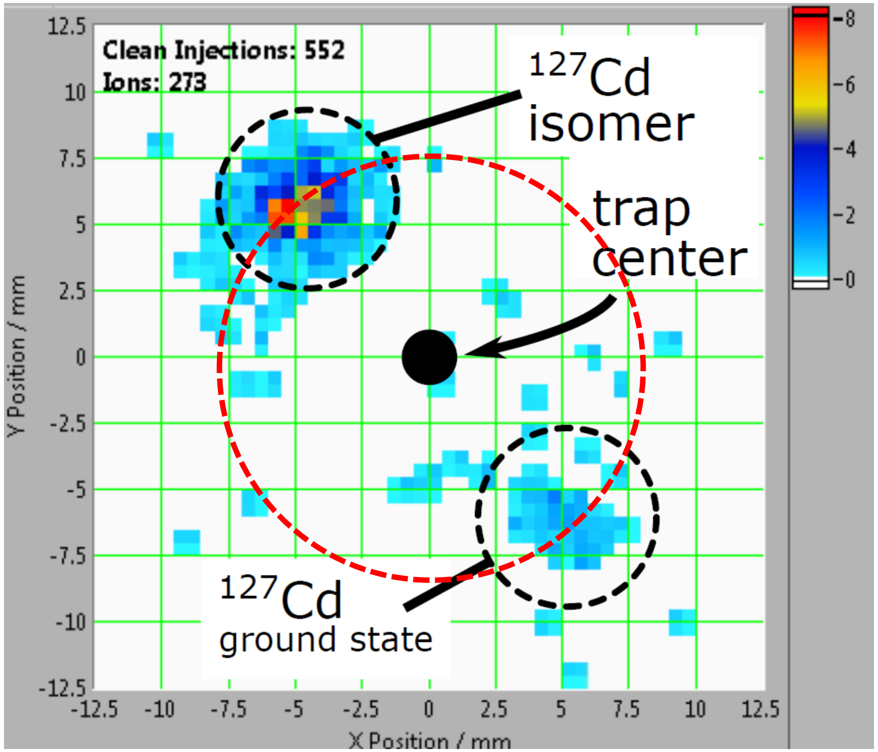
Future post-trap decay spectroscopy

- MR-TOF + Penning trap
  - Preparation of “big” bunches
  - E.g. superallowed beta decay $T_{1/2}$ and BR
- Phase-dependent cleaning
  - Separation of ~50 keV isomers
  - Commissioning on-going

Phase dependent cleaning

- Isomerically clean beams available with unprecedented resolving power!
- Phase-sensitive cleaning
  - For A/q = 100
  - 50 keV isomer
  - 45 deg phase difference
  - Need 200 ms
  - $\frac{M}{\Delta M} \approx 2 \times 10^6$

250 ms



g.s. of ^{127}Cd delivered to TASISPEC

Final remarks

- JYFLTRAP has a very comprehensive physics program
- Mass measurements
  - Astrophysics
  - Fundamental physics
  - Nuclear structure
- Post-trap spectroscopy
  - Integral part of activities
  - Collaboration with many outside groups

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JYFL theory:
J. Dobaczewski, J. Suhonen

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WWU MÜNSTER
UPPSALA UNIVERSITET
UNIVERSITY OF LIVERPOOL

Thank you for your attention!

http://research.jyu.fi/igisol