Status the Canadian Penning Trap Mass Spectrometer

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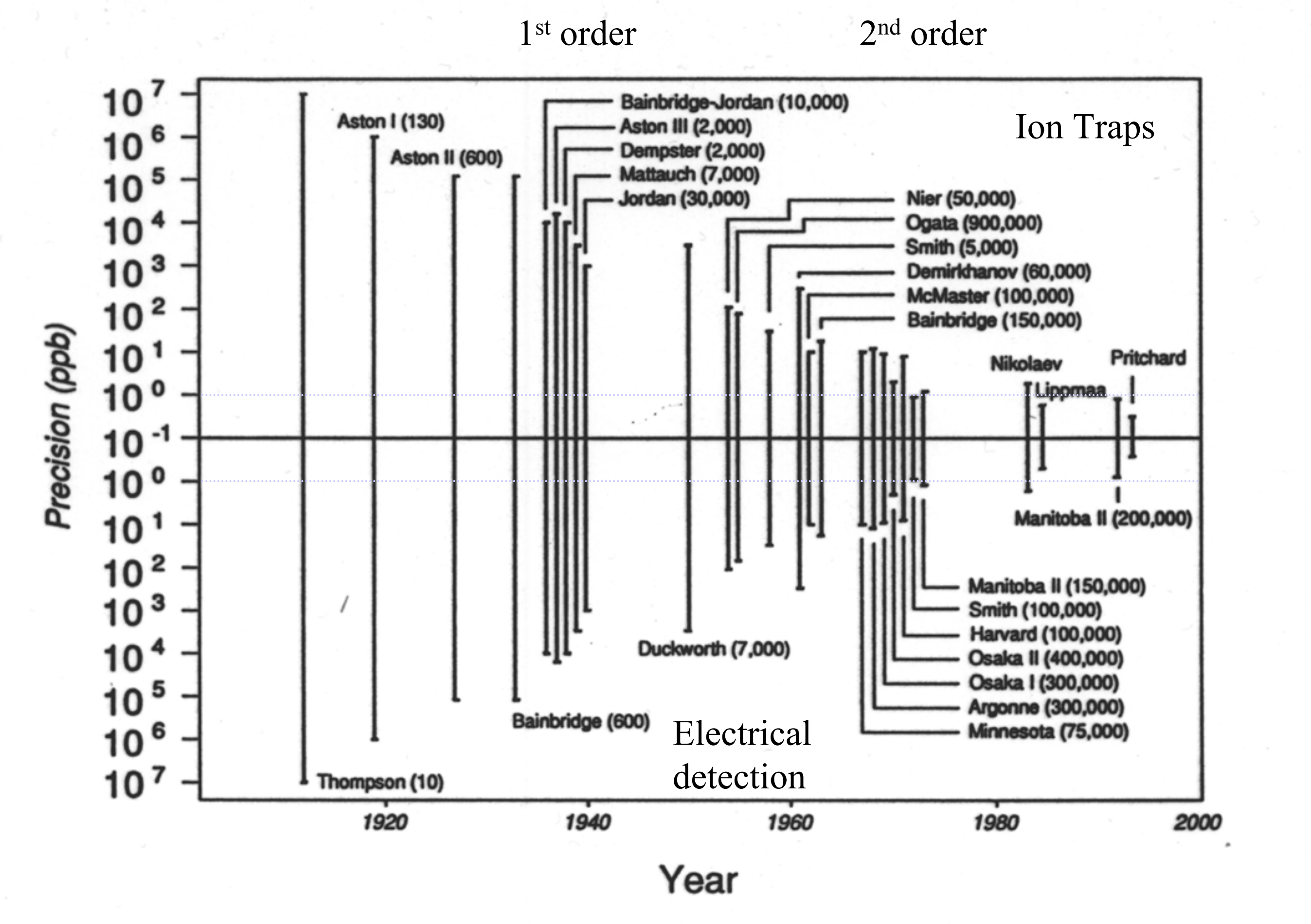
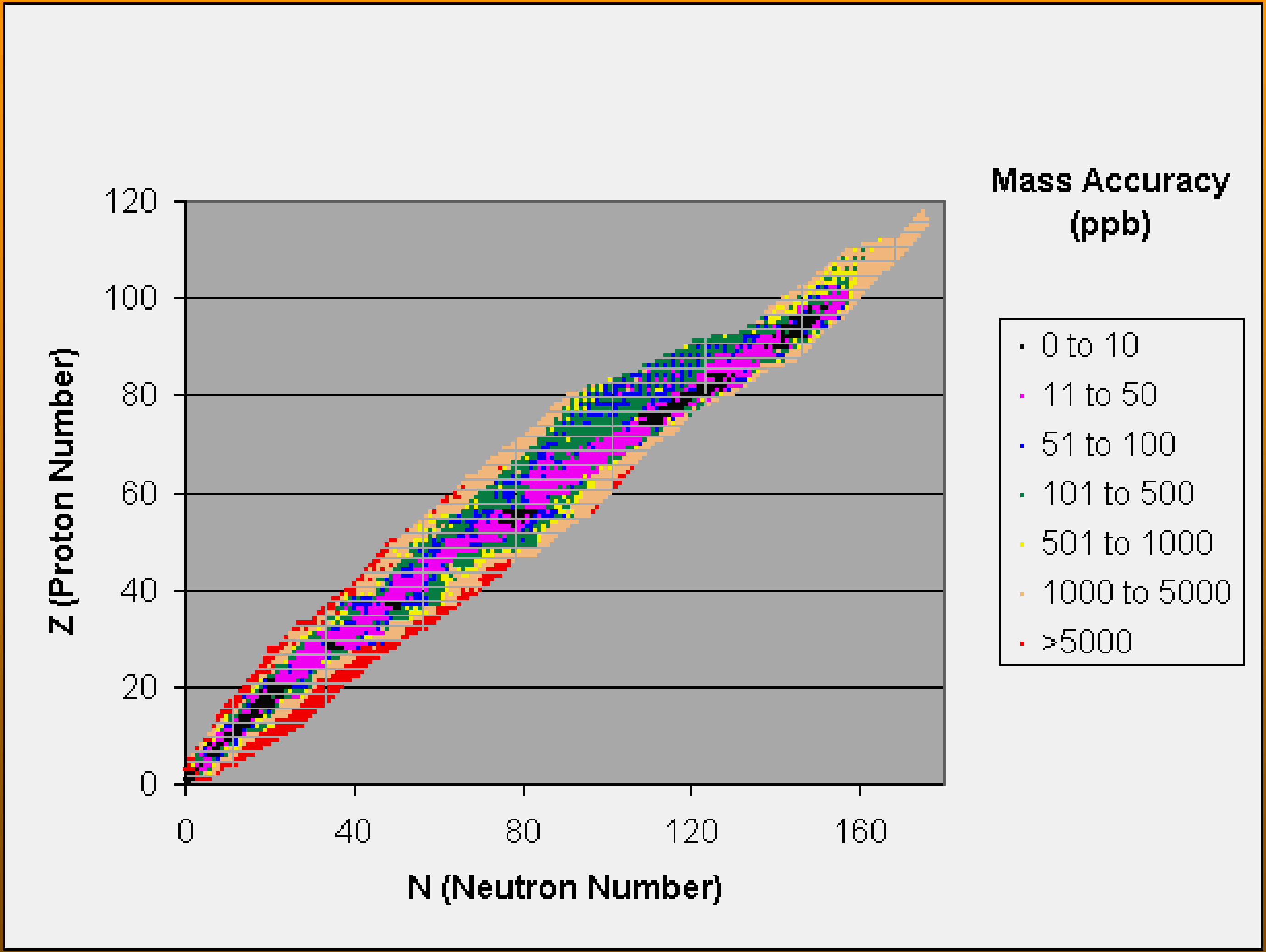
Outline

- Status of Atomic masses
- The instrument
- Some results
- Conclusion
- Cast of players

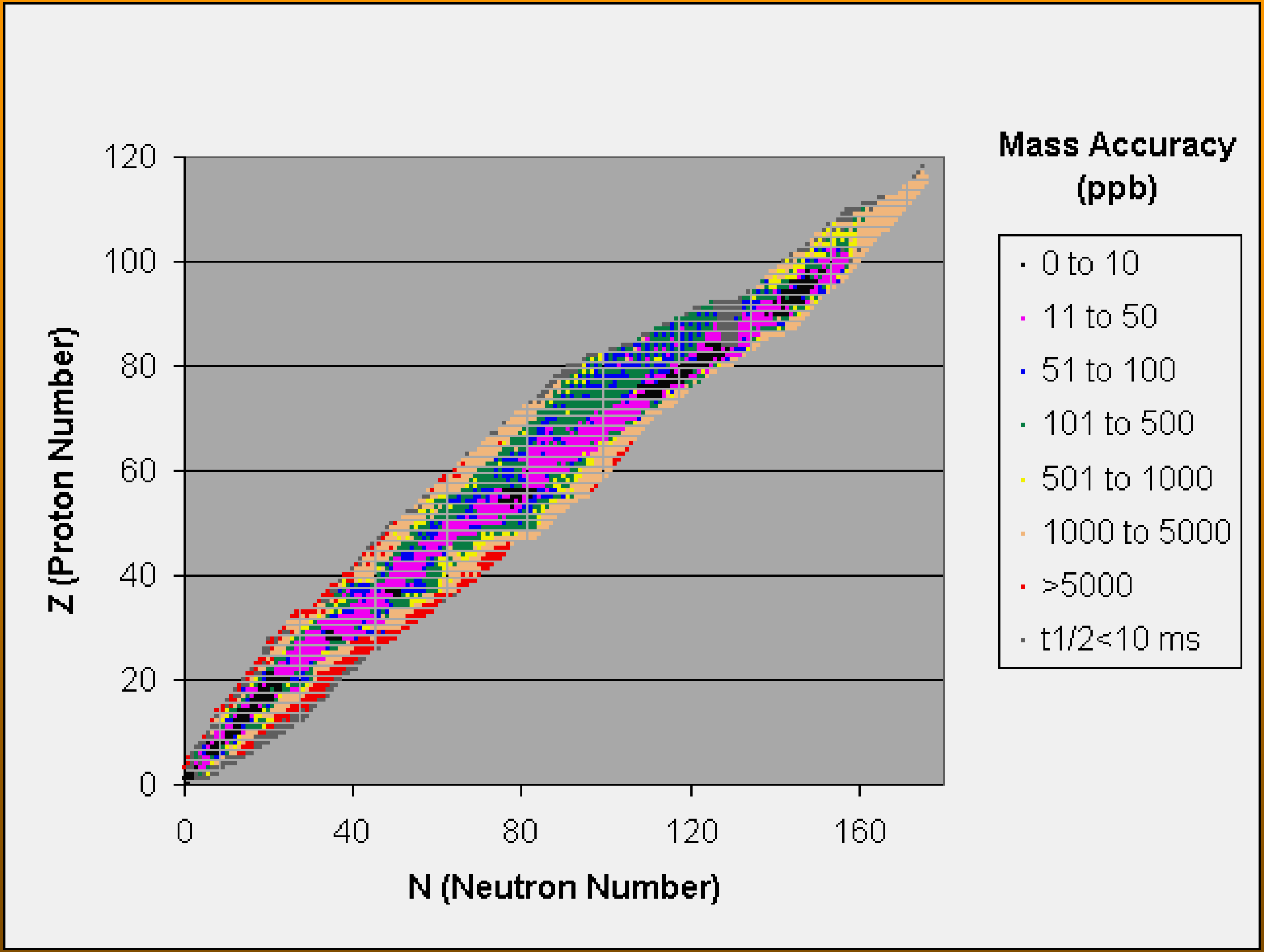
Evolution of precision



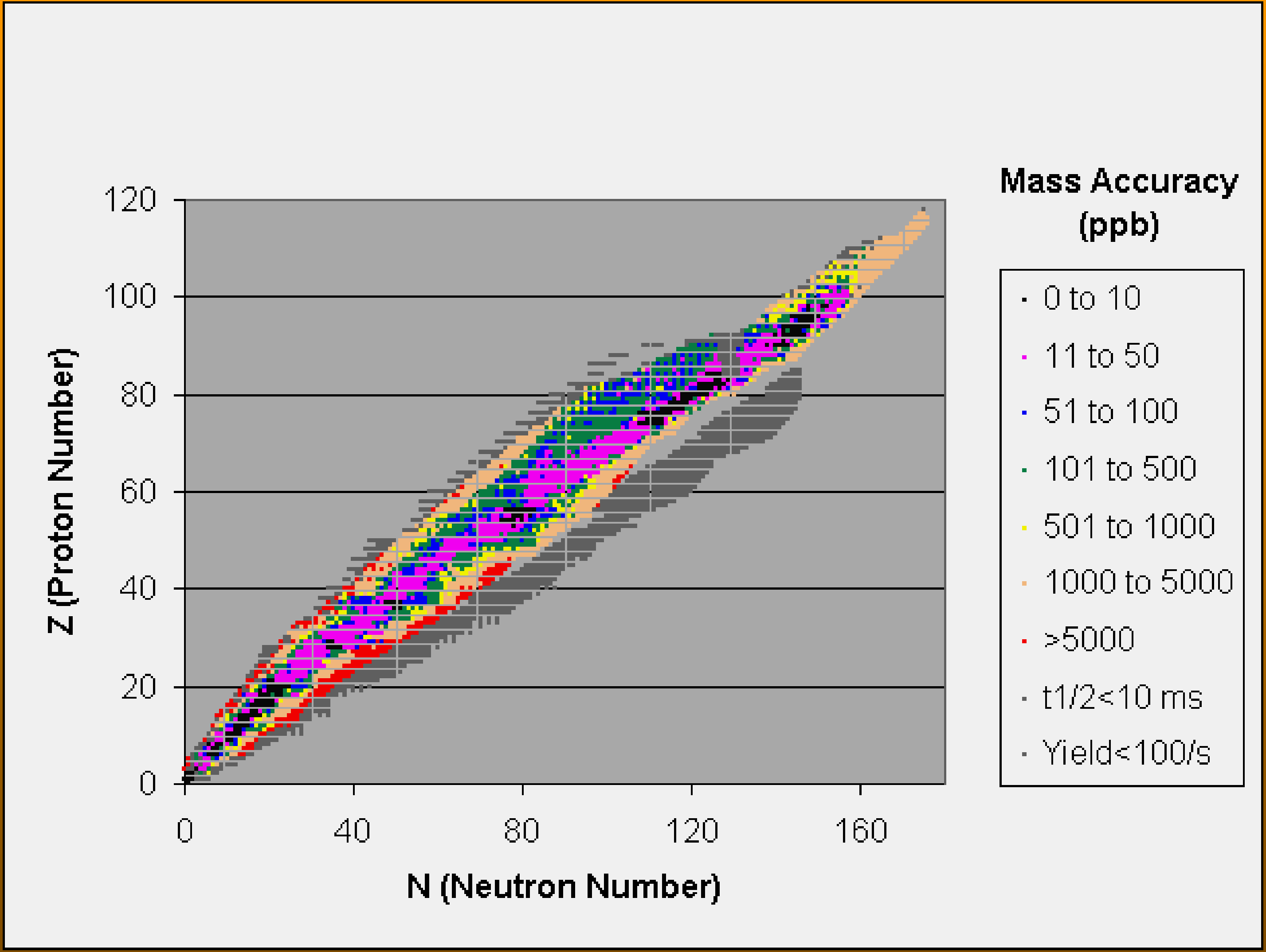
Precision of masses in AME03



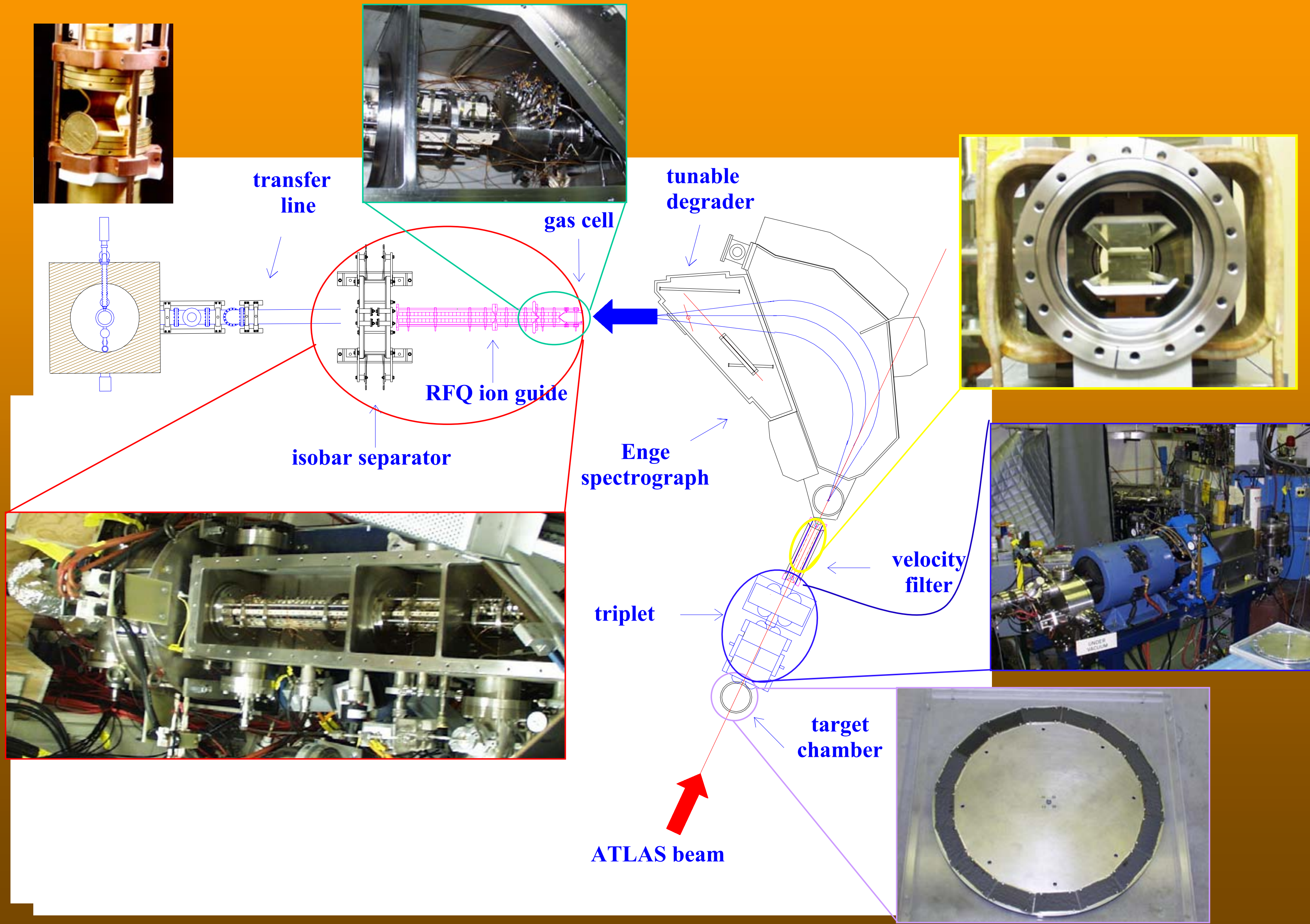
Half-life allowed



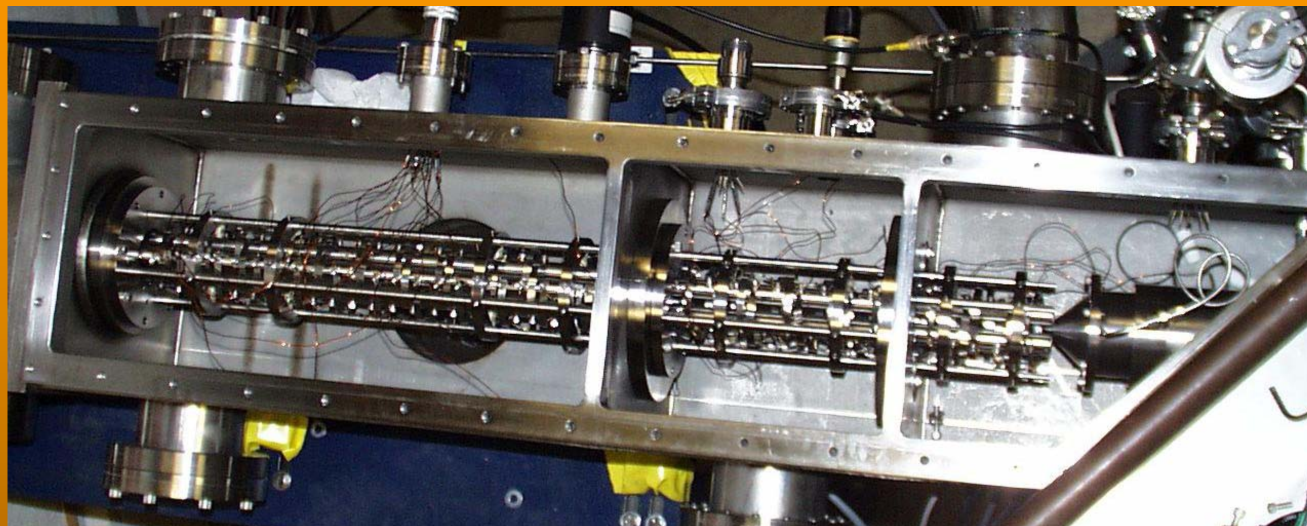
Half-life and rate allowed

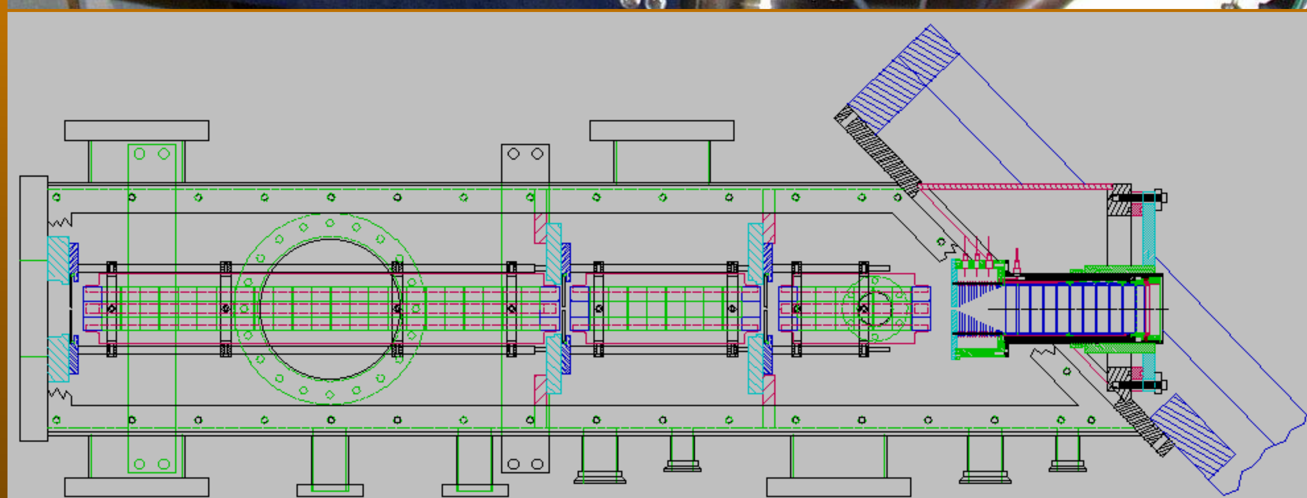


Overview of the CPT apparatus at ANL

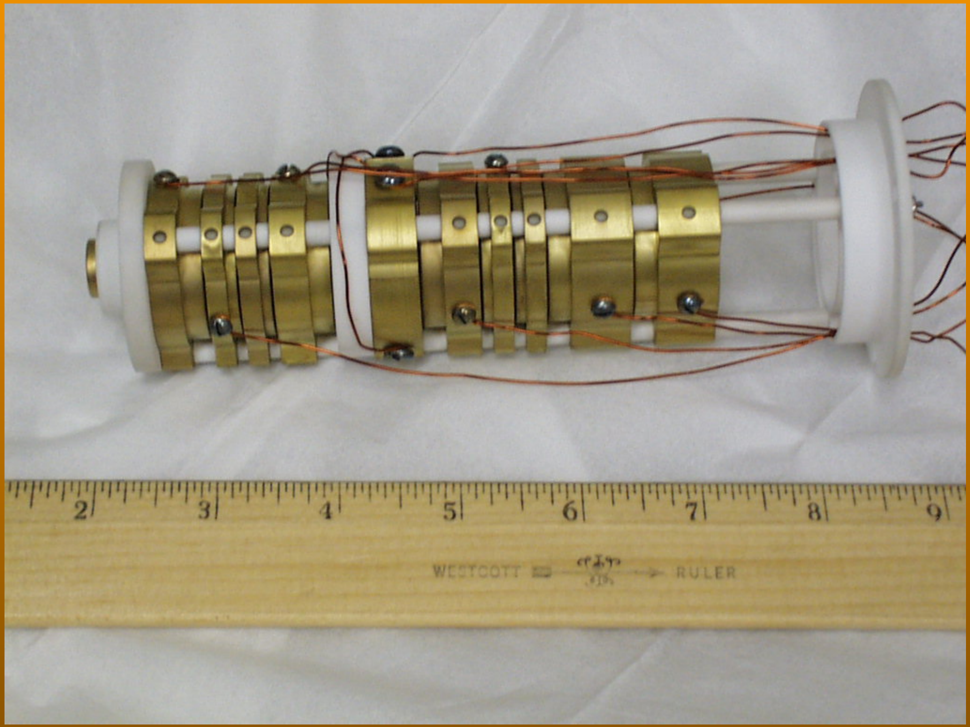


The gas catcher system



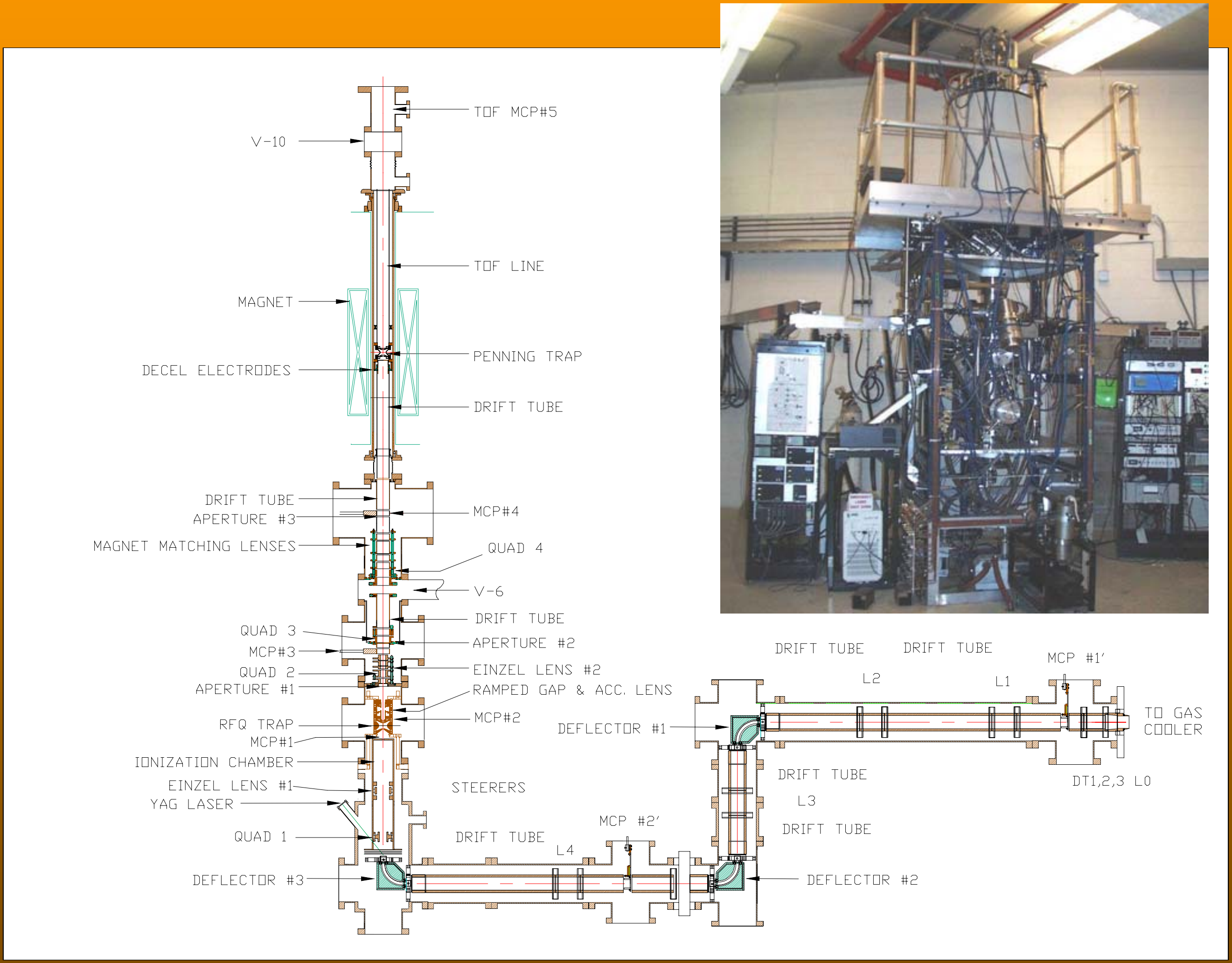


The “isotope separator”

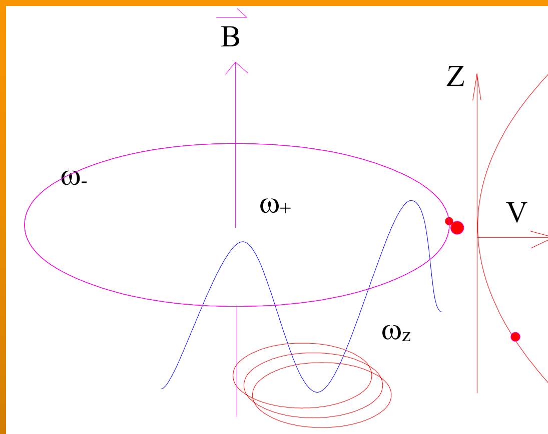


- B = 1 T
- Cylindrical Penning trap
- Gas filled
- Use ω_c quadrupole excitation to centre, cool and select ions.
- Resolving power ~800

The CPT Spectrometer



Ion motions in a Penning Trap



Three independent eigenmotions in a Penning trap:

- Modified cyclotron motion
- Magnetron motion
- Axial motion

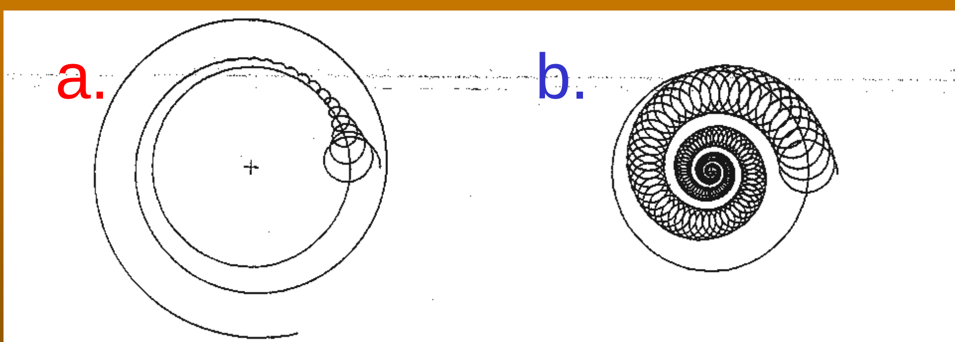


Fig. 1. Runge–Kutta integration of the equations of motion (including a damping force proportional to velocity) in a plane perpendicular to the magnetic field for an ion in a Penning trap. The cross represents the center of the trap, the circle the initial magnetron radius. On the left, a fast damping of the cyclotron motion and a slow blow up of the magnetron motion are observed. On the right, the effect of an additional resonant quadrupole field at ω_c is shown. Both cyclotron and magnetron radii are decreased.

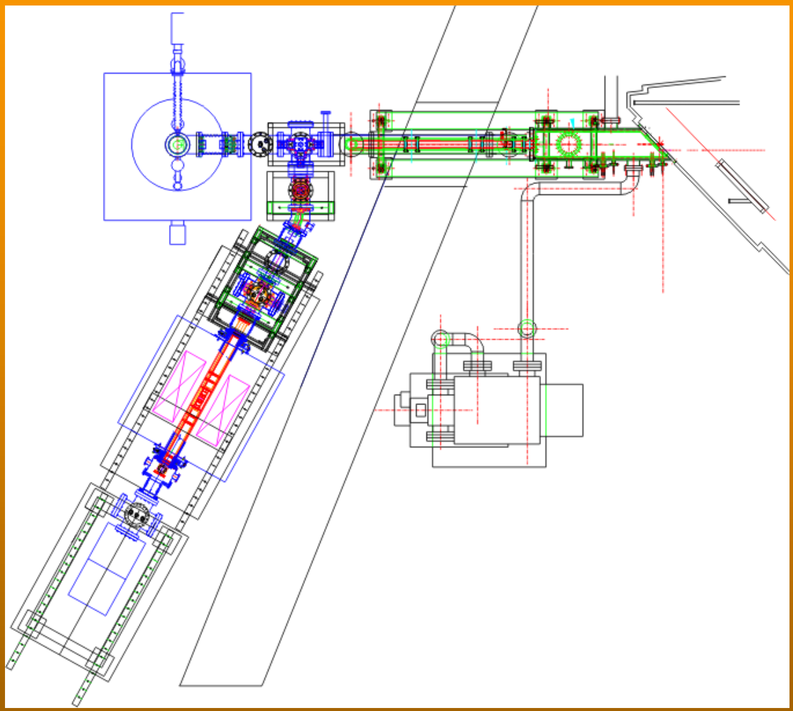
G. Savard et al, Phys. Lett. A158 (1991) 247

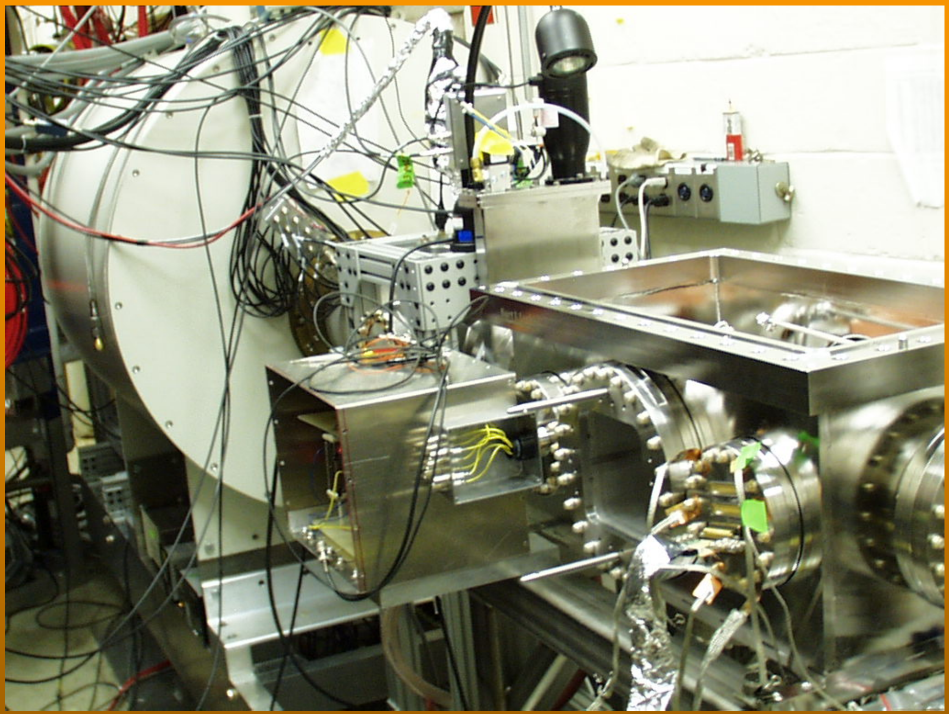
Mass Selective cooling and centering of ion motion when damped by the presence of buffer gas:

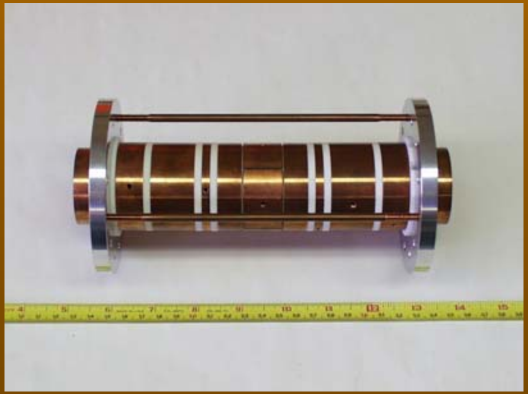
a. With no excitation applied

b. With the application of a quadrupole excitation at the cyclotron frequency

A new isotope separator – The APT

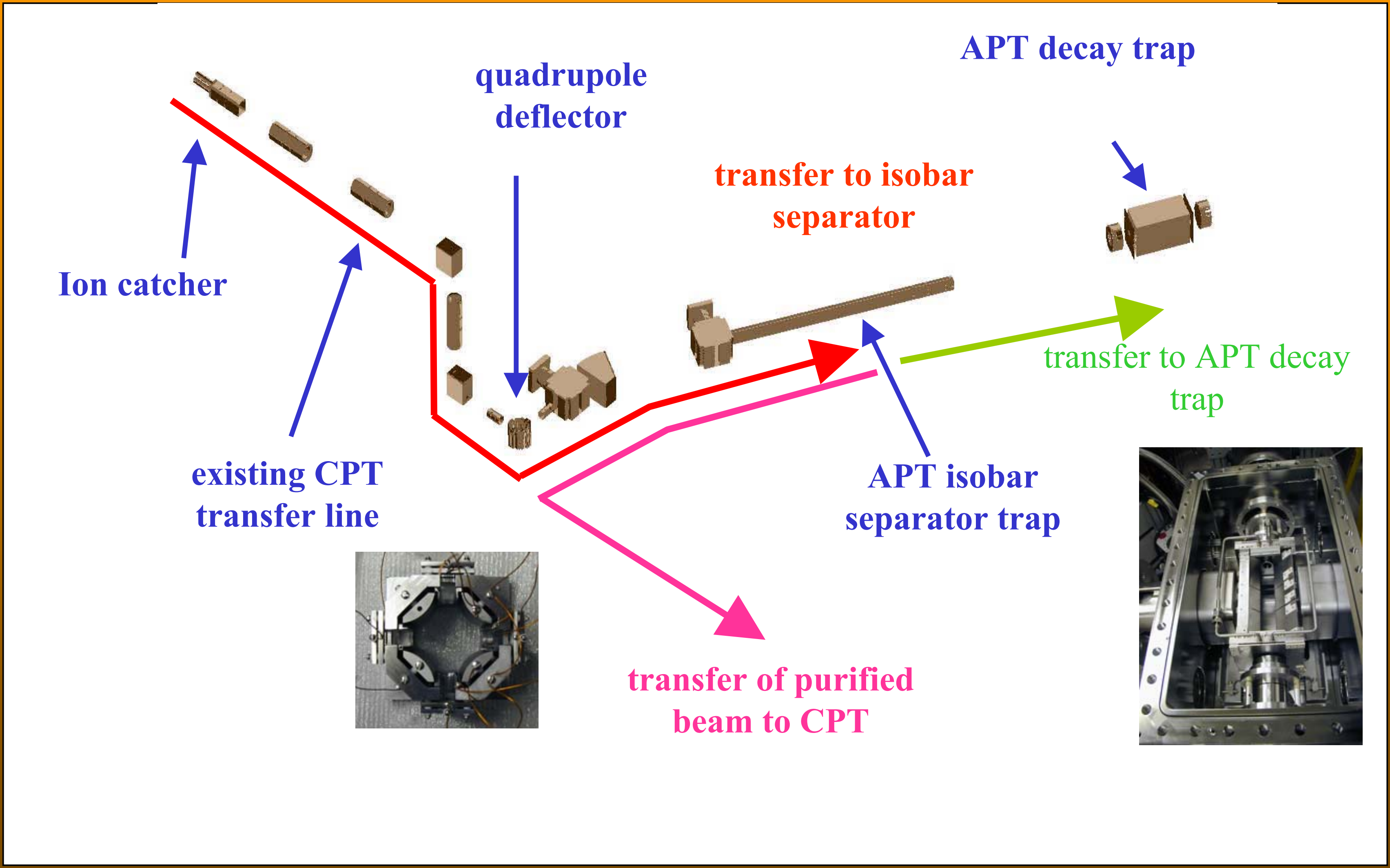




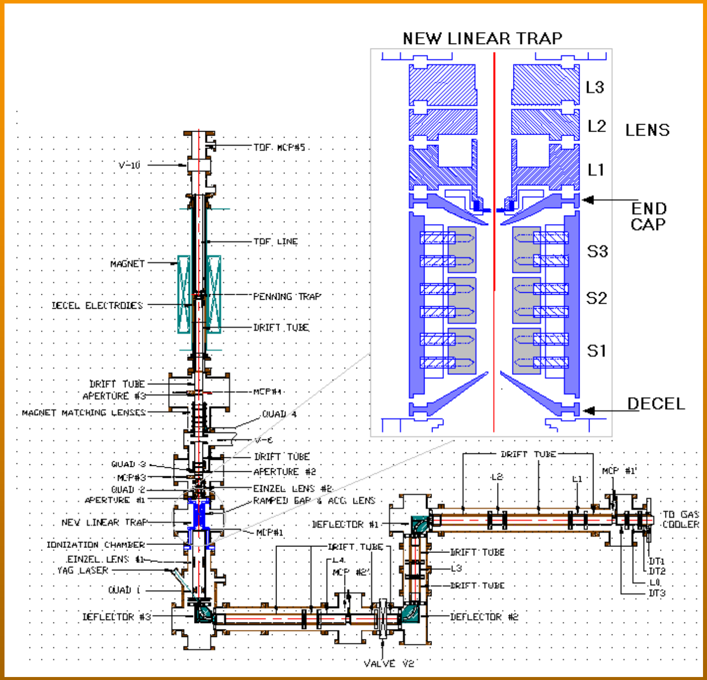


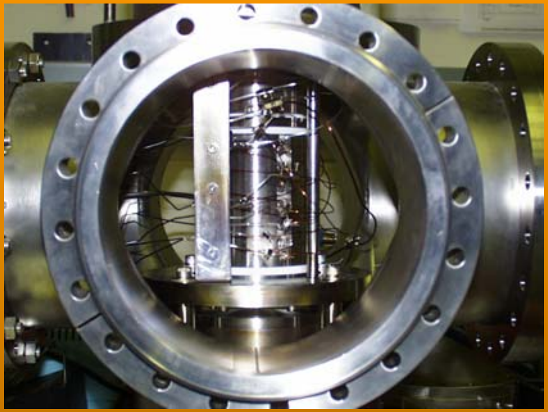
- Superconducting magnet, B = 7 Tesla – higher resolving power
- Magnetic field stability and uniformity $<10^{-7}$
- Expected max. resolving power of 10^5

The APT/CPT Shared Beamline



The accumulation RFQ trap

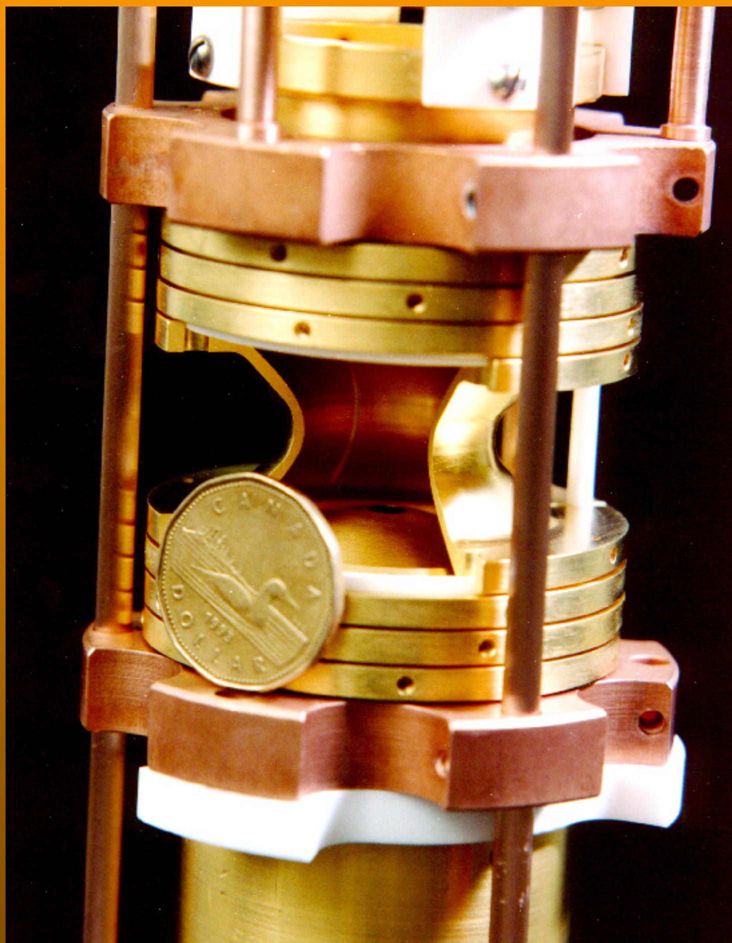




A "linear" RFQ trap provides:

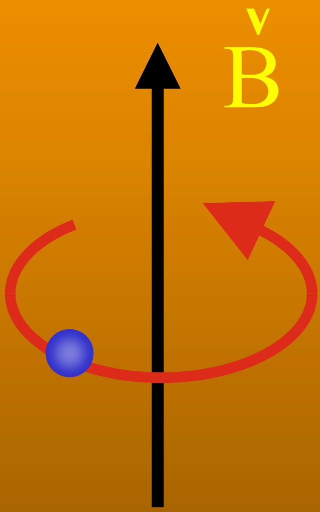
- Ease of operation and construction
- Better capture parameters
- Lower energy spreads for extracted ions

The anatomy of a Penning trap



- Shapes of the electrodes
- Correction electrodes
- Carefully chosen materials

How a Penning Trap works-1

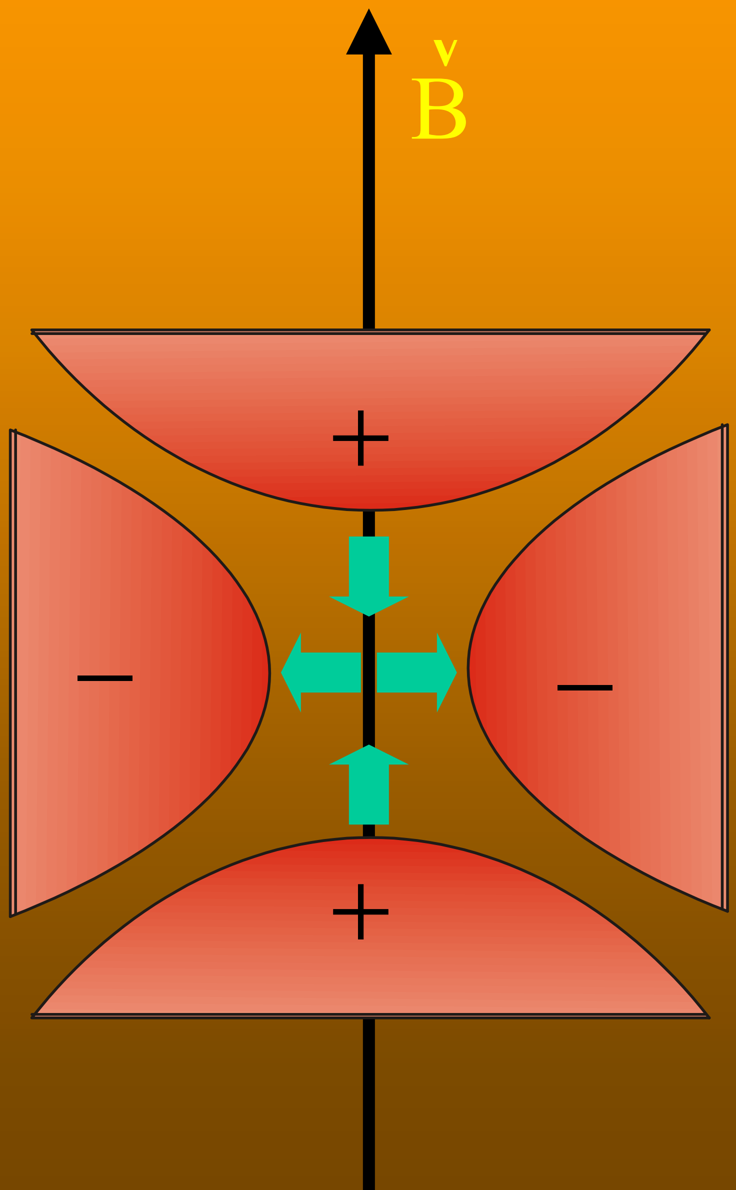


- **Constant axial magnetic field**
- **particle orbits in horizontal plane**

$$\omega_c = \frac{qB}{m}$$

- **free to escape axially**

How a Penning Trap works-2



- Add an axial harmonic electric field to confine particles

- axial oscillations:

$$\omega_z = \sqrt{\frac{eV}{md^2}}$$

- Radial motion split into two components by electric field:

→ ω_+ : reduced cyclotron freq.

→ ω_-: magnetron frequency

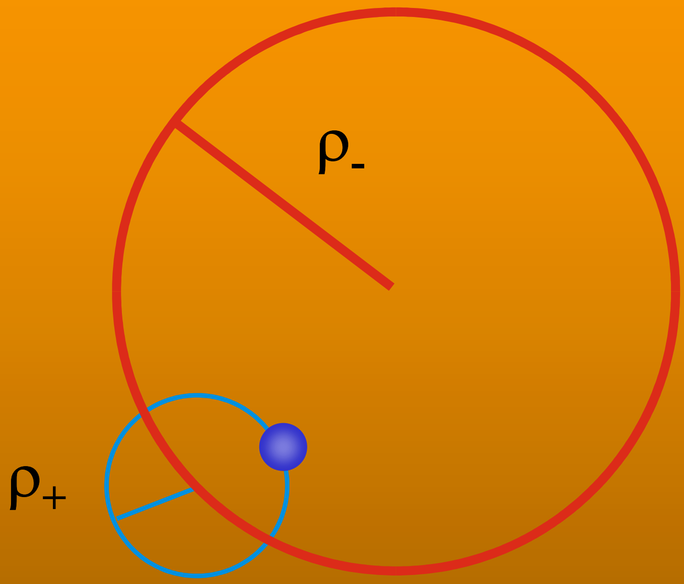
How a Penning Trap works-3

Where:

$$\omega_c^2 = \omega_+^2 + \omega_-^2 + \omega_z^2$$

and

$$\omega_c = \omega_+ + \omega_-$$



Ion motion in the radial plane:

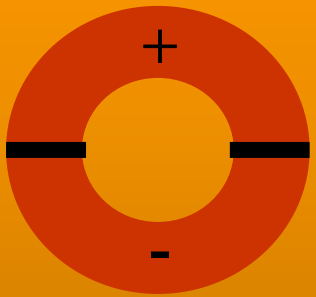
$$v_x = -\rho_+\omega_+ \sin(\omega_+ t) - \rho_-\omega_- \sin(\omega_- t)$$

$$v_y = \rho_+\omega_+ \cos(\omega_+ t) + \rho_-\omega_- \cos(\omega_- t)$$

Power absorbed by ion in electric field: $P = q\vec{v} \cdot \vec{E}$

How a Penning Trap works-4

For a dipole field: $E_y = E_0 \sin(\omega_d t)$



Power absorbed: $P = q\vec{v} \cdot \vec{E}$

$$= -qE_0 \sin(\omega_D t)[\rho_+ \omega_+ \sin(\omega_+ t)$$

$$+ \rho_- \omega_- \sin(\omega_- t)]$$

Resonances at $\omega_D = \omega_+$ and ω_-

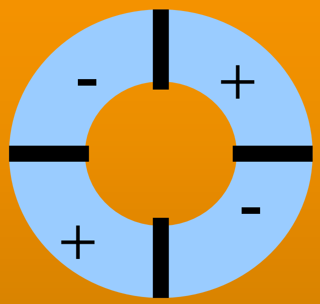
How a Penning trap works-4a

- Dipole excitation can be used to increase the radius of motion for a particular mode.
- Use ω_+ motion for mass selective “cleaning” with good resolution.
- Use ω_- motion for parking ions at a given orbit in a non-selective manner.

How a Penning Trap works-5

For a quadrupole field: $E_x = E_0 \cos(\omega_Q t)$

$$E_y = E_0 \cos(\omega_Q t)$$



Power absorbed:

$$P = q\vec{v}\cdot\vec{E} = -qE_0\cos(\omega_Q t)[\rho_+^2\omega_+\cos(2\omega_+ t)$$

$$+\rho_-^2\omega_-\cos(2\omega_- t)$$

$$+\rho_-\rho_+(\omega_- + \omega_+)\cos(\omega_+ t + \omega_- t)]$$

Resonances at $\omega_Q = 2\omega_-$, $2\omega_+$ and $\omega_+ + \omega_- = \omega_c$

How a Penning trap works-5a

- Quadrupole excitation at ω_c used for mass measurements.
- In the presence of a gas can be used to cool and center ions of a specific mass (as used in the isobar separator).

How a Penning Trap works-6

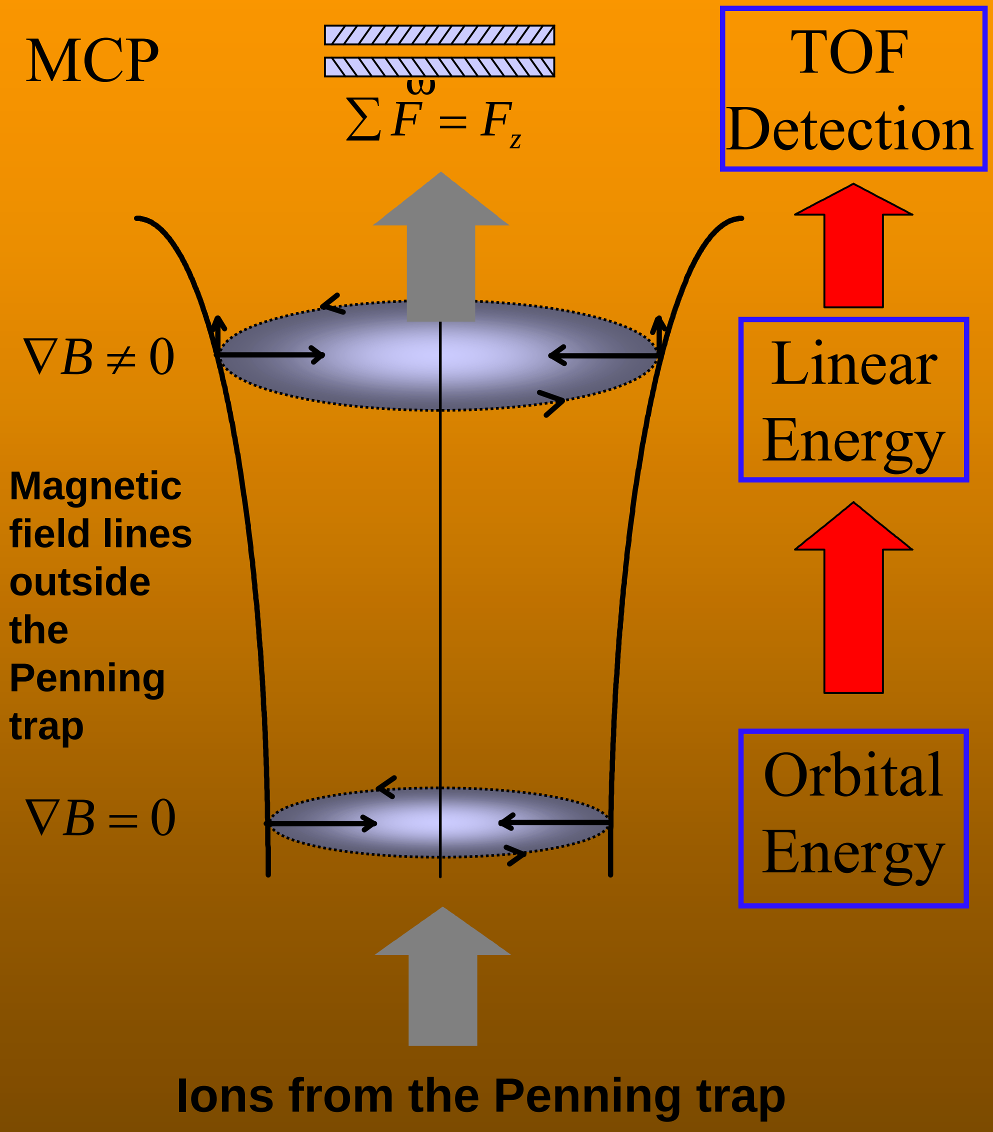
Recall: $$\omega_c = \frac{qB}{m}$$

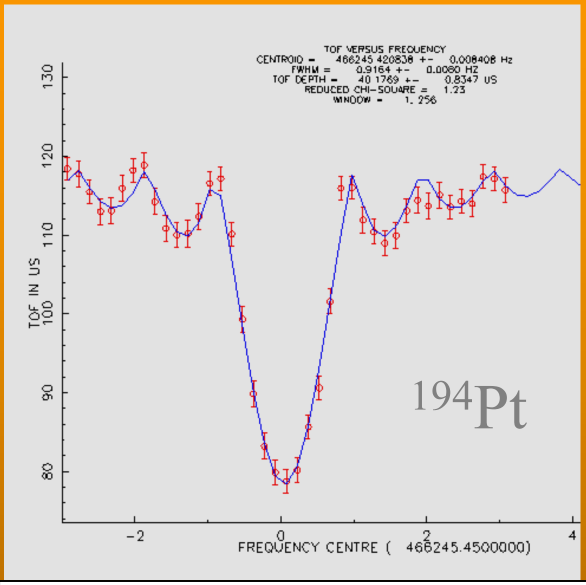
ω_c depends only on:

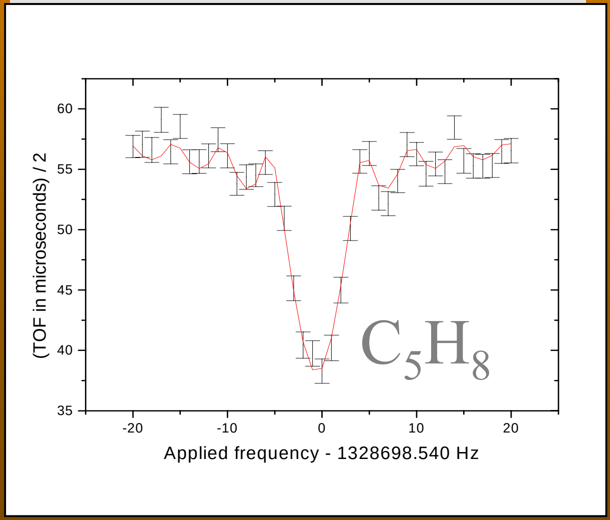
- the mass
- the magnetic field
- not on the electric fields

Can use ω_c to make accurate and precise mass measurements

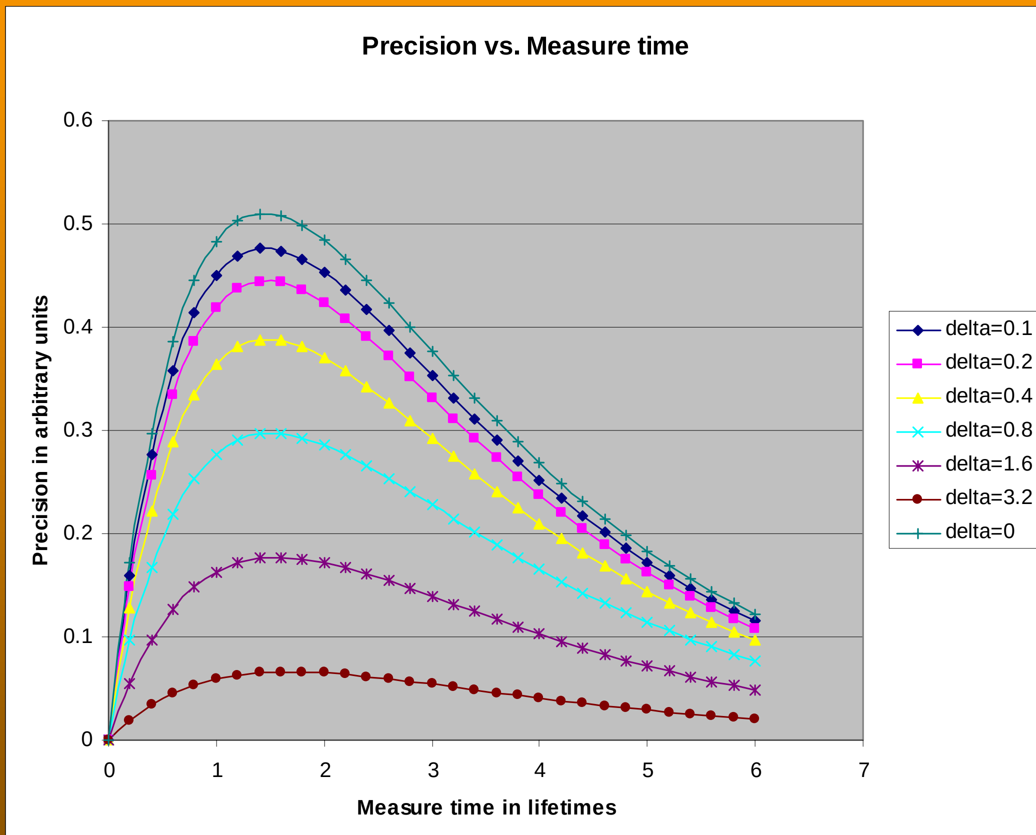
Detection of the resonance



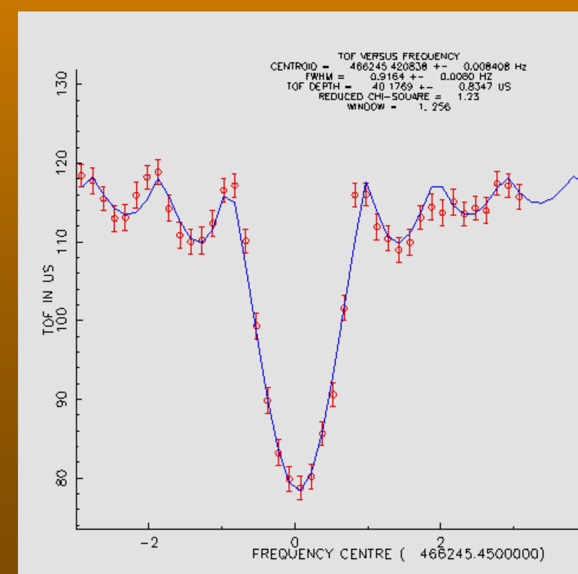




The effects of the observation time



- FWHM = $0.8/T_{obs}$
- Side bands caused by finite excitation time
- Choose the longest observation time that is compatible with the half life ($T_{obs} \sim 2\ T_{1/2}$)



Measurement procedure

•Create ions with the laser ion source or gas catcher

•Accumulate and cool ions in RFQ

•Remove unwanted species with the isotope separator

•Transfer ions to the precision Penning trap

•Clean out unwanted species (Dipole ω_+ resonance)

•“Evaporate” higher energy ions.

•Locate ions in a selected orbit (Dipole ω_- resonance)

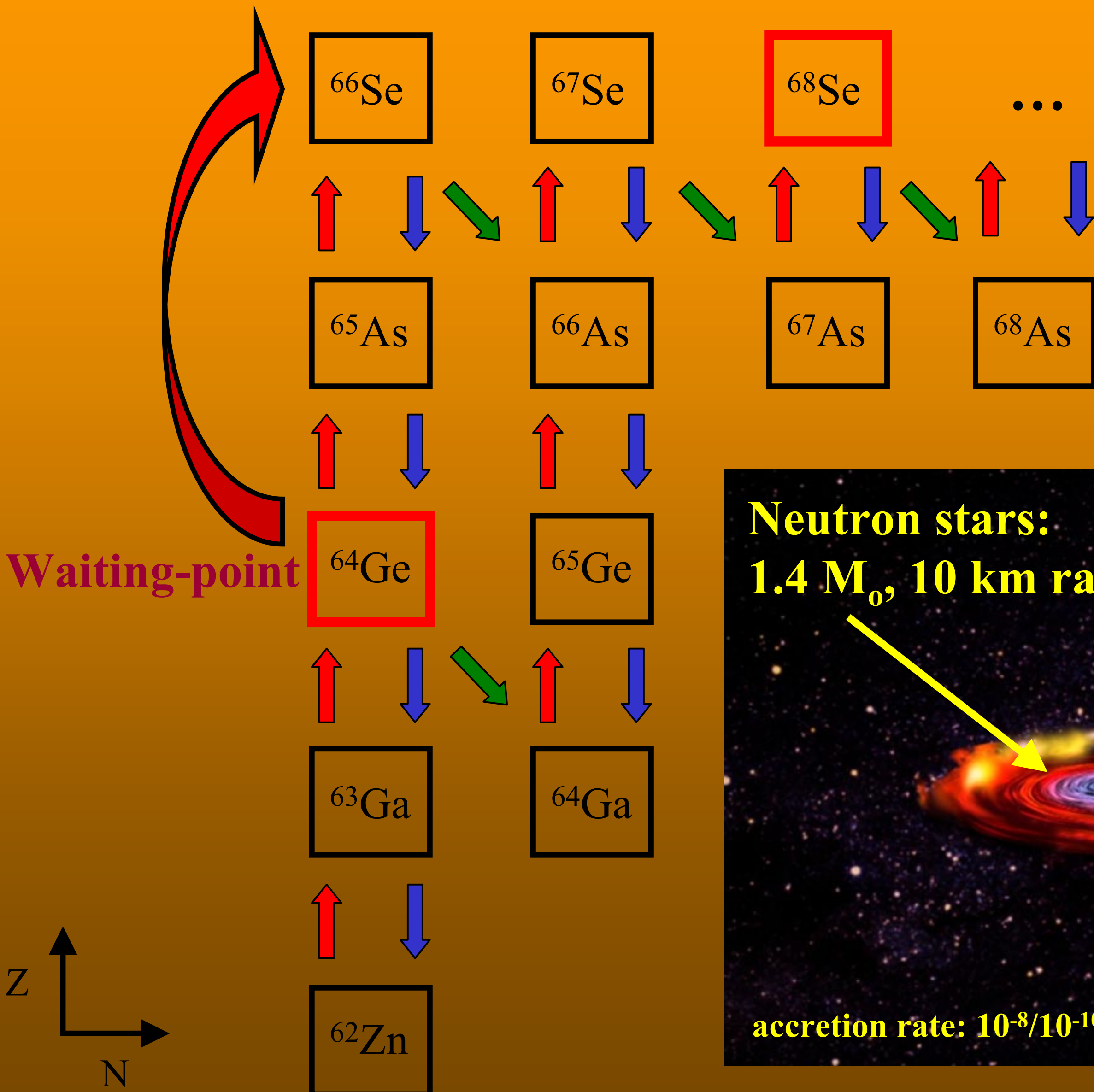
•Convert ω_- motion into ω_+ motion (quadrupole ω_c resonance)

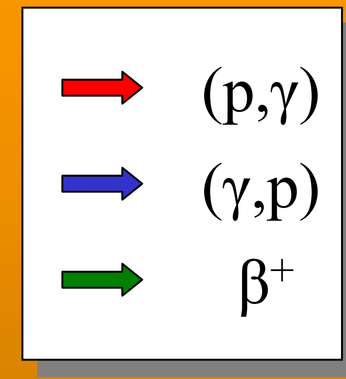
•Eject ions from the trap and measure the mean TOF

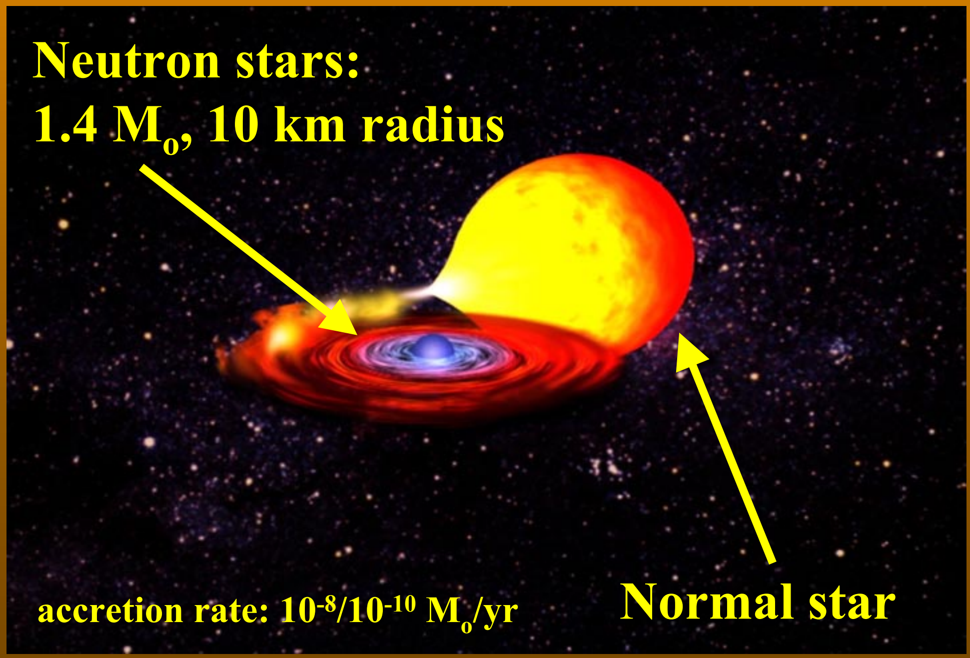
r & rp-process measurements

- Observed elemental abundances cannot be reproduced by only considering nuclear reactions in quiescent stars.
- Need to consider some explosive processes as well:
  - X-ray bursts – rp-process (involves proton rich nuclides)
  - Supernovae – r-process (involves neutron rich nuclides)

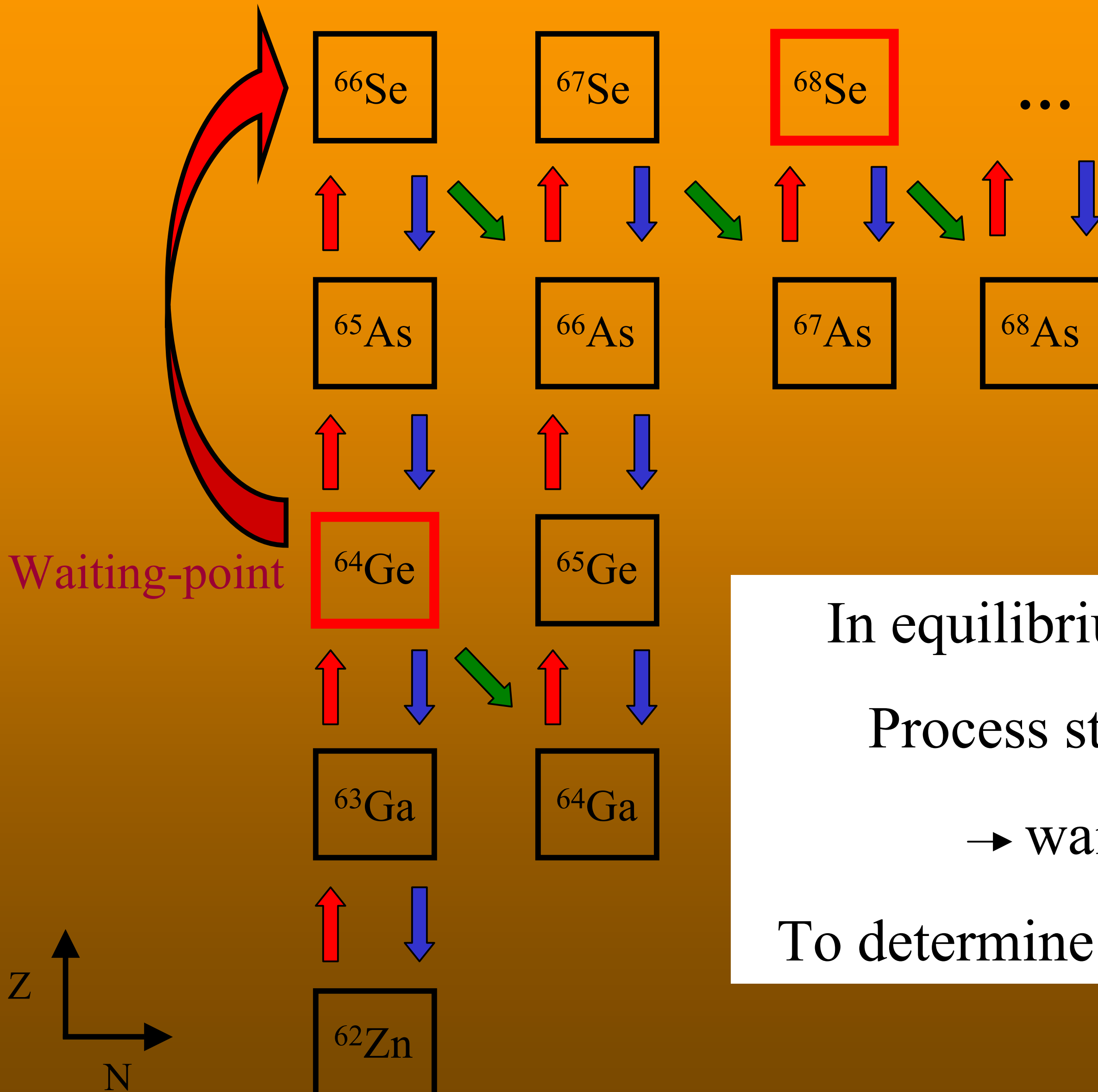
rp-process path

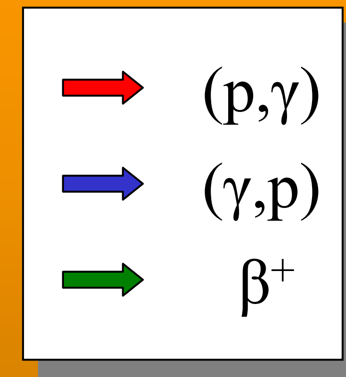






rp-process path





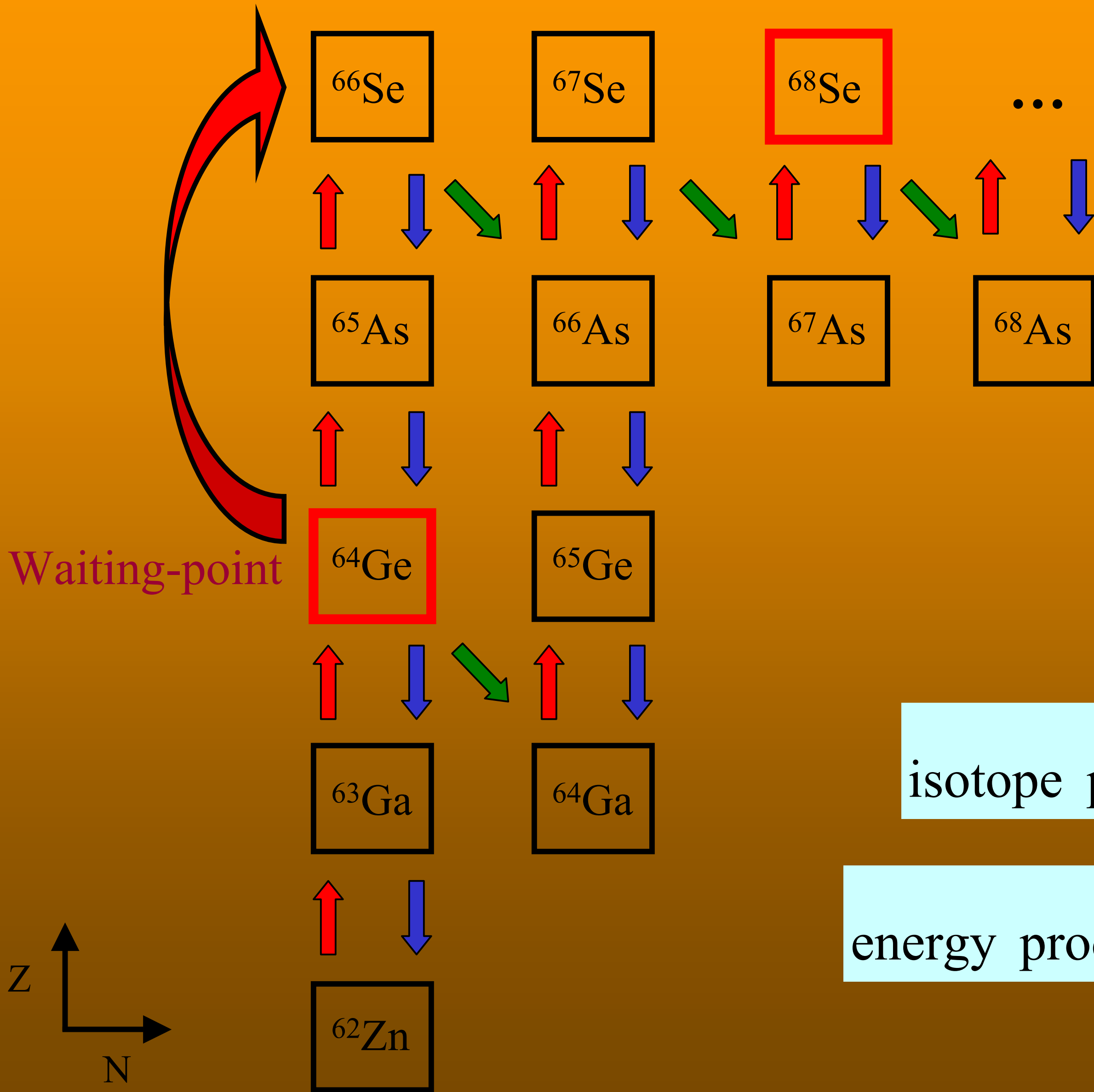
In equilibrium: (p,γ) ↔ (γ,p)

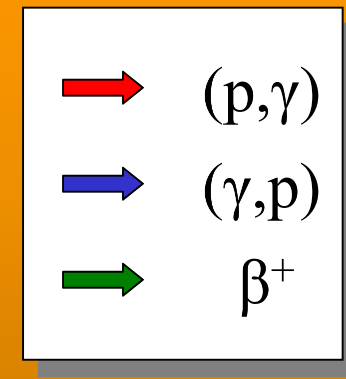
Process stalls until β-decay

→ waiting-point nuclide

To determine equilibrium, need Q_p

rp-process path





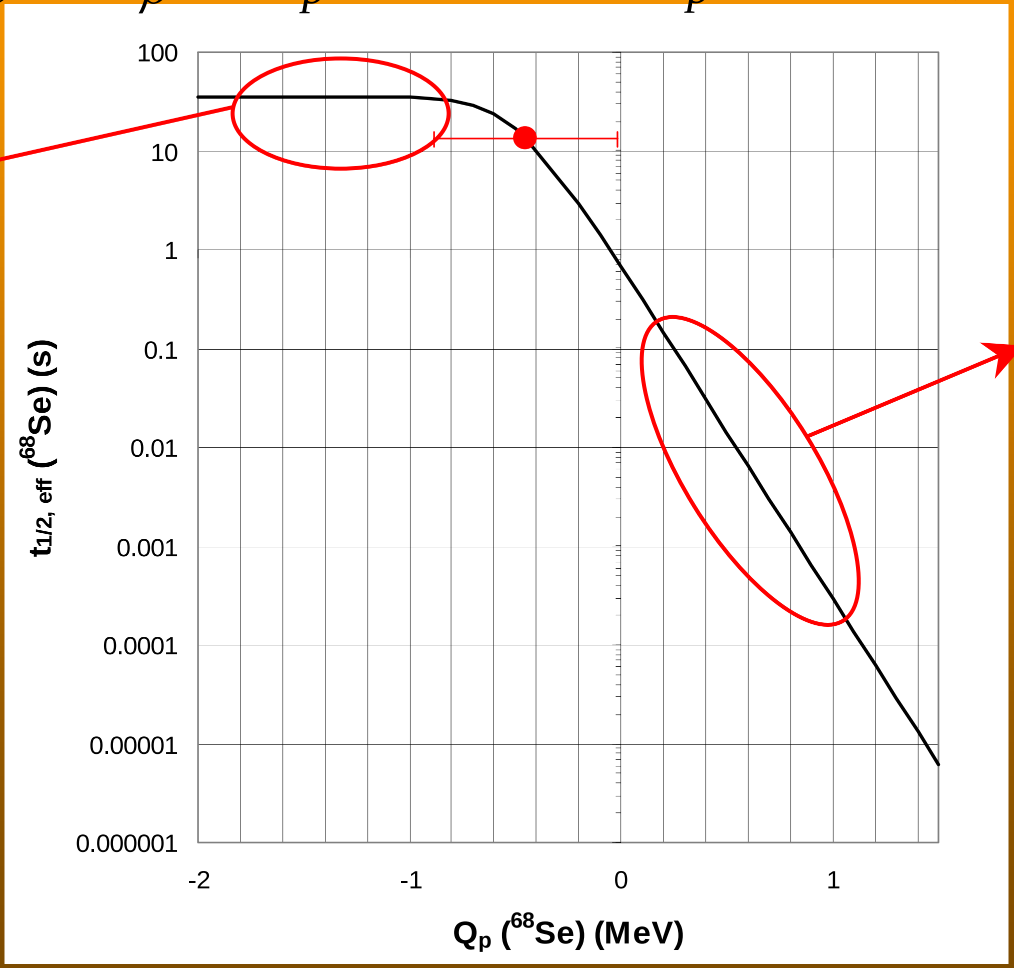
$$\text{time}-\text{scale} \propto \frac{e^{-\frac{Q}{kT}}}{A(Q)}$$

$$\text{isotope production} \propto A(Q)\cdot e^{\frac{Q}{kT}}$$

$$\text{energy production} \propto A(Q)\cdot Q\cdot e^{\frac{Q}{kT}}$$

Effective lifetime of waiting-point nuclides

$$\lambda_{effective} = \lambda_\beta + \lambda_p \qquad \lambda_p \propto \exp\{Q_p / kT\}$$



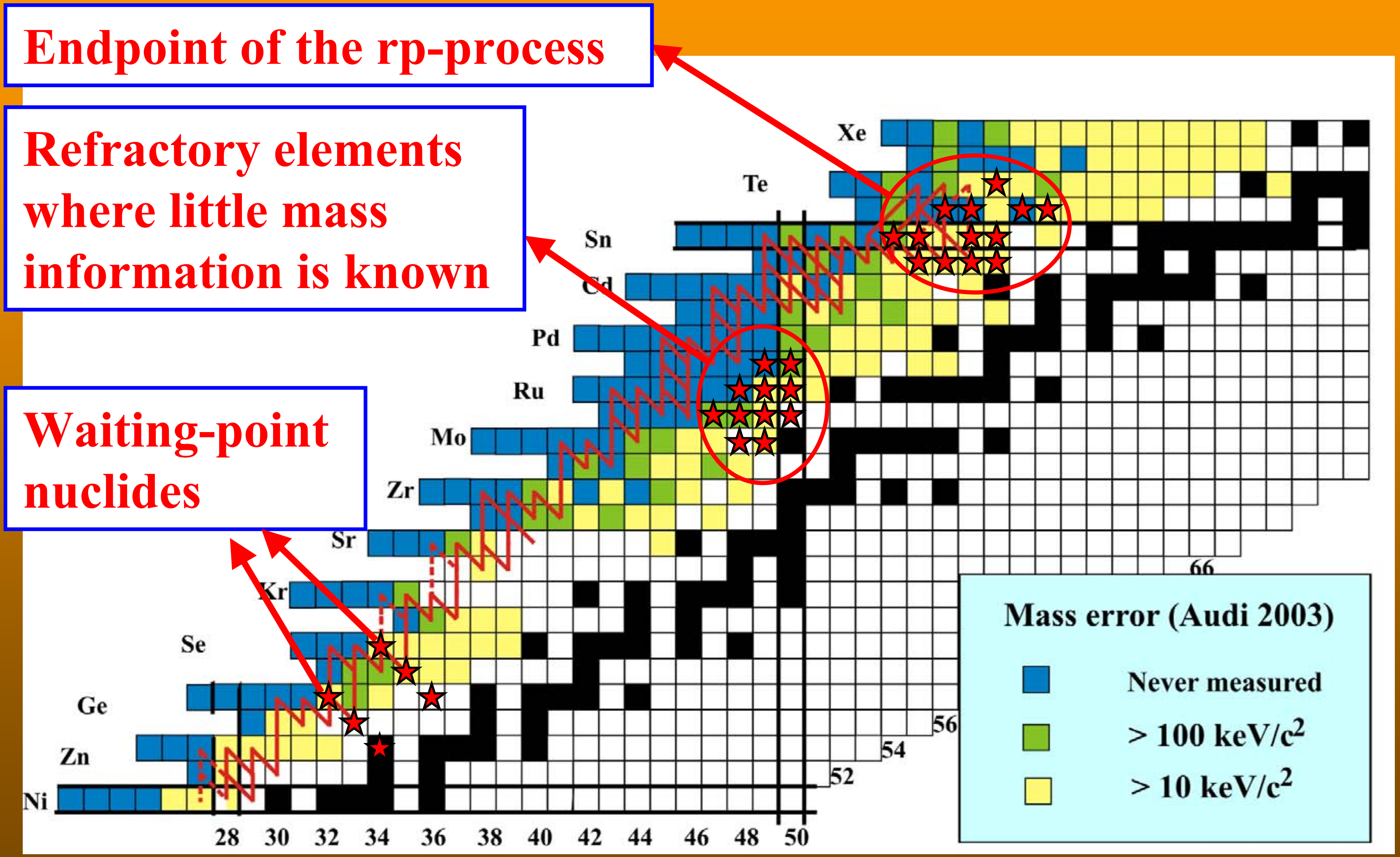
Dominated by β-decay

Effect of proton capture

Precision required ~ kT ~ 100 keV (~ 1.5/10^6)

● G. Audi and A.H. Wapstra, Nucl. Phys. **A595,** 409 (1995).

rp-process – measurements completed



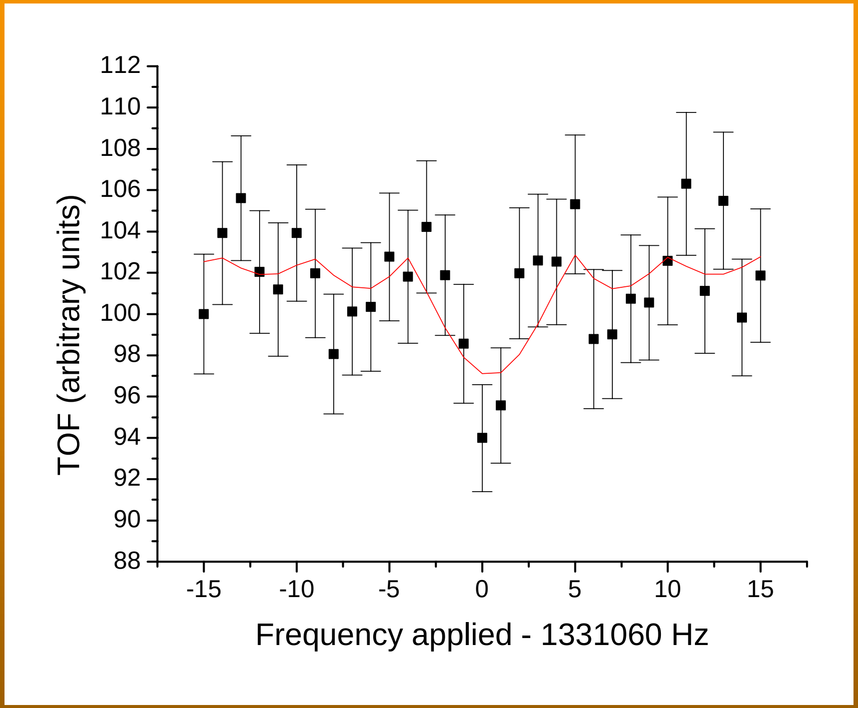
Jason Clark, University of Manitoba, PhD Thesis (2005)

Resonance obtained of ^{68}Se

200 ms excitation

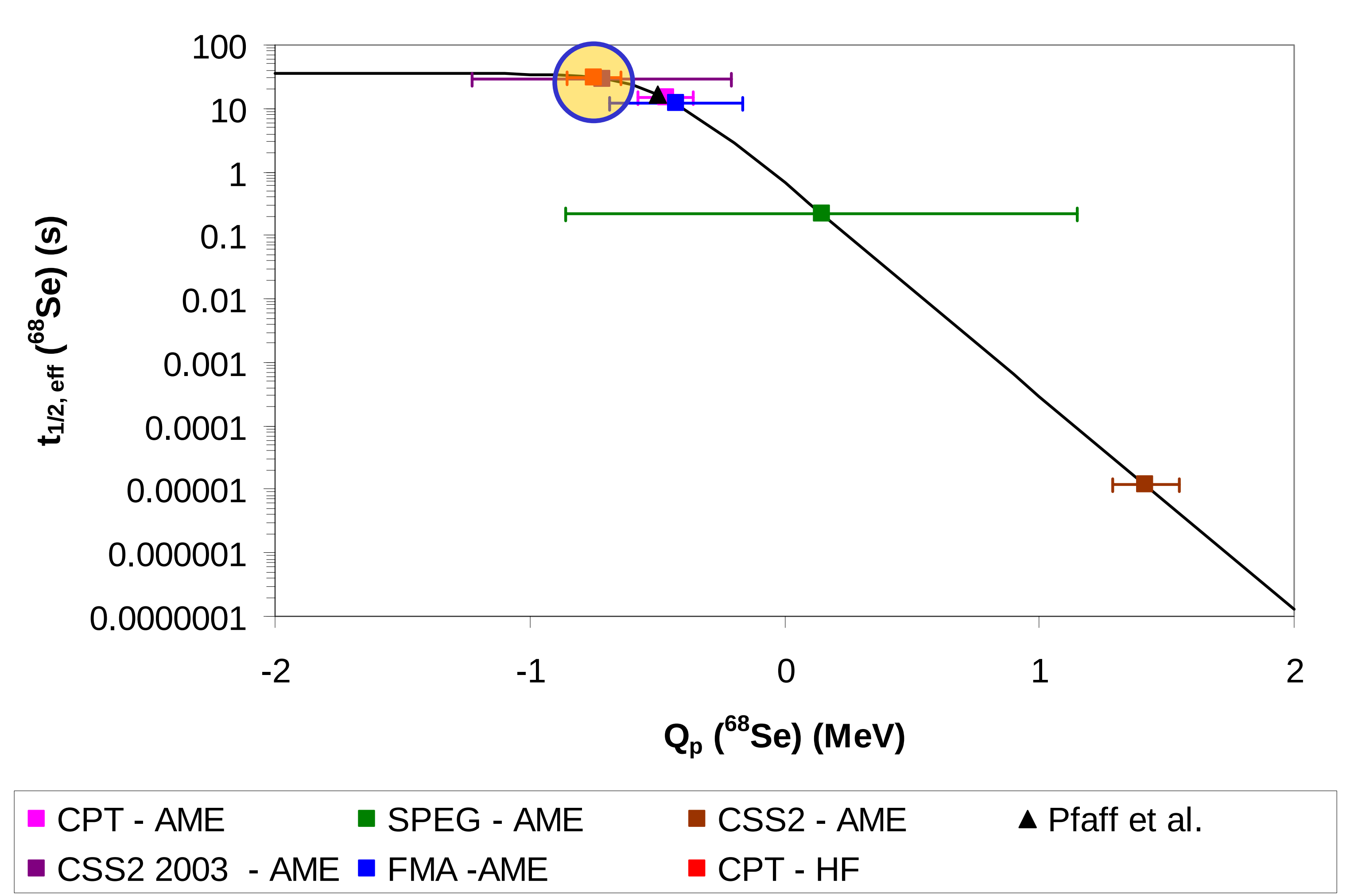
FWHM ~ 5 Hz

~ 250 keV



With all data collected, ΔM = **-54232 (19)** keV

Effective lifetime of the waiting-point nuclide ^{68}Se



CPT: J.A. Clark *et al.*, Phys. Rev. Lett. **92,** 192501 (2004).

AME: G. Audi *et al.*, Nucl. Phys. **A729,** 337 (2003).

SPEG: G.F. Lima *et al.*, Phys. Rev. C **65,** 044618 (2002).

CSS2: A.S. Lalleman *et al.*, Hyperfine Interact. **132**, 315 (2001).

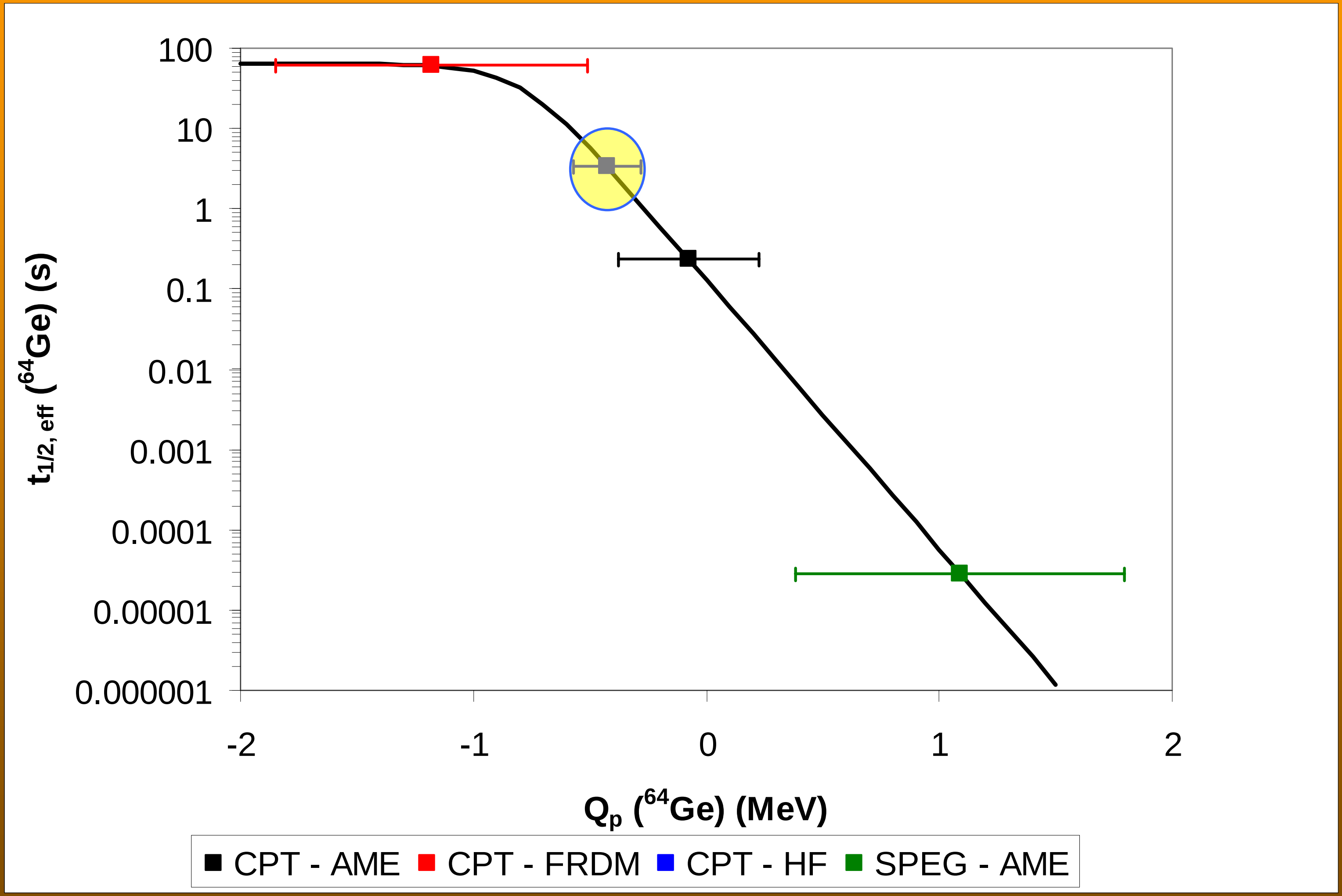
Pfaff: R. Pfaff *et al.*, Phys. Rev. C **53**, 1753 (1996).

CSS2 2003: D. Lunney, private communication.

FMA: A. Wöhr *et al.*, Nucl. Phys. **A742,** 349 (2004).

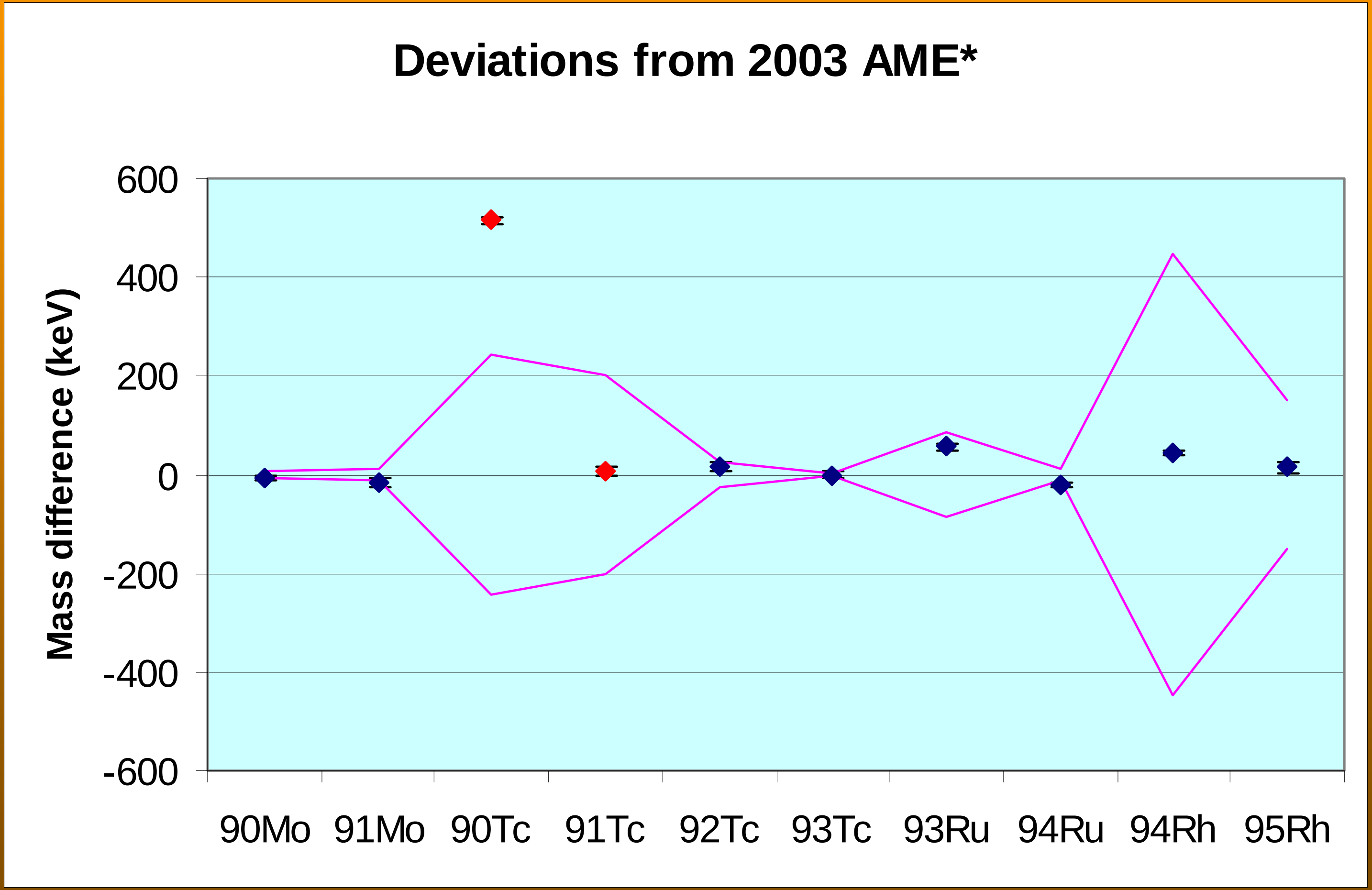
HF: B. A. Brown *et al.*, Phys. Rev. C **65**, 045802 (2002).

Effective lifetime of the waiting-point nuclide ^{64}Ge



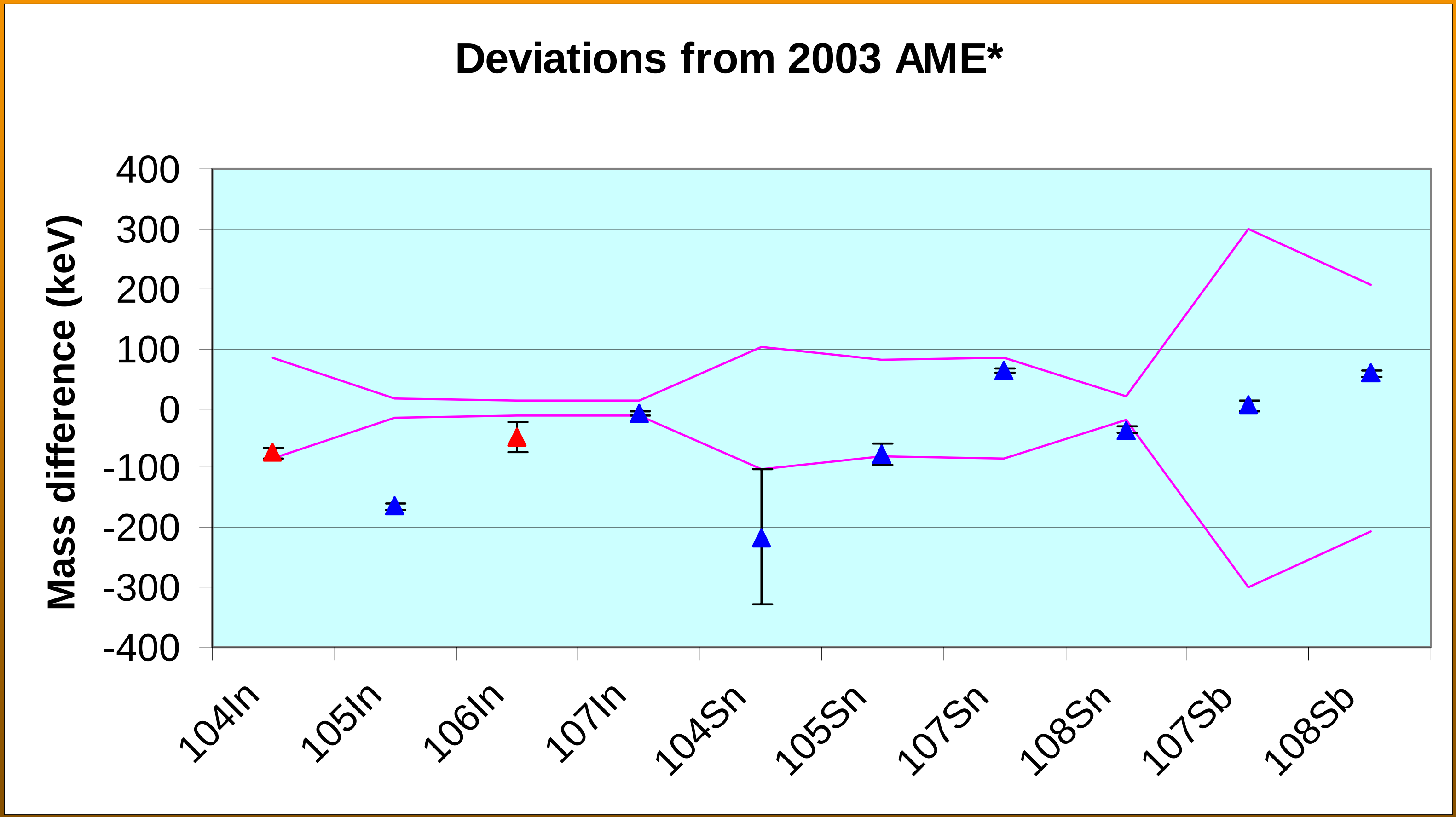
AME: G. Audi *et al.*, Nucl. Phys. **A729,** 337 (2003).
FRDM: P. Möller *et al.*, At. Data Nucl. Data Tables **59**, 185 (1995).
HF: B. A. Brown *et al.*, Phys. Rev. C **65**, 045802 (2002).
SPEG: G.F. Lima *et al.*, Phys. Rev. C **65,** 044618 (2002).

Continuing measurements along the rp-process



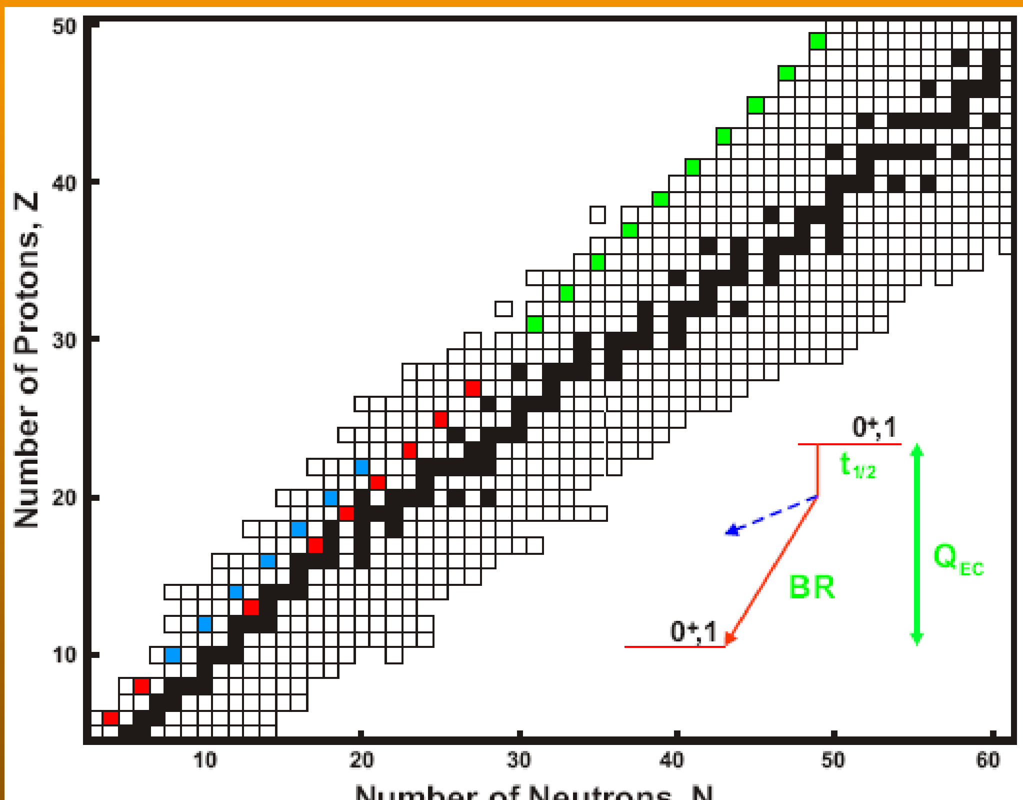
* G. Audi *et al.*, Nucl. Phys. **A729,** 337 (2003).

Endpoint of the rp-process



* G. Audi *et al.*, Nucl. Phys. **A729,** 337 (2003).

Super allowed beta decay Q-values



Lifetime

Branching Ratio

Q-values

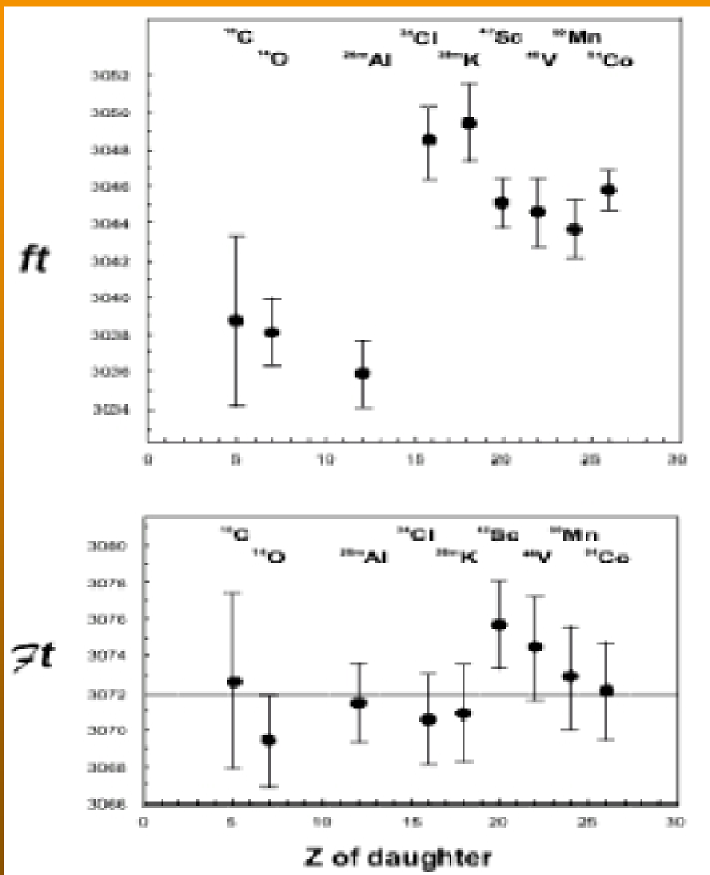
Theory

Ft- values

Muon Decay

V_{ud}, Symmetry tests

Nine well known cases:



Remarkable agreement!

Q-value + Branching ratio + half life

$\rightarrow$ ft value

Corrections are needed.

FT (average) = ft $(1+\delta'_R)(1+\delta_{NS}-\delta_C)$ = 3072.7(8)

With $\chi^2/\upsilon = 0.42$

Where:

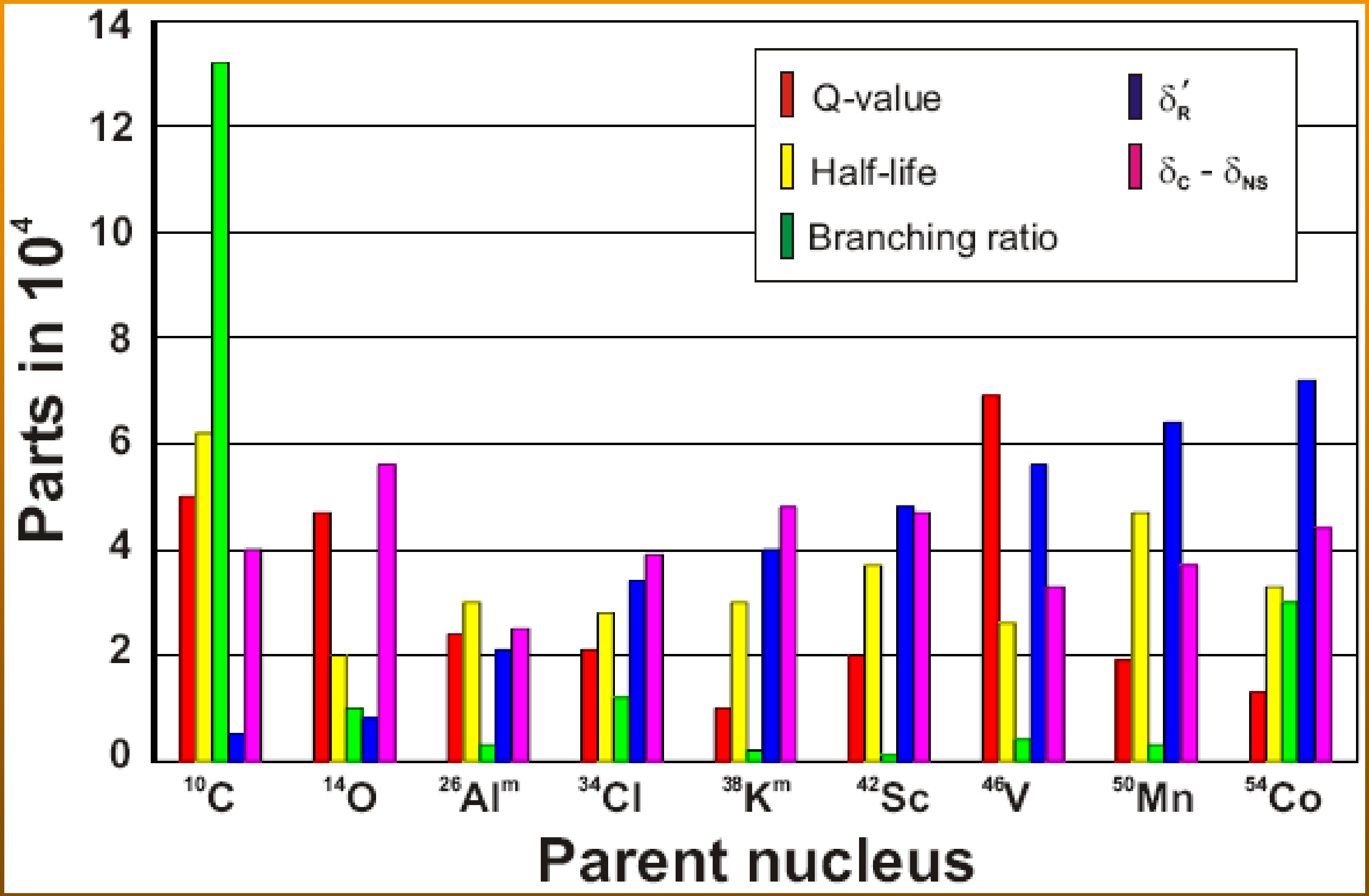
δ_R: Coulomb correction

δ_C: nucleus dependent radiative correction

Δ_R: nucleus independent radiative correction

Contribution of all three correction terms: on the order of 1% with 0.1% uncertainty.

Contributions to the uncertainty



CKM matrix element V_{ud}

$$Ft \equiv ft(1+\delta'_R)(1+\delta_{NS}-\delta_C) = \frac{K}{2G_V^2(1+\Delta_R^V)}$$

$$|V_{ud}| = G_V / G_F$$

f – statistical rate function

t – partial half life (lifetime and B.R.)

δ_{NS} *and* δ_C – nuclear structure dependent corrections

Combine average Ft value with G_F to obtain the best available value for $|V_{ud}| = 0.9738(4)$.

THIS DOMINATES THE CURRENT VALUE FOR V_{ud} !

From: Hardy and Towner PRL 94, 092502 (2005)

Unitarity tests of the CKM matrix

Until recently:

- $V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.9968\ (14)$
- 2.2 s deviation from expected value of 1

Recent measurements at BNL and FNL provide a new value: $|V_{US}| = 0.2259(0.0018)$

- With this the sum becomes 0.9996(11)!
- Caution: discrepancies between these values and other measured values need to be reconciled.

PRL 94, 092502 (2005), PRL 91, 261802 (2003), PRL 93, 181802 (2004)

How do we check our result for consistency?

Extend the data set to cases beyond the initial 9 candidates.

Accuracy required

$$f \propto Q^5 \Rightarrow \frac{df}{f} = 5\frac{dQ}{Q}$$

For example:

To determine f to 0.1% we need Q to 0.02%

For a Q = 10 MeV we need dQ < 2 keV

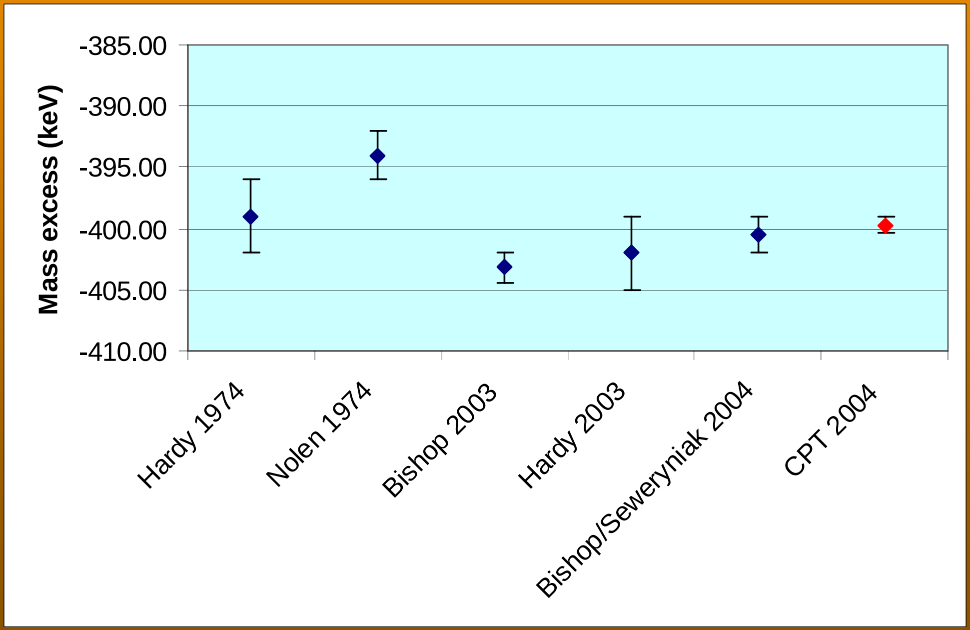
Required precision (δM/M) of ~2×10^{-8}

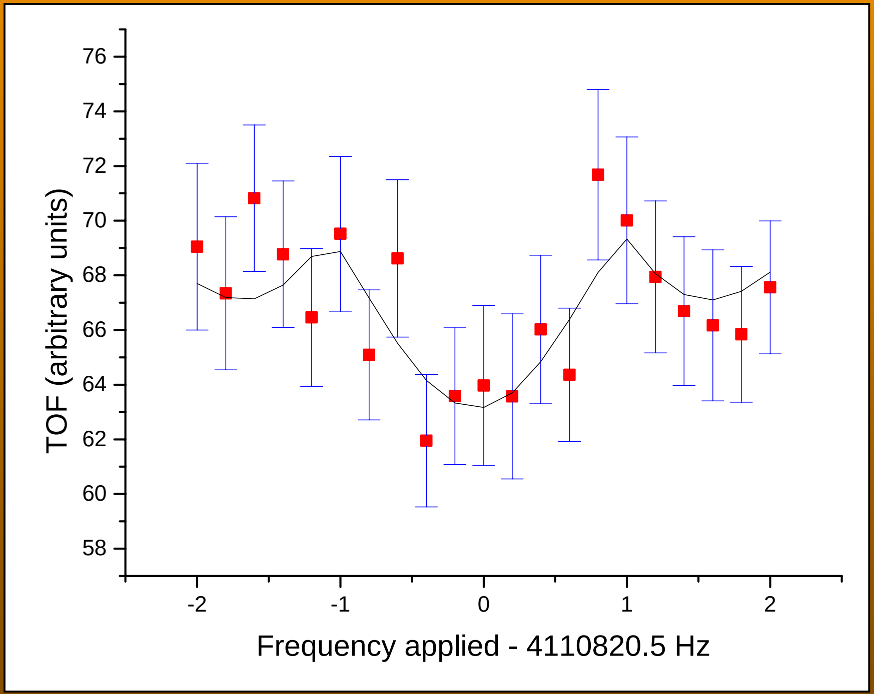
- Improve Q-values for the "well-known" cases.
- Measure masses of parent/daughter for the "new" cases to determine the Q-value.
- Verify if the corrections are correct for the extended data set.
- Need measurements from different groups to confirm data.

^{22}Mg mass measurement

Motivations:

- **uncertainty in the ^{21}Na(p,γ) rate in novae**
- **test the unitarity of the CKM matrix**





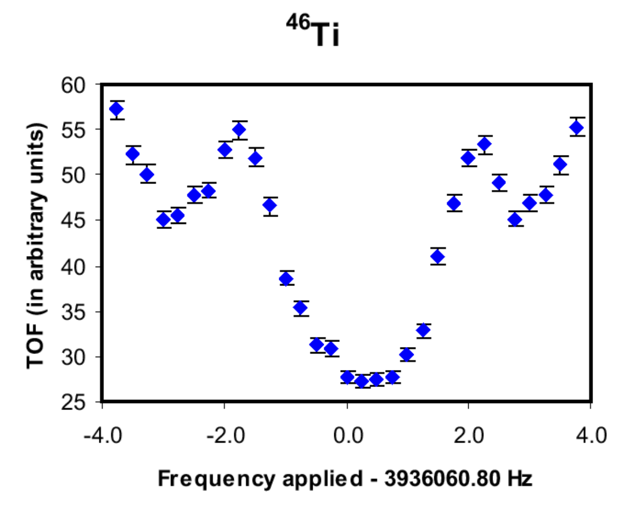
ΔM = -399.73(67) keV

Ft = 3081(8) s

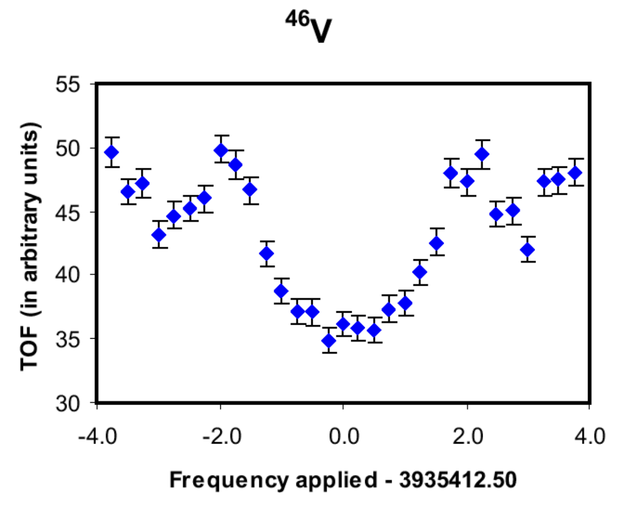
^{46}V mass measurement

Motivation:

- Improve the precision – ^{46}V has the largest uncertainty among the nine well known cases.
- Successfully measured the cyclotron frequencies for $^{46}V^{++}$, $^{46}Ti^{++}$ and $^{22}Ne^{+}$ to a precision of 10^{-8}.

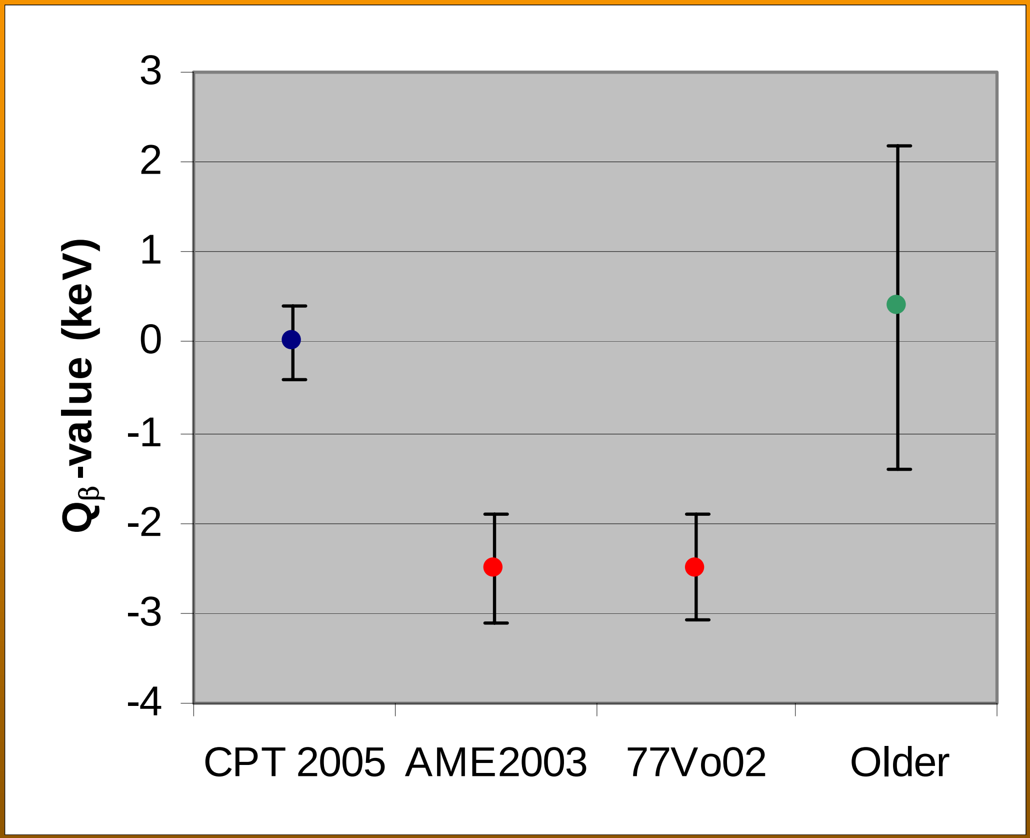


- 400 ms ω_c excitation
- FWHM 2.2 Hz



From: Savard et al (2005) submitted PRL.

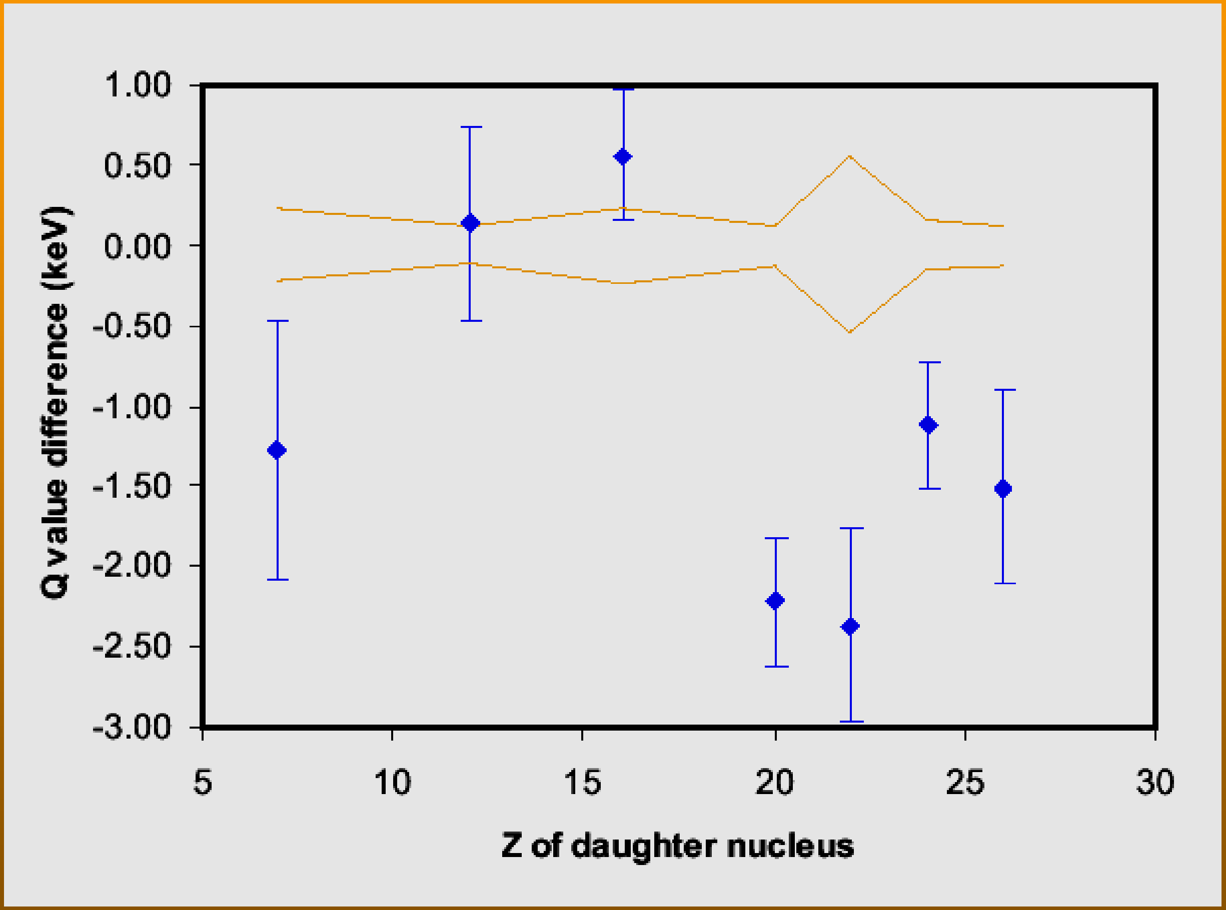
Comparison with existing data



- Q_{EC} = 7052.90(40) keV
- previous average value 7050.71(89) keV
- Ft = 3079.9 (2.3) s
- "World" data

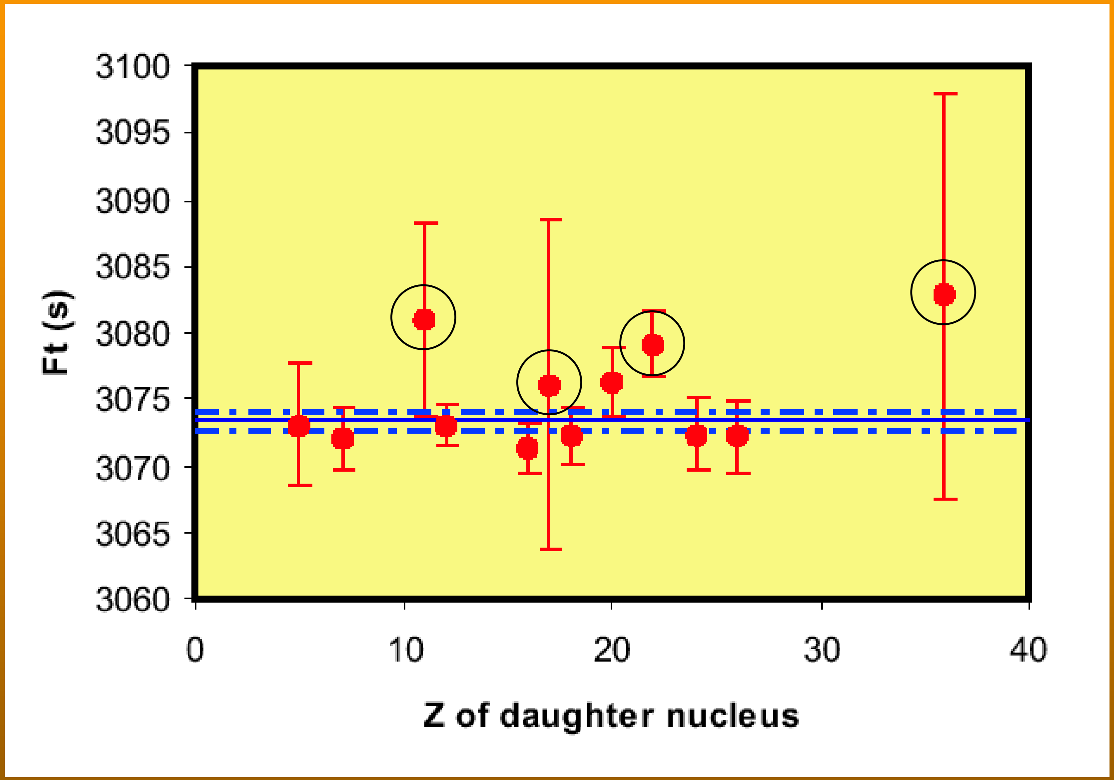
From: Savard et al (2005) submitted PRL.

Q-value difference between 77Vo02 and all other data



From: Savard et al (2005) submitted PRL.

Ft- values from modified data set

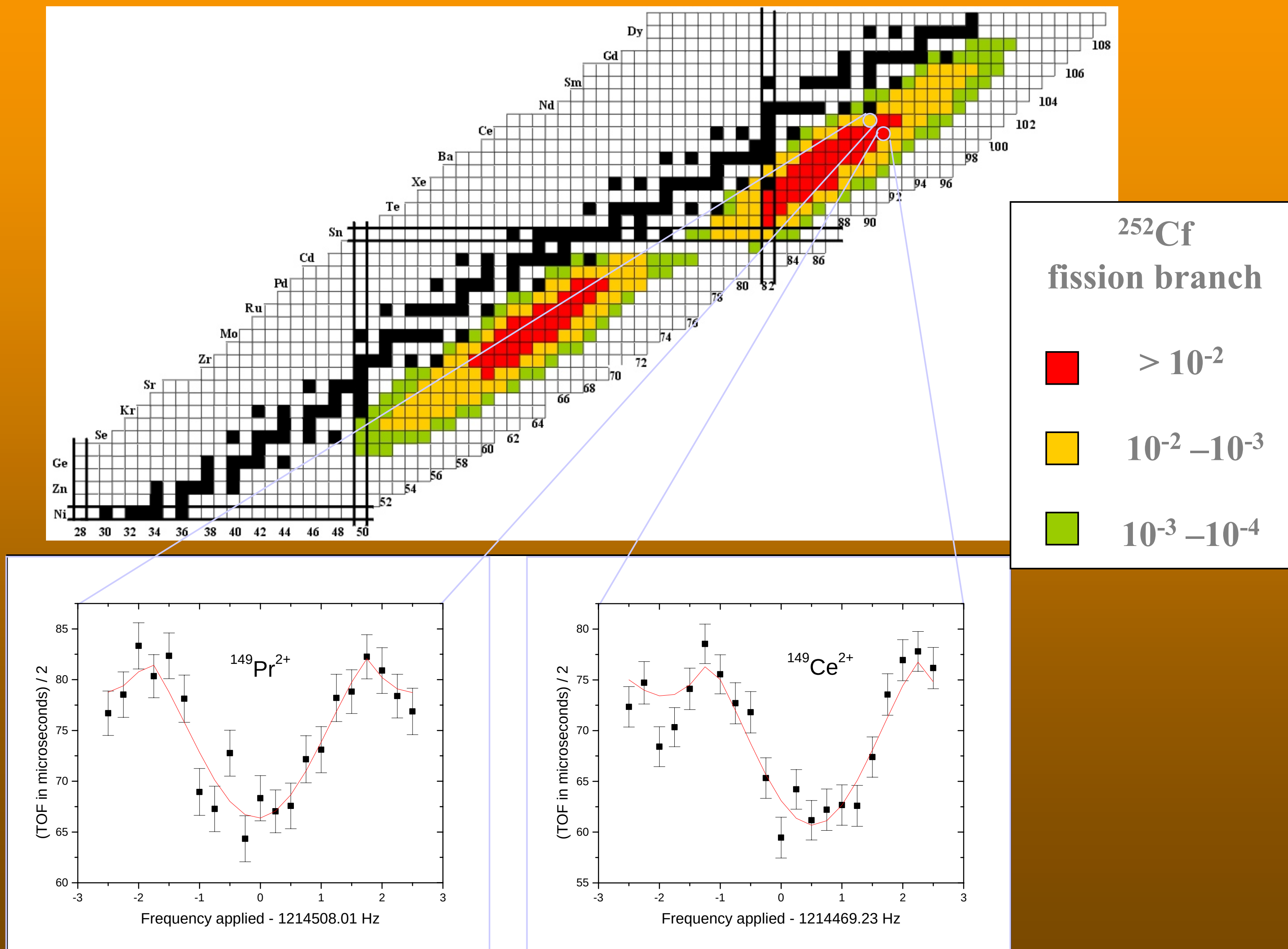


With this data set:

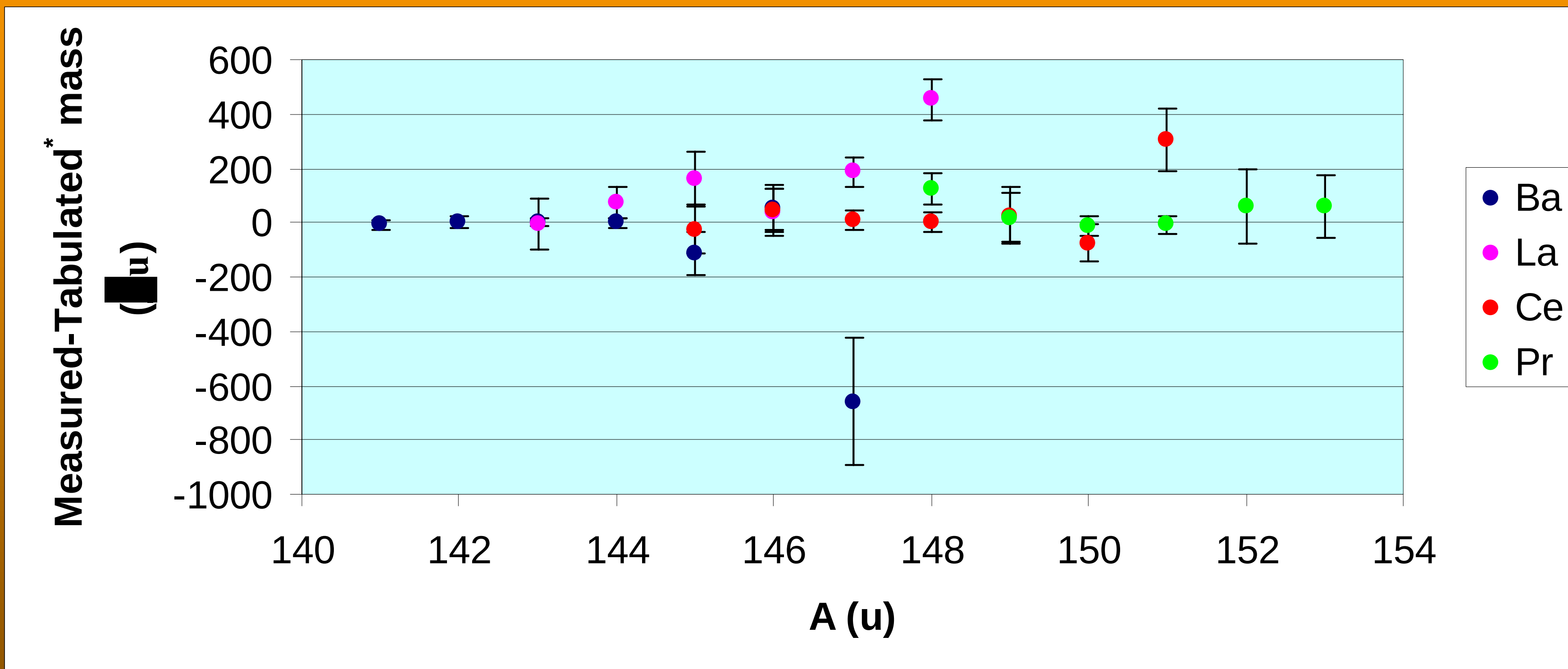
• $V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.9993\ (16)$

From: Savard et al (2005) submitted PRL.

Measurement of neutron-rich nuclides



Our results


Measured-Tabulated* mass
([redacted]u)
600
400
200
0
-200
-400
-600
-800
-1000
140
142
144
146
148
150
152
154
A (u)
Ba
La
Ce
Pr

Conclusion

- Over 70 masses determined:
  - Much of the rp-process path has been covered.
  - We are moving towards the r-process path on the neutron-rich side.
  - Q-values for super allowed beta decays are providing interesting results.
- Improvements to the instrument will make many more measurements possible.

CPT Collaboration

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