Non-Exponential Two-Body Beta Decay of Stored Hydrogen-Like Ions

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Joint HEPD - TPD seminar

PNPI, Gatchina, Russia
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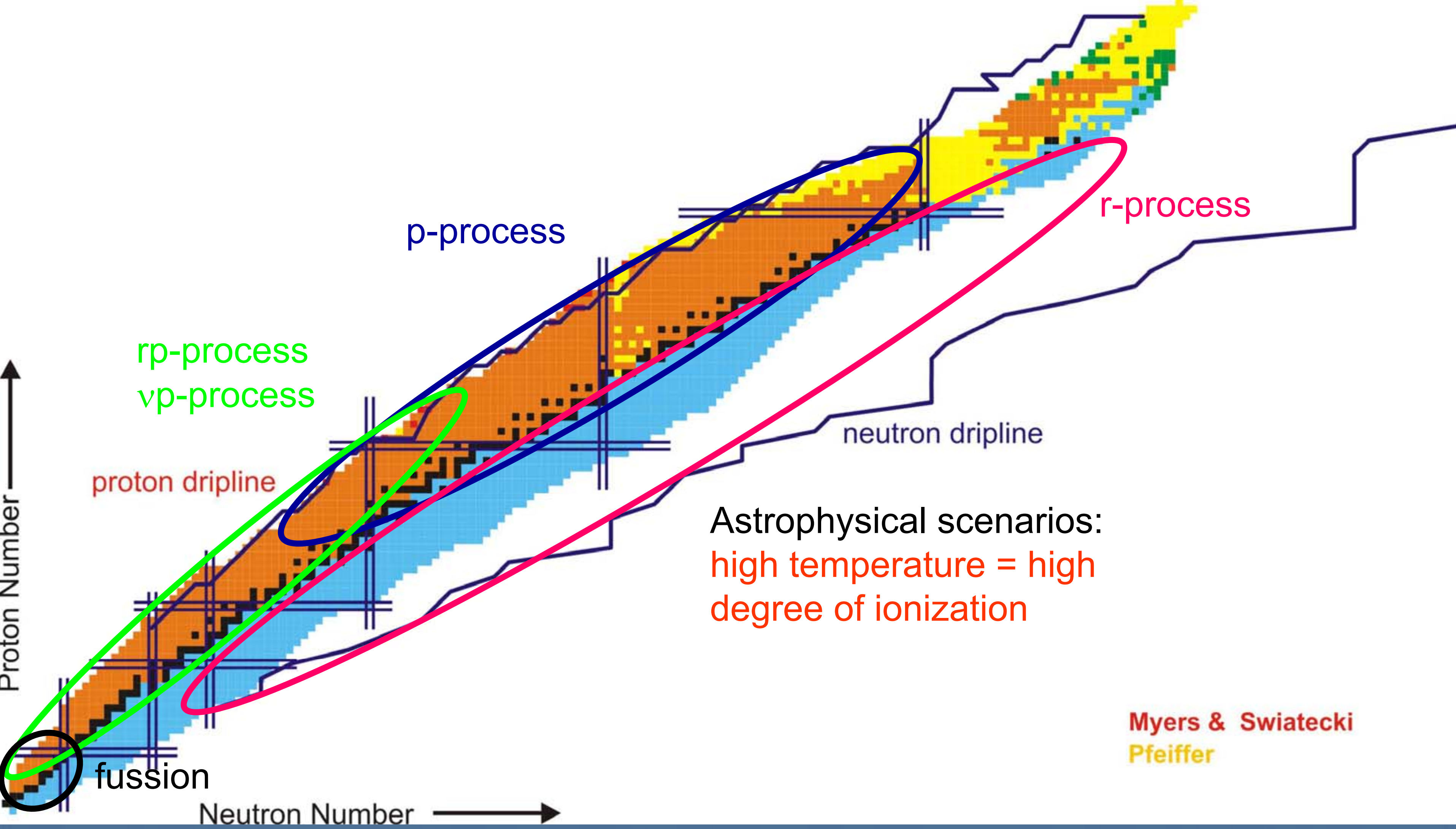
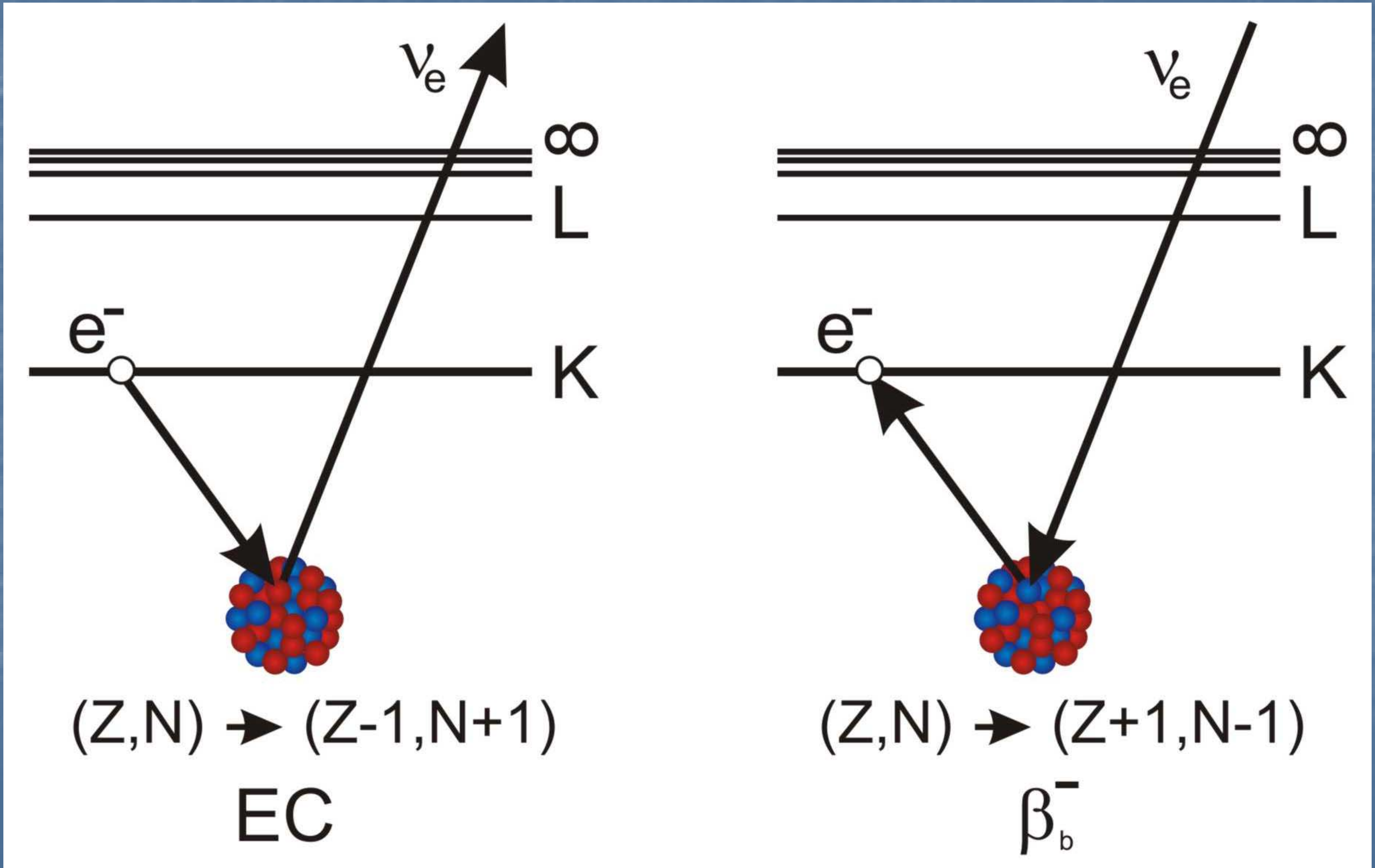
Beta-decay on the Chart of Nuclides

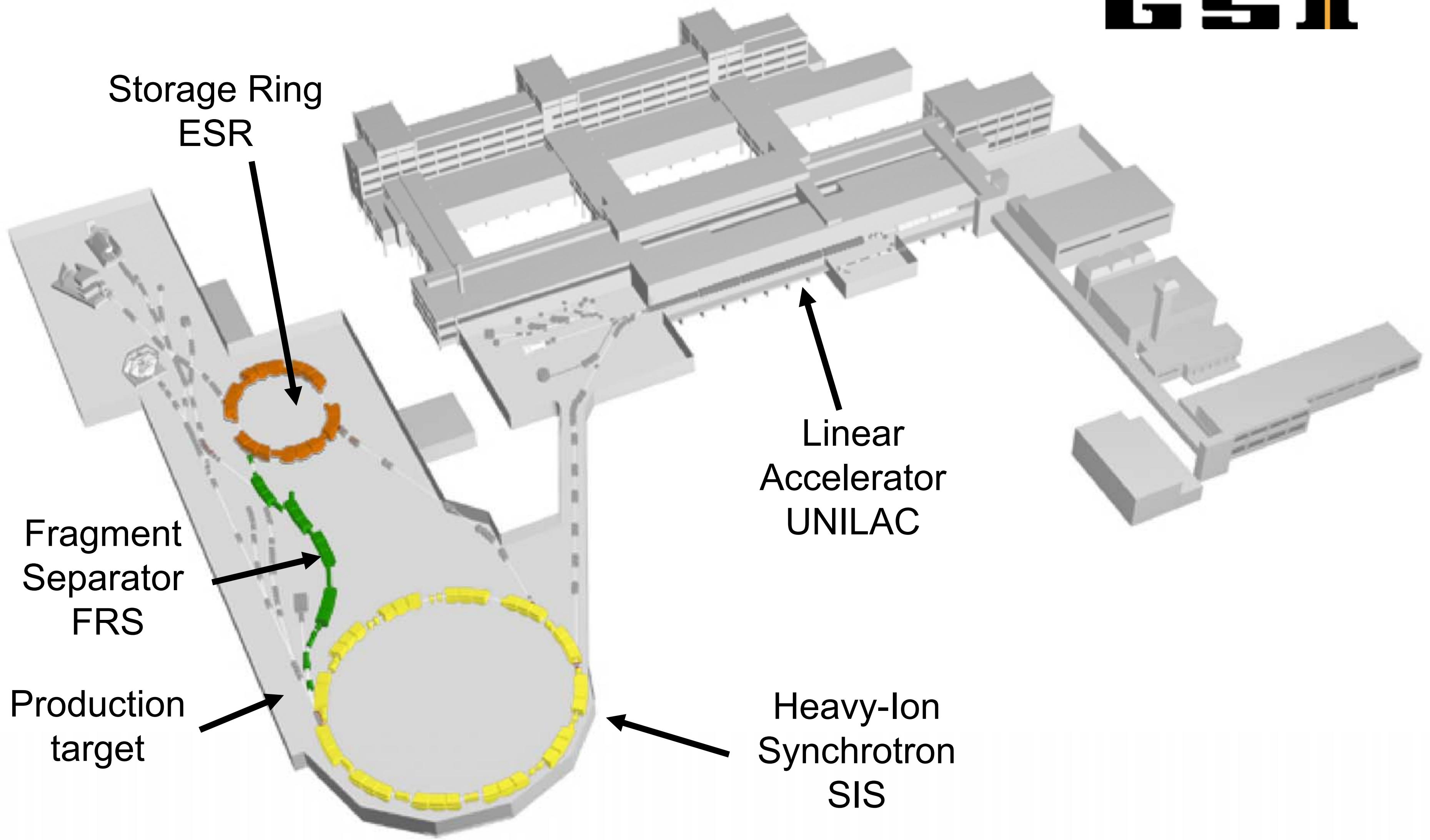


Astrophysical scenarios:
high temperature = high degree of ionization

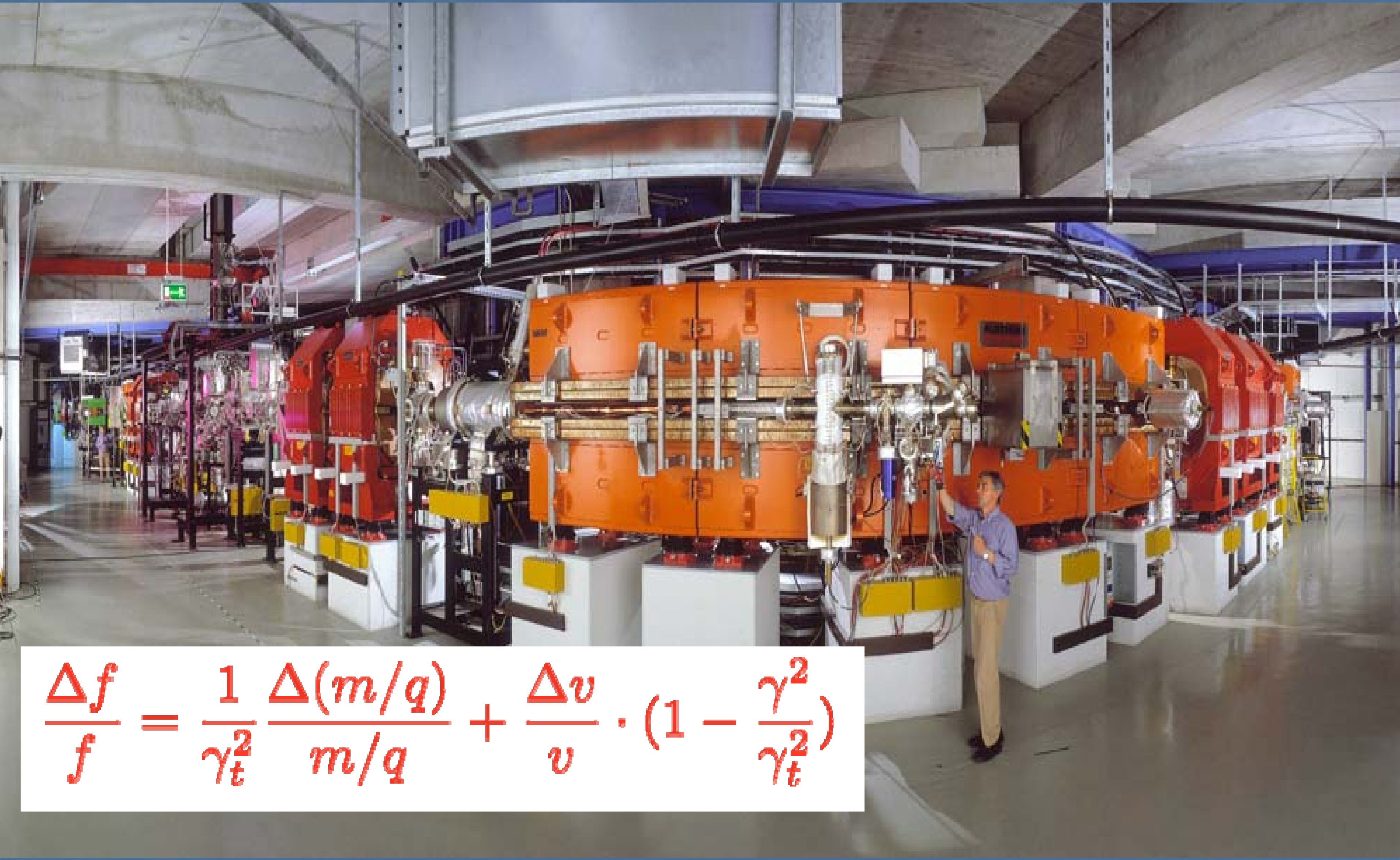
Two-body beta decay of stored and cooled highly-charged ions



Production, storage and cooling of HCI at GSI



ESR : E_{max} = 420 MeV/u, 10 Tm; e^-, stochastic cooling

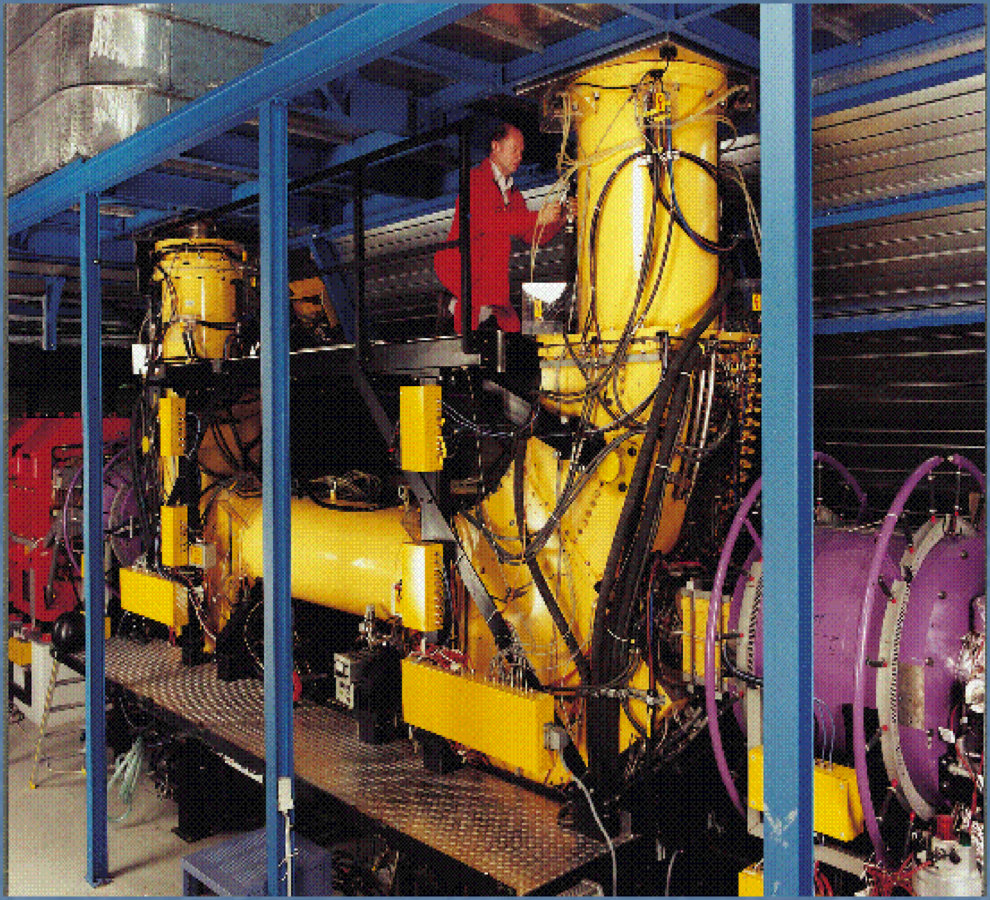


$$\frac{\Delta f}{f} = \frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\cdot\left(1 - \frac{\gamma^2}{\gamma_t^2}\right)$$

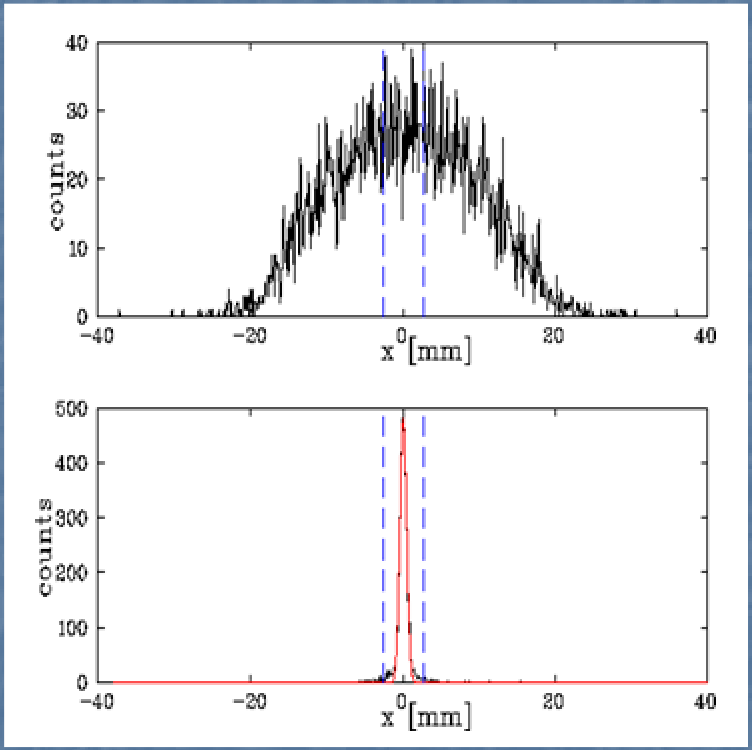
ESR: B. Franzke, NIM B 24/25 (1987) 18

Stochastic cooling: F. Nolden et al., NIM B 532 (2004) 329
Electron cooling: M. Steck et al., NIM B 532 (2004) 357

Electron Cooling

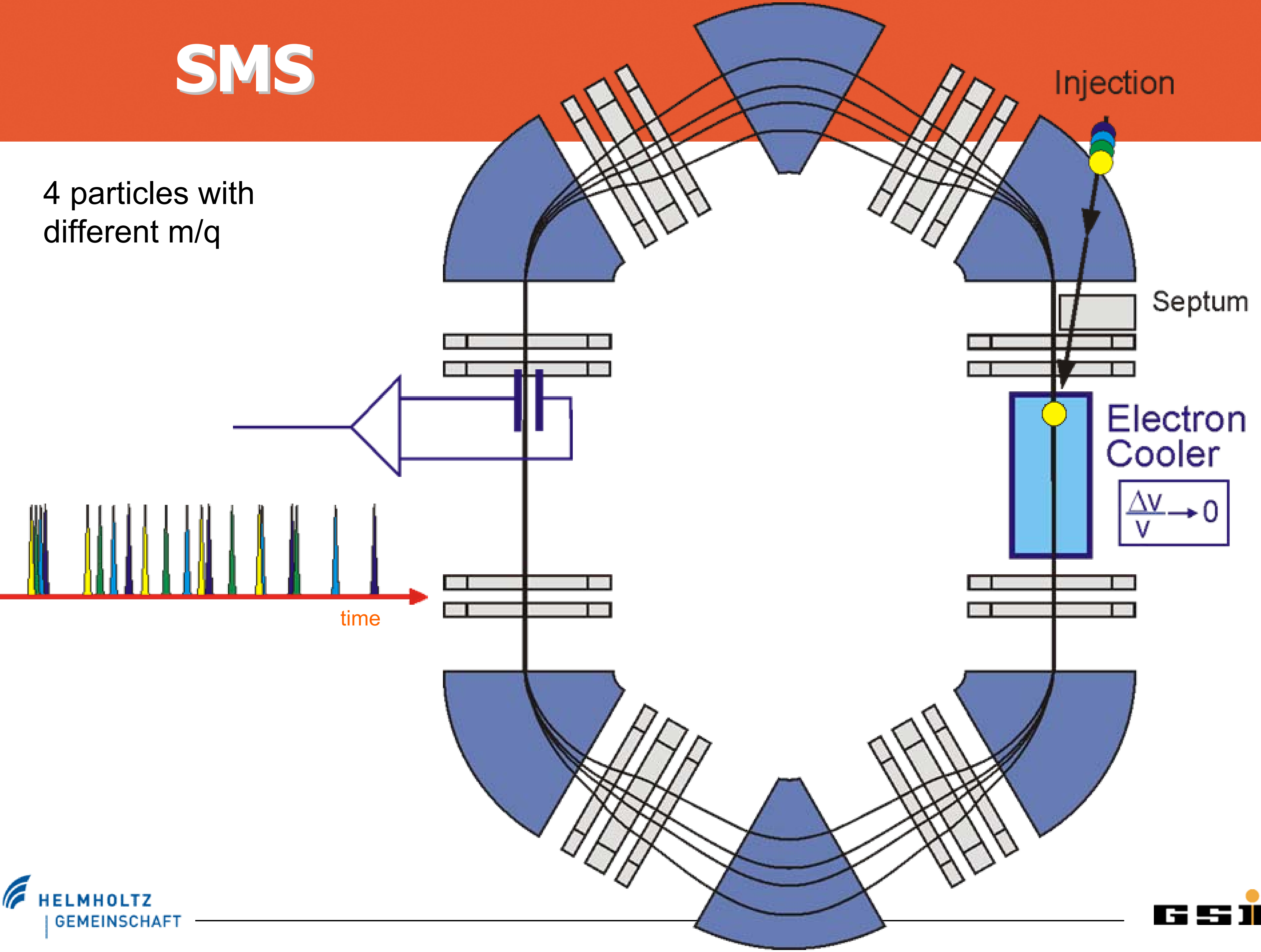


momentum exchange with 'cold', collinear e- beam. The ions get the sharp velocity of the electrons, small size and divergence

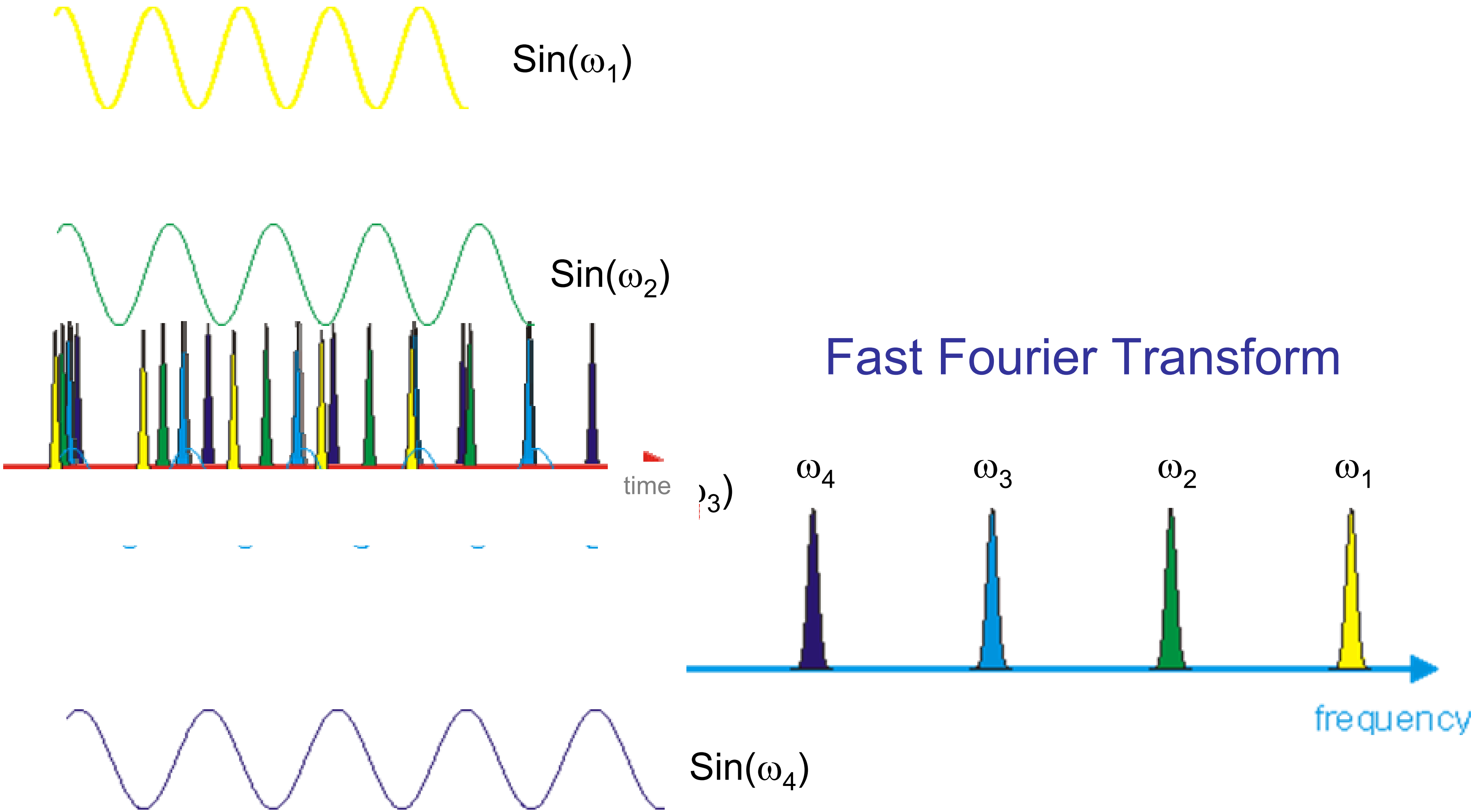


SMS

4 particles with
different m/q

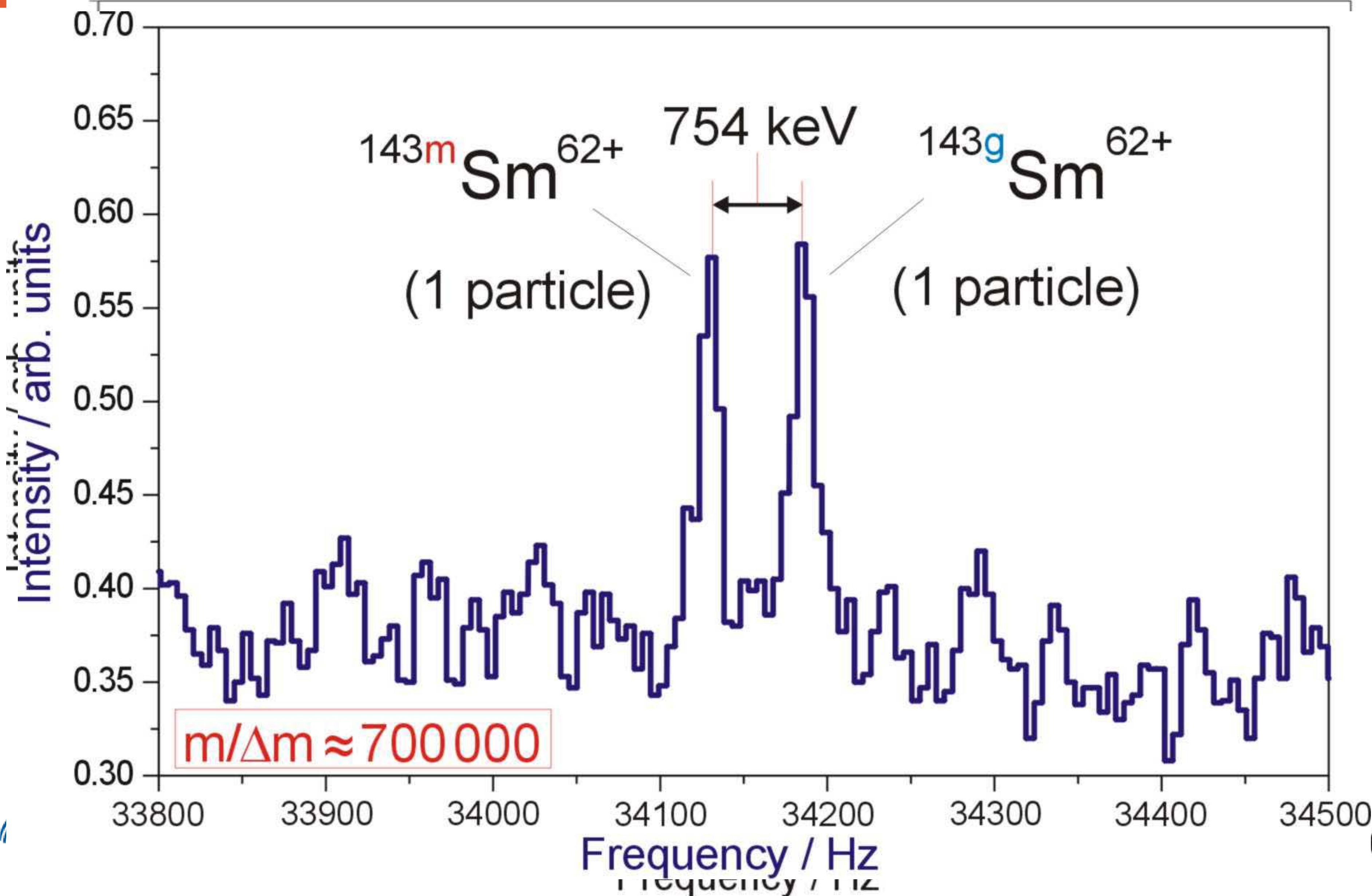


SMS



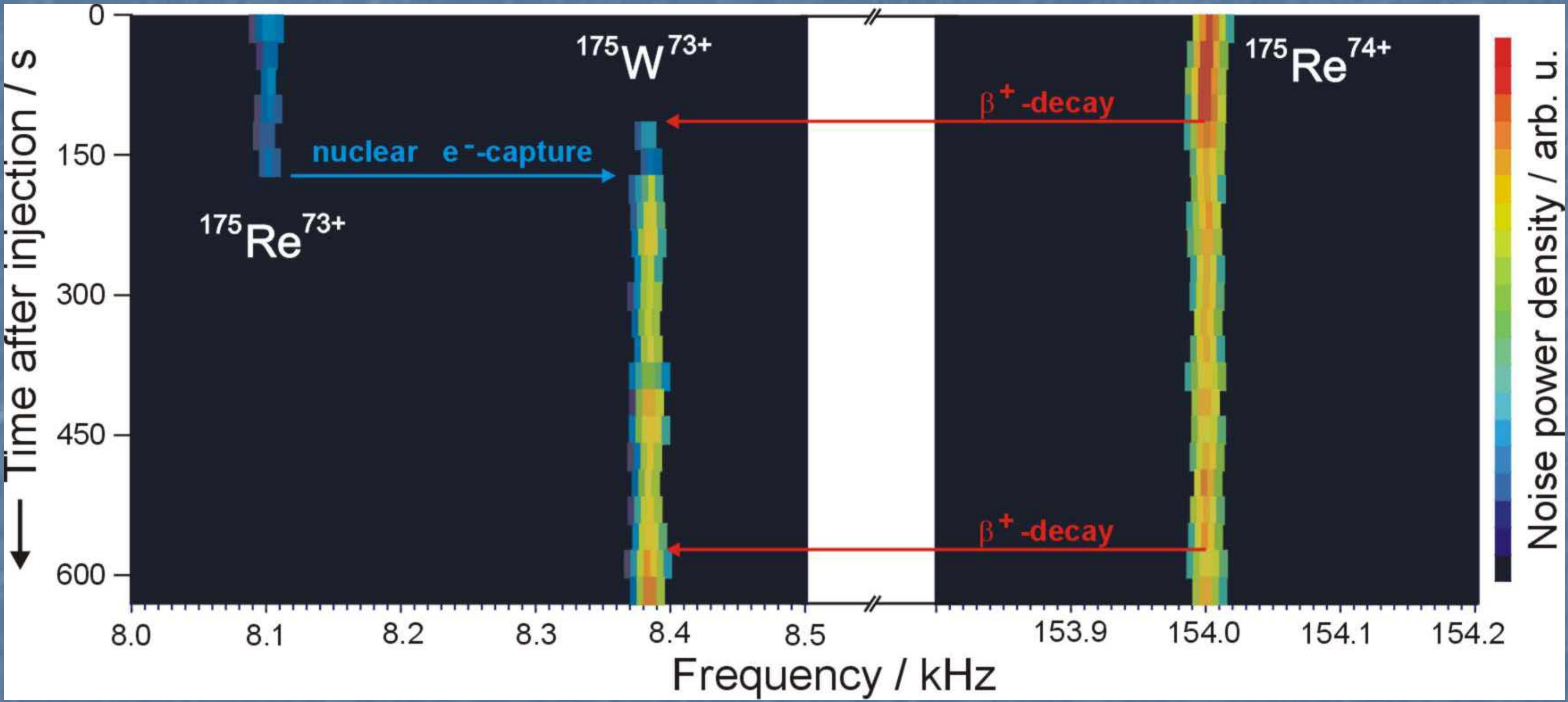
HELMHOLTZ
GEMEINSCHAFT

SMS: Broad Band Frequency Spectra



Nuclear Decays of Stored Single Atoms

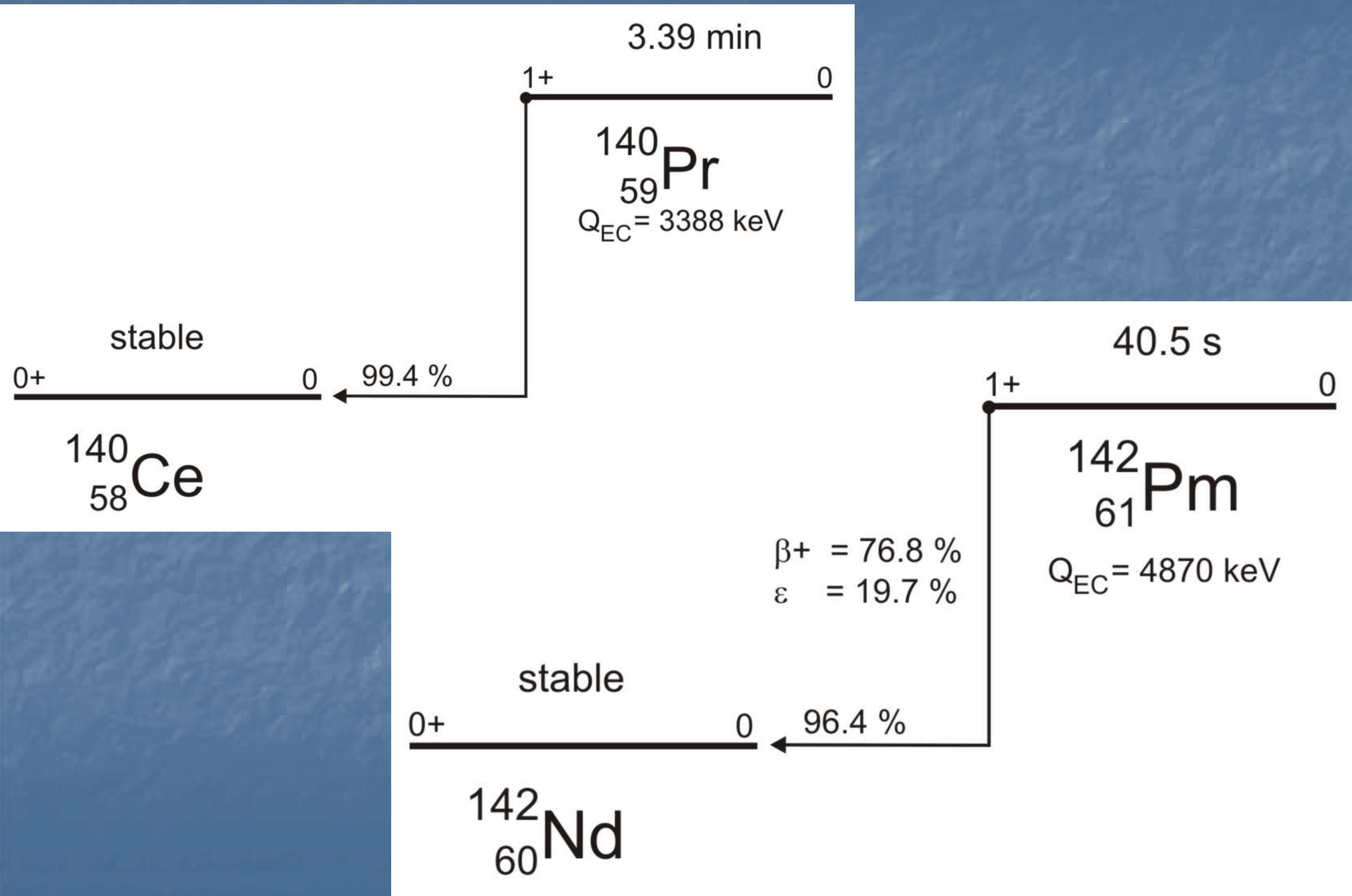
Time-resolved SMS is a perfect tool to study dynamical processes in the ESR

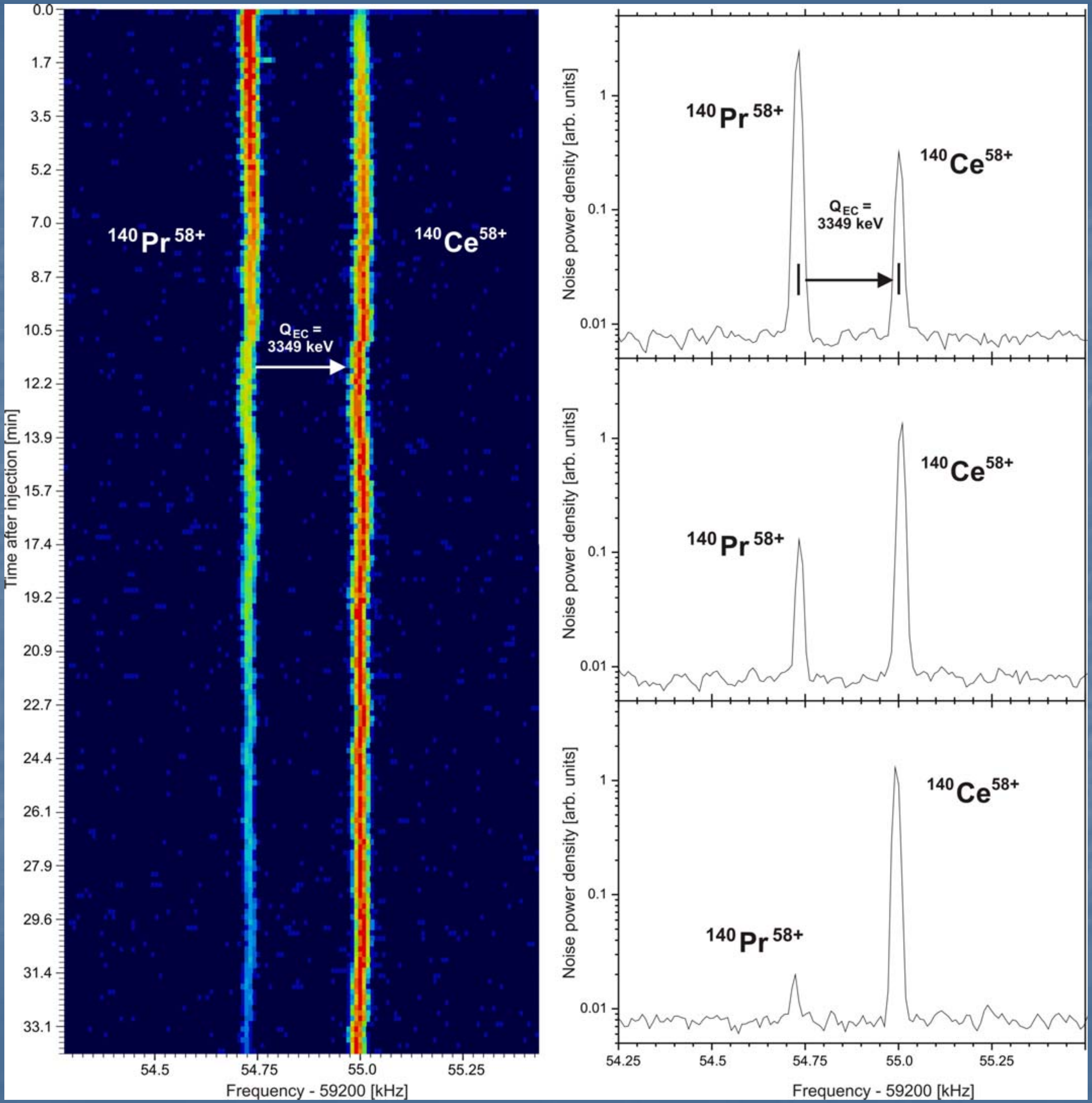


Nuclear electron capture, β+,β- and bound-β decays were observed

Yu.A. Litvinov et al., NP A 734 (2004) 473
Yu.A. Litvinov et al., NP A 756 (2005) 3

Decay schemes H-like ions; g.s. → g.s.; no third particle





Time after injection [min]
0.0
1.7
3.5
5.2
7.0
8.7
10.5
12.2
13.9
15.7
17.4
19.2
20.9
22.7
24.4
26.1
27.9
29.6
31.4
33.1
140Pr 58+
140Ce58+
QEC =
3349 keV
54.5
54.75
55.0
55.25
Frequency - 59200 [kHz]
Noise power density [arb. units]
1
0.1
0.01
140Pr 58+
140Ce58+
QEC =
3349 keV
54.25
54.5
54.75
55.0
55.25
Frequency - 59200 [kHz]

EC in Hydrogen-like Ions

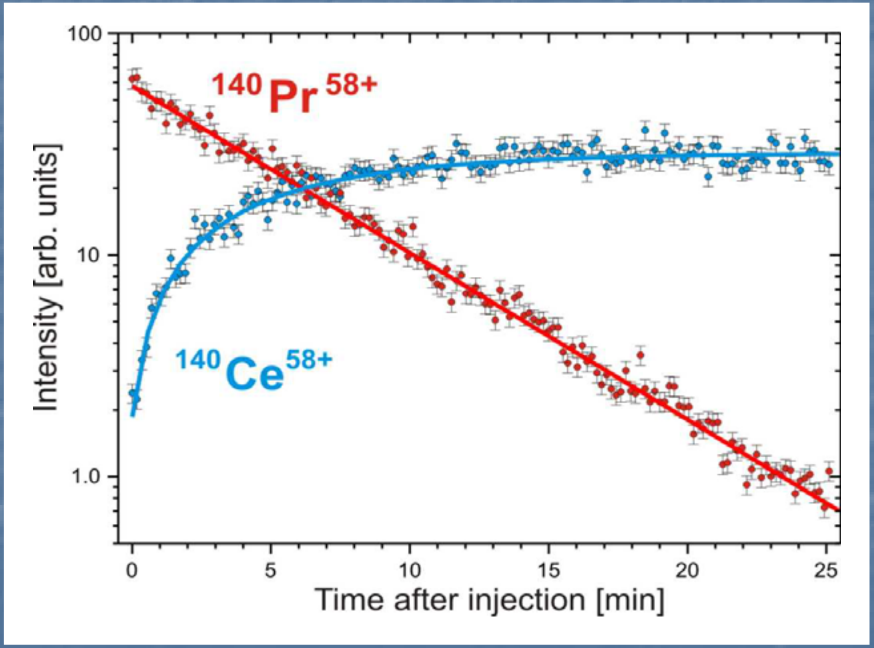
Expectations: λ_{EC}(H-like)/λ_{EC}(He-like) ≈ 0.5

^{140}Pr

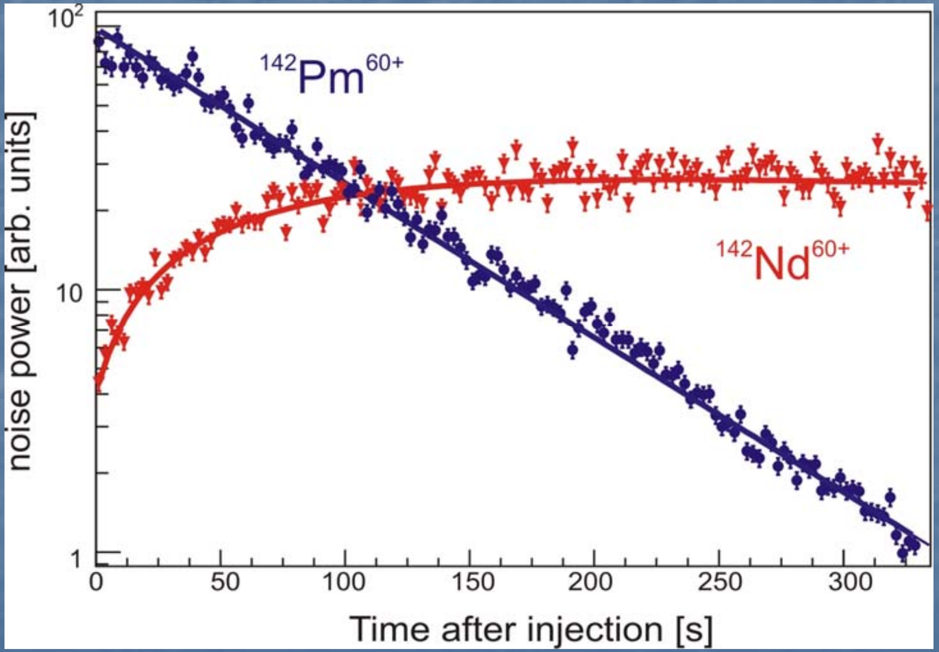
λ_{EC}(H-like)/λ_{EC}(He-like) = 1.49(8)

^{142}Pm

λ_{EC}(H-like)/λ_{EC}(He-like) = 1.44(6)



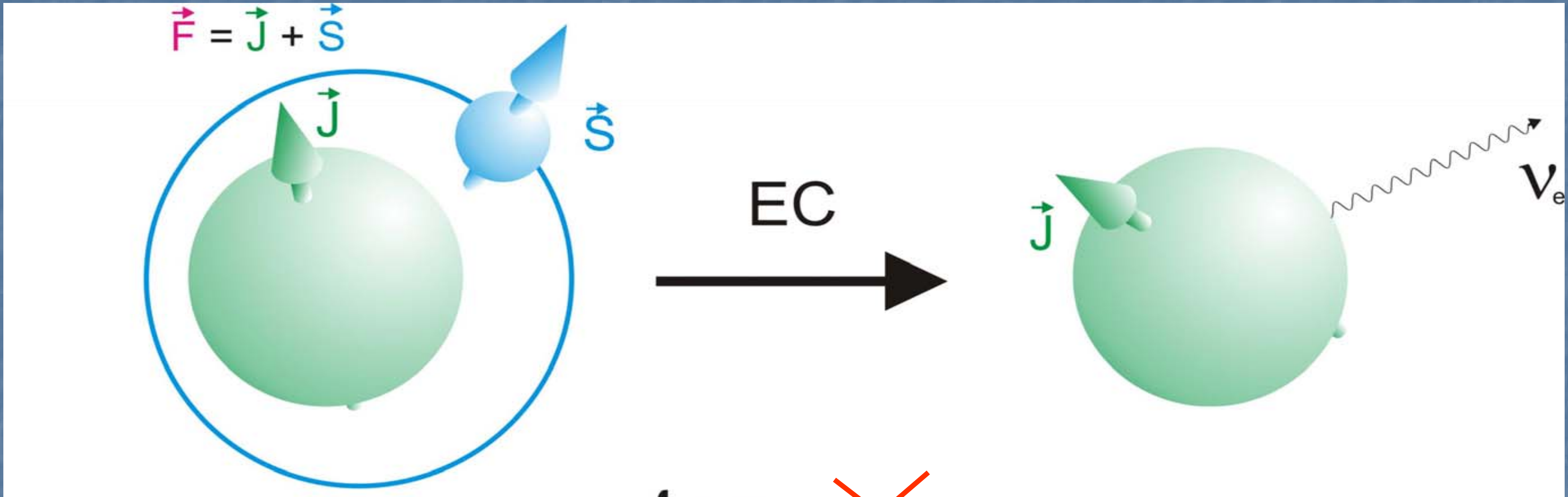
Yu.A. Litvinov et al., Phys. Rev. Lett. 99 (2007) 262501



N. Winckler et al., Phys. Lett. B579 (2009) 36

Electron Capture in Hydrogen-like Ions

Gamow-Teller transition $1^+ \rightarrow 0^+$

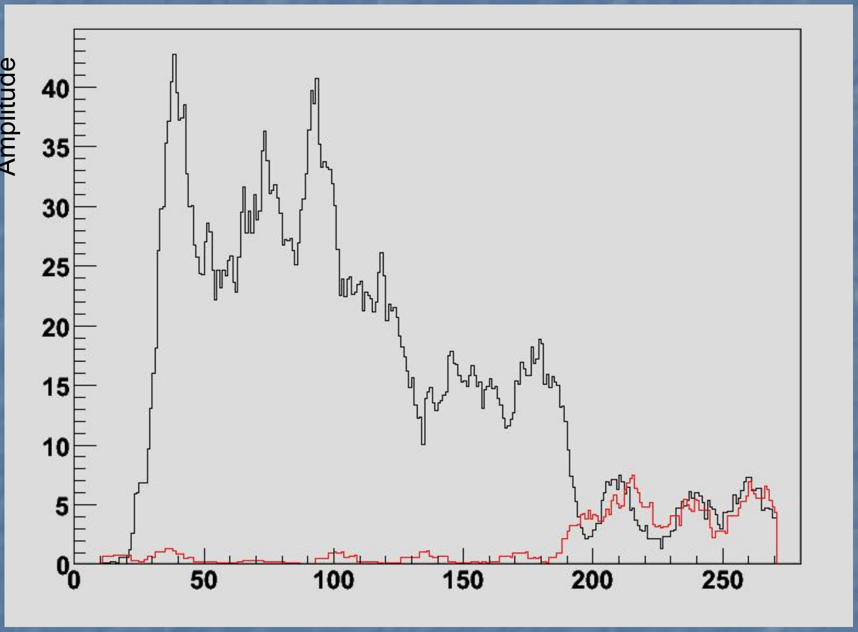


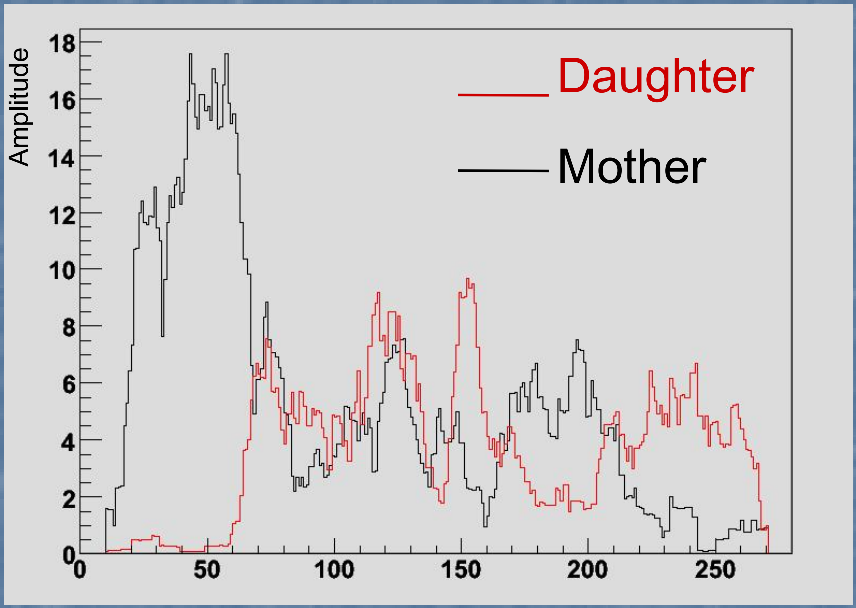
$$F(^{140}Pr^{58+}) = 1 \pm 1/2 = \begin{cases} 3/2 \\ 1/2 \end{cases} \quad F(^{140}Ce^{58+} + \nu_e) = 1/2$$

Z. Patyk et al., Phys. Rev. C 77 (2008) 014306
A. Ivanov et al., Phys. Rev. C 78 (2008) 025503

Why we have to restrict onto 3 injected ions at maximum ?

The variance of the amplitude gets larger than the step 3→4 ions

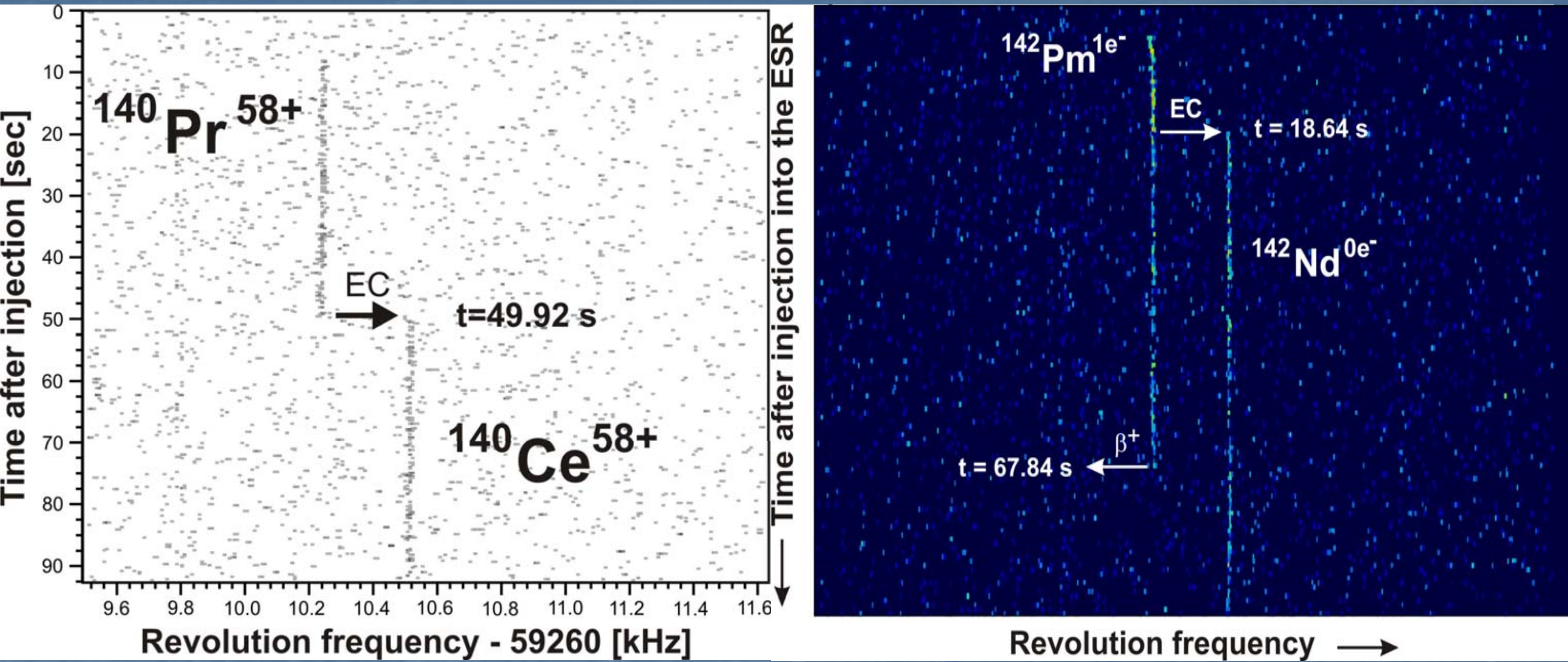




Evaluation of amplitude distributions
corresponding to 1,2,3-particles

Nicolas Winckler

Examples of Measured Time-Frequency Traces



Continuous observation

Parent/daughter correlation

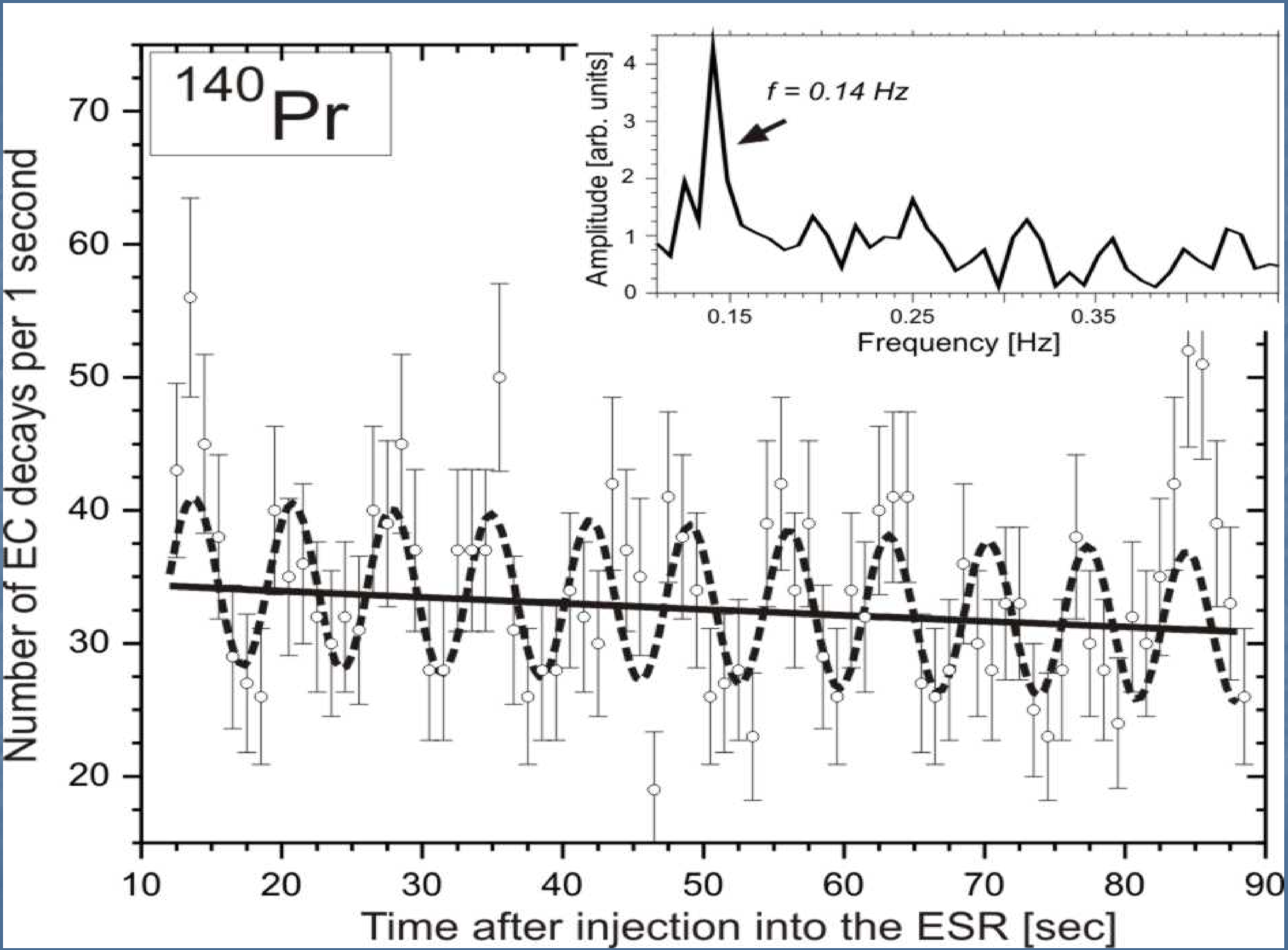
Well-defined creation and decay time

Detection of ALL EC decays

Delay between decay and "appearance" due to cooling

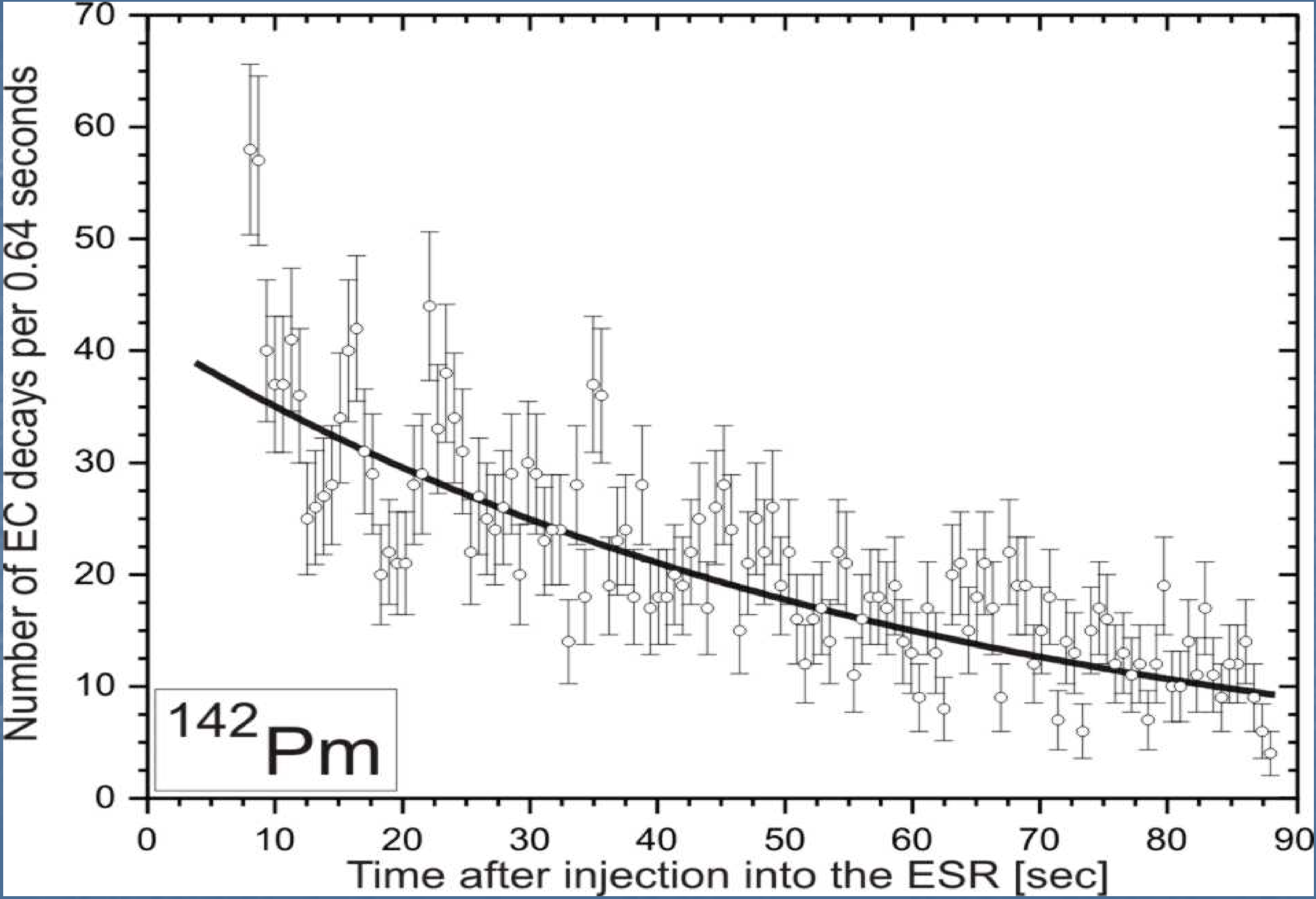
No third particle involved

^{140}Pr : 2650 EC decays from 7102 injections



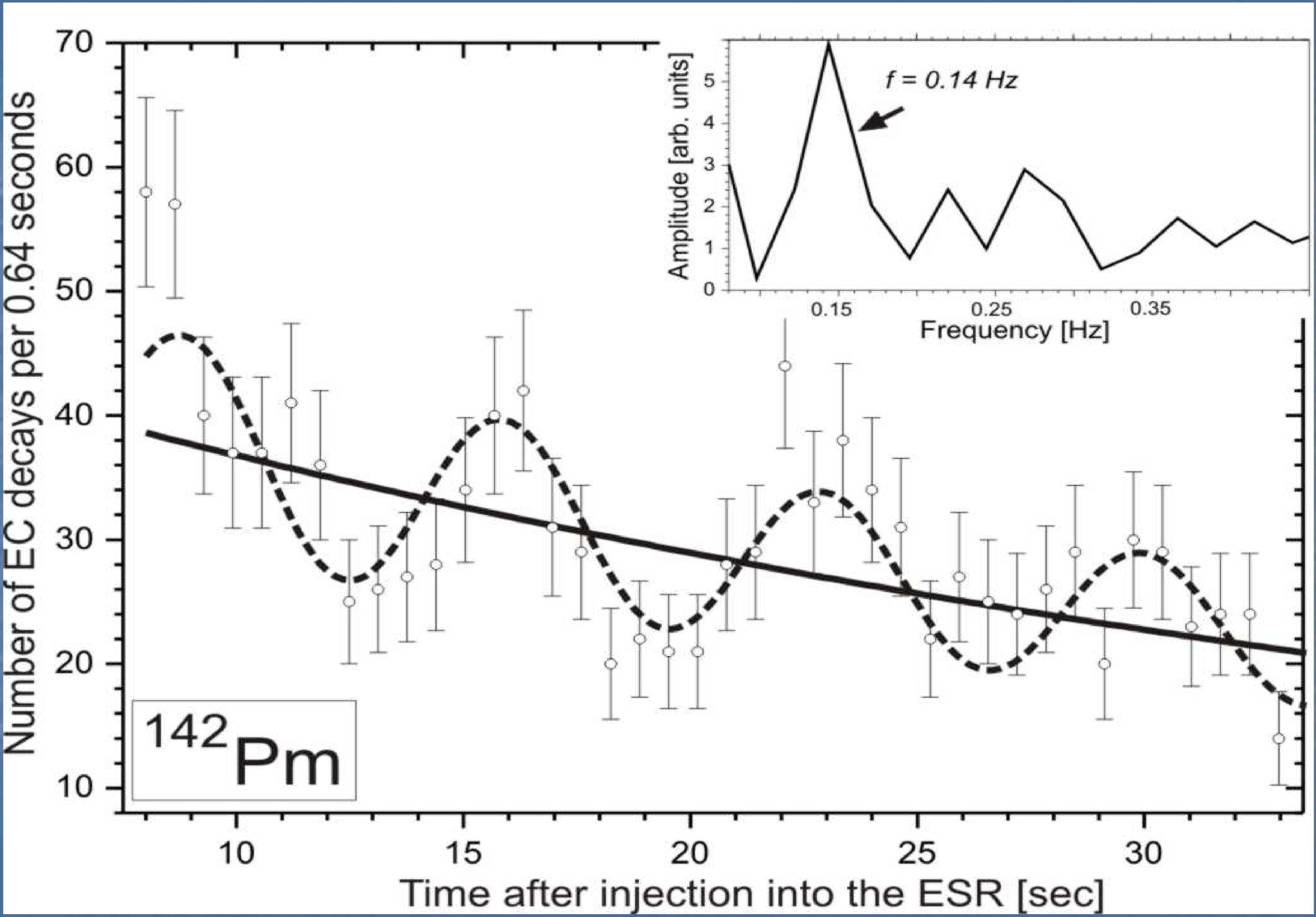
Yu.A. Litvinov et al., PL B 664 (2008) 162

^{142}Pm: 2740 EC decays from 7011 injections



Yu.A. Litvinov et al., PL B 664 (2008) 162

^{142}Pm: zoom on the first 33 s after injection



Yu.A. Litvinov et al., PL B 664 (2008) 162

Synopsis (^{140}Pr & ^{142}Pm)

mass	ω(1/s)	Period (s)	Amplitude	φ(rad)
140	0.890(10)	7.06(8)	0.18(3)	0.4(4)
142	0.885(27)	7.10(22)	0.23(4)	- 1.6(4)

Yu.A. Litvinov et al., PL B 664 (2008) 162

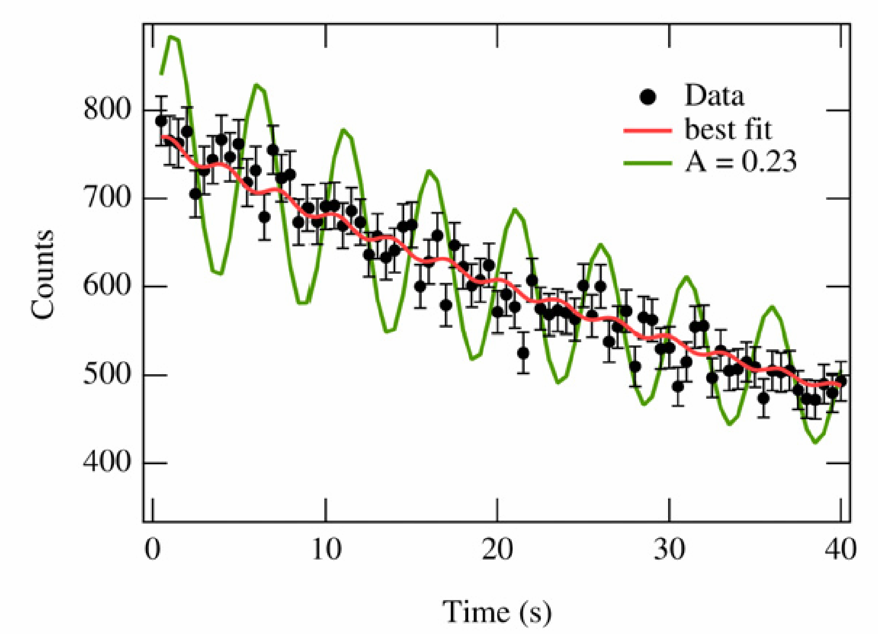
Straightforward Questions

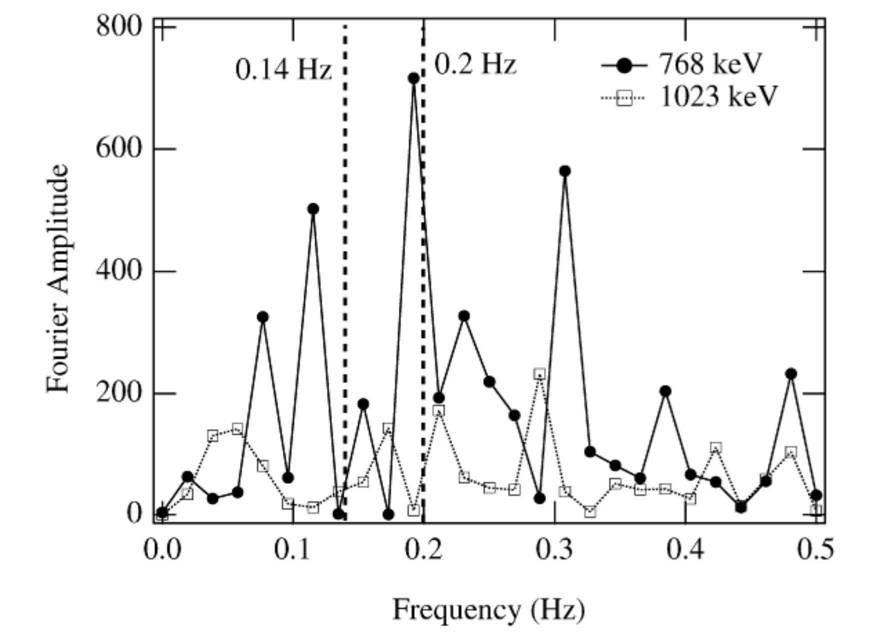
- 1. **Are the periodic modulations real ?**

2. **Can coherence be preserved over macroscopic times for a confined motion, interacting ions and at continuous observation ?**

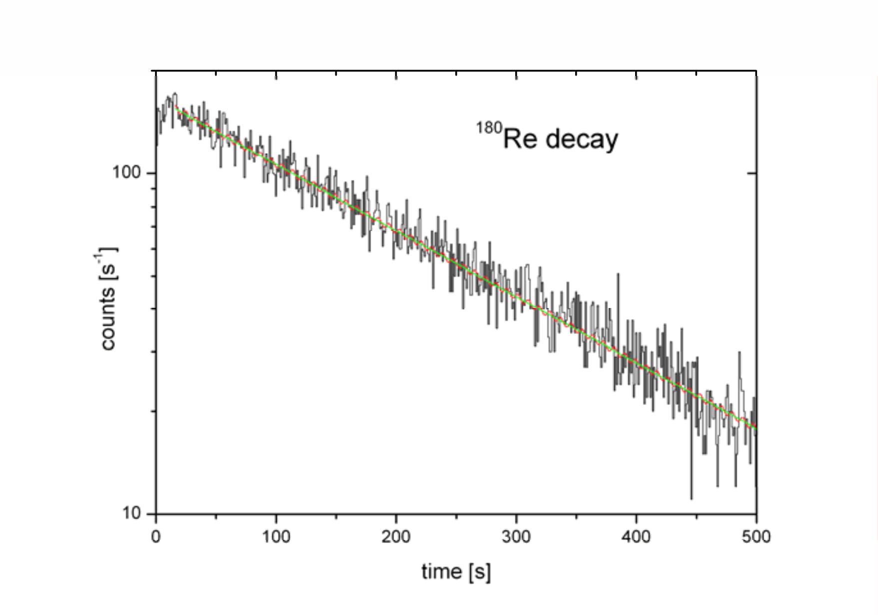
3. **If "yes", what could be the origin ?**

EC decay of implanted ^{142}Pm & ^{180}Re



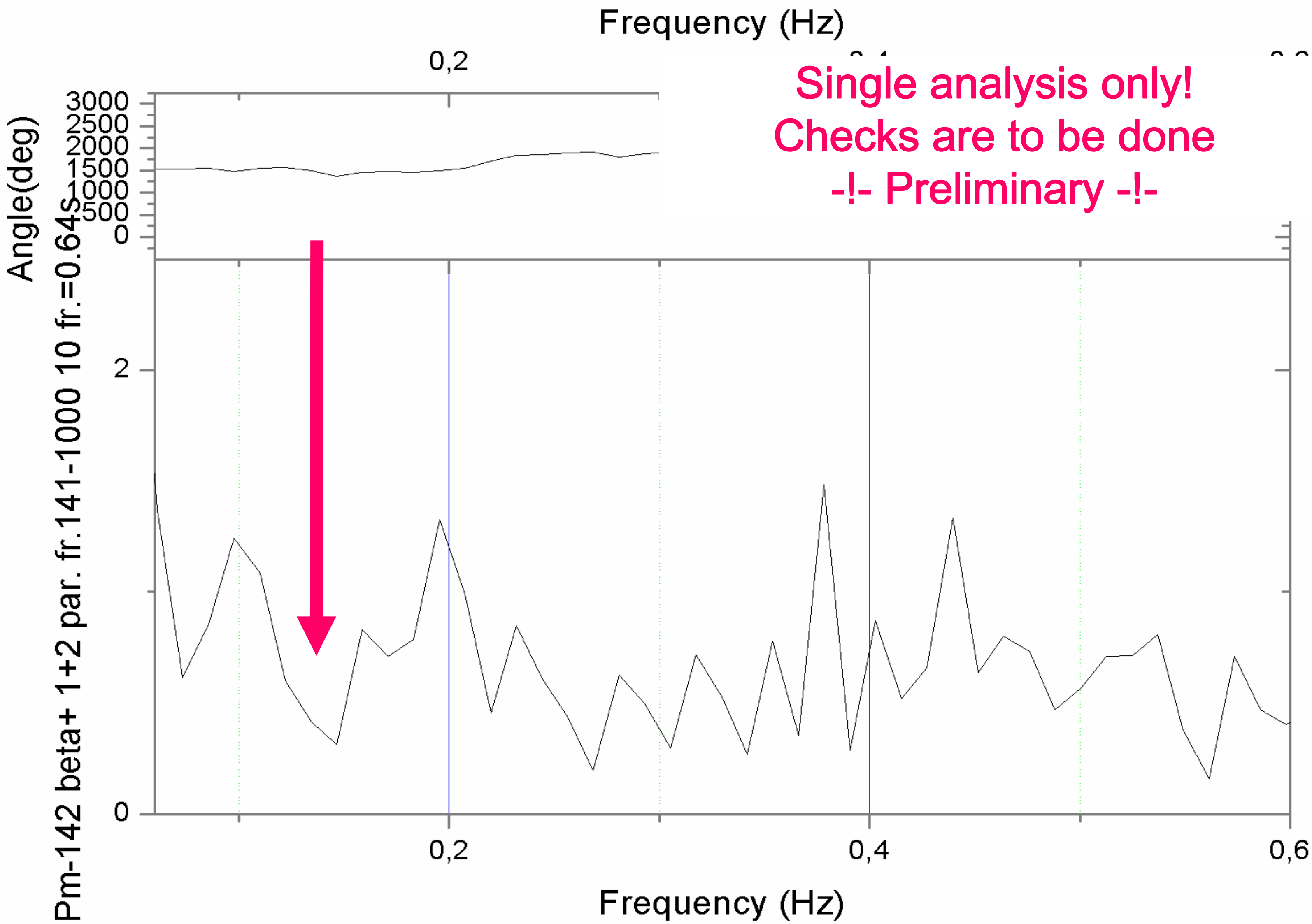


P.A. Vetter et al., Phys. Lett. **B 670** (2008) 196



Th. Faestermann et al., Phys. Lett. **B 672** (2009) 227

EC-decay vs. Beta-decay for 142Pm



Single analysis only!
Checks are to be done
-!- Preliminary -!-

Quantum Beats Phenomenon

Coherent excitation of an electron in two quantum states, separated by ΔE at time t_0

The phase correlation imprinted at t_0 is preserved until the emission of the photons at time t

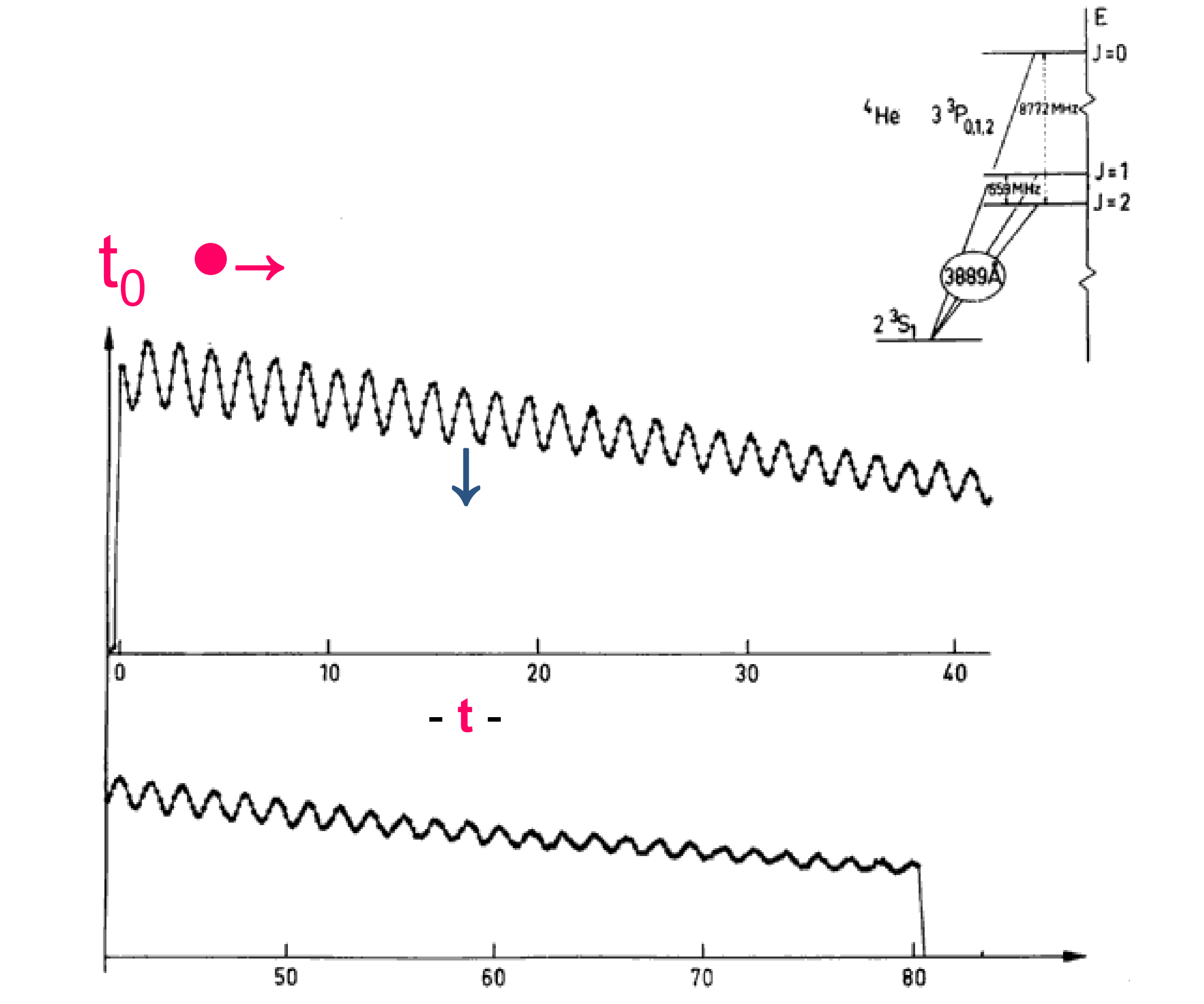


Fig. 24. Zero-field oscillations between the 1s 3p $^3P_1$ and 1s 3p $^3P_2$ states in He I (659 MHz), Wittmann [248]. The oscillations are superimposed on the exponential decay of the 1s 3p ^3P term (96 ns). To record this decay curve about 10 hours beam time (a few μA) and more than 20 carbon foils were needed.

Chow et al., PR A11(1975) 1380

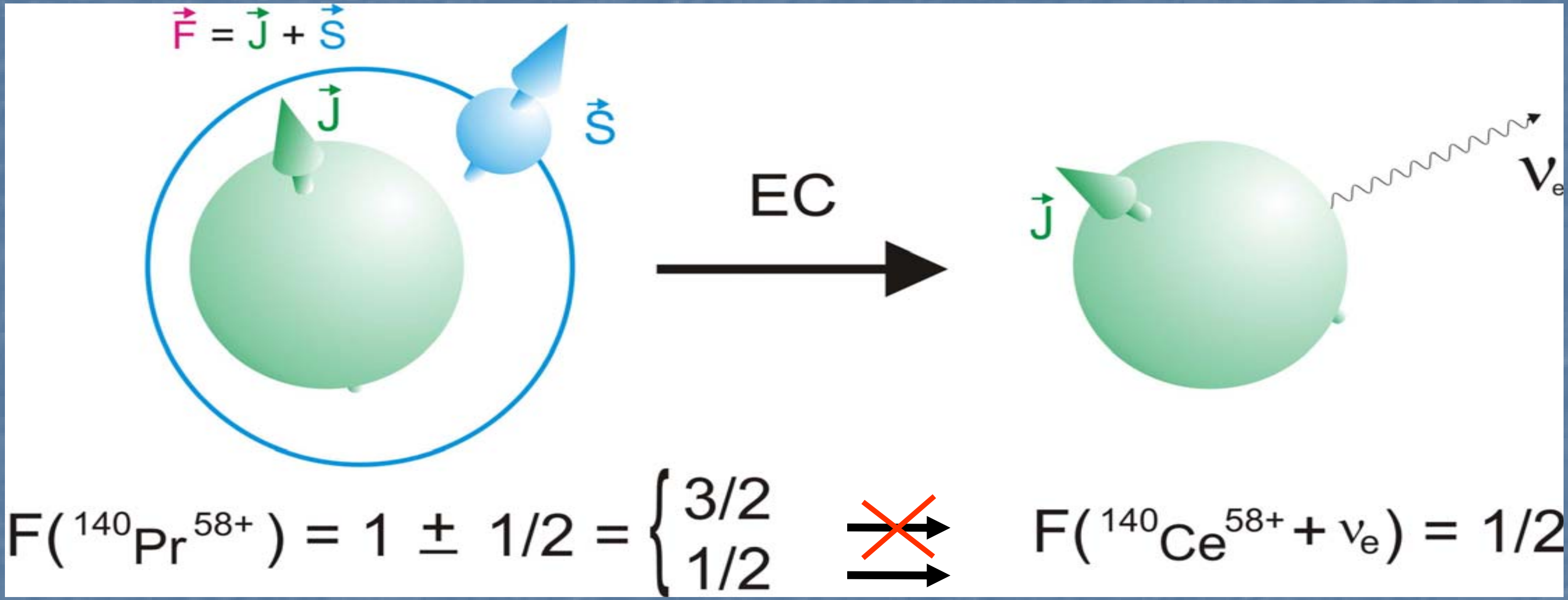
“Classical” Quantum Beats vs. EC-decay in the ESR

- Quantum beats
- \- two initial states with different quantum numbers
- \- excited atom moves free in space
- \- observation time nanoseconds - microseconds
- EC - decay of H-like ions stored in a ring
- \- parent atom created in one initial state
- \- moves confined by electromagnetic forces
- \- interacts with e^- of the cooler, atoms, beam pipe..
- \- observation time some 10 seconds

"Quantum Beats" from the Hyperfine States

Coherent excitation of the 1s hyperfine states **F = 1/2, F= 3/2**

Beat period T = h/ΔE; for ΔE ≈ 1 eV → **T ≈ 10^{-15} s**



$\mu = +2.7812\ \mu_N$ (calc.)

Decay can occur only from the **F=1/2** (ground) state

Yu.A. Litvinov et al., PRL 99 (2007) 262501

Periodic spin flip to "sterile" F=3/2 ? → λ_{EC} reduced

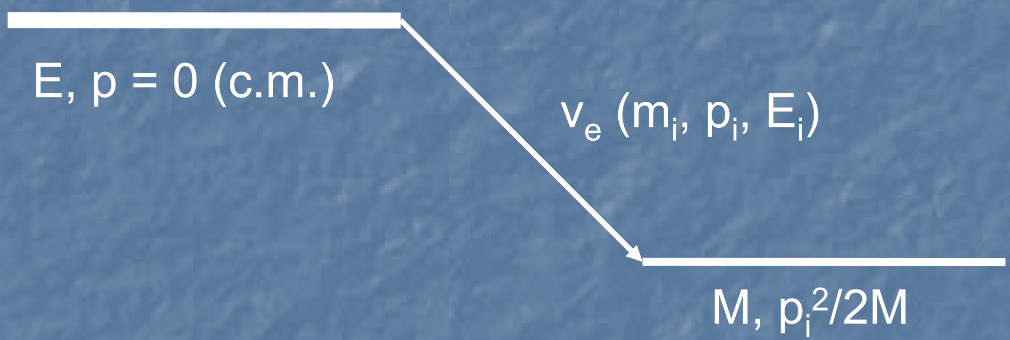
Periodic transfer from F = 1/2 to "sterile" F = 3/2 ?

- 1. Decay constants for H-like ^{140}Pr and ^{142}Pm should get smaller than expected. $\longrightarrow$ NO
- 2. Statistical population in these states after
- $t \approx \max\,[1/\lambda_{flip},\ 1/\lambda_{dec.}]$
-
- 3. Phase matching over many days of beam time?

Beats due to neutrino being not a mass eigenstate?

The electron neutrino appears as coherent superposition of mass eigenstates

The recoils appear as coherent superpositions of states entangled with the electron neutrino mass eigenstates by momentum- and energy conservation



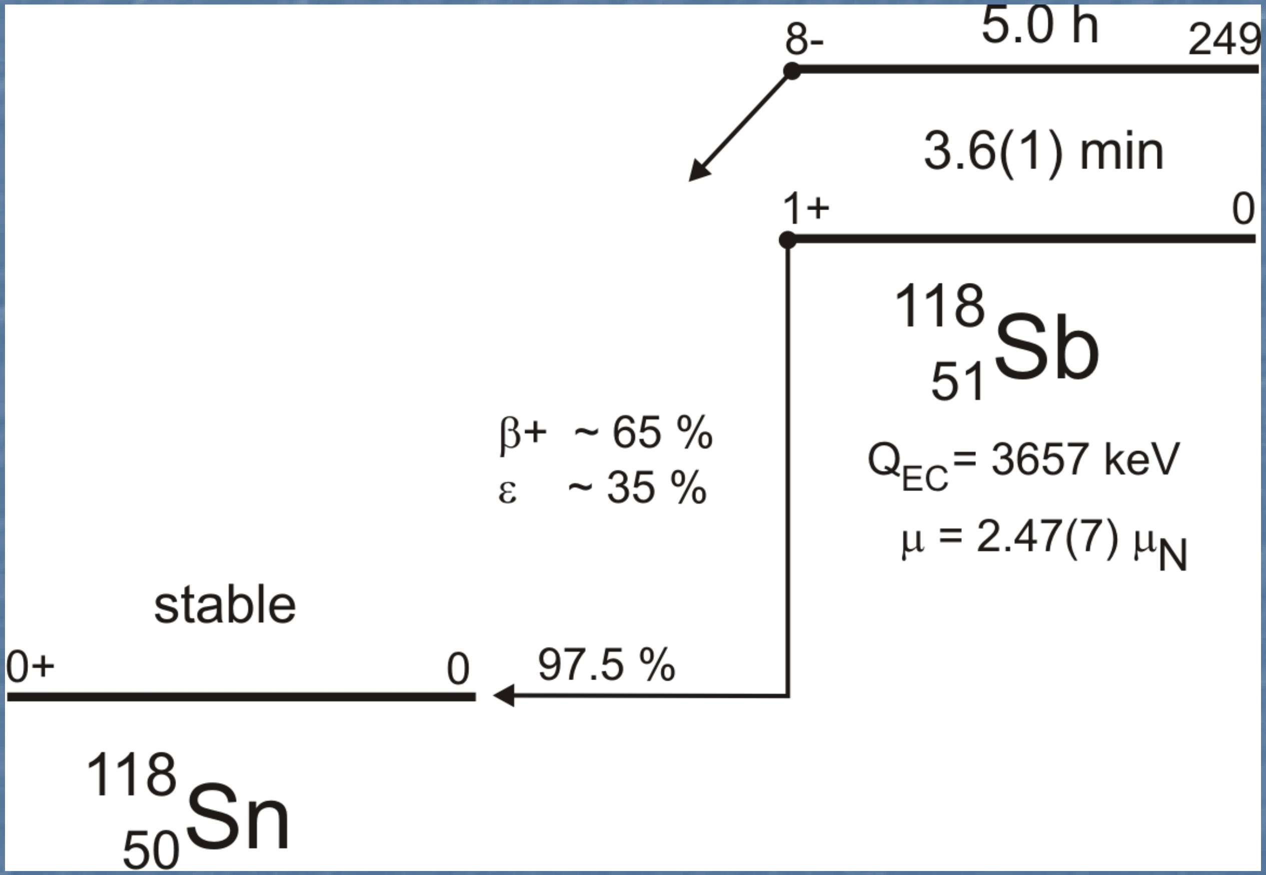
$M + p_1^2/2M + E_1 = E$
$M + p_2^2/2M + E_2 = E$
"Asymptotic" conservation of E, p

$$\Delta E_\nu \approx \Delta m^2/2M = 3.1 \cdot 10^{-16}\ \mathrm{eV}$$

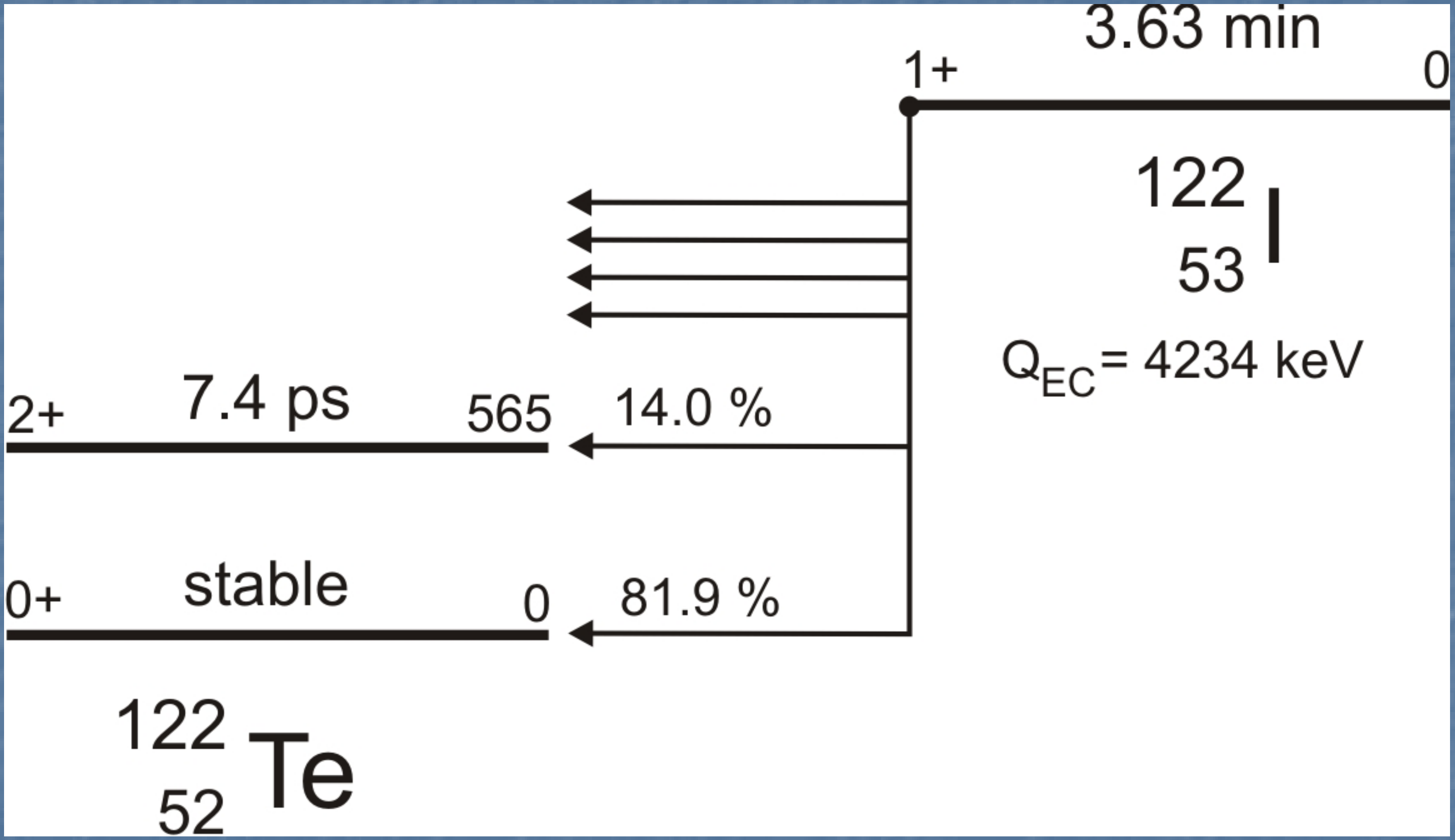
$m_1^2 - m_2^2 = \Delta m^2 = 8 \cdot 10^{-5}\ \mathrm{eV}^2$
$E_1 - E_2 = \Delta E_\nu$

Oscillation period T proportional to nuclear mass M ?

New Experiment



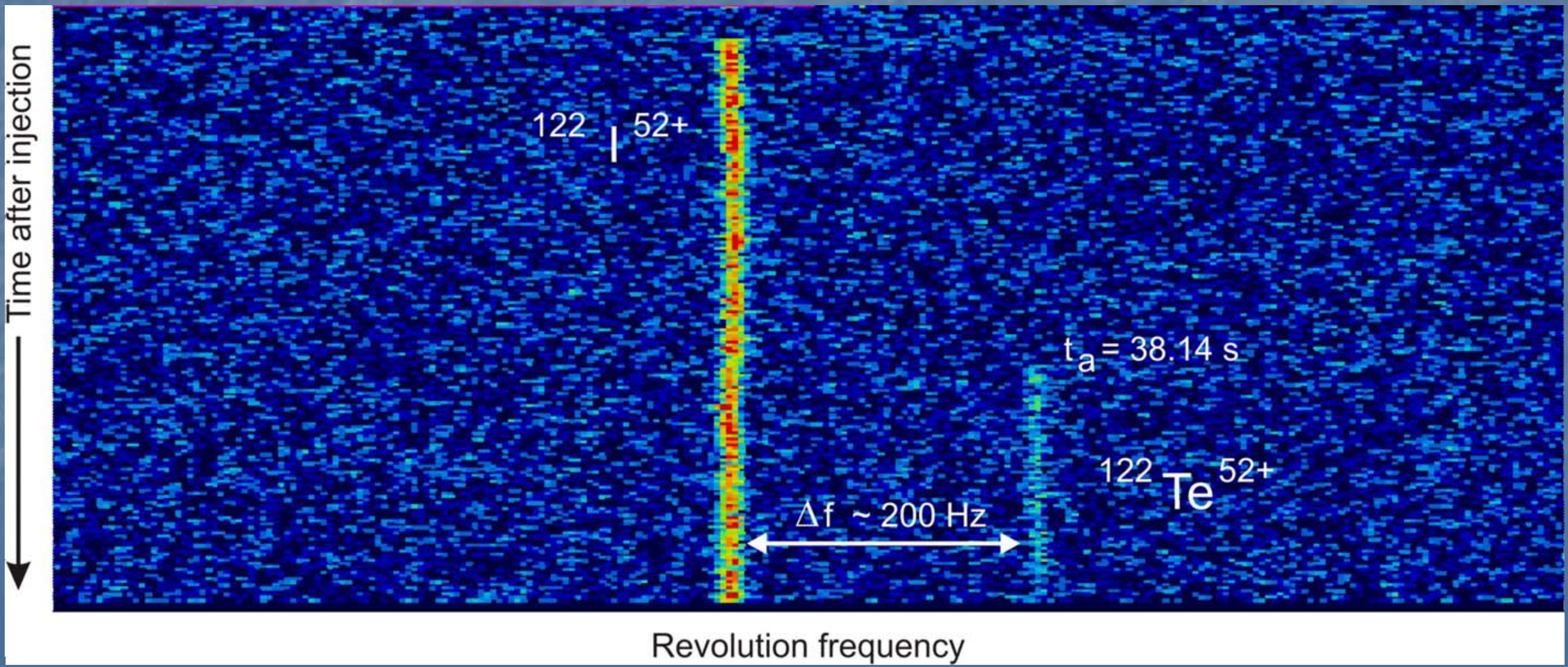
New Experiment on H-like ^{122}I ions



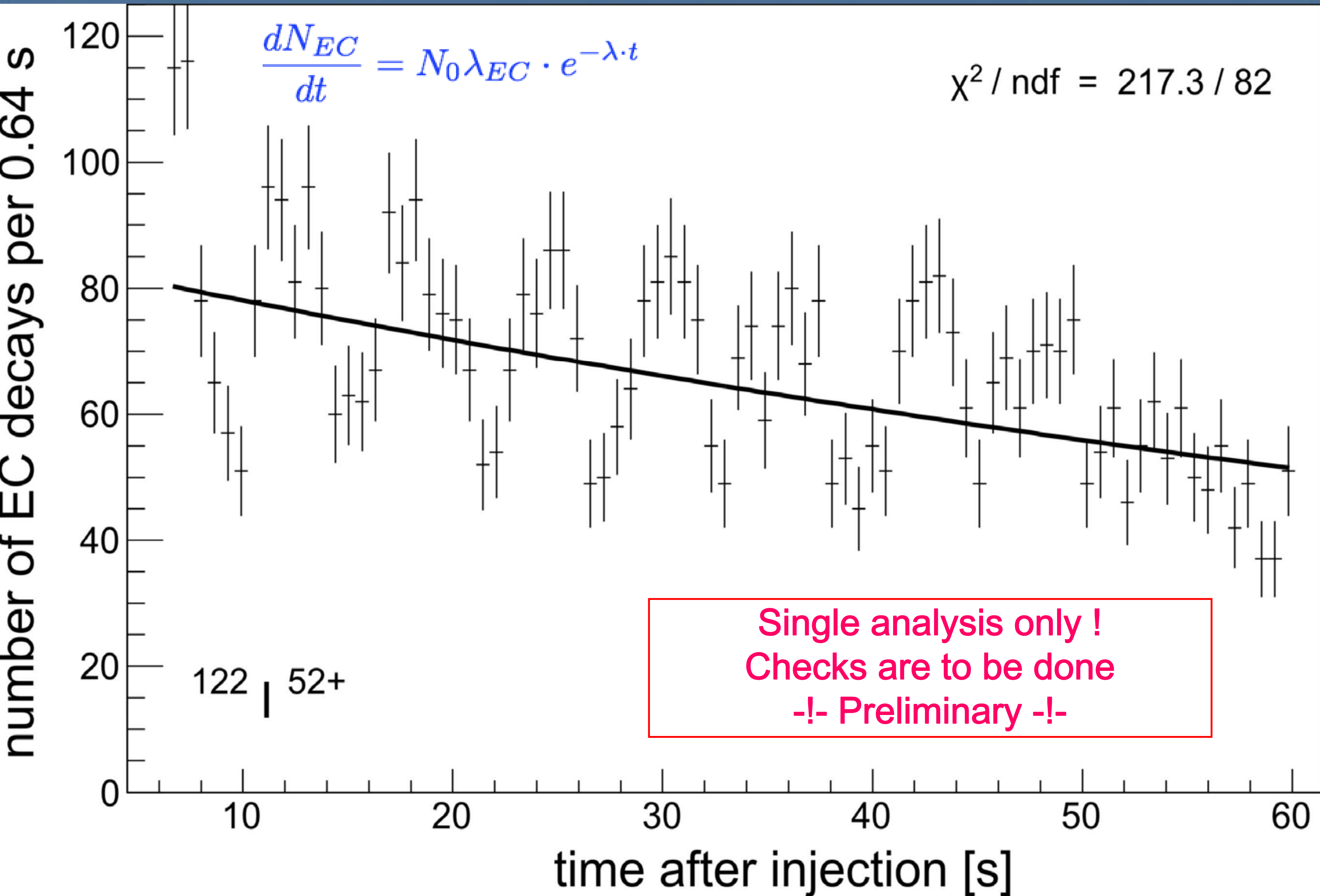
Experiment: 31.07.2008-18.08.2008

Decay Statistics

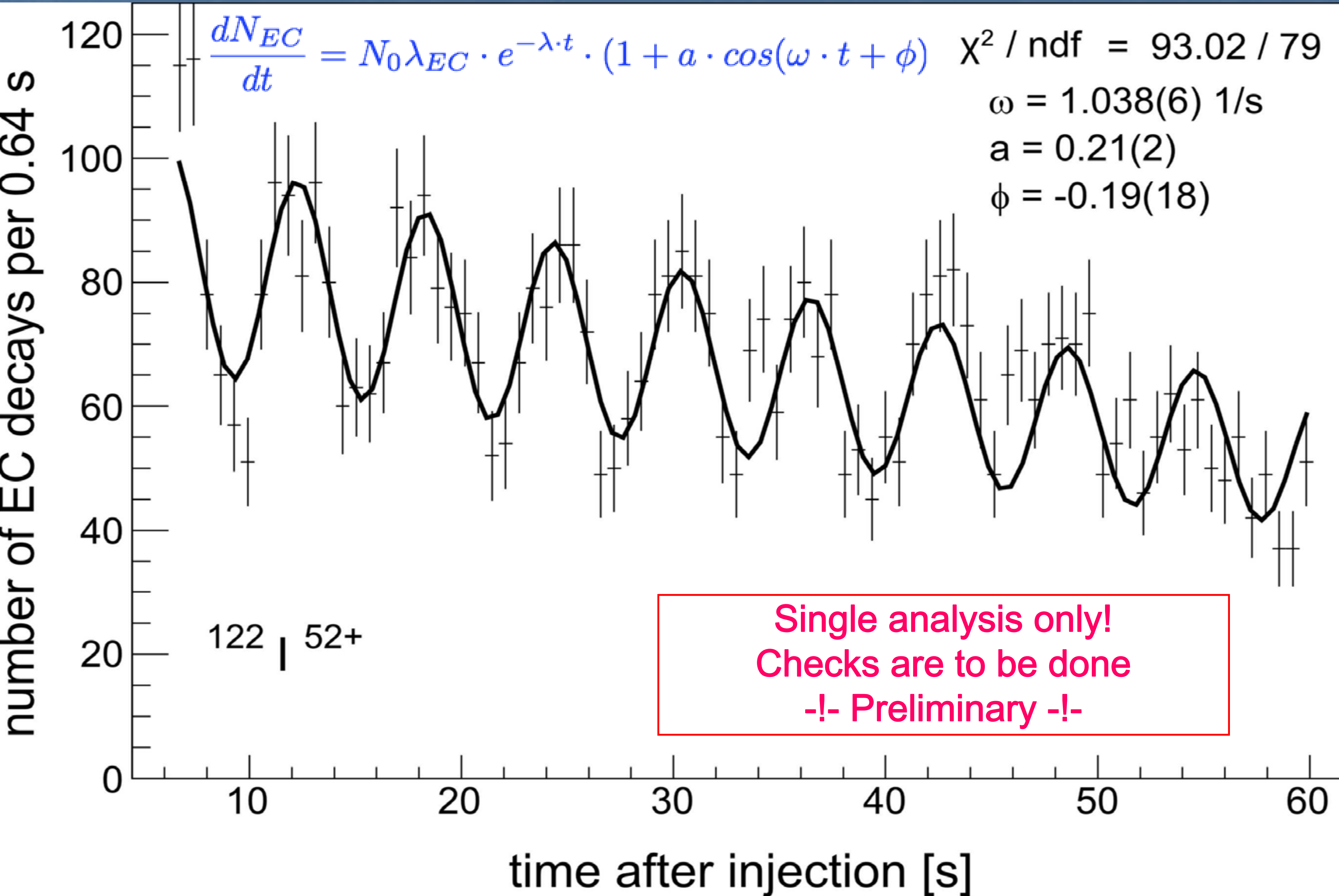
Correlations: 10.808 injections ~ 1080 EC-decays
Many ions: 5718 injections ~ 5000 EC-decays



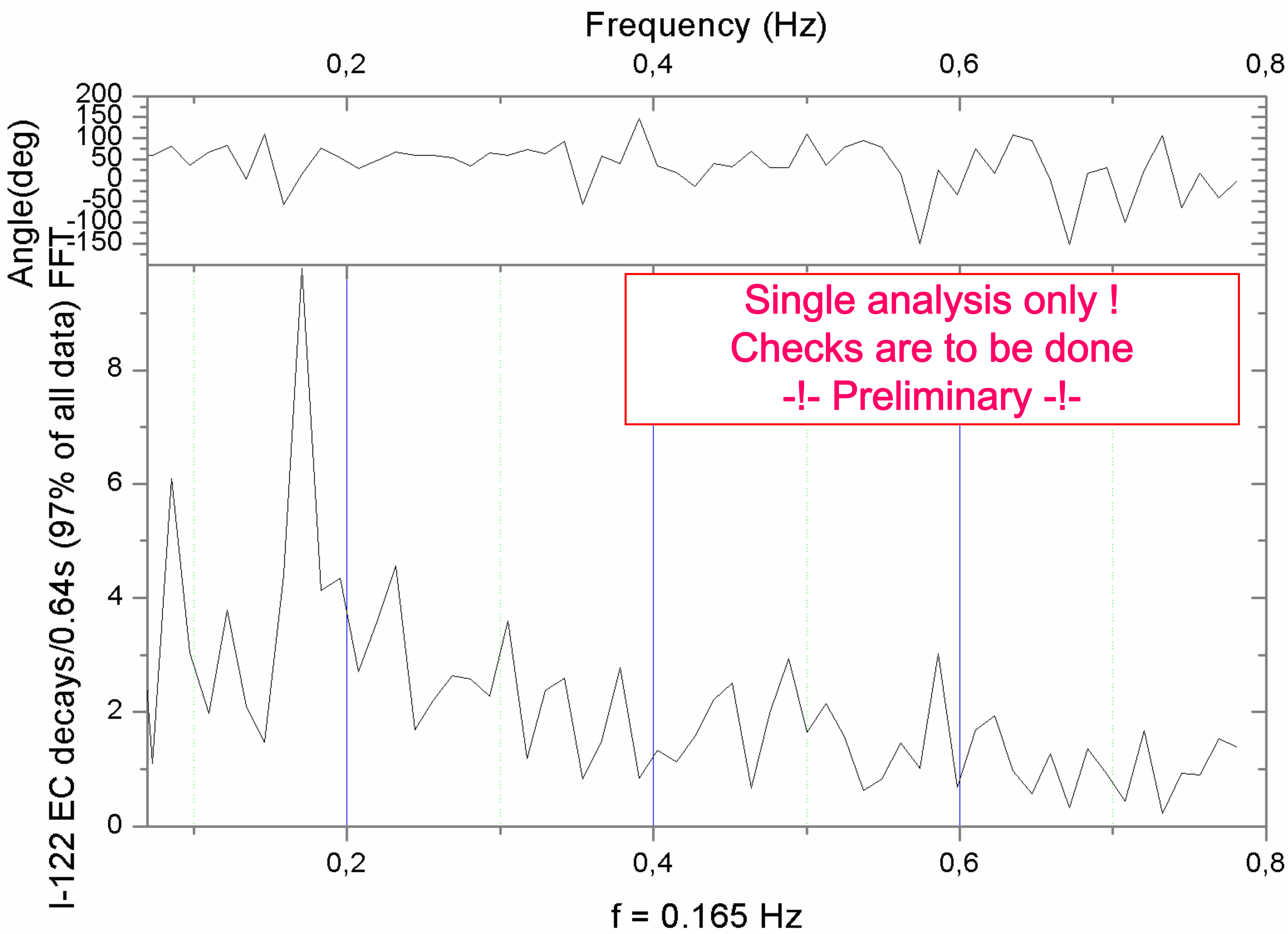
Exponential Fit



Exponential + Modulation Fit



Sum of All Evaluated EC Decays



Synopsis (^{140}Pr & ^{142}Pm)

mass	ω(1/s)	Period (s)	Amplitude	φ(rad)
122(*)	1.036(8)	6.05(4)	0.21(2)	-0.2(2)
140	0.890(10)	7.06(8)	0.18(3)	0.4(4)
142	0.885(27)	7.10(22)	0.23(4)	- 1.6(4)

(*) -!- Preliminary -!-

Outlook

- Can the observed effect be a tricky technical artifact?
- In the preliminary analysis we see two different frequencies
- In the preliminary analysis we see no modulation in the β^+ - decay channel
- More experiments are needed.

- Can the effect be due to a hypothetical interaction of the bound electron with the surrounding?
- \- Will be checked by studying the EC decay of He-like ^{142}Pm ions (March 2010).

- Can the frequency scaling with the nuclear mass be due to an unknown effect that depends on the nuclear mass (magnetic rigidity)
- \- Will be checked with the same ion type at different velocities (magnetic rigidities)

- Can the effect be due to a "neutrino"-driven quantum beat phenomenon?
- \- Modulation periods scale with the nuclear mass
- \- Extremely long coherence time

- **Independent verification at another facility is urgently needed**
- **(CSRe ring at IMP/Lanzhou; WITCH setup at ISOLDE/CERN)**

Experimental Collaboration

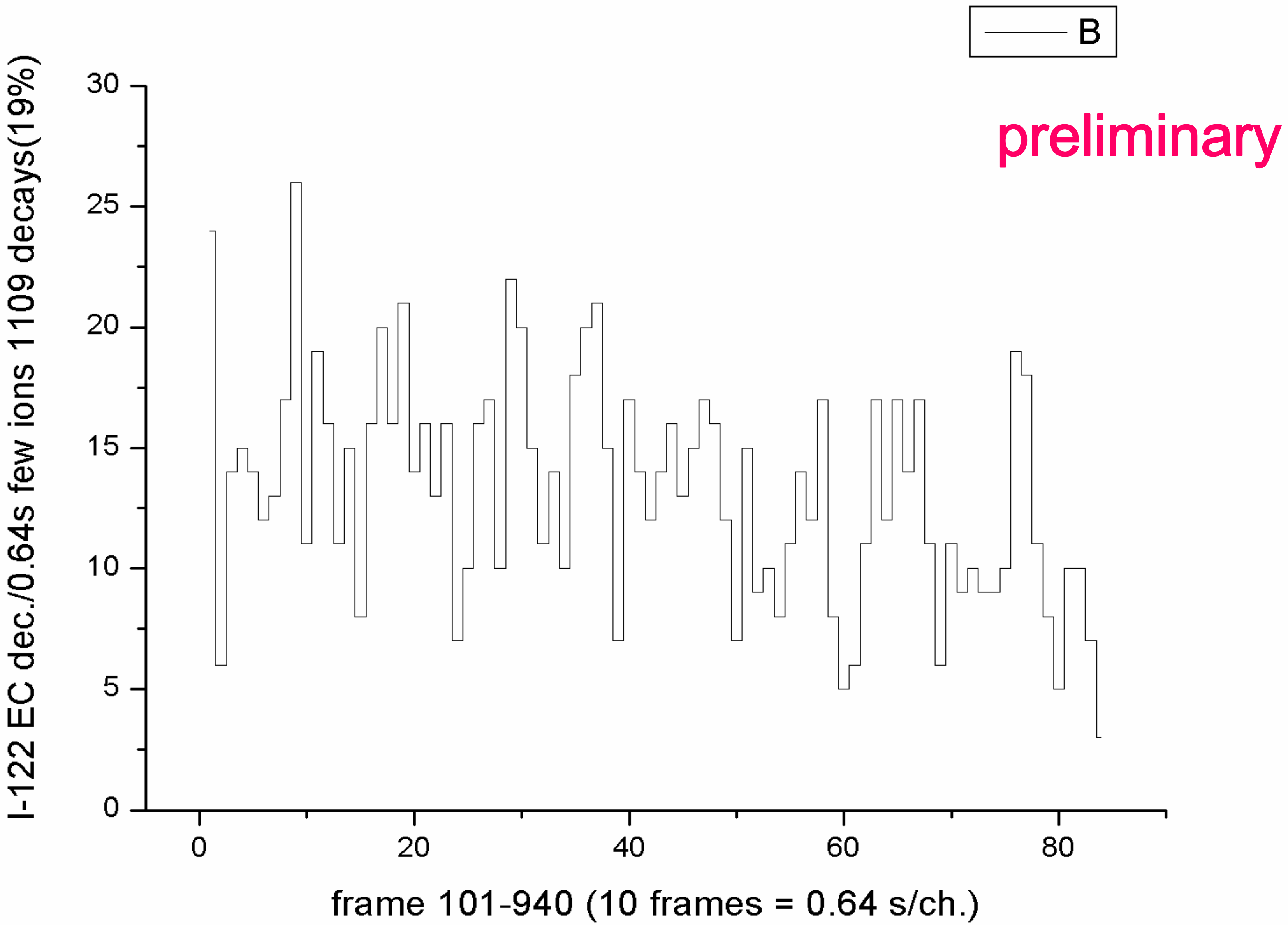
F. Bosch, D. Boutin, C. Brandau, L. Chen, Ch. Dimopoulou, H. Essel, Th. Faestermann, H. Geissel, E. Haettner, M. Hausmann, S. Hess, P. Kienle, Ch. Kozhuharov, R. Knöbel, J. Kurcewicz, S.A. Litvinov, Yu.A. Litvinov, L. Maier, M. Mazzocco, F. Montes, A. Musumarra,
G. Münzenberg, C. Nociforo, F. Nolden, T. Ohtsubo, A. Ozawa, W.R. Plass, A. Prochazka,
R. Reuschl, Ch. Scheidenberger, U. Spillmann, M. Steck, Th. Stöhlker, B. Sun, T. Suzuki, S. Torilov, H. Weick, M. Winkler, N. Winckler, D. Winters, T. Yamaguchi

Sudoku

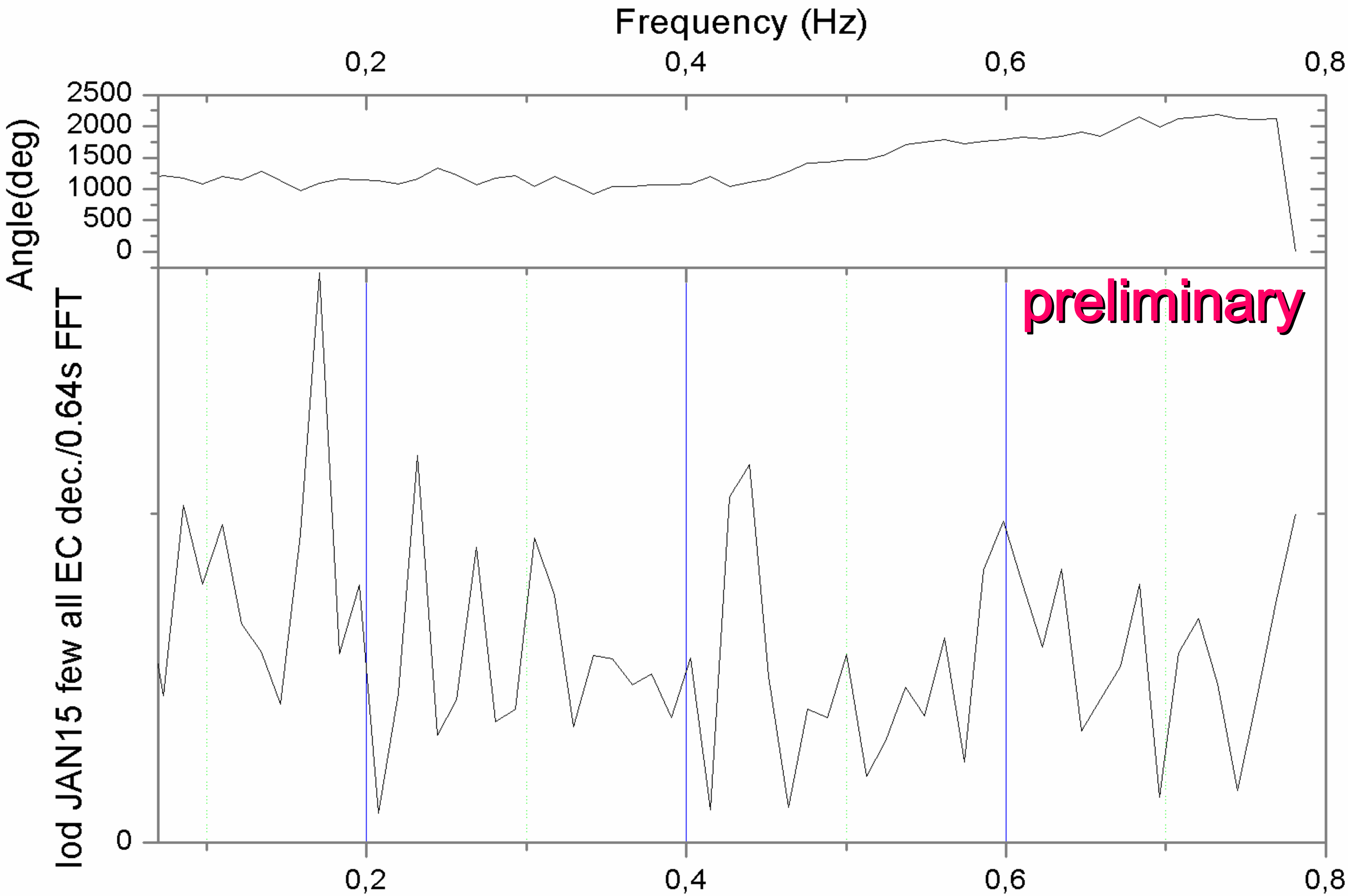
Hard #1

ν_μ		ν_τ		ν_1		ν_3	W^+	
	Z	W^+						
			ν_μ					ν_1
ν_τ		Z	ν_1					
ν_2			Z		ν_e			ν_μ
					ν_3	ν_τ		W^+
W^-					Z			
						Z	ν_3	
	ν_3	ν_e		W^-		ν_μ		ν_2

Few (1..3) stored parents 1109 EC decays

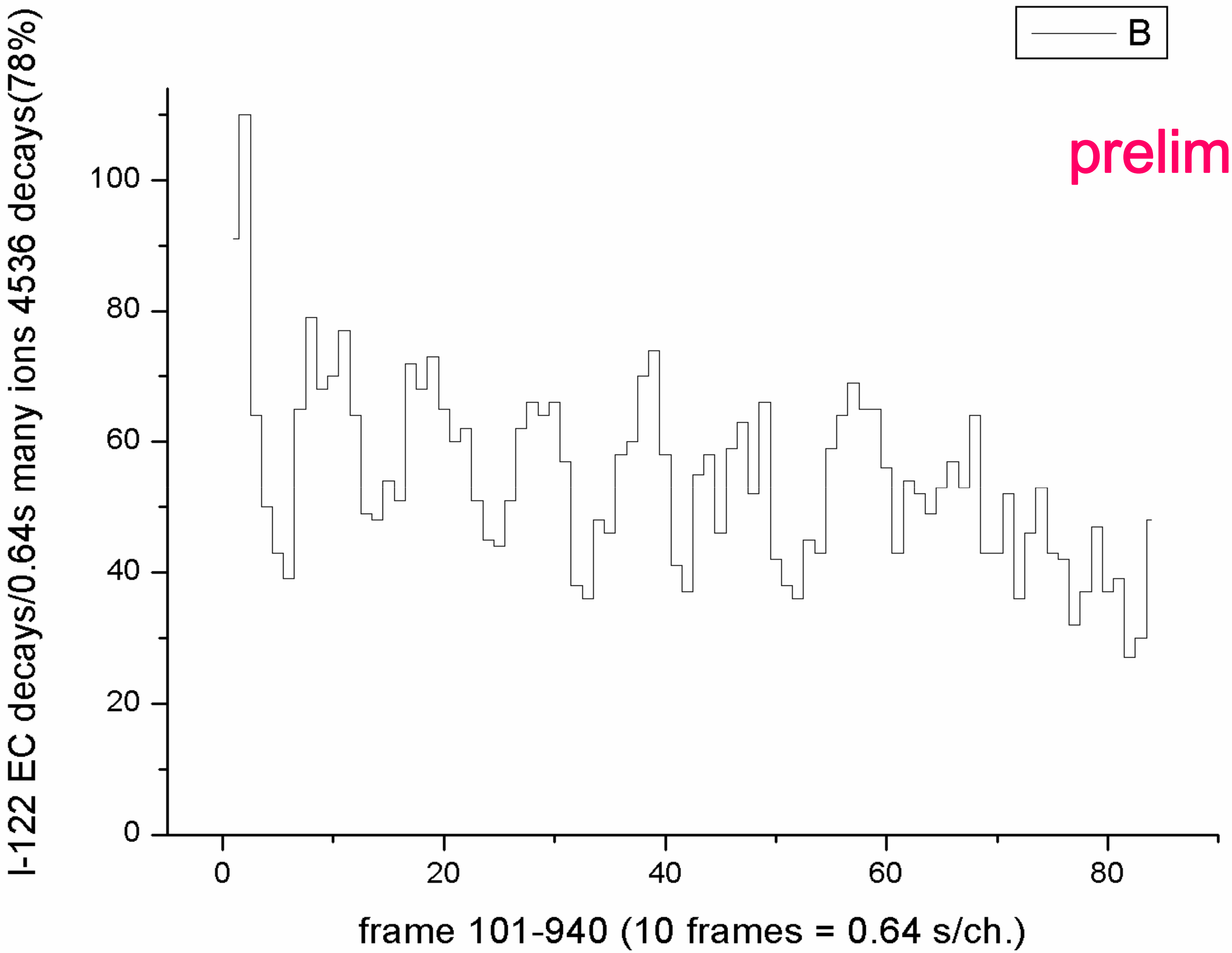


Few (1..3) stored parents – FFT

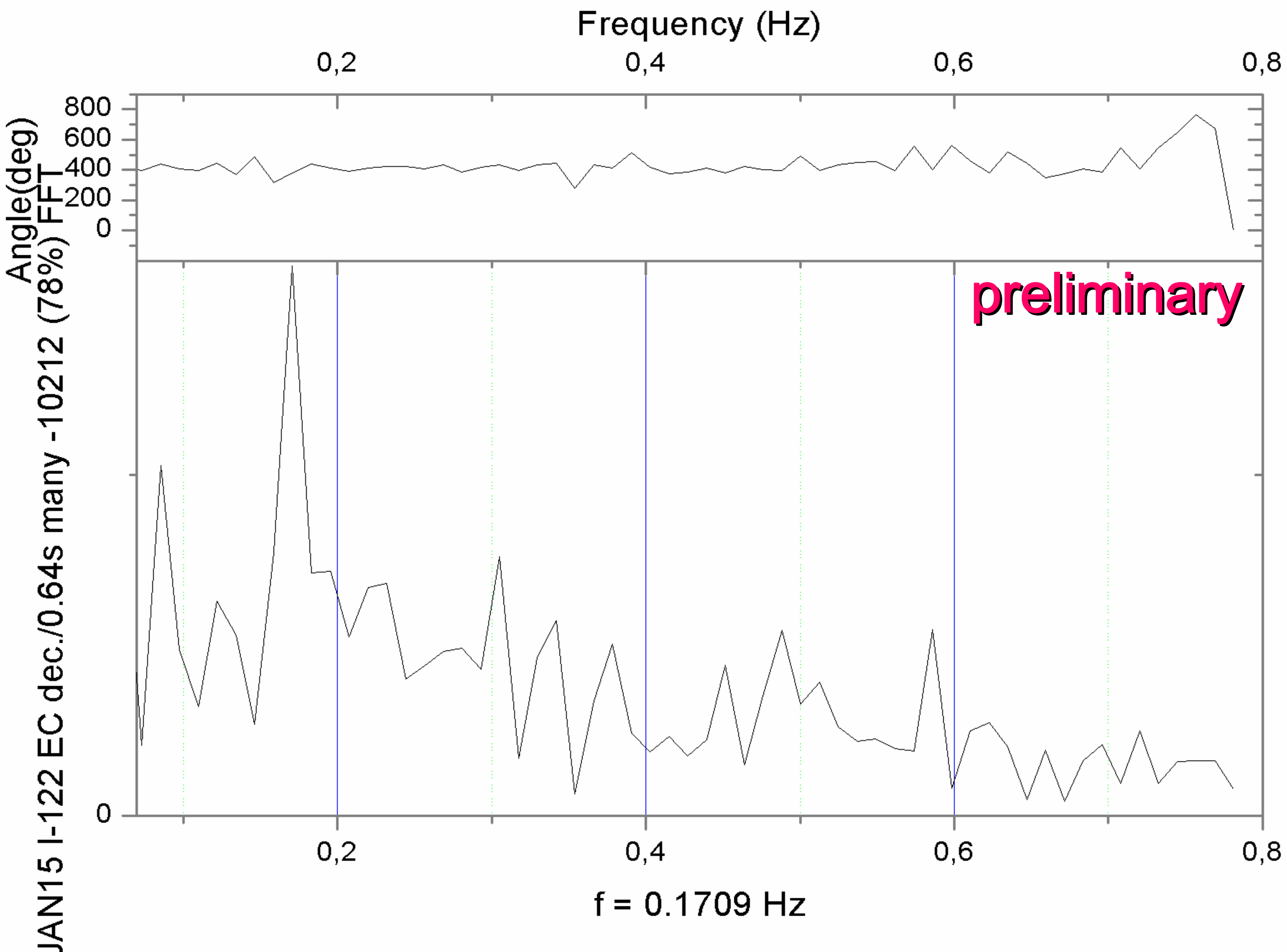


f = 0.1709 Hz

Many (10..30) parent ions 4536 EC decays



Many (20..30) stored parents – **FFT**



Implantation of daughter ions into a lattice: Final state:

Neutrino, daughter ion and **phonon(s)** with energies α_k

Projected wave function:

$$|\psi_f|^2 \sim 1/2 \sin^2 2\theta \{\cos(\Delta E_{12} t + \varphi)] + \cos[(\Delta E_{12} + \Delta\alpha_{kl}) t + \varphi)] + \cos[\Delta\alpha_{kl} t + \varphi)]\}$$

$\Delta\alpha_{kl} = \alpha_k - \alpha_l$ (depends on phonon level density, lattice site...)

→ could wash-out mono-periodic modulations