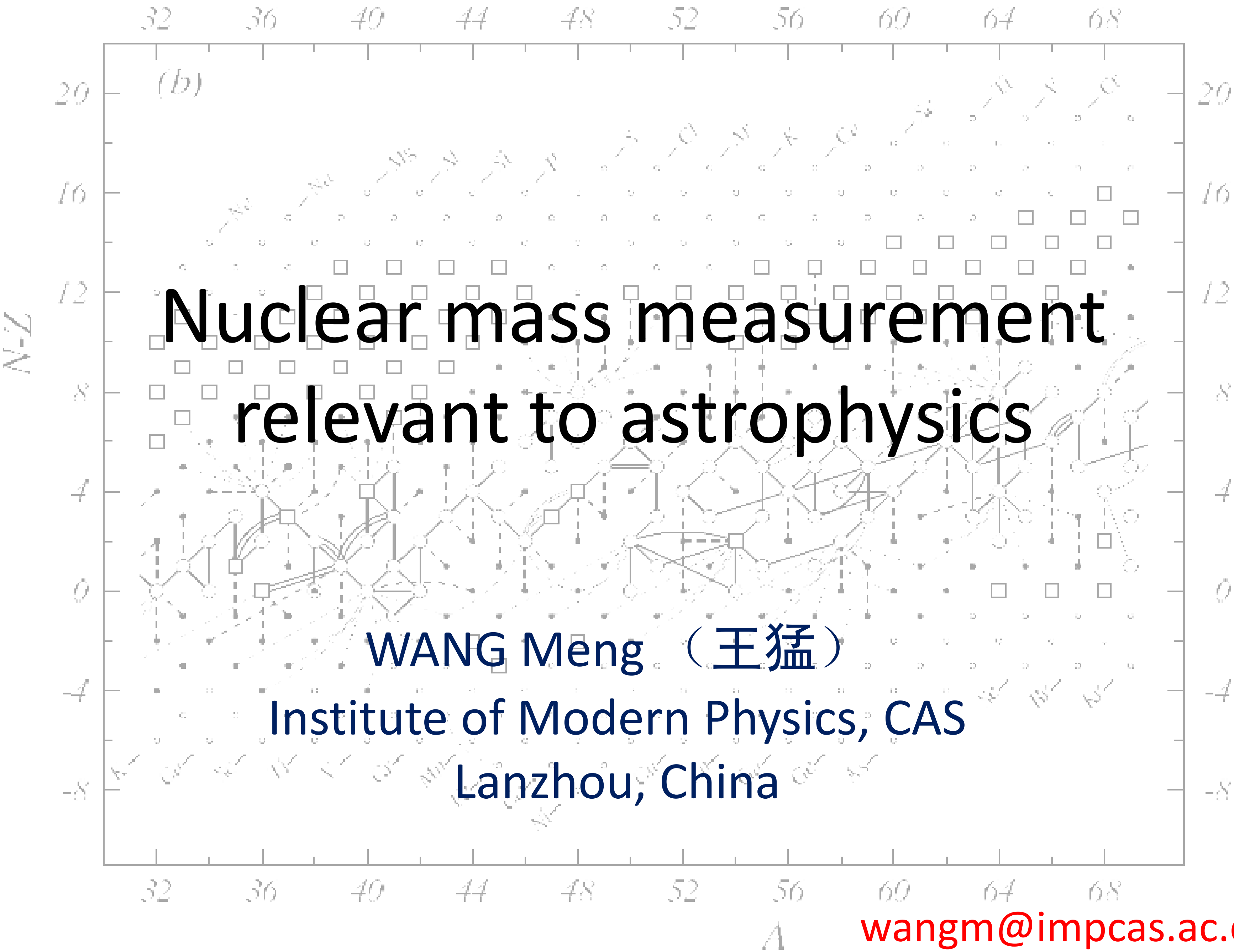
Shanghai, 2016.12.16



Nuclear mass measurement relevant to astrophysics

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Lanzhou, China

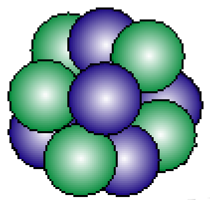
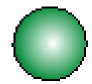
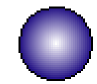
wangm@impcas.ac.cn

Outline

- Background
- recent progresses
- Results from Lanzhou
- Future perspective

Mass → binding energy → interaction

E=mc^2

 $= N \times$  $+ Z \times$ 

$-$ binding energy

Filed of application	Required uncertainty
Chemistry: identification of molecules	10^{-5}–10^{-6}
Nuclear physics: shells, sub-shells, pairing	10^{-6}
Nuclear fine structure: deformation, halos	10^{-7}–10^{-8}
Astrophysics: r-process, rp-process, waiting points	10^{-7}
Nuclear models and formulas: IMME	10^{-7}–10^{-8}
Weak interaction studies: CVC hypothesis, CKM unitarity	10^{-8}
Atomic physics: binding energies, QED	10^{-9}–10^{-11}
Metrology: fundamental constants, CPT	10^{-10}

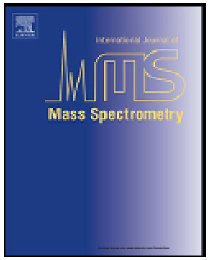
K. Blaum, Physics Reports 425 (2006) 1–78

International Journal of Mass Spectrometry 349–350 (2013) 181–186

Contents lists available at ScienceDirect

International Journal of Mass Spectrometry

journal homepage: www.elsevier.com/locate/ijms



Nuclear masses in astrophysics

H. Schatz *

Nuclear masses play a fundamental role in nuclear astrophysics.

Masses for the rp-process in X-ray bursts

Masses for the r-process

Masses for neutron star crusts

DEPENDENCE OF X-RAY BURST MODELS ON NUCLEAR MASSES

H. Schatz[1,2,3] and W.-J. Ong [1,2,3]

Draft version October 26, 2016

ABSTRACT

X-ray burst model predictions of light curves and final composition of the nuclear ashes are affected by uncertain nuclear physics. Nuclear masses play an important role. Significant

arXiv:1610.07596 [astro-ph.HE]

Mass relevant to astrophysics

PRL **116,** 121101 (2016) PHYSICAL REVIEW LETTERS week ending 25 MARCH 2016

Impact of Nuclear Mass Uncertainties on the *r* Process

D. Martin,[1,2,*] A. Arcones,[1,2,†] W. Nazarewicz,[3,4,‡] and E. Olsen[5,§]

Nuclear masses play a fundamental role in understanding how the heaviest elements in the Universe are created in the r-process…

Review Progress in Particle and Nuclear Physics 86 (2016) 86–126

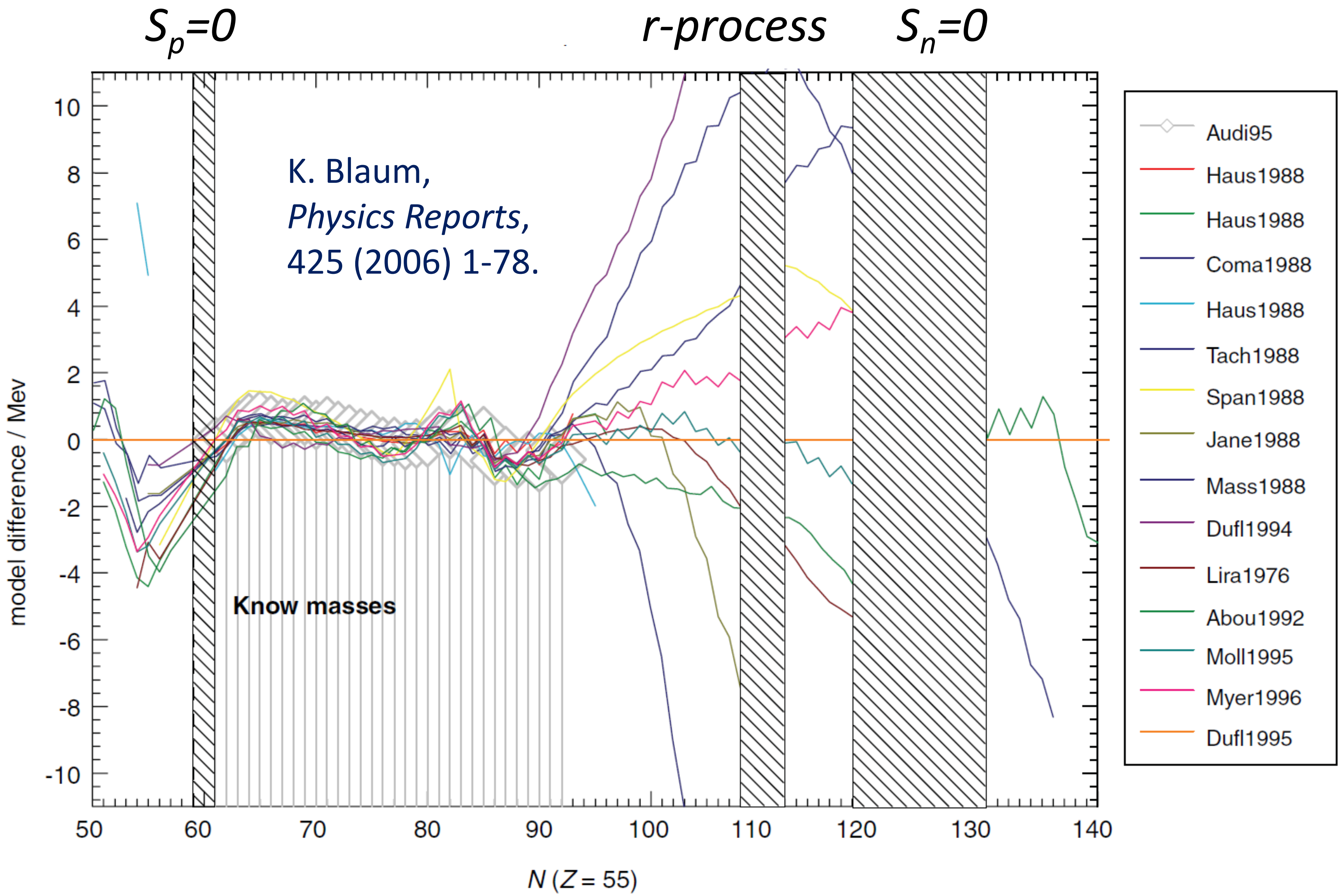
The impact of individual nuclear properties on *r*-process nucleosynthesis

CrossMark

M.R. Mumpower [a], R. Surman [a,*], G.C. McLaughlin [b], A. Aprahamian [a]

Knowledge of nuclear physics properties such as masses, β-decay and neutron capture rates, as well as β-delayed neutron emission probabilities are critical inputs that go into calculations of r-process nucleosynthesis.

Mass predictions



Better measured than predicted

Selected for a Viewpoint in *Physics*
PRL **111,** 061102 (2013) PHYSICAL REVIEW LETTERS week ending 9 AUGUST 2013

First Results from the CARIBU Facility: Mass Measurements on the *r*-Process Path

J. Van Schelt,[1,2] D. Lascar,[3,1] G. Savard,[1,2] J. A. Clark,[1] P. F. Bertone,[1] S. Caldwell,[2,1] A. Chaudhuri,[4,1] A. F. Levand,[1] G. Li,[5,1] G. E. Morgan,[4] R. Orford,[5] R. E. Segel,[3,1] K. S. Sharma,[4] and M. G. Sternberg[2,1]

Physics

Physics **6**, 88 (2013)

Viewpoint

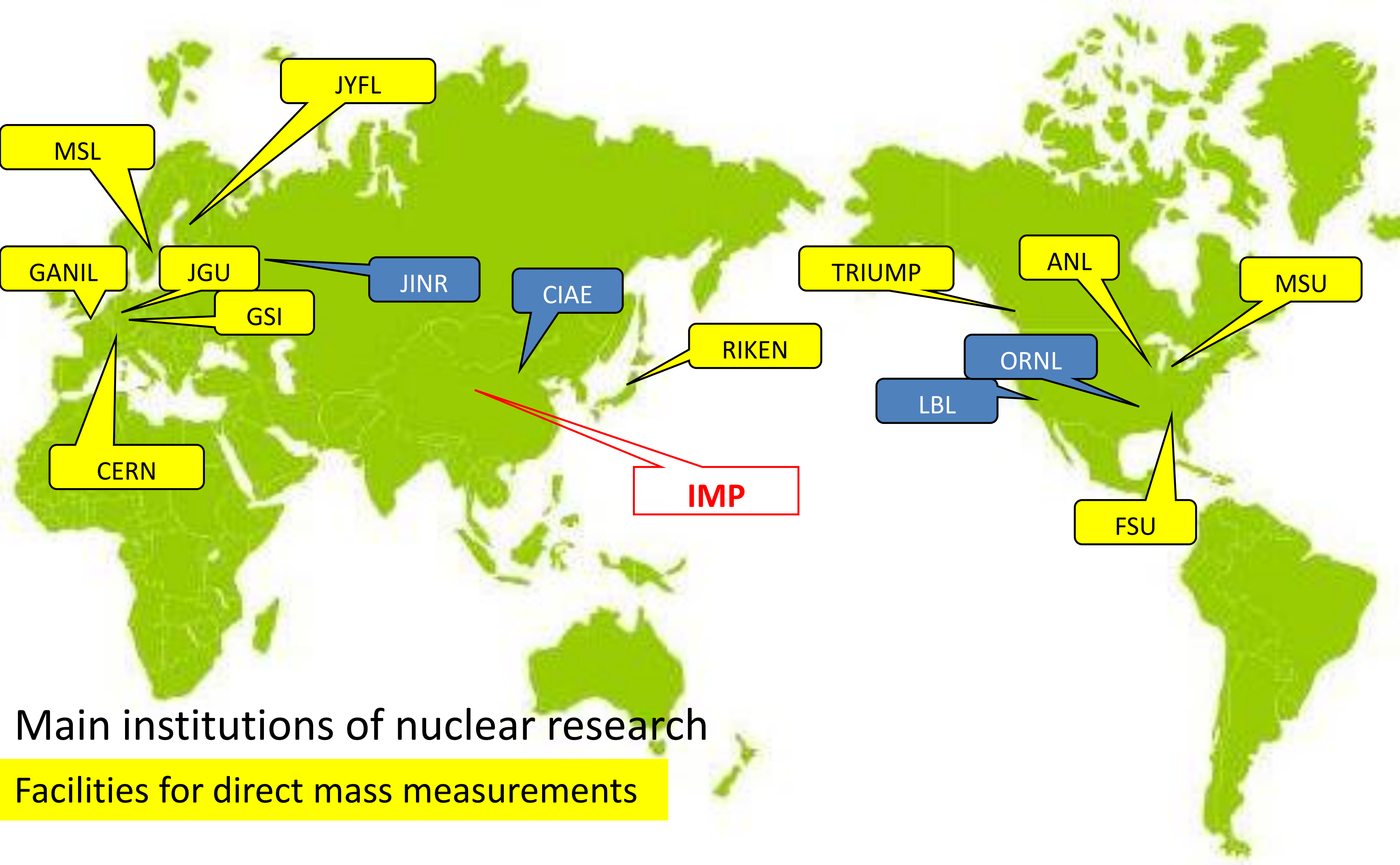
Stellar Abundances: Better Measured Than Predicted

Susanne Kreim
CERN, CH-1211 Geneva 23, Switzerland and
Max Planck Institute for Nuclear Physics, 69029 Heidelberg, Germany

Published August 5, 2013

The masses of exotic nuclei must be measured or calculated very precisely to explain how they led to the formation of heavy elements.

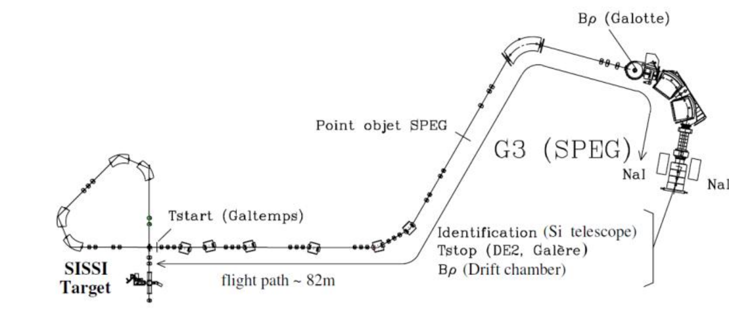
Mass measurement worldwide

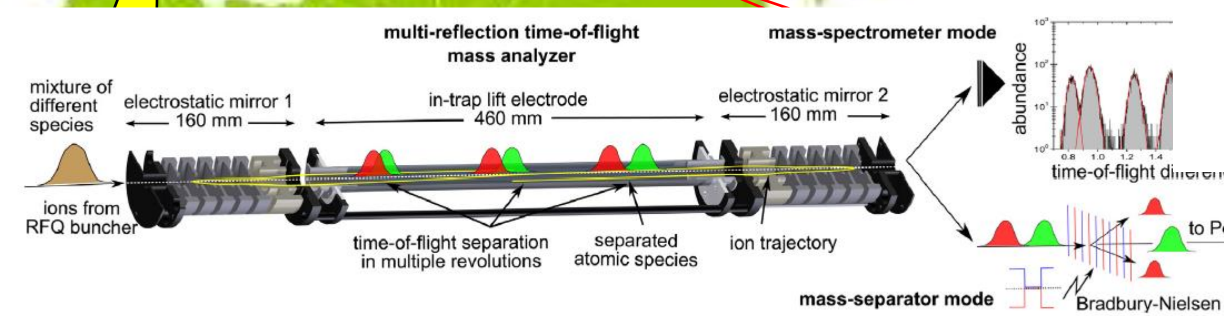


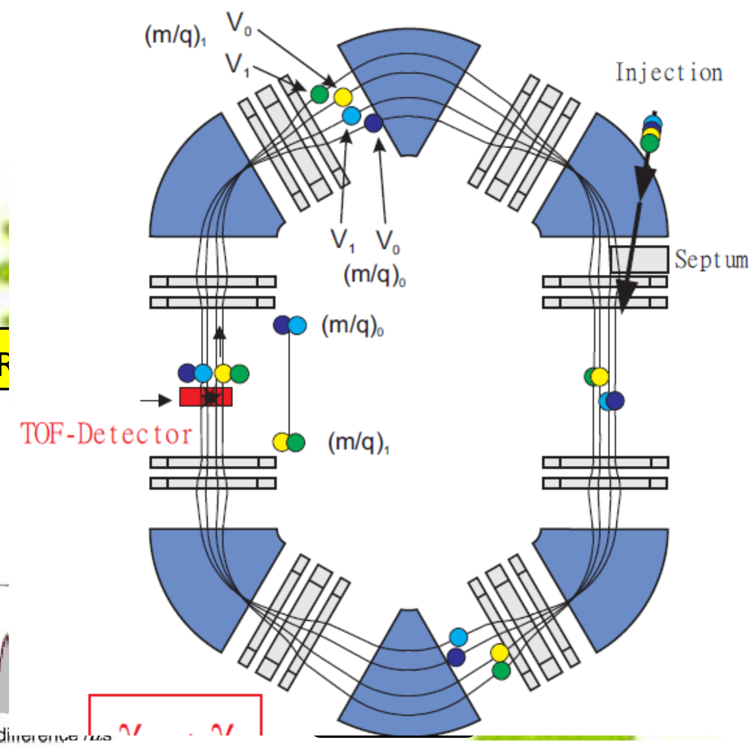
Main institutions of nuclear research

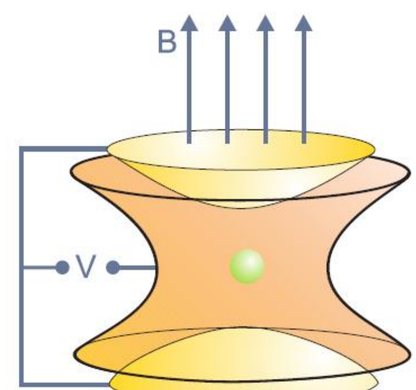
Facilities for direct mass measurements

Mass measurement worldwide





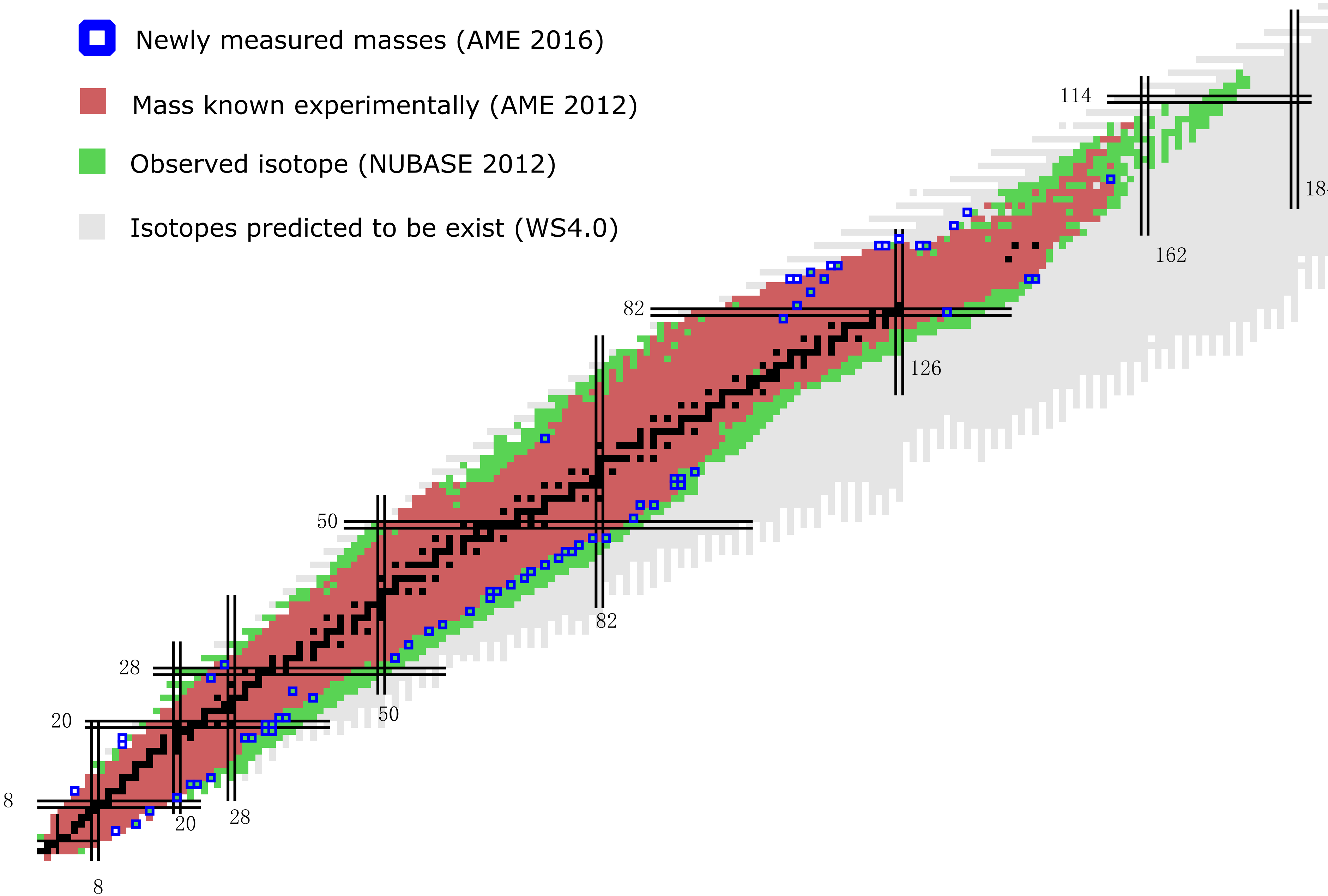




Main institutions of nuclear research

Facilities for direct mass measurements

Nuclear masses: AME2016



Outline

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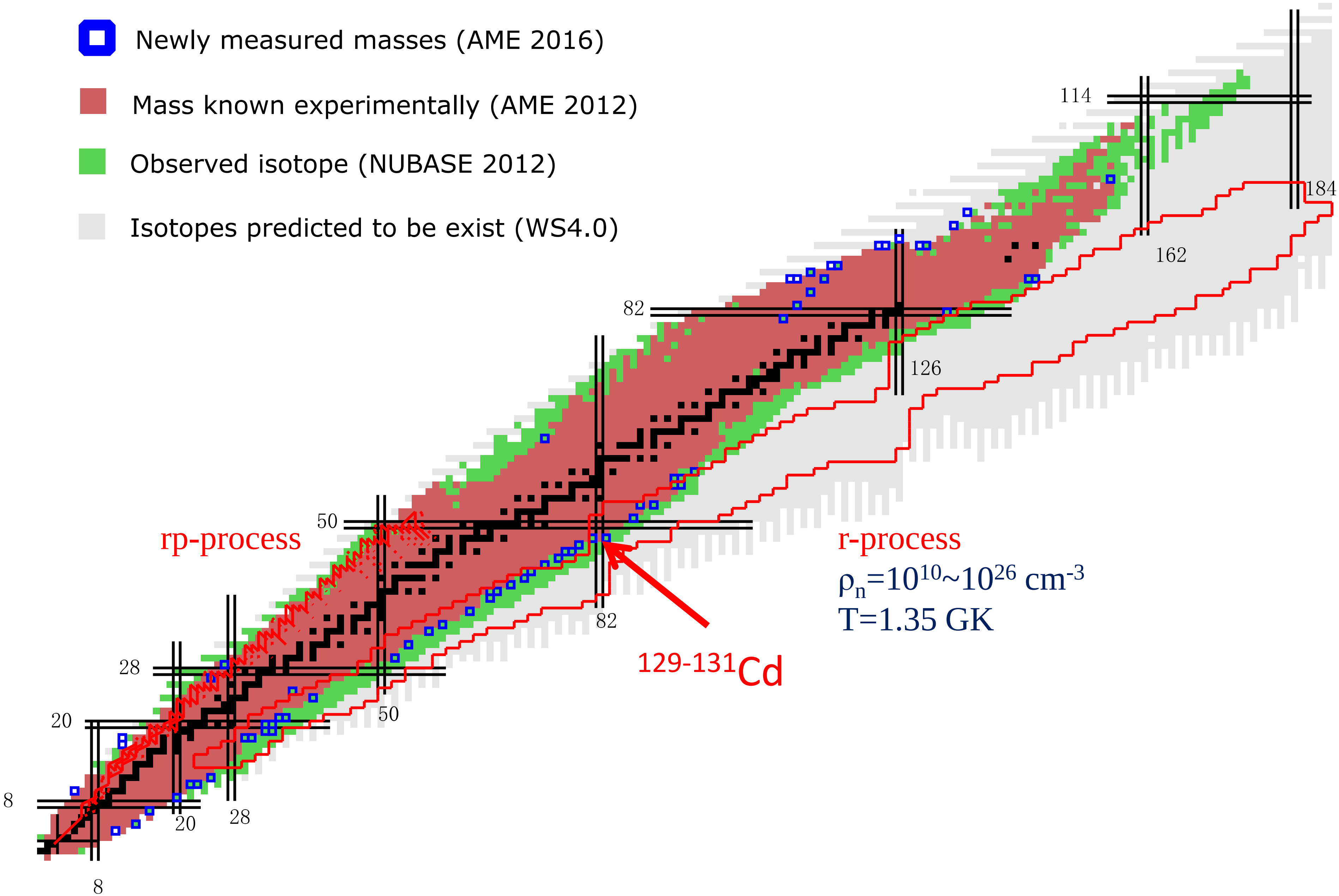
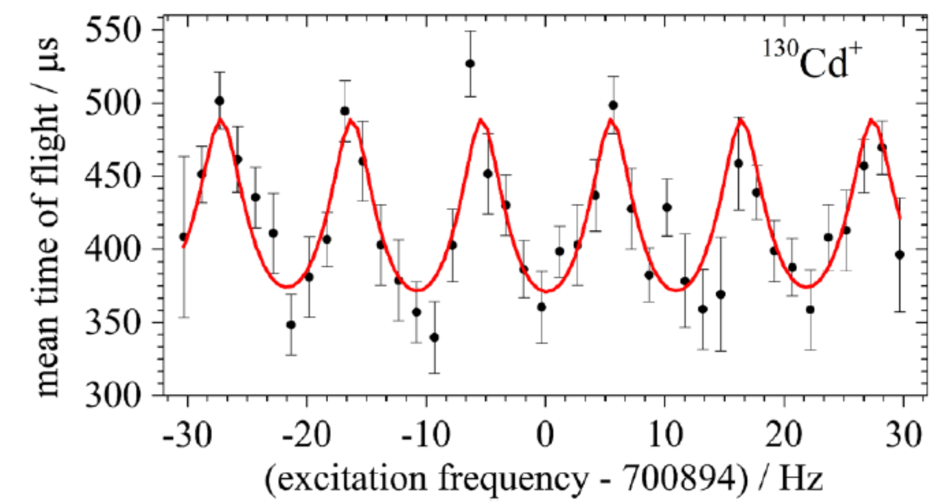
- recent progresses
- Results from Lanzhou
- Future perspective

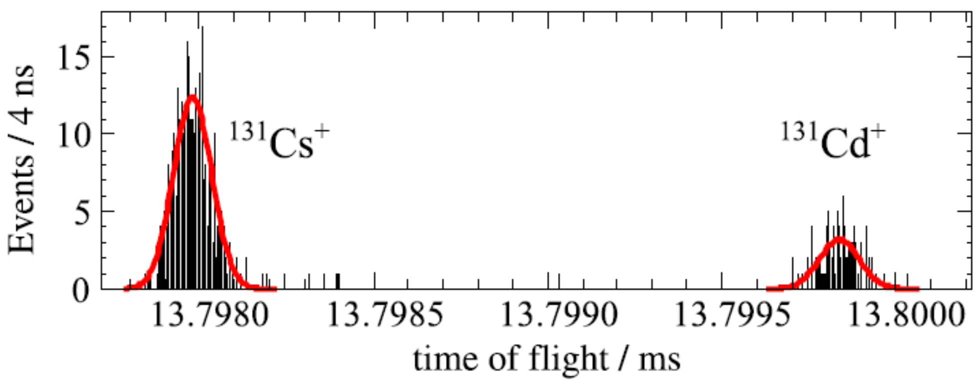
Nuclear masses: astrophysics

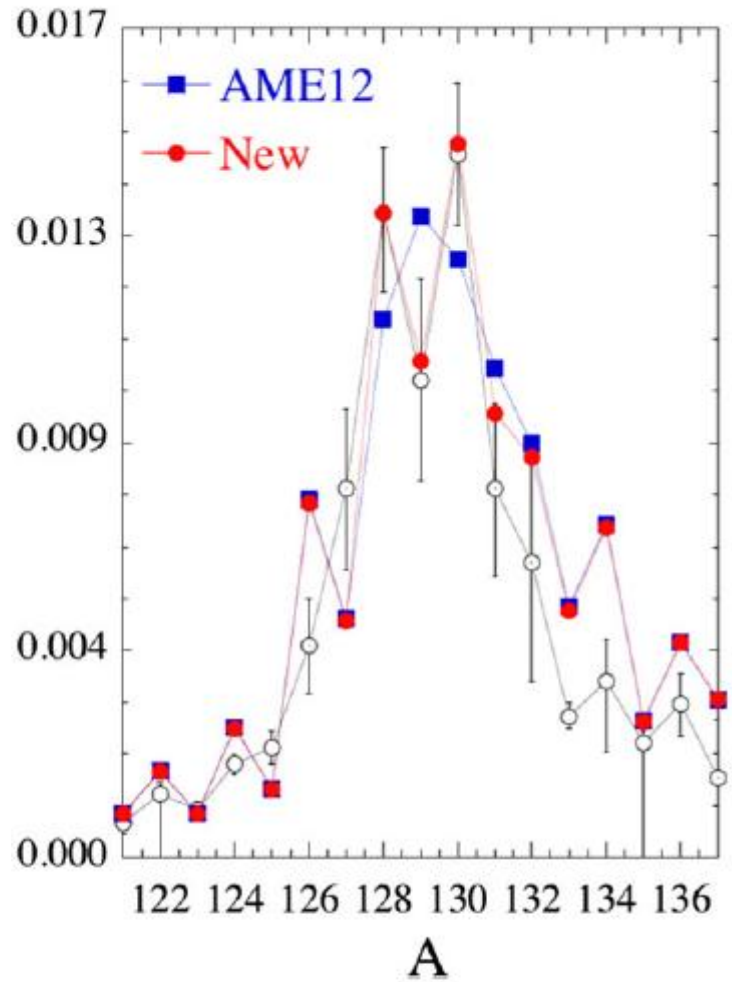


PRL **115,** 232501 (2015) PHYSICAL REVIEW LETTERS week ending 4 DECEMBER 2015

Precision Mass Measurements of $^{129-131}$Cd and Their Impact on Stellar Nucleosynthesis via the Rapid Neutron Capture Process

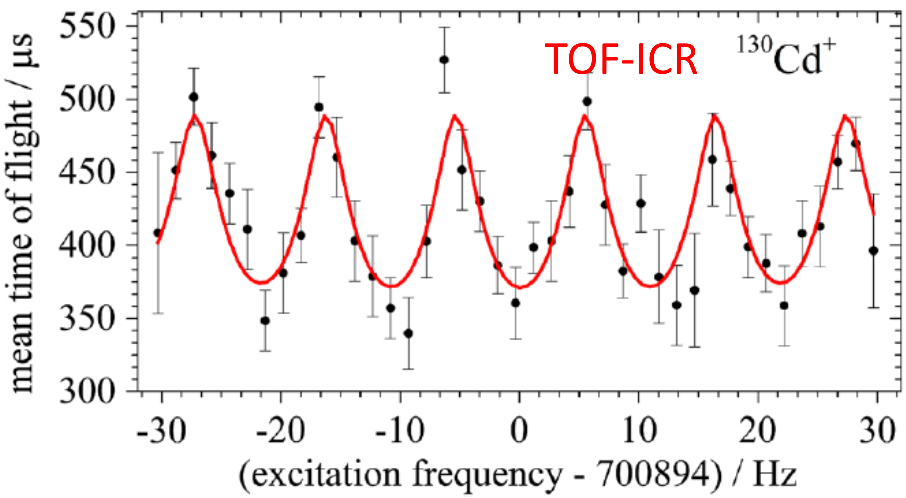


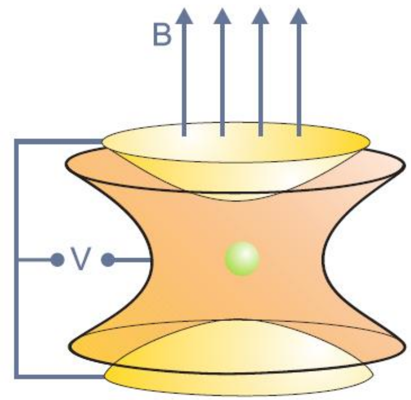




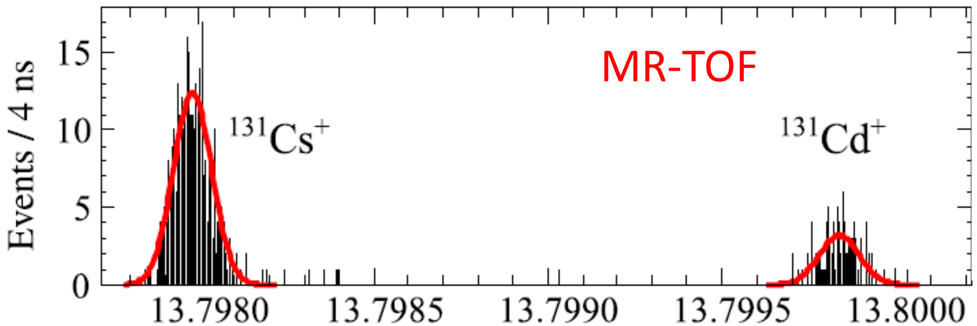
PRL 115, 232501 (2015) PHYSICAL REVIEW LETTERS week ending 4 DECEMBER 2015

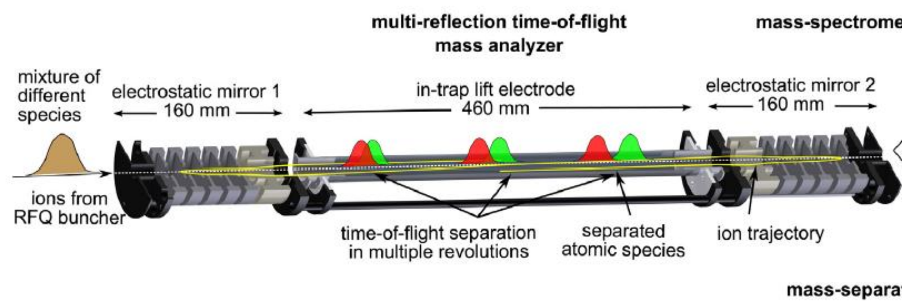
Precision Mass Measurements of $^{129-131}$Cd and Their Impact on Stellar Nucleosynthesis via the Rapid Neutron Capture Process





σ_m=22 keV





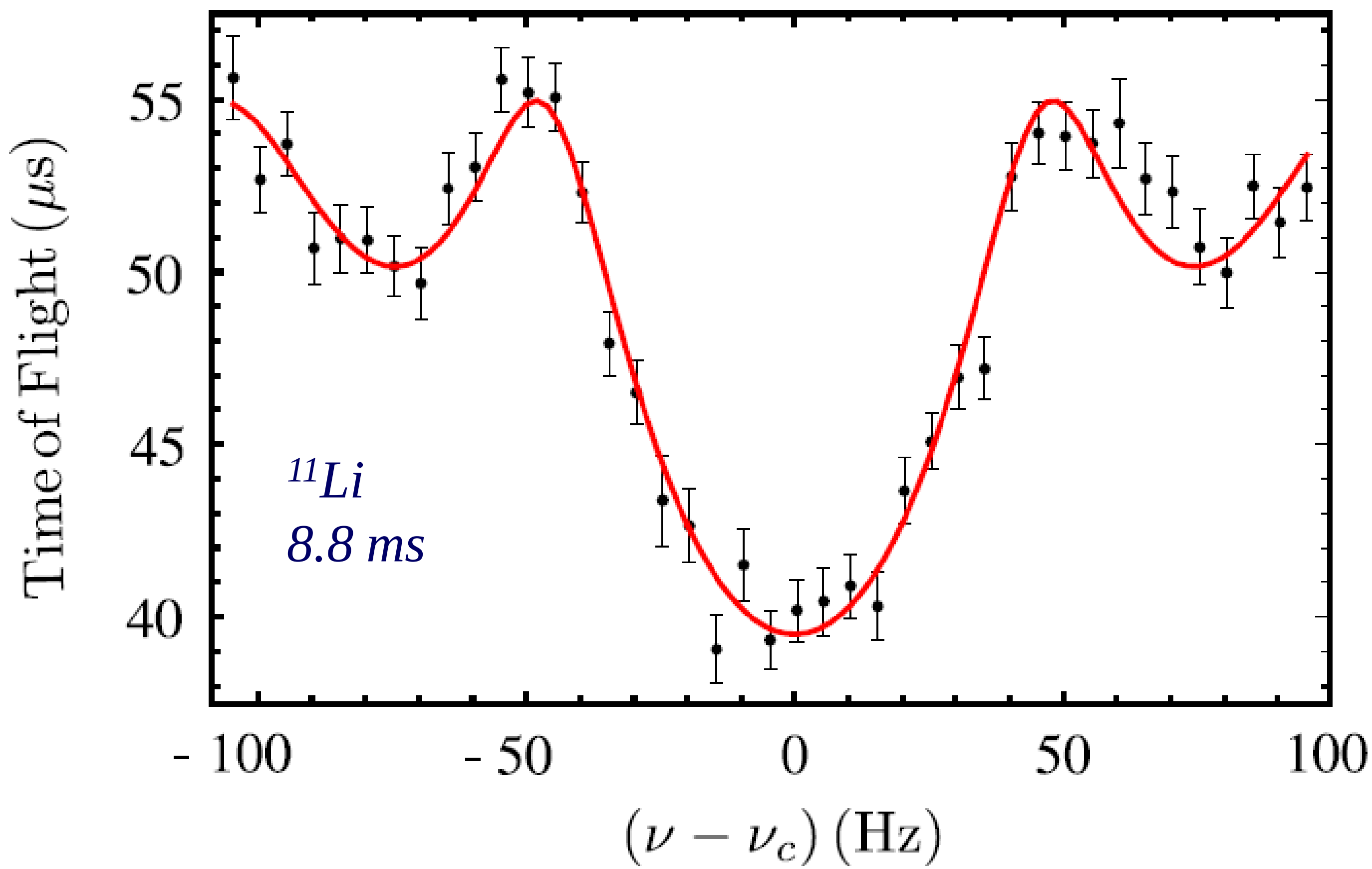
σ_m=100 keV

^{82}Zn: R.N.Wolf et al, PRL 110, 041101 (2013)

^{53,54}Ca, F.Wienholtz et al., Nature 498, 346 (2013)

^{52,53}K, M.Rosenbusch et al., PRL 114, 202501 (2015)

PRL **101**, 202501 (2008)



Question 1:

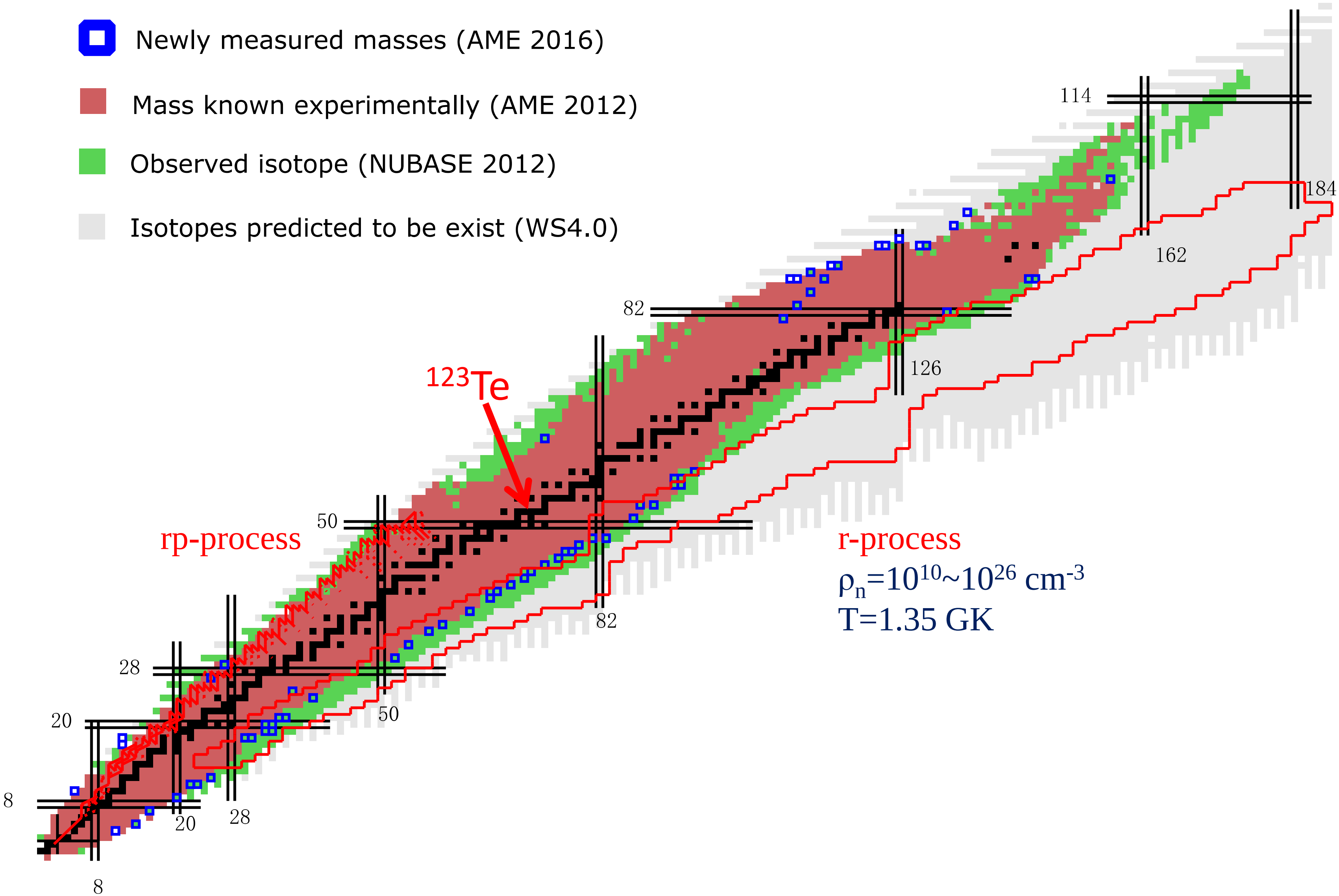
T_{rf} = 20 ms, B=3.7 T

Resolving power: m/Δm~ ?

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

$$\Delta\nu \approx 1/T_{\rm rf}$$

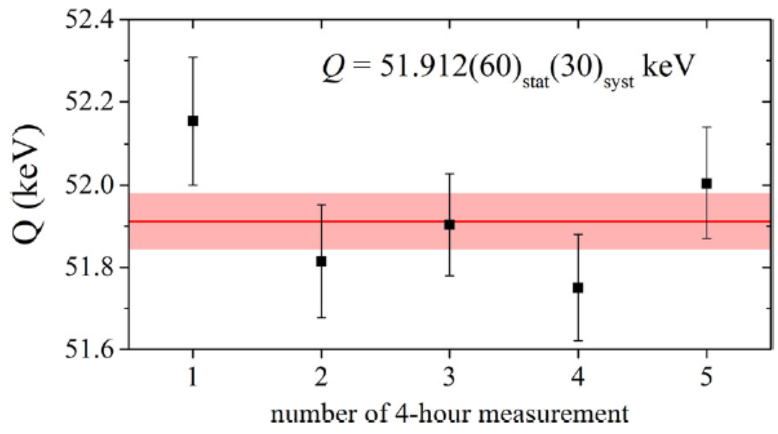
Nuclear masses: astrophysics

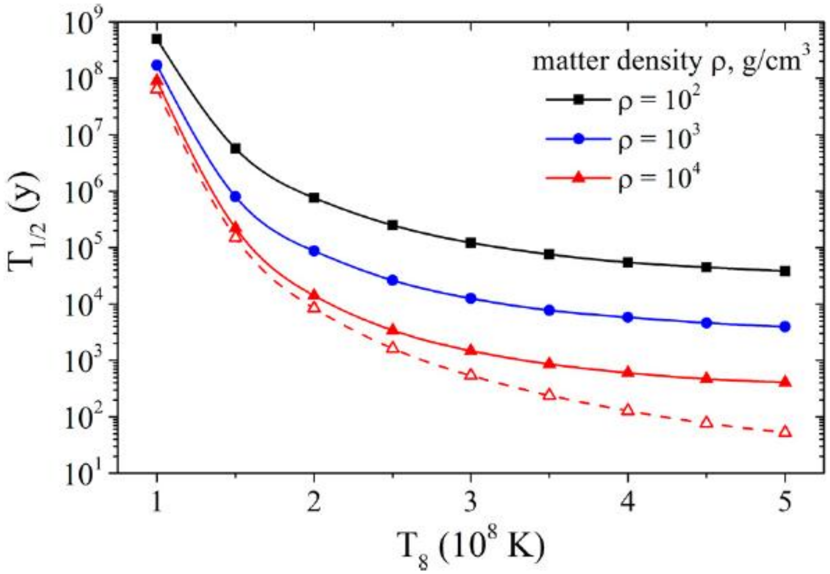


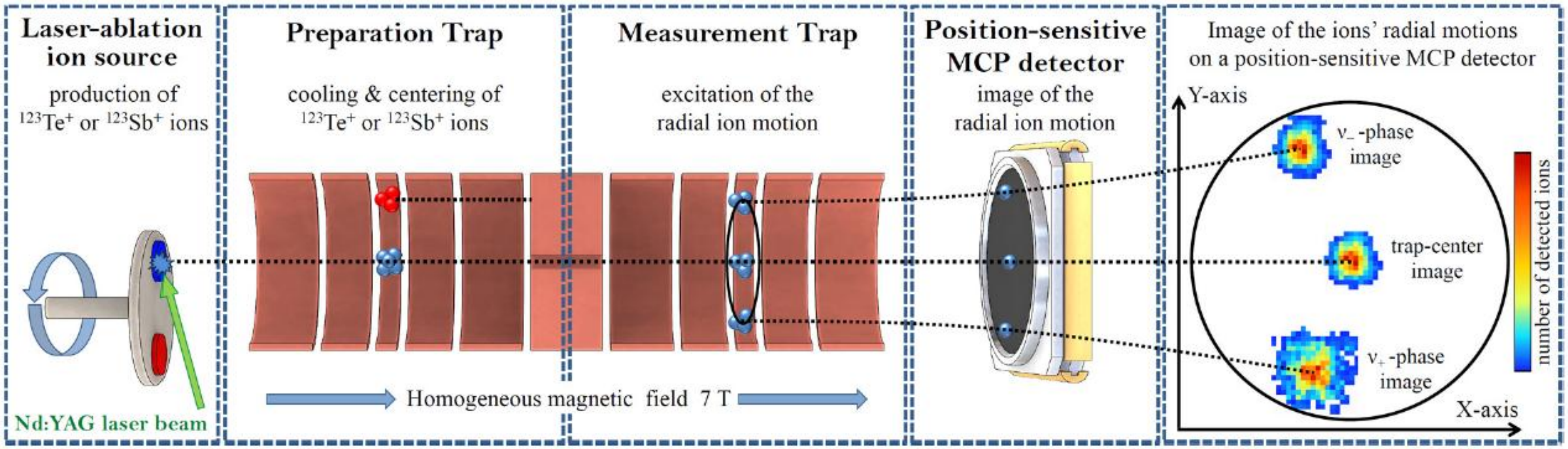
The decay energy of the pure s-process nuclide ^{123}Te

P. Filianin et al., Phys. Lett. B 758 (2016) 407-411.

$Q_{EC}(^{123}Te)=51.912(0.067)$ keV

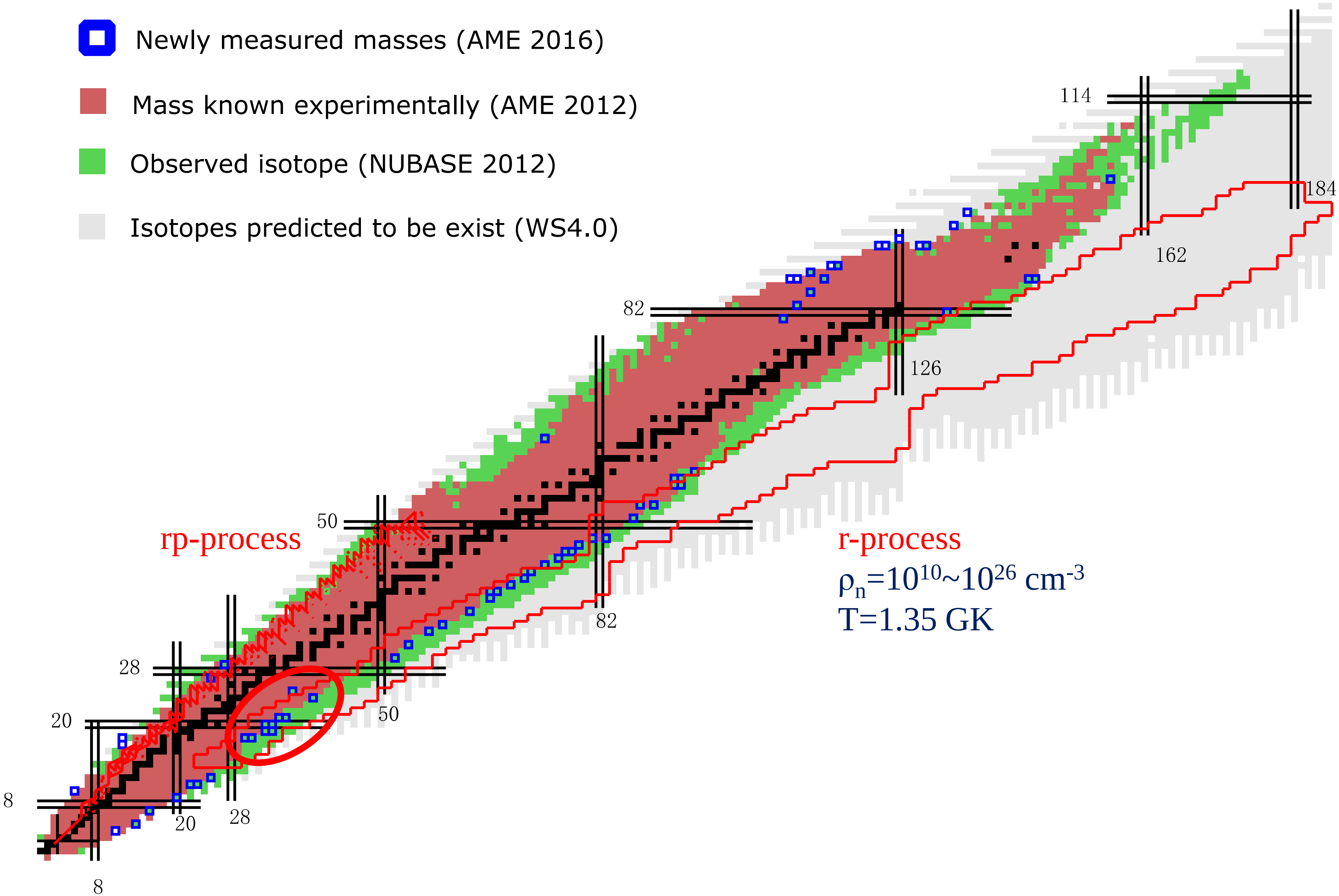




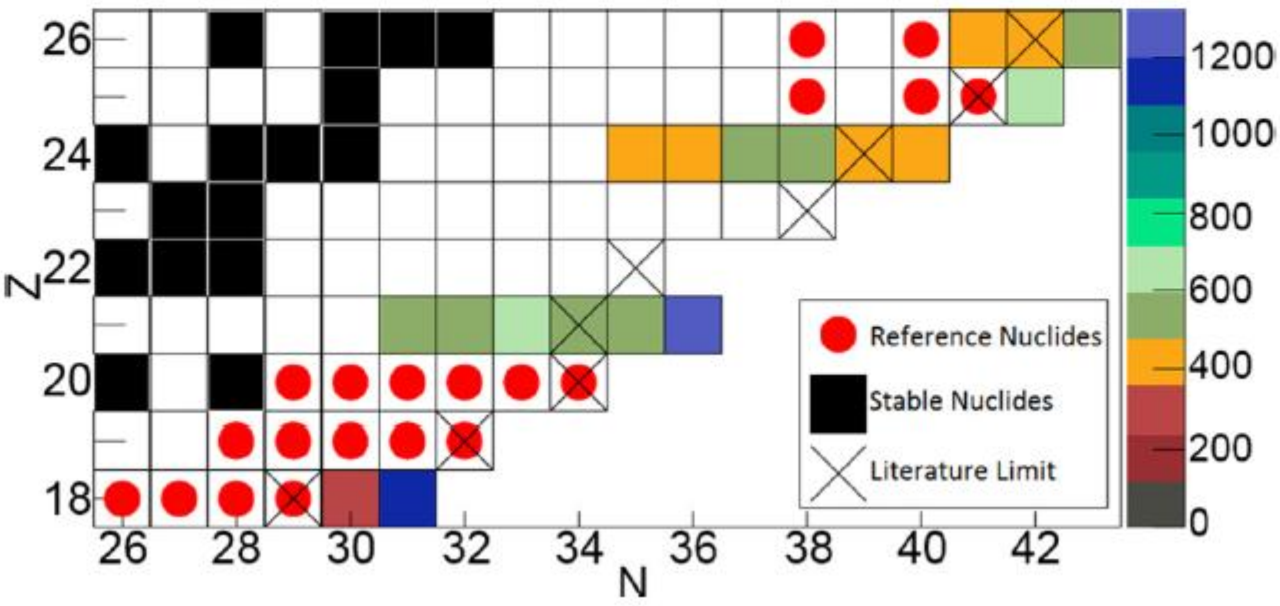


Nuclear masses: astrophysics

- Newly measured masses (AME 2016)
- Mass known experimentally (AME 2012)
- Observed isotope (NUBASE 2012)
- Isotopes predicted to be exist (WS4.0)

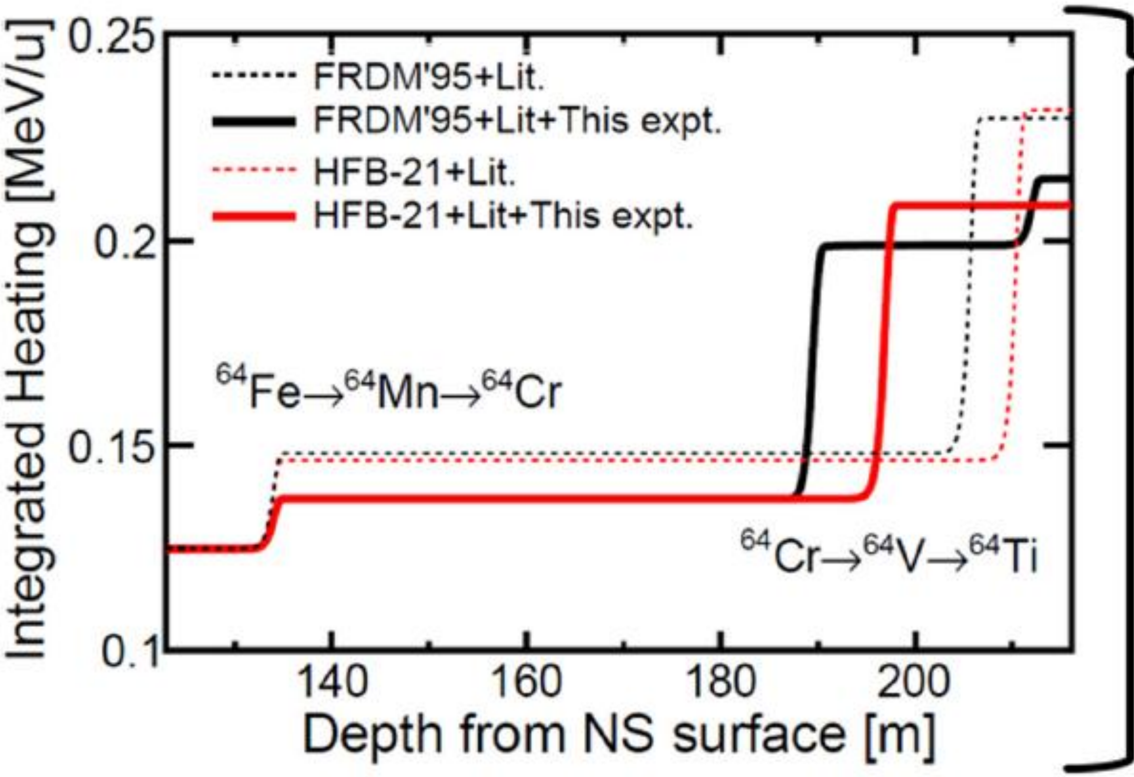


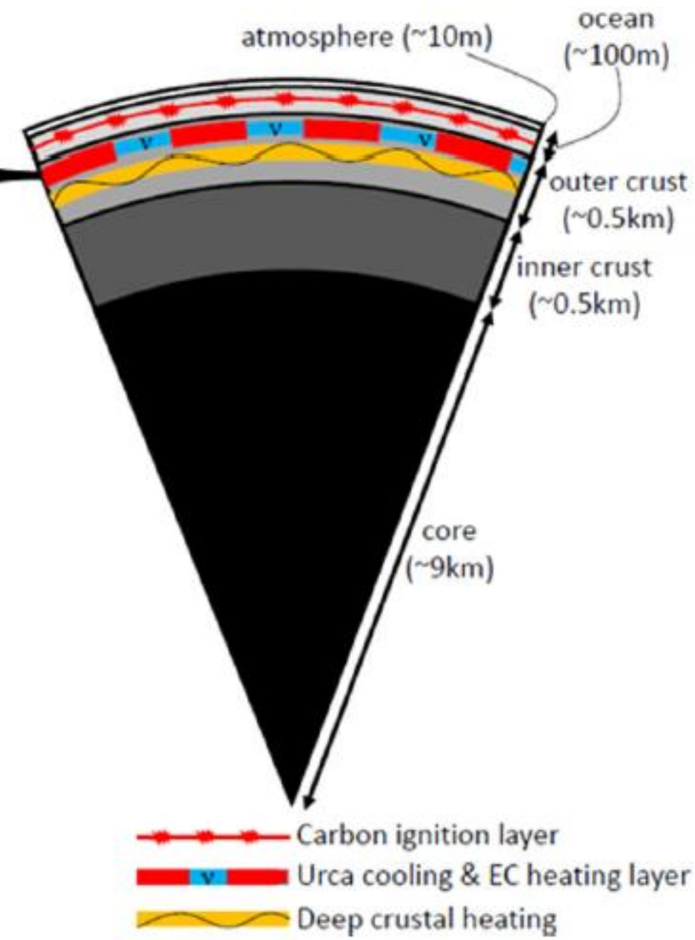
Bρ-TOF at MSU



Z. Meisel et al., PRL 114, 022501 (2015);
PRL 115, 162501 (2015);
PRC 93, 035805 (2016).

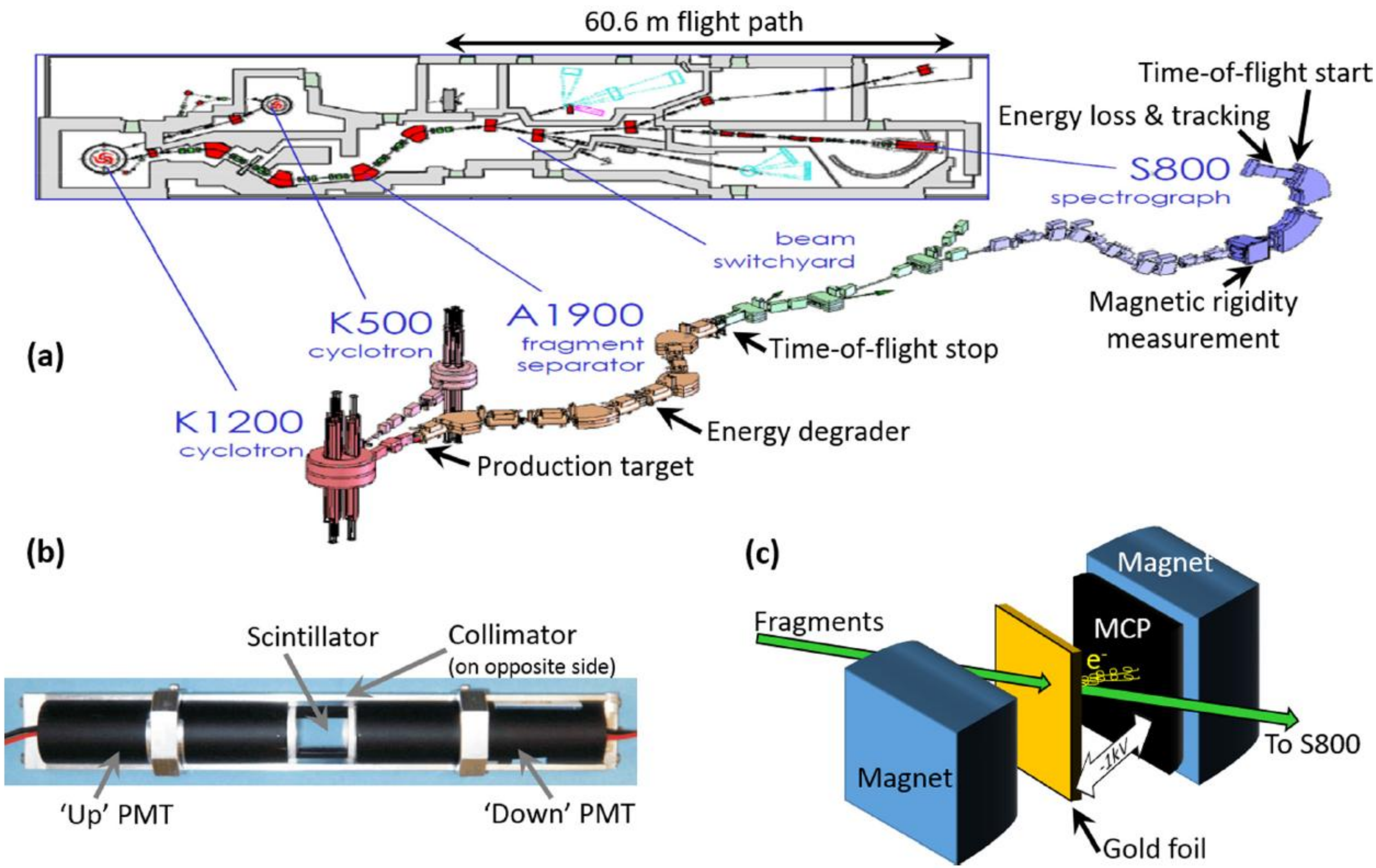
Bρ-TOF at MSU





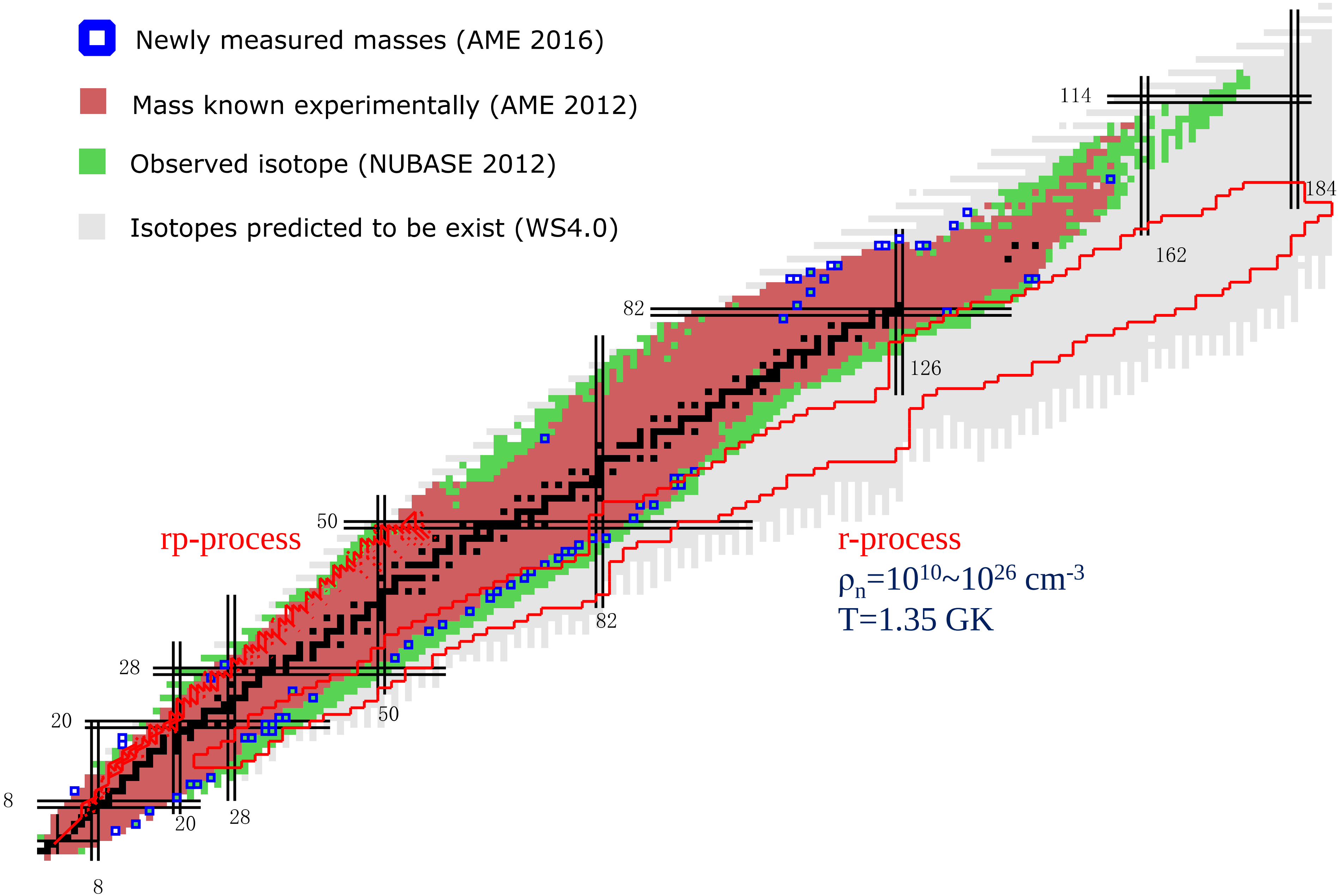
PRC 93, 035805 (2016).

Bρ-TOF at MSU



60.6 m flight path
Time-of-flight start
Energy loss & tracking
S800
spectrograph
beam
switchyard
Magnetic rigidity
measurement
K500
cyclotron
A1900
fragment
separator
(a)
Time-of-flight stop
K1200
cyclotron
Energy degrader
Production target
(b)
(c)
Magnet
Scintillator
Collimator
(on opposite side)
Fragments
MCP
e⁻
To S800
-1kV
Magnet
'Up' PMT
'Down' PMT
Gold foil

Nuclear masses: astrophysics



Outline

- Background
- recent progresses
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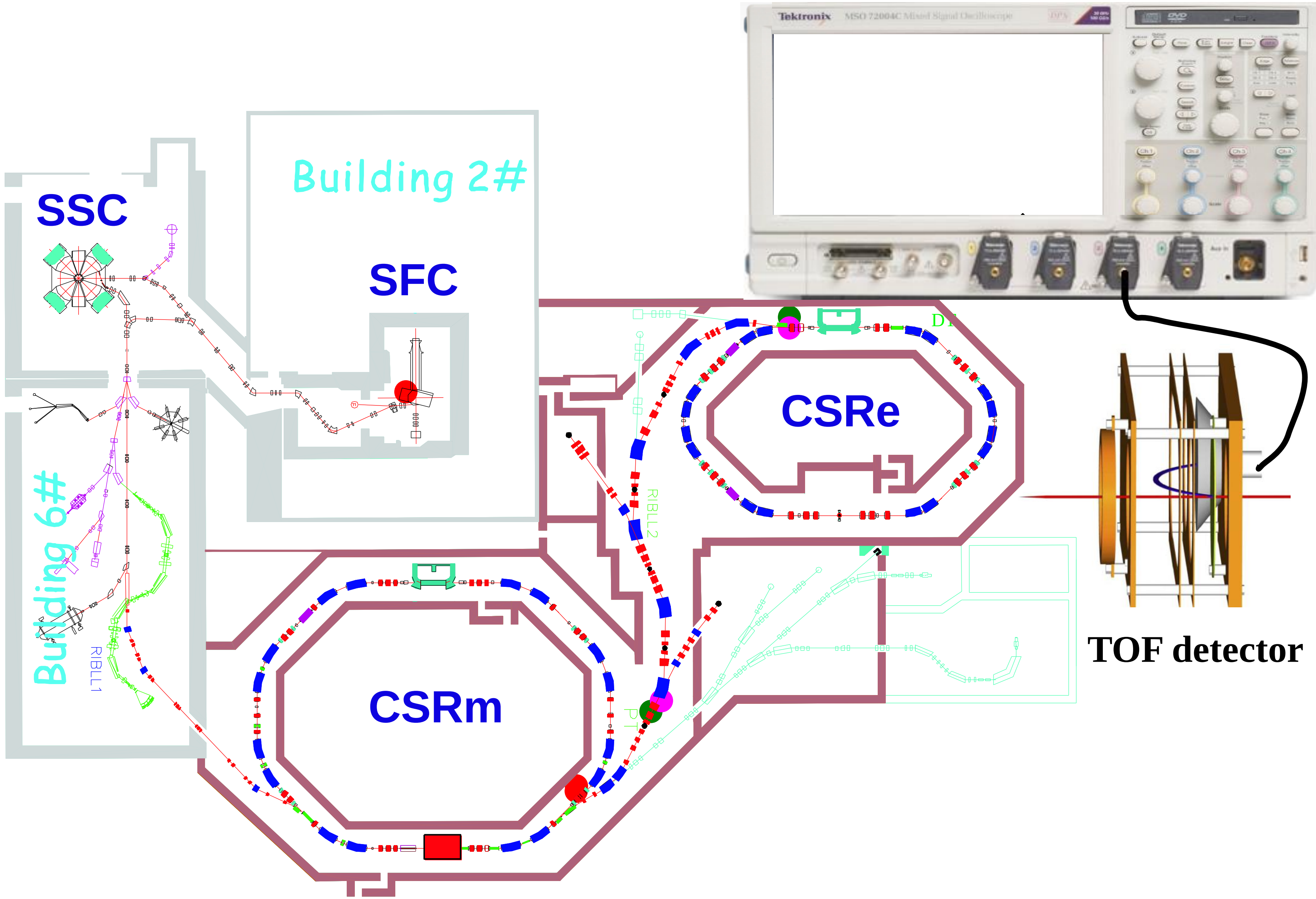
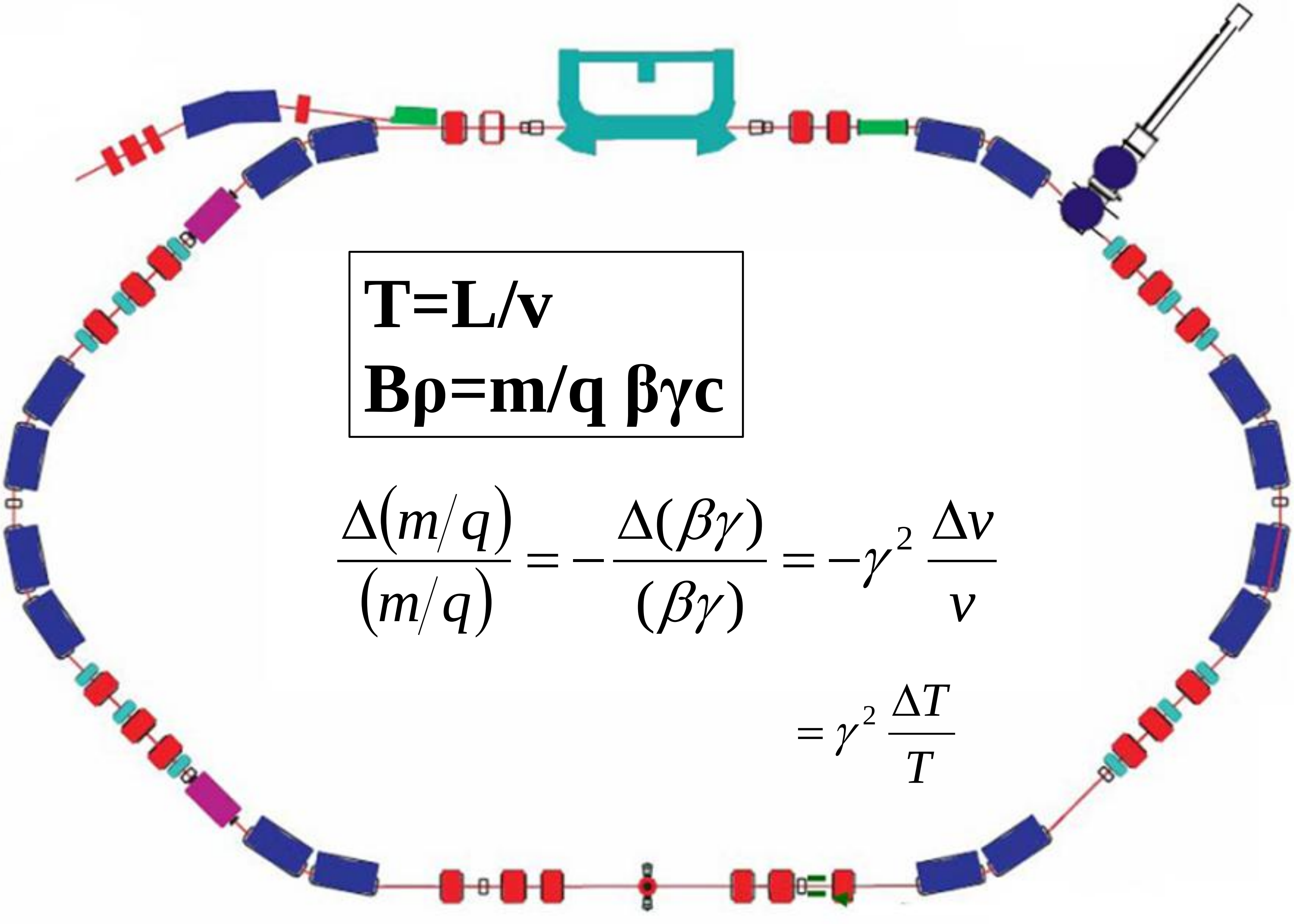
Procedure of mass measurements



Principle



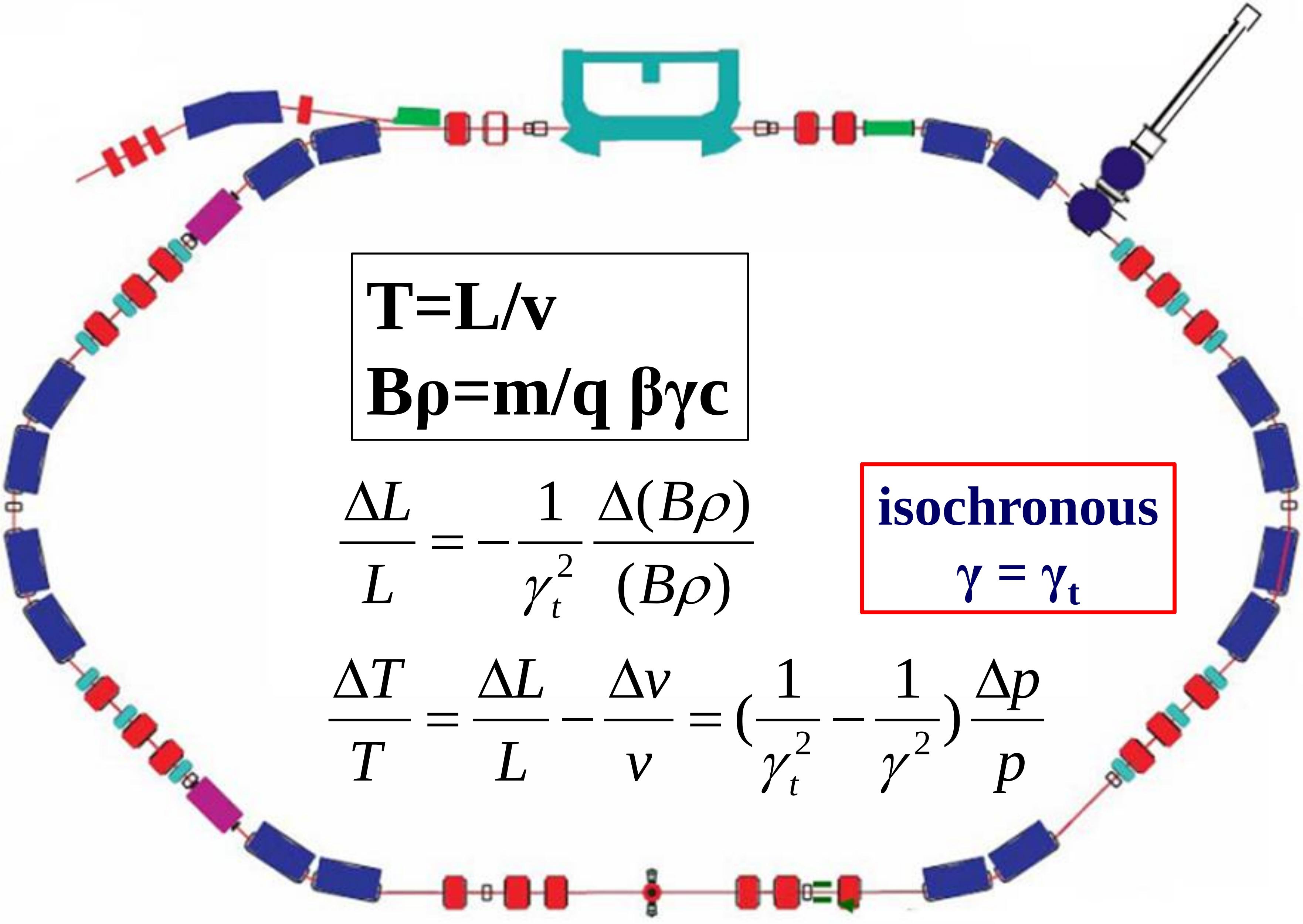
T=L/v

Bρ=m/q βγc

$$\frac{\Delta(m/q)}{(m/q)} = -\frac{\Delta(\beta\gamma)}{(\beta\gamma)} = -\gamma^2 \frac{\Delta v}{v}$$

$$= \gamma^2 \frac{\Delta T}{T}$$

Principle : isochronous mass spectrometry



T=L/v

Bρ=m/q βγc

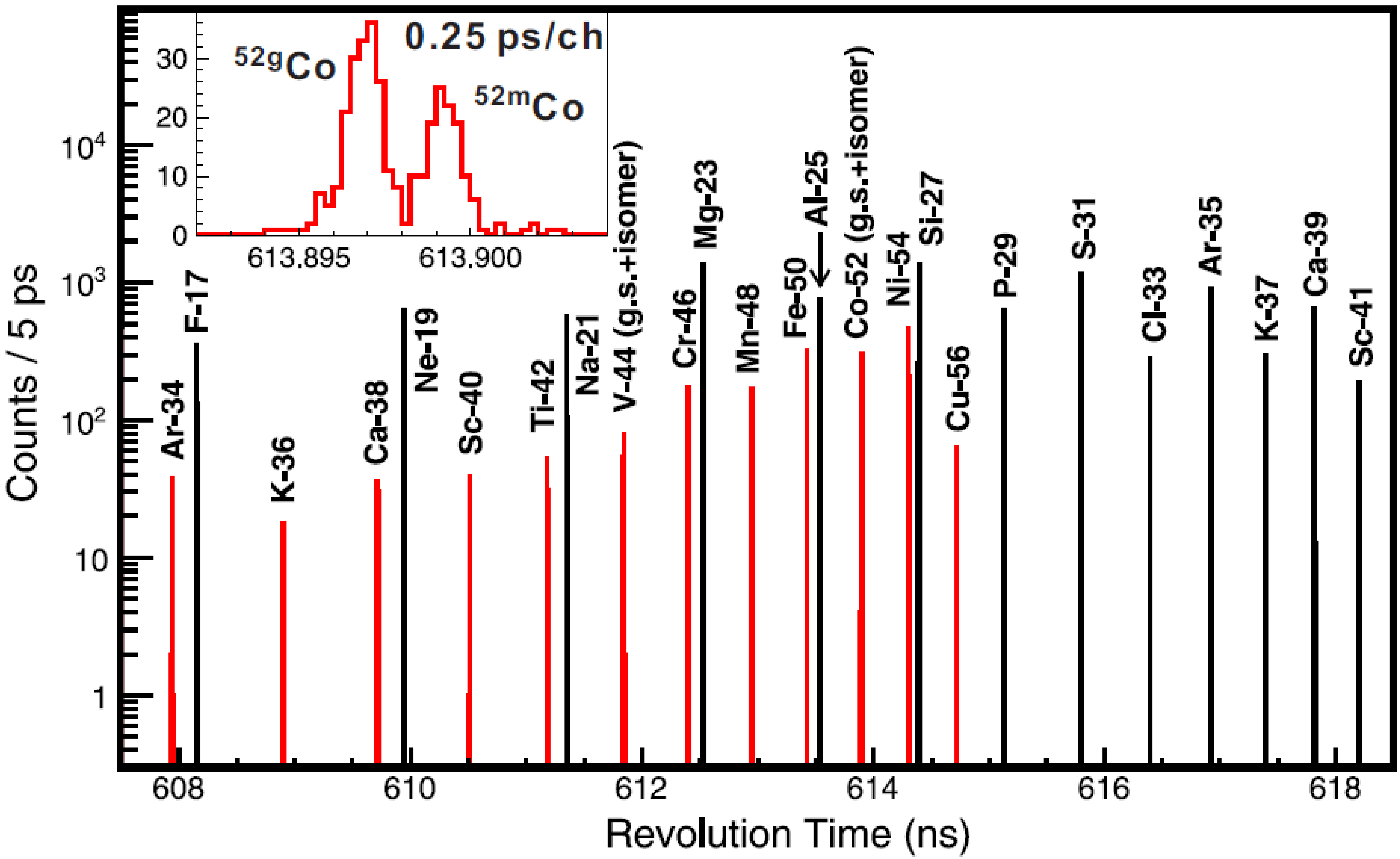
$$\frac{\Delta L}{L} = -\frac{1}{\gamma_t^2}\frac{\Delta(B\rho)}{(B\rho)}$$

$$\frac{\Delta T}{T} = \frac{\Delta L}{L} - \frac{\Delta v}{v} = (\frac{1}{\gamma_t^2} - \frac{1}{\gamma^2})\frac{\Delta p}{p}$$

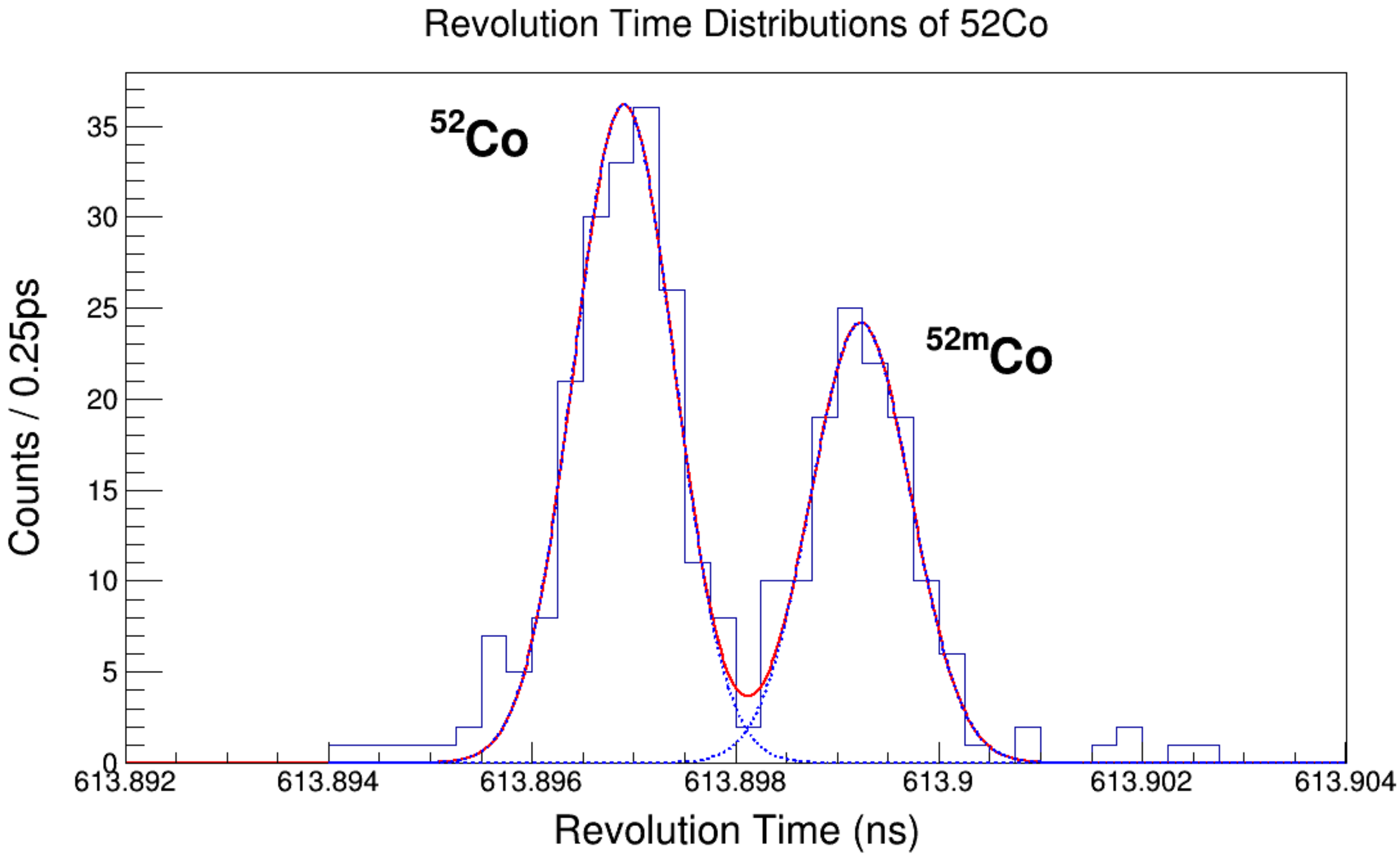
isochronous

$\gamma = \gamma_t$

Revolution time spectrum



Resolving power



$$\frac{m}{\Delta m_{(FWHM)}} \approx 210{,}000$$

$B\rho = m/q\ \beta\gamma c$

Question 2:

Isochronous settings for ^{52}Co,

$\gamma_t = 1.4$,

$B\rho$： ?

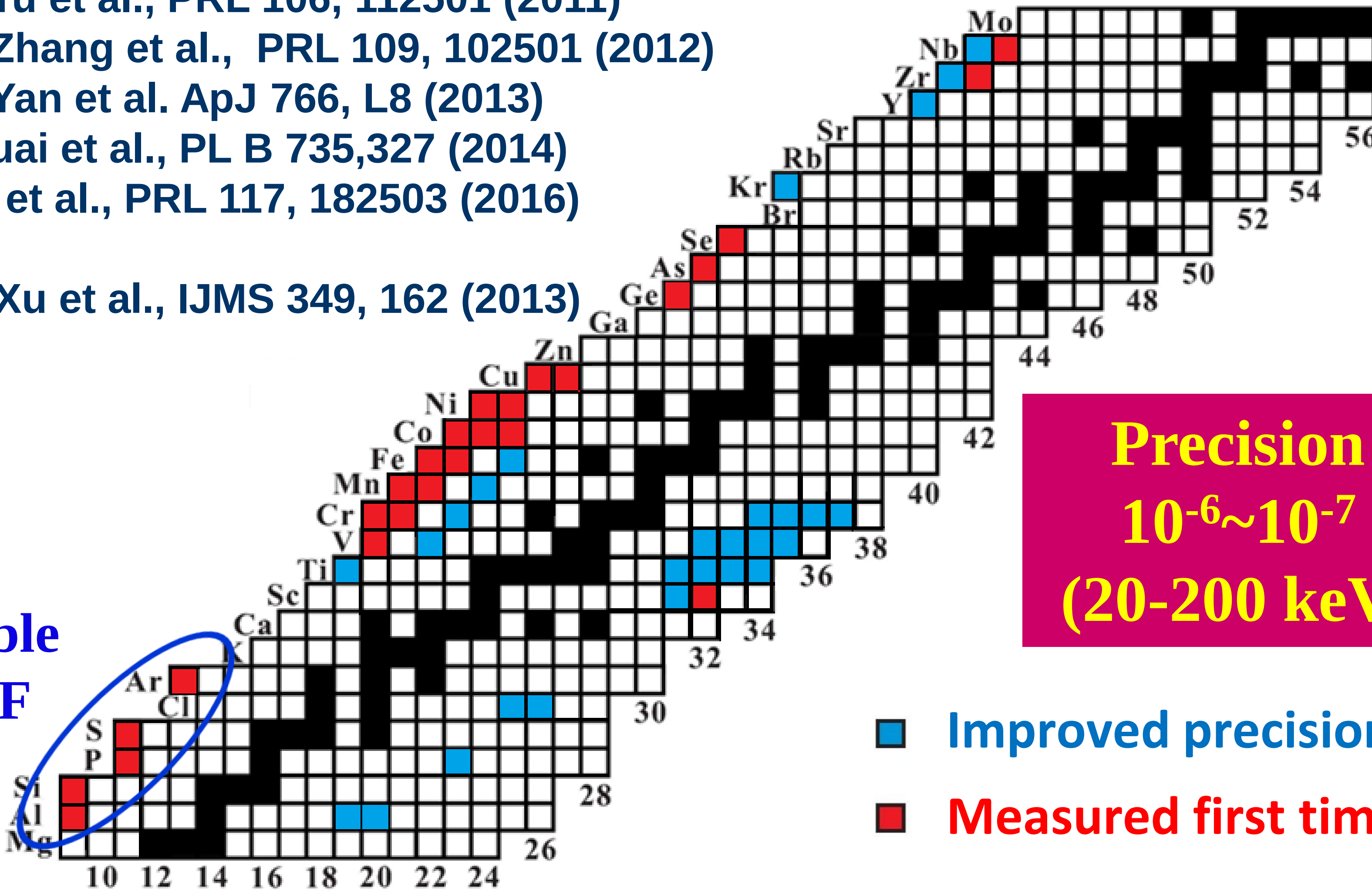
Overview of experimental results

SHUAI Peng, YAN Xinliang,
this afternoon

Beams: ^{78}Kr, ^{58}Ni, ^{86}Kr, ^{112}Sn, ^{58}Ni, ^{36}Ar

X. L. Tu et al., PRL 106, 112501 (2011)
Y. H. Zhang et al., PRL 109, 102501 (2012)
X. L. Yan et al. ApJ 766, L8 (2013)
P. Shuai et al., PL B 735,327 (2014)
X. Xu et al., PRL 117, 182503 (2016)

H. S. Xu et al., IJMS 349, 162 (2013)



Double TOF

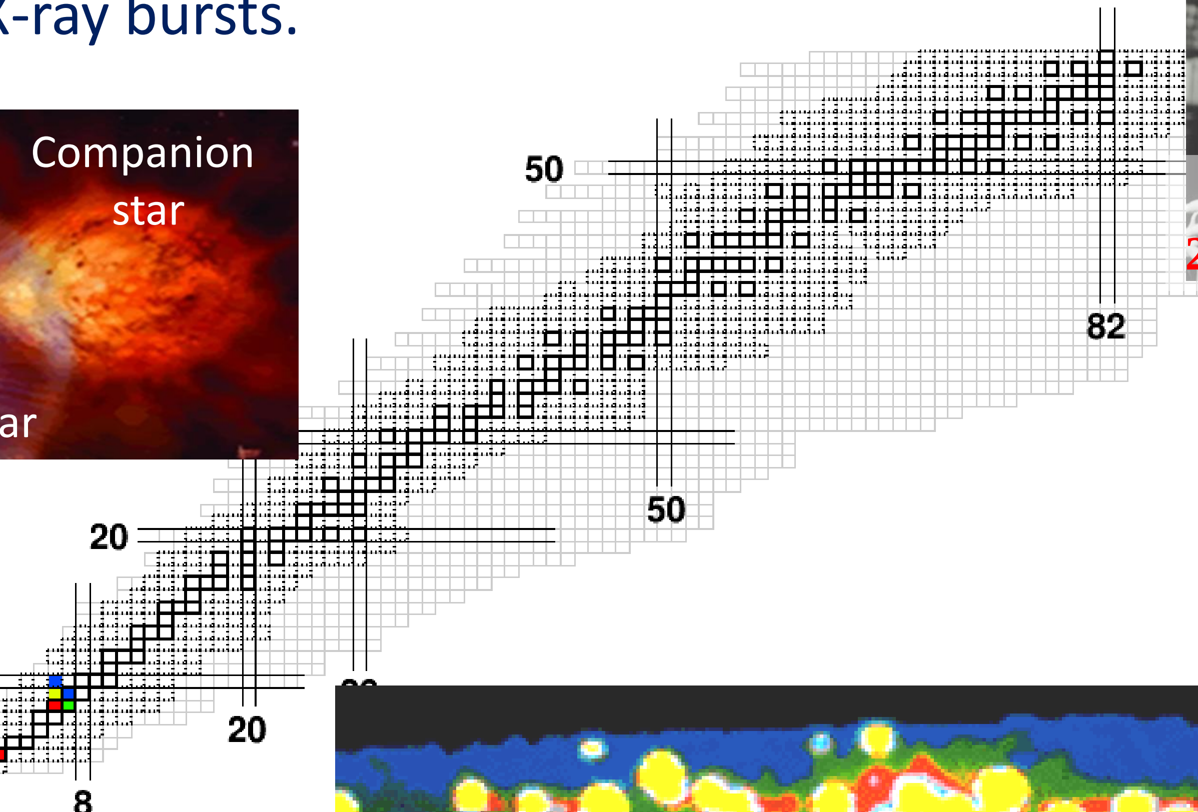
Precision
10^{-6}~10^{-7}
(20-200 keV)

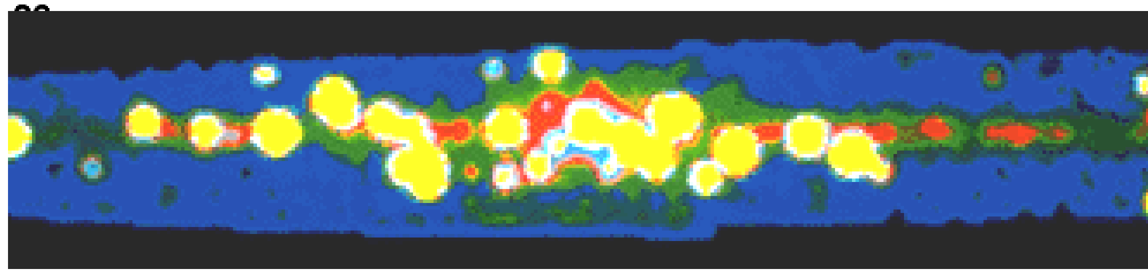
Improved precision

Measured first time

Results from CSRe: (1) waiting point ^{64}Ge

The rapid proton capture process (rp process) powers the type 1 X-ray bursts.

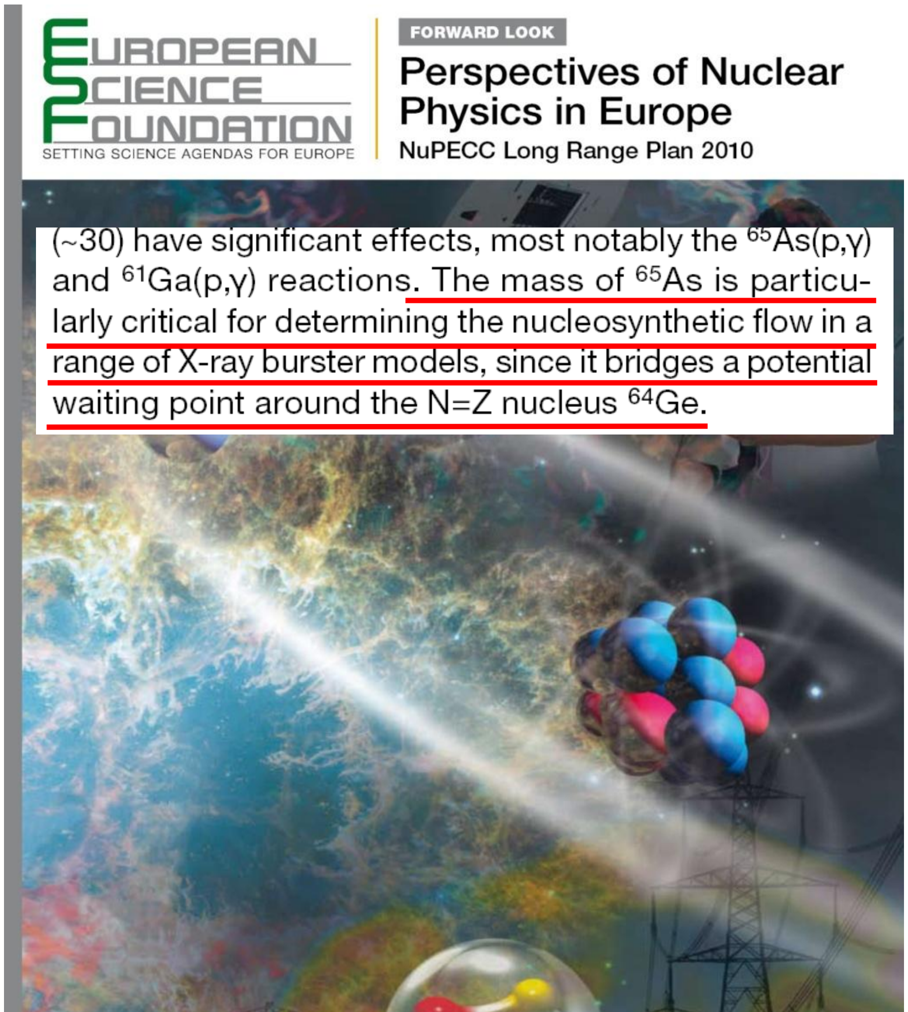


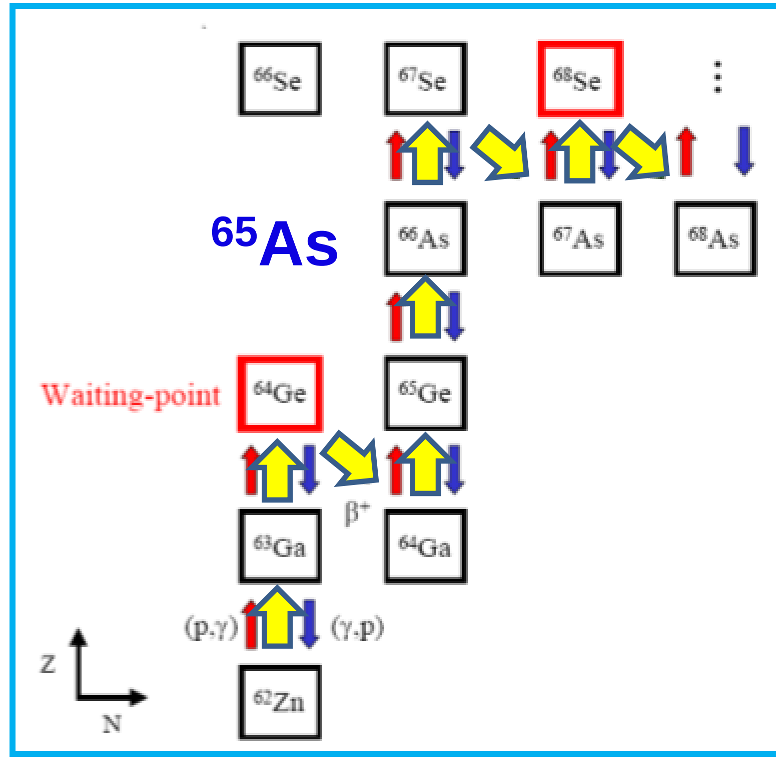


Reliable nuclear physics input, including precise mass values, is needed for the nuclides along the rp-process path.

Results from CSRe: (1) waiting point ^{64}Ge

Waiting point at ^{64}Ge in the Type I X-ray burst ?



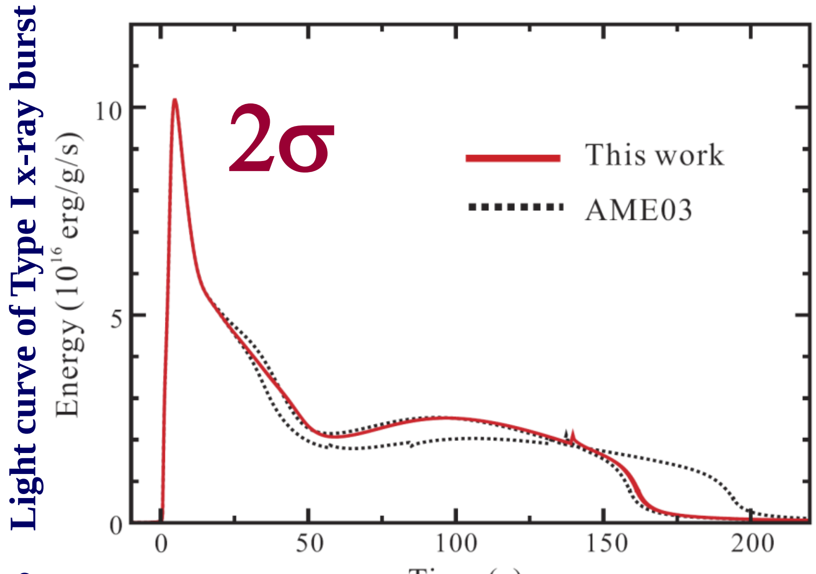


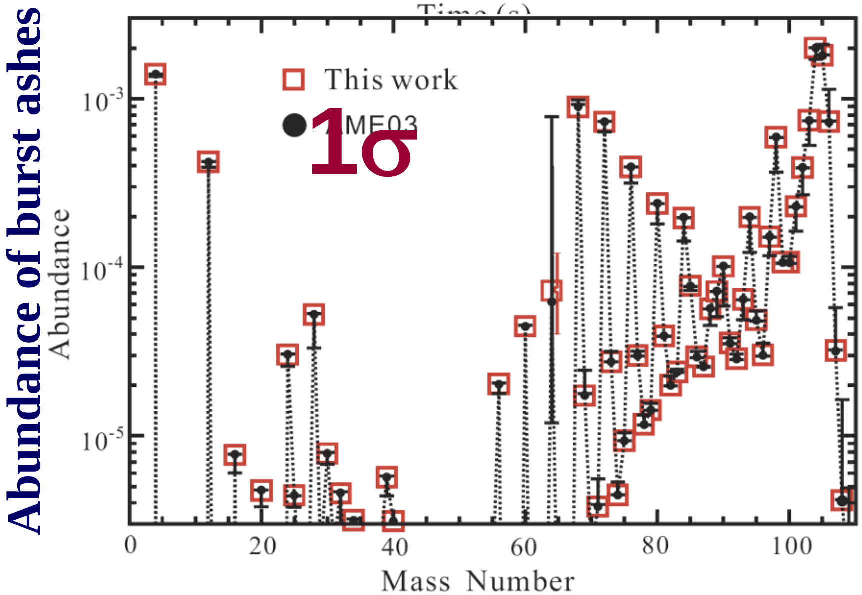
$S_p(^{65}As)$ >-250 keV (AME2003)

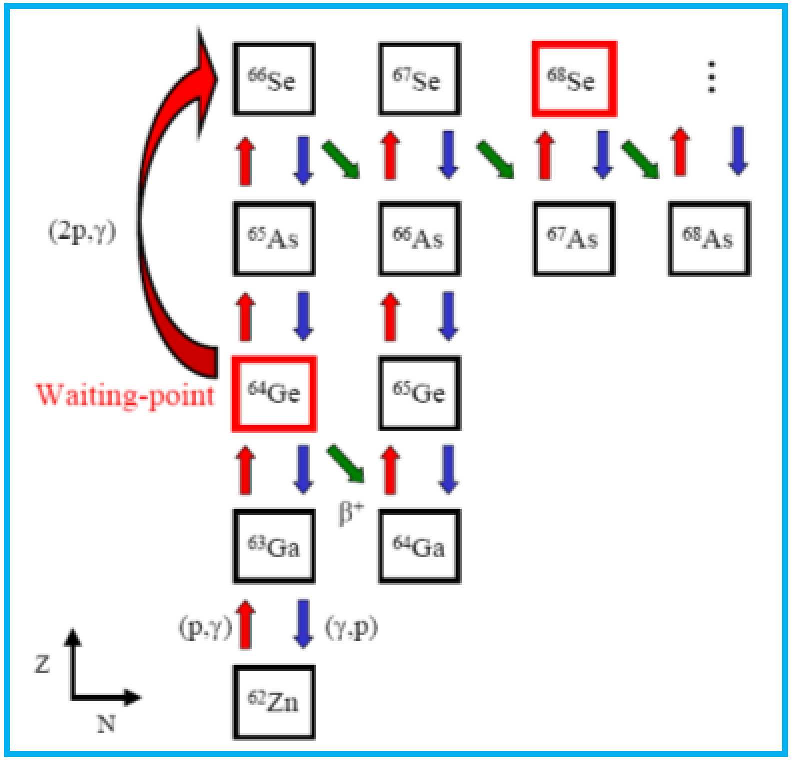
Waiting points:
Reaction path
Light curve
Element abundance

Results from CSRe: (1) waiting point ^{64}Ge

X.L. Tu et al., PRL 106, 112501 (2011)







$S_p(^{65}As) = -90\ (85)$ keV

89%–90% of the reaction flow passes through ^{64}Ge via proton capture indicating that:

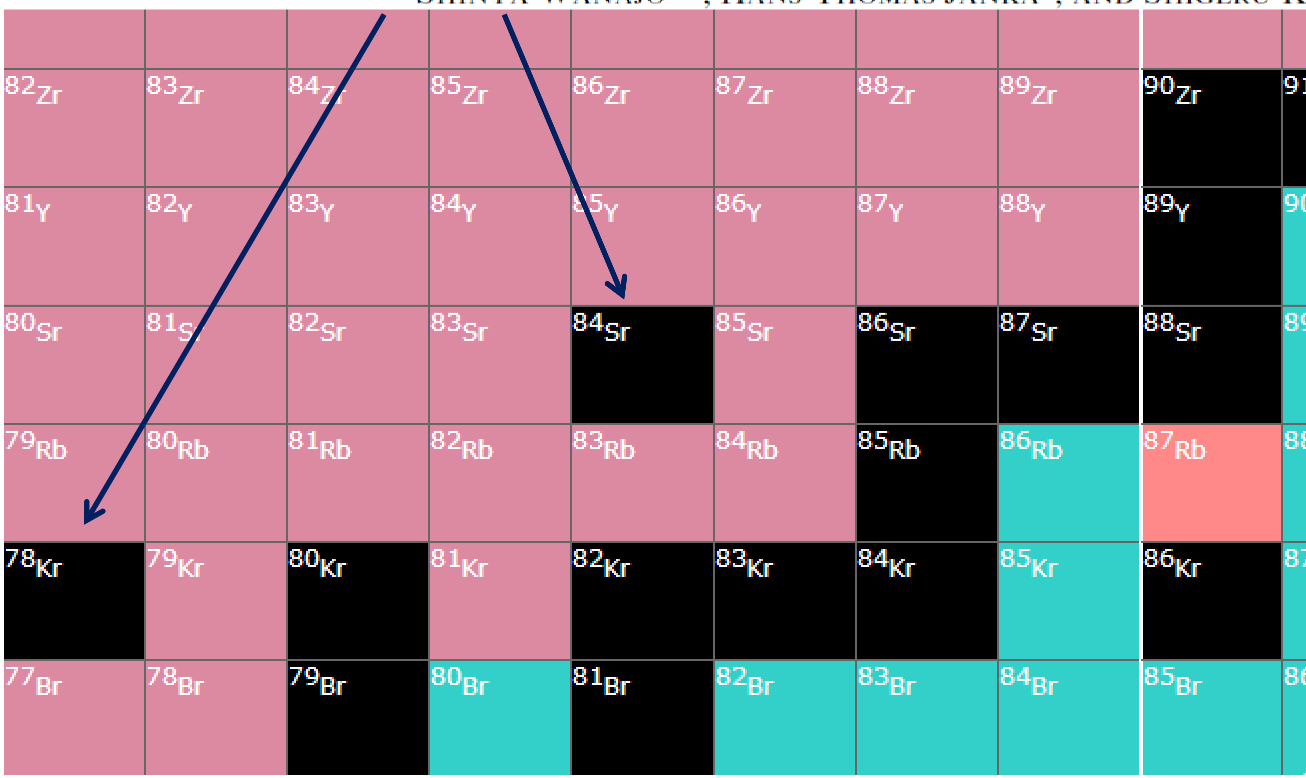
^{64}Ge is not a significant rp-process waiting point.

νp-process as the origin of p-nuclei

THE ASTROPHYSICAL JOURNAL, 729:46 (18pp), 2011 March 1 doi:10.1088/0004-637X/729/1/46

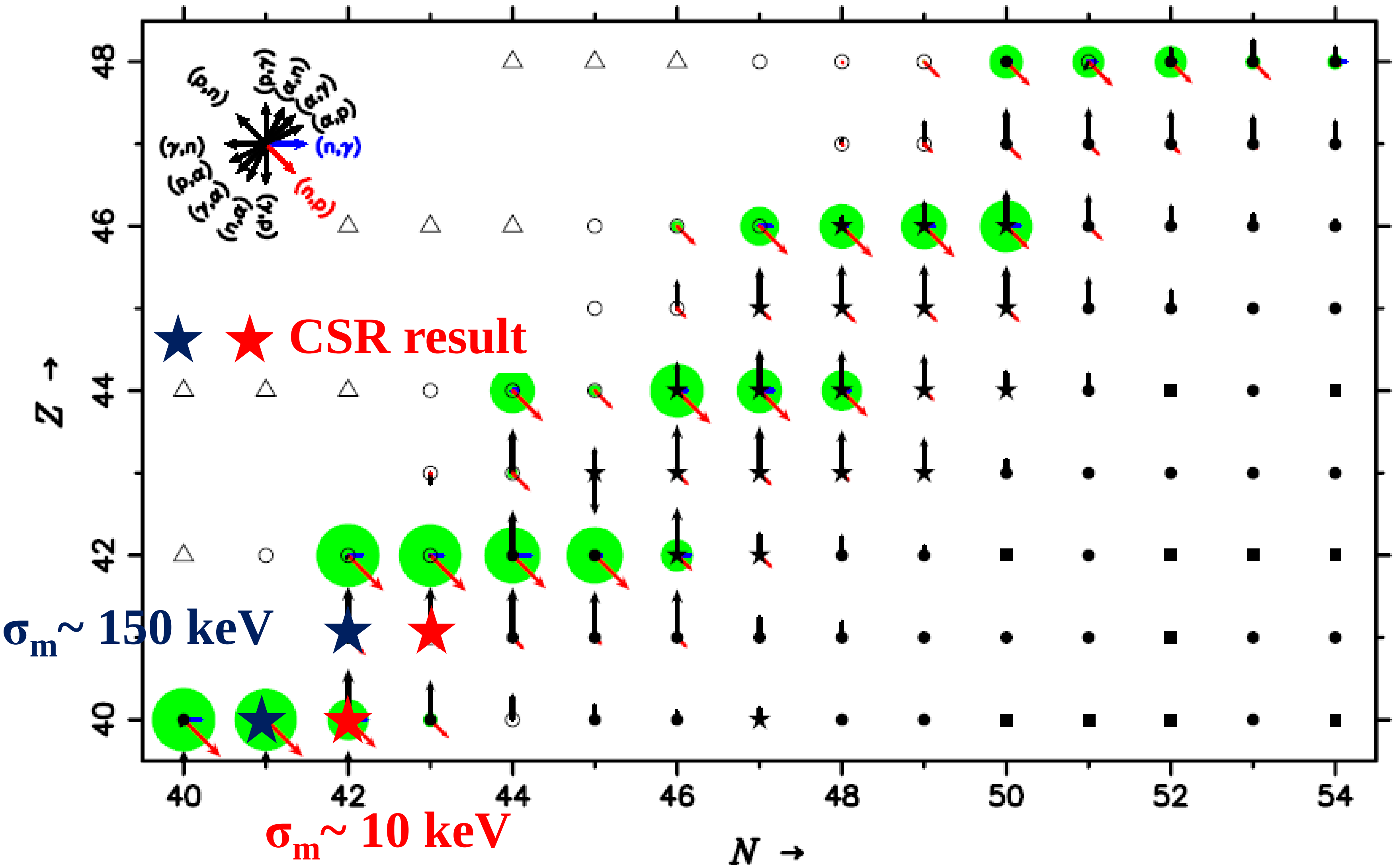
UNCERTAINTIES IN THE *νp*-PROCESS: SUPERNOVA DYNAMICS VERSUS NUCLEAR PHYSICS

SHINYA WANAJO[1,2], HANS-THOMAS JANKA[2], AND SHIGERU KUBONO[3]



…… The uncertainty in the nuclear mass of ^{82}Zr can lead to a factor of two reduction in the abundance of the *p*-isotope ^{84}Sr.

Nuclear flows and abundances



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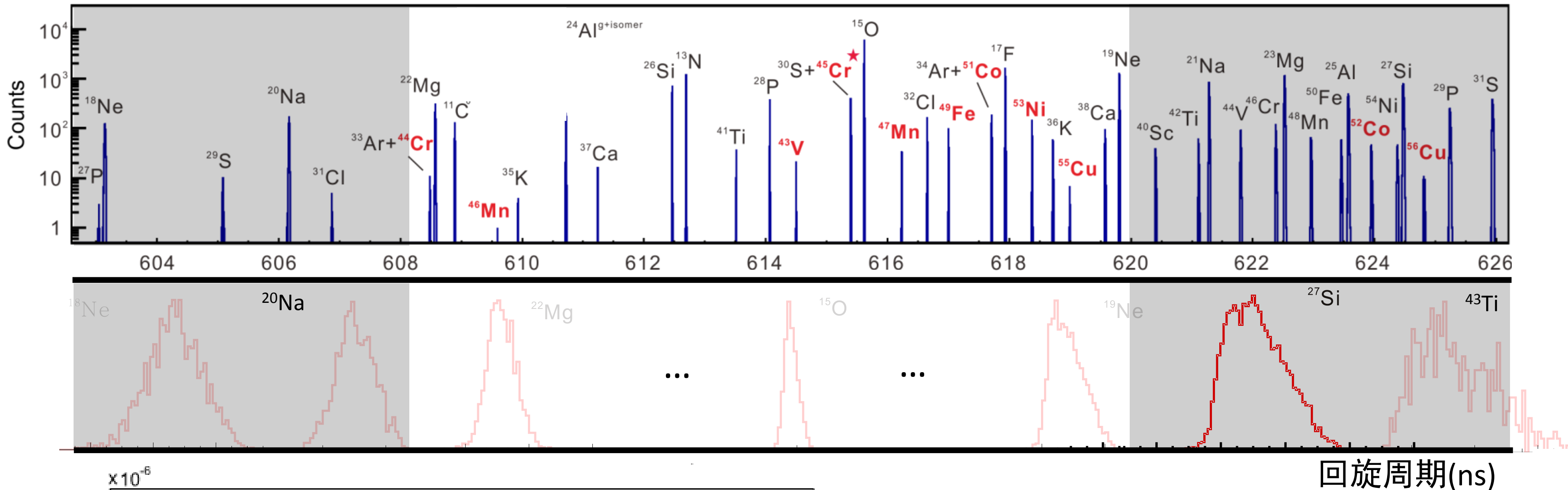
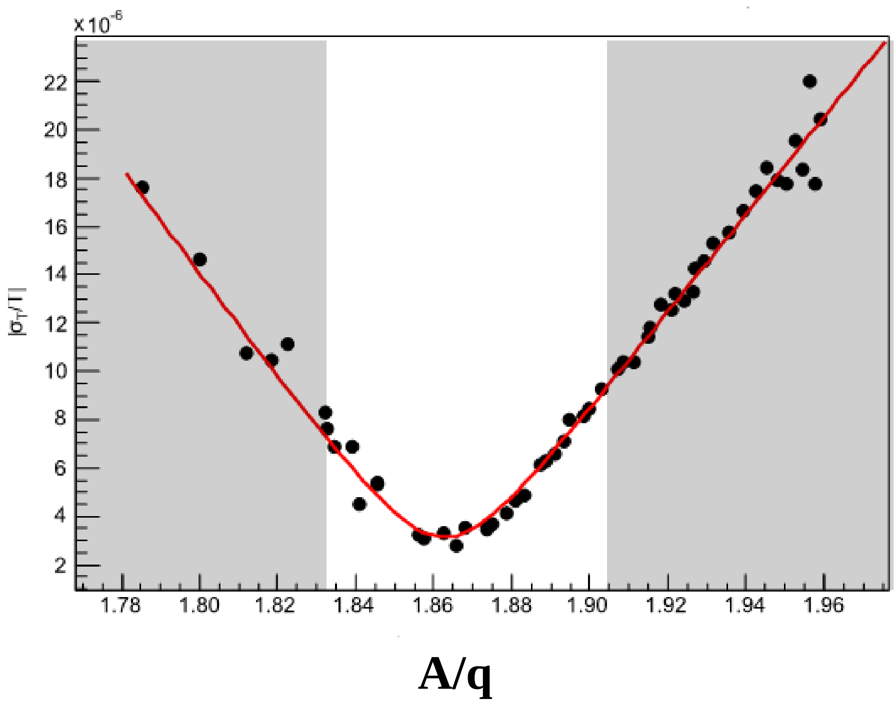
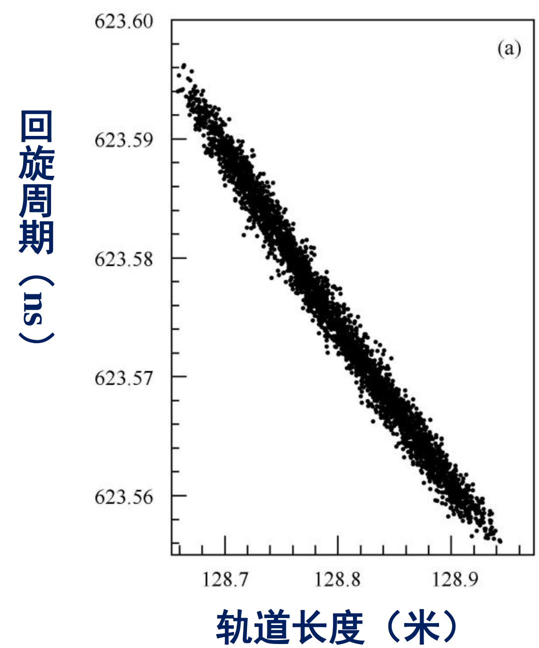
Double-TOF IMS at CSRe

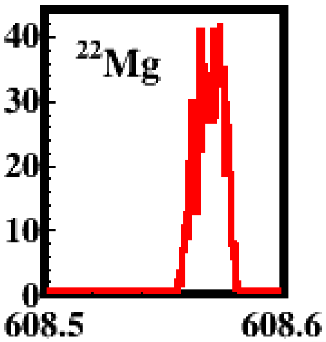




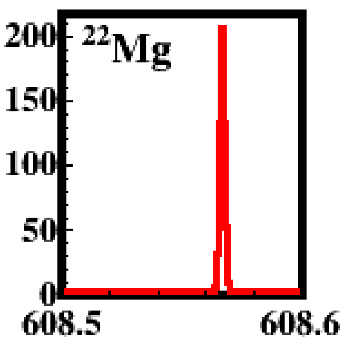


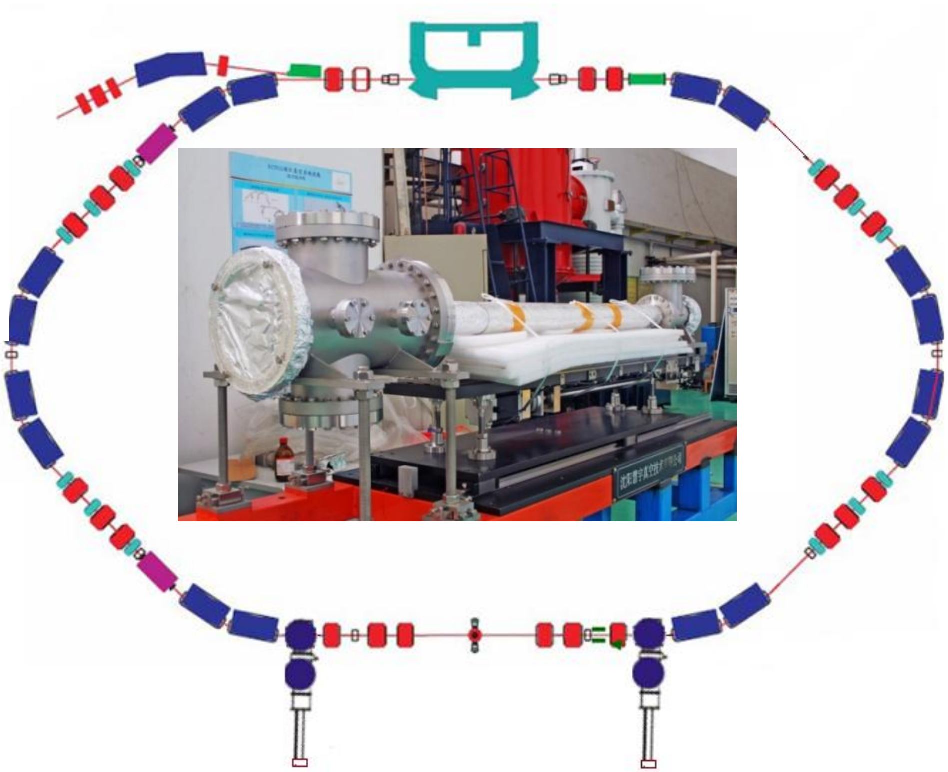
Double-TOF IMS at CSRe

Singal TOF

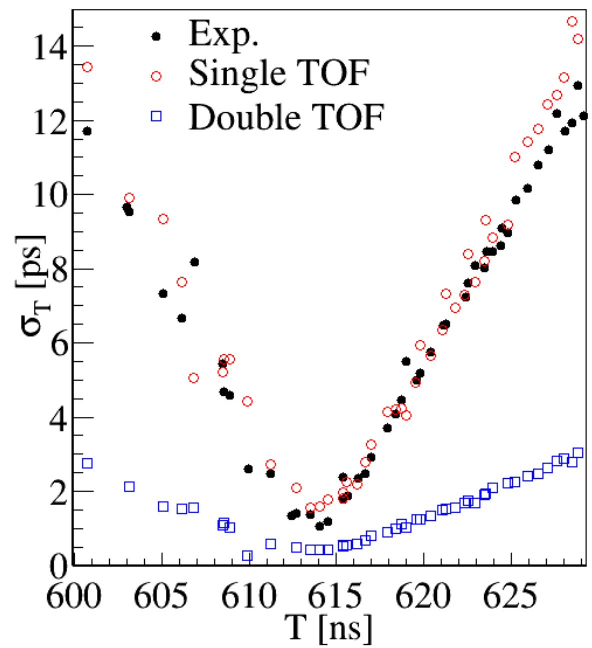


Doubel TOF



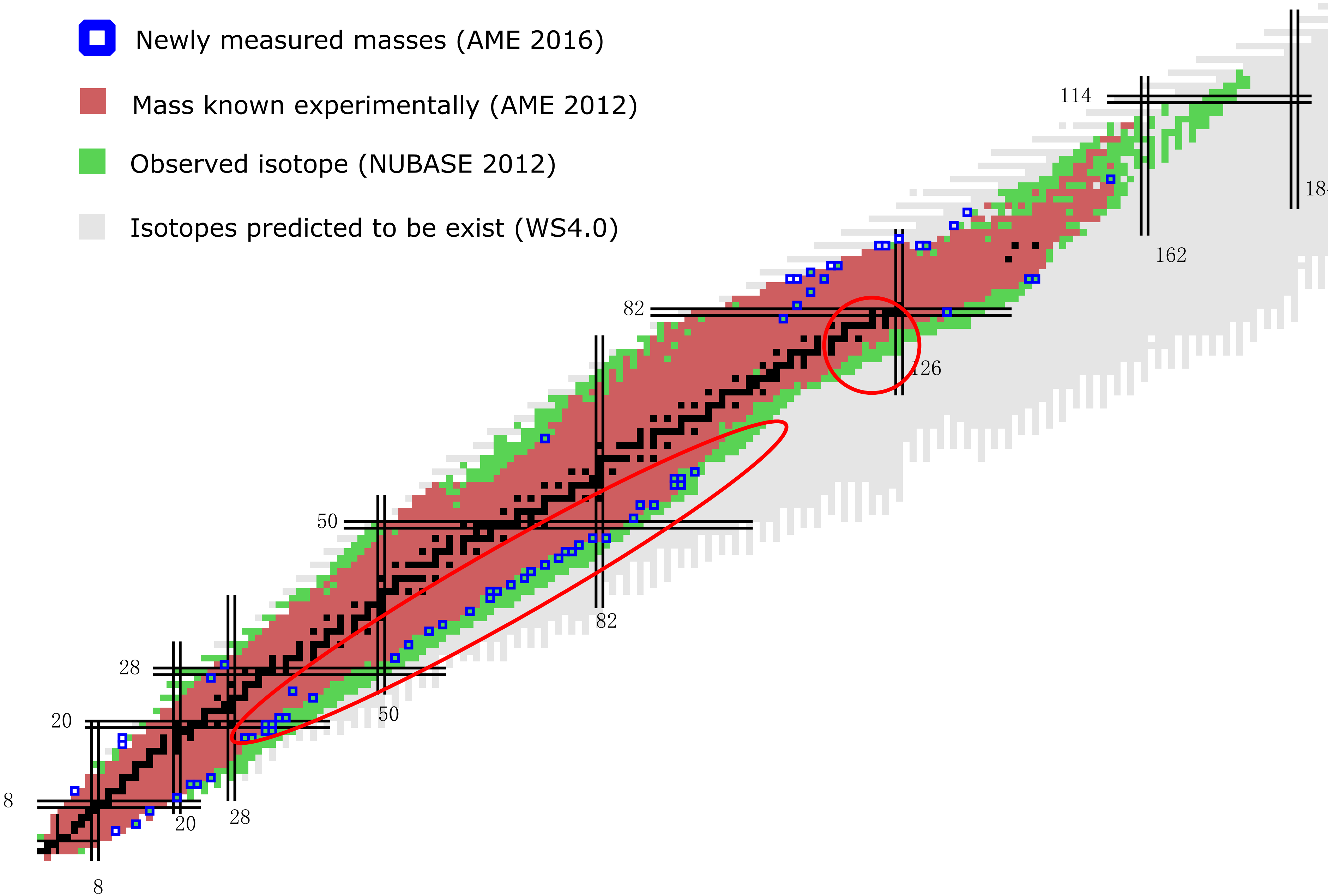


Two ToF detectors:
ds=18 m

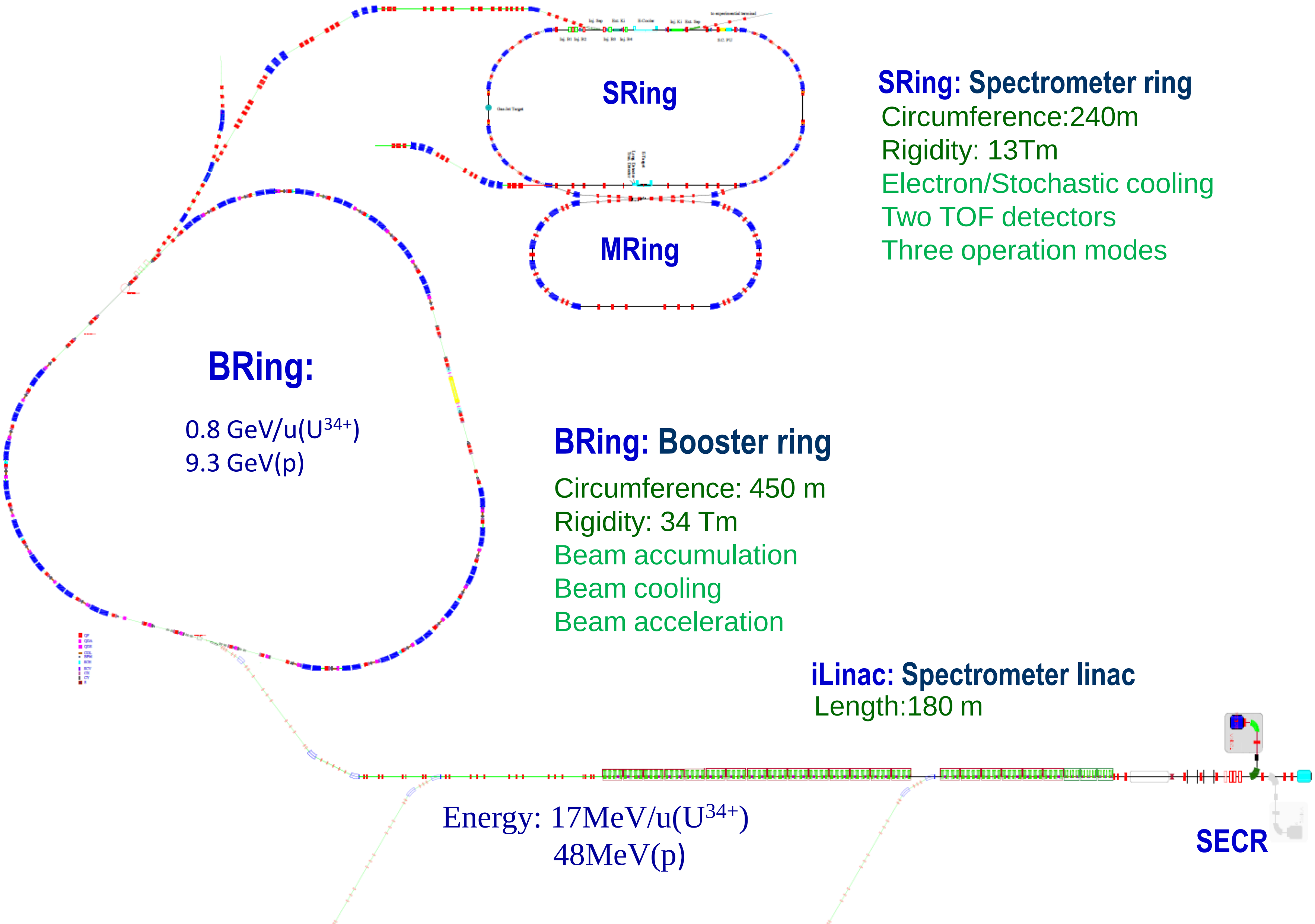


X. Xu et al.,
Chin.Phys.C 39, 106201 (2015)

Nuclear masses: future



High-Intensity Heavy Ion Accelerator Facility



SRing: Spectrometer ring

Circumference:240m
Rigidity: 13Tm
Electron/Stochastic cooling
Two TOF detectors
Three operation modes

BRing: Booster ring

Circumference: 450 m
Rigidity: 34 Tm
Beam accumulation
Beam cooling
Beam acceleration

iLinac: Spectrometer linac

Length:180 m

CSRe mass measurement collaboration

H. S. Xu, Y. H. Zhang, M. Wang, R. J. Chen, X. C.Chen, C. Y. Fu, B. S. Gao, P. Shuai, M.Z. Sun, X. L.Tu, Y.M. Xing, X. Xu, X. L. Yan, Q. Zeng, X. H. Zhou, Y. J. Yuan, J. W. Xia, J. C. Yang, Z. G. Hu, S. Kubono, X. W. Ma, R. S. Mao, B. Mei, G. Q. Xiao, H. W. Zhao, T. C. Zhao, W. L. Zhan (IMP-CAS, Lanzhou, China)

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K. Blaum (MPIK, Heidelberg, Germany)

Y. Sun (Shanghai Jiao Tong University, Shanghai, China)

Baohua SUN (Beihang University)

H. Schatz, B. A. Brown (MSU, USA)

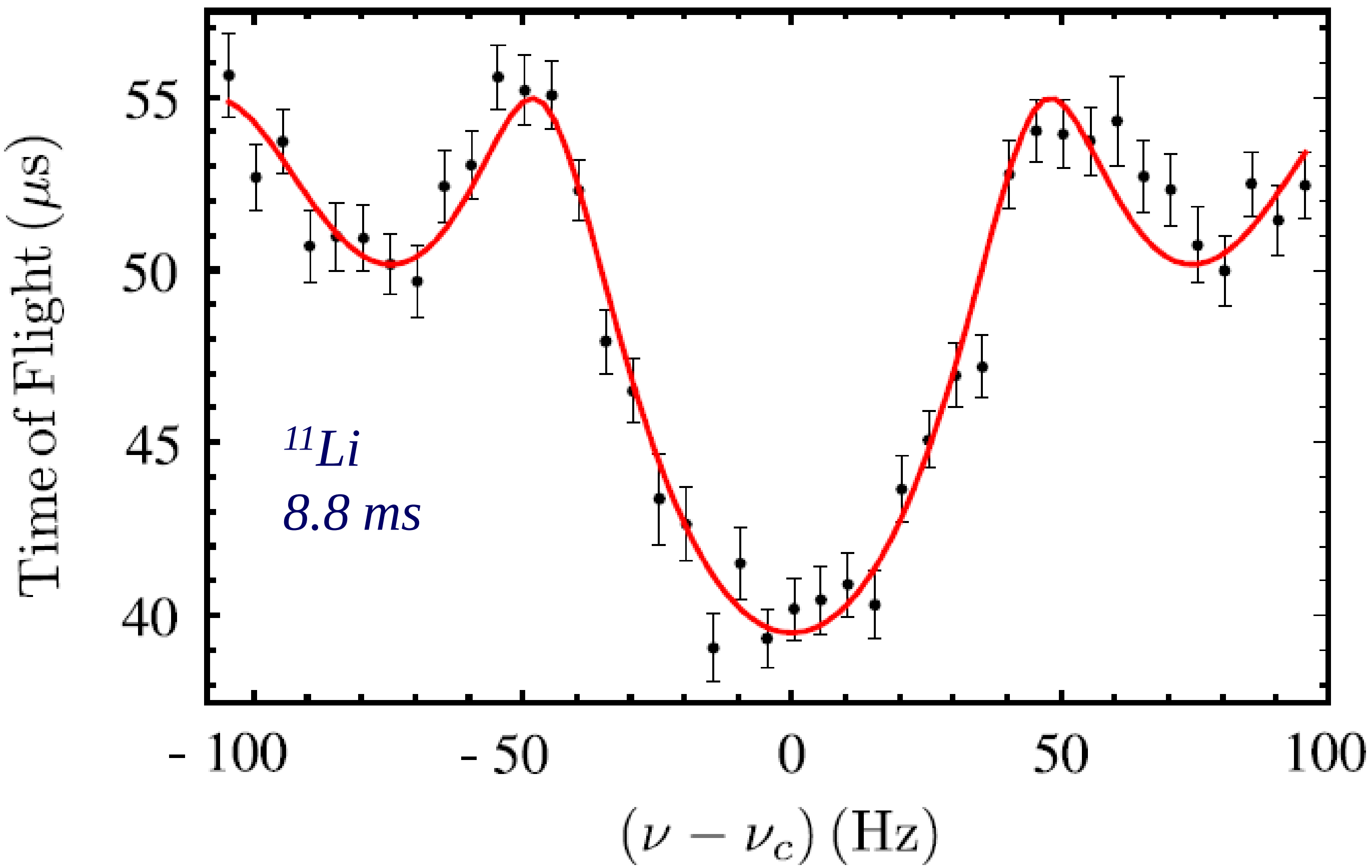
G. Audi (CSNSM-IN2P3-CNRS, Orsay, France)

T. Yamaguchi (Saitama University, Saitama, Japan)

T. Uesaka, Y. Yamaguchi (RIKEN, Saitama, Japan)

Thank you for your attention!

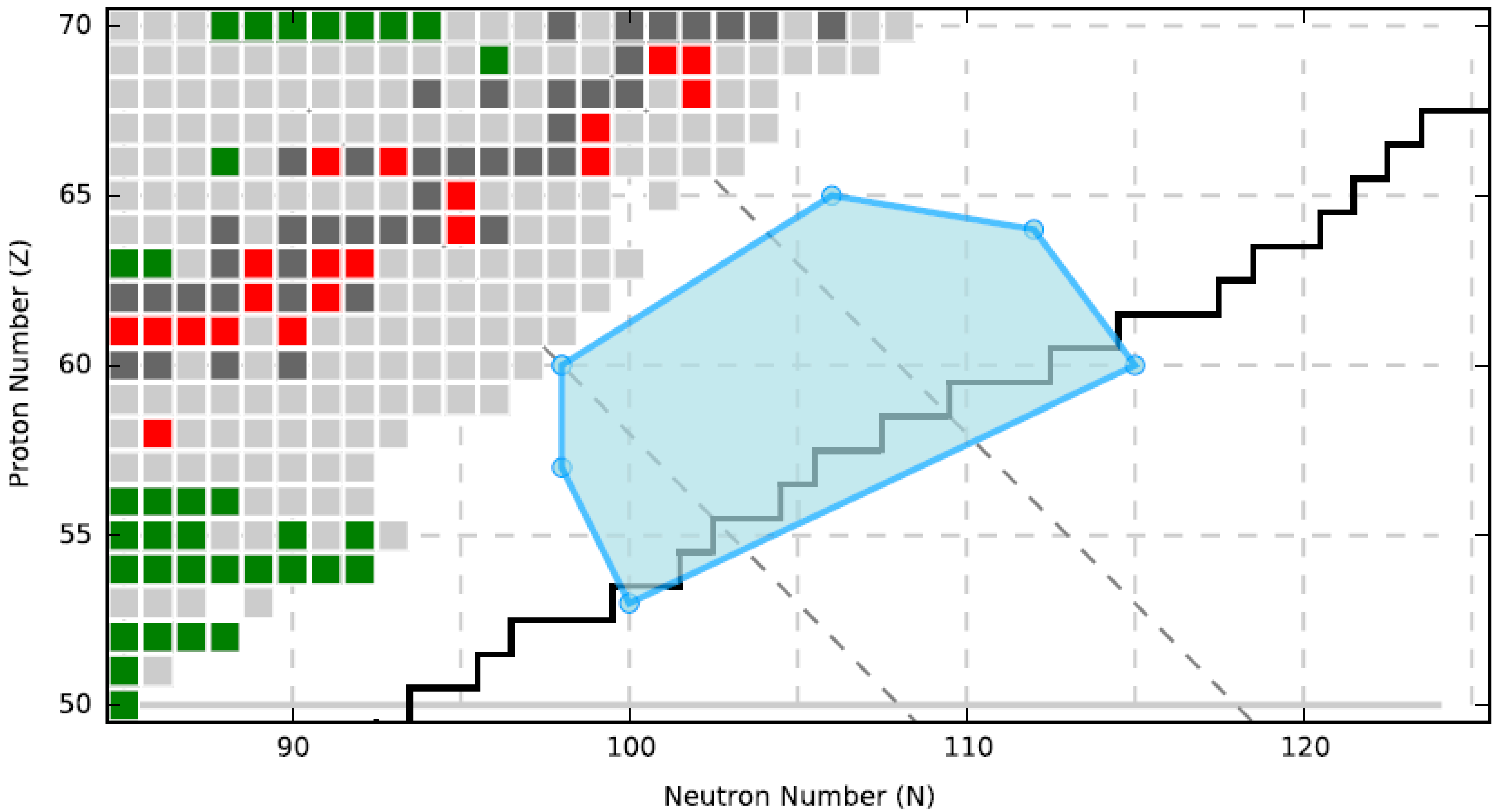
PRL **101**, 202501 (2008)



Resolving power： m/Δm~80,000

Relative uncertainty： 6×10^{-8}

Nuclei for the formation of the rare earth peak



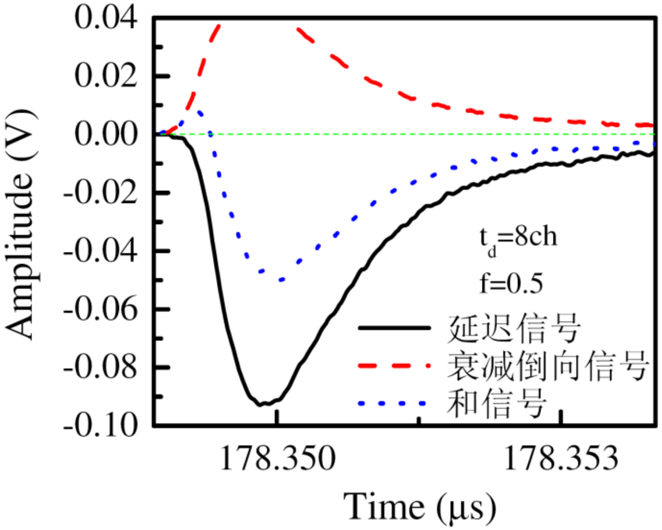
M.R. Mumpower, R. Surman, G.C McLaughlin, A. Aprahamian,
The impact of individual nuclear properties on r-process nucleosynthesis,
Prog. Part. Nucl. Phys. 86, 86 (2016)

Questions and answers

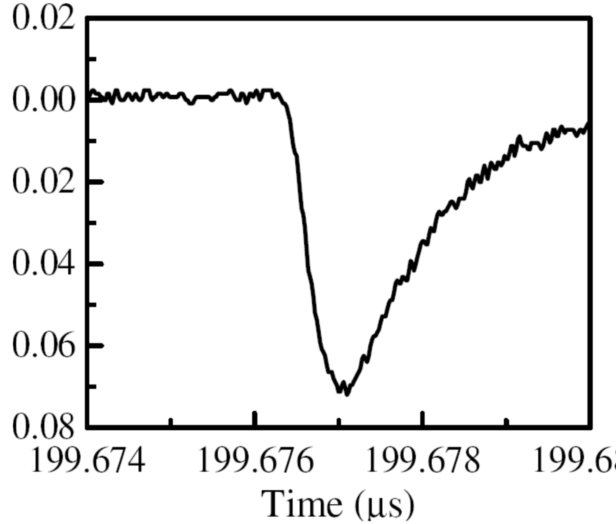
- How do we measure the revolution time?
- The lower limit of half-lives.

Data analysis

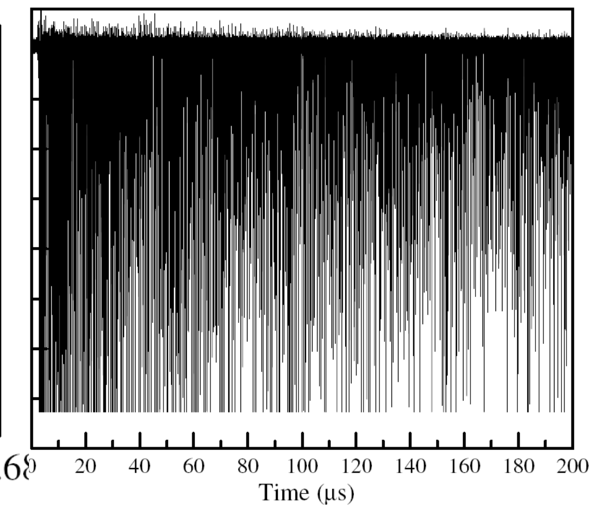
3. CF



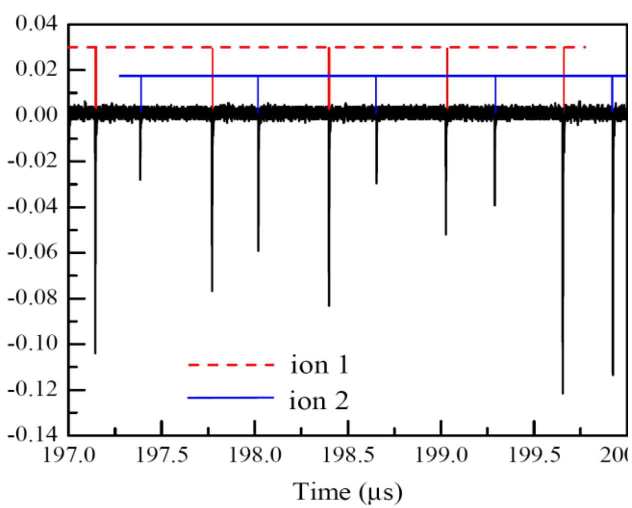
2. smoothing



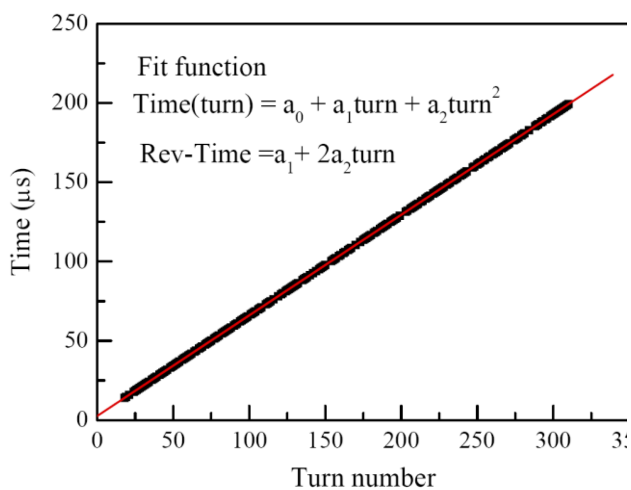
1. Original signals



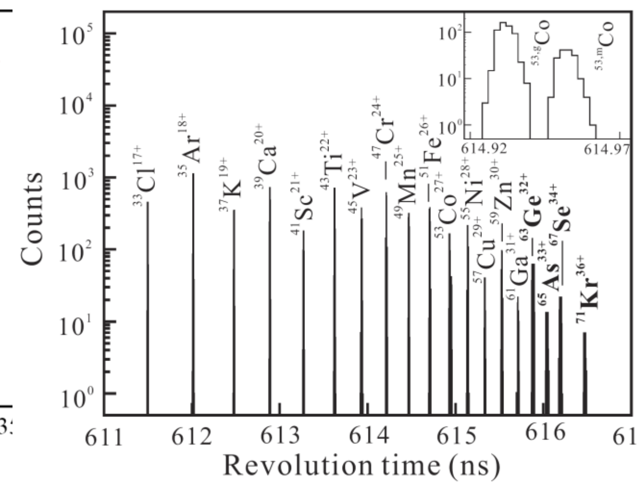
4. tracing

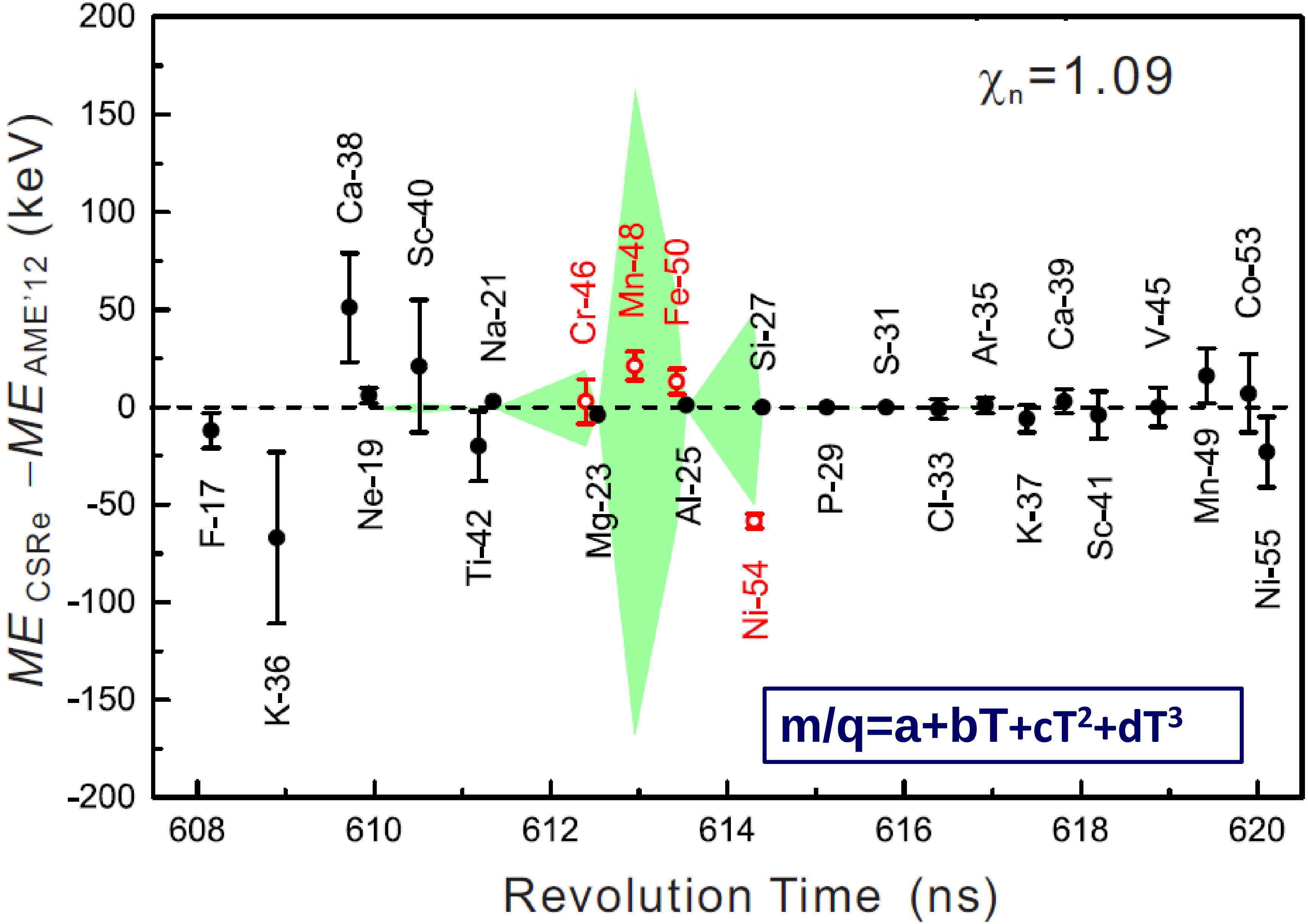


5. fitting



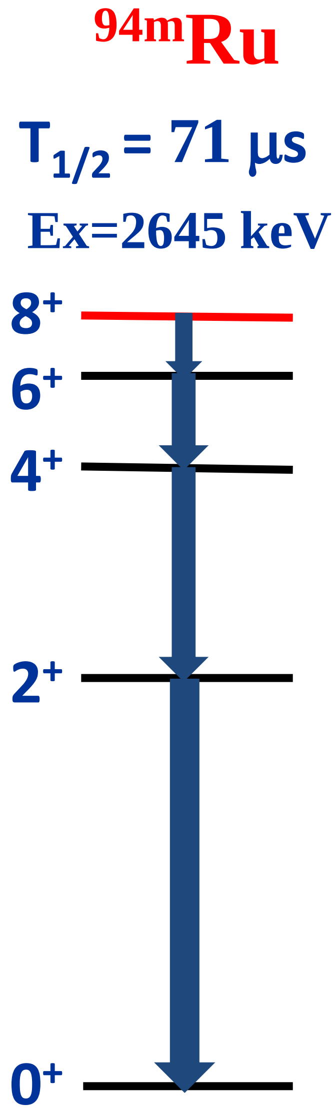
6. Revolution time

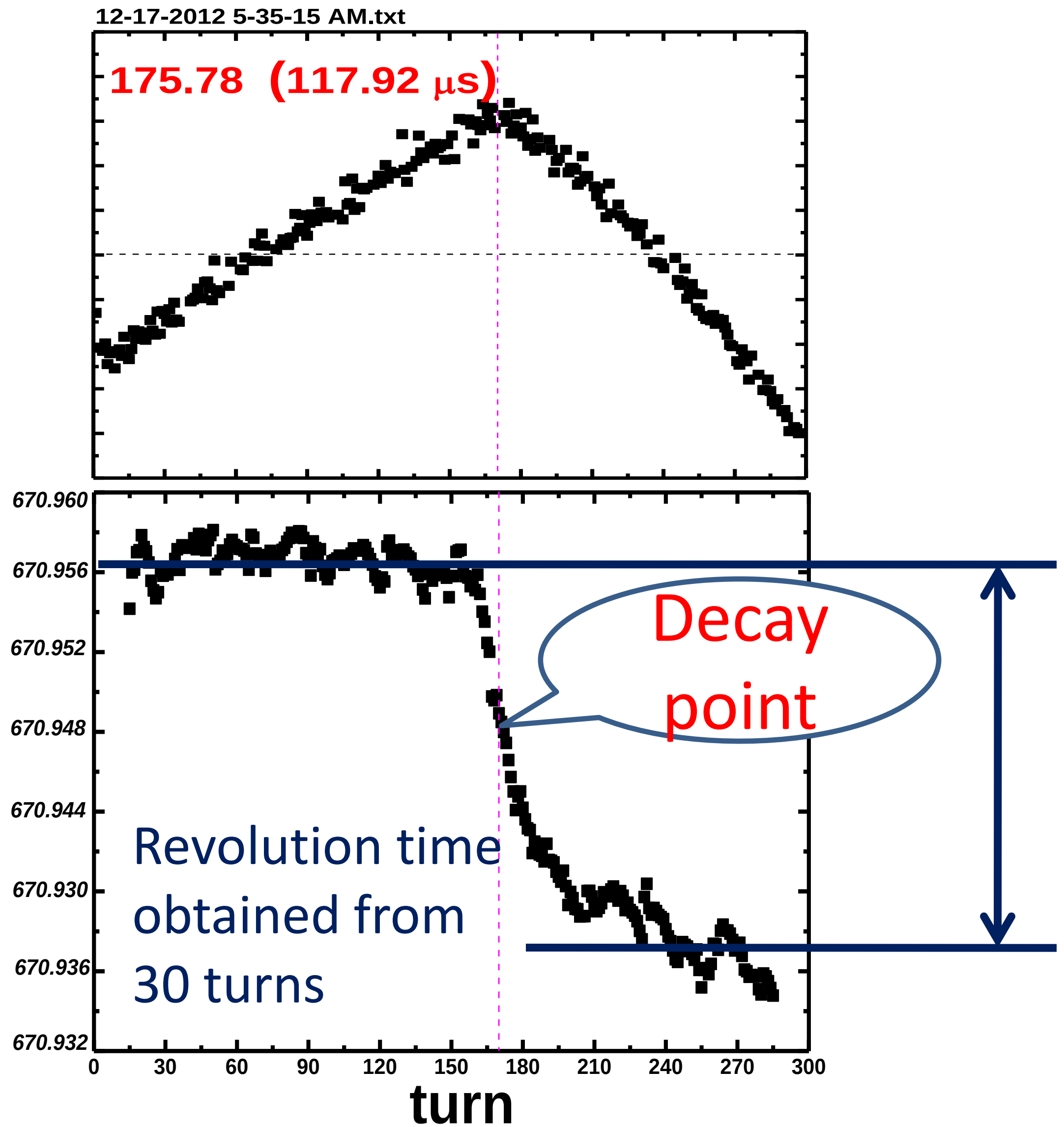




χn=1.09
m/q=a+bT+cT²+dT³
ME CSRe −ME AME'12 (keV)
Revolution Time (ns)
F-17
K-36
Ca-38
Ne-19
Sc-40
Ti-42
Na-21
Cr-46
Mg-23
Mn-48
Fe-50
Al-25
Si-27
Ni-54
P-29
S-31
Cl-33
Ar-35
K-37
Ca-39
Sc-41
V-45
Mn-49
Co-53
Ni-55

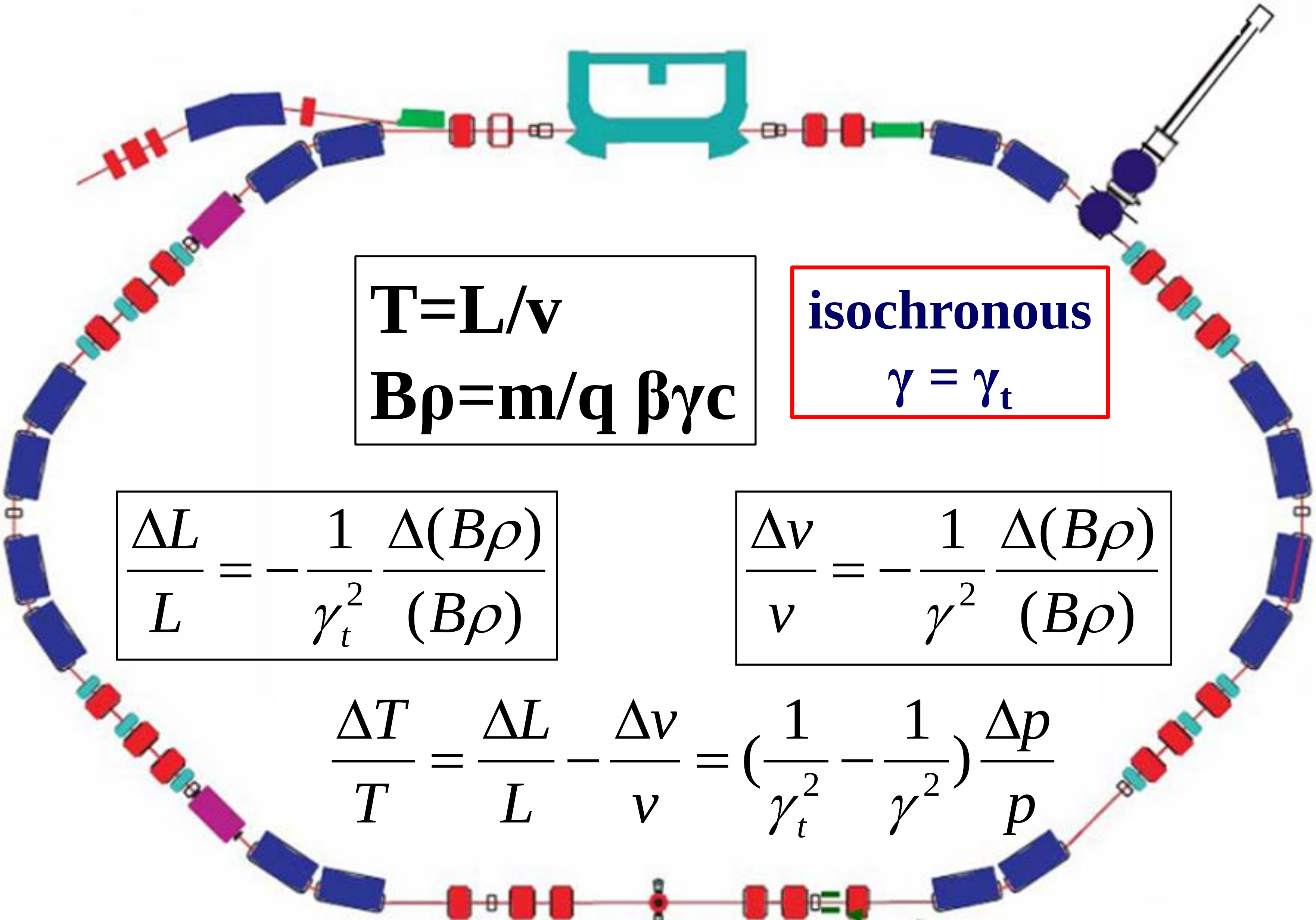
In-ring decay of $T_{1/2}$ = 71 μs Isomer in ^{94}Ru





In progress

Principle : isochronous mass spectrometry



T=L/v

Bρ=m/q βγc

isochronous

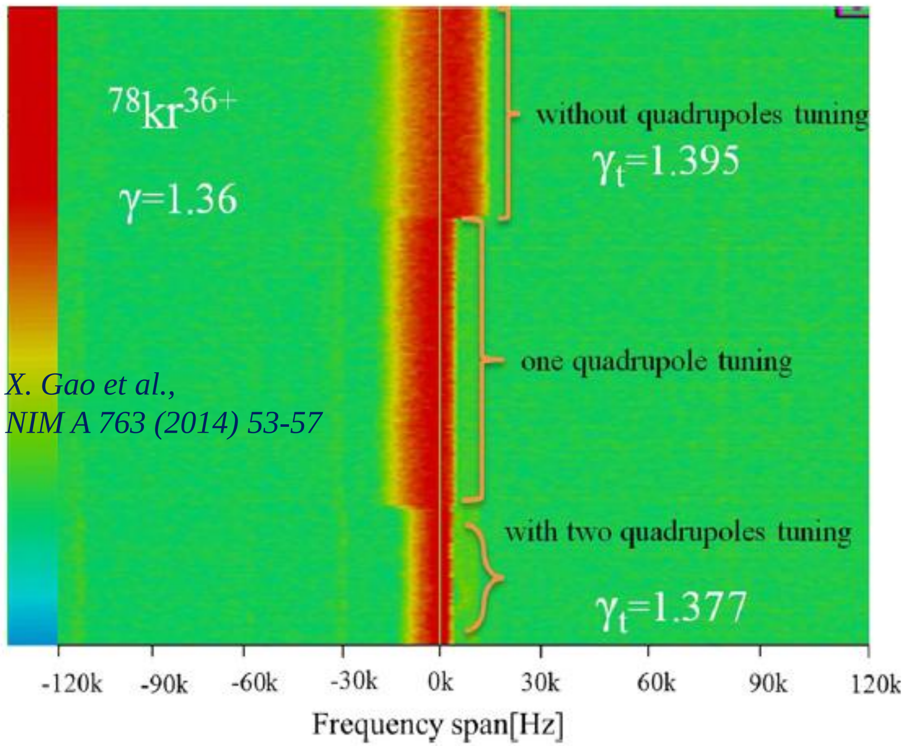
$\gamma = \gamma_t$

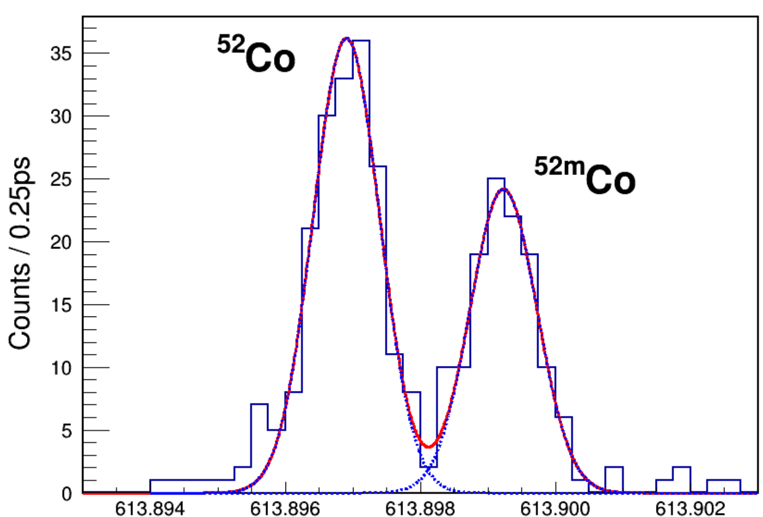
$$\frac{\Delta L}{L} = -\frac{1}{\gamma_t^2}\frac{\Delta(B\rho)}{(B\rho)}$$

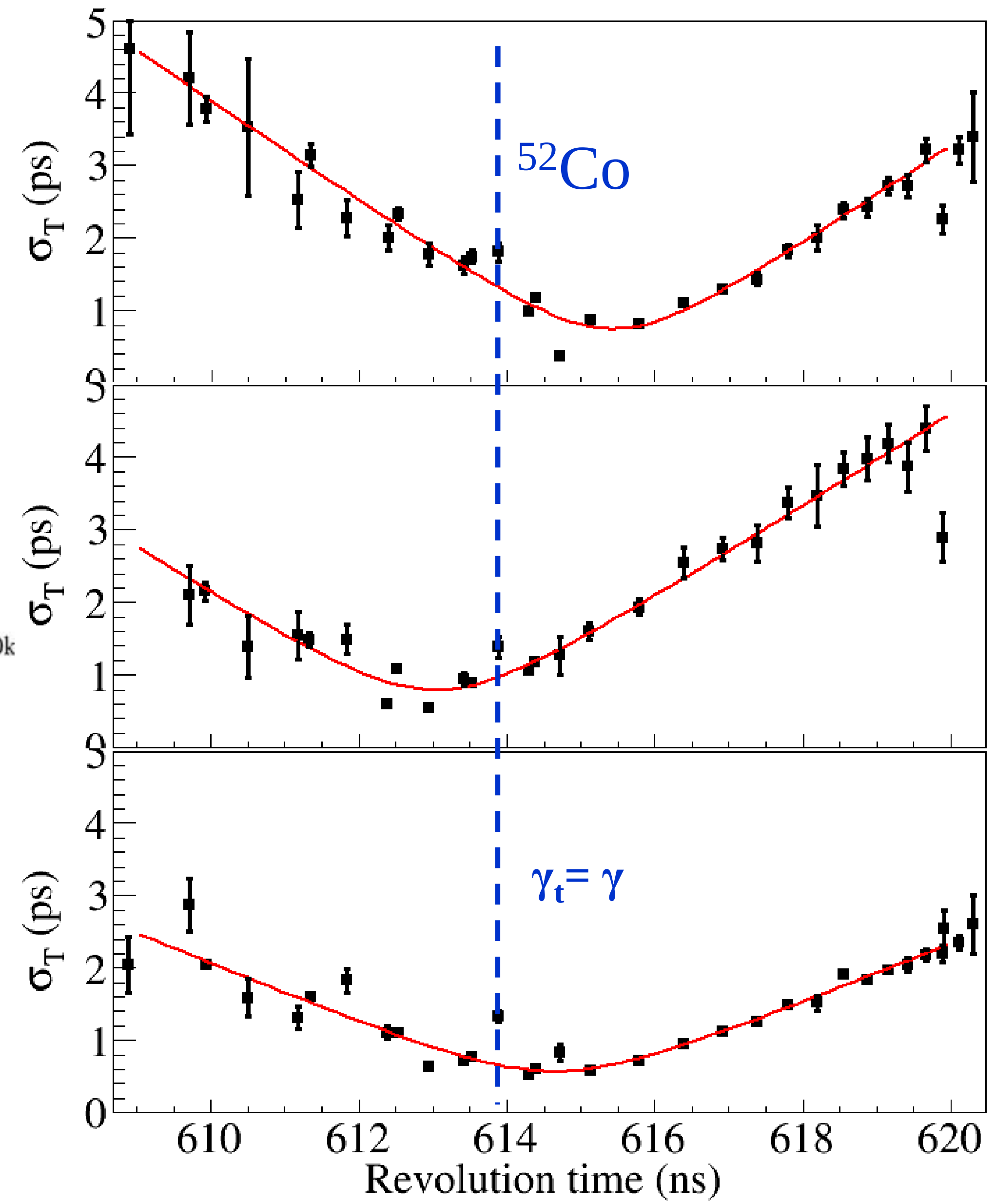
$$\frac{\Delta v}{v} = -\frac{1}{\gamma^2}\frac{\Delta(B\rho)}{(B\rho)}$$

$$\frac{\Delta T}{T} = \frac{\Delta L}{L} - \frac{\Delta v}{v} = (\frac{1}{\gamma_t^2} - \frac{1}{\gamma^2})\frac{\Delta p}{p}$$

Isochronous setting







- Uncertainties in our measurements:

- Statistical
- Calibration
- Systematic

$$\chi^2 = \sum_{i=1}^{n} \frac{\left[\left(\frac{m}{q}\right)_i^{exp} - \left(\frac{m}{q}\right)_i^{table} \right]^2}{\left[\sigma_{stat} \left(\frac{m}{q}\right)_i \right]^2 + \left[\sigma_{table} \left(\frac{m}{q}\right)_i \right]^2 + \sigma_{syst}^2} = 1$$

- Particle identification

Most of the ions are “bare”.

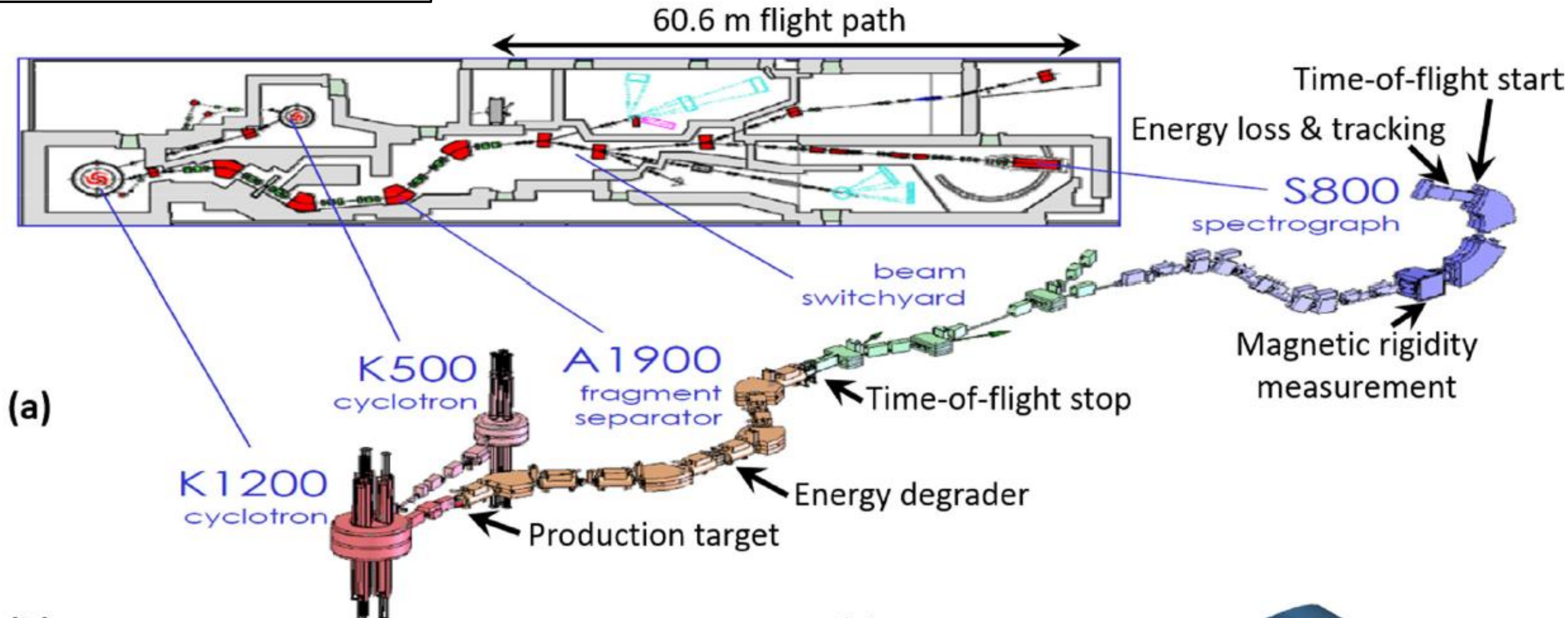
$^{52}Co^{27+}$ $^{52}Ni^{27+}$

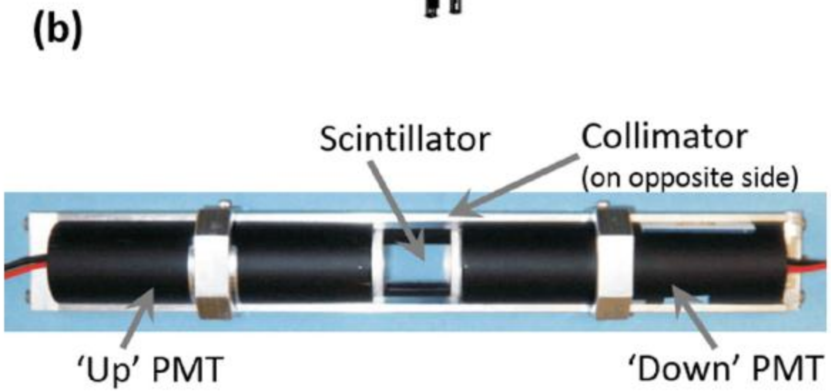
Hydrogen-like ion could contaminate the spectrum on neutron-rich side.

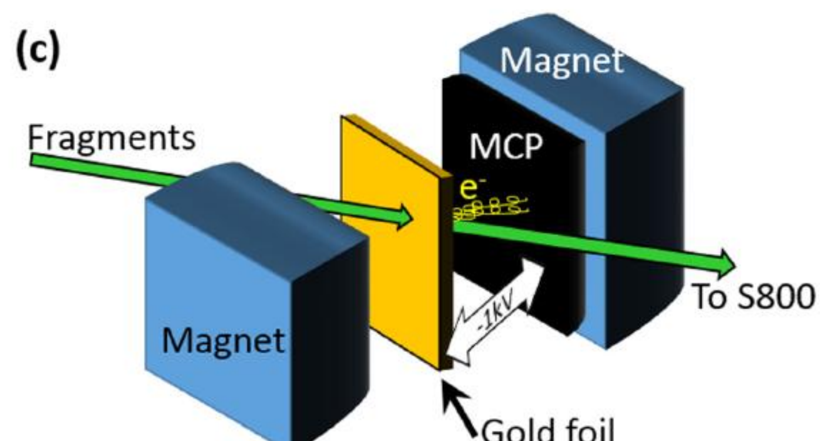
Bρ-TOF at MSU

T=L/v

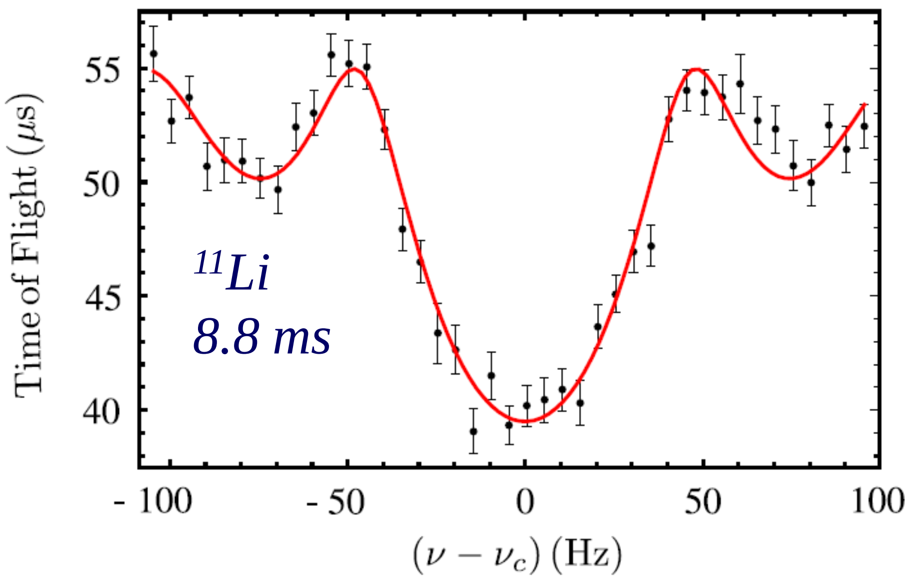
Bρ=m/q βγc



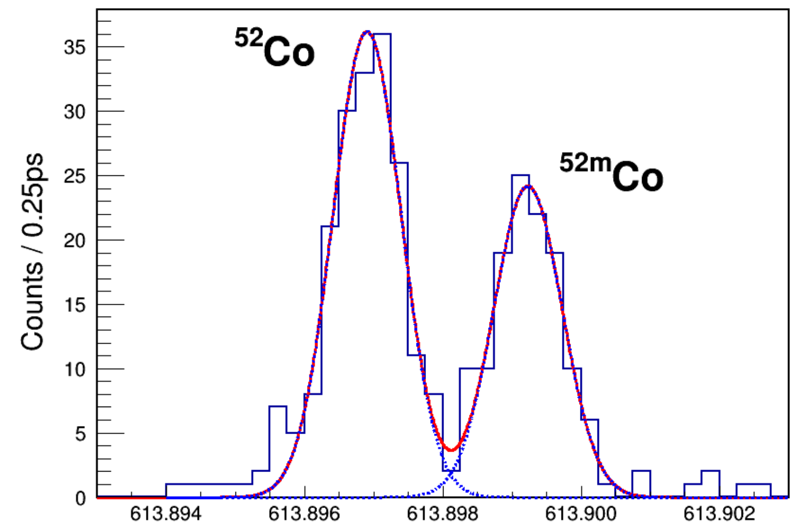




PRL **101**, 202501 (2008)

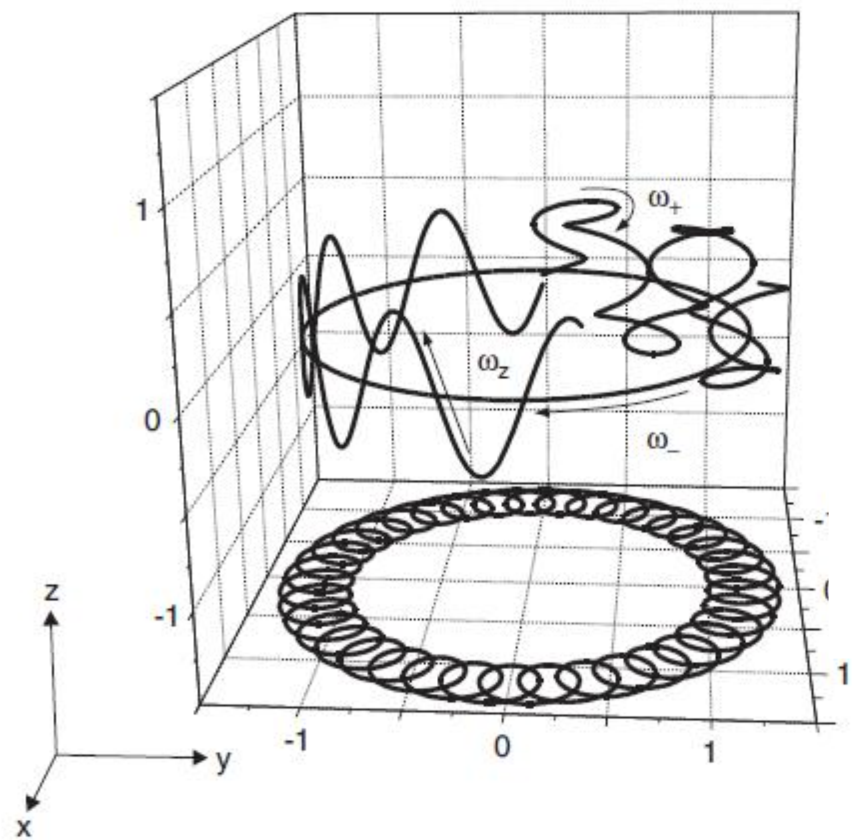


PRL **117**, 182503 (2016)



Resolving power：m/Δm~80,000 **m/Δm~210,000**

Relative uncertainty：6×10^{-8} **2×10^{-7}**



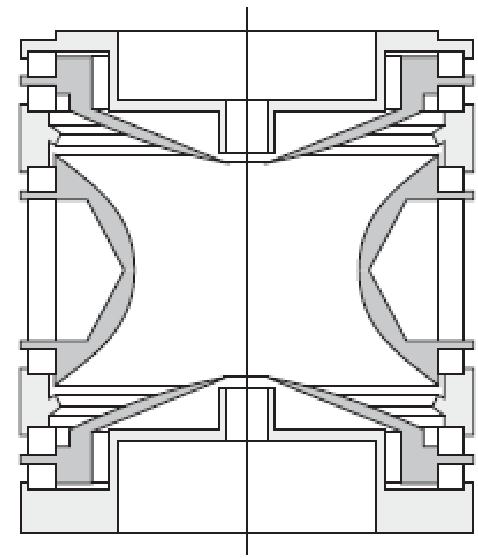
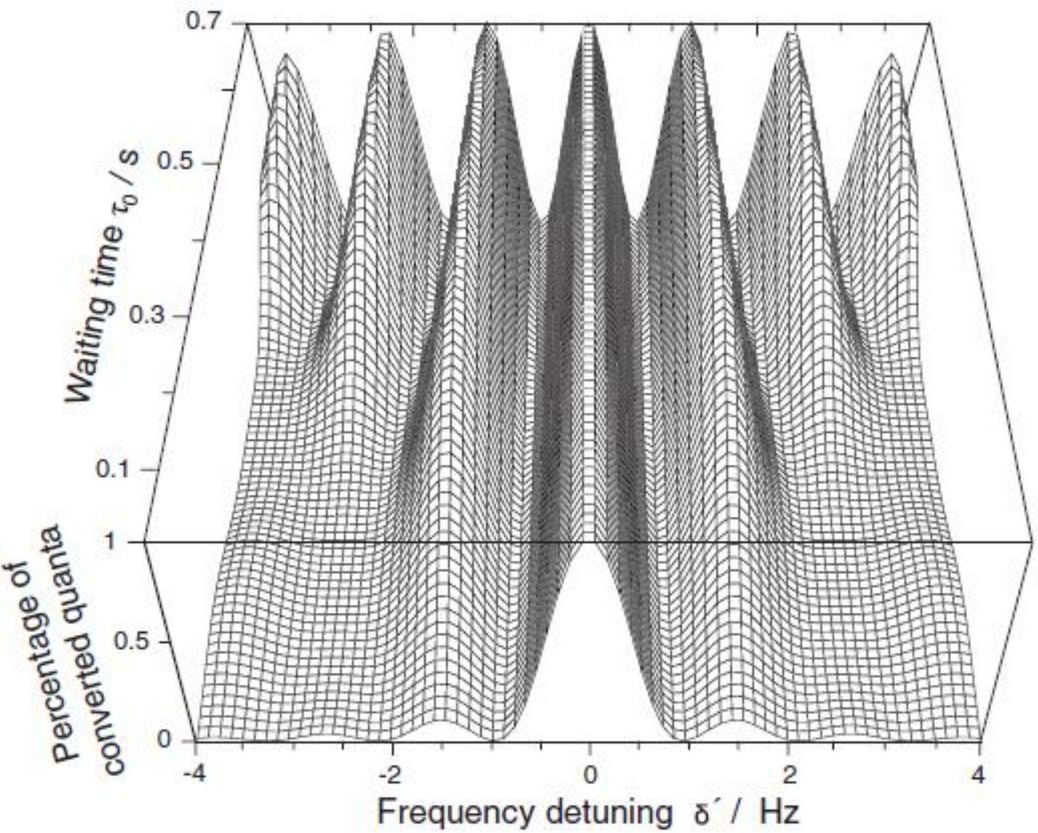
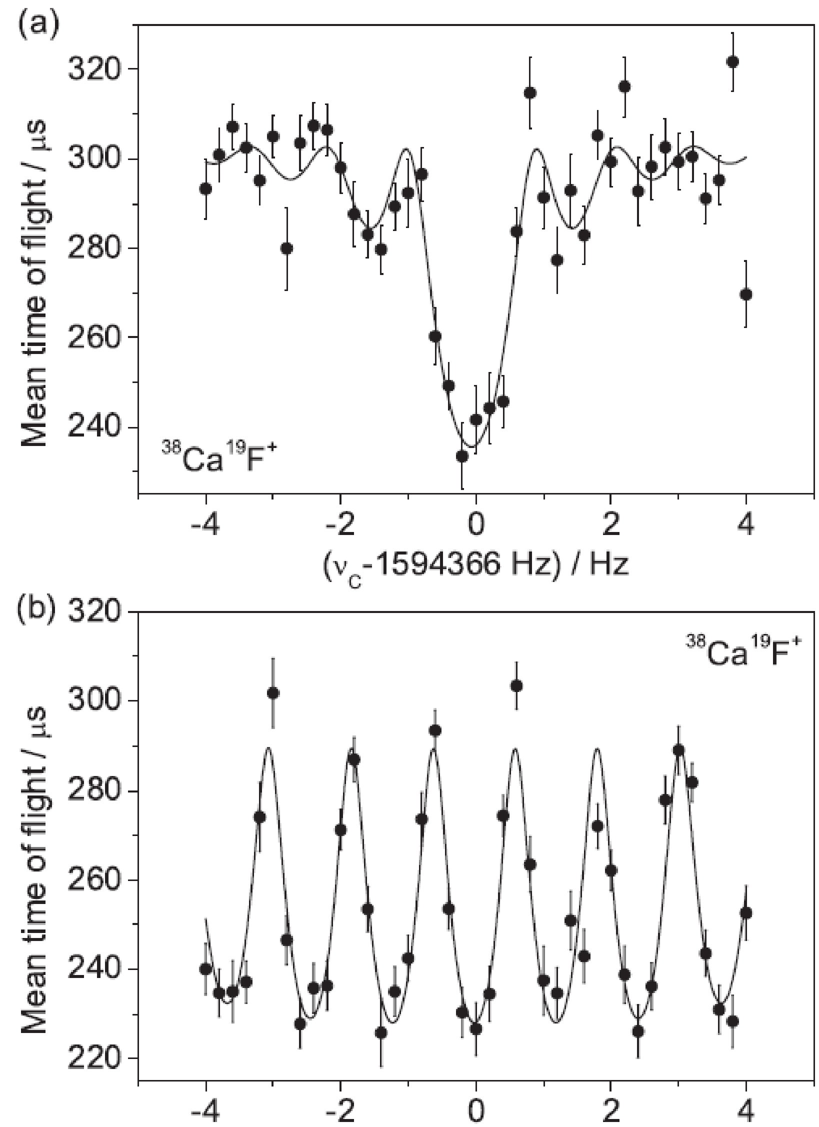
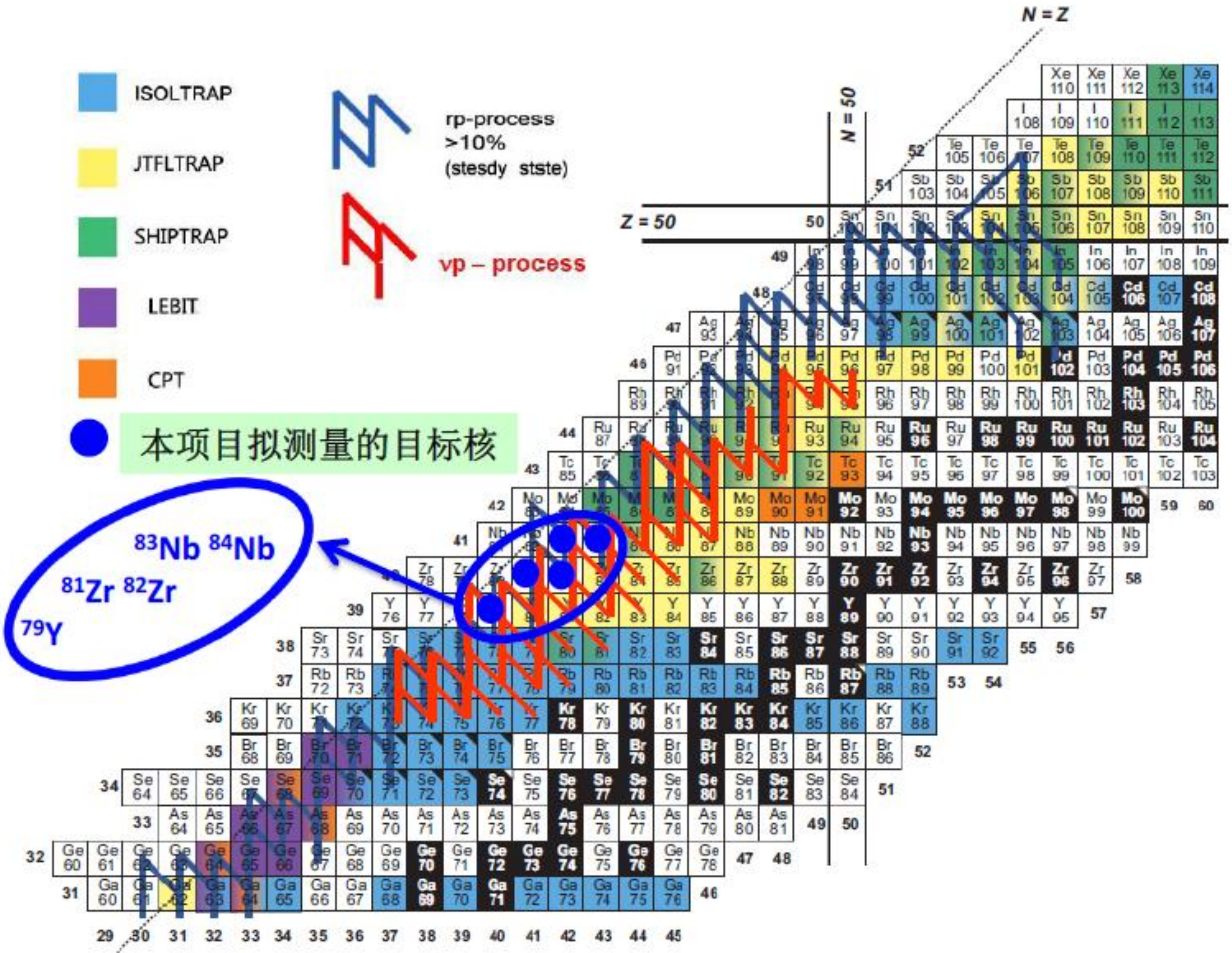


Fig. 10. Schematic trajectory (three-dimensional and projection onto the x–y-plane) with ideally three independent eigenmotions of an ion in a Penning trap: a harmonic oscillation in the axial direction (axial motion with frequency ω_z), and a radial motion that is a superposition of the modified cyclotron motion with frequency ω_+ and the magnetron motion with frequency ω_-.

Ramsey Method of Separated Oscillatory Fields for High-Precision Penning Trap Mass Spectrometry






ISOLTRAP
JTFLTRAP
SHIPTRAP
LEBIT
CPT
rp-process
>10%
(stesdy stste)
νp – process
本项目拟测量的目标核
^{83}Nb ^{84}Nb
^{81}Zr ^{82}Zr
^{79}Y
N = Z
N = 50
Z = 50

International Journal of Mass Spectrometry 349–350 (2013) 181–186

Contents lists available at ScienceDirect

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Nuclear masses in astrophysics

H. Schatz *

The fact that the site of the r-process is still unknown is one of the biggest open questions in nuclear astrophysics. This also means that any statements about the importance of nuclear masses refer to a specific r-process model. This is not a limitation. By providing the data required to confirm for falsify a specific r-process scenario through comparison with observations, nuclear physics plays a critical role in addressing this open question.

Nuclear masses: AME2016