Mass measurements of short-lived nuclides at CSRe

Meng WANG

Institute of Modern Physics, Chinese Academy of Sciences
Lanzhou 730000, China

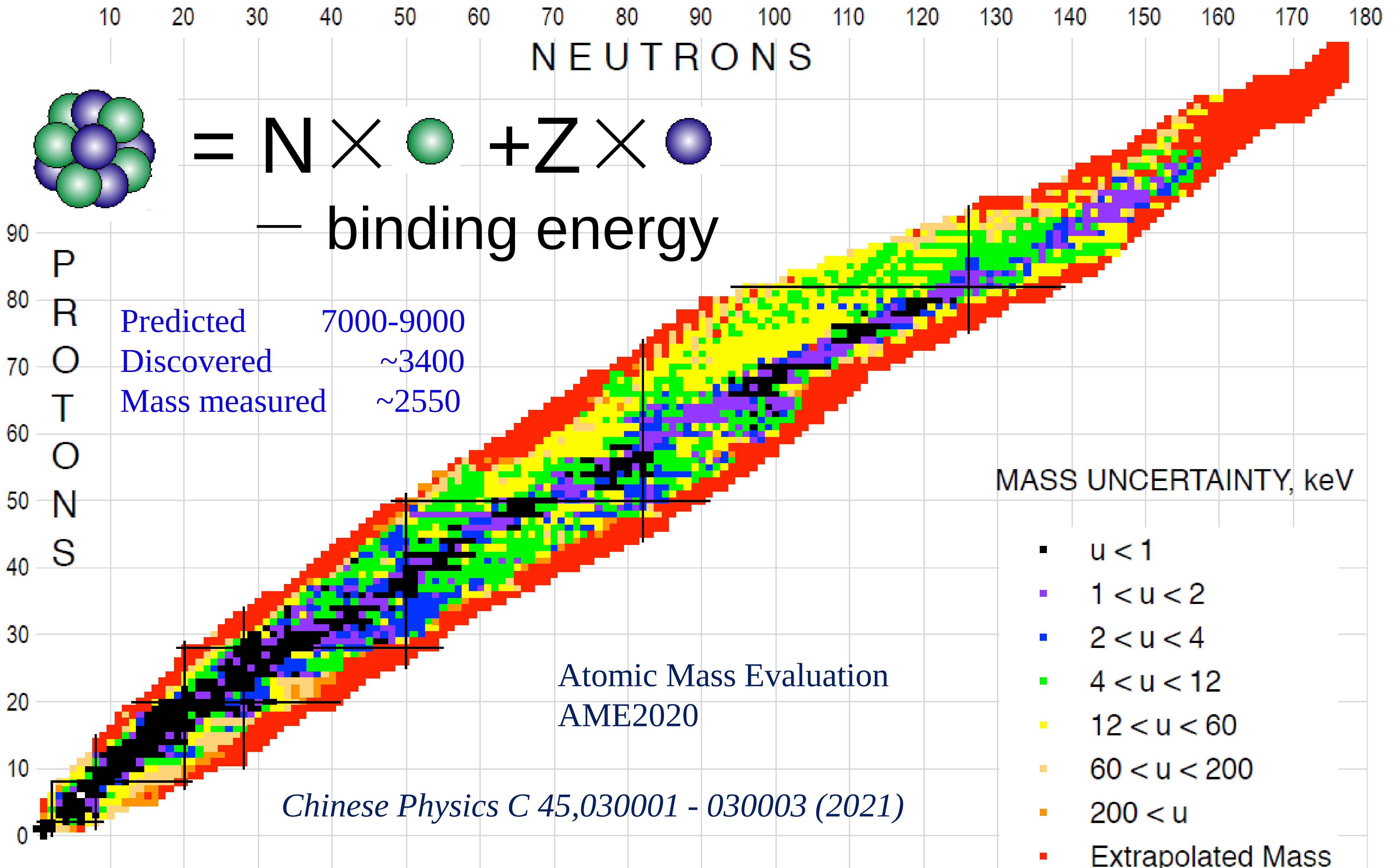
Outline

1 Introduction and background

2 Isochronous mass spectrometry (Bρ-defined)

3 Mass results and recent progress

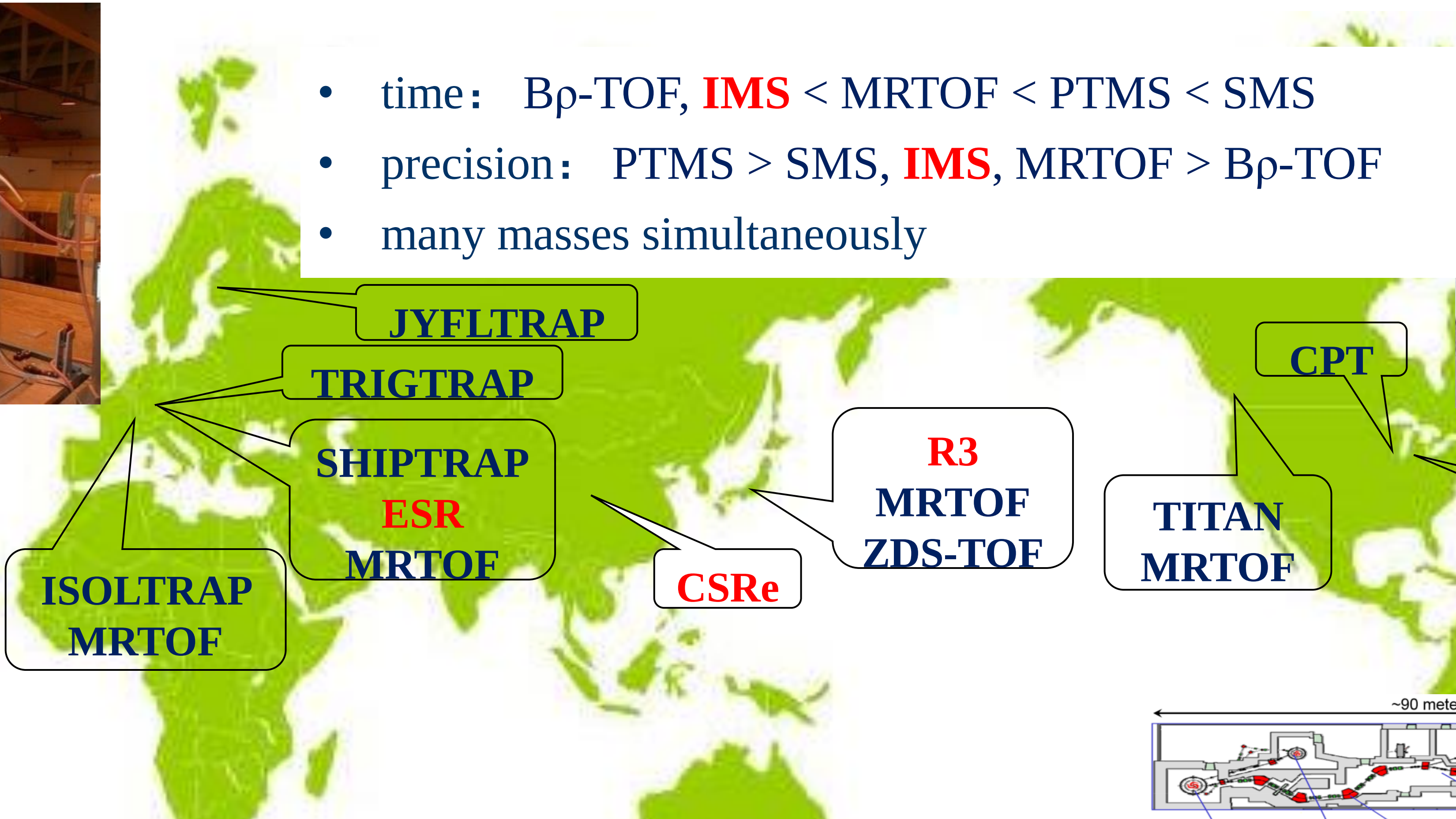
4 Future plan

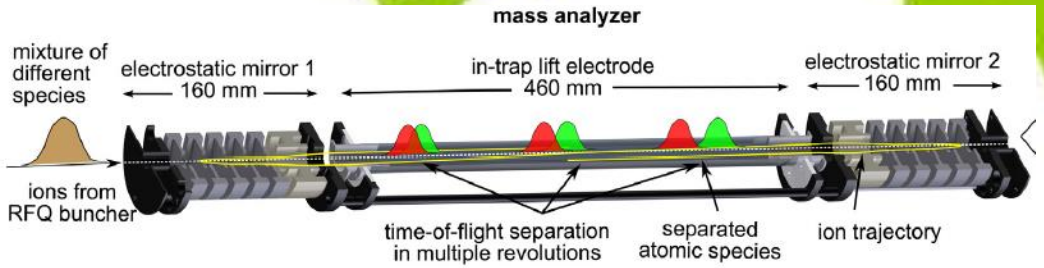


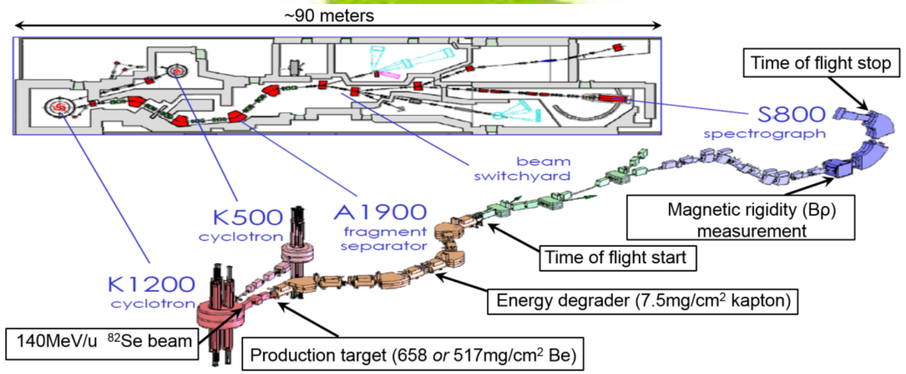
NEUTRONS
PROTONS
= N × ● + Z × ●
− binding energy
Predicted 7000-9000
Discovered ~3400
Mass measured ~2550
MASS UNCERTAINTY, keV
u < 1
1 < u < 2
2 < u < 4
4 < u < 12
12 < u < 60
60 < u < 200
200 < u
Extrapolated Mass
Atomic Mass Evaluation
AME2020
Chinese Physics C 45,030001 - 030003 (2021)

Nuclear mass measurements

- time： Bρ-TOF, **IMS** < MRTOF < PTMS < SMS
- precision： PTMS > SMS, **IMS**, MRTOF > Bρ-TOF
- many masses simultaneously







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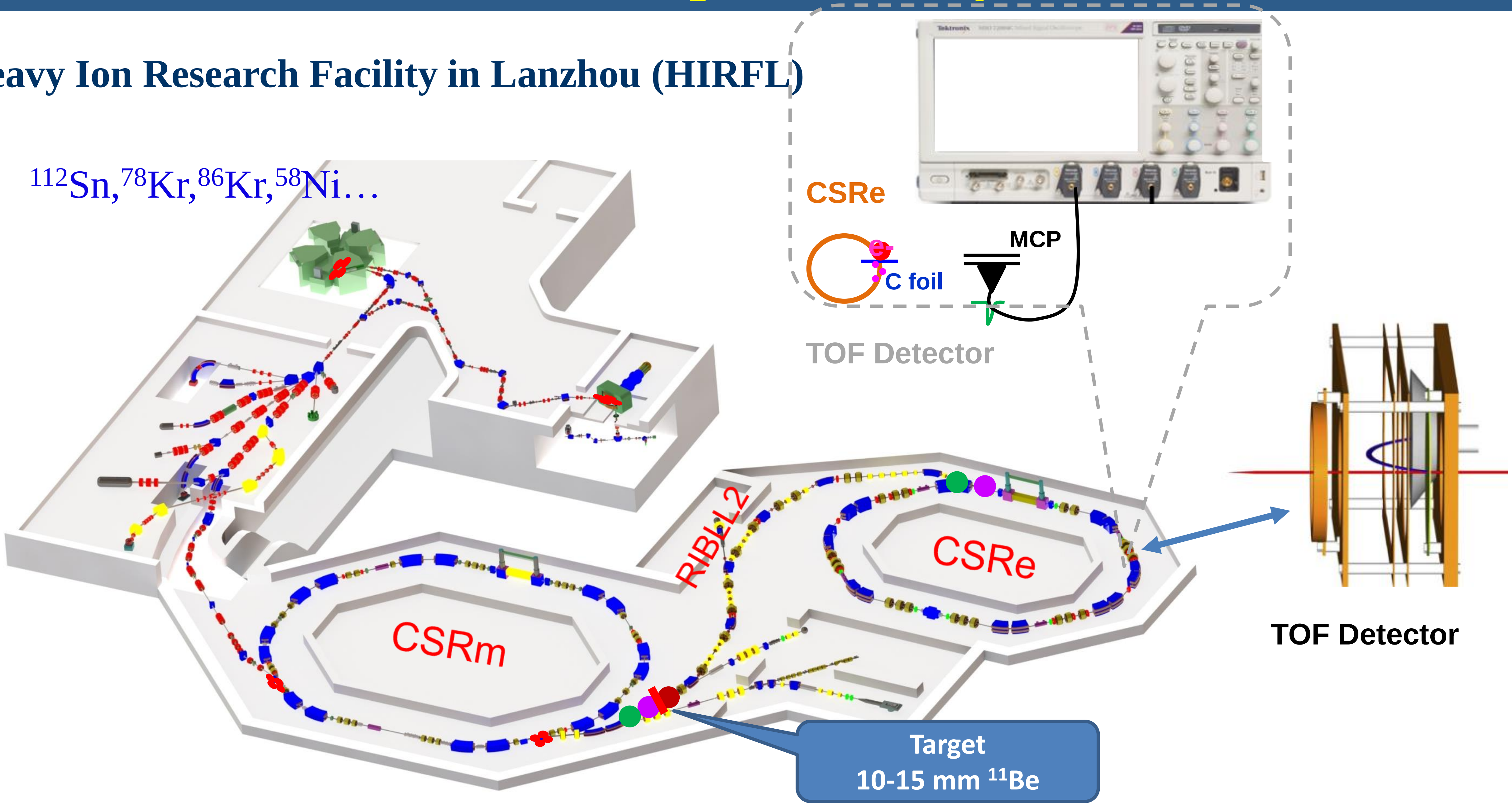
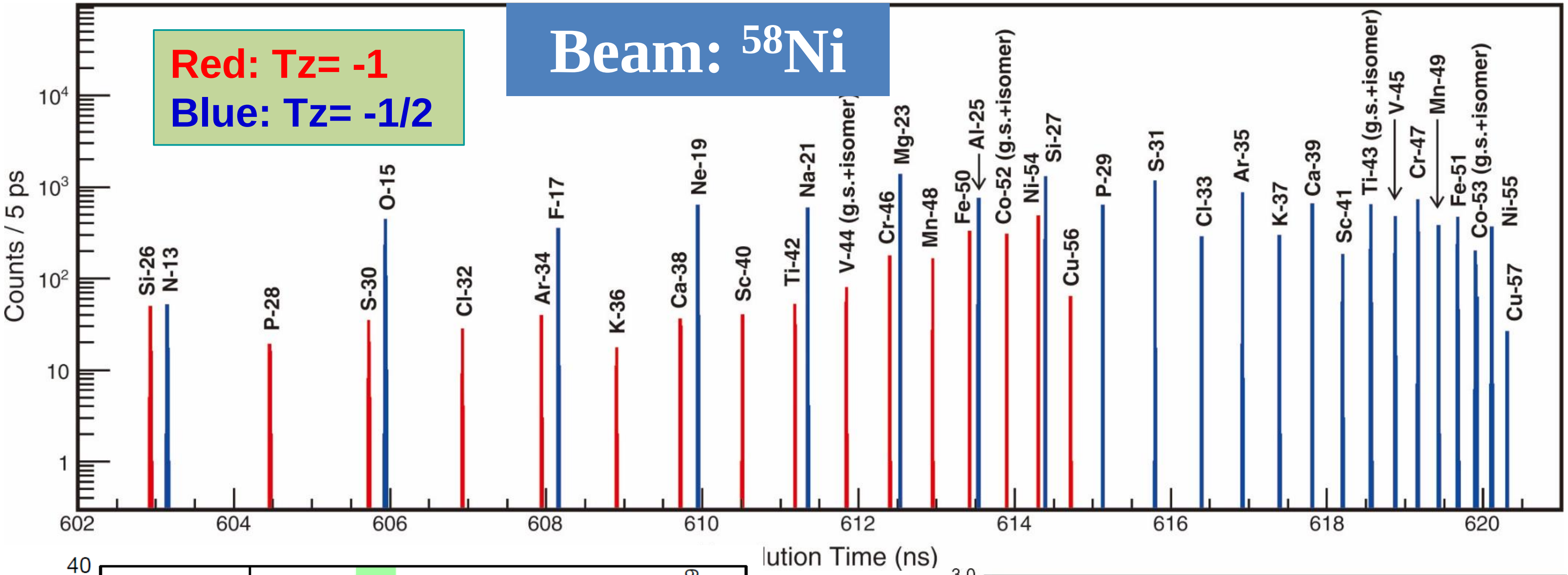
Isochronous mass spectrometry at CSRe

Heavy Ion Research Facility in Lanzhou (HIRFL)

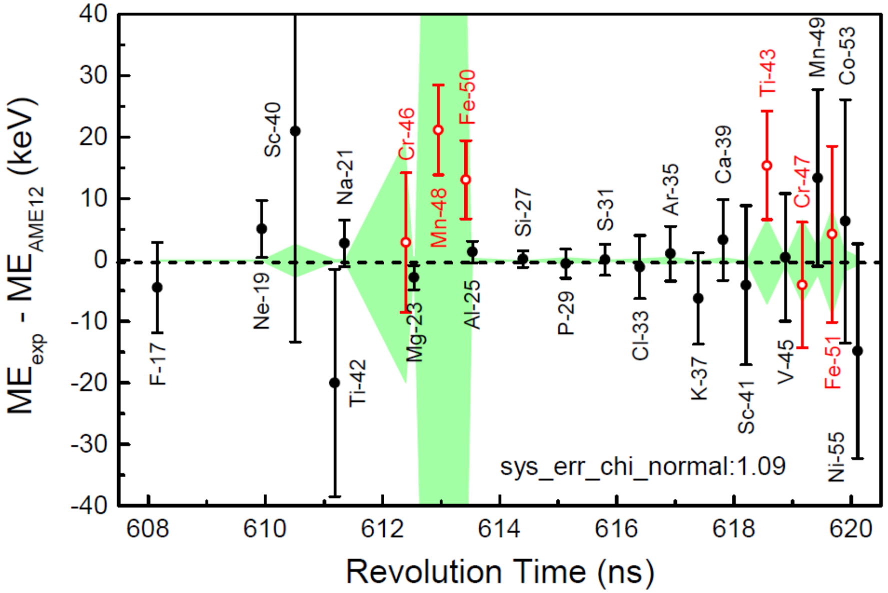


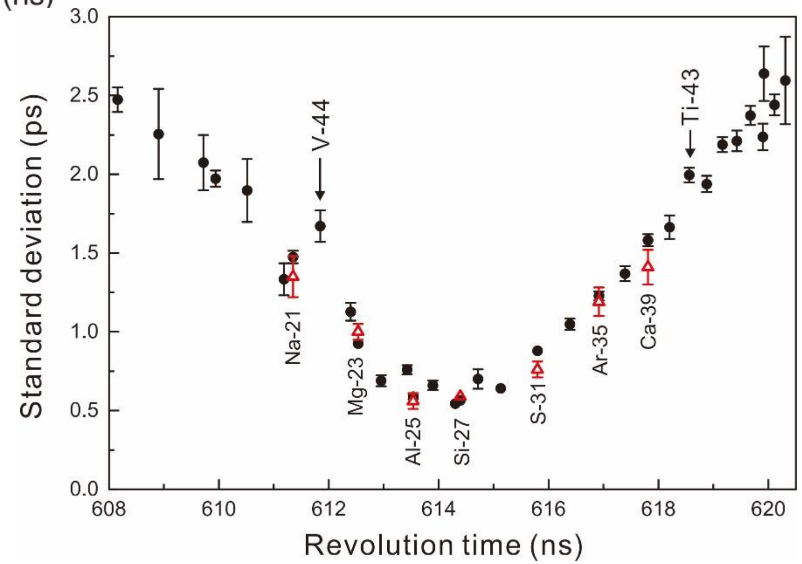
Isochronous mass spectrometry at CSRe

Beam: ^{58}Ni



Measurement time：200 μs





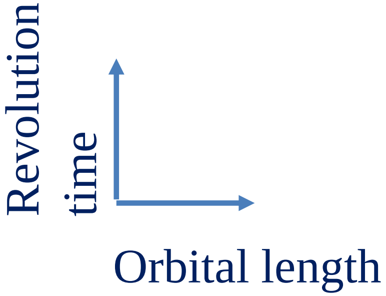
Isochronous mass spectrometry at CSRe

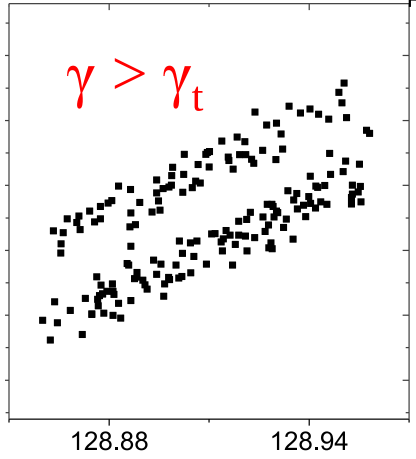
$$T = \frac{C}{v}$$

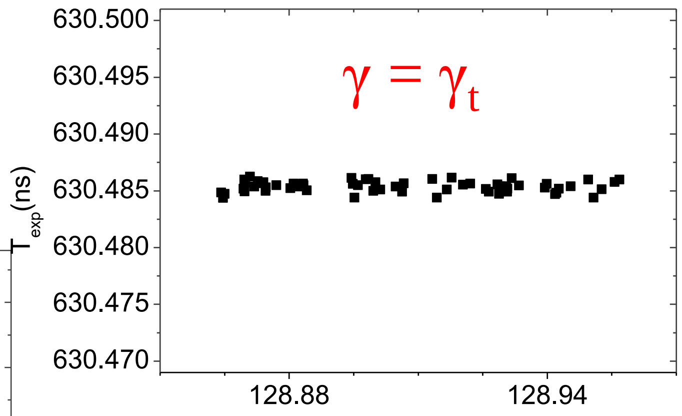
$$\frac{\mathrm{d}T}{T} = \frac{\mathrm{d}C}{C} - \frac{\mathrm{d}v}{v}$$

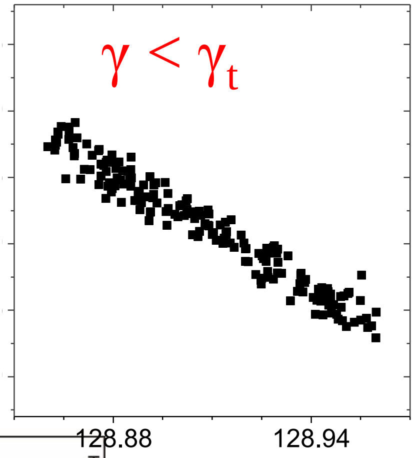
$$= \frac{1}{\gamma_t^2}\frac{dB\rho}{B\rho} - \frac{1}{\gamma^2}\frac{dB\rho}{B\rho}$$

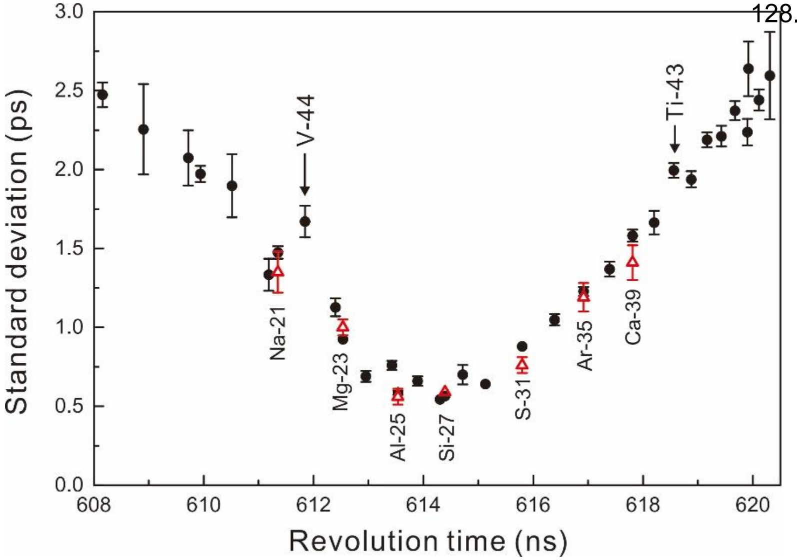
$$= \left(\frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}\right)\frac{dB\rho}{B\rho}$$











New scheme for mass measurements

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **31** (2005) S1779–S1783 doi:10.1088/0954-3899/31/10/072

Precision experiments with relativistic exotic nuclei at GSI

H Geissel[1,2] and Yu A Litvinov[1,2]

the narrow range where the isochronous conditions are fulfilled. The analysis with only one time-of-flight (ToF) detector positioned inside the ESR lattice [26] requires, in principle, a strong restriction on the accepted mass-to-charge ratio. A solution is to measure the velocity of each fragment in addition to the revolution time. This will provide a correlation to account for the deviations from the strict isochronous condition. For this purpose, additional detectors could be placed within the FRS, inside the ESR, and behind the extraction channel from the ESR. Within the FRS both magnetic rigidity and time-of-flight measurements are possible. However, a restriction is certainly the higher particle rate compared to the actually stored ions in the ESR. The advantage with a second ToF detector within the ESR is the turn-by-turn velocity correlation measurement. The velocity measurement of the extracted beam after many revolutions in the ESR also has advantages. For example, the velocity can be measured

New scheme for mass measurements

2013 — Installation of two TOFs (NIM A 756 (2014) 1)

2014 — First online test (Chin. Phy. C 39 (2015) 106201; Phys. Scr. T166 (2015) 014010)

2015–2016 — Optimizations of the optical settings (NIM A 898 (2018) 111)

2017 — Laser calibration system (NIM A 931 (2019) 52)

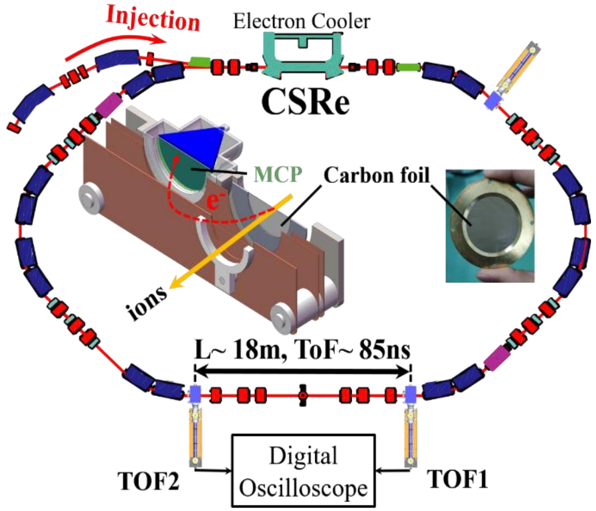
2018 — First physics experiment ^{58}Ni beam (Phys. Rev. Accel. Beams 24 (2021) 042802; NIM A 1027 (2022) 166329)

2019–2020 — ^{86}Kr beam

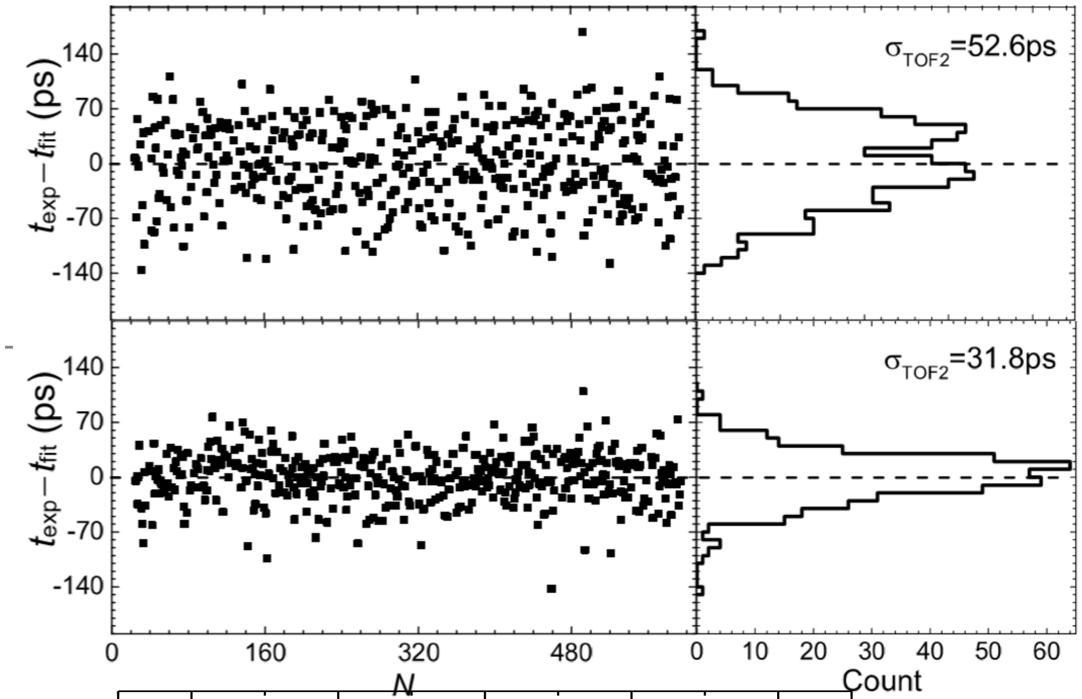
2020–2021年 — Fist new masses ^{78}Kr beam

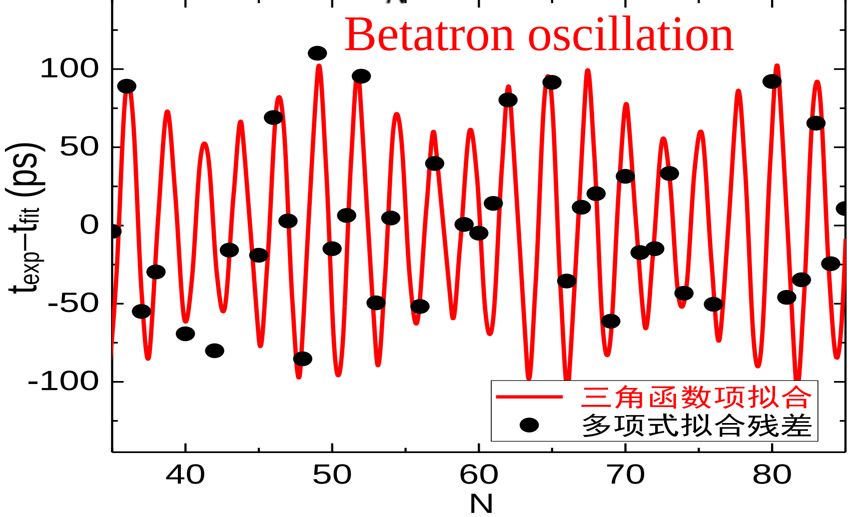
2021年 — ^{36}Ar beam

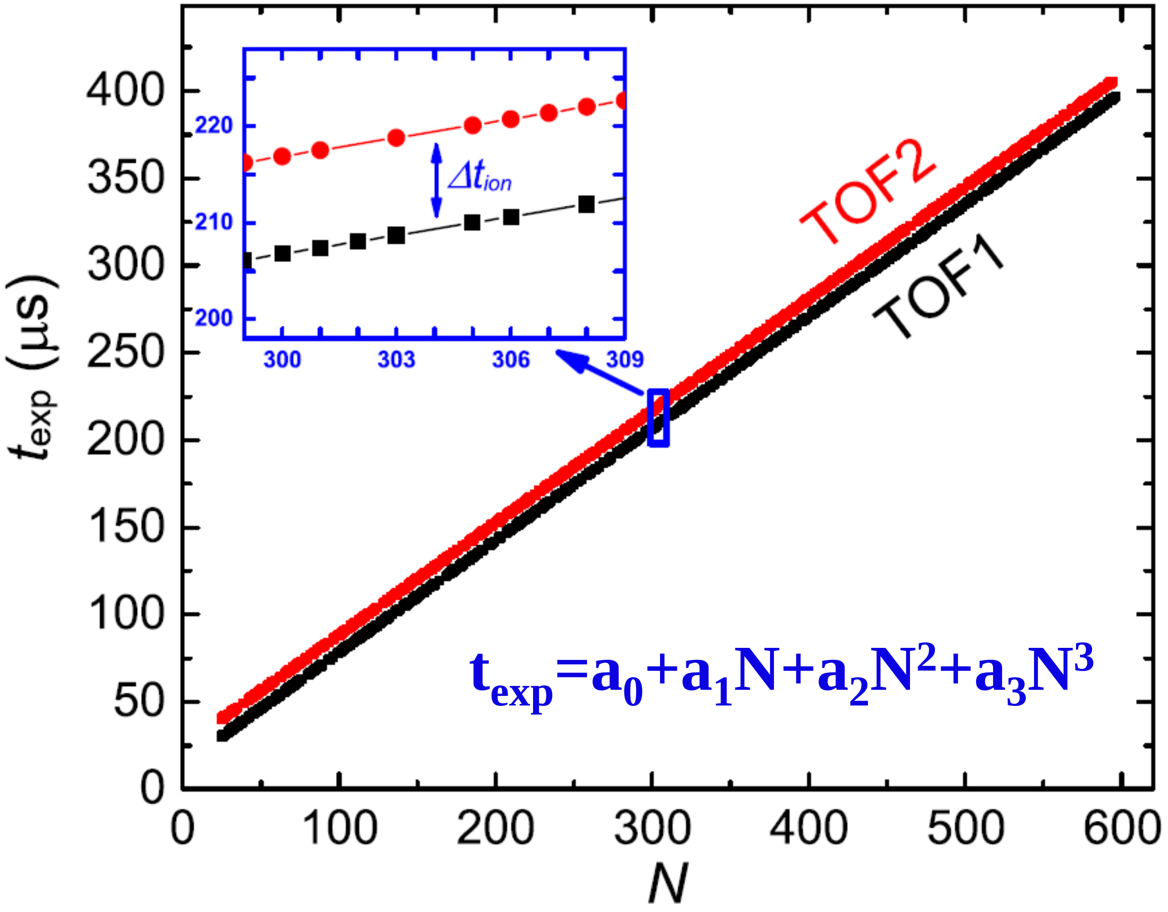
Precision velocity measurement, accurate calibration, correction for the fluctuations of magnetic fields……



Bρ-defined isochronous mass spectrometry

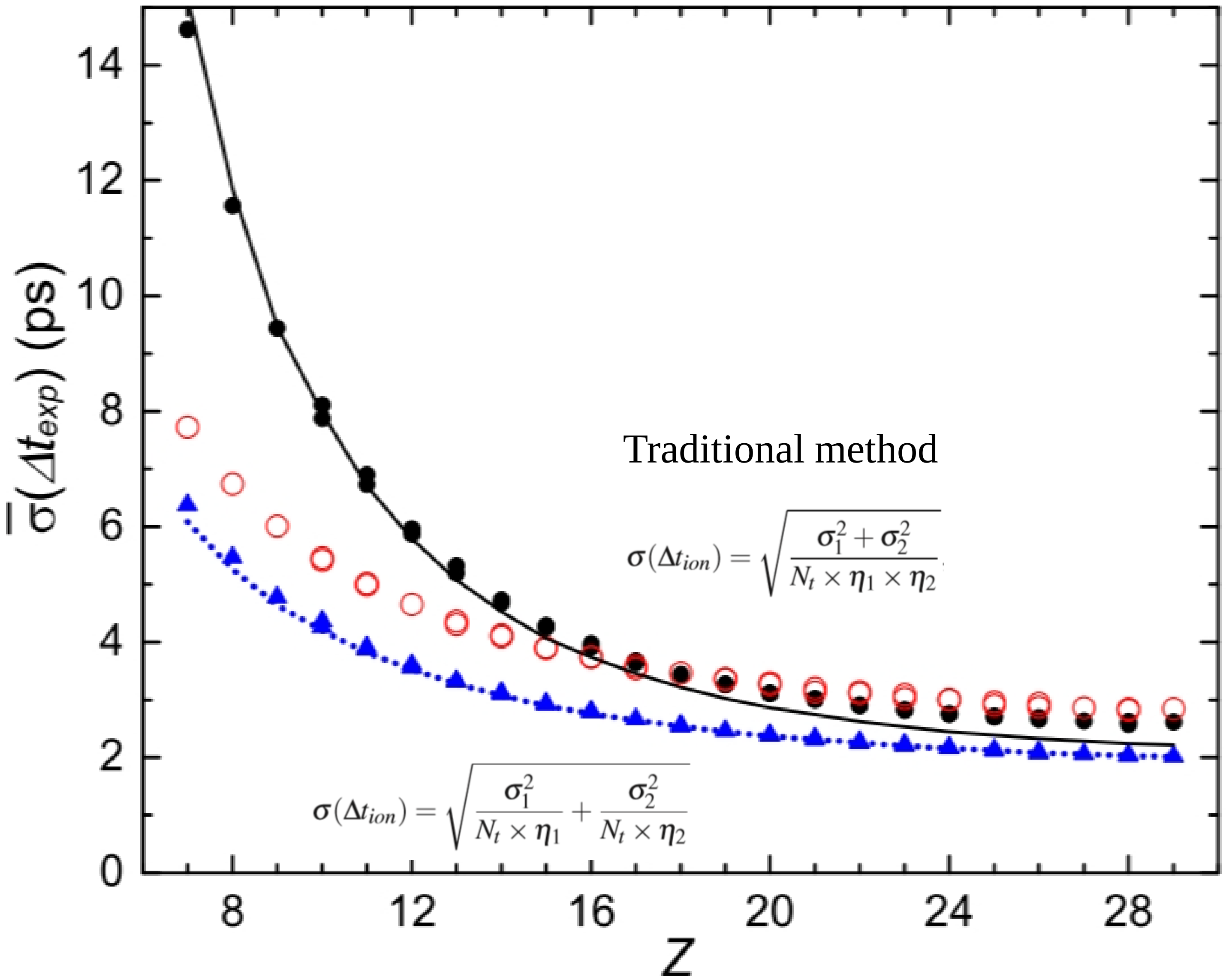






- ➢ Precision in-ring velocity measurement
- ➢ Impact of the Betatron oscillation

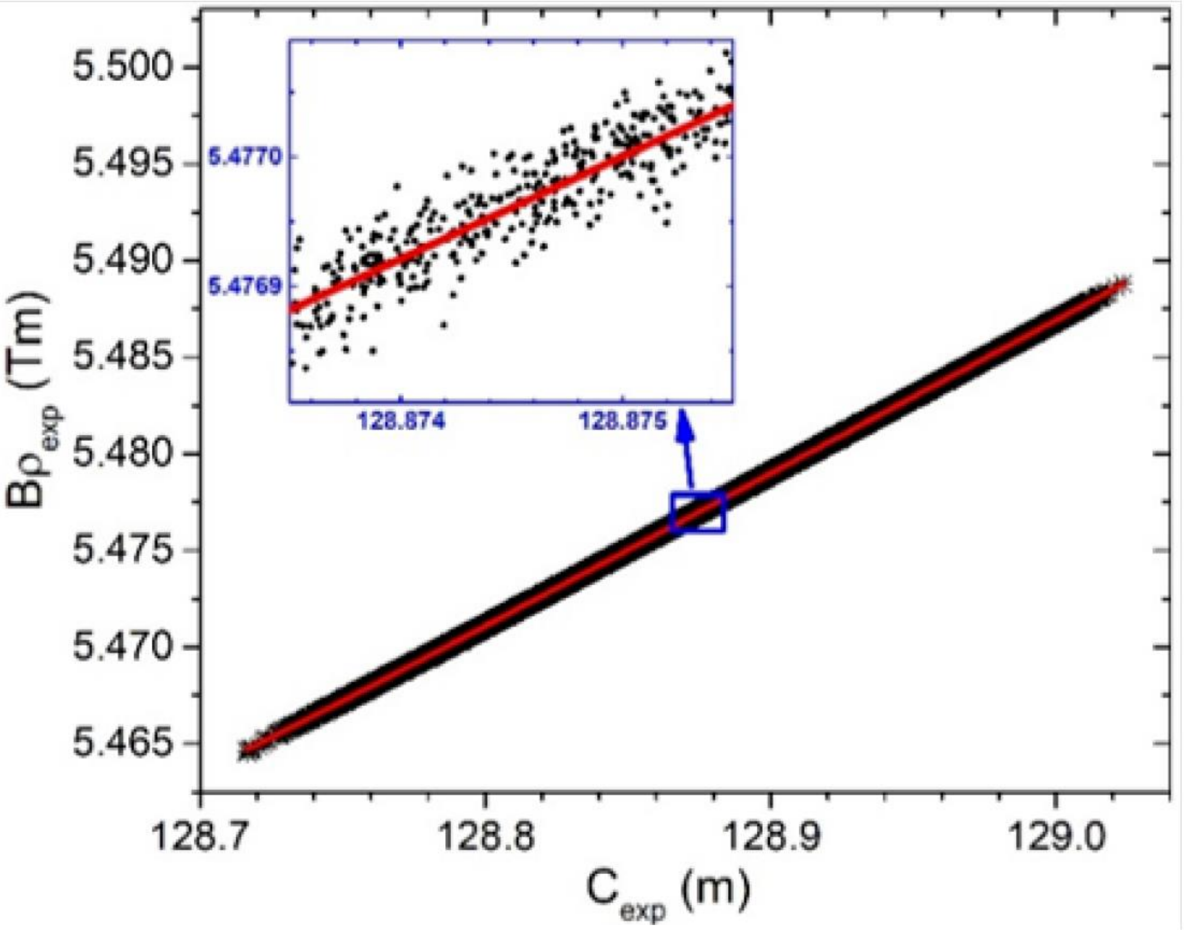
Bρ-defined isochronous mass spectrometry



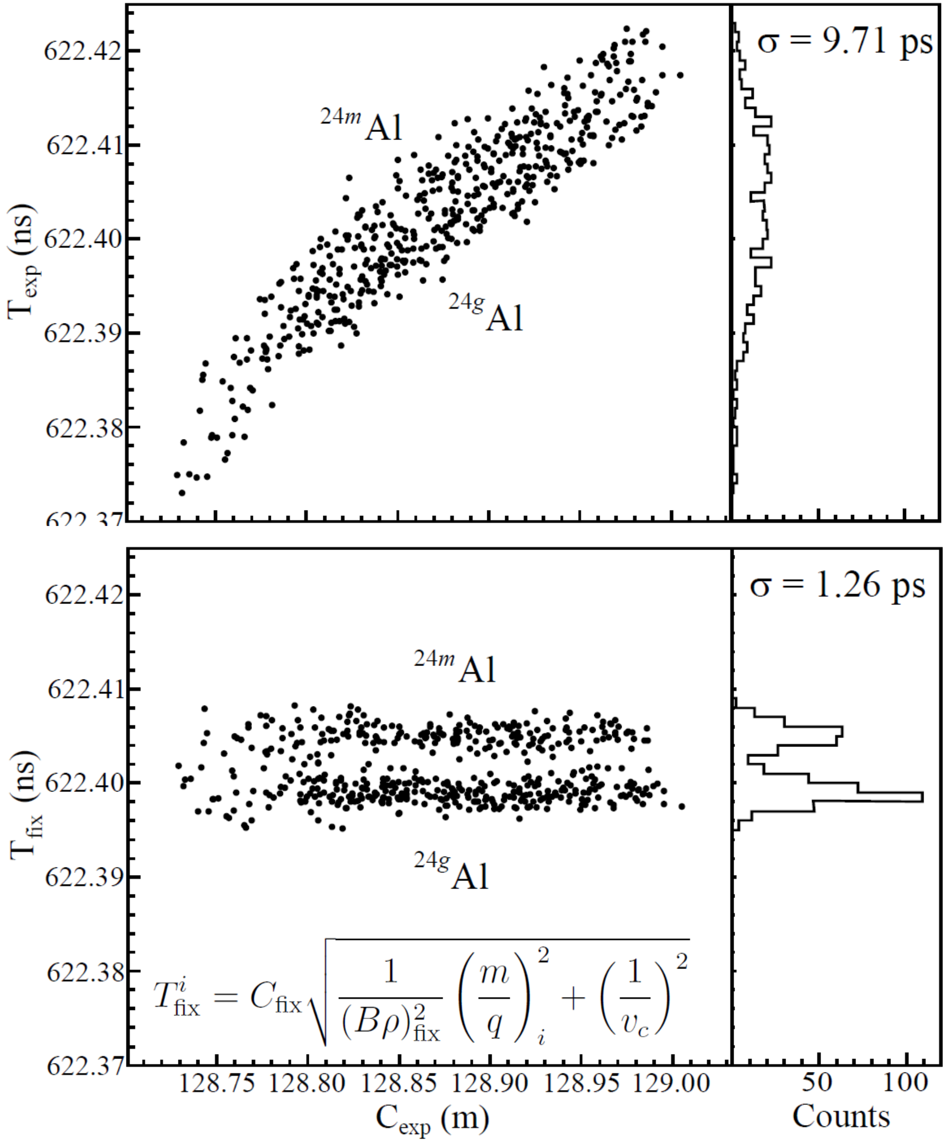
X. Zhou el al., *Physical Review Accelerators and Beams*, 24 (2021) 042802

Bρ-defined isochronous mass spectrometry

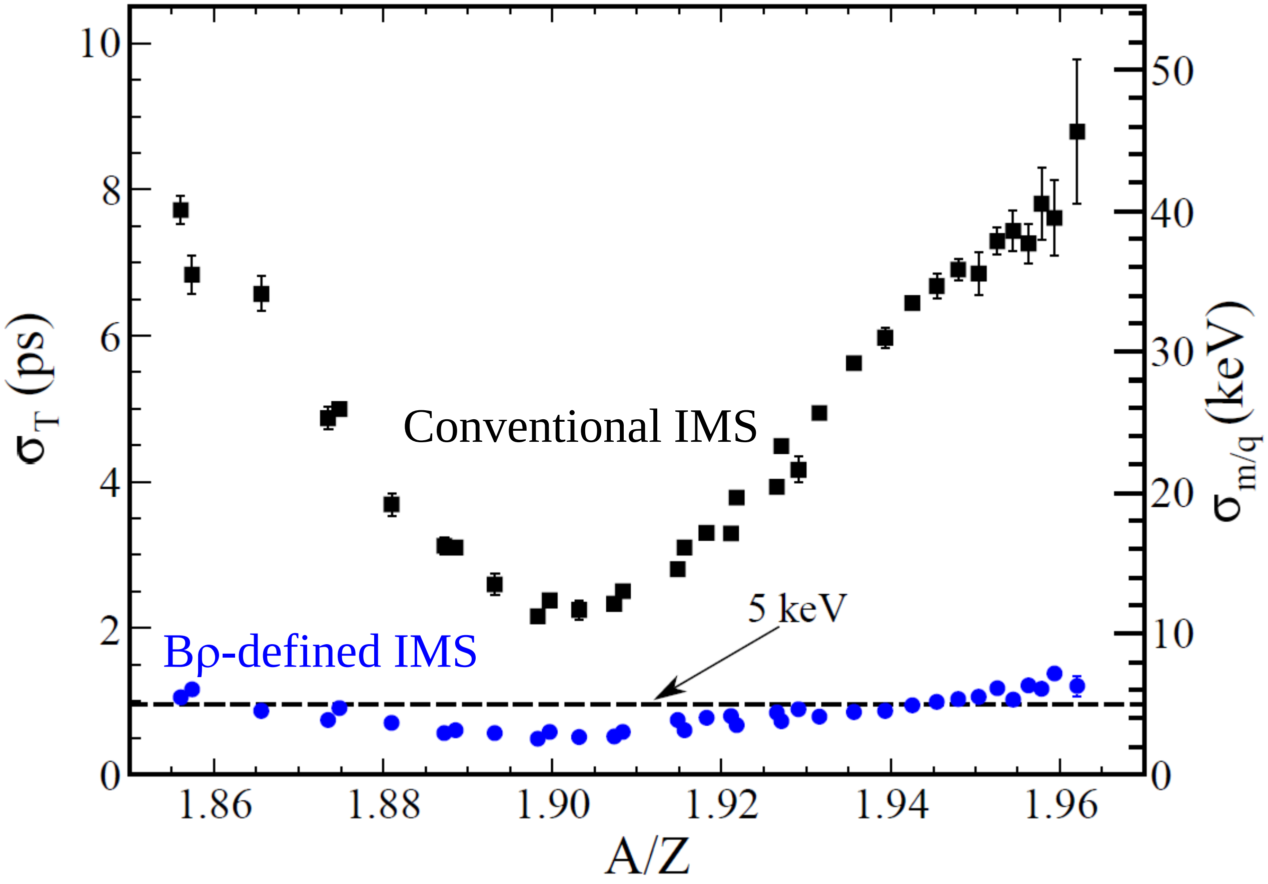
$$B\rho = \frac{m}{q} \cdot \gamma v, \qquad C = T_{exp} \cdot v$$

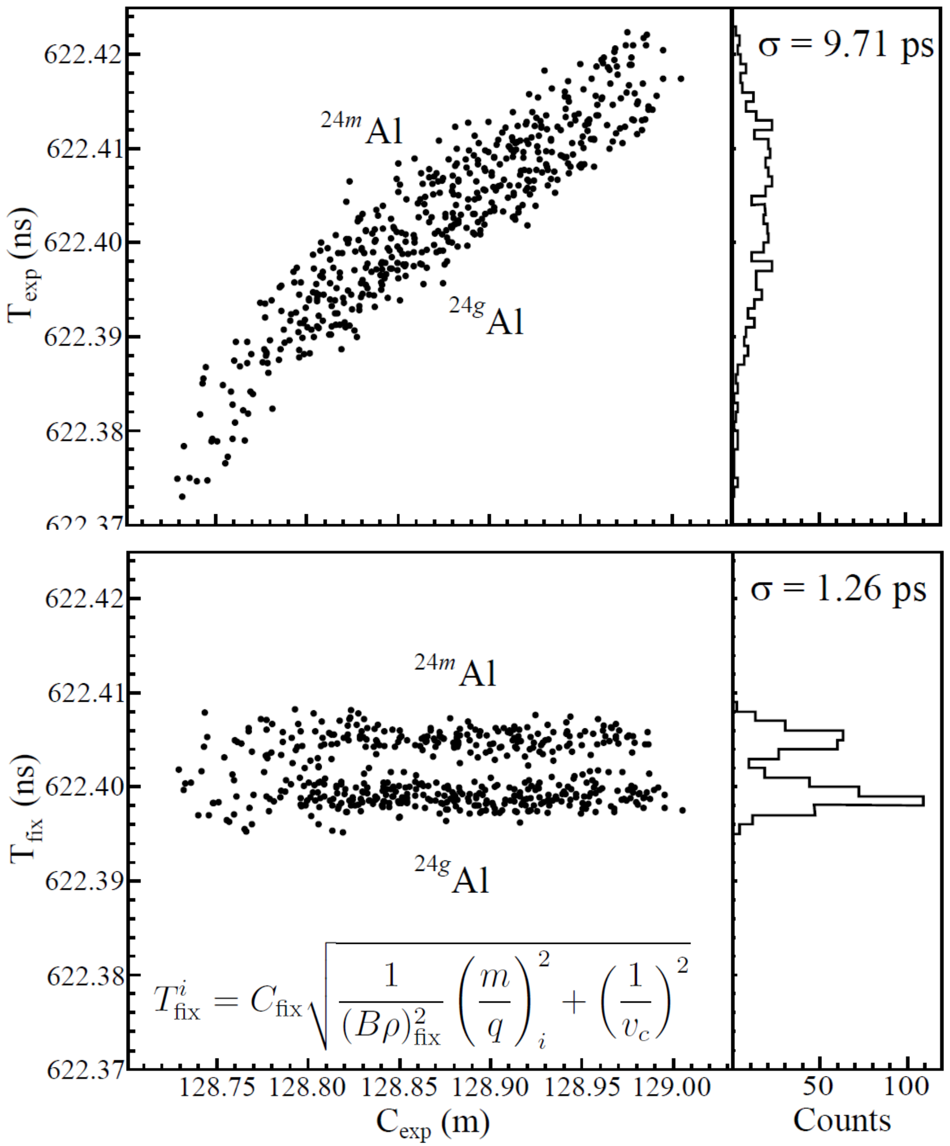


$$\left(\frac{m}{q}\right)_i = \frac{f(C^i_{exp})}{(\gamma v)^i} \qquad i = 1,\ 2,\ 3, \ldots,$$



Bρ-defined isochronous mass spectrometry





high resolving power, high precision, single-particle sensitivity, short measurement time, broadband

M. Wang et al., Phys.Rev. C 106, L051301 (2022)
M. Zhang et al., Eur.Phys.J. A 59, 27 (2023)

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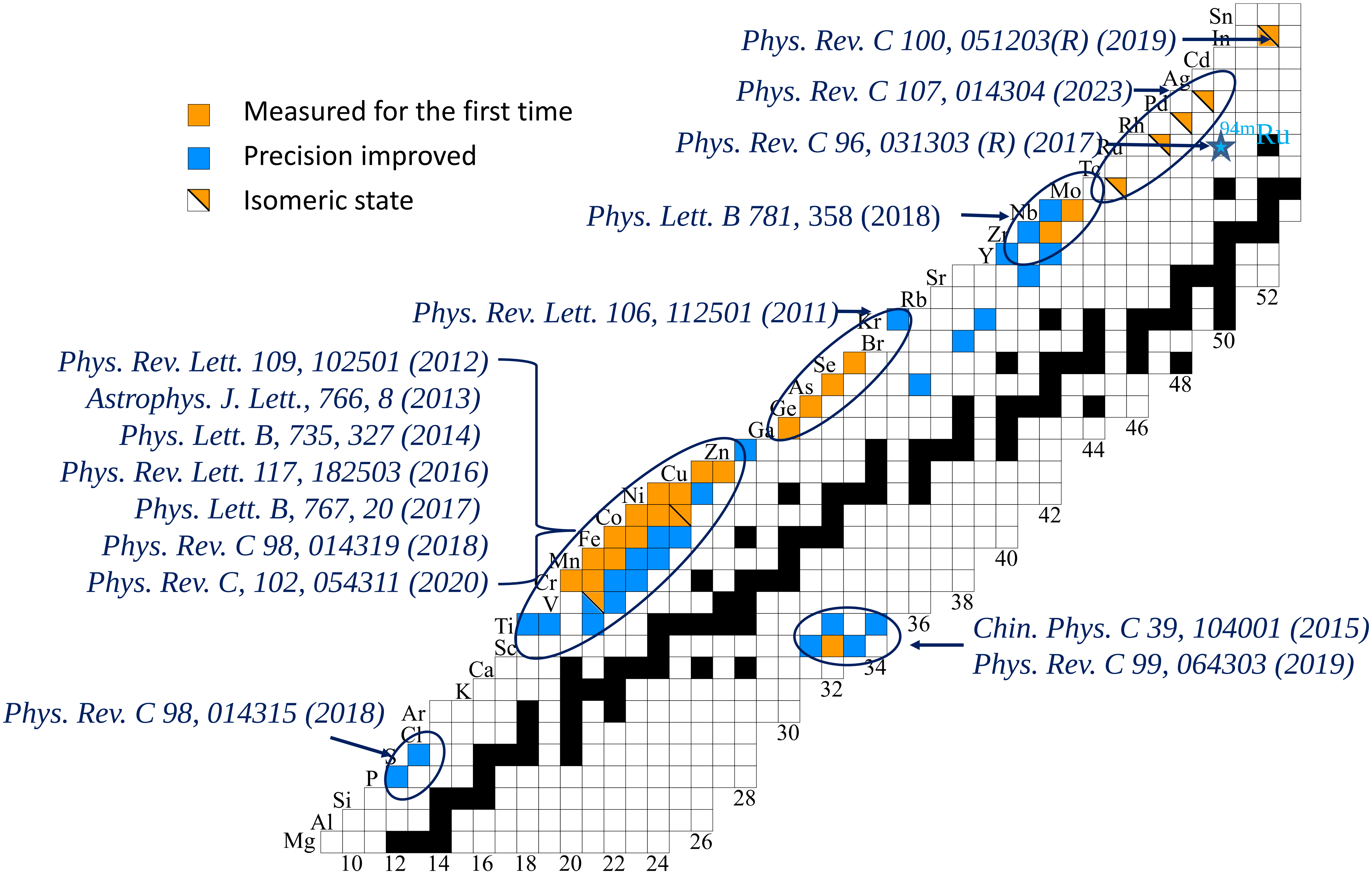
2. **Isochronous mass spectrometry (Bρ-defined)**
3. **Mass results and recent progress**
4. **Future plan**



Measured for the first time
Precision improved
Isomeric state
Phys. Rev. C 100, 051203(R) (2019)
Phys. Rev. C 107, 014304 (2023)
Phys. Rev. C 96, 031303 (R) (2017)
Phys. Lett. B 781, 358 (2018)
Phys. Rev. Lett. 106, 112501 (2011)
Phys. Rev. Lett. 109, 102501 (2012)
Astrophys. J. Lett., 766, 8 (2013)
Phys. Lett. B, 735, 327 (2014)
Phys. Rev. Lett. 117, 182503 (2016)
Phys. Lett. B, 767, 20 (2017)
Phys. Rev. C 98, 014319 (2018)
Phys. Rev. C, 102, 054311 (2020)
Chin. Phys. C 39, 104001 (2015)
Phys. Rev. C 99, 064303 (2019)
Phys. Rev. C 98, 014315 (2018)
^{94m}Ru
Sn
In
Cd
Ag
Pd
Rh
Ru
Tc
Mo
Nb
Zr
Y
Sr
Rb
Kr
Br
Se
As
Ge
Ga
Zn
Cu
Ni
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Sc
Ca
K
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Cl
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Si
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Mg
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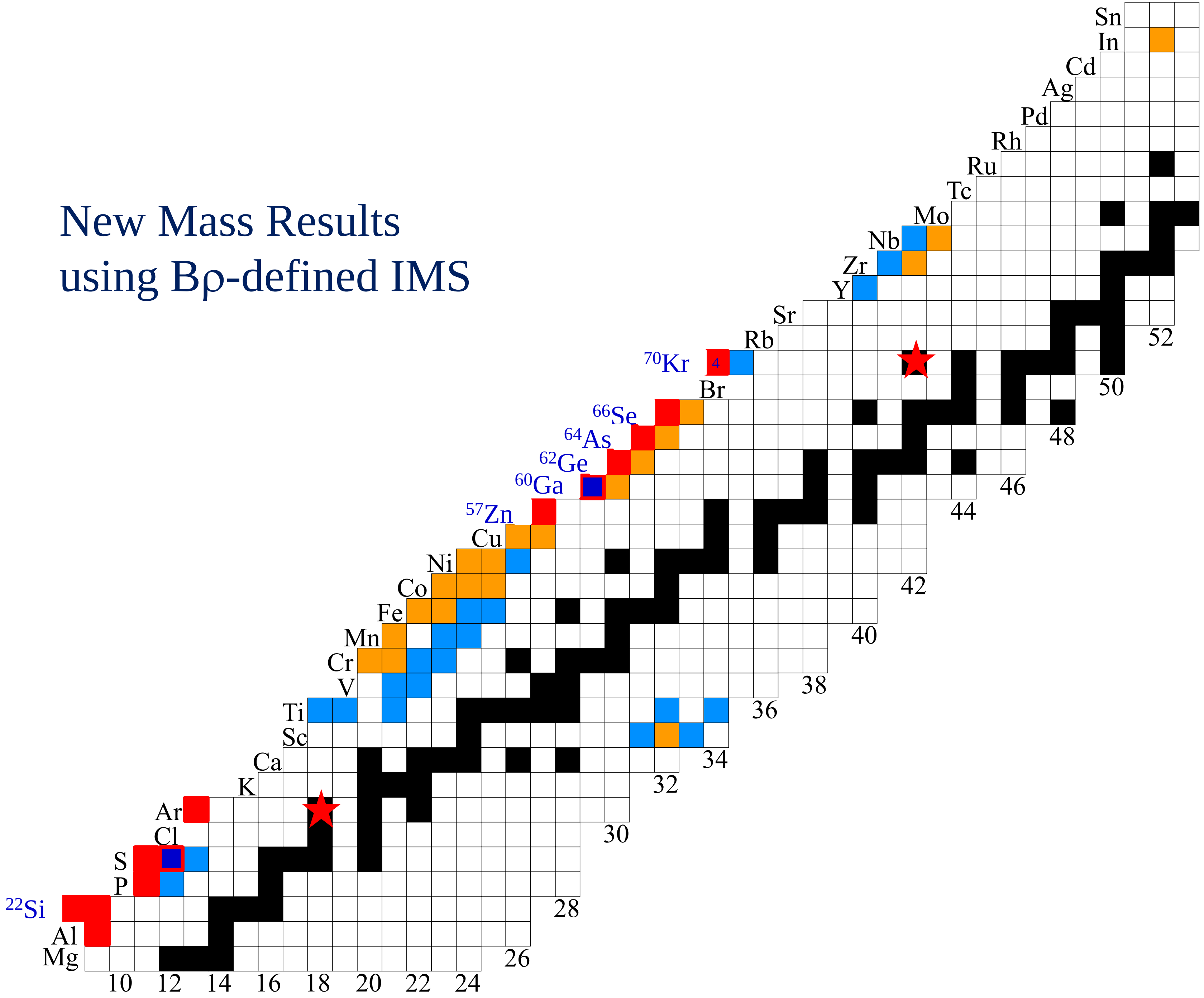
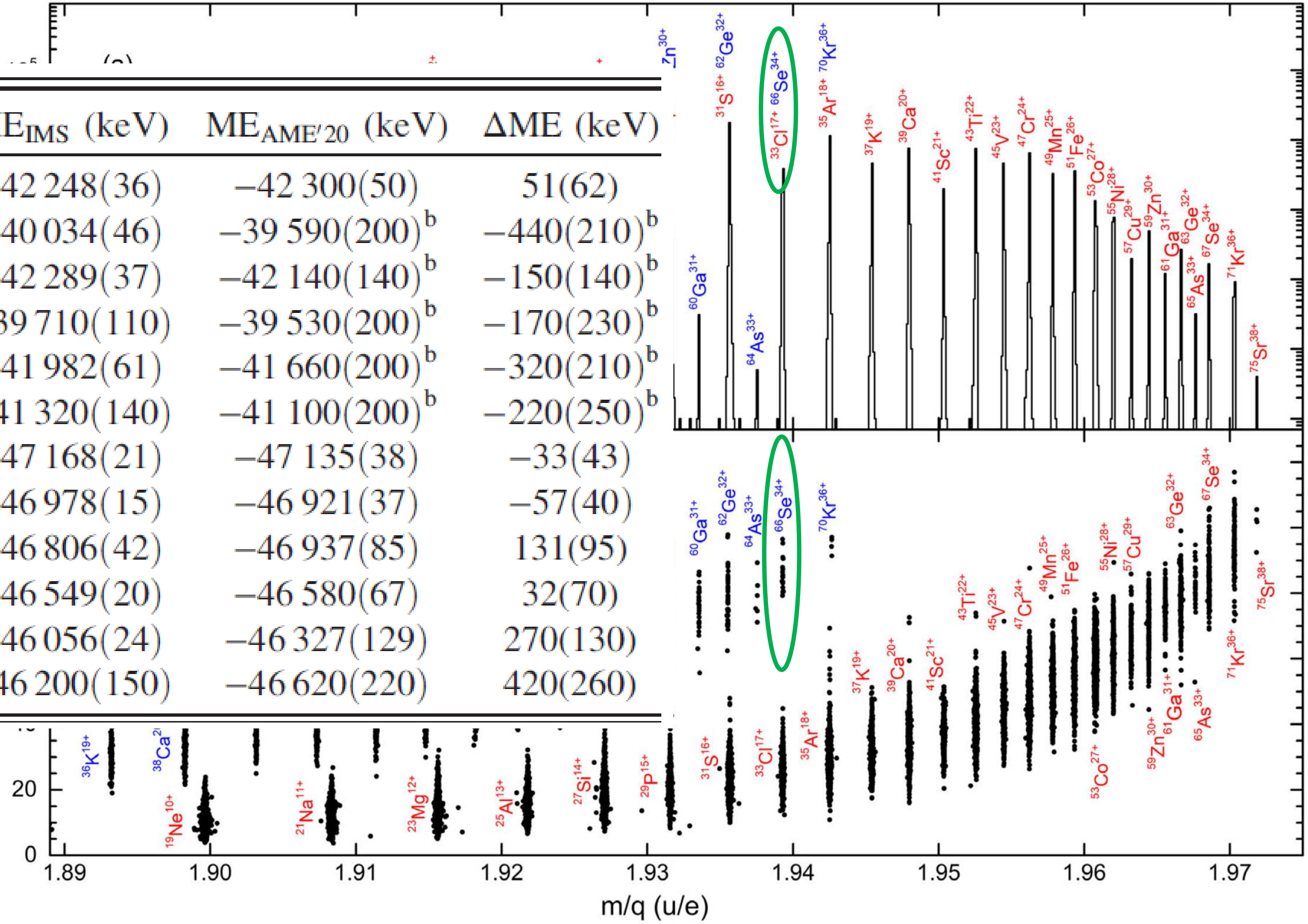
New Mass Results using Bρ-defined IMS

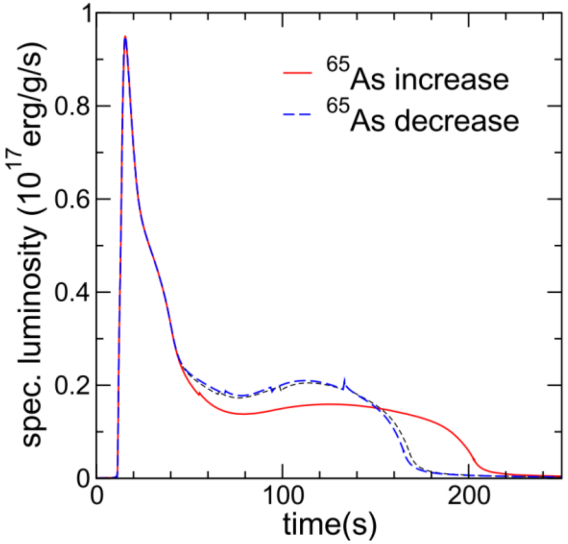


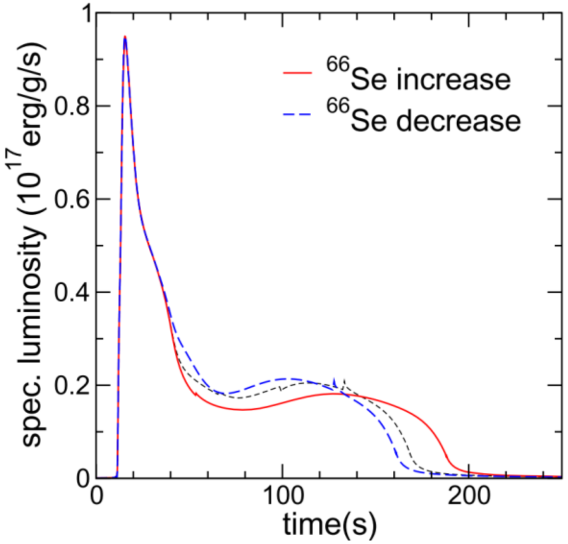
New mass results

Atom	Counts	ME_{IMS} (keV)	$ME_{AME'20}$ (keV)	ΔME (keV)
^{58}Zn	51	−42 248(36)	−42 300(50)	51(62)
^{60}Ga	32	−40 034(46)	−39 590(200)[b]	−440(210)[b]
^{62}Ge	47	−42 289(37)	−42 140(140)[b]	−150(140)[b]
^{64}As[a]	6	−39 710(110)	−39 530(200)[b]	−170(230)[b]
^{66}Se[a]	20	−41 982(61)	−41 660(200)[b]	−320(210)[b]
^{70}Kr	4	−41 320(140)	−41 100(200)[b]	−220(250)[b]
^{61}Ga	124	−47 168(21)	−47 135(38)	−33(43)
^{63}Gs[a]	279	−46 978(15)	−46 921(37)	−57(40)
^{65}As[a]	33	−46 806(42)	−46 937(85)	131(95)
^{67}Se[a]	174	−46 549(20)	−46 580(67)	32(70)
^{71}Kr	148	−46 056(24)	−46 327(129)	270(130)
^{75}Sr	4	−46 200(150)	−46 620(220)	420(260)

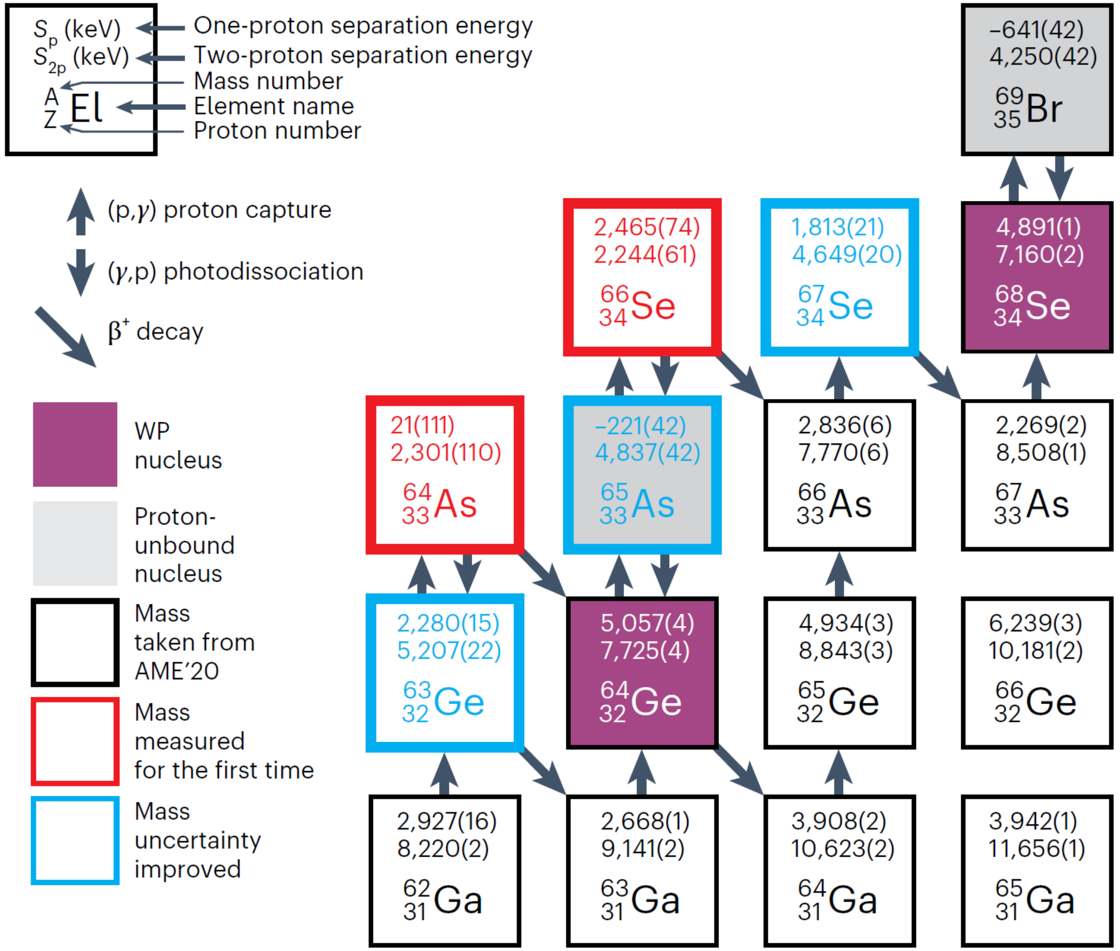


New mass results



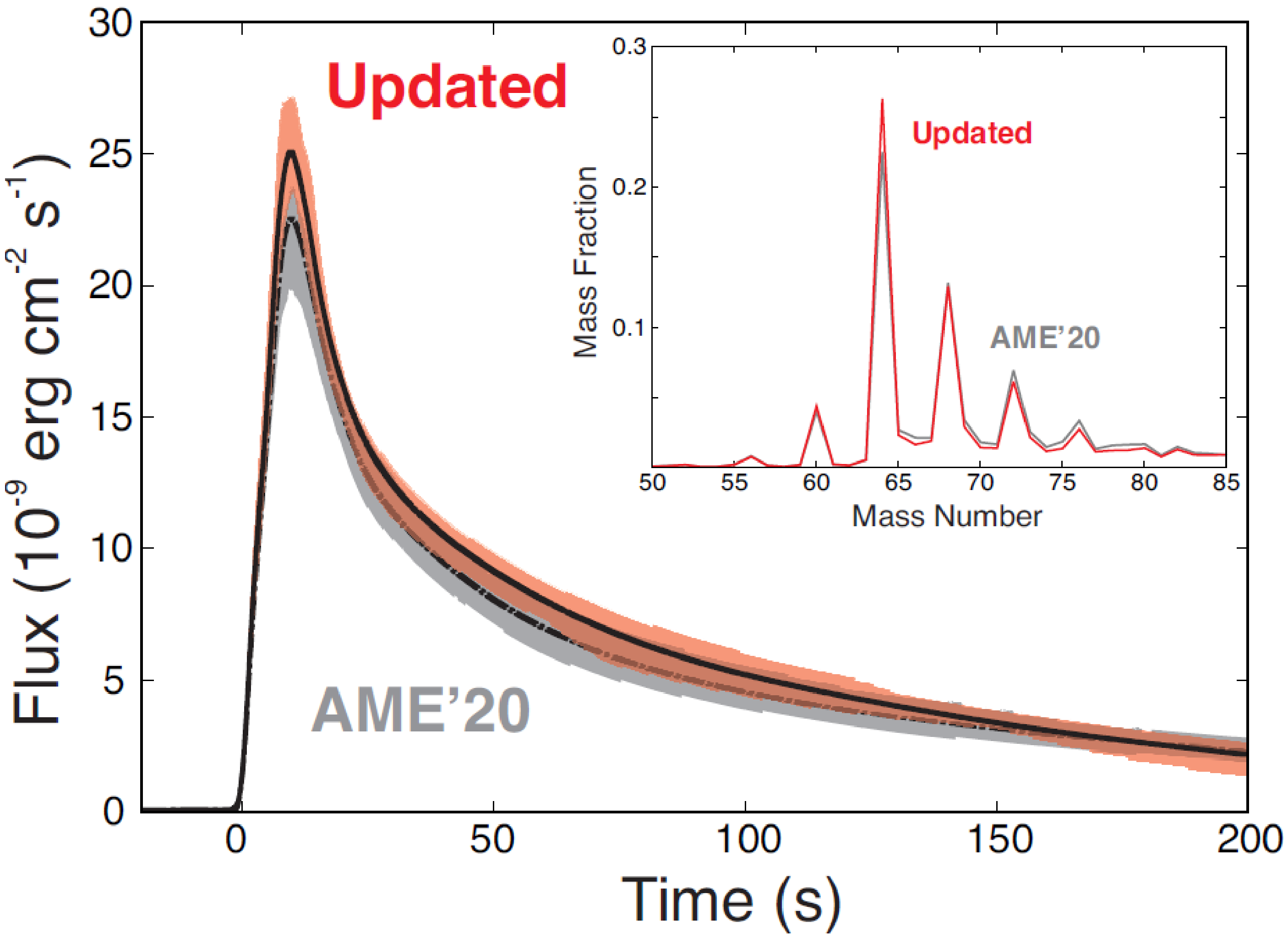


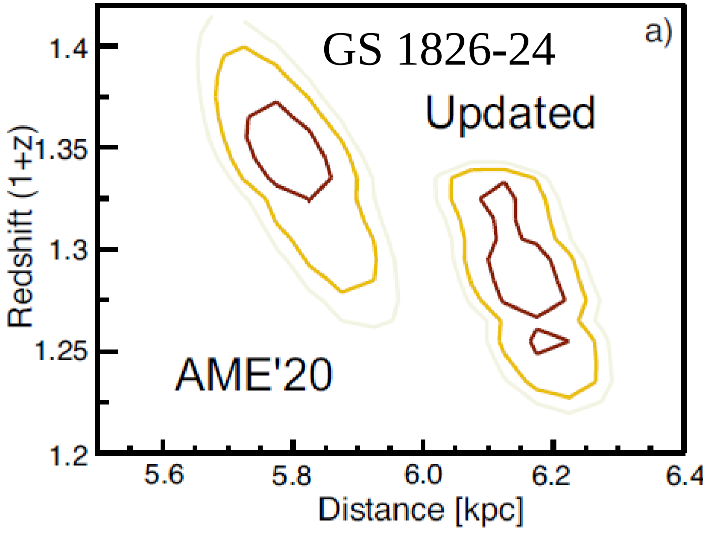
H. Schatz, W.J. Ong, The Astrophysical Journal, 844,139 (2017)

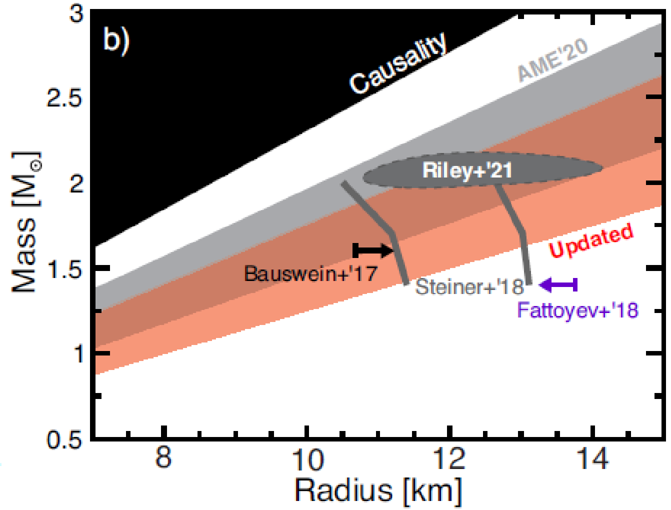


All relevant separation energies around the ^{64}Ge waiting point are precisely determined.

New mass results







X. Zhou et al., Nature Physics 19, 1091 (2023)

nature physics

Article https://doi.org/10.1038/s41567-023-02034-2

Mass measurements show slowdown of rapid proton capture process at waiting-point nucleus ^{64}Ge

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Accepted: 24 March 2023

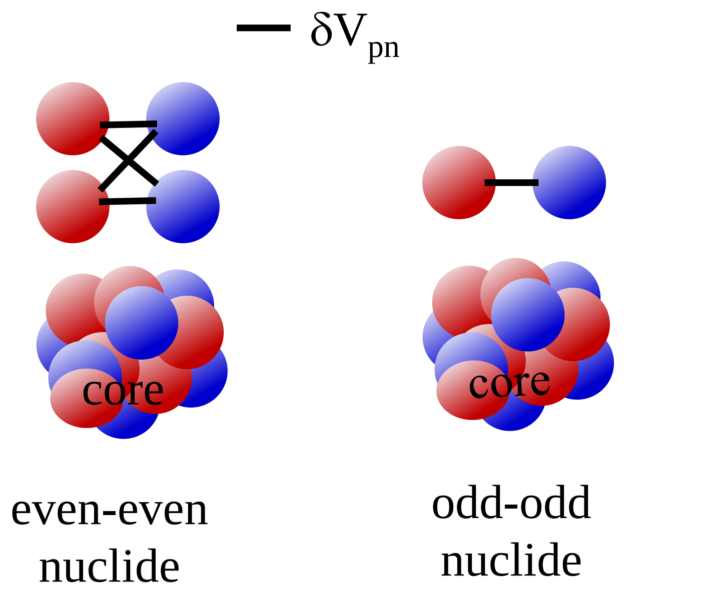
Published online: 1 May 2023

Check for updates

X. Zhou[1,2], M. Wang[1,2] ✉, Y. H. Zhang[1,2] ✉, Yu. A. Litvinov[1,3] ✉, Z. Meisel[4], K. Blaum[5], X. H. Zhou[1,2], S. Q. Hou[1,2,6], K. A. Li[1], H. S. Xu[1,2], R. J. Chen[1,3], H. Y. Deng[1,2], C. Y. Fu[1], W. W. Ge[1], J. J. He[7], W. J. Huang[1,8], H. Y. Jiao[1,2], H. F. Li[1,2], J. G. Li[1], T. Liao[1,2], S. A. Litvinov[1,3], M. L. Liu[1], Y. F. Niu[9], P. Shuai[1], J. Y. Shi[1,2], Y. N. Song[1,2], M. Z. Sun[1], Q. Wang[1,2], Y. M. Xing[1], X. Xu[1], F. R. Xu[10], X. L. Yan[1], J. C. Yang[1,2], Y. Yu[1,2], Q. Yuan[10], Y. J. Yuan[1,2], Q. Zeng[11], M. Zhang[1,2] & S. Zhang[10]

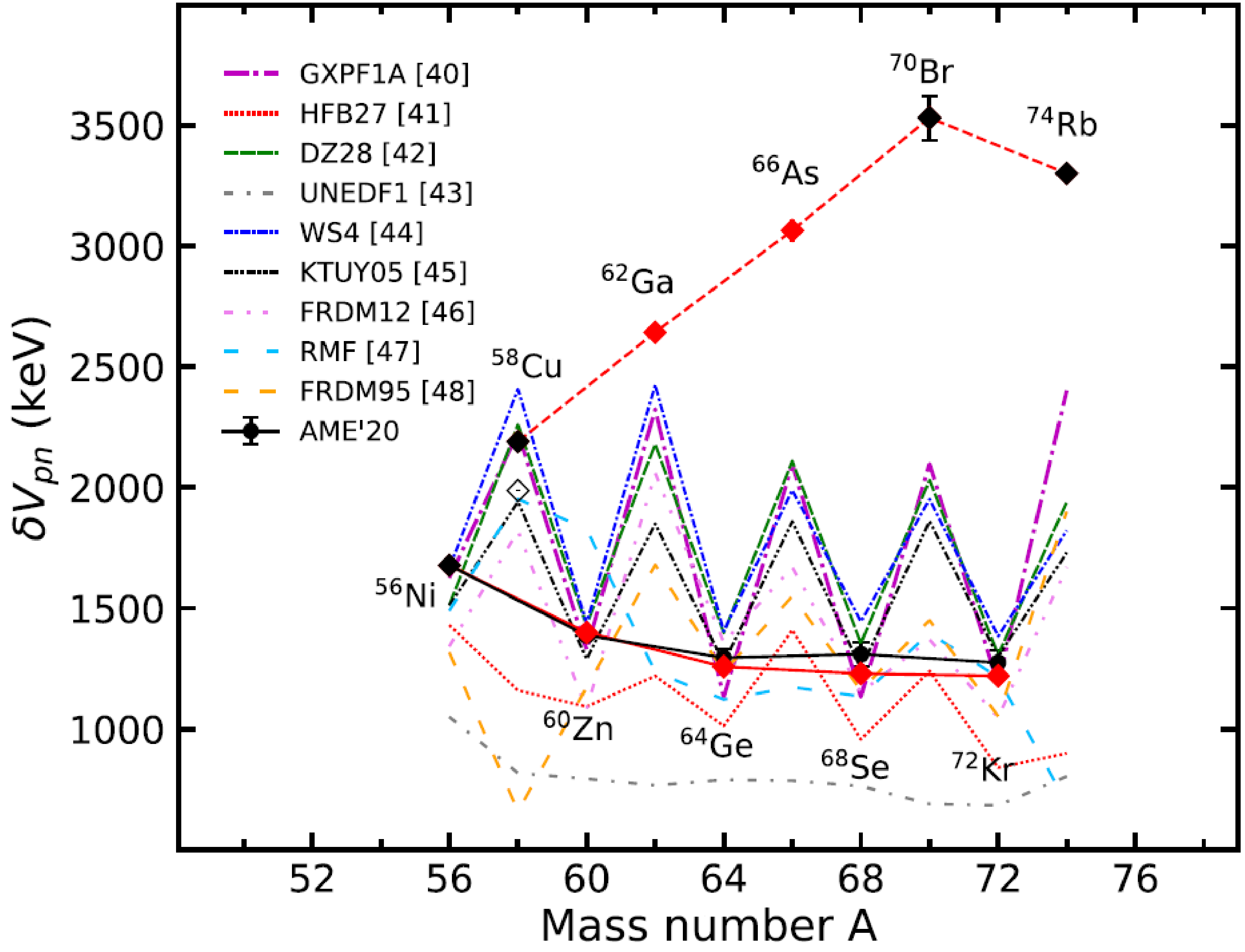
New mass results

Proton-neutron interaction and the three-nucleon force



$$\delta V_{pn}^{ee}(Z,N) = \frac{1}{4}[B(Z,N) - B(Z,N-2) - B(Z-2,N) + B(Z-2,N-2)],$$

$$\delta V_{pn}^{oo}(Z,N) = [B(Z,N) - B(Z,N-1) - B(Z-1,N) + B(Z-1,N-1)],$$



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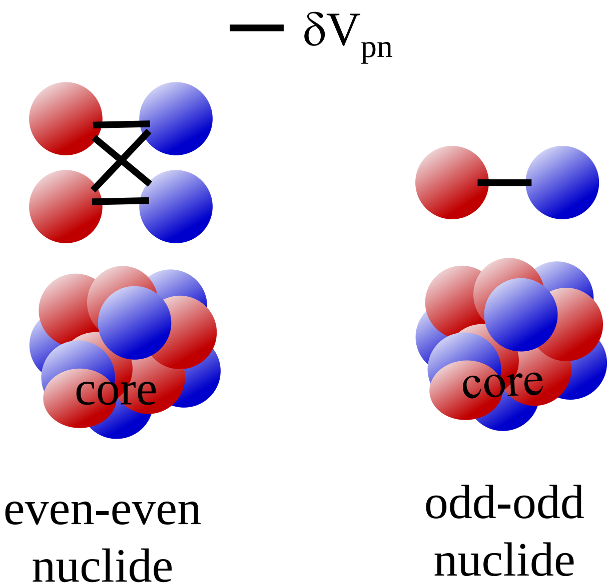
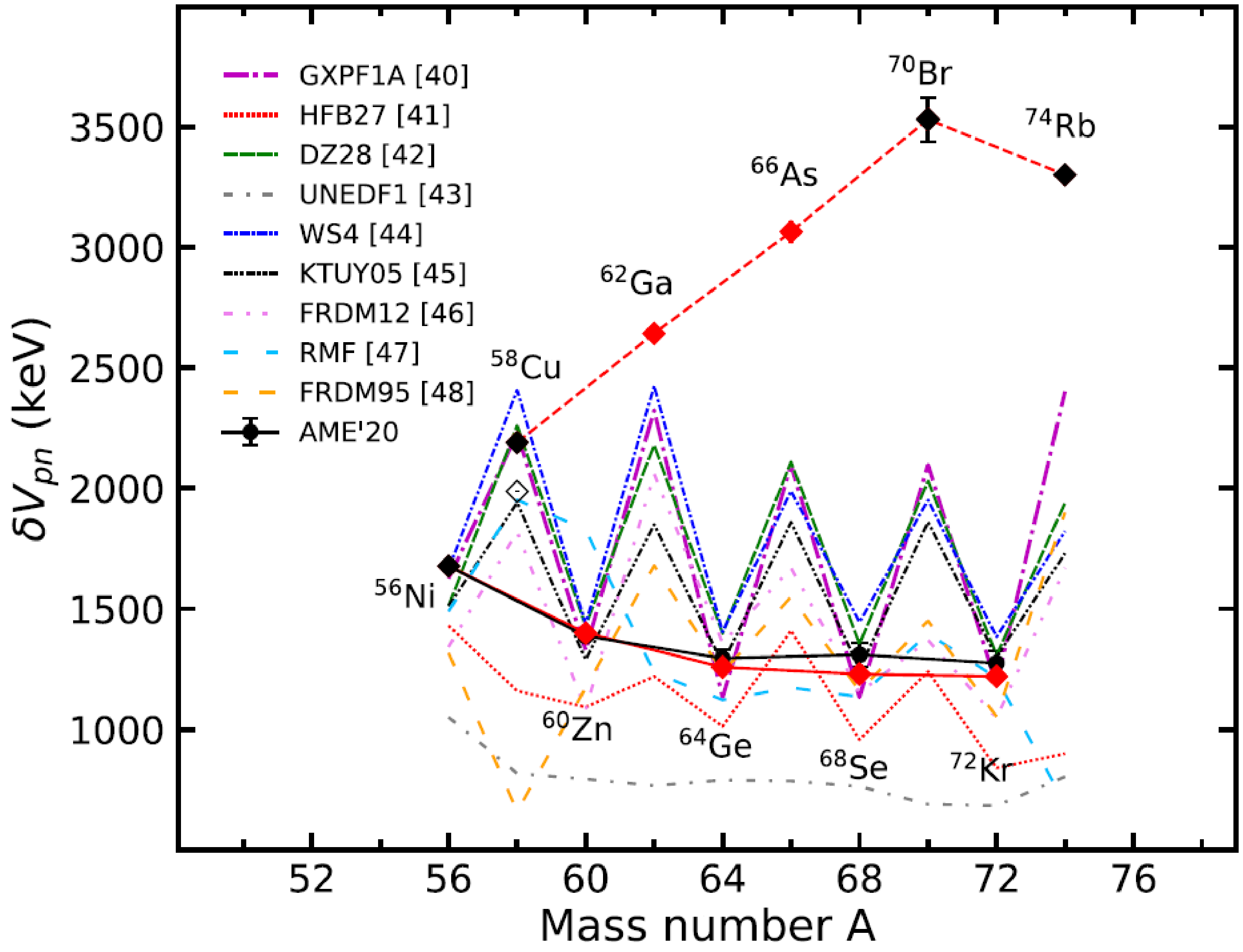
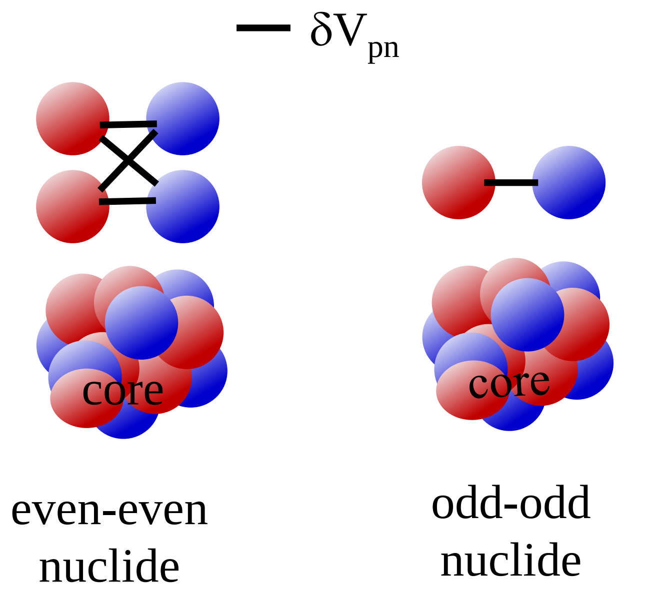




- Residual proton-neutron interactions (δVpn) decrease (increase) with increasing mass A for even-even (odd-odd) nuclei.
- Ab initio calculations with a chiral three-nucleon force (3NF) included indicate the enhancement of the T=1 pn pairing over the T=0 pn pairing in this mass region.

New mass results

Proton-neutron interaction and the three-nucleon force



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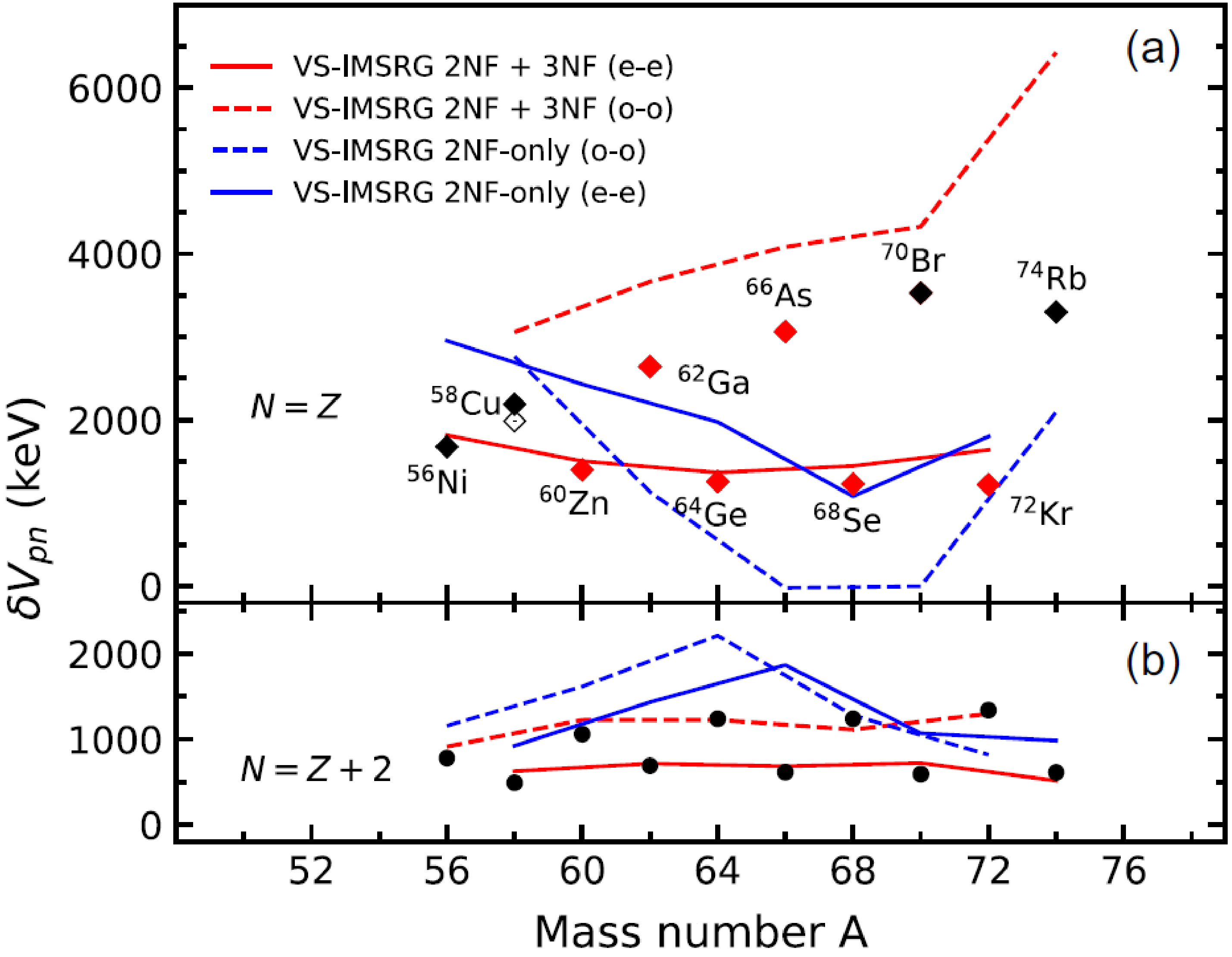

M. Wang et al., Phys. Rev. Lett. 130, 192501 (2023)

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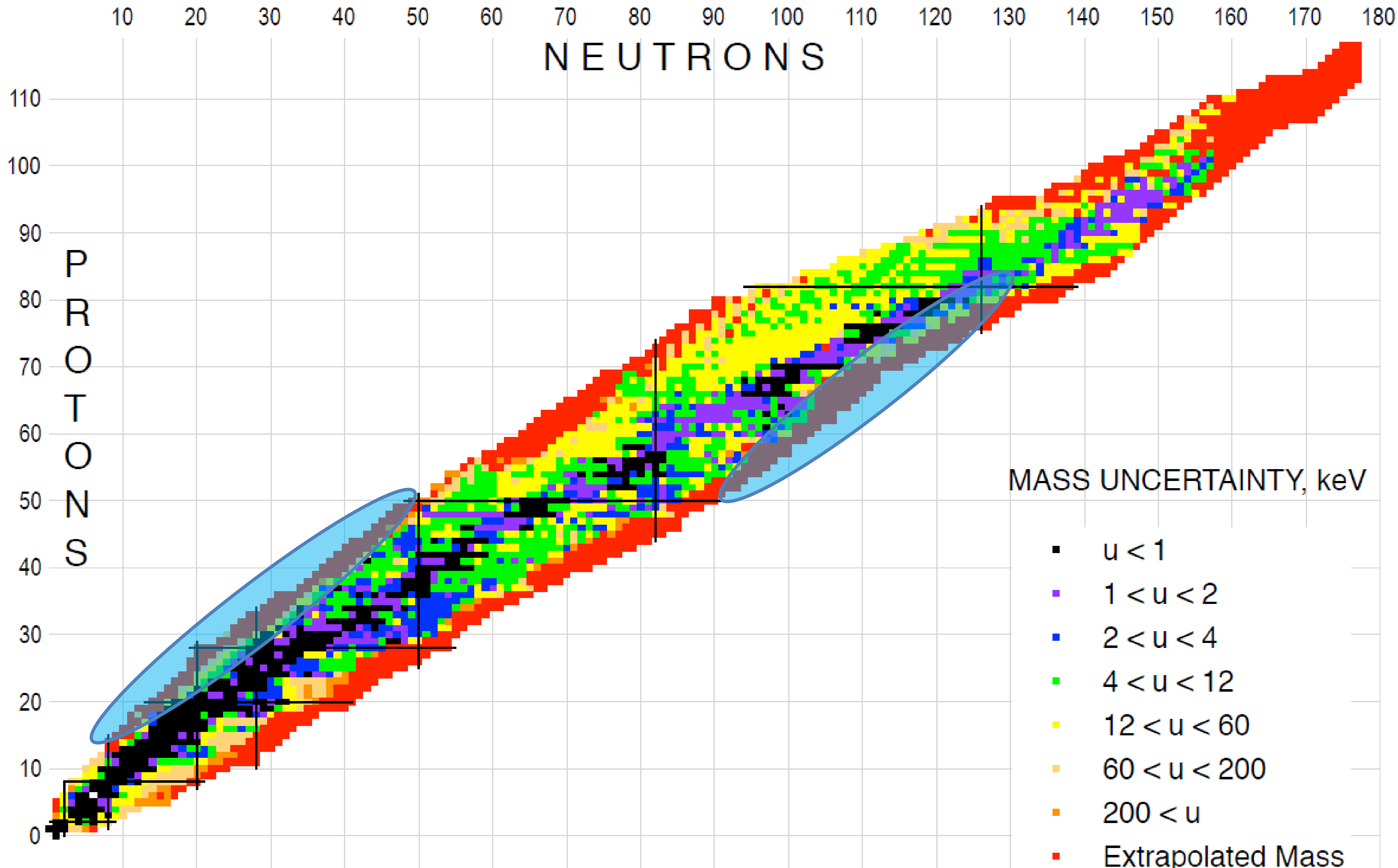
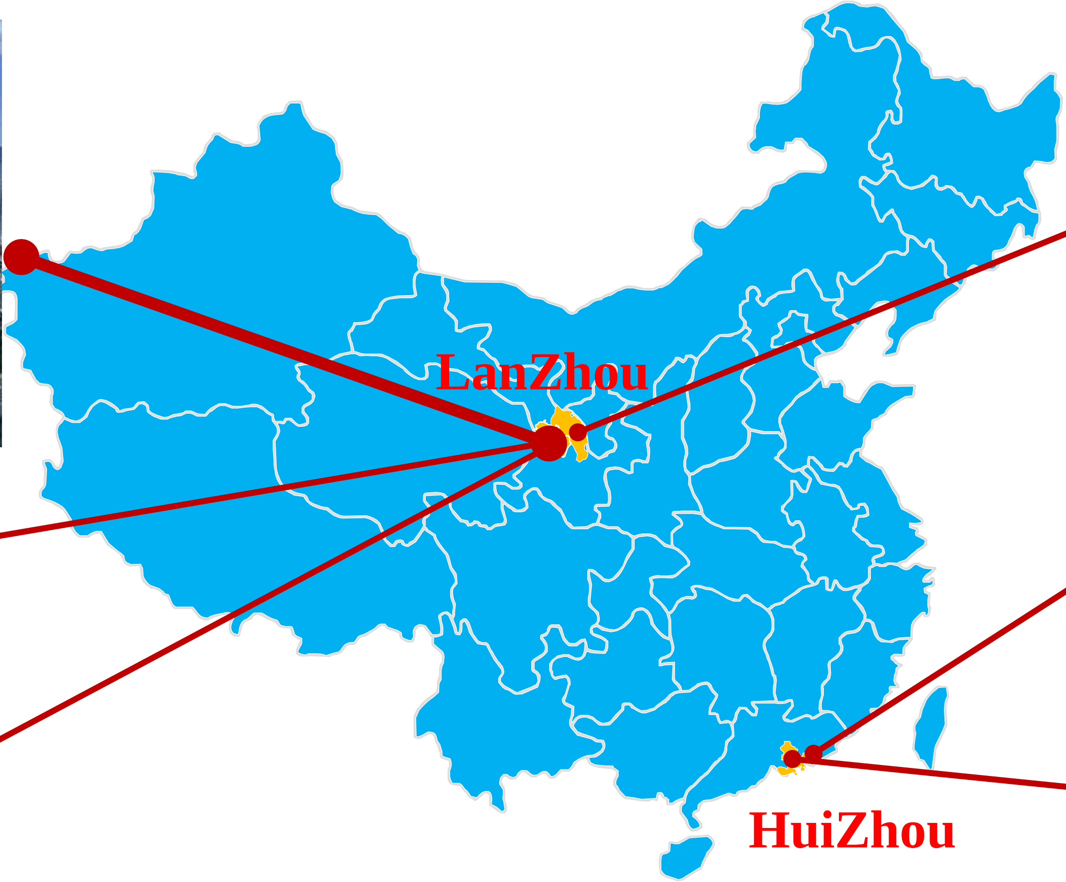


10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
NEUTRONS
0 10 20 30 40 50 60 70 80 90 100 110
PROTONS
MASS UNCERTAINTY, keV
u < 1
1 < u < 2
2 < u < 4
4 < u < 12
12 < u < 60
60 < u < 200
200 < u
Extrapolated Mass

Institute of Modern Physics, CAS

research center for heavy-ion science and technology in China

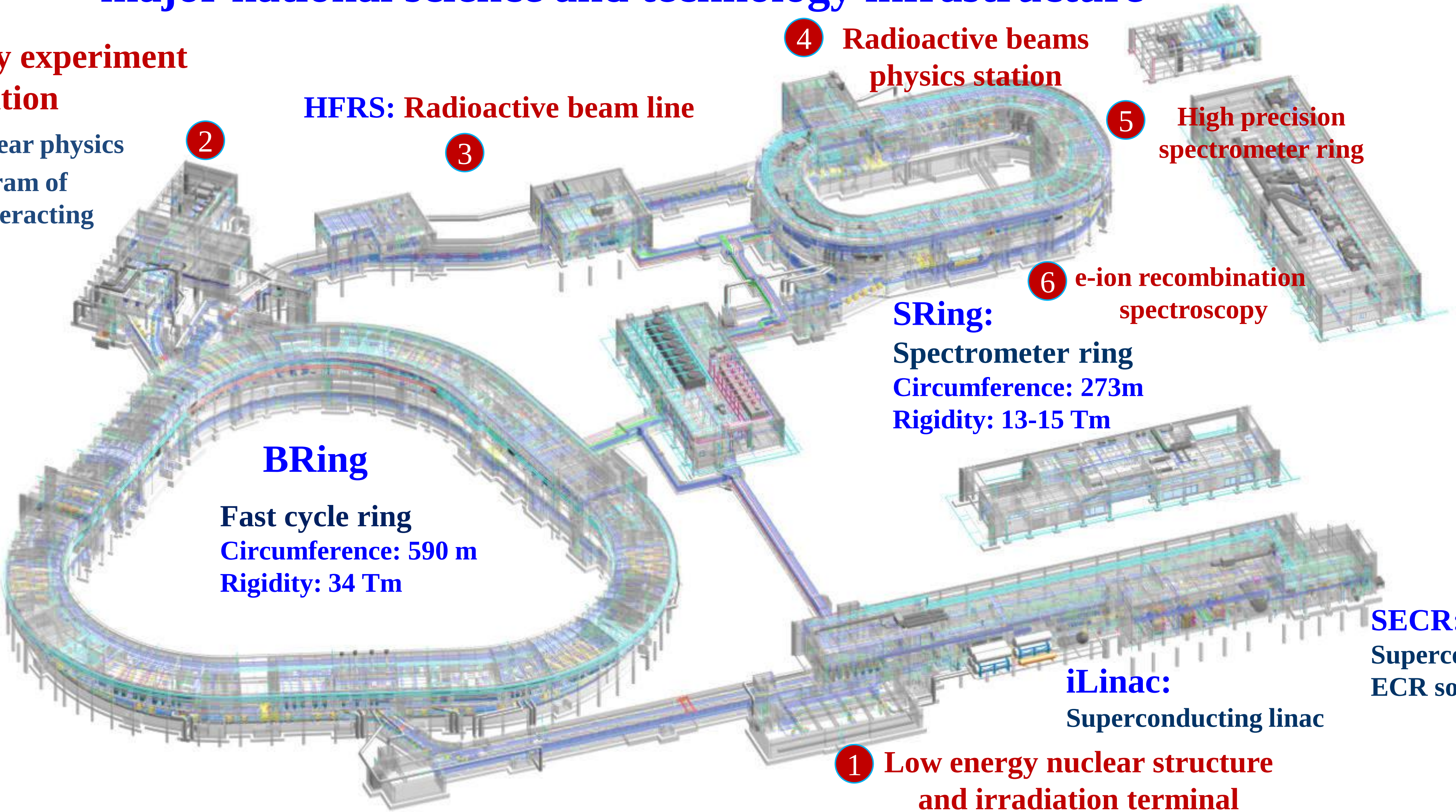
Founded
in 1957



Staff : 990
Students: 543

High-Intensity Heavy Ion Accelerator Facility-HIAF

major national science and technology infrastructure



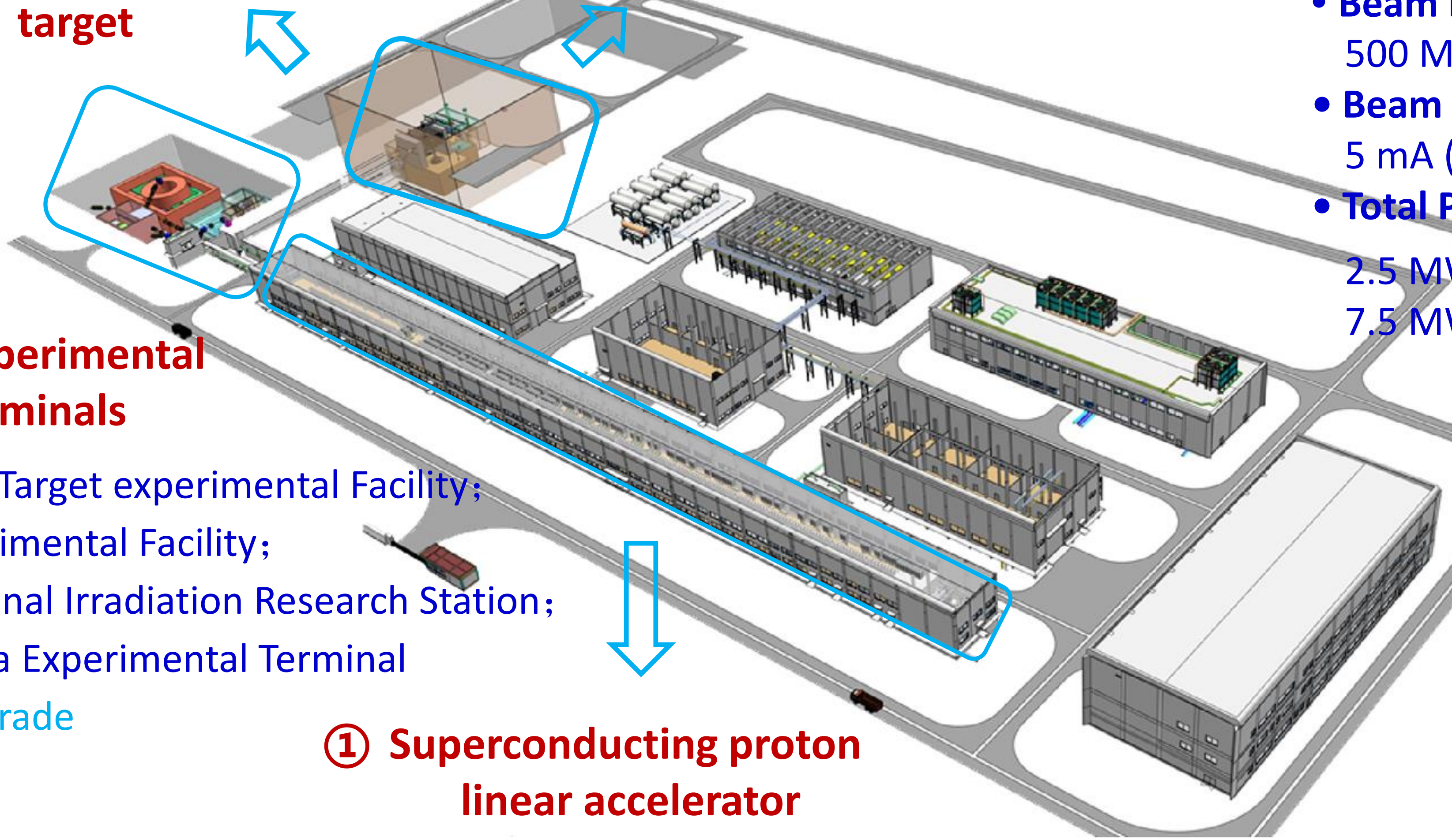
BIM (Building information model) of HIAF facility

construction started in 2018

CiADS-China Initiative Accelerator Driven System

Accelerator-driven subcritical systems (ADS) is considered to be the most effective and promising method to solve the nuclear waste. CiADS will be the world's first prototype of ADS facility

***Megawatt level** to explore the safe and proper technology of nuclear waste disposal*



② High power lead-bismuth eutectic (LBE) spallation target

③ Sub-critical lead-bismuth eutectic (LBE) fast reactor

④ The experimental terminals

- High power Target experimental Facility;
- Muon experimental Facility;
- Multifunctional Irradiation Research Station;
- Nuclear Data Experimental Terminal
- ISOL for upgrade

① Superconducting proton linear accelerator

- **Beam Energy:**
  500 MeV (upgrade to 2.0 GeV)
- **Beam Current:**
  5 mA (upgrade to 10 mA)
- **Total Power: <10 MW**
  2.5 MW beam power,
  7.5 MWth reactor power

The total budget is 4.0 billion CNY

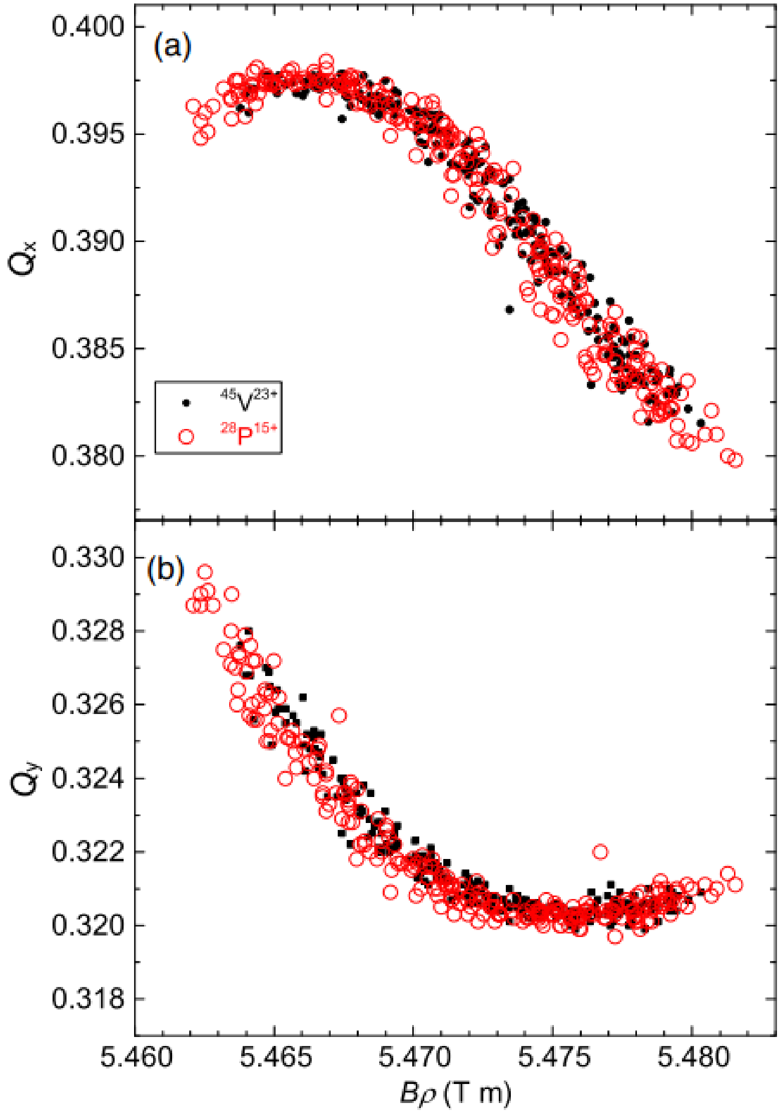
Construction period: 2021-2027, 6 years

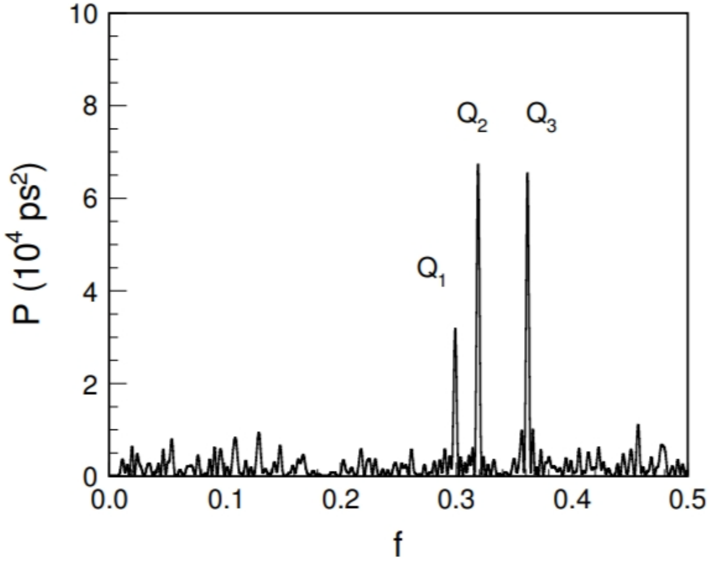
The same campus with HIAF

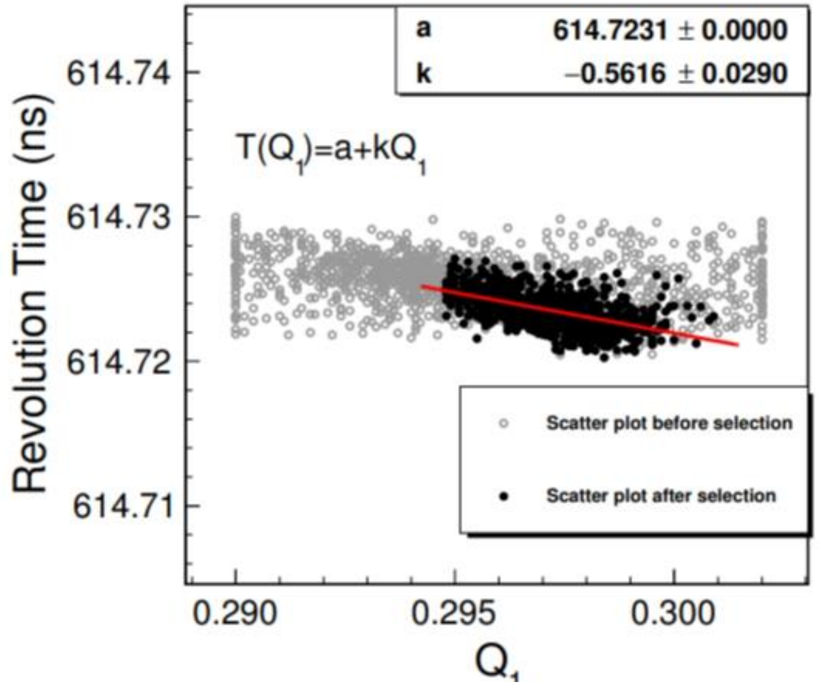

Thank you!

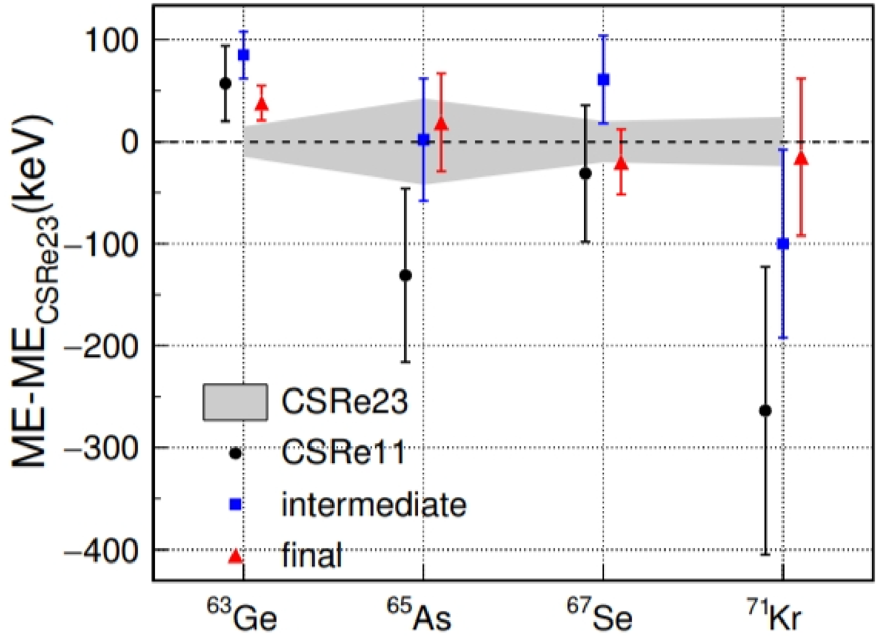
Summary

1) We have developed Bρ-defined IMS, improving significantly the sensitivity and precision of isochronous mass spectrometry.
2) New mass results have been obtained and used to study issues in nuclear astrophysics and nuclear structure.
3) The new research facility HIAF is being constructed and will provide new opportunities for nuclear physics.


(a)
(b)
Q_x
Q_y
$^{45}V^{23+}$
$^{28}P^{15+}$
0.400
0.395
0.390
0.385
0.380
0.330
0.328
0.326
0.324
0.322
0.320
0.318
5.460
5.465
5.470
5.475
5.480
$B\rho$ (T m)


Q_1
Q_2
Q_3
P (10^4 ps^2)
f
0.0
0.1
0.2
0.3
0.4
0.5


a 614.7231 ± 0.0000
k −0.5616 ± 0.0290
$T(Q_1)=a+kQ_1$
Revolution Time (ns)
614.74
614.73
614.72
614.71
Scatter plot before selection
Scatter plot after selection
0.290
0.295
0.300
Q_1


$ME\text{-}ME_{CSRe23}$(keV)
100
0
−100
−200
−300
−400
CSRe23
CSRe11
intermediate
final
^{63}Ge
^{65}As
^{67}Se
^{71}Kr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Huizhou, 2025

Thank you for your attention !

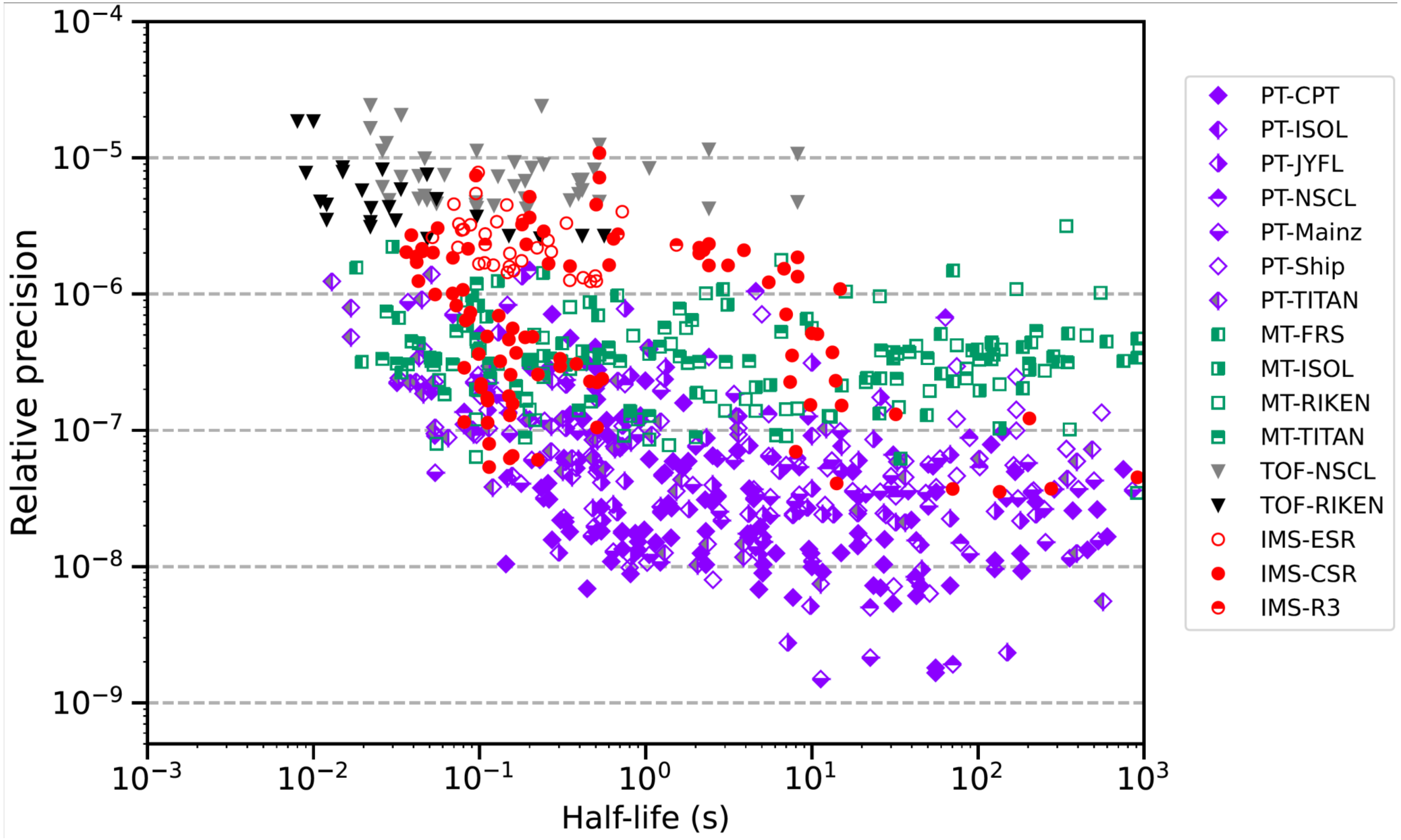
CSR-IMS collaboration

M. Wang,[1,2] Y. H. Zhang,[1,2,*] X. Zhou,[1,2] X. H. Zhou,[1,2,†] H. S. Xu,[1,2] M. L. Liu,[1] J. G. Li,[1] Y. F. Niu,[3,4] W. J. Huang,[1,5] Q. Yuan,[6] S. Zhang,[6] F. R. Xu,[6,‡] Yu. A. Litvinov,[1,7] K. Blaum,[8] Z. Meisel,[9] R. F. Casten,[10] R. B. Cakirli,[11] R. J. Chen,[1,7] H. Y. Deng,[1,2] C. Y. Fu,[1] W. W. Ge,[1] H. F. Li,[1,2] T. Liao,[1,2] S. A. Litvinov,[7,1] P. Shuai,[1] J. Y. Shi,[1,2] Y. N. Song,[1,2] M. Z. Sun,[1] Q. Wang,[1,2] Y. M. Xing,[1] X. Xu,[1] X. L. Yan,[1] J. C. Yang,[1,2] Y. J. Yuan,[1,2] Q. Zeng,[12] and M. Zhang[1,2]

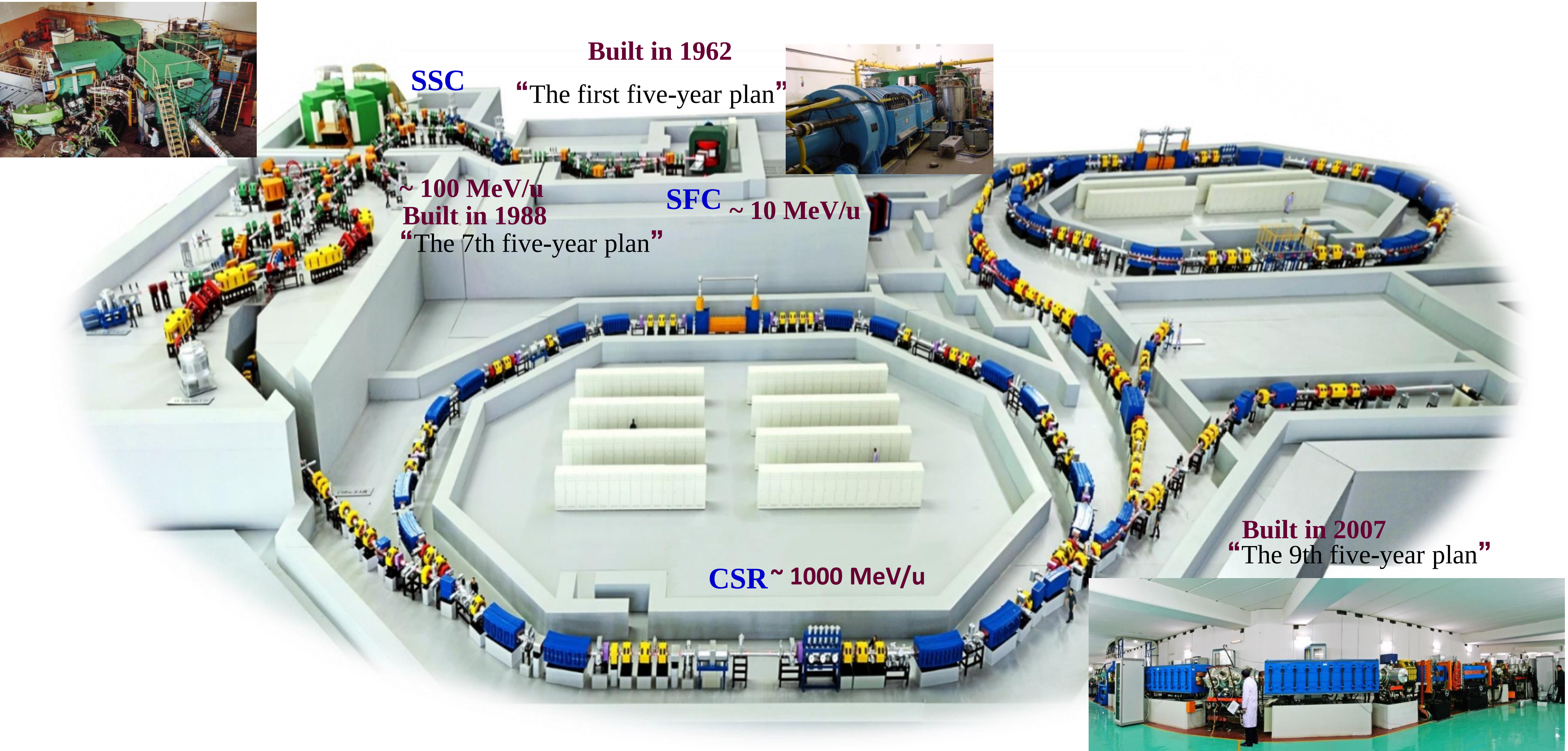
[1]*CAS Key Laboratory of High Precision Nuclear Spectroscopy, Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*
[2]*School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, China*
[3]*School of Nuclear Science and Technology, Lanzhou University, Lanzhou 730000, China*
[4]*Frontiers Science Center for Rare isotope, Lanzhou University, Lanzhou 730000, China*
[5]*Advanced Energy Science and Technology Guangdong Laboratory, Huizhou, 516007, China*
[6]*State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, People's Republic of China*
[7]*GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, 64291 Darmstadt, Germany*
[8]*Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*
[9]*Institute of Nuclear and Particle Physics, Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701, USA*
[10]*Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520-8124, USA*
[11]*Department of Physics, Istanbul University, Istanbul 34134, Turkey*
[12]*School of Nuclear Science and Engineering, East China University of Technology, Nanchang 330013, China*

Phys. Rev. Lett. 130, 192501 (2023)

Nuclear mass measurements



Heavy Ion Research Facility in Lanzhou (HIRFL)



Bρ-defined isochronous mass spectrometry

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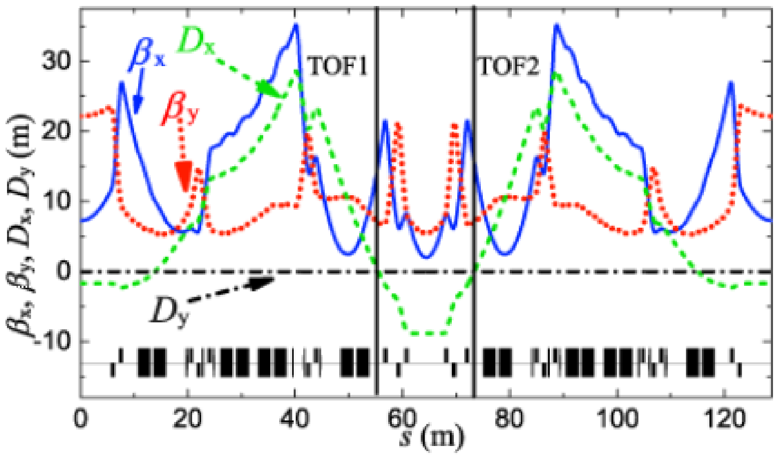


EDITORS' SUGGESTION

In-ring velocity measurement for isochronous mass spectrometry

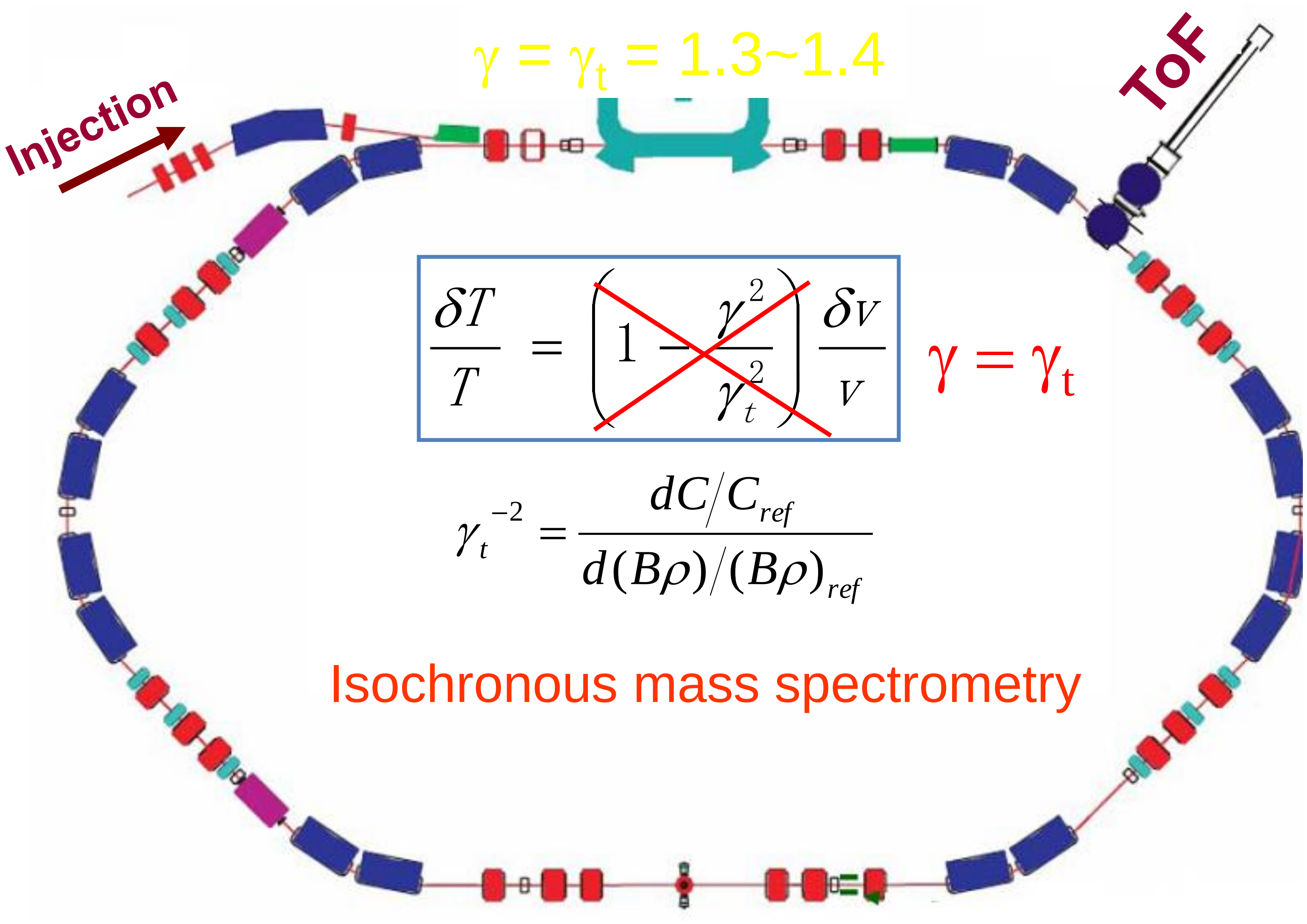
X. Zhou *et al.*

Phys. Rev. Accel. Beams **24**, 042802 (2021)

Detecting the time difference between traversals of two thin foils, 18 m apart, allows measuring the velocity of short-lived nuclei, circulating in a storage ring over a few hundred turns, with a relative precision of 10 ppm.

$$v = \frac{L}{\Delta t_{\mathrm{TOF}}} = \frac{L}{\Delta t_{\mathrm{exp}} - \Delta t_{\mathrm{d}}}$$

Isochronous mass spectrometry at CSRe



$$\boxed{\frac{\delta T}{T} = \cancel{\left(1-\frac{\gamma^2}{\gamma_t^2}\right)}\frac{\delta v}{v}}$$

$\gamma = \gamma_t$

$$\gamma_t^{-2} = \frac{dC/C_{ref}}{d(B\rho)/(B\rho)_{ref}}$$

Isochronous mass spectrometry

X. L. Tu et al., NIM A 654, 213 (2011)

Bρ-defined isochronous mass spectrometry

Eur. Phys. J. A (2023) 59:90
https://doi.org/10.1140/epja/s10050-023-01009-4

THE EUROPEAN PHYSICAL JOURNAL A

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Regular Article - Experimental Physics

Recent achievements at the Rare-RI Ring, a unique mass spectrometer at the RIBF/RIKEN

Sarah Naimi[1,2,a], **Yoshitaka Yamaguchi**[2], **Takayuki Yamaguchi**[3,4], **Akira Ozawa**[4]

[1] Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France
[2] RIKEN Nishina Center for Accelerator Based Science, Wako, Saitama 351-0198, Japan
[3] Department of Physics, Saitama University, Saitama, Saitama 338-8570, Japan
[4] Institute of Physics, University of Tsukuba, Tsubuka, Ibaraki 305-8571, Japan

[10]. Recently, a milestone was achieved at the CSRe after establishing a new measurement method, namely Bρ-defined isochronous mass spectrometry. With this new method record mass precision and accuracy was reached for short-lived nuclei in storage ring operated as IMS [11,12].

11. M. Wang, M. Zhang, X. Zhou, Y.H. Zhang, Y.A. Litvinov, H.S. Xu, R.J. Chen, H.Y. Deng, C.Y. Fu, W.W. Ge, H.F. Li, T. Liao, S.A. Litvinov, P. Shuai, J.Y. Shi, M. Si, R.S. Sidhu, Y.N. Song, M.Z. Sun, S. Suzuki, Q. Wang, Y.M. Xing, X. Xu, T. Yamaguchi, X.L. Yan, J.C. Yang, Y.J. Yuan, Q. Zeng, X.H. Zhou, $B\rho$-defined isochronous mass spectrometry: an approach for high-precision mass measurements of short-lived nuclei. Phys. Rev. C **106**, 051301 (2022). https://doi.org/10.1103/PhysRevC.106.L051301
12. M. Zhang, X. Zhou, M. Wang, Y.H. Zhang, Y.A. Litvinov, H.S. Xu, R.J. Chen, H.Y. Deng, C.Y. Fu, W.W. Ge, H.F. Li, T. Liao, S.A. Litvinov, P. Shuai, J.Y. Shi, R.S. Sidhu, Y.N. Song, M.Z. Sun, S. Suzuki, Q. Wang, Y.M. Xing, X. Xu, T. Yamaguchi, X.L. Yan, J.C. Yang, Y.J. Yuan, Q. Zeng, X.H. Zhou, $B\rho$-defined isochronous mass spectrometry and mass measurements of ^{58}Ni fragments. Eur. Phys. J. A **59**(2), 27 (2023). https://doi.org/10.1140/epja/s10050-023-00928-6

Nuclear Science and Techniques (2023) 34:104
https://doi.org/10.1007/s41365-023-01250-y

RESEARCH HIGHLIGHT

Double-up for single-ion masses

Philip M. Walker[1]

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A cunning addition for the determination of nuclear masses provides world-leading sensitivity for accurate measurements. This is already opening up new physics and applications.

The double TOF technique will be adopted at other storage rings being planned or under construction, including at the HIAF facility in China [5] and the FAIR facility in Germany [6]. Indeed, the concept was discussed by the ILIMA collaboration [7] at FAIR, foreseeing the possibilities at the Lanzhou storage ring. Its implementation is a most welcome development.