Precision mass measurements of short-lived nuclei at heavy ions storage ring CSRe in Lanzhou

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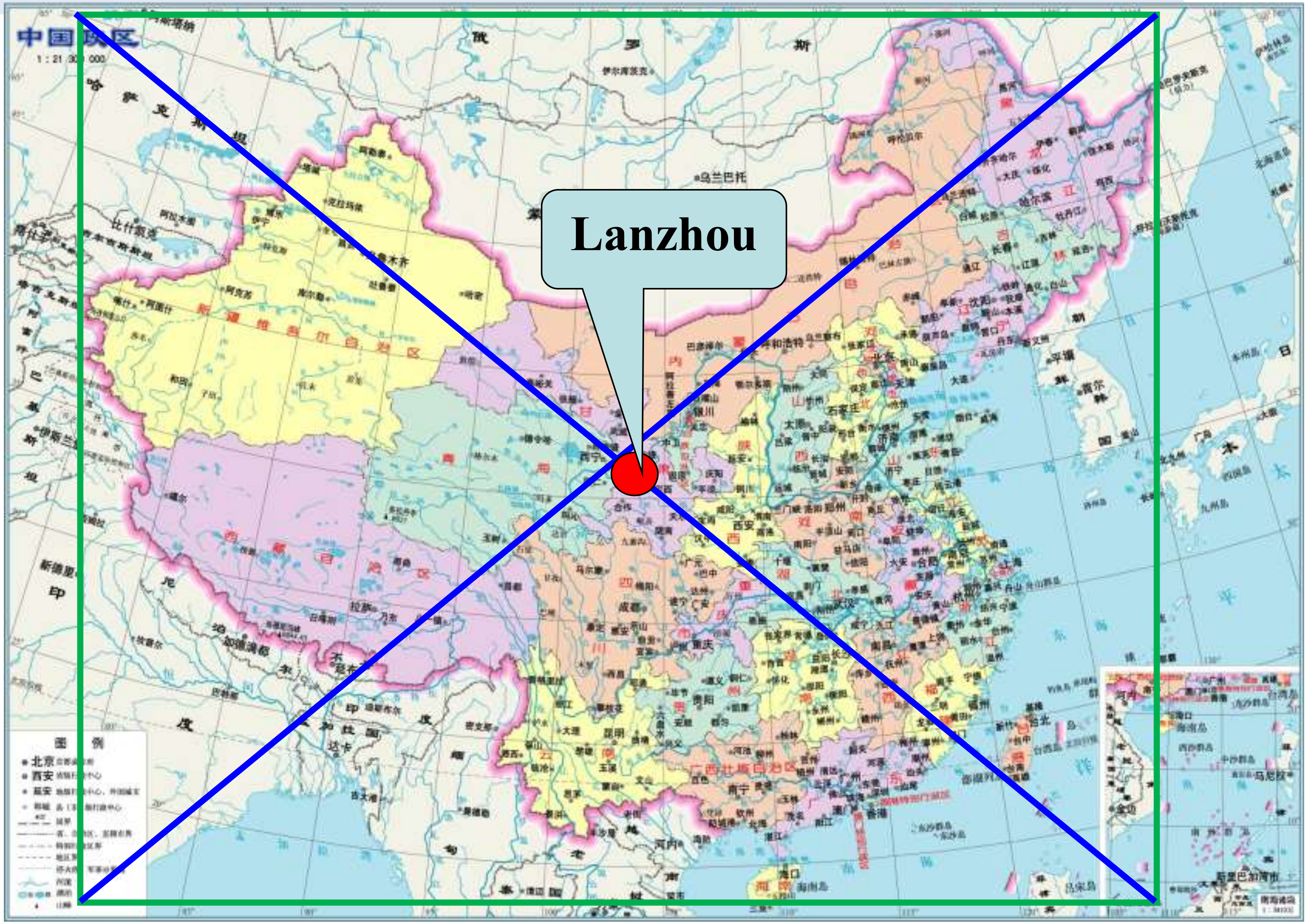
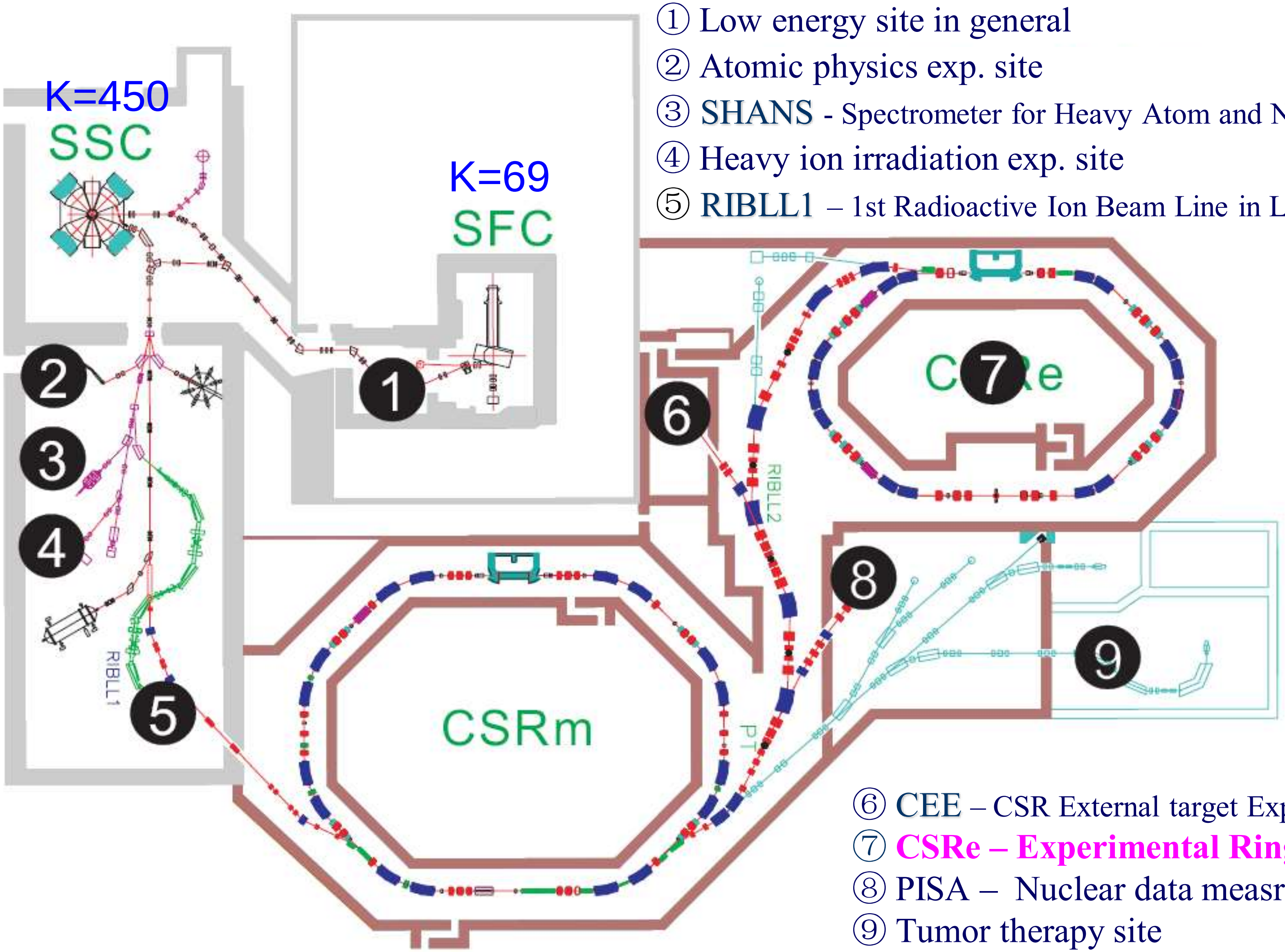
Tsukuba Global Science Week 2024, 9/30mon-10/4Fri




Downtown area of Lanzhou
IMP
First steel bridge

Institute of Modern Physics, CAS

Layout of experimental terminals at HIRFL-CSR in IMP



① Low energy site in general
② Atomic physics exp. site
③ SHANS - Spectrometer for Heavy Atom and Nuclear Structure
④ Heavy ion irradiation exp. site
⑤ RIBLL1 – 1st Radioactive Ion Beam Line in Lanzhou

⑥ CEE – CSR External target Experiment
⑦ **CSRe – Experimental Ring**
⑧ PISA – Nuclear data measrements
⑨ Tumor therapy site

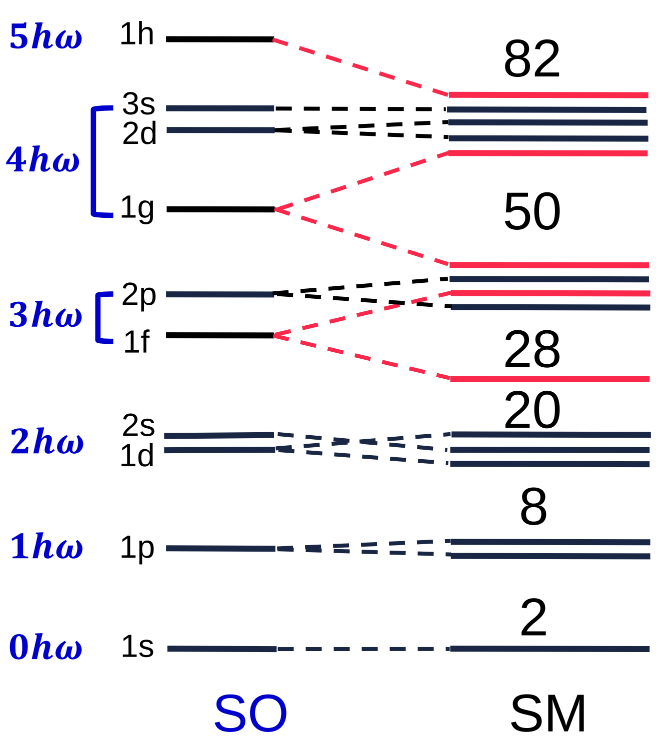
1. Introduction
2. $B\rho$-defined isochronous mass spectrometry IMS
3. New masses from $B\rho$-IMS and its impacts on nuclear structure & nuclear astrophysics
4. Summary & perspective

1. Introduction:

Importance of mass measurements

M.G Mayer

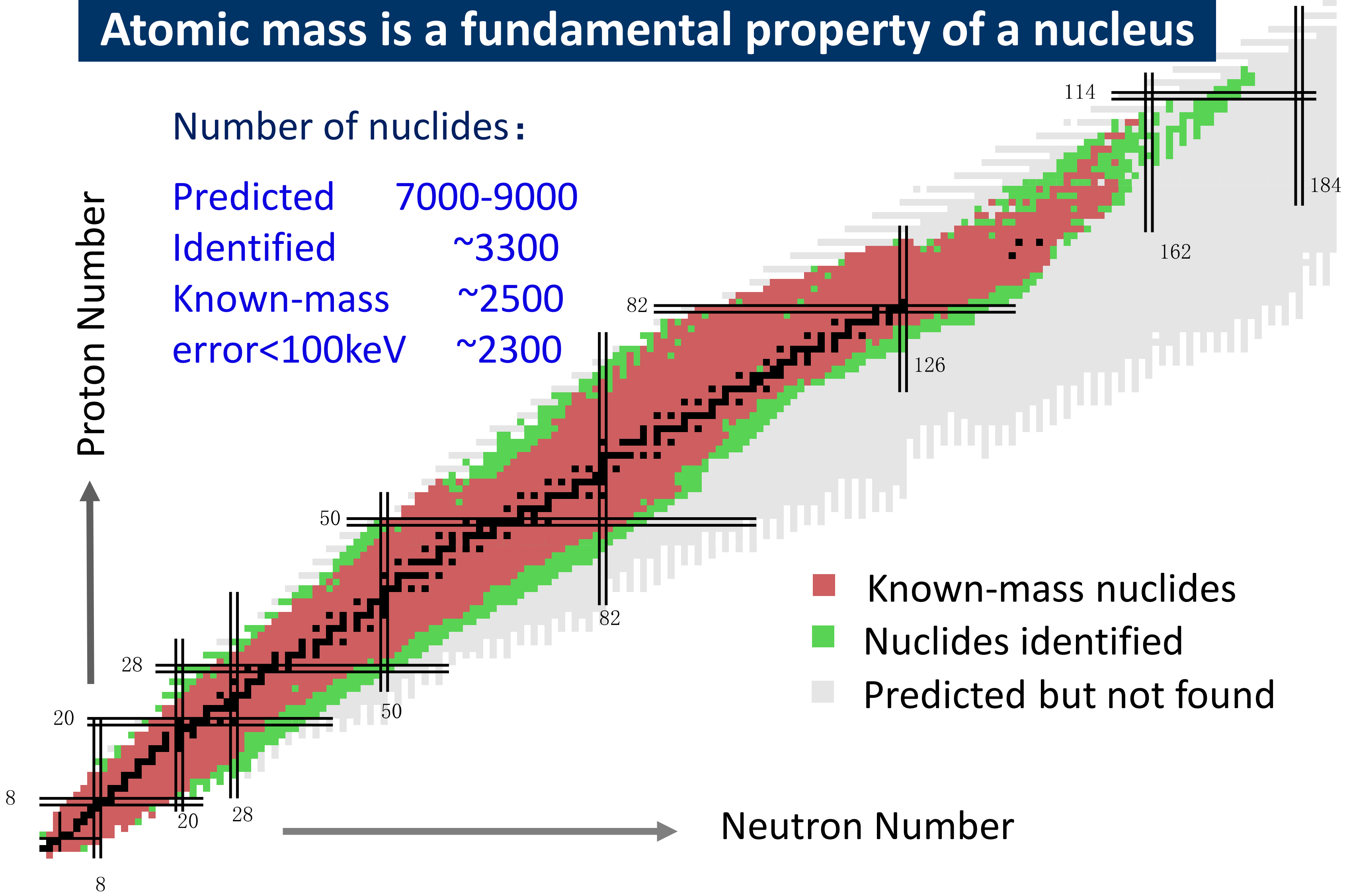
J.H.D.Jensen



Atomic mass is a fundamental property of a nucleus

Number of nuclides：

Predicted	7000-9000
Identified	~3300
Known-mass	~2500
error<100keV	~2300



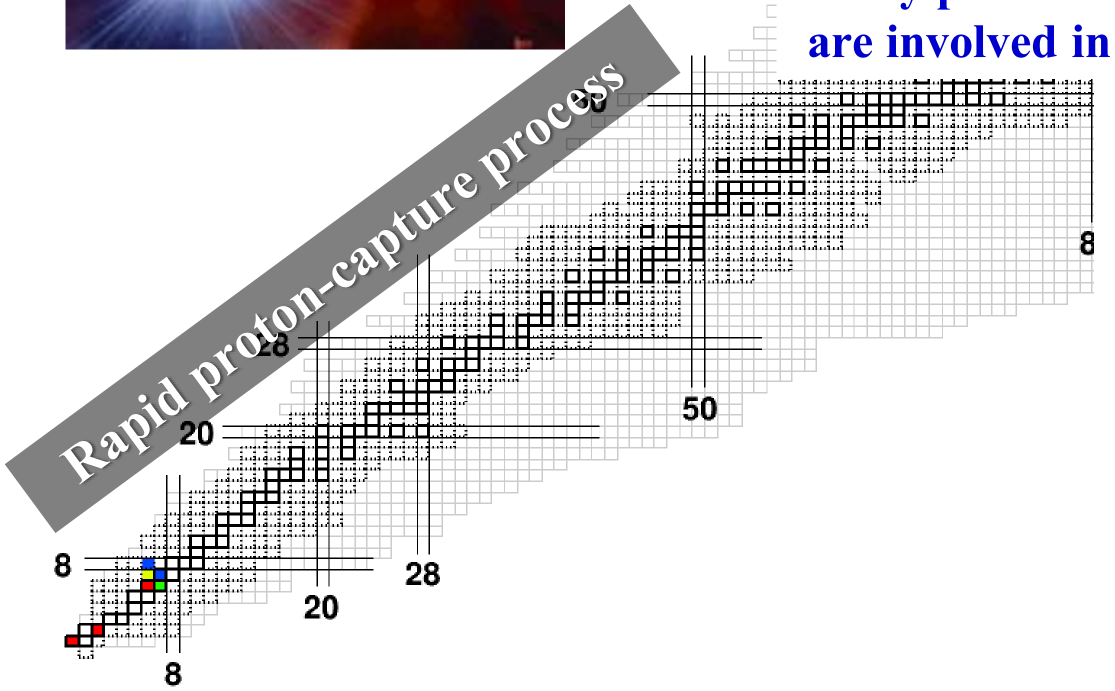
1. Introduction:

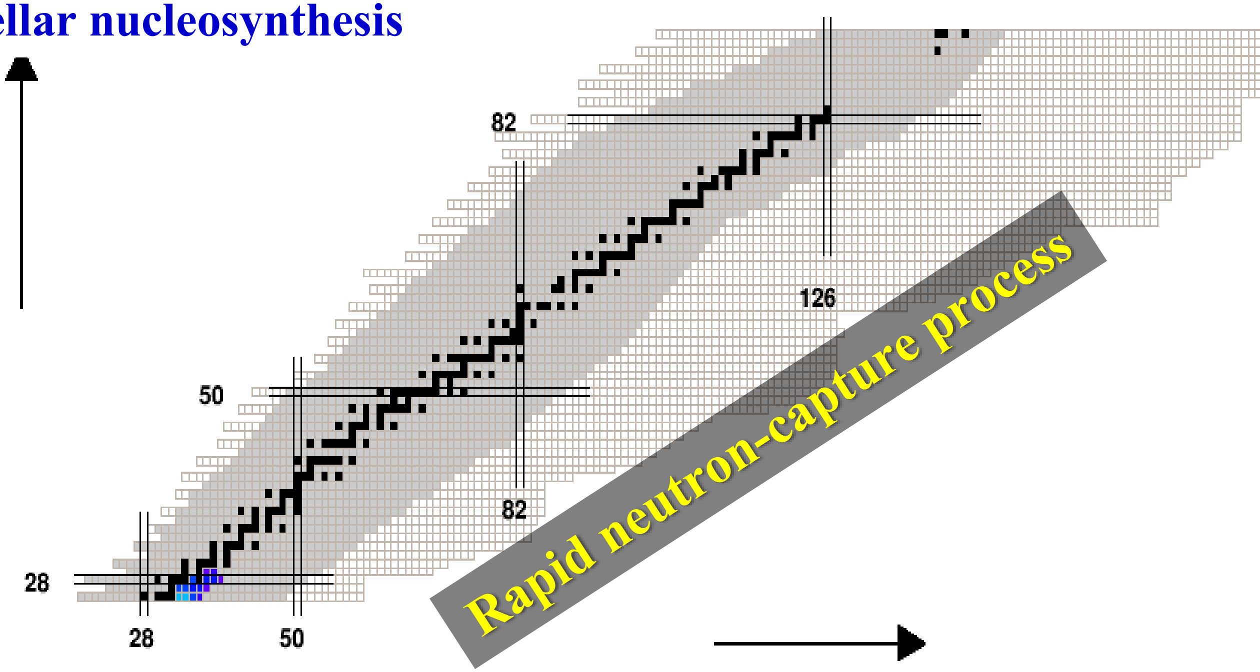
Importance of mass measurements

Applications in nuclear astrophysics

Nuclear physics input:
Atomic masses, lifetimes, reaction rates, etc

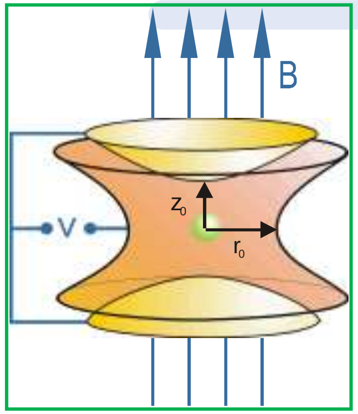
Very proton-rich or neutron-rich nuclei are involved in the stellar nucleosynthesis



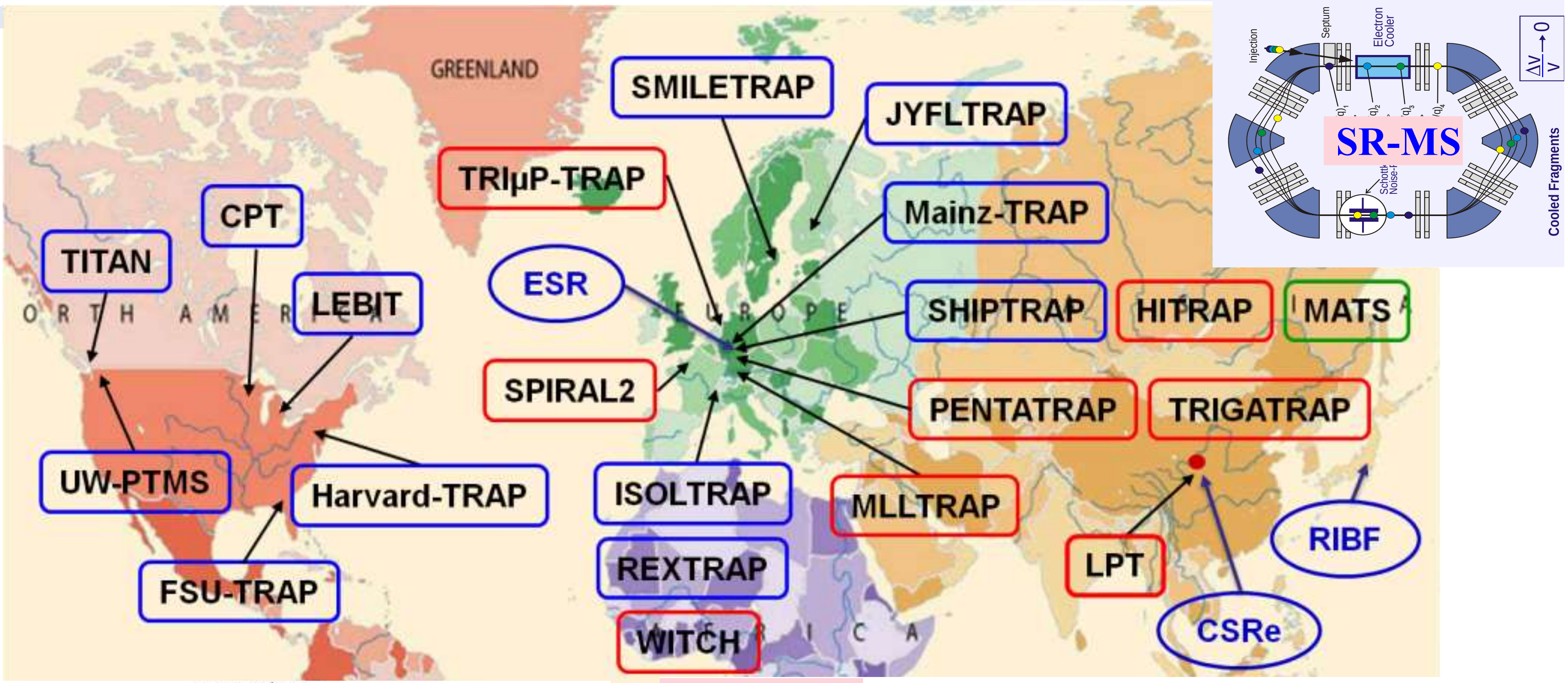


1. Introduction:

Advanced mass spectromery

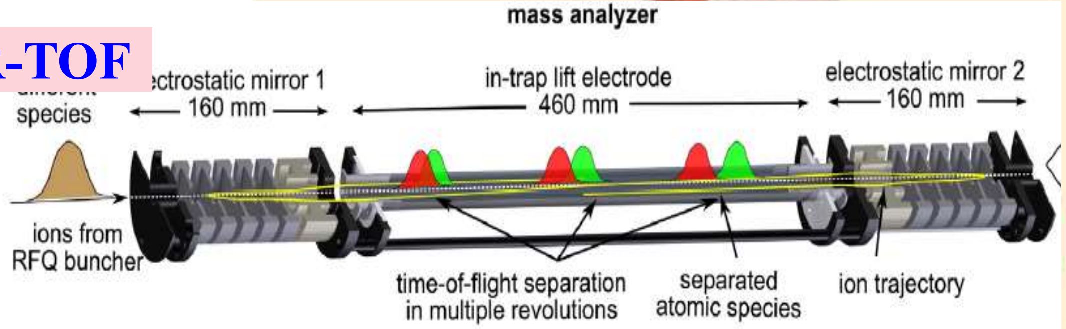


Penning Trap

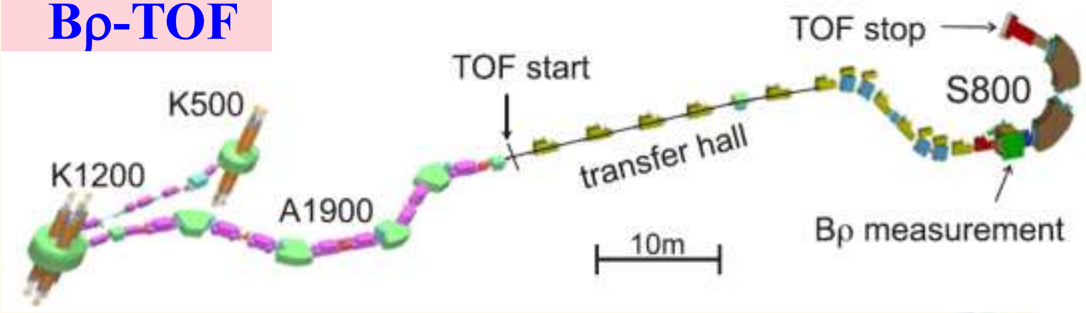


SR-MS

MR-TOF



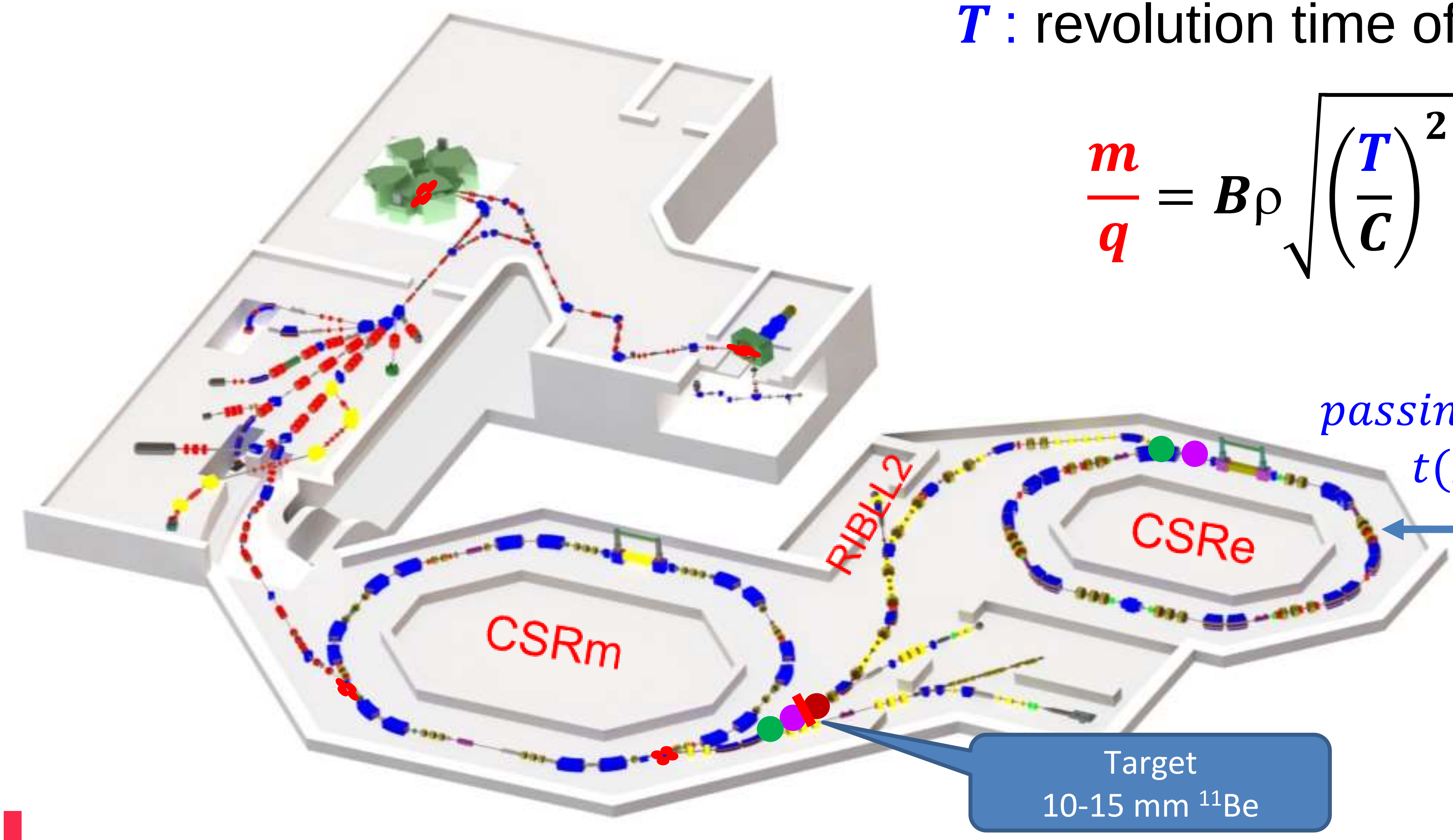
Bρ-TOF

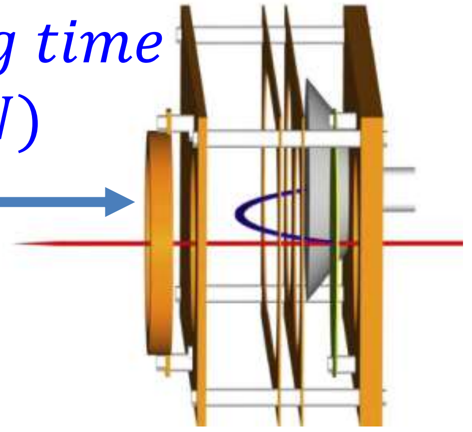


1. Introduction

T : revolution time of stored ions

$$\frac{m}{q} = B\rho\sqrt{\left(\frac{T}{C}\right)^2 - \left(\frac{1}{v_c}\right)^2}$$





TOF Detector

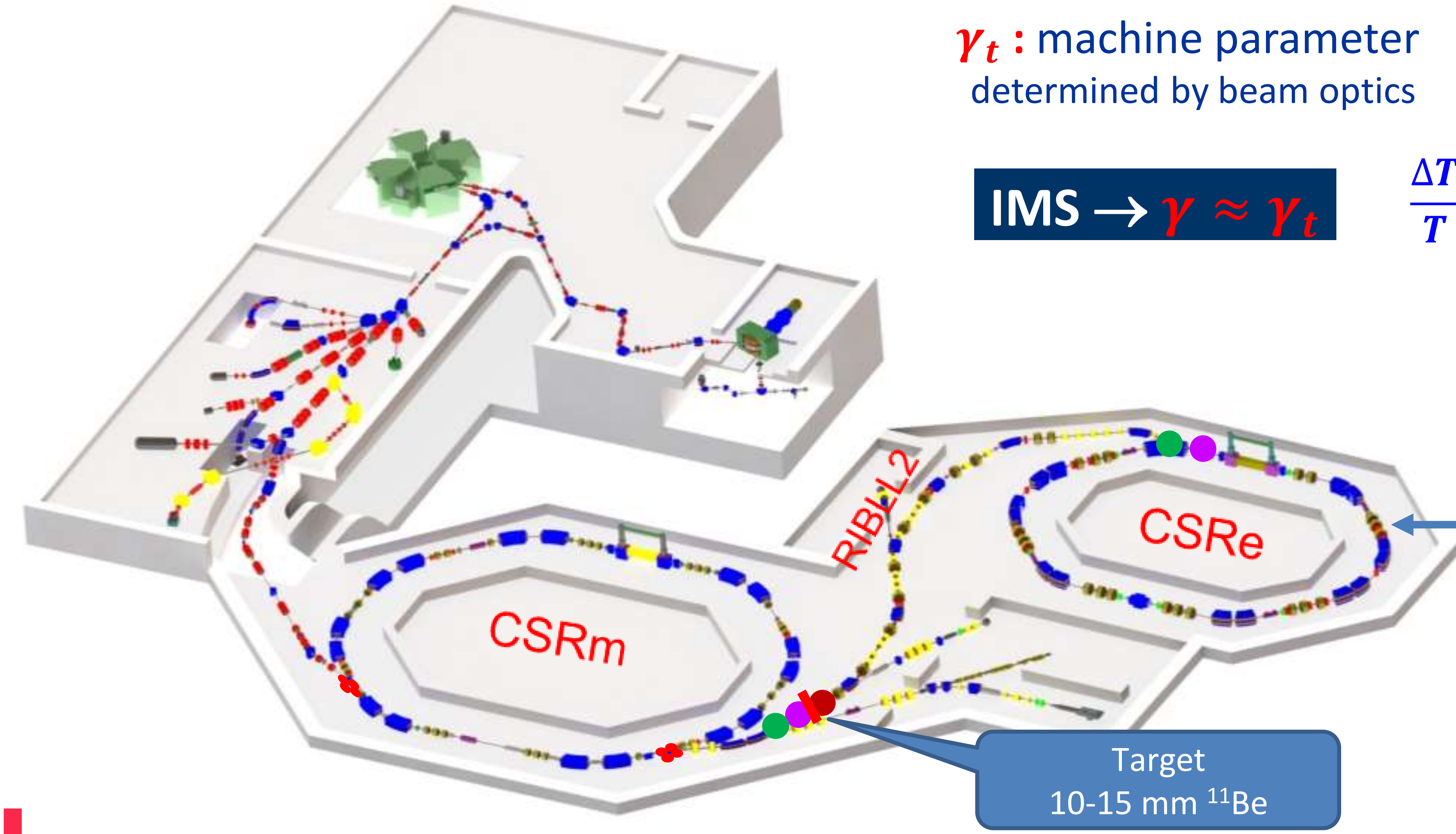
1. Introduction

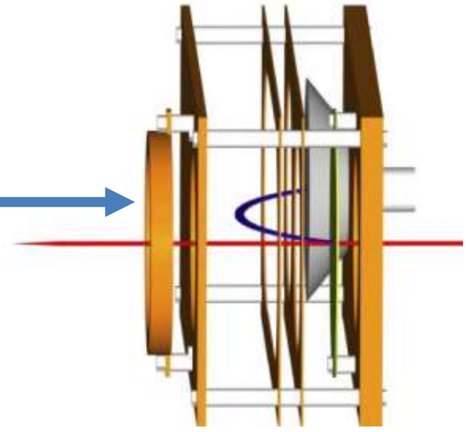
γ_t : machine parameter determined by beam optics

$$\gamma_t^{-2} = \frac{\Delta C/C}{\Delta(B\rho)/(B\rho)}$$

IMS → $\gamma \approx \gamma_t$

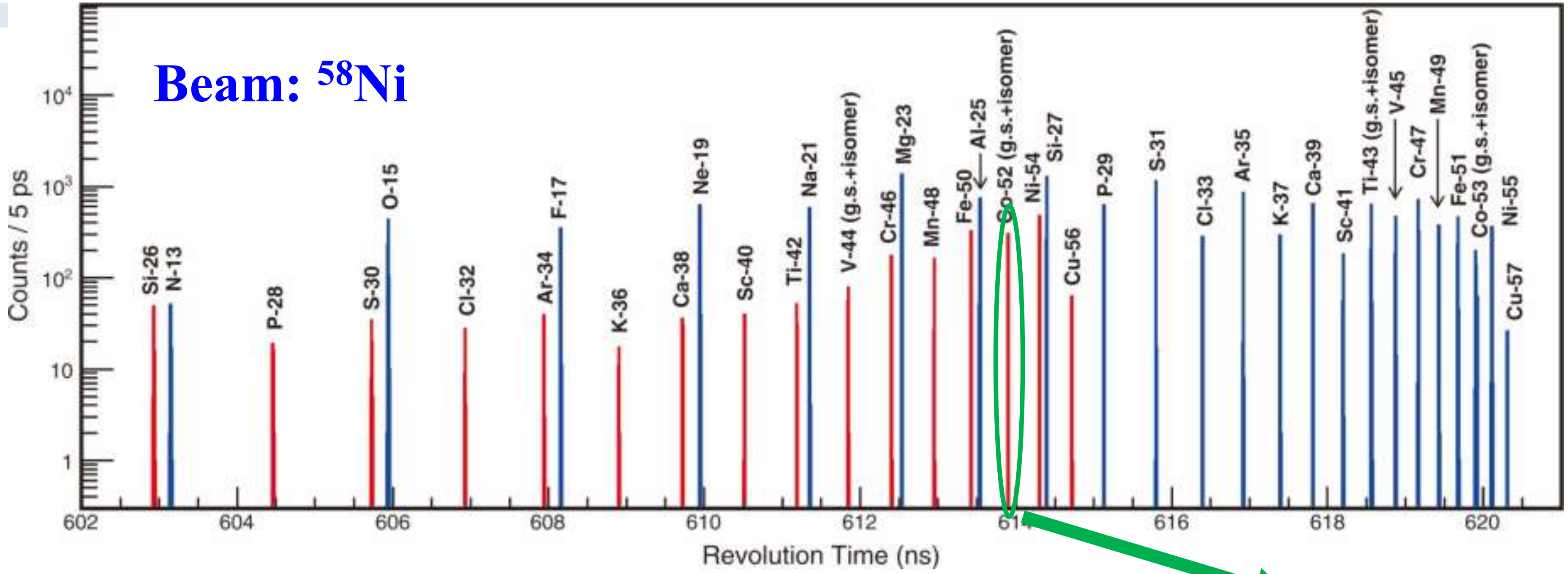
$$\frac{\Delta T}{T} \approx \left(\frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}\right)\frac{\Delta(B\rho)}{B\rho}$$

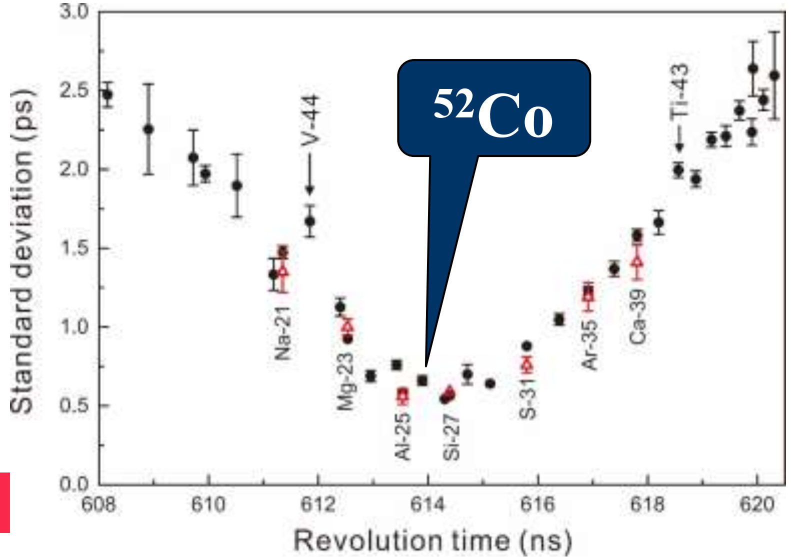




TOF Detector

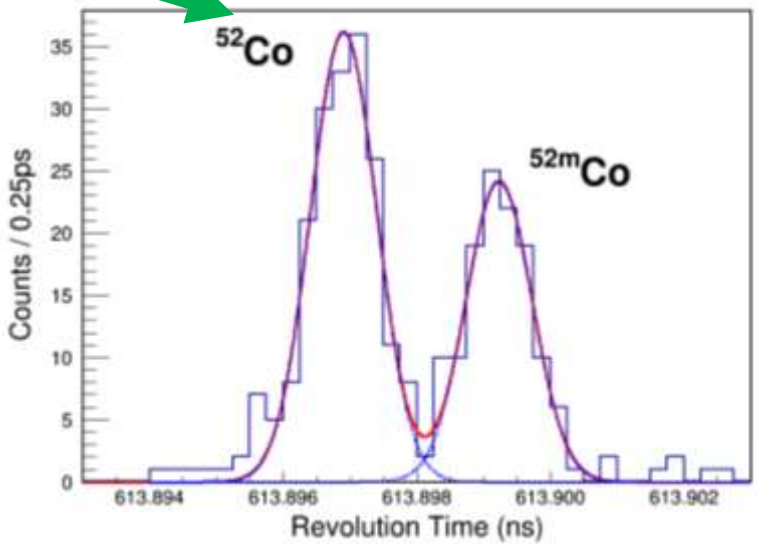
1. Introduction



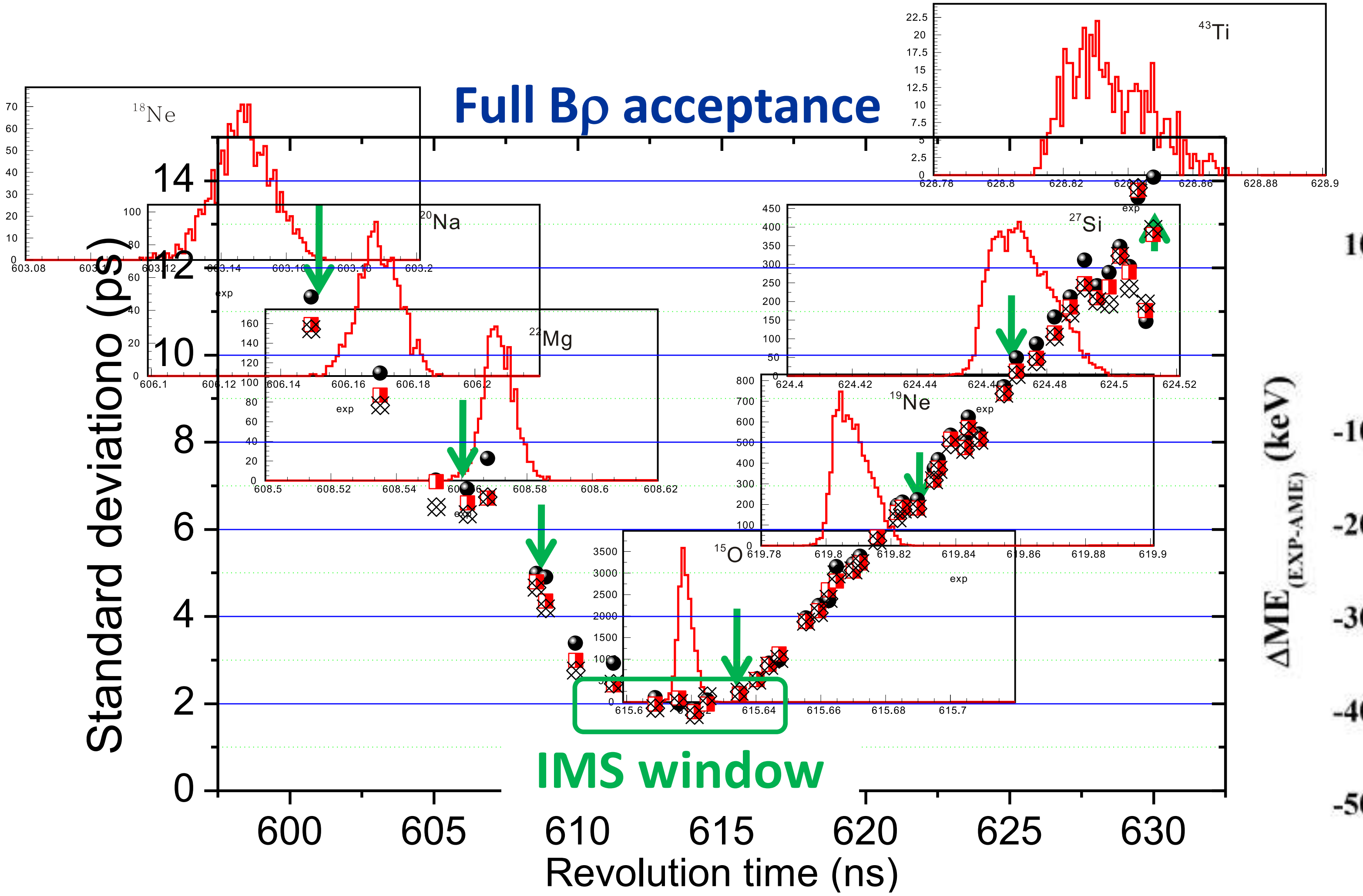


a slit is used to constrain the Bρ acceptance

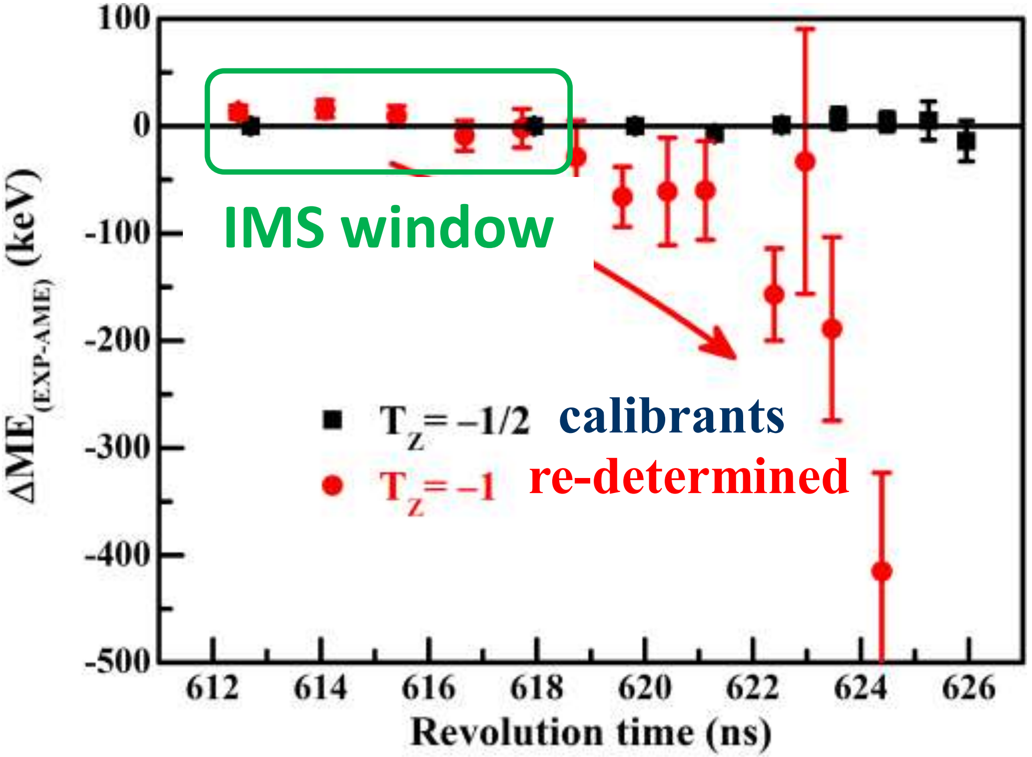
1 ps ➡150 keV



1. Introduction



Full Bρ acceptance causes **systematic deviation**



2. $B\rho$-defined isochronous mass spectrometry IMS

Principle of mass determinations with $B\rho$-IMS

P. M. Walker, et al.,
ILIMA Technical Proposal, GSI, 2005.

H. Geissel and Yu. A. Litvinov,
J. Phys. G: Nucl. Part. 31, S1779 (2005)

Measurements

T_i, v_i
$(i = 1, 2, \ldots N)$

→

Calibration

$$(B\rho)_i = \left(\frac{m}{q}\right)_i \cdot (\gamma v)_i$$

$$C_i = v_i \cdot T_i$$

$B\rho(C)$
using nuclei with known m/q

→

Outputs

$$\left(\frac{m}{q}\right)_i = \frac{(B\rho)_i}{(\gamma v)_i}$$

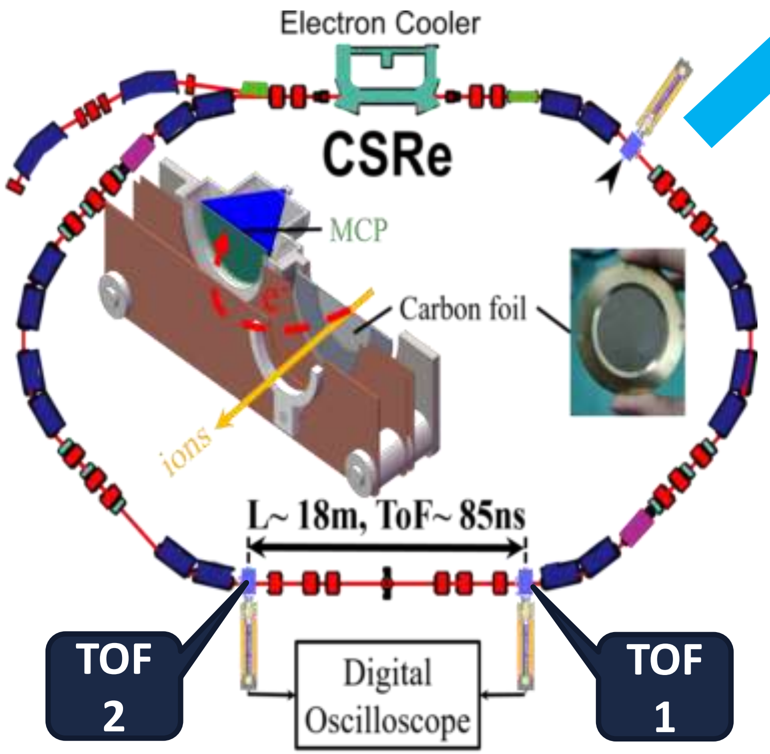
New $(m/q)_i$
using $(B\rho)^i_{fit}$

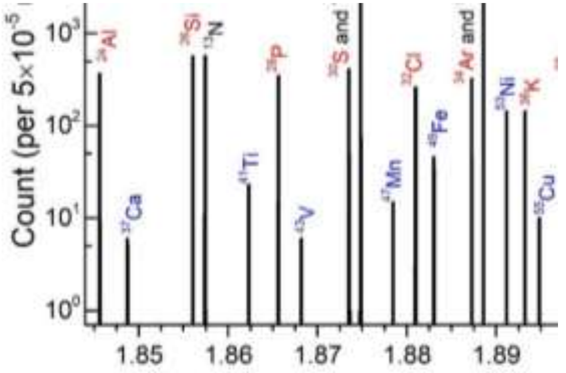
2. $B\rho$-defined isochronous mass spectrometry IMS

From $\left\{T, v, \frac{m}{q}\right\}$, $\rightarrow$ $B\rho, C$

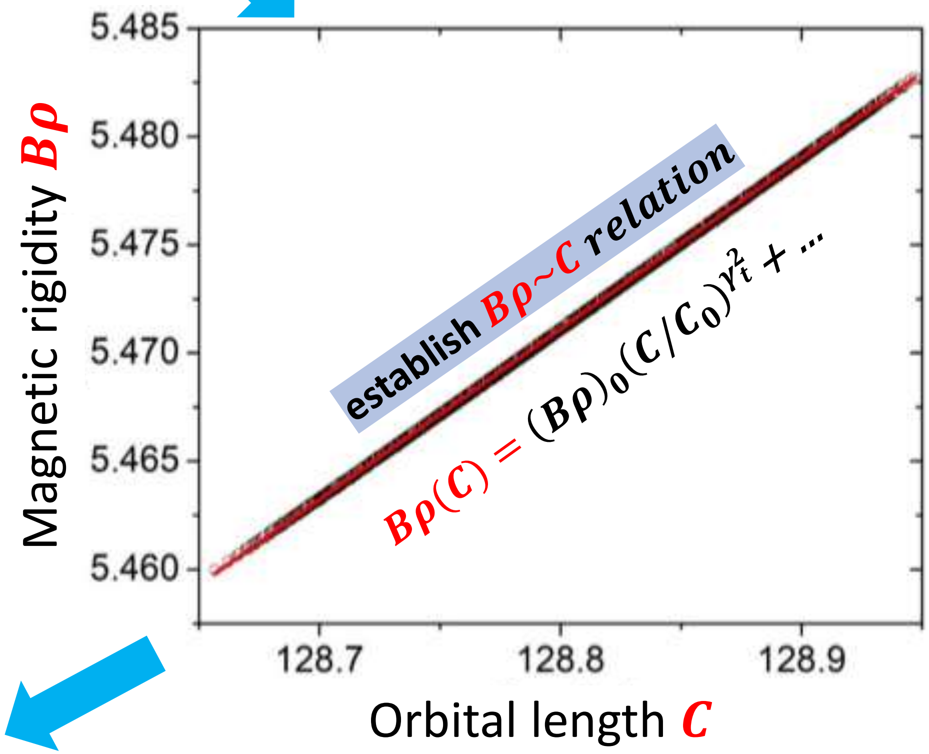
$B\rho = m/q \cdot \gamma v$

$C = T \cdot v$

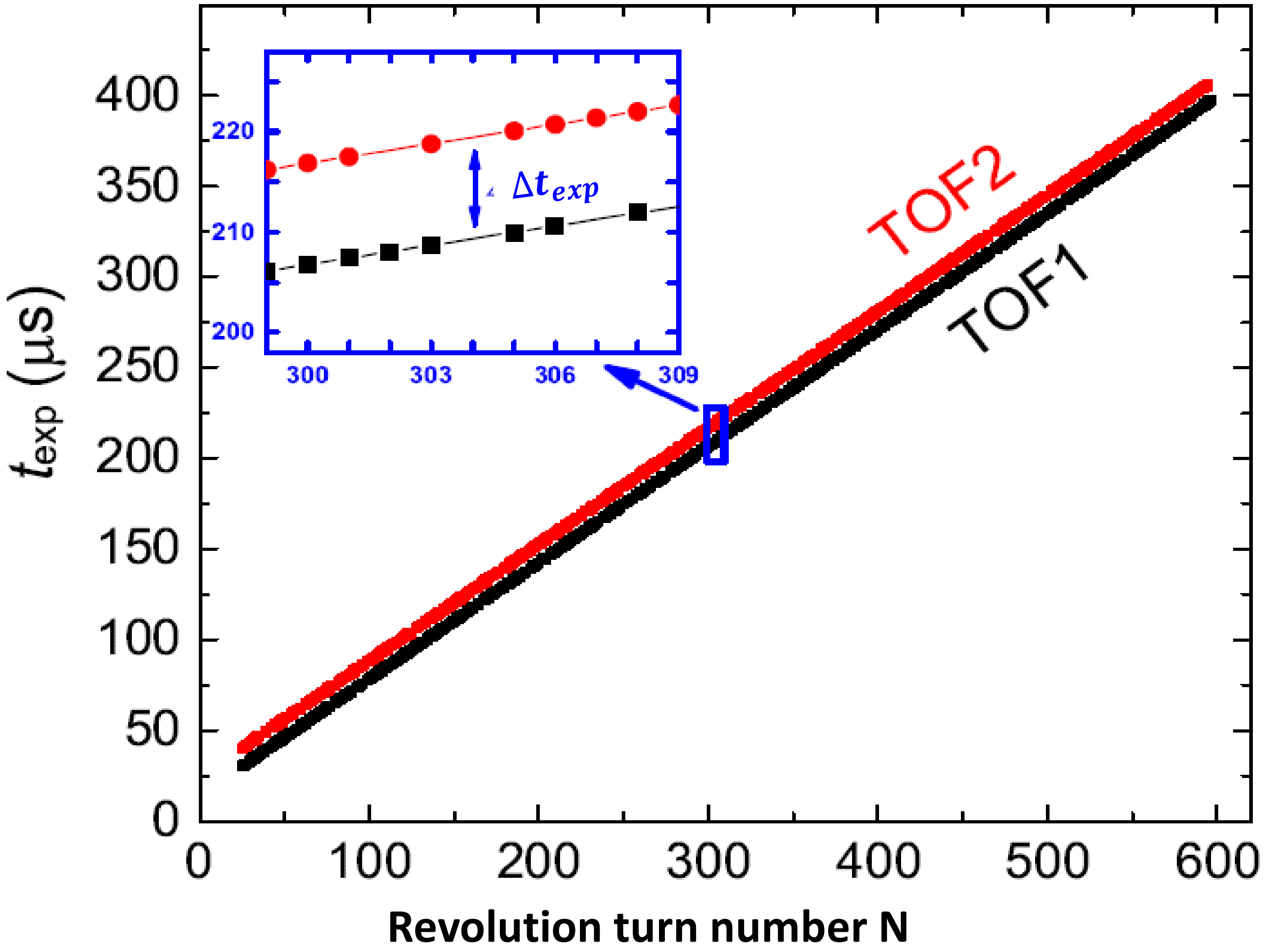




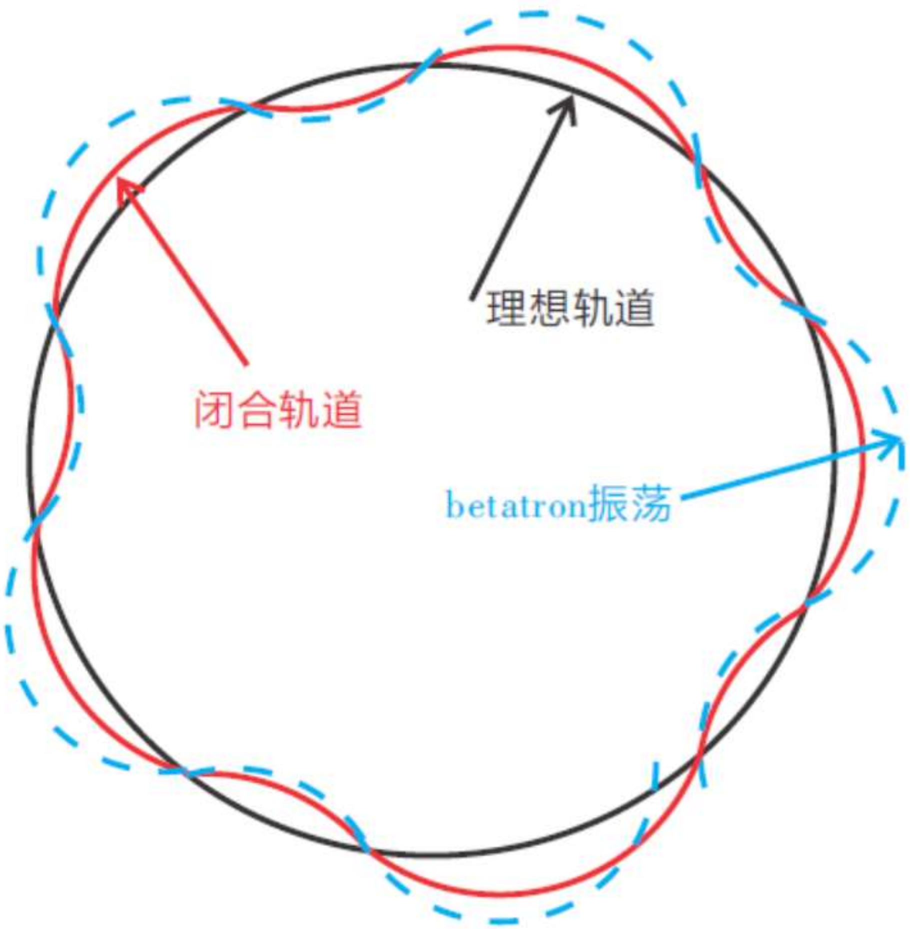
$$\left(\frac{m}{q}\right)_i = \frac{(B\rho)_i}{(\gamma v)_i}$$



2. $B\rho$-defined isochronous mass spectrometry IMS



Betatron oscillation

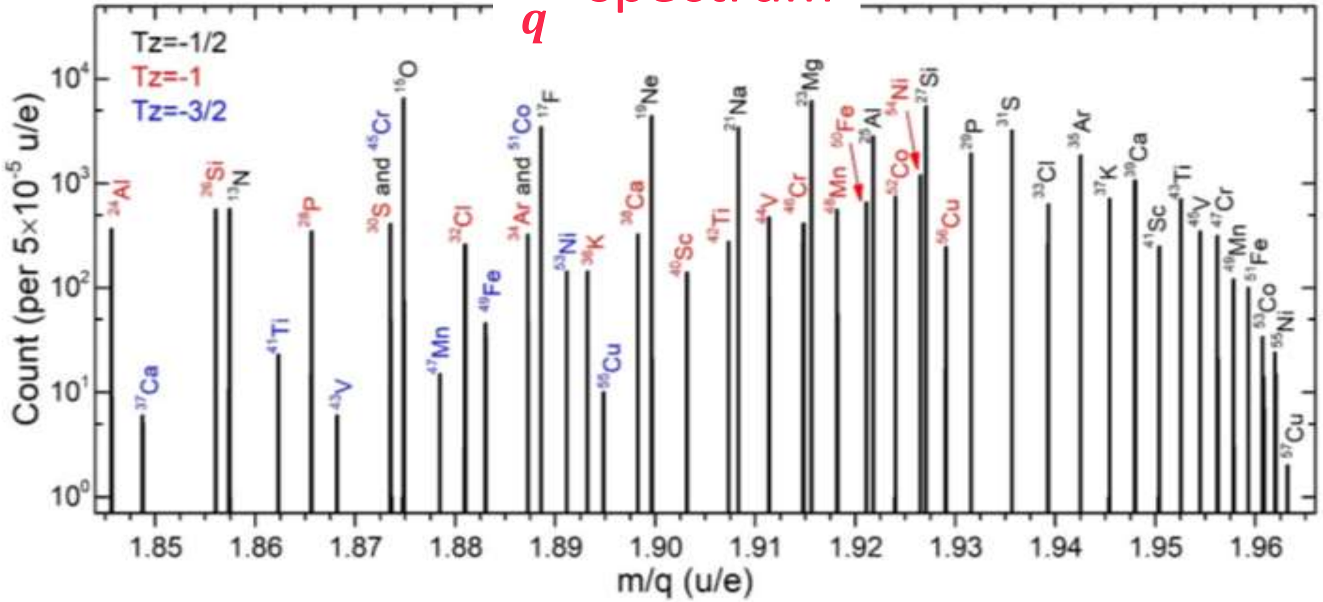


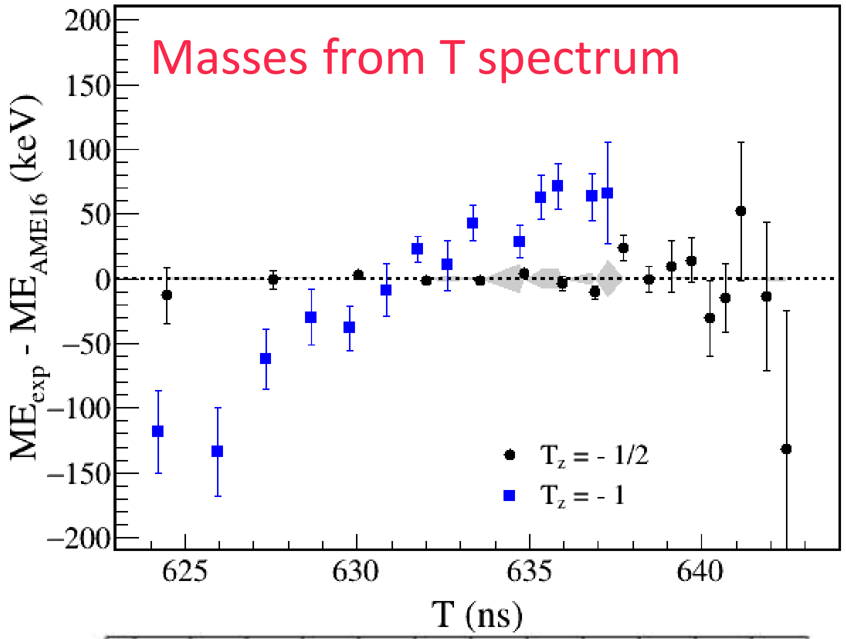
2. $B\rho$-defined isochronous mass spectrometry IMS

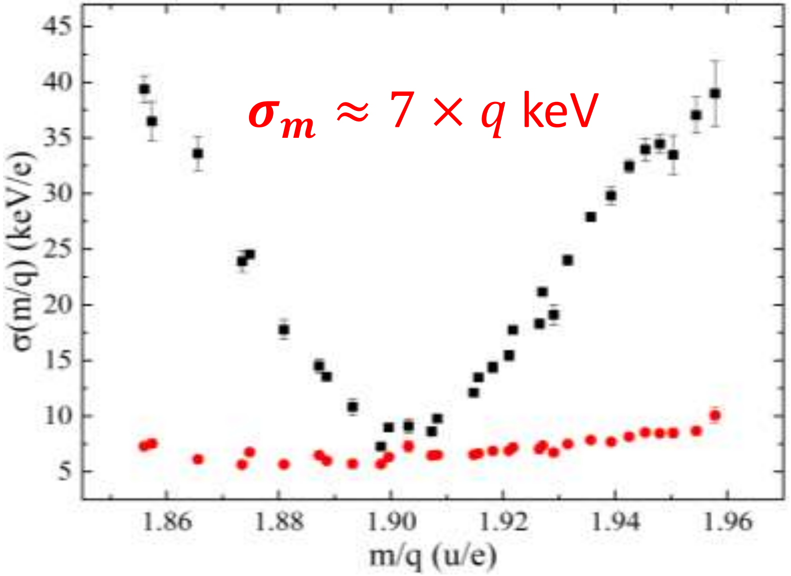
Masses determinations

$$(m/q)^{i}_{exp} = \frac{B\rho(C^{i}_{exp})}{(\gamma v)^{i}_{exp}}, \qquad i = 1, 2, 3, \ldots N_t$$

$\frac{m}{q}$ spectrum





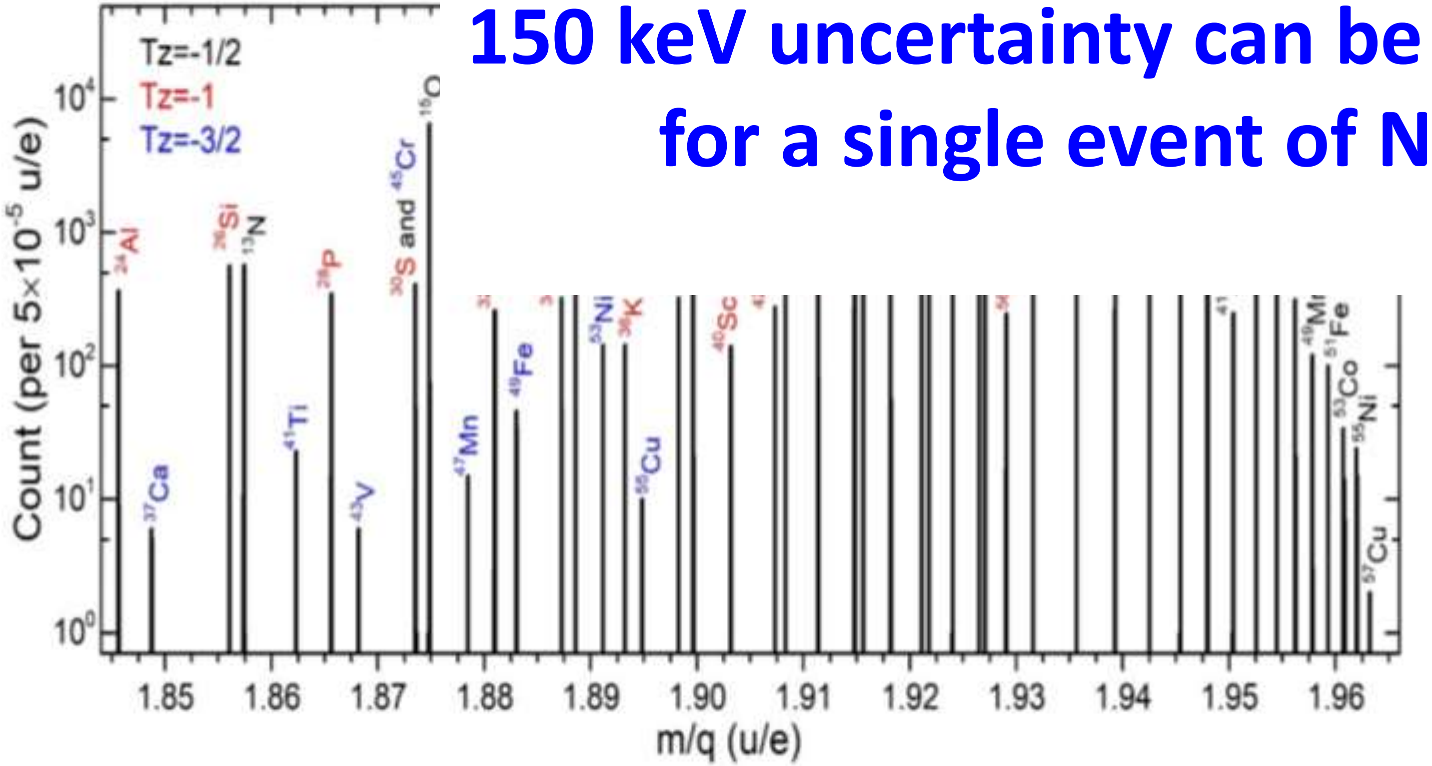


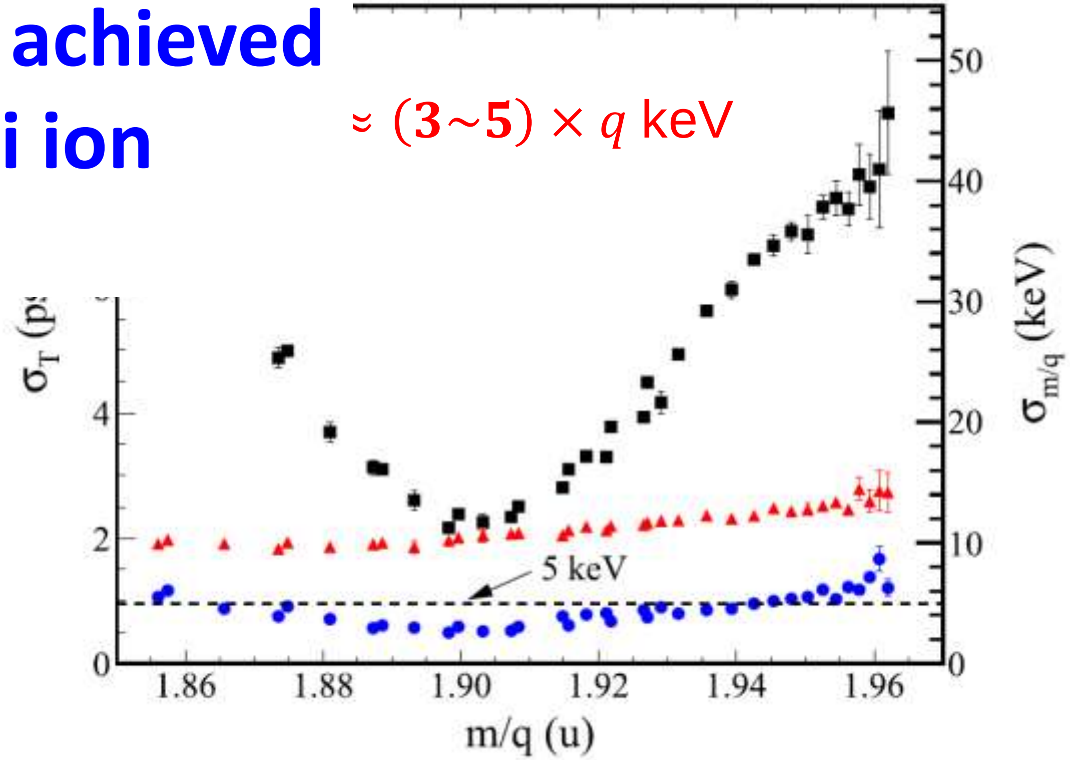
2. $B\rho$-defined isochronous mass spectrometry IMS

Mass resolving powers are significantly improved after field drift correction for all nuclides in the large *m/q*-range of $\Delta(m/q) \approx 0.10\ ue^{-1}$

^{58}Ni beam

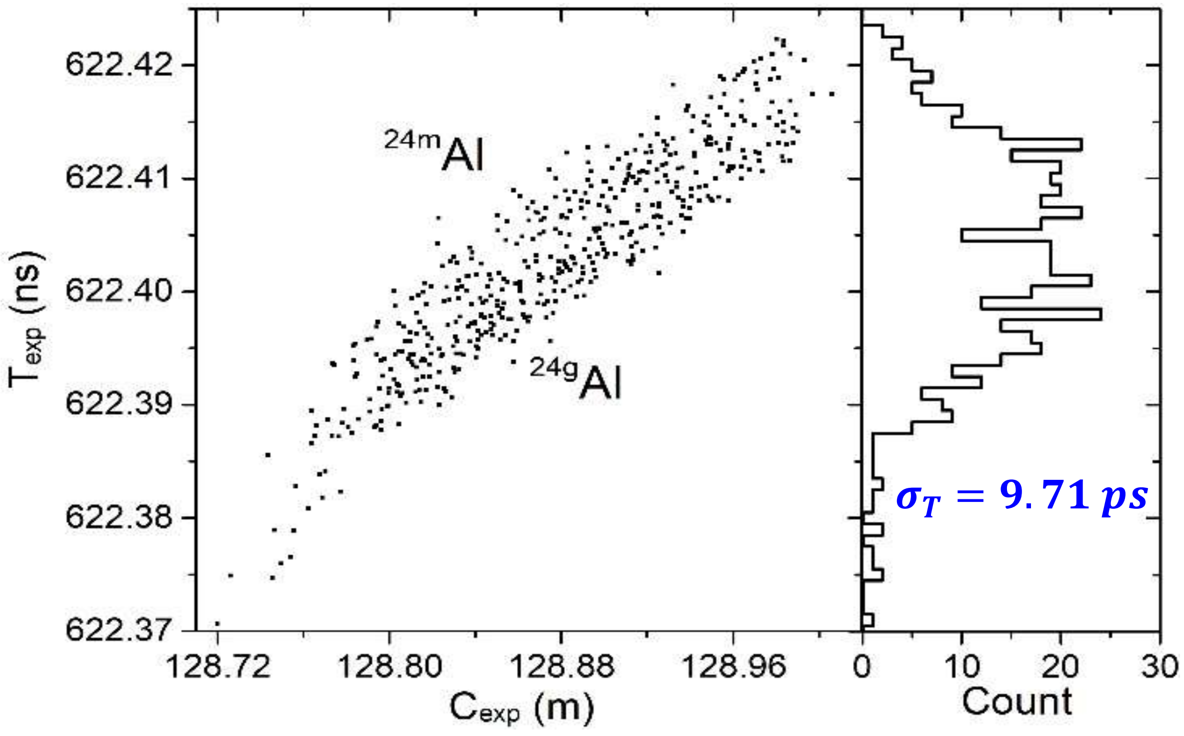
150 keV uncertainty can be achieved for a single event of Ni ion

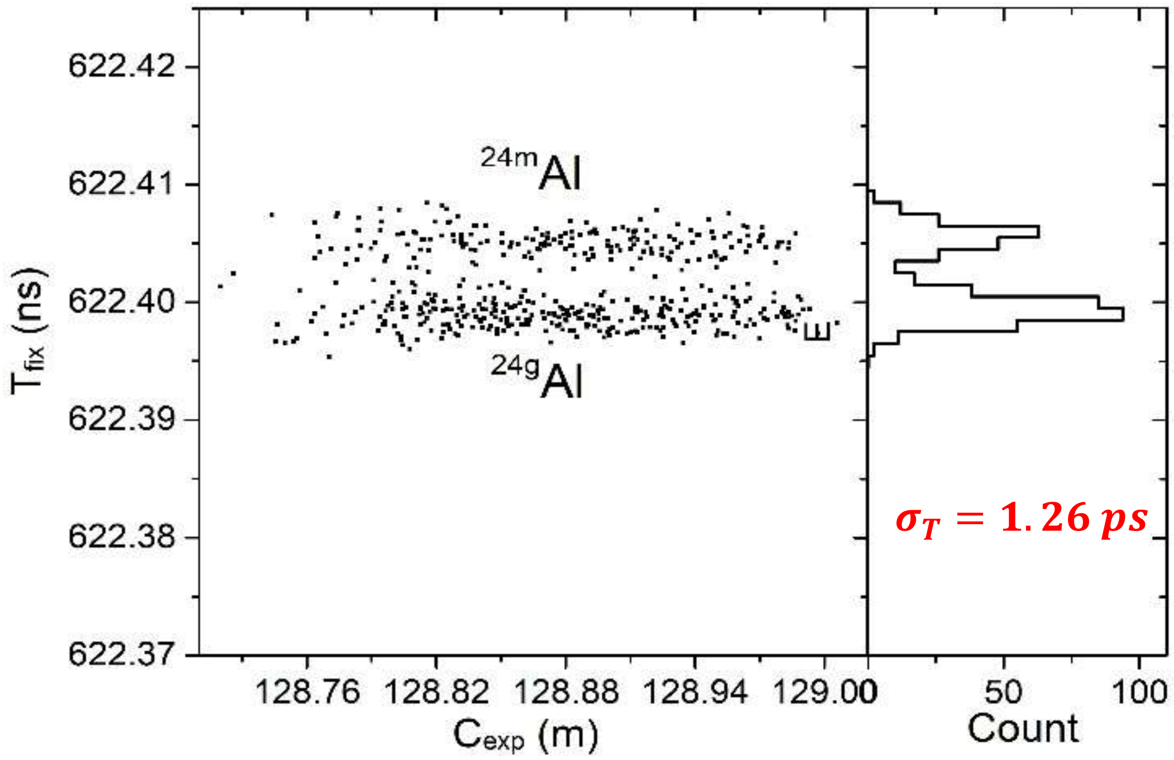




2. $B\rho$-defined isochronous mass spectrometry IMS

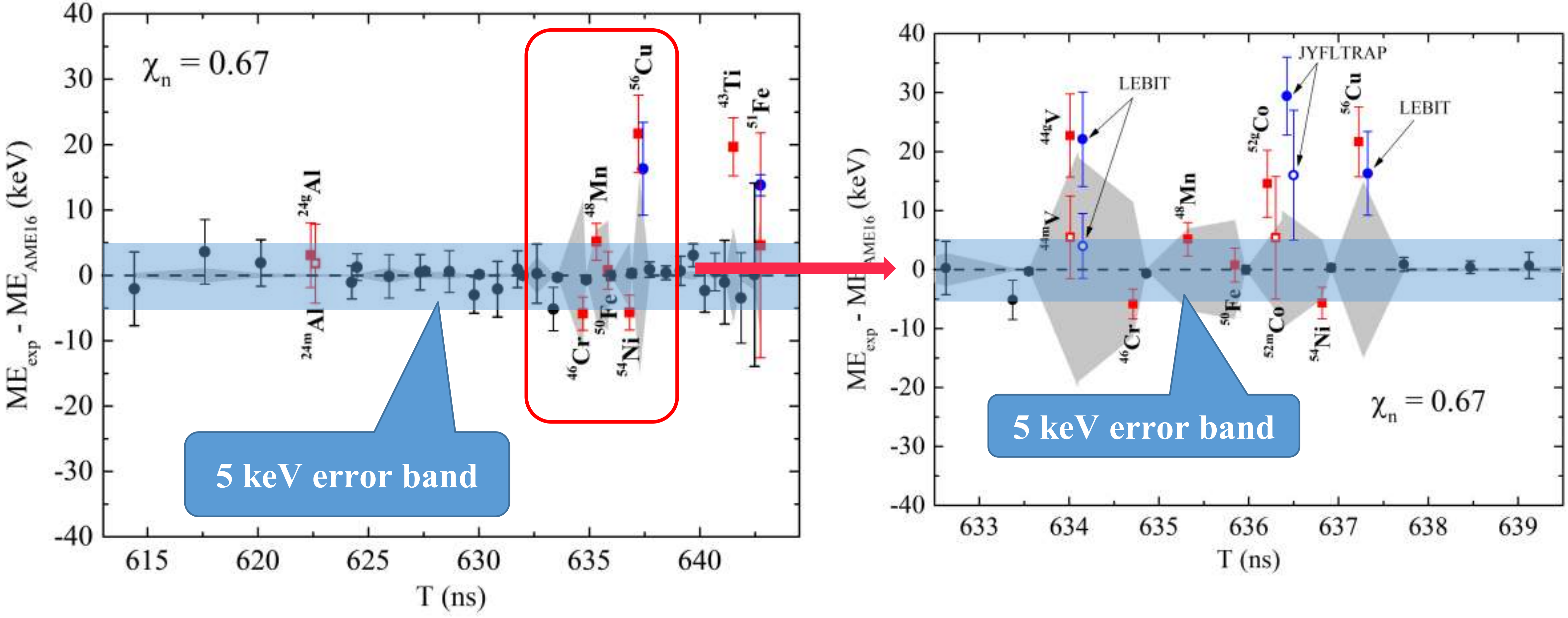
$$T_{fix}^{i} = C_{fix} \cdot \sqrt{\frac{1}{(B\rho)_{fix}^{2}} \cdot \left[\left(\frac{m}{q}\right)_{exp}^{i}\right]^{2} + \left(\frac{1}{v_c}\right)^{2}}, \qquad i = 1, 2, 3 \ \dots$$





2. $B\rho$-defined isochronous mass spectrometry IMS

Re-determined masses of $T_z = -1$ nuclei

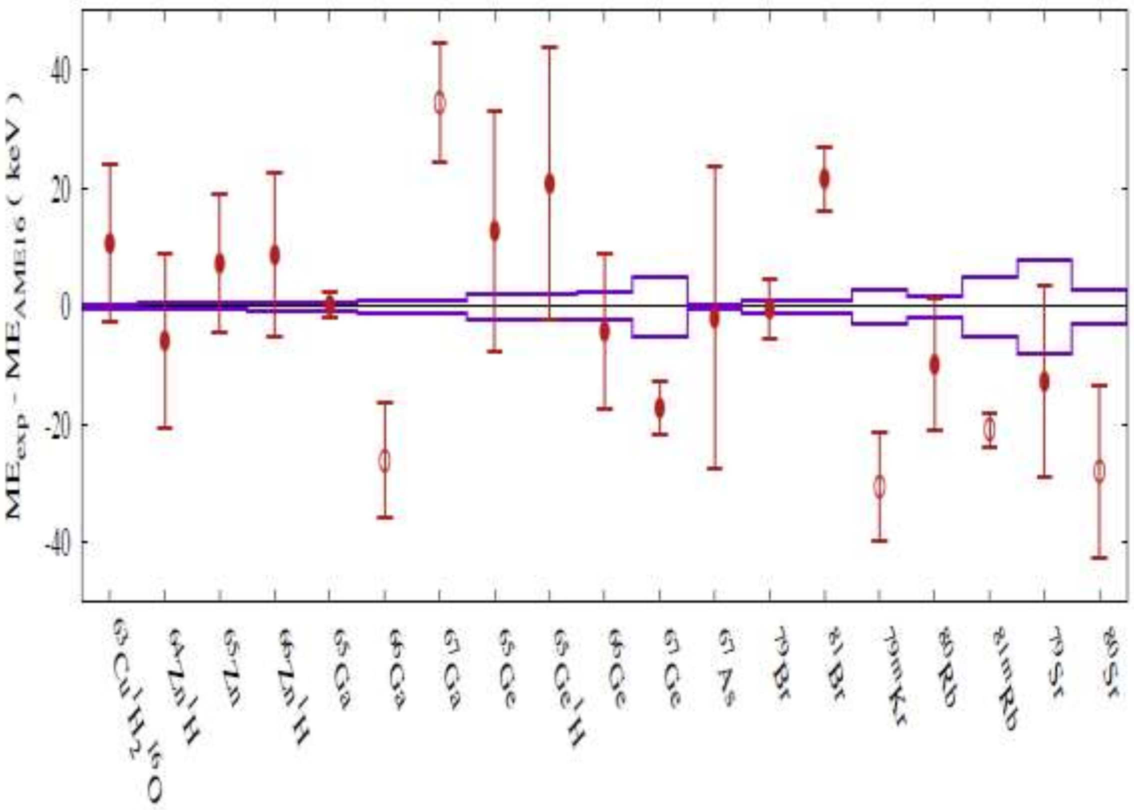


2. $B\rho$-defined isochronous mass spectrometry IMS

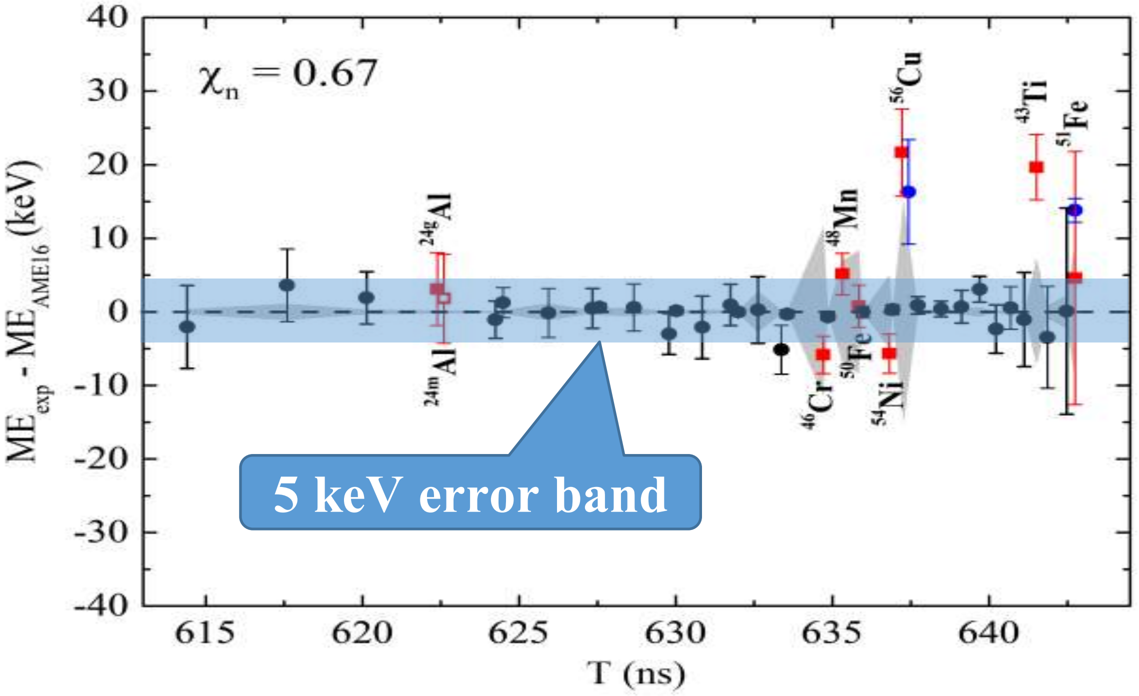
Comparison with MR-TOF-MS@RIKEN

Mass accuracy using MR-TOF-MS at RIKEN

S. Kimura et al., IJMS 430, 134(2018)



Mass accuracy using $B\rho$-IMS at IMP



Advantages of $B\rho$-defined IMS

1) Fast measurement: $t_{exp} \approx 0.1\ ms$
2) High sensitivity: $a\ single\ \ ion, \sigma_m \approx (3{\sim}5) \times q$ (keV)
3) High efficiency: $tens\ of\ ions\ in\ a\ single\ run$
4) High precision: *on par with PTMS for short-lived nuclei*
5) Zero background: *background-free measurements*

2. $B\rho$-defined isochronous mass spectrometry IMS

PHYSICAL REVIEW C **106**, L051301 (2022)

Letter

$B\rho$-defined isochronous mass spectrometry: An approach for high-precision mass measurements of short-lived nuclei

M. Wang,[1,2,*] M. Zhang,[1,2] X. Zhou,[1,2] Y. H. Zhang,[1,2,†] Yu. A. Litvinov,[1,3,‡] H. S. Xu,[1,2] R. J. Chen,[1,3] 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,[1,3] P. Shuai,[1] J. Y. Shi,[1,2] M. Si,[1,2] R. S. Sidhu,[3] Y. N. Song,[1,2] M. Z. Sun,[1] S. Suzuki,[1] Q. Wang,[1,2] Y. M. Xing,[1] X. Xu,[1] T. Yamaguchi,[4] X. L. Yan,[1] J. C. Yang,[1,2] Y. J. Yuan,[1,2] Q. Zeng,[5] and X. H. Zhou[1,2]

Eur. Phys. J. A (2023) 59:27
https://doi.org/10.1140/epja/s10050-023-00928-6

THE EUROPEAN PHYSICAL JOURNAL A

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Regular Article - Experimental Physics

$B\rho$-defined isochronous mass spectrometry and mass measurements of ^{58}Ni fragments

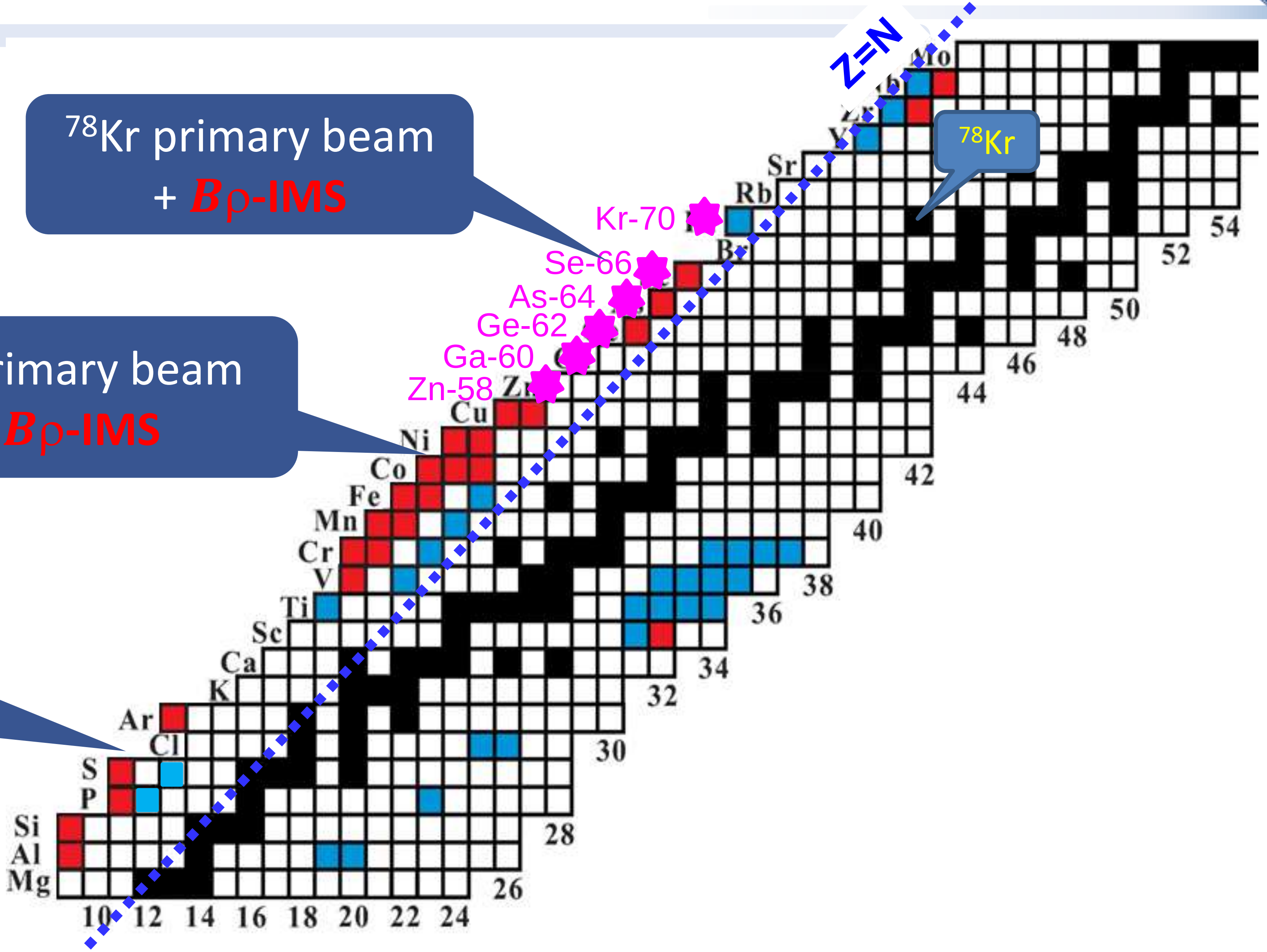
M. Zhang[1,2], X. Zhou[1,2], M. Wang[1,2,a], Y. H. Zhang[1,2,b], Yu. A. Litvinov[1,3,c], H. S. Xu[1,2], R. J. Chen[1,3], H. Y. Deng[1,2], C. Y. Fu[1], W. W. Ge[1], H. F. Li[1,2], T. Liao[1,2], S. A. Litvinov[3,1], P. Shuai[1], J. Y. Shi[1,2], R. S. Sidhu[3], Y. N. Song[1,2], M. Z. Sun[1], S. Suzuki[1], Q. Wang[1,2], Y. M. Xing[1], X. Xu[1], T. Yamaguchi[4], X. L. Yan[1], J. C. Yang[1,2], Y. J. Yuan[1,2], Q. Zeng[5], X. H. Zhou[1,2]

3. New masses from $B\rho$-IMS and it impacts on NS & NucA

^{78}Kr primary beam
+ $B\rho$-IMS

^{58}Ni primary beam
+ $B\rho$-IMS

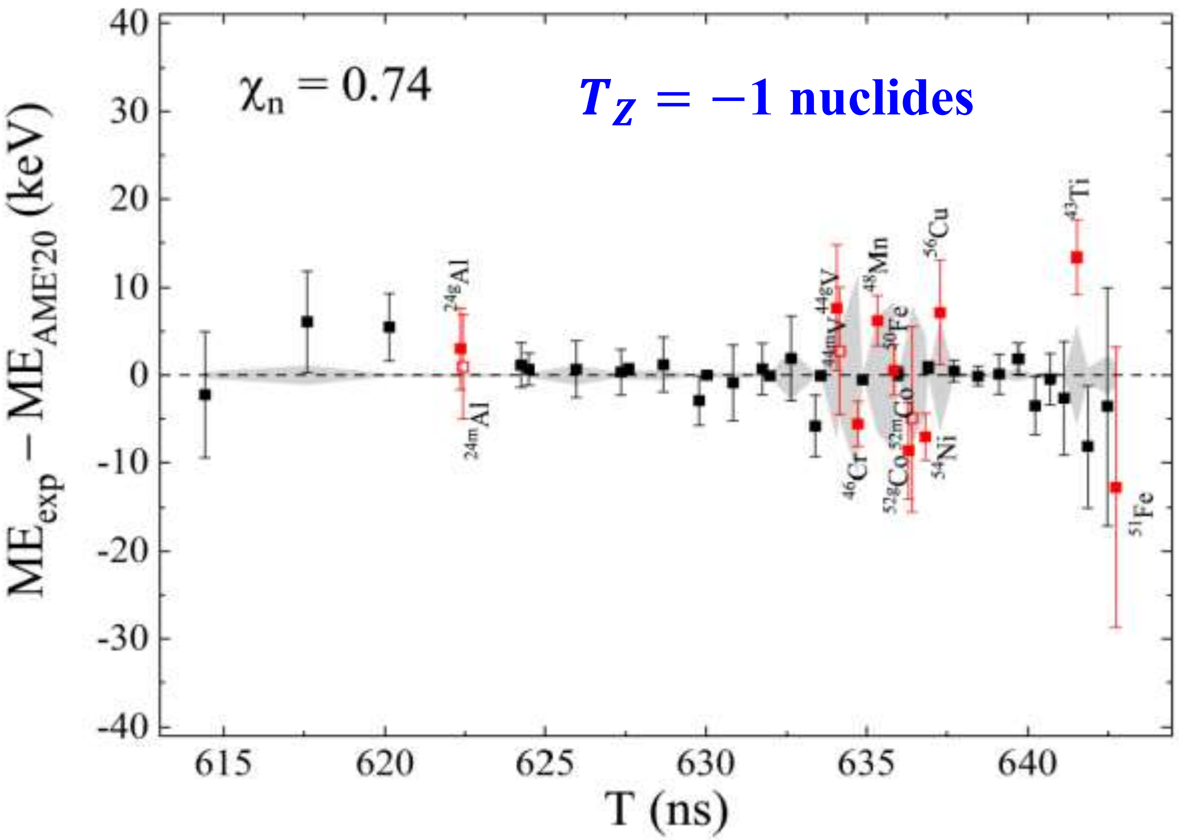
^{36}Ar primary beam
+ $B\rho$-IMS



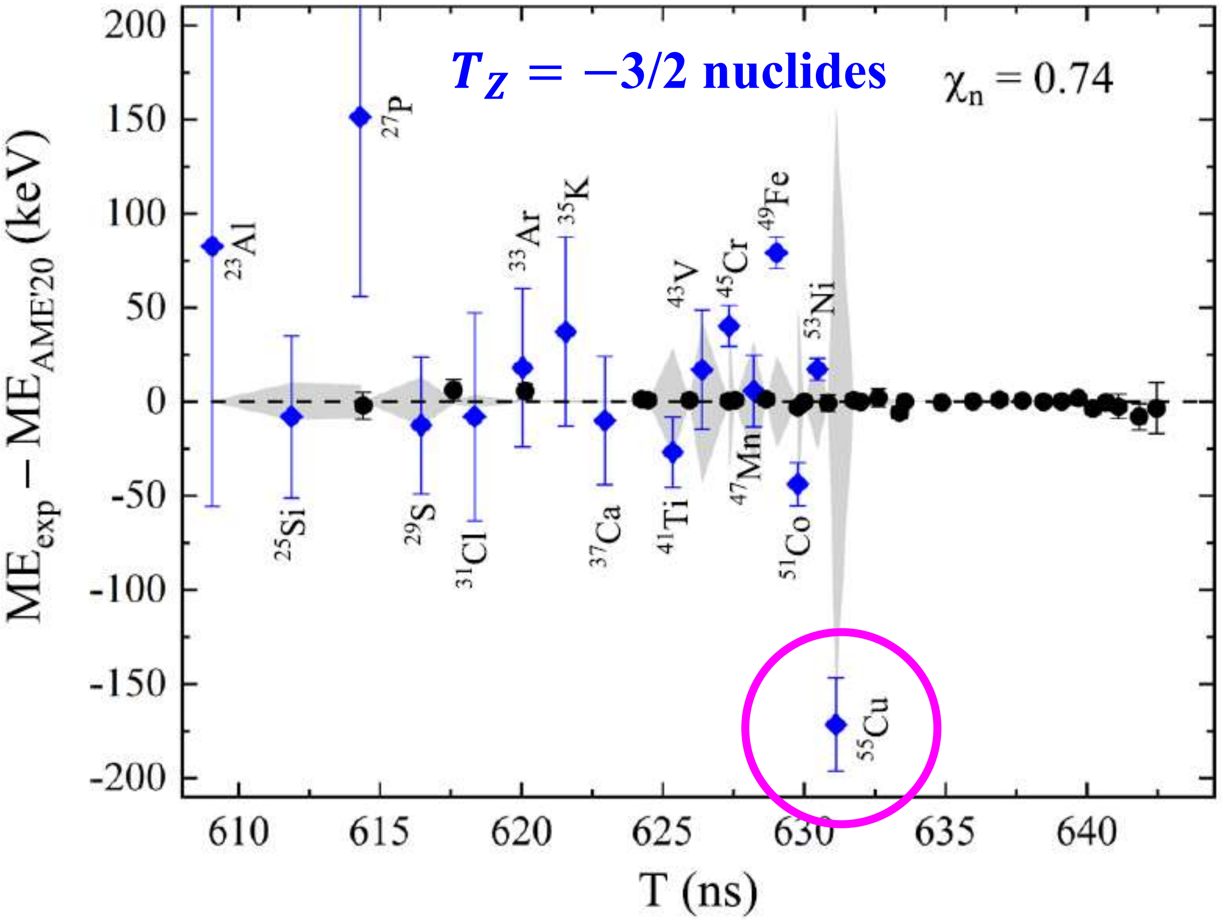
3. New masses from $B\rho$-IMS and it impacts on NS & NucA

^{58}Ni beam

M. Wang et al., PRC 106, L051301(2022)

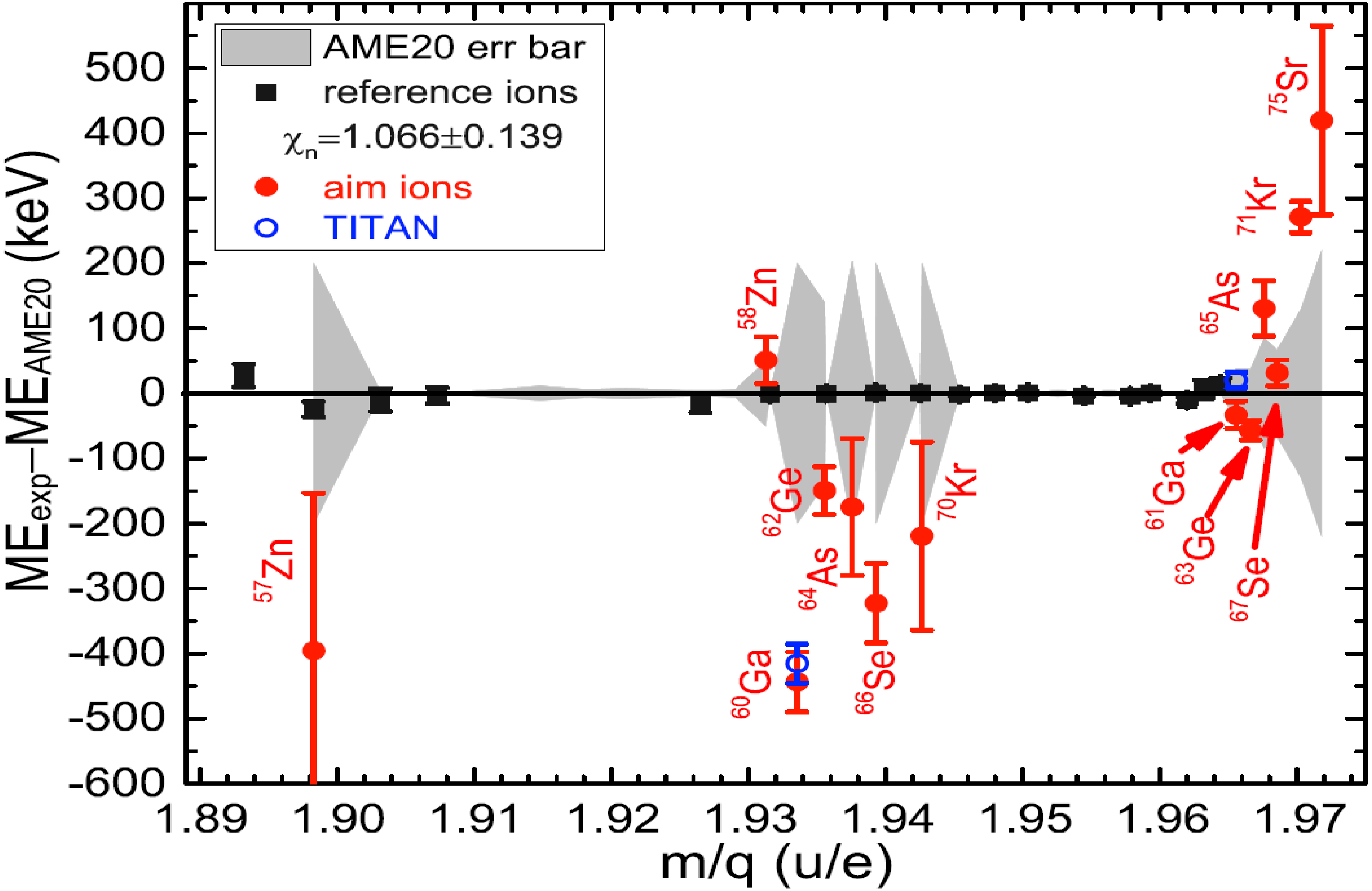


M. Zhang et al., Eur. Phys. J. A 59: 27(2023)

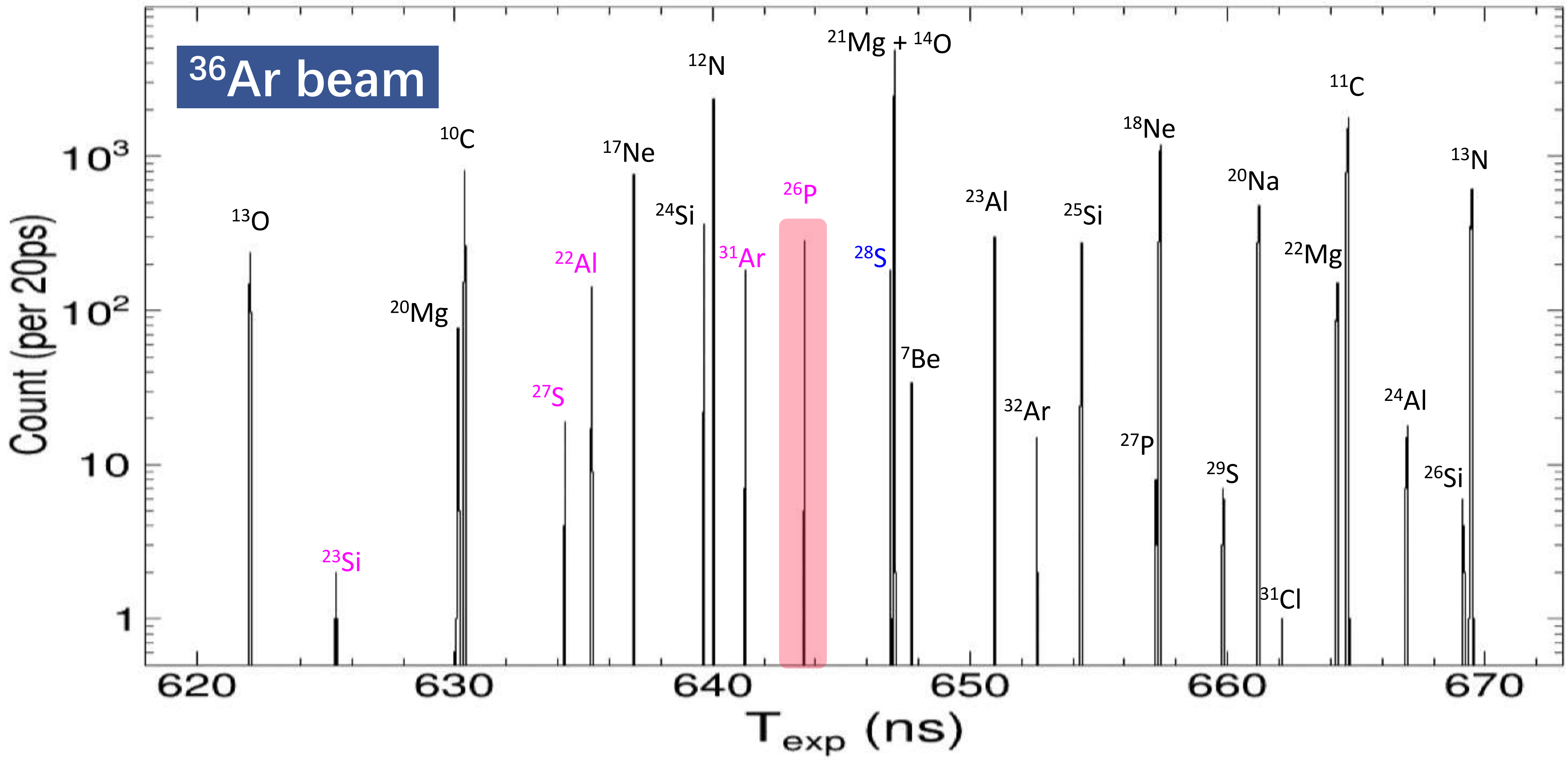


3. New masses from *B*ρ-IMS and it impacts on NS & NucA

^{78}Kr beam



3. New masses from $B\rho$-IMS and it impacts on NS & NucA



3. New masses from $B\rho$-IMS and it impacts on NS & NucA

^{36}Ar beam

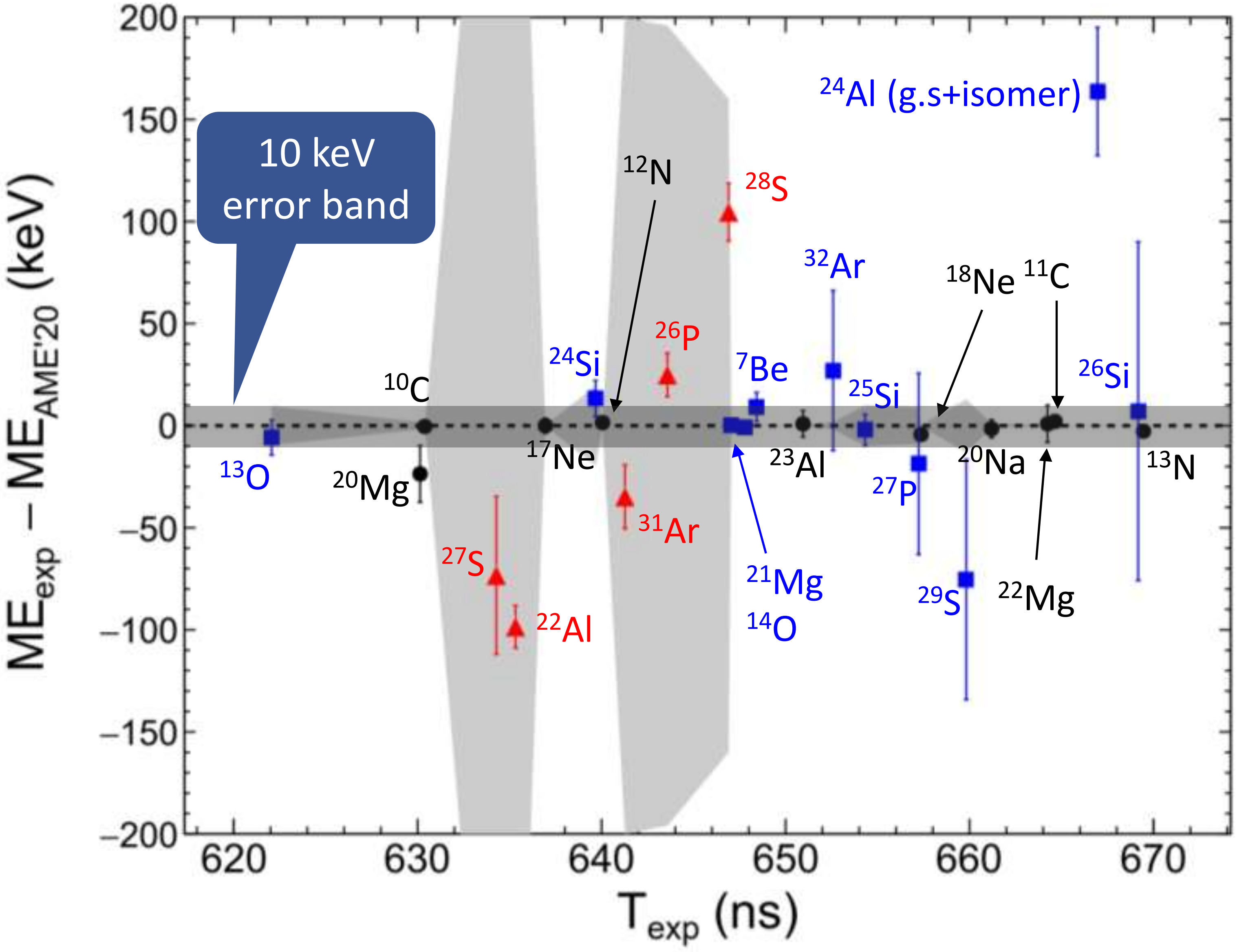
$$\chi_n = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\frac{(\bar{M}_{\exp} - M_{ame})_i^2}{(\sigma_{stat}^2 + \sigma_{fit}^2 + \sigma_{ame}^2)_i}}$$

$$\chi_n = 0.69 \pm 0.22$$

Black： reference nuclei used in calibration

Blue: re-determined masses for checking the reliability of our measurement

Red: New masses



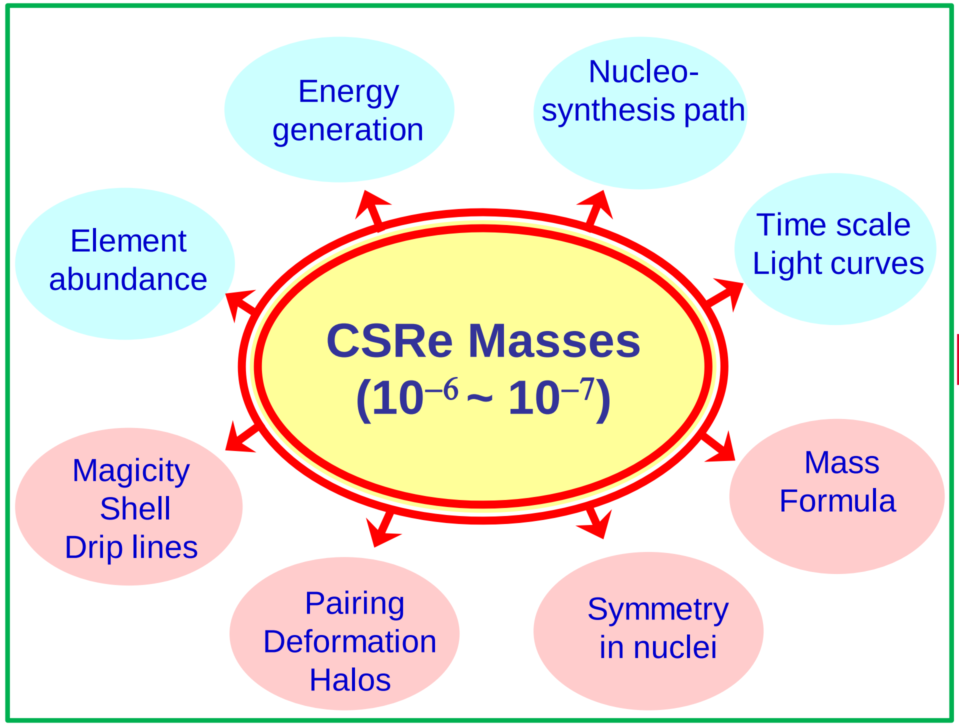
3. New masses from $B\rho$-IMS and it impacts on NS & NucA

Nuclear Astrophysics

- Waiting point ^{64}Ge
  PRL 106, 112501 (2011)
  ApJ 818, 78 (2016)
  Nature Physics, Vol. 19, 1091-1097 (2023)
- Ca-Sc cycle
  ApJLett. 766, L8 (2013)
  PRC 98 (2018) 014319
- ^{42}Ti(p,γ)^{43}V reaction rate
  PRC 89, 035802 (2014)
- Zr-Nb cycle and ^{84}Sr abundance
  PLB 781, 358 (2018)

… …

One mass → several issues



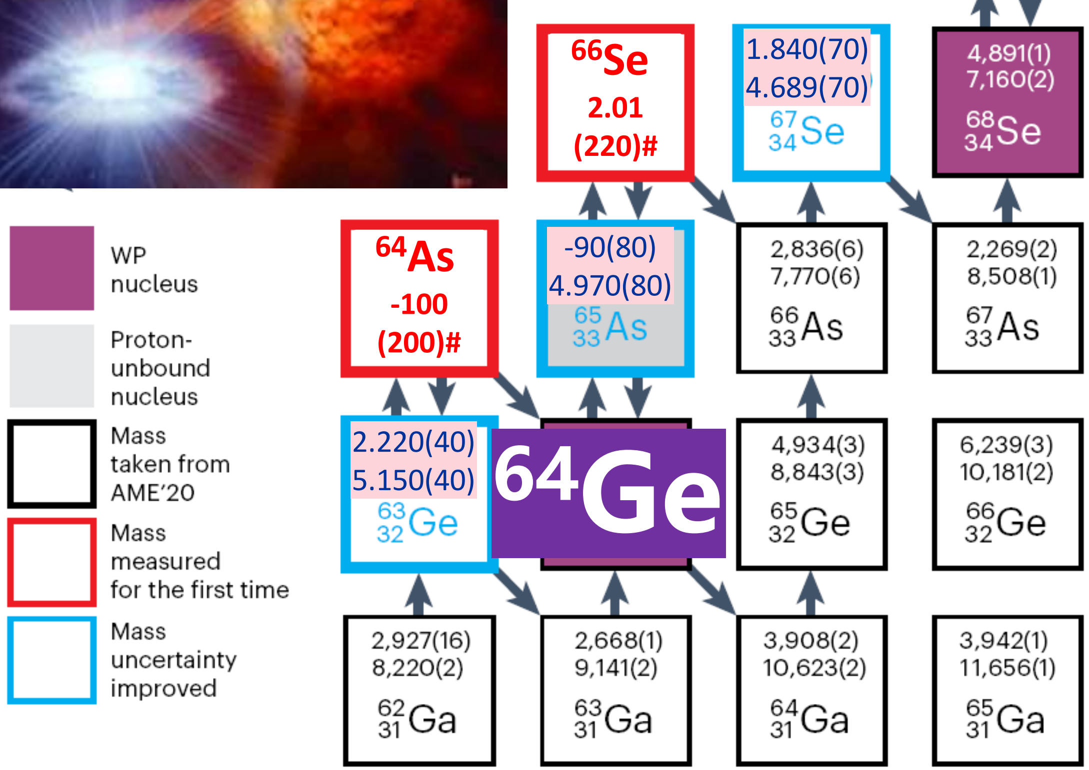
Nuclear structure

- IAS and IMME
  PRL 109, 102501 (2012)
  PRL 117, 182503 (2016)
  PRC 98, 014319 (2018)
  PRC 102, 054311 (2020)
  PRC 108, 034301 (2023)
  EPJ A 59 (2023)
- Isospin non-conserving force
  PLB 735, 327 (2014)
- Magic number and tensor force
  CPC 39, 104001 (2015)
  PRC 99, 064303 (2019)
  PRC 100, 051303(R) (2019)
- CVC test
  PLB 767, 20 (2017)
- sd-shell nucler radius
  PRC 98, 014319 (2018)
- np residual interaction & 3NF
  PRL 130, 192501 (2023)

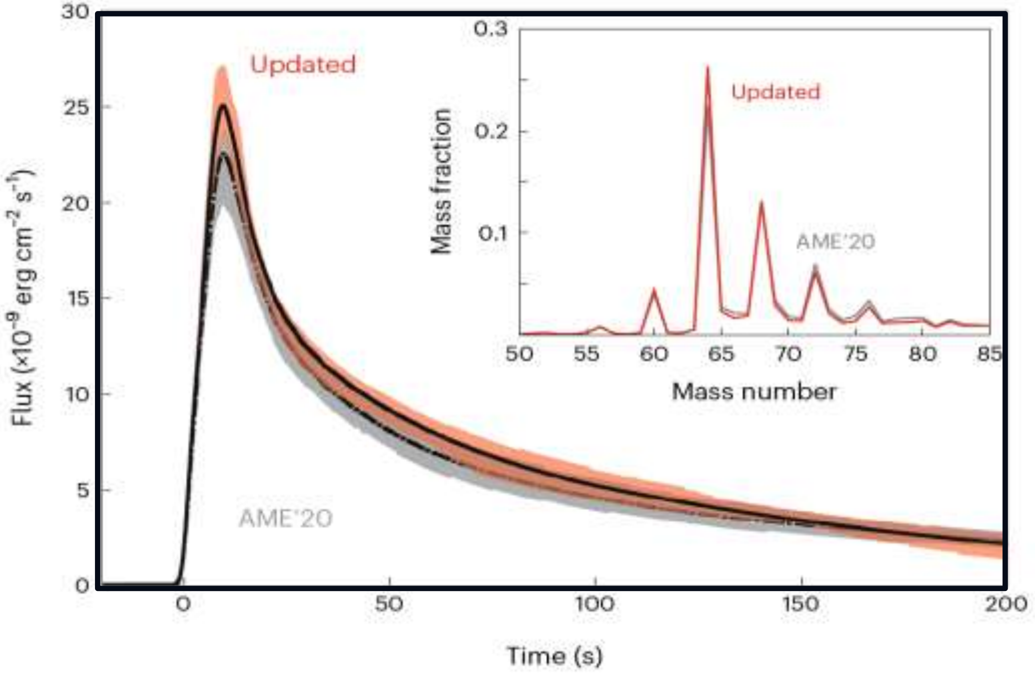
Waiting point ^{64}Ge in the rp-process of Type I X-ray bursts

All Q-values of (p,γ) reaction around ^{64}Ge obtained

less bound: ^{65}As
more bound: ^{66}Se,



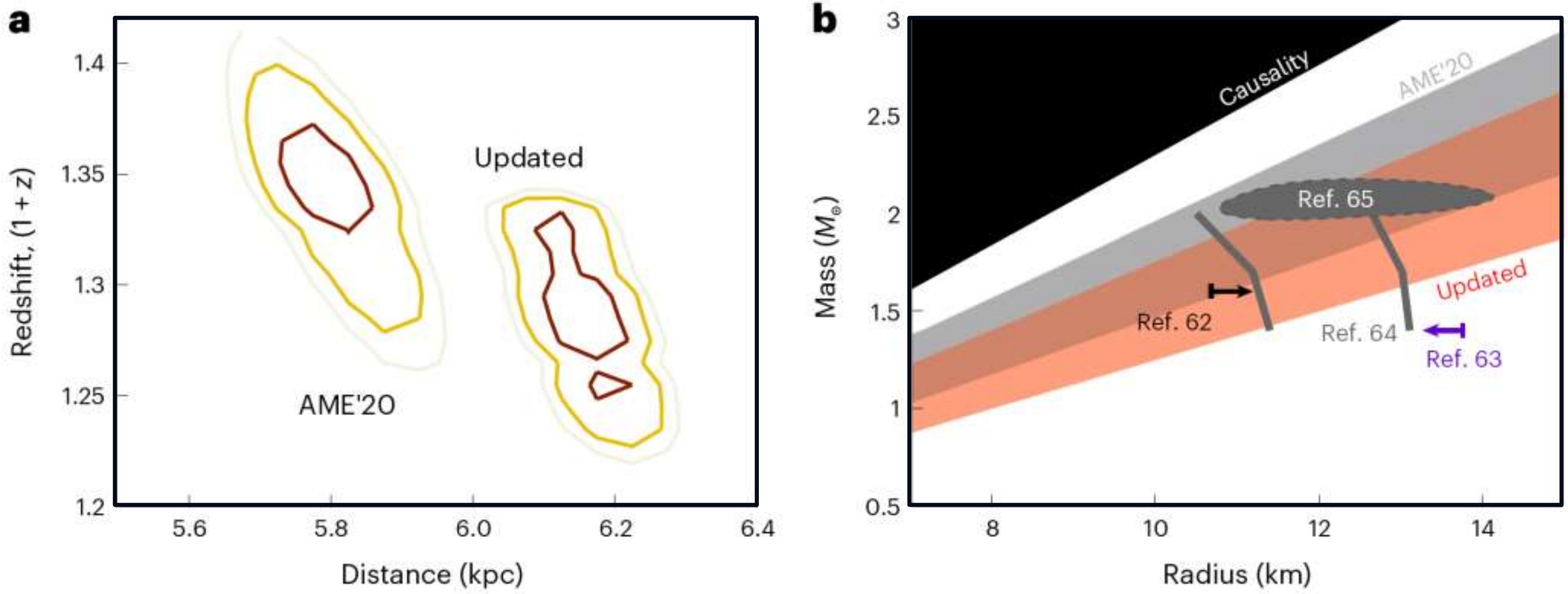
Multizone X-ray burst simulations



- peak luminosity (flux) increased
- A=64 mass fraction increased by 17%
- A=65 mass fraction decreased by 14%

Waiting point ^{64}Ge in the rp-process of Type I X-ray bursts

New light curve enables us to set new constraints on the optimal *d* and (1 + *z*) parameters



- the neutron star in GS1826-24 is 6.5% farther away (0.4 kpc=1300 ly) from us !
- reduced 1+z value indicates weaker gravitation than believed !

- mass and radius are constrained

Waiting point ^{64}Ge in the rp-process of Type I X-ray bursts

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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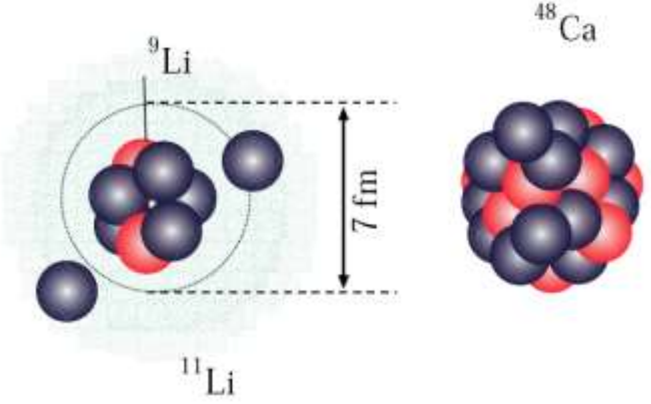
Proton-halo structures in sd-shell nuclei

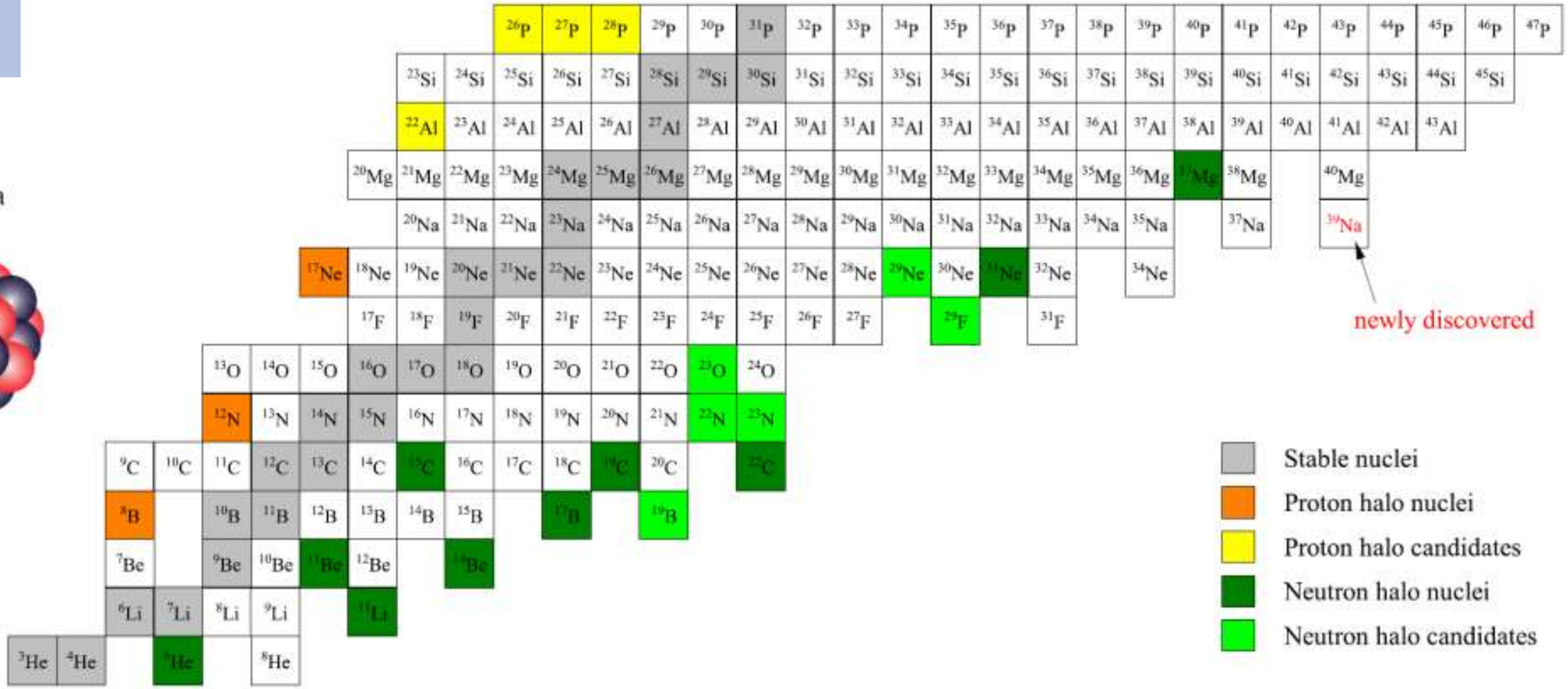
I. Tanihata et al., Prog. in Part. & Nucl. Phys. 68, 215 (2013)
K. Y. Zhang et al., Phys. Rev. C 107, L041303 (2023)

Discovered
by Tanihata in 1985

Halo nuclei

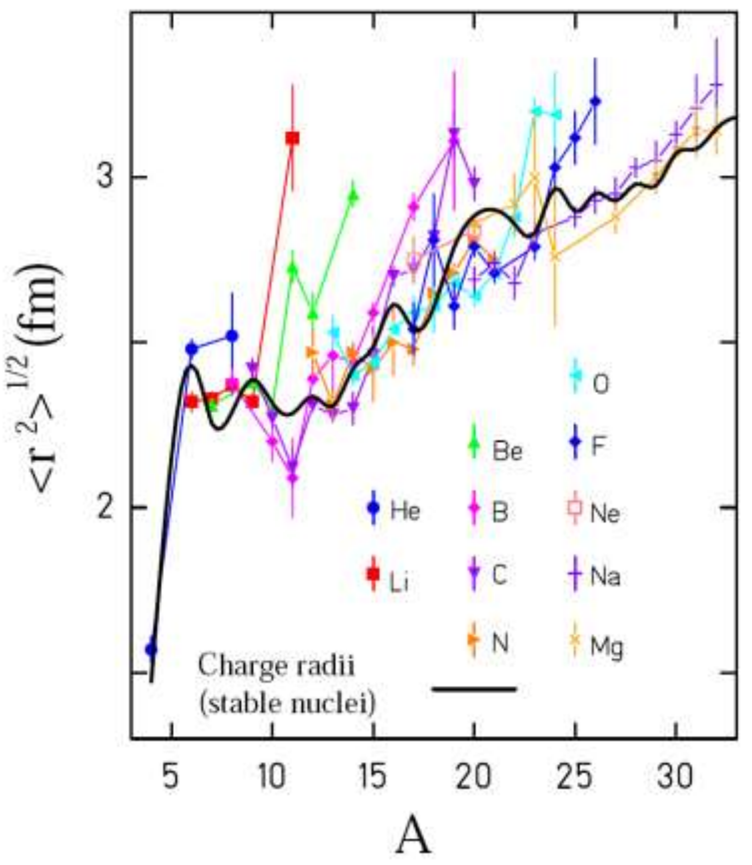


$$R \approx r_0 A^{1/3}$$



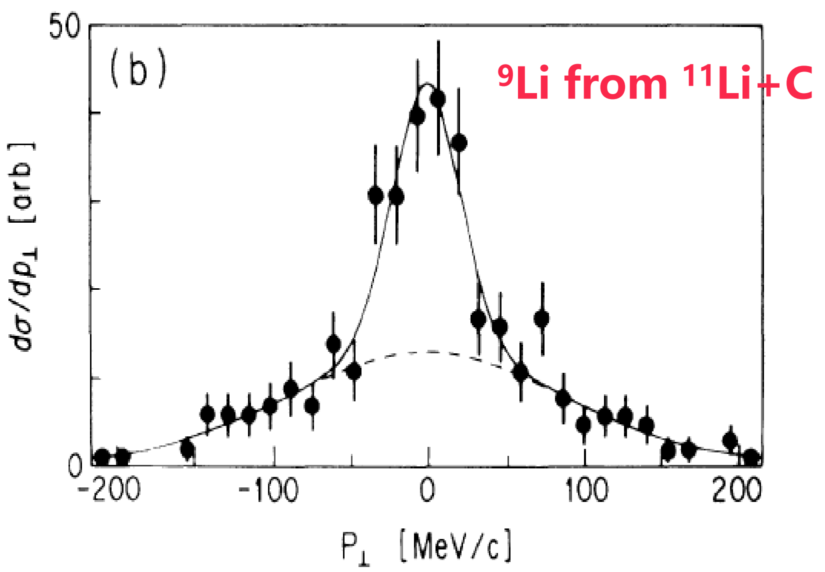
Proton-halo structures in sd-shell nuclei

Matter radii



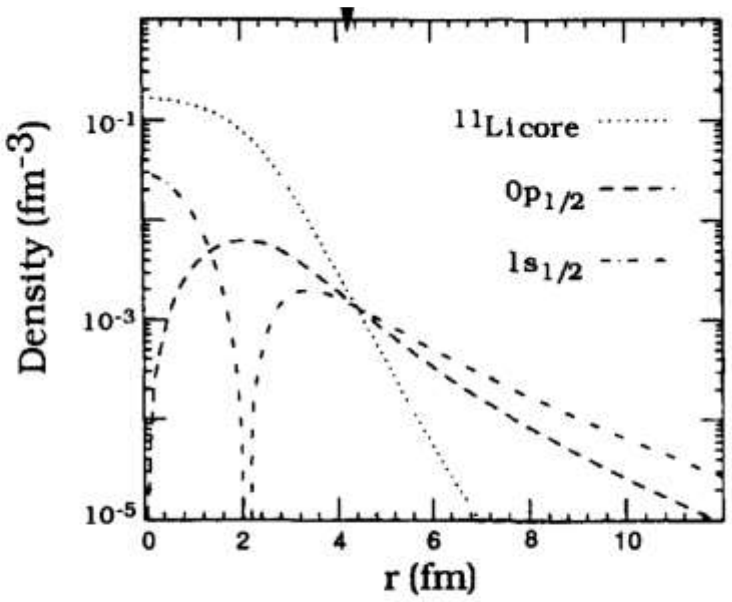
momentum distribution

T. Kobayashi el al., PRL 60 (1988) 2599



Density distribution

B. Jonson,
Nuclear Physics A574 (1994) 151c-166



It is treated as confirmed by observations of
(1) enhancement of the cross section, and
(2) narrow momentum distribution

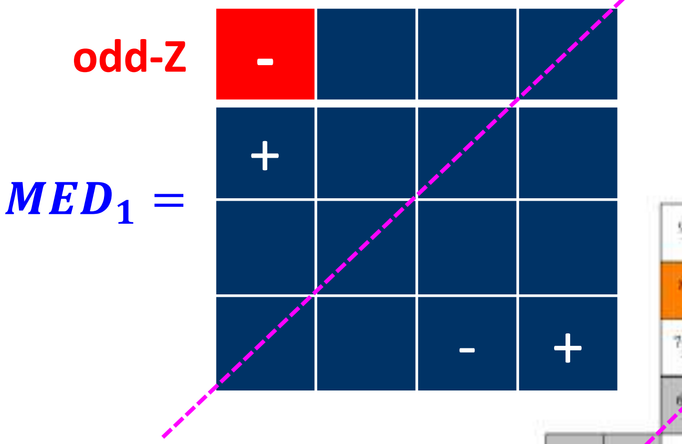
Proton-halo structures in sd-shell nuclei

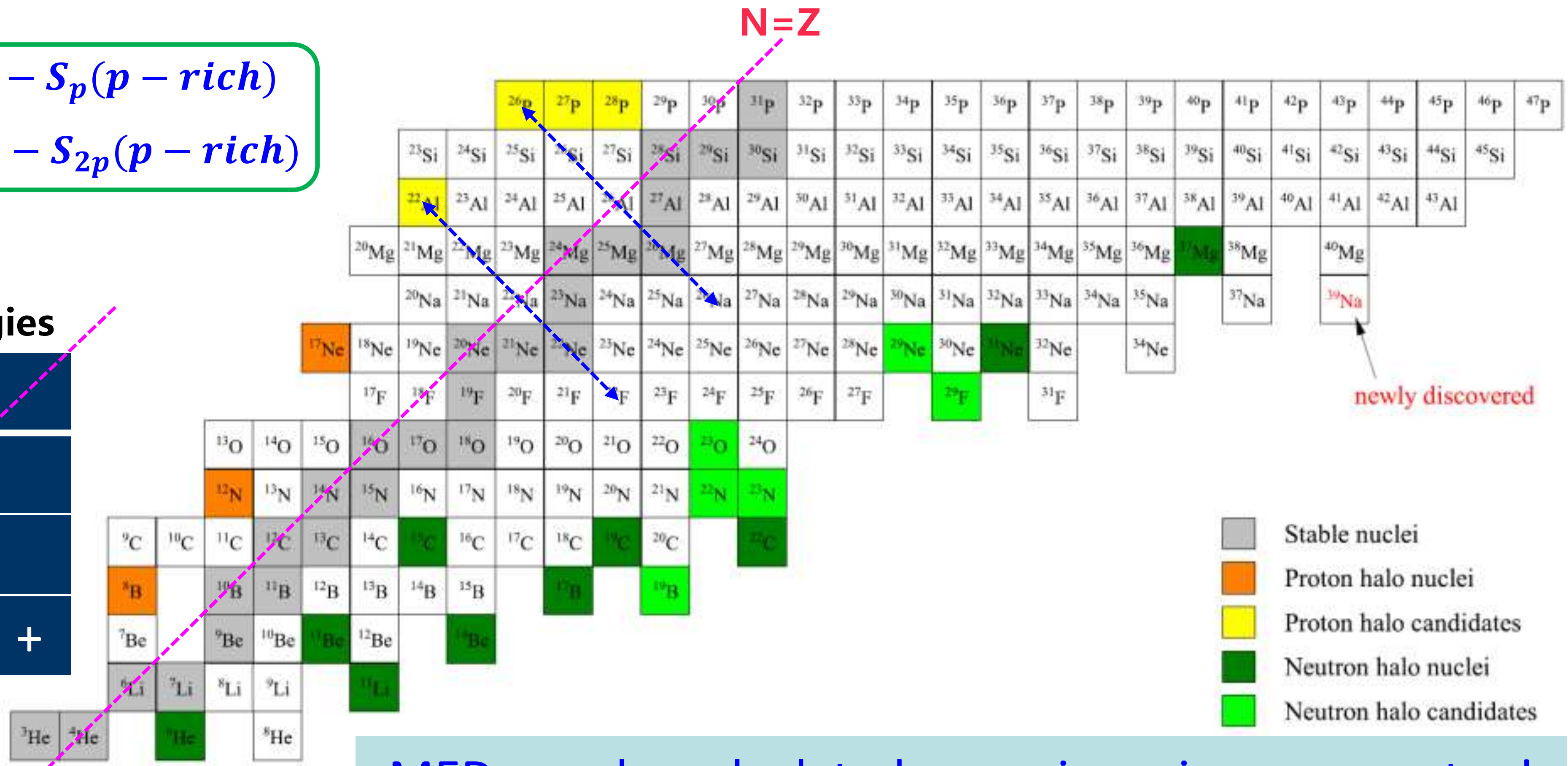
New indicator of proton-halo structures from mirror energy differences (MEDs)

$$MED_1 = S_n(n-rich) - S_p(p-rich)$$

$$MED_2 = S_{2n}(n-rich) - S_{2p}(p-rich)$$

Binding energies



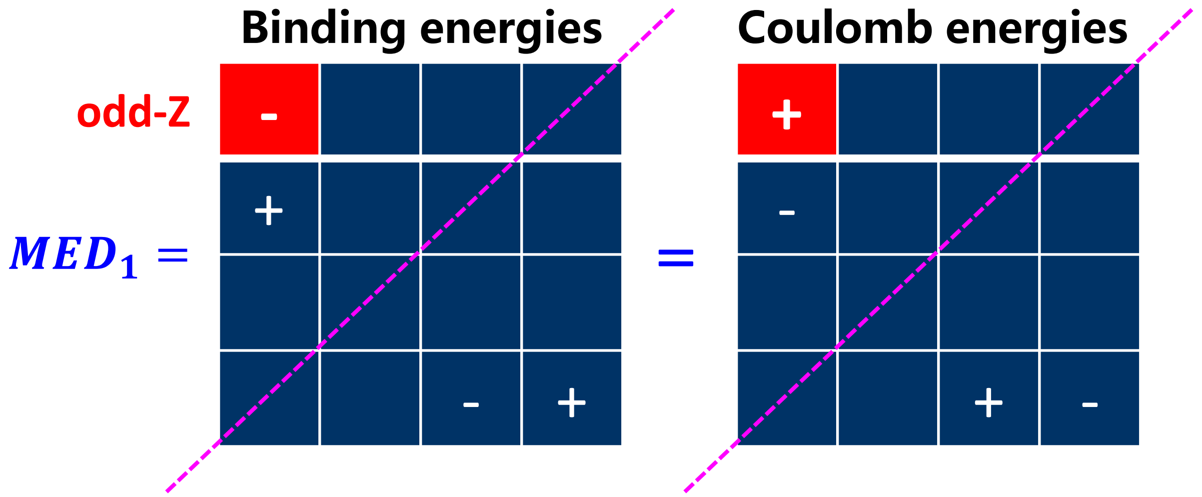


MEDs can be calculated assuming mirror symmetry !

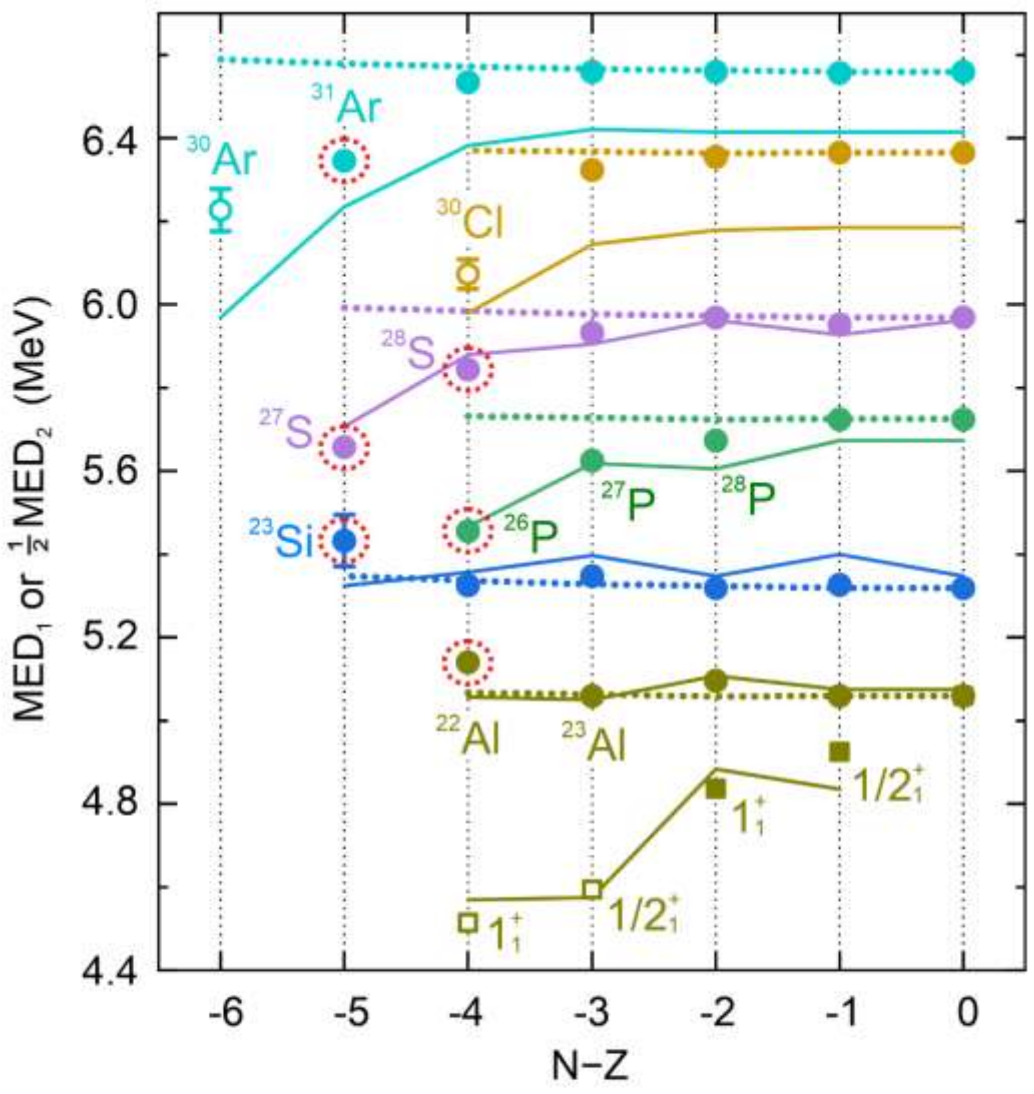
Proton-halo structures in sd-shell nuclei

J. Jänecke, Phys. Rev. 147, 735 (1966)

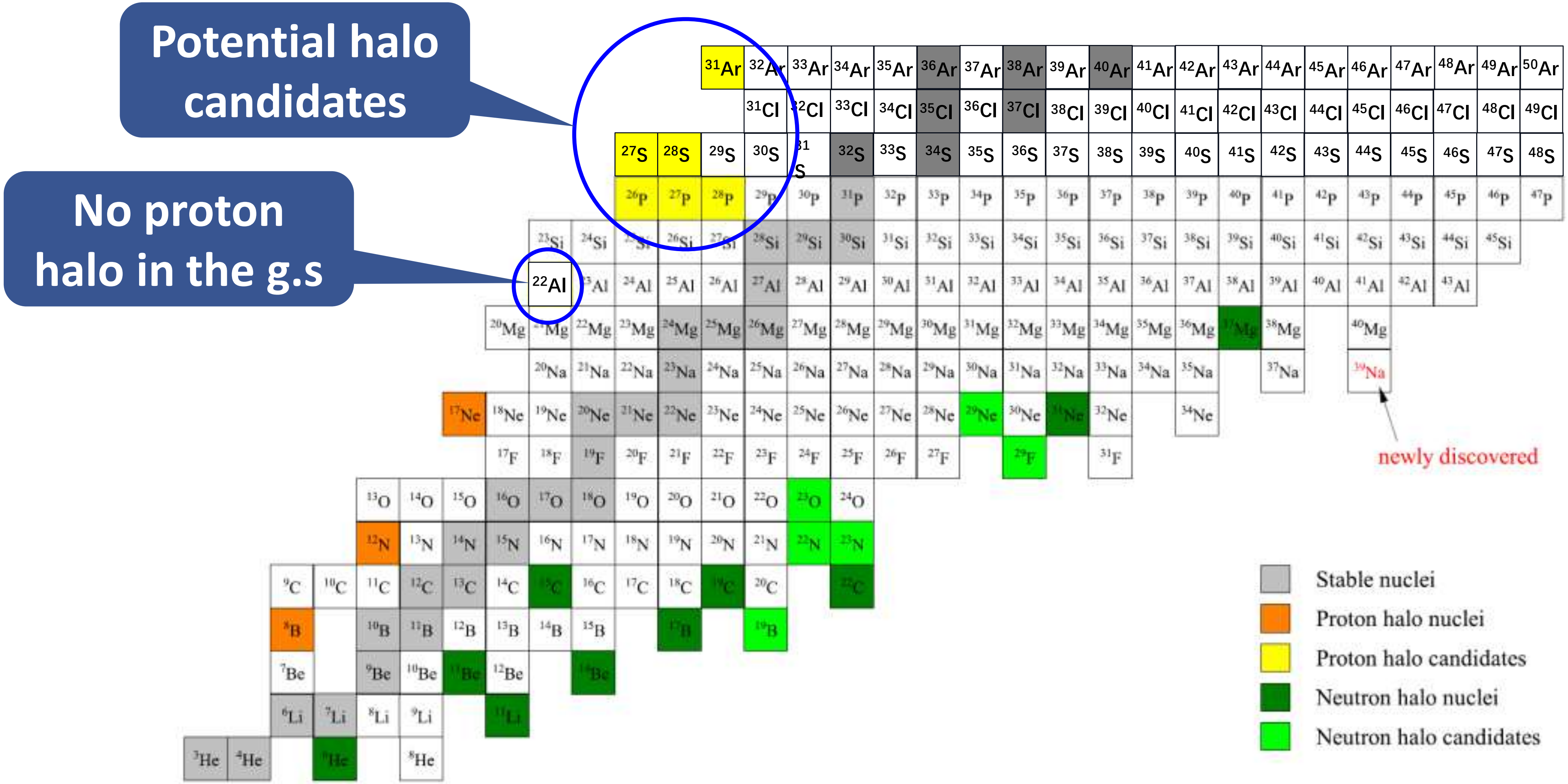
$$M(A,T,T_z) = M_0(A,T) + E_c(A,T,T_z) + T_z\Delta m_{n-H}$$



$$E_c = \{0.6Z^2 - 0.46Z^{4/3} - 0.15[1-(-1)^Z]\}\frac{e^2}{R_{eq}}$$



Proton-halo structures in sd-shell nuclei



Proton-halo structures in sd-shell nuclei

Submitted to Physical Review Letters

Nuclear structure of dripline nuclei elucidated through precision mass measurements of ^{23}Si, ^{26}P, ^{27,28}S, and ^{31}Ar

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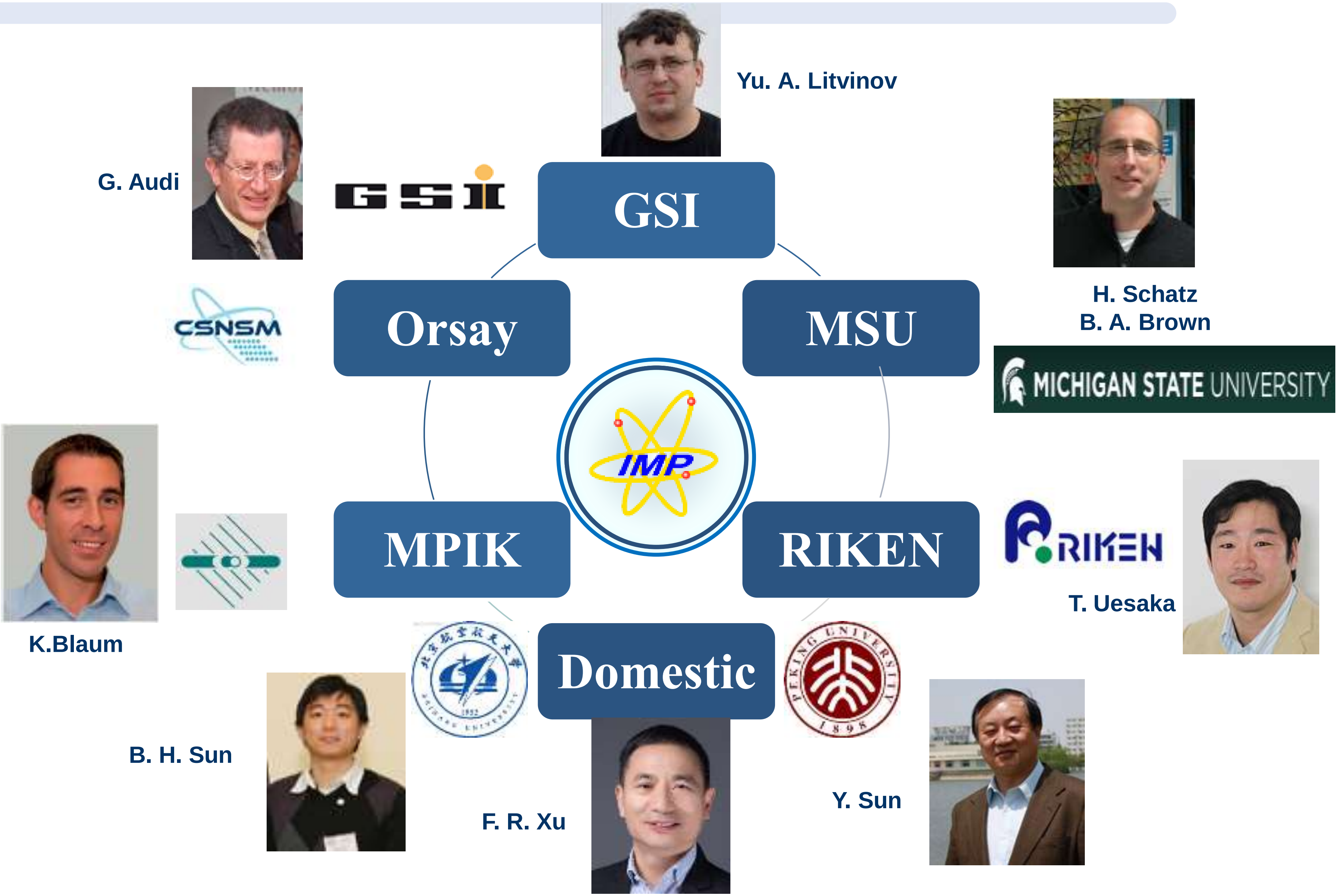
(Dated: September 14, 2024)

4. Summary and perspectives

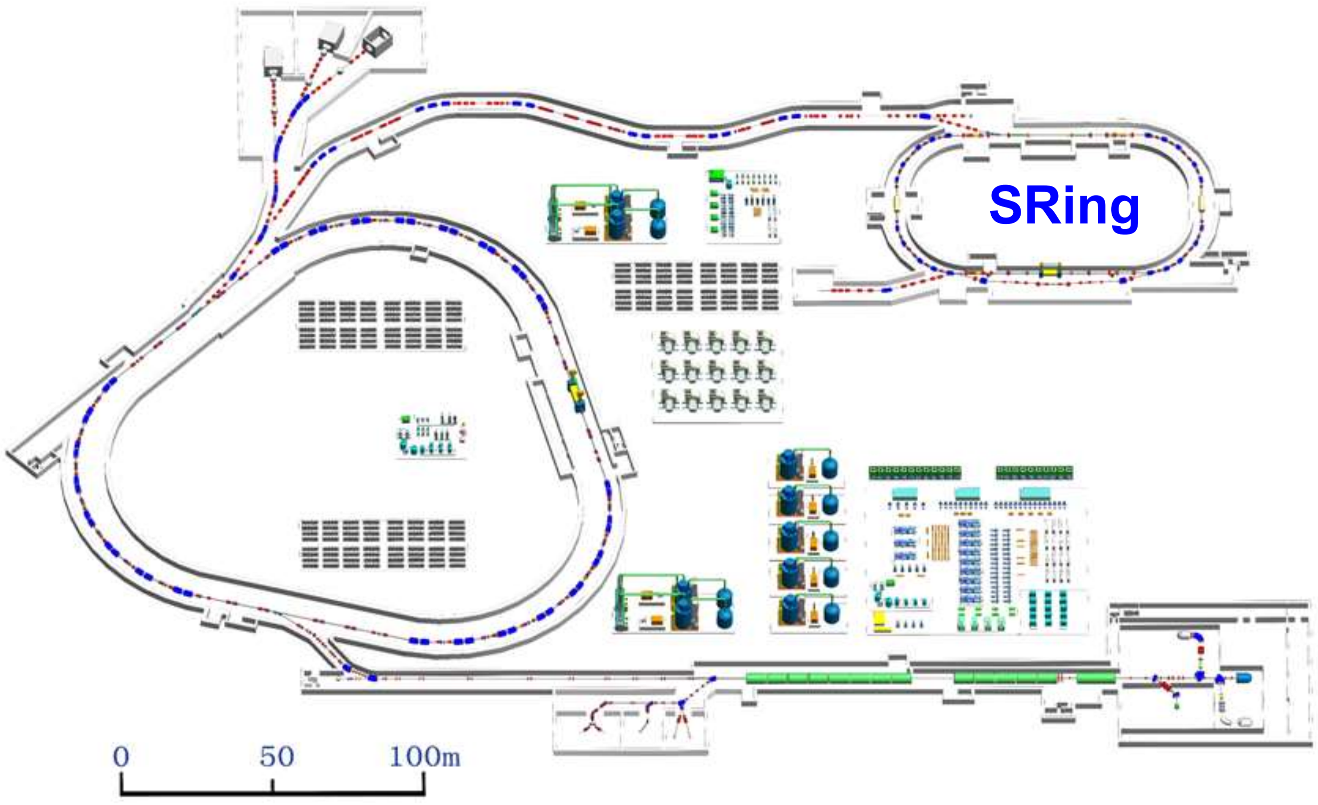
1. $B\rho$-defined IMS has been established in CSRe which shows several advantages in mass measurement of short-lived nuclei.
2. Masses of ^{78}Kr, ^{58}Ni, ^{36}Ar fragments have been measured, enabling to address several issues in nuclear structure and nuclear astrophysics.
3. $B\rho$-defined IMS will be installed in the SRing of HIAF facility and the masses of heavy and n-rich exotic nuclei will be addressed in future.
4. We need close collaborations both in experiment and in theory

CSRe mass measurement collaboration



4. Summary and perspectives

High Intensity Accelerator Facility (HIAF)



Plan to be commissioned at the end of 2026

High-Intensity Heavy Ion Accelerator Facility-HIAF

HIAF is one of the major national science and technology infrastructure under construction with the support of both central and local governments

The project is proposed and constructed by IMP, CAS

The total budget is 3.0 billion CNY

The construction of project started at the end 2018, and the period is 7 years

Courtesy of Jiancheng Yang


Let’s cross the bridge and collaborate !
Many thanks for your attention