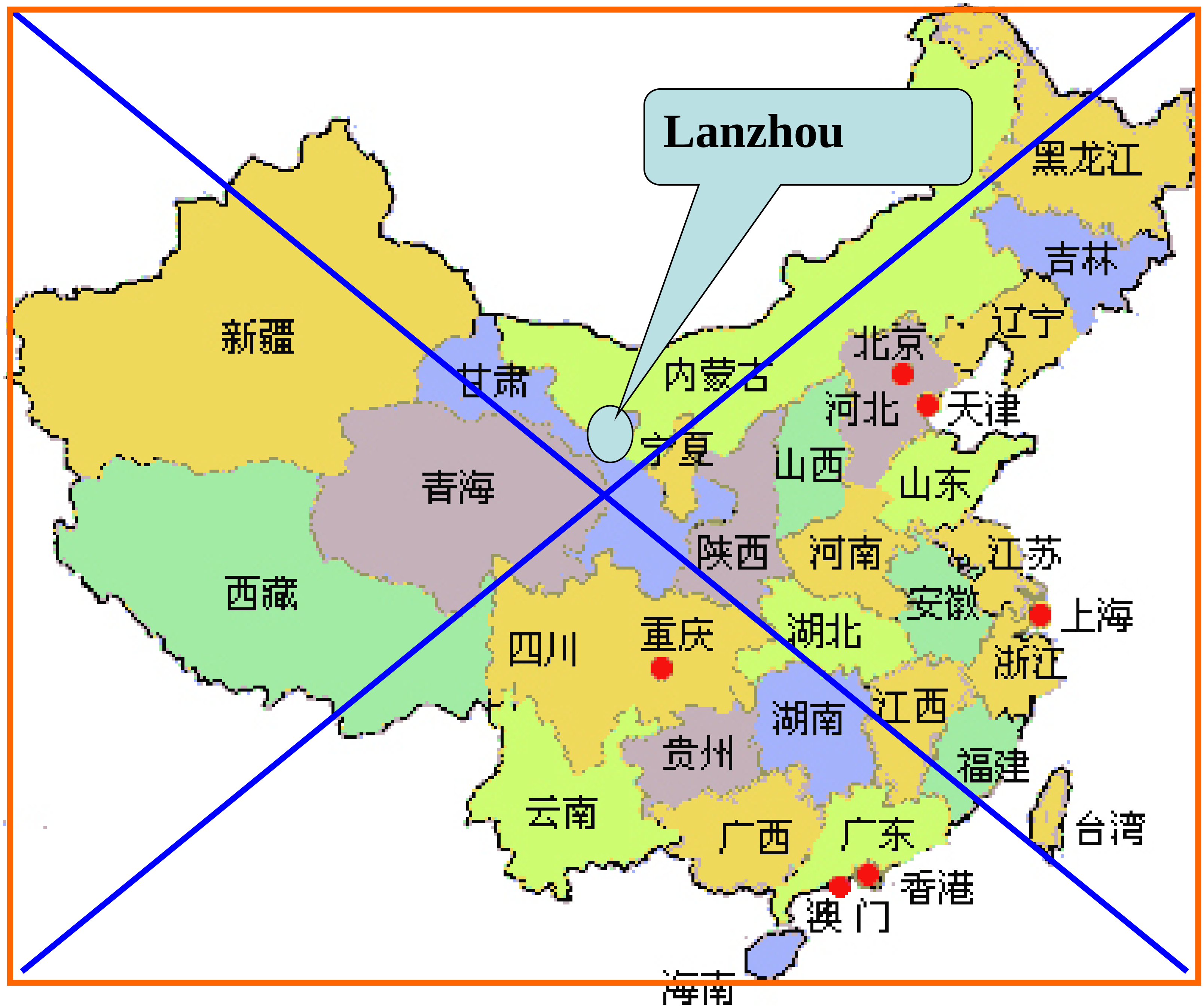
Progress of mass measurements of short-lived nuclides at the heavy-ion storage ring in Lanzhou

Yu-Hu Zhang & CSRe mass measurement collaboration

CAS Key Laboratory of High Precision Nuclear Spectroscopy
Institute of Modern Physics, Chinese Academy, of Sciences
Lanzhou 730000, China

3 through 5 April in Daejeon, Korea


Lanzhou
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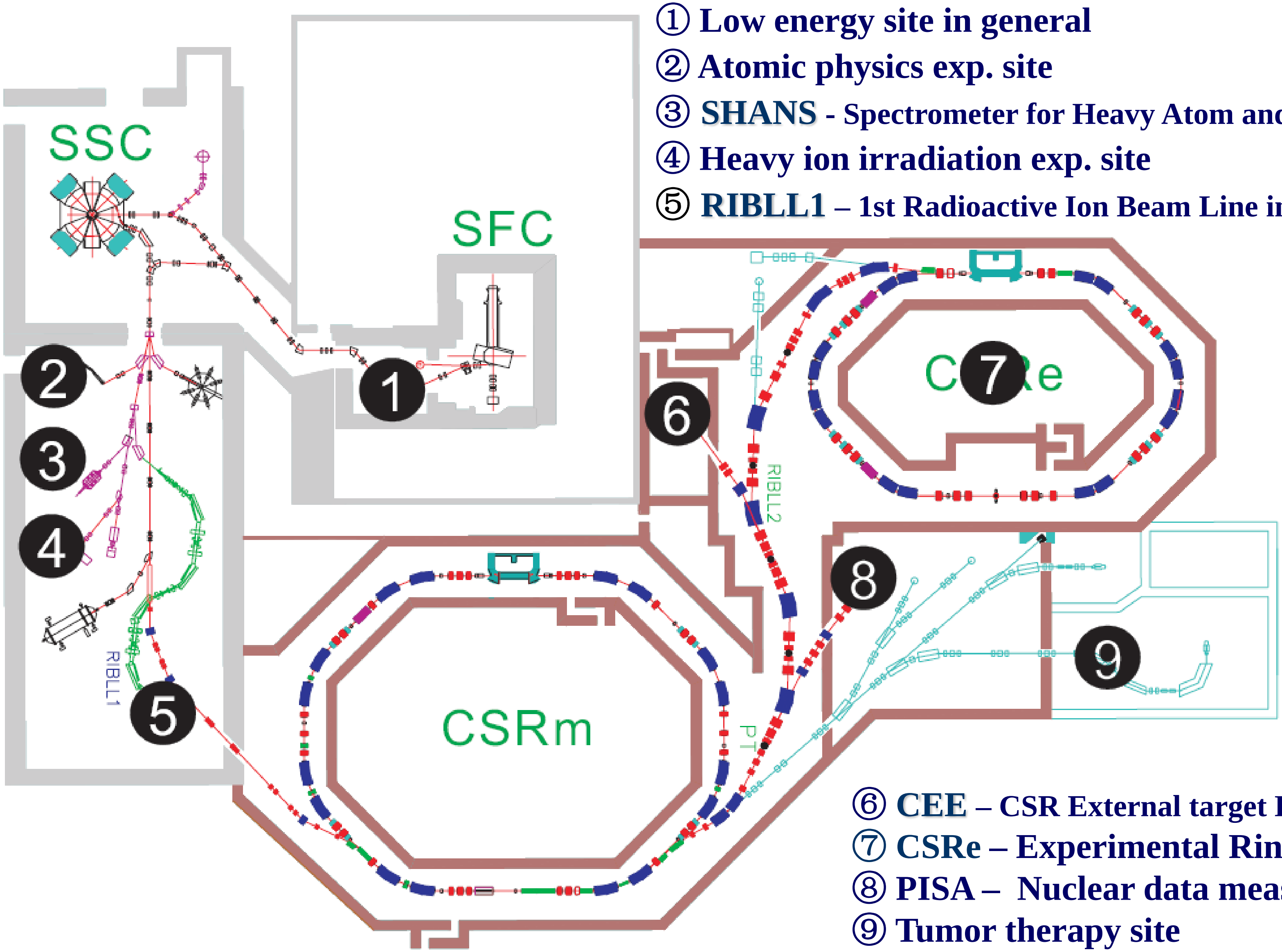
海南

Institute of Modern Physics, CAS

Layout of experimental terminals at HIRFL

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

Outline

1 Introduction to mass measurements in CSRe

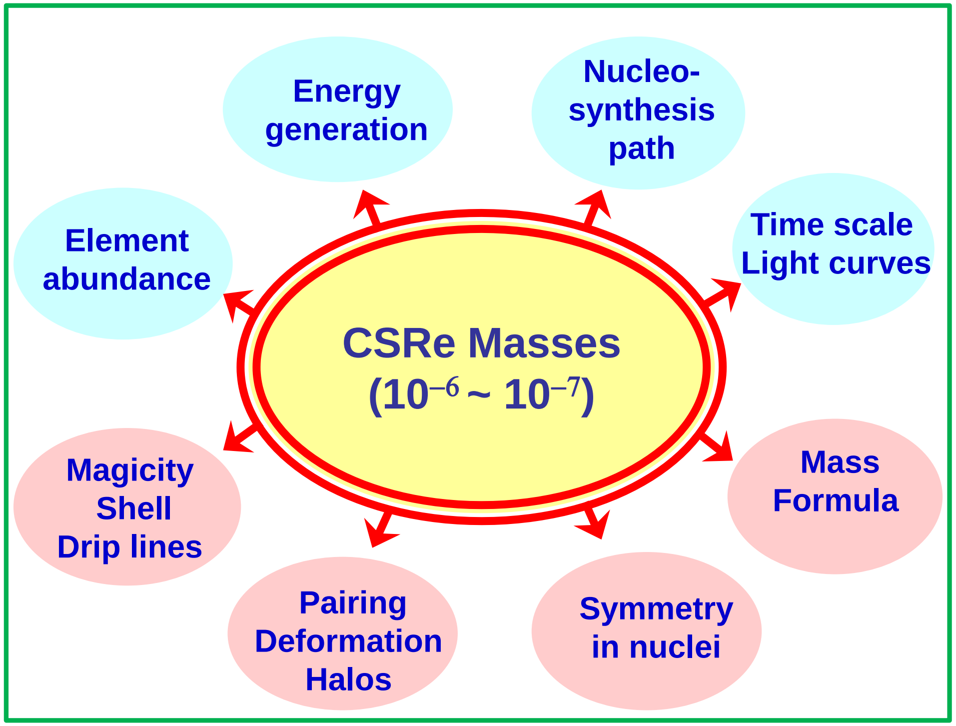
2 Some issues in nuclear astrophysics and NS

3 Summary & perspectives

1. Introduction to mass measurements in CSRe

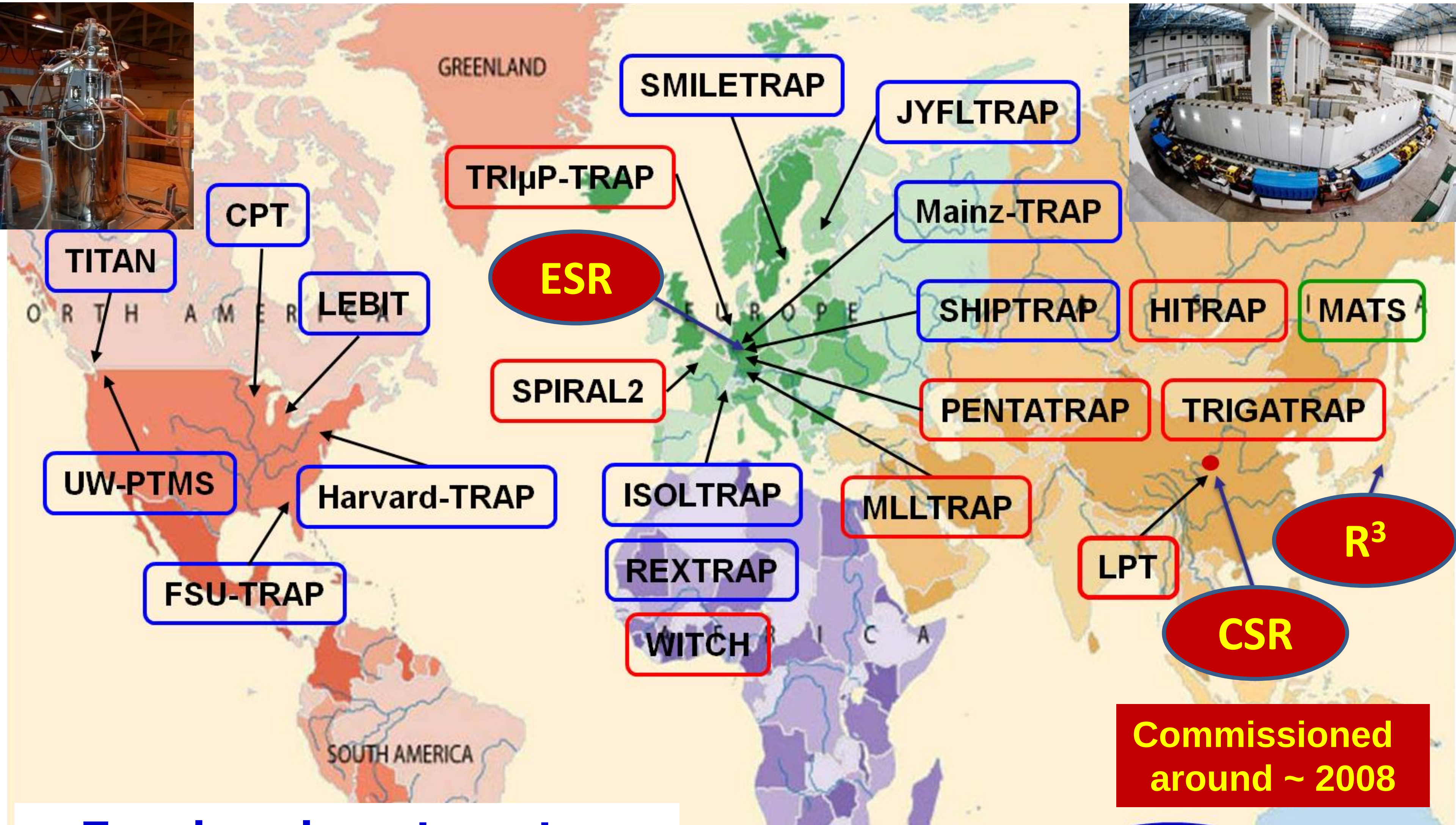
Nucleus: quantum, many-body, complex system
Mass or binding energy: a fundanmental property of nuclei

Physics Issues	Precision
General physics & chemistry	$\leq 10^{-5}$
Nuclear structure	$\leq 10^{-6}$
Nuclear astrophysics	$\leq 10^{-7}$
Weak interaction	$\leq 10^{-8}$
Fundamental constants & neutrino physics	$\leq 10^{-9}$
CPT test	$\leq 10^{-10}$
QED test	$\leq 10^{-11}$



One measurement
➔ several issues

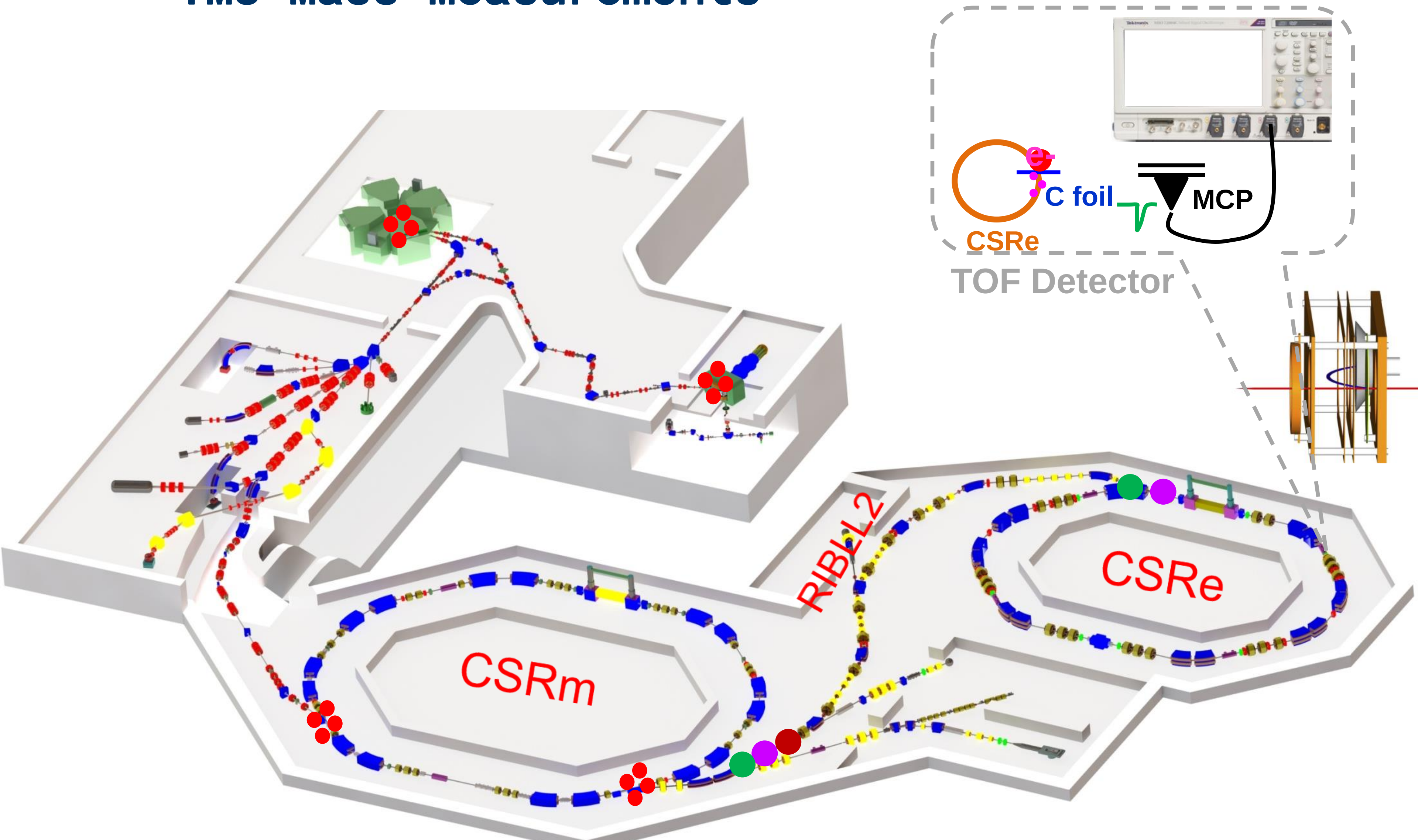
1. Introduction to mass measurements in CSRe



Trap-based spectrometry:
Very high precision up to 10^{-11} but limited by $T_{1/2}$ and yield

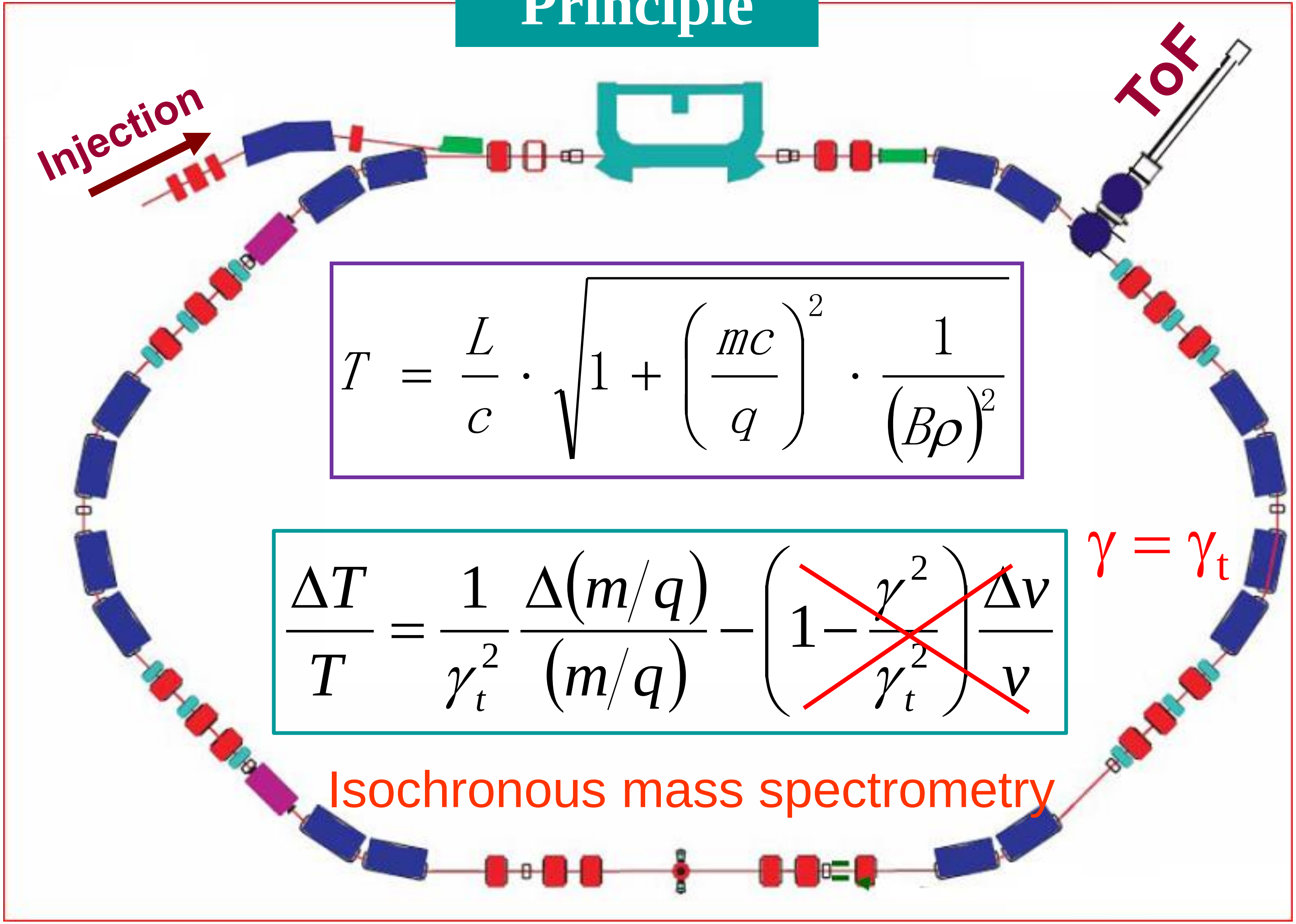
Ring-based spectrometry:
Low production yield, short-lived

IMS Mass Measurements



1. Introduction to mass measurements in CSRe

Principle



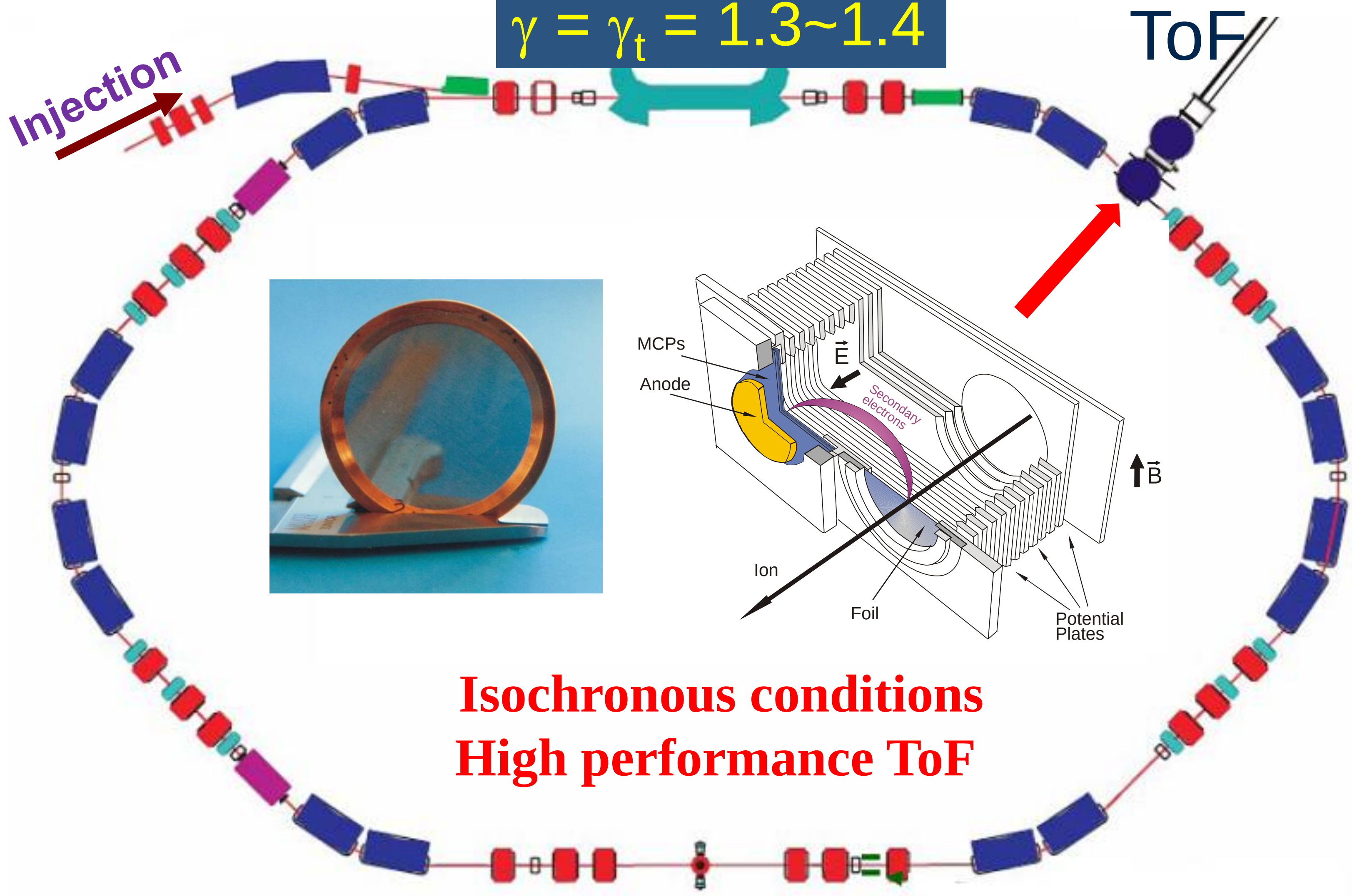
$$T = \frac{L}{c} \cdot \sqrt{1 + \left(\frac{mc}{q}\right)^2 \cdot \frac{1}{(B\rho)^2}}$$

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

$\gamma = \gamma_t$

Isochronous mass spectrometry

$\gamma = \gamma_t = 1.3\sim1.4$



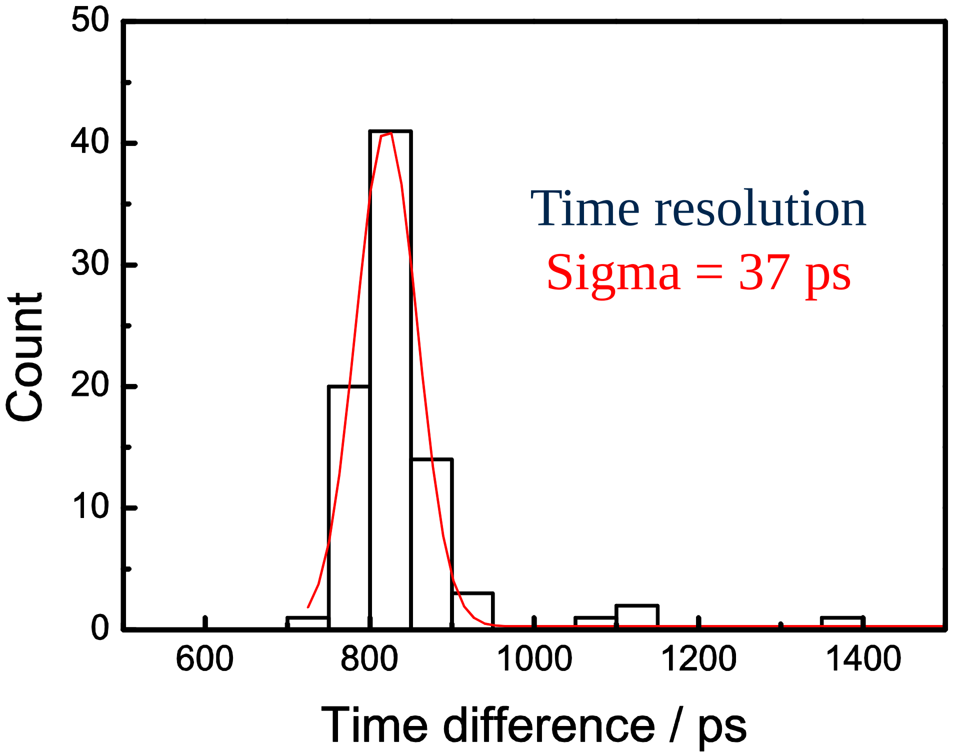
Isochronous conditions

High performance ToF

Of most importance relies on a ToF detector with good time resolution

1. Introduction to mass measurements in CSRe

Continuous effort to improve the time resolution of ToF
Sigma=70 ps to 37 ps



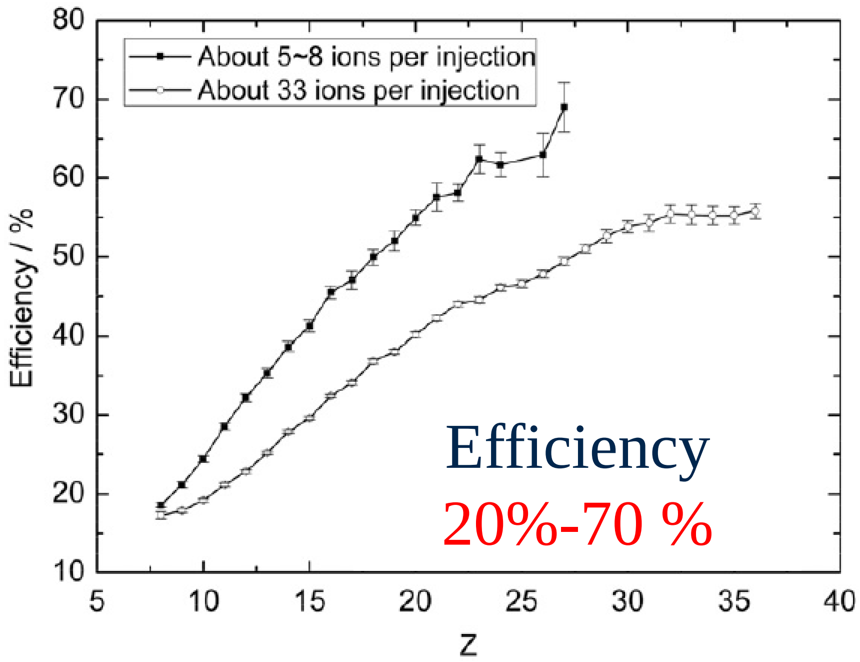
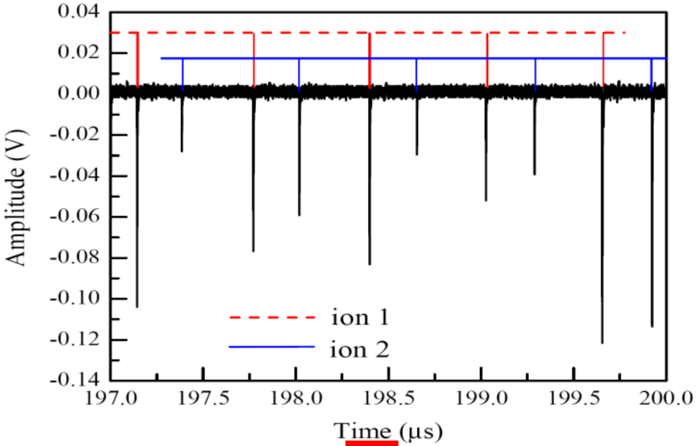


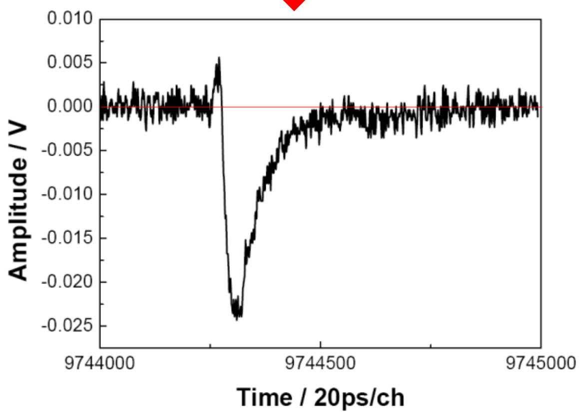
Fig. 7. Detection efficiency dependence on *Z* of ions and the number of ions circulating in the CSRe per injection.

B. Mei et al., NIM A 624, 109 (2010)
X. L. Tu et al., NIM A 654, 213 (2011)
W. Zhang et al., NIM A 756, 1 (2014)

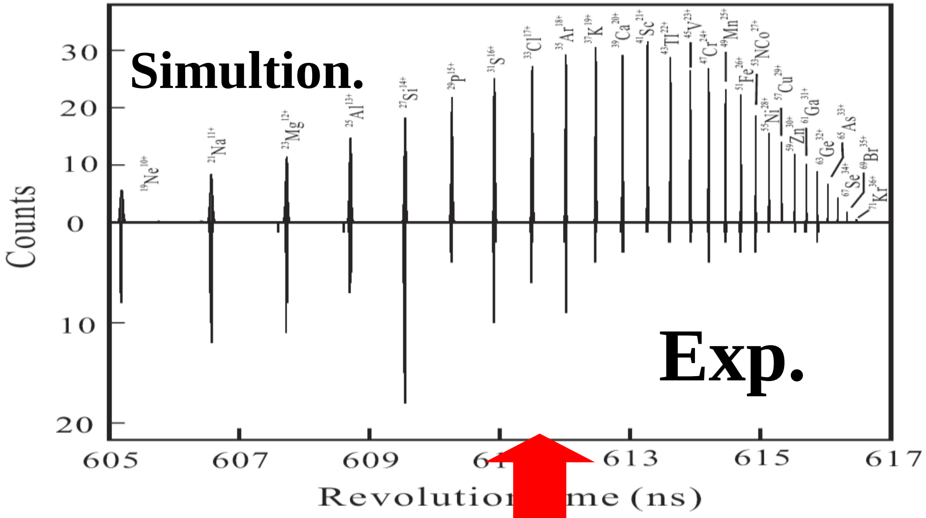
Beam: ^{78}Kr

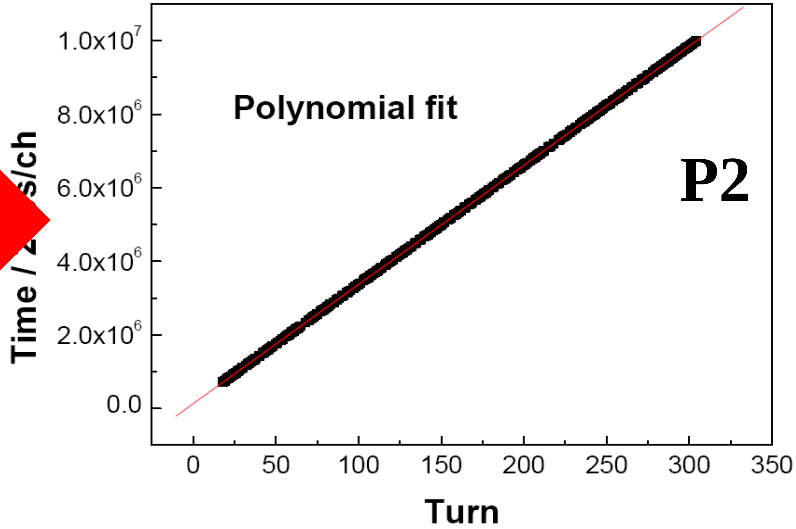
Signals in Oscilloscope



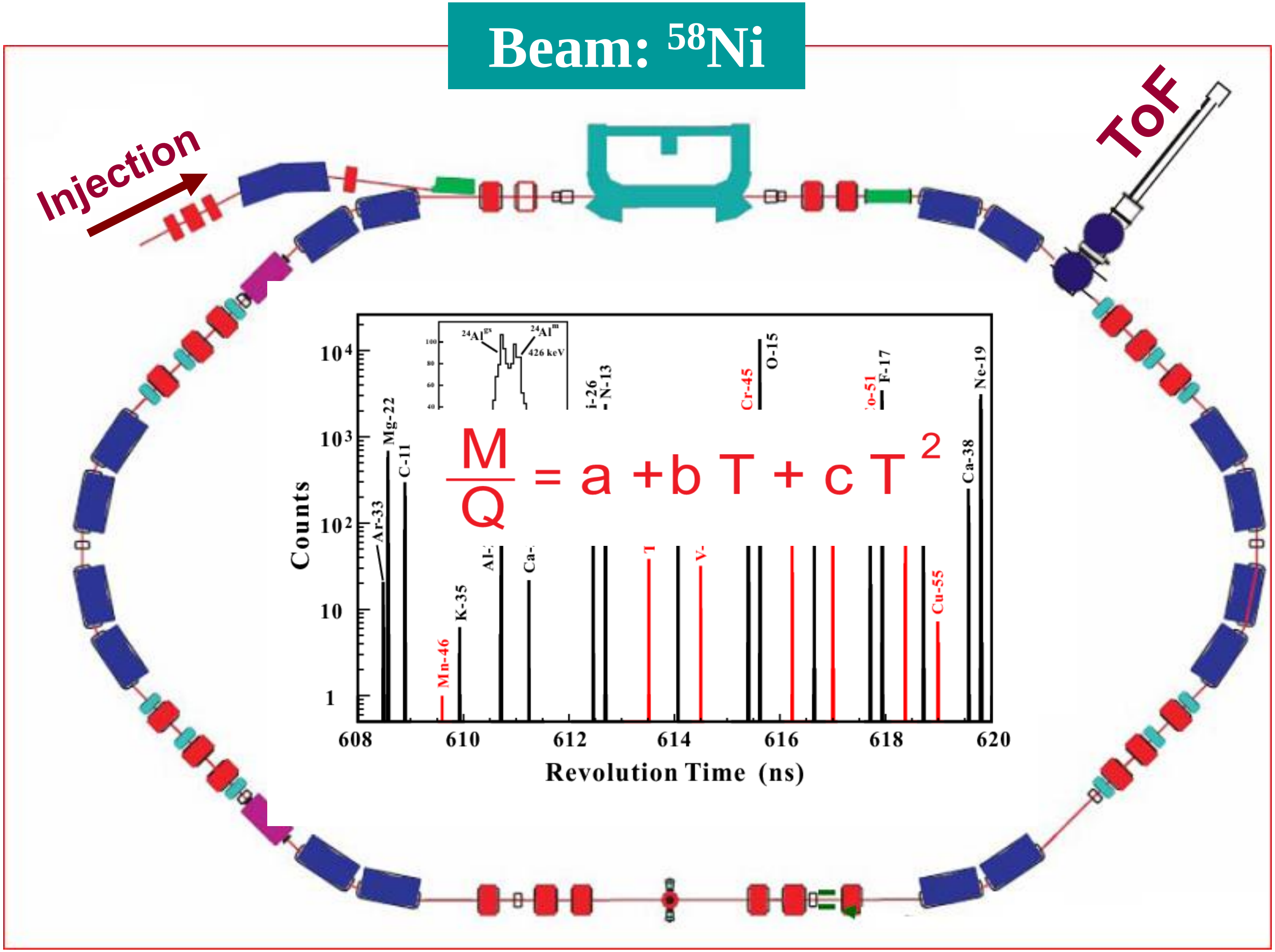


Particle identification

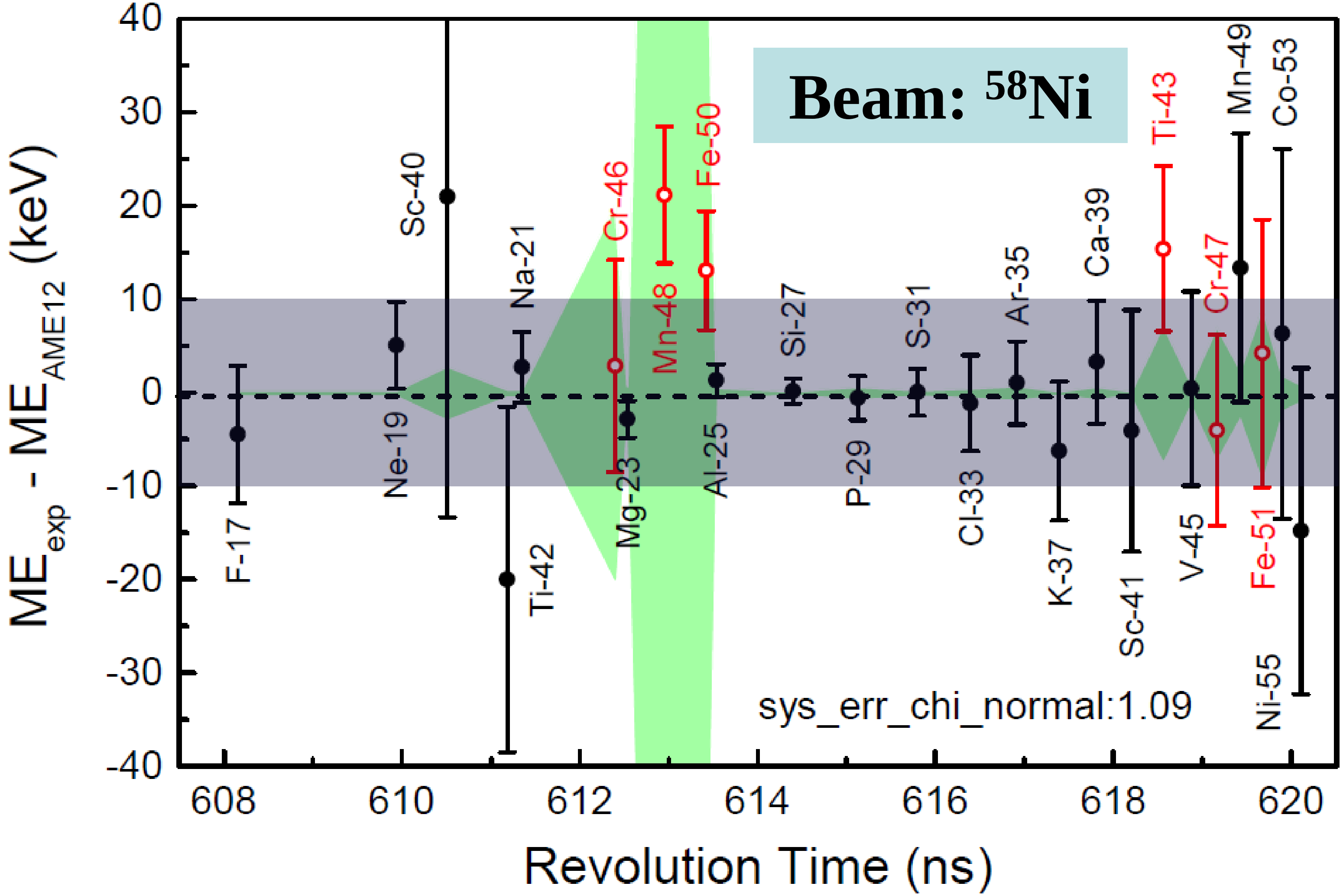




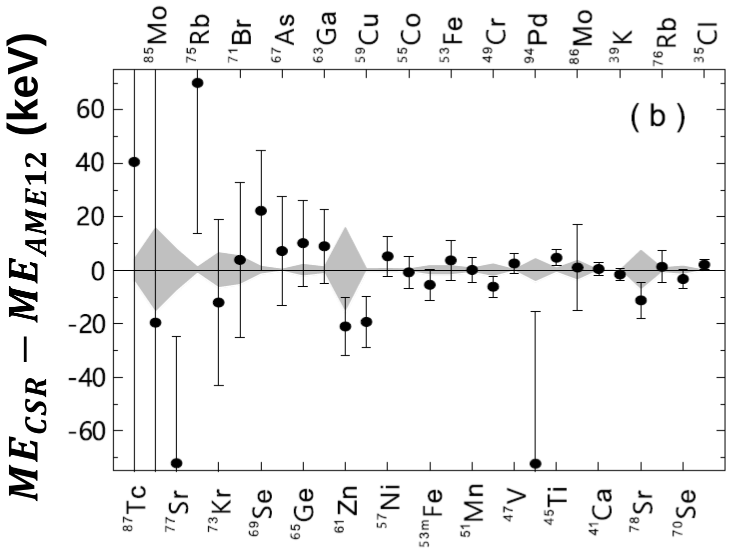
1. Introduction to mass measurements in CSRe



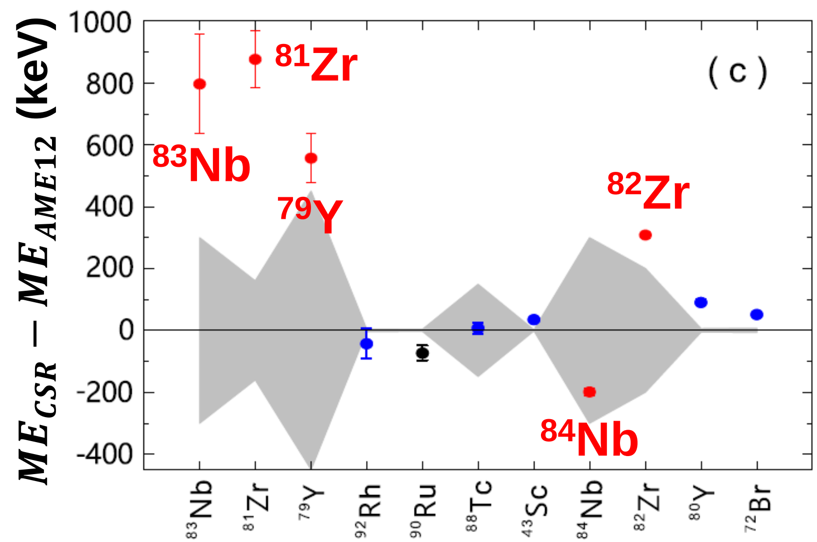
Self-checking using well-known mass nuclei

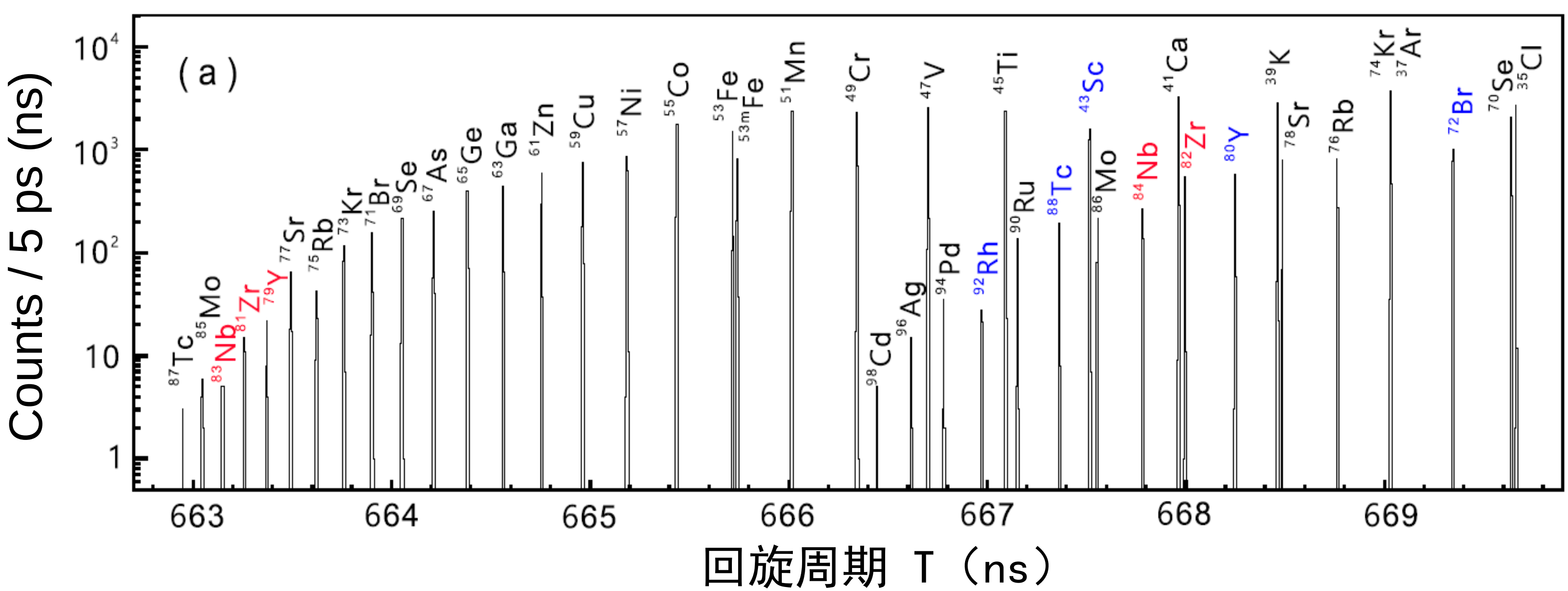


1. Introduction to mass measurements in CSRe



Beam:
^{112}Sn





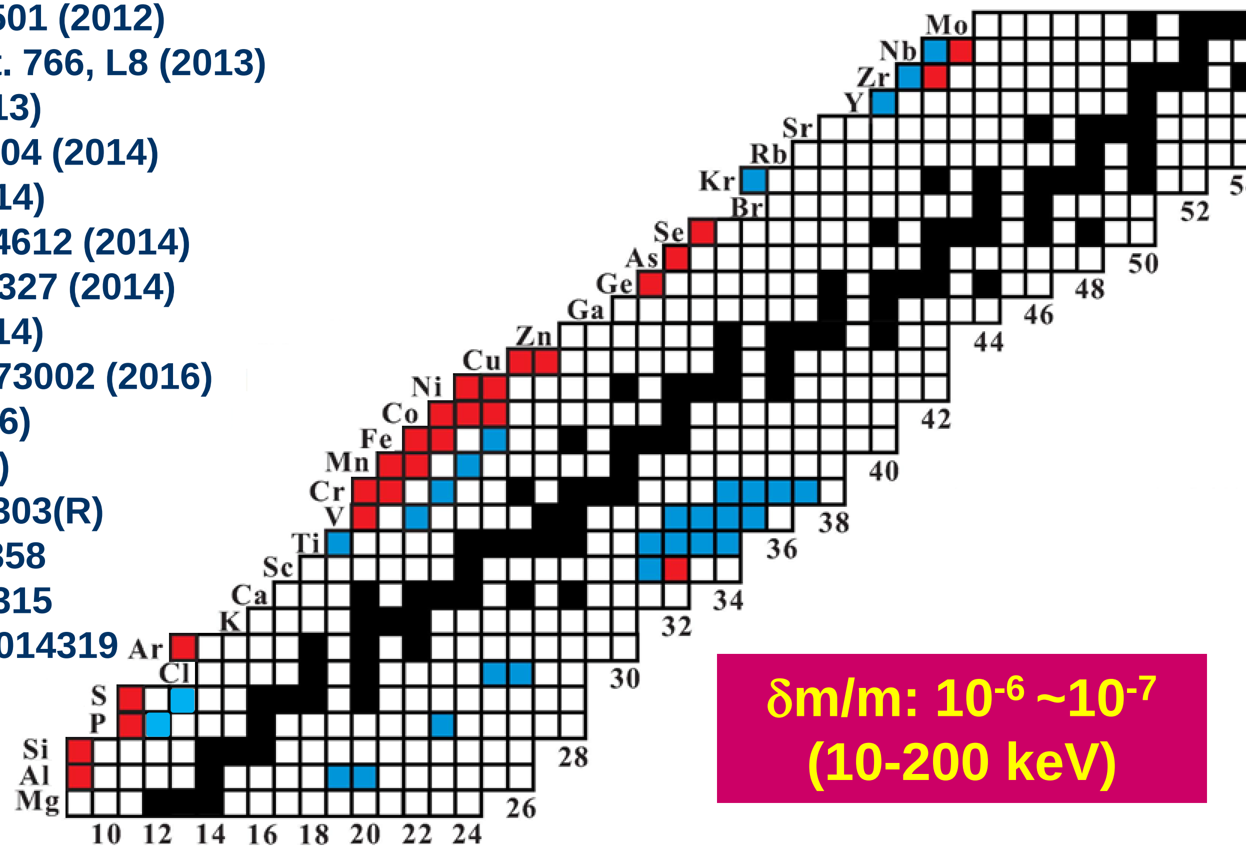
1. Introduction to mass measurements in CSRe

Primary beams: ^{36}Ar, ^{40}Ar, ^{58}Ni×3, ^{78}Kr ×2, ^{86}Kr, ^{112}Sn×2

1. B. Mei et al., NIM A 624, 109 (2010)
2. X. L. Tu et al., PRL 106, 112501 (2011)
3. X. L. Tu et al., NIM A 654, 213 (2011)
4. Y. H. Zhang et al., PRL 109, 102501 (2012)
5. X. L. Yan et al. Astrophys. J. Lett. 766, L8 (2013)
6. H. S. Xu et al., IJMS 349, 162 (2013)
7. X. L. Tu et al., J. Phys. G41, 025104 (2014)
8. W. Zhang et al., NIM A 756, 1 (2014)
9. B. Mei et al., Phys. Rev. C 89, 054612 (2014)
10. P. Shuai et al., Phys. Lett. B 735,327 (2014)
11. J.J. He et al., PRC 89, 035802 (2014)
12. Y.H. Zhang et al., Phys. Scr. 91, 073002 (2016)
13. X. Xu et al., PRL 117, 182503 (2016)
14. P. Zhang et al., PLB 767, 20 (2017)
15. Q. Zeng et al., PRC 96 (2017) 031303(R)
16. Y. M. Xing et al., PLB 781 (2018) 358
17. C. Y. Fu et al., PRC 98 (2018) 014315
18. Y. H. Zhang et al., PRC 98 (2018) 014319

Precision improved

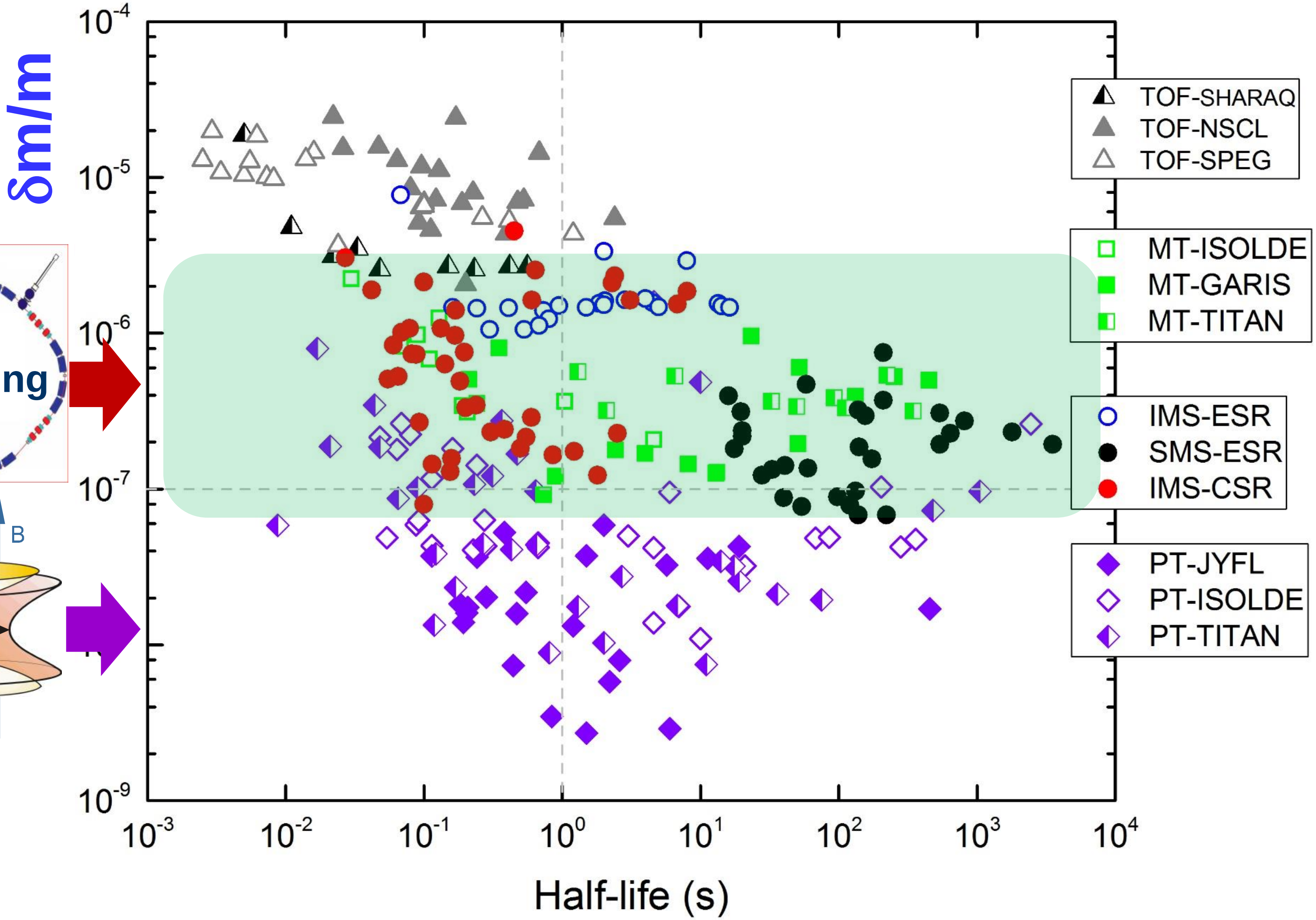
Measured for the first time

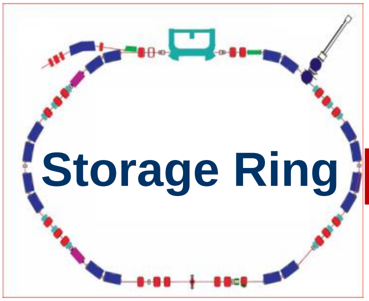


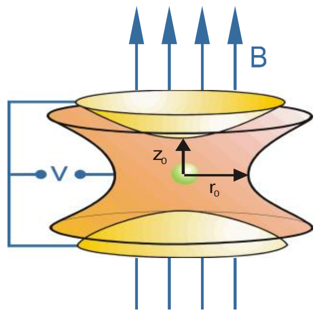
δm/m: 10^{-6} ~10^{-7} (10-200 keV)

1. Introduction to mass measurements in CSRe

Precisions of new masses since 2010

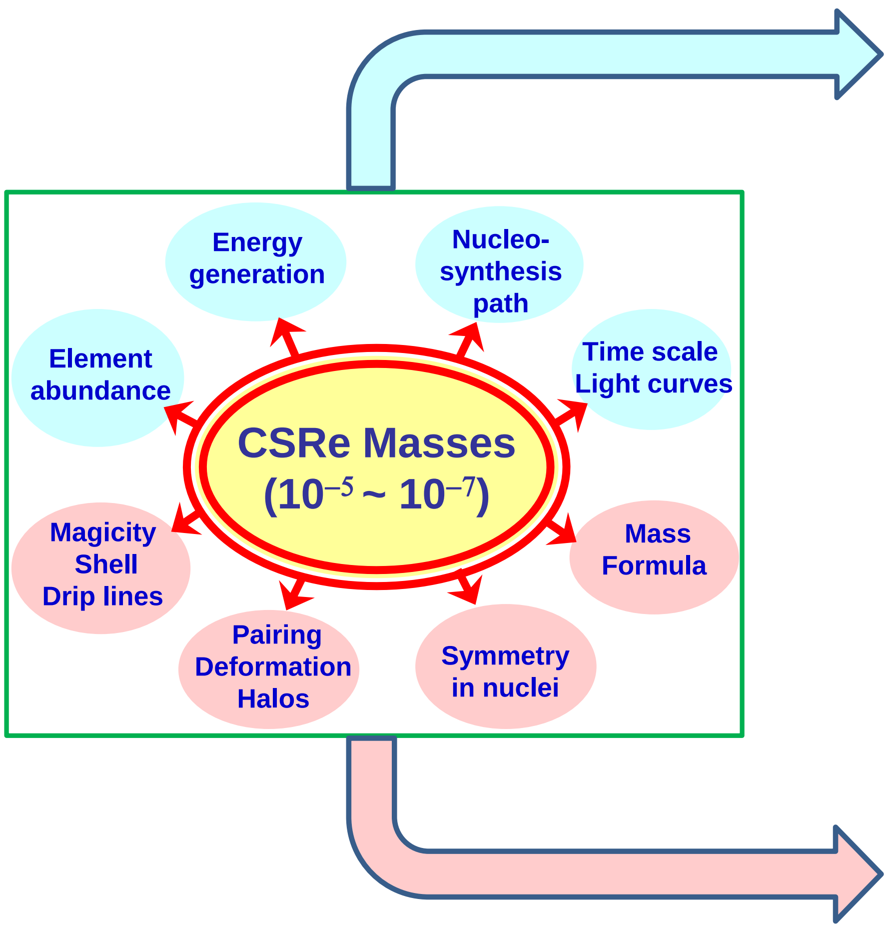






2. Some issues in nuclear astrophysics and NS

Nuclear Astrophysics



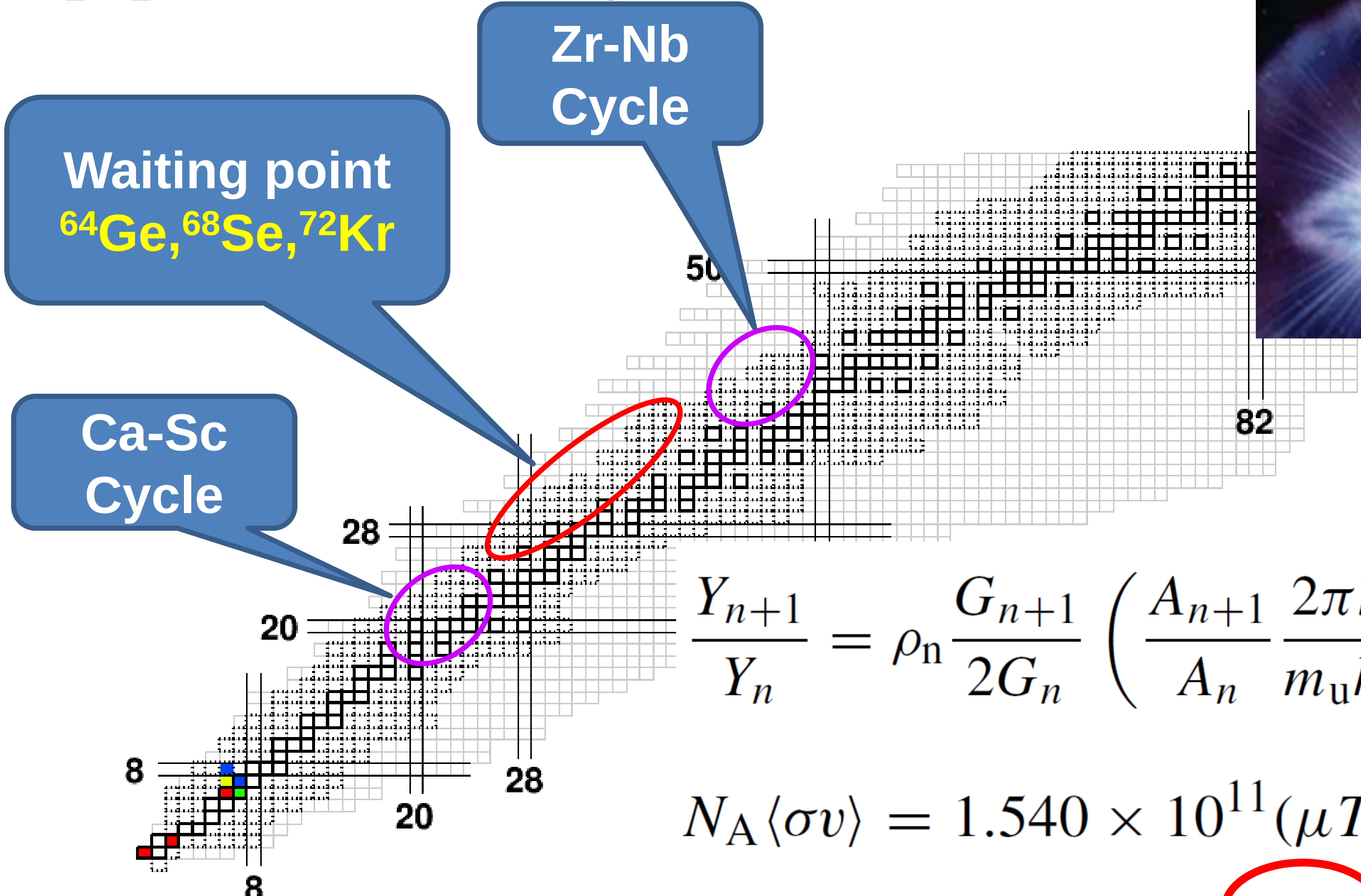
Nuclear Structure

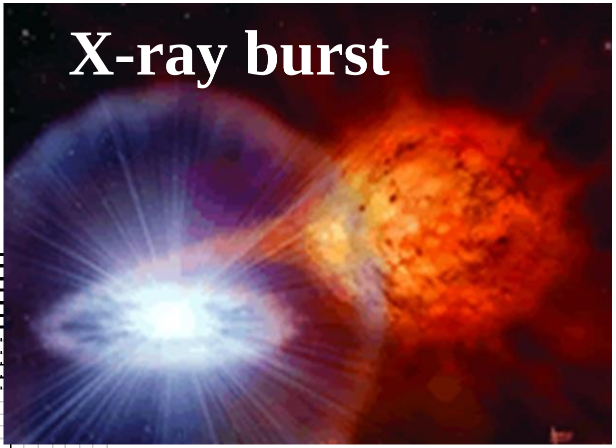
- ^{65}As: ^{64}Ge waiting point in rp-process
  PRL 106, 112501 (2011)
- ^{45}Cr: Ca-Sc cycle in rp-process
  Astrophys. J. Lett. 766, L8 (2013)
- ^{43}V: ^{42}Ti(p,γ)^{43}V rate in type-I XRB
  PRC 89, 035802 (2014)
- ^{65}As: ^{64}Ge(p,γ)^{65}As & ^{65}As(p,γ)^{66}Se in XRB
  Astrophys. J. 818, 78 (2016)
- ^{82}Zr: Zr-Nb cycle in rp-process &
  Abundance of *p*-nucleus ^{84}Sr
  Phys. Lett. B 781, 358 (2018)

- ^{53}Ni: Isospin Multiplet Mass Equation
  PRL 109, 102501 (2012)
- ^{51}Co: Isospin non-conserving forces
  Phys. Lett. B 735, 327 (2014)
- ^{53}Sc: N=32 neutron magic number
  CPC Vol.39, 104001 (2015)
- ^{52}Co: Identification of IAS & β+/EC decay
  PRL 117, 182503 (2016)
- ^{54}Ni: CVC test in Standard Model
  Phys. Lett. B 767, 20 (2017)
- ^{94}Ru: mass & half-life measurement
  PRC 96, 031303(R) (2017)

2. Some issues in nuclear astrophysics and NS

rp-process in X-ray burst





$$\frac{Y_{n+1}}{Y_n} = \rho_\mathrm{n} \frac{G_{n+1}}{2G_n} \left(\frac{A_{n+1}}{A_n} \frac{2\pi\hbar^2}{m_\mathrm{u} kT} \right)^{3/2} \exp\left(\frac{S_{n+1}}{kT} \right)$$

$$N_\mathrm{A}\langle\sigma v\rangle = 1.540 \times 10^{11} (\mu T_9)^{-3/2} \times \sum_j \omega\gamma_j \, e^{-E_j/(kT)} \ \mathrm{cm^3\,s^{-1}\,mole^{-1}}$$

Nuclear inputs:

Masses, Half-lifes, Reaction rates

2. Some issues in nuclear astrophysics and NS

➔ Masses needed in modelling the *rp*-process

1) A. Parikh, et al., PRC79, 045802 （2009）, and Prog. Part. Nucl. Phys., 69 (2013) 225–253
2) H. Schatz and W.-J. Ong, arXiv:1610.07596v1

Reaction	$Q \pm \Delta Q$ (keV)	Model affected
$^{25}Si(p,\gamma)^{26}P$	140 ± 196	short
$^{26}P(p,\gamma)^{27}S$	719 ± 281	K04, low*Z*,[a] short
$^{30}S(p,\gamma)^{31}Cl$	294 ± 50	hi*T*, short
$^{42}Ti(p,\gamma)^{43}V$	192 ± 233	S01, low*T*, low*Z*, short
$^{45}Cr(p,\gamma)^{46}Mn$	694 ± 515	F08
$^{46}Cr(p,\gamma)^{47}Mn$	78 ± 160	K04, low*T*, hi*T*, low*Z*, short
$^{50}Fe(p,\gamma)^{51}Co$	88 ± 161	short
$^{55}Ni(p,\gamma)^{56}Cu$	555 ± 140	K04, low*T*, low*Z*, short
$^{60}Zn(p,\gamma)^{61}Ga$	192 ± 54	K04, low*T*, hi*T*,[a] low*Z*
$^{64}Ge(p,\gamma)^{65}As$	-80 ± 300	K04,[a] S01,[a] low*T*,[a] hi*T*,[a] low*Z*,[a] hi*Z*, hi*Z*2, long,[a] short
$^{68}Se(p,\gamma)^{69}Br$	-450 ± 100	hi*T*
$^{89}Ru(p,\gamma)^{90}Rh$	992 ± 711	long
$^{98}Cd(p,\gamma)^{99}In$	932 ± 408	S01
$^{105}Sn(p,\gamma)^{106}Sb$	357 ± 323	hi*T*
$^{106}Sn(p,\gamma)^{107}Sb$	518 ± 302	S01[a]

[a]Variation of this reaction *Q*-value affects the nuclear energy generation rate in this model (see text).

Isotope	σ^b	A^c	r_{Comp}
^{79}Y	450	78	5.0
		79	0.048
^{79}Zr	461	78	2.5
^{80}Zr	1490	26	1.2
		28	0.79
		64	0.81
		68	0.75
		72	0.77
		76	0.78
		79	50.
		80	0.16
		82	1.4
		83	1.3
		87	1.2
		108	1.2
^{81}Zr	165	81	0.16
		82	0.56
		84	1.4
		85	1.3
		86	1.2
^{82}Zr	200	82	0.34
		83	2.4
^{82}Nb	298	81	8.4
		82	1.6
		83	1.4
		108	1.2
^{83}Nb	300	82	10.
		83	0.22
		84	0.61
		85	0.77
^{84}Nb	300	83	1.5

^{43}V
^{45}Cr
^{46}Mn
^{47}Mn
^{51}Co
^{56}Cu
^{79}Y
^{81}Zr
^{82}Zr
^{83}Nb
^{84}Nb
^{103}Sn

2. Some issues in nuclear astrophysics and NS

H. Schatz (MSU)

S. Kubono (Riken)

G. Martinez-Pinedo (GSI)

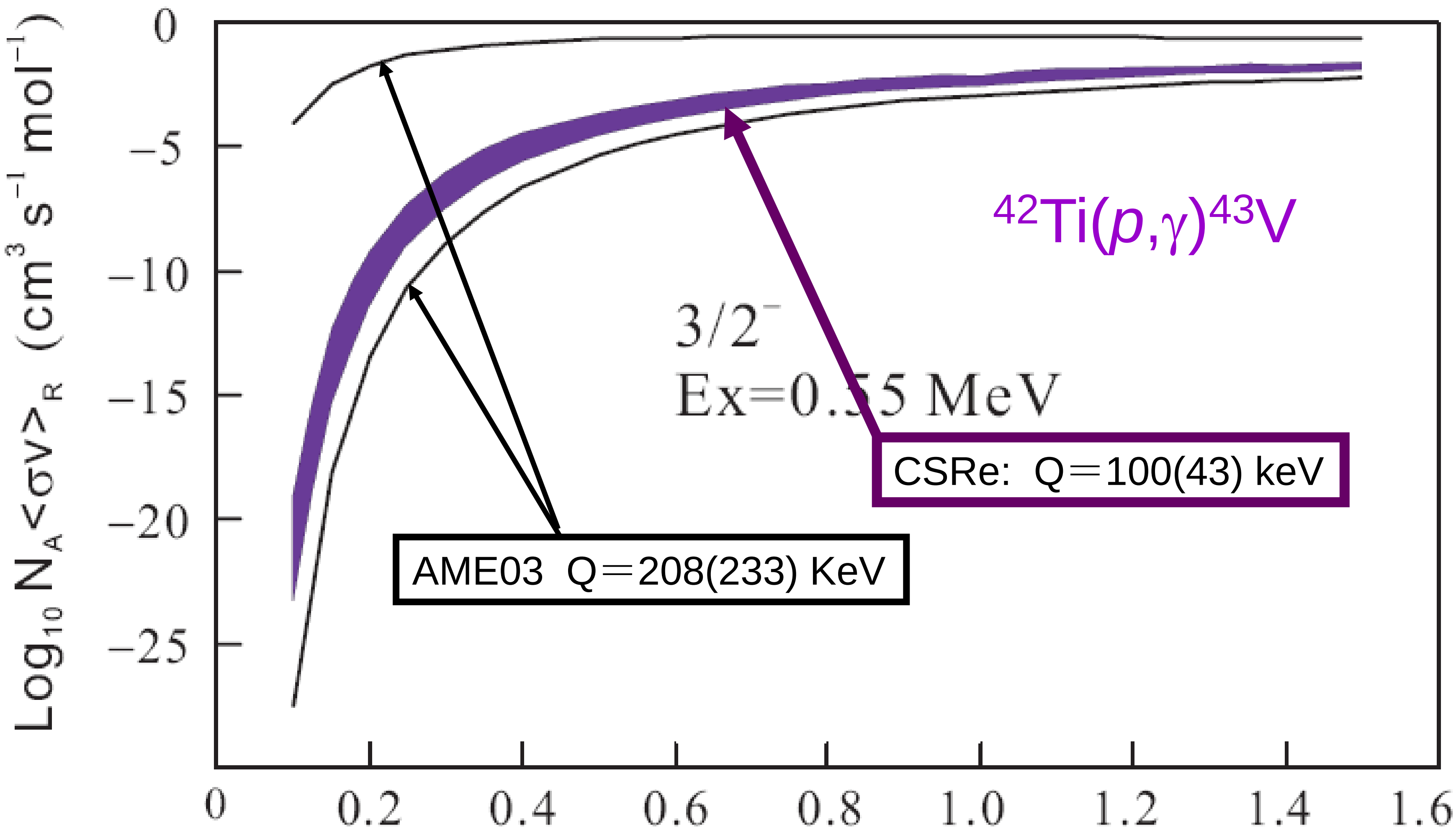
A. Sieverding (GSI)

S. Wanajo (Riken)

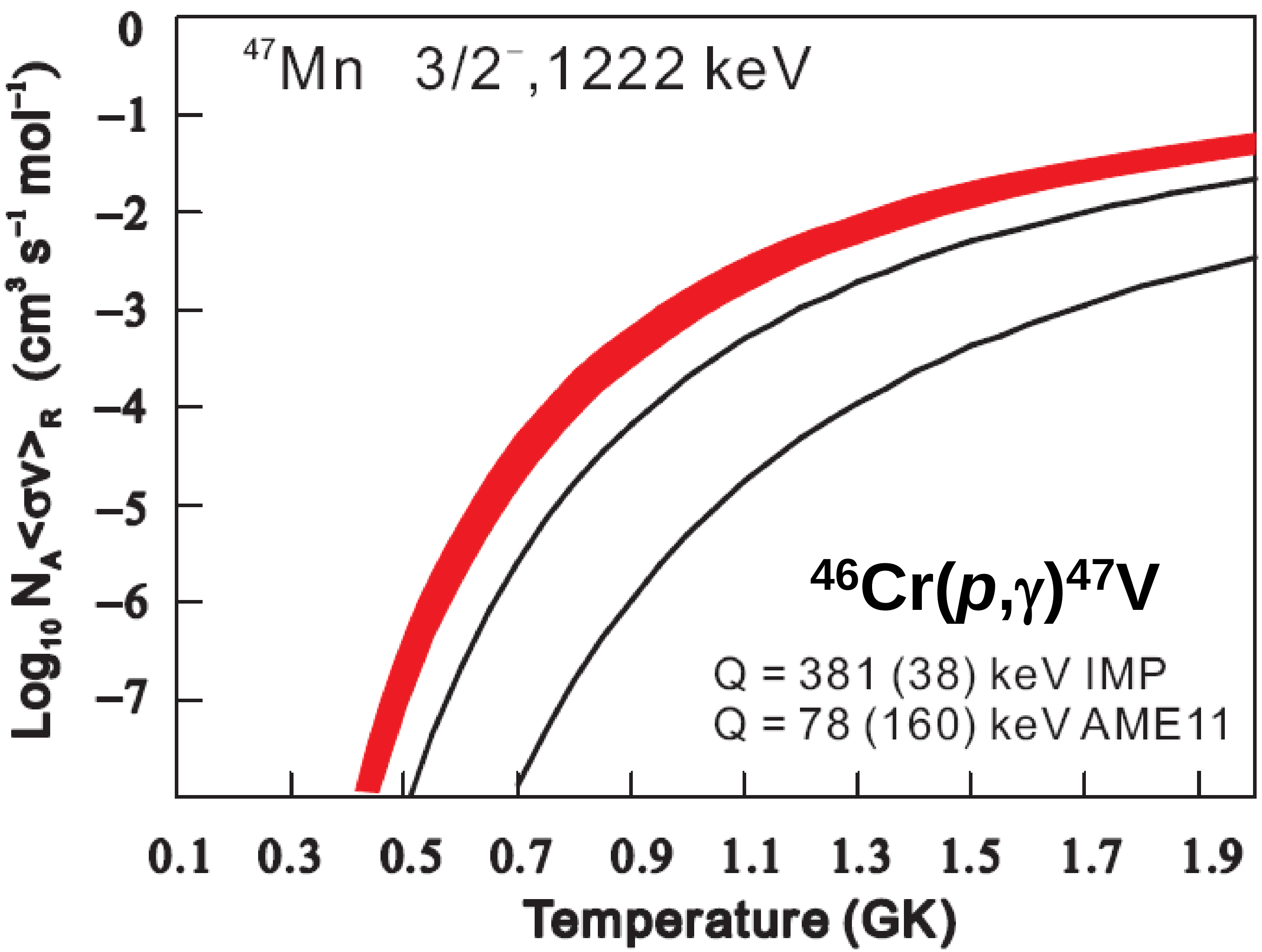
X.D. Tang (IMP)

- → (*p*,*γ*) reaction rates in the *rp*-process of type-I XRB
- → waiting point nucleus ^{64}Ge in the rp-process
- → Ca-Sc and Zr-Nb cycles in the rp-process
- → Overproduction of *p*-nucleus ^{84}Sr in the ν*p*-process
- → Abundance ratio of ^{92}Mo/^{94}Mo in the ν*p*-process

➔ (*p*,*γ*) reaction rates in the *rp*-process of type-I XRB

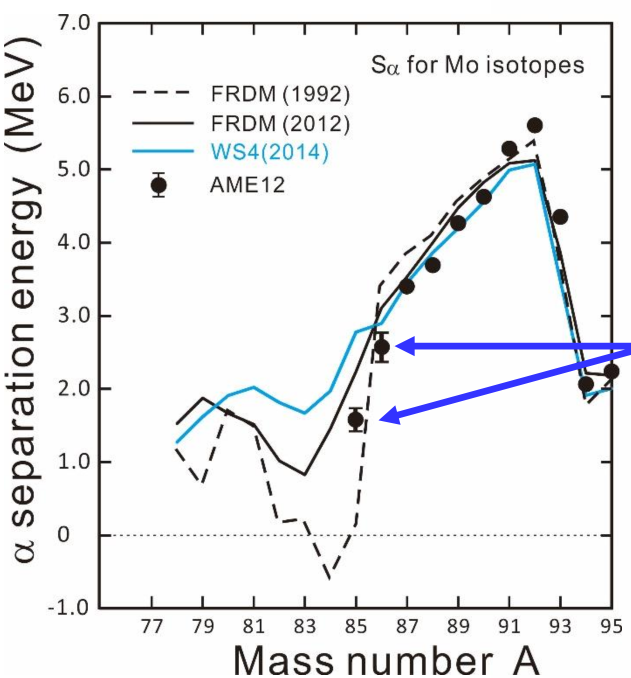


➔ (p,γ) reaction rates in the *rp*-process of type-I XRB



➔ Zr-Nb cycle in the rp-process of X-ray bursts

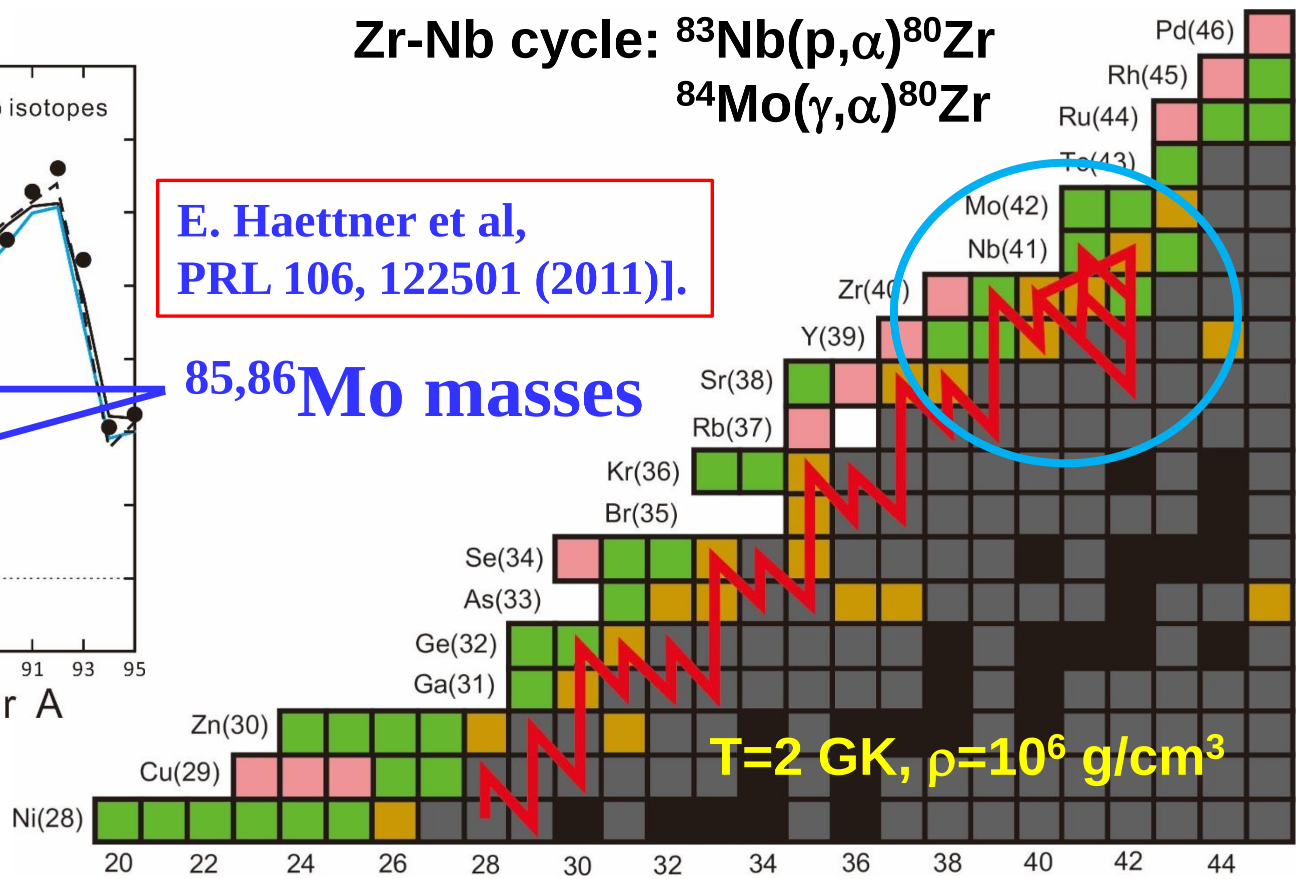
Zr-Nb cycle was proposed by H. Schatz et al, Phys. Rep. 294, 167 (1998) based on the FRDM mass prediction in 1992, which show a very low or even negative α separation energy of ^{84}Mo.



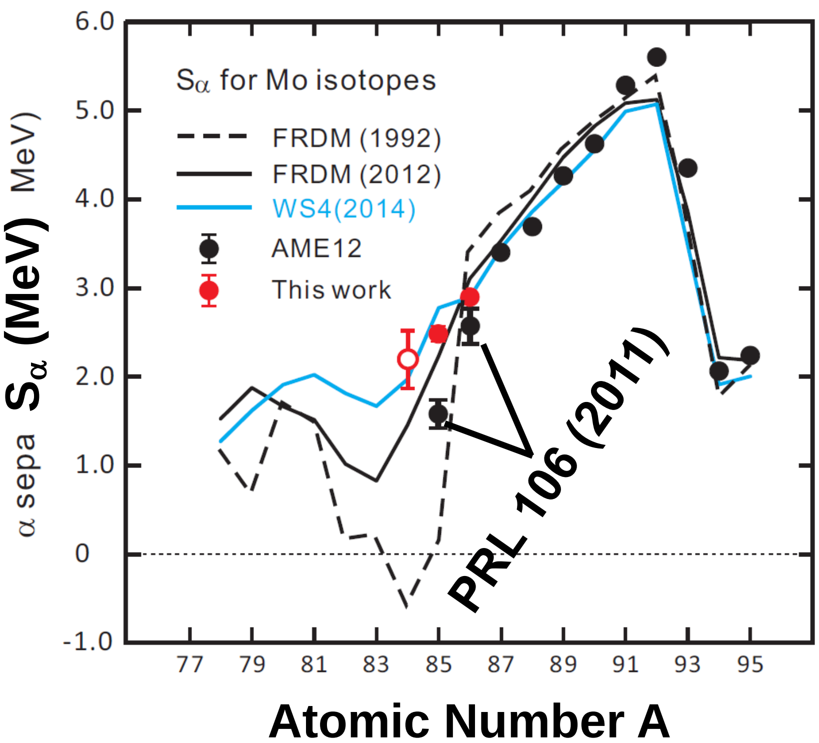
Zr-Nb cycle: ^{83}Nb(p,α)^{80}Zr
^{84}Mo(γ,α)^{80}Zr

E. Haettner et al,
PRL 106, 122501 (2011)].

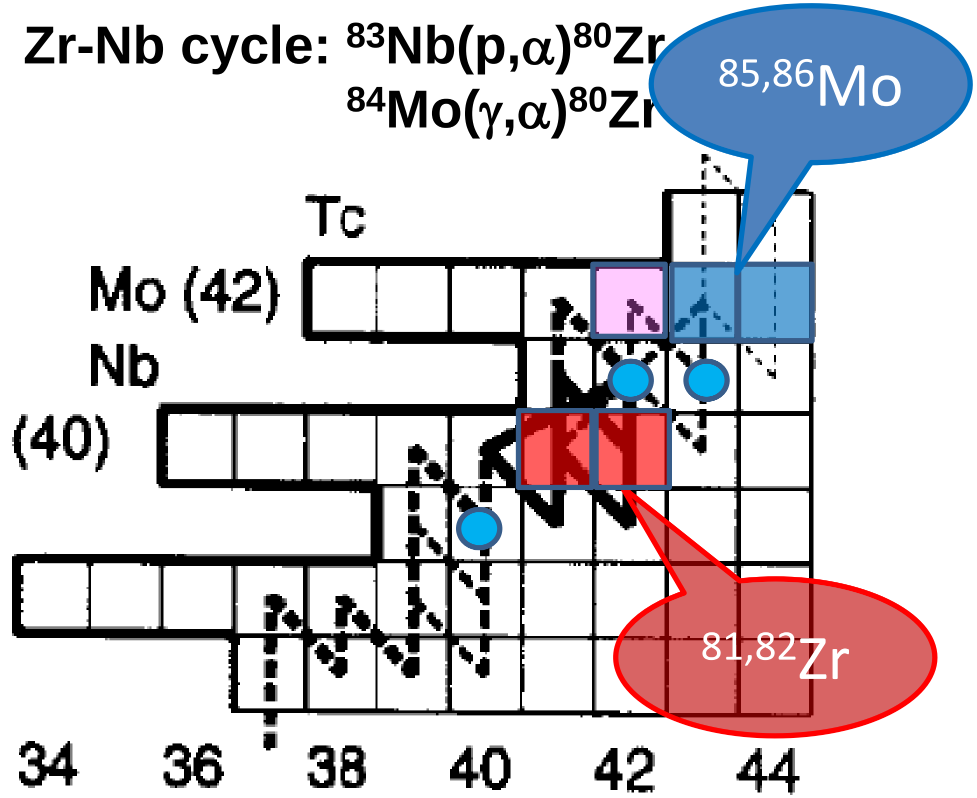
^{85,86}Mo masses



➔ Zr-Nb cycle in the rp-process of X-ray bursts



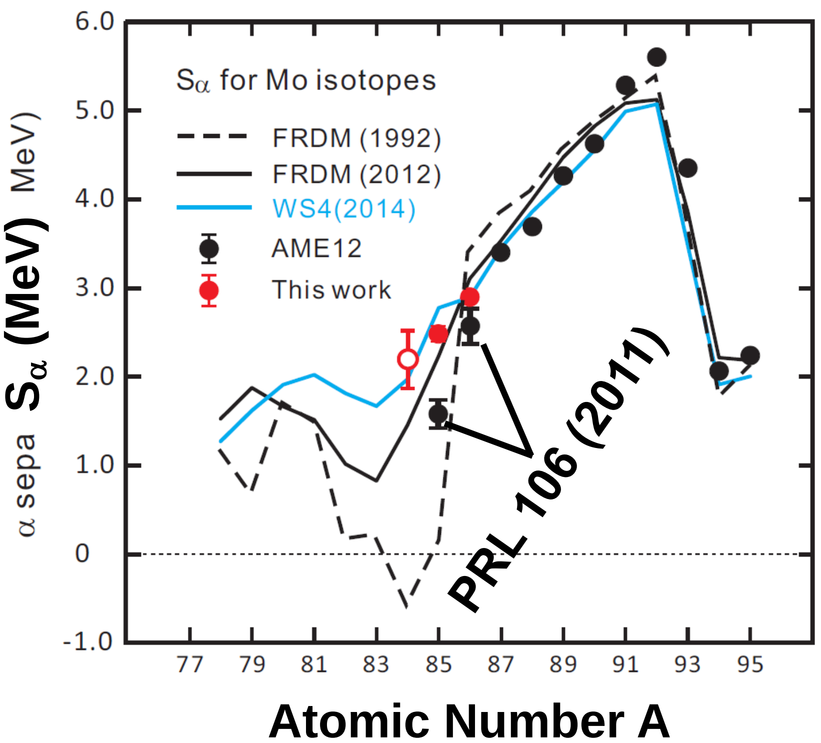
Zr-Nb cycle: $^{83}Nb(p,\alpha)^{80}Zr$
$^{84}Mo(\gamma,\alpha)^{80}Zr$

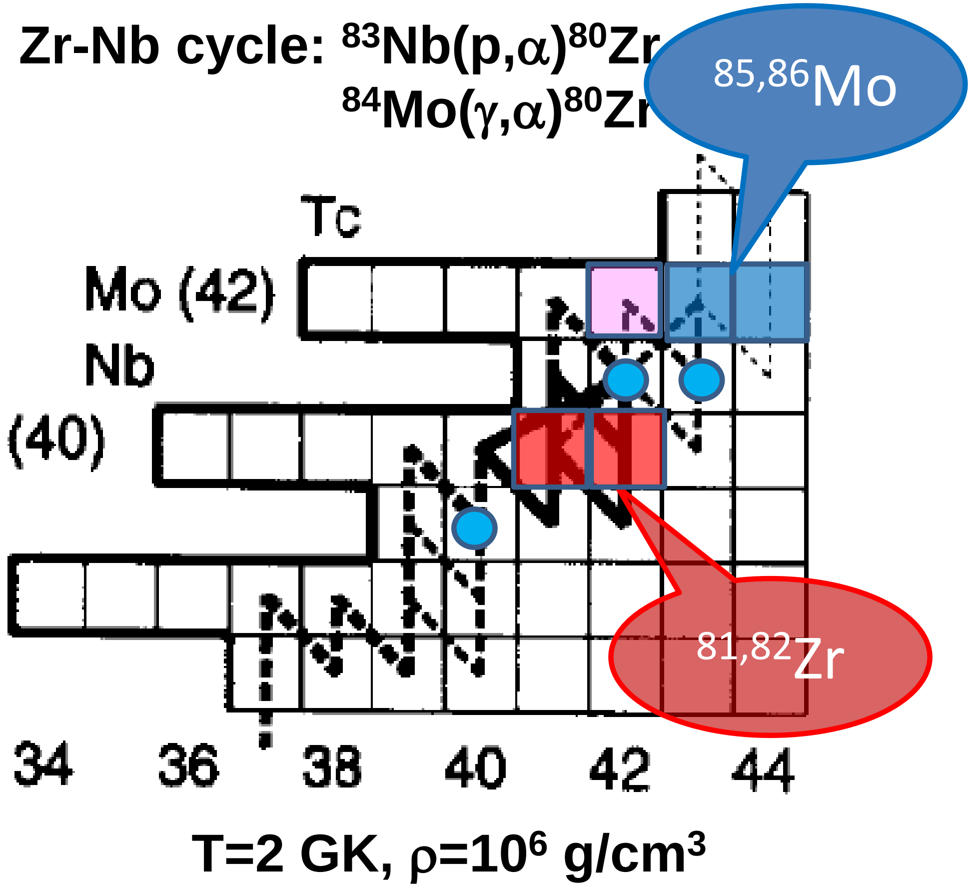


T=2 GK, $\rho=10^6$ g/cm^3

No pronounced island of very low S_α for Mo isotopes !

→ Zr-Nb cycle in the rp-process of X-ray bursts



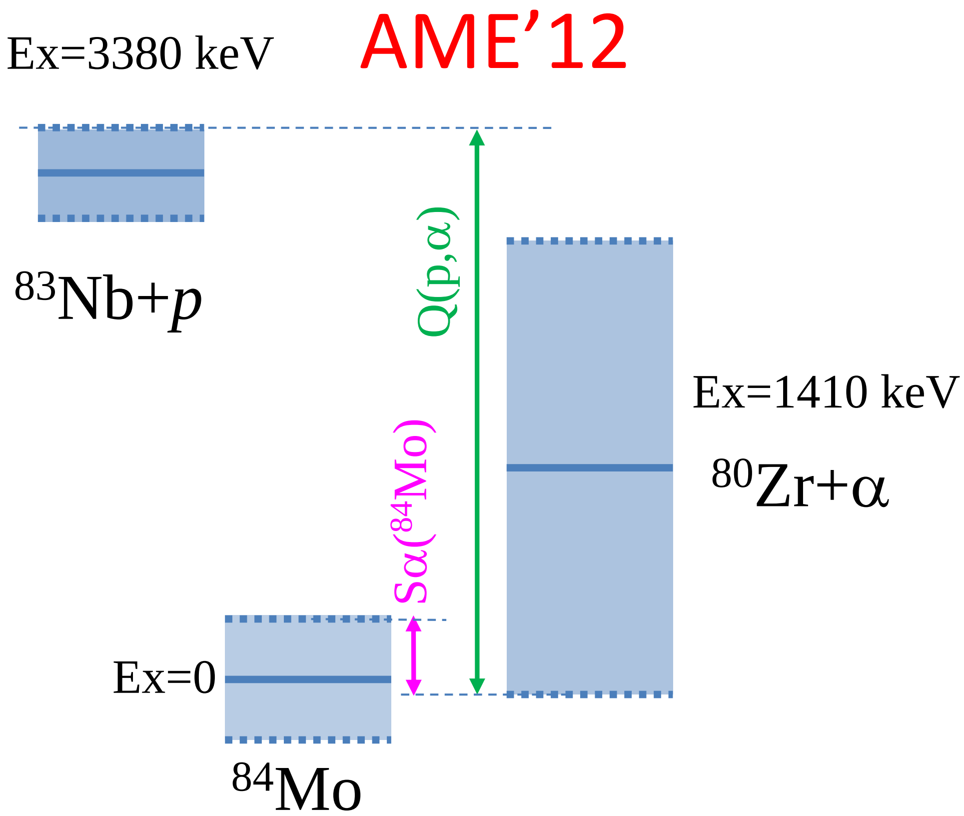


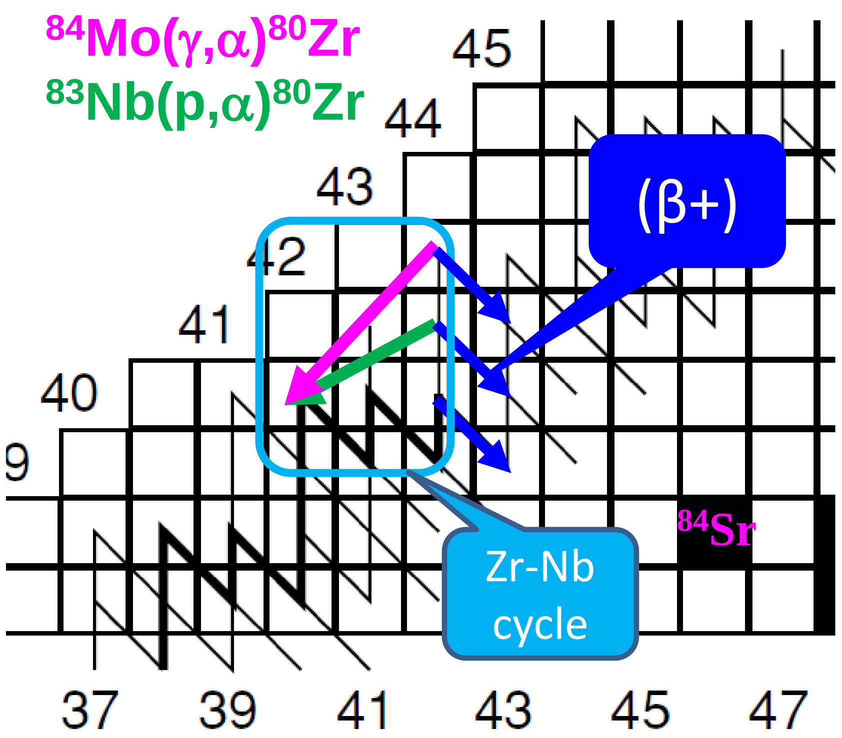
No pronounced island of very low S_α for Mo isotopes !

Favorable conditions for the formation of Zr-Nb cycle:

Largest Q(p,α) favoring ^{83}Nb(p,α)^{80}Zr reaction
Smallest Sα(^{84}Mo) favoring ^{84}Mo(γ,α)^{80}Zr reaction

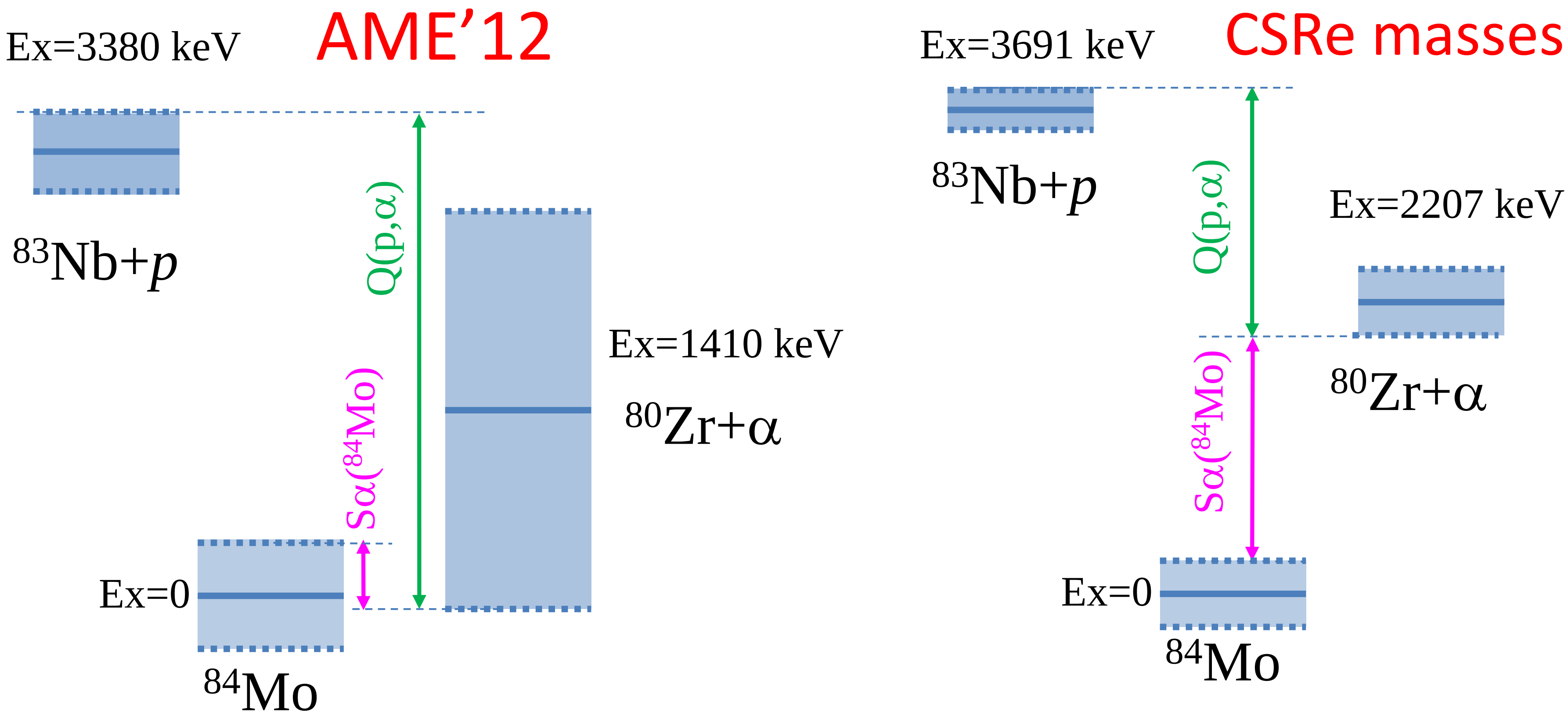
E. Haettner et al, PRL 106, 122501 (2011)]





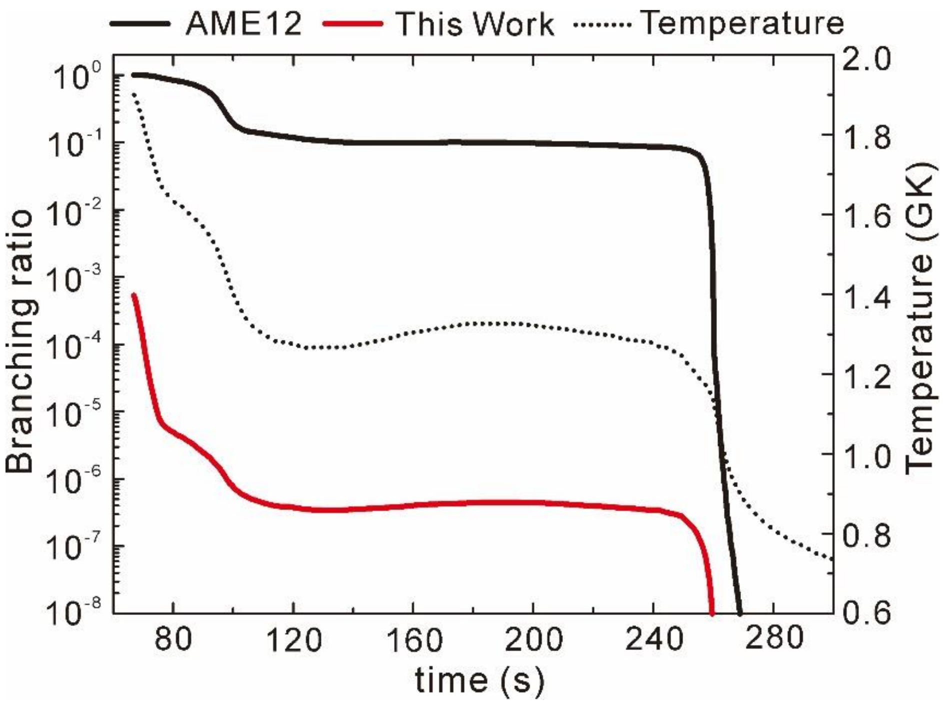
Favorable conditions for the formation of Zr-Nb cycle:

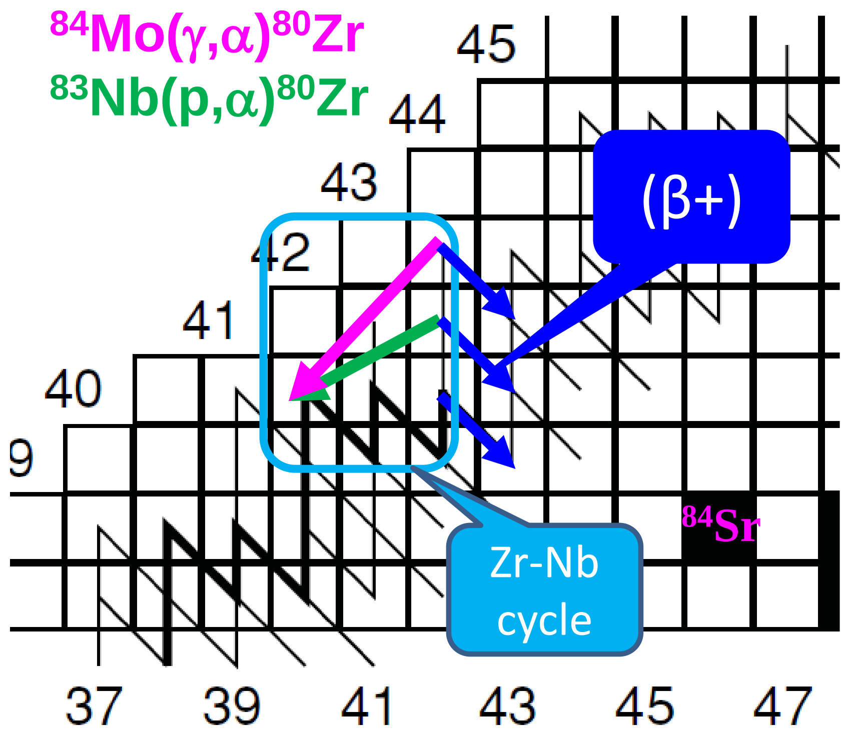
Largest Q(p,α) favoring ^{83}Nb(p,α)^{80}Zr reaction
Smallest Sα(^{84}Mo) favoring ^{84}Mo(γ,α)^{80}Zr reaction



Zr-Nb cycling Branching ratio is defined as the Flow of $^{83}Nb(p,\alpha)+^{84}Mo(\gamma,\alpha)$ divided by the flow of

$$^{83}Nb(p,\alpha)+^{84}Mo(\gamma,\alpha)+^{84}Mo(p,\gamma)+^{84}Mo(\beta^+)+^{83}Nb(\beta^+)+^{82}Zr(\beta^+)+^{81}Y(\beta^+)$$





no Zr-Nb cycle exists in the rp-process !

Masses of ^{52g}Co and ^{52m}Co

Previous investigations on the β decay of ^{52}Ni

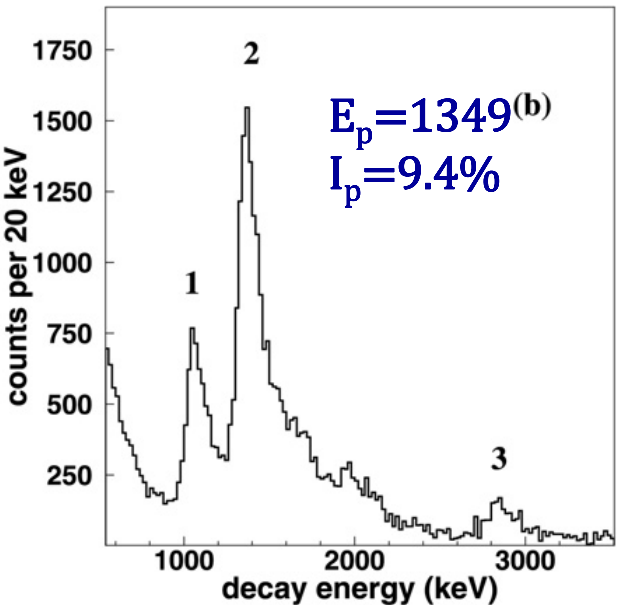
1) L. Faux et al., Phys. Rev. C 49, 2440 (1994).
2) C. Dossat, et al., Nucl. Phys. A792, 18(2007).
3) S. E. A. Orrigo et al., Phys. Rev. C 93, 044336 (2016).

- β-delayed proton and gammas measured,
- Decay level scheme of ^{52}Ni established.
- T=2 Isobaric analog state (IAS) in ^{52}Co identified
- Isobaric multiplet mass equation (IMME) tested

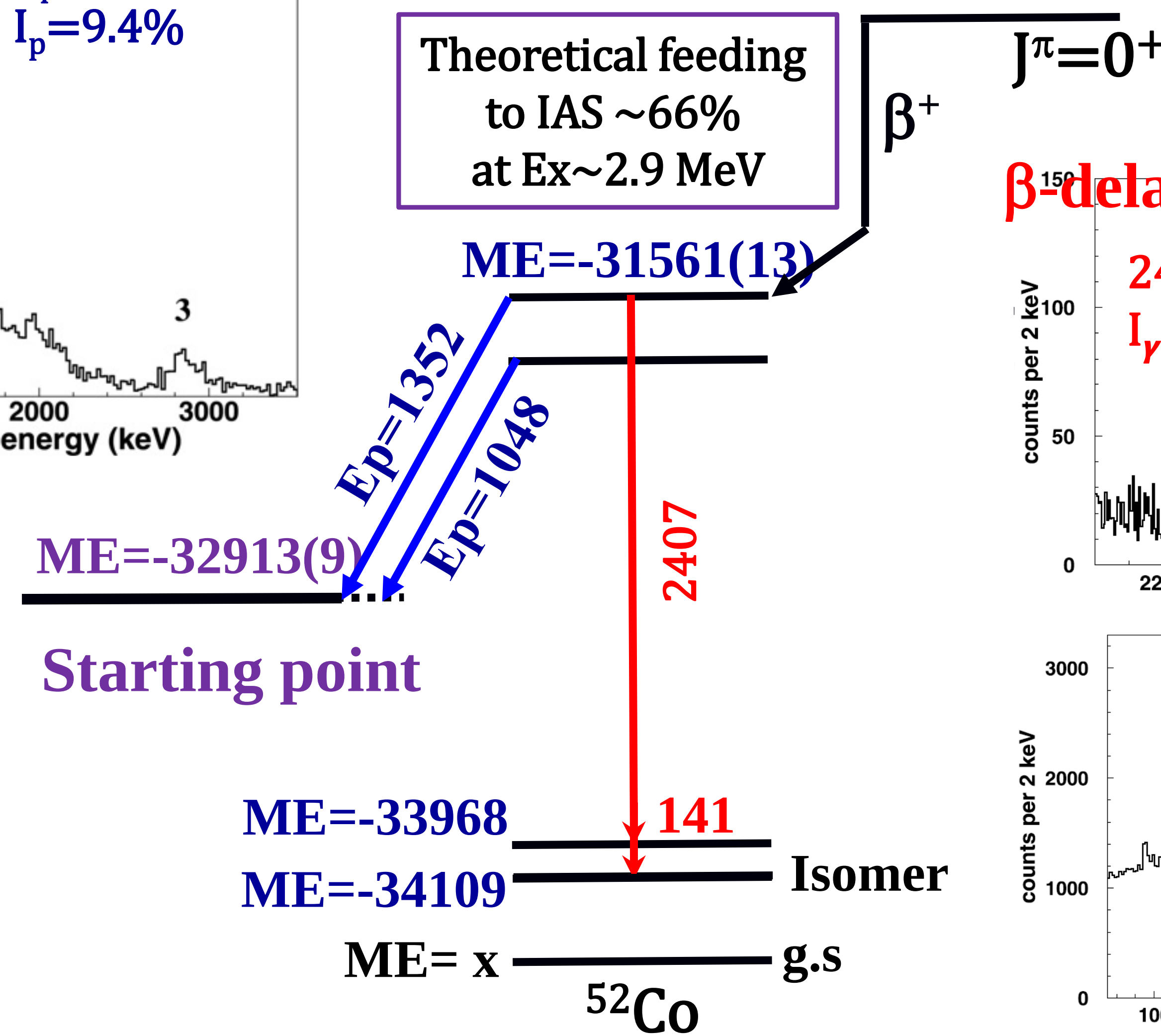
…… there is a puzzule !

2. Some issues in nuclear astrophysics and NS

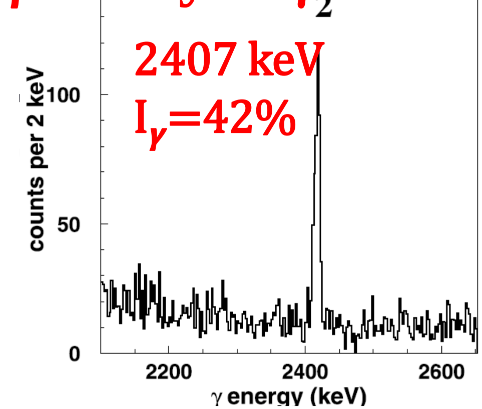
β-delayed protons of ^{52}Ni

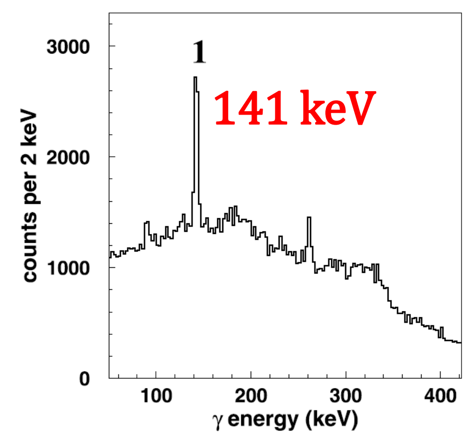


Existing information



β-delayed γ_2 of ^{52}Ni

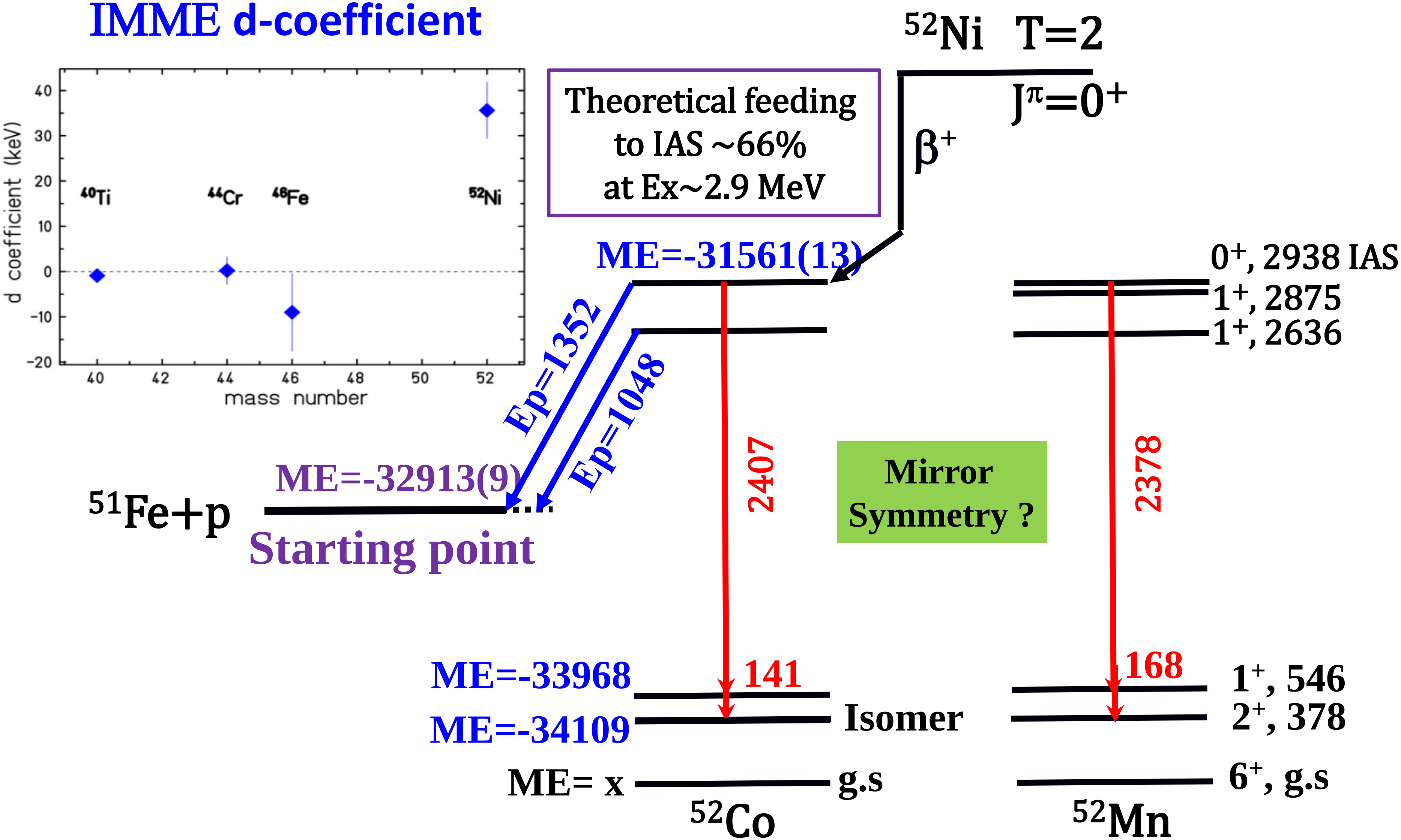




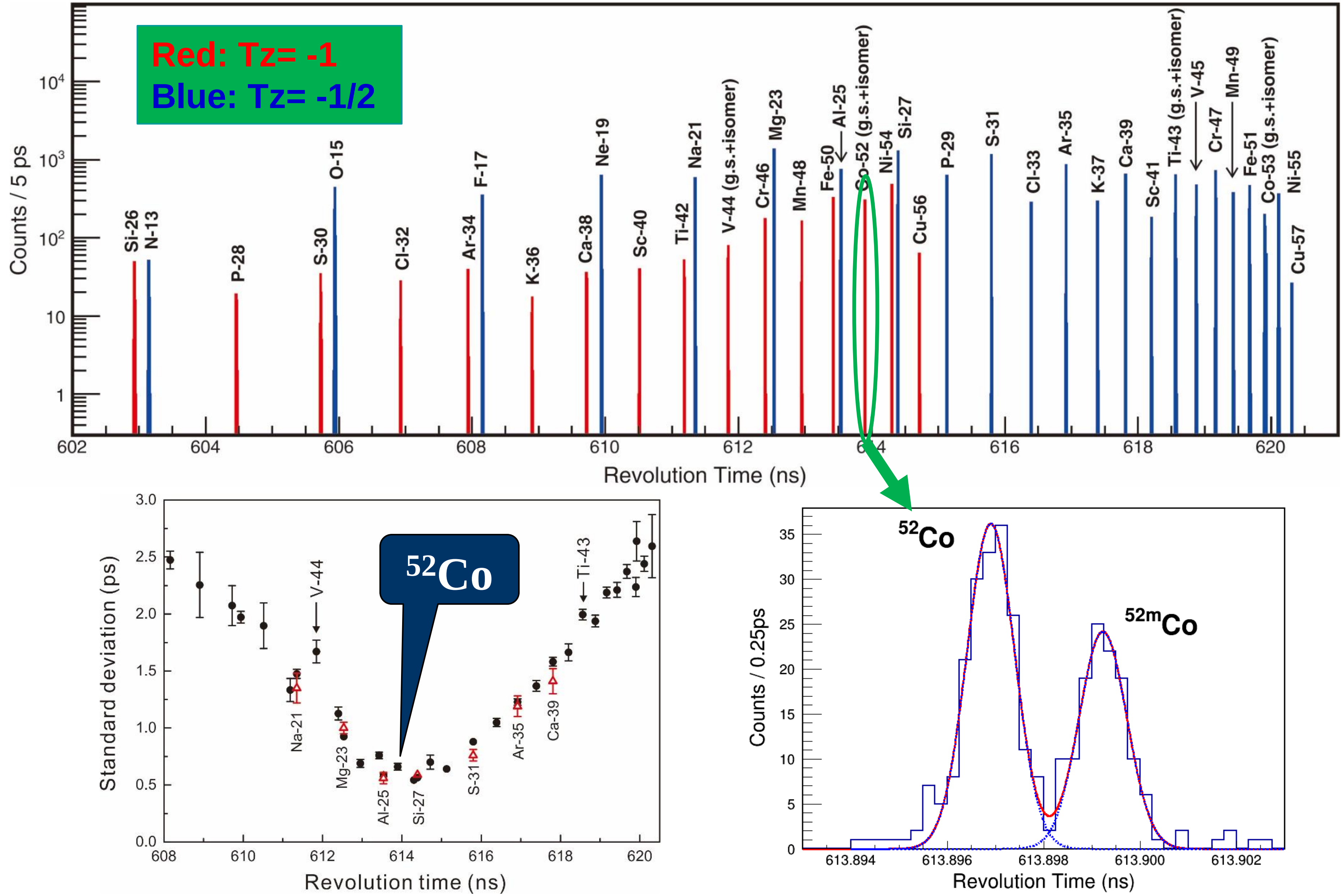
2. Some issues in nuclear astrophysics and NS

$$M(T,A,T_3) = a(T,A,) + b(T,A)T_3 + c(T,A)T_3^2 + d(T,A)T_3^3$$

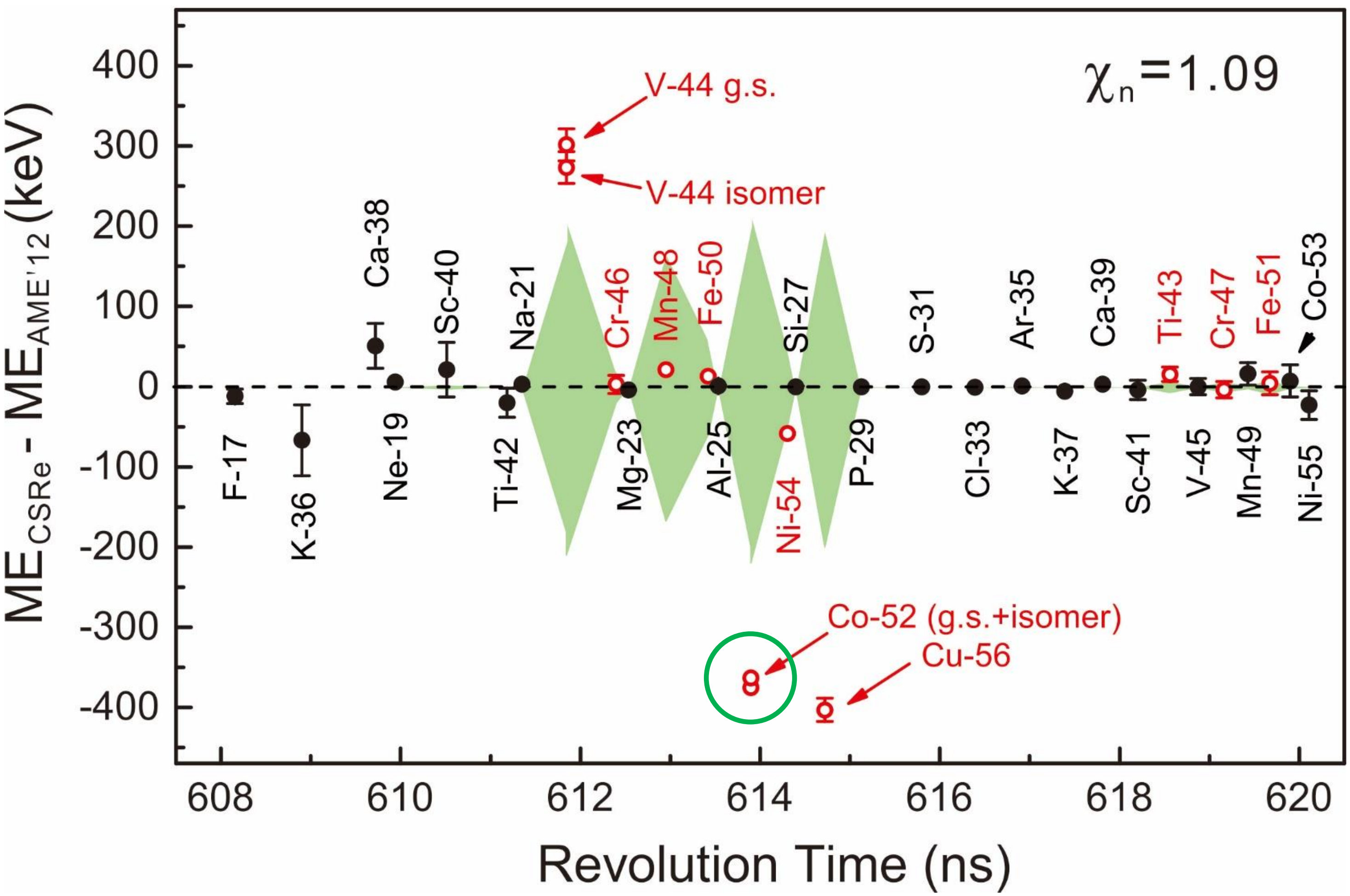
IMME d-coefficient



2. Some issues in nuclear astrophysics and NS



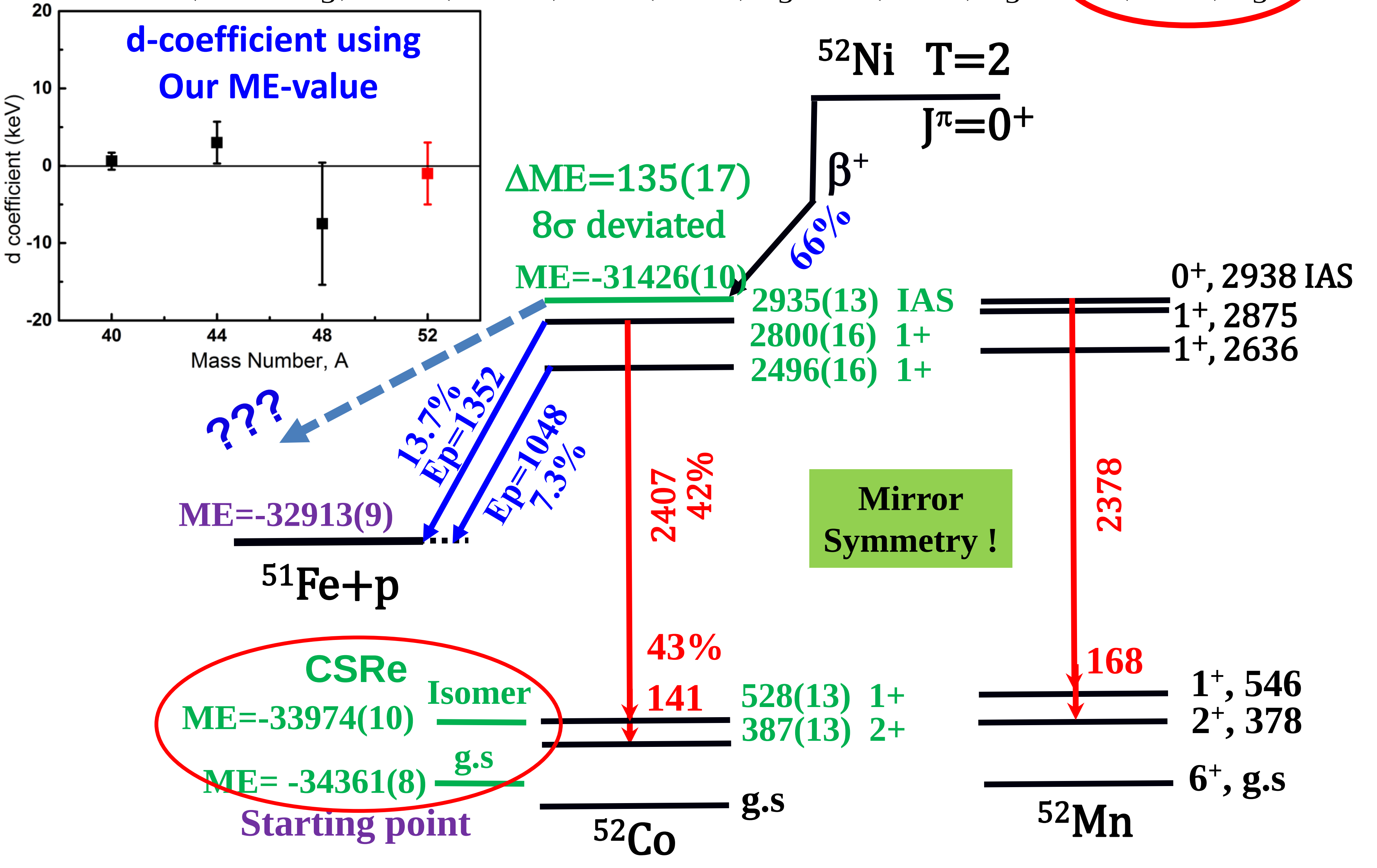
2. Some issues in nuclear astrophysics and NS



ME(^{52g}Co)= –34361(8) keV, ME(^{52m}Co)= –33974(10) keV

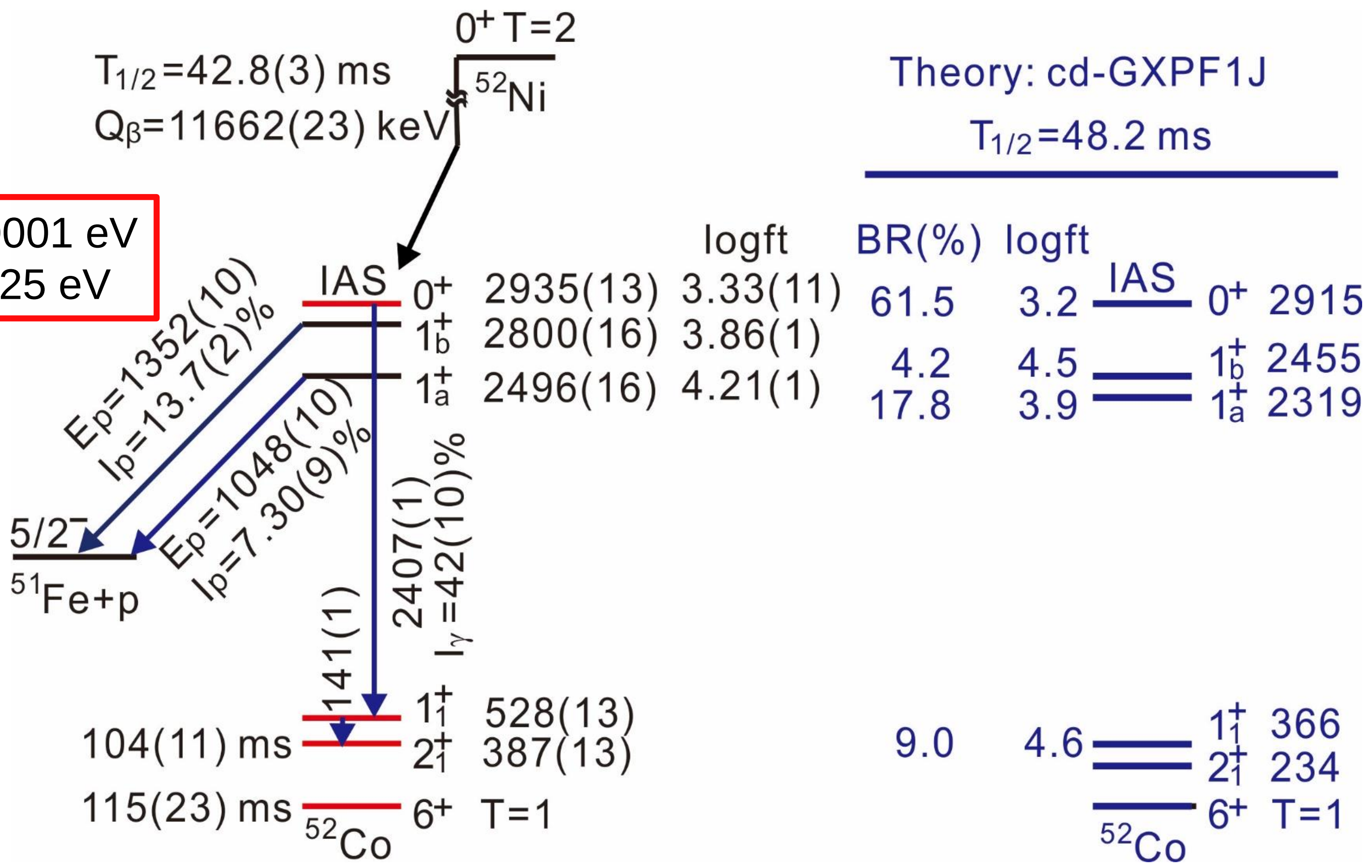
2. Some issues in nuclear astrophysics and NS

$$M(T,A,T_3) = a(T,A) + b(T,A)T_3 + c(T,A)T_3^2 + d(T,A)T_3^3$$



Comparison with theoretical calculations

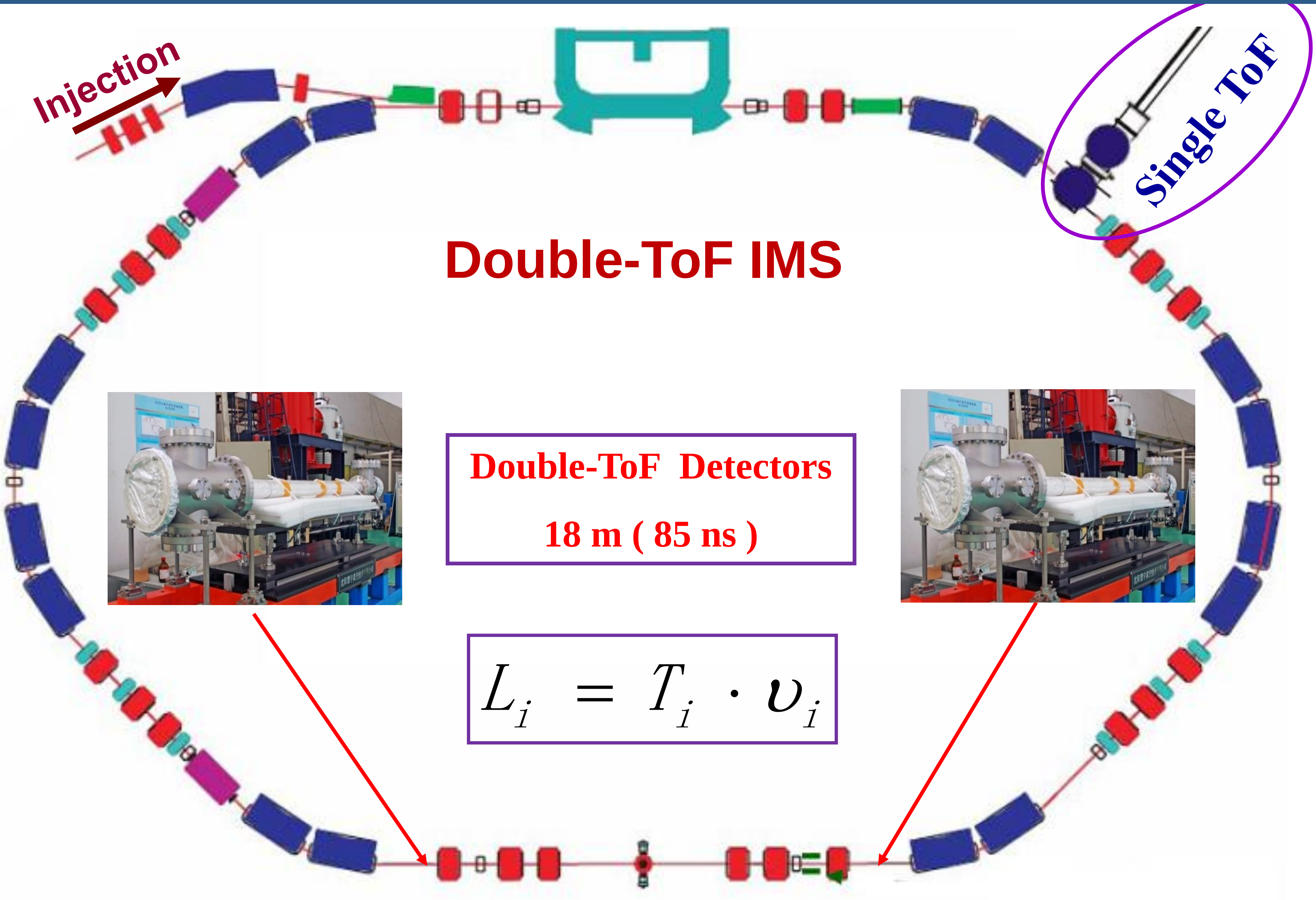
Γp=0.0001 eV
Γγ=0.25 eV



3. Summary and perspectives

1) **IMS becomes available in CSRe-Lanzhou and some results have been obtained in the very neutron-deficient region below A=100**
2) **Some issues in the studies of nuclear astrophysics and nuclear structure have been touched on the basis of mass measurements in CSRe.**
3) **In-ring decay is observed and partial half-life measured which shows the capability of IMS at CSRe**
4) **Mass measurement for the shortest state of 70 μs is achieved which may be a "record " in the IMS technique**
5) **We will develop and use a Double-ToF IMS technique, which may further improve the precision of IMS in CSRe.**

3. Summary and perspectives



Double-ToF IMS

Double-ToF Detectors

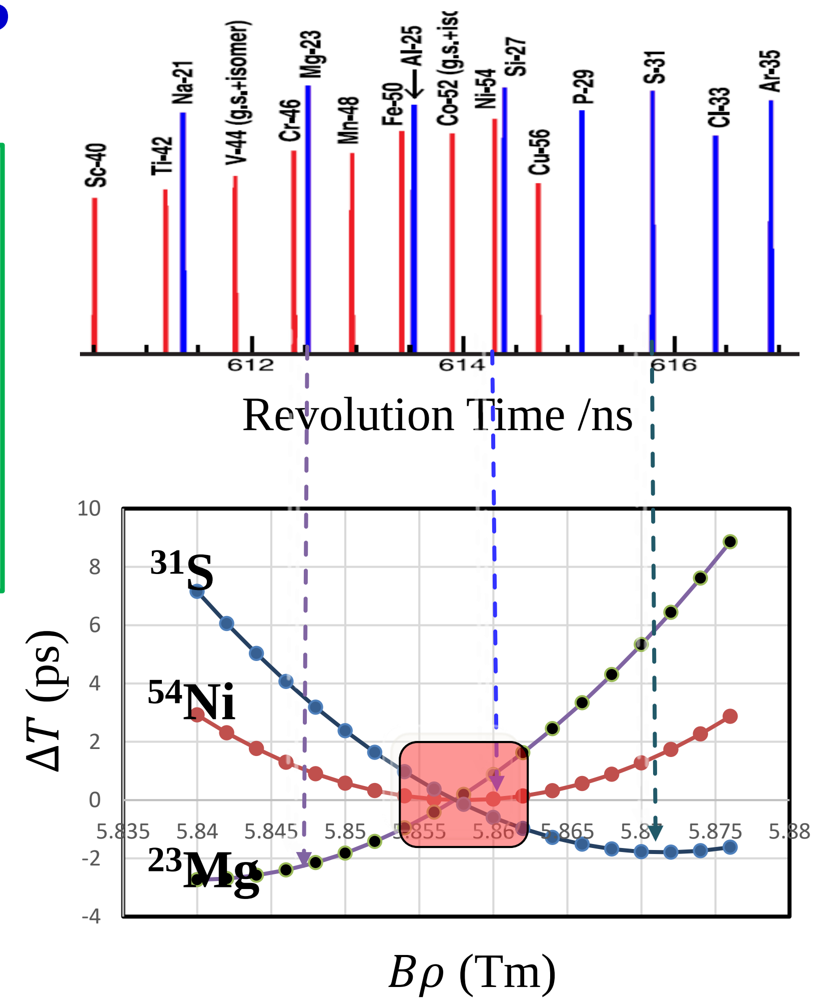
18 m (85 ns)

$$L_i = T_i \cdot \upsilon_i$$

Why velocity measurement ?

For a specific ion species, the $B\rho$ (or orbit length C, or vilocity v) is not constant. it changes in the acceptance range $\Delta(B\rho)$, therefore the revolution time, T, changes according to:

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



Consequences:

T spectrum is broaden & non-symmetric due to $\Delta(B\rho)$ (or ΔC or Δv)

3. Summary and perspectives

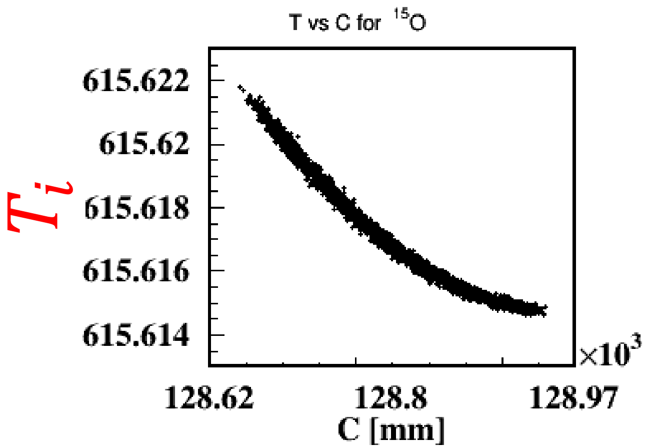
Principle:

If T_i and v_i are measured, we have $C_i = v_i \cdot T_i$,

Then the revolution time T_0^i at the ideal orbit length C_0=12880 cm can be deduced.

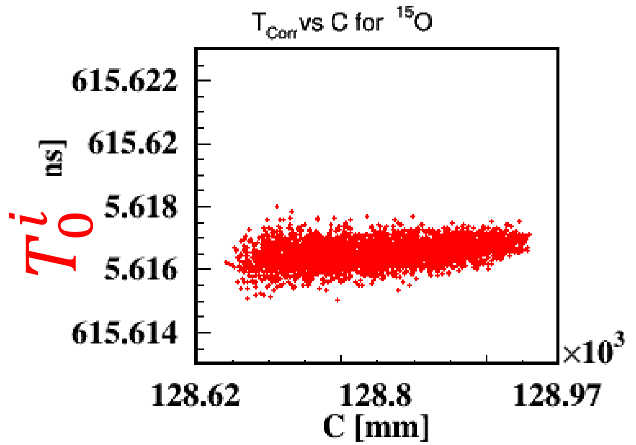
$$C_i = v_i \cdot T_i, \quad \gamma_i = 1/\sqrt{1-\beta_i^2}$$

$$T_0^i = T_i + T_i \cdot \left(1 - \frac{\gamma_t^2}{\gamma_i^2}\right) \cdot \frac{C_0 - C_i}{C_i}$$

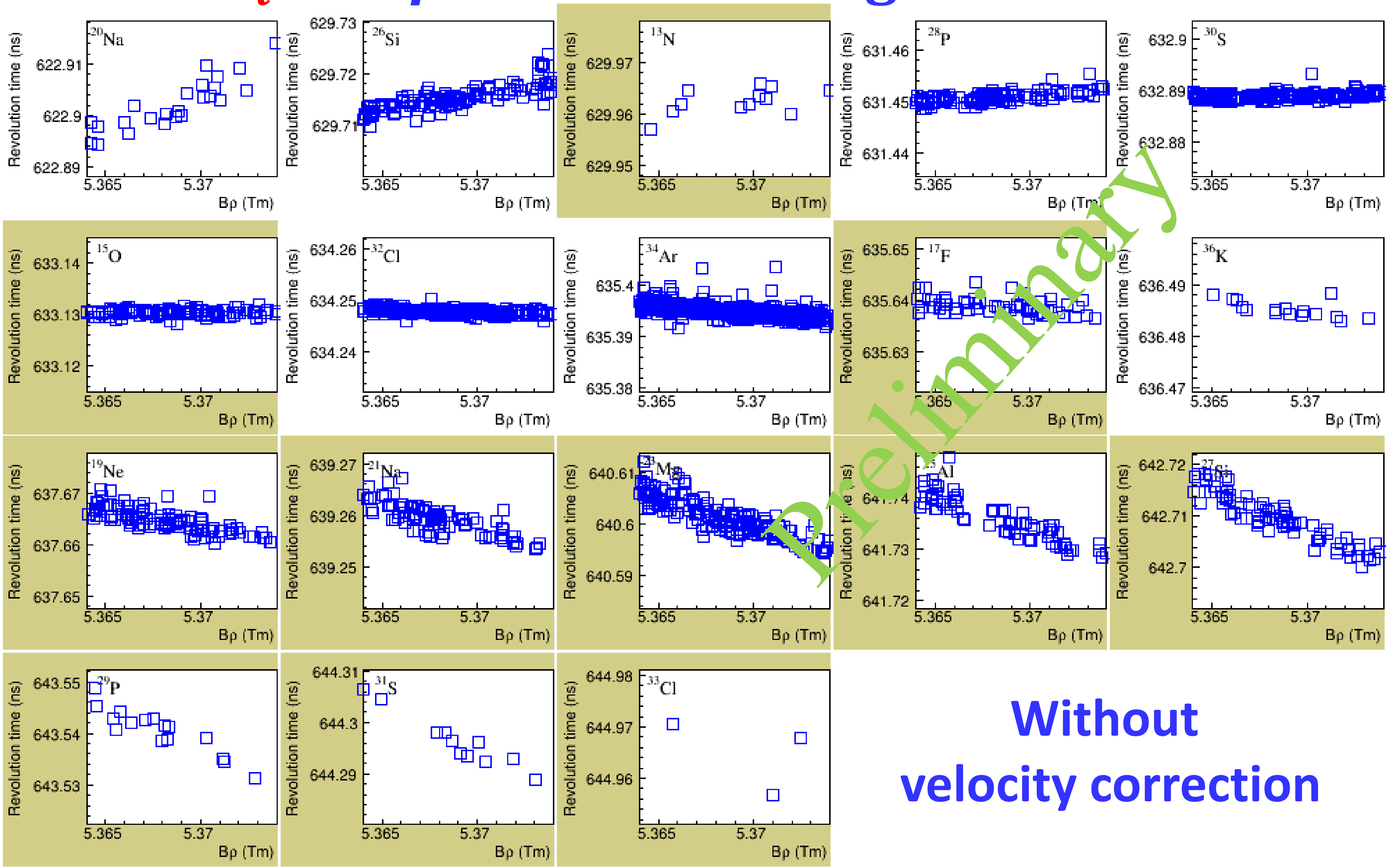


T_0^i @ C_0=12880cm

Simulation

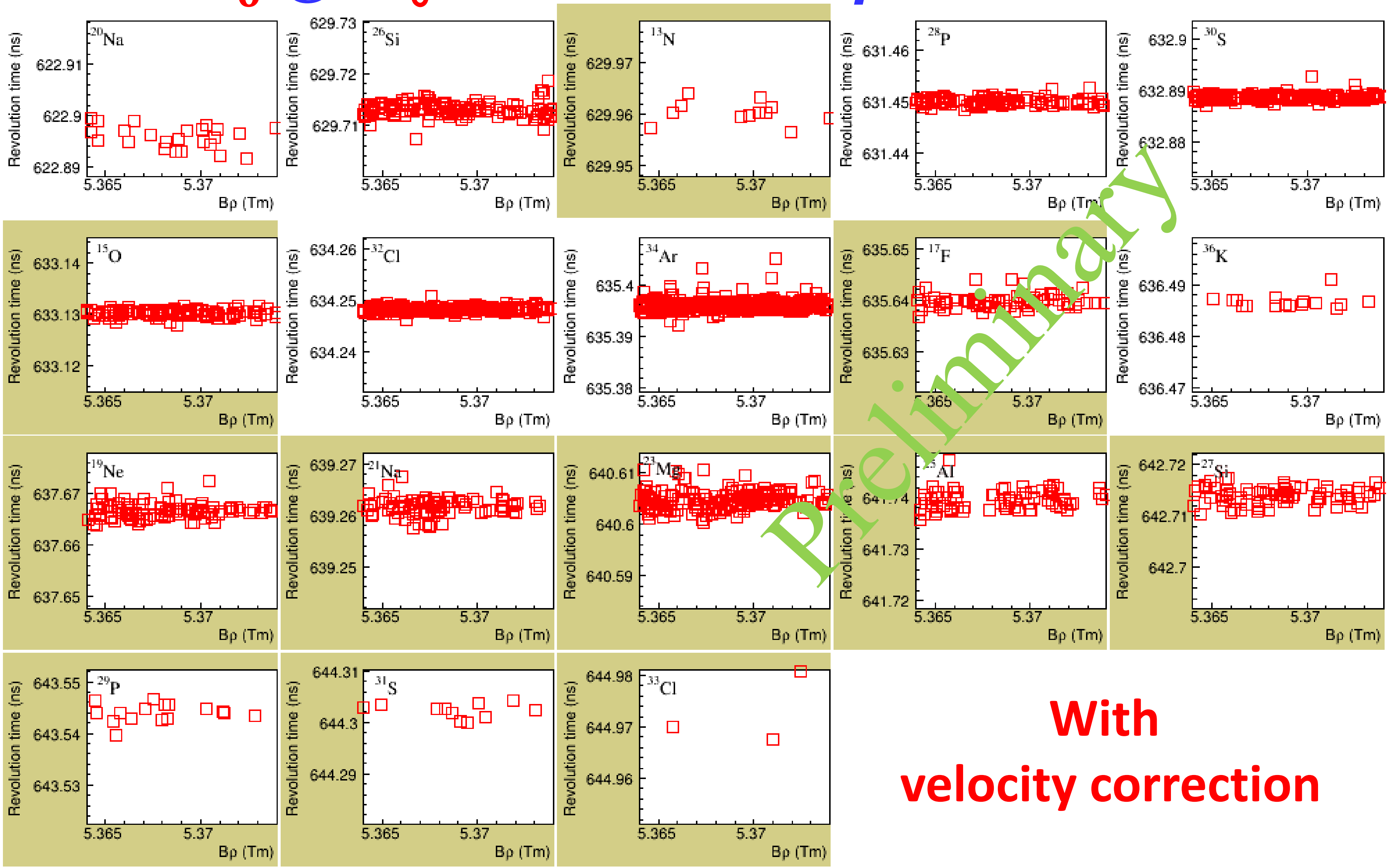


Plot of T_i vs $B\rho$ from ^{36}Ar fragmentation



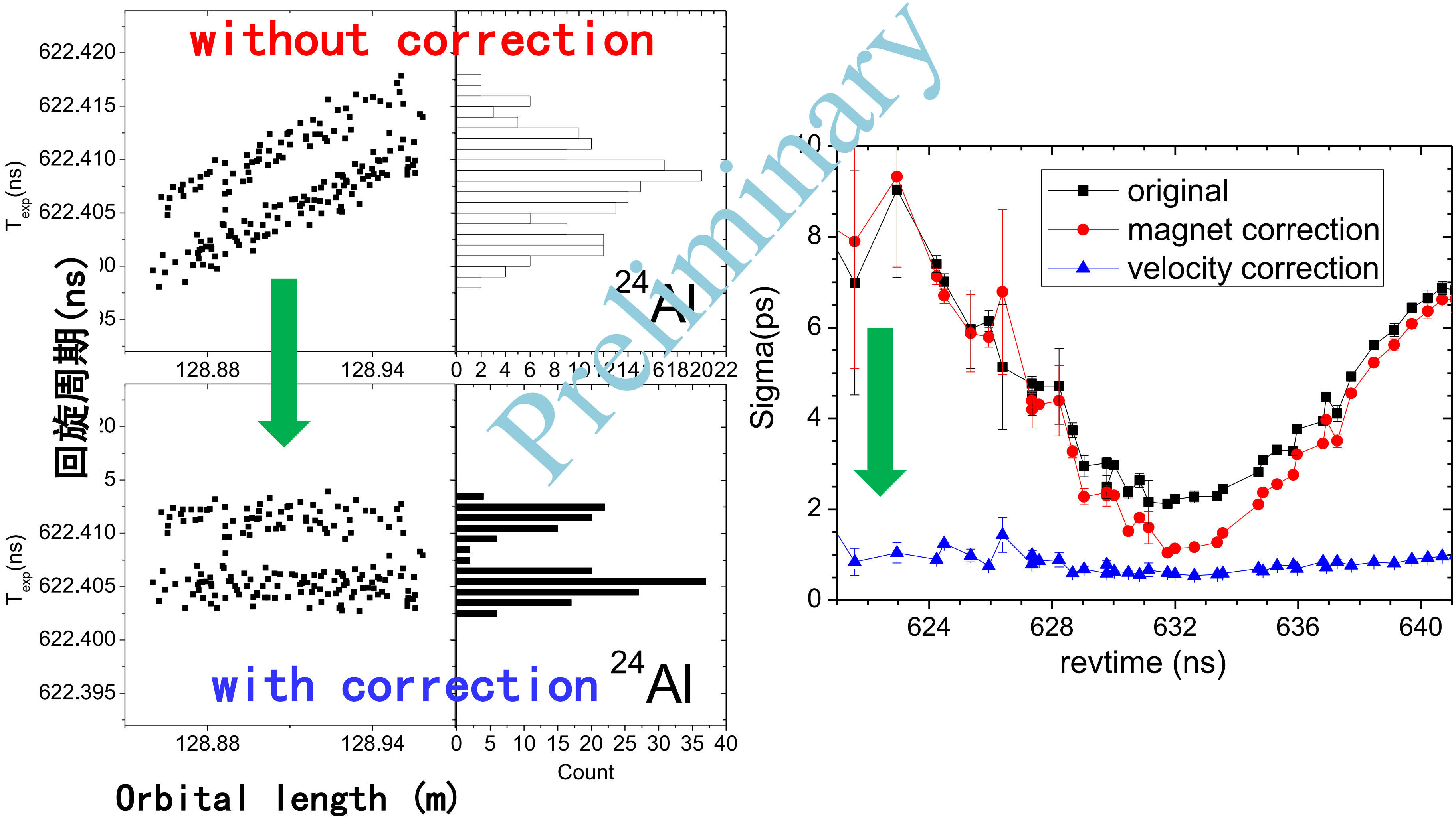
Without velocity correction

Plot of T_0^i @ C_0=12880cm vs $B\rho$

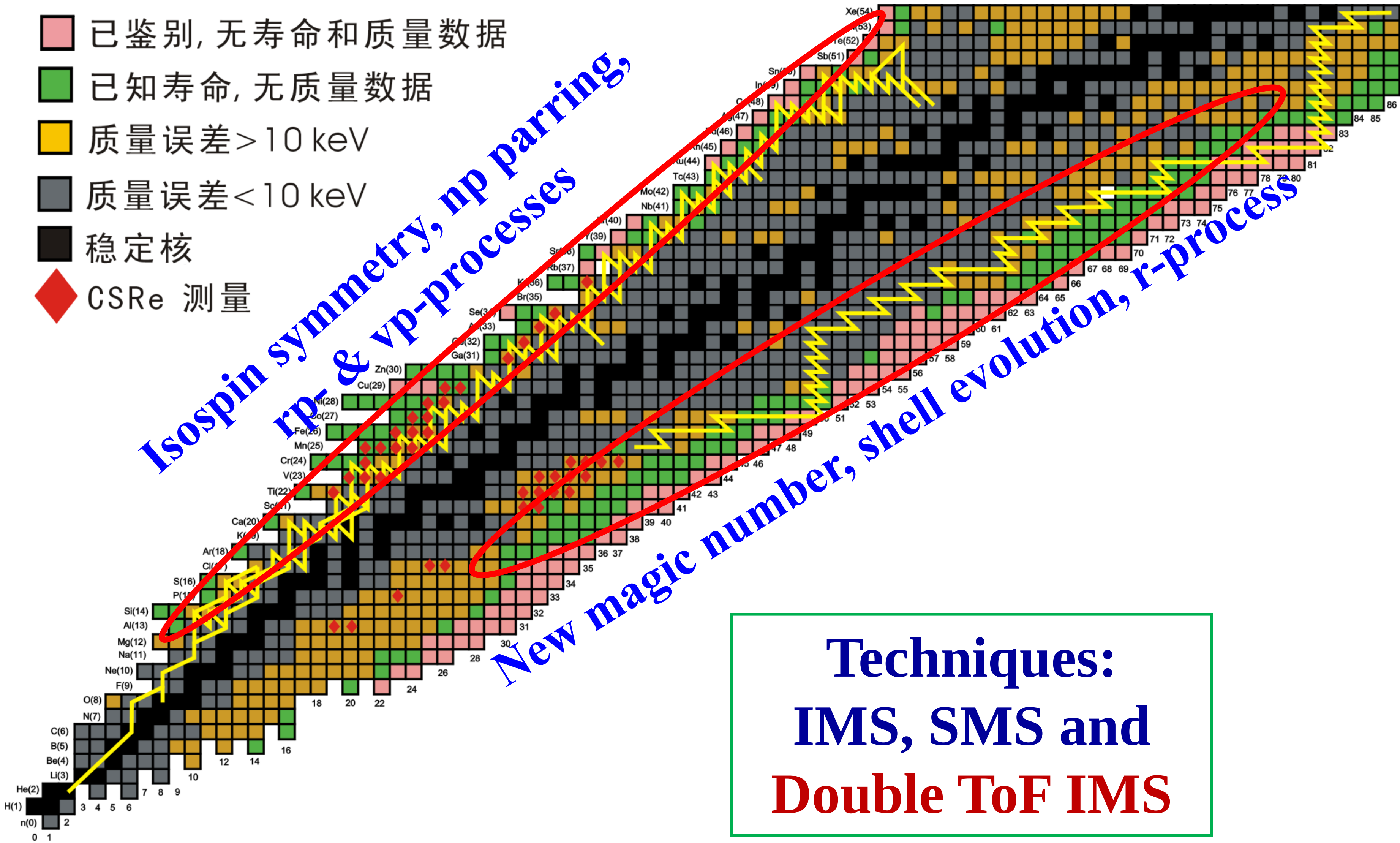


With velocity correction

Results from ^{58}Ni fragmentation

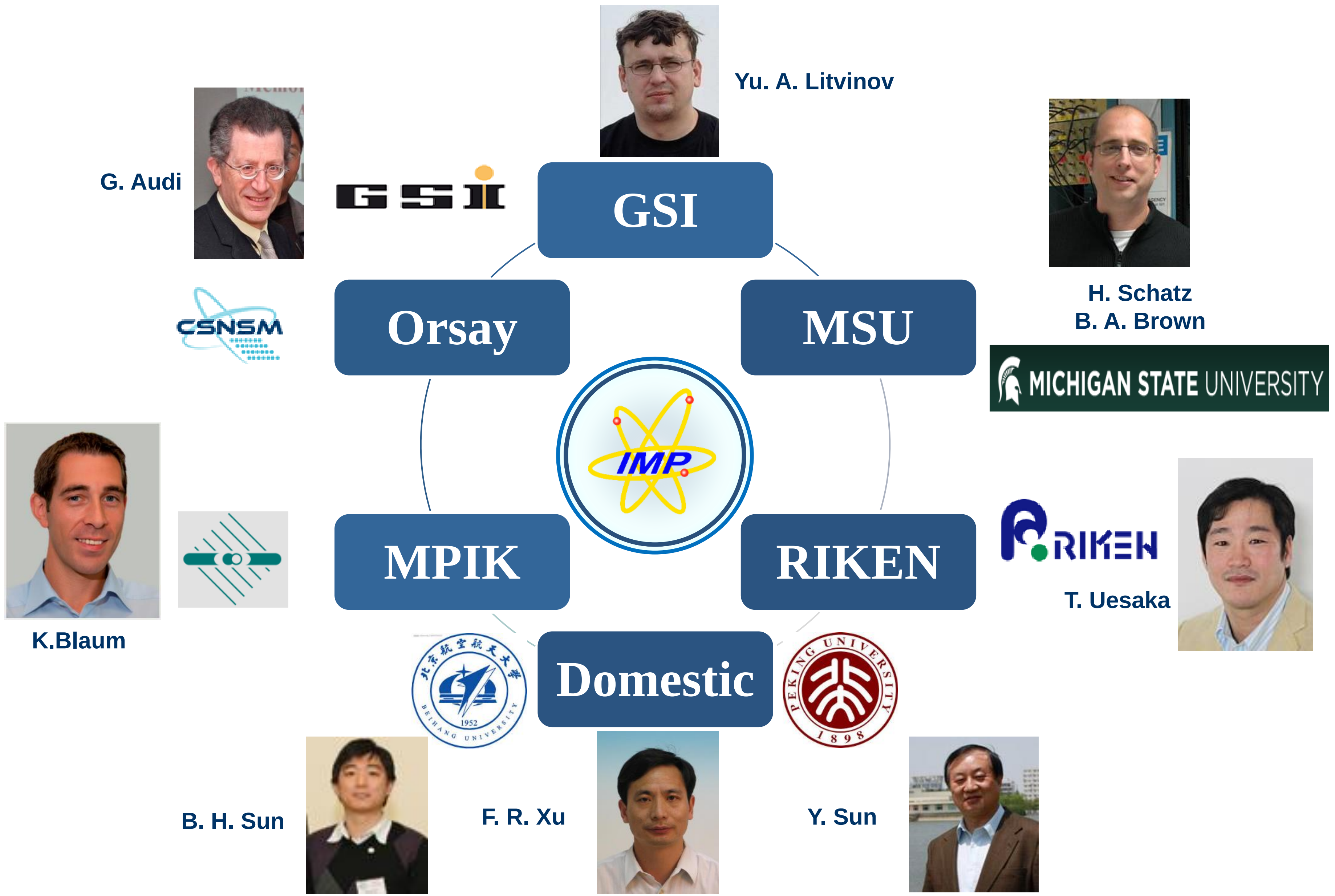


3. Summary and perspectives



Techniques:
IMS, SMS and
Double ToF IMS

CSR mass measurement collaboration



CSR mass measurement collaboration

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

Yu.A. Litvinov, S.Typel (GSI, Darmstadt, Germany)

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

T. Yamaguchi (Saitama University, Saitama, Japan)

A. Ozawa (University of Tsukuba, Japan)

Yhzhang@impcas.ac.cn