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

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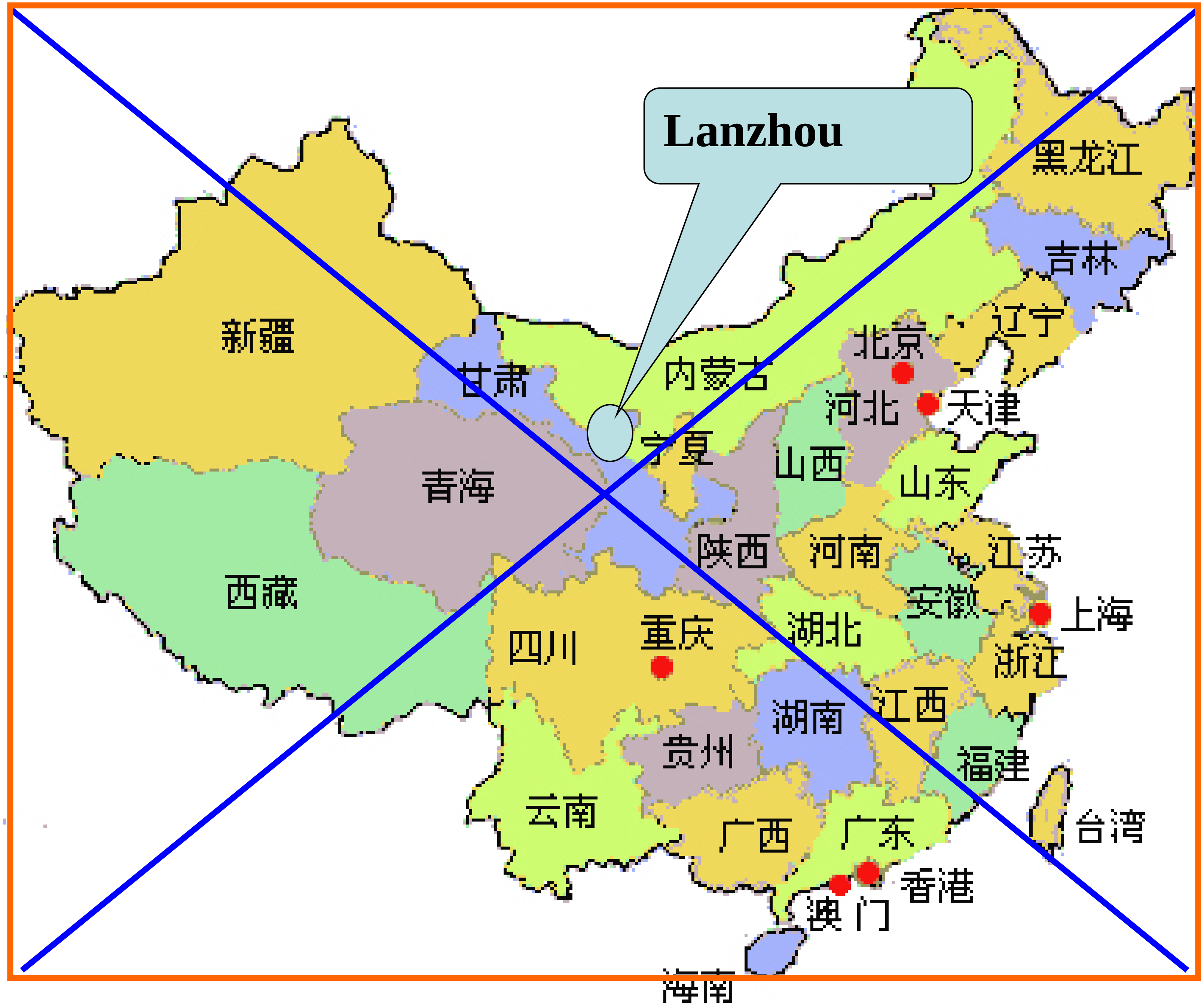
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山西
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青海
陕西
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台湾
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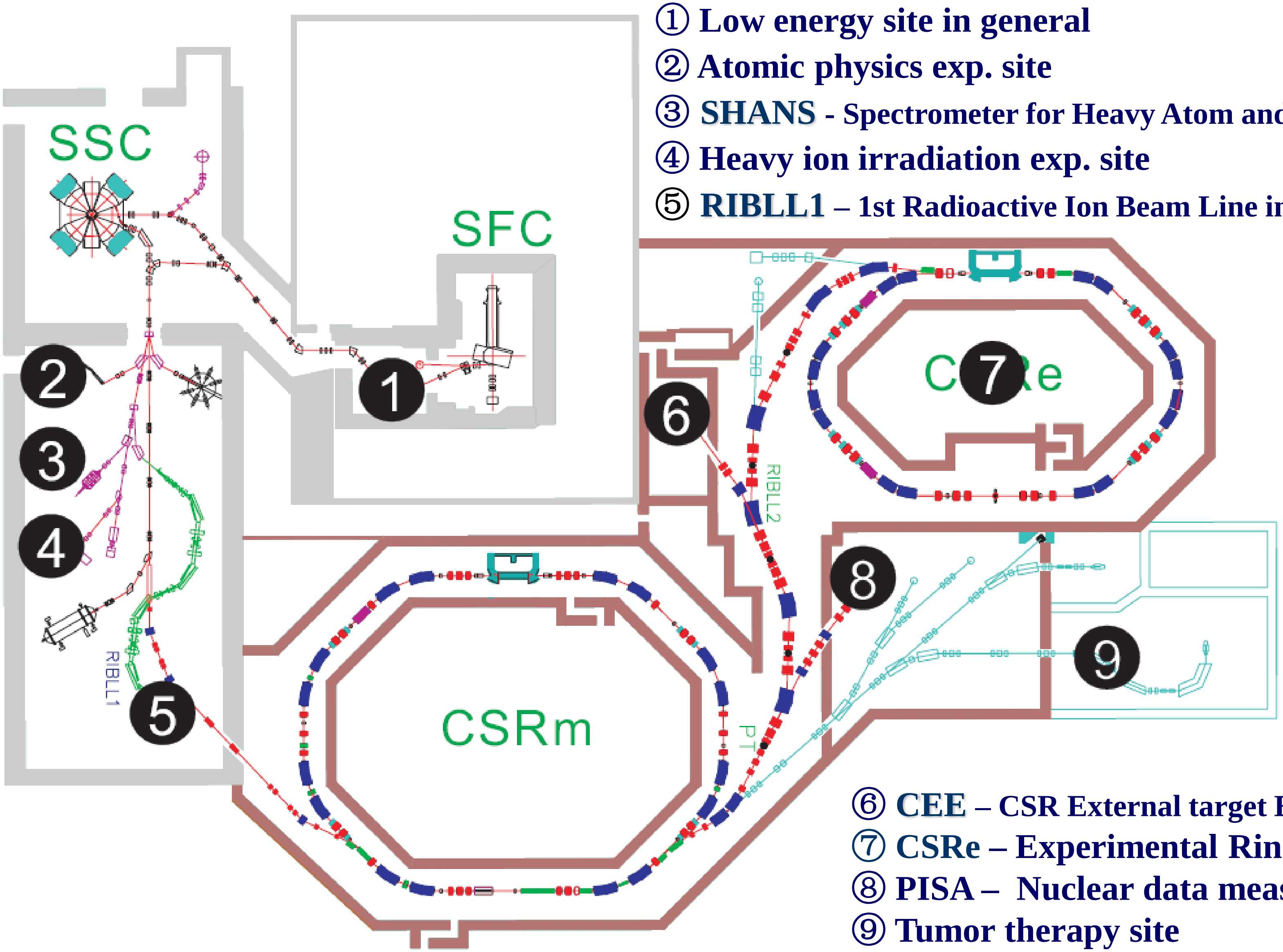
广东
香港
澳 门
海南

Lanzhou

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

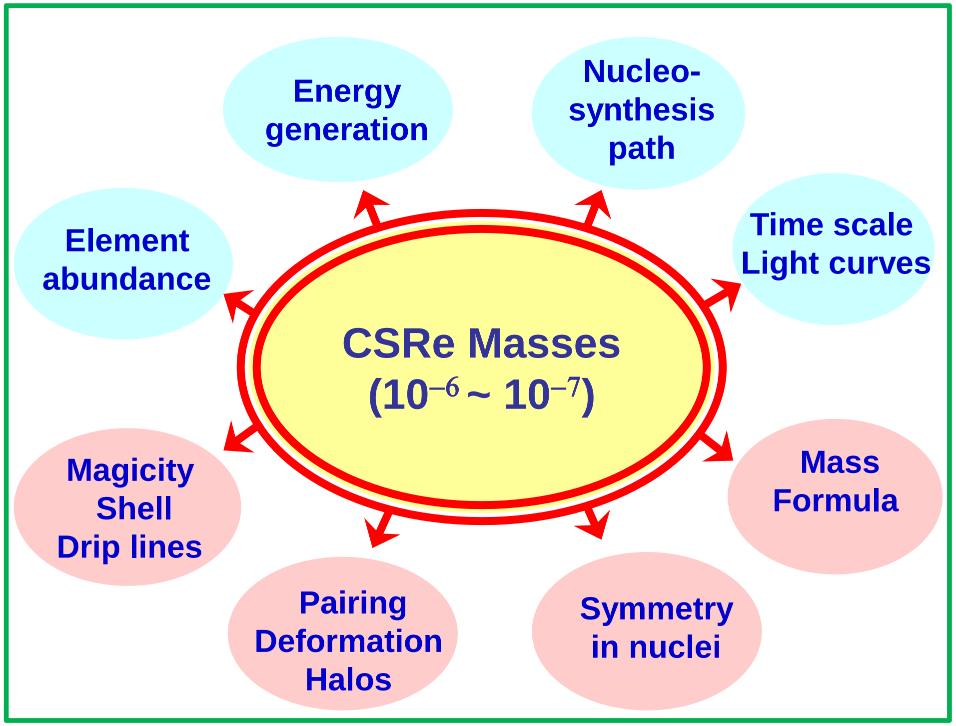
Outline

1. Introduction to mass measurements in CSRe
2. Impact on the studies of nuclear astrophysics
3. Impact on the studies of nuclear structure
4. 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	$\leq 10^{-11}$



CSRe Masses
($10^{-6} \sim 10^{-7}$)

Energy generation

Nucleo-synthesis path

Time scale
Light curves

Mass Formula

Symmetry in nuclei

Pairing
Deformation
Halos

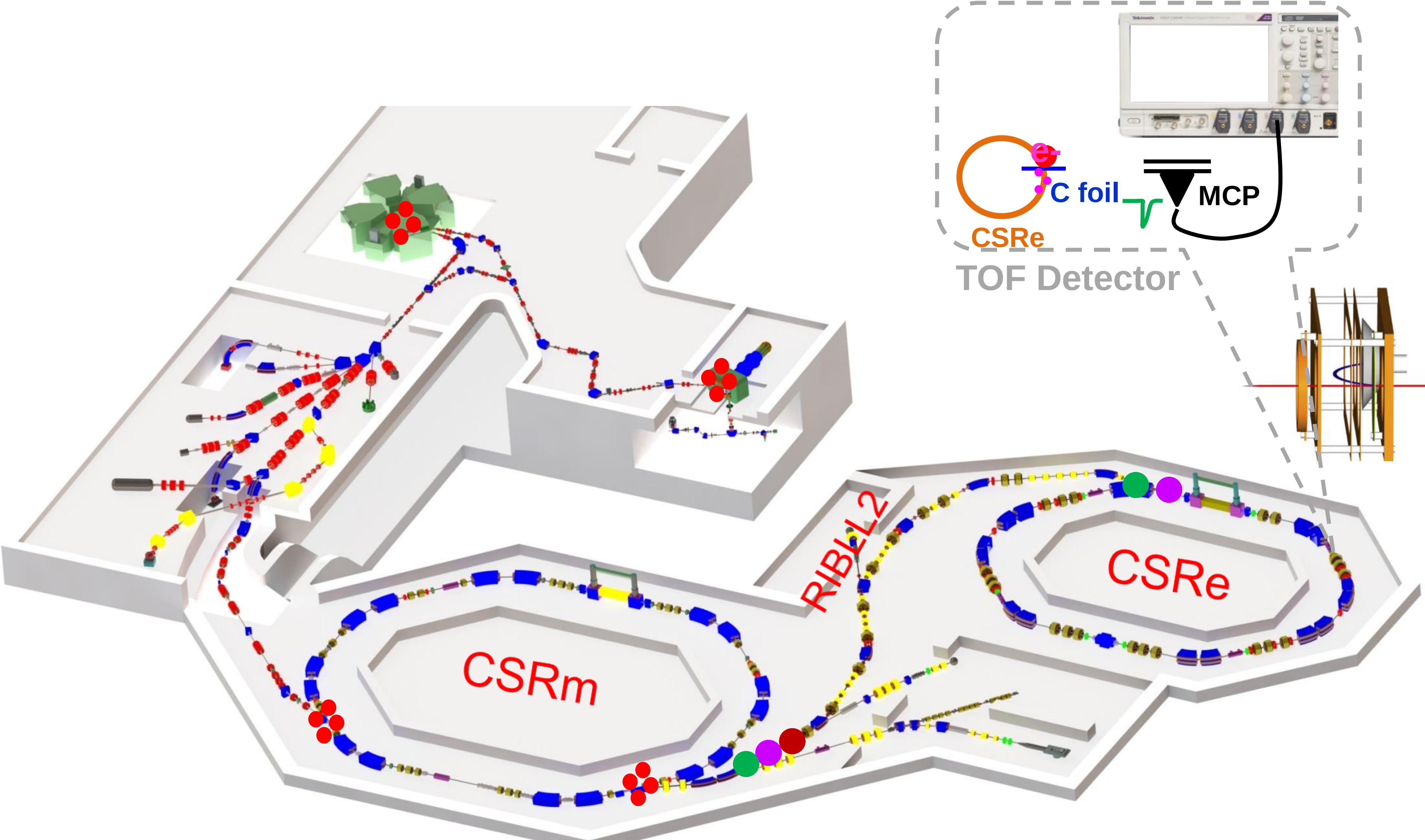
Magicity
Shell
Drip lines

Element abundance

One measurement
→ several issues

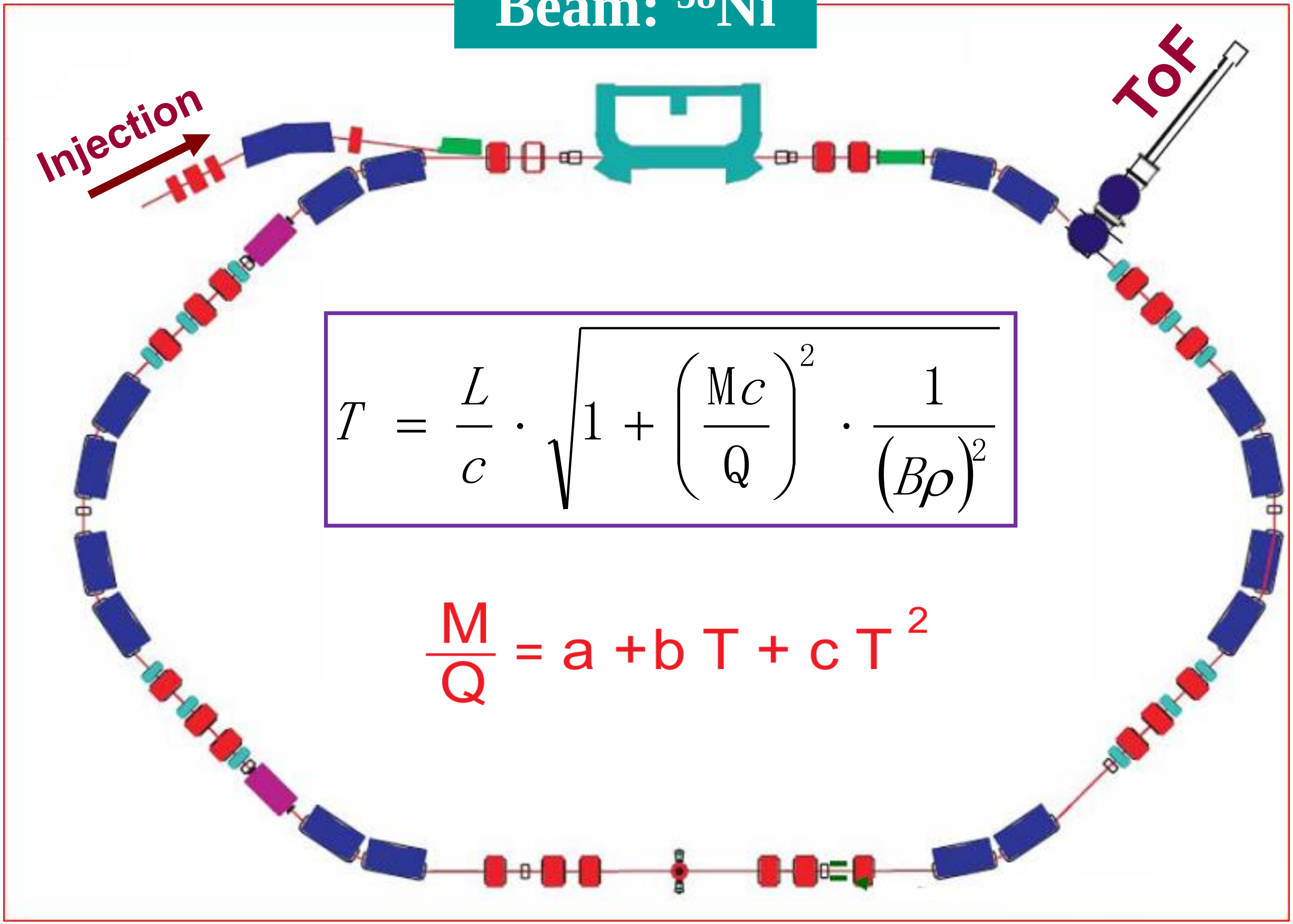
1. Introduction to mass measurements in CSRe

IMS Mass Measurements



1. Introduction to mass measurements in CSRe

Beam: ^{58}Ni

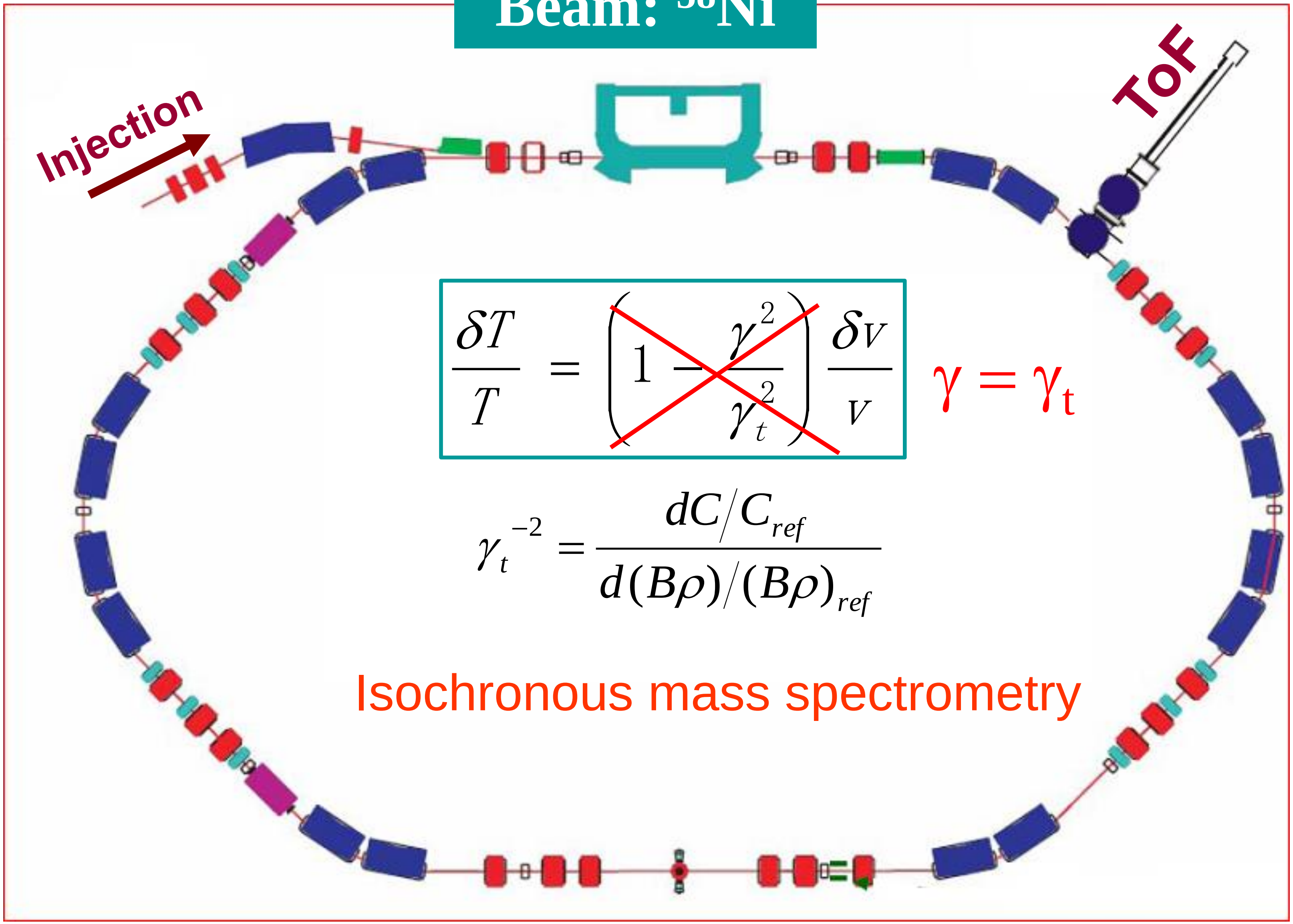


$$T = \frac{L}{c} \cdot \sqrt{1 + \left(\frac{Mc}{Q}\right)^2 \cdot \frac{1}{(B\rho)^2}}$$

$$\frac{M}{Q} = a + b\,T + c\,T^2$$

1. Introduction to mass measurements in CSRe

Beam: ^{58}Ni



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

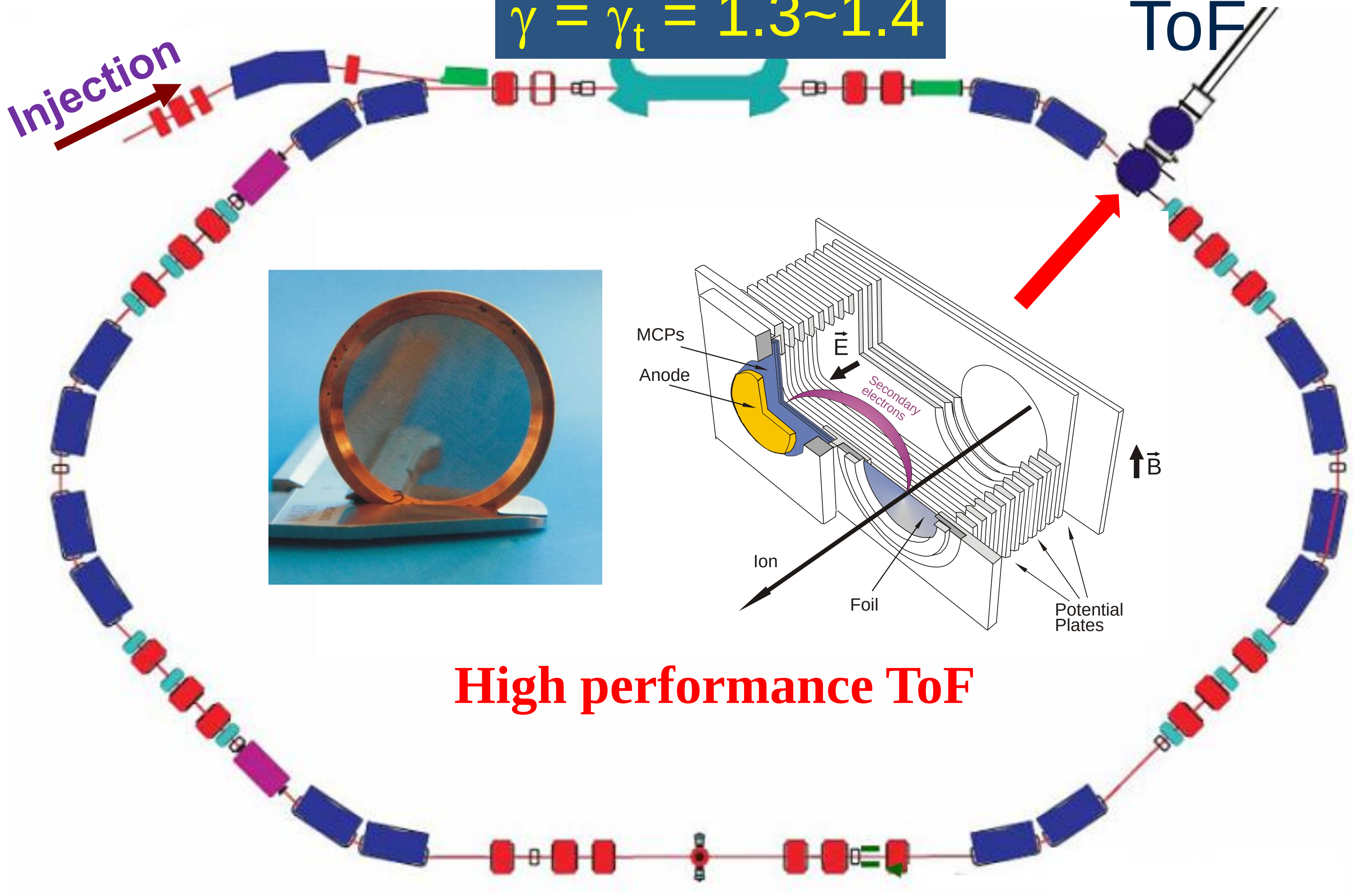
$\gamma = \gamma_t$

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

Isochronous mass spectrometry

1. Introduction to mass measurements in CSRe

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

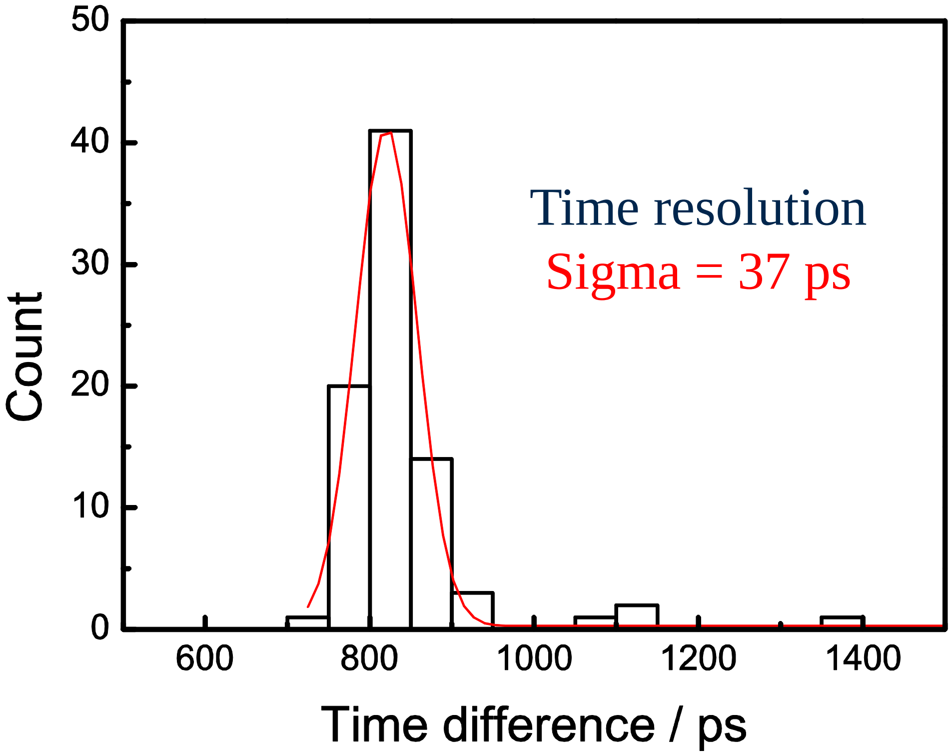


High performance ToF

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

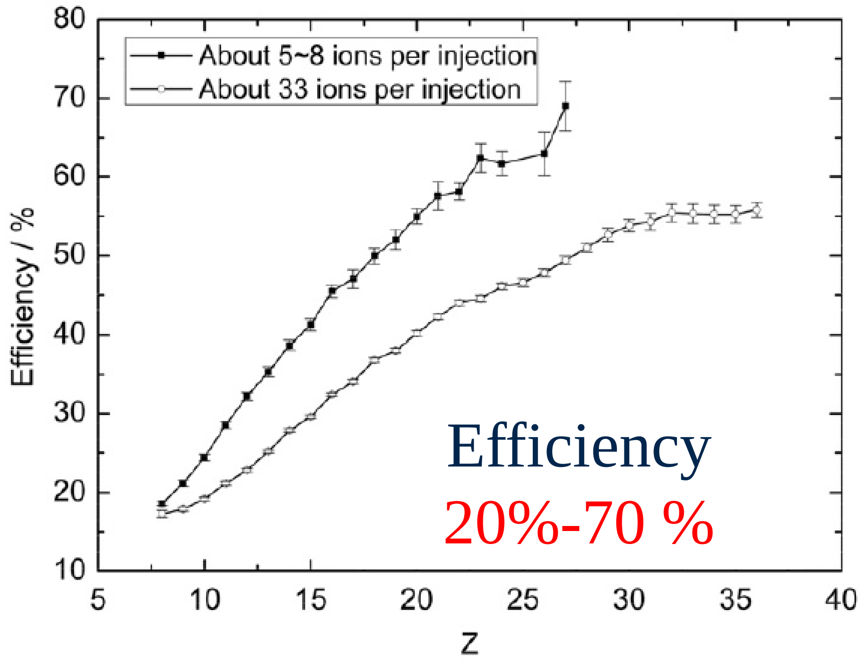
1. Introduction to mass measurements in CSRe

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



Time resolution

Sigma = 37 ps



Efficiency

20%-70 %

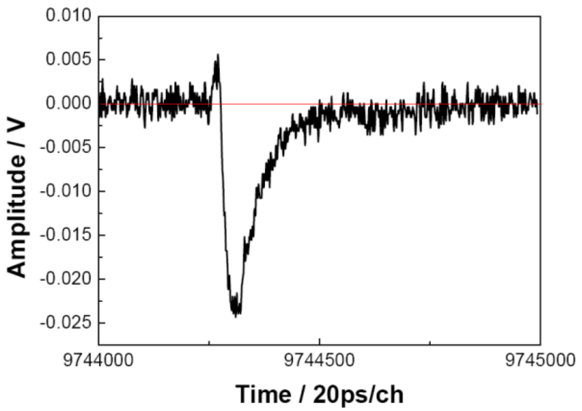
Fig. 7. Detection efficiency dependence on *Z* of ions and the number of ions circulating in the CSRe per injection.

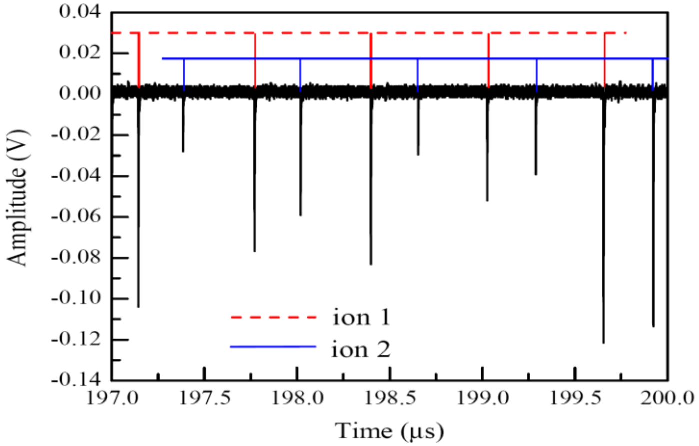
B. Mei et al., NIM A 624, 109 (2010)
X. L. Tu et al., NIM A 654, 213 (2011)
W. Zhang et al., NIM A 756, 1 (2014)

1. Introduction to mass measurements in CSRe

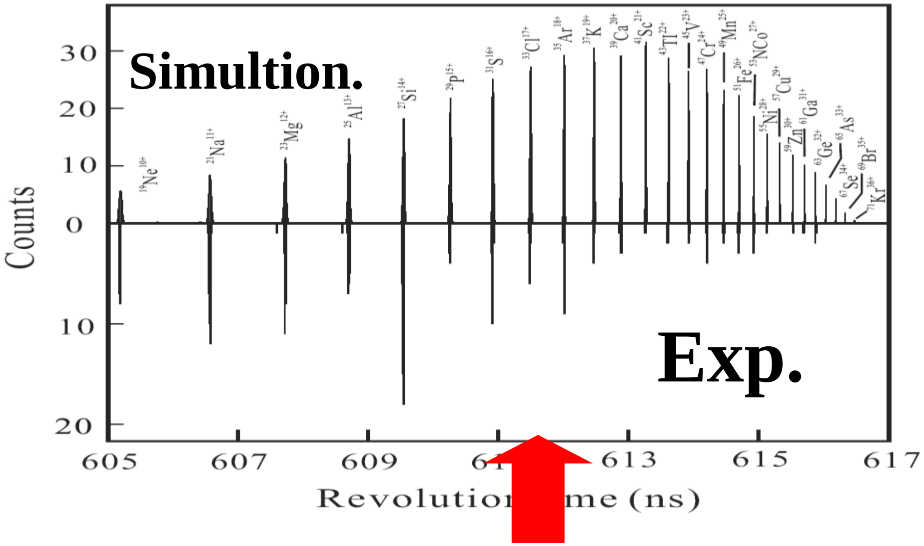
Beam: ^{78}Kr

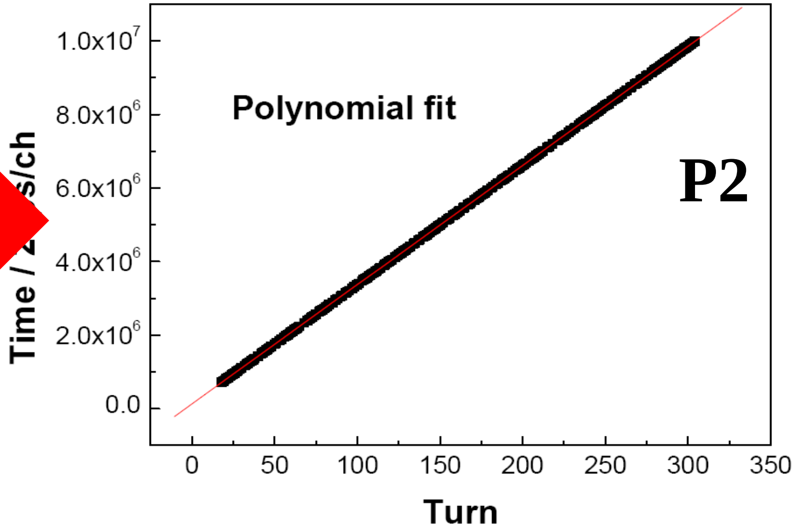
Signals in Oscilloscope



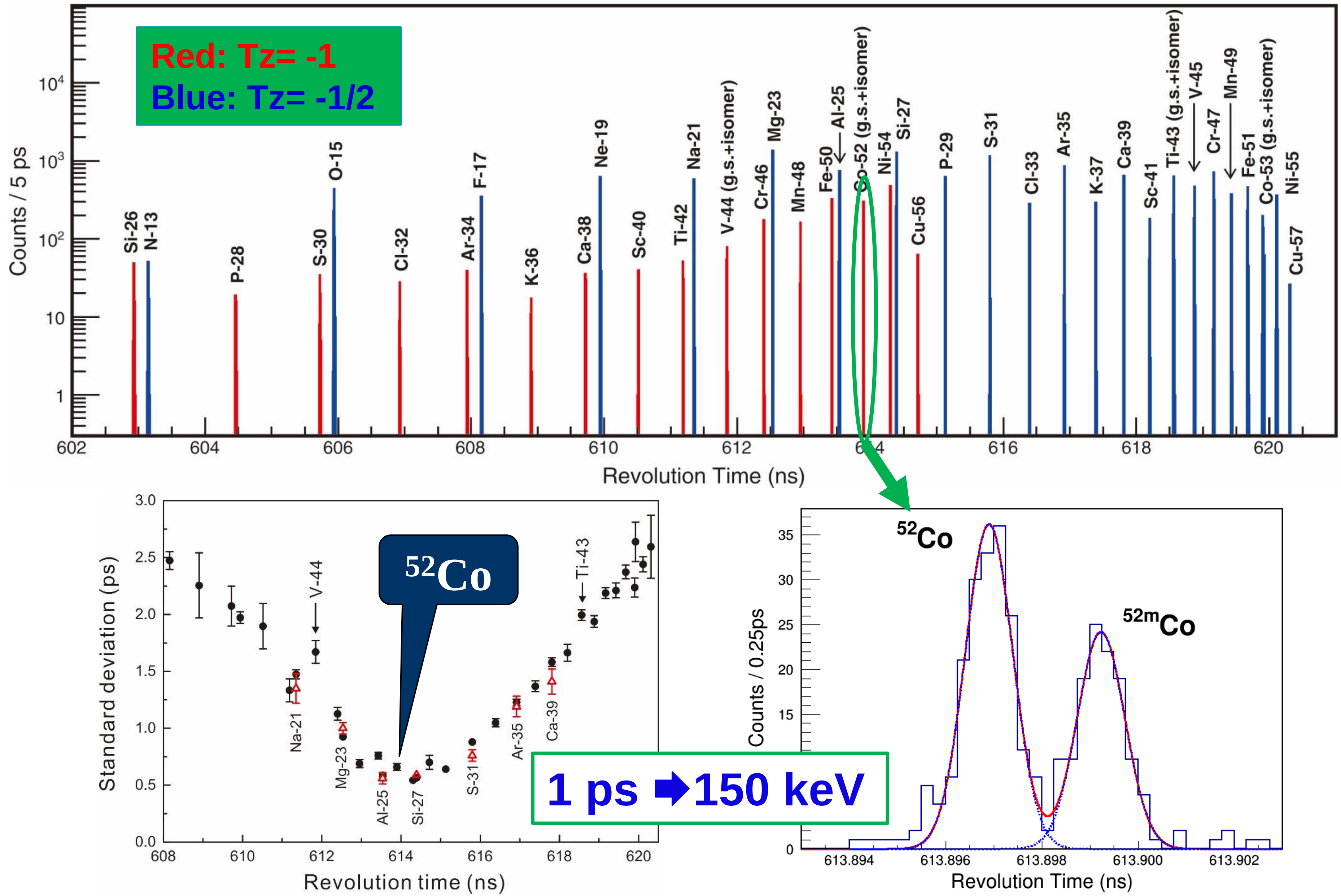


Ions Identification





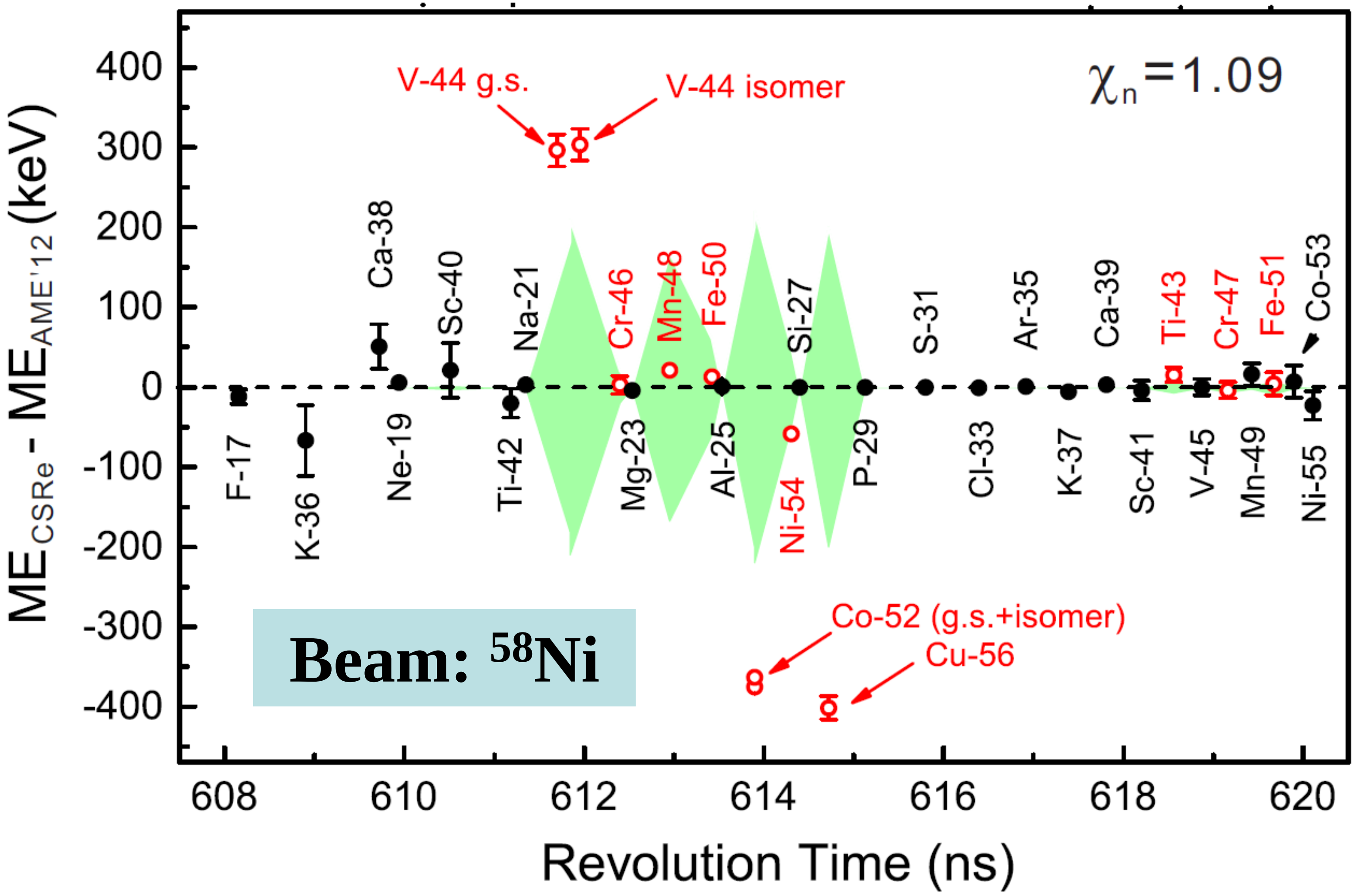
1. Introduction to mass measurements in CSRe



1 ps ➡150 keV

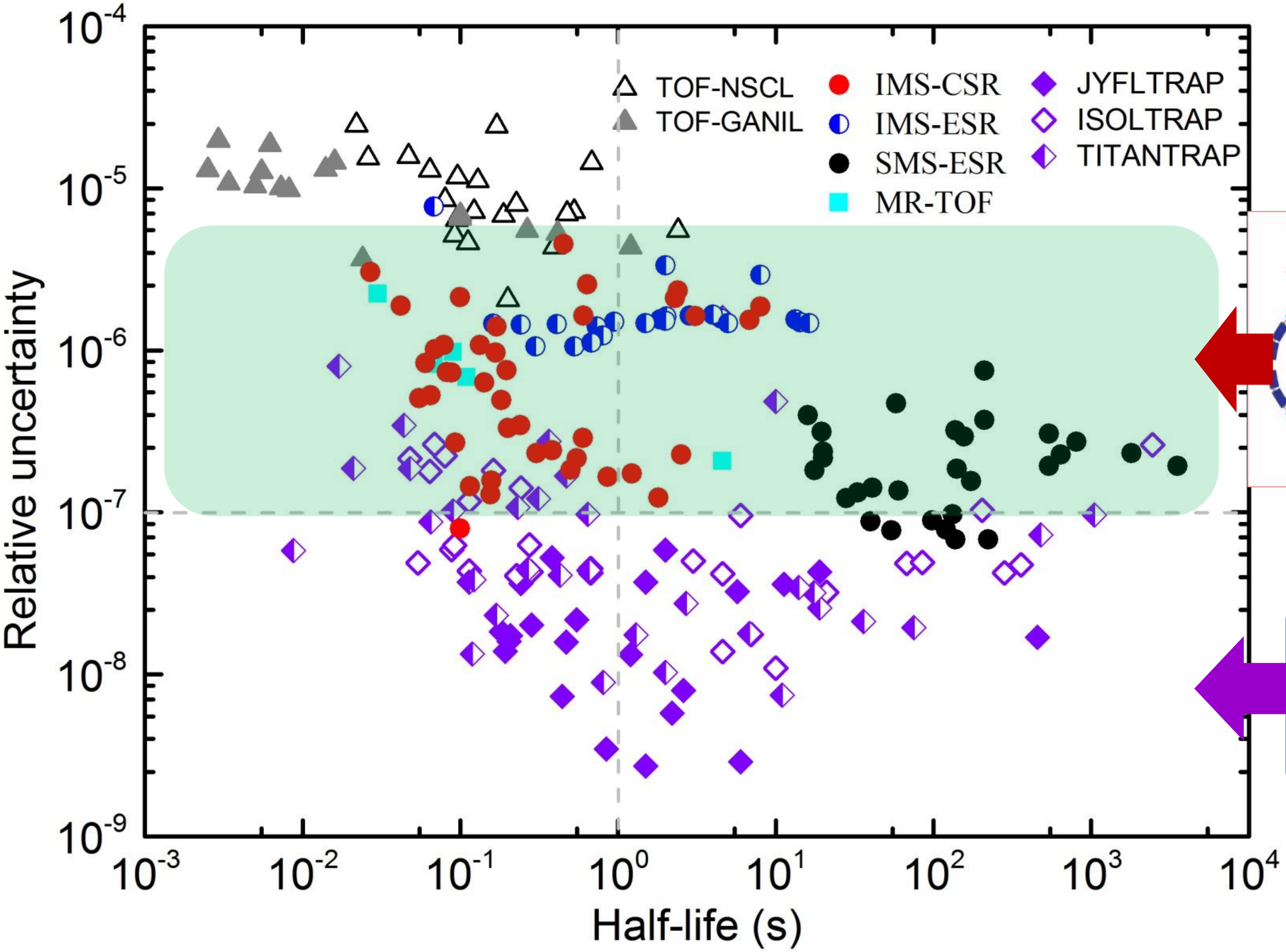
1. Introduction to mass measurements in CSRe

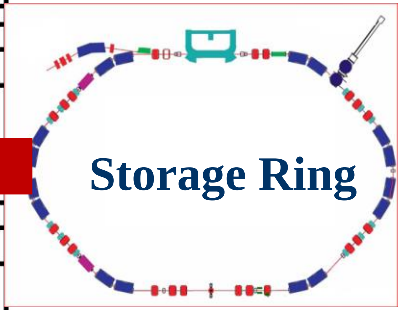
Self-checking using well-known mass nuclei



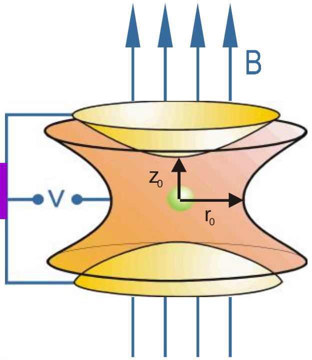
1. Introduction to mass measurements in CSRe

Precisions of new masses since 2010





Storage Ring



1. Introduction to mass measurements in CSRe

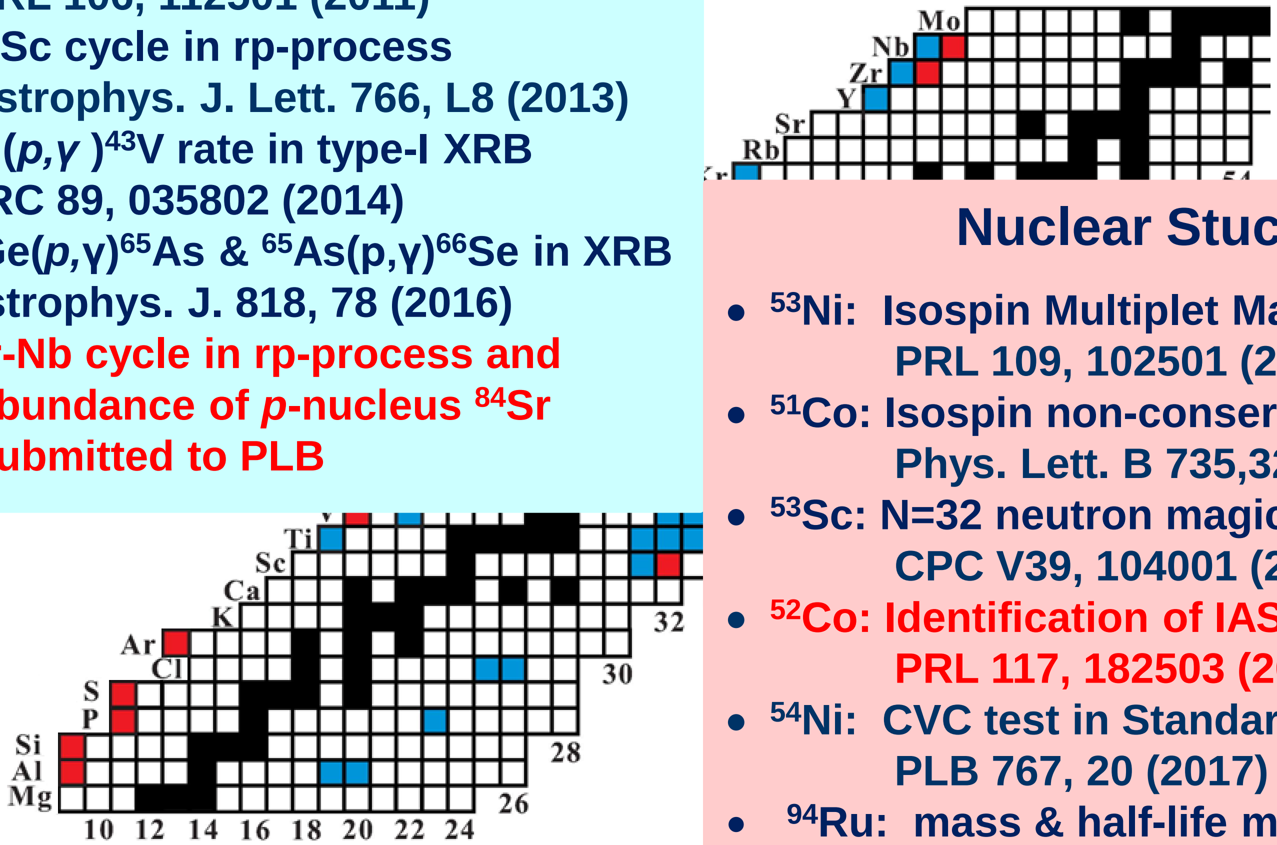
Primary beams: ^{36}Ar, ^{40}Ar, ^{58}Ni×3, ^{78}Kr ×2, ^{86}Kr, ^{112}Sn×2

Nuclear Astrophysics

- ^{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 and
  Abundance of *p*-nucleus ^{84}Sr
  Submitted to PLB

🟦 **Precision improved**

🟥 **Measured for the first time**

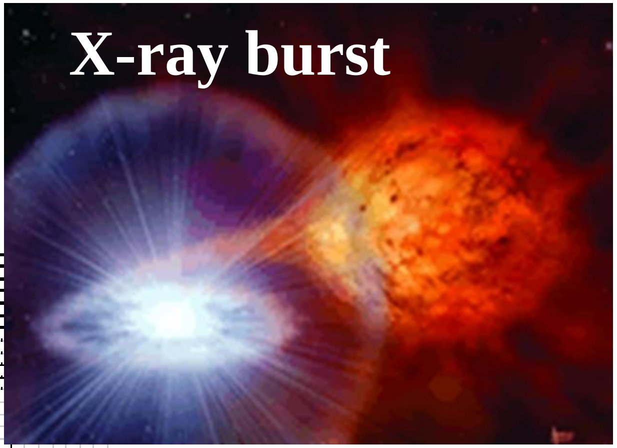


Nuclear Stuctrue

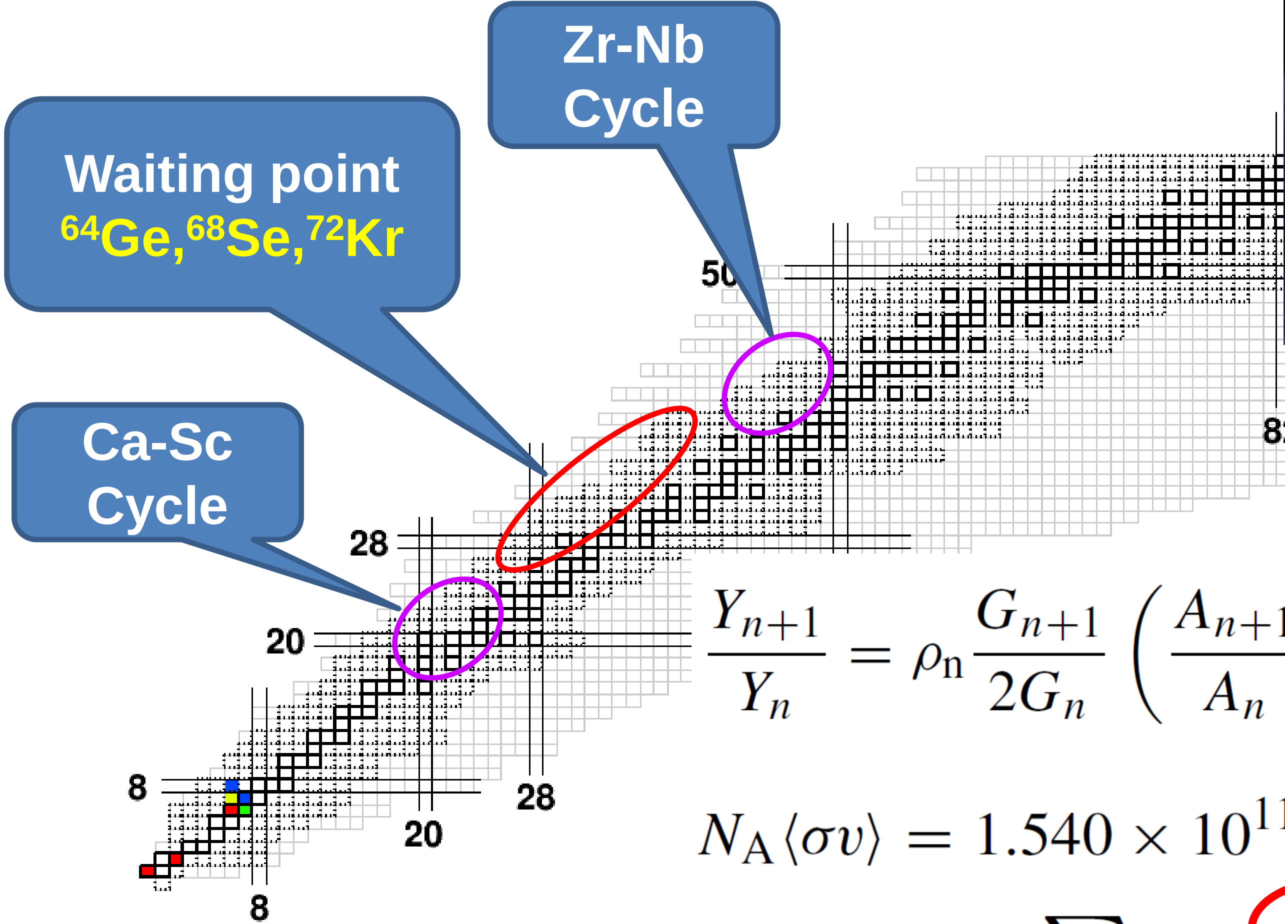
- ^{53}Ni: Isospin Multiplet Mass Equation
  PRL 109, 102501 (2012)
- ^{51}Co: Isospin non-conserving forces
  Phys. Lett. B 735,327 (2014)
- ^{53}Sc: N=32 neutron magic number
  CPC V39, 104001 (2015)
- ^{52}Co: Identification of IAS & β^+/EC decay
  PRL 117, 182503 (2016)
- ^{54}Ni: CVC test in Standard Model
  PLB 767, 20 (2017)
- ^{94}Ru: mass & half-life measurement
  PRC 96, 031303(R) (2017)

2. Impact on the studies of nuclear astrophysics

rp-process in X-ray burst



X-ray burst



Zr-Nb Cycle

Waiting point ^{64}Ge,^{68}Se,^{72}Kr

Ca-Sc Cycle

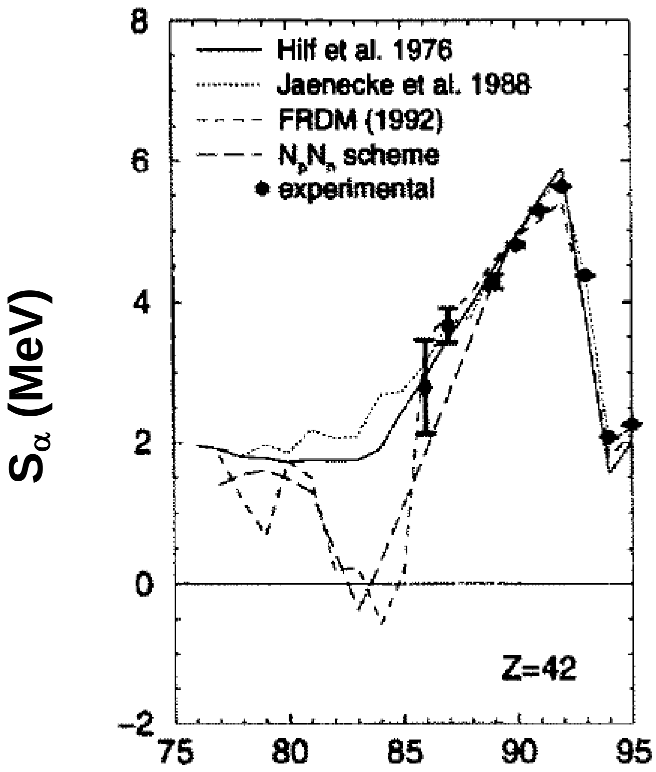
$$\frac{Y_{n+1}}{Y_n} = \rho_{\mathrm{n}} \frac{G_{n+1}}{2G_n} \left(\frac{A_{n+1}}{A_n} \frac{2\pi\hbar^2}{m_{\mathrm{u}}kT} \right)^{3/2} \exp\left(\frac{S_{n+1}}{kT} \right)$$

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

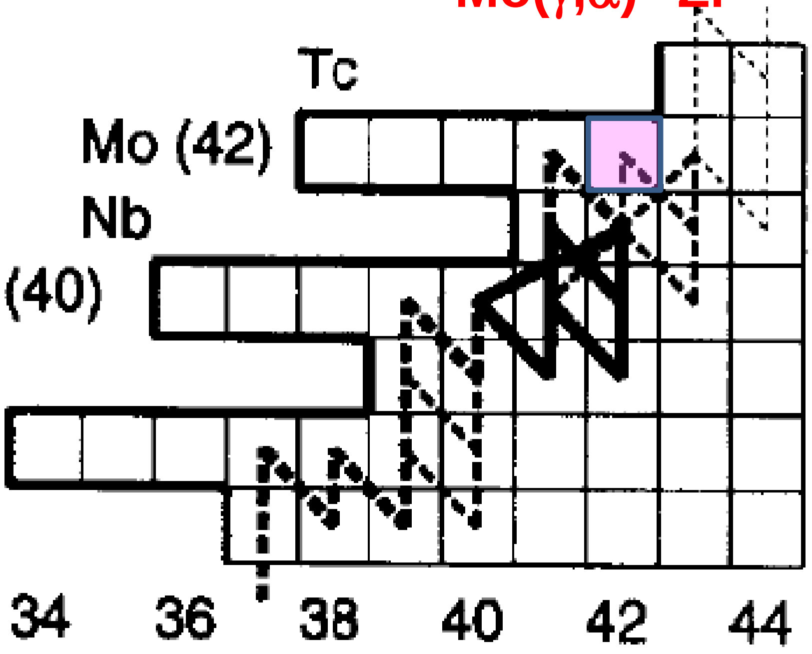
Nuclear inputs:
Masses, Half-lifes, Reaction rates

2. Impact on the studies of nuclear astrophysics

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



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

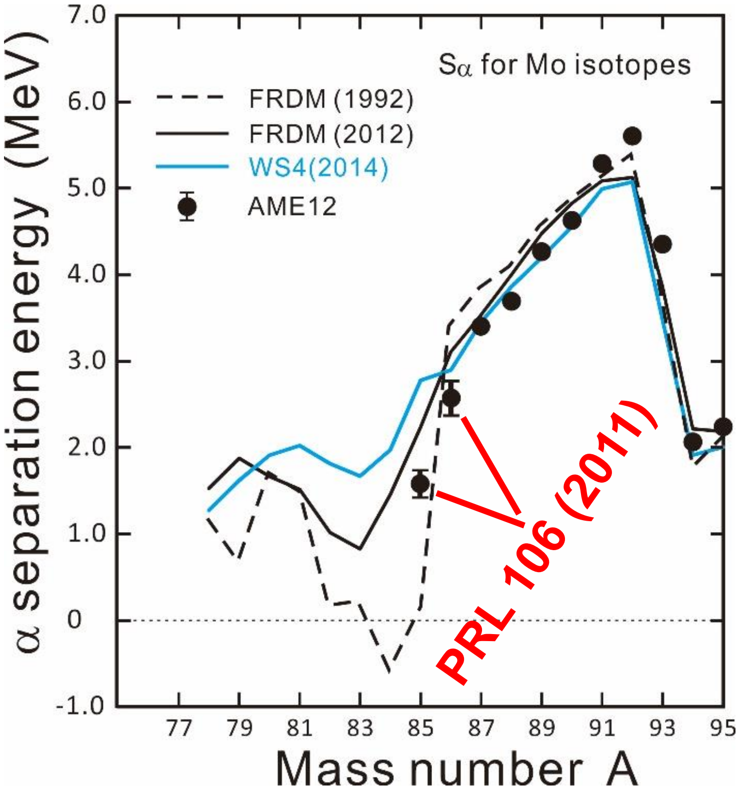


T=2 GK, $\rho=10^6$ g/cm^3

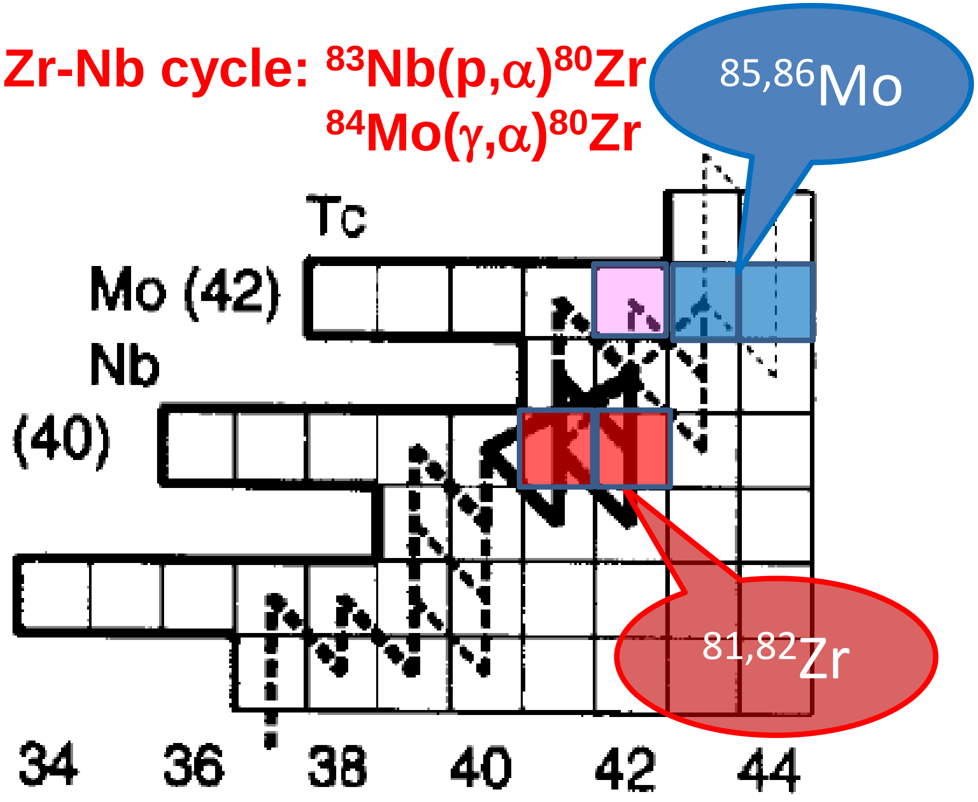
Zr-Nb cycle was proposed by H. Schatz et al, Phys. Rep. 294, 167 (1998) based on the FRDM mass prediction in 1992, which show a very low or even negative α separation energy of ^{84}Mo.

3. Impact on the studies of nuclear astrophysics

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



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



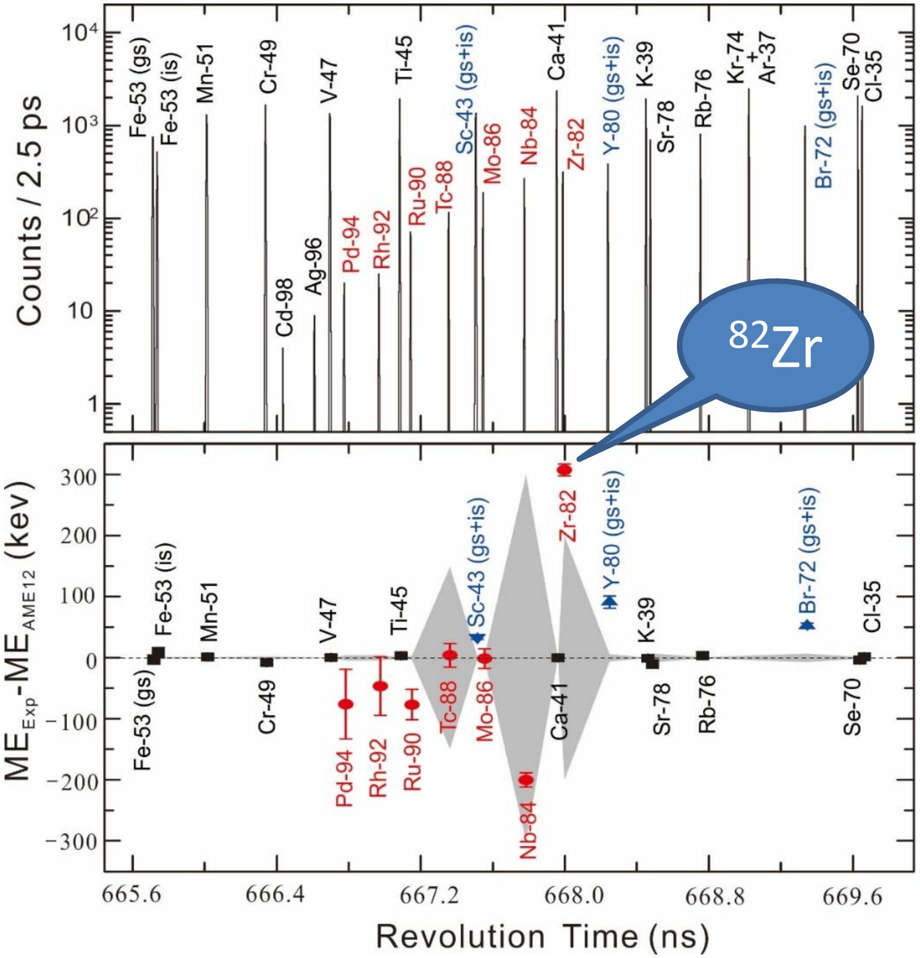
T=2 GK, ρ=10^{6} g/cm^{3}

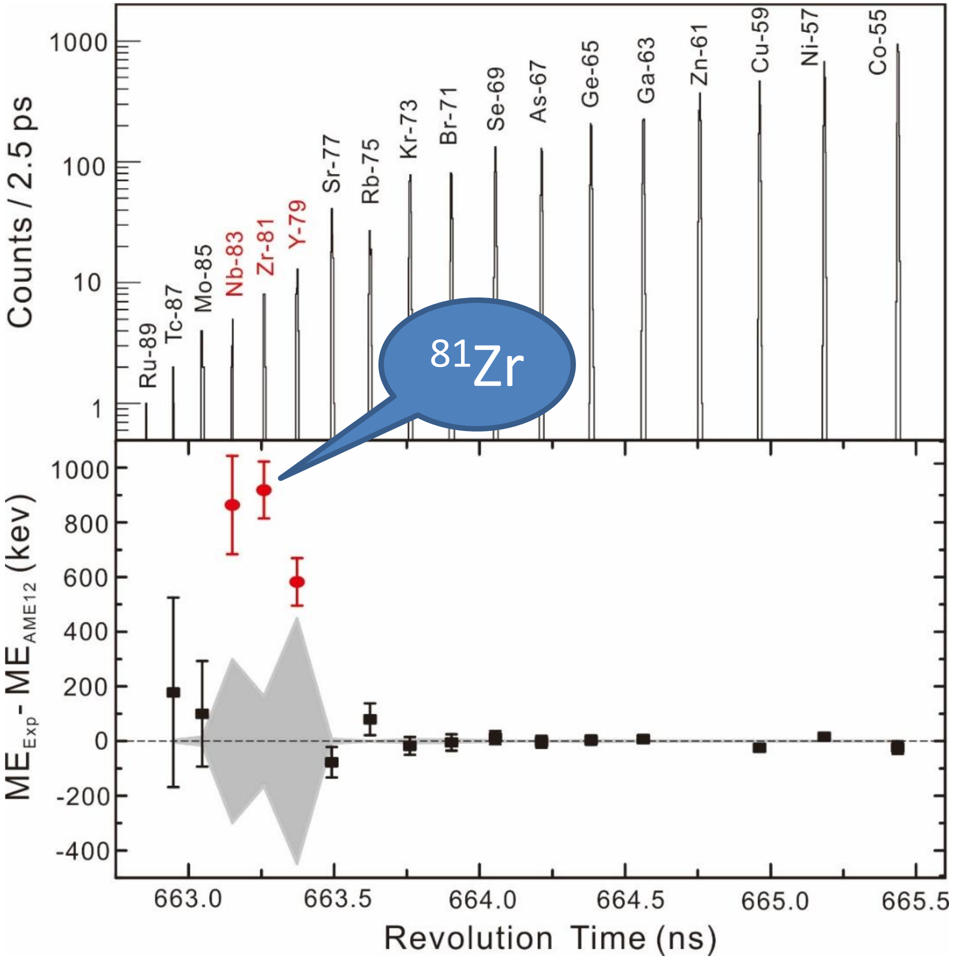
Mass measurements of ^{85,86}Mo from SHIPTRAP support the mass prediction of FRDM, indicating the possible existence of the Zr-Nb cycle

2. Impact on the studies of nuclear astrophysics

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

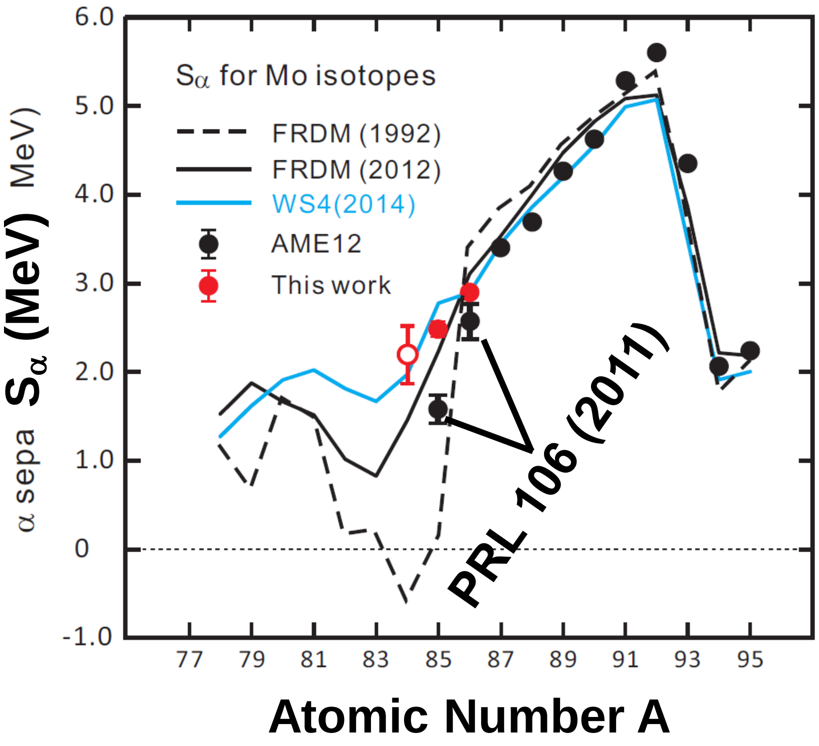
Precise S_α values of ^{85,86}Mo need precise masses of ^{81,82}Zr



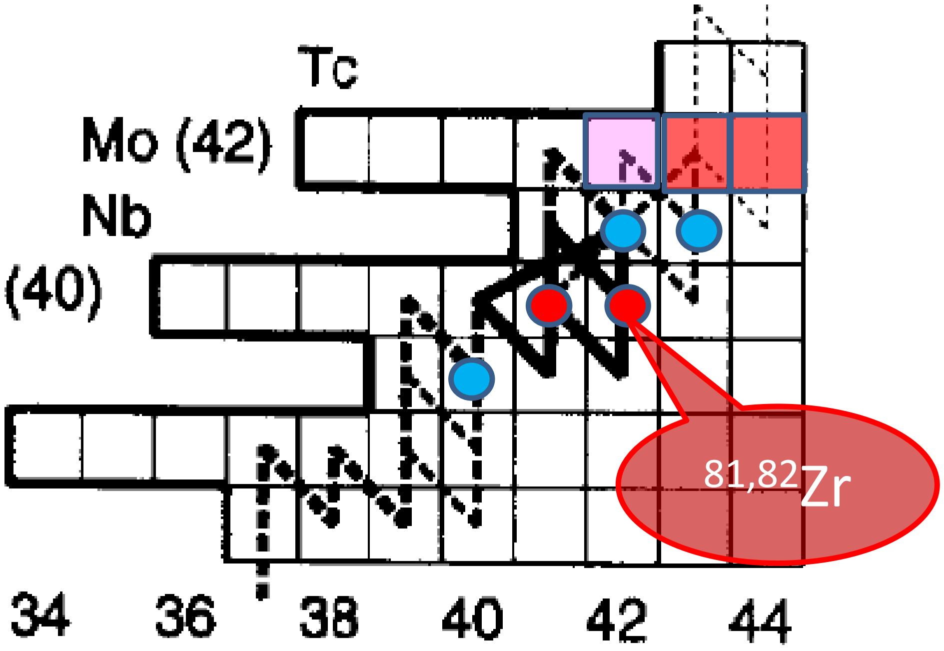


2. Impact on the studies of nuclear astrophysics

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



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



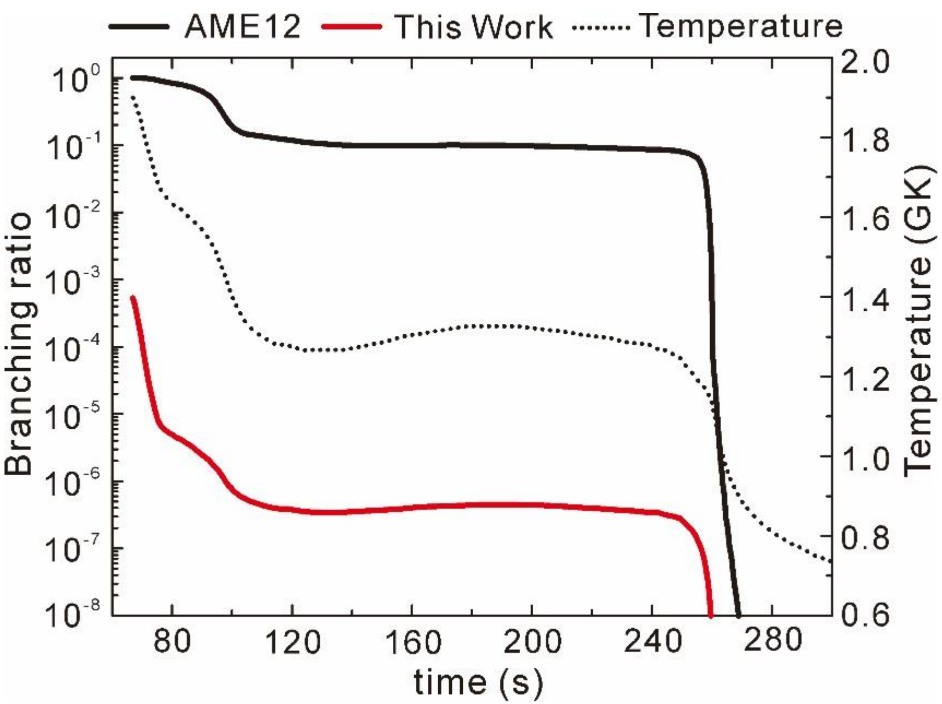
T=2 GK, $\rho=10^6$ g/cm^3

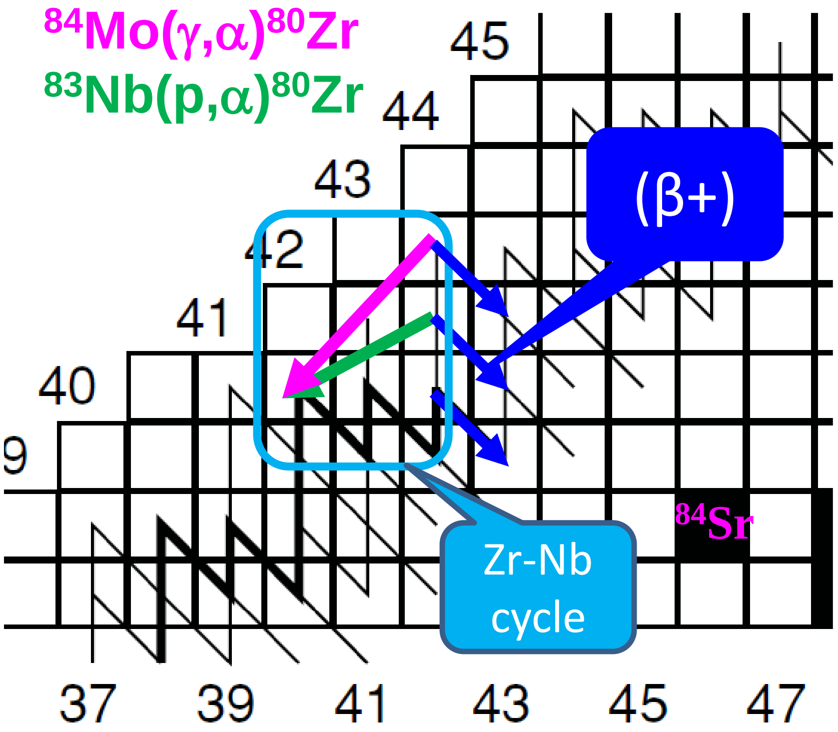
No pronounced island of very low S_α for Mo isotopes !

2. Impact on the studies of nuclear astrophysics

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

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



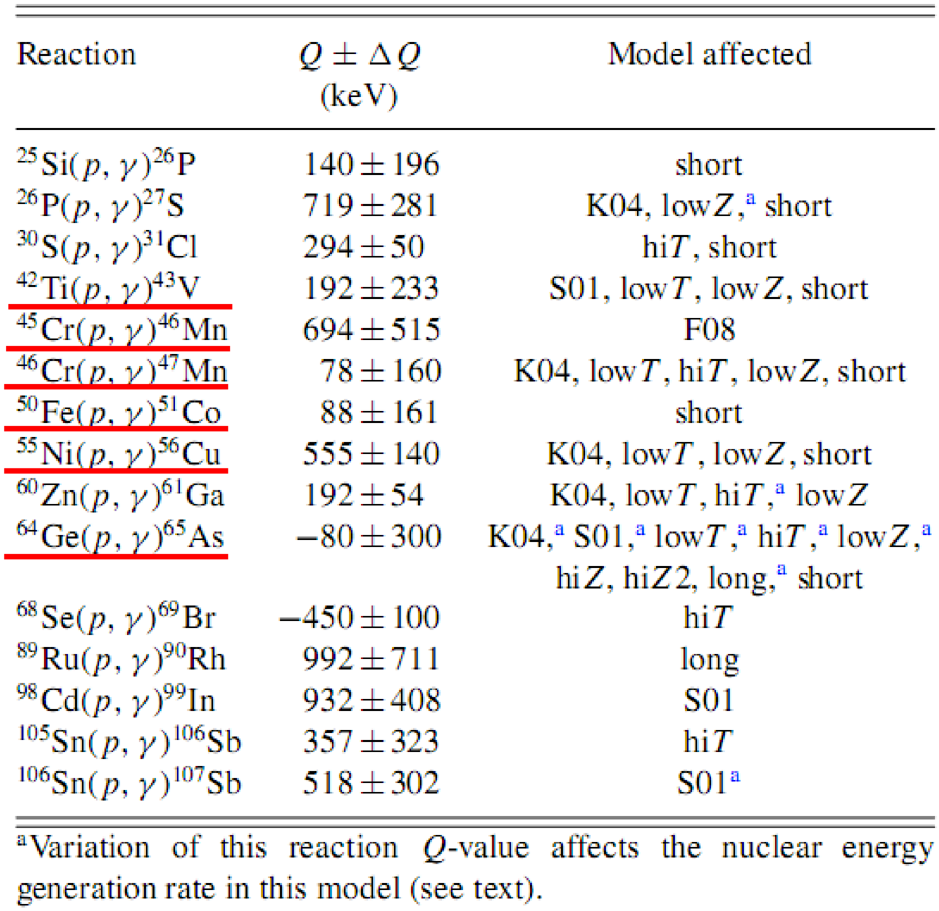


no Zr-Nb cycle exists in the rp-process !

2. Impact on the studies of nuclear astrophysics

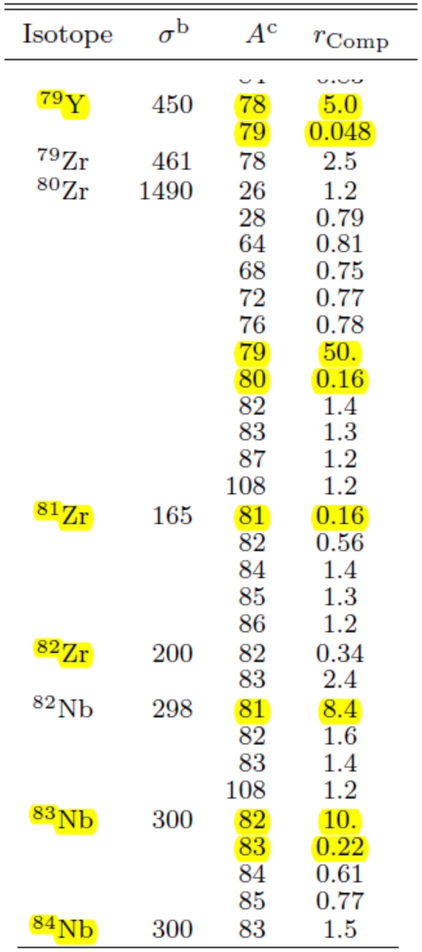
➔ Masses needed in modelling the *rp*-process

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).

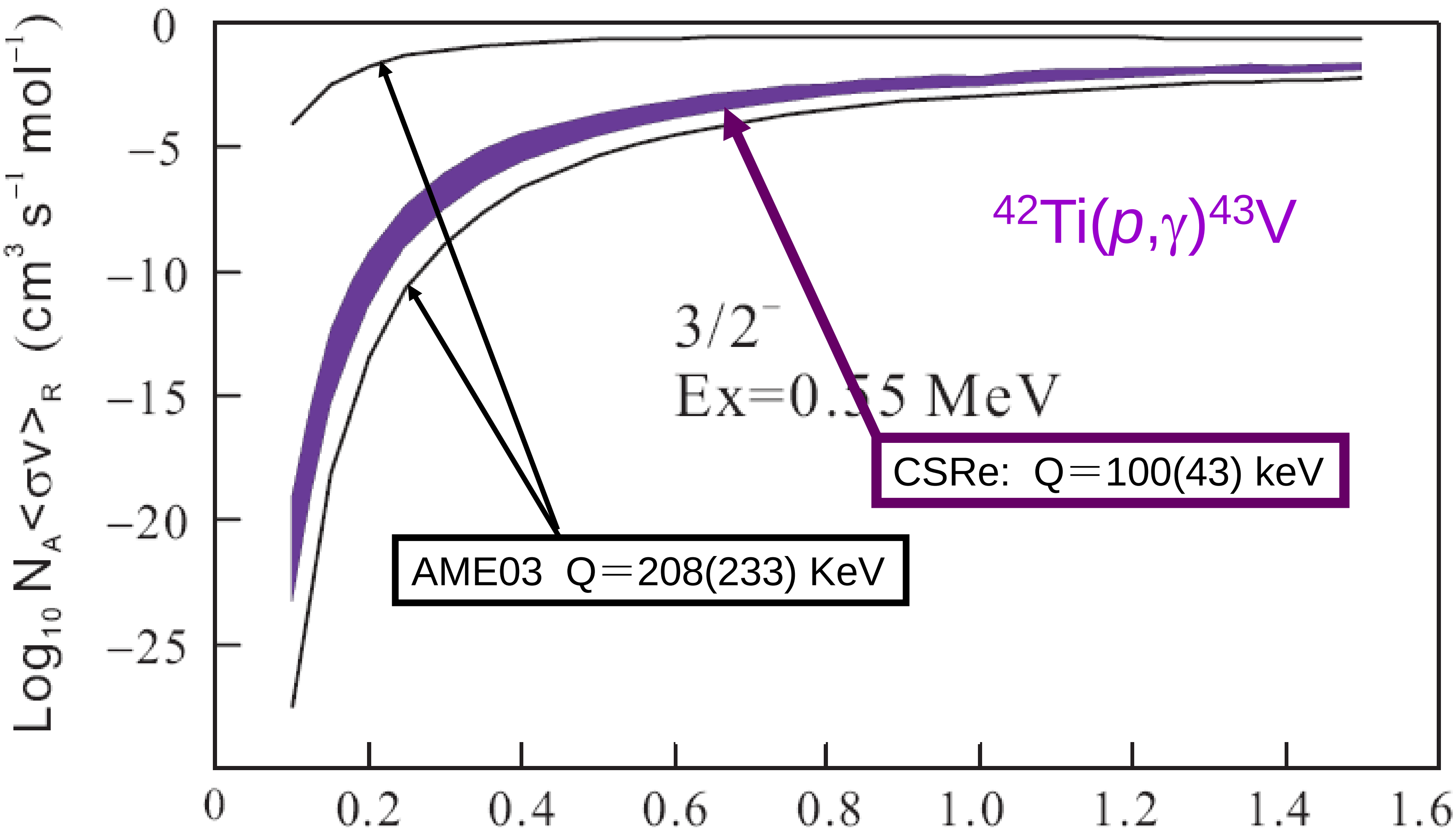


Isotope	σ^{b}	A^{c}	r_{Comp}
^{79}Y	450	78	5.0
		79	0.048
^{79}Zr	461	78	2.5
^{80}Zr	1490	26	1.2
		28	0.79
		64	0.81
		68	0.75
		72	0.77
		76	0.78
		79	50.
		80	0.16
		82	1.4
		83	1.3
		87	1.2
		108	1.2
^{81}Zr	165	81	0.16
		82	0.56
		84	1.4
		85	1.3
		86	1.2
^{82}Zr	200	82	0.34
		83	2.4
^{82}Nb	298	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. Impact on the studies of nuclear astrophysics

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



CSRe: Q = 100(43) keV

AME03 Q = 208(233) KeV

3. Impact on the studies of nuclear structures

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

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

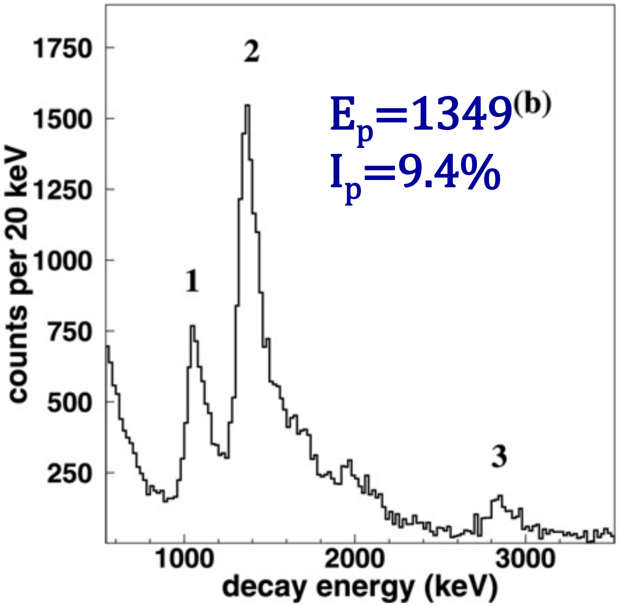
1) **L. Faux et al., Phys. Rev. C 49, 2440 (1994).**
2) **C. Dossat, et al., Nucl. Phys. A792, 18(2007).**
3) **S. E. A. Orrigo et al., Phys. Rev. C 93, 044336 (2016).**

- **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 !

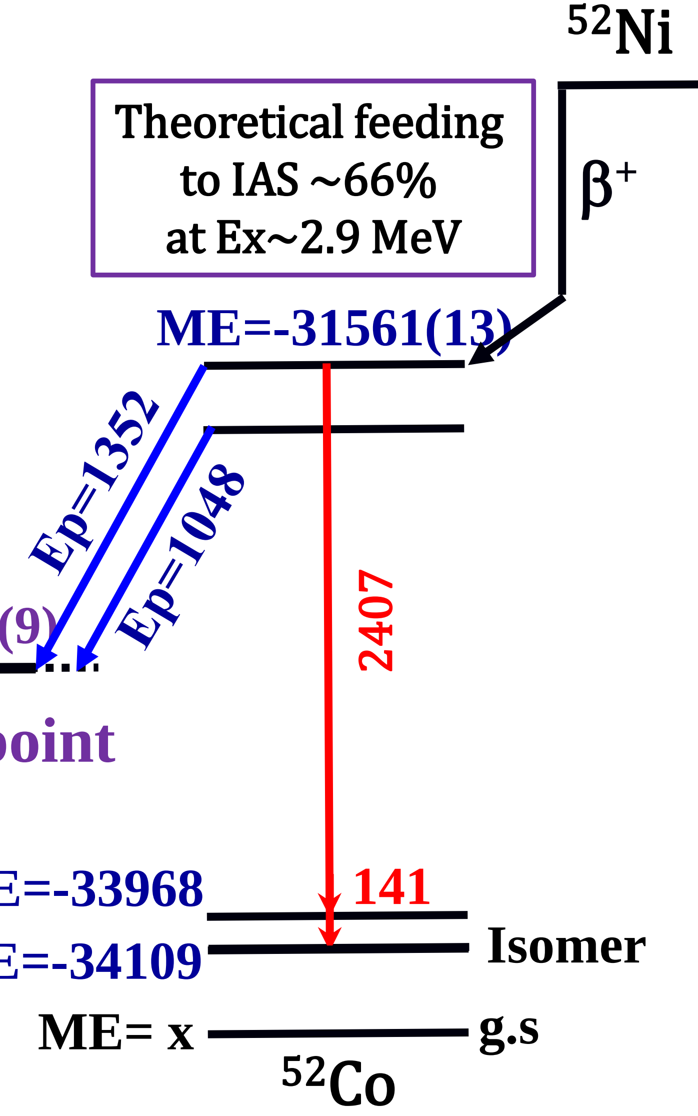
3. Impact on the studies of nuclear structures

β-delayed protons of ^{52}Ni



$E_p=1349^{(b)}$
$I_p=9.4\%$

Existing information



^{52}Ni T=2

$J^{\pi}=0^{+}$

β^{+}

Theoretical feeding
to IAS ~66%
at Ex~2.9 MeV

ME=-31561(13)

Ep=1352

Ep=1048

2407

ME=-32913(9)

^{51}Fe+p

Starting point

ME=-33968

141

ME=-34109

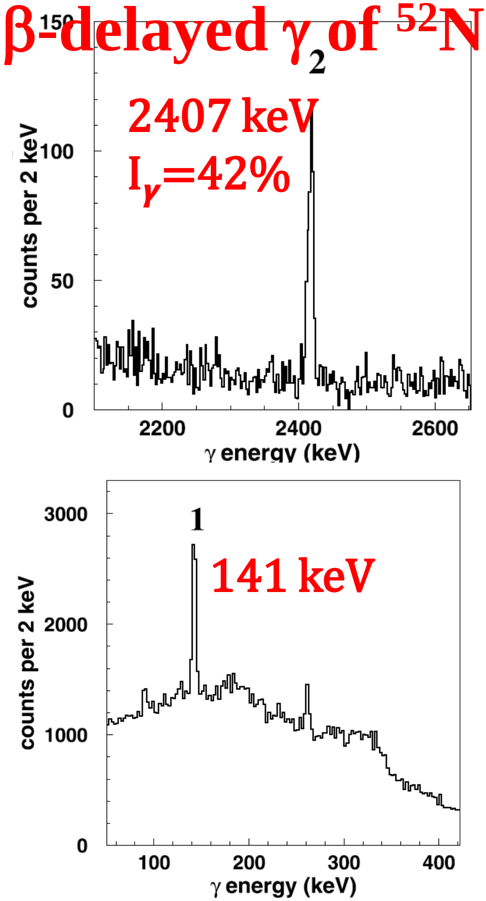
Isomer

ME= x

g.s

^{52}Co

β-delayed γ of ^{52}Ni



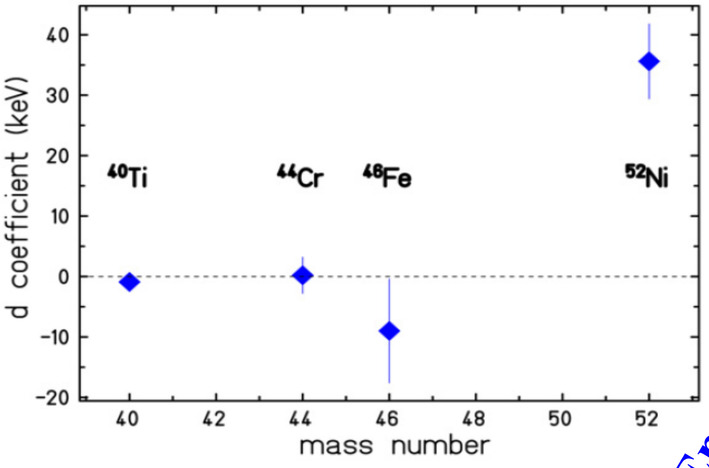
2407 keV
$I_\gamma=42\%$

141 keV

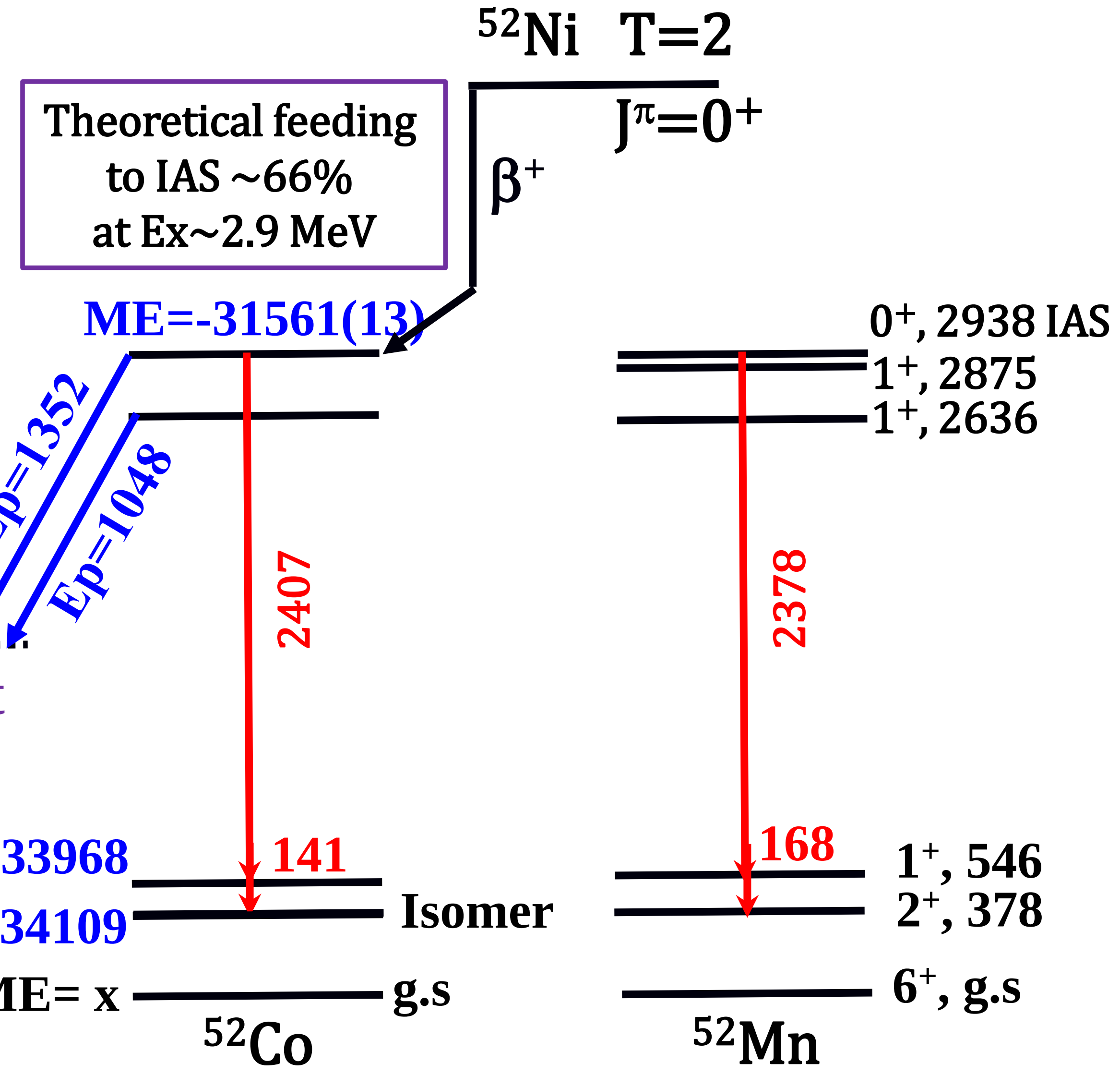
3. Impact on the studies of nuclear structures

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

IMME d-coefficient



Theoretical feeding
to IAS ~66%
at Ex~2.9 MeV



^{52}Ni T=2

J$^{\pi}$=0^{+}

β^+

ME=-31561(13)

Ep=1352

Ep=1048

^{51}Fe+p

ME=-32913(9)

Starting point

2407

141

2378

168

0^{+}, 2938 IAS

1^{+}, 2875

1^{+}, 2636

ME=-33968

ME=-34109

Isomer

ME= x

g.s

^{52}Co

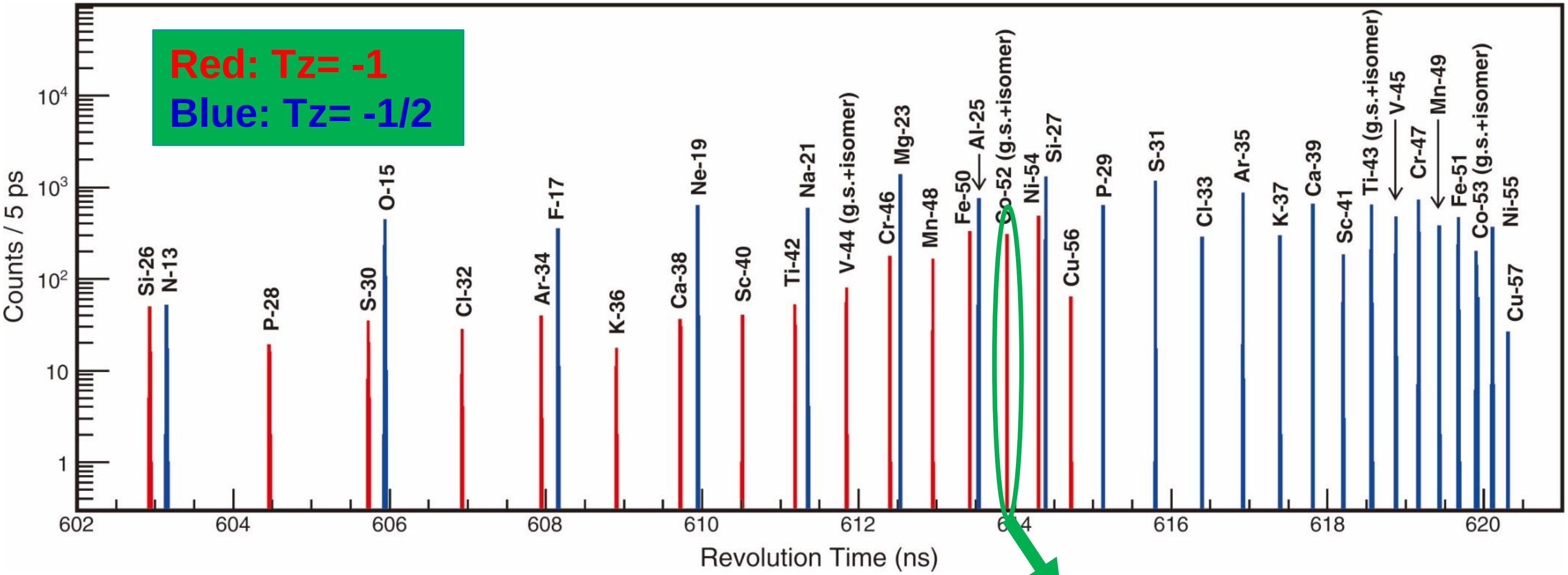
1^{+}, 546

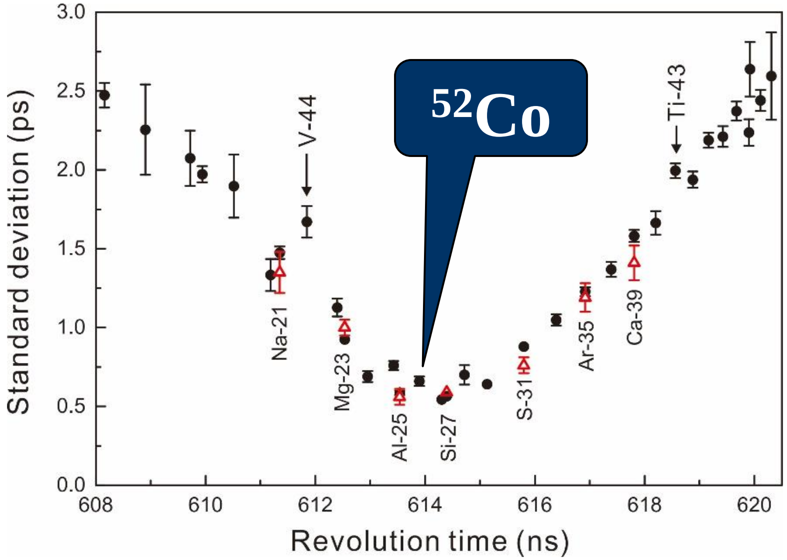
2^{+}, 378

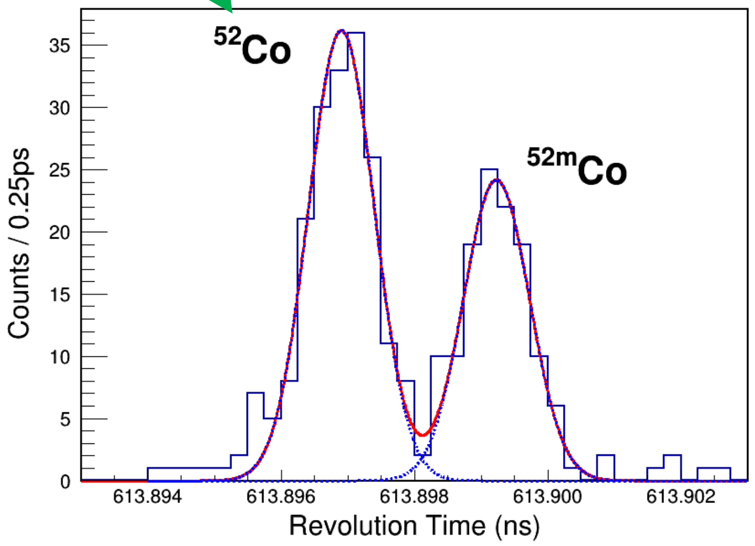
6^{+}, g.s

^{52}Mn

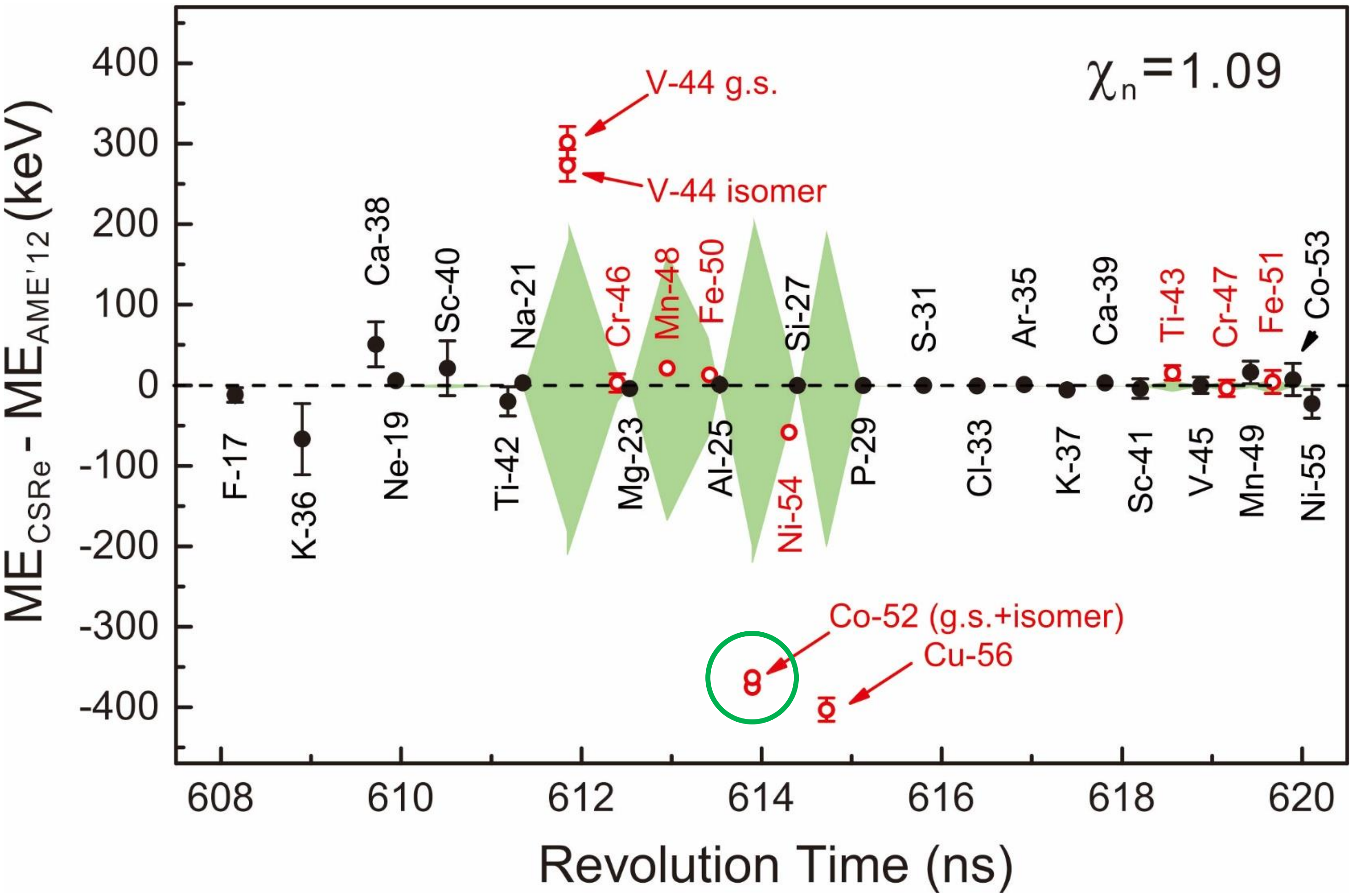
3. Impact on the studies of nuclear structures







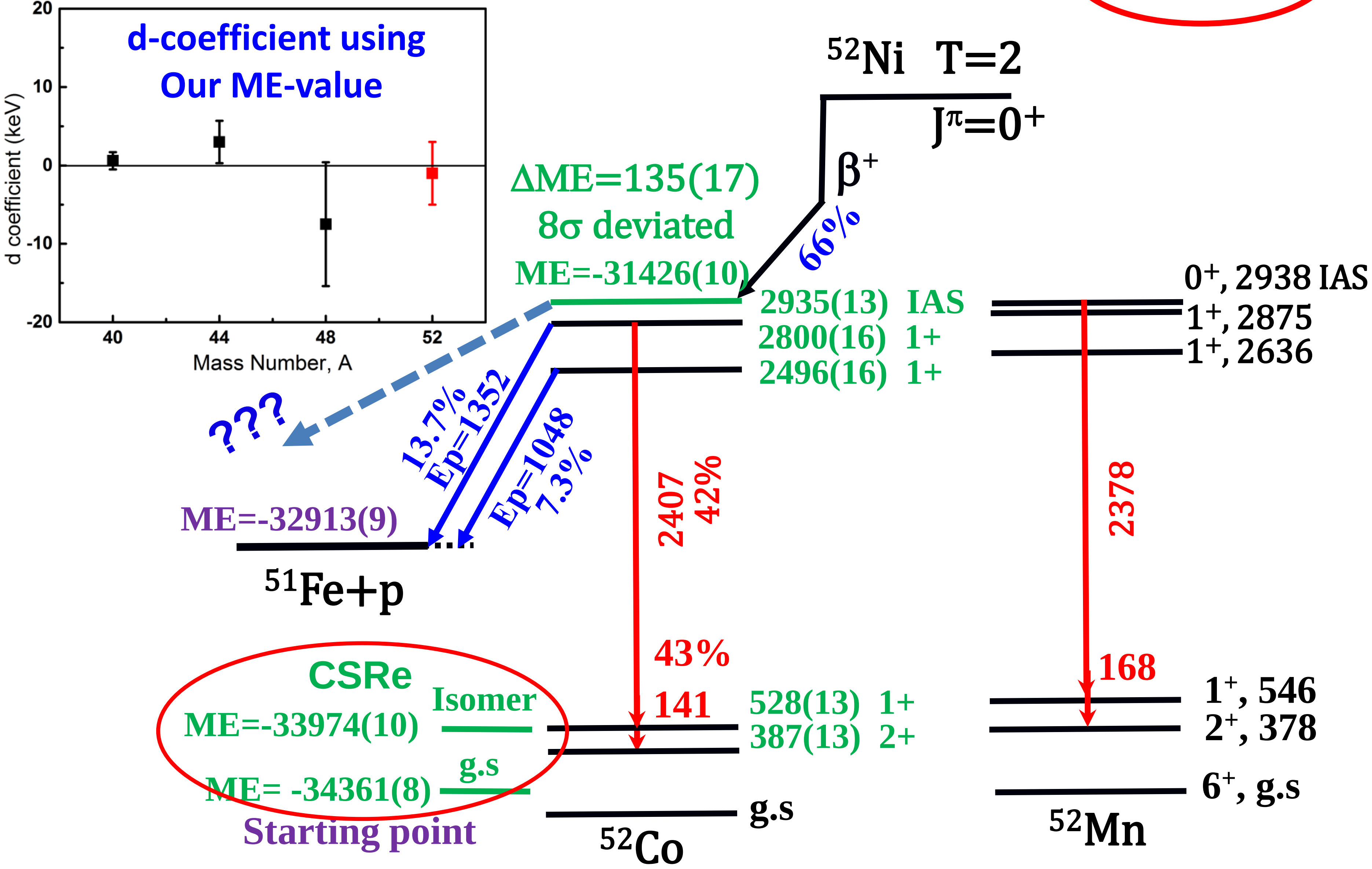
3. Impact on the studies of nuclear structures



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

3. Impact on the studies of nuclear structures

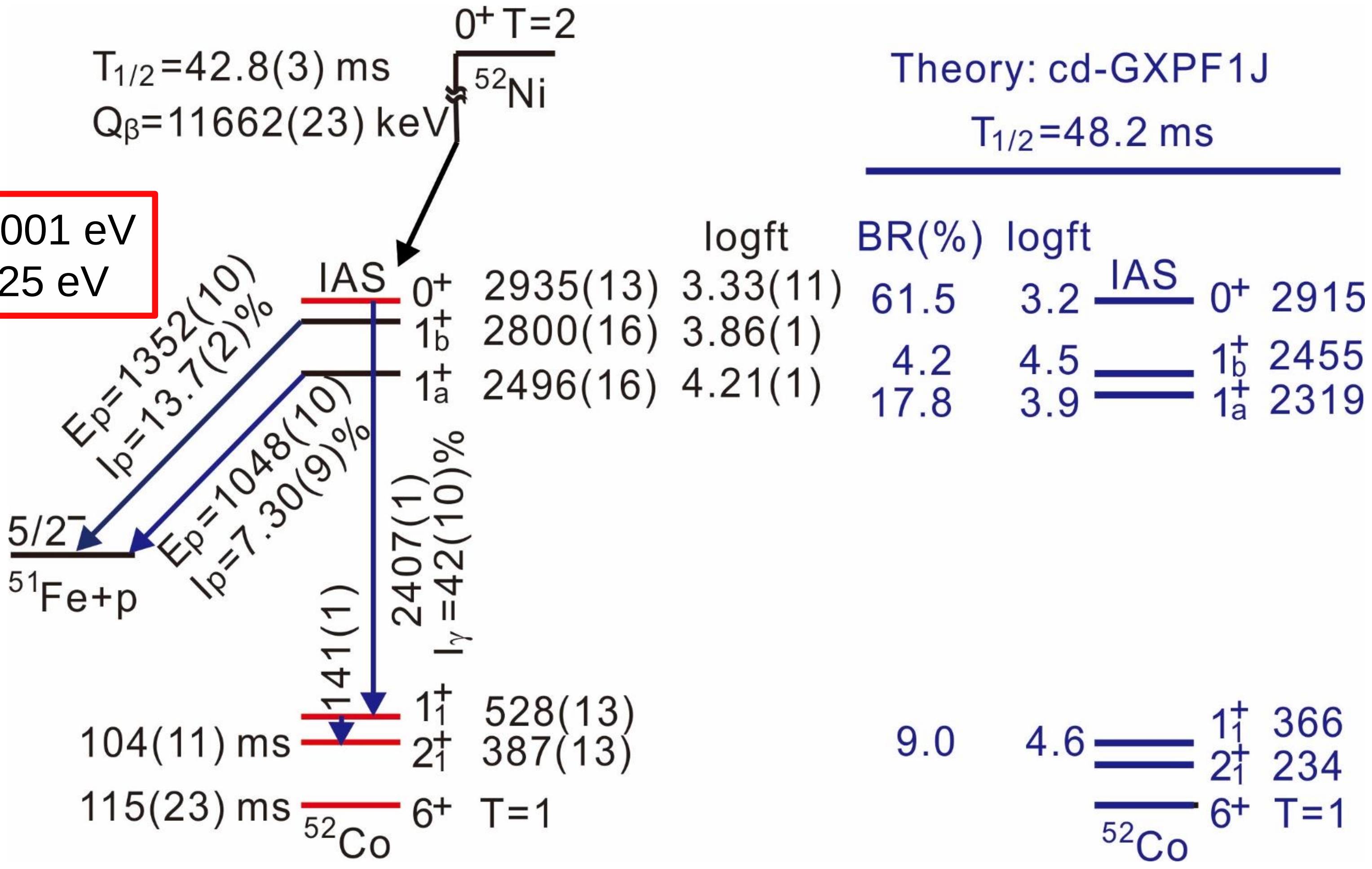
$$M(T,A,T_3)=a(T,A,)+b(T,A)T_3+c(T,A)T_3^2+d(T,A)T_3^3$$



3. Impact on the studies of nuclear structures

Comparison with theoretical calculations

Γp=0.0001 eV
Γγ=0.25 eV



4. 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**

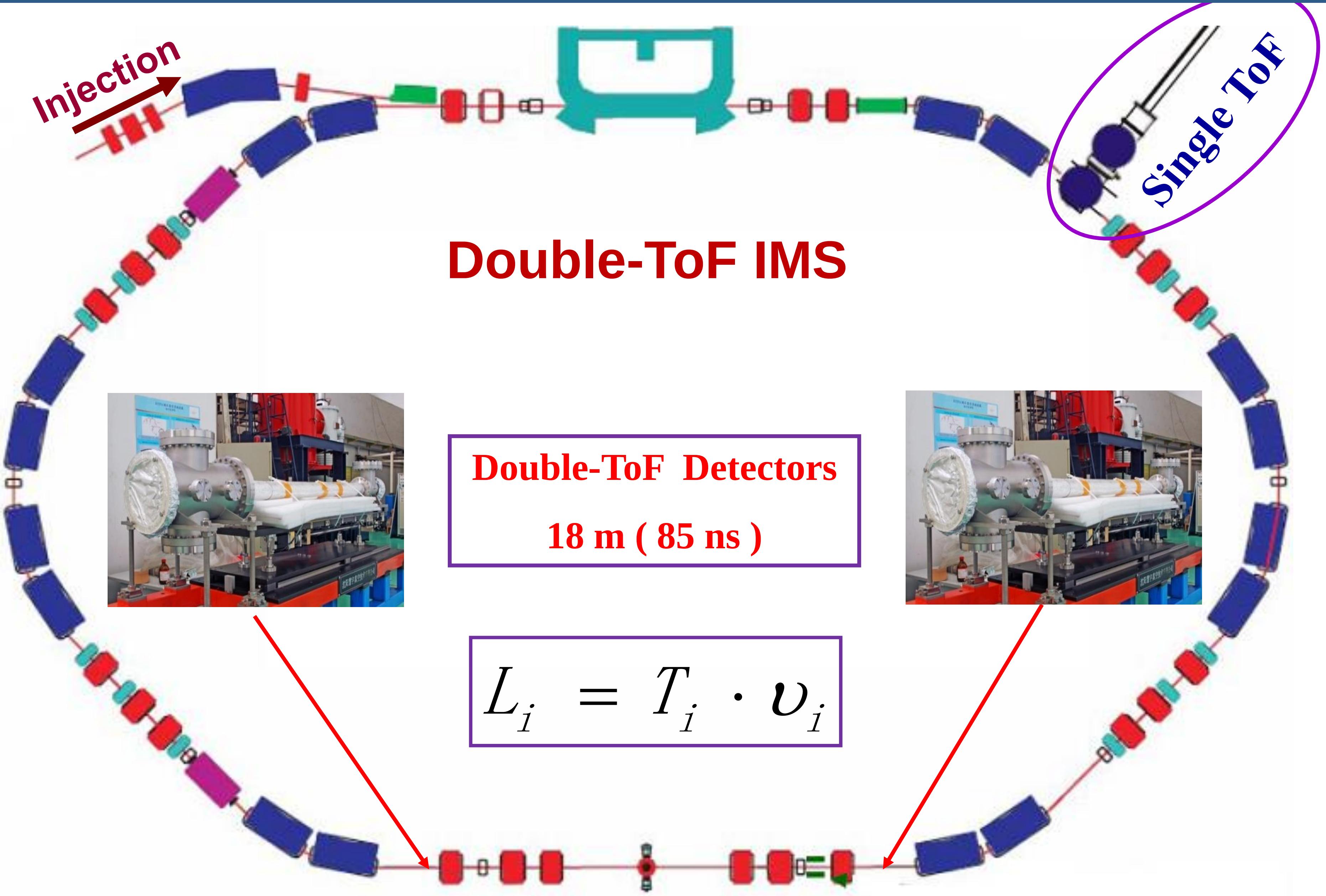
2) **Some issues in the studies of nuclear astrophysics and nuclear structure have been addressed on the basis of mass measurements in CSRe.**

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.**

4. Summary and perspectives



Double-ToF IMS

Double-ToF Detectors

18 m (85 ns)

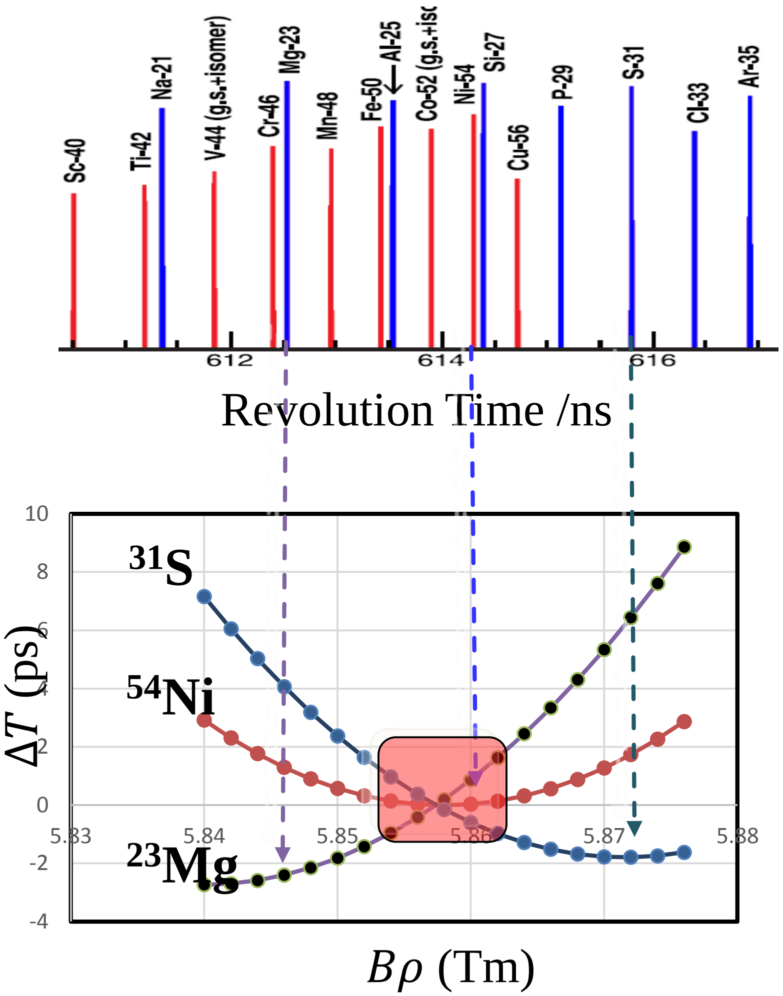
$$L_i = T_i \cdot \upsilon_i$$

4. Summary and perspectives

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 spread & non-symmetric due to $\Delta(B\rho)$ (or ΔC or Δv)

4. Summary and perspectives

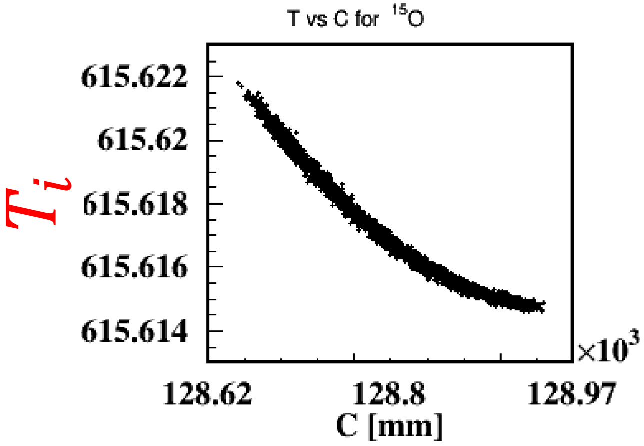
Principle:

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

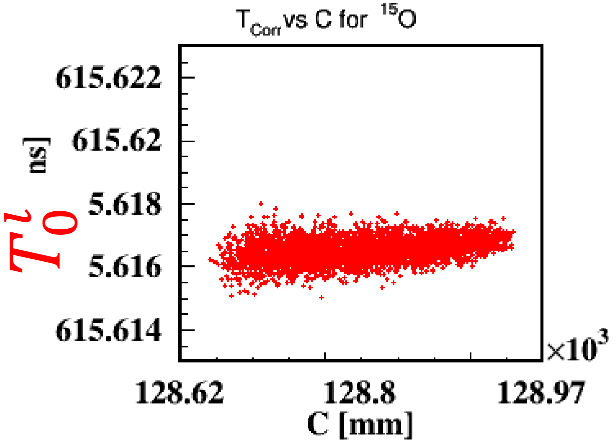
Then the revolution time T_0^i at the ideal orbit length C_0=12880 cm can be deduced.

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

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

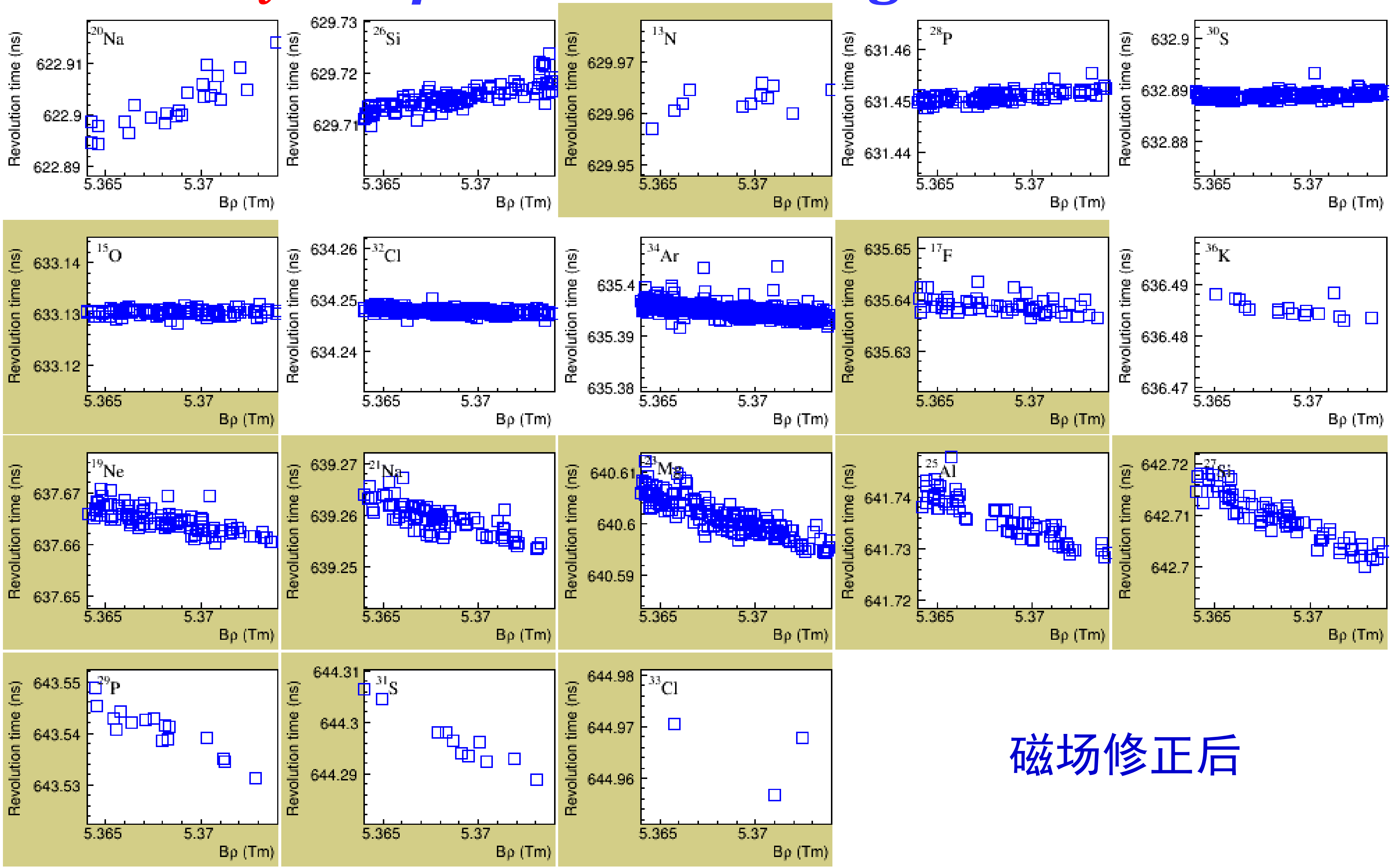


T_0^i @ C_0=12880cm



4. Summary and perspectives

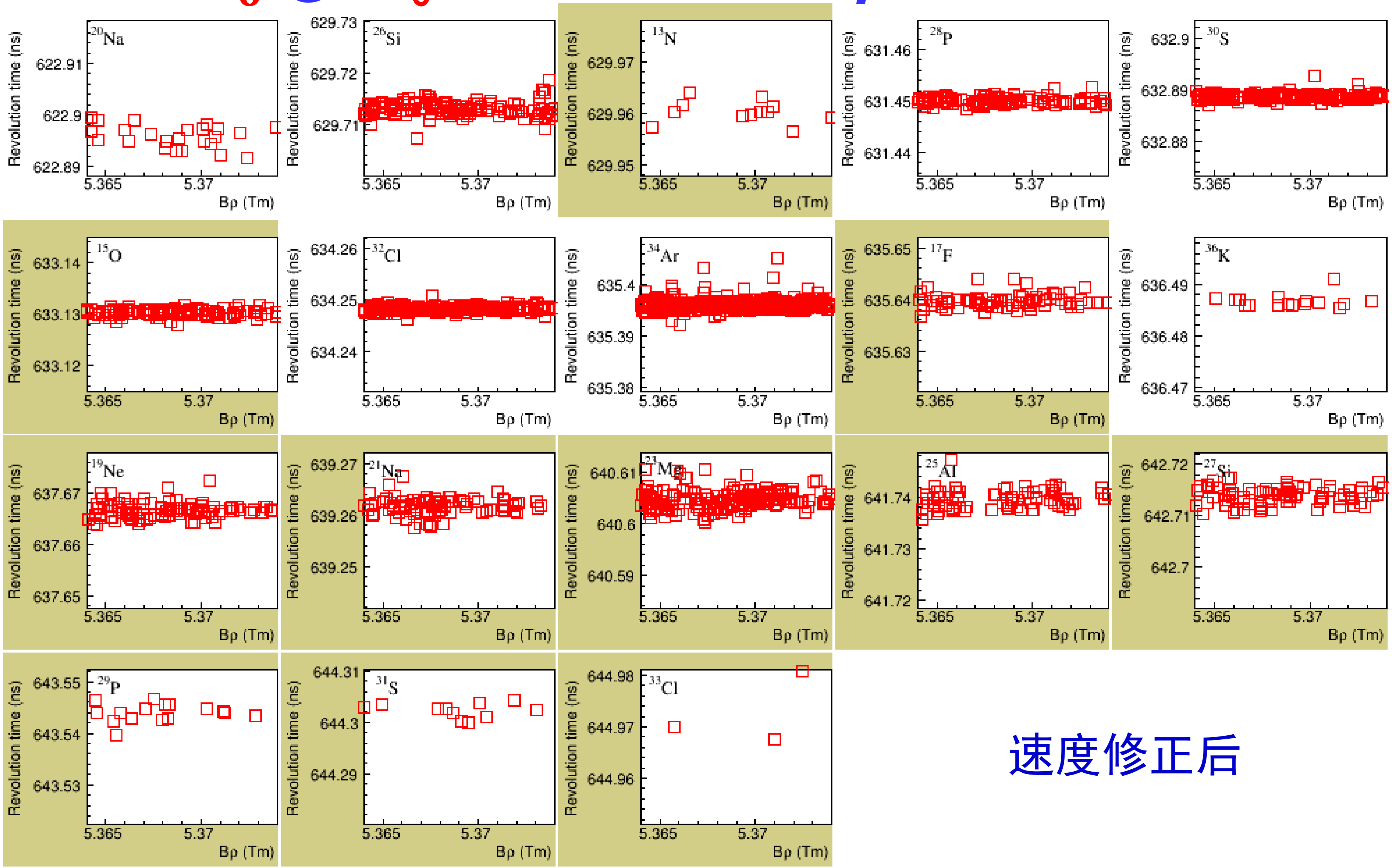
Plot of T_i vs $B\rho$ from ^{36}Ar fragmentation



磁场修正后

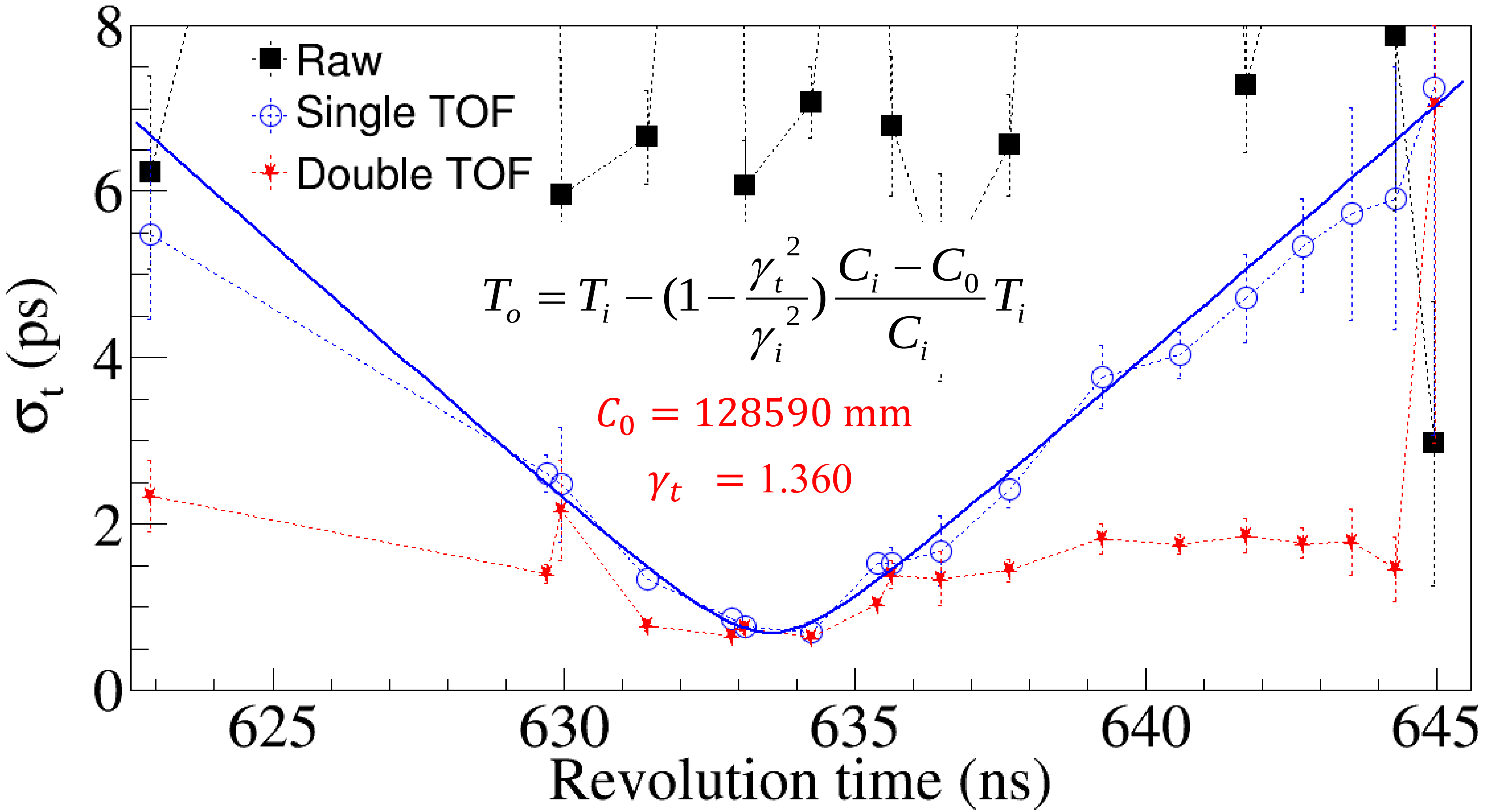
4. Summary and perspectives

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



速度修正后

4. Summary and perspectives



$$T_o = T_i - \left(1 - \frac{\gamma_t^{\,2}}{\gamma_i^{\,2}}\right)\frac{C_i - C_0}{C_i} T_i$$

$C_0 = 128590$ mm

$\gamma_t = 1.360$

CSR mass measurement collaboration

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CSR mass measurement collaboration


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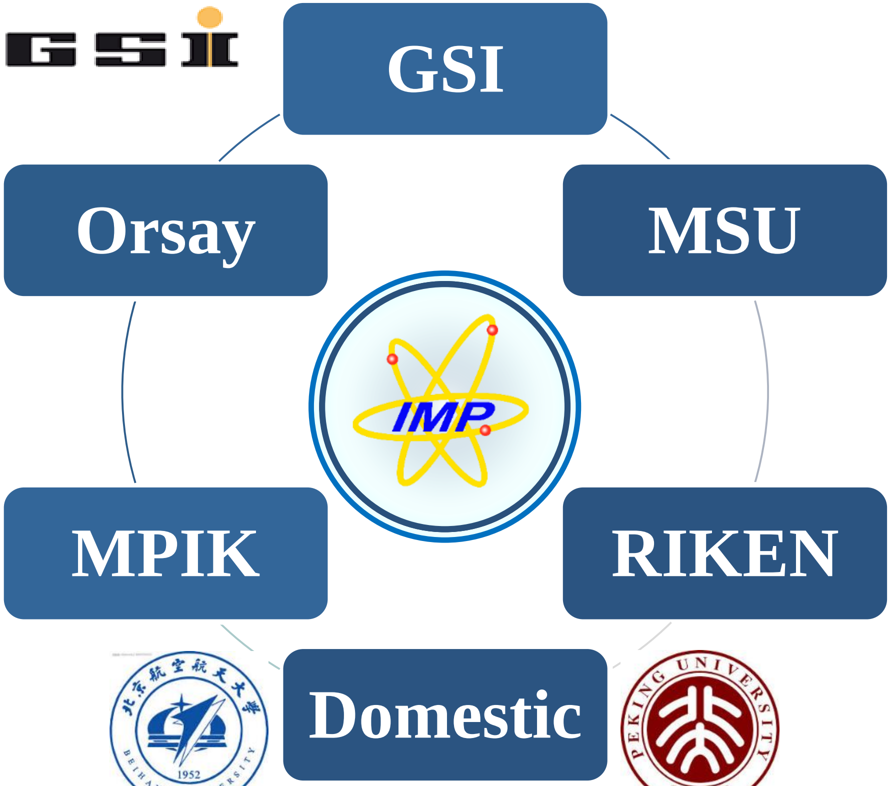
GSI

Orsay

MSU

IMP

MPIK

RIKEN

Domestic


K.Blaum

T. Uesaka

B. H. Sun

F. R. Xu

Y. Sun

2. Impact on the studies of nuclear astrophysics

Favorable conditions for the formation of Zr-Nb cycle:

Largest $Q(p,\alpha)$ favoring ^{83}Nb$(p,\alpha)^{80}$Zr reaction
Smallest $S\alpha(^{84}\mathrm{Mo})$ favoring ^{84}Mo$(\gamma,\alpha)^{80}$Zr reaction