Mass measurements of short-lived nuclides in CSRe and its impact on nuclear astrophysics

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On behalf of the CSRe mass measurement collaboration

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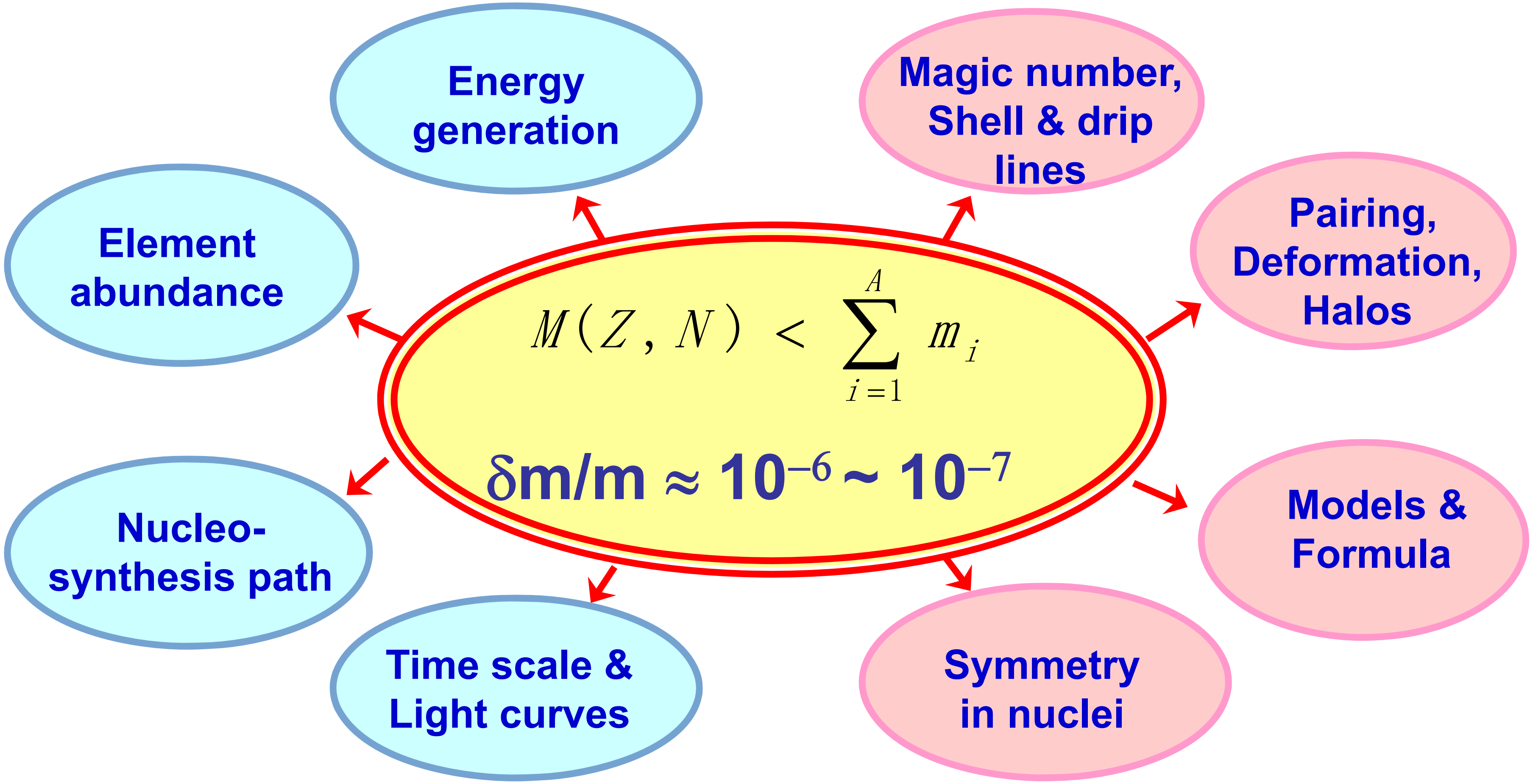
Outline

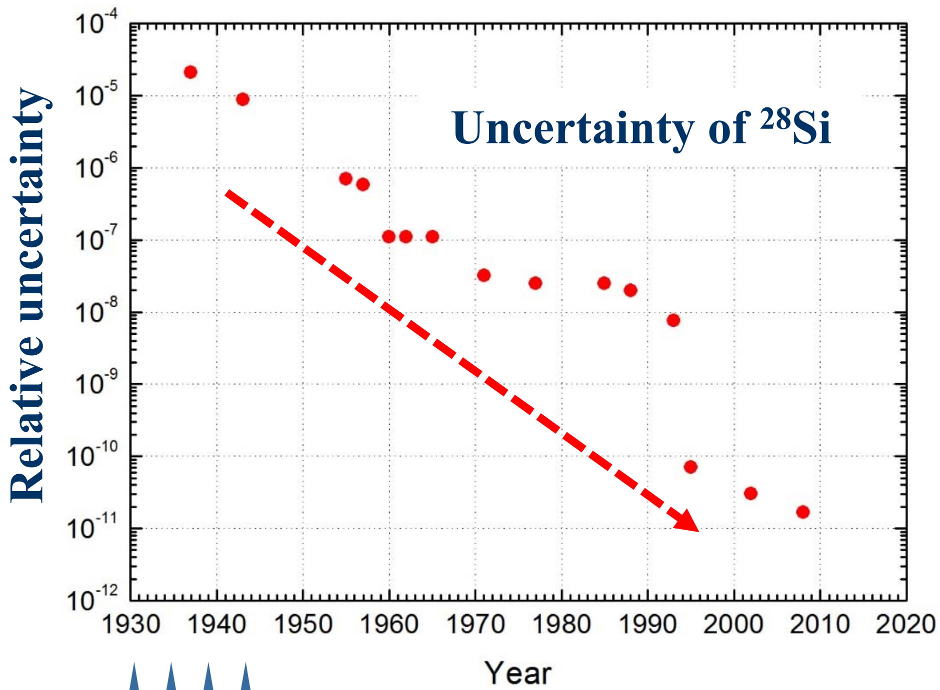
1. Introduction to mass measurements in CSRe
2. Experimental details and brief results
3. Impact on the studies of nuclear astrophysics
4. Summary & perspectives

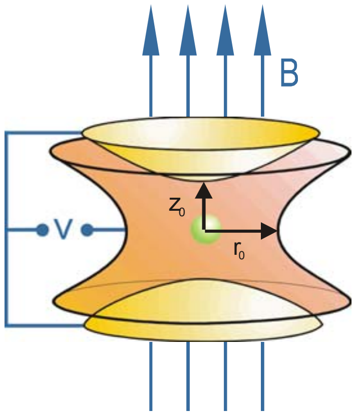
1. Introduction to mass measurements in CSRe

Masses, Binding energies → Interactions
(Storage-rings-based IMS → Precision 10^{-6}~10^{-7})

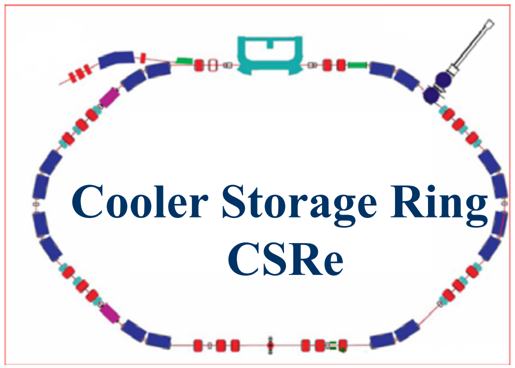


1. Introduction to mass measurements in CSRe





Penning Trap
$\Delta M/M \approx 10^{-8} \sim 10^{-11}$



Short-lived species
$\Delta M/M \approx 10^{-5} \sim 10^{-7}$

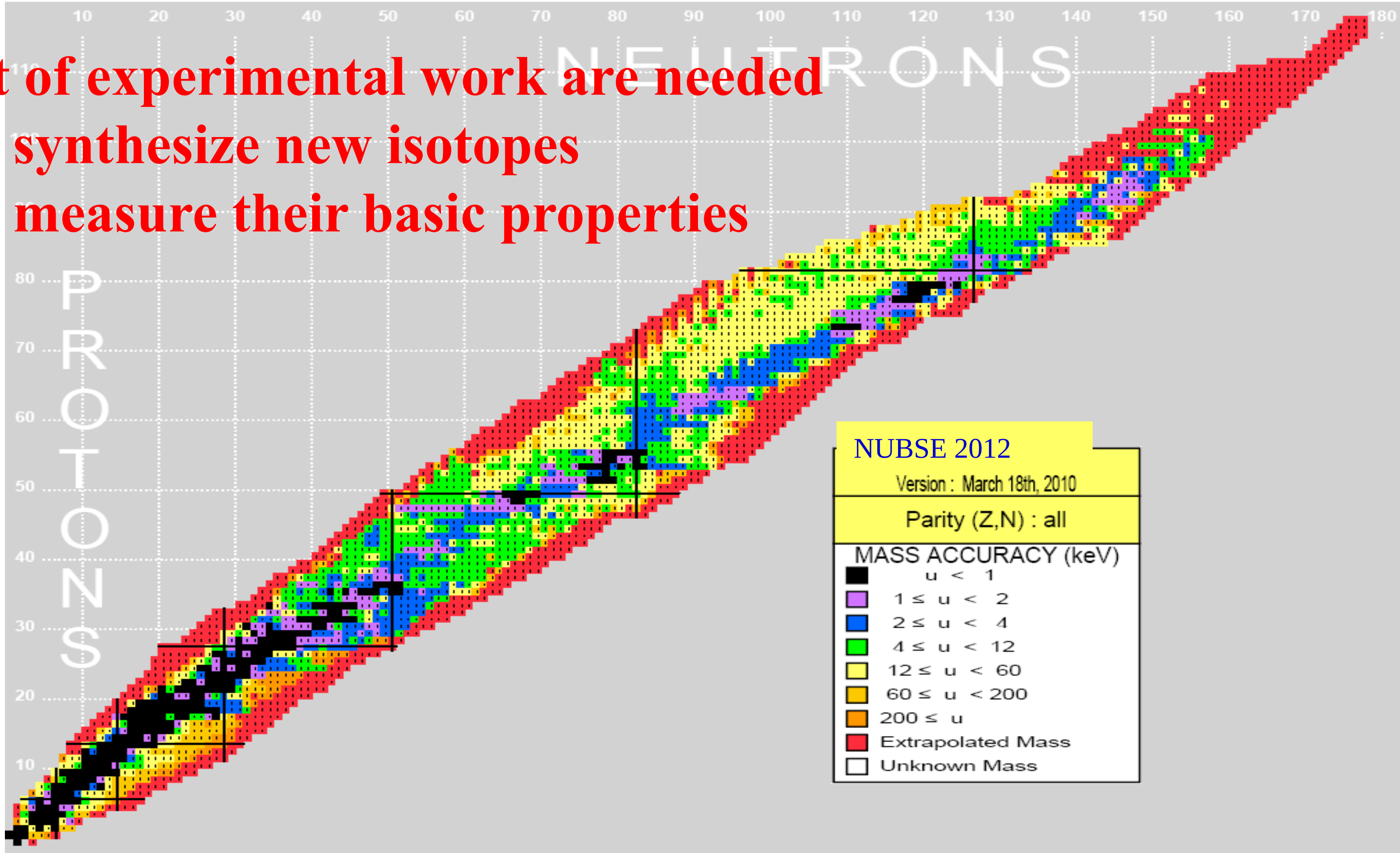
Physics issues touched at different levels of precision

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	$\leq 10^{-11}$

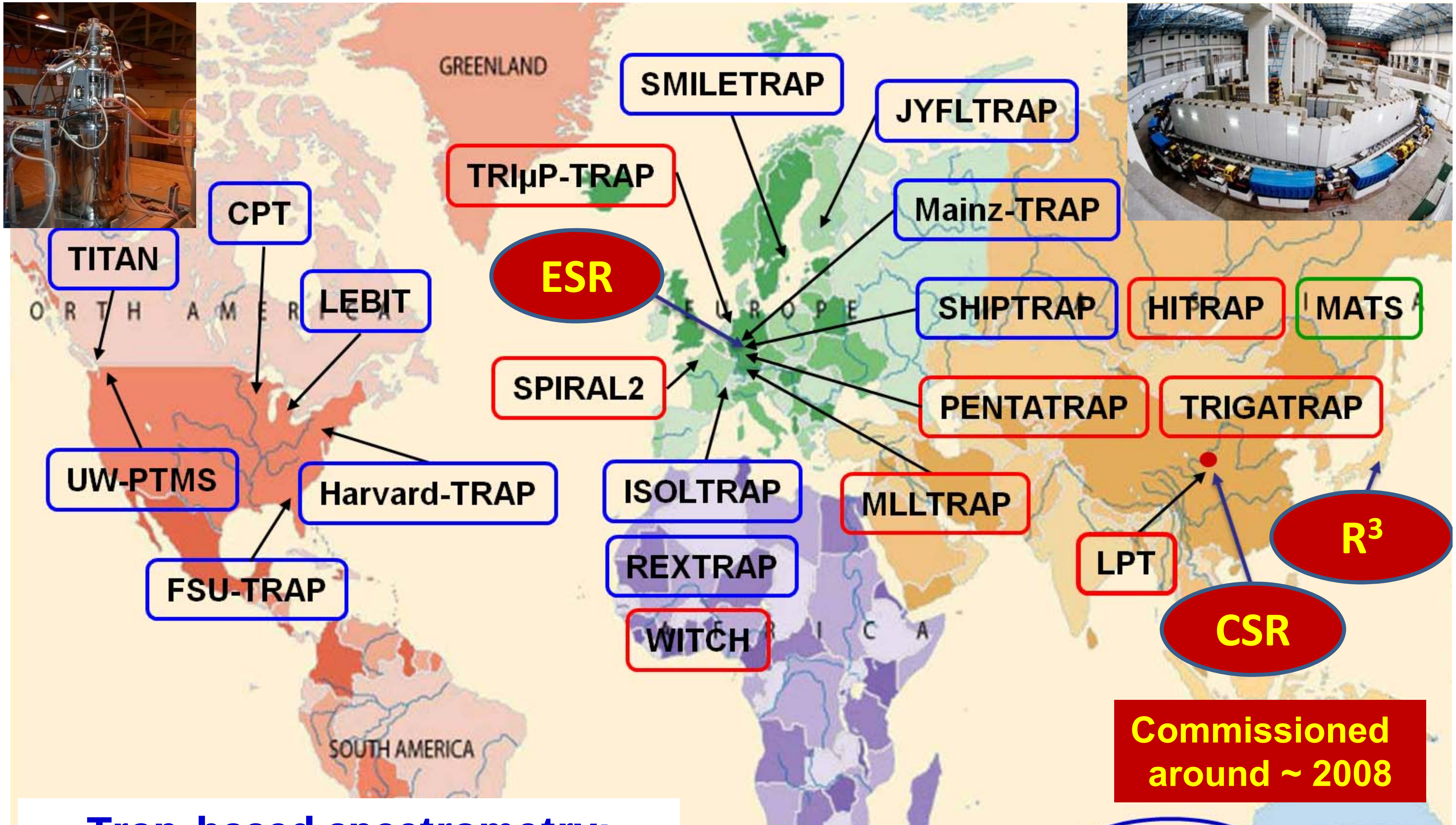
1. Introduction to mass measurements in CSRe

~8000 nuclides predicted
~3100 nuclides observed
~ 2400 masses measured

A lot of experimental work are needed
---to synthesize new isotopes
---to measure their basic properties



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

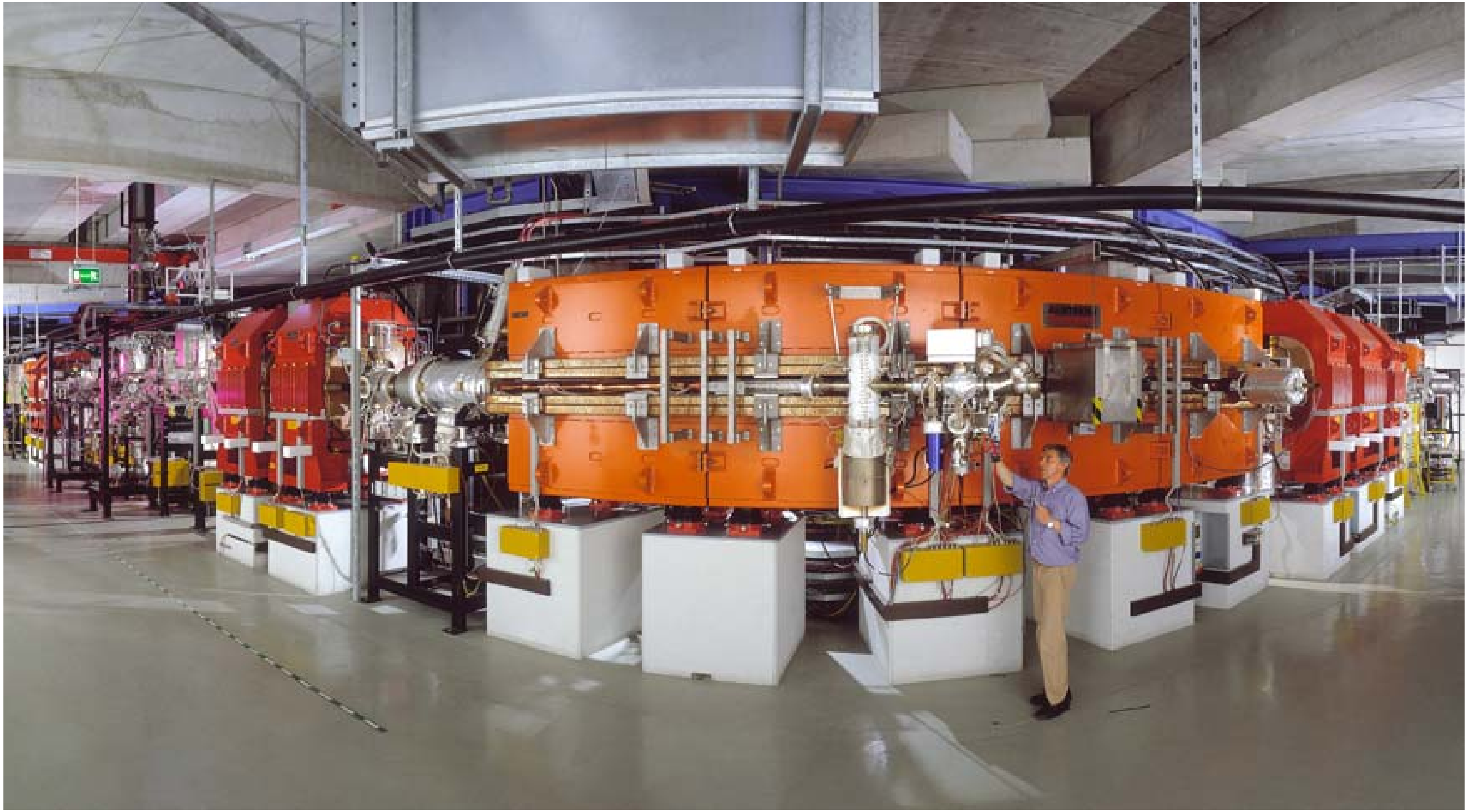
1. Introduction to mass measurements in CSRe

“九五”大科学装置：HIRFL-CSR


SSC加速器（K=450）(1988)

中科院近代物理所 CSR

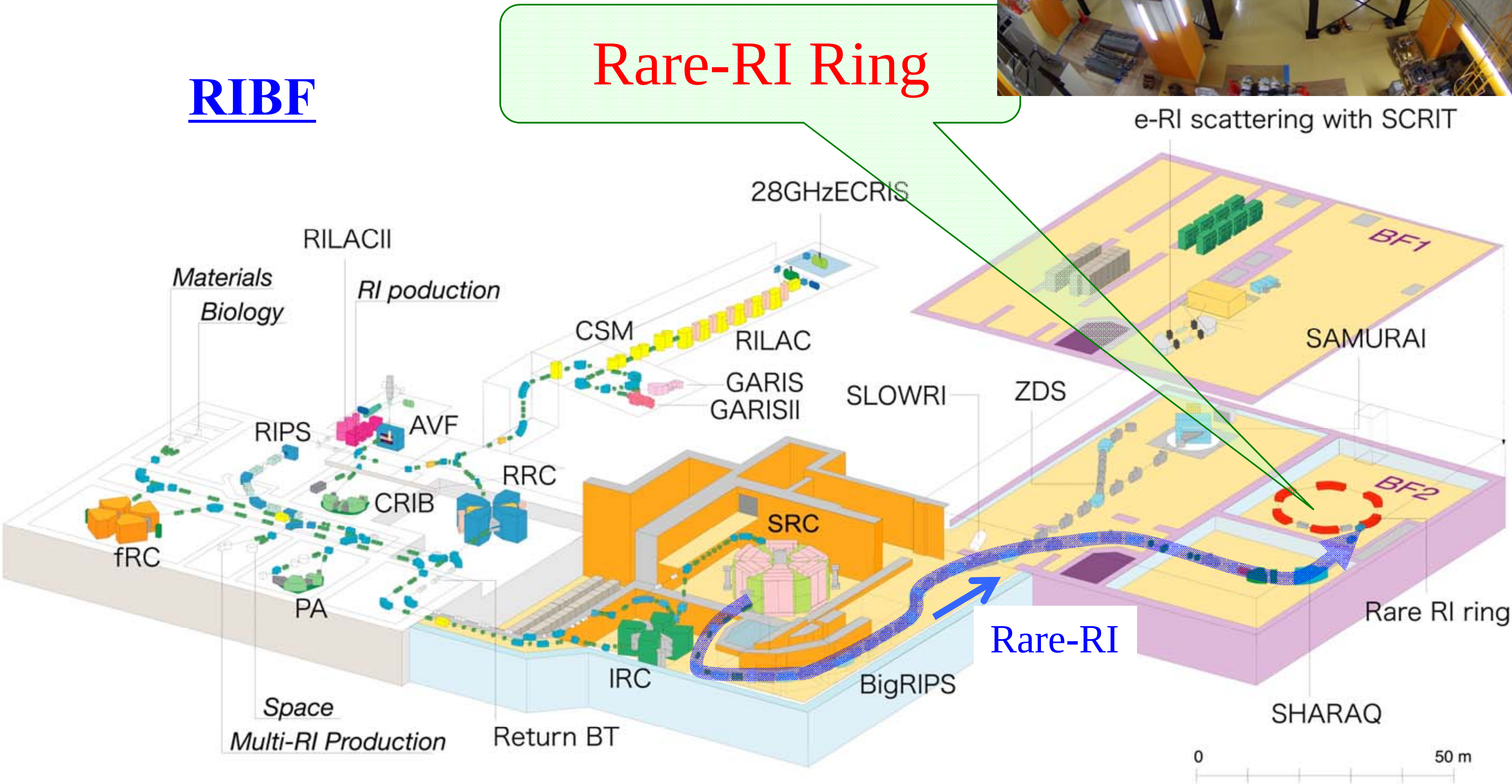
Storage rings at GSI



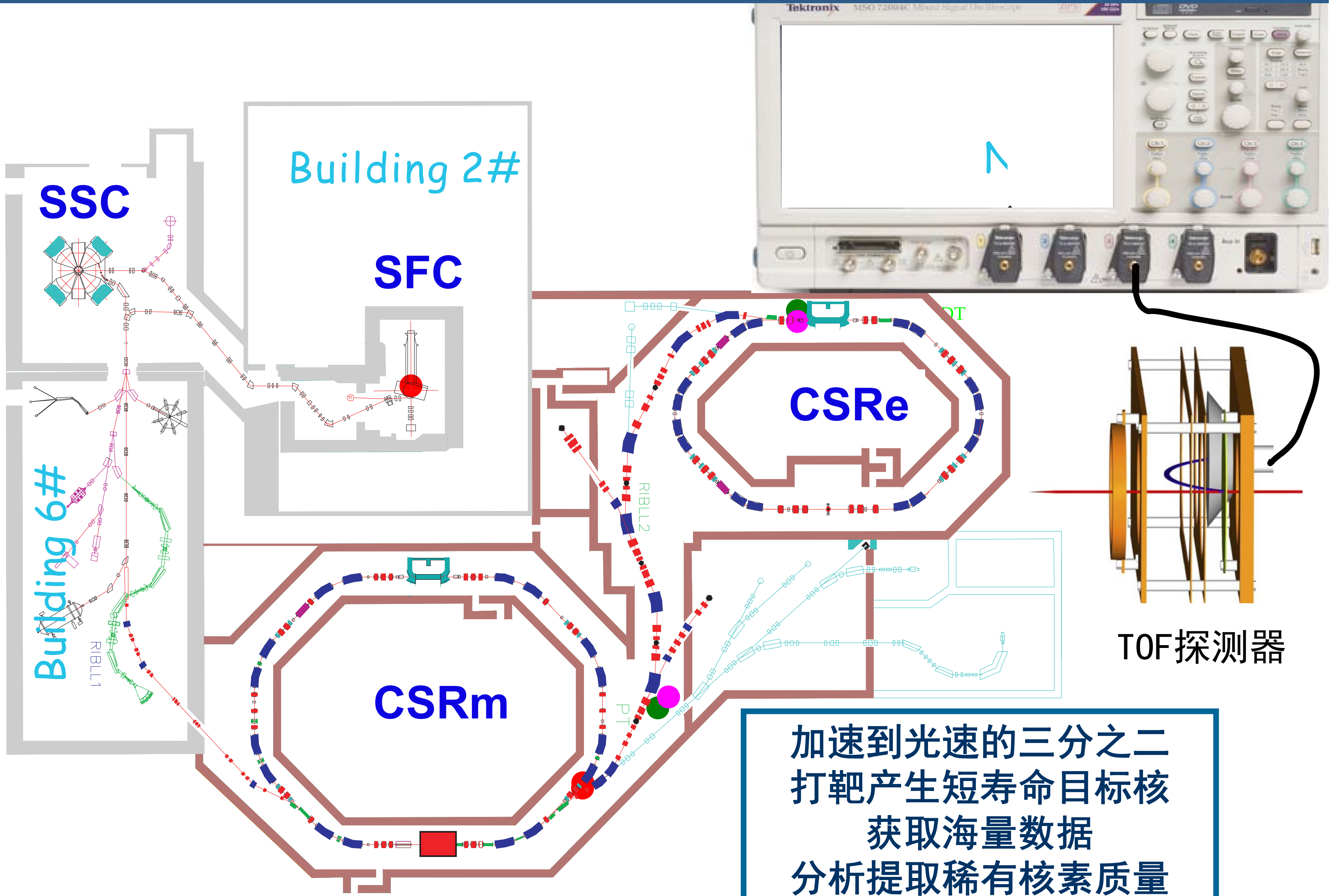
§ Rare-RI Ring at RIBF

Prog. Theor. Exp. Phys. 2012, 03C009.

RIBF

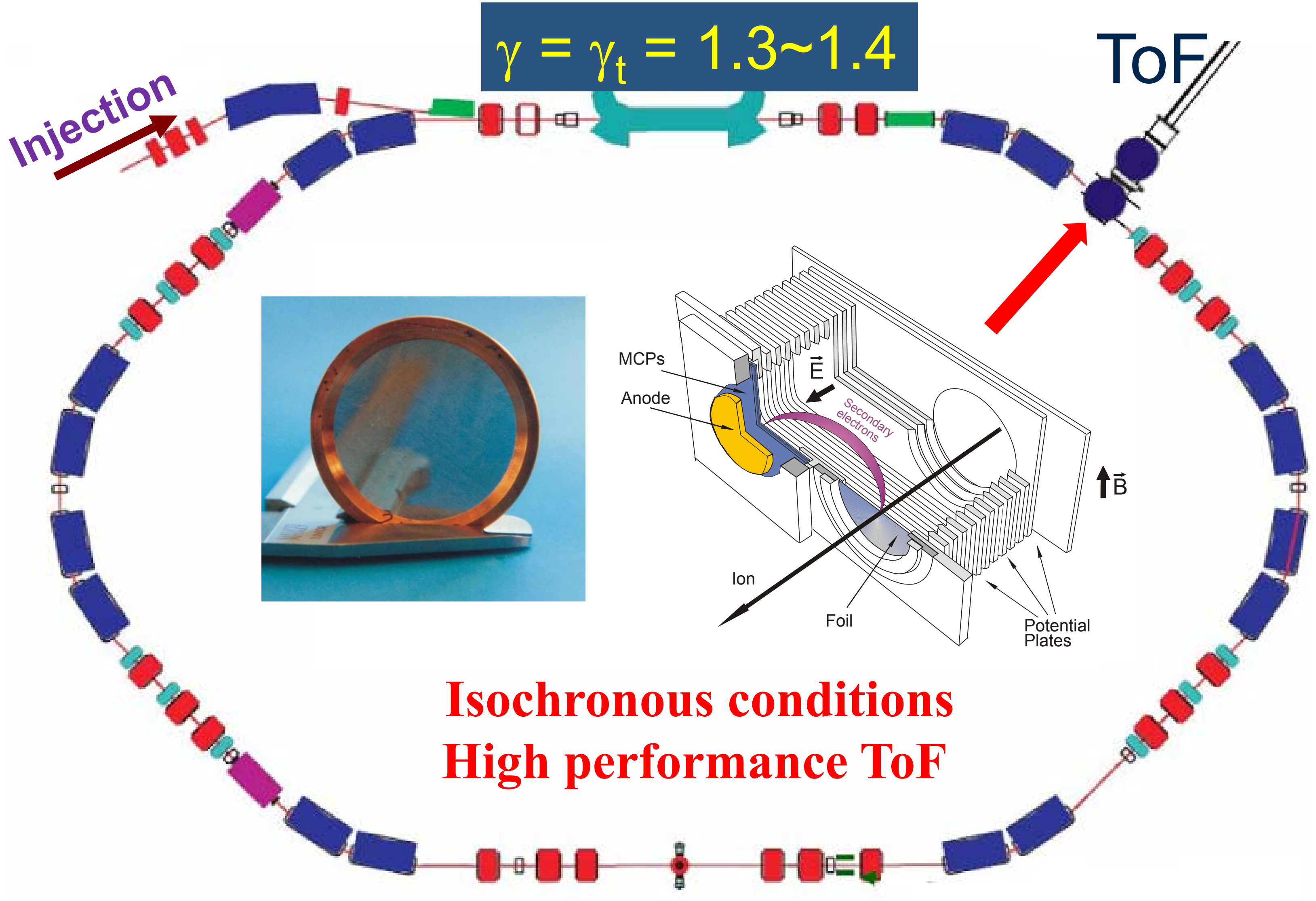


2. Experimental details and brief results



加速到光速的三分之二
打靶产生短寿命目标核
获取海量数据
分析提取稀有核素质量

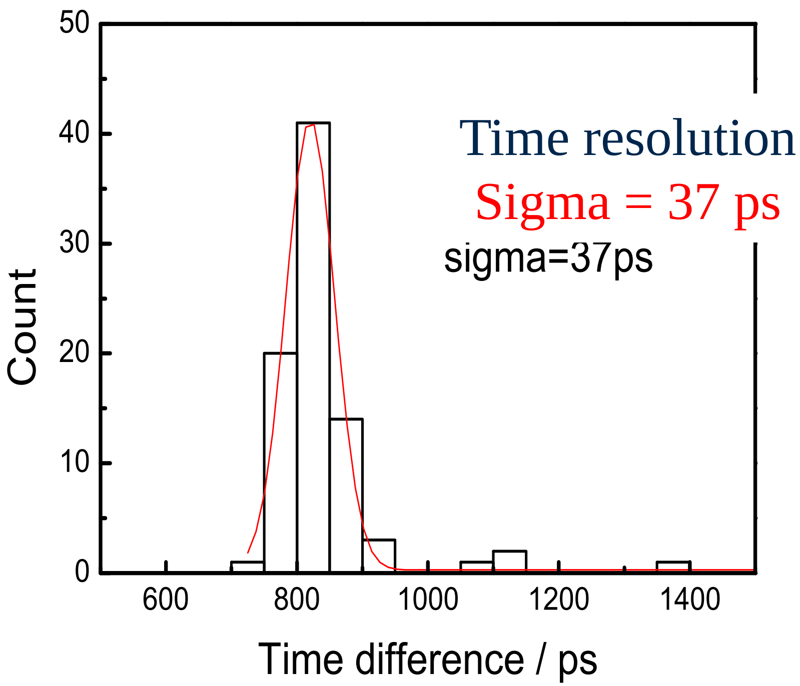
2. Experimental details and brief results



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

2. Experimental details and brief results

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



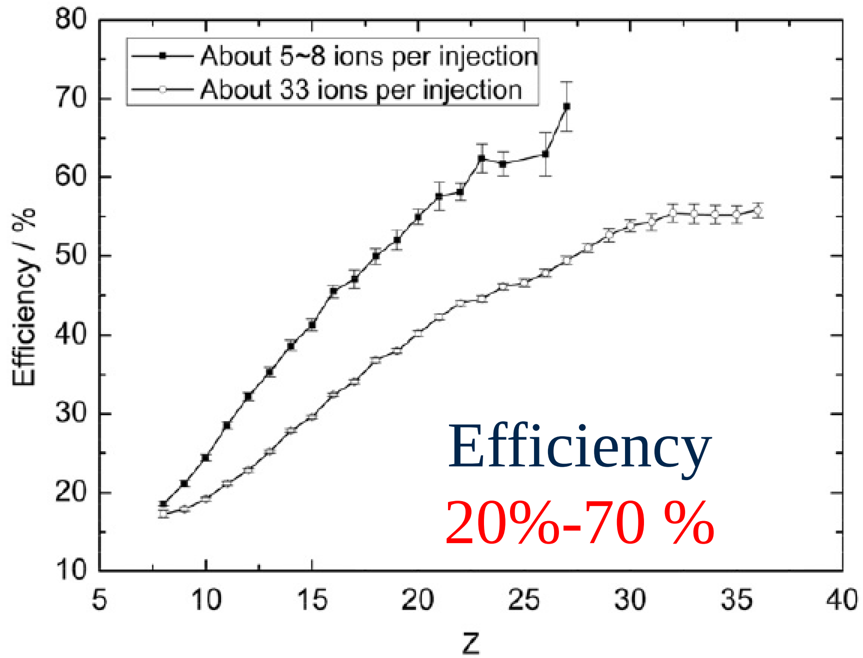
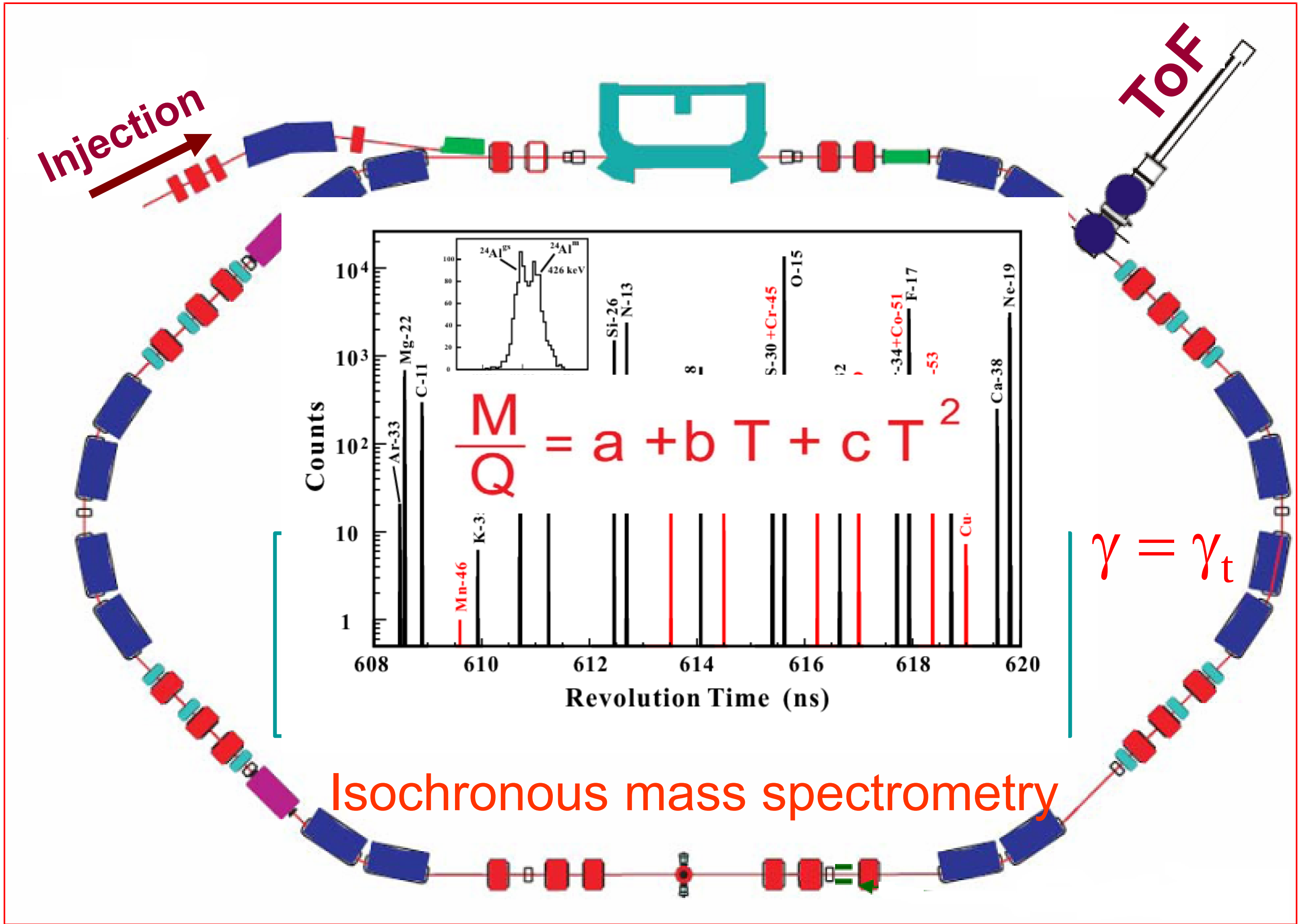


Fig. 7. Detection efficiency dependence on *Z* of ions and the number of ions circulating in the CSRe per injection.

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)

2. Experimental details and brief results



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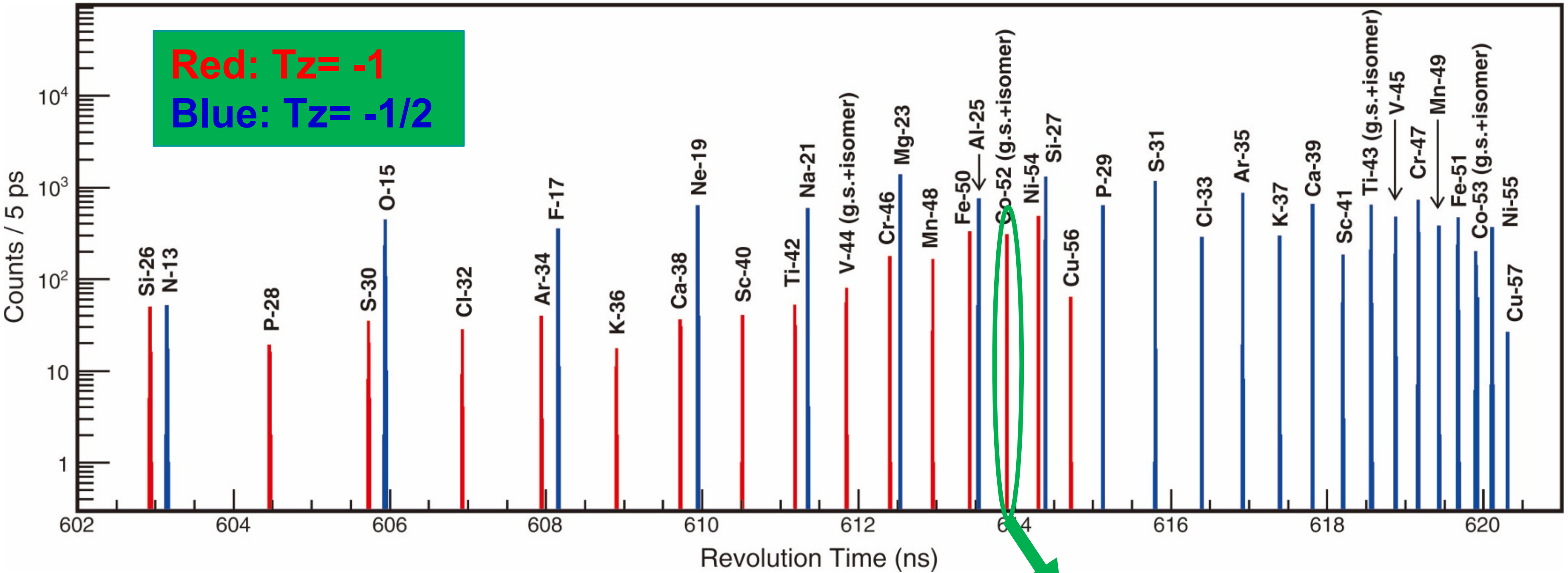

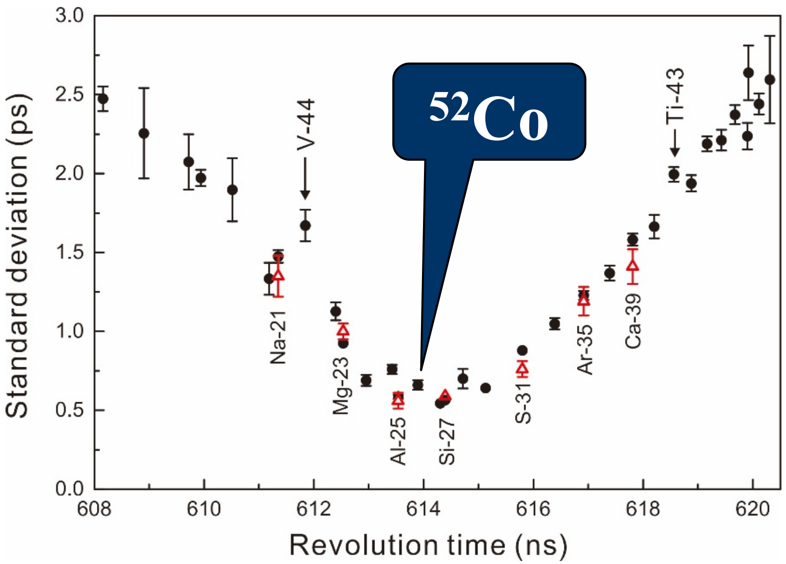

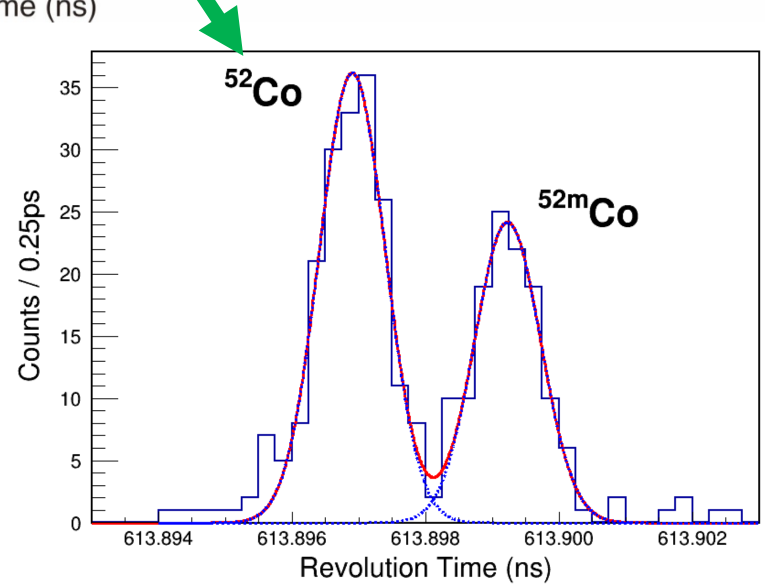

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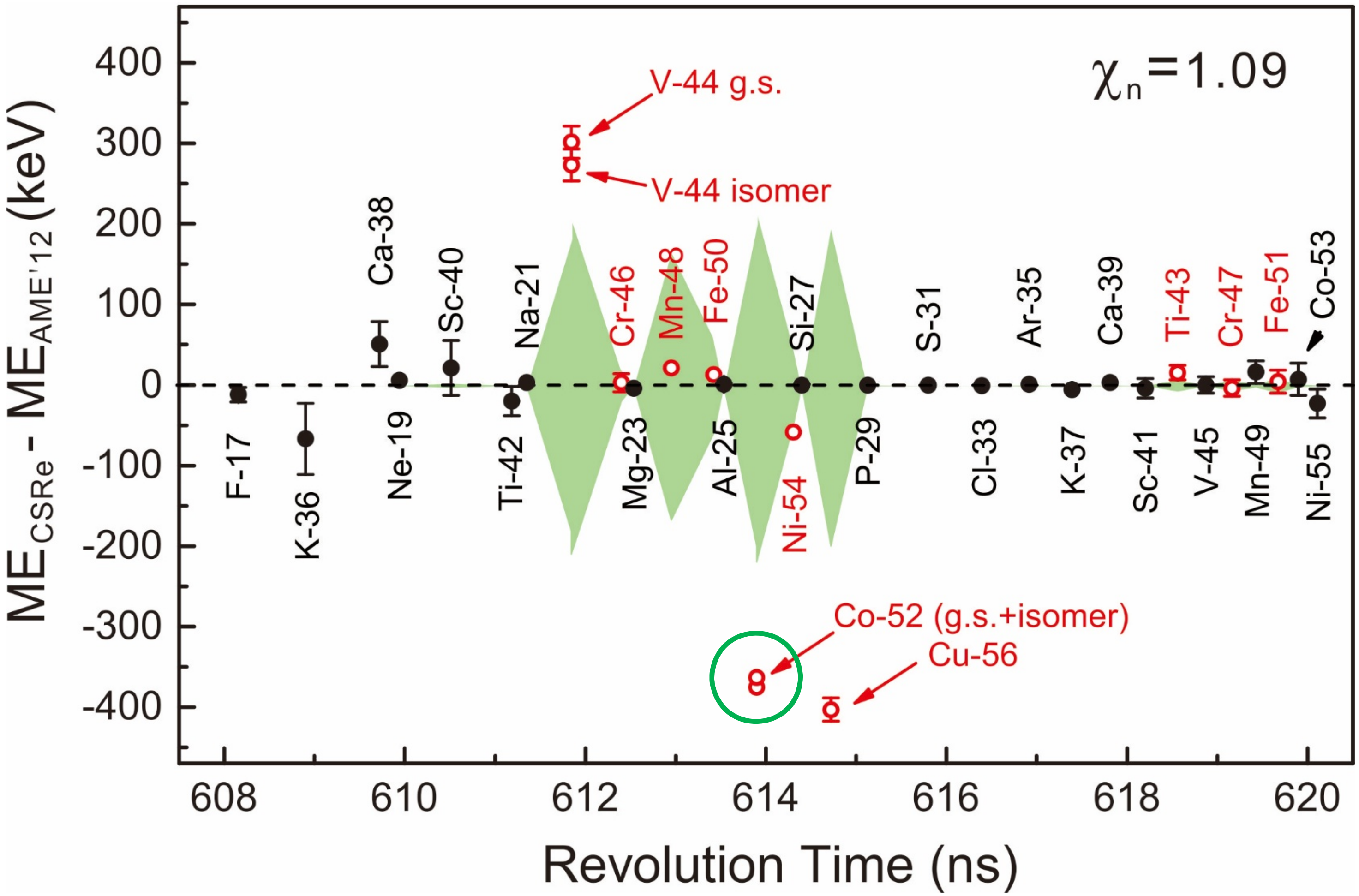


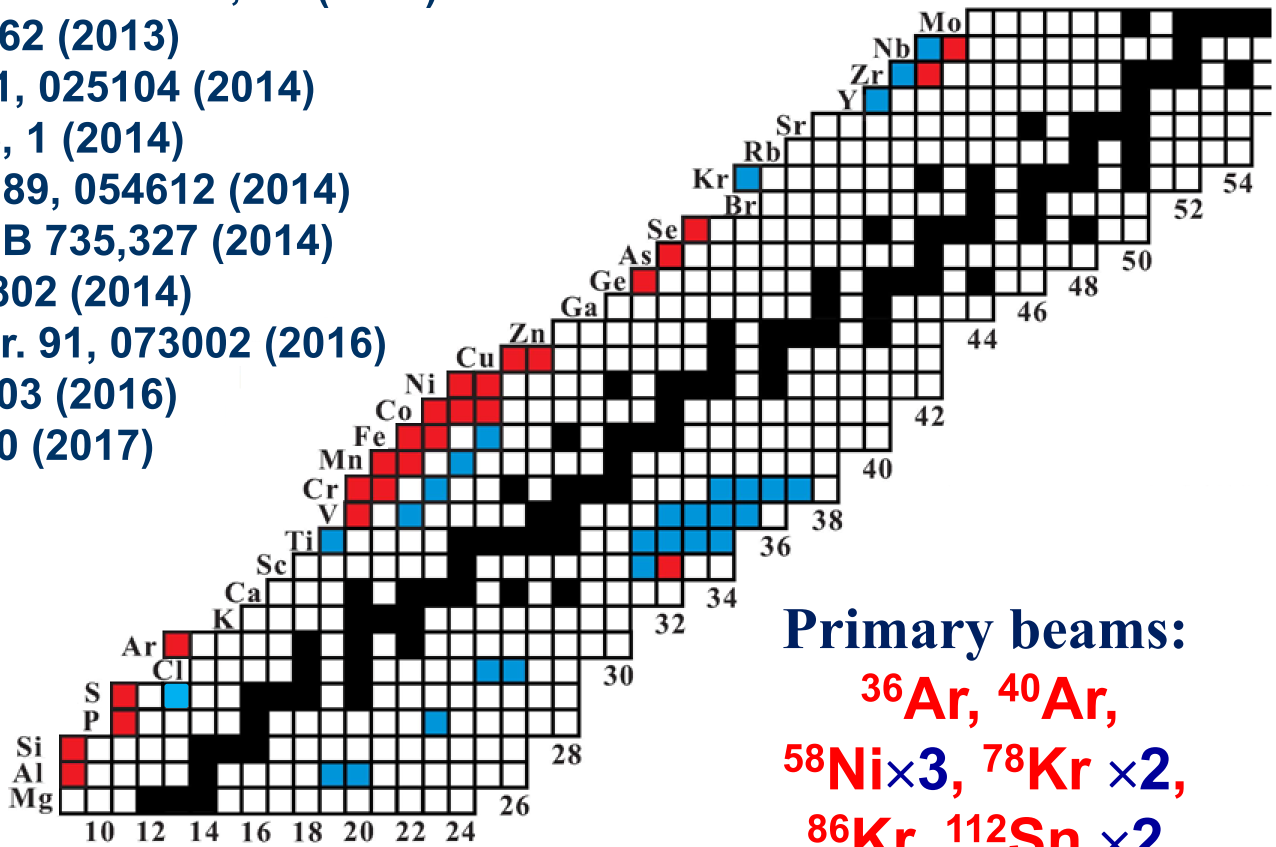
ME(^{52g}Co)= –34361(8) keV, ME(^{52m}Co)= –33974(10) keV

2. Experimental details and brief results

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)

■ Measured for the first time

■ Precision improved

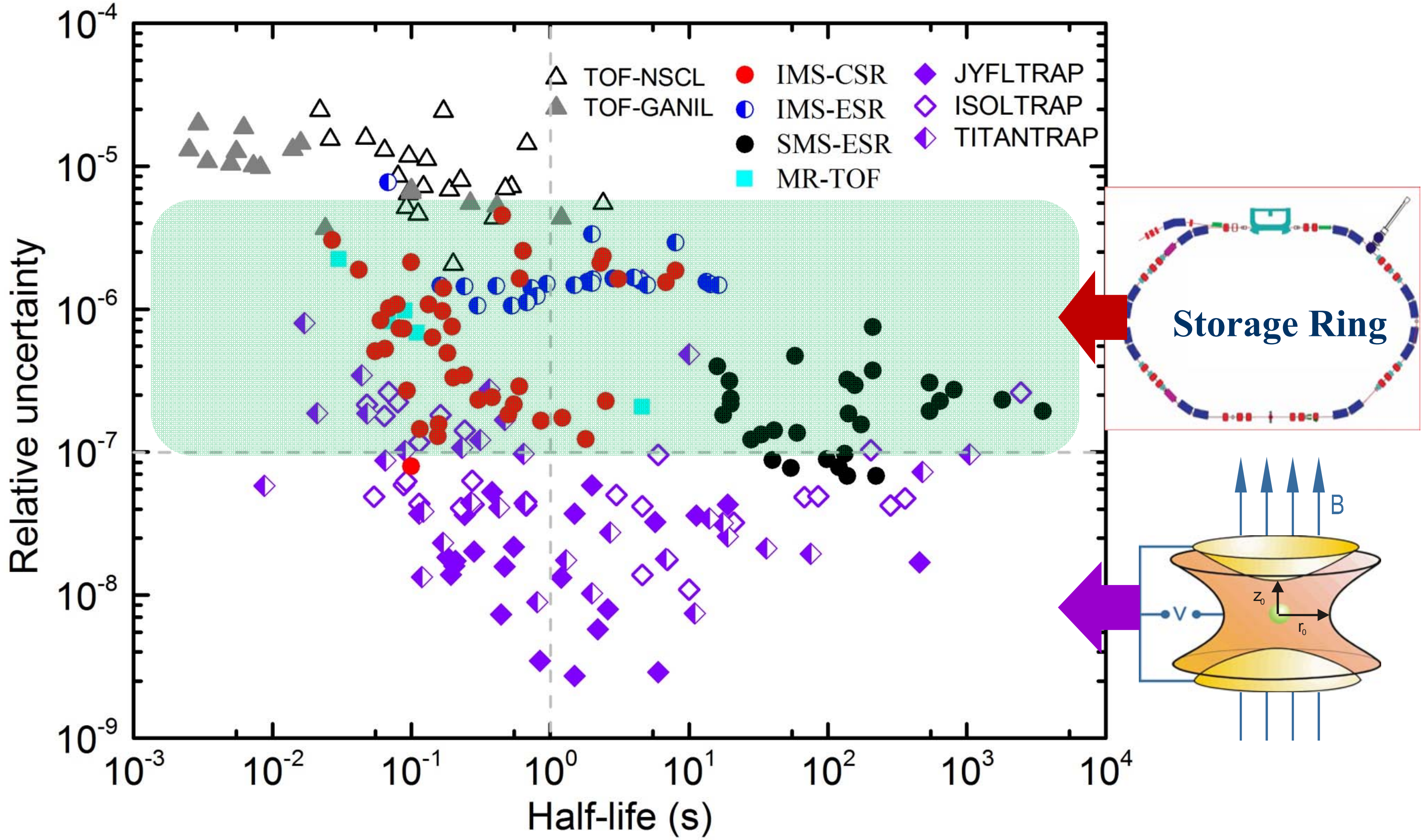


Precision
10^{-6}~10^{-7}
(10-200 keV)

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

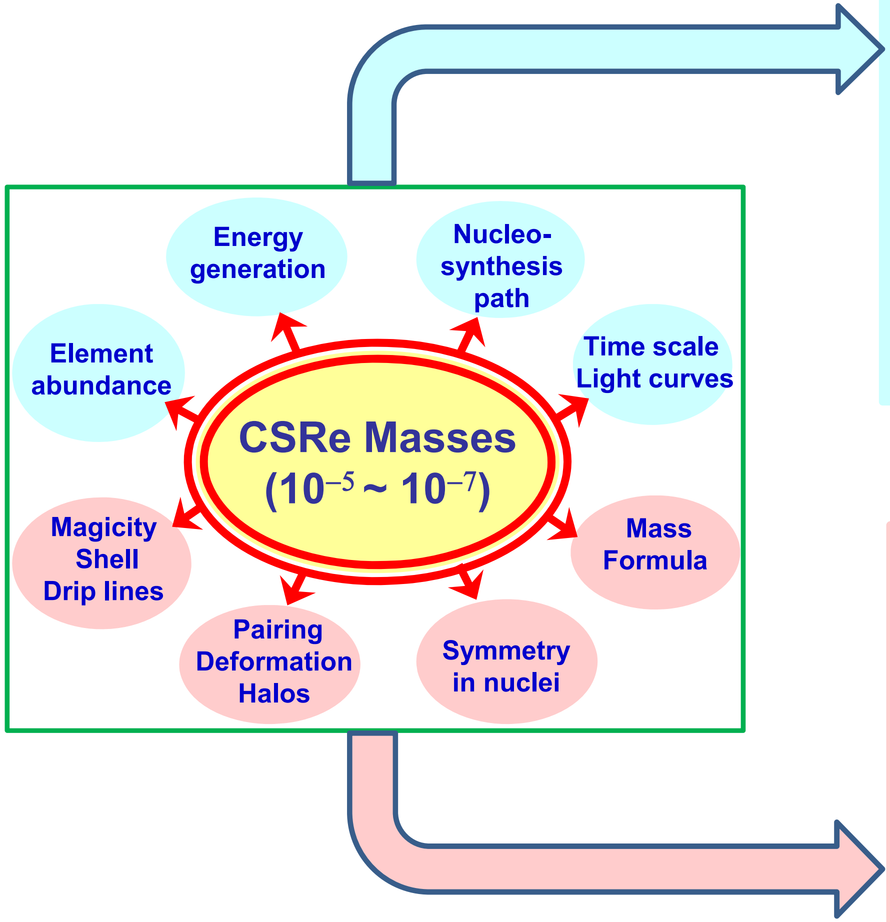
2. Experimental details and brief results

Precisions of new masses since 2010



2. Experimental details and brief results

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$(p,\gamma)^{43}$V rate in type-I XRB
  PRC 89, 035802 (2014)
- ^{65}As: ^{64}Ge$(p,\gamma)^{65}$As & ^{65}As$(p,\gamma)^{66}$Se in XRB
  Astrophys. J. 818, 78 (2016)
- ^{82}Zr: Abundance of *p*-nucleus ^{84}Sr
  in progress

- ^{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)

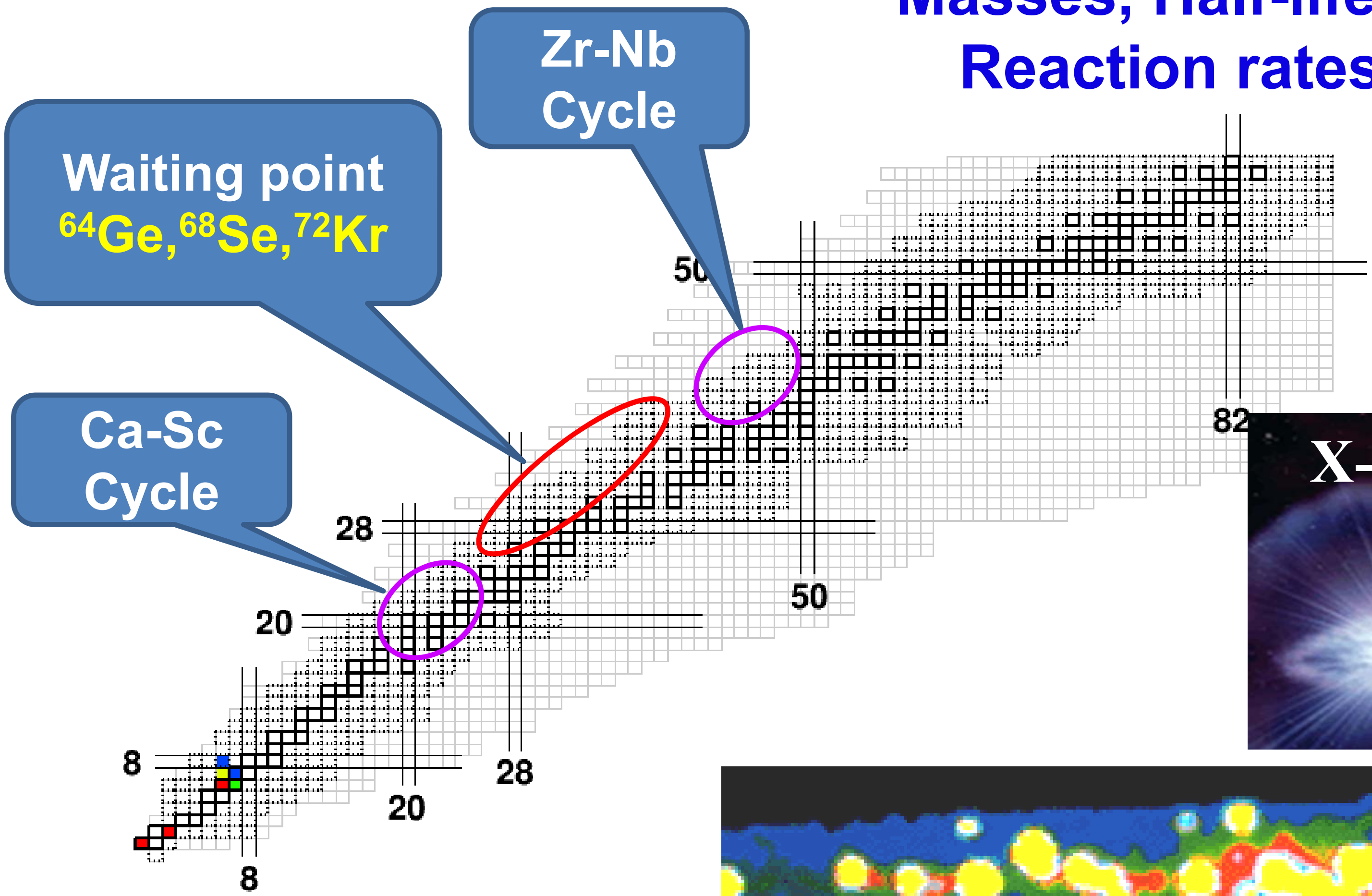
3. Impact on the studies of nuclear astrophysics

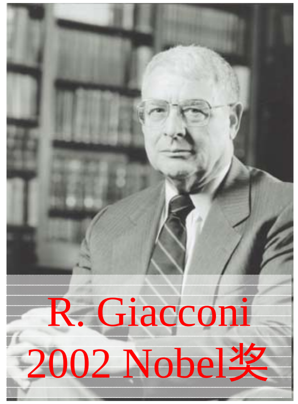
- ➔ (p,γ) reaction rates in the *rp*-process of type-I XRB
- ➔ waiting point nucleus ^{64}Ge in the rp-process
- ➔ Ca-Sc and Zr-Nb cycles in the rp-process
- ➔ Overproduction of *p*-nucleus ^{84}Sr in the νp-process
- ➔ Abundance ratio of ^{92}Mo/^{94}Mo in the νp-process

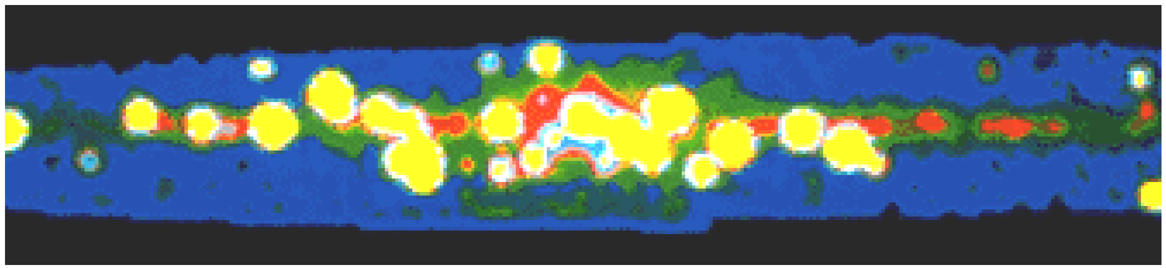
3. Impact on the studies of nuclear astrophysics

rp-process in X-ray burst

Nuclear inputs:
Masses, Half-lifes,
Reaction rates







3. Impact on the studies of nuclear astrophysics

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

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

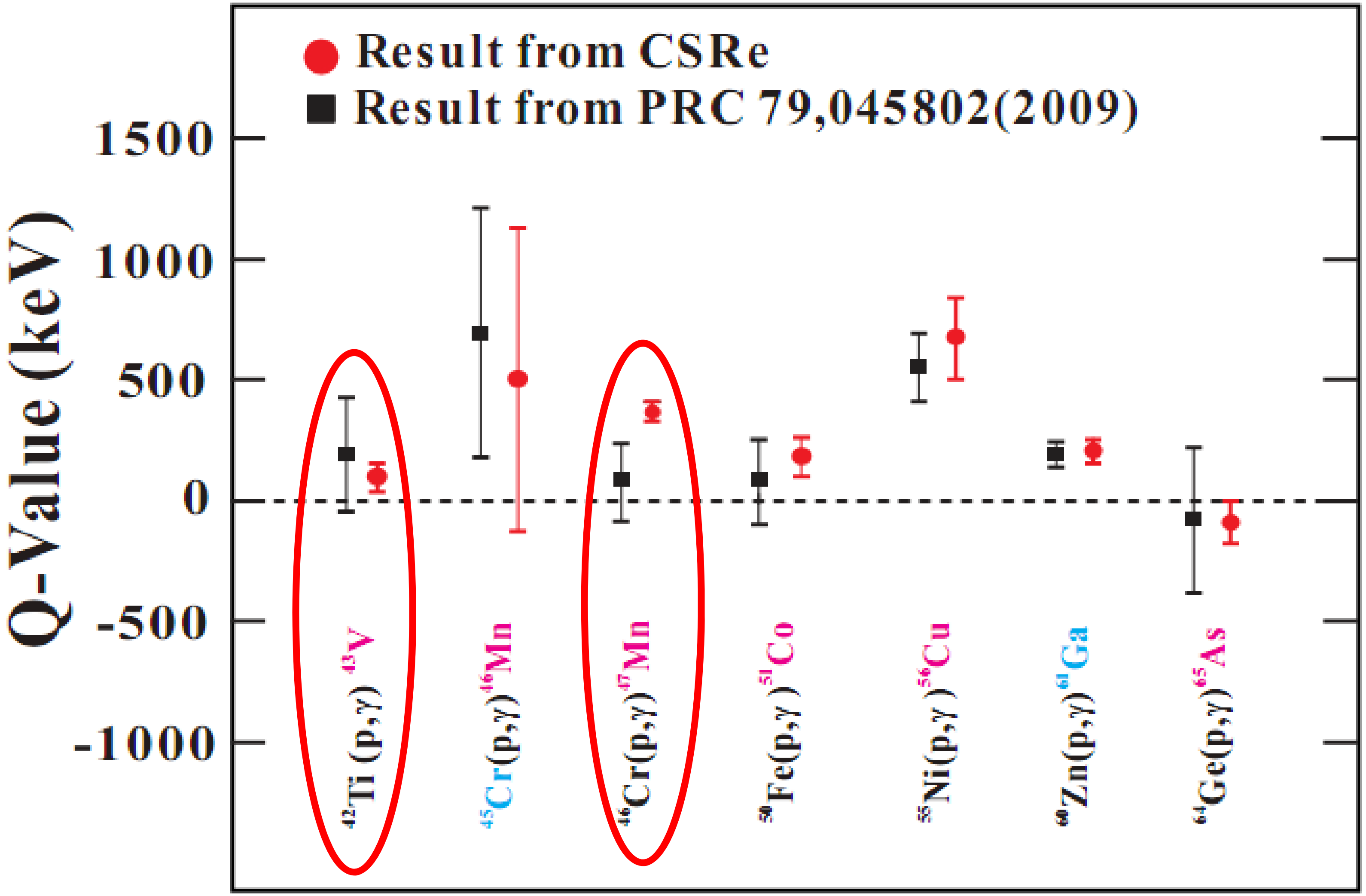
[a]Variation of this reaction Q-value affects the nuclear energy generation rate in this model (see text).

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

3. Impact on the studies of nuclear astrophysics

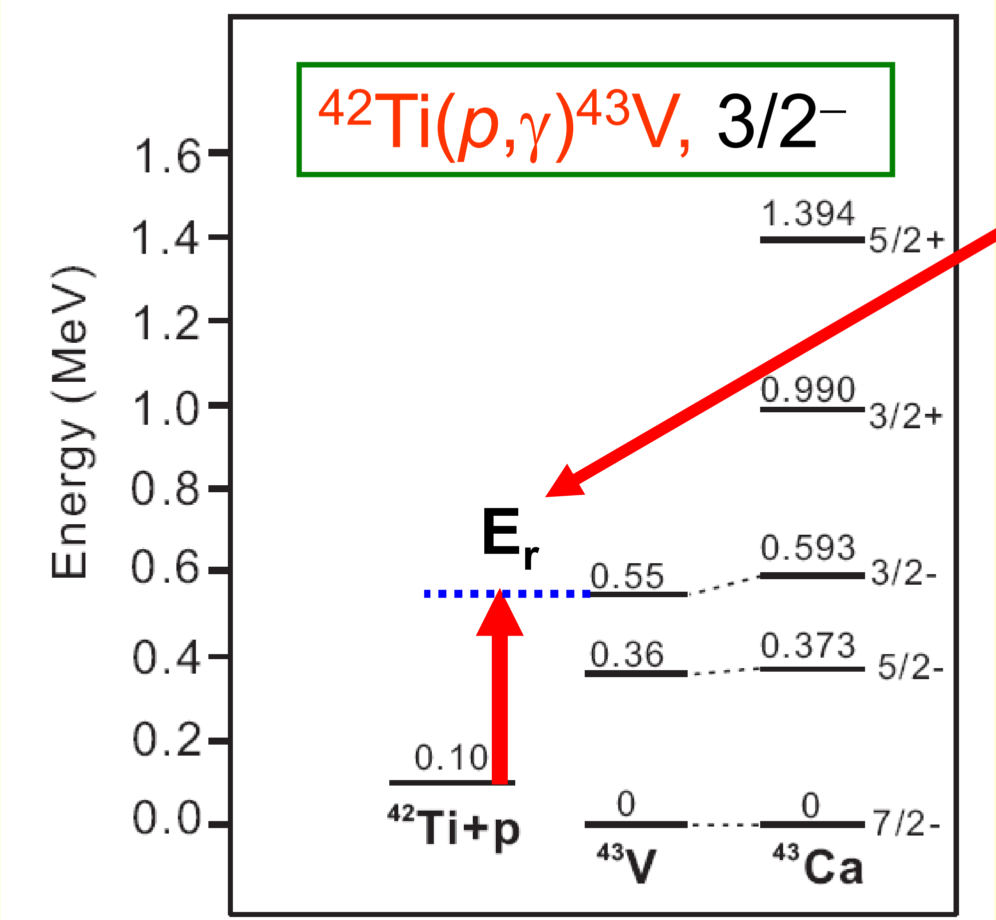
➔ **(*p*,*γ*) reaction rates in the *rp*-process of type-I XRB**



3. Impact on the studies of nuclear astrophysics

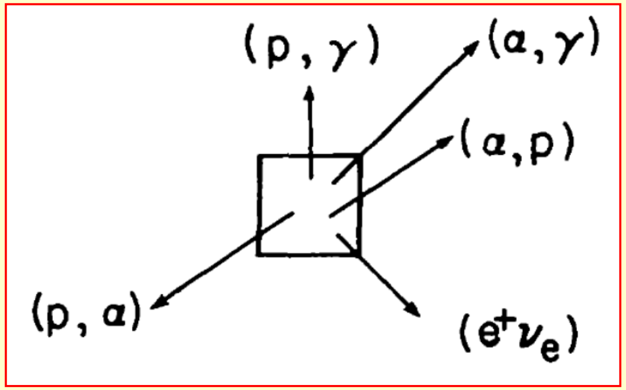
➔ **(p,γ) reaction rates in the *rp*-process of type-I XRB**

$$N_A\langle\sigma v\rangle_r = 1.54 \times 10^{11}(AT_9)^{-3/2}\omega\gamma[\text{MeV}]\exp\left(\frac{-11.605 E_r[\text{MeV}]}{T_9}\right)$$



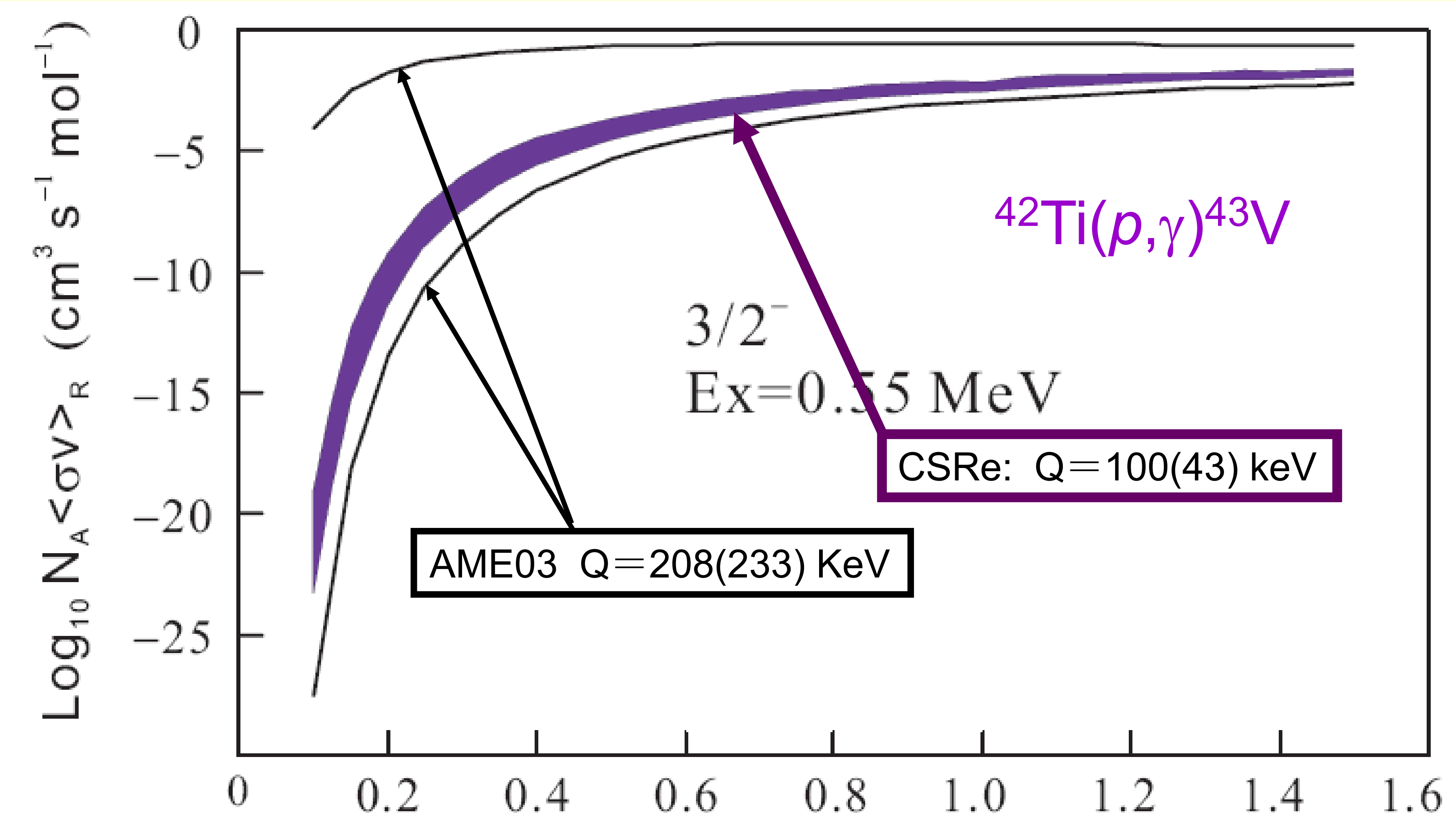
$$\omega\gamma = \frac{2J+1}{2(2J_T+1)}\frac{\Gamma_p \times \Gamma_\gamma}{\Gamma_{tot}}.$$

ωγ =5.98 X 10^{-6} (eV)
PRC52, 1078 (1995)



3. Impact on the studies of nuclear astrophysics

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



3. Impact on the studies of nuclear astrophysics

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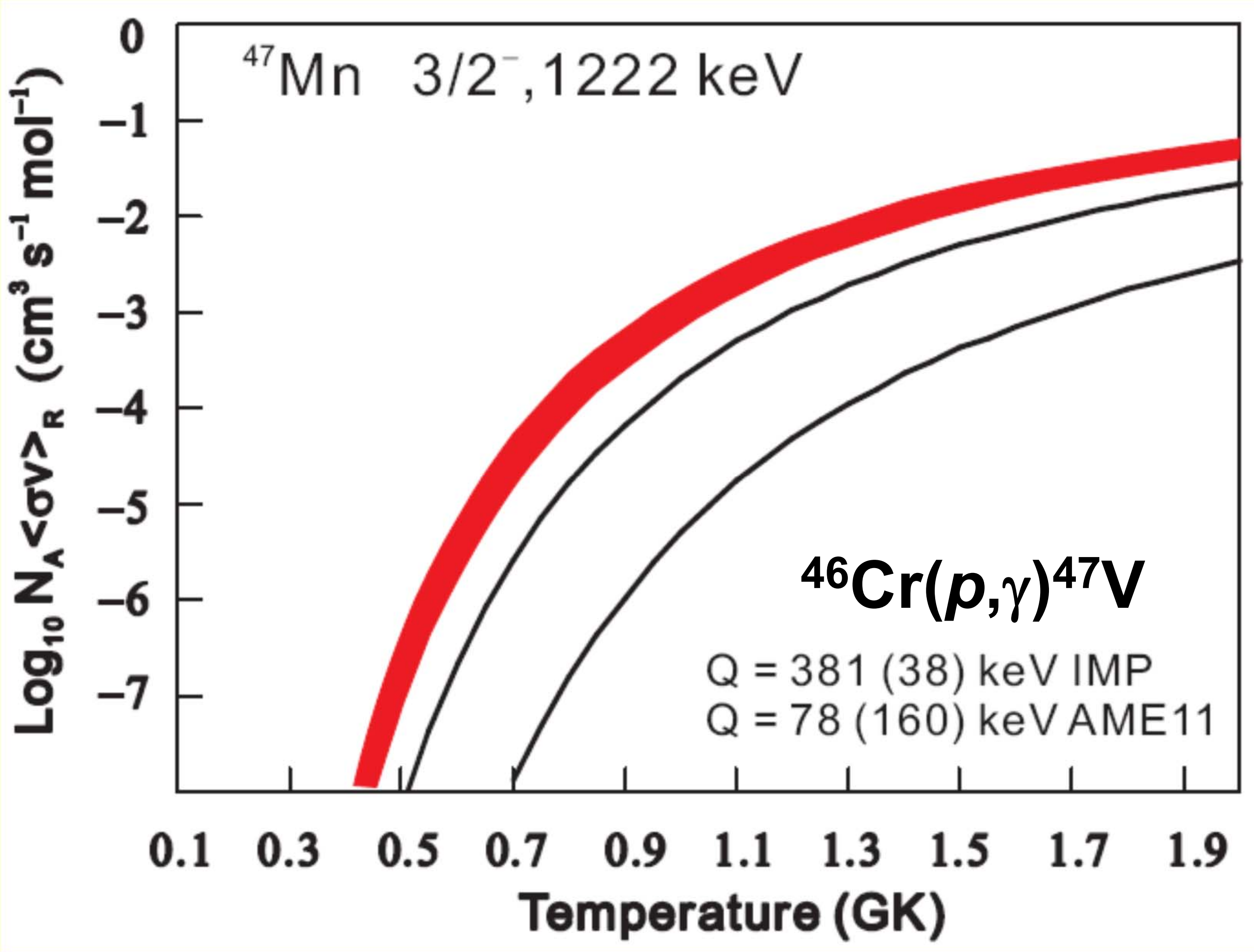

3. Impact on the studies of nuclear astrophysics

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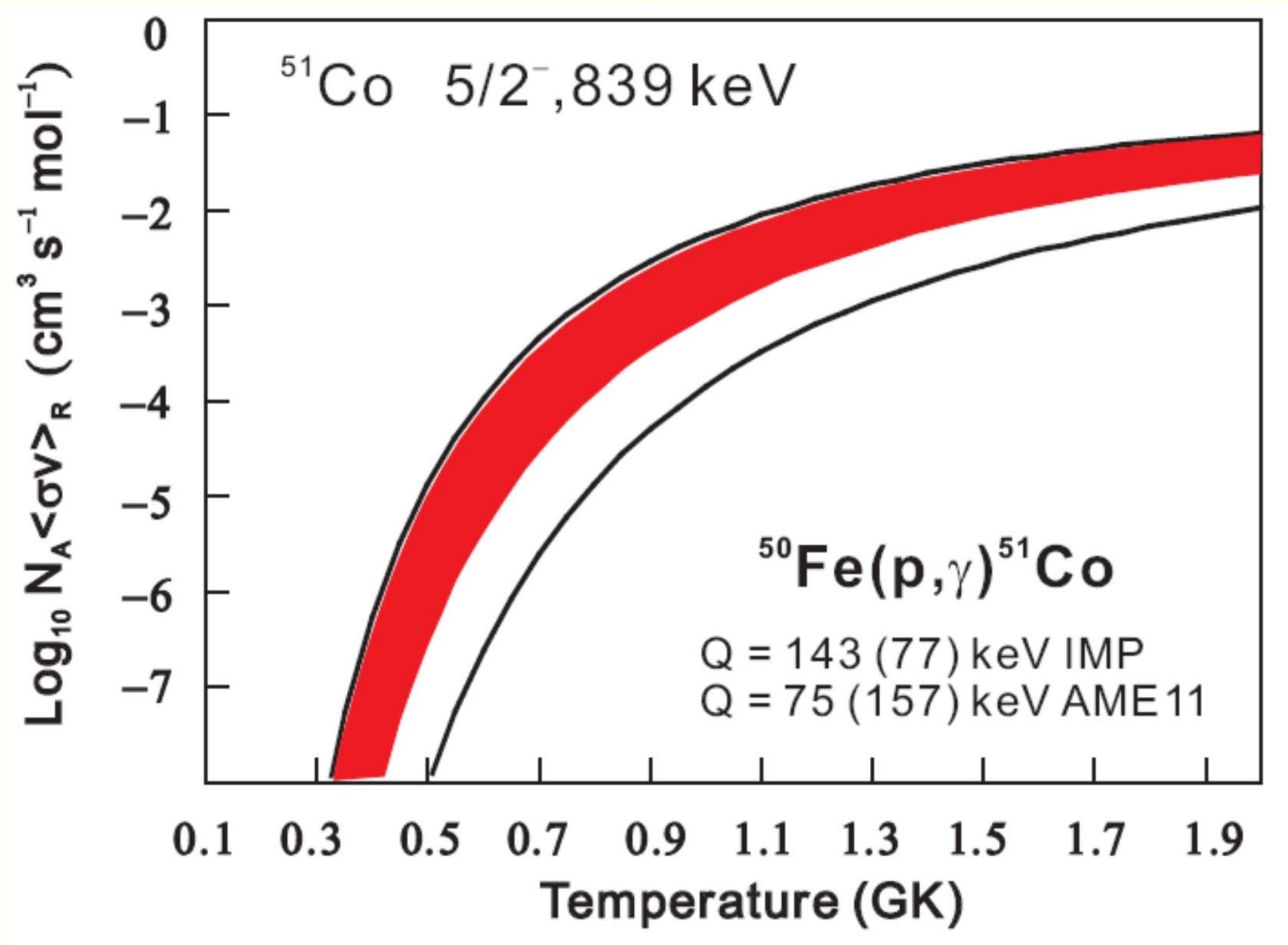
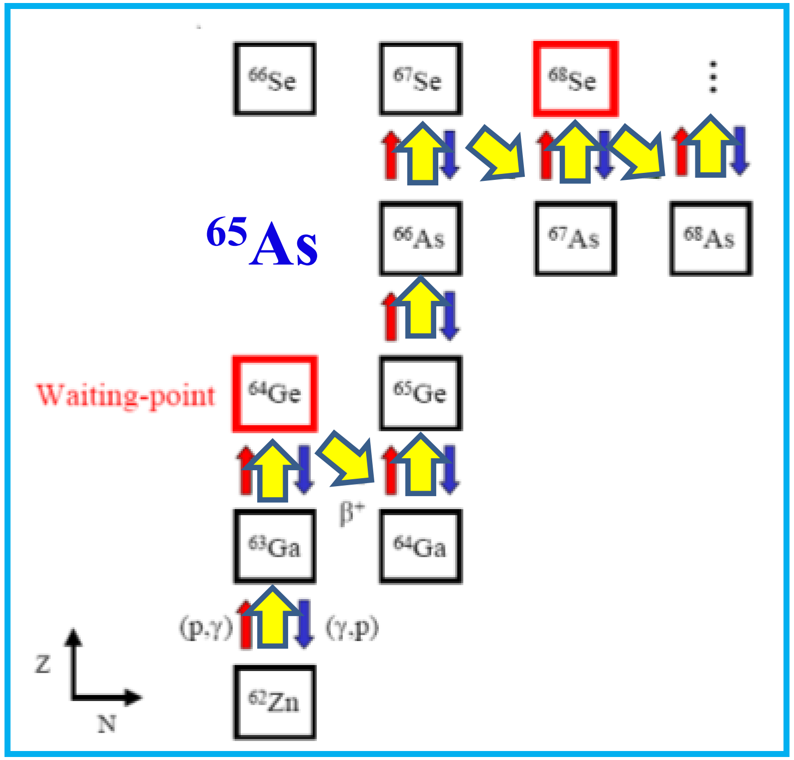
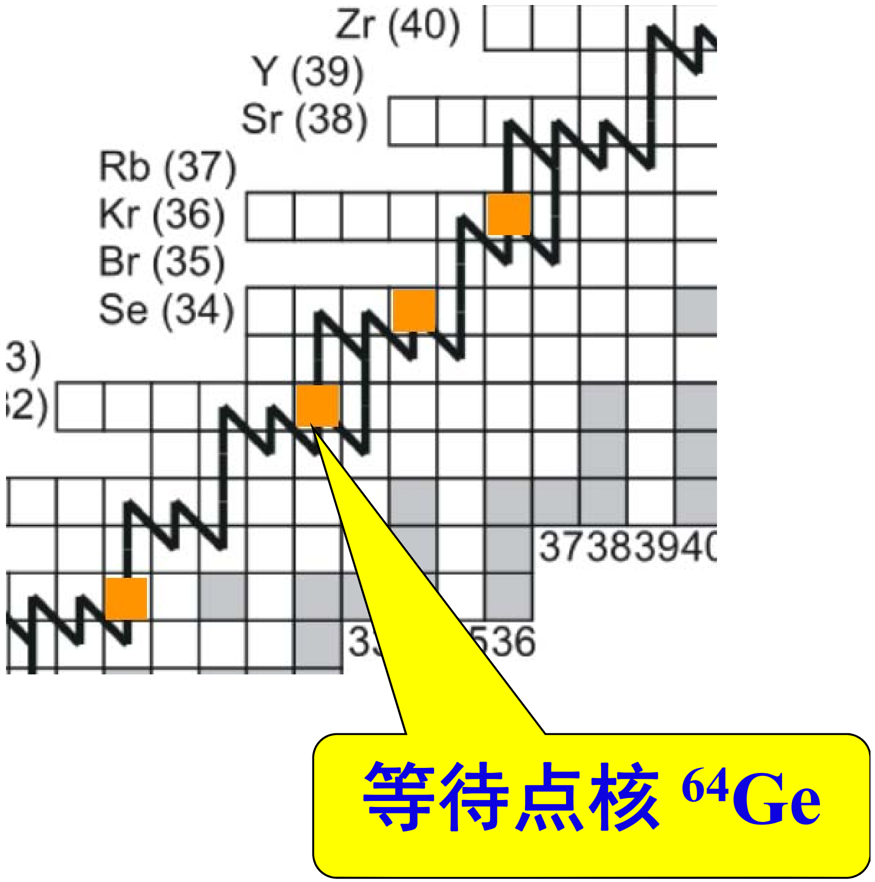


3. Impact on the studies of nuclear astrophysics

→ **waiting point nucleus ^{64}Ge in the rp-process**

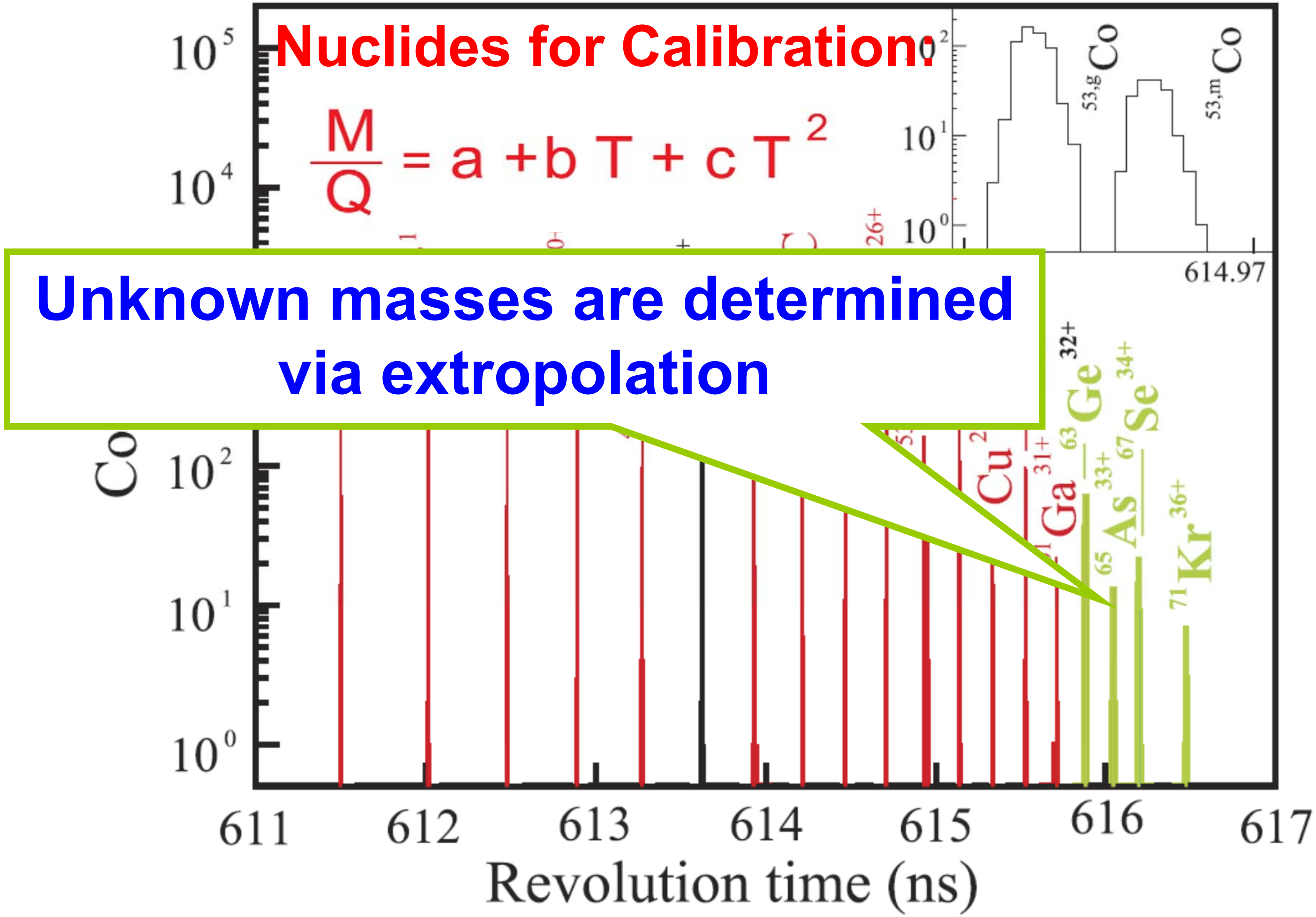




$S_p(^{65}As)$ >-250 keV (AME2003)

3. Impact on the studies of nuclear astrophysics

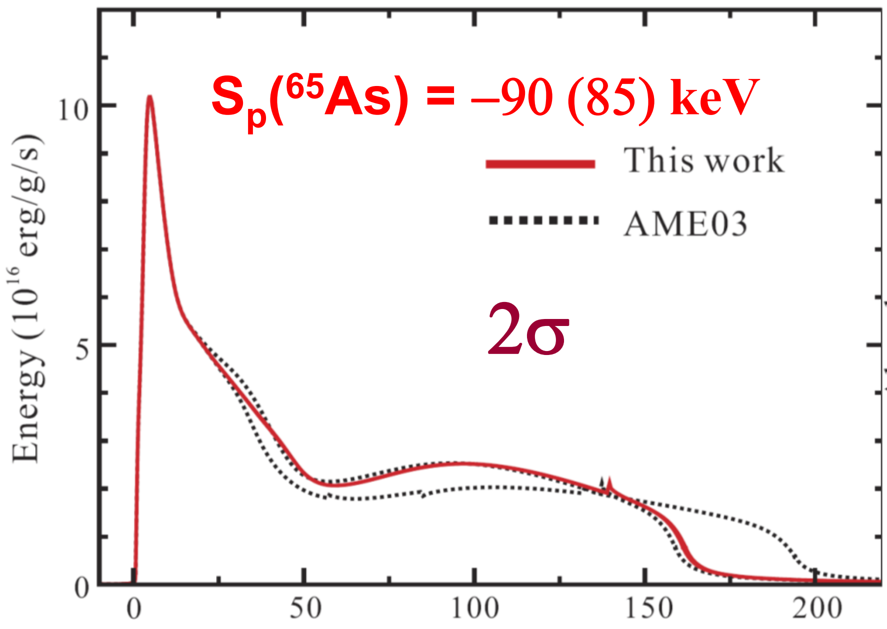
➔ **waiting point nucleus ^{64}Ge in the rp-process**



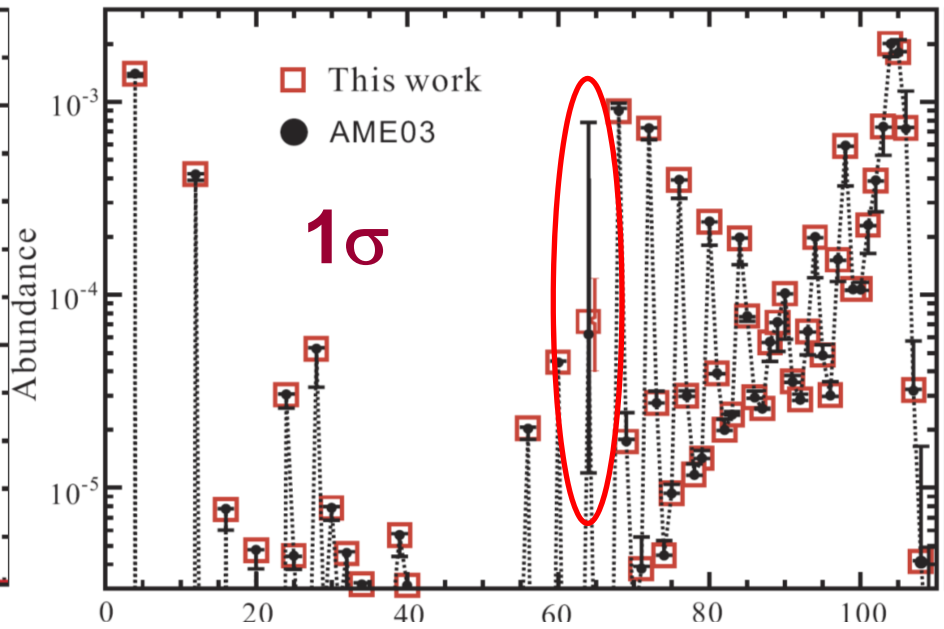
3. Impact on the studies of nuclear astrophysics

➔ waiting point nucleus ^{64}Ge in the rp-process

Light curve shape of Type I x-ray burst



Abundance of x-ray burst ashes

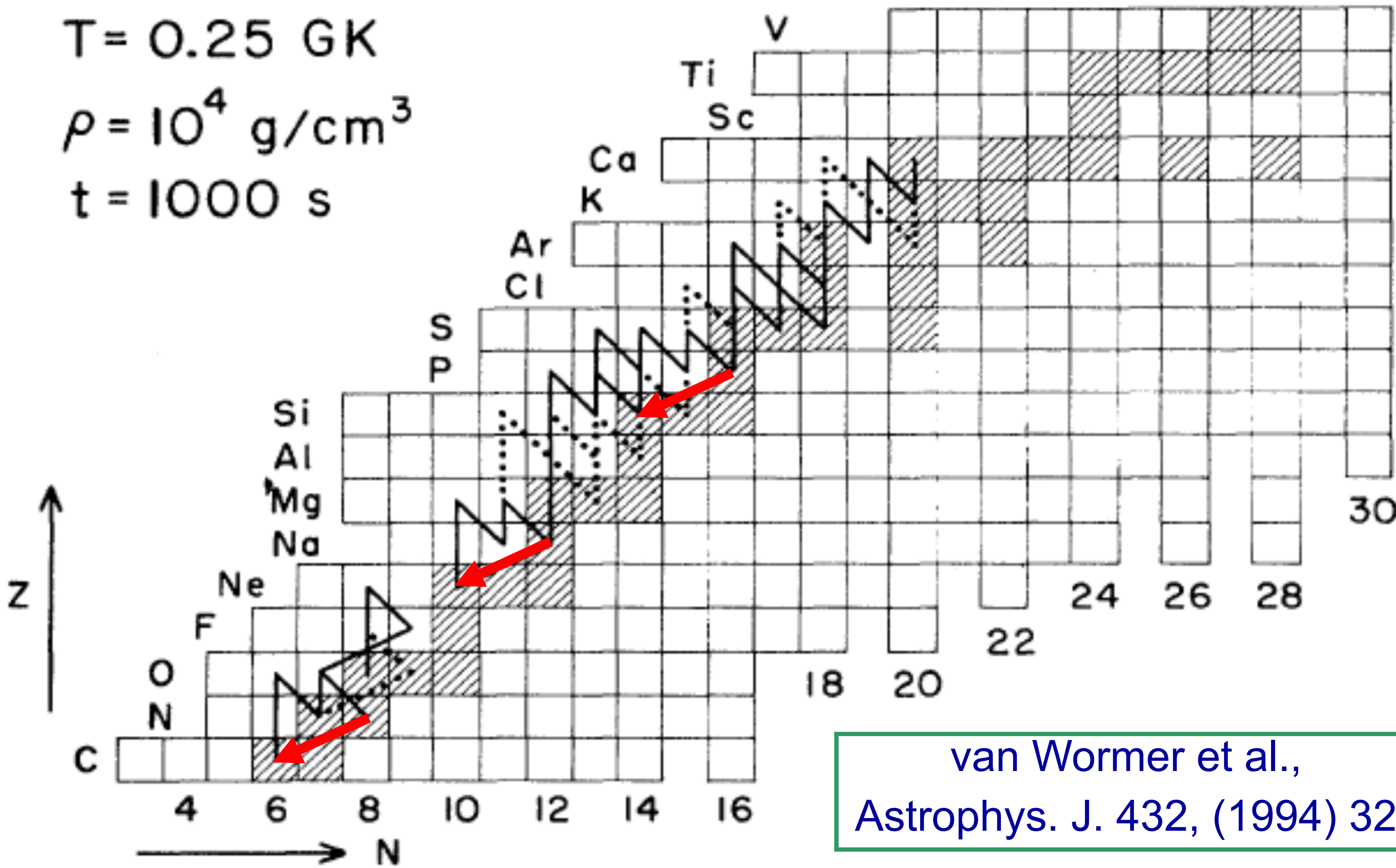


89%–90% of the reaction flow passes through ^{64}Ge via proton capture indicating that:

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

3. Impact on the studies of nuclear astrophysics

→ Ca-Sc and Zr-Nb cycles in the rp-process



van Wormer et al.,
Astrophys. J. 432, (1994) 326

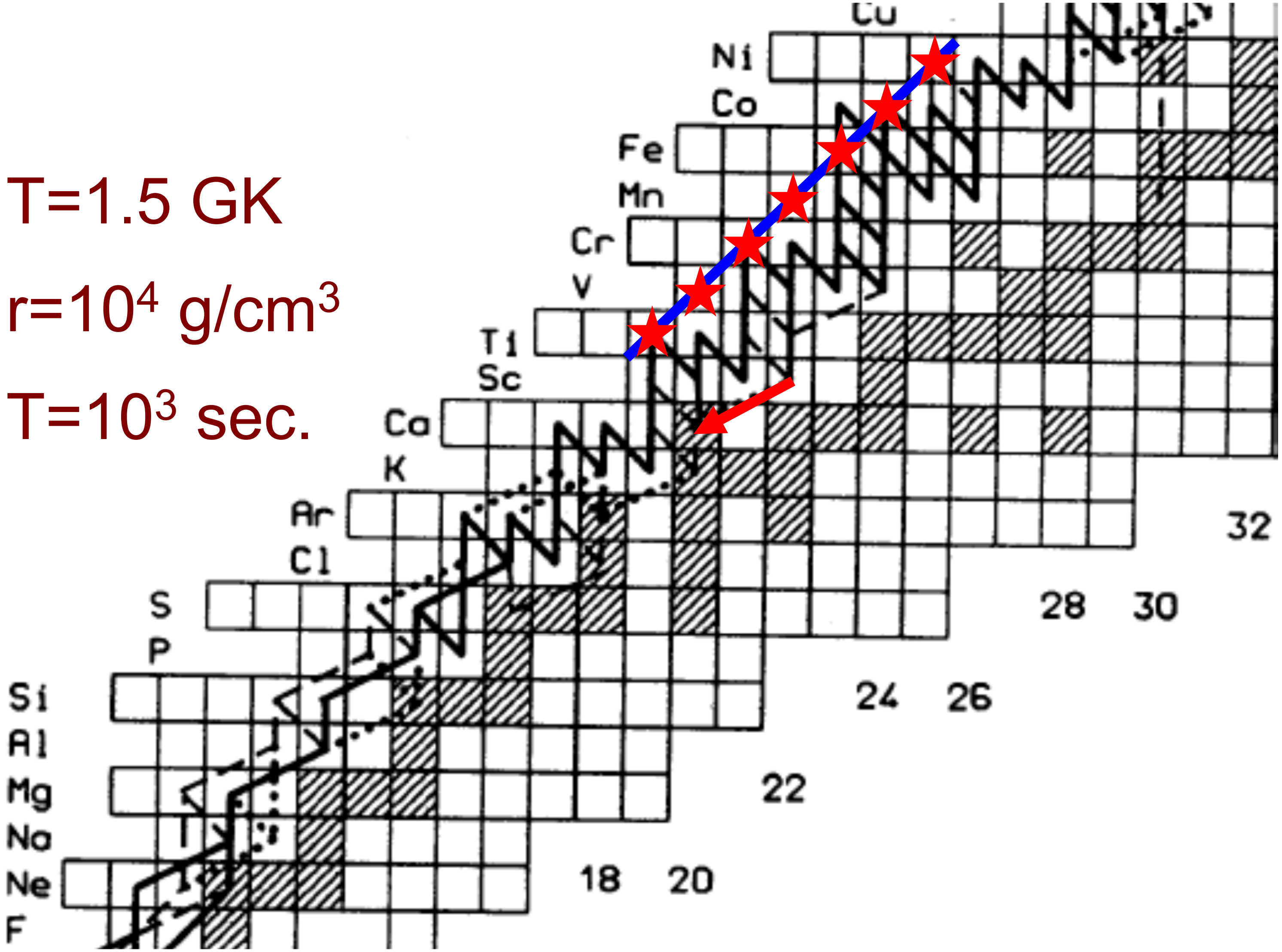
3. Impact on the studies of nuclear astrophysics

→ Ca-Sc and Zr-Nb cycles in the rp-process

T=1.5 GK

r=10^4 g/cm^3

T=10^3 sec.



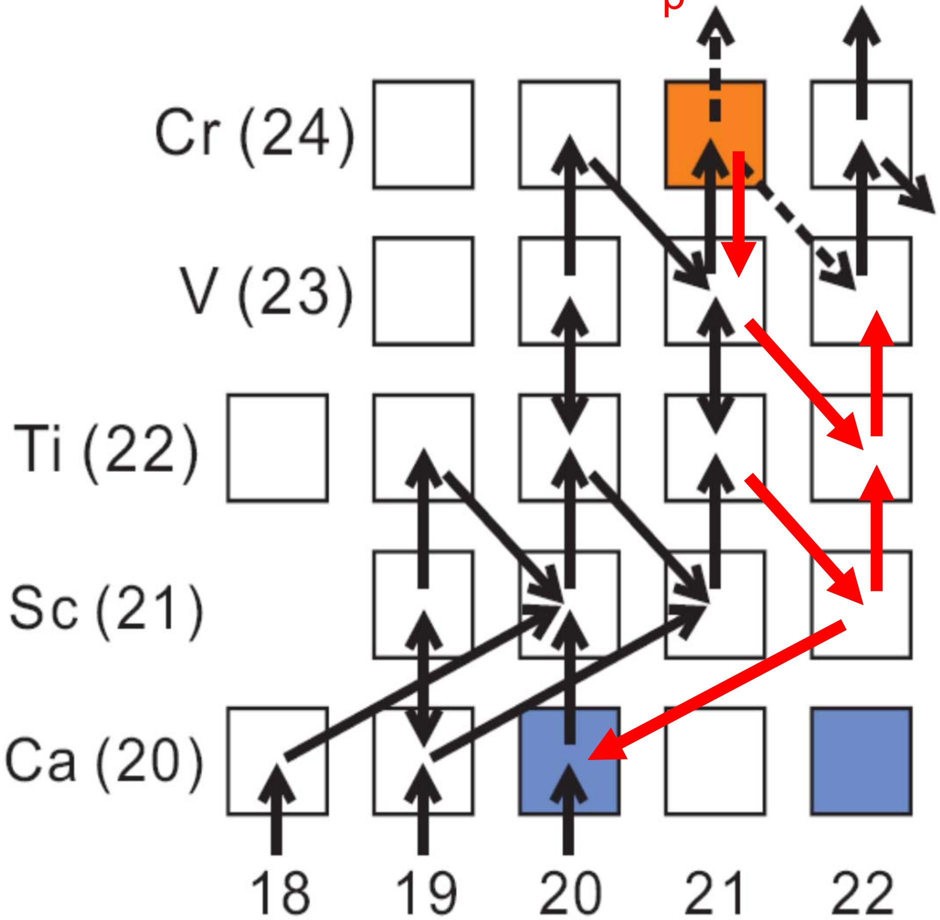
3. Impact on the studies of nuclear astrophysics

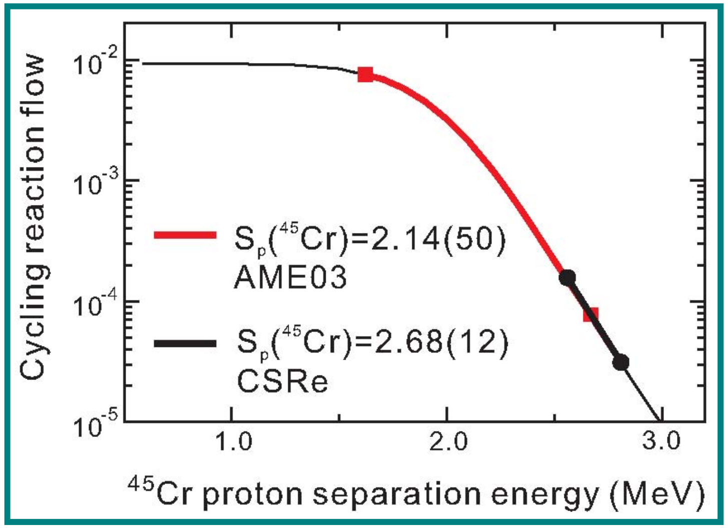
➔ Ca-Sc and Zr-Nb cycles in the rp-process

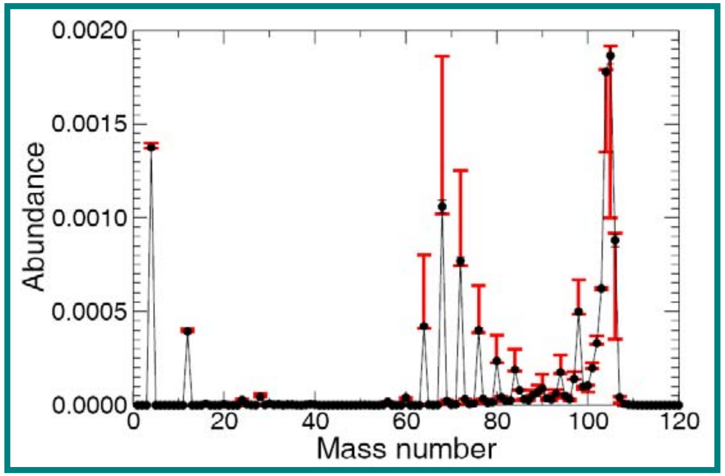
X. L. Yan *et al.* 2013 *ApJ* 766 L8

AME03 up limit >>> $S_p+3\sigma$

AME03 low limit >>> $S_p-3\sigma$



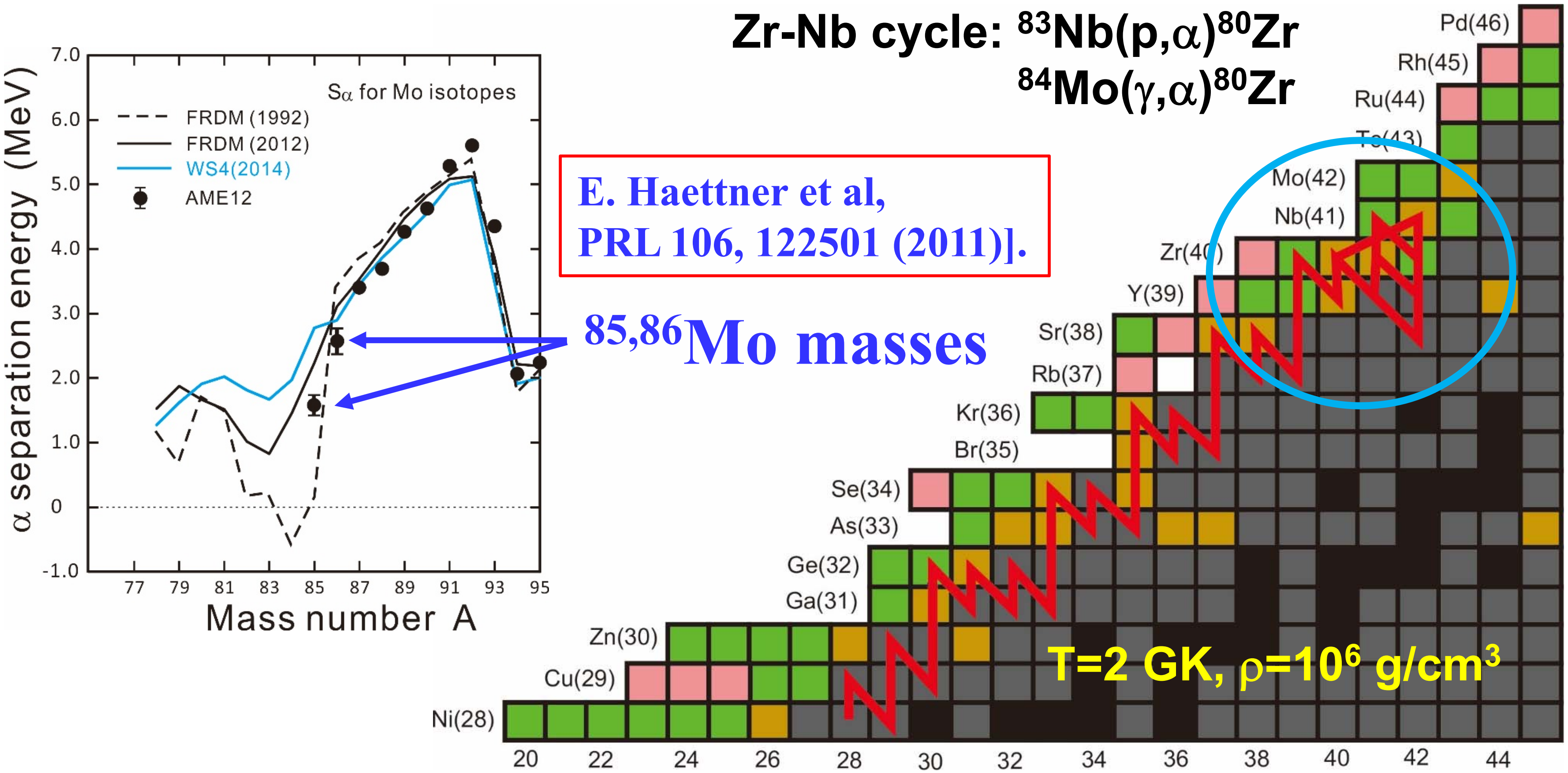




3. Impact on the studies of nuclear astrophysics

➔ Ca-Sc and Zr-Nb cycles in the rp-process

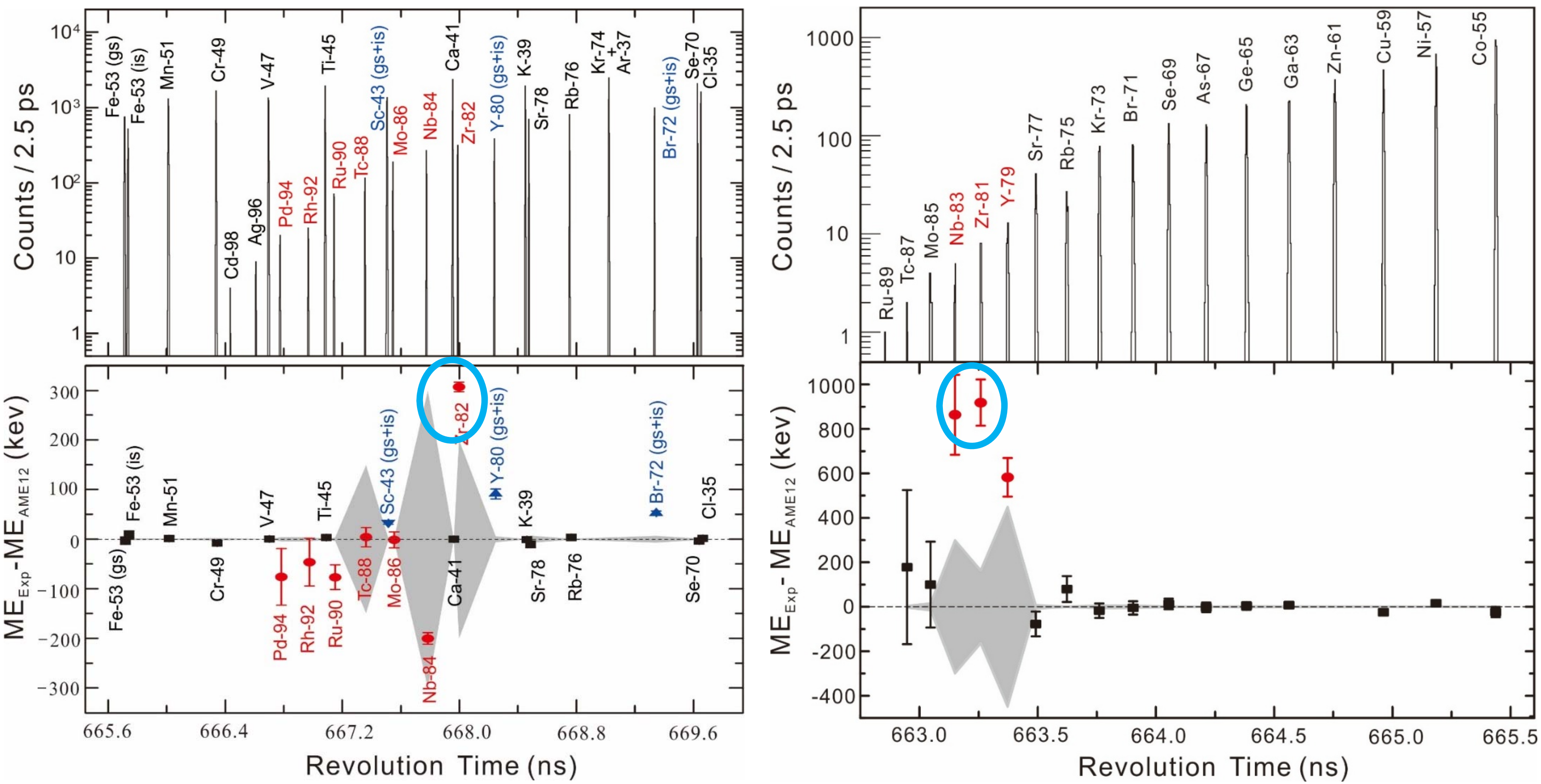
Zr-Nb cycle was proposed by H. Schatz et al, Phys. Rep. 294, 167 (1998) based on the FRDM mass prediction in 1992, which show a very low or even negative α separation energy of ^{84}Mo.



3. Impact on the studies of nuclear astrophysics

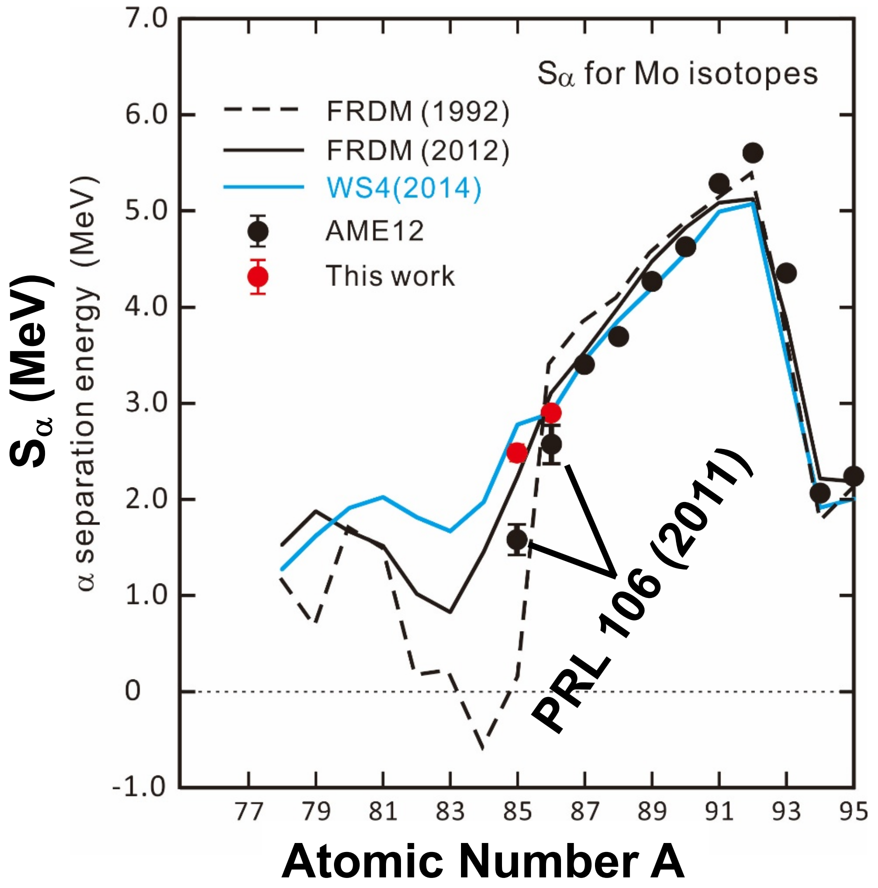
→ Ca-Sc and Zr-Nb cycles in the rp-process

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

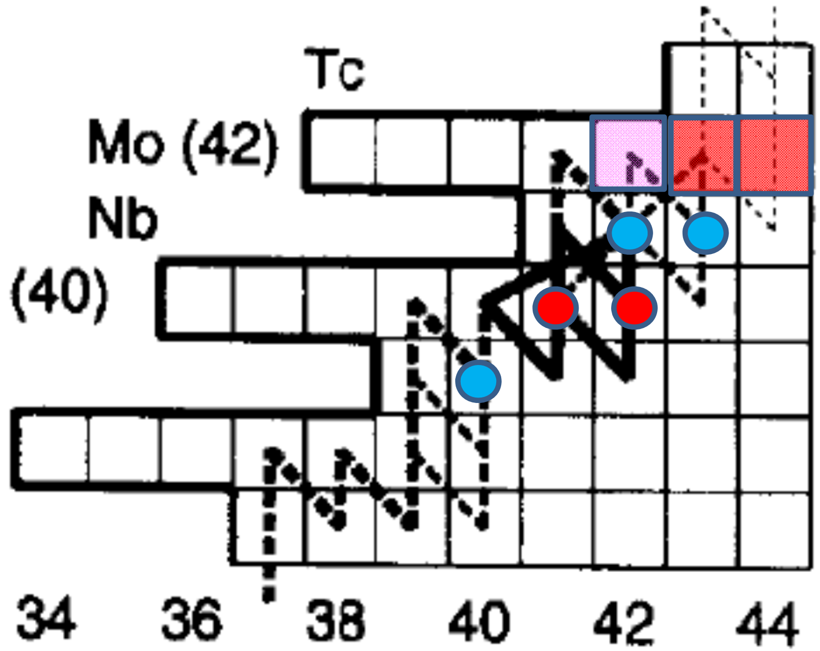


3. Impact on the studies of nuclear astrophysics

→ **Ca-Sc and Zr-Nb cycles in the rp-process**



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

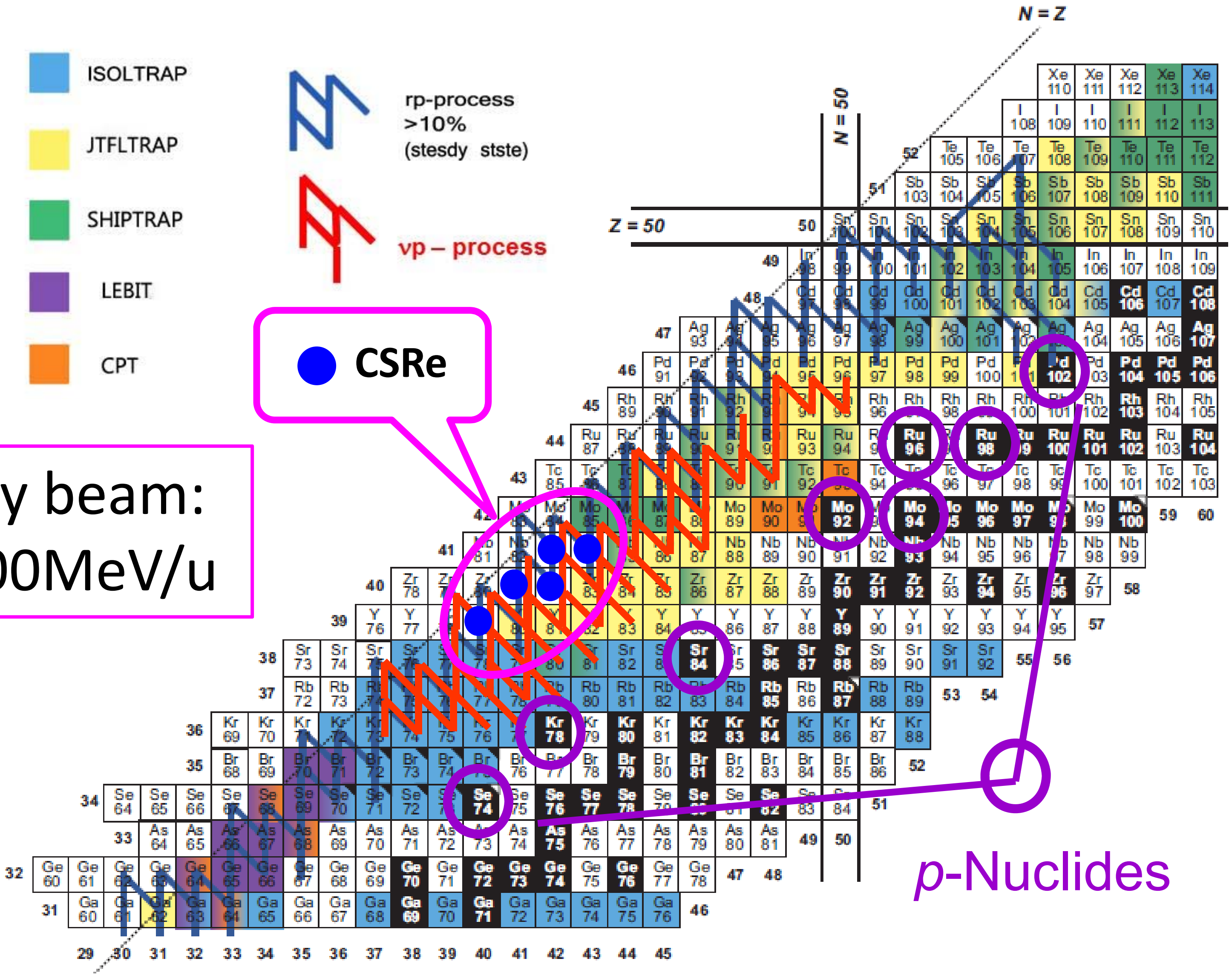


T=2 GK, ρ=10^6 g/cm^3

From our S_α values and reasonable extrapolation to ^{84}Mo, the Zr-Nb cycle should be weaker or disappeared.

3. Impact on the studies of nuclear astrophysics

➔ **Overproduction of *p*-nucleus ^{84}Sr in the ν*p*-process**



CSR primary beam:
$^{112}Sn^{35+}$ @400MeV/u

3. Impact on the studies of nuclear astrophysics

➔ **Overproduction of *p*-nucleus ^{84}Sr in the ν*p*-process**

Solar

Table 4
p-Nuclei Abundances and Their Possible Sources

Species	Abundance[a]	Fraction[b] (%)	γ-Process[c]	ν-Process[d]	*p*-QSE[e]	ν*p*-Process[f]
^{74}Se	0.58	0.889	Yes	No	Yes	Yes
^{78}Kr	0.20	0.362	Yes	No	Yes	Yes
^{84}Sr	0.13124	0.5551	Yes	No	Yes	Yes
^{92}Mo	0.386	14.8362	No	No	Yes	Yes
^{94}Mo	0.241	9.2466	No	No	No	Yes
^{96}Ru	0.1053	5.542	No	No	No	Yes
^{98}Ru	0.0355	1.8688	No	No	No	Yes
^{102}Pd	0.0146	1.02	No	No	No	Yes
^{106}Cd	0.01980	1.25	No	No	No	Yes
^{108}Cd	0.01410	0.89	No	No	No	Yes
^{113}In	0.0078	4.288	No	No	No	[Yes]
^{112}Sn	0.03625	0.971	[Yes]	No	No	[Yes]
^{114}Sn	0.02460	0.659	[Yes]	No	No	[Yes]
^{115}Sn	0.01265	0.339	No	No	No	[Yes]

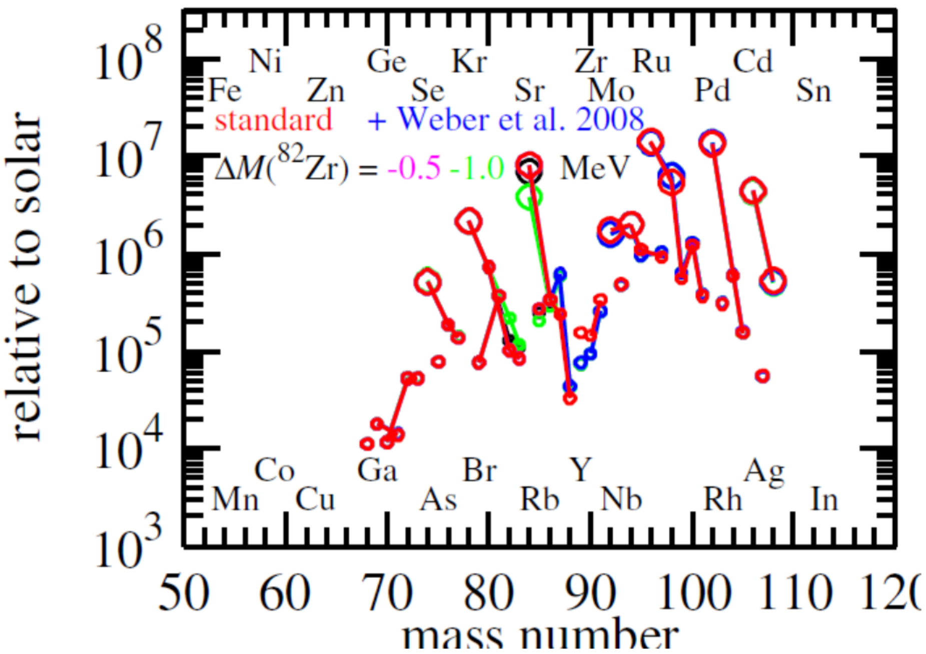
Calculated abundance ratio of ^{84}Sr/^{94}Mo should be lower than the observed one

Shinya Wanajo, Hans-Thomas Janka, and Shigeru Kubono, The Astrophysical Journal, 729:46 (18pp), 2011 March 1, UNCERTAINTIES IN THE *νp*-PROCESS: SUPERNOVA DYNAMICS VERSUS NUCLEAR PHYSICS

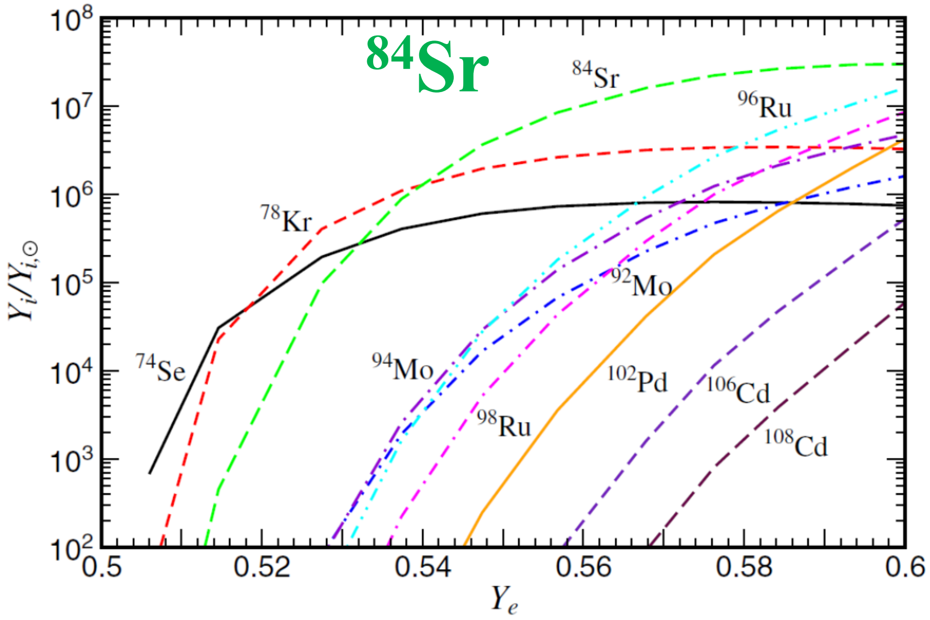
3. Impact on the studies of nuclear astrophysics

➔ **Overproduction of *p*-nucleus ^{84}Sr in the ν*p*-process**

S. Wanajo et al., ApJ, 729:46 (2011)



C. Frohlich et al., PRL **96,** 142502 (2006)

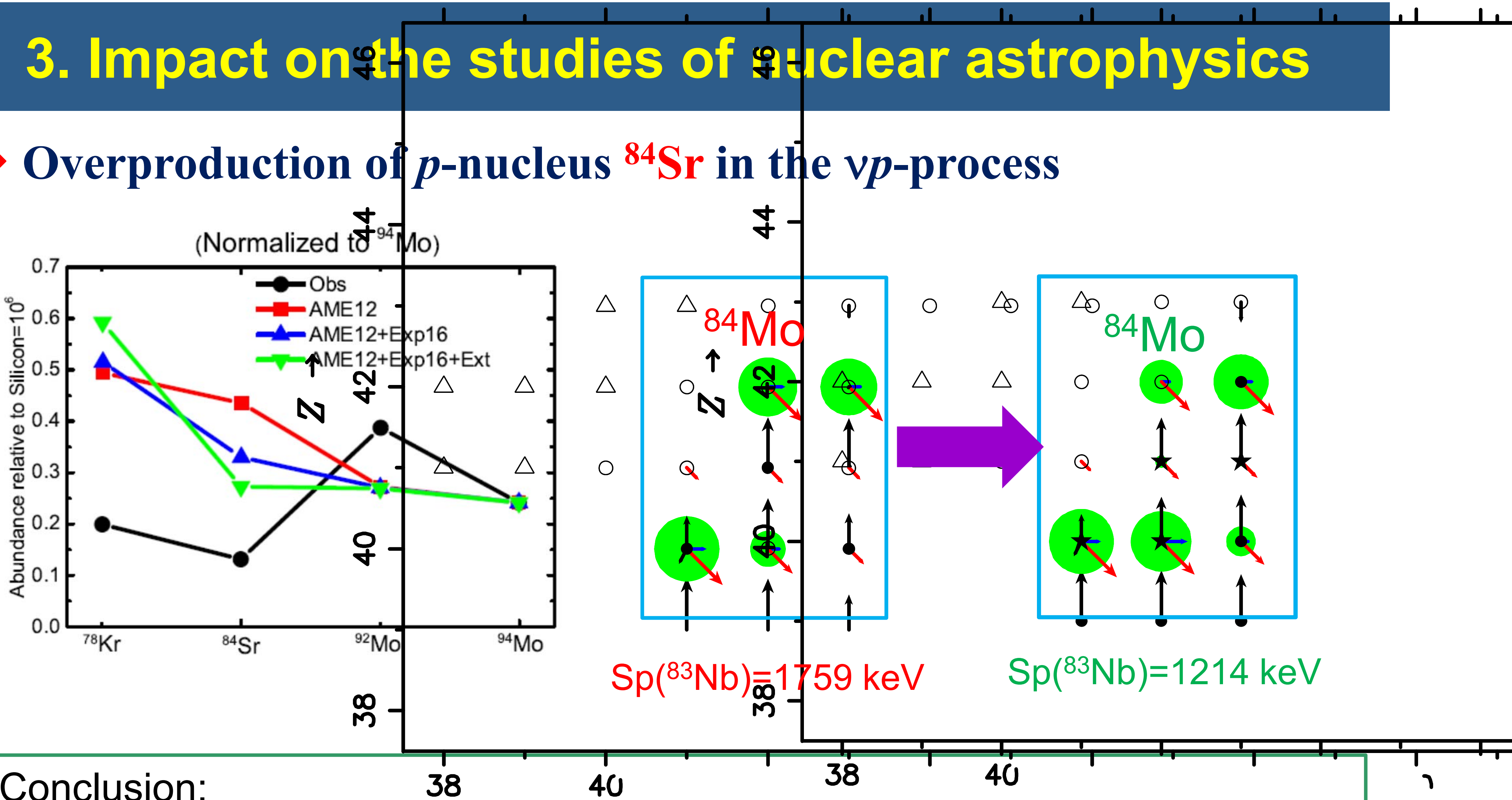


S. Wanajo et al., ApJ, 729:46 (2011)

"Future precision measurements of both ^{82}Zr and ^{83}Nb are thus highly desired."

3. Impact on the studies of nuclear astrophysics

➔ **Overproduction of *p*-nucleus ^{84}Sr in the ν*p*-process**



Conclusion:
Sp(^{83}Nb) is reduced by 0.545 MeV, the (p,γ) reaction flow from ^{82}Zr to ^{83}Nb is suppressed because of the competition of (γ,p) reaction of ^{83}Nb. Then a reduction of ^{84}Mo, which is the precursor of ^{84}Sr, will lead to a less abundance of ^{84}Sr.

3. Impact on the studies of nuclear astrophysics

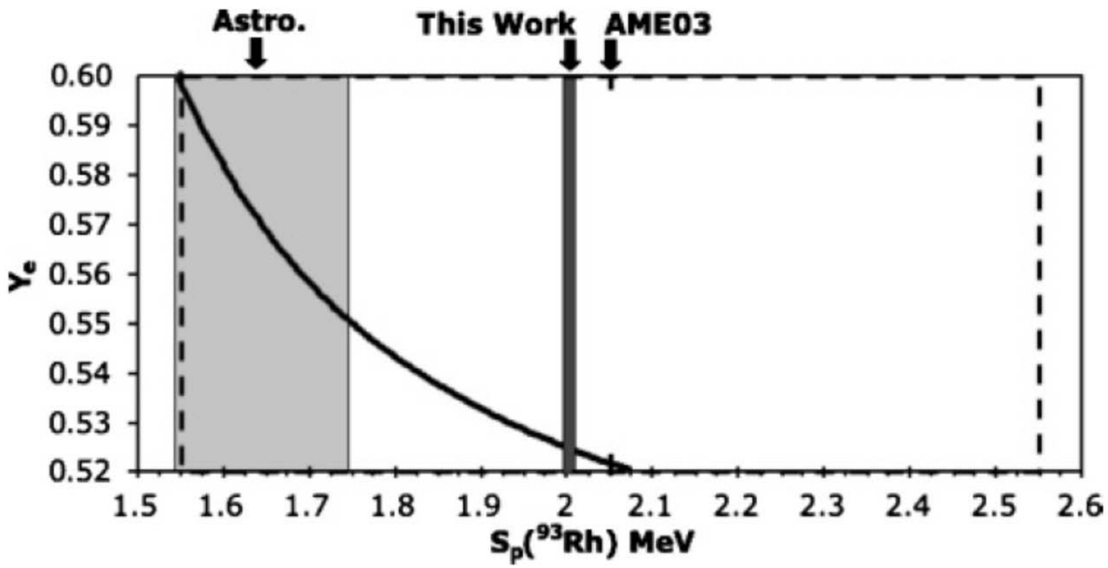
➔ **Abundance ratio of ^{92}Mo/^{94}Mo in the νp-process**

the ^{92}Mo/^{94}Mo solar abundance ratio =1.57

vp process in the inner ejecta of core-collapse supernovae

Y_e (electron fraction)=0.57, ➡ Sp(^{93}Rh)=1.64±0.1 MeV [J. L. Fisker et al.,]

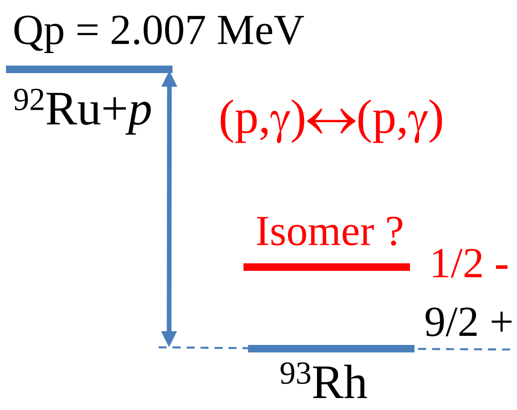
J. FALLIS *et al.*

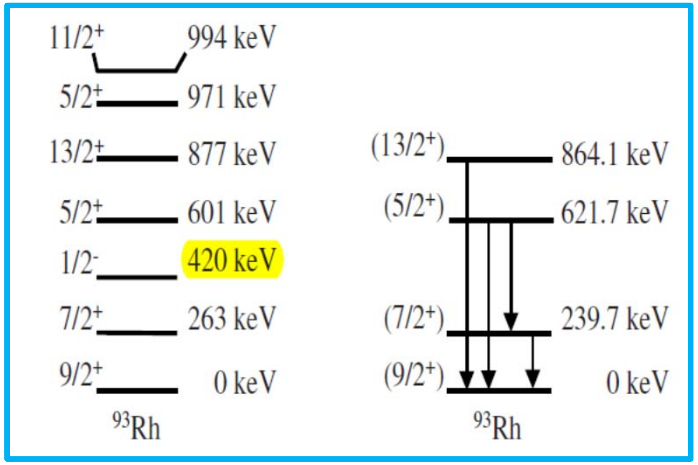


J. Fallis et al., PHYSICAL REVIEW C **78**, 022801(R) (2008) Sp(^{93}Rh)=2.007±0.001 MeV

3. Impact on the studies of nuclear astrophysics

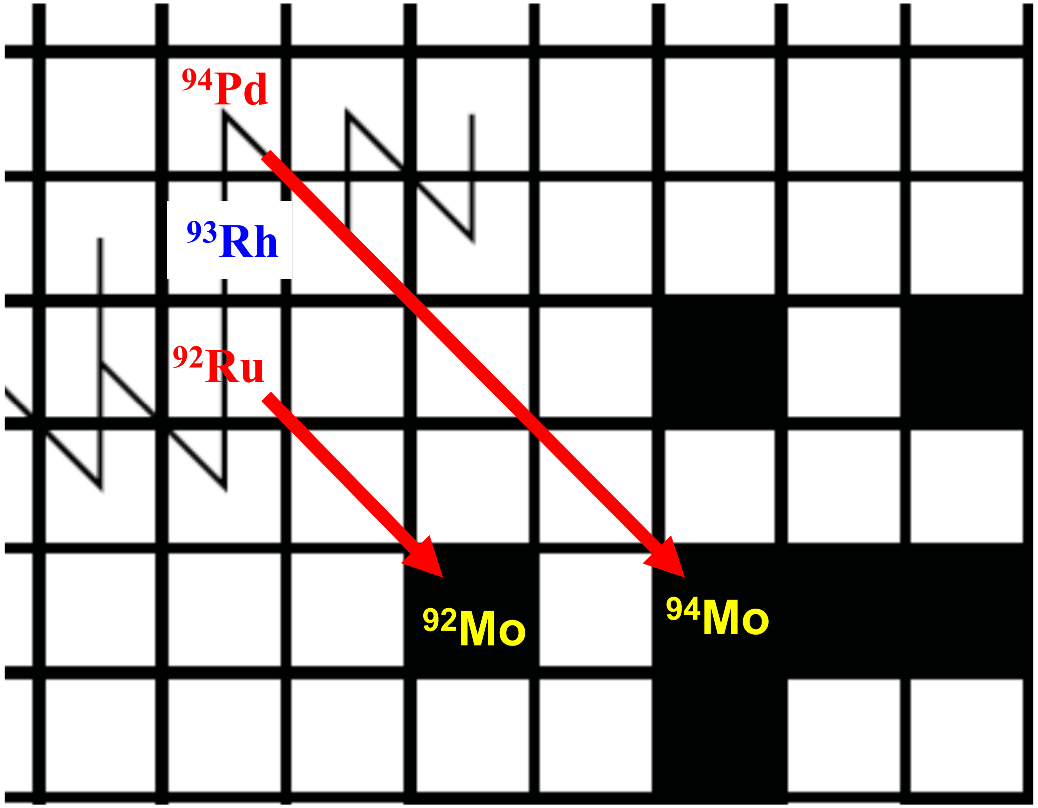
➔ Abundance ratio of ^{92}Mo/^{94}Mo in the νp-process



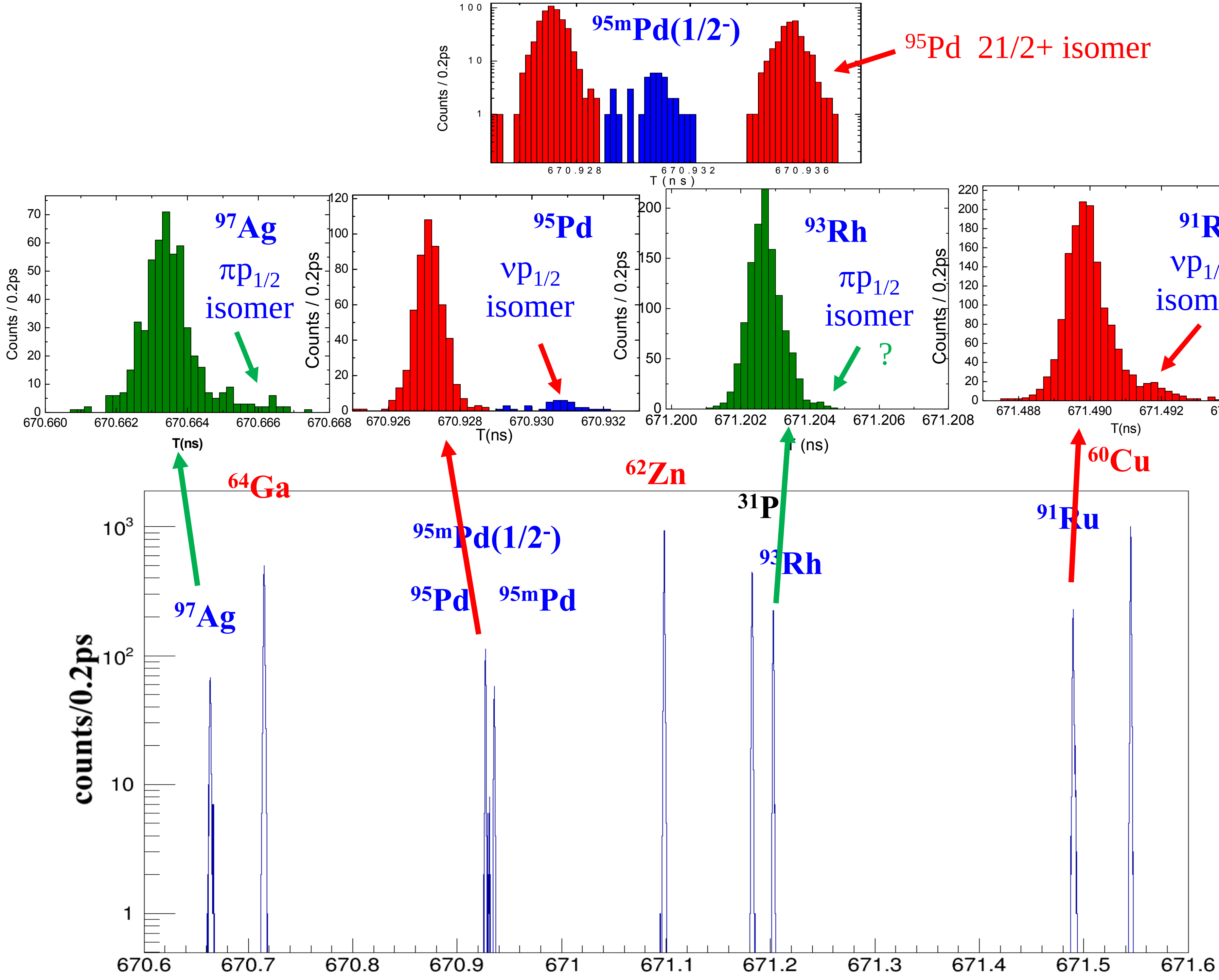


K. Schmidt et al., EPJ. A **8**, 303 (2000)

Searching for the long-lived isomer in ^{93}Rh



C. Weber et al., PRC **78**, 054310 (2008)

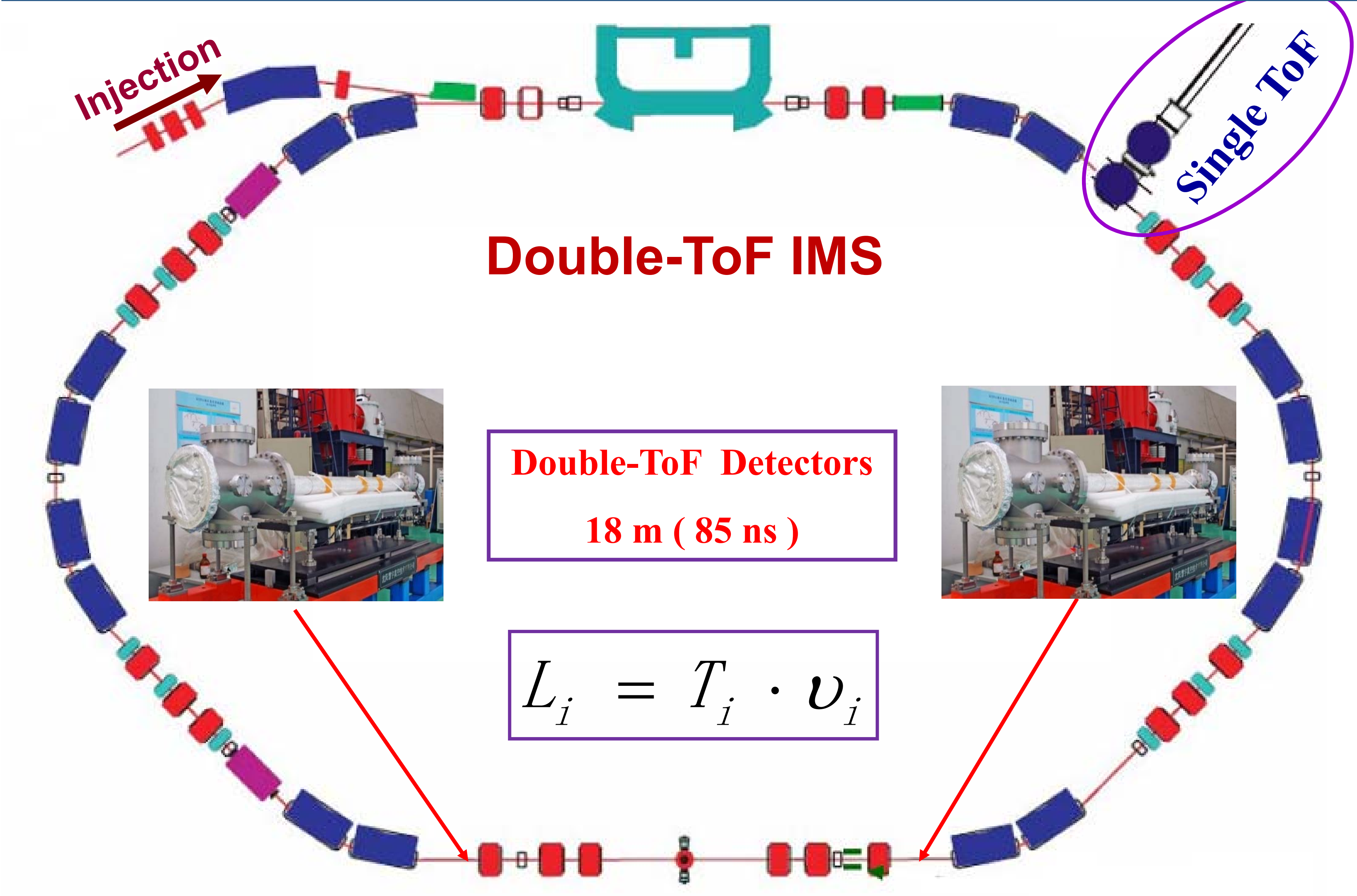


95mPd(1/2-)
95Pd 21/2+ isomer
Counts / 0.2ps
T (ns)
97Ag
πp1/2
isomer
95Pd
νp1/2
isomer
93Rh
πp1/2
isomer
?
91Ru
νp1/2
isomer
T(ns)
64Ga
62Zn
31P
60Cu
95mPd(1/2-)
95Pd
95mPd
97Ag
93Rh
91Ru
counts/0.2ps

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 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.**

4. Summary and perspectives

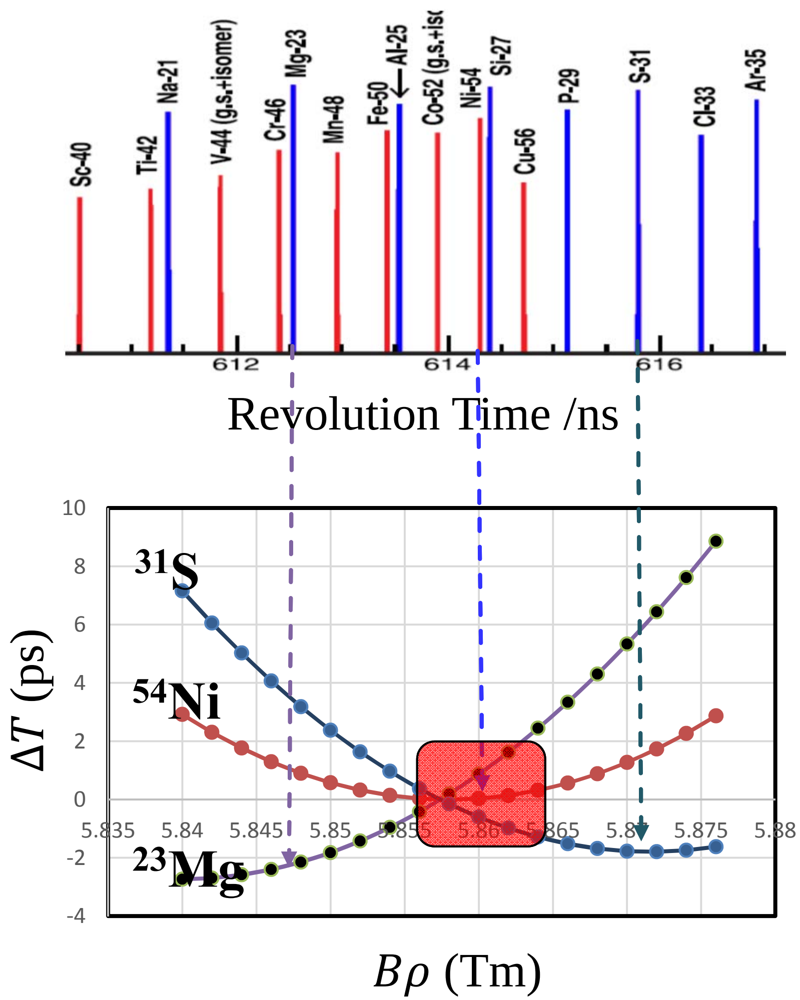


4. Summary and perspectives

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

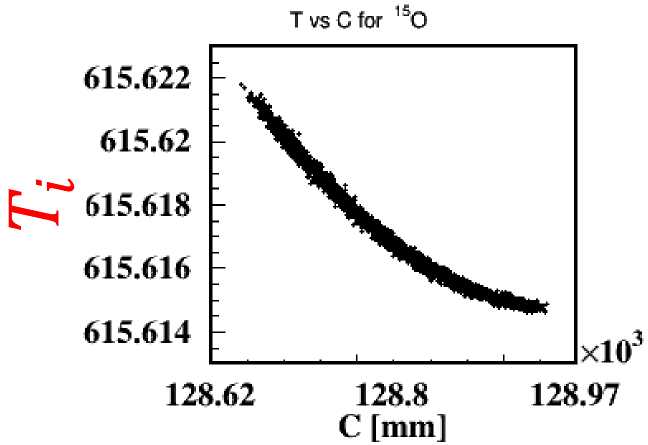
Principle:

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

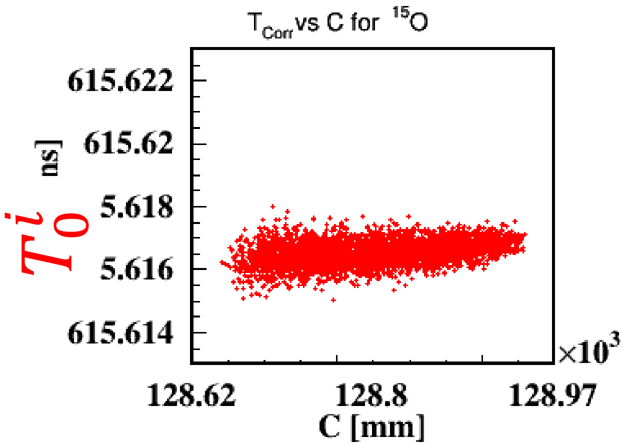
Then the revolution time T_0^i at the ideal orbit length C_0=12880 cm can be deduced.

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

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

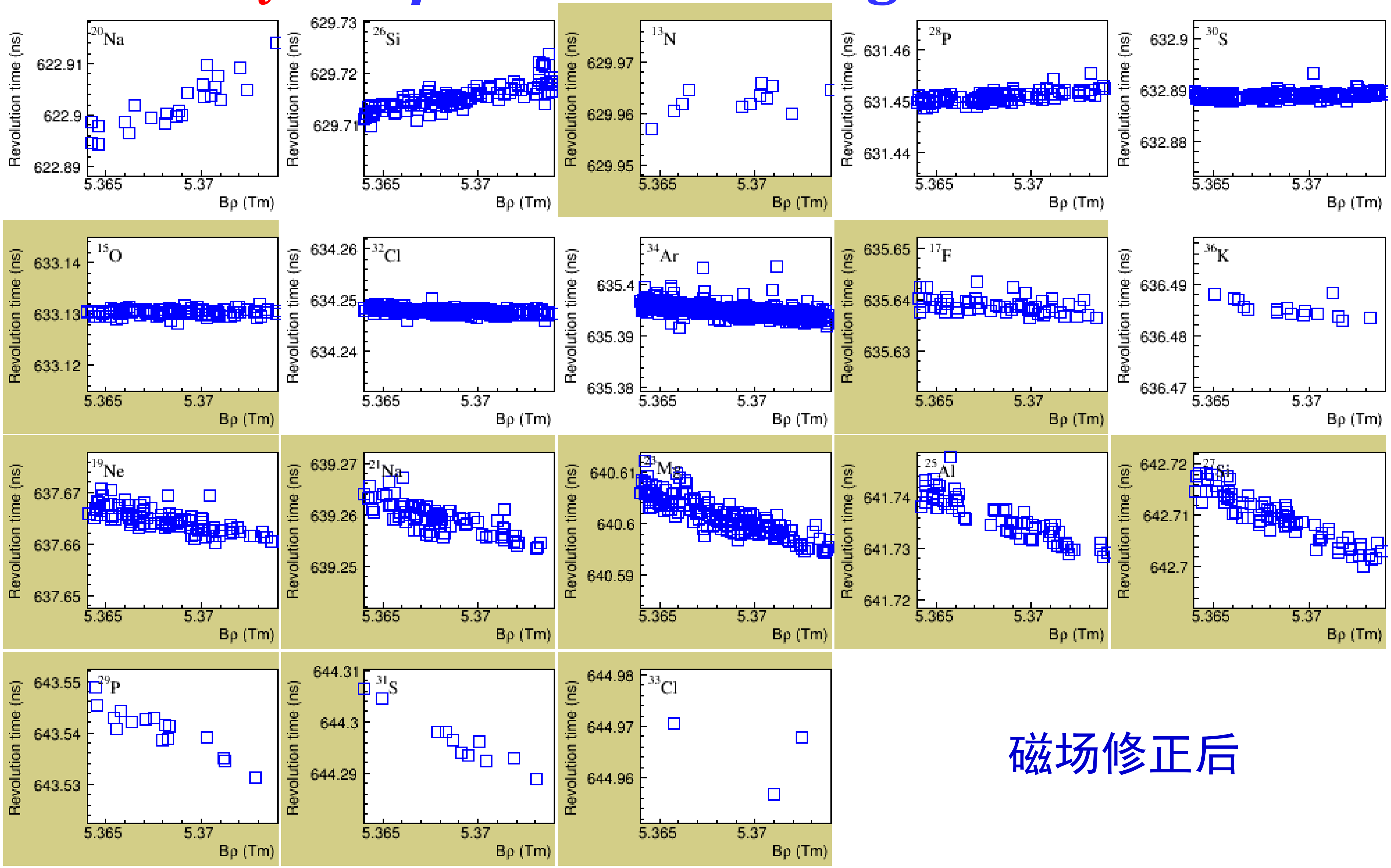


T_0^i @ C_0=12880cm



4. Summary and perspectives

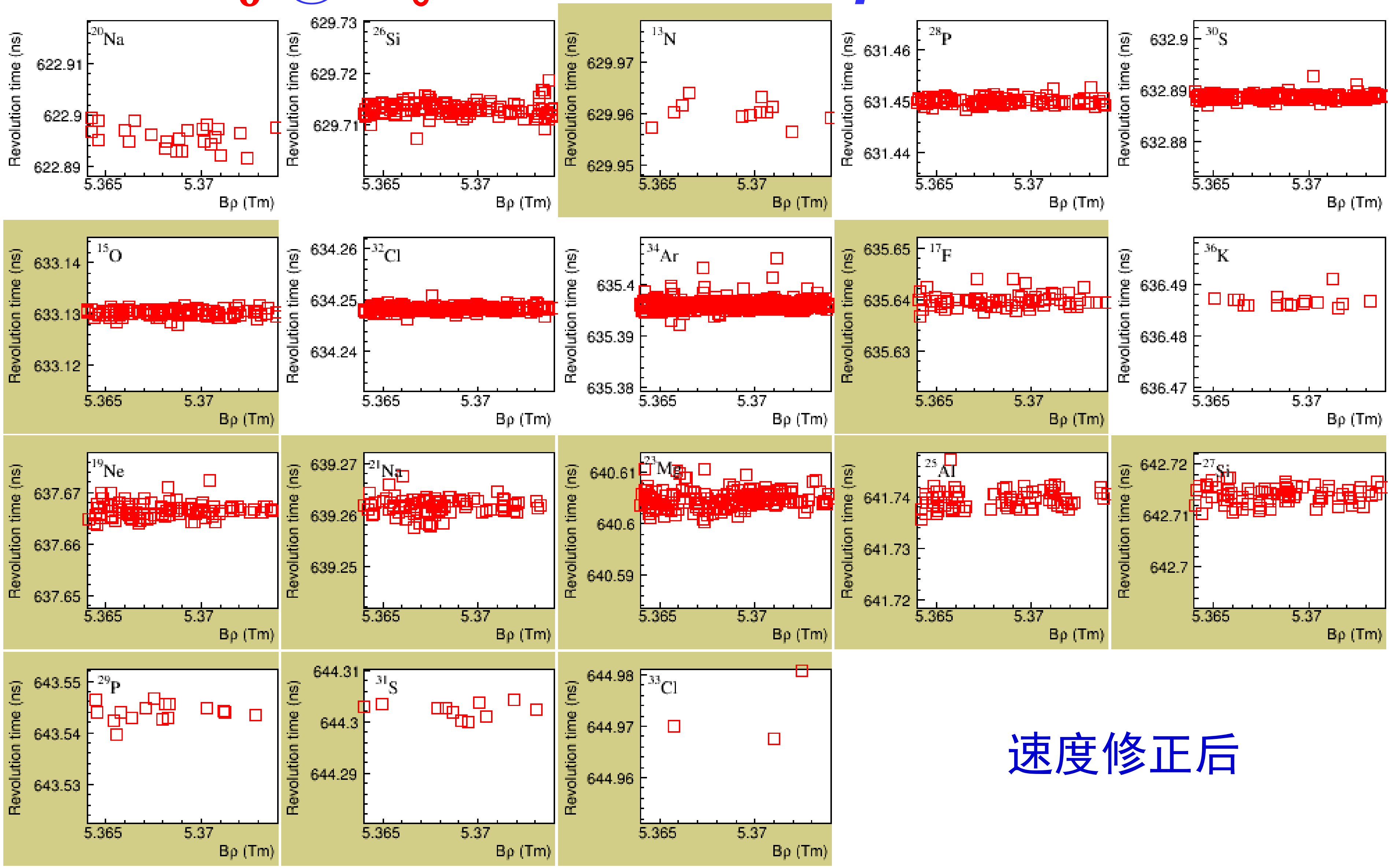
Plot of T_i vs $B\rho$ from ^{36}Ar fragmentation



磁场修正后

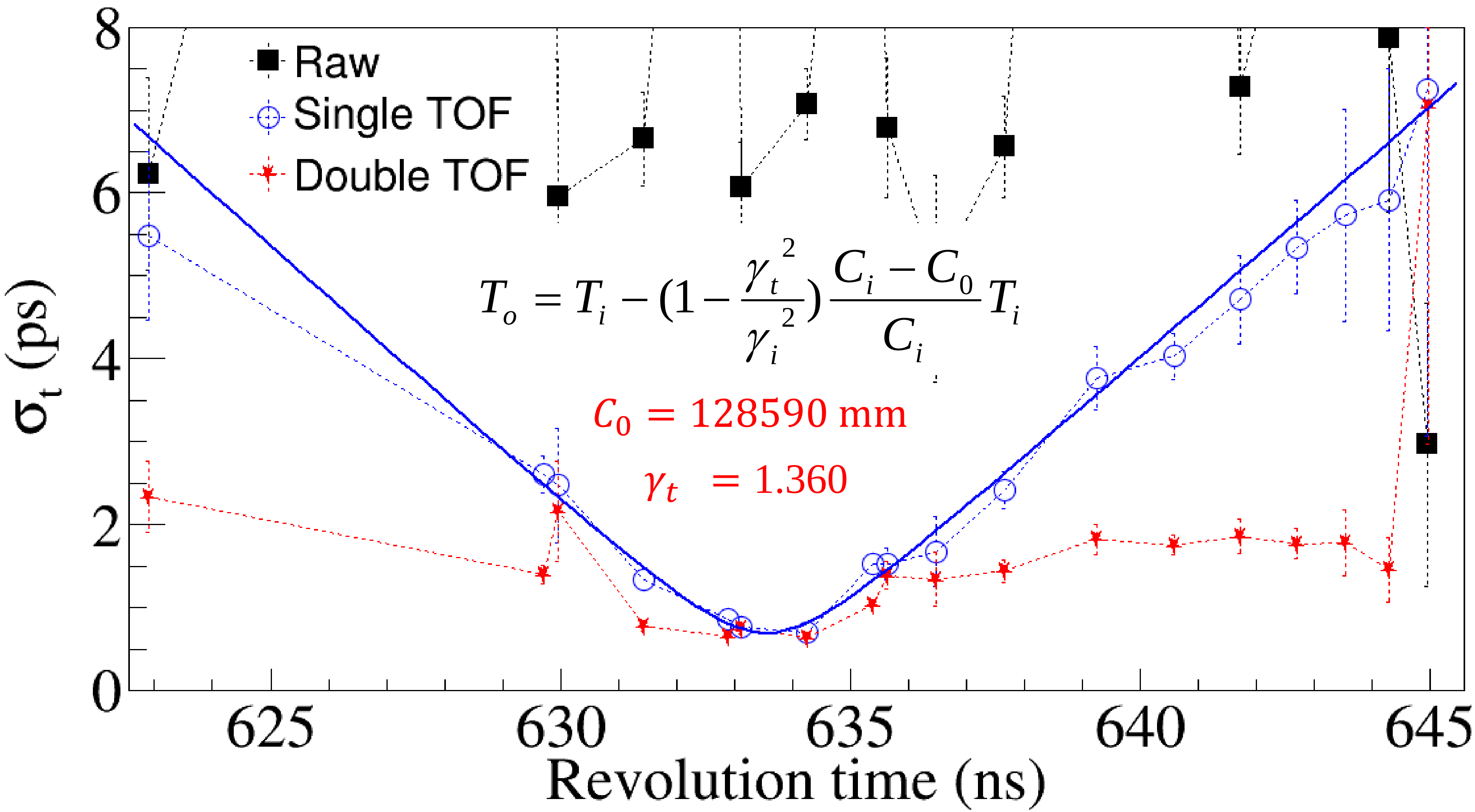
4. Summary and perspectives

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

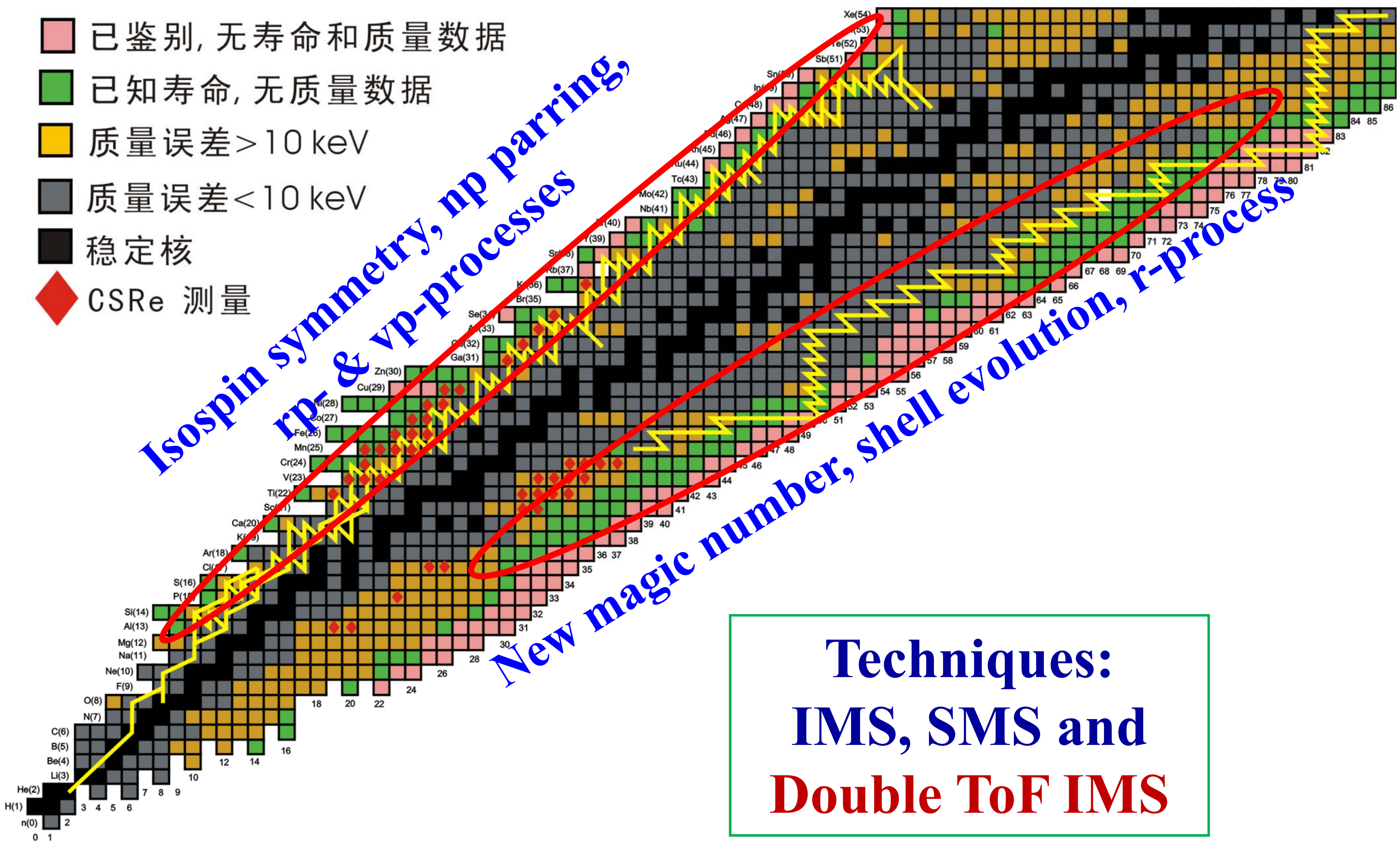


速度修正后

4. Summary and perspectives



4. Summary and perspectives



Techniques:
IMS, SMS and
Double ToF IMS

Thank you for your attention !

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