Precision mass measurements at CSRe storage ring in Lanzhou

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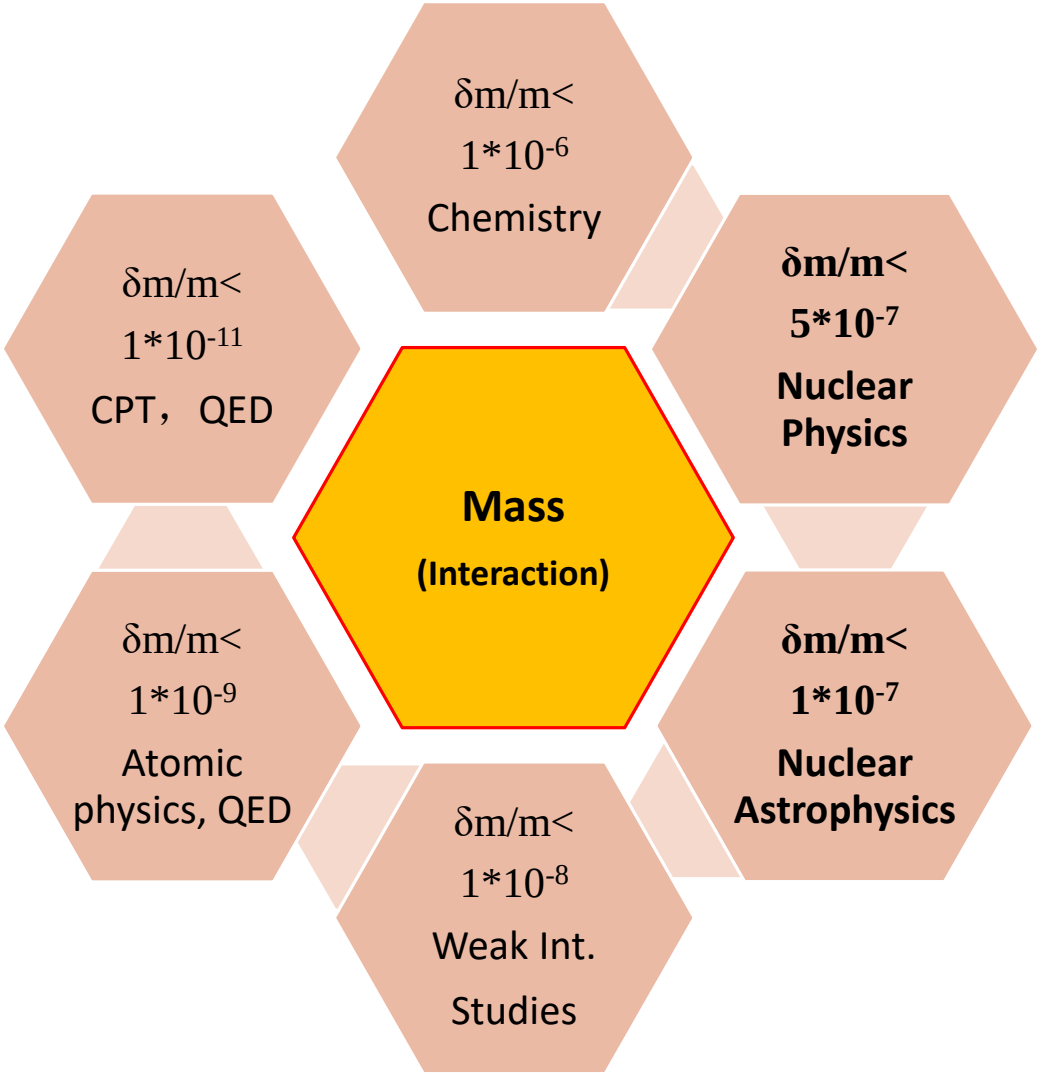
(1)Motivation
(2)Experiment & results
(3)Recent technical developments
(4)Outlook

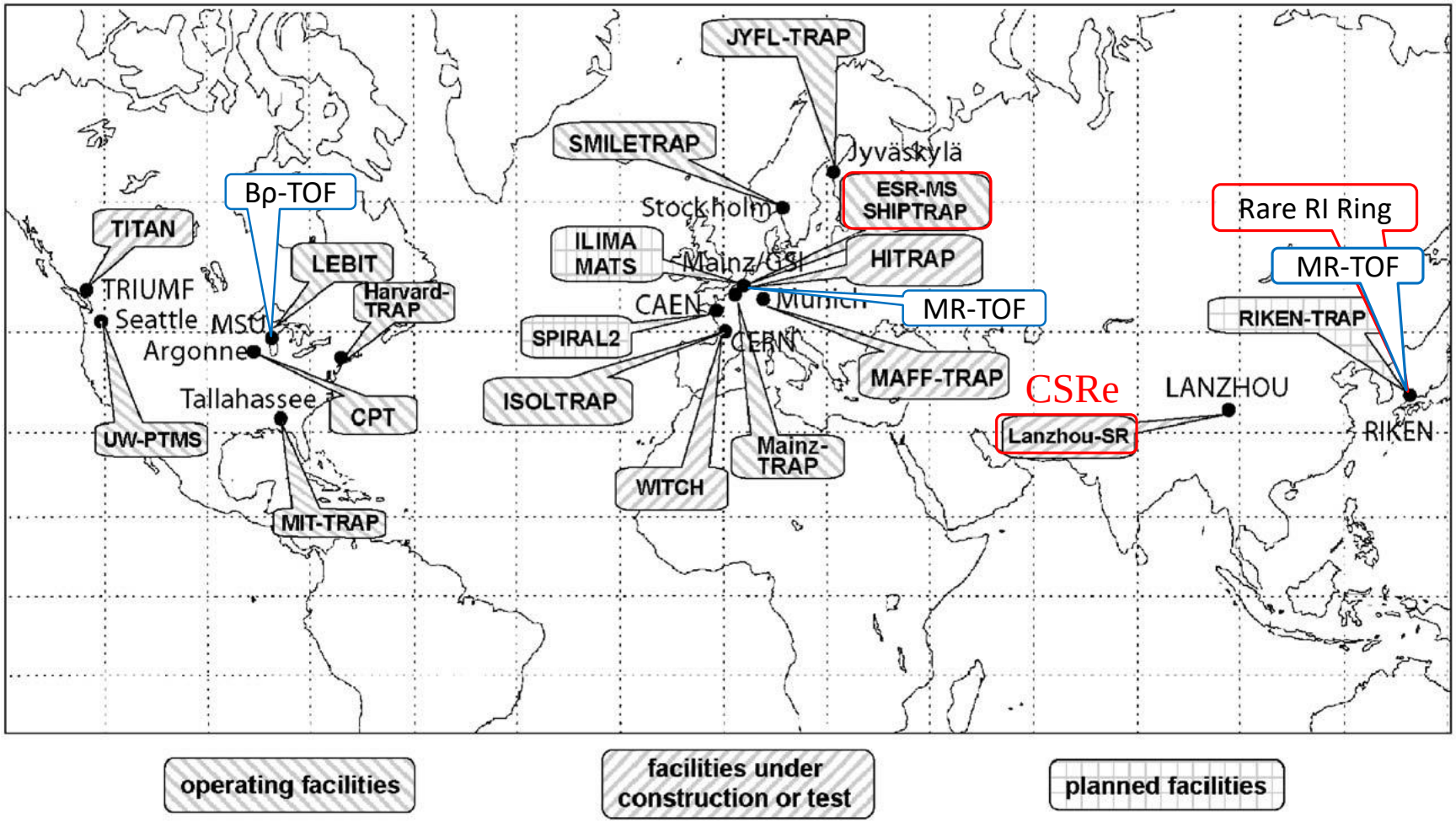
Motivation



K. Blaum, *Phys. Reports* 425, 1(2006)

Mass spectrometers for short-lived nuclei

MR-TOFs or Bρ-TOFs | Penning traps | Storage rings



K. Blaum, *Phys. Reports* 425, 1(2006)

CSRe (experimental Cooler Storage Ring)

CSRe Isochronous Mass Spectrometry

Unique features:

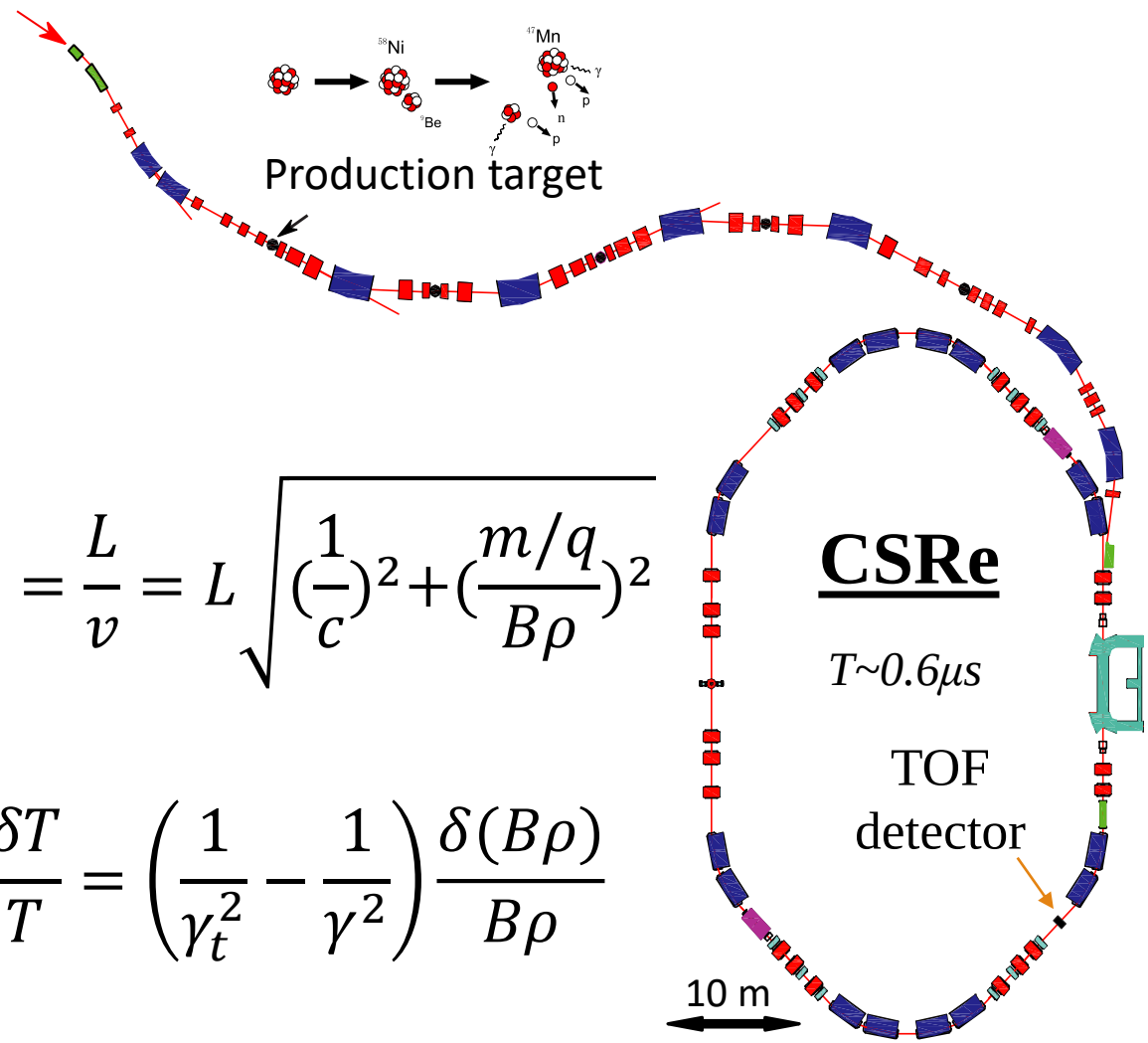
① Fast in production and detection: lower limit >0.05ms;

② Sensitive to single ion;

③ Broadband coverage of m/q in one experiment;

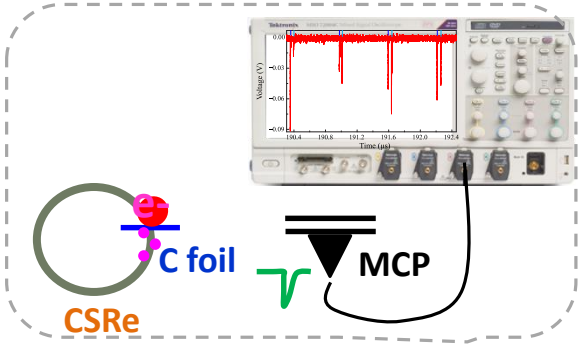
④ Accurate: isochronous condition (R~10^5)

Pulsed primary beam from CSRm, 1e8 ppp, v/c ~0.7

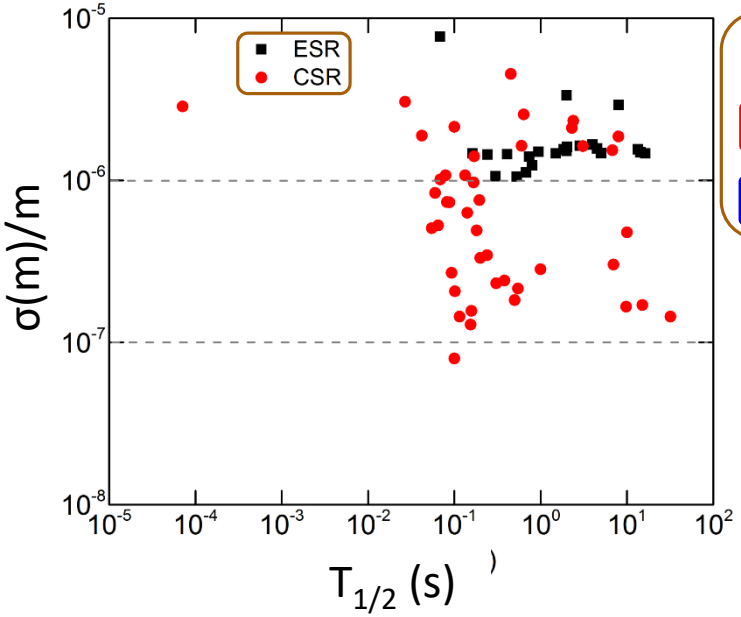


$$T = \frac{L}{v} = L\sqrt{\left(\frac{1}{c}\right)^2 + \left(\frac{m/q}{B\rho}\right)^2}$$

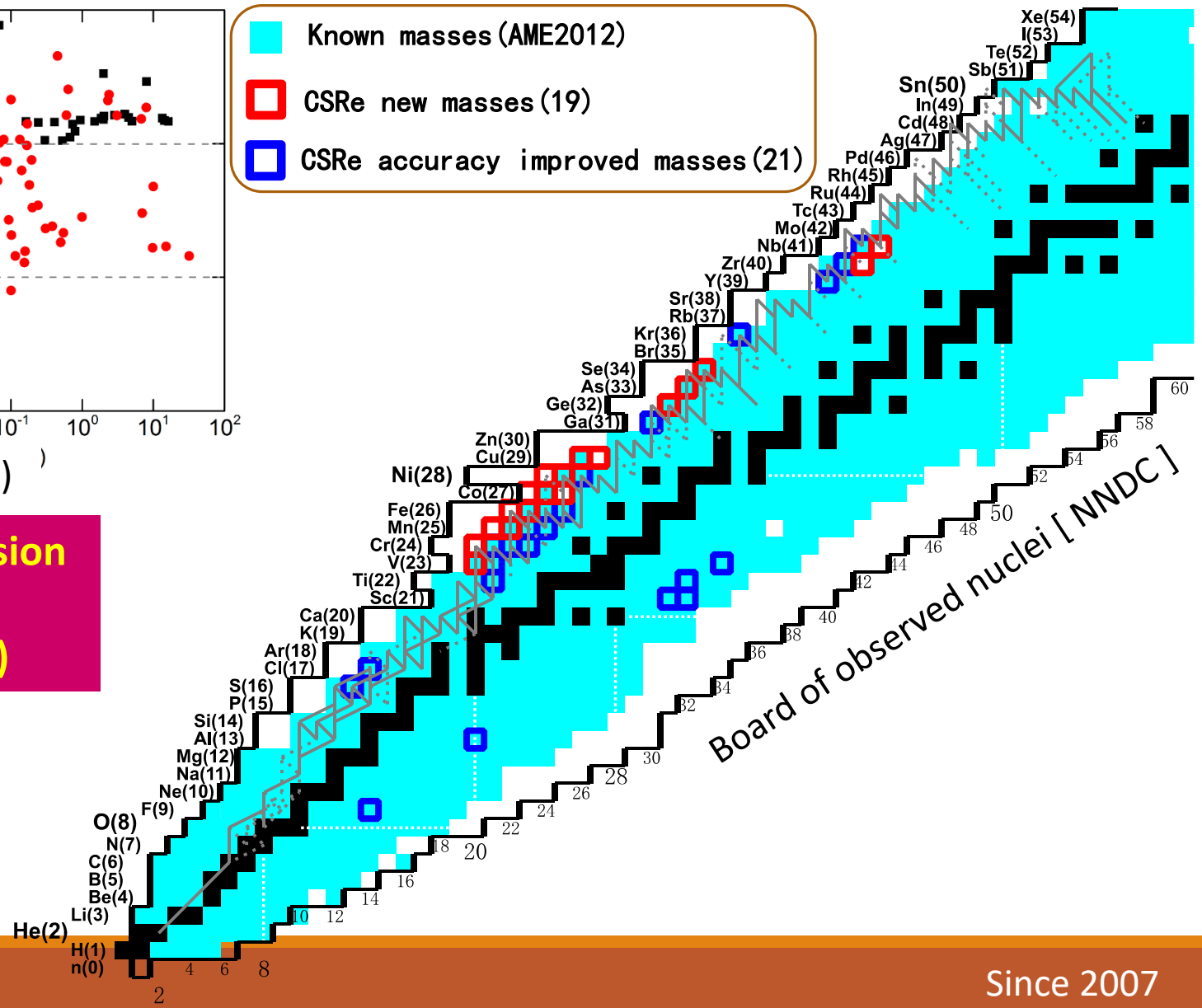
$$\frac{\delta T}{T} = \left(\frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}\right)\frac{\delta(B\rho)}{B\rho}$$



Summary: mass results from CSRe



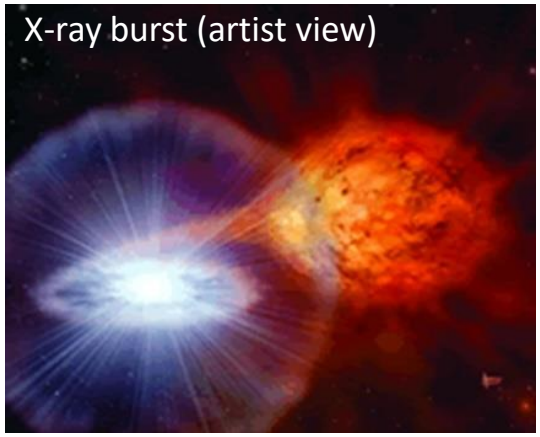
Achieved precision
10^{-6}~10^{-7}
(10-200 keV)

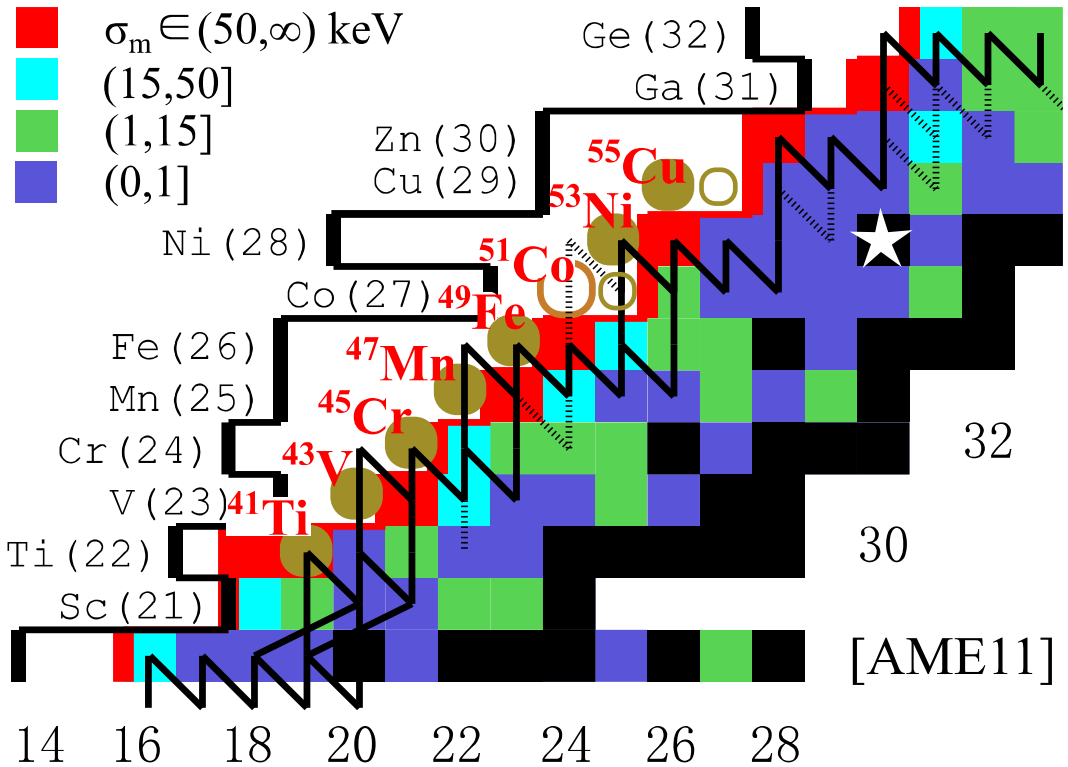


Since 2007

Experiment with ^{58}Ni fragments

Precision mass measurements of **short-lived** N=Z−3 nuclei which were relevant to the rp-process (Rapid proton capture process).





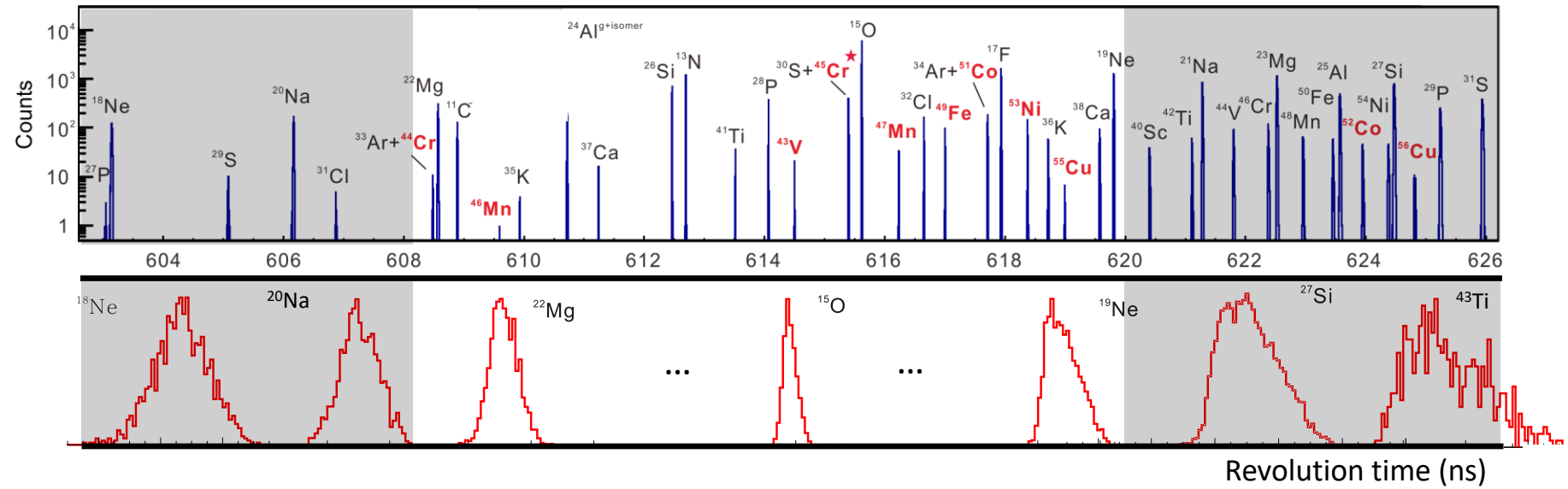
$$(p,\gamma) \rightleftharpoons (\gamma,p)\ equilibrium$$

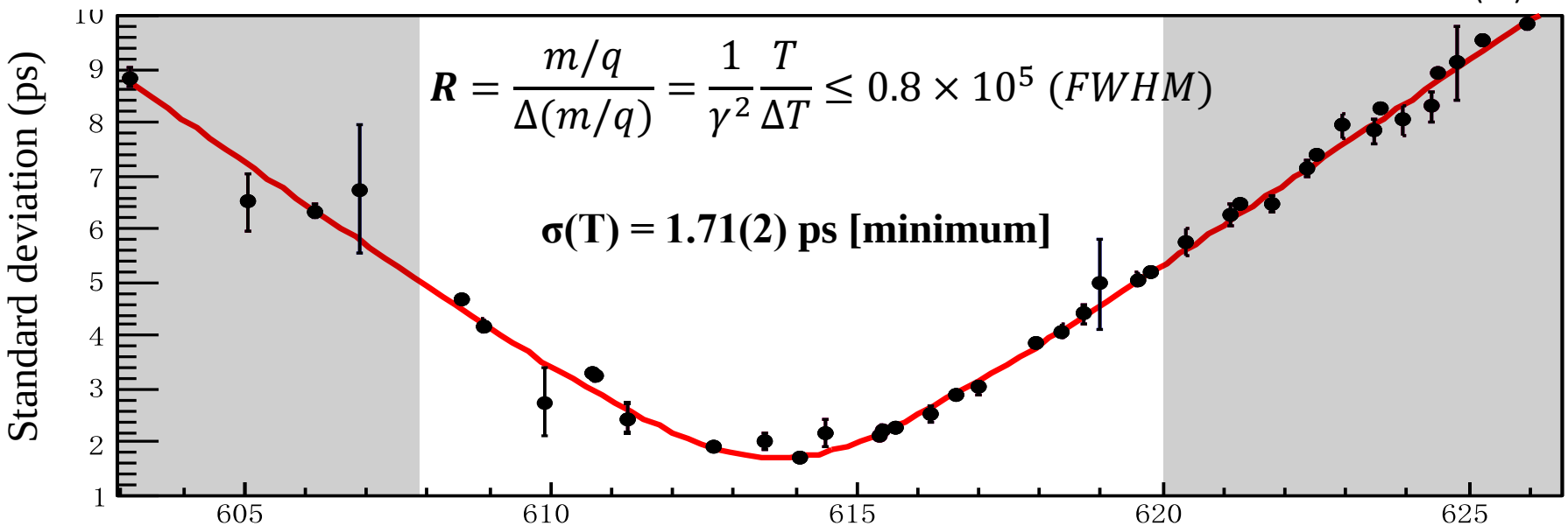
$$\frac{Y(Z+1,N)}{Y(Z,N)} \propto \rho * \exp[\frac{-M_{(Z+1,N)} + M_{(Z,N)} + M_p}{kT}]$$

For some key nuclei, σ(m) < 50 keV are required in the X-ray burst model calculations.

X.L. Yan, *PhD* Thesis(2014)

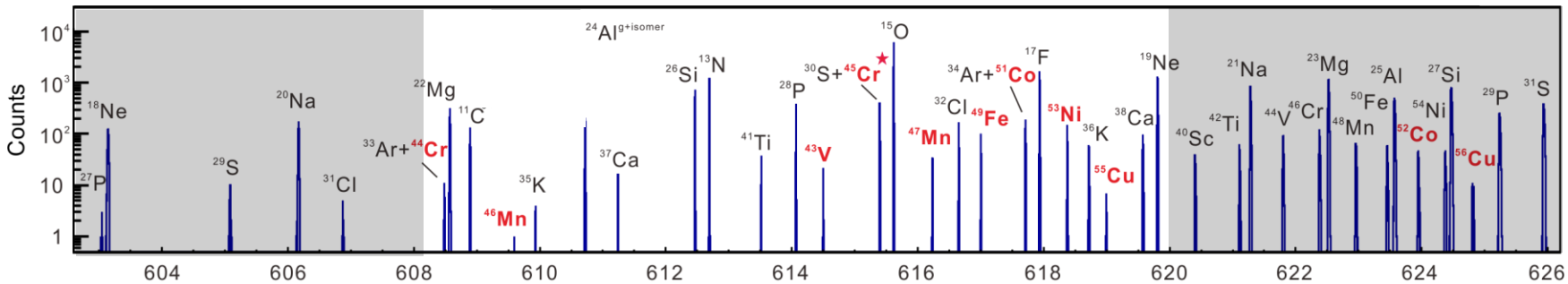
Experimental results

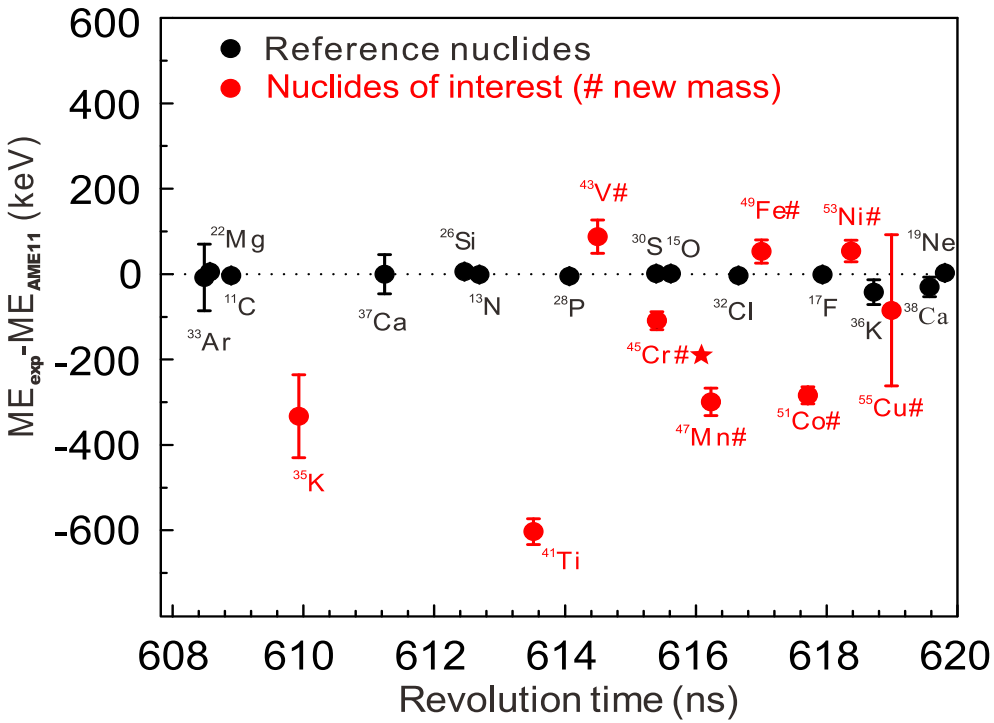




X.L. Yan, *PhD* Thesis(2014)

Experimental results



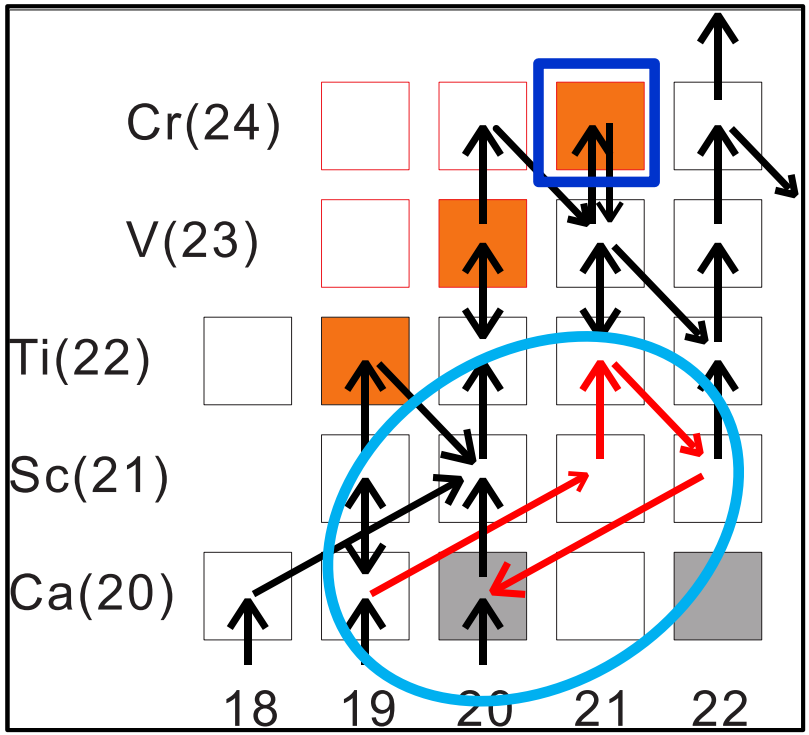


Nuclide	Count	ME(CSRe)	$T_{1/2}$(Atom)	
^{41}Ti	76	−15698(28)	82.6(5)min	
^{43}V	42	−17916(42)	79(2) ms	#
^{45}Cr	218	−19514(35)	60.9(4) ms	#
^{47}Mn	119	−22566(32)	88(1) ms	#
^{49}Fe	338	−24750(23)	64.7(3) ms	#
^{53}Ni	651	−29630(25)	55.2(7) ms	#
^{55}Cu	19	−31635(181)	27(8) ms	#

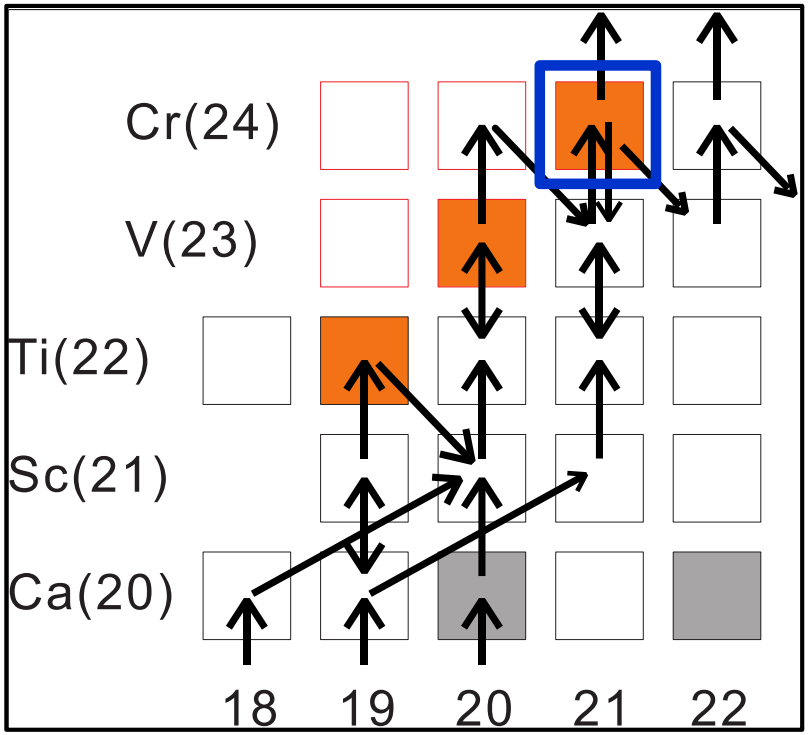
$\sigma(m)/m \sim 0.5 - 3.5\times10^{-6}$

Y. H. Zhang, et al, *Phys. Rev. Lett.* **109**, 102501 (2012)

Effects of the newly measured masses



ME(^{45}Cr) = −18970(500) keV

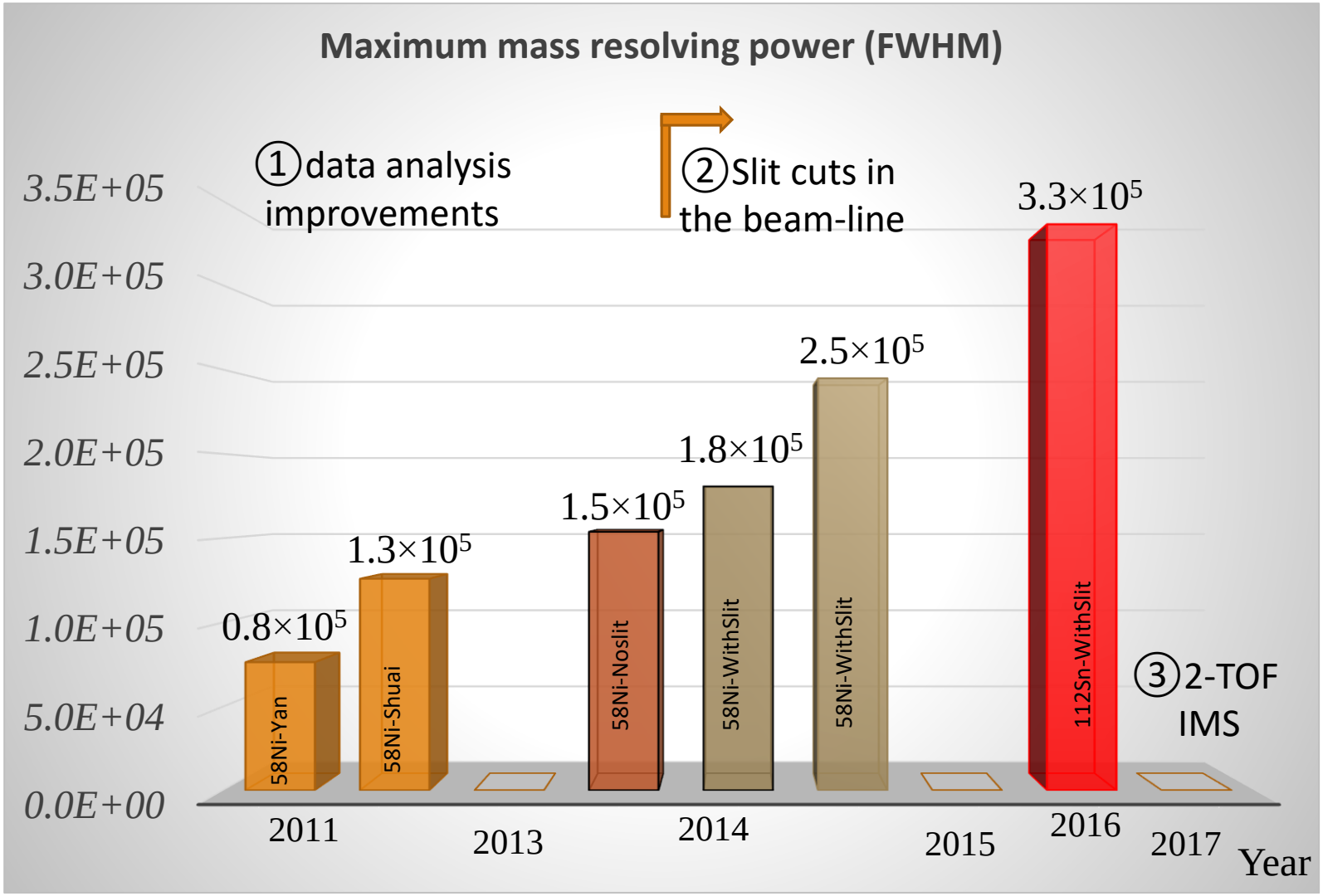


ME(^{45}Cr) = −19515(35) keV

With our new measurement of the ^{45}Cr mass, we obtain Sp(^{45}Cr) = 2.69 ± 0.13 MeV, basically excluding the formation of a significant Ca–Sc cycle in X-ray bursts. One uncertainty in rp-process caused by ^{45}Cr nuclear mass has been removed.

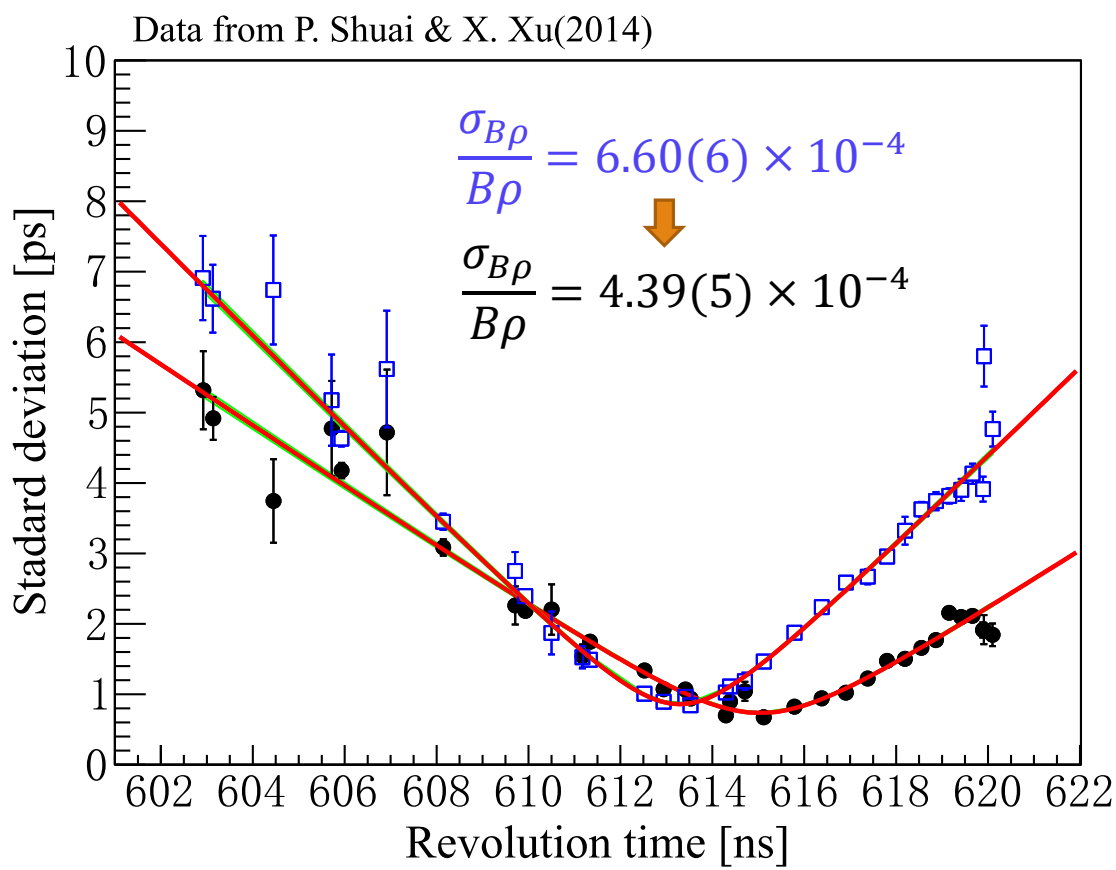
X. L. Yan et al. *Astrophys. J. Lett.* ***766****, L8 (2013)*

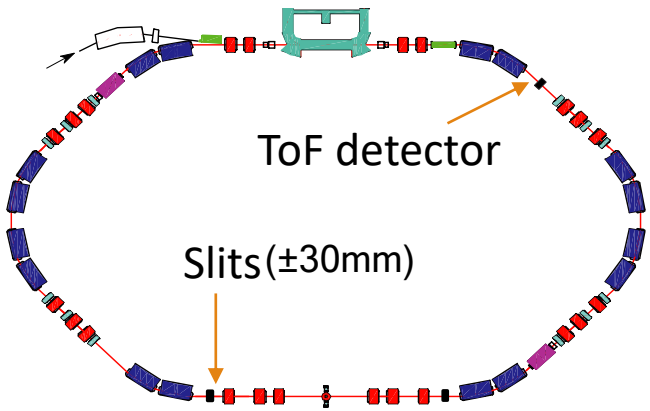
Recent developments



New direction: 2-TOF IMS

Slit cuts in the beam-line





$$\boldsymbol{R} = \frac{m/q}{\Delta(m/q)} = \frac{1}{\gamma^2}\frac{T}{\Delta T}$$

$$\boldsymbol{R \leq 1.5 \times 10^5 (FWHM)}$$

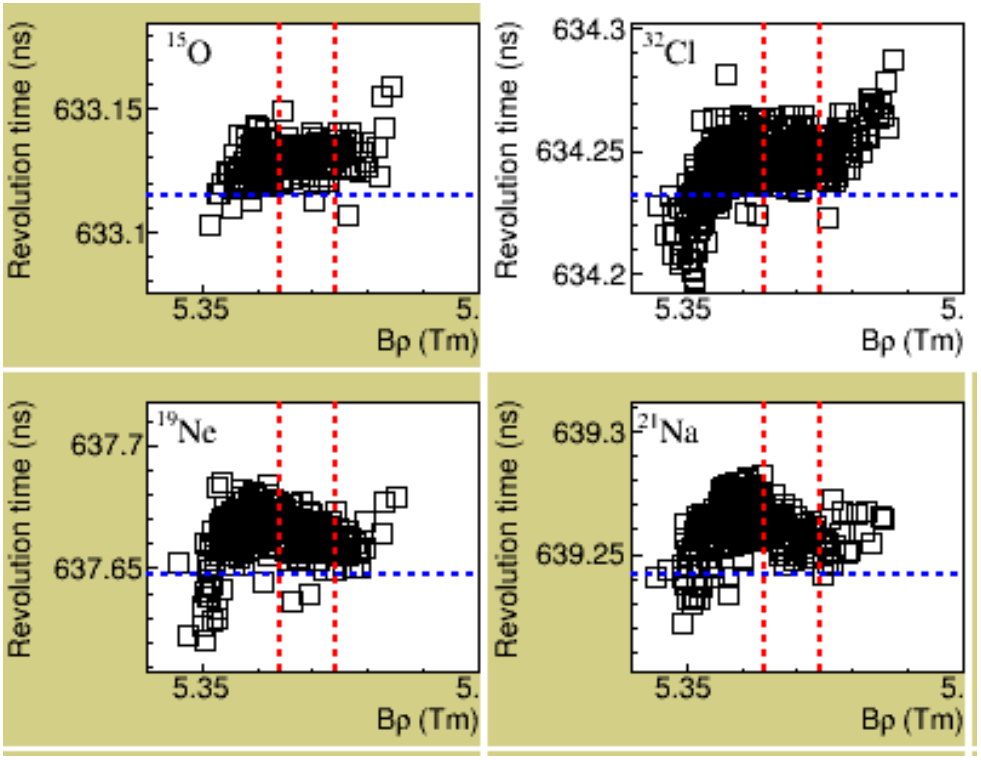
$$\boldsymbol{R \leq 1.8 \times 10^5 (FWHM)}$$

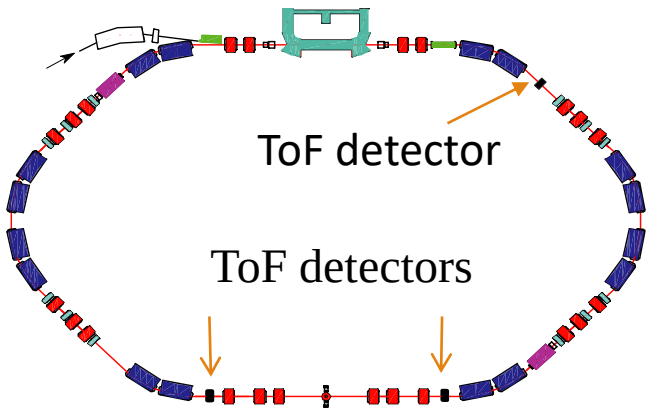
$$\boldsymbol{R} = \frac{m/q}{\Delta(m/q)} = \frac{1}{\gamma^2}\frac{T}{\Delta T} = \frac{1}{\gamma^2}\frac{T}{2.355\sigma(T)} = \frac{1}{2.355}\left(\frac{1}{\gamma^2/\gamma_t^2} - 1\right)\frac{B\rho}{\sigma(B\rho)}$$

Side effect: the statistics will be reduced.

In-ring velocity measurement

Preliminary results from R. J. Chen (2016)





$$v = \frac{l}{t} \qquad B\rho = \frac{m}{q}\gamma v$$

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

The technical challenges in order to achieve improved mass resolving power :

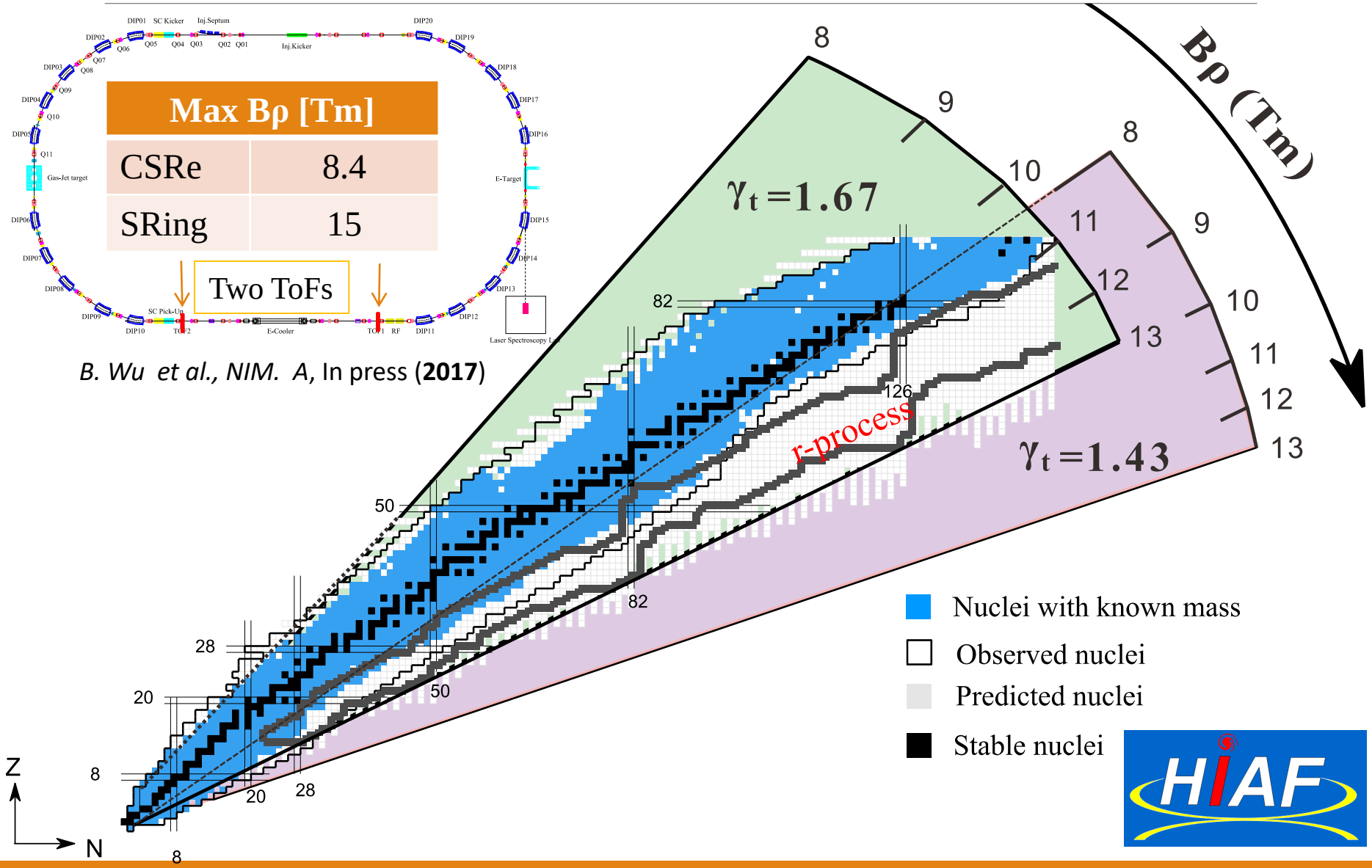
$$\frac{\sigma(\gamma_t)}{\gamma_t} \leq 1 \times 10^{-4} \;\&\&\; \frac{\sigma(v_i)}{v_i} \leq 1 \times 10^{-5} \quad \left(\Rightarrow \frac{\sigma(l)}{l}, \frac{\sigma(t)}{t} \leq 1 \times 10^{-5} \right)$$

Outlook: a new storage ring SRing

Max Bρ [Tm]	
CSRe	8.4
SRing	15

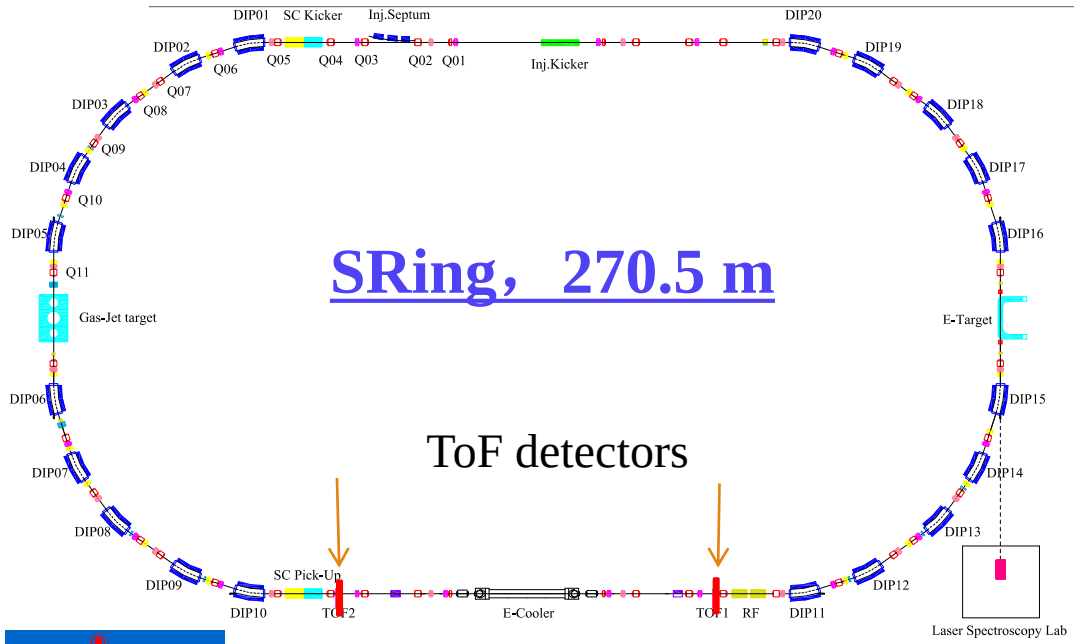
Two ToFs

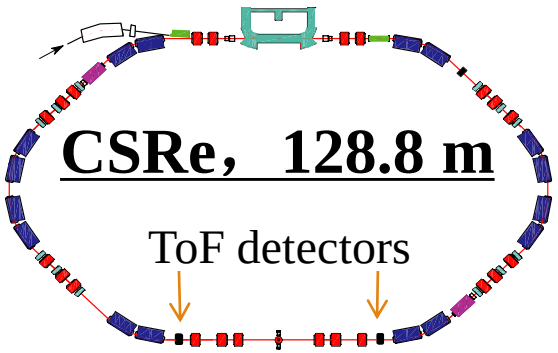
B. Wu et al., NIM. A, In press (**2017**)



Thanks for listening

A new storage ring SRing @ HIAF





Max Bρ [Tm]	
CSRe	8.4
SRing	15

Bρ acceptance	
CSRe	~0.2%
SRing	~0.2%

@Isochronous mode

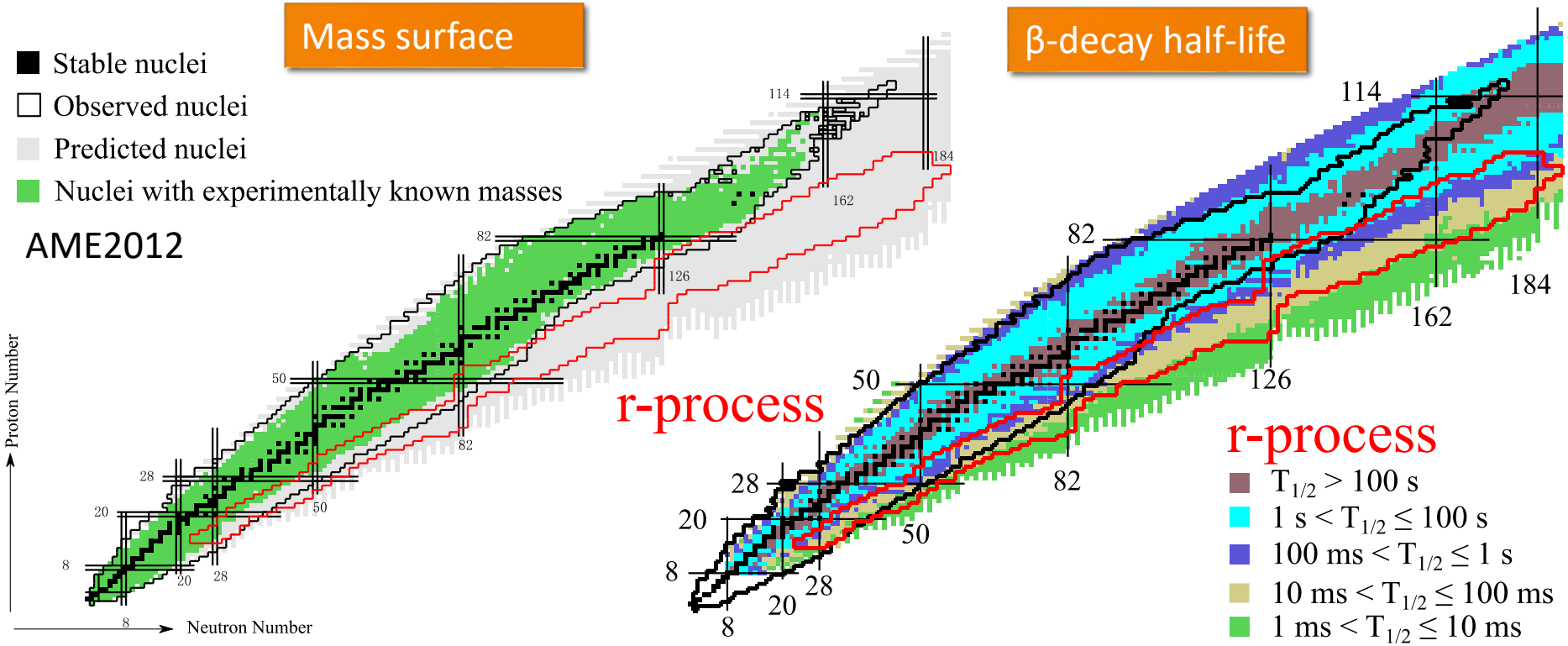
Typical intensity [ppp]	
CSRm	1×10^{8}
BRing	1×10^{11}

B. Wu et al., NIM. A, In press (**2017**)

Research vision

Precision mass measurements of short-lived neutron-rich nuclei relevant to r-process.

How are the elements from iron to uranium produced in the Universe?



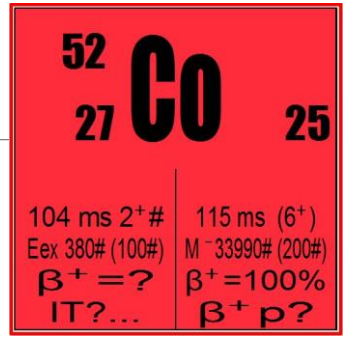
For modelling of r-process nucleosynthesis, basic knowledge such as masses, beta-decay and neutron capture rates etc. are critical inputs. It is stated that a mass precision of $\delta m/m$ in the order of 10^{-6} is needed, whereas 10^{-7} or even better is necessary for specific cases such as waiting-point nuclei in the r-process path.

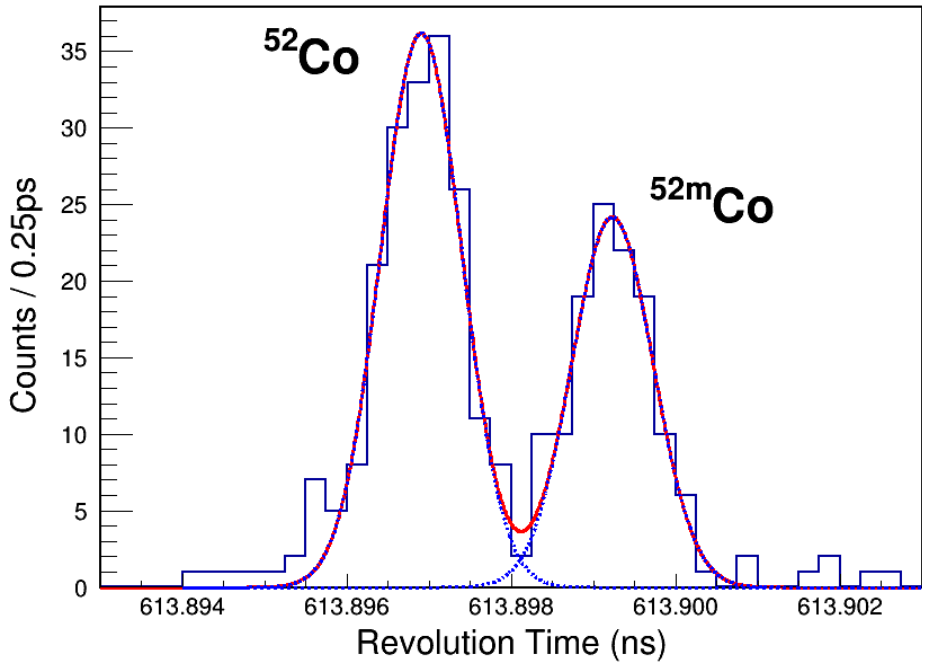
B. H. Sun et al. *Front. Phys.* 10, 102102 (2015).

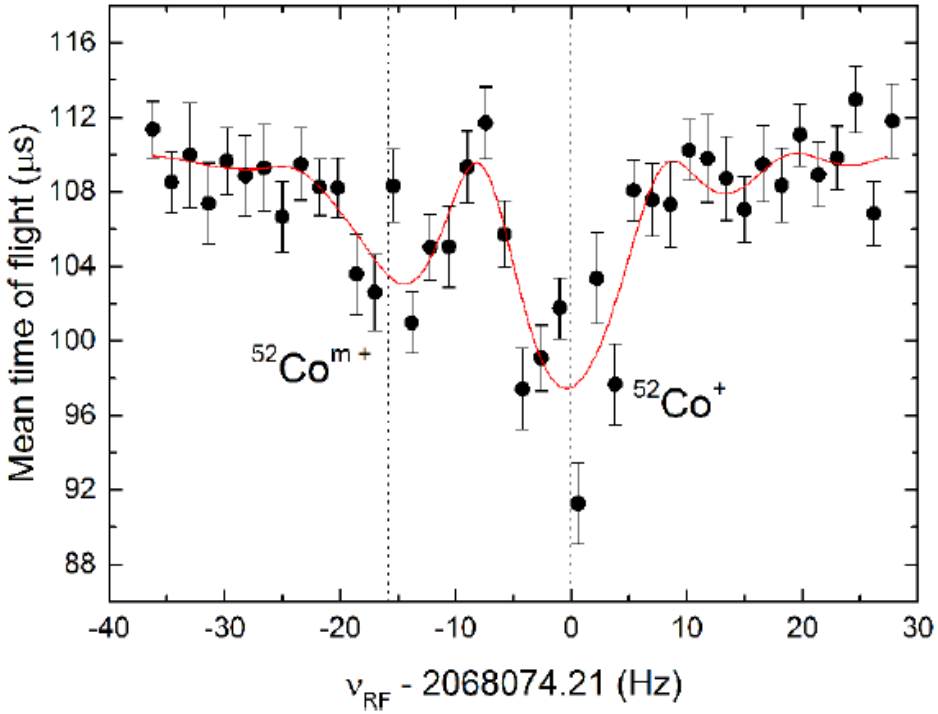
N. Wang et al., Phys. Lett. B734,215 (2014)

P. Möller et al., Phys. Rev. C 67,055802(2003)

CSRe VS Penning trap



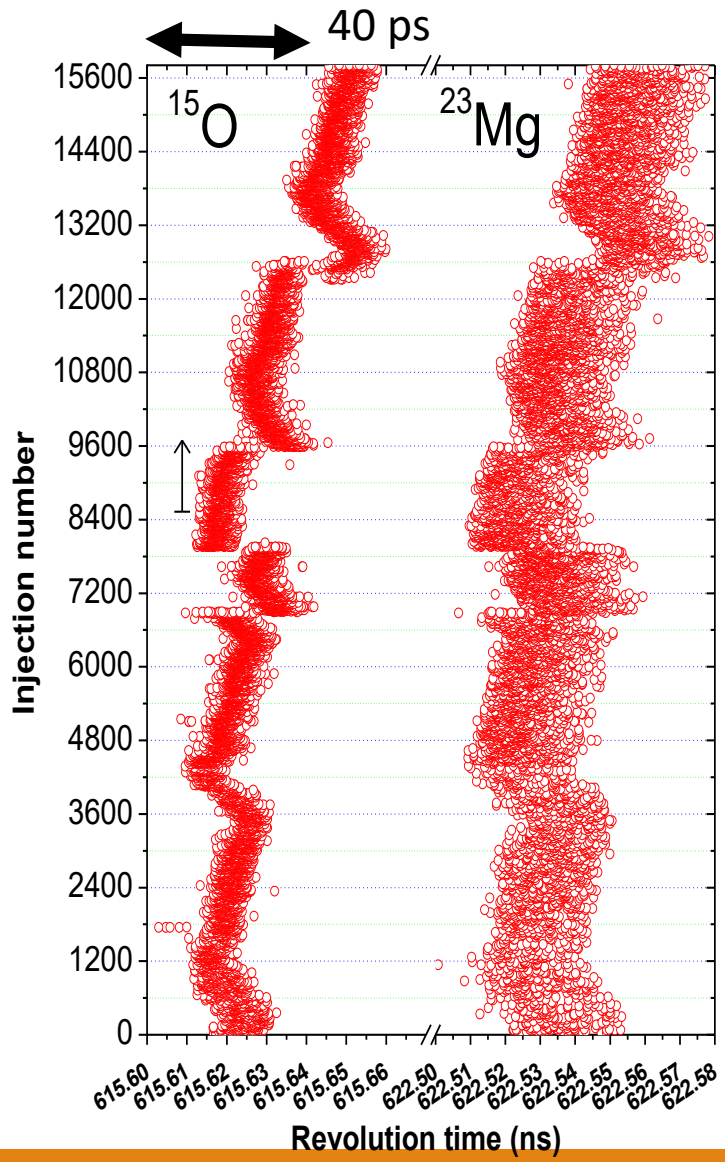


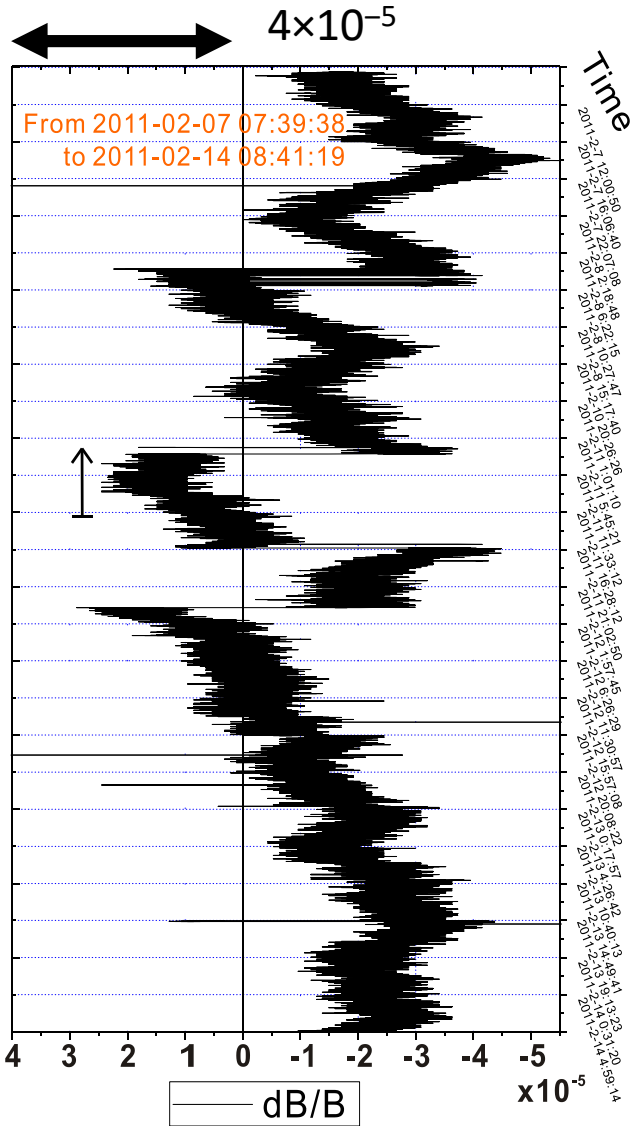


X. Xu et al.,
PRL 117, 182503 (2016)

D.A. Nesterenko et al.,
J. Phys. G 44, 065103 (2017)

Experimental challenges

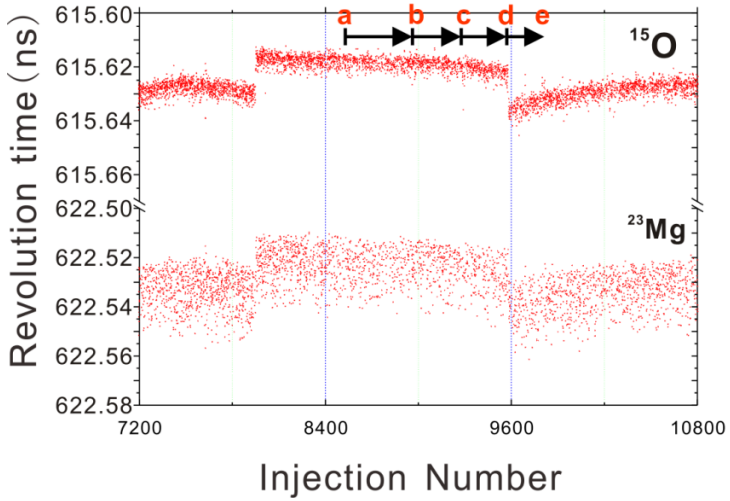


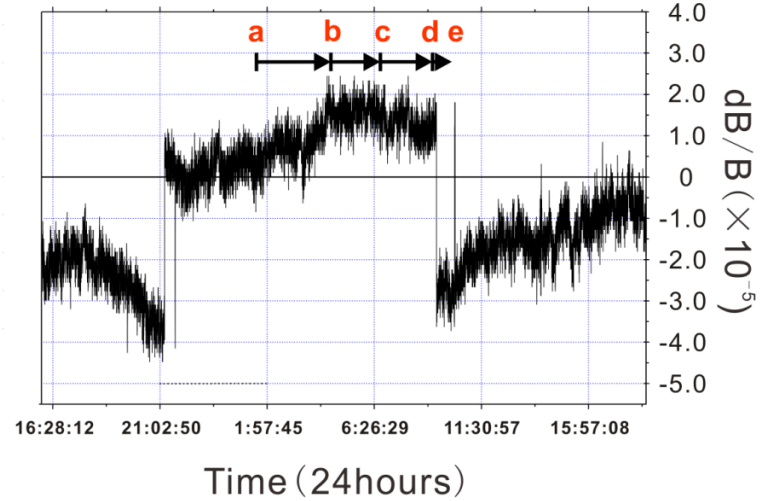


Revolution-time drifts caused by fluctuations of CSRe dipole magnetic field

The effects of ΔB on ΔT

40 ps



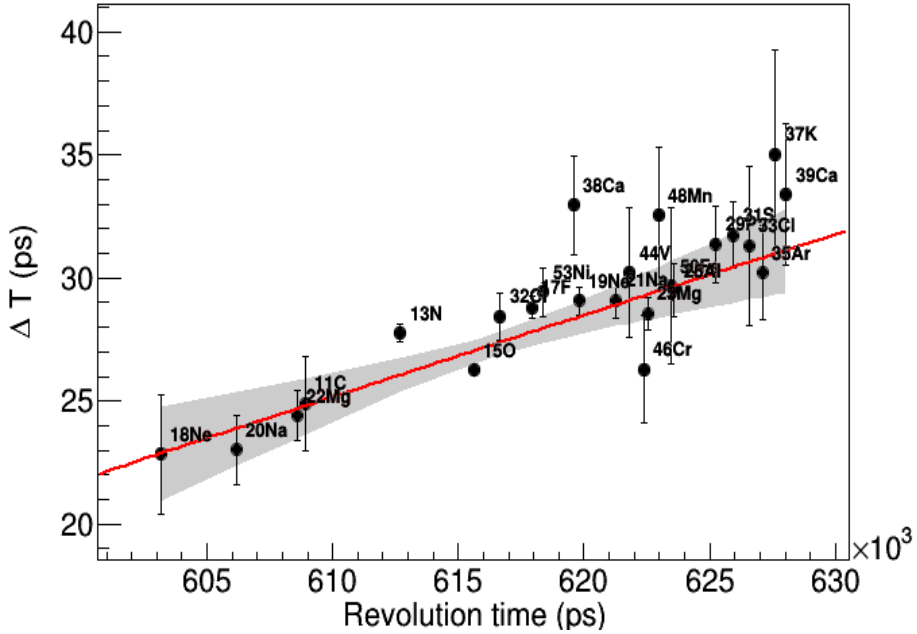


4×10^{-5}

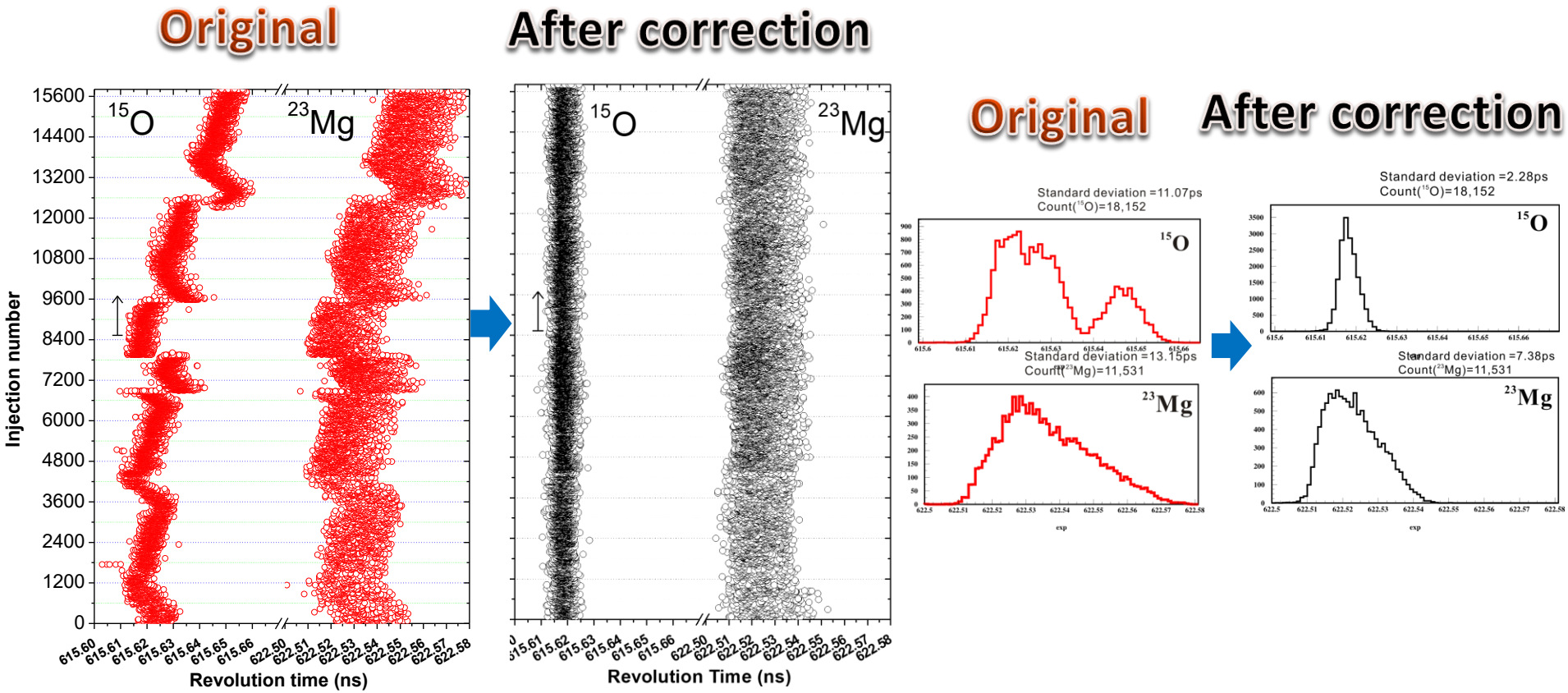
$$\frac{\Delta T}{T} = \frac{\Delta L}{L} - \frac{\Delta v}{v} \xRightarrow{\Delta L=0} \frac{\Delta T}{T} = \frac{1}{\gamma^2}\frac{\Delta B}{B}$$

$$\frac{\Delta B}{B}\Big|_{\text{fitted}} = 3.6(2)\times10^{-5}$$

$$\frac{\Delta B}{B}\Big|_{\text{hall-probe}} = 3.14(2)\times10^{-5}$$



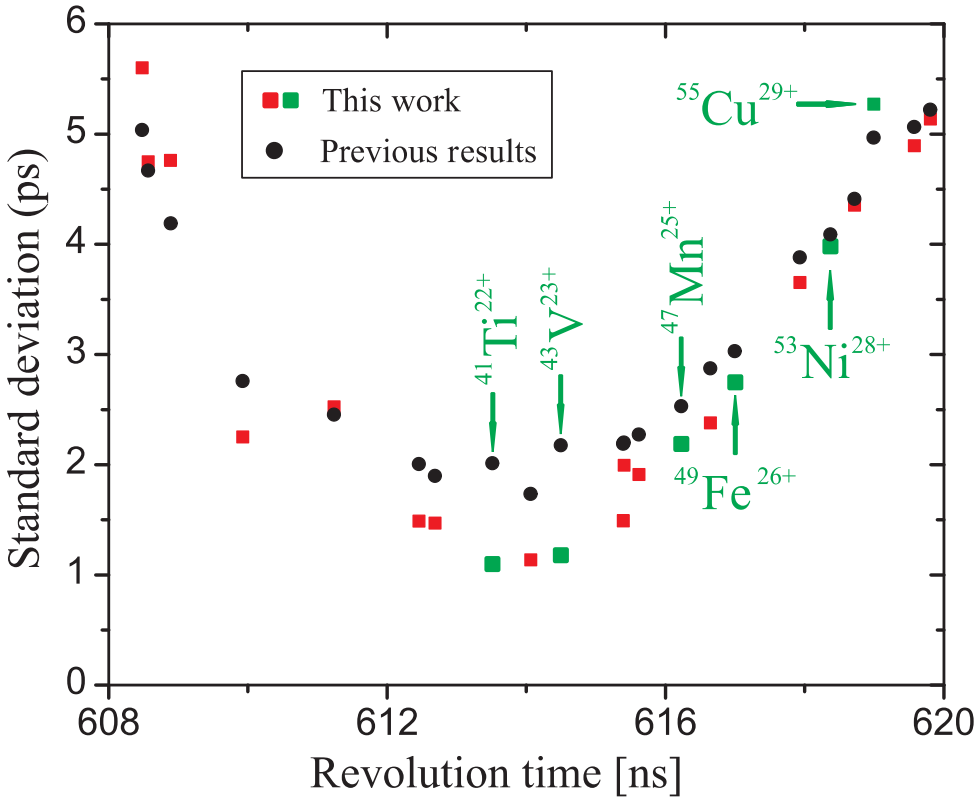
Off-line correction of the revolution-times

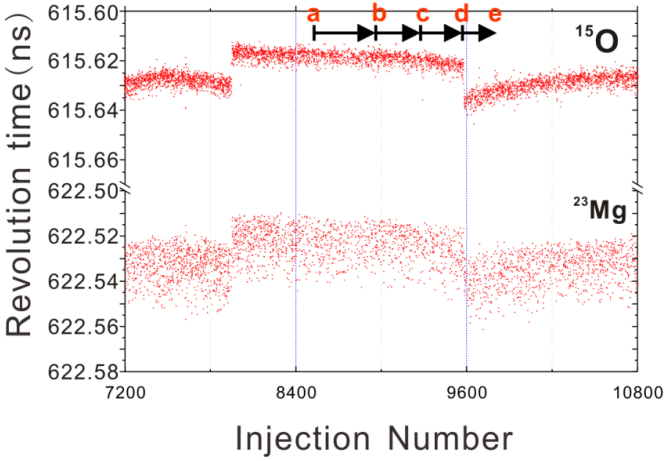


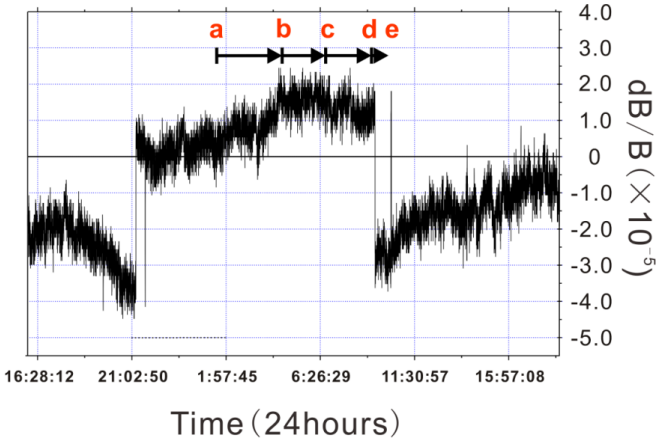
$$\text{grouped into 761 sub-spectra;} \qquad \Delta T = -\frac{\Delta B}{B}T + \frac{L^2}{c^2}\frac{\Delta B}{B}\frac{1}{T} = aT + \frac{b}{T} \approx kT + b$$

Further development 1: data analysis

P. Shuai, PhD Thesis(2015)







$R \leq 0.8 \times 10^5 (FWHM)$ σ(T) = 1.73 ps [minimum]

$R \leq 1.3 \times 10^5 (FWHM)$ σ(T) = 1.05 ps [minimum]

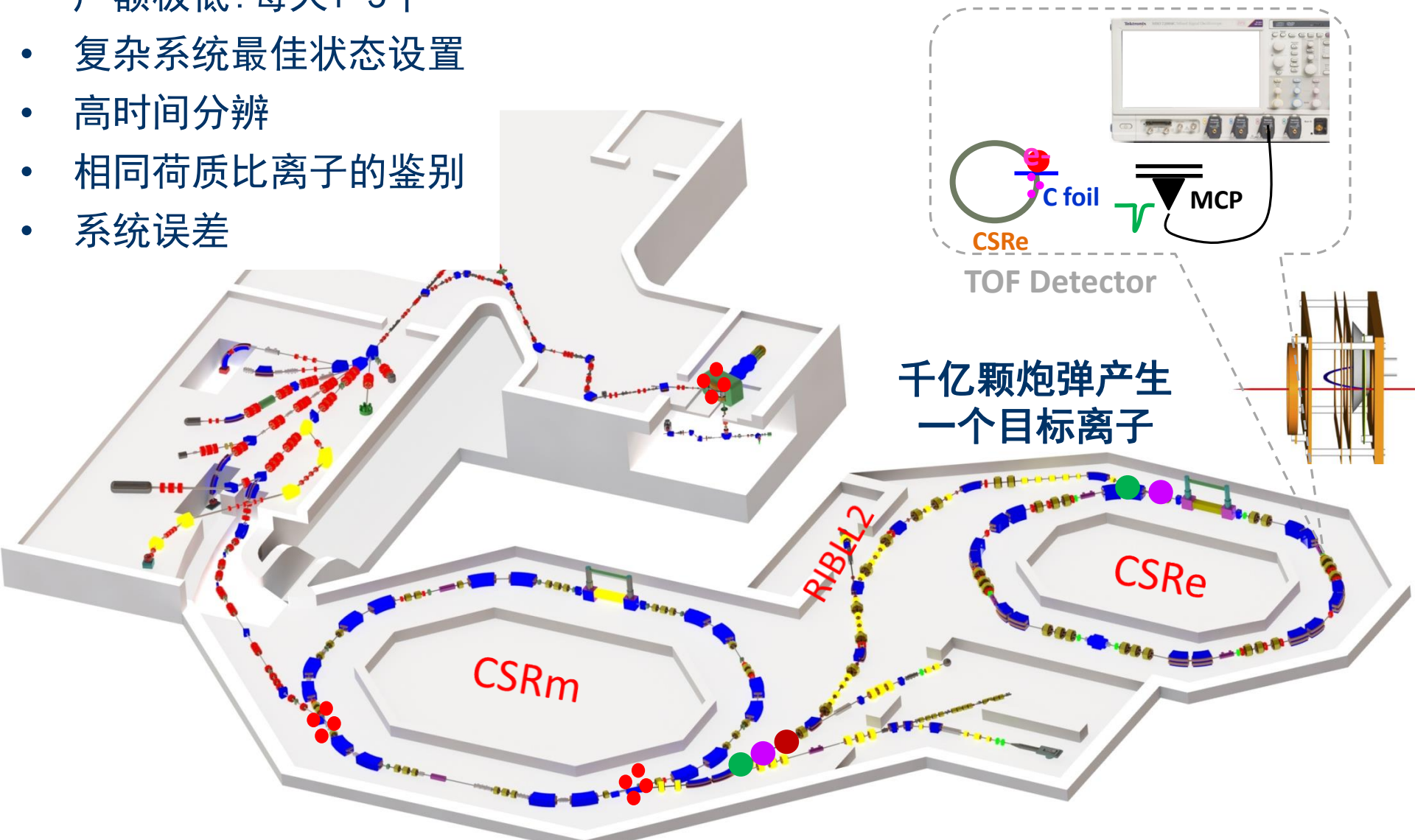
$$\frac{\Delta T}{T} = \frac{1}{\gamma^2}\frac{\Delta B}{B}$$

CSR质量测量方法

建立先进的等时性质谱仪

难点：

- 产额极低：每天1–5个
- 复杂系统最佳状态设置
- 高时间分辨
- 相同荷质比离子的鉴别
- 系统误差



The Collaborations

Y. H. Zhang, H.S. Xu, Y.A. Litvinov, H. Schatz, X. L. Tu, K. Blaum, X. H. Zhou, B. H. Sun, J. J. He, Y. Sun, M. Wang, Y. J. Yuan, J. W. Xia, J. C. Yang, G. Audi, G. B. Jia, Z. G. Hu, X. W. Ma, R. S. Mao, B. Mei, P. Shuai, Z. Y. Sun, S. T. Wang, G. Q. Xiao, X. Xu, T. Yamaguchi, Y. Yamaguchi, Y. D. Zang, H. W. Zhao, T. C. Zhao, W. Zhang, W. L. Zhan …