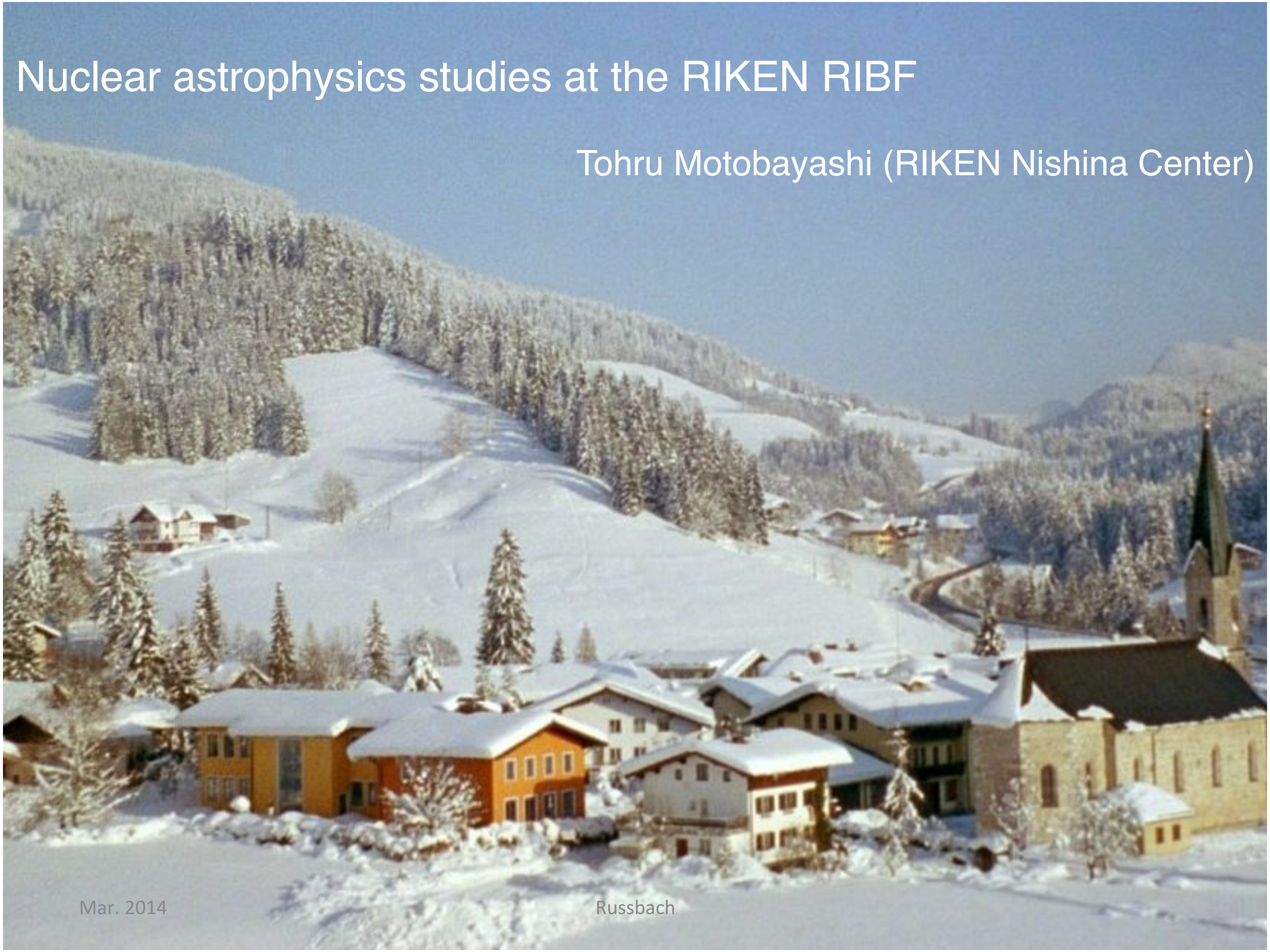
Nuclear astrophysics studies at the RIKEN RIBF

Tohru Motobayashi (RIKEN Nishina Center)



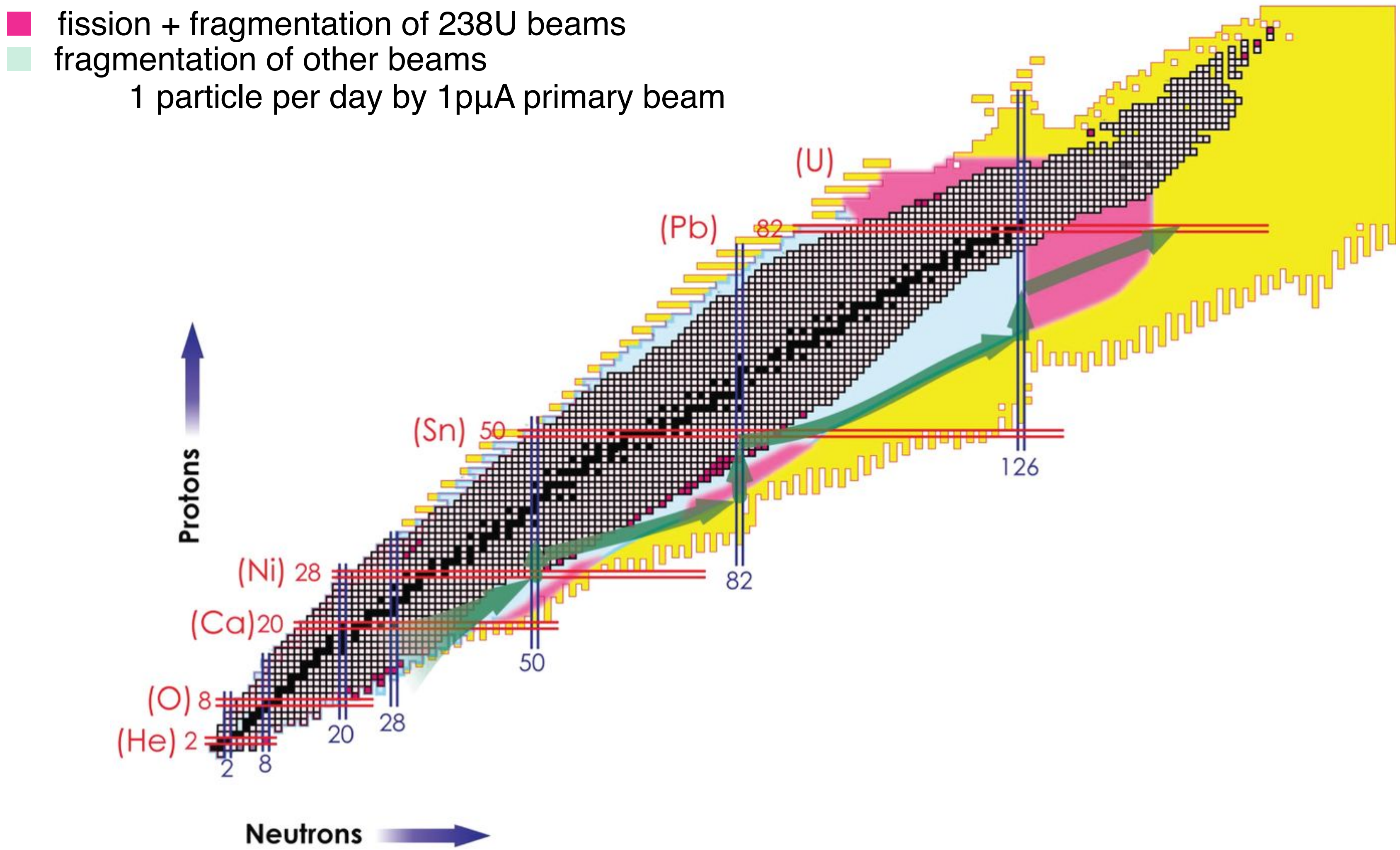
Nuclear astrophysics studies at the RIKEN RIBF,
a new-generation RIB facility

Some new results from Japan

Challenges at RIBF

- recent results
- experiments on-going
- future programs

Nuclear chart potentially covered by RIBF



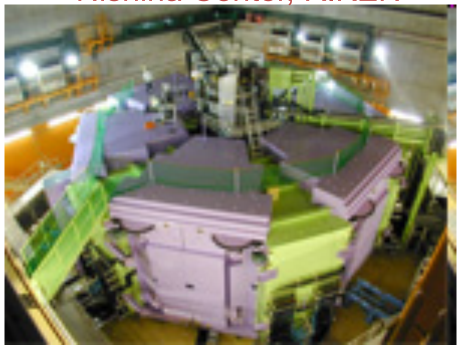
Motobayashi T , and Sakurai H Prog. Theor. Exp. Phys. 2012;2012:03C001

PTEP
Progress of Theoretical and Experimental Physics

Large

Japanese Accelerators available for Nuclear Physics Community

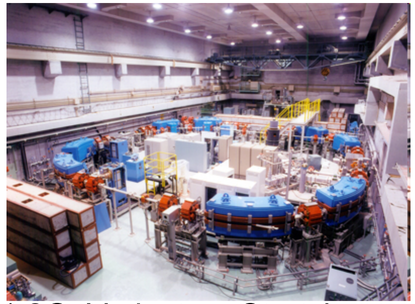
Nishina Center, RIKEN



K2600 **RIBF**

RI beam

Research Center for Electron Photon Science, Tohoku University (**ELPH**)



1.2GeV electron Stretcher

e$^-$

SPring-8 (RIKEN/JASRI)

8GeV e - Synchrotron

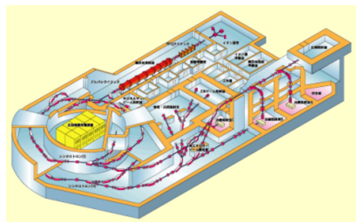
photon

RCNP, Research Center for Nuclear Physics, Osaka University

K400 Cyclotron

light ion

HIMAC at National Institute of Radiological Sciences



800MeV/A Synchrotron

heavy ion

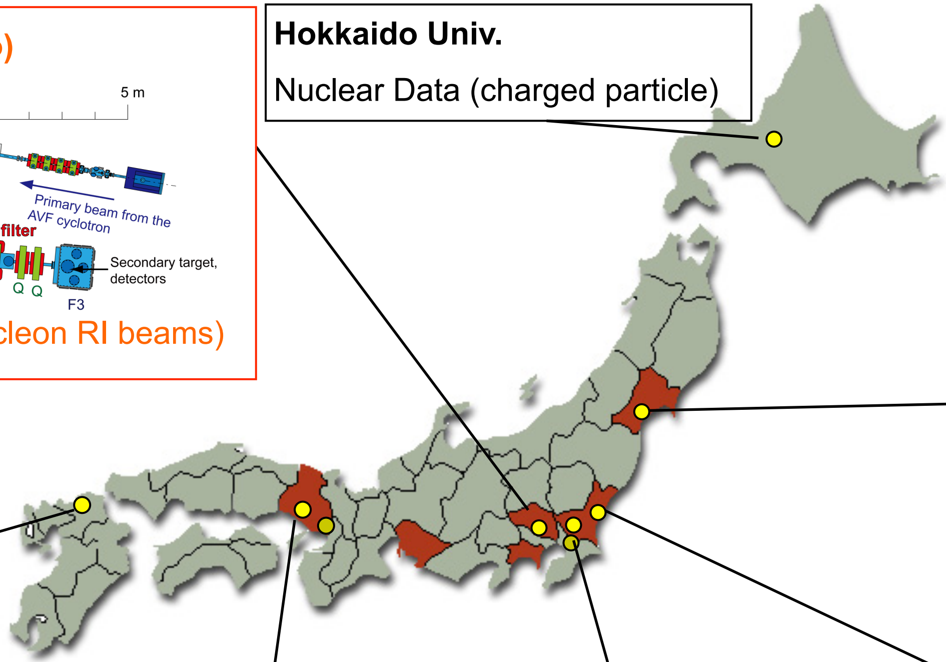
J-PARC, KEK/JAEA)

30GeV Proton Synchrotron

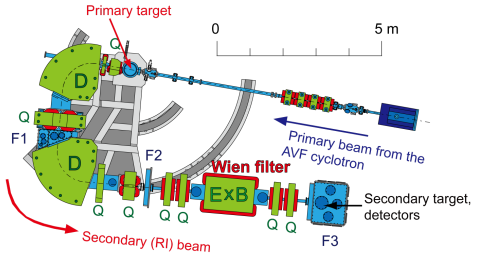
π, K, μ, n, (ν)

Small

Japanese Accelerators available for Nuclear Physics Community



CNS (Univ. Tokyo)



CRIB (~5 MeV/nucleon RI beams)

RI beam

Hokkaido Univ.

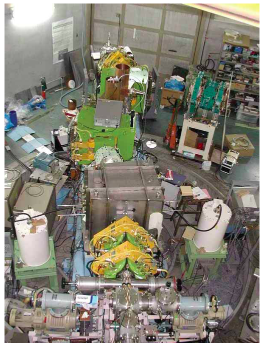
Nuclear Data (charged particle)

CYRIC (Tohoku Univ.)

Cyclotron (p 90 MeV)

light ions

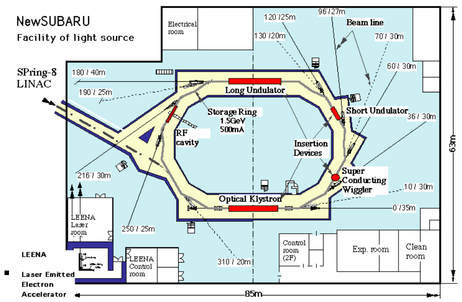
Kyushu Univ.



Tandem (~9 MV)

p, d, C, O, ..

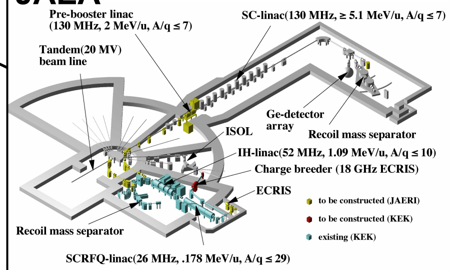
NEW SUBARU



SOR (2-10 MeV photons)

photon (inverse Compton)

JAEA



TRIAC (RI beams) → Tandem

heavy ions

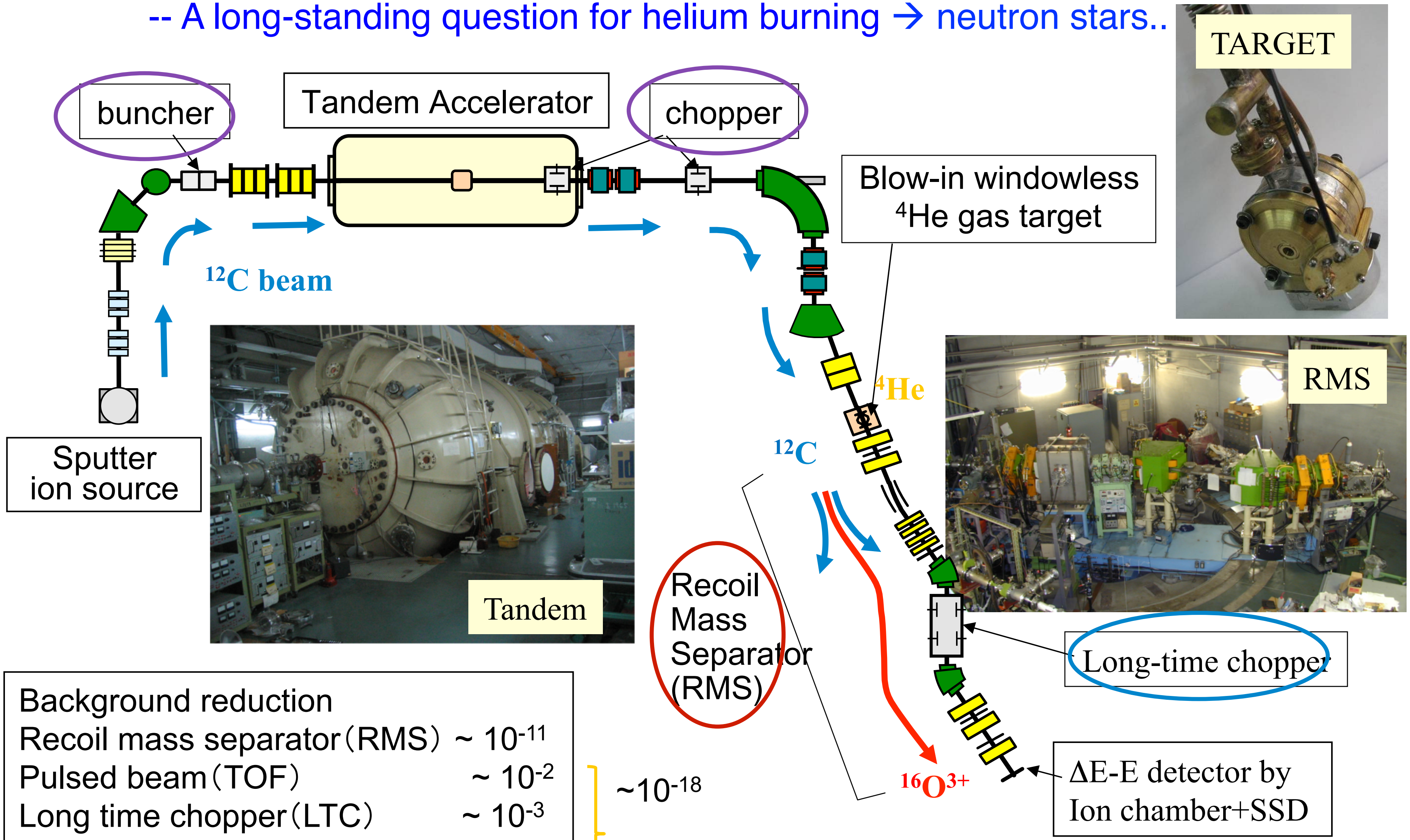
Tsukuba Univ.

Tandem → Vdg. (earthquake)

Kyushu U. Tandem

Challenge for low-energy $^{12}C(\alpha,\gamma)^{16}O$ cross sections

-- A long-standing question for helium burning → neutron stars..



Background reduction	
Recoil mass separator (RMS)	~ 10^{-11}
Pulsed beam (TOF)	~ 10^{-2}
Long time chopper (LTC)	~ 10^{-3}
DE-E counter	~ 10^{-2}

~10^{-18}

Mar. 2014 Russbach

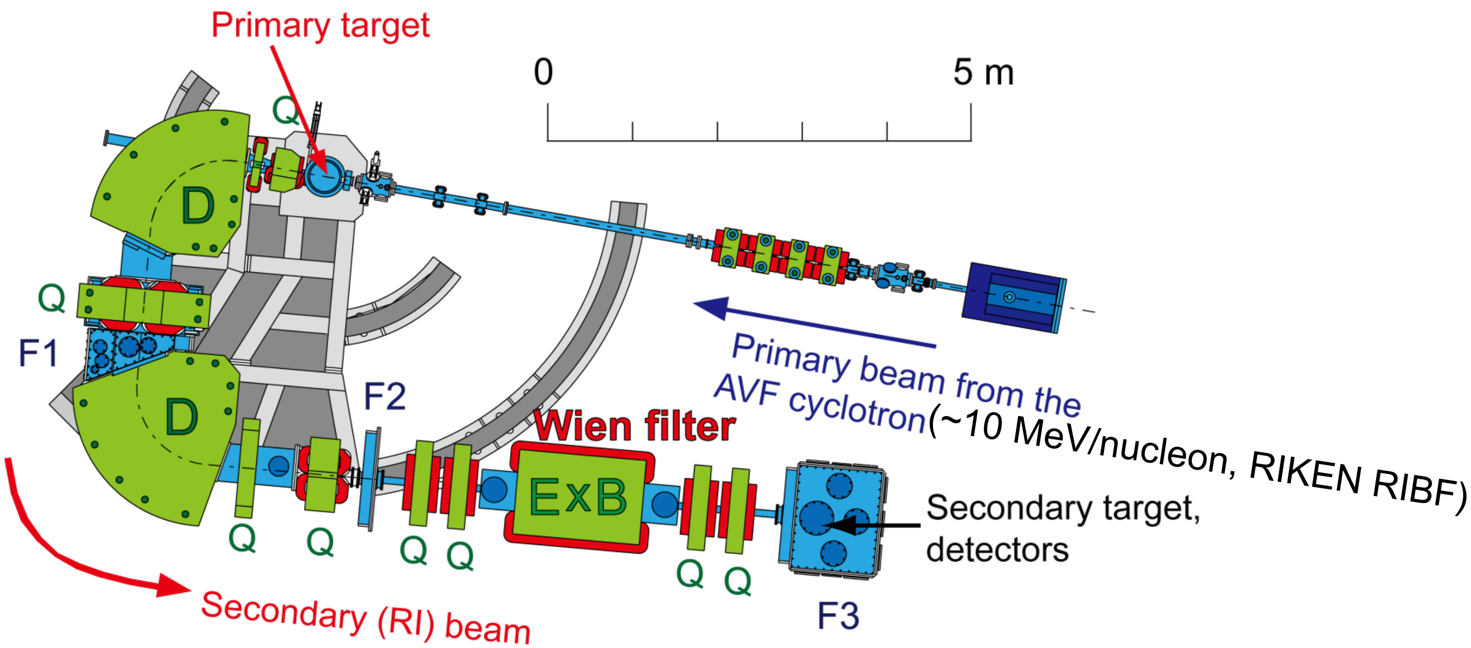
Courtesy of Kenshi Sagara

CNS, U. Tokyo

$^{7}Be(\alpha,\gamma)$ study at CRIB

- CNS Radio-Isotope Beam separator , operated by CNS (Univ. of Tokyo), located at RIBF (RIKEN Nishina Center).

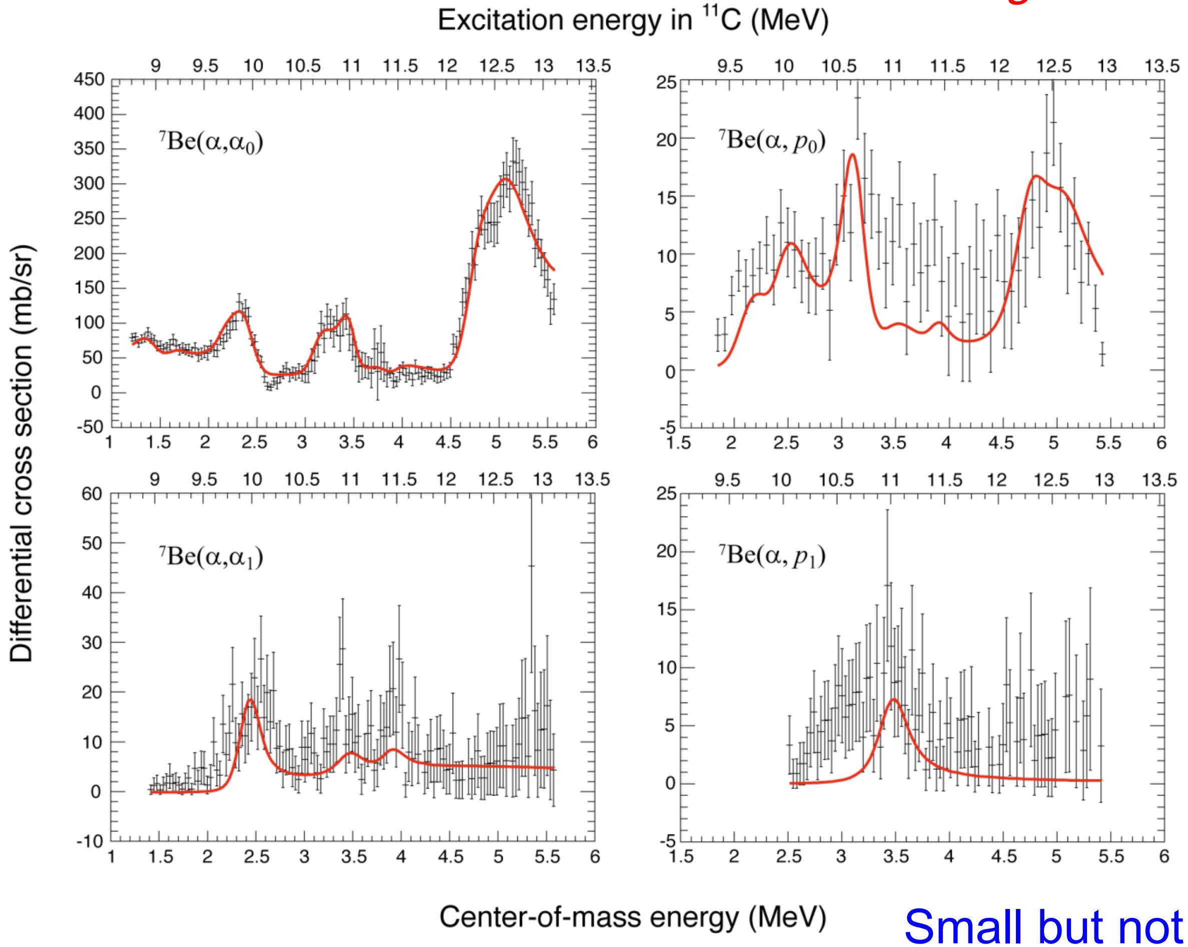
Is this reaction competitive to triple-α in νp process?



Courtesy of Hidetoshi Yamaguchi

^{7}Be+α Excitation functions

- For 4 excitation functions… *H. Yamaguchi et al., PRC (2013).*

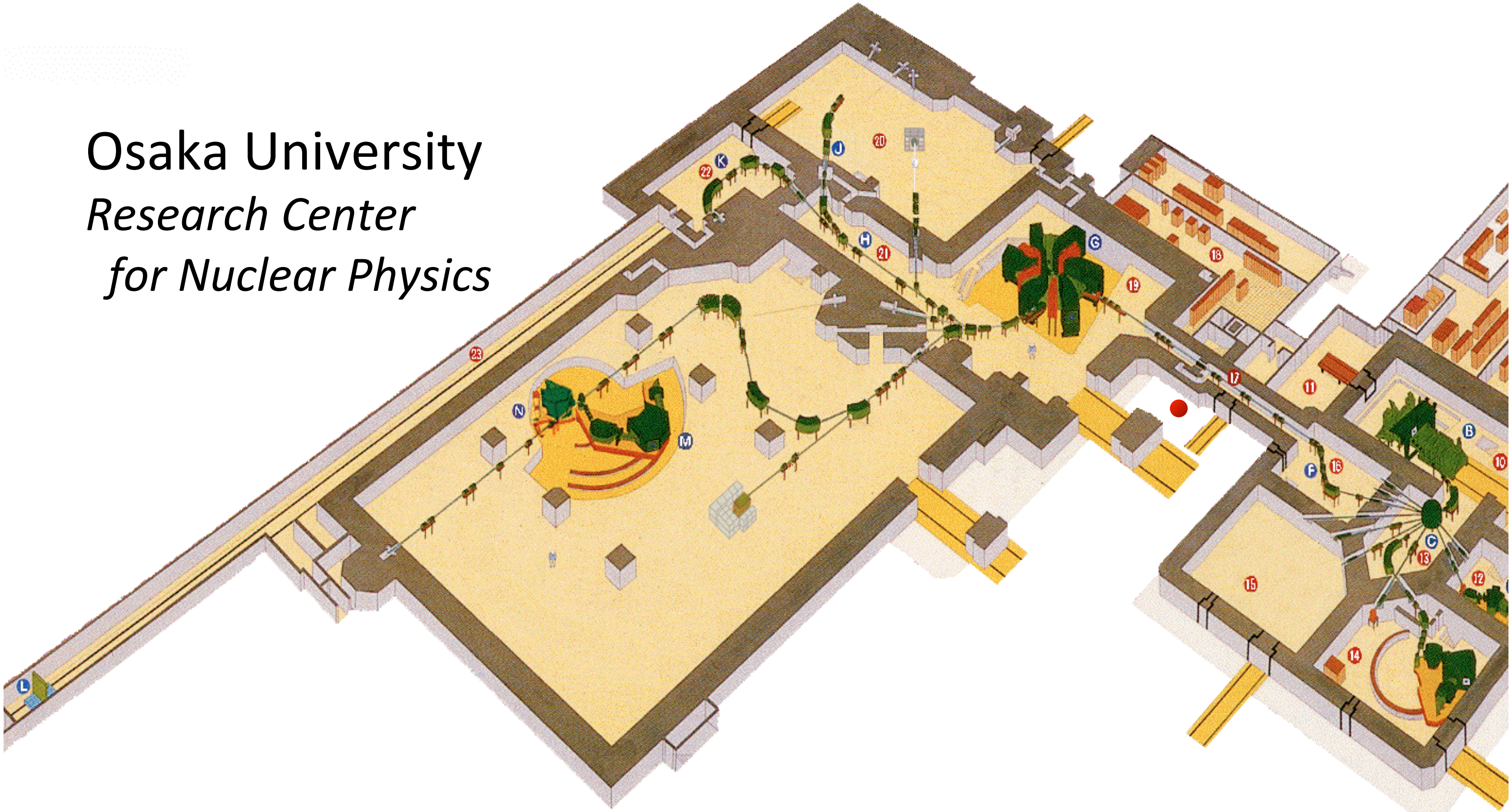


Small but not negligible contribution from the **newly-identified resonances** compared to lower-lying states (~10%).

RCNP, Osaka

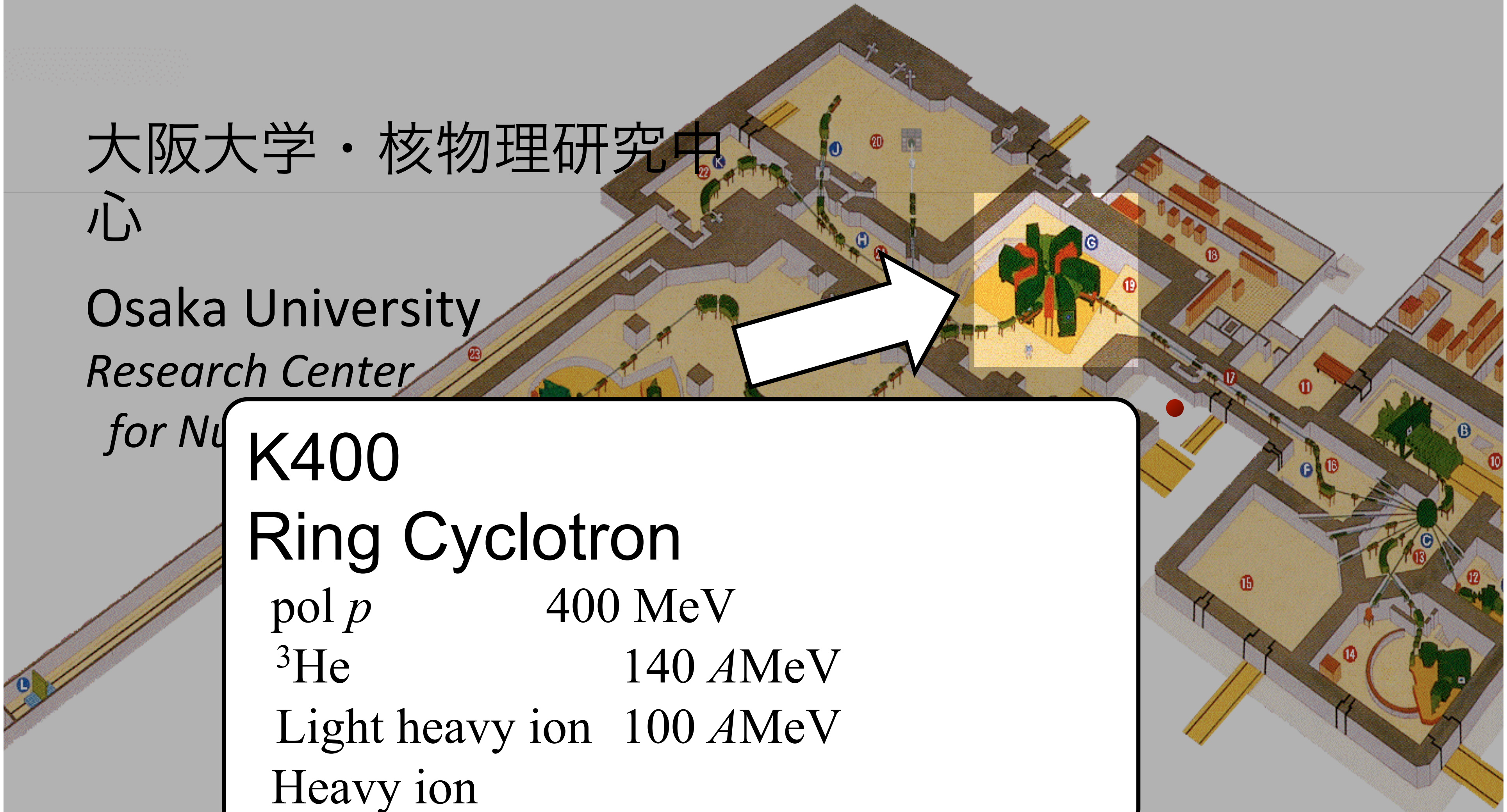
RCNP Cyclotron Facility

Osaka University
Research Center
for Nuclear Physics



Courtesy of Nori Aoi

RCNP Cyclotron Facility



大阪大学・核物理研究中心

Osaka University

Research Center

for Nu

K400

Ring Cyclotron

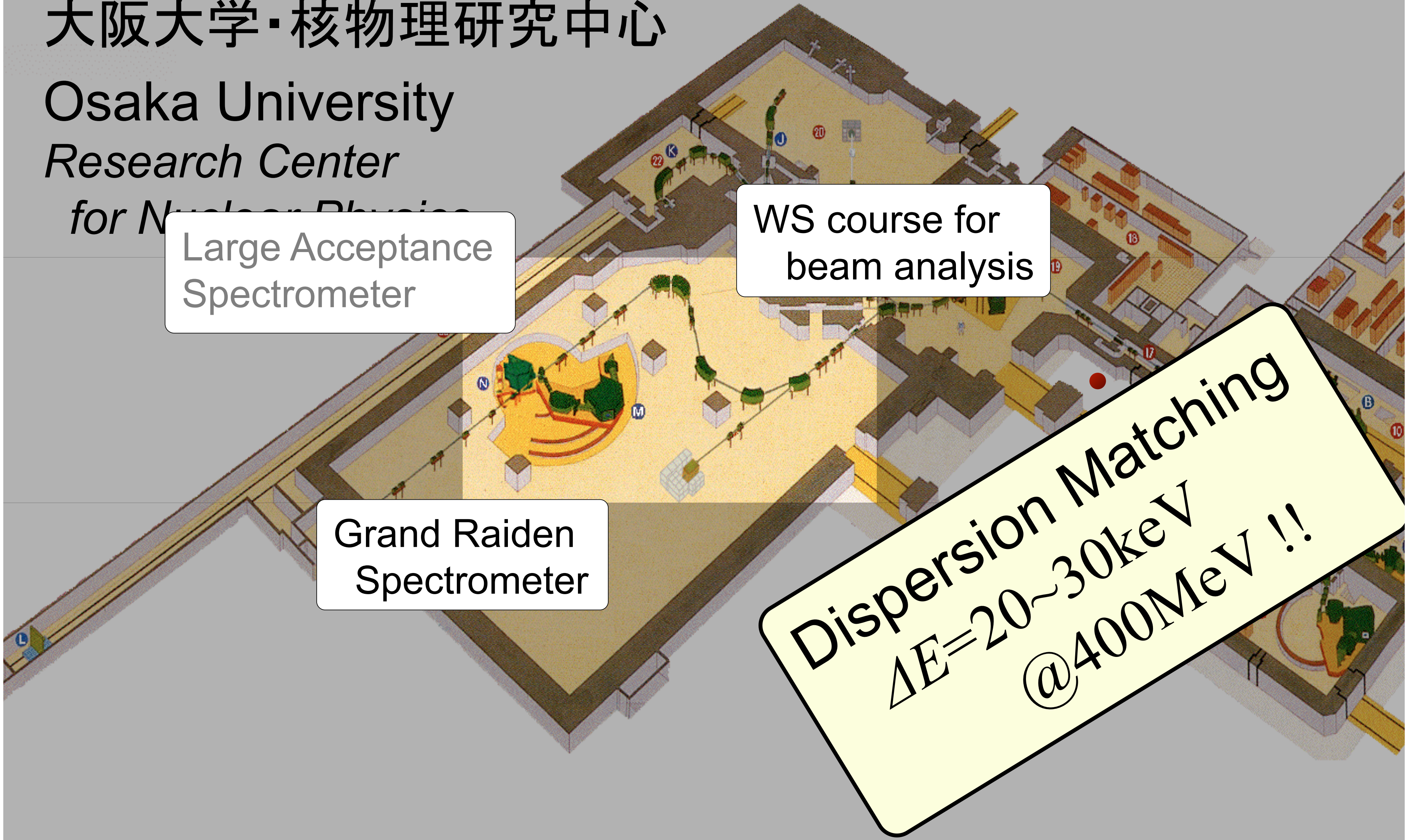
pol p	400 MeV
^{3}He	140 AMeV
Light heavy ion	100 AMeV
Heavy ion	

High-resolution particle spectroscopy at RCNP

大阪大学･核物理研究中心

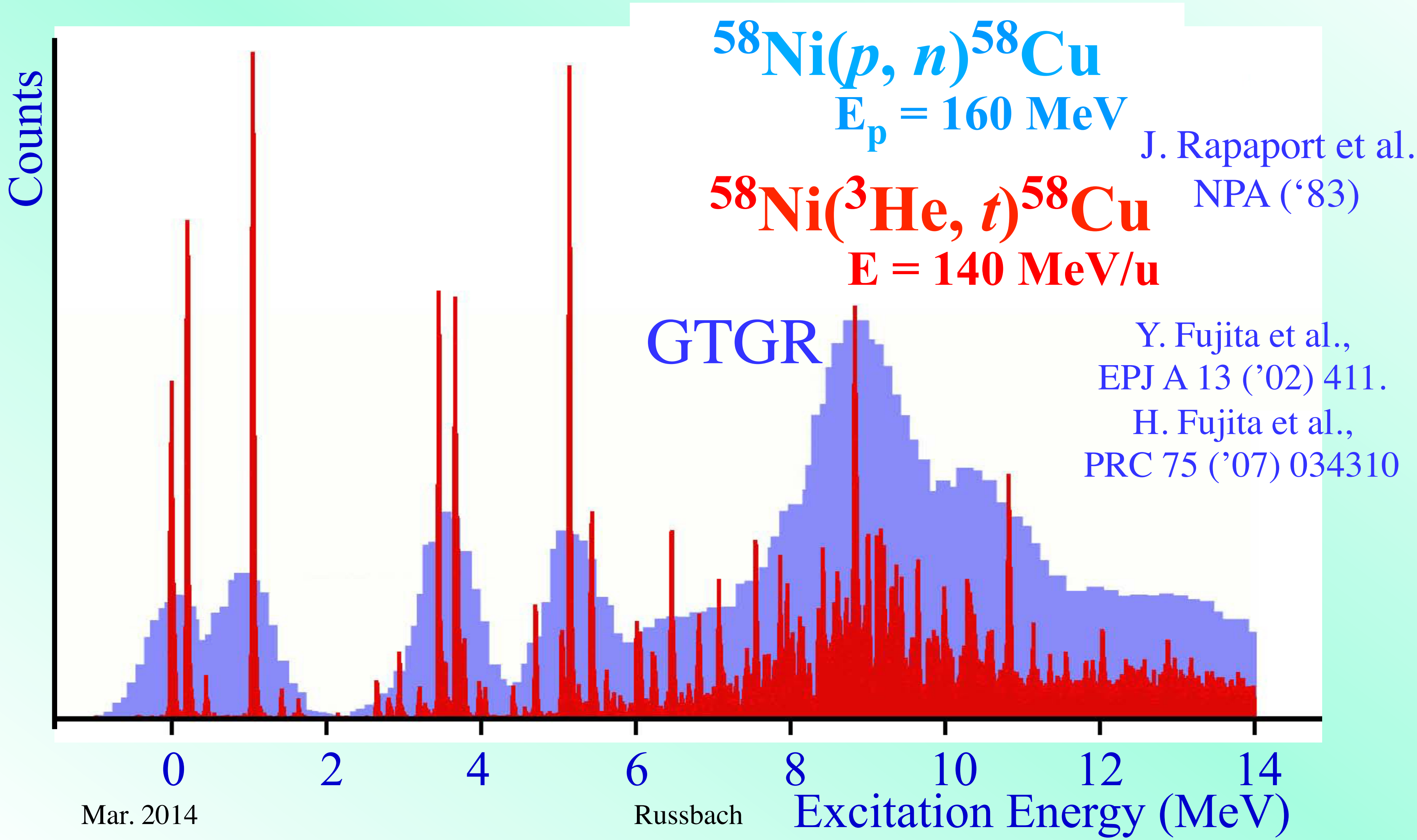
Osaka University

Research Center
for Nuclear Physics



GT (στ) excitations by high-resolution (^{3}He,t)

c.f. weak reaction rates



RIKEN RIBF

RIKEN RIBF

A new-generation RIB facility

Major motivations of studying unstable nuclei

nuclear structure / response

halo, skin, ….

shell structure *e.g.* (dis)appearance of magic numbers

asymmetric nuclear matter

explosive nuclear burning

reaction cross section

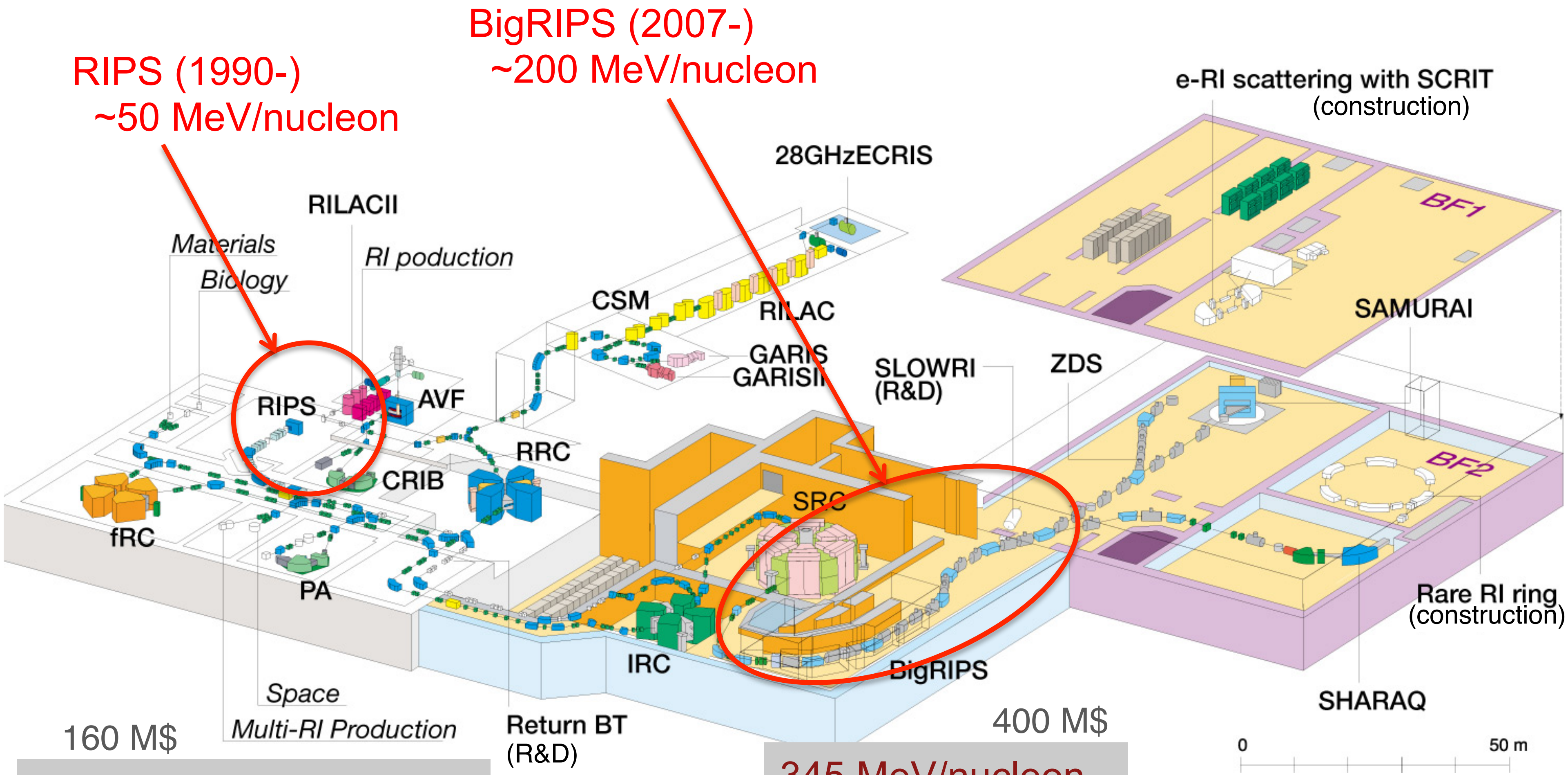
mass (Q value), half-life, …

First RI beams

LBL in 1985	**“Fragmentation” method**
Louvain la Neuve in 1989	**“ISOL” method**
RIKEN in 1990	“Fragmentation” method

RIKEN RIBF (RI Beam Factory) -- fragmentation-based RI bems (1990- / 2007-)

RIBF – a new generation RIB facility in operation
with world highest capability of providing RI beams in coming years!



160 M$

135 MeV/nucleon
for light nuclei (1986-)

400 M$

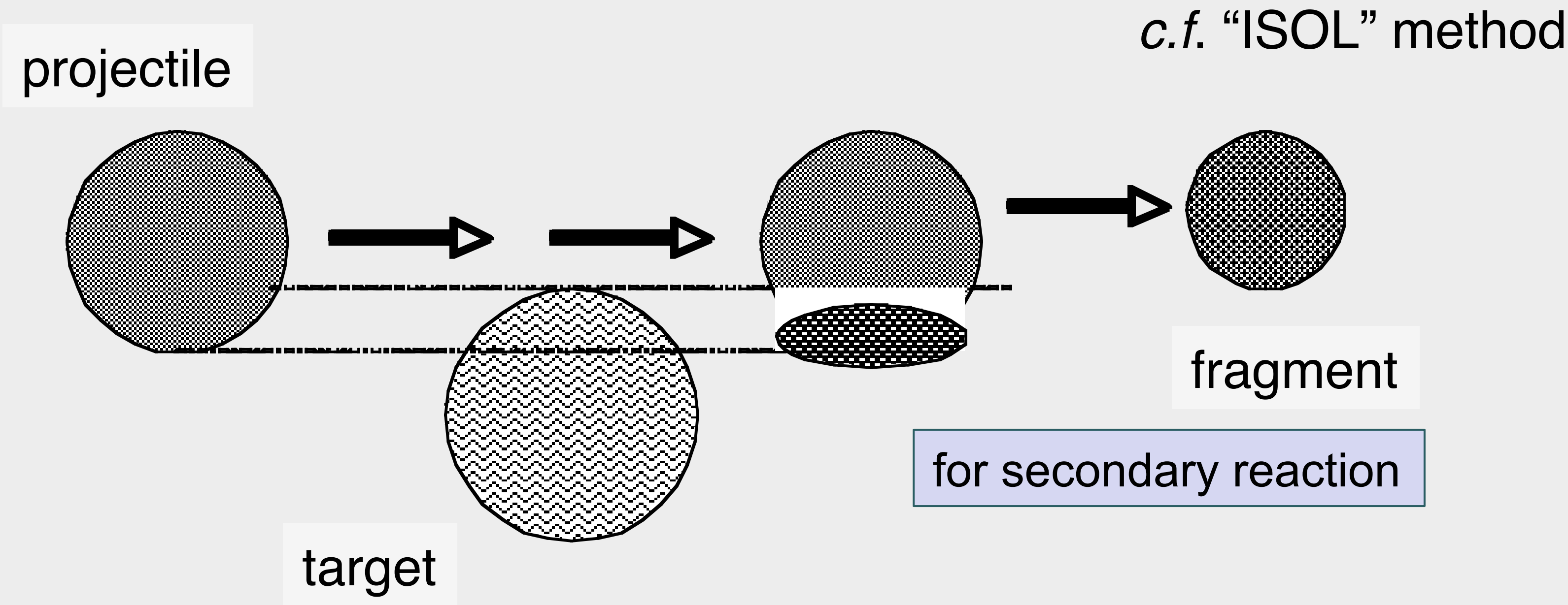
345 MeV/nucleon
up to U (2006-)

experimental equipment

Mar. 2014

Russbach

RI beam production by “projectile fragmentation*”



Projectile with 20-70% of light speed

→ fragment in similar velocity and direction

Various products → selection

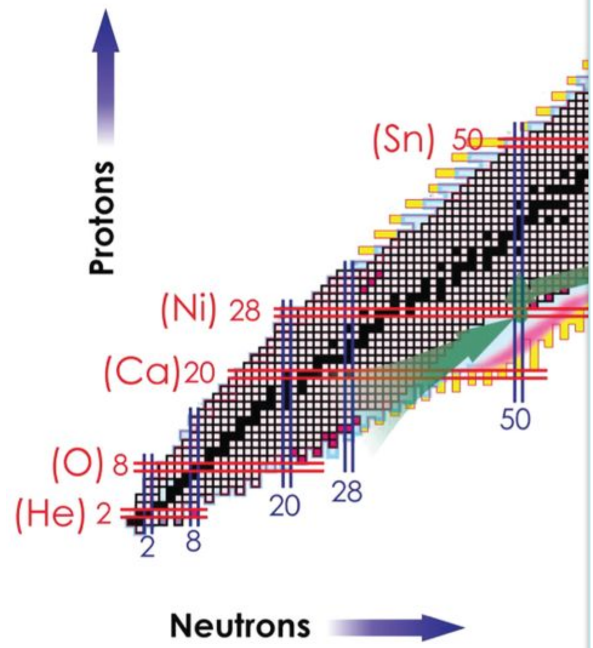
→ secondary beams of unstable nuclei (RI beams)

RIBF uses “projectile fission” in addition.

* known in cosmic-ray studies

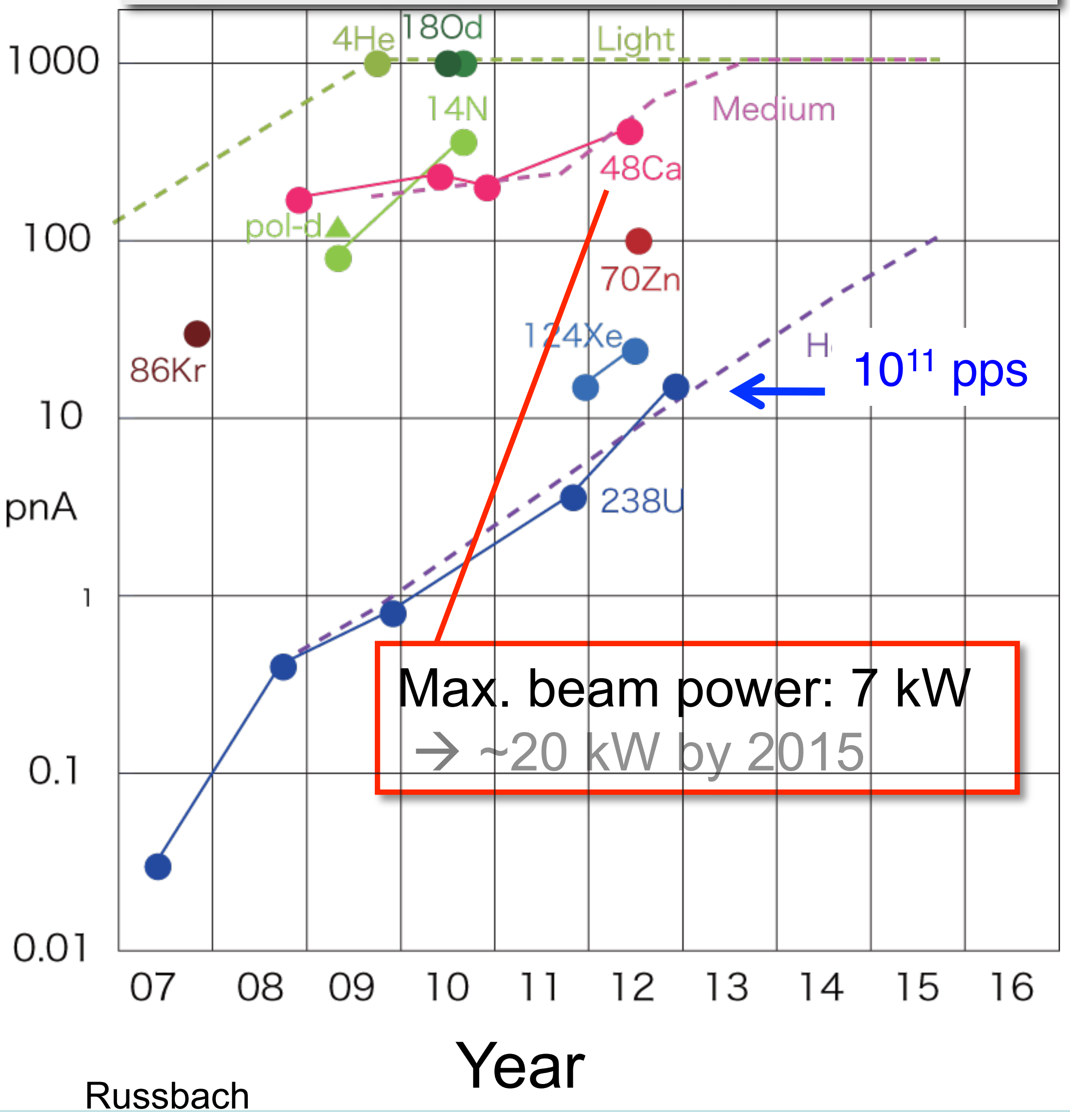
Nuclear chart potentially covered by RIBF

- fission + fragmentation of ^{238}U beam
- fragmentation of other beams
  - 1 particle per day by 1pμA prima



Motobayashi T , and Sakurai H Prog. Theo
2012;2012:03C001

Evolution of beam intensities at RIBF
Okuno, Fukunishi, Kamigaito,
Prog. Theor. Exp. Phys. 03C002 (2012).



Progress of Theoretical and Experimental Physics

Challenges at RIBF for nuclear astrophysics

1. β decay half lives of r-process nuclei -- Nishimura

2. spectroscopy of neutron-rich nuclei → shell quenching (around N=50, 82,..)
   -- Nishimura (decay)

3. Coulomb dissociation at SAMURAI → rp (r) process, s-process

4. fission of n-rich nuclei at SAMURAI → fission barrier height

5. weak processes by charge-exchange reactions in inverse kinematics

6. "Rare RI Ring": being constructed → masses of r-process nuclei w. Tsukuba

7. "SLOWRI": financed → *e.g.* precision mass measurements by MRTOF
   → r, rp process

8. Kiss project for spectroscopy in the "blank spot" - r process 3rd peak

9. CRIB (CNS) → low-energy studies → OEDO project (slowdown RI-beams)

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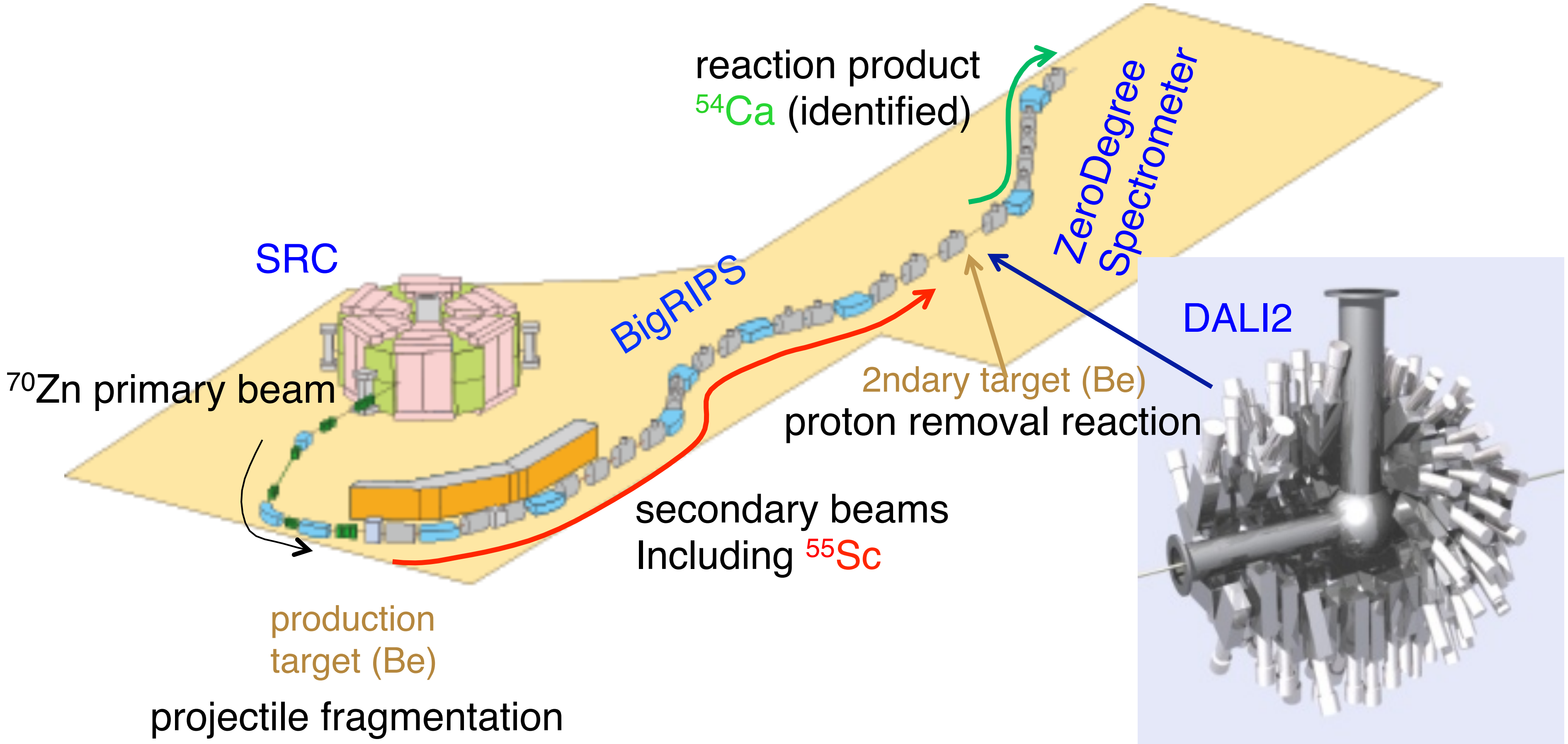
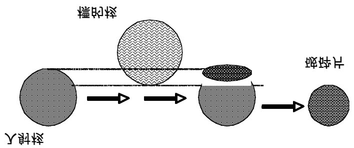
2^+ energy of ^{54}Ca: measured by deexcitation γ-rays with DALI2

a recent highlight -- an example of RIBF experiments



γ-ray measurement
186 NaI(Tl) schintillators
with Doppler-shift correction



LETTER

Nature, **502** (2013) 207

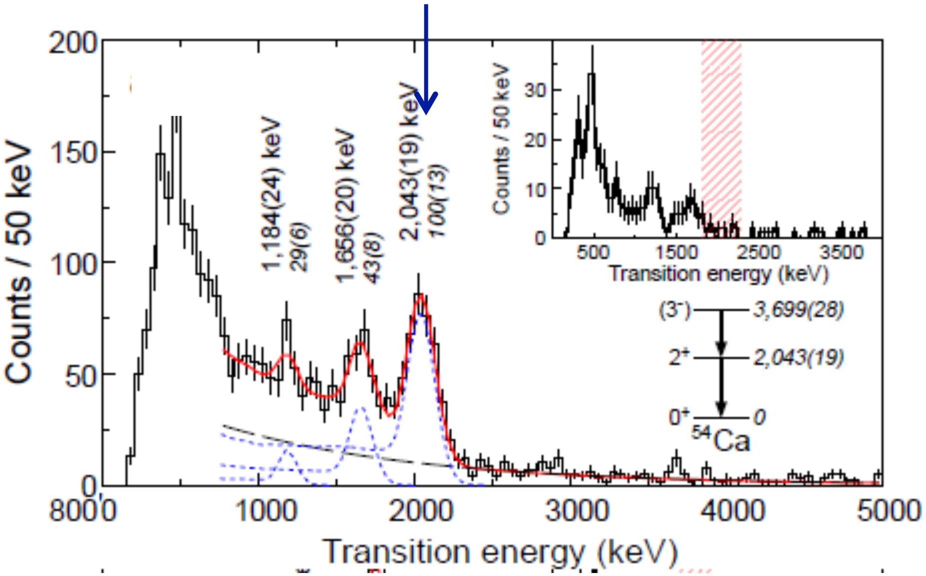
doi:10.1038/nature12522

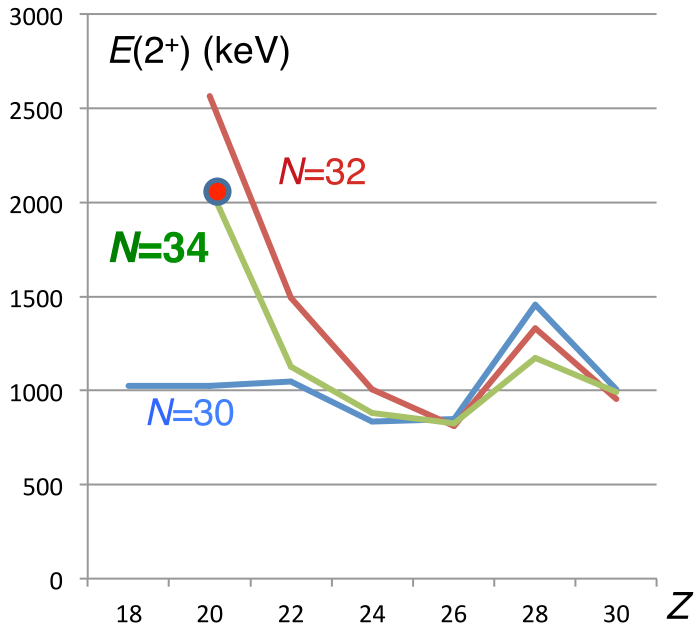
Evidence for a new nuclear 'magic number' from the level structure of ^{54}Ca

D. Steppenbeck[1], S. Takeuchi[2], N. Aoi[3], P. Doornenbal[2], M. Matsushita[1], H. Wang[2], H. Baba[2], N. Fukuda[2], S. Go[1], M. Honma[4], J. Lee[2], K. Matsui[5], S. Michimasa[1], T. Motobayashi[2], D. Nishimura[6], T. Otsuka[1,5], H. Sakurai[2,5], Y. Shiga[7], P.-A. Söderström[2], T. Sumikama[8], H. Suzuki[2], R. Taniuchi[5], Y. Utsuno[9], J. J. Valiente-Dobón[10] & K. Yoneda[2]

N=34 shell gap in ^{54}Ca? ➔ Yes

2^+ at 2043(19) keV

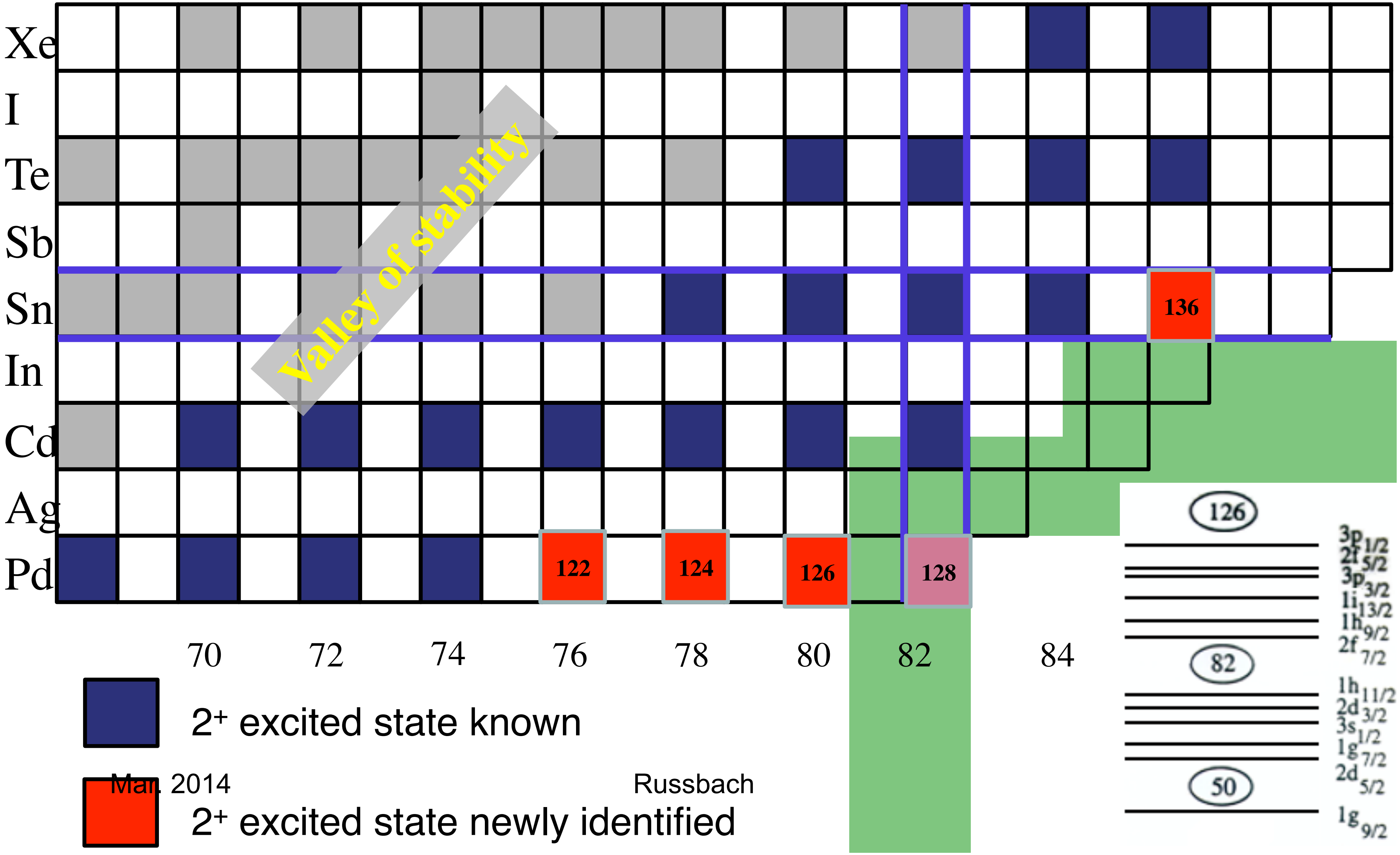




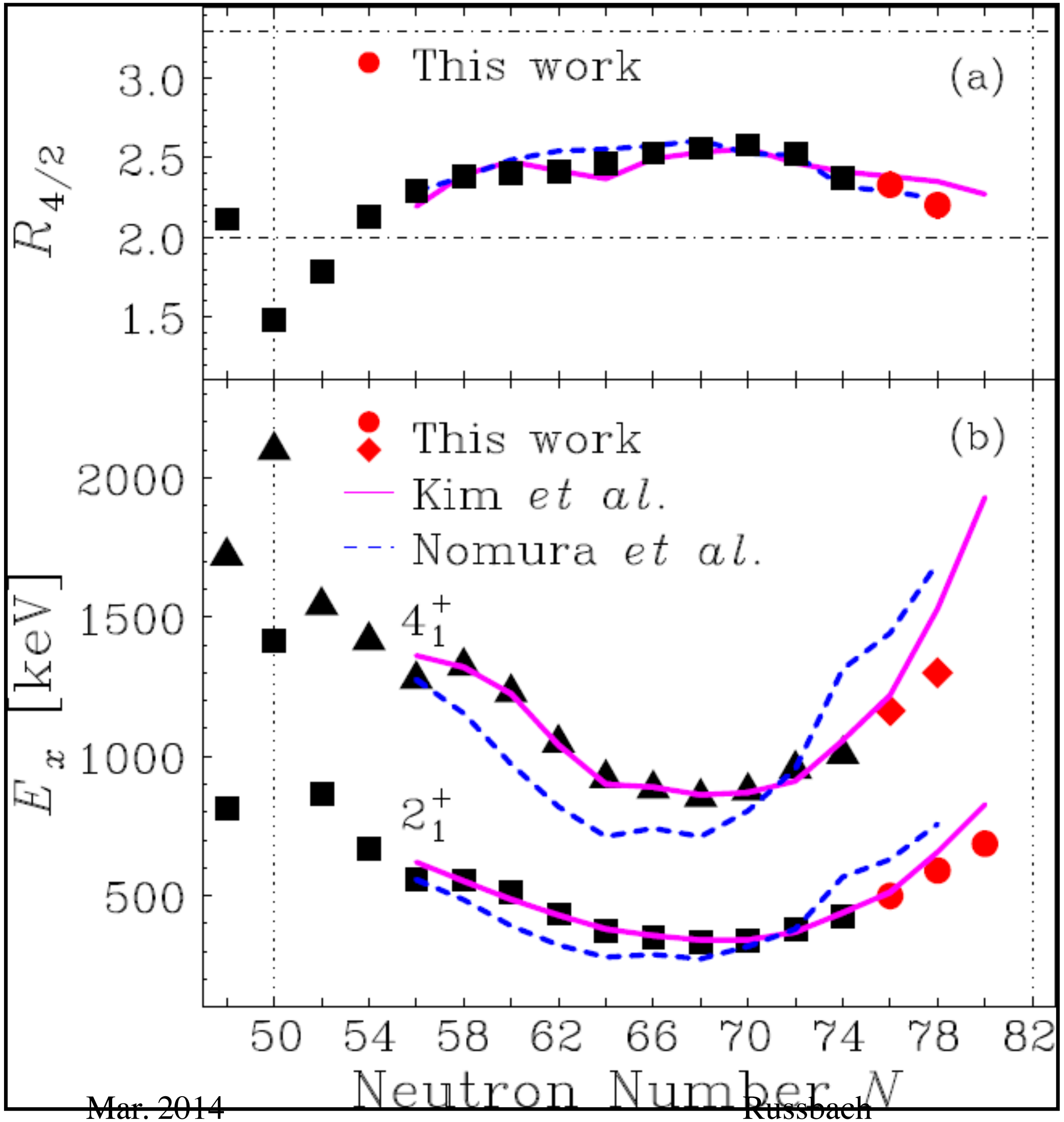

Neutron number
34 makes exotic
calcium-54 isotopes
doubly magic
PAGE 207
MAGIC MOMENTS

Excitation energies of 2^+ states

H. Wang *et al.*, PRC **88** (2013) 054318
H. Watanabe *et al.*, PRL **111** (2013) 152501
H. Wang *et al.*, PTEP **2014** (2014) 023D02



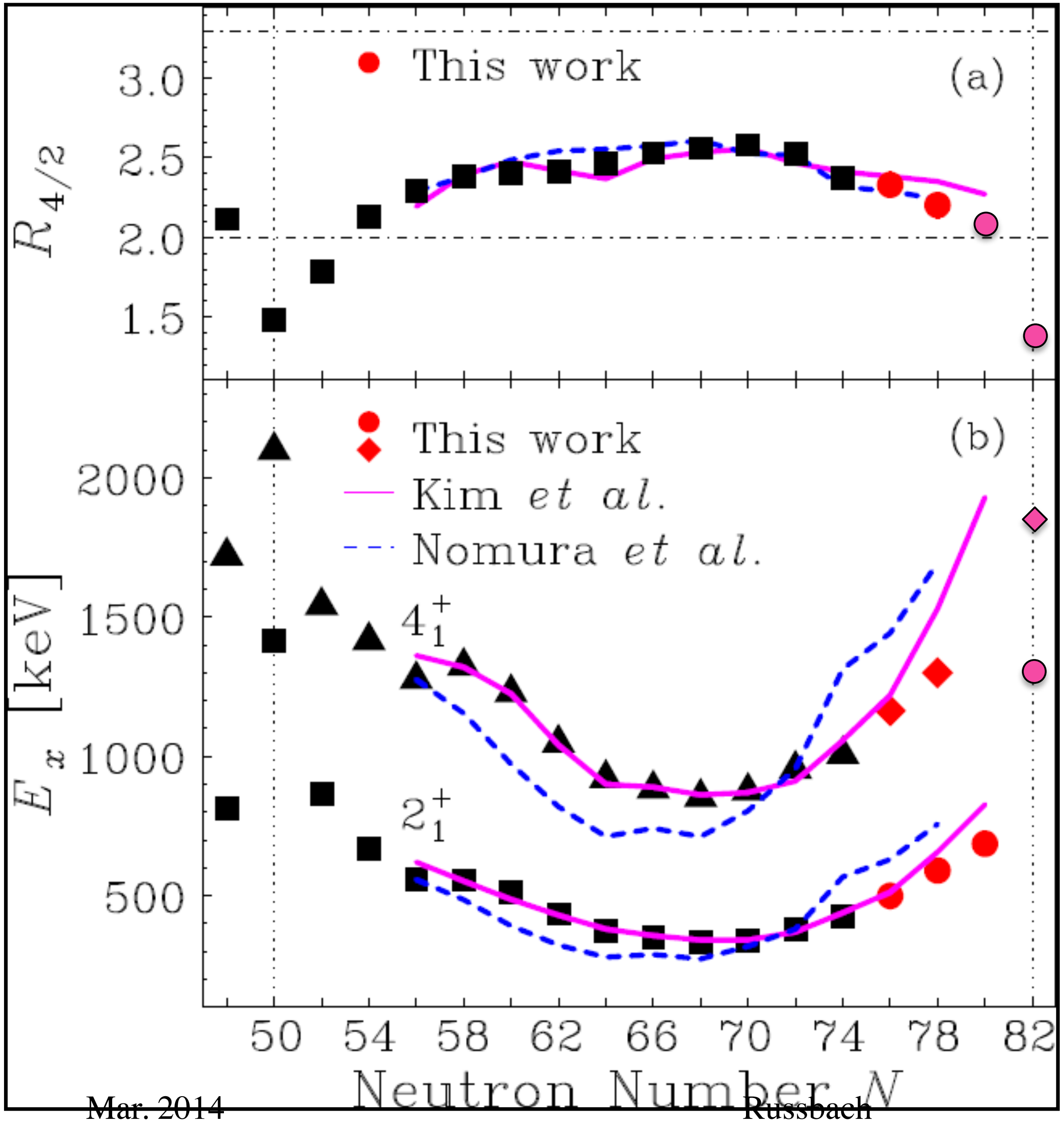
New Ex(2⁺) and Ex(4⁺) data



No significant Quenching

Useful information for understanding r-process.

New Ex(2$^+$) and Ex(4$^+$) data



No significant Quenching

c.f. Isomer study at Eurica (Nishimura)

Useful information for understanding r-process.

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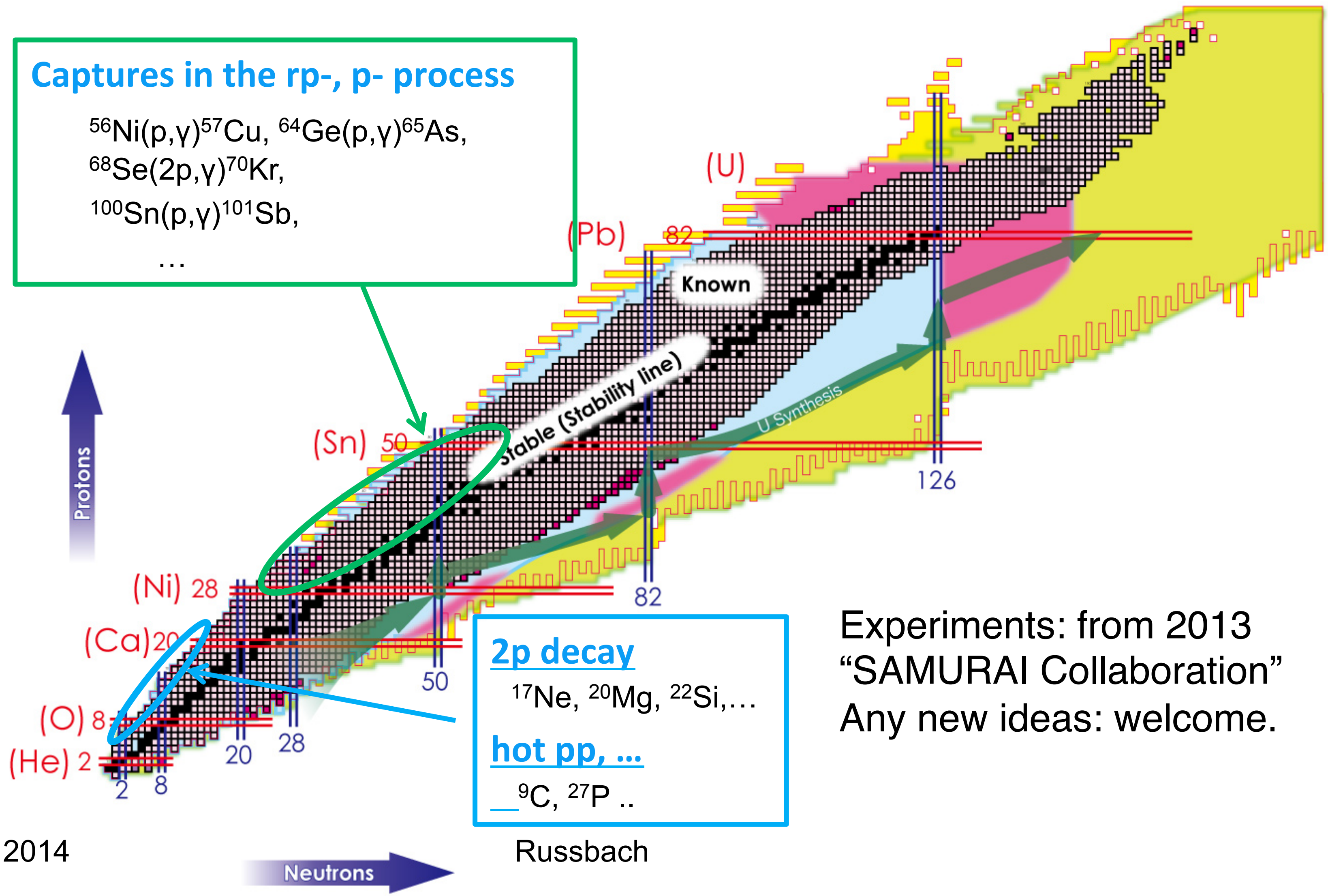
SAMURAI large acceptance spectrometer at RIBF secondary beam experiments (2012-)

Possible experiments in the first stage



Experiments: from 2013
"SAMURAI Collaboration"
Any new ideas: welcome.

If the Brink Hypothesis is applicable, γ-ray strength function is obtained by Coulomb dissociation. Utsunoiya (Konan U.)

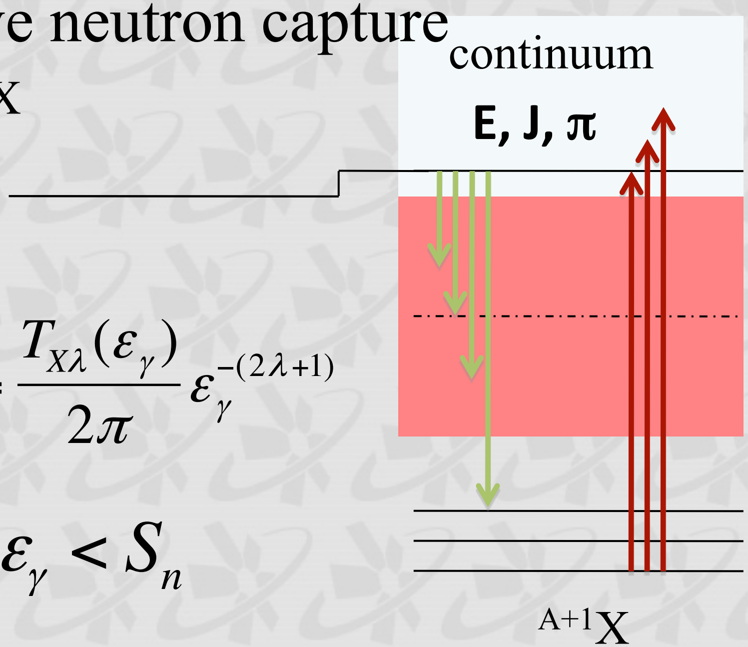
Radiative neutron capture

$^{A}X(n,\gamma)^{A+1}X$

Photoneutron emission

$^{A+1}X(\gamma,n)^{A}X$

n+^{A}X



$$f_{X\lambda}(\varepsilon_\gamma)\downarrow = \frac{T_{X\lambda}(\varepsilon_\gamma)}{2\pi}\varepsilon_\gamma^{-(2\lambda+1)}$$

$$\varepsilon_\gamma < S_n$$

$$f_{X\lambda}(\varepsilon_\gamma)\uparrow = \frac{\varepsilon_\gamma^{-2\lambda+1}}{(\pi\hbar c)^2}\frac{\langle\sigma_{X\lambda}^{abs}(\varepsilon_\gamma)\rangle}{2\lambda+1}$$

$$\varepsilon_\gamma > S_n$$

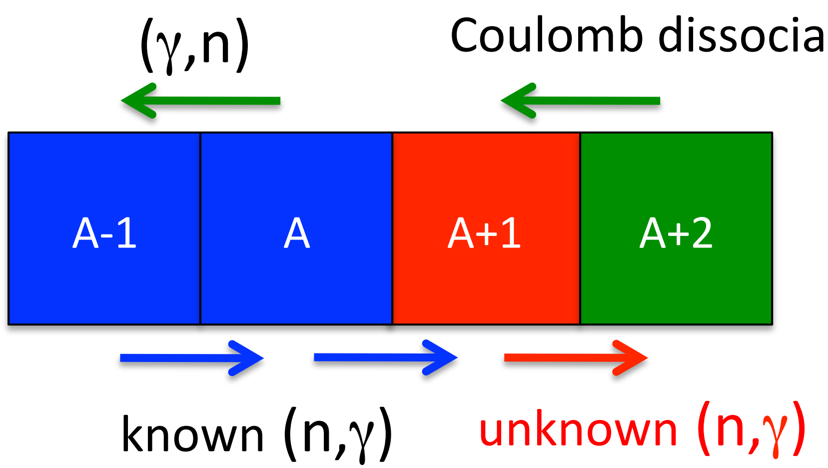
$$\sigma_{X\lambda}^{\gamma n}(\varepsilon_\gamma) = \sigma_{X\lambda}^{abs}(\varepsilon_\gamma)\times\frac{T_n}{T_n+T_\gamma}$$

Brink Hypothesis

$$f_{X\lambda}(\varepsilon_\gamma)\uparrow \cong f_{X\lambda}(\varepsilon_\gamma)\downarrow$$

Courtesy of H. Utsunomiya

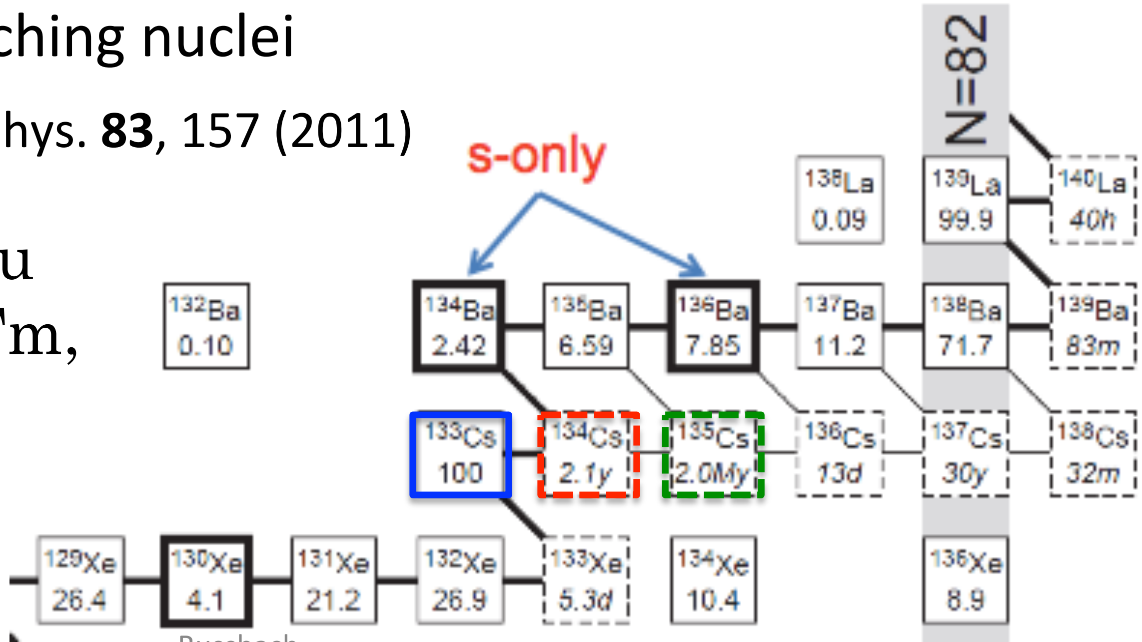
γSF Method with Coulomb dissociation



Important **s-process** branching nuclei

F. Käppeler *et al.*, Rev. Mod. Phys. **83**, 157 (2011)

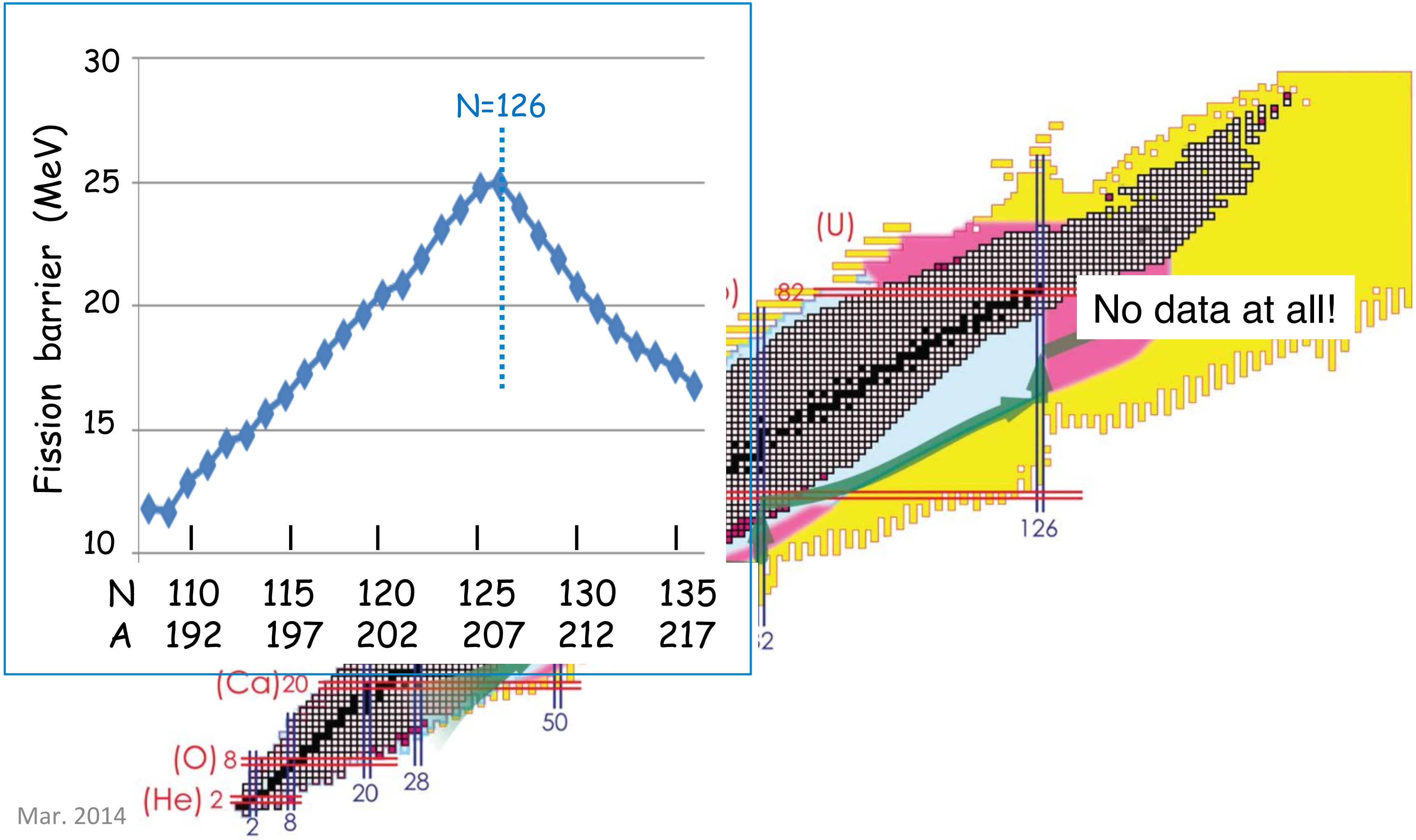
^{134}Cs, ^{135}Cs, ^{154}Eu, ^{155}Eu
^{160}Tb, ^{163}Ho, ^{170}Tm, ^{170}Tm,
^{179}Ta, ^{204}Tl



Courtesy of H. Utsunomiya

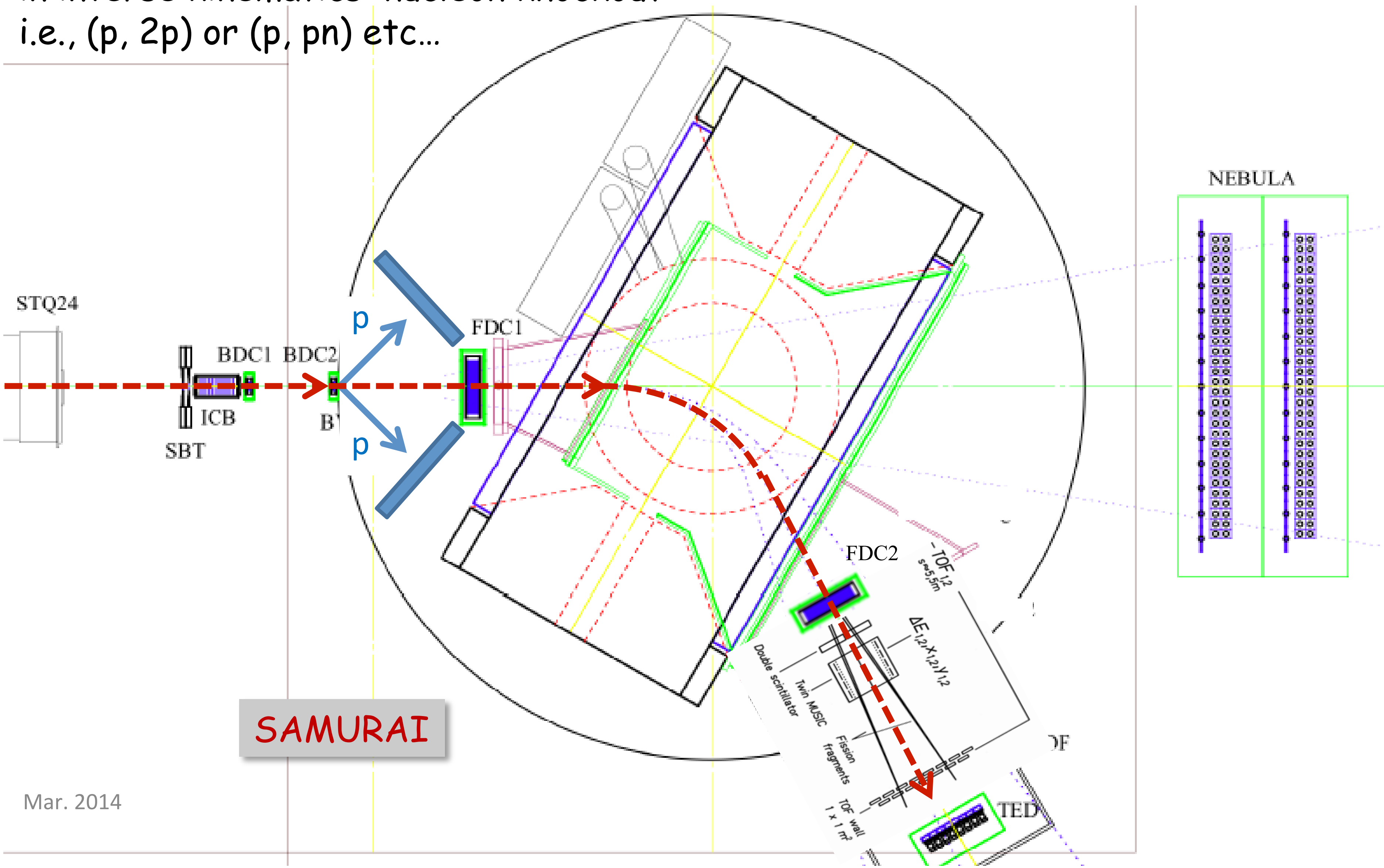
Fission Barriers of Lead Isotopes

P. Möller et al.; Phys. Rev. C **79** (2009) 064304



Courtesy of W. Henning **Neutrons**

Approach at high energies with RIBs
in inverse kinematics: nucleon knockout
i.e., (p, 2p) or (p, pn) etc…



Mar. 2014

Courtesy of W. Henning

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Process can be (mostly) controlled by the reaction *Q*-values (not by σ). *e.g.* r-process?

equilibrium in explosive conditions: between the inverse processes

e.g. radiative capture ←→ photo-disintegration

Saha equation for A+n ←→ (A+1)+γ

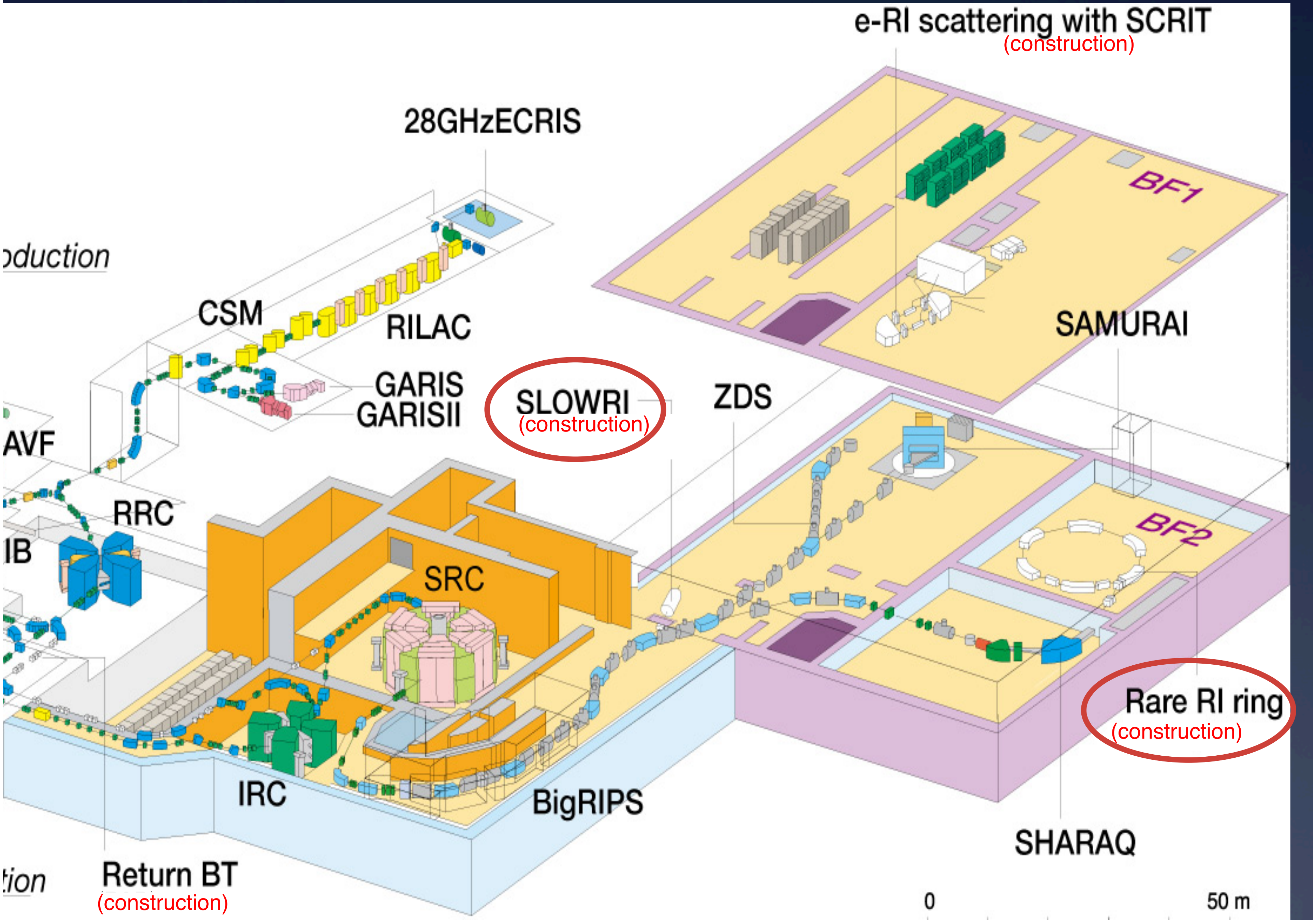
$$\frac{N(Z,A+1)}{N(Z,A)} = N_n \left(\frac{h^2}{2\pi m_{An} kT}\right)^{3/2} \frac{2j_{Z,A+1}+1}{(2j_{Z,A}+1)(2j_n+1)} \frac{G^{norm}_{Z,A+1}}{G^{norm}_{Z,A}} e^{Q_{n\gamma}/kT}$$

level (density)
temperature

nuclear mass

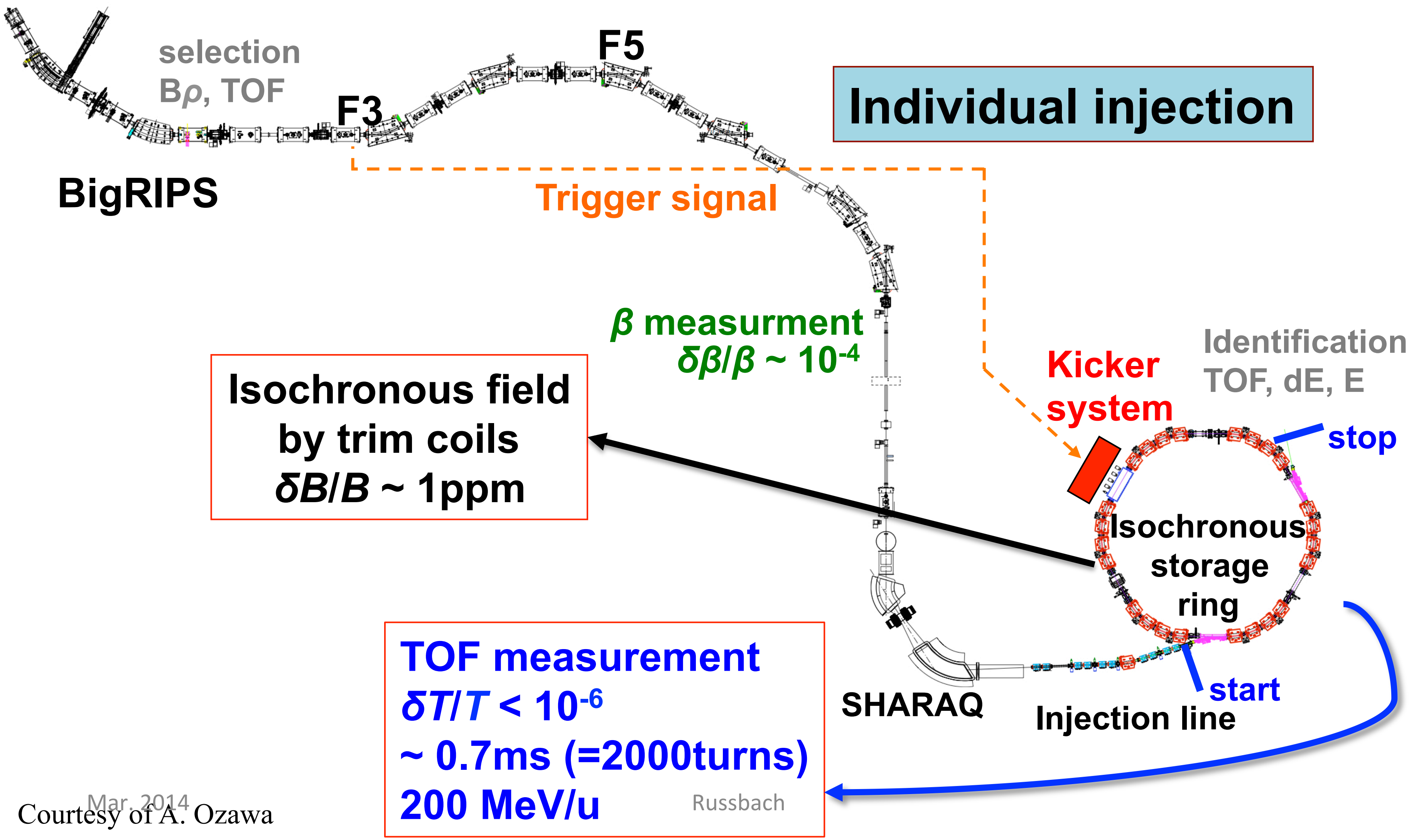
$$Q_{n\gamma} = m(\mathrm{A})c^2 + m(\mathrm{n})\,c^2 - m(\mathrm{A}+1)\,c^2$$

Equipment and detectors in RIKEN RIBF – mass measurements



Isochronous storage ring method -- under construction

1event/day, 1ms, 1ppm (10^{-6} precision)

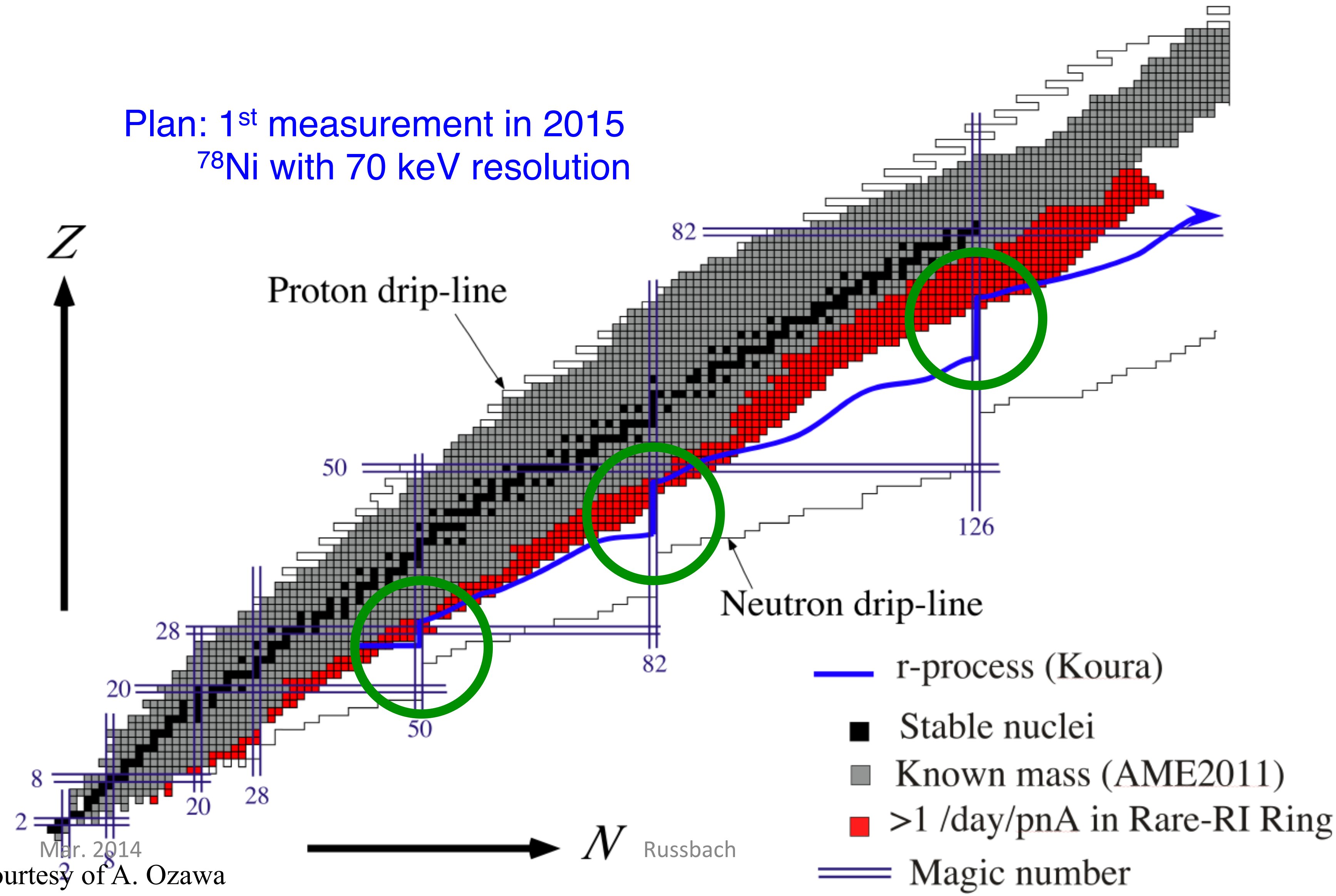


Courtesy of A. Ozawa

Systematic mass measurements

Waiting-point of the r-process path

Plan: 1st measurement in 2015
^{78}Ni with 70 keV resolution

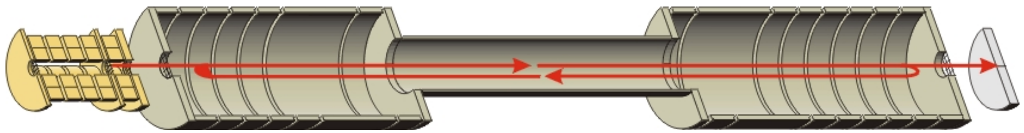


Courtesy of A. Ozawa

Ion Trap

Detector

$$ToF = L\sqrt{\frac{m}{2K}}$$



SLOWRI – MR TOF

another method of mass measurements

10^{-7} precision

Data: by M. Wada

r-process path

with Main Beam

known mass

82(39 parasitic) New Masses in this region

top: log(Yield)
bottom: log(T1/2)

Mass measurements at SLOWRI using MRTOF

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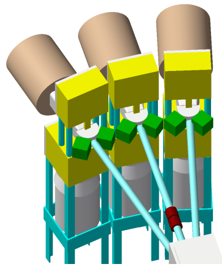
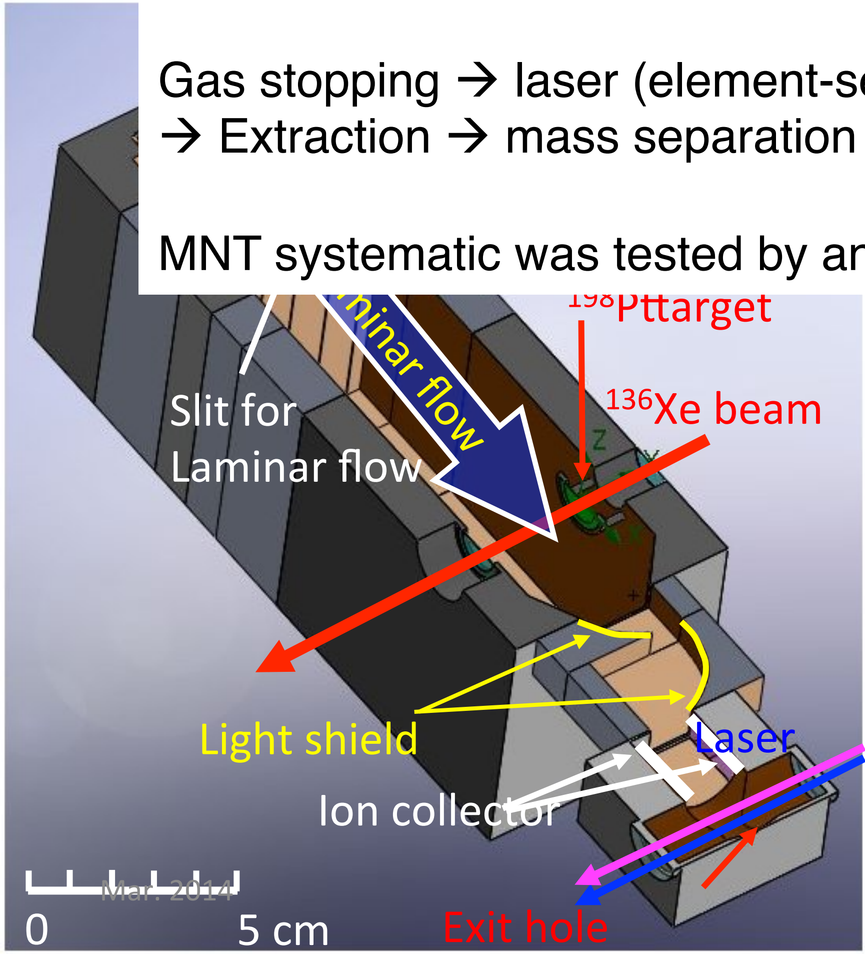
KISS
KEK Isotope Separation System



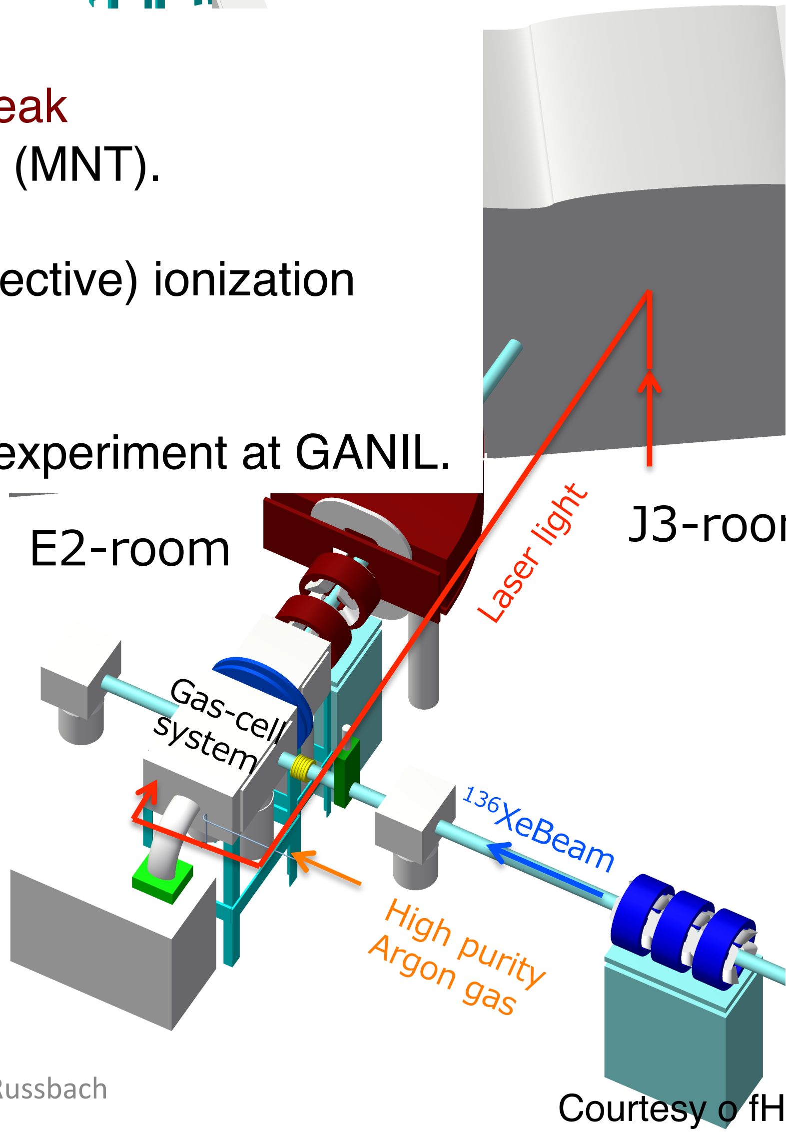
Study of neutron-rich nuclei
in the vicinity of the r-process 3rd peak
produced by multi-nucleon transfer (MNT).

Gas stopping → laser (element-selective) ionization
→ Extraction → mass separation

MNT systematic was tested by an experiment at GANIL.

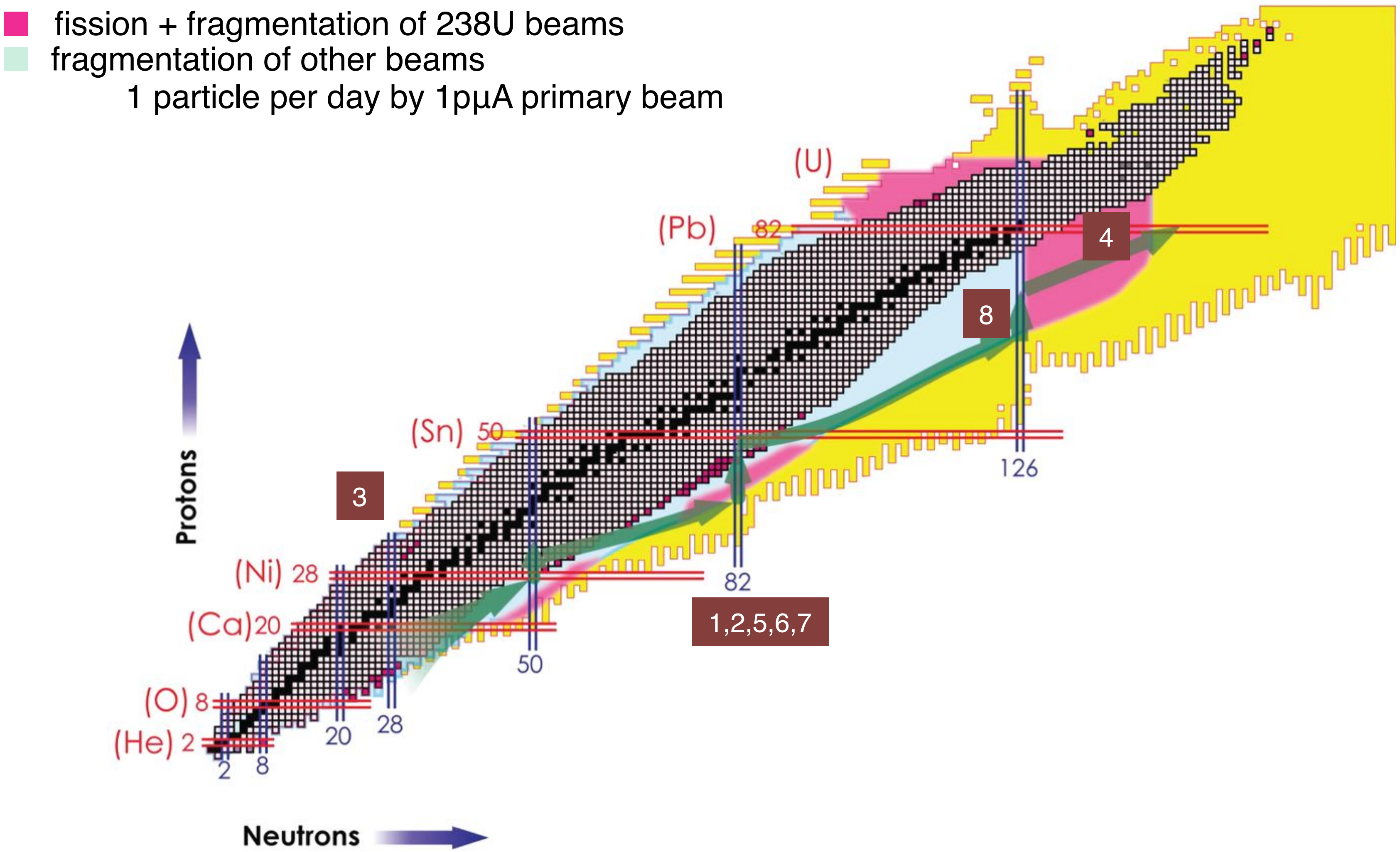


Russbach



Courtesy o fH. Miyatake

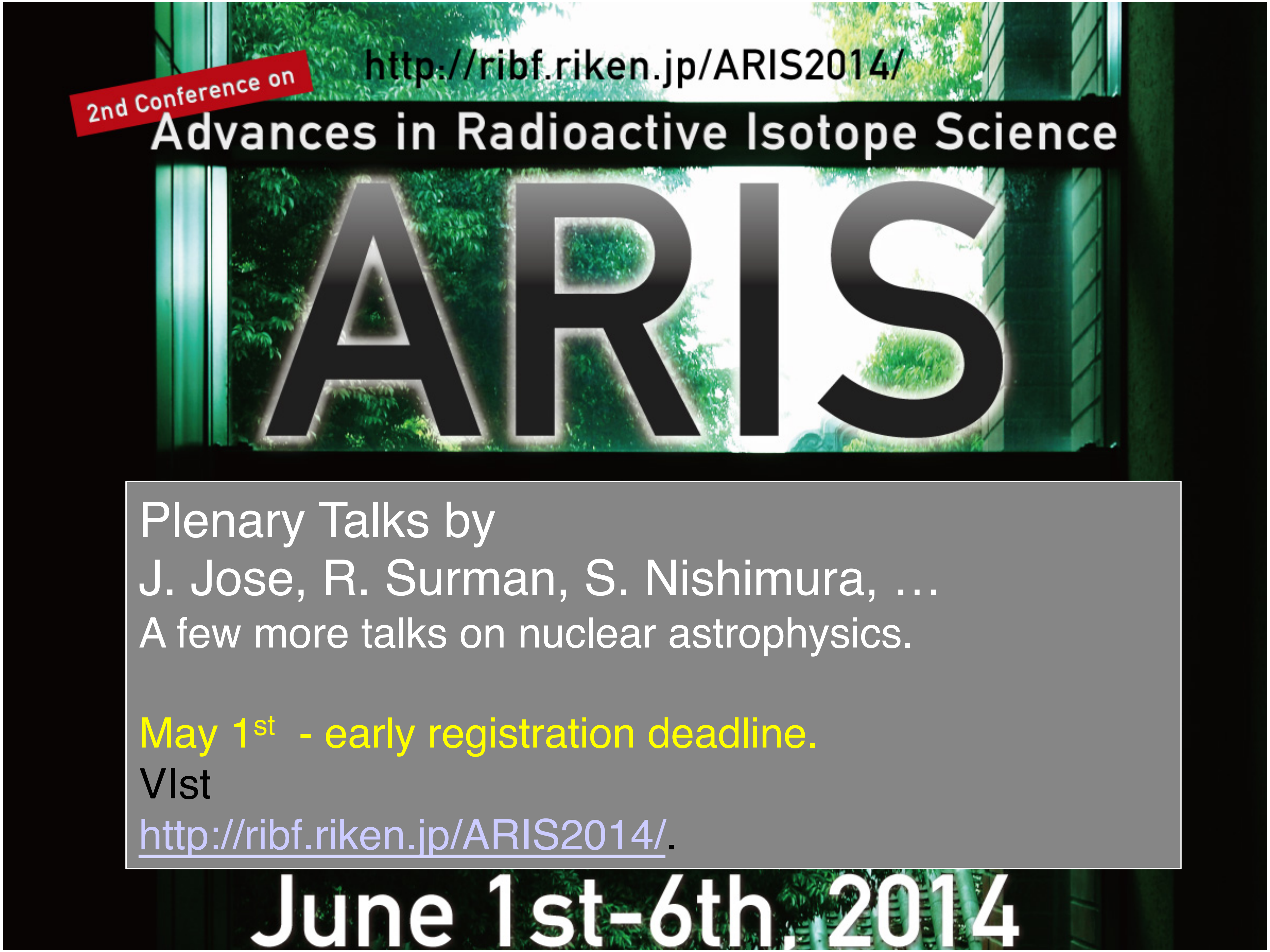
Nuclear chart potentially covered by RIBF



Motobayashi T , and Sakurai H Prog. Theor. Exp. Phys. 2012;2012:03C001

PTEP
Progress of Theoretical and Experimental Physics


http://ribf.riken.jp/ARIS2014/
2nd Conference on
Advances in Radioactive Isotope Science
ARIS
2014
IN TOKYO, JAPAN
June 1st-6th, 2014



Plenary Talks by
J. Jose, R. Surman, S. Nishimura, …
A few more talks on nuclear astrophysics.

May 1st - early registration deadline.
VIst
http://ribf.riken.jp/ARIS2014/.

Challenges at RIBF for nuclear astrophysics

1. β decay half lives of r-process nuclei -- Nishimura

2. spectroscopy of neutron-rich nuclei → shell quenching (around N=50, 82,..)
   -- Nishimura (decay)

3. Coulomb dissociation at SAMURAI → rp (r) process, s-process

4. fission of n-rich nuclei at SAMURAI → fission barrier height

5. weak processes by charge-exchange reactions in inverse kinematics

6. "Rare RI Ring": being constructed → masses of r-process nuclei w. Tsukuba

7. "SLOWRI": financed → *e.g.* precision mass measurements by MRTOF
   → r, rp process

8. Kiss project for spectroscopy in the "blank spot" - r process 3rd peak

9. CRIB (CNS) → low-energy studies → OEDO project (slowdown RI-beams)