r過程原子核の実験的研究に向けて

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Limited to: RIBF
r-process nucleosynthesis

cf. low-energy RI beams
neutron rich matter
explosion related inputs
e.g. GT strength around 56Ni
hydrogen (charged particle) burning

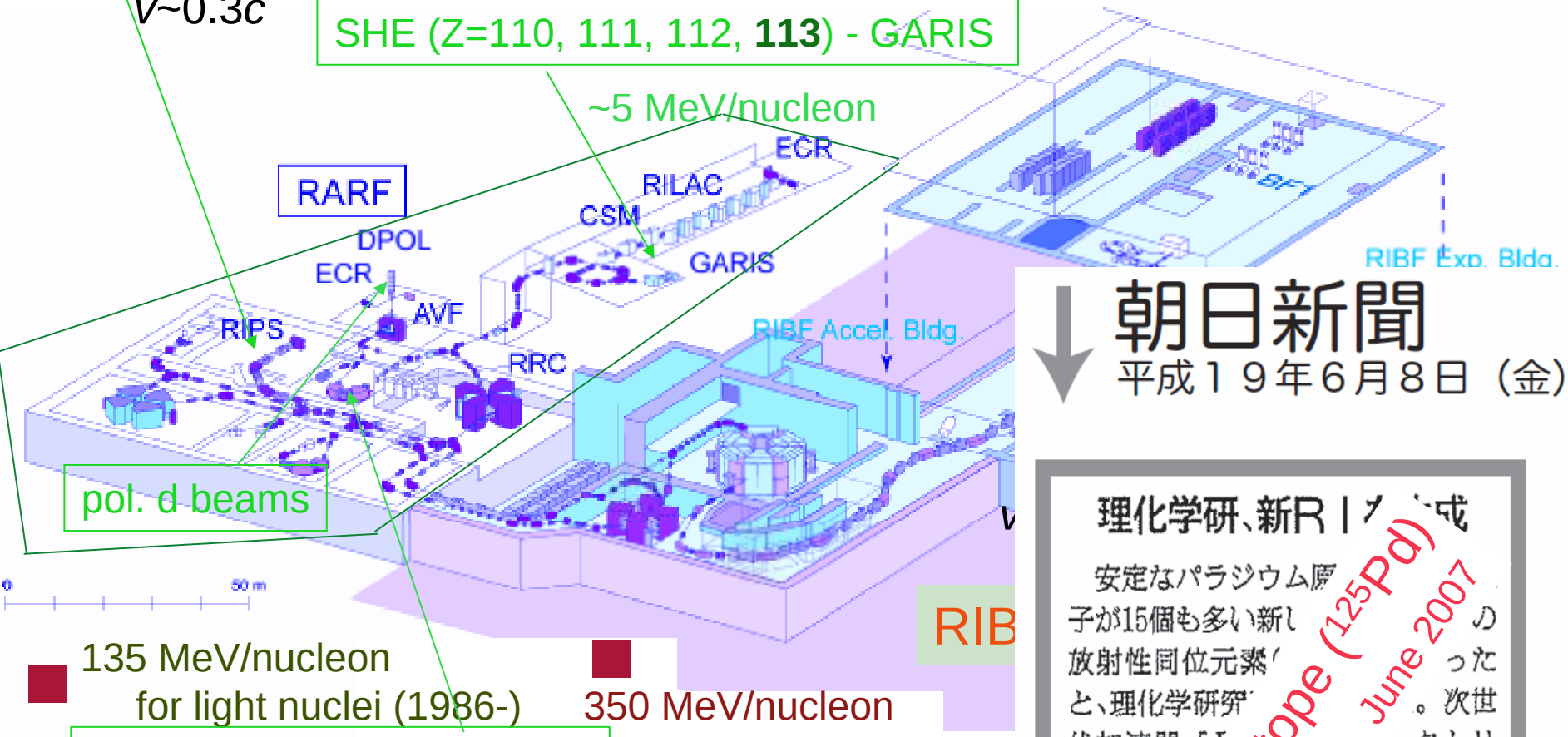
RIBF: Accelerator Complex in RIKEN Nishina Center

Fast RI beams - RIPS

v~0.3*c*

SHE (Z=110, 111, 112, **113**) - GARIS

~5 MeV/nucleon



pol. d beams

135 MeV/nucleon
for light nuclei (1986-)

RI beams (<5 AMeV) - CRIB

350 MeV/nucleon
up to U

CNS

v~0.1*c*

1st beam in Dec. 200
U beam in Mar. 2007
RI beams with U-fiss

朝日新聞
平成１９年６月８日（金）

理化学研、新R｜ｱ ｰ成

安定なパラジウム原
子が15個も多い新し の
放射性同位元素 った
と、理化学研究 。次世
代加速器「 ァクトリ
ー」の初期 成果。光速
の70%ま ランのイオン
ビー の標的に衝突さ
せたと ンが壊れてほぼ狙
い通りのR 生まれたという。

new isotope (125Pd) June 2007

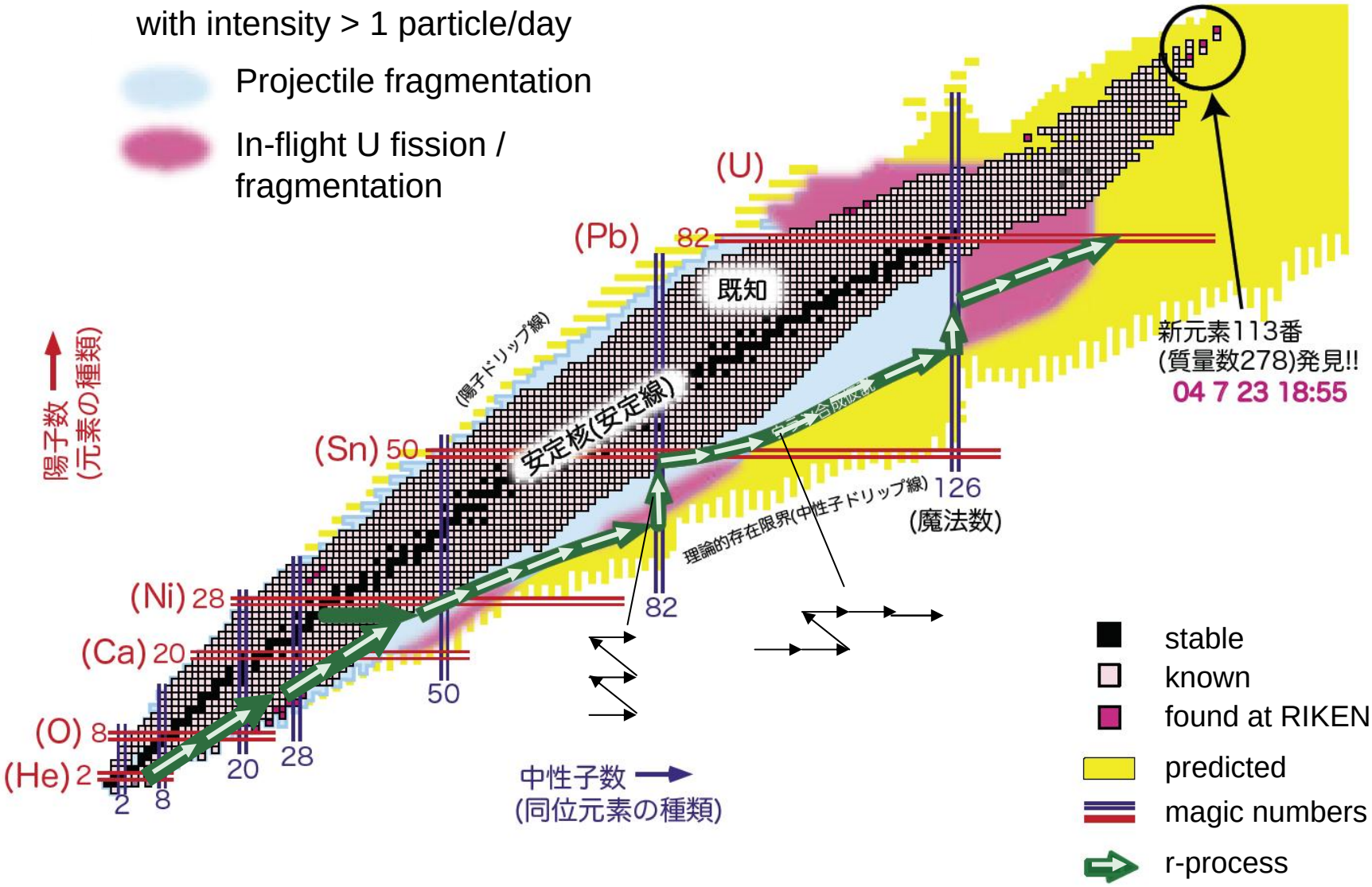
Sep08

RIBF can go further (furthest) from the stability valley.

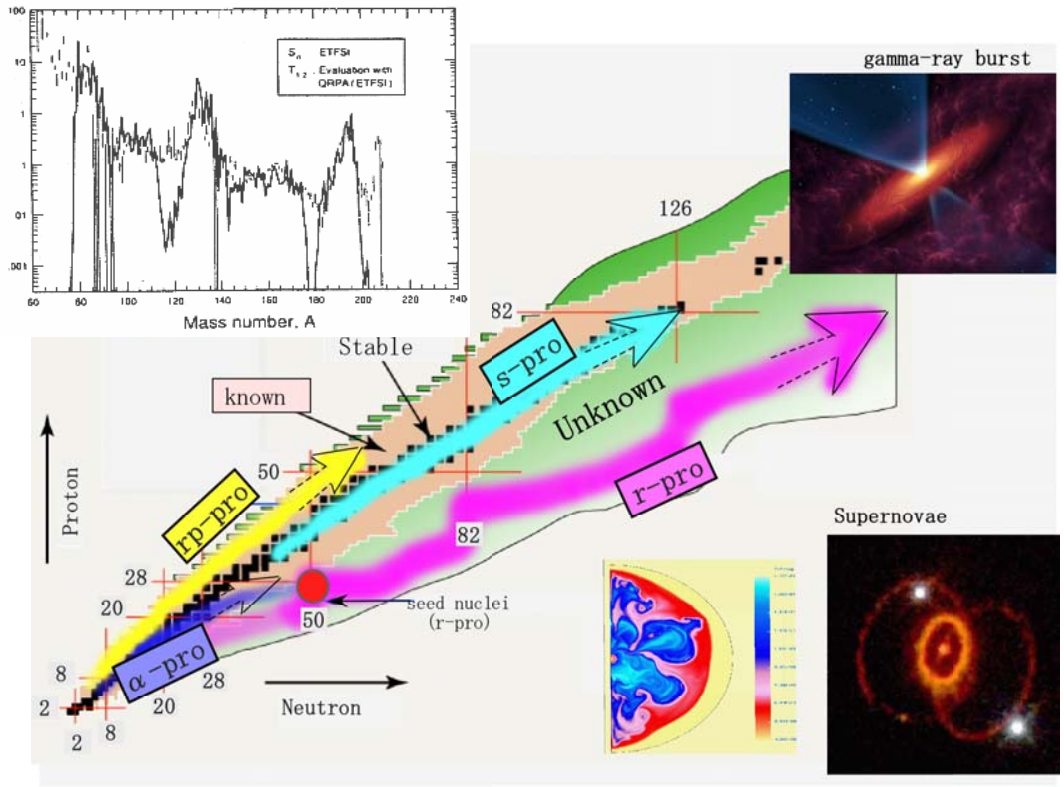
Produced at RIBF
with intensity > 1 particle/day

Projectile fragmentation

In-flight U fission / fragmentation



Basic parameters for r-process



☆ **Half-lives** ($T_{1/2}$)
→ abundance
→ process speed

☆ **Cross sections**
→ location of the path
Masses (A, Q_β)
Resonances
Continuum

☆ **β-delayed neutron** (P_n)
→ final abundances

Theory

Thousands of nuclei
along r-process

Sep08

Very low
production yield

data

High precision
measurements

Nisimura, RIKEN (modified)

Experimental information

- Half lives $T_{1/2}$
- Level : *e.g.* $E(2^+)$
- n emission prob. (P_n)
- Mass <= direct, Q_β ⇕
- Cross sections
- GT strength

Systematic Study

Nuclear structure

Shell quenching ?
Deformation ?
Fate of magic numbers
– Appearance / Disappearance

Feedback to Nuclear Theory

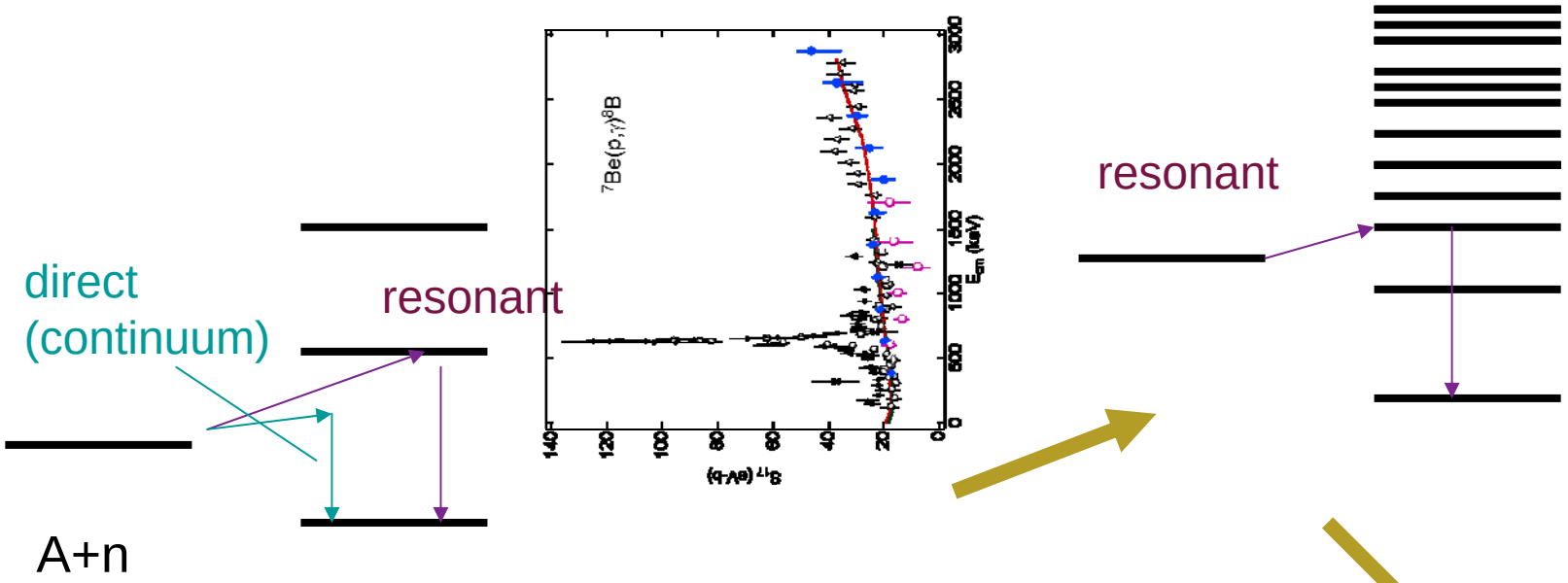
Inputs

Supernova simulation

r-Process network calculation

Nisimura, RIKEN (modified)

(n,γ) (or (p,γ)) of astrophysical interest



level density: low

light nuclei

closed shell

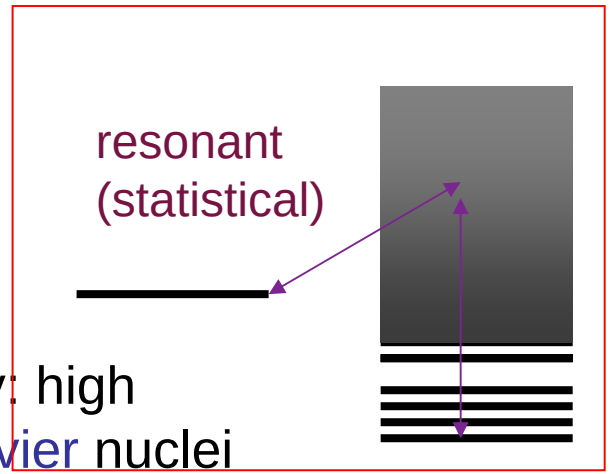
near the drip line

Direct measurement of σ

Indirect methods

Coulomb dissociation, ANC,….

mass

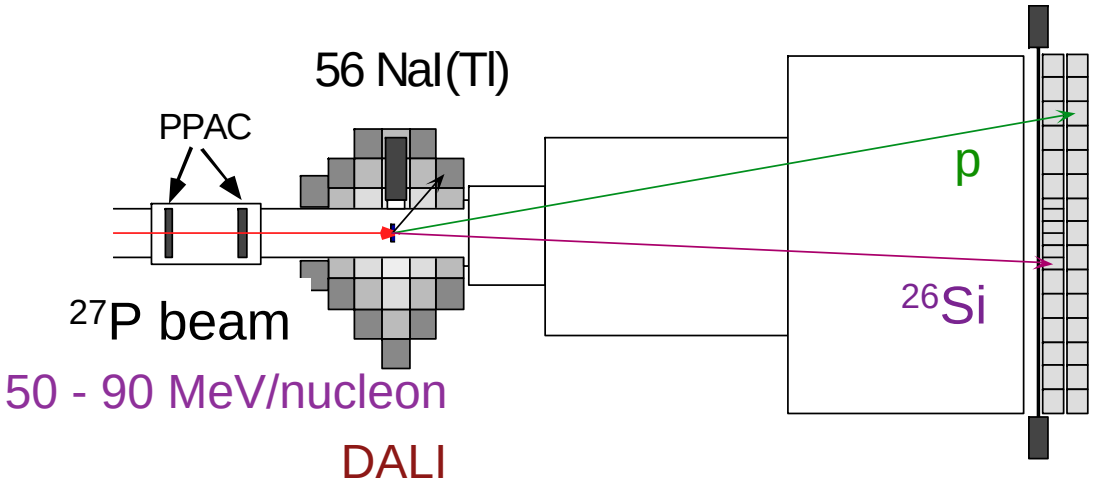


level density: high

heavier nuclei

Invariant mass measurement

- Coulomb dissociation for astrophysical (p,γ) reactions applicablet to (n,γ)

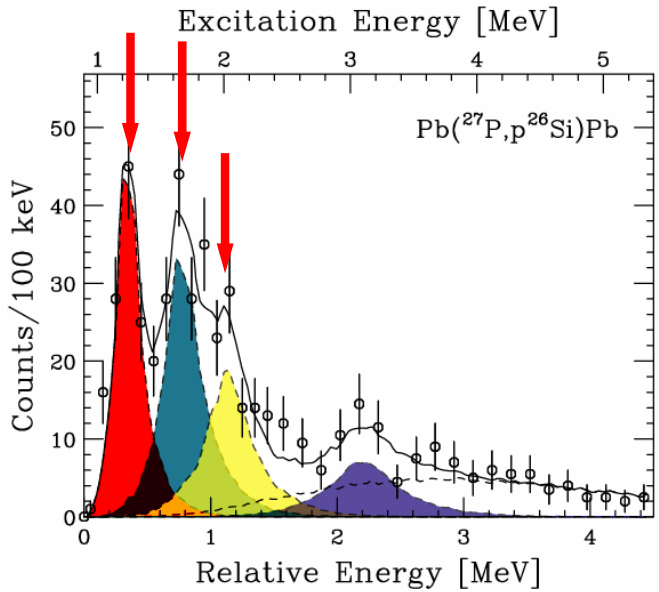


50 - 90 MeV/nucleon

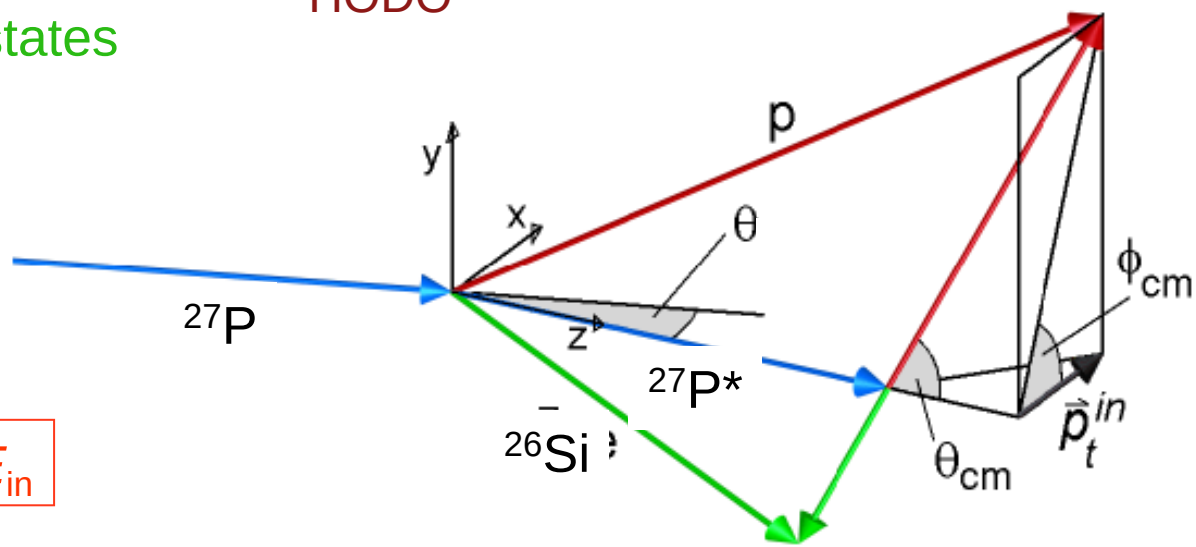
DALI

γ ray

- bound states



HODO



ΔE_{rel} : Independent of ΔE_{in}

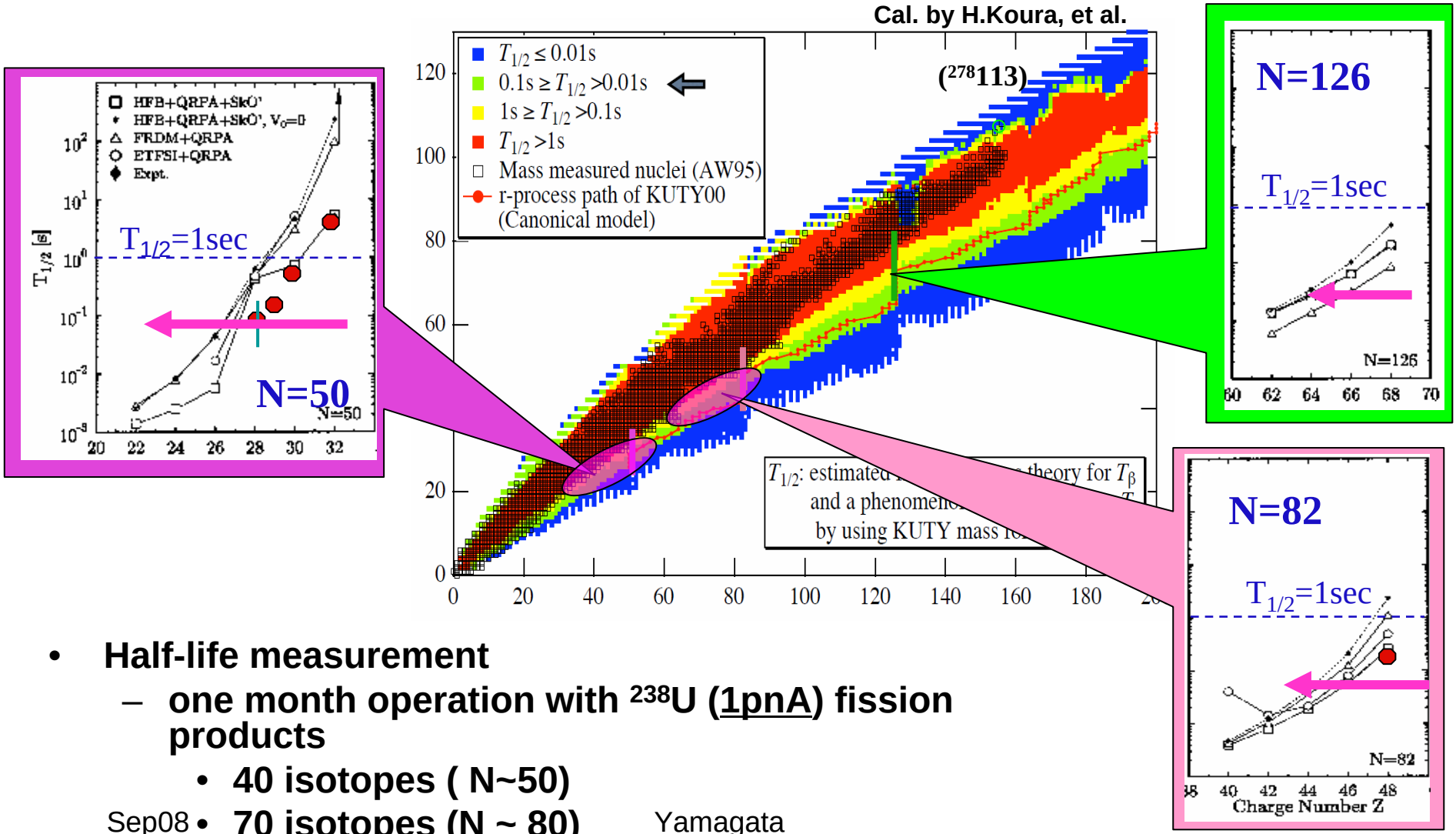
@RIBF

first series of experiments

beam developments

new equipment

Half-life ($T_{1/2}$) measurements



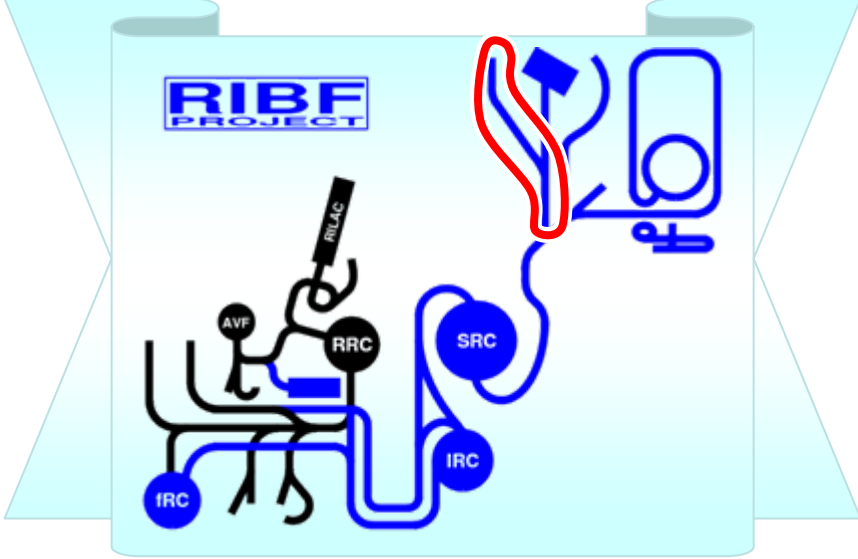
- **Half-life measurement**
  - **one month operation with ^{238}U (1pnA) fission products**
    - **40 isotopes (N~50)**

Sep08 • **70 isotopes (N ~ 80)** Yamagata

Nisimura, RIKEN (modified)

Zero-degree spectrometer

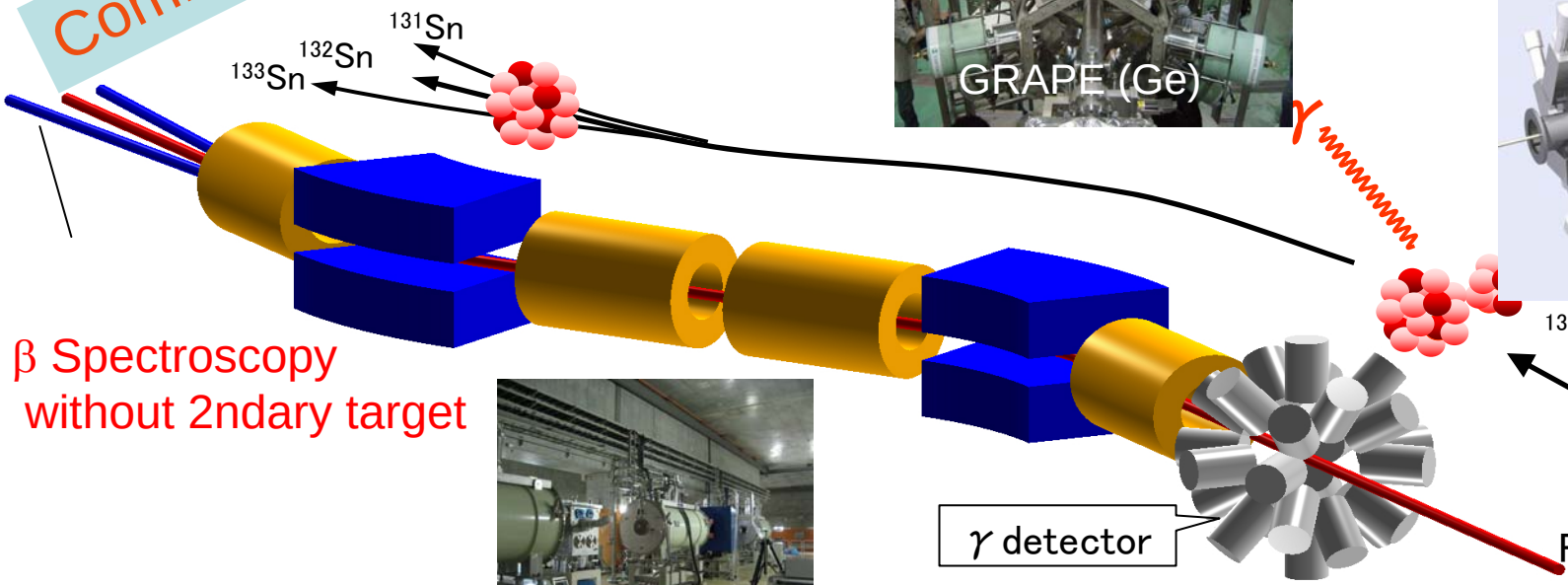
particle ID / momentum analysis



e.g. Doppler shifted γ-ray measurements
with identification of products
(angle-integrated cross section)

Multi-functio
Mediu ion
Δp ~2000 - 4000
~3%

Commissioning in 2008

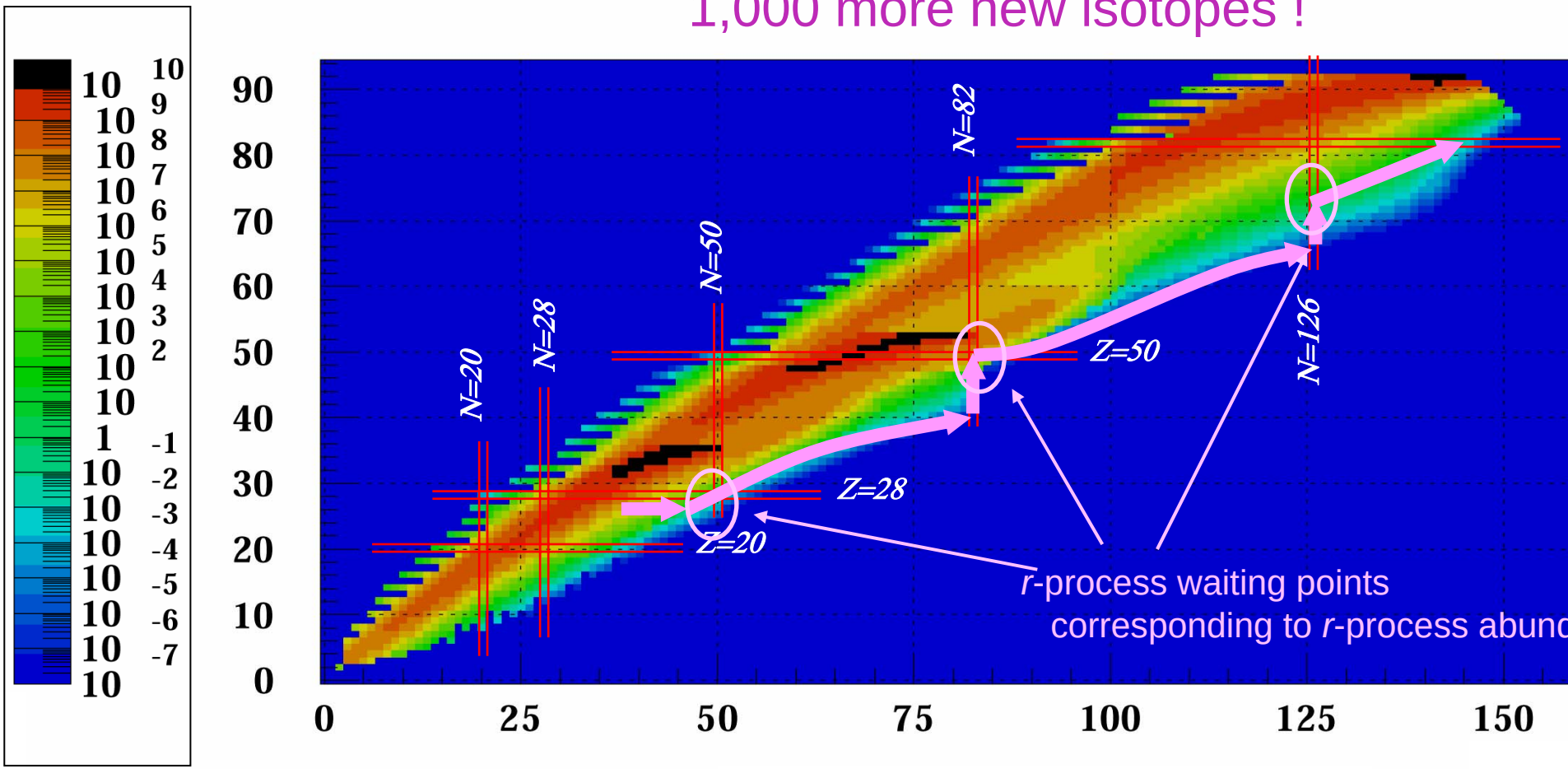


β Spectroscopy
without 2ndary target

Estimated beam intensity at BigRIPS

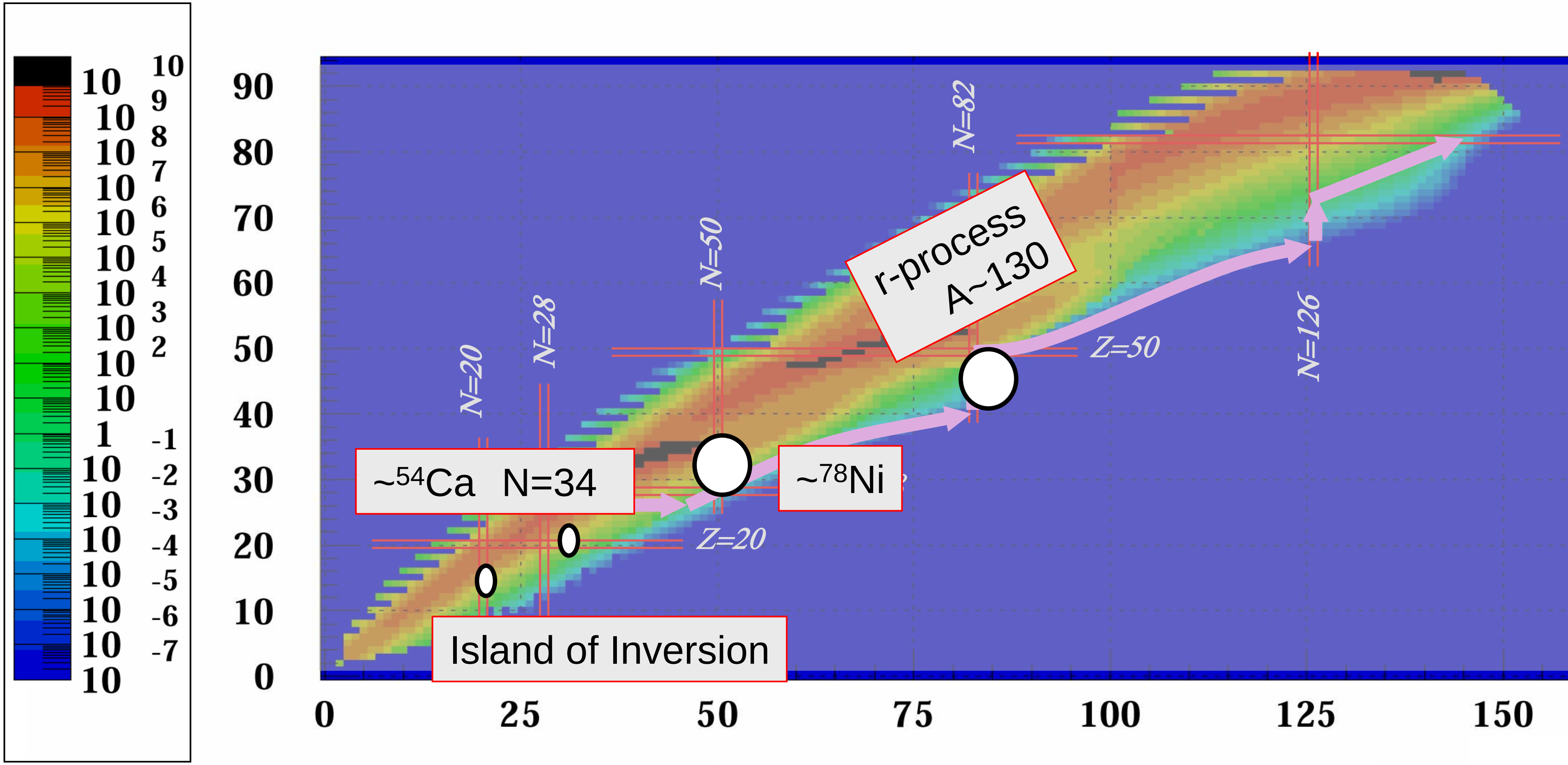
$^{86}Kr/^{136}Xe/^{238}U$ 1pμA

1,000 more new isotopes !



Estimated beam intensity at BigRIPS

$^{86}Kr/^{136}Xe/^{238}U$ 1pμA



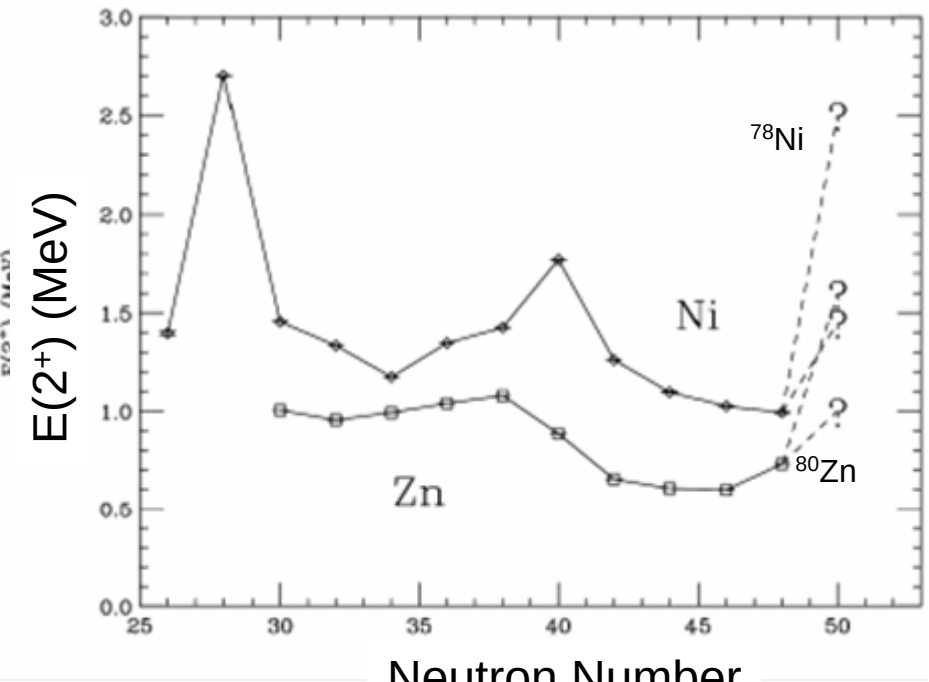
PAC-approved studies

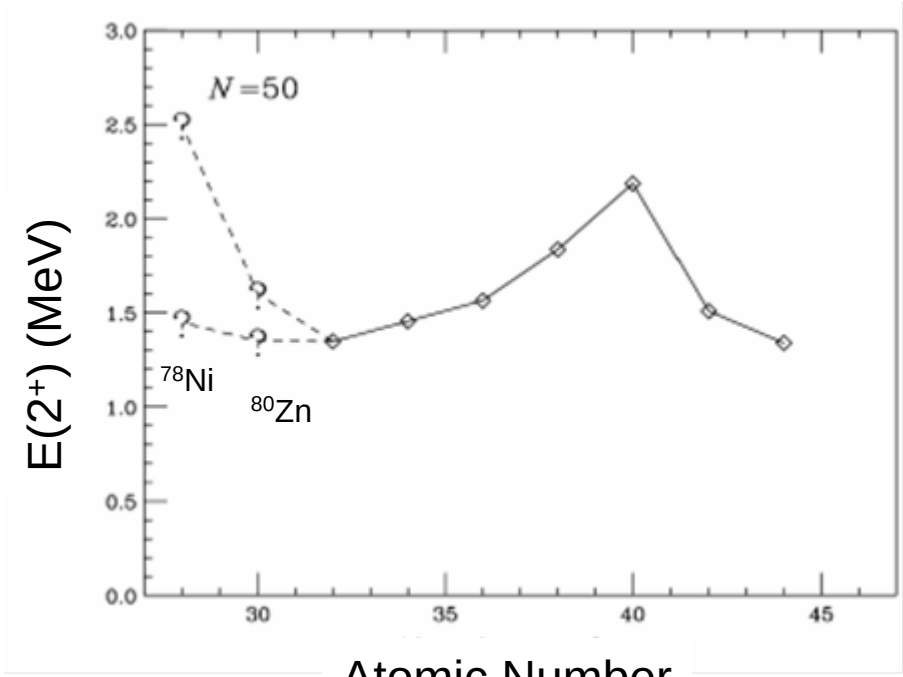
Energy of the first excited 2^+ state

1^{st} 2^+ state energy of even-even nuclei

… first spectroscopic information to be measured

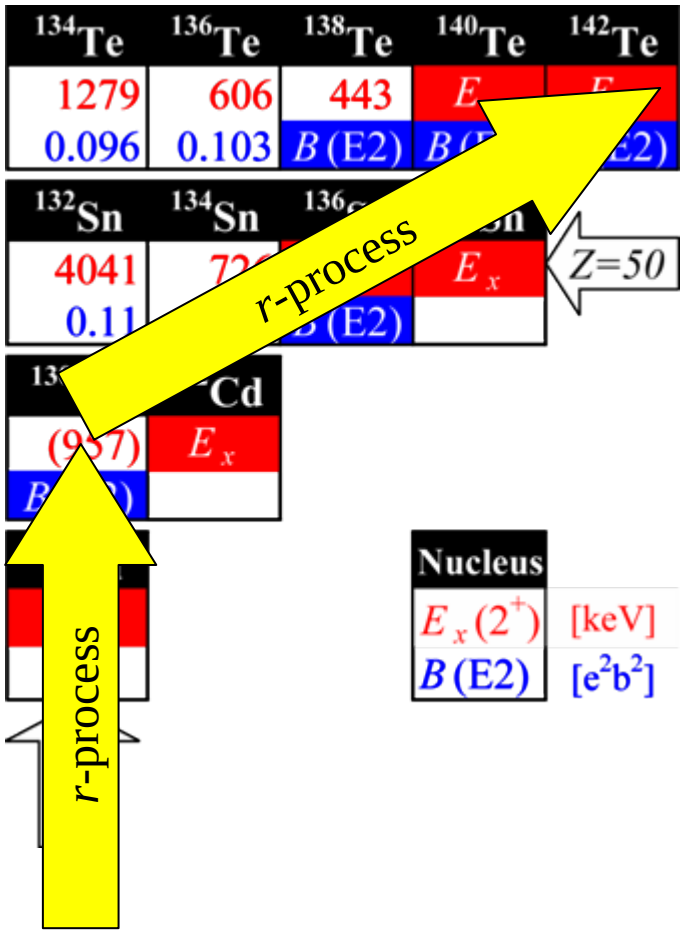
→ primary systematic trend of shell closure/melting





Determine 2^+ state energies of ^{80}Zn and ^{78}Ni

Structure study of neutron-rich nuclei beyond ^{132}Sn



Physics Motivation

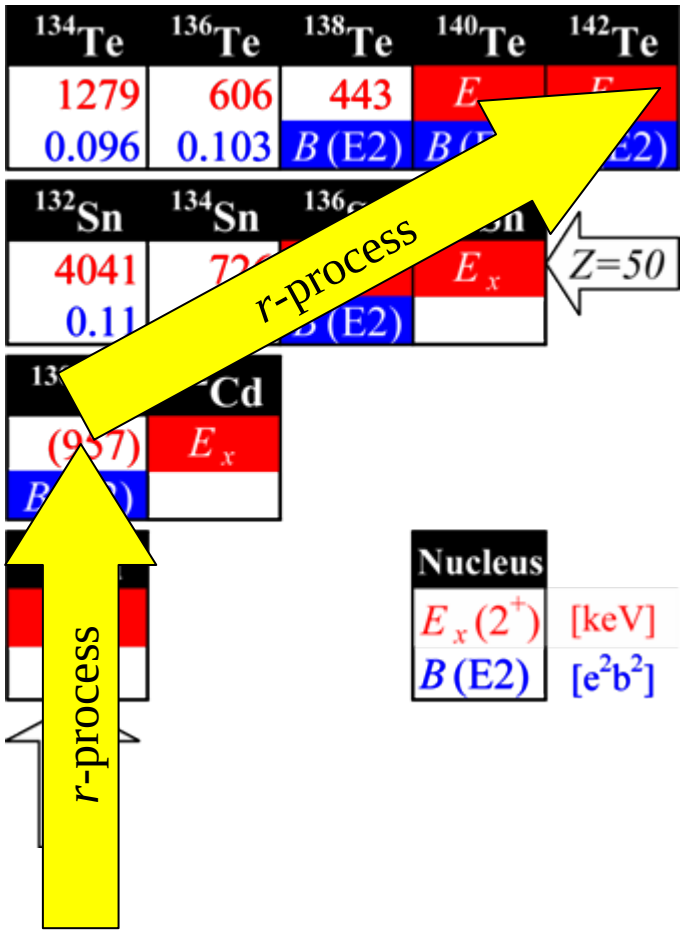
1. Comprehensive understanding of known exotic structure
   --- Breaking of Grodzins' rule
   More neutron rich nucei?

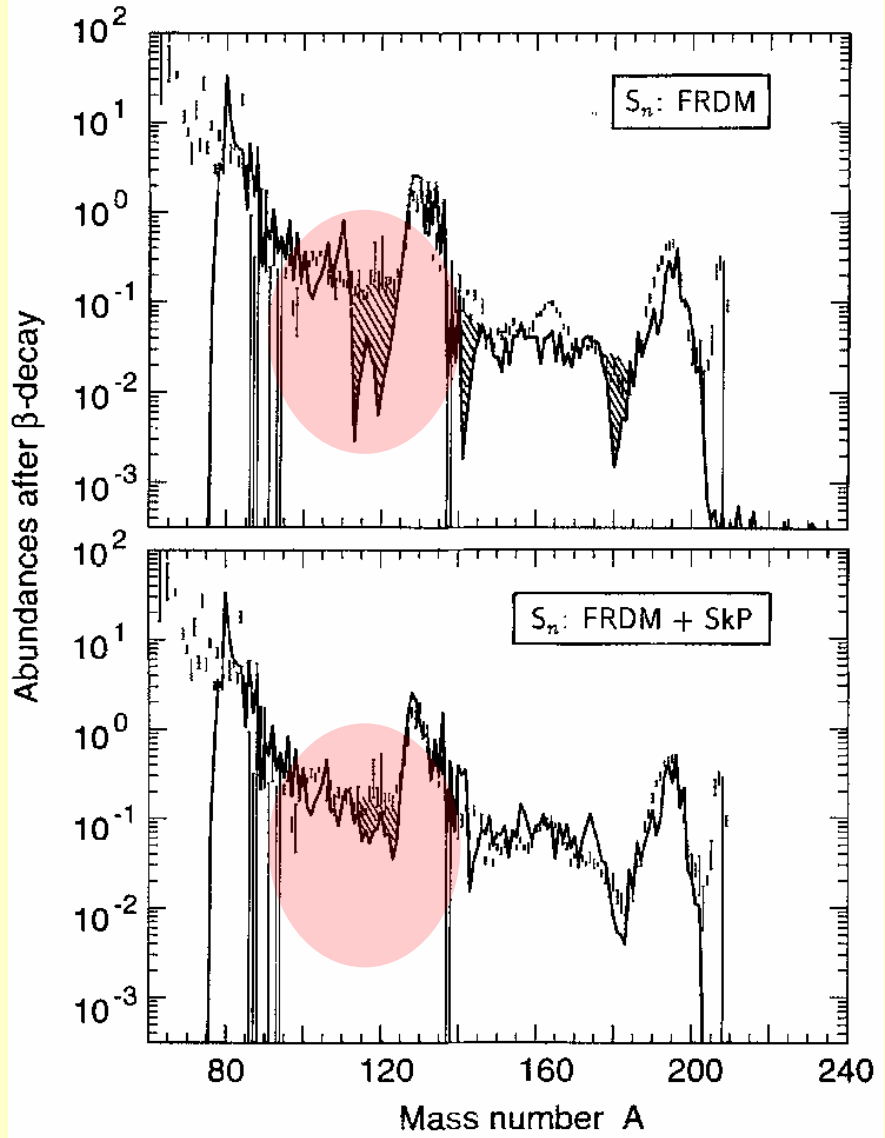
2. Explore unknown exotic structure
   --- Breaking of N=82 or Z=50 magicity?
   * Strong Isospin dependent interaction?
     T.Otsuka et al., PRL97(06)162501.
   * Weak binding
     J. Dobaczewski et al., PRC53(96)2809.
   * ls-force, Neutron Skin ….

3. r-process

Waiting point approximation . Using KUTY
Private comm. with Dr. Y. Mochizuki.

Structure stud… of neutron-rich nuclei be…





B.Chen et al., PLB355(95)37.

on?

9.

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Waiting point approximation . Using KUTY

Private comm. with Dr. Y. Mochizuki.

@RIBF

first series of experiments

beam developments

new equipment

Summary of the present accelerator performance

$^{86}Kr^{34+}$ 1.1 eμA (30 pnA) 345 MeV/u
Nov. 10th, 2007

$^{238}U^{86+}$ ~5 enA (0.04 pnA) 345 MeV/u
Jun. 29th, 2007

ε_{trans} <3% (~50% ^ 5 accelerators)

$\varepsilon_{stripper\ (RRC-SRC)}$ <5% (15% * 30%)

I_{RRC} ~15 pnA

Tuning of Accelerators, BT
Flat-Top operation (phase acceptance)
Stripper,
New Injector, New IS *x100*

10 pnA U
feasible in 2008

1 pμA U
need more investigation, investment

@RIBF

first series of experiments

beam developments

new equipment

RIBF current and future plans

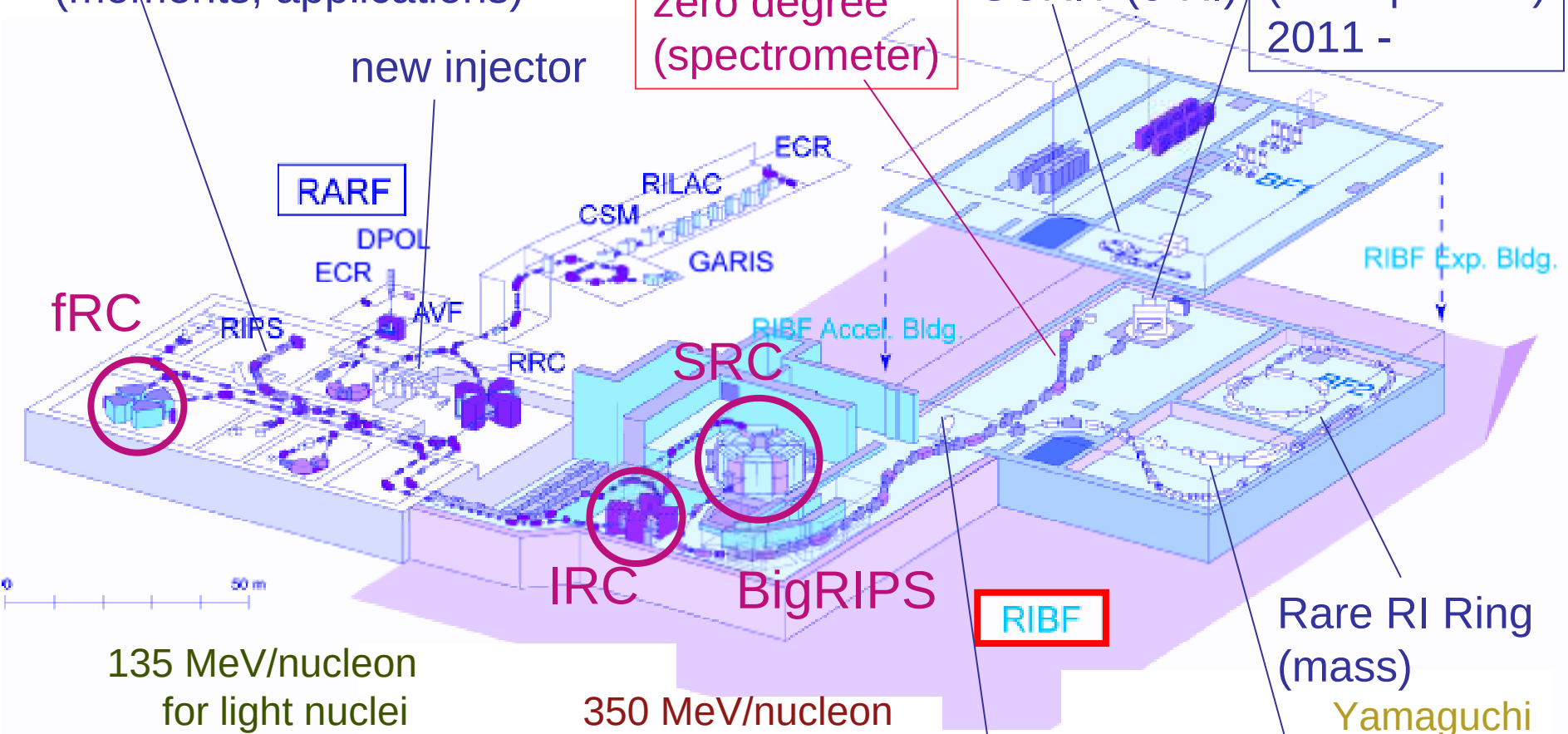
use of IRC beams
(moments, applications)

new injector

zero degree
(spectrometer)

SCRIT (e-RI)

SAMURAI
(multi-particle)
2011 -



135 MeV/nucleon
for light nuclei

350 MeV/nucleon
up to U

Slow RI
(gas stopper)

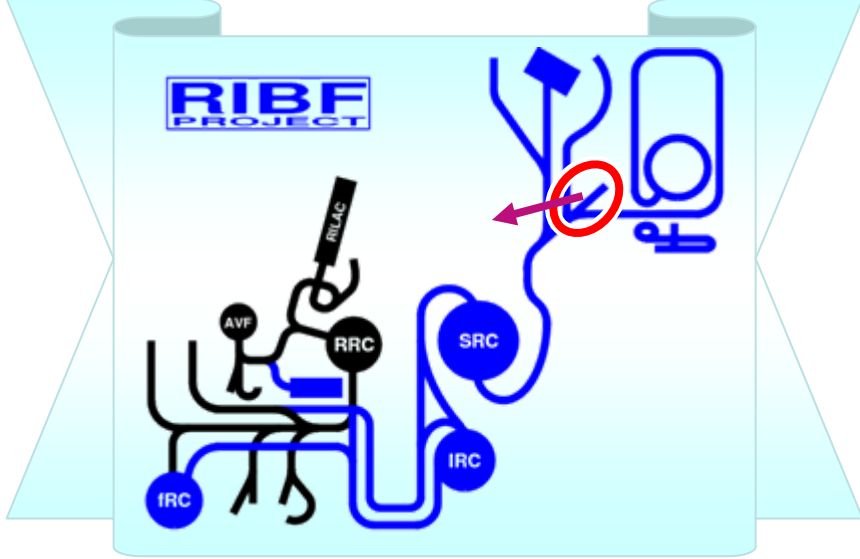
Rare RI Ring
(mass)

Yamaguchi

SHARAQ (UT)
(high-resolution
Missing mass)
2008 (end) -

SLOWRI

RIKEN (M. Wada)

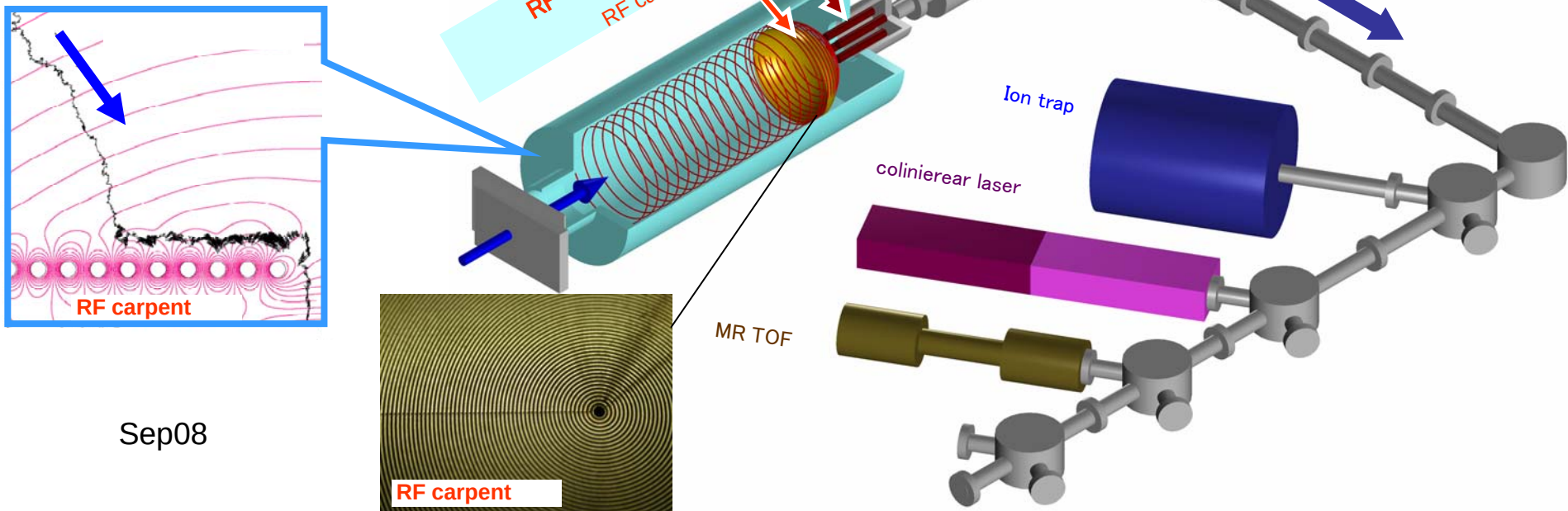


Universal slow RI beam production based on the rf ion guide method

- No Chemical Processes in Production & Separation
- No Isobar No Isotone Contamination

<=> ISOL

- trap
- laser
- MRTOF mass



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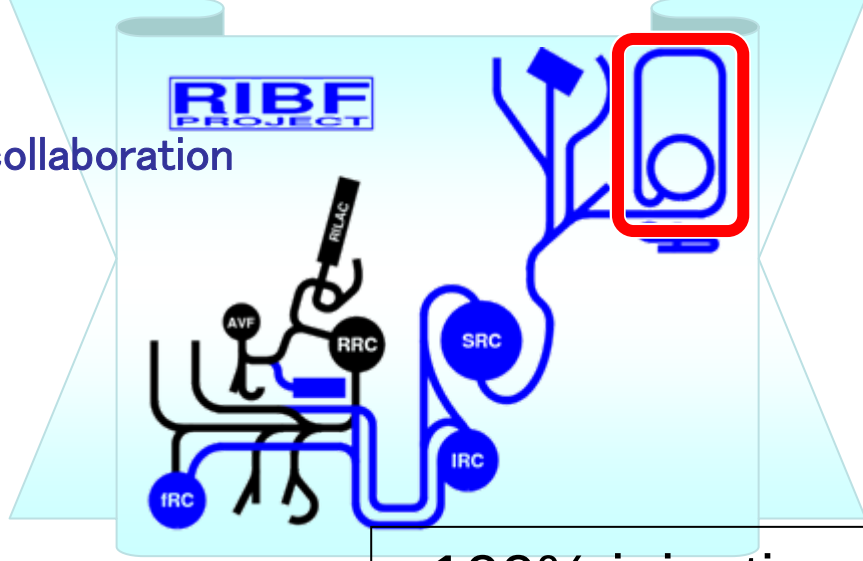
Rare RI ring

Tsukuba (Ozawa), … – RIKEN collaboration

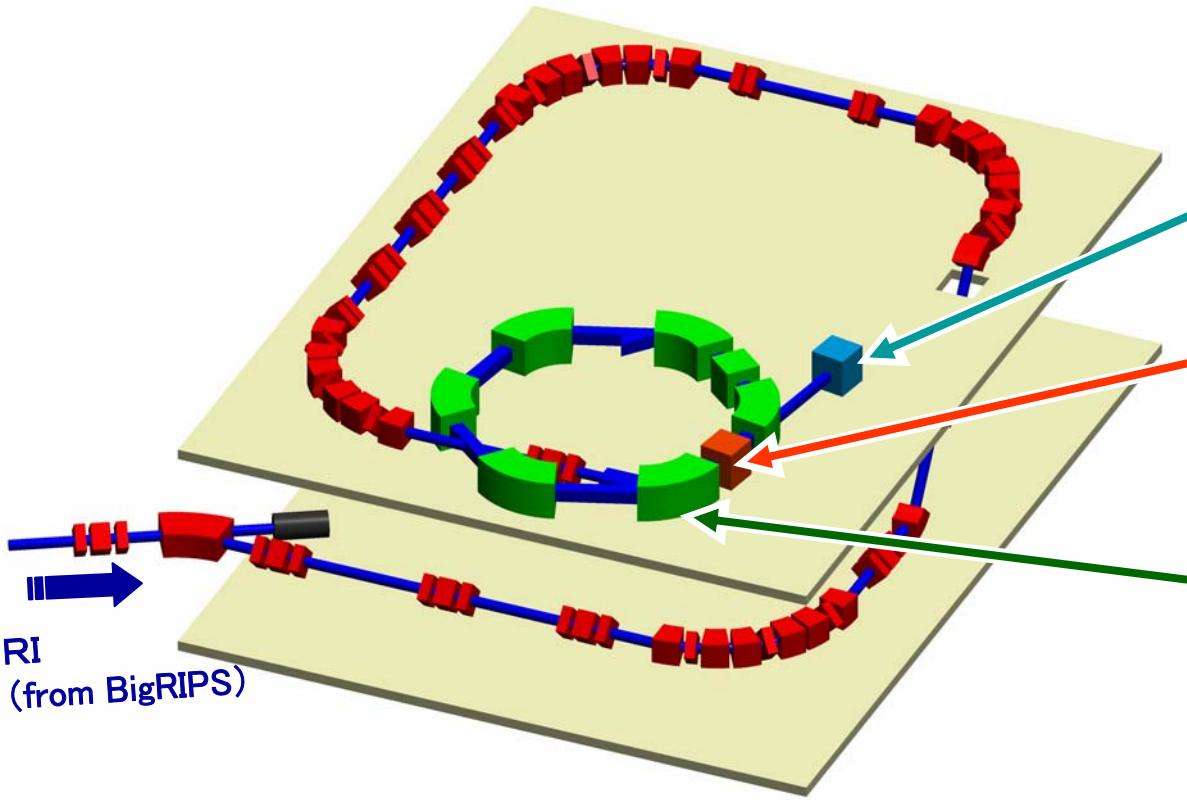
Isochronous ring
with individual injection

Yamaguchi



~100% injection
< 100 s^{-1}

mass measurement for
short-lived rarely-produced
nuclei



particle ID

kicker magnet

Mass $\Delta m/m$~10^{-6}*
Beta decay, …

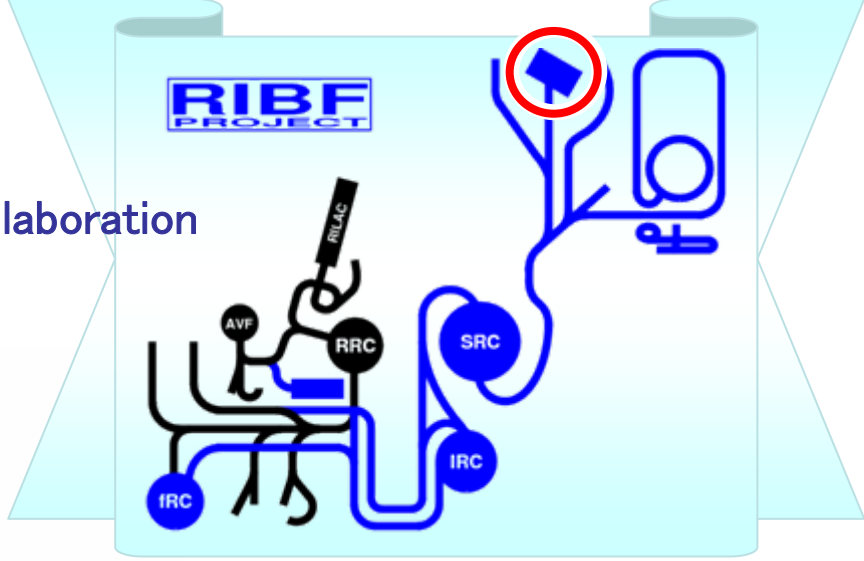
Isochronous ring

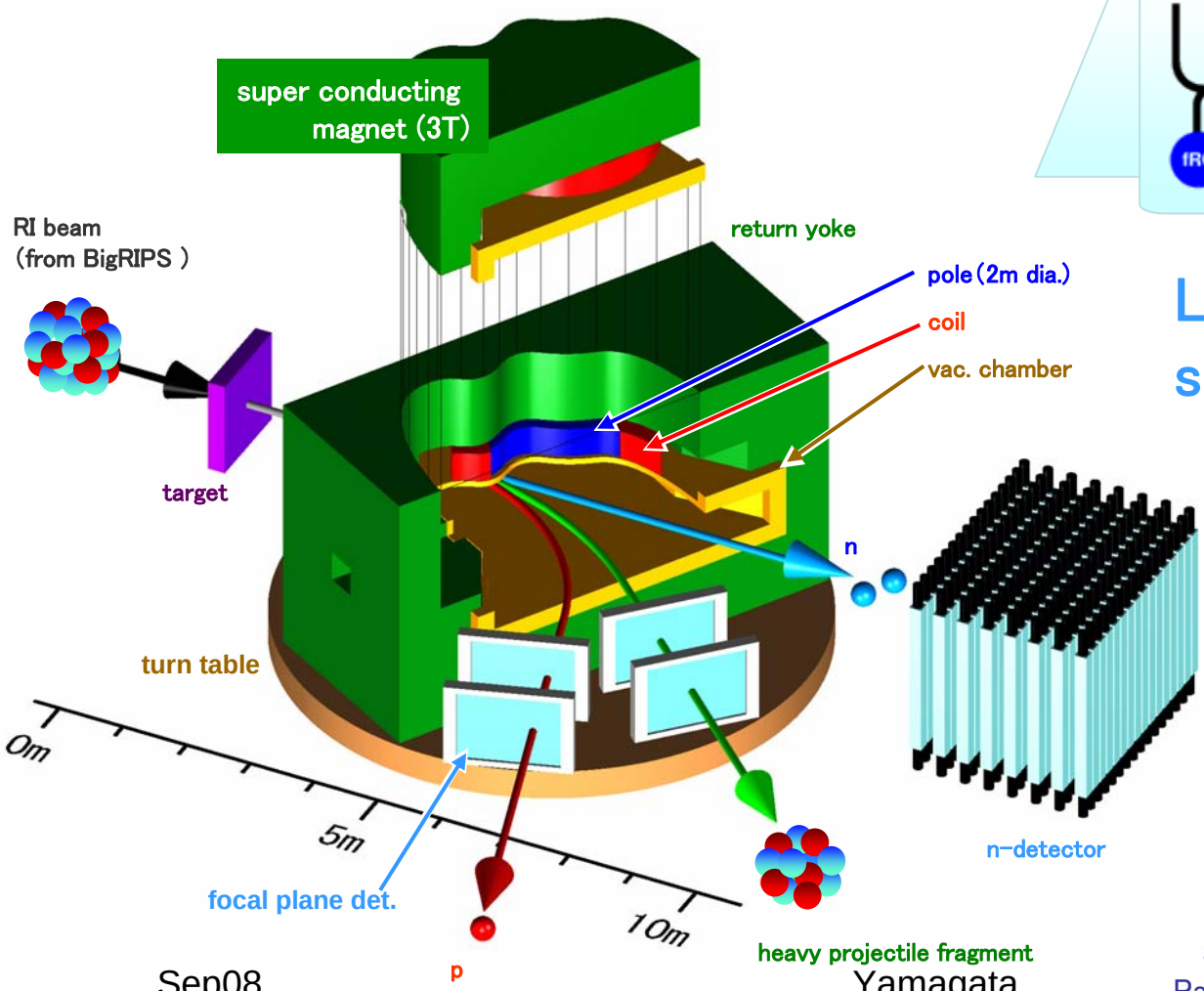
* 200 keV for A=200

SAMURAI7

Tohoku (Kobayashi), TiTech, Kyoto, ··· RIKEN collaboration

constructed in 2008-2011





Large solid-angle spectrometer

particle correlation

unbound sates

(p,2p)

astrophy. (p,γ), (n,γ)

nucl. matter

SAMURAI7 (Superconducting Analyzer for MUlti Particles from RAdioIsotope Beams with 7 Tm)

☆ **Cross sections**
→ **location of the path**
Masses (A, Q_β)

しかし…..

Hauser Feshbach formula

a + A → C → b + B (C: compound nucleus)

α β

$$\sigma^c(\alpha \to \beta) = \frac{(-1)^{I_A - s_\alpha - I_B + s_B}}{4(2s_a+1)(2I_A+1)k_a^2} \sum_{J,\Pi_j,L} \tau(\alpha)\frac{\tau(\beta)}{\sum_\gamma \tau(\gamma)} P_L(\cos\theta_b)$$

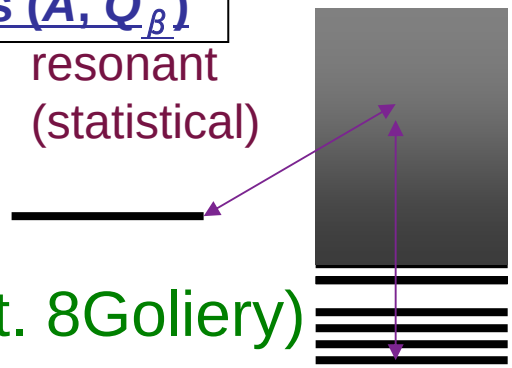
$$\tau(x) = \sum_{l,j} \Delta(l,x,\Pi_{J)(}(2J+1)Z(l,j,o,j;s,L)W(j,J,j,J;I.L)T_{l,j}$$

$$T_{l,j} = 1 - \left|S_{l,j}\right|^2$$

C formation

☆ **Cross sections**
→ **location of the path**
Masses (*A*, Q_β)

resonant
(statistical)



T ← optical pot. / fusion (partial) σ
experimental challenge !?

c.f. isospin dependence in opt. pot. 8Goliery)

RIBF (new facility)

high-intensity (80 kW max.) fast H.I. beams (up to U)
wide range of RI beam production

first beam: Dec. 28, 2006, ^{27}Al, 345 MeV/nucleon
first result: ^{125}Pd , end of May 2007 w. 1/100,000 U-intensity
2008 beam development (intensity, specy, ..)
several PAC-approved experiments (^{48}Ca campaign)
ZeroDegree (with BigRIPS) in operation
SHARAQ (high resolution) comissioning
SAMURAI (large acceptance) construction (- 2011)
various experimental equipments are planned

Current intensity ➔ extension of "standard" study
Experimental examination of nucl. phys. inputs to ..

PAC

NP-PAC (Nucl. Phys., with CNS): twice a year
4th: 20-21 Nov. 2008
internatinal users meeting: 22 Nov. 2008
Visit http://www.nishina.riken.jp/UsersGuide/Nuc

budget (5 months operation in FY 2008)

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