Direct Reaction Studies at RIKEN RI* Beam Factory

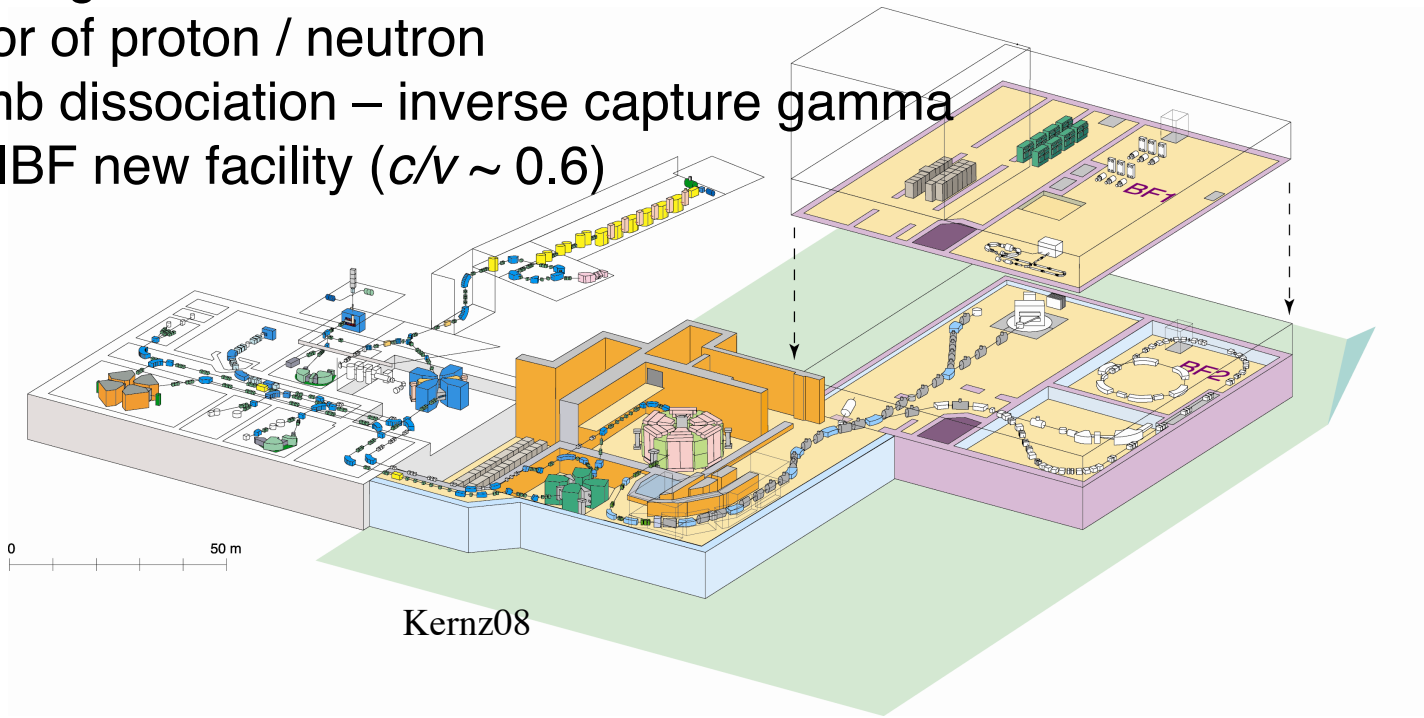
* radioactive isotope

Tohru Motobayashi
(RIKEN Nishina Center for Accelerator-Based Science)

RI beam by fragmentation (+ fission)

fast RI beams ($c/v \sim 0.3$)
direct reaction studies
- fate of magic number
- behavior of proton / neutron
- Coulomb dissociation – inverse capture gamma

RI beams at RIBF new facility ($c/v \sim 0.6$)



RIBF: Accelerator Complex in RIKEN Nishina Center

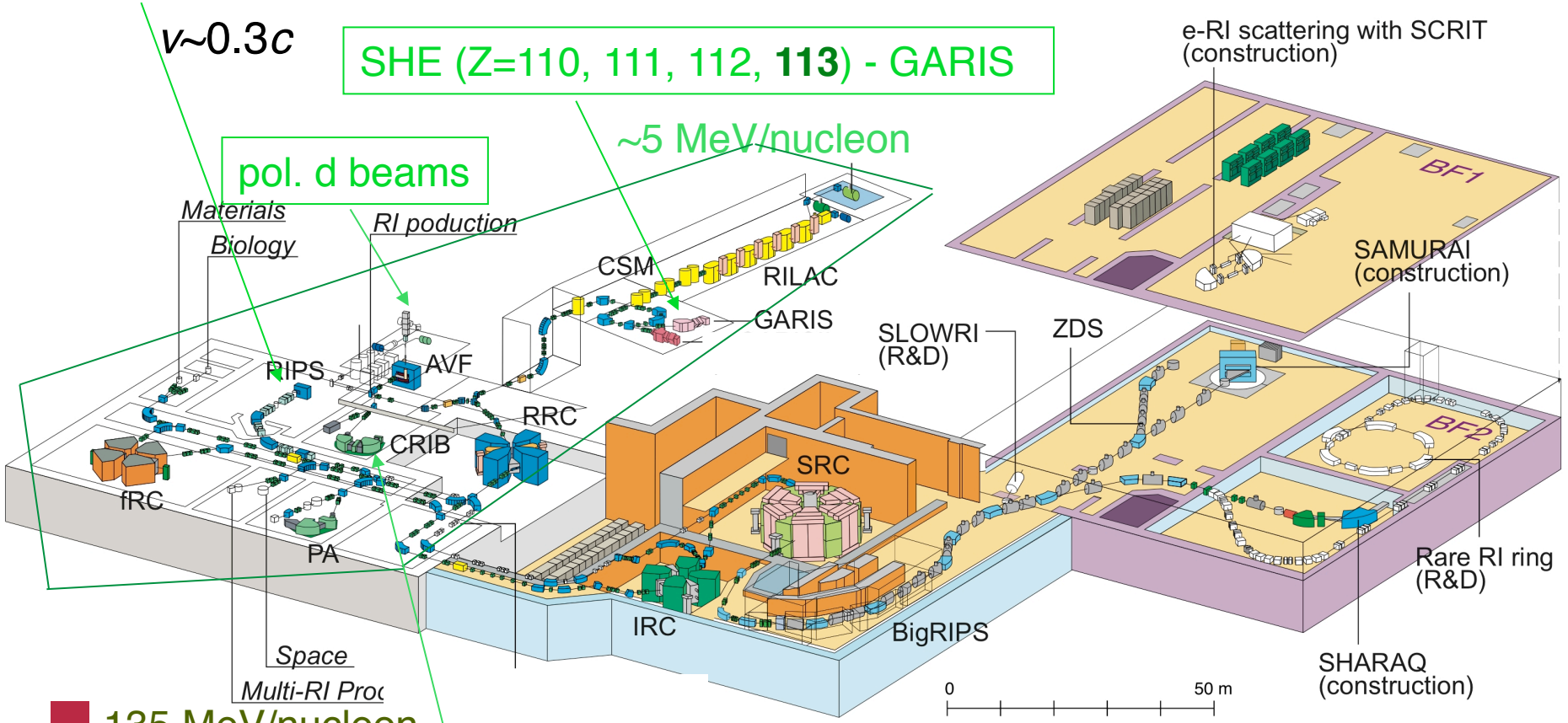
Fast RI beams
- RIPS (1990-)

v~0.3*c*

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

~5 MeV/nucleon

pol. d beams



135 MeV/nucleon
for light nuclei (1986-)

new facility fast RI beams with *v*~0.6*c*

RI beams (<5 AMeV) - CRIB
CNS *v*~0.1*c*

350 MeV/nucleon
up to U

Being constructed
or planned

fast RI beams ⟵ straight forward production by fragmentation

relatively easy to go very far from stability

direct reaction ⟵ Nuclear structure (level, J^{π}, **amplitudes** …)
⟵ understanding of reaction mechanism

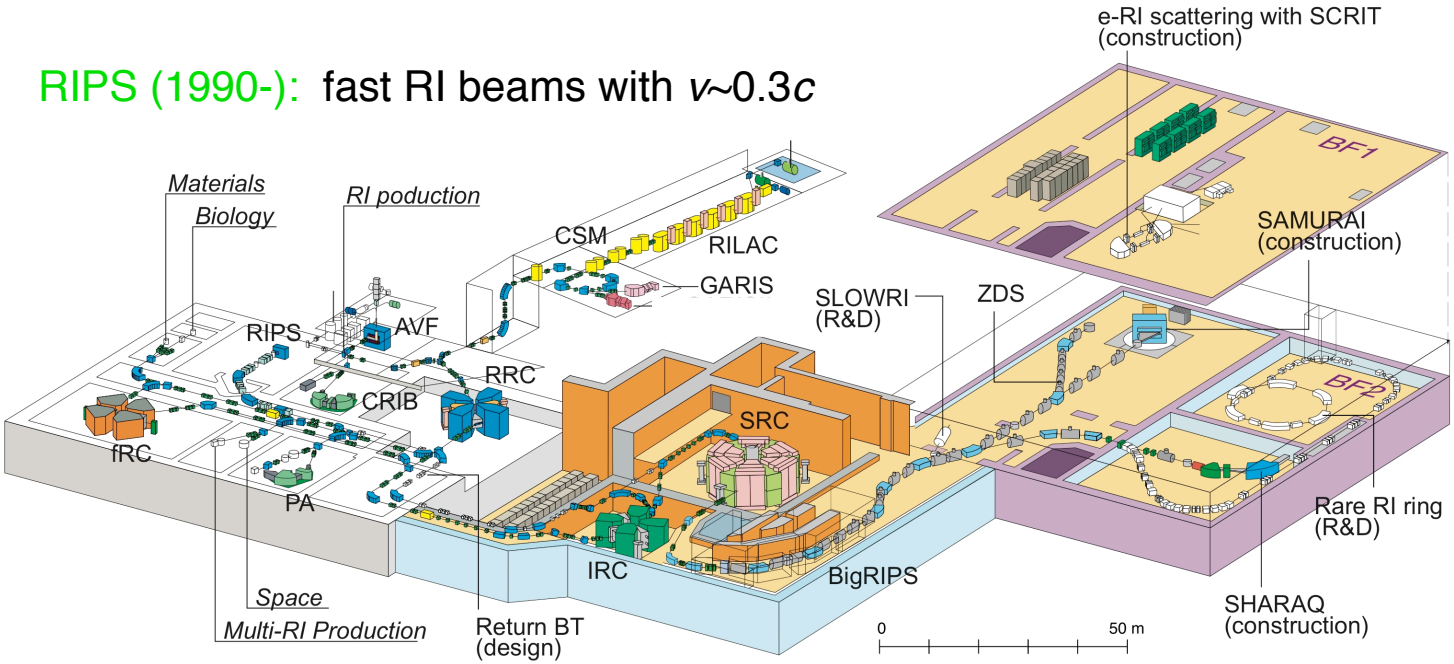
Nuclear structure study using direct reactions with fast RI beams

High(est)-intensity **fast** beams of unstable nuclei @ RIKEN

GANIL
MSU
GSI
…..

***E* = 50-100 MeV/nucleon (1990-)**: light nuclei

RIPS (1990-): fast RI beams with v~0.3c



new facility: fast RI beams with v~0.6c

***E*=200-300 MeV/nucleon (RIBF new facility)**

wide-range of nuclei., more intense beams

Disadvantages of fast RI beams

poor (intensity)
0.1 - 10^5 pps → efficient setups
good reactions
(large σ)

dirty (emittance)
2cm ϕ, 1~2 deg. Spread → γ-ray measurement
invariant mass
beam measurement

less supported (data)
e.g. optical potential → systematics
theoretical support

high energy — thick targets
forward focusing
simple mechanism

High(est)-intensity **fast** beams of unstable nuclei @ RIKEN

GANIL
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.....

***E* = 50-100 MeV/nucleon (1990-)**: light nuclei

inverse kinematics, large energy- / momentum-spreads
very far from stability => new methods for DR studies
development of equipment

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GANIL
MSU
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.....

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inverse kinematics, large energy- / momentum-spreads
very far from stability => new methods for DR studies
development of equipment

DR studies with γ measurements (bound states)
coulex, (p,p'), fragmentation, transfers…
collectivity, shell structure, p/n-decoupling, …..

Aoi* (Tuesday)

DR studies with particle measurements (unbound states)
Coulomb dissociation, nuclear breakup
H-burning, n-halo structure, cluster states

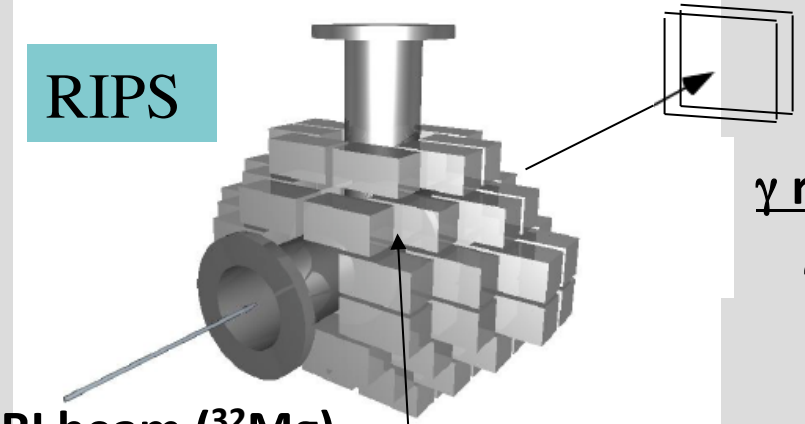
Kondo (Friday)

***E*=200-300 MeV/nucleon (RIBF new facility)**
wide-range of nuclei., more intense beams

Direct reaction measurement with γ-ray detection

example: Coulomb excitation of ^{32}Mg (1995)

Inverse kinematics



RI beam (^{32}Mg)

300 s^{-1}

~50 *A* MeV

Target (^{208}Pb)

350 mg/cm^2

weak

fast

thick

Charged particles (Si stack - *ΔE-E*)

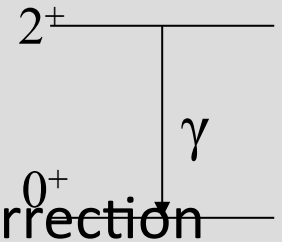
particle ID for ejectiles (^{32}Mg)

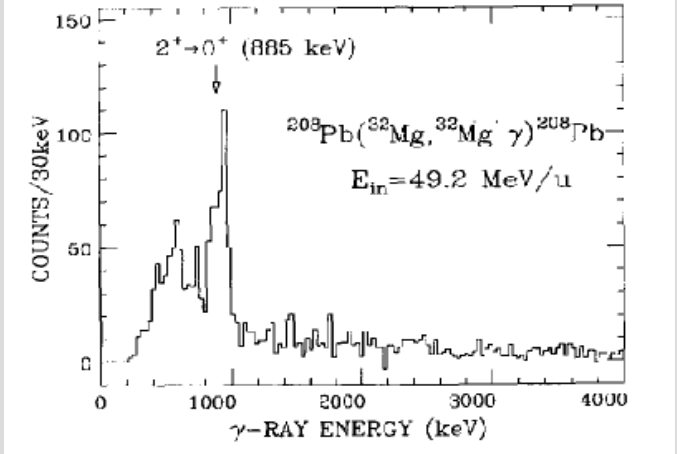
γ rays (DALI -NaI(Tl) array)

γ-ray energy => state ID

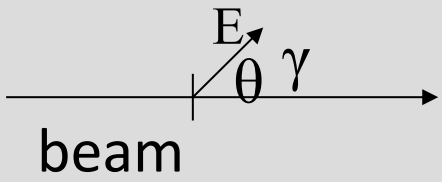
emission angle

=> Doppler correction





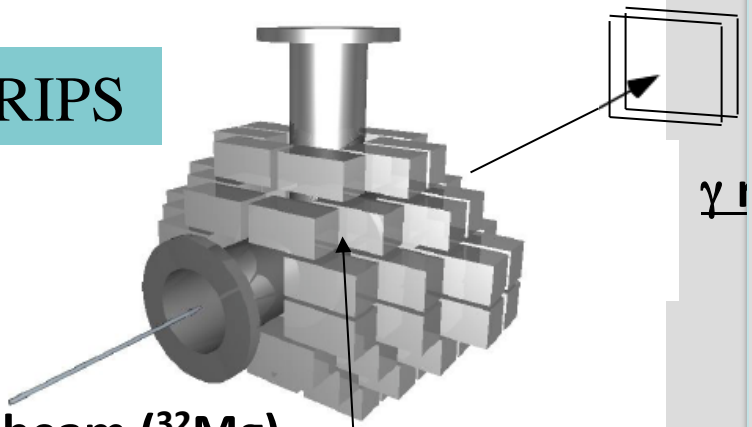
Doppler-shift corrected spectrum



Direct reaction measu

Inverse kinematics

RIPS



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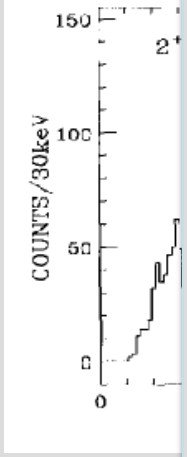
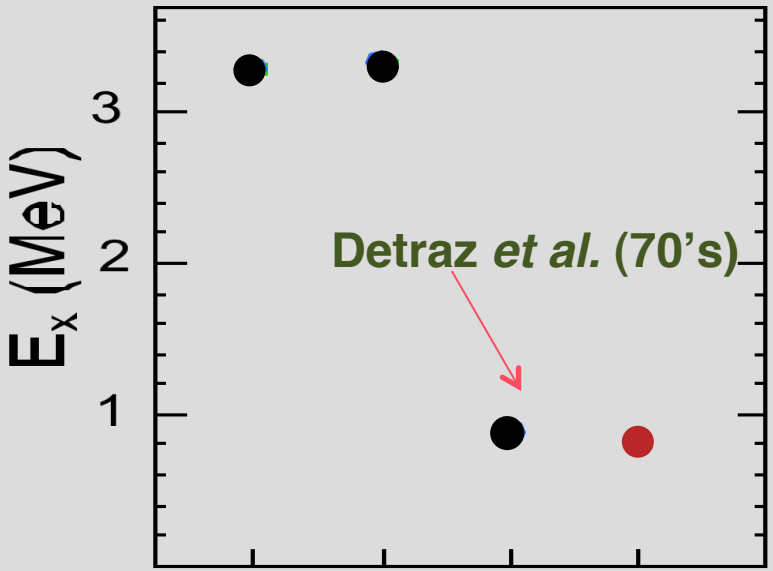
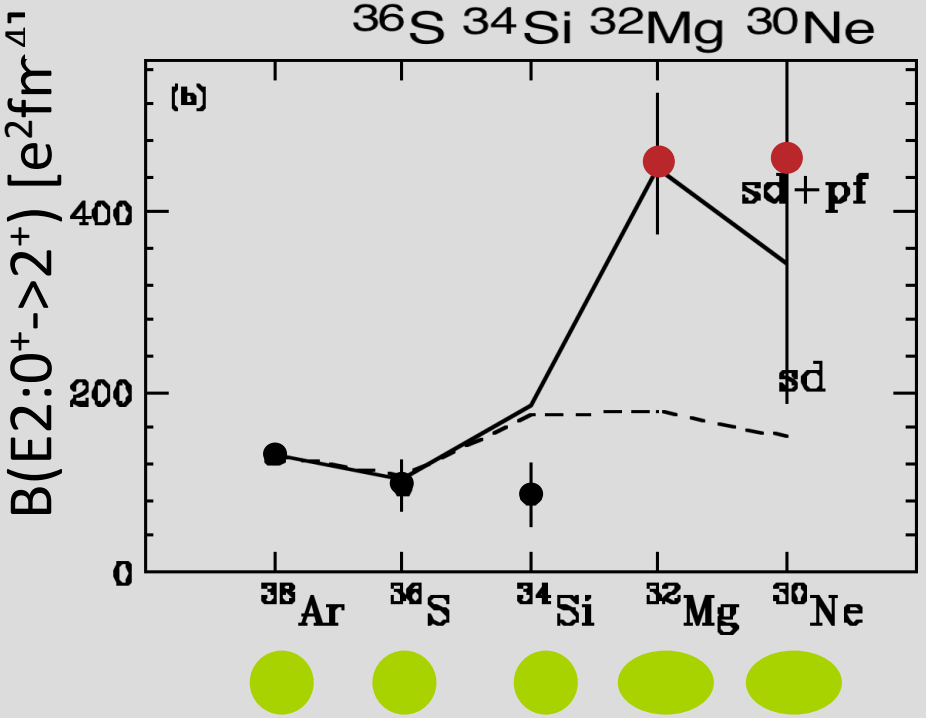


Motobayashi *et al.*, PLB 346 (95) 9

Yanagisawa *et al.*, PLB 566 (03) 84

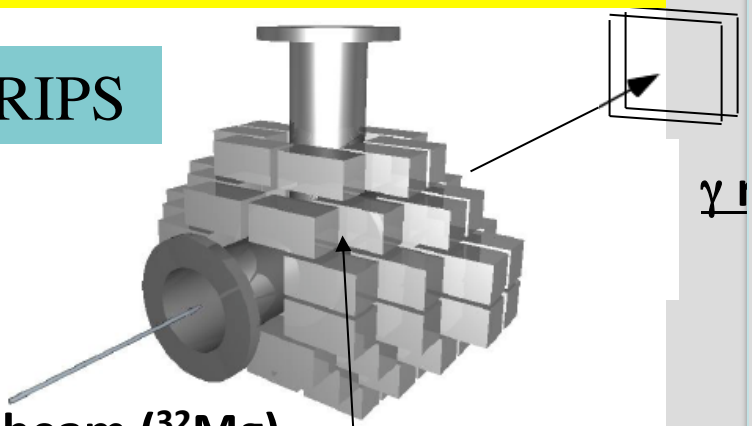




Direct reaction measu

Disappearance
sd-pf shell gap(*N*=20)
in ^{32}Mg and ^{30}Ne

RIPS



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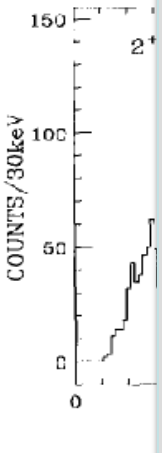

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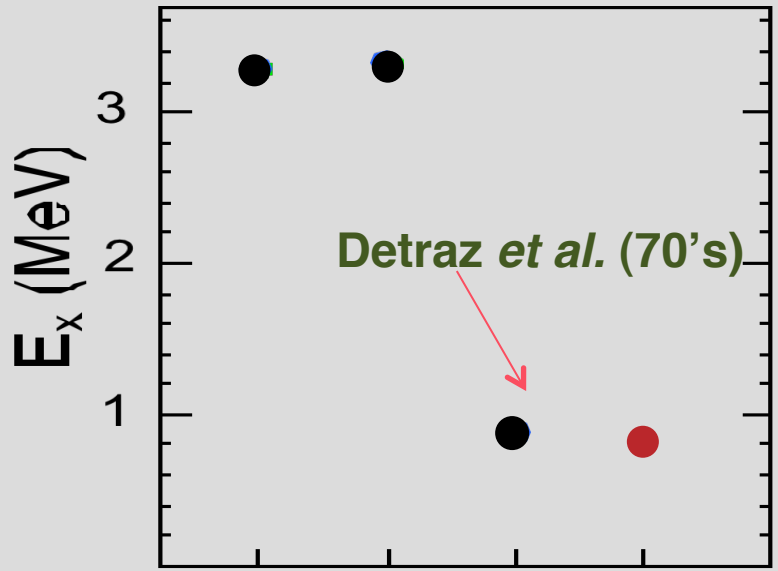

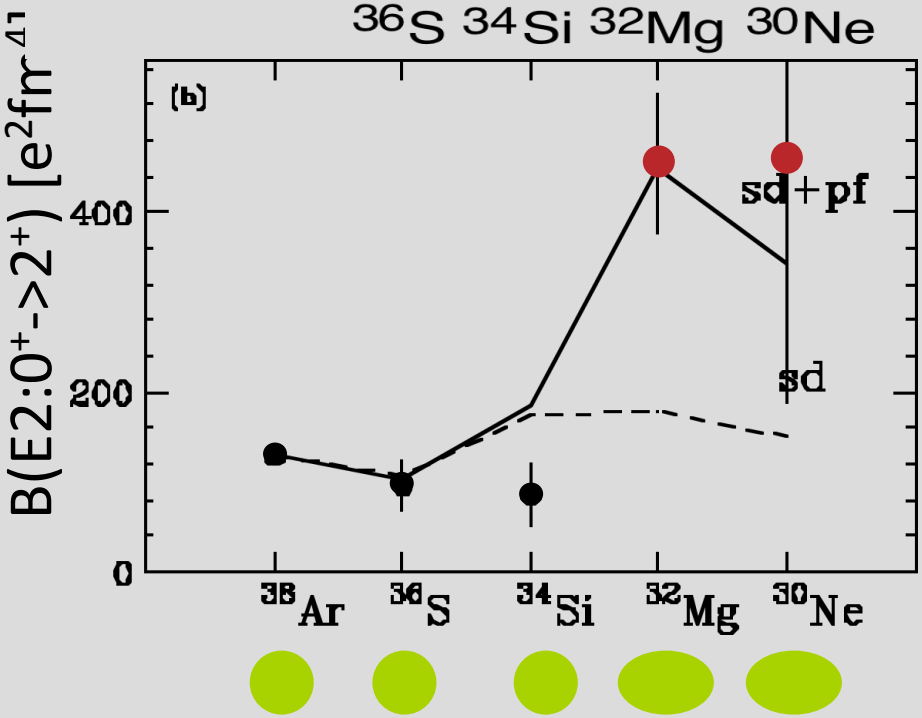

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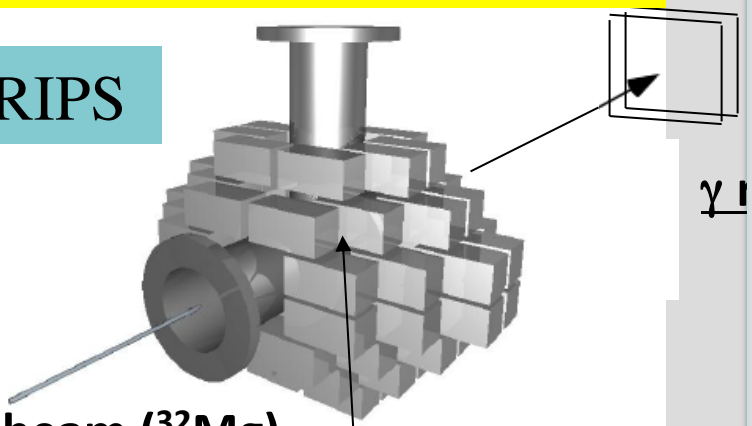

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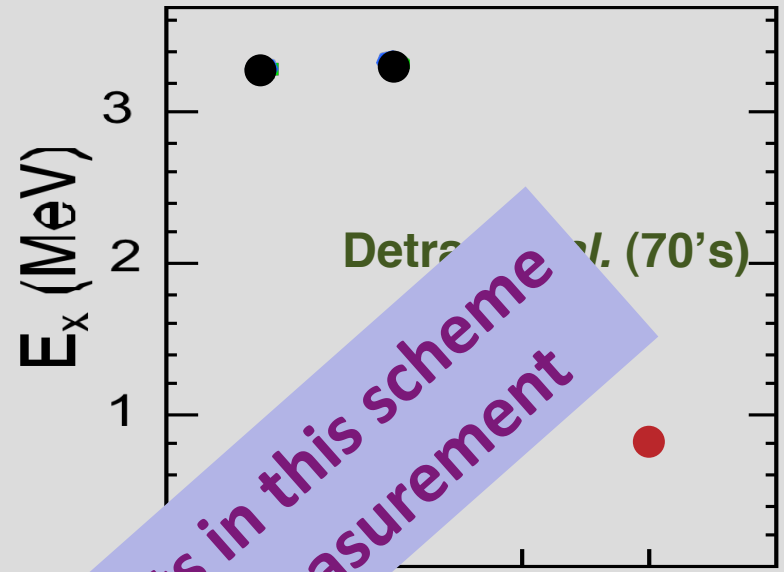
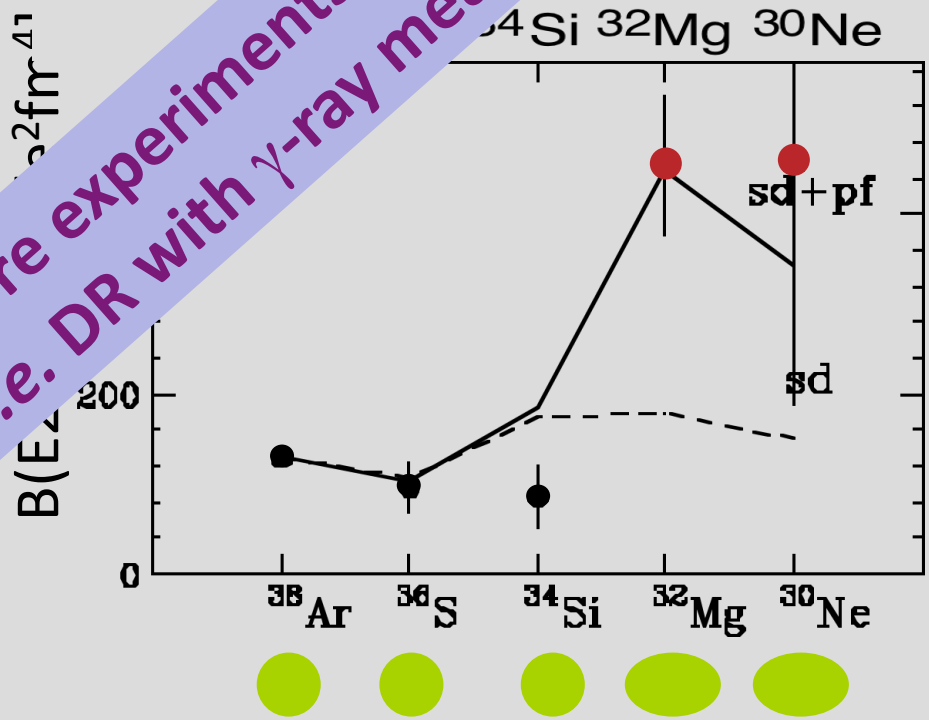
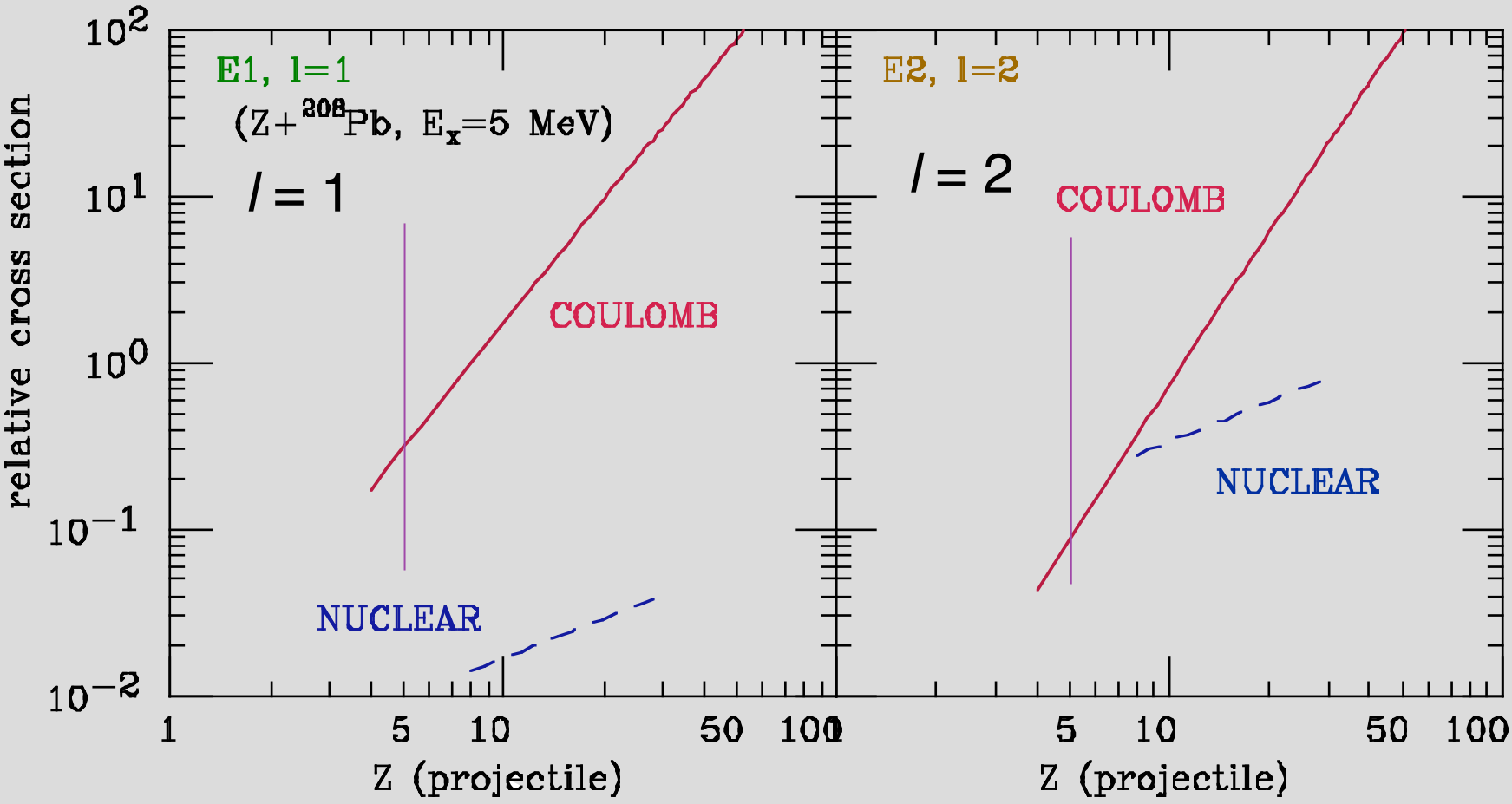




Many more experiments in this scheme *i.e.* DR with γ-ray measurement

Nuclear excitation is negligible or well controlled in certain cases (l=1 and l=2 with Z>10)



C > N

C ~ N

^{32}Mg(p,p') with high statistics ← DALI2, liq H_2 target, ..

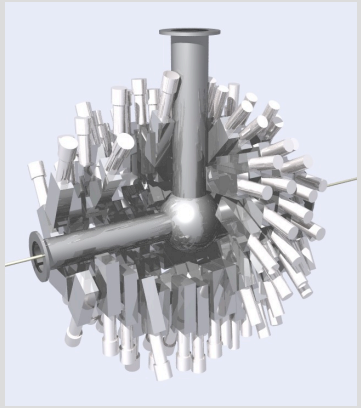
→AOI*

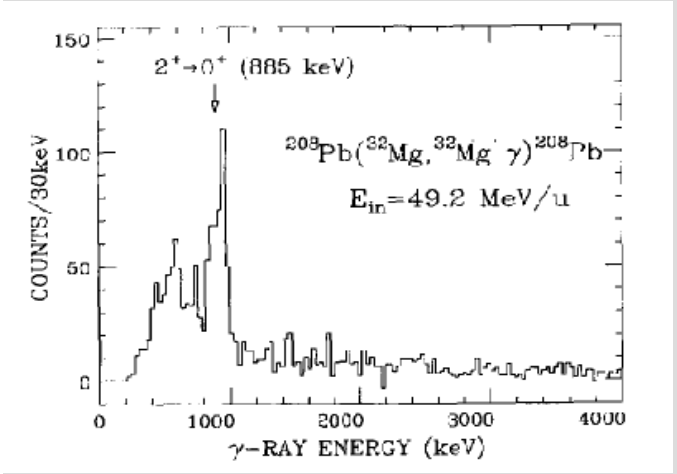
nuclear excitation

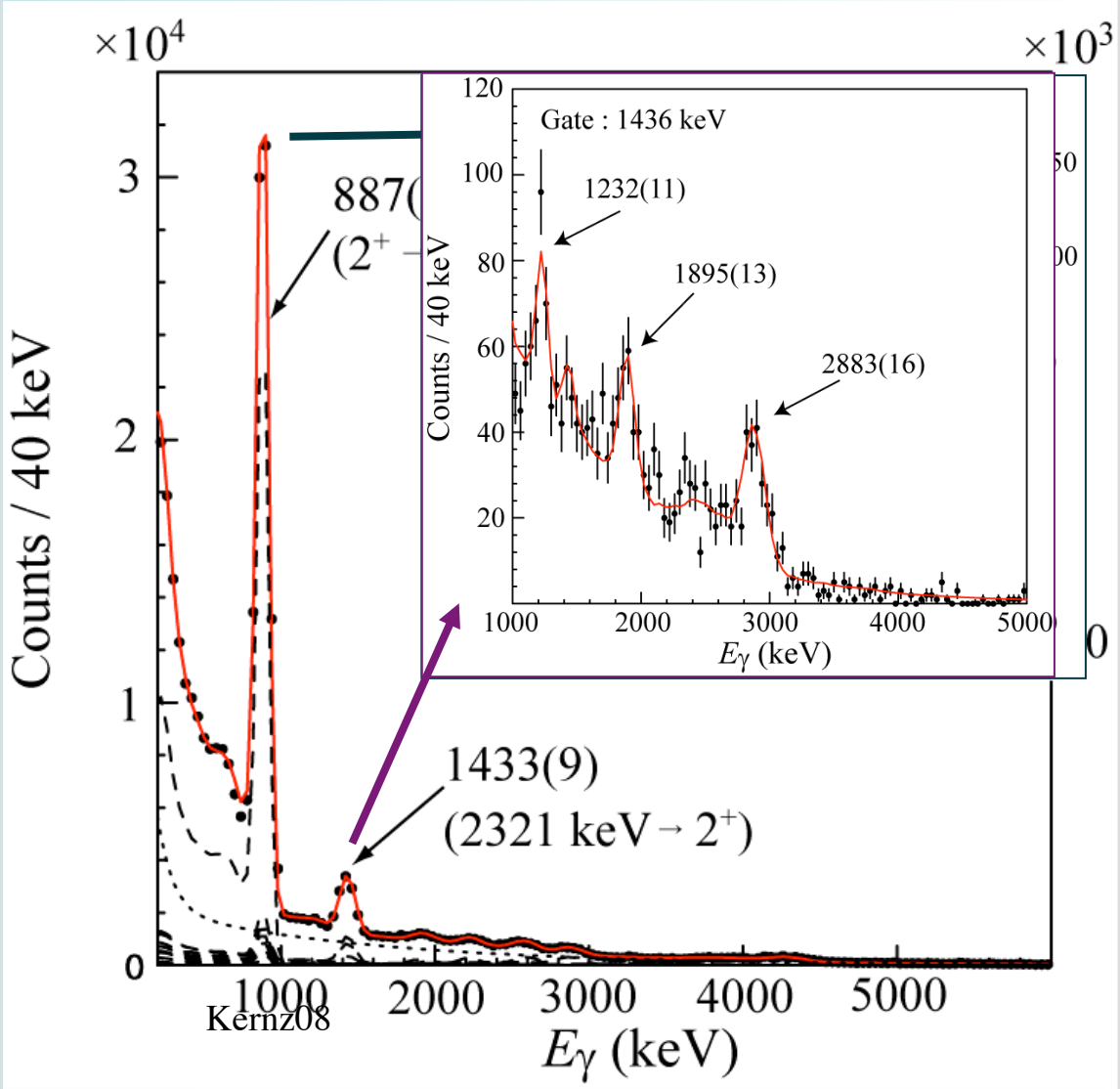
→ γγ, γγγ / angular distribution

RIPS

By DALI2





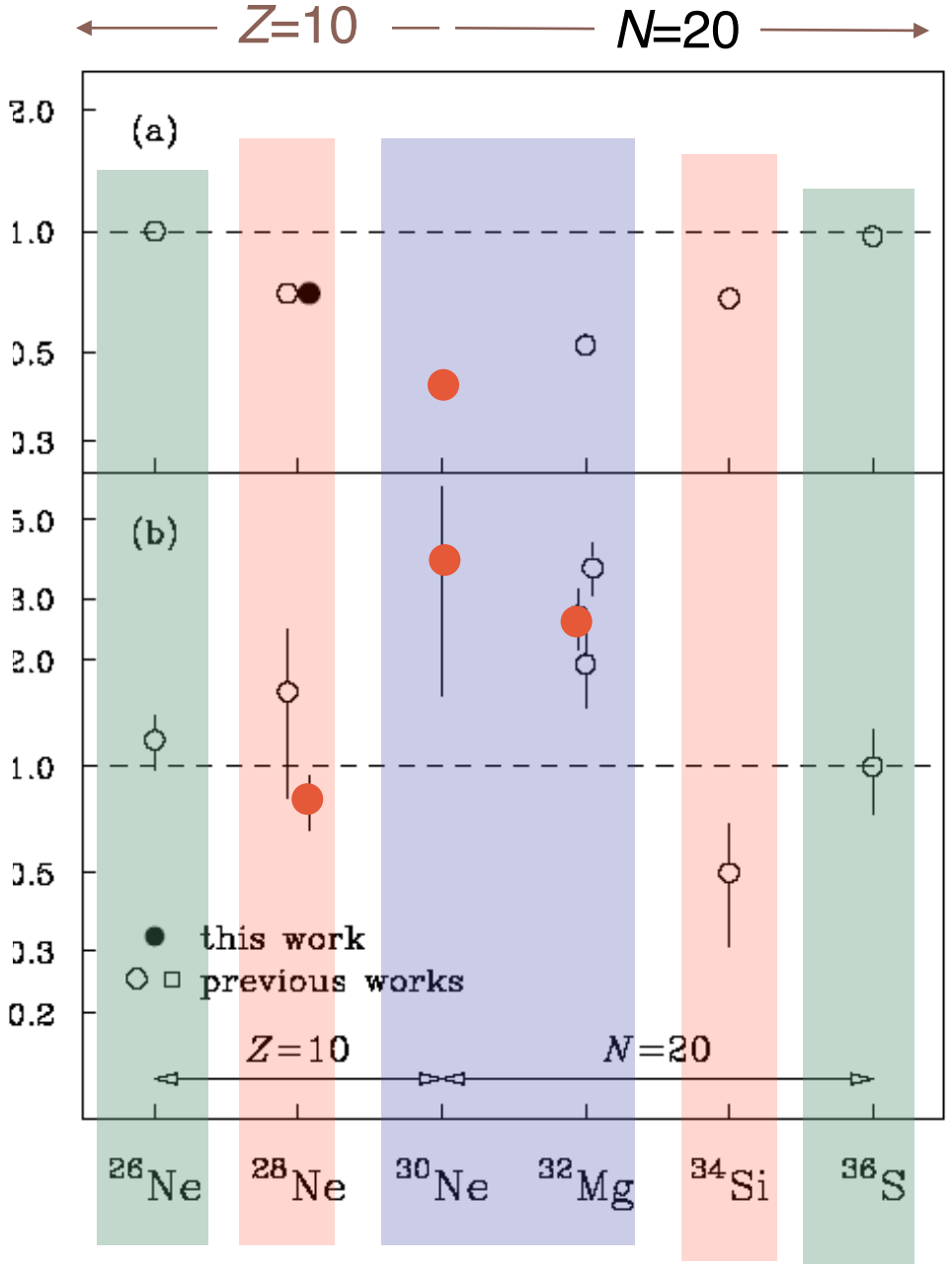


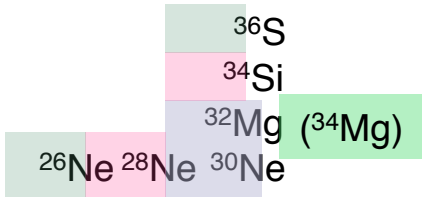
Nov. 08 **S. Takeuchi** Kernz08

$E(2^+)/\ E(2^+)_{sd}$

$B(E2)/\ B(E2)_{sd}$

(coulex)





Nov. 08

"normal" transitional Island of inversion transition "normal"

2^+ of ^{16}C

- p-n decoupling ?

sensing p/n motion by various methods

Coulomb-nuclear interference

Lifetime recoil shadow, Doppler

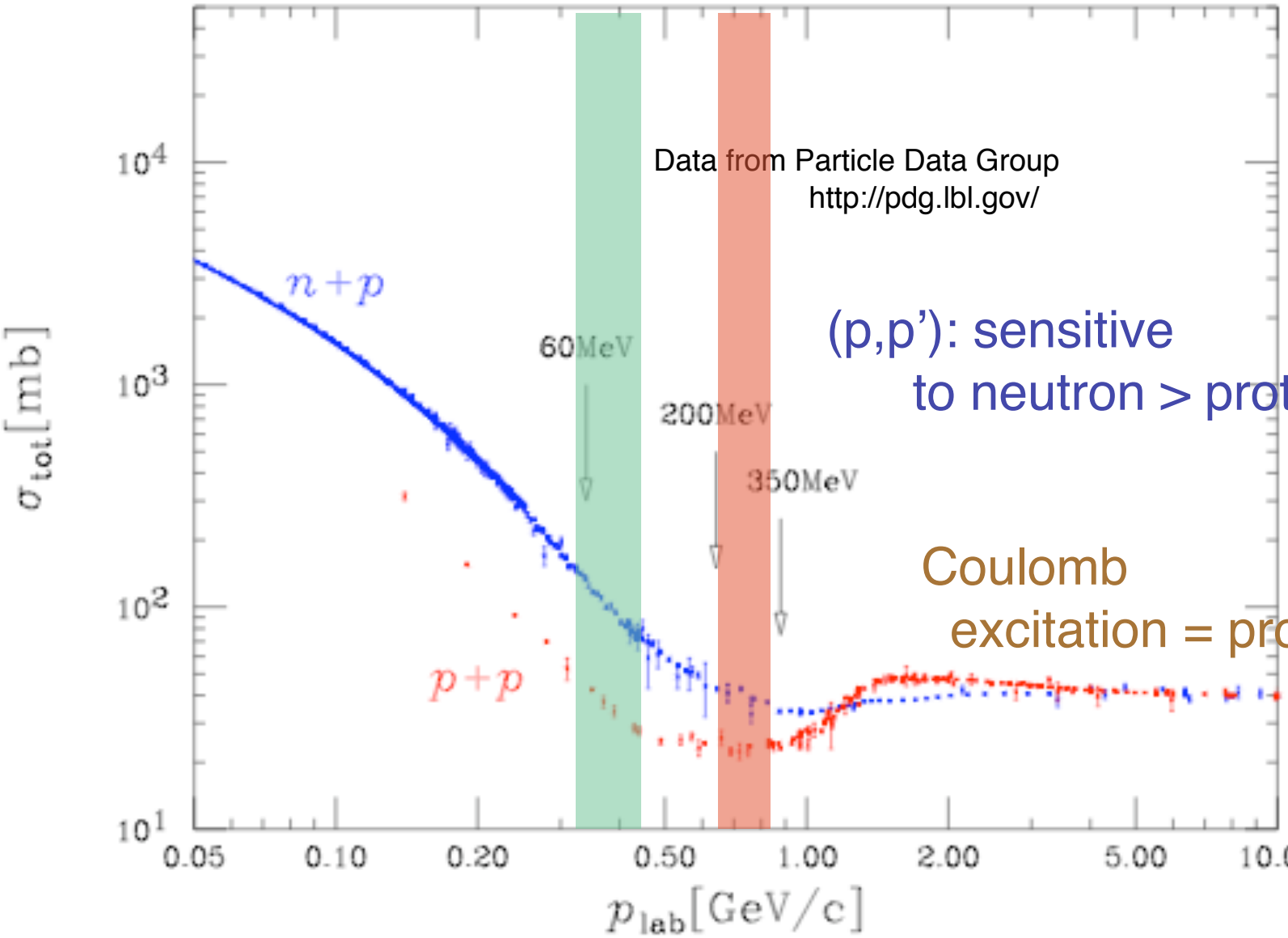
(p,p')

(Pb,Pb')

M_n *v.s.* M_p

(*Q* moments of neighboring nuclei)

NN cross section

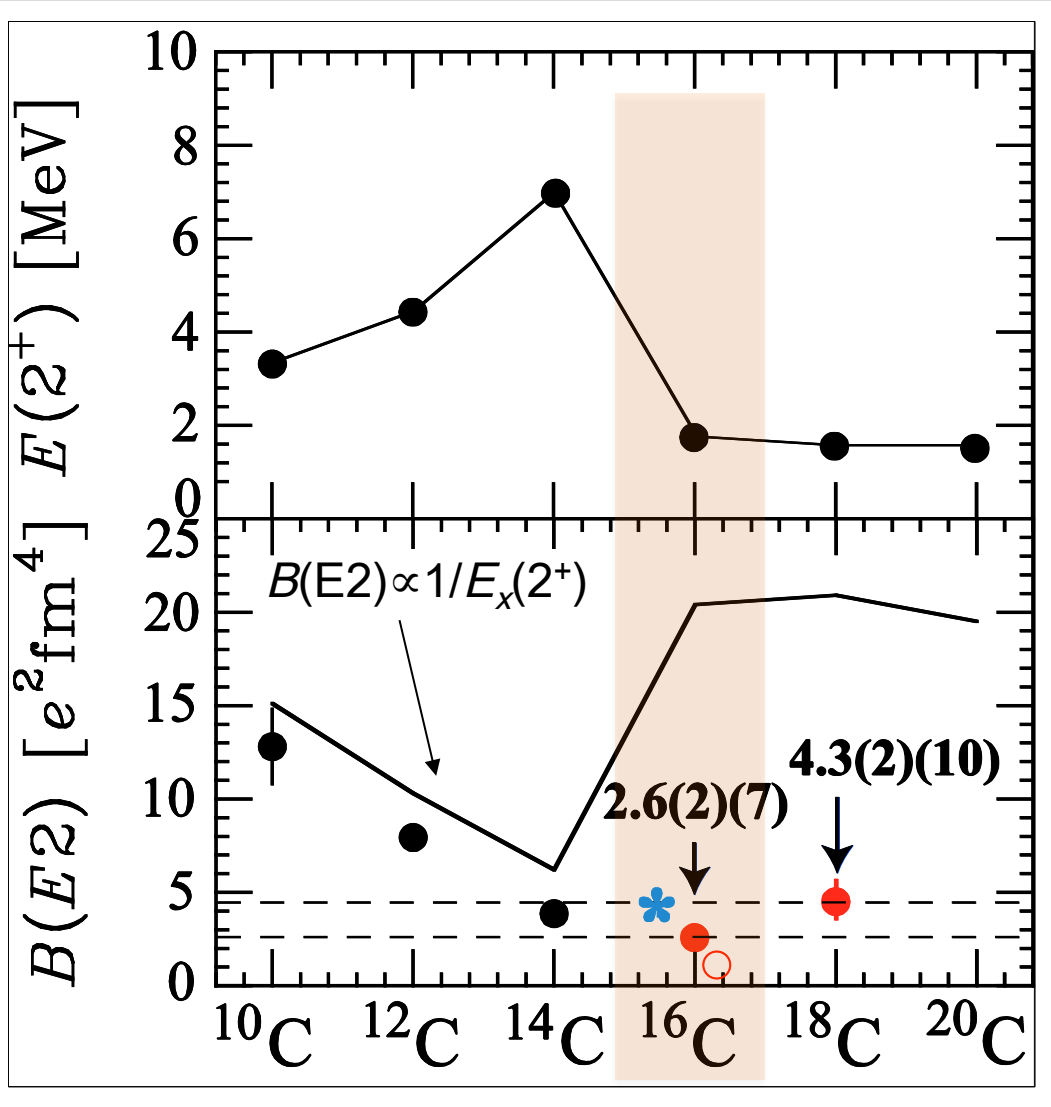


(p,p'): sensitive
to neutron > proton

Coulomb
excitation = proton

Small *B(E2)* for 0^+ - 2^+ in ^{16}C

RIPS

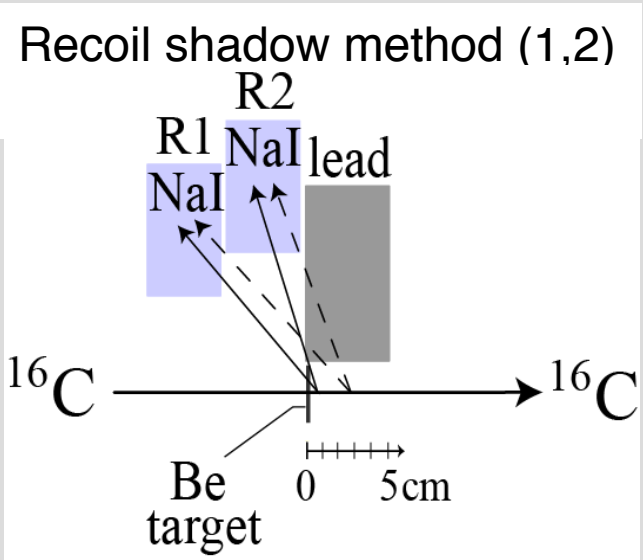


Smaller than the one expected from low $E_x(2^+)$

^{16}C

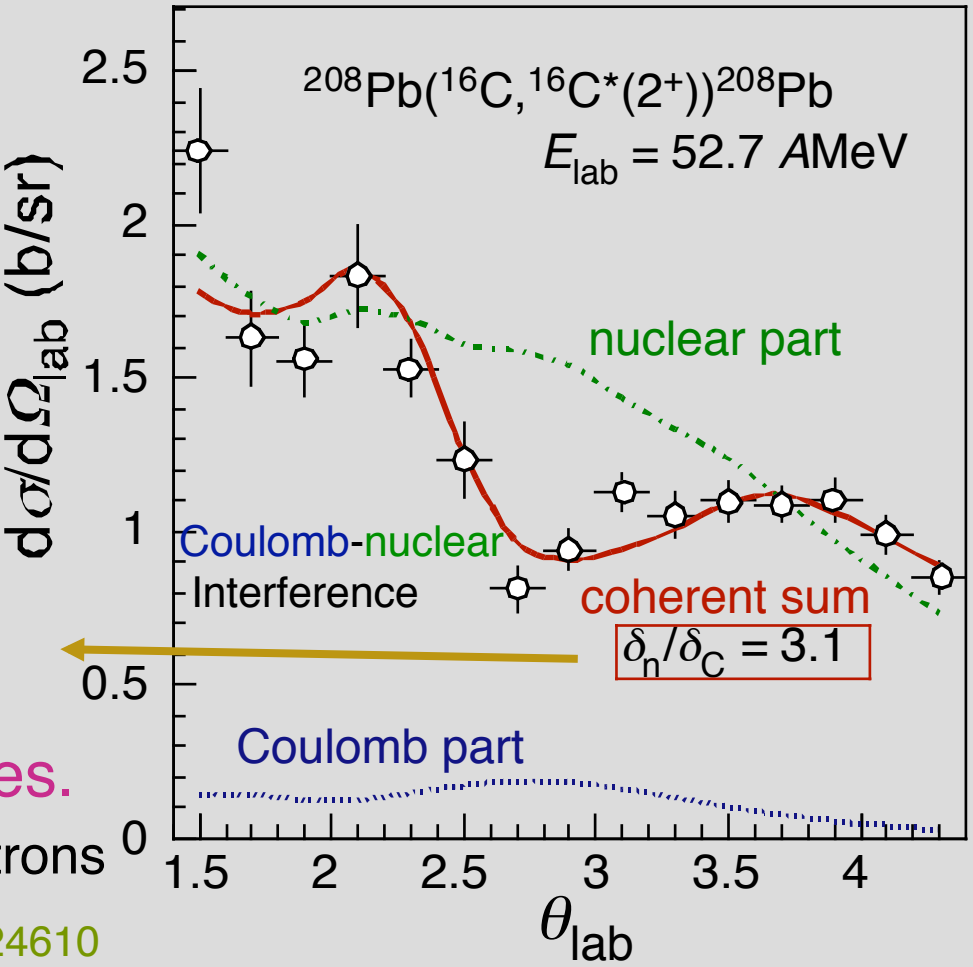
- ○ Prev.[1] : 0.63(13)(16) e^2fm^4
- ● New[2] : 2.6(2)(7) e^2fm^4
- * LBNL[3]: 4.15(73) e^2fm^4

1 Imai et al., PRL**92** (2004) 062501
2 Ong et al., PRC**78** (2008) 014308
3 Wiedeking *et al.*,PRL**100** (2008) 152501



$^{16}C + ^{208}Pb$ Inelastic scattering

Elekes *et al.*, Phys. Lett. B586 (2004) 34
Japan-Hungary (ATOMKI) collaboration



2^+ excitation:
almost only by neutrons ?

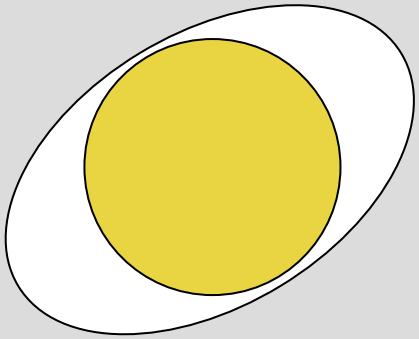
(p,p')* supports this pictures.

* more sensitive to neutrons

Ong *et al.* , Phys. Rev. C73 (2006) 024610

c.f. small *Q* of $^{15,17}B$
$^{15,17}B+^{12}C$ inelastic

“egg-like” structure in ^{16}C ?



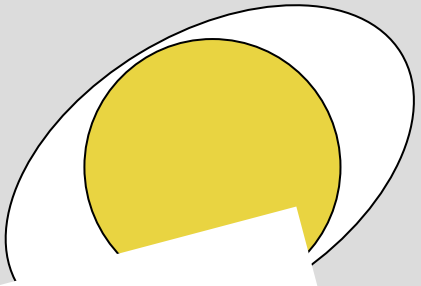
2^+ : almost entirely by neutrons.

strong
p-n interaction

Coulomb-nuclear inteference in ^{16}C+^{208}Pb inelastic
Lifetime measurements *v.s.* (p,p’) result
^{16}C+^{208}Pb inelastic *v.s.* (p,p’) result
Elekes *et al.*, PRC**78** (2008) 027301

small *Q* of ^{15,17}B
^{15,17}B+^{12}C

“egg-like” structure in ^{16}C ?



2^+ : almost entirely by neutrons.

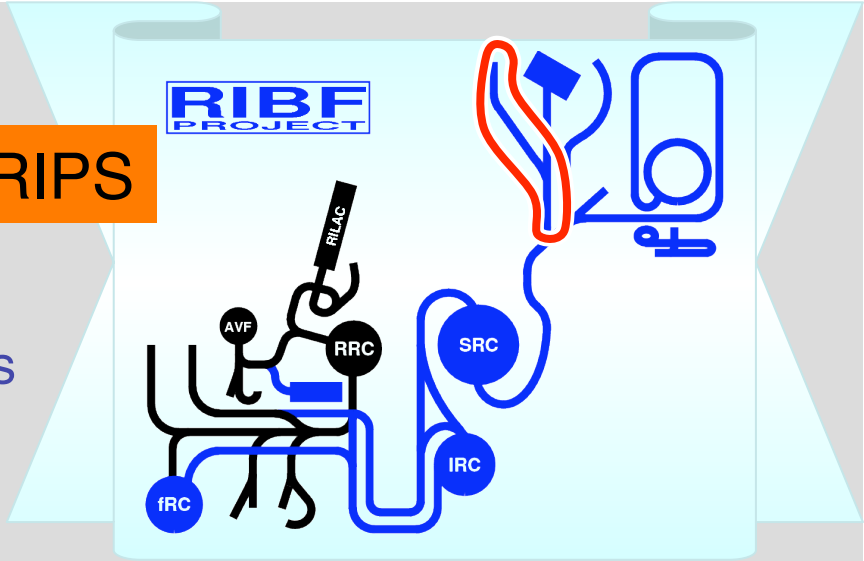
The “p-n difference” is moderated
in recent lifetime measurements at LBL and RIKEN,
but still significant.
New analysis of ^{16}C+^{208}Pb gives a consistent result.
arguments on effective charges

...elastic
...) result
...(p,p’) result
..., PRC**78** (2008) 027301

small Q of ^{15,17}B
^{15,17}B+^{12}C

Zero-degree spectrometer

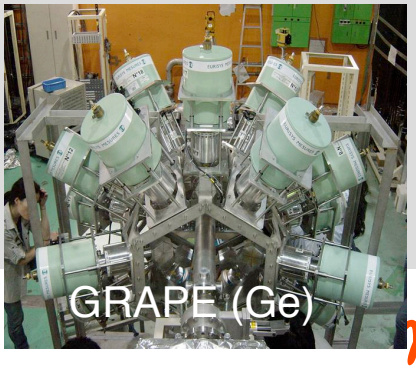
BigRIPS

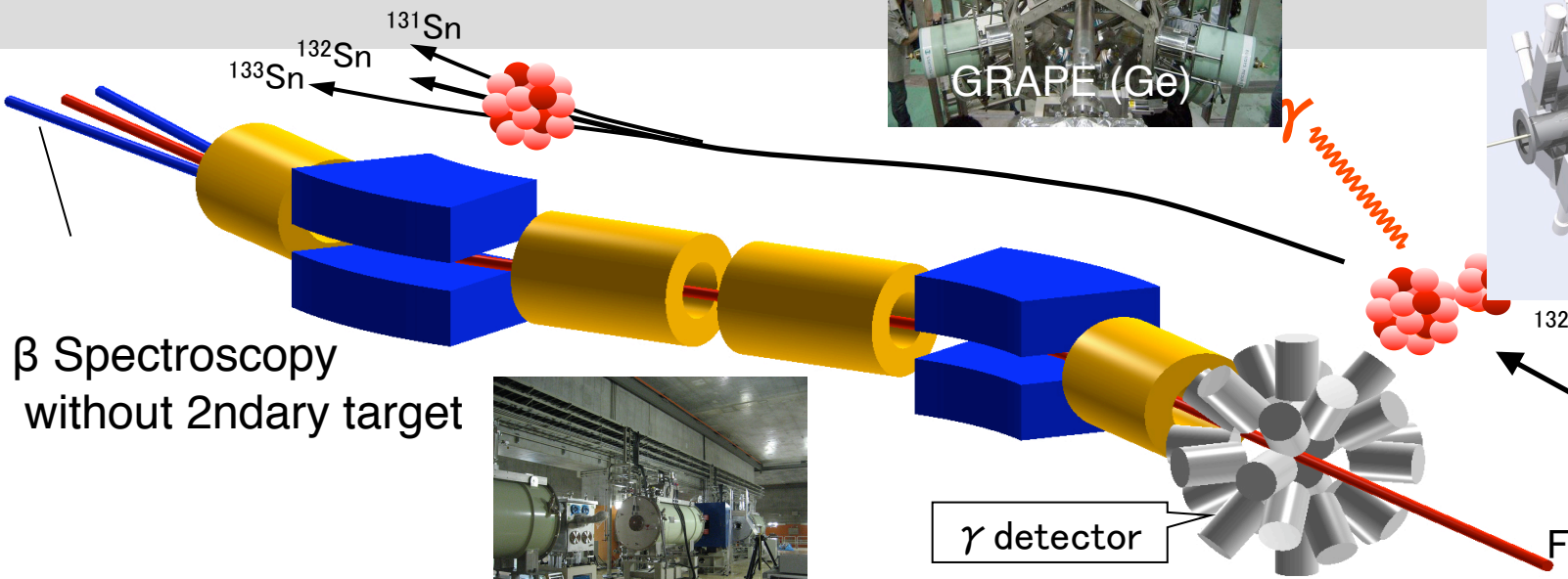


particle ID / momentum analysis

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

Multi-function BT line
Medium resolution
p/δp ~2000 - 4000
p_{acc} ±3%



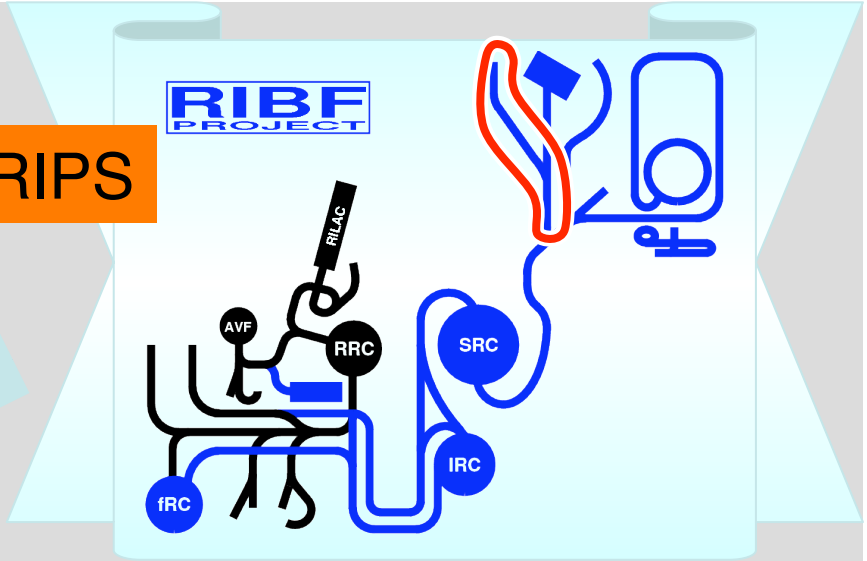


β Spectroscopy
without 2ndary target

Zero-degree spectrometer

BigRIPS

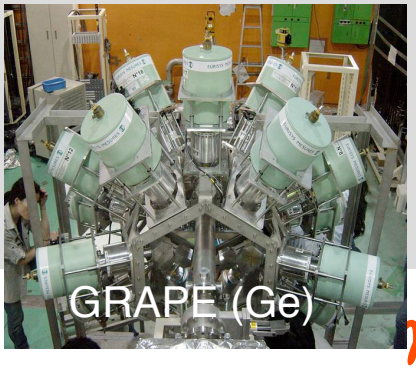
particle ID / momentum analysis

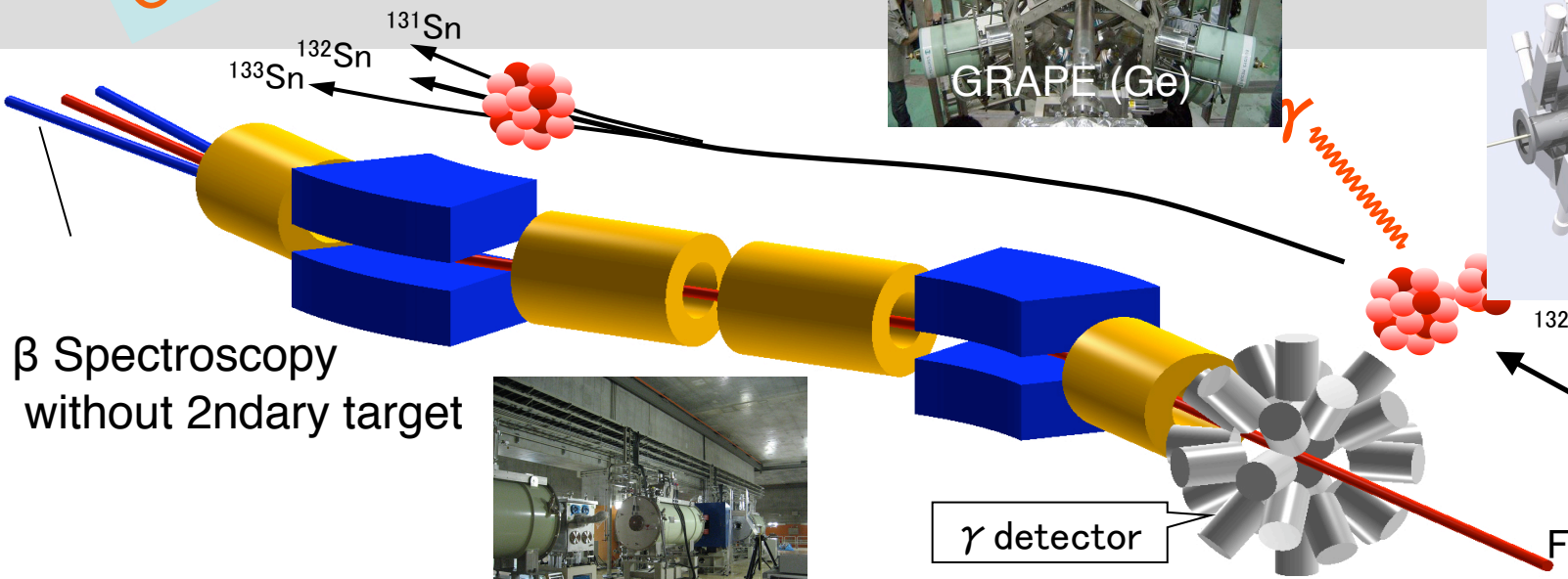


e.g. Doppler shifted γ-ray measure
with identification of prod
(angle-integrated cr tion)

Multi-funct e
Medi ation
p/δp ~2000 - 4000
±3%

Commissioning: made in Nov. 2008





β Spectroscopy
without 2ndary target

Coulomb dissociation
Inverse radiative capture

astrophysical (p,γ) reactions

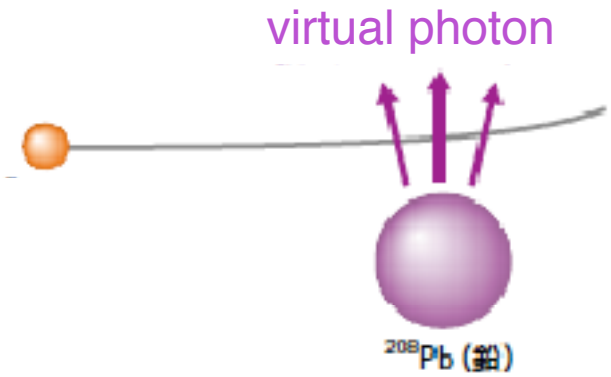
^{7}Be(p,γ)^{8}B - pp chain (solar fusion)

^{23}Al(p,γ)^{23}Mg, ^{26}Si(p,γ)^{27}P - rp

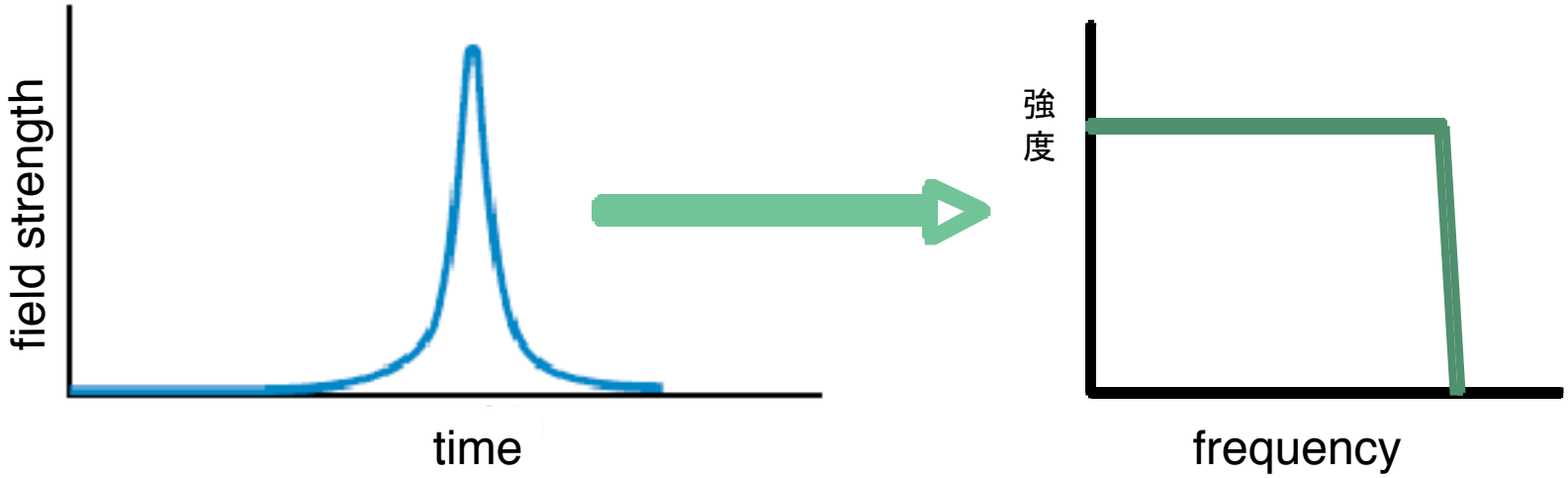
structure of loosely bound nuclei

^{11}Li, ^{11}Be, …

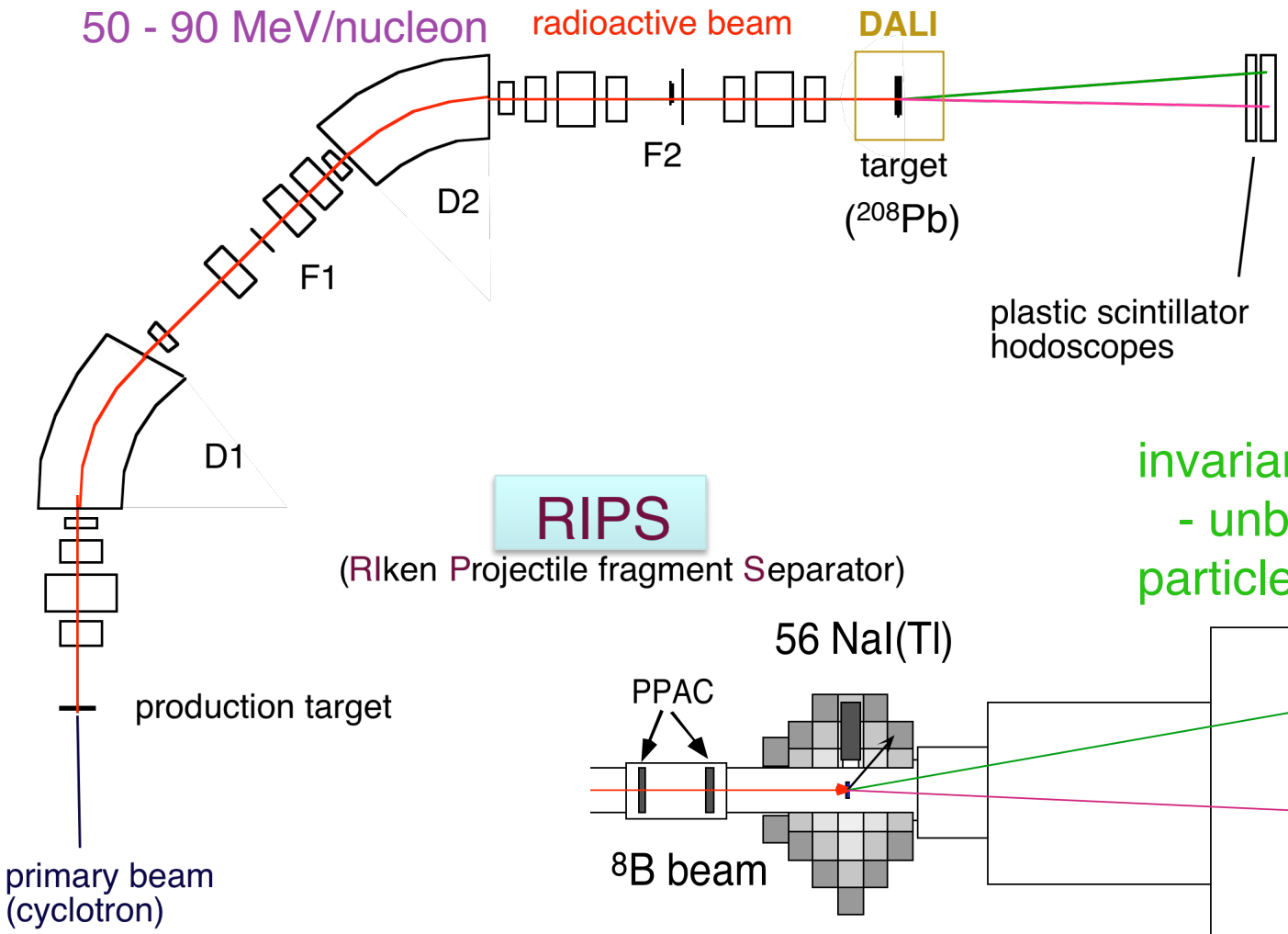
High-energy photon production by fast Coulomb excitation (dissociation)



large cross section
thick target
charged particle detection



spectroscopy of unstable nuclei / nucl. astrophysics



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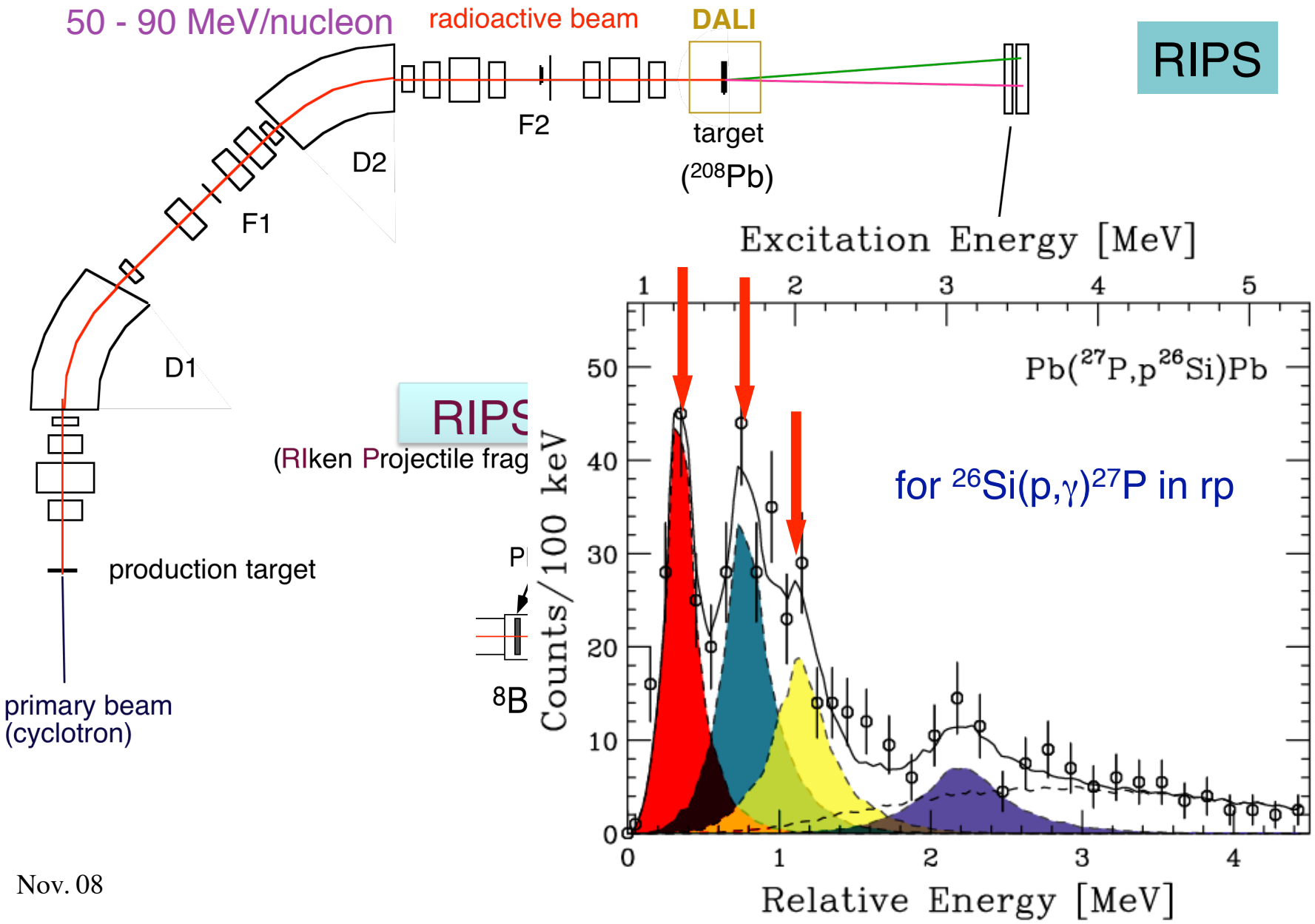
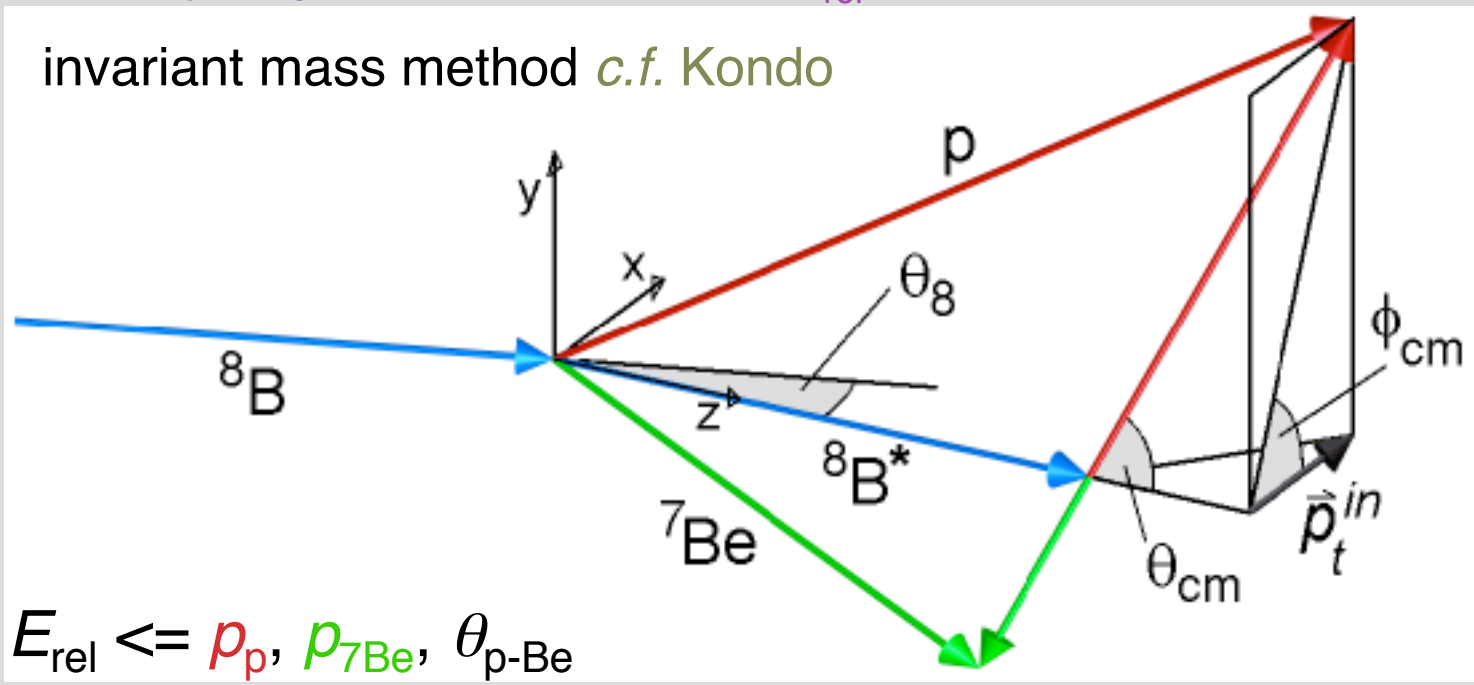


Poor beam quality does not affect the E_{rel} resolution.

invariant mass method *c.f.* Kondo



E_{rel} <= p_p, p_{7Be}, $\theta_{p\text{-}Be}$

ΔE_{rel} : independent to ΔE_{in}

$$\Delta E_{rel} \approx 2\sqrt{\frac{A_1 A_2}{A_1 + A_2}}\sqrt{T_0 E_{rel}}\,\Delta\chi$$

$$\Delta\chi = \Delta\theta,\ \Delta v / v$$

p+X, T_0=100 *A*MeV, E_{rel}=1 MeV,

$\Delta\theta$=0.5 deg. Δv=1%

↓

ΔE_{rel}=200 keV

optical potential for ^{8}B breakup analysis

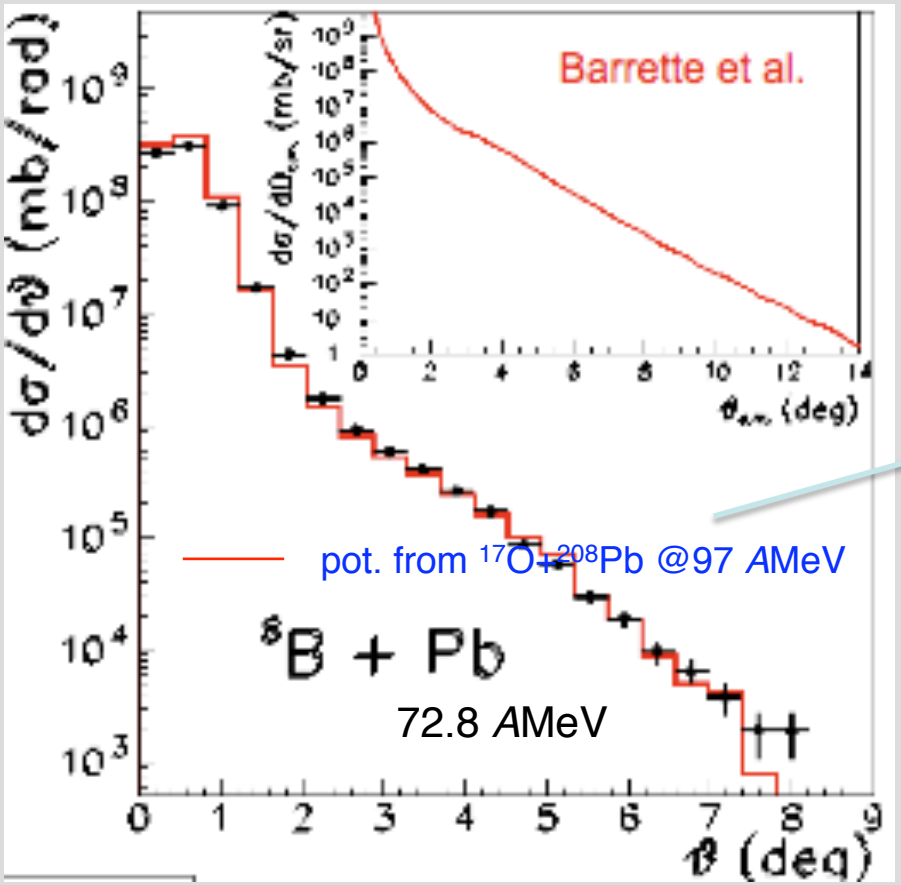
Yeild ➔ σ ➔ $B(E\lambda)$ or $\sigma(p,\gamma)$

detector response

reaction theory – DWBA, CC, CDCC, …

optical pot.

from other systems
made in our previous analyses
constructed theoretically
difficult for composite particle?
experimentally determined
confirmed

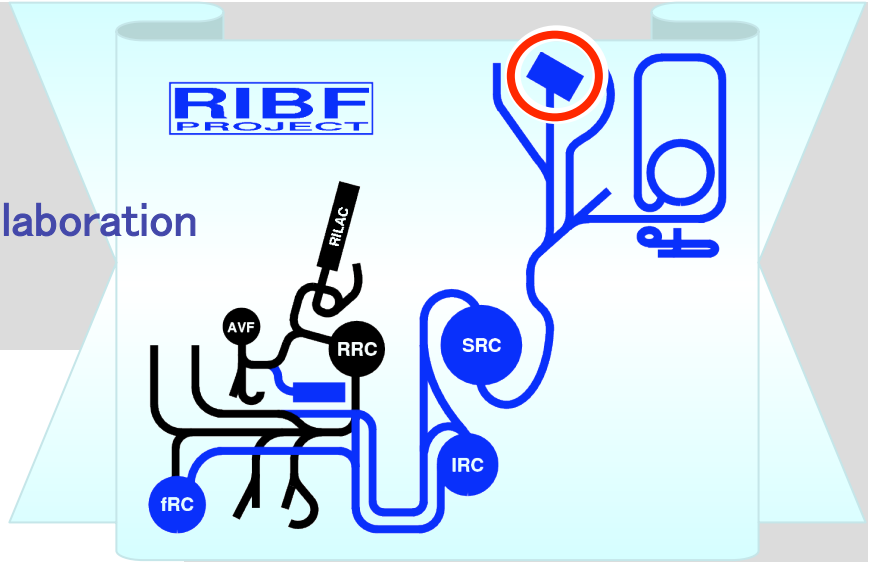


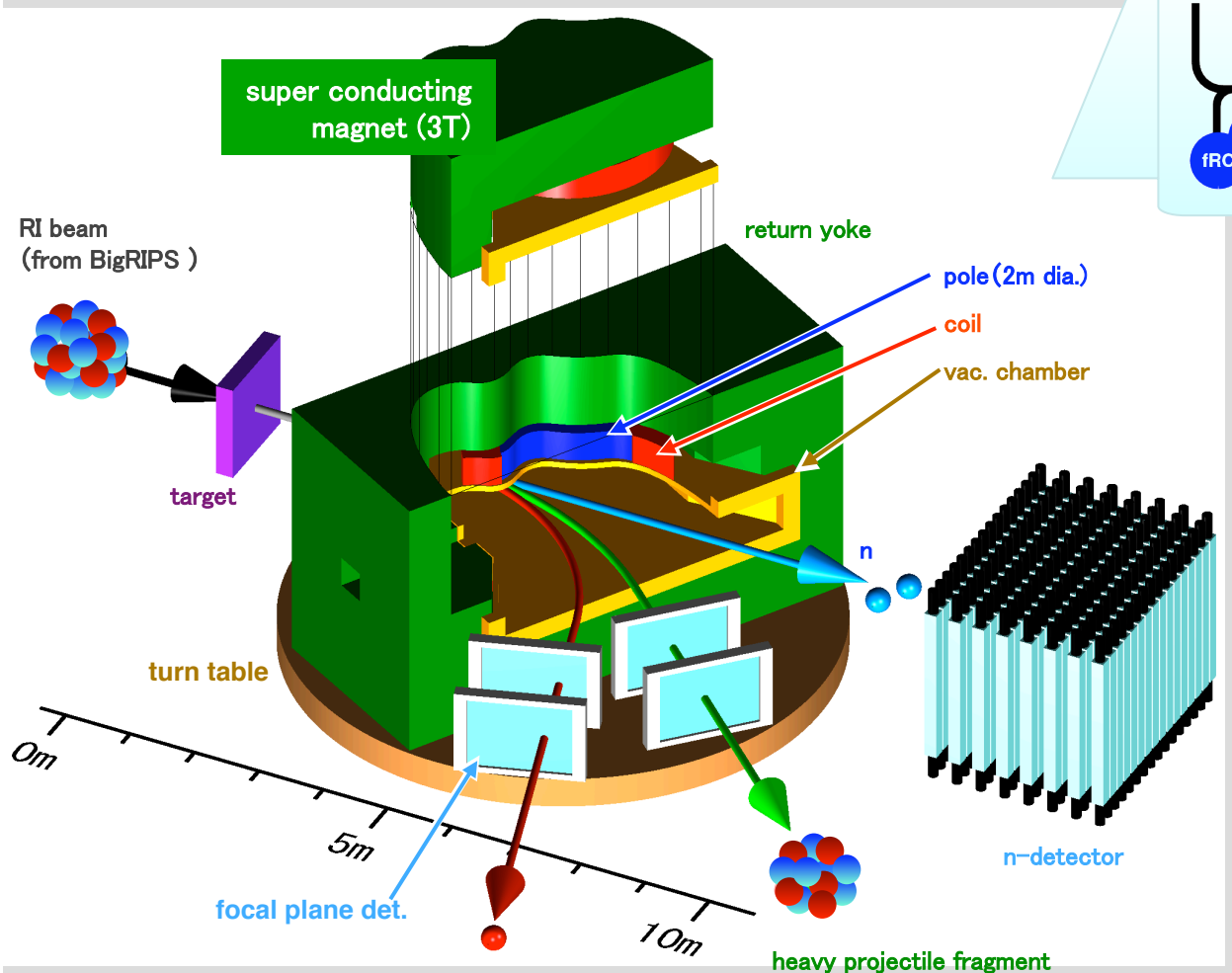
Coulomb dissociation (excitation)
less sensitive to opt. pot. or nuclear density,
depends on nucl. absorption radius.

SAMURAI7

BigRIPS

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





Large solid-angle spectrometer

particle correlation

unbound sates (p,2p)

astrophys. (p,γ)

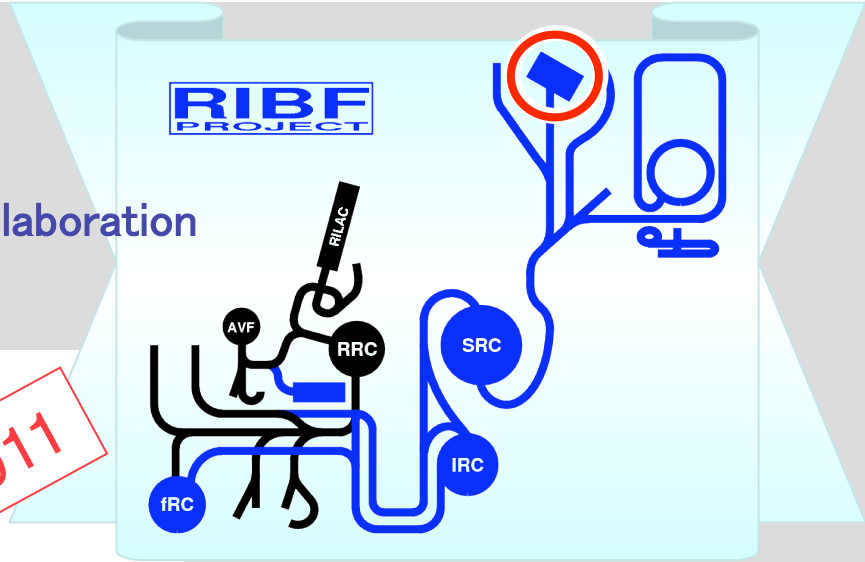
nucl. matter

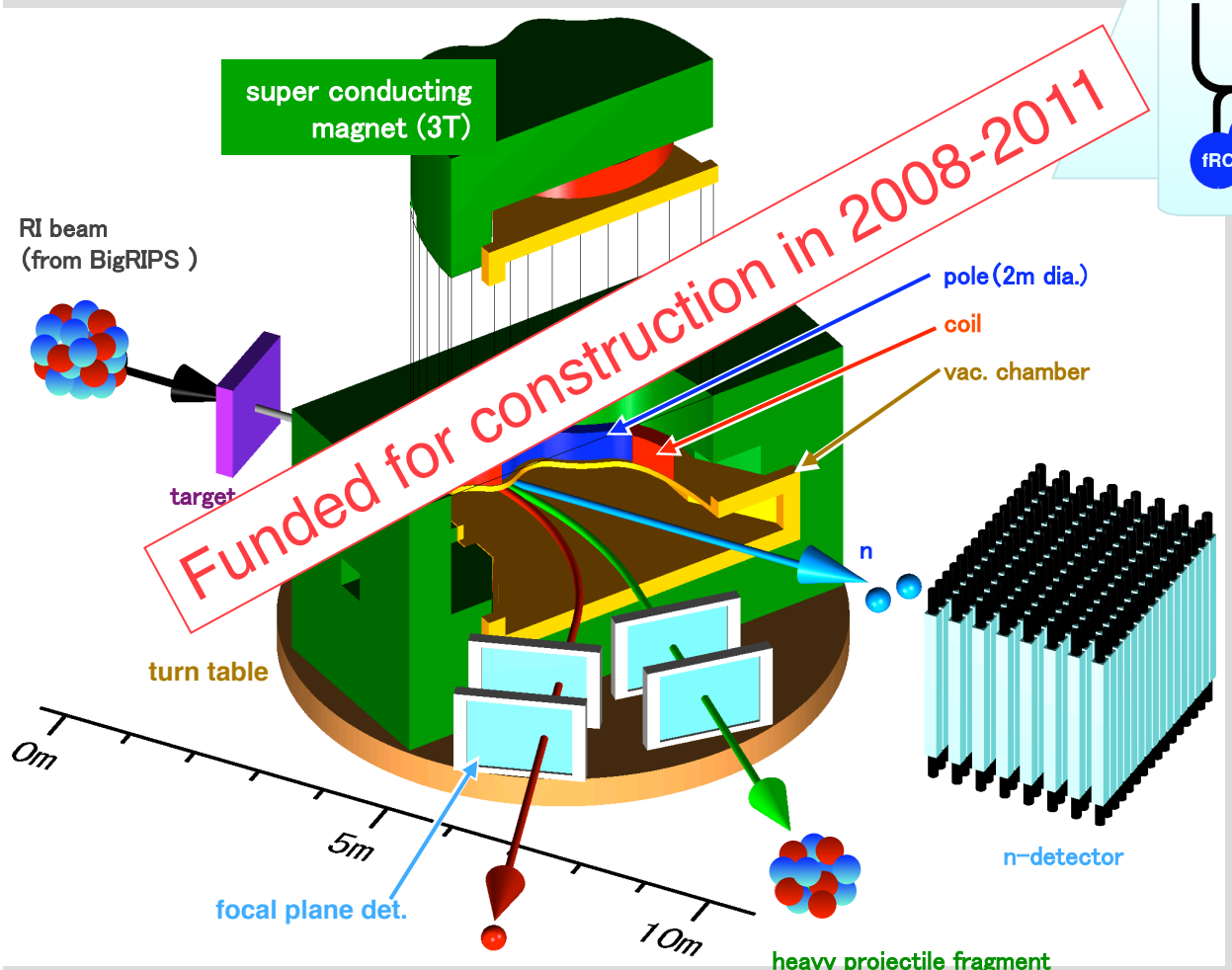
SAMURAI7 (Superconducting Analyzer for MUlti Particles from RAdioIsotope Beams with 7 Tm)

SAMURAI7

BigRIPS

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





Funded for construction in 2008-2011

Large solid-angle spectrometer

particle correlation

unbound sates

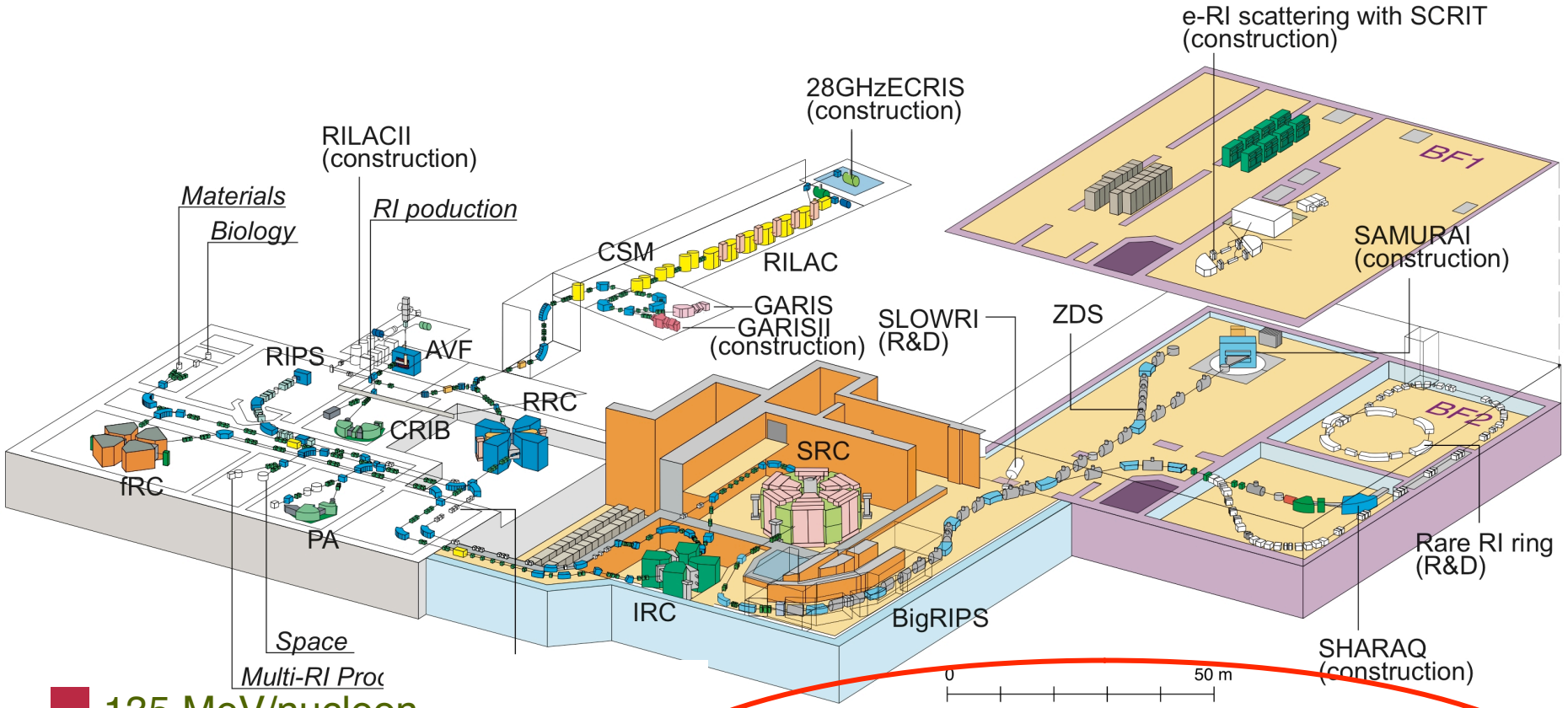
(p,2p)

astrophys. (p,γ)

nucl. matter

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

RIBF: Accelerator Complex in RIKEN Nishina Center



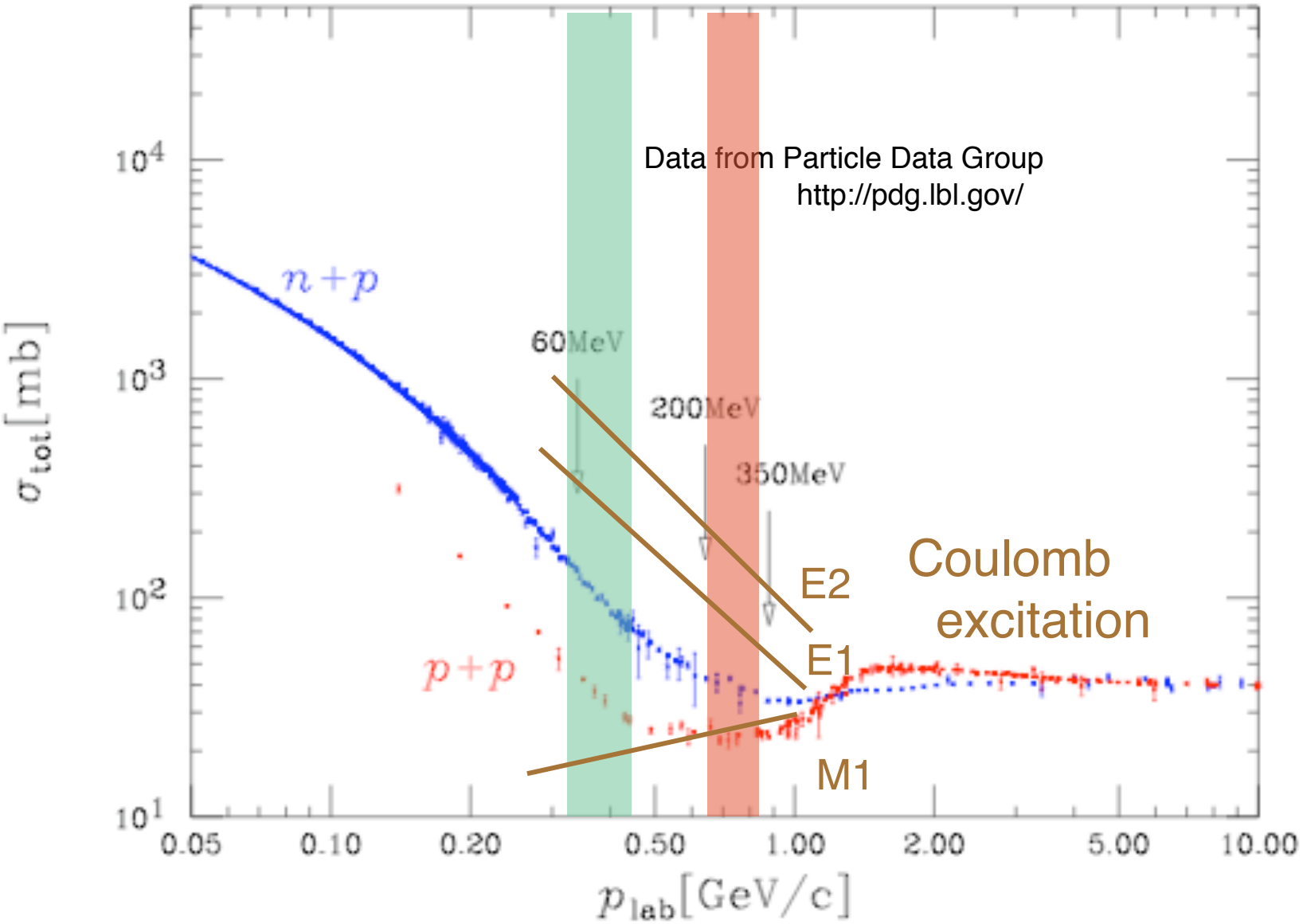
135 MeV/nucleon
for light nuclei (1986-)

350 MeV/nucleon
up to U

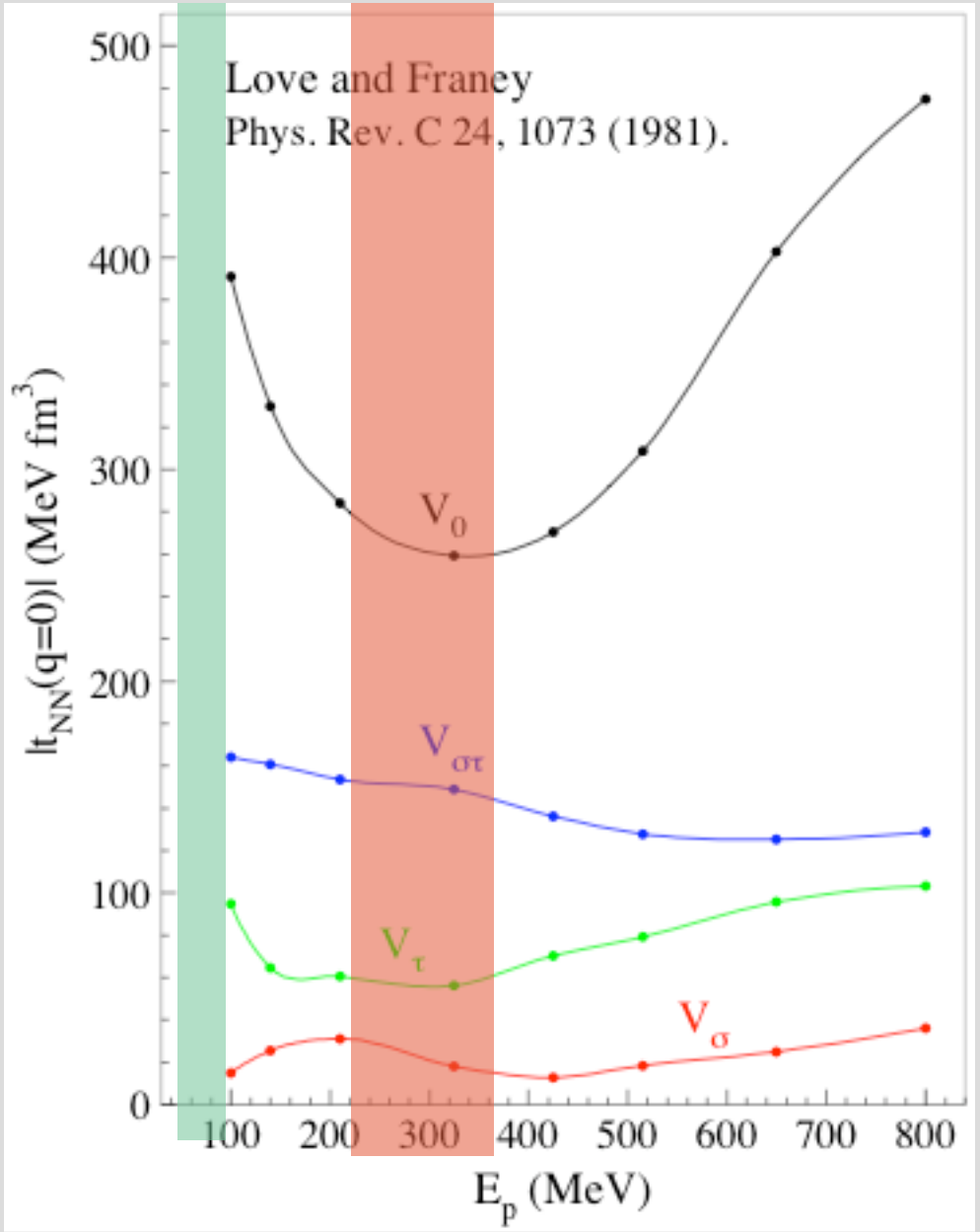
RIBF new facility v~0.6c

Being constructed
or planned

NN cross section



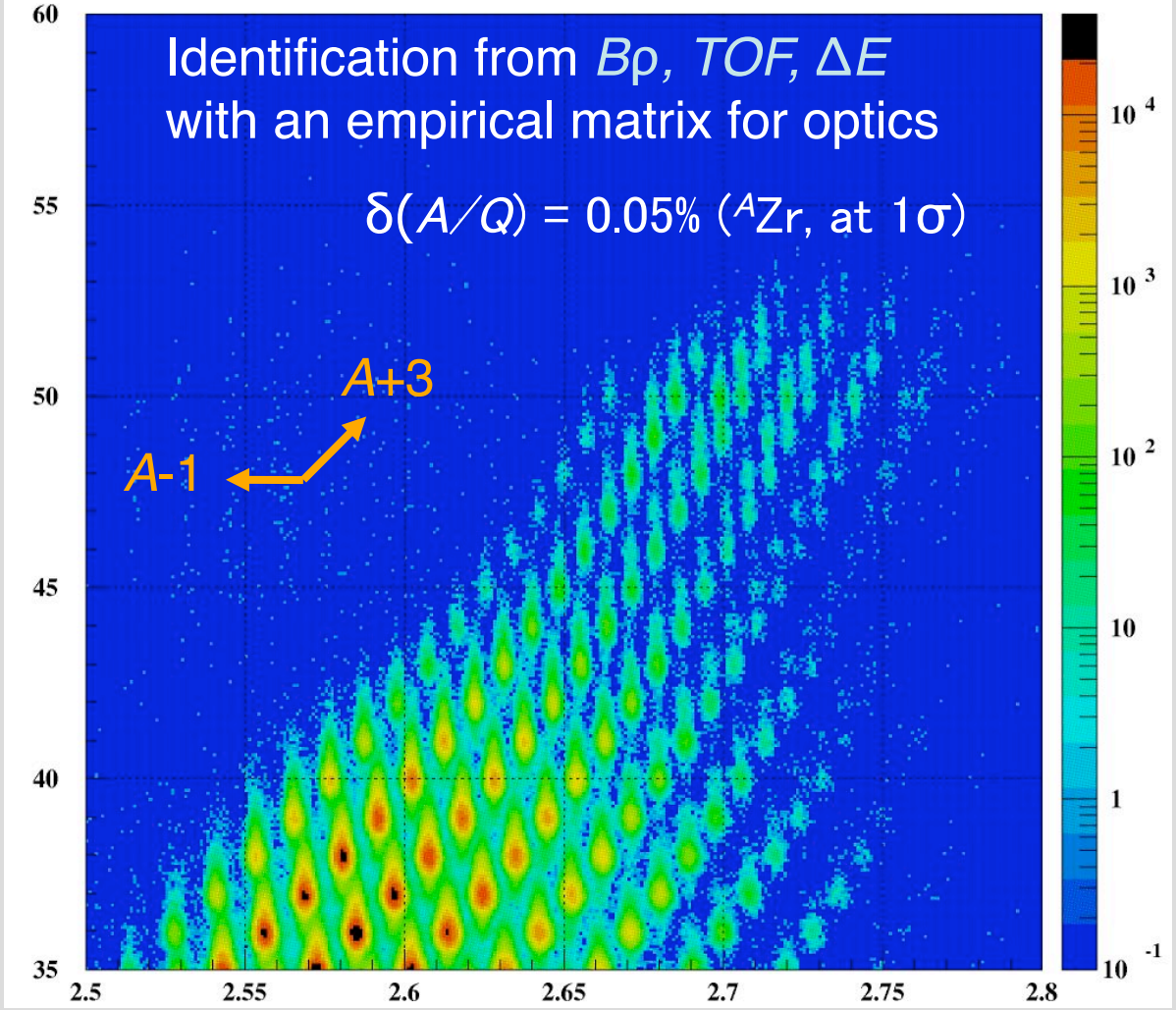
NN effective interaction



Transparent
- nucl. Interior
- single scattering
  - p-elastic => density

large $V_{\sigma\tau}/V_0$
- spin-isospin modes
  - GT, spin dipole …

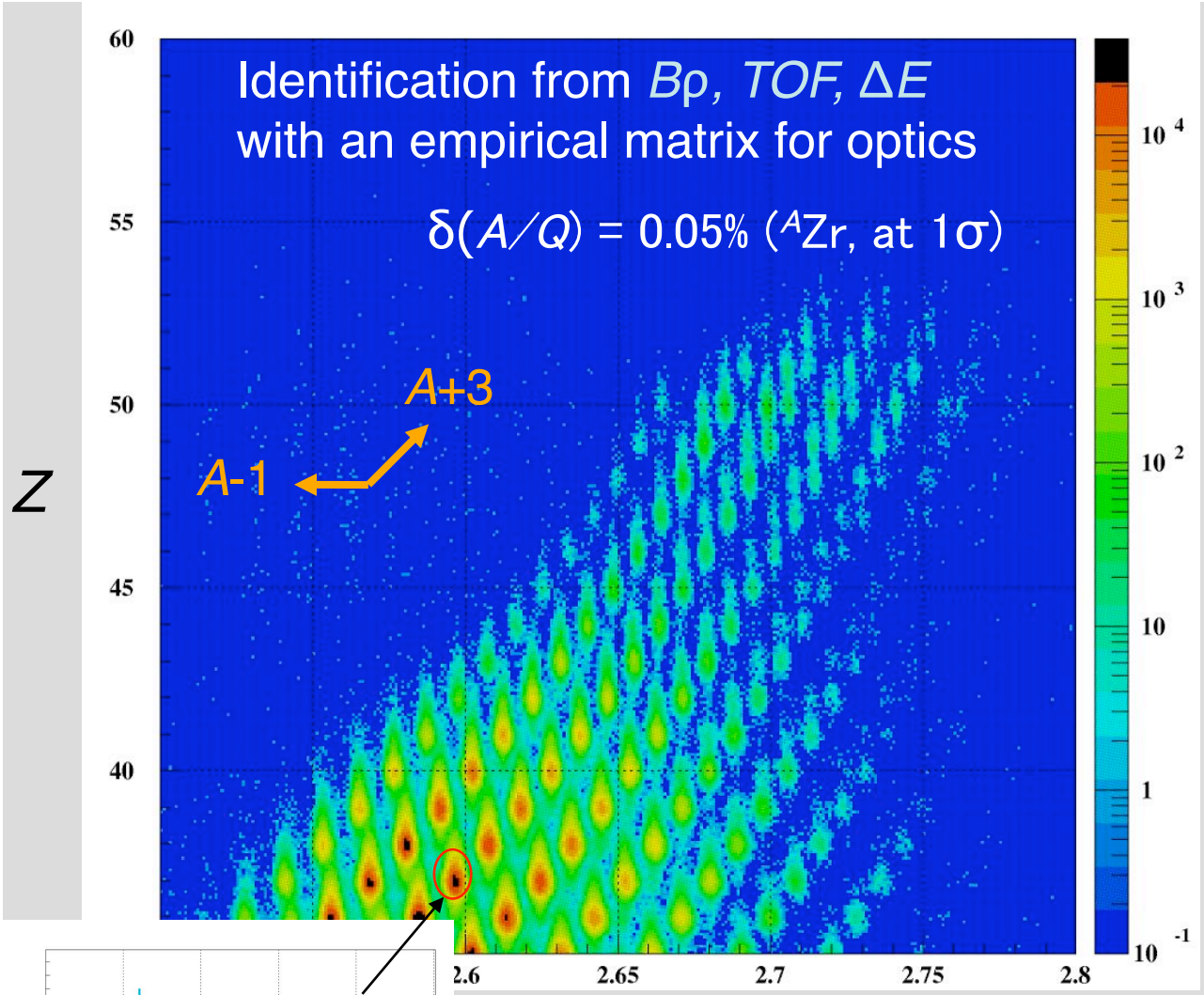
→ Sakai

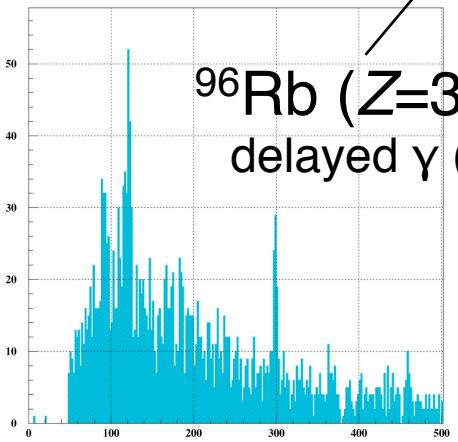


May 2007
new isotope

BigRIPS

Big RIPS: spectrometer



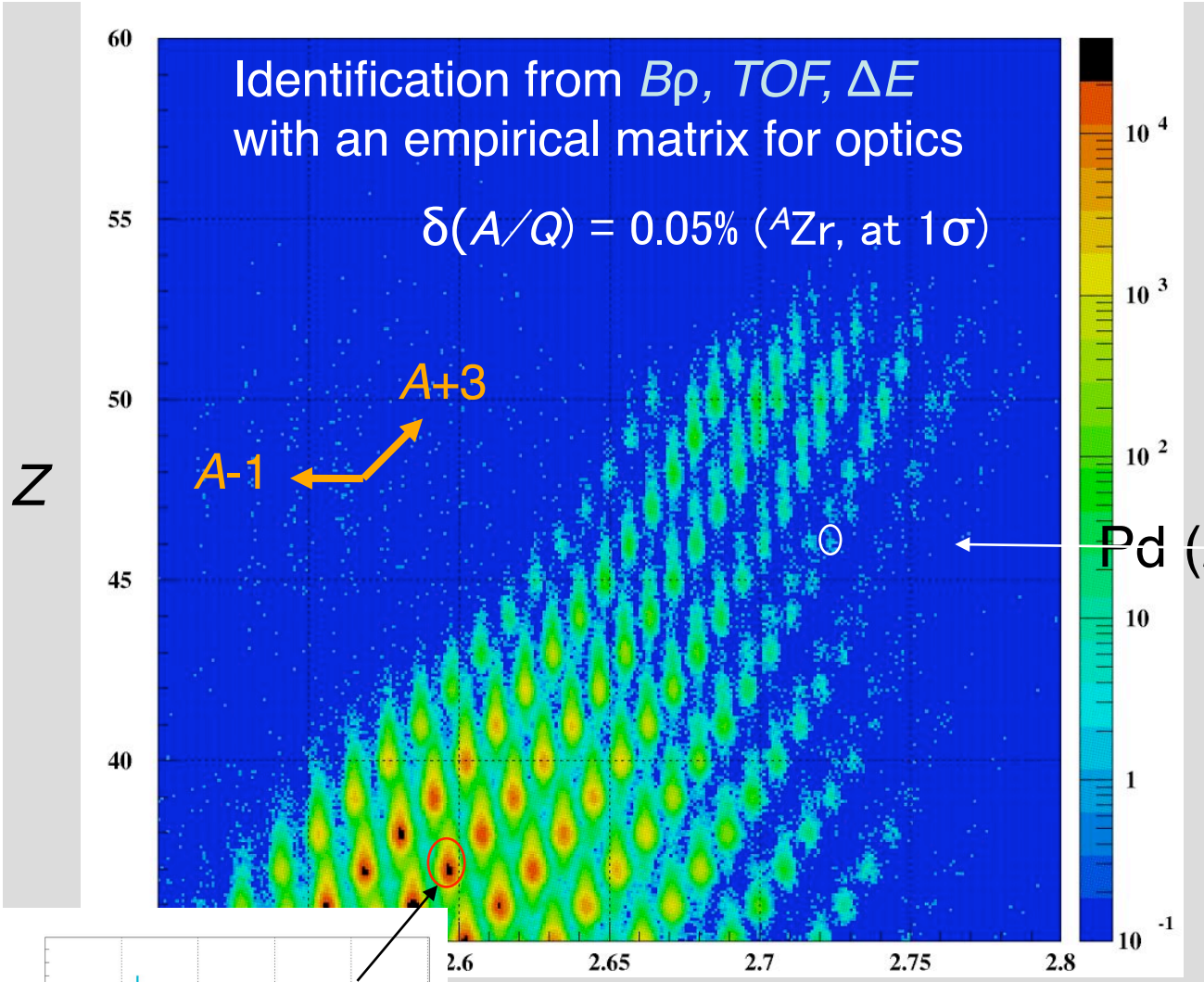


May 2007
new isotope

BigRIPS

Big RIPS: spectrometer

Kernz08

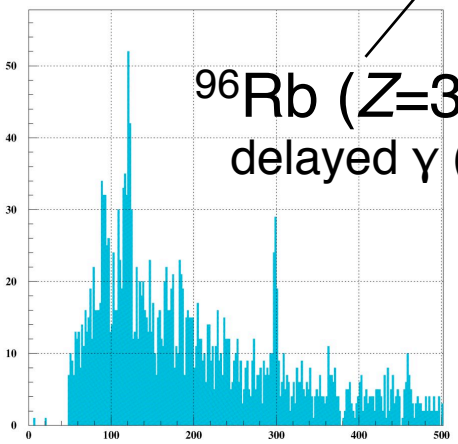


May 2007
new isotope

BigRIPS

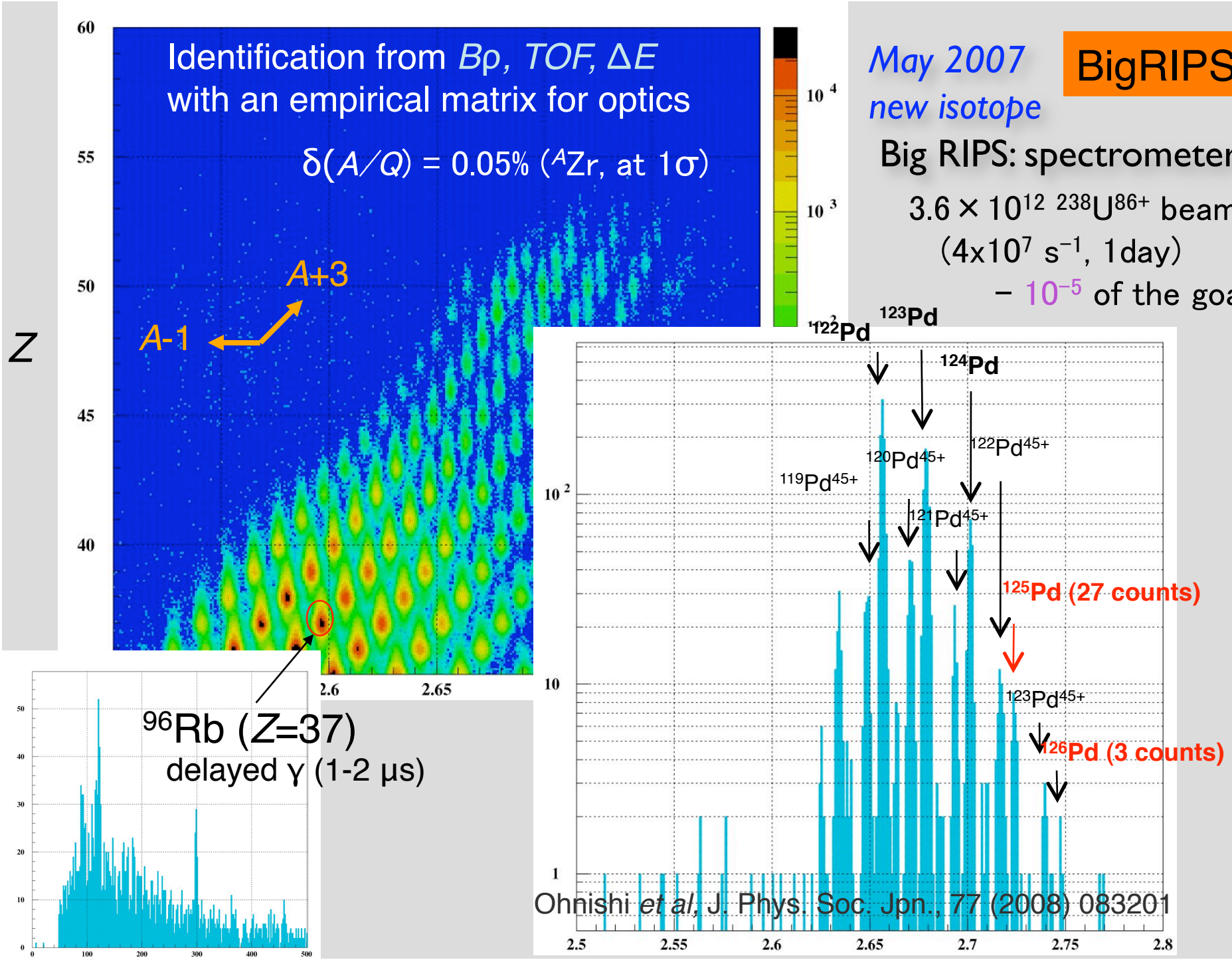
Big RIPS: spectrometer

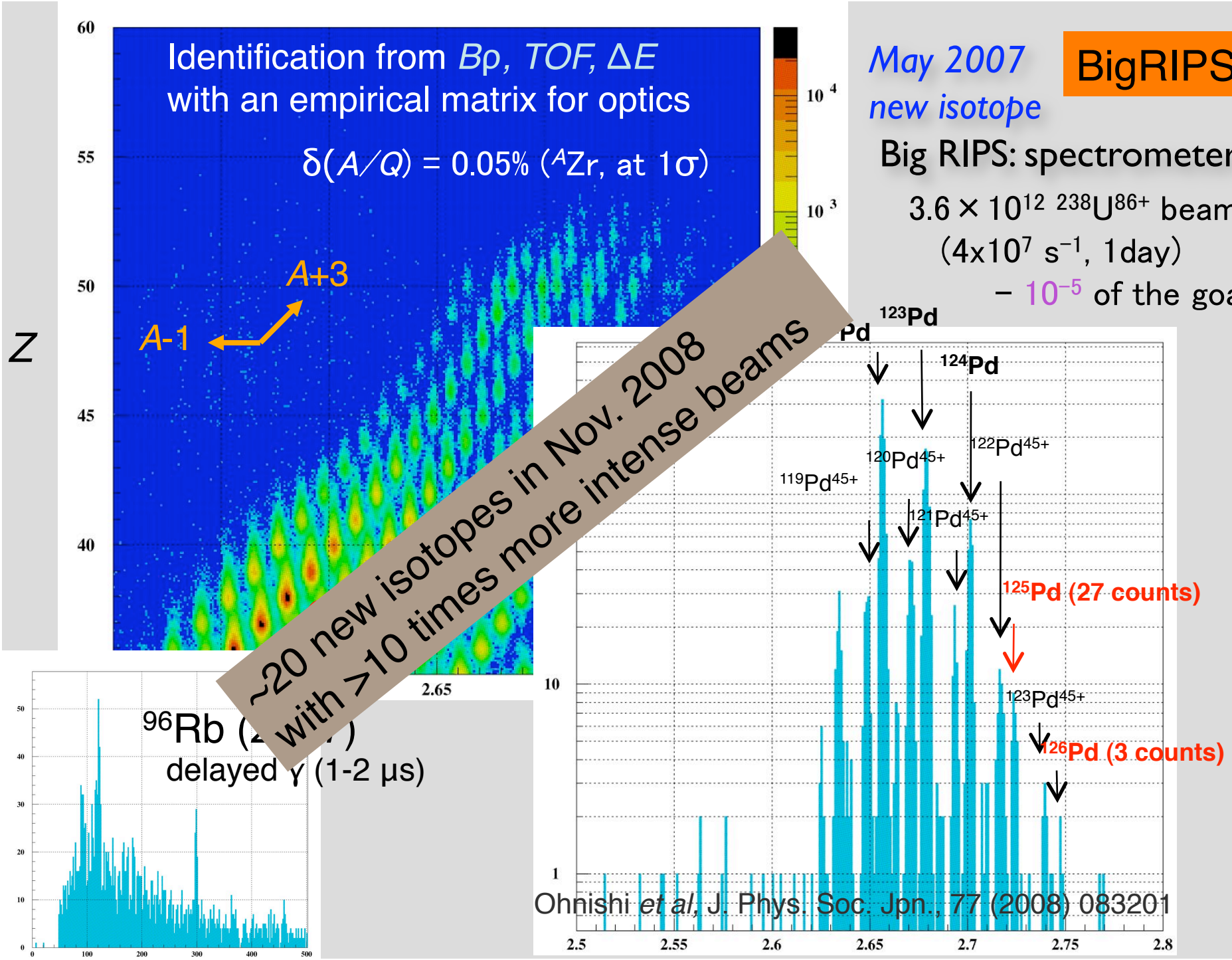
Pd (*Z*=46)



^{96}Rb (*Z*=37)
delayed γ (1-2 μs)

Kernz08

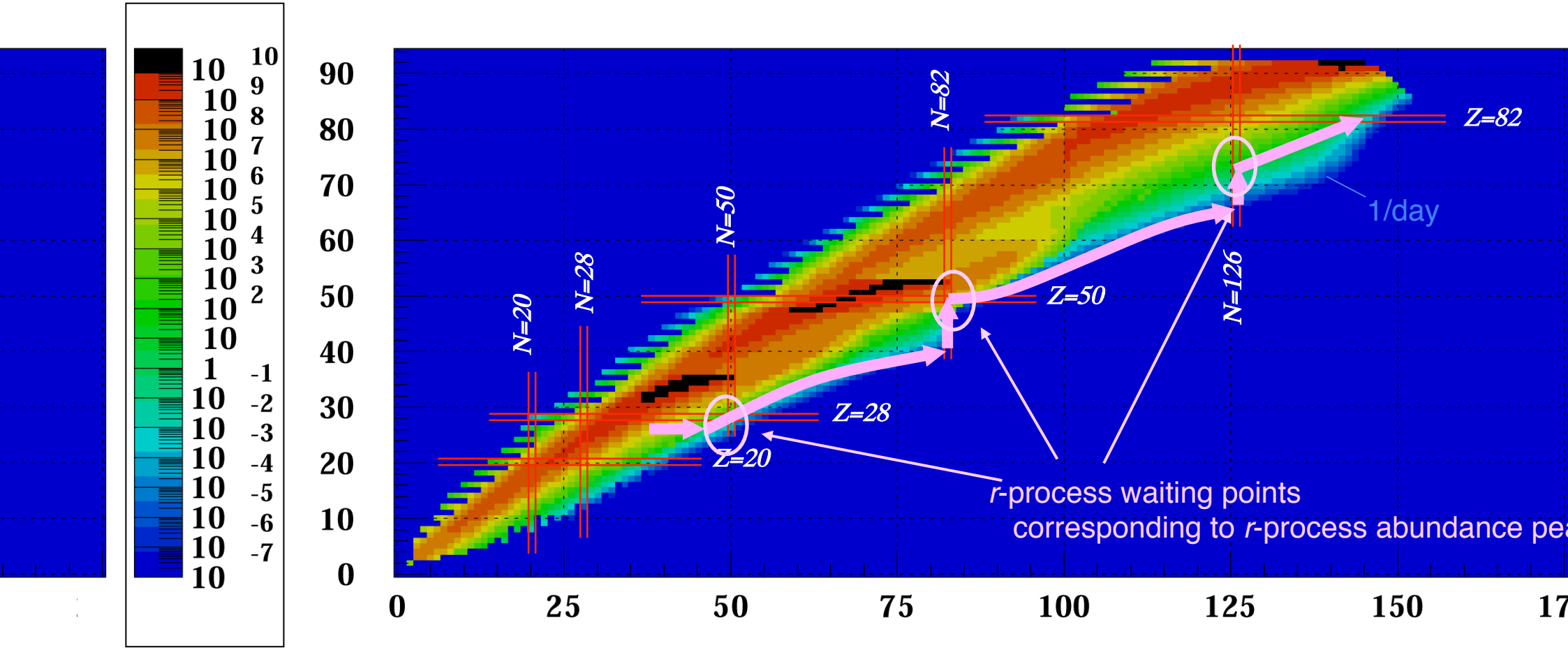

Identification from Bρ, TOF, ΔE
with an empirical matrix for optics
δ(A/Q) = 0.05% (AZr, at 1σ)
A+3
A-1
Z
60
55
50
45
40
2.6
2.65
96Rb (Z=37)
delayed γ (1-2 μs)
May 2007
new isotope
BigRIPS
Big RIPS: spectrometer
3.6 × 10^12 238U86+ beam
(4x10^7 s^-1, 1day)
– 10^-5 of the goal
123Pd
122Pd
124Pd
120Pd45+
122Pd45+
119Pd45+
121Pd45+
125Pd (27 counts)
123Pd45+
126Pd (3 counts)
Ohnishi et al, J. Phys. Soc. Jpn., 77 (2008) 083201



Ohnishi *et al*, J. Phys. Soc. Jpn., 77 (2008) 083201

Estimated beam intensity at BigRIPS

$^{86}Kr/^{136}Xe/^{238}U$ 1pμA



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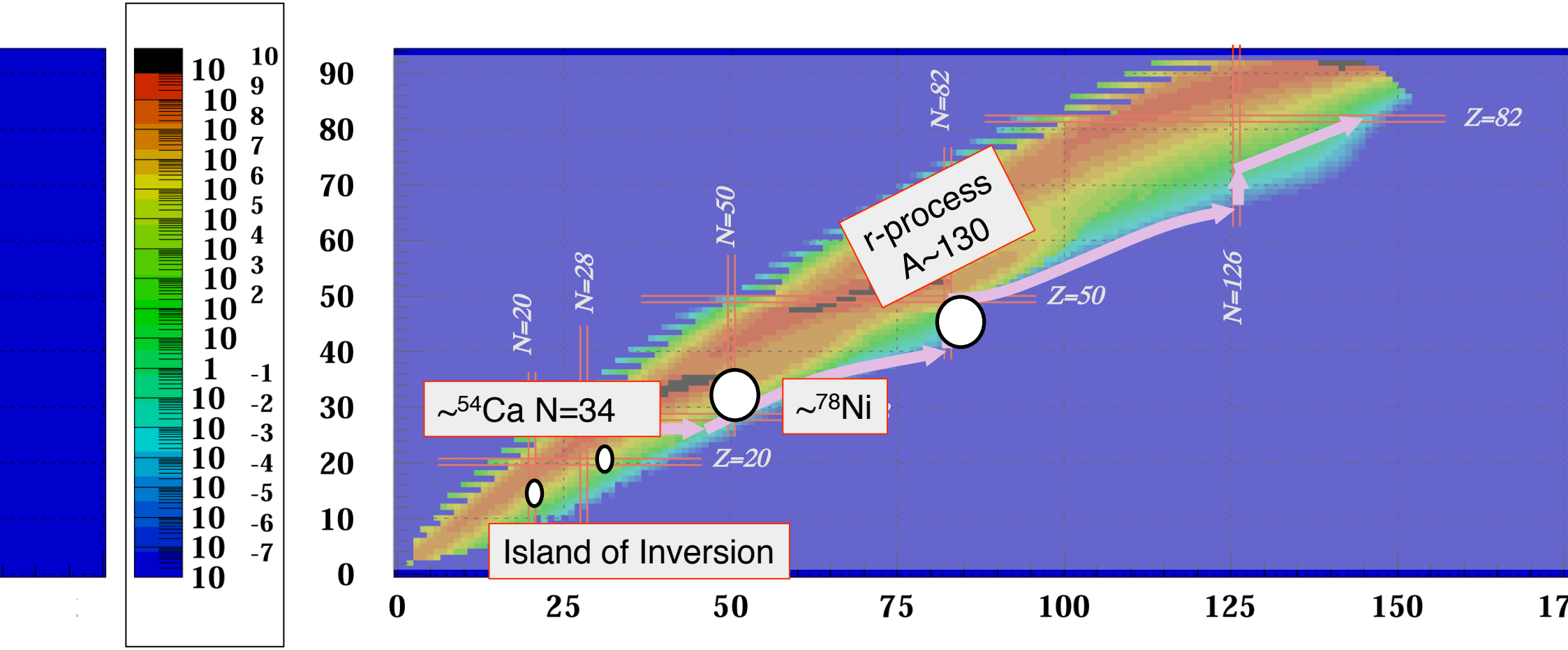

PAC-approved studies

Summary

direct reaction with fast RI beam -- nuclear structure

- intense RI beams (← fragmentation (fission))
- γ ray measurement / invariant mass measurement
- choice of reactions (with large cross section)
- development of experimental devices
  - γ-array, spectrometers, …
- reaction theory
- shell closure – collectivity, p/n motions, astro. process

RIBF new facility

- more intense (higher energy) beams ➔ more exotic
- energy dependence – E2/M1, spin-isospin modes, …

more (theory) efforts

- reaction mechanism with poor experimental information
- sophisticated (microscopic) theoretical treatments
- more theoretical control for parameters
  - *e.g.* optical pot. (imaginary part)
- theory suitable for 200-300 MeV/nucleon (*e.g.* eikonal CDCC)