Nuclear physics in Japan - I*
nuclear structure and reactions, low energy

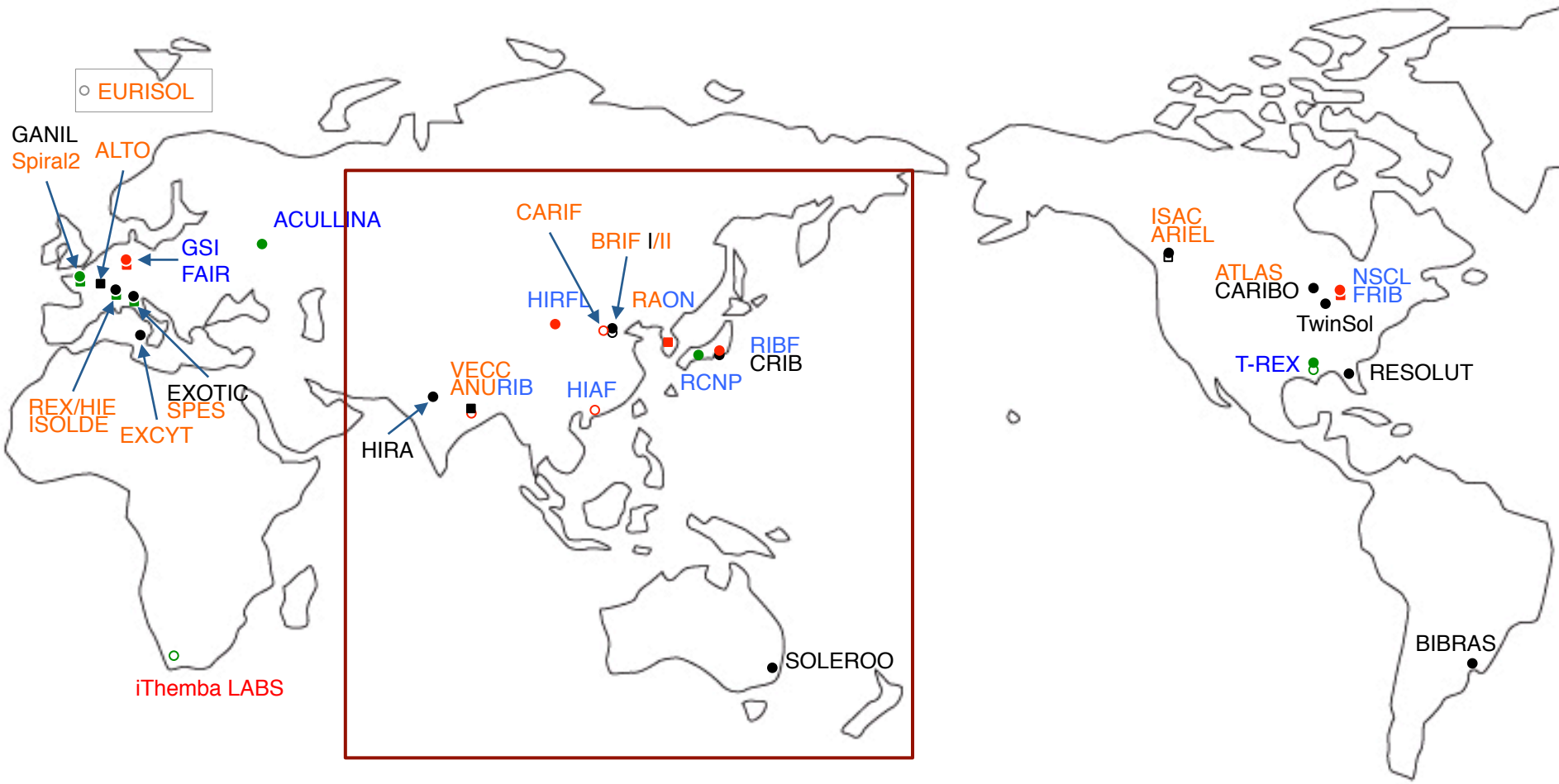
--- Nuclear physics and nuclear astrophysics ---

Tohru Motobayashi
RIKEN Nishina Center

1. Facilities in Japan
2. Recent studies at
   - CNS, U. Tokyo ← S. Shimoura
   - RCNP, Osaka Univ. ← N. Aoi
   - RIKEN RIBF

* “Nuclear physics in Japan (hadron, high energy)” tomorrow by K. Tanaka

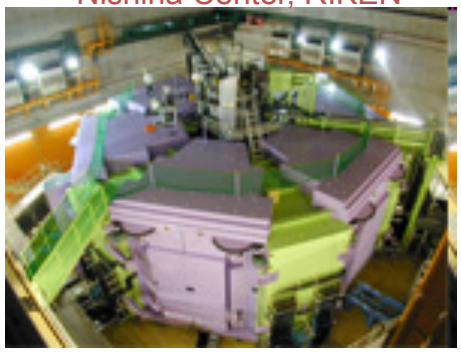
Asian activity expanding -- RI beam facilities as an example



World map of RI beam facilities

Accelerator facilities for nuclear physics in Japan - 1

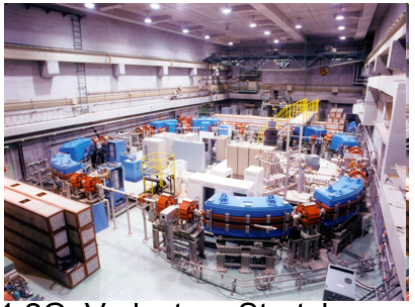
Nishina Center, RIKEN



K2600 **RIBF**

Heavy ion (RIB)

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 / light heavy ion

HIMAC at National Institute of Radiological Sciences

800MeV/A Synchrotron

heavy ion (therapy)

J-PARC, KEK/JAEA)

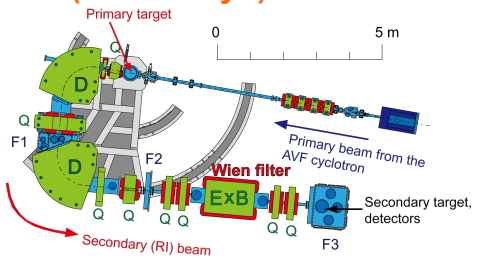
30GeV Proton Synchrotron

π, K, μ, n, (ν)

Smaller

Japanese Accelerators available for Nuclear Physics Community

CNS (Univ. Tokyo)

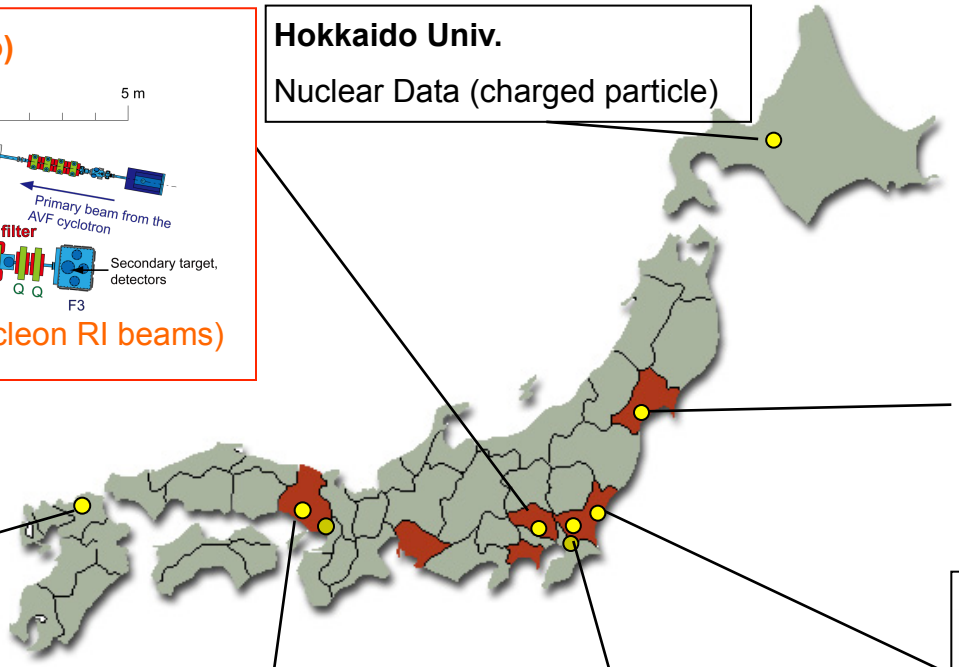


CRIB (~5 MeV/nucleon RI beams)

RI beam

Hokkaido Univ.

Nuclear Data (charged particle)

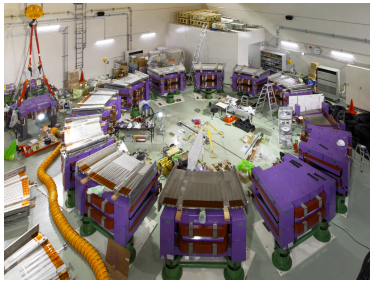


CYRIC (Tohoku Univ.)

Cyclotron (p 90 MeV)

lignt ions

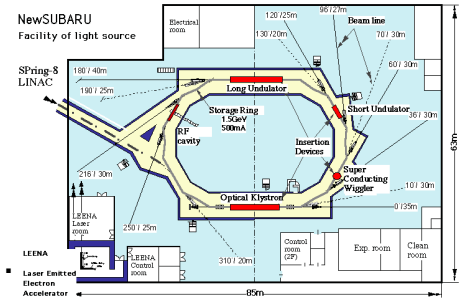
Kyushu Univ.



FFAG

p (150 MeV)

NEW SUBARU



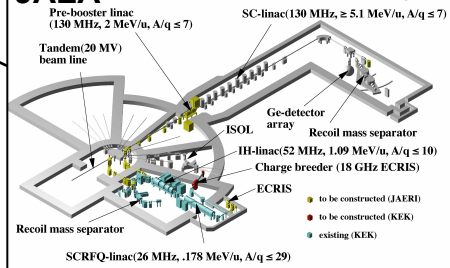
SOR (2-10 MeV photons)

photon (inverse Compton)

Tsukuba Univ.

Tandem → Vdg. (earthquake)

JAEA



TRIAC → Tandem

→ KISS (@RIKEN), Korea

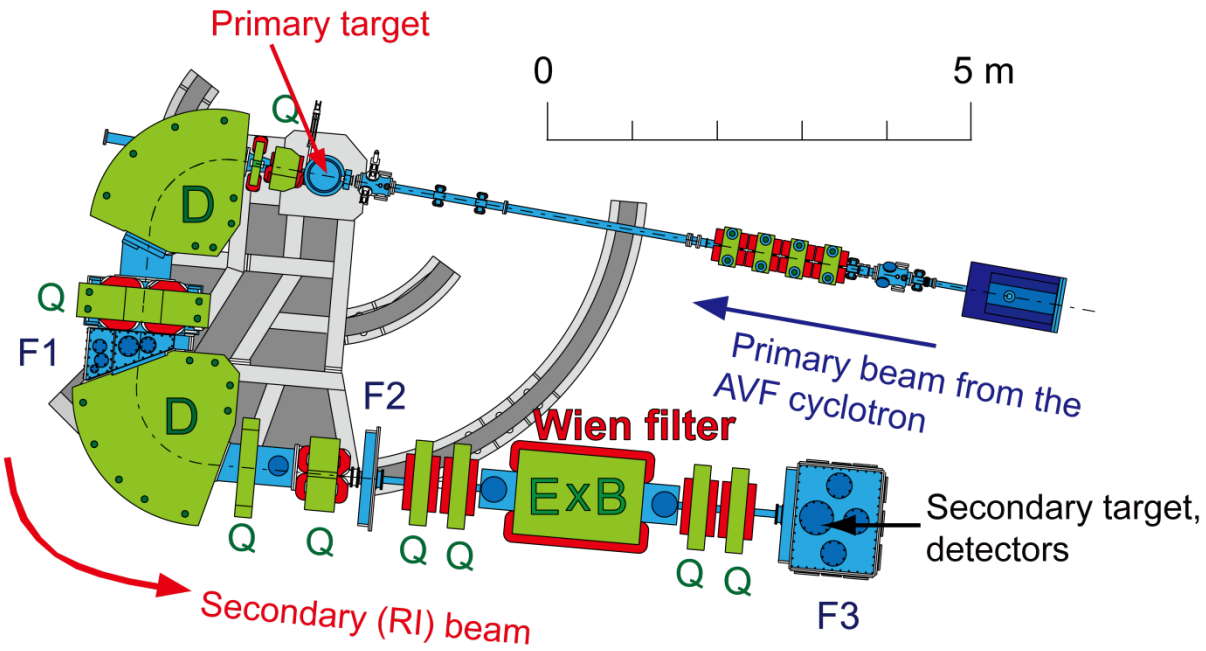
heavy ions

CNS, U. Tokyo

Located at RIBF (RIKEN Nishina Center)

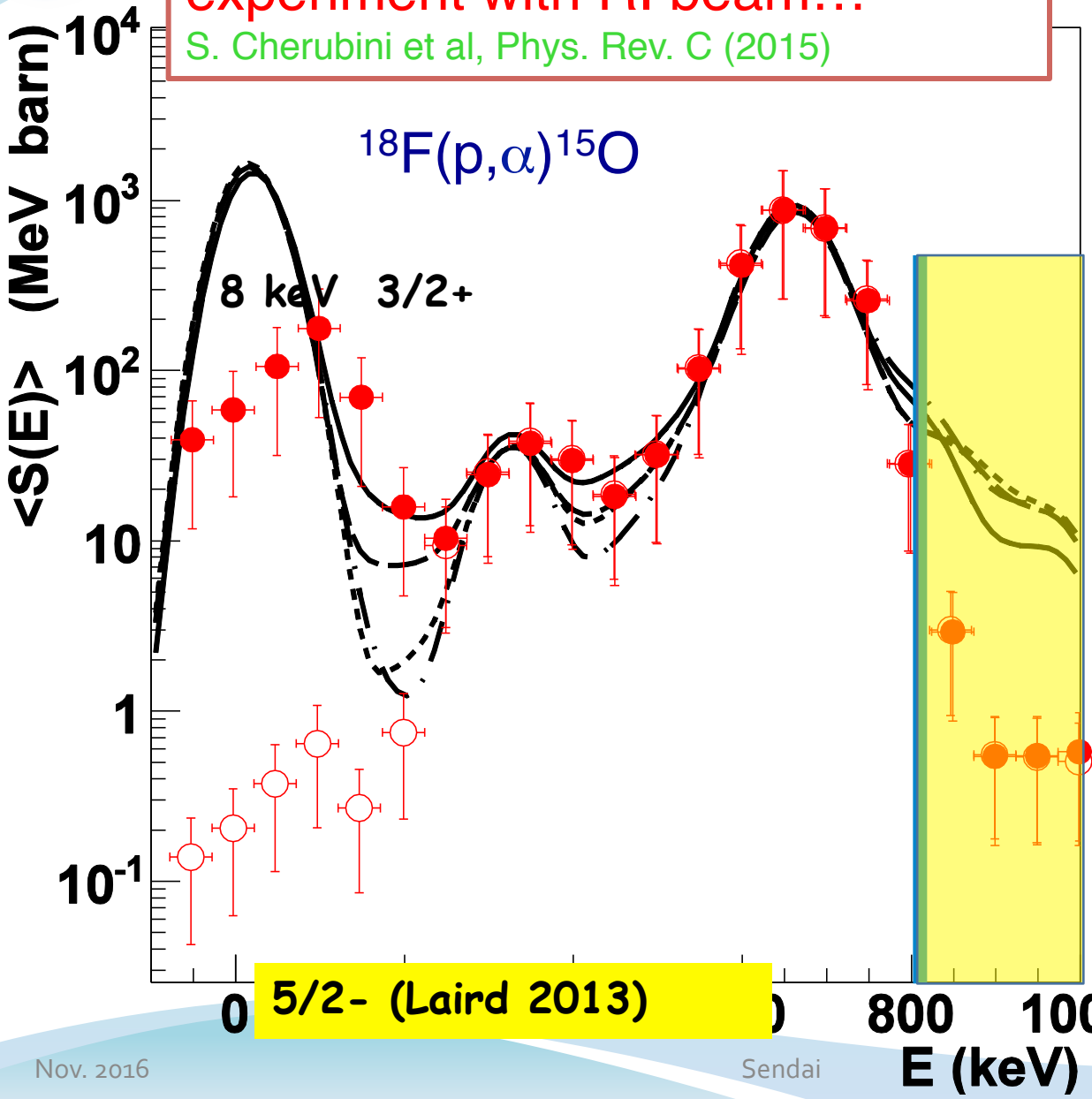
CRIB

- CNS Radio-Isotope Beam separator , constructed and operated by CNS
  - Low-energy(<10MeV/u) RI beams by in-flight method.
  - Primary beam from K=70 AVF cyclotron (an injector of RIBF).
  - Momentum (Magnetic rigidity) separation by "double achromatic" system, and velocity separation by a Wien filter.
  - Orbit radius: 90 cm, solid angle: 5.6 msr, momentum resolution: 1/850.



The **first** Trojan Horse experiment with RI beam…

S. Cherubini et al, Phys. Rev. C (2015)



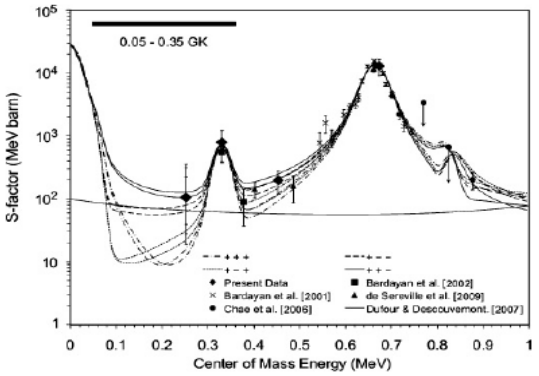


FIG. 3. The $^{18}F(p,\alpha)^{15}O$ S factors, calculated using the R matrix, for eight possible interference terms. The range in possible S factors arises from the interference between the $J^\pi = 3/2^+$ resonances. The interference between resonances dominates in the region of interest, resulting in four groups of S-factor curves. The upper and lower curves of each group are shown in the figure. The legend gives the assumed phase, for the 8-, 38-, and 665 keV resonances, respectively, for each pair of curves. Also plotted are the measured S factors from this work, those from previously published data [4,10,12,19], and the proposed contribution from $1/2^+$ states predicted in Ref. [6].

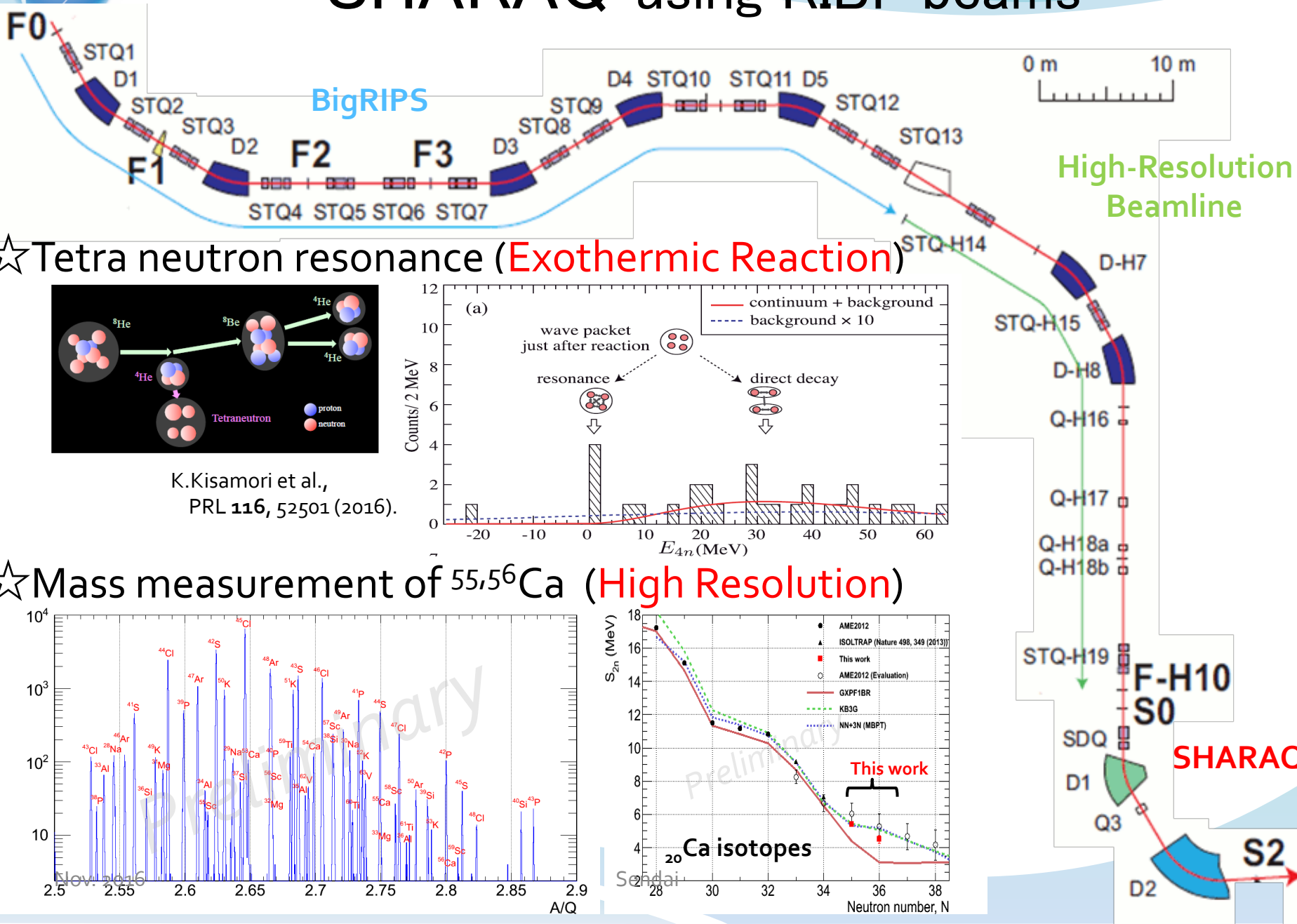
Direct data…C.E. Beer, et al.

THM data

C.E. Beer, Phys. Rev. C 83, 042801(R) (2011)

Smeared to THM resolution

SHARAQ using RIBF beams



☆Tetra neutron resonance (Exothermic Reaction)

K.Kisamori et al.,
PRL **116**, 52501 (2016).

☆Mass measurement of ^{55,56}Ca (High Resolution)

RCNP, Osaka

大阪大学
OSAKA UNIVERSITY

RCNP Cyclotron Facility

RI Beam
Unstable nucleus

Ultra cold neutron
Fundamental science

Ring Cyclotron
K=400 MeV, Since 1992

Quasi-mono energetic neutron
Nuclear data

Grand Raiden
Precise physics

MuSIC
Muon science

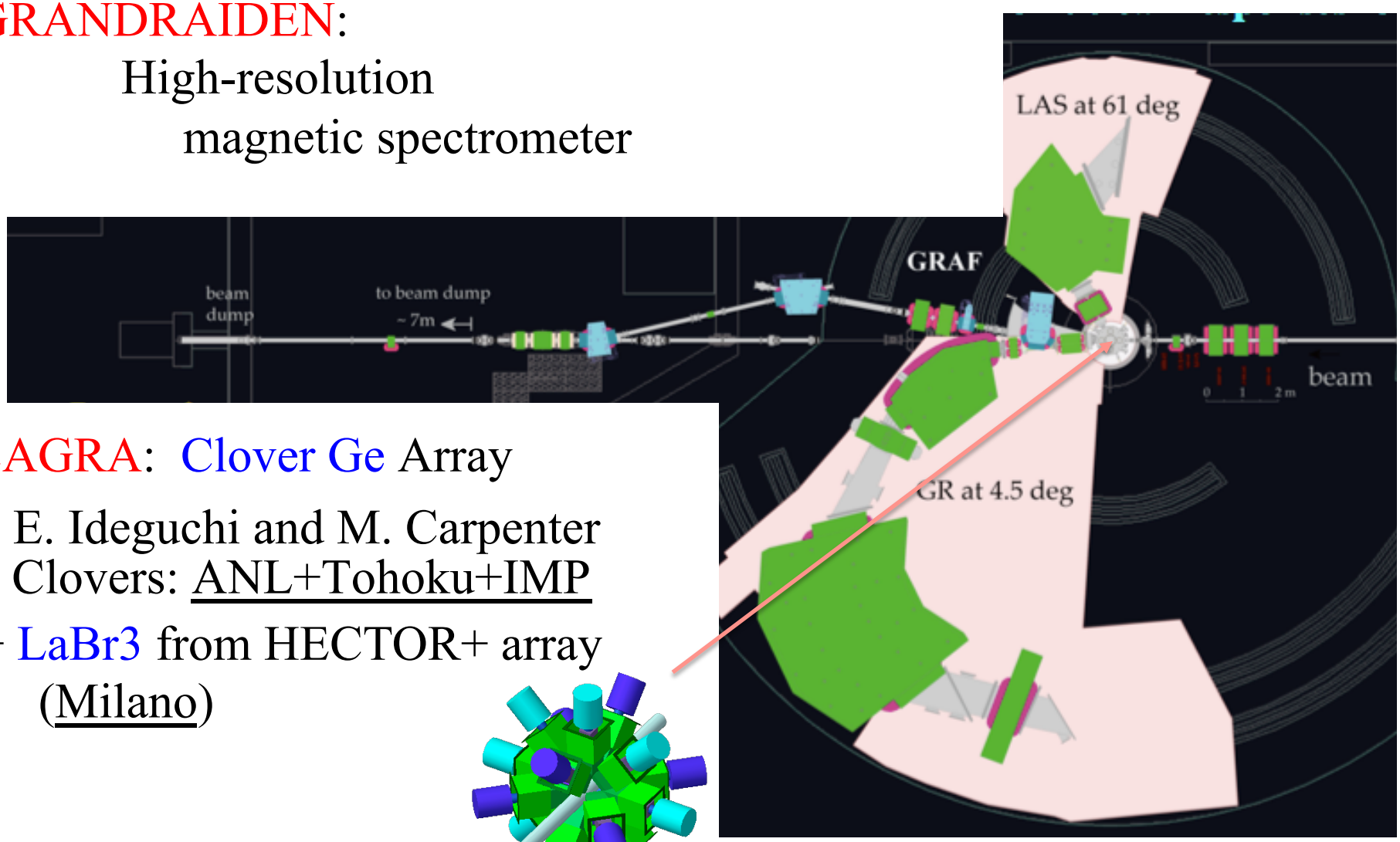
White neutron irradiation
Semiconductor

AVF Cyclotron
K=140 MeV, Since 1973

GRANDRAIDEN:

High-resolution

magnetic spectrometer



CAGRA: Clover Ge Array

E. Ideguchi and M. Carpenter

Clovers: ANL+Tohoku+IMP

+ LaBr3 from HECTOR+ array (Milano)

CAGRA+GR Campaign Exp. From Oct. 2016

A. Tamii (RCNP)

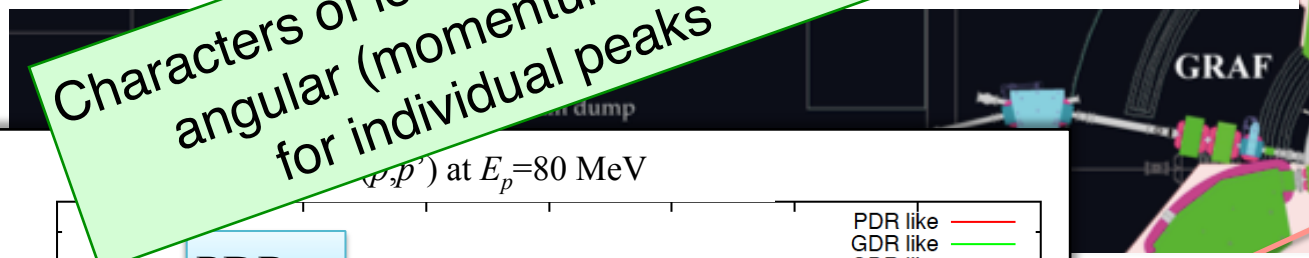
1. Structure of the PDR *1 ($\alpha,\alpha'\gamma$) and ($p,p'\gamma$) on ^{58}Ni, ^{90,94}Zr, ^{120,124}Sn, ^{206,208}Pb

2. Inelastic ν-nucleus response

3. Super-deformed states, high-spin st

*1 A. Bracco, F. Crespi, V. De… …hioto, P. von Neumann-Cosel … …mer, and A. Zilges *et al.*

Characters of low-energy dipole excitation
angular (momentum transfer) distributions
for individual peaks



(p,p') at E_p=80 MeV

PDR like
GDR like
GDR like
GDR like
demo (stat.err. = 5%)
demo (stat.err. = 7%)
demo (stat.err. = 10%)

PDR mode

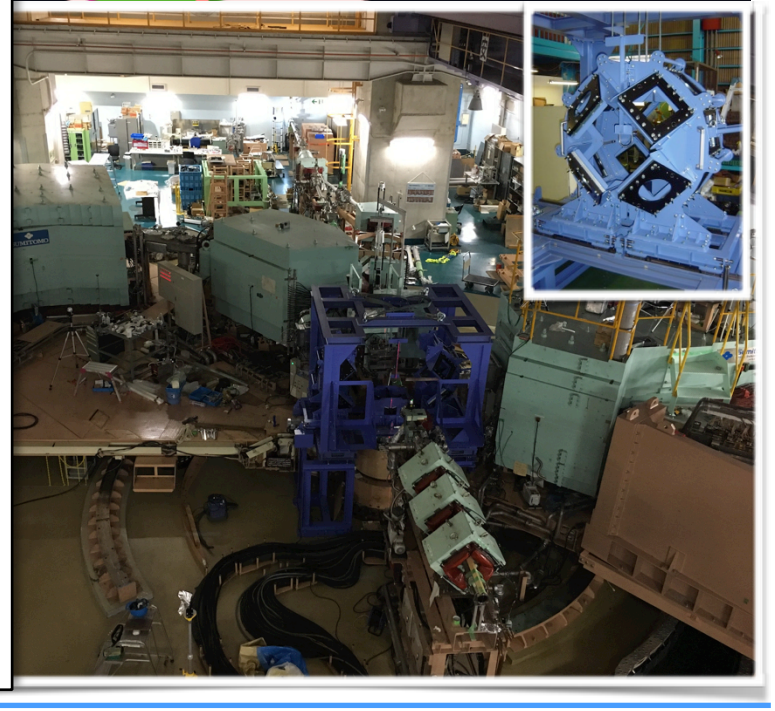
GDR mode

Estimated size of the statistical uncertainties

q-dep. of the PDR excitation for ^{208}Pb

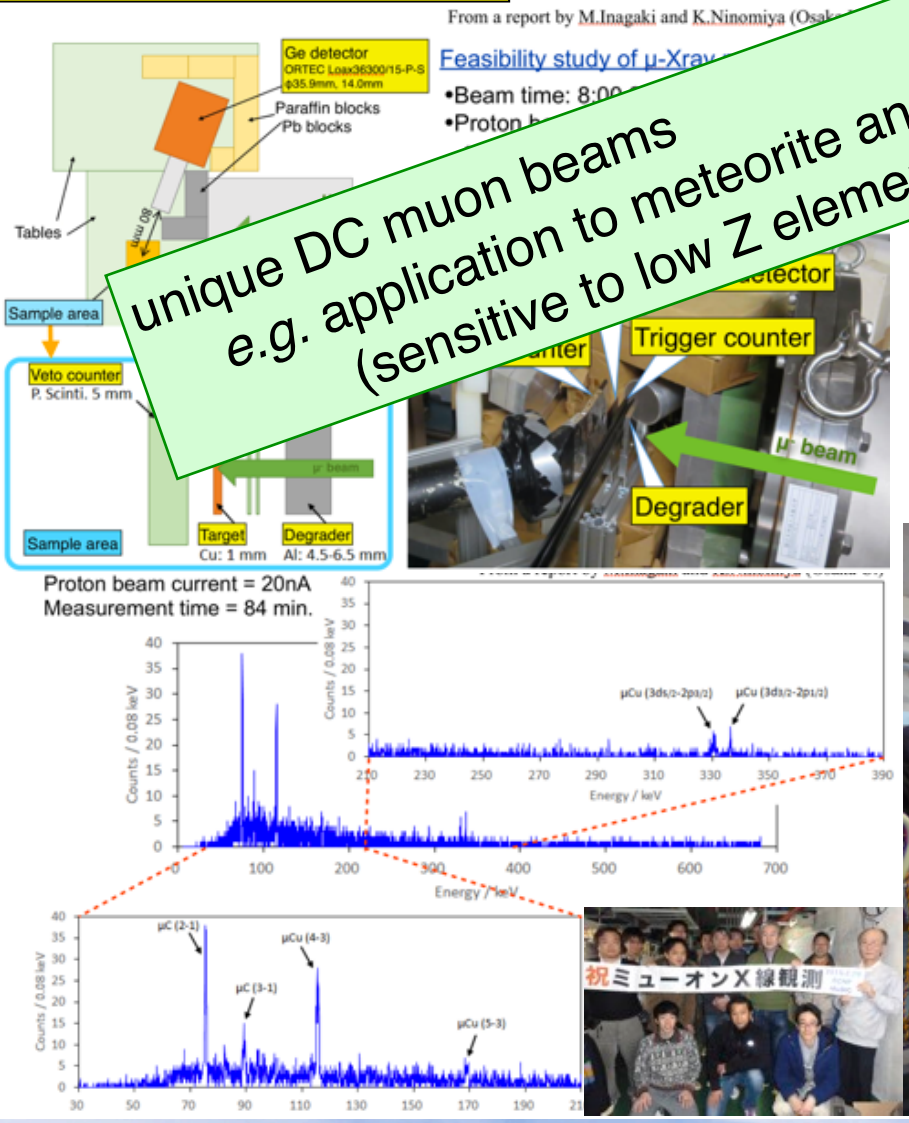
$d\sigma/d\Omega$ (mb/sr)

θ_{cm} (deg)



X- and γ-ray experiments with negative muon@ MuSIC

Feasibility study in Feb. 2015

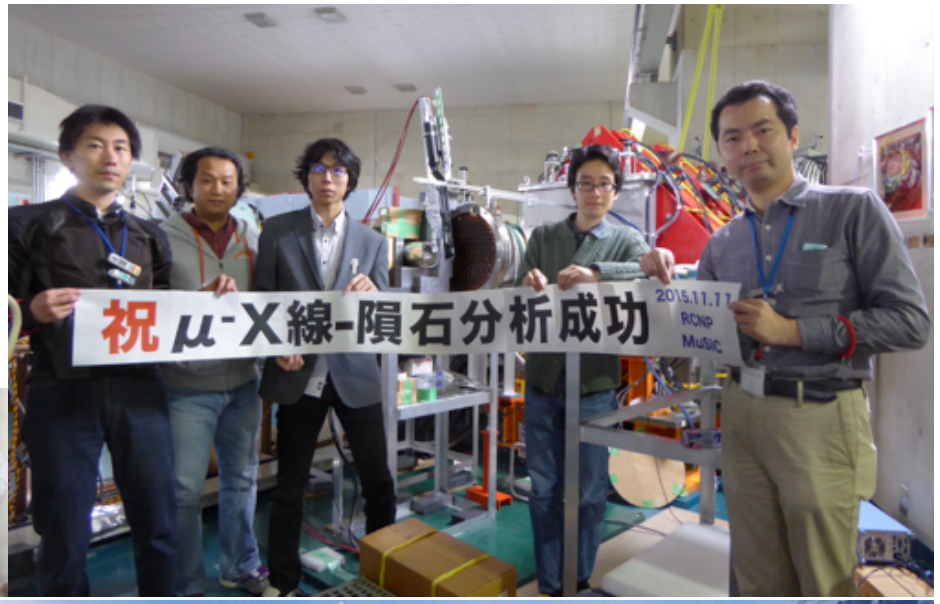


The first user beam time in Nov. 2015

11, the first user beam time for MuSIC, has been from 9th to 11th November 2015.

"Development on non-destructive elemental analysis of planetary materials by using high intensity μ⁻ beam", Sporks person: Kentaro Terada, Osaka Univ.

Non-distractive element analysis for meteorites was successfully performed with muonic X-rays.



RIKEN RIBF

RIBF – a new generation RIB facility in operation

2 (3) parallel injectors followed by 4 consecutive cyclotrons

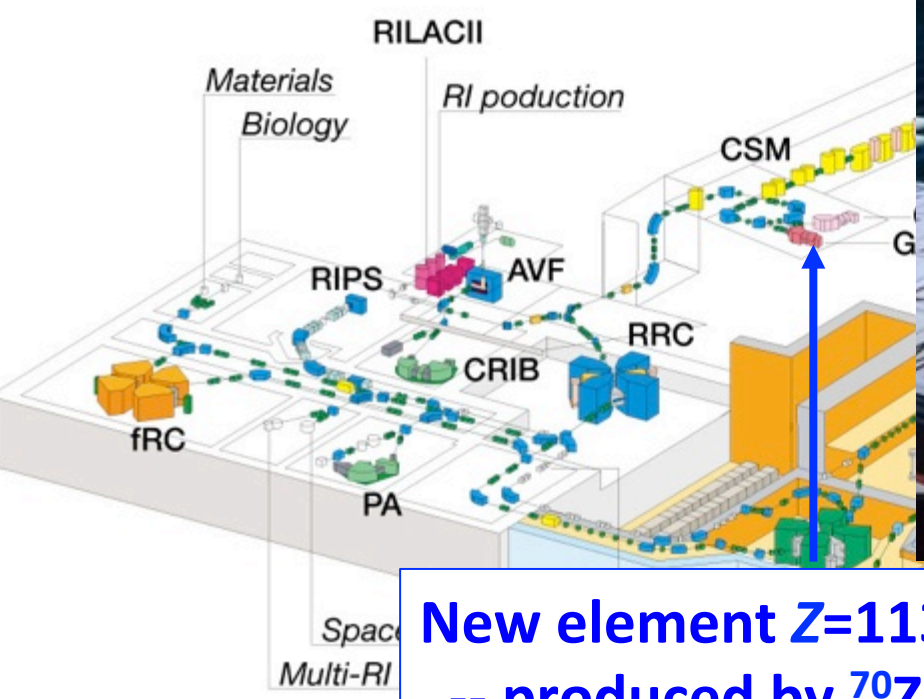
135 MeV/nucleon
for light nuclei (1986-)

345 MeV/nucleon
up to U (2006-)

experimental
equipment

Sendai

RIBF – a new generation RIB facilit



New element *Z*=113 (Nh, Nihonium – IUPAC proposing)
-- produced by ^{70}Zn+^{209}Bi fusion

135 MeV/nucleon
for light nuclei (1986-)

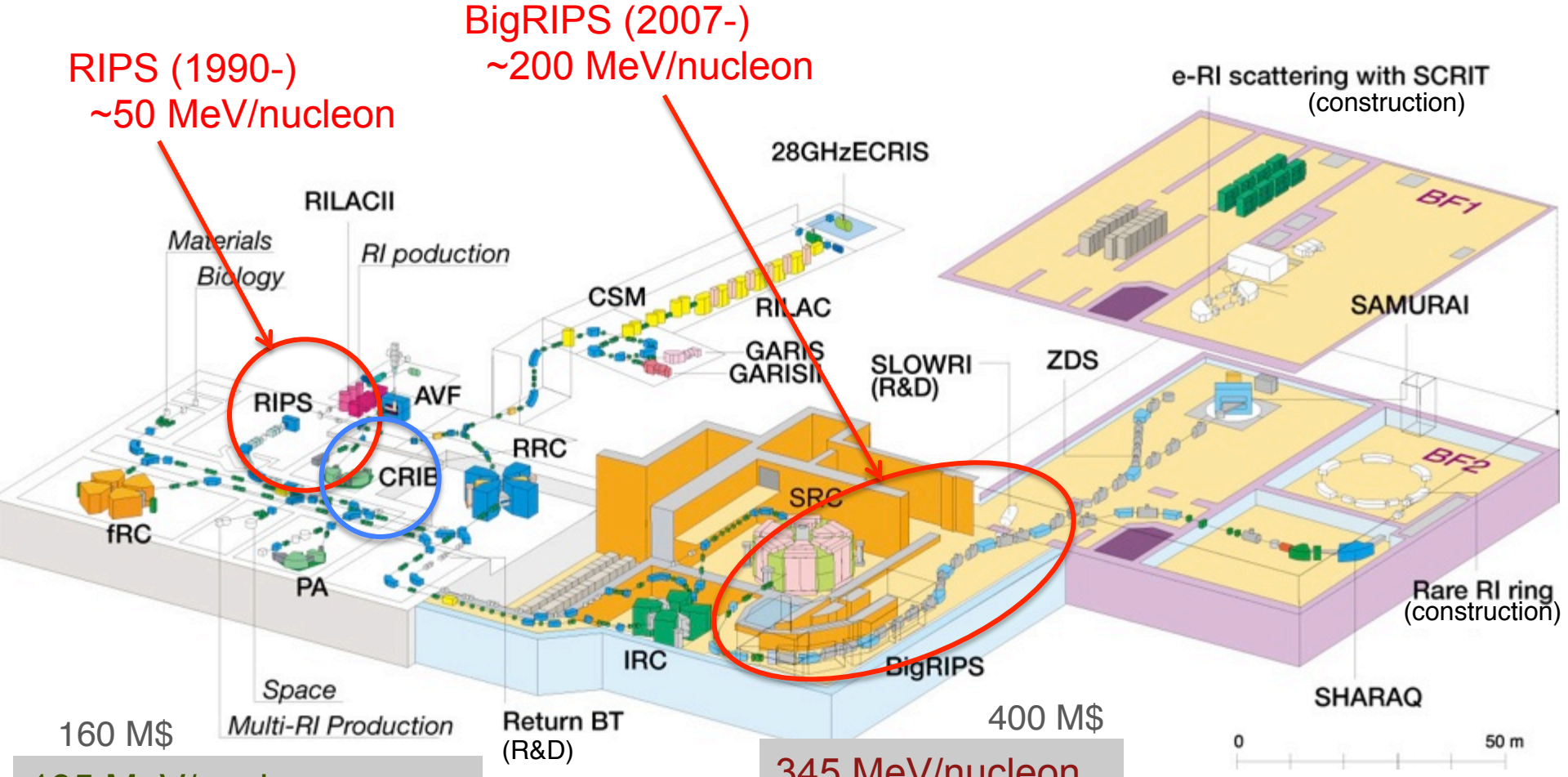
up to U (2006-)

experimental equipment

Sendai

Nov. 2016

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



160 M$

135 MeV/nucleon
for light nuclei (1986-)

400 M$

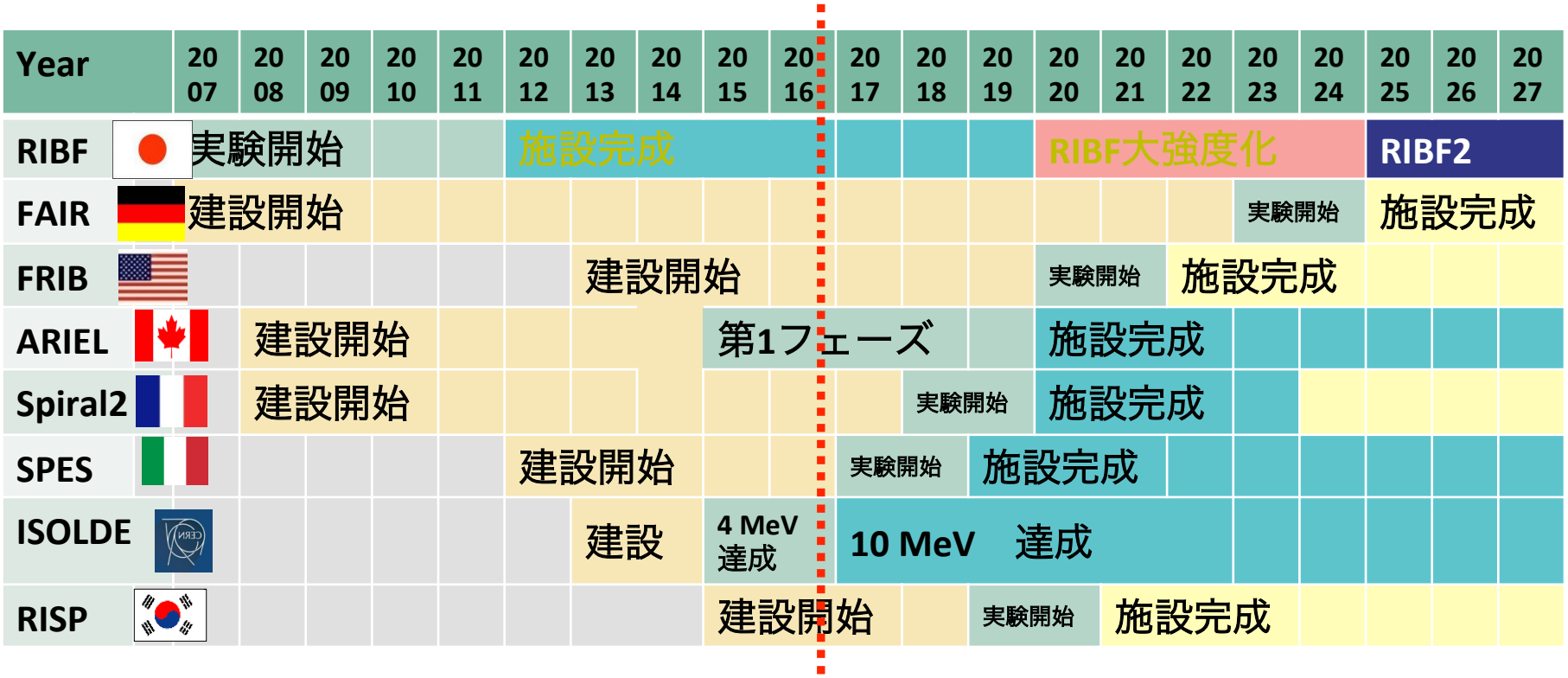
345 MeV/nucleon
up to U (2006-)

experimental
equipment

Sendai

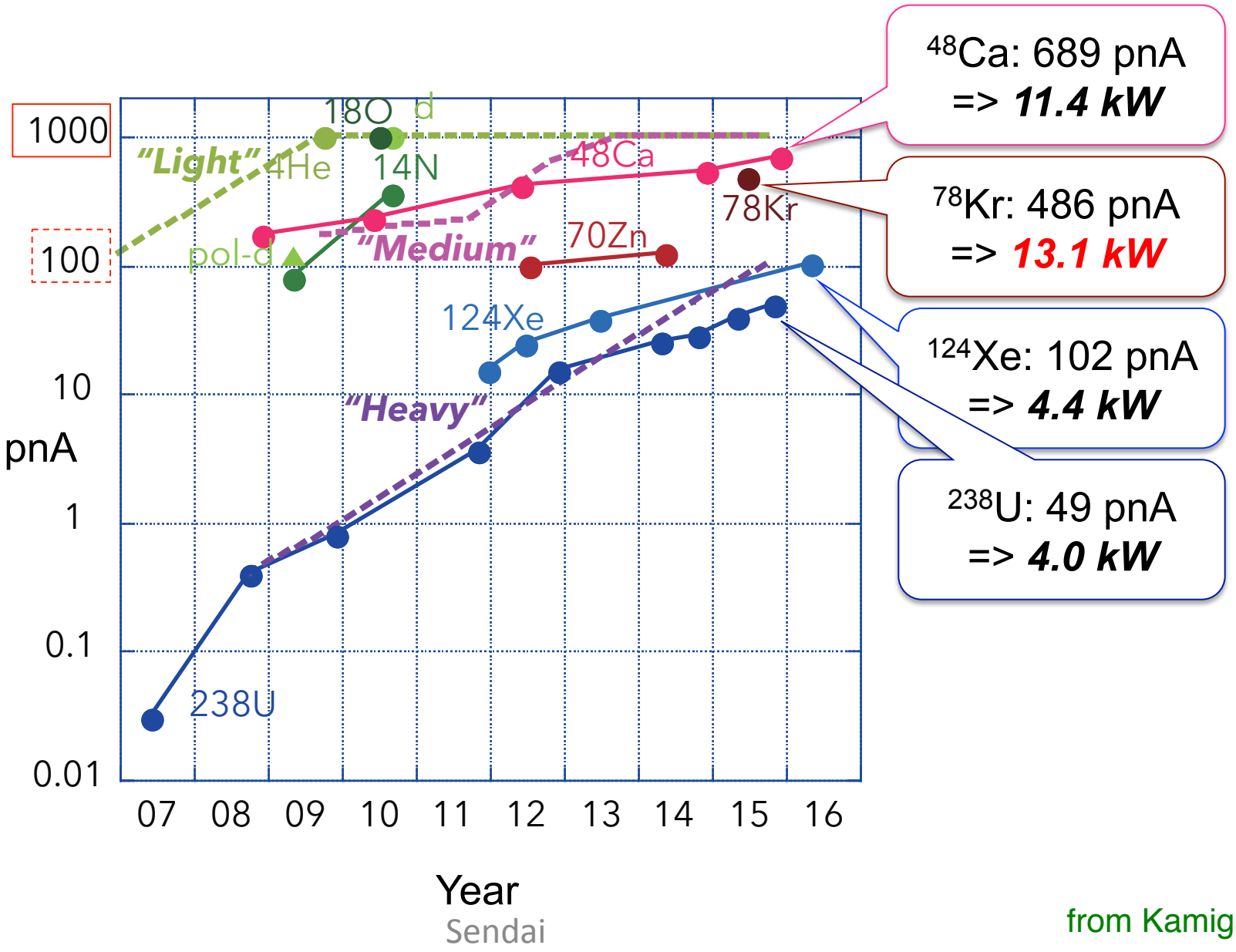
Nov. 2016

RIBF – a new-generation RIB facility in operation (fully)



HIAF China
ANURIB India
EURISOL Europe
..

(primary beam) intensity upgrade at RIBF



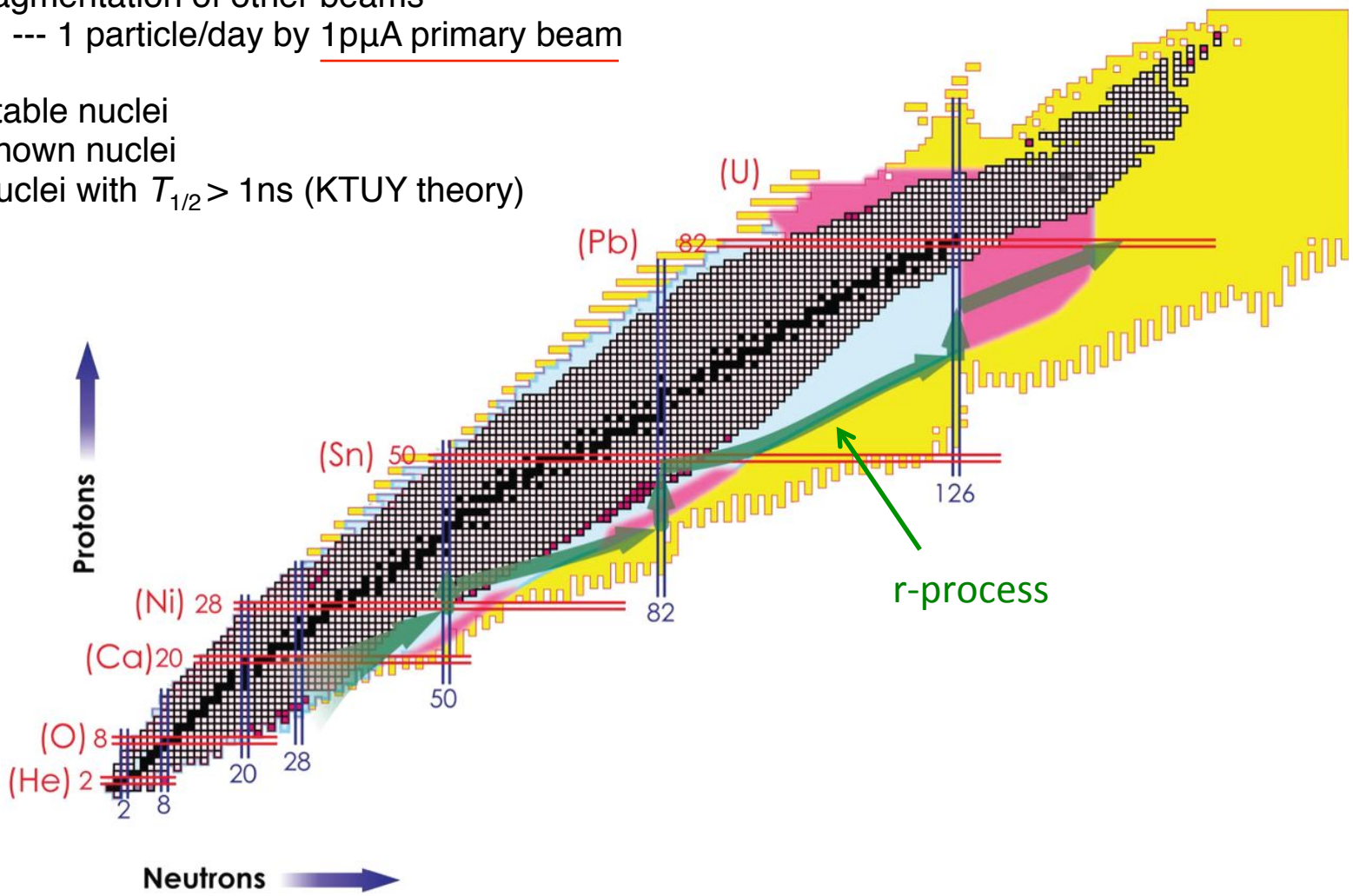
from Kamigaito

Nov. 2016

Nuclear chart potentially covered by RIBF

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

- Stable nuclei
- Known nuclei
- Nuclei with $T_{1/2}$ > 1ns (KTUY theory)



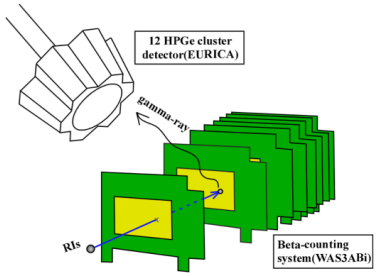
Motobayashi T , and Sakurai H Prog. Theor. Exp. Phys. 2012;2012:03C001

Recent results

1. **r-process** is being reached. -- nuclear astrophysics

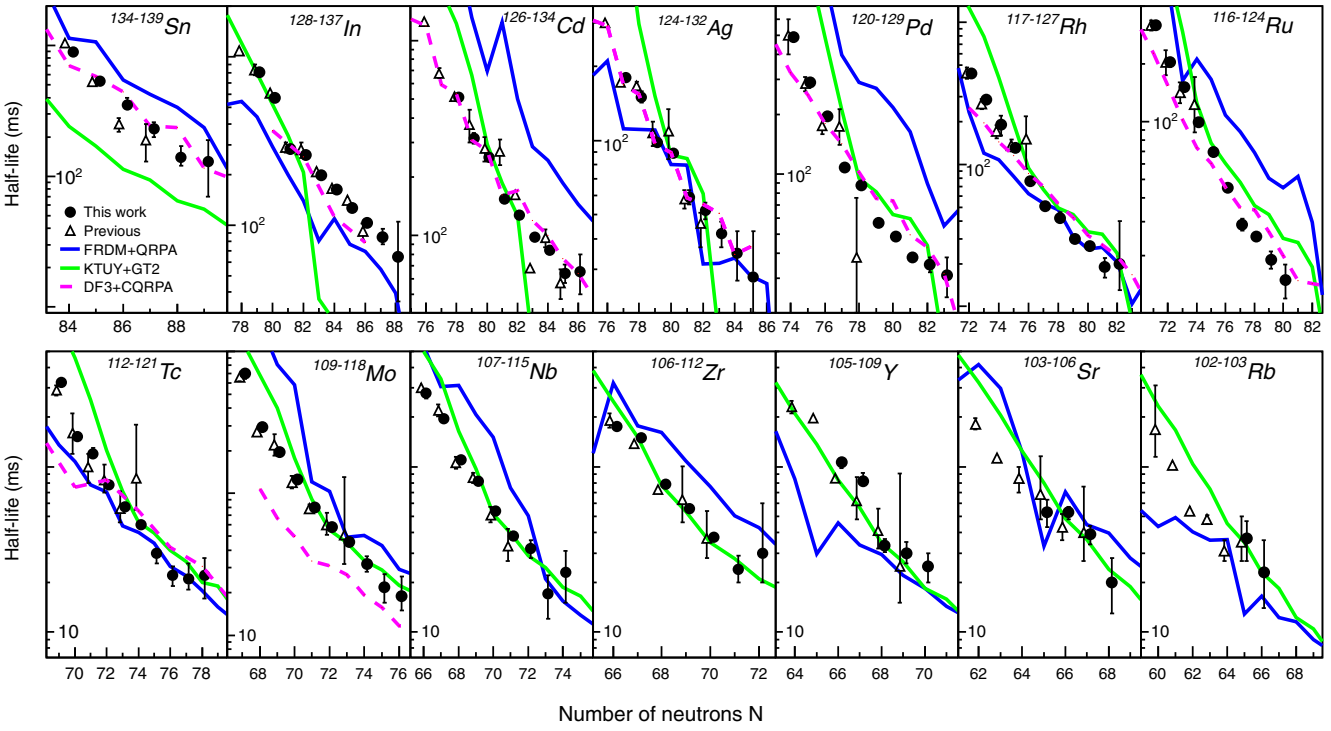
110 (40 new) half lives measured

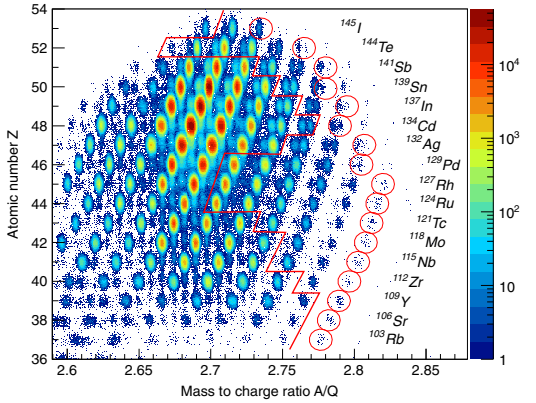
EURICA + WASABI



many r-process nuclei

12 EUROBALL clusters at RIKEN

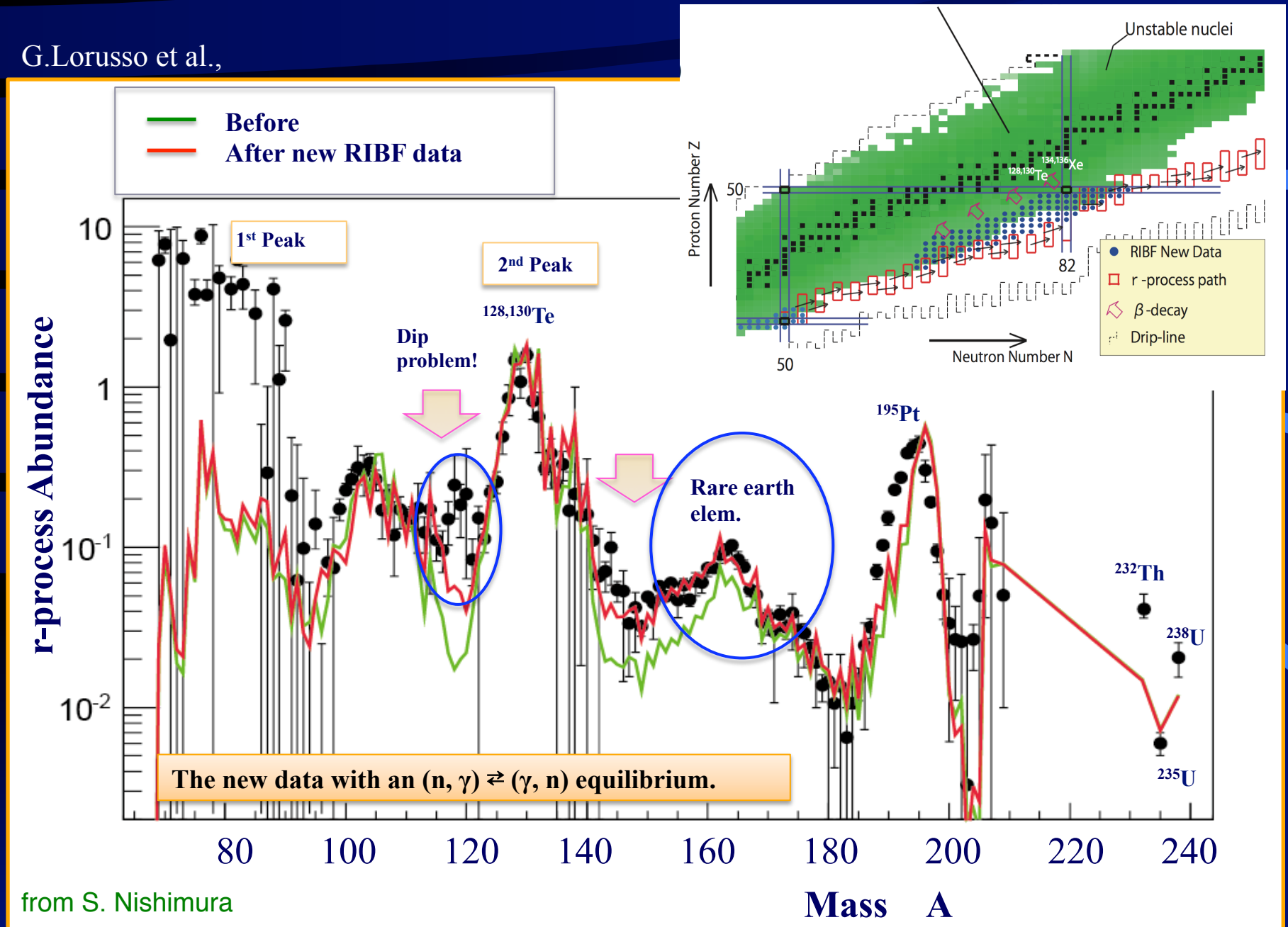




Lorusso, Nishimura, *et al.*, PRL 114, 192501 (2015)

Impacto to r-process abundance with new $T_{1/2}$ (RIBF)

G.Lorusso et al.,



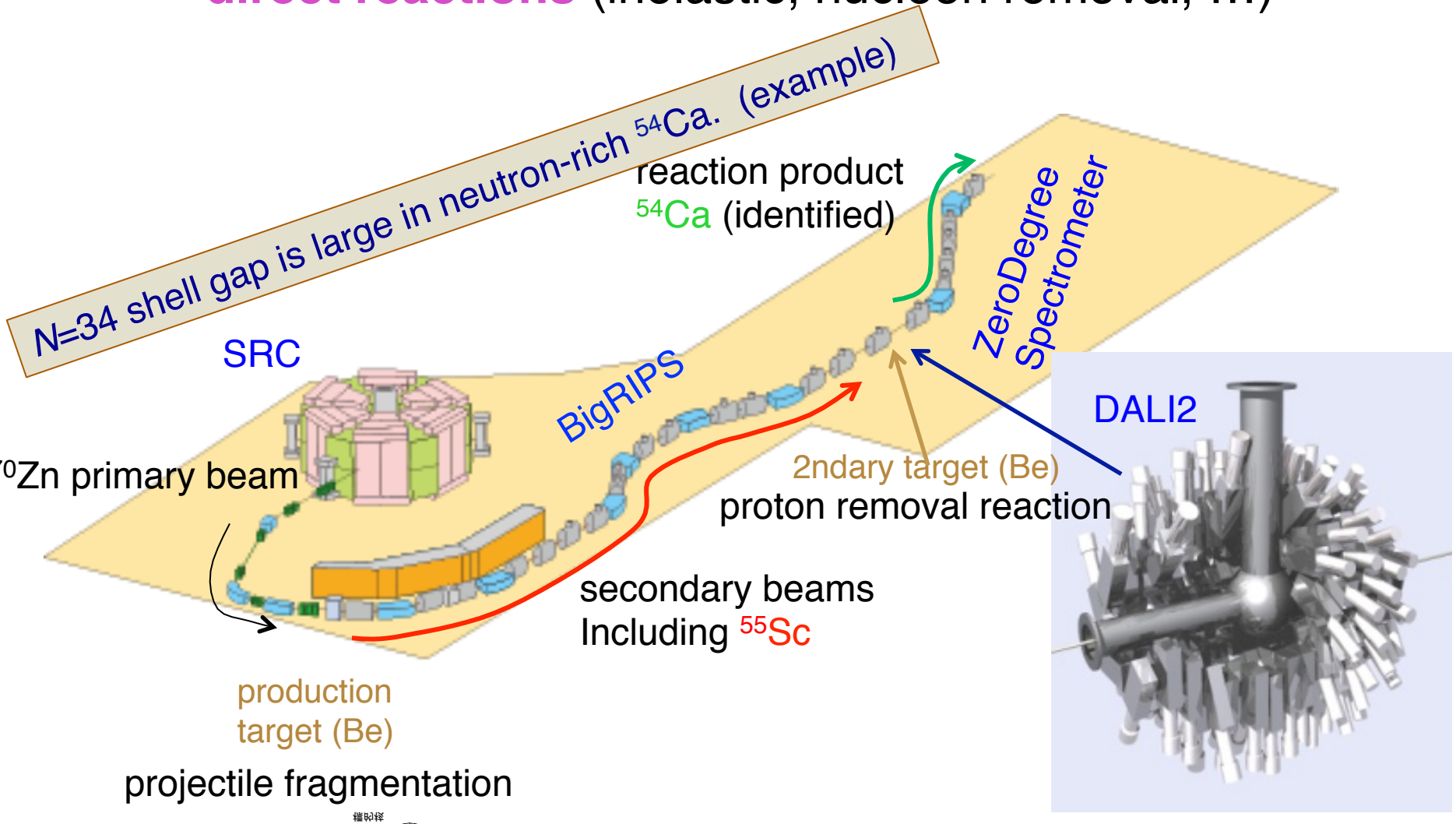
from S. Nishimura

Resent results

1. r-process is reached. -- nuclear astrophysics
2. n-rich **shell** structure explored -- nuclear structure
   - magic numbers, deformation -

* “Theory on magic numbers” tomorrow by T. Otsuka

Low-lying states measured by deexcitation γ-rays with DALI2 direct reactions (inelastic, nucleon removal, …)



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

Islands → New region of large deformation? ^{34,36,38}Mg (^{40}Mg soon)

S. Takeuchi *et al.*, PRC 79 499 (2009) 054319

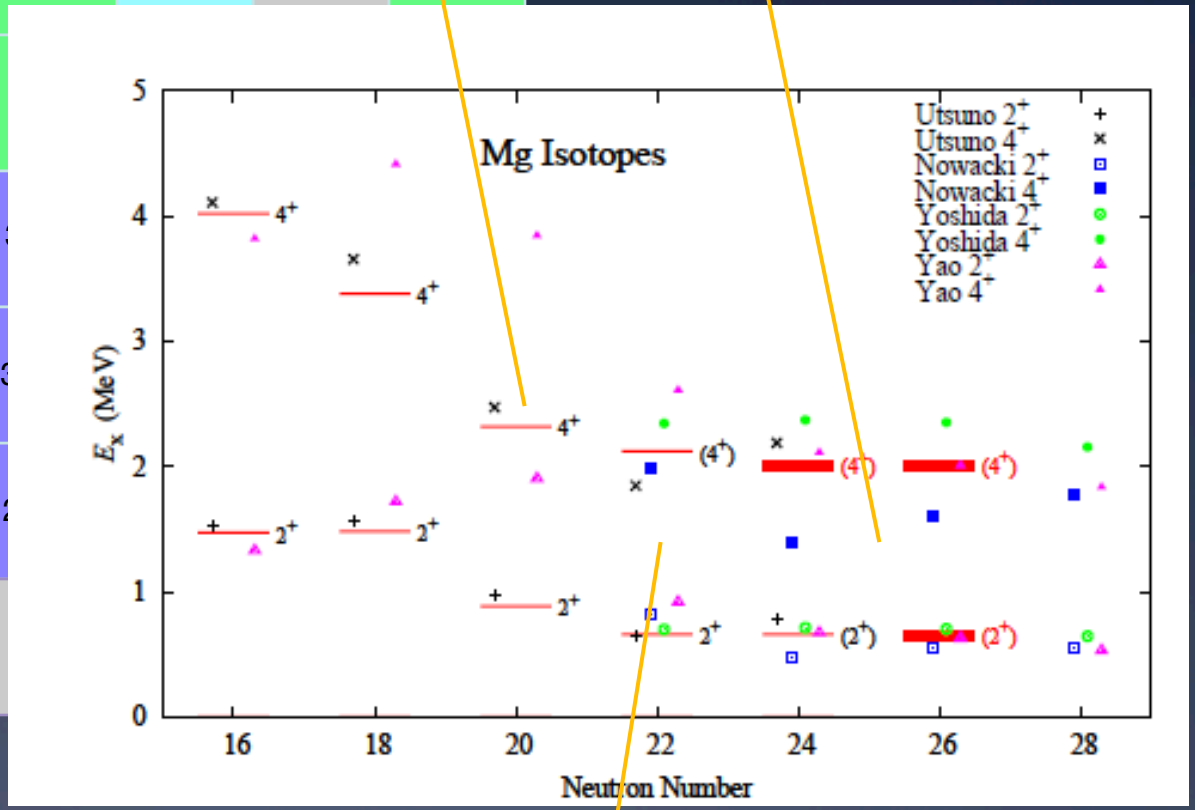
Dornenbal, Scheit, Takeuchi, *et al.*, PRL111 (2013) 212502

N=20

^{31}Si	^{32}Si	^{33}Si	^{34}Si	^{35}Si	^{36}Si
^{30}Al	^{31}Al				
^{29}Mg	^{30}Mg				
^{28}Na	^{29}Na				
^{27}Ne	^{28}Ne				
^{26}F	^{27}F				

mass
2^+, B(E2)
4^+
μ, Q

β-NMR

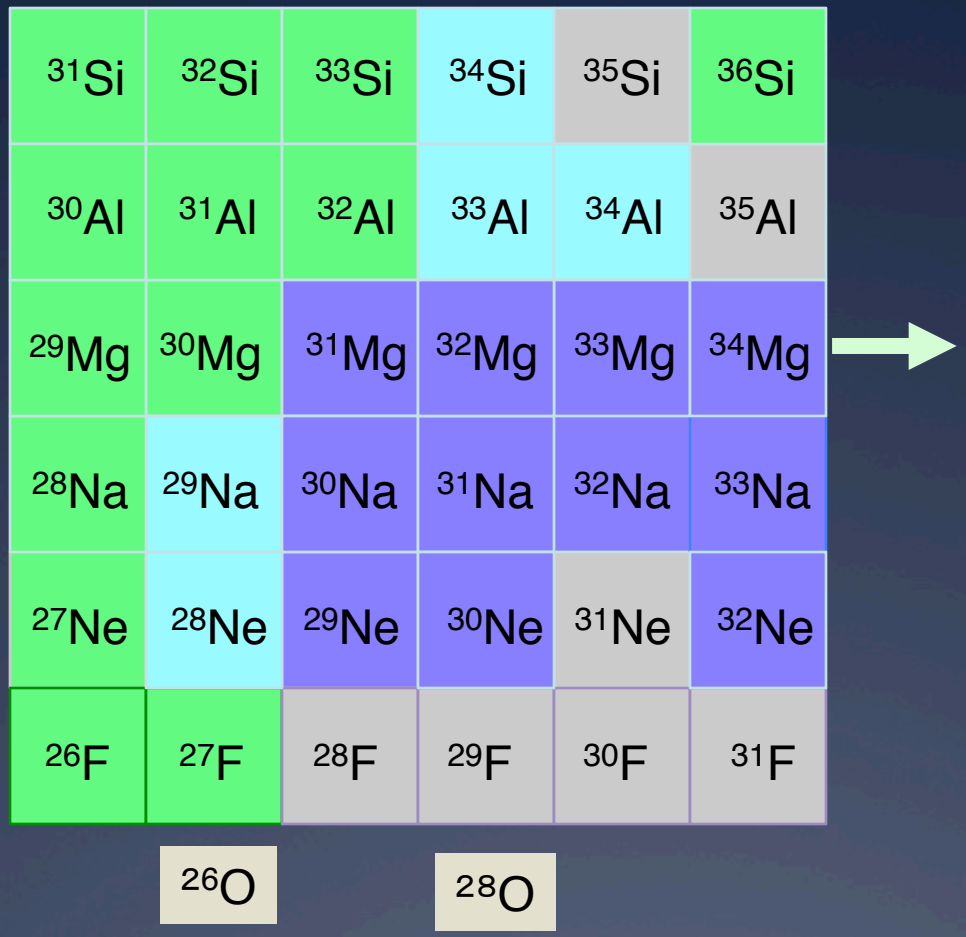


K. Yoneda *et al.*, PLB 499 (2001) 233

Mapping of the Island of Inversion (n-rich region around *N*=20)

mass
2^+, *B*(E2)
4^+
μ, *Q*

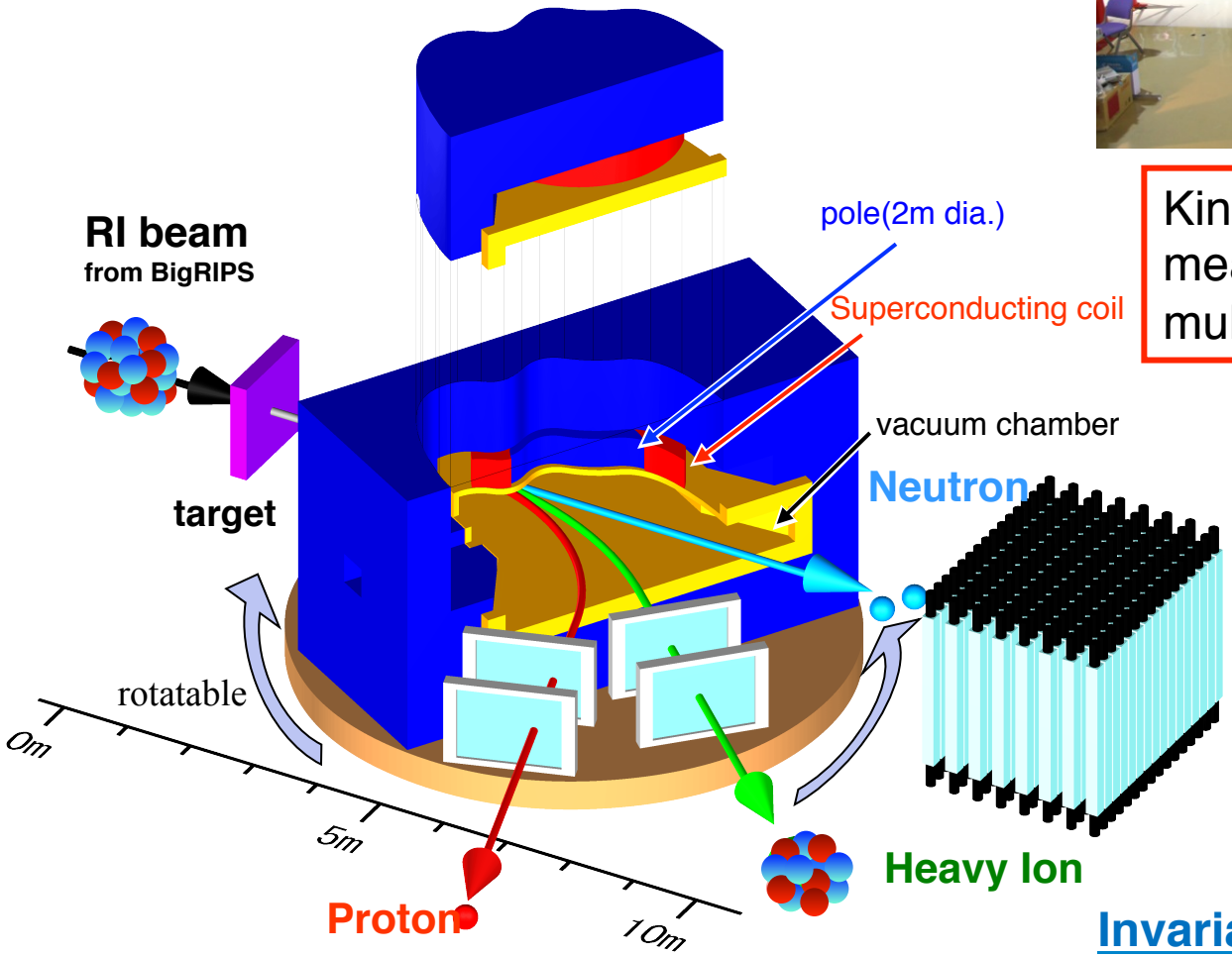
β-NMR



SAMURAI

Superconducting **A**nalyzer for **MU**lti-particle from **RA**dio **I**sotope Beam with 7Tm of bending power

in operation since **2012**

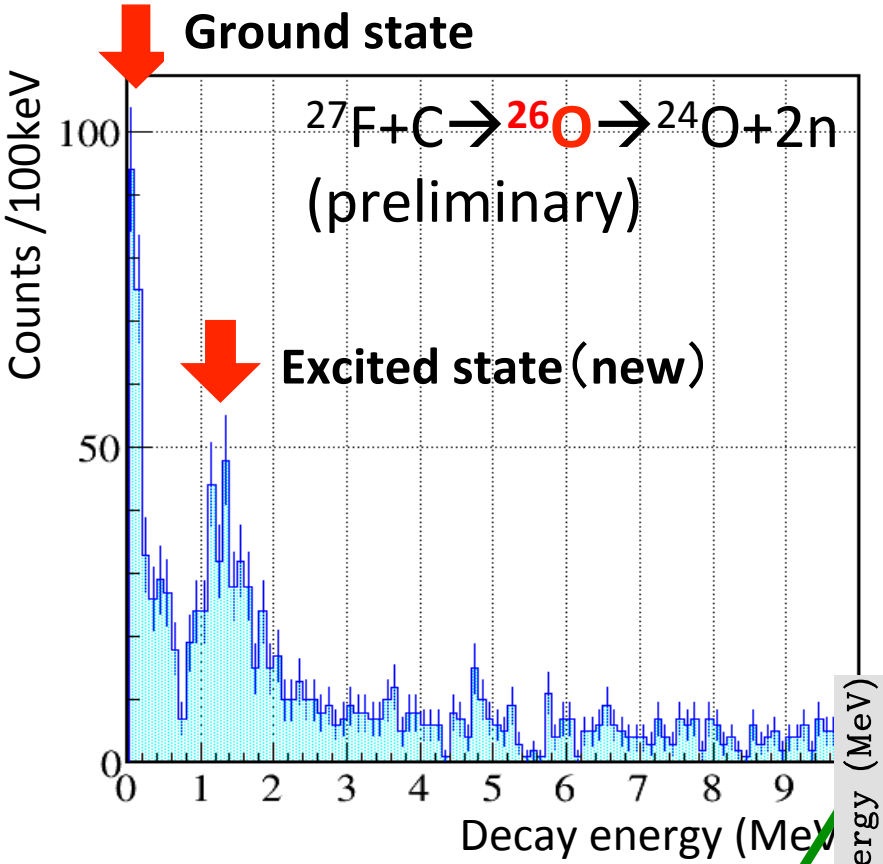


Kinematically complete measurements by detecting multiple particles in coincidence

- Superconducting Magnet
  3T with 2m dia. pole
  (designed resolution 1/700)
  80cm gap (vertical)
- Heavy Ion Detectors
- Proton Detectors
- Neutron Detectors
- Large Vacuum Chamber
- Rotational Stage

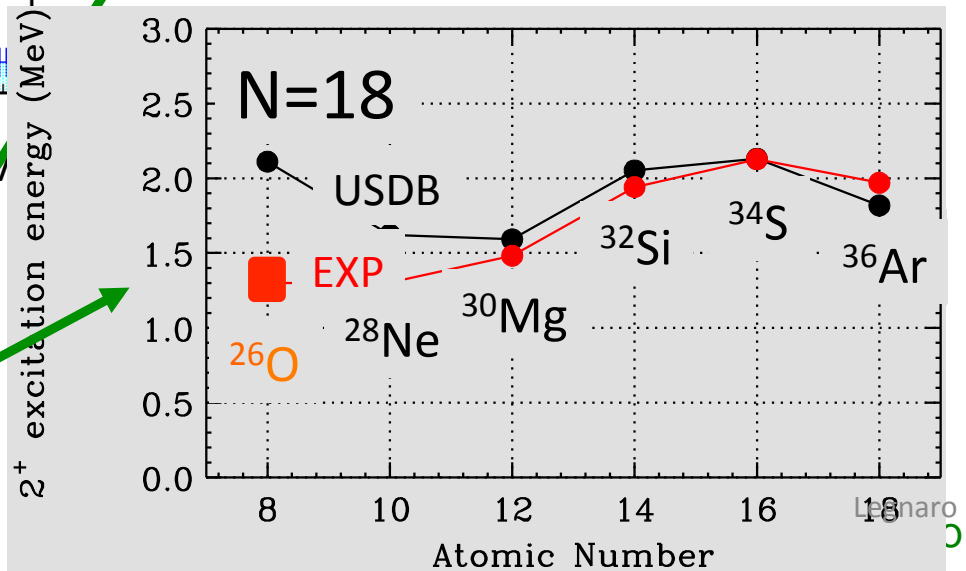
Invariant Mass Measurement
Missing Mass Measurement

Spectroscopy of (unbound) ^{26}O



^{28}O (N=20) soon
← Neuland n-detector (FAIR)

$(^{26}O_{gs}) = 18 \pm 3(stat) \pm 4(syst)$ keV

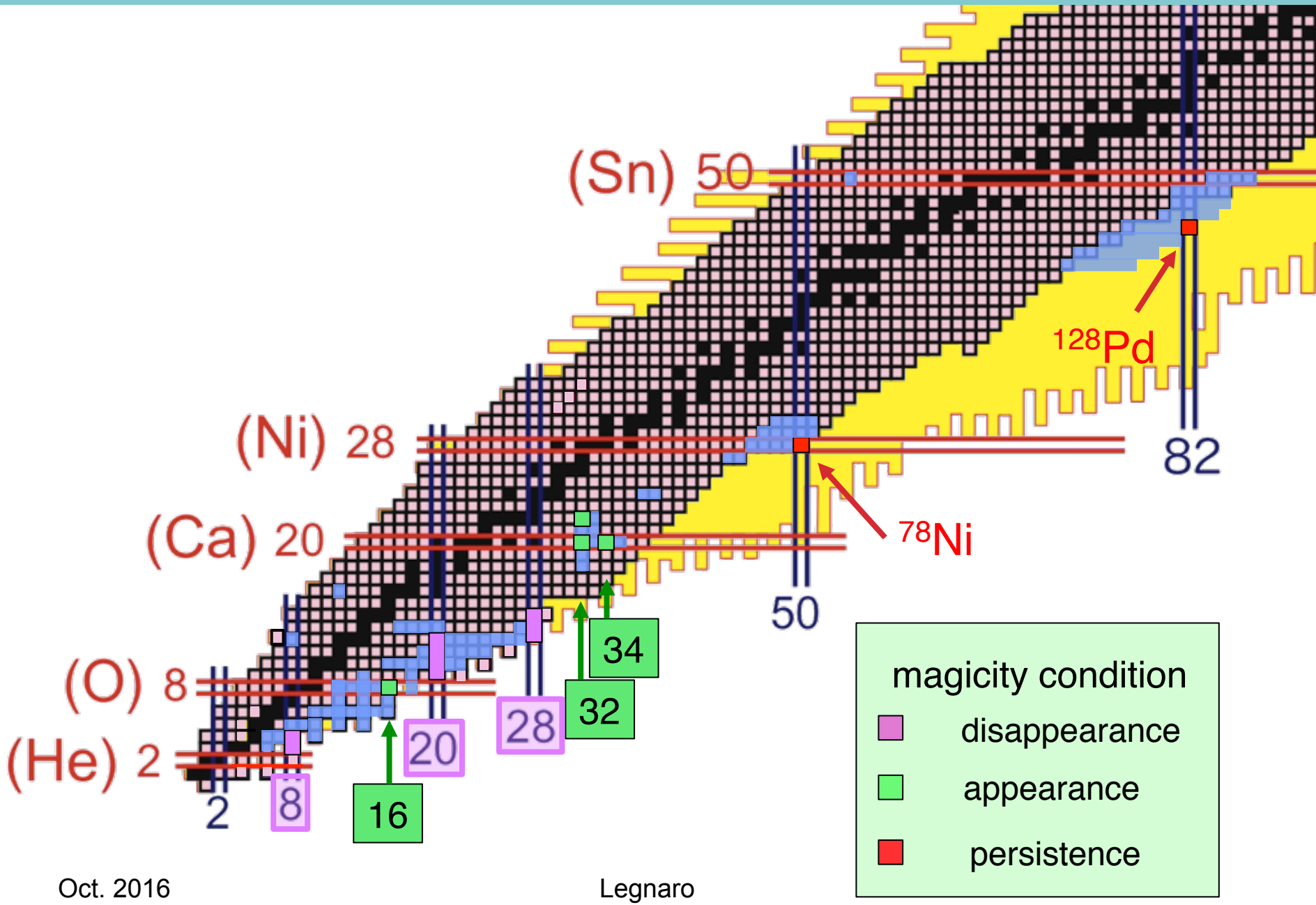


Ground state
- 5 times higher statistics
- →better determination of energy

Excited state at ~1.3MeV
- First observation
- Most probably 2^+

No peak at ~4.2MeV

“Magicity” of n-rich nuclei studied at RIBF



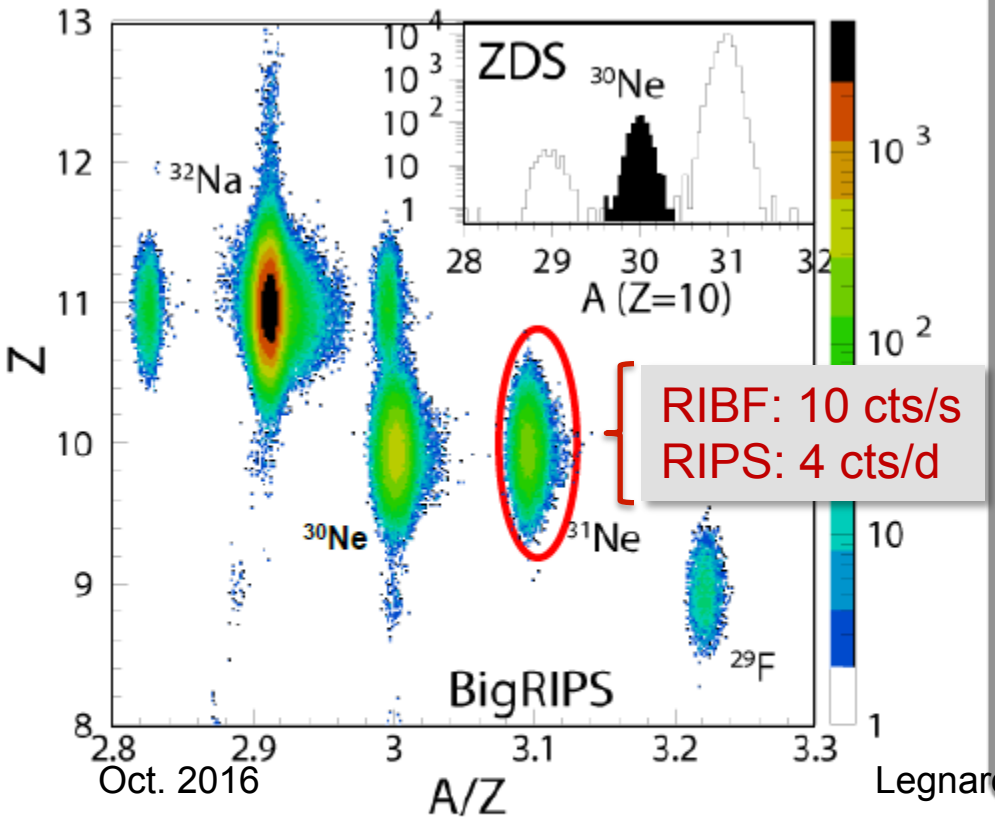
Recent resutls

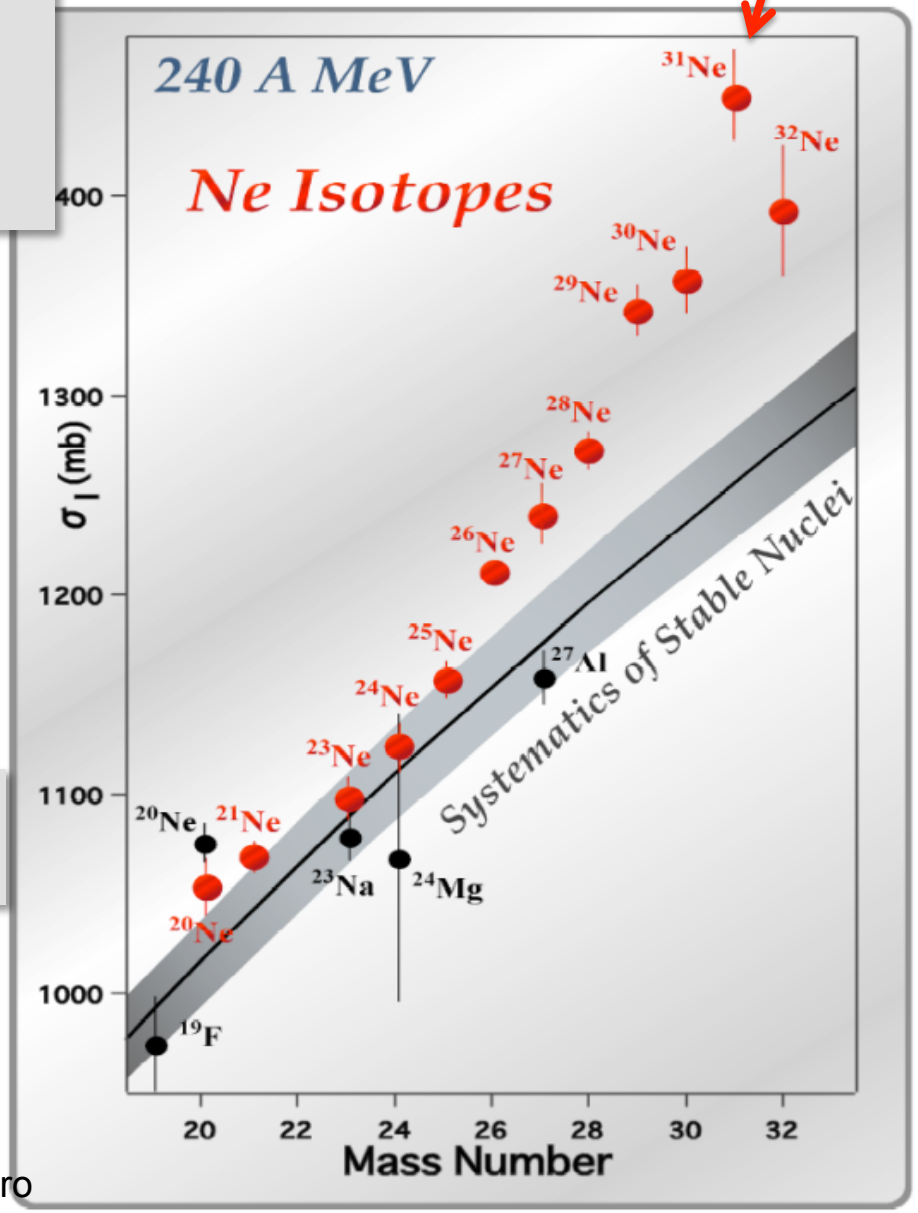
1. r-process is reached. – nuclear astrophysics
2. n-rich shell structure explored – nuclear structure
   - magic numbers, deformation
3. Neutron **halo** in deformed nuclei – nuclear structure

Deformed halo ? in Ne Isotopes

Transmission & Interaction Cross Section Measurements

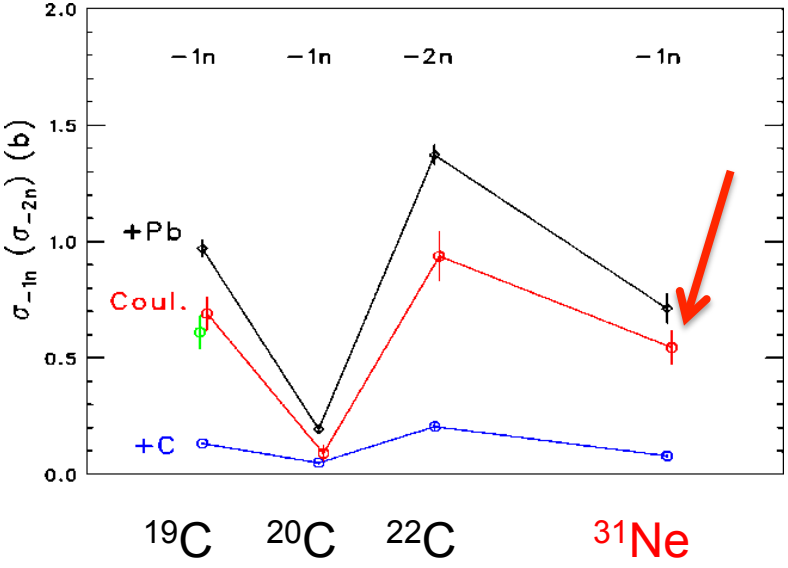
M. Takechi et al., Phys. Lett. B707 (2012) 357





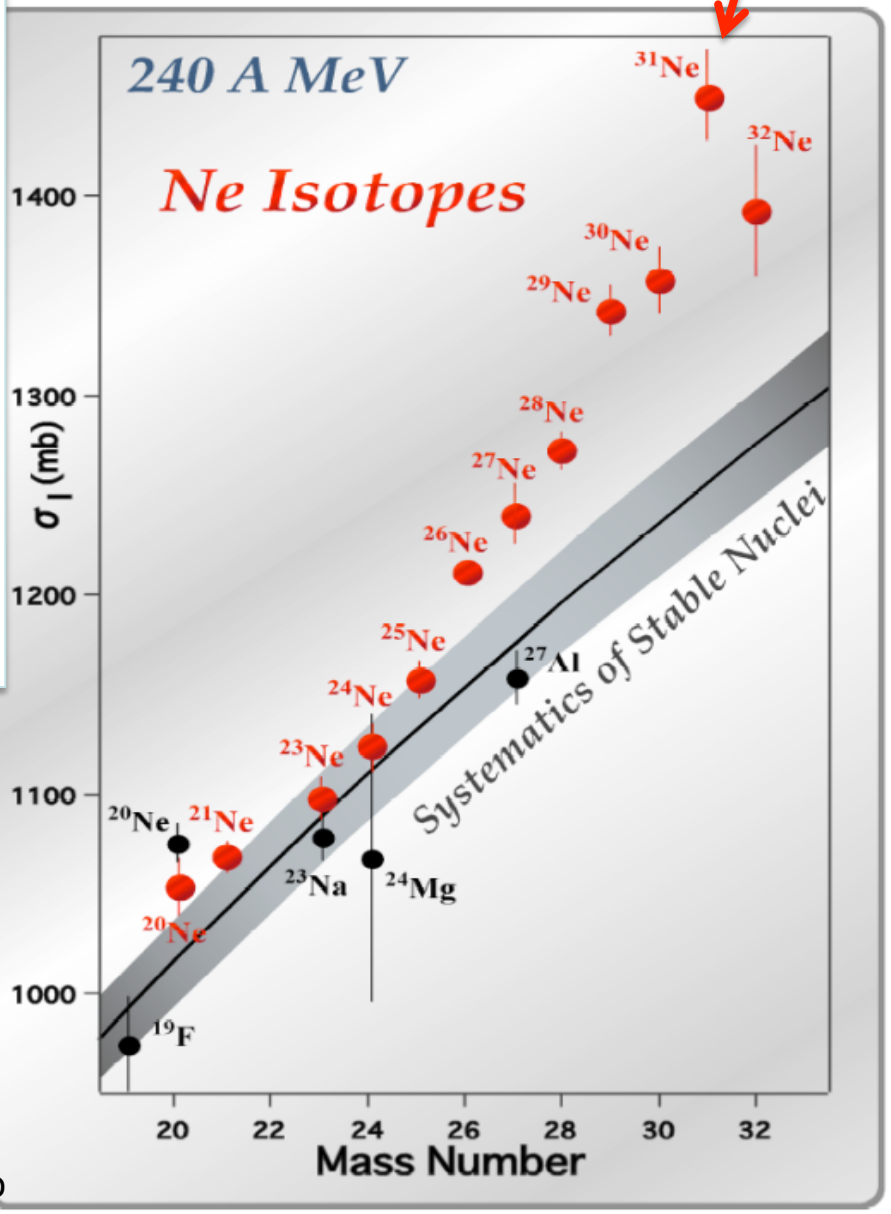
Large Coulomb breakup σ for ^{31}Ne

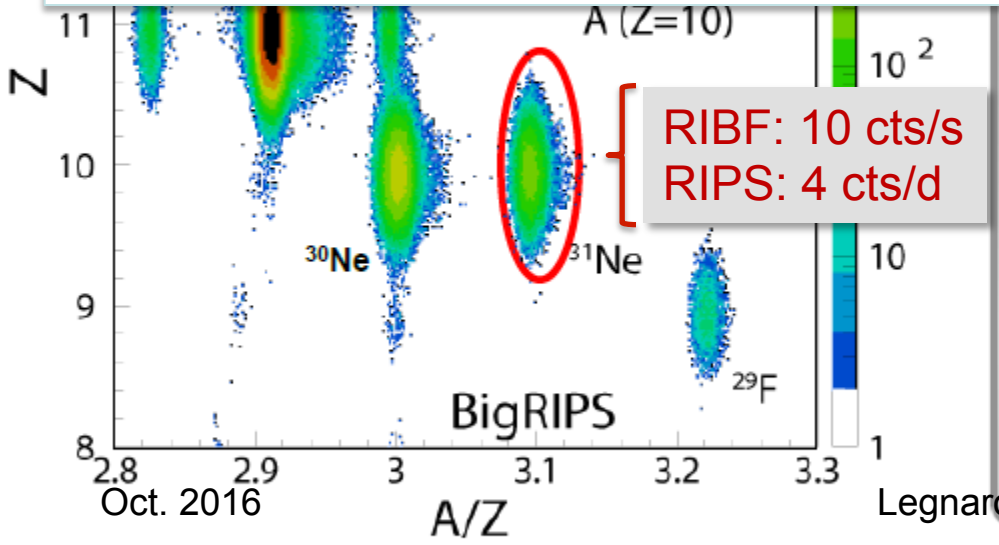
→ p-wave halo in deformed nucleus



Nakamura et al., PRL 103, 262501(2009)

Similar in ^{37}Mg





RIBF: 10 cts/s

RIPS: 4 cts/d

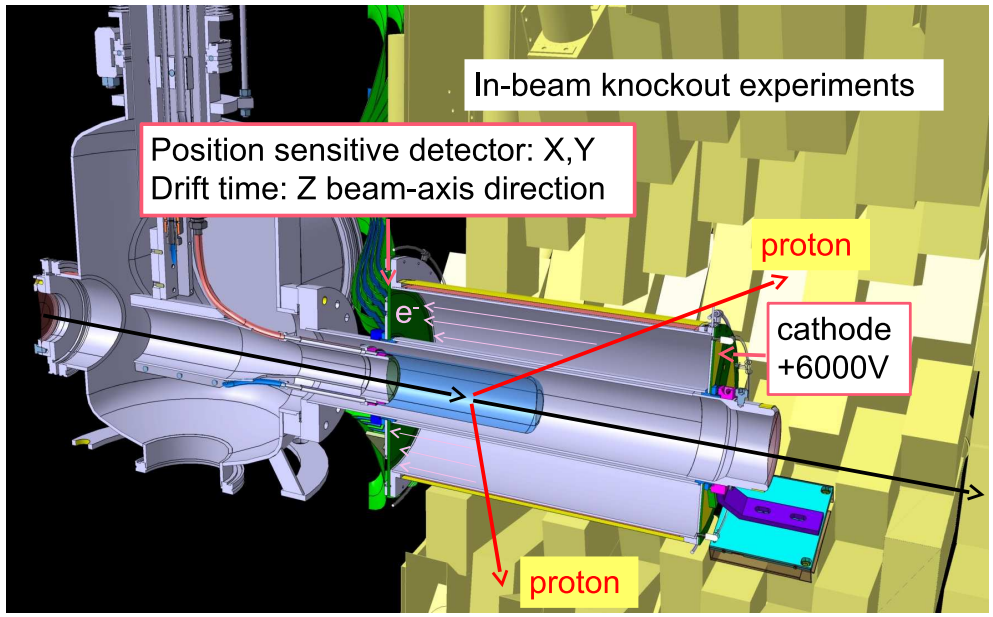
Recently

Collaborations* with instrumentation brought to or installed at RIBF
by groups outside
EURICA (Europe), Neuland (FAIR), MINOS (Saclay) – **SEASTER**,
SAMURAI TPC (MSU), BRIKEN, SHRAQ (CNS) ….

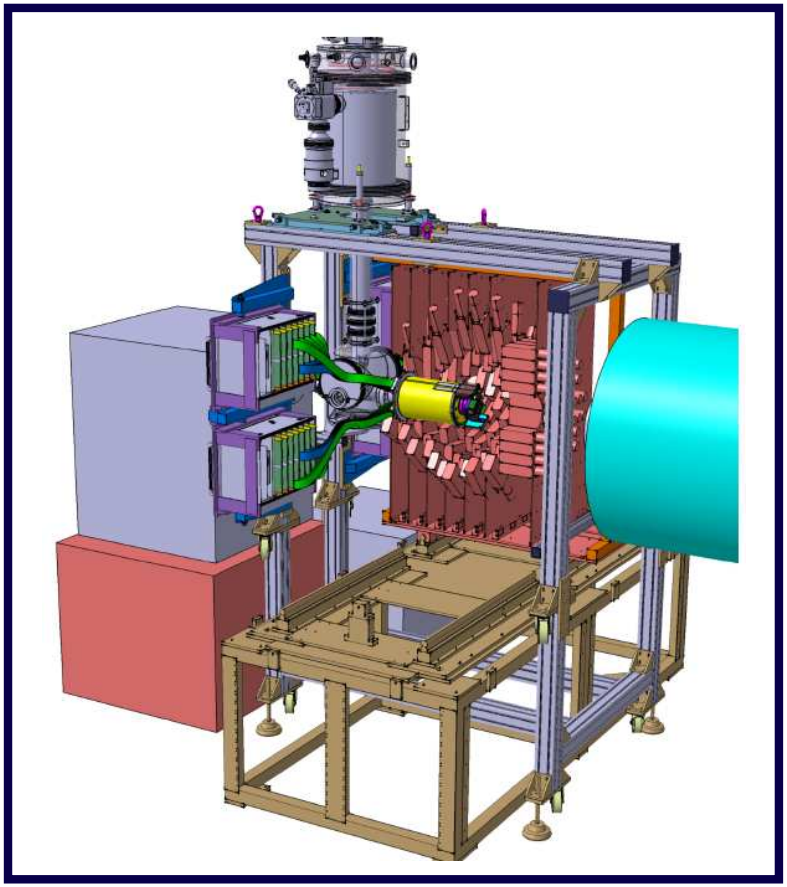
* SEASTER, - CNS-RIKEN: Koha's talk

Interests in lower energy ions or beams produced from fast RI beams
SLOWRI, KISS (KEK), **OEDO** (CNS), …

SEASTER* campaign
with MINOS (a liq. H_2 target + a TPC) + DALI2
- spectroscopy of (p,2p)# residues -



no mass transfer



MagIc Numbers Off Stability

`http://minos.cea.fr`

- ☐ Up to 1 g/cm^2 liquid hydrogen target
- ☐ Position sensitive TPC
  - Driftime → Z-beam axis
  - Vertex position reconstruction
  - Achieved ≈5 mm (FWHM)

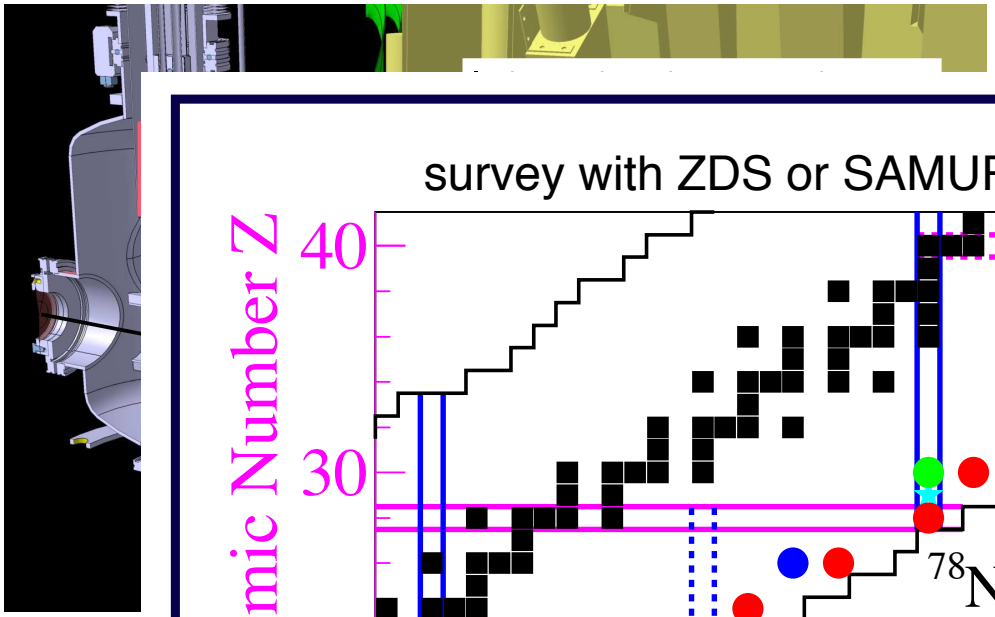
A. Obertelli *et al.*, Eur. Phys. J. A 50, 8 (2014).

- Shell Evolution And Search for Two-plus energies At RIBF

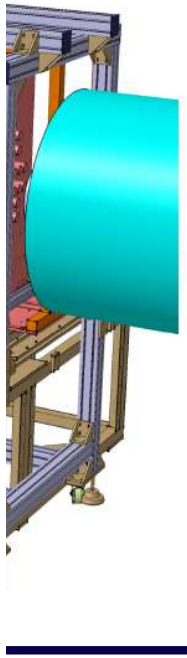
from Doornenbal

SEASTER* campaign
with MINOS (a liq. H_2 target + a TPC) + DALI2
- spectroscopy of (p,2p)# residues -

no mass transfer



survey with ZDS or SAMURAI



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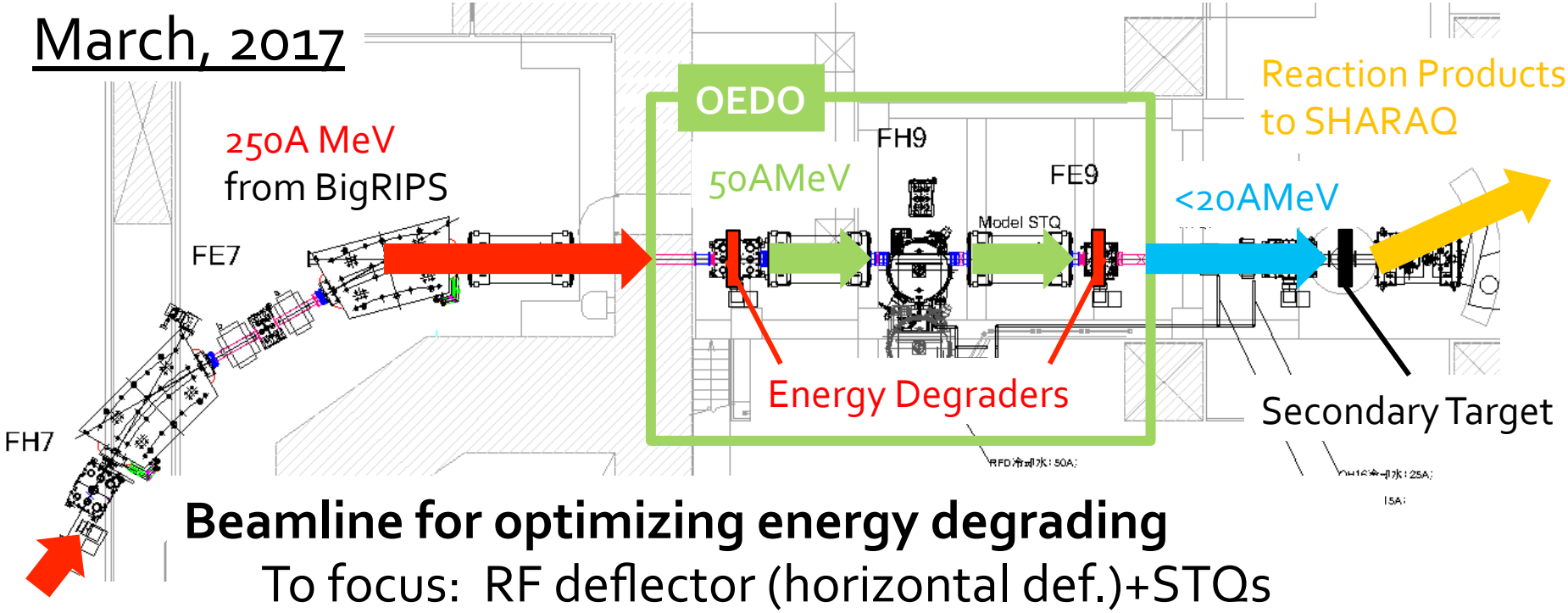
A. Obertelli *et al.*, Eur. Phys. J. A 50, 8 (2014).

from Doornenbal

OEDO–SHARAQ Project

March, 2017



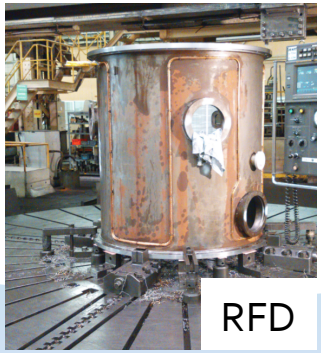
Beamline for optimizing energy degrading

To focus: RF deflector (horizontal def.)+STQs

To tag induced reactions: SHARAQ spectrometer

Now Manuscripting
of New Beam Elements

Installation starts in Dec.,2016


RFD


STQ