Status of RIKEN
- research at RIBF

Tohru Motobayashi
RIKEN Nishina Center

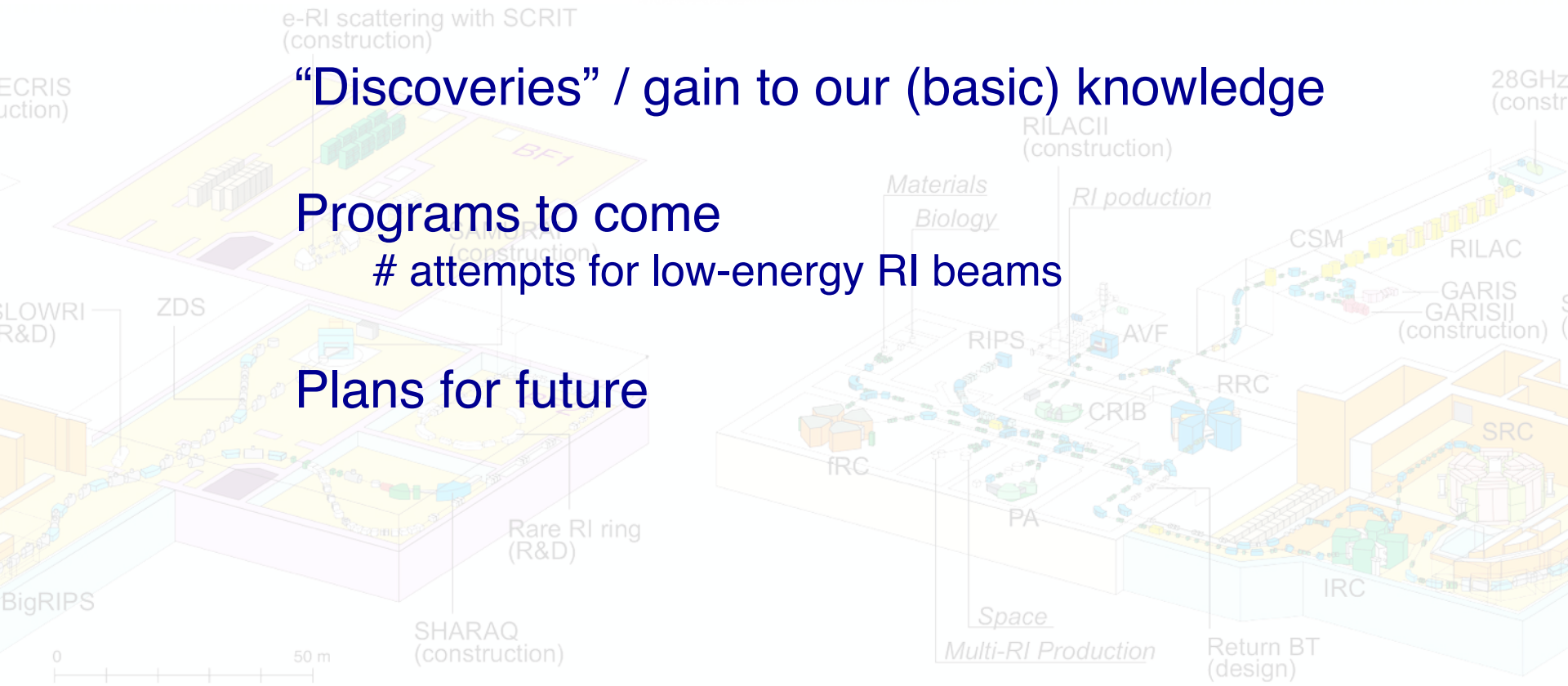
RIKEN RIBF* (2007-)

"Discoveries" / gain to our (basic) knowledge

Programs to come

attempts for low-energy RI beams

Plans for future



* Radioactive Isotope Beam Factory

Status of RIKEN
- research at RIBF

Tohru Motobayashi
RIKEN Nishina Center

RIKEN RIBF (2007-)

"new generation" RIB facilities

today

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027
RIBF	実験開始					施設完成								RIBF大強度化					RIBF2		
FAIR	建設開始																実験開始		施設完成		
FRIB							建設開始							実験開始		施設完成					
ARIEL		建設開始							第1フェーズ					施設完成							
Spiral2		建設開始										実験開始		施設完成							
SPES						建設開始					実験開始		施設完成								
ISOLDE							建設		4 MeV 達成		10 MeV 達成										
RISP									建設開始				実験開始		施設完成						

experiment

From En'yo

RIBF – a new generation RIB facility in operation

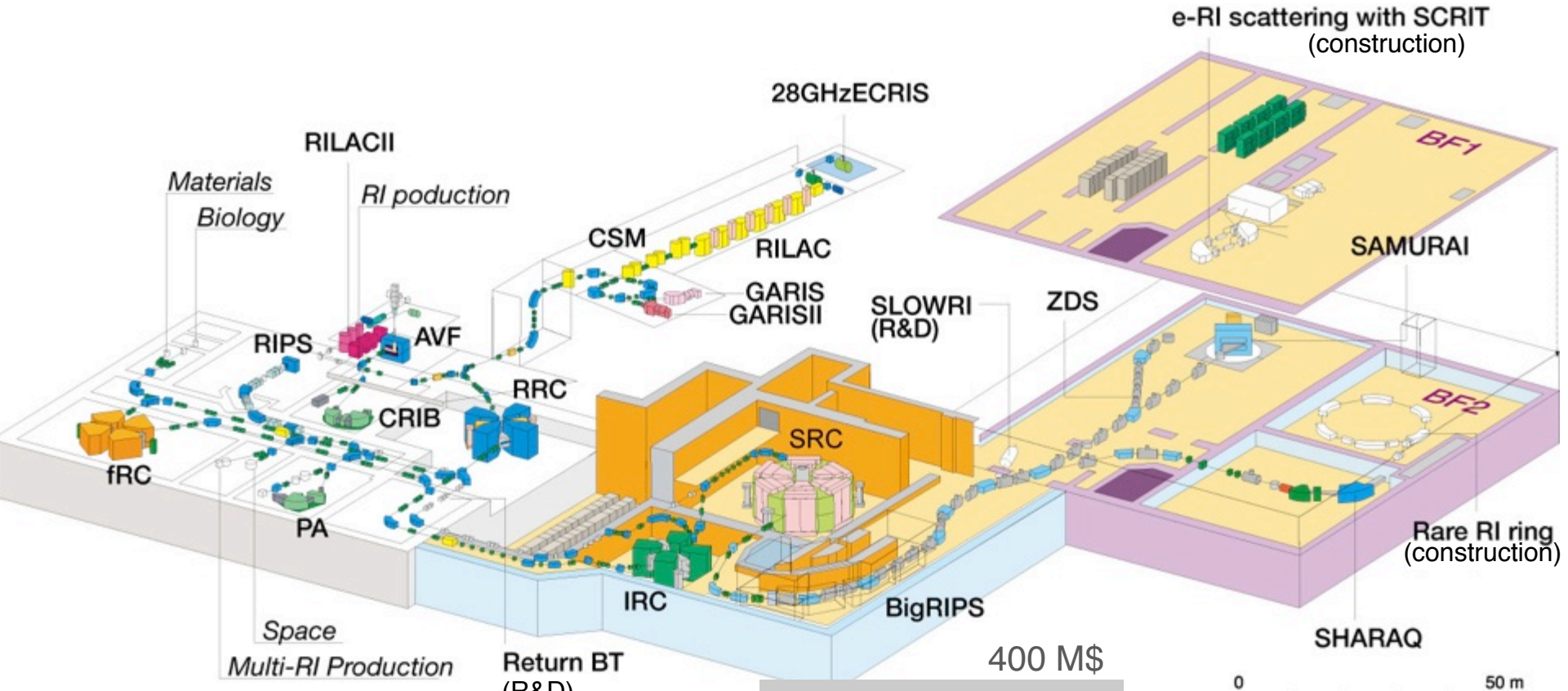
2 (3) parallel injectors followed by 4 consecutive cyclotrons

135 MeV/nucleon
for light nuclei (1986-)

345 MeV/nucleon
up to U (2006-)

experimental
equipment

RIBF – a new generation RIB facility in operation



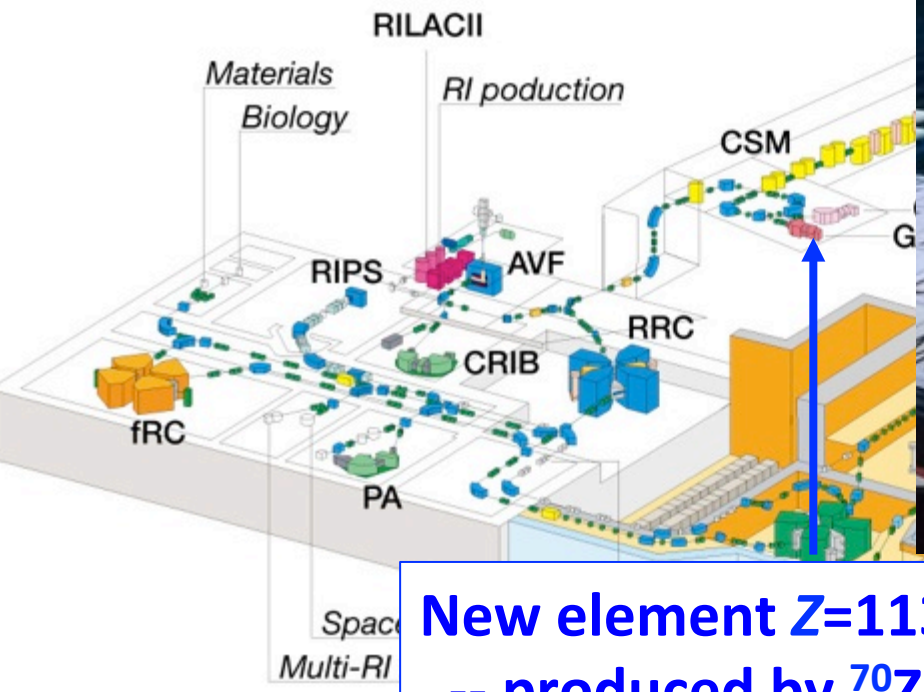
135 MeV/nucleon
for light nuclei (1986-)

400 M$

345 MeV/nucleon
up to U (2006-)

experimental
equipment

RIBF – a new generation RIB facilit



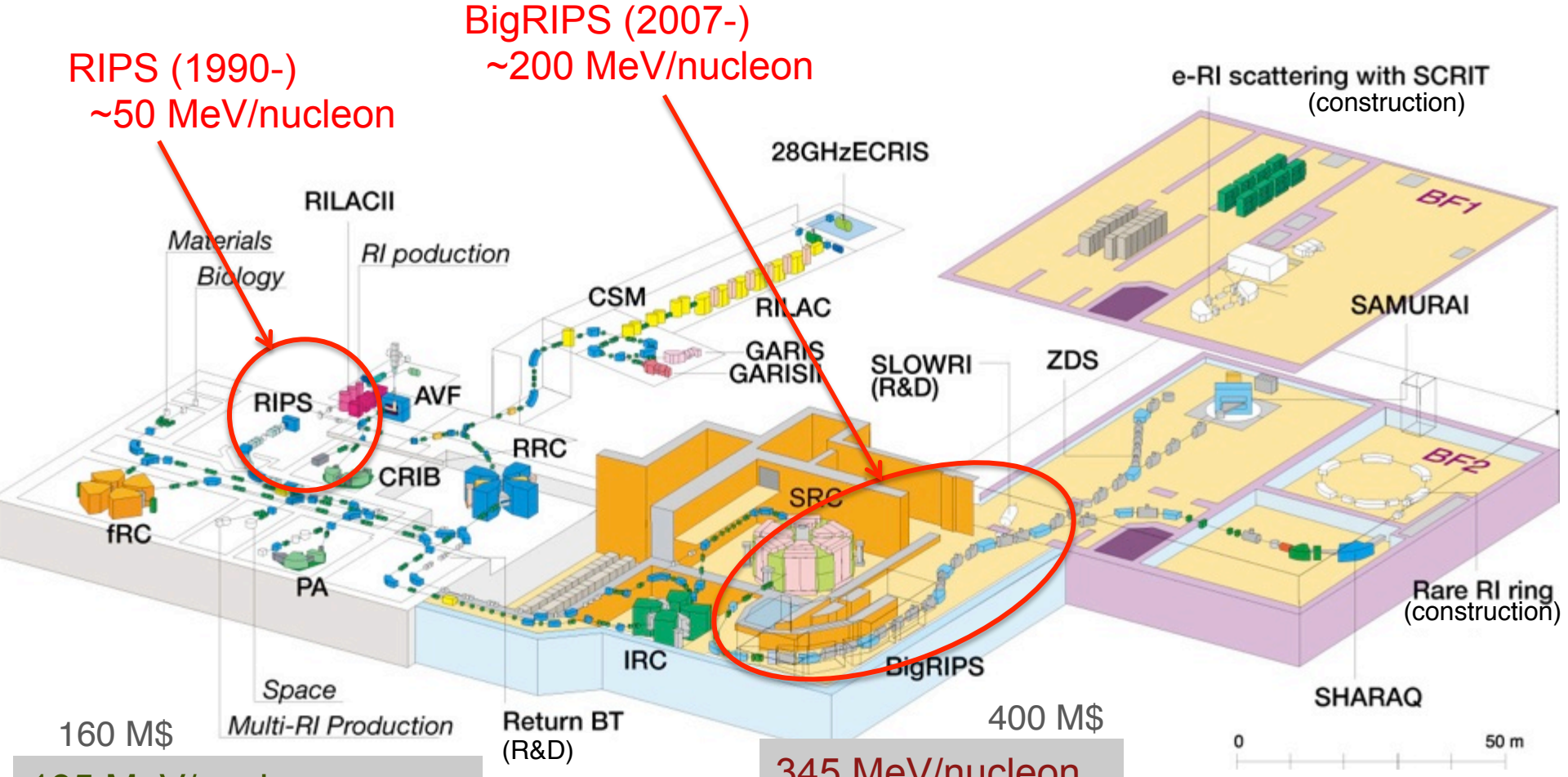
New element *Z*=113 (Nh, Nihonium – IUPAC proposing)
-- produced by ^{70}Zn+^{209}Bi fusion

135 MeV/nucleon
for light nuclei (1986-)

up to U (2006-)

experimental
equipment

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-)

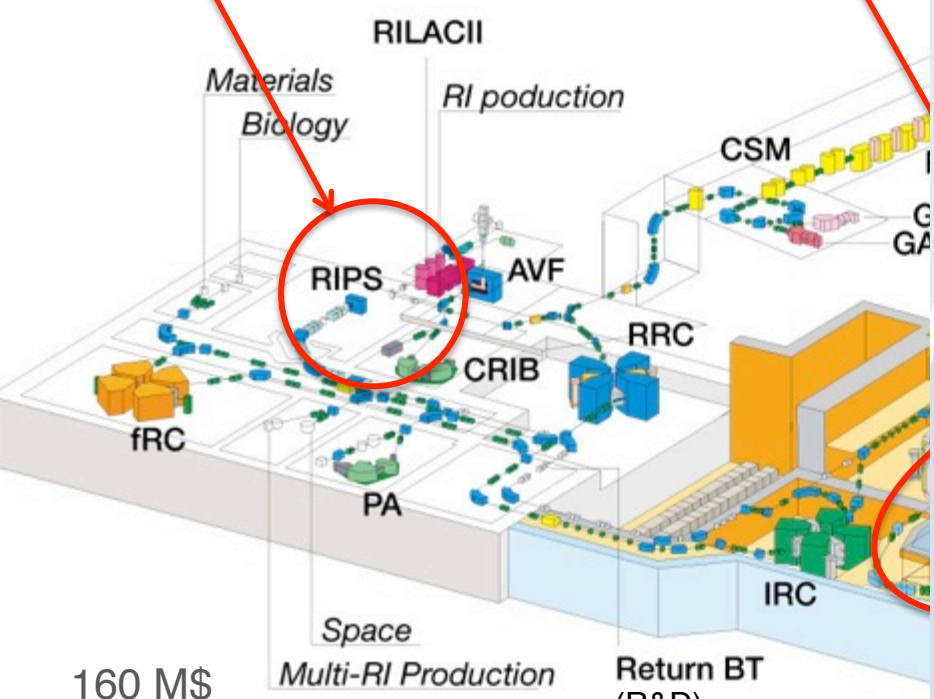
experimental
equipment

fast RI beams by fragmentation / fission in-flight

RIBF – a new generation RIB facility
with world highest capability of p

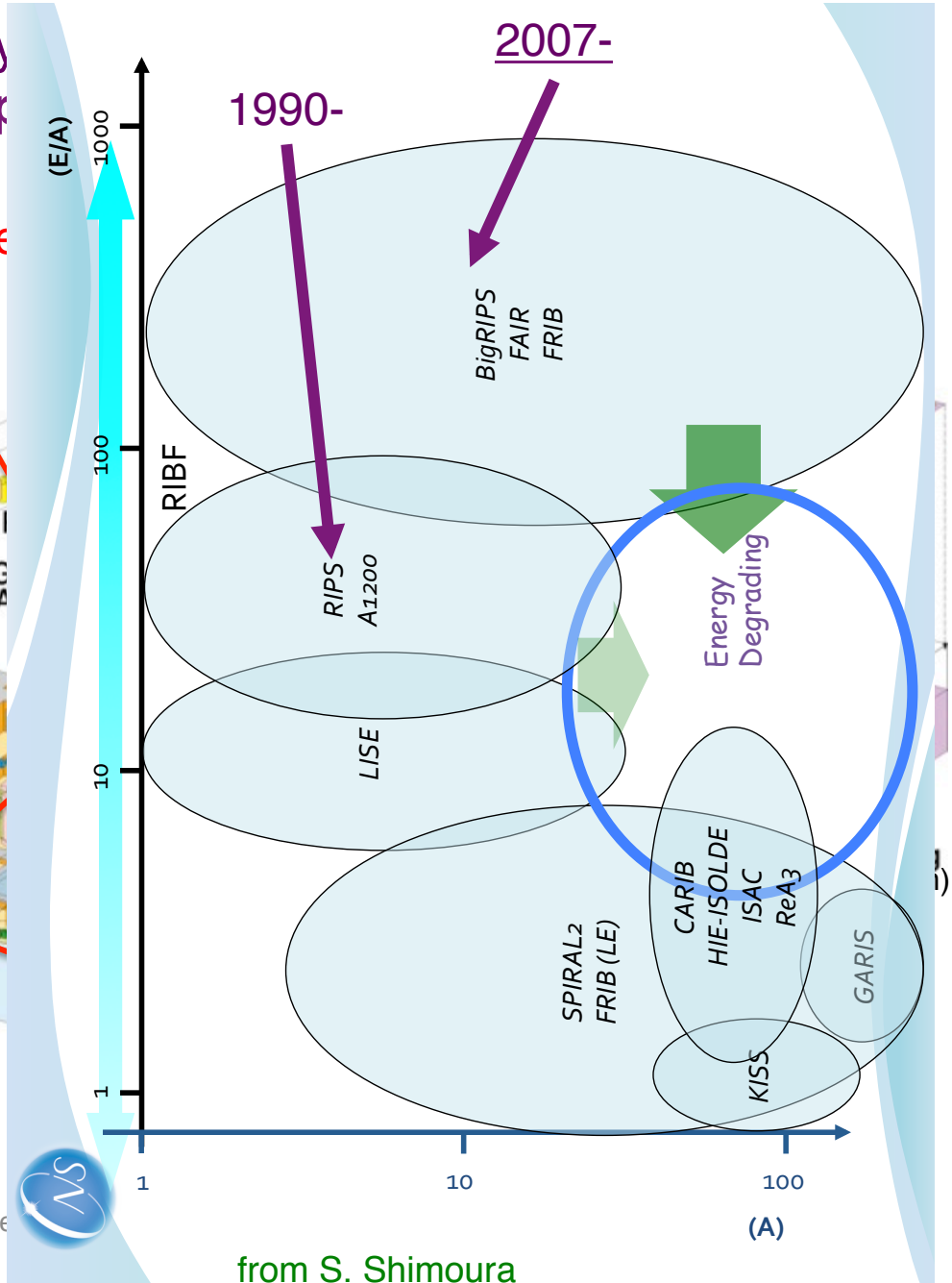
RIPS (1990-)
~50 MeV/nucleon

BigRIPS (2007-)
~200 MeV/nucle



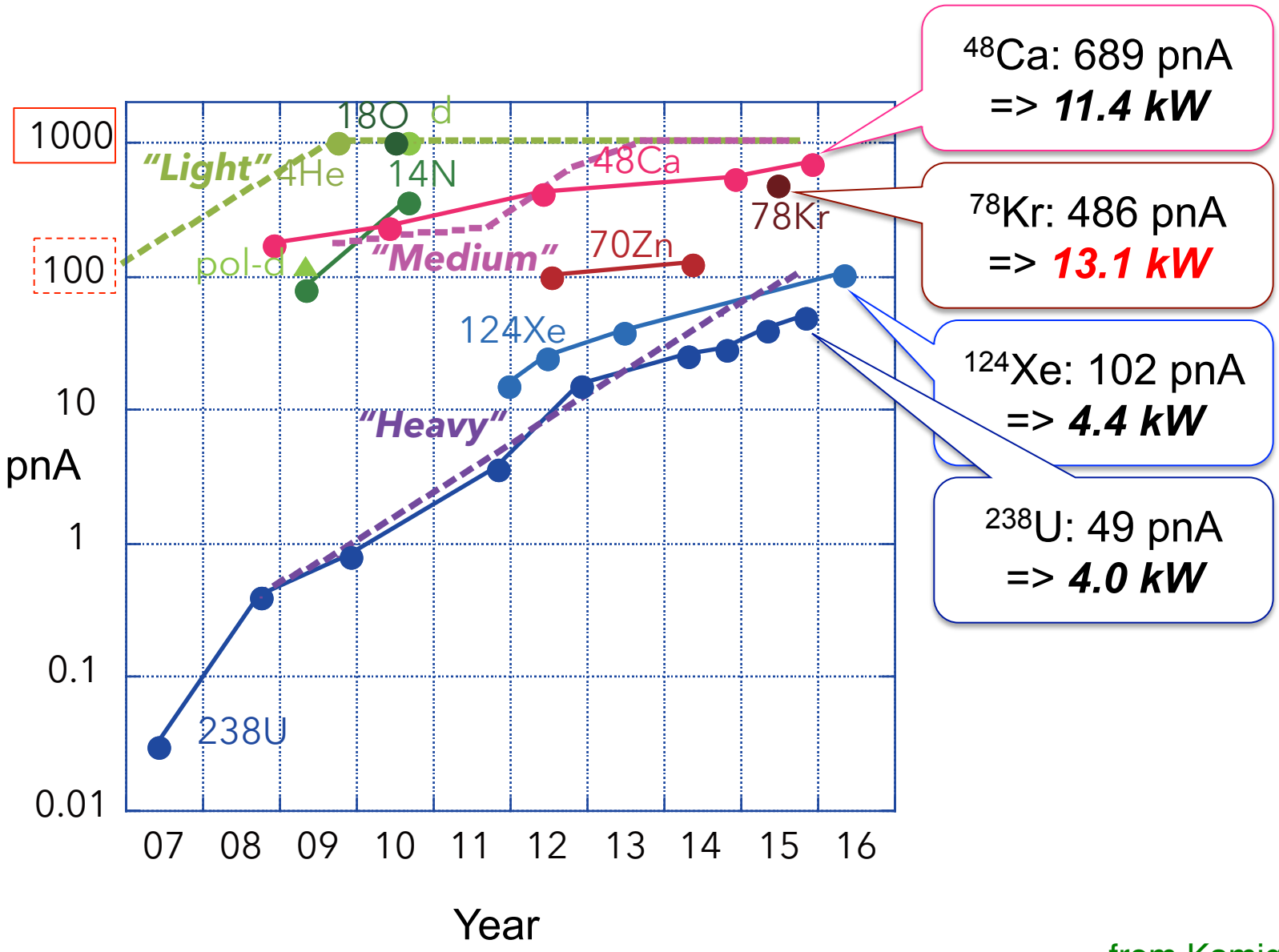
160 M$

135 MeV/nucleon
for light nuclei (1986-)



from S. Shimoura

(primary beam) intensity upgrade at RIBF

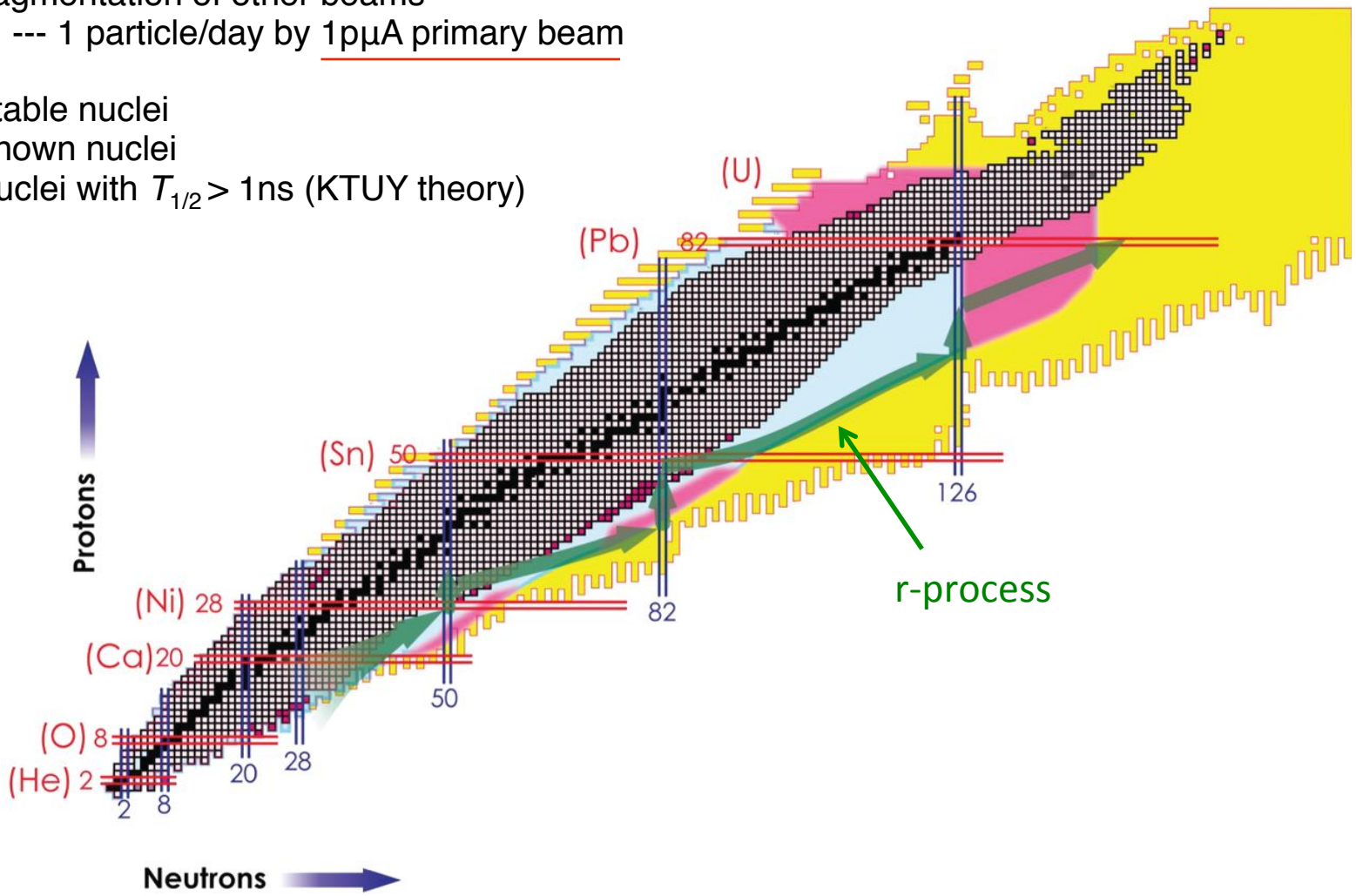


from Kamigaito

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

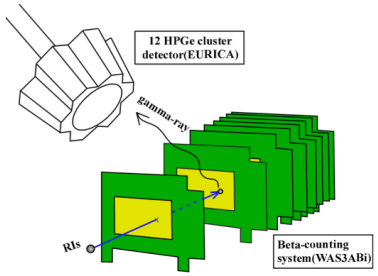
PTEP Progress of Theoretical and Experimental Physics

Discoveries / gain to our (basic) knowledge

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

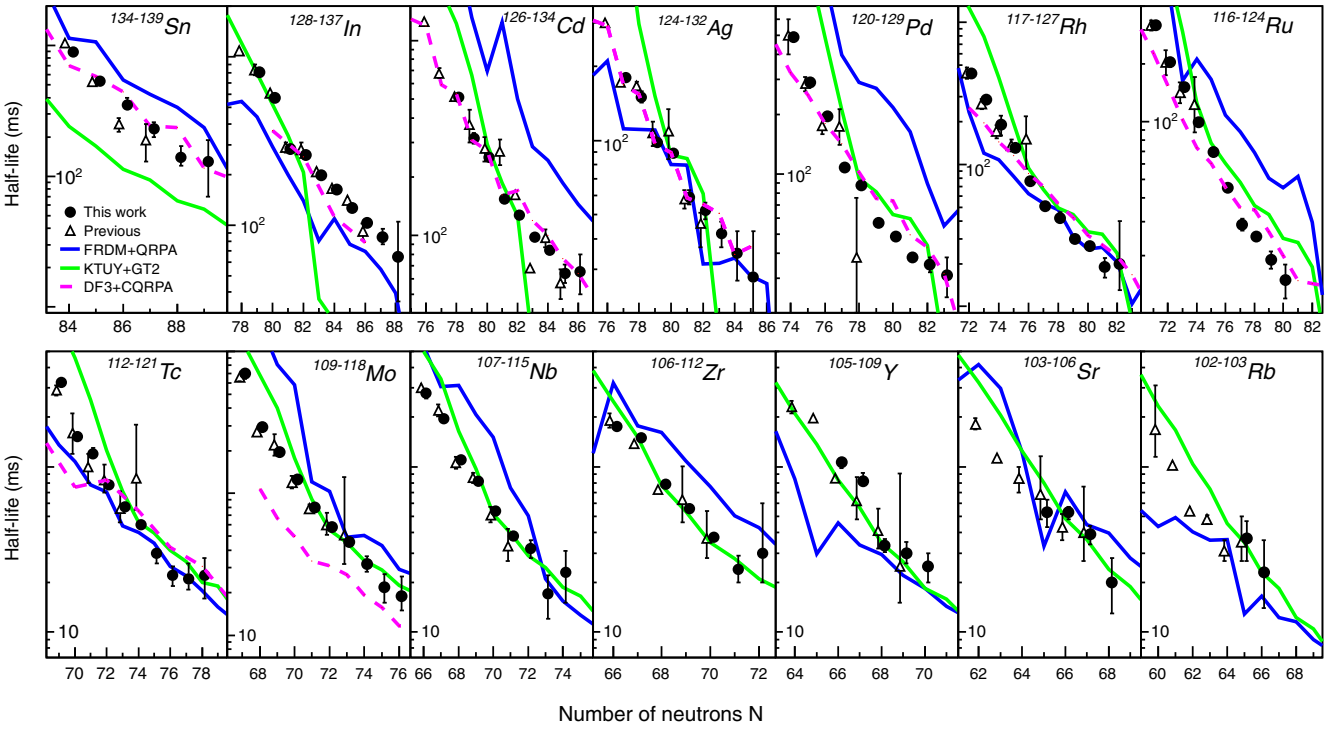
110 (40 new) half lives measured

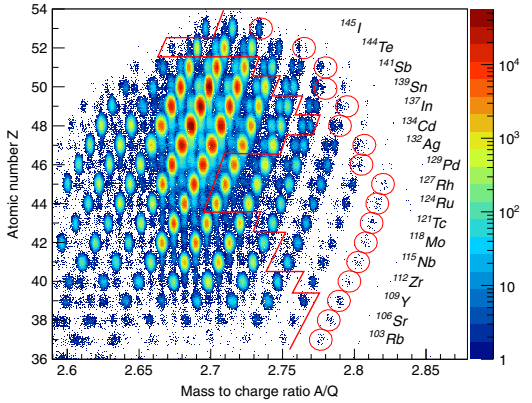
EURICA + WASABI



many r-process nuclei

12 EUROBALL clusters at RIKEN

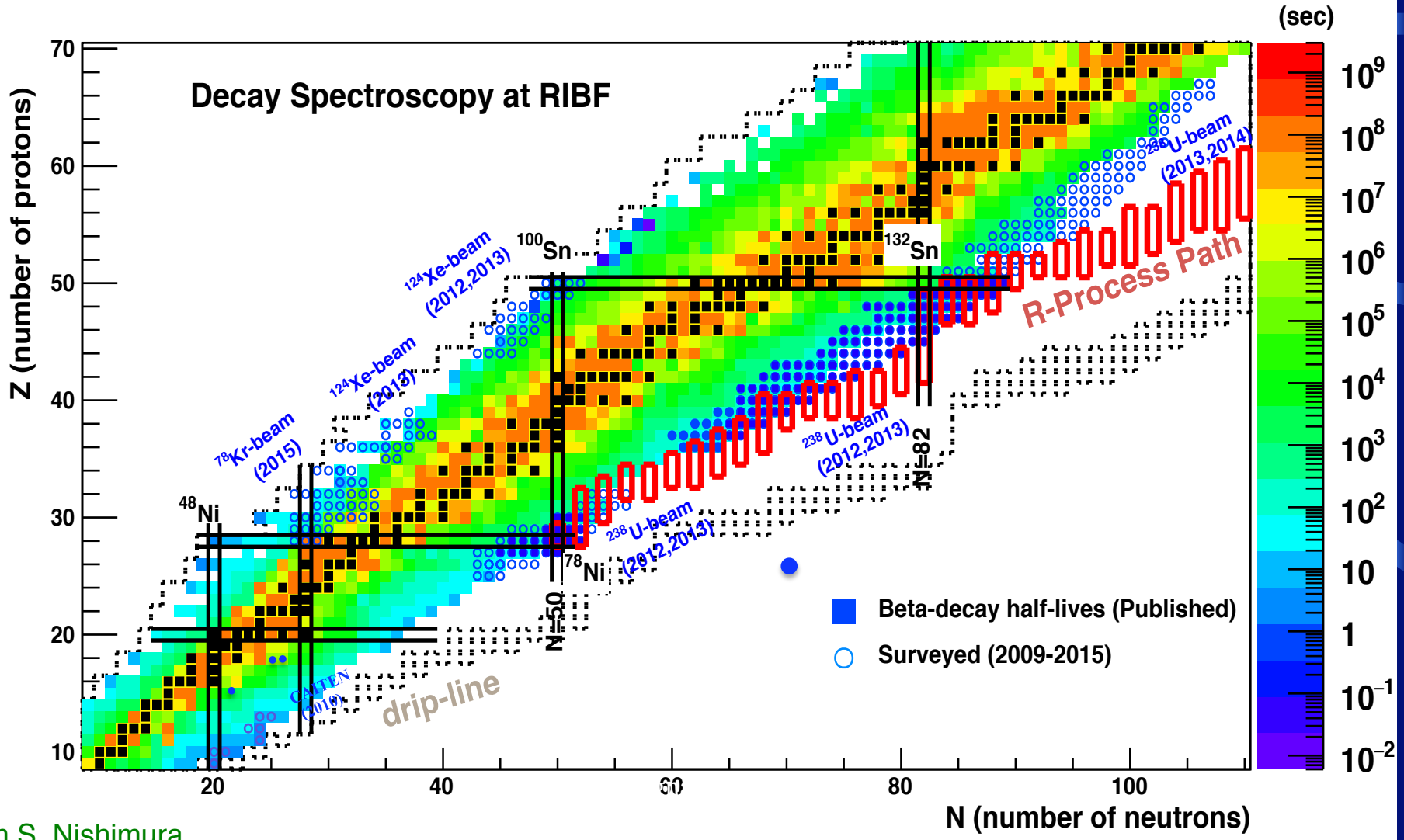




Lorusso, Nishimura, *et al.*, PRL 114, 192501 (2015)

β decay half-lives at RIBF

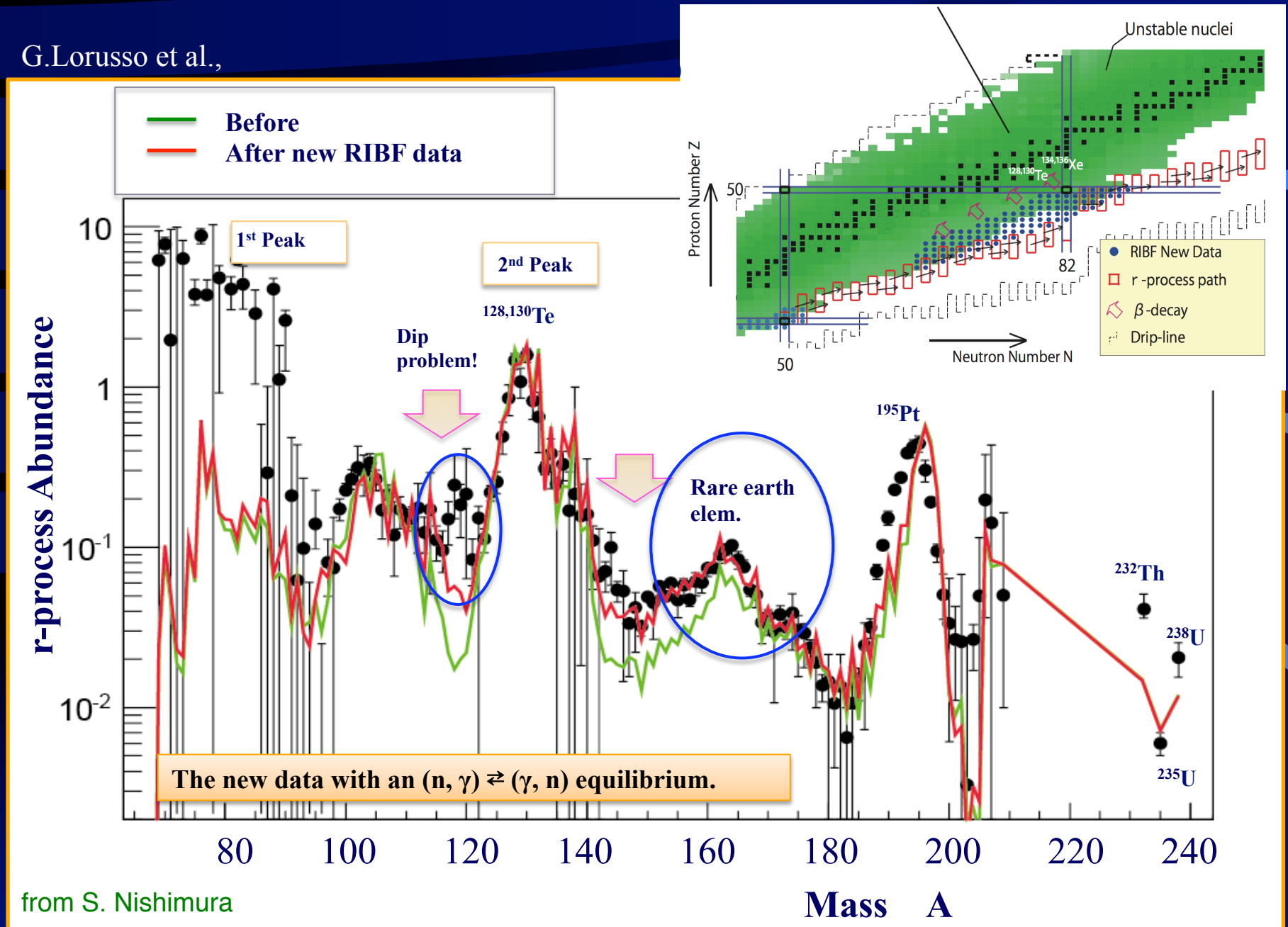
- touching the r-process path



from S. Nishimura

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

G.Lorusso et al.,

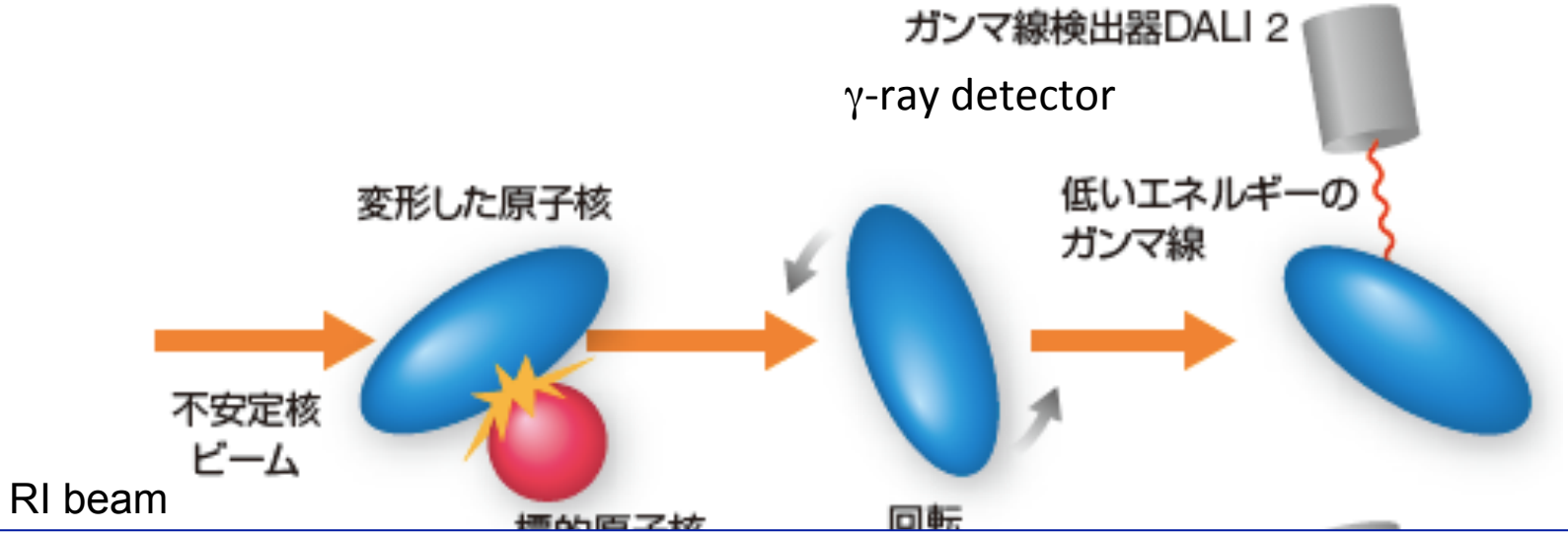


from S. Nishimura

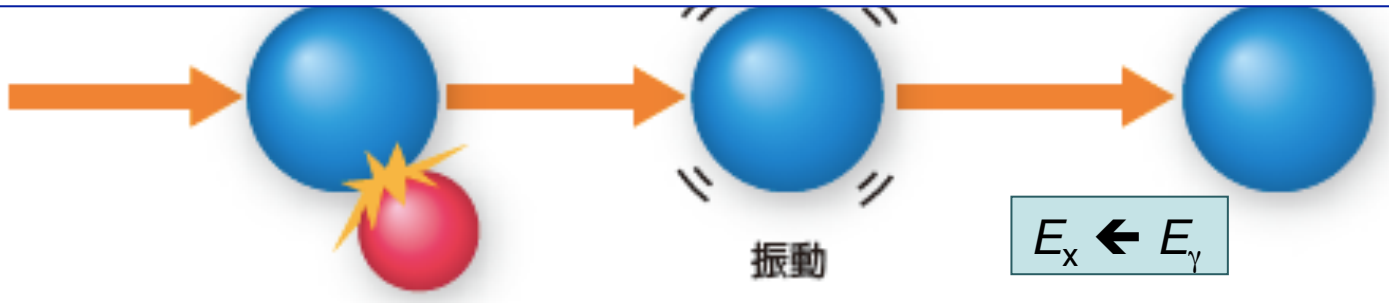
Discoveries / gain to our (basic) knowledge

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

direct reaction* in inverse kinematics

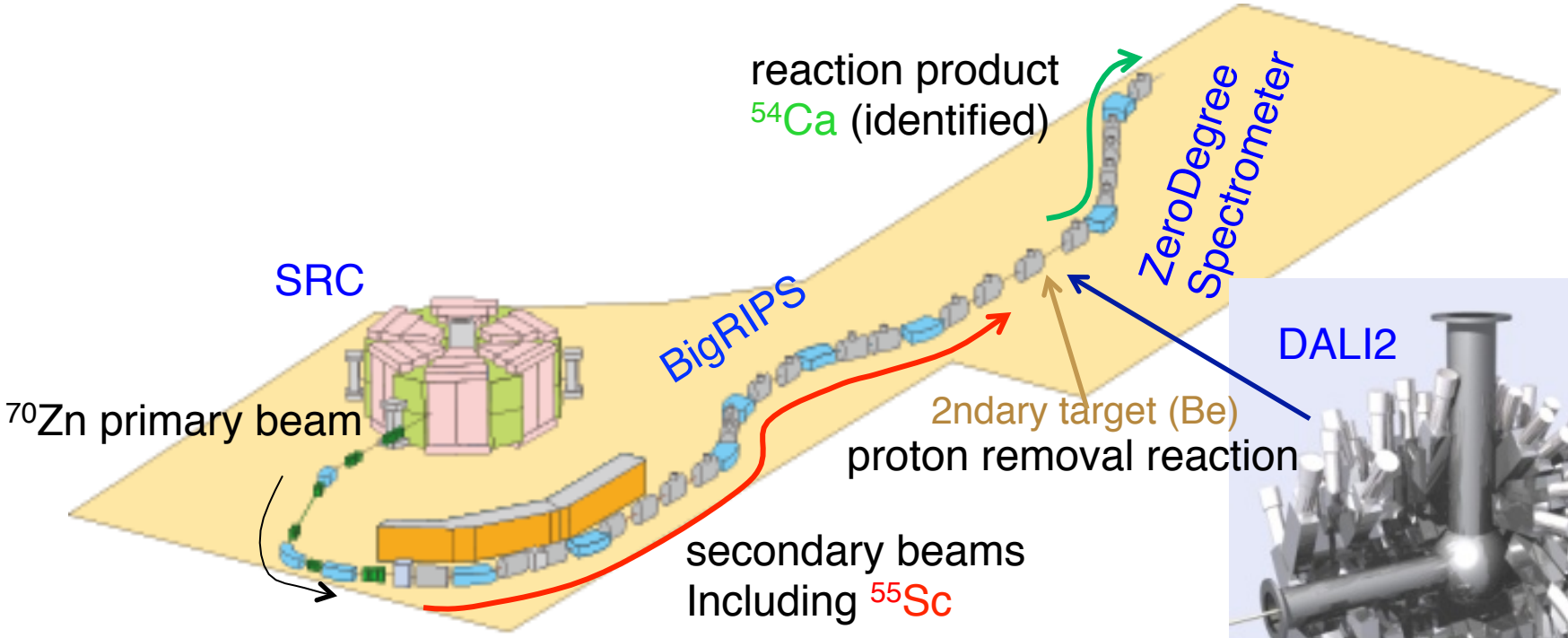


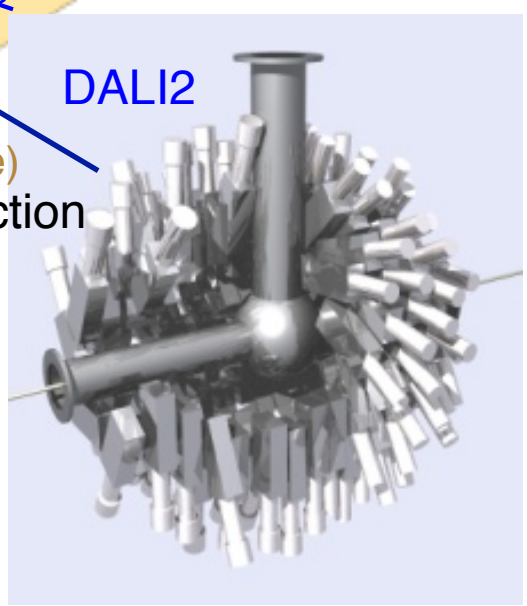
Bound states excited → (Doppler shifted) γ ray measurements
unbound states excited → particle decay
→ Invariant mass (particle correlation) measurements



* Inelastic scattering, nucleon(s) removal / knockout, charge exchange -- no mass transfer

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

LETTER

Nature, **502** (2013) 207

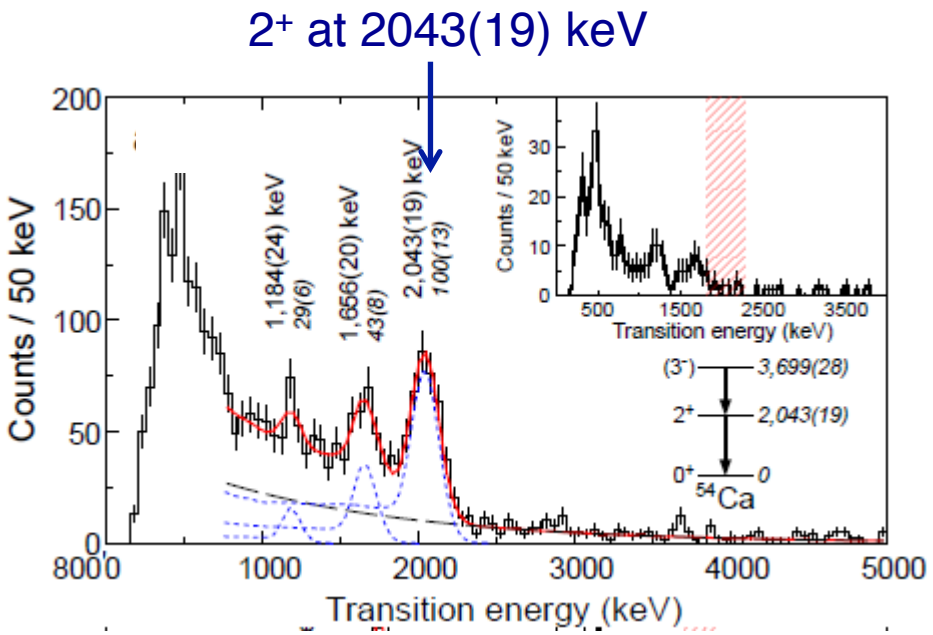
ure12522

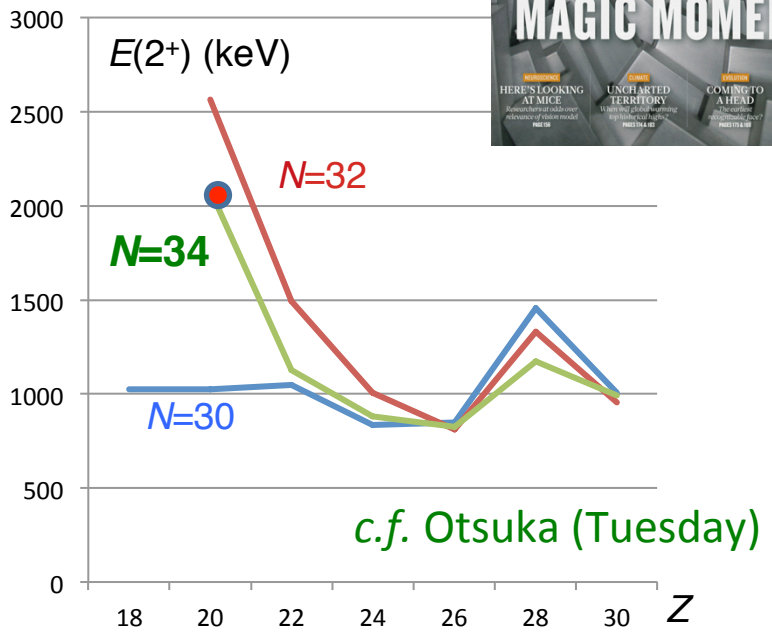
at RIBF

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], 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], T. Sumikama[8], H. Suzuki[2], R. Taniuchi[5], Y. Utsuno[9], J. J. Valiente-Dobón[10] & K. Yoneda[2]

N=34 shell gap large in ^{54}Ca? ➔ Yes





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

mass
2^+, *B*(E2)
4^+
μ, *Q*

β-NMR

N=20

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

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

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

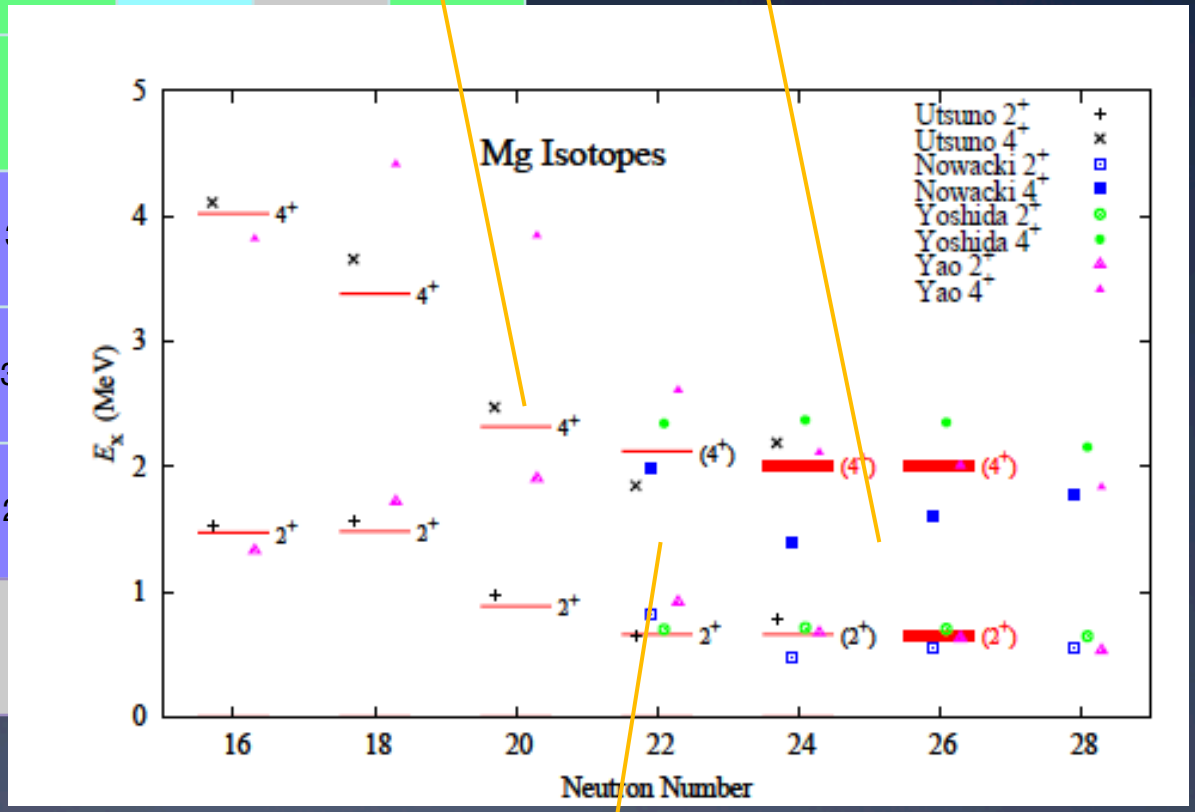
Dornenbal, Scheit, Takeuchi, *et al.*, PRL111 (2013) 212502

mass
2^+, B(E2)
4^+
μ, Q

β-NMR

N=20

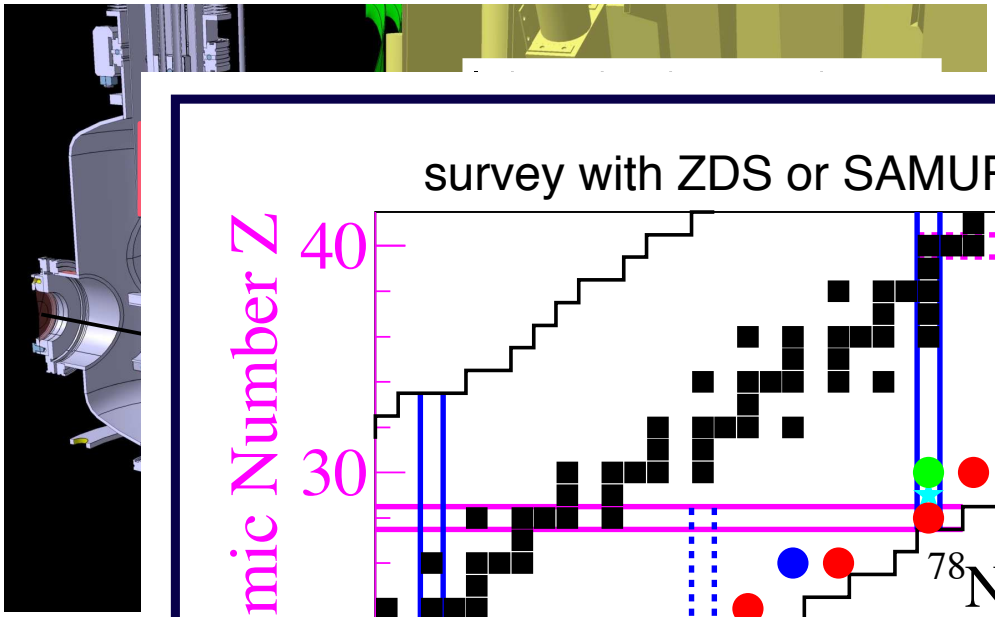
^{31}Si	^{32}Si	^{33}Si	^{34}Si	^{35}Si	^{36}Si
^{30}Al	^{31}Al				
^{29}Mg	^{30}Mg				
^{28}Na	^{29}Na				
^{27}Ne	^{28}Ne				
^{26}F	^{27}F				

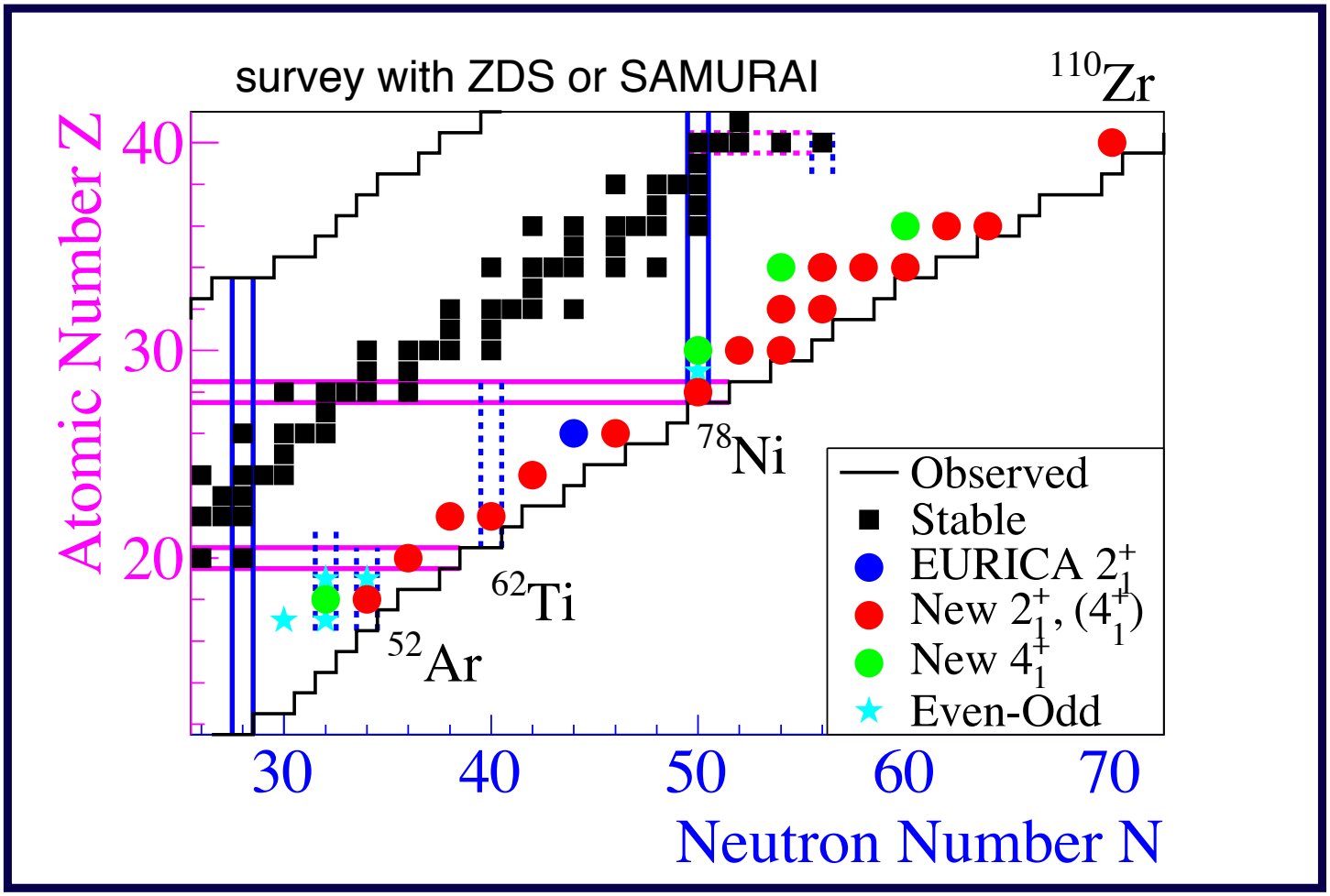


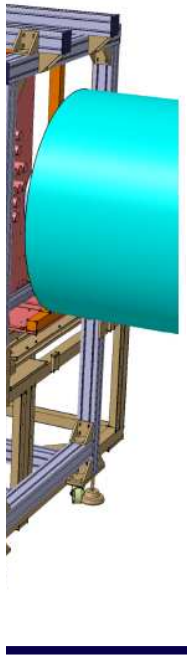
K. Yoneda *et al.*, PLB 499 (2001) 233

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

no mass transfer







Ma

http

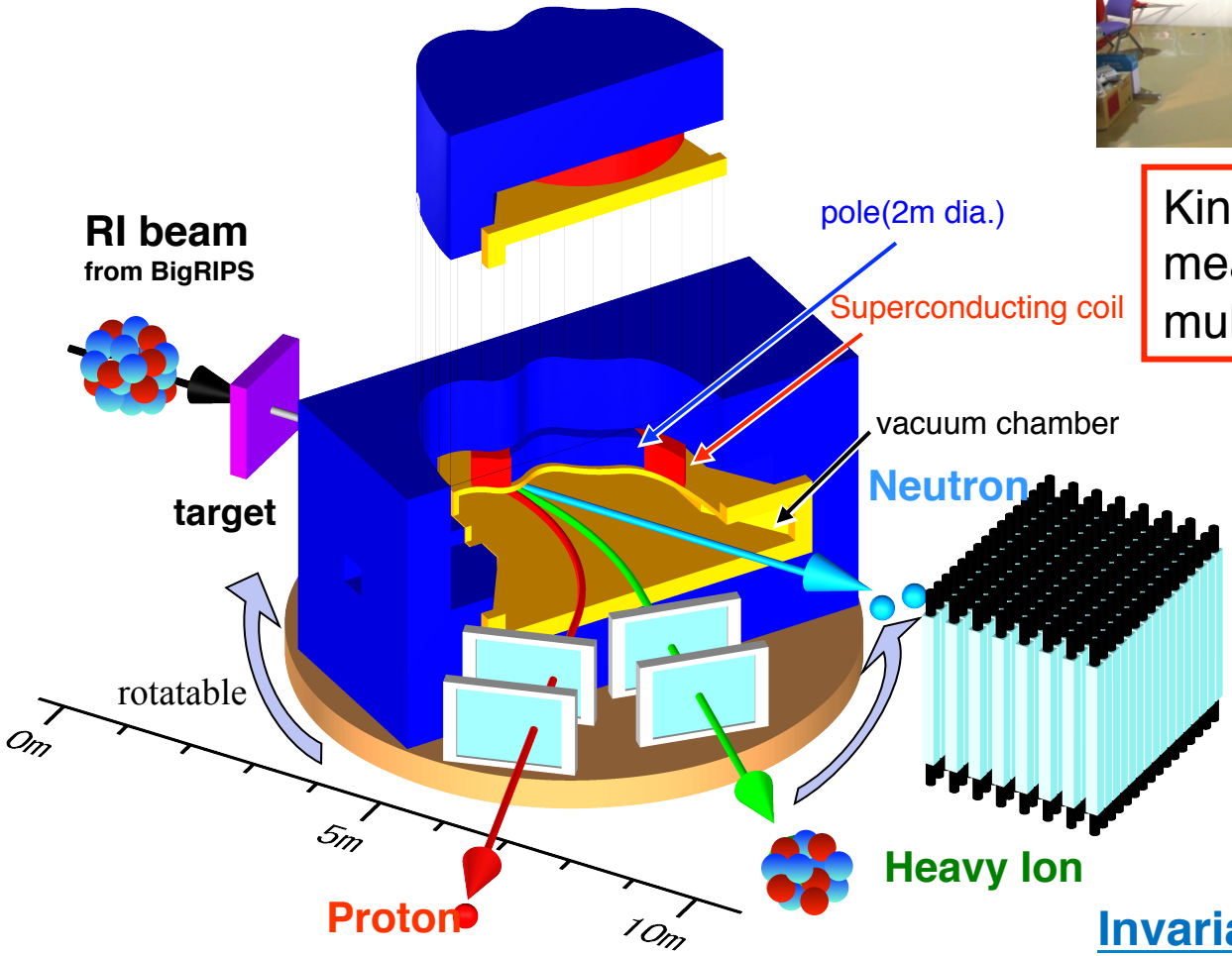
A. Obertelli *et al.*, Eur. Phys. J. A 50, 8 (2014).

from Doornenbal

SAMURAI

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

in operation since **2012**



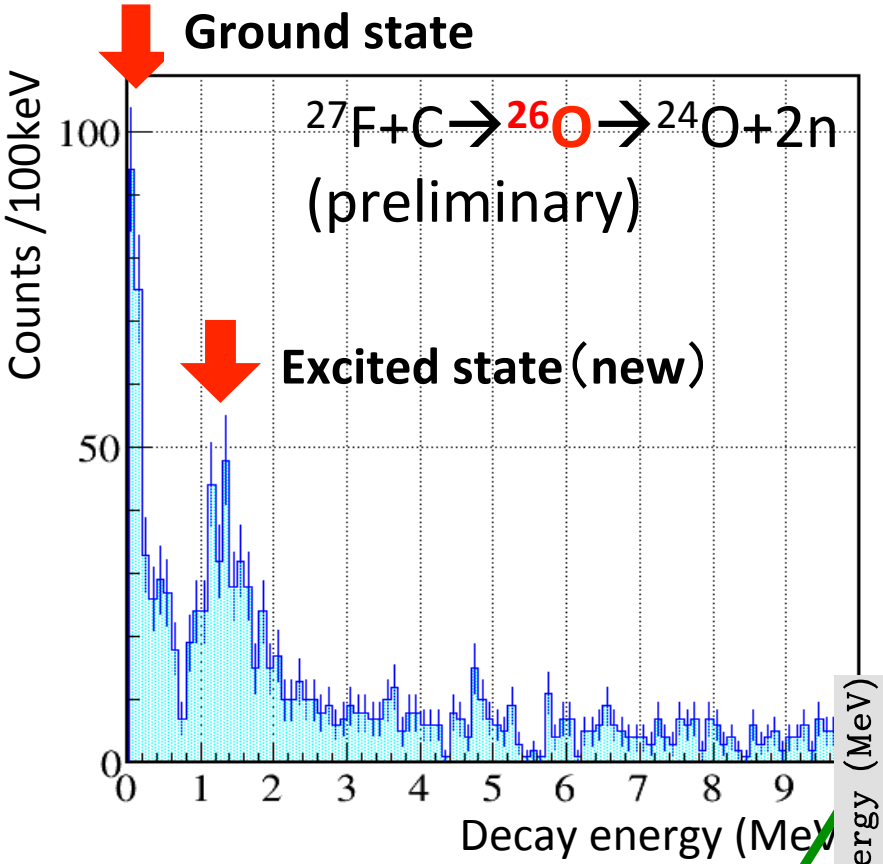
Kinematically complete measurements by detecting multiple particles in coincidence

- 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



Ground state

5 times higher statistics

→better determination of energy

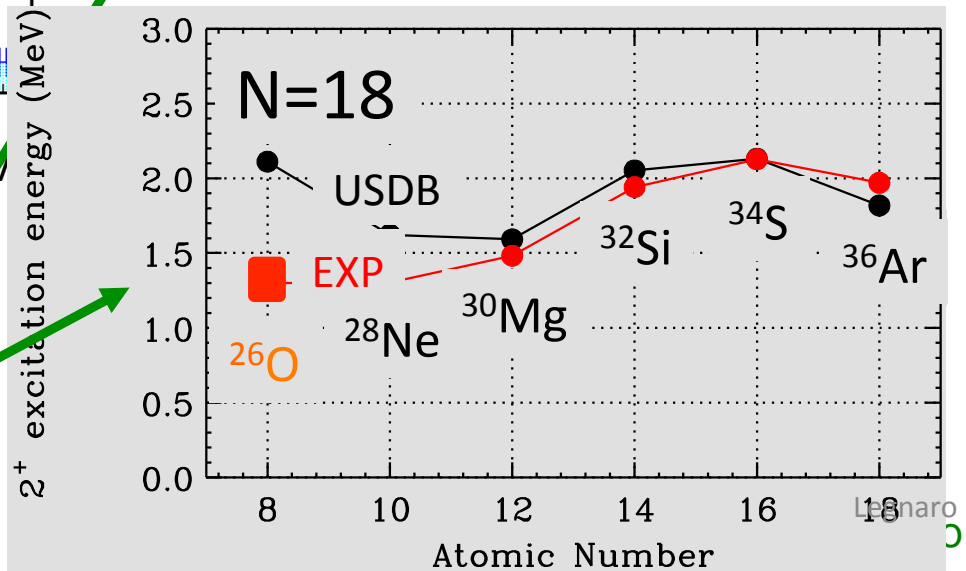
Excited state at ~1.3MeV

First observation

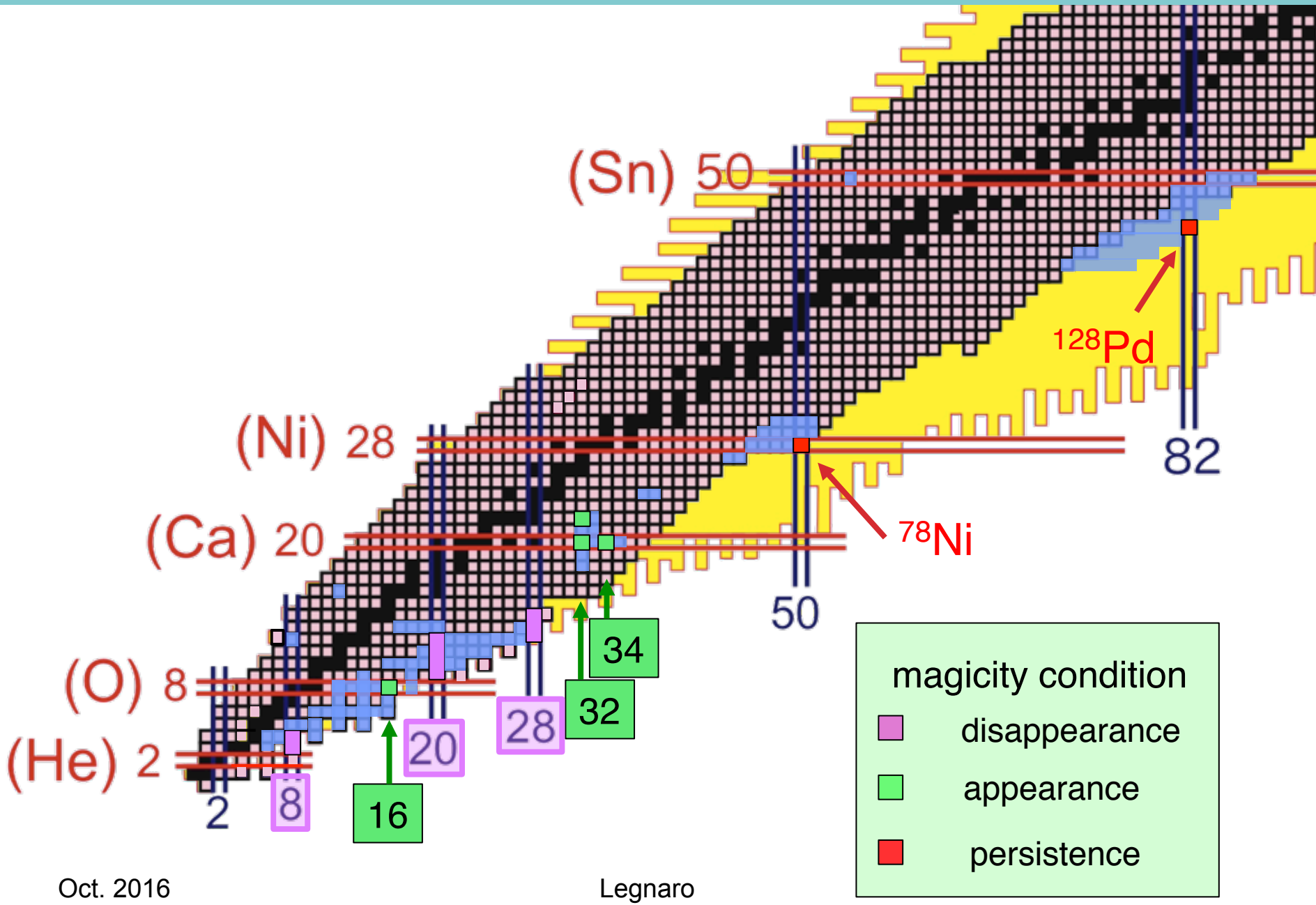
Most probably 2$^+$

No peak at ~4.2MeV

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



“Magicity” of n-rich nuclei studied at RIBF



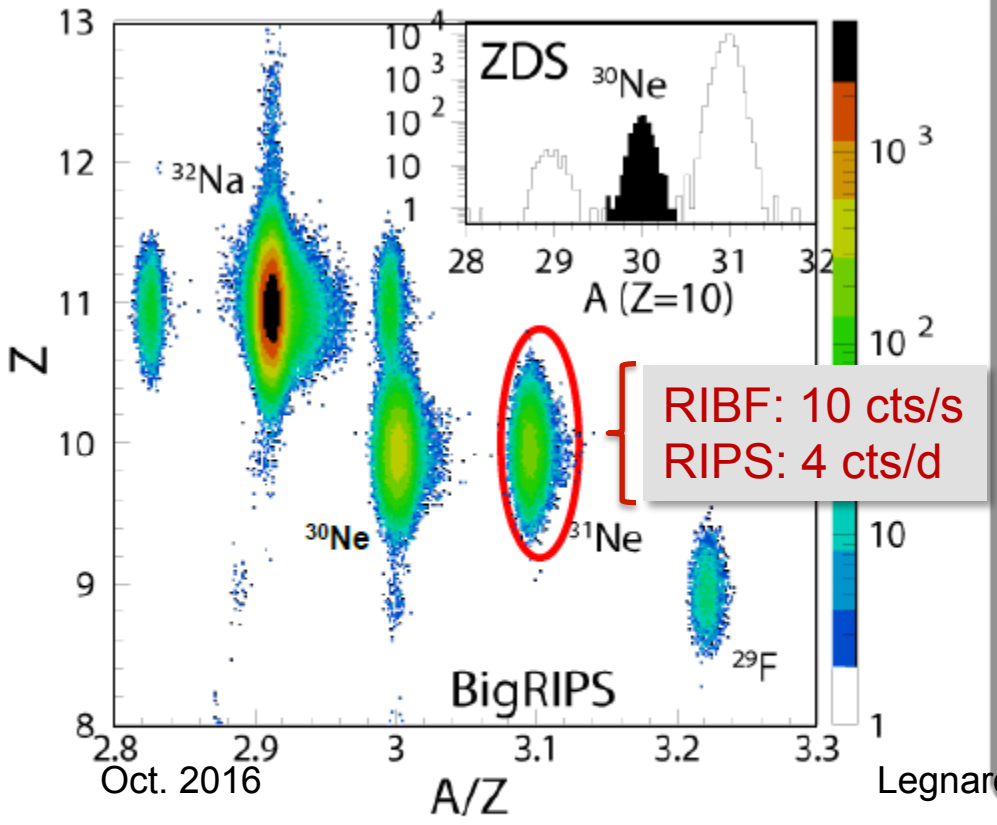
Discoveries / gain to our (basic) knowledge

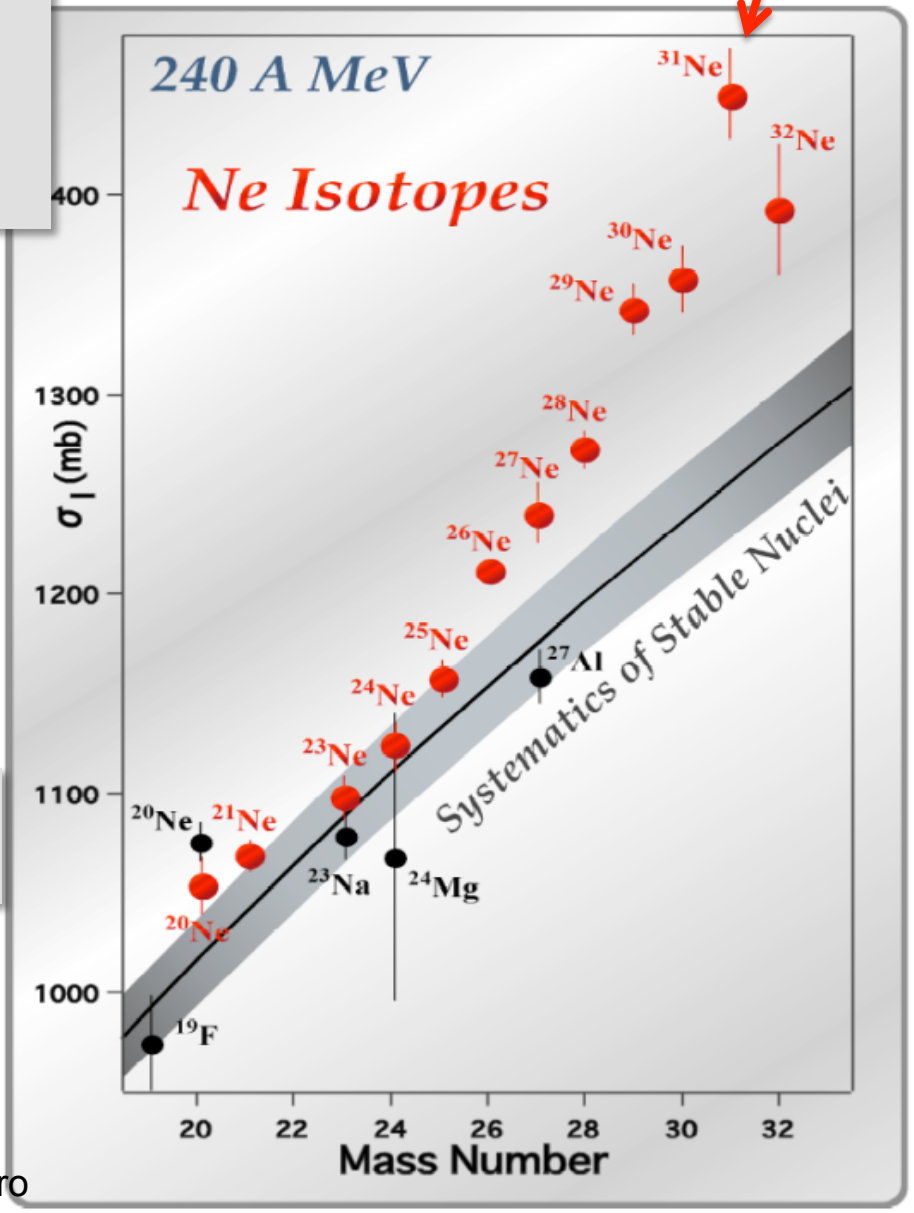
1. r-process is reached. – nuclear astrophysics
2. n-rich shell structure explored – nuclear structure
   - magic numbers, deformation
3. Neutron **halo** in deformed nuclei – nuclear structure

Deformed halo ? in Ne Isotopes

Transmission & Interaction Cross Section Measurements

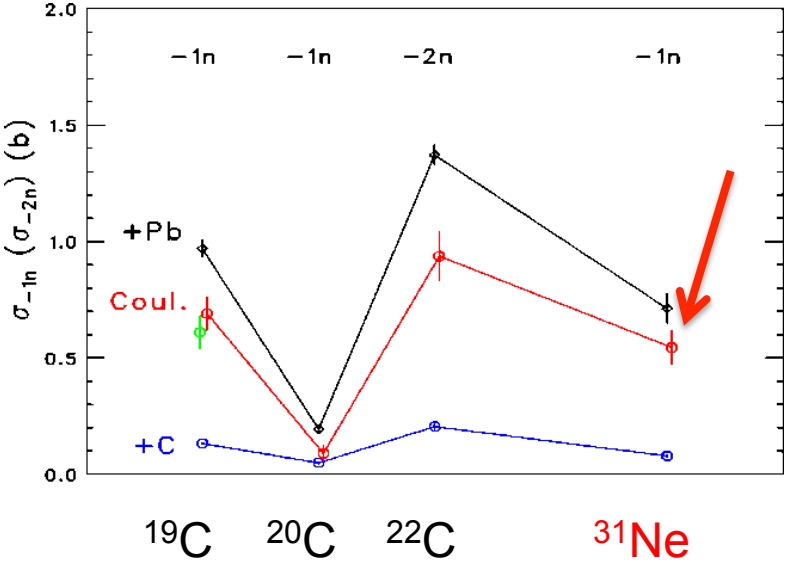
M. Takechi et al., Phys. Lett. B707 (2012) 357





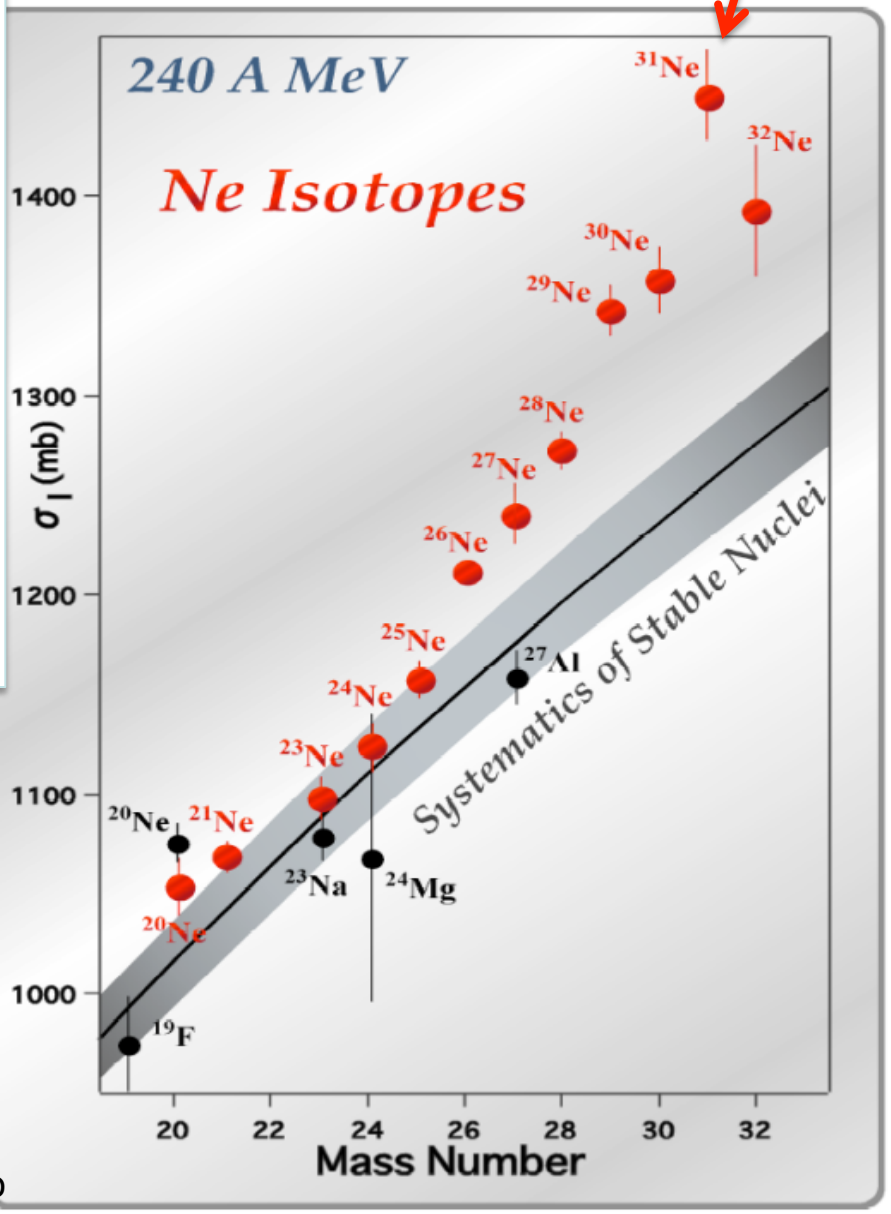
Large Coulomb breakup σ for ^{31}Ne

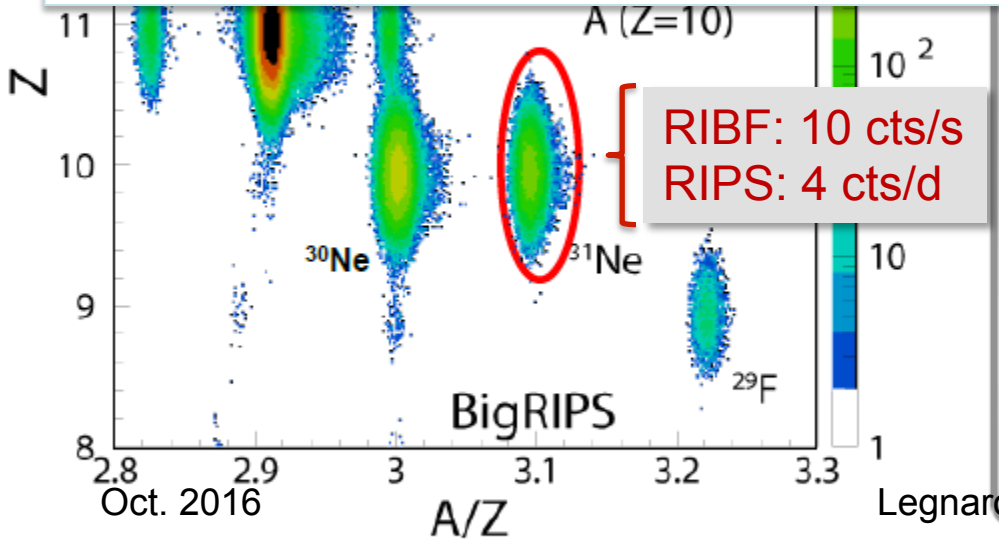
→ p-wave halo in deformed nucleus



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

Similar in ^{37}Mg





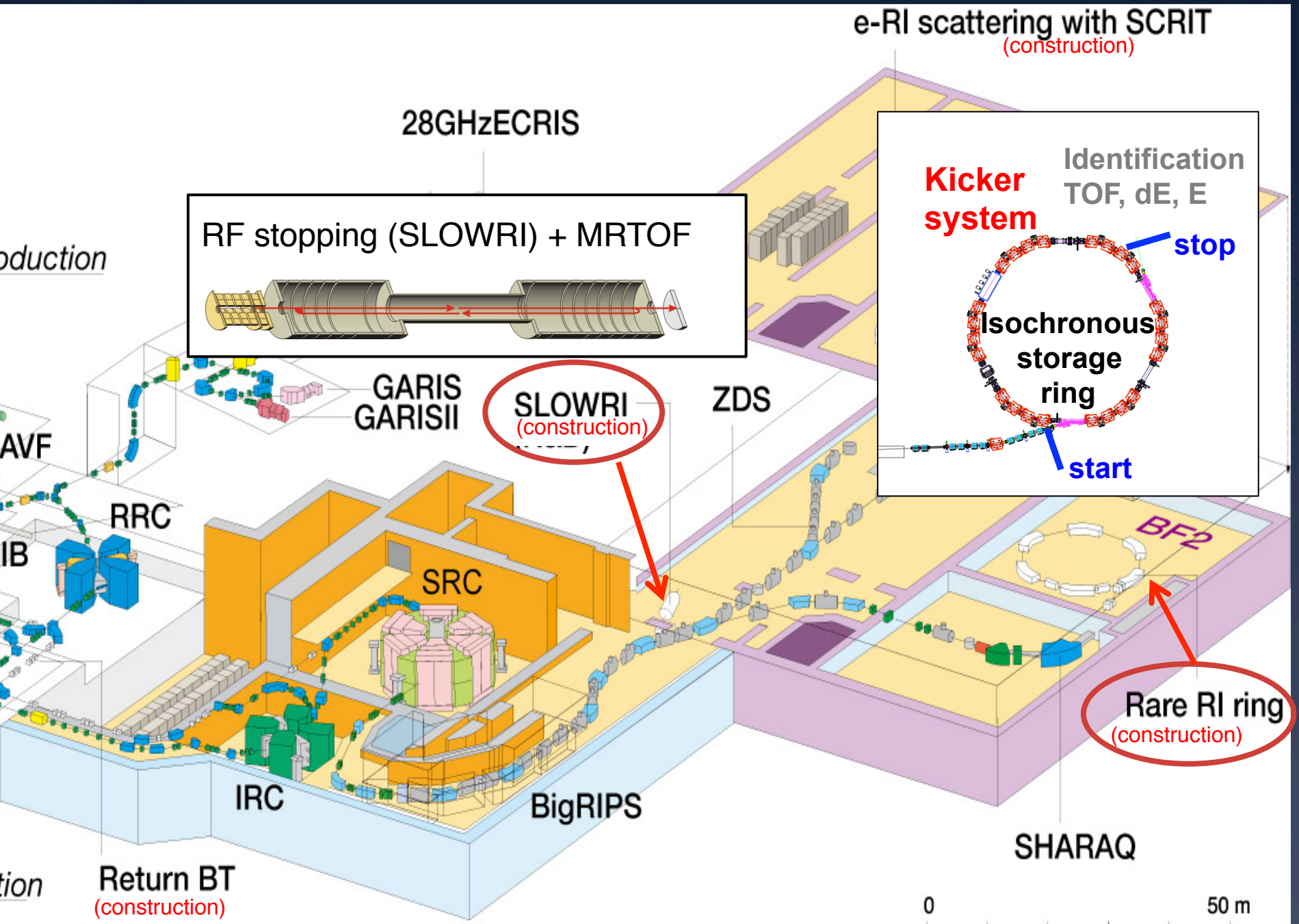
RIBF: 10 cts/s

RIPS: 4 cts/d

Programs to come

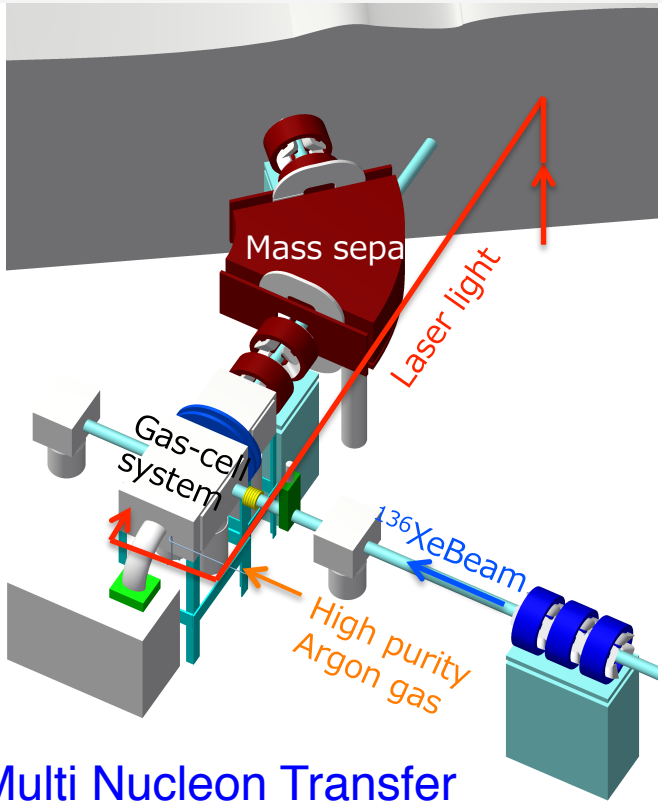
- direct mass measurements by “Rare RI Ring” / MR TOF ..
- e-RI scattering by SCRIT

Equipment and detectors under construction – mass measurements



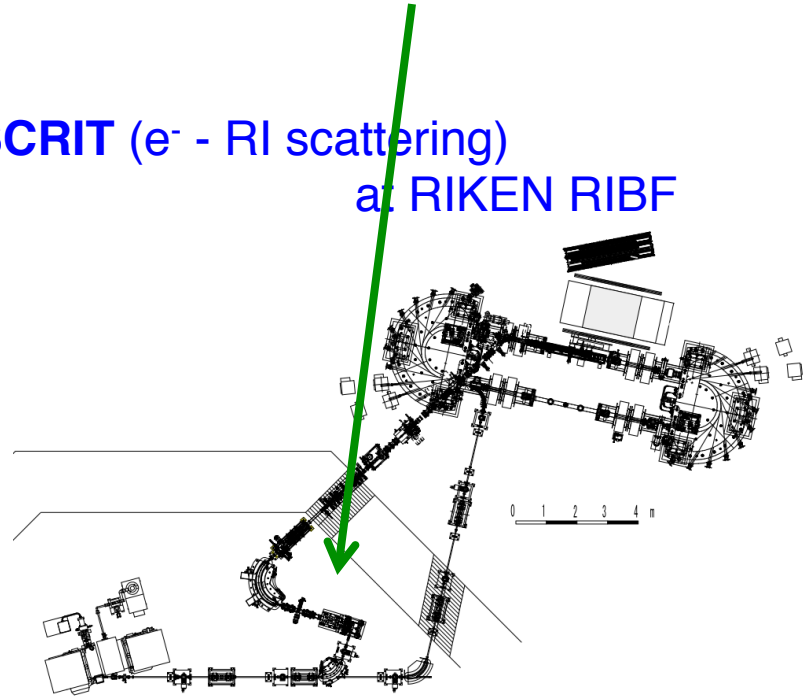
KEK started KISS at RIKEN RIBF.

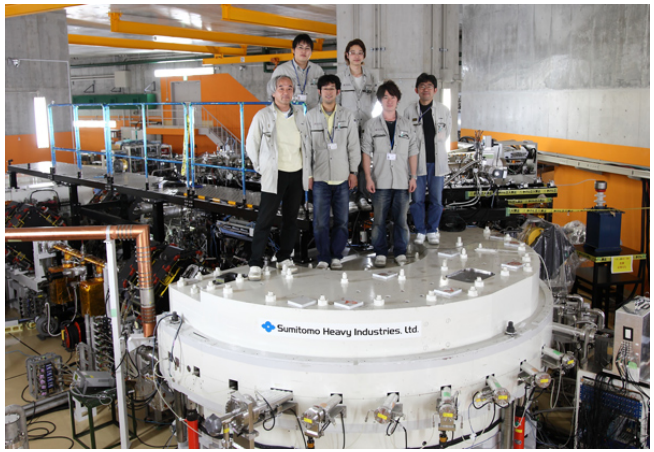
(selective) laser ionization of MNT* products



* Multi Nucleon Transfer
by RI beams (in future)

SCRIT (e^- - RI scattering)
at RIKEN RIBF





M. Wakasugi *et al.*, NIMB 317 (2013) 668

Programs to come

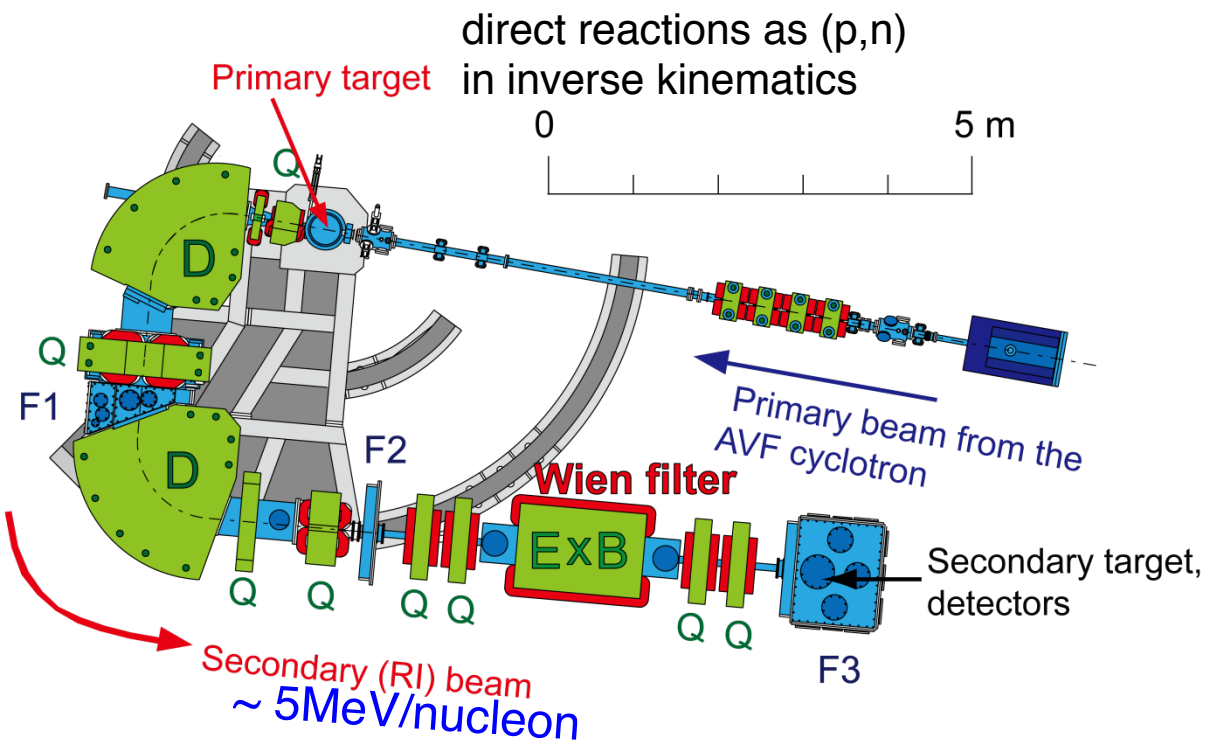
- direct mass measurements by “Rare RI Ring” / MR TOF ..
- e-RI scattering by SCRIT
- Low-energy RI beams (CNS, U. Tokyo)
  - CRIB – in operation
  - OEDO – new project

CRIB* uses ~10 MeV/nucleon HI beams from the AVF injector of RIKEN RIBF.

* CNS Radio-Isotope Beam separator

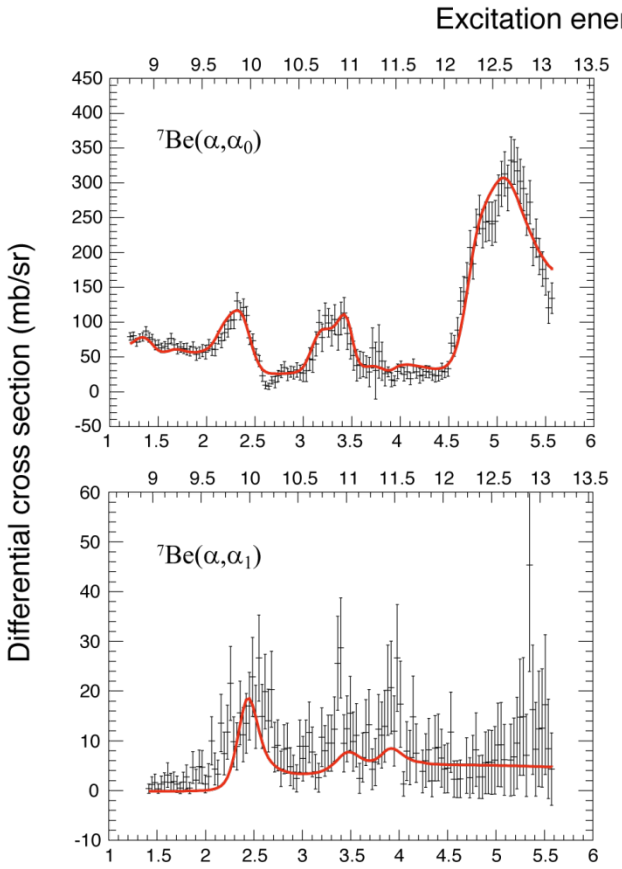
operated by **CNS (Univ. of Tokyo)**, located at RIBF (RIKEN Nishina Center).

~ EXOTIC



e.g. $^{7}Li + {}^{1}H \rightarrow {}^{7}Be$

$^{7}Be(\alpha,\gamma)$ of astrophysical interest



H. Yamaguchi *et al.*, PRC (2013)

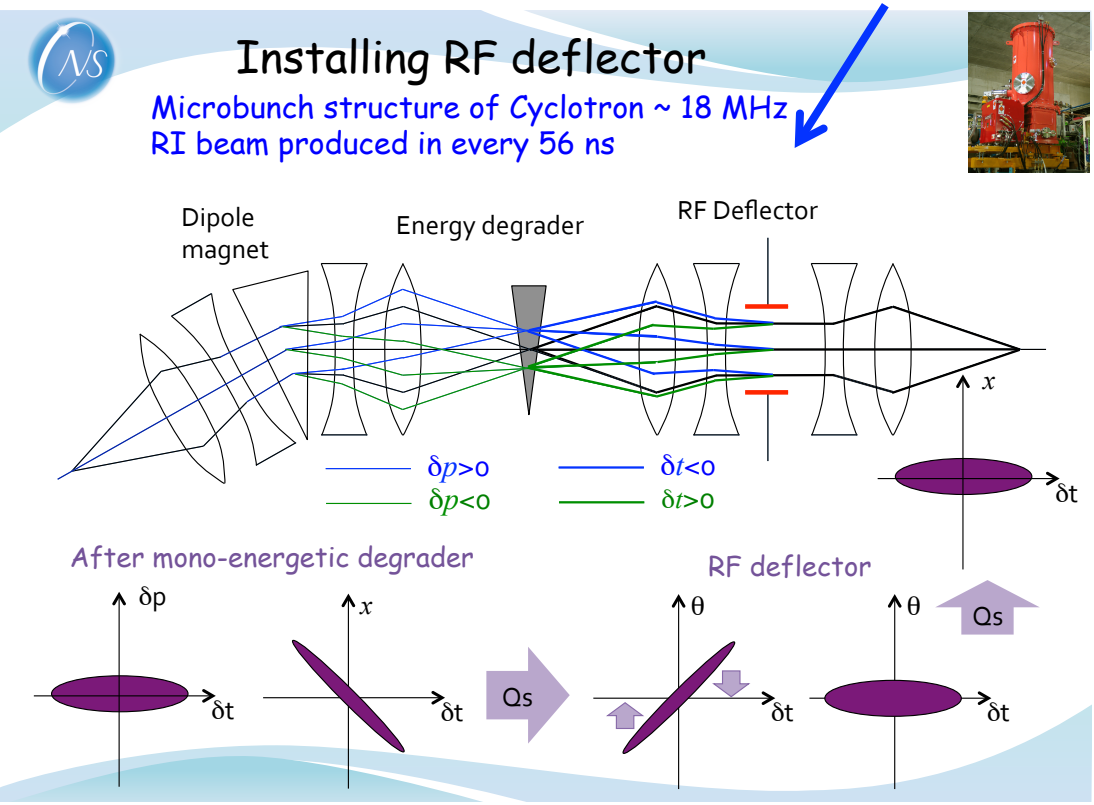
Courtesy of Hidetoshi Yamaguchi

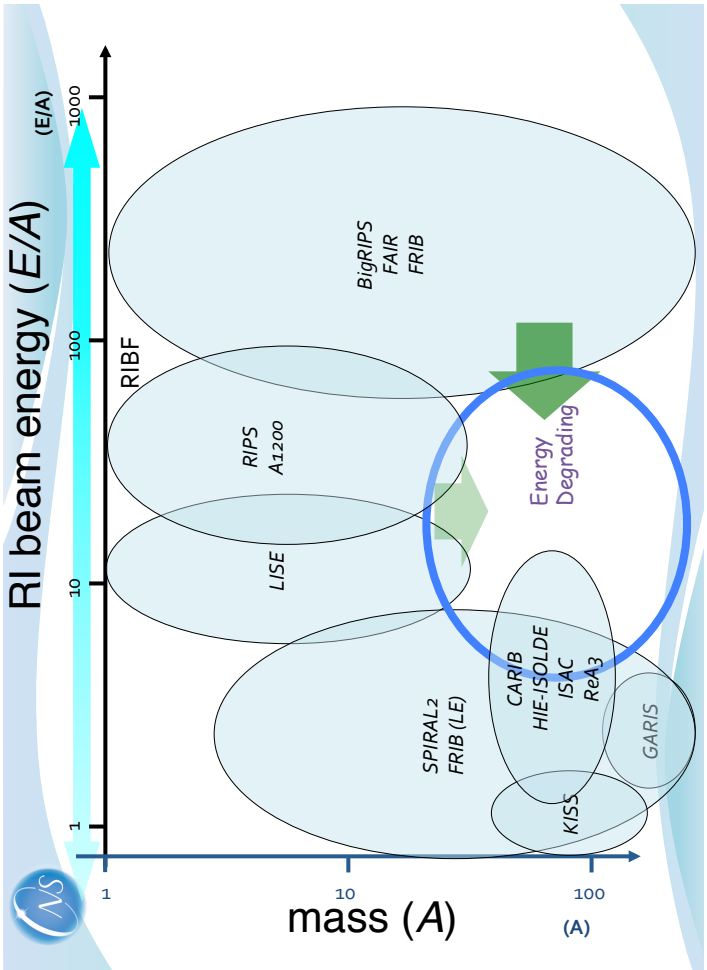
Legnaro

Oct. 2016

OEDO reduces the beam-spot size using the arrival-time difference
by an RF deflector (synchronized with the cyclotron RF)
even with a large energy-loss in the degrader (*e.g.* 200 → 20 MeV/nucleon)
to realize (versatile) fragmentation-based degraded beams of tens MeV/nucleon

bunched beam from cyclotron

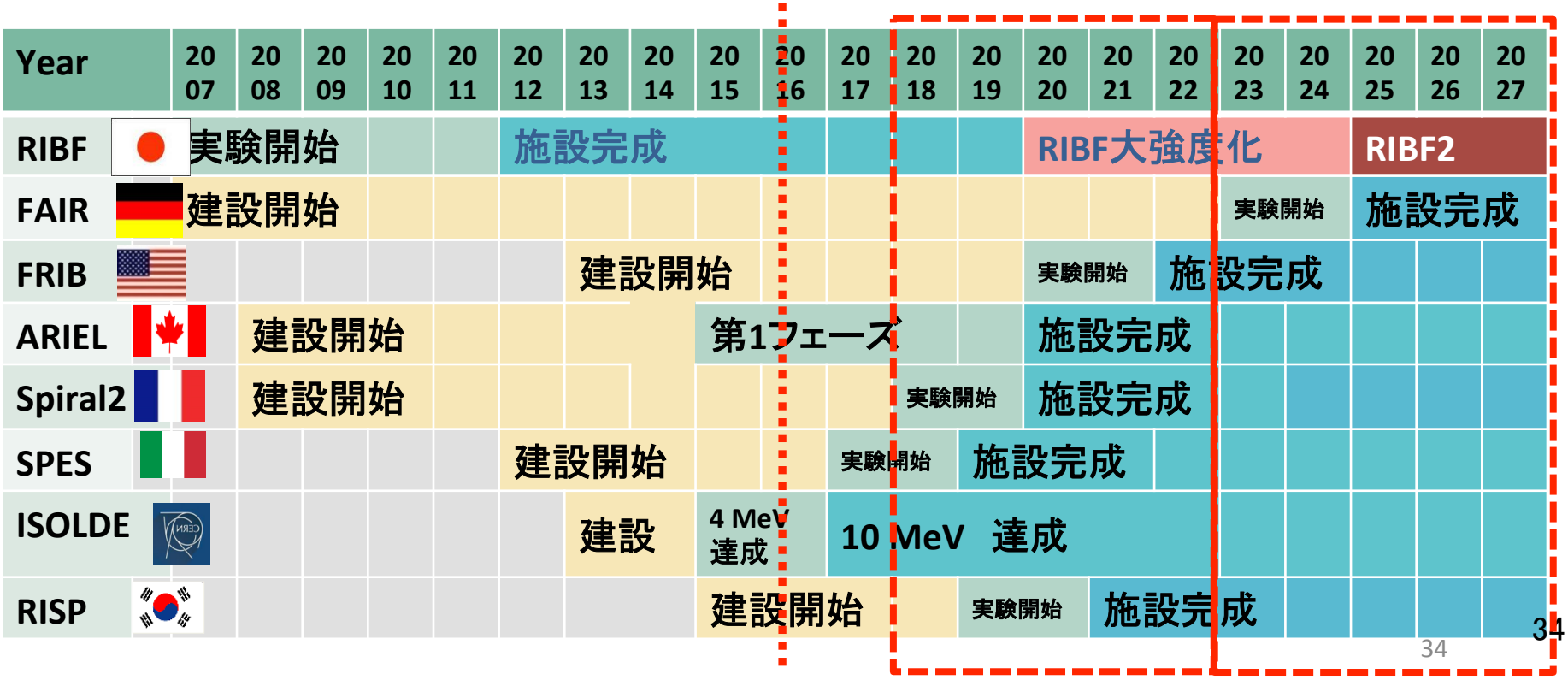




Courtesy of S. Shimoura

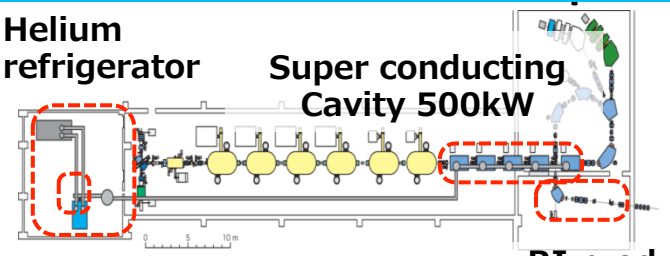
Plans for future RIBF

To be competitive also after 2025

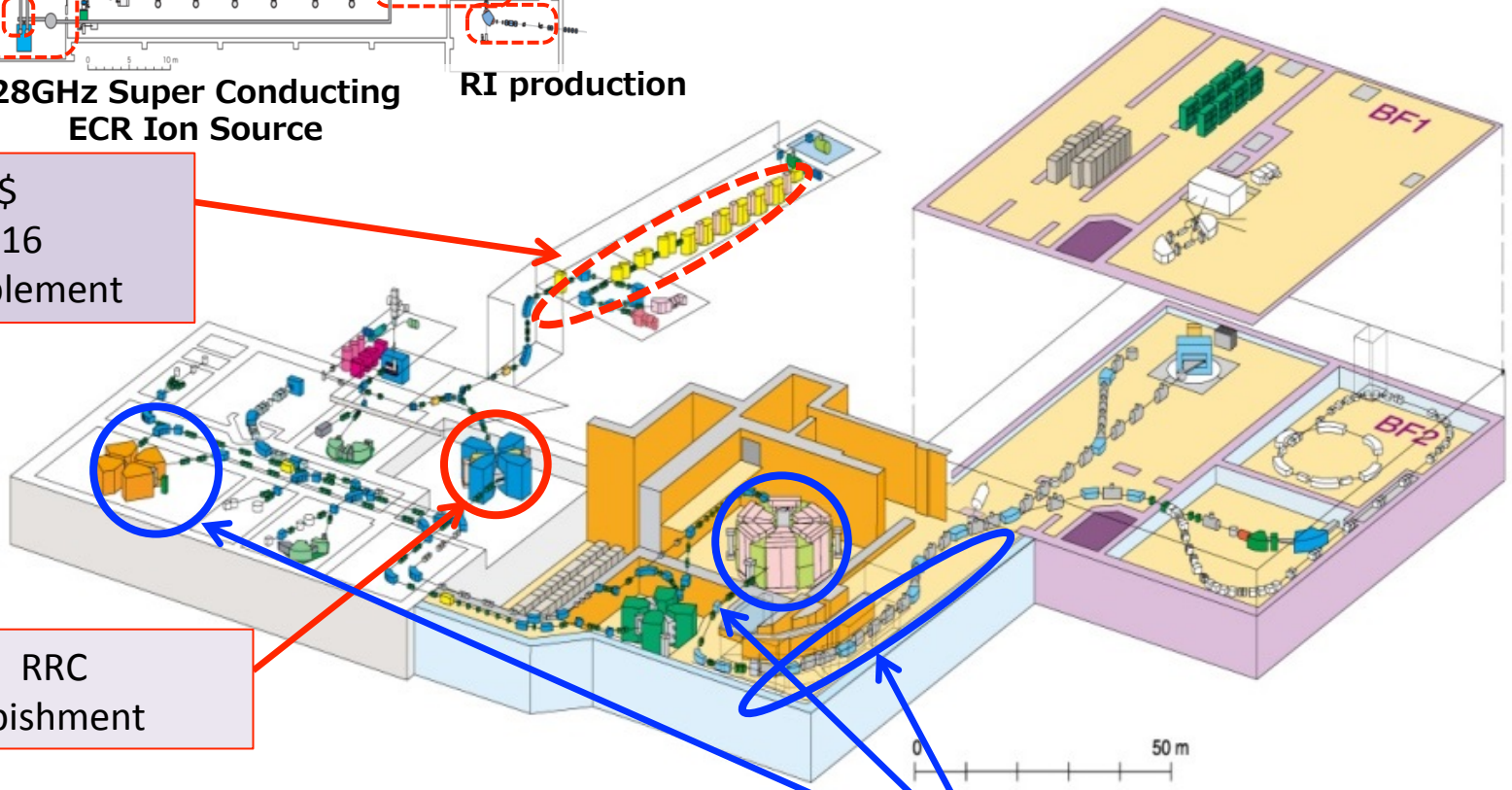


An RIBF upgrade **plan** was submitted to Science Council of Japan - partly approved

RIBF upgrade plan submitted to Science Council of Japan (146M$) - partly approved



SHEs 119 and beyond
More neutron-rich (heavy) nuclei



32M$ FY2016 Supplement

12M$ RRC refurbishment

103M$

Toward 1st experiments in 2025
with >10 times higher RI beam intensities

Status of RIKEN
- research at RIBF

RIKEN RIBF*

- experiments since 2007
- fast RI beams by projectile fragmentation / fission
- world highest capability of RI beam production

Discoveries / gain to our (basic) knowledge

- r-process, shell evolution, neutron halo

Programs to come

- Direct mass measurements, e-RI scattering
- OEDO - low-energy RI beams OEDO

Plans for future

applications – plant breeding, RI production, abrasion test, σ for transmutation,