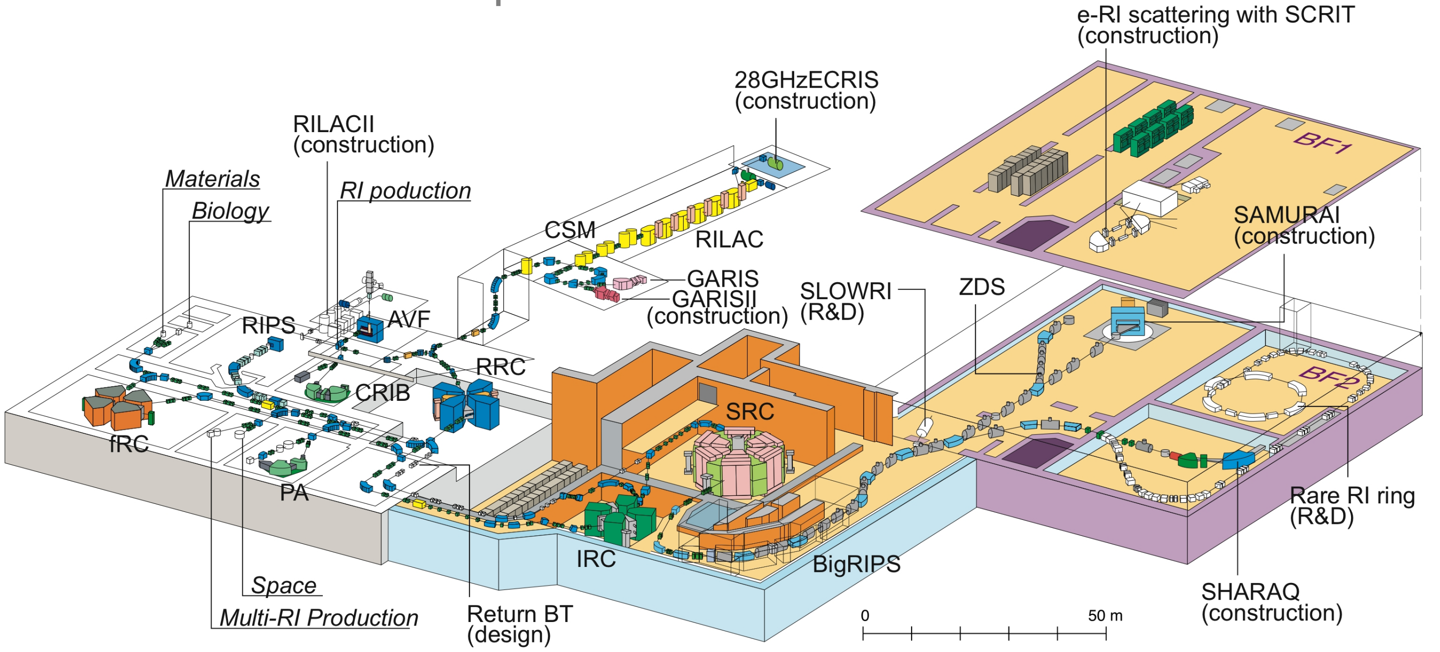
Studies with RI beam for explosive burning

Tohru Motobayashi
RIKEN Nishina Center

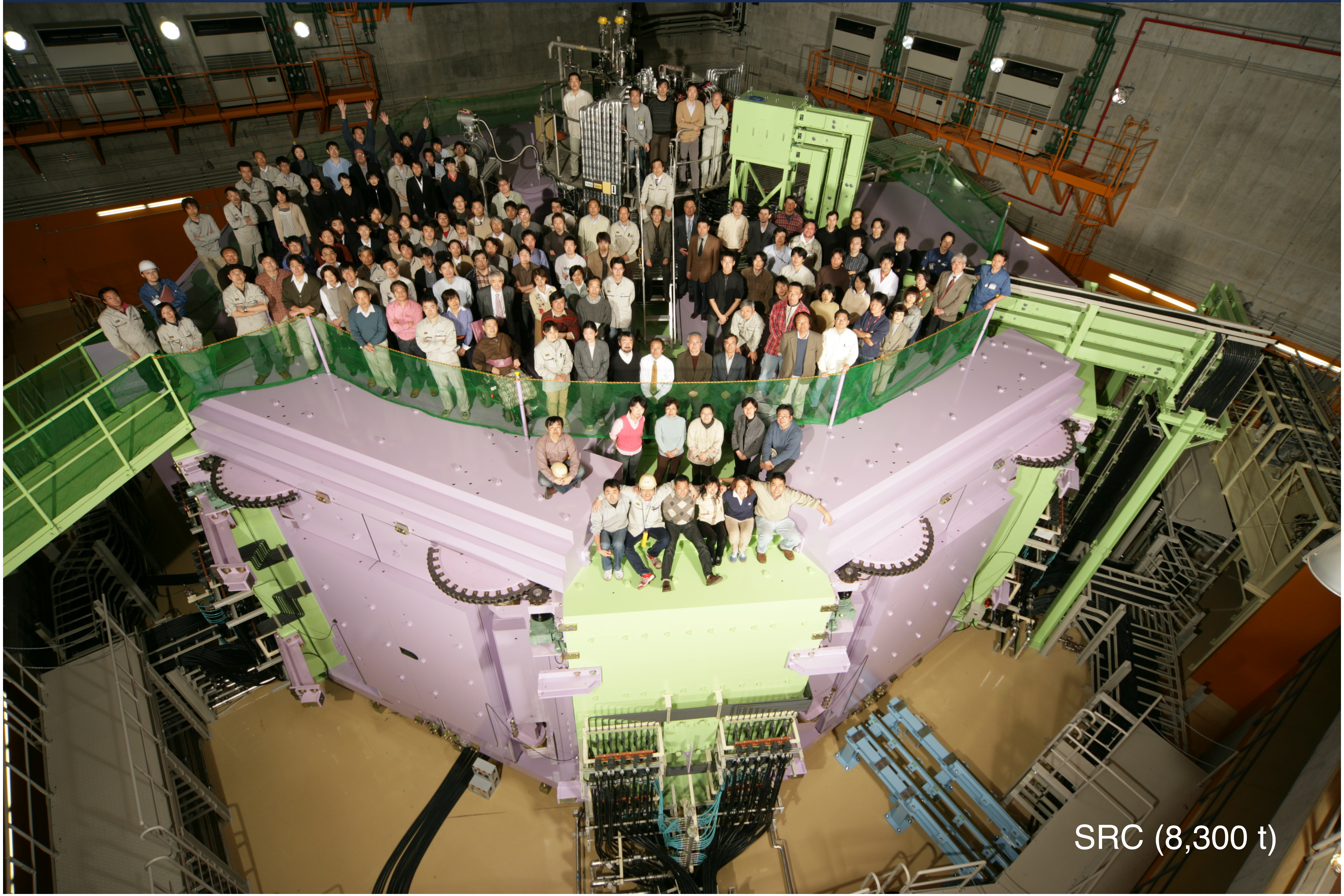
RIBF accelerator complex



1986-

2007-

Studies with RI beam for explosive burning



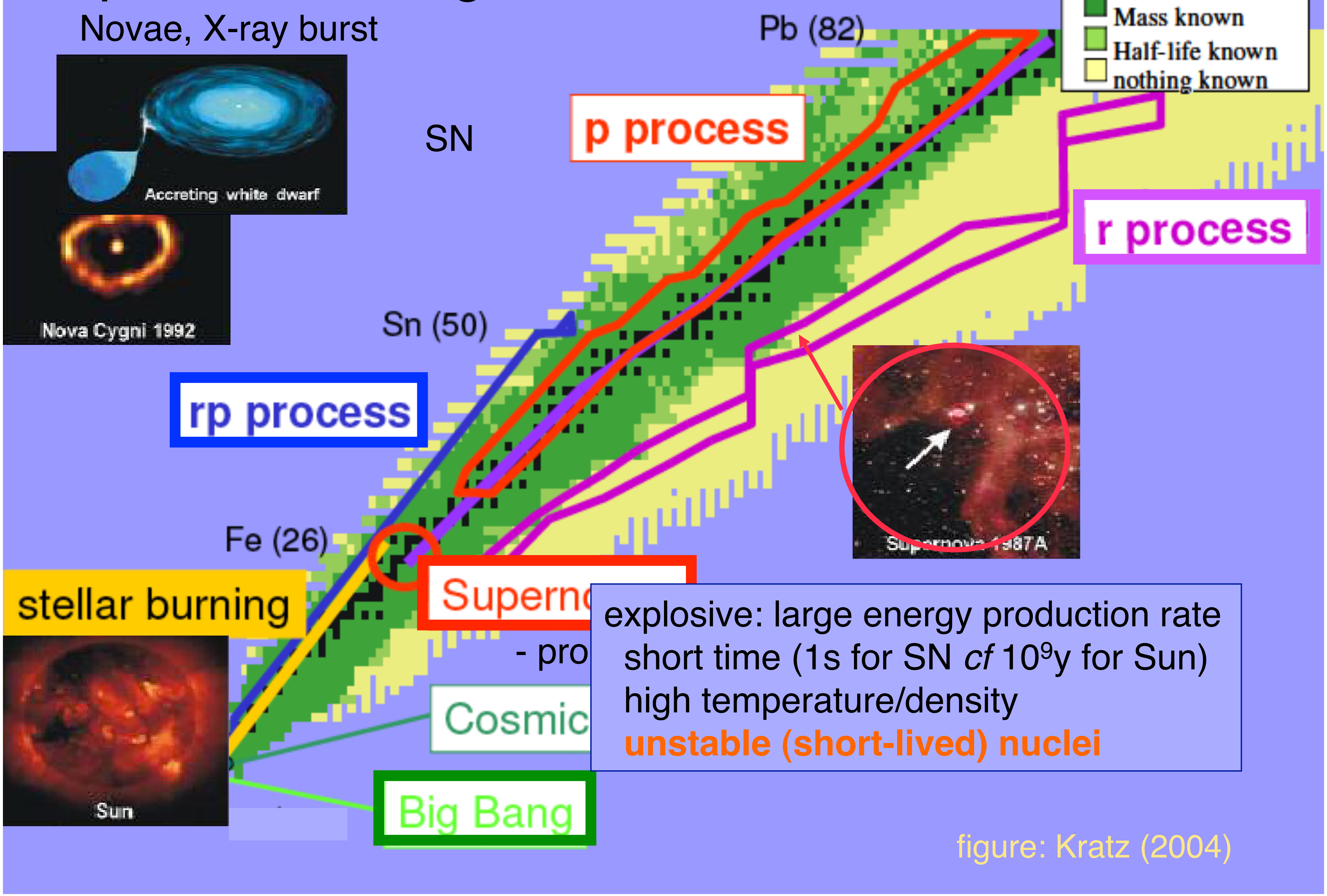
Studies with RI beams for explosive burning

(fast)

Tohru Motobayashi
RIKEN Nishina Center

1. nuclear processes in explosive burning
2. explosive hydrogen burning
   Coulomb dissociation with RI beams
3. toward r proces
   production, life, mass

Explosive burning

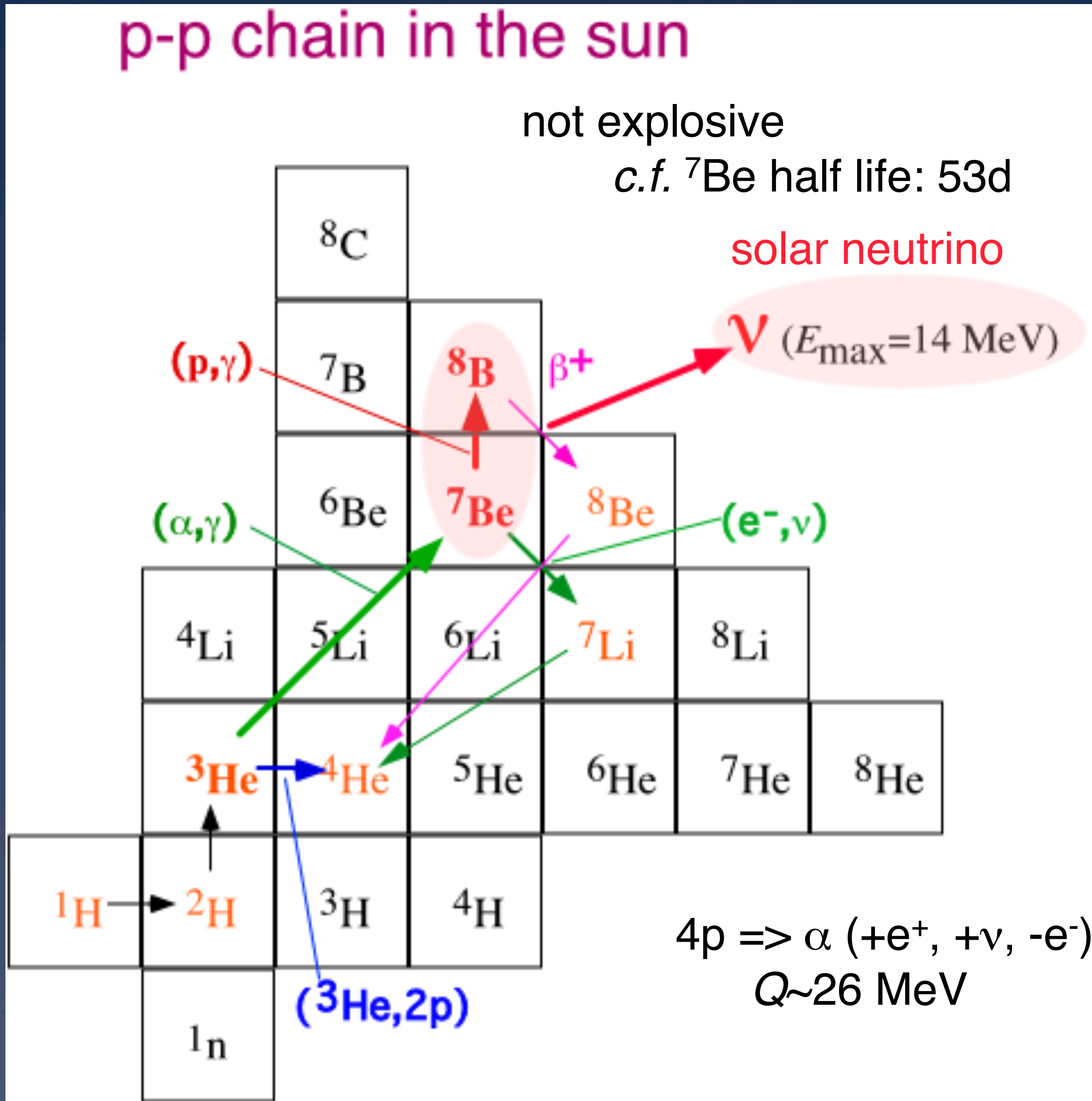


explosive: large energy production rate
short time (1s for SN *cf* 10^9y for Sun)
high temperature/density
unstable (short-lived) nuclei

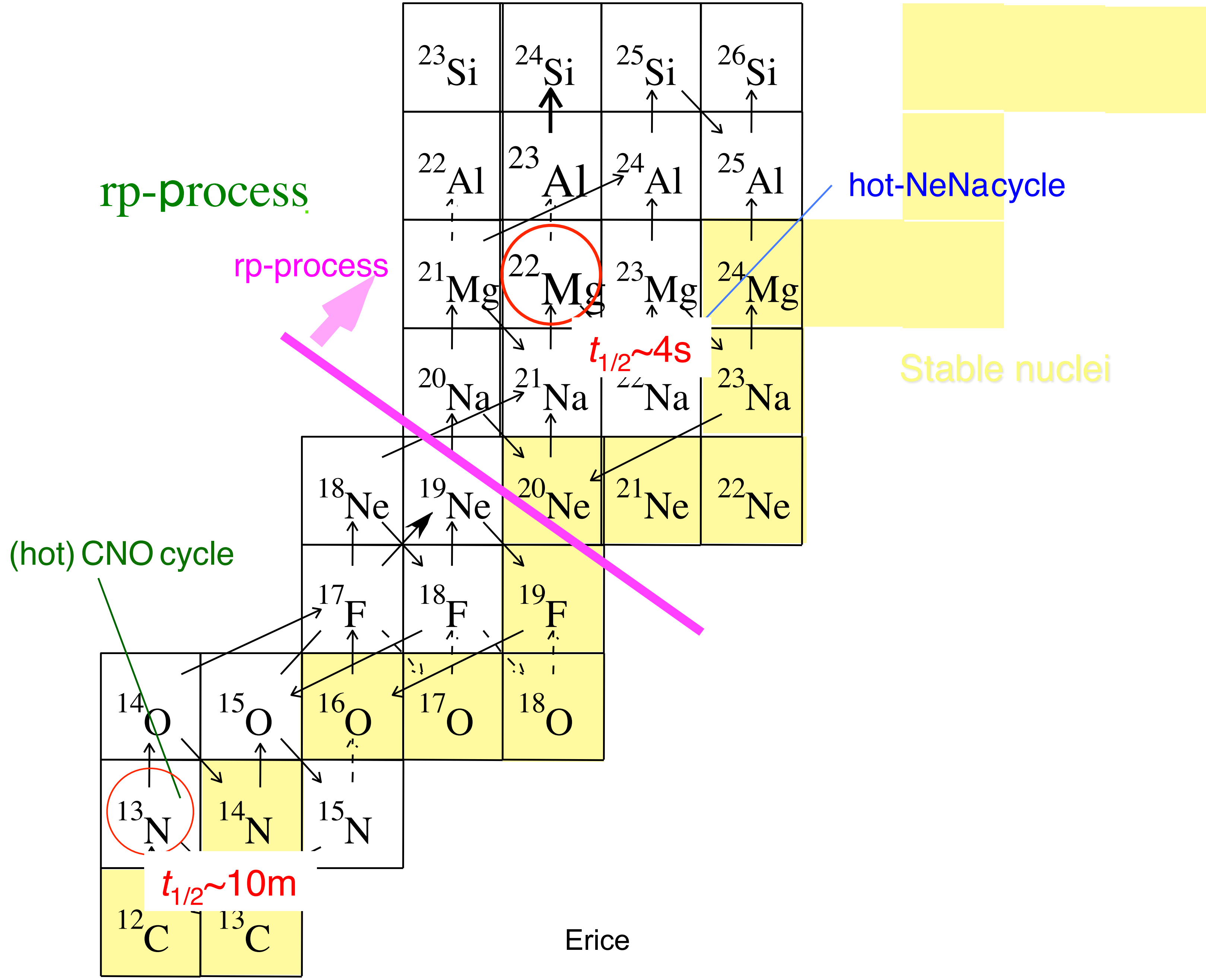
figure: Kratz (2004)

Competition between fusion (p,γ) and β^+ decay

➔ measurements of σ / lifetime



In explosive burning, short-lived nuclei can capture proton



(fast*) RI beams are useful.

2. Coulomb dissociation
   explosive hydrogen burning

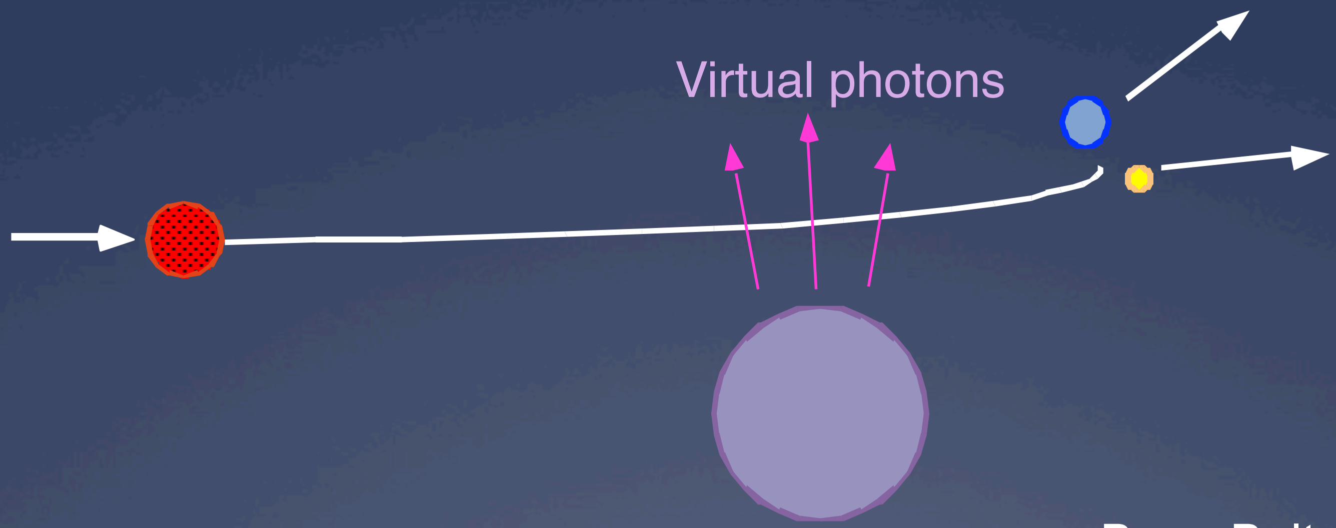
3. production, mass, life, nuclear structure
   toward r-process nuclei

* β~0.2 or large   RI beams by fragmentation / in-flight fission

c.f. RIKEN RI Beam Factory (RIBF):
1st new-generation facility for RI beams in operation.

§2 Coulomb dissociation - an example of fast RI-beam experiment

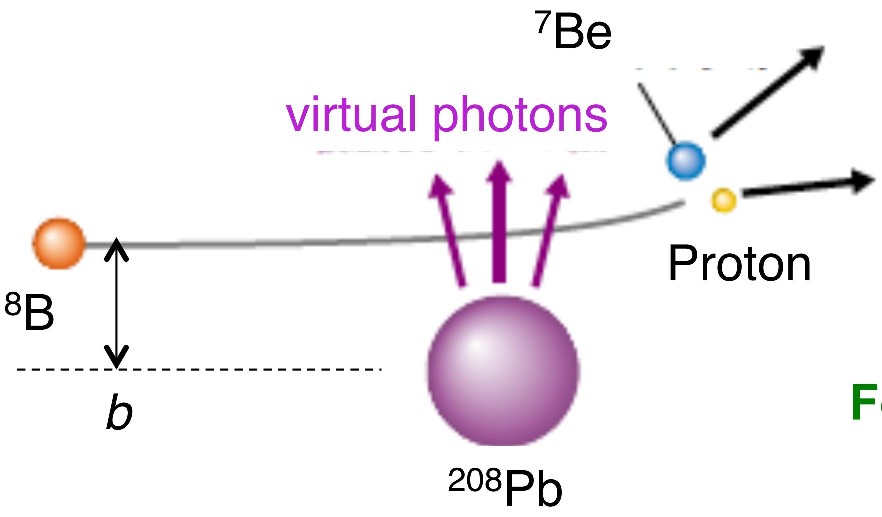
simulation for inverse radiative-capture of astrophysical interest
(or neutron halo)



Baur, Beltulani, Rebel,
N.P. A458 (1986) 188

Baur, Rebel, J. Phys. G20 (1994) 1;
Ann. Rev. Nucl. and Part. Sci. 46 (1996) 321

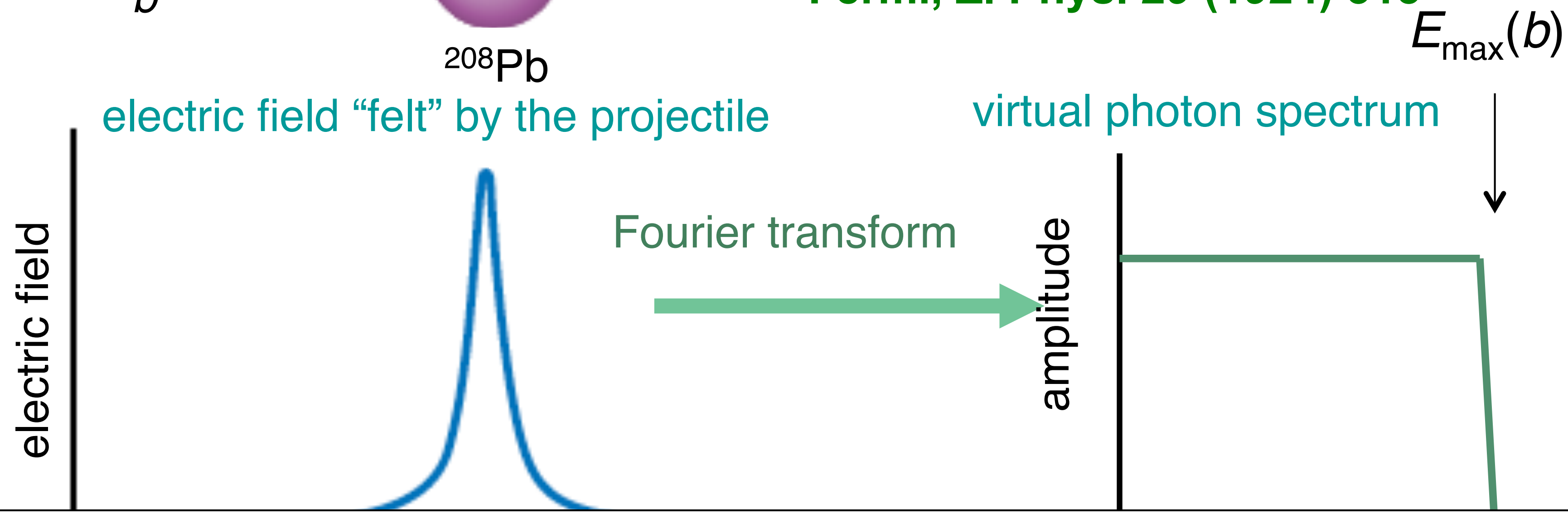
§2 Coulomb dissociation = photodisintegration by virtual photon: an old idea in 1924



E_{in} ↗ : E_{max} ↗

b ↗ : E_{max} ↘

Fermi, Z. Phys. 29 (1924) 315



"Fast beam" can cover the energy range of nuclear excitation.

~ photon energy
($E=h\nu$)

§2 Coulomb dissociation - Cross section or yield is expected to be large.

detailed balance

$$\sigma_{(\gamma,\mathrm{p})} = \frac{(2j_7+1)(2j_1+1)}{2(2j_8+1)} \frac{k_{17}^2}{k_\gamma^2} \sigma_{(\mathrm{p},\gamma)}$$

100 ~ 1000

virtual photon number (intermediate energy)

$$\left(\frac{d\sigma}{dE_\gamma}\right)_{\mathrm{C.D.}} = \frac{n}{E_\gamma} \sigma_{(\gamma,\mathrm{p})}$$

100 ~ 1000

dipole transition dominates

thick target

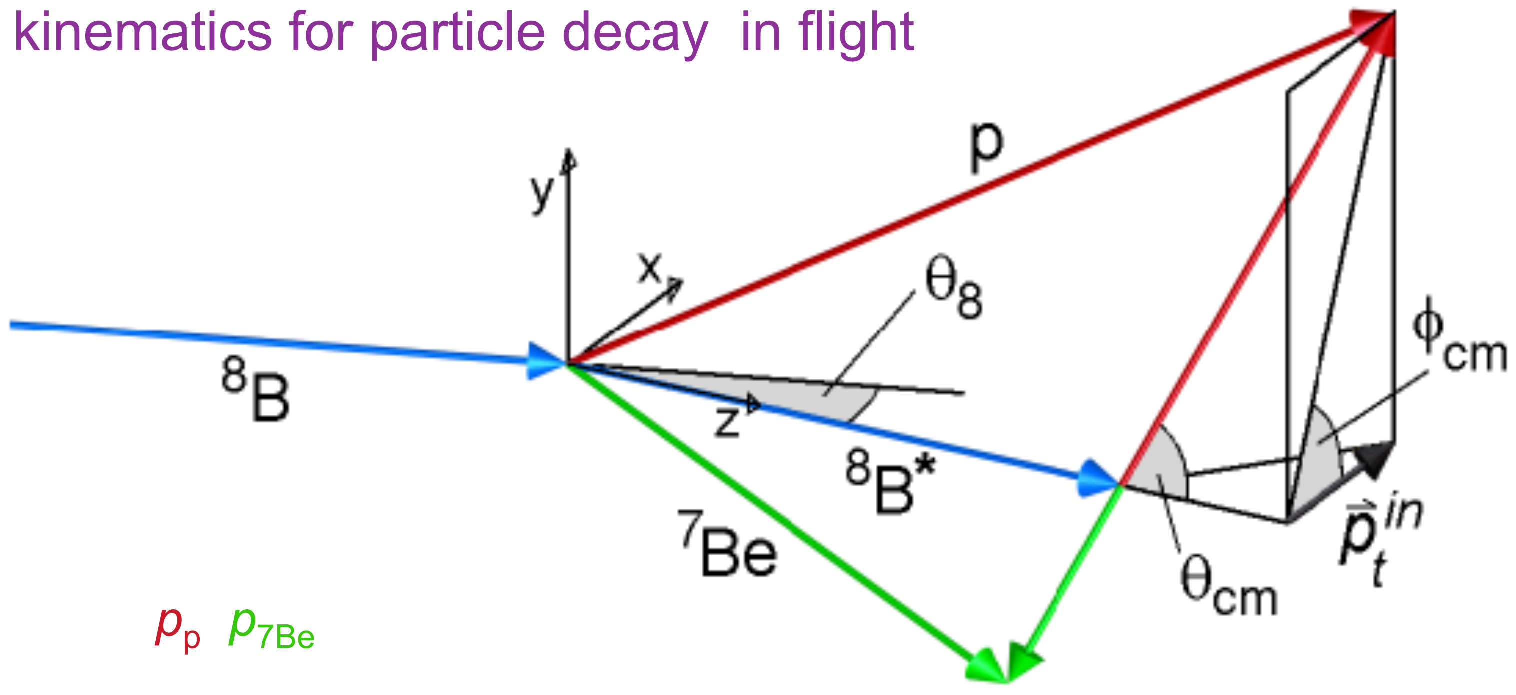
charged particle detection

large σ、thick target (fast beam) ➔ experiments with R.I. beams

but

indirect *i.e.* nucl. force / higher order / E2

§2 Coulomb dissociation - Resolution is independent of the (large) beam spread.



ΔE_{rel} : Independent of ΔE_{in}

good for experiments with poor-quality RI beams

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

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

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

$\Delta\theta$=0.5 deg. Δv=1%

↓

ΔE_{rel}=200 keV

absorption of virtual photons

mostly dipole <-- nuclear response *c.f.* $N_\gamma(E1) < N_\gamma(E2)$

σ_{CD}: amplified (large) at intermediate energies ($v/c > 0.3$)

inverse kinematics measurement

high experimental efficiency

reasonable E_x resolution with fast RI beams

invariant mass: independent of the beam quality

examples:

$^3H(\alpha,\gamma)^7Li$ Shotter, Utsunomiya 1988

$^2H(\alpha,\gamma)^6Li$ Hesselbarth 1988, Kiener 1989

$^{13}N(p,\gamma)^{14}O$ Motobayashi 1991, Kiener 1993

$^7Be(p,\gamma)^8B$ Motobayashi 1994, Iwasa 1999, Davids 2001

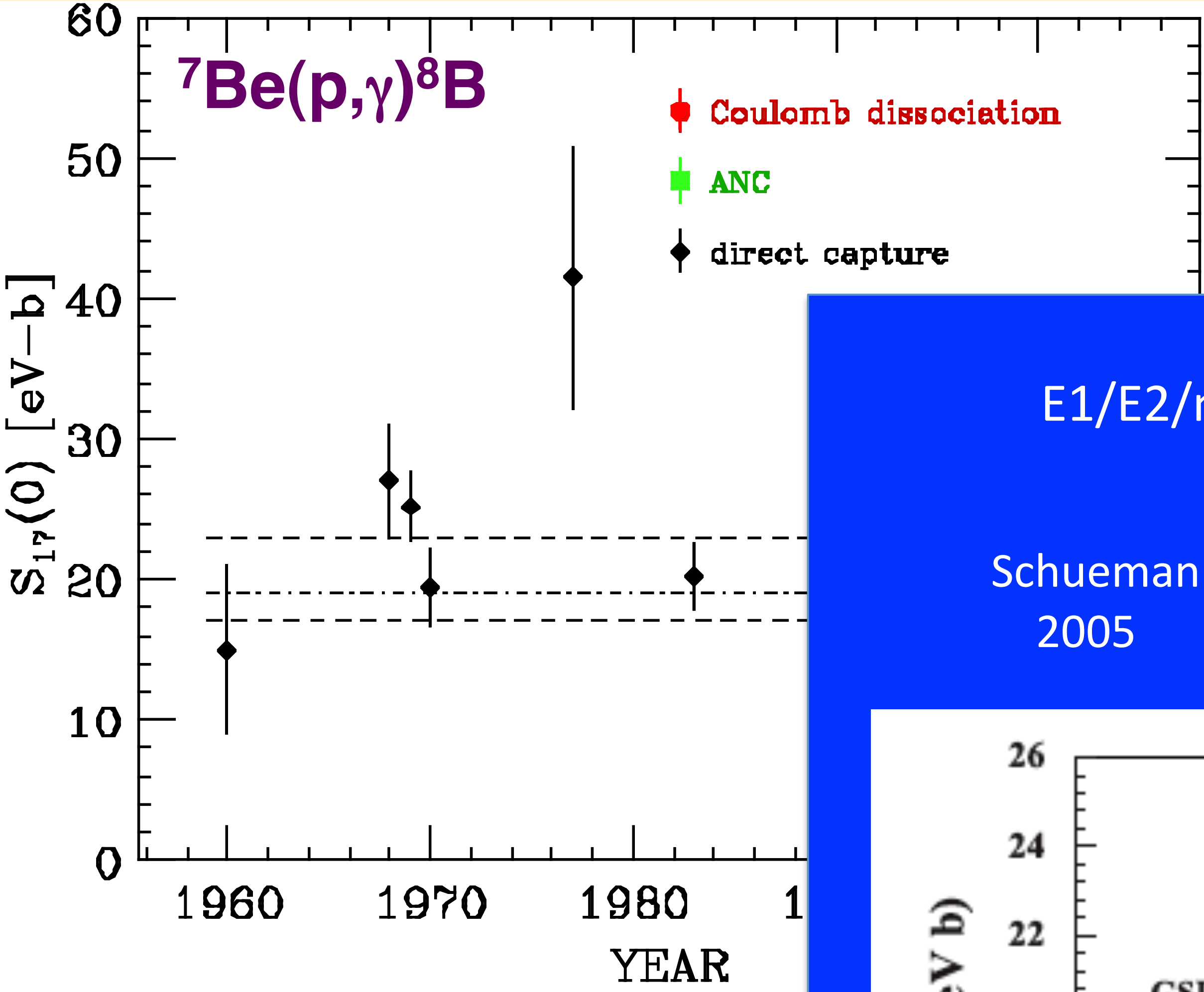
$^{11}C(p,\gamma)^{12}N$ Lefebvre 1995

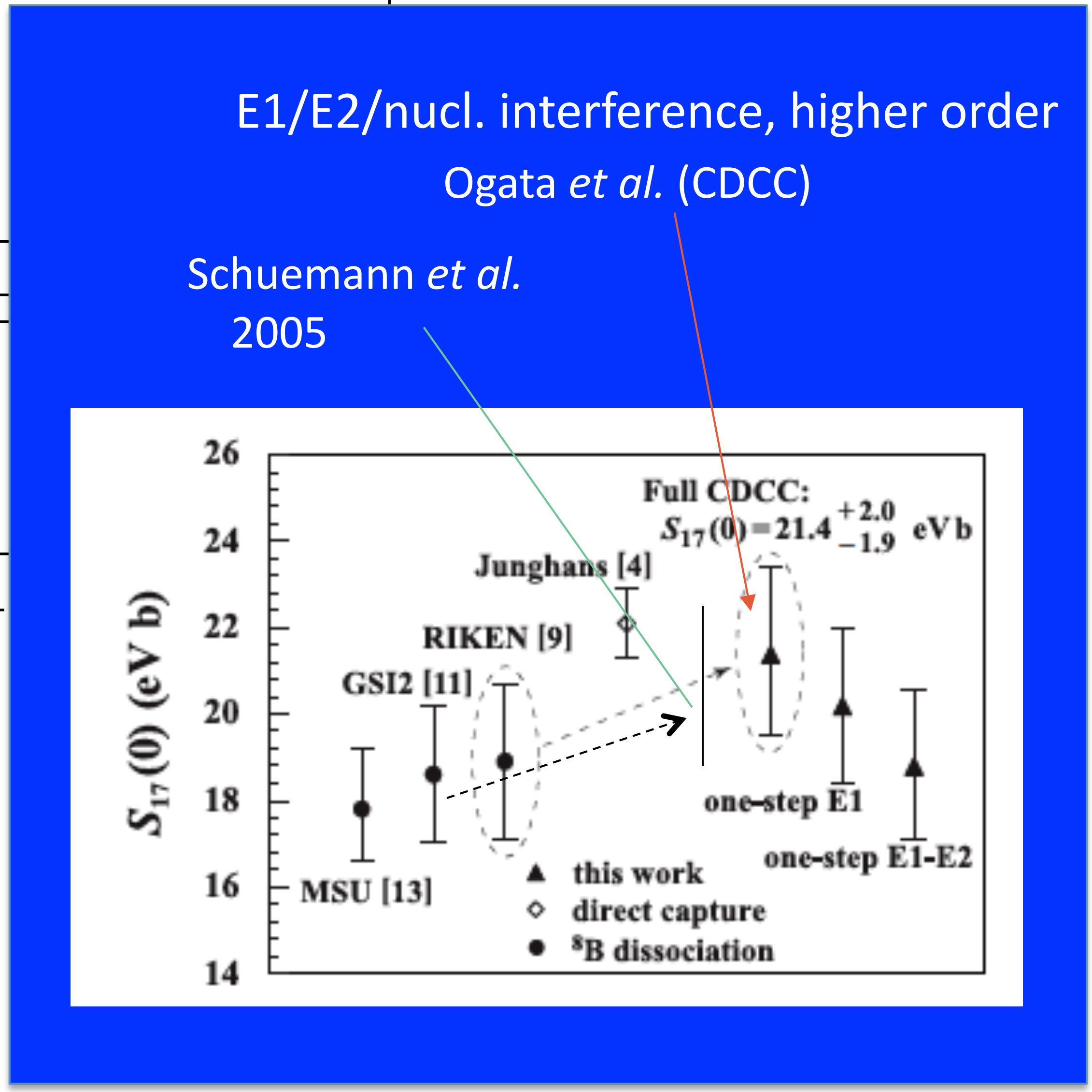
$^{12}N(p,\gamma)^{13}O$, $^{14}C(n,\gamma)^{15}C$

$^{22}Mg(p,\gamma)^{23}Al$, $^{26}Si(p,\gamma)^{27}P$

§2 Coulomb dissociation   The solar ν production process $^7Be(p,\gamma)^8B$: much studied.

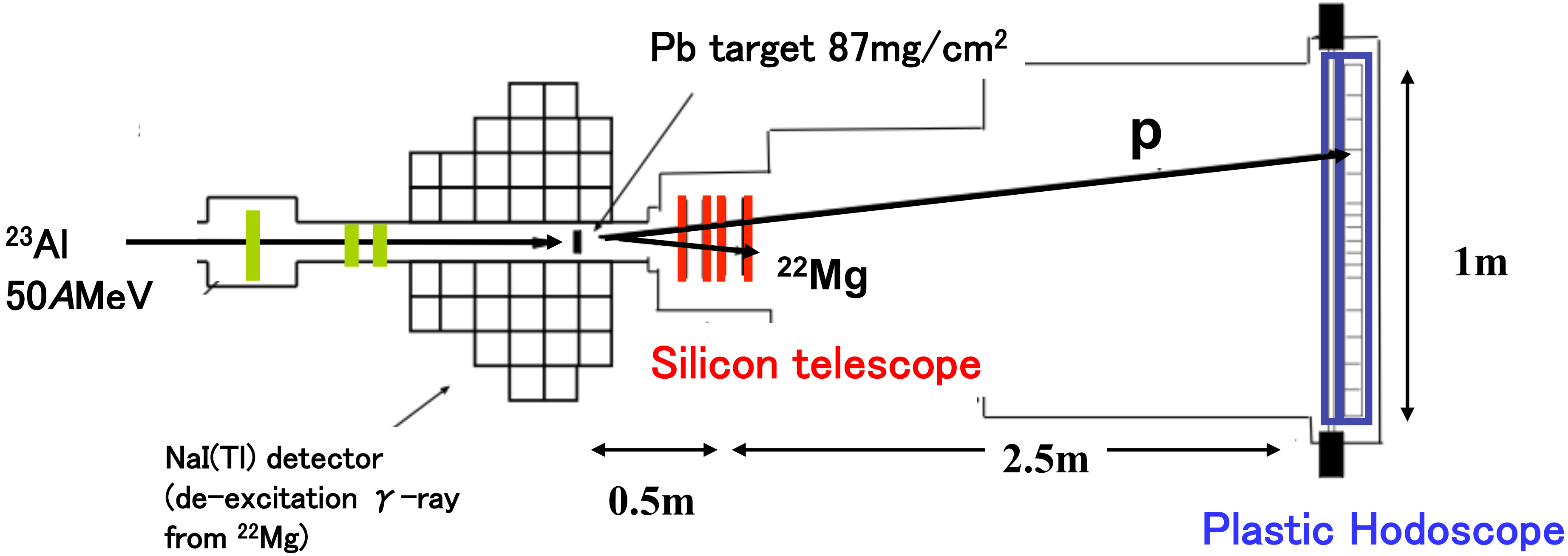
S_{17} at E=0

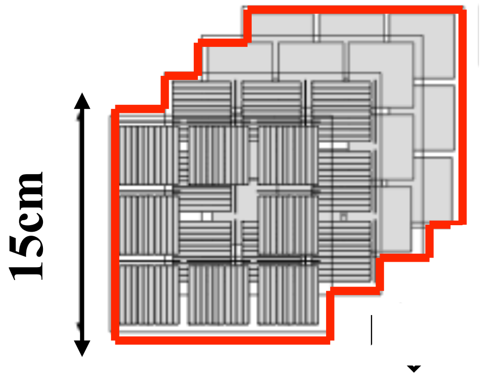




Experimental Setup

- RIKEN RIPS beamline -



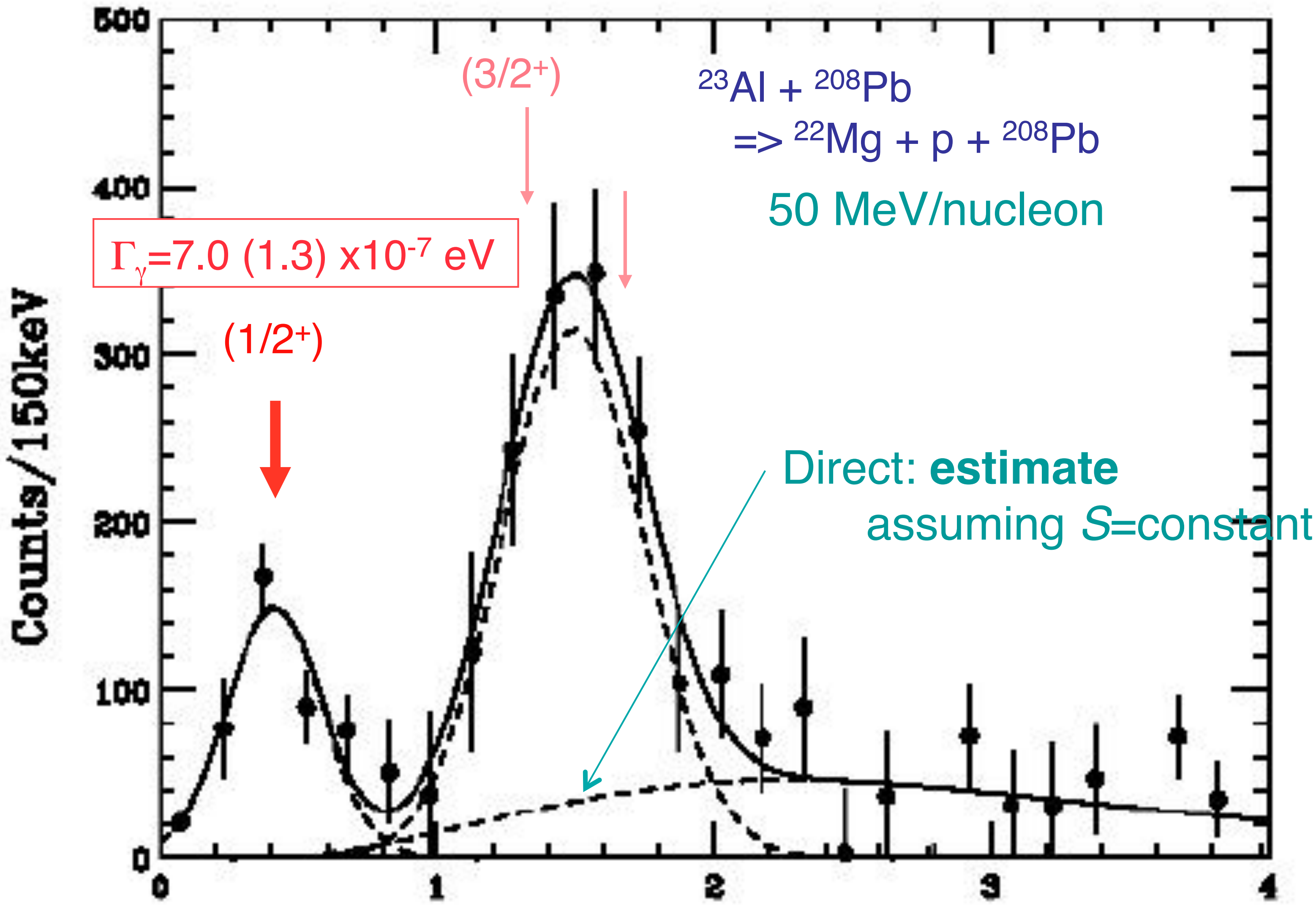


Position-sensitive (5mm width strips)

- suitable detectors for each particle
- momentum vector
- γ-ray detector (to confirm the final state)

Coulomb dissociation - 10^4 pps ^{23}Al

←→10^{12} pps ^{22}Mg ! + ^{1}H



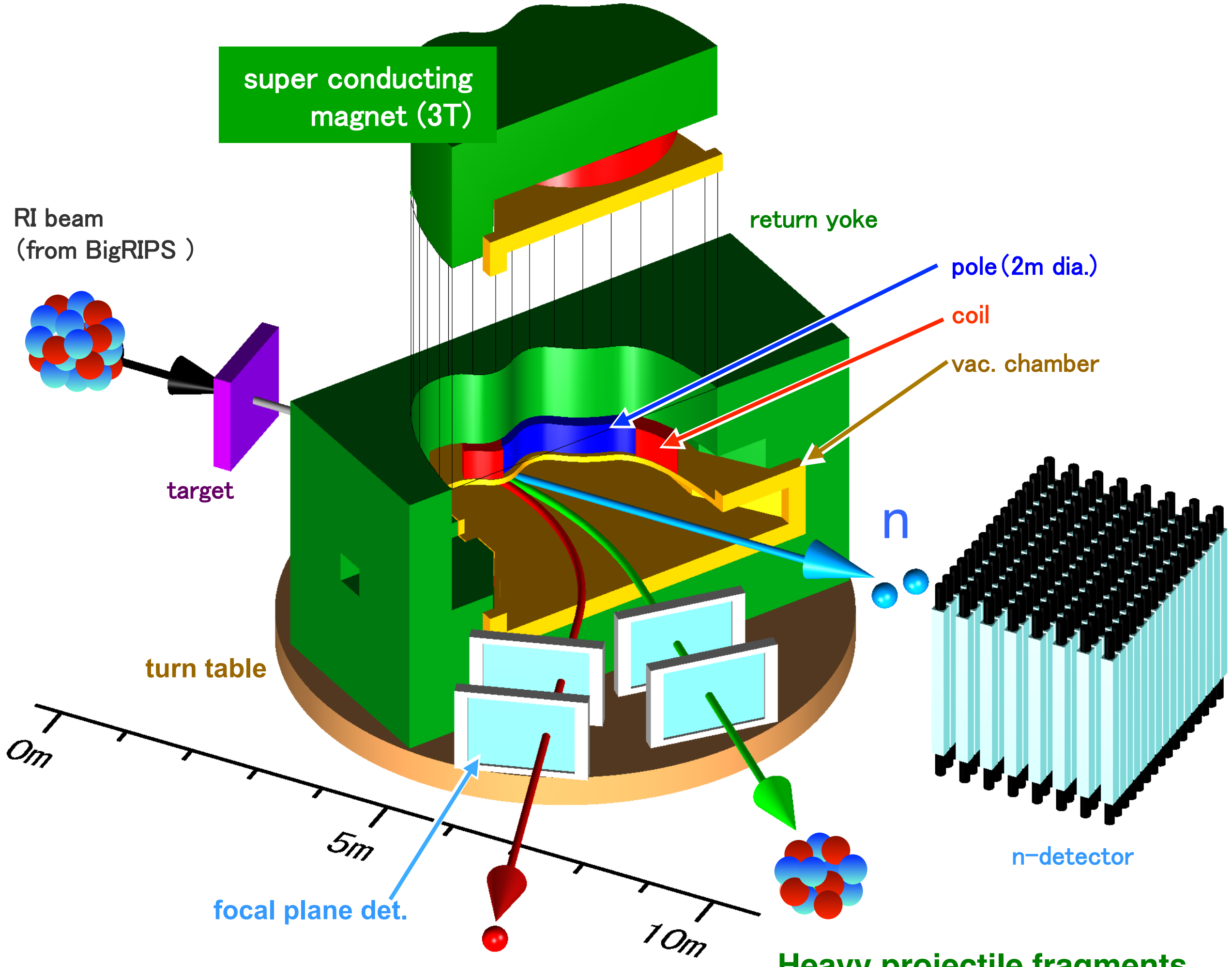
^{22}Mg-p relative energy [MeV]

SAMURAI Spectrometer -- Tohoku (Kobayashi), TiTech, Kyoto, .. RIKEN collaboration

NSCL MSU, Texas A&M

Large solid-angle, momentum-range spectrometer 2011-

for RIBF new facility (300-300 MeV/nucleon)



Bending Magnet
- Superconducting
- Large $B \cdot \rho$ (7Tm)
- Large pole gap (80cm)
- Weight ~ 600 ton

particle correlation
- unbound sates
- (p,2p)
- w. TAMU .. astrophys. (p,γ)
- w. MSU.. nucl. matter
- d+p for 3NF
- ...

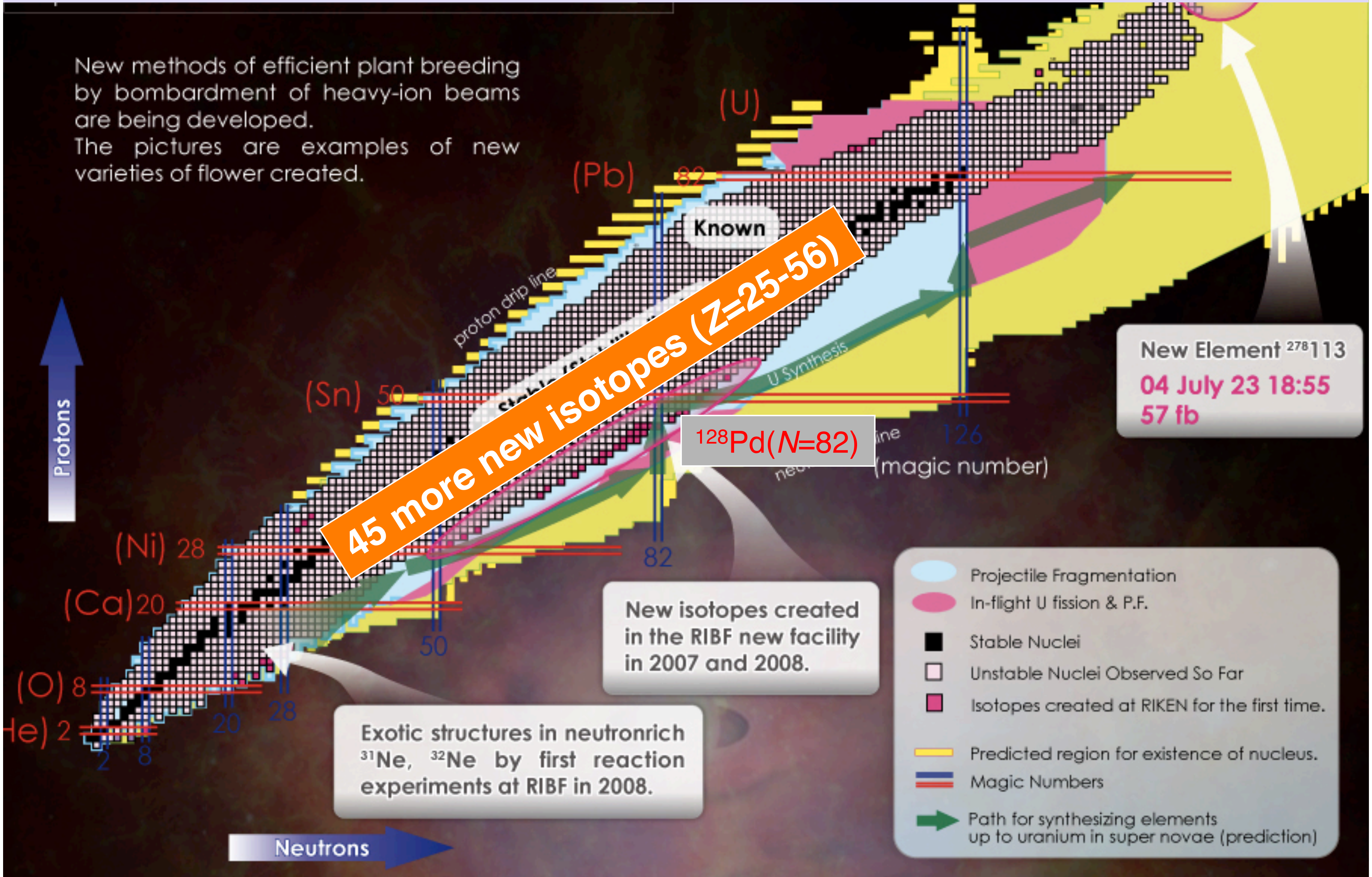
(fast) RI beams are useful

2. Coulomb dissociation
   explosive hydrogen burning

3. production, mass, life, nuclear structure
   toward r-process nuclei

c.f. RIKEN RI Beam Factory (RIBF):
   1st new-generation facility for RI beams in operation.

Toward the r-process path



Fast ^{238}U beams at RIBF created 47 new isotopos.

Identification scheme

magnetic rigidity $B\rho \propto p/Q \rightarrow A/Q$

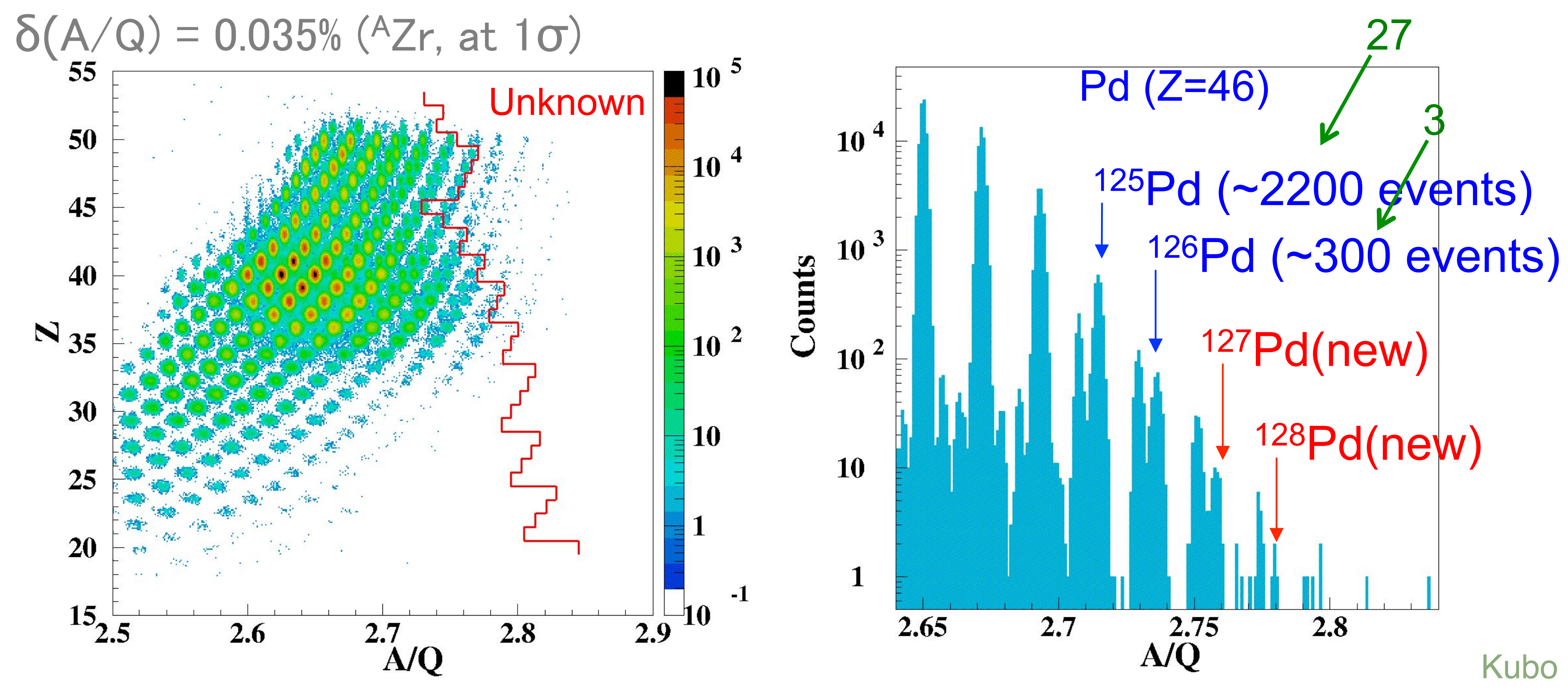
magnetic field setting, ρ measurement with an empirical matrix for optics

time-of-flight $TOF \propto 1/v$

measured between two detectors in BigRIPS

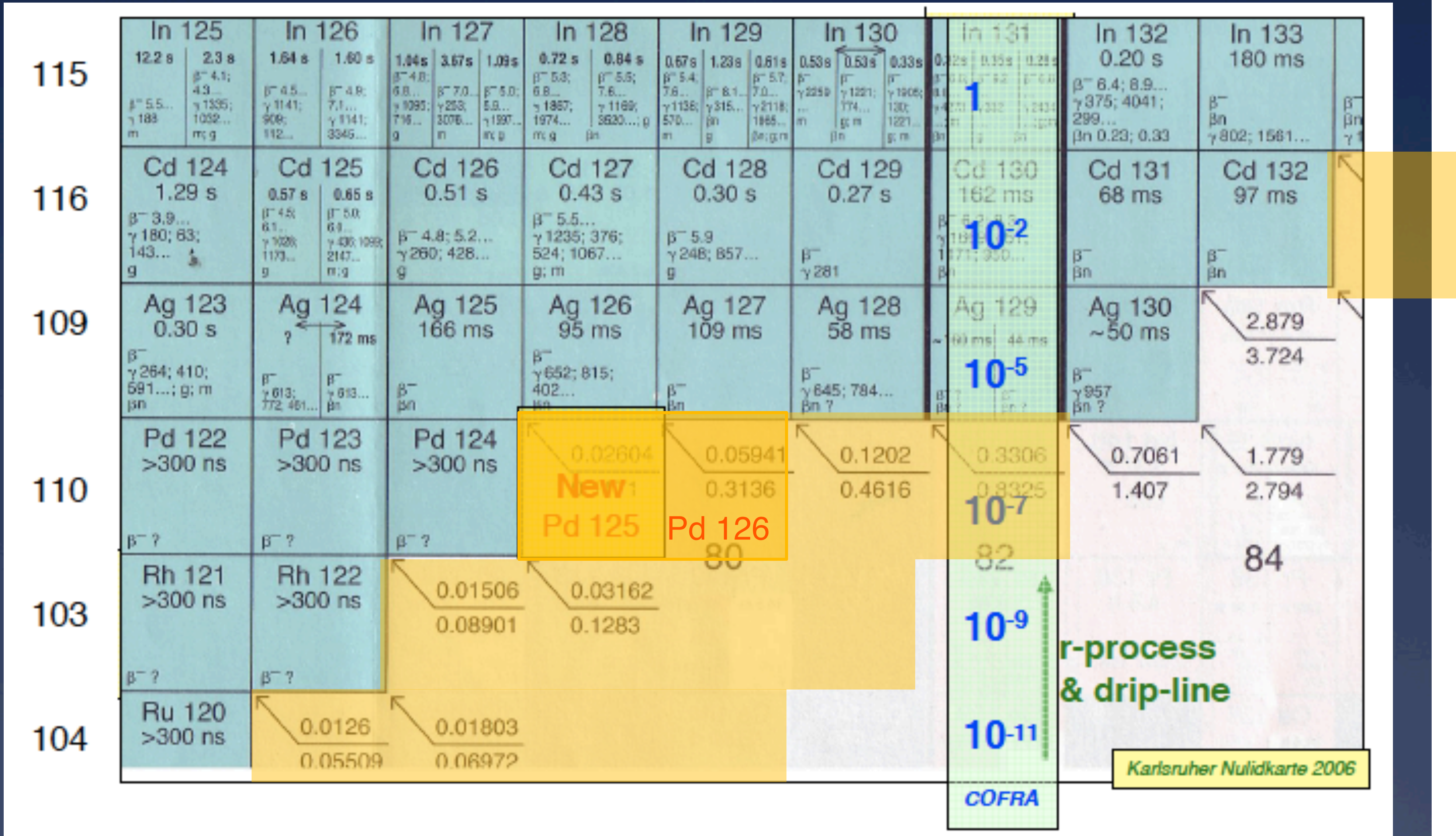
stopping power $dE/dx \propto AZ^2/E \rightarrow Z^2$

measured by a detector in BigRIPS



Kubo

Approaching to the "waiting points". 2007 2008

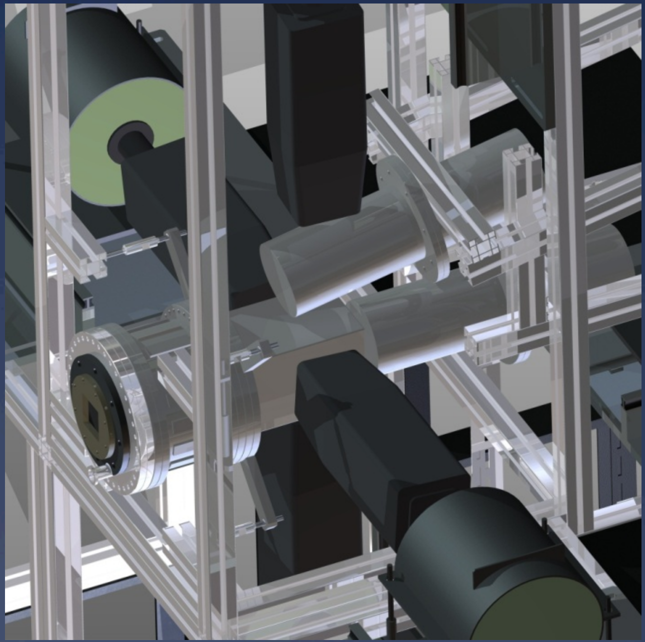


original: by P. Butler

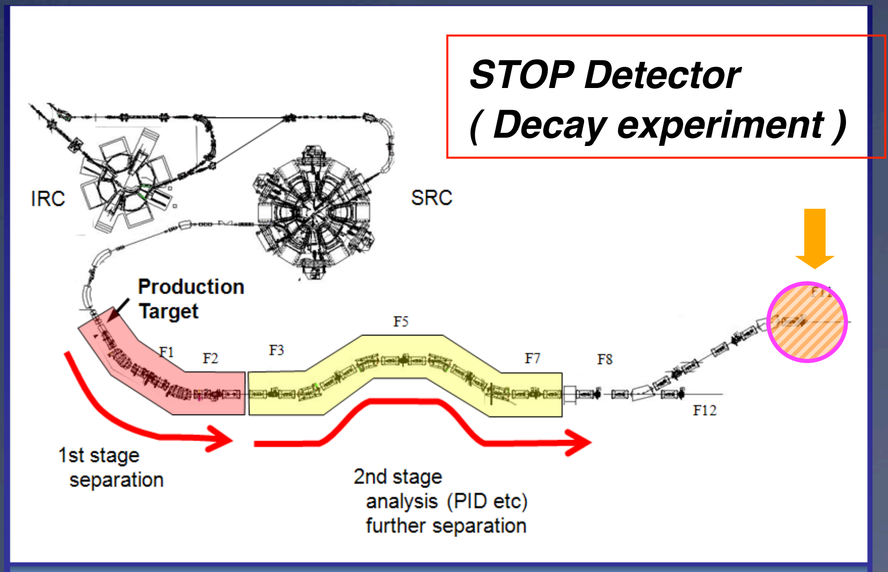
1st β decay measurements - toward the r-process path

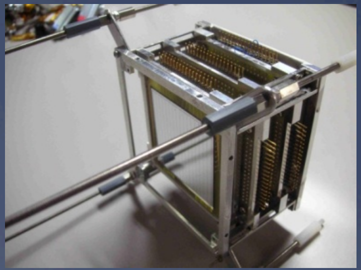
2009 Dec.
U beam to access A~110 region
Intensity 0.8 pnA max.
0.1-0.2 pnA on average

Sumikama, Nishimura, et al.



Half life measurements for r-process nuclei
Beta-gamma spectroscopy
Delayed gamma spectroscopy for isomers





Clovers (RIKEN)
$LaBr_3$ (Milano)
9 layers of DSSD (RIKEN, TUS)

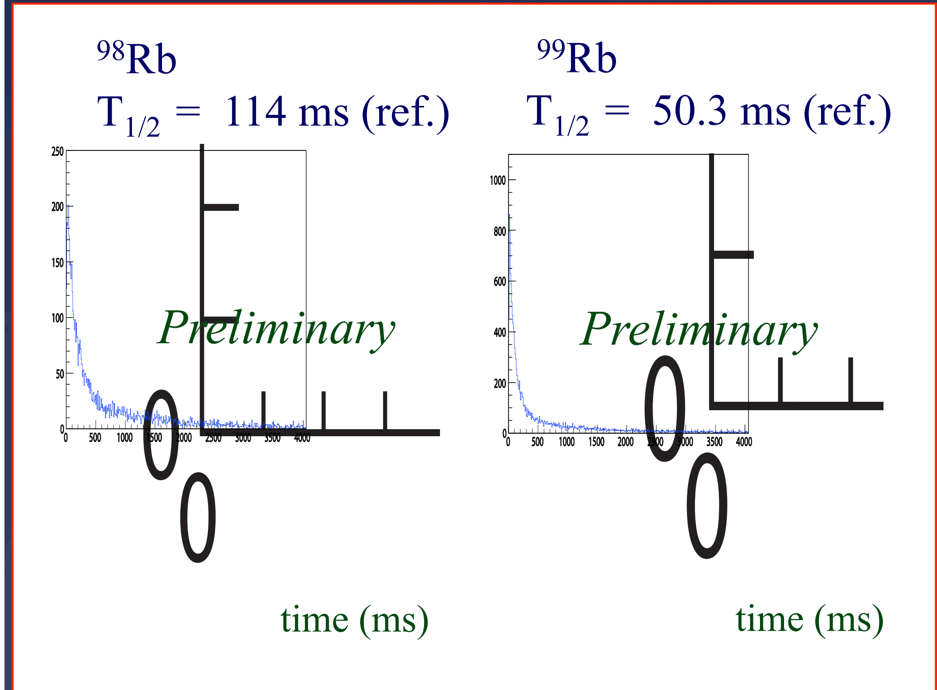
1st β decay measurements - toward the r-process path

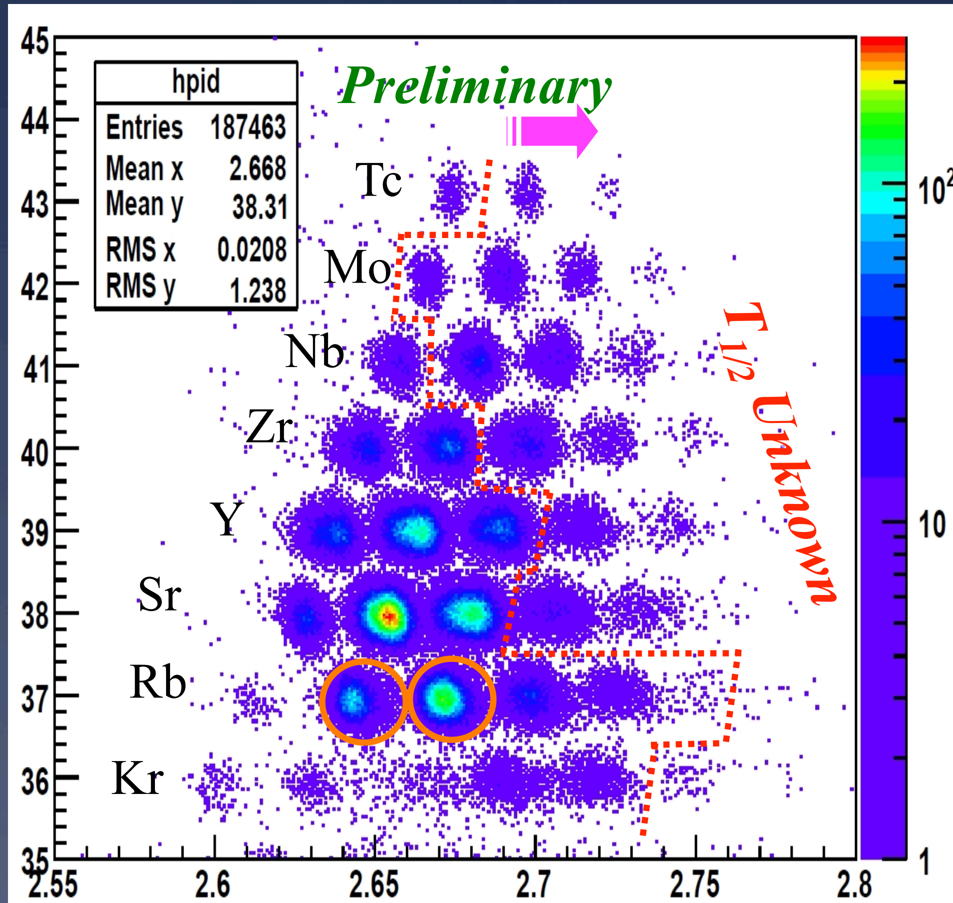
Decay curves & new half-lives

Nishimura, OMEG10

Event by event association
between RI implantation and beta-decay

8 hours
Low implantation rate : 5 ~ 10 cps





Confirmation of known decay curves
for consistency check.

Clean decay curves are obtained !

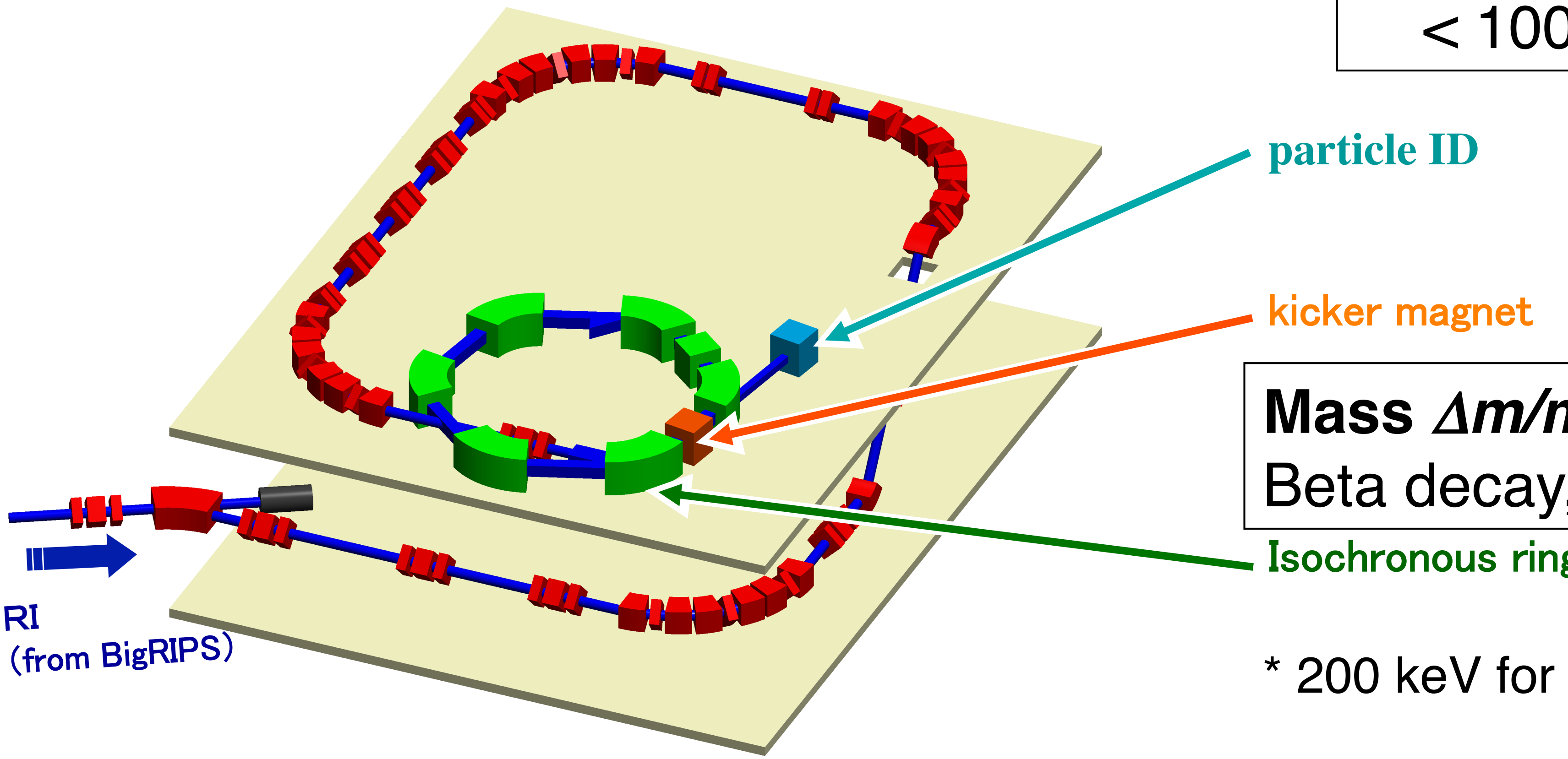
Data is under analysis

Tsukuba (Ozawa), ··· – RIKEN collaboration

Isochronous ring
with individual injection

mass measurement for
short-lived rarely-produced
nuclei

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



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

* 200 keV for *A*=200

Summary

1. nuclear processes in explosive burning
   β decays and reactions on unstable nuclei
2. explosive hydrogen burning
   σ determination by
   Coulomb dissociation with RI beams
3. toward r proces
   production, life, mass, … at RIBF