Experimental determination of reaction rates *via* Coulomb dissociation

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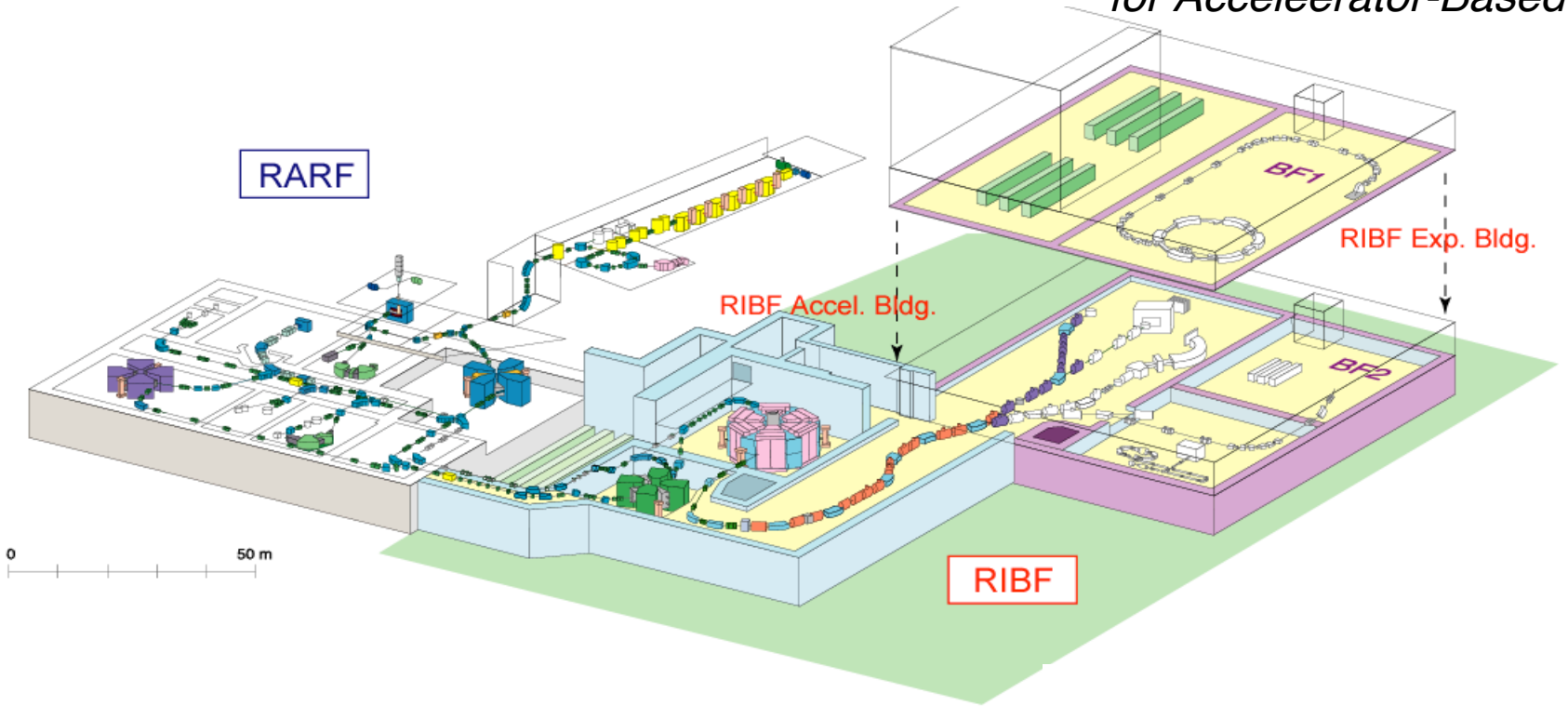


Coulomb dissociation (excitation) - radiative capture

ANC method - radiative capture

Trojan Horse method

^{6}LI breakup

Hammache

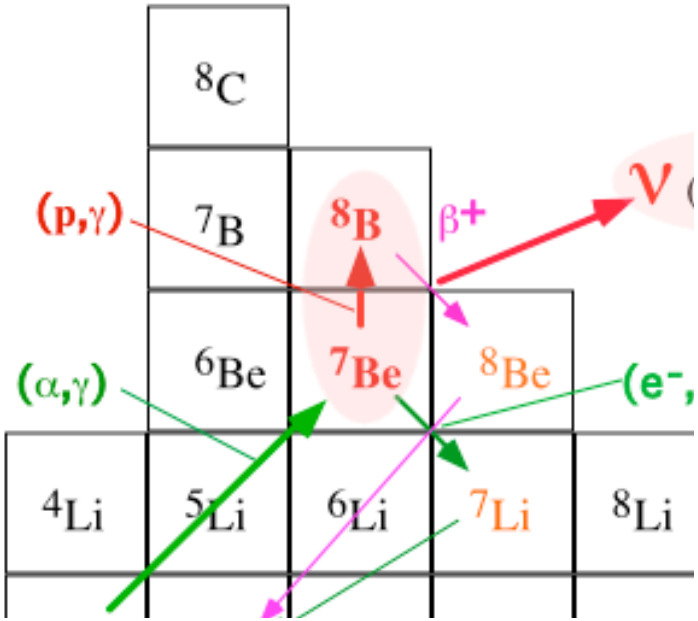
^{7}Be(p,γ)^{8}B reaction - a “bench-mark”, continuum, E1+E2

pp chain / solar neutrino

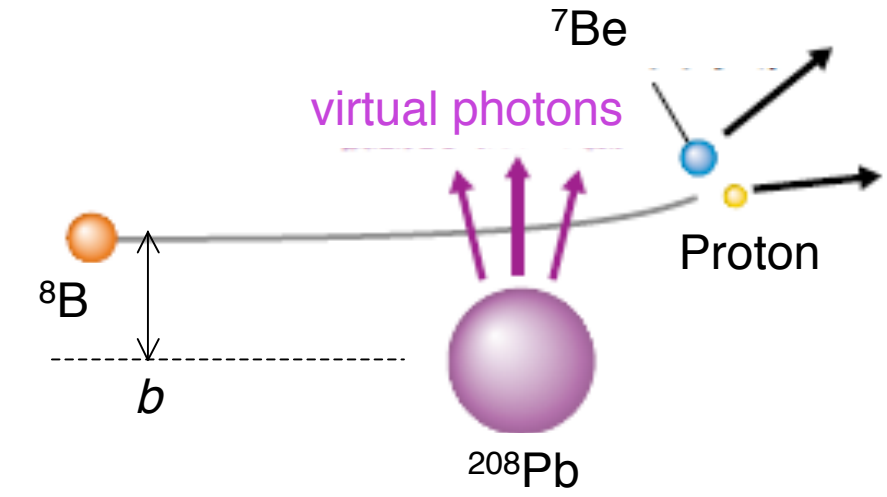
^{23}Al breakup resonance, E2

rp process

RI Beam Factory



electric field “felt” by the projectile



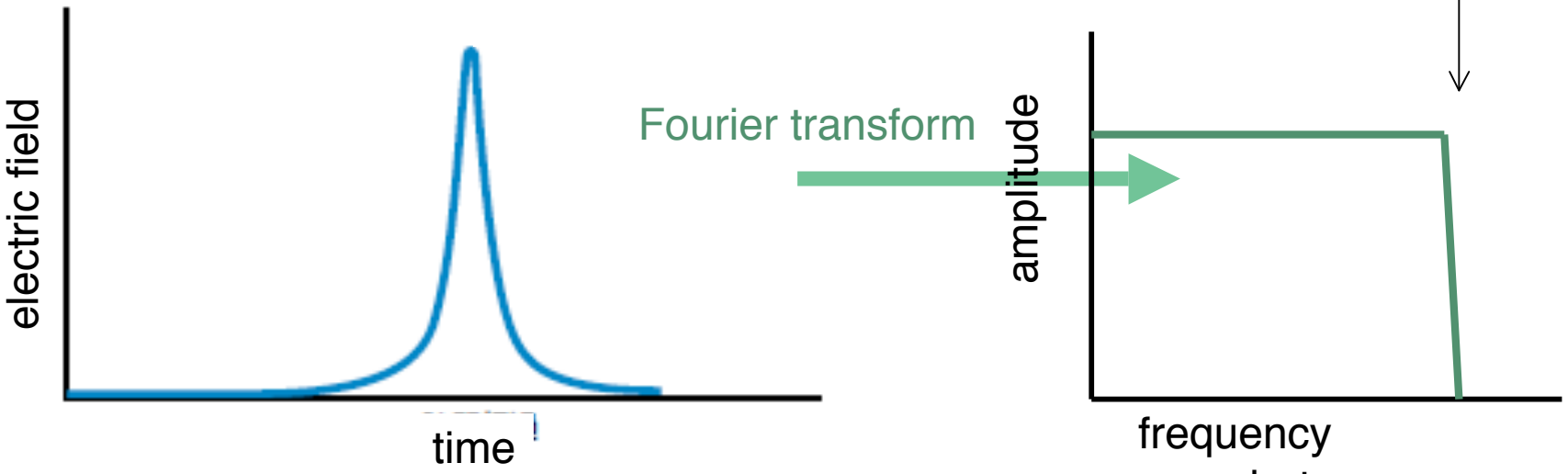
“photodisintegration”

Fermi (1930’s)
Bertulani, Baur, Rebel (1986)

Shotter, Utsunomiya, Kiener,…

E_{in} ↗ : E_{max} ↗
b ↗ : E_{max} ↘

$E_{max}(b)$



$^{8}B+^{208}Pb \rightarrow {}^{7}Be+p+^{208}Pb$ (C.D.)

↓ virtual photon theory or DWBA

$^{8}B(\gamma,p)^{7}Be$ (abs.)

↓ detailed balance

$^{7}Be(p,\gamma)^{8}B$ (capt.)

Large yield

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

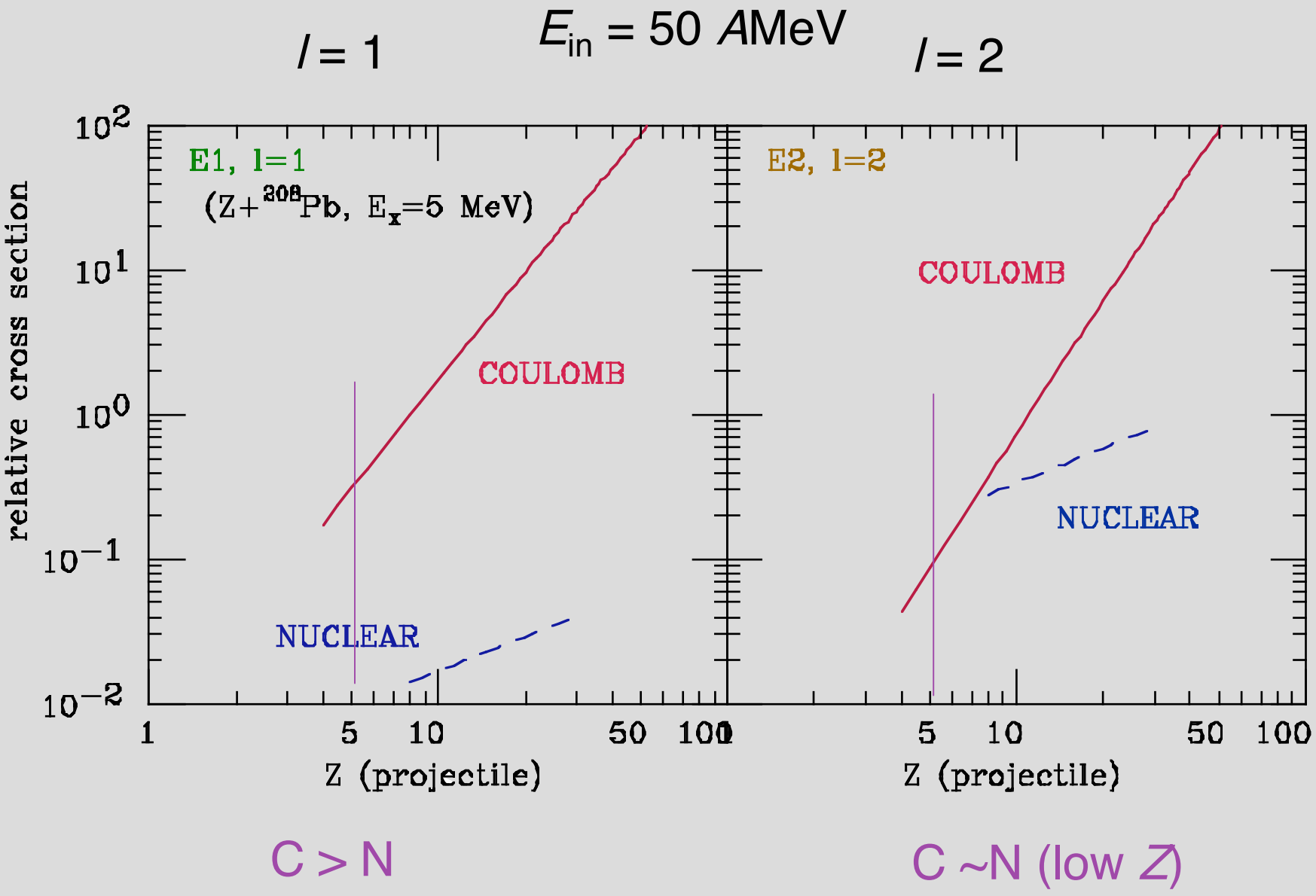
thick target

charged particle detection

but

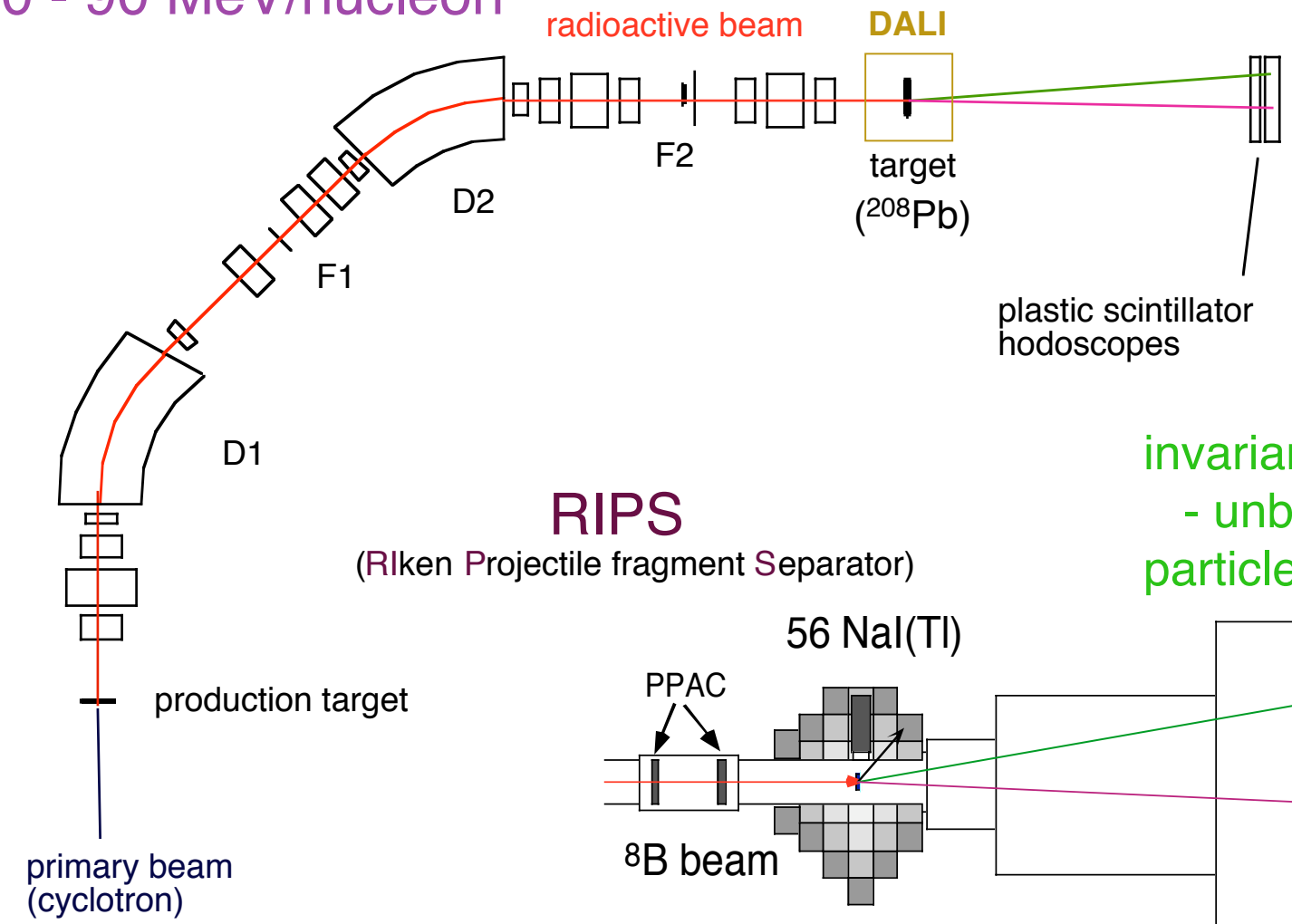
experiments with R.I. beams

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


E_{in} = 50 *A*MeV
l = 1
l = 2
relative cross section
E1, l=1
(Z+^{208}Pb, E_x=5 MeV)
COULOMB
NUCLEAR
E2, l=2
COULOMB
NUCLEAR
Z (projectile)
Z (projectile)
C > N
C ~N (low *Z*)

spectroscopy of unstable nuclei

50 - 90 MeV/nucleon



RIPS

(RIken Projectile fragment Separator)

invariant mass
- unbound states

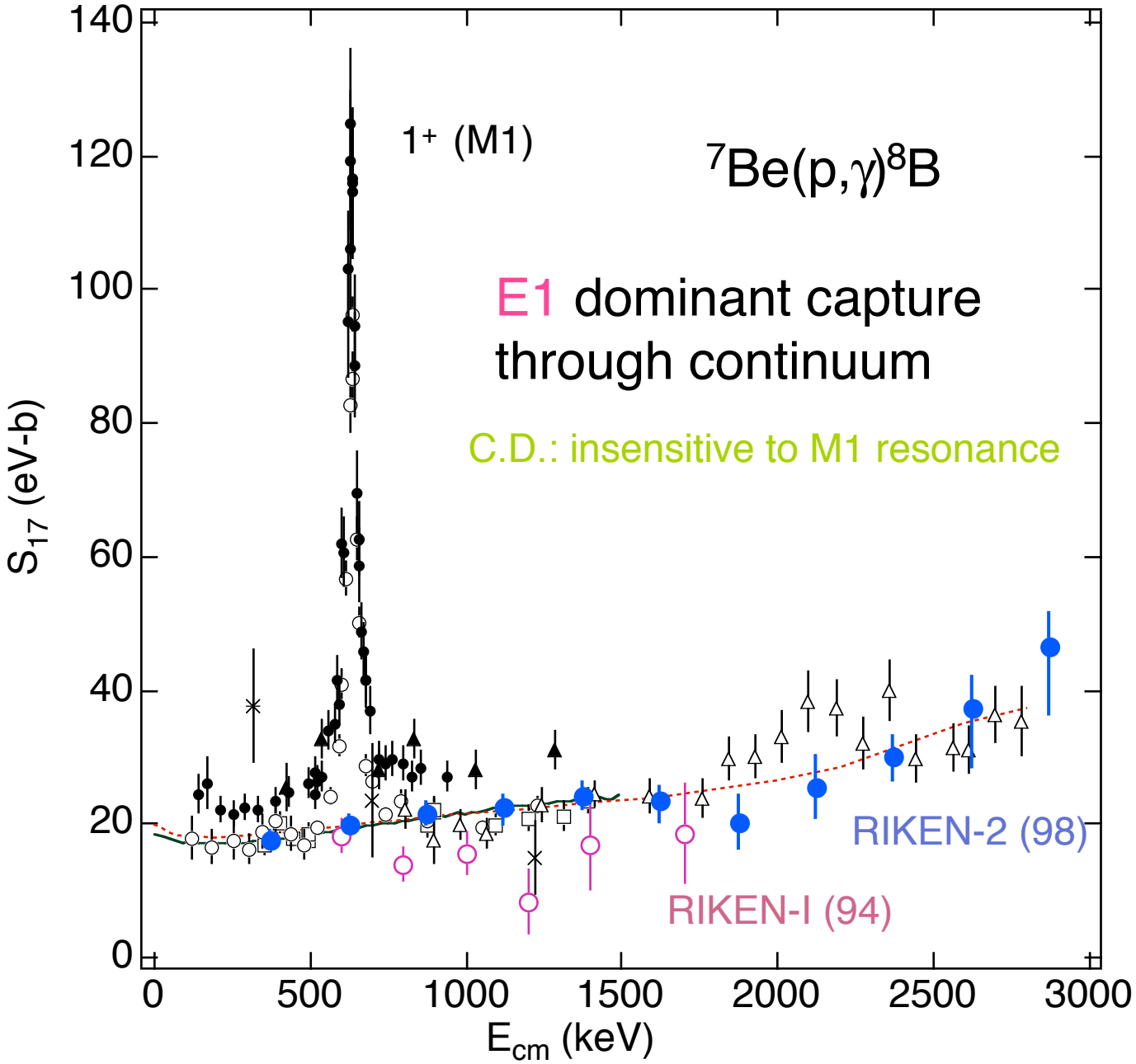
particle ID

DALI

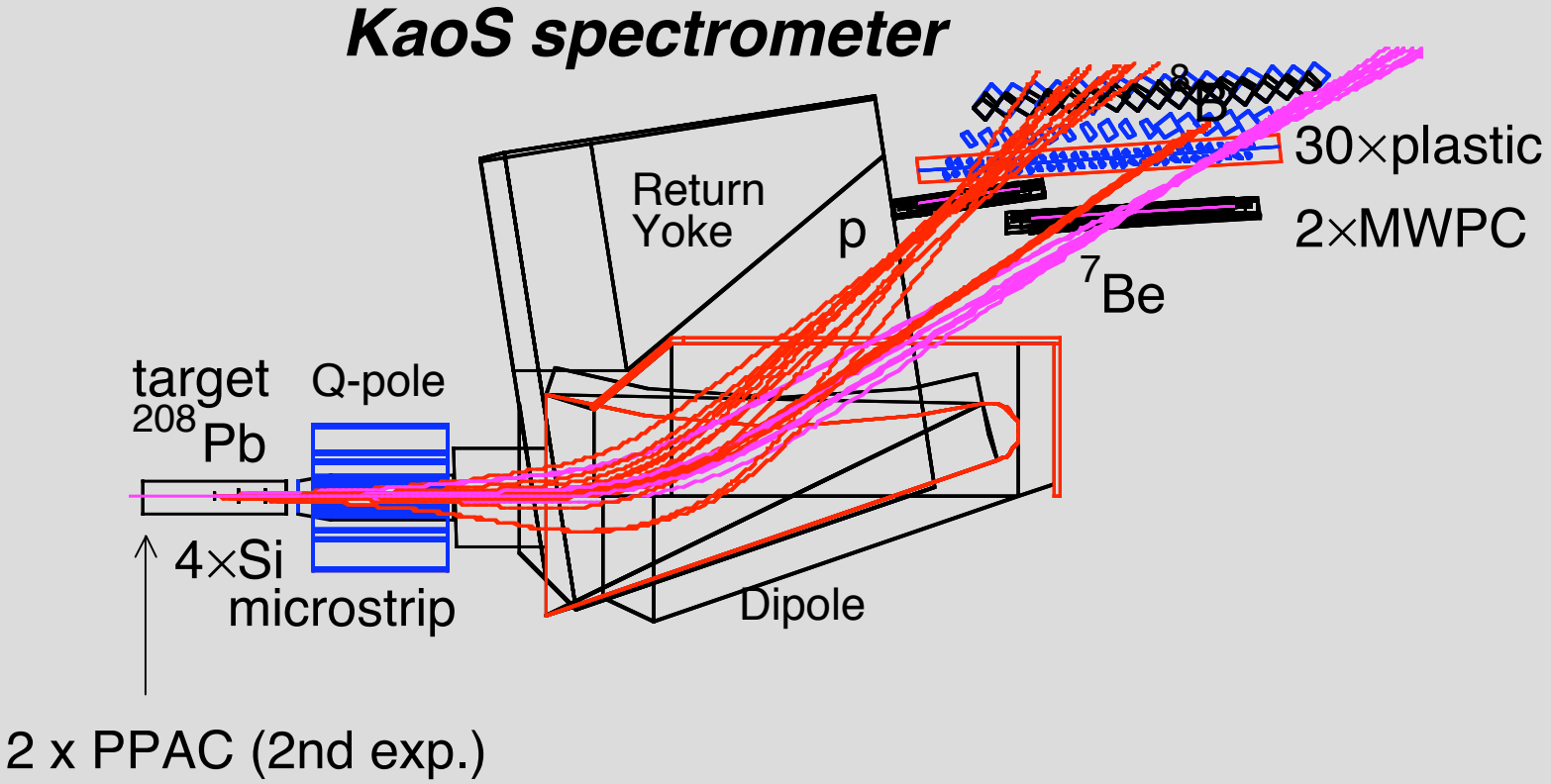
γ ray
- bound states

HODO

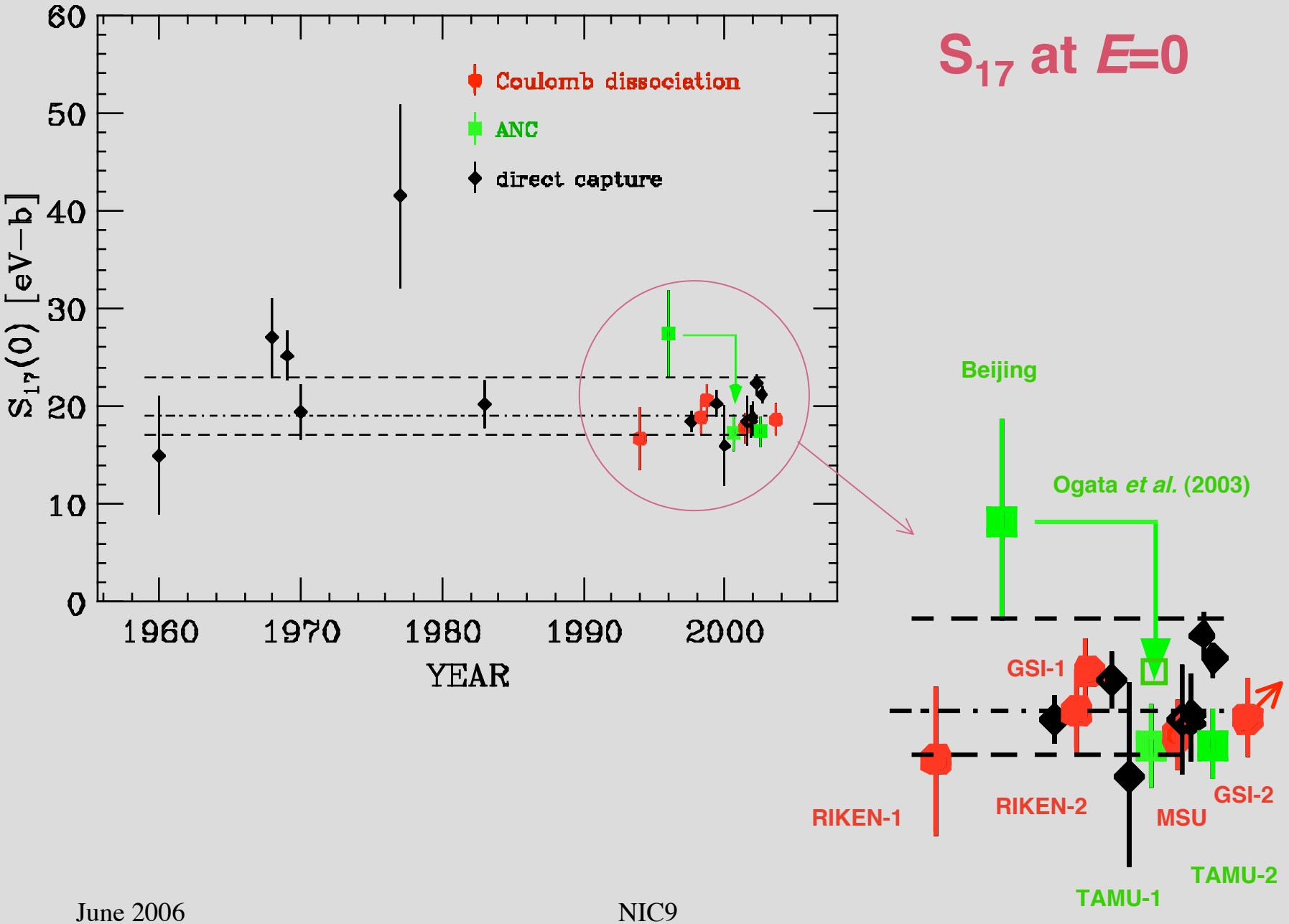
strong (light) RI beams


140
120
100
80
60
40
20
0
S_{17} (eV-b)
0
500
1000
1500
2000
2500
3000
E_{cm} (keV)
1^+ (M1)
$^7Be(p,\gamma)^8B$
E1 dominant capture
through continuum
C.D.: insensitive to M1 resonance
RIKEN-2 (98)
RIKEN-I (94)

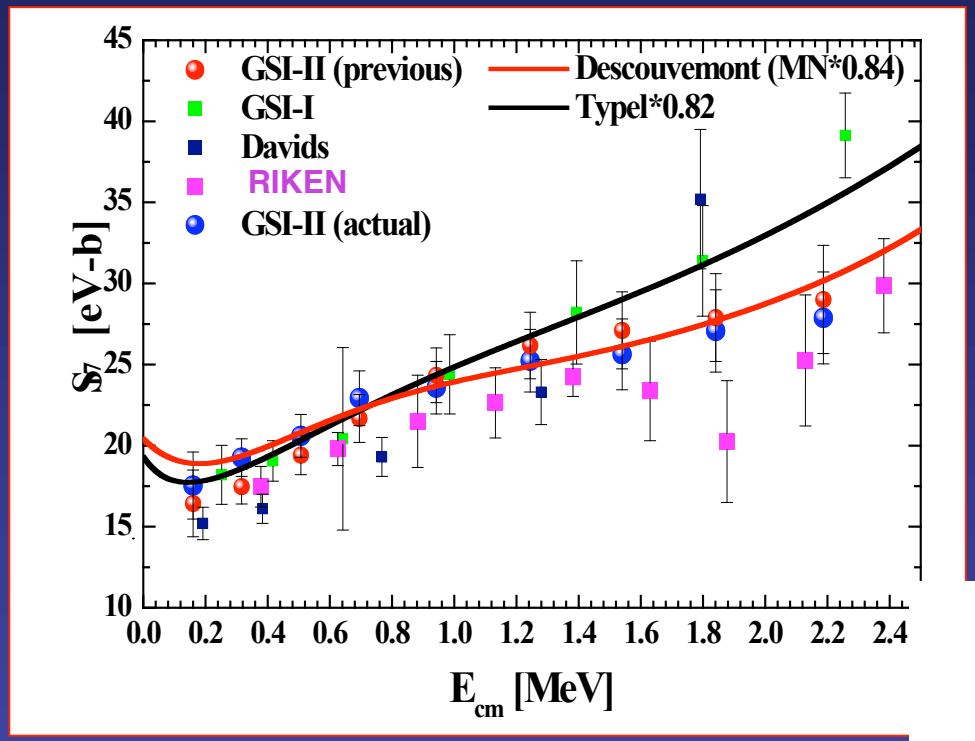
@ GSI 254 MeV/nucleon



S_{17} at E=0


Coulomb dissociation
ANC
direct capture
$S_{17}(0)$ [eV–b]
YEAR
60
50
40
30
20
10
0
1960
1970
1980
1990
2000
Beijing
Ogata *et al.* (2003)
GSI-1
RIKEN-1
RIKEN-2
MSU
GSI-2
TAMU-1
TAMU-2

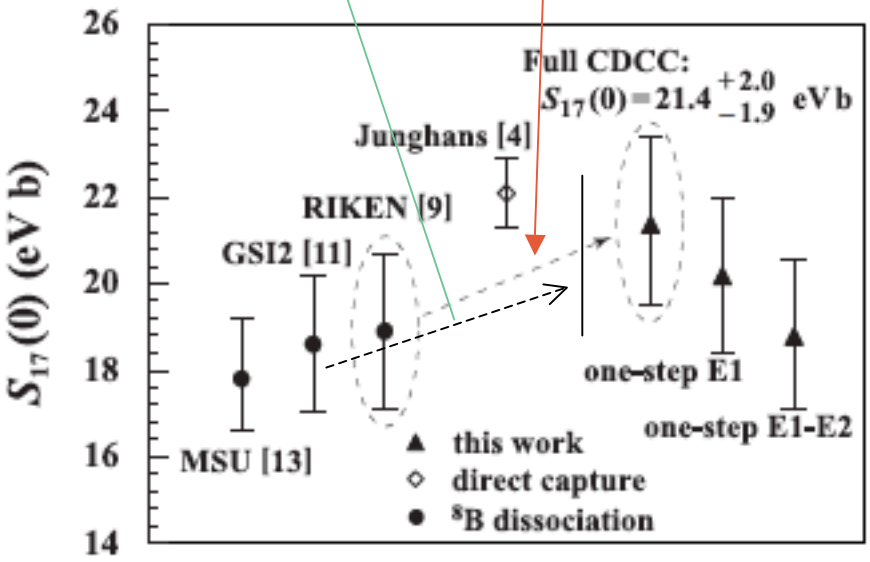
S_{17} - Factor

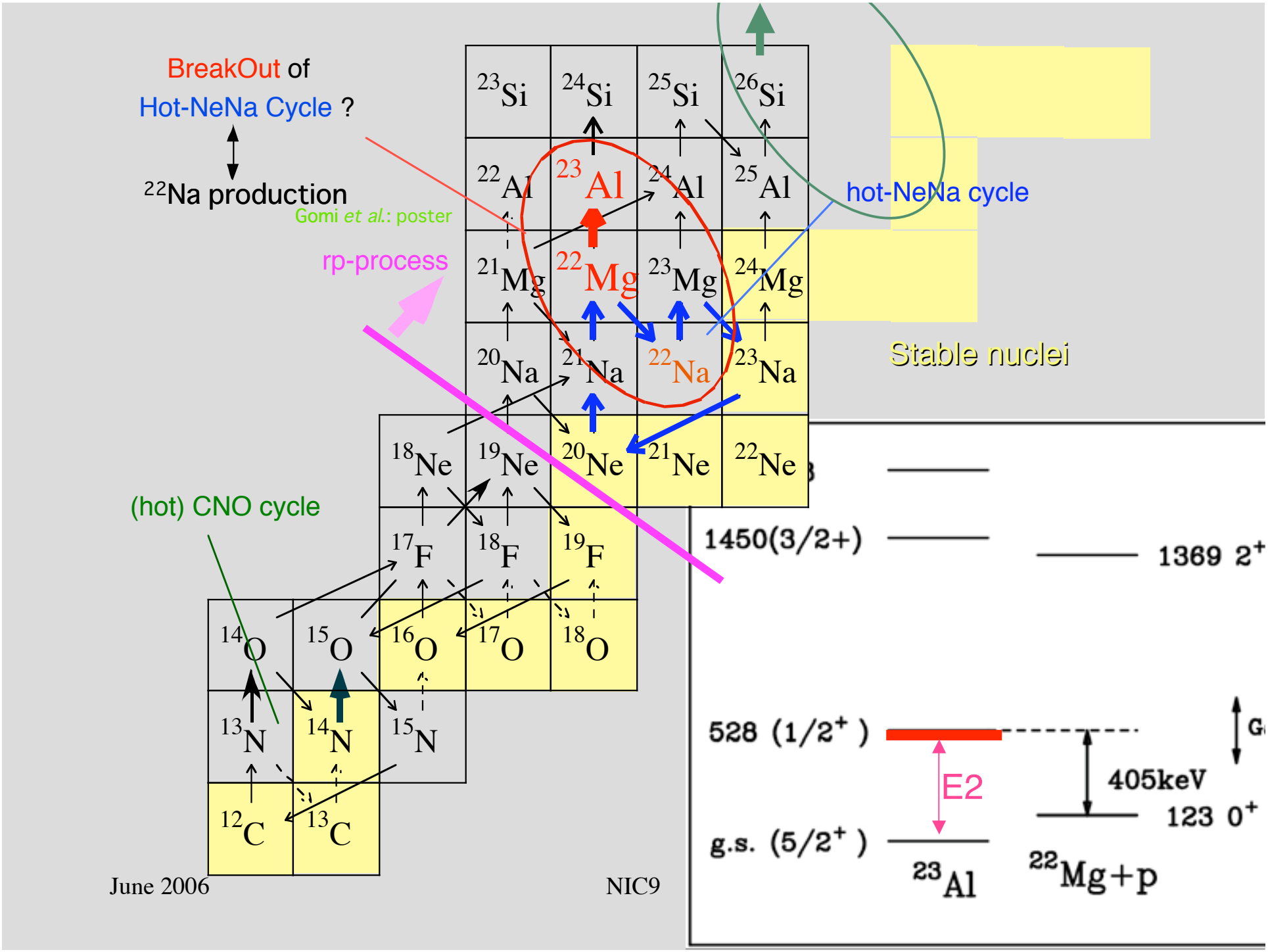


Possible ambiguities
In optical potentials
=> Bishop (poster 107)

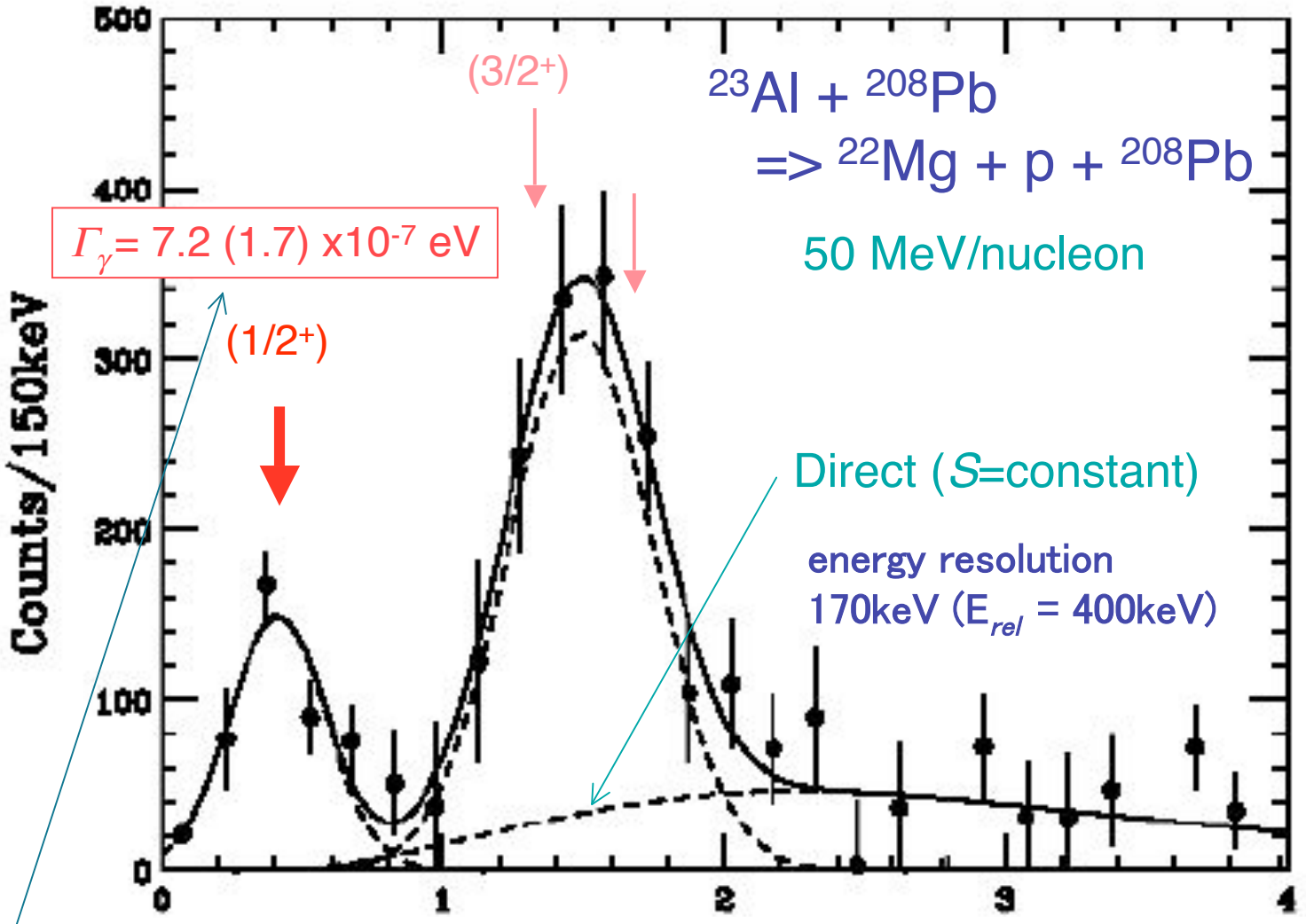
E1/E2/nucl. Interference (CDCC)
Ogata *et al.* PRC, 2005

Schumann *et al.*
P. R. C 2005




BreakOut of
Hot-NeNa Cycle ?
^{22}Na production
Gomi *et al.*: poster
rp-process
hot-NeNa cycle
Stable nuclei
(hot) CNO cycle
^{23}Si ^{24}Si ^{25}Si ^{26}Si
^{22}Al ^{23}Al ^{24}Al ^{25}Al
^{21}Mg ^{22}Mg ^{23}Mg ^{24}Mg
^{20}Na ^{21}Na ^{22}Na ^{23}Na
^{18}Ne ^{19}Ne ^{20}Ne ^{21}Ne ^{22}Ne
^{17}F ^{18}F ^{19}F
^{14}O ^{15}O ^{16}O ^{17}O ^{18}O
^{13}N ^{14}N ^{15}N
^{12}C ^{13}C
1450(3/2+)
1369 2$^+$
528 (1/2$^+$)
E2
405keV
123 0$^+$
g.s. (5/2$^+$)
^{23}Al
^{22}Mg+p

E_{rel} spectrum - 10^4 pps ^{23}Al ⇔ 10^{12} pps ^{22}Mg ! + ^{1}H



Caggiano *et.al.* (2001)
5.49×10^{-7} eV

Gomi et al., Nucl. Phys. A734 (04) E77

Stellar reactions studied by Coulomb dissociation using RI beams

Steady burning

pp chain (solar neutrino)	$^{7}Be(p,\gamma)^{8}B$	GSI (254*A*MeV) RIKEN, MSU (50～80*A*MeV) Notre Dome (3*A*MeV)	Direct, ANC
CNO cycle	$^{14}N(p,\gamma)^{15}O$	RIKEN (100*A*MeV)	D
	(Coulomb excitation, sub-threshold state)		

Explosive burning

hot CNO cycle	$^{12}C(p,\gamma)^{13}N$	RIKEN (78*A*MeV)	D
	$^{13}N(p,\gamma)^{14}O$	RIKEN (88*A*MeV), GANIL (70*A*MeV)	D
hot pp mode	$^{8}B(p,\gamma)^{9}C$	RIKEN (70*A*MeV)	A
	$^{11}C(p,\gamma)^{12}N$	GANIL,RIKEN (70*A*MeV)	A
	$^{12}N(p,\gamma)^{13}O$	RIKEN (84*A*MeV)	A
rp-process	$^{22}Mg(p,\gamma)^{23}Al$	RIKEN (50*A*MeV)	
	$^{26}Si(p,\gamma)^{27}P$	RIKEN (50*A*MeV)	

Poster 163

Neutron capture	inhomogeneous BBN	$^{8}Li(n,\gamma)^{9}Li$	MSU (40*A*MeV)	
		$^{14}C(n,\gamma)^{15}C$	GSI (605*A*MeV), RIKEN (70*A*MeV),	D
	r-process		MSU (35*A*MeV)	
		$^{18}C(n,\gamma)^{19}C$	RIKEN (67*A*MeV)	

RIKEN Radioactive Isotope Beam Factory
RIBF

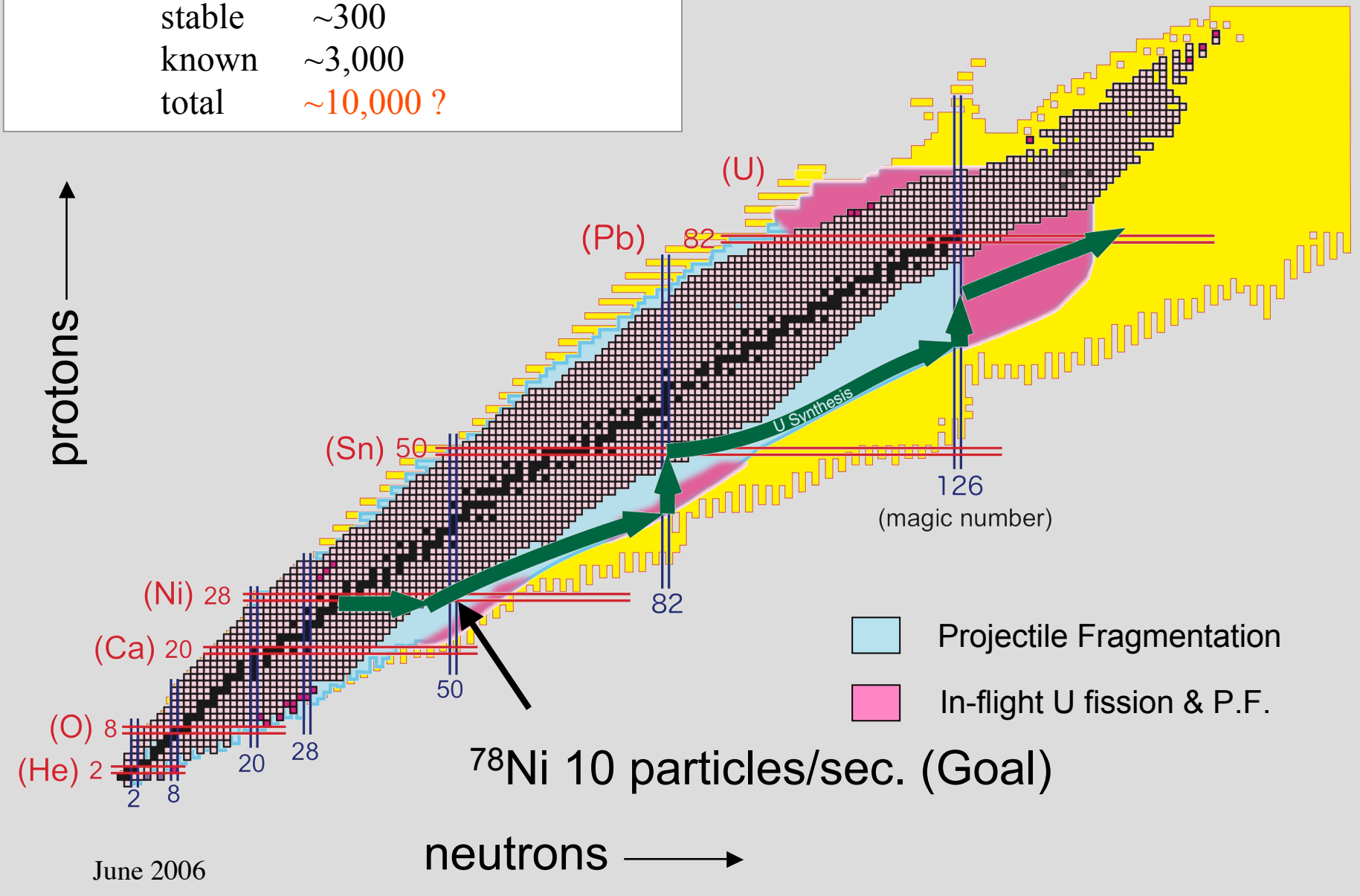
1st realization of next-generation RIB facilities
* RIA, GSI - FAIR

Intense primary beams (1pμA up to U, 350 *A*MeV)
=> farther from the stability valley
by fragmentation and fission

1st beam: in 2006, experiments: 2007-

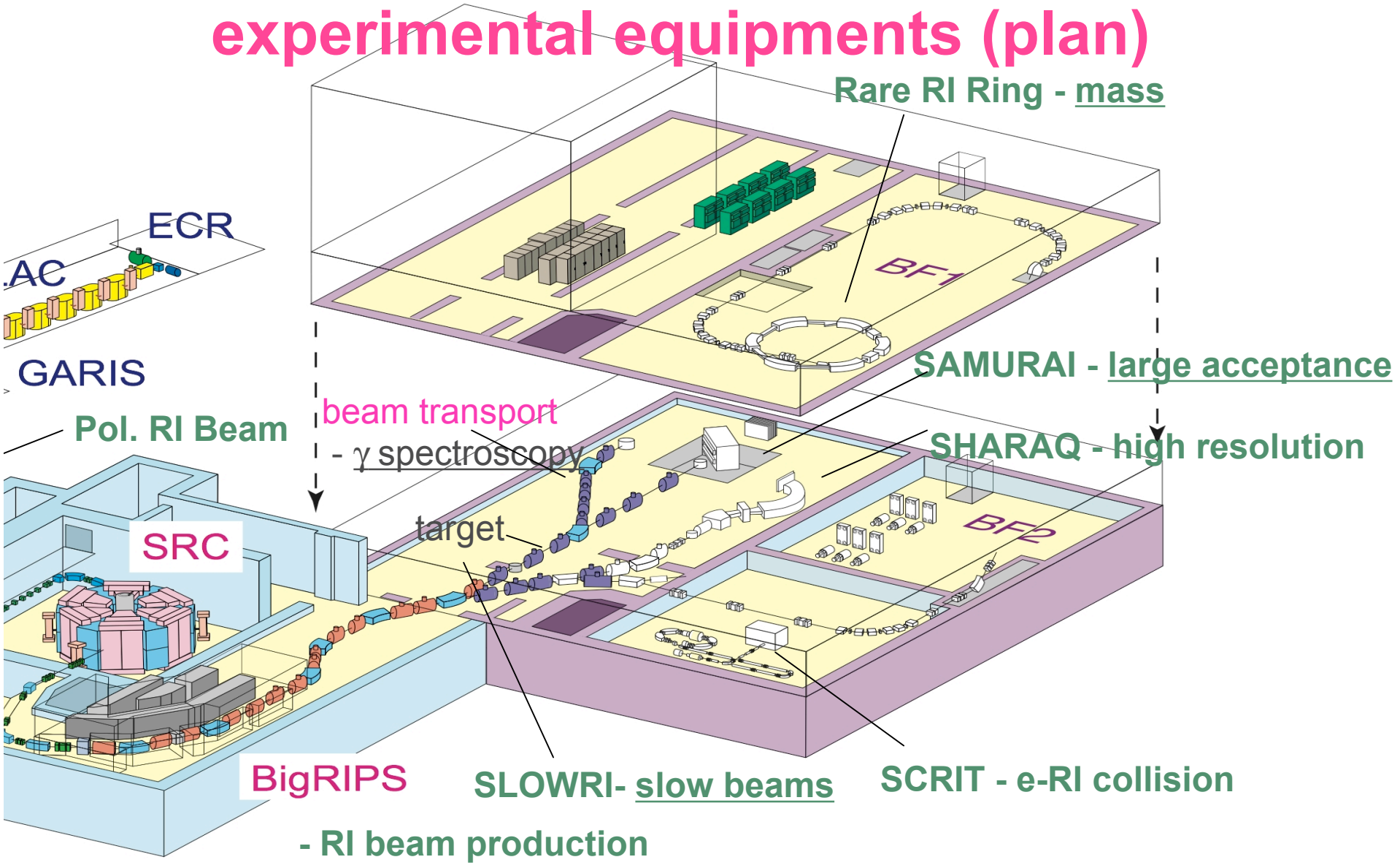
Atomic nuclei (isotopes)

stable	~300
known	~3,000
total	~10,000 ?



June 2006

RIKEN RIBF
experimental equipments (plan)



Summary

C.D. for astrophysical $\sigma(p,\gamma)/\sigma(n,\gamma)$ on unstable nuclei

continuum

resonance: E1, E2, M1

RI-beam

Questions - control of reaction mechanism

higher order / E2-related corrections / nuclear excitations

theory

experiment

Future: more (p,γ), (n,γ) / $(2p,\gamma)$, (α,γ) ….

Intense beam

efficient setup

RIBF - 1st beam: 2006

covering the “r-process path”

c.f. Motizuki (poster 136)

RIBF International Users Meeting: Aug. 3, 4 (2006)

Visit the users group page:

http://ribfwww.riken.go.jp/exp/RIBF_uec_eng/

registration: ribfusr_meeting06@rarf.riken.jp

PAC: end of 2006 or early 2007

23rd INPC (INPC07): Tokyo, June 3-8, 2007

DREB (Direct Reaction with Exotic Beams) as a pre sympo.