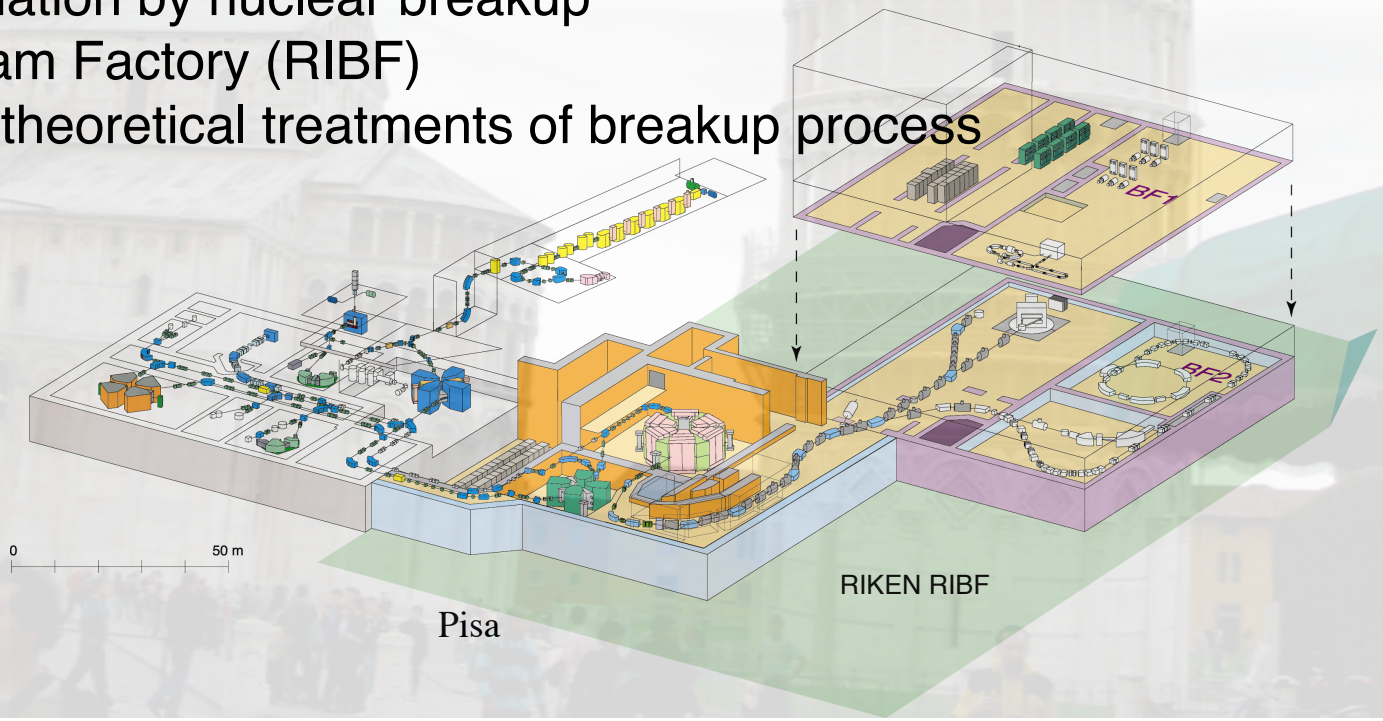
Experimental studies of unbound states of astrophysical interest using fast RI* beams

* radioactive isotope

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

Nuclear reactions in astrophysical sites
Coulomb dissociation – inverse capture gamma
ANC determination by nuclear breakup
RIKEN RI Beam Factory (RIBF)
Questions on theoretical treatments of breakup process

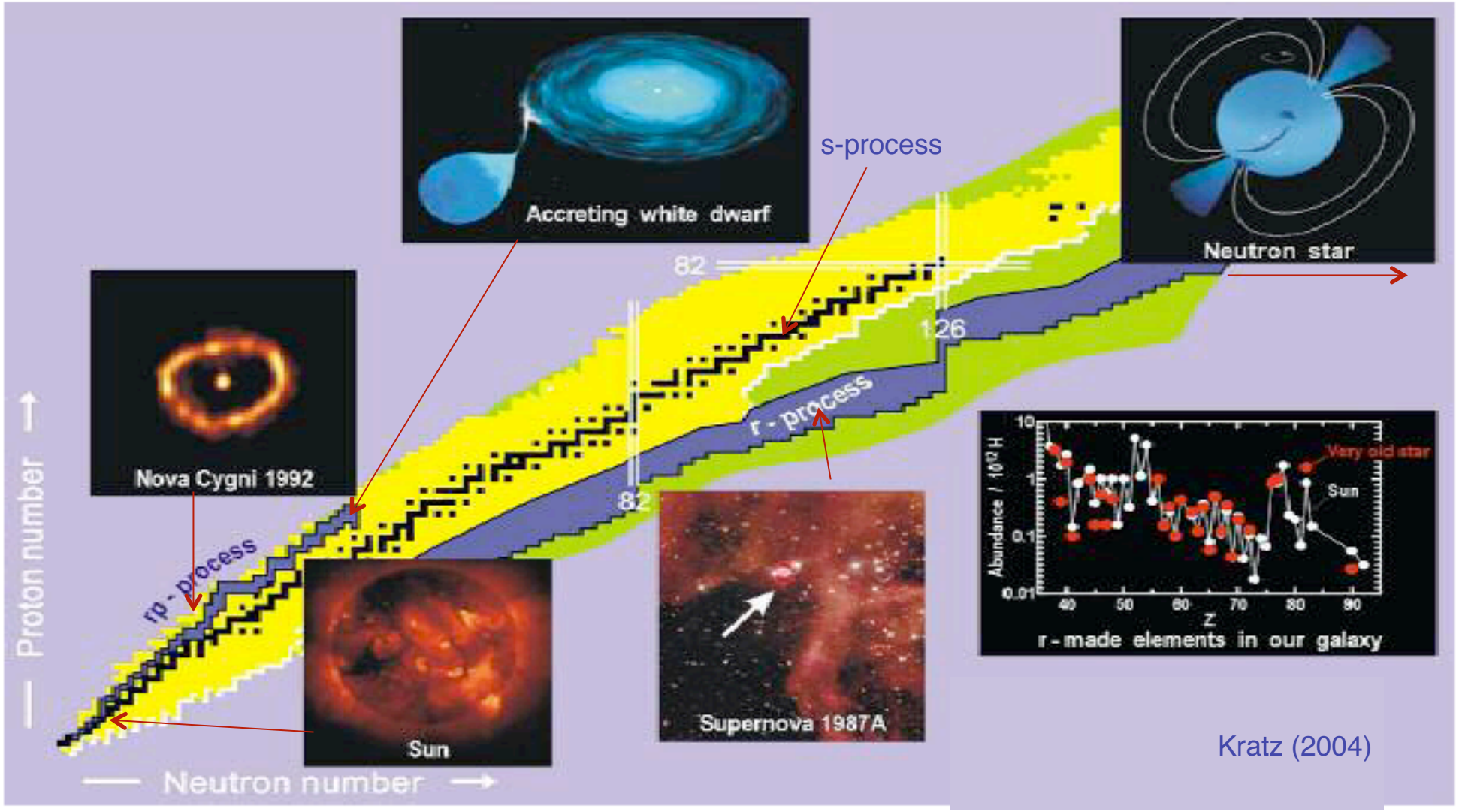


RIKEN NISHINA CENTER

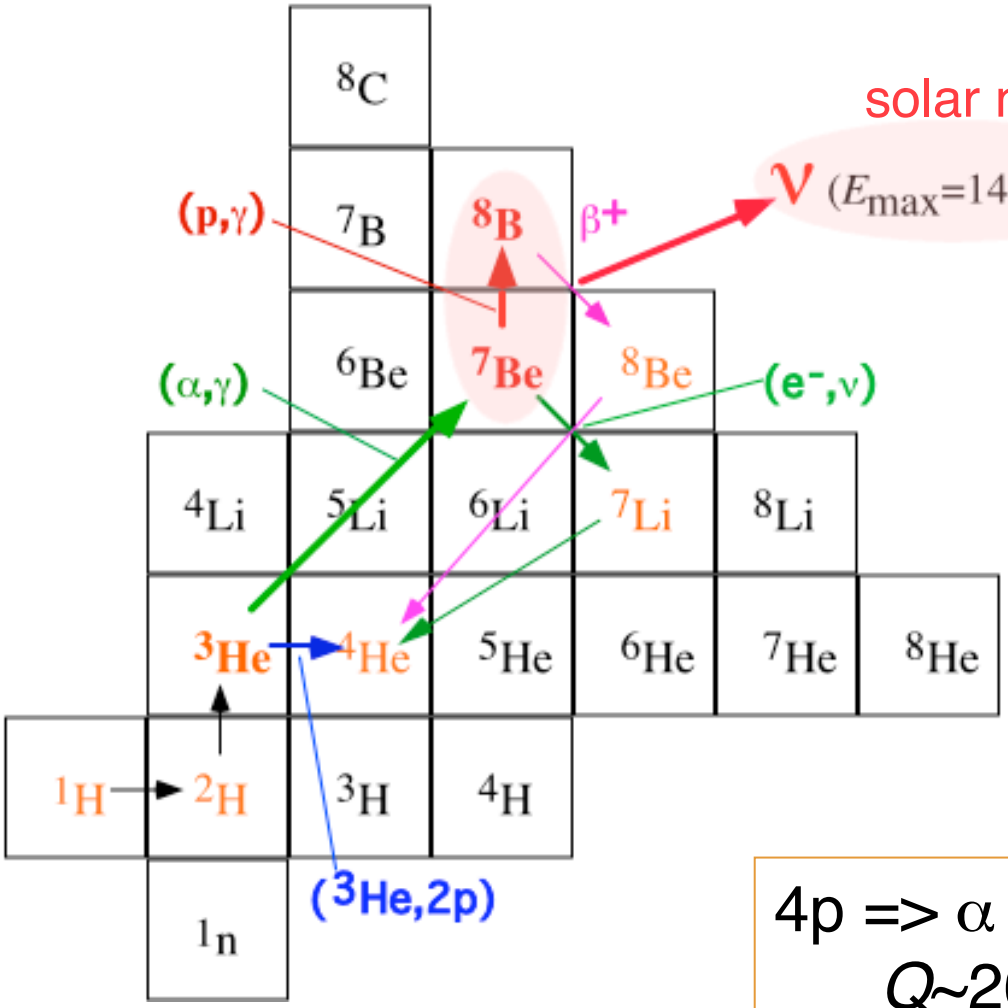
Nov. 2008

Pisa

nuclear burning in the universe

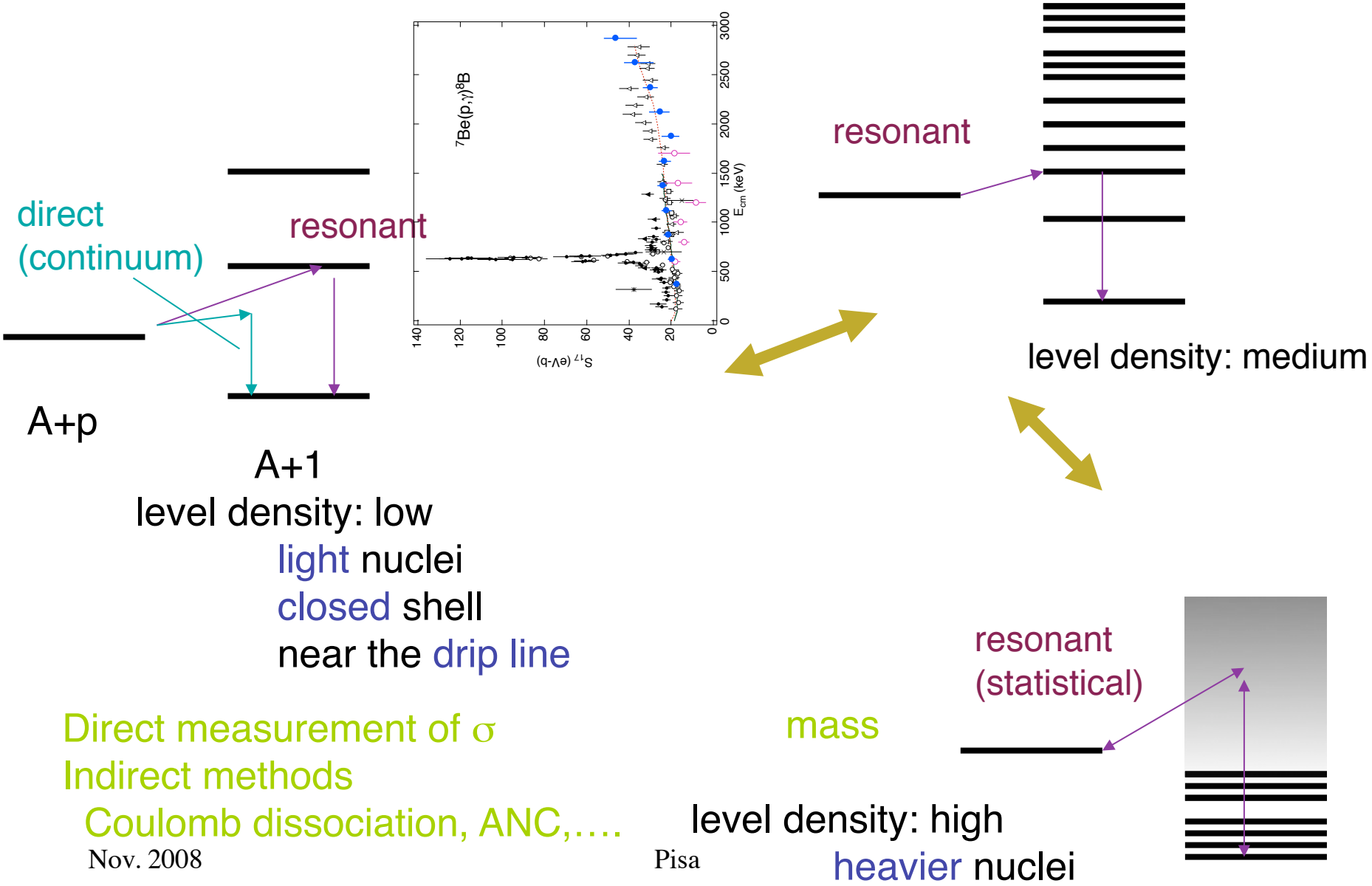


p-p chain in the sun



4p => α (+e$^+$, +ν, -e$^-$)
Q~26 MeV

(p,γ) (or (n,γ)) of astrophysical interest (<MeV)



Coulomb dissociation

Inverse radiative capture

astrophysical (p,γ) reactions

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

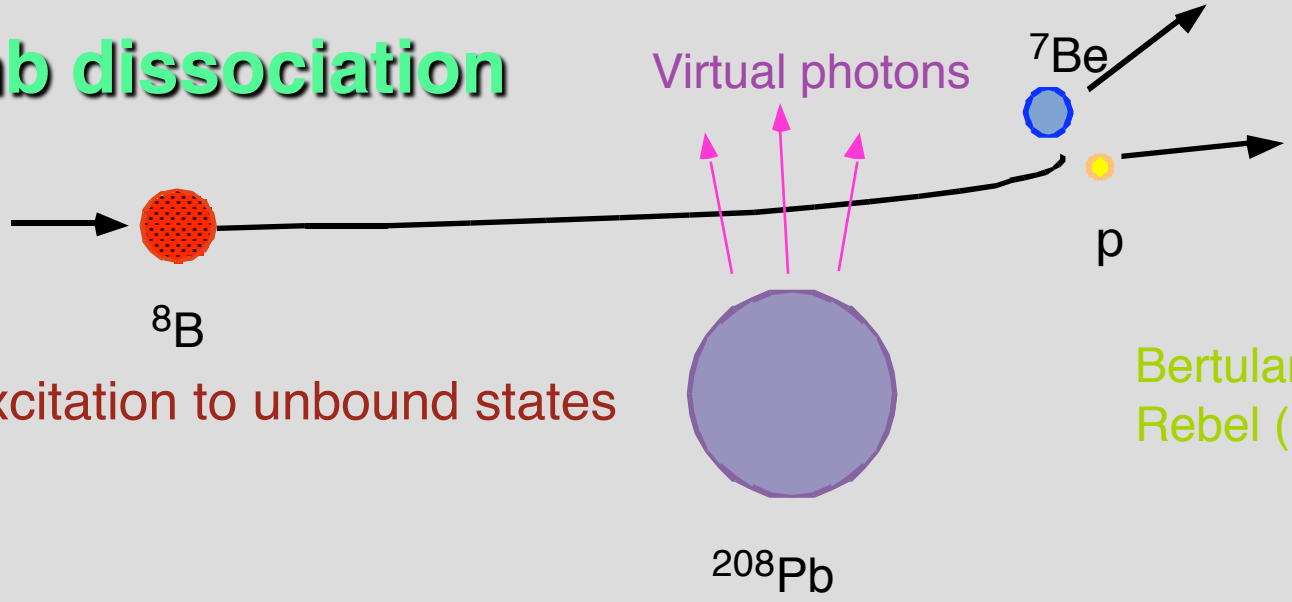
^{23}Al(p,γ)^{23}Mg, ^{26}Si(p,γ)^{27}P – rp process

EM excitation to (neutron) unbound states

structure of loosely bound nuclei *Nakamura*

^{11}Li, ^{11}Be, …

Coulomb dissociation



= Coulomb excitation to unbound states

Bertulani, Baur, Rebel (1986)

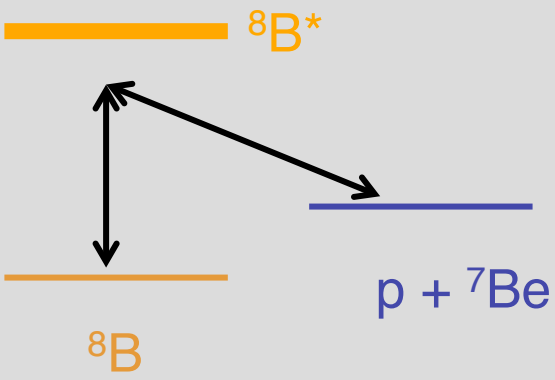
^{8}B+^{208}Pb -> ^{7}Be+p+^{208}Pb (C.D.)

↓ virtual photon theory or DWBA

^{8}B(γ,p)^{7}Be (abs.)

↓ detailed balance

^{7}Be(p,γ)^{8}B (capt.)



Large yield

detailed balance → $\sigma(\gamma,p) >> \sigma(p,\gamma)$

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

100 ~ 1000

virtual photon number → $\sigma_{CD} >> \sigma(\gamma,p)$ @ $E_{in} > 50$ *A*MeV

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

100 ~ 1000

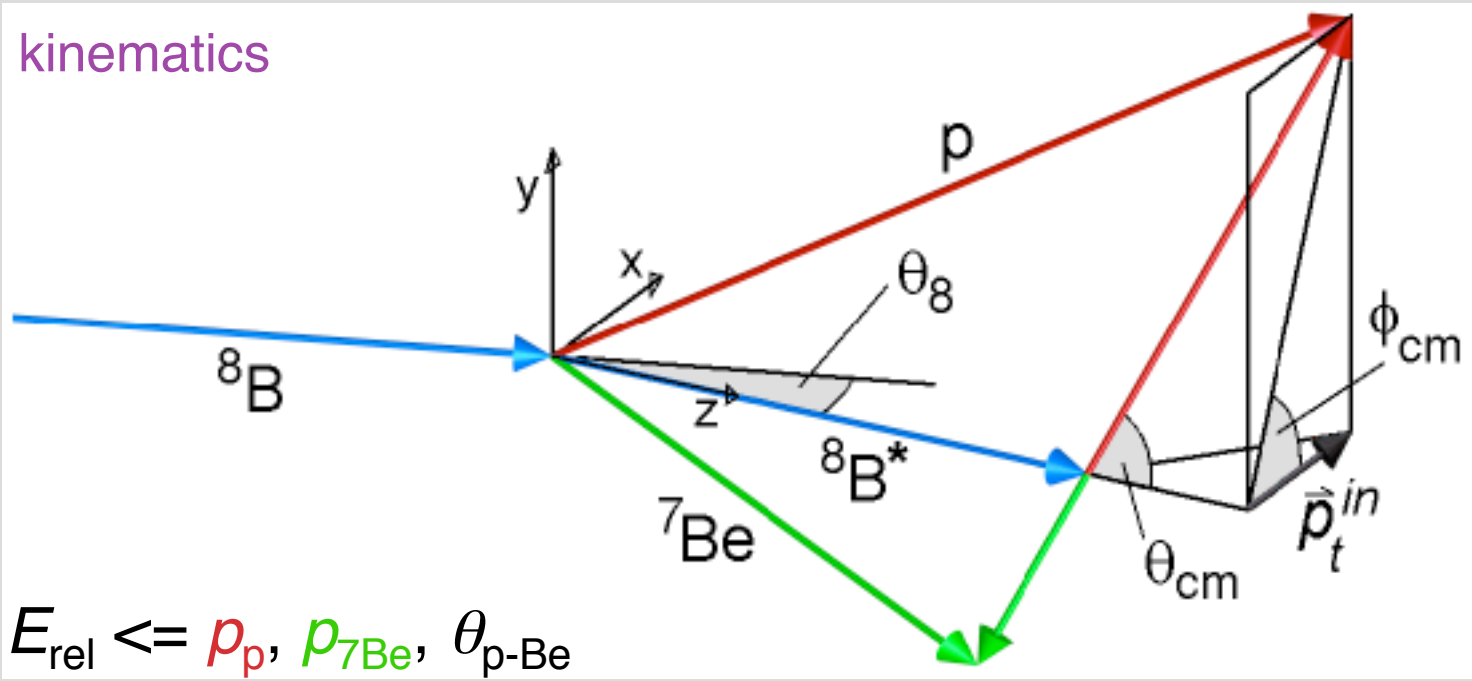
thick target ← $E_{CD} >> E_{(p,\gamma)}$

Reasonable resolution with poor-quality RI beams →
Applicable for resonant and direct captures

experiments with R.I. beams => explosive burning

Simple interpretation of the reaction ⇔ hadronic probes
But…
indirect *i.e.* nuclear force / higher order / E2

kinematics



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

ΔE_{rel} : Independent of 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

Large yield

detailed balance → $\sigma(\gamma,p) >> \sigma(p,\gamma)$

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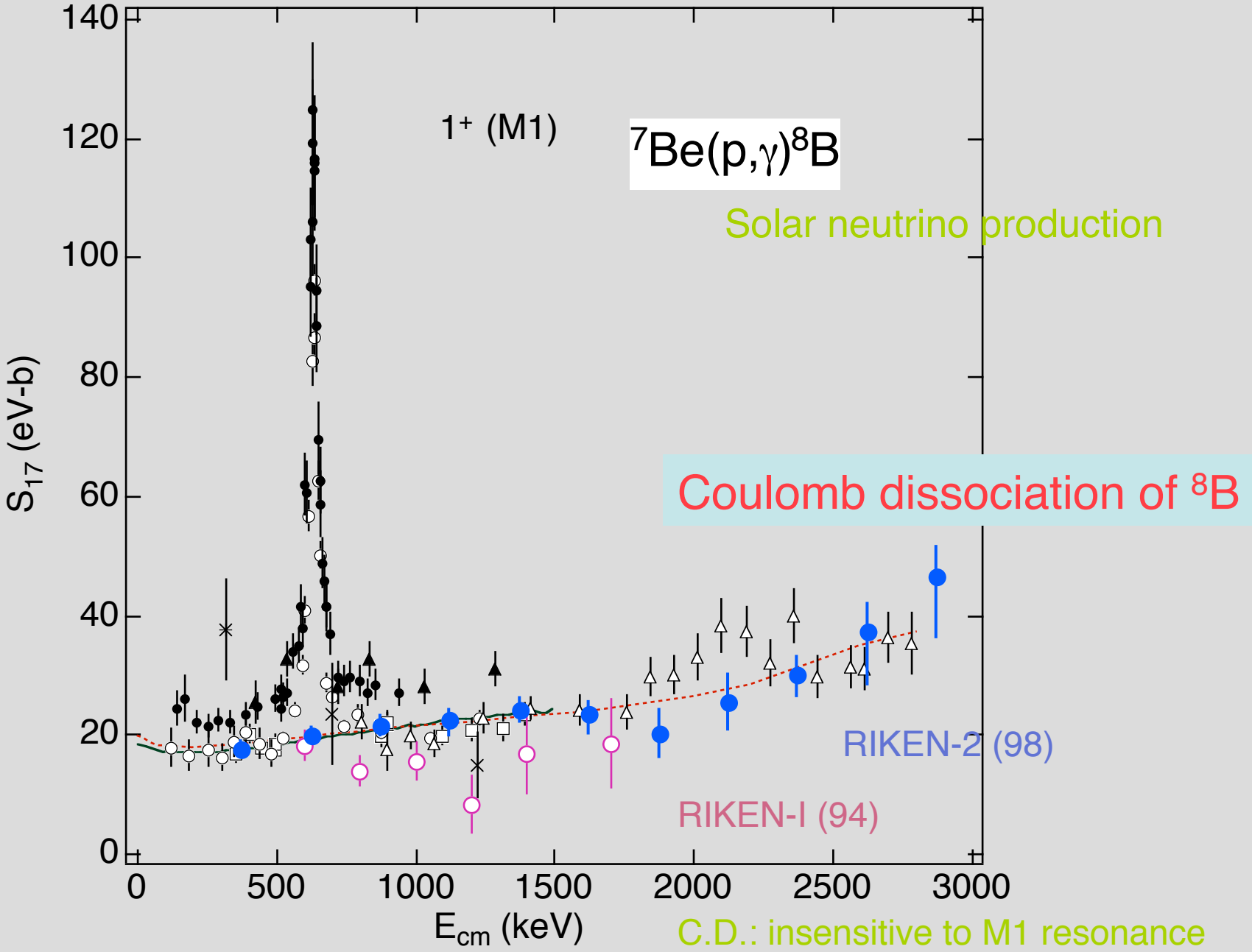
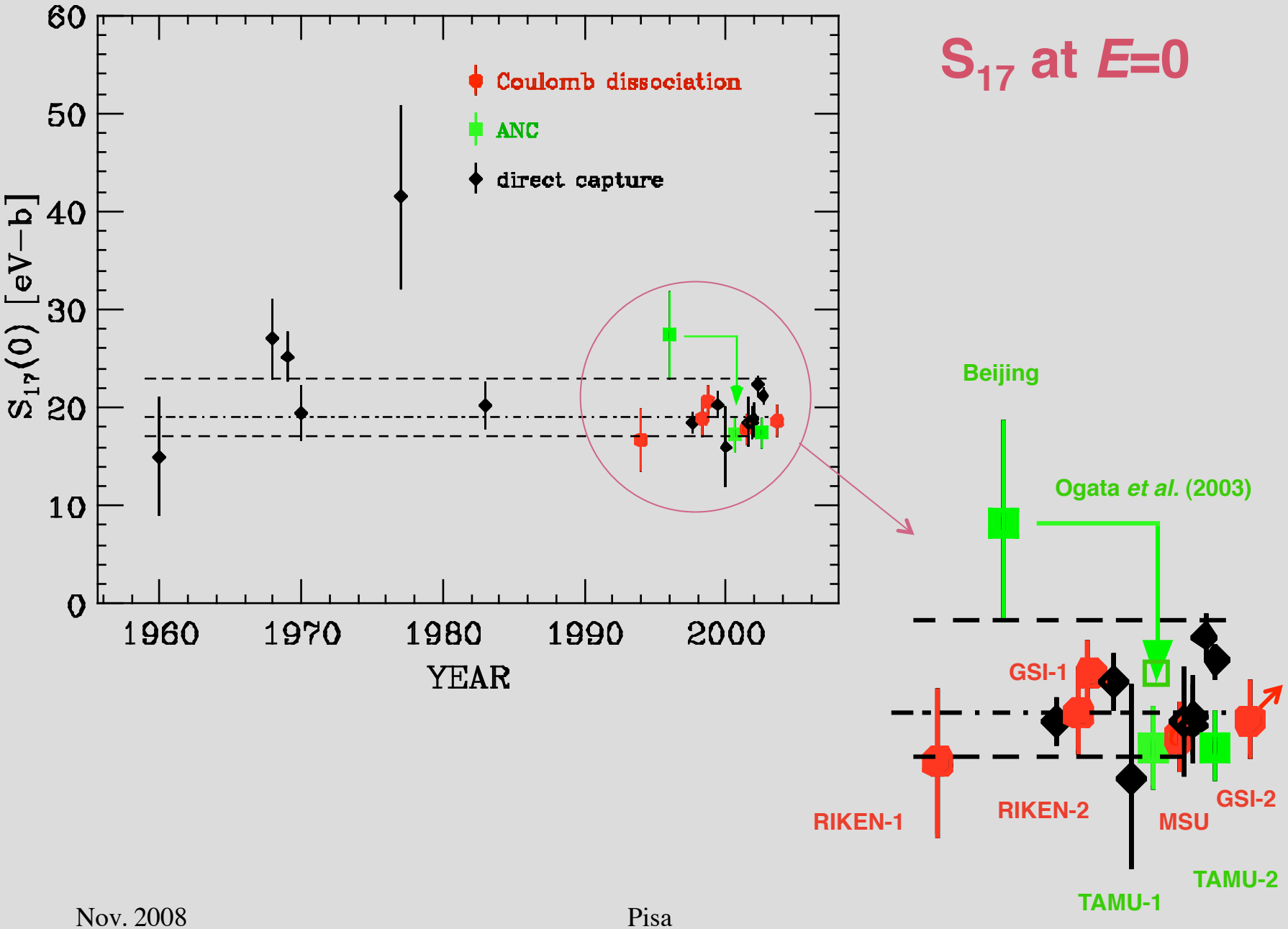
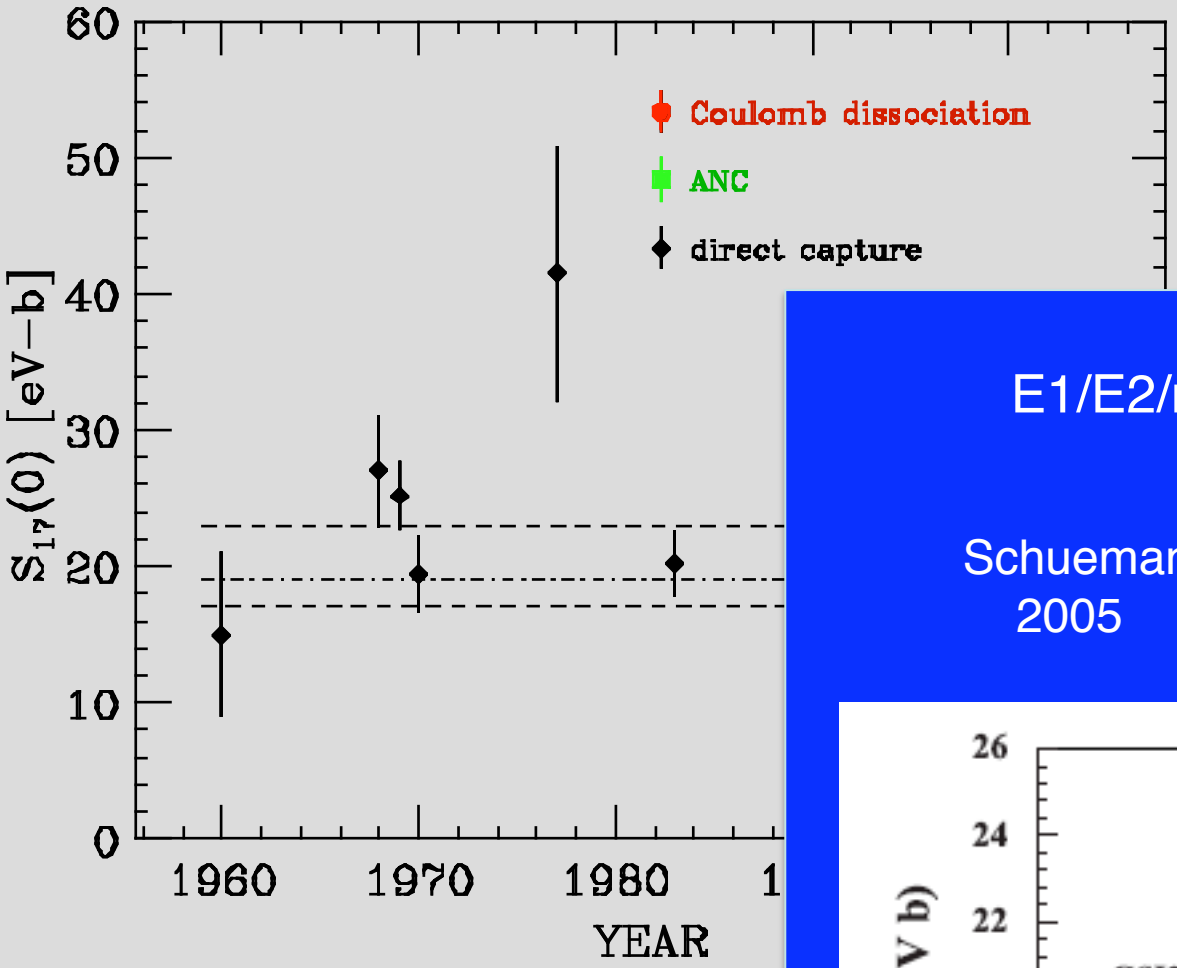

140
120
100
80
60
40
20
0
0
500
1000
1500
2000
2500
3000
S_{17} (eV-b)
E_{cm} (keV)
1^+ (M1)
$^7Be(p,\gamma)^8B$
Solar neutrino production
Coulomb dissociation of ^8B
RIKEN-2 (98)
RIKEN-I (94)
C.D.: insensitive to M1 resonance

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

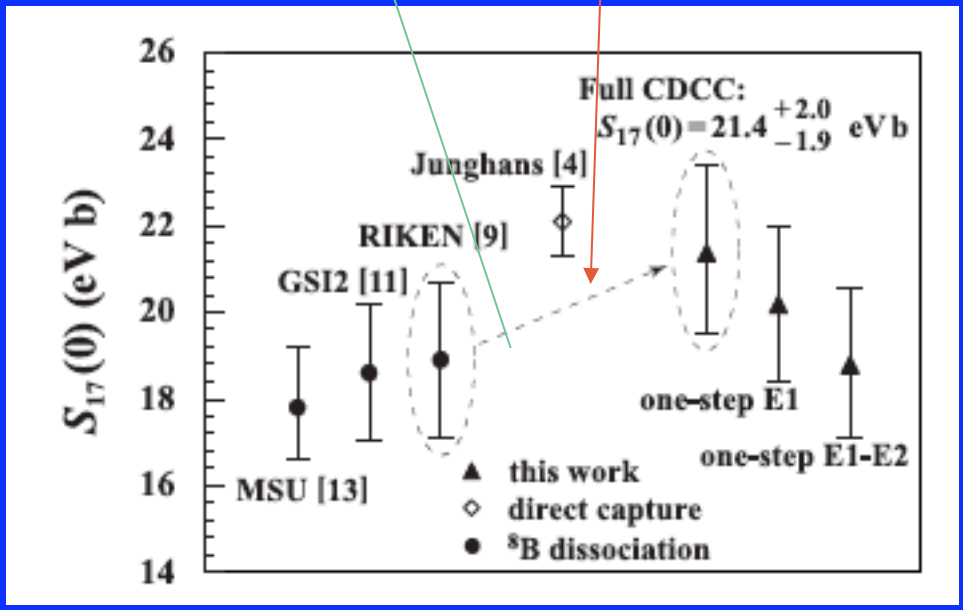
S_{17} at E=0



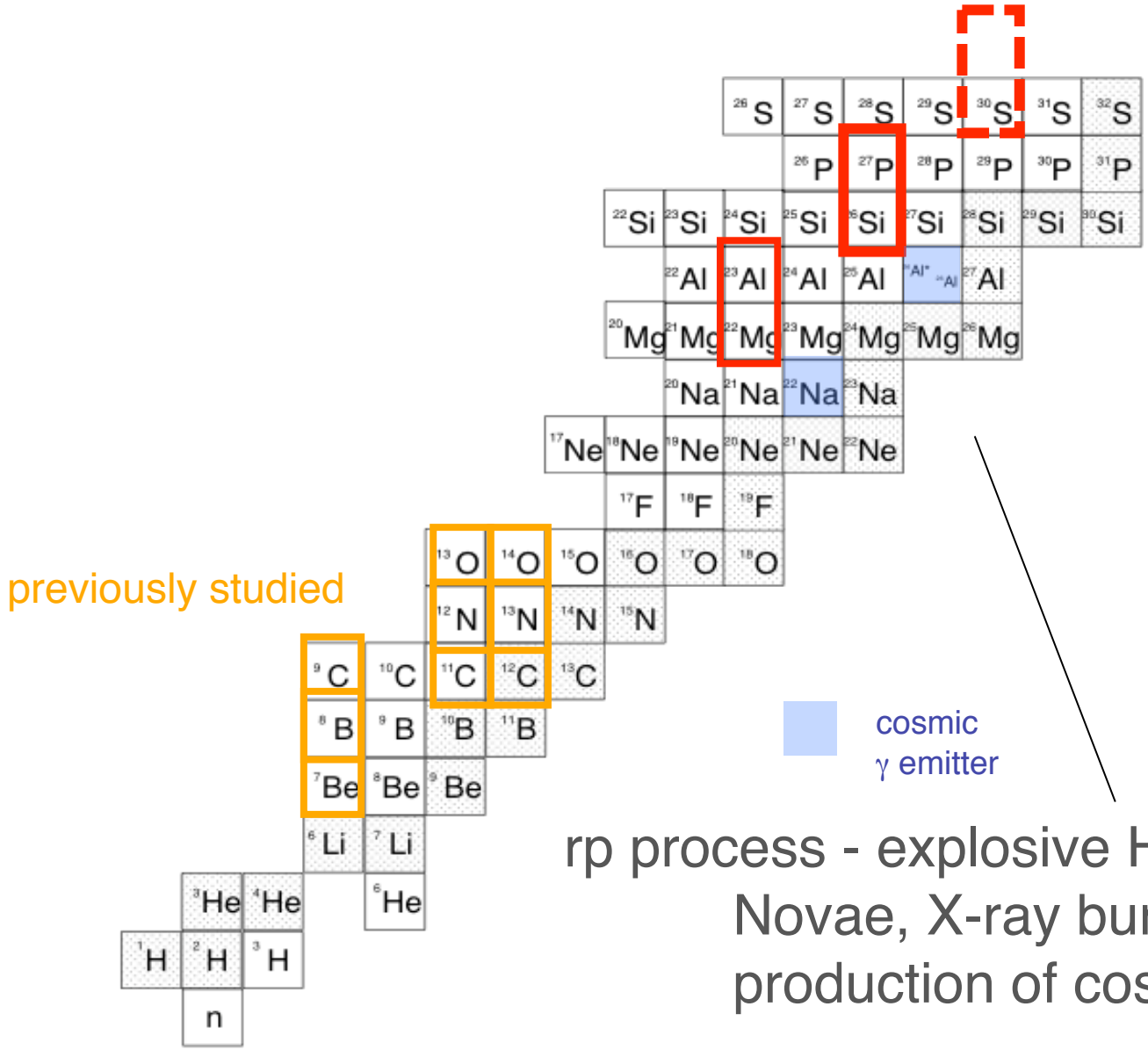
E1/E2/nucl. interference

Ogata *et al.* (CDCC)

Schuemann *et al.* 2005



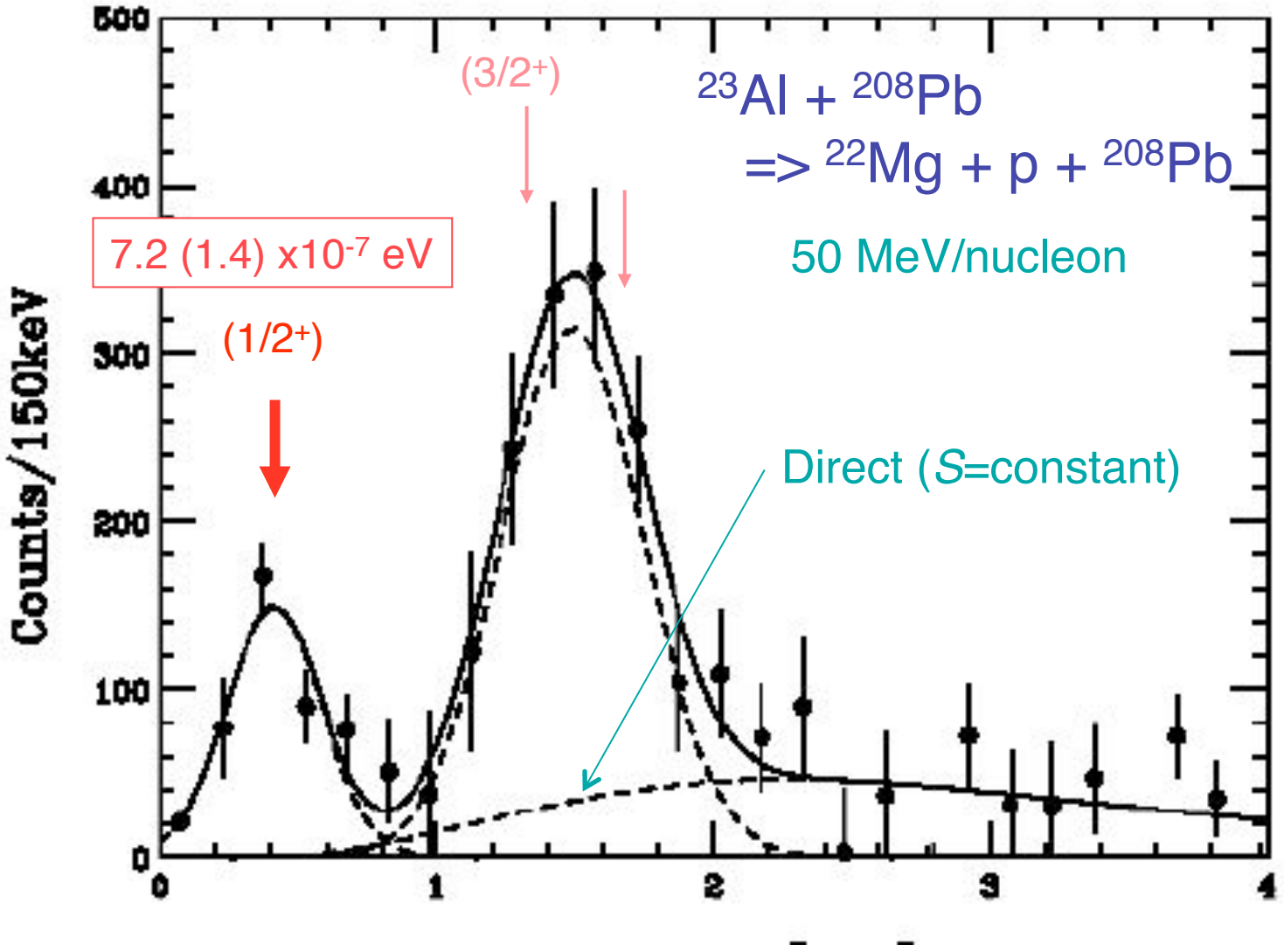
Nov. 2008



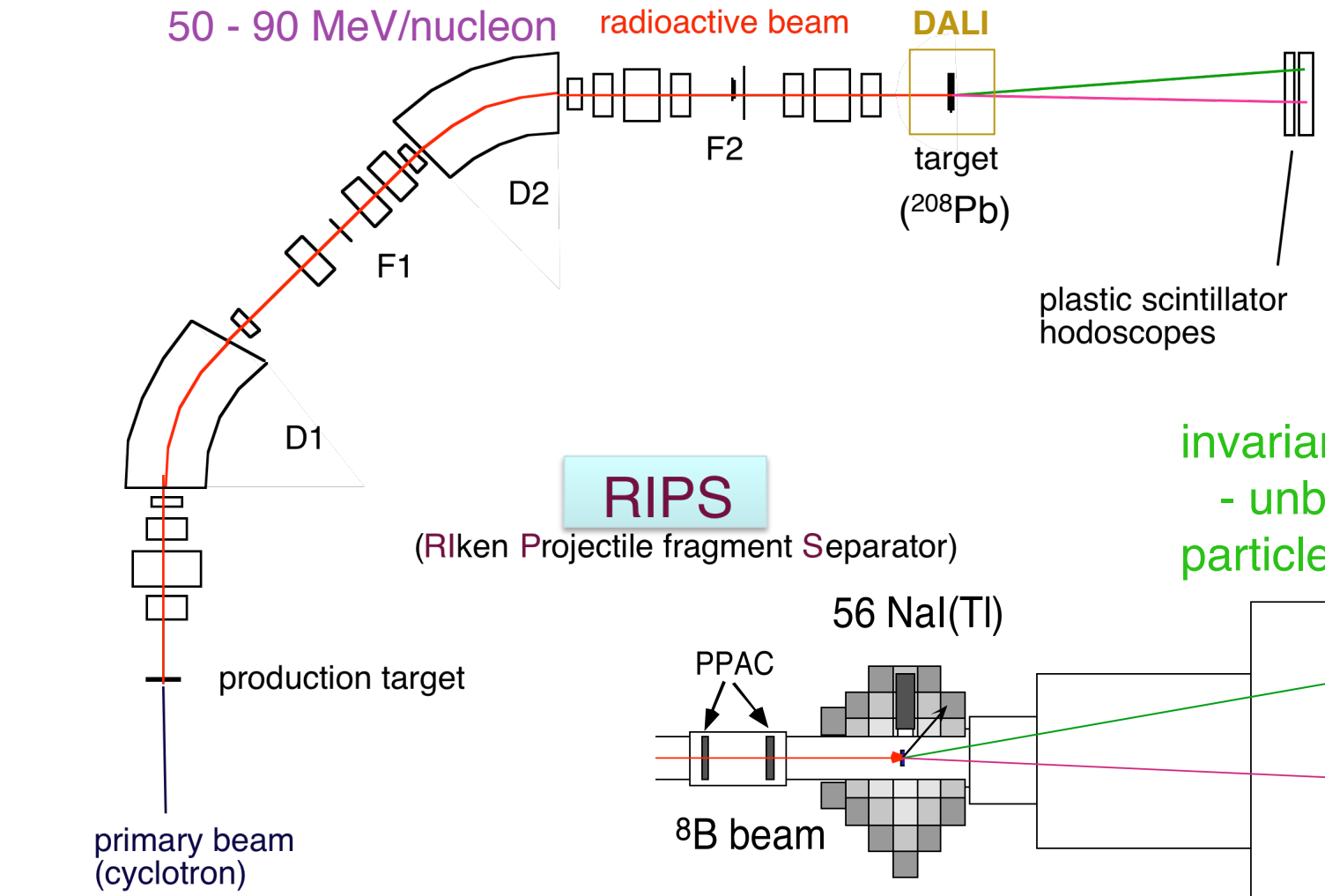
rp process - explosive H burning
Novae, X-ray bursts
production of cosmic γ emitters

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

←→10^{12} pps ^{22}Mg ! + ^{1}H

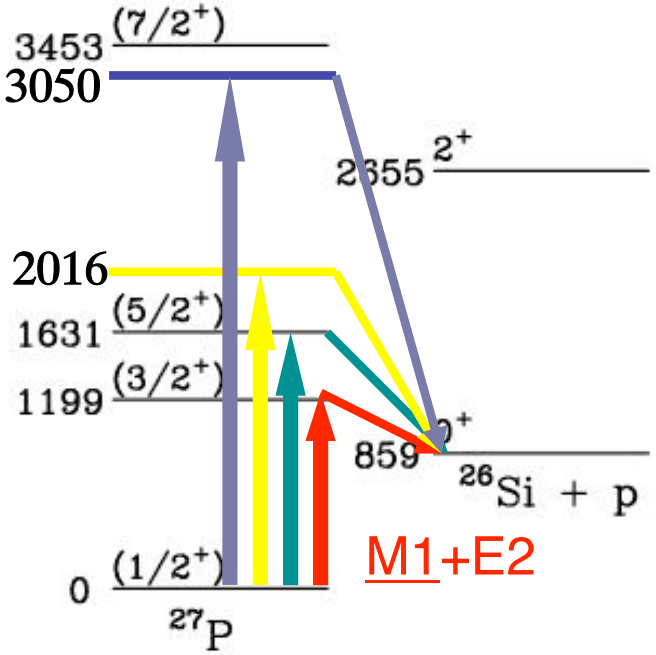


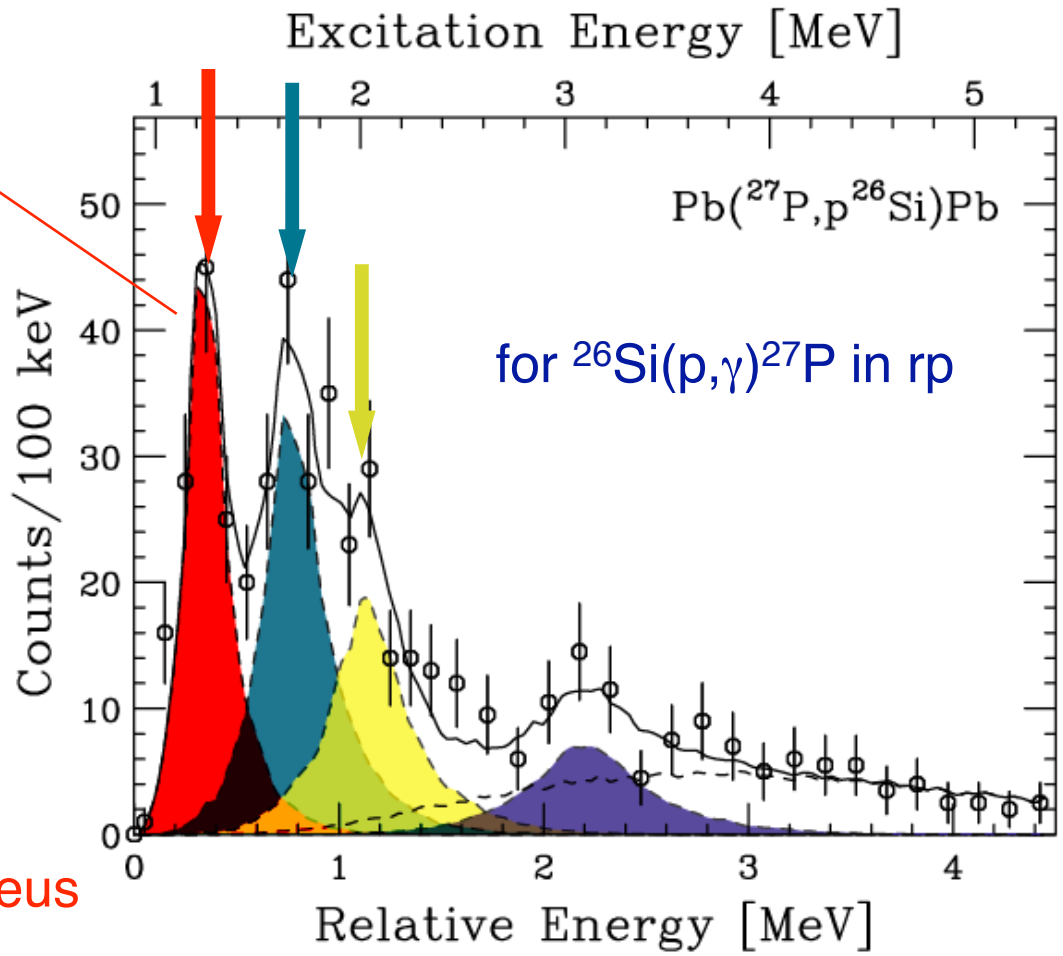
spectroscopy of unstable nuclei / nucl. astrophysics



$\Gamma_\gamma\Gamma_p/\Gamma = (4.2\pm1.3)\times10^{-3}$

RIPS

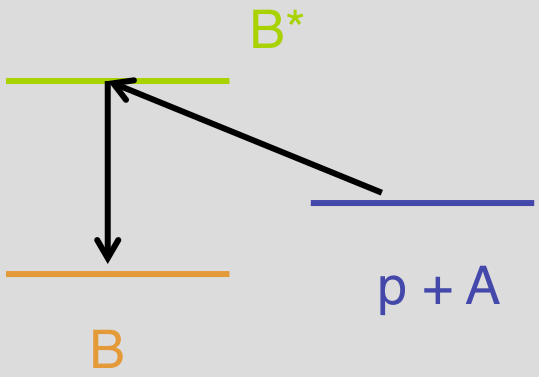




M1(1199): estimated <= mirror nucleus

Resonant capture

p + A => B* => γ + B



$$\sigma_{(p,\gamma)} = \pi\lambda\!\!\!^{-2}\omega \frac{\Gamma_p \Gamma_\gamma}{(E - E_0)^2 + \frac{1}{4}\Gamma^2}$$ (Breit-Wigner formula)

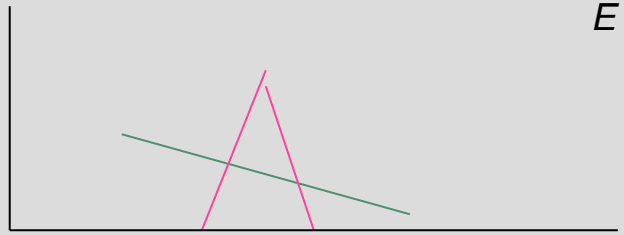
ω : spin factor

$$= 4\pi\lambda\!\!\!^{-2}\omega \frac{\Gamma_p \Gamma_\gamma}{\Gamma^2} \qquad \text{at } E = E_0$$

$$\omega = \frac{2I_{B^*} + 1}{(2I_p + 1)(2I_A + 1)}$$

$$= \frac{2I_{B^*} + 1}{2(2I_A + 1)}$$

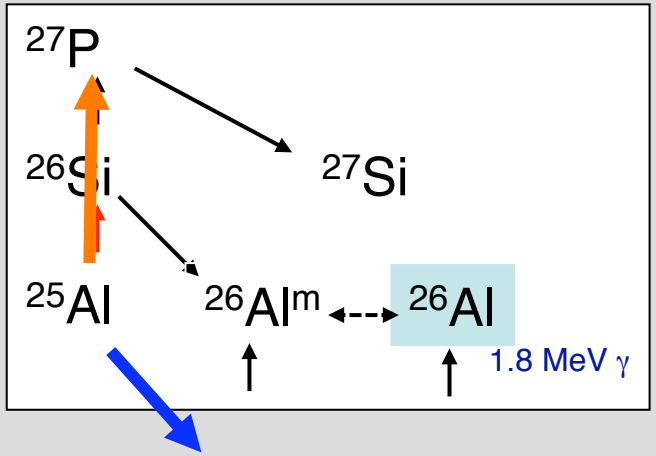
$$\approx 4\pi\lambda\!\!\!^{-2}\omega \frac{\Gamma_\gamma}{\Gamma} \qquad \text{if } \Gamma_p \approx \Gamma >> \Gamma_\gamma$$



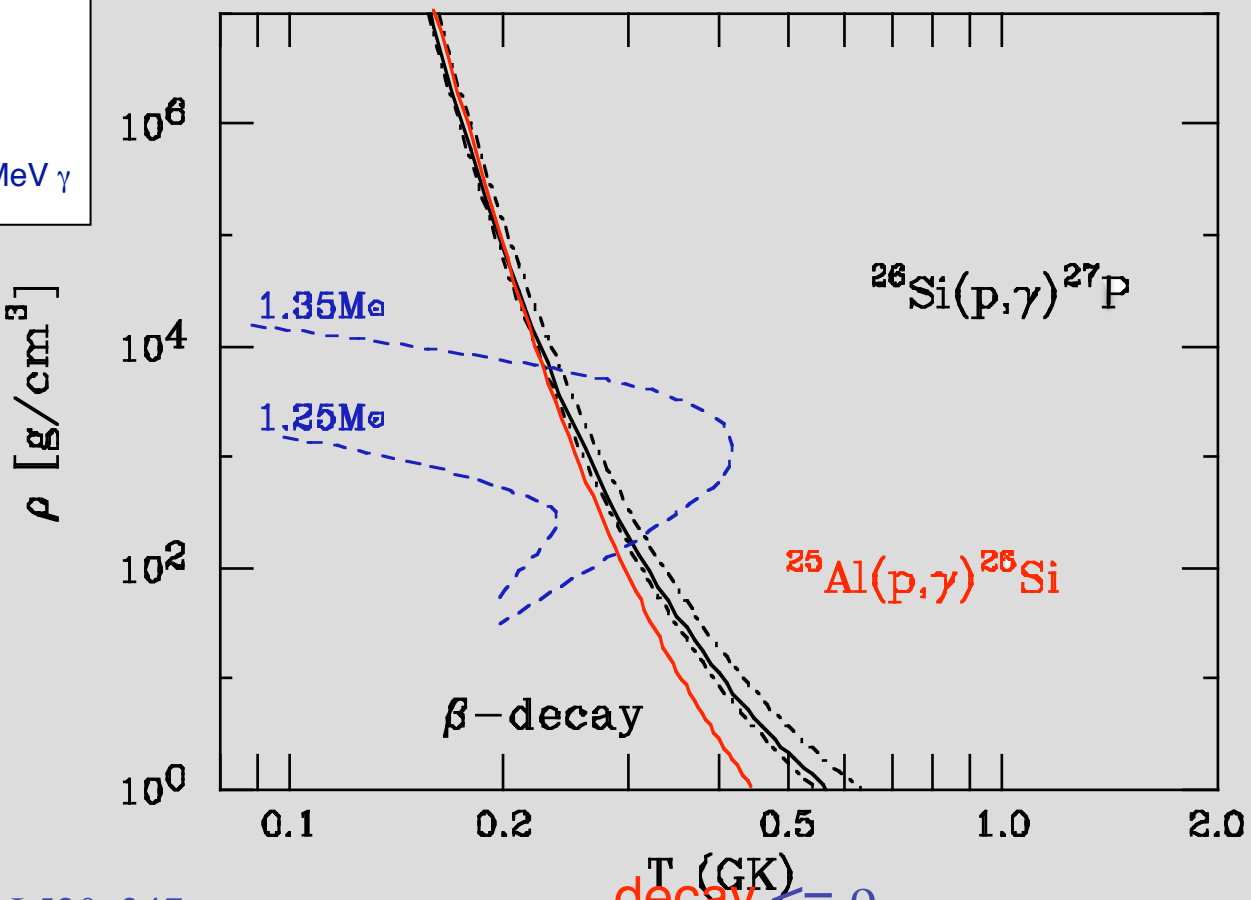
reaction rate : $\sigma(E_0)\Gamma <= \omega\Gamma_\gamma(\Gamma_p/\Gamma)$

$$\langle \sigma v \rangle = \left(\frac{}{\pi\mu_{12}(kT)^3}\right)^{1/2} \int dE\sigma(E)E\exp\left[\frac{-E}{kT}\right]$$

Coulomb dissociation



^{25}Al-^{26}Si-^{26}Al^{m}-^{26}Al is not likely.



J. Jose et al. ApJ 520, 347

C. Iliadis et al. ApJ Supl. 142, 105

decay <= ρ_{Si}

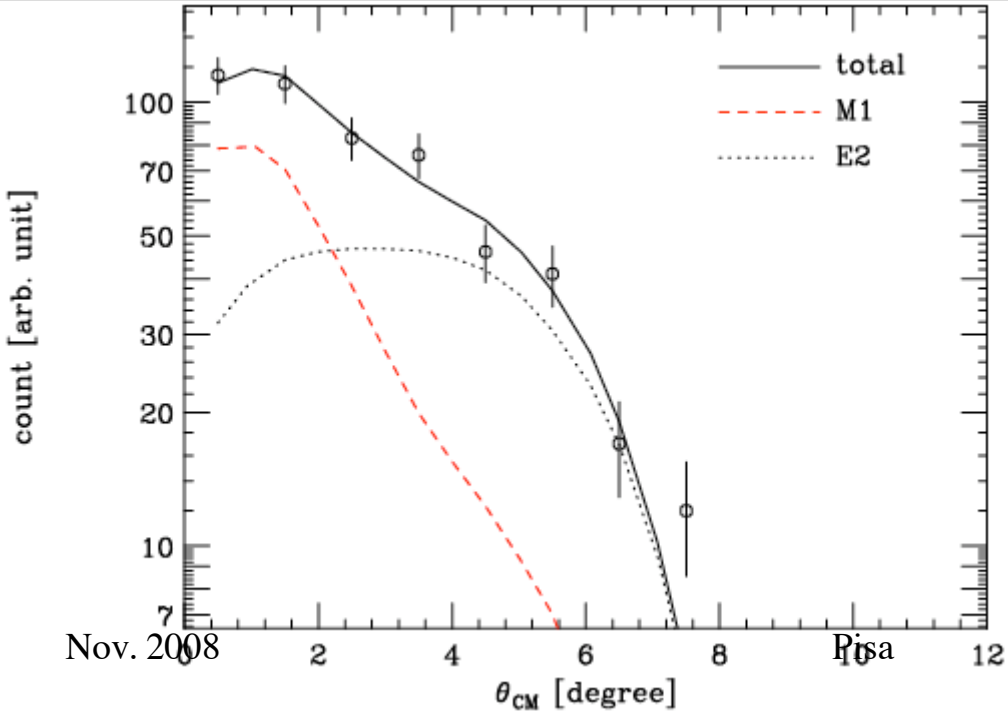
V.S.

(p,γ) <= ρ_{Si}, ρ_p , T $\sigma(E)$

Improvement in

extraction of M1 component

- Differential cross section
  - M1: peak at forward angle
  - E2 : plateau to the grazing angle



Simulation for ^{31}Cl C.D.

E2/M1 = 0.01

Angular resolution = 0.7°

DWBA

nuclear absorption in CD

nuclear excitation

ANC determination by nuclear breakup

ANC Determination by transfer or (nuclear) breakup

Asymptotic Normalization Coefficient (ANC)

capture cross section

$$\sigma(\mathrm{p},\gamma) \propto \left| \left\langle \Psi_c \| T(\mathrm{E}\lambda) \| \Phi_b \right\rangle \right|^2$$

transfer cross section

$$\frac{d\sigma}{d\Omega}_{\mathrm{DWBA}} \propto \left| \left\langle \chi_f^{(-)} \Phi_b \left| V_{\mathrm{DWBA}} \right| \Phi_b^{(\mathrm{proj})} \chi_i^{(+)} \right\rangle \right|^2$$

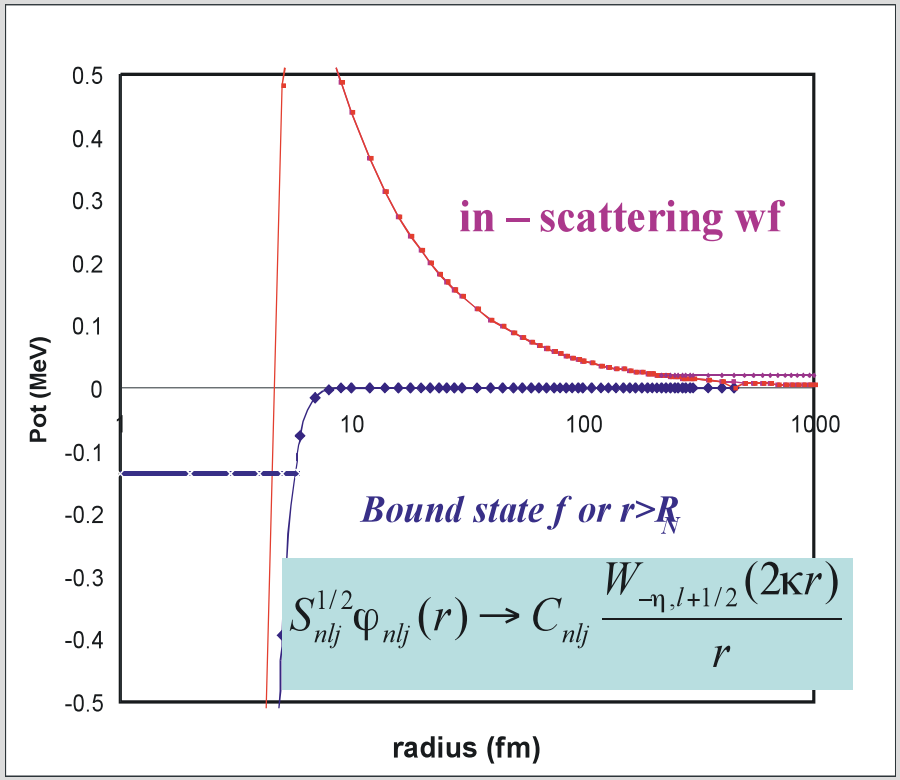
transfer reaction
also → breakup

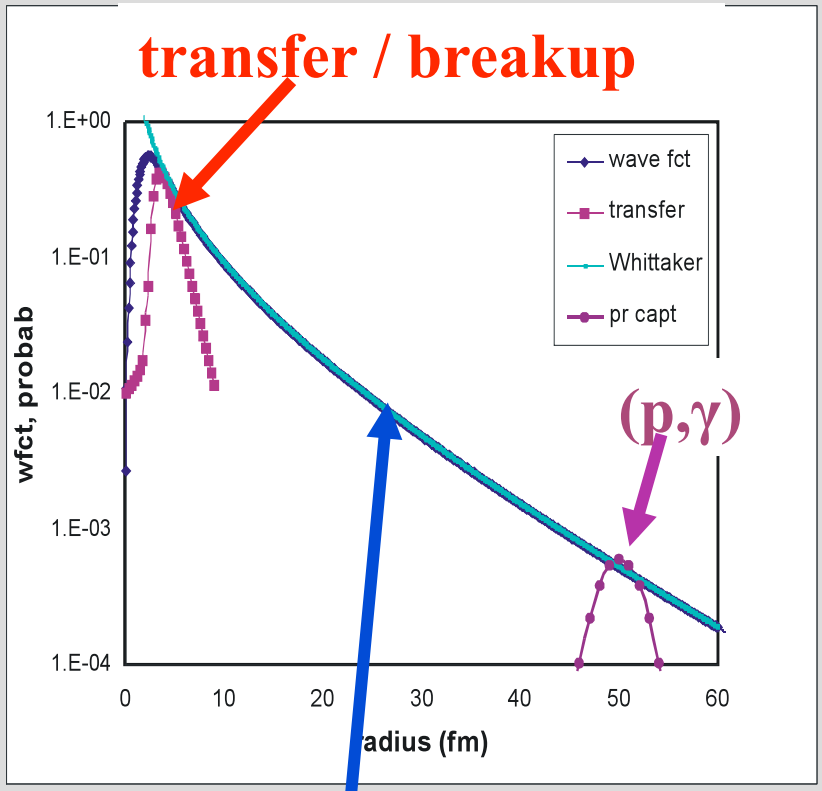
$$C^2 = Sb^2$$

$$b = \left\langle \frac{u^{\mathrm{sp}}(r)}{W^{+}(r)} \right\rangle_{\mathrm{tail}}$$

"tail" amplitude of the bound state (p+A) wave function:

less model dependent (*e.g.* radius)
⇔ spectroscopic factor
c.f. Gales



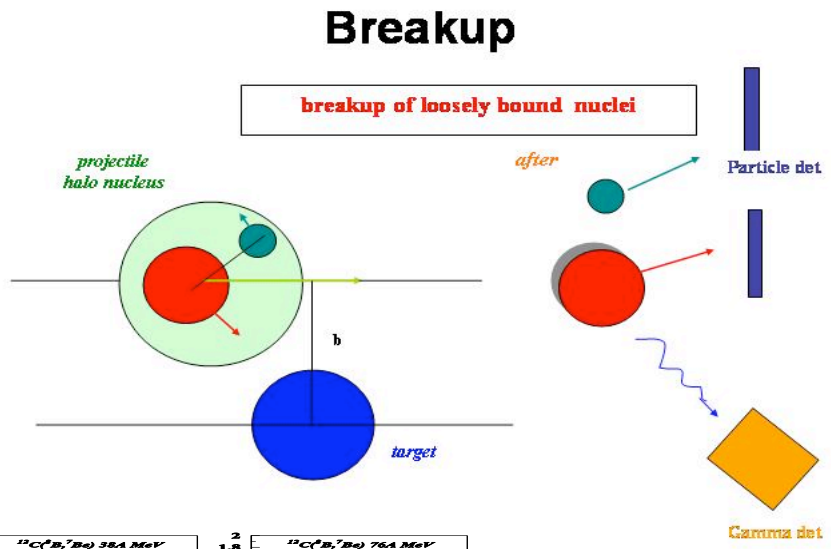


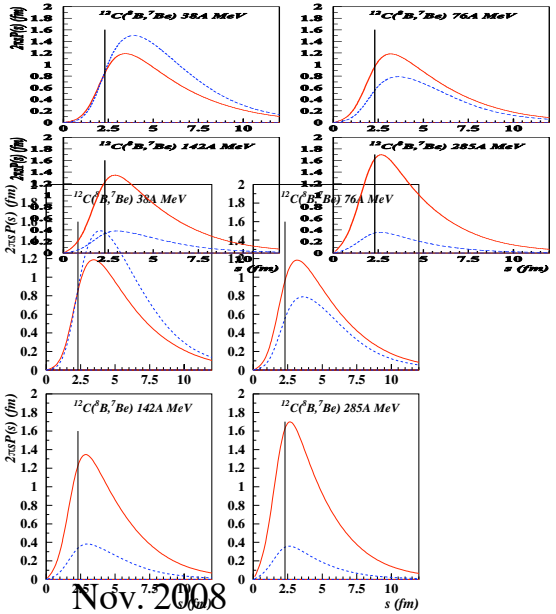
$$(T + V_{coul})Y(\hat{r})\varphi(r) = -\varepsilon Y(\hat{r})\varphi(r)$$

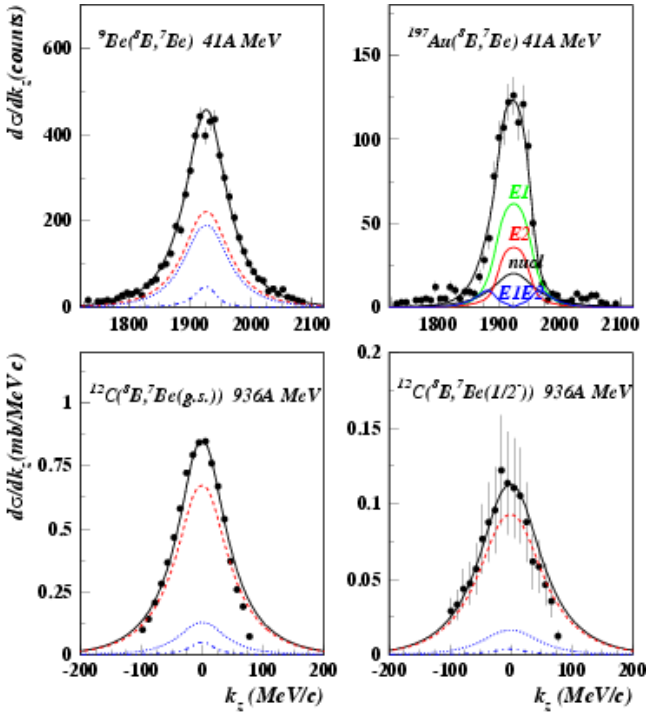
Asymptotic behavior of w.f. is robust.

Trache et al. (Texas A&M)

Breakup reactions for nuclear astrophysics







Peripheral

Momentum distributions → *nlj*
Cross section → ANC (only!!!)
Gamma rays → config mixing

Need: $V_{p\text{-target}}$ & $V_{core\text{-target}}$
and reaction mechanism model

***c.f.* ^{23}Al breakup @ GANIL**

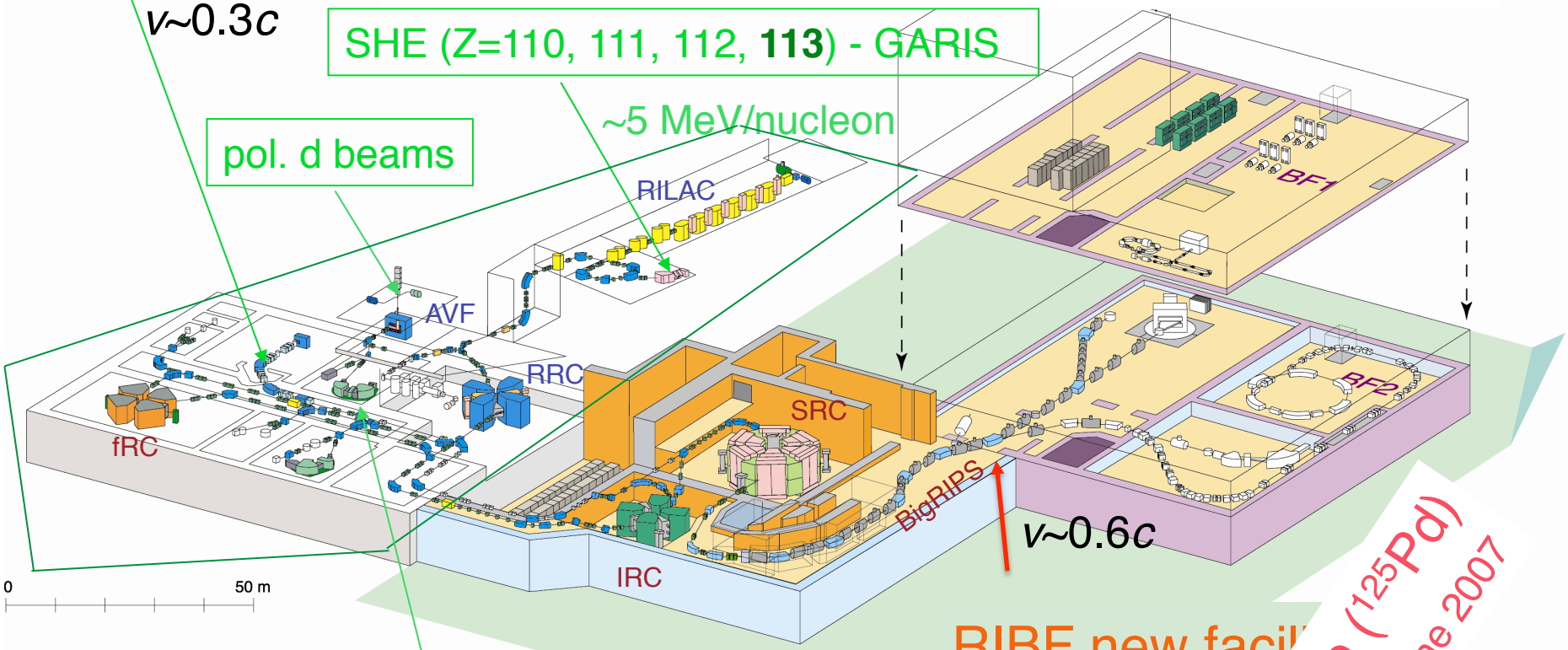
Trache et al. (Texas A&M)

RIKEN RI Beam Factory (RIBF)

Nov. 2008 Pisa

Fast RI beams - RIPS

RIBF: Accelerator Complex in RIKEN Nishina Center



RIBF new facil

■ 135 MeV/nucleon for light nuclei (1986-)

■ 350 MeV/nucleon up to U

■ to lt

new isotope (^{125}Pd) June 2007

RI beams (<5 AMeV) - CRIB

CNS v~0.1c

1st beam in Dec. 2006
U beam in Mar. 2007
RI beams with U-fission: Mar 2007 -

Nov. 2008

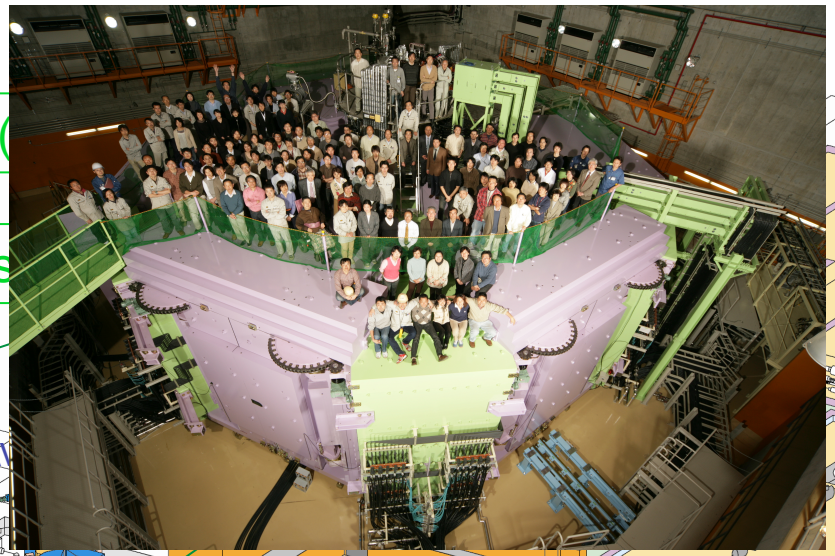
RIBF: Accelerator Complex in RIKEN Nishina Center

Fast RI beams - RIPS

v~0.3*c*

SHE (

pol. d beams



v~0.6*c*

135 MeV/nucleon
for light nuclei (1986-)

350 MeV/
up to

w facility

to be built

RI beams (<5 AMeV) - CRIB

CNS *v*~0.1*c*

RIBF: Accelerator Complex in RIKEN Nishina Center

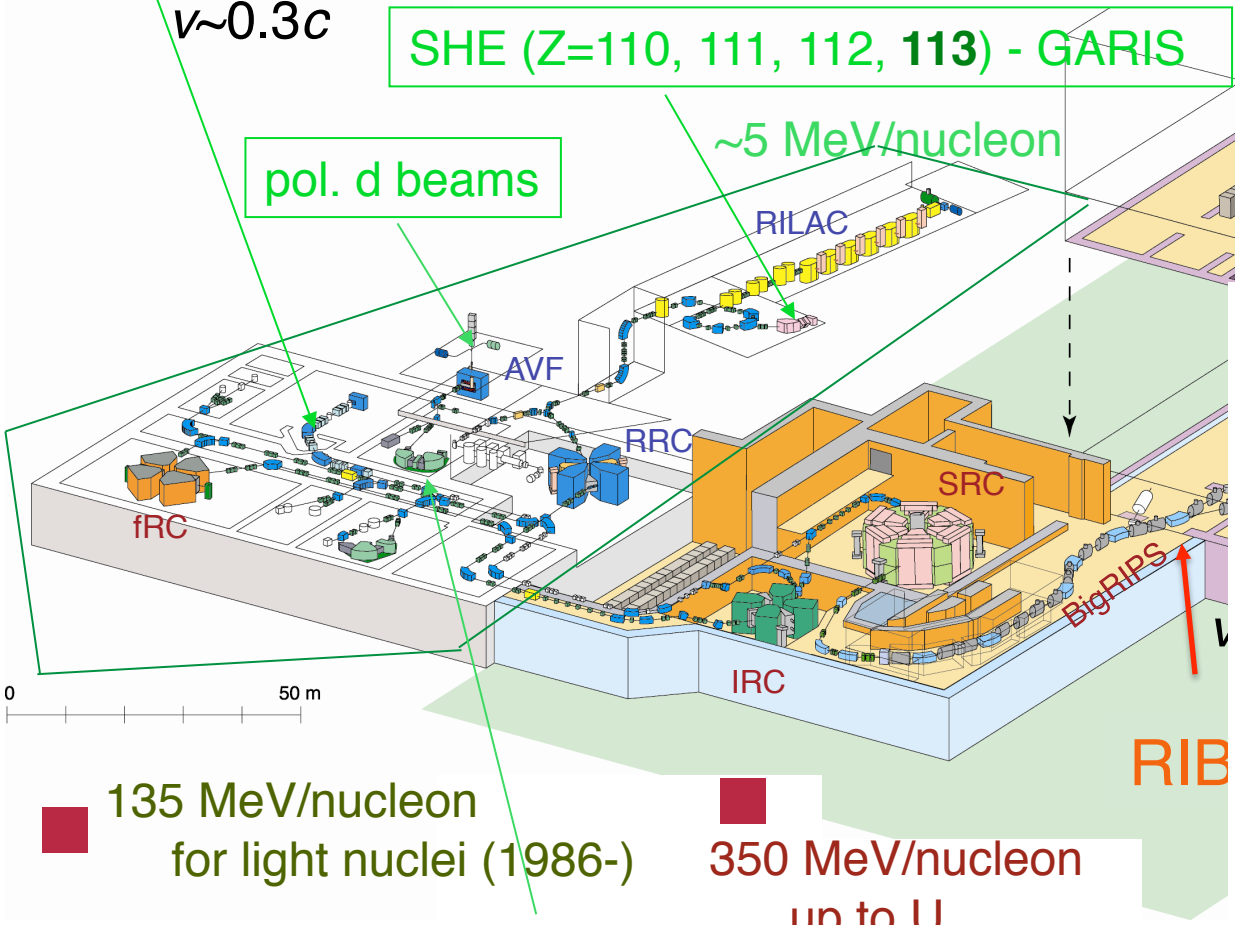
Fast RI beams - RIPS

v~0.3*c*

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

~5 MeV/nucleon

pol. d beams



135 MeV/nucleon
for light nuclei (1986-)

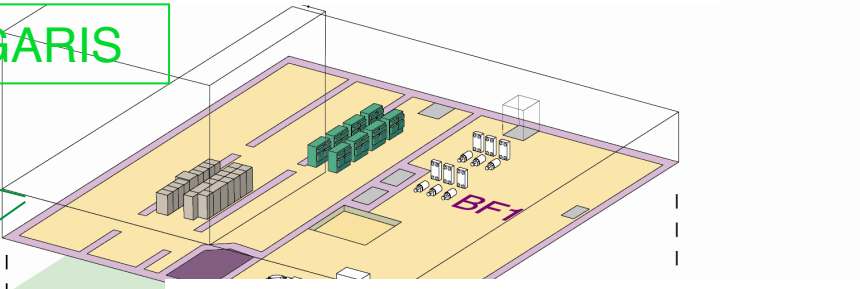
350 MeV/nucleon
up to U

RI beams (<5 AMeV) - CRIB

CNS *v*~0.1*c*

1st beam in Dec. 200
U beam in Mar. 2007
RI beams with U-fiss

Nov. 2008



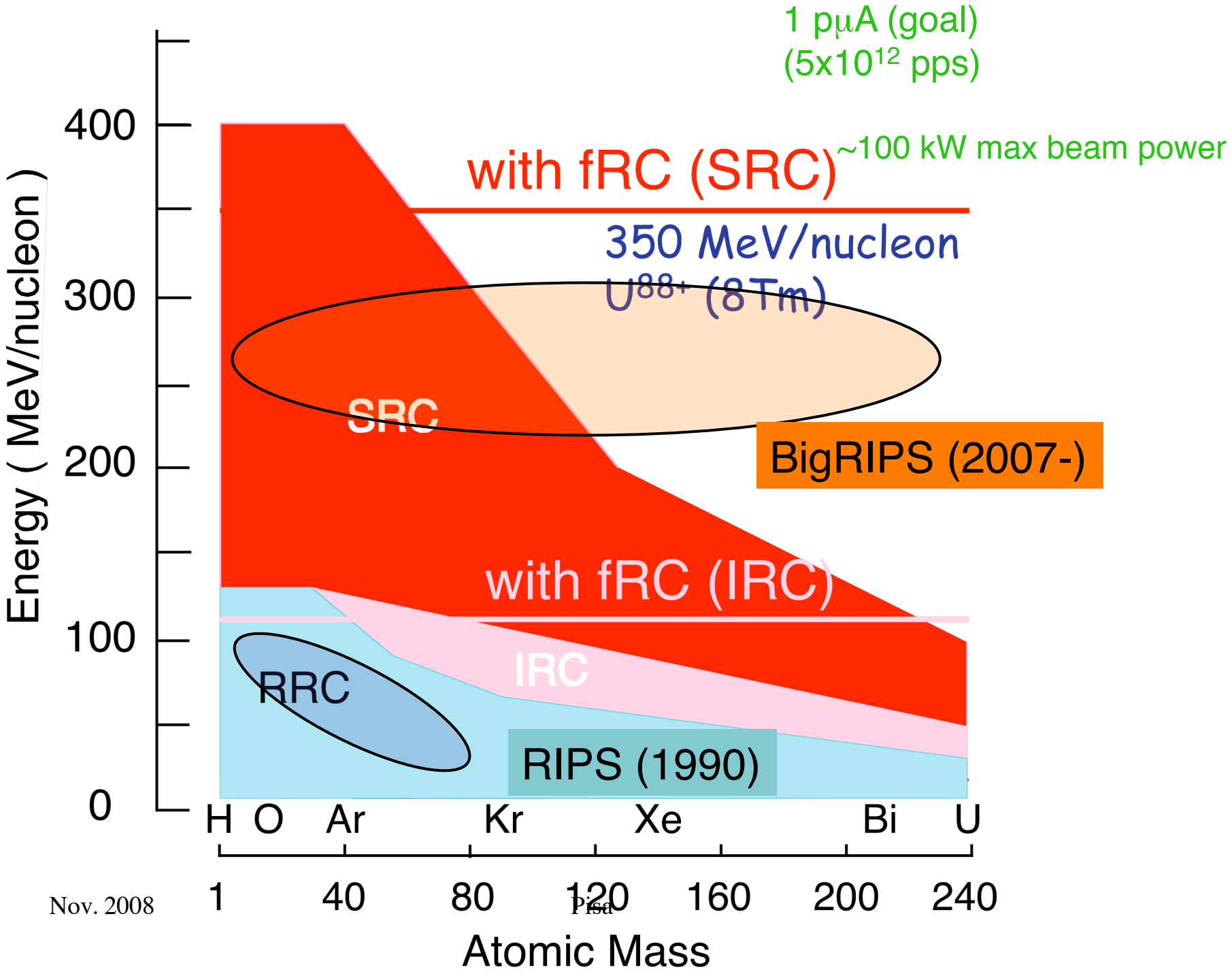
朝日新聞
平成１９年６月８日（金）

理化学研、新Ｒ｜

安定なパラジウム原
子が15個も多い新し
放射性同位元素
と、理化学研究
代加速器「
ー」の初
の70%ま
ビー
せたと
い通りのＲ

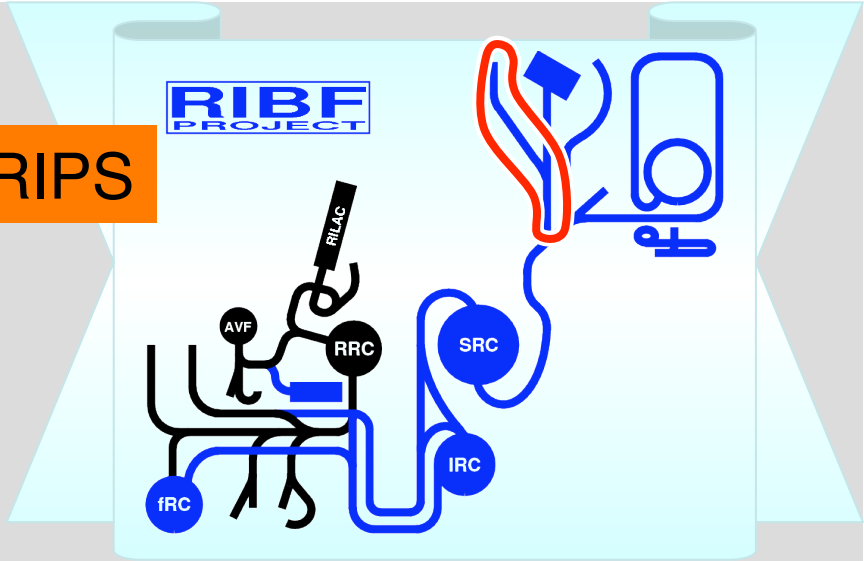
成果。光速
ランのイオン
の標的に衝突さ
ンが壊れてほぼ狙
生まれたという。

new isotope (^{125}Pd)
June 2007


1 pμA (goal)
(5x10^12 pps)
with fRC (SRC)
~100 kW max beam power
350 MeV/nucleon
U88+ (8Tm)
SRC
BigRIPS (2007-)
with fRC (IRC)
IRC
RRC
RIPS (1990)
Energy (MeV/nucleon)
400
300
200
100
0
H O Ar Kr Xe Bi U
1 40 80 120 160 200 240
Atomic Mass

Zero-degree spectrometer

BigRIPS



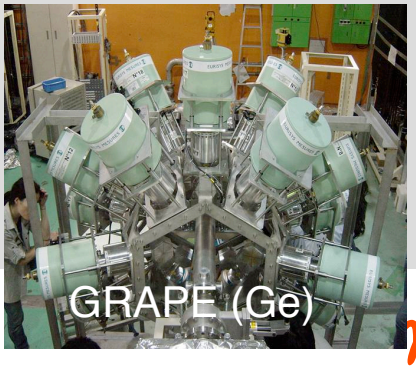
particle ID / momentum analysis

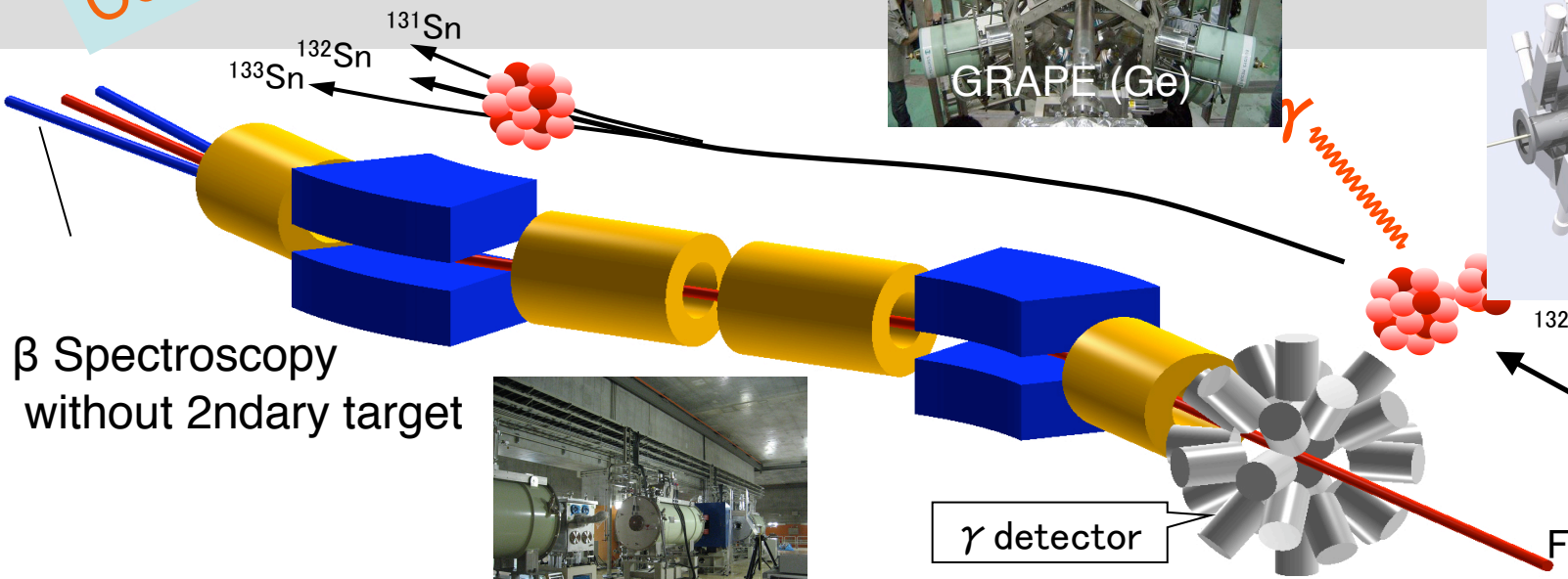
e.g. Doppler shifted γ-ray measurements
with identification of products
(angle-integrated cross section)

Inclusive breakup =>

Multi-fun... ...ne
Me... ...lution
p/δp ~2000 - 4000
...acc ±3%

Commissioning in fall 2008

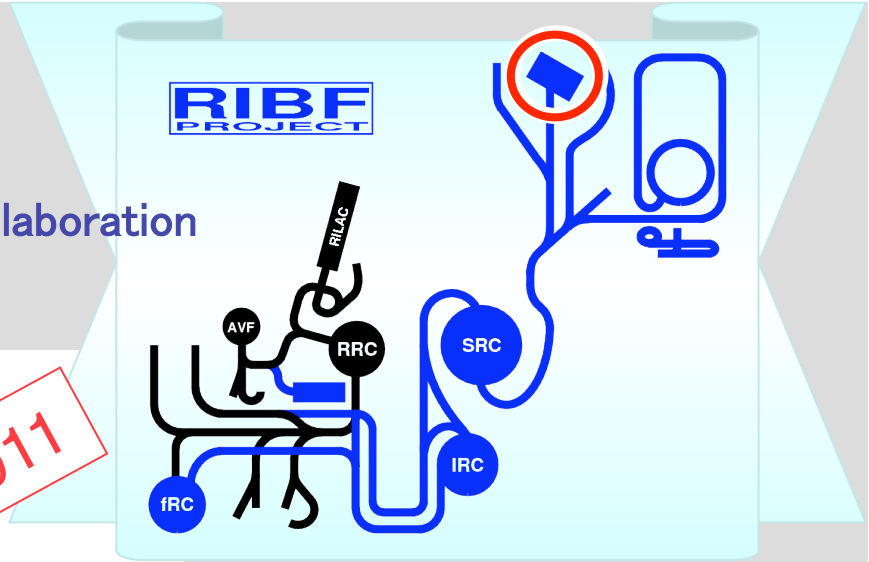


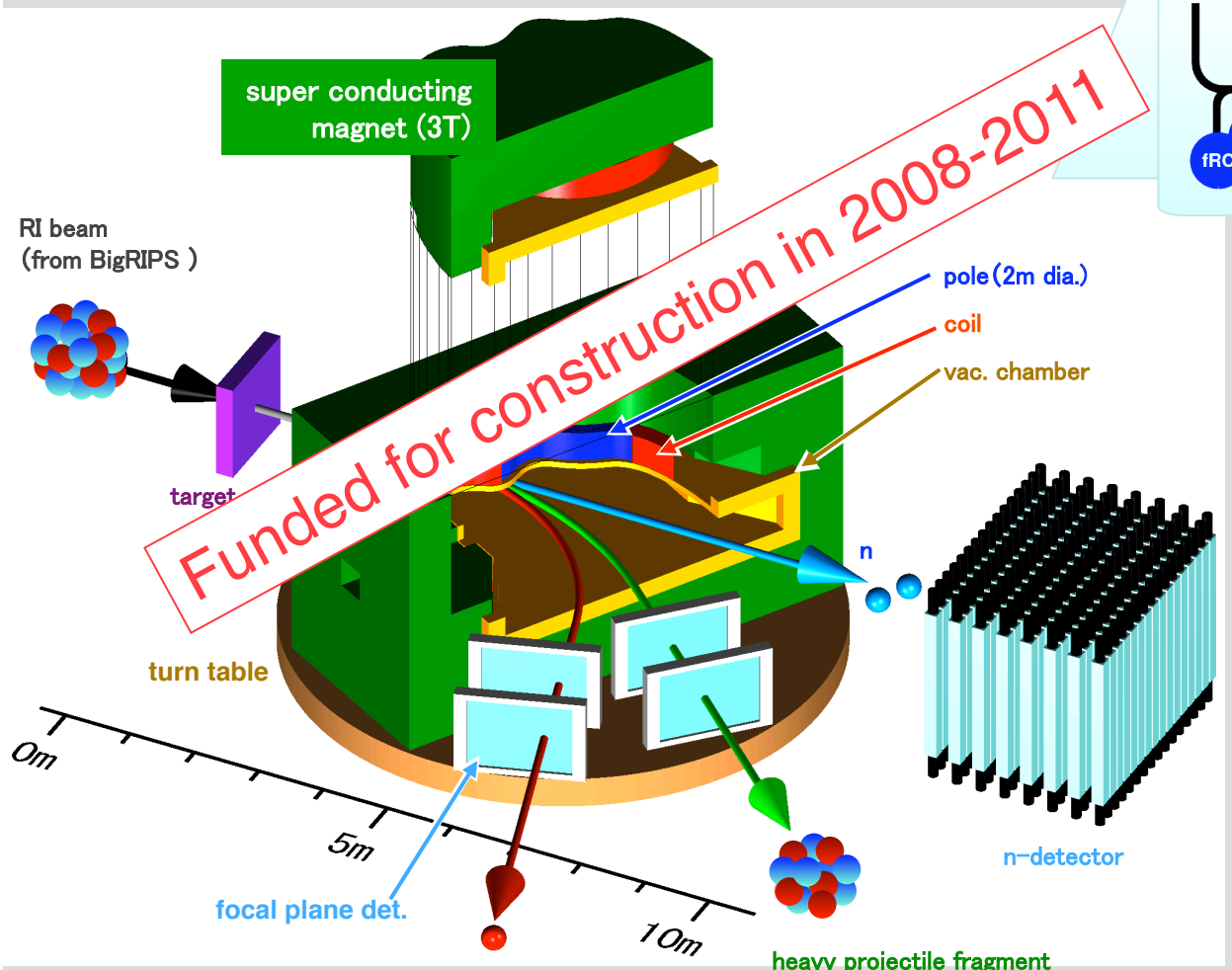


SAMURAI7

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), (2p,γ)
nucl. matter

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

Nov. 2008 Pisa

Summary / discussions

Nuclear reactions in astrophysical sites
- difficult-to-measure reactions (explosive burning)
- direct capture – resonant capture - statistical

Coulomb dissociation – inverse capture gamma
- a method for (p,γ) or (n,γ) near the drip line (direct and resonant captures)
- useful also for structure study of loosely bound nuclei
- pp (solar neutrino) / rp (Nova and X-ray burst) / r -limited cases

ANC determination by nuclear breakup
- another method (for direct capture)
- nuclear breakup for fast RI beam

(my) questions on theoretical treatments of breakup process
- "inelastic" and "knockout"
- three body nature
  - CDCC / possible extension of impulse approximation?
  - "genuine" 3 body or Faddeev approach?
    - c.f. Coulomb Faddeev calc.
      - ➔ 10% effect for 8B CD at 70 *A*MeV

RIKEN RI Beam Factory (RIBF)
- new facility: various RI beams with (hopefully) highest intensities
- structure studies, lifetime, mass … for r (rp) proceses
- nuclear reactions by CD and breakup (ANC) – light nuclei, near the drip lines
- pigmy resonances / GT strength …