

Investigation of the symmetry energy using electric dipole response of neutron-rich nuclei

Yasuhiro Togano
Tokyo Institute of Technology



Nuclear equation of state

$$\frac{E}{A}(\rho, \delta) = \frac{E}{A}(\rho, 0) + E_{sym}(\rho) \delta^2 + O(\delta^4)$$

$$\frac{E}{A}(\rho, 0) = \frac{E}{A}(\rho_0) + \frac{K_\infty}{2} x^2 + \dots$$

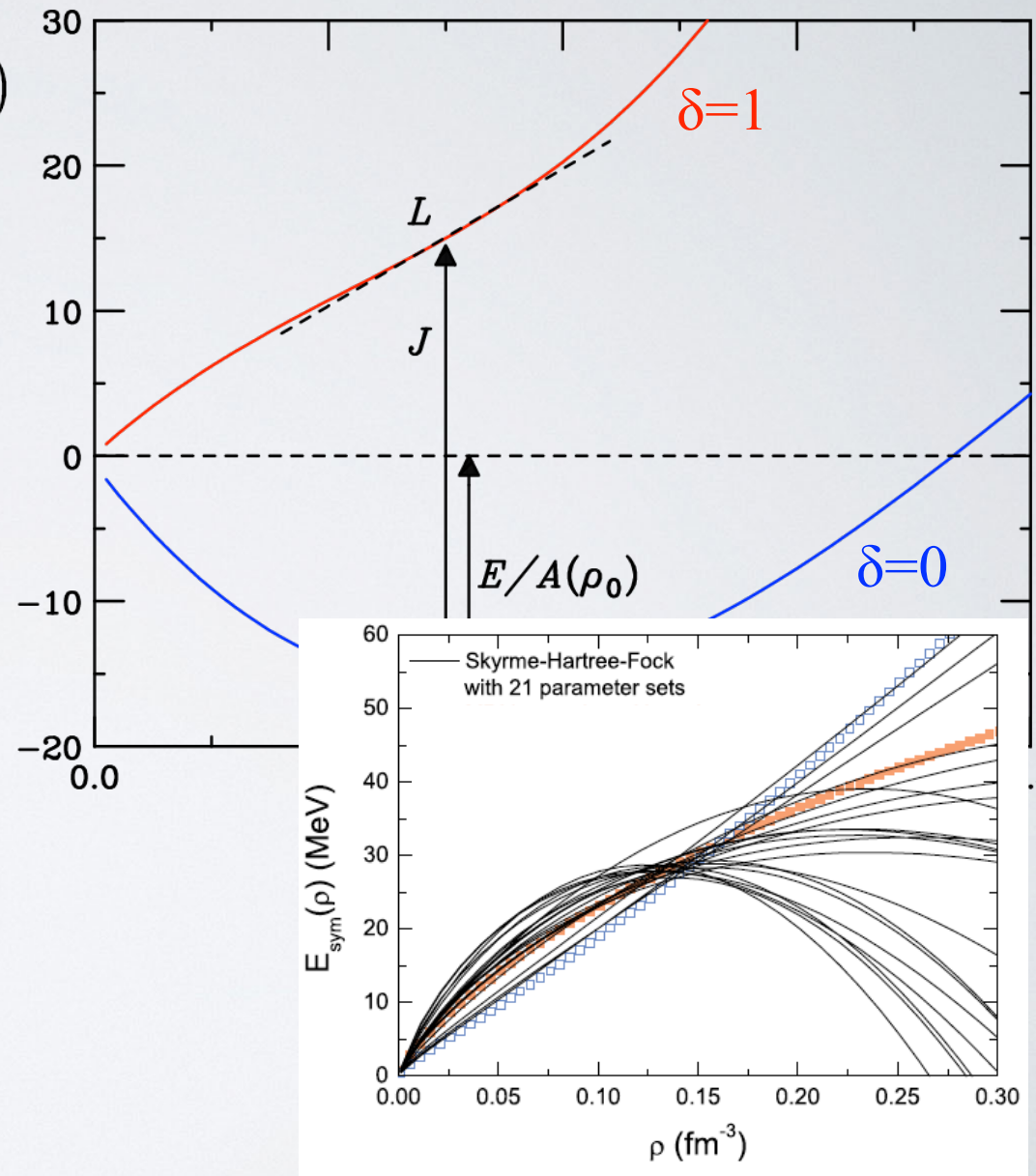
$$E_{sym}(\rho) = J + Lx + \frac{K_{sym}}{2} x^2 + \dots$$

$$\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p} \simeq \frac{N - Z}{A}, \quad x = \frac{\rho - \rho_0}{3\rho_0}$$

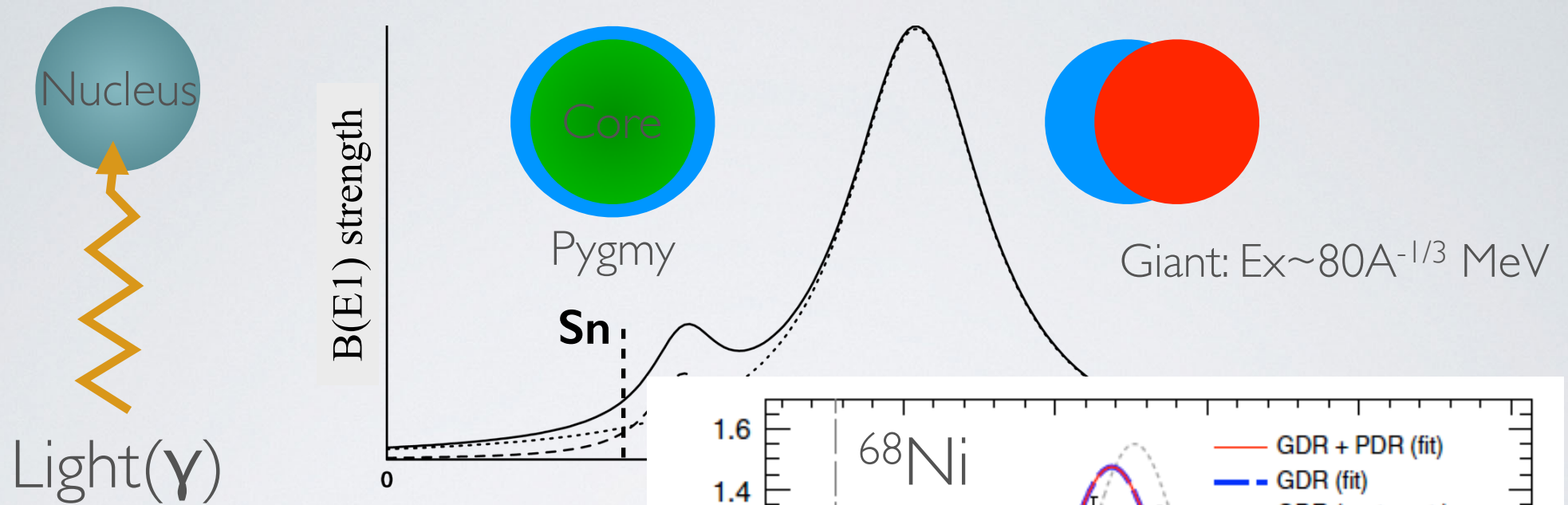
$$\frac{E}{A}(\rho_0) \sim 16 \text{ MeV}$$

$$J \sim 32 \text{ MeV} \quad \text{B. Tsang et al. PRC 86, 015803 (2012).}$$

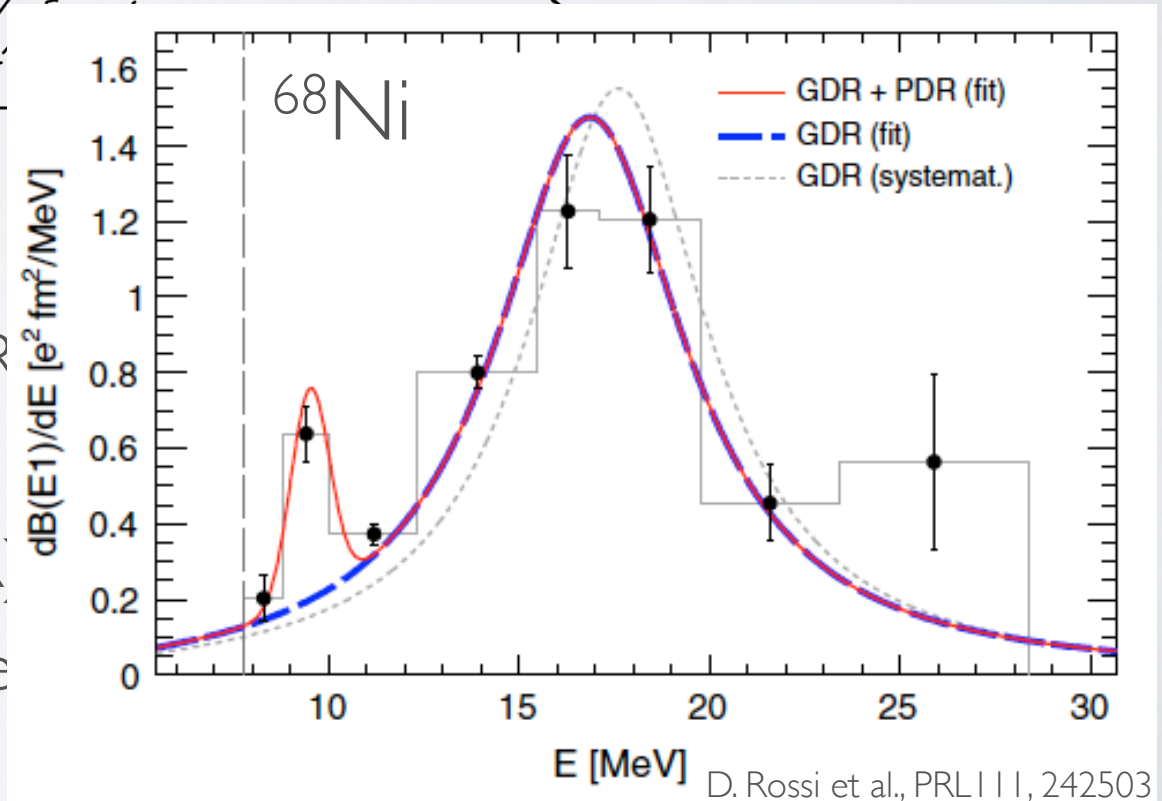
L: large uncertainty



E1 response of neutron-rich nuclei



- Pygmy dipole resonance (PDR)
 - Skin oscillation
- Giant dipole resonance (GDR)
 - Restoring force: symmetry energy



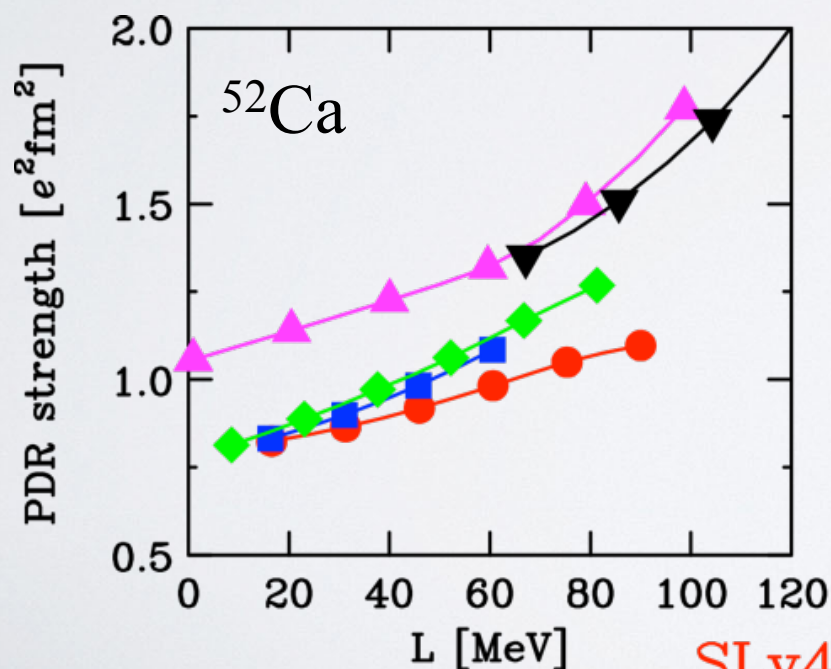
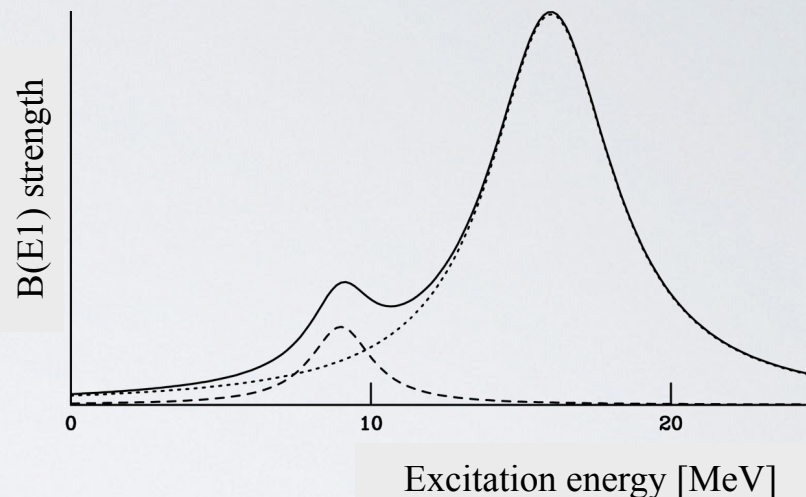
Correlation of E1 response

$$E_{sym}(\rho) = J + \textcolor{red}{L}x + \frac{K_{sym}}{2}x^2 + \dots$$



PDR strength

$$\alpha_D = \frac{8\pi}{9} \int \frac{dB(E1)}{\omega}$$



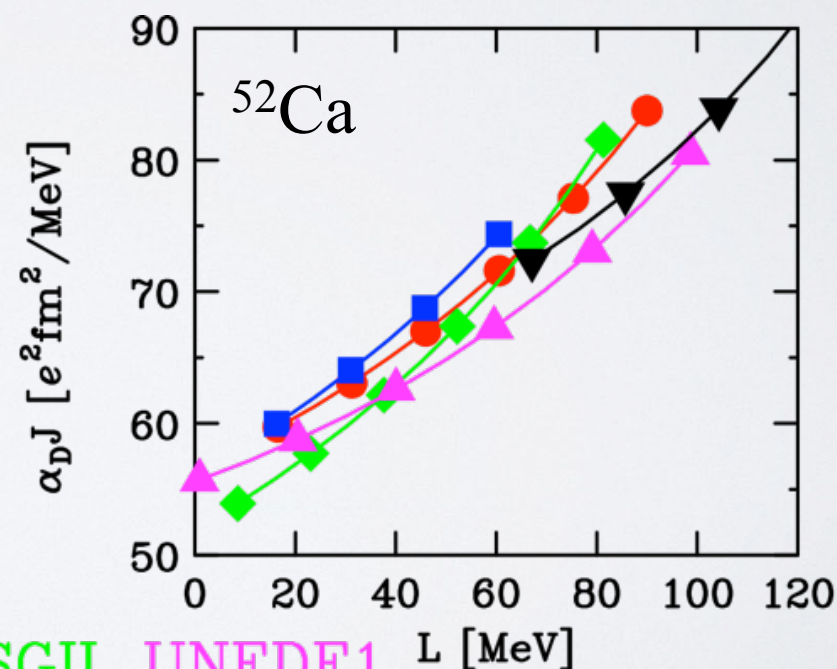
SLy4

SGII

UNEDF1

SkM*

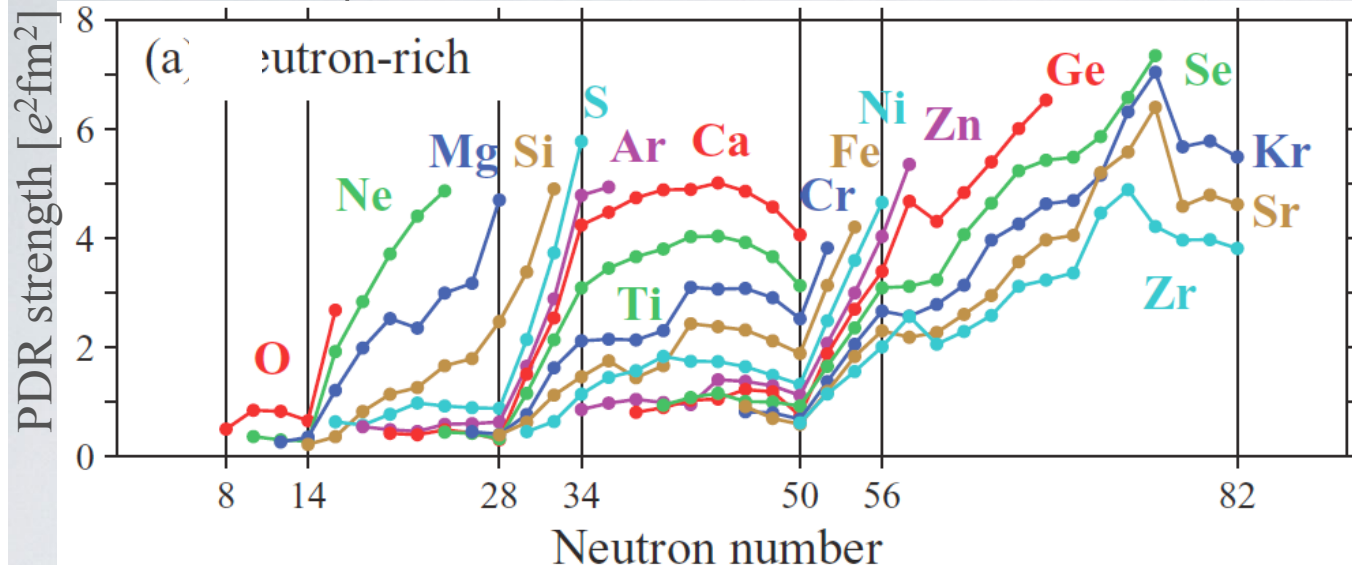
SkI2



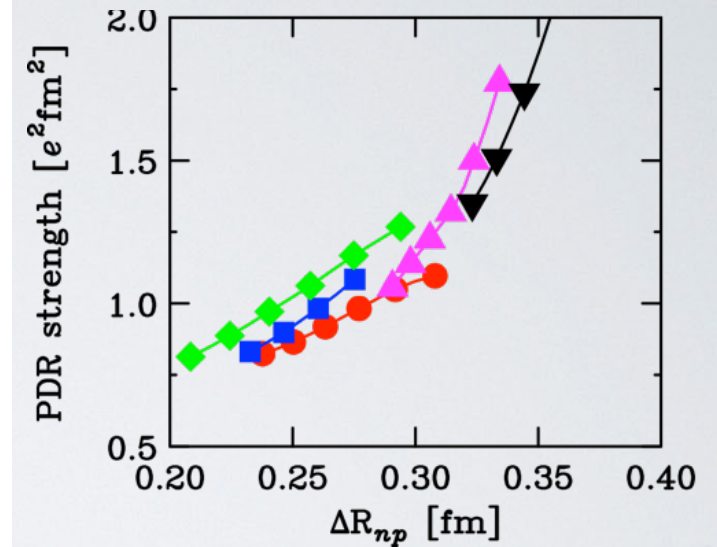
RPA calc. by Inakura-san

PDR strength of Ca isotopes

- Ca: Rapid increase at $N=28\sim 34$



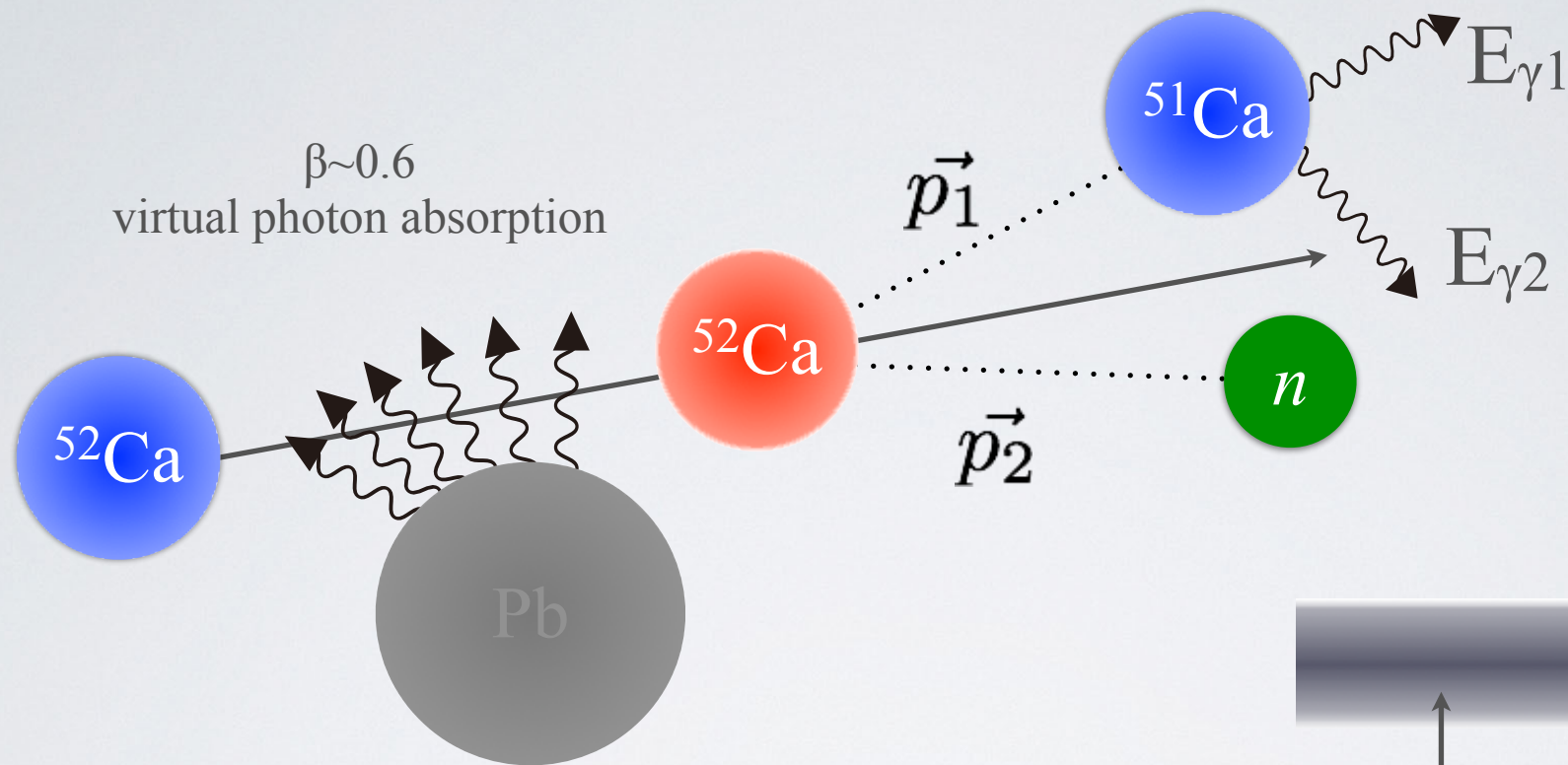
T. Inakura et al., PRC84, 021302 (2011)



El response of $^{48-52}\text{Ca}$

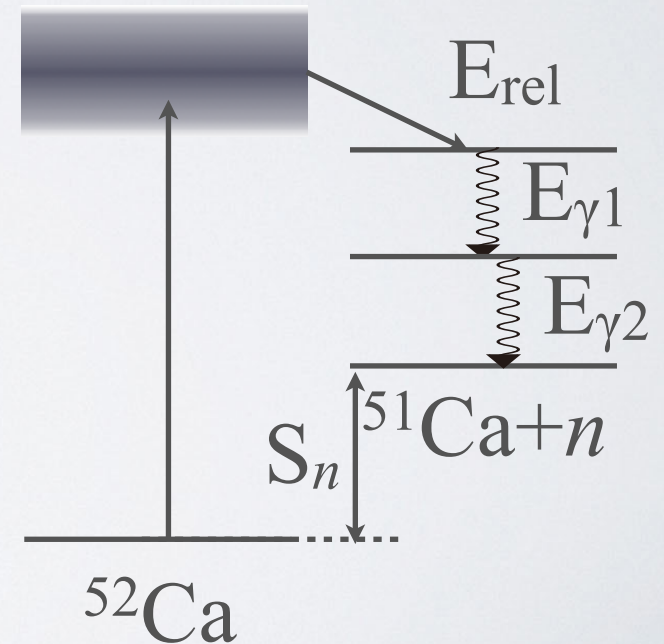
- Evolution of PDR
- Evolution of skin at $2p$ orbital
- Restriction of L

Coulomb excitation and invariant mass method

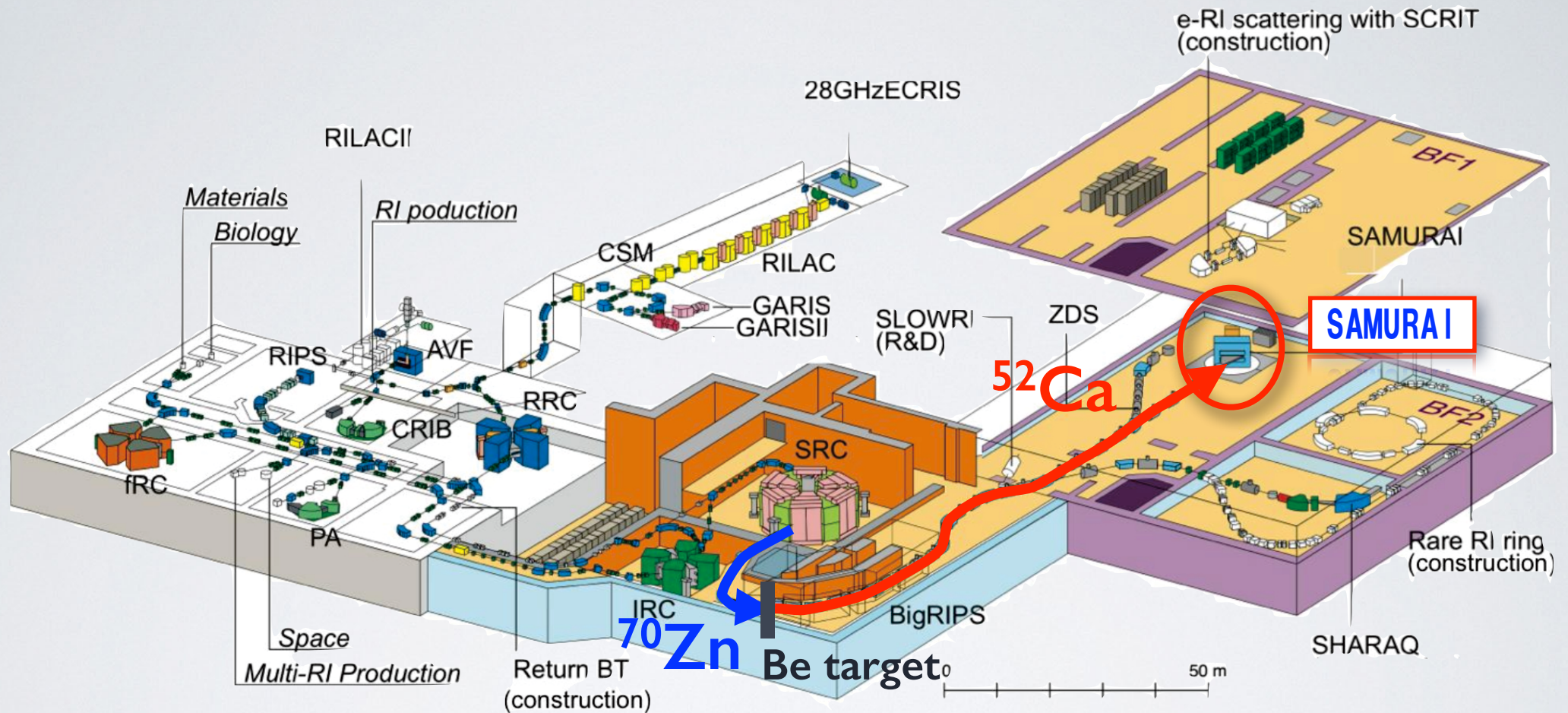


$$E_{rel} = \sqrt{\left(\sum E_i\right)^2 + \left(\sum \vec{p}_i\right)^2} - (m_{^{51}\text{Ca}} + m_n)$$

$$E_x = E_{rel} + S_n + \sum E_{\gamma i}$$

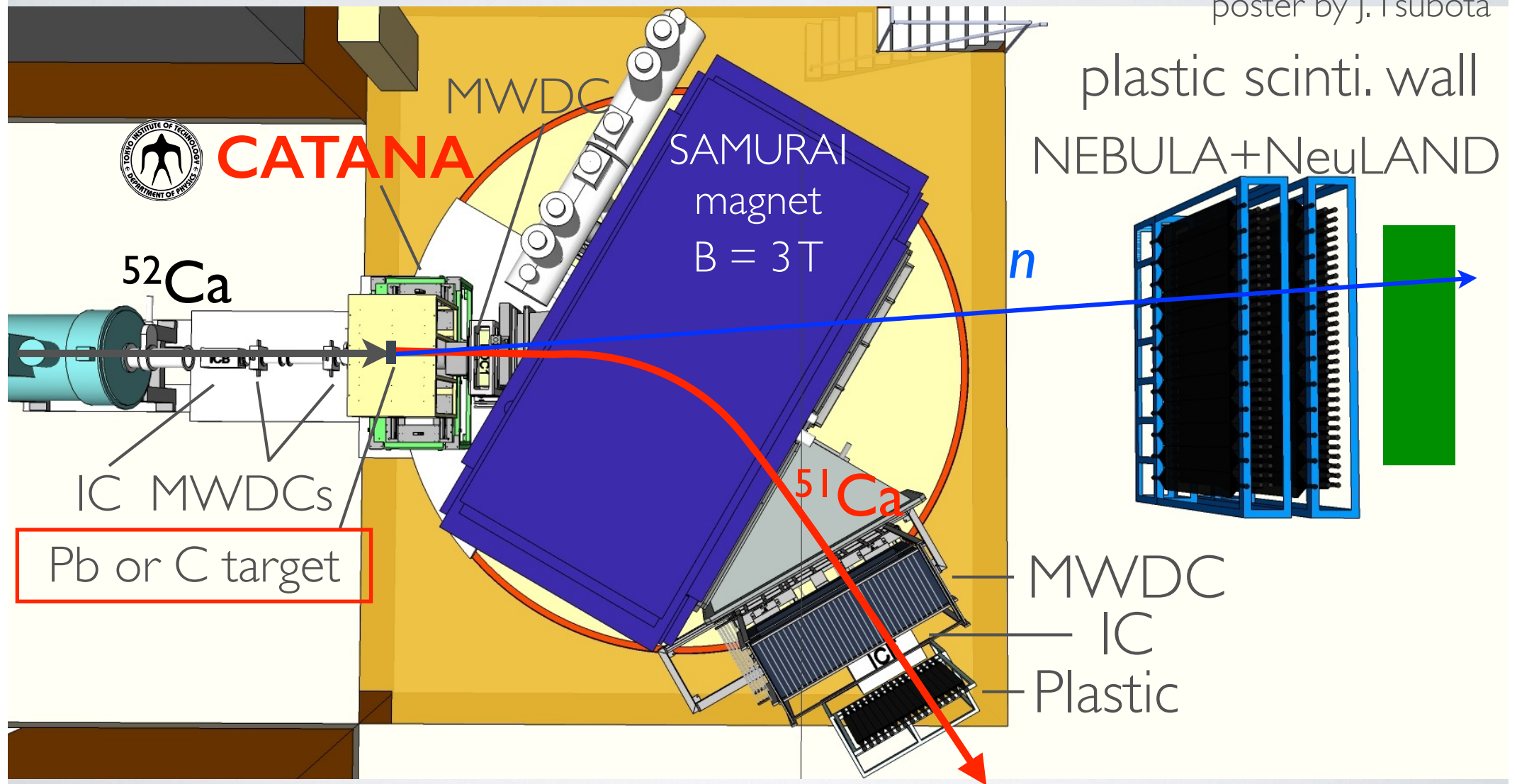


RIKEN Nishina Center



$^{70}\text{Zn}@ 345 \text{ MeV/nucleon } (\sim 5 \times 10^{11} \text{ Hz})$
 $\rightarrow ^{48,50,52}\text{Ca}(10^2 \sim 10^4 \text{ Hz})@ 250 \text{ MeV/nucleon}$

SAMURAI setup

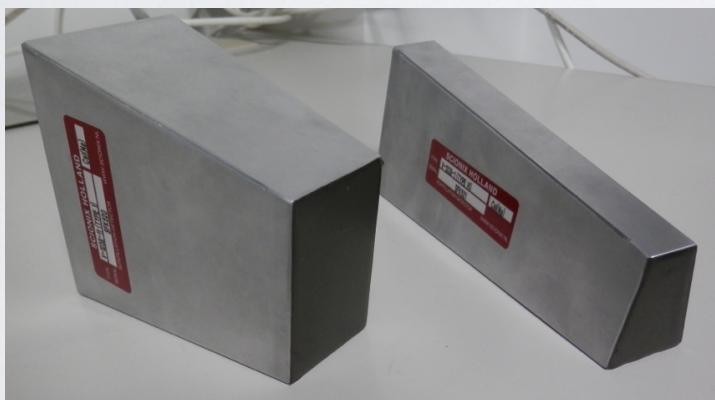




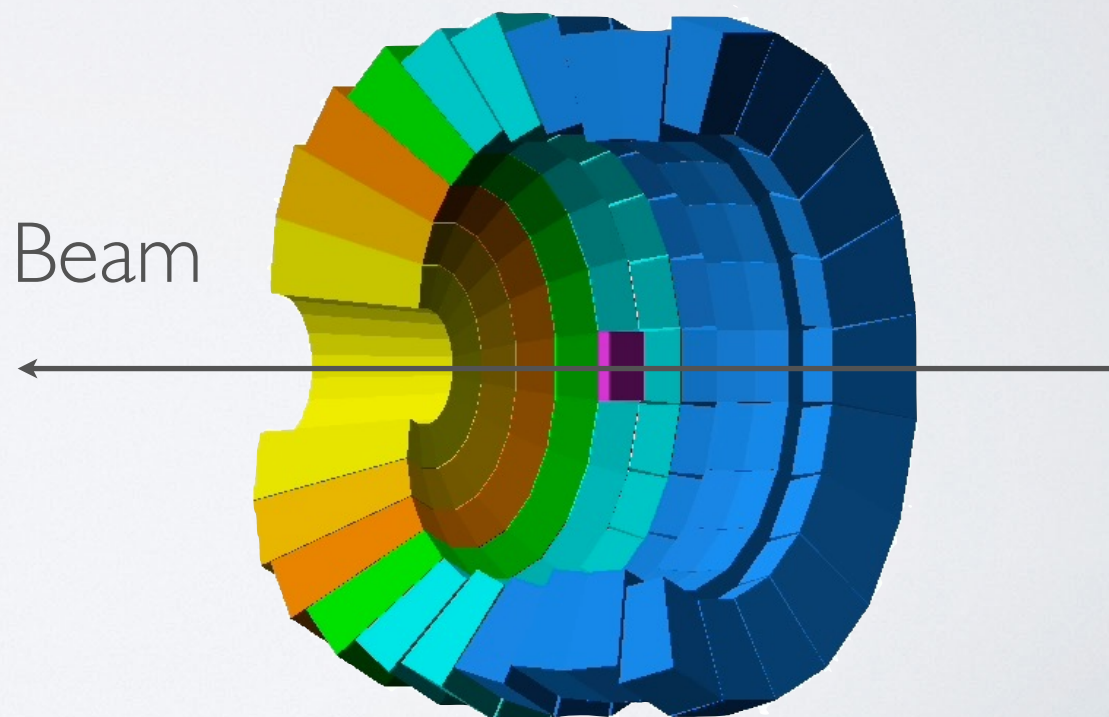
CATANA

Calorimeter for γ -ray **T**ransitions in
Atomistic **N**uclei at high isospin **A**symmetry

- High detection efficiency: 56% for 1 MeV, $\sim 35\%$ for 10 MeV
 - CsI(Na)
 - housing: 0.5 mm Al



prototype CsI(Na) crystals



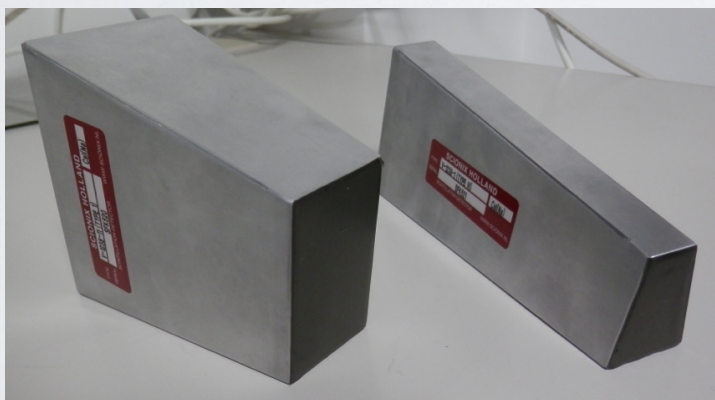
Complete in 2015 summer



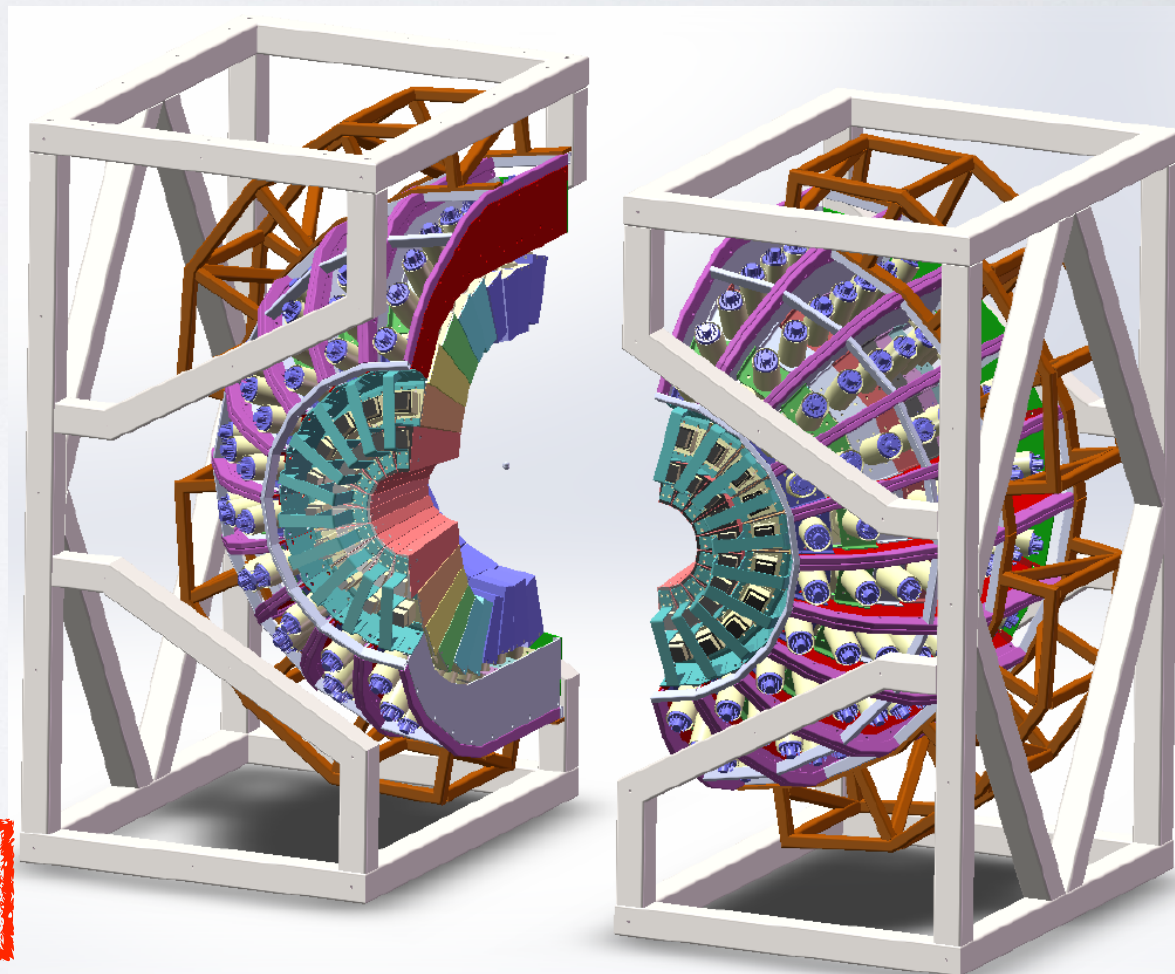
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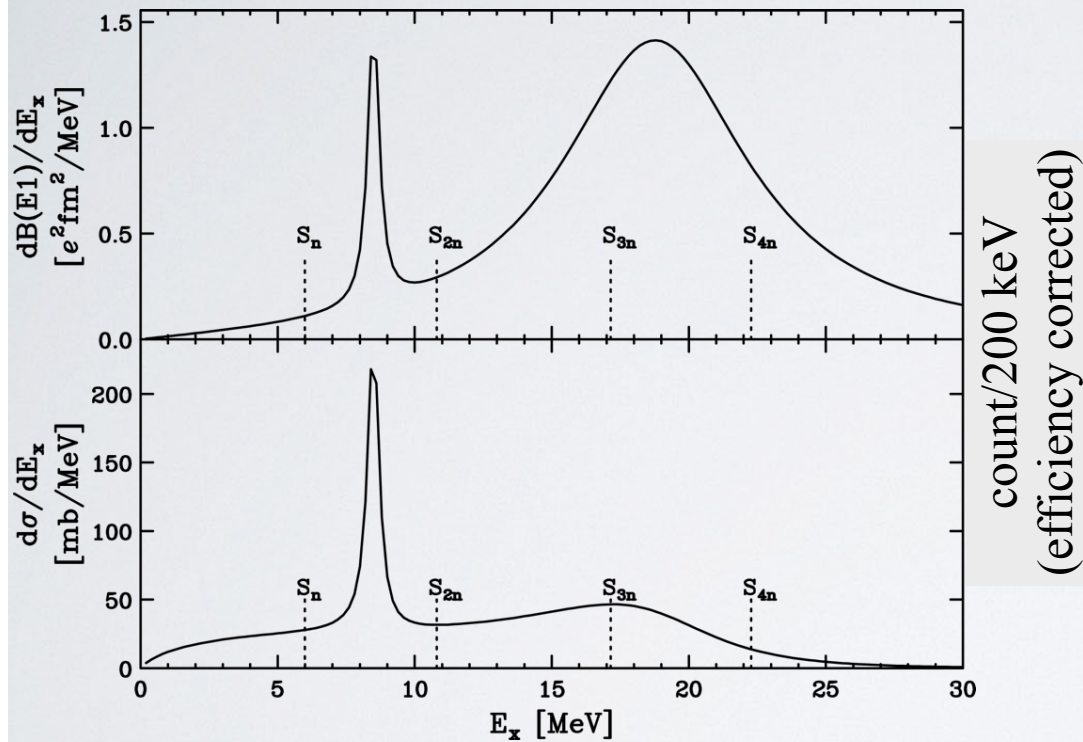
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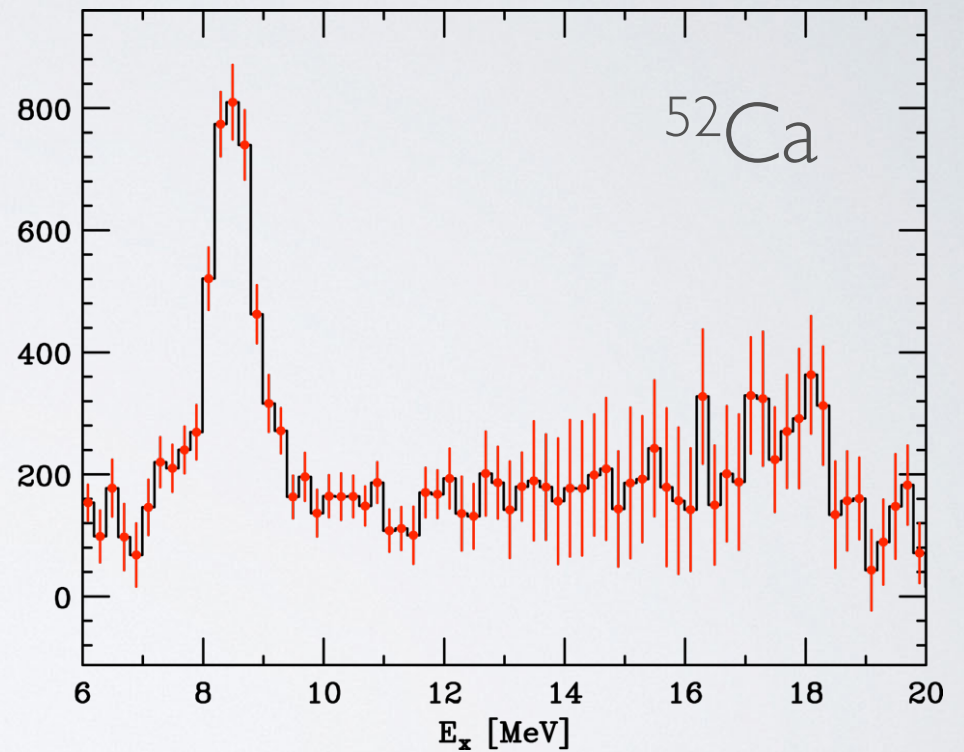
Complete in 2015 summer

Ex reconstruction

- B(E1)dist. : PDR + GDR



Simulation



7 days beam time approved at RIKEN

Summary

- El response of $^{48-52}\text{Ca}$
 - Evolution of PDR and information on the symmetry energy
- CATANA construction is ongoing
 - Design and specification finalized
- Experiment: late 2015