Symmetry energy and electric dipole response of neutron-rich nuclei

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Contents

- Introduction
- Previous researches
- Future plan
- Recent experimental results
- Related topics

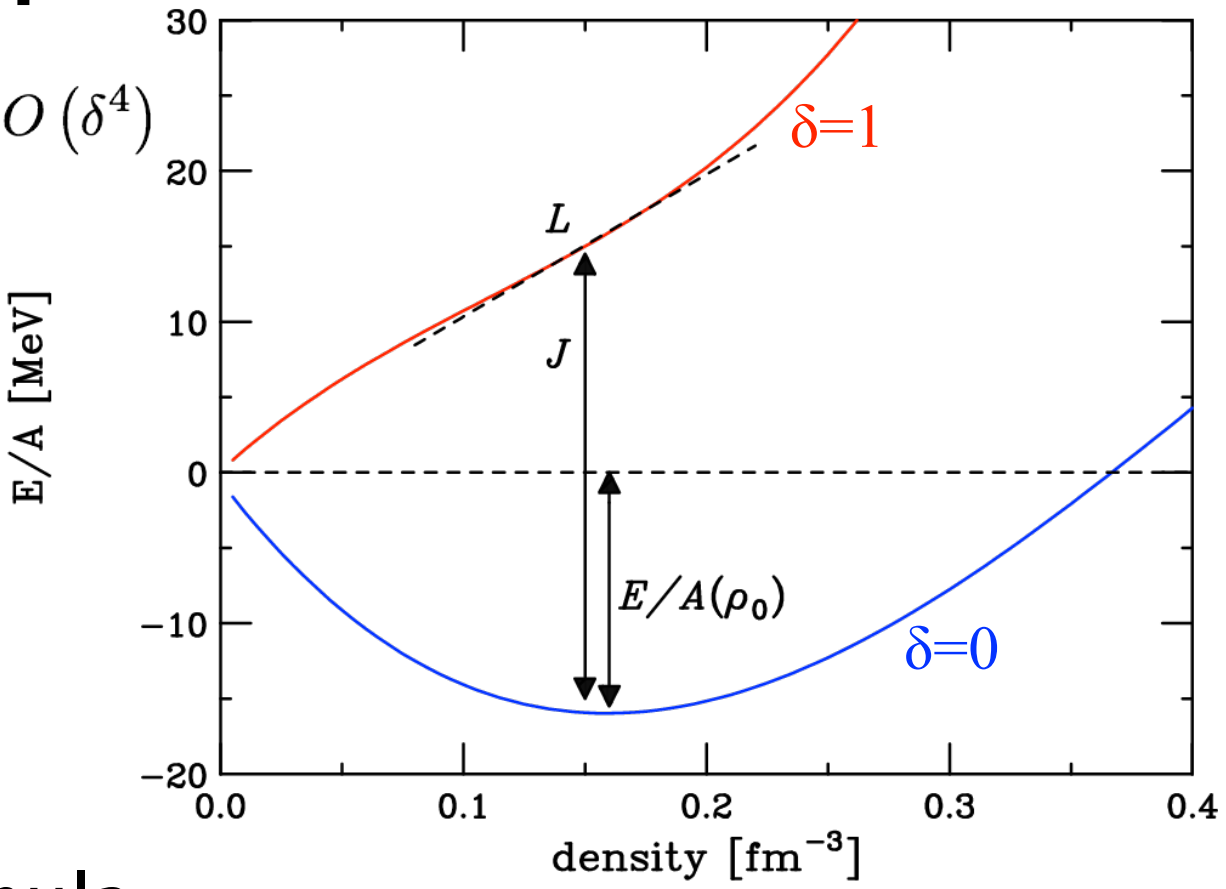
Nuclear equation of state

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

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

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

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



Bethe-Weizsäcker's formula

$$\frac{B(N,Z)}{A} = a_{vol} - \frac{a_{surf}}{A^{1/3}} - a_{coul}\frac{Z^2}{A^{4/3}} - a_{sym}\frac{(N-Z)^2}{A^2} + \ldots$$

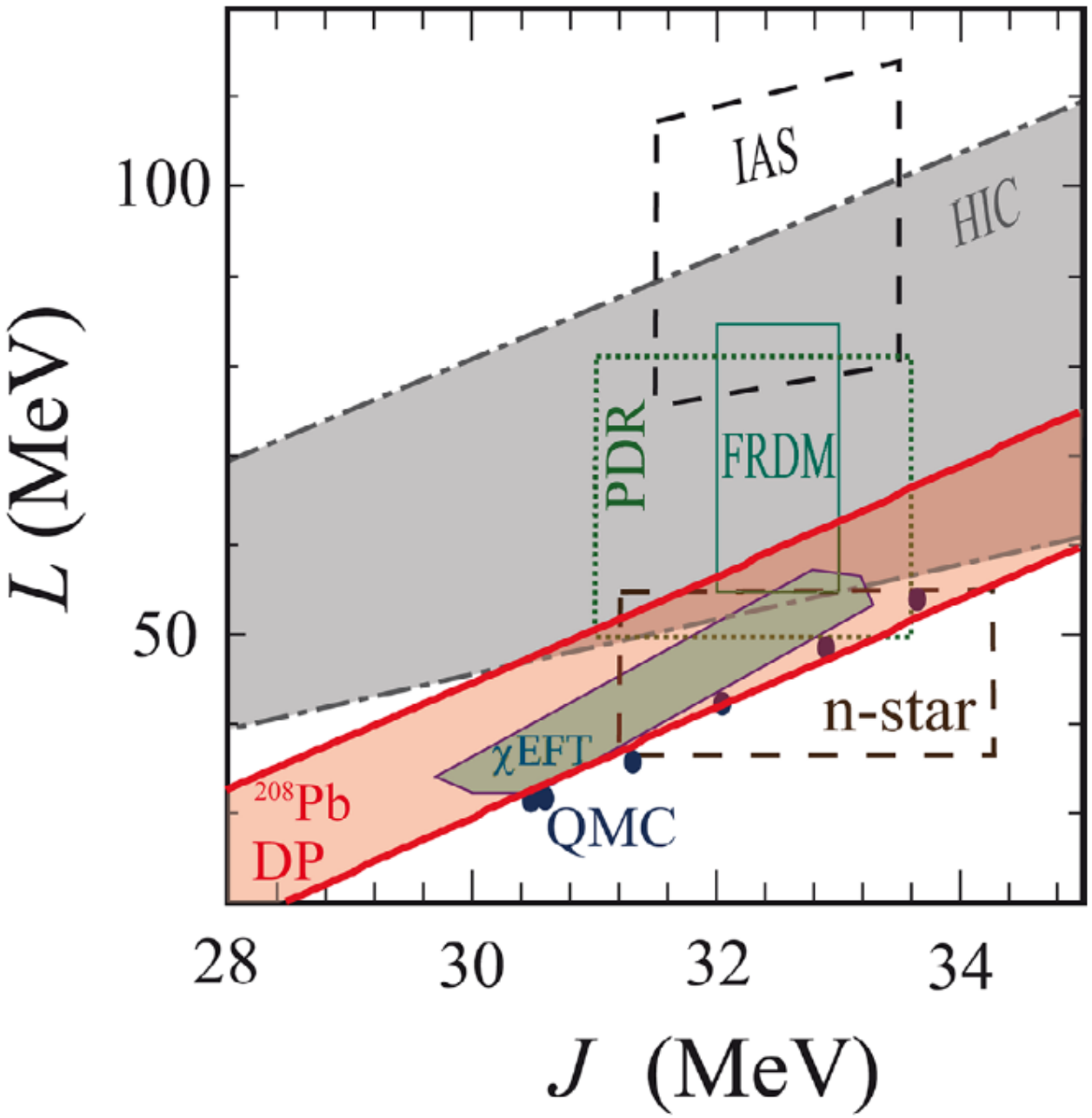
$$\frac{E}{A}(\rho_0) \simeq a_{vol} \sim 16\,\mathrm{MeV}$$

$$J \simeq a_{sym} + a_{vol} \sim 32\,\mathrm{MeV}$$

L: Large uncertainty

M. B. Tsang et al., PRC 86, 015803

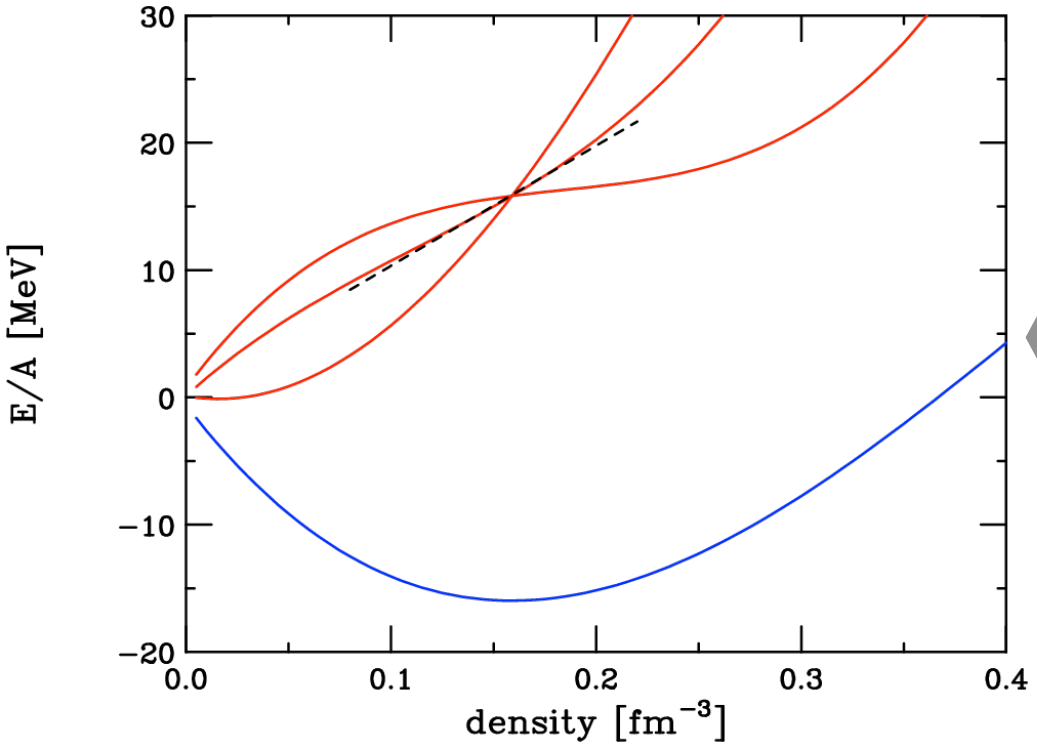
Status of L and J

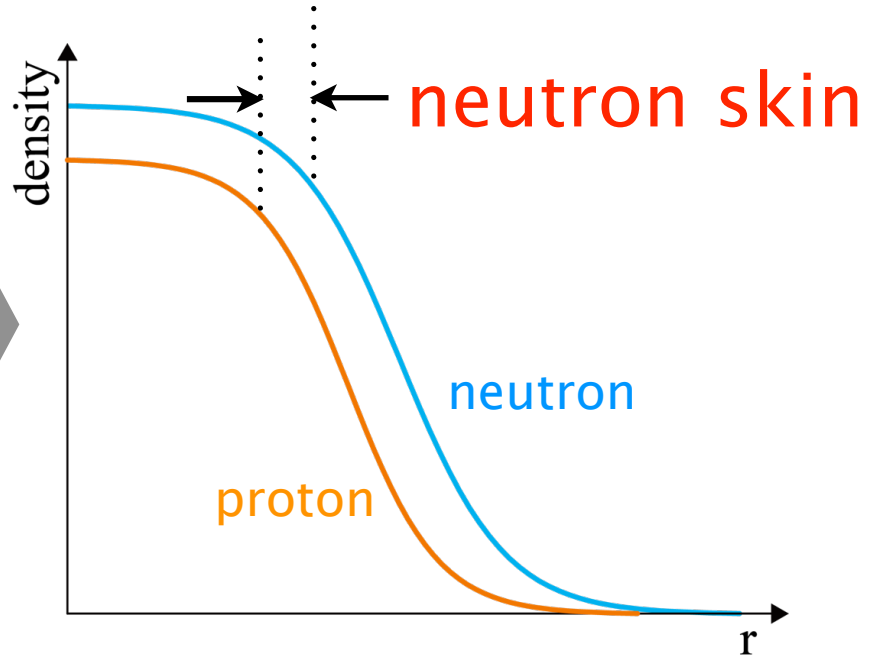


IAS: Isobaric analog state
HIC: Heavy Ion Collision
PDR: Pygmy dipole resonance
FRDM: Finite Range Droplet Model
n-star: neutron star observation
cEFT: Chiral Effective Field Theory
QMC: Quantum Monte-Carlo
DP: Dipole polarizability

A. Tamii et al., EPJA 50, 28 (2014)

L and neutron skin

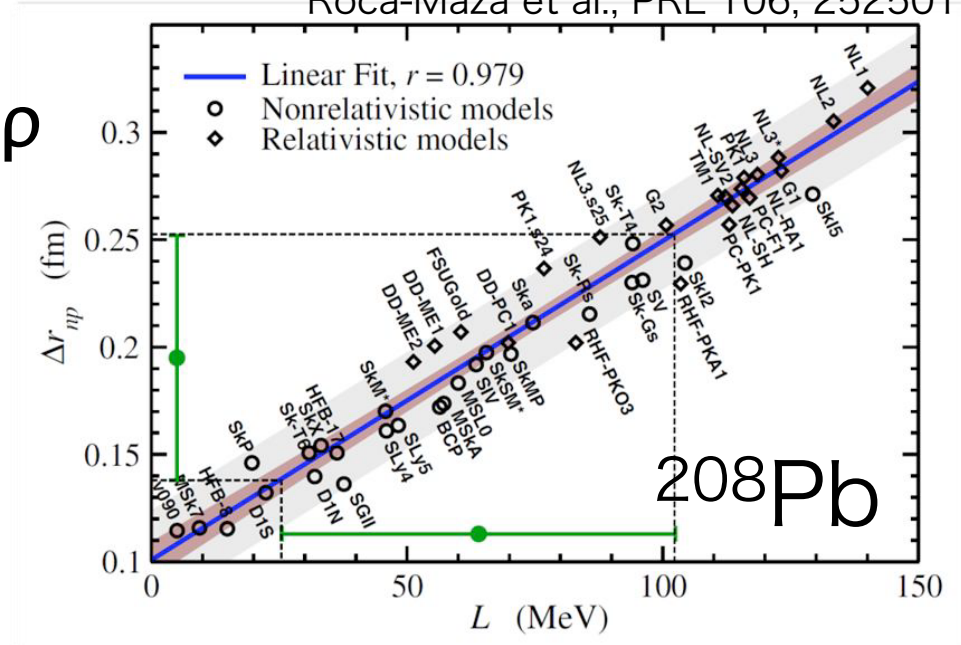




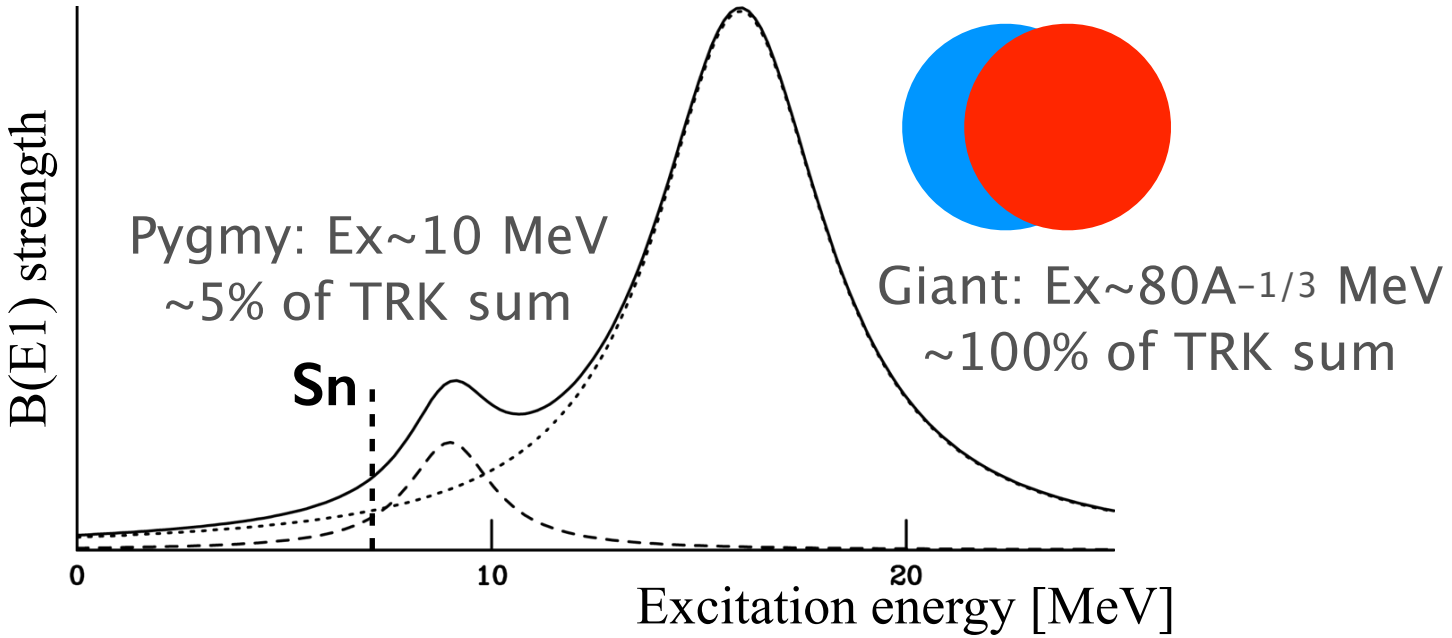
Large L → Small Esym in low-ρ

→ Thick n-skin

Roca-Maza et al., PRL 106, 252501



E1 response of neutron-rich nuclei



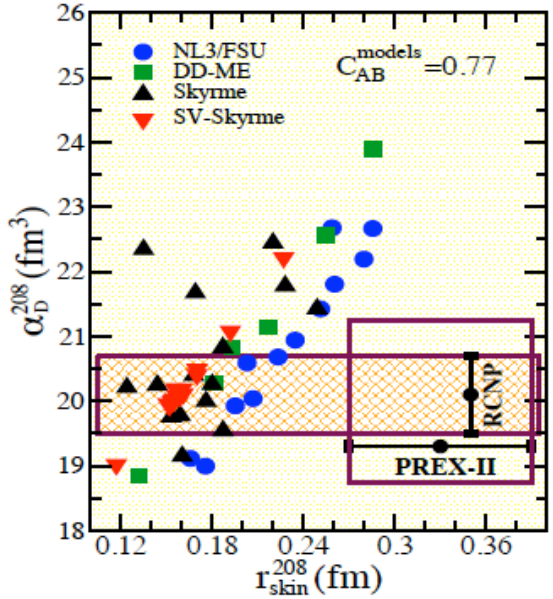
- Giant dipole resonance (GDR): All stable nuclei
  - Restoring force: symmetry energy
- Pygmy dipole resonance (PDR): Neutron-rich nuclei
  - ^{208}Pb, ^{132}Sn, ^{68}Ni etc…
  - Oscillation of neutron skin? → symmetry energy?

Dipole polarizability α_D

- Inversely energy weighted sum rule

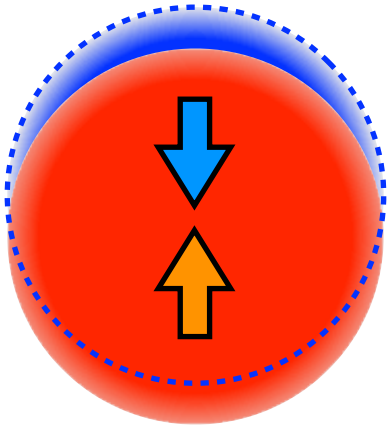
$$\alpha_D = \frac{\hbar c}{2\pi}\int \frac{\sigma_{abs}}{\omega^2}d\omega = \frac{8\pi}{9}\int \frac{dB(\mathrm{E1})}{\omega}$$

- polarizability due to E1 field



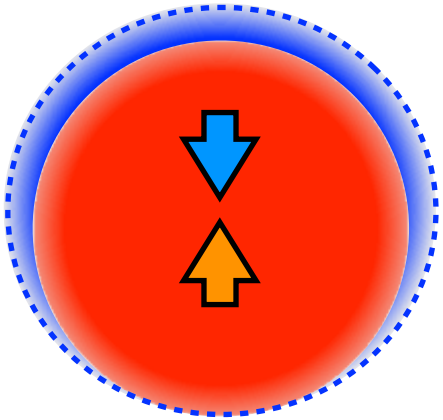
J. Piekarewicz, arXiv:1307.7746

Without skin



larger restoring force
→ smaller α_D

With skin

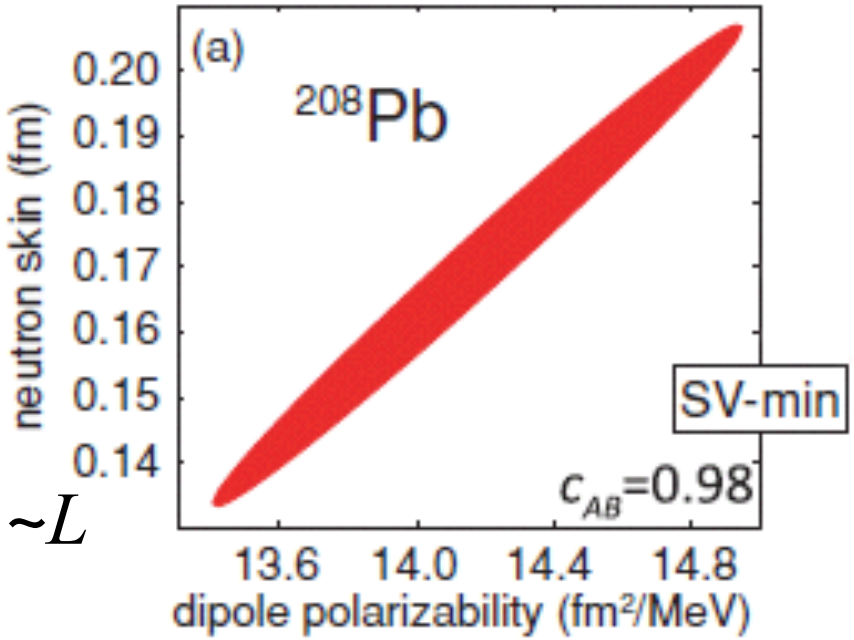


smaller restoring force
→ larger α_D

Previous research: ^{208}Pb

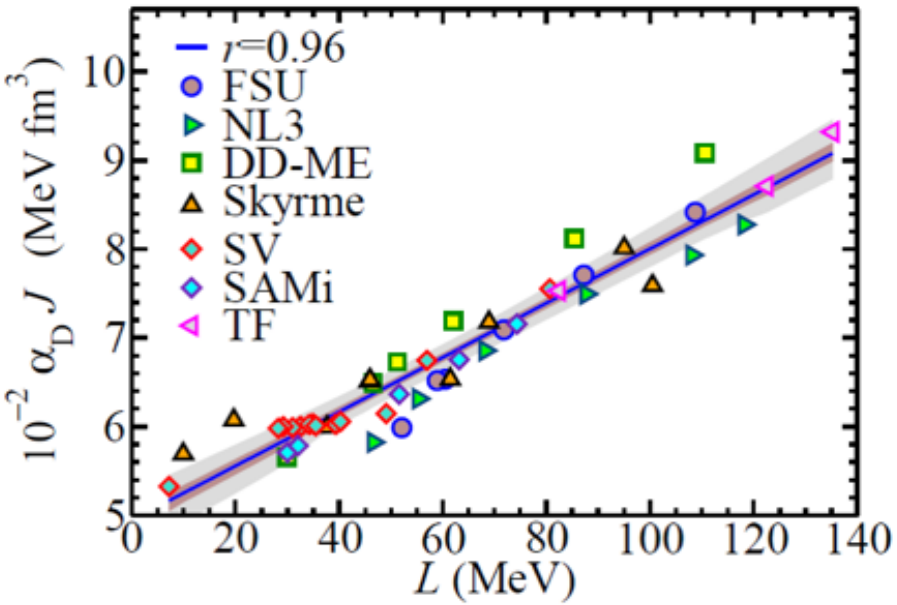
P. G. Reinhard and W. Nazarewicz, PRC 81, 051303

Covariance analysis of EDF calc.
→ Strong correlation



$\sim L$

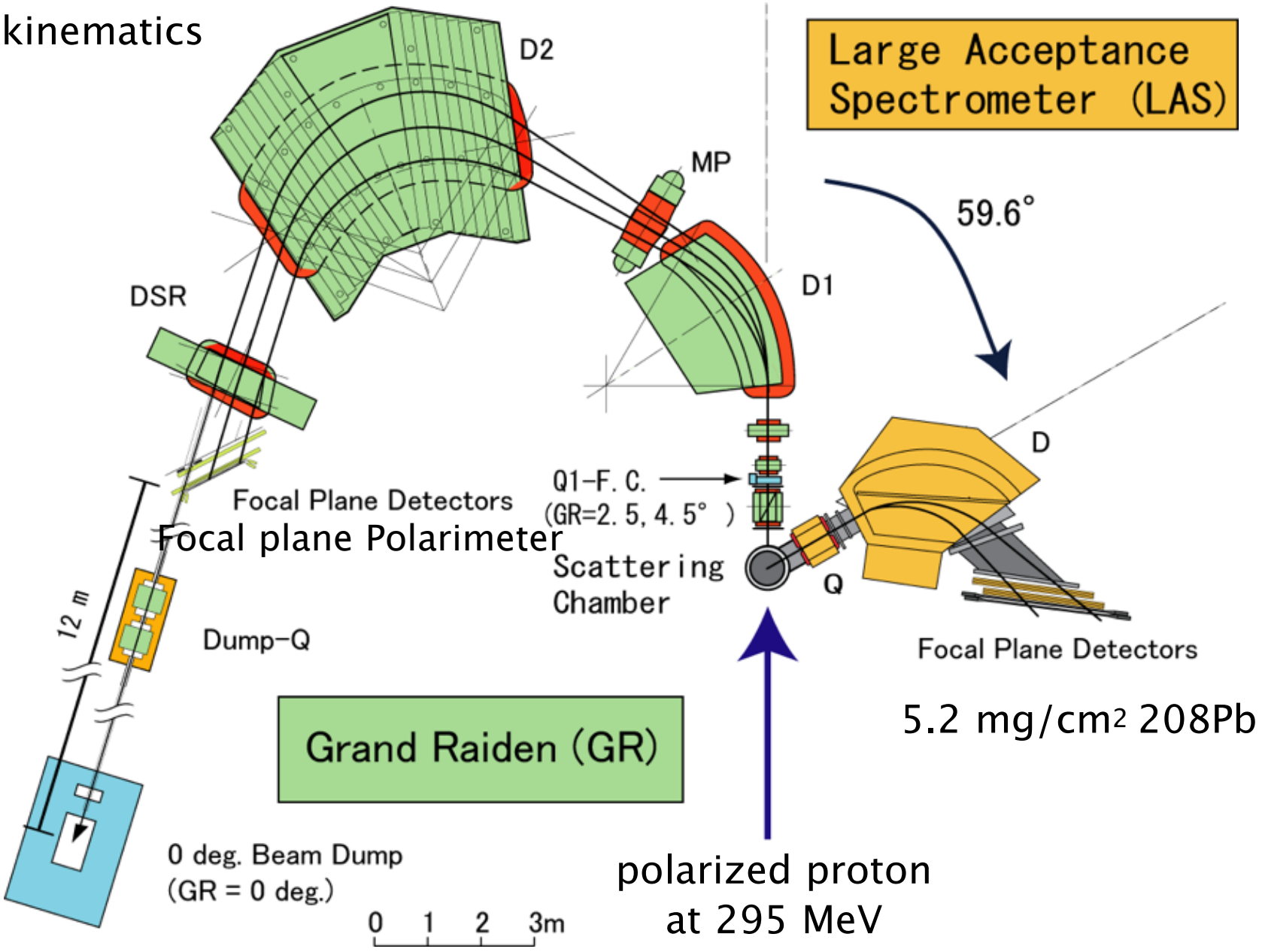
New correlation
← droplet model



X. Roca-Maza et al., PRC 88, 024316

Coulomb excitation of ^{208}Pb

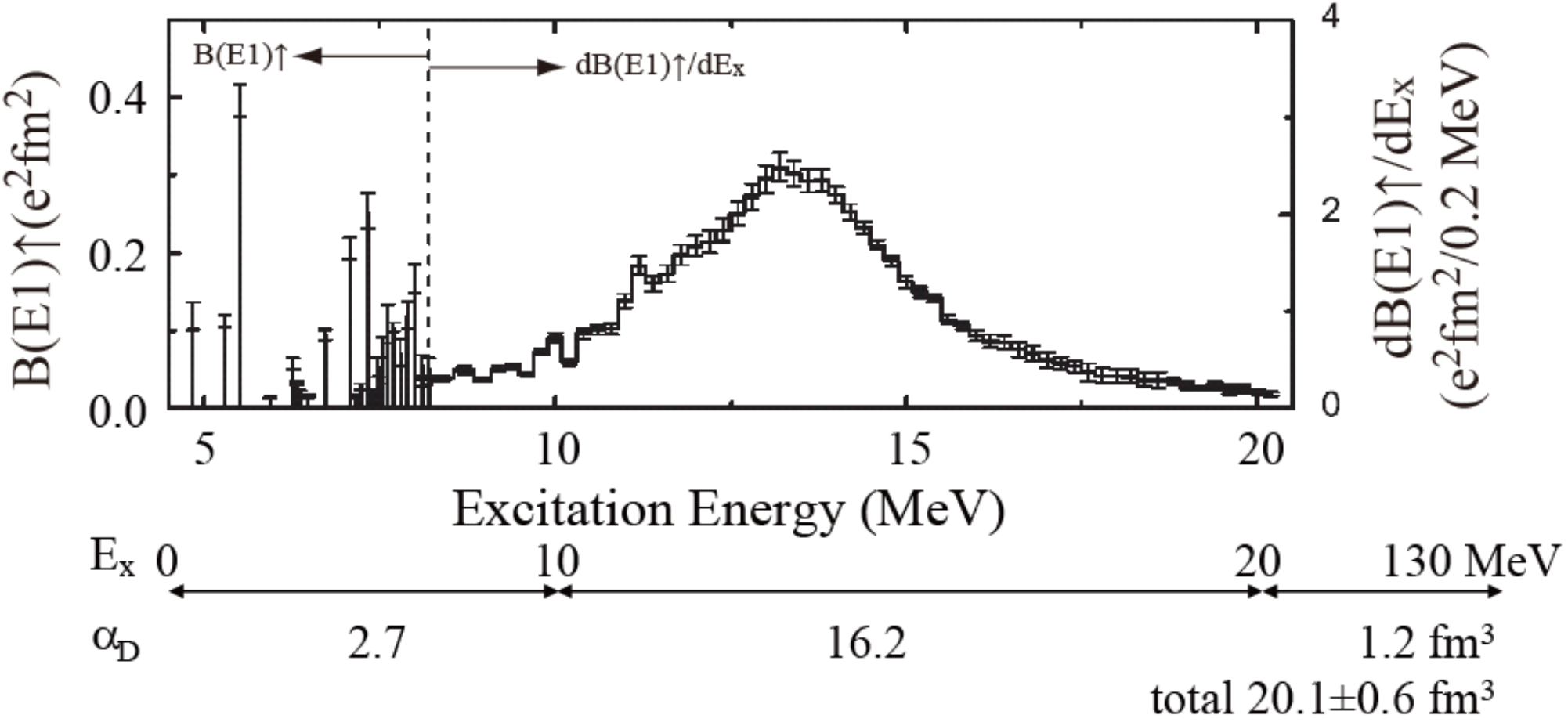
Normal kinematics



5.2 mg/cm^2 ^{208}Pb

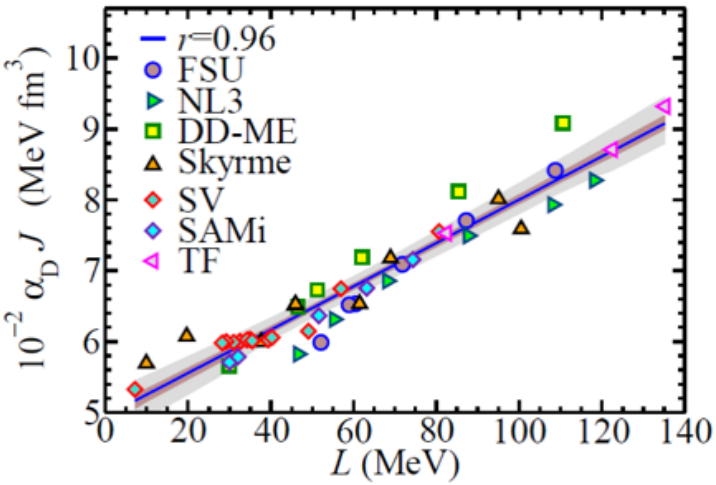
Dipole response of ^{208}Pb

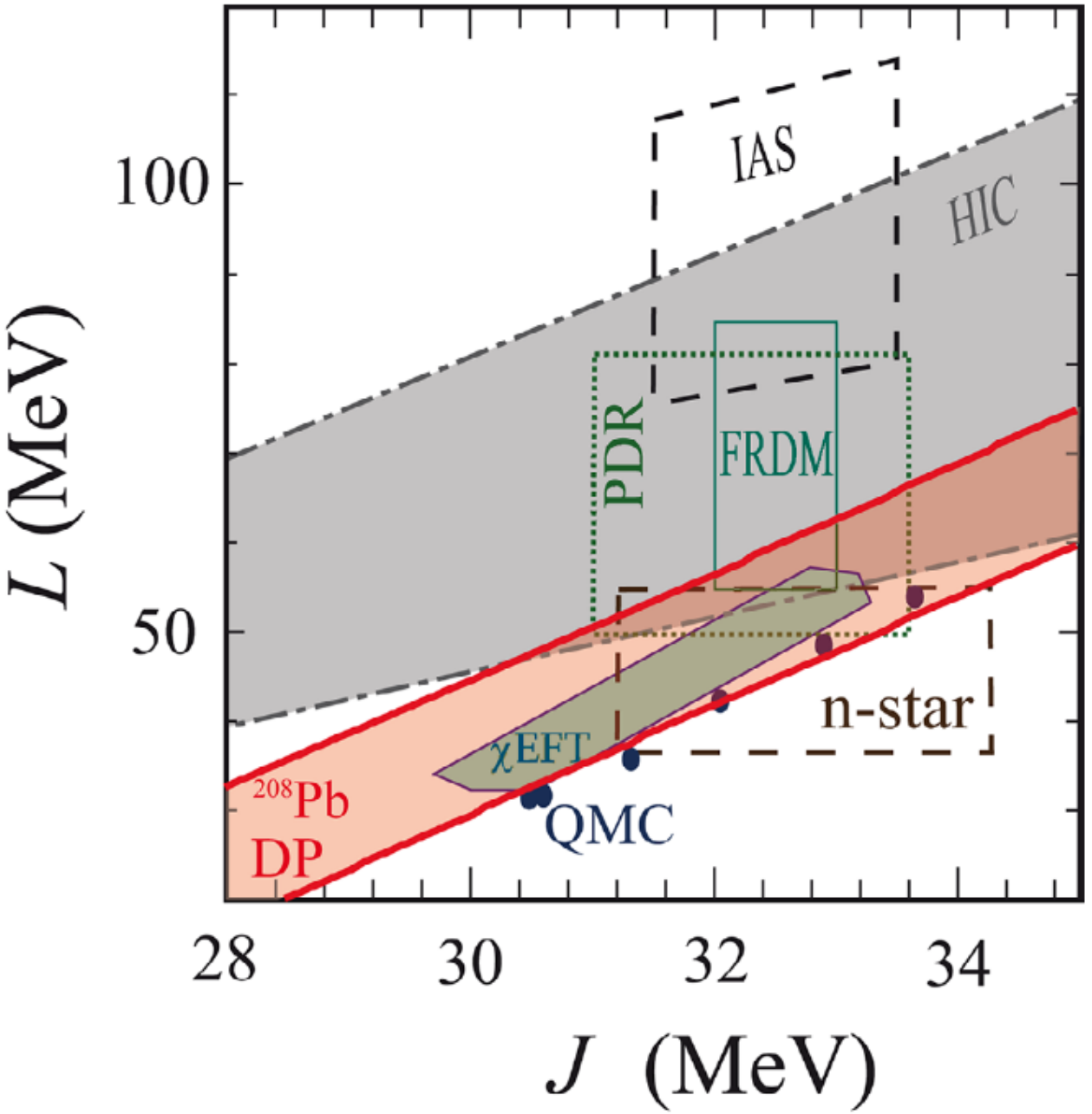
A. Tamii et al., PRL 107, 062502



Dipole response of ^{208}Pb

$\alpha_D = 20.1 \pm 0.6$ fm^3



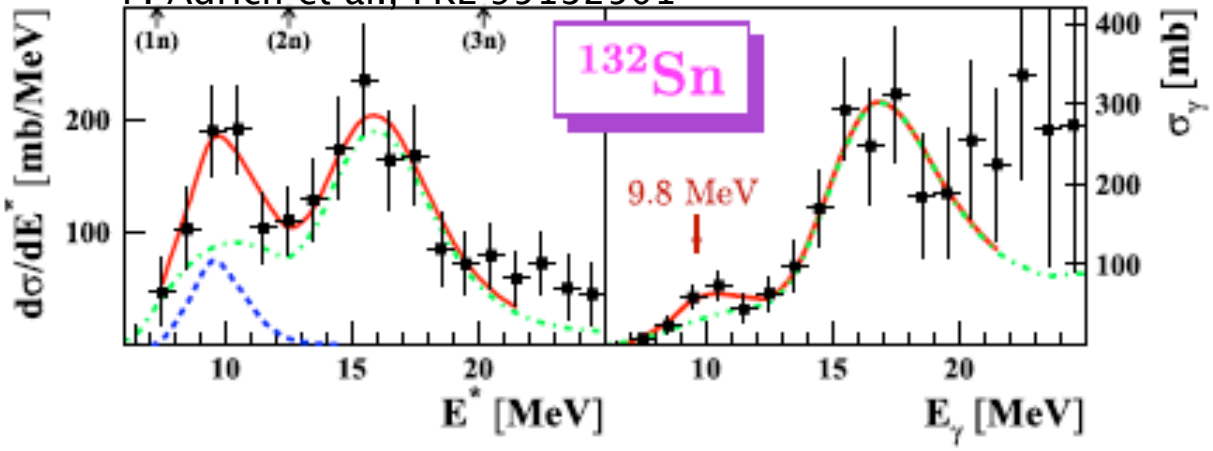


A. Tamii et al., EPJA 50, 28 (2014)

Symmetry energy and PDR

PDR of unstable ^{68}Ni and ^{132}Sn by Coulomb excitation

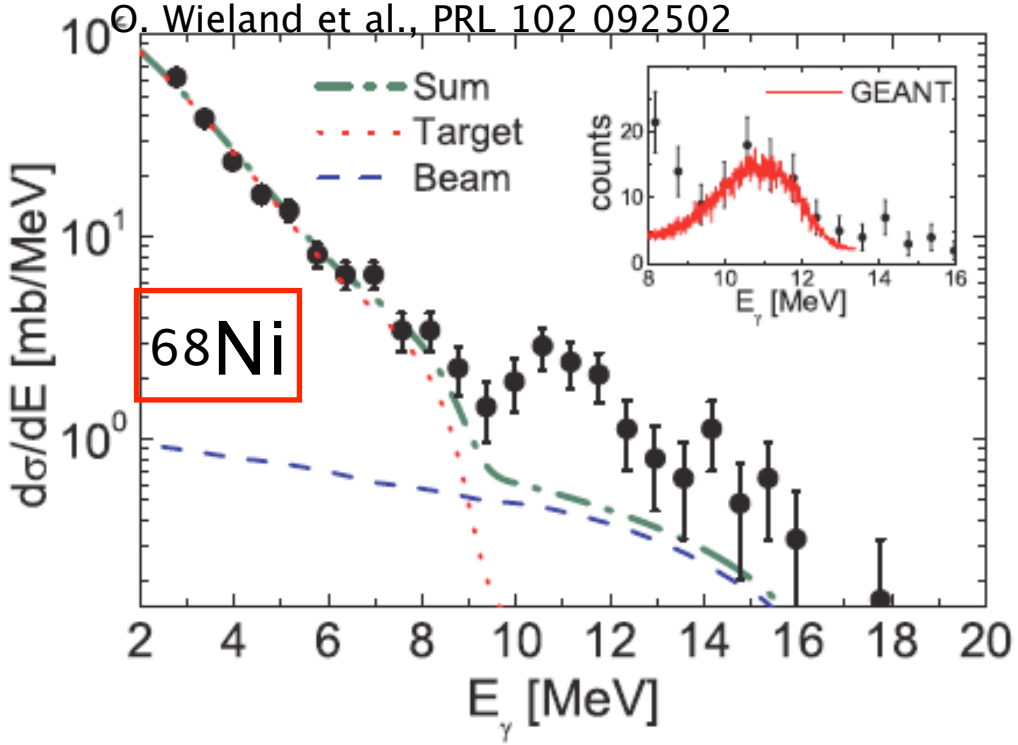
P. Adrich et al., PRL 95132501

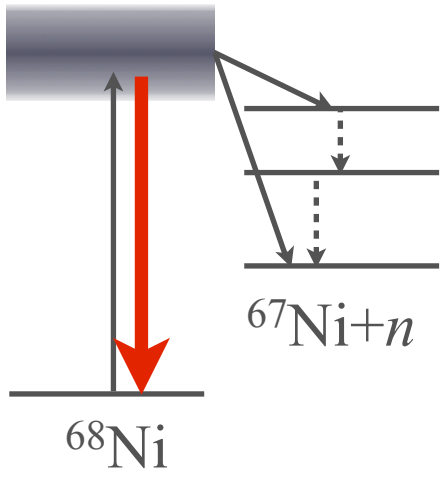


E_{PDR} = 9.8(7) MeV

S_{EWSR} = 4(3)%

O. Wieland et al., PRL 102 092502





E_{PDR} = 11 MeV

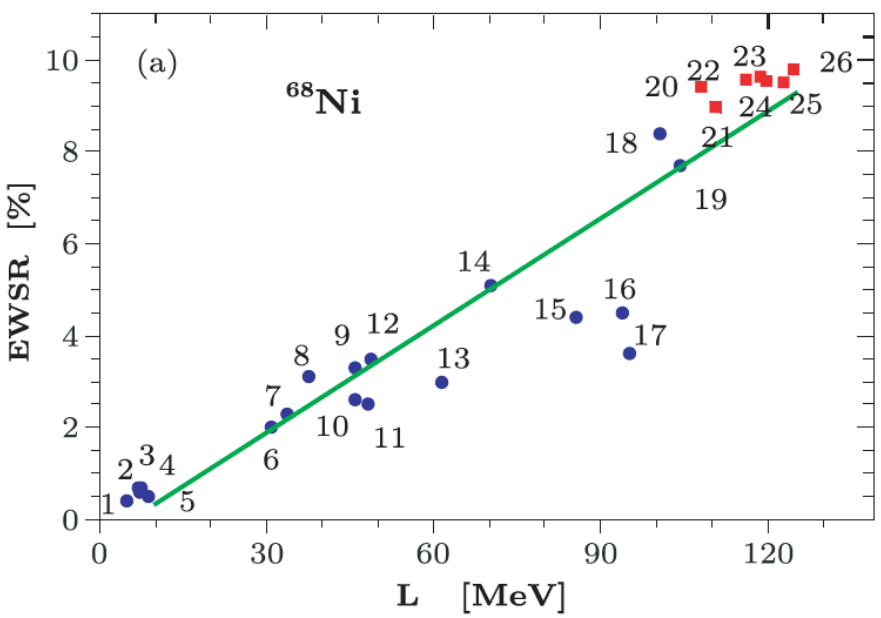
S_{EWSR} = 5%

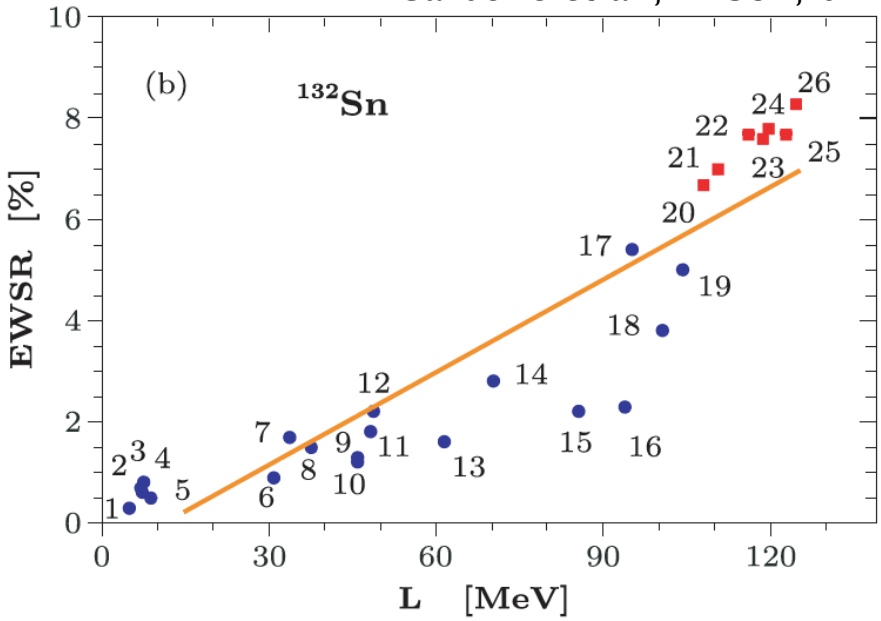
branching ratio = 4%

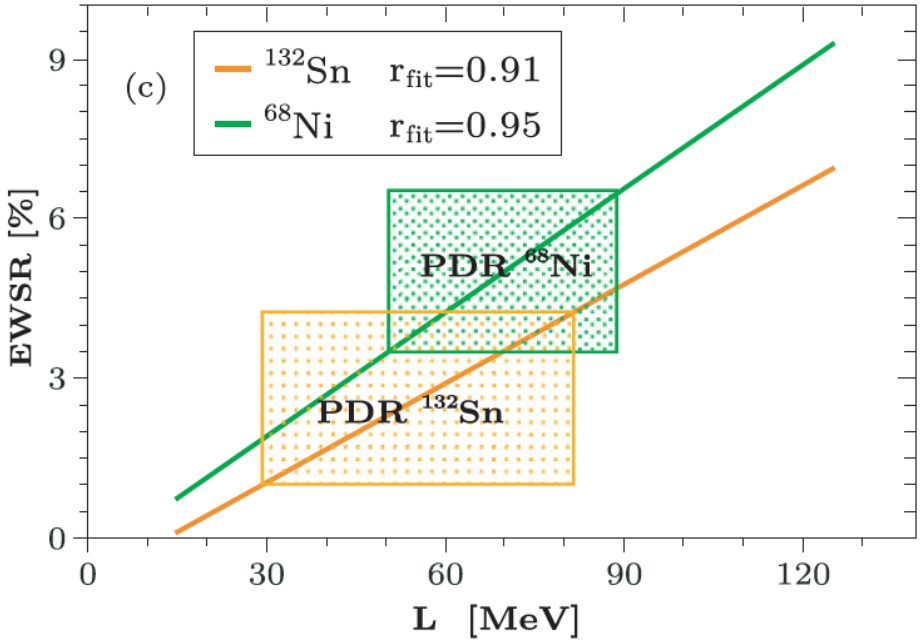
Symmetry energy and PDR

- relativistic EDF calculation

A. Carbone et al., PRC81, 041301(R)

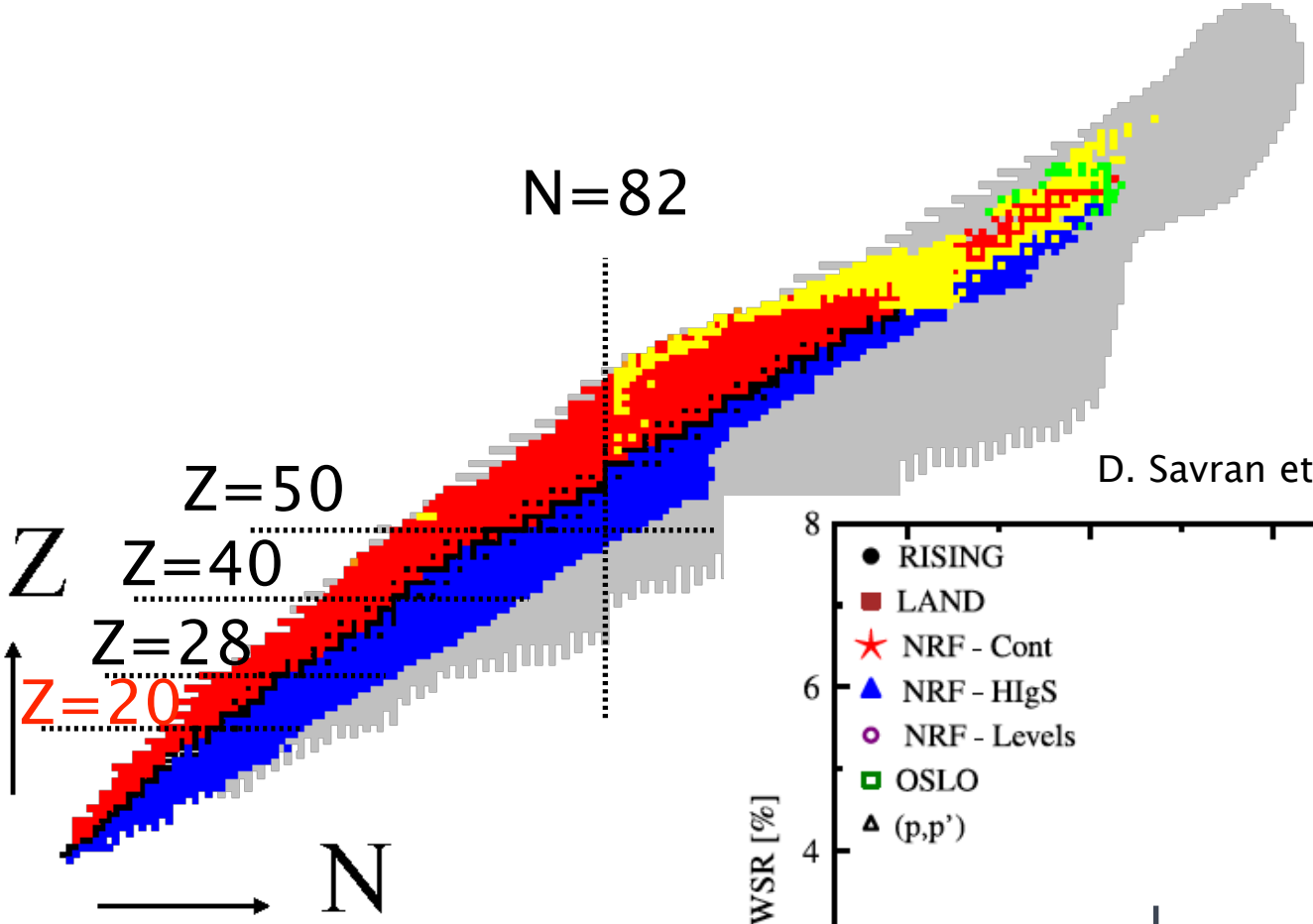




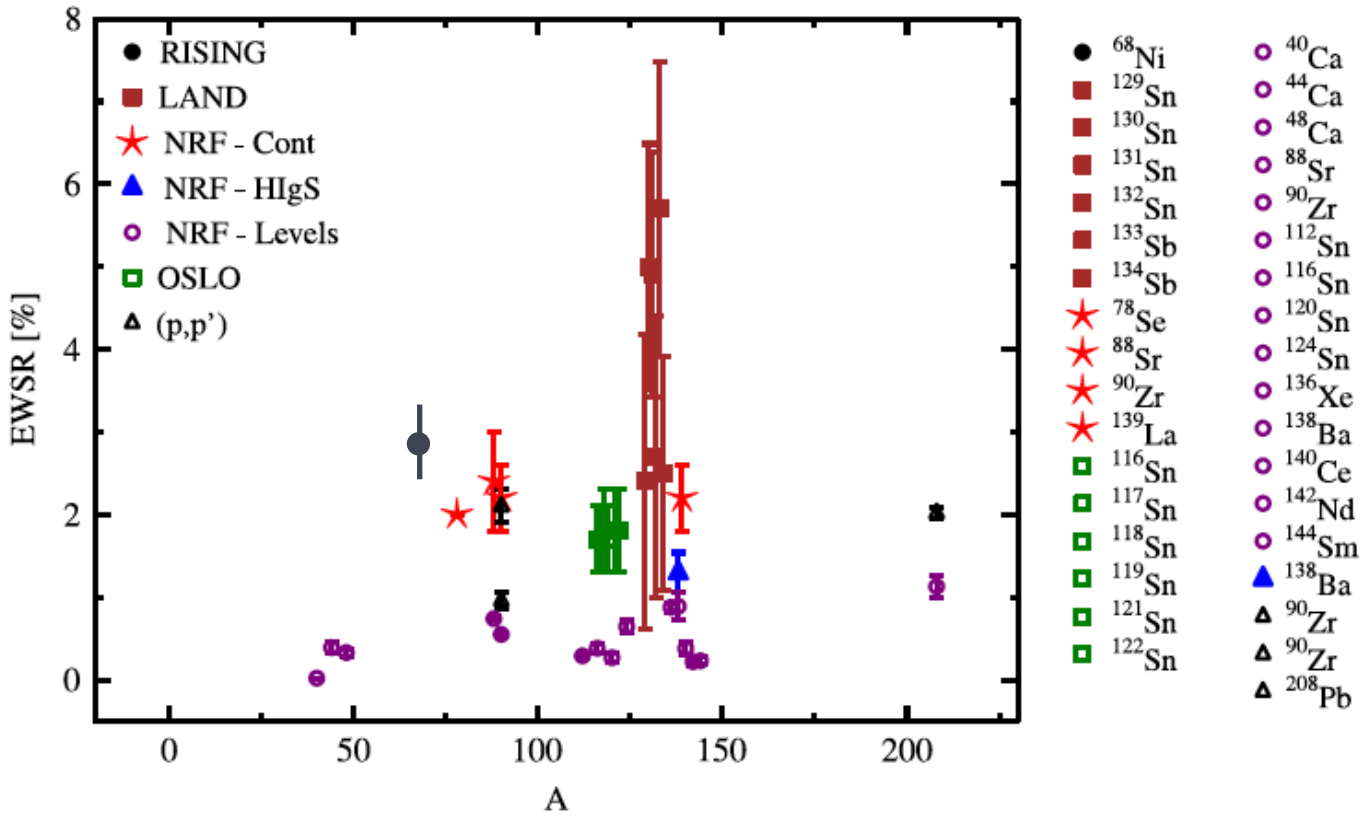


Combined analysis
J = 32.3 ± 1.3 MeV
L = 64.8 ± 15.7 MeV

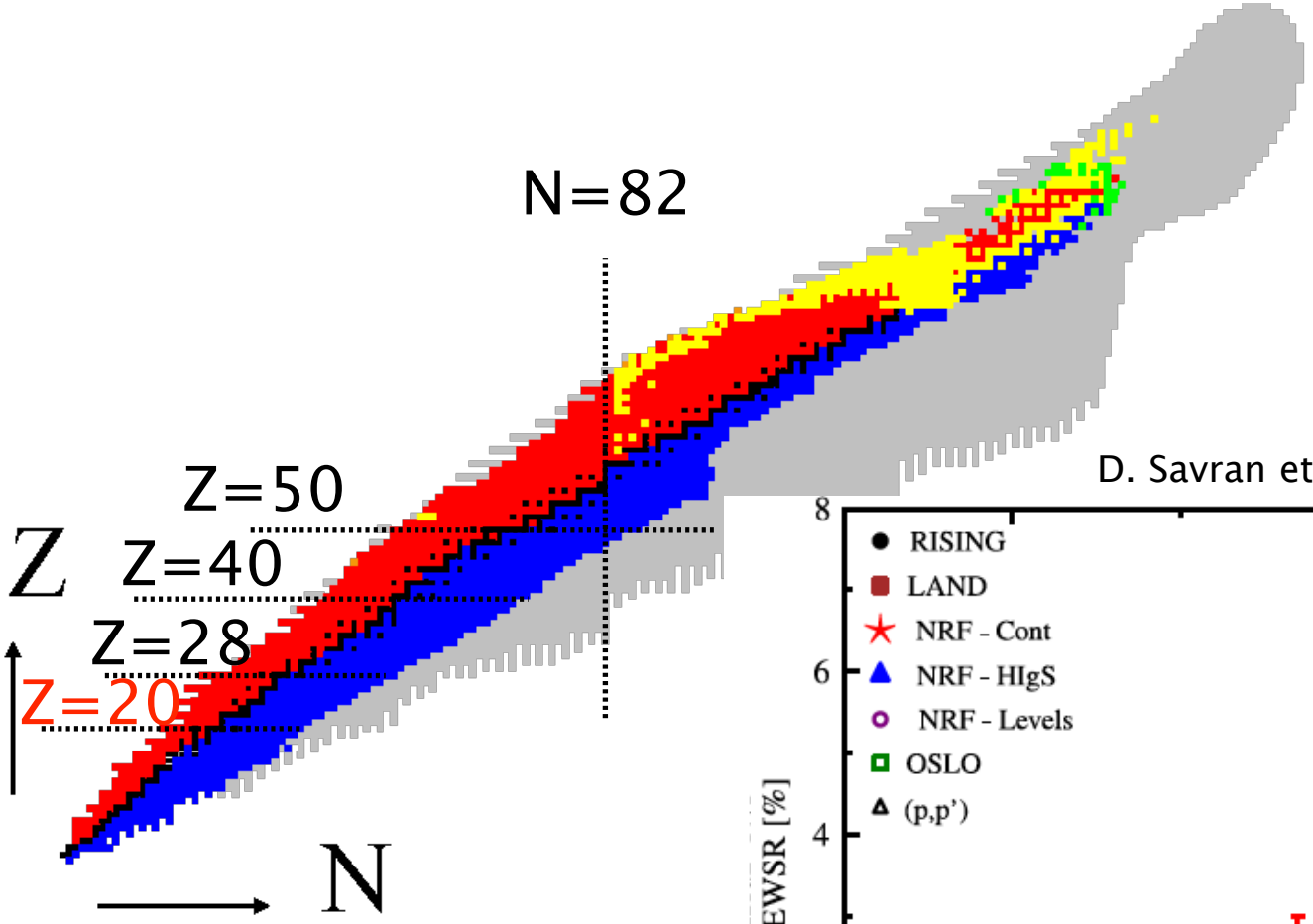
Experimental efforts for PDR



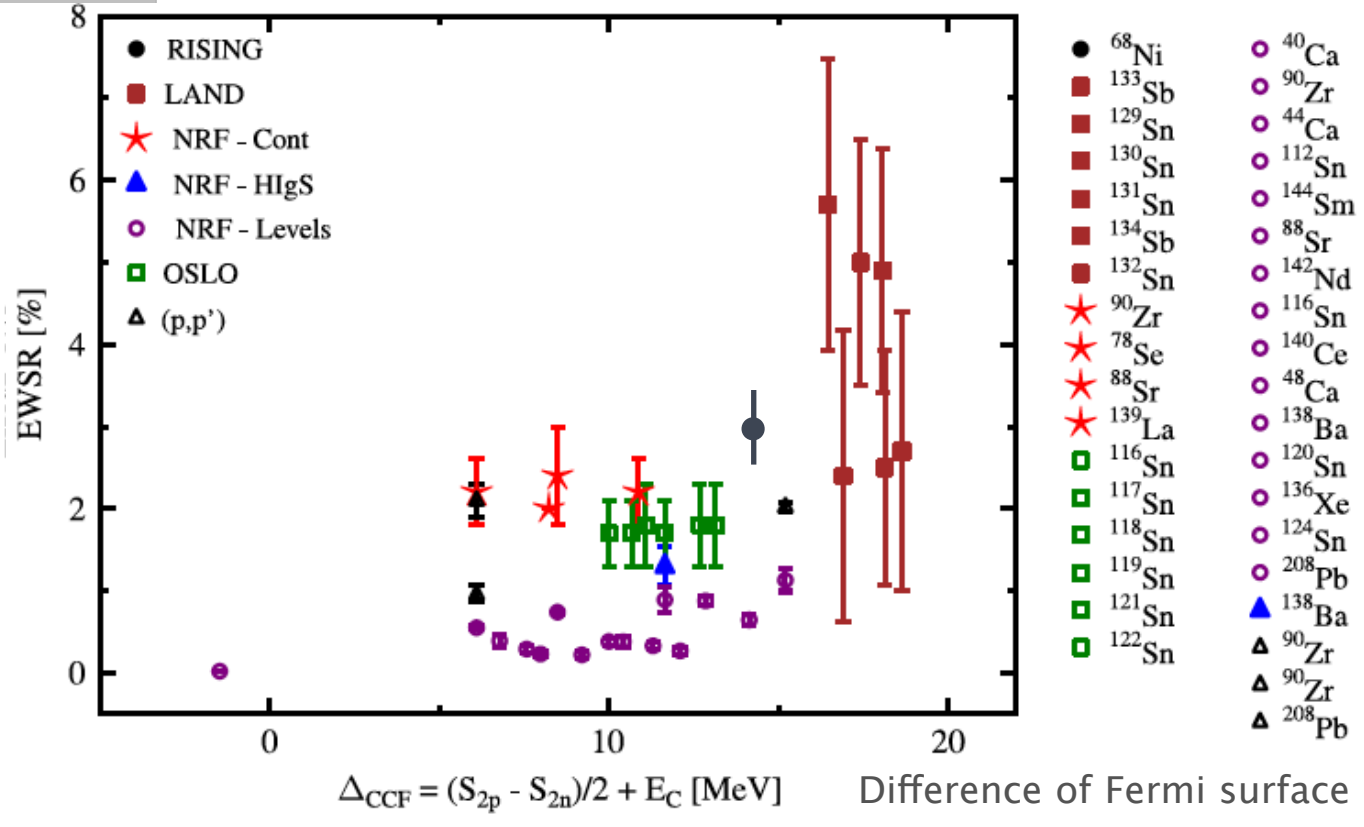
D. Savran et al., Prog. Part. Nucl. Phys. 70, 210 (2013).



Experimental efforts for PDR

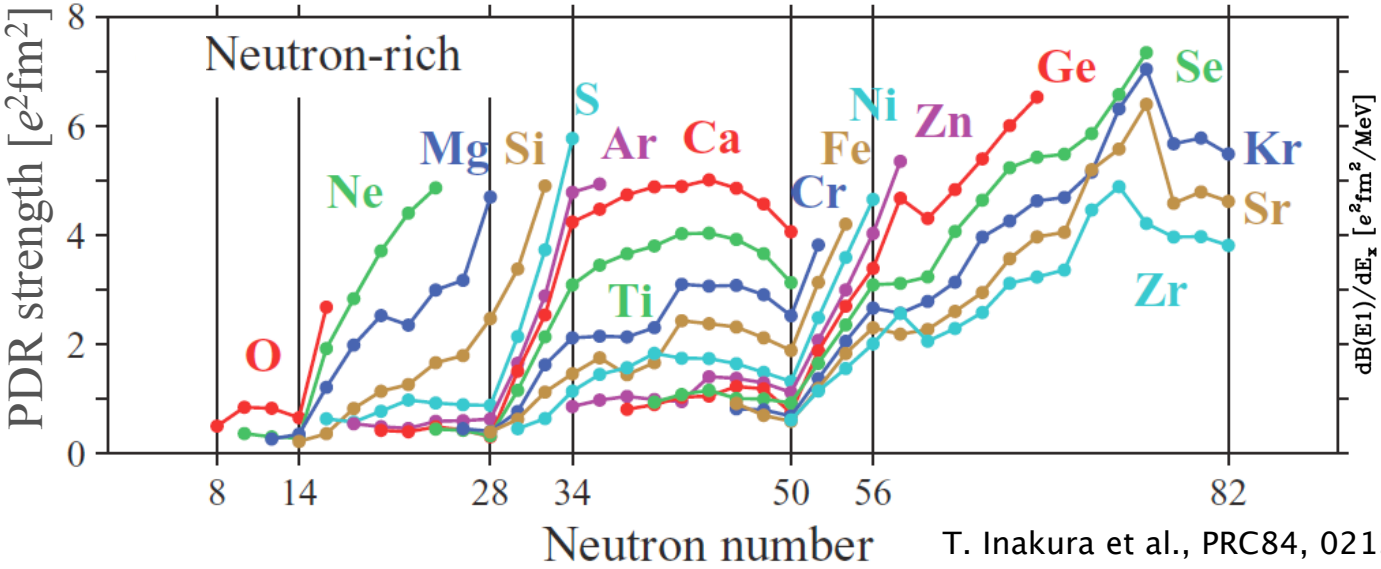


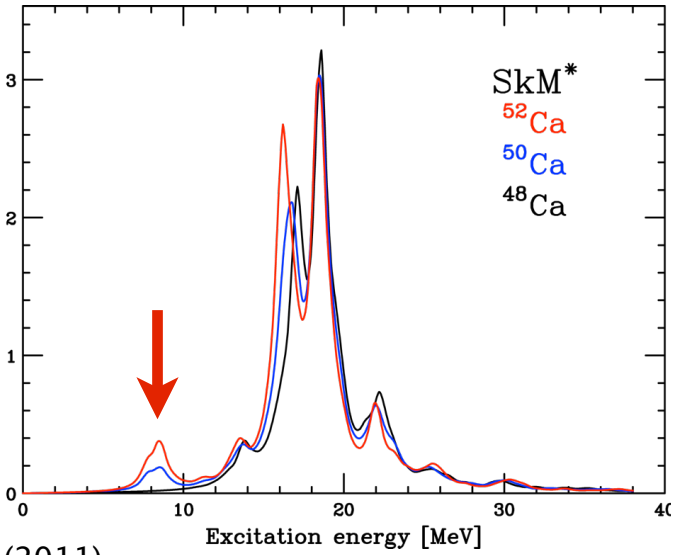
D. Savran et al., Prog. Part. Nucl. Phys. 70, 210 (2013).



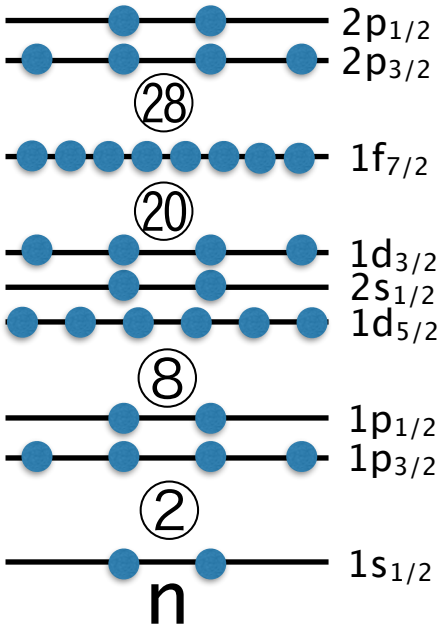
Difference of Fermi surface

PDR strengths of Ca isotopes





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



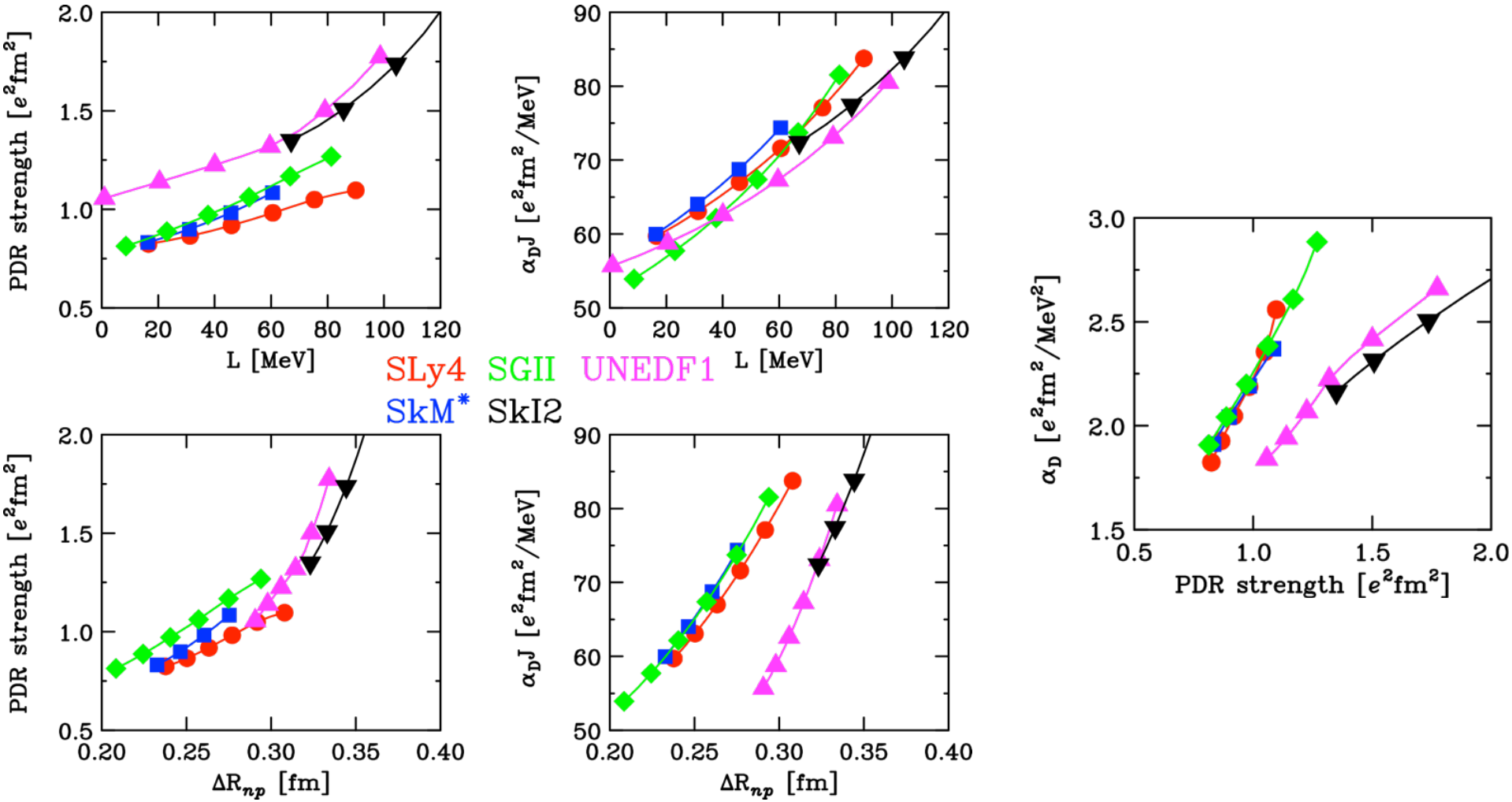
low-l orbit → larger PDR strength

PDR is not collective?

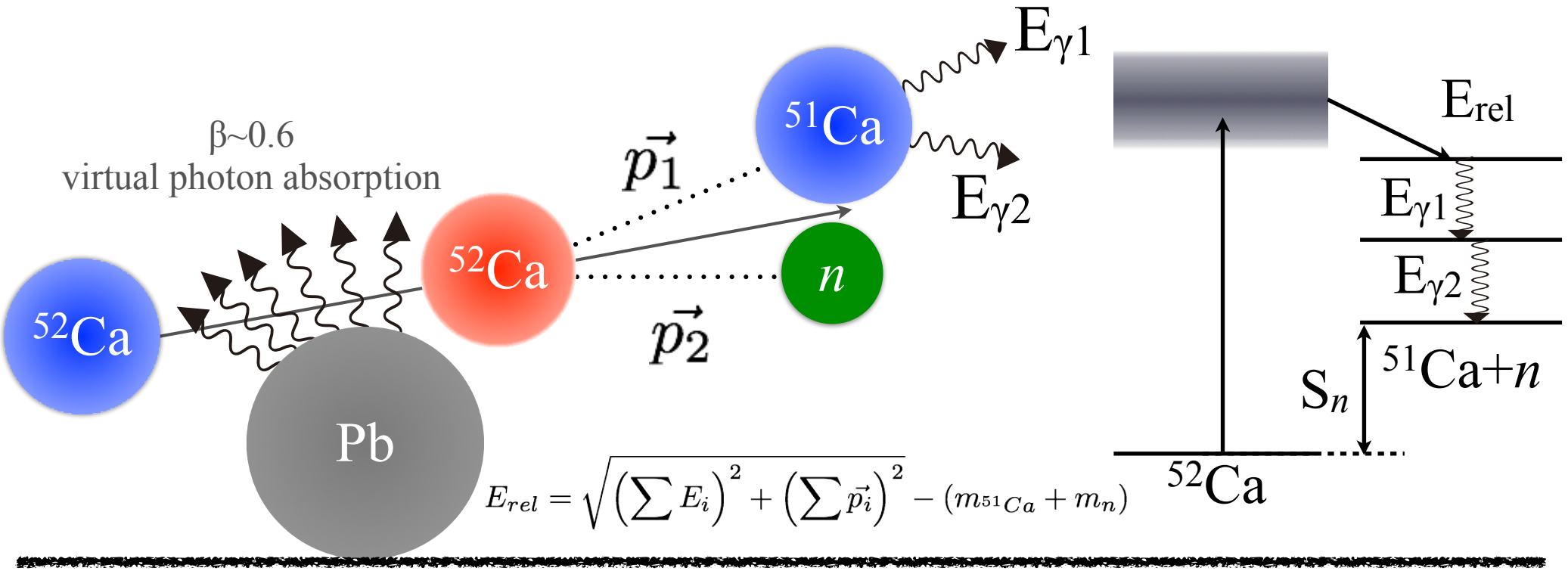
E1 response of ^{48,50,52}Ca@RIBF

E1 response of ^{52}Ca and symmetry energy

- RPA calculation by Inakura-san

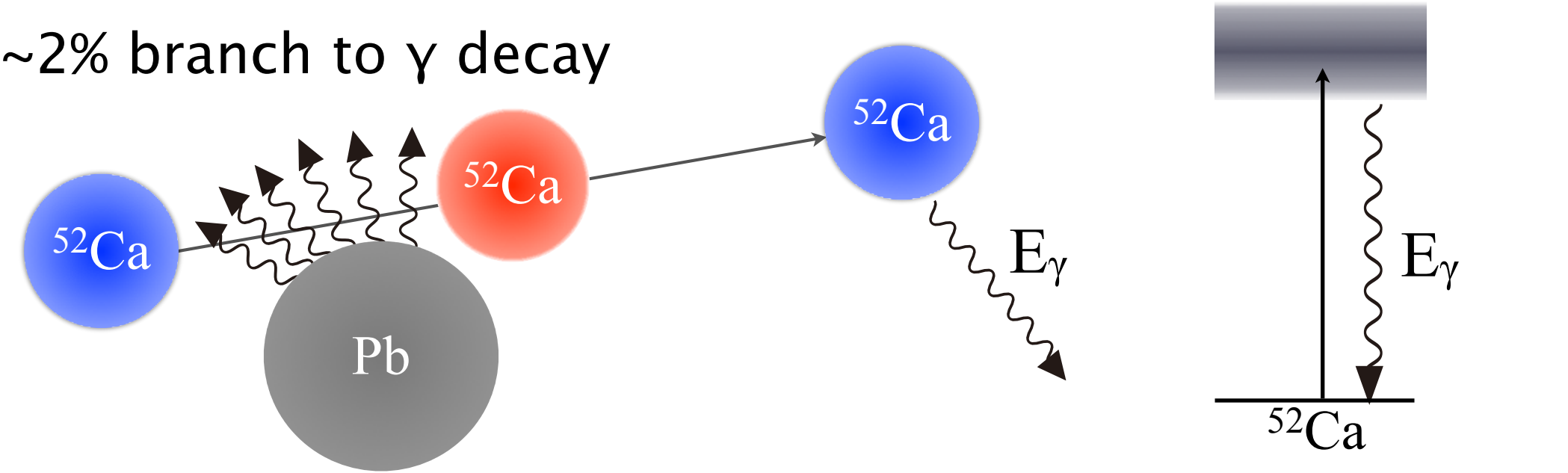


Experimental procedure

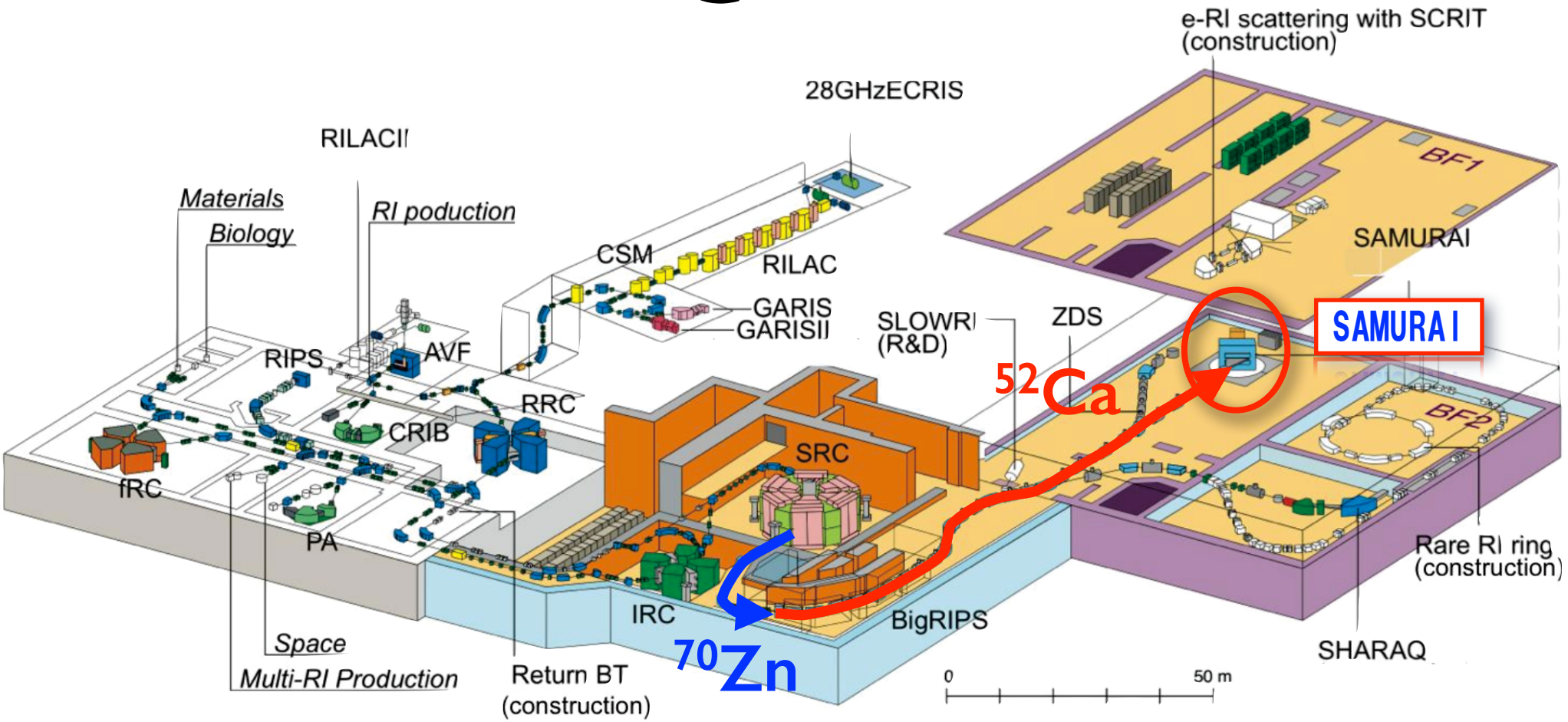


$$E_{rel} = \sqrt{\left(\sum E_i\right)^2 + \left(\sum \vec{p_i}\right)^2} - (m_{^{51}Ca} + m_n)$$

~2% branch to γ decay



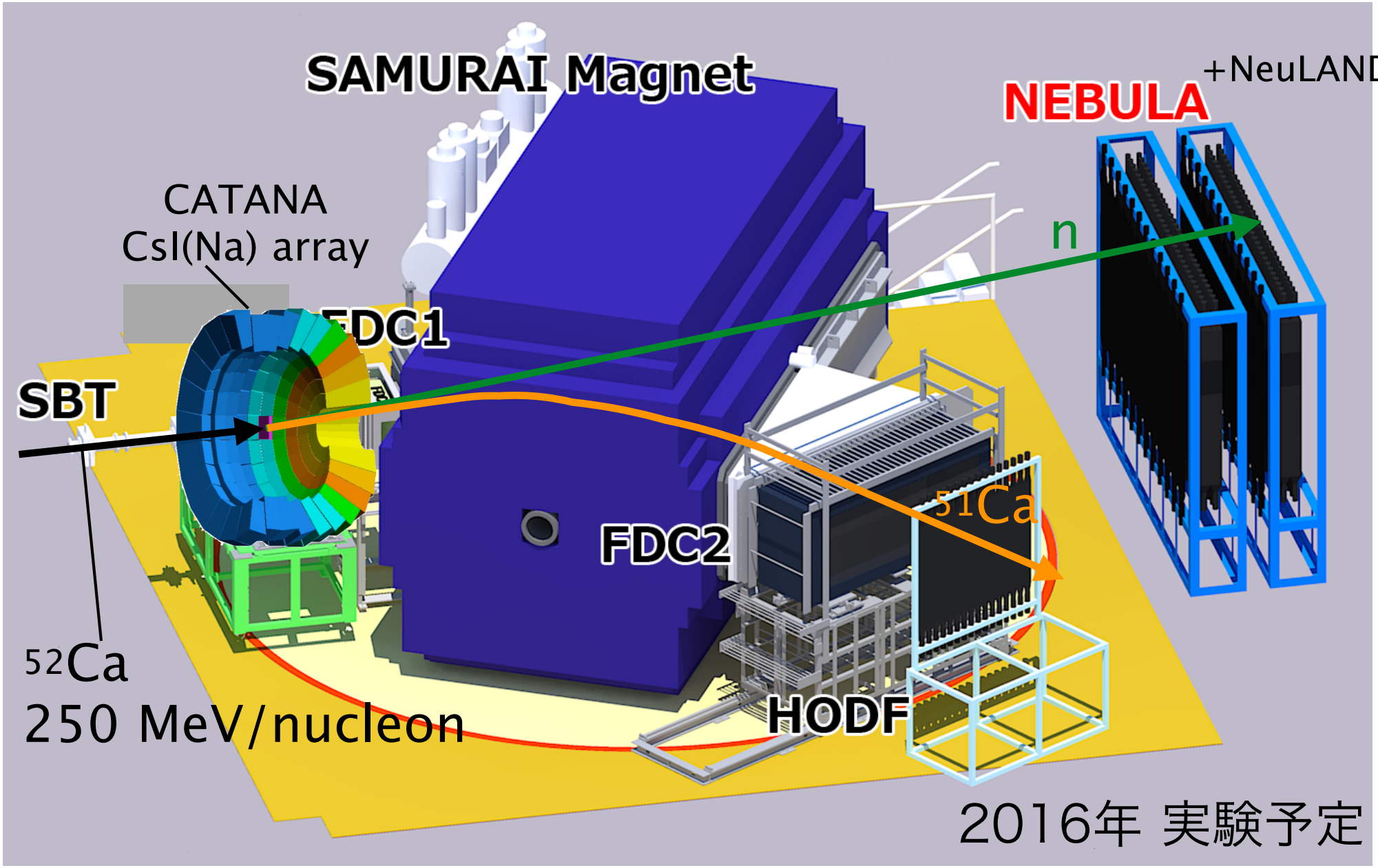
RIBF @ RIKEN



Primary beam ^{70}Zn@ 345 MeV/nucleon

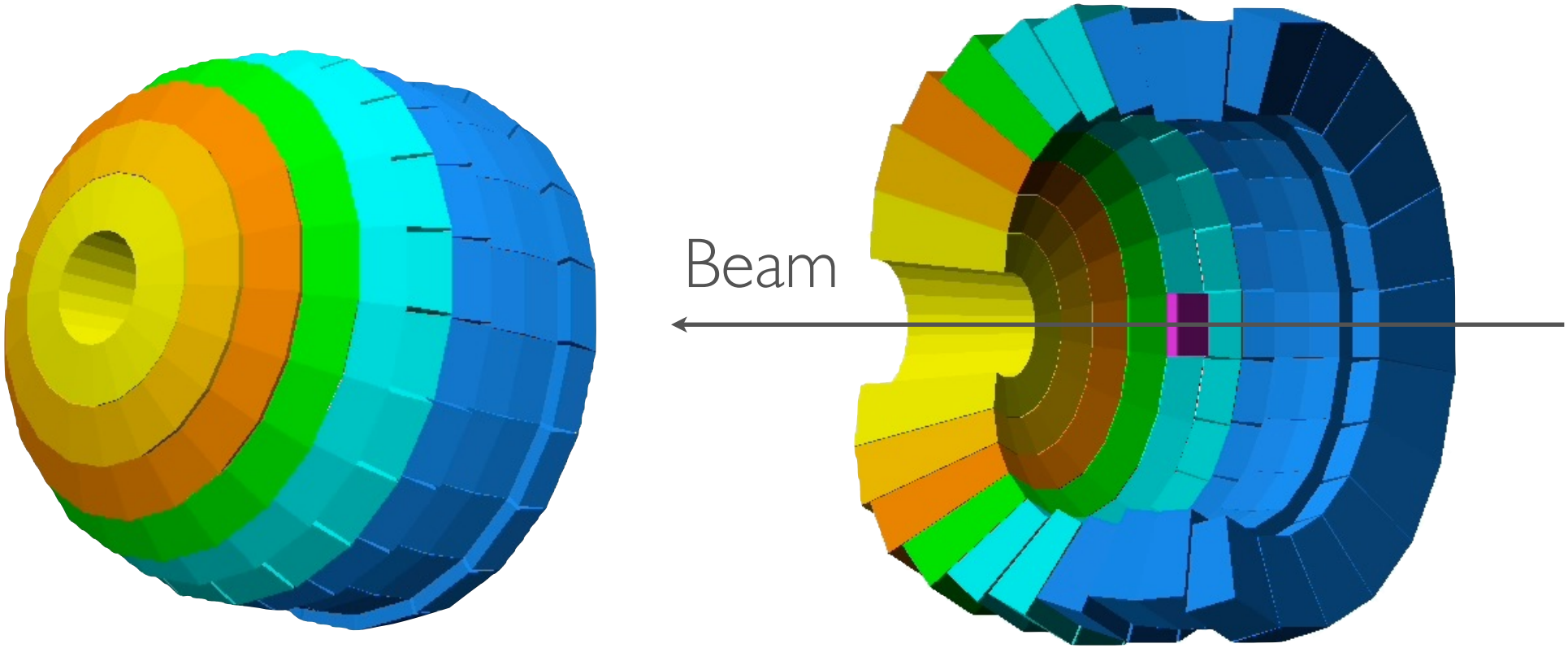
→Secondary beam ^{48,50,52}Ca(10^2~10^4 cps)

Experimental setup

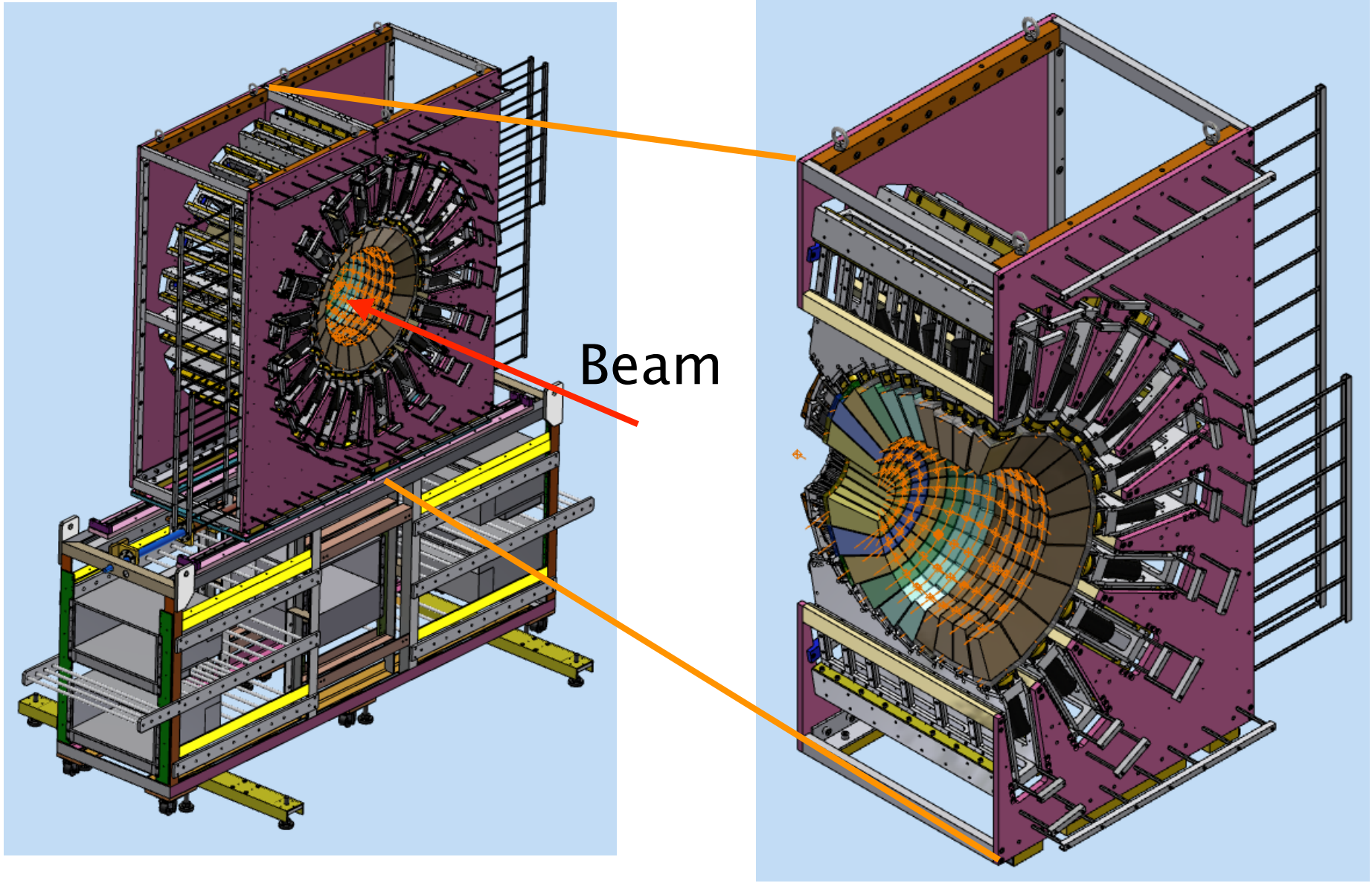


CATANA

- CAesium iodide array for γ-ray Transitions in Atomic Nuclei at high isospin Asymmetryの略
- crystal: CsI(Na), 20 crystals per ring
- High detection efficiency: ~60% for 1 MeV gamma

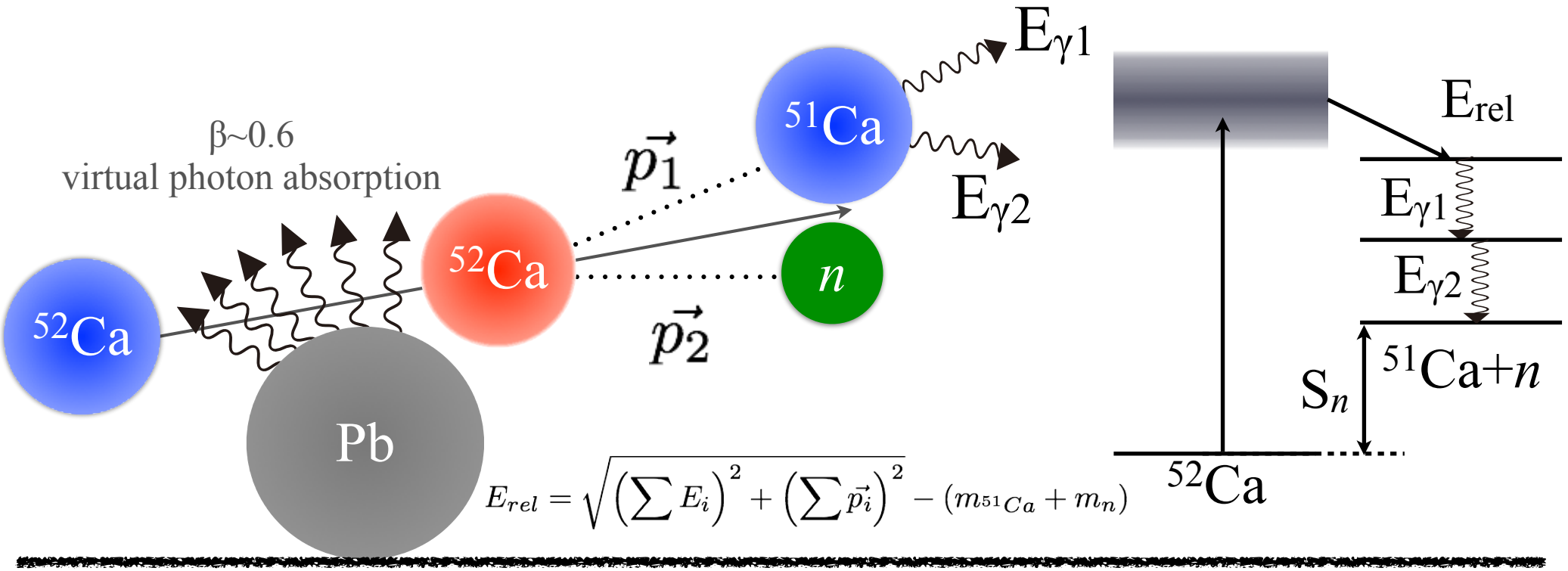


Supporting frame



Designed by N. Chiga (RIKEN)

gamma decay from PDR



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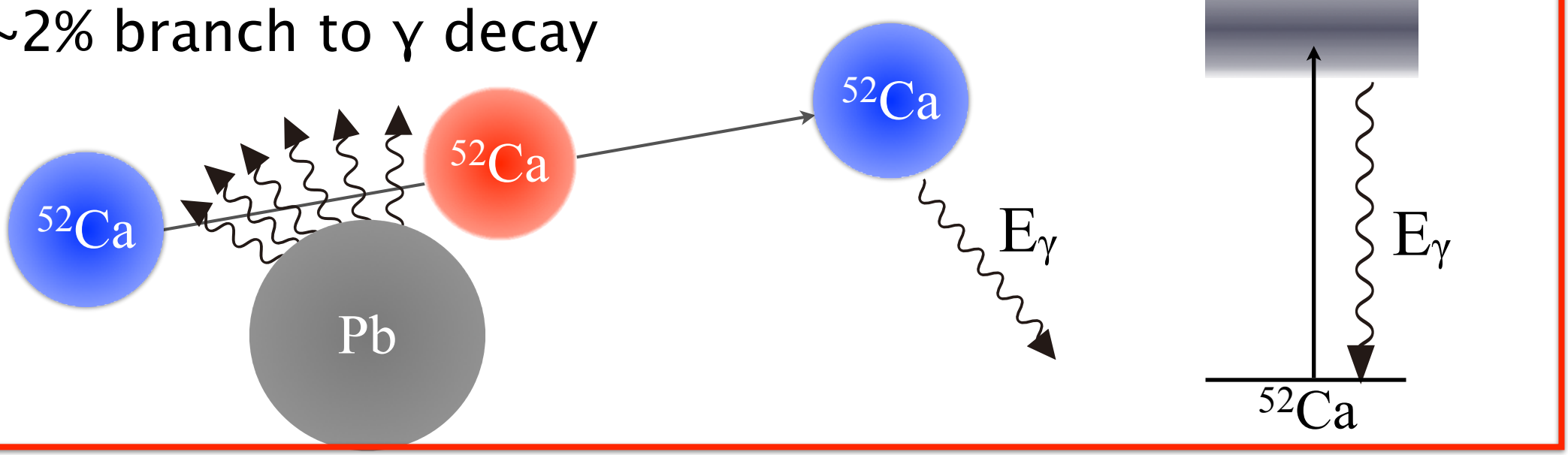
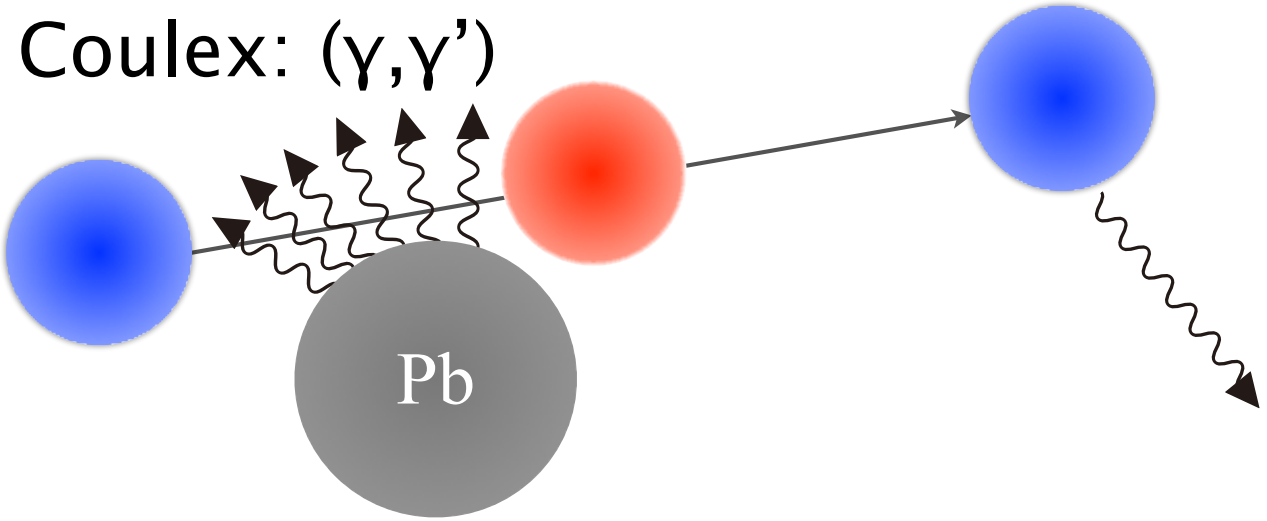
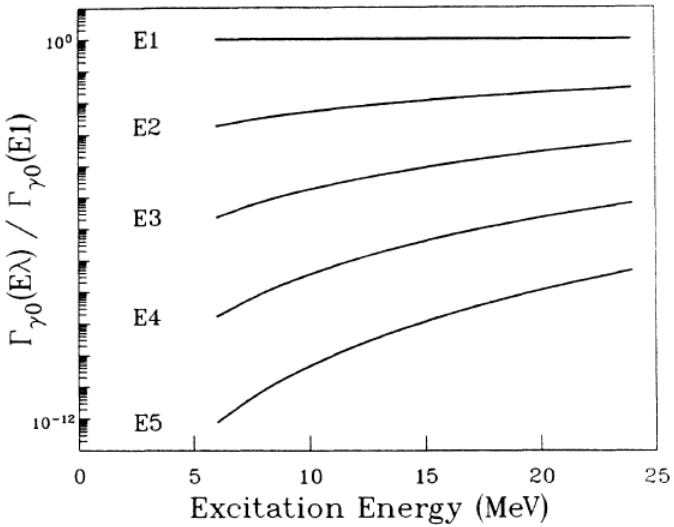
~2% branch to γ decay



gamma decay from PDR

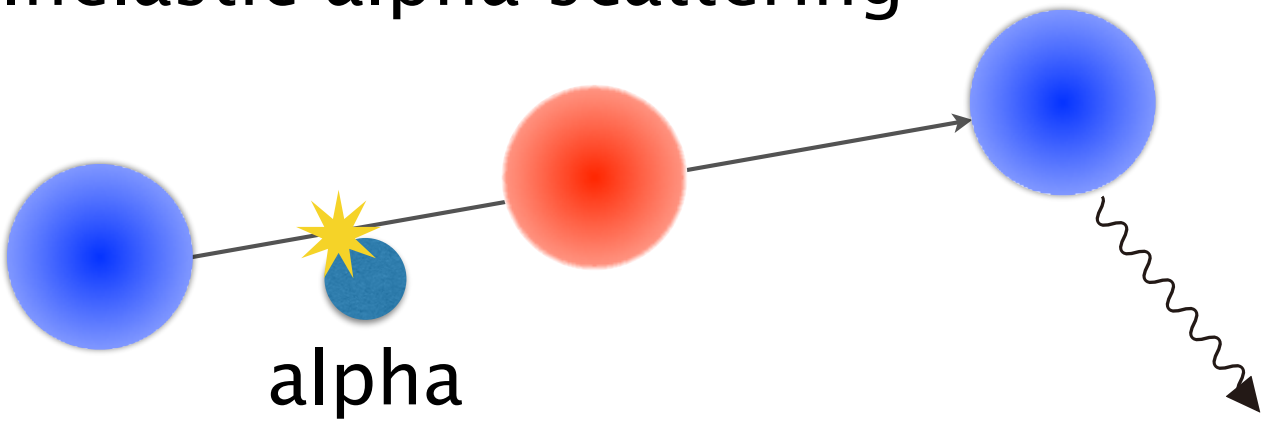
Coulex: (γ,γ')





J. R. Beene et al., PRC41, 920

Inelastic alpha scattering

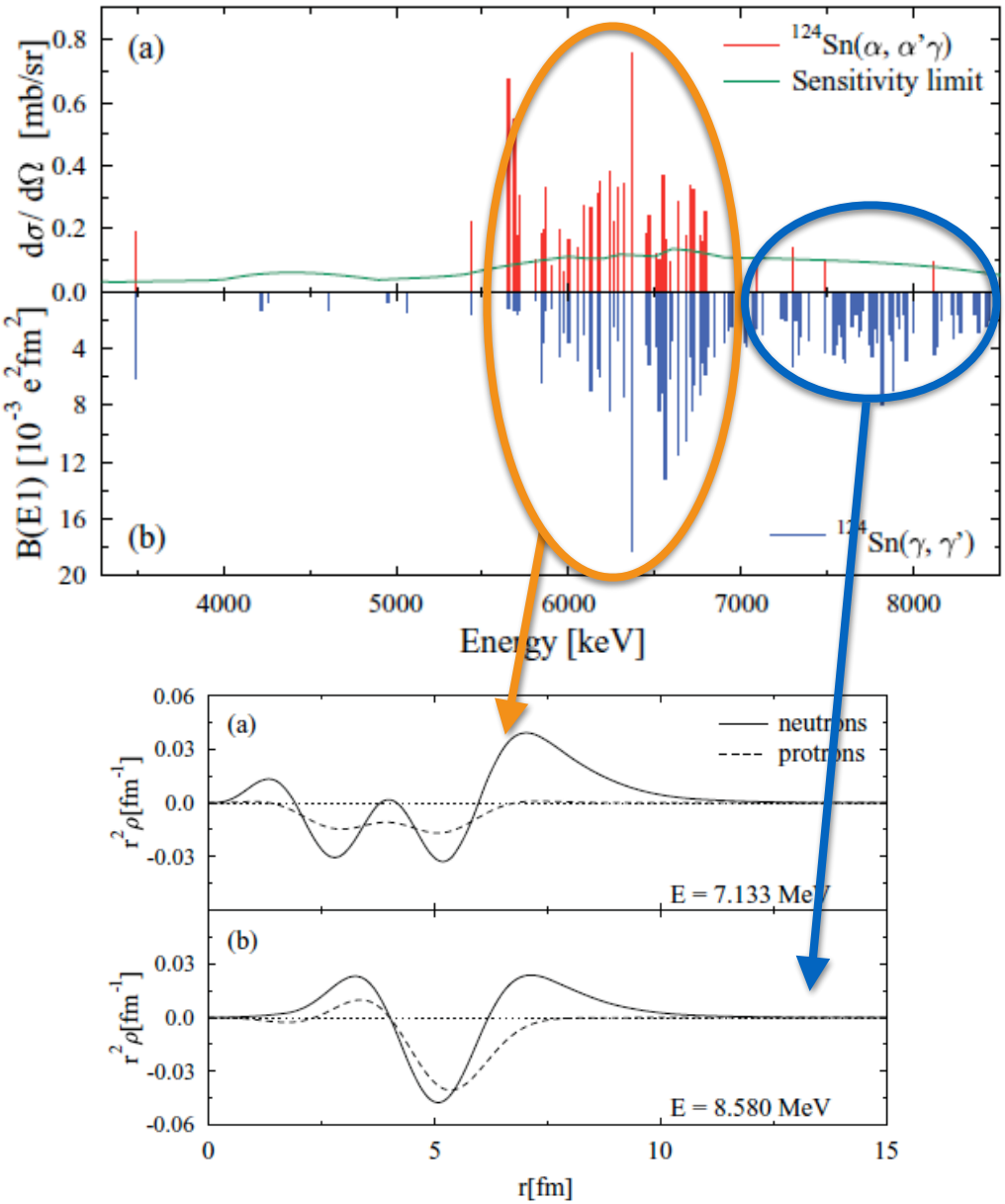


Decay to GS = E1 multipolarity

Isovector/Isoscaler property of PDR

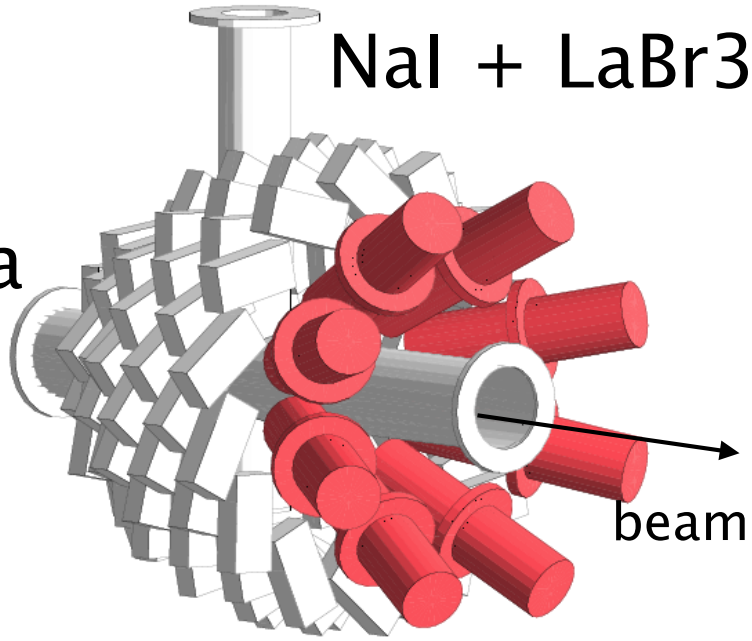
- Core + neutron: both isovector and isoscaler

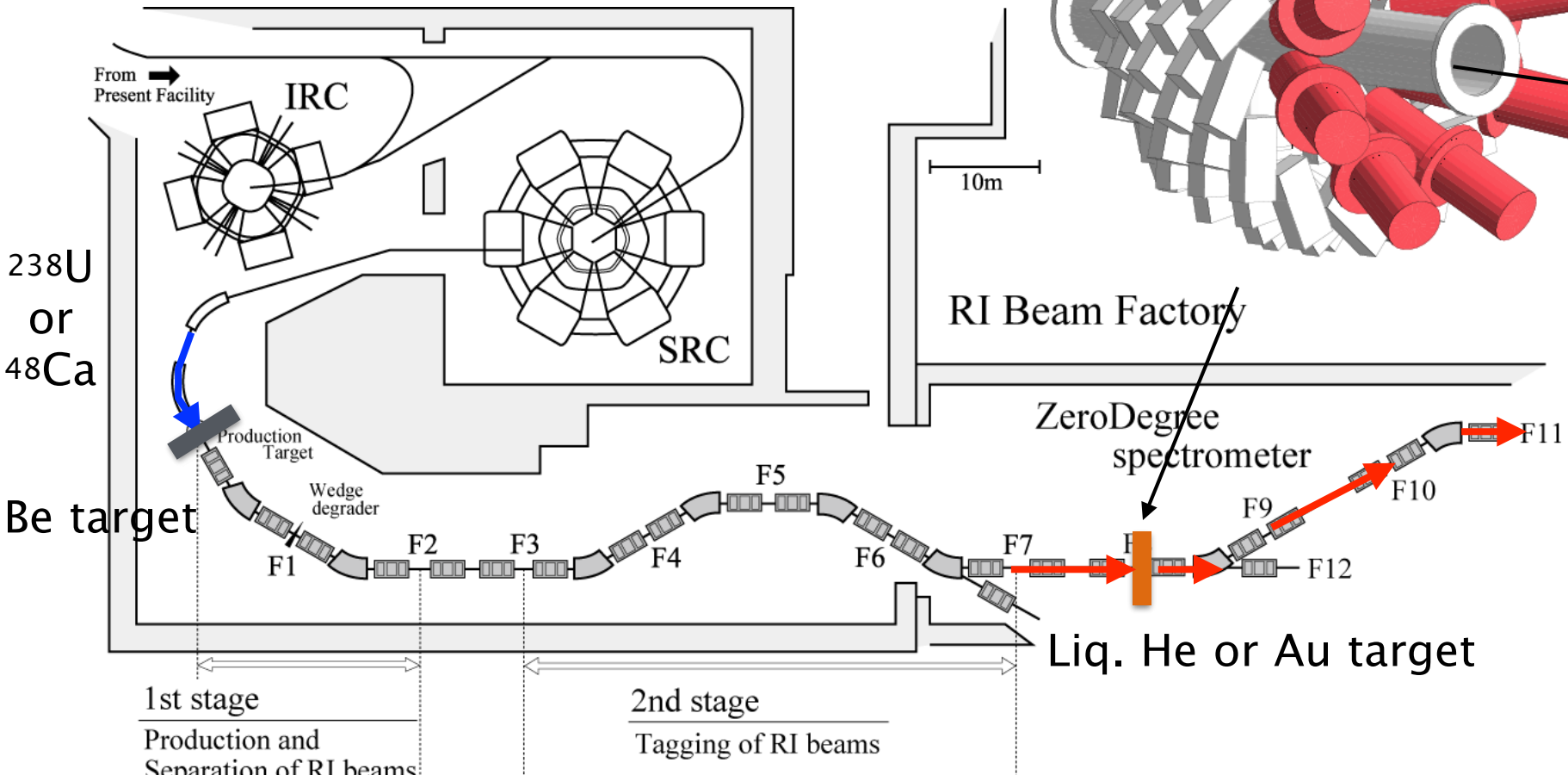
J. Endres et al., PRL 105 212503



PDR gamma experiments@RIKEN

- Series of experiments at RIKEN RIBF in 2014
  - ^{132}Sn(α,α'γ): T. Aumann
  - ^{70}Ni(γ,γ'): O. Wieland
  - ^{20,22,24}O(α,α'γ), (γ,γ'): H. Baba



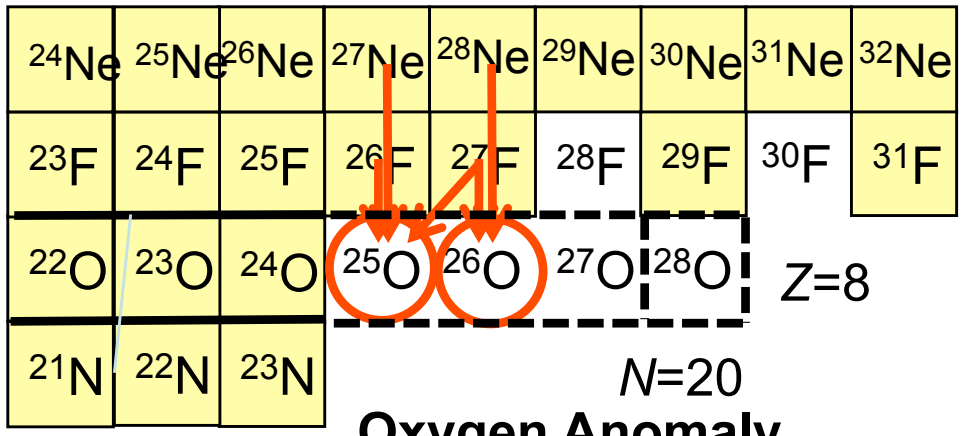


Summary for E1 response

- E1 response of n-rich nuclei → Symmetry energy
  - Dipole polarizability, PDR
- Experiment for ^{48,50,52}Ca E1 response
  - in spring 2016 @ RIBF
- gamma branch of PDR: measured at RIBF
  - ^{132}Sn, ^{70}Ni, ^{20,22,24}O

Related topics

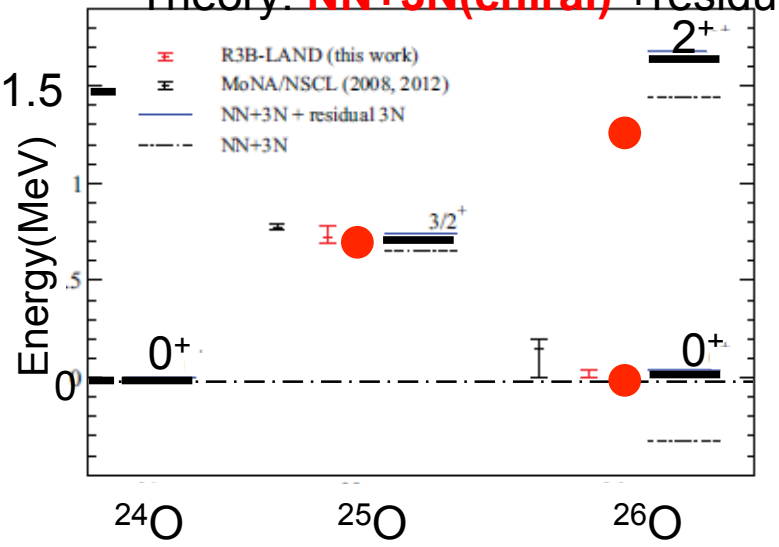
Production of Unbound ^{26}O states: Y. Kondo et al.



Oxygen Anomaly

C.Caesar et al.(GSI,Data), A.Schwenk (Theory)PRC88,034313 (2013)

Theory: **NN+3N(chiral)** +residual 3N



Experimental Result:

~1.3MeV (2^+)

0.75MeV

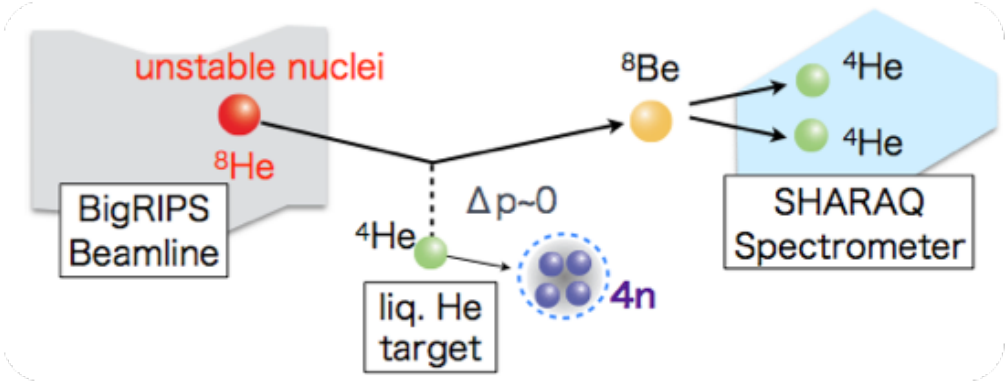
<50keV 0^+_{gs}

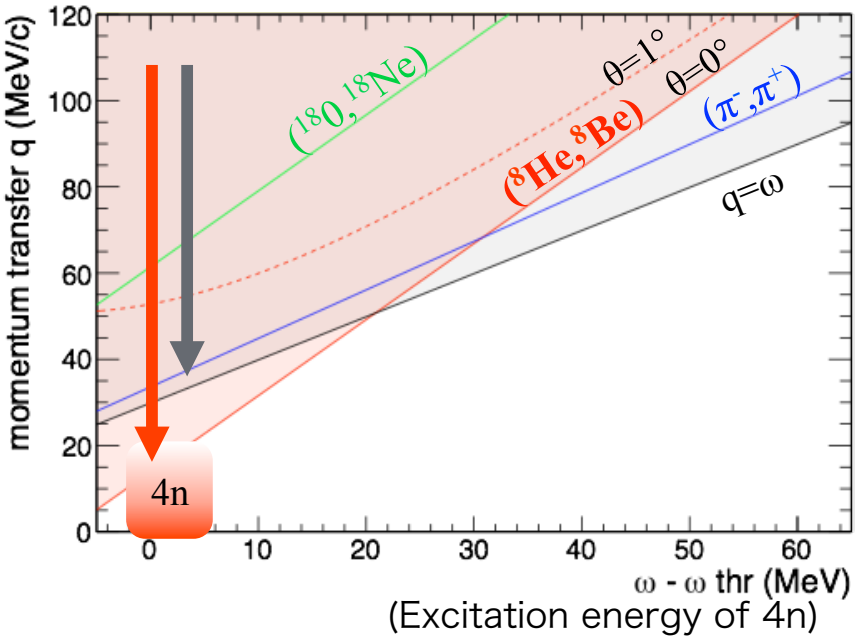
^{24}O+2n ^{25}O+n ^{26}O

PhD Thesis of K. Kisamori

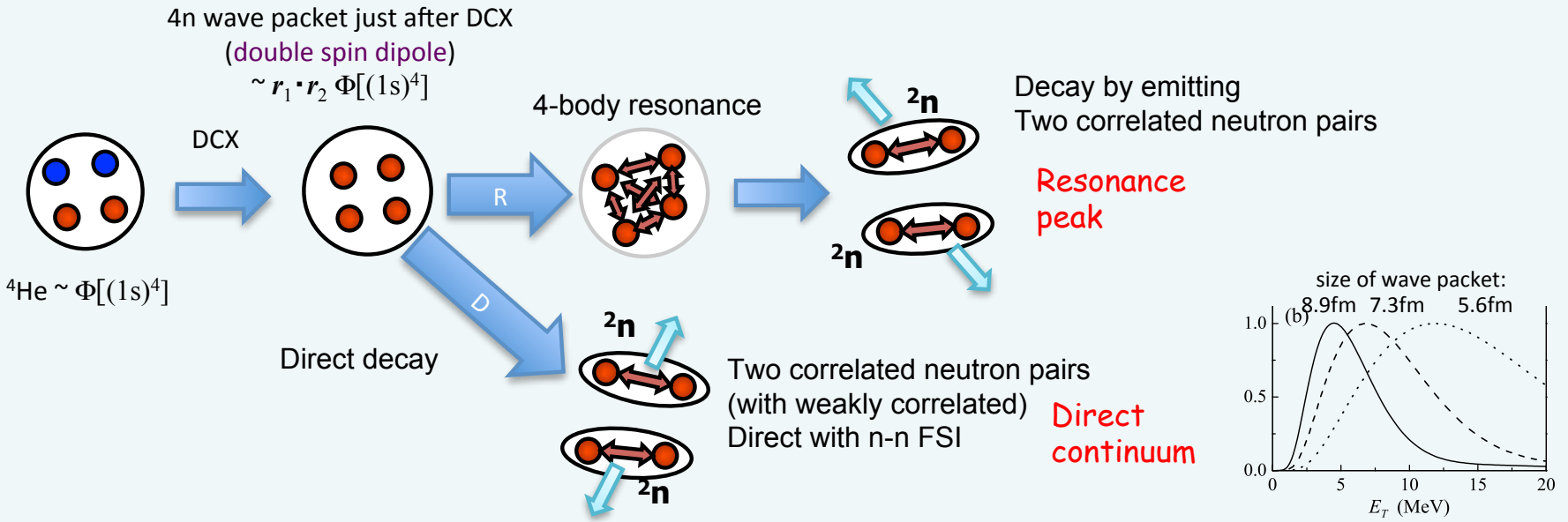
Missing-mass measurement by DCX

- **Exothermic reaction ^{4}He(^{8}He,^{8}Be)4n** at 200 AMeV.
  - Exothermic reaction
    → **small momentum transfer.**
    (almost recoil less condition)
- Missing-mass spectroscopy
  - Energy resolution: ~ 1 MeV

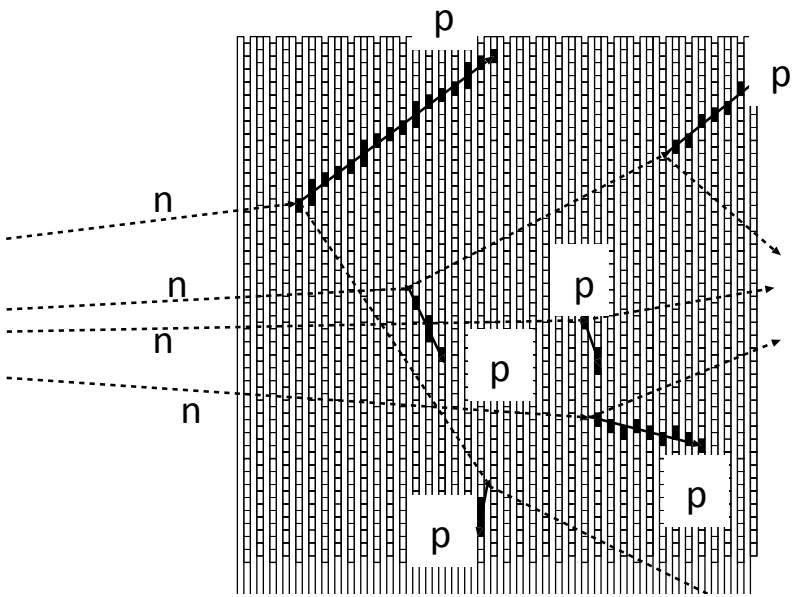


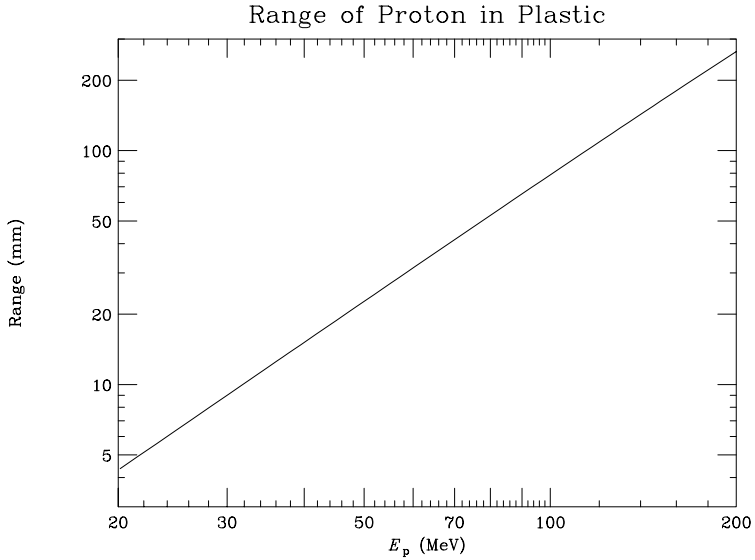


Picture of reaction

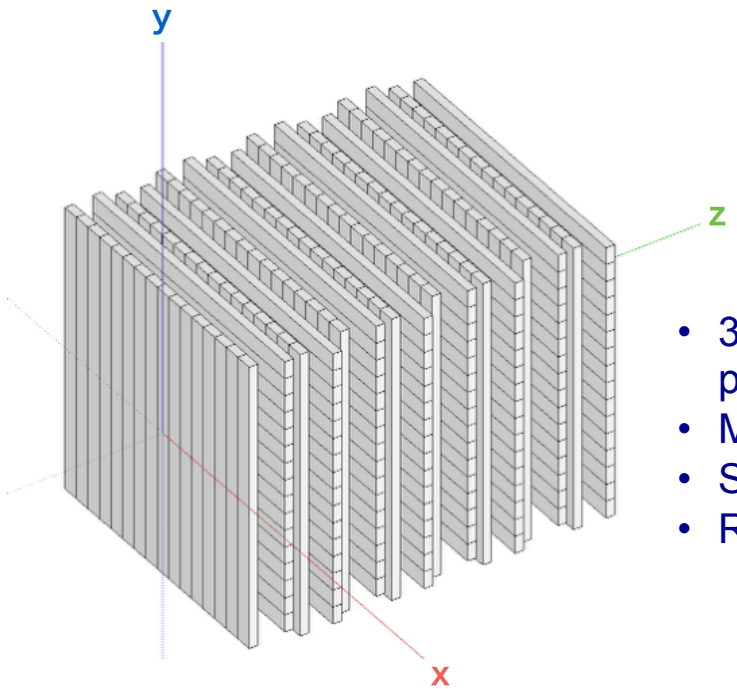


For Direct measurement of multi-neutrons:
R&D of Multi-neutron tracker



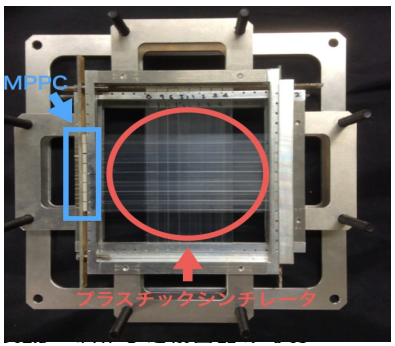


Range of proton above 30 MeV > 9mm
Tracking of recoil protons ->
identification of cross talk from a single neutron



Prototype module (micro-hodoscope)

- $3^t \times 6^w \times 100^l$ mm^3 plastic scintillator (BC408) × 16 per plane
- MPPC (S12572) or sensL for sensing scintillation
- Supporting frame for Four micro-hodoscopes
- Readout using EASIROC



Summary

- E1 response of n-rich nuclei → Symmetry energy
  - Dipole polarizability, PDR
- Experiment for ^{48,50,52}Ca E1 response
  - in spring 2016 @ RIBF
- gamma branch of PDR: measured at RIBF
  - ^{132}Sn, ^{70}Ni, ^{20,22,24}O
- Unbound Oxgen isotopes -> 3N force
- tetra neutron -> pure neutron matter