Experimental approach to Ktau using CAT-M active target and Grand Raiden spectrometer

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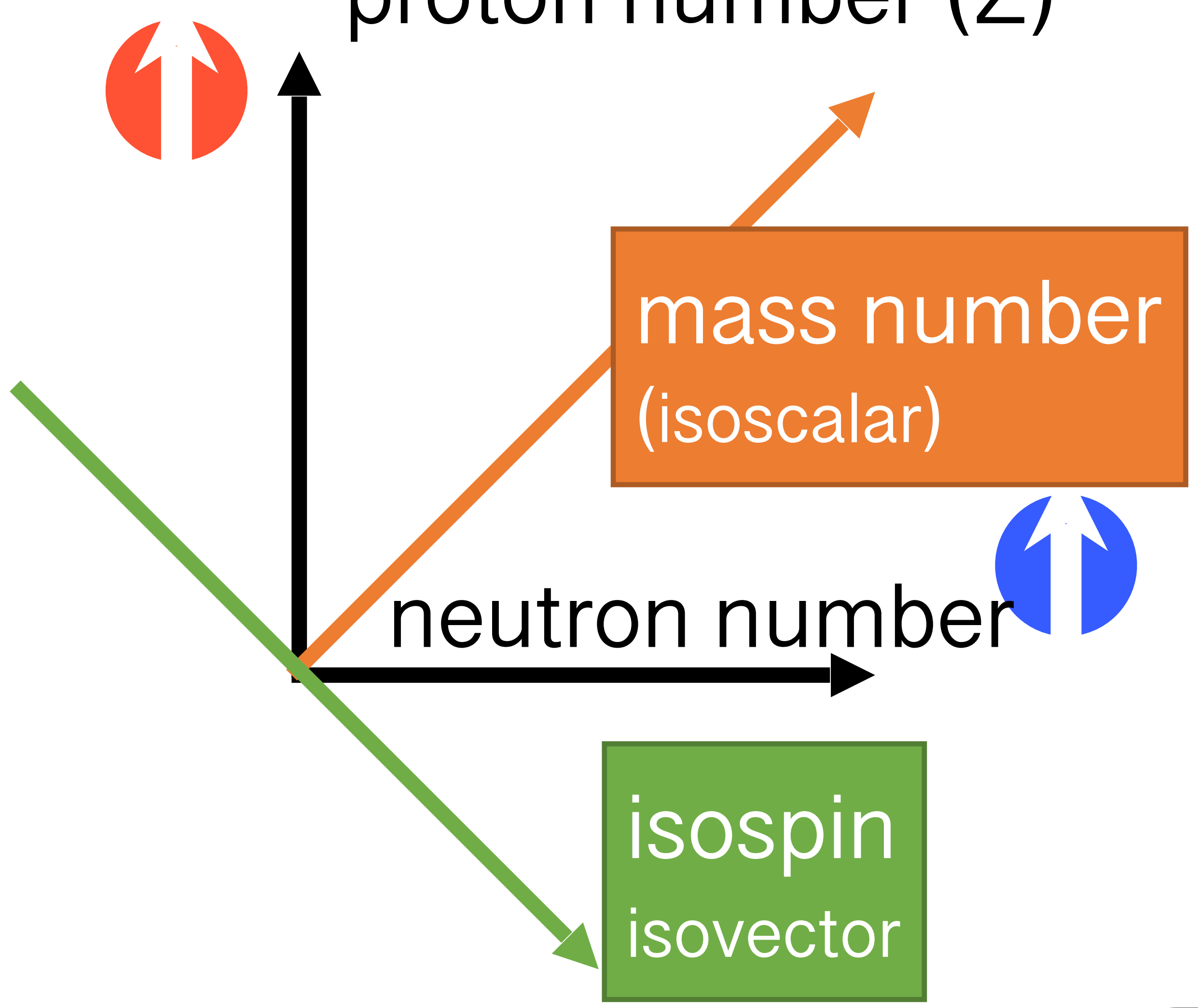
Contents

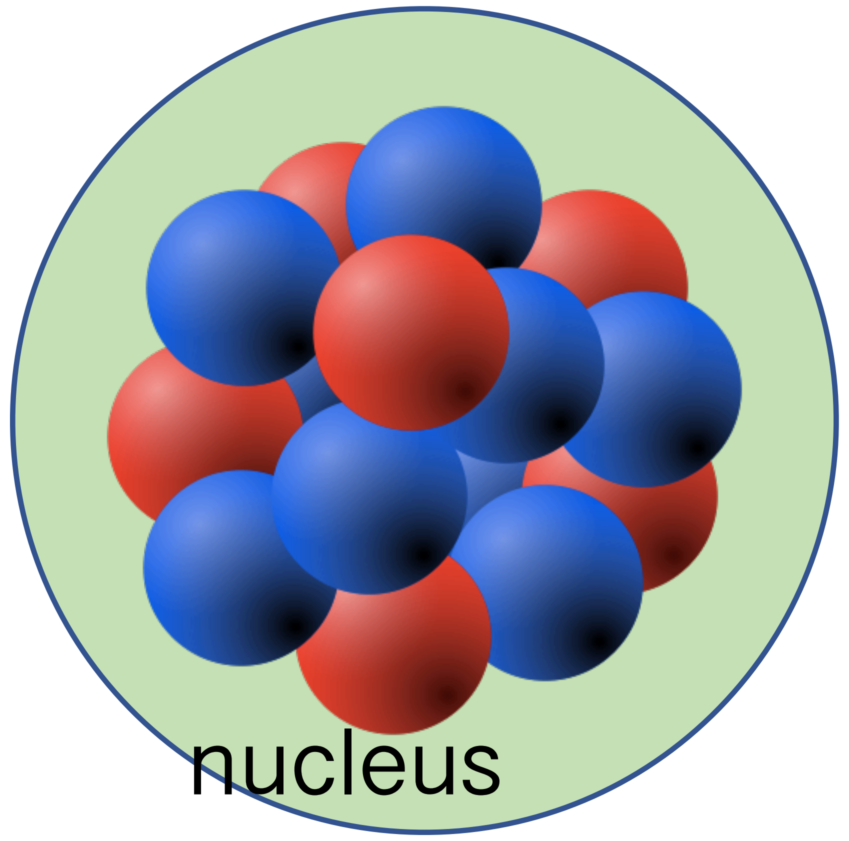
- Nuclear responses and matter property
- Experimental approach to Ktau
- Systematic measurement with CAT-M and GRAND RAIDEN
    - Recent upgrade of CAT-M and systematic measurement
    - Status of RCNP and GRAND RAIDEN
- Summary and Outlook

Nucleon system : micro and macro

Variable in nucleus

nuclear response





1 fm, 1-300u

density: const. , temp. 0

spin/orbit angular mom.

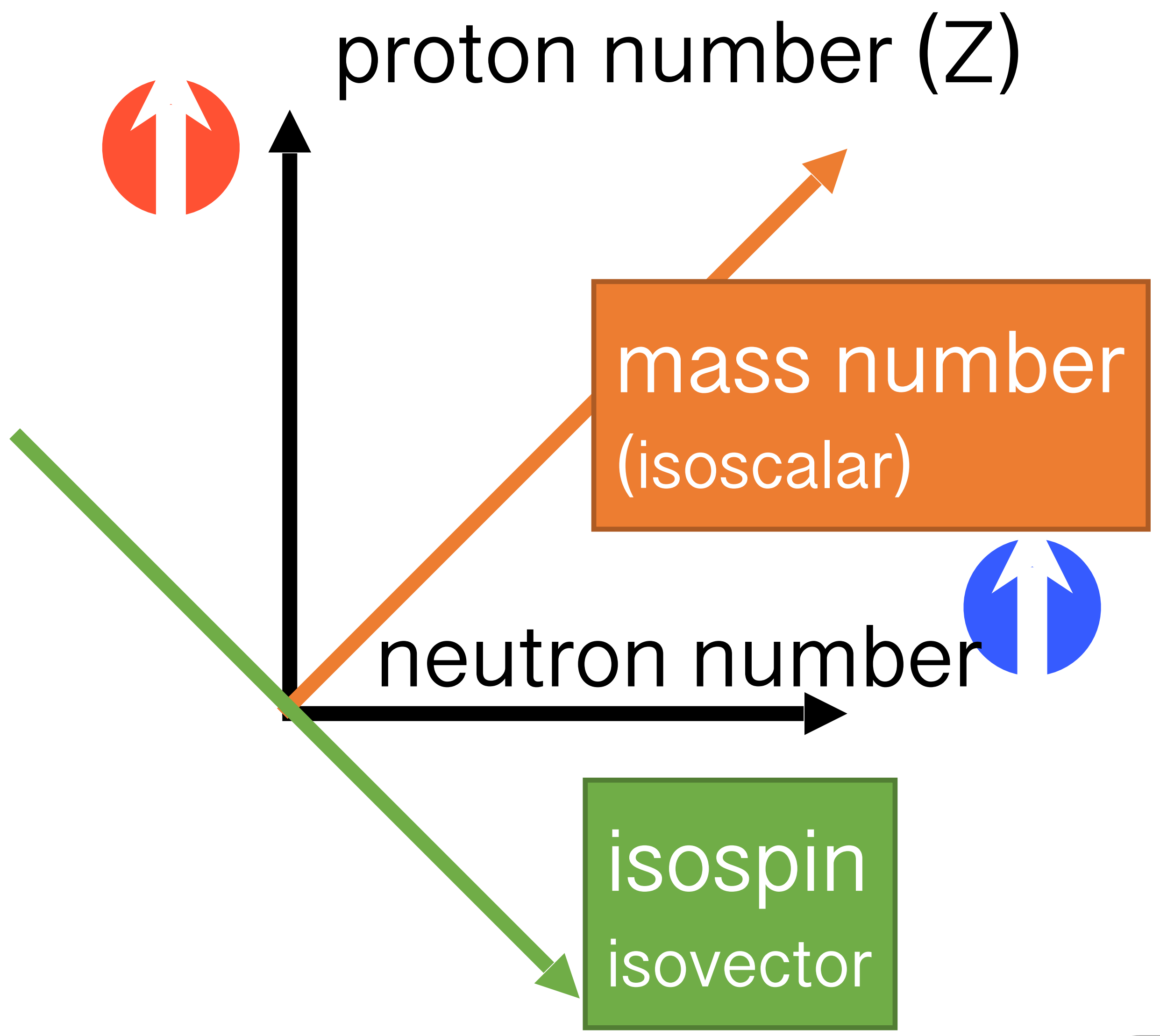
finite effect
shell, deformation, surface

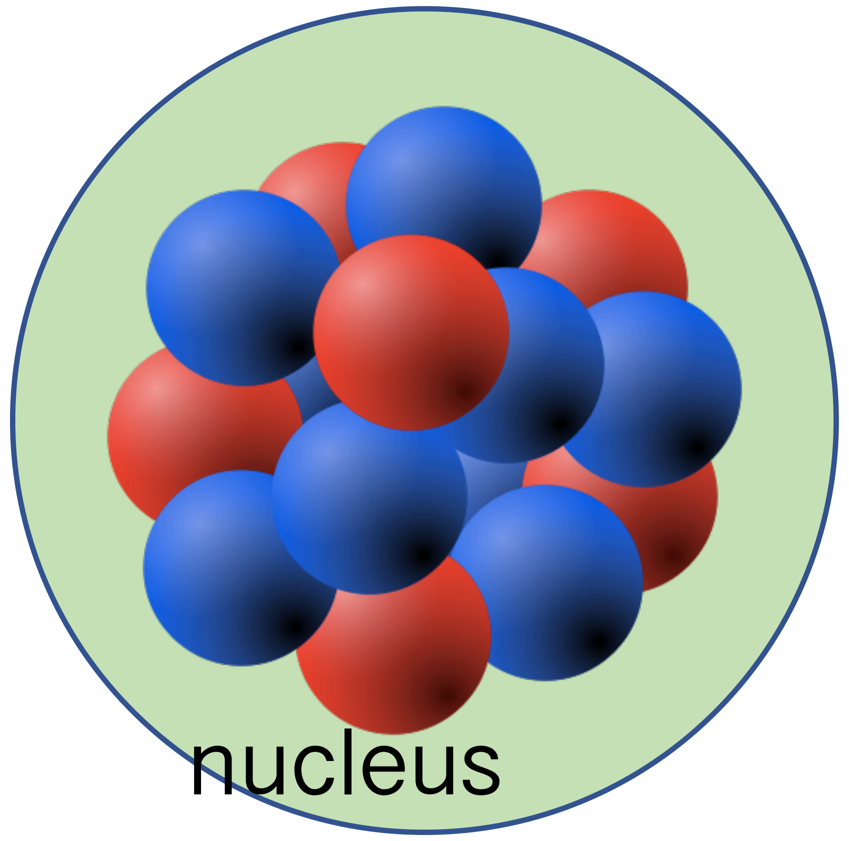
- electron system
- pair condensation

Nucleon system : micro and macro

Variable in nucleus

nuclear response





1 fm, 1-300u

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spin/orbit angular mom.

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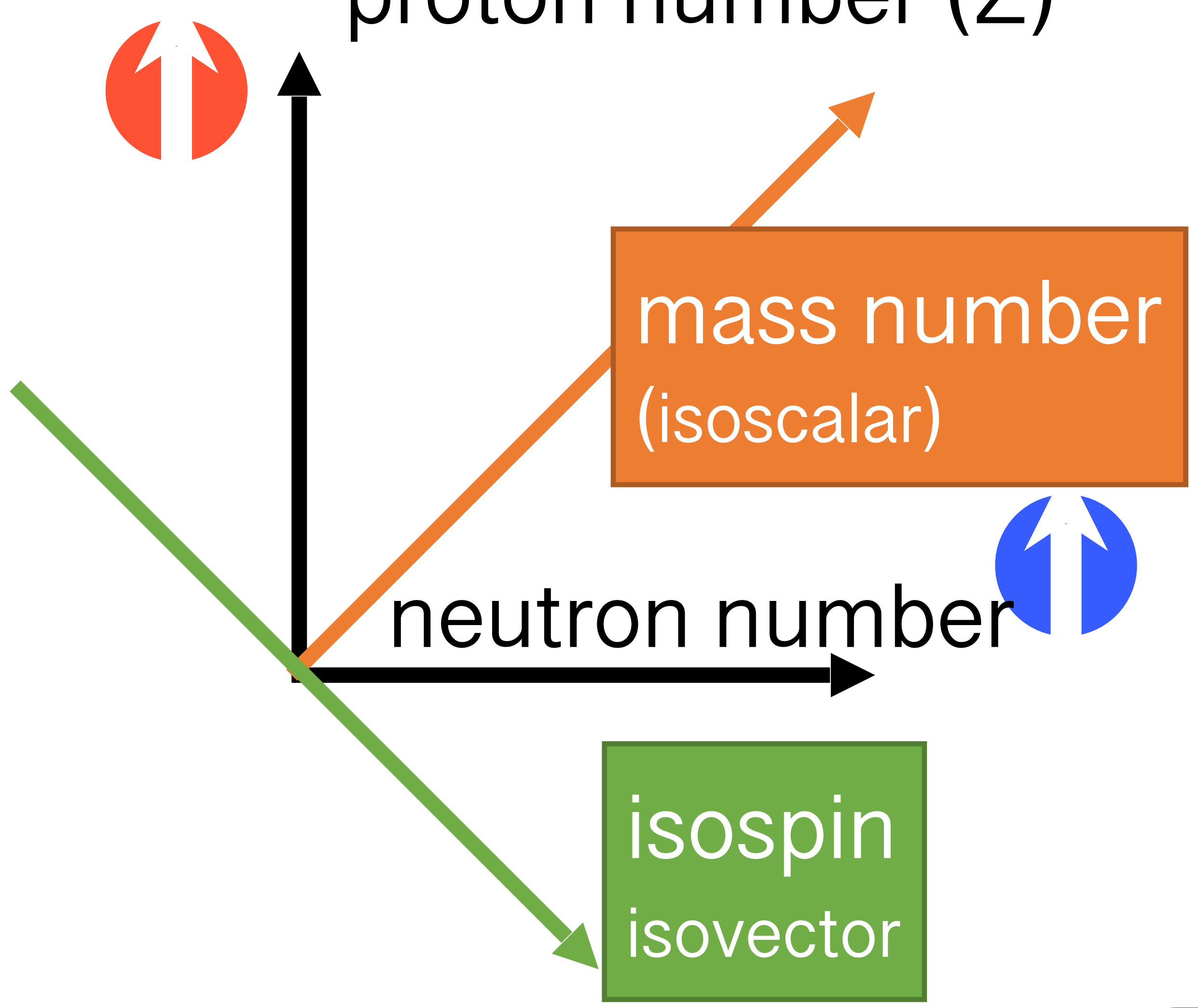
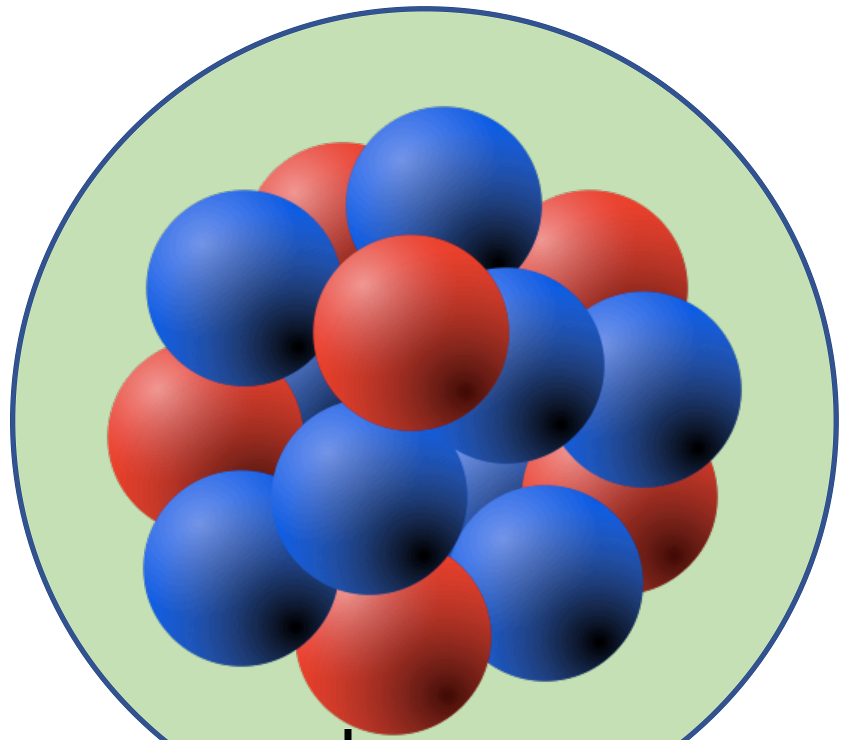
finite effect
shell, deformation, surface

Property of macroscopic nucleon system
Phase, EoS, Physical property

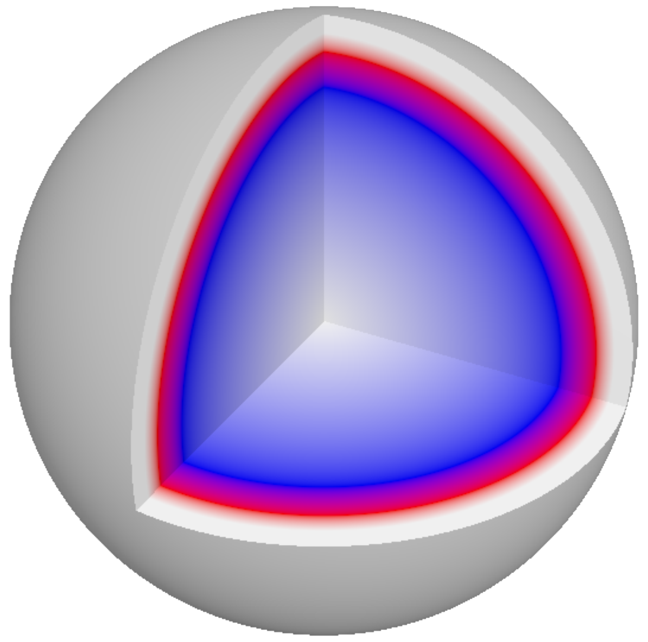
Nucleon system : micro and macro

Variable in nucleus — nuclear response ⟷ mode, physical property — macroscopic system

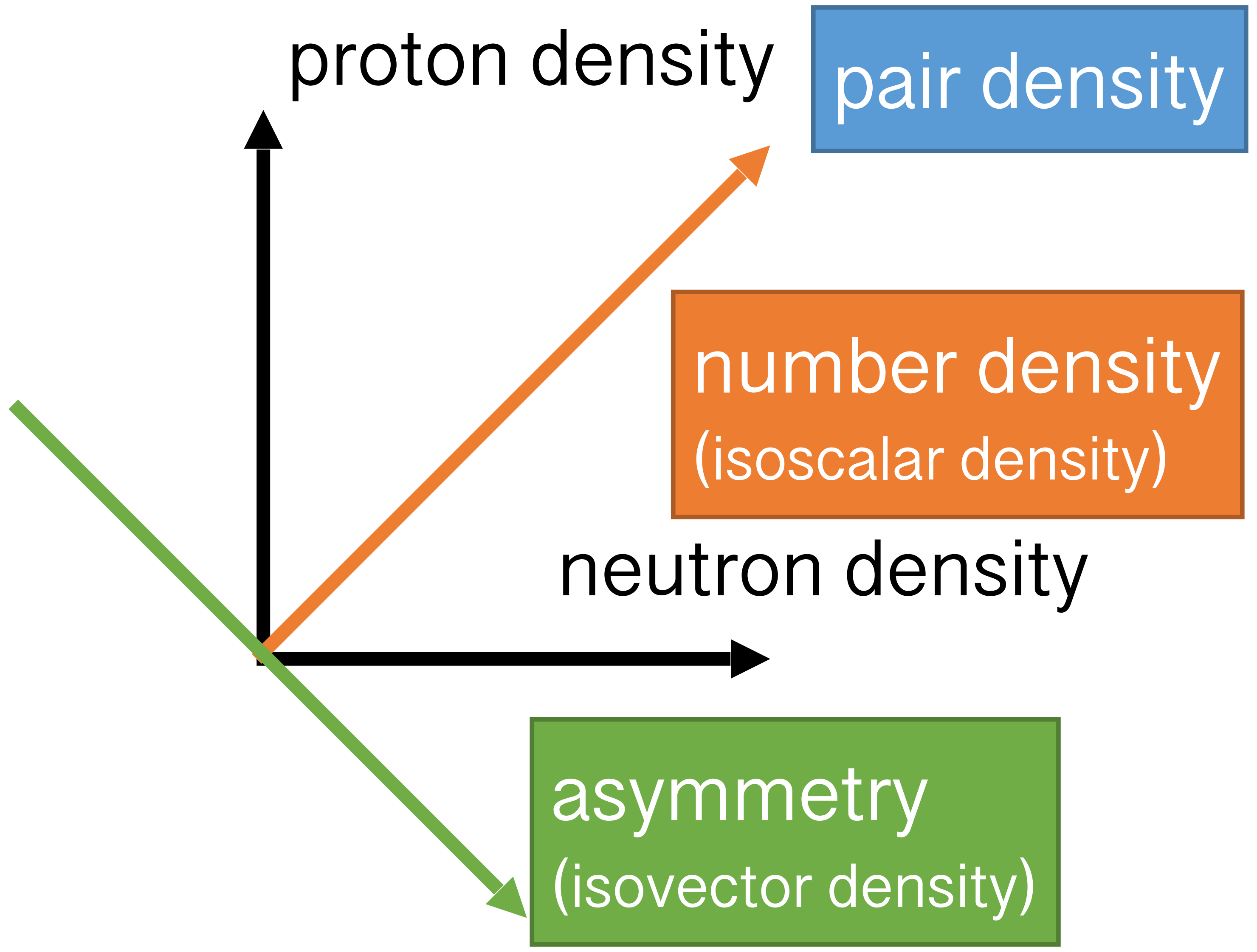




nucleus
1 fm, 1-300u



neutron star
10 km, 10^{57}u



density: const. , temp. 0

spin/orbit angular mom.

- electron system
- pair condensation

finite effect
shell, deformation, surface

Property of macroscopic nucleon system
Phase, EoS, Physical property

finite temperature
(but T=0 in this talk)

Astrophysics, Astronomy
Neutron star: cooling, M-R
Supernova, Gravitational wave

Physical property (in general)

For **a certain phase of matter**

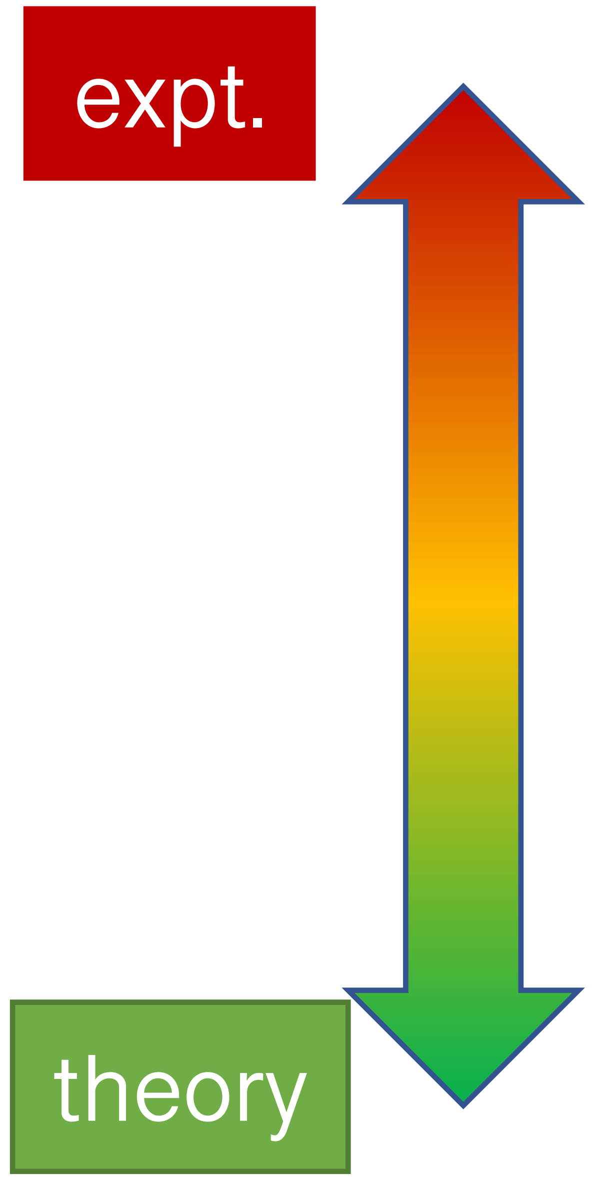
- density
- permittivity / electric susceptibility / polarizability
- permeability / magnetic susceptibility
- electrical conductivity
- elastic modulus
- boiling / melting point / transition point
- thermal conductivity
- specific heat capacity
- …

Theoretical approach to physical property

- In the field of condensed matter physics and material science, physical properties are being derived from energy density functional (ex. PHASE https://azuma.nims.go.jp/)
- In the field of nuclear physics, of course, the theoretical researchers estimate the physical properties of macroscopic nucleon system using the same technique.
  - It's difficult to quantify the medium effect or to validate the local density approximation in so-called nuclear matter.
  - The energy density functional of macroscopic nucleon system is still unknown
- We have to harry up, since the astronomical observation, which is the good reference of the theoretical calculation, goes fast!

Approach from Nuclear Physics

How to extract the macroscopic properties?



Select a probe and target
sensitive to the mode of interest

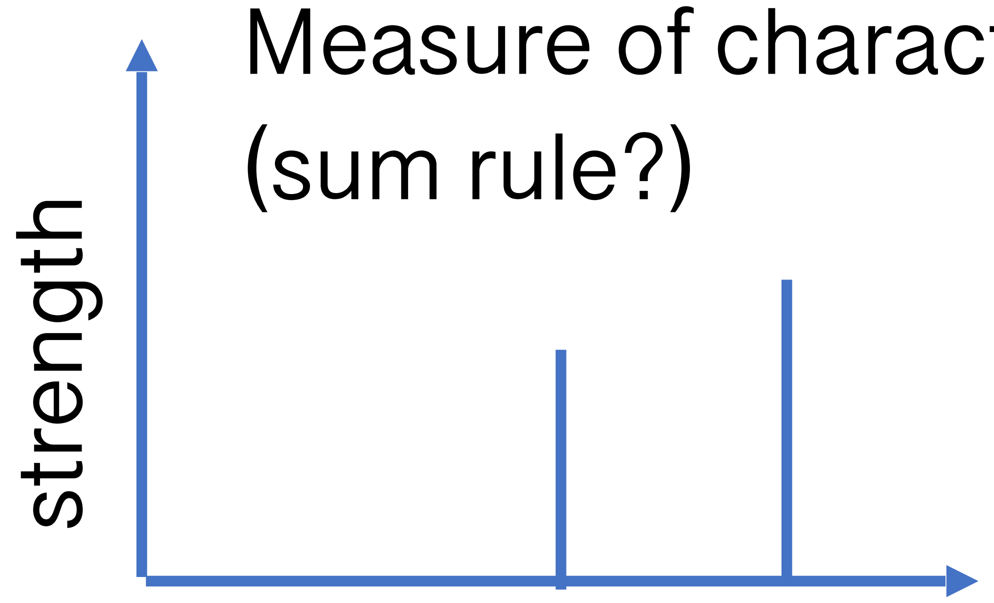
Measure the nuclear response
corresponding to the mode

Quantify the amount of characteristic

Extract the macroscopic properties from the systematics

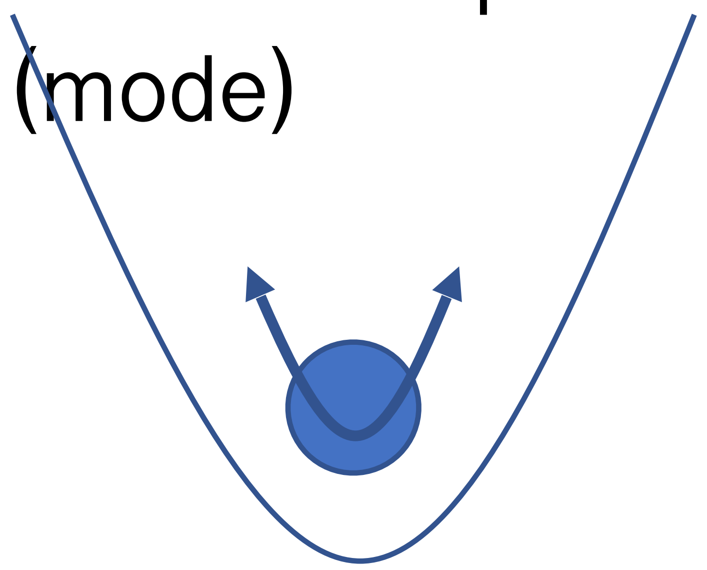
Important pieces in experiment
for this approach

Measure of characteristic
(sum rule?)

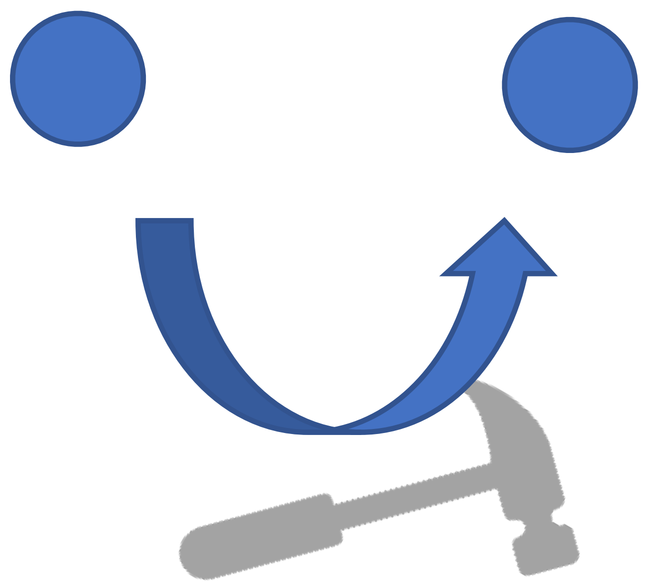


excitation energy

Nuclear response
(mode)

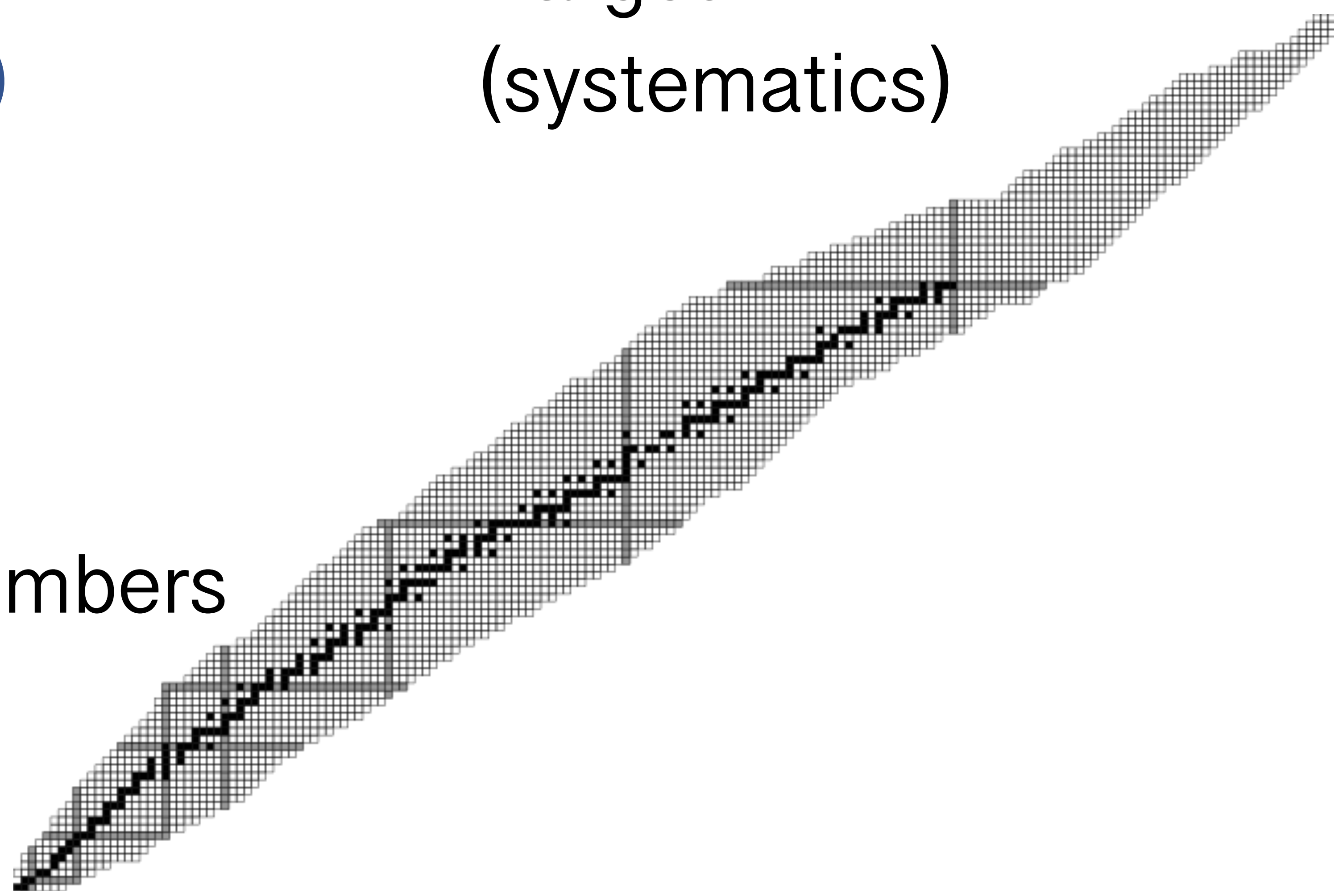


Probe



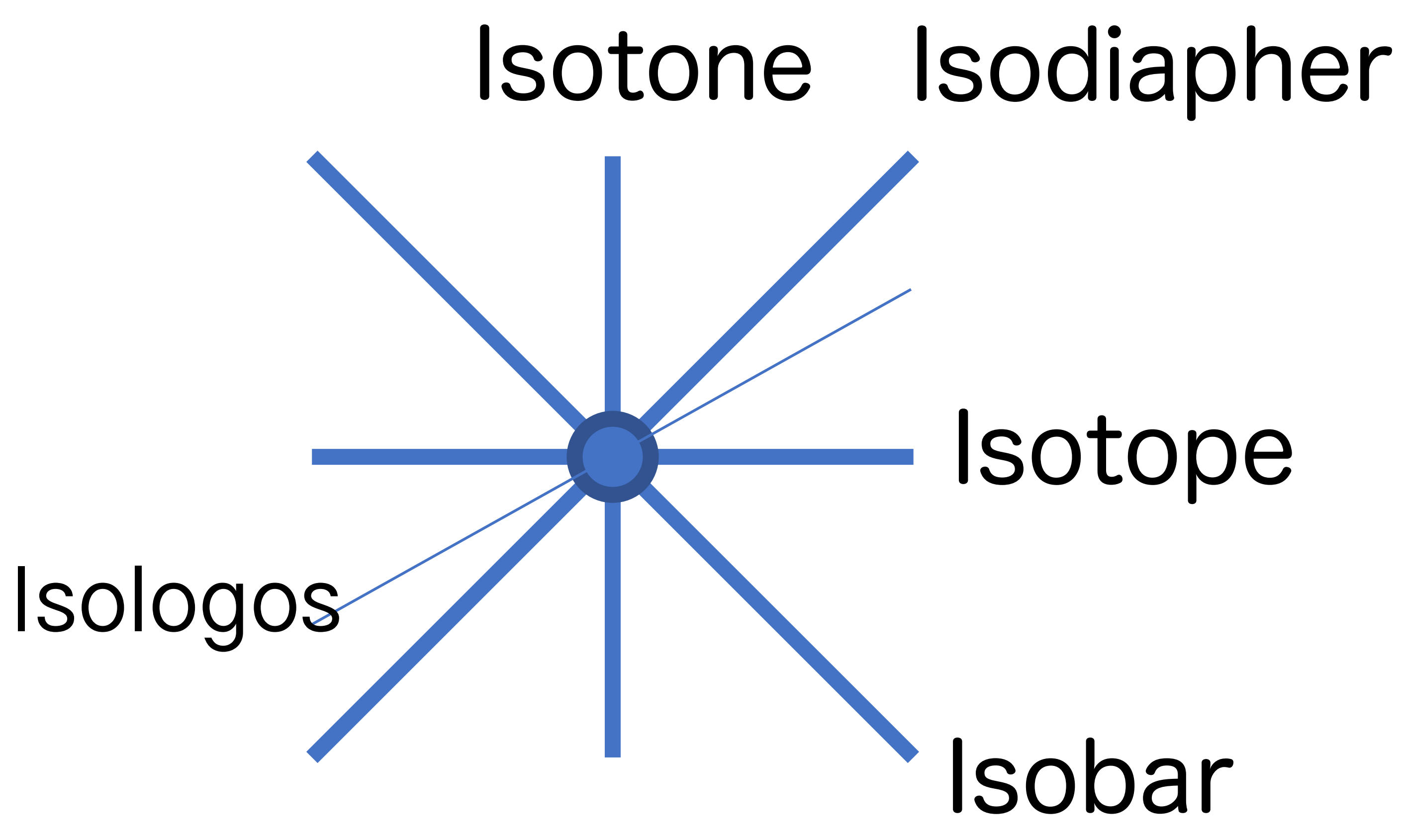
Control quantum numbers

Target
(systematics)



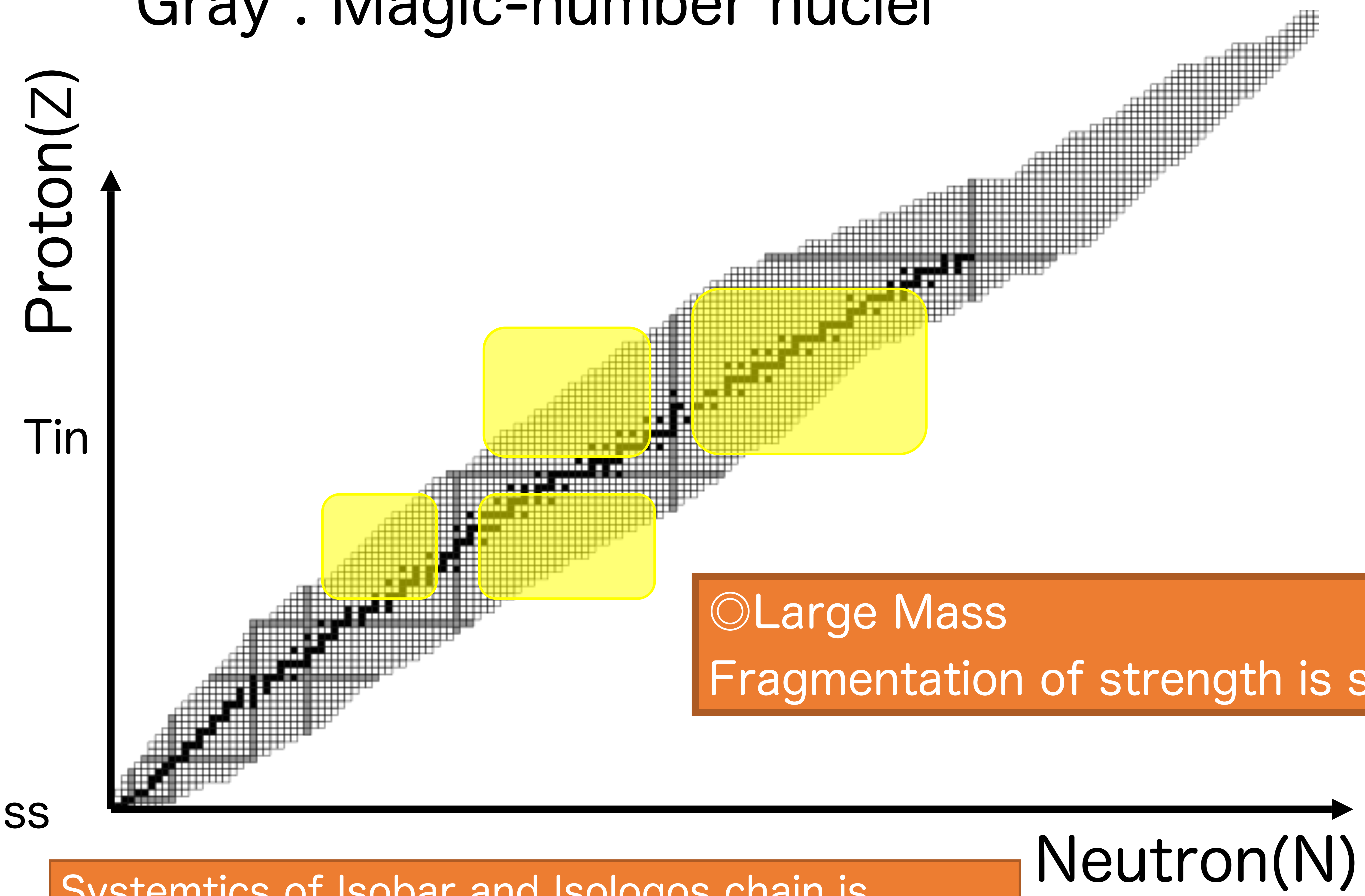
Selection of target

Systemtics



Isotope : Z = const => Neutron
Isotone : N = const => Proton
Isobar : A = const => Isovector
Isodiapher : N-Z = const => Isoscalar
“Isologos?” : (N-Z)/A or A/Z = const => Mass
(neologism)

Black: Stable nuclei
Gray : Magic-number nuclei



◎Large Mass
Fragmentation of strength is sn

Systemtics of Isobar and Isologos chain is important.

Various reactions as probes

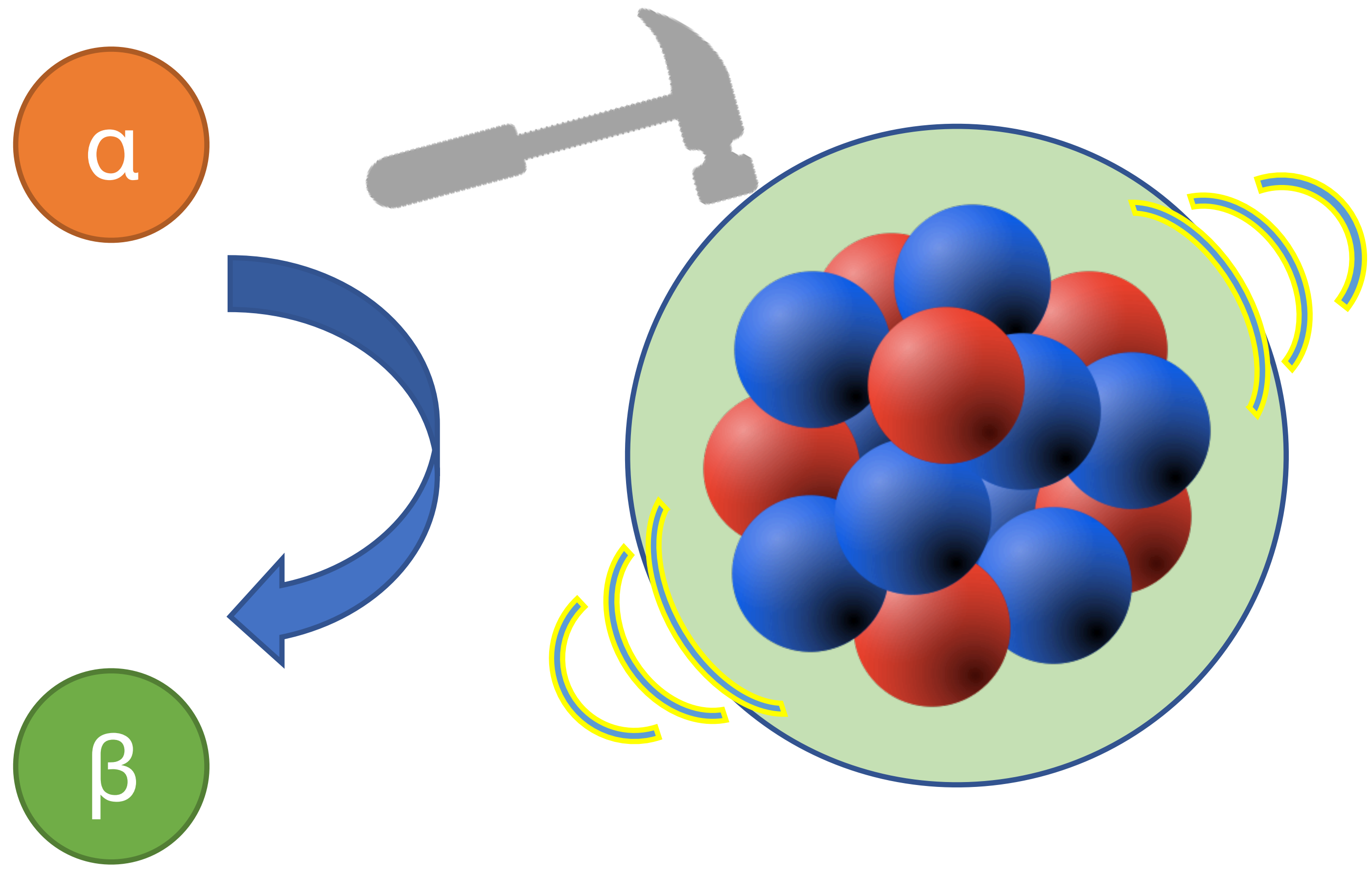
Various quantum changes

- Macroscopic properties will be revealed from the systematics of the featured values of the strength distributions.

Due to the finite-system effect, there will be,

- Strength fragmentation
- Cross section

Quantum Change
Mass number ΔA
Spin ΔS
Isospin ΔT
Angular momentum ΔL



Space-symmetric responses

	ΔS=0, ΔT=0, ΔA=0	ΔS=1, ΔT=0, ΔA=0	ΔS=0, ΔT=1, ΔA=0	ΔS=1, ΔT=1, ΔA=0	ΔA=2, ΔS, ΔT
Variable	Number density	Spin density	Isovector density	Isovector spin density	Pair density
Property	Incompressibility	Magnetism	Symmetry energy	?	Pair condensation
Probe	(a,a), (d,d)	(p,p‘), (6Li,6Li*)	(7Li,7Be*), (6He,6Li*)	(p,n),(n,p),(d,2p)…	(a,6He),(a,6Li),(a,d), (a,pn), (d,a), (n,3He), (3He,n)

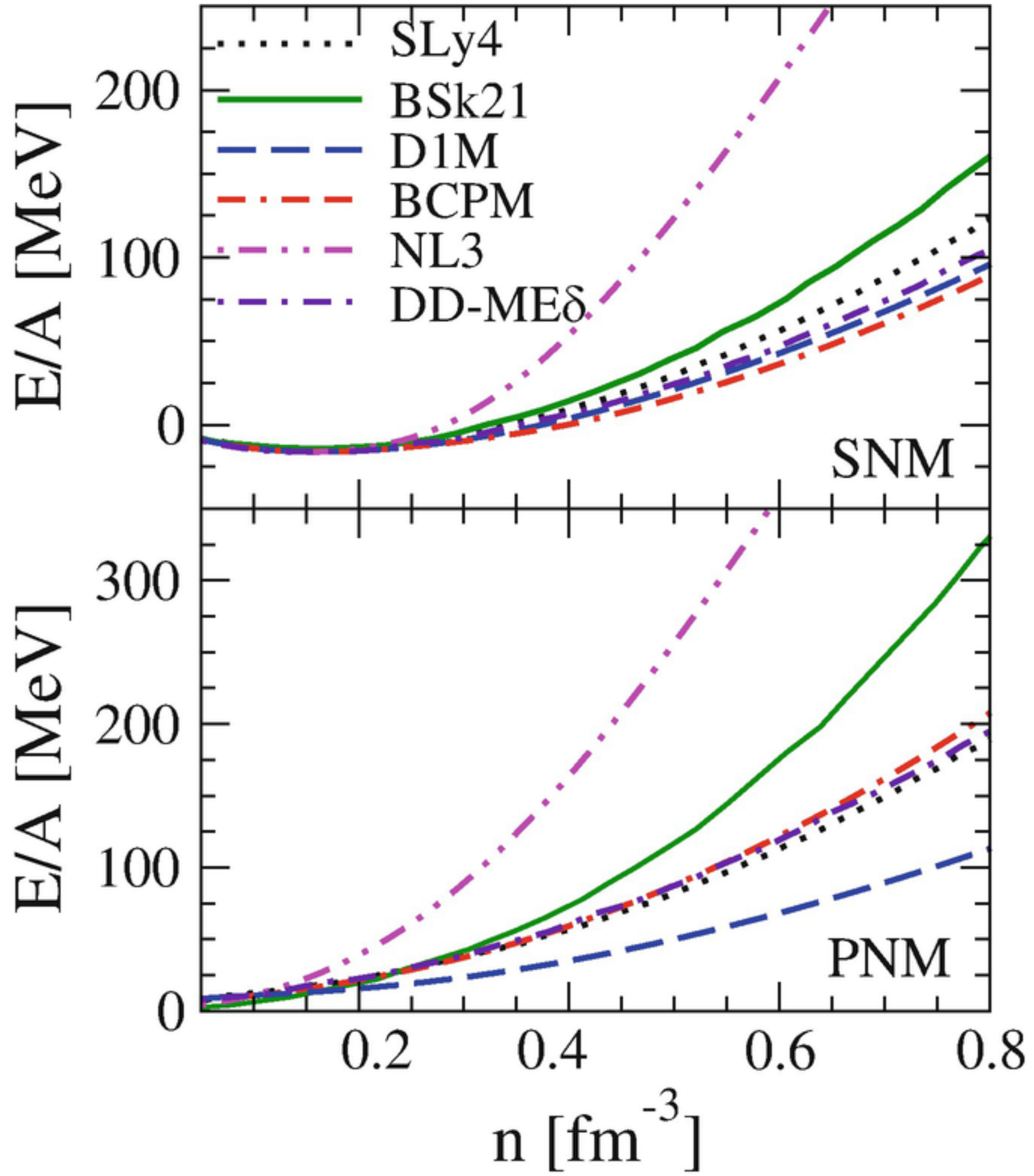
PHANES Project

(Phases and Equation of State)

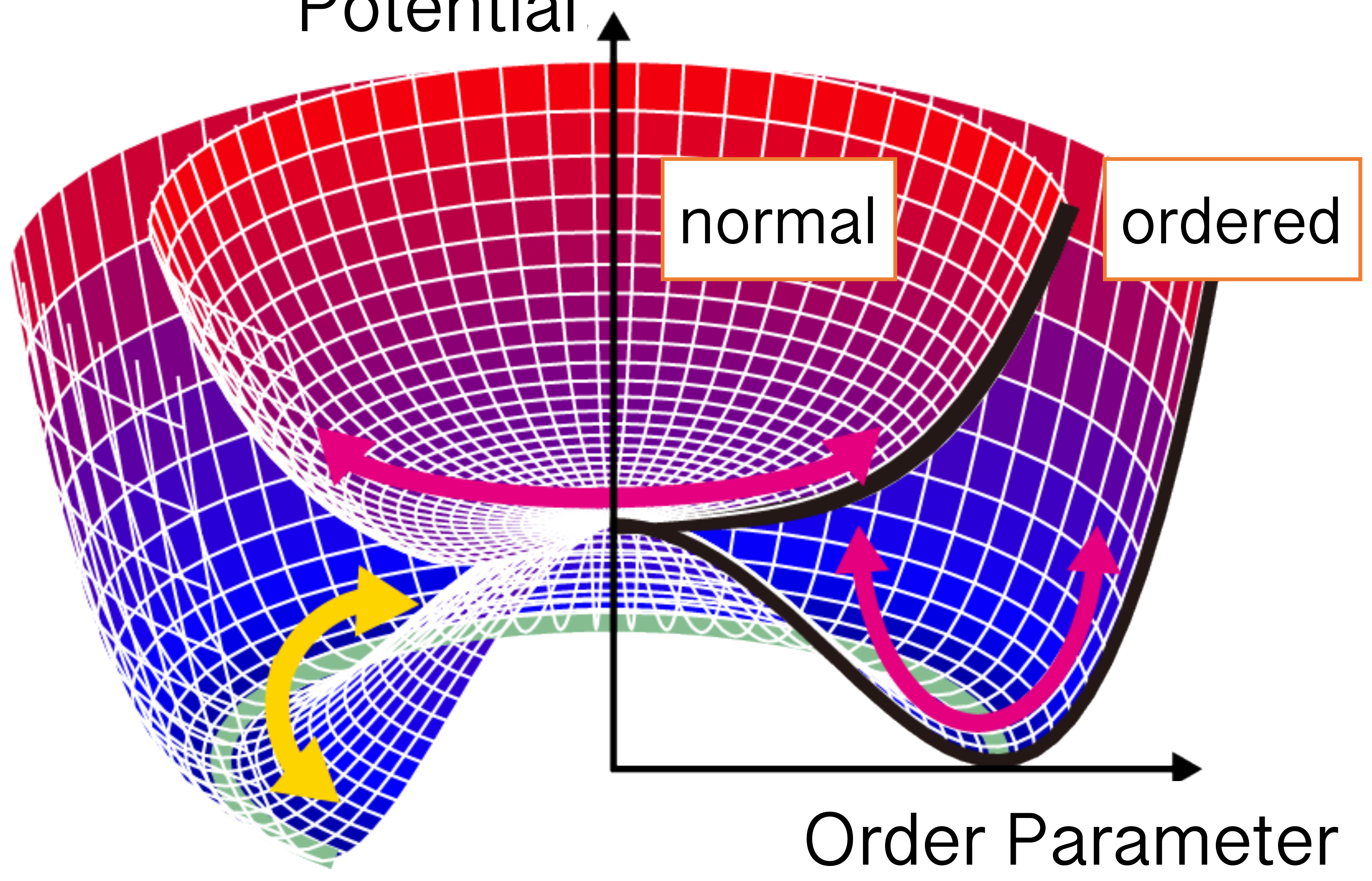
Quantify the bulk modulus and order parameter of condensations

Exp. : RCNP, Kyoto, CNS, RIKEN ..
Ther. : Niigata, Kyoto,…

Equation of state
density oscillation mode ⇔ bulk modulus



Potential vs Order parameter



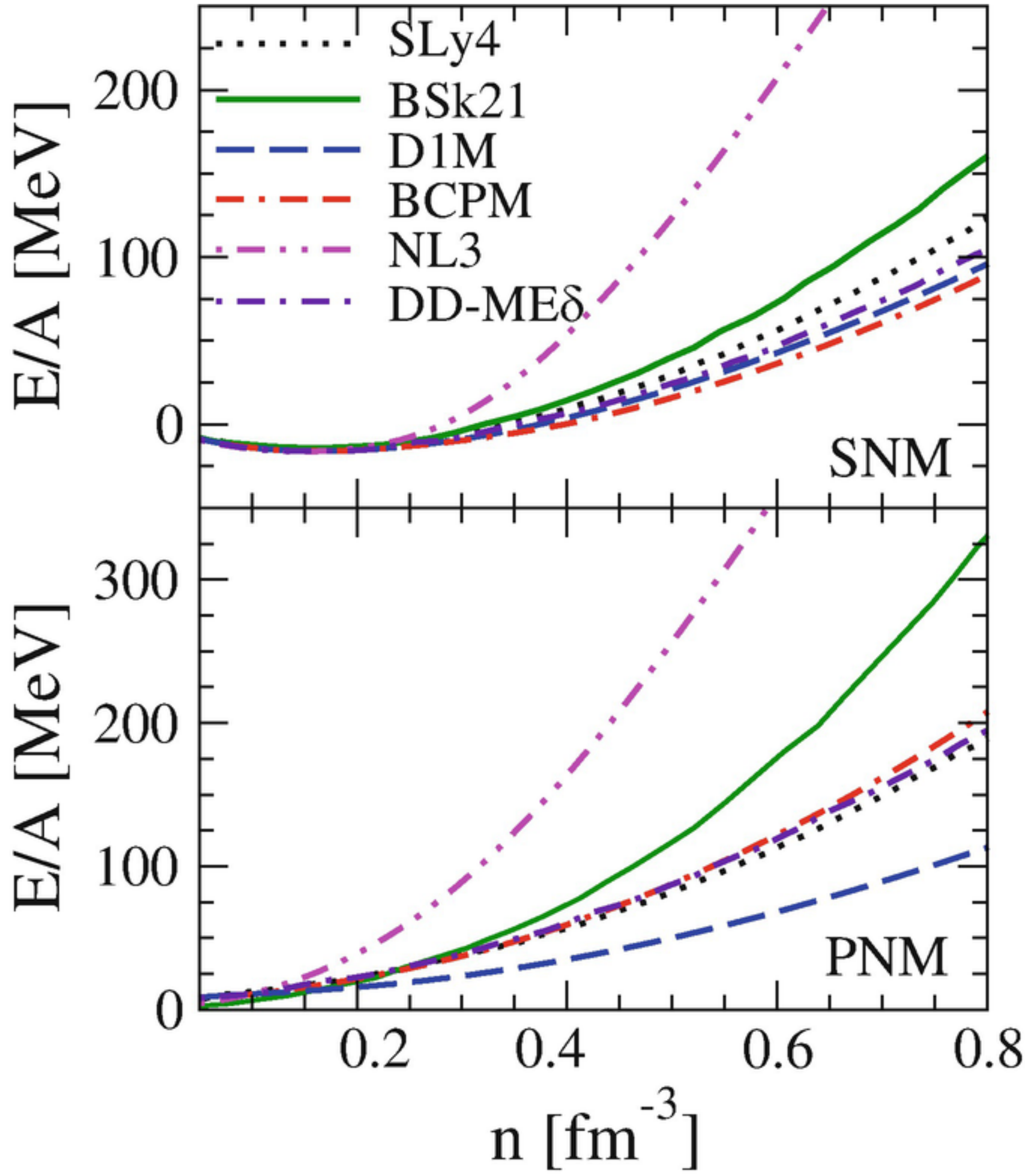
condensed phases (pair, pion, alpha …)
phase mode and amplitude mode ⇔ order parameter

Equation of state and Ktau

Is the nucleonic matter is soft or hard?

$$x = (\rho - \rho_0)/(3\rho_0), \rho = \rho_n + \rho_p, \alpha = \rho_n - \rho_p$$

$$\mathscr{E}(\rho,\alpha) \approx (\varepsilon_0 + J\alpha^2) + L\alpha^2 x + \frac{1}{2}(K_0 + \alpha^2 K_{\mathrm{sym}})x^2 + \frac{1}{6}(Q_0 + \alpha^2 Q_{\mathrm{sym}})x^3 + \mathcal{O}(x^4)$$



At a new saturation density $\bar{\rho}$, and $\bar{x}$,

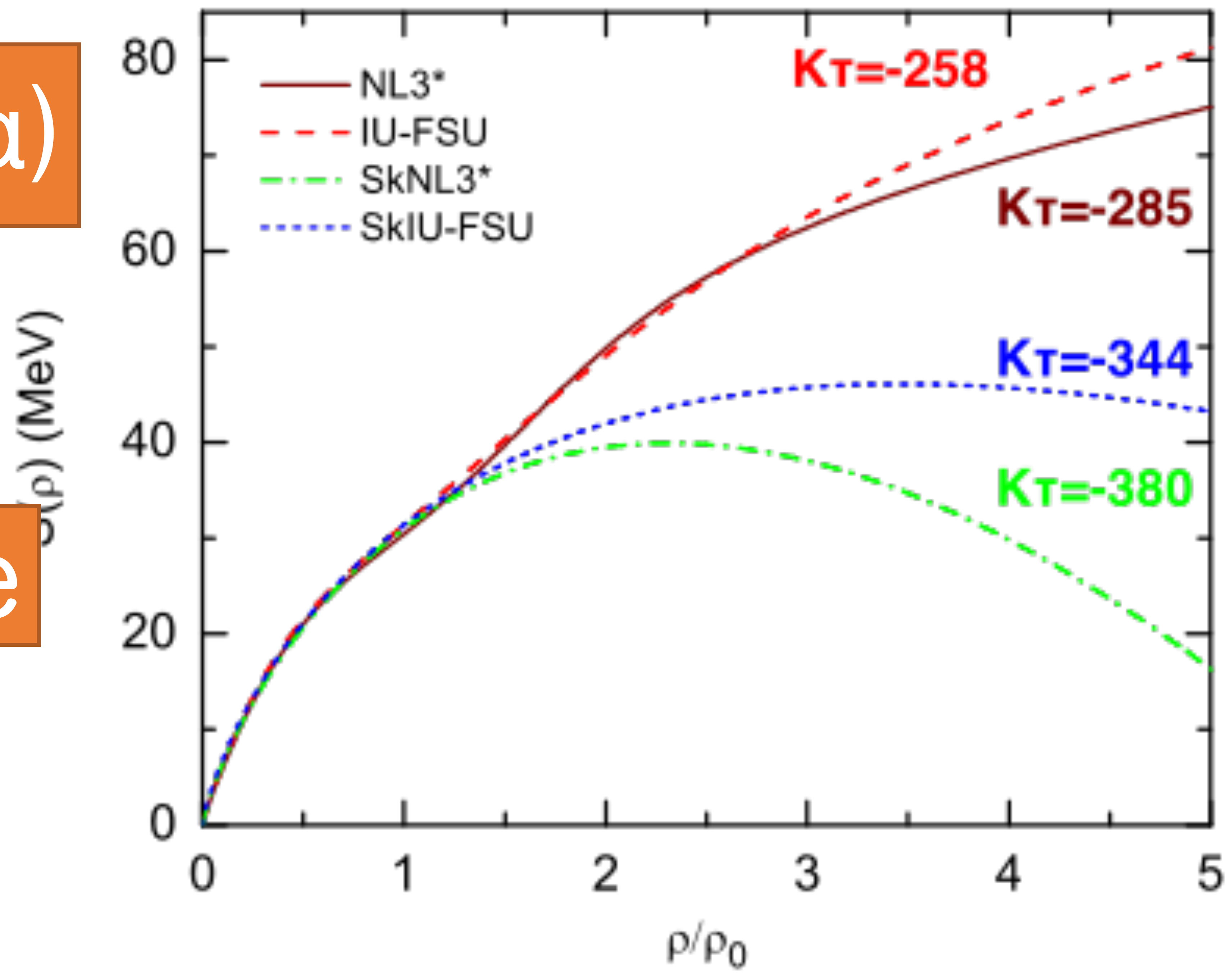
Incompressibility $K_0(\alpha)$

$$\mathscr{E}(\rho,\alpha) \equiv \varepsilon_0(\alpha) + \frac{1}{2}K_0(\alpha)\bar{x}^2 + \cdots$$

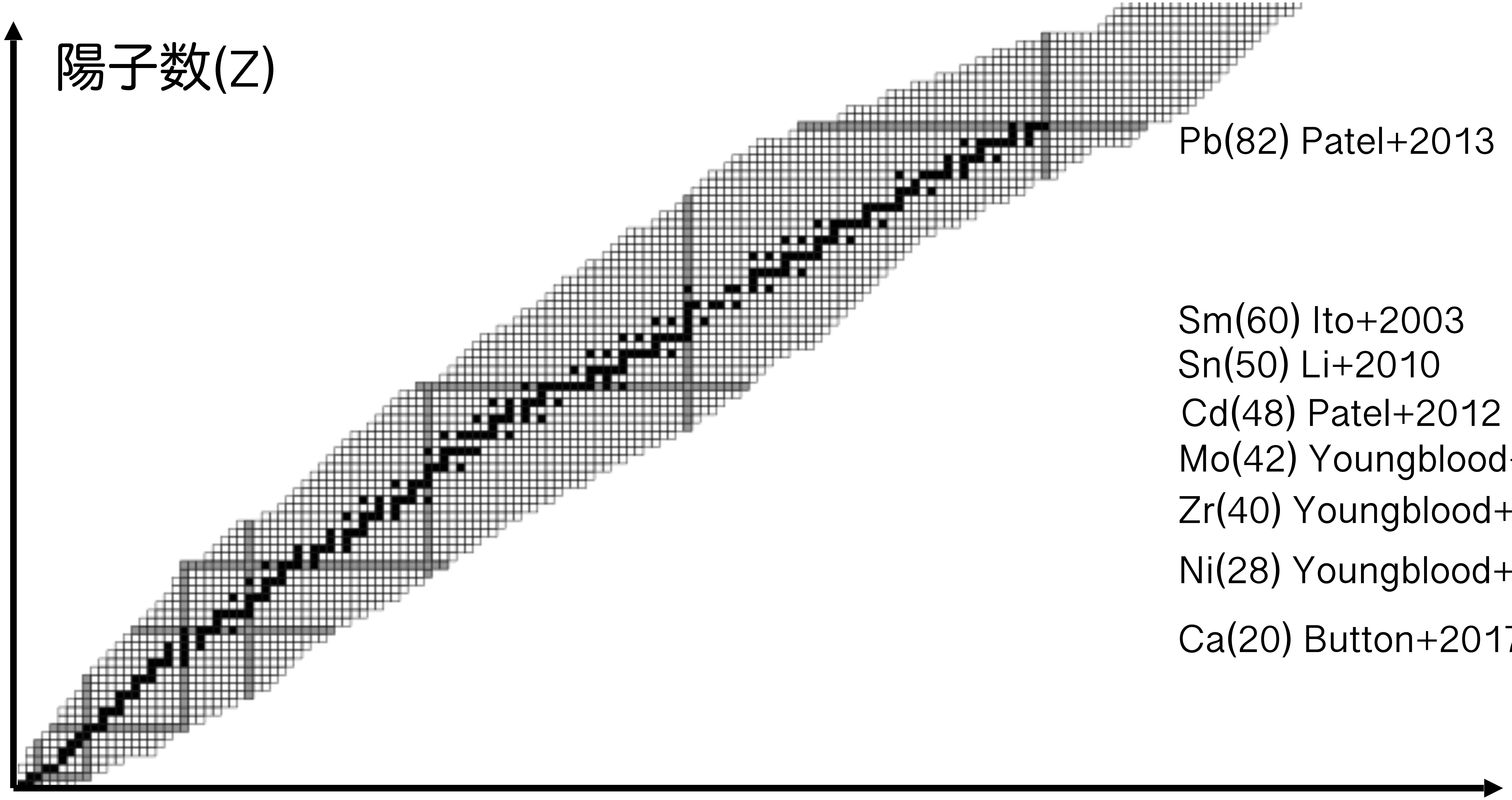
$$K_0(\alpha) = K_0 + K_\tau \alpha^2 + \mathcal{O}(\alpha^4)$$

Isosopin dependence

$$K_\tau = K_{\mathrm{sym}} - 6L + \frac{Q_0}{K_0}L$$



History of ISGMR measurement (Z>=20)



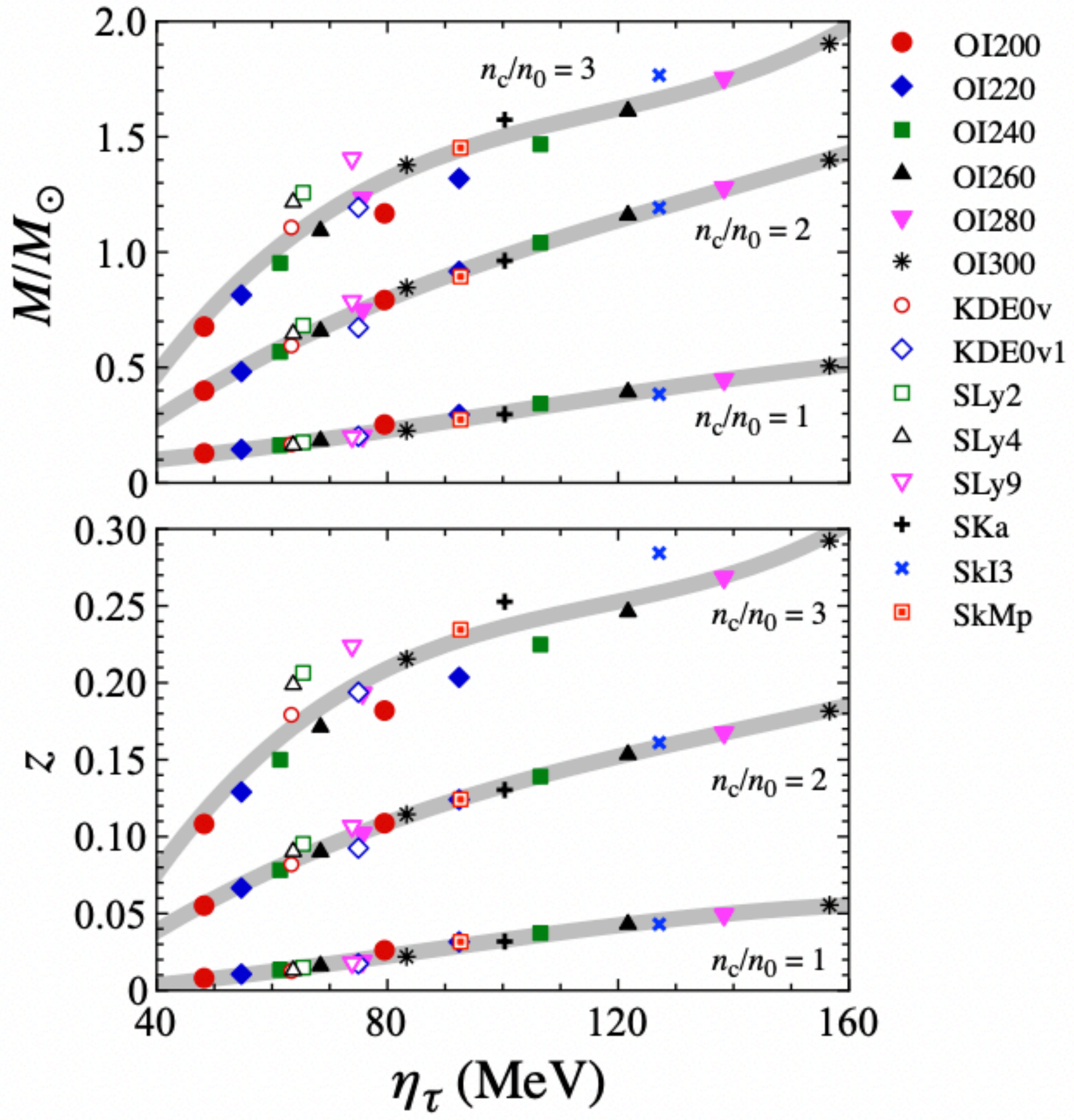
Pb(82) Patel+2013

Sm(60) Ito+2003
Sn(50) Li+2010
Cd(48) Patel+2012
Mo(42) Youngblood+2015, Howard+2020
Zr(40) Youngblood+2015, Gupta+2018
Ni(28) Youngblood+2018,

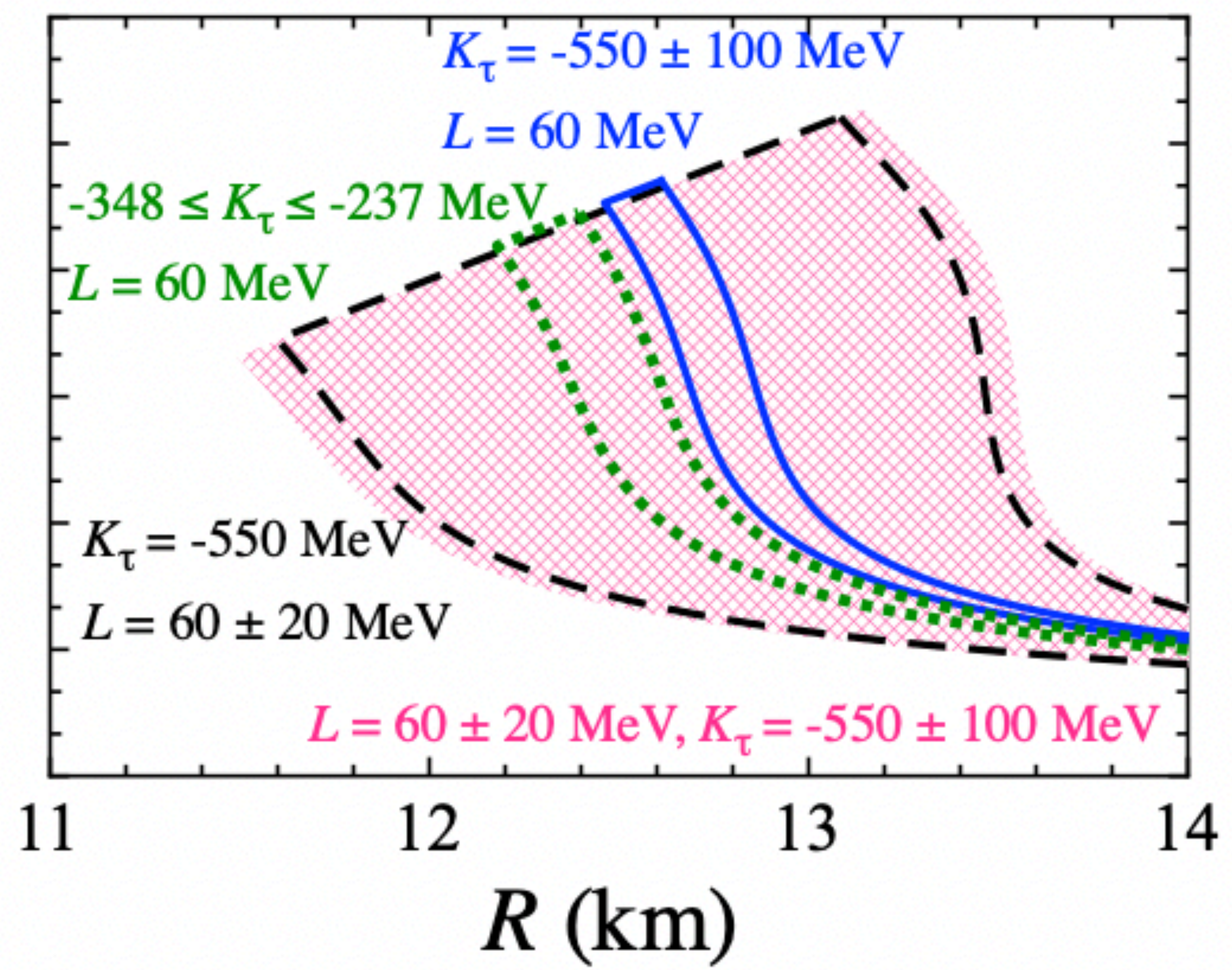
Ca(20) Button+2017, Howard+2020

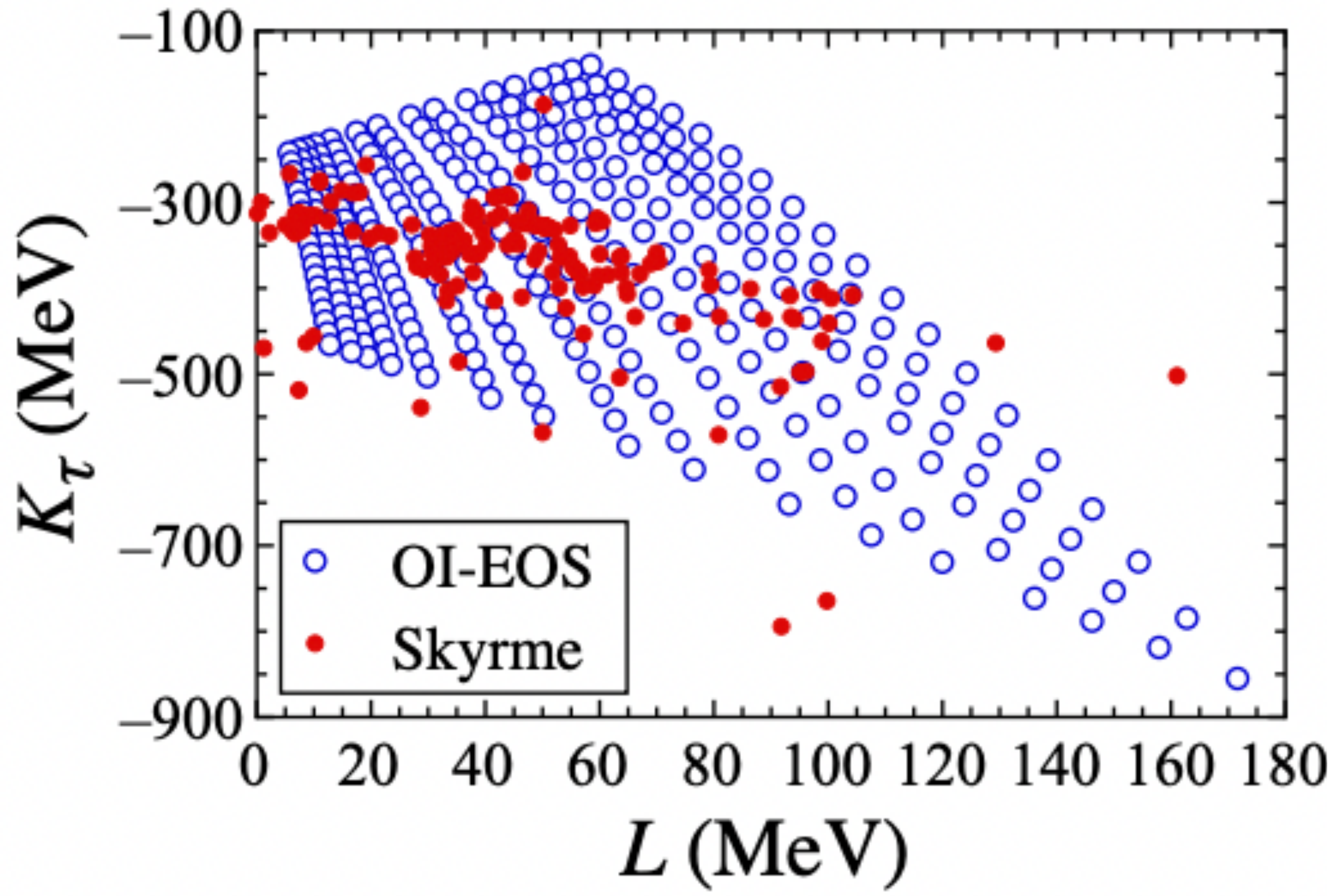
Effect of uncertainty

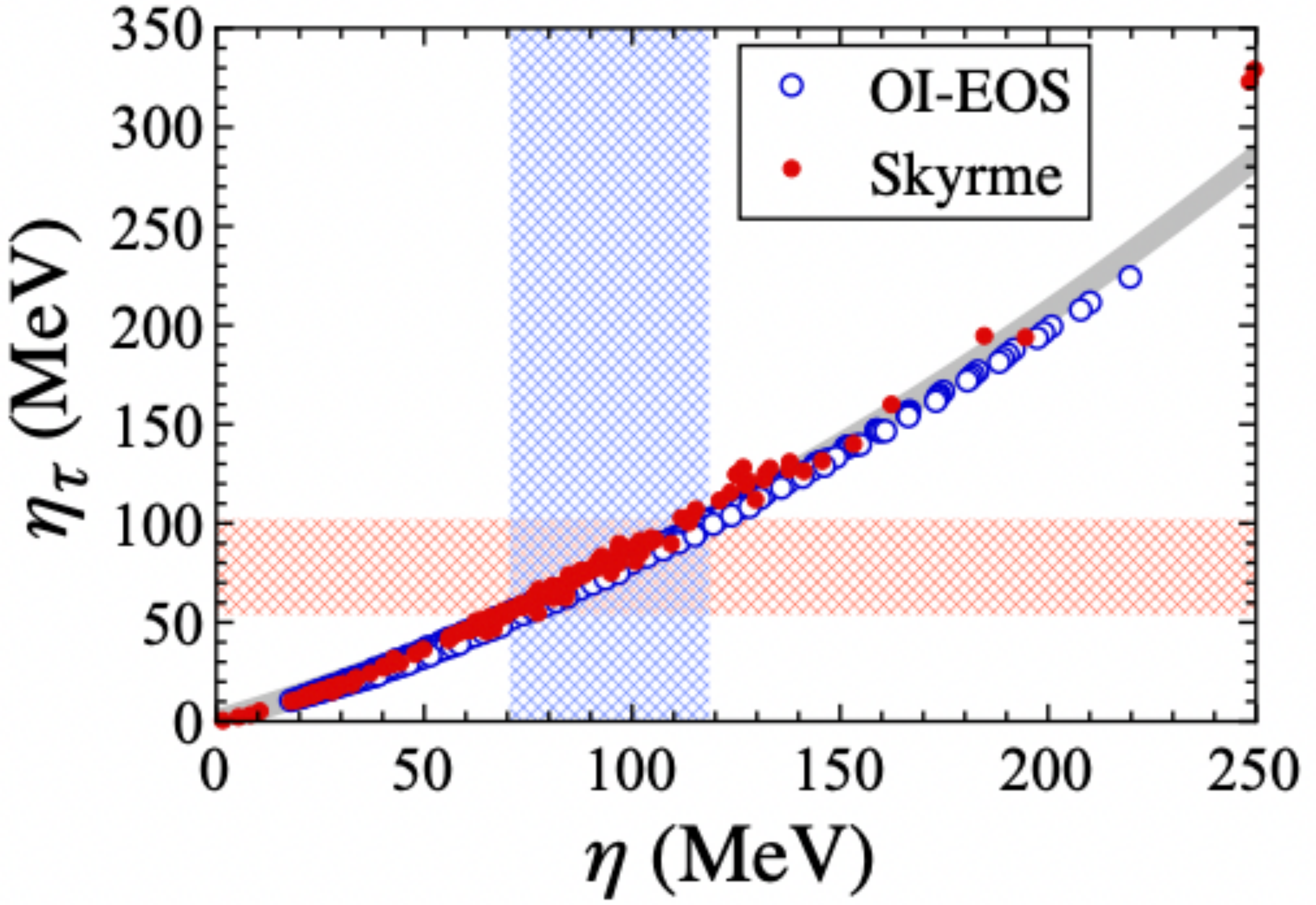
- A new scaling parameter $\eta_\tau = (-K_\tau L^5)^{1/6}$ is suggested in the same manner with $\eta = (K_0 L^2)^{1/3}$ (Sotani+2014 and Sotani+2022)
- In the M-R relation, uncertainty arises mainly from L parameter for now. But uncertainty or accuracy of K_τ



H. Sotani and SO to be submitted







Scaling using η_τ

$$\eta_\tau = (-K_\tau L^5)^{1/6}$$

$$\eta = (K_0 L^2)^{1/3}$$

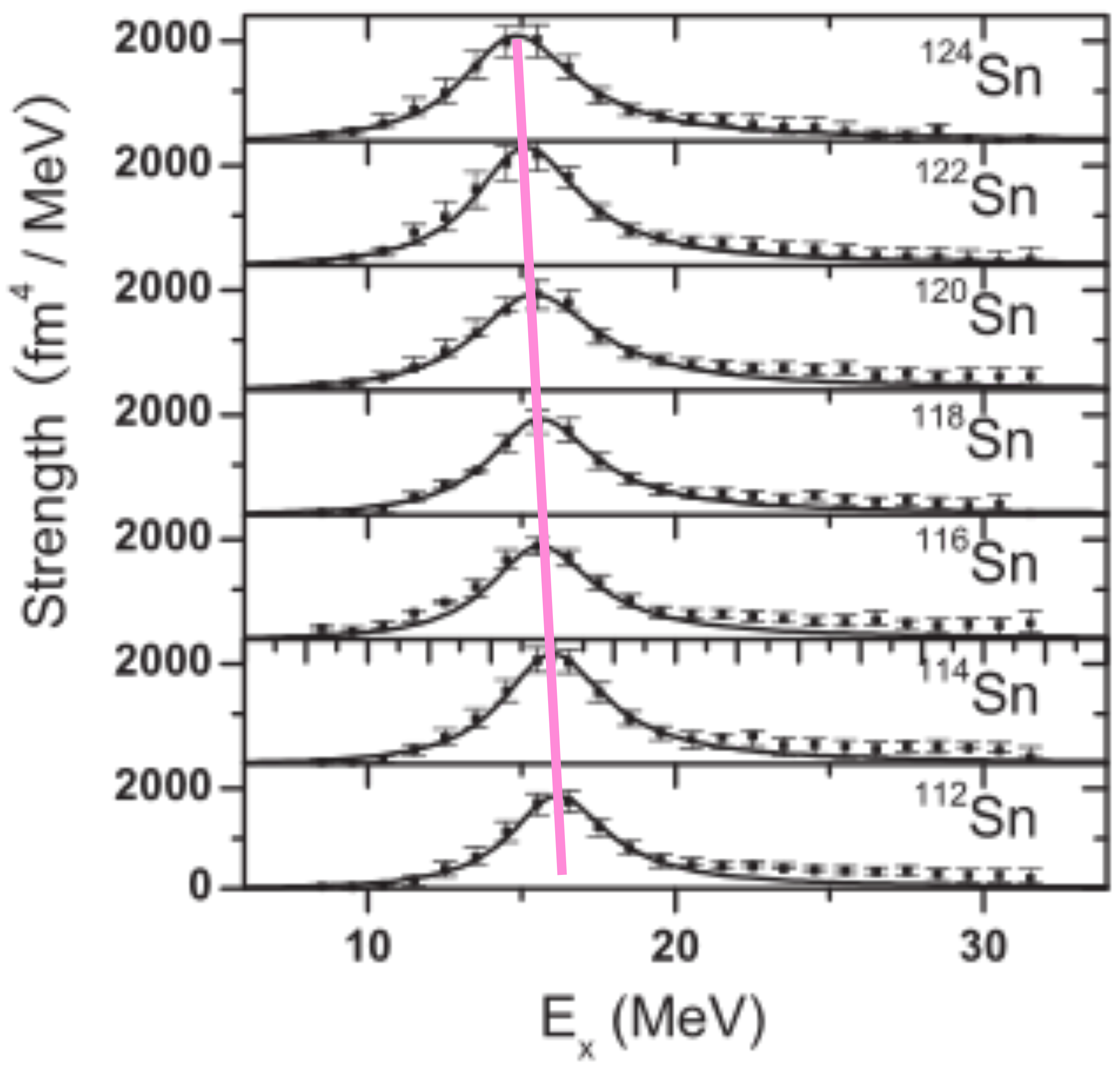
H. Sotani and SO to be submitted

Experimental approach to macroscopic property

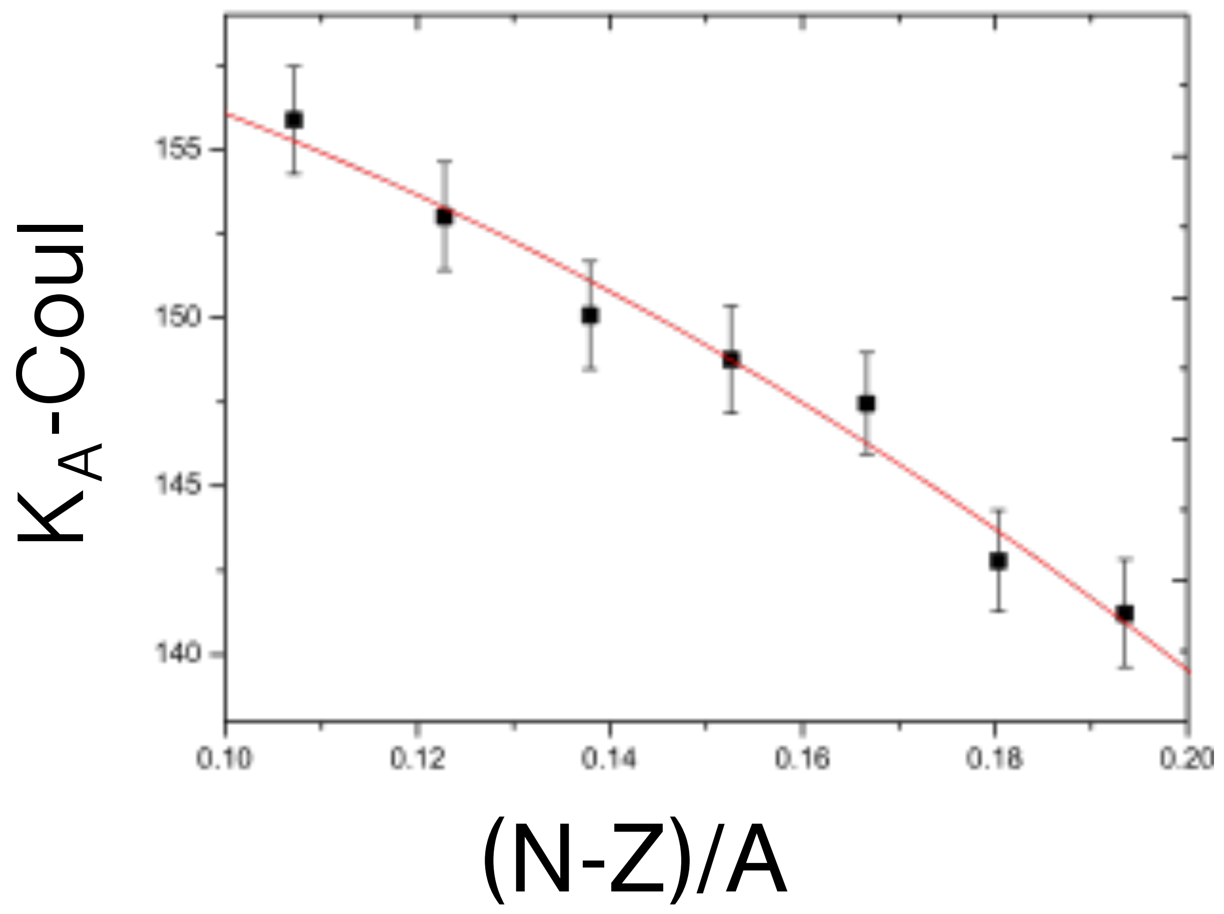
Is the neutron matter is soft or hard?

Incompressibility and ISGMR Energy

$$E_{\mathrm{GMR}} = \hbar\sqrt{\frac{K_A}{m\langle r^2\rangle}}$$



T. Li, U. Garg et al.



$K_{\tau,V}$ = -550 +-100 MeV (large uncertainty)

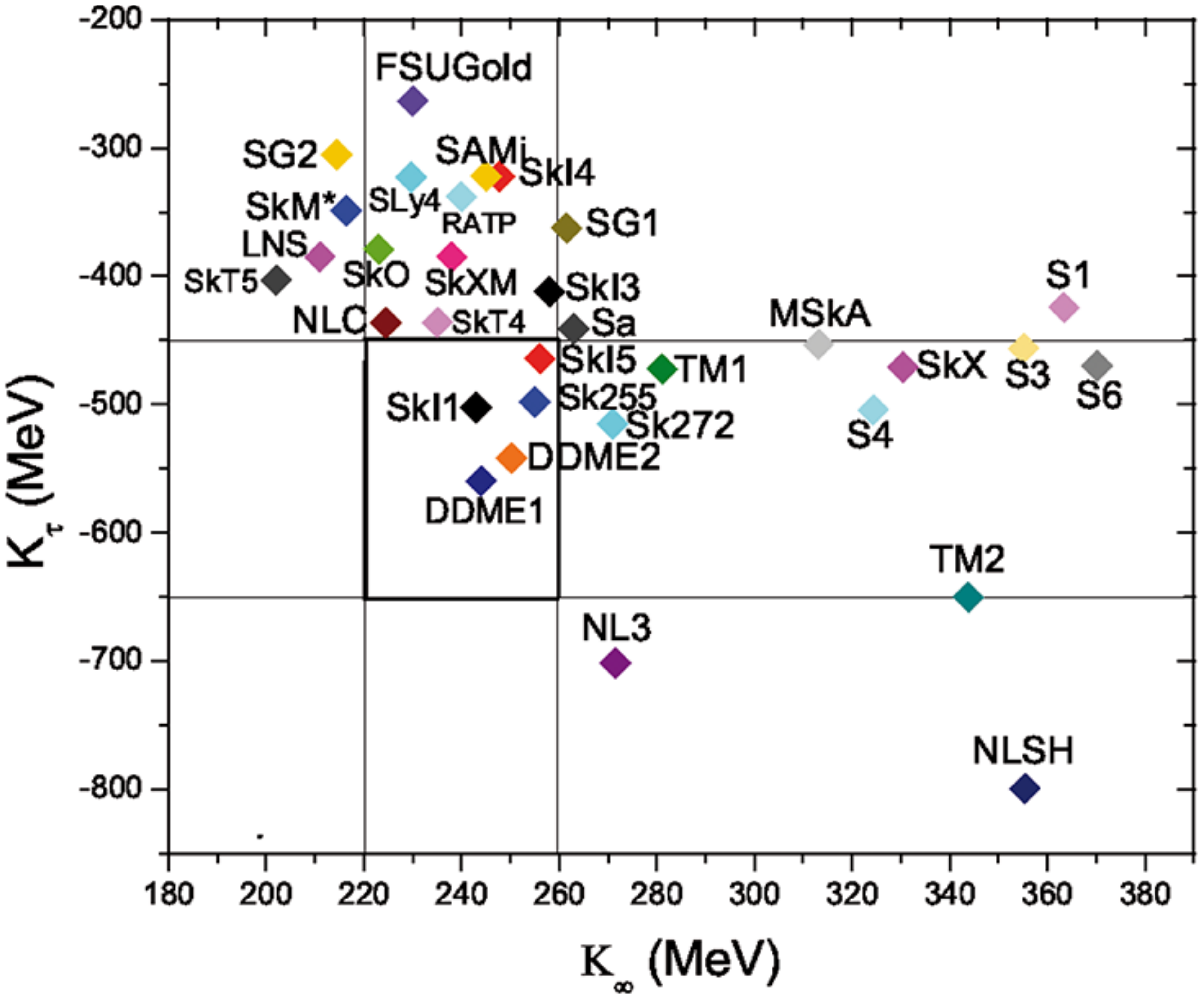
$$K_A = K_{0,V} + K_{0,\mathrm{S}}A^{-1/3} + (K_{\tau,V} + K_{\tau,\mathrm{S}}A^{-1/3})\frac{(N-Z)^2}{A^2} + K_{\mathrm{Coul}}\frac{Z^2}{A^{4/3}} + \mathcal{O}(A^{-2/3})$$

Incompressibility SNM

Asymmetry term of incompressibility

Incompressibility from theory

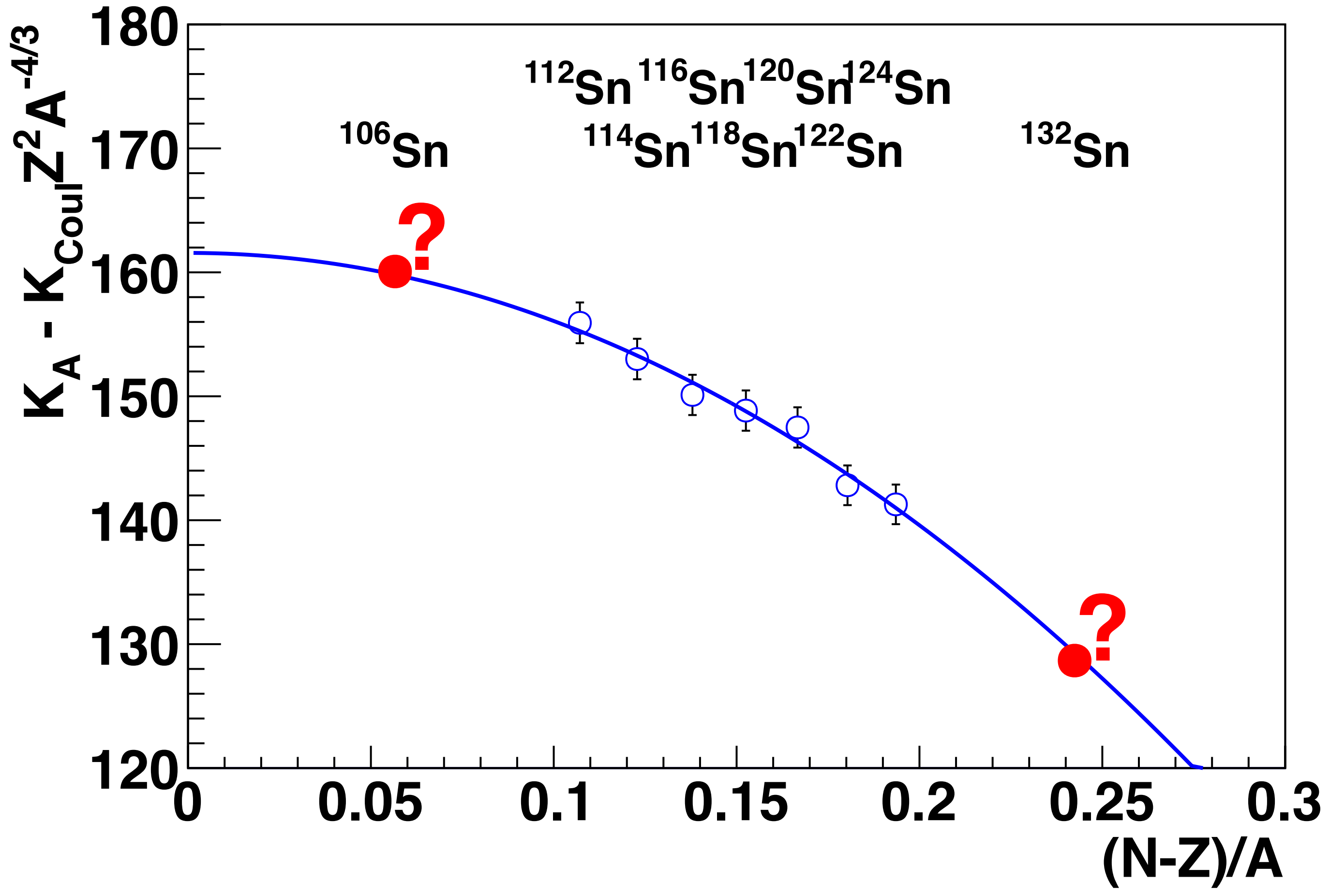
- Scatter in wide range of each parameter and correlation is almost nothing
- Many of interactions are out of candidates?

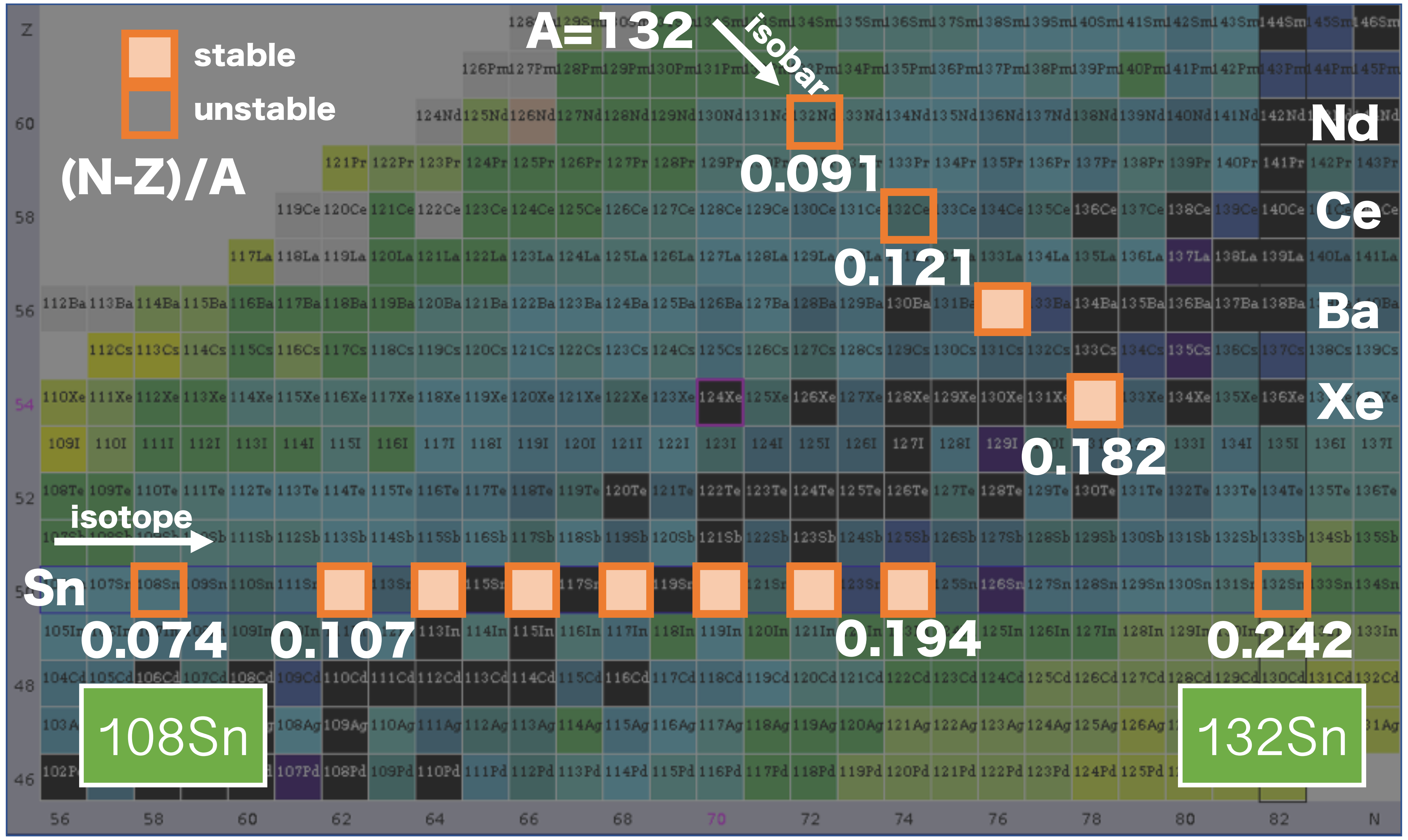


Colo+2014

How about the neutron matter?

The systematics including the unstable nuclei is desired.





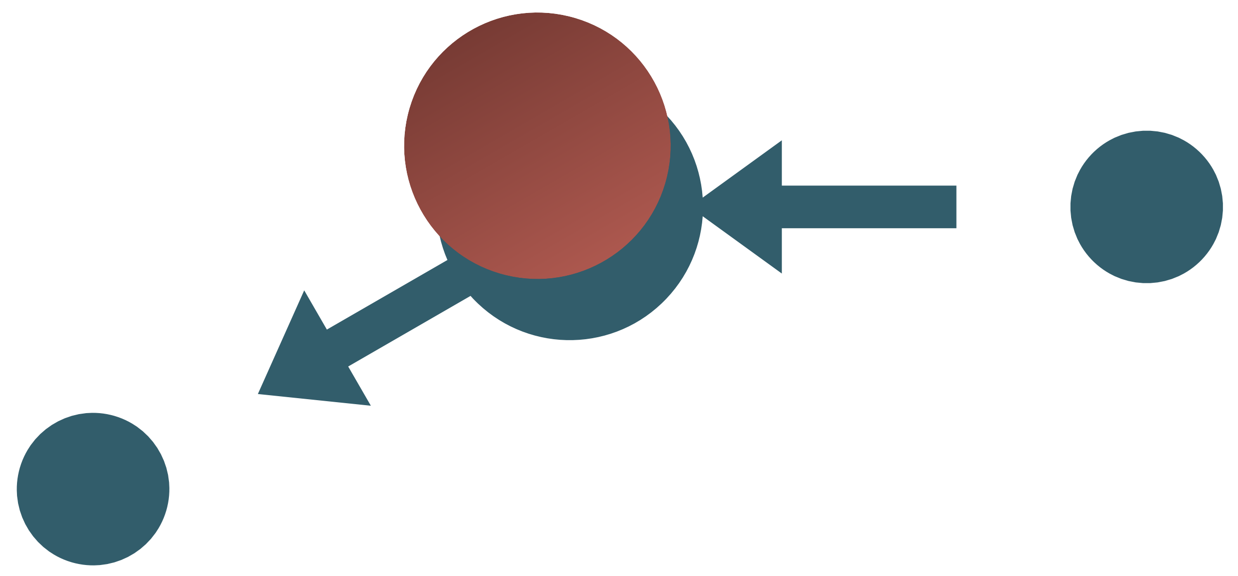
$$K_A = K_{0,V} + K_{0,\mathrm{S}} A^{-1/3} + (K_{\tau,V} + K_{\tau,\mathrm{S}} A^{-1/3}) \frac{(N-Z)^2}{A^2} + K_{\mathrm{Coul}} \frac{Z^2}{A^{4/3}} + \mathcal{O}(A^{-2/3})$$

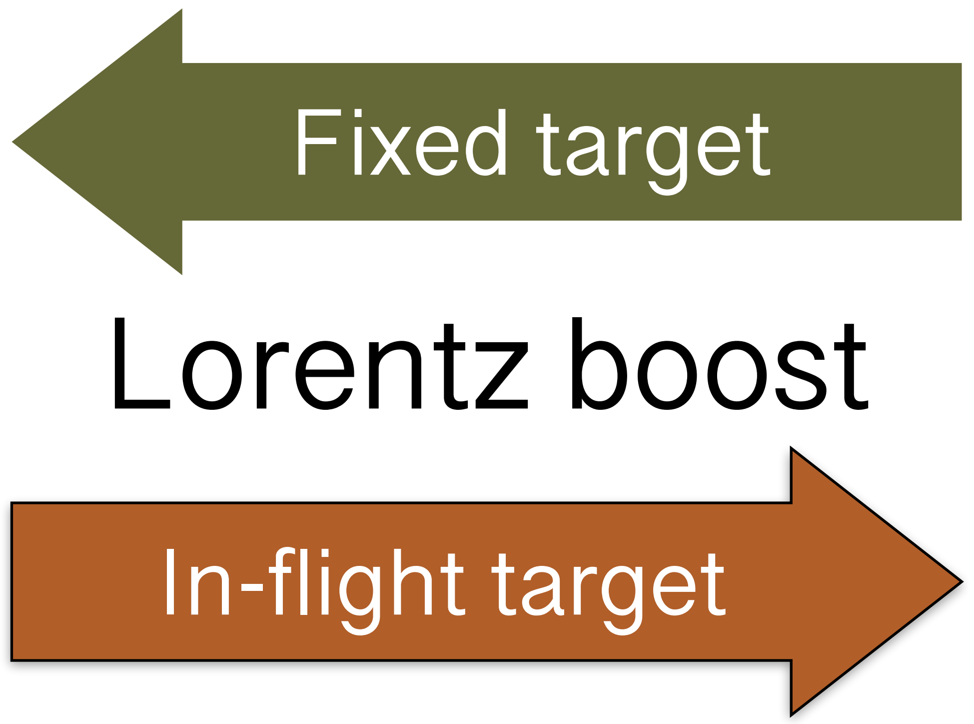
Incompressibility of symmetric matter

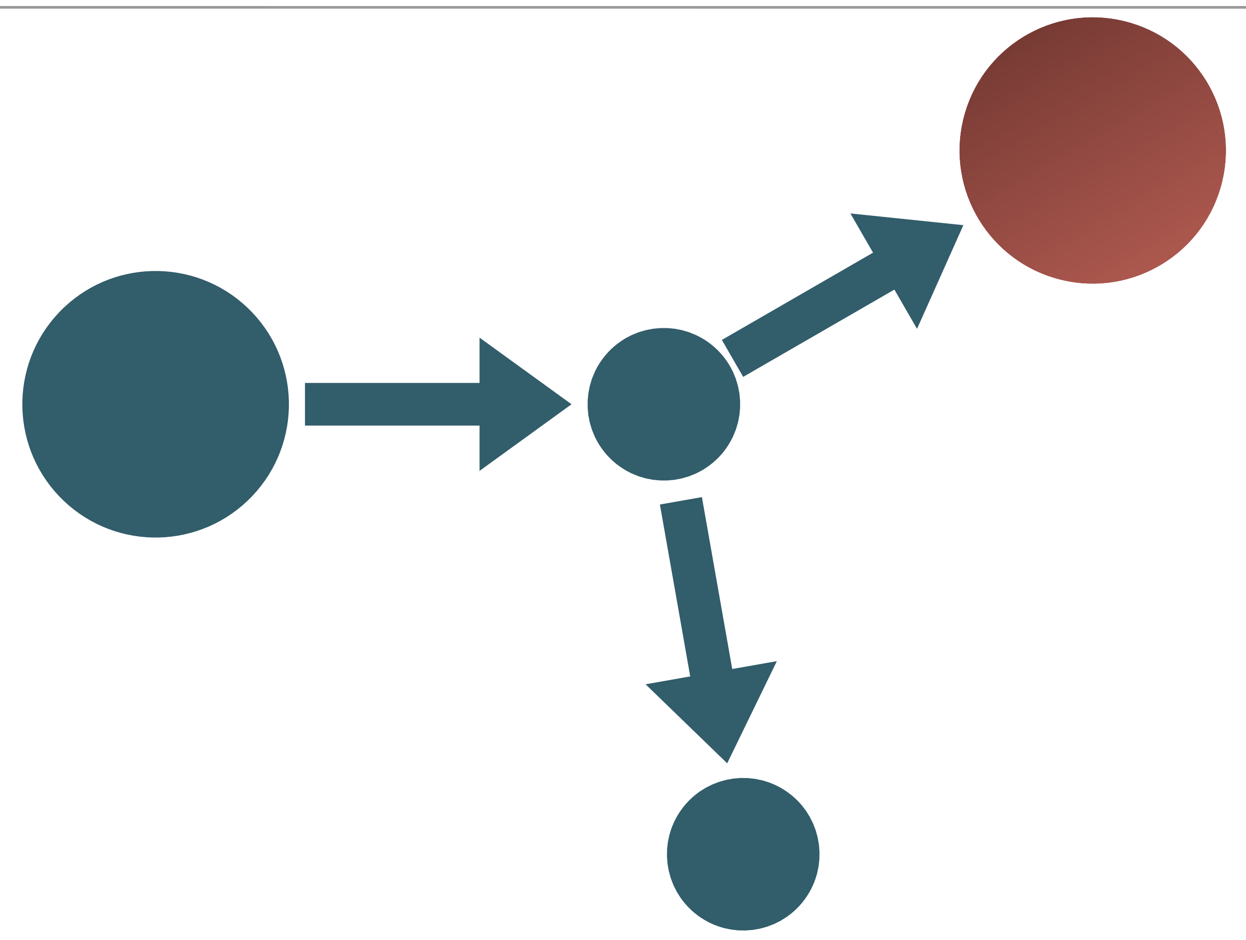
Isospin dependence

Systematic measurement with CAT-M and GRAND RAIDEN

Implementation of nuclear reaction in the laboratory frame

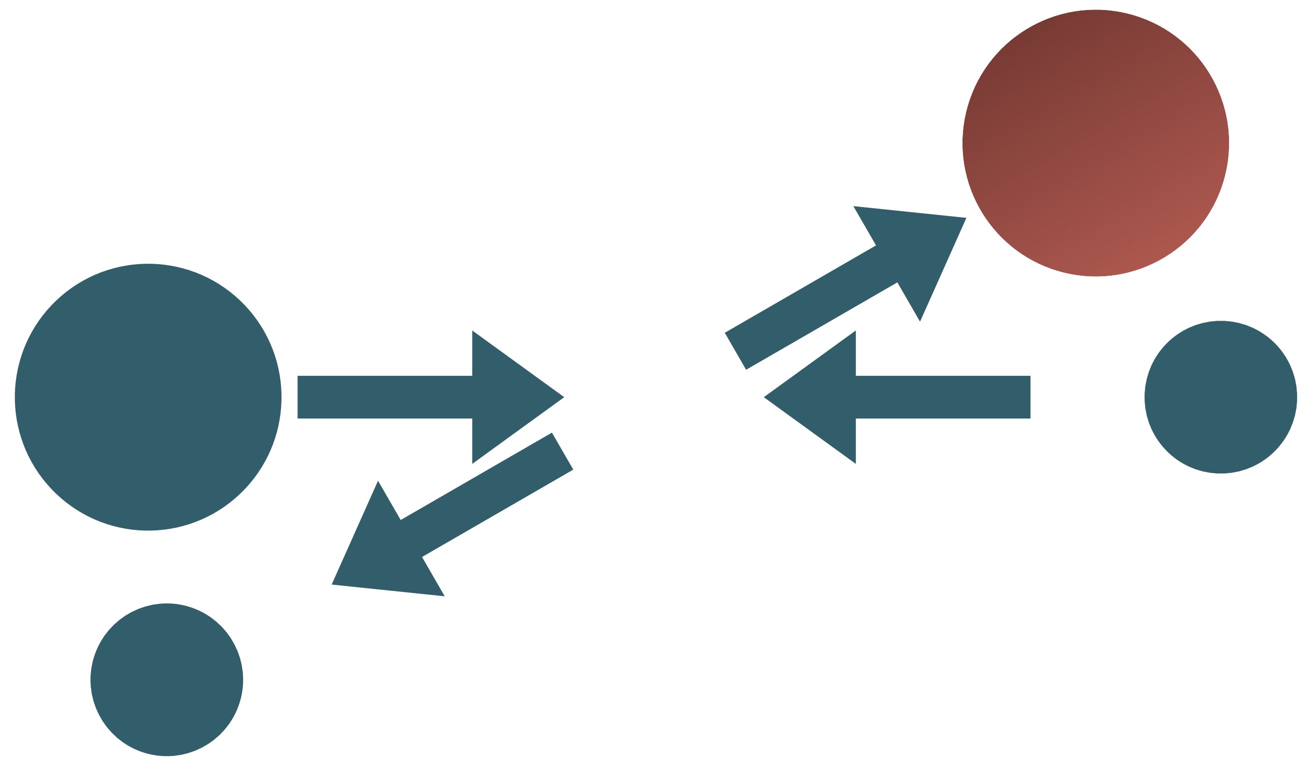






Forward kinematics
• Stable nucleus • High resolution   • (w/ spectrometer)

Center-of-mass frame
• Collider experiment



Inverse kinematics

• Unstable nucleus
• Large acceptance
  • Angle
  • Excitation energy
• Decay measurement

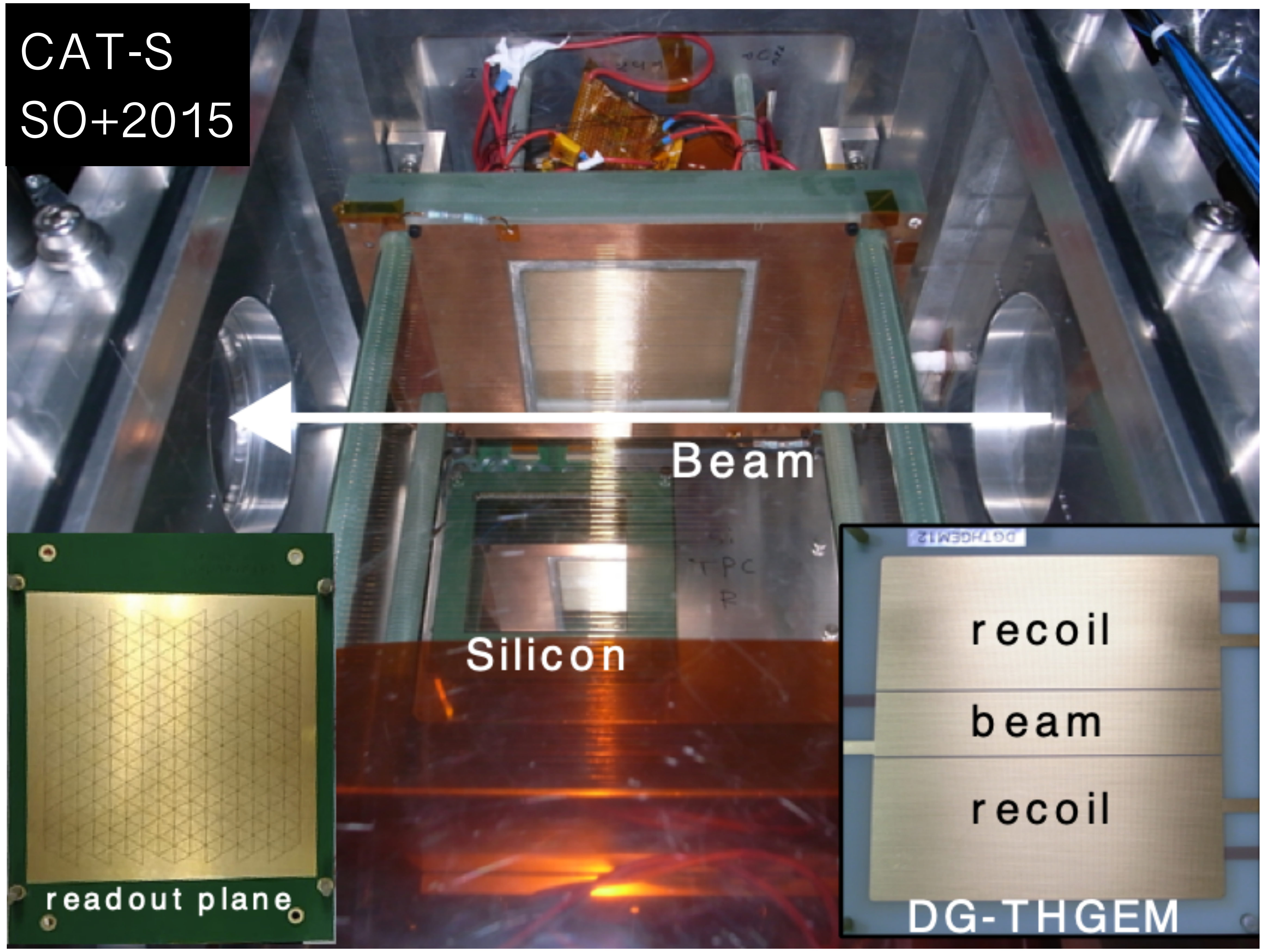
CAT Active target
GMR Measurement with Unstable Nuclei

Gaseous active target for high-Intensity-beam experiments

Upto 1 MHz

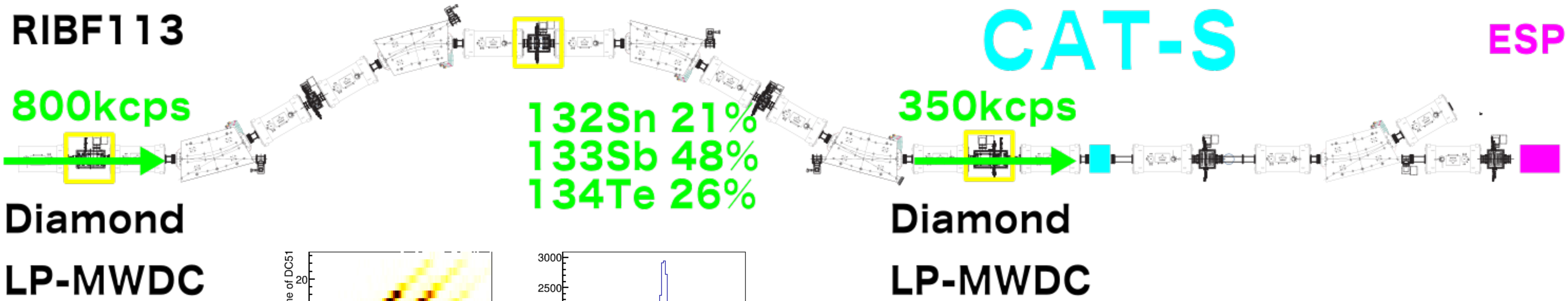
- Regular triangle shape
- Dual-gain thickGEM
- High-rate DAQ system

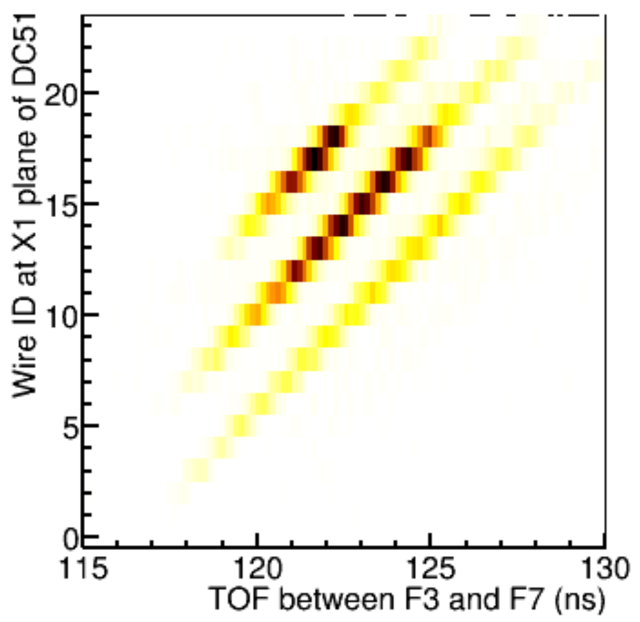
=> Measurement for the Tin isotope

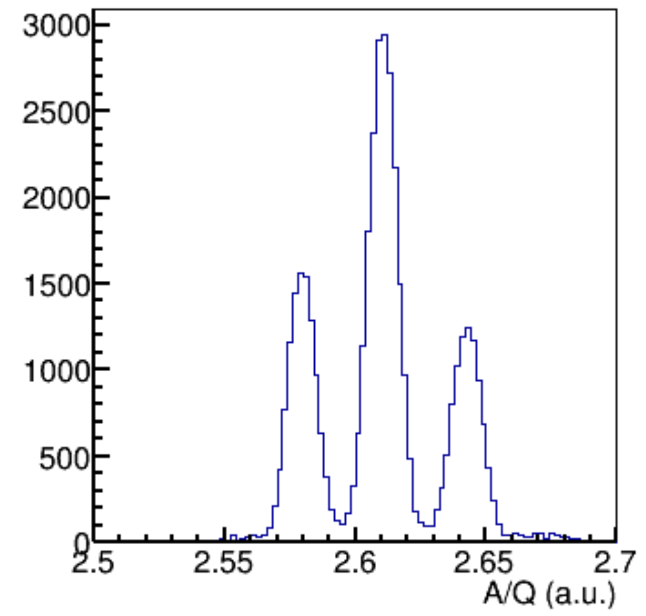


Measurement of 132Sn at RIBF

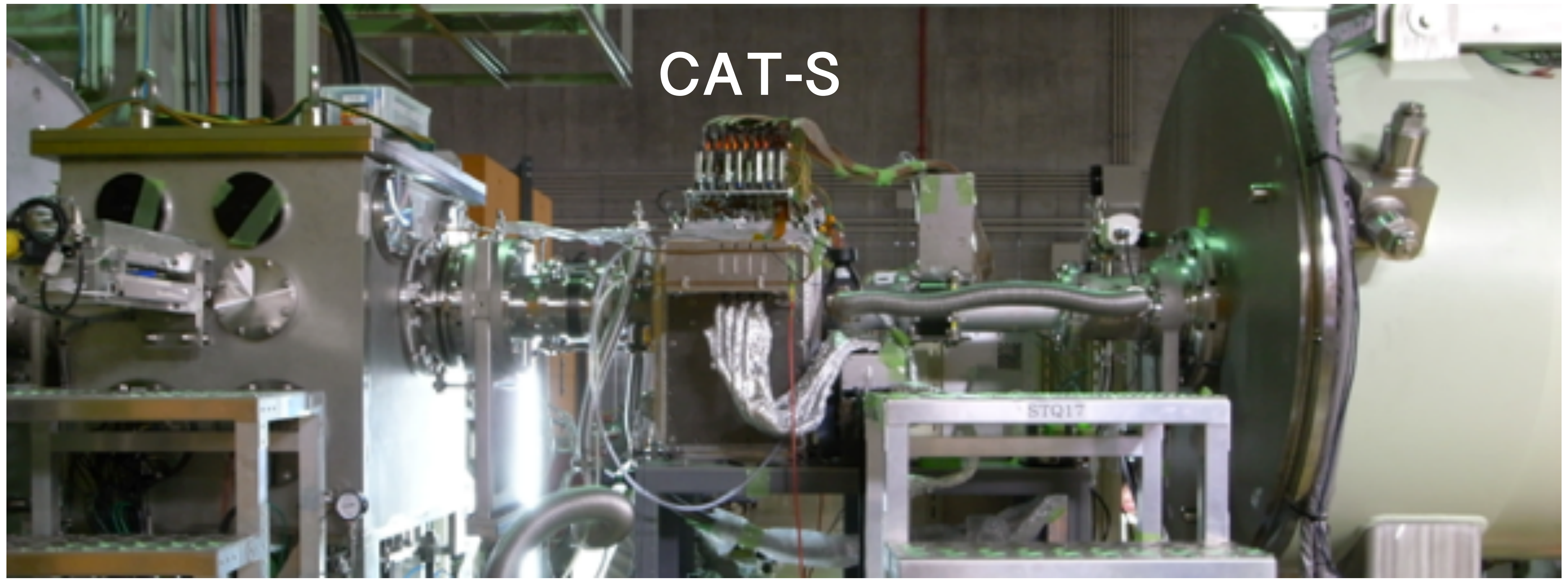
Exp by S.Ota and U.Garg



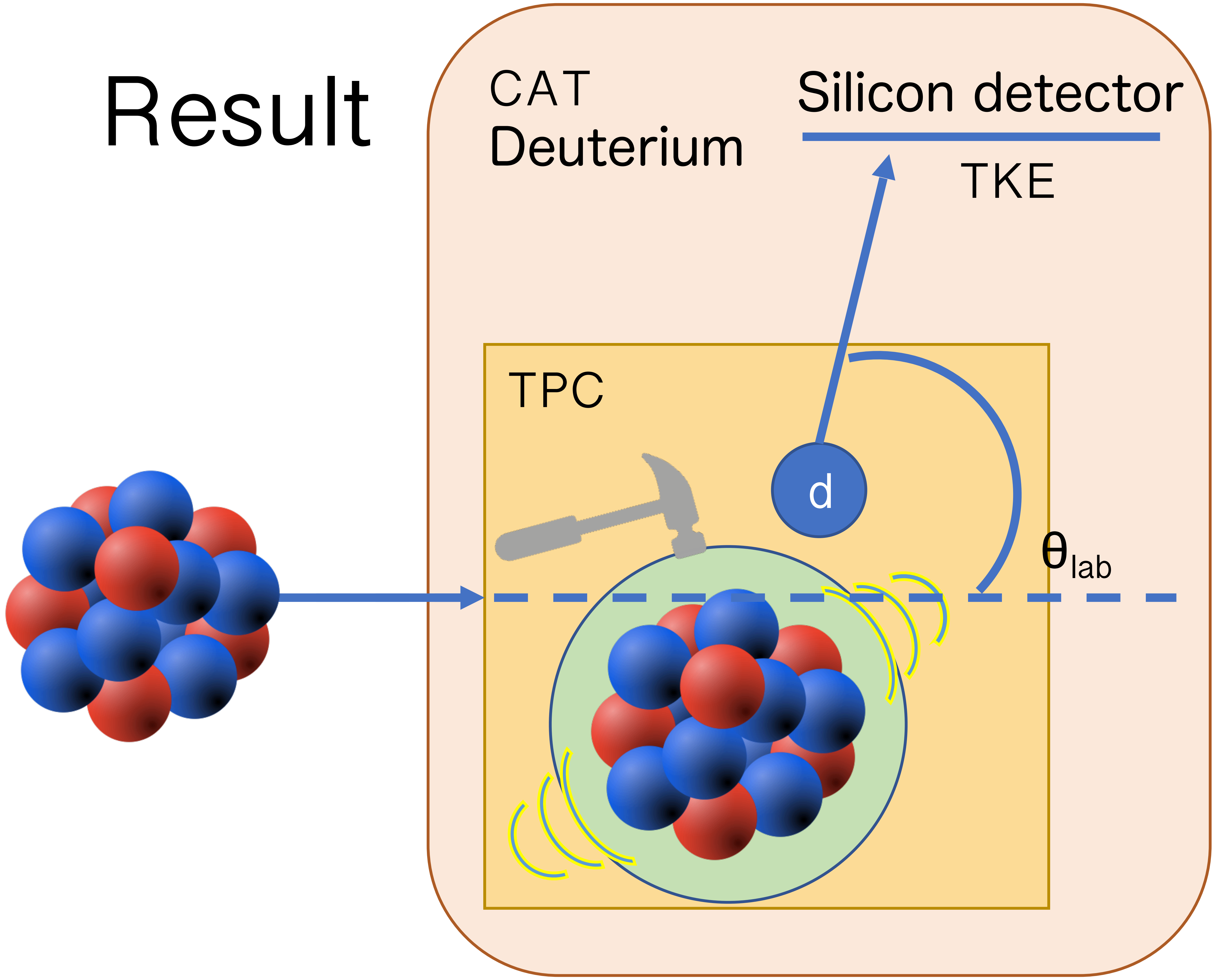


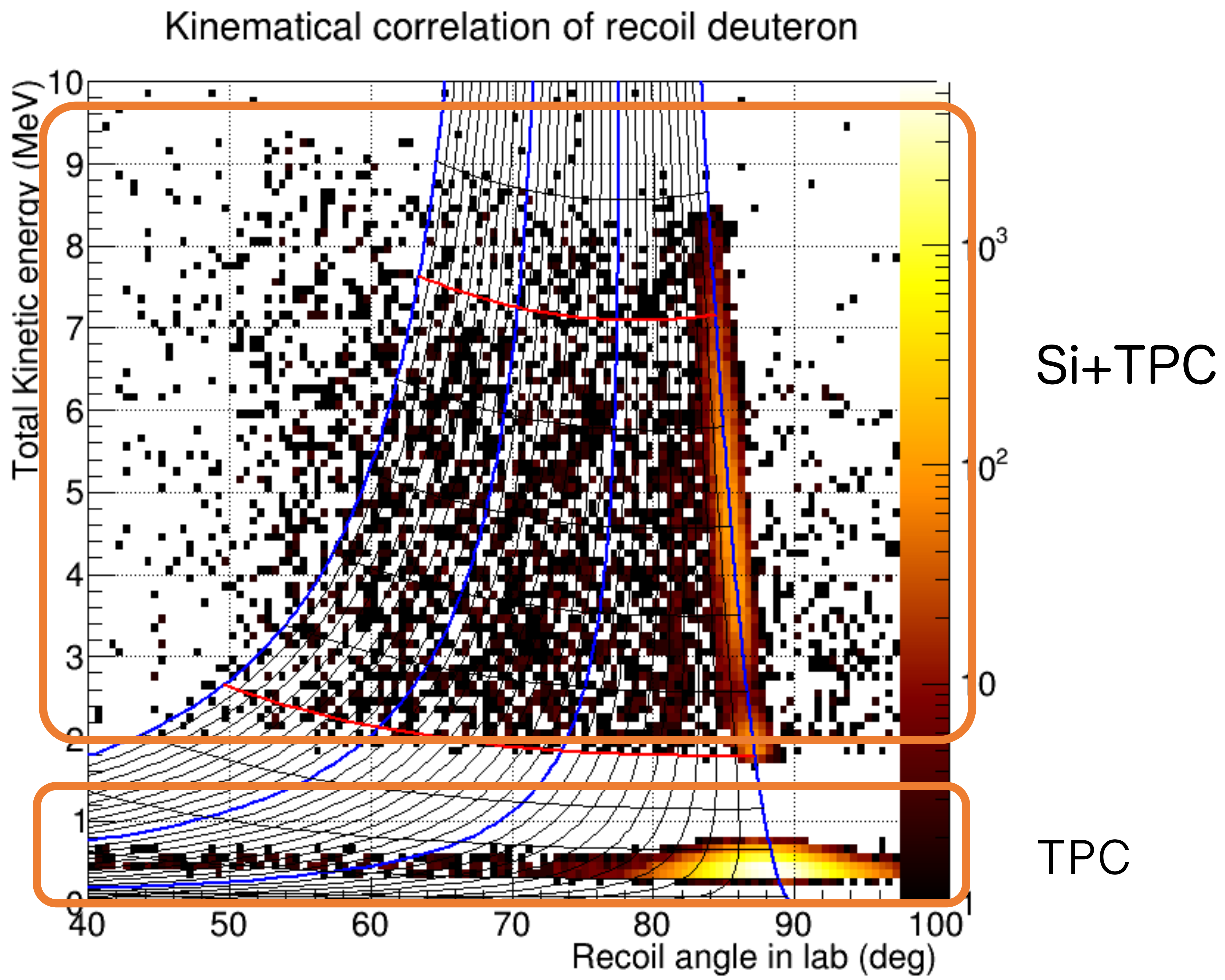


- 350kcps cocktail beam including 132Sn, 133Sb and 132Te
- Particles are analyzed and identified by using BigRIPS Spectrometer
- (d,d') with CAT-S



Result



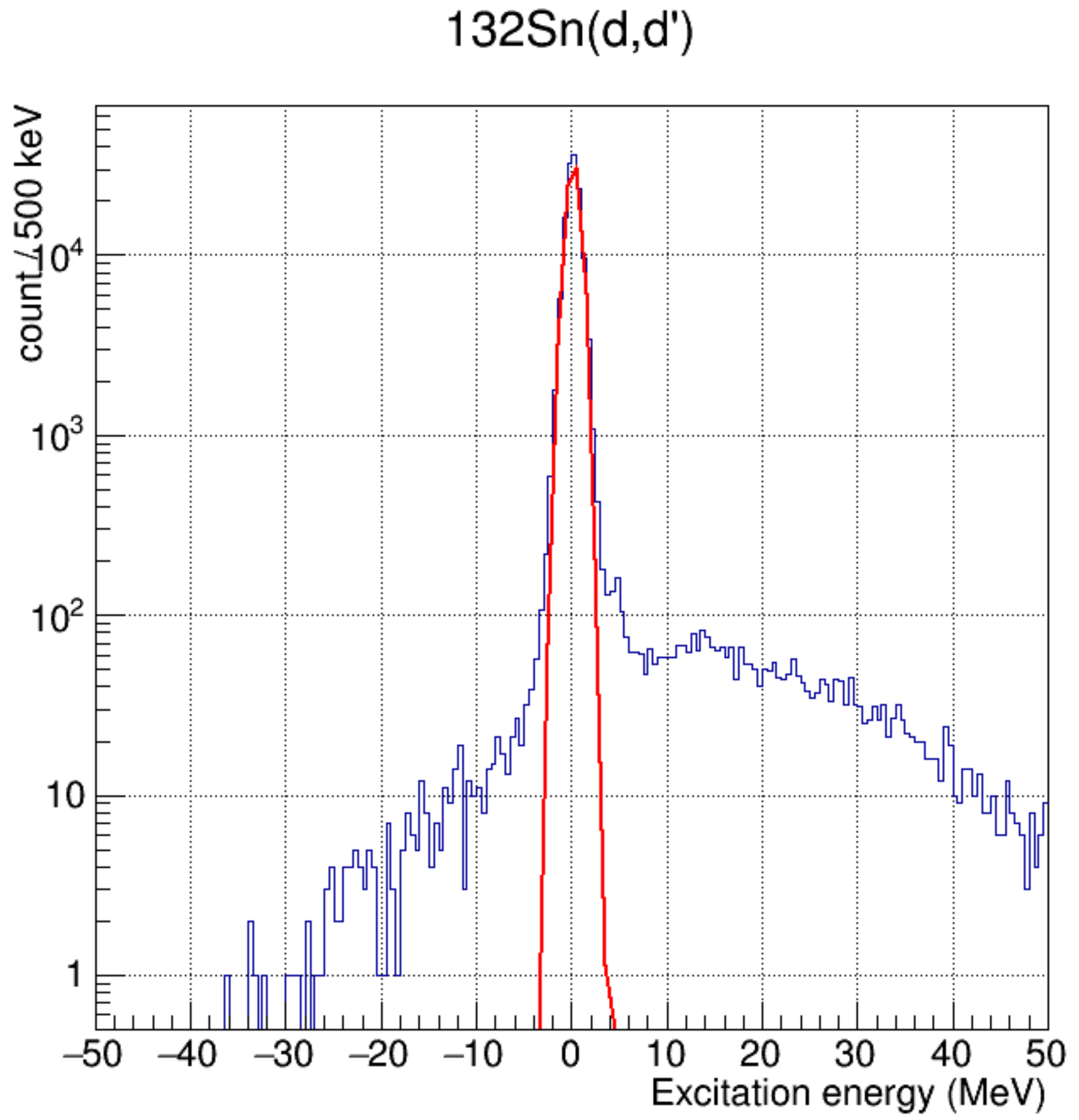


Background by delta-rays are discriminated using pulse height and angular-hough-transform technique

Performance of CAT-S

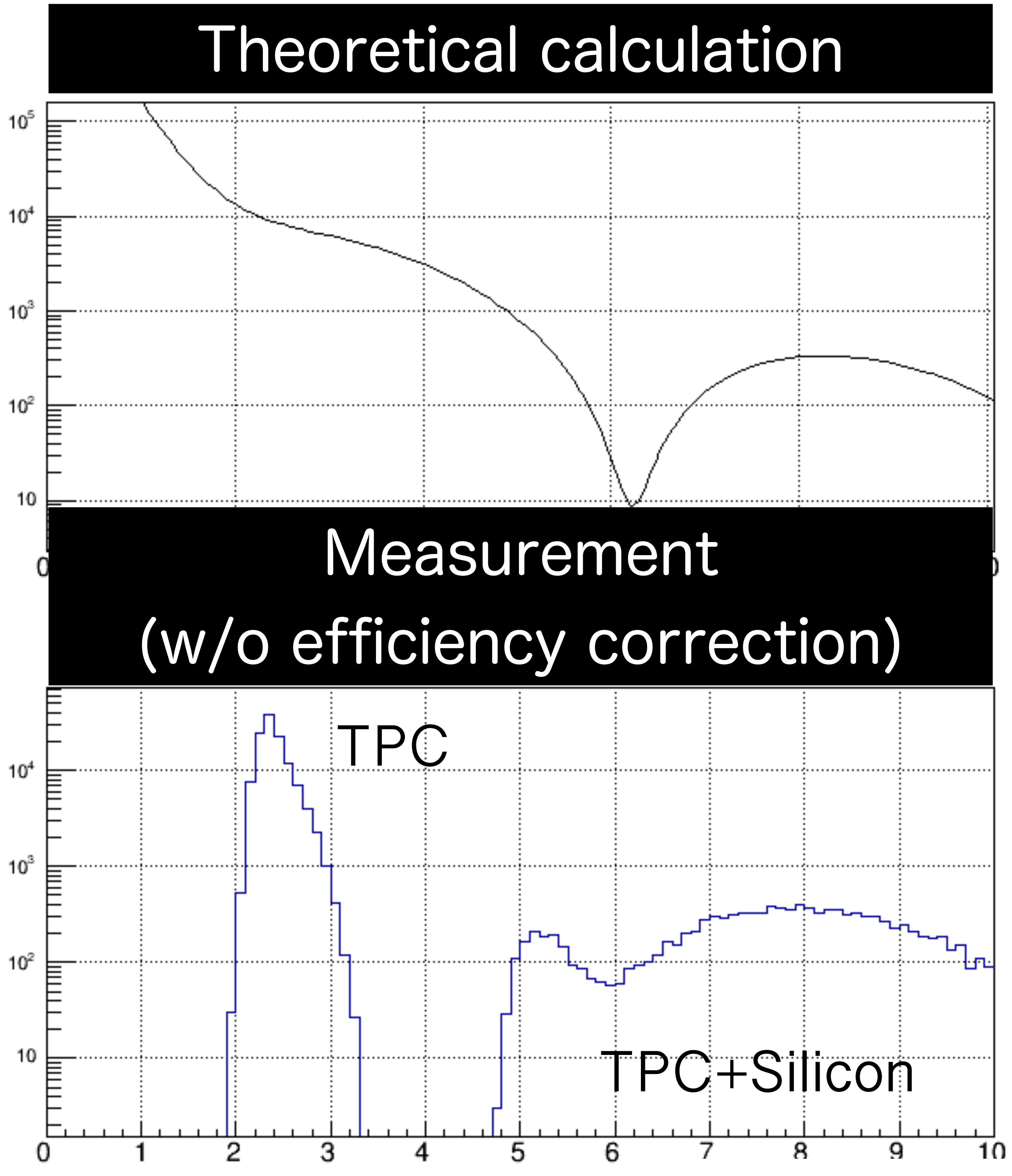
Excitation energy distribution

0.6 MeV (σ)



Good resolution for the measurement

Angular distribution of elastic scattering



Strength of ISGMR

- Lorentzian fitting Assuming :
  - Width of the resonance
  - Energy difference between ISGQR
- **Escale = 15.77+1.3-1.0 (10-20 MeV)**
- Egqr = 12.3+0.63-0.75 MeV

Preliminary plot was removed

Isospin dependence of the incompressibility

Statistical error is large, but

the door to measuring the incompressibility of tin-region unstable nuclei, is opened

Next step is to increase the statistics

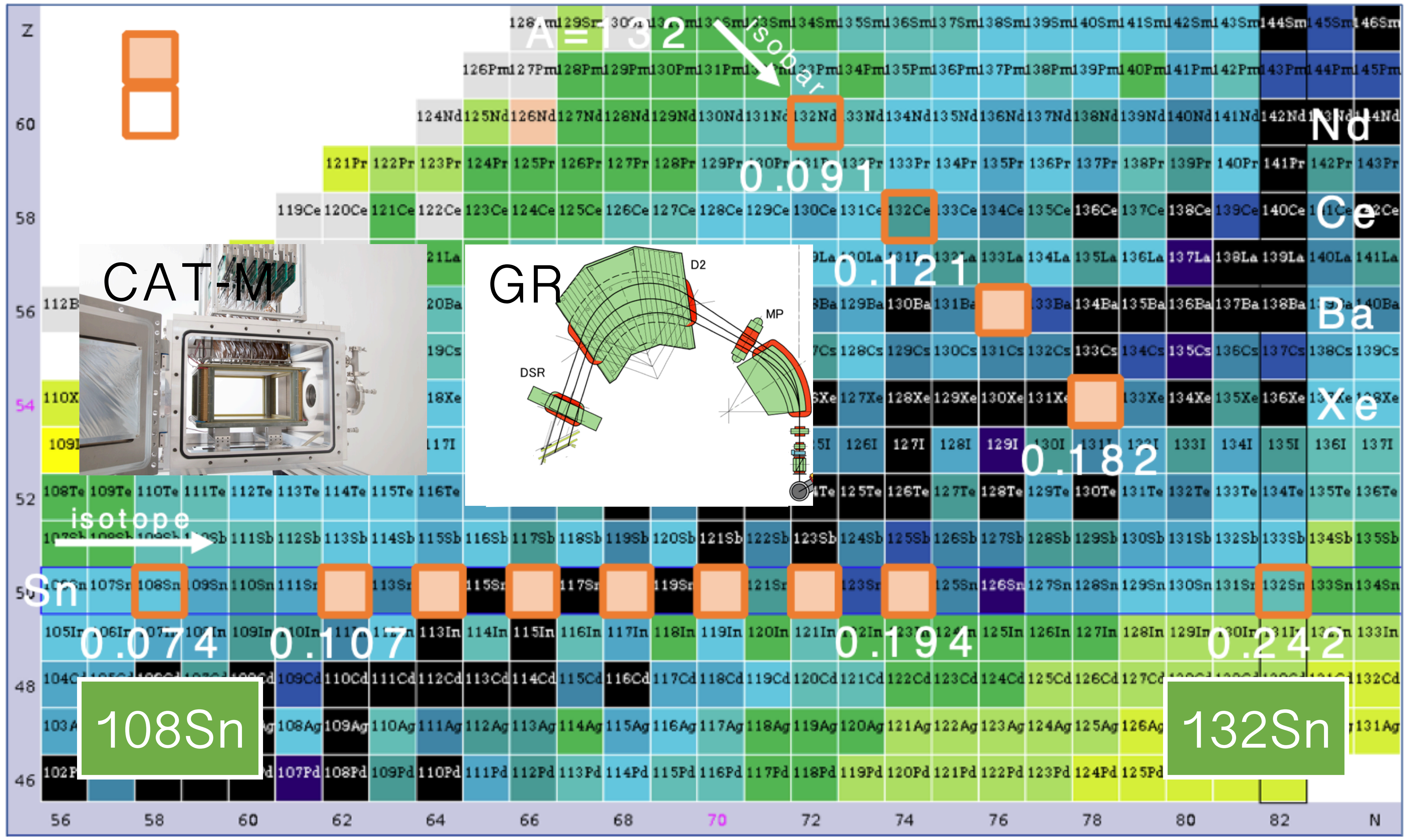
Preliminary plot was removed

For high accuracy and precision determination

$$K_A = K_{0,V} + K_{0,\mathrm{S}}A^{-1/3} + (K_{\tau,V} + K_{\tau,\mathrm{S}}A^{-1/3})\frac{(N-Z)^2}{A^2} + K_{\mathrm{Coul}}\frac{Z^2}{A^{4/3}} + \mathcal{O}(A^{-2/3})$$

Stable isotopes：RCNP Grand RAIDEN

Unstable isotopes：RIBF + CAT-M



New approaches to higher accuracy

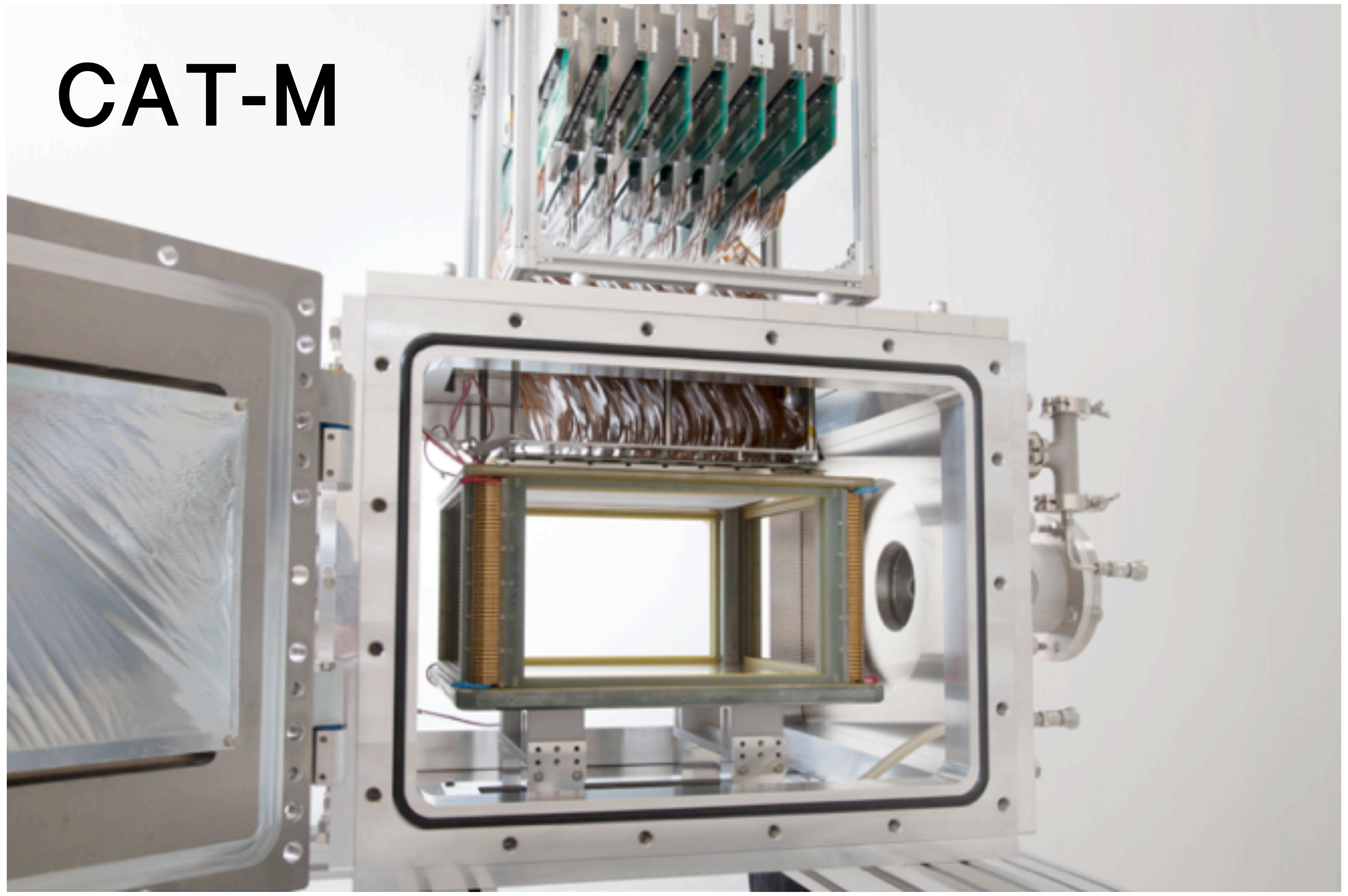
- Isobar：Fixed mass (or surface) effect
- Isotone：Proton degrees of freedom
- Isologos：Mass (or surface) effect
- Deformed nuclei：Deofrmation

Dometic

- RCNP, CNS, RIKEN, Kyoto, Tohoku…

International

- Prof. U. Garg (Notre Dame)
- Prof. R. Raabe (KU Leuven) HIIMAC
- Prof. X. Tang (IMP)
- Prof. J. Gibelin (LPC Caen)



Inverse kinematics

Systematic measurements with active target

$$K_A = K_{0,V} + K_{0,\mathrm{S}}A^{-1/3} + (K_{\tau,V} + K_{\tau,\mathrm{S}}A^{-1/3})\frac{(N-Z)^2}{A^2} + K_{\mathrm{Coul}}\frac{Z^2}{A^{4/3}} + \mathcal{O}(A^{-2/3})$$

CAT-M Active Target

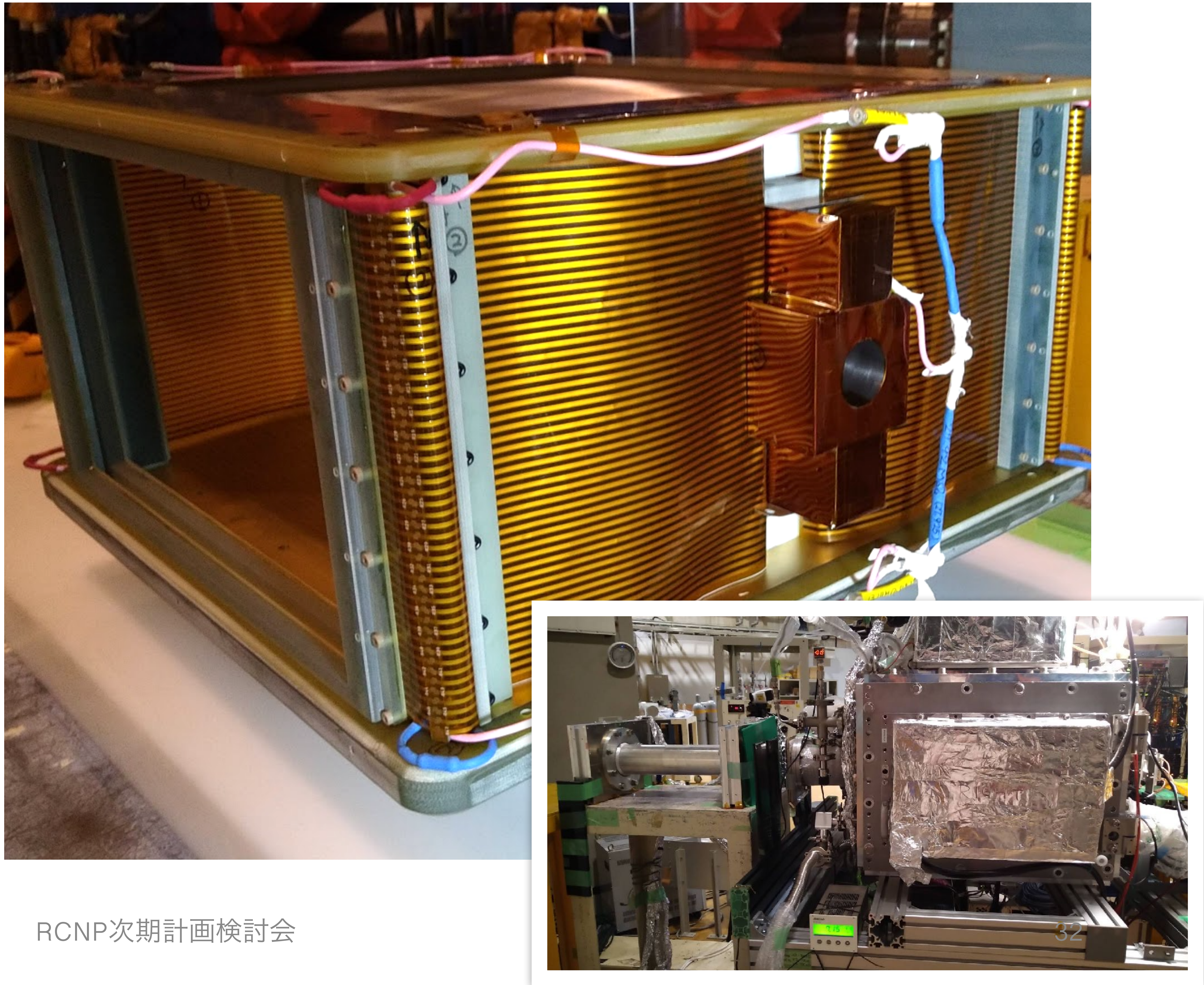
- **10 times larger statistics**
- double-layered wire field cage
  - 40x40x20 cm^3
- M-THGEM (or THGEMs)
  - 32 x 28 x 20 cm^3 active volume
- Gas type: Hydrogen, Duterium, He+CO2
- Gas pressure : 0.2-0.4 atm.
- Readout pads
  - Regular triangular shape with 7-mm side
    - Capability of better resolution than the size
  - Num of readout pads : 4046

TPC + Magnet

Construction of TPC field cage + Magnet was done on 07/09.

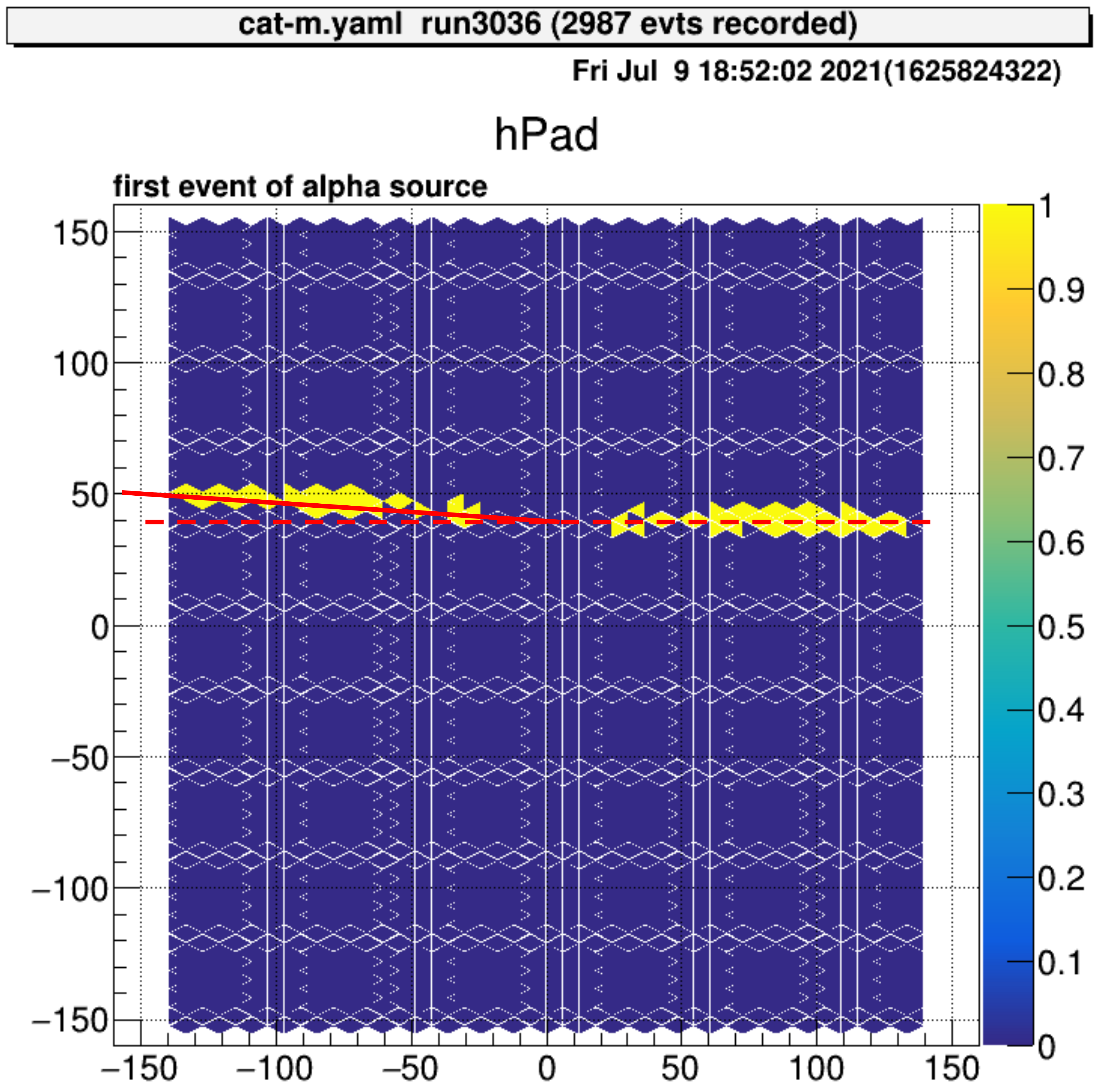
The test of biasing to the field cage + magnet was done at CNS without wire plane. The achieved electric field strength was 0.85 kV/cm/atm.

But with the wire plane, it becomes lower to be 0.69 kV/cm/atm and the slightly lower strength of 0.63kV/cm/atm was chosen for stable operation, which is also acceptable.



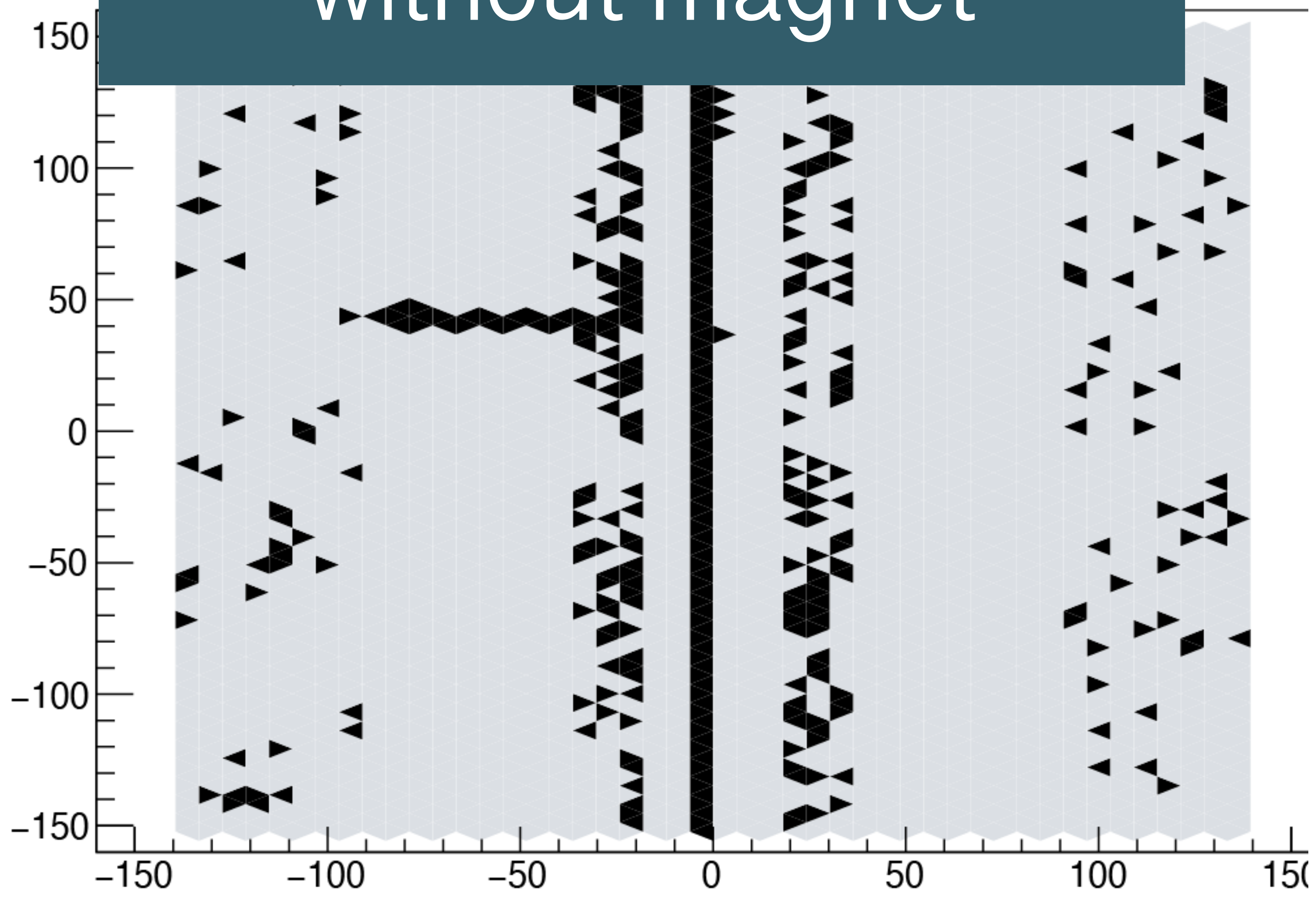
Alpha with magnet

The first event display of the alpha source with magnet taken on 2021/07/09!



H307-10 (only one event)

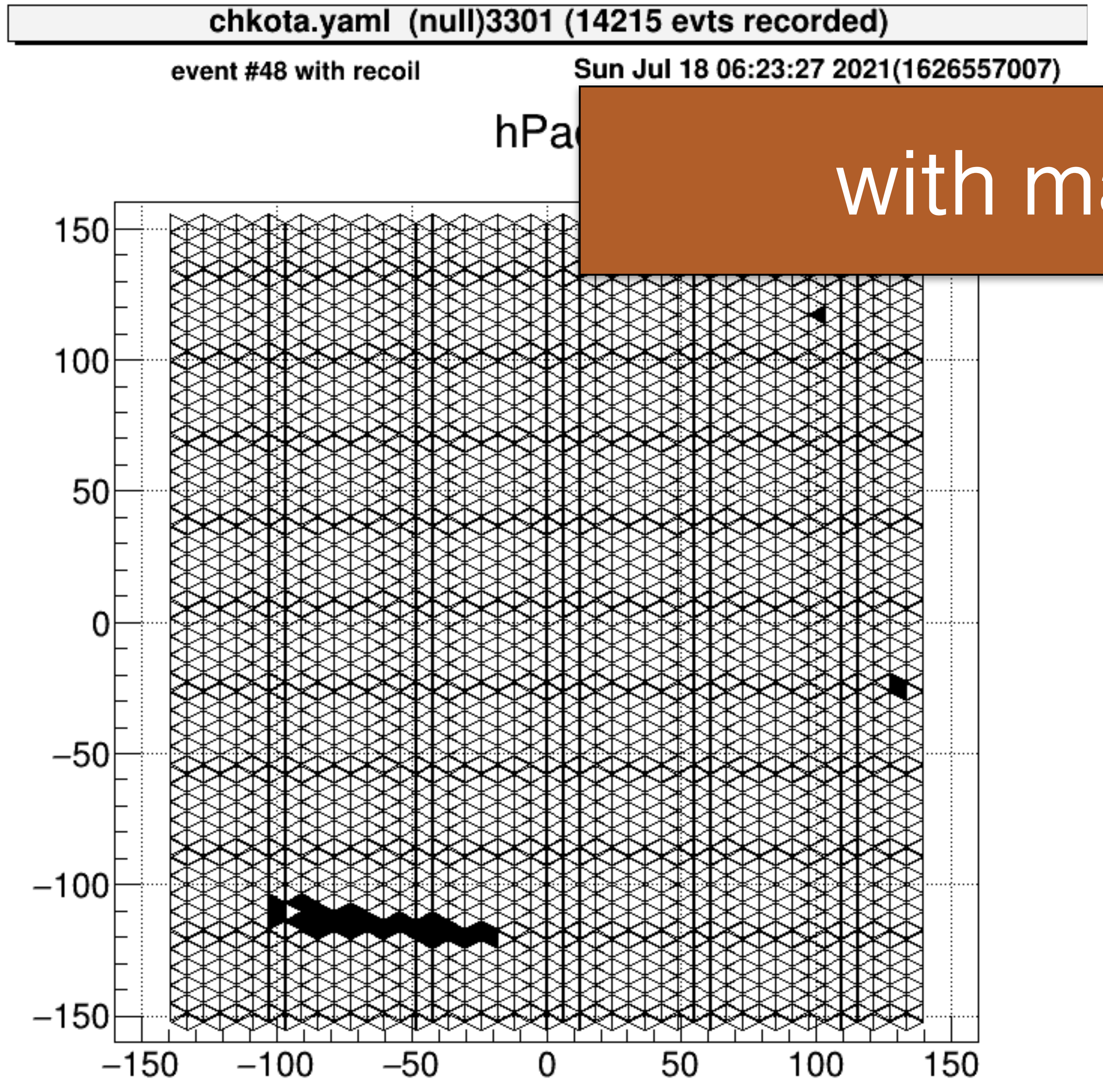
without magnet

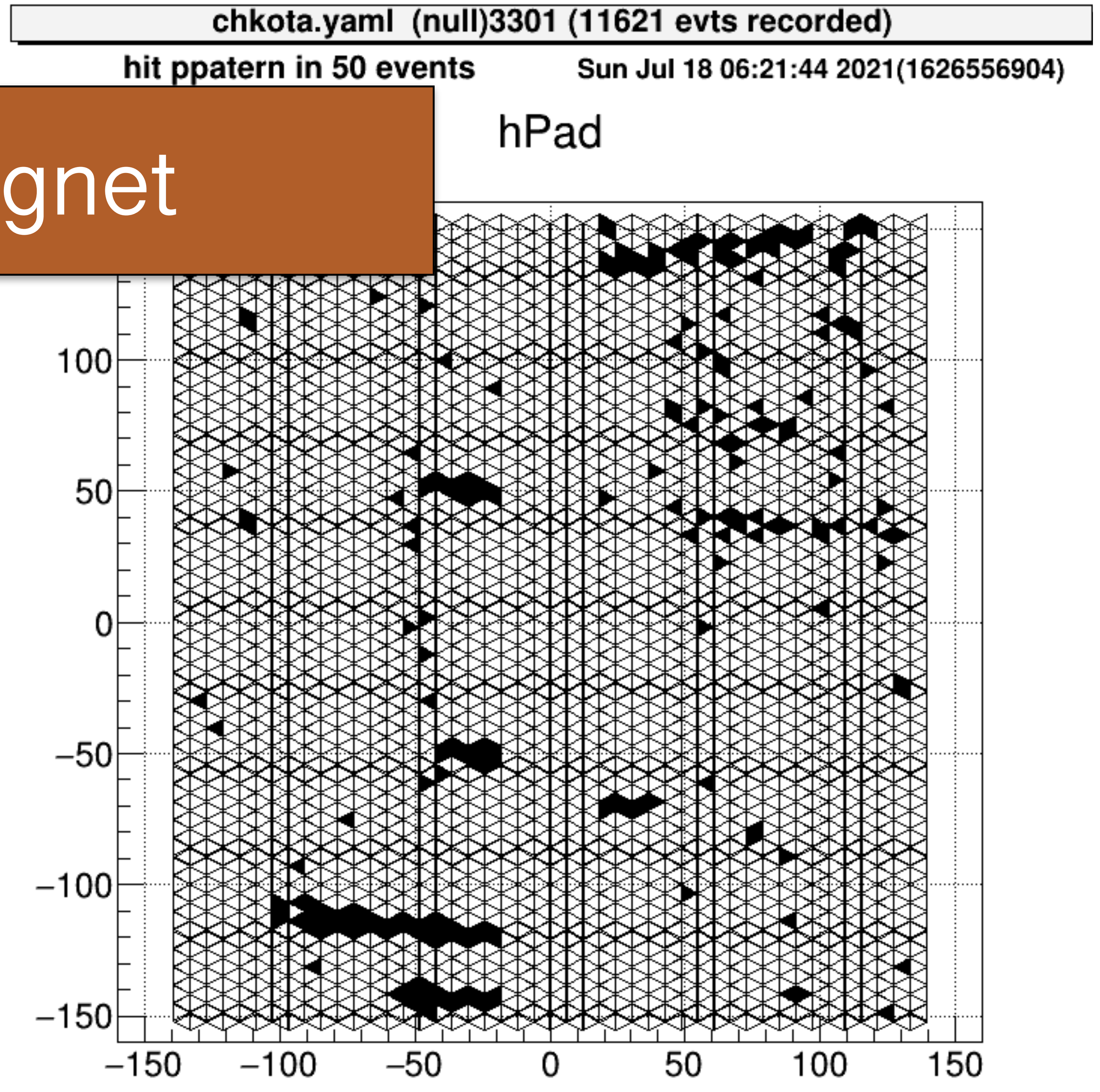


30<|x|<90 has higher threshold,

many delta-rays are recorded

with magnet





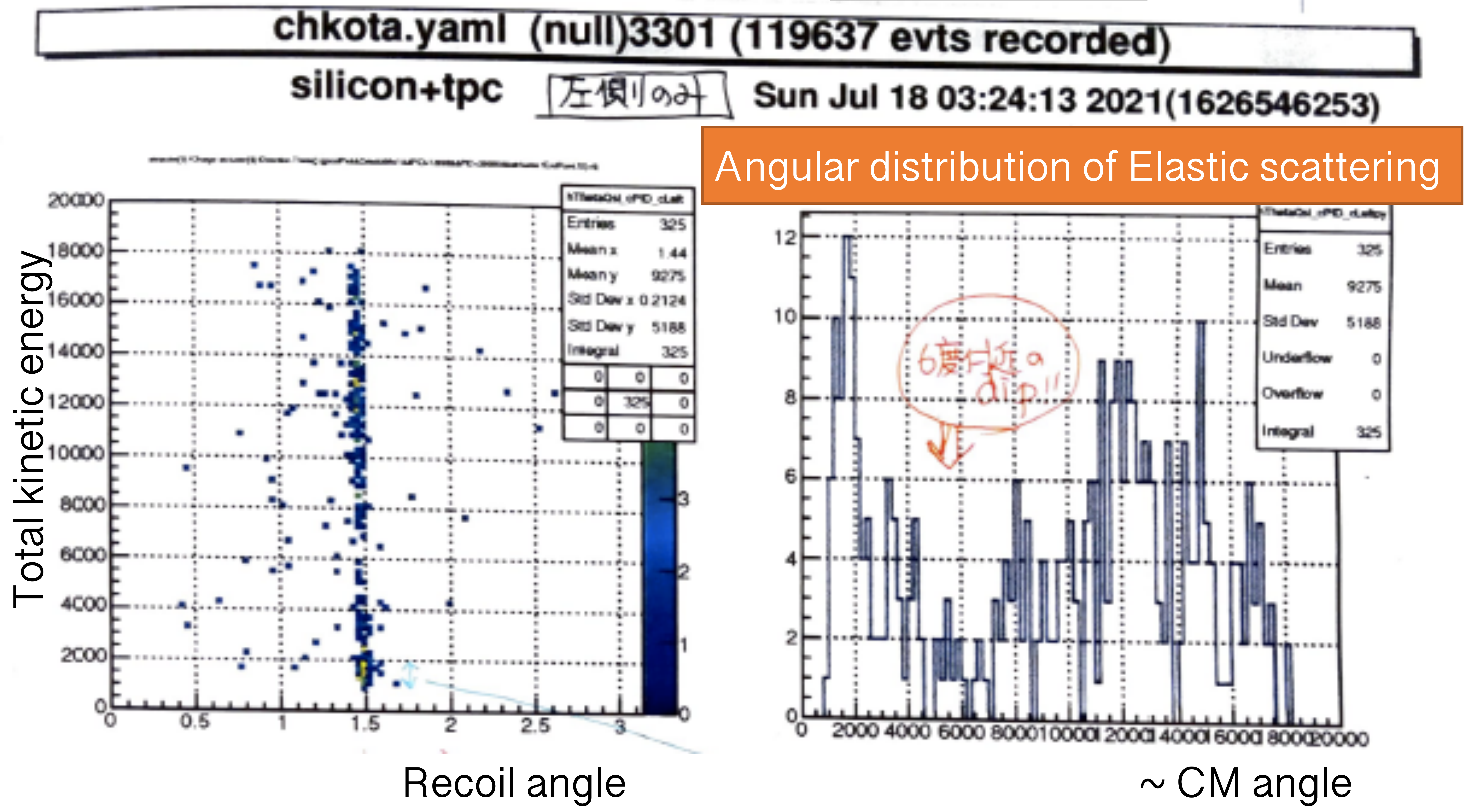
H445-1 : one event (left), 50 events (right)
(30-50) has higher threshold

Comparison with / without magnet

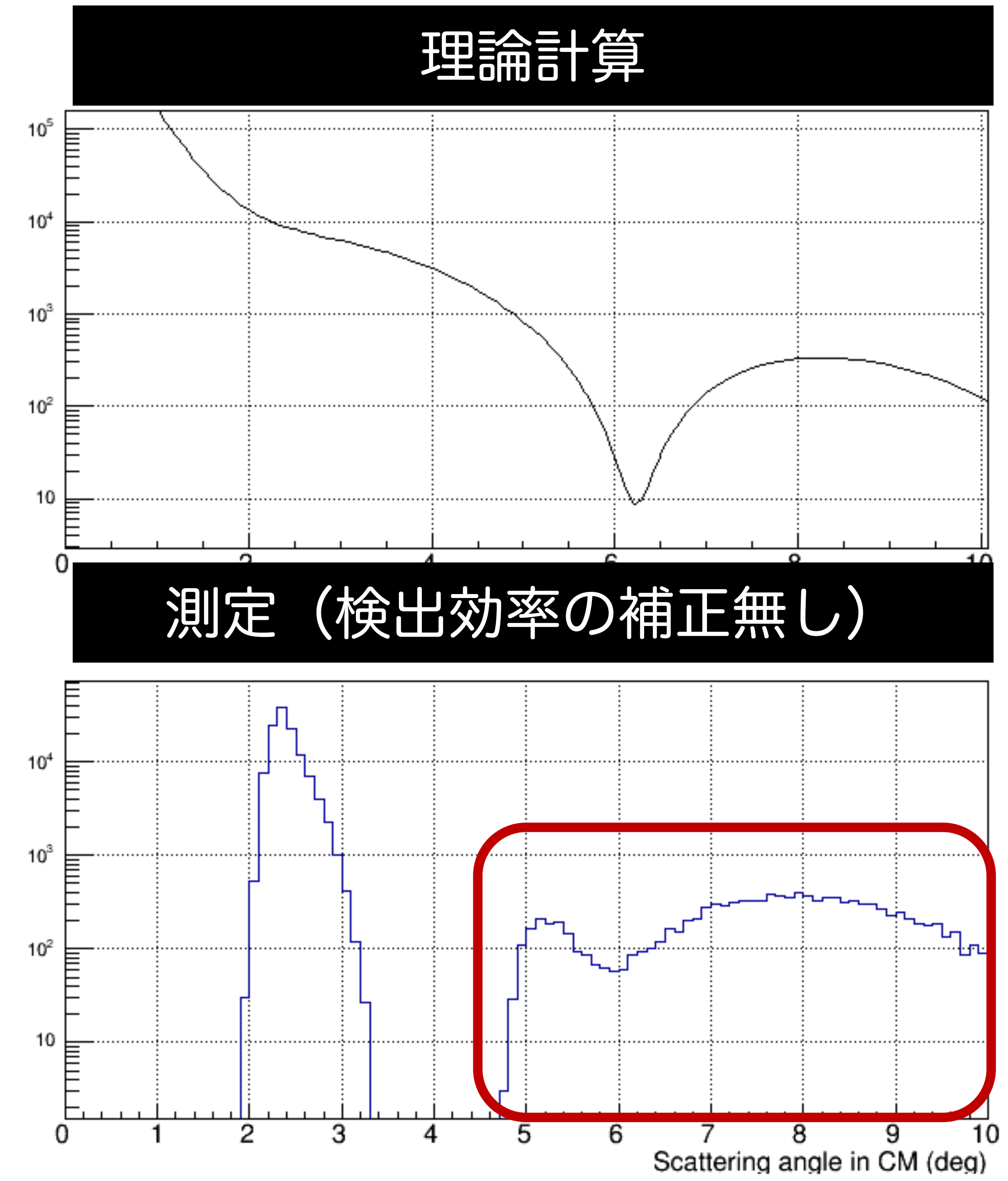
136Xe(d,d’) at 100 MeV/u at HIMAC (21H445)

Performance of CAT-M w/ Magnet

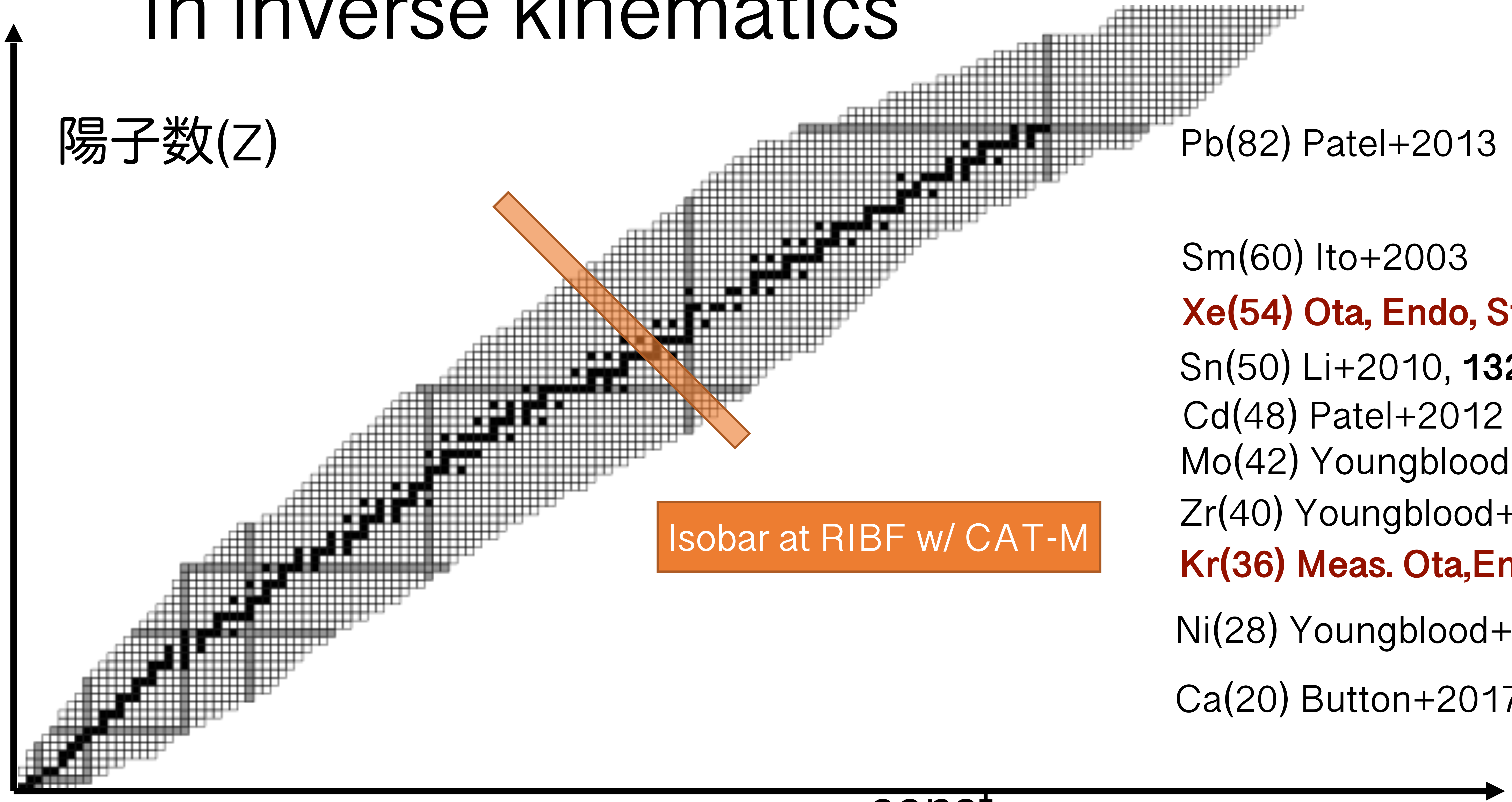
10 minutes data



c.f.) 132Sn(d,d) for 5days



Strategy of ISGMR measurement In inverse kinematics



Pb(82) Patel+2013

Sm(60) Ito+2003

Xe(54) Ota, Endo, Stefano … (2021)

Sn(50) Li+2010, **132Sn Ota at RIBF / Garg (a,a) at FRI**

Cd(48) Patel+2012

Mo(42) Youngblood+2015, Howard+2020

Zr(40) Youngblood+2015, Gupta+2018

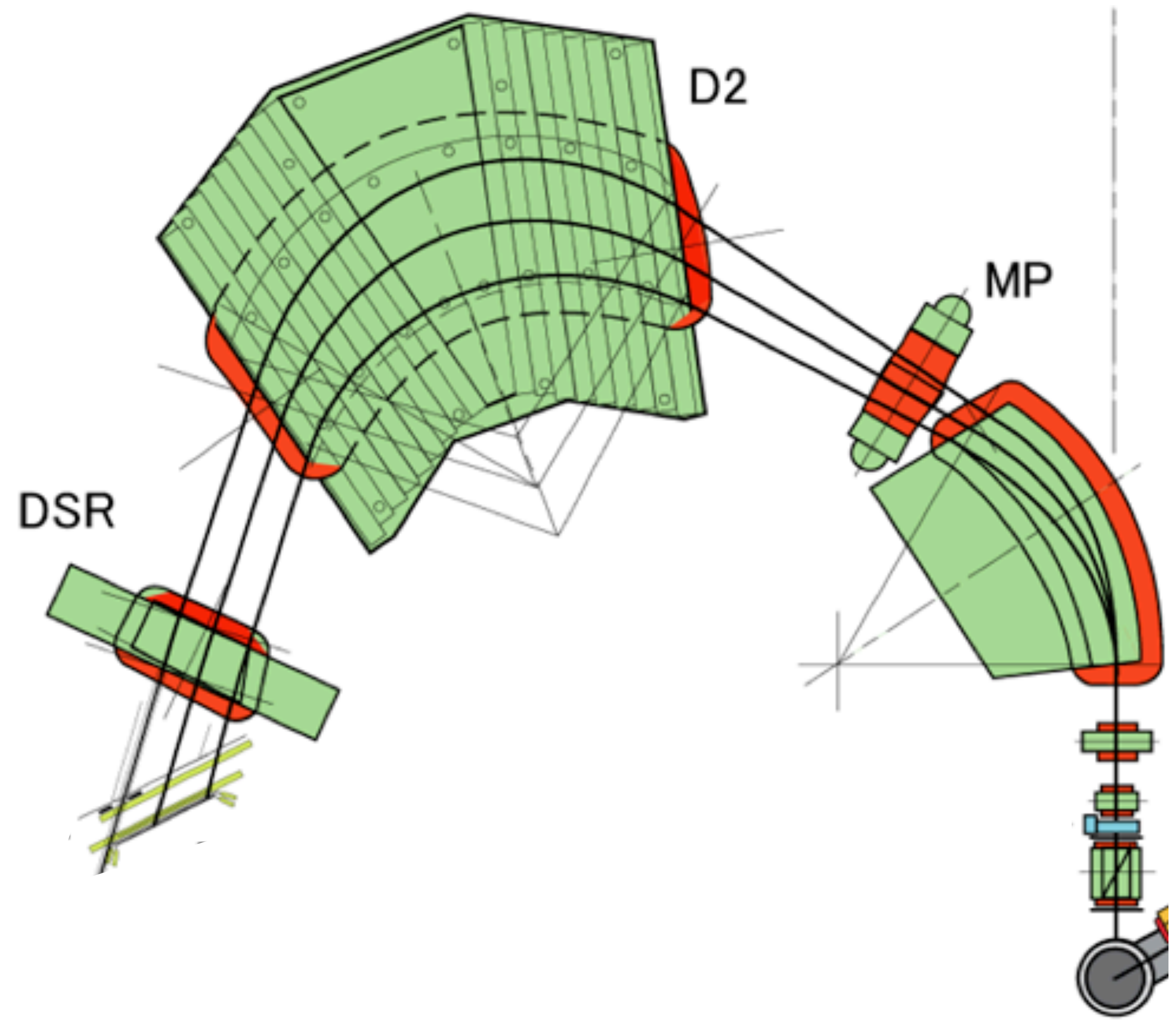
Kr(36) Meas. Ota,Endo, Stefano …. 2021, 2022

Ni(28) Youngblood+2018, **58, 64Ni GANIL**

Ca(20) Button+2017, Howard+2020

$$K_A = K_{0,V} + K_{0,\mathrm{S}}A^{-1/3} + (K_{\tau,V} + K_{\tau,\mathrm{S}}A^{-1/3})\frac{(N-Z)^2}{A^2} + K_{\mathrm{Coul}}\frac{Z^2}{A^{4/3}} + \mathcal{O}(A^{-2/3})$$

GRAND RAIDEN



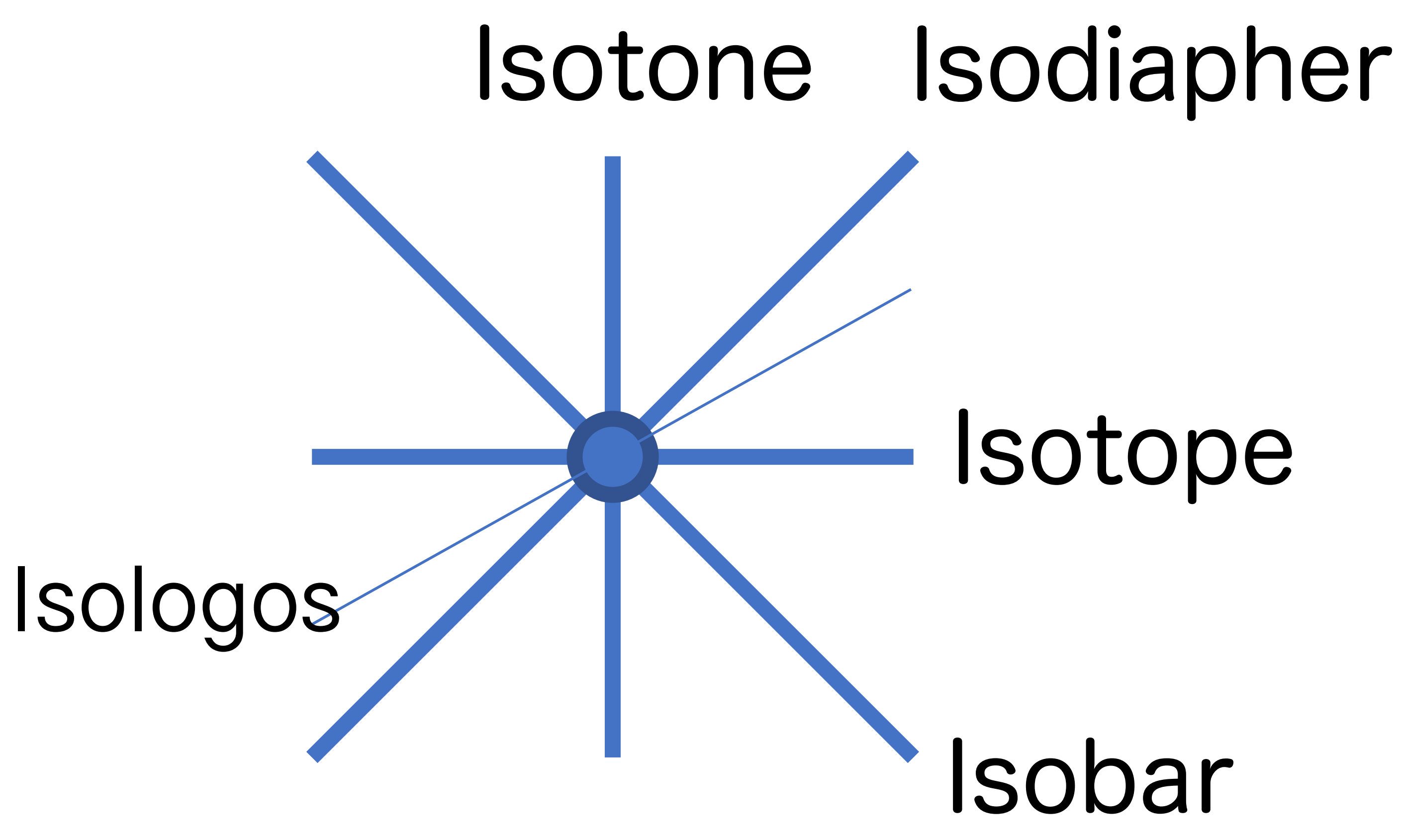
Forward kinematics

High precision measurement with GRAND RAIDEN

$$K_A = K_{0,V} + \boxed{K_{0,\mathrm{S}} A^{-1/3}} + (K_{\tau,V} + K_{\tau,\mathrm{S}} A^{-1/3}) \frac{(N-Z)^2}{A^2} + K_{\mathrm{Coul}} \frac{Z^2}{A^{4/3}} + \boxed{\mathcal{O}(A^{-2/3})}$$

Systematic measurements

from magic-number nuclei to mid-shell nuclei



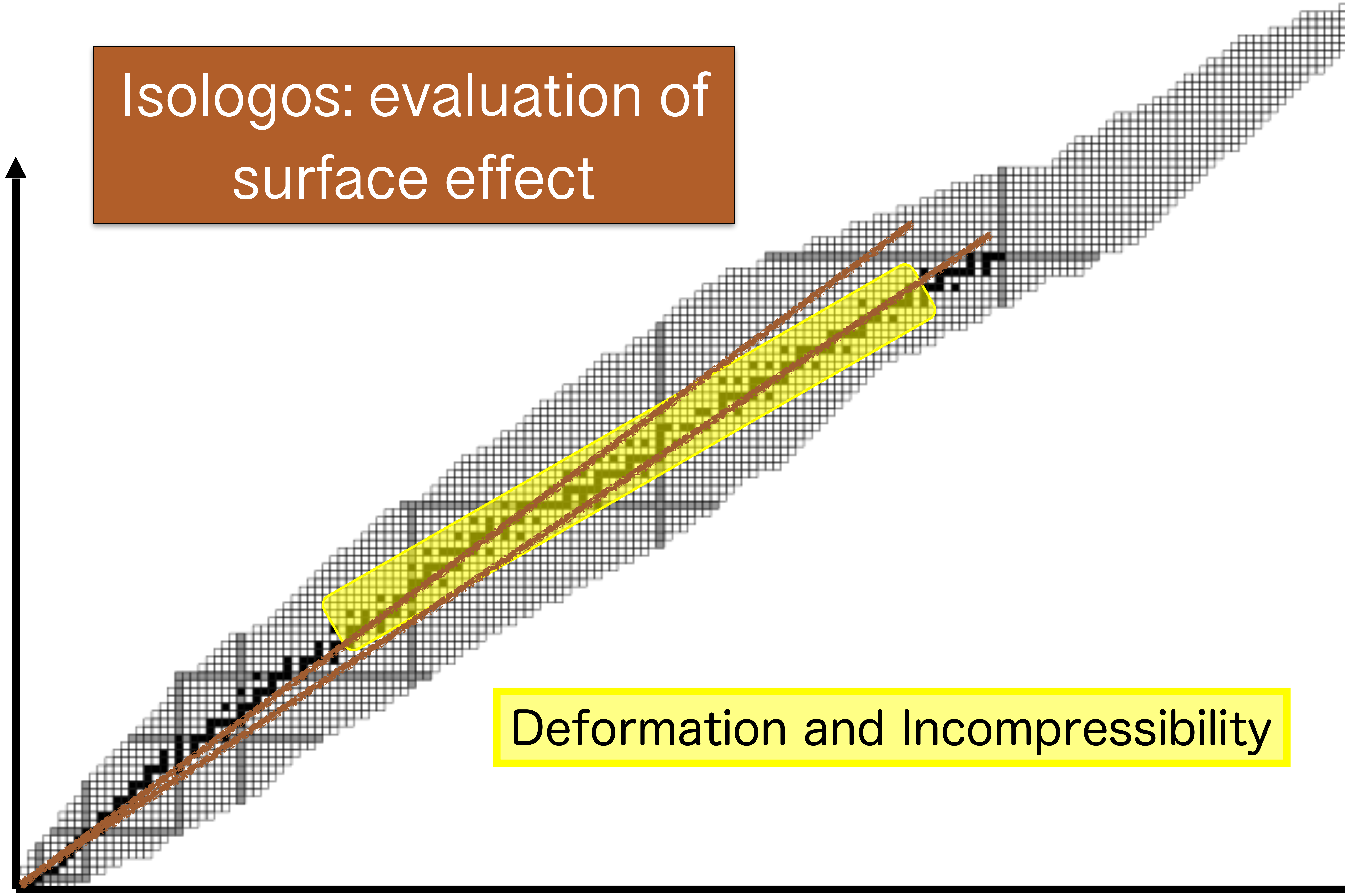
Isotope : Z = const => Neutron

Isotone : N = const => Proton

Isobar : A = const => Isovector

Isodiapher : N-Z = const => Isoscalar

“Isologos?” : (N-Z)/A or A/Z = const => Mass



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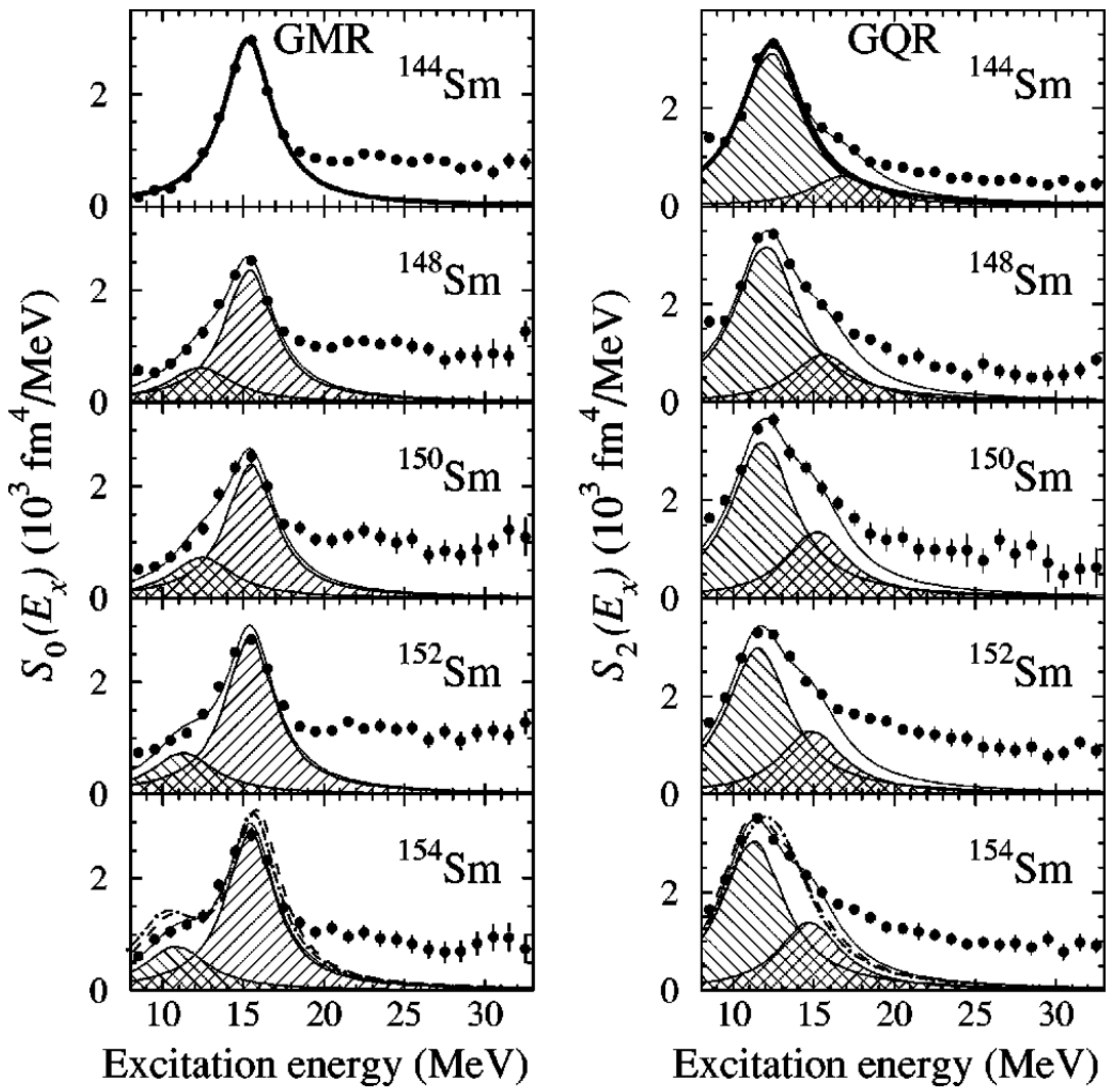
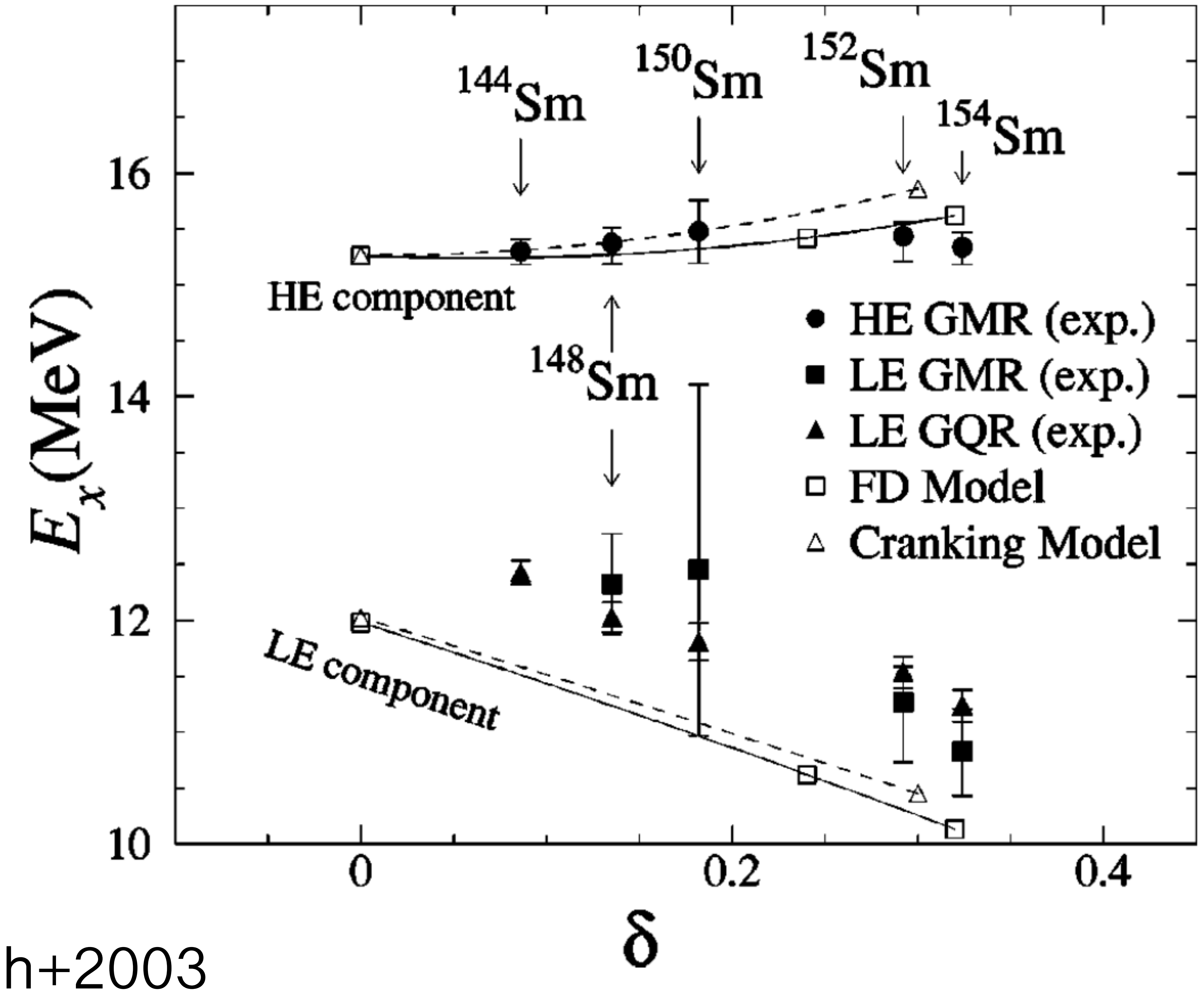
Deformation effect in ISGMR





Itoh+2003

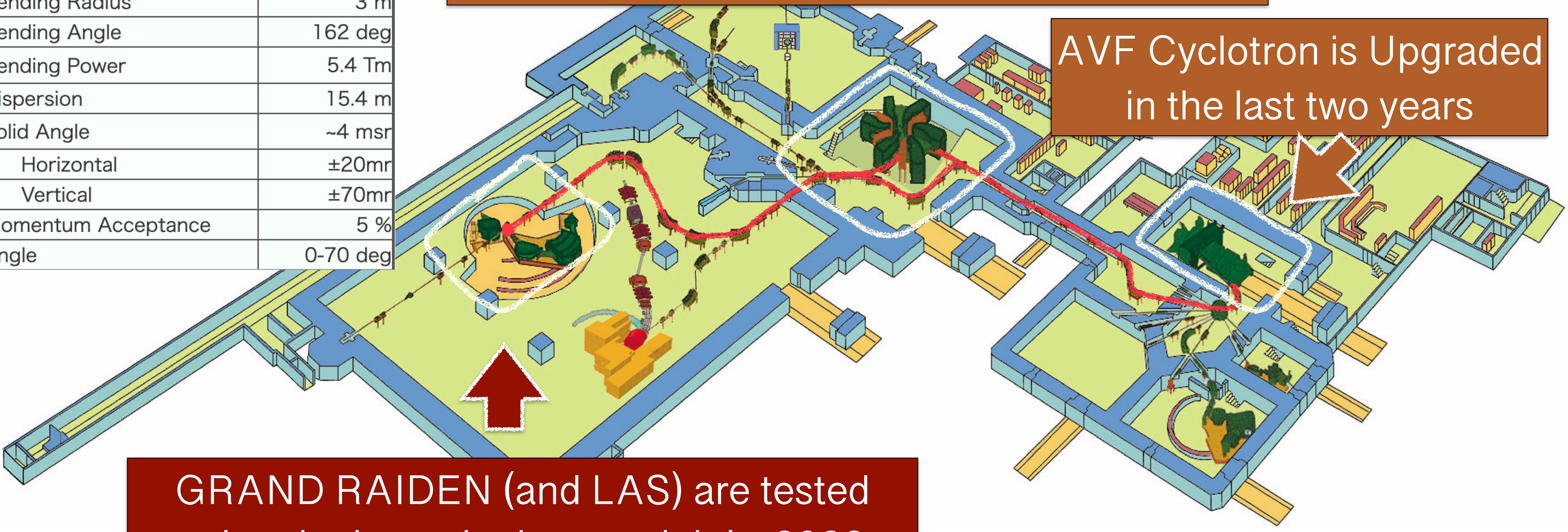
My question: How can we derive nuclear incompresibilities in deformed nuclei

Present status of RCNP ring cyclotron facility

Grand Raiden	
Resolving Power	37,000
Bending Radius	3 m
Bending Angle	162 deg
Bending Power	5.4 Tm
Dispersion	15.4 m
Solid Angle	~4 msr
Horizontal	±20mr
Vertical	±70mr
Momentum Acceptance	5 %
Angle	0-70 deg

Rinc Cyclotron will be operated in this autumn
p up to 400 MeV, a up to 400 MeV etc.

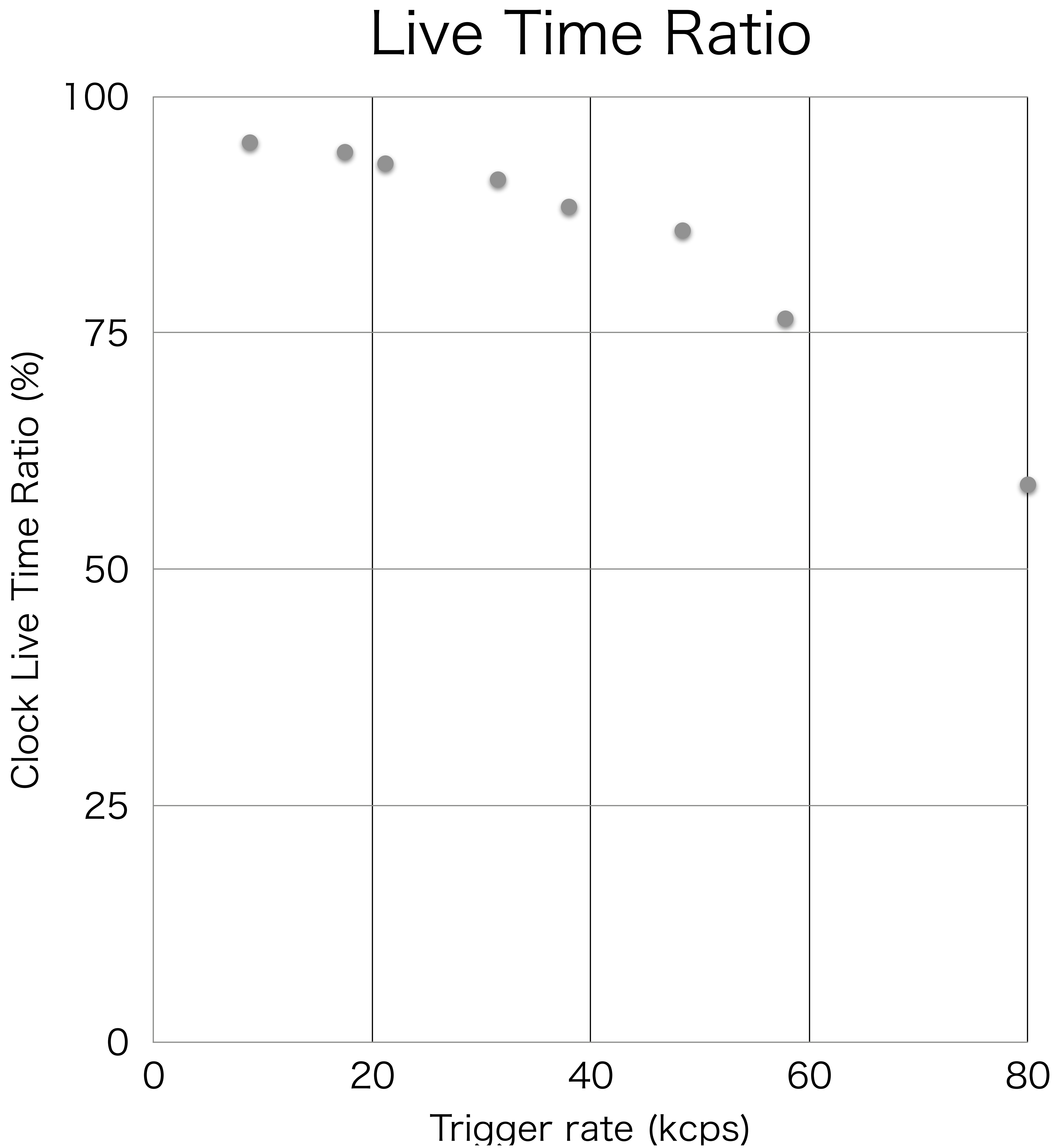
AVF Cyclotron is Upgraded
in the last two years



GRAND RAIDEN (and LAS) are tested
using the beam in June and July, 2022

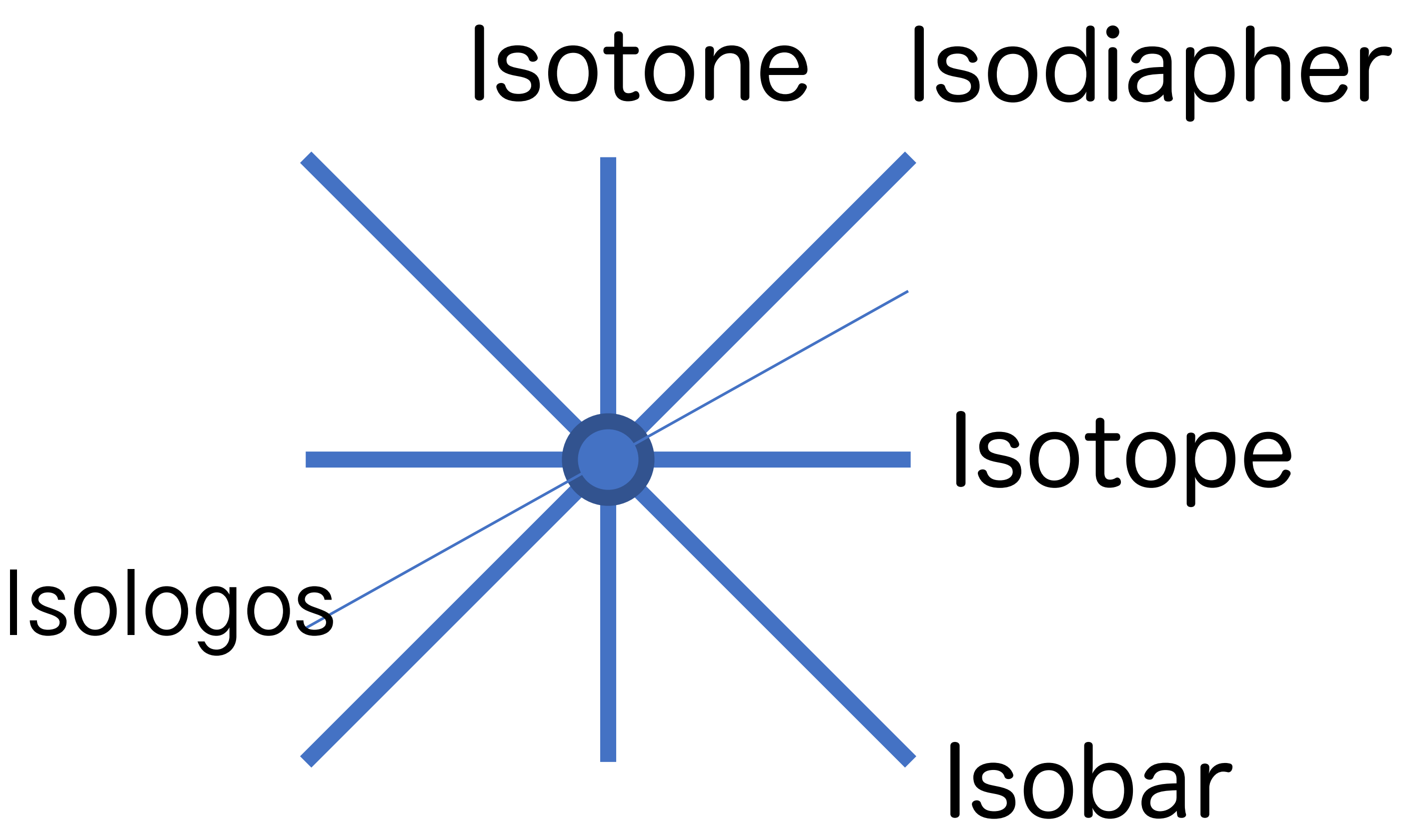
DAQ Upgrade in GRAND RAIDEN / LAS

- CAMAC-Based system, with which the trigger rate more than 5 kcps can be handled, is replaced with the VME-based system.
- VME modules that have multi-event buffer are employed.
- Live time ratio more than 80% is achieved even with the trigger rate of 50 kcps.
  - Of course, depending on the number of hits in the detectors and on what kind of data is stored.



Many nuclei are waiting for being measured its monopole.

Systemtics



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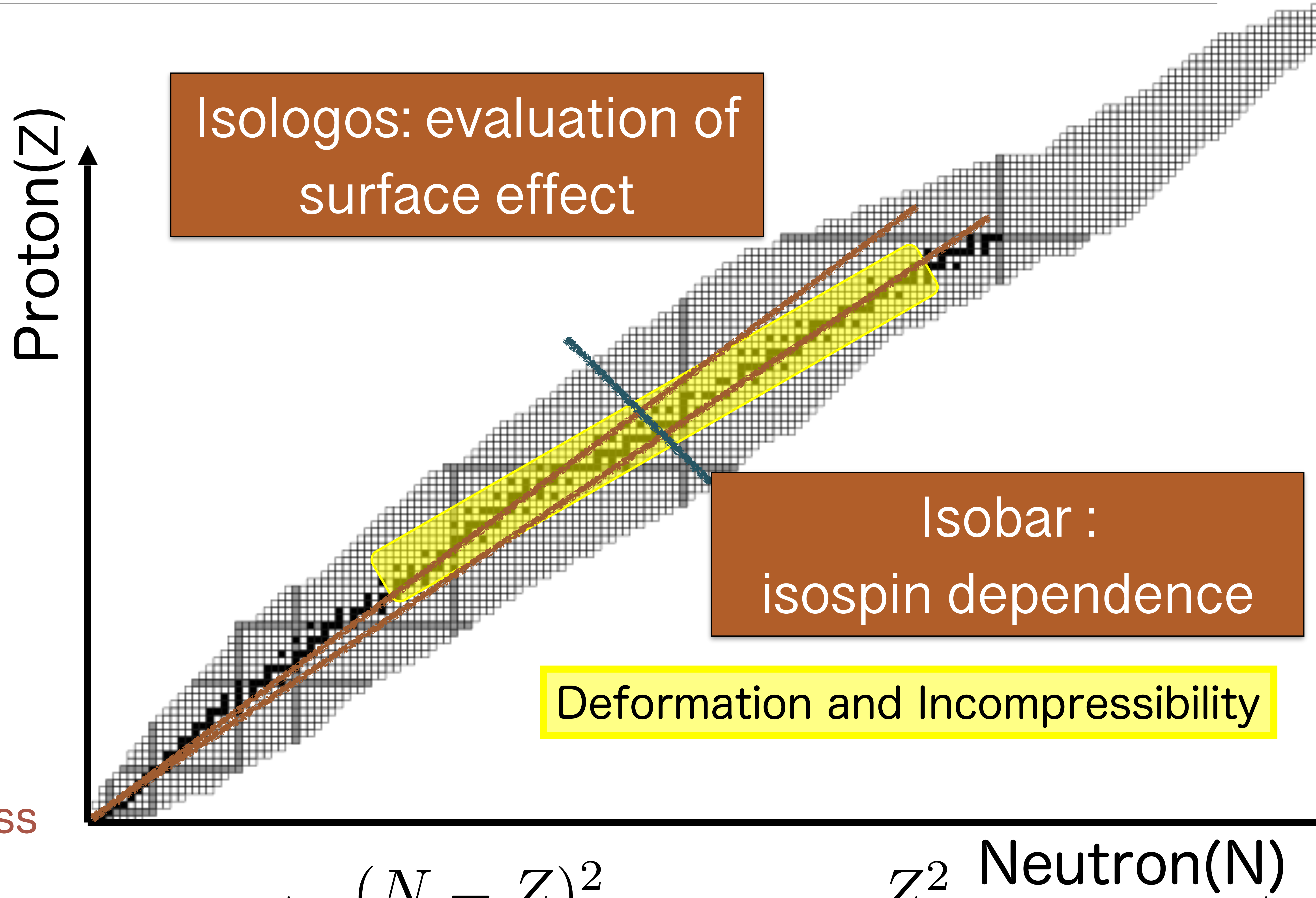

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Summary and Outlook

- Ktau value contains the information on higher order coefficients
- Experimentally deduced Ktau value or the systematically measured values of nuclear incompressibility will provide the robust reference to the theory
- To evaluate the Ktau value more accurately, the systematic measurement with various mass number is required.
  - CAT-M (+ other active targets in the world!!!) and GRAND RAIDEN
  - Systematic measurement along isobar chain with CAT-M and Isologos chain with GRAND RAIDEN will start
  - Connection between deformation and nuclear incompressibility should be discussed.
- Man power is needed! Please come to Japan and perform experiment!
  - Please make a contact !